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Master Thesis of

Your Name

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

Reviewer:	Prof. Dr. Wim de Boer
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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.

**Karlsruhe, 14th January 2018**

.....  
**(Your Name)**



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# Introduction

*Awesome introduction.*





# 1. Theory

## 1.1. Physic of cosmic rays

### 1.1.1. Creation of CR

### 1.1.2. 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 the stars to molecular clouds or any distribution of charged particles. It is not particularly strong (**put values**) compared to the heliosphere or what we can create 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 backtrace its 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 the highest.

**ToDo**

All these influences can be modeled by a diffusion model, mainly defined by its diffusion coefficient, which describes the average distance traveled in 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!**).

**ToDo**

**ToDo**

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 escape 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 magnetic field and small gas and dust density. However, the bubble region is outside the disk and has a higher concentration of CR other regions outside the disk. This is due to a direct outward emission of CR from the GC region in the disk. With a high diffusion coefficient, those

CR are ejected light years away **(put values)**, forming two symmetric region extending north and south up to 40 degrees in latitude. **ToDo**

### 1.1.3. 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.

#### 1.1.3.1. Pion decay

The high energy protons can produce  $\pi^0$  which decay almost immediately in 2 gammas of equal energy.

#### 1.1.3.2. Bremsstrahlung

The electrons passing near another charged particle, or in a magnetic field will be deflected by the electromagnetic interaction. In the process, the electron 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 magnetic field or the charge of the other particle. The more the electron is deflected, the higher the energy of the emitted photons. **(give numbers for B field and proton in MC)**

**ToDo**

#### 1.1.3.3. Inverse Compton

A third interaction can link the cosmic ray electrons to gamma rays and it is inverse Compton. 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 interstellar radiation field (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 stars are concentrated. The starlight emits as a blackbody, 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.

**ToDo**

**(talk about synchrotron and ionization losses)**

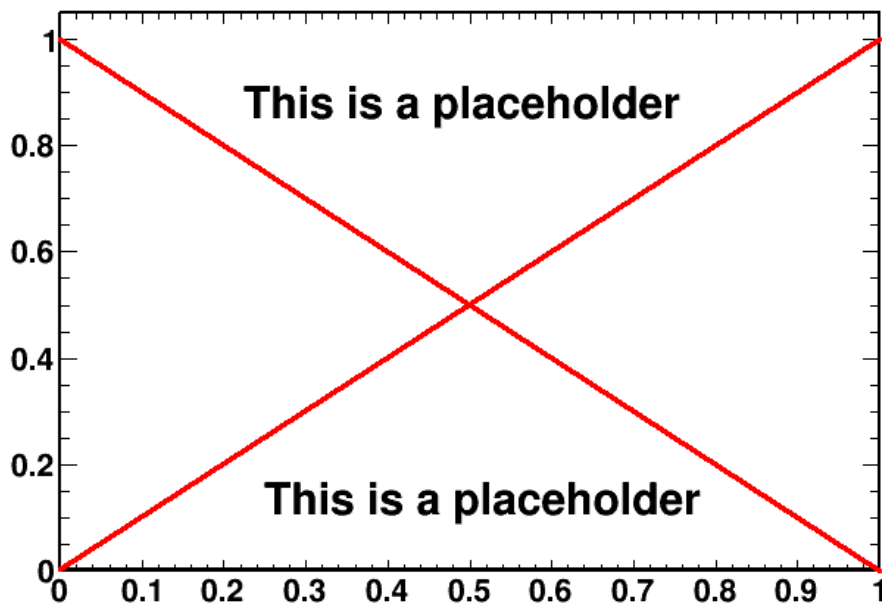


Figure 1.1.: chi2 distribution of first fits (not mines)

#### 1.1.4. Gamma ray observation

Several instruments in the world observe gamma rays. For example the Fermi Large Area Telescope (LAT) mounted on the ISS. This instrument maps the gamma ray sky between 20MeV and 300GeV (**(cite)**). The diffuse cosmic ray emission that we are interested in can be obtained after modeling and subtracting the contribution of the over sources. This allows us to compare the observation with the models we obtain from the previous three interactions.

**ToDo**

## 1.2. What are the unresolved problems of the precedent chapter

Several studies have already tried to see how our predictions of the gamma rays emission and our observations compare. The three main phenomena were modeled as explained to try to recreate the spectrum observed from Earth. The results are clear, there are somethings missing in our interpretation. The fit is clearly not working in the galactic plane and the bubbles (as shown on Fig. 1.2. The spatial templates used in those fits also show a spherical excess of gamma rays of about 2GeV in the galactic center (GC).

Two main ideas have emerged to explain this 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) 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 50GeV, the expected gamma spectrum would peak around 2GeV, 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.

**ToDo**

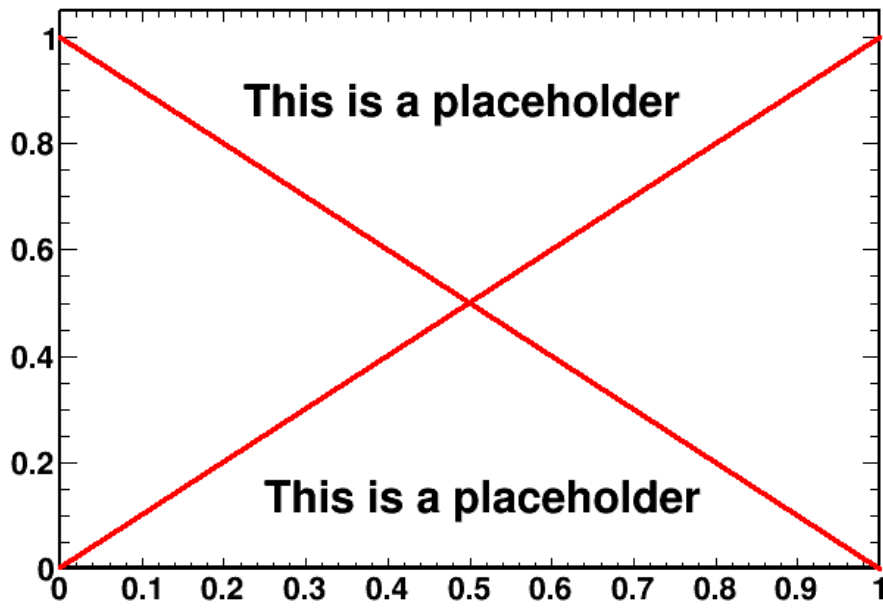


Figure 1.2.: shape of the excess

The second theory does not involve new physic, but inobserved milli-second pulsars. They would also be spherically distributed around the GC and their gamma spectrum peaks around 2GeV. A few thousands of them would be needed to recreate the intensity of excess. The main default of this explanation resides in the fact that we have observed only a few hundreds? at most. That would requires a very high concentration and a reason why we can not observe them more easely.

## 2. Method

### 2.1. Data origin

The data I used are taken from the Fermi collaboration Large Area Telescope (LAT). They are available on the web and can be treated by anybody using the software given by Fermi.

Part of my jobs has been to update the old data we used to use, passing from pass 7 to pass 8. It results in better statistics because of a longer observation period, better systematic errors, wider energy range and better point source subtraction.

For our study we are only interested in the diffuse sources of gamma-rays from inside or outside the milky way. The mandatory step to obtain this is to subtract the point source emission from stars, or other direct sources.

The Fermi Large Area Telescope Third Source Catalog (3FGL) was used as a reference to subtract the point sources from the raw data. It lists more than 3000 sources and their associated spectra in the 100 MeV-300 GeV range.

### 2.2. Model components

#### 2.2.1. Basic components

##### 2.2.1.1. $\pi^0$ production by propagated cosmic rays (PCR)

The initial propagated proton spectrum for the PCR template is obtained from the locally observed proton data from AMS-02 ([cite\[55\]](#)). A good approximation is an unbroken power law ( $R - \alpha$ ) with a spectral index ( $\alpha$ ) of 2.85 at rigidities above 45 GV. At lower rigidities the data are below the power law because of solar modulation ([cite\[56\]](#)), as can be seen from Fig. 2.2, where the AMS-02 data are plotted as well. To find the best

**ToDo**

**ToDo**

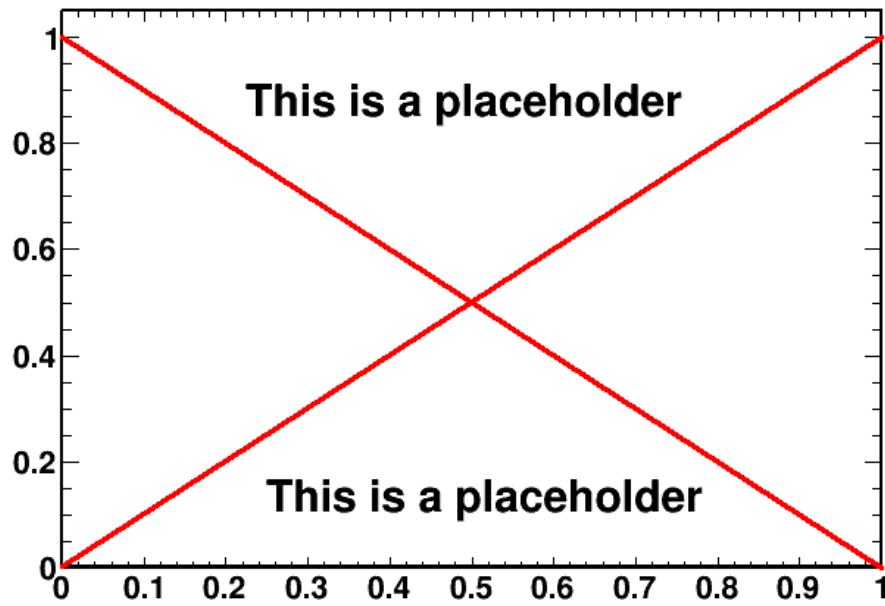


Figure 2.1.: figures of raw data, and after point source subtraction. Maybe also some spectrum with pass7 and pass8 to see the differences.

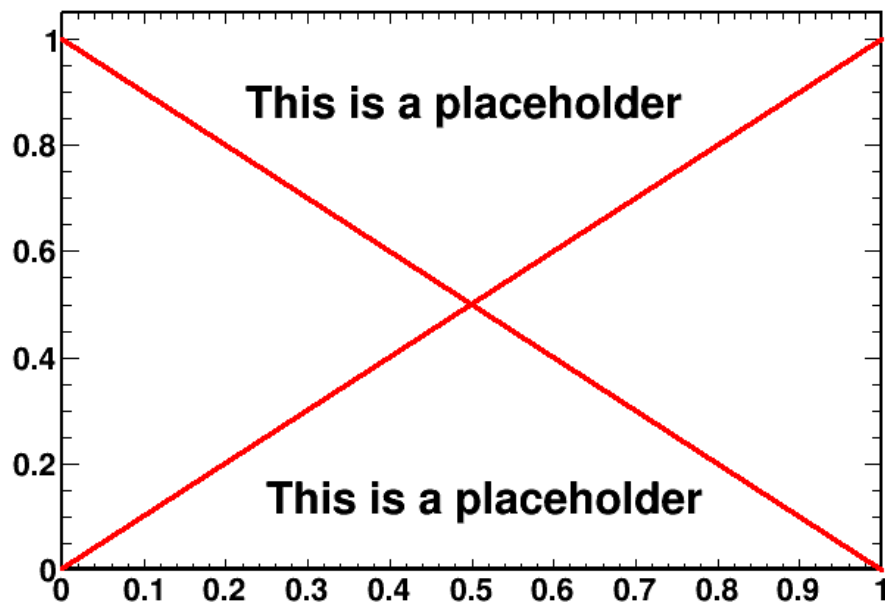


Figure 2.2.: images for proton spectrum for PCR, MCR, SCR, data

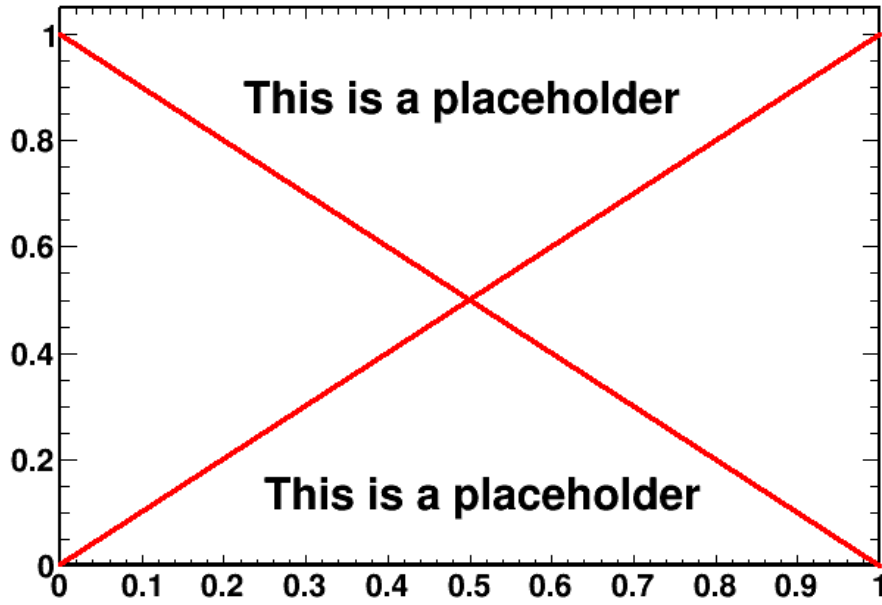


Figure 2.3.: images for electron spectrum for IC, BR, data

parametrization a set of broken power laws with a grid of breaks and spectral indices above and below the break was constructed and the optimal parametrization was found by interpolation between the fits with the best test statistic. The gamma-ray data are well described by an unbroken power law for the protons with a spectral index ( $\alpha$ ) of 2.85 at all rigidities.

There is also the possibility to introduce a break around a few GeV, to have a slightly harder spectrum at lower energies.

#### 2.2.1.2. Inverse compton (IC) and bremsstrahlung (BR)

The interstellar electron spectra needed a break around **(1 GeV)** with a spectral index of 3.21 above the break, which is compatible with the locally observed electron spectrum (see Fig. 2.3). Below the break the optimal spectral index is 0.81, which implies a suppression of electrons. The break point might be related to the fact that around 1 GeV electrons have the smallest energy losses, since above this energy synchrotron, BR and IC dominate the energy losses, while below this energy ionization losses become strong, thus depleting the electron spectrum below 1 GeV. A similar break in the electron spectrum was needed in the Fermi diffuse model (**cite[46]**).

ToDo

ToDo

The targets for the production of gamma-rays are the interstellar gas and the interstellar radiation field, which are both strongly dependant of position, , so the photon composition varies with sky direction. Hence, for the IC templates we have to calculate the templates for each sky direction. The variation over the sky is about  $\pm 10\%$ , as shown in 2.4; for the BR template the spread is considerably smaller, as shown in 2.4.

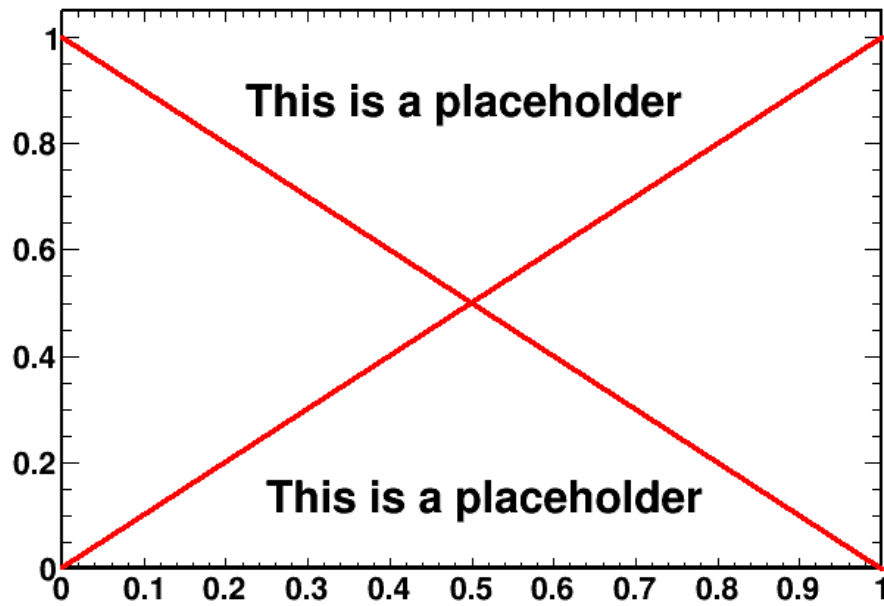


Figure 2.4.: images IC and BR variations over the sky

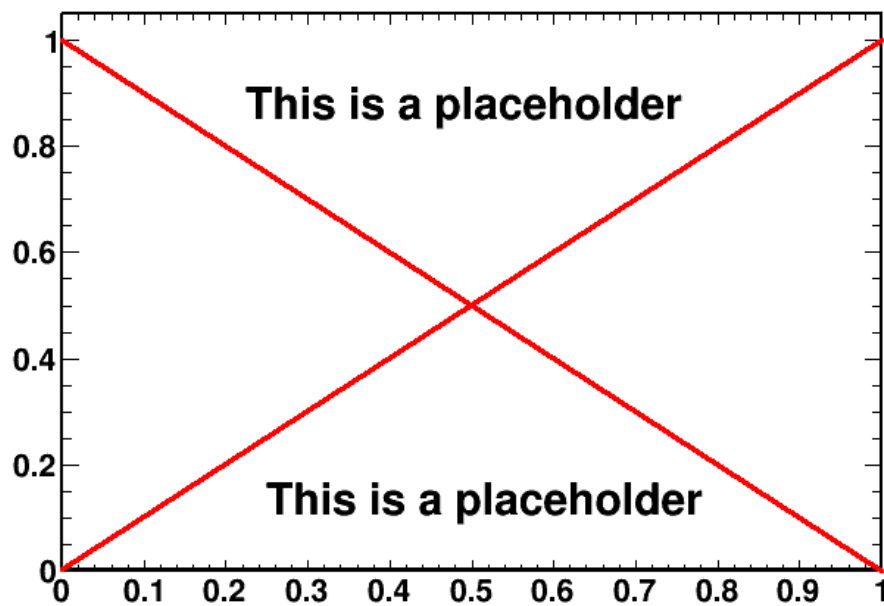


Figure 2.5.: images of MCR, MSP, DM on single plot.



## 2.2.2. Additional components

### 2.2.2.1. SCR component

The proton spectra for the SCR template can be described by an unbroken power law with a spectral index of 2.1, as obtained from the best fit. The index 2.1 for the SCR template agrees with the data from the Fermi Bubbles, shown by the data points inside the shaded band in Fig. 2.2; the index 2.1 is expected from diffuse shock wave acceleration. **(cite[60, 61])** The fact that the Fermi Bubbles and the cosmic rays inside sources have the same spectrum strongly suggests that they are connected by point sources providing advective outflows of gas in the Galactic center. **(cite[44])**

ToDo

ToDo

### 2.2.2.2. MCR component

The decreasing gamma-ray emissivity from MCs below 2 GeV could be parametrized by a break in the power law of the corresponding proton spectrum. Above the break the 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. But below the break, which varies according to the fit from 6 to 14 GV for the different clouds, the optimal spectral index is 0.7, thus providing a significant suppression of protons below the break, as can be seen from Fig. 2.3. Energy losses alone cannot reproduce such a suppression of the proton spectrum below the break, but magnetic cutoffs are able to do so. Such a cutoff is well known from cosmic rays entering the Earth's magnetic field: particles below typically 20 GV entering near the magnetic equator do not reach the Earth, but are repelled into outer space by the geomagnetic cutoff. **(cite[62])** The rigidity cutoff of 20 GV is proportional to the magnetic moment. Although the magnetic field near the Earth (0.5 G) is orders of magnitude higher than the typical magnetic fields in dense MCs **(cite[63])**, the much larger sizes of MCs - or its substructure of filaments and cloudlets **(cite[64])** - yield magnetic moments of the same order of magnitude as the Earth's magnetic moment, so similar magnetic cutoffs are plausible. Variations in the magnetic cutoff in MCs are expected from the variations in size and in magnetic field; the latter increases with MC density. **(cite[63])** The variations of the break in the proton spectrum between 6 and 14 GV varies the maximum of the gamma-ray spectrum from 2 to 1 GeV(**??, as shown in Fig. ref??**). The fit prefers a constant spectral index below the break for all sky directions. Such a constant spectral index is plausible with regular magnetic fields oriented in the disk **(cite[65, 66])** and the "cloudlets" inside MCs **(cite[64])** form magnetic dipole fields. Then the maximum cutoff occurs for cosmic rays entering from the halo perpendicular into the cloud for any orientation of the magnetic dipole. For a given entrance angle the cutoff would provide a sharp break, but for an isotropic distribution of entrance angles the break points are smeared. A distribution of break points will provide a slope below the maximum break determined largely by the isotropic distribution of the entrance angles into the disk. Since this distribution is the same for all MCs the slopes below the break will be similar for all MCs, even if the maximum break (= maximum magnetic cutoff) varies.

ToDo

ToDo

ToDo

ToDo

ToDo

ToDo

ToDo

### 2.2.2.3. Dark matter (DM)

DM particles are expected to annihilate and just like in electron-positron annihilation the annihilation energy of roughly twice the WIMP mass will lead to the production of hadrons, thus producing copiously gamma-rays from  $\pi^0$  decays. A smaller fraction of

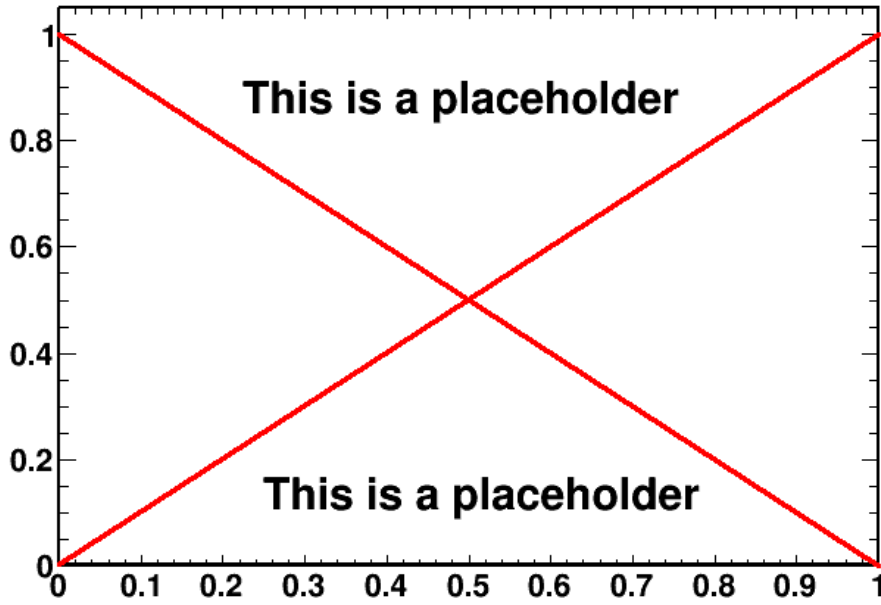


Figure 2.6.: Images to illustrate isotropic calibration

WIMP annihilation is expected to lead to tau lepton pairs, which can lead to  $\pi^0$  production in the hadronic tau decays. This contribution is expected to be small and is neglected. The DM template can be calculated with DarkSusy. (cite[67, 68]) The annihilation signal peaking at 2-3 GeV requires a WIMP mass around 45 GeV, as shown in Fig. 2.5 as well. The difference to the MCR template is the cutoff at twice the WIMP mass, which is absent in the MCR template.

ToDo

#### 2.2.2.4. Milli-second pulsars (MSP)

ToDo

The MSP spectrum is directly taken from the Fermi study (cite Fermi)

#### 2.2.2.5. Isitropic component

The isotropic template represents the contribution from the isotropic extragalactic background and hadron misiden-tification. Its spectral shape and absolute normalization are provided within the Fermi software. (cite[51]) The isotropic template was redetermined for our analysis in the following way.

ToDo

We fit the data in regions outside the Bubbles and Galactic disk using the isotropic template from the Fermi software as an initial estimate in the fit. 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. However, if there is a missing or too high isotropic contribution, this leads to an offset at the origin of the linear curve, since the isotropic component is by definition the same for all cones, so it shifts the whole curve up and down for each energy bin. An example of such a fit is shown in Figure 2.6 for an energy bin between (3.7-5.2 GeV). The offset can be determined for each energy bin, which yields the spectral template of the isotropic component. The final spectral template is obtained by iteration until zero offset at the origin is reached. The resulting template in our analysis has deviations from the Fermi template up to 35% above 2 GeV, as shown in the insert of 2.6.

ToDo

## 2.3. Fitting method

The fitted data can be seen as a data cube whose dimension are longitude, latitude and energy. The sky is divided in  $720 \times 360$  cones of  $0.5^\circ \times 0.5^\circ$ . Every cone contains 30 energy bins depending on the data set used. This allows to treat each portion of the sky independently of one another. Since the cones do not have the same solid angle, the grid I will use most often is composed of 797 cones of different sizes whether they are close to the poles or near the equator. This allows a better statistic in lower flux regions at high latitudes. It is also way faster to compute.

The model uses a certain number of components (from three to six) each corresponding to a certain phenomenon. They all have a certain energy spectra, that can vary with the position in the sky (for PCR, BR and IC). The fit then only scale every template up and down so that their sum is the closest to the data. The closest is found when the  $\chi^2$  is minimized. The  $\chi^2$  is calculated as follows:

$$\chi^2 = \sum_{i=1}^{30} \left[ \frac{(D_i - \sum_{j=1}^n n_j \cdot T_{ij})^2}{\sigma^2} \right] \quad (2.1)$$

where:

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

The fitting routine is executed using the ROOT software.

This method allows to fit any region of the sky independently.

The fit is also very well constrained with only 5 degrees of freedoms against 30 data points.

On the other hand, it is not possible to implement a spatial template where the spatial shape of a component would be fixed in advance. For example a component with a spherical distribution around the GC. The hope is to let the fit find reasonable shapes by itself only using the  $\chi^2$  minimization.

It allows to study at the same time the different contributions in one portion of the sky, and the skymaps of every component.

## 2.4. Introduction of results

Recreation of previous studies (GC excess, problems).  
Introduction of new component to take care of those problems (SCR for high energies, MCR, Dm or MSP for 2GeV excess)



## 3. Results

### 3.1. Recreating previous results

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

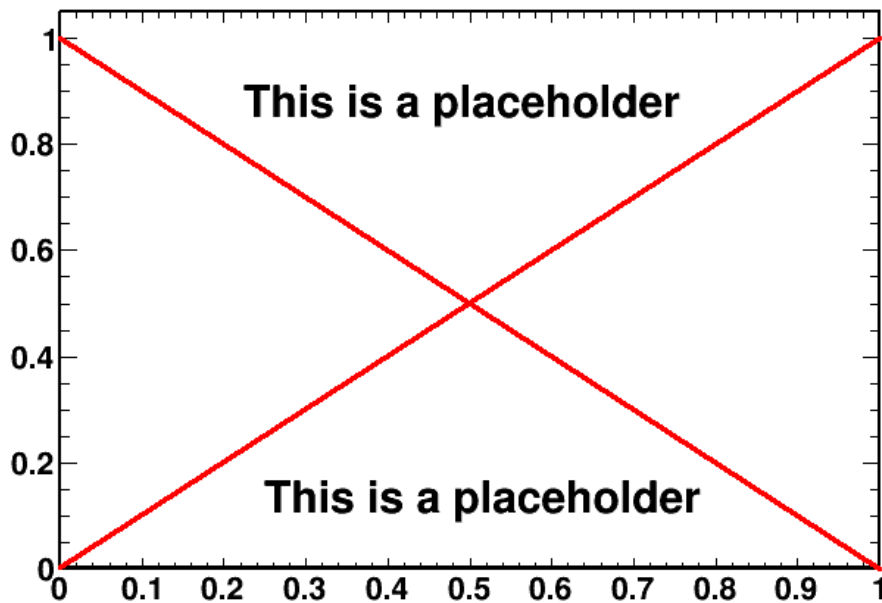


Figure 3.1.: Some weniger plots to show the GC excess

Before trying upgrade the model in use, it is important to make sure we can recreate it with the same parameters. Fig. 3.2 shows the results of a fit using only the PCR, IC and BR components. The shape and intensity of the previously observed excess are found (cite). **ToDo**

It can also be observed that the fit is particularly bad in the bubbles and the disk (see Fig. 3.2) where the high energy spectrum is harder (see Fig. 3.3). In this region, the

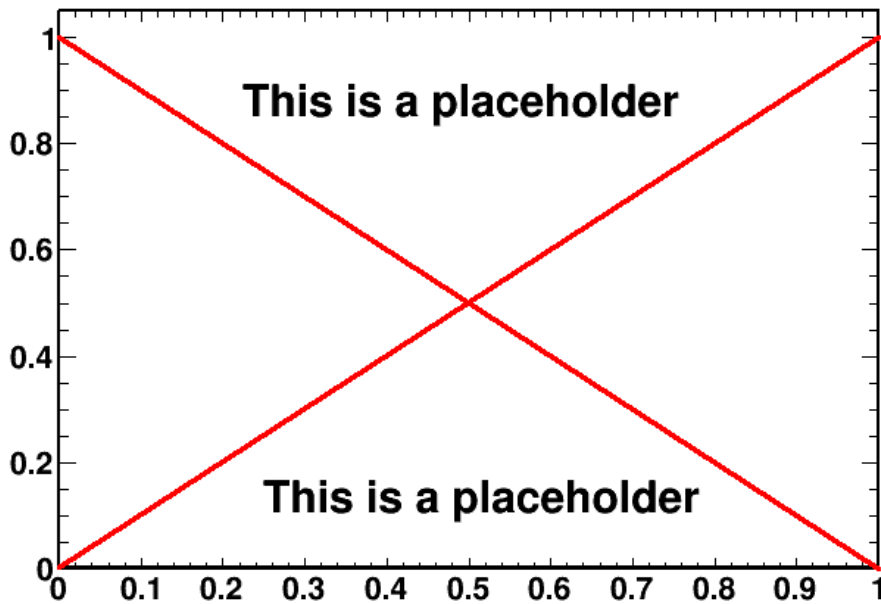


Figure 3.2.: Picture of GC excess, (compare with previous papers?), a chi2 map too

PCR spectrum falls off too quickly, and the IC spectrum which usually takes care of high energies is blocked by the low energy flux drop.

### 3.2. Introducing SCR

Introducing the SCR template, a clear improvement can be noted in the  $\chi^2$  distribution (see Fig. 3.4). The bubble shape that was clear before has now disappeared. Even if the fit is still not perfect everywhere, the improvement is significant.

From Fig. 3.5a and 3.5a we see the role of the SCR template at high energies, taking care of the high flux. It also permits a better fit of low energies by PCR and IC since they do not have to be everywhere at the same time.

**ToDo** (Here the bad chi2 comes from 0.1GeV region, where the PCR template does not fit the data. not from the 2GeV excess.) A problem still remains in the disk and diffuse regions around the galactic anticenter.

### 3.3. Introducing SCR and MCR

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

Three dots appear to have a really high  $\chi^2$ , but that is only due to the point source subtraction that is not perfect (see Chapt. 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

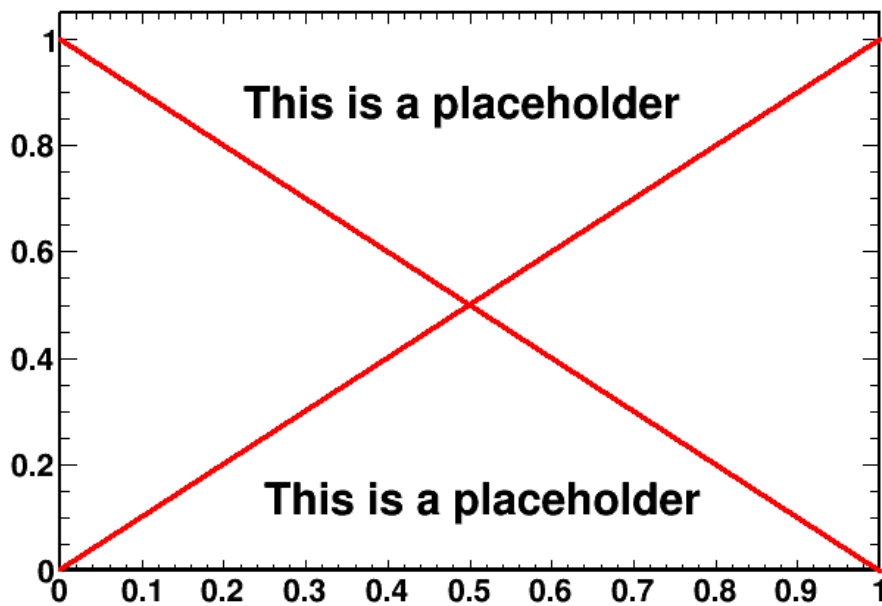


Figure 3.3.: Picture background only spectra with bad fit (high energies too hard) Compare bubble or disk region and outside

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

### 3.3.1. Discussion on spatial shapes

Fig. ?? shows the spatial distribution of the flux of each component around 2GeV, 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 sperical, 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.

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

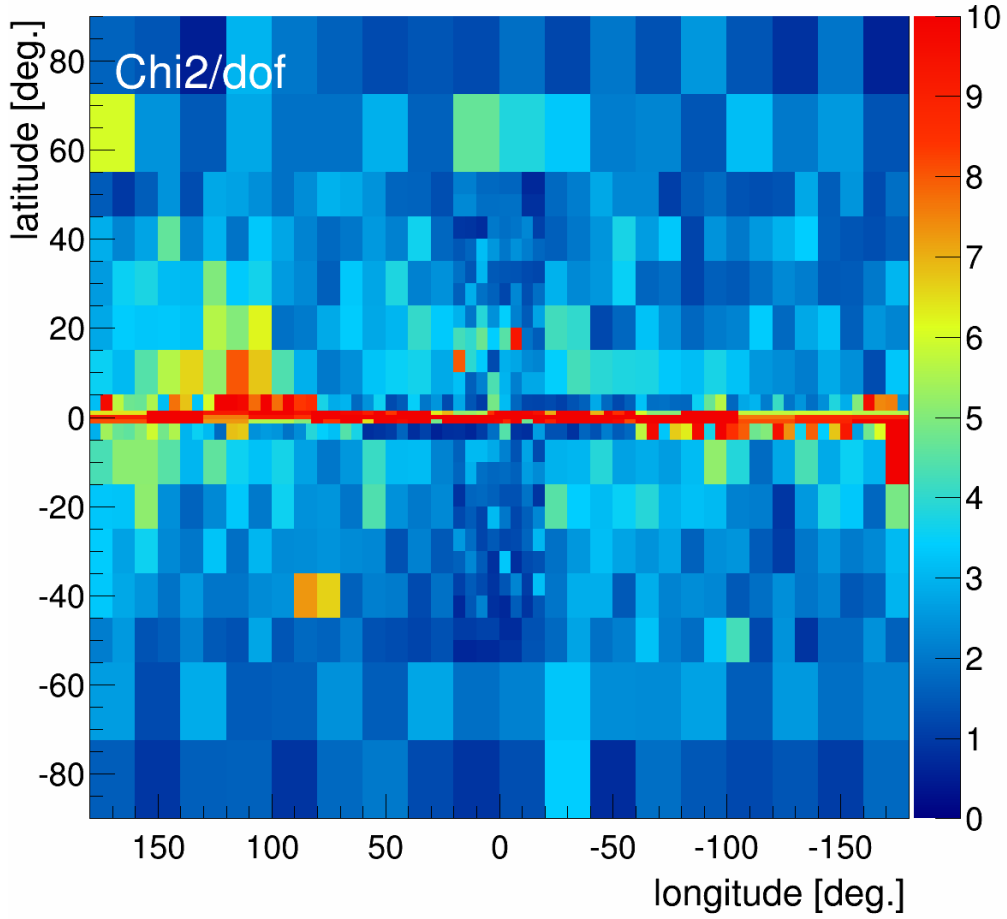


Figure 3.4.: Chi2 distribution of SCR only fits.

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.

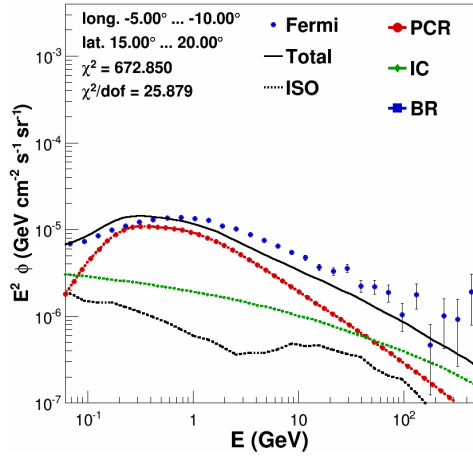
The MCR template also follows the spatial distribution of molecular clouds in our galaxy. It is a good sign since it is supposed to come from those regions. It is not spherical at all. That could have happened if the excess component has a DM origin, since it is supposed to be spherically distributed.

### 3.4. Introducing SCR and DM

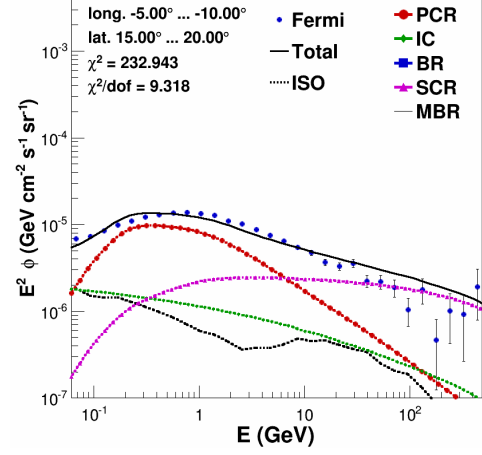
The first step is to determine which mass for the WIMP particles would produce the best spectrum for our fit. Fig. 3.9 shows the best fit for the CMZ region, with the WIMP mass as a free parameter. It chooses a mass of 52.3 GeV, peaking around a few GeV, as expected in (ref theory section). Since the 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.

ToDo





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



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

Once the mass is determined for the entire sky, the fit gives the following results. The  $\chi^2$  distribution (Fig. 3.10) is comparable to the MCR fit for the major part but is significantly worst in the disk.

As seen on Fig. 3.11, 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  $\chi^2$  distribution of the MSP only fit (Fig 3.12) is the similitudes with the DM only fit (Fig. 3.10). 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  $\chi^2$  is generally worst.

ToDo

(add picture of residuals at low energy maybe?)

ToDo

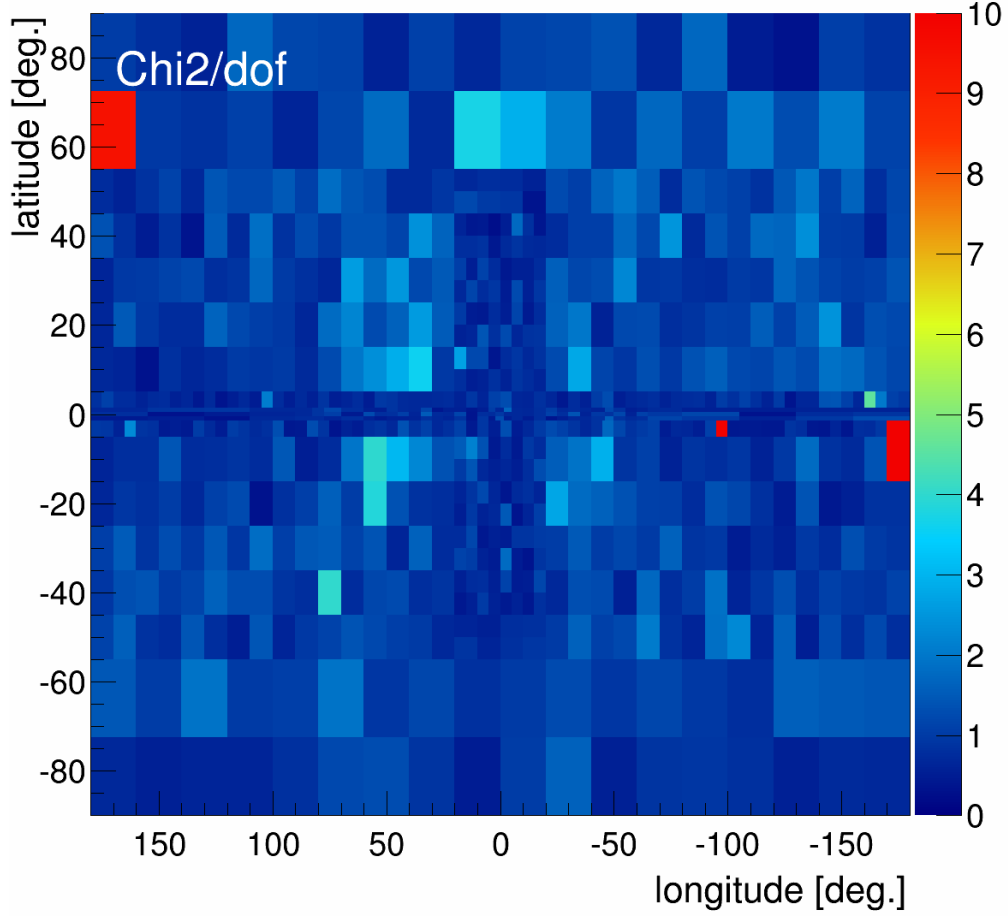
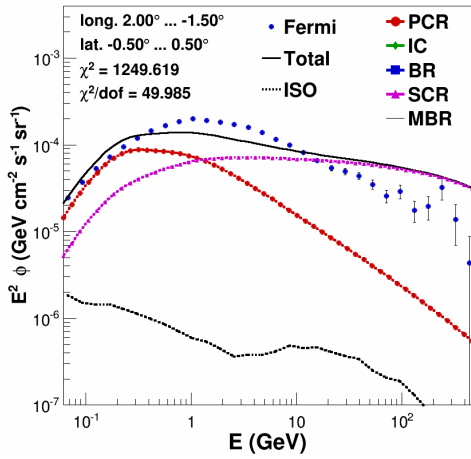
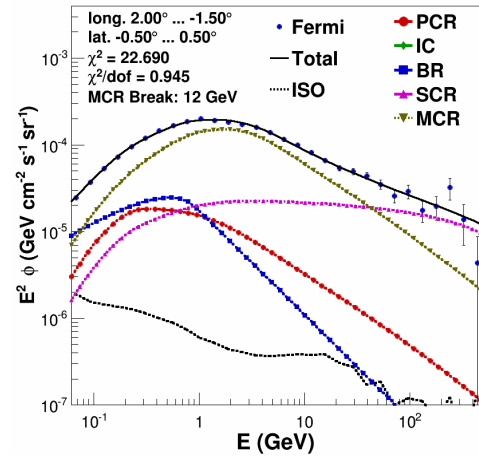


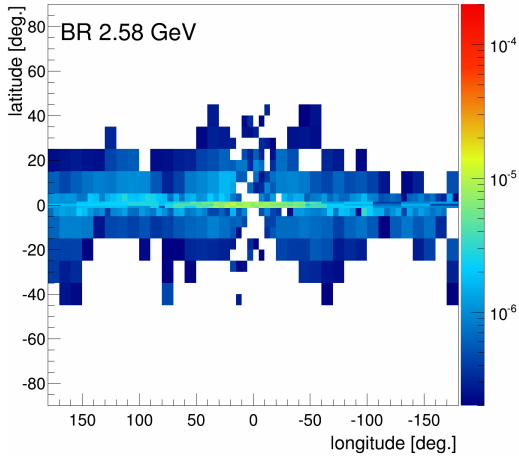
Figure 3.6.: Chi2 maps of MCRonly fits compared to background only



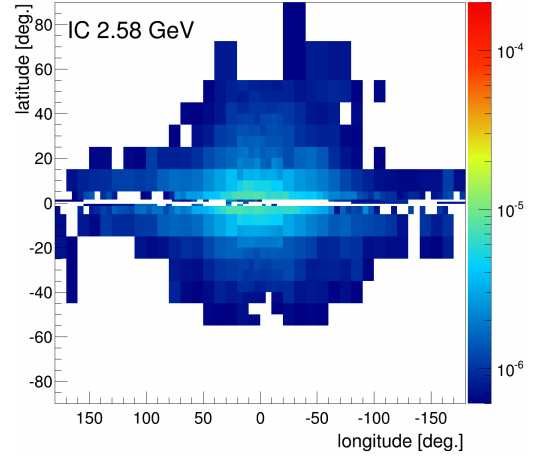
(a) SCR fit in the CMZ region



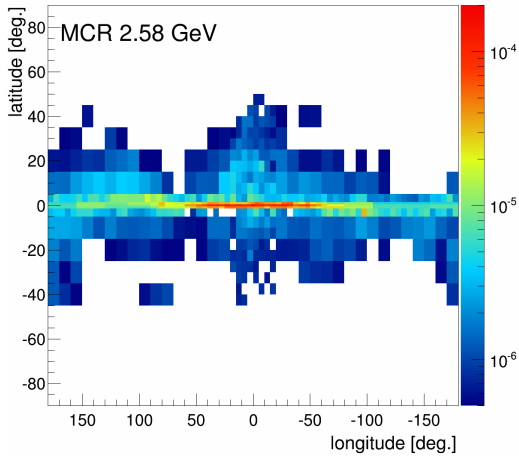
(b) MCR fit in the CMZ region



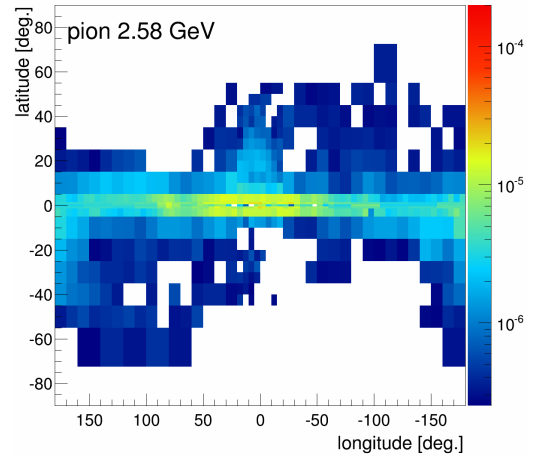
(a) Flux distribution of bremsstrahlung (BR)



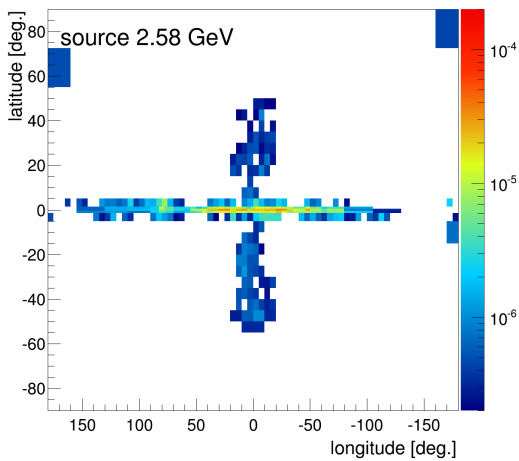
(b) Flux distribution of inverse compton (IC)



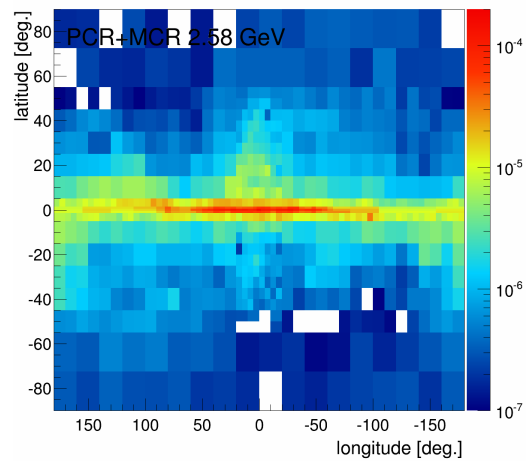
(c) Flux distribution of MCR



(d) Flux distribution of PCR



(e) Flux distribution of SCR



(f) Flux distribution of PCR + MCR

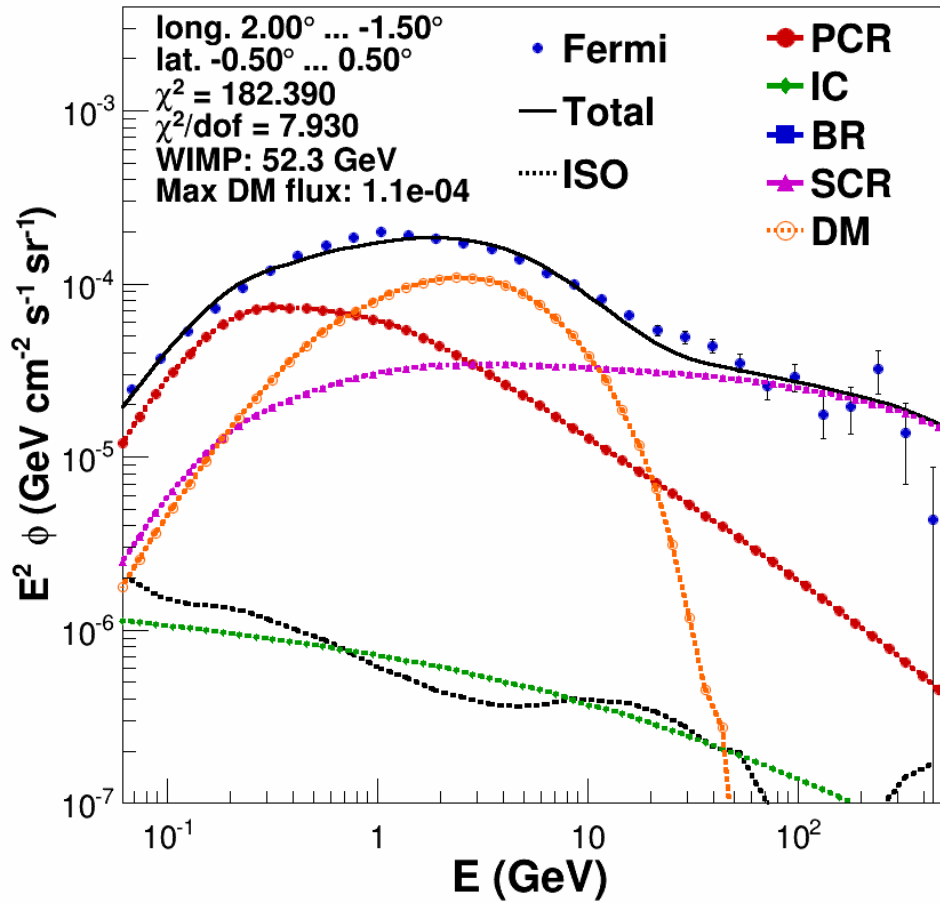


Figure 3.9.: spectrum of best mass DM fitted in CMZ. Also pictures of DM distribution compared to gas map.

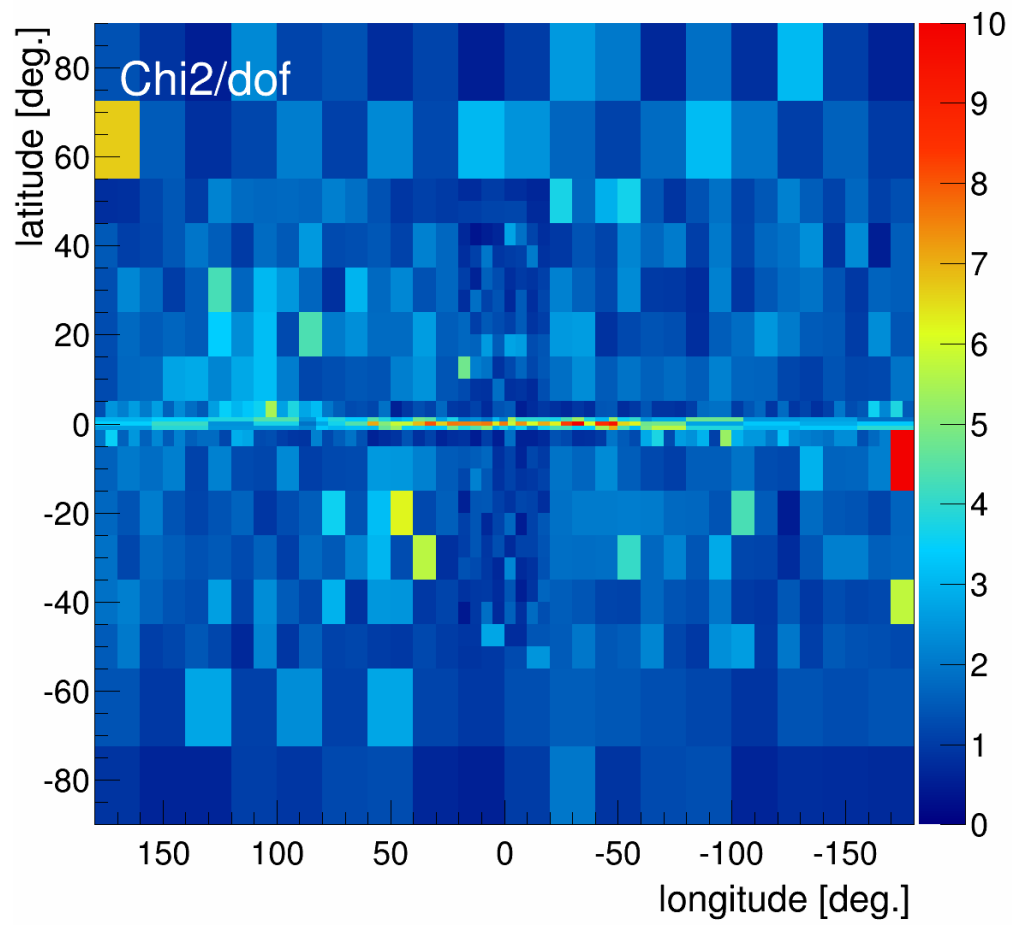


Figure 3.10.: DM fit chi2 distribution

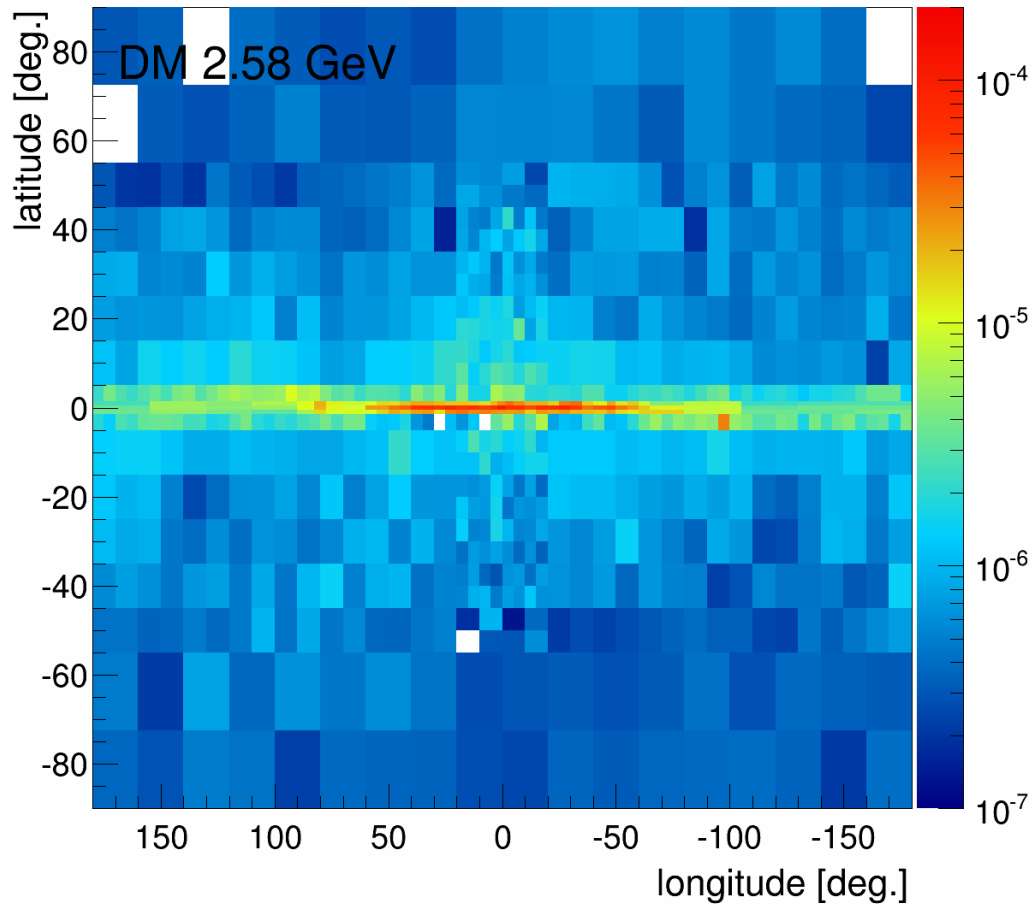
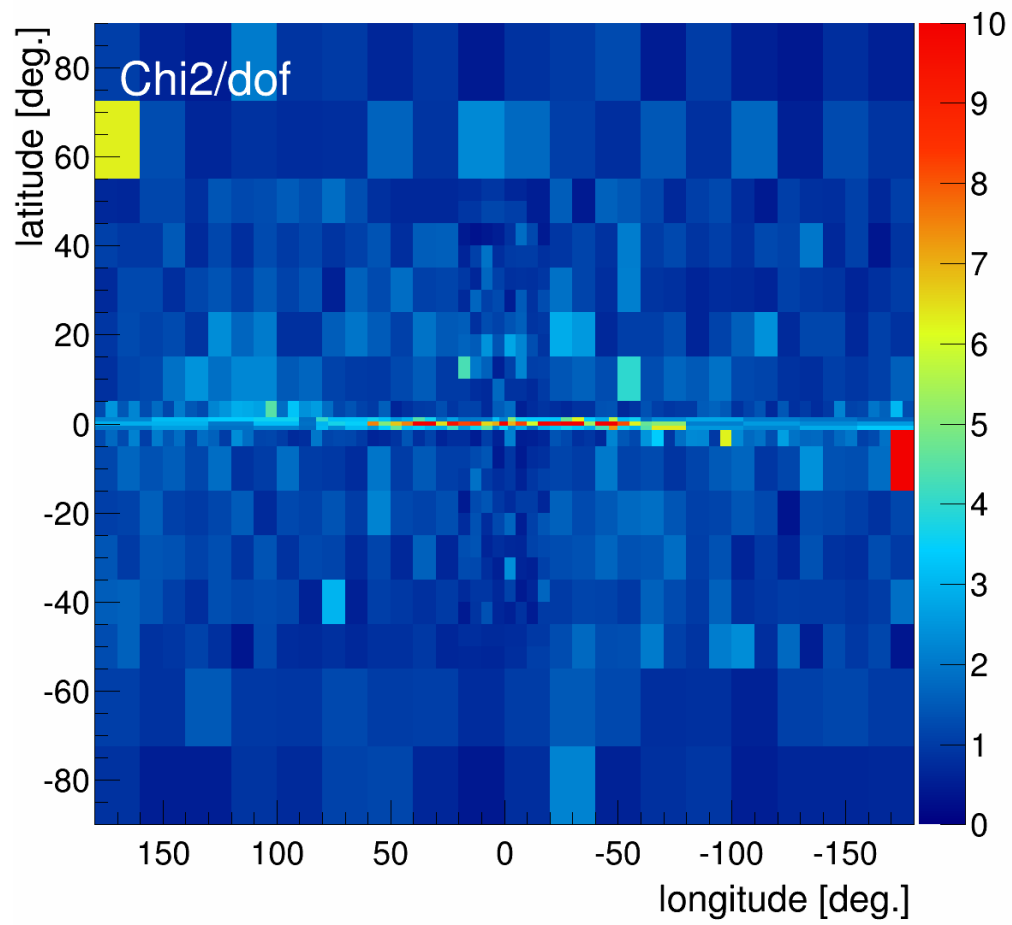


Figure 3.11.: DM distribution compared to gas map.

Figure 3.12.:  $\chi^2$  distribution of MSP only fit

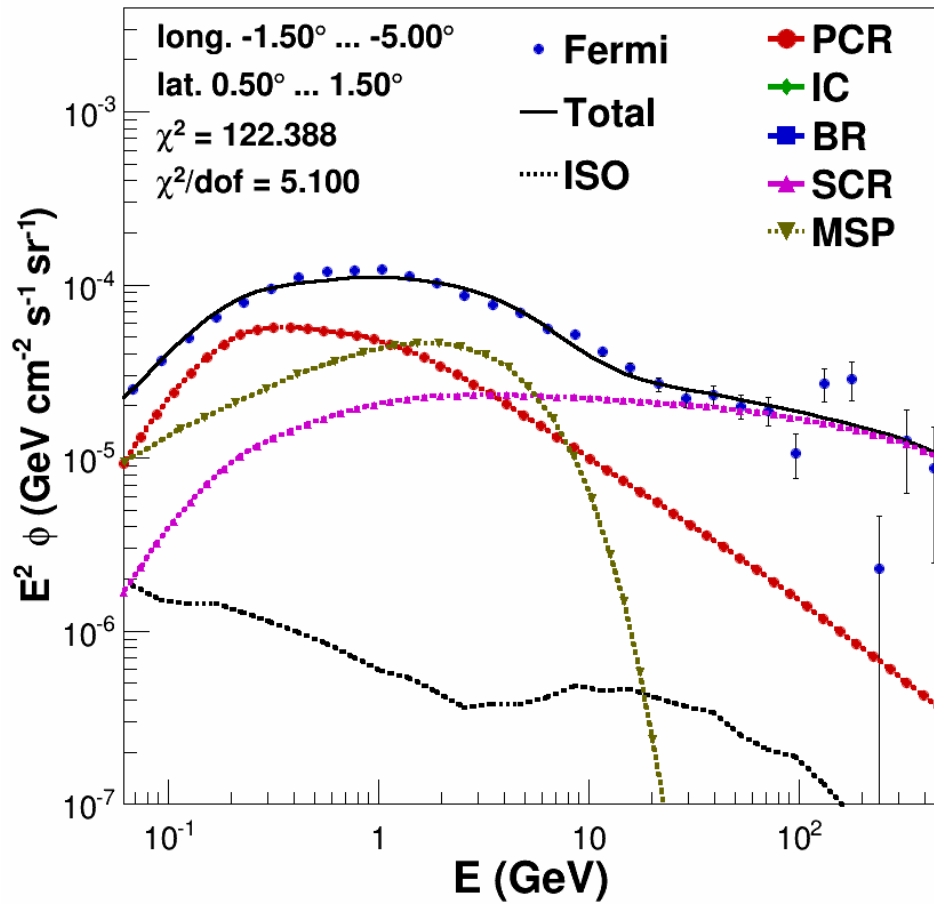


Figure 3.13.: Fit with SCR and MSP spectrum in the CMZ region.



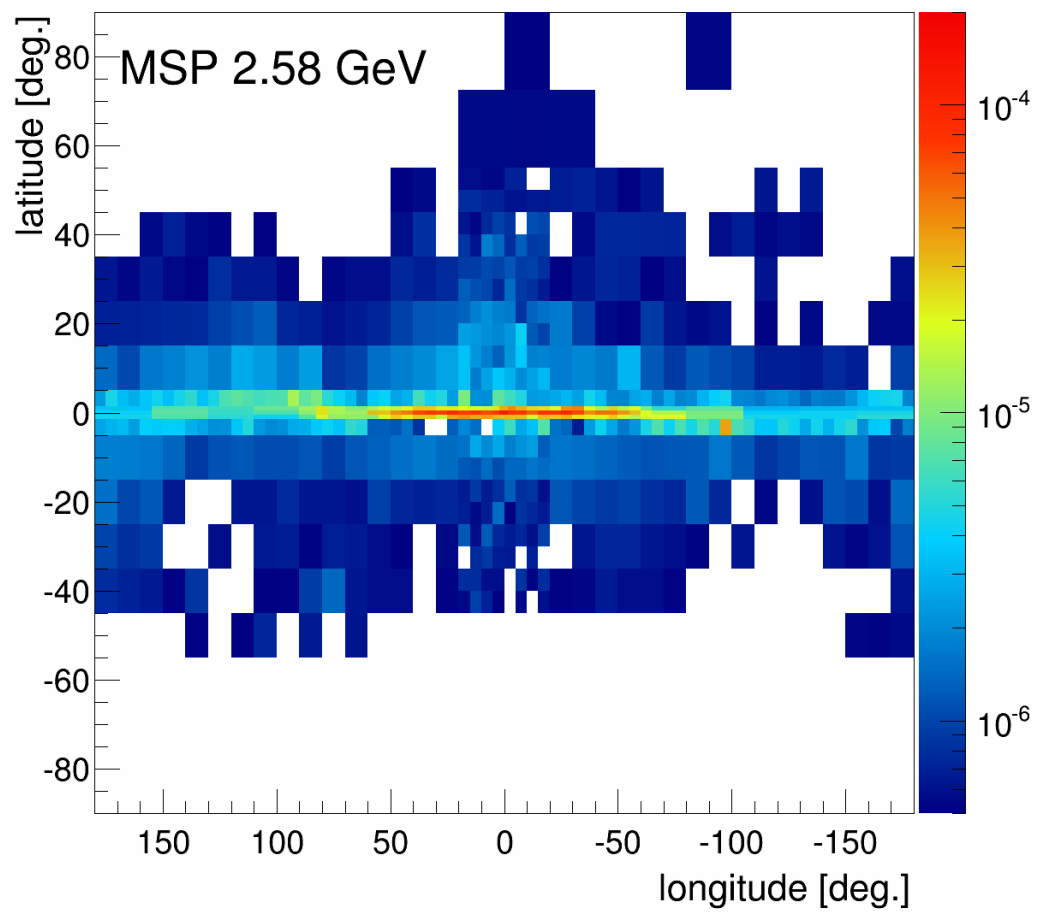


Figure 3.14.: Flux distribution of MSP around 2.5GeV.



## **4. Discussion**

### **4.1. Interpretation of spatial shapes**

### **4.2. Why is MCR better than DM or MSP**

Gavering 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.

First of all, comparing the  $\chi^2$  skymaps is pretty clear. Adding a fifth component over SCR is a improvement in all cases, but the best fits are obtained with MCR, especially in the disk.

### **4.3. How do these results fit in context**



## 5. Conclusion

Here you write some Conclusion.



# **Bibliography**





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# **Appendix**

## **A. Some appendix section**

This appendix chapter contains ...

