MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Ultra High Energy ɣ-ray emission from Giant Molecular Clouds

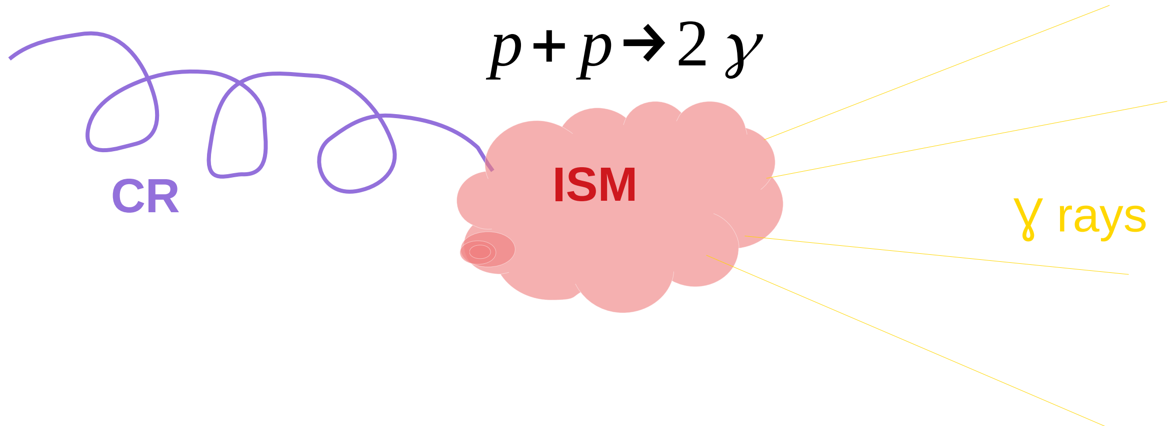
Giada Peron

Outline

- Gamma-ray emissivity from MCs
- Visibility and results at low energies (Fermi-LAT)
- Potential of LHAASO

Gamma-rays from Molecular Clouds

$$p + p \rightarrow 2\gamma$$



$$F_\gamma = \frac{dN}{dE\,dA\,dt} = \xi_N \int \frac{dV\,n}{4\pi d^2} \int dE_p \frac{d\sigma_{pp\rightarrow\gamma}}{dE_p} J(E_p)$$ *flux measured at Earth*

$$= \xi_N \int N_{col}\, d\theta \int dE_p \frac{d\sigma_{pp\rightarrow\gamma}}{dE_p} J(E_p)$$

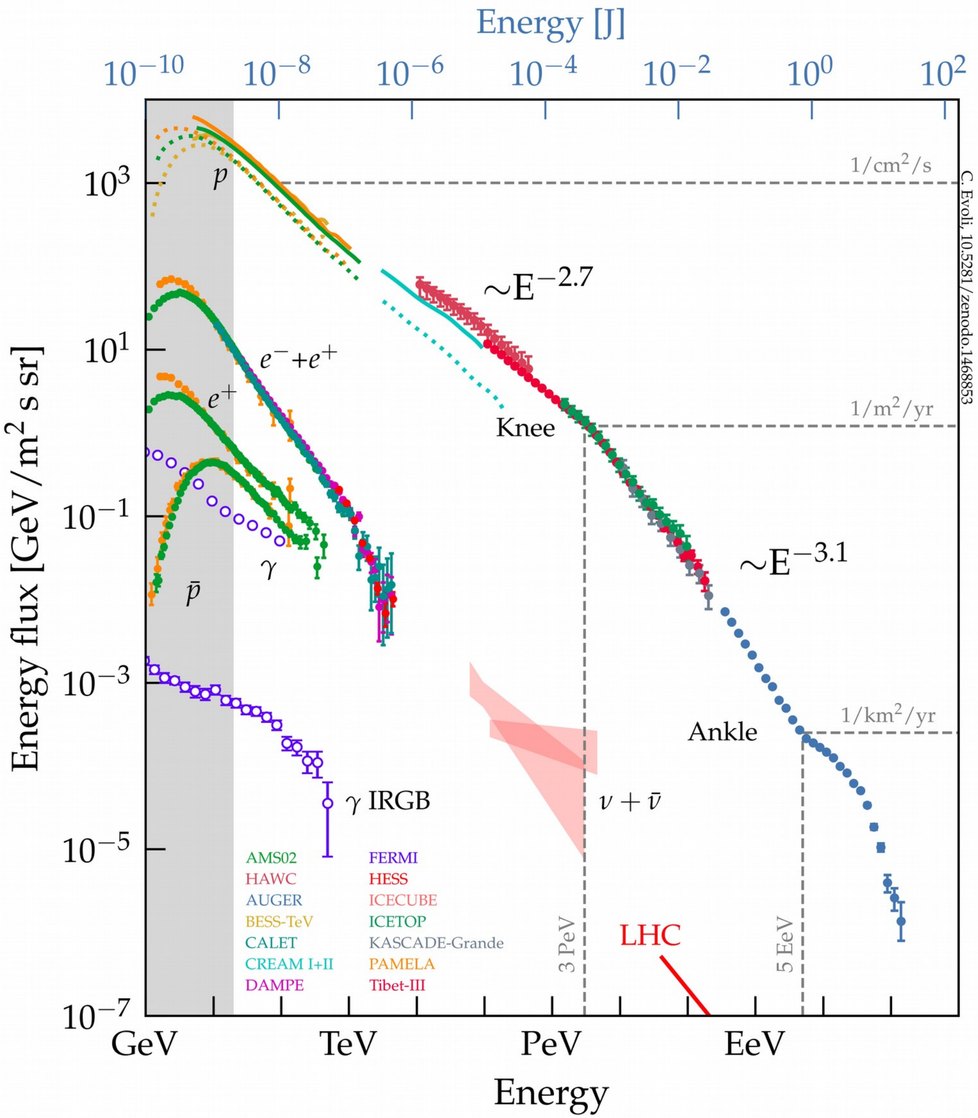
Fraction of heavier nuclei (ξ_N)

Density of the target (N_{col})

Distribution of CR ($J(E_p)$)

Cosmic Ray spectrum

$$F_{\gamma} = \xi_N \int N_{col}\, d\theta \int dE_p \frac{d\sigma_{pp\rightarrow\gamma}}{dE_p} J(E_p)$$



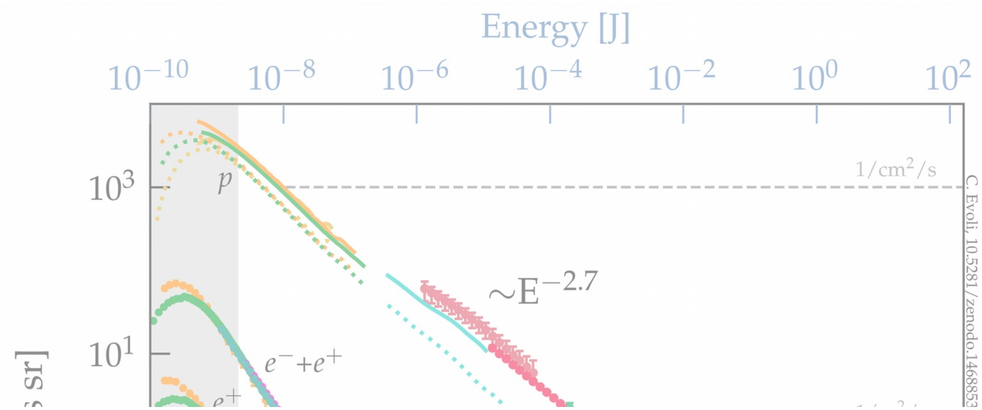
Local spectrum:

~ $E^{-2.7}$ Power Law

several sub features (knee,ankle,…)

Cosmic Ray spectrum

$$F_\gamma = \xi_N \int N_{col}\, d\theta \int dE_p \frac{d\sigma_{pp\to\gamma}}{dE_p} J(E_p)$$



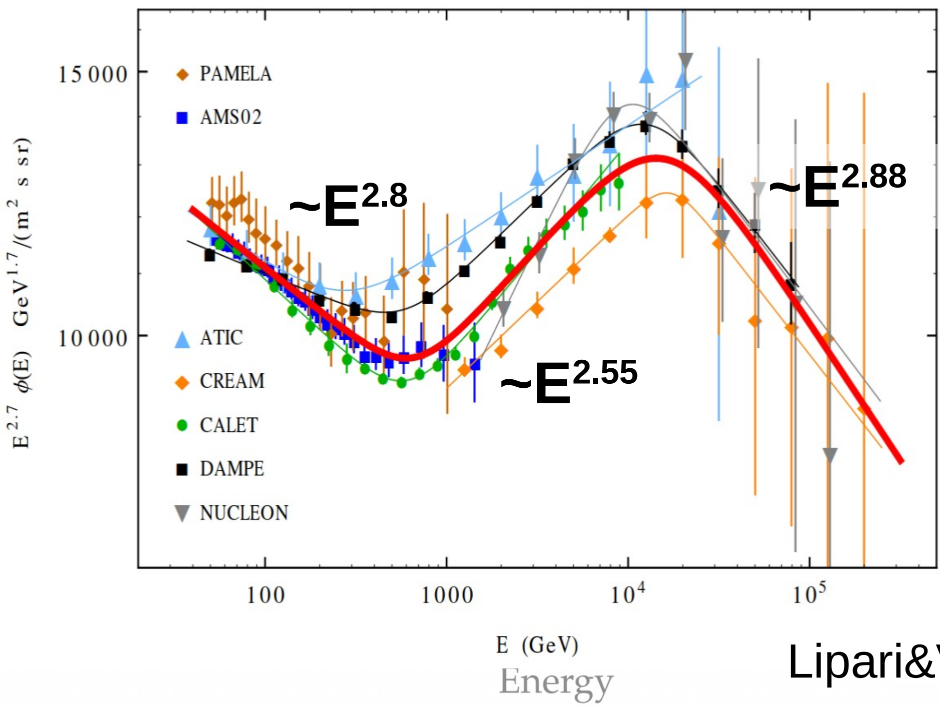
Local spectrum:

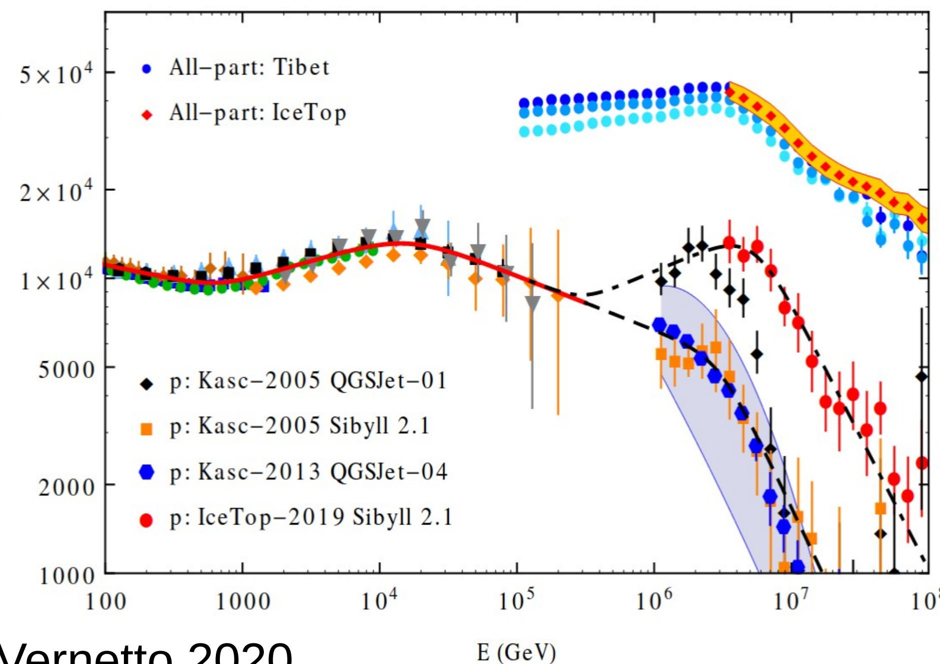
~ $E^{-2.7}$ Power Law

several sub features: knee,ankle,…

…several breaks

disagreement at PeV energies



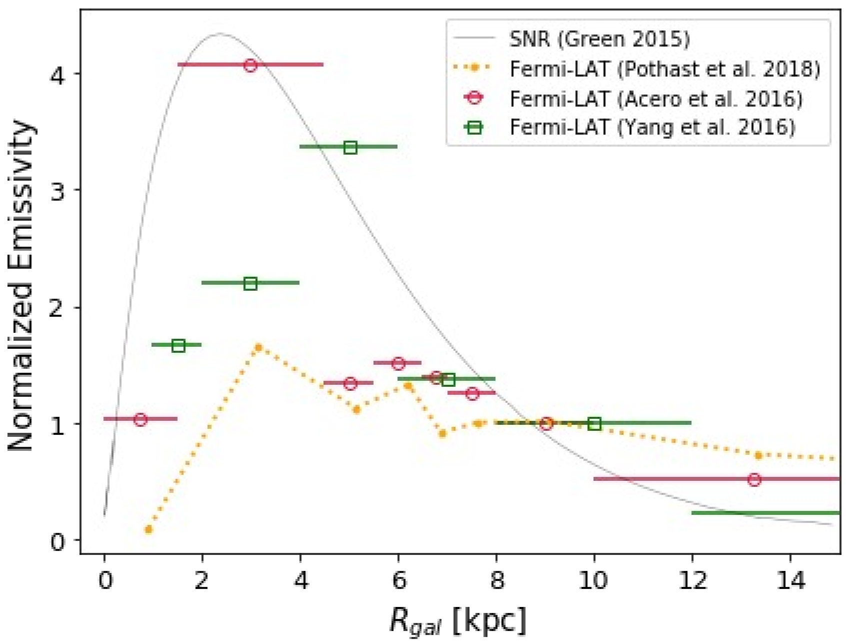


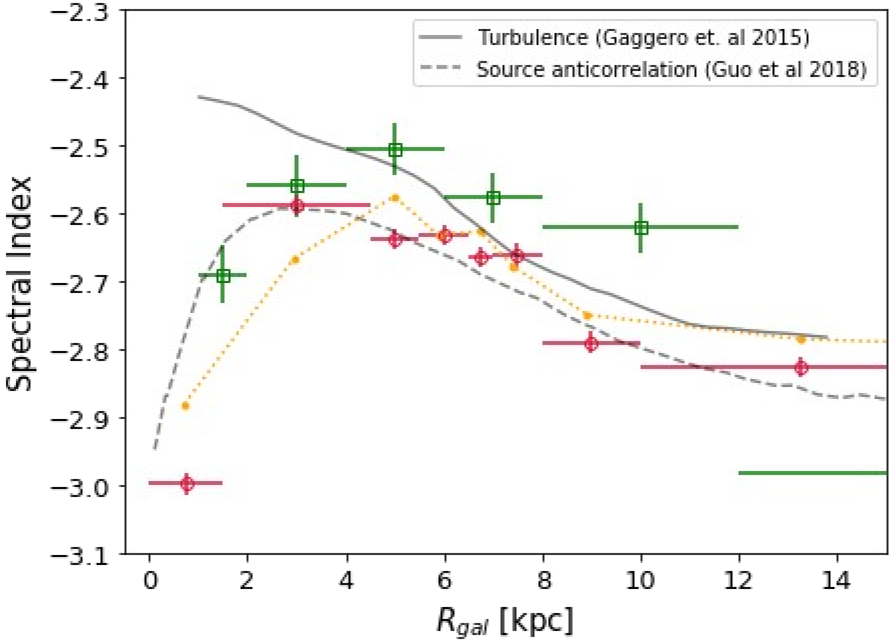
Lipari&Vernetto 2020

Cosmic Ray spectrum

$$F_\gamma = \xi_N \int N_{col}\, d\theta \int dE_p \frac{d\sigma_{pp\to\gamma}}{dE_p} J(E_p)$$

Galactic spectrum:
Enhanced and harder towards the galactic center





The target: diffuse medium

$$F_\gamma = \xi_N \int N_{col}\, d\theta \int dE_p \frac{d\sigma_{pp\rightarrow\gamma}}{dE_p} J(E_p)$$

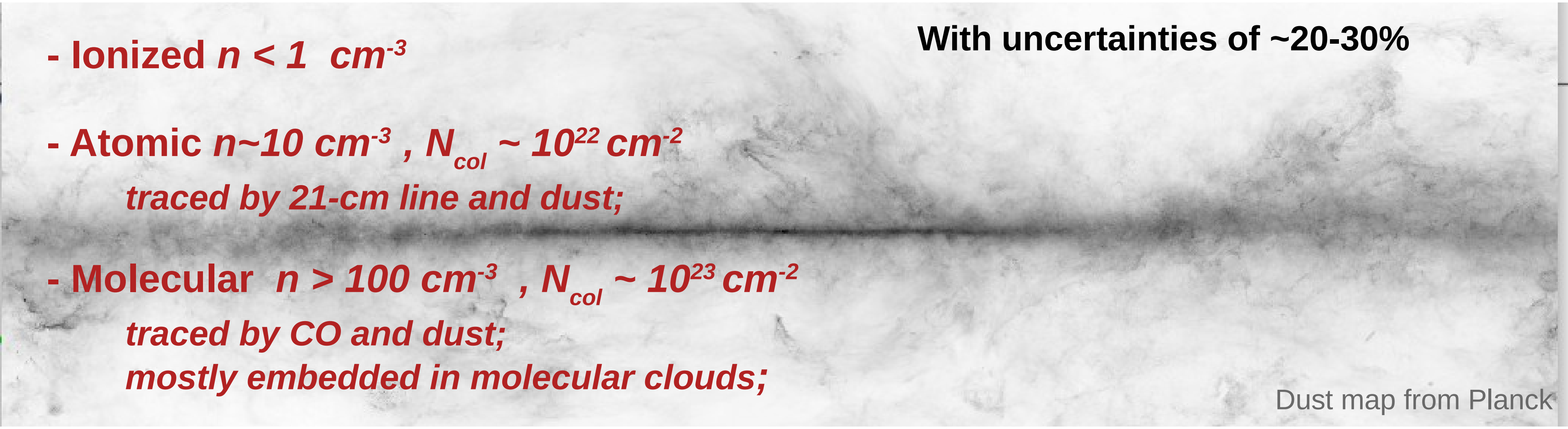
$$N_{lb,col} = X_{tracer} \int dv\, T^B_{lb}(v)_{tracer}$$

With uncertainties of ~20-30%

- **Ionized** ***$n < 1$ cm^{-3}***

- **Atomic** ***n~10 cm^{-3} , N_{col} ~ 10^{22} cm^{-2}***
  traced by 21-cm line and dust;

- **Molecular** ***$n > 100$ cm^{-3} , N_{col} ~ 10^{23} cm^{-2}***
  traced by CO and dust;
  mostly embedded in molecular clouds;



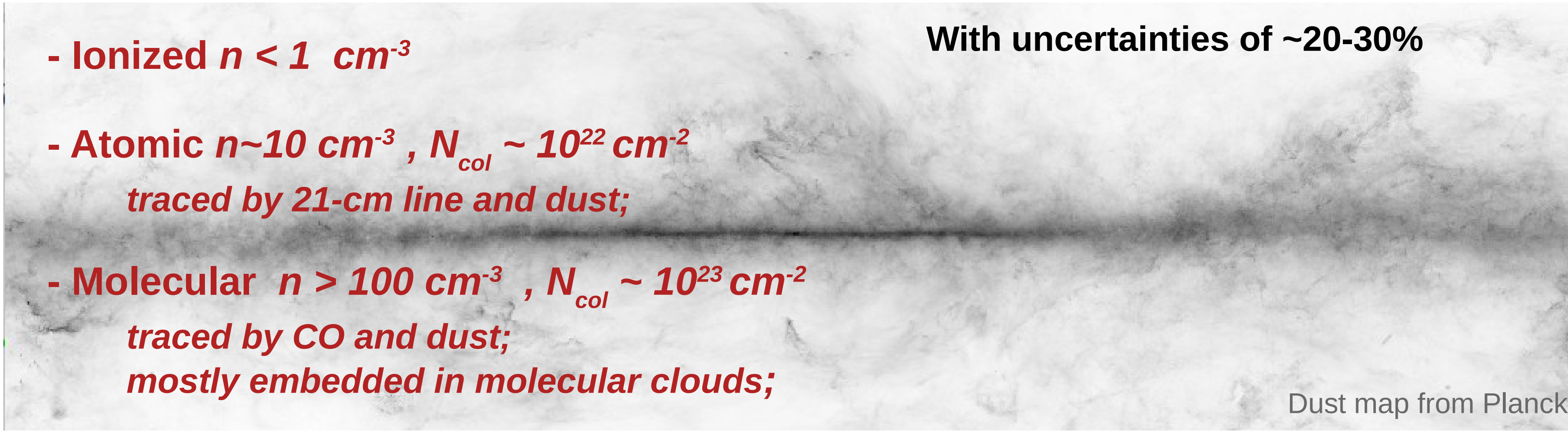
Dust map from Planck

The target: diffuse medium

$$F_{\gamma}=\xi_N \int N_{col}\, d\theta \int dE_p \frac{d\sigma_{pp\rightarrow\gamma}}{dE_p} J(E_p)$$

$$N_{lb,col}=X_{tracer}\int dv\, T^{B}_{lb}(v)_{tracer}$$

With uncertainties of ~20-30%



- Ionized *$n < 1$ cm^{-3}*

- Atomic *$n \sim 10$ cm^{-3} , $N_{col} \sim 10^{22}$ cm^{-2}*

  traced by 21-cm line and dust;

- Molecular *$n > 100$ cm^{-3} , $N_{col} \sim 10^{23}$ cm^{-2}*

  traced by CO and dust;

  mostly embedded in molecular clouds;

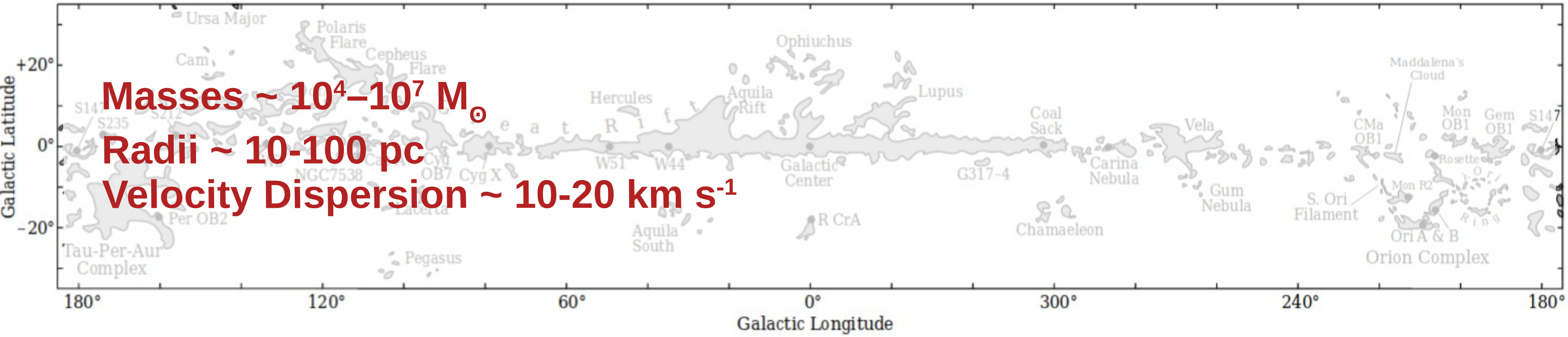
Flux from a big area:

✔ High density, high signal
✗ Only *integral* information (Wash out possible variations)
✗ Possible contamination of mis-modelled sources
✗ Dominated by most massive molecular clouds

Strong et al. 1996
Acero et al. 2016
Yang et al. 2016
Pothast et al. 2018

The target: molecular clouds

Dame et al. 2001



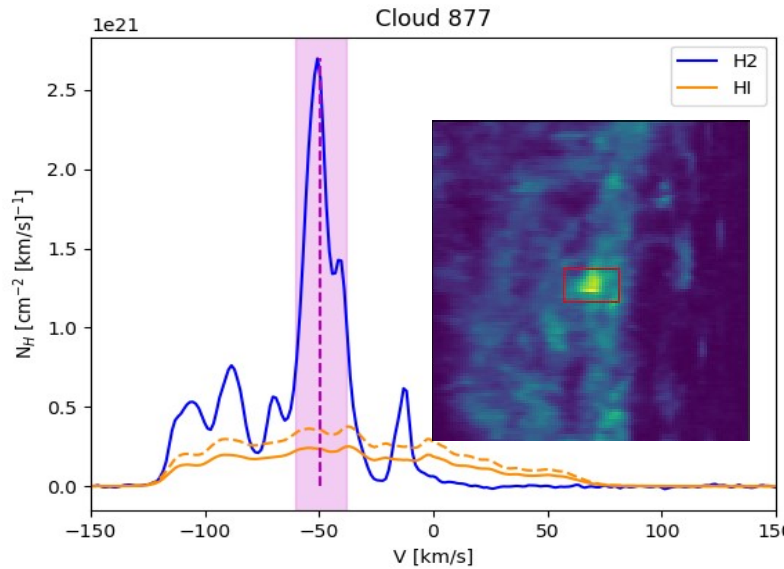
Masses ~ 10^4–10^7 $M_\odot$

Radii ~ 10-100 pc

Velocity Dispersion ~ 10-20 km s^{-1}

Flux from a small region:

- ✔ Localized, differential information
- ✔ Sensitive to fluctuations;
- ✔ Reduced contamination;
- ✗ Lower signal;



Aharonian 2001
Casanova et al. 2010
Yang et al. 2015
Neronov et al. 2017
Aharonian et al. 2020

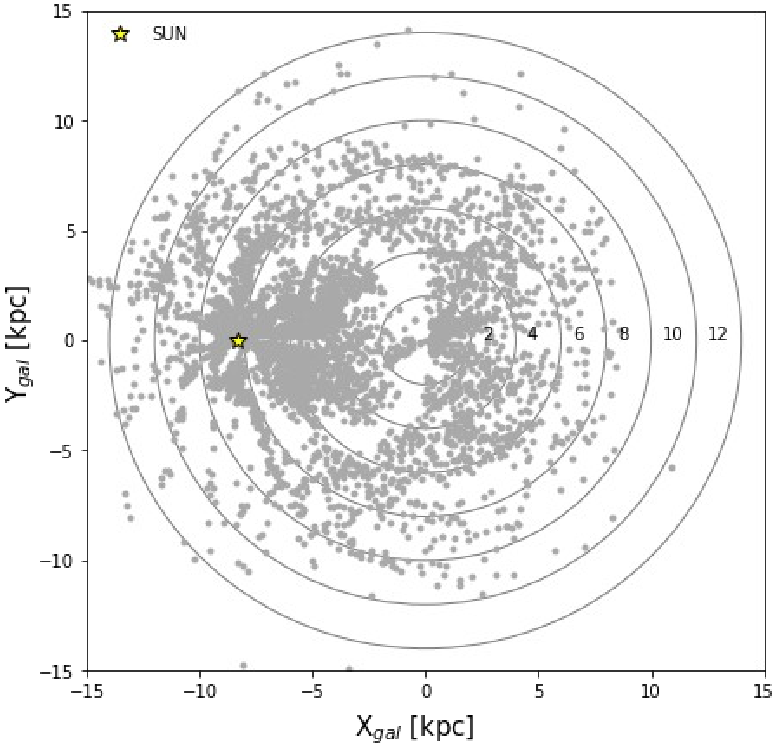
Molecular clouds in the Milky Way

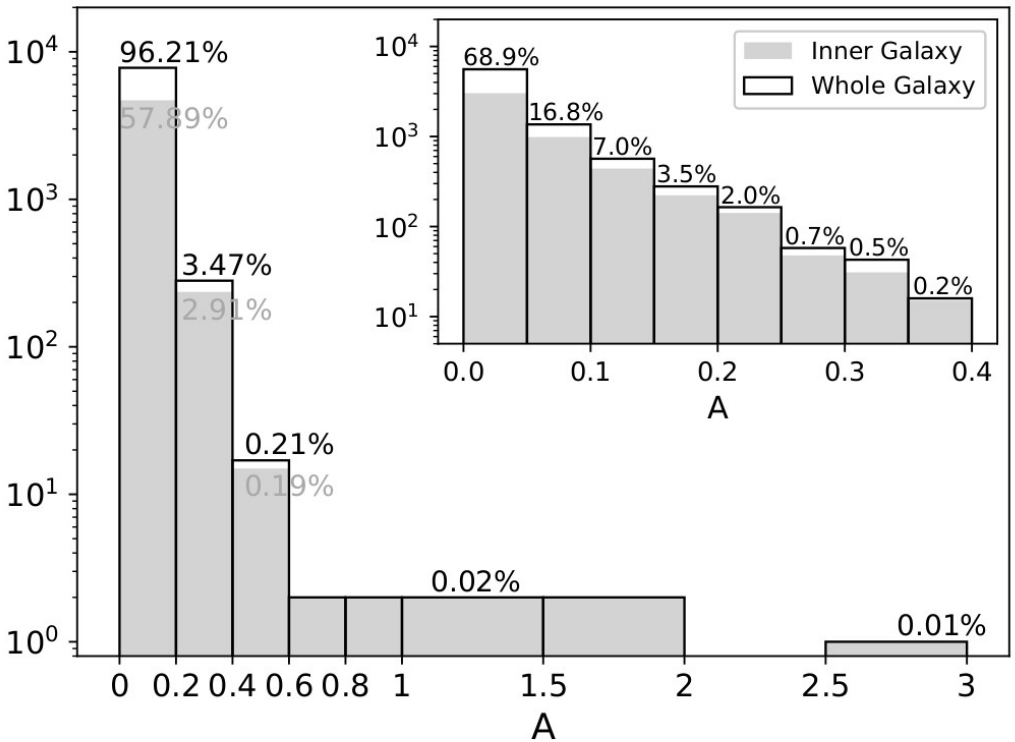
8107 MCs catalogued by ***Miville Deschenes et al. (2016)***
Correspond to 98% of all molecular medium

$$F_\gamma = \xi_N \int N_{col}\, d\theta \int dE_p \frac{d\sigma_{pp\to\gamma}}{dE_p} J(E_p) \propto A \int dE_p \frac{d\sigma_{pp\to\gamma}}{dE_p}$$

$$A = \frac{M_5}{d_{kpc}^2} \sim 8\times10^{-20} \frac{N_{col}}{cm^{-2}}\, d\theta$$

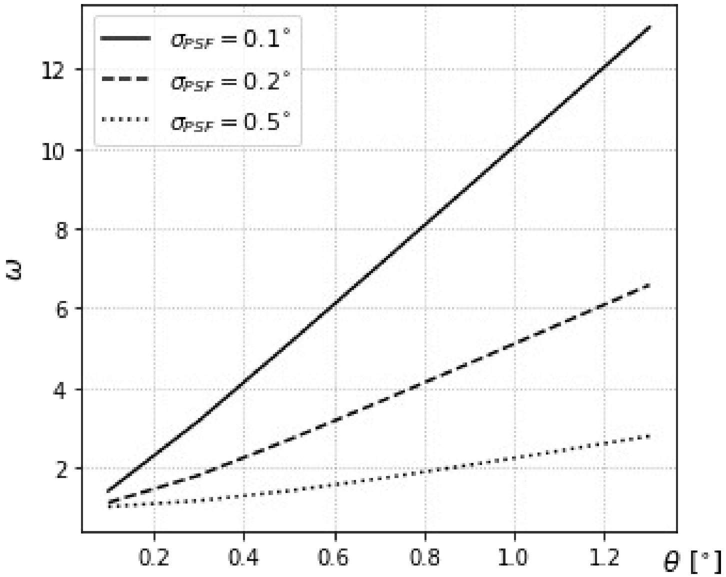
Peron & Aharonian (in prep.)

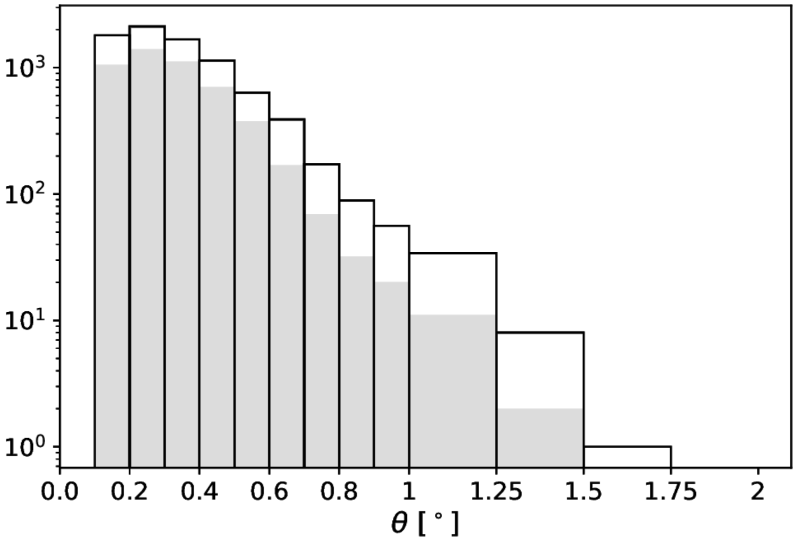


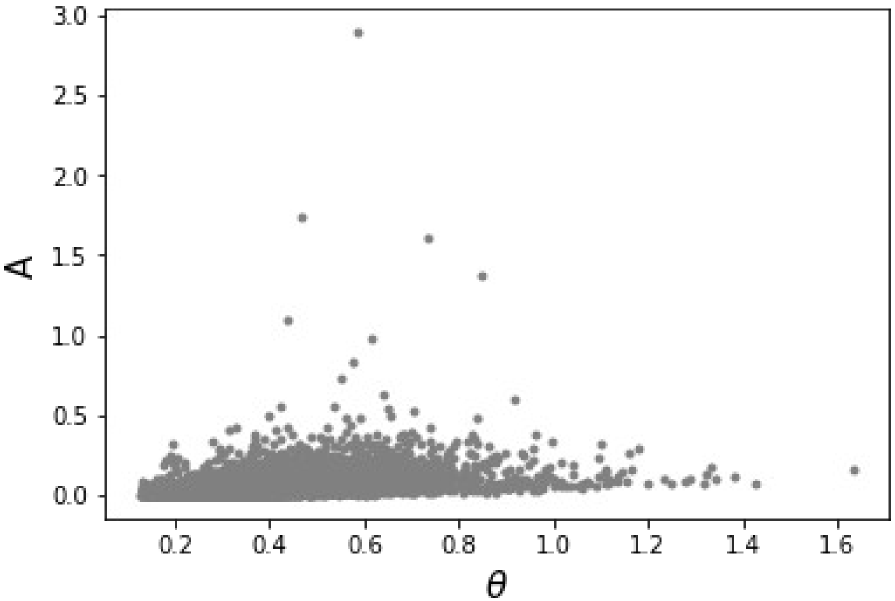


Molecular clouds: extension

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







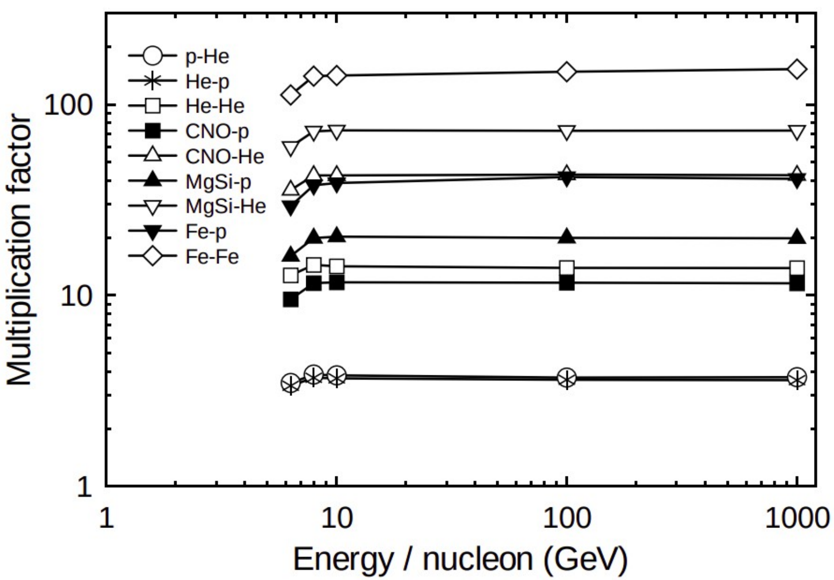
Peron & Aharonian (in prep.)

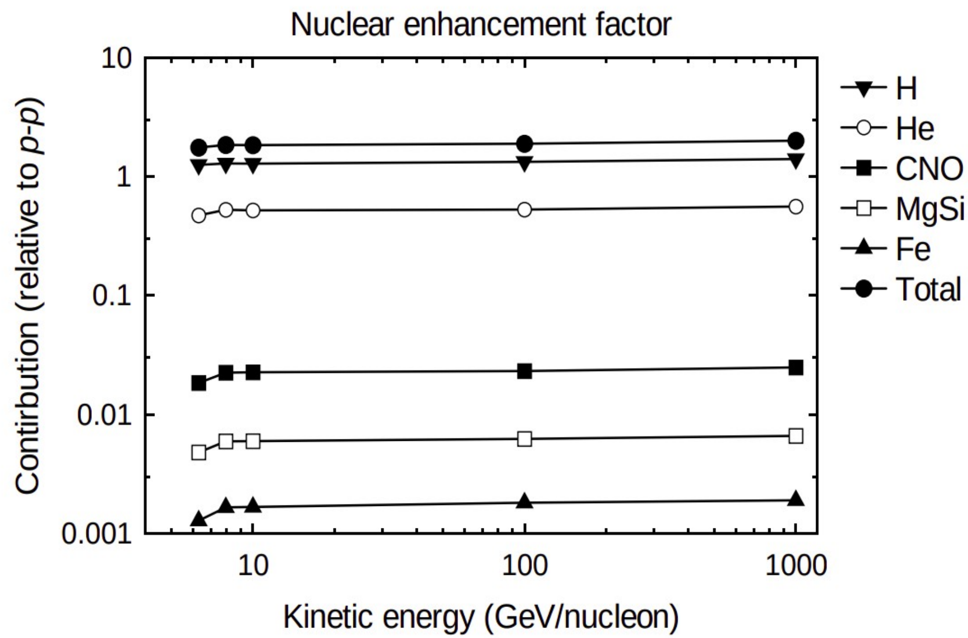
Nuclear enhancement factor

$$F_\gamma = \xi_N \int N_{col}\, d\theta \int dE_p \frac{d\sigma_{pp\rightarrow\gamma}}{dE_p} J(E_p)$$

$$\xi_N = \sum m_{ip} \frac{J_i(E_i)}{J_p(E_p)} + \sum m_{i\alpha} \frac{J_i(E_i)}{J_p(E_p)} \frac{r}{1-r}$$

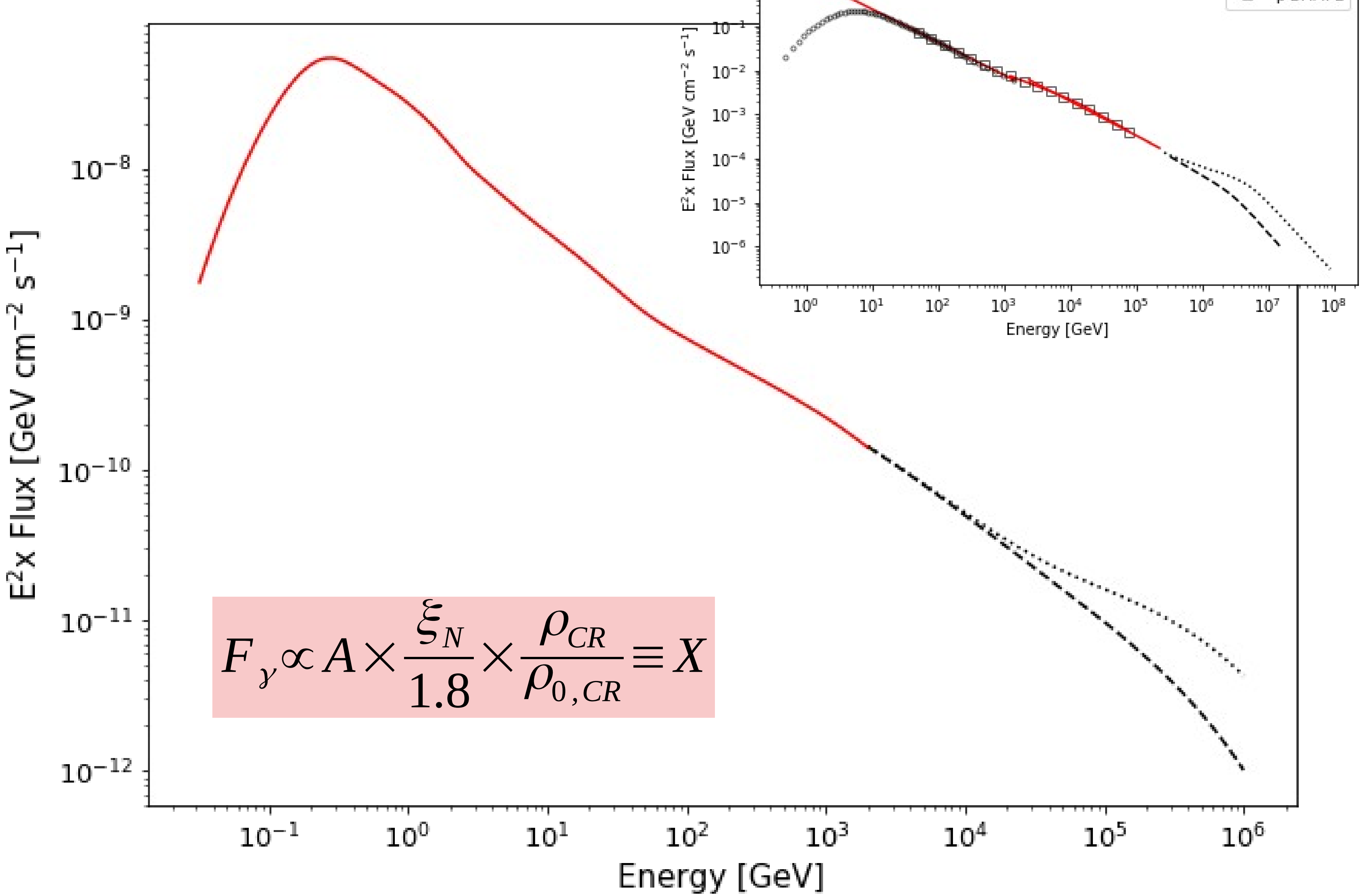
For solar composition $\xi_N \sim 1.8-2$





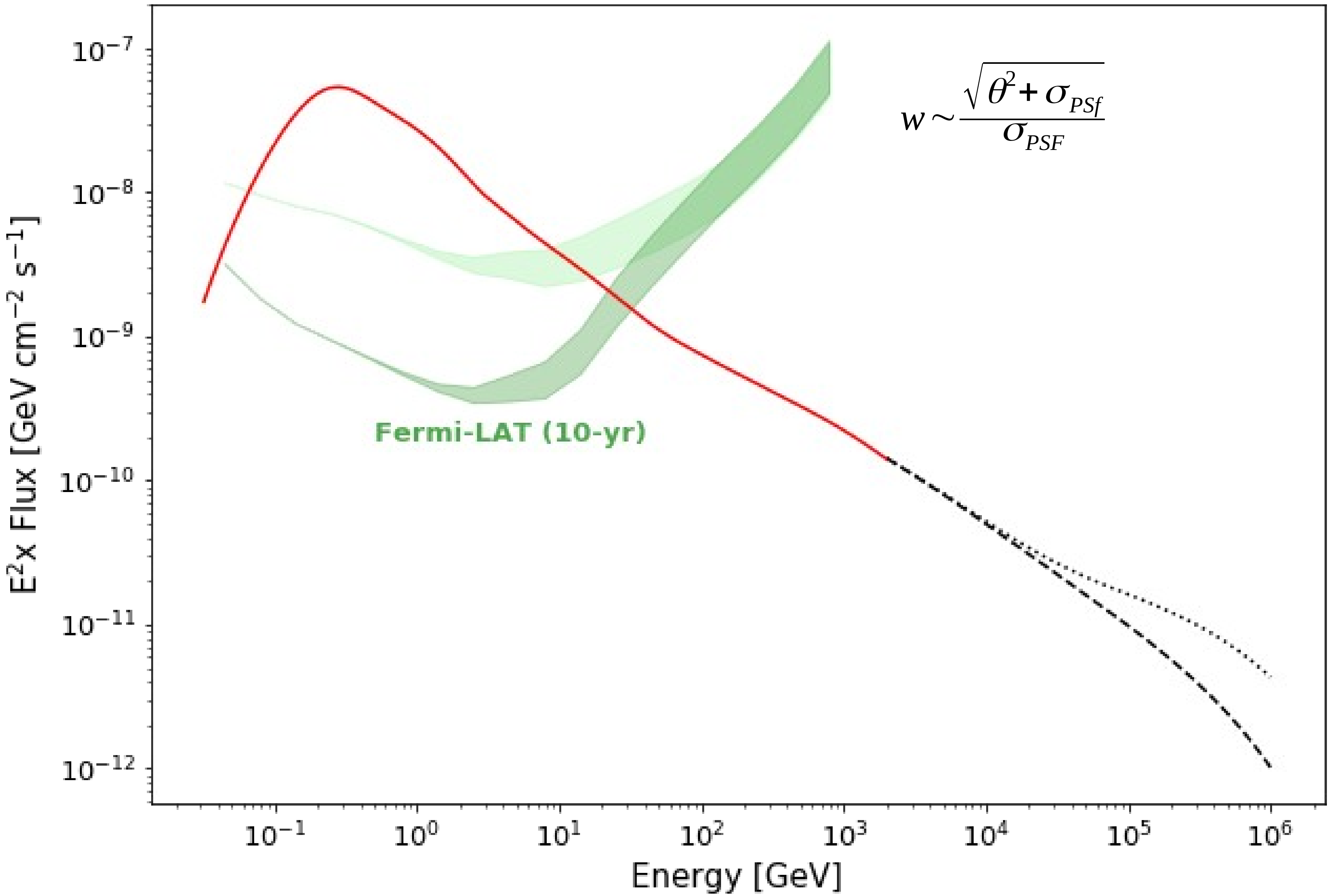
Mori 2009

Visibility of MCs



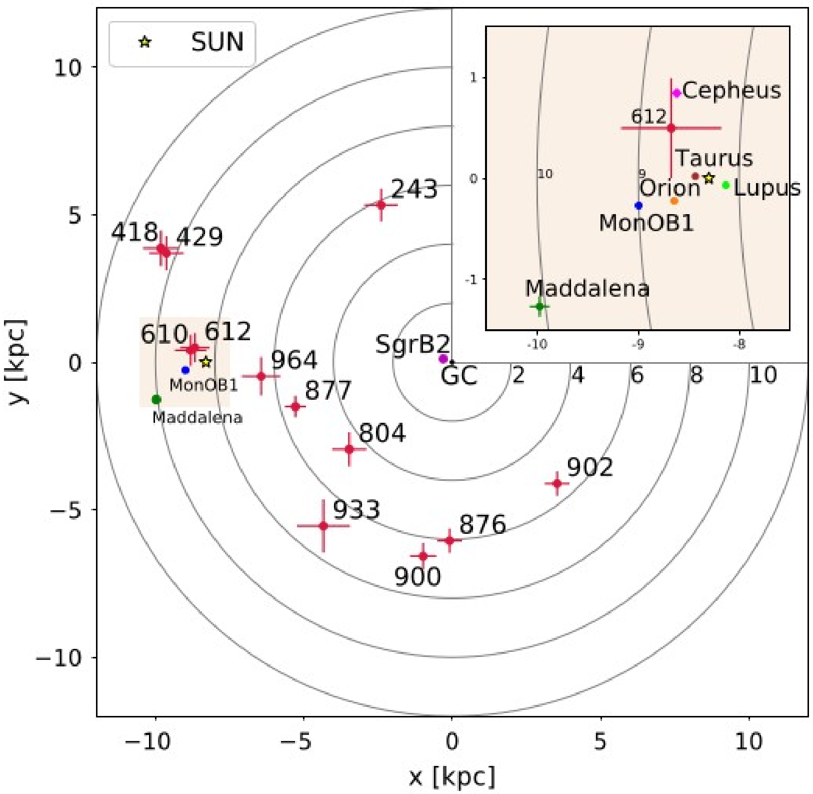
$$F_\gamma \propto A \times \frac{\xi_N}{1.8} \times \frac{\rho_{CR}}{\rho_{0,CR}} \equiv X$$

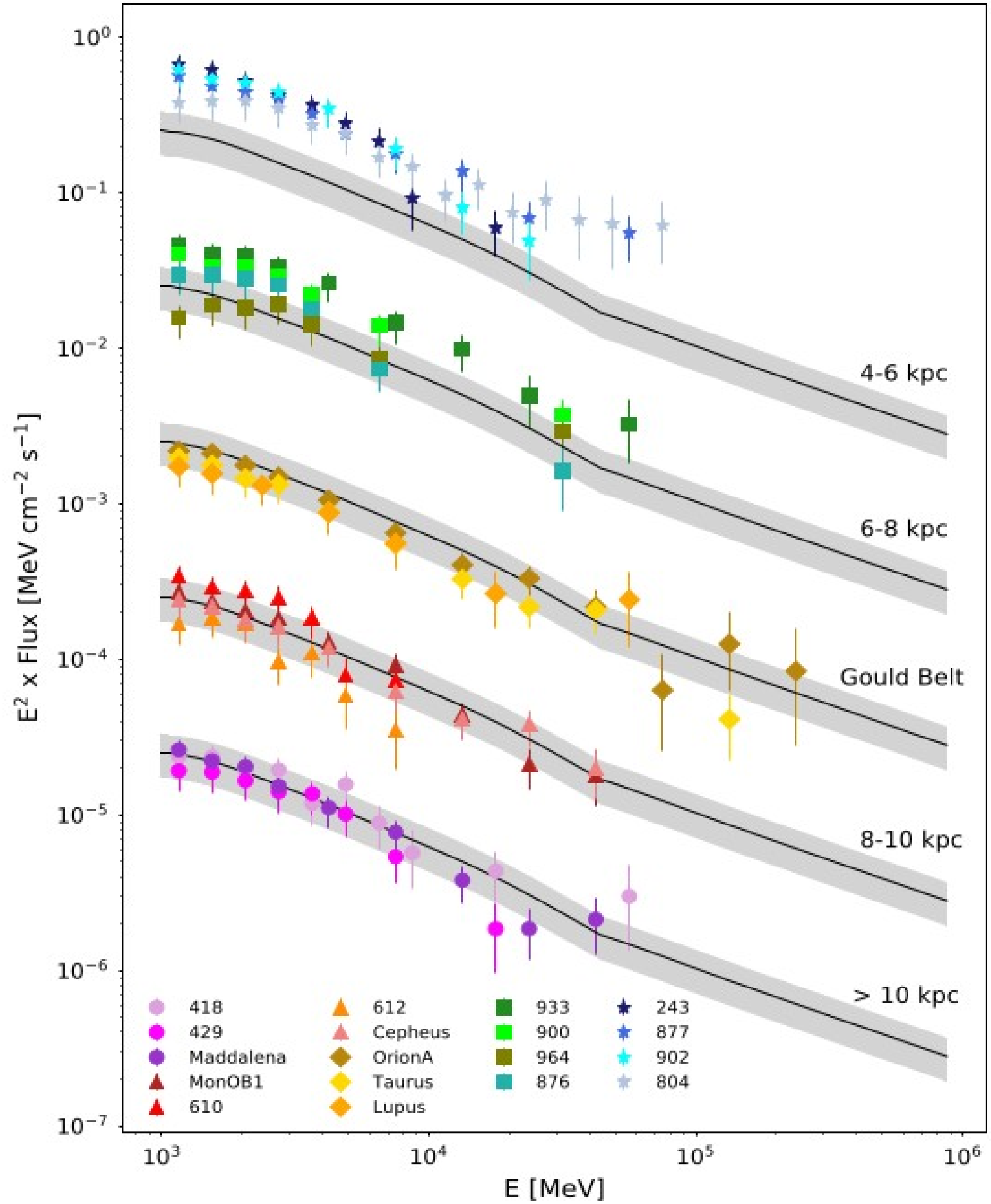
Visibility of MCs



Some results from Fermi-LAT

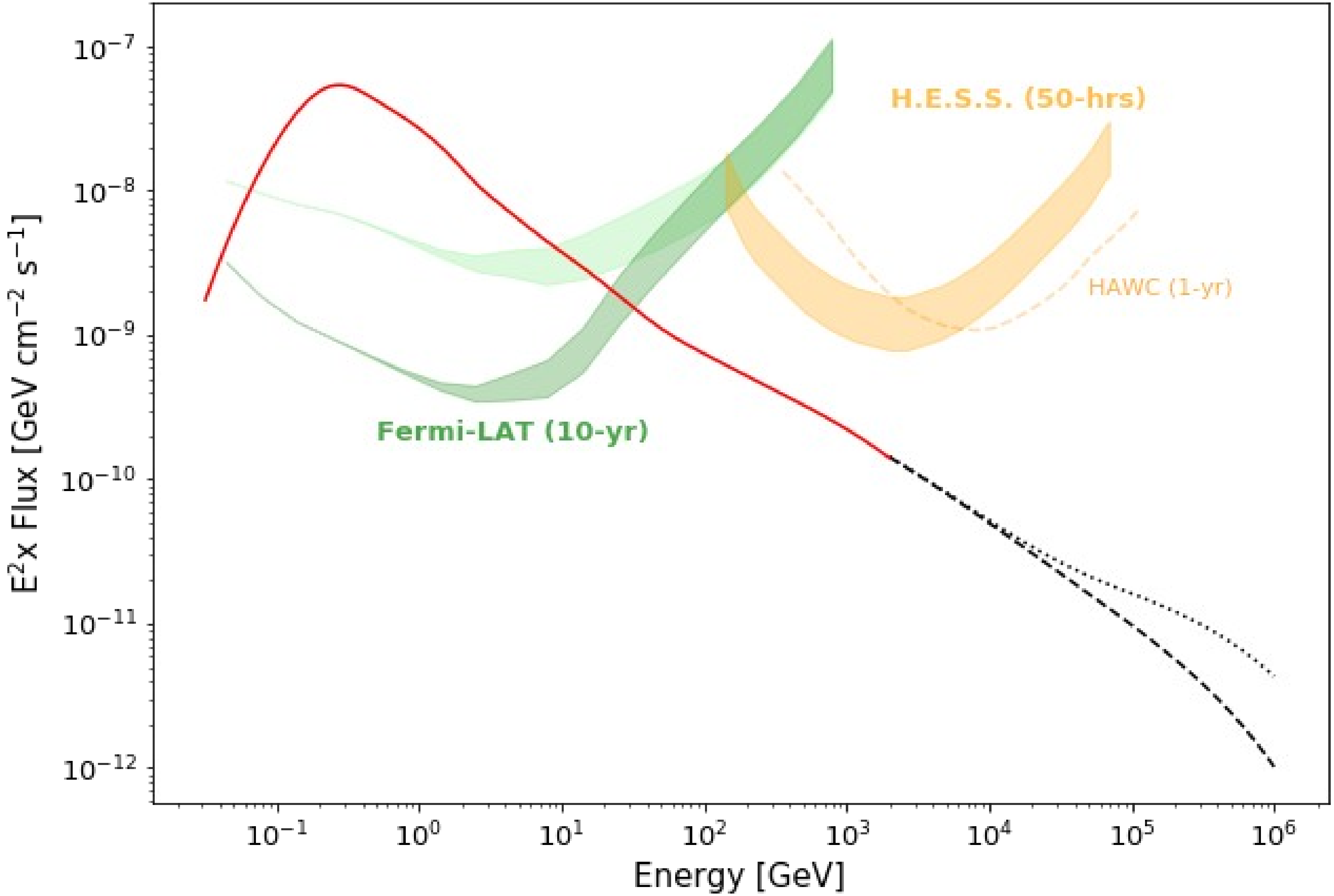
Spectrum of 19 molecular clouds
In different locations



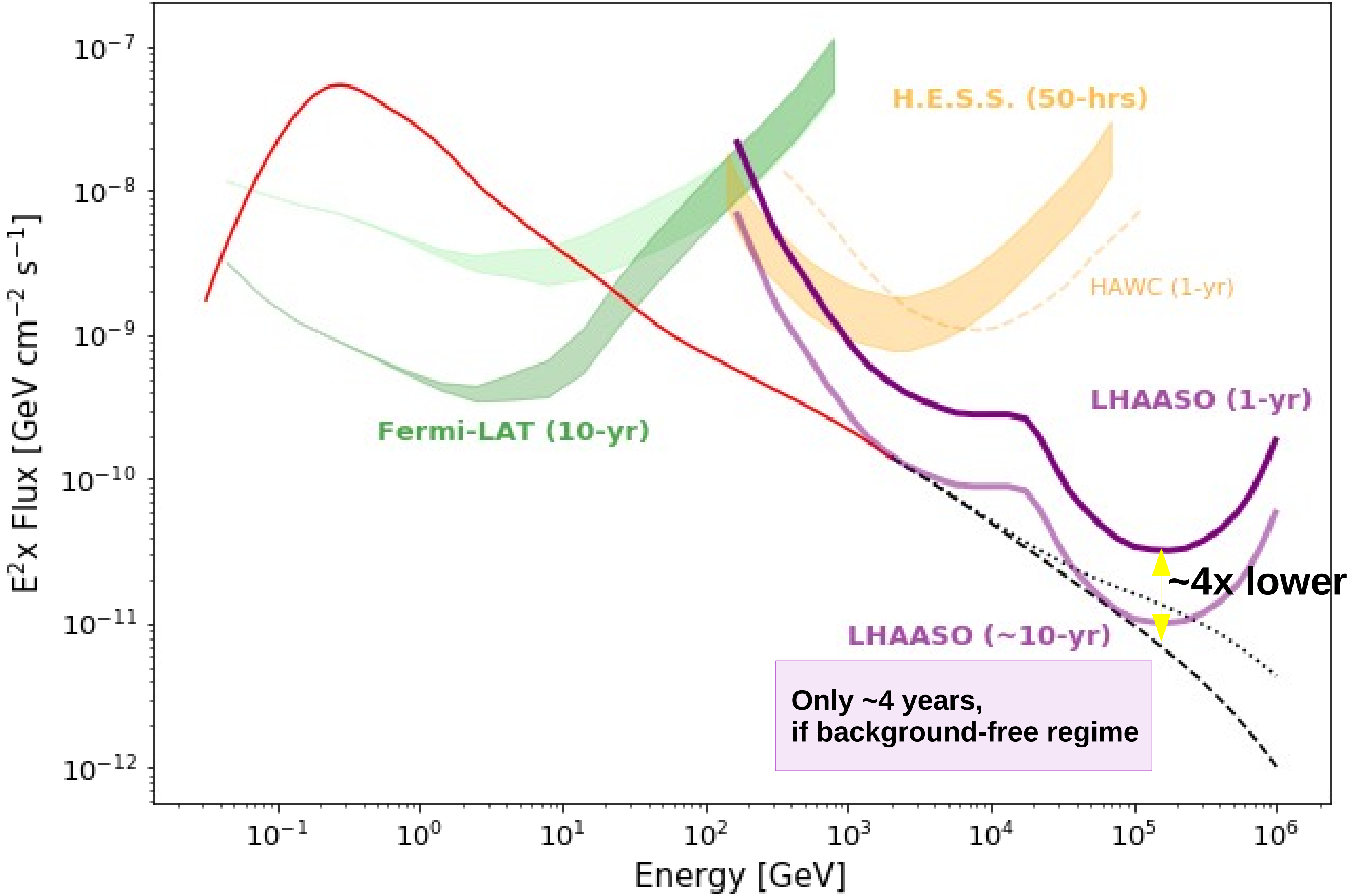


Aharonian et al, 2020

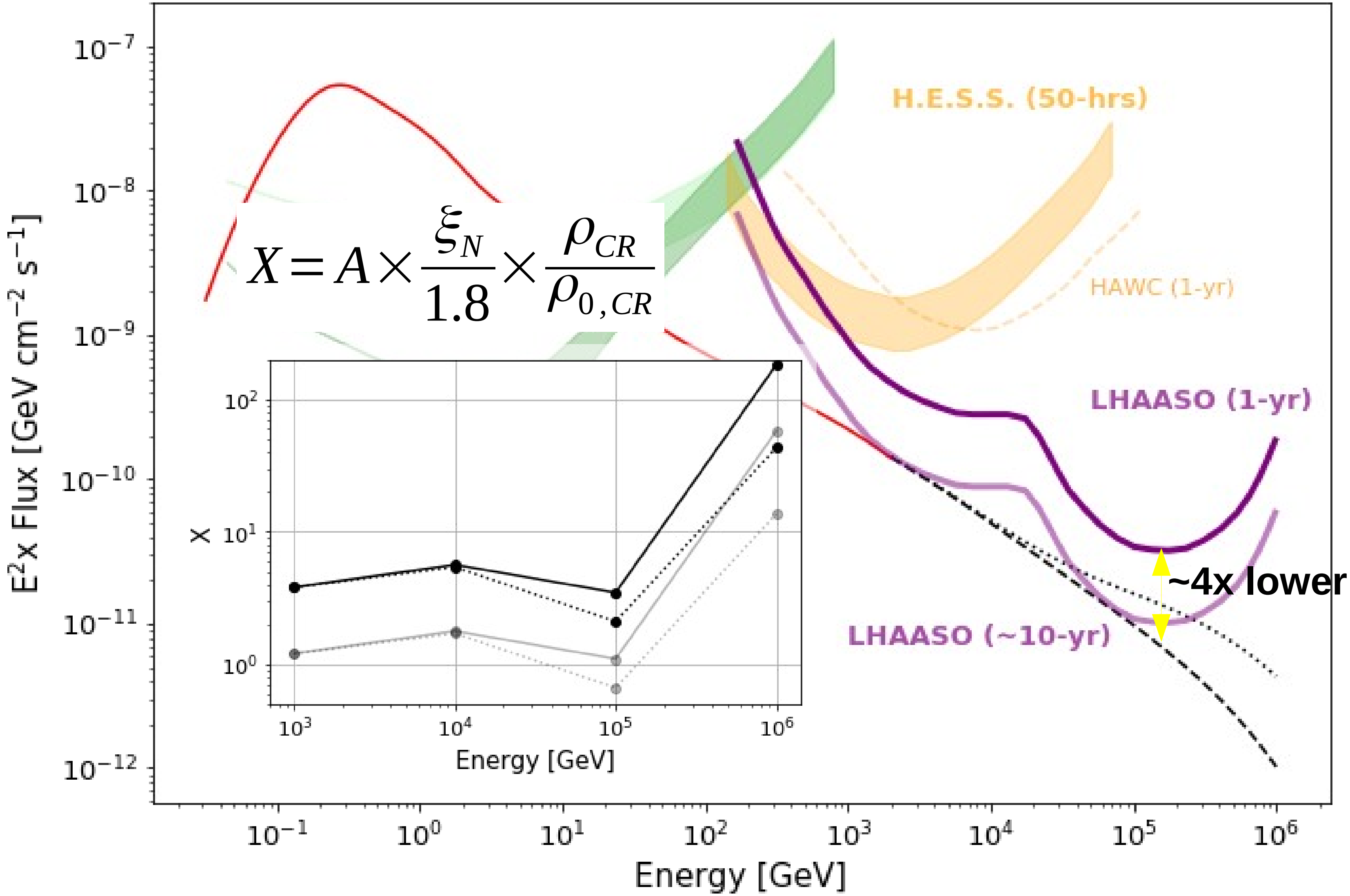
Visibility at VHE energy



Visibility at UHE energy



Visibility at UHE energy

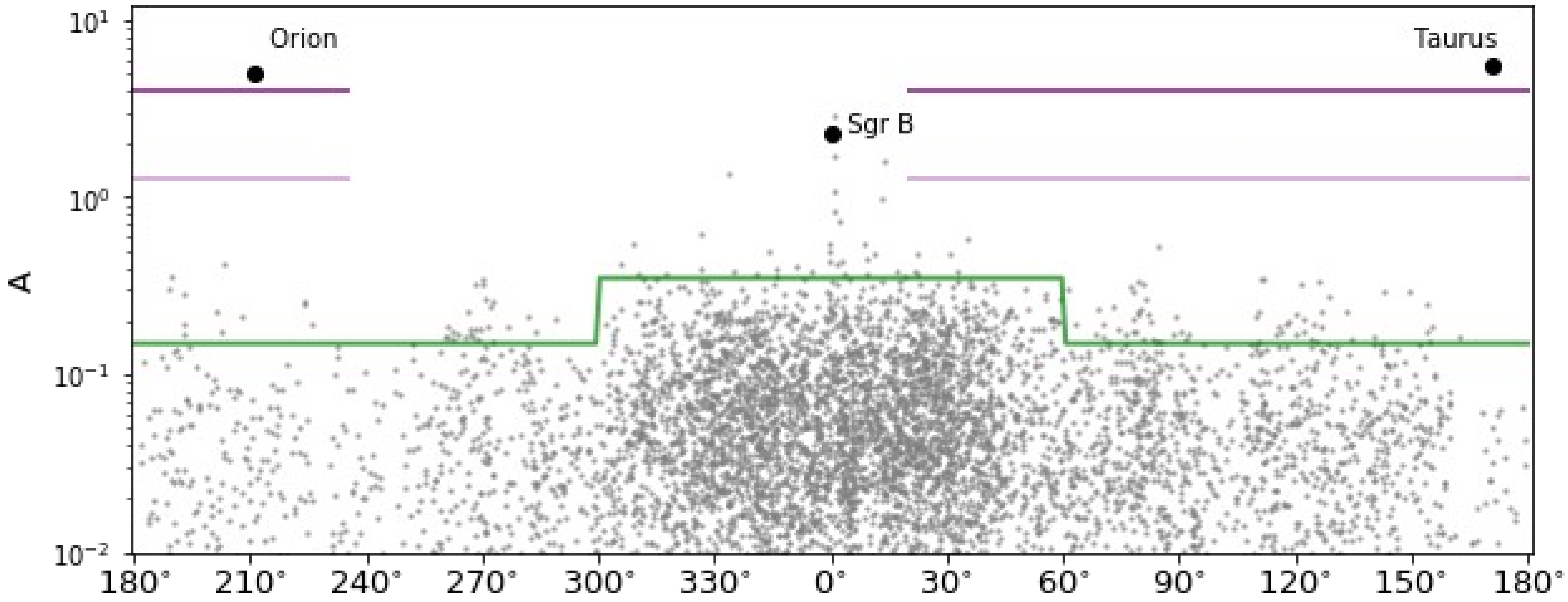


$$X = A \times \frac{\xi_N}{1.8} \times \frac{\rho_{CR}}{\rho_{0,CR}}$$

Factors that improve the visibility

1. MCs with the highest A factor:

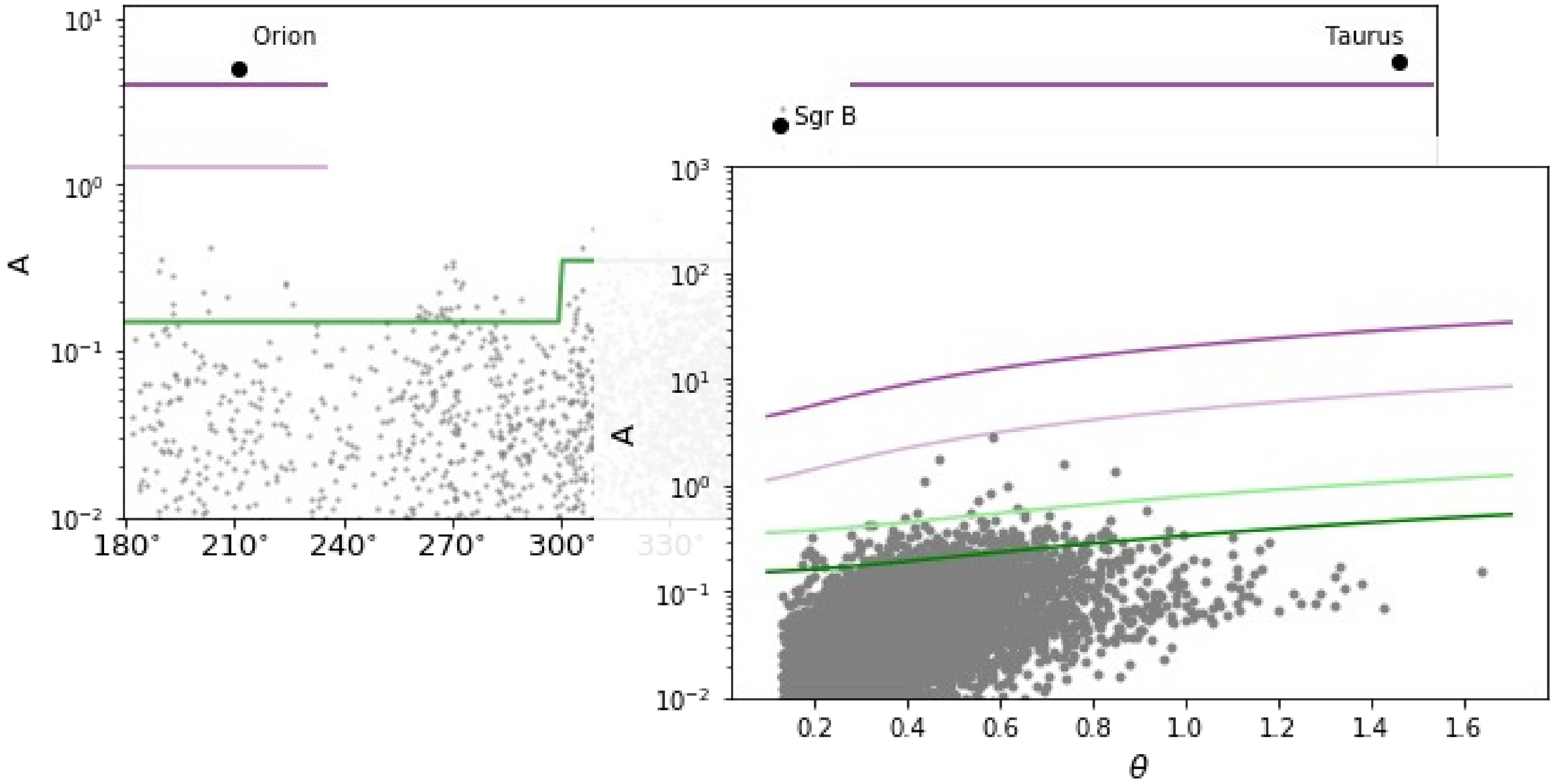
- e.g. Gould Belt clouds (A[Taurus]~6, A[Orion]~3)
- *good compromise needs to be found with the angular extension*



Factors that improve the visibility

1. MCs with the highest A factor:

- e.g. Gould Belt clouds (A[Taurus]~6, A[Orion]~3)
- *good compromise needs to be found with the angular extension*

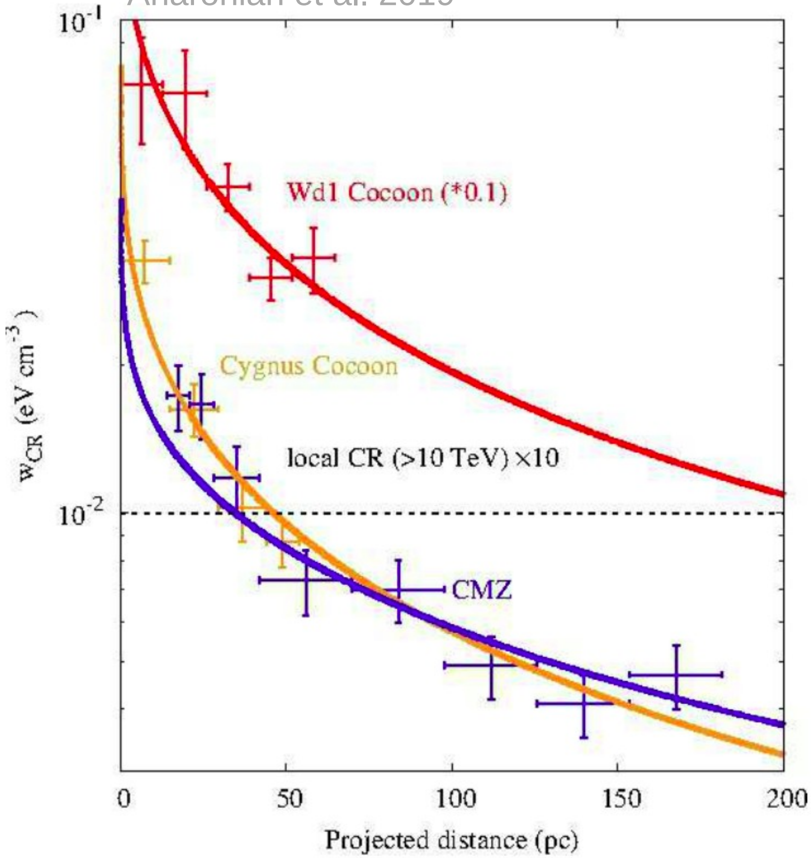


Factors that improve the visibility

2. Enhance the CR density:

- In the vicinity of one (or more) accelerator CR density is higher;
- Near an accelerator the CR spectrum is harder;

Aharonian et al. 2019



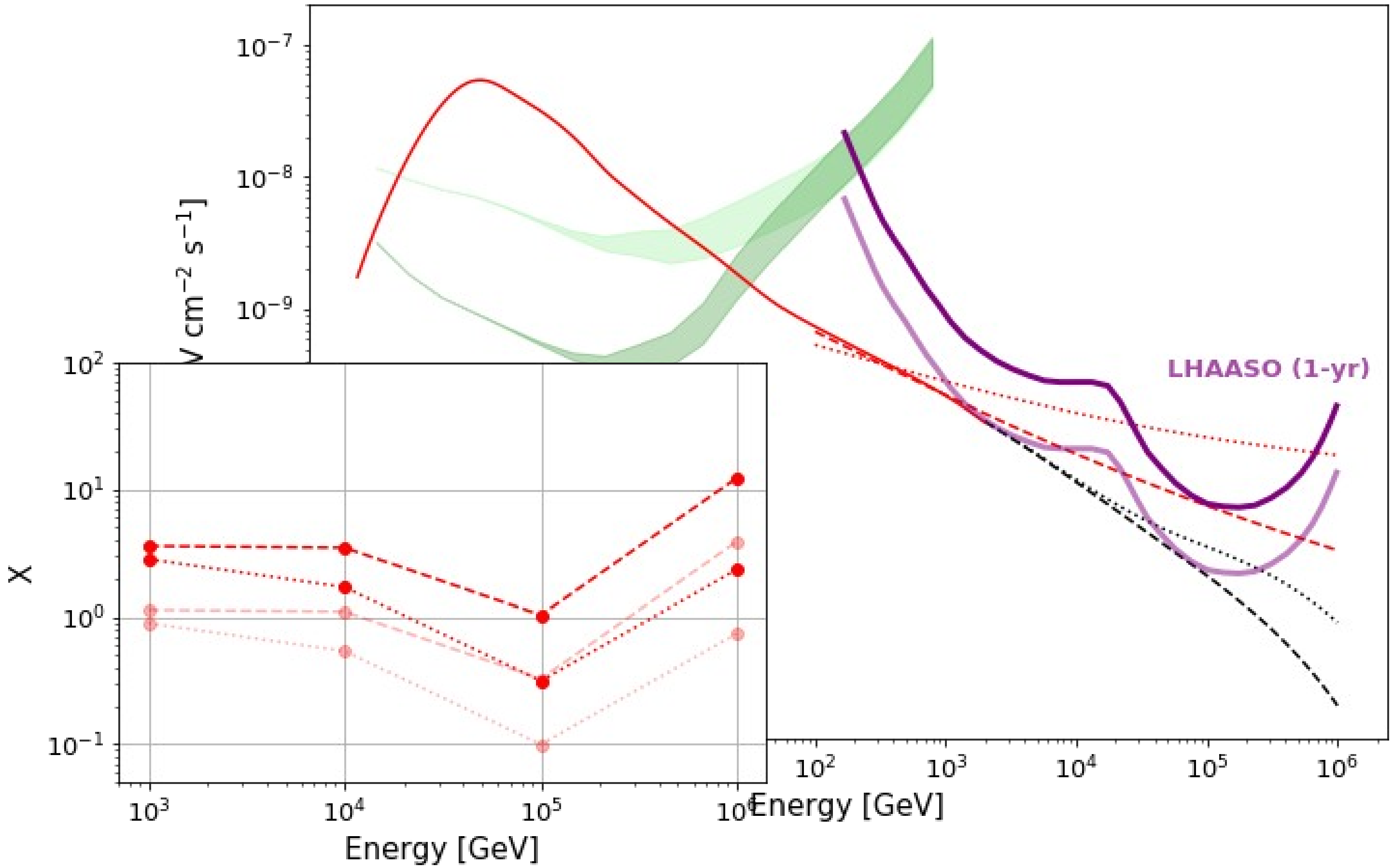
$$F_\gamma \propto A \times \frac{\xi_N}{1.8} \times \frac{\rho_{CR}}{\rho_{0,CR}} \equiv X$$

Cosmic ray density could be orders of magnitude higher than the local one in the proximity of an accelerator

Factors that improve the visibility

2. MCs with enhanced CR density:

- In the vicinity of one (or more) accelerator CR density is higher;
- Near an accelerator the CR spectrum is harder;



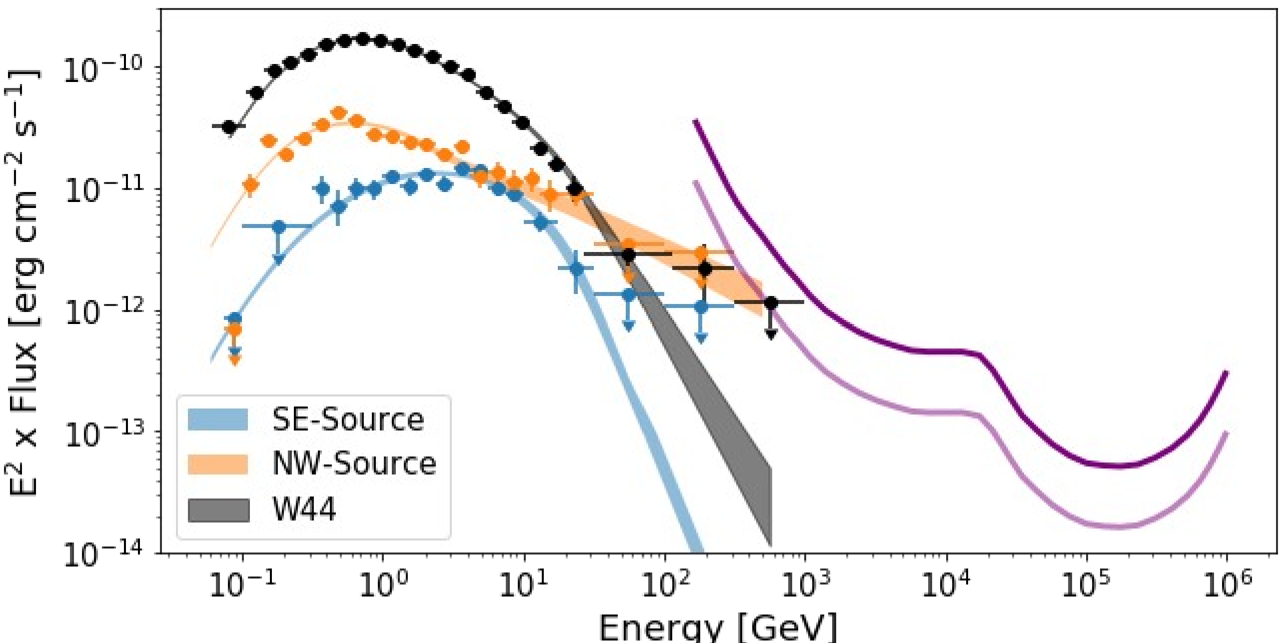
Factors that improve the visibility

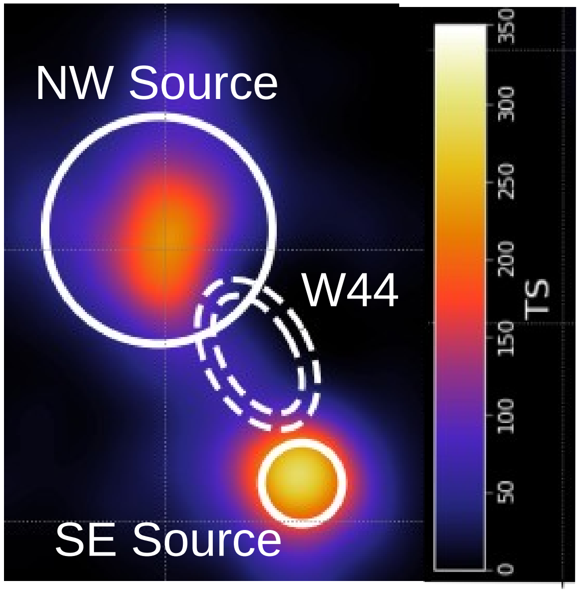
2. MCs with enhanced CR density:

- In the vicinity of one (or more) accelerator CR density is higher;
- Near an accelerator the CR spectrum is harder;

"CR clouds" near W44

Adapted from Peron et al. 2020





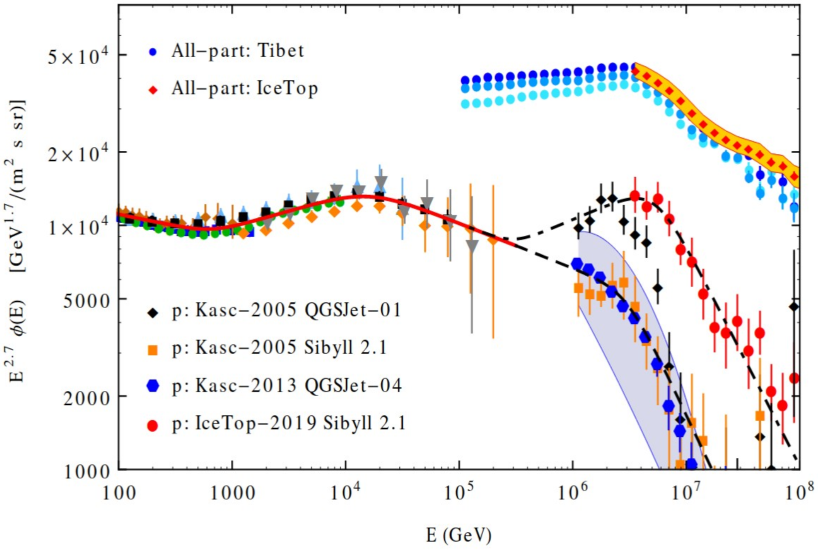
$$R^2 = D\,t \quad ; \quad D(E) = 3\times10^{28}\left(\frac{E}{10\,GeV}\right)^{0.5}\frac{cm^2}{s}$$

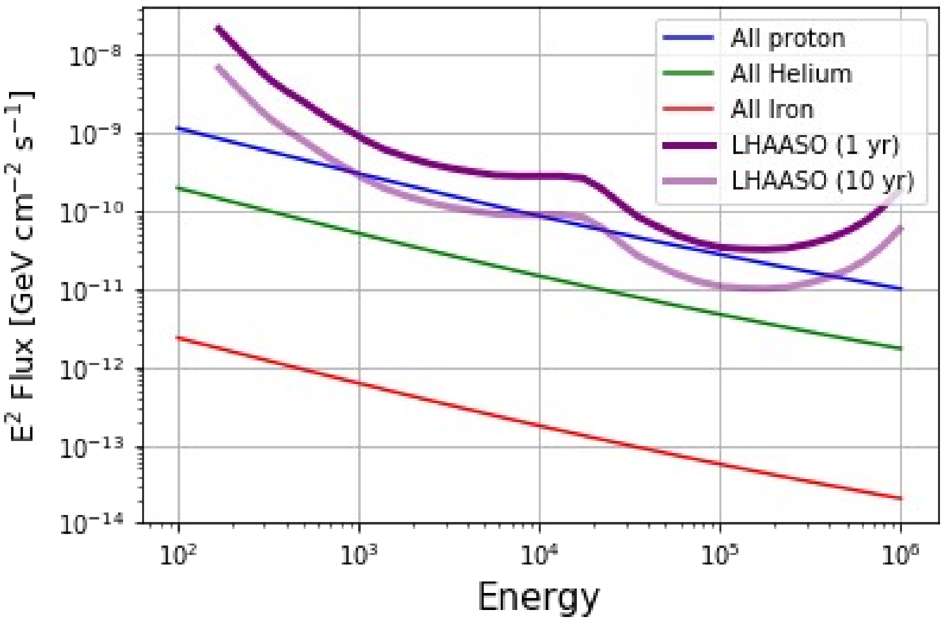
$$R(10^4\,yr, 1\,PeV) \sim 0.5\,kpc$$

Factors that improve the visibility

3. Higher nuclear enhancement factor:

- Heavier composition of Cosmic Rays at UHE;



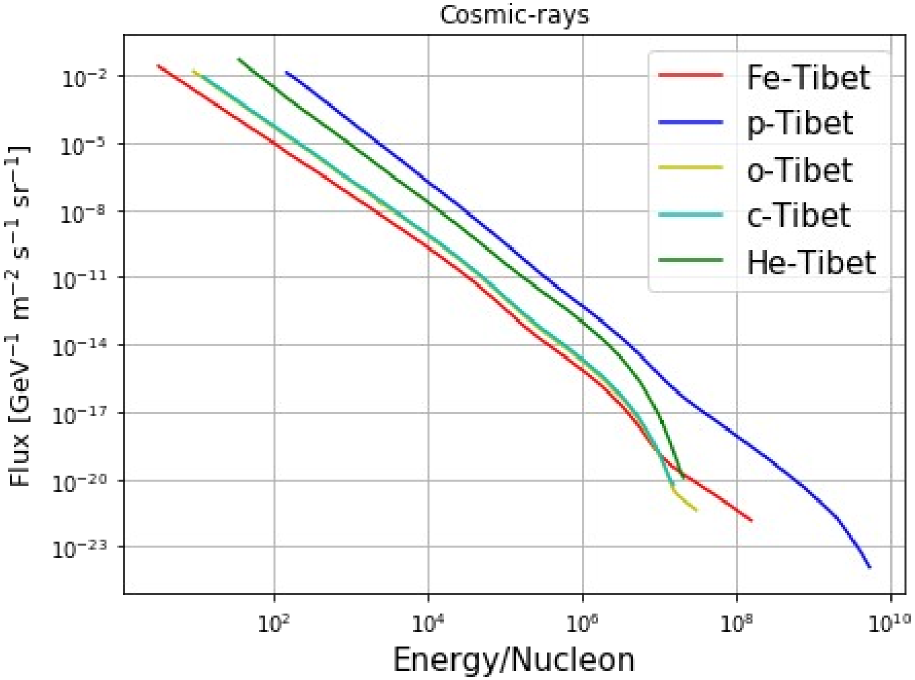


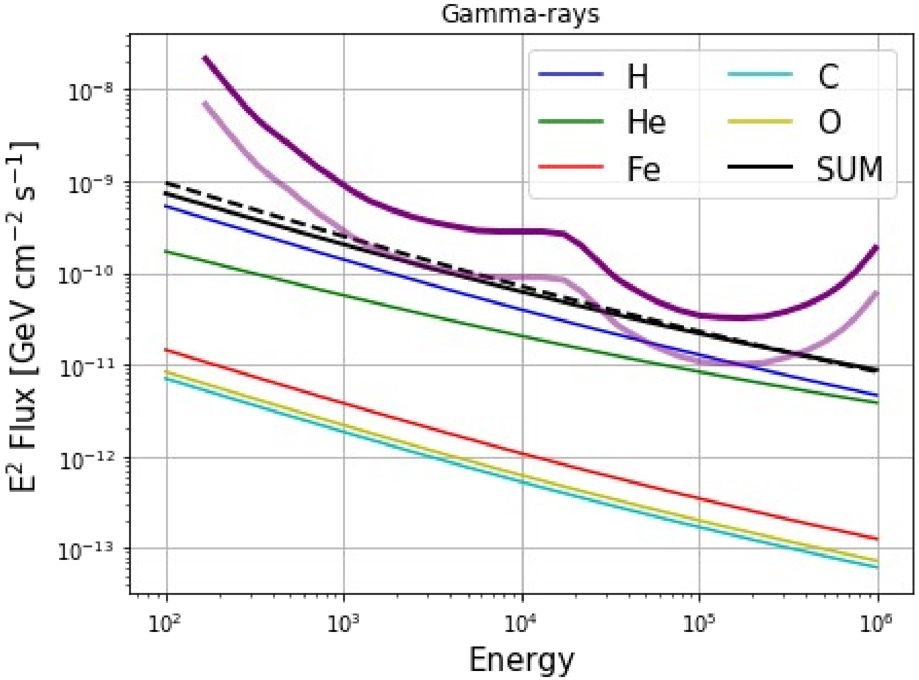
Lipari&Vernetto 2020

Factors that improve the visibility

3. Higher nuclear enhancement factor:

- Heavier composition of Cosmic Rays at UHE;

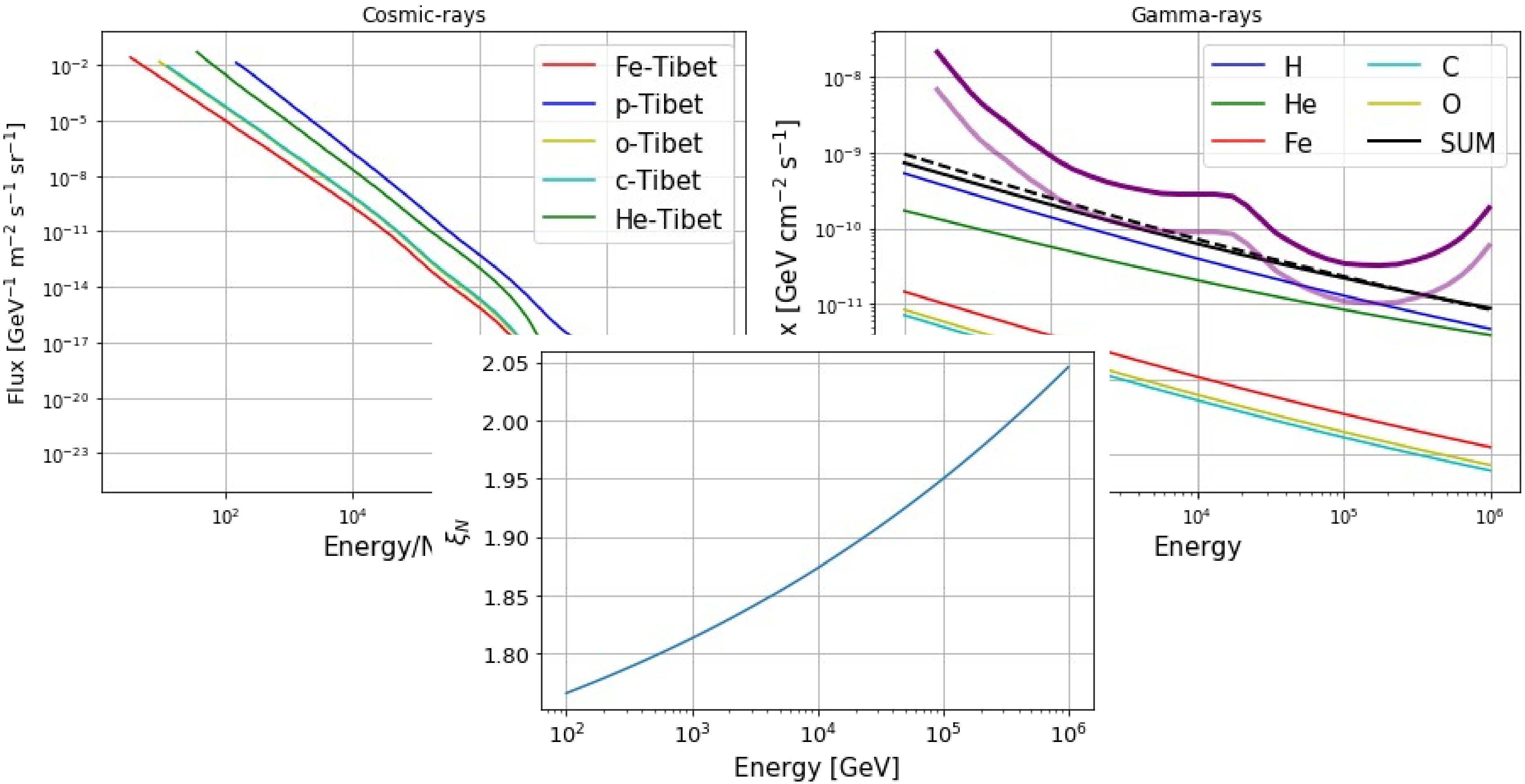




Factors that improve the visibility

3. Higher nuclear enhancement factor:

- Heavier composition of Cosmic Rays at UHE;



Conclusions

- Molecular Clouds constitute a perfect target both for mapping the overall Galactic cosmic ray distribution and for studying the escaped particles near accelerators;
- Most of the energy falls in the GeV energy band, but an extension of the spectrum to UHE is possible with LHAASO
- LHAASO in a few years can measure the spectrum of passive MCs and distinguish between different end of the proton spectrum;
- LHAASO will be very suitable for exploring the surrounding of accelerators;