MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Giant Molecular Clouds as Probes of Galactic Cosmic Rays with Fermi-LAT

Giada Peron

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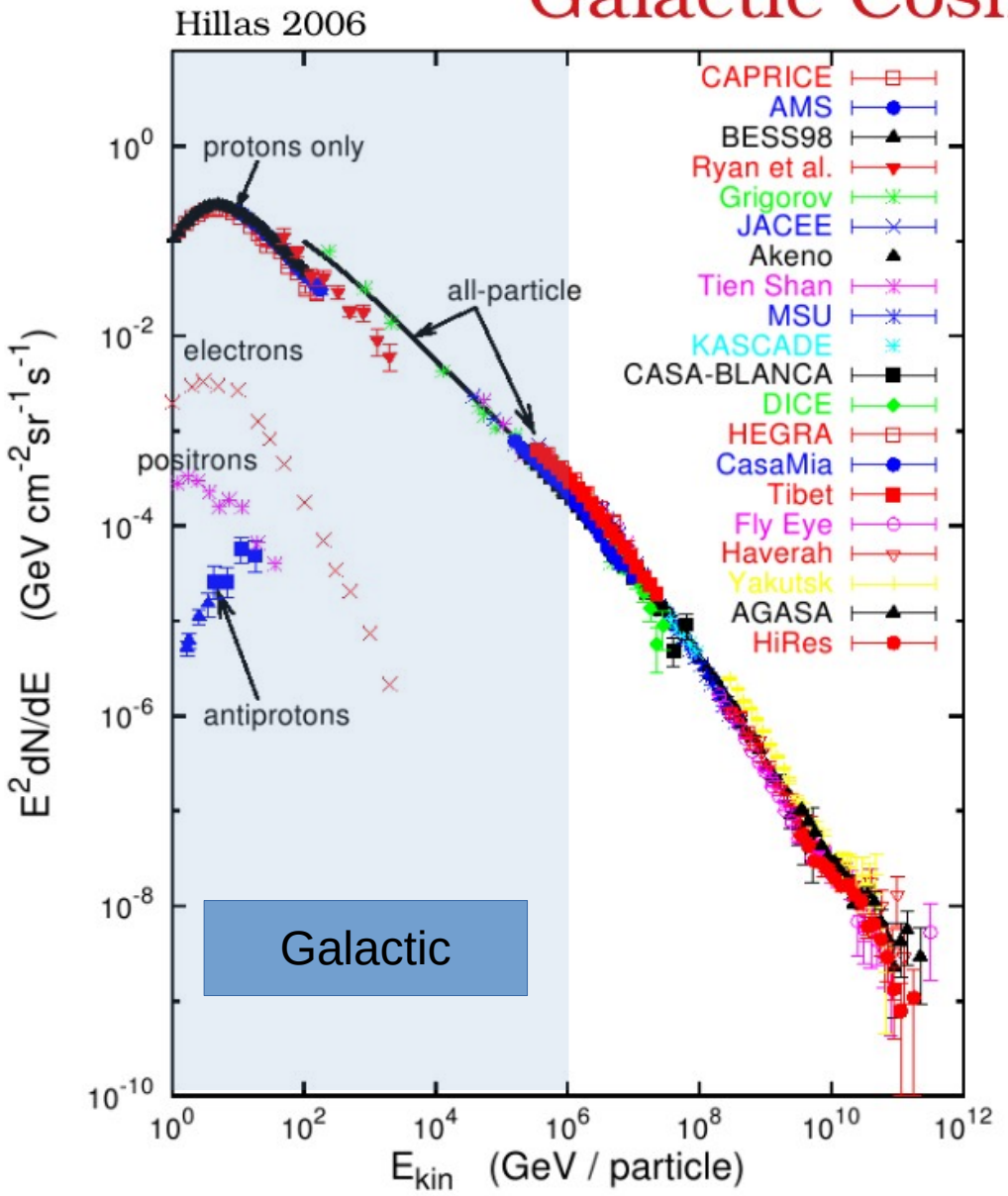
Overview

- Galactic Cosmic Rays
- Molecular Clouds as CR barometers
- Results from Fermi-LAT
- Summary and Conclusions

Galactic Cosmic Rays



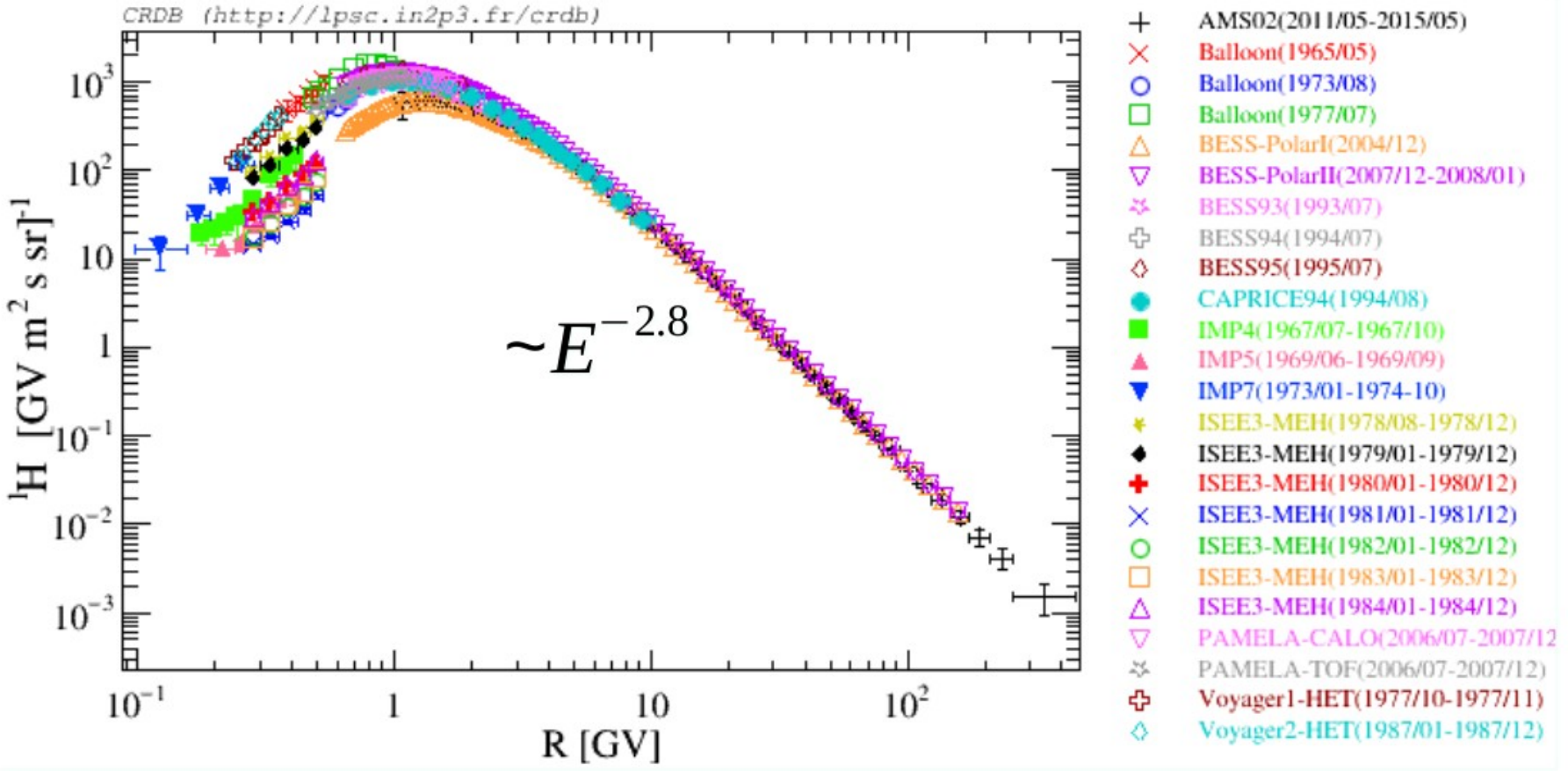
CR with E < 10^{15} eV are produced inside the Galaxy

- ✔ Power supply from SNe
- ✔ Confinement $(r_L < r_{gal})$
- ✔ Knee in the Spectrum

- ✗ SNRs cutoff at 100 TeV

Aharonian+2004
Longair 2011
Gaisser+2016
Gabici+2019
Many others..

Galactic Cosmic Rays: Protons



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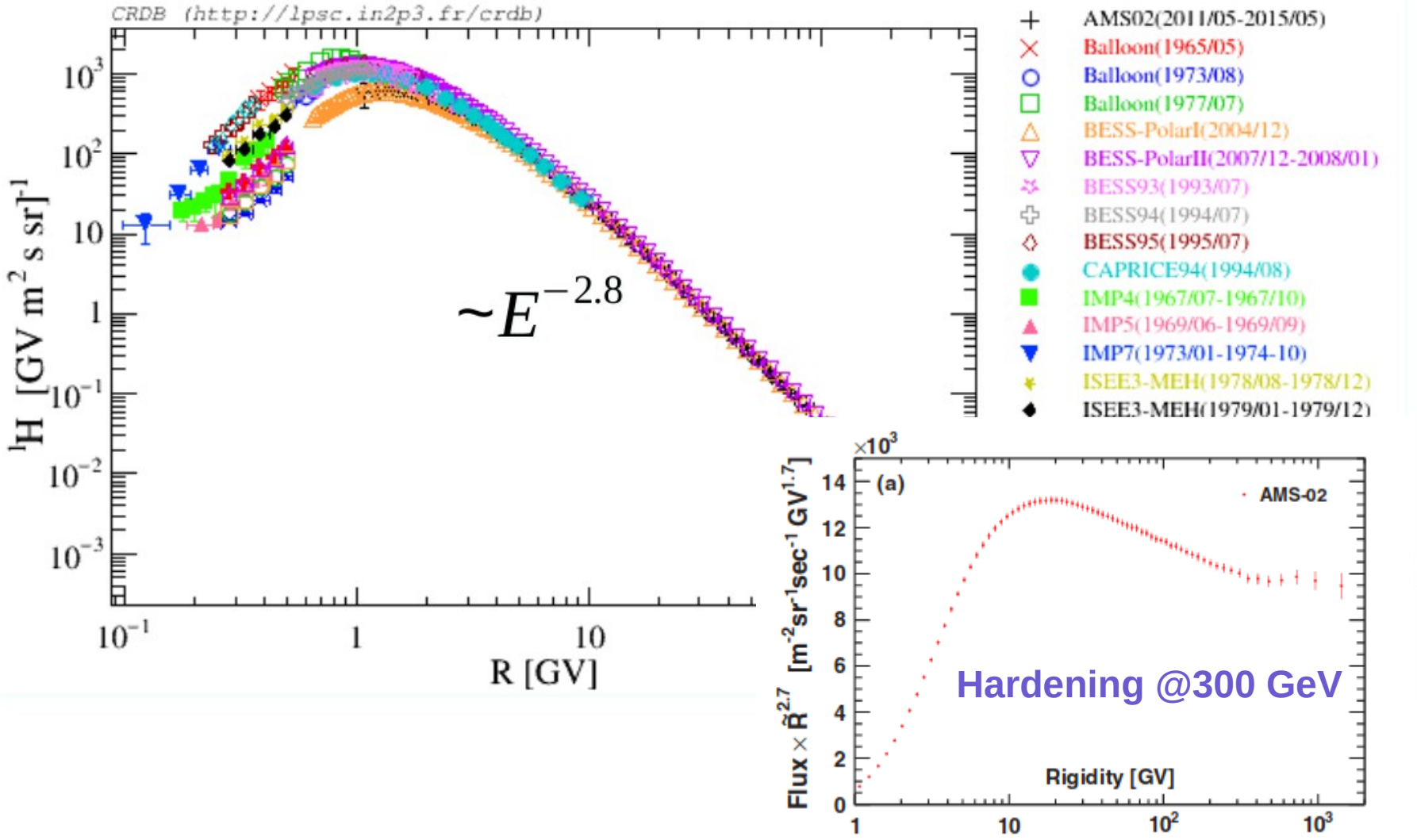
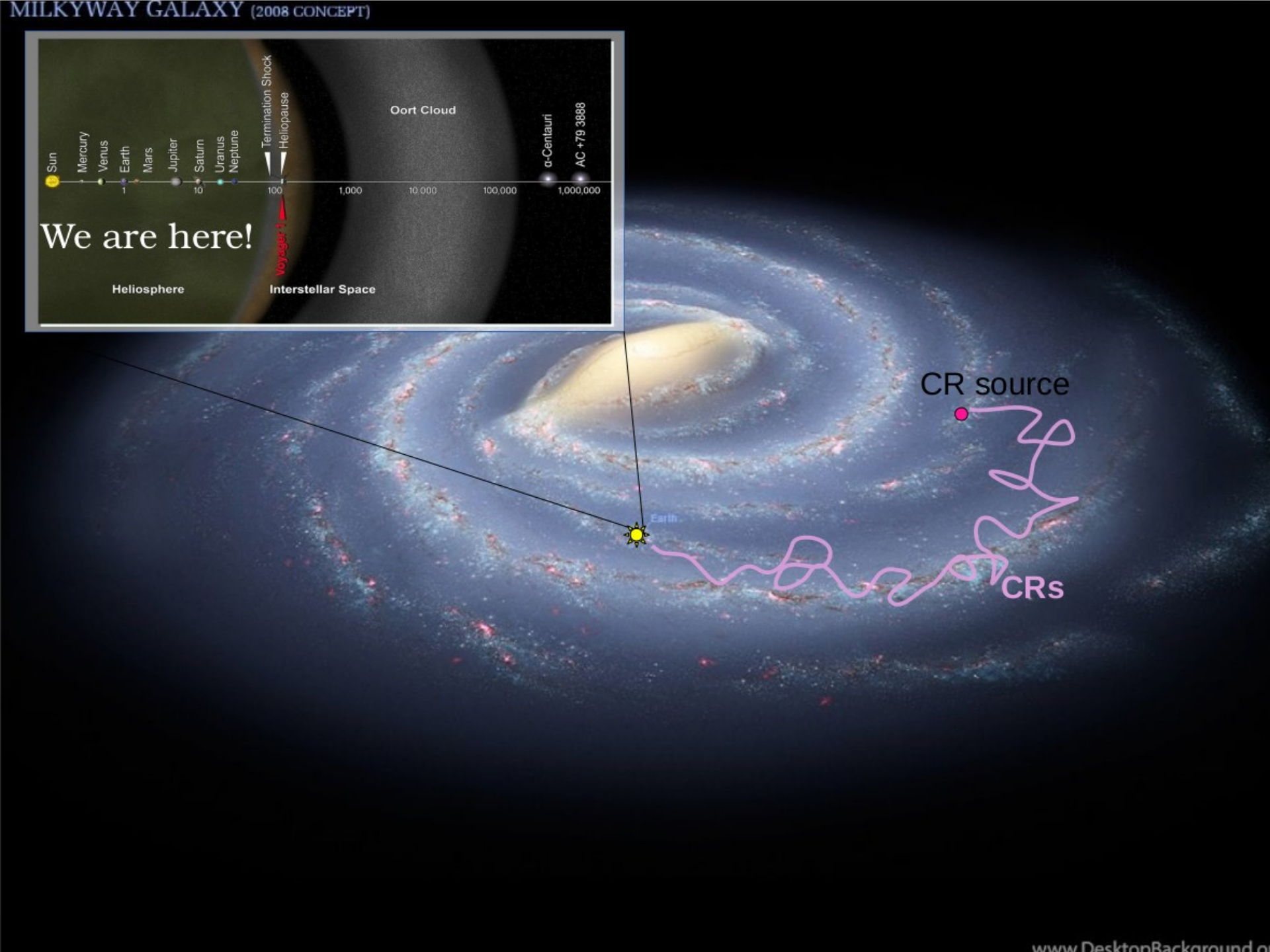
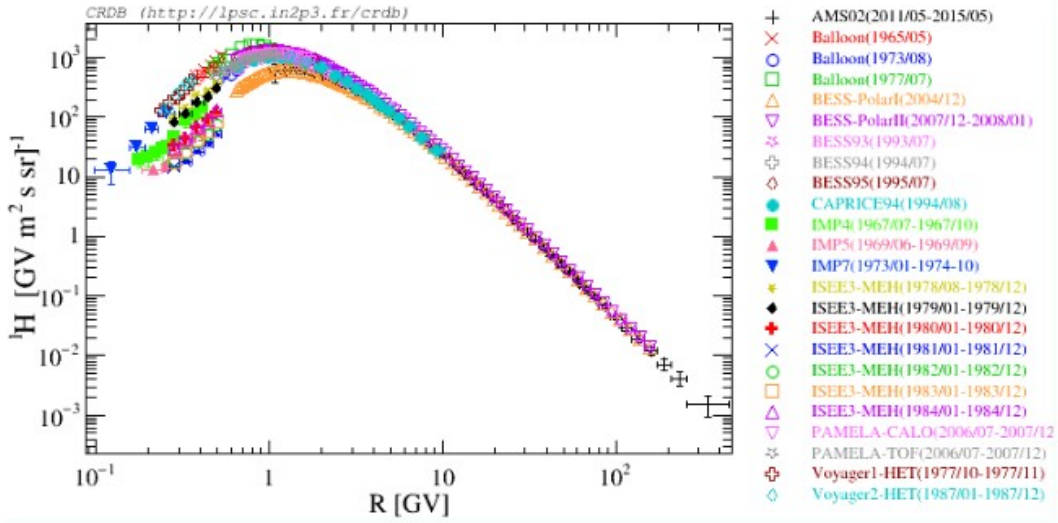


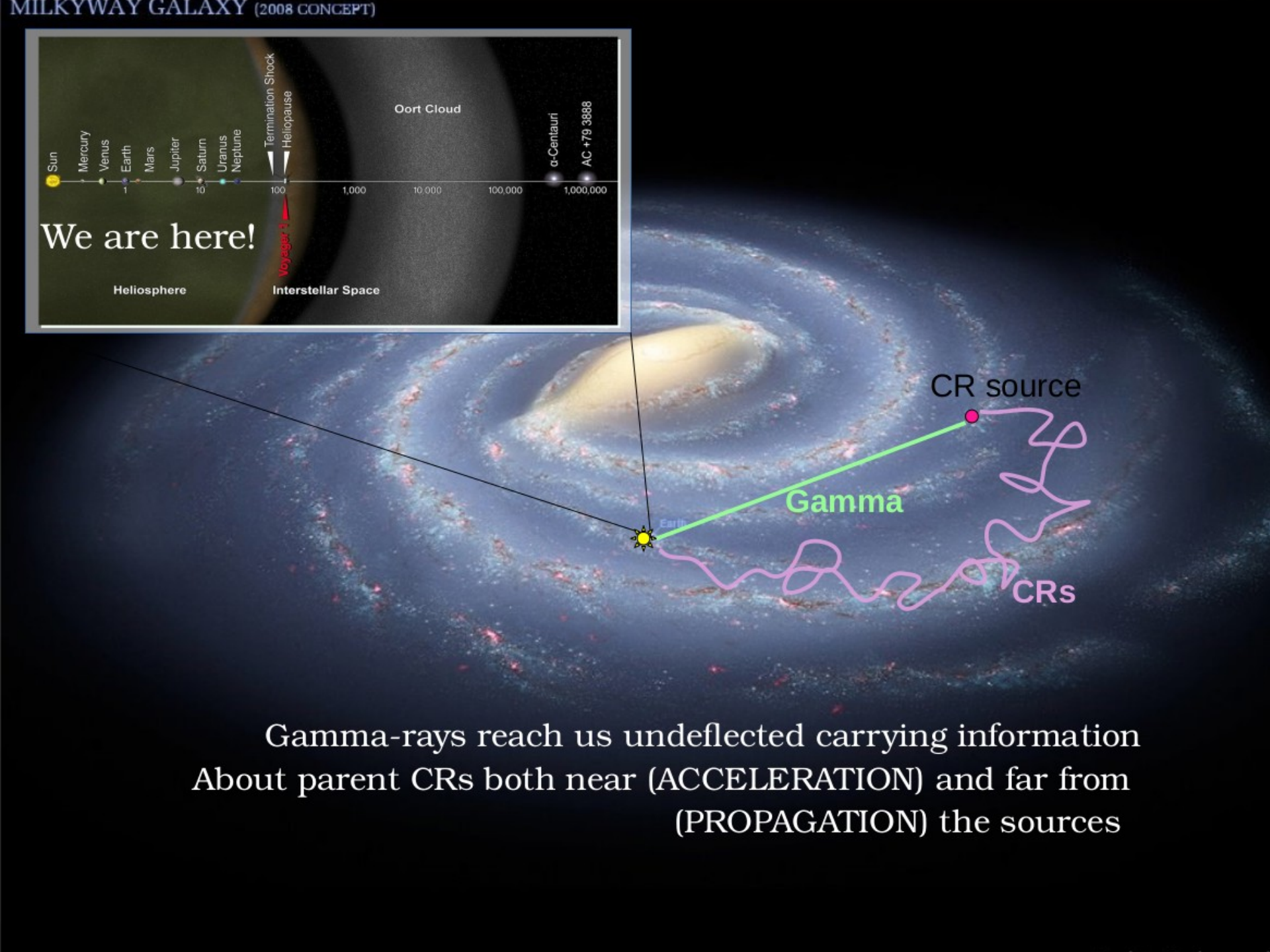

MILKYWAY GALAXY (2008 CONCEPT)
Sun
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
Termination Shock
Heliopause
Oort Cloud
α-Centauri
AC +79 3888
1
10
100
1,000
10,000
100,000
1,000,000
We are here!
Voyager 1
Heliosphere
Interstellar Space
CR source
Earth
CRs

Is there a SEA of Galactic Cosmic Rays?

Direct measurements of CR are limited to the Solar System edges

- Is the spectrum the same everywhere in the Galaxy?
  - CRs and are deflected in the ISM and spread uniformly in the Galaxy $t_{esc} \gg t_{acc}$ =*Sea of Galactic Cosmic Rays*
- How to test that?

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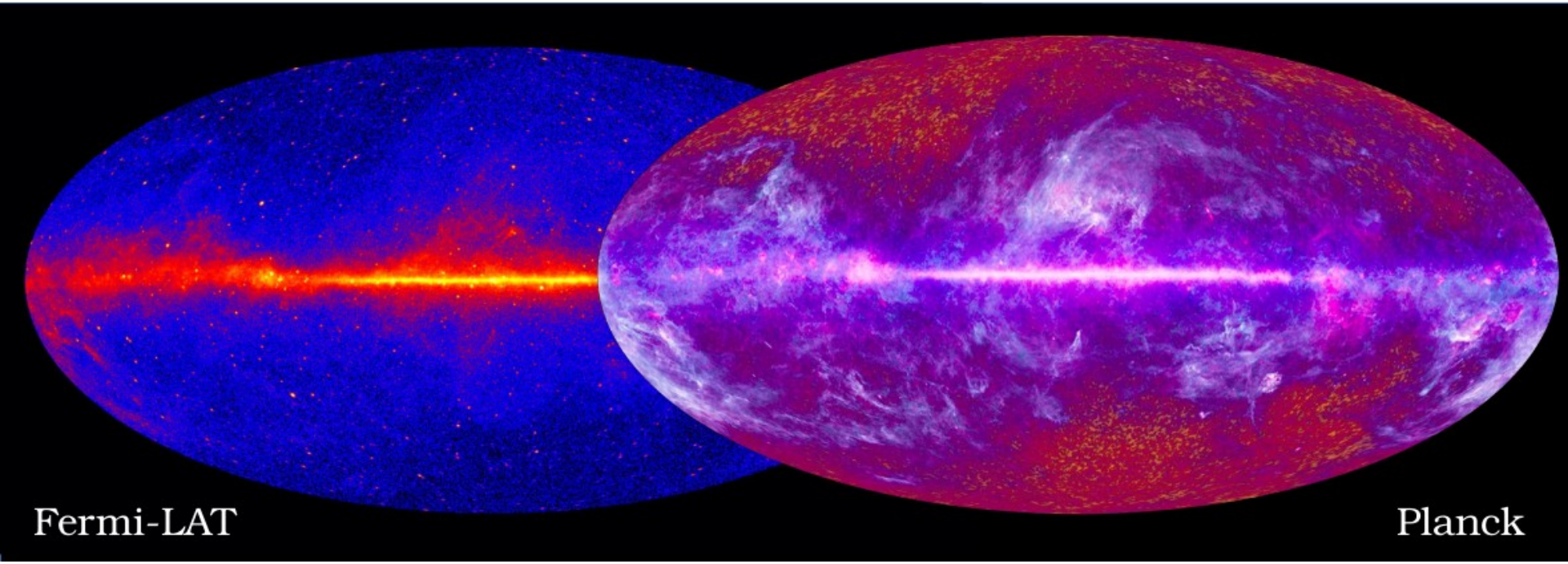
We are here!
Voyager 1
Heliosphere
Interstellar Space
CR source
Gamma
Earth
CRs
Gamma-rays reach us undeflected carrying information
About parent CRs both near (ACCELERATION) and far from
(PROPAGATION) the sources

Cosmic Rays produce Gamma Rays

$$p + p \rightarrow \pi^0 \rightarrow 2\,\gamma$$

CR ISM

$$F_\gamma = \frac{dN_\gamma}{dE_\gamma\, dt\, dA\, d\,\omega} = n_{col} \int dE_p\, d\frac{\sigma}{dE_\gamma}(E_p, E_\gamma)\, F_p(E_p)$$



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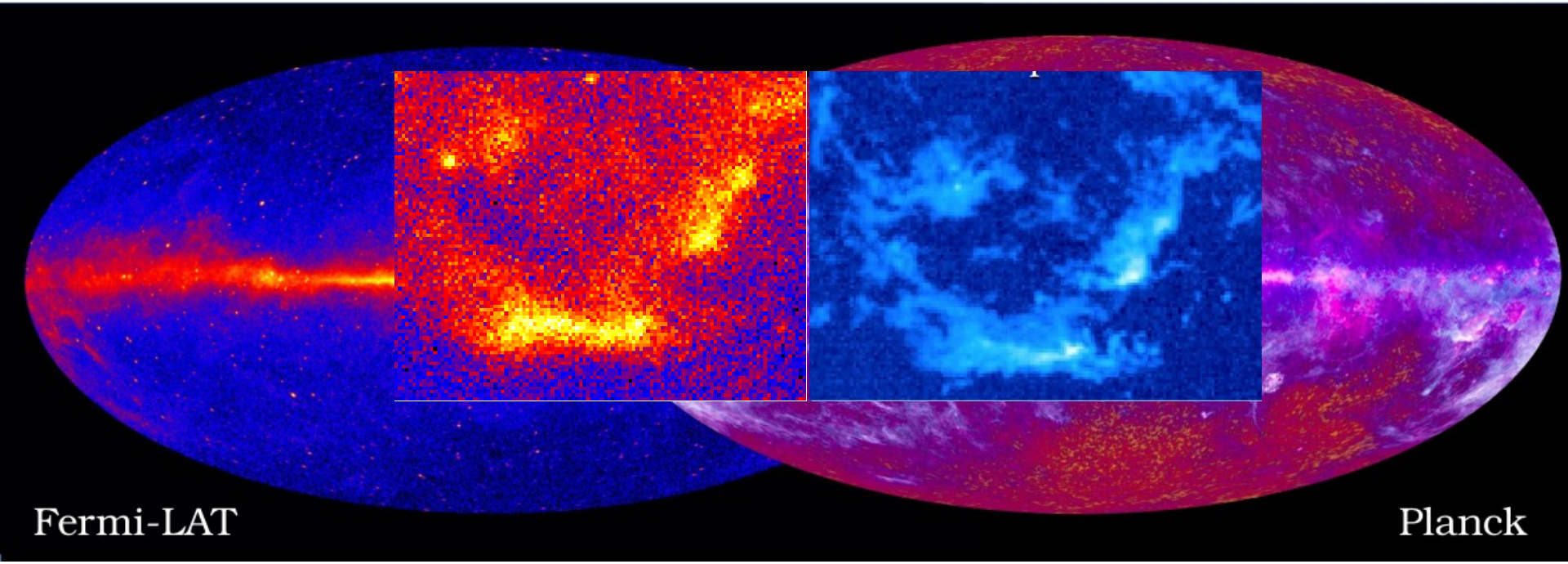
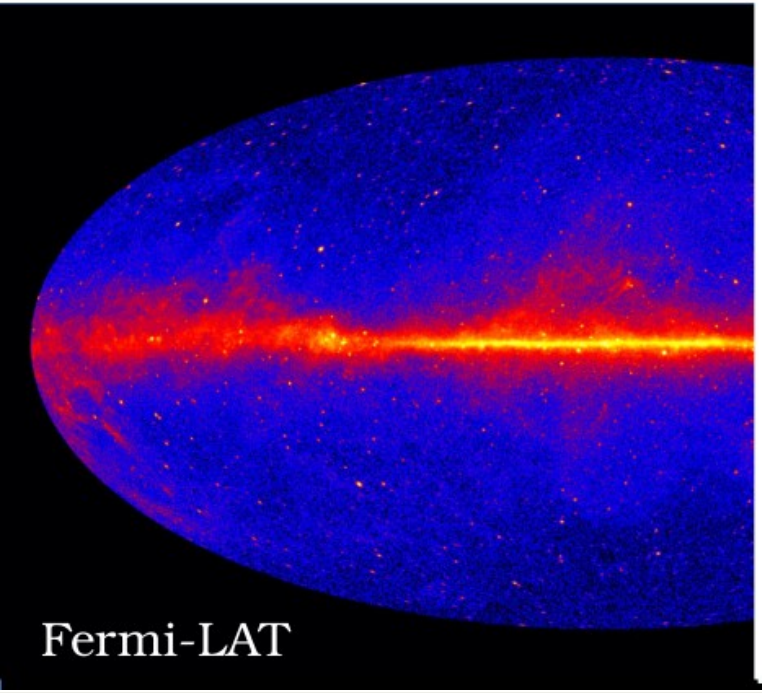


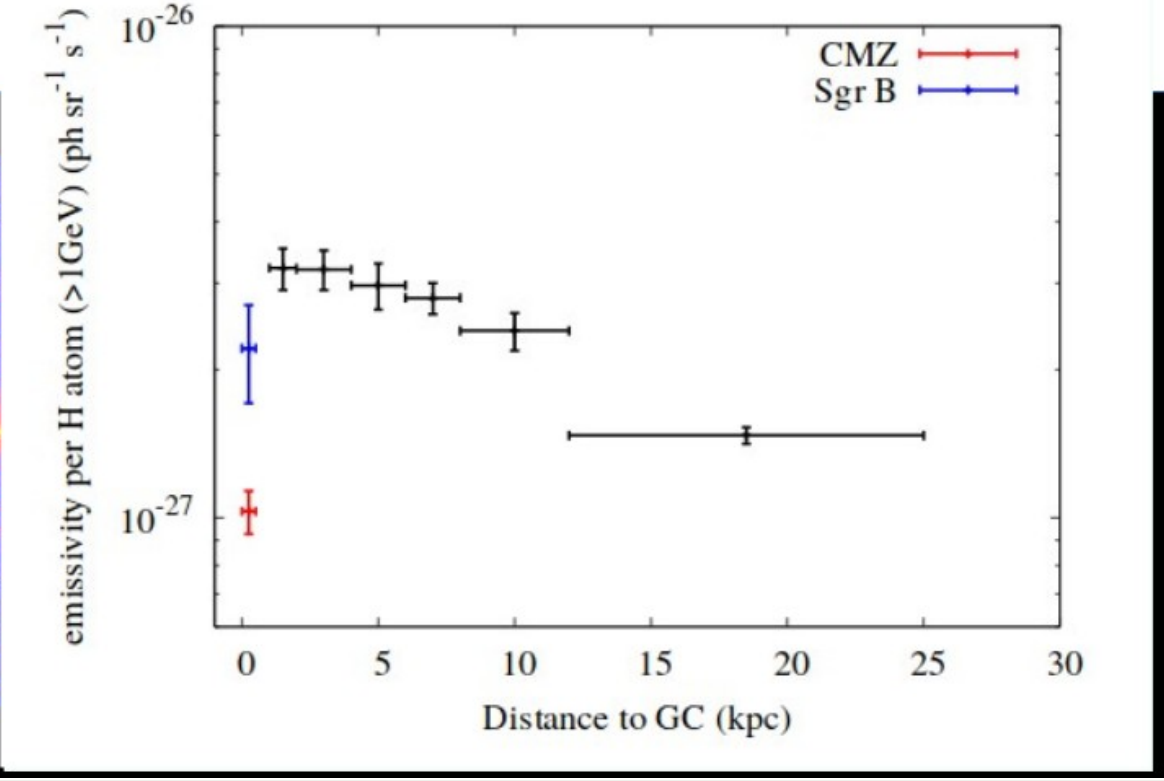
Cosmic Rays produce Gamma Rays

$$p + p \rightarrow \pi^0 \rightarrow 2\,\gamma$$

CR ISM

Fermi-LAT observation of the diffuse emission show that the CR energy distribution is not constant. (Yang+2016, Acero+2016)

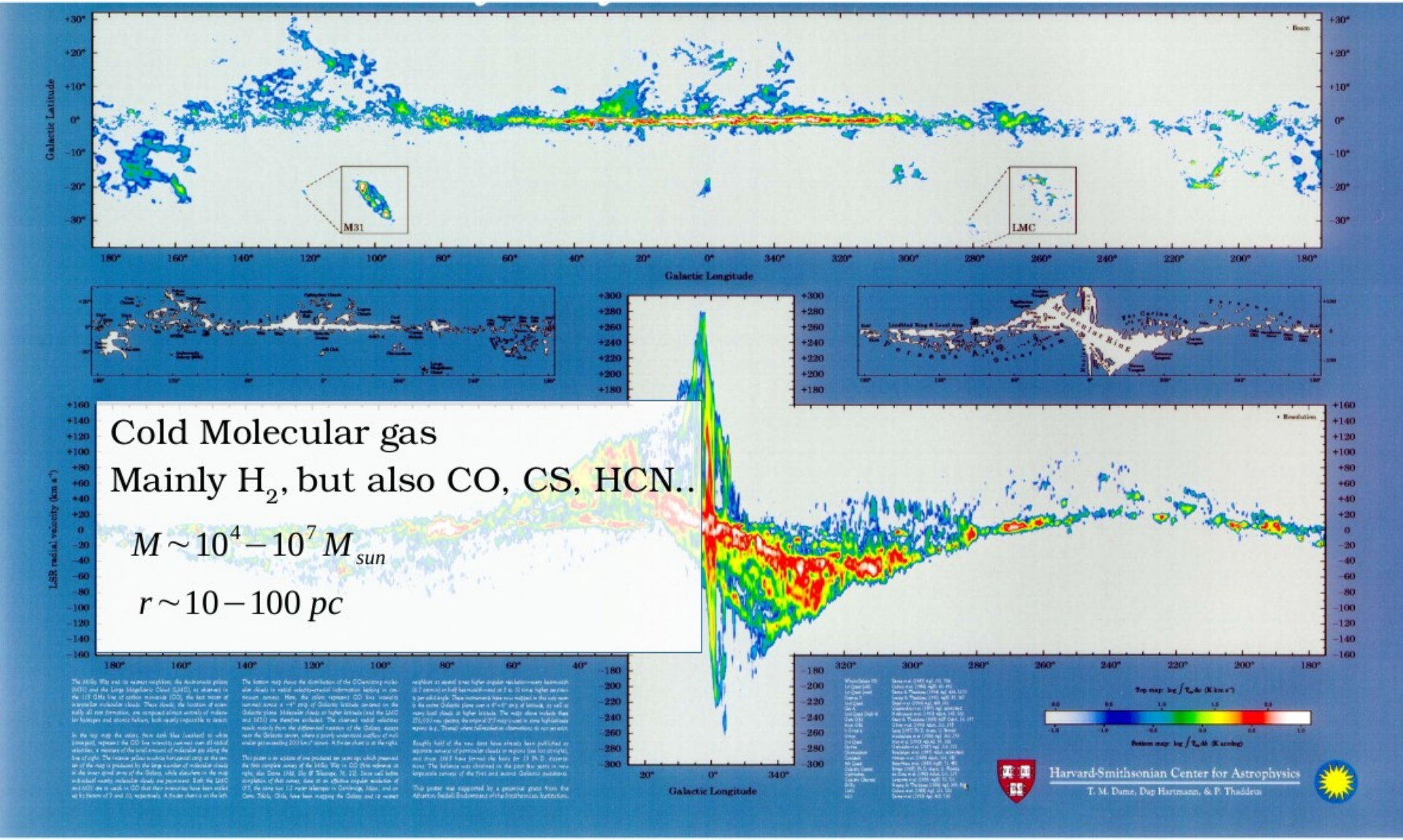




Why Molecular Clouds?

Molecular Clouds

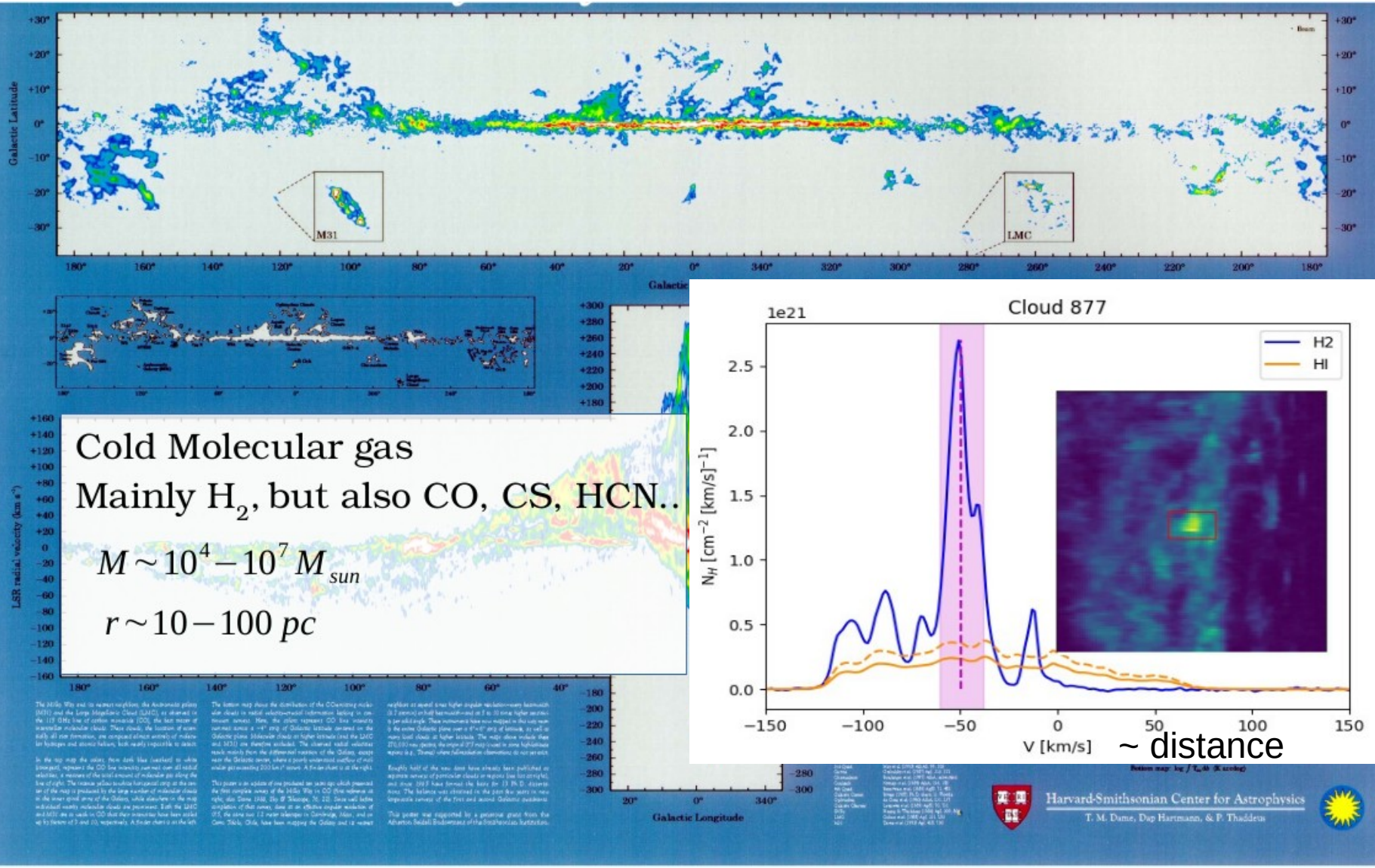
Aharonian+1991
Aharonian+2001
Casanova+2010



Dame+2001

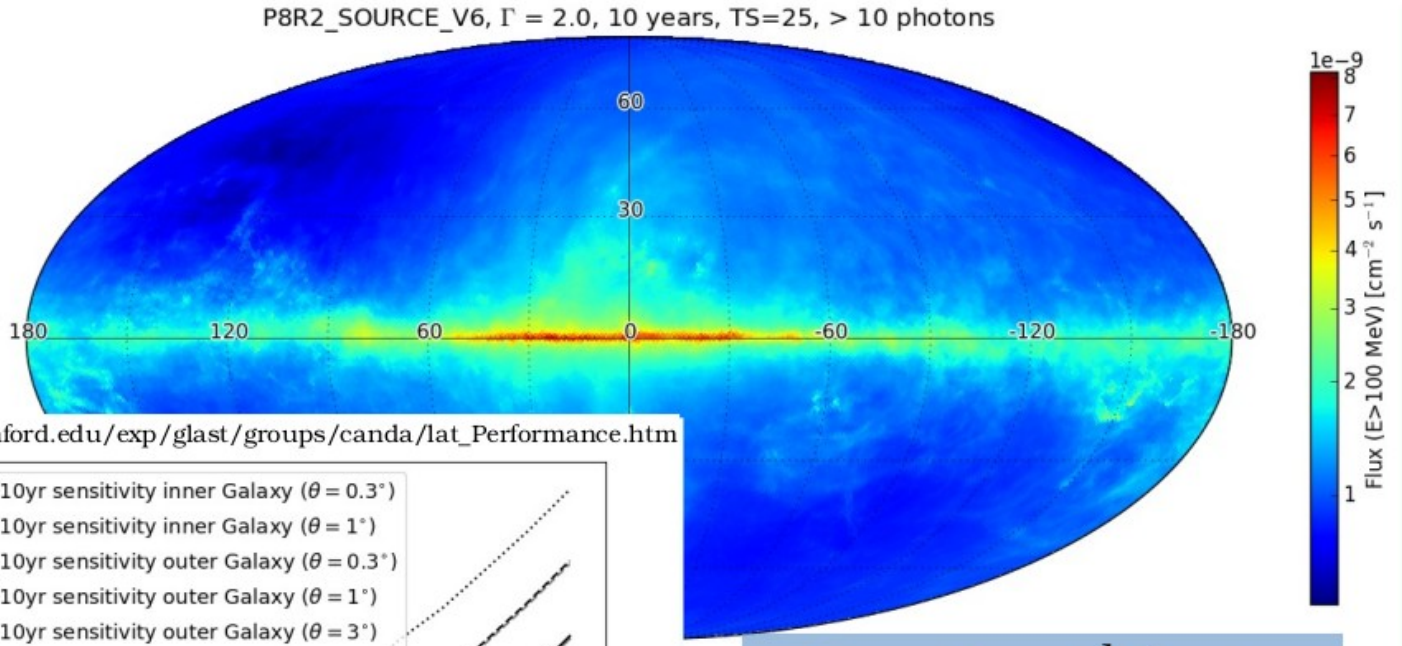
Molecular Clouds

Aharonian+1991
Aharonian+2001
Casanova+2010

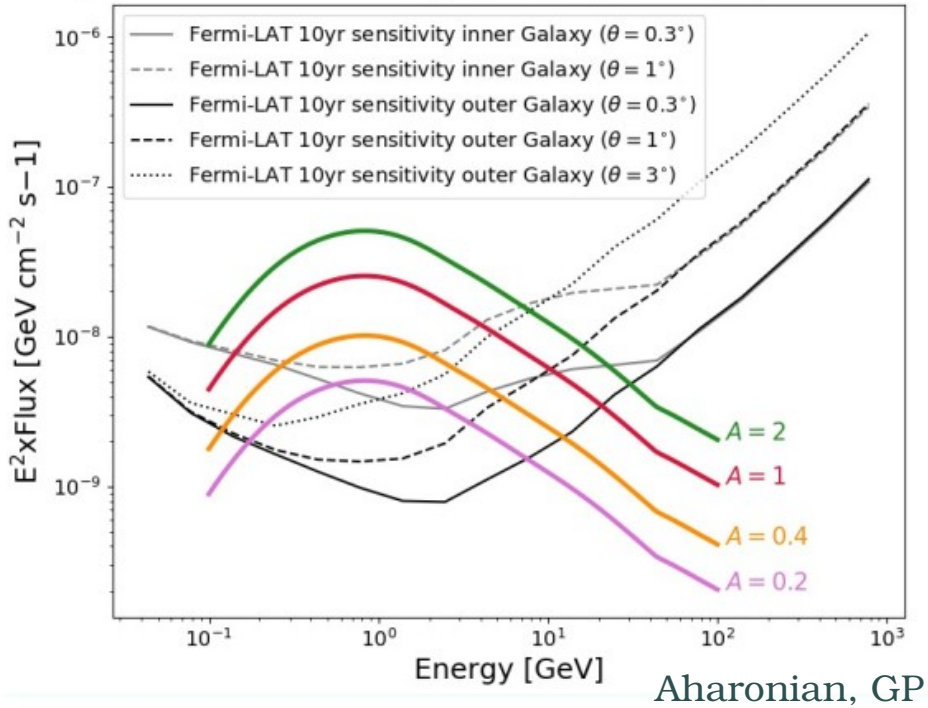


Dame+2001

Molecular Clouds vs. Fermi-LAT



http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm



$$F_\gamma^{MC} \propto A \int dE_p \frac{d\sigma}{dE_\gamma} F_p(E_p) \qquad \left(A \equiv \frac{M_5}{d_{kpc}^2}\right)$$

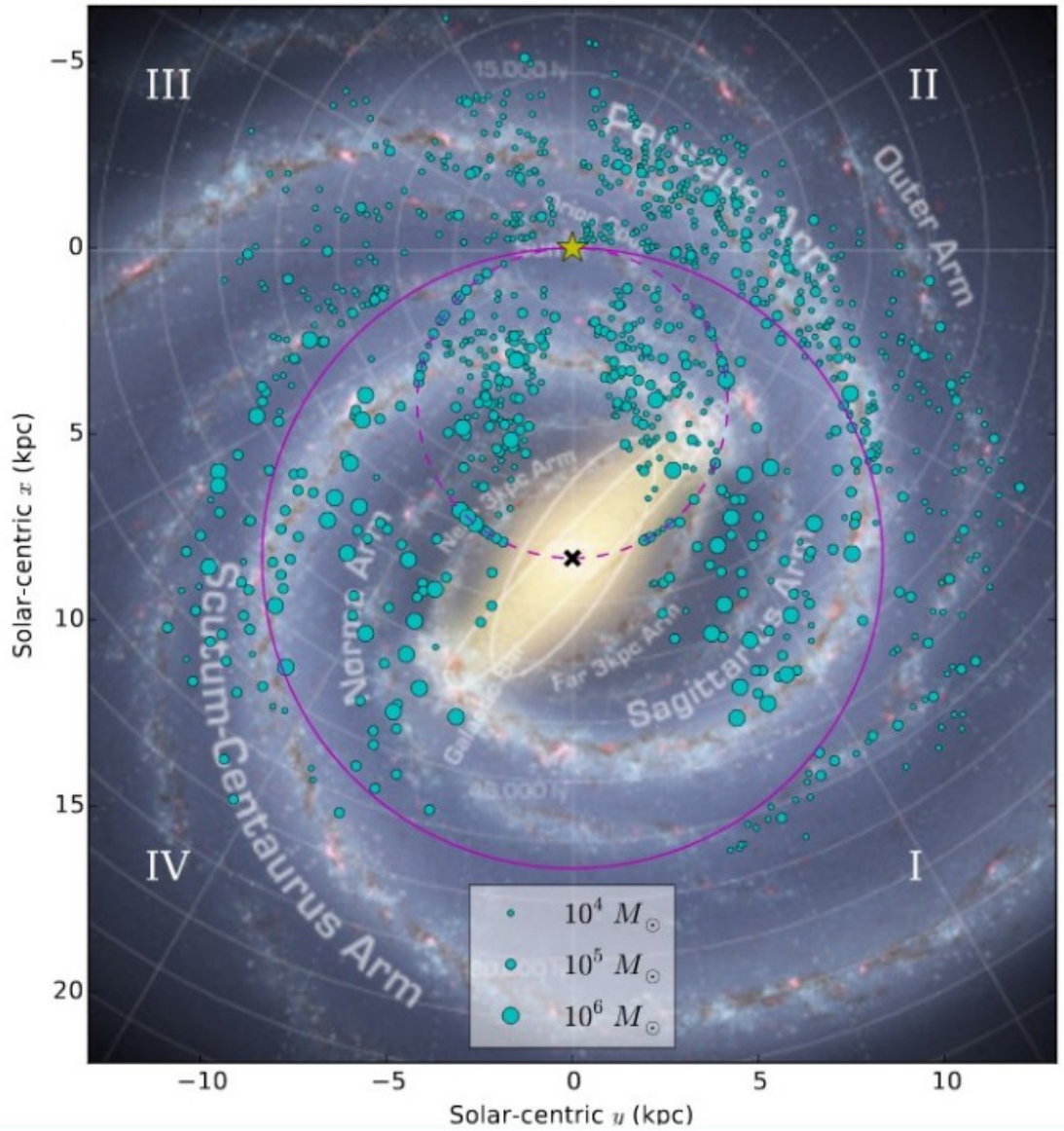
Kafexhiu+2014 AMS02 2015

$$sens_{wide} \approx sens_{point} \frac{\sqrt{\sigma_{PSF}^2 + \theta^2}}{\sigma_{PSF}}$$

Aharonian, GP et al. 2019 (submitted to PRD)

Which Molecular Clouds?

Rice+2016



Well known:

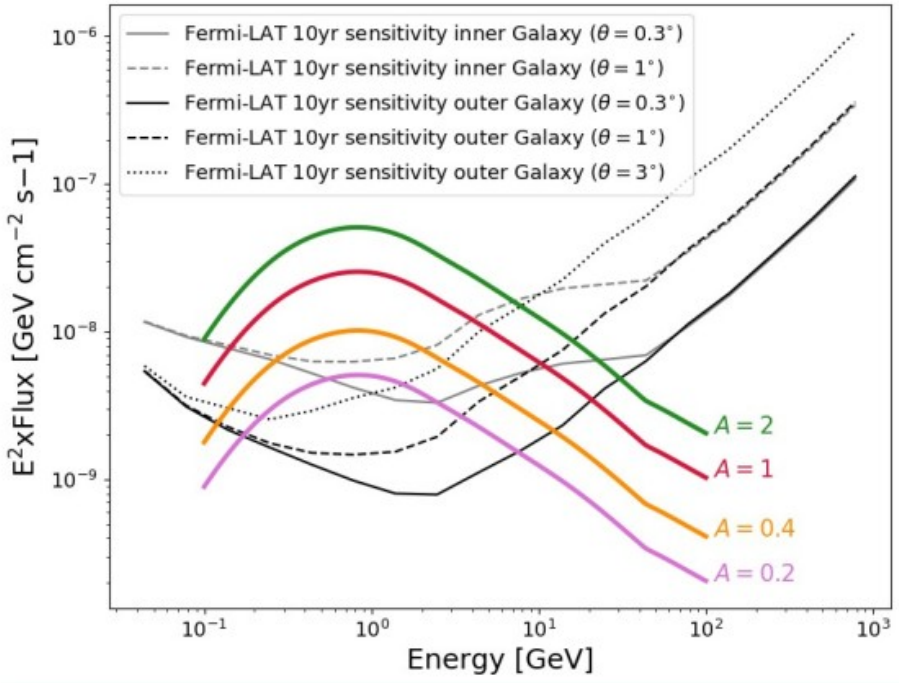
- Gould Belt Clouds
- Central Molecular Zone

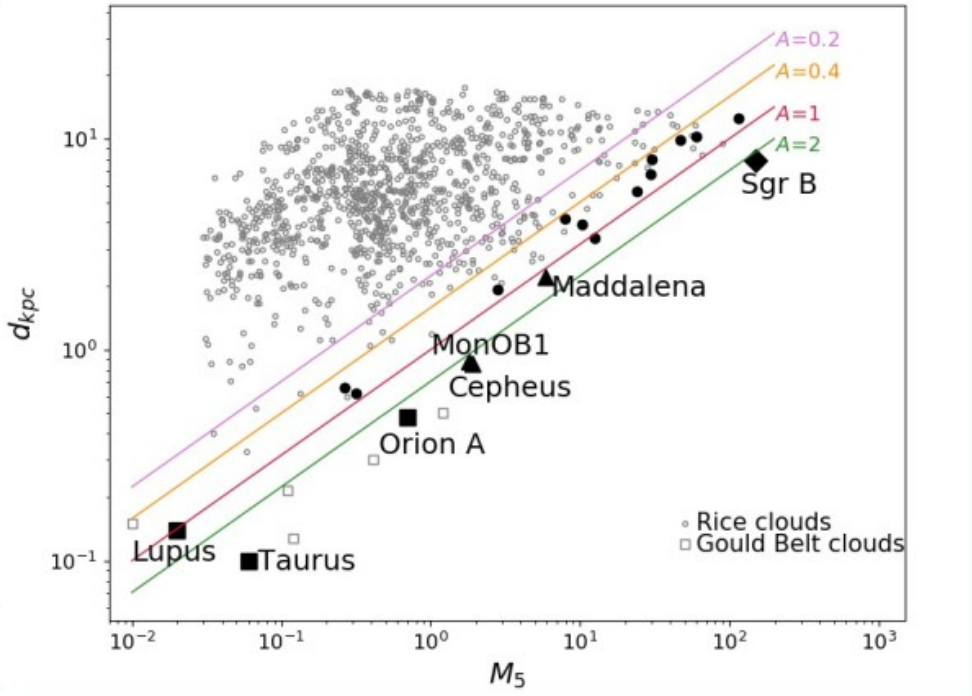
Recent:

- Identification of 1064 molecular clouds (Rice+2016)
- New determination of the distance (Schlafly+2014, updated by Zucker+2019)

Which Molecular Clouds?

We want our clouds to be massive and close:
threshold on A due to Fermi-LAT sensitivity

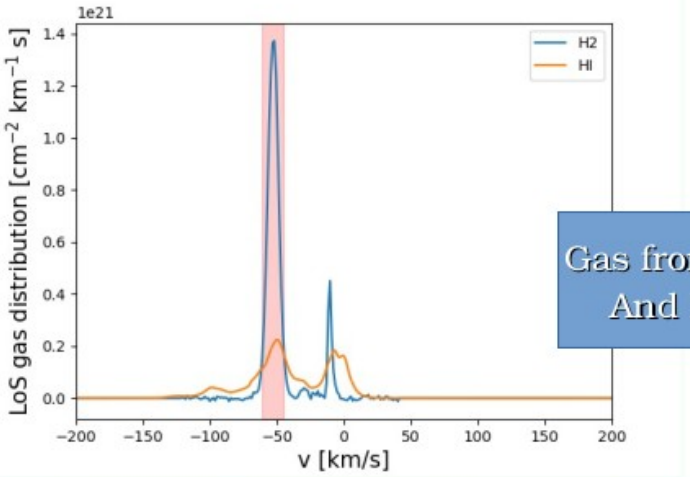


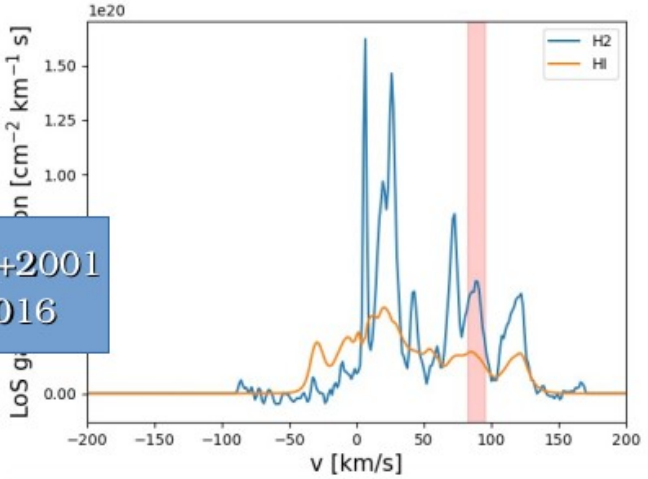


Aharonian, GP et al. 2019 (submitted to PRD)

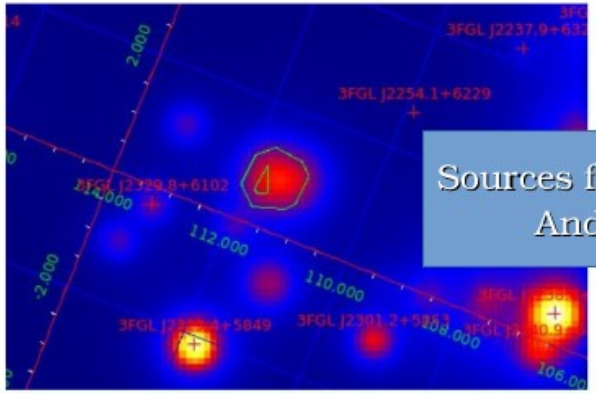
Which Molecular Clouds?

We discarded clouds that had
Other sources in the line of sight

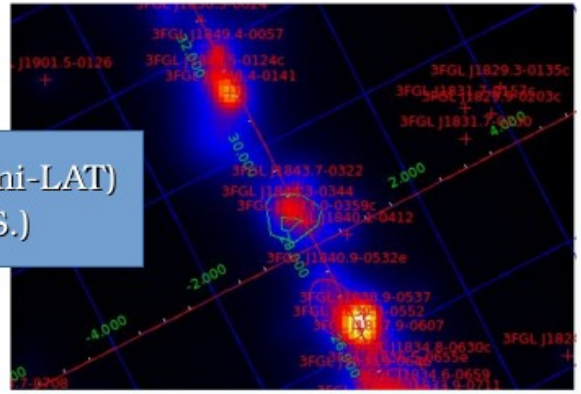


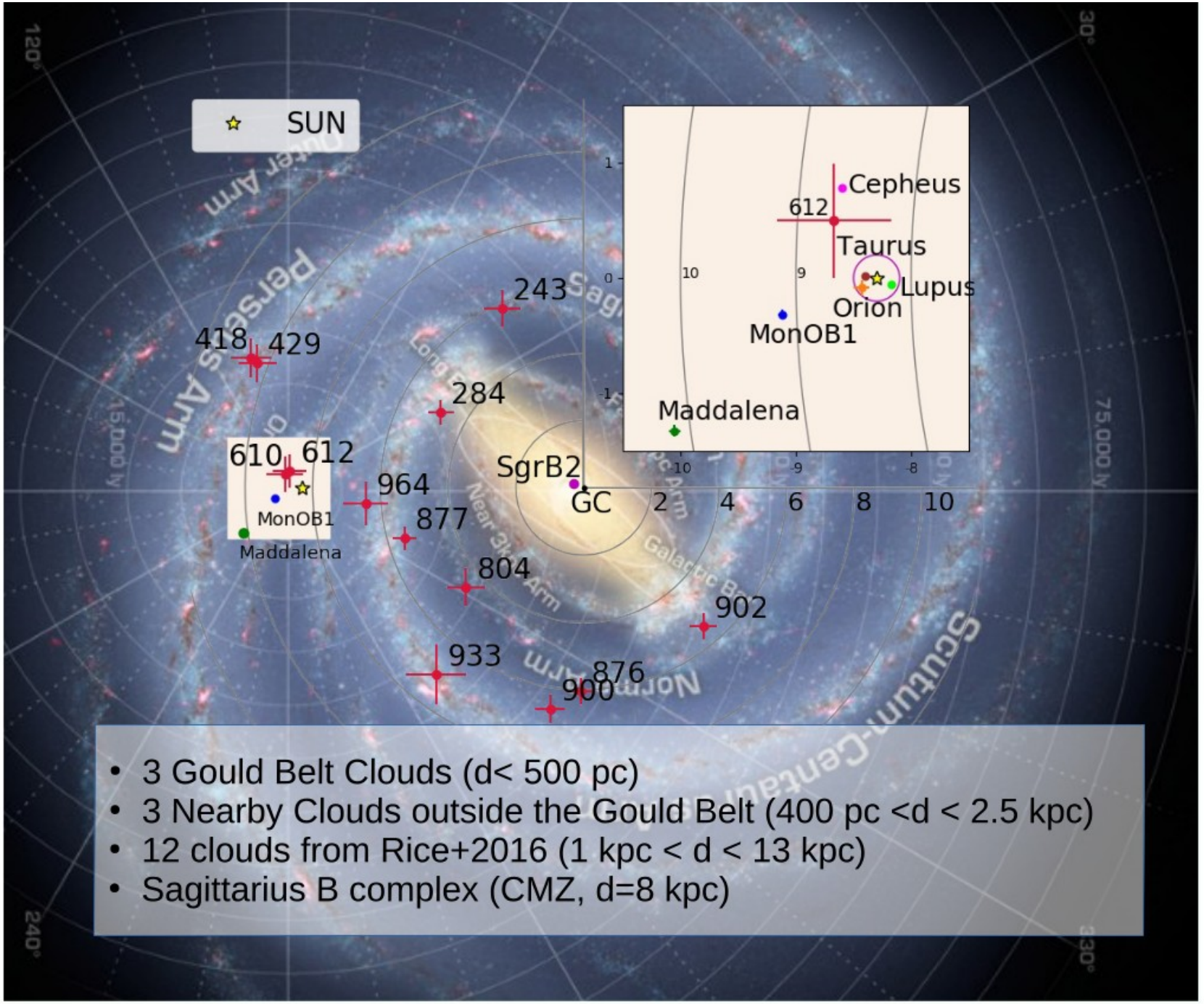


Gas from Dame+2001
And HI4PI+2016



Sources from 3FGL (Fermi-LAT)
And HGPS (H.E.S.S.)





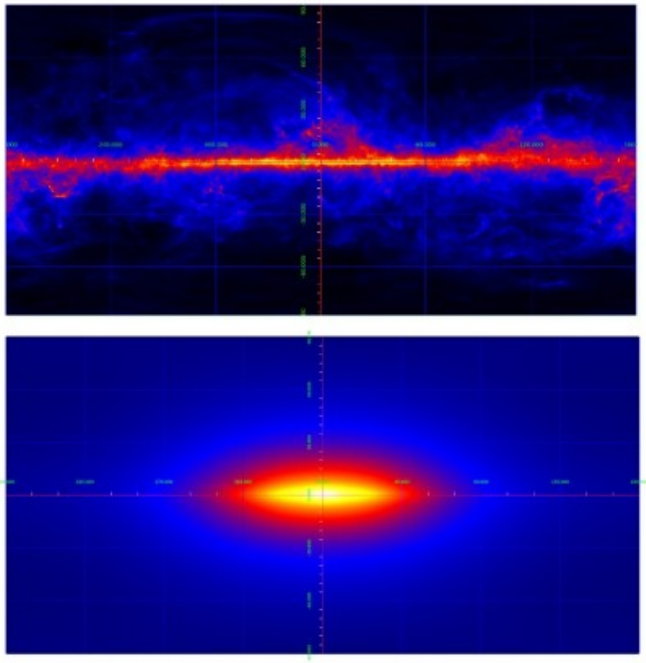
- 3 Gould Belt Clouds (d< 500 pc)
- 3 Nearby Clouds outside the Gould Belt (400 pc <d < 2.5 kpc)
- 12 clouds from Rice+2016 (1 kpc < d < 13 kpc)
- Sagittarius B complex (CMZ, d=8 kpc)

Fermi-LAT analysis

- Data type: Pass8, evtype=3, evclass=128, zmax=90°
- Time: > 9 years of data
- ROI: 10° x 10°
- Energy range : >800 MeV

BACKGROUND:

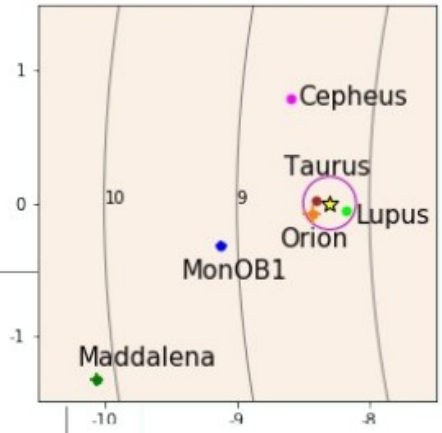
- Diffuse Gas emission (Pion Decay)
  - Planck dust opacity 2D map for nearby clouds
  - HI 3D map from HI4PI (2016)
    + CO 3D map from Dame+2001
- Inverse Compton scattering (galprop v54)
- Isotropic extragalactic diffuse: computed by fitting a region of 30 degrees centered in l,b=(150°,90°)
- Sources from 3FGL (Fermi catalog)

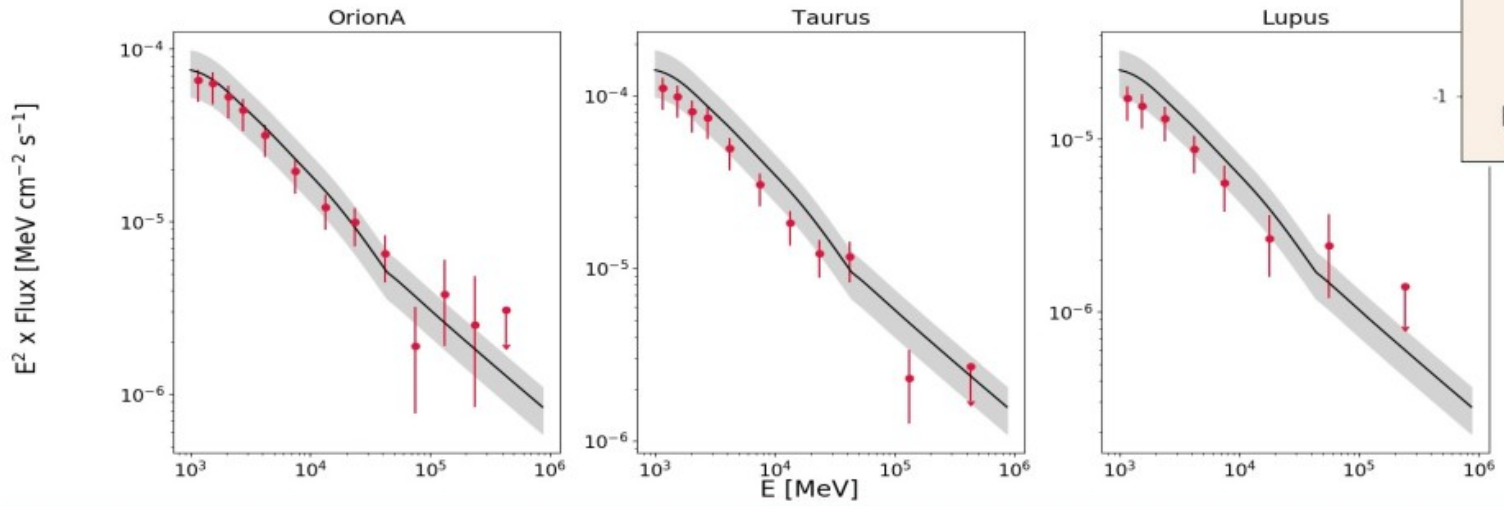


Results….

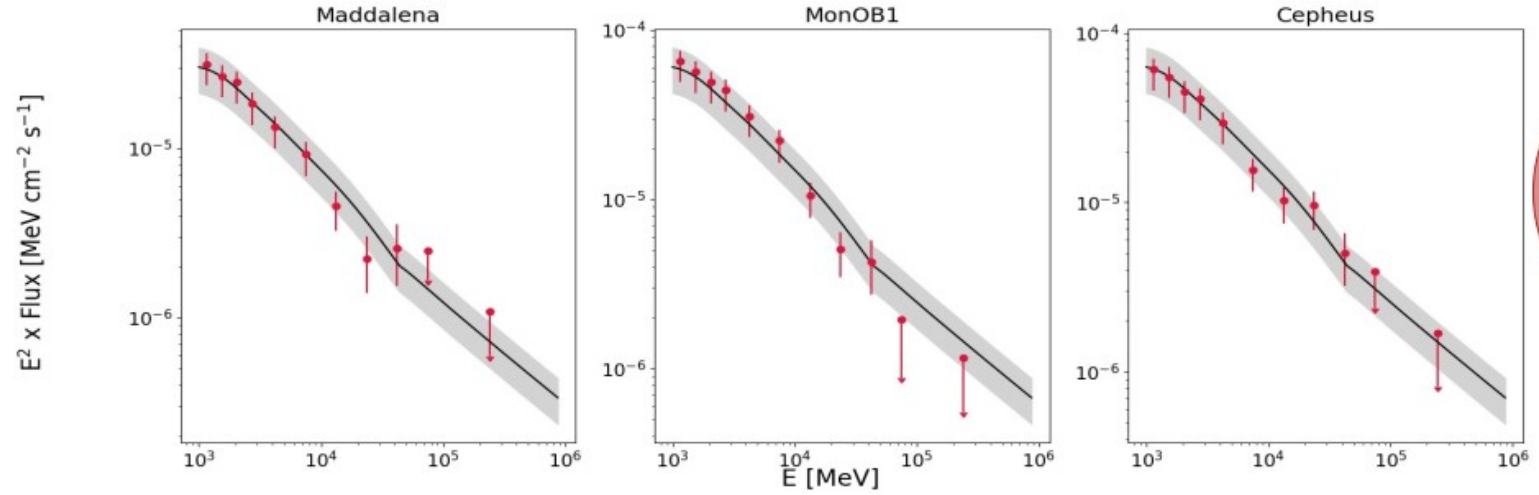
Aharonian, GP et al. 2019 (submitted to PRD)

Gould Belt results are consistent with what found by others (Yang+2014,Neronov+2017)





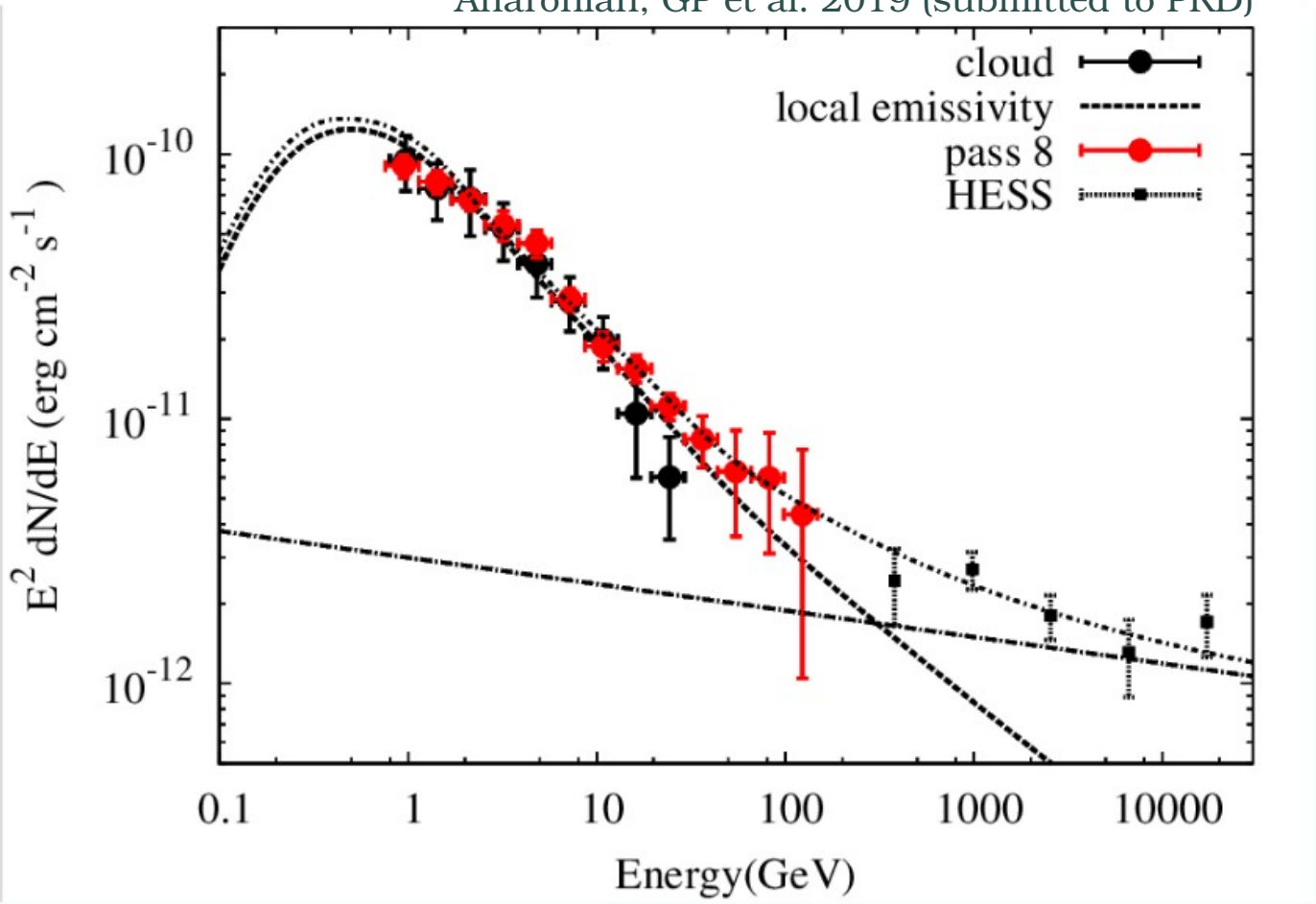
We find the same behaviour for nearby clouds outside of the Gould Belt



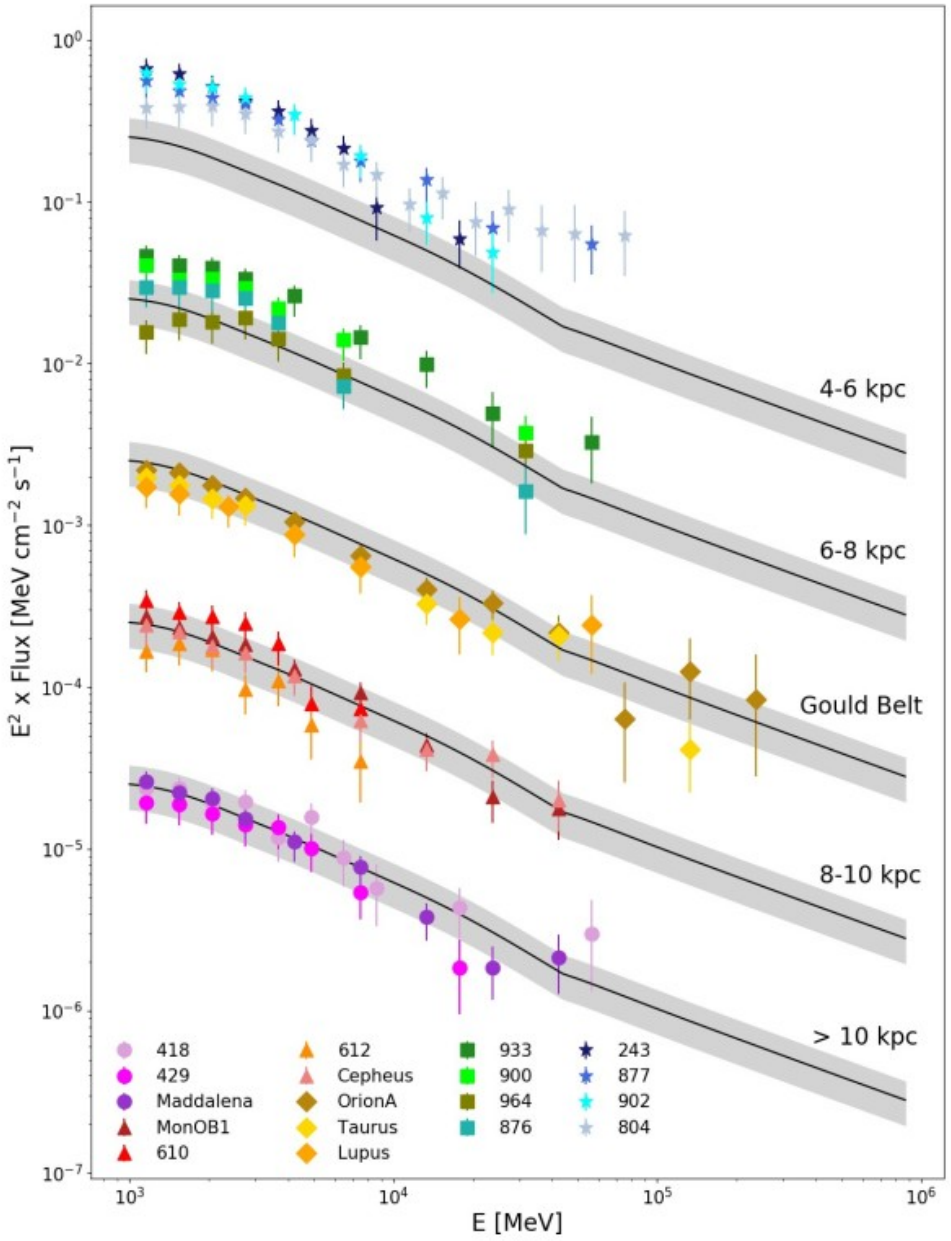
Consistent With AMS02 !

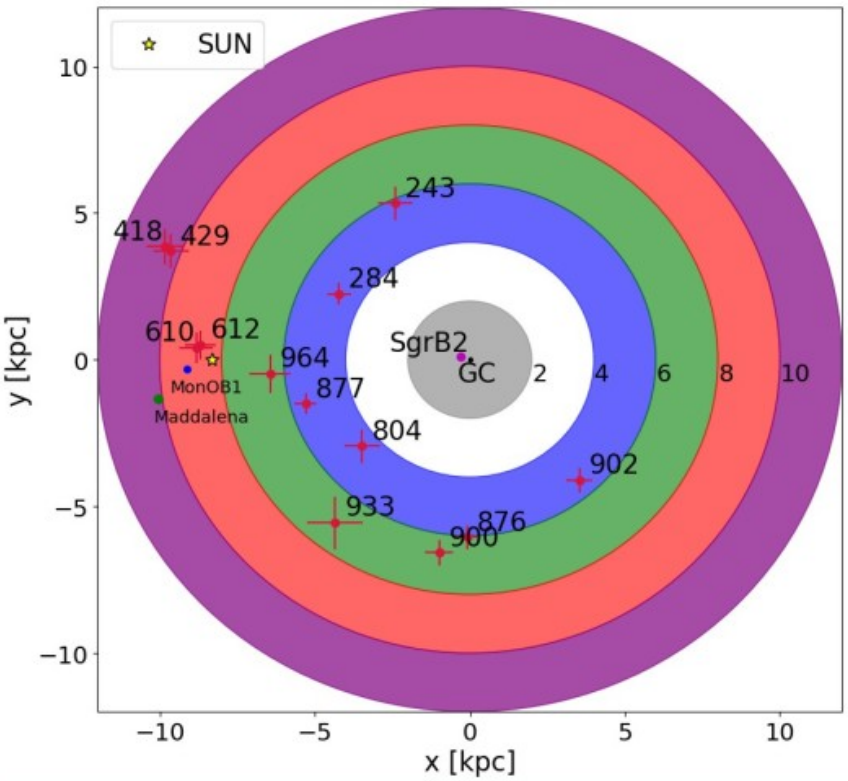
Sagittarius B complex

Aharonian, GP et al. 2019 (submitted to PRD)



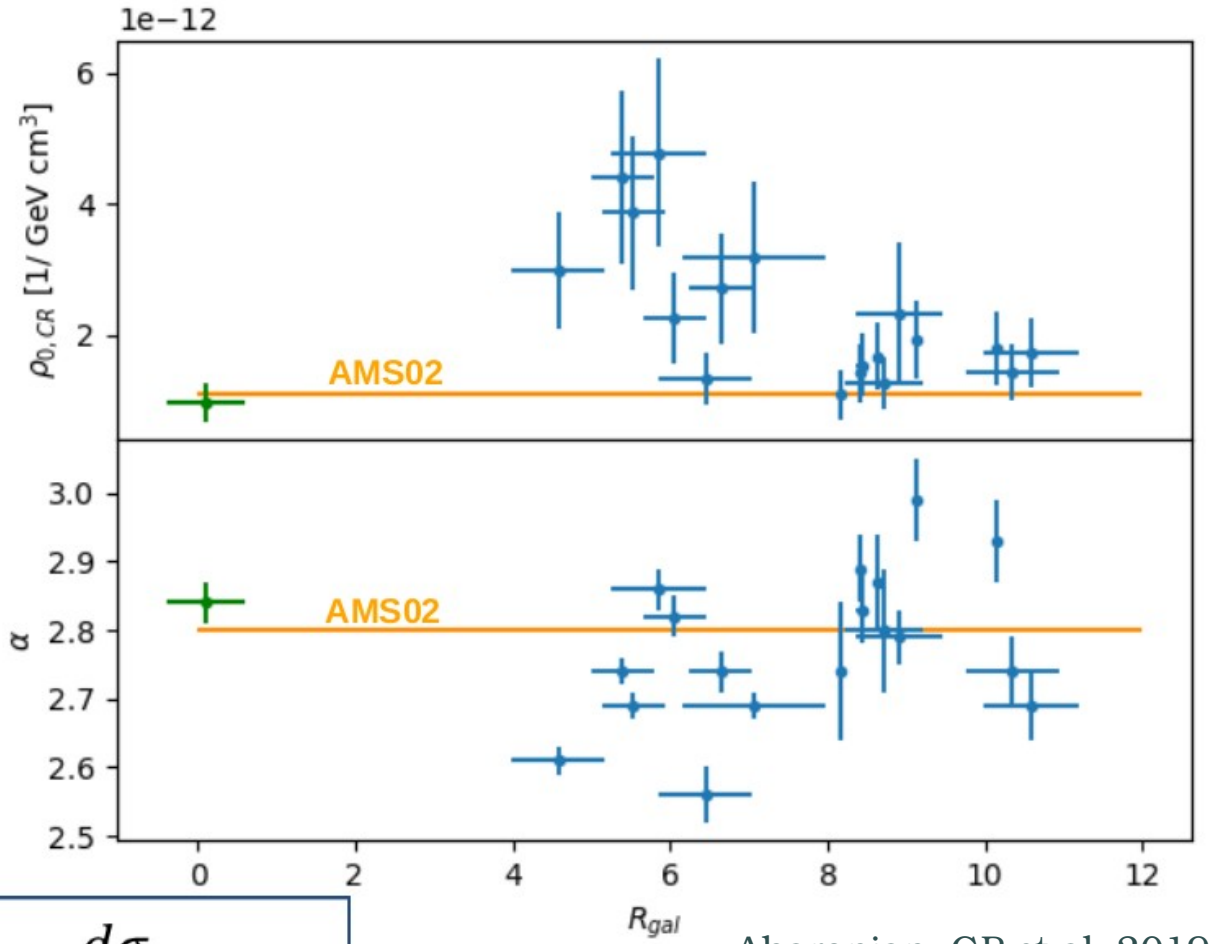
Consistency with AMS02 local spectrum even in the GC





Aharonian, GP et al. 2019 (submitted to PRD)

Cosmic Ray Parameters across the Galaxy



$$F_\gamma \propto \int dE \, \frac{d\sigma}{dE} \boldsymbol{\rho_{CR}}$$

(naima, Zabalza 2015)

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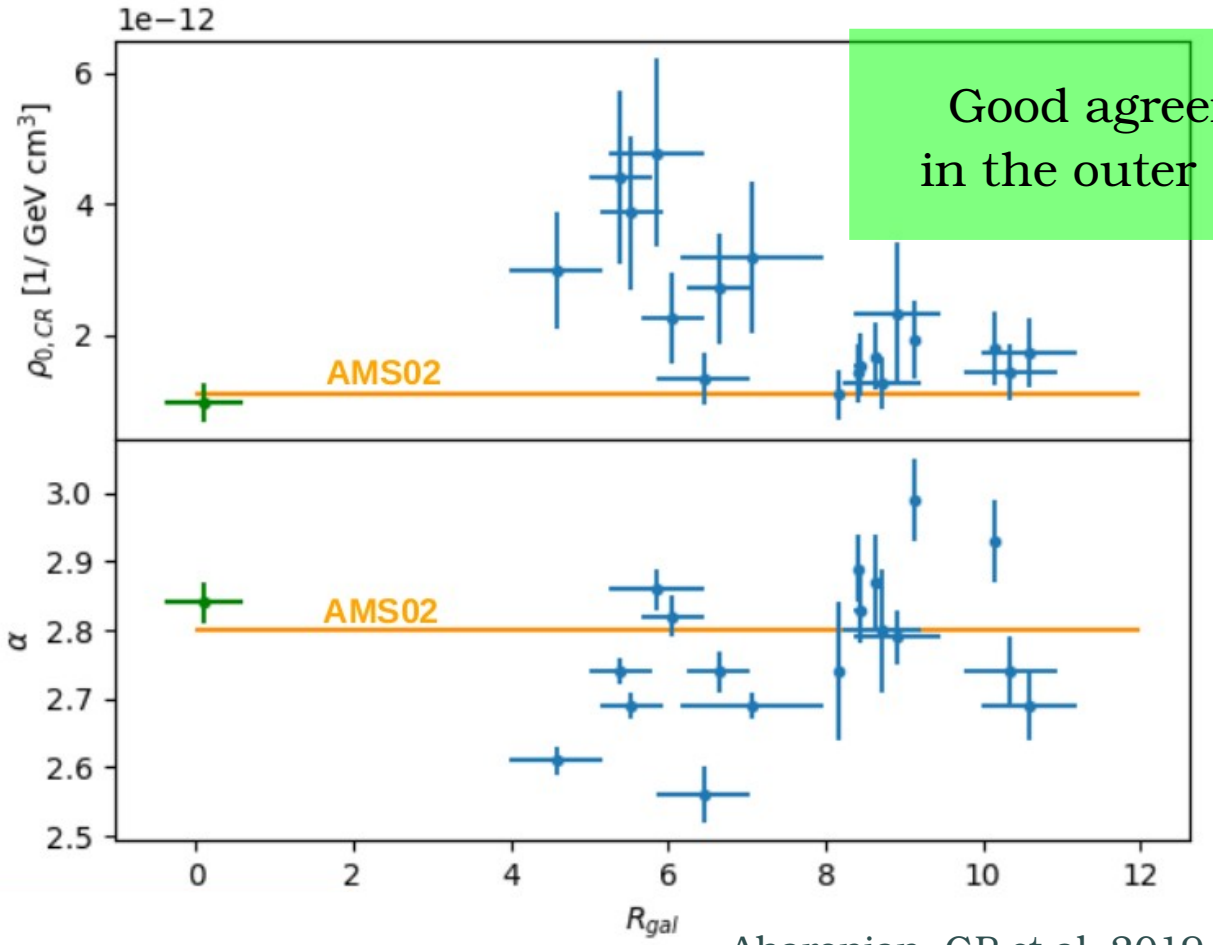


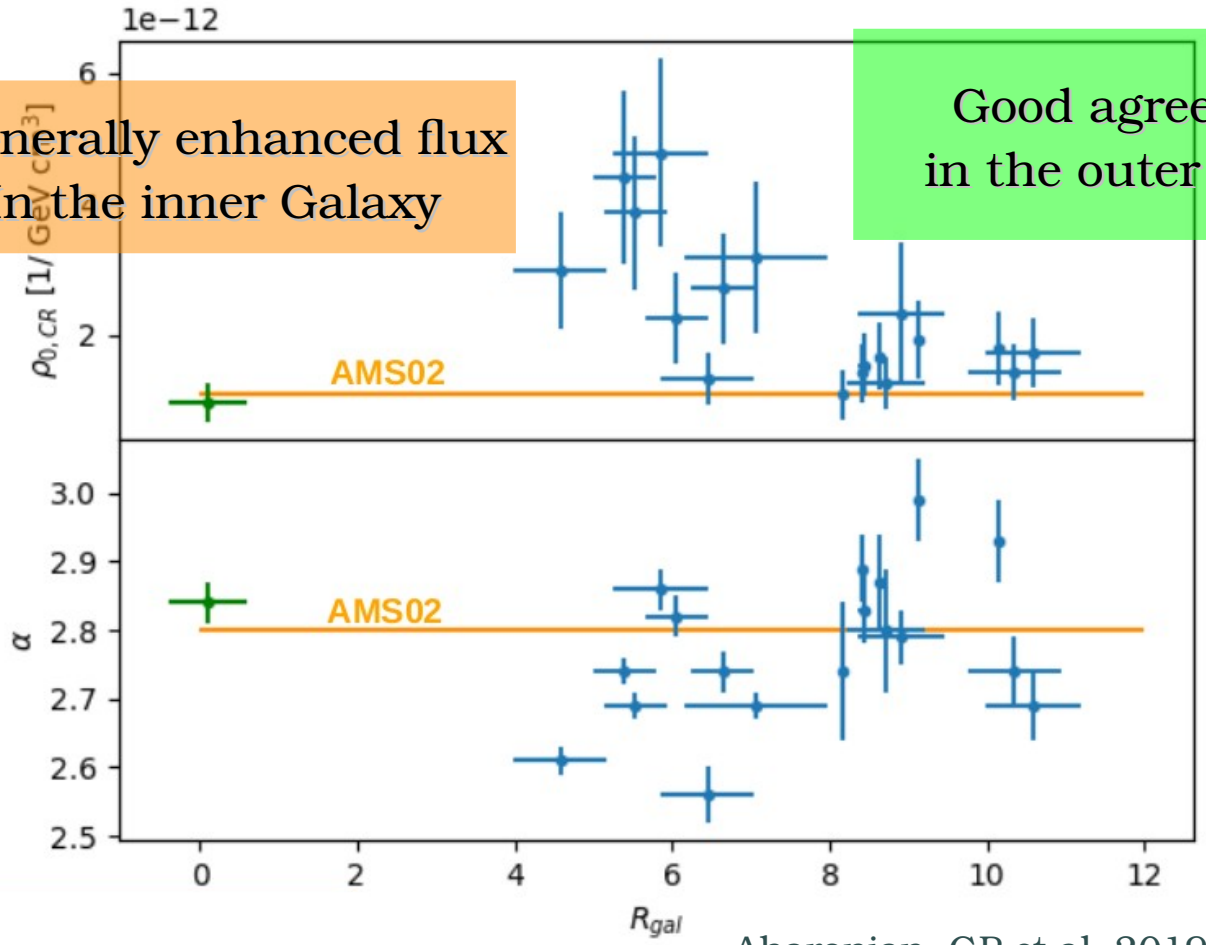
Good agreement
in the outer Galaxy

Aharonian, GP et al. 2019 (submitted to PRD)

Cosmic Ray Parameters across the Galaxy

Generally enhanced flux
In the inner Galaxy

Good agreement
in the outer Galaxy

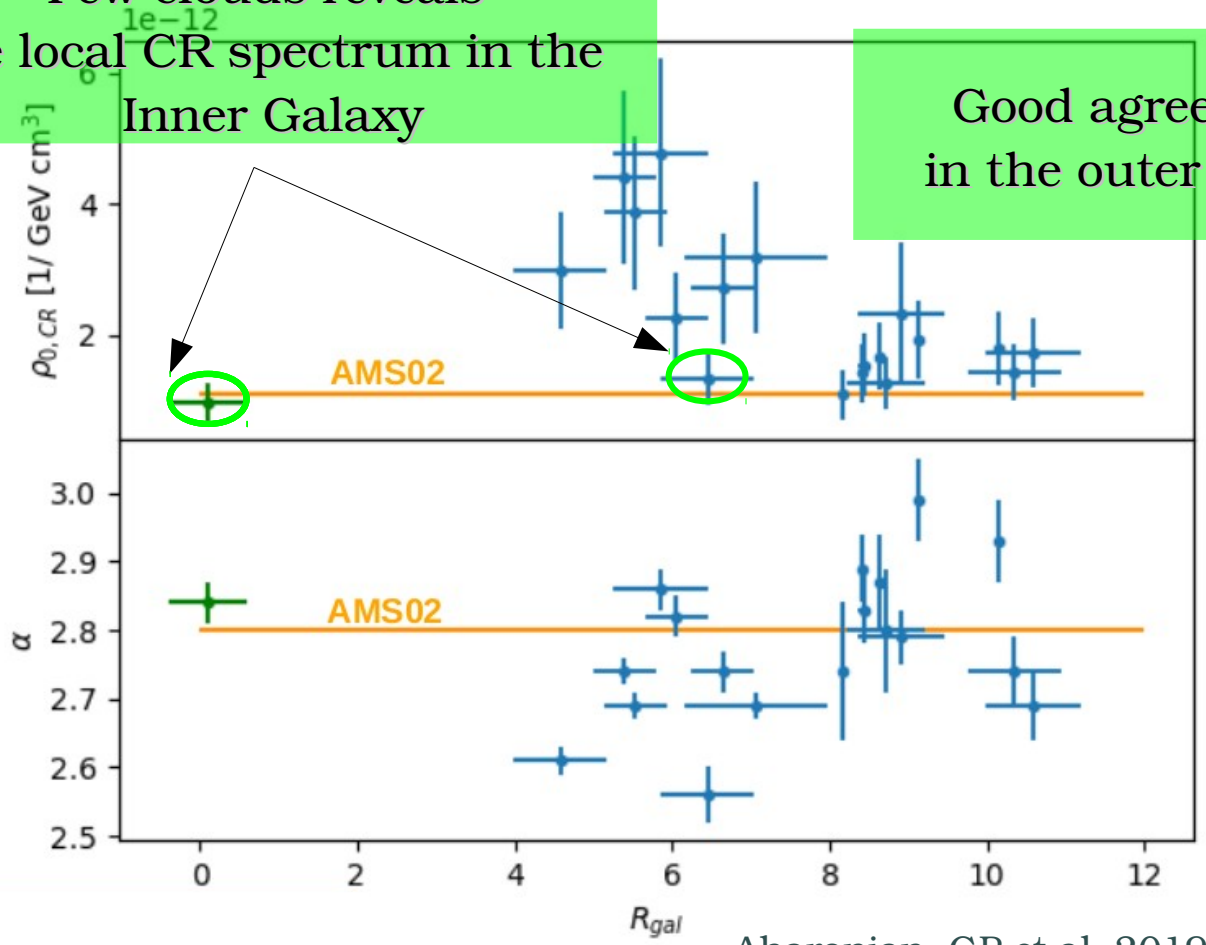


Aharonian, GP et al. 2019 (submitted to PRD)

Cosmic Ray Parameters across the Galaxy

Few clouds reveals the local CR spectrum in the Inner Galaxy

Good agreement in the outer Galaxy



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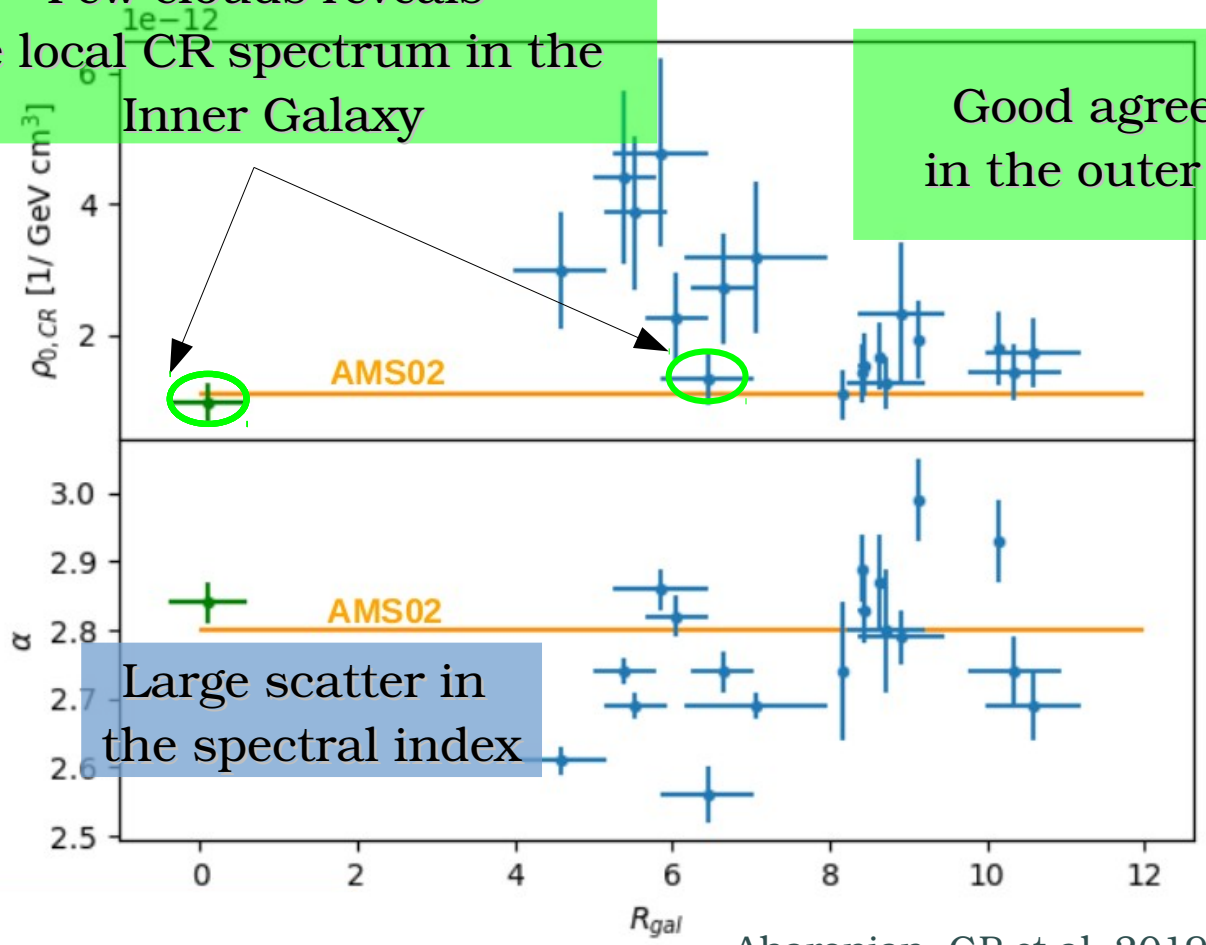

Large scatter in the spectral index

Aharonian, GP et al. 2019 (submitted to PRD)

Summary

- Molecular Clouds are the best way to derive CR properties in specific regions of the Galaxy;
- For the first time CR spectrum has been derived in specific location all around the Galaxy;
- Derived CR spectrum is compatible with the local (AMS02) data in different regions suggesting that there is actually a SEA;
- We see deviation in the form of 'excess', that can be due to local accelerator, we observe no sub-luminous cloud.
- Enhancement emission observed in the 4-6 kpc ring is interpreted as bigger density of CR accelerator in that region.