Diffuse Galactic gamma ray flux at very high energy

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

- The knowledge of the **CRs flux and spectra in the whole Galaxy** is fundamental to study the origin and propagation of cosmic rays
- Cosmic ray spectra are only measured **locally**
- How the CR flux changes at different distances from the Galactic center ?
- Is the CR spectral shape equal in all the Galaxy ?
- **Diffuse gamma rays are the most poweful method** to answer these questions

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

- CR propagating in the Galaxy interact with with gas and radiation producing a **diffuse flux of γ-rays and neutrinos,** that arrive at Earth **encoding the space and energy distribution of CR in the whole Galaxy**

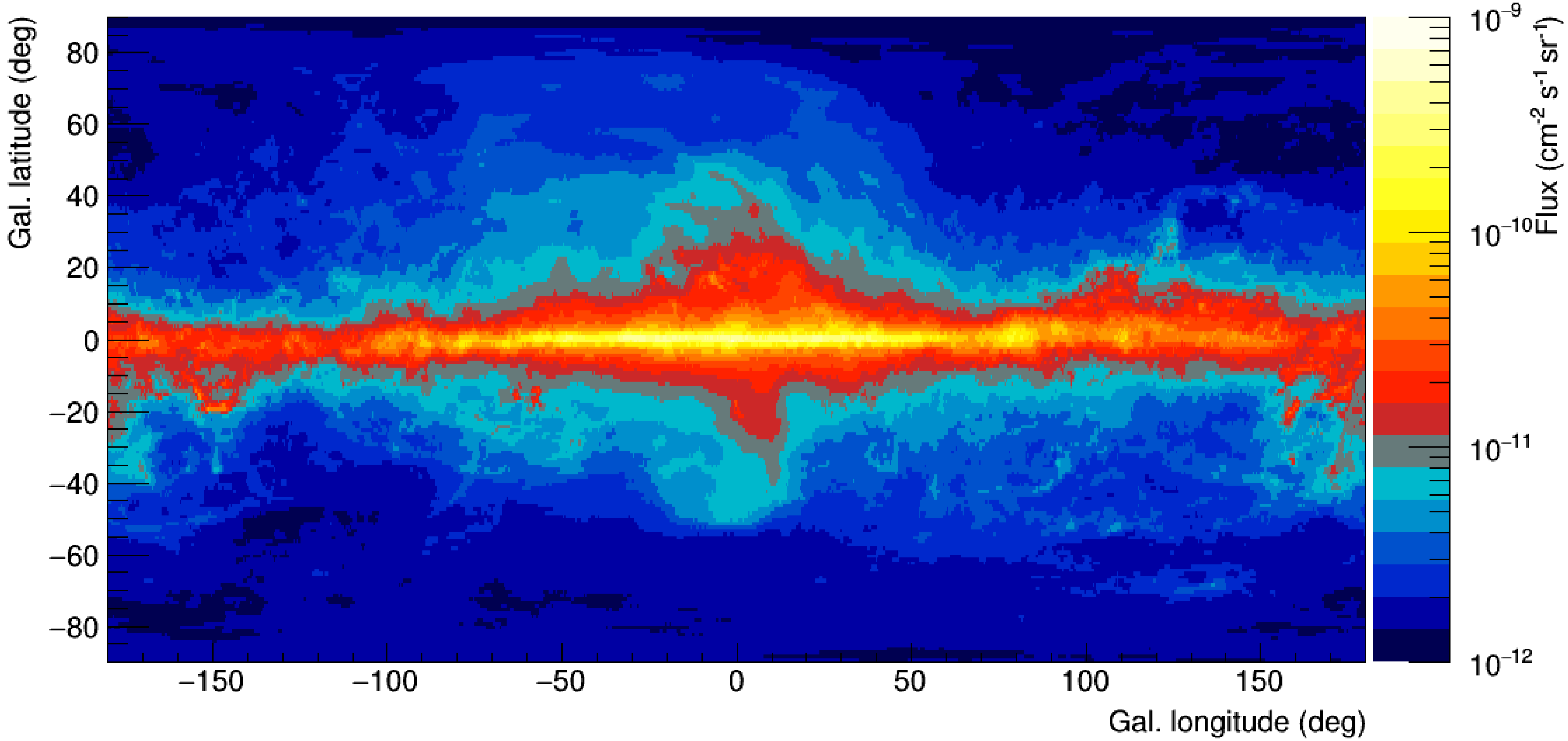
- We built **two models** for the diffuse γ-ray flux **up to 10 PeV** based on simple assumptions on the CR spectral behaviour in the Galaxy

- **The two models predict very different gamma spectra at high energy, in particular above 30 TeV**

- Existing measurements of diffuse γ-rays: Fermi, Milagro, ARGO.
  Above 30 TeV: only upper limits by CASA-MIA and KASCADE-GRANDE

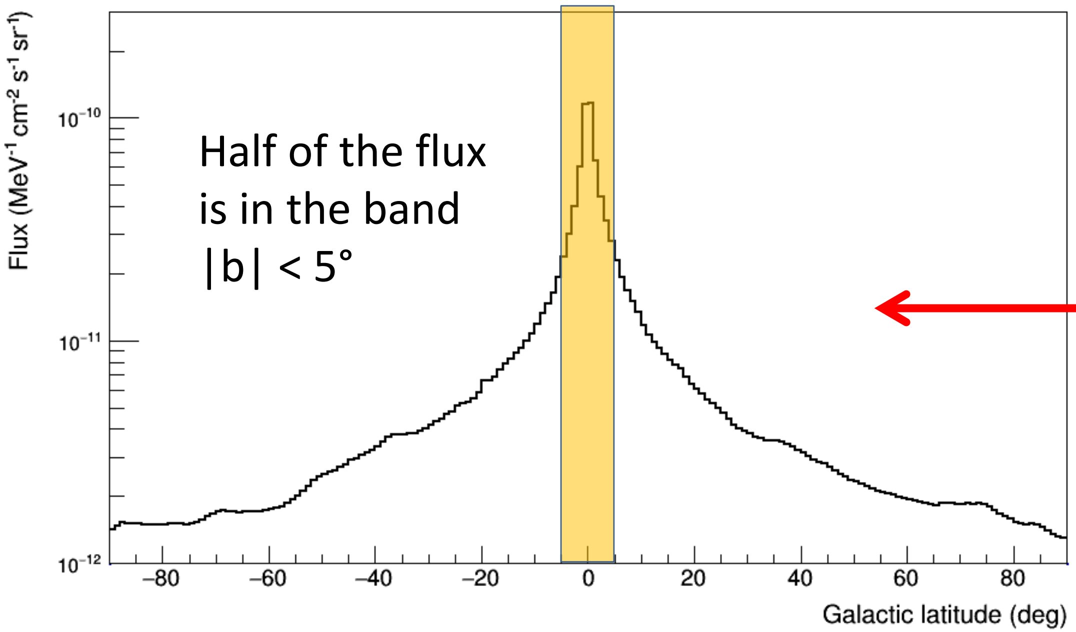
S.Vernetto & P.Lipari, Phys.Rev. D 98, 043003, 2018

Fermi diffuse gamma ray flux at 12 GeV



Fermi made a template of diffuse Galactic gamma ray flux to be used as a background for the search of point sources.
The maps are given for 30 energies, **from ~60 MeV to ~ 500 GeV**

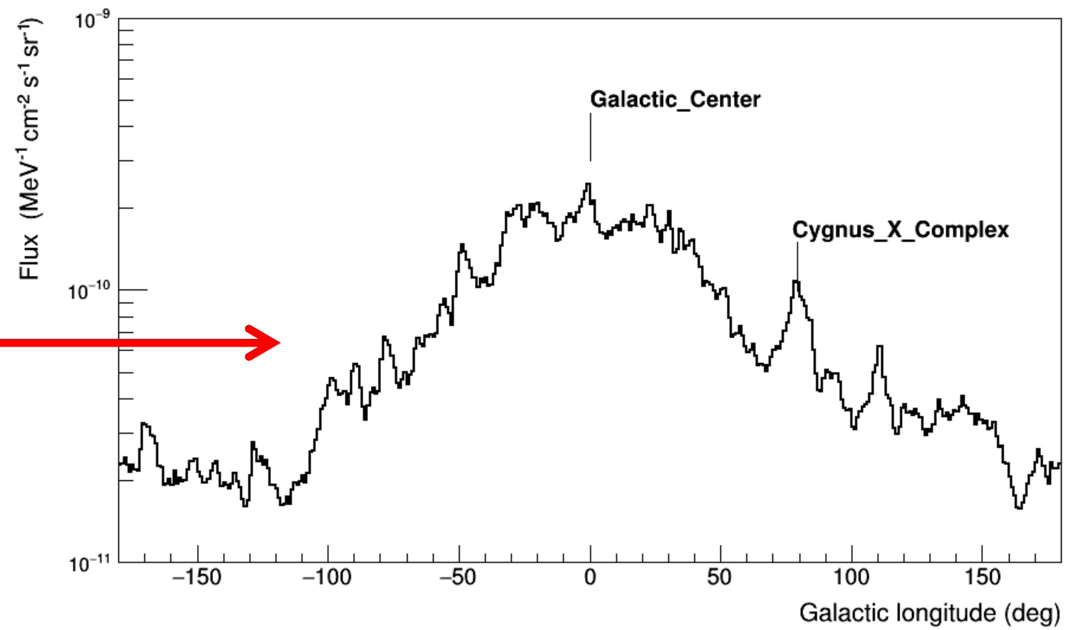
Fermi diffuse γ-ray flux at 12 GeV



Galactic latitude distribution (integrated over the longitude)

Galactic longitude distribution

Latitude |b| < 3°



Ingredients for the calculation of the diffuse gamma ray flux

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 of the flux along the line of sight
- Calculation of the absorption of gamma ray by pair production in the Galaxy radiation field

Steps in the calculation of the diffuse γ-ray flux

Taking into account the available data, we developed:

- A model for the spatial distribution of the interstellar matter
- A model for the radiation field in the Galaxy to evaluate the absorption of gamma ray by pair production
- A model for the cosmic ray spectra in all the Galaxy

The interstellar matter

Gas ~99% Dust ~ 1%

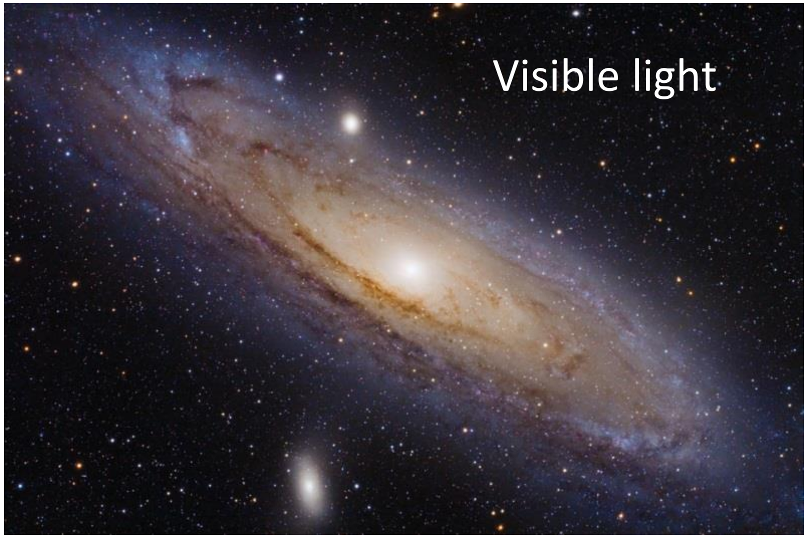
Local gas composition: ~ 90% Hydrogen, ~ 9% Helium, ~ 1% other

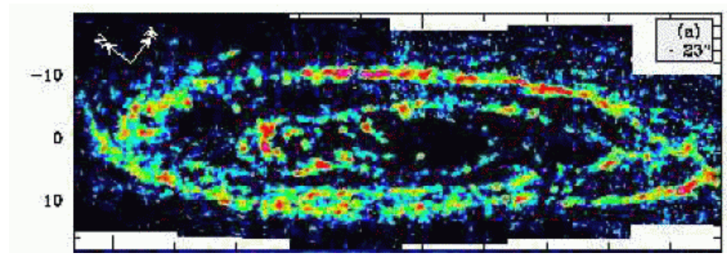
Hydrogen components in the Galaxy:

- Atomic **H** - 21 cm line -> H column density
  - Doppler shift -> radial velocity -> distance from GC
  - need to know the Galaxy rotation curve v(r)
- Molecular **H_2** - carbon monoxide ^{12}CO and ^{13}CO emission -> H_2 column density
  - need to know the ratio CO/H_2 and the Galaxy rotation curve
- Ionized **H^+** - H-α line at 6563 A (absorbed by dust)

They are spatially distributed in different ways
Structures are present at all scales: spiral arms, spurs, clouds, filaments...
A bar is observed in the center
The disk is warped and asymmetric

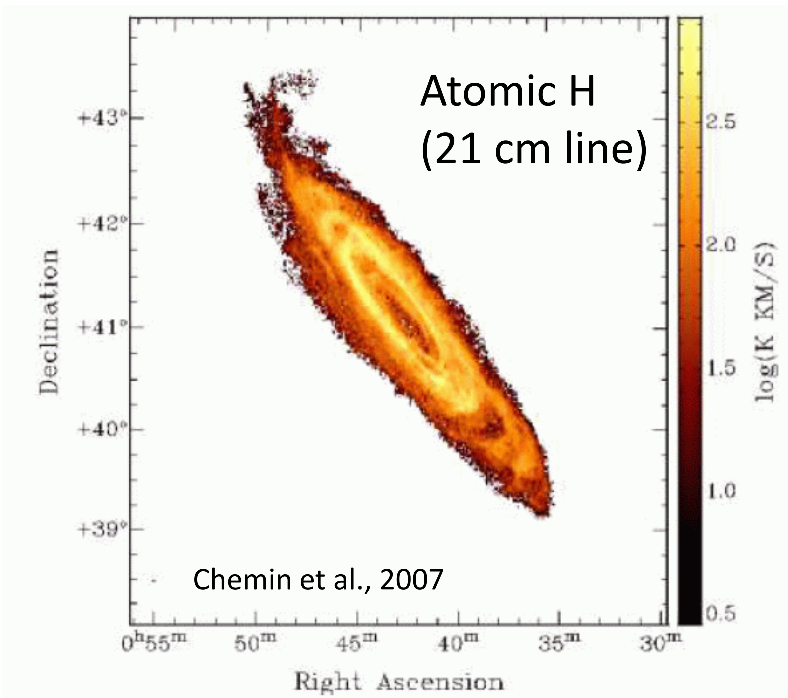
Interstellar matter in M31

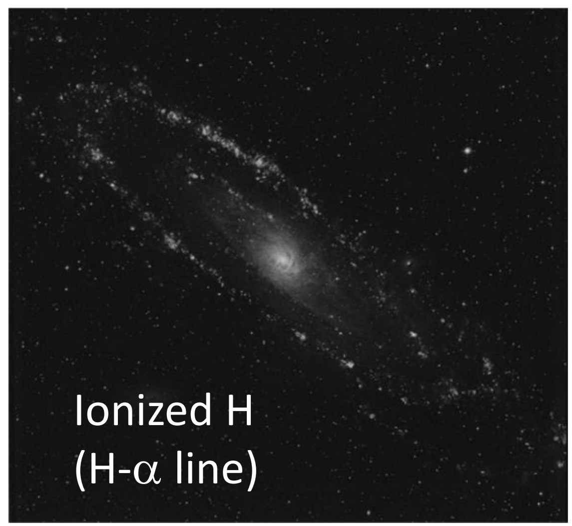


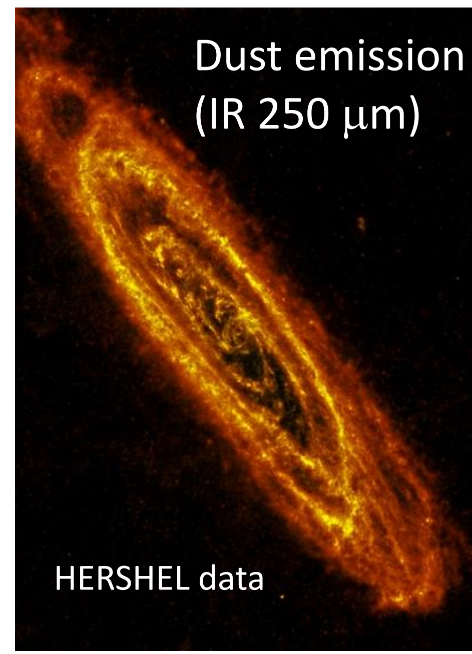


Molecolar H_2
(^{12}CO line)

Nieten et al., 2005



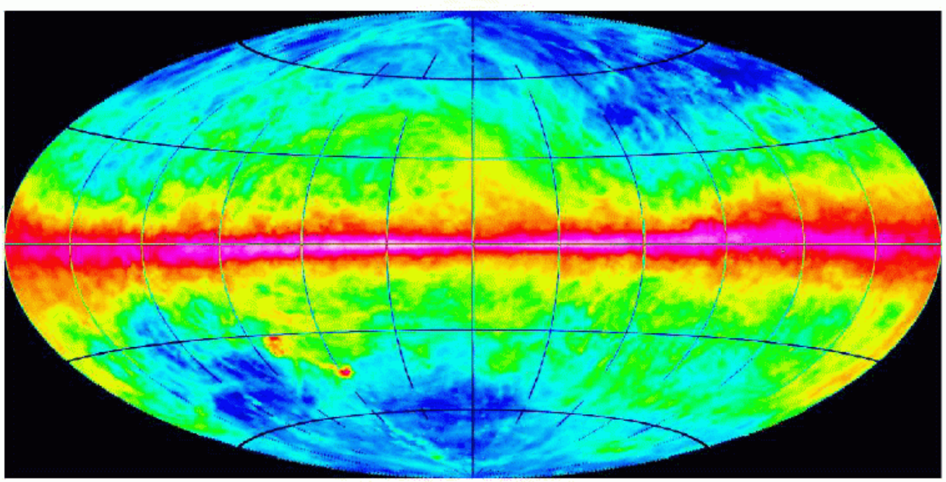


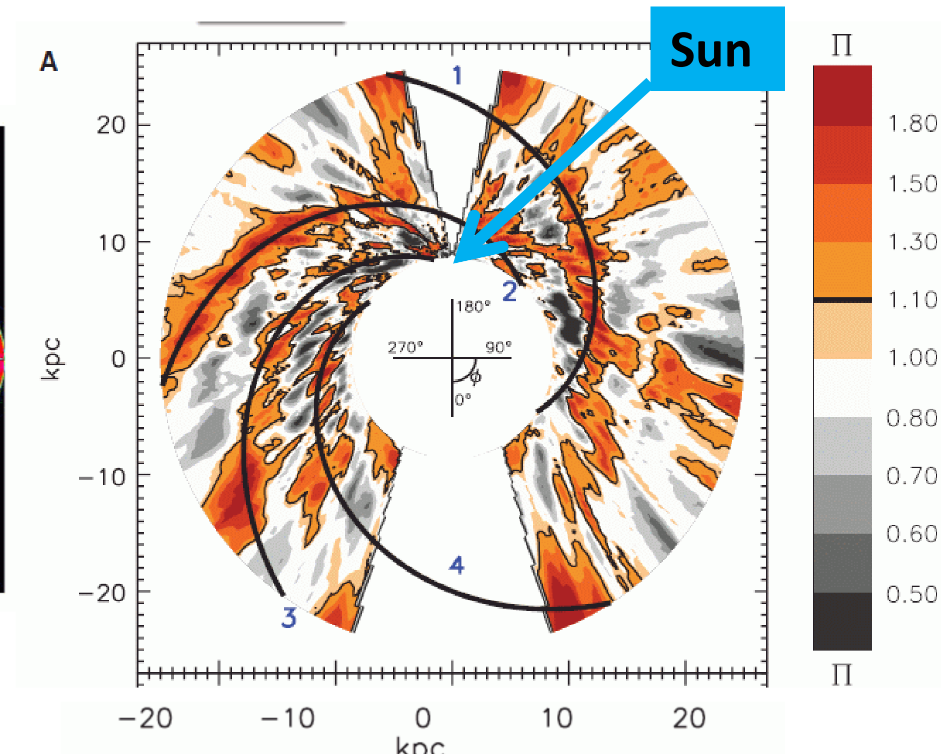


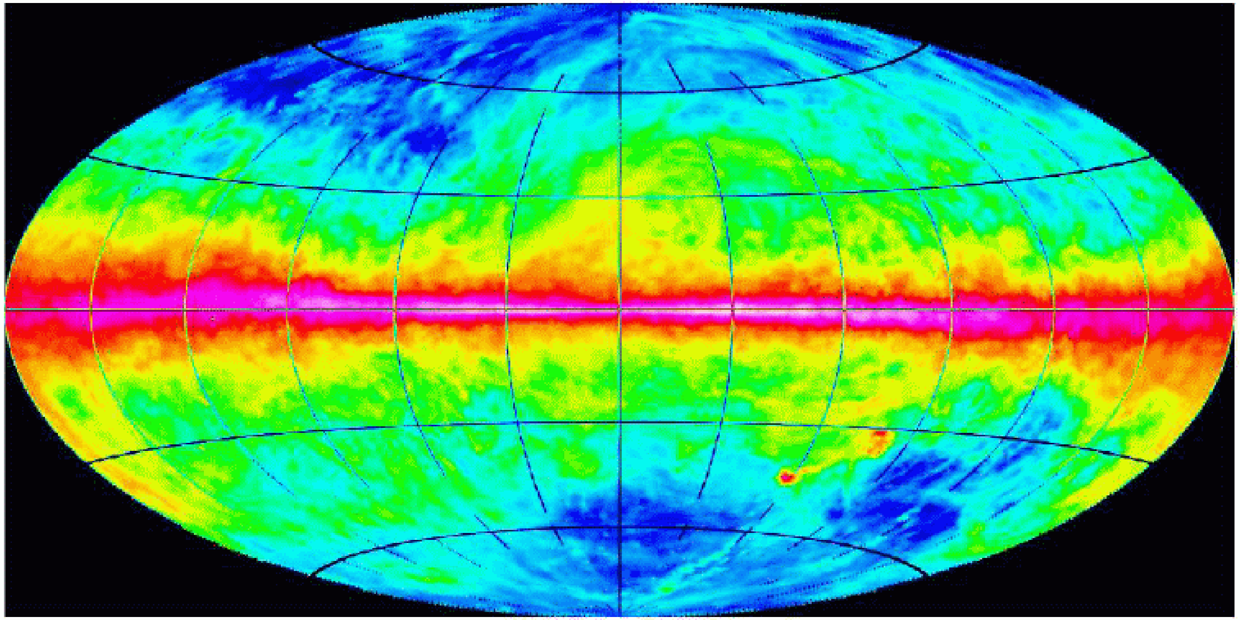
Atomic Hydrogen in our Galaxy

H emission (21 cm) integrated over the velocity range -400 < v < +400 km s^{-1} (LAB dataset, Kalberla et al., 2005)

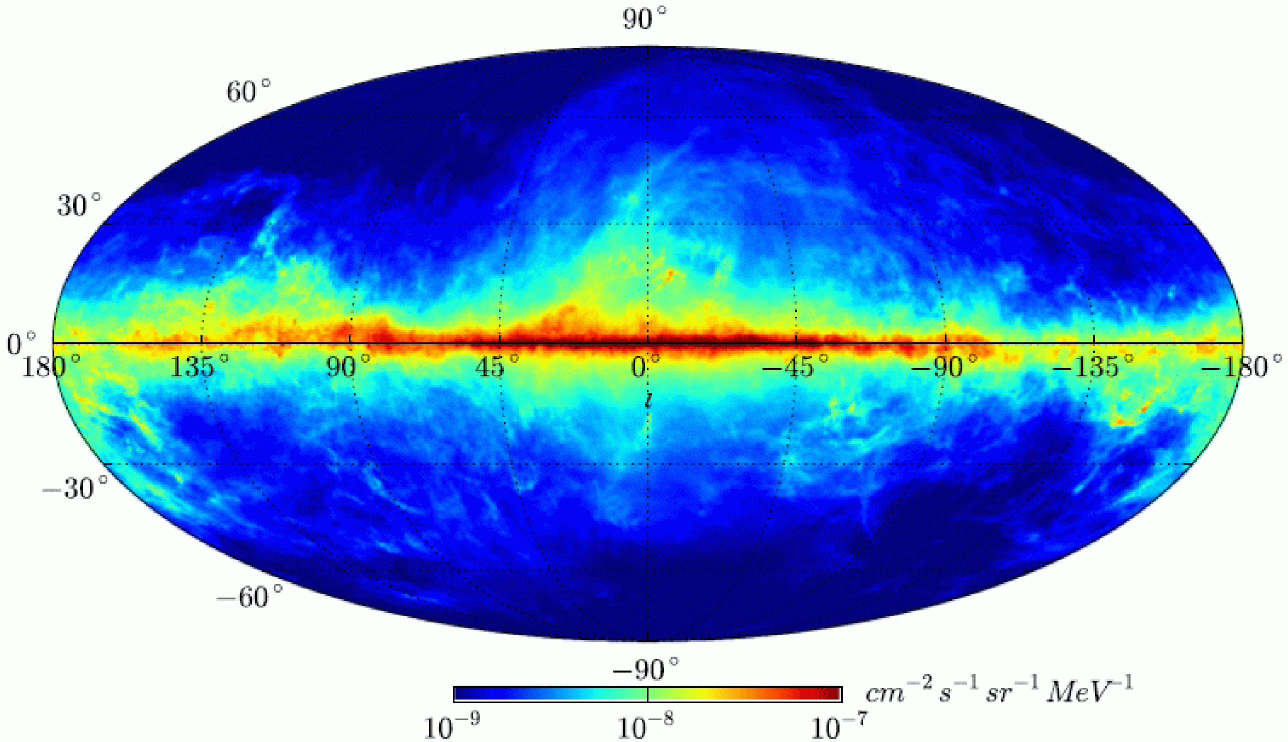
H surface density
Spiral arms fit
(LAB dataset, Levine et al, 2006)







Atomic Hydrogen Column density

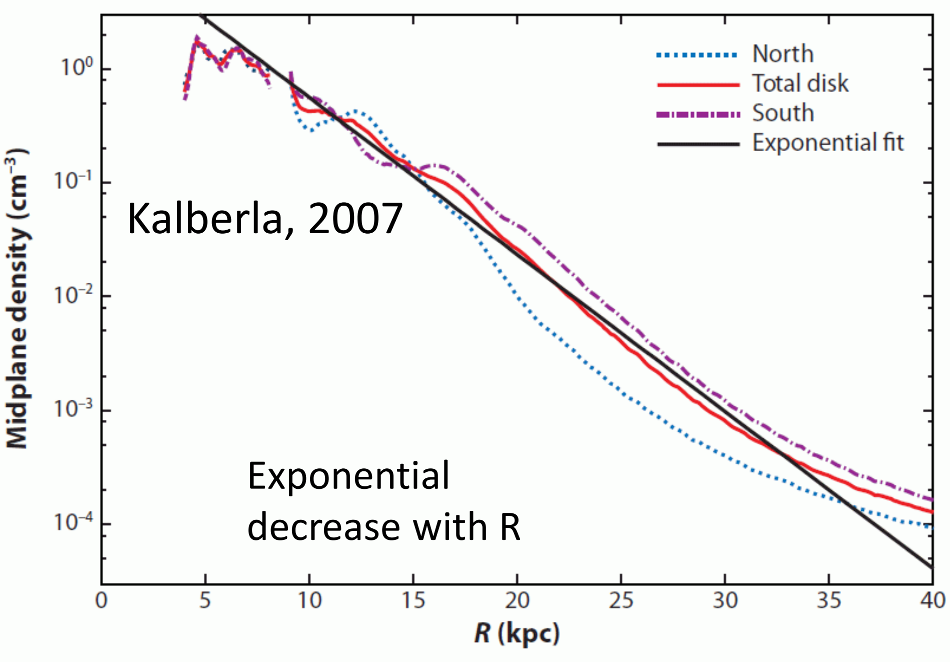


Fermi gamma rays 1 GeV

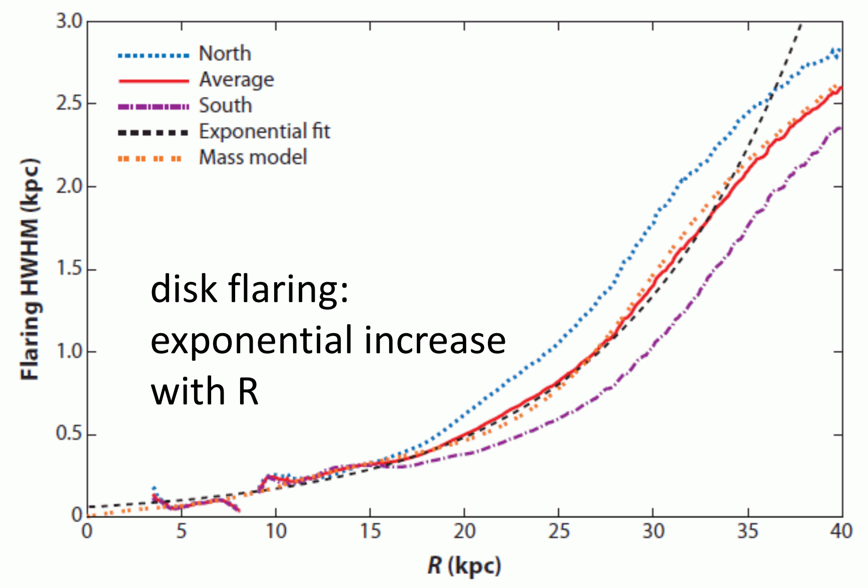
Average distribution of atomic H in the Galaxy

The atomic hydrogen is the main component at R > 5 kpc

Average H midplane density vs. R



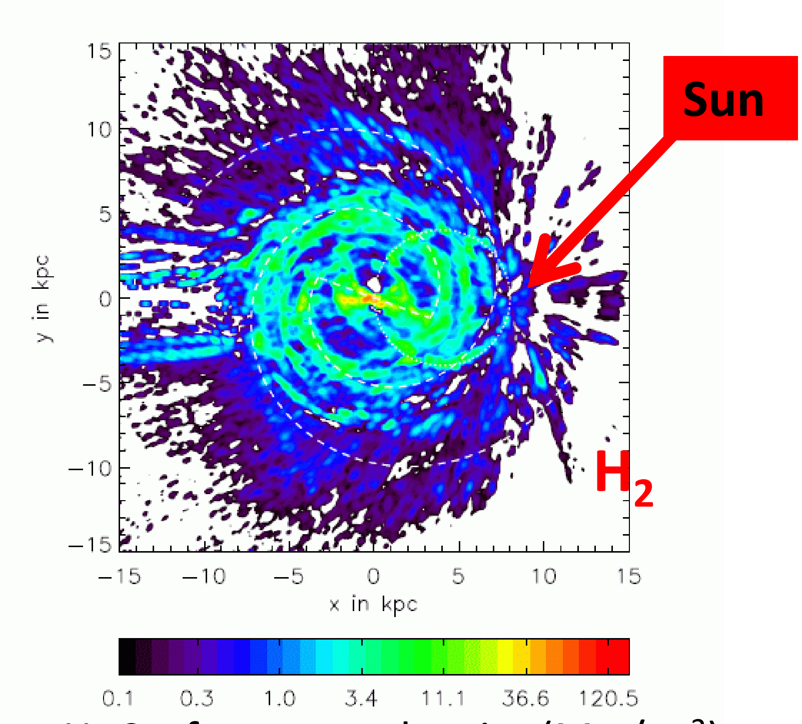
Average H disk thickness vs. R



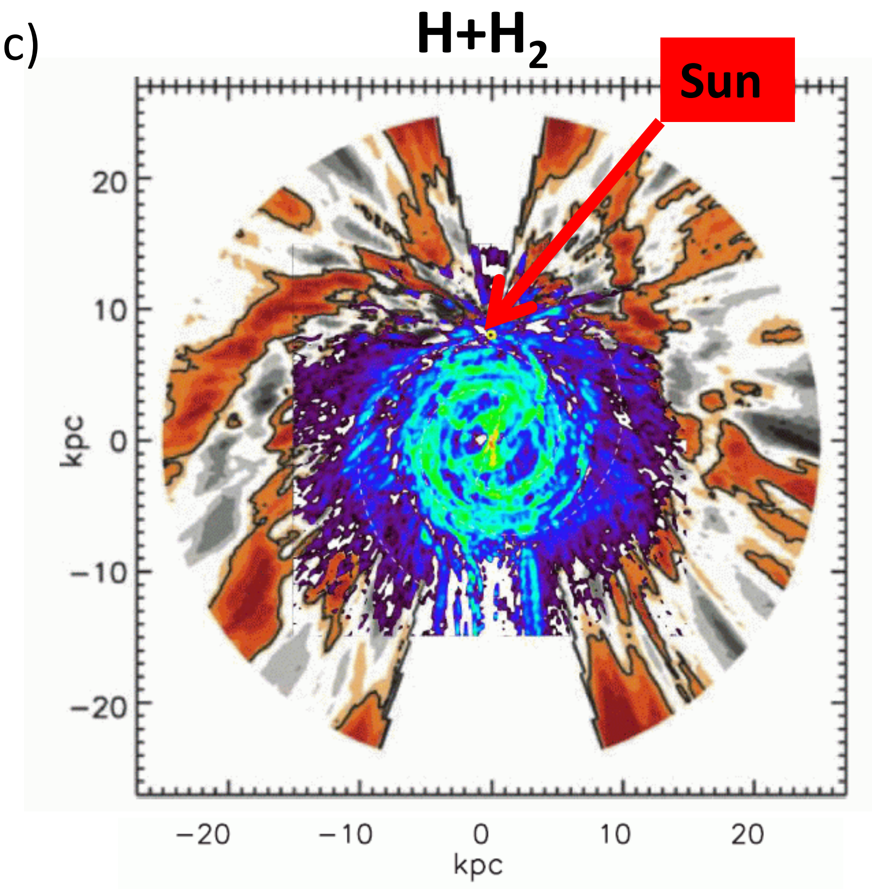
Molecular Hydrogen in the Galaxy

H2 is the main component for R < 5 kpc

1) Molecular ring (R ~4-5 kpc)
2) Central Molecular Zone (R < 250 pc)
3) Central bar ?



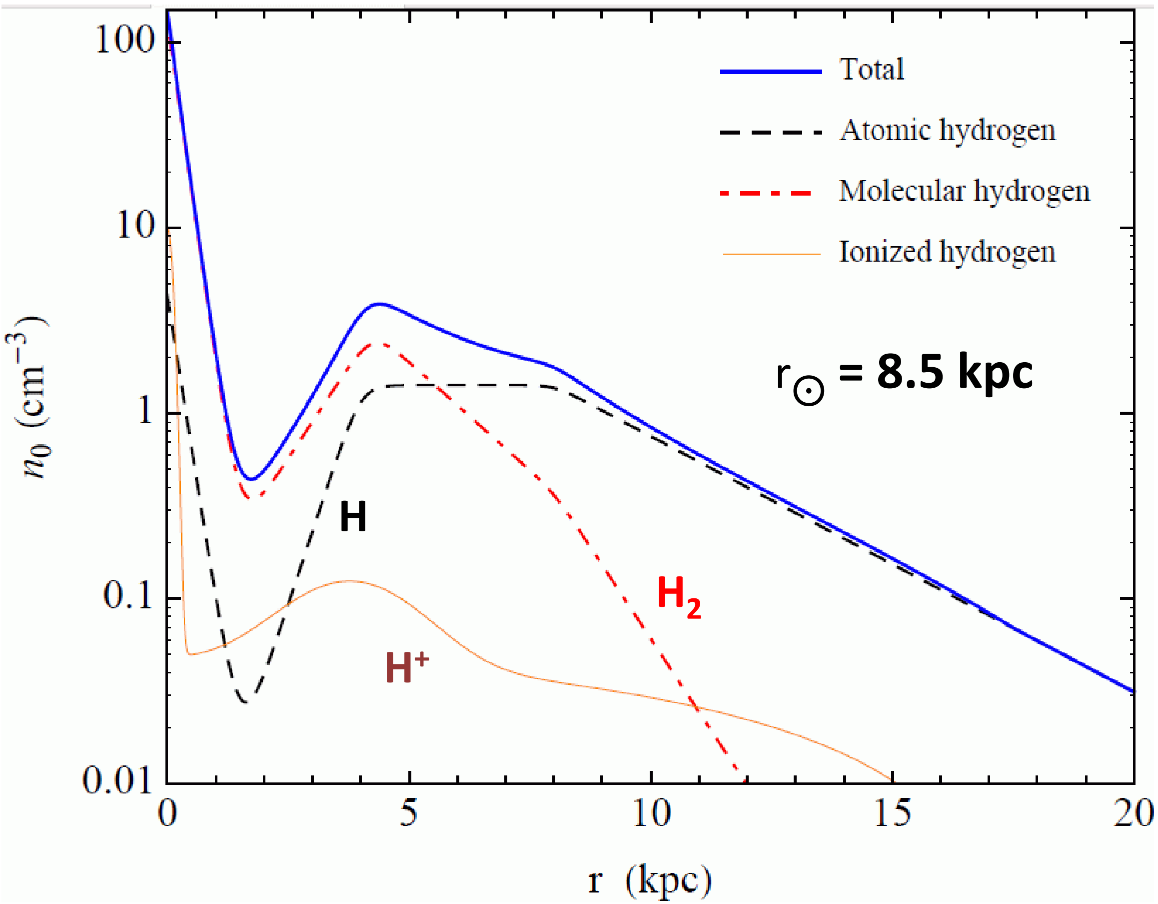
H_2 Surface mass density ($M_\odot/pc^2$)
(Pohl et al. 2007)



(Englmaier et al. 2008)

Our model for the Hydrogen spatial distribution

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**

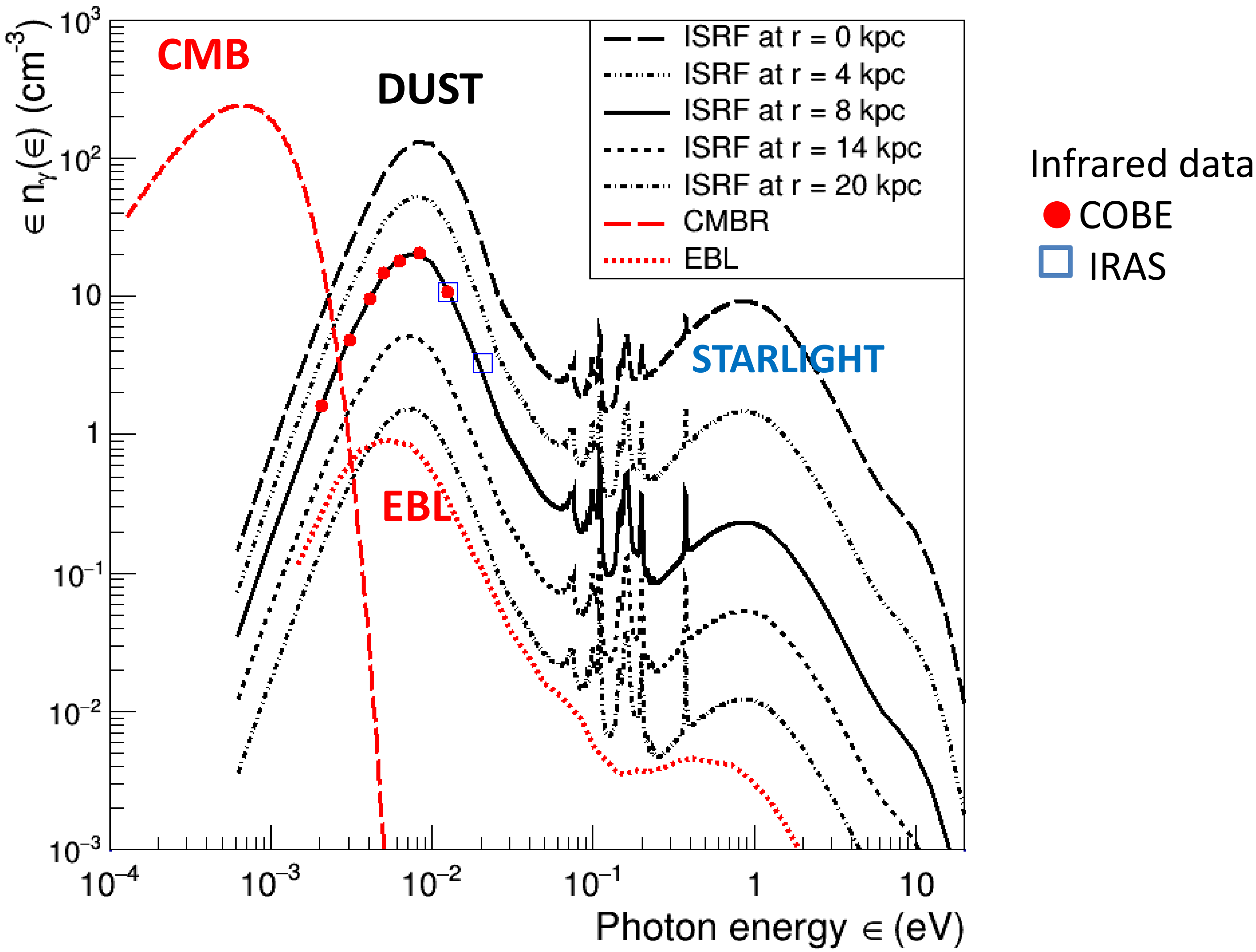
Atomic H: $M_H = 5.3\ 10^9\ M_{sun}$

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

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

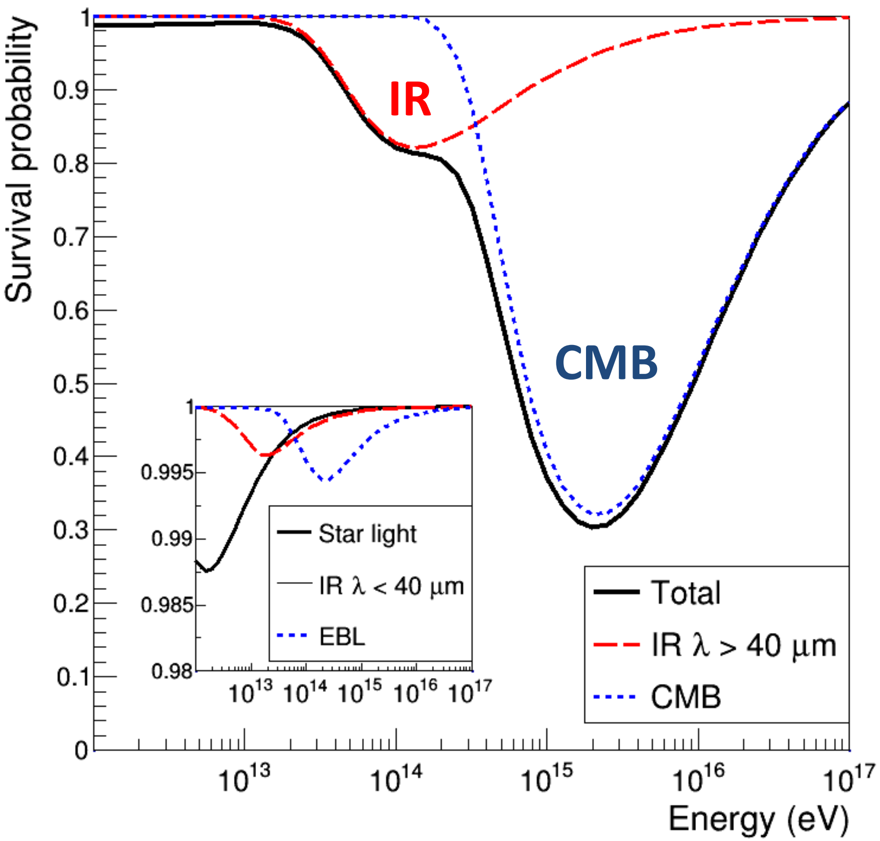
Total mass
(H+other elements)
= **1.42 M_H**

Model for radiation fields in the Galaxy

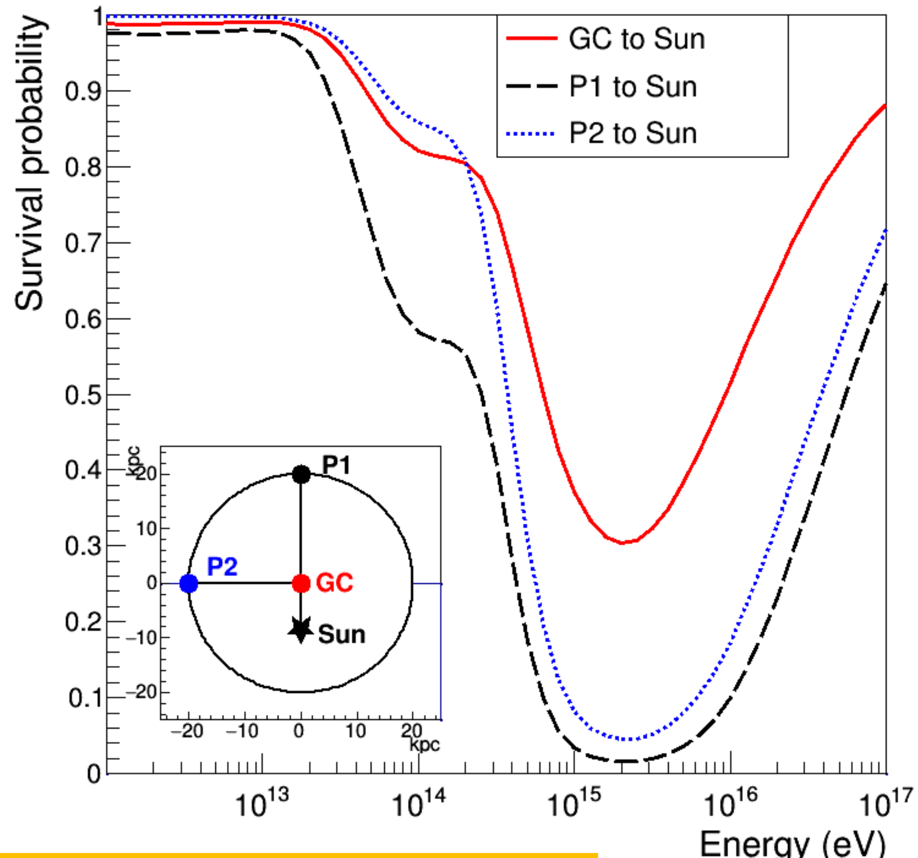


Survival probability vs. gamma ray energy

γ-rays from Galactic center



γ-rays from 3 source positions



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

CR distribution - Model 1

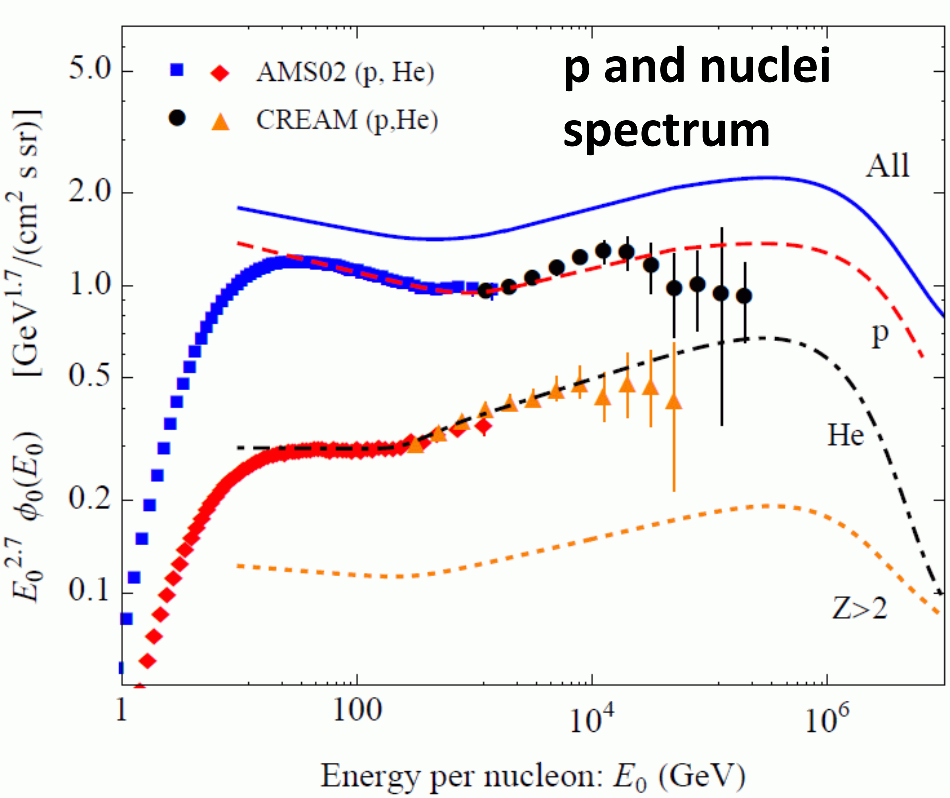
Model 1 : CRs have the same spectral shape in all the Galaxy

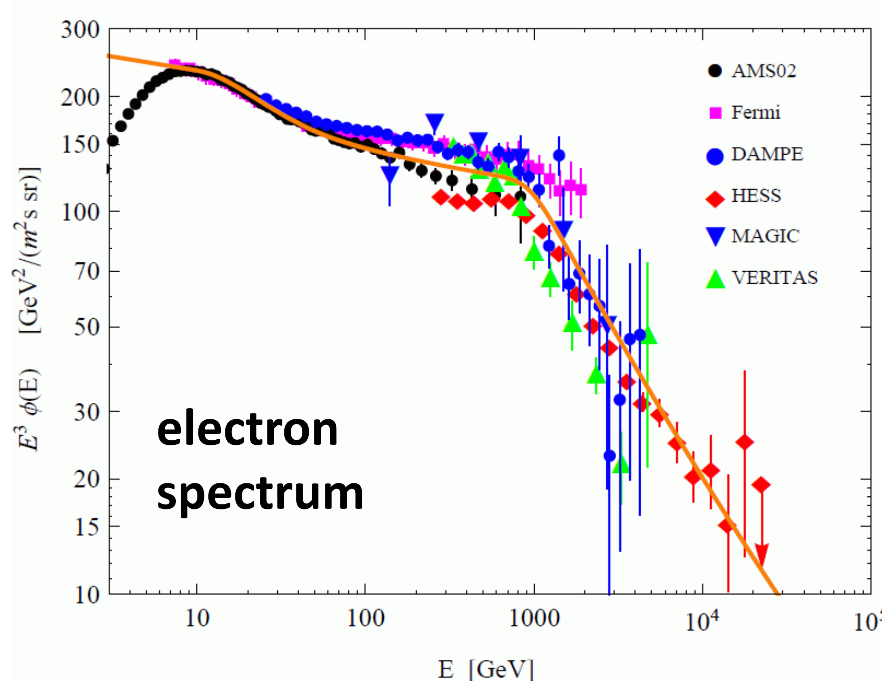
Conditions:

- Sources generate CR with equal spectra in all the Galaxy
- CRs are in a stationary state (sources compensate losses)
- Diffusion coefficient has the same rigidity dependence in all the Galaxy
- Energy losses during propagation are negligible

➡ γ-rays are produced with the same spectral shape in all the Galaxy

Cosmic rays local spectra



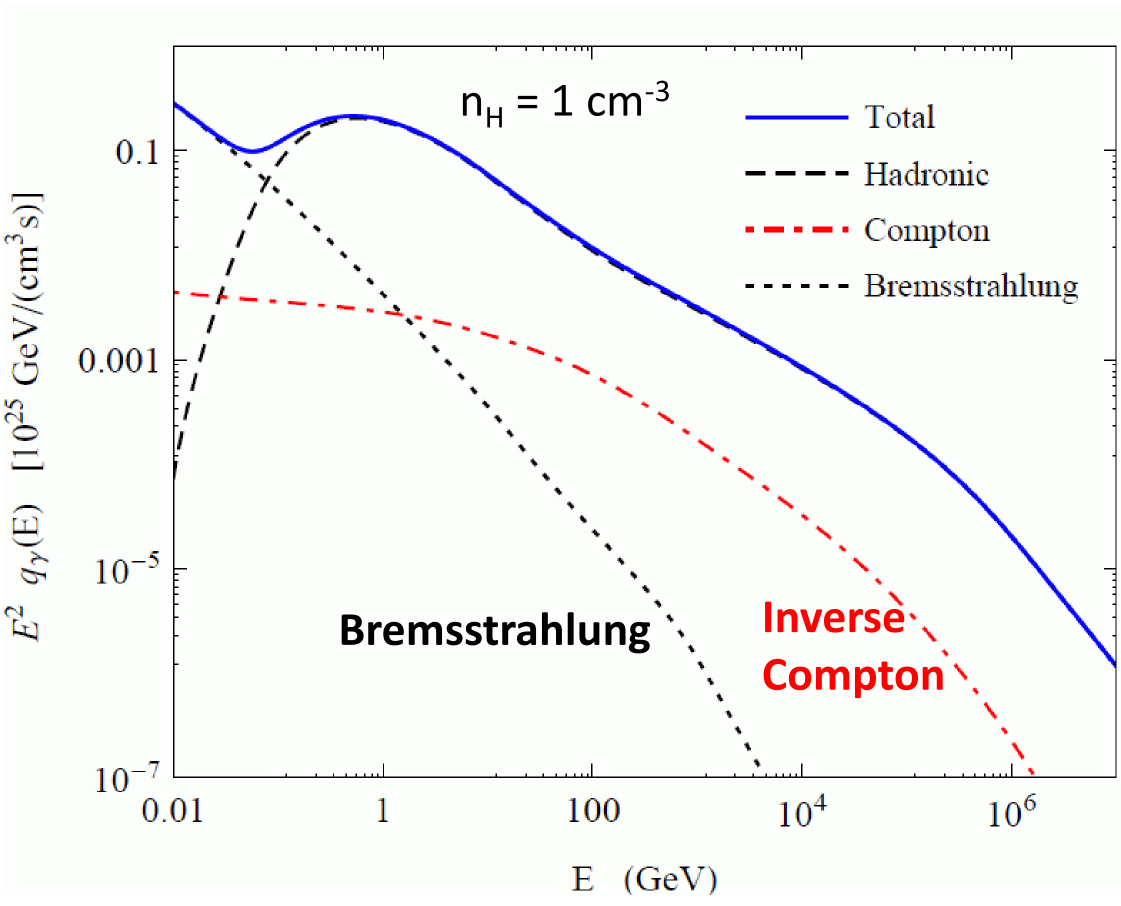


Hadronic γ-ray production:
Gamma rays are mostly produced **by π^0 decay** in interactions
Target: interstellar matter

Leptonic γ-ray production:

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

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_π /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

Model 1 – Production of gamma rays

γ-rays are produced with the same spectral shape in all the Galaxy:

$$q(E,\vec{r}) = q_{loc}(E)\ f(\vec{r})$$

the emission q(E,r) is **factorized** in E and r

$$f(\vec{r}) = \frac{n_H(\vec{r})}{n_H(\vec{r}_\odot)} \frac{\Phi(\vec{r})}{\Phi(\vec{r}_\odot)}$$

spatial dependence of the emission

$$f(\vec{r}_\odot) = 1$$

$\vec{r}_\odot$ = Sun position
$n_H(\vec{r})$ = H atoms number density

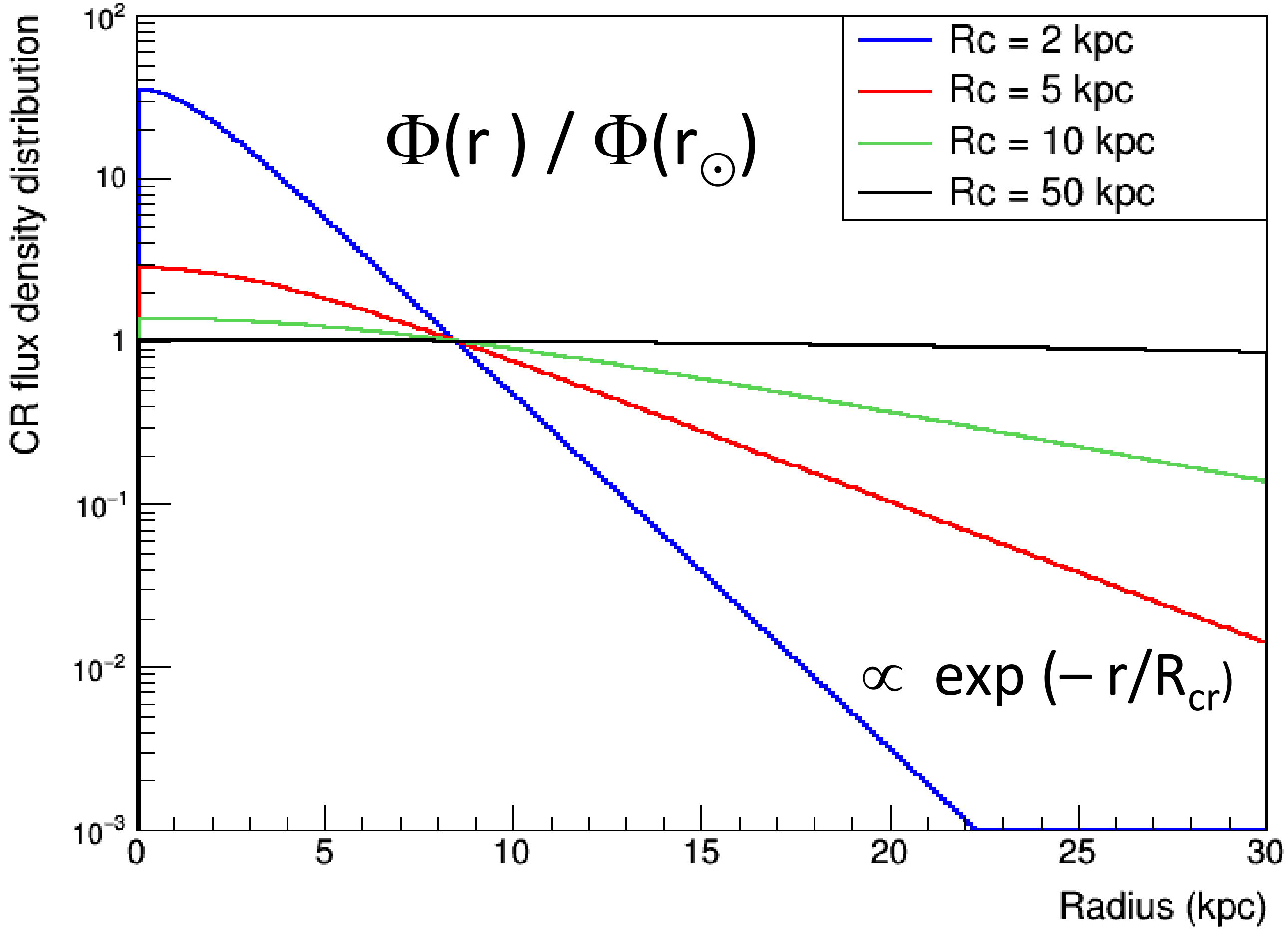
$\Phi(r) = \Phi_\odot\ \mathrm{sech}(-r/\mathbf{R}_{cr}) / \mathrm{sech}(r_\odot/\mathbf{R}_{cr})$ CR flux normalization

R_{cr} is a free parameter: the only parameter of the model

Φ is assumed constant in z for z < 0.5 kpc (where the interstellar gas density is higher)

Model for the CR flux vs. r

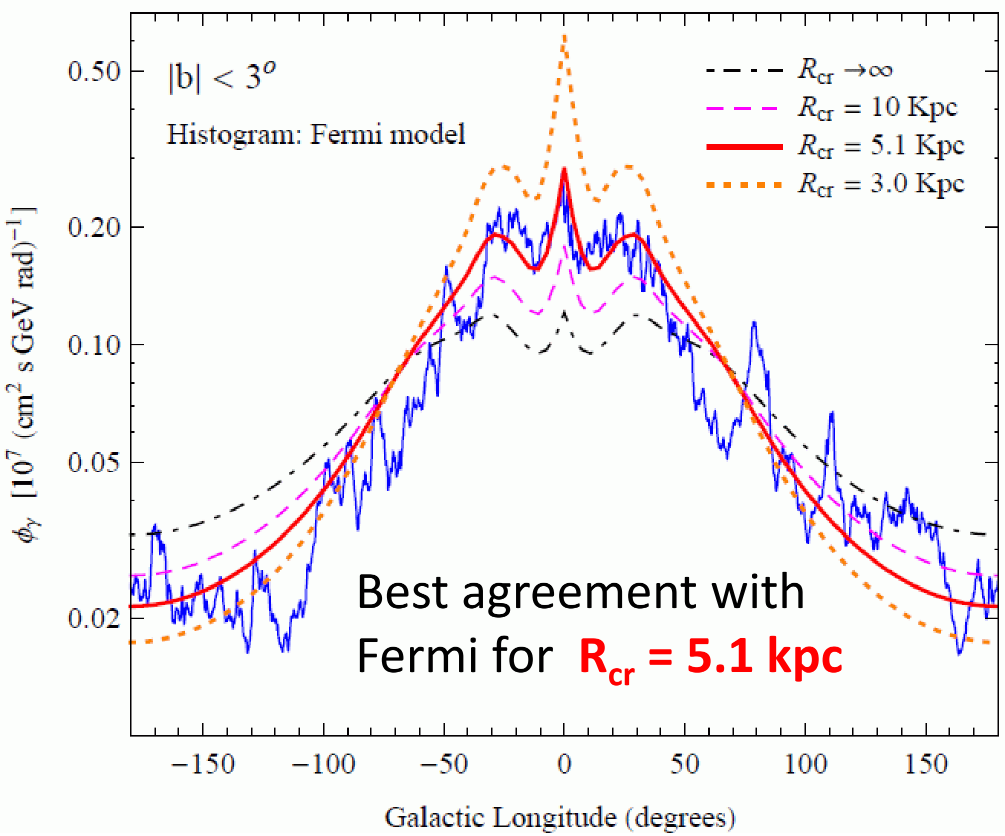
$$\Phi(r) = \Phi_{\odot} \operatorname{sech}(-r/R_{cr}) / \operatorname{sech}(r_{\odot}/R_{cr})$$



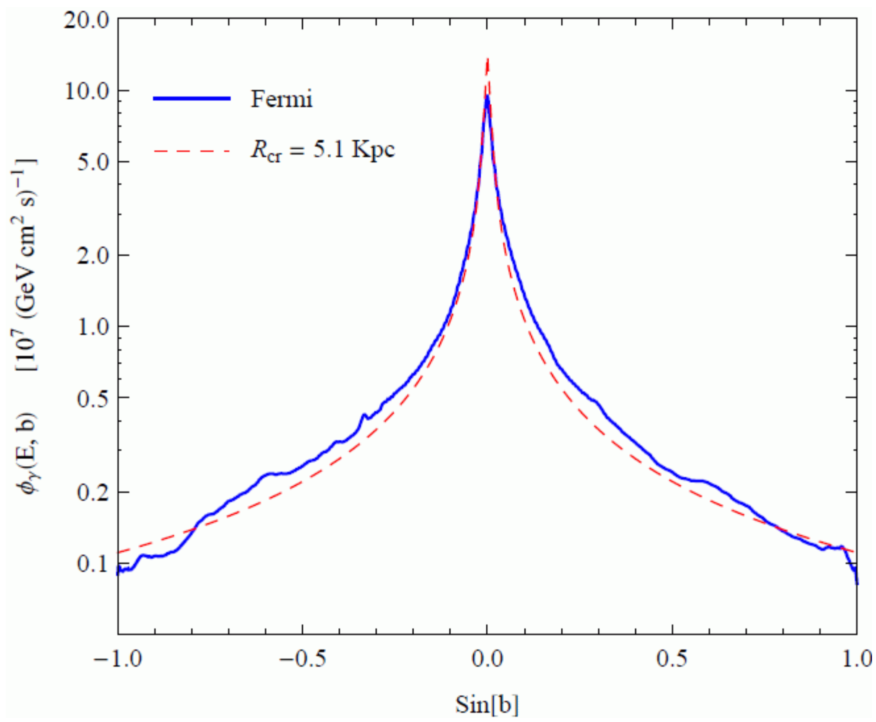
Model 1: prediction for the γ-ray flux at 12 GeV and comparison with Fermi data

Absolute flux prediction

Galactic longitude distribution



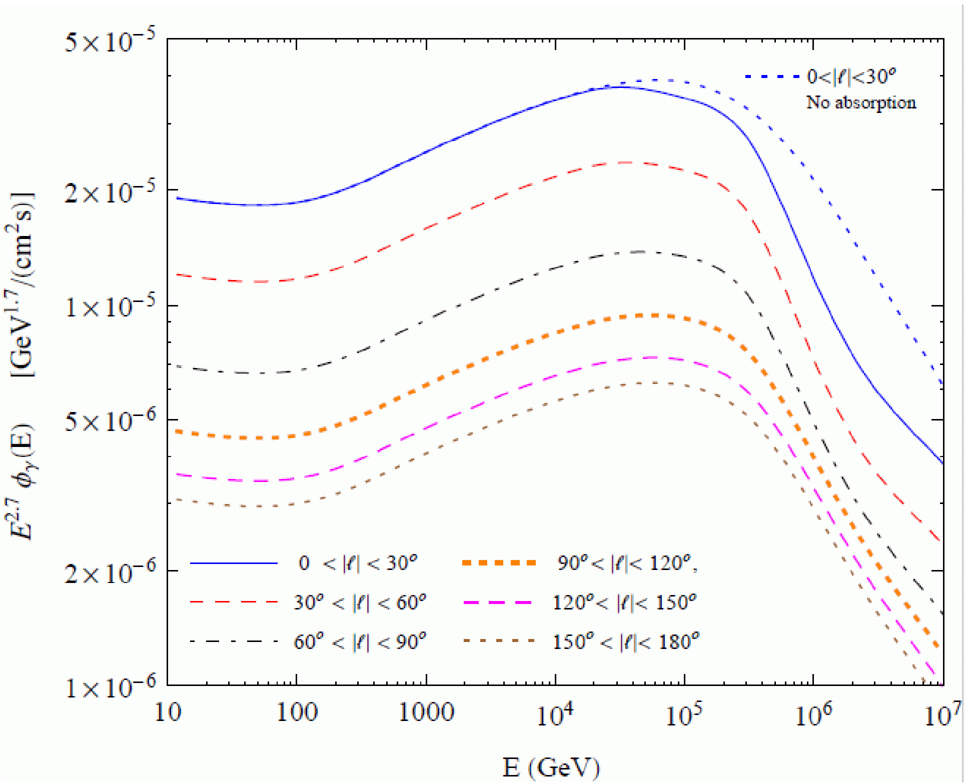
Galactic latitude distribution (integrated over the longitude)



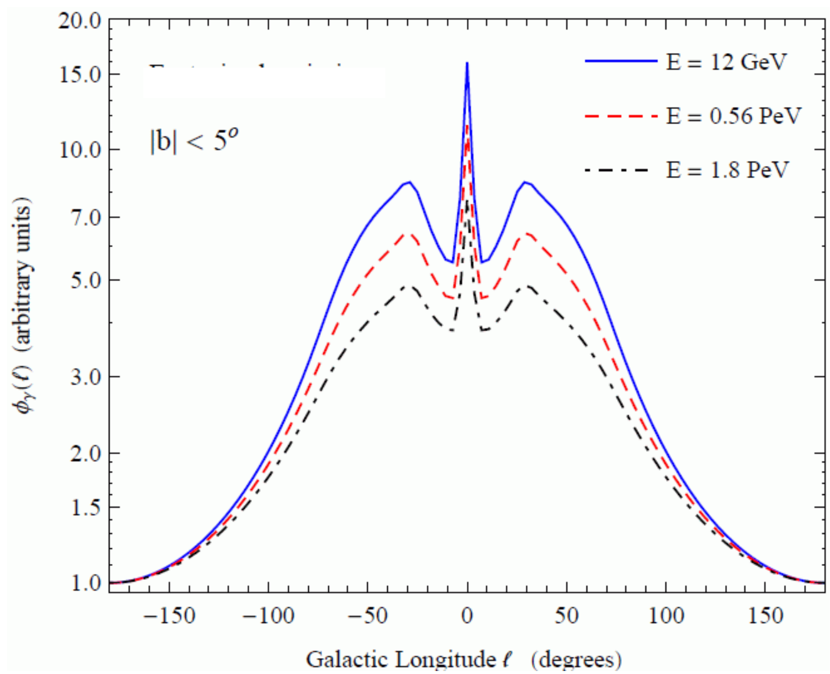
Model 1: prediction for gamma rays up to 10 PeV

Absorption must be taken into account

Gamma rays coming from the central regions are more **absorbed (above 30 TeV)**



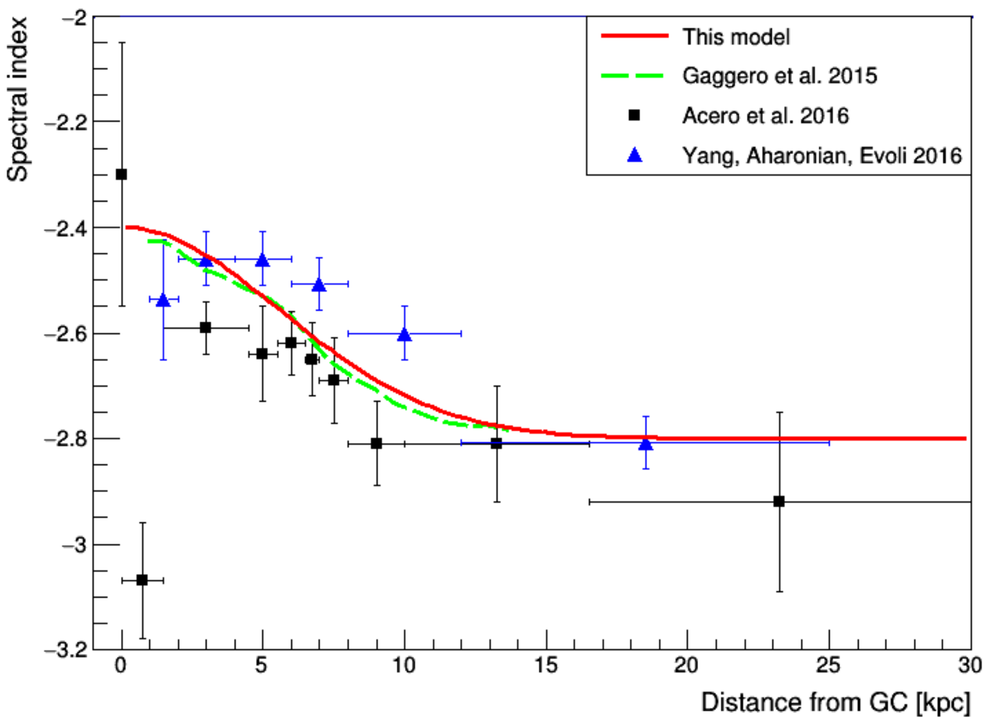
Because of absorption the longitude distribution **changes with energy**



CR distribution - Model 2

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**

Does the diffusion coefficient change with r ?

The diffusion coefficient $D(\rho)$ is usually assumed to have the same rigidity dependence in all the Galaxy:

$D(\rho,r) \propto F(r)\, \rho^{\delta}$ ρ = rigidity

These new data could indicate that δ depends on r

Model 2 – Production of gamma rays

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

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

non-factorized form

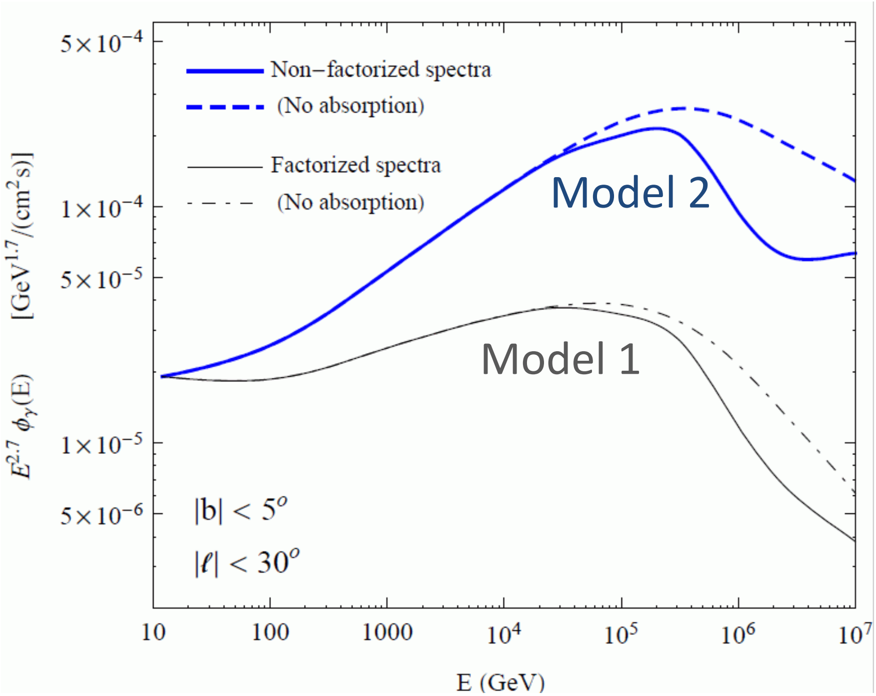
α depends on r:
α = - 2.4 at r=0
α = - 2.75 at $r_\odot$
α = - 2.8 at r > 15 kpc

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

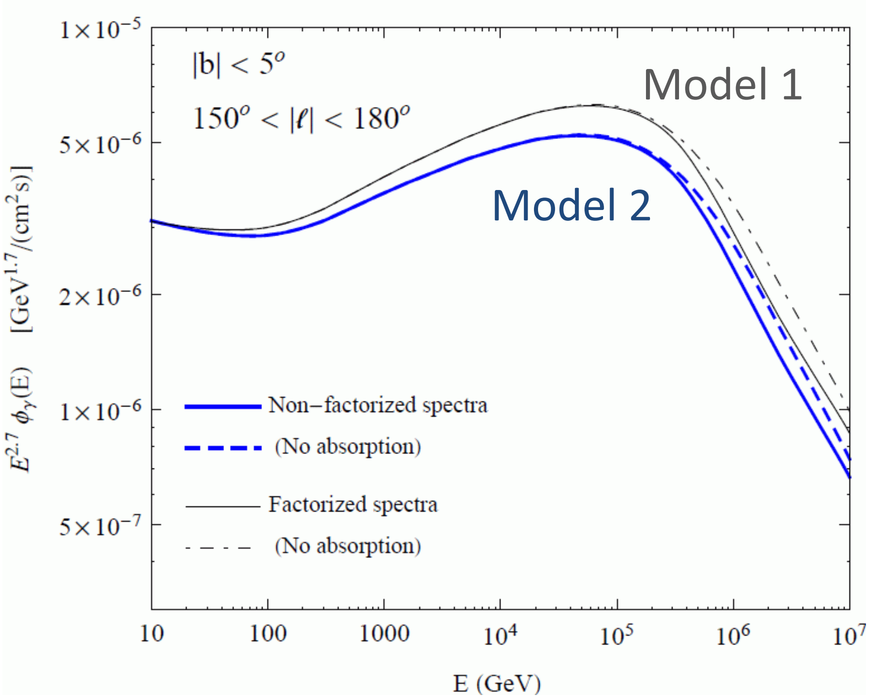
At energy E = E_{ref} the two models give the same flux and spectrum

Model 2 – predictions

γ-ray spectrum towards the Galactic center



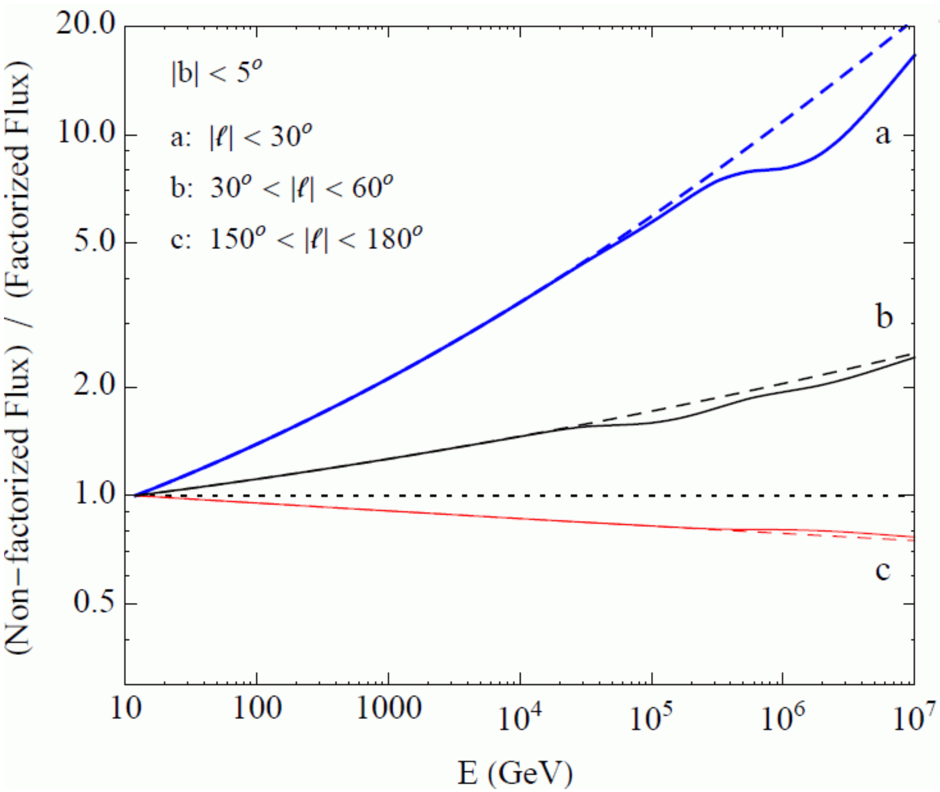
γ-ray spectrum towards the anti-center



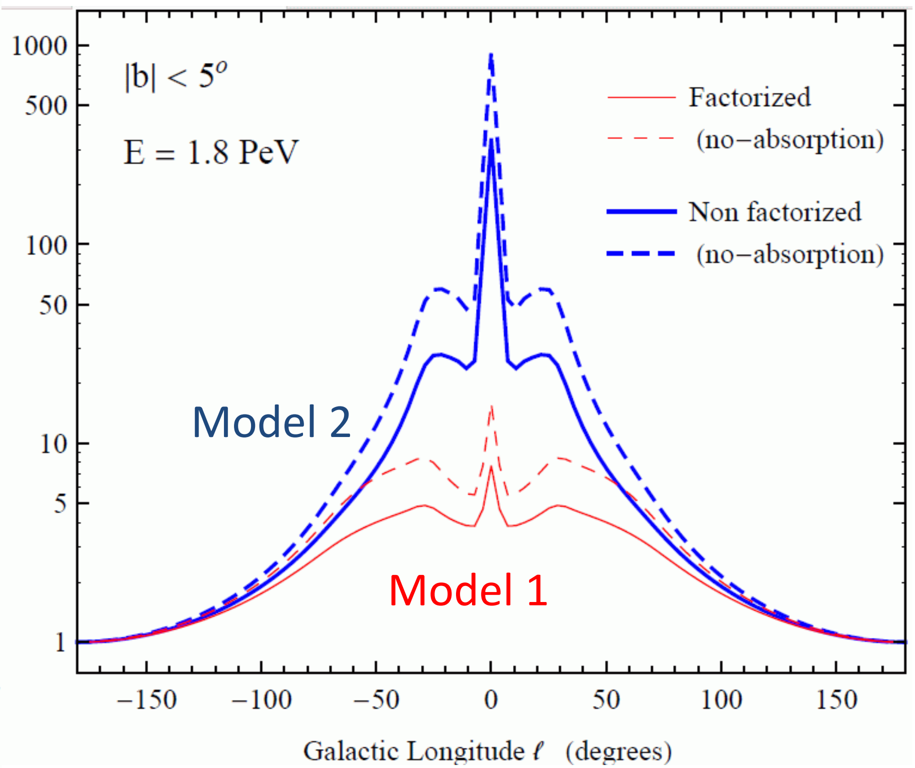
In model 2 the high energy flux is much higher in the direction of the Galactic center with respect to Model 1

Model 2 – predictions

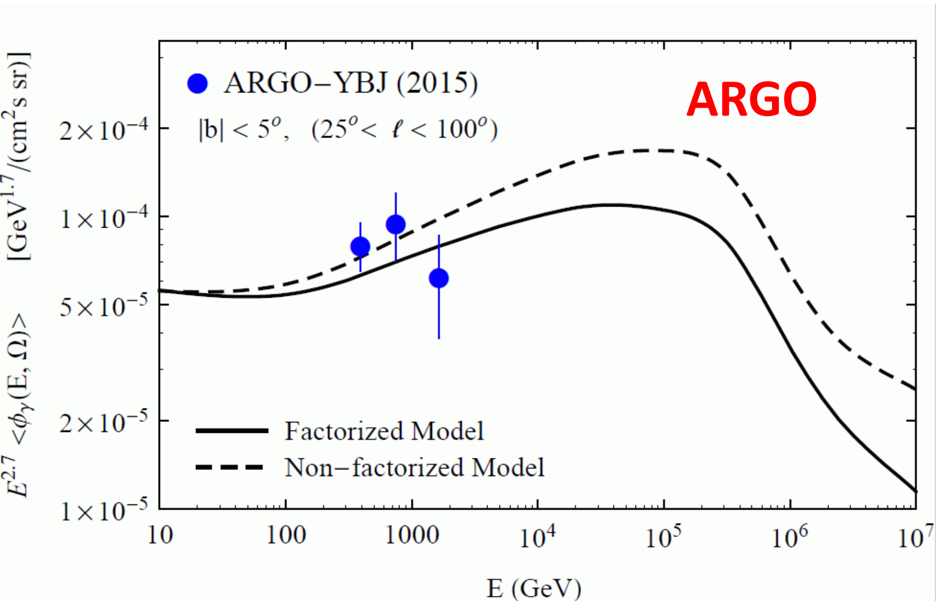
Flux ratio: Model 2 / Model 1

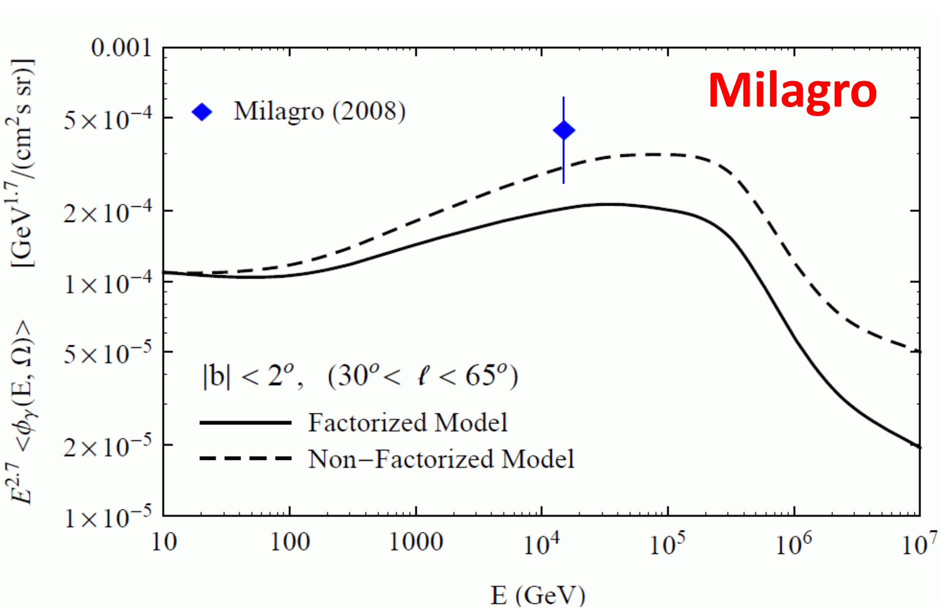


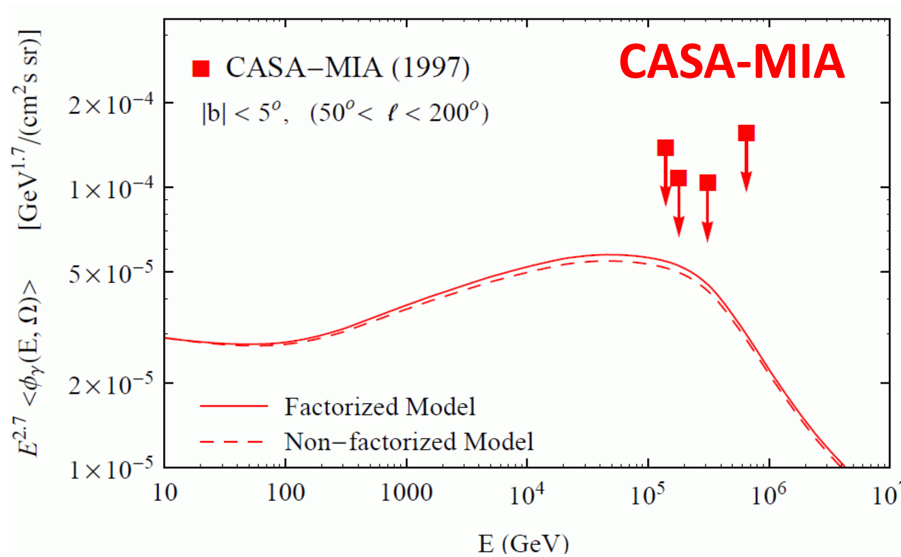
Longitudinal distribution



Model – data comparison



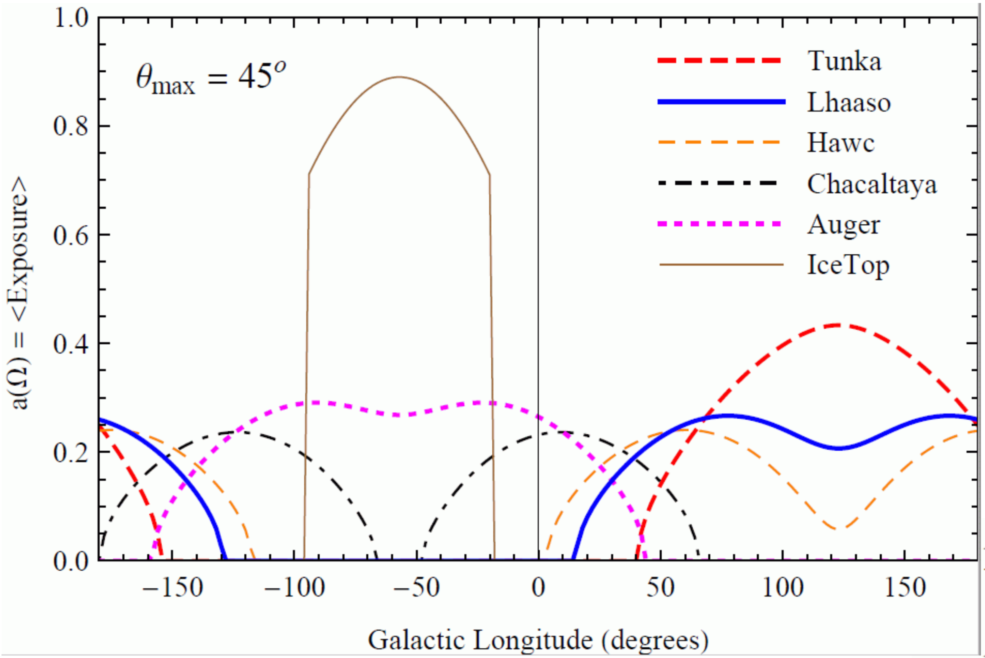




The available data are not able to discriminate between the two models

It is necessary to measure the diffuse flux at higher energies

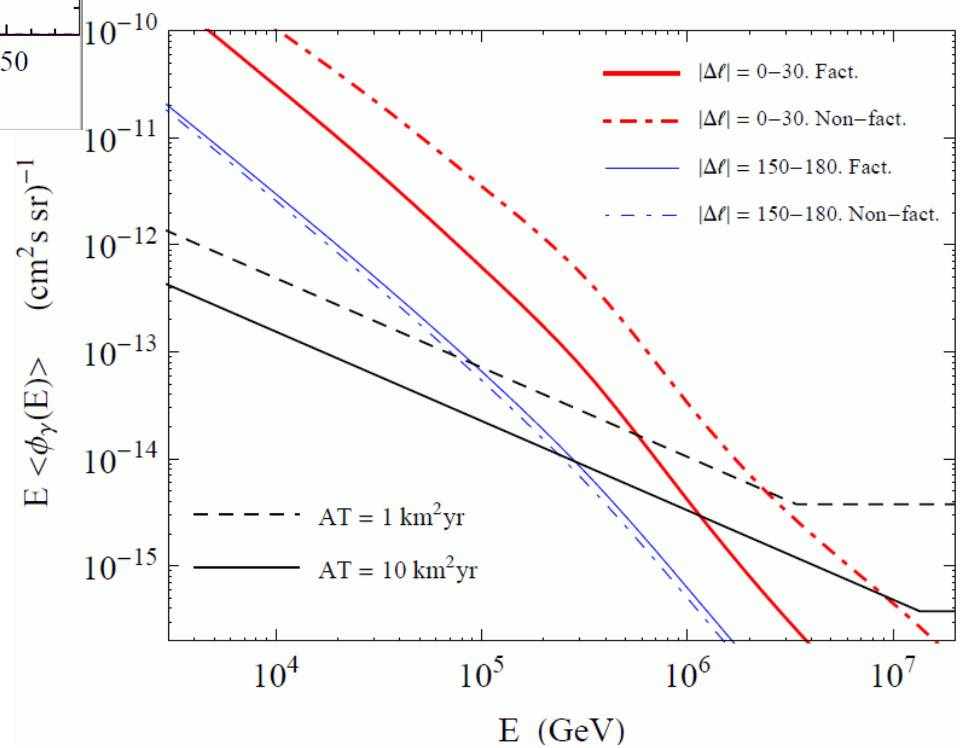
Detection sensitivity



Exposure for the galactic plane (fraction of the day when the plane is visible, i.e. zenith angle θ < 45°)

Minumum flux detectable at 3 sigma by an air shower array, assuming:

Hadron rejection = 10^{-4}
Gamma ray efficiency = 0.8



Conclusions

- The measurements of gamma ray diffuse flux is a fundamental tool to study cosmic ray origin and propagation in the Galaxy
- Fermi data indicate a hardening of the diffuse gamma ray spectra in the central region of the Galaxy
- If this hardening is not due to the contribution of **unresolved sources**, it could be due to the hardening of the parent CRs
- This hardening produces a distortion of the gamma ray longitudinal distribution, **much more evident in the range 100-1000 TeV**
- It is important to perform high energy measurements along **the whole galactic plane**, hence to have detectors at different latitudes