Unveiling the cosmic-ray density with gamma-ray observations of molecular clouds

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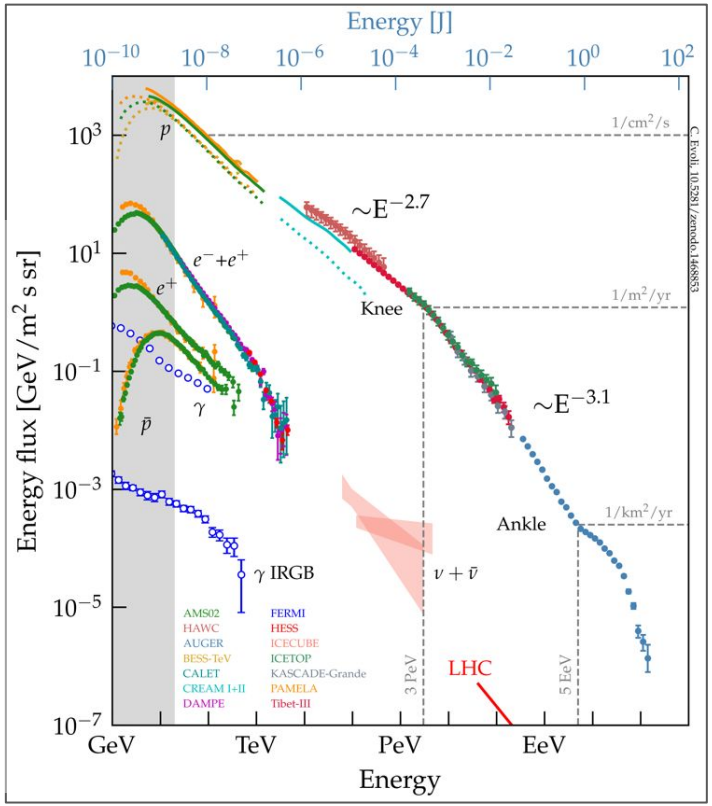
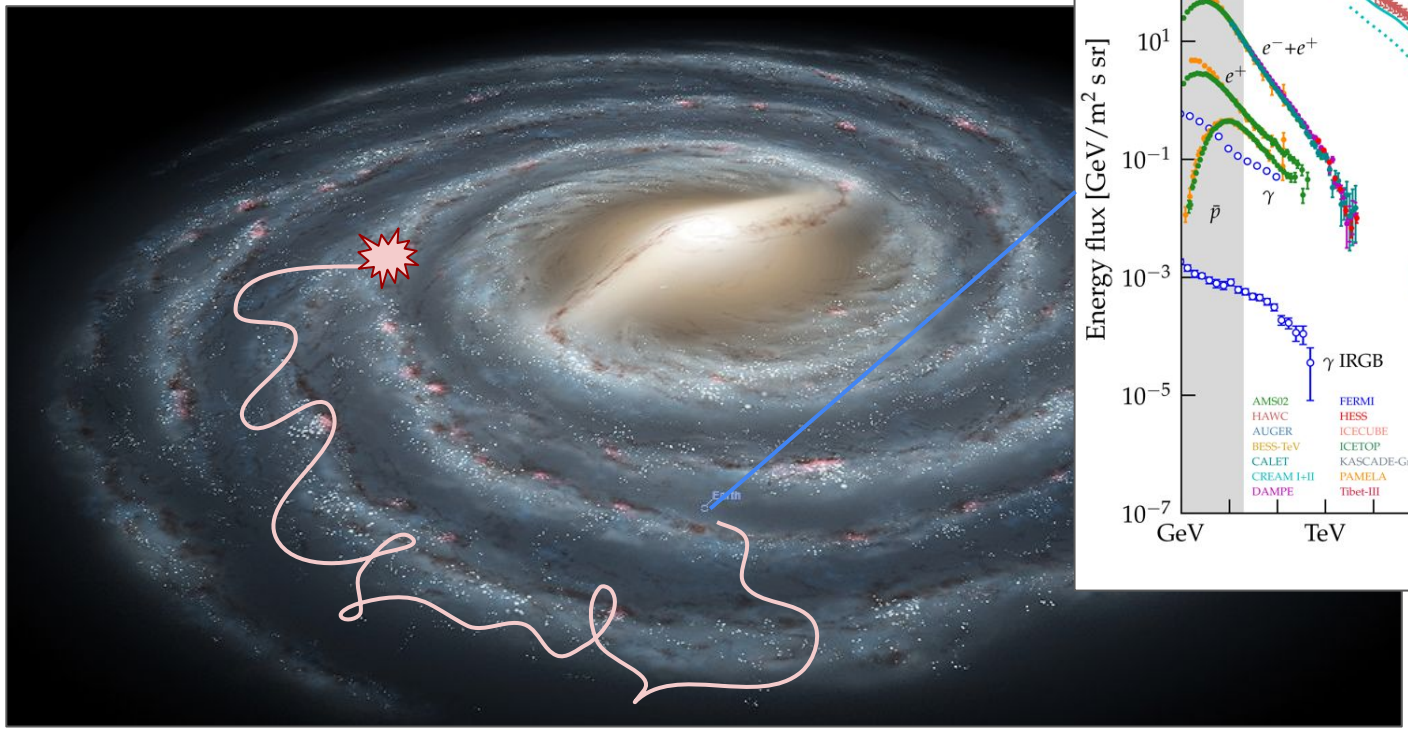
Cosmic rays

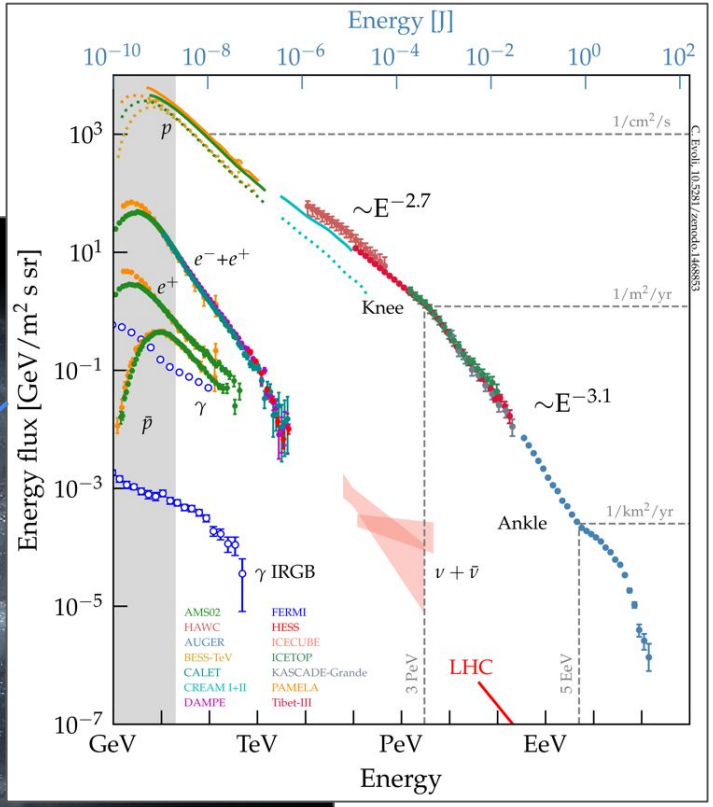
THE PARADIGM

- **isotropy** → cosmic origin;
- **composition** → confinement for ~ 10^7 yr
  → diffusion;
- $E^{-2.7}$ → acceleration (E^{-2} – $^{-2.3}$)
  + propagation ($E^{-0.4}$– $^{-0.6}$)
- **"knee" at ~10^{15} eV** (1 PeV) → galactic origin
- ρ **= 1 eV cm^{-3}** → powered by SNRs

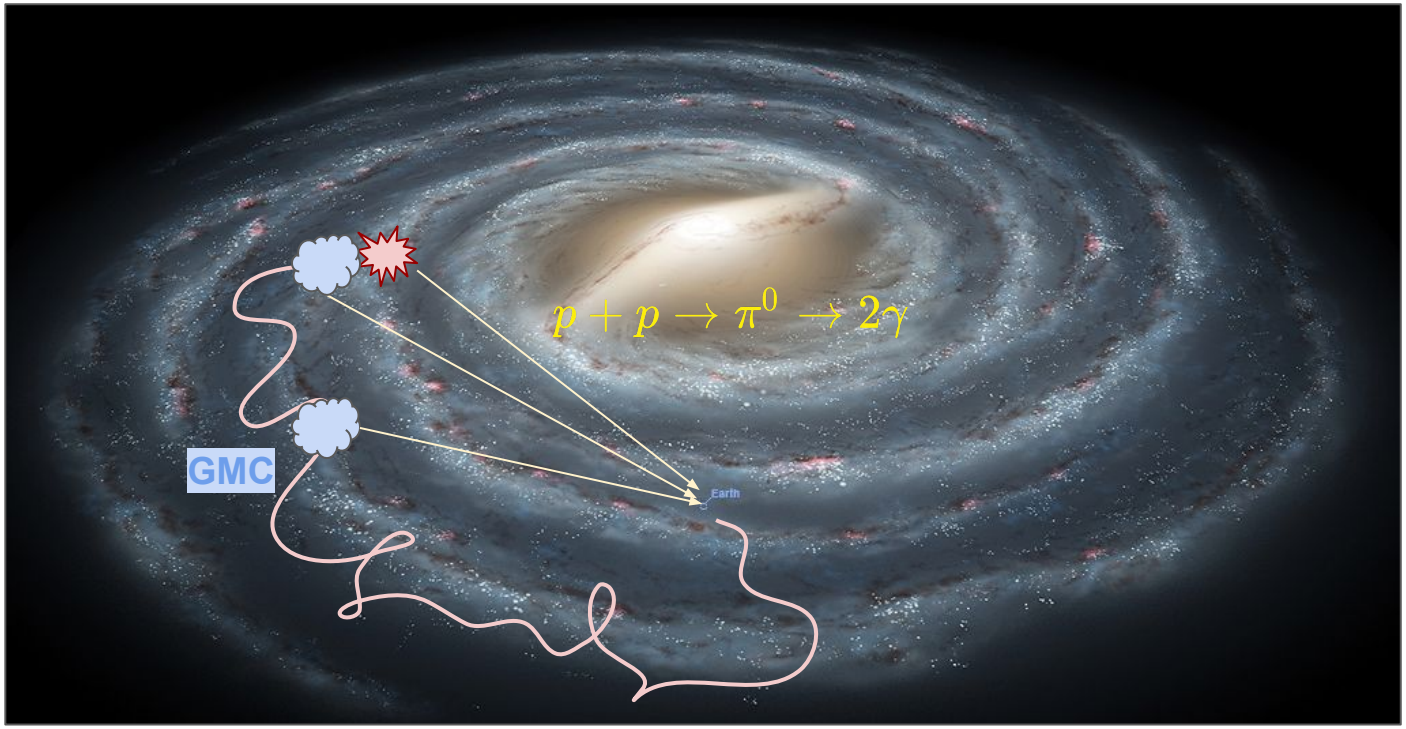


Local Cosmic rays

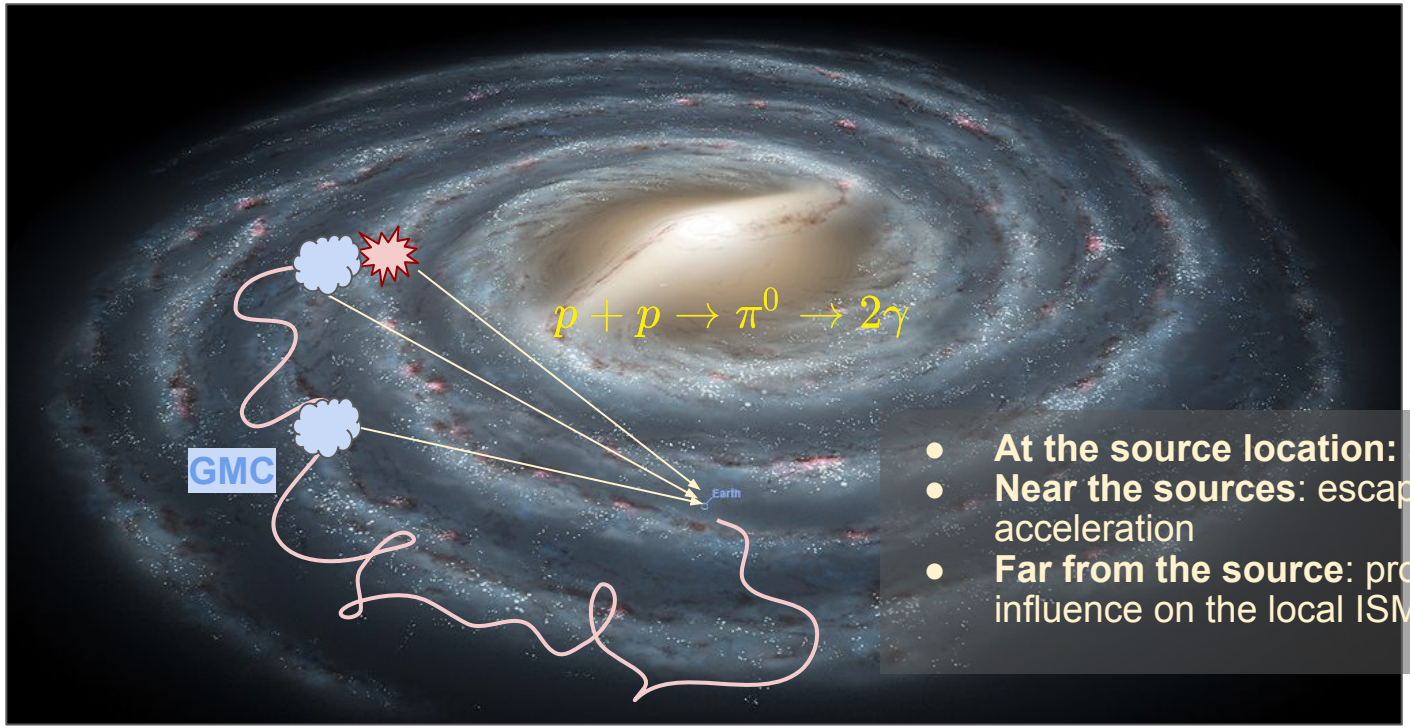




Galactic Cosmic rays

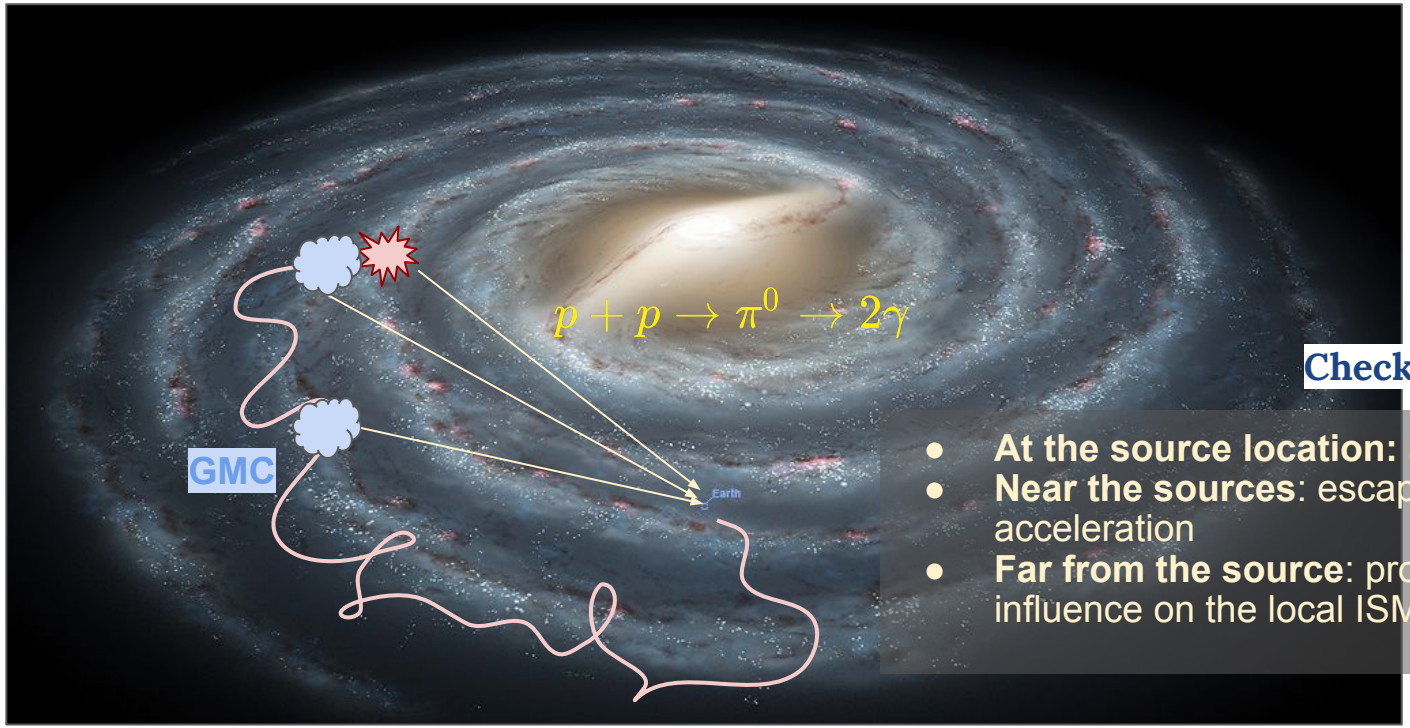


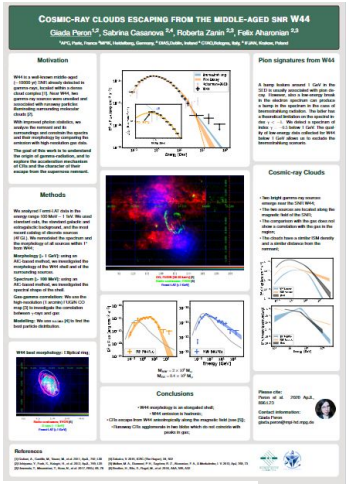
Galactic Cosmic rays



- **At the source location:** acceleration
- **Near the sources**: escape and former acceleration
- **Far from the source**: propagation + influence on the local ISM

Galactic Cosmic rays




COSMIC-RAY CLOUDS ESCAPING FROM THE MIDDLE-AGED SNR W44

Giada Peron[1,2], Sabrina Casanova[3,4], Roberta Zanin[2,3], Felix Aharonian[2,5]

Motivation

Methods

Pion signatures from W44

Cosmic-ray Clouds

Conclusions

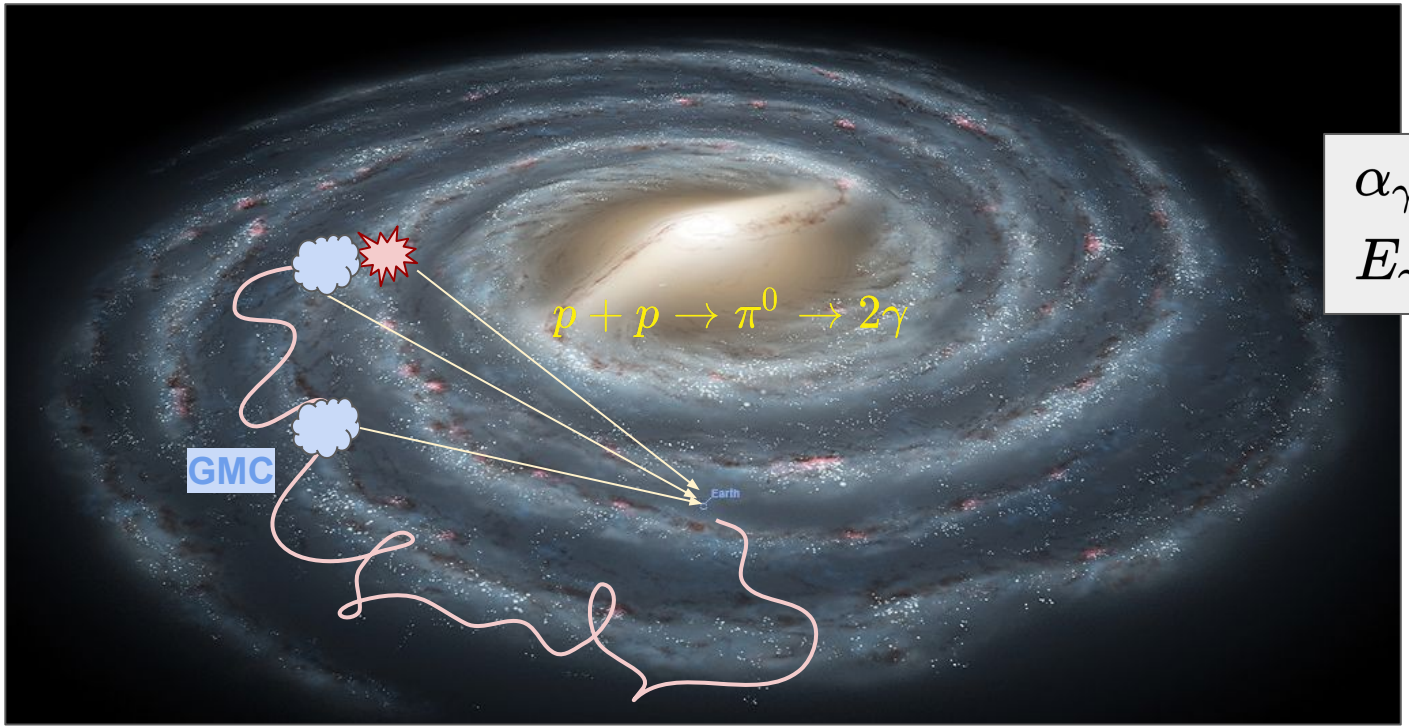
References

Check out my poster!

- **At the source location:** acceleration
- **Near the sources**: escape and former acceleration
- **Far from the source**: propagation + influence on the local ISM

Galactic Cosmic rays

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



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

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

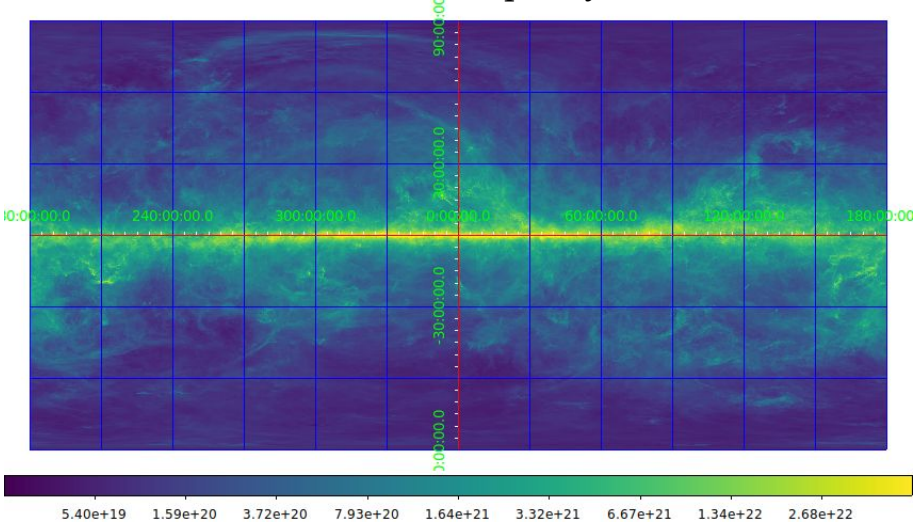
Cosmic rays *far* from sources

Diffuse gas

$n_H \sim 1\ cm^{-3}$
$R > kpc$

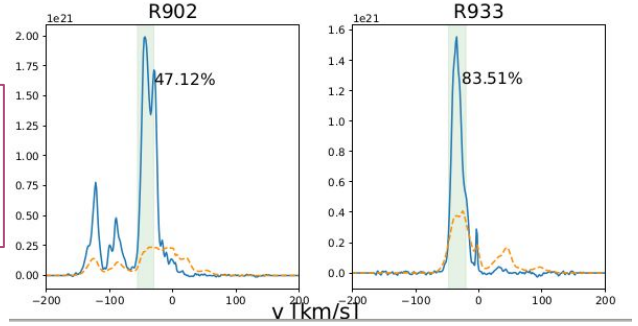
Traced by

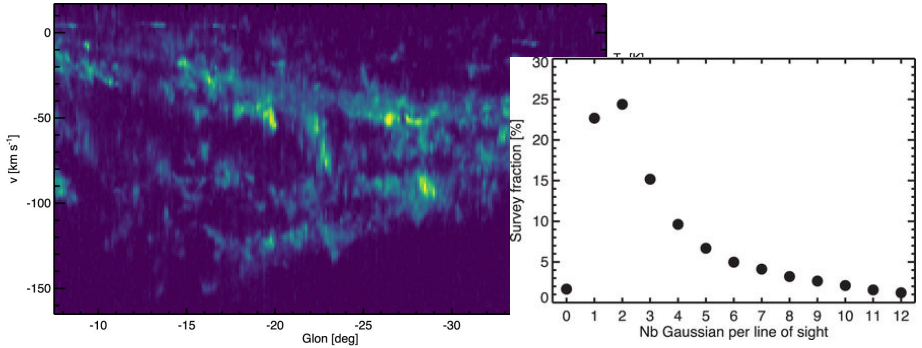
- molecular and atomic lines (e.g. CO and HI)
- dust opacity



Molecular Clouds

$n_H \sim 1000\ cm^{-3}$
$R \sim 10\text{-}100\ pc$

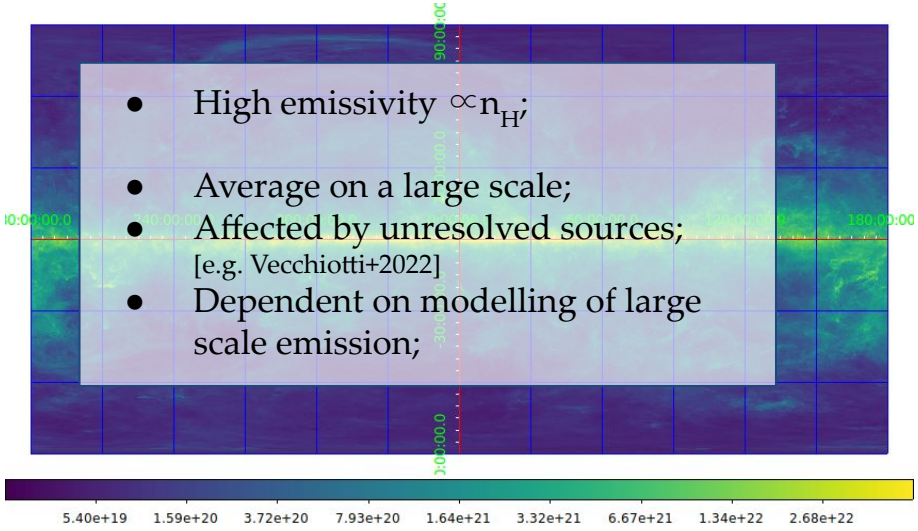




Cosmic rays *far* from sources

Diffuse gas

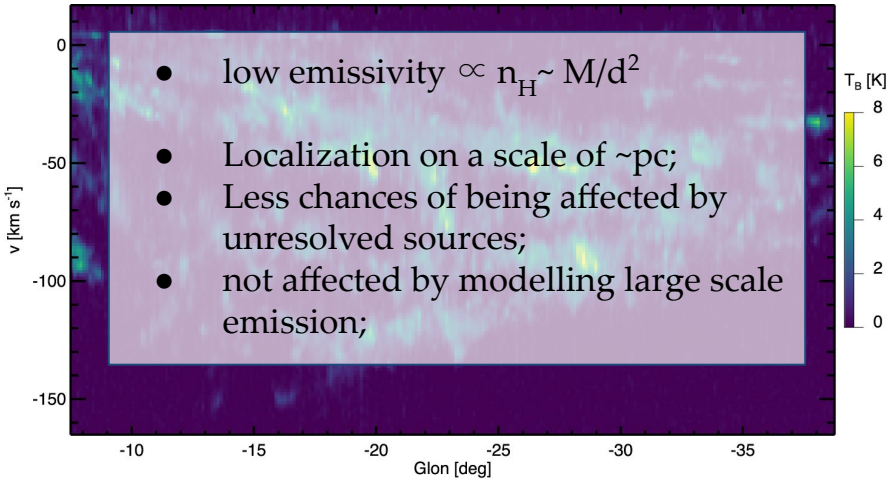
[Acero+2016, Yang+2016, Pothast+2018]



- High emissivity $\propto n_H$;
- Average on a large scale;
- Affected by unresolved sources; [e.g. Vecchiotti+2022]
- Dependent on modelling of large scale emission;

Molecular Clouds

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

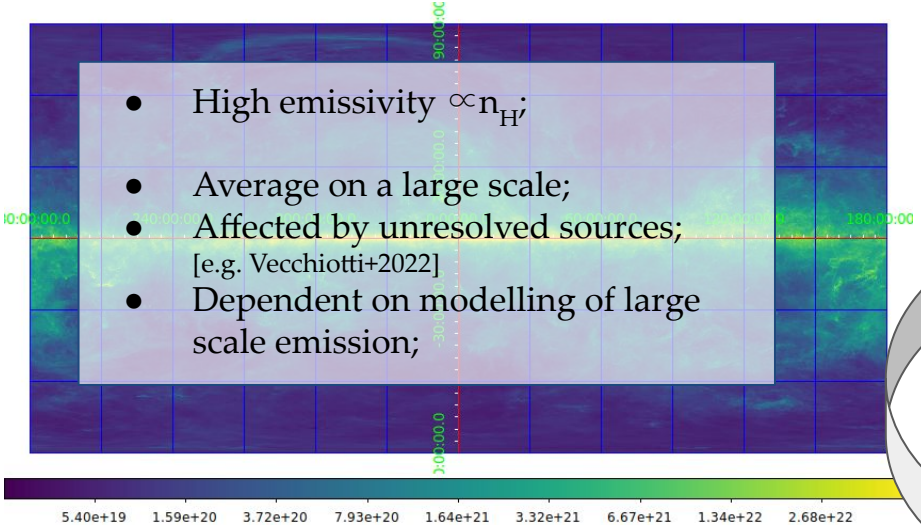


- low emissivity $\propto n_H \sim M/d^2$
- Localization on a scale of ~pc;
- Less chances of being affected by unresolved sources;
- not affected by modelling large scale emission;

Cosmic rays *far* from sources

Diffuse gas

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



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Molecular Clouds

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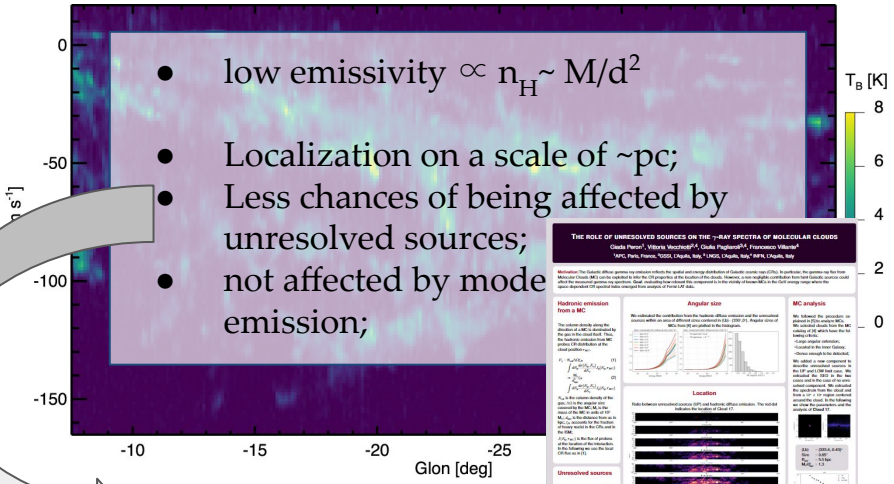


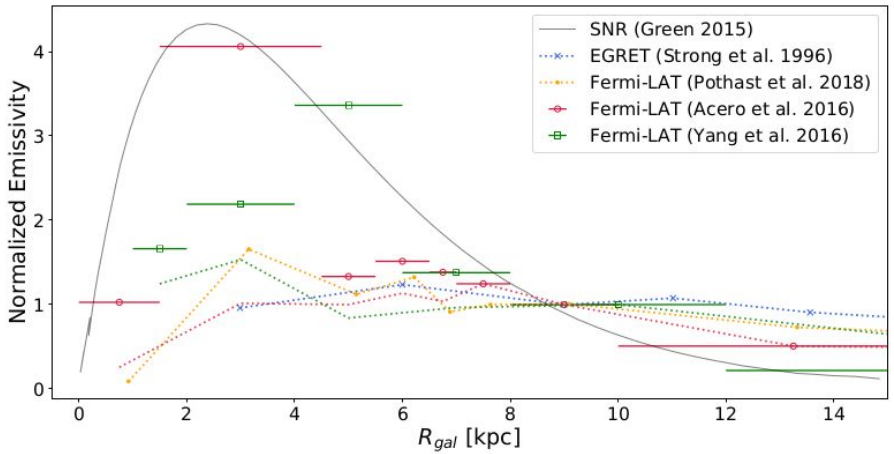
- low emissivity $\propto n_H \sim M/d^2$
- Localization on a scale of ~pc;
- Less chances of being affected by unresolved sources;
- not affected by mode emission;

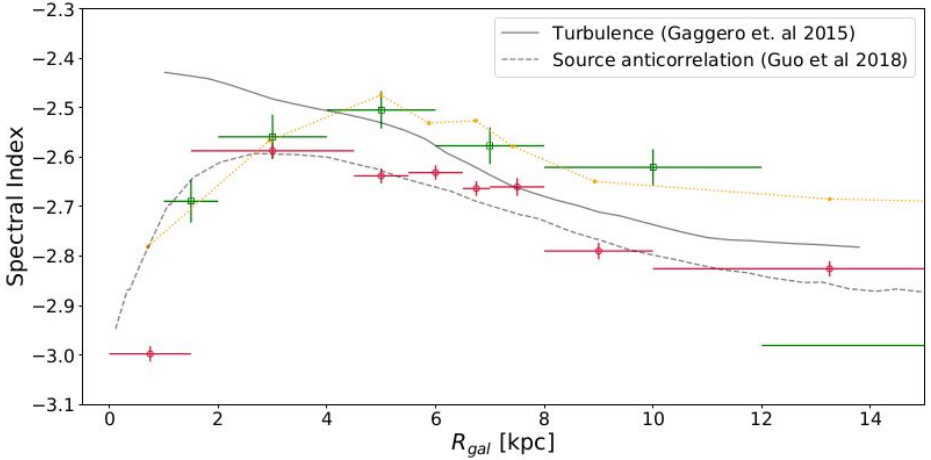
Check out our poster!

Cosmic rays from diffuse gas

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

Diffuse gas @ GeV energies



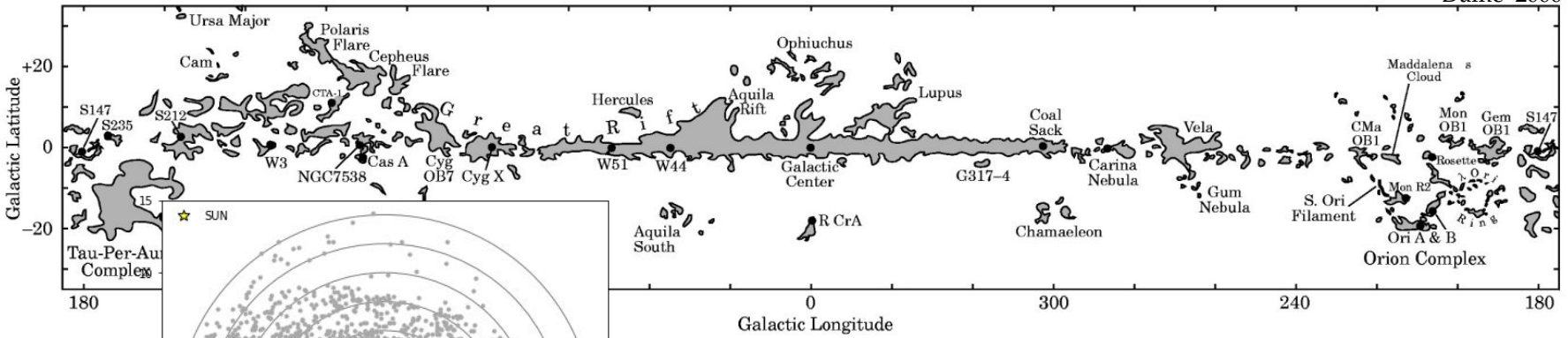


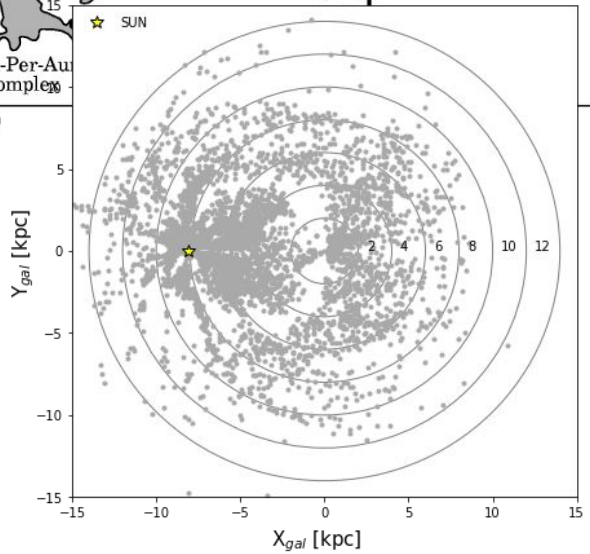
Enhancement and hardening towards the GC

- is this a global effect? (e.g. due to propagation)
- is this a local effect? (e.g. due to sources)
- is the contamination of unresolved sources? [see Vecchiotti et al. 2022]

Molecular clouds in the Milky Way

Dame+2000



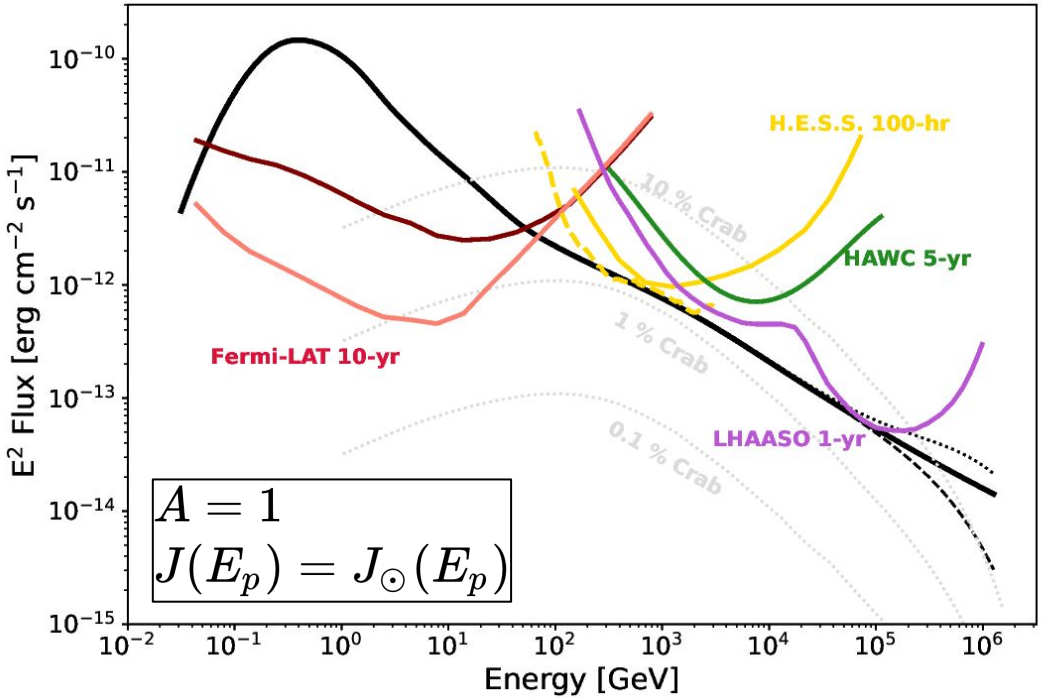


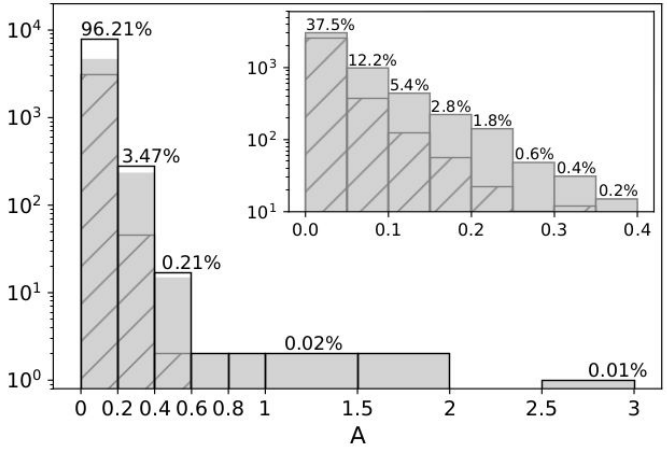
> 8000 MCs identified in the MW by Miville-Deschenes+2016

Molecular clouds detection

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

$$A \equiv \frac{M_5}{d_{kpc}^2} = 8 \times 10^{-20} \int n_H d\Omega$$





Peron & Aharonian 2022

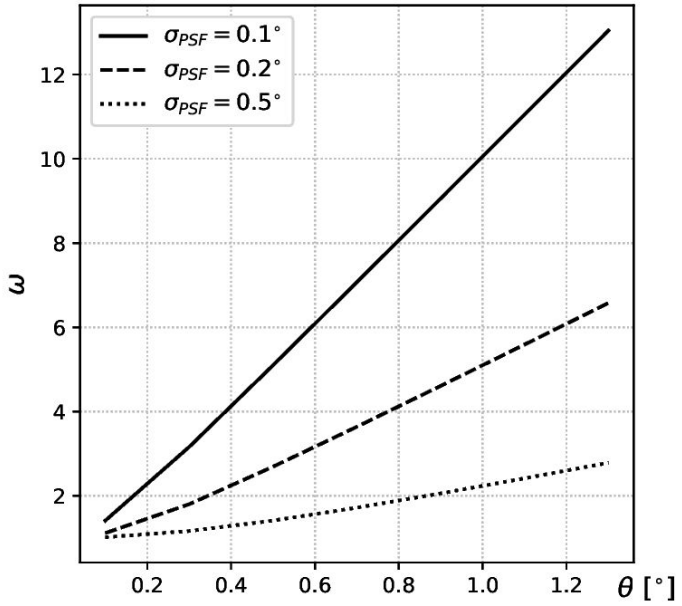
Molecular clouds detection

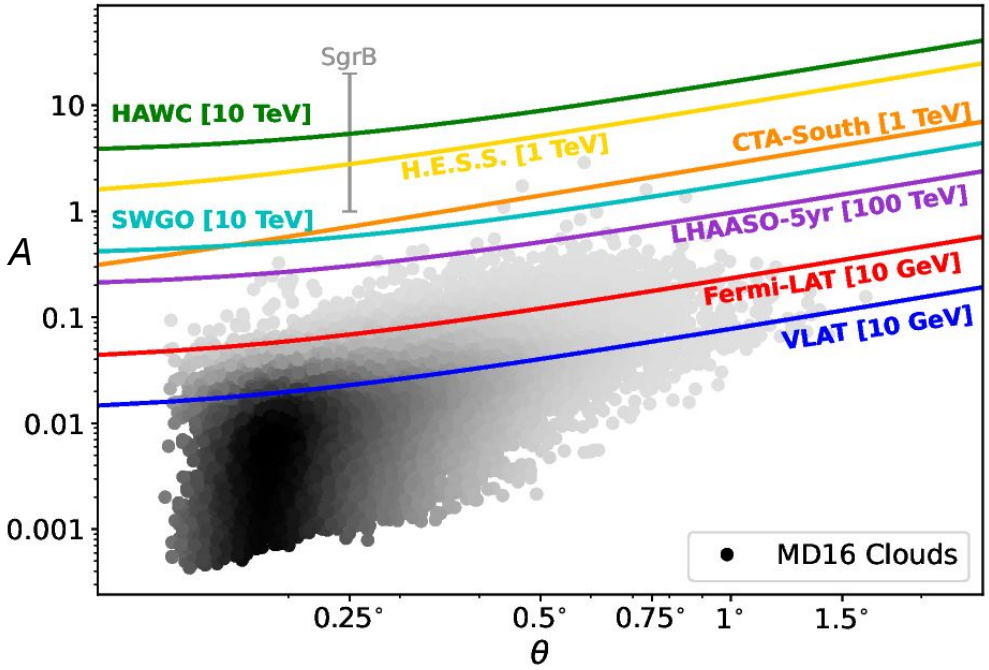
VLAT = Very Large area telescope, an hypothetical extension of Fermi-LAT by a factor of 3. [Peron & Aharonian 2022]

Clouds are extended…

$$\omega \propto \frac{\sqrt{\sigma_{PSF}^2+\theta^2}}{\sigma_{PSF}}$$

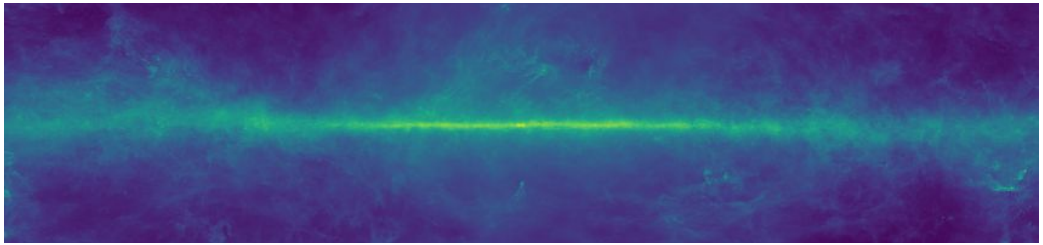
→ approximate worsening in the sensitivity





Peron & Aharonian 2022

Analysis of sources



@ GeV energies Fermi-LAT

TEMPLATE FITTING

Galactic diffuse emission:

- **Pion decay** produced by interaction of CR nuclei with interstellar gas;
- **Inverse Compton** produced by interaction of CR electrons with radiation fields (CMB, IR);

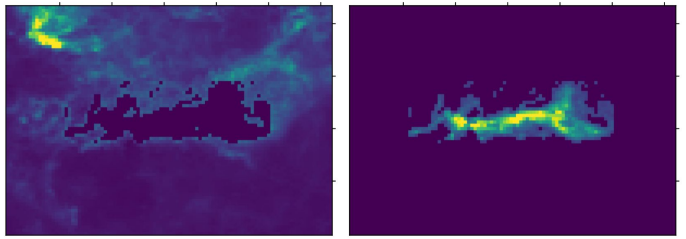
Extragalactic isotropic emission

- Contributed by extragalactic sources;

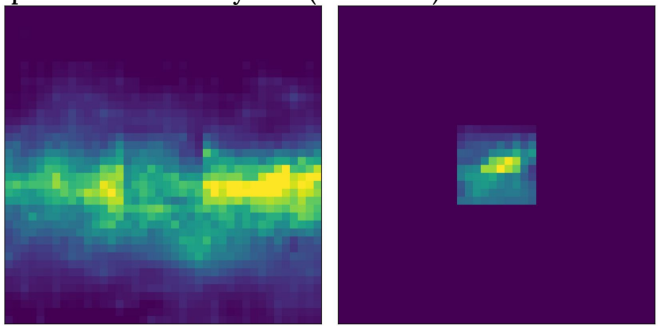
Discrete sources

- e.g. 4FGL catalog;

Space-cut (e.g. from dust)

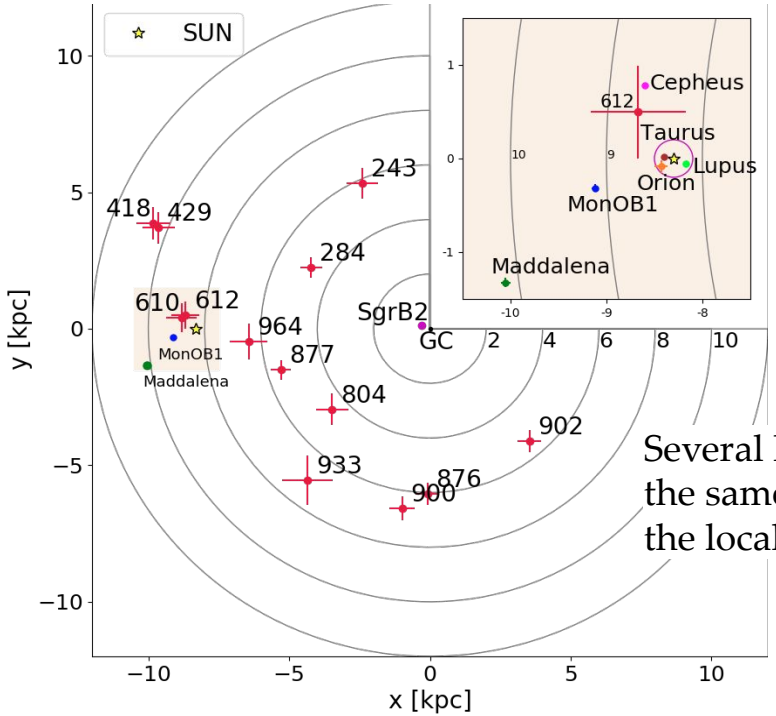


Space and velocity cut (from CO)

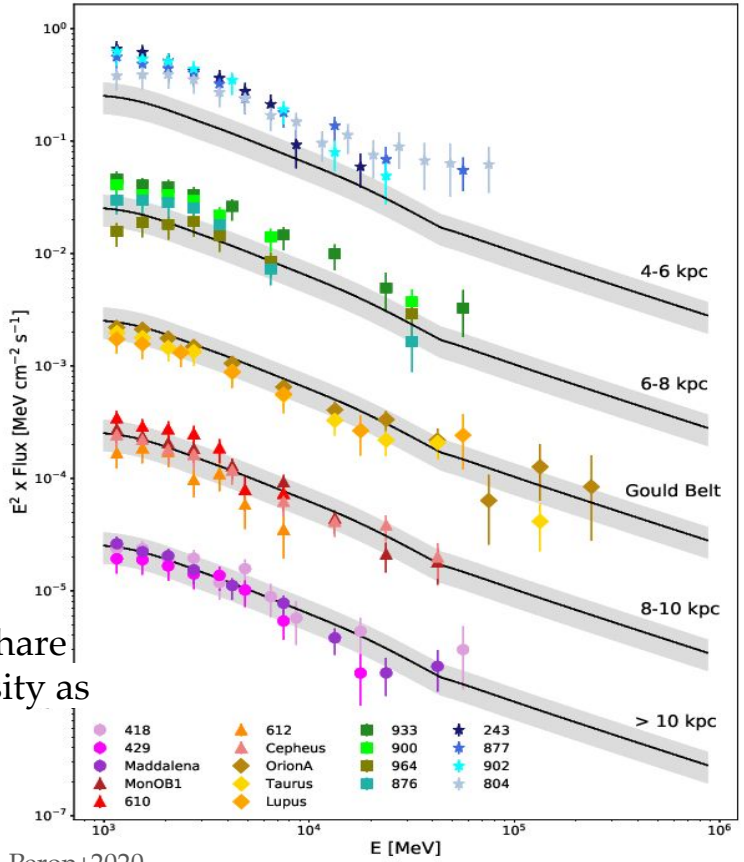


Cosmic rays from GMCs

GMCs @ GeV energies



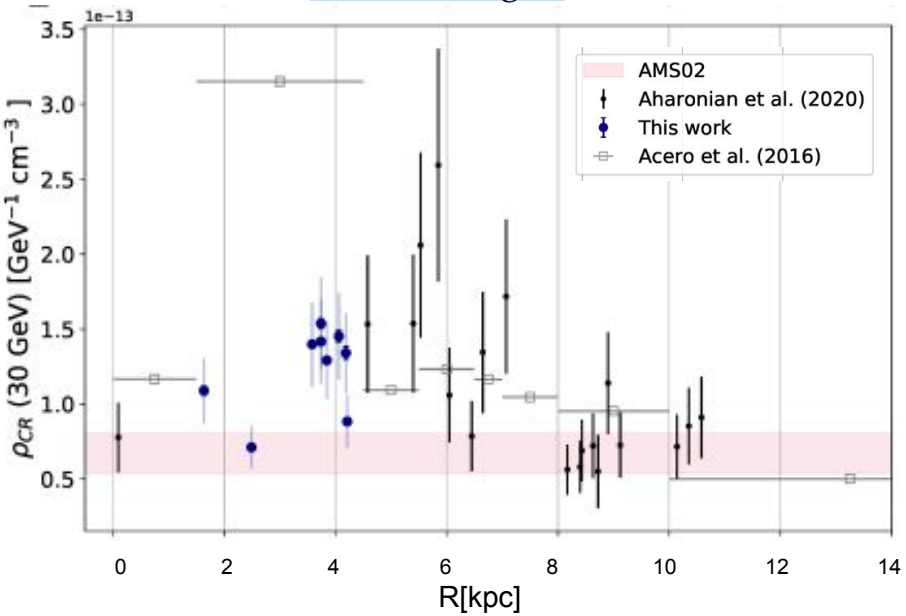
Several location share the same CR density as the local one.

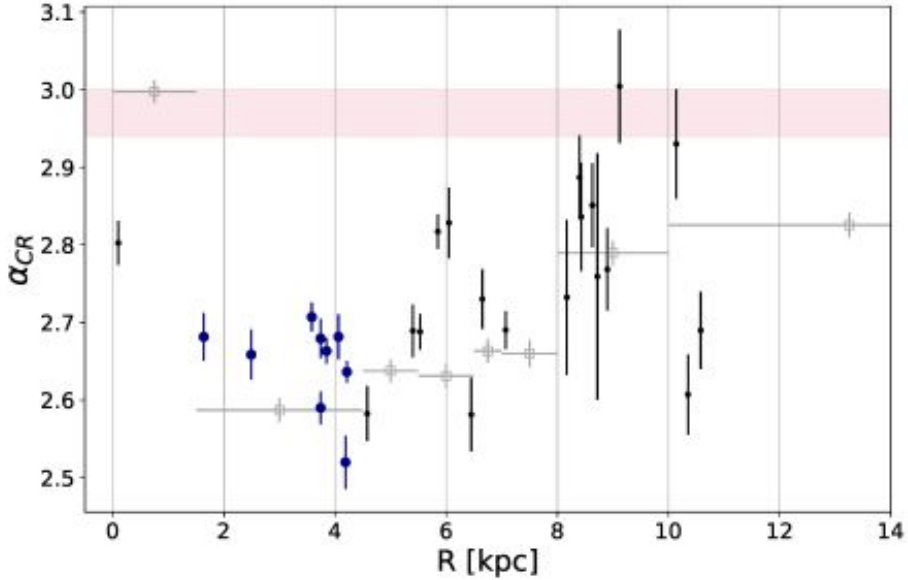


Aharonian,Peron+2020

Cosmic rays from GMCs vs diffuse

@ GeV energies

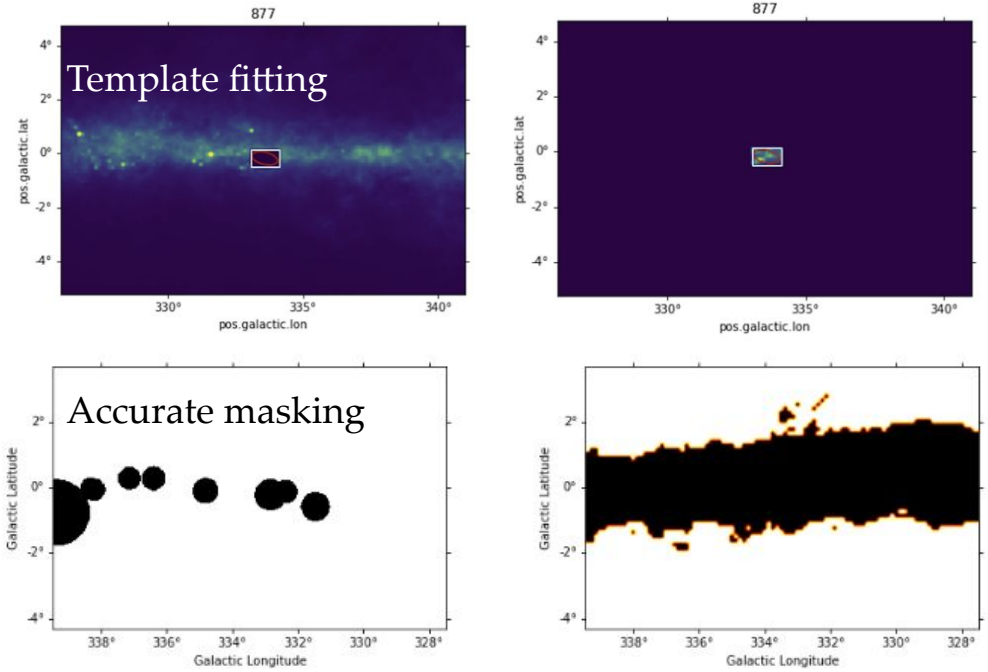




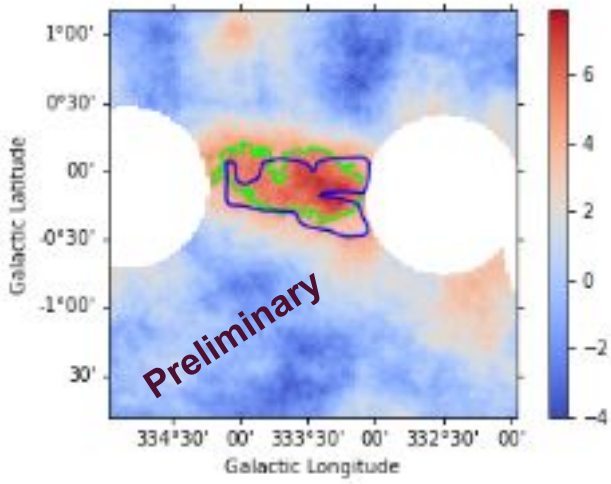
Peron+2021

Cosmic rays from GMCs

GMCs @ TeV energies

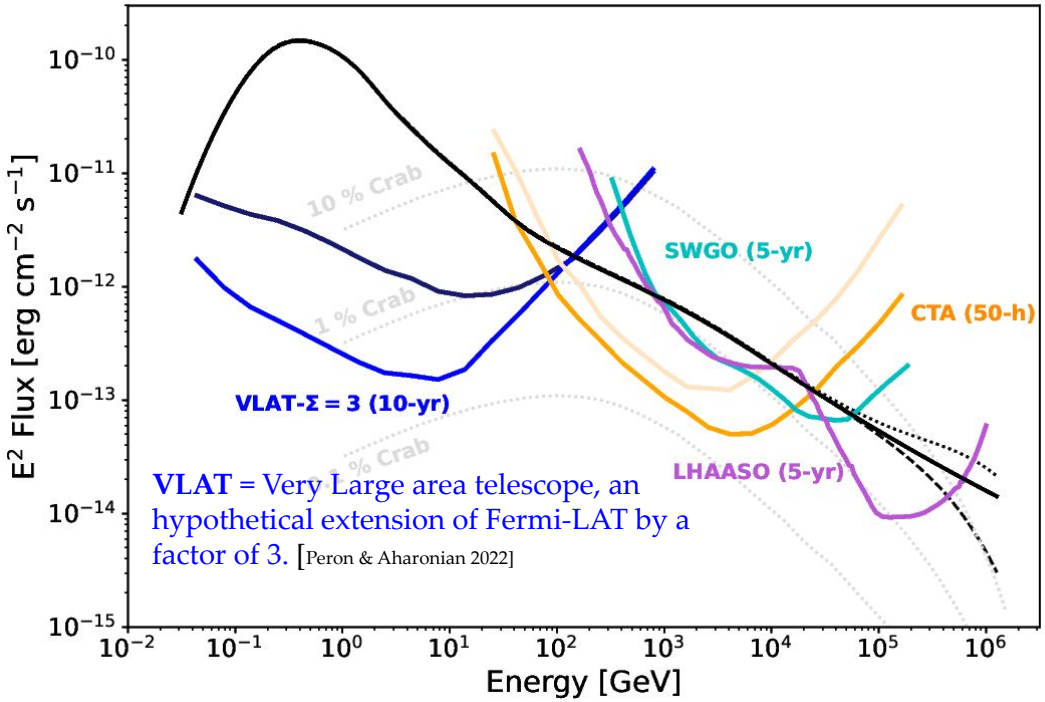


Sinha+2021



Successful detection of passive cloud at TeV energies with H.E.S.S.

The prospects for the future



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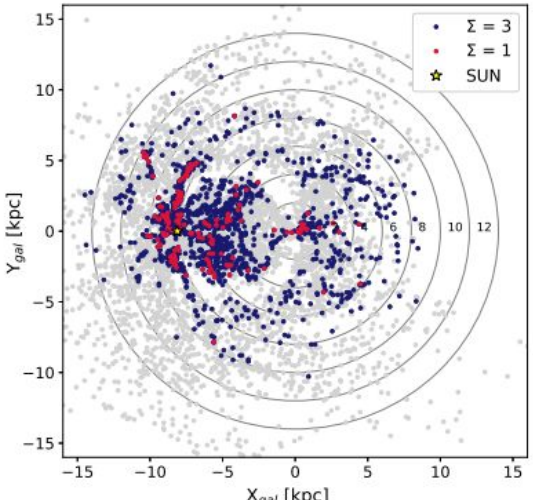
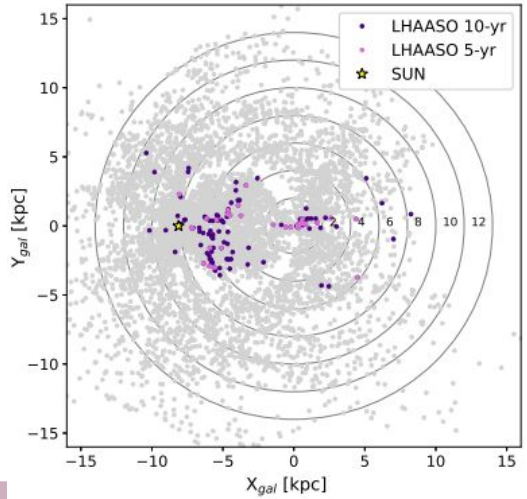
Peron & Aharonian+2022





Summary

- Cosmic rays are an important component of the Milky Way and regulates several astrophysical processes;
- Their spatial and spectral distribution can be traced by mean of gamma-ray observations;
- Analysis of the large scale diffuse emission is biased by the presence of unresolved sources and does not allow localization;
- Molecular Clouds allow localization and an unbiased determination of the level of CRs;
- Special analysis techniques are needed in order to account for faint extended emission;
- Analysis technique is showing the first results, will be improved for future instruments;

THANK YOU!