Probing Galactic cosmic rays with γ -ray observations of giant molecular clouds

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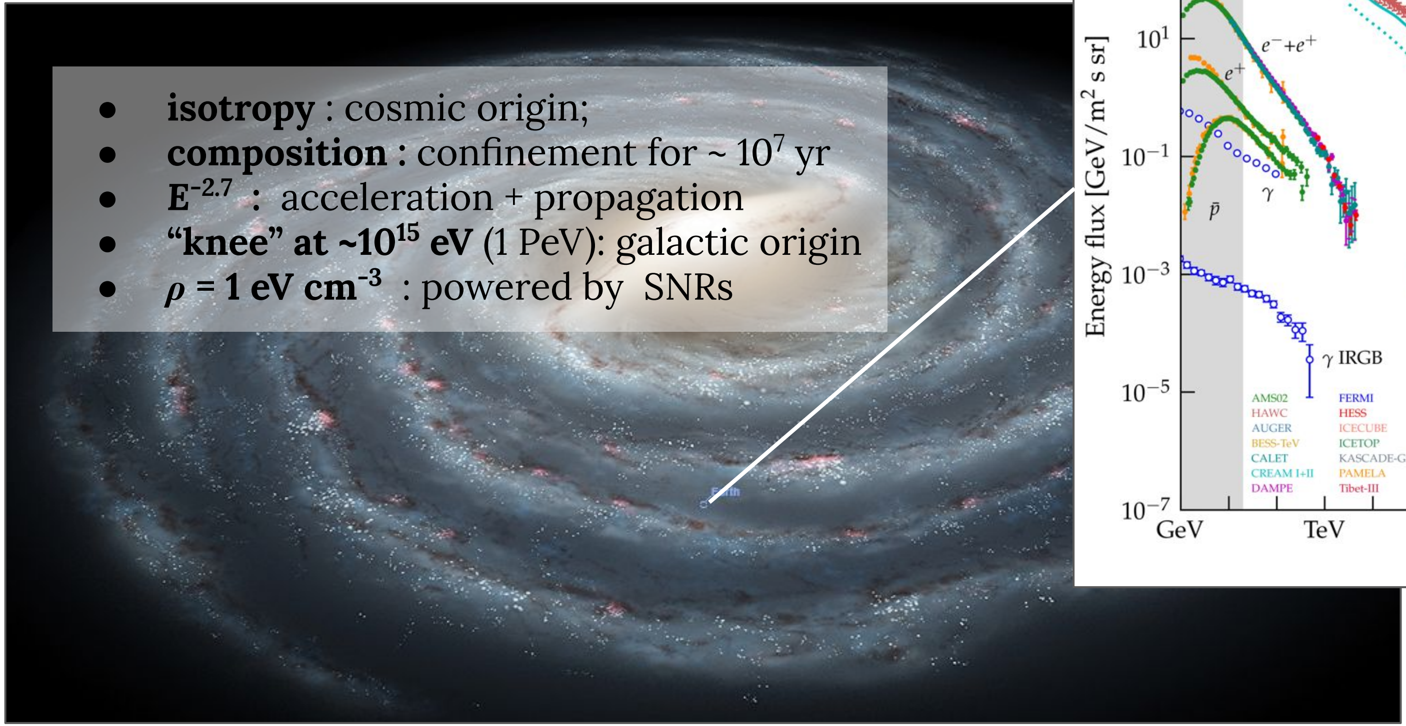
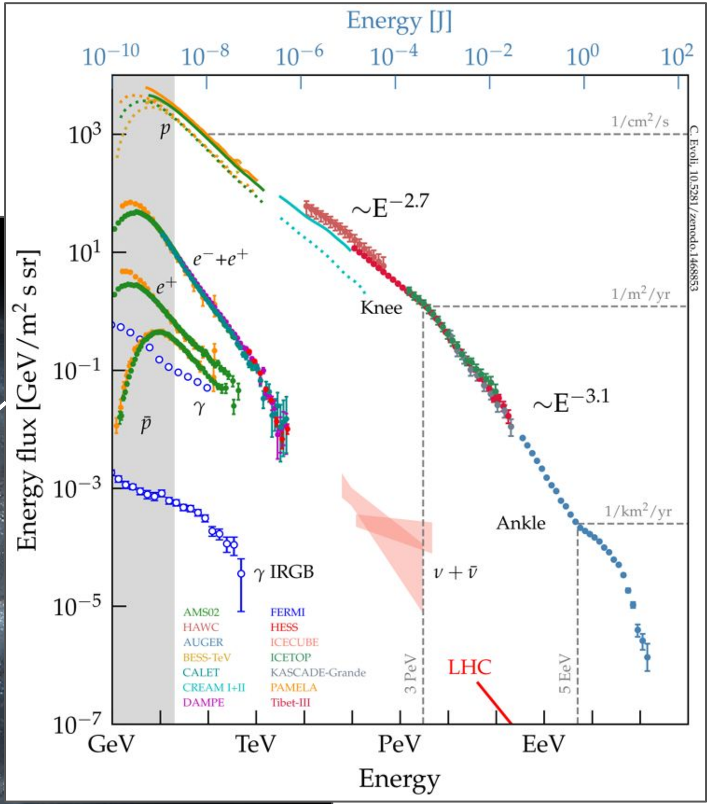
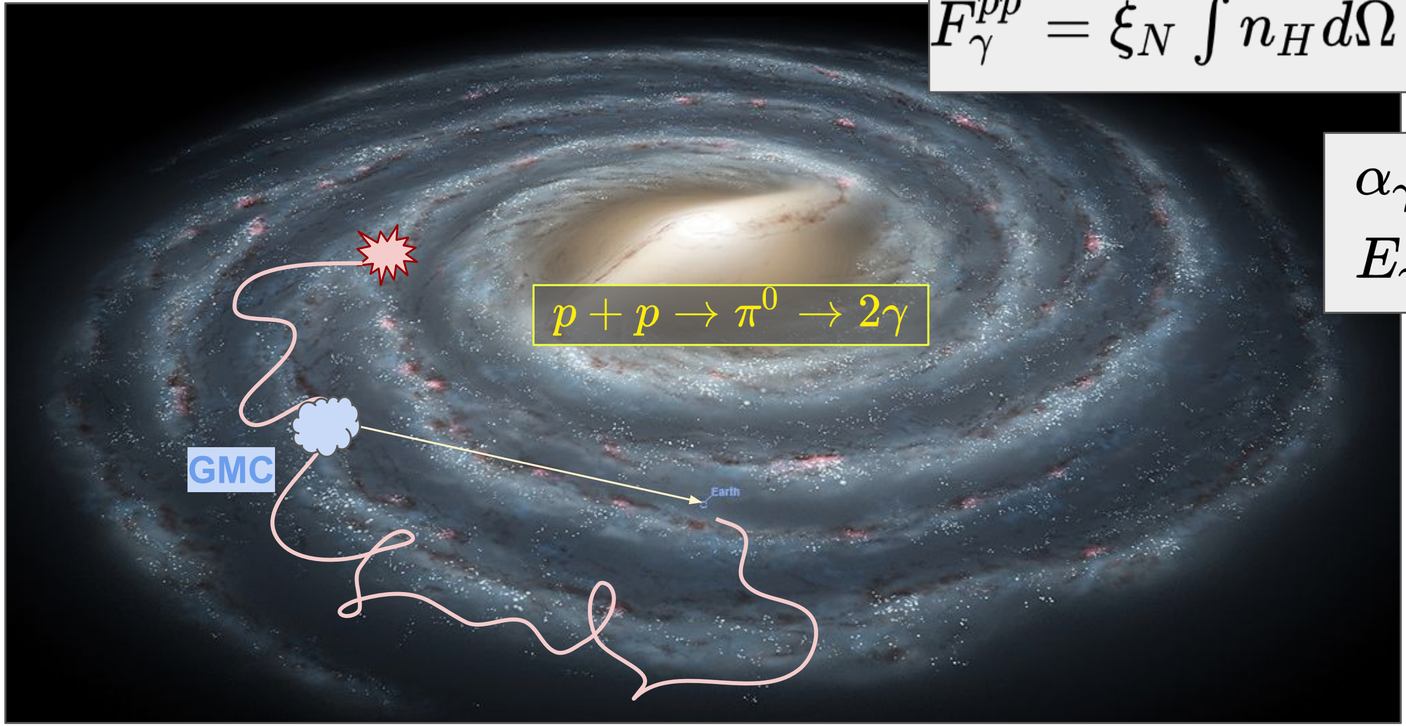
Local Cosmic Rays

- **isotropy** : cosmic origin;
- **composition** : confinement for ~ 10^7 yr
- $\mathbf{E^{-2.7}}$: acceleration + propagation
- **“knee” at ~$\mathbf{10^{15}}$ eV** (1 PeV): galactic origin
- $\boldsymbol{\rho}$ **= 1 eV cm^{-3}** : powered by SNRs





Galactic Cosmic Rays



$$F_\gamma^{pp} = \xi_N \int n_H d\Omega \int dE_p \frac{d\sigma}{dE_\gamma} J(E_p)$$

$$\alpha_\gamma \sim \alpha_p + 0.1$$
$$E_\gamma \sim 0.1 E_p$$

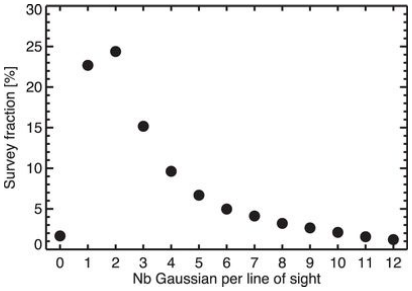
Galactic Cosmic Rays

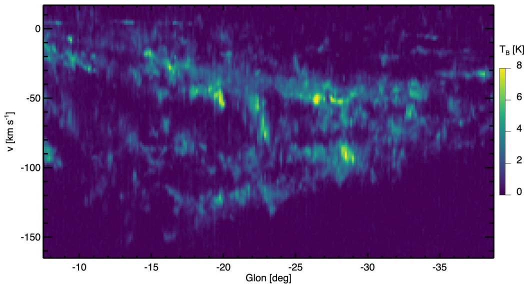
$$F_\gamma^{pp} = \xi_N \int n_H d\Omega \int dE_p \frac{d\sigma}{dE_\gamma} J(E_p)$$

Diffuse gas

[Acero+2016, Yang+2016, Pothast+2018]

- High emissivity $\propto n_H$;
- Average on a large scale;
- Affected by unresolved sources;
- Affected by mis-modeled large scale emission;



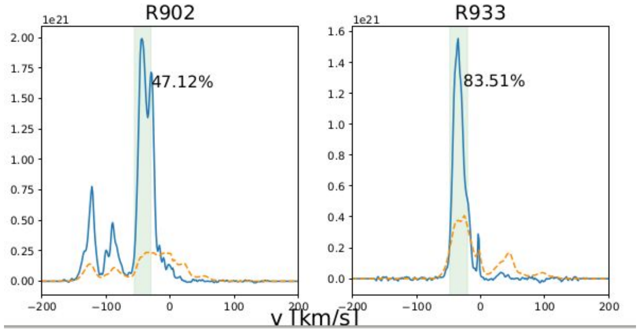


Miville-Deschenes+2016

Molecular Clouds

[Aharonian+1996, Casanova+2010, Aharonian+2020, Peron+2021]

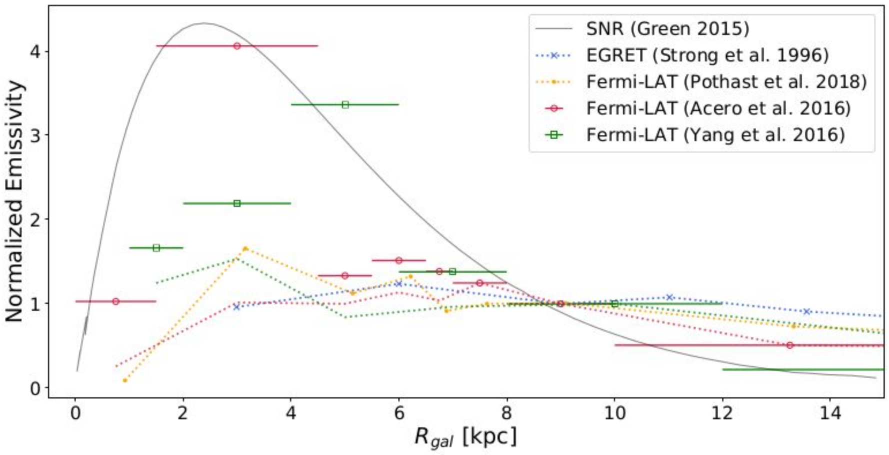
- low emissivity $\propto n_H \sim M/d^2$
- Localization on a scale of ~pc;
- Less chances of being affected by unresolved sources;
- not affected by mis-modeled large scale emission;

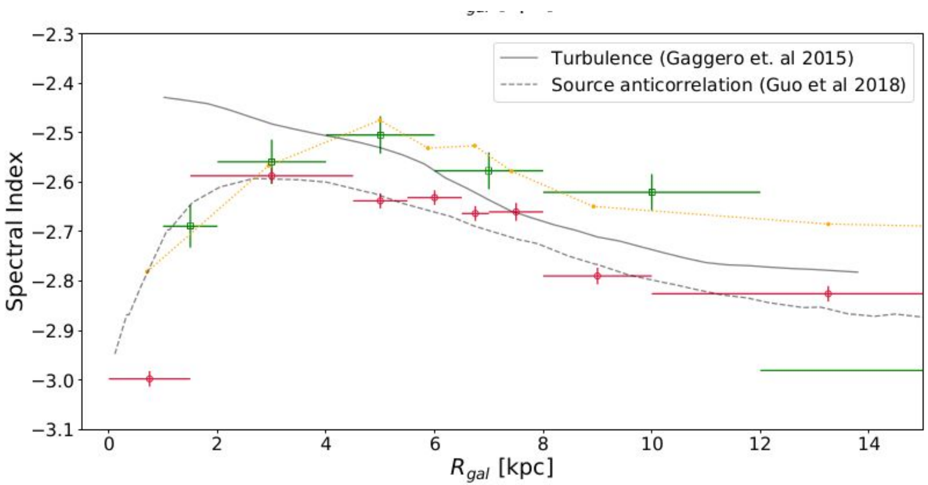


Galactic Cosmic Rays

$$F_\gamma^{pp} = \xi_N \int n_H d\Omega \int dE_p \frac{d\sigma}{dE_\gamma} J(E_p)$$

Diffuse gas





Enhancement and hardening towards the GC

- is this a global effect? (e.g. due to propagation)
- is this a local effect? (e.g. due to sources)

→ MCs allows us to discriminate

$$F_\gamma^{pp} = \xi_N \int n_H d\Omega \int dE_p \frac{d\sigma}{dE_\gamma} J(E_p)$$

Molecular clouds selection

$$A = M_5/d^2_{kpc} = 8 \times 10^{-20} \int n_H d\Omega$$

$(M_5 = M/10^5\ M_\odot\ ;\ d_{kpc} = d/1\ kpc)$

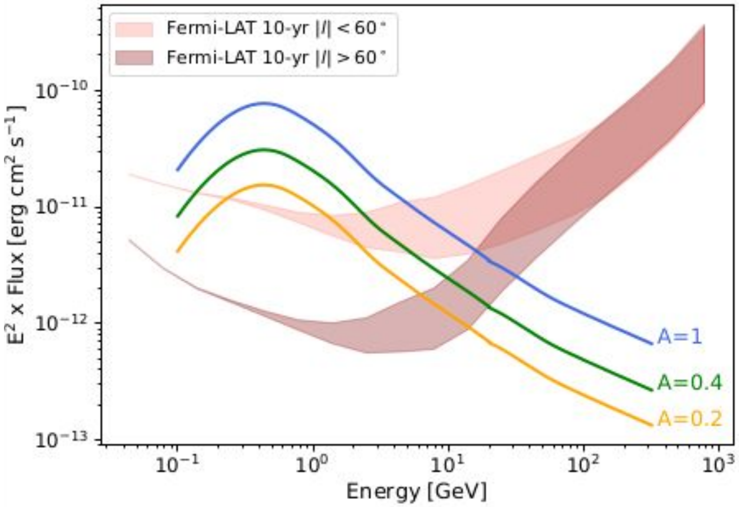


Figure adapted from Aharonian+2020

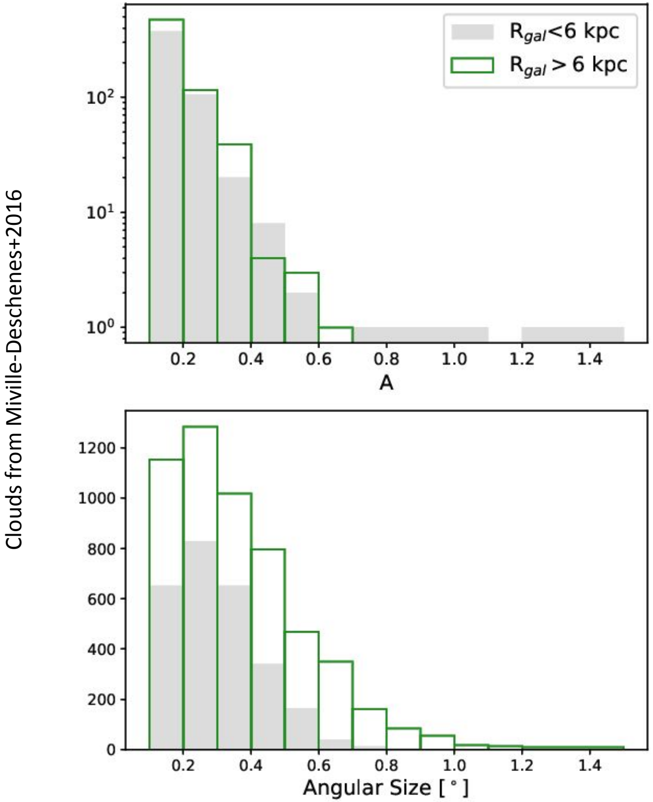
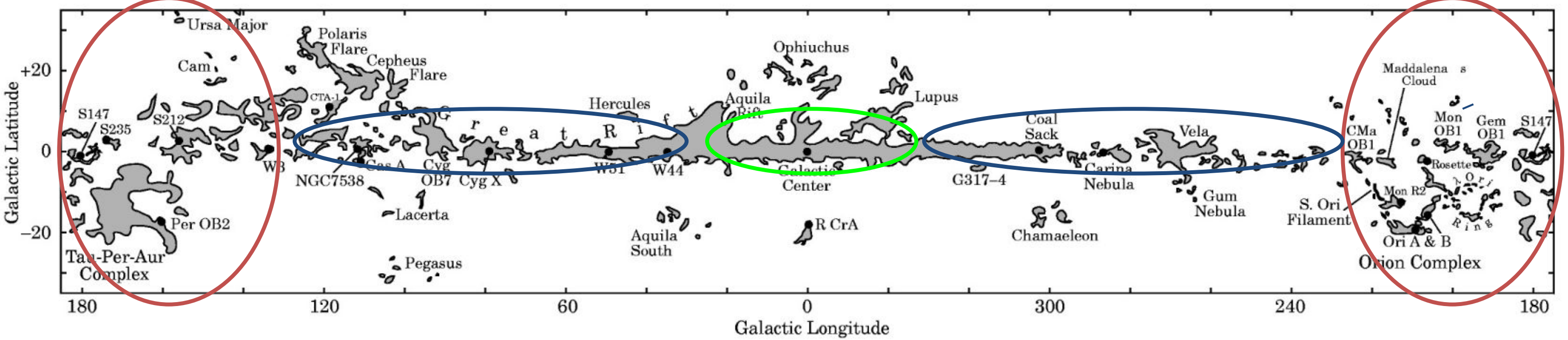


Figure adapted from Peron PhD thesis (2020)

Molecular clouds
S

$$F_\gamma^{pp} = \xi_N \int n_H d\Omega \int dE_p \frac{d\sigma}{dE_\gamma} J(E_p)$$

Dame+2001



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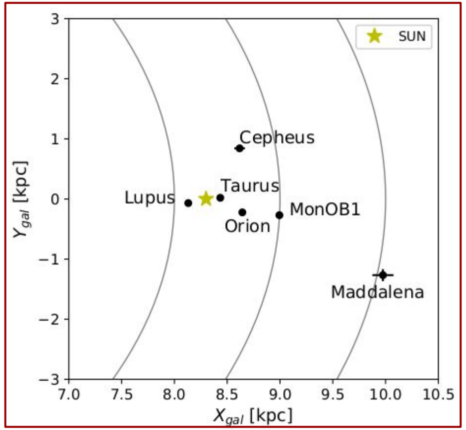
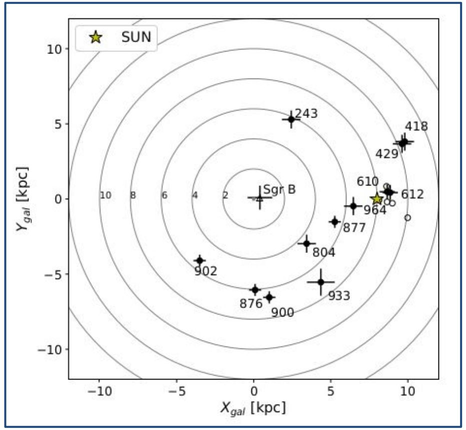
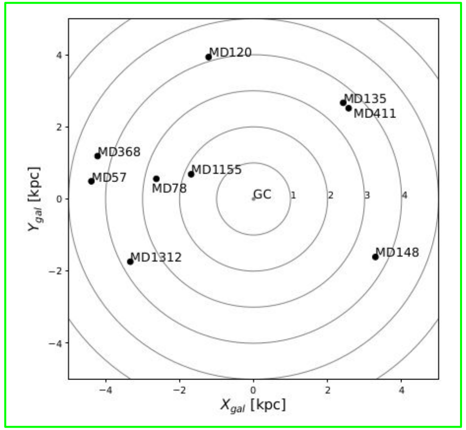






Clouds from:
Rice+2016
Miville-Deschênes+2016

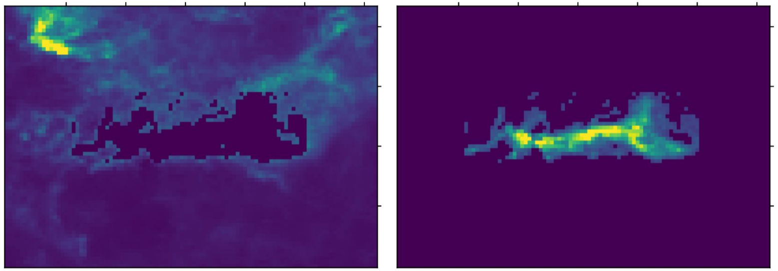
Analysis procedure

Need to separate the cloud

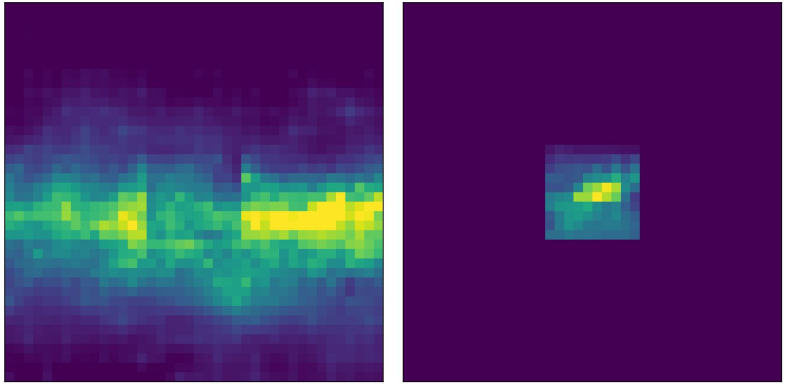
The model included:

- Fermi point sources (3FGL, 4FGL);
- Extragalactic background;
- Galactic background:
  - IC (galprop)
  - Pion decay:
    - Spatial: template based on gas;
    - Spectral: Power Law;

Space-cut from dust

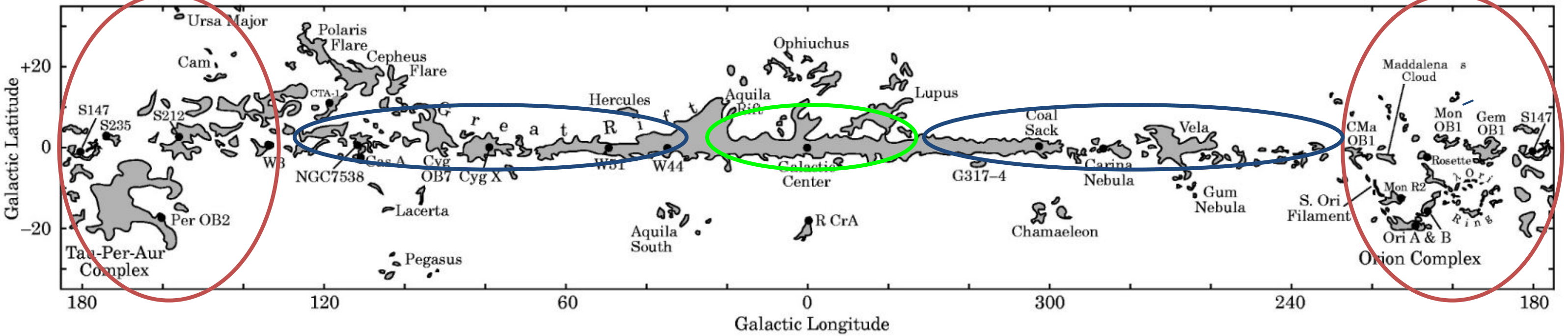


Space and velocity cut from CO



Analysis procedure

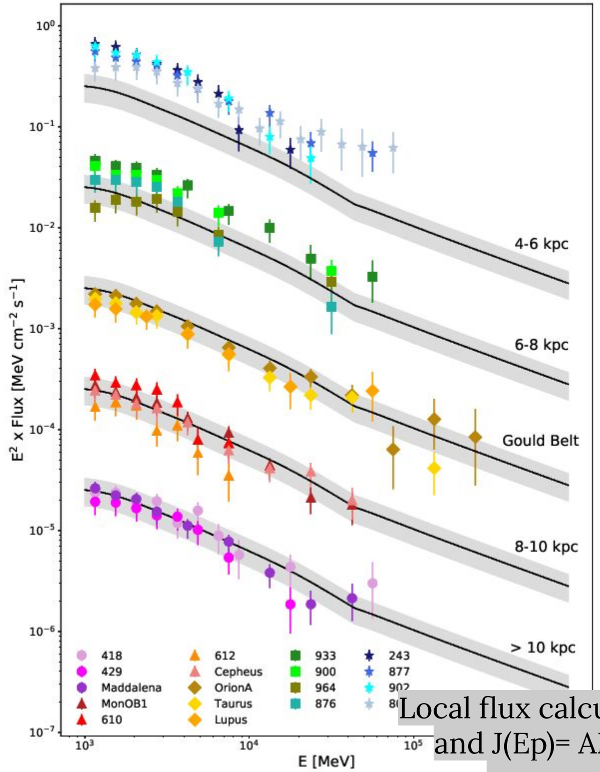
Dame+2001



Dust: high latitude, clear line of sight;
CO+HI: need a velocity decomposition to account for foreground gas;
Dust: uncertain velocity decomposition in the inner Galaxy; saturation of CO at high densities;

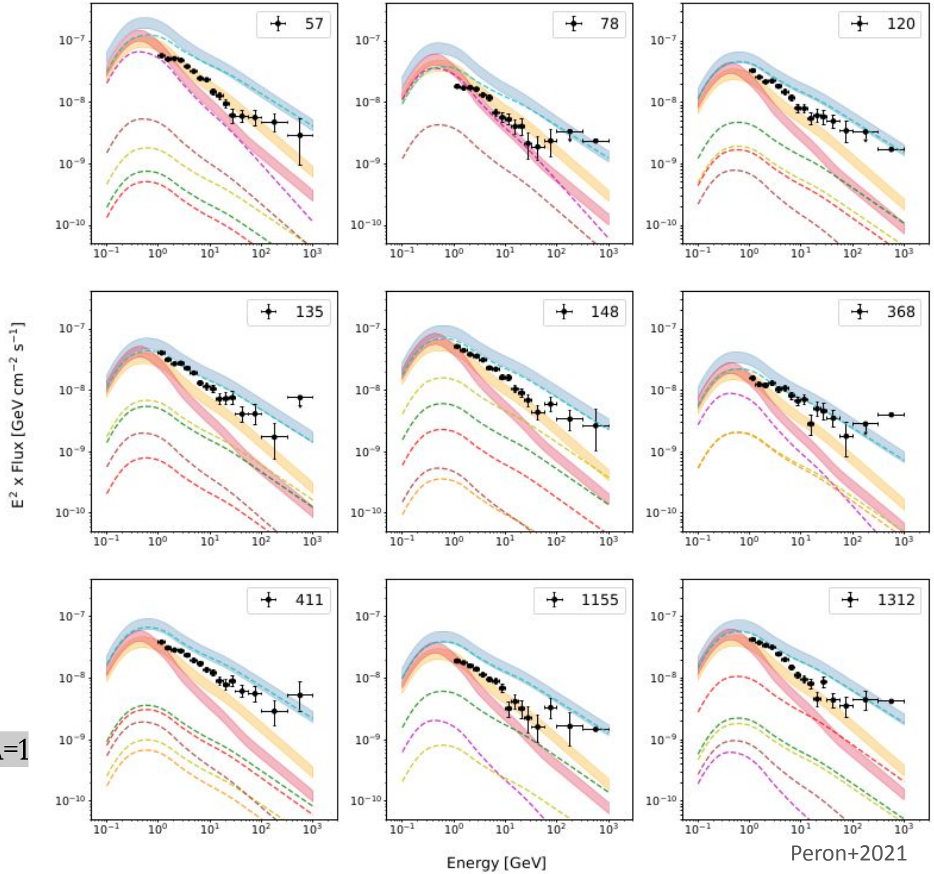
Results

Sum of the contribution of different rings as in Acero 2016;
Local emissivity (8-10 kpc) as in Acero+2016;
Local emissivity calculated from AMS02



Aharonian+2020

Local flux calculated for A=1 and J(Ep)= AMS proton measurements



Peron+2021

Results

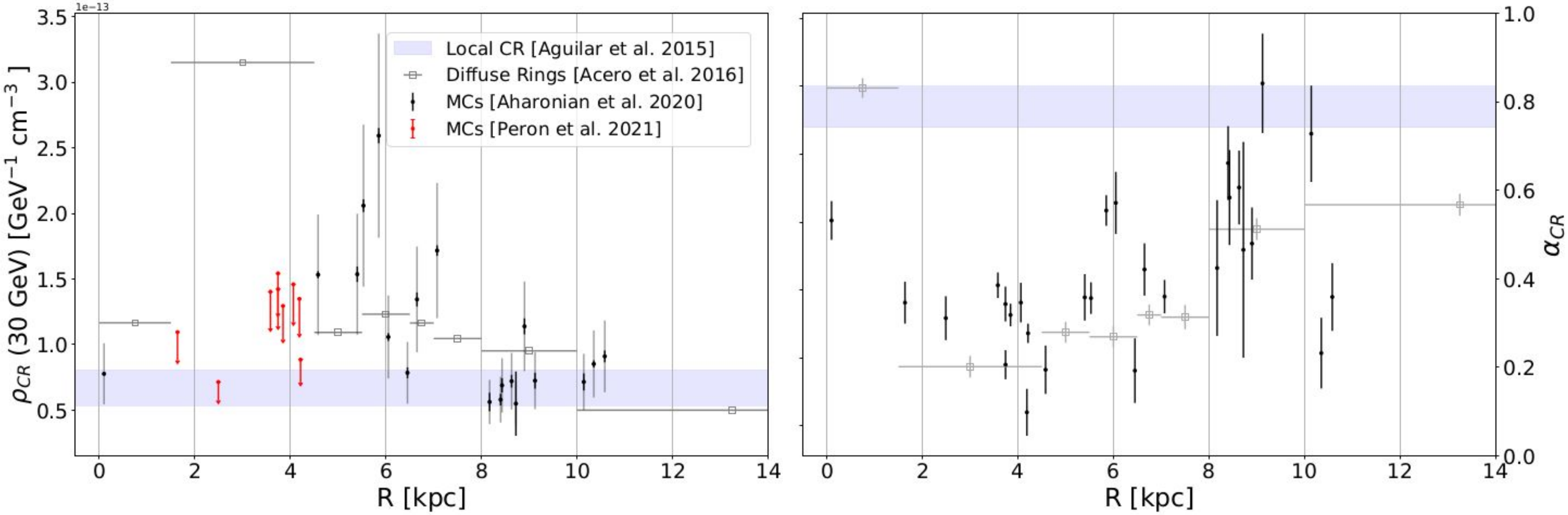


Figure adapted from Peron+2021

Summary

- To confirm the CR paradigm, the spectrum has to be probed in location different from Earth;

- Analysis of molecular clouds provide localized information on the CR spectrum far from Earth;

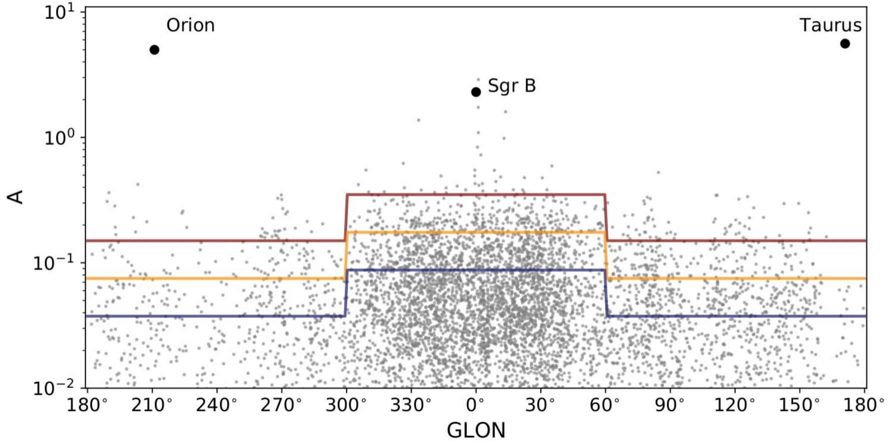
- Results from GMCs show deviations from the local emissivity only in the inner Galaxy, around 4-6 kpc. The deviations are fluctuating, discouraging a global variation;

- The measure in the inner 1.5-4.5 kpc ring do not agree with the average ring value;

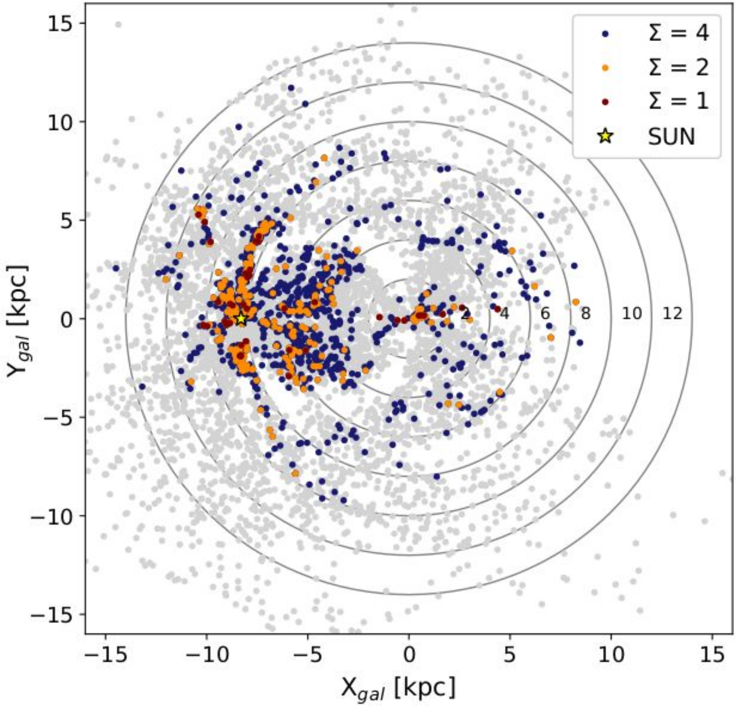
- Further analysis are limited by instrument sensitivity.

Outlook

- Improving the sensitivity of a factor Σ=2 (Σ=4) will largely improve the visible clouds.
- Achievable by enlarging the area of the detector



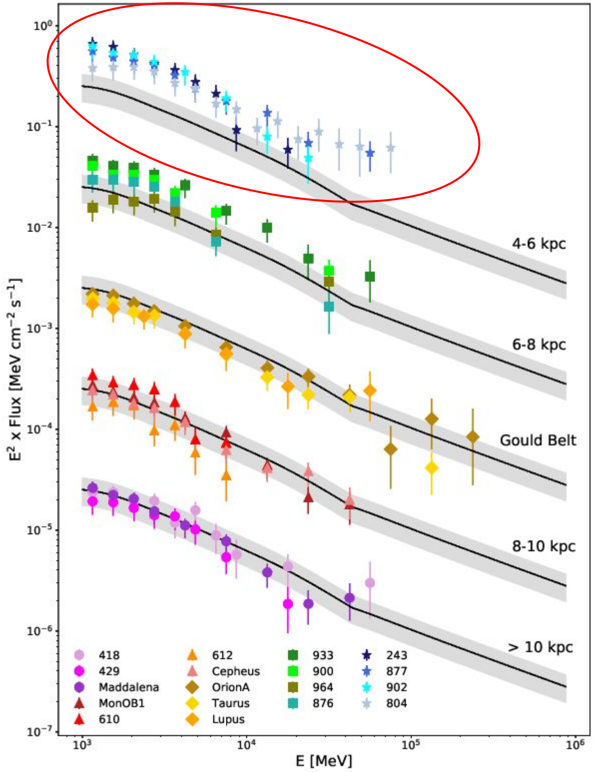
Peron&Aharonian, in prep. (2021)



Outlook

- Enhanced/harder flux can be detected at TeV energy

  → **see Atreyee Sinha's talk #277**



Thank you!