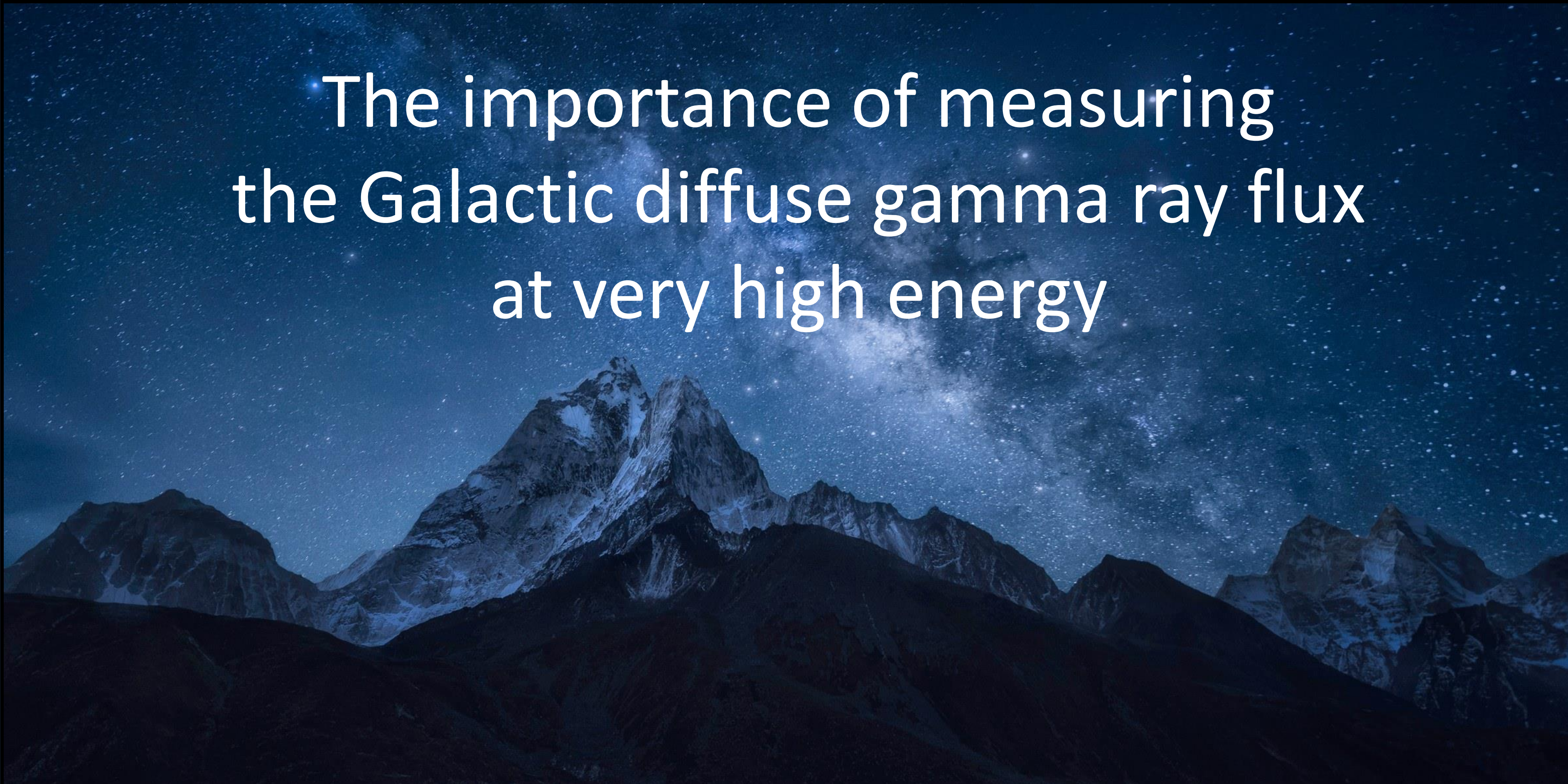
The importance of measuring the Galactic diffuse gamma ray flux at very high energy



LHAASO Scientific Observation
and Multi-messenger Astronomy Workshop
2019 April 25-26, Chengdu

S.Vernetto & P.Lipari

Diffuse γ-rays - a fundamental tool to study the origin and propagation of CRs in the Galaxy

- Cosmic ray spectra and composition are only measured **locally** and with large uncertainties, in particular above 100 TeV
- Knowing the CR properties **in the whole Galaxy** is fundamental to understand the origin and propagation of cosmic rays
- CRs in the Galaxy interact with gas and radiation producing a **diffuse flux of γ-rays** (and neutrinos) that **encodes the space and energy distribution of the parent CRs in the whole Galaxy**

Hadronic γ-ray production by cosmic ray nuclei:

Mostly by π^0 **decay** produced in interactions of CR nuclei
Target: interstellar matter

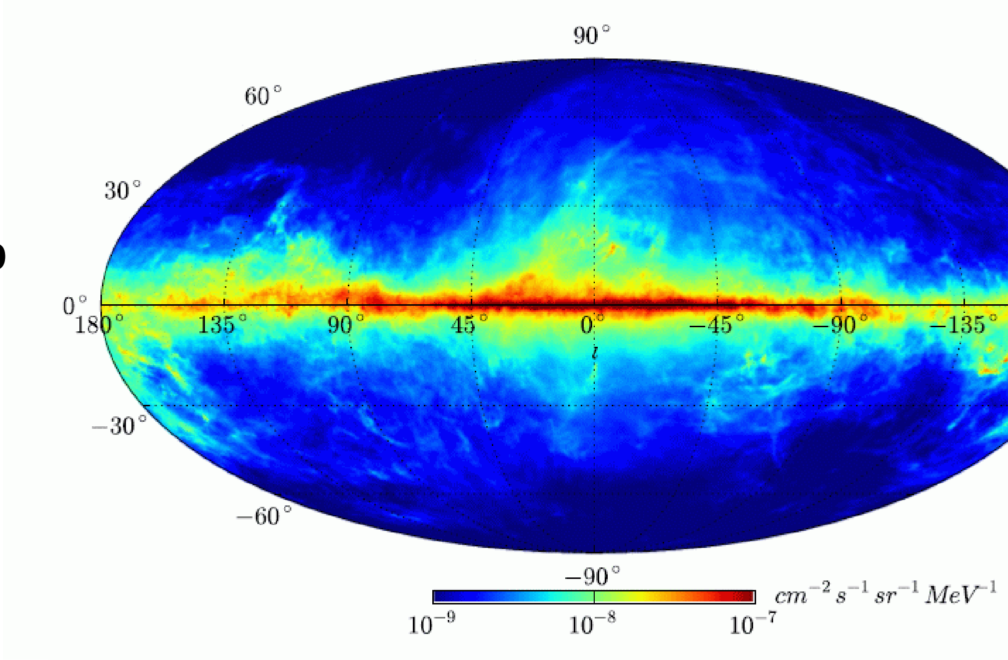
Leptonic γ-ray production by electrons and positrons:

- **Bremsstrahlung**
  Target: Interstellar matter

- **Inverse Compton**
  Target: radiation fields (CMBR – dust & star emission)

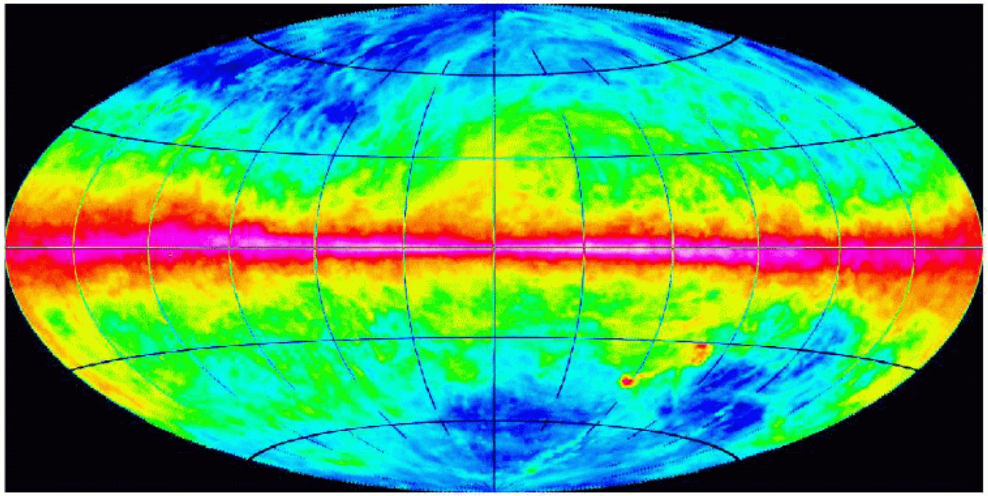
Galactic diffuse γ-ray flux data: Fermi

Fermi γ-ray map at 1 GeV



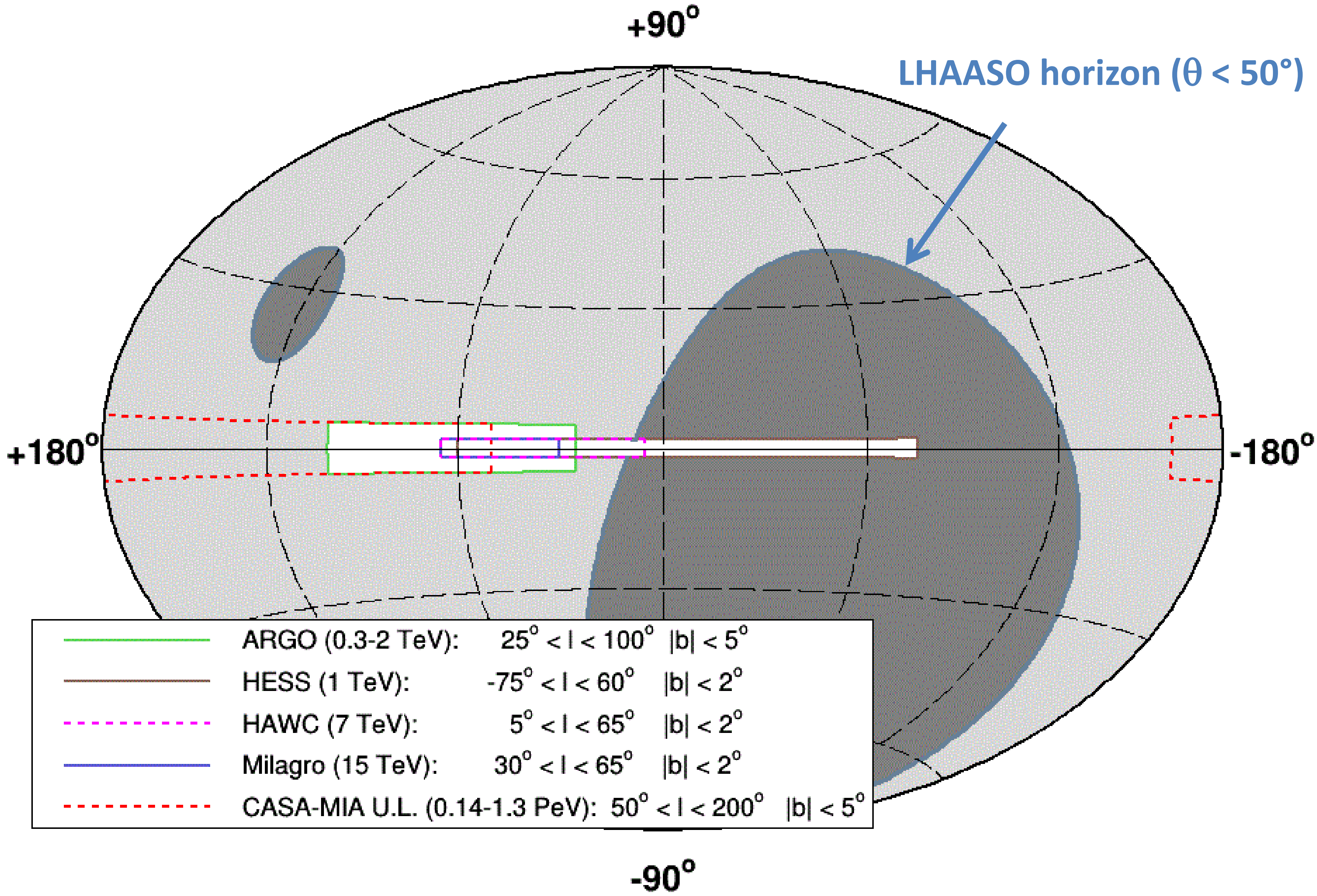
Fermi maps :
30 energies
from ~60 MeV to ~ 500 GeV

Atomic hydrogen column density (21 cm radio emission)



The γ-ray emission traces the H distribution

At higher energies very few data



What is the expected flux at 30-1000 TeV ?

It will be detectable by the new experiments ?

What we can learn from this measurement ?

→ Can we get information on the cosmic ray composition at the knee?
Is it possible to check the «ARGO p+He knee»?

Ingredients for the calculation of the diffuse gamma ray flux at high energy

Gamma ray production in every point of the Galaxy

- Cosmic ray spectrum (p,He,nuclei,e^-)
- Target density:
  Interstellar matter (H, He, heavy nuclei)
  Radiation fields (CMB, dust & star emission)
- Cross sections *pp, p-nuclei, nuclei-nuclei ->* γ

Gamma ray propagation

- Integration along the line of sight, taking into account the absorption of gamma ray by pair production

We have developed...

1) Model for the spatial distribution of the interstellar matter

2) Model for the radiation field in the Galaxy

3) Model for the cosmic ray spectra in all the Galaxy

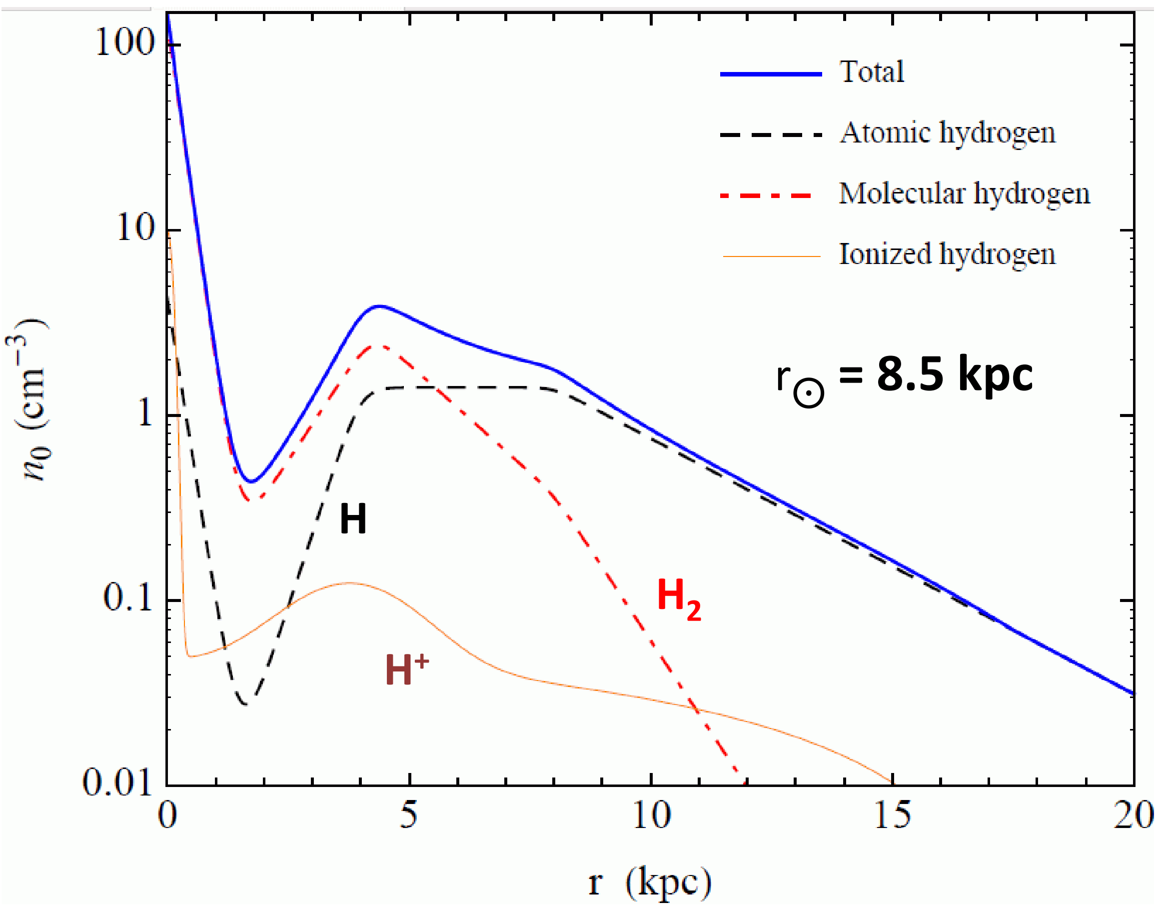
Details in: P. Lipari & S. Vernetto, Phys.Rev. D 98, 043003, 2018

1^{st} step

Model for the interstellar matter distribution

Our model for the hydrogen spatial distribution (axially symmetric)

Average H midplane density vs. r



Using the results of different authors, we build a model for **the Hydrogen distribution as a function of r and z**

Atomic H: $M_H = 5.3\ 10^9\ M_{sun}$

Molec. H: $M_H = 7.2\ 10^8\ M_{sun}$

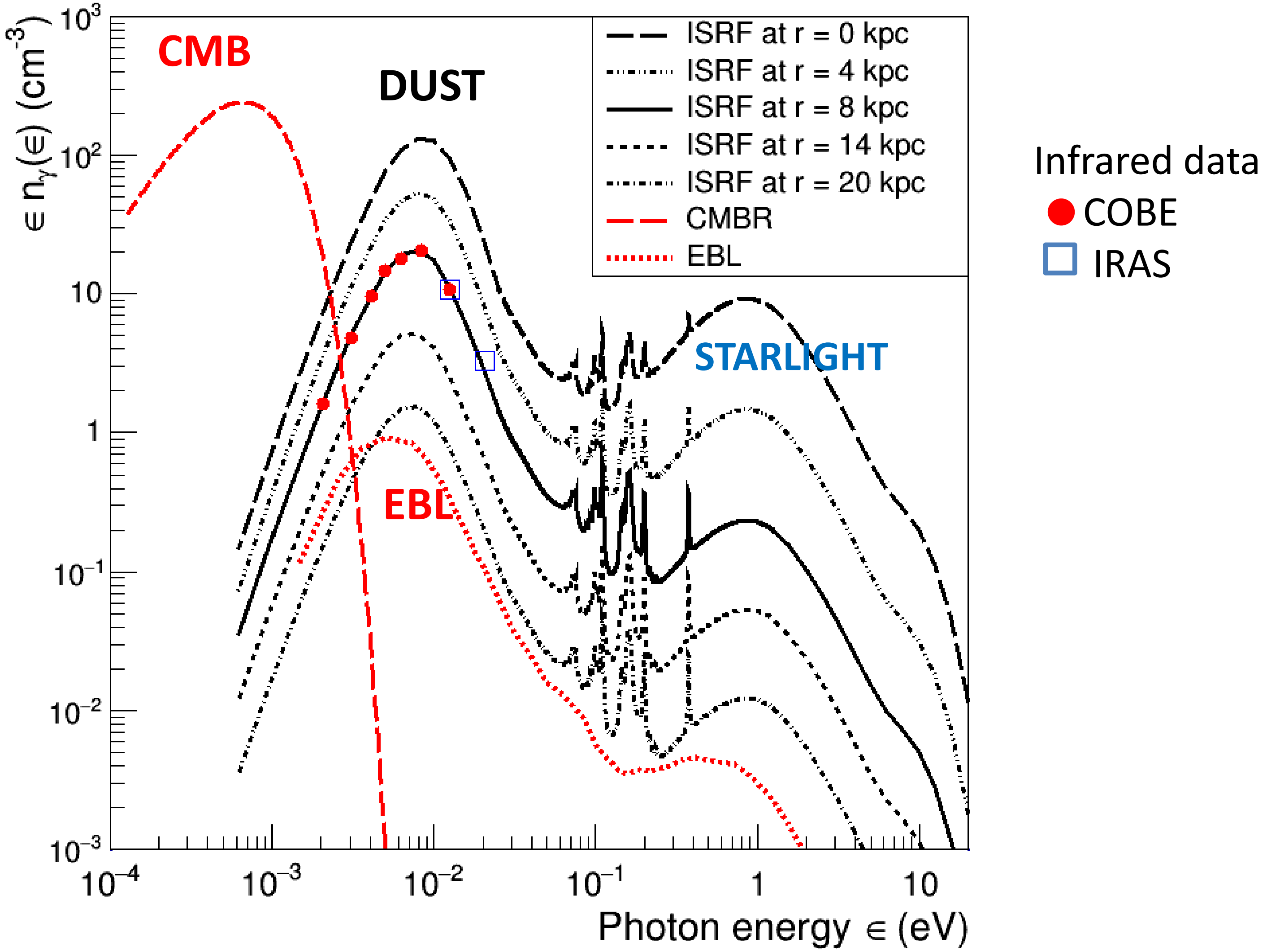
Ionized H: negligible except in the Galaxy center (R < 200 pc)

Total mass (H+heavier elements) = **1.42 M_H**

2^{nd} step

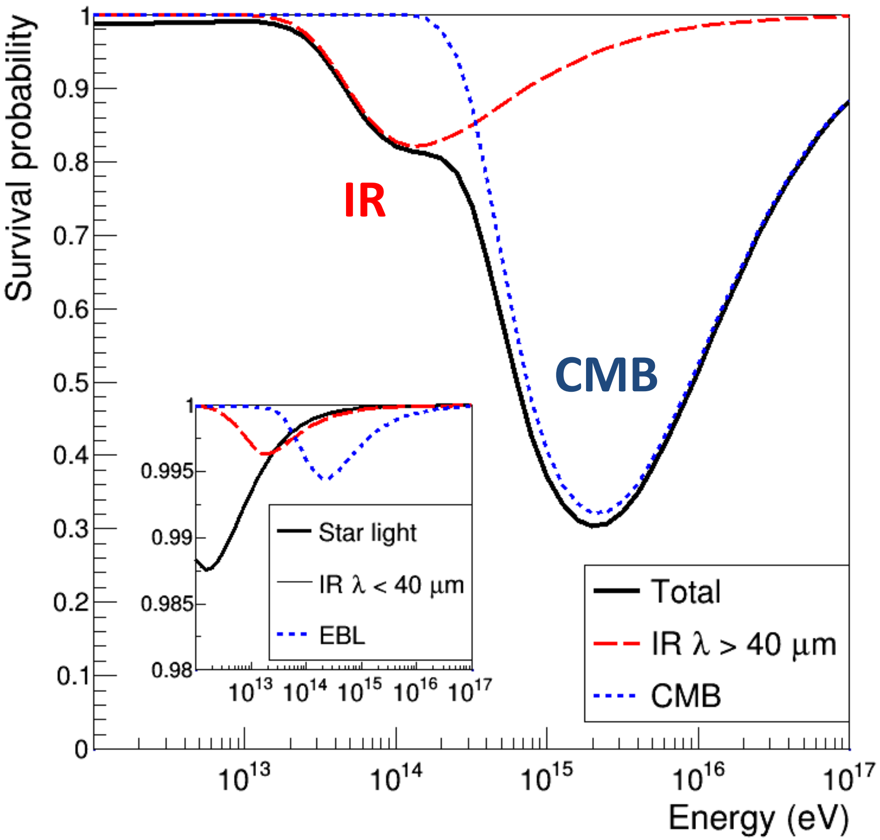
Model for the Galactic radiation field

Our model for radiation fields in the Galaxy

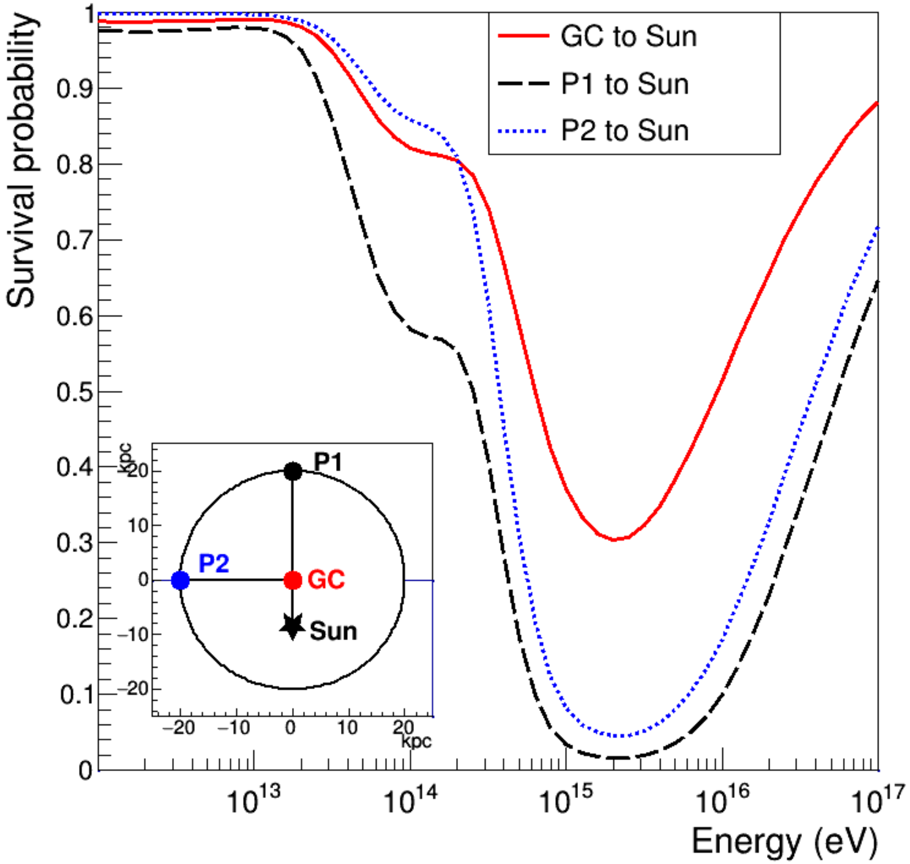


Survival probability vs. gamma ray energy

γ-rays from Galactic center



γ-rays from 3 source positions



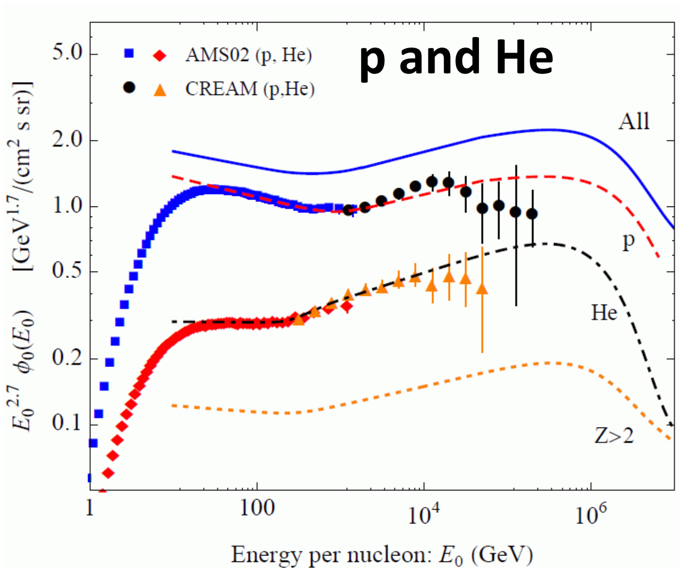
Details in: S.Vernetto & P.Lipari, Phys.Rev. D 94, 063009, 2016

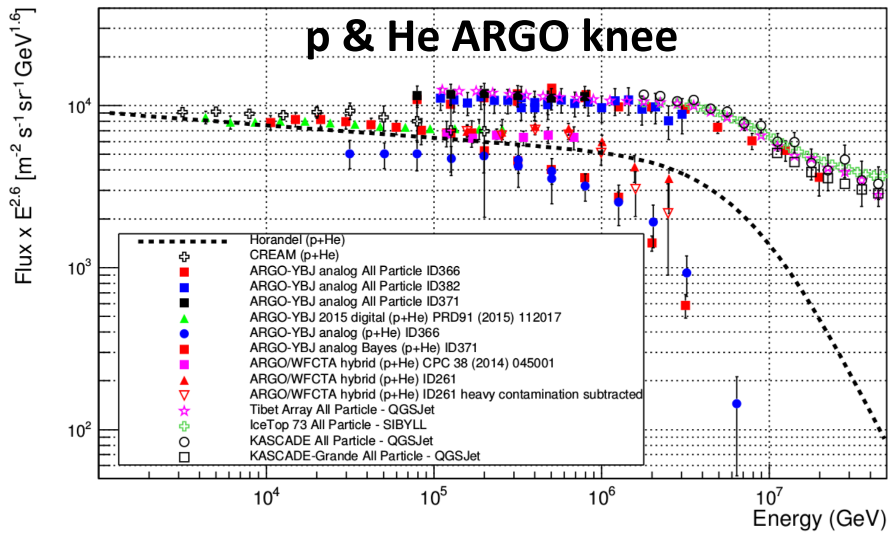
3rd step

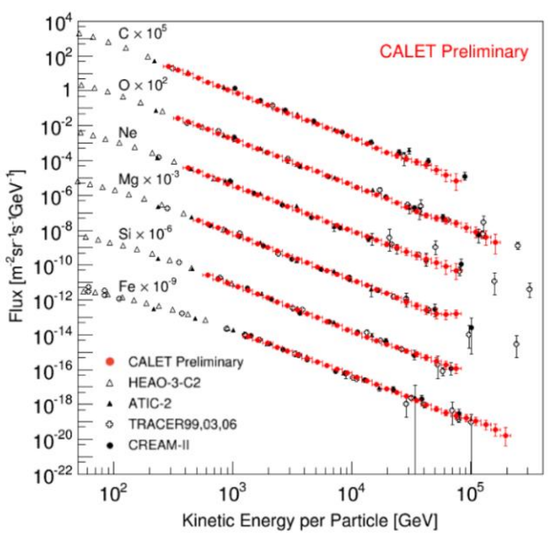
Model for the Cosmic Ray spectra

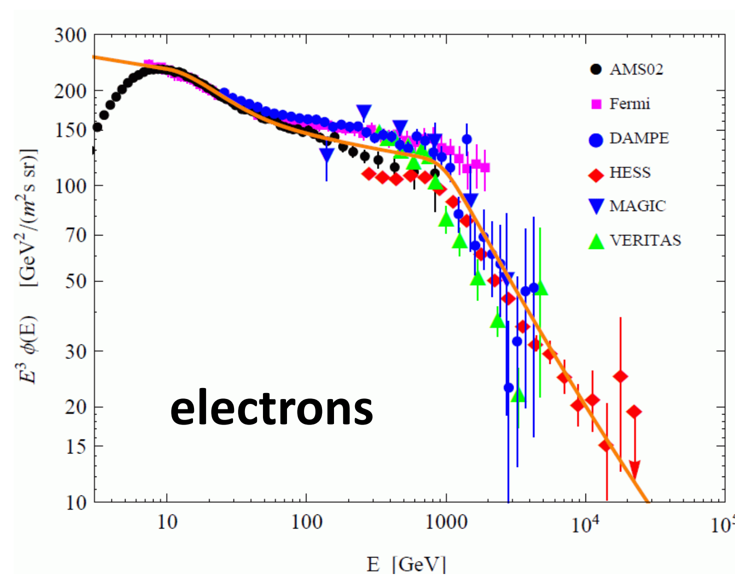
- local
- everywhere in the Galaxy

Cosmic rays local spectra measurements

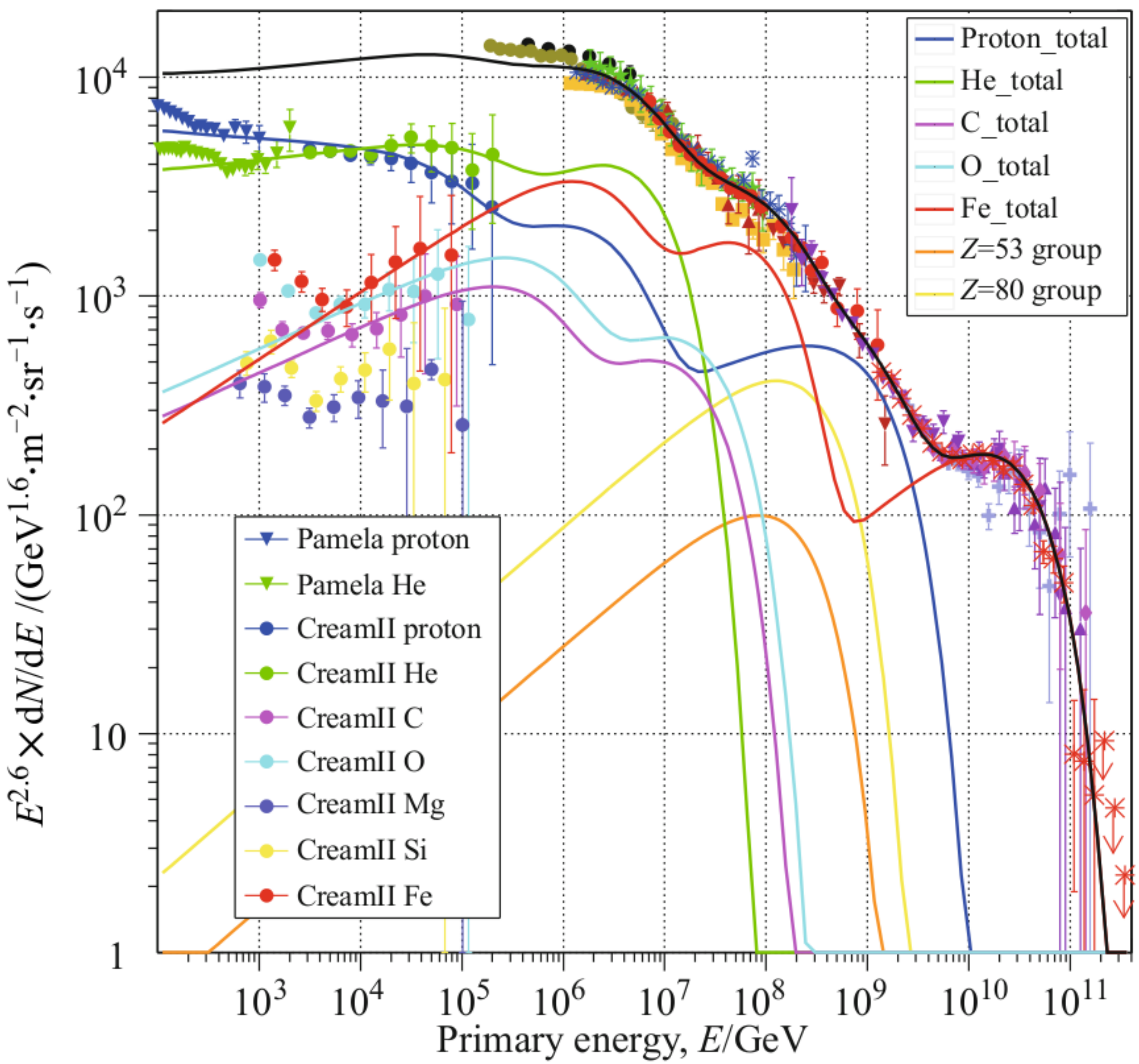






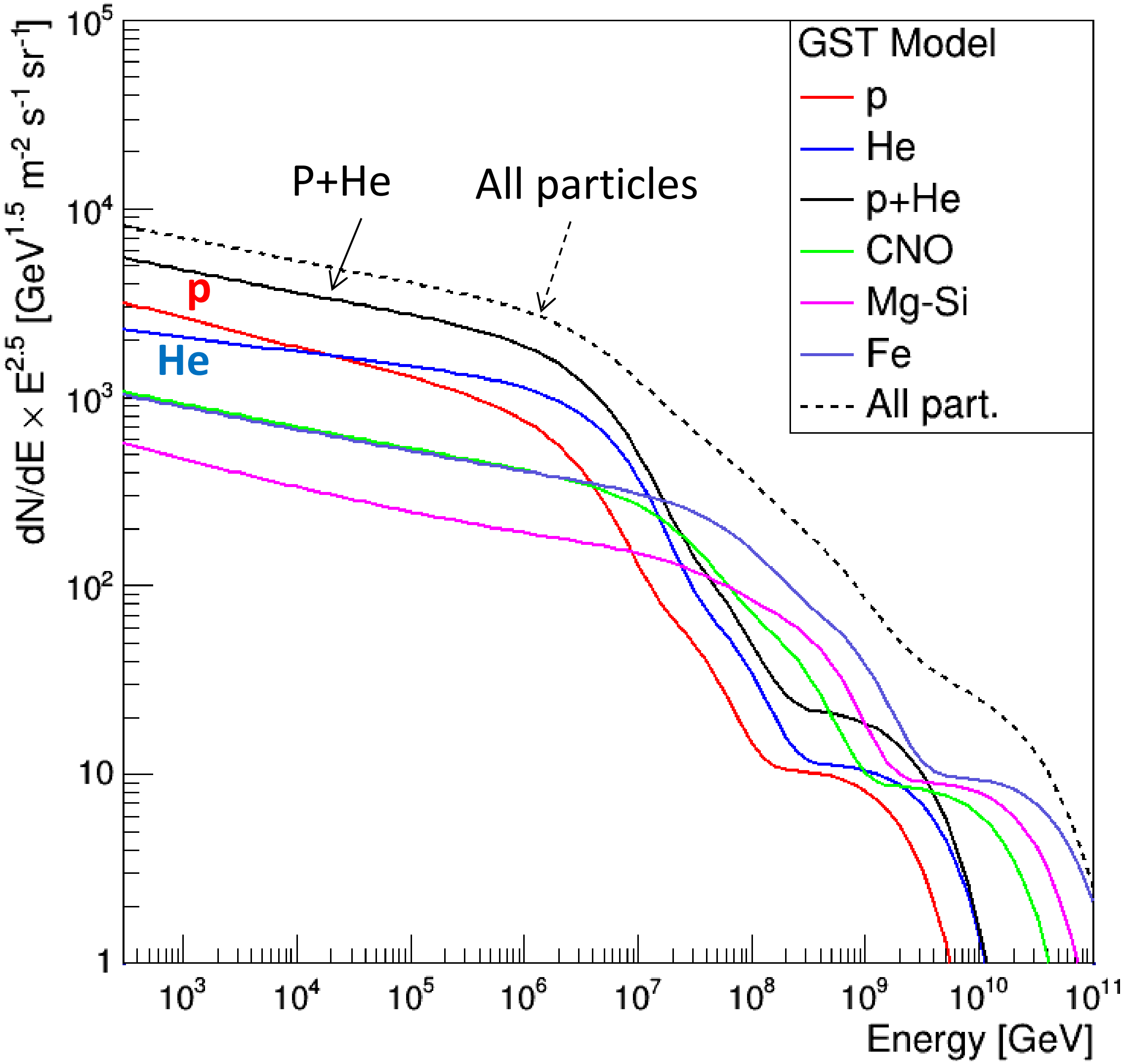


All particle spectrum



Gaisser et al. 2013

Gaisser-Stanev-Tilav (GST) model

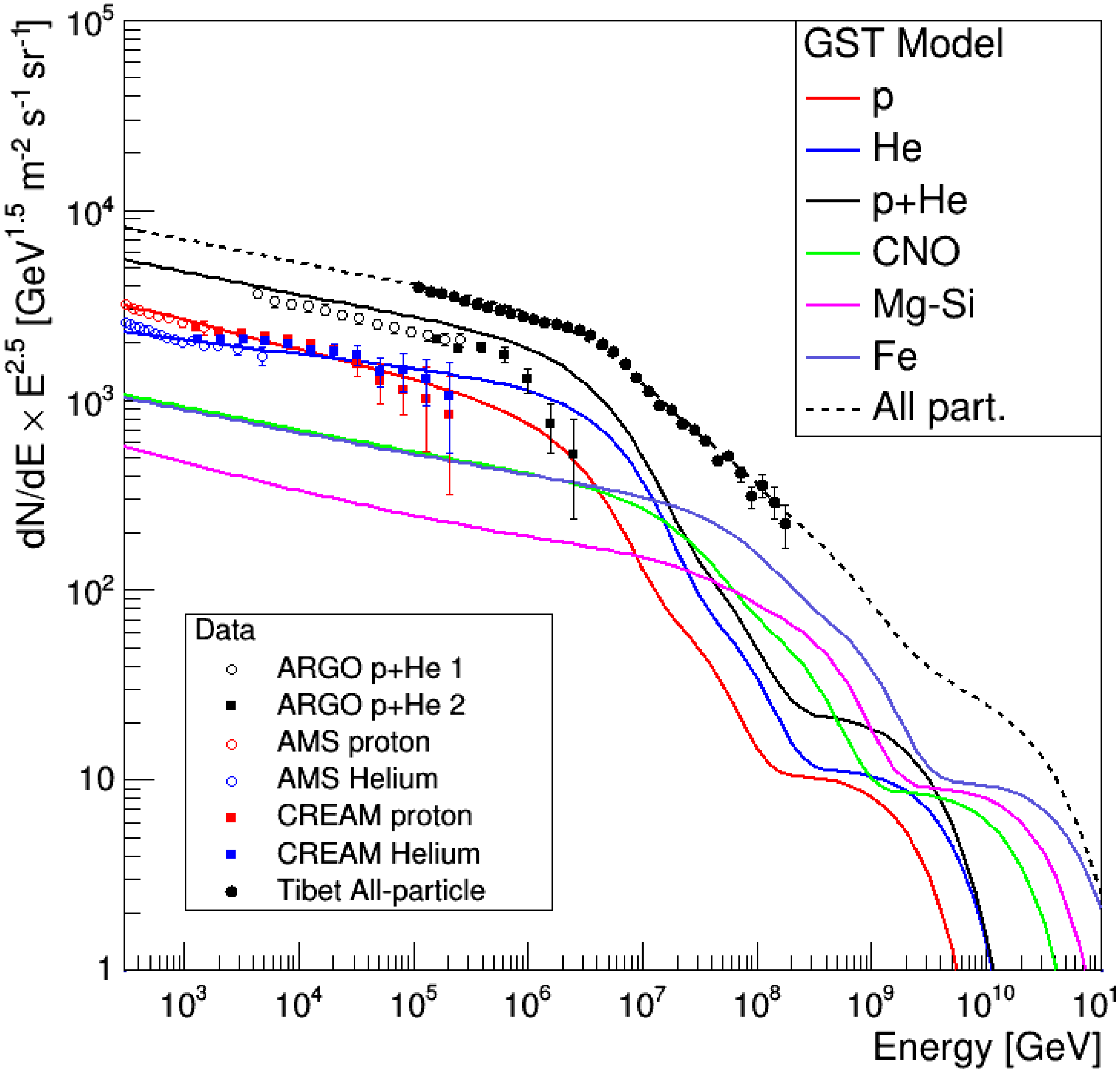


5 mass groups

3 populations:
1st galactic
2nd galactic
3rd extragalactic

Knee energy
$E_k \propto Z$

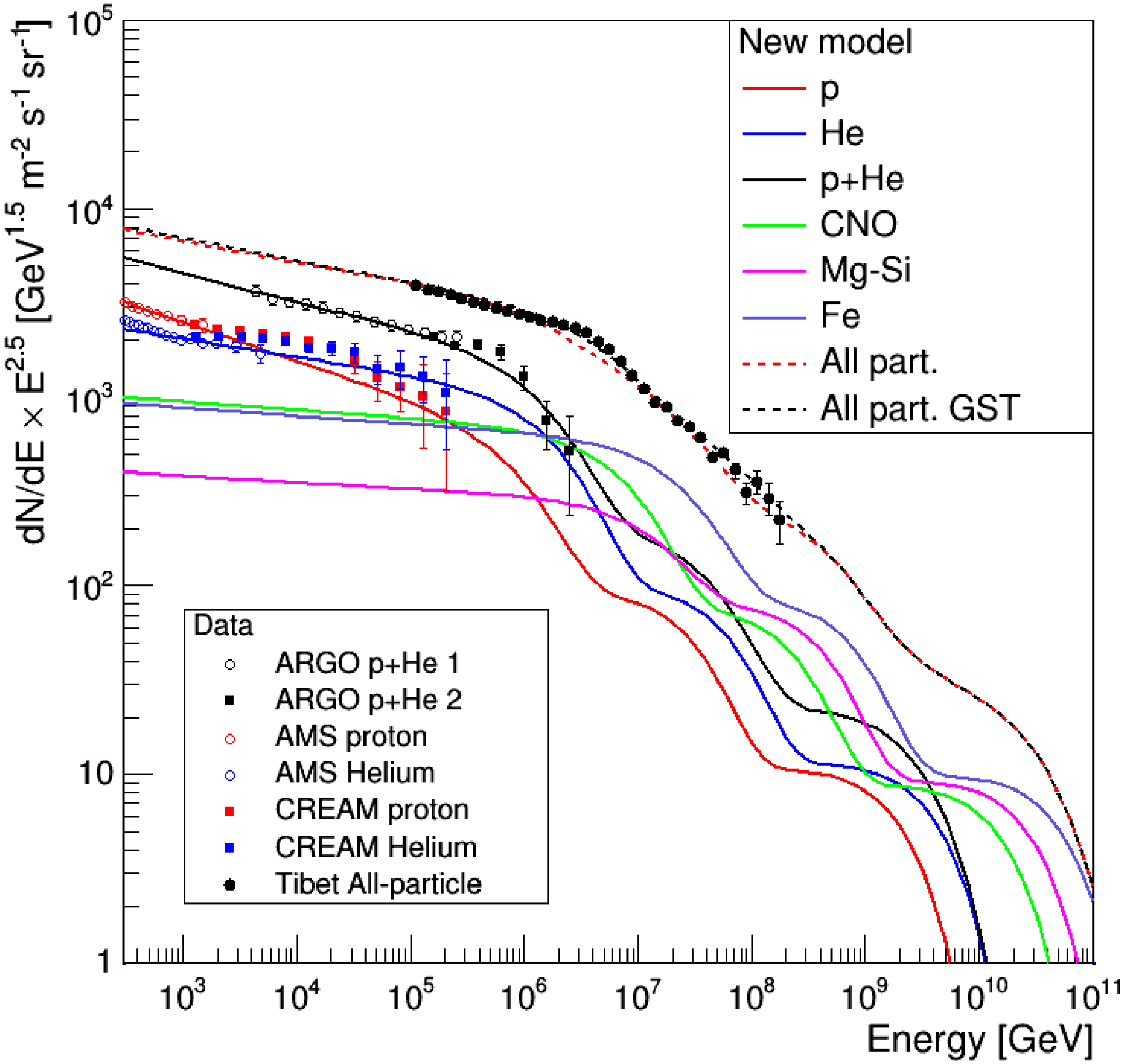
Gaisser-Stanev-Tilav (GST) model



Not very good agreement with data...

...in particular with the ARGO p+He data

Our «ARGO-knee» model



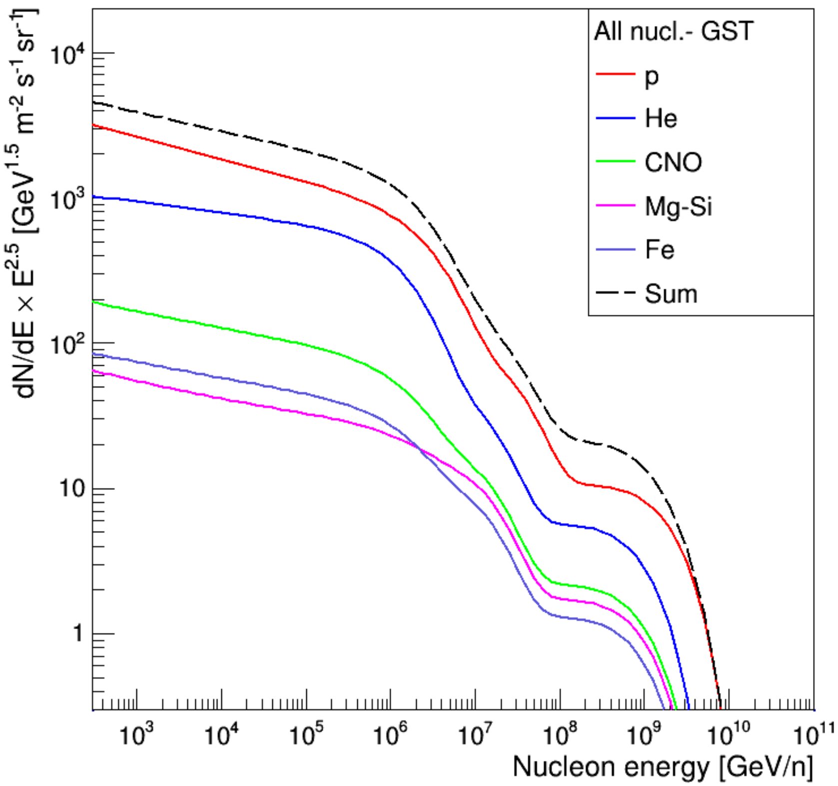
Differences from GST model only for pop. 1

P & He: cutoff energy E_k smaller by a factor 3

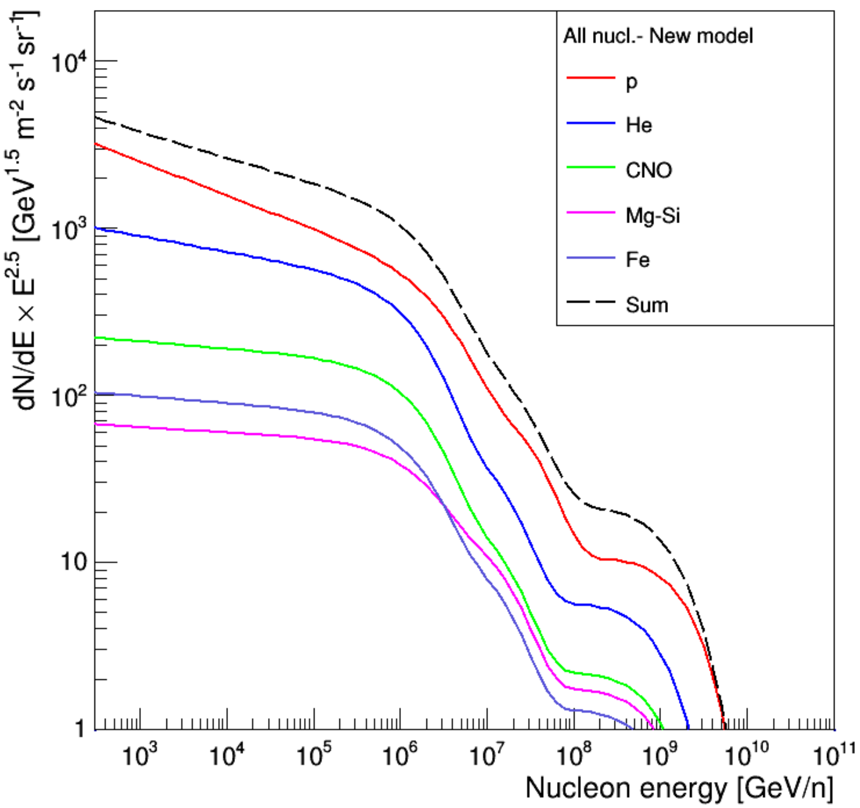
Different slope for all mass groups

All nucleon spectra

GST model

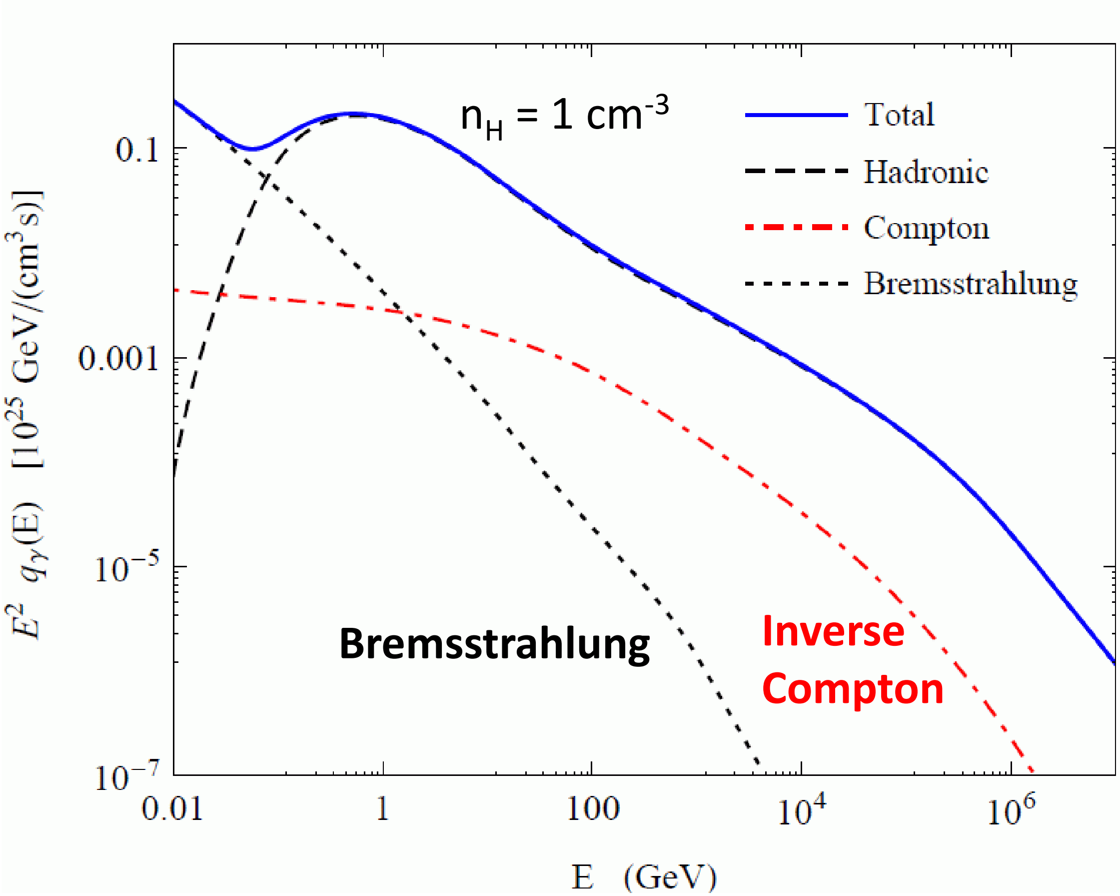


ARGO knee model



In both cases heavy nuclei give a small contribution to the all-nucleon spectrum

GST - Local gamma ray production $q_{loc}(E)$



Most of gamma rays above 1 GeV are produced in hadronic interaction via π^0 decay

Gamma ray spectral shape:

- Simmetry around E= $m_\pi/2$ **(π^0 bump)**
- Scaling property -> at high energy the gamma ray spectral slope follows the nucleon slope
- Median nucleon energy producing a gamma ray of energy E: **$E_0 \sim 6\ E$**

In the following we will consider only the hadronic production

Models for the c.r. spectra in the Galaxy

- **Model 1 (*standard model)***

Cosmic rays have the same spectral shape in all the Galaxy

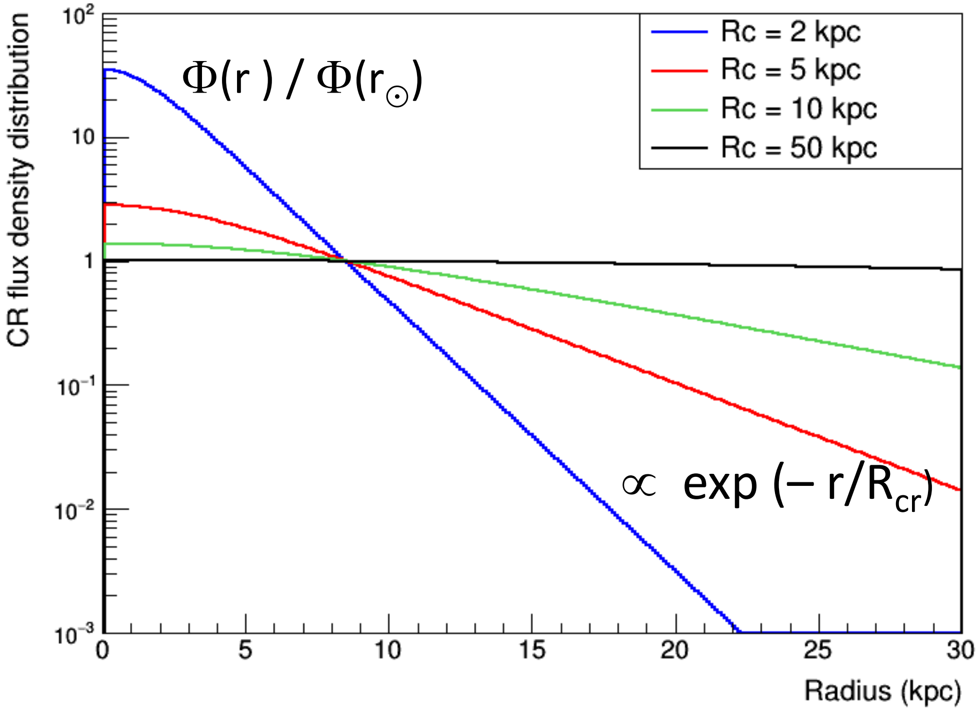
- **Model 2**

Cosmic rays have a spectral shape depending on r

Model 1

- **CRs have the same spectral shape in all the Galaxy**
- **The spectrum normalization changes with the galactocentric distance r**

$$\Phi(r) = \Phi_\odot \, \mathrm{sech}(-r/R_{cr}) \,/\, \mathrm{sech}(r_\odot/R_{cr})$$



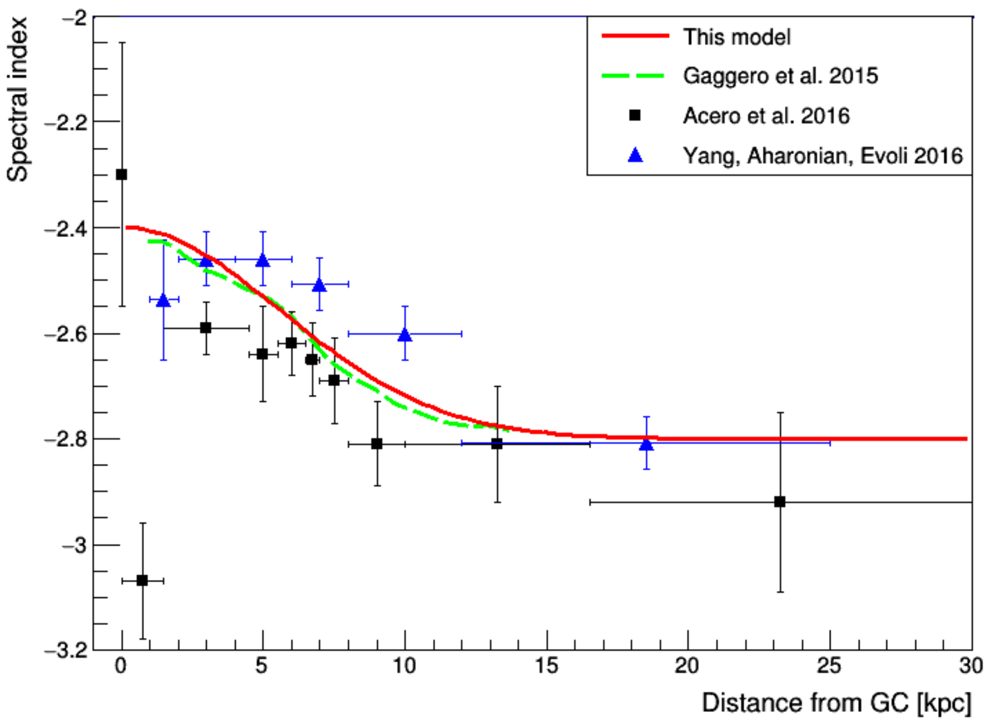
R_{cr} is a free parameter

the only free parameter of the model

Model 2

- **CRs have a spectral shape depending on r**

Analyzing Fermi data on diffuse gamma ray flux, some authors conclude that the gamma ray spectral index depends on the distance from the Galactic center



This could imply that the **CR spectrum becomes harder approaching to the Galactic center**

Model 2 – Production of gamma rays

γ-rays are produced with a spectral shape depending on r:

$$q(E,\vec{r}) = q_{Mod1}(E,\vec{r}) \left(\frac{E}{E_{ref}}\right)^{-[\alpha(r)-2.75]}$$

α depends on r:
α = - 2.4 at r=0
α = - 2.75 at $r_\odot$
α = - 2.8 at r > 15 kpc

E_{ref} = 12 GeV reference energy of the Fermi map

At energy E = E_{ref} the two models give the same flux and spectrum

Summary – 4 CR spectral models

- GST + Model 1 (standard)
- GST + Model 2

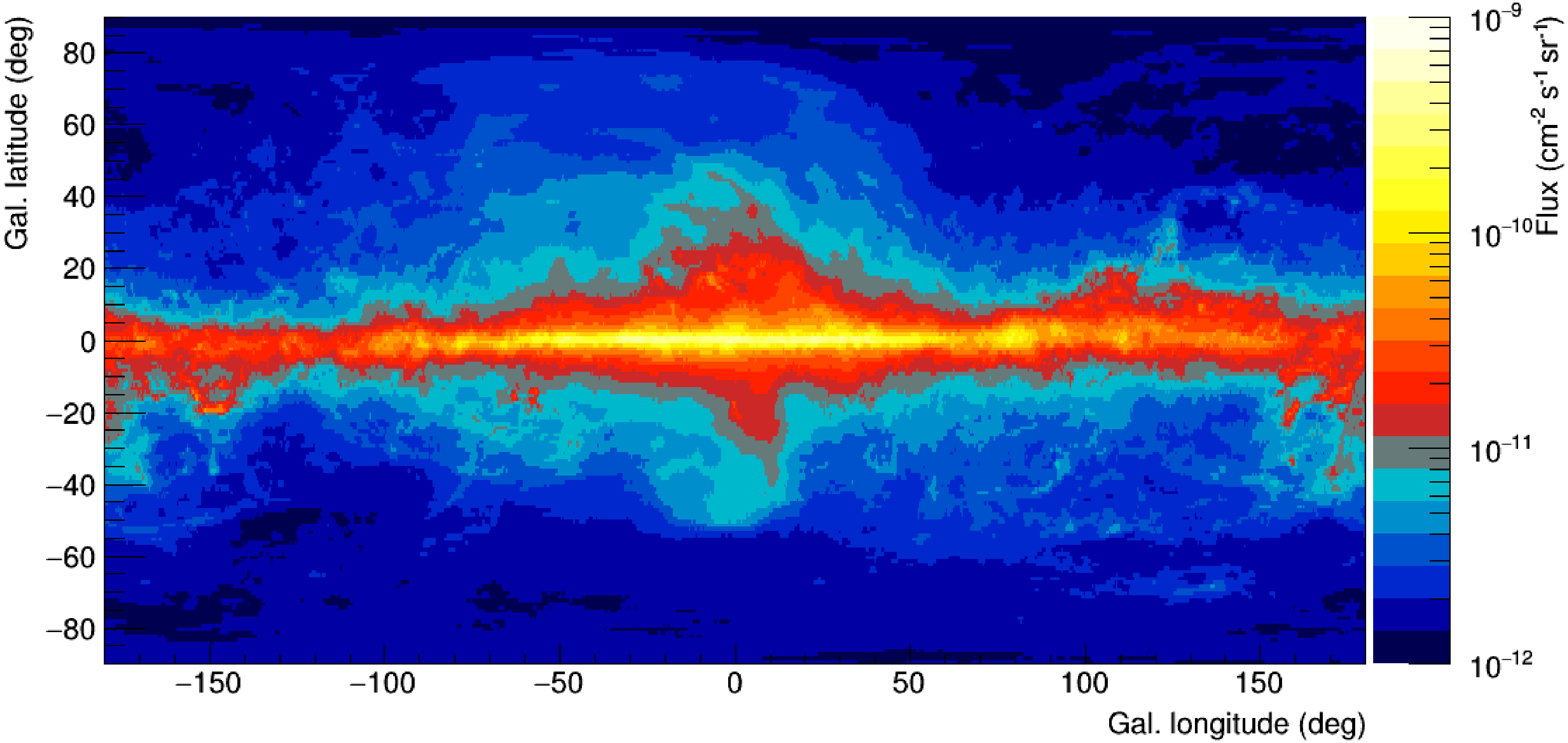
- ARGO-knee + Model 1
- ARGO-knee + Model 2

Model 1 = same c.r. spectral shape in all the Galaxy
Model 2 = spectral hardening towards the Galactic center

Comparison with Fermi data at 12 GeV

(all models give the same flux at this energy)

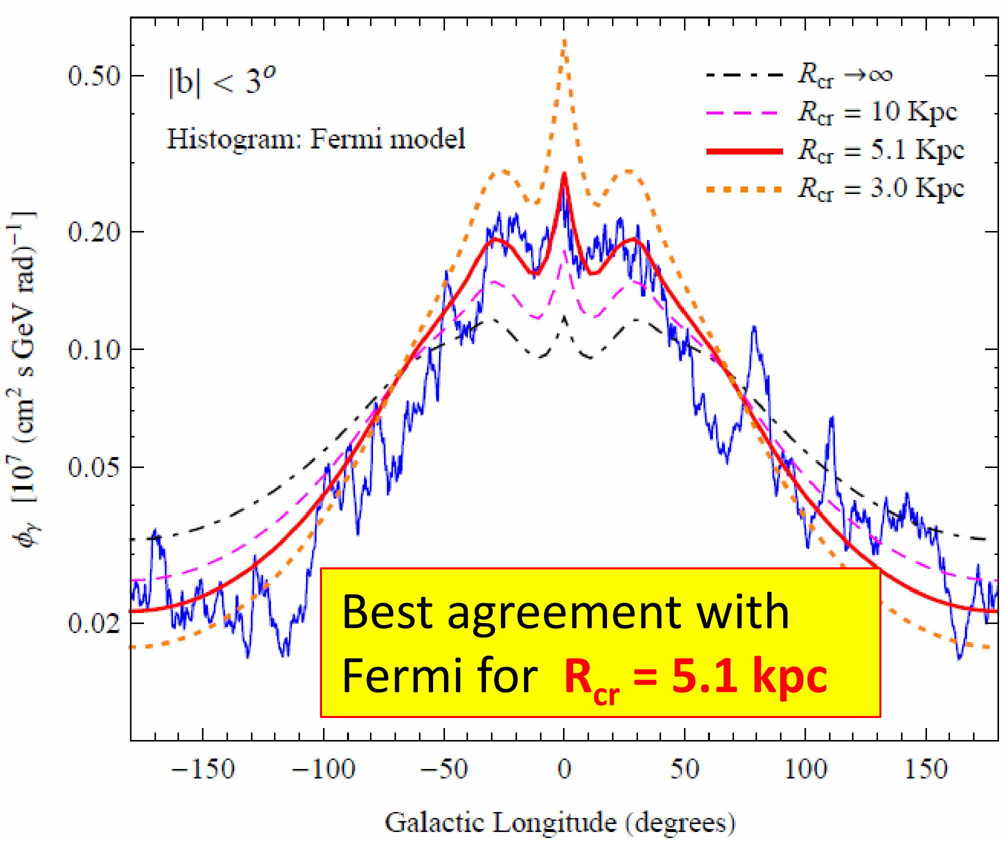
Fermi diffuse gamma ray flux at 12 GeV



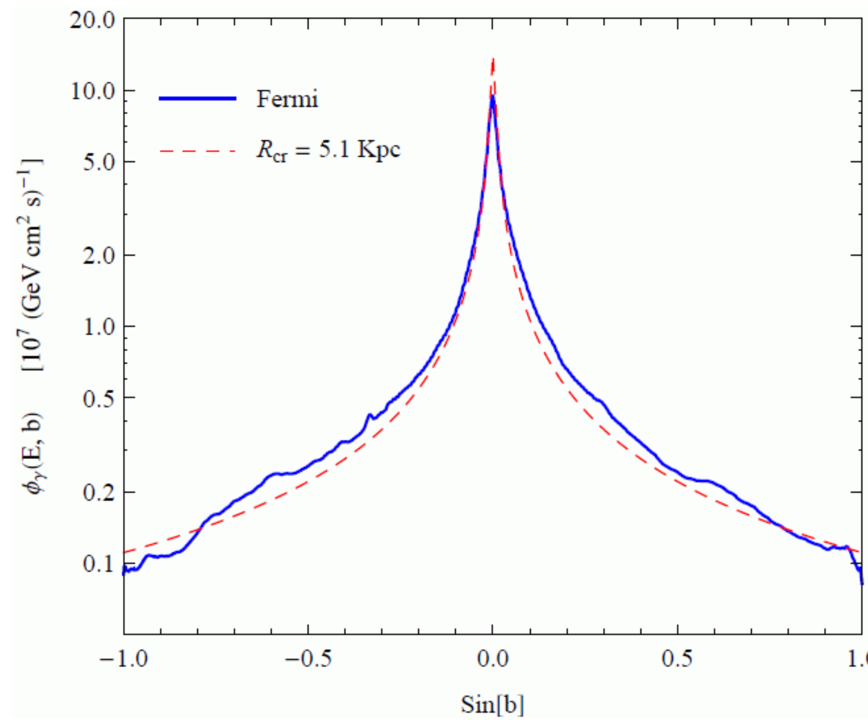
Comparison with Fermi data at 12 GeV

Absolute flux prediction

Galactic longitude distribution



Galactic latitude distribution (integrated over the longitude)

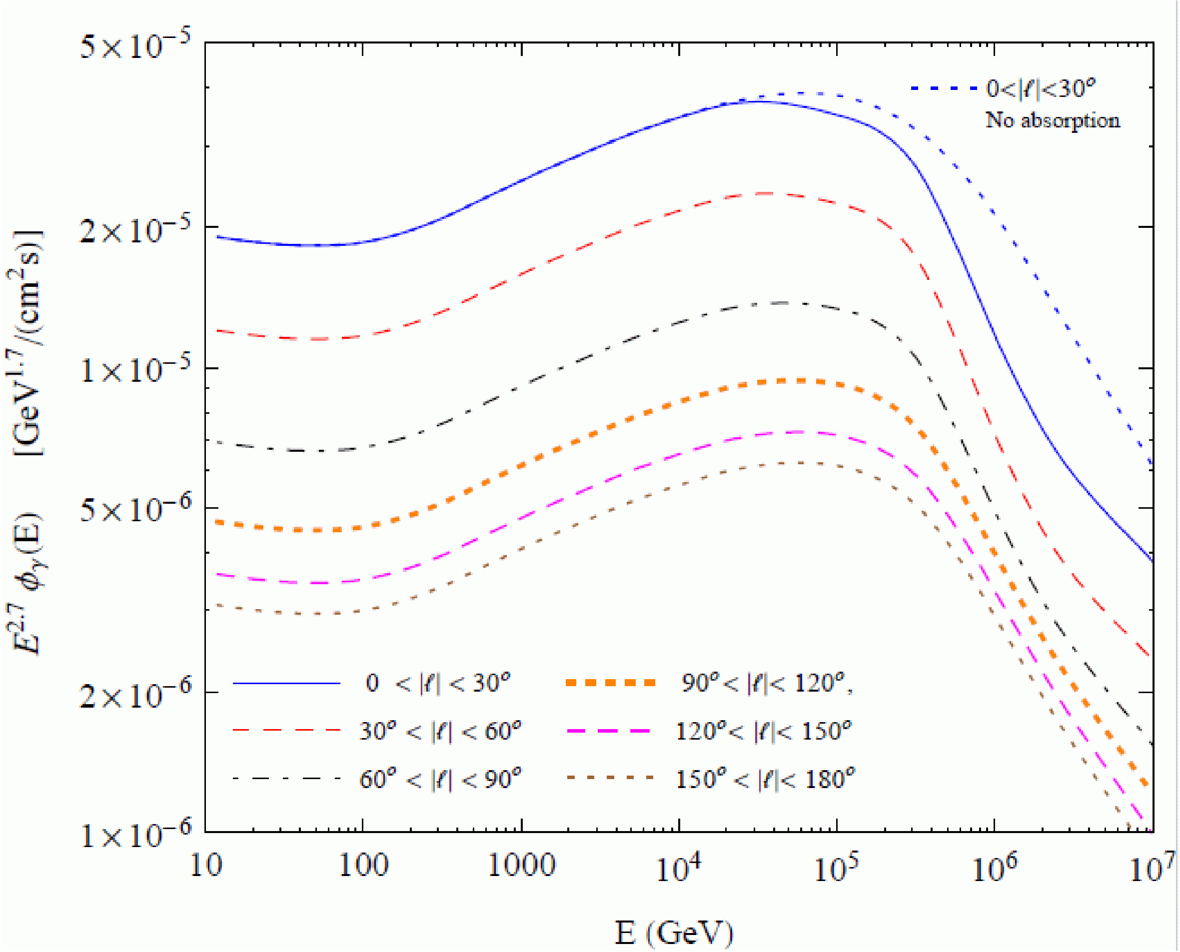


Gamma ray spectra and angular distributions at higher energies

GST + Model 1

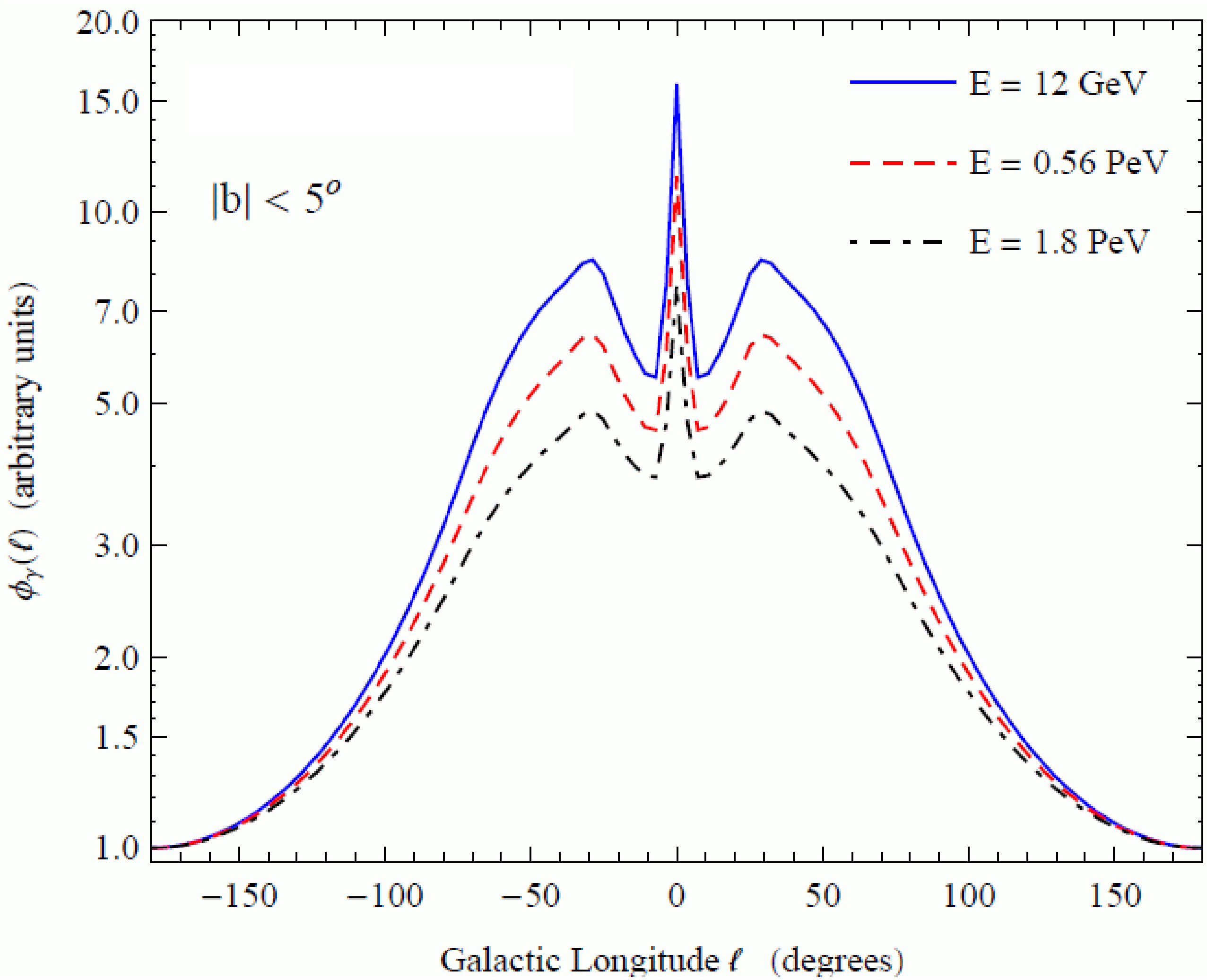
γ-ray spectra from 10 GeV to 10 PeV

Above 30 TeV absorption must be taken into account



Gamma rays coming from the central regions are more **absorbed**

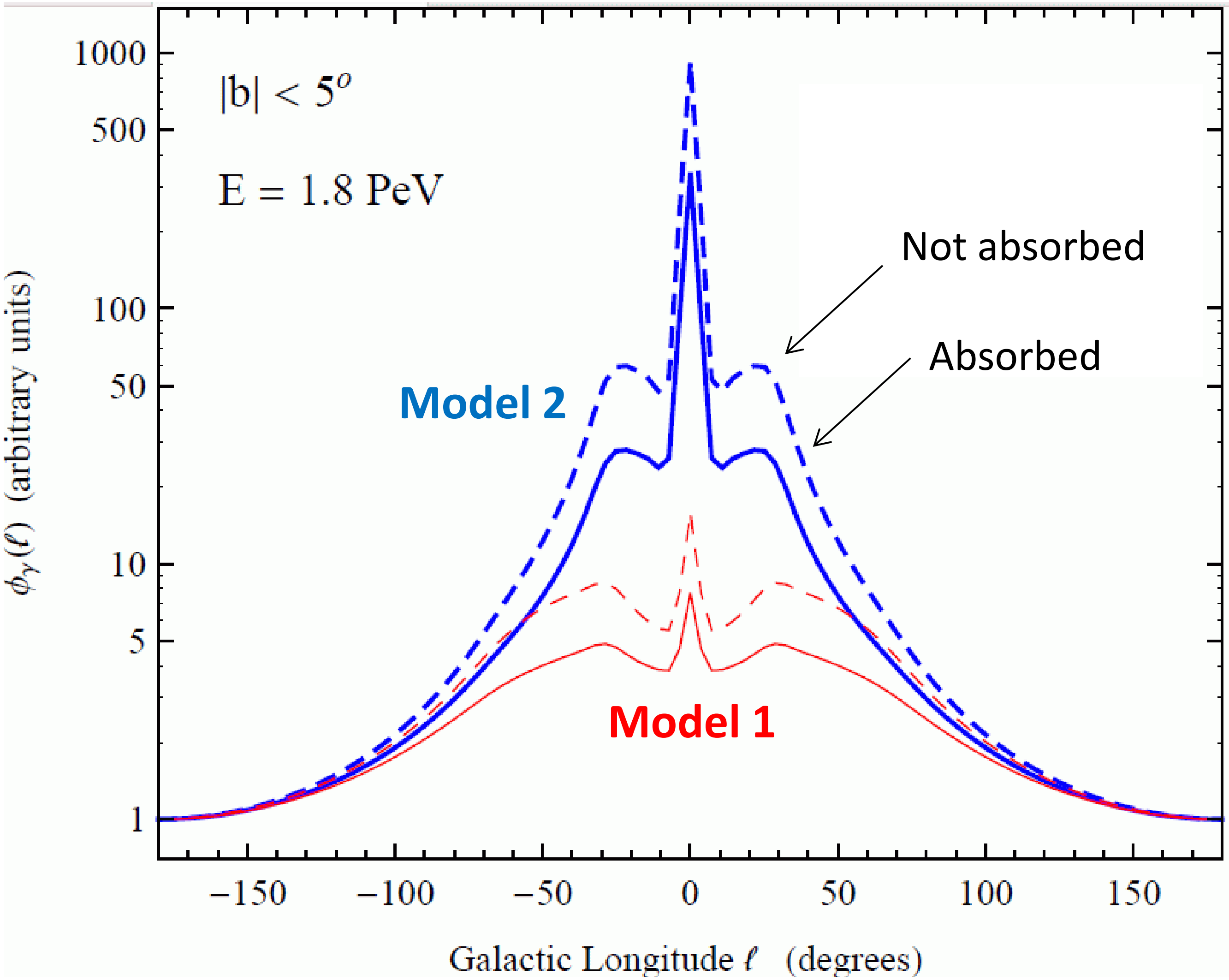
GST+ Model 1
longitude distribution at different energies



The longitude distribution **changes with energy** because of absorption

GST + Model 1 & 2

longitude distribution at 1.8 PeV

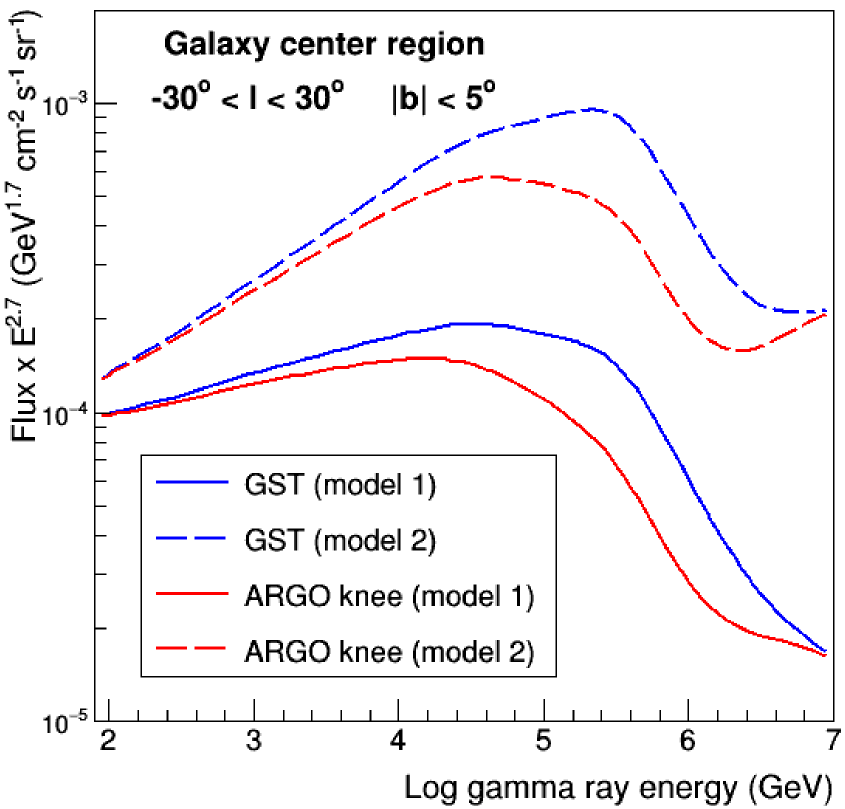


Model 2 predicts a **larger** γ-ray flux from the **central regions**

Gamma ray spectra for the 2x2 models and comparison with data

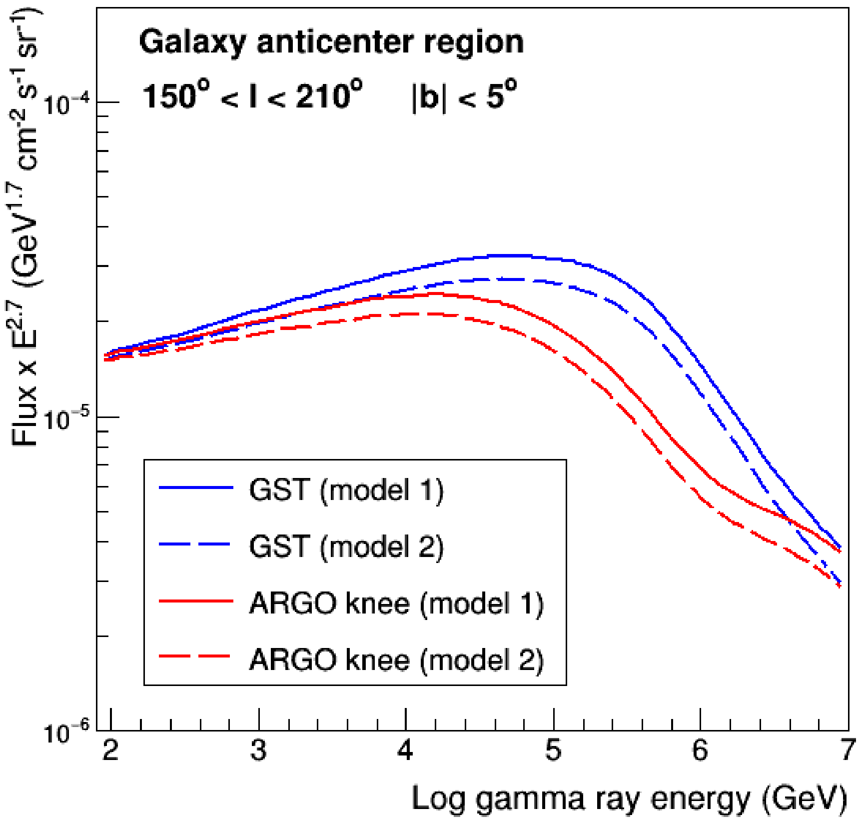
Prediction for gamma ray spectra

Galaxy center region



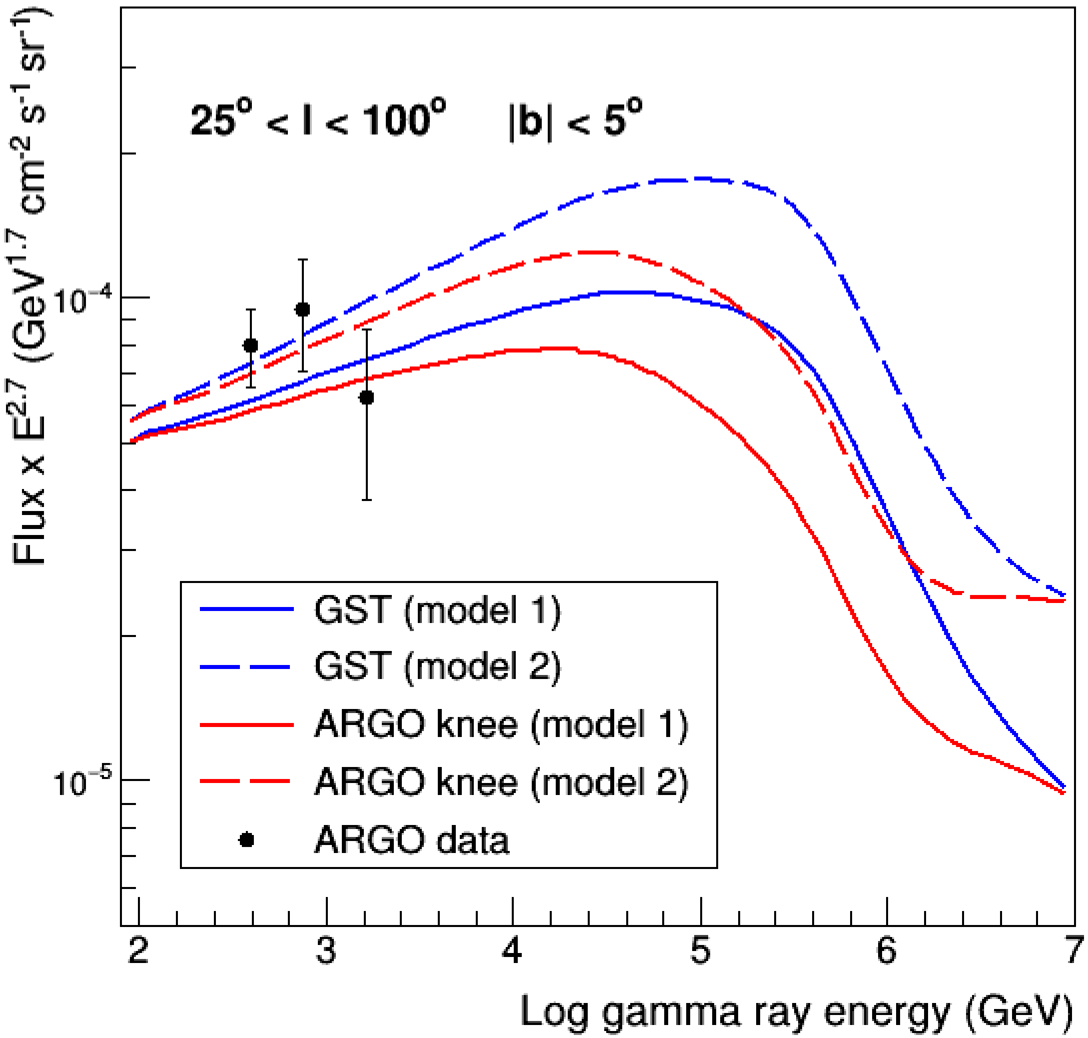
Flux model 2 > Flux model 1

Anticenter region



Flux model 2 < Flux model 1

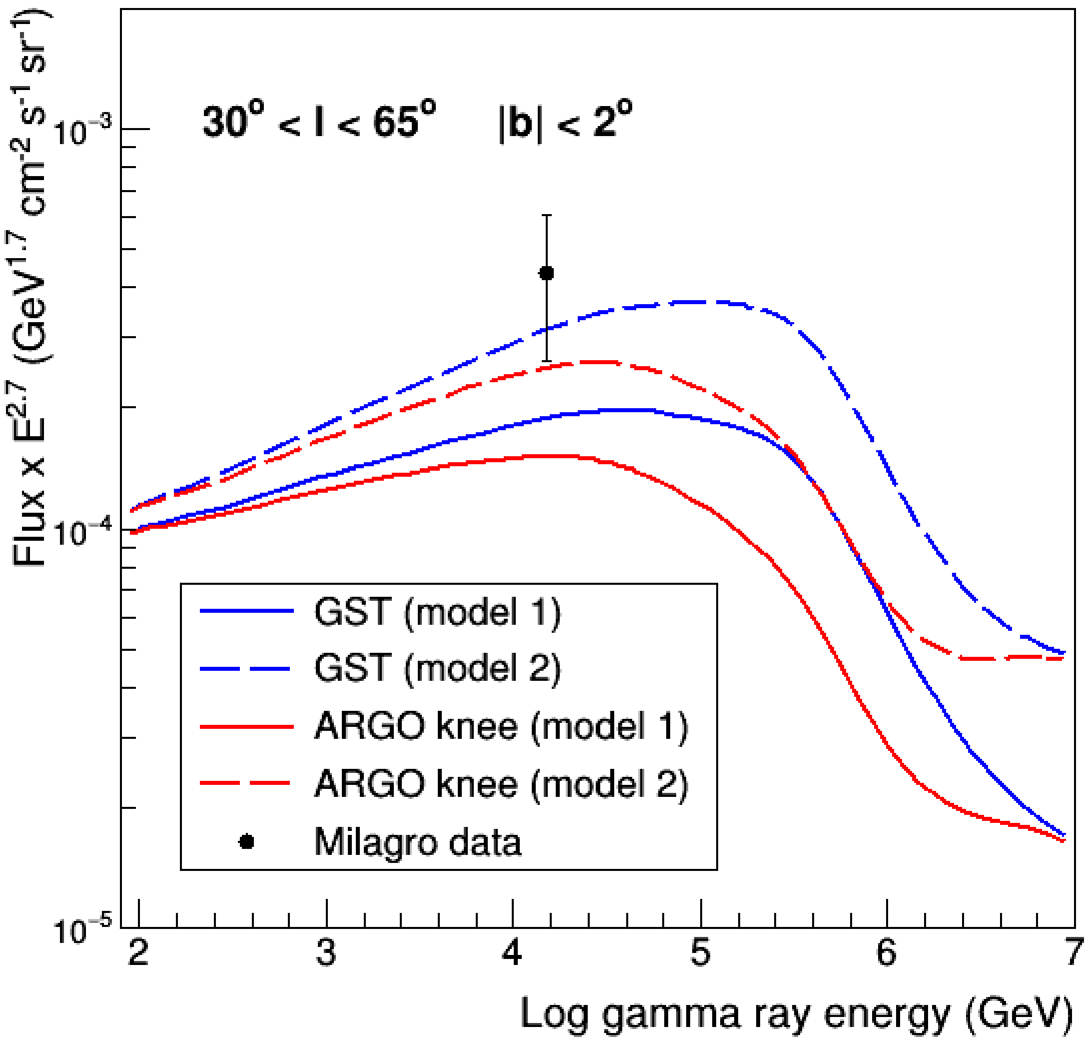
ARGO data (2015)



E = 0.35-2 TeV

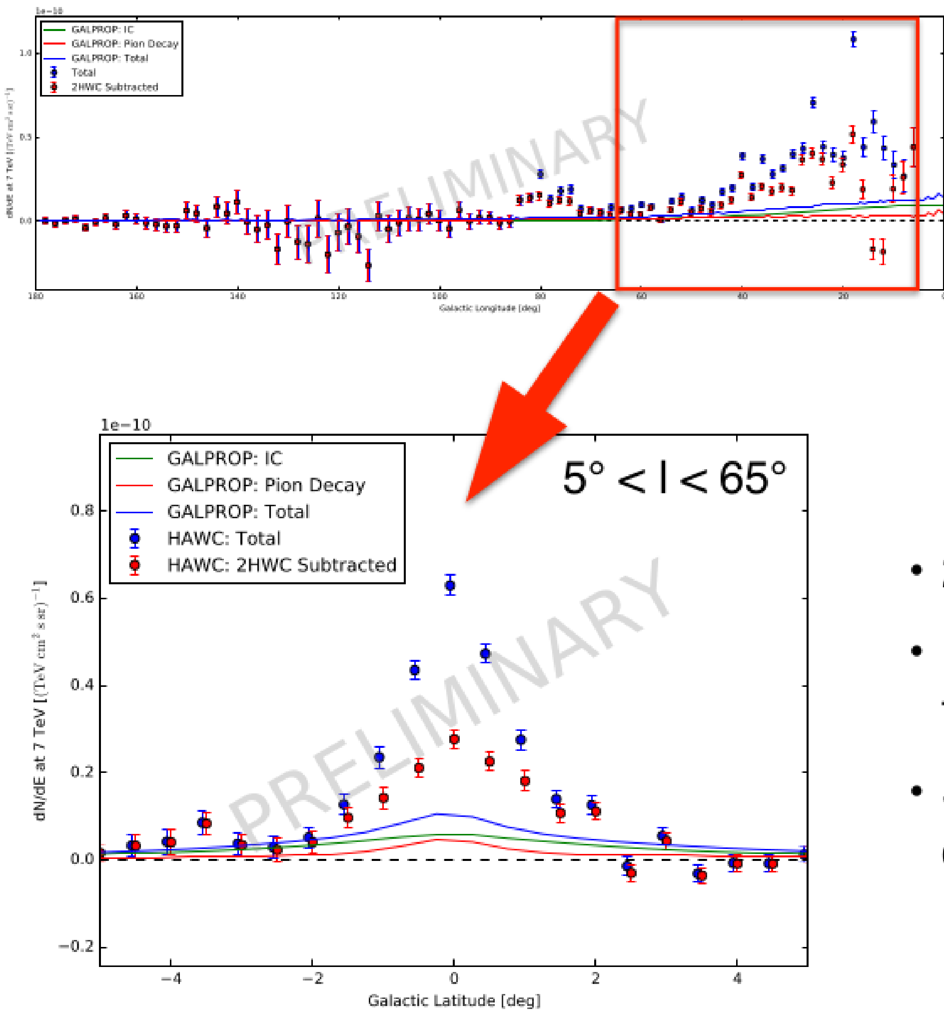
The same FOV as LHAASO

Milagro data (2008)



E = 15 TeV

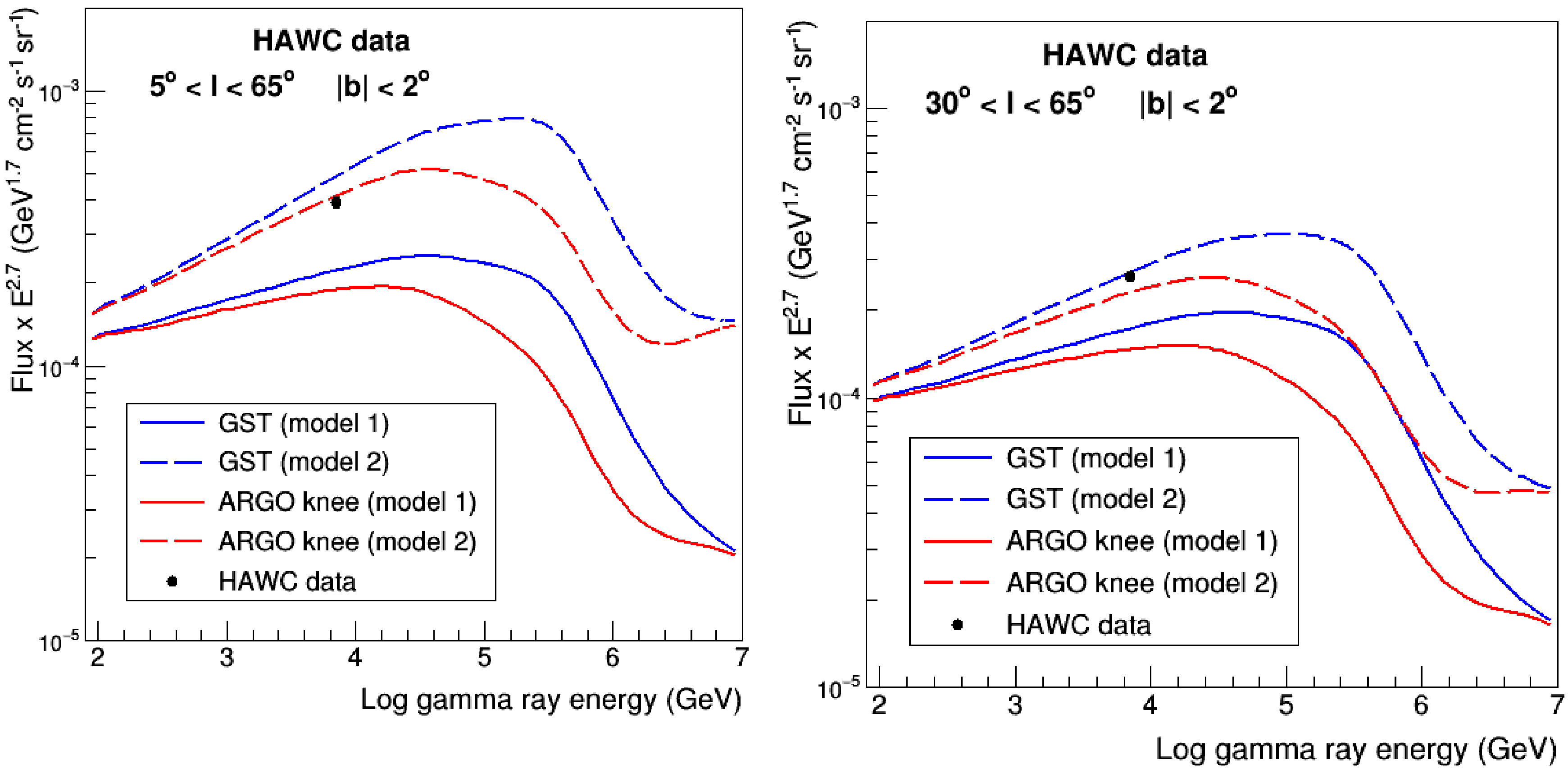
HAWC - ICRC 2017 Preliminary data



- 24 sources identified in 2HWC
- Resolved sources account for about one third of the total emission
- Source-subtracted emission is 2-3 times of the emission predicted by GALPROP

HAWC preliminary data (ICRC 2017)

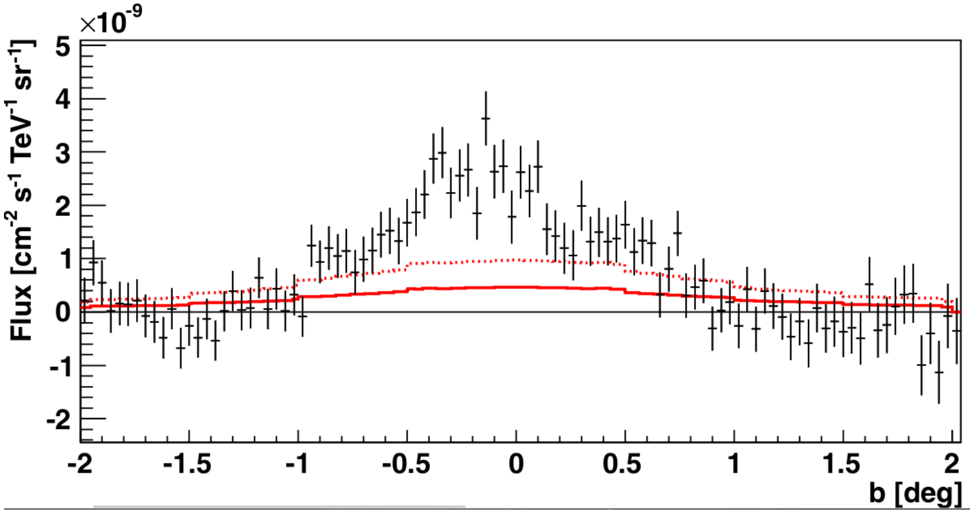
E = 7 TeV



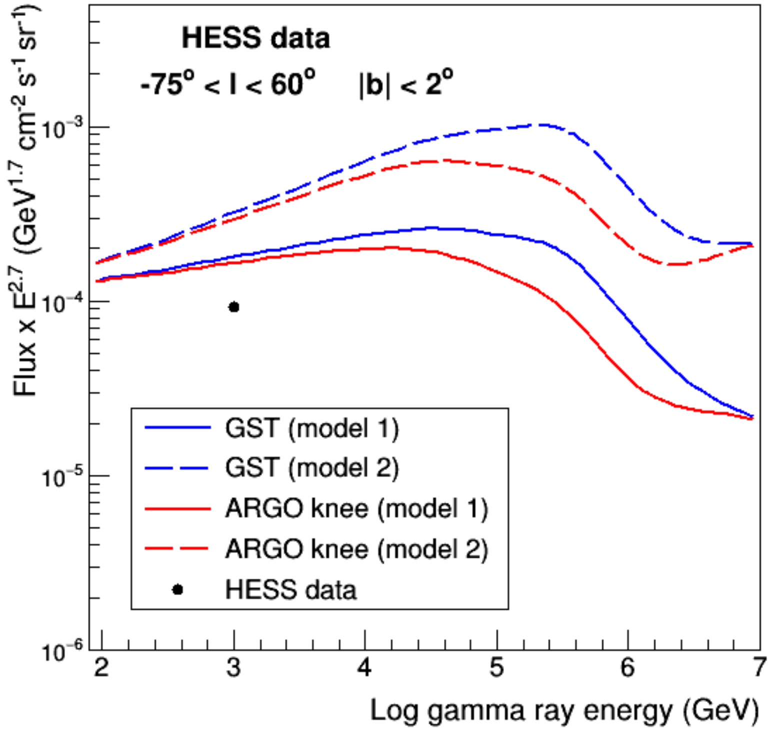
Contribution from unresolved sources must be estimated

HESS data (2014)

Latitude distribution
-75° < longitude < 60 °

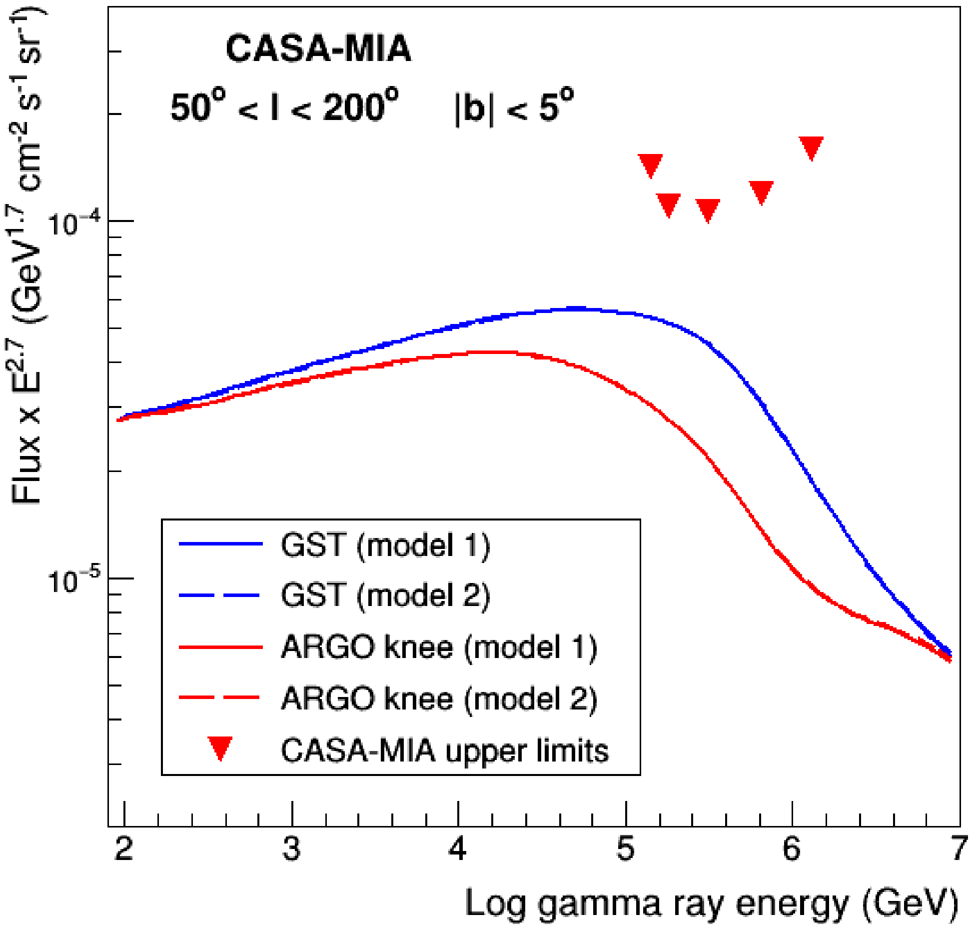


E = 1 TeV



The signal is possibly underestimated because of the overestimation of the background (small FOV)

CASA-MIA upper limits



E = 140-1300 TeV

In this region model 1 and 2 give has similar spectra

Conclusions

- The diffuse gamma ray flux at high energy contains the imprint of the energy and space distributions of cosmic rays in the Galaxy.
- The gamma ray fux at energy > 30 TeV is sensitive to the properties of c.r. in the knee region.
- If the light component has a knee below 1 PeV, the gamma ray spectra will be suppressed with respect to the standard scenario.
- If the c.r. spectra has a space dependence, this will be observable as an angular dependence of the gamma ray spectral shape.
- To observe this angular dependence it is desirable to have high energy measurements along **a large portion of the galactic plane**, with detectors at different latitudes.
- The problem of the **unresolved sources** must be carefully addressed