The Fermi GeV-Excess and its Correlation with Molecular Clouds

Master’s Thesis of

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I declare that I have developed and written the enclosed thesis completely by myself, and have not used sources or means without declaration in the text.

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1. Introduction

In the 17th century Galileo Galilei invented the optical telescope, which was the basis for modern astronomy. In 1912 Victor Hess discovered that not only light but also cosmic rays penetrate the atmosphere. In 1923 Edwin Hubble proofed the existence of other galaxies besides the Milky Way with an optical telescope. Unfortunately for further studies, physicists were limited as they could not observe the sky in different wavelengths besides optical. In the years after Galilei, in particular in the 19th and 20th century, telescopes became better enabling researchers to study the sky in different wavelengths, which led to many discoveries developing astronomy. Nevertheless, telescopes and experiments were still bound to Earth so that the atmosphere prevented a unbiased view. In 1968, when humankind sent the first space telescope into Earth’s orbit namely the Radio Astronomy Explorer-A (RAE-A), a clear view on the universe was achieved for the first time. The RAE-A observed the sky in the radio regime [1]. In the years after, many more telescopes were sent above the atmosphere. Finally, the universe could be seen in before blocked wavelengths from the radio regime to the γ-regime. The latter is observed by Fermi-LAT, which is the main instrument of the Fermi Gamma-Ray Space Telescope, which orbits earth since 2008 collecting data of the γ-rays arriving earth from any direction.

Studying cosmic rays and radiation helps to understand what is happening in the galaxy and connects particle physics to astronomy and cosmology. Astro-particle physics links galactic and extra-galactic incidents and processes with well known particle physics. Basic γ-ray producing processes like π⁰-decay, inverse Compton scattering, bremsstrahlung, synchrotron emission, radioactive decay etc. are well understood. Observed γ-rays tell researchers about their origin and indirectly about the amount of stars, dust and gas, which leads to a deeper knowledge about the Milky Way, its structures and the physics of stars, supernovae and pulsars. The exact energy of observed γ-rays may indicate extra-galactic or exotic sources like Dark Matter annihilation and thus may lead to new physics. Studying γ-rays has an advantage over studying charged cosmic rays since the former are not deflected by the interstellar medium nor magnetic fields thus propagate in straight lines, which means that their arrival direction directly points back towards their source.

The Fermi collaboration measures the galactic γ-ray energy spectrum. This thesis is written to analyze the Fermi-LAT data focusing on the spectral composition and spatial distribution of the diffuse γ-rays reaching Earth. An excess of high energetic γ-rays in the galactic disk was discovered for the first time by the authors of [2]. The so-called Fermi GeV-excess is characterized by a shift of the maximum of the γ-ray spectrum towards 2 GeV and a hard high energy tail that could not be explained by standard propagation models, which only include the most common γ-ray producing processes: Bremsstrahlung, π⁰-production and inverse Compton scattering (see figure A.1 in the appendix). The excess
is either due to an unresolved detector effect or the consequence of real physics that was not taken into account by standard approaches. If the latter is true, the shift of the maximum can be explained either by a new γ-ray source whose spectrum peaks at 2 GeV or by a depletion of γ-rays below this energy. Possible sources peaking at 2 GeV are either Dark Matter annihilation [3] or millisecond pulsars [4] [5]. Dark Matter with a mass of around 50 GeV may annihilate into b-b-pairs that produce γ-rays during their decay. Therefore, several papers propose the Fermi GeV-excess stemming from Dark Matter annihilation motivated by the excess having a morphology like a NFW-profile in latitude, which is assumed to describe the Dark Matter distribution in the Milky Way and its halo. However, the excess is not spherical as expected from a Dark Matter signal but distributed along the galactic disk. The second possible source are millisecond pulsars, which are fast rotating neutron stars emitting γ-rays whose spectrum also peaks at 2 GeV [4] [5].

For excess studies common approaches use spatial templates of the gas distribution and the interstellar radiation field to calculate γ-ray emission, which are fraught with uncertainties especially in the galactic disk thus are not suitable to describe the disk properly. Besides, previous works applied a new spectral template fit to the data [6] [7] [8]. A spectral template fit uses spectral templates of the energy spectrum of the standard γ-ray producing processes π0-decay, inverse Compton scattering and bremsstrahlung, which eliminates the need of the poorly known spatial templates, and can add spectral templates at will. The spectral templates then can be fitted to the data. So, they showed that neither Dark Matter annihilation nor millisecond pulsars can explain the GeV-excess properly indicated by bad fits in the disk. Instead, they proposed that the first hallmark of the GeV-excess, a shift of the maximum in the γ-ray spectrum towards 2 GeV, stems from a depletion of low energetic γ-rays from molecular clouds (MC) due to a suppressed π0-production by low energetic protons in MCs and the second hallmark, the hard high energy tail, stems from hard γ-rays produced in sources by the hard proton injection spectrum. Introducing two new spectral templates corresponding to these effects can describe the excess. Standard propagation models do not consider these contributions.

This thesis attempts to further improve the fit quality building up on previous works [6] [7] [8]. A recent paper for the first time ever gives theoretical support of the before phenomenologically described suppressed π0-production in molecular clouds. The authors of the paper theoretically deduce that the diffusion coefficient changes in molecular clouds, which changes the spectral index of the cosmic ray spectra below a certain energy. This spectral index is impressively near the spectral index that was obtained from data by the authors of [7] before and which they used for the molecular cloud template. In this thesis the published theoretical predictions for cosmic ray propagation within molecular clouds are applied to the molecular cloud template that therefore is changed slightly. Since previous works only applied the effect of molecular clouds to cosmic ray protons but not to cosmic ray electrons although there is no reason why electrons should behave differently than protons, an additional spectral template referring to bremsstrahlung within molecular clouds is freshly introduced to the fit following the theoretical predictions. As the fit is extended by one degree of freedom the fit quality can be further improved. Introducing an additional template with regard to inverse Compton scattering within molecular clouds does not improve the fit.
Furthermore, the amount of templates referring to bremsstrahlung in the diffuse interstellar medium is increased. As cosmic ray electrons suffer strong energy losses during propagation it is plausible that electrons have a different energy spectrum everywhere in the Milky Way. Before, the spectral fit was only offered a single bremsstrahlung template that was derived from a single electron spectrum. Therefore, more bremsstrahlung templates derived from different electron spectra are introduced to the fit in this thesis, too.

This thesis is organized as following. In chapter 2 the theoretical background is provided including general properties of the Milky Way and its structures, cosmic ray origin and propagation, used cosmic ray spectra and γ-ray production. Chapter 3 gives a overview over the Fermi data, binning and the fit algorithm as well as technical challenges. The results are presented in chapter 4 including detailed analysis of the spectral composition of the Fermi γ-ray sky and its spatial distribution. Additionally, exemplary spectra of selected regions of the sky are shown including a special focus on the Fermi bubbles and its spectra as well as the correlation between the spectral templates. Eventually, the results are summarized and concluded in chapter 5, which also contains an outlook on further studies.
2. From Cosmic Ray Sources to diffuse Gamma-Rays

This chapter provides the theoretical basis of this thesis required for the understanding of the results. Firstly, in section 2.1 an overview over our galaxy the Milky Way is given including the most important structures and properties. The Milky Way is not only a huge conglomerate of stars, planets, gas and dust but also contains sources for cosmic rays (section 2.2). During propagation the cosmic rays are scattered and interact with matter and radiation, thus suffer energy losses, which are examined in section 2.3. Hence, cosmic rays of different energies exist in the galaxy, which can be described by the energy spectra that are introduced in section 2.4. Eventually, the cosmic rays produce \( \gamma \)-rays by several processes well known from particle physics (section 2.5).

2.1. The Milky Way - General Properties and Structures

The Solar System including the Sun and the Earth is located in the Milky Way, which is a barred spiral galaxy and disk-shaped. The gas disk of the Milky Way has a diameter of around 30 kpc and the galactic disk is around 1 kpc thick [9]. The Solar System lies within the galactic disk around 8 kpc from the Galactic Center, hence, seen from Earth the Milky Way looks like a narrow band, which sometimes is visible by eye in the night sky. As skymaps and spectra in this thesis are interpreted in the light of the galaxy’s main structures and compositions a short overview of the Milky Way is necessary for the understanding of the analysis and is provided in the following.

• **Spiral Arms:** Being a spiral galaxy the Milky Way consists of several spiral arms radiating from the galactic bar and the central bulge. The two major spiral arms of the Milky Way are the Scutum-Centaurus Arm and the Perseus Arm tangent the galactic bar. Besides the two major arms two minor arms are worth mentioning namely the Carina-Sagittarius Arm and the Orion-Cygnus Arm. Latter is where the Solar System lies within. Crossing large parts of the line-of-sight for certain fields of view the spiral arms are supposed to be visible in the skymaps by enhanced \( \gamma \)-ray flux from this direction due to enhanced gas density and radiation field intensity, which are described hereafter.

• **Gas Component of the Interstellar Medium:** The space between stars is filled with diffuse or dense gas and dust, which belongs to the interstellar medium (ISM). Interstellar gas is mainly made up of hydrogen being the most abundant element in the universe. In diffuse regions hydrogen appears atomic (HI). In molecular clouds, which are the densest regions of the ISM, hydrogen is molecular (H\(_2\)) because only
there the number density is high enough for hydrogen atoms to form molecules catalyzed by dust grains. Molecular and atomic hydrogen is often referred as cold and neutral gas whereas hot ionized hydrogen (HII) occurs in regions associated with hot stars and supernovae. Gas and dust is relatively bound to the galactic disk and only found up to altitudes of a few hundred parsec above the disk. An overview over the hydrogen distribution in the galaxy can be obtained from figure 2.1a. The ISM is strongly not homogeneous thus the gas and dust composition differs for every field of view.

Furthermore, in 2010 the Fermi collaboration discovered two large-scale structures above and below the galactic disk emitting high energetic $\gamma$-rays. The so-called Fermi bubbles are not yet fully understood but often referred to be a convective outflow from the densest parts of the galactic disk, thus may contain gas and dust, too.

- **Molecular Clouds:** Cold and dark molecular clouds (MCs) are dense gas clouds strongly bound to the galactic disk that are continuously gaining mass due to their gravitational potential and mainly composed of molecular hydrogen. However, even more complex molecules like CO are also found within molecular clouds. MCs have number densities of $n = 10^4 - 10^7 \, \text{cm}^{-3}$ and bind 40% [10] of the gas. CO is the second most abundant molecule within molecular clouds ($n_{\text{CO}}/n_{\text{H}_2} = 10^{-4}$) and emits millimeter wavelength photons if it is de-excited by collisions with H$_2$. The CO radio-emissivity is assumed to be proportional to the MC column density and is useful to map the molecular cloud distribution. This is necessary as MCs are not transparent for UV-starlight hence can only be detected indirectly by radio detection of CO molecules that therefore trace molecular clouds. MCs are generally associated with less dense diffuse envelopes ($n = 10^1 - 10^3 \, \text{cm}^{-3}$), which play a role in cosmic ray propagation within MCs [11], [9].

Dense molecular clouds are interesting objects in astrophysics and one of the main aspects of this thesis since MCs are star forming regions: Once a molecular cloud is dense enough it collapses and forms a star by initializing the nuclear fusion process inside. As dense molecular clouds are located within the spiral arms and the galactic bar these regions are where most of the stars are found, consequently. During a star’s life cycle it permanently emits photons into the interstellar medium where they either can be absorbed and re-emitted by enclosed gas and dust or interact with charged cosmic rays. Thus, UV- and IR-emission is most likely observed in the spiral arms and the galactic bar, too. At the end of a star’s life cycle the nuclear fusion process stops and the star, under certain circumstances, becomes a supernova, which creates lots of high energetic particles including protons and electrons and injects them into the ISM where they propagate as charged cosmic rays. If a dying star becomes a pulsar, it even continues producing electrons and positrons. Hence, stars act as sources for ISRF-photons during their life cycle and for cosmic rays at the end of their life cycle, which underlines the importance of MCs.

- **Interstellar Radiation Field:** The interstellar radiation field (ISRF) is present whole over the galaxy and contains photons mainly stemming from three sources:
2.2. Sources of Cosmic Rays

Both the galactic bar and the spiral arms contain billions of celestial objects, in particular stars which are continuously emitting photons with a wide rage in wavelength. The energy spectrum of that photons is similar to a black body spectrum. As claimed by Wien’s displacement law the wavelength of maximum emission depends on the star’s surface temperature and is most likely supposed to lie in the ultraviolet (UV) range. If interstellar gas and dust absorbs starlight, it will be re-emitted isotropically during de-excitation with a longer wavelength thus lies in the infrared (IR) range. The intensity of both starlight and dust emission decreases with distance from the source squared as the total flux through a spherical surface is constant. Therefore, UV and IR radiation only significantly contributes to the ISRF within the galactic disk because stars, dust and gas are bound to the galactic plane whereas photons of the cosmic microwave background (CMB) are isotropic in the whole universe and in the Milky Way, consequently. Hence, CMB photons are the dominant contributor to the ISRF outside the galactic disk. A compilation of the ISRF is given in figure 2.1b.

The ISRF is strongly non-homogeneous. Starlight, dust emission and CMB are the major components of the interstellar radiation field whose relative contributions differ for every field of view.

- **Magnetic Fields**: According to electrodynamics moving charged particles create electromagnetic fields. Since the Milky Way consists of ionized gas (plasma) and propagating charged cosmic rays strongly non-homogeneous and turbulent magnetic fields are found everywhere in the the galaxy. Additionally, rotating stars, pulsars and other celestial objects generate magnetic fields. Therefore, a complex electromagnetic field is present all over the Milky Way in any scales where charged cosmic rays are permanently scattered off.

2.2. Sources of Cosmic Rays

As discovered by Hess cosmic rays mainly made up of protons stemming from galactic and extra-galactic sources penetrate the Earth’s atmosphere. Ground based experiments measured cosmic ray’s energies extending up to EeV-range, which is above the highest energy reachable with man made experiments. Therefore, huge celestial incidents are necessary to accelerate particles to such energies. Most of the cosmic rays originate from sources in the Milky Way. However, for the highest energies one needs to consider extra-galactic sources like active galactic nuclei (AGN). Though, in this thesis AGN are negligible as such high energies are not of interest in this thesis.

Within the Milky Way there are several sources for cosmic rays that may contribute to the diffuse γ-ray spectrum in the galaxy by its interactions. Sources are solar flares and supernovae but also exotic sources like Dark Matter (DM) annihilation [3] and millisecond pulsars [4] [5] are conceivable. The latter are fast rotating neutron stars that emit γ-rays with an energy spectrum that peaks at around 2 GeV making millisecond pulsars a possible source for the GeV-excess. The author of [8] has already studied the ability of pulsars to explain the Fermi GeV-excess and found no relevance. Therefore, pulsars are also neglected in this thesis. Furthermore, Dark Matter annihilation is of interest in this thesis.
Figure 2.1.: **Interstellar Hydrogen Distribution and Interstellar Radiation Field.** (a) Radial distribution of the molecular (red), atomic (blue) and ionic (green) component of hydrogen along the galactic disk. The solid colored lines correspond to different altitudes above the gactic disk where the upper is 0 kpc, the middle is 0.1 kpc and the lower is 0.2 kpc. The figure is taken from [12]. (b) Components of the ISRF where A is the radio radiation, B is the CMB, C is the IR radiation, D is the UV radiation and E is the x-ray radiation. Figure taken from [9].

neither since previous works showed that the Fermi GeV-excess is not described by DM annihilation properly, although DM may annihilate into $b\bar{b}$-pairs, which create $\gamma$-rays during their decay. Gamma-rays from annihilation of DM with a mass of around 50 GeV also peak at 2 GeV. [8] [7].

A star produces energy by a nuclear fusion process inside that starts when a dense molecular cloud collapses freeing enough energy to fuse two protons to deuterium. In the beginning hydrogen is burnt to helium. If a star is massive enough, heavier elements are created by fusion of helium, carbon etc. later. Depending on the star’s mass all elements up to nickel may be created in several shells with iron as the heaviest element in the center. Heavier elements than nickel can not be produced by an exothermic nuclear fusion. At the end of a star’s life cycle the nuclear fusion process inside stops due to a lack of fuel (burnable elements lighter than nickel). Light stars with a mass comparable to the Sun’s mass then drop their shell and become a white dwarf. For heavier stars, the outward directed thermal and radiation pressure is no longer capable of opposing the inward directed gravitational pressure resulting in a collapse of the inner core of the star that initializes a supernova. Depending on its mass the dying star either becomes a neutron star or a black hole, which remain in the center, whereas the shells is pushed away. By
accumulating additional mass a white dwarf also can become a supernova. In this case, after the explosion nothing remains in the center.

A supernova is initialized by a core collapse, which immediately stops due to degeneracy pressure and rebounds to the opposite direction facing the infalling matter of the shell. This results in an enormous shock wave propagating outside that carries the star’s shell away and produces high energetic particles as well as heavier elements than nickel. Therefore, former stars are surrounded by an expanding envelope called supernova remnant (SNR).

In a SNR particles gain kinetic energy by a diffuse shock wave acceleration process often referred as first order Fermi acceleration. Already accelerated charged particles that enter an expanding shock wave like a SNR are repeatedly reflected on magnetic turbulences within the SNR thus gain energy with every scattering. Because of this process charged particles are trapped within the shock wave while increasing velocity. Cycling through the shock wave particles not only gain energy but also suffer energy losses by interacting with matter they are colliding with hence produce pions with a high probability. Scattering on matter decreases the particle’s velocity again but as long as its energy is above a certain limit the acceleration process continues. The higher the particle’s velocity the higher the probability that particles are able to escape the shock wave. It can be shown that the resulting energy spectrum of freshly accelerated cosmic rays in an expanding shock front is a power law

\[ \frac{\text{d}N(E)}{\text{d}E} \propto E^{-\gamma} \]  

with spectral index \( \gamma \approx 2.1 \) [13]. A similar re-acceleration process occurs when charged particles enter a moving cloud, which is called second order Fermi acceleration.

During a supernova magnesium rich stars can produce \(^{26}\text{Al}\), too, by proton capture of \(^{25}\text{Mg}\). The radioactive \(^{26}\text{Al}\) isotope then decays via inverse \(\beta\)-decay or K-capture into excited \(^{25}\text{Mg}\) that emits a characteristic 1.8 MeV photon to reach ground state. Hence, this emission line traces cosmic ray sources in form of supernovae [14].

\[ ^{25}\text{Mg} + p^+ \rightarrow ^{26}\text{Al} \rightarrow ^{25}\text{Mg}^* + X \rightarrow ^{25}\text{Mg} + \gamma + X \]  

\[ (2.2) \]

### 2.3. Propagation and Energy Losses

Once they are injected to the ISM cosmic rays propagate through the galaxy. The charged cosmic rays, this thesis focuses on protons and electrons, interact with the ISM, ISRF and cosmic magnetic fields thus change their propagation direction while suffering energy losses. Being repeatedly scattered on matter, photons and electromagnetic fields charged cosmic rays perform somehow a random walk through the galaxy. Therefore, the arrival directions of charged cosmic rays not only never point back to the cosmic rays’ origin but also are isotropic, even. Lately, the author of [15] indeed found no anisotropy in the arrival direction of charged cosmic rays. This fact emphasizes the importance of \(\gamma\)-ray
studies since γ-rays travel through the galaxy in straight lines, thus their arrival direction directly points back to their origin.

2.3.1. Propagation Model

Cosmic ray propagation is a diffusion process and can be described by the diffusion equation

\[
\frac{\partial N}{\partial t} = q + \nabla \cdot (D \nabla N) - \frac{\partial}{\partial t}(bN) - (n v \sigma + \frac{1}{\tau})N + \sum_j (n v \sigma_j + \frac{1}{\tau_j})N_j \tag{2.3}
\]

where \( N = N(t, x, E) \) is the number density of a cosmic ray species and function of time \( t \), position \( x \) and energy \( E \). The source term \( q \) describes the spectrum of cosmic rays production, \( \nabla \cdot (D \nabla N) \) is the diffusion term with diffusion coefficient \( D \) that determines the diffusion timescale, \( -\frac{\partial}{\partial t}(bN) \) is the energy loss time term, \( -(n v \sigma + \frac{1}{\tau})N \) corresponds to the particle losses via inelastic scattering on the ISM with density \( n \), velocity \( v \) and cross section \( \sigma \) and via radioactive decay with lifetime \( \tau \) (this term is negligible for protons and electrons since they are stable), \( \sum_j (n v \sigma_j + \frac{1}{\tau_j})N_j \) corresponds to the particle gains by inelastic scattering and decay of heavier nuclei. [16]

Cosmic Rays are produced in sources, which are mainly located in the spiral arms and the galactic bar, whereas cosmic ray production vanishes in the outer regions of the galaxy. Hence, one expects a spatial gradient of cosmic ray density that leads to a particle diffusion with a certain diffusion coefficient. If the diffusion coefficient is small, particles will need longer to escape their origin region. The galactic disk in general is a small diffusion coefficient region.

The particle’s rigidity \( R \) is a measure of its ability to resist the influence of magnetic fields. Given that both have the same rigidity the paths of protons and electrons are bent the same. However, as electrons faster lose energy than protons their rigidity faster decreases. As the diffusion coefficient is energy-dependent, electrons have shorter propagation lengths than protons. Thus, it is plausible that the electron spectrum differs at every point in the galaxy.

In contrast, cosmic ray protons do only suffer marginal energy losses due to their around 2000 times higher mass leading to a long propagation length. Because of this it is well reasoned that one assumes protons to have a similar spectrum in the entire galaxy.

As mentioned in equation 2.1, cosmic rays are injected to the ISM with a hard \(-2.1\) spectrum. During propagation the spectrum softens due to several processes. For protons energy losses are negligible but as they have a long propagation length their probability to escape the galaxy enhances with energy. High energetic protons leaving the galaxy more likely than low energetic protons leads to a depletion of the former compared to the latter. Hence, the proton spectrum softens.

For electrons, galaxy escaping is less probable due to their short propagation length. Nevertheless, as for protons the energy spectrum of electrons softens during propagation. In contrast, the softening occurs due to fast energy losses, which are described hereafter.
2.3. Propagation and Energy Losses

As introduced in the diffusion equation 2.3, a term corresponds to the energy loss times of charged cosmic rays. There are several processes that reduce the particle’s energy during propagation. Every time a charged particle is scattered on matter of the ISM or photons of the ISRF it loses energy. Charged particles also lose energy via synchrotron radiation.

- **Ionization and Coulomb Losses:** Cosmic rays see interstellar gas while propagating through the galaxy. Particles collide with atomic or molecular gas that then becomes excited or ionized by absorbing a small part of the particles energy. In equation 2.4 $CR$ is a cosmic ray and $CR'$ is the same particle with different energy.

$$CR + H_2 \text{ resp. HI} \rightarrow CR' + H_2^* \text{ resp. HI}^* \quad (2.4)$$

An excited atom or molecule that re-reaches ground state emits a photon, the same holds for recombining ions. However, in case of hydrogen emitted photons carry an maximal energy of 13.6 eV, which is way to low to be recognized by Fermi-LAT. Hence, these photons do not contribute to the diffuse γ-ray spectrum in the galaxy. If the fraction of lost energy compared to the particle’s kinetic energy is large, ionization and coulomb losses are efficient energy loss processes. Ionization and Coulomb losses are the dominant energy losses of cosmic rays if they are the fastest energy losses, which is true for low energetic cosmic rays.

- **Bremsstrahlung:** If charged cosmic rays pass a coulomb field of another charged particle (free electrons, ionized hydrogen, charged cosmic rays) it may lose energy via bremsstrahlung by emitting a photon. In equation 2.5 the $e^-$ is an electron and $e^-'$ is the same electron with different energy.

$$e^- + p^+ \rightarrow e^-' + p^+ + \gamma \quad (2.5)$$

Hence, in presence of electric fields, in particular in hot HII-regions, cosmic rays are decelerated. Bremsstrahlung significantly contributes to the diffuse γ-ray spectrum measured by Fermi-LAT. Bremsstrahlung depends inversely on the projectile’s mass, thus is negligible for protons due to their large mass but is strongly relevant for electrons and nearly independent on their energy.

- **Synchrotron Radiation:** Charged cosmic rays that are deflected by magnetic fields perform gyration thus emit photons, which carry energy away. The naming is as in equation 2.5.

$$e^- \rightarrow e^-' + \gamma \quad (2.6)$$

Synchroton radiation losses increase with the particles momentum but are also negligible for protons due to their larger mass.
2. From Cosmic Ray Sources to diffuse Gamma-Rays

- **Inverse Compton Scattering**: On their way through the galaxy, cosmic ray electrons not only see matter and magnetic fields but also meet photons of the ISRF. Scattering between low energetic photons and high energetic electrons leads to an energy transition from the latter to the former. In equation 2.7 $e^- (\gamma)$ is an electron (photon) and $e^-' (\gamma')$ is the same electron (photon) with different energy.

$$e^- + \gamma \rightarrow e^-' + \gamma'$$

(2.7)

While electrons lose energy photons reach the energy range that can be recognized with Fermi-LAT. An photon with energy $h\nu$ that is scattered off an electron with velocity $v$ increases its energy to $E_\gamma$ where

$$E_\gamma \approx \gamma^2 h\nu \text{ for } q \ll 1$$
$$E_\gamma \approx \gamma m_e c^2 \text{ for } q \gg 1$$

(2.8)

and $\gamma = \frac{E_e}{m_e c^2} = 1/\sqrt{1 - \frac{v^2}{c^2}}$ and $q = \frac{y h\nu}{m_e c^2}$ [9]. Inverse Compton scattering and synchrotron radiation is the dominant energy loss process for the high energy region.

Since all processes mentioned above occur simultaneously it is reasonable to give the energy loss times shown in figure 2.2. The energy loss time is defined as the duration it takes for a charged particle to lose so much of its energy, that it only carries $\frac{1}{e}$ of its initial energy any more. For protons the energy loss time is basically given by the ionization and coulomb losses, as they are the only relevant processes. For electrons, the energy loss time is calculated as the inverse sum of the relevant processes.

As can be seen in figure 2.2 the total energy loss time of electrons computed for an average gas density has a maximum at $\approx 0.1 \text{ GeV}$, which approximately corresponds to the energy where ionization resp. coulomb losses equal inverse Compton resp. synchrotron losses, and shows asymptotic properties above and below the maximum (in the following referred as slope). As each individual energy loss process depends on the target density (bremsstrahlung, ionization resp. coulomb and IC), which is hardly homogeneous in the galaxy, the individual energy loss times must be re-scaled for a given field of view. In particular the energy loss times are supposed to differentiate between within the galactic disk and outside but even within the disk the energy losses are hardly identical everywhere. By re-scaling each energy loss time one will obtain different maximums and slopes for the total energy loss time. In a region where the gas density is larger than average bremsstrahlung and ionization resp. coulomb loss times will be down-scaled leading to a shift of the maximum of the total loss time towards higher energies. Simultaneously, the fraction of bremsstrahlung becomes more relevant. Therefore, the slope of the total energy loss time will become more energy independent below the maximum because it approaches asymptotically to the dominant individual loss time. In the following, this fact is used to motivate the galactic electron spectra.
2.4. Cosmic Ray Spectra

In this thesis a spectral template fit is performed to analyze the Fermi data by fitting seven γ-ray energy spectra (templates) corresponding to the three standard γ-ray producing processes π⁰-production and -decay, bremsstrahlung and inverse Compton scattering to the data. Details are provided in chapter 3.

The γ-ray templates are derived from energy spectra of cosmic ray protons and electrons, which are the projectiles. Gamma-rays are produced everywhere in the galaxy but unfortunately physicists do not know the exact proton and electron spectra at every point in the galaxy, thus they need to argue. Hence, the simplest approach possible is done by describing the cosmic ray spectra with broken or unbroken power laws either following recent theoretical predictions or motivated by the local measured flux or determined in an iterative data-driven way. The authors of [7] previously motivated cosmic ray spectra or determined them in an iterative data-driven way: They found exactly those cosmic ray spectra that lead to the templates that optimally describe the data. Firstly, they chose electron spectrum to calculate the templates from. Then, they performed a fit. Afterwards, they slightly changed the spectrum and repeated the procedure until the electron spectrum leading to the best fit results was found. The same was done for a broken proton spectrum. The resulting spectra are presented in the following as well as changes that were applied in this thesis.

**Interstellar Proton Spectrum**: The parametrization of the proton spectrum was motivated. Since protons have a large propagation length due to negligible energy losses a single interstellar proton spectrum is assumed to be the same at every point in the galaxy. In particular, the local measured proton flux at Earth is assumed to be representative for the whole galaxy.
2. From Cosmic Ray Sources to diffuse Gamma-Rays

Figure 2.3.: **Proton and Electron Spectra.** Proton resp. electron spectra used for calculation of the γ-ray spectrum templates. Blue dots are the local proton resp. electron spectrum measured by AMS-02. The yellow (cyan) solid lines represent the low rigidity part of the broken power law used for protons (electrons) within molecular clouds for breaks between 14 GV and 4 GV and spectral index $-1.0$ below the break as predicted by [11]. The high rigidity part remains unchanged compared to the interstellar spectra. (a) The red solid line represents the interstellar propagated proton spectrum, which well describes the data above 45 GV. The spectral index $-2.849$ is obtained by the AMS-02 collaboration [17]. The pink solid line corresponds to the spectrum of freshly accelerated protons in sources resulting in a power law with spectral index $-2.1$. The spectra are normalized at around 50 GV. (b) The green solid line is the electron spectrum with break at 0.2 GV and spectral index $-0.81$ below used for calculation of the IC template only. Break position and spectral index below the break is the same as in [8]. The spectral index $-3.21$ of the high rigidity part is in good agreement with the one obtained by the AMS-02 collaboration and describes the data well above 10 GV [18].

The AMS-02 collaboration measured the local proton flux, which can be obtained from figure 2.3a. Despite the AMS-02 collaboration uses a different parametrization, the local measured proton flux can be approximated with an unbroken power law with spectral index $-2.849$ for rigidities between 45 GV and 300 GV. This index corresponds to a softer spectrum than the $-2.1$ source spectrum matching the expectation since protons can leave the galaxy if their rigidity is high enough to oppose a strong bending of their propagation direction, which softens the spectrum. Thus, the local measured proton spectrum is assumed be representative for the whole galaxy and a good choice for the interstellar propagated spectrum.
2.4. Cosmic Ray Spectra

Figure 2.4. Electron Spectra for BR. Electron spectra (blue solid lines) used for calculation of the γ-ray spectrum template of bremsstrahlung (BR) only. Pink dots are the local electron spectrum measured by AMS-02 [18]. (a) Shown are the spectra with exemplatory spectral index $-1.2$ below the break for all possible break positions (see table 2.1). (b) Shown are the spectra with exemplatory break at 1.6 GV for all possible spectral indexes below the break (see table 2.1). Note that all slopes are possible for all breaks. The spectral index $-3.21$ above the break is in good agreement with the one obtained by AMS-02 collaboration [18] and describes the data well above 10 GV.

Below 45 GV the local proton flux is suppressed due to solar modulation. Above 300 GV a spectral hardening is observed, which is not yet well understood. Most promising approaches link the hardening of the proton flux with a local source or a modification in propagation. The former would only be a local feature and thus is negligible for a spectrum that has to be representative for the whole galaxy, the latter only occurs for high energy protons. Since these protons above 300 GV produce γ-rays that only contribute with a small fraction in the energy range relevant for Fermi-LAT, the spectral hardening in the local proton spectrum is negligible, too. Therefore, both solar modulation and the hardening are not taken into account for the proton spectrum that is defined as an unbroken power law $\Phi_p(R) \propto R^{\alpha}$ with spectral index $\alpha = -2.849$.

Interstellar Electron Spectra: In previous works the electron spectrum has been determined in an iterative data-driven way by testing a set of broken and unbroken power laws. They found that the interstellar energy spectrum of electrons modeled by a broken power law with spectral index $\alpha$ below and $\beta$ above the break at rigidity $R_0$. 

\[ R^2 \Phi_e(R) \propto \begin{cases} R^{\alpha} & \text{if } R < R_0 \\
R^{\beta} & \text{if } R \geq R_0 \end{cases} \]
\[ \Phi_e^-(R) = \Theta(R_0 - R)BR^\alpha + \Theta(R - R_0)AR^\beta \]
\[ = \Theta(R_0 - R)AR^{\beta - \alpha}R^\alpha + \Theta(R - R_0)AR^\beta \] (2.9)

best describes the data. \( \Theta(R) \) is the Heaviside step function and the second line follows from the first line if \( \Phi_e^-, \text{below}(R_0) = \Phi_e^-, \text{above}(R_0) \). This approach is admittedly simple as it takes a smooth transition between the two power laws not into account. The authors of [7] obtained an break at 1 GV and spectral indexes \(-0.81\) below and \(-3.21\) above from the data to lead to the best fit whereas the author of [8], who could use the latest data with more statistics, found the best break position at 0.2 GV.

A broken power law might be related to the in section 2.3.2 mentioned energy loss times. The total energy loss time of electrons has a maximum at a certain energy depending on the strength of the individual energy losses (0.1 GeV in this calculation, see figure 2.2). The maximum indicates the energy at which electrons lose energy the slowest whereas at any other energy electrons lose energy faster leading to a suppression of electrons above and below the maximum’s energy, which might result in the broken energy spectrum obtained from the data. Additionally, the energy loss time of low energetic electrons is dominated by different processes (ionization resp. coulomb losses) than the energy loss time of high energetic electrons (sychrotron resp. inverse Compton losses), which supports the assumption that the electron spectrum can be described by a broken power law since a break in energy spectra often refers to a change in underlying physics (for instance the hardening in the local proton spectrum or the ankle and knee in the cosmic ray spectrum).

In previous works only one single electron spectrum was used to calculate \( \gamma \)-ray templates from, which is questioned in this thesis because, as described in section 2.3.1, electrons have smaller propagation lengths than protons. The energy losses individual electrons suffer depend on the exact composition of the ISM and ISRF at their local area. Since the energy losses determine the hardening of the source spectrum below and the softening above the break and since the ISM and the ISRF is not homogeneous the electron spectra in the galaxy hardly are. Therefore, it is well reasoned that electrons have different spectra everywhere in the galaxy. Thus, in this thesis electrons are modeled by different parametrizations of the energy spectrum.

Previous works indeed tested a set of parametrizations of the electron spectrum but they applied it to the data of the whole sky. Therefore, one needs to find a satisfying approach with respect to different electron spectra existing simultaneously. In this thesis instead, a set of templates calculated from several electron spectra is offered to the fit, which then decides which template fits best in every field of view independently. In the following different electron spectra are motivated.

The spectral index above the break was found to be \(-3.21\), which is in good agreement with the data of the local electron flux at Earth for \( R > 10 \text{ GV} \) measured by AMS-02 [18]. The local electron flux is shown in figure 2.3b. However, only the local electron flux is known that not necessarily represents a global spectrum as reasoned above. Nevertheless, the spectral index \(-3.21\) above the break was chosen to be identical in each electron
spectrum. This is motivated by the fact that above a certain energy inverse Compton and synchrotron losses definitely will dominate the total energy loss time. If one assumes that the energy losses determine the slope of the electron spectrum and the energy losses for high energetic electrons are similar despite inhomogeneous magnetic fields and ISRF, the local electron spectrum will be similar to all electron spectra for the highest energies at least.

Local electrons below 10 GV are suppressed due to solar modulation, which is not taken into account for interstellar spectra. Nevertheless, one expects a similar depletion of low energetic electrons as of high energetic electrons because of bremsstrahlung and ionization resp. coulomb losses, which presumably determine the slope below the break. If one looks at the energy loss times for electrons in figure 2.2, one will agree that re-scaling the individual energy loss times leads to a shift of the maximum of the total energy loss time and a change in slope below. As exact energy losses are poorly predictable, an amount of spectral indexes below the break as well as various break positions are used in this thesis, therefore, namely indexes $\in (-0.1, -0.4, -0.6, -0.81, -1.0, -1.1, \ldots, -1.9)$ and breaks $\in (0.1, 0.2, 0.4, \ldots, 1.2, 1.6)$ given in GV. Admittedly, the spectral indexes below the break as well as the break position are somehow arbitrary. Additional breaks and spectral indexes were not used to avoid strong correlations between the individual spectra. The final set of broken power laws used as electron spectra is shown in figure 2.4.

Note that all electron spectra are simplified in two features: First, the high energy index is assumed to be equal in every direction. Second, the description of the electron spectrum with a broken power law only is an approximation as a smooth transition between the two indexes would probably describe the reality much better. As this thesis is phenomenological and attempts to give a propose for further interpretations the assumed broken spectrum must be good enough. At least, the grid of break points and slopes below the break is nearer the reality than the fixed break and index below that was used in previous works.

**Molecular Cloud Spectra:** The Fermi GeV-excess that is characterized by a shift of the maximum of the $\gamma$-ray spectrum towards 2 GeV is either a detector effect, a real excess explained by considering an additional $\gamma$-ray source that peaks at around 2 GeV or a depletion of low energetic $\gamma$-rays. The latter has been tested previously by introducing an additional proton spectrum modeled by a broken power law that implies suppression of low energetic protons. [6] [7] [8]

As the Fermi GeV-excess is strongest in the Central Molecular Zone (CMZ), a region rich in dense molecular clouds containing 5% of the total galactic gas [19] [20], the excess might be related to molecular clouds. Possible additional sources are millisecond pulsars [4] [5] or Dark Matter annihilation [3]. Both have been studied lately and were found to not provide as good fit results as the molecular cloud hypothesis [7] [8]. Therefore, previous works obtained the parametrization of the new broken proton spectrum from the data of the CMZ in an iterative data-driven way [6] [7]. They found a broken power law with break at 13 GV and a spectral index $-0.7$ below the break provides the best fit. The spectral index above the break remained unchanged in comparison to the interstellar propagated proton spectrum.
A break in the proton spectrum might be linked to a modified cosmic ray propagation within dense molecular clouds that leads to a suppression of low energetic protons. Possible explanations are either energy losses similar to solar modulation observed in the local proton spectrum, proton-proton collisions, ionization or magnetic effects [11]. Energy losses alone could hardly explain a sharp decrease of the proton flux below a certain energy but a magnetic cutoff can. The suppression of low energetic protons can be motivated by a magnetic cutoff similar to the geomagnetic cutoff: As the particle’s gyroradius directly depends on its rigidity cosmic rays with rigidities below 20 GV entering earth’s magnetic field are repelled into space indicated by a sharp break in the spectrum. Given that molecular clouds contain magnetic dipole fields the authors of [7] proposed a similar effect for cosmic rays in molecular clouds. It is plausible that magnetic fields in molecular clouds prevent low energetic protons to penetrate the dense cores whereas the paths of high energetic protons are bent less, though, which could be the reason for an unchanged spectral index above the break. Then, the break position would be dependet on the size of MCs and the strength of their magnetic fields, which increases with density. Indeed, break positions between 13 GV and 6 GV were obtained from different clouds whereas the fit prefers a uniform spectral index $-0.7$ below the break for all clouds, which might be due to isotropic entrance angles (see [7] and references within).

In general, there actually is no reason why a suppression should only occur for protons but not for electrons as magnetic effects affect all charged particles. However, a suppression of electrons in molecular clouds was not yet taken into account.

For the first time ever a recent paper finally gives a theoretical approach for a modified cosmic ray propagation that is applied to the proton spectrum in this thesis. Whereas the proton spectra for molecular clouds were determined in an data-driven way before, they are now modeled following the theoretical predictions. Furthermore, the paper’s predictions affect all charged cosmic rays, particularly also electrons that were ignored before. The test of the new approach is one of the major topics in this thesis.

Usually, dense molecular clouds are surrounded by diffuse weakly-ionized gas, heated by the MCs’ emissivity. Charged cosmic rays entering the ionized gas envelopes create magnetohydrodynamic (MHD) waves, thus, create magnetic disturbances. The authors of [11] theoretically derive that these MHD waves are differently damped than in diffuse gas, which changes the diffusion coefficient below a certain energy. Consequently, low energetic charged cosmic rays are prevented to enter MCs and produce pions within resulting in a depletion of low energetic $\gamma$-rays and a shift of the maximum of the spectrum towards higher energies.

The theoretical mechanism provided by the recent paper predicts three features:

- **Sharp Break in Cosmic Ray Spectrum:** The change of the diffusion coefficient due to the different damping of self-generated MHD waves results in a sharp break in the charged cosmic ray spectrum. For protons, this has already been done in previous works as mentioned above. For electrons it will be introduced in this thesis.

- **Break Position:** The break position inversely depends on the density of the cloud’s envelopes, which means that one will expect a break at low rigidities for the most
massive clouds. In particular, the lowest break is expected to occur in the CMZ, where the giant molecular clouds are. This contrasts former approaches that suggested the break position to be dependent on the strength of the magnetic field, which increases with density of MCs. In this interpretation, one would expect the highest break in the CMZ. The break is identical for protons and electrons.

- **Spectral Index:** The recent paper also provides a prediction for the spectral index below the break that eliminates obtaining it from data as done before. The spectral index is $-1.0$ uniform for all energies below the break for all species of charged cosmic rays, in particular also for electrons.

The well derived reason for breaks in the proton and electron spectrum and the clear prediction of the break position as well as the slope below are a great improvement of the molecular cloud hypothesis. Furthermore, it is quite fascinating that the theoretically predicted break positions in the proton spectrum for MCs as well as the spectral index below (see figure 2.5) are so similar to the ones that were determined in a data-driven way before although no theoretical basis existed.

![Predicted Proton Spectra for MCs](image)

**Figure 2.5:** Predicted Proton Spectra for MCs. Recently predicted proton spectra for molecular clouds with envelopes of different density that are indicated in the figure (black solid line) compared to the proton spectra with different breaks used in this thesis (red solid line). The figure was adapted from Fig. 4 of [11] by removing the normalization $S_{DD}$ thanks to a personal correspondence between Wim de Boer and the authors of [11].

Motivated by the paper’s prediction, an additional electron spectrum is introduced in this thesis. This has never been done before, but has already been suggested in [8] to improve the fit. As for protons, the new electron spectrum is modeled by a broken power law. Figure 2.3 shows both the proton and electron spectrum for molecular clouds for breaks between 4 GV and 14 GV. The spectral index for electrons and protons is $-1.0$ below the break and the spectral index above the break was chosen to be the same as for propagated interstellar cosmic rays: $-2.849$ for protons and $-3.21$ for electrons. An
Table 2.1: **Parametrization of the Cosmic Ray Spectra**: Unbroken power law spectra of interstellar propagated protons and freshly accelerated protons in sources. Broken spectra of protons and electrons in MCs where the break position (in GV) is $R_0 \in (4, 5, \ldots, 14)$. Broken spectra for interstellar propagated electrons where the break position (in GV) is $R_0 \in (0.1, 0.2, 0.4, \ldots, 1.2, 1.6)$ and the spectral index is $\alpha \in (-0.1, -0.4, -0.6, -0.81, -1.0, -1.1, \ldots, -1.9)$.

<table>
<thead>
<tr>
<th>Species (template)</th>
<th>Spectral index $\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interstellar protons (PCR)</td>
<td>-2.849</td>
</tr>
<tr>
<td>Source protons (SCR)</td>
<td>-2.1</td>
</tr>
<tr>
<td>MC protons (MCR)</td>
<td>-1.0 for $R &lt; R_0$</td>
</tr>
<tr>
<td></td>
<td>-2.849 for $R &gt; R_0$</td>
</tr>
<tr>
<td>MC electrons (MBR)</td>
<td>-1.0 for $R &lt; R_0$</td>
</tr>
<tr>
<td></td>
<td>-3.21 for $R &gt; R_0$</td>
</tr>
<tr>
<td>Interstellar electrons (IC)</td>
<td>-0.81 for $R &lt; 0.2$ GV</td>
</tr>
<tr>
<td></td>
<td>-3.21 for $R &gt; 0.2$ GV</td>
</tr>
<tr>
<td>Interstellar electrons (BR)</td>
<td>$\alpha$ for $R &lt; \bar{R}_0$</td>
</tr>
<tr>
<td></td>
<td>-3.21 for $R &gt; \bar{R}_0$</td>
</tr>
</tbody>
</table>

additional break in the electron spectrum at lower rigidities referring to different electron spectra in the galaxy was not taken into account.

**Source Spectrum**: The proton spectrum in sources is modeled as an unbroken power law with spectral index $-2.1$, which is expected for freshly accelerated cosmic rays in expanding shock waves occurring during a supernova. The so-called Fermi bubbles found by the Fermi collaboration in 2010 are characterized by a $\gamma$-ray spectrum with a hard high energy tail. A spectral index $-2.1$ leads to a hard $\gamma$-ray spectrum that matches the data of the bubbles well [21] [22]. Figure 2.3a shows the proton spectrum for sources.

That the same index corresponding to sources is found to well describe the bubbles provides evidence for a connection between Fermi bubbles and cosmic ray sources: Particles cycling in a shock wave not only gain velocity but also scatter on matter within, which leads to $\pi^0$-production and -decay, consequently. Further, it is commonly believed that the Fermi bubbles are a convective outflow from the disk driven by cosmic ray pressure, which carries gas and dust with them. In this interpretation, a fraction of freshly accelerated hard cosmic rays are not ejected to the ISM where they would propagate and soften their spectrum but bound to the flowing out matter. Hence, $\gamma$-rays are created far above and below the disk in the bubbles by an unpropagated hence still hard proton spectrum. Therefore, it is a reasonable assumption that the $\gamma$-ray spectrum with hard high energy tail found in the bubbles stems from the hard proton spectrum in sources. Further details on the Fermi bubbles will be discussed in section 4.6.5.

Table 2.1 provides a overview over the used cosmic ray spectra in this thesis.
2.5. Diffuse Gamma-Ray Production and spectral Templates

In the previous section cosmic ray spectra were motivated and introduced. The spectra represent freshly accelerated or propagated cosmic rays, modified spectra in molecular clouds as well as several electron spectra in the Milky Way. In order to analyze the Fermi data, which come as γ-ray flux per energy and solid angle, with a spectral template fit one needs to calculate γ-ray templates corresponding to the galactic γ-ray energy spectra for the most relevant γ-ray producing processes namely π⁰-decay, bremsstrahlung and inverse Compton scattering. Therefore, one can use the GAMMA-SKY code from DRAGON [23].

The γ-ray emissivity at a certain position in the galaxy depends on the cosmic-ray density, the target density and the cross sections, in principle. GAMMA-SKY contains spatial templates of the gas distribution and the ISRF in the Milky Way, which determine the shape of the γ-ray spectra. In contrast to common approaches on does not need to consider gas density in a spectral fit since this just re-scales the spectrum. The cosmic-ray density is calculated from the cosmic-ray spectra introduced in section 2.4, which are the only input for the code. The cross-sections are known from fixed target and accelerator experiments and also included in the code.

Once the γ-ray emissivity is determined it must be integrated over the line-of-sight. Depending on the direction the sky is observed in, different γ-ray sources are located in the field of view. The γ-ray flux measured at Earth is the integrated γ-ray emissivity of all γ-ray sources in the given field of view divided through their distance squared, which is calculated with the line-of-sight integral.

The code calculates the integrals in an iterative way following the references given within: [24], [25], [26], [27], [28].

The Line-of-Sight Integral: Physicists can only locally measure the amount and energy of cosmic-rays arriving Earth from a certain direction. Once emitted γ-rays travel in straight lines as they do not interact with the ISM nor magnetic fields. The total flux through a spherical surface around a source is constant, thus assuming an isotropic emission the γ-ray flux that can be measured at a certain position with distance \( r \) from the source decreases with the distance squared \( \Phi_{\gamma}(r) \propto \frac{1}{4\pi r^2} \). The obtained γ-ray flux per energy and solid angle at Earth is the total emissivity of all celestial sources in a given direction divided by their distance \( x \) squared. This is referred as line-of-sight integral for a given field of view \( l \times b = (l_1 - l_0) \times (b_1 - b_0) \) with solid angle \( \Omega = \int_{l_0}^{l_1} dl \int_{b_0}^{b_1} \cos(b) \, db \)

along the path \( x \)

\[
\Phi_{\gamma,\text{local}} = \frac{\int_{l_0}^{l_1} dl \int_{b_0}^{b_1} \cos(b) \, db \int_{0}^{\infty} q(E_{\gamma}, x) \frac{1}{4\pi x^2} x^2 \, dx}{\Omega} \tag{2.10}
\]

where \( q(E_{\gamma}, x) \) is the γ-ray emissivity at point \( x \). The denominator in equation 2.10 is the normalization per solid angle.
2. From Cosmic Ray Sources to diffuse Gamma-Rays

In the following the theoretical calculation of the seven γ-ray templates used in the fit is shown, important information about the templates is presented and their shape is shown in figures 2.6 and 2.7.

Figure 2.6: Gamma-Ray Templates. (a) Templates corresponding to decaying π⁰s produced by 1) propagated cosmic ray protons in diffuse gas (PCR, red solid line) superimposed for the entire galaxy, 2) propagated cosmic ray protons in molecular clouds (MCR, yellow solid lines) and 3) freshly accelerated protons in sources (SCR, pink solid line). Note the similar shape of the MCR and PCR templates. (b) Templates derived from the electron spectra with exemplary break at 1.6 GV for every spectral index between −0.1 and −1.9 below the break. (c) Templates corresponding to bremsstrahlung 1) in molecular clouds (MBR, cyan solid lines) and 2) in diffuse gas (BR, blue solid lines). Shown are the BR templates derived from the electron spectra with exemplary spectral index −1.2 below the break for every break between 0.1 GV and 1.6 GV. Note that BR templates for every combination of breaks and spectral indexes below were computed. All templates are normalized at ≈ 11 GeV, which allows comparison of shape not of absolute flux.

- PCR and MCR Templates: The PCR template corresponds to γ-rays originating from decaying π⁰'s that are produced by propagated cosmic ray protons in the diffuse interstellar gas and dust, thus are calculated from the propagated interstellar proton spectrum with spectral index −2.849.

The γ-ray emissivity \( q(E_γ, x) \) is the number of γ-rays that are produced at position \( x \) in the galaxy per volume, γ-ray energy and time and is dependent on the proton flux per energy \( \Phi_{p'}(E_{p'}, x) \) and the target density \( n_i \) of the species \( i \) at this position as well as the differential cross section \( dσ_{π⁰}(E_γ, E_{p'})/dE_γ \). The target species for protons to produce π⁰'s are molecular, neutral and ionized hydrogen. To gain the total emissivity one has to sum over all species. The γ-ray emissivity can be calculated from the integral over all proton energies, in principle.
2.5. Diffuse Gamma-Ray Production and spectral Templates

Figure 2.7.: Superimposed IC and BR Templates. (a) IC templates both derived from the electron spectrum with break at 0.2 GeV and spectral index $-0.81$ below the break superimposed for entire galaxy (lower) and superimposed for all possible electron spectra (upper) for a single cone (see table 2.1). (b) BR template derived from the electron spectrum with break at 0.2 GeV and spectral index $-0.81$ below the break superimposed for entire galaxy. All templates are normalized at $\approx 11$ GeV, which allows comparison of shape not of absolute flux.

\[
q(E_\gamma, x) = \sum_i \int \Phi_p^i(E_{p^+}, x)n_i \frac{d\sigma_{\pi^0}(E_\gamma, E_{p^+})}{dE_\gamma} \, dE_{p^+},
\]

(2.11)

where $q(E_\gamma, x)$ is given in units of GeV$^{-1}$ m$^{-3}$ s$^{-1}$, the proton flux $\Phi_p^i(E_{p^+}, x)$ is given in GeV$^{-1}$ m$^{-2}$ s$^{-1}$ and $n_i$ is given in m$^{-3}$. The differential cross section $d\sigma_{\pi^0}(E_\gamma, E_{p^+})/dE_\gamma$ is given in units of m$^2$ GeV$^{-1}$ and known from fixed target experiments. The $\gamma$-ray flux per field of view (cone) then follows from the line-of-sight integral of the emissivity.

Since the ISM is non-homogeneous the shape of the PCR template differs slightly for every cone depending on the fraction of H$_2$, HI and HII in the field of view. One can obtain the deviation of its shape in figure 2.6a, which shows the PCR flux superimposed for the entire galaxy. By eye one notices no difference. Therefore, the MCR templates are only calculated for a single cone ignoring different compositions of the gas to reduce the size of the template files.

Since protons are the most abundant species heavier nuclei (helium, lithium etc.) were not taken into account. The $\gamma$-ray production process is

\[
p^+ + p^+ \rightarrow \pi^0 + X \rightarrow 2\gamma + X.
\]

(2.12)
The PCR template is characterized by a soft high energy tail and a sharp cutoff below 280 MeV that is the pion production threshold.

Furthermore, eleven MCR templates corresponding to $\pi^0$-decay within molecular clouds were computed from the proton spectra with breaks between 4 GV and 14 GV and spectral index $-1.0$ below following the predictions of [11]. The MCR templates are characterized by a shift of the maximum towards $1-2$ GeV in comparison to the PCR template and the maximum at the lowest energy correspond to the spectrum with lowest break. Breaks below 4 GV were not used to avoid strong correlations in shape with the PCR template although they are allowed in principle. Otherwise, PCR and MCR would not be distinguishable. The PCR and all MCR templates are shown in figure 2.6a.

**IC Template:** The IC template corresponds to $\gamma$-rays stemming from inverse Compton scattering between electrons and photons of the ISRF and is calculated from the electron spectrum with spectral index $-0.81$ below the break at 0.2 GV as done in [8].

The $\gamma$-ray emissivity $q(E_\gamma, x)$ is defined as in equation 2.11 and given in the same units. It depends on the electron flux per energy $\Phi_e (E_e, x)$ and the differential target density $dn_{ph}/dE_{ph}$ as well as the differential cross section $d\sigma_{IC}(E_\gamma, E_{e^-}, E_{ph})/dE_\gamma$. The target for electrons is the ISRF, which is composed of photons from starlight, dust emission and CMB with different energies. Thus one needs to integrate not only over the electron but also over the photon energies. That is the main difference to $\pi^0$-production or bremsstrahlung, where the targets are fixed. The $\gamma$-ray emissivity can be calculated from

$$q(E_\gamma, x) = \int \int \Phi_e (E_e, x) \frac{dn_{ph}}{dE_{ph}} \frac{d\sigma_{IC}(E_\gamma, E_{e^-}, E_{ph})}{dE_\gamma} dE_e^- dE_{ph} (2.13)$$

where $dn_{ph}/dE_{ph}$ is given in units of $m^{-3} GeV^{-1}$. The cross section is known from accelerator experiments. The $\gamma$-ray flux per cone is the line-of-sight integral of the emissivity.

Since the exact composition of the ISRF differs for every field of view the IC template shows deviations in shape for every cone, which can be obtained from the lower graph in figure 2.7a, which shows the IC template superimposed for the entire galaxy. The deviations are around 30% at 0.6 GeV.

As motivated in section 2.4 various electron spectra are used in this thesis. In principle, one has to derive an IC template for each spectrum, consequently. Anyhow, this was given up because of technical reasons. Thus, one needs to compromise between templates for each electron spectrum but without deviation in shape and one single template derived from a certain electron spectrum that differs for every cone. Since the shape of the IC template stronger depends on the ISRF composition of each field of view ($\approx 30\%$) than on the parametrization of the electron spectrum, which is around 15% (at 0.6 GeV), one rather uses a single IC template that differs for
every cone than many IC templates with fixed shape. The upper graph in figure 2.7a shows IC templates derived from every possible electron spectrum (see table 2.1) for a single cone superimposed. If one compares the deviations in shape of upper to the lower graph, one will agree and appreciate that the former was given up in favor of the latter. This is because electrons with rigidities below 1.6 GV (the highest break in the electron spectra) are not capable of scattering photons up to energies relevant for Fermi-LAT. Thus, neither changes in spectral index below the break nor lower break positions do not affect the shape of the IC template significantly. Additionally, the calculation of the inverse Compton spectrum (see equation 2.13) implies two integrals of both the photon and electron spectrum that smears out the effect of different slopes of the electron spectrum.

Perhaps, one may propose introducing additional MIC templates corresponding to inverse Compton scattering between electrons and photons in molecular clouds derived from the electron spectra with breaks between 4 GV and 14 GV and slope \(-1.0\) that were predicted recently. However, these templates were dropped because 1) as described above the inverse Compton spectrum is not very sensitive for modifications in the initial electron spectrum because integrating over all photon and electron energies smears out the effect so that MIC templates would hardly be distinguishable from the IC template and 2) the inverse Compton contribution to the diffuse \(\gamma\)-ray spectrum within molecular clouds may be suppressed, as will be discussed in section 4.2.

- **BR and MBR Templates**: The BR templates correspond to \(\gamma\)-rays that are emitted when electrons are decelerated in the Coulomb field of interstellar diffuse gas, dust and other charged cosmic rays referred as bremsstrahlung.

The calculation of the bremsstrahlung emissivity \(q(E_\gamma, x)\) is similar to equation 2.11. It depends on the electron flux per energy \(\Phi_e^{-}(E_e^{-}, x)\) at position \(x\), the target density \(n_i\) and the cross section \(\sigma_{BR}(E_\gamma, E_e^{-})/dE_\gamma\). As for \(\pi^0\) production, the targets for electrons to emit bremsstrahlung is the interstellar gas that is composed of three hydrogen species \(i\), thus one needs to sum over all species.

\[
q(E_\gamma, x) = \sum_{i} \int \Phi_e^{-}(E_e^{-}, x)n_i\frac{d\sigma_{BR}(E_\gamma, E_e^{-})}{dE_\gamma} \, dE_e^{-}
\] (2.14)

As the emissivity is inverse proportional to the mass of the projectile particle bremsstrahlung from protons is strongly irrelevant due to their around 2000 times higher mass. The flux then is calculated from the line-of-sight integral of the emissivity.

Since the gas distribution is non-homogeneous the shape of the BR template differs for every cone. Figure 2.7b provides the BR template derived from the electron spectrum with break at 0.2 GV and spectral index \(-0.81\) below superimposed for the entire galaxy. The deviation is less than for IC namely around 20% (at 0.6 GeV) but greater than in PCR. In comparison, figure 2.6b shows the BR templates calculated for a single cone for a fixed break position of the electron spectrum and varying
spectral indexes below. One obtains $\approx 700\%$ (at 0.6 GeV) difference. Figure 2.6c shows the BR templates for a fixed spectral index but varying break positions, which also varies strongly. Because of technical reasons described above one needs to decide whether to use one template taking care of the gas distribution in every cone or several templates with respect for different electron spectra but without deviation in shape. In contrast to the IC template, the BR templates strongly depend on the parametrization of the electron spectrum, hence a single BR template, which takes care of field of views, was quit for the benefit of many BR templates corresponding to many electron spectra.

Furthermore, eleven MBR templates corresponding to bremsstrahlung within molecular clouds were computed from the electron spectra with breaks between 4 GV and 14 GV and spectral index $-1.0$ below. They also have a fixed shape because of the same reason as above. The MBR templates can be obtained from figure 2.6c.

- **SCR Template:** The SCR template corresponds to hard $\gamma$-rays which originate from decaying $\pi^0$s that are produced by freshly accelerated protons in the expanding shock wave of point sources. It is calculated from the hard proton spectrum with spectral index $-2.1$. There is no template for freshly accelerated electrons, though. The SCR template is characterized by a cutoff at twice the pion mass and a hard tail for high energies as can be obtained from figure 2.6a. As the SCR $\pi^0$-production is bound to sources there is no need for differences in shape. It is not very significant, anyhow, as seen for the PCR template.

- **ISO Template:** The ISO template corresponds to the isotropic $\gamma$-ray background including extra galactic $\gamma$-rays as well as misidentified hadrons in the detector as recommended by the Fermi collaboration. Previous works re-tuned the ISO template in an iterative way [7] [8]. They performed a fit over the regions in the halo and plotted the Fermi data against the model of each cone for every energy bin. For a perfect model one expects a linear function with slope 1 and zero off-set. If an off-set was found, the ISO template was adjusted and the procedure repeated.

In this thesis the original isotropic background recommended by the Fermi collaboration was used as a re-tuning of the background template revealed buggy features at high energies (see figure 2.8b), which could not be explained or solved. Despite, a re-tuning does not significantly improve the fit as the background is already good indicated by a slope of the linear fit function being consistent with 1 (see figure 2.8a).

In table 2.1 one can obtain an overview over the used proton and electron spectra, their parametrization and the templates that are derived from the individual spectra.
2.5. Diffuse Gamma-Ray Production and spectral Templates

Figure 2.8: Isotropic Background Tuning. (a) Fermi data plotted against the total model flux at 1.91 GeV for every pixel outside the Fermi bubbles and the disk. Parameter $p_0$ is the slope of the fitted linear function, which is in agreement with 1, and parameter $p_1$ is the offset. (b) Isotropic offset recommended by the Fermi collaboration (black solid line) in comparison to the adjusted isotropic background (red solid line, with error bars) after tuning. Below $\approx 20$ GeV the recommended background is only smoothed whereas above the adjusted background differs from the old especially for energies above 200 GeV.
As in previous works [6] [7] [8] in this thesis the analysis of the Fermi data on the diffuse γ-rays follows a different approach than commonly applied. Conventionally, groups use standard cosmic ray propagation codes like GALPROP or DRAGON to simulate cosmic ray propagation from sources to Earth through the ISM and ISRF by numerically solving the diffusion equation until a steady-state is reached. The propagated steady-state spectrum of protons is similar in the entire galaxy whereas the electron spectra differ. These propagation models need spatial templates like 3D-maps of the cosmic ray targets. Gas and photons are the targets for cosmic ray electrons and protons to produce γ-rays via bremsstrahlung, inverse Compton scattering and π⁰-production and -decay, respectively. Hence, spatial templates of the gas distribution and density and of the ISRF composition and intensity, as well, must be reconstructed from astronomical data like CO-maps or modeled. As mentioned in sections 2.1 CO radio emission traces molecular clouds. However, such spatial templates are not sufficient for high signal regions like the disk as they smear out the effect of extended sources like molecular cloud emission and not suitable for searches of new unresolved sources as spatial fits vanish point sources. Furthermore, since the gas distribution is only poorly known especially in the disk the spatial approach leads to bad uncertainties and an incorrect description of the disk.

The code then calculates the total γ-ray emissivity of a field of view from the propagated steady-state spectra and the same spatial templates by the use of γ-ray-codes. The emissivity not only depends on the target density but also on the cosmic ray density at a certain position as well as the cross sections. This approach leads to a determination of the diffuse γ-ray background, which then can be compared to the Fermi data. Since propagation models neither take modified propagation within MCs nor hard source cosmic rays into account subtraction of the model emissivity from the data leads to a signal indicated by a bad description of the disk and the bubbles that is referred as the GeV-excess. In particular, spatial template fits do not include what is called SCR and MCR in this thesis.

This thesis follows a different approach namely an analysis with spectral templates. The spectral templates are either calculated from data-optimized or motivated cosmic ray spectra thus represent each standard γ-ray producing process as well as new processes like π⁰-production in MCs and sources, which is an advantage over the spatial approach. The spectral approach eliminates the need to know the gas and ISRF density and the cosmic ray density because these parameters are absorbed in the normalization factor of the template, which the fit determines for every cone independently (details are provided in section 3.3). However, the ISRF and gas composition is taken into account for template calculation as described in section 2.5. The spectral fit is able to obtain the spectral decomposition of the Fermi spectrum of a certain cone, which can be arbitrary small, in principle. This allows a high spatial resolution of the diffuse γ-ray sky, which resembles the gas distri-
3. Technical Background

bution, molecular clouds and Fermi bubbles, for instance, just by data. The spectral fit has the ability to both determine the standard background and to find a possible signal, simultaneously. Additionally, bad fit results indicate that new processes are needed.

3.1. Galactic Coordinate System

In this thesis galactic coordinates are used. The galactic coordinate system is a spherical system and has the Sun in its center.

Figure 3.1.: Galactic Coordinate System - The Milky Way. Illustration of the Milky Way including an indication of longitudes of the galactic coordinate system with the Sun in its center. Note that in the thesis negative longitudes are used whereas in the image they are replaced by positive values above 180°. Artwork taken from [29].

The galactic longitude \( l \) measures the angle distance of an celestial object in mathematically positive direction (anticlockwise) with positive values \( 0 \leq l \leq 180^\circ \) and in mathematically negative direction (clockwise) with negative values \( 0 \geq l \geq -180^\circ \) measured in degrees. Thus, longitudes \( l = 180^\circ \) and \( l = -180^\circ \) point to the same direction, which means that the left and the right border of skymaps shown in this thesis correspond to the same direction, too. Longitude \( l = 0^\circ \) points to the galactic center. The galactic latitude \( b \) measures the angle distance of an celestial object northwards with positive values \( 0 \leq b \leq 90^\circ \) and southwards with negative values \( 0 \geq b \geq -90^\circ \). In contrast to longitude, latitude \( b = \pm 90^\circ \) does not correspond to the same directions but refers to the galactic north and south pole. Therefore, skymaps in this thesis are to read like common rectangular world maps.

Figure 3.1 shows an illustrative artwork of the Milky Way including the longitudes of the galactic coordinate system. From this picture one can obtain the coordinates of the
most interesting regions introduced in section 2.1. As the Solar System including the Sun and Earth is located in the galactic disk the latter is seen from within. Hence, the galactic disk including the center and the spiral arms appears as a narrow band for latitudes $-1.5^\circ \leq b \leq 1.5^\circ$ and longitudes $-180^\circ \leq l \leq 180^\circ$. The Central Molecular Zone (CMZ), which contains the densest molecular clouds, is near the galactic center and visible in a rectangular zone for longitudes $-1.5^\circ \leq l \leq 2^\circ$. The galactic bar is visible for longitudes between $-20^\circ \leq l \leq 30^\circ$. The Carina-Sagittarius Arm lies between longitudes $-80^\circ \leq l \leq -60^\circ$ and the Orion-Cygnus Arm is at longitudes $70^\circ \leq l \leq 90^\circ$. Furthermore, the near tangent point of the Scutum-Centaurus Arm can be found between longitudes $-50^\circ \leq l \leq -40^\circ$. Eventually, the Fermi bubbles are found for longitudes $l \leq \pm 20^\circ$ and latitudes $b \leq |55^\circ|$ above and below the galactic disk. The regions with latitudes $b \geq |55^\circ|$ are defined to belong to the galactic poles. As there are only poor data the poles are unsuited for analysis and ignored in the following.

3.2. Fermi Data and Binning

The Fermi Gamma-Ray Space Telescope was launched into a low orbit in June 2008. Its primary instrument is the Large Area Telescope (LAT). It covers the energy range from below 20 MeV to more than 300 GeV [30]. Pass 8 allows to extend the energy range above 1 TeV [31]. In this thesis the diffuse $\gamma$-rays in the energy range between 59 MeV and 513 GeV collected by Fermi-LAT in 9 years (PASS 8 FERMI CLEAN) are analyzed. The data selection is like in [8]: Misidentified hadrons are included in the isotropic background given by the Fermi collaboration and point sources were subtracted (see figure 3.2) providing the Fermi data in a skymap of flux per energy, which is binned in longitude and latitude in $0.5^\circ \times 0.5^\circ$ bins. This skymap-file is inputted into the code where it can be re-binned at will. The Fermi data at every energy can be obtained from figure A.2 in the appendix.

The high statistics allows fine binning of the Fermi $\gamma$-ray spectra for each pixel, thus the spectra are binned in 30 bins $E_n$ ($1 \leq n \leq 30$) from 0.059 GeV to 513 GeV where the bin borders $E_{n\text{low}}$ and $E_{n\text{high}}$, respectively, are calculated from

$$E_{n\text{high}} \approx E_{1\text{low}} \cdot 1.35^n \approx 0.059 \text{ GeV} \cdot 1.35^n,$$

where $E_{n\text{high}} = E_{(n+1)\text{low}}$ resulting in an equidistant bin width on a logarithmic scale with base 10. All $\gamma$-rays collected that belong to a certain bin are added to gain the total flux per energy bin. In the spectra the total flux in a given bin $n$ is represented by a point at energy $E_n$ that is the geometric mean of the bin: $E_n = \sqrt{E_{n\text{low}} E_{n\text{high}}}$. The statistical errors of each energy bin are given by the square root of the counts in a single bin $\sqrt{N}$ whereas the systematic errors are recommended by the Fermi collaboration to be 10% below 100 MeV, 5% at 562 MeV, 20% above 10 GeV and linear interpolated in between. As the fit finds a $\chi^2$/d.o.f. $\ll 1$ the systematic errors are adjusted and re-scaled by a factor 0.5. This re-scaling does not effect the relative contribution of each template but is only proceeded to obtain a $\chi^2$/d.o.f. $\approx 1$.

As mentioned above, the Fermi data are provided in a skymap binned in longitude and
3. Technical Background

Figure 3.2.: Fermi Gamma-Ray Sky. (a) Raw Fermi data including diffuse γ-rays and point sources. (b) Point sources from the third Fermi point source catalog [32]. (c) Diffuse Fermi data after subtraction of the point sources. The skymaps are binned in longitude and latitude in $1.0^\circ \times 1.0^\circ$ bins. The z-axis shows the flux per solid angle at energy $E = 0.57 \text{ GeV}$ multiplied with $E^2$ in units of $\text{GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1}$.

latitude in $0.5^\circ \times 0.5^\circ$ bins. This leads to a sky divided into 259,200 individual cones. Since the fit treats every cone independently, as will be explained in section 3.3, analyzing this amount of cones would cause a dramatic long duration of code running. Therefore, for particular skymaps a binning of at least $1.0^\circ \times 1.0^\circ$ is used to emphasize interesting features. However, for most analyses even larger bins are chosen to save calculation time:

The most skymaps are non-equal $l \times b$ binned leading to a good compromise between spatial resolution and statistics. In the poles, where the fewest of all γ-rays are recognized, the Fermi data are combined to $20^\circ \times 17.5^\circ$ cones to gain statistics but lose spatial resolution, which is acceptable. The more interesting regions are binned finer. As the statistics in the disk are high, one can choose a finer $5^\circ \times 1^\circ$ binnig in the disk for the central bulge and enlarge the bins stepwise to $25^\circ \times 1^\circ$ for the galactic anti-center. The spiral arms and CMZ are binned separately to take care of possible features occurring there. The Fermi bubbles are mainly divided into $5^\circ \times 5^\circ$ bins. For the halo $10^\circ \times 10^\circ$ bins are sufficient. The exact binning can be obtained from the skymaps in this thesis. In total, the Fermi diffuse γ-ray sky is divided into 797 cones with full sky coverage.

3.3. Fitting Algorithm

The Fermi γ-ray spectrum in a given direction can be described as a linear combination of the γ-ray templates.

$$ \Phi_{\text{total}} = n_1 \Phi_{\text{PCR}} + n_2 \Phi_{\text{BR}} + n_3 \Phi_{\text{IC}} + n_4 \Phi_{\text{SCR}} + n_5 \Phi_{\text{MCR}} + n_6 \Phi_{\text{MBR}} + \Phi_{\text{ISO}} $$ (3.2)

where $\Phi_{\text{total}}$ corresponds to the mean Fermi γ-ray flux in a given field of view and $n_i$ are the normalization factors of each template $\Phi_i$. The ISO template is constant per definition.
3.3. Fitting Algorithm

The individual templates correspond to the resulting \( \gamma \)-ray flux energy spectra of each process. The energy spectra are known from accelerator experiments and shown in section 2.5. The \( \gamma \)-ray emissivity of a given region depends on the cross sections of each individual process, which are known, and the cosmic ray density and target density, which are not known. In a spectral template fit this three variables are absorbed by the normalization factor \( n_i \) thus eliminates the need to know them individually. A spectral template fit has an advantage over the spatial fit, as former is suitable to determine the background and the excess simultaneously in a arbitrary spatial resolution that is only limited by the data’s spatial resolution. Unless one was limited by CPU performance, one could perform a fit over the 259,200 cones, in principle.

In the following the fit algorithm is described qualitatively.

1. The Fermi data skymap binned in \( 0.5^\circ \times 0.5^\circ \) bins as well as the templates for each process are loaded into the code.

2. The Fermi data skymap and the templates that vary with direction (PCR, IC) are re-binned at will (e.g. into 797 cones or into \( 1^\circ \times 1^\circ \) skymaps) depending on which region the user is interested in. In principle, every binning is possible limited by the solid angle resolution of the data. To obtain the flux in a pixel larger than the native \( 0.5^\circ \times 0.5^\circ \) the code adds the fluxes of each individual bin weighted with their solid angle and divides the sum through the total solid angle. In other words, the flux in a large bin is the mean flux of the combined native small bins. Templates without directional variation are of the same shape in every direction per definition thus do not have to be adjusted.

3. The code loops over all cones and determines the lowest \( \chi^2 \) independently for each cone using the TVirtualFitter class of the CERN Root software. The \( \chi^2 \) is calculated from

\[
\chi^2 = \sum_{i=1}^{30} \frac{(data_i - \sum_{k=1}^{7} n_{ik} \cdot template_{ik})^2}{\sigma_i^2}
\]  

(3.3)

where \( i \) corresponds to the i-th energy bin and \( k \) to the k-th template. For every separate cone the fit calculates the difference between the Fermi data, which are flux at energy \( i \), and the total flux of the model, which is the sum of the fluxes at energy \( i \) of every template. On that account, the fit chooses normalization factors \( n_i \) the templates are multiplied with \( (n_7 = n_{ISO} \equiv 1) \) and evaluates the flux at a given energy bin \( i \). If the template, which is a energy spectrum of the flux, has no entry at energy \( i \), the fit uses linear interpolation. The difference is divided by the error of the data \( \sigma_i \) at energy \( i \) squared, which is calculated from \( \sigma_i = \sqrt{\sigma_i^2, \text{stat.} + \sigma_i^2, \text{sys.}} \). Then, the fit changes the values of the \( n_i \)s and repeats the procedure until the minimum is found. As the Fermi spectrum is divided into 30 energy bins and there are only 6 free parameters (normalization factor of 6 templates, ISO is constant) the fit is well constrained.
a) For MCR and MBR there are 11 templates for breaks between 4 GV and 14 GV. Once a minimal $\chi^2$ is found for the first template the fit loads the next template and repeats 3. of the algorithm in order to find a smaller $\chi^2$. Note that the fit does not loop over $11 \cdot 11 = 121$ combinations but is forced to fix the MBR break to the MCR break as they are predicted to be equal. So, the fit tests the $\chi^2$ 11 times and saves the break that leads to the smallest $\chi^2$.

b) The BR templates were calculated for each combination of spectral indexes and break position of the cosmic ray electron spectra (see table 2.1). Thus, there are $14 \cdot 8 = 112$ different BR templates. Every time the fit is done with testing the $\chi^2$ function for a certain MCR resp. MBR break it loops over all BR templates repeating 3. of the algorithm in order to find a smaller $\chi^2$ and saves the best combination of BR break and spectral index below. The fit then proceeds with the next MCR resp. MBR break.

4. Once the combination of MCR, MBR and BR templates leading to the smallest $\chi^2$ is found and saved the fit proceeds with the next cone. With this algorithm the relative spectral contribution of each template is found for every cone independently. Eventually, one can illustrate the results by spectra, skymaps, profile plots etc.
4. Evaluation of the spectral Gamma-Ray Composition

The 7 templates were fitted to the measured Fermi data in each cone independently leading to a spectral decomposition of the Fermi spectrum in each cone, which indicates the relative contribution of each template. The relative contribution is determined by the normalization factor the template is multiplied with found by the fit. This leads to a spatial flux distribution of each γ-ray component. Furthermore, the fit determines the optimal break position in the molecular cloud spectra for electrons and protons as well as the optimal electron spectrum for bremsstrahlung. In the following, the results are presented by skymaps of the flux of each component and the relative errors of their normalization factors and by additional profile plots or correlations between two components if necessary.

Figure 4.1: $\chi^2$ Skymap of the new and the previous Model. The skymap shows the values of $\chi^2$/d.o.f. for each pixel, which were obtained from the fit with (a) the new model and (b) the previous model. The new skymap is flat with most values around 1 whereas the previous skymap consists of more pixels with $\chi^2$/d.o.f. > 1 than (a).

The fit provides impressive good results as indicated by the $\chi^2$/d.o.f. skymap, which is flat around 1 for every pixel except for three problematic pixels with $\chi^2$/d.o.f. $\gg$ 1 (see figure 4.1a). The mean $\chi^2$/d.o.f. (reduced $\chi^2$) per pixel is 1.13. Note that the systematic
Figure 4.2.: **Residual Skymap of the new and the previous Model.** The skymap shows the residual of (a) the new model and (b) the previous model at 0.57 GeV for each pixel defined as the difference between Fermi data and the model divided through the error of the data. The z-axis corresponds to the $5\sigma$-range.

errors of the data recommended by the Fermi collaboration where multiplied with 0.5 to reach a reduced $\chi^2$ around 1, which is a fantastic result for a such simplified model. If one used the original systematic errors suggested by the Fermi collaboration, one would obtain an even significant smaller reduced $\chi^2$.

Figure 4.1b shows the reduced $\chi^2$ skymap that results from the fit of the previous model, which found the mean reduced $\chi^2$ per pixel to be 1.72. As a reminder, the previous model did not include a MBR template. Furthermore, the MCR templates were derived from broken proton spectra with spectral index $-0.7$ below the break before (now $-1.0$) and the possible break positions were between 6 GV and 14 GV (now between 4 GV and 14 GV). Finally, the previous fit only had one BR template derived from the electron spectrum with break at 0.2 GV and spectral index $-0.81$ below whereas it could now chose between several BR templates. [8]

Due to one degree of freedom more (MBR template) the new model provides better results since the mean reduced $\chi^2$ could be cut to 66% of the former value.

Figure 4.2a shows the residual skymap at 0.57 GeV. The residuals for the other energies can be found in figure A.3 in the appendix. For each pixel the residual is calculated from the difference between the measured Fermi flux and the total flux of the fitted model divided through the error of the data for each energy bin: $(\Phi_{\text{Fermi Data}} - \Phi_{\text{Model}})/\sigma_{\text{Fermi Data}}$. For most pixels the residuals are below $2\sigma$. In particular, the residuals in the disk, halo and bubbles could be further reduced in comparison to the old model (see figure 4.2b) where way more residuals at $2\sigma$ and even above are found.
4.1. Pion Production in diffuse Gas

In the following a phenomenological analysis of each component of the diffuse Fermi γ-ray sky as well as a detailed view on selected regions of the sky is provided. Skymaps are used to show the spatial distribution of each γ-ray component. The skymaps show the flux of a certain component integrated over the 30 energy bins from $E_{\text{1low}} = 0.059 \text{ GeV}$ to $E_{\text{30high}} = 513 \text{ GeV}$. The integral is calculated approximately as a discrete sum from

$$
\int_{E_{\text{low}}}^{E_{\text{high}}} \Phi_{\text{Comp}}(E) \, dE \approx \sum_{i=1}^{30} \Phi_{\text{Comp}}(E_i) \Delta E_i
$$

where $\Phi_{\text{Comp}}(E_i)$ is the flux of the given component at energy $i$ and $\Delta E_i$ is the bin width of the $i$-th energy bin. The skymaps for each energy bin separately can be found in figures A.4 - A.9 in the appendix.

4.1. Pion Production in diffuse Gas

Figure 4.3a shows the spatial distribution of the PCR component in the galaxy integrated over all energies.

The strongest contribution occurs above and below the galactic bar at longitude $-30^\circ < l < 40^\circ$ for latitudes $|1.5^\circ| \leq b \leq |5^\circ|$ where the flux is around one too two magnitudes higher than in the halo. A slightly increased flux is also visible in direction of the local Taurus molecular cloud in the galactic anti-center, the Orion-Cygnus Arm, the Scutum-Centaurus Arm and the Carina-Sagittarius Arm.

Since the galactic bar and the spiral arms contain most of the diffuse gas, which are the targets for pion production, this observation is not surprising. Although the galactic disk is only 1 kpc thick, from earth seen as a narrow band for latitudes $b < |1.5^\circ|$, the fit finds a broad band for latitudes $b < |15^\circ|$ with significant PCR contribution. As every pixel corresponds to the sum of the γ-ray emissivity along the line-of-sight the exact position of the π⁰-decay is not known, in particular it could be local or far away. However, no gas is found at such altitudes above or below the disk, which indicates a local origin of the γ-rays. This implication is plausible due to the line-of-sight crossing small parts of the disk nearby earth for every latitude. This argument is important and will frequently be adduced for several other skymaps in the following and probably also causes the flux at latitudes $b > |15^\circ|$.

Eventually, a depletion of the PCR component in the galactic bar region for latitudes $b < |1.5^\circ|$ can be recognized although the gas density is supposed to be the highest in this direction. But in this region also dense molecular clouds are found, which are described by the MCR component, which indeed is strong in exactly this direction (see figure 4.9a). The depletion of PCR in the galactic bar may be due to the MCR component absorbing a fraction of PCR. This could indicate a wrong MCR template.

The fit quality is good, indicated by the relative errors of the PCR template’s normalization factors being small for most pixels in the interesting regions (see figure 4.3b).
4. Evaluation of the spectral Gamma-Ray Composition

Figure 4.3: PCR Skymaps. (a) Skymap of the $\gamma$-ray flux integrated from 0.059 GeV to 513 GeV (see equation 4.1) that originates from decaying $\pi^0$s produced by propagated cosmic ray protons in the diffuse ISM. The z-axis shows the flux in units of $\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$. Dark blue pixels correspond to values that are below or equal the lowest value of the z-axis. (b) Skymap of the relative errors of the PCR normalization factors derived from MINUIT. White pixels correspond to cones with less than $5 \cdot 10^{-6} \text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ PCR contribution.

4.2. Inverse Compton Scattering

Figure 4.4a shows the skymap of the IC component in the galaxy and figure 4.4b the relative errors of the normalization factors of the IC template in each cone. As expected from the fact that ISRF intensity increases towards the center the fit provides a nearly spherical distribution of $\gamma$-rays from inverse Compton scattering around the galactic center and enhanced contributions in the the lower latitudes of the bubbles, at least. Additionally, significant IC contributions occur outside the bubbles and the disk as well.

If one studies the IC skymaps at every energy bin (see figure A.5 in the appendix) and compares the skymaps at higher energies to the skymaps at lower energies, one will note that the flux in the outer pixels reduces faster than in the inner pixels. This is due to a softer IC spectrum in the halo: In the halo propagated cosmic ray electrons mostly scatter off photons of the CMB as they are the dominant contributor to ISRF there leading to a softer IC spectrum because CMB photons are less likely scattered up to energies above 10 GeV than photons of starlight or dust emission. The nearer the line-of-sight is to the galactic center the more dominates the fraction of middle energetic photons from hot dust emission and high energetic starlight photons in the ISRF, which hardens the IC spectrum in the center preventing a fast decrease of IC flux at higher energies. This circumstances were already taken into account for the IC template calculation, which takes varying ISRF composition into account.
4.2. Inverse Compton Scattering

Figure 4.4: IC Skymaps. (a) Skymap of the $\gamma$-ray flux integrated from 0.059 GeV to 513 GeV (see equation 4.1) that originates from inverse Compton scattering of propagated cosmic ray electrons on photons of the ISRF. The z-axis shows the flux in units of cm$^{-2}$s$^{-1}$sr$^{-1}$. Dark blue pixels correspond to values that are below or equal the lowest value of the z-axis. (b) Skymap of the relative errors of the IC normalization factors derived from MINUIT. White pixels correspond to cones with less than $5 \times 10^{-6}$ cm$^{-2}$s$^{-1}$sr$^{-1}$ IC contribution.

In [8] an unsolved deficiency of bremsstahlung in the disk appeared whereas inverse Compton distribution matched the expectations. In contrast, in this analysis an opposite behavior can be identified as a lack of inverse Compton $\gamma$-rays appears in the disk for latitudes $b < |1.5^\circ|$, instead, where a clear suppression of two to three orders of magnitude arises. This may be due to the simplified cosmic ray spectra and could disappear by further improving the electron templates:

- The IC template is derived by the use of spatial templates of the ISRF composition of the $\gamma$-ray-code GAMMA-SKY from DRAGON although it contains uncertainties.
- The electron spectrum for IC is modeled with a broken power law ignoring a smooth transition between the two power laws, which would be more realistic. Additionally, the break position and the spectral indexes above and below were obtained from data and are not based on theoretically deduced facts.
- The electron spectrum for IC is the same at every position in the galaxy ignoring the possibility of many electron spectra in the galaxy (which is only due to technical reasons, admittedly, and can be resolved for further studies).

Furthermore, the BR and IC components are apparently strongly correlated (see figure 4.5) in the whole sky. For most cones the correlation is $\pm 1$ unless the BR or IC normalization
factor equals zero, then correlation is defined as zero, too. Thus, on the one hand, little changes in the spectra and templates, consequently, as done in this thesis might induce a suppression of either bremsstrahlung or inverse Compton radiation in the galactic bar. On the other hand, the suppression might be real physics as proposed hereafter.

Besides foregoing reasons, the following provides a reasonable explanation of the inverse Compton deficit by a conceivably happening process: Once formed by the collapsing dense core of a molecular cloud stars usually are surrounded by gas and dust remnants of the cloud. During their life cycle stars are continuously emitting radiations of all wavelengths typically peaking in the UV-range. Especially in the galactic bar, where the IC depletion occurs, MCs are very dense thus non-transparent for UV-light as gas envelopes repeatedly absorb most of it resulting in a photon’s mean free path shorter than the size of molecular clouds. The re-emitted photons lie in the IR-range with energies around two orders of magnitude lower than the initial UV-photon’s energy (see figure 2.1b). Since the cross section for inverse Compton scattering is proportional to $E^2$ it requires electrons with ten times higher energy to scatter the IR-photons to the same energy as UV-photons. Due to the electron spectrum being roughly proportional to $E^{-3}$ electrons with ten times higher energy are thousand times less abundant. Hence, the IC flux is supposed to be suppressed by the same factor.

The skymap does not exactly support this factor 1000 suppression, possibly as the foreground also contributes non-suppressed and MCs do not cover the entire field of view.

As mentioned in section 2.5 a MIC template corresponding to inverse Compton scattering within dense molecular clouds is not needed to obtain a good fit as inverse Compton is suppressed there. One can cross check this proposal by comparing the IC skymap with the
4.3. Bremsstrahlung

Figure 4.6.: **IC and MCR Latitude Distribution.** (a) Latitude distribution of the IC component at 1.91 GeV averaged for longitudes $l \leq |1.5^\circ|$, which shows increasing flux towards the galactic disk as expected from a spherical distribution of ISRF intensity. One notes a strong suppression of the IC contribution at latitude $b \leq |0.5^\circ|$ exactly where the MCs are located. (b) Latitude distribution of the MCR component at 1.91 GeV averaged for longitudes $l \leq |1.5^\circ|$. One notes a strong enhancement of the MCR contribution at latitude $b \leq |1.5^\circ|$ exactly where IC is suppressed.

MCR skymap (see figure 4.9a). If there actually is a correlation between IC suppression and molecular clouds, one will see a sharp cutoff in the latitude profile of IC at latitudes $b \leq |0.5^\circ|$ simultaneously arising with a sharp increase in the MCR latitude profile at the same latitude, which indicates massive MCs. Figure 4.6 confirms this feature providing evidence that the MCs indeed may cause IC flux suppression. Nevertheless, this could be due to a wrong MCR template.

**4.3. Bremsstrahlung**

The analysis of the BR component contributing to the diffuse $\gamma$-rays measured with Fermi-LAT is divided into two parts. The first part focuses on the skymap and its features. The second part gives an overview of the preferred electron spectrum in each cone.

**Analysis of the BR Component:** Figure 4.7a shows the skymap of the integrated BR component. The relative errors of the normalization factors can be obtained from figure 4.7b, which are low possibly due to the big variety of BR templates allowing the fit to chose the best template for each pixel. As expected from the fact that the targets of electrons to produce bremsstrahlung, which are gas and dust, are bound to the disk (see figure
4. Evaluation of the spectral Gamma-Ray Composition

Figure 4.7: BR Skymaps. (a) Skymap of the γ-ray flux integrated from 0.059 GeV to 513 GeV (see equation 4.1) that originates from bremsstrahlung of propagated cosmic ray electrons in the diffuse ISM. The z-axis shows the flux in units of cm\(^{-2}\)s\(^{-1}\)sr\(^{-1}\). Dark blue pixels correspond to values that are below or equal the lowest value of the z-axis. (b) Skymap of the relative errors of the BR normalization factors derived from MINUIT. White pixels correspond to cones with less than 5 \(\cdot\) 10\(^{-6}\) cm\(^{-2}\)s\(^{-1}\)sr\(^{-1}\) BR contribution.

2.1a) the strongest bremsstrahlung flux occurs in the galactic bar between longitudes \(-20^\circ < l < 30^\circ\). However, the skymap shows bremsstrahlung even at higher latitudes.

As one observes only the sum of the emissivity along the line-of-sight the bremsstrahlung origin is not clear and could, in principle, occur from electrons passing local gas or gas at high altitudes above and below the galactic disk. However, it is more likely that the bremsstrahlung contribution comes form local gas and dust as the line-of-sight crosses parts of the disk nearby earth for every latitude whereas no gas is found way above nor below the disk.

In [8] an unexplained suppression of bremsstrahlung in the disk occurred that contradicts the expectation. The lack of bremsstrahlung might trace back to the correlation with IC as mentioned in 4.2 or is due either to molecular clouds like in the PCR distribution, which then should lead to a substitution of BR by MBR, or to a unsuitable electron spectrum that could not describe the disk properly. Based on this, the fit was now offered a set of templates derived from several electron spectra. Apparently, the fit finds bremsstrahlung in the disk now. Hence, this prefers that the former electron spectrum was just not appropriate to describe the disk properly making the fit find no BR contribution there.

Analysis of the preferred Electron Spectrum: The fit was offered a set of BR templates
4.4. Pion Production and Bremsstrahlung in Molecular Clouds

corresponding to different electron spectra. In figure 4.8 one can obtain the preferred spectral indexes and breaks for each cone. The fit finds spectral indexes $-0.8 < \alpha \leq -0.2$ for most pixels in the galactic bar whereas in the halo the fit mainly finds spectral indexes below $-1.0$. In the bubbles all spectral indexes are found. Additionally, the fit finds break positions at $R > 1$ GV in the disk, in the bubbles and for regions in the halo. As no gas is located in such altitudes, the feature may occur from a very local gas accumulation crossed by the line-of-sight. Eventually, breaks at 0.2 GV and 0.4 GV are found for the rest of the pixels in the halo.

Obtained break positions and spectral indexes in the bar differ from the electron spectrum that was used in [8]. As a reminder, in [8] a fixed electron spectrum with break at 0.2 GeV and spectral index $-0.81$ below the break was used. The fit determines the best break position to be at higher rigidities than 0.2 GV and spectral indexes that are lower than $-0.81$. This observation supports the assumption made above that the lack of bremsstrahlung in the bar was due to a unsuited electron spectrum.

Figure 4.8.: Breaks and Spectral Indexes below Break of the Electron Spectrum.
Position of the break in GV (a) and spectral index below the break (b) of the electron spectrum used for calculation of the BR template.

Based on the fact that the fit finds a variety of preferred electron spectra whole over the galaxy it seems to be true that electrons with different energy spectra simultaneously exist in the galaxy at different positions and thus electrons suffer different energy losses depending on the exact gas density and ISRF intensity locally at the position of their origin, which determine the shape of the electron spectrum.
Figure 4.9.: **MCR Skymaps.** (a) Skymap of the γ-ray flux integrated from 0.059 GeV to 513 GeV (see equation 4.1) that originates from decaying π⁰s produced by propagated cosmic ray protons inside molecular clouds. The z-axis shows the flux in units of cm⁻²s⁻¹sr⁻¹. Dark blue pixels correspond to values that are below or equal the lowest value of the z-axis. (b) Skymap of the relative errors of the MCR normalization factors derived from MINUIT. White pixels correspond to cones with less than 5 · 10⁻⁶ cm⁻²s⁻¹sr⁻¹ MCR contribution.

### 4.4. Pion Production and Bremsstrahlung in Molecular Clouds

While in previous works the MCR template was obtained in a data-driven way and suggested to originate from magnetic cutoffs in this thesis it is modeled from the theoretical approach that deduces modified cosmic ray propagation in MCs because of a different damping of MHD waves in the MC envelopes, which changes the diffusion coefficient. Additionally a MBR template was freshly introduced. However, despite the new MCR parametrization and the new MBR template the fit is able to reproduce previous results that were obtained with the old MCR parametrization namely 1) good fits, especially in the galactic disk, signalized by both reduced χ² values near 1 (see figure 4.1a) and residuals below 2σ (see figure 4.2a), 2) an excess morphology indicated by the spatial MCR and MBR distribution similar to CO maps that trace molecular cloud’s column density and 3) a good description of the CMZ spectrum where the excess is the strongest (see figure 4.20), which provides for the first time ever not only a phenomenological but also a theoretical based evidence that the Fermi GeV-excess is indeed correlated with MCs regardless whether the GeV-excess is real physics or only a detector effect.

**Proton Component of Molecular Cloud Cosmic Rays:** Figure 4.9a shows the skymap of the integrated MCR flux. One clearly observes an strong MCR flux in the galactic bar and extended regions exactly were a suppression of PCR flux was found. Additionally, the
longitude profile plot of the MCR component along the disk at 1.91 GeV in figure 4.10a emphasizes an enhanced MCR flux in direction of the Cygnus-Orion (70° ≤ l ≤ 90°), Scutum-Centaurus (−50° ≤ l ≤ −40°) and Carina-Sagittarius (−80° ≤ l ≤ −60°) spiral arm where MCs are located, which supports the molecular cloud hypothesis. Eventually, the fit finds a broad band of significant MCR contribution for latitudes b < |15°| as in the PCR skymap originating from parts of the line-of-sight crossing the galactic disk nearby earth.

In figure 4.11 one can obtain the break position of the proton spectrum for every cone and a longitude profile of the distribution of the breaks in the disk. The authors of [11] show that the break position depends inverse proportional on the density of the molecular cloud’s envelope. Following this approach, the fit is supposed to find the lowest breaks in the CMZ and the spiral arms where one finds the densest clouds and increasing break positions for any other longitude. Alternatively, if the break in the spectra corresponds to the strength of the MCs’ magnetic fields, which increase with density, like proposed by [6], [7] and [8], one expects an inverse shape of the break distribution with the highest breaks occurring for CMZ and the spiral arms and lower breaks for any other latitude.

Unfortunately, the fit satisfyingly finds neither first nor second shape. On the one hand, the highest break in the disk (11 GV) is found in direction of Orion-Cygnus Arm that contains of the nearest MCs as the Solar System is located there. On the other hand, in the direction of the Carina-Sagittarius Arm the lowest break possible (4 GV) fits best. Furthermore, the skymap of breaks shows high breaks (> 10 GV) even outside the disk. Since no MCs are located there the MCR contribution must stem from local molecular clouds crossed by the line-of-sight, which are probably less dense than in the central bulge. This observations supports the theoretical prediction. Otherwise, the break towards CMZ is at 8 GV, which is neither the highest nor the lowest break, thus does not match any prediction. As a conclusion, as the obtained breaks in the proton spectrum for molecular clouds show no preferred behavior both hypothesis may play a significant role so that the breaks are mixing up both.

**Electron Component of Molecular Cloud Cosmic Rays:** The authors of [11] derive the modified propagation in molecular clouds not only for protons but uniformly for charged cosmic rays, therefore particularly also for electrons. This led to the introduction of a new MBR template corresponding to cosmic ray electrons emitting bremsstrahlung in MCs. As deduced by [11] the break position in the proton and electron spectrum has to be identical, thus figure 4.11, which shows the breaks in the proton spectrum, also holds for the electron spectrum.

The resulting spatial MBR flux distribution as well as the relative errors of the normalization factors can be obtained from figure 4.12. In general, the MBR skymap resembles the morphology of the MCR component, especially in the bar and in direction of the spiral arms the MBR contribution is enhanced (see figure 4.10b). The MBR flux is significant lesser, which is reasonable due to the smaller fraction of electrons in cosmic rays compared to protons.

**Correlations:** In order to analyze the morphology of the MCR and MBR component
in detail the fit was repeated in a $1^\circ \times 1^\circ$ binning around the galactic center for longitudes $l \leq |40^\circ|$ and latitudes $b \leq |40^\circ|$. The resulting integral skymaps of each component can be found in figure A.10 in the appendix. Since MCR and MBR both should be correlated to molecular clouds in the following the sum of them is taken. Figure 4.13b shows the skymap of the sum of MCR and MBR integrated over all energies, whose morphology matches the map of the CO $J = 2 \rightarrow 1$ radio emission [33] measured by the Planck satellite that traces molecular cloud’s column density, which can be obtained from 4.13a.

The denser a molecular cloud is the more targets are seen by penetrating protons and electrons, thus, molecular cloud emissivity increases with its density indicated by a strong MCR and MBR component. The same holds for CO emission. The matching morphology of CO and the sum of MCR and MBR is emphasized in figure 4.13c where the integrated flux of the $\gamma$-ray components in a certain pixel is plotted against the corresponding CO emission in the same pixel. This was done for all pixels in the galactic disk for latitudes $l \leq |2^\circ|$. In figure A.11 in the appendix one can find the scatter plots of CO and all $\gamma$-ray components. The correlation between CO and the sum of MCR and MBR is stronger than the correlation between CO and other $\gamma$-ray components. This fact shows clear evidence for a threefold correlation between the Fermi GeV-excess traced by a strong contribution of the MCR and MBR component and the molecular cloud column density traced by the CO map measured by the Planck satellite.

All things considered the results obtained with the new MCR and MBR templates provide stunning support of the theoretical predictions. Note that the CO morphology was no input in the fit but the fit resembles it just from the data, which is impressive since the
4.5. Pion Production in Sources

As like for the MCR component, this thesis manages to reproduce results of previous works on the SCR component \[21\] \[22\], which are presented in the following.

Figure 4.14 shows the fit results of the SCR component, which corresponds to the hard γ-ray emissivity of point sources. As can be obtained from figure 4.14a the fit finds strong SCR contribution in the galactic bar although the point sources were subtracted from the Fermi data. Furthermore, the SCR component contributes significantly to the γ-ray flux in the bubbles, which is expected from the fact that the hard $-2.1$ proton injection spectrum leads to a γ-ray spectrum that describes the data of the Fermi bubbles well, whereas nearly no SCR contribution is found in the halo. As always, the SCR template was allowed in each cone so that the fit itself could decide whether to use it or not. The fact that the fit is able to resemble the Fermi bubbles without having spatial information inputted is impressive. This observation matches the results of previous works and provides evidence of a connection between the bubbles and the disk, which is discussed later in section 4.6.5.

The hard $-2.1$ proton injection spectrum is expected for freshly accelerated protons in SNRs. Being the final stage of a star supernovae are located in the bar and the spiral arms where the star forming molecular clouds are. So, the SCR contribution in the disk

MCR and MBR templates were allowed in every cone but the fit only uses strong MCR and MBR contributions in the cones where molecular clouds are found.

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MCR and MBR templates were allowed in every cone but the fit only uses strong MCR and MBR contributions in the cones where molecular clouds are found.
4. Evaluation of the spectral Gamma-Ray Composition

Figure 4.12: **MBR Skymaps.** (a) Skymap of the $\gamma$-ray flux integrated from 0.059 GeV to 513 GeV (see equation 4.1) that originates from bremsstrahlung of propagated cosmic ray electrons in molecular clouds. The $z$-axis shows the flux in units of cm$^{-2}$s$^{-1}$sr$^{-1}$. Dark blue pixels correspond to values that are below or equal the lowest value of the $z$-axis. (b) Skymap of the relative errors of the MBR normalization factors derived from MINUIT. White pixels correspond to cones with less than $5 \cdot 10^{-6}$ cm$^{-2}$s$^{-1}$sr$^{-1}$ MBR contribution.

...probably originates from unresolved point sources that produce $\gamma$-rays in their expanding shock waves if protons scatter on matter within producing $\pi^0$s. If this is true, an enhanced SCR contribution in the disk should occur exactly there where the MCR and MBR component contributes strongly since MCR and MBR are correlated with molecular clouds. This can be checked by comparison of the longitude profile plots.

Such a longitude profile plot of the SCR component in the disk at 1.91 GeV for latitudes $b \leq |1.5^\circ|$ is shown in figure 4.15a. Indeed, the distribution is similar to the MCR and MBR profile (see figures 4.10a and 4.10b). In order to get a more detailed view on the correlation between SCR, MCR and MBR the disk was re-binned in a $1^\circ \times 1^\circ$ binning and the fit procedure was repeated. The resulting integrated SCR flux (see figure A.10 in the appendix) in each pixel in the disk then is plotted against the sum of the integrated MCR and MBR flux, which emphasizes the correlation as can be obtained from figure 4.15b. The correlation coefficient between SCR and the sum of MCR and MBR is 0.75. A correlation between the SCR and the former MCR component was already found in previous works. In this thesis the correlation between the SCR and the new MCR component is found to be 0.71 and the correlation factor with the MBR component is 0.5. The correlation between SCR and the other $\gamma$-ray components is less (see figure A.12 in the appendix), which indicates a real connection between SCR and molecular clouds traced by the MCR and MBR component.
4.6. Selected Regions of the Sky

Figure 4.13: Spatial Distribution of MCR+MBR around the Galactic Center and Correlation with CO Radio Emission. (a) Skymap of CO $J = 2 \rightarrow 1$ transition emission that traces molecular cloud’s column density [33]. (b) Detailed spatial distribution of the sum of the MCR and MBR component around the galactic center integrated from 0.059 GeV to 513 GeV (see equation 4.1) for longitudes $l \leq |40^\circ|$ and latitudes $b \leq |40^\circ|$ in a fine $1^\circ \times 1^\circ$ binning. (c) Scatter plot of the sum of the fluxes of the MCR and MBR component integrated from 0.059 GeV to 513 GeV (see equation 4.1) and CO for latitudes $b < |2^\circ|$.

For further evidence, one can compare the SCR contribution in the disk with the $^{26}$Al-decay emission maps in figure 4.16a [34]. As explained in section 2.2, $^{26}$Al is produced in magnesium rich sources and traces sources, consequently.

The scatter plot of the integrated SCR flux and $^{26}$Al-decay emission can be obtained from figure 4.16b. The correlation between SCR and $^{26}$Al-decay emission is not perfect but still stronger than the correlation between $^{26}$Al and the other $\gamma$-ray components, which can be found in figure A.13 in the appendix. Since the aluminum cores propagate before they decay their decay position not necessarily matches their origin. Therefore, a perfect strong correlation with SCR was not expected. Note that the fit resembles the sources traced by $^{26}$Al just by data.

4.6. Selected Regions of the Sky

Having studied the distribution and details of each spectral component of the $\gamma$-ray sky in the following selected regions of the sky are of interest and analyzed with respect to the shape of the Fermi spectrum and its spectral composition. Then, the spectra are interpreted and compared to the expectation. Furthermore, the correlation between the $\gamma$-ray components are shown and analyzed.
4. Evaluation of the spectral Gamma-Ray Composition

Figure 4.14: SCR Skymaps. (a) Skymap of the γ-ray flux integrated from 0.059 GeV to 513 GeV (see equation 4.1) that originates from decaying π⁰s produced by freshly accelerated cosmic ray protons in sources. The z-axis shows the flux in units of cm⁻²s⁻¹sr⁻¹. Dark blue pixels correspond to values that are below or equal to the lowest value of the z-axis. (b) Skymap of the relative errors of the SCR normalization factors derived from MINUIT. White pixels correspond to cones with less than 5 · 10⁻⁶ cm⁻²s⁻¹sr⁻¹ SCR contribution.

4.6.1. Whole Sky

If one decides to run the fit algorithm for the whole sky as one bin, which is a field of view with solid angle 4π, one studies the average γ-ray flux reaching earth from any direction. The mean γ-ray spectrum of the whole sky as one bin is shown in figure 4.17. One obtains that the fit finds contributions of all 7 templates used.

The BR template dominates up to energies of ≈ 1 GeV as both the Fermi data and the BR template have similar shapes in this energy region. The fit finds a break in the electron spectrum at 1.2 GV and a spectral index −1.7 below to best describe the data. Above the break the BR spectrum softens and thus does not longer dominate for higher energies. Instead, the MCR template peaking at ≈ 2 GeV contributes the strongest to the Fermi spectrum. The fit finds a break at 10 GV in the proton spectrum for molecular clouds to best describe the data. Since the MCR flux decreases faster with energy than the total Fermi flux one needs a harder γ-ray component to compensate. This is done by the SCR template, which dominates above ≈ 30 GeV. Additionally, the fit finds contributions of the PCR, IC and MBR component whose break equals the MCR break per definition. In total, the Fermi data averaged for the whole sky are incredible well described by the model indicated by a χ²/d.o.f. well below 1, although the systematic errors recommended by the Fermi-collaboration were multiplied with 0.5.
4.6. Selected Regions of the Sky

Figure 4.15: **SCR Longitude Distribution in the Disk and Correlation between SCR and MCR+MBR.** (a) Longitude distribution of the SCR flux times $E^2$ at $E = 1.91$ GeV averaged for latitudes $b \leq |1.5^\circ|$. (b) Scatter plot of the sum of the fluxes of the MCR and MBR component integrated from 0.059 GeV to 513 GeV (see equation 4.1) with and the integrated SCR component for latitudes $b \leq |2^\circ|$.

The fact that MCR (corresponding to $\pi^0$-production within MCs) contributes stronger than PCR (corresponding to $\pi^0$-production in diffuse gas) is not expected as only 40% of the interstellar gas is bound in molecular clouds. This may be due to a wrong MCR template, which may absorb a fraction of PCR as observed in the PCR skymap (see figure 4.3a).

Furthermore, it is quite surprising that IC is below the isotropic background at every energy although inverse Compton scattering is the only process that with high probability occurs in the halo as CMB photons electrons scatter on are present everywhere. This result could perhaps be due to the correlation between IC and BR, which is $-0.91$ (see correlation matrix $M_{\text{Whole Sky}}$). A strong correlation between IC and BR in nearly every cone was already shown in 4.5 but not for the whole sky.

$$M_{\text{Whole Sky}} = \begin{pmatrix} \text{PCR} & IC & BR & \text{SCR} & \text{MCR} & \text{MBR} \\ \text{PCR} & 1.00 & -0.66 & 0.89 & 0.66 & 0.78 & -0.34 \\ IC & -0.66 & 1.00 & -0.91 & -0.98 & -0.28 & 0.74 \\ BR & 0.89 & -0.91 & 1.00 & 0.91 & 0.50 & -0.64 \\ \text{SCR} & 0.66 & -0.98 & 0.91 & 1.00 & 0.25 & -0.72 \\ \text{MCR} & 0.78 & -0.28 & 0.50 & 0.25 & 1.00 & 0.26 \\ \text{MBR} & -0.34 & 0.74 & -0.64 & -0.72 & 0.26 & 1.00 \end{pmatrix} (4.2)$$
4. Evaluation of the spectral Gamma-Ray Composition

Figure 4.16: Galactic $^{26}\text{Al}$ Emission Map and Correlation between SCR and $^{26}\text{Al}$ Emission. (a) Skymap of the galactic $^{26}\text{Al}$-decay emission map that traces sources [34]. (b) Scatter plot of the SCR component integrated from 0.059 GeV to 513 GeV (see equation 4.1) and $^{26}\text{Al}$-decay emission for latitudes $|b| \leq 2^\circ$.

A strong negative correlation between IC and BR means that if one increases the IC flux, the BR flux will decrease. Thus, a fraction of BR could be replaced by IC, which then reduces the relative contribution of BR and enhances the relative contribution of IC simultaneously.

**Correlations:** If one studies the correlation matrix for the whole sky, one will notice that most components are strongly correlated with every other component. This is because the whole sky is treated as one pixel. Since the observed galaxy is the same for each component the strong correlations are not surprising.

4.6.2. The Galactic Disk

In the following the mean $\gamma$-ray spectrum of the galactic disk is studied. Therefore, the disk is re-binned into one single bin extending over all longitudes and latitudes $b \leq 1.5^\circ$ and a fit is performed. The resulting $\gamma$-ray spectrum can be obtained from figure 4.18.

The $\gamma$-ray spectrum is characterized by a maximum at around 1 GeV and a hard high energy tail. The fit finds contributions of all spectral components but the contribution of IC is nearly zero thus not visible. This is expected from the observation, that the IC template is suppressed in the disk (see figure 4.4a), which may be due to a wrong IC template or real physics as explained in section 4.2. The fit finds an electron spectrum with break at 1.2 GeV and a spectral index $\sim 0.8$ below to best describe the data. The BR component is dominant in the low energy regime. At around 0.7 GeV the MCR component becomes dominant and determines the Fermi $\gamma$-ray spectrum, which matches the expectation since the MCR template describes the Fermi GeV-excess that is the strongest in the disk. Above
4.6. Selected Regions of the Sky

Figure 4.17: Spectrum of the whole Sky. Spectral composition of the diffuse Fermi γ-ray spectrum for the whole sky as one bin. Shown is the flux per energy multiplied with $E^2$ for each component contributing to the Fermi γ-ray spectrum as well as the total flux of the model (black solid line), which well describes the Fermi data (blue dots). The black dashed line corresponds to the isotropic background, which is equal for each field of view. The legend indicates the exact solid angle of the field of view, the break position of the proton and electron spectrum for molecular clouds (MCR break), the break position of the interstellar electron spectrum (BR break) for BR and the spectral index below the break (BR index), the $\chi^2$ value and the reduced $\chi^2$ per degree of freedom.

Around 10 GeV the SCR component that corresponds to hard γ-rays from sources is the dominant contributor, which is fine since the sources are located in the disk and thus a strong SCR contribution is expected. The Fermi γ-ray spectrum shows a kink at the same energy. The fit quality is good indicated by a reduced $\chi^2$ well below 1. The correlation matrix is $M_{\text{Disk}}$.

$$M_{\text{Disk}} = \begin{pmatrix}
PCR & 1.00 & 0.11 & -0.83 & 0.51 & -0.16 & -0.44 \\
IC & 0.11 & 1.00 & -0.21 & 0.23 & -0.19 & -0.20 \\
BR & -0.83 & -0.21 & 1.00 & -0.85 & 0.63 & 0.79 \\
SCR & 0.51 & 0.23 & -0.85 & 1.00 & -0.76 & -0.75 \\
MCR & -0.16 & -0.19 & 0.63 & -0.76 & 1.00 & 0.91 \\
MBR & -0.44 & -0.20 & 0.79 & -0.75 & 0.91 & 1.00
\end{pmatrix} \quad (4.3)$$

**Correlation:** In the following the correlations observed for the whole sky as one pixel are
4. Evaluation of the spectral Gamma-Ray Composition

Figure 4.18: Spectrum of the Galactic Disk. Spectral composition of the diffuse Fermi \( \gamma \)-ray spectrum for the galactic disk as one bin. Shown is the flux per energy multiplied with \( E^2 \) for each component contributing to the Fermi \( \gamma \)-ray spectrum as well as the total flux of the model (black solid line), which well describes the Fermi data (blue dots). The black dashed line corresponds to the isotropic background, which is equal for each field of view. The legend indicates the exact solid angle of the field of view, the break position of the proton and electron spectrum for molecular clouds (MCR break), the break position of the interstellar electron spectrum (BR break) for BR and the spectral index below the break (BR index), the \( \chi^2 \) value and the reduced \( \chi^2 \) per degree of freedom.

compared with the correlations that are found if one studies only the spectral composition of the galactic disk spectrum. Every \( \gamma \)-ray component except IC corresponds to \( \gamma \)-ray production in gas via either \( \pi^0 \)-production (PCR, MCR, SCR) or bremsstrahlung (BR, MBR) whereas IC corresponds to inverse Compton scattering between electrons and photons. As gas is only found in the disk (and maybe in the Fermi bubbles) but photons are apparent everywhere in the halo, one expects the absolute correlation coefficients between IC and the other "disk-shaped" components to reduce. This is indeed found: The correlation between IC and BR decreases from \(-0.91\) to \(-0.21\) and the correlation between IC and SCR is reduced from \(-0.98\) to \(0.23\), for example.

Furthermore, one expects the absolute correlations between the "disk-shaped" components to increase, which also can be confirmed: The correlation between SCR and MCR increases from \(0.25\) to \(-0.76\) and the correlation between MCR and MBR increases from \(0.26\) to \(0.91\) for instance. Eventually, the correlation between PCR and MCR decreases which contradicts the expectation since both contribute strongly in the disk. This may be due to the small latitude region chosen \((b \leq 1.5^\circ)\). As observed in the skymaps of PCR and MCR (see figures 4.3a and 4.9a), PCR does not contribute there whereas MCR is
strong perhaps because the MCR template absorbs a fraction of PCR. Thus, they can not be correlated.

4.6.3. The Galactic Bar

In the following the spectrum of the galactic bar is studied. The galactic bar lies in the center of the Milky Way where the spiral arms are radiating from and contains the most molecular clouds and cosmic ray sources, consequently. Therefore, it is a interesting region of the sky. The field of view is chosen to be $b \leq |1.5^\circ|$ in latitude and $-30^\circ \leq l \leq 40^\circ$ in longitude, which includes the outer parts of the bar, though. The mean $\gamma$-ray spectrum measured by Fermi-LAT can be obtained from figure 4.19.

Figure 4.19.: **Spectrum of the Galactic Bar.** Spectral composition of the diffuse Fermi $\gamma$-ray spectrum for the galactic bar as one bin. Shown is the flux per energy multiplied with $E^2$ for each component contributing to the Fermi $\gamma$-ray spectrum as well as the total flux of the model (black solid line), which well describes the Fermi data (blue dots). The black dashed line corresponds to the isotropic background, which is equal for each field of view. The legend indicates the exact solid angle of the field of view, the break position of the proton and electron spectrum for molecular clouds (MCR break), the break position of the interstellar electron spectrum (BR break) for BR and the spectral index below the break (BR index), the $\chi^2$ value and the reduced $\chi^2$ per degree of freedom.

In comparison to the galactic disk spectrum the galactic bar spectrum looks similar in shape but the $\gamma$-flux is increased: In the disk spectrum the flux at 1 GeV is $\approx 5 \cdot 10^{-5}$ GeV$^{-1}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$ whereas in the bar spectrum it is around twice as much ($\Phi \approx 1 \cdot 10^{-4}$ GeV$^{-1}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$). The fit finds contributions of all $\gamma$-ray components, in particular also IC which was not found in the disk spectrum (see figure 4.18). The shape of the $\gamma$-ray spectrum is determined by the MCR template, which dominates for energies below
10 GeV, and the SCR template, which is the dominate component above leading to a kink in the $\gamma$-ray spectrum. The fit finds the electron spectrum with break at 1 GeV and spectral index $-0.1$ below to best describe the data. The reduced $\chi^2$ is 1.031. The correlation matrix of the normalization factors of the templates is $M_{\text{Bar}}$.

$$
M_{\text{Bar}} = \begin{pmatrix}
PCR & IC & BR & SCR & MCR & MBR \\
PCR & 1.00 & 0.09 & 0.65 & -0.27 & -0.005 & 0.21 \\
IC & 0.09 & 1.00 & 0.76 & -0.82 & 0.82 & 0.80 \\
BR & 0.65 & 0.76 & 1.00 & -0.81 & 0.73 & 0.80 \\
SCR & -0.27 & -0.82 & -0.81 & 1.00 & -0.80 & -0.73 \\
MCR & -0.005 & 0.82 & 0.73 & -0.80 & 1.00 & 0.94 \\
MBR & 0.21 & 0.80 & 0.80 & -0.73 & 0.94 & 1.00 \\
\end{pmatrix}
$$

**Correlation:** In the following, the correlations observed for the galactic disk are compared to the correlations found in the galactic bar. The galactic bar is where the molecular clouds and consequently the sources for cosmic rays are located. The templates corresponding to molecular clouds and sources, respectively, are MCR and MBR and SCR. Therefore, one expects the absolute correlations between these three "bar-shaped" components to increase whereas the absolute correlations with the "disk-shaped" components BR and PCR as well as IC should decrease.

Indeed, the correlation between PCR and SCR decreases from 0.51 to $-0.27$, PCR and MCR decreases from $-0.16$ to $-0.005$ and the correlation between PCR and MBR is reduced from $-0.44$ to 0.21. The correlations between SCR, MCR and MBR remain strong. Unfortunately, the correlations between BR and the "bar-shaped" components are only slightly changed whereas the correlations with IC are even increased. This observation may be due to a wrong IC and BR template.

**4.6.4. Central Molecular Zone**

The Fermi GeV-excess is found in the galactic disk and is the strongest in the Central Molecular Zone, which is a rectangular shaped ($l \times b = 3.5^\circ \times 1.0^\circ$) region in direction of the center of the Milky Way. It contains 5% of the total mass of the Milky Way bound in dense molecular clouds, which mask the rest of the galaxy behind. Therefore, it is an interesting region of the sky. Figure 4.20 shows the $\gamma$-ray spectrum measured by Fermi as well as its spectral composition found by the fit. The $\gamma$-ray spectrum is characterized by the maximum between 1 GeV and 2 GeV and a hard tail at energies above $\approx 15$ GeV that are the hallmarks of the Fermi GeV-excess.

The MCR component contributes the strongest and follows the shape of the $\gamma$-ray spectrum dominating up to energies around 15 GeV. The fit choses the proton spectrum for molecular clouds with break at 8 GV to get the smallest $\chi^2$ value, which is 24.915. The $\chi^2$ per degree of freedom is 1.083 $\approx 1$, which indicates the fit quality. The MBR and BR components are also contributing strongly in the CMZ. The fit was offered several BR templates computed
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Figure 4.20: **Spectrum of the CMZ.** Spectral composition of the diffuse Fermi $\gamma$-ray spectrum for the CMZ. Shown is the flux per energy multiplied with $E^2$ for each component contributing to the Fermi $\gamma$-ray spectrum as well as the total flux of the model (black solid line), which well describes the Fermi data (blue dots). The black dashed line corresponds to the isotropic background, which is equal for each field of view. The legend indicates the exact solid angle of the field of view, the break position of the proton and electron spectrum for molecular clouds (MCR break), the break position of the interstellar electron spectrum (BR break) for BR and the spectral index below the break (BR index), the $\chi^2$ value and the reduced $\chi^2$ per degree of freedom.

from a set of interstellar electron spectra. The fit chose the one with break at 1.2 GV and spectral index $-0.1$ below the break to best describe the data. The break in the electron spectrum for molecular clouds from which the MBR template was calculated equals the MCR break per definition. The SCR component dominates above energies around $\approx 15$ GeV leading to a kink in the total flux at that energy. The PCR component is nearly negligible as it contributes a factor 100 less than the MCR component. Eventually, the fit found no IC contribution in the CMZ.

The MCR (and MBR) template was motivated by the hypothesis that within molecular clouds $\gamma$-ray emissivity is suppressed below a certain energy, which leads to a shift of the maximum towards $\approx 2$ GeV. If this was true, one expects a strong MCR and MBR contribution in the CMZ as it contains the most massive MCs, which is validated by the fit result and provides evidence that the GeV-excess is linked with molecular clouds.

The SCR component corresponds to $\gamma$-rays produced in sources. Since sources are connected with molecular clouds and since the hard SCR component can describe the high energy tail in the $\gamma$-ray spectrum one expects a strong SCR contribution in the CMZ, too. The fit confirms this. As observed in the skymaps of PCR and MCR (see figures 4.3a and 4.9a) the MCR template substitutes the PCR template within molecular. Indeed, the fit
4. Evaluation of the spectral Gamma-Ray Composition

finds a factor 100 lesser PCR flux compared to MCR which contradicts the expectation since diffuse gas is also found in the CMZ. Therefore, there is no reason why PCR should be suppressed. This may be due to a wrong MCR template.

The fact that IC does not contribute supports the hypothesis that inverse Compton scattering within MCs is suppressed because high energetic starlight is immediately absorbed by surrounding gas and dust so that electrons are not able to scatter enough photons up to the GeV regime, thus IC photons can not be detected with Fermi-LAT. However, the foreground should contribute nevertheless. The normalization factors of IC and BR are strongly correlated as mentioned in section 4.2, particularly in the disk and the bubbles, so that IC could appear if one finetuned the model. The correlation can only be calculated for non-zero normalization factors. Unfortunately, the IC normalization factor in the CMZ equals zero, which means that the correlation coefficient could not be determined. The correlation matrix is $M_{\text{CMZ}}$.

$$M_{\text{CMZ}} = \begin{pmatrix}
PCR & IC & BR & SCR & MCR & MBR \\
PCR & 1.00 & -0.89 & 0.22 & -0.09 & -0.05 \\
IC & - & - & - & - & - \\
BR & -0.89 & - & 1.00 & -0.23 & 0.45 & 0.24 \\
SCR & 0.22 & - & -0.23 & 1.00 & -0.22 & 0.43 \\
MCR & -0.09 & - & 0.45 & -0.22 & 1.00 & 0.67 \\
MBR & -0.05 & - & 0.24 & 0.43 & 0.67 & 1.00
\end{pmatrix}$$

Correlations: Except for PCR and BR the correlations between the $\gamma$-ray components are relatively low or decreased, at least, in comparison to the correlations observed for the galactic bar. Low correlation coefficients indicate that the fit is able to differentiate between the offered templates. This may be due to the CMZ being a high signal region.

4.6.5. Fermi Bubbles

The Fermi bubbles are two large scale $\gamma$-ray emitting structures symmetrically extending to latitude 55° above and below the galactic disk, which have a width of 40° in longitude and a sharp edge. Figure 4.21 shows an illustration. The Fermi bubbles are visible just from data without any analysis as can be obtained in figure 4.22a, which shows a skymap of the Fermi data at 21.45 GeV binned in 797 bins. To check whether this structure only occurs because of a smaller binning in this region, then it would only be an optical illusion, or is indeed a feature in flux distribution one can plot a longitude profile, which vanishes the effect of a different binning. A longitude plot of the Fermi data at latitude $b = 25^\circ$, just in the middle of the bubbles, can be found in figure 4.22b. Indeed, one notes a roughly flat flux distribution ($E^2 \cdot \Phi \lesssim (6 - 7) \cdot 10^{-7} \text{GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1}$) for longitudes $l > |40^\circ|$ and an increasing flux for longitudes $l \leq |40^\circ|$, where the bubbles are found, with a maximum flux of $\approx 2 \cdot 10^{-6} \text{GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1}$. 

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![Illustration of the Fermi Bubbles](image)

Figure 4.21: **Illustration of the Fermi Bubbles.** Illustrative image of the Fermi bubbles symmetrically extending $\approx 10$ kpc above and below the galactic disk with a width of 55° in longitude and a width of 40° in latitude. Picture taken from [35].

The bubbles are characterized by a relatively uniform hard $\gamma$-ray spectrum above a few GeV whose shape is connected with and determined by SCR and/or IC as they are the only templates contributing at higher energies leading to an excess of high energy photons. IC is weakly correlated with SCR with the correlation factor $-0.19$. This means the fit can distinguish both templates they can not replaced by each other since both are needed in the bubbles. Additionally, the Fermi bubbles’ spectra partly have a maximum at $1 - 2$ GeV. Figure 4.23 shows an exemplary bubble spectrum as well as its spectral composition of a cone towards the southern Fermi bubble, which is representative for every cone towards the bubbles. The exact solid angle is $5^\circ \leq l \leq 10^\circ$ and $-35^\circ \leq b \leq -30^\circ$. The correlation matrix is $M_{\text{Bubble}}$.

$$M_{\text{Bubble}} = \begin{pmatrix}
PCR & IC & BR & SCR & MCR & MBR \\
PCR & 1.00 & -0.26 & 0.73 & 0.26 & -0.43 & 0.35 \\
IC & -0.26 & 1.00 & -0.81 & -0.19 & 0.87 & -0.79 \\
BR & 0.73 & -0.81 & 1.00 & 0.23 & -0.91 & 0.81 \\
SCR & 0.26 & -0.19 & 0.23 & 1.00 & -0.25 & -0.17 \\
MCR & -0.43 & 0.87 & -0.91 & -0.25 & 1.00 & -0.89 \\
MBR & 0.35 & -0.79 & 0.81 & -0.17 & -0.89 & 1.00
\end{pmatrix}$$

(4.6)

If one compares the spectra of each pixel within the Fermi bubbles, one notices that the maximums in the spectra are distinct for small latitudes and vanish for higher latitudes. The strength of the maximum is linked with contributions from MCR, MBR or BR since these templates (for certain break positions) peak at energies that are similar to the maximum’s energy. When the maximum vanishes at higher latitudes the contributions of MCR, MBR and BR decrease, too. Furthermore, the behavior of the MCR, MBR and BR component at higher latitudes ($b \geq |15^\circ|$) at longitudes that are associated with the bubbles ($l \leq |20^\circ|$) does not differ from its behavior at longitudes outside the bubbles ($l \geq |20^\circ|$). Thus, one can conclude that the maximum obtained in the Fermi bubbles’ spectra is no intrinsic
4. Evaluation of the spectral Gamma-Ray Composition

Figure 4.22: **Fermi Data Skymap and Longitude Distribution of the Data.** (a) Skymap of the Fermi data at 21.45 GeV binned in 797 bins. The z-axis shows the flux multiplied with $E^2$ in units of GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$. (b) Longitude profile of the Fermi data at $E = 21.45$ GeV and latitude $b = 25^\circ$.

feature of the bubbles but stems from the line-of-sight crossing larger (smaller) parts of the disk for lower (higher) latitudes.

Now, one can check if this is also true for the hard tail above a few GeV. As the hard energy tail is similar in every pixel in the bubbles and does not depend on the latitude and since it is not found in spectra outside the bubbles it must indeed be an intrinsic feature of the bubbles providing evidence that the bubbles indeed are a far-away structure.

**Discussion of the Literature:** Further, the literature also prefers the explanation that the bubbles are a far-away structure over being local due to several features of the bubbles, particularly the symmetry of the bubbles and the hard spectrum. Latter is linked with sources, which if they were close would be also visible in synchrotron emission for instance, which they are not. It is more reasonable that the bubbles are connected with the galactic center and were formed either by the central black hole (jets, outflows or accretion events) or by supernovae in the central bulge or by an AGN-activity of the Milky Way in the past (see [36] and references within), which has already been observed in other galaxies yet. The authors of [37] even link the Fermi bubbles to a signal of Dark Matter annihilation.

The Fermi collaboration founds that the hard $\gamma$-ray spectrum can be explained by either proton collisions with gas in the bubbles and secondary leptons or by inverse Compton scattering between the ISRF and high energetic electrons. The corresponding proton (electron) spectrum can be approximated by a power law with spectral index $-2.13$ ($-2.17$), which is near the expected value for freshly accelerated cosmic rays in sources. Further
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Figure 4.23: Spectrum of the Fermi Bubbles. Spectral composition of the diffuse Fermi γ-ray spectrum for a cone towards the Fermi bubbles. Shown is the flux per energy multiplied with $E^2$ for each component contributing to the Fermi γ-ray spectrum as well as the total flux of the model (black solid line), which well describes the Fermi data (blue dots). The black dashed line corresponds to the isotropic background, which is equal for each field of view. The legend indicates the exact solid angle of the field of view, the break position of the proton and electron spectrum for molecular clouds (MCR break), the break position of the interstellar electron spectrum (BR break) for BR and the spectral index below the break (BR index), the $\chi^2$ value and the reduced $\chi^2$ per degree of freedom.

more, they found the electron hypothesis to better describe the data than the proton hypothesis even when one includes secondary leptons. As there is no significant variation in the bubbles’ spectra for different latitudes and if high energetic electrons are responsible for the Fermi bubble spectrum, one needs to explain both how electrons manage to reach altitudes of 10 kpc above and below the disk and how they do it without suffering energy losses. In other words, how is the electron spectrum kept hard during propagation in the bubbles? The Fermi collaboration proposes that electrons are either fast transported to high altitudes or re-accelerated within the bubbles. The authors of [38] support latter and propose electrons beeing stochastical accelerated (second order Fermi acceleration) by plasma wave turbulences in the bubbles. [36]

As inverse Compton scattering between electrons and photons is the only standard process leading to relatively hard γ-ray spectrum it is natural to propose that the Fermi bubbles’ spectrum stems from high energetic electrons scattering on photons of the ISRF. The authors of [39] question this approach but prefer a hadronic origin of the bubble spectrum. They show that a hard $-2.1$ proton spectrum could explain the observation if protons are
trapped within and confined to the bubbles for large timescales. This seems achievable if one assumes diffusive confinement due to the turbulent plasma of the bubbles.

Such a proton spectrum is expected for freshly accelerated protons in sources. Since protons suffer only negligible energy losses the spectrum only softens because of high energetic protons leaving galaxy more likely. However, if protons are trapped within the bubbles they cannot escape and their spectrum keeps hard. Due to their large propagation length a usual galactic wind is sufficient to push protons to altitudes of 10 kpc, which does not hold for electrons since latter would need larger velocities. However, protons only reach a steady-state with hard spectrum if they are continuously injected into the bubbles (by stars and supernovae). This supports that the bubbles are an convective outflow of the galactic center as only there the star formation ratio is high enough to ensure a continuous injection. Additionally, the authors of [39] show that the galactic center indeed supplies enough power by supernovae to explain the the emissivity of the bubbles.

Discussion of the Phenomena: Like in [39] in this thesis a hard proton spectrum with spectral index $-2.1$ was found to best describe the Fermi bubble spectrum, too. Additionally, the results of thesis match the observations of the authors of the paper and confirm their given explanation that the bubble spectrum originates from protons that produce $\pi^0$s uniformly whole over the bubbles. This can be obtained from figure 4.14a, where clearly is visible that the SCR component contributes with similar order of magnitude in the bubbles independent on the latitude. Further, the longitude profile of the SCR component is characterized by a sharp edge in flux at longitude $l = \pm 20^\circ$ whereas no SCR contribution is found anywhere else in the halo. Hence, it is plausible that the protons are confined to the bubbles.

Furthermore, this thesis supports the explanation of [38] and [36] that the bubbles’ spectrum has a leptonic origin: As can be obtained from figure 4.4a the IC component contributes not only in the bubbles but also in the halo, admittedly. This was also found for all the other $\gamma$-ray templates as said above but, in contrast, the IC distribution in the bubbles indeed differs from its distribution outside, which was not true for the other components. Since it is difficult to see in the IC skymap figure 4.24 provides profile plots that indicate the different behavior of IC within the bubbles:

Figure 4.24a shows the longitude distribution of the IC component at 0.07 GeV at latitude $b = 25^\circ$, which crosses the northern bubble. Though the IC flux varies strongly for different longitudes the trend is a sharp increase at $l \approx \pm 20^\circ$. This trend is found for every IC longitude profile through the bubbles, which indicated that one finds more radiation in the bubbles than in the halo.

Additionally, the IC latitude profile through the bubbles and the galactic center (see figure 4.6a) reveals a stepwise increasing flux from latitude $b = \pm 55^\circ$ on. This is exactly where the bubbles begin and indicates that the electron density in the bubbles increases with lower altitudes. In contrast, the latitude profiles for longitudes outside the bubbles show somehow a plateau of nearly constant IC flux, which only strongly increases in the disk but not in the halo (see figures 4.24b and 4.24c). This provides evidence that the electrons in the halo do not reach similar altitudes like in the bubbles.

Both things considered, the increase in IC both in latitude and longitude along the bubbles
4.6. Selected Regions of the Sky

Figure 4.24: IC Longitude and Latitude Distribution through the Fermi Bubbles.  
(a) Longitude distribution of the IC component at 0.07 GeV at latitude $b = 25^\circ$. 
(b,c) Latitude distribution of the IC component at 0.07 GeV at longitude $l = 30^\circ$ and $l = -30^\circ$.

and the sharp edge in SCR exactly where the Fermi bubbles are found, provide evidence that the spectrum of the Fermi bubbles has both a hadronic and a leptonic origin. Electrons contribute stronger in the lower parts of the bubbles than in the upper parts, which is plausible since less electrons reach high altitudes due to short propagation lengths. Nevertheless, because of the cosmic ray pressure in the central bulge electrons are carried further above and below the disk within the bubbles than anywhere else, at least. Protons instead contribute similar all over the bubbles driven by the cosmic ray pressure, which is plausible since they have longer propagation lengths allowing them to reach 10 kpc altitude without significant losses.
5. Conclusion and Outlook

The Fermi GeV-excess was found by analyzing the Fermi data of the diffuse γ-rays arriving Earth from any direction with standard propagation models, which simulate the propagation of cosmic rays from sources to Earth and the γ-ray emissivity from the three standard γ-ray producing processes π⁰-decay (PCR), inverse Compton scattering (IC) and bremsstrahlung (BR) by the use of spatial templates of the ISM and ISRF. The determined background γ-ray emissivity then can be subtracted from the Fermi data in order to find a signal.

Unfortunately, the source and gas distributions are only poorly known, which leads to large uncertainties, and the standard propagation models do not include modified π⁰-production in molecular clouds and sources leading to a bad description of the disk, especially, indicated by an excess of high energetic γ-rays referred to as the Fermi GeV-excess.

Therefore, previous works, which are the basis for this thesis, follow an alternative approach namely performing an spectral fit of the Fermi data instead of an spatial fit eliminating the need of the spatial templates. The spectral templates each correspond to an energy spectrum of different γ-ray producing processes in the galaxy and are derived from broken and unbroken power laws that model the galactic proton and electron energy spectra whose parametrization is obtained from data or motivated. All spectral templates are offered to the fit simultaneously, which then can decide which linear combination of the templates best describes the data. This leads to a spectral decomposition of the Fermi spectrum including a determination of both the background and the signal in an arbitrary fine spatial resolution, which is only limited by the data’s spatial resolution and statistics.

Previous works showed that PCR, IC and BR alone are not suitable to describe the disk properly but introducing γ-ray optimized templates that correspond to modified γ-ray production within molecular clouds (MCR) and unresolved point sources (SCR) explains the excess of high energetic γ-rays although the spectral fit is based on a very simple model. Despite the simpleness, the model leads to a nearly perfect description of the Fermi γ-ray sky making as few assumptions as possible.

This thesis attempted to improve the model which succeeded. In this thesis the range of possible break positions in the broken proton spectrum, which models the effect of molecular clouds, was extended and the spectral index below the break, which was determined to be −0.7 in a data-driven way before, was changed to −1 following the predictions of a recent paper [11] that for the first time ever theoretically deduced a mechanism of modified cosmic ray propagation in molecular clouds. The theoretically predicted parametrization of the cosmic ray spectra within molecular clouds was near the data-optimized parametrization, which is a stunning evidence of the correctness of the molecular cloud hypothesis. This is underlined by the fact that previous results on the morphology of the excess could.
be reproduced with the new model. The results are that the first hallmark of the Fermi-GeV excess, the shift of the maximum of the γ-ray spectrum towards 2 GeV, traced by the contributions of the MCR template has a morphology like the CO radio emission maps, which trace molecular cloud’s column density. Consequently, the Fermi GeV-excess is correlated with molecular clouds regardless whether it is a real physical excess or a detector effect. Furthermore, the hard high energy tail, the second hallmark of the Fermi-GeV excess, is correlated with unresolved sources in the disk, which lie within molecular clouds, indicated by strong contributions of the SCR template, which follows the source distribution traced by the $^{26}$Al emission line.

Additionally, the MBR template corresponding to bremsstrahlung in molecular clouds that was proposed by previous works to improve the fit was finally introduced in this thesis but with a different parametrization following the predictions of the recent paper. The MBR template shows the same morphology like MCR, which supports the molecular clouds hypothesis.

Additional MIC templates corresponding to inverse Compton scattering within molecular clouds were not taken into account in this thesis as they do not significantly improve the fit since the shape of the inverse Compton spectrum does not strongly depend on the electron spectrum.

Furthermore, in this thesis for the first time ever several BR templates were simultaneously offered to the fit motivated by the cosmic ray electrons having small propagation lengths due to strong energy losses which leads to the plausible assumption, that electrons in the Milky Way can be described by different broken energy spectra, whose parametrization depends on the exact gas and ISRF density each electron sees. The high energy part of the spectrum was chosen to be identical in each spectrum whereas the low energy part is modeled with a set of spectral indexes and break positions. Unfortunately, the deviations in shape of the individual BR templates due to a different gas composition in each field of view needed to be disregarded in favor of a the variety of BR templates. Nevertheless, since the amount of BR templates was increased the fit quality could be further improved indicated by smaller $\chi^2$ values whole over the sky and reduced residuals. The new set of BR templates also eliminated the unphysical lack of bremsstrahlung in the disk that occurred in the analysis of the spatial distribution of bremsstrahlung in [8].

Instead, a lack of IC in the galactic bar exactly where the molecular clouds are occurred in this thesis. On the one hand, a suppression of IC within molecular clouds can be well reasoned by starlight being absorbed in the dense medium of molecular clouds and re-emitted with a larger wavelength, which leads to a reduction of high energetic photons that can be scattered up to energies relevant for Fermi-LAT. On the other hand, the lack of IC in the galactic bar could equally probable be induced by the choice of the electron spectra and disappear when small changes are applied because the IC template is strongly correlated with BR, which in contrast to IC is dependent on the parametrization of the electron spectrum. The large correlations between BR and IC observed in the fit may be caused by the simpleness of the model.
An idea to improve the model is the introduction of a smooth transition between the two separate power laws that build a broken power law. Additionally, one could take heavier cores like helium, lithium etc. into account for diffuse $\pi^0$-production as well as secondary protons.

All things considered, the current model of the diffuse Fermi $\gamma$-ray sky is already able to nearly perfectly describe the data although it is so simple, in particular it provides a possible explanation for the GeV-excess by proving that the excess is correlated with molecular clouds and unresolved point sources, which could not be found by standard propagation models, regardless whether the excess is real physics or actually caused by a detector effect.
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A. Appendix

Figure A.1: The GeV-Excess in the Central Molecular Zone. The Central Molecular Zone fitted with the three standard γ-ray producing processes π⁰-decay (red), inverse Compton Scattering and bremsstrahlung (both too small for the selected scale). The black solid line (nearly identical to the red line) corresponds to the total γ-ray flux obtained by the best fit. Obviously, the data are not well described.
Figure A.2: 

**Fermi Gamma-Ray Sky.** Diffuse Fermi data after subtraction of the point sources at every of the 30 energy bins multiplied with $E^2$. The skymaps are binned in longitude and latitude in $1.0^\circ \times 1.0^\circ$ bins. The $z$-axis shows the flux per solid angle in units of GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$. 
Figure A.3.: **Residual Skymaps of the new Model.** The skymaps show the residuals of the new model at every of the 30 energy bins as indicated. Residuals are defined as the difference between Fermi data and the model divided through the error of the data. The z-axis corresponds to the 5σ-range.
Figure A.4: **PCR Skymaps.** Skymaps of the $\gamma$-ray flux that originates from decaying $\pi^0$s produced by propagated cosmic ray protons in the diffuse ISM at every of the 30 energy bins multiplied with $E^2$. The z-axis shows the flux in units of GeVcm$^{-2}$s$^{-1}$sr$^{-1}$. Dark blue pixels correspond to values that are below or equal the lowest value of the z-axis.
Figure A.5: IC Skymaps. Skymap of the γ-ray flux that originates from inverse Compton scattering of propagated cosmic ray electrons on photons of the ISRF at every of the 30 energy bins multiplied with $E^2$. The z-axis shows the flux in units of GeVcm$^{-2}$s$^{-1}$sr$^{-1}$. Dark blue pixels correspond to values that are below or equal the lowest value of the z-axis.
Figure A.6: **BR Skymaps.** Skymaps of the γ-ray flux that originates from bremsstrahlung of propagated cosmic ray electrons in the diffuse ISM at every of the 30 energy bins multiplied with $E^2$. The z-axis shows the flux in units of GeVcm$^{-2}$s$^{-1}$sr$^{-1}$. Dark blue pixels correspond to values that are below or equal the lowest value of the z-axis.
Figure A.7: MCR Skymaps. Skymaps of the γ-ray flux that originates from decaying π⁰’s produced by propagated cosmic ray protons inside molecular clouds at every of the 30 energy bins multiplied with $E^2$. The z-axis shows the flux in units of GeVcm⁻²s⁻¹sr⁻¹. Dark blue pixels correspond to values that are below or equal the lowest value of the z-axis.
Figure A.8: **MBR Skymaps.** Skymaps of the γ-ray flux that originates from bremsstrahlung of propagated cosmic ray electrons in molecular clouds at every of the 30 energy bins multiplied with $E^2$. The z-axis shows the flux in units of GeVcm$^{-2}$s$^{-1}$sr$^{-1}$. Dark blue pixels correspond to values that are below or equal the lowest value of the z-axis.
Figure A.9: **SCR Skymaps.** Skymaps of the γ-ray flux that originates from decaying $\pi^0$s produced by freshly accelerated cosmic ray protons in sources at every of the 30 energy bins multiplied with $E^2$. The z-axis shows the flux in units of GeVcm$^{-2}$s$^{-1}$sr$^{-1}$. Dark blue pixels correspond to values that are below or equal the lowest value of the z-axis.
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Figure A.10.: **Integrated Skymaps.** Detailed spatial distribution of the $\gamma$-ray components around the galactic center integrated from 0.059 GeV to 513 GeV (see equation 4.1) for longitudes $l \leq |40^\circ|$ and latitudes $b \leq |40^\circ|$ in a fine $1^\circ \times 1^\circ$ binning. The z-axis shows the flux in units of cm$^{-2}$s$^{-1}$sr$^{-1}$. Dark blue pixels correspond to values that are below or equal the lowest value of the z-axis.

Figure A.11.: **Scatter Plots of CO Radio Emission and the Gamma-Ray Components.** Scatter plot of CO and the $\gamma$-ray components integrated from 0.059 GeV to 513 GeV (see equation 4.1) for latitudes $b < |2^\circ|$. 

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Figure A.12.: Scatter Plots of the SCR component and the other Gamma-Ray Components. Scatter plot of the SCR component integrated from 0.059 GeV to 513 GeV (see equation 4.1) and the other integrated $\gamma$-ray components for latitudes $b < |2^\circ|$.

Figure A.13.: Scatter Plots of Al-26 Decay Emission and the Gamma-Ray Components. Scatter plot of $^{26}$Al-decay emission and the $\gamma$-ray components integrated from 0.059 GeV to 513 GeV (see equation 4.1) for latitudes $b < |2^\circ|$.
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Figure A.14: Spectra for latitudes $90^\circ \geq b \geq 72.5^\circ$. Longitudes decreasing from $180^\circ$ to $-180^\circ$.

Figure A.15: Spectra for latitudes $72.5^\circ \geq b \geq 55^\circ$. Longitudes decreasing from $180^\circ$ to $-180^\circ$. 
Figure A.16.: Spectra for latitudes $55^\circ \geq b \geq 45^\circ$. Longitudes decreasing from $180^\circ$ to $-180^\circ$. 
Figure A.17: Spectra for latitudes \(45^\circ \geq b \geq 35^\circ\). Longitudes decreasing from \(180^\circ\) to \(-180^\circ\).
Figure A.18.: Spectra for latitudes $35^\circ \geq b \geq 25^\circ$. Longitudes decreasing from $180^\circ$ to $-180^\circ$. 
Figure A.19.: Spectra for latitudes \( 25^\circ \geq b \geq 15^\circ \). Longitudes decreasing from \( 180^\circ \) to \(-180^\circ \).
Figure A.20.: **Spectra for latitudes** $15^\circ \geq b \geq 5^\circ$. Longitudes decreasing from $180^\circ$ to $-180^\circ$. 
Figure A.21.: Spectra for latitudes $5^\circ \geq b \geq 1.5^\circ$. Longitudes decreasing from $180^\circ$ to $0^\circ$. 
Figure A.22: Spectra for latitudes $5^\circ \geq \theta \geq 1.5^\circ$. Longitudes decreasing from $0^\circ$ to $-180^\circ$. 
Figure A.23.: Spectra for latitudes $1.5^\circ \geq b \geq 0.5^\circ$. Longitudes decreasing from $180^\circ$ to $-180^\circ$. 
Figure A.24: Spectra for latitudes $0.5^\circ \geq b \geq -0.5^\circ$. Longitudes decreasing from $180^\circ$ to $-180^\circ$. 
Figure A.25.: **Spectra for latitudes** $-0.5^\circ \geq b \geq -1.5^\circ$. Longitudes decreasing from $180^\circ$ to $-180^\circ$. 
Figure A.26: Spectra for latitudes $-1.5^\circ \geq b \geq -5^\circ$. Longitudes decreasing from $180^\circ$ to $-0^\circ$. 
Figure A.27.: Spectra for latitudes $-1.5^\circ \geq b \geq -5^\circ$. Longitudes decreasing from $0^\circ$ to $-180^\circ$. 

A. Appendix
Figure A.28.: Spectra for latitudes $-5^\circ \geq b \geq -15^\circ$. Longitudes decreasing from $180^\circ$ to $-180^\circ$. 
Figure A.29: Spectra for latitudes $-15^\circ \geq b \geq -25^\circ$. Longitudes decreasing from $180^\circ$ to $-180^\circ$. 
Figure A.30: Spectra for latitudes $-25^\circ \geq b \geq -35^\circ$. Longitudes decreasing from $180^\circ$ to $-180^\circ$. 
Figure A.31.: Spectra for latitudes $-35^\circ \geq b \geq -45^\circ$. Longitudes decreasing from $180^\circ$ to $-180^\circ$. 
Figure A.32: *Spectra for latitudes* $-45^\circ \geq b \geq -55^\circ$. Longitudes decreasing from $180^\circ$ to $-180^\circ$. 
Figure A.33: **Spectra for latitudes** \(-55^\circ \geq b \geq -72.5^\circ\). Longitudes decreasing from 180° to \(-180^\circ\).

Figure A.34: **Spectra for latitudes** \(-72.5^\circ \geq b \geq -90^\circ\). Longitudes decreasing from 180° to \(-180^\circ\).