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Master Thesis of

Your Name

At the Department of Physics
Institut für experimentelle Teilchenphysik
(ETP)

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Duration: 1. March 2017 – 28. February 2018

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.

Karlsruhe, 18th February 2018

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(Your Name)

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Introduction

History of CR and GR detection. -> 20th century to today Why are they so important -> highest particle energy, we are not able to recreate that -> good understanding of their origin and evolution can inform on the sources, the galaxy, all that we havn't thought of yet (DM?) GC excess in GR -> problem in our understanding of CR -> Something is missing : DM, MSP or MCs Lets compare the 3 main hypothesis -> fitting the latest observations with current theory

Problem : Which of these hypothesis works better ?

Plan: -> theory -> method -> results and discussion

Conclusion

Resume what I did -> fit -> method

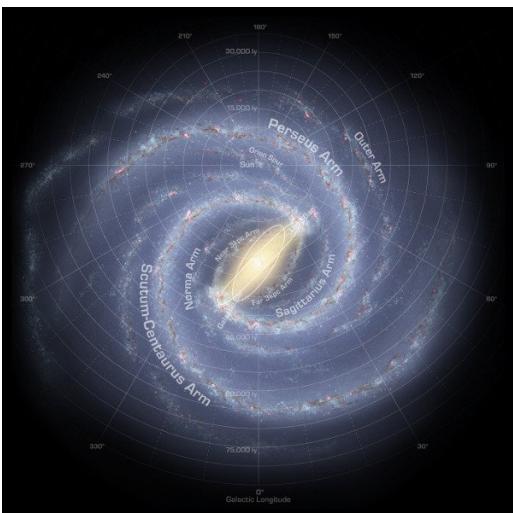
Results -> MCR is the fit winner -> DM and MSP also work, but do not follow their predictions

Opening -> Put limit on DM mass and cross-section -> Find other ways to study DM

1. Theory

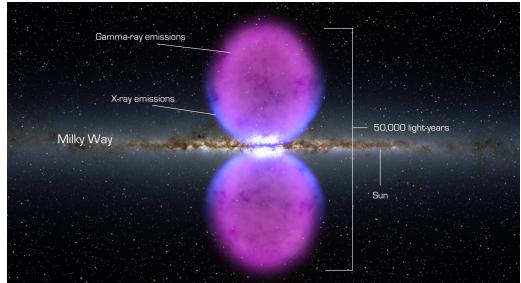
1.1. Our Milky Way

1.1.1. General properties



(a) source:

<http://galaxymap.org/drupal/node/171>



(b) source: NASA's Goddard Space Flight Center

Figure 1.1.: The Milky Way, as seen from two different angles.

For a long time, people thought the universe was constituted of only one galaxy, the Milky Way, the one in which the Sun and the Earth orbit. The discoveries of other galaxies in the universe came only in the 20's thanks to Edwin Hubble. There is still a lot of unknown around those objects, but the Milky way is pretty well known and will play a major role in the following chapters. Its shape, density and composition are three main factors playing a role in cosmic ray physics and can not be avoided.

First of all, the Milky Way is a barred spiral arm galaxy, meaning it has two main spiral arms, connected in their center by a straight galactic bar. Those arms and bar have higher matter concentration than the rest due to the way stars orbit around the center.

Its diameter exceeds 40 kpc for a mass of around $10^{12} M_{\odot}$ and a thickness under 1 kpc. The Sun and the Earth are rotating 8 kpc from its center in 240 Myr. All the different objects of the galaxy can be found in this thin disk of matter, mainly in the spiral arms. It includes the stars, planets and over massive objects, but also all the dust and gas clouds. As seen from the Earth, the disk looks like a narrow band of a few degrees in latitude, but with a very high concentration of gas and dust. In 2010, two large scale structures were detected to the north and the south of the GC. With a diameter of 7kpc, these two "bubbles" extend up to 40 degrees in latitude and 20 in longitude. They are a source of high energy gamma-rays and were detected by the Fermi Large Area Telescope (LAT).

The disk of the Milky way is composed of matter in different forms, like stars, gas or dust. Stars are one of the first source of the interstellar radiation field (ISRF). They can be compared to black body radiating at different energies depending on their temperature. They are the main source of UV photons, that play a major role in the gas evolution. Stars are forming inside gas and dust clouds, collapsing on themselves under their own gravitational pressure. The gas is composed in the vast majority of hydrogen, but heavier elements and even molecules can be found at the center of large clouds where ultra-violet light can not penetrate. One of these is the CO molecule, often used to as a tracer of molecular clouds. Even if molecules can only be found where the UV starlight can not break them apart, molecular clouds (MC) will designate large region of gas and dust, that can possibly contain stars inside. (**add gas/dust ratio**) Dust is also present in the galactic disk. It can be warmed by the starlight, and cooled via infrared light emission. This IR source is also part of the ISRF.

To Do

Electromagnetic field runs all across the milky way, taking its source in rotating stars, molecular clouds, or any moving charged particle. It has been observed and measured, but it is very complex and has no favorite direction at small scales (interstellar scale).

1.1.2. Dark Matter

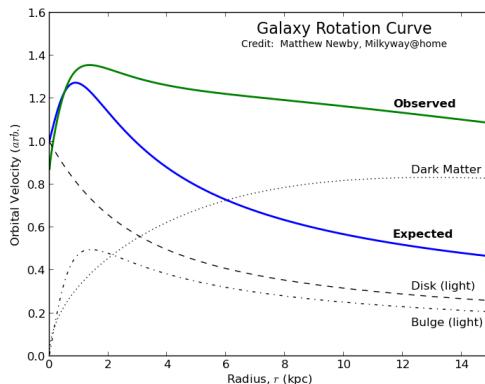


Figure 1.2.: Orbital velocity of the Milky Way as a function of the radius. A clear discrepancy between the theory and the observation can be seen above a 2 kpc radius. Source: Matthew Newby, Milkyway@home

The shape of spiral galaxies is well known today, with thousands of examples throughout the universe. This knowledge can be used to mathematically simulate them, and in particular their rotation speed as a function of the distance to the center. It was a big

surprise when the observed angular speed did not match the theory. One of the solution to explain this difference was the introduction in the standard model of dark matter (DM), which was suppose to bring a lot of invisible mass into the system. It still has not been observed and a few theories exist on its exact nature. But even without knowing exactly what it is, its mass distribution can still be deduced from the observed rotation curve of the galaxy. The predicted distribution is a spherical halo extending way beyond the 40 kpc of the galactic matter disk. Its density peaks in the GC, and decrease with the radius following a particular density profile. The exact profile is not known, but a popular one is the Navarro-Frenk-White (NFW) profile defined as follows :

$$\rho(r) \propto \frac{1}{(r/r_S)(1+r/r_S)^2} \quad (1.1)$$

where r_S is the scale radius.

One of the most popular is the Weakly Interacting Massive Particles (WIMP). They are supposed to be non standard particles with a large mass, neutral, and only sensitive to the weak force, making them very difficult to observe. But no particles of the standard model has the right properties.

1.2. Tools

To speak about cosmic-rays, one often speaks about their spectral shape, or energy spectrum. These terms refer to the particle flux (Φ in $GeV^{-1}.s^{-1}.cm^{-2}.sr^{-1}$) as a function of their energy (in GeV). In other terms, how many particles of a given energy would a one centimeter square instrument observe in one second. This can often be modeled by a power law of the form $\Phi \propto E^{-\alpha}$ where α is called the spectral index. If α is small, the spectrum is said to be "hard", because there are an important proportion of high energetic particles. On the contrary, a "soft" spectrum has a bigger spectral index and describe a lower density of high energy particles compared to low energies.

In the following chapter though, the preferred representation of the energy distribution is via the energy flux (in $GeV.s^{-1}.m^{-2}.sr^{-1}$), simply obtained by multiplying the particle flux by its energy square ($E^2 \times \Phi(E)$). In other terms, how much energy does the instrument receive every second for particles of a given energy E . This is only done to facilitate the reading of the graphs and does not affect the underlying physics.

The terms of "soft" and "hard" can be applied to any kind of energy spectrum, even if it is not a power law, it will only describe the relative proportion of high and low energy particles.

1.3. Physic of cosmic rays

1.3.1. Creation of CR

Several sources of cosmic rays exist in the universe. Cosmic rays are very energetic and thus can only be produced by very energetic phenomena. Particularly powerful events are supernovae, ejecting relativistic particles during the burst. The dying star will eject a lot of its mass to form a supernova remnant (SNR) surrounding either a white dwarf, a neutron star or a black hole depending on the initial mass of the star. These SNR

could also play a role after the explosion via the Fermi process. An already energetic particle would bounce in the shock wave created by the explosion, and gain energy via hydrodynamic or magneto-hydrodynamic before escaping when the energy is sufficient. An other important source of cosmic rays are the pulsars. These rapidly rotating neutron stars and their intense electromagnetic field create high energy particles such as protons and electrons. This can last as long as the pulsar rotates fast enough, but it can takes 10 to 100 Myrs before the turn-off occurs. A third source are the actives galactic nuclei (AGN), also known as quasars. These objects consist of a super-massive black hole at the center of a galaxy. First discovered thanks to their radio emission, they are also able to eject CR, certainly via Fermi or centrifugal acceleration.

1.3.2. Propagation of CR

Once they are emitted, the cosmic rays propagate through the galaxy under the influence of different interactions. The first one to notice is the complex magnetic field created by all sorts of objects, from stars to molecular clouds or any distribution of charged particles. It is not particularly strong (**put values**) compared to the heliosphere or what can be created on Earth, but its very large scale suffice to bend the CR's path in all direction until the point where it is impossible to backtrack their origin. An other possible interaction is the collisions with other particles. It will obviously depends on the density distribution of those colliders in the galaxy. We can expect a higher number of those in the disk, where the density of molecular clouds is the highest.

All these influences can be modeled by a diffusion model, mainly defined by its diffusion coefficient D, which describes the average distance traveled by the particles during a certain time. The higher the coefficient, the faster a particle will diffuse in the galaxy. Each phenomenon can be attributed one of those coefficient to describe its effect on the cosmic rays. (**give values for D_{mag}, D_{coll}...**) While the diffusion coefficient for the galactic magnetic field can be taken as constant throughout the milky way, the diffusion coefficient due to collision is proportional to the particles density. We can then expect a smaller coefficient in molecular clouds, where the density can reach (**value!**).

This coefficient will also define the cosmic ray densities in various locations of the galaxy. Indeed, the more a particle's path is twisted and convoluted, the harder it will be to move away from its origin. This way, a higher density of cosmic rays can be found in low diffusion coefficient areas like molecular clouds. In comparison, the region outside the galactic disk has a low density of CR due to a weak electromagnetic field and small gas and dust density. However, the bubble region is outside the disk and has a higher concentration of CR than other regions outside the disk. This is due to a direct outward emission of CR from the GC region. With a high diffusion coefficient, these CR are ejected light years away (see Fig. 1.1b), forming two symmetric regions extending north and south up to 40 degrees in latitude.

The consequences of such diffusion processes is an isotropic cosmic-ray sky on Earth. In whatever direction the instruments look at, they measure the same CR flux. This complicate a lot their study, since no information about their origin or their journey can be learned from direct observation. It is where gamma-rays enter the scene to play a major role in the indirect detection methods.

ToDo

ToDo

ToDo

1.3.3. Gamma-ray creation

Since the cosmic rays we observe on Earth can not give us a clue about their origin, some indirect detection methods are required. Luckily, cosmic rays interact in a lot of ways with their environment, as described in the previous section. These interactions can leave detectable traces that can be observed. The most common is the production of light, via creation of high energy photon in the GeV range. Once created, these gamma rays can be blocked or absorbed, but not deflected. Linking the gamma-ray and cosmic ray requires to know the processes in play. Here is a list of the main phenomena.

1.3.3.1. Pion decay

The interaction between hadronic cosmic rays and the interstellar medium can lead to π^0 production through different reaction. These newly created particles can rapidly decay into a pair of gamma-rays.

1.3.3.2. Bremsstrahlung

The charged CR passing near an other charged particle of the ISM or in a magnetic field will be deflected by the electromagnetic interaction. In the process, the CR will lose energy via the emission of photons. The energy of the latter will depend on the energy of the electron and the intensity of the electromagnetic field. The more the electron is deflected, the higher the energy of the emitted photons. Even though proton CR are charged, the main source of bremsstrahlung gamma-rays is electrons and positrons. This is due to the much lower mass of the electrons, making them easier to deflect.

(give numbers for B field and proton in MC)

ToDo

1.3.3.3. Inverse Compton

A third process can take create gamma-rays when the CR electrons interact with a photon of the interstellar radiation field (ISRF). When a high energy electron collides with a low energy photon, the electron can transfer some of its kinetic energy to the photon, giving him enough energy to enter the gamma range.

So number of gamma rays coming from inverse Compton is directly linked to the electron distribution and the ISRF of the galaxy. The latter is composed of three major components, the starlight, the dust emission and the cosmological microwave background (CMB). The first component is directly linked to the star distribution, and will be dominant in the disk, where all the star are concentrated. The starlight emits as a black body, peaking in the UV range. The dust emission comes from the infra-red emission of warm dust. It will also be mainly present in the disk, since the dust clouds are pretty flat. Finally, the CMB is peaking in the microwave range but is uniformly present everywhere in the universe, and therefore in the galaxy. It will be dominant where the two others are negligible, namely outside the galactic disk.

(talk about synchrotron and ionization losses)

ToDo

1.3.3.4. Other sources

The three previously described processes are general processes that can happen everywhere at any energy. But even though the process might always be the same, two class

of sources can be defined: the diffuse and the point sources. The first correspond to all the CR propagating through the ISM and interacting with its components. It will be the object of study of the following chapters. The second are the gamma-rays produced directly at the CR origin (in SNR, AGN or pulsars as described in section 1.3.1). Every one of these event should be studied separately and are still not understood perfectly. Since these sources are very far away and can not be resolved by the instruments, they will be referred to as point sources in the following chapters. The spectral shape of these events is generally known and categorized as a function of the event type. This makes the recognition easier and both emissions can be separated this way.

1.3.4. Gamma-ray observations

Gamma-rays are not easy to observe from Earth, simply because they are absorbed by the atmosphere. It is a chance for life to develop, but complicates their observation. To measure them, the instrument has to be launched in orbit above the atmosphere, where gamma-rays are not yet absorbed. For example the Fermi Large Area Telescope (LAT) mounted on the ISS do the job with a lot of success. This instrument maps the gamma ray sky between 20 MeV and 300 GeV ([cite](#)), detecting all the point sources emission, but also the diffuse background emission.

To Do

In theory, the knowledge of the processes that generate gamma-rays from cosmic-rays and the precise composition of the Milky Way should allow to explain the observations. Propagation models and simulations are able to output the expected energy spectrum of gamma-rays reaching Earth from an initial distribution of cosmic-rays (not taking the point sources into account). But some problems show up when confronting the theory and the observations, as will be discussed in the following section.

1.4. What are the unresolved problems of the precedent chapter

Several studies have already tried to see how the predictions of the gamma rays emission and the observations compare. The three main phenomena were modeled to try to recreate the spectrum observed here on Earth. The results are clear, they do not always match. Even though the observations of the poles or any high latitude regions can be well explained by a PCR, BR and IC component, the models have troubles to reproduce the surroundings of the galactic disk, and in particular the GC or the Bubbles. Two main problems can be identified. A high energy deficit in the models, where the high energy tail (> 50 GeV) observed can not be reproduced, and a spherical excess centered in the GC around 2 GeV.

The first one shows a lack of high energy cosmic-rays in the models. A mean of injecting more relativistic particles has to be found in order to fill this gap. One explanation could be that we do not observe only diffuse emission in the disk. The point source emission could not be totally subtracted due to the high density of sources. The CR that do not have the time to propagates have a harder spectrum, thus providing a higher ratio of high energy gamma-rays.

Two main ideas have emerged to explain the spherical excess. First is the presence of dark matter in the galaxy in the form of weakly interacting massive particles (WIMP). The spatial distribution of these particles would follow a Navarro-Frank-White (NFW)

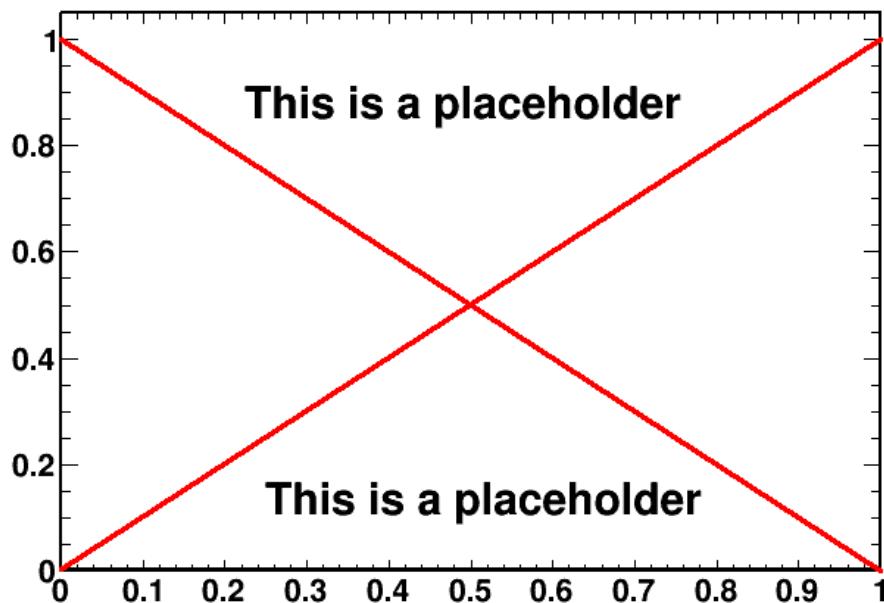


Figure 1.3.: chi2 distribution of first fits (not mines)

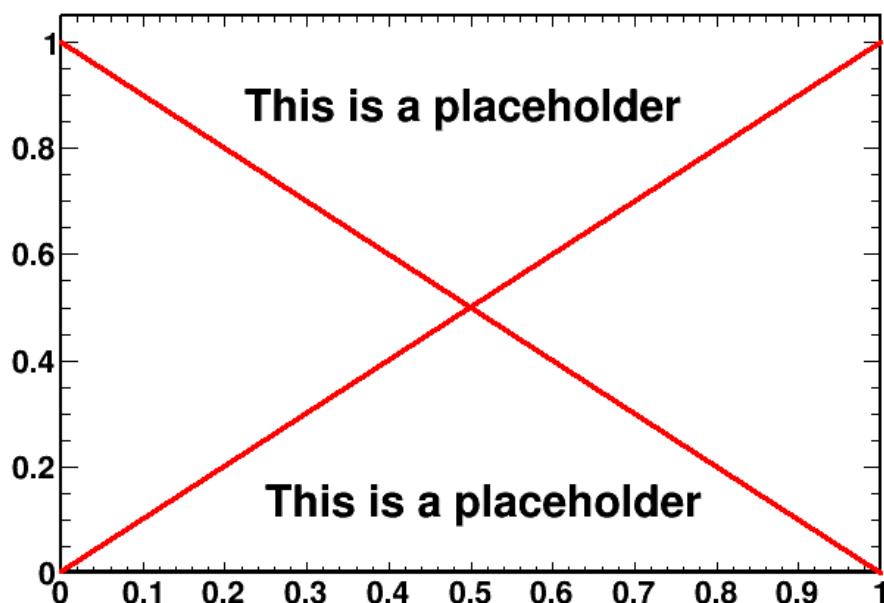


Figure 1.4.: shape of the excess

profile centered at the GC. They are also expected to produce gamma rays when annihilating with each other via hadrons production. In theory, if the mass of a WIMP particle is around 50 GeV, the expected gamma spectrum would peak around 2 GeV, where the excess is observed. (**cite**) The study of the excess could put strong limits on the mass and annihilation cross section of such WIMP and confirm, or infirm the theory. The second theory does not involve new physic, but unobserved millisecond pulsars. They would also be spherically distributed around the GC and their gamma spectrum peaks around 2 GeV. A few thousands of them would be needed to recreate the intensity of the excess. The main default of this explanation resides in the fact that we have observed only a few hundreds pulsars so far when we expect ten times more.

ToDo

2. Method

2.1. Data origin

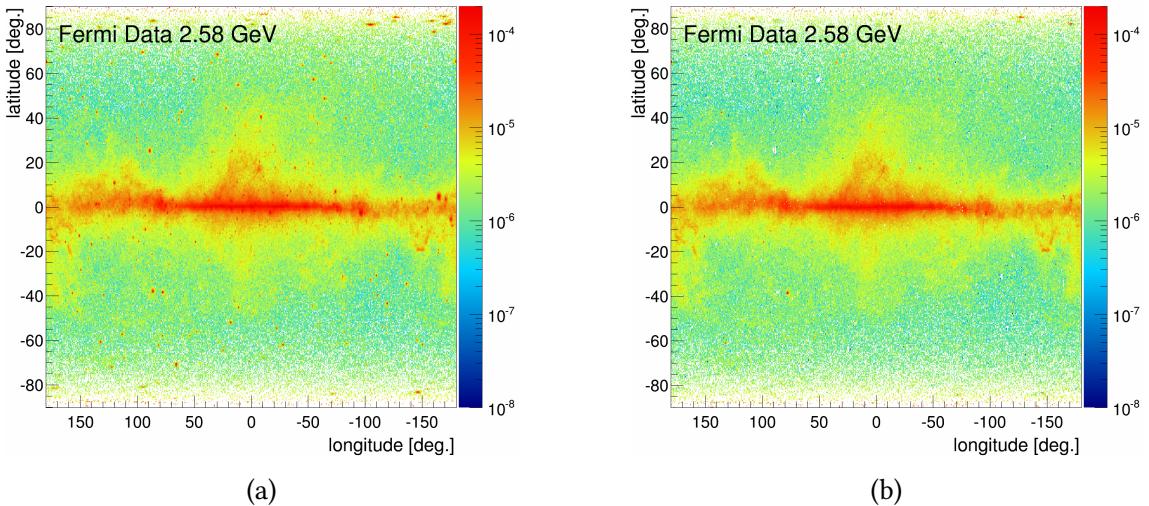


Figure 2.1.: Measured gamma ray flux before (left) and after (right) point source subtraction in $\text{GeV}/\text{s}/\text{m}^2/\text{sr}$. Most of the spots formed by point sources have disappeared, leaving only the diffuse background emission. The subtraction is not perfect, and can create artificial "holes" in the map (for example at coordinates (90, 25) or (50, 60)).

All the following work is based on the measurement of gamma rays coming from intra- and extra-galactic sources. The quality and accuracy of the data is one of the most important point that will determine the general quality of the results. Thus it is capital to be certain that the gathering and treatment was done properly.

The Fermi Large Area Telescope (LAT) observed the gamma-ray sky since 2008 and provides all the data of this work. All the information and data are available on the web and anybody can access them, using the tools given by Fermi.

Since the observation is still on-going it is important to stay up-to-date. The reconstruction method is also being improved regularly, improving every time the statistics, the systematic errors and the point source subtraction. One of the most important step in the treatment process is the first one, the selection of the events. Every photon measured is saved along with all its properties in a big data file. Then this long list is filtered to keep only the interesting observations. The filter can be based on the incoming direction, the energy or the time of observation, but also on the quality of the event reconstruction. This last cut can be critical. It will determine the chances that the measured event is in fact a gamma ray, and not some background noise polluting the data. Of course, the more strict the filter is, the less events are kept for analysis and the statistical errors can become large. This work uses the CLEAN class recommended by the Fermi team for diffuse emission analysis. ([cite Fermi sciencetools](#))

ToDo

The main parameters of the selection can be found in Tab 2.1.

Parameter name	Parameter value	Description
Event class	256 (CLEAN)	Quality parameter. Varies the level of background noise.
Event type	3	Back+front event.
Time boundaries	INDEF	Selecting all events since beginning of observation
Minimum energy (MeV)	58.4731	Minimum energy of the event.
Maximum energy (MeV)	513056	Maximum energy of the event.
zmax (degrees)	90	Maximum zenith angle to get rid of the Earth limb contaminations, as recommended by the LAT instrument team

Table 2.1.: List of the main parameters used for data selection.

An other important point is the creation of the exposure map. It basically tells how long the telescope spend observing a given part of the sky. After dividing the count map by the exposure, a flux map is obtained that does not depends on the observation time of particular regions.

The goal of this work is to study the diffuse sources of gamma-rays from inside and outside the milky way. Of course, the LAT does not differentiate them from point sources gamma rays. This has to be done manually as the last step in the treatment process. A large catalog of gamma ray point sources (3FGL) is available on line on NASA website ([cite site](#)). This catalog lists most of the known and identified point sources, along with their spectral shape and flux. This information can then be used to model the number of counts coming from point sources and their spatial and energetic distribution. To achieve this, the point sources properties must be combined with the instrument properties. For example, the point source flux is multiplied by the exposure time corresponding to its position. This flux must also pass through the instrument and its defaults will deform the initial shape of the source. For a point source, the final image obtain on the detector is the Point Spread Function (PSF) of the telescope and is given with the fermi tools. Every point source is convoluted by the PSF corresponding to the initial event selection, creating the final point source map as would be observed by the instrument. Once this model map is obtained, it is subtracted from the data to only keep the diffuse emission (see Fig. 2.1). Since the models are never perfect and all point sources are not listed, errors

ToDo

or anomalies in the observations can appear. Keeping the dataset up-to-date allows to use the latest catalogs and avoid a lot of mistakes.

Once all the treatment is done, a flux map of the entire sky in $\text{counts}/\text{s}/m^2/\text{GeV}/\text{sr}$ is produced. The map is divided in bins of 0.5×0.5 degrees on a Cartesian projection. Every bin contains 30 logarithmic energy bins ranging from 60 MeV to 513 GeV with a 1.2 multiplicative step. The final data cube is thus of dimension $720 \times 360 \times 30$. For visibility purposes, every energy bin is multiplied by its energy squared, becoming an energy flux in $\text{GeV}/\text{s}/m^2/\text{sr}$. This will be the default units used for the rest of this work.

The errors on the data are coming from two sources. First are systematic errors introduced by the instrument or the treatment process. They are around 3%, but can increase for low or high energies (Fig. 2.2). These errors have multiple causes, mainly the PSF and the energy resolution (or energy dispersion) of the instrument. The plot shows how the systematic errors varies when correcting or not for these effects. The treatment done here accounts for energy dispersion. The second source is the statistical errors, proportional to the square root of counts. This property will make them decrease when the acquisition time will increase. They are dominant at high energy (above 50 GeV) where events are rare. On contrary at low energies (around 100 MeV), the systematic errors dominate. The final equation is the following :

$$\sigma_{tot} = \sqrt{\sigma_{sys}^2 + \sigma_{stat}^2} = \sqrt{\sigma_{sys}^2 + \frac{1}{N}} \quad (2.1)$$

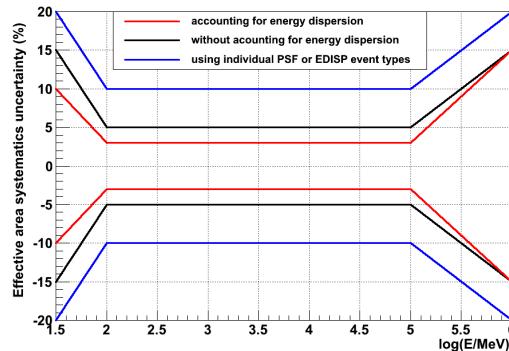


Figure 2.2.: Systematic error for Pass 8 data as function of the energy and the treatment quality. The energy dispersion is the energy resolution of the instrument. This effect is known and can be corrected (in red), lowering the systematic errors. This is what was done here. The black line does not account for energy dispersion. The blue line shows the systematics for specific event types, a kind of analysis that does not make sens for this work. The few percents gained at very low energies (below a few hundred MeV), where the statistical uncertainties are not dominant anymore, can be critical.

2.2. Model components

2.2.1. From cosmic rays to gamma-rays

The gamma-ray spectra used in this study are directly calculated from the cosmic ray spectra. The next section describes the cosmic ray distribution used to get the gamma-ray spectra corresponding for every processes that are modeled. Once the CR spectrum

To Do

is defined, a propagation code ([cite](#)), DRAGON, is used to determine the gamma-rays spectrum emitted. For most of the components, the spectral shape does not vary depending on the direction, only its normalization, but that does not play a role in the fitting method (cf ([section on fitting method](#))). The code uses a model of the galaxy (ISRF, matter distribution, etc...) and the input CR spectra for protons and electrons to produce gamma-ray spectra as an output for pion decay, bremsstrahlung and inverse compton. The inverse compton is slightly different from the others because of the ISRF.

To Do

2.2.2. Basic components

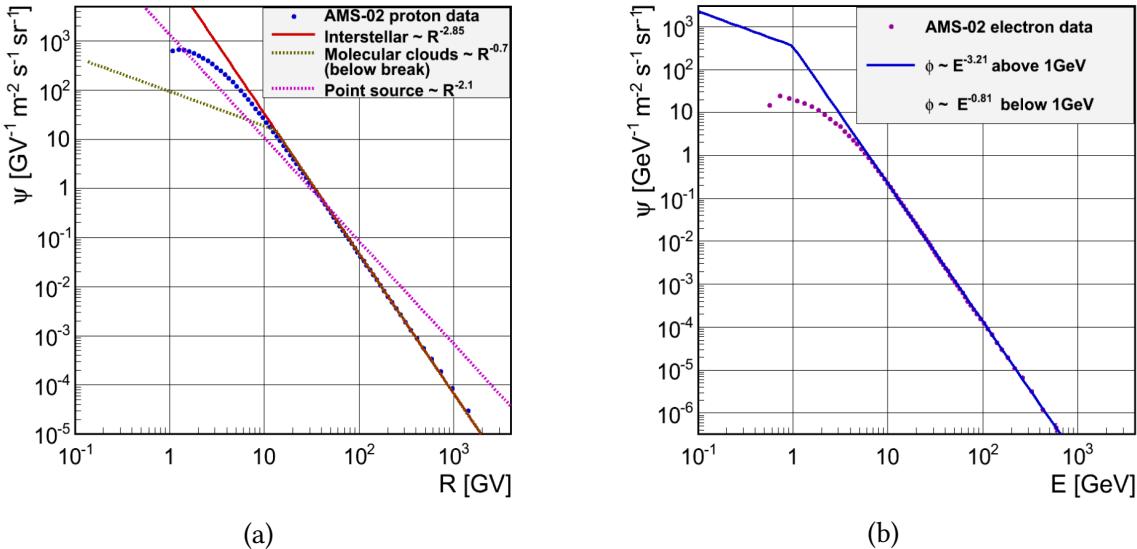


Figure 2.3.: Cosmic ray spectra used to determine the gamma ray templates. (a): Power-law proton spectra used to produce the PCR, MCR and SRC templates. In comparison, the measured data by AMS-02. (b): Power-law electron spectra used to produce the IC and BR templates, compared once again with AMS-02 data.

2.2.2.1. π^0 production by propagated cosmic rays (PCR)

The initial propagated proton spectrum for the PCR template is obtained from the observed proton data from AMS-02. A good approximation is an unbroken power law ($R-\alpha$) with a spectral index (α) of 2.85 at rigidities above 45 GV. At lower rigidities the data are below the power law because of solar modulation , as seen in Fig. 2.3a, where the AMS-02 data are plotted as well. To find the best parametrization, several indexes and breaks were tested. The optimal parametrization was found by interpolation between the fits with the best test statistic. Finally, the gamma-ray data are well described by an unbroken power law for the protons with a spectral index (α) of 2.85 at all rigidities.

2.2.2.2. Inverse Compton (IC) and bremsstrahlung (BR)

The interstellar electron spectra needs a break around 0.2 GeV with a spectral index of 3.21 above. This is compatible with the locally observed electron spectrum (see Fig. 2.3b). Below the break the optimal spectral index is 0.81, which implies a suppression of electrons. The targets for the production of gamma-rays are the interstellar gas for

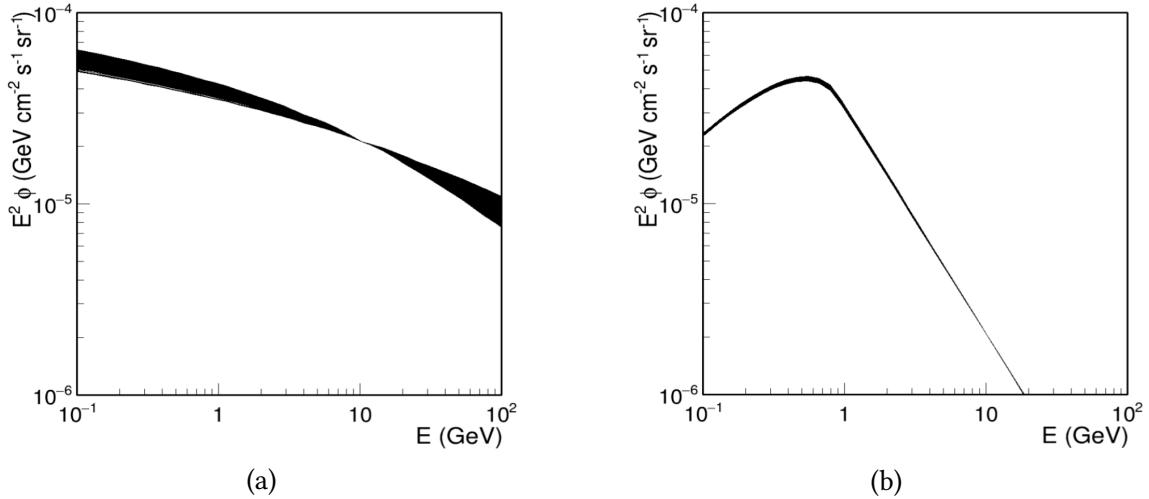


Figure 2.4.: (a): Superposition of the inverse Compton template in every sky direction, normalized at 10GeV. (b): Superposition of the bremsstrahlung template in every sky direction, normalized at 10GeV.

BR and the interstellar radiation field (IRF) for IC, which are both strongly dependent of position, so the photon composition varies with sky direction. For this reason, we have to calculate the IC templates for each sky direction. The variation over the sky is about $\pm 10\%$, as shown in 2.4a. The BR template only depends on the interstellar gas distribution, decreasing the variations considerably compared to IC, as shown in 2.4b.

2.2.3. Additional components

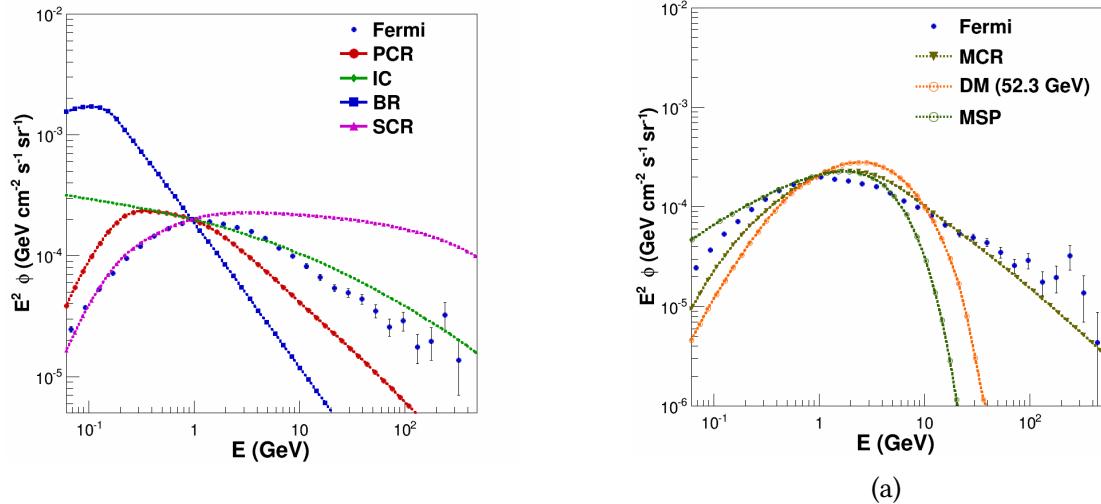


Figure 2.5.: (a): Comparison of PCR, IC, BR and SCR templates, normalized at 1 GeV. Measured data from the central molecular zone is shown as well. (b): Comparison of the three excess components, along with the data from the CMZ.

2.2.3.1. π^0 production by source cosmic rays (SCR)

The proton spectra producing the SCR template can be described by a power law with a spectral index of 2.1, as obtained from the best gamma-ray template fit. The index

2.1 for the SCR template is expected from diffuse shock wave acceleration. The source cosmic rays are accelerated, or escape from the galaxy, hence a harder spectrum at high energies.

2.2.3.2. π^0 production by molecular clouds cosmic rays MCR)

A proton spectrum with broken power-law can parametrize the decreasing gamma-ray emissivity from MCs below 2 GeV. The break can vary from 6 to 14 GeV for different clouds according to the fit. Above the break an optimal spectral index of 2.85 was found to be the same as for the PCR spectrum, as expected if the high energy propagated protons are above a certain magnetic cutoff. Below the break, the spectral index is 0.7, thus providing a significant suppression of protons below the break, as can be seen from Fig. 2.3a. This lower break spectral index does not have a strong influence on the fit and therefore was taken to be 0.7 GeV. Variations in the magnetic cutoff in MCs are expected from the variations in size and in magnetic field, the latter increasing with MC density. These variations between 6 and 14 GeV varies the maximum of the gamma-ray spectrum around a few GeV.

2.2.3.3. Dark matter annihilation (DM)

Dark matter particles are expected to annihilate and produce hadrons of roughly twice the WIMP mass, just like in electron-positron annihilation. This should produce copious amounts of gamma-rays from π^0 decays. A smaller fraction of WIMP annihilation can lead to tau lepton pairs, which can lead to π^0 production in the hadronic tau decays. This contribution is expected to be small and is neglected. The DM template can be calculated with the DarkSusy software. ([cite\[67, 68\]](#)) An annihilation signal peaking around 2-3 GeV requires a WIMP mass around 50 GeV, as shown in Fig. 2.5a. The DM template falls down to zero for energies above twice the WIMP mass, which differentiate it from the MCR spectrum with a much softer spectrum.

ToDo

2.2.3.4. Milli-second pulsars gamma-ray production (MSP)

The MSP template is directly taken from the Fermi study . They simulated the emission of 1700 milli-second pulsars with different energies around the galactic center. The high energy shape of the spectrum resemble closely the DM template, but the main difference with DM and MCR is for low energies. Indeed, below 1 GeV, the MSP template is a lot softer and this feature makes it discernible from the two others.

2.2.3.5. Isotropic component

ToDo

The isotropic template represents the contribution from the isotropic extragalactic background and hadron mis-identification. Its spectral shape and absolute normalization are provided within the Fermi software ([cite\[51\]](#)), but it was redetermined for the analysis as follow. A first fit of the data in regions outside the Bubbles and the Galactic disk using the isotropic template from the Fermi software is produced as an initial estimate. If one plots the total observed gamma-ray flux versus the fitted flux in the various cones in a certain energy bin, one expects a linear relation crossing the origin if the isotropic flux is estimated correctly (See Fig. 2.6). However, if the isotropic contribution is either too low or too high, an offset at the origin is introduced in the linear relation. Since the isotropic component is by definition the same for all cones for a given energy, this offset can be

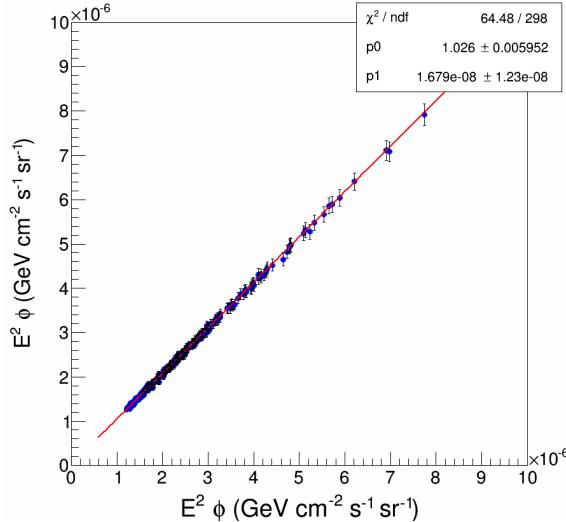


Figure 2.6.: The fitted data (abscissa) versus the observed data (ordinate) in every region of the sky for a given energy of 1 GeV. A linear fit is performed to find the offset at the vertical axis. This number represent the amount the isotropic component shifts the data in all cones. Once this is done for every energy bin, the offset is added to the previous isotropic template and the process is repeated until convergence.

subtracted from the Fermi template to improve the fit. Once the offset is determined for each energy bin and subtracted from the original template, the process is repeated until the offset converges to zero.

2.3. Fitting method

The fitted data can be seen as a data cube whose dimension are longitude, latitude and energy. The finest spatial grid is divided in 720×360 cones of $0.5^\circ \times 0.5^\circ$. Every cone contains 30 energy bins. This allows to treat different portions of the sky independently of one another. Since the cones do not have the same solid angle and the statistic in a small binning can be problematic, the grid is more often composed of 797 bins of different sizes, bigger at the poles and smaller near the equator. This allows a better statistic in lower flux regions and where a high spatial resolution is not needed (i.e. at high latitudes). In the same time, the equator and the GC have a lot more counts and can be treated in a smaller binning. This binning is faster to compute than a regular grid with an good enough output quality to study the results.

The fit uses a certain number of components (three at least) each corresponding to a certain phenomenon and described earlier. They all have a certain energy spectra, that can vary with the position in the sky in the case of IC (See Fig. 2.5).

The fits are done for every bin independently. After choosing the templates used for the fit, their scaling factor is the only degree of freedom allowed. So, using a ROOT TVirtualFitter object, every template is scaled up or down until their sum comes the closest to the data. Mathematically, the minimum distance between the model and the data is found when the χ^2 value is lowest. It is calculated as follows:

$$\chi^2 = \sum_{i=1}^{30} \left[\frac{(D_i - \sum_{j=1}^n [n_j \cdot T_{ij}]^2) + iso}{\sigma_i^2} \right]^2 \quad (2.2)$$

where:

- D_i is the data flux in the $i^t h$ energy bin.
- n_j is the scaling factor for the $j^t h$ model component.
- T_{ij} is the model flux of the $j^t h$ in the $i^t h$ energy bin.
- σ_i is the geometric mean of the statistical and systematical error of the Fermi data point i .

The MCR break position does not vary in a single fit. A fit is done for every MCR break independently, and the one with the best χ^2 is kept. This break position is not counted as a degree of freedom in the fit.

The fit is very well constrained with only five or six degrees of freedoms depending on the model against 30 data points. A useful value is the $\chi^2/d.o.f$ where $d.o.f = \#data\ points - \#degrees\ of\ freedom - 1$. This rescaling has the advantage to bring the perfect χ^2 value down to one, thus making the comparison between different fits easier. This rescaling will be applied every time when speaking about χ^2 in the rest of the discussion, except if explicitly told. The closest a χ^2 value is to one, the better the model follows the data. The higher it gets, the lower the quality of the fit. It can also happen that it gets lower than one. This can happen when the fit is good, but the error bars on the data are too big.

Since every bin is fitted independently, it is not possible to implement a spatial template, i.e. where the spatial shape of a component would be fixed in advance. For example a component with a spherical distribution around the GC, as can be done in other works ([cite](#)). The hope is to let the fit find reasonable shapes by itself only using the χ^2 minimization technique.

ToDo

This fitting method offers many ways to look at the results, depending on the interest. It is possible to produce flux maps of each component to study their spatial shapes at different energies. This can for example show a correlation between a certain template and a galactic feature such as the disk or the bubbles. An other way is to create a spectrum of one cone to look at the relative quantity of every template at different energies. This can put into evidence problems in the models and help perfect the spectral shape of the components.

The first step when testing a new model is to see if it can reproduce results of previous studies. Only once it works and can be confidently used can it produce new results.

3. Results

3.1. Recreating previous results

Introduce the weniger plots here (or in the state of the research?) to show excess in GC.

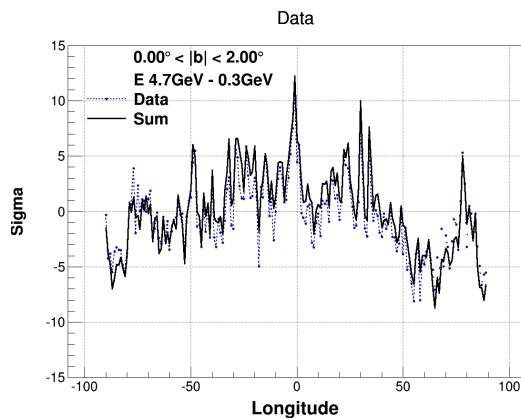


Figure 3.1.: Some weniger plots to show the GC excess

Before trying to upgrade the current model, it is important to make sure it can be recreated starting from the same parameters. Fig. 3.2a shows the results of a fit using only the background components (PCR, IC and BR). The shape and intensity of the previously observed excess are found ([cite](#)). Excluding the galactic disk for latitudes below two degrees, the excess extends to 30° in all directions from the GC. ToDo

Looking at the χ^2 skymap (Fig. 3.2a), the bubbles and the disk appear clearly in red, showing a high χ^2 value. The fit does not give proper results in those regions, with the high energy part of the spectrum not described by the three background templates. On the other hand, outside these regions, the fit works better with a χ^2 not much higher than three. This is not perfect, but in comparison with the disk, it is undeniably better. Overall, the results are expected and confirm that the model is incomplete. The introduction of a new template like SCR should help improve the fit.

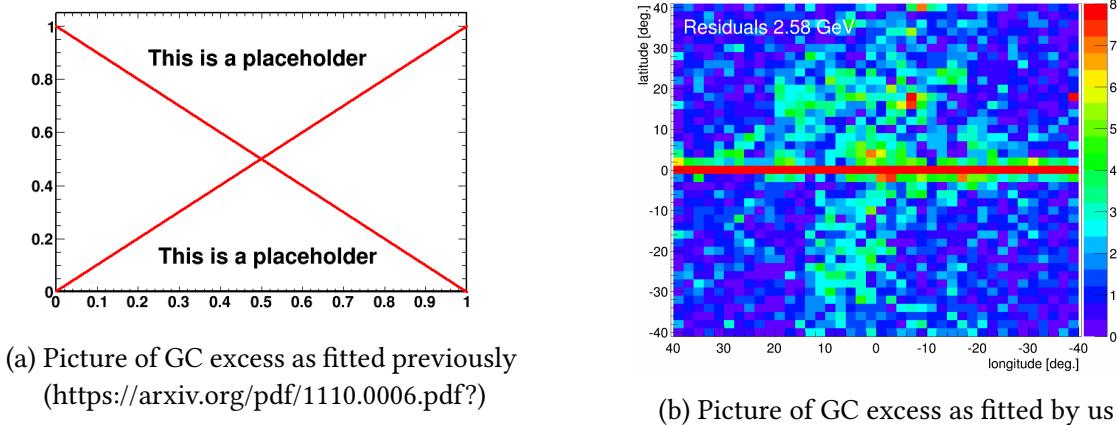


Figure 3.2.: Picture of the GC excess as obtained previously and with our fit

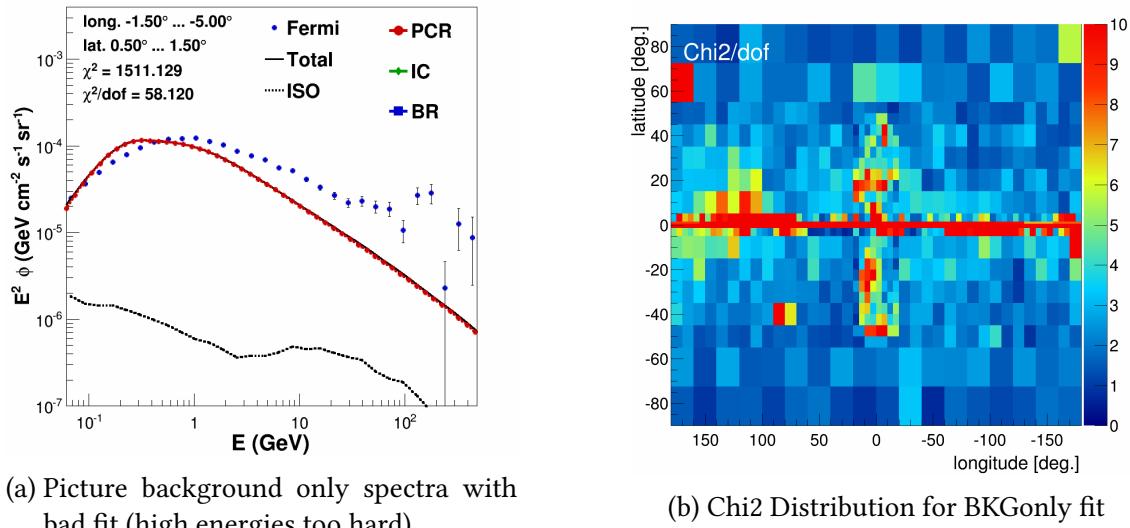


Figure 3.3.: Example of fit and chi2 map of BKG only fit

3.2. Introducing SCR

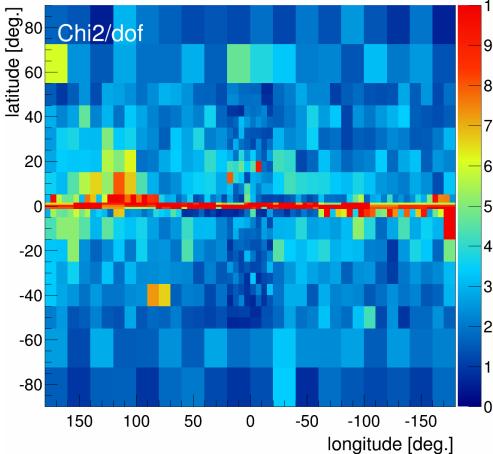
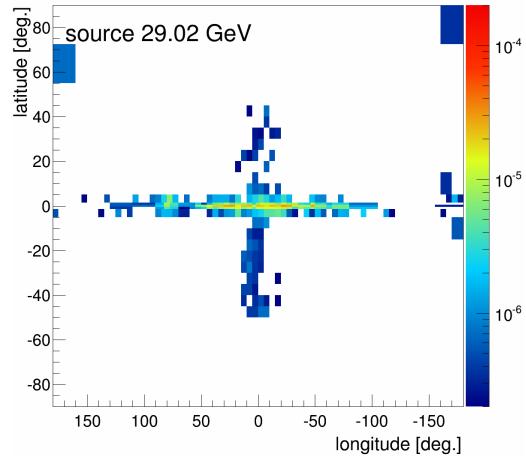
After introducing the SCR template, a clear improvement can be noted in the χ^2 distribution (see Fig. 3.4a). The bubble shape that was delimited before by a bad χ^2 zone has now disappeared. Even if the fit is still not perfect everywhere, the improvement is significant. For example, the disk is still not fitted properly, with very high χ^2 values. Some structures can be seen along the disk for absolute longitudes over 90°

To Do

The SCR template is present only in the disk and the bubbles ([add fig](#)), as expected since it represents the point sources and CR that did not diffuse in the disk. The high energy parts (above 100 GeV) of the spectra are dominated by SCR.

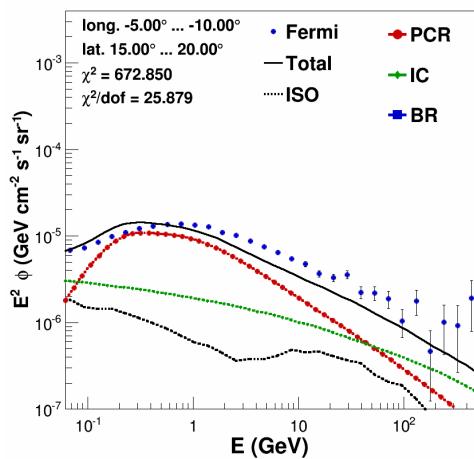
To Do

(check if the GC excess still exist, if yes, talk about it. Then introduce the excess components)

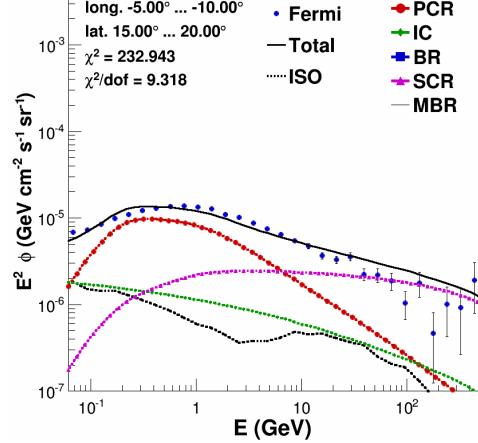
(a) Chi₂ distribution of SCR only fits.

(b) Flux distribution of SCR only fits.

(c) Source results



(a) Spectrum from a bubble with SCR only and background only.



(b) Spectrum from a bubble with background models only and background only.

3.3. Introducing SCR and MCR

As shown on Fig. 3.6a, the addition of a new template improve significantly the χ^2 distribution in all directions. The bubbles and the disk structures are not visible anymore.

Three dots appear to have a really high χ^2 , but that is only due to the point source subtraction that is not perfect (see Chapter 2.1).

Fig. ?? shows the central molecular zone (CMZ) fitted with and without the MCR component. The gas density is very high in this region, hence it is the first region where we would expect the MCR emission to be present, if not dominant compared to PCR. Indeed the fit chooses this configuration, with the MCR template dominating all the others and we can directly see the improvement in the MCR fit. The energies around 2GeV had a clear excess that the four components of the SCR fit could not account for. The MCR template peaking in this region, it comes in very handy and fill this gap, leaving the SCR template taking care of the high energies and PCR and BR for the low energies. (Why To Do

isn't there IC? -> Wait to see if we change the models)

3.4. Introducing SCR and DM

The first step is to determine which mass for the WIMP particles would produce the best spectrum for our fit. Fig. 3.6d shows the best fit for the CMZ region, with the WIMP mass as a free parameter. It chooses a mass of 52.3 GeV, peaking around a few GeV, as expected in (ref theory section). Since the excess is the most significant in this region, it is also the best place to define our mass for the rest of the sky. This is what is done in the following section.

Once the mass is determined for the entire sky, the fit gives the following results. The χ^2 distribution (Fig. 3.6c) is comparable to the MCR fit for the major part but is significantly worst in the disk.

As seen on Fig. 3.7c, the DM distribution of the fit traces closely the distribution of molecular gas distribution (as traced by CO).

3.5. Introducing SCR and MSP

The first thing that can be noticed when seeing the χ^2 distribution of the MSP only fit (Fig 3.6e) is the similitudes with the DM only fit (Fig. 3.6c). The fit succeeds pretty well outside the disk, but gets significantly worst when $|b| < 2$.

Using the MSP spectrum predicted by fermi (cite) to fit the CMZ region does not give entire satisfaction. The CMZ is in the disk, where the χ^2 is generally worst.

The distribution of MSP in the sky resembles the distribution of MCR and DM obtained in previous sections. Present everywhere in the disk, with a higher flux in GC and the bubbles.

ToDo

(add picture of residuals at low energy maybe?)

3.5.1. Discussion on spatial shapes

Fig. 3.8 shows the spatial distribution of the flux of each component around 2 GeV, as returned by the fit.

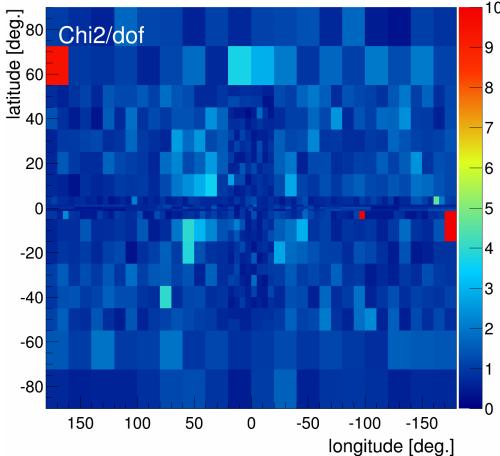
The bremsstrahlung component is consistent with the the expectations. Present everywhere, it is strong in the disk, and decrease a little in the bubbles.

(Though the general shape is spherical, the IC component has an unexpected feature in the form of a strong depletion in the disk, like a "sandwich" structure. This is surprising in the sense that this is where the interstellar radiation field (ISRF) and electron density are supposed to be maximal, creating a higher IC flux. A possible explanation could be coming from the dust distribution, screening the starlight component of the ISRF. Thus depriving the ISRF of its main component and leaving only the dust infra red emission and the CMB to interact with the electrons. This could result in a lower IC gamma-ray flux in the disk.) ToDo

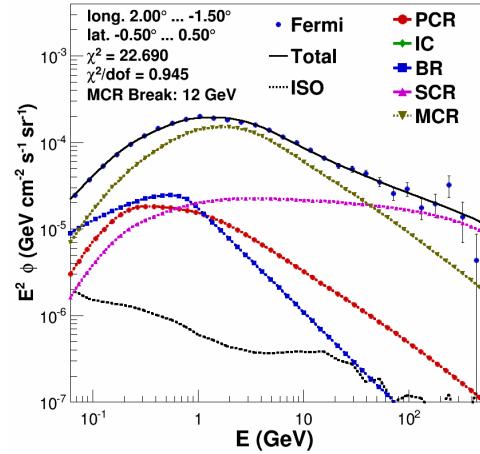
The SCR component is playing his role, filling the bubbles and the disk, where the high energy portion of the spectra needs a harder spectrum. It traces the sources distribution in the disk and the outflow of high energy protons in the bubbles.

The general shape of PCR looks coherent with he shape of the galaxy, with a strong flux in the bar and the galactic disk in general. When looking closely, one can see the same kind of depletion in the disk than for IC, even if the effect is less remarkable. This finds its cause in the MCR distribution with a very high flux in the disk. The sum of both templates (MCR + PCR) shows no sign of such a feature, which tends to show that some of the PCR photons are absorbed by the MCR template. But the total is coherent, with no unexplainable central gap.

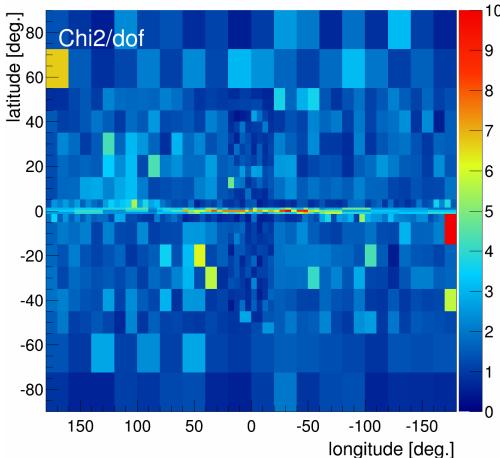
The MCR template also follows the spatial distribution of molecular clouds in our galaxy. It is a good sign since it is supposed to come from those regions. It is not spherical at all. That could have happened if the excess component has a DM origin, since it is supposed to be spherically distributed.



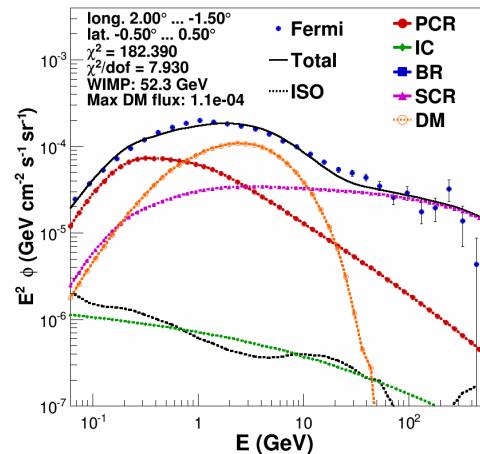
(a) Chi2 maps of MCRonly fits compared to background only



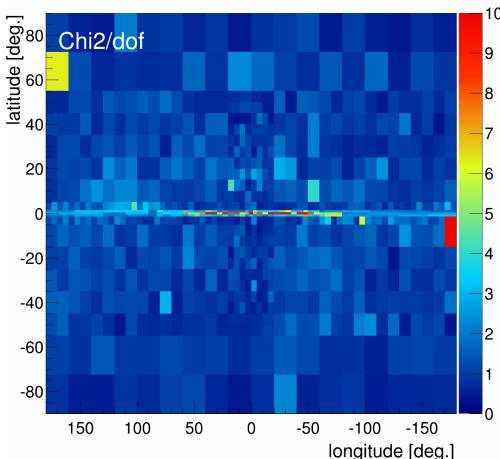
(b) MCR fit in the CMZ region



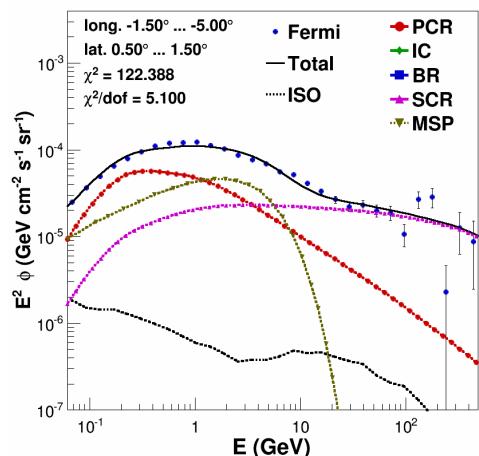
(c) DM fit chi2 distribution



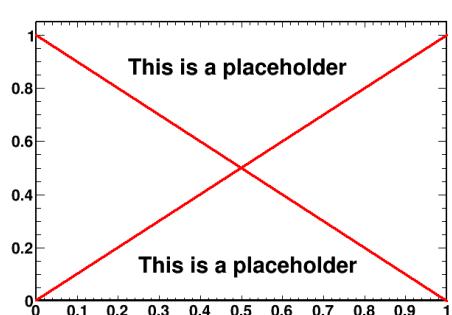
(d) spectrum of best mass DM fitted in CMZ. Also pictures of DM distribution compared to gas map.



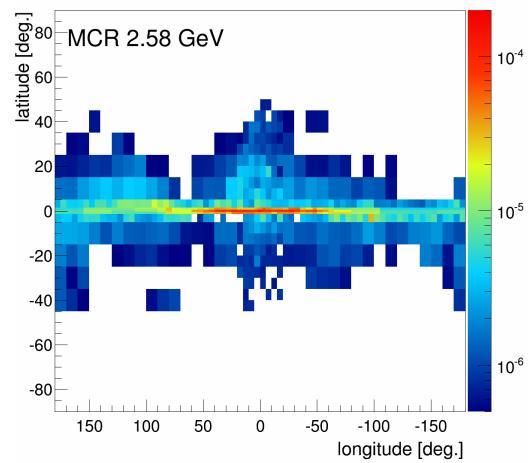
(e) Chi2 distribution of MSP only fit



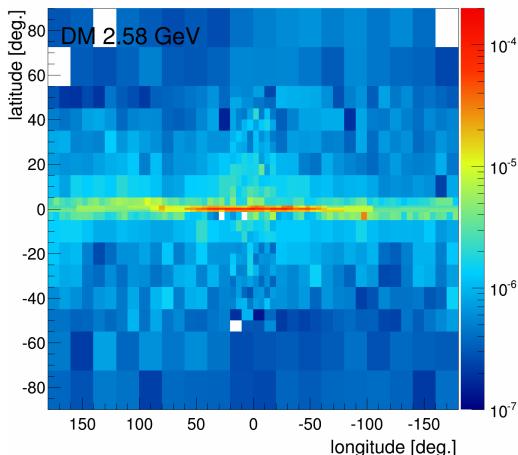
(f) Fit with SCR and MSP spectrum in the CMZ region.



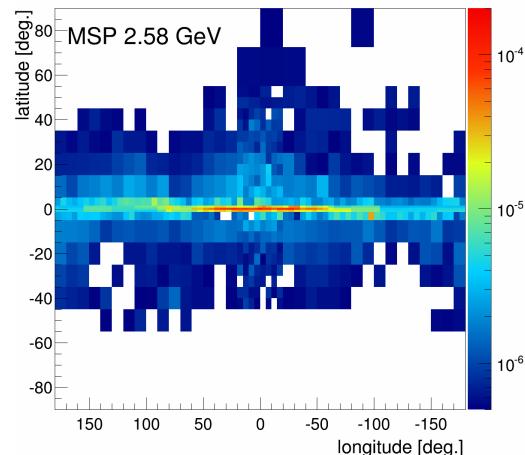
(a) CO skymap



(b) Flux distribution of MCR



(c) DM distribution compared to gas map.



(d) Flux distribution of MSP around 2.5GeV.

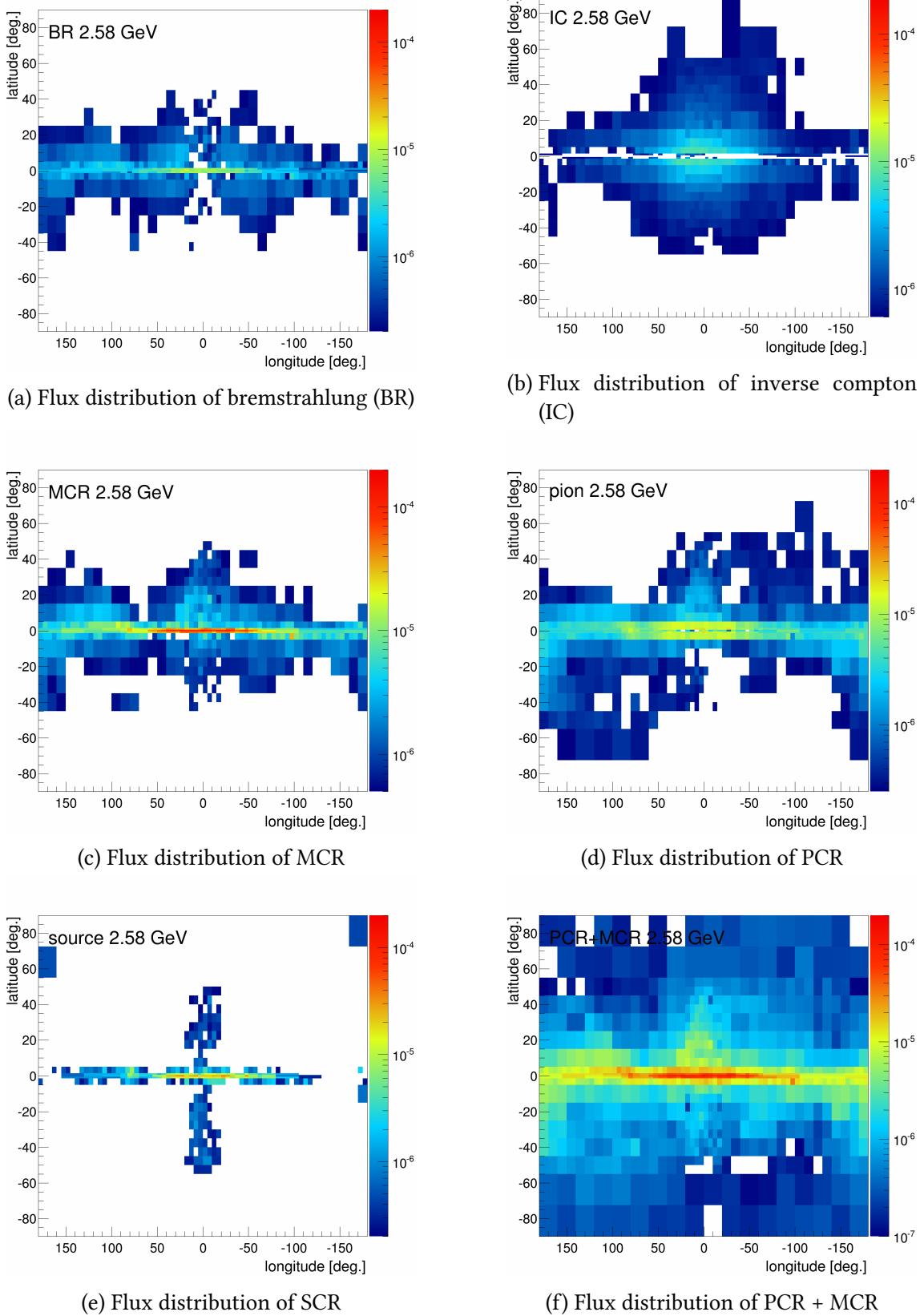


Figure 3.8.

4. Discussion

4.1. Interpretation of spatial shapes

4.2. Why is MCR better than DM or MSP

Gathering the results of the previous section, a conclusion tends to emerge : the fit clearly prefers the MCR hypothesis over DM and MSP. We will discuss why in this section.

A first step can be to compare the χ^2 skymaps. The higher the χ^2 is, the worst is the fit. Looking at the background only fit (with PCR, IC and BR), the disk and the bubbles clearly define a bad χ^2 zone. The high energies are not described at all, with a fitted flux too low (see previous chapter). It indicates that the fit misses a high energy component that could be able to bring a high energy contribution. This is done by the SCR component. This component is obtained from a proton injection spectrum with a spectral index of 2.1 (instead of 2.85 for PCR). This harder spectrum is representing the proton population that did not yet diffuse in the galaxy, therefore the high energy protons did not have the time to lose their energy. This new template is expected to be used in the disk and the bubbles. In the disk because there is a very high density of point sources, and the 3FGL catalog does not list all of them. These sources can produce gamma-rays from their expelled CRs in their near surrounding, thus providing a very hard proton spectrum. It is also expected in the bubbles since they are also composed of relativistic CR ejected from the GC directly outward the disk. These CRs do not propagate, at least less than in the disk, thus keeping a hard spectrum in those regions. The first results with SCR added to the three background component is a success with clear improvement in the bubbles. They are not visible anymore when looking only at the χ^2 skymap and this is a very good sign. On the other hand, the disk is still not fitted correctly, as can be seen from the large χ^2 band at latitudes below a few degrees. Even if there is a small improvement, the addition of a fifth component can be beneficial. Now that the high energies are taken care of, the excess shows around a few GeV. There are three different candidates for the job: MCR, DM and MSP. All three correspond to a unique process with clear definition and expectations.

The first hypothesis to be proposed for this excess is the presence of DM in the GC. As explained before, the DM halo is expected to be spherical around the GC, following a

NFW profile, since it does not interact with matter. And since the gamma-ray production from DM is directly proportional to the DM density, the DM component is expected to be spherical around the GC. There is no reasons for it to be correlated with the spatial shape of the Milky Way. Looking at the results of the fit, this does not meet these theoretical expectations of DM distribution. Even if the χ^2 in the disk is decreased everywhere, that is not sufficient to say the observed excess is due to DM. First because there are still some regions near the GC where it stays high, and because the distribution of DM predicted by the fit is not spherical at all. On the contrary, it seems to follow the disk gas distribution when comparing the DM and CO maps ([add figure](#)). The MSP fit, also expected to have a spherical distribution of gamma-rays from millisecond pulsars, gives similar results. The flux seems to be needed in the disk along the gas distribution. Again, the fit is improved after adding the MSP template, but some regions with high χ^2 remain in the disk. Finally, the addition of MCR leads once again to the same kind of results, but this time, the spatial distribution is expected to follow the MCs. The χ^2 map is a little better than for the other two with the disappearance of the remaining bad fits in the disk. A χ^2 around one is obtain on the entire sky. The distribution of MCR is resemble closely the DM and MSP distributions obtained before. The fact that this distribution tends to be the same for all three additional component could be expected, since their energy spectra are similar. But the interesting point is that no spherical distribution is observed, nor needed, to fill the 2 GeV excess. This quick comparison of the excess component distributions and the χ^2 maps gives a good overview of the results. But even if a preference for MCR can start to emerge, further investigation is required before being able to conclude.

4.2.1. Comparison of the excess spectral shape

The only difference between the three excess components that the fit cares about is the spectral shape. It is explained in the Method chapter that all three templates peak around 2 GeV, but the slopes at low or high energies are different. For energies inferior to 2 GeV, MCR and DM have a similar shape, when MSP is much softer. For energies above 2 GeV, its the MSP and DM spectrum that look alike, with a very soft spectrum, when MCR is harder. These differences are the only reasons the fits does not give the same results three times. Indeed, the low energy spectrum of the Fermi observations in the disk is hard and does not vary significantly ([add fig](#)). This plays a major role in differentiating MSP from MCR and DM. The MSP spectrum is softer than Fermi at low energies. On the other hand, the MCR and DM spectra fall down with the observed data with the same gradient. Thus, the MSP component can not be as dominant as MCR or DM would be in the disk, since the Fermi data puts a upper limit on the low energies that MSP reaches faster than the other two. So the contribution of MSP at 2 GeV is lower even if it is higher at 100 MeV. This process keeps MSP low and does not allow to account completely for the excess in the GC. On the other side of the spectrum, above 2 GeV, it is MCR that behave differently than MSP and DM with a harder spectrum. When DM and MSP are completely insignificant above 50 GeV, MCR still plays a role at least as important as the PCR spectrum since they both have the same spectra at high energies. Above 4 GeV, the Fermi data present an almost constant spectral index with very little variations in the disk. This makes all the difference to distinguish between MCR and MSP or DM. In fact, the important point here is the energy at which the SCR component takes over the excess component. In the CMZ, this turnover happens at 50 GeV for MCR, against only 10 GeV and 6 GeV for DM and MSP respectively. This causes the DM and MSP fits to

ToDo

ToDo

present a dip around 11 GeV with a clear change in spectral index. This does not follow the shape of the data. Because of this, the SCR has to overshoot the very high energies (above 100 GeV), to minimize the size of the dip. The PCR component could be a good help with a constant spectral index at high energies, but its contribution is limited by low energies. Indeed, the PCR spectrum peaks around 200 MeV where the Fermi data are already decreasing rapidly. So the MCR spectrum presents the right shape at high energies, with a constant spectral index hard enough to allow the SCR component to take the relay without a big change in spectral indexes.

Overall, two major differences in the spectral shape of the three excess component allow to predict the most adapted. The low energy spectral index difference between MSP and Fermi spectra leaves the MSP behind the MCR and DM hypothesis. Furthermore, the harder spectrum of MCR at high energies improve the fit significantly compared with MSP and DM. So the only spectrum that presents the right shape at low and high energies is MCR, making him the best candidates for the fit.

4.2.2. Discuss the spatial distributions of the other components.

The spatial distribution of a component can teach a lot about the fit. Every component is closely linked to a known physical process taking place in a known galaxy. The exact details of every cone can not be predicted, but the general shape can. This way, it is possible to verify the goodness of the fit by comparing the fitted spatial distribution of the different templates and the predicted one. For example, the distribution of the ISRF is expected to be spherical around the GC in the UV range, where most of the starlight is emitted. It can also follow the dust distribution in the disk in the infra-red range. This can be used to check if the IC component is coherent in the fit. Hopefully, the results show a spherical IC component centered on the GC. The different distribution of each component will be discussed in the following section.

4.2.2.1. PCR flux distribution

The PCR component is produced by diffuse CR protons which react to form a pion which in turn decays into two photons. So the PCR flux is directly proportional to the diffuse CR, the gas and the dust density along the line of sight in the galaxy. So it is expected to present in every direction, with a stronger flux in the disc, and less at high latitudes. The bubbles have a harder CR proton spectrum, that is different from the CR proton forming the PCR template, so it should not be too much present, with SCR instead.

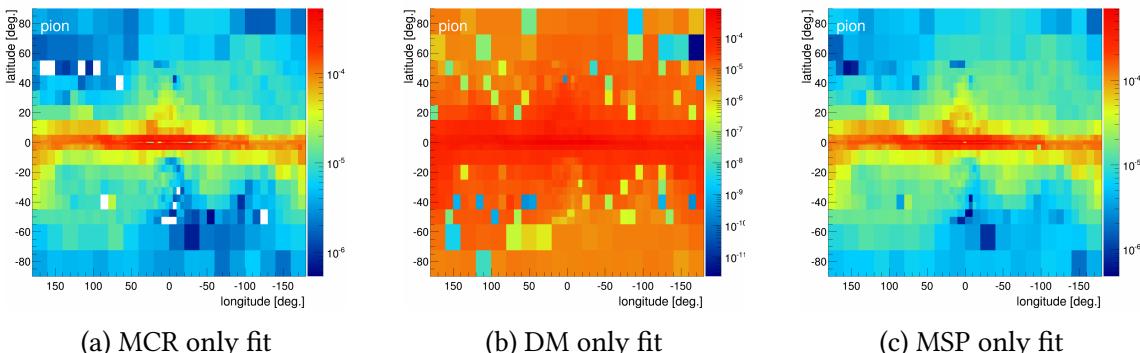


Figure 4.1.: PCR spatial distribution for the three different excess components

4.2.2.2. IC flux distribution

The inverse compton component is directly proportional to the ISRF and the electrons CR. Electrons are present everywhere in the galaxy, and the ISRF is dominant in the GC for the UV range, but follows the dust in the IR range and is isotropic in the radio range. This distribution should be visible in the IC component of the fit. Indeed, a spherical distribution can clearly be identified for the three different fits with DM, MCR and MSP. Nonetheless, there is a noticeable difference in the disk between the IC distribution for the MCR fit and the DM and MSP fits. In the MCR fit, the disk presents a high IC flux when DM and MSP do not. On the contrary, the MSP and DM fit present a clear dip in the galactic disk. This gap is unexpected, since the ISRF is supposed to be the strongest in the disk, and the diffuse electrons are also produced mainly here. ([explain this](#))

To Do

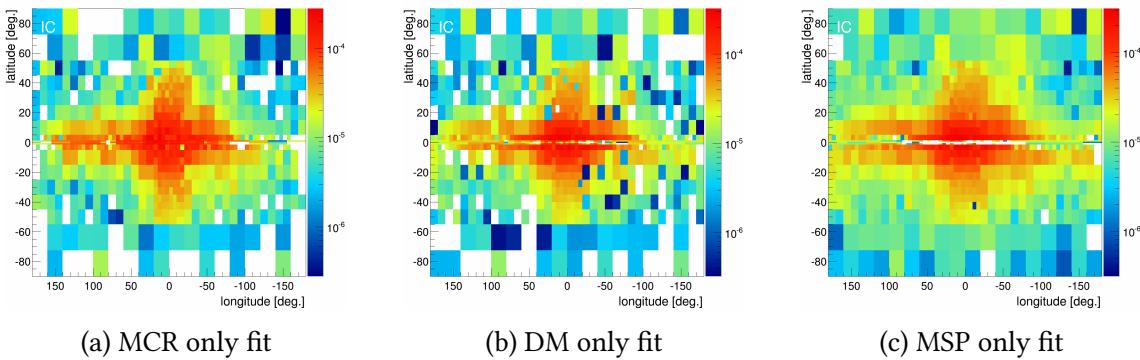


Figure 4.2.: IC spatial distribution for the three different excess components

4.2.2.3. BR flux distribution

The BR component is linked to the CR electron density along the line of sight, and the electromagnetic fields in the galaxy. It should then be present everywhere.

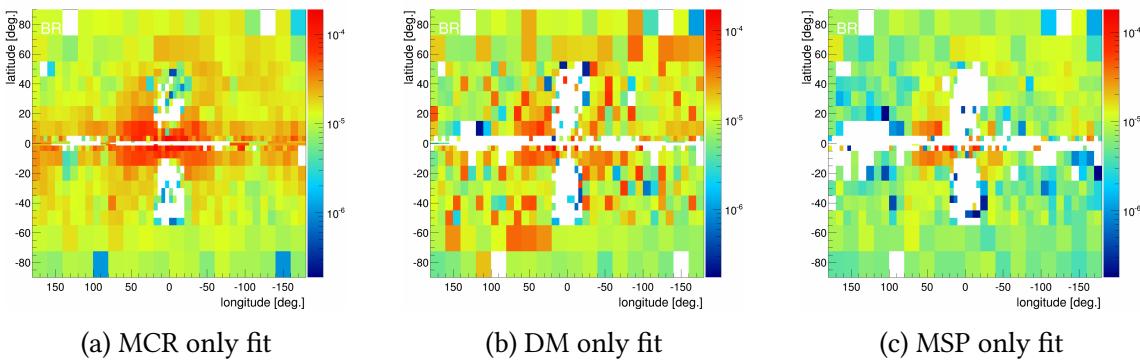


Figure 4.3.: BR spatial distribution for the three different excess components

4.2.2.4. SCR flux distribution

The SCR distribution is expected to follow the disc, where point sources can still remains, and the bubbles, where the proton CR spectra is harder. And indeed, the spatial distribution obtain in the three different fits are similar and correspond perfectly to the expectations.

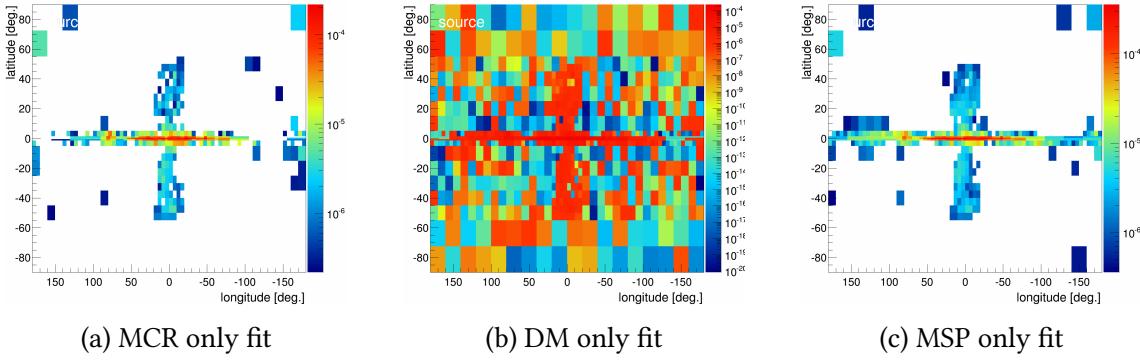


Figure 4.4.: SCR spatial distribution for the three different excess components

4.3. Adding the MBR component

The theory behind the MCR component involves a magnetic cut-off for low rigidity CR protons, that changes the gamma-ray spectrum at low energies. Such a cut-off only depends on the rigidity of the CR and the intensity of the electromagnetic field. So there is no reason for it to be only applied to protons, and not to electrons. This is the reasoning that led to introducing a new template, called MBR in the fit, equivalent to the BR template, but calculated from a different electron CR spectra. This new CR spectra present two parts, with two different power laws for high or low energies. It has the exact same spectral indexes than the spectrum for IC and BR, but the break is moved up between 6 and 14 GeV. Then, the break is taken to have the same value than the MCR brake. This way, the magnetic cut-off is applied the same way to the electrons and protons CR. Once again, this component is expected to follow the MCs distribution, or at least to be only present in the disk.

A MIC component was tested as well, but it was not kept for physical reasons. First, the ISRF is not dependent of the electromagnetic field, photons do not carry any electric charge. It is also present in MC, where stars are formed and evolve.

4.4. Add DM late

(difference with DM+MCR. Results and discussion.)

ToDo

Now the results are clear. MCr is a good solution to the gamma-ray GeV excess in the GC, and could replace the first hypothesis of the DM halo or hidden MSPs. Yet, the DM theory is strongly supported by other measurements (**cite**), for example the rotation curves of galaxies, and is one of the most important questions of modern physics. And the fact that it is not the primary cause of the effect observed here does not mean it does not exist. On the contrary, under the hypothesis that MCR is really the cause of the excess, the fit could put strong limits on the DM models.

ToDo

This section will present a few ways to study the current DM WIMP model using the fit method of this thesis.

4.4.1. DM and MCR

(add figure)

ToDo

A first idea is to let the fit choose for every cone the template that offers the best χ^2 value. Taking a 52.3 GeV WIMP mass and the MCR template with free breaks, the fit has the choice between the two. The results are without much surprise in favor of MCR. Indeed, the previous comparisons of the χ^2 distribution for a MCR or a DM fit showed a clear preference toward MCR. The χ^2 map of a MCR fit is flat around one, even in the disk, whereas a DM fit does not work well for small latitudes. It is then only expected that the fit chooses MCR when it has the choice.

4.4.2. DMlate

This method can not say much else than what was already showed in the previous sections. The second idea that comes to mind is to take the MCR template for granted, and see if there is space to add DM contribution at the end of the fit. In other words, a first fit is performed with the classical templates (PCR, IC, BR), the source (SCR) and the MCR templates. Once the best relative contributions are found, the fit tries to add a DM template to improve the χ^2 . Following the Ockham's razor principle, the least amount of contributions are accepted as true, and any additional component must be treated carefully. This way, the necessity of a DM template is checked, and its contribution can not be mistaken for a classical one. (**add pic**) Such a fit was performed and the results will be discussed in this section. First of all, the DM flux distribution is very sparse and degrees of magnitude below the other components. This was expected since the χ^2 of the MCR only fit was already good. Only very small changes could improve it without changing the classical contributions. Using the same CMZ region in the GC, the optimal mass was determined to be (**mass DM late**).

ToDo

ToDo

Further studies of this kind could help to determine limits on the DM particle mass and cross-section.

4.5. How do these results fit in context

5. Conclusion

See the introduction for the plan, it is better to have both plans at the same place

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Appendix

A. Some appendix section

This appendix chapter contains ...

