MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

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

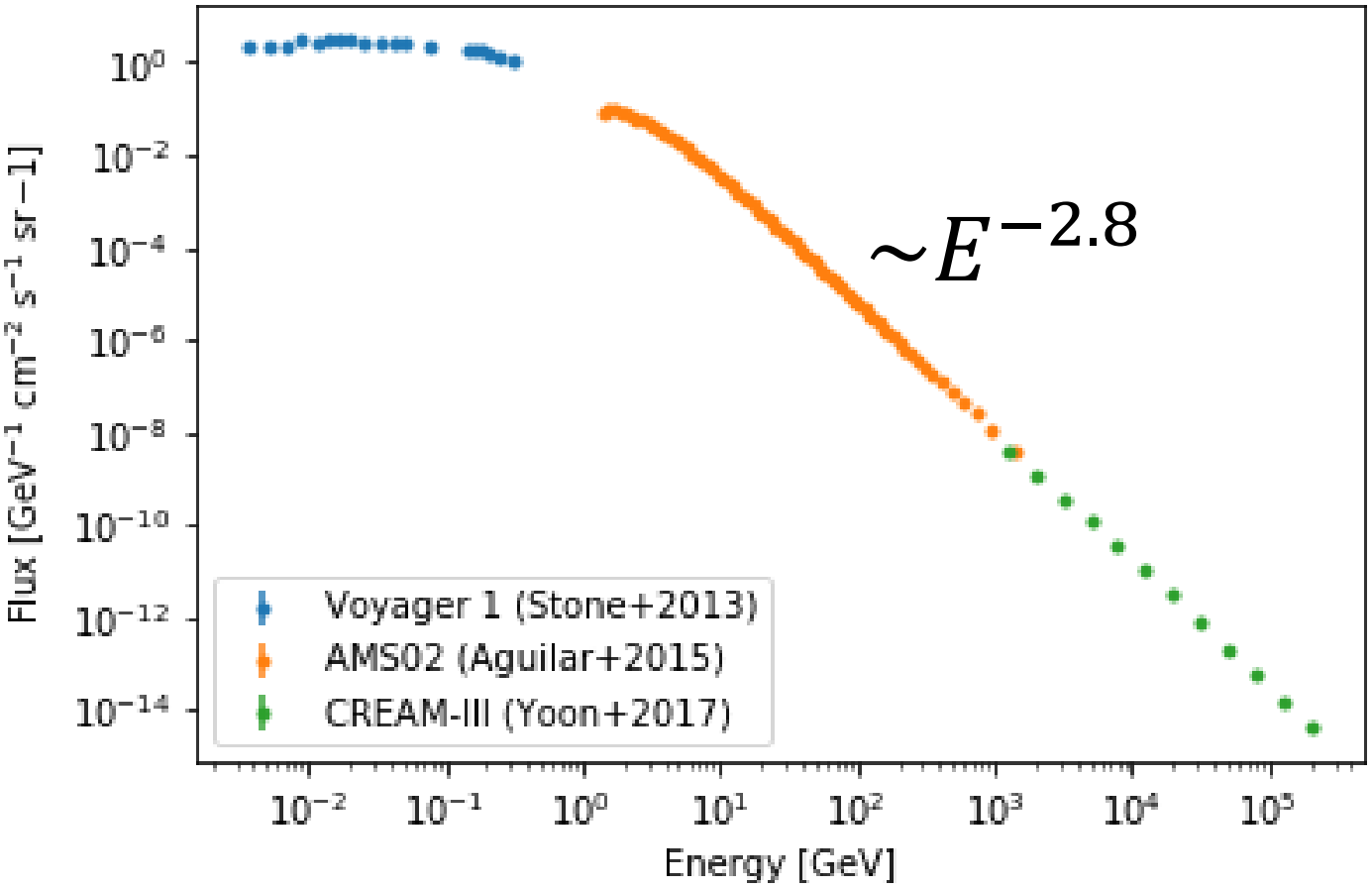
Giada Peron

Co-authors: F. Aharonian, R. Yang, R. Zanin, S. Casanova

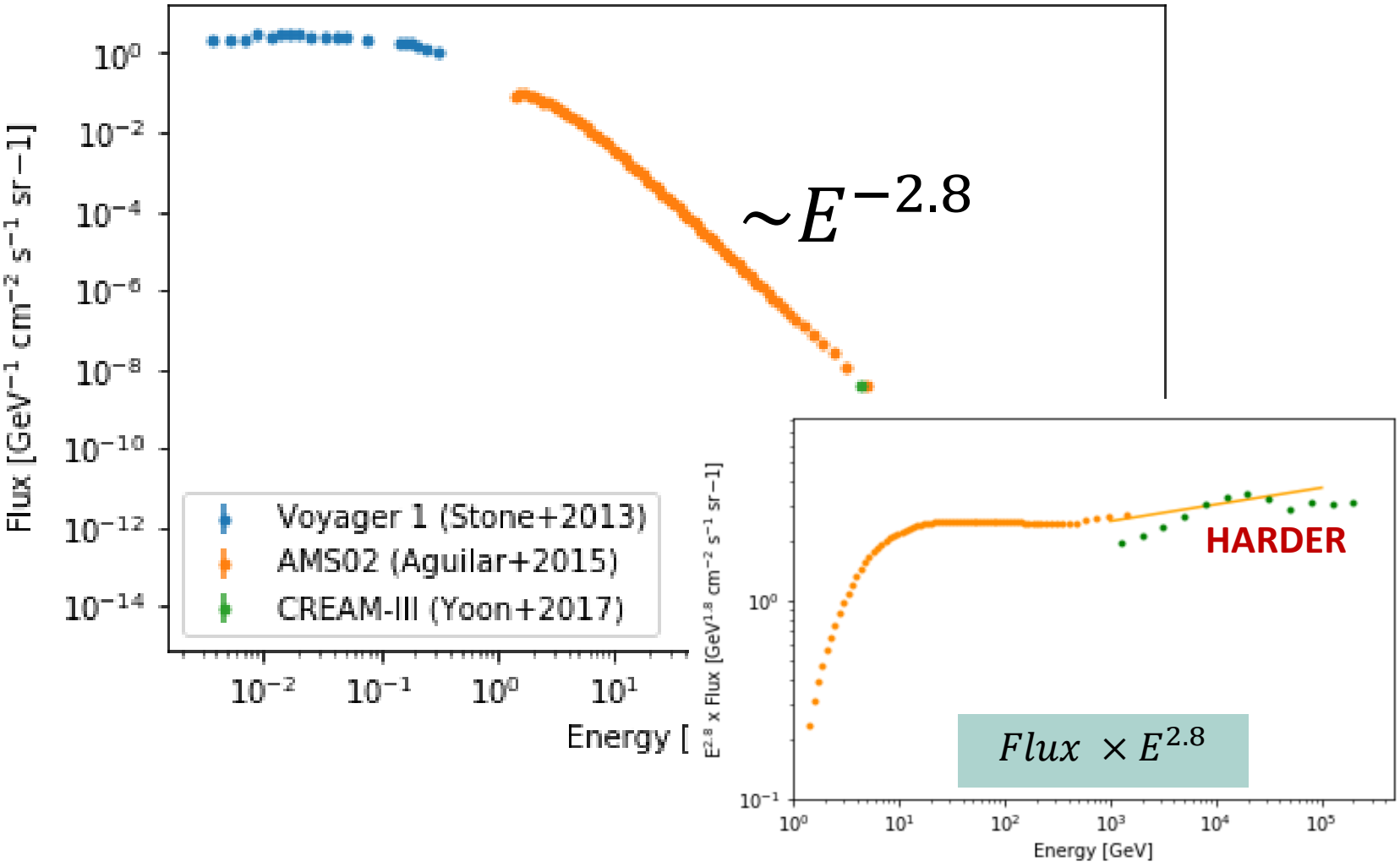
Outline

- Cosmic Rays (main spectral properties)
- Measuring Galactic CR with Gamma-Rays
- Molecular Clouds as CR barometer
- Fermi-LAT analysis of Gamma Ray data
- Results from Molecular Clouds
- Summary and Conclusion

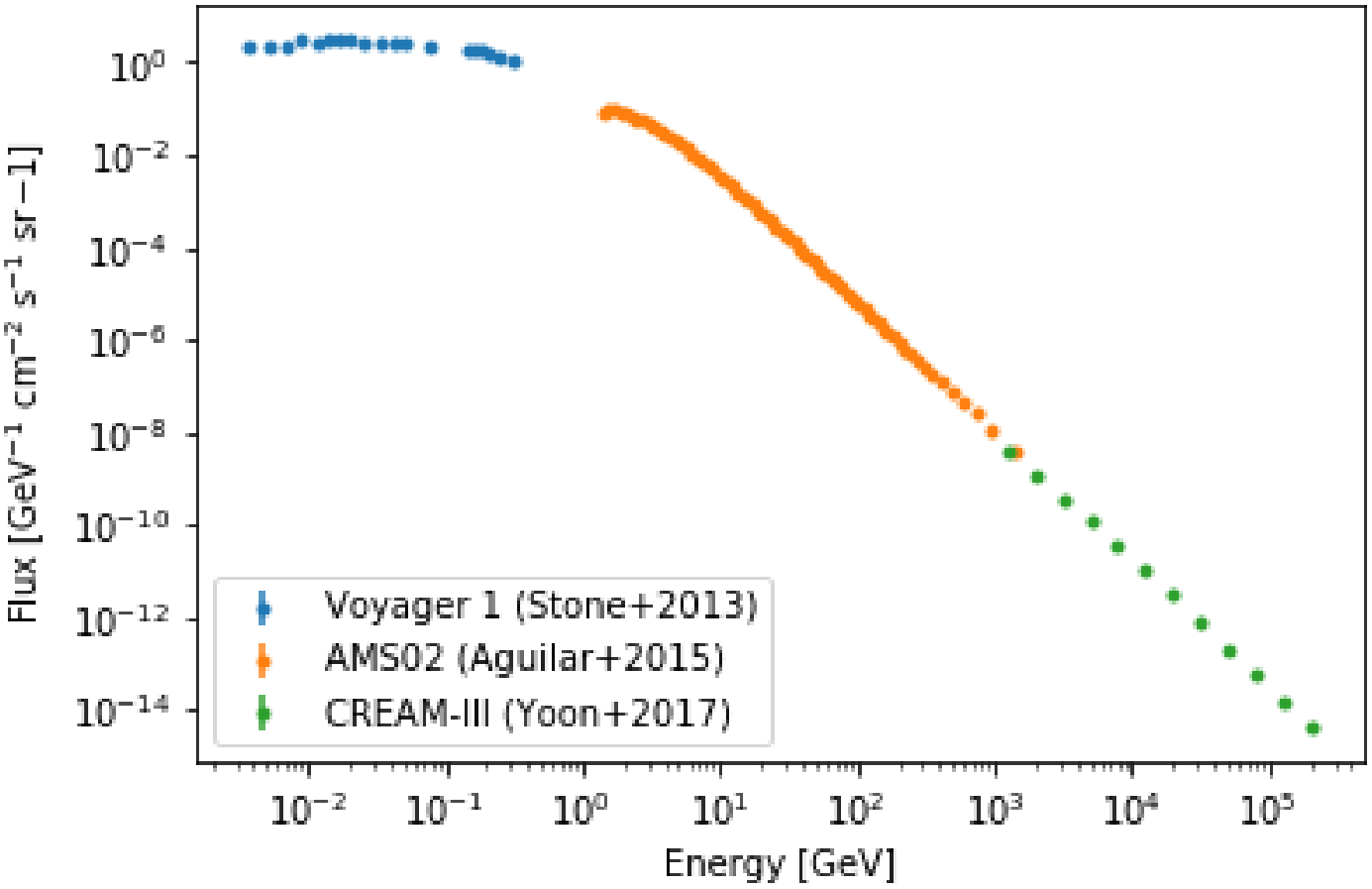
CR protons: the spectrum



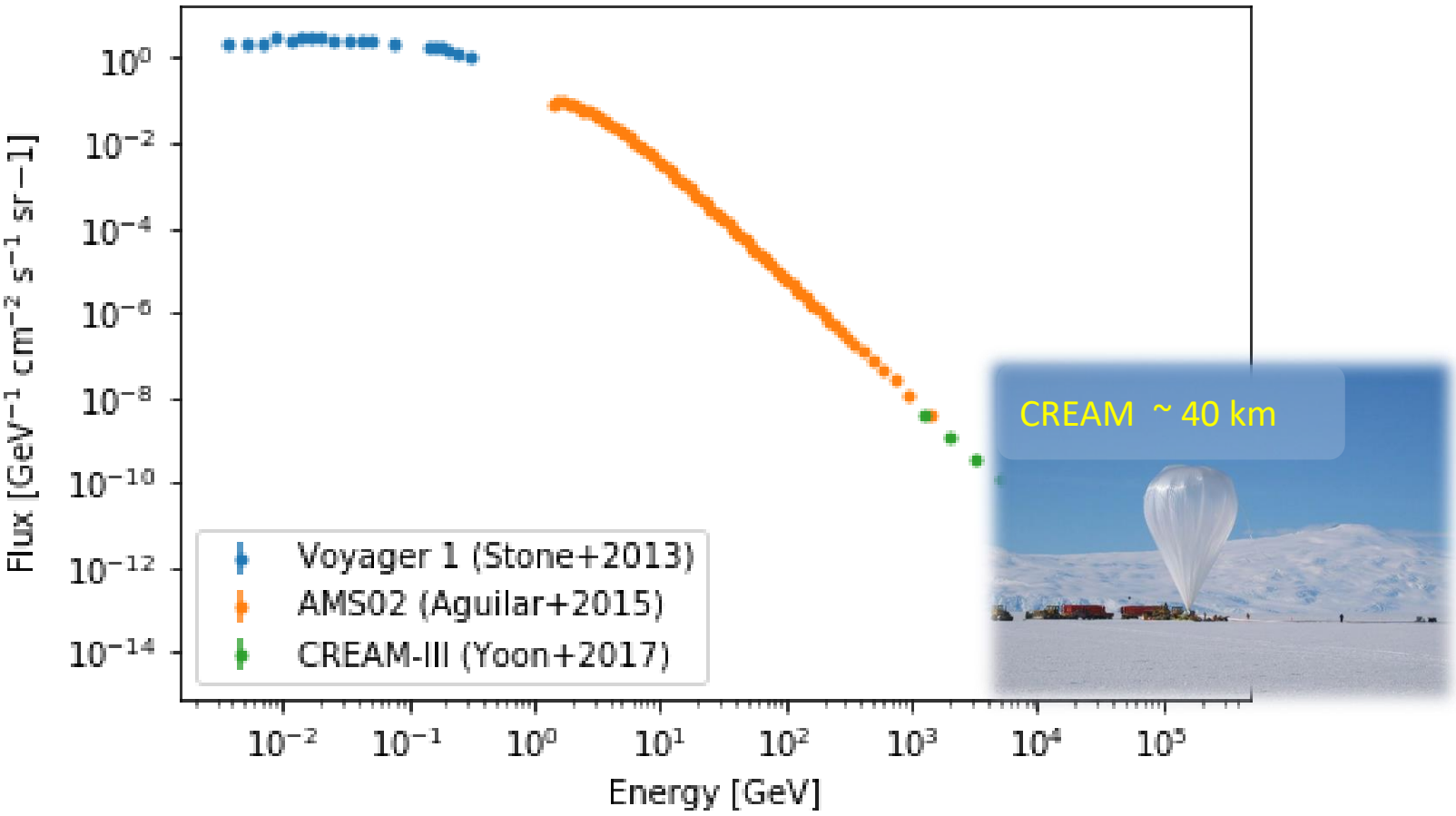
CR protons: the spectrum



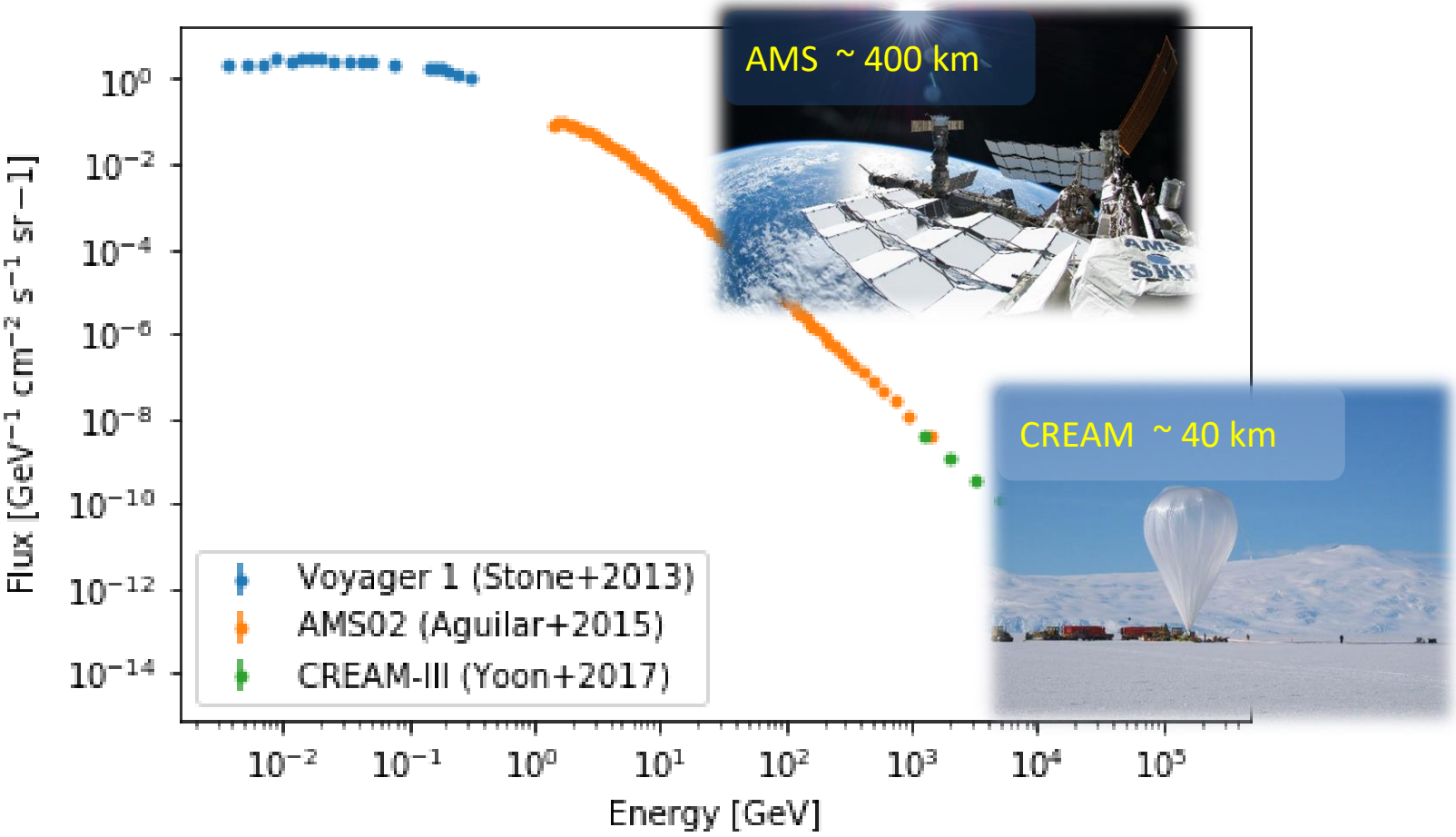
CR protons: the spectrum



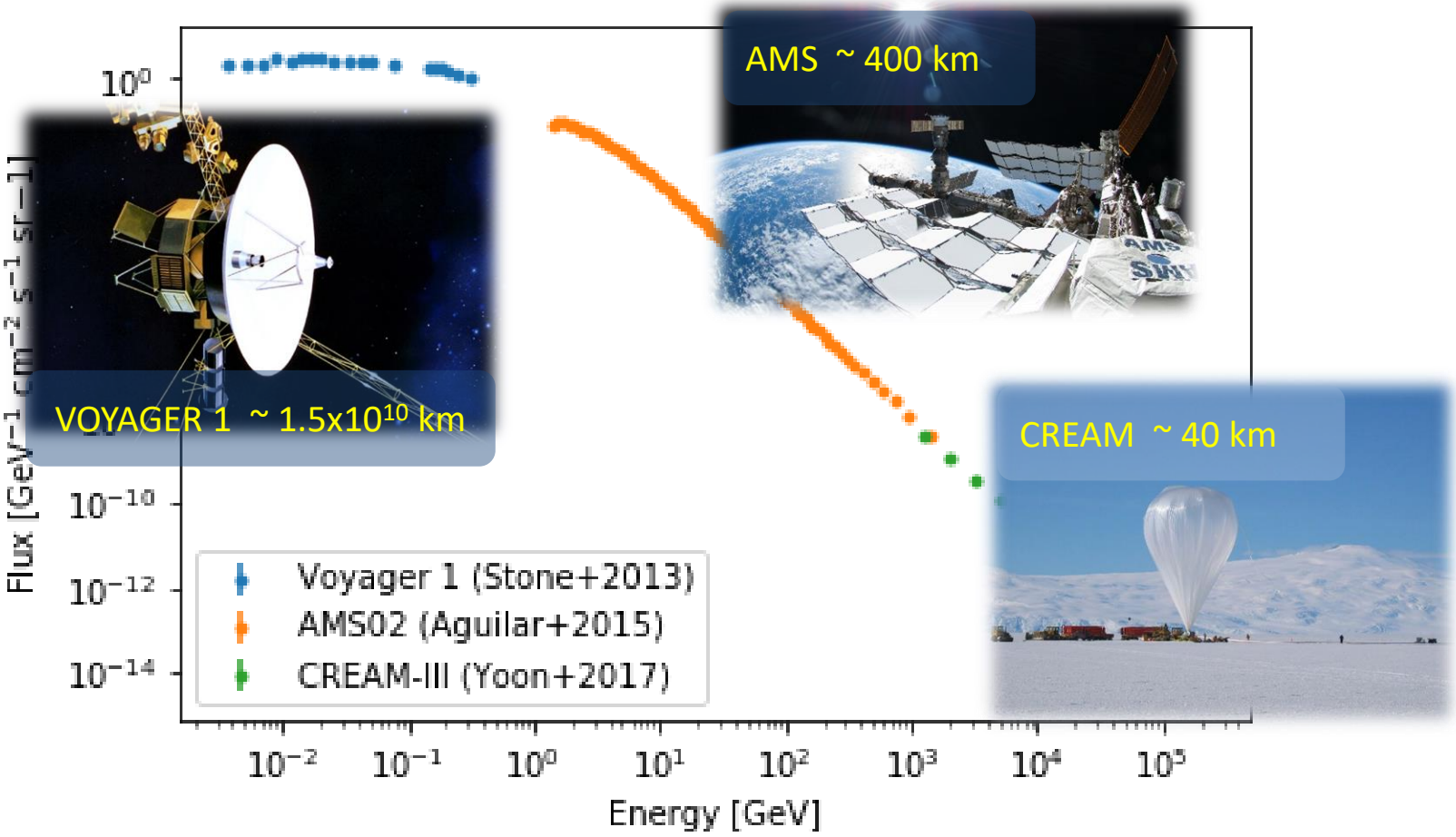
CR protons: the spectrum



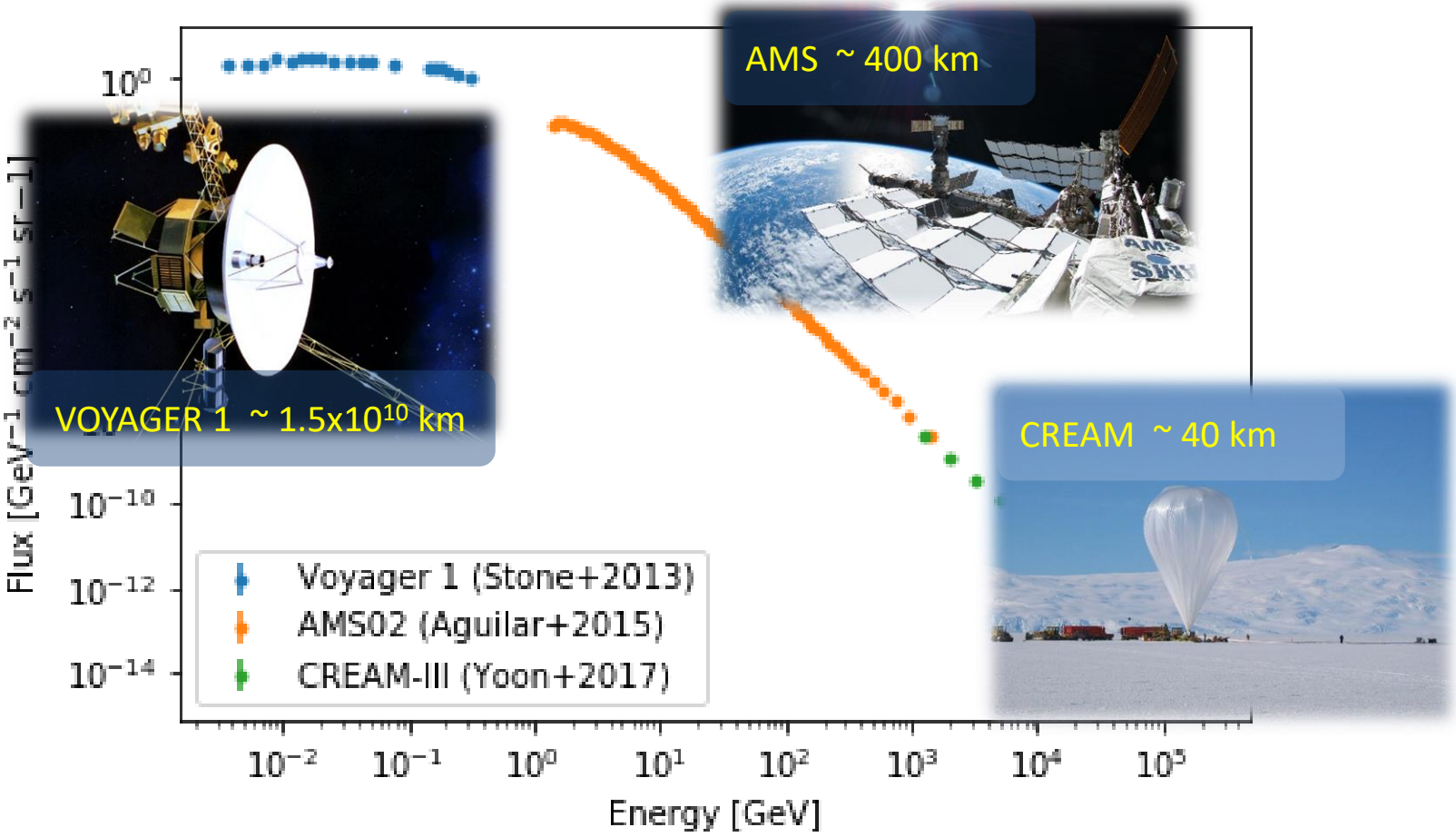
CR protons: the spectrum

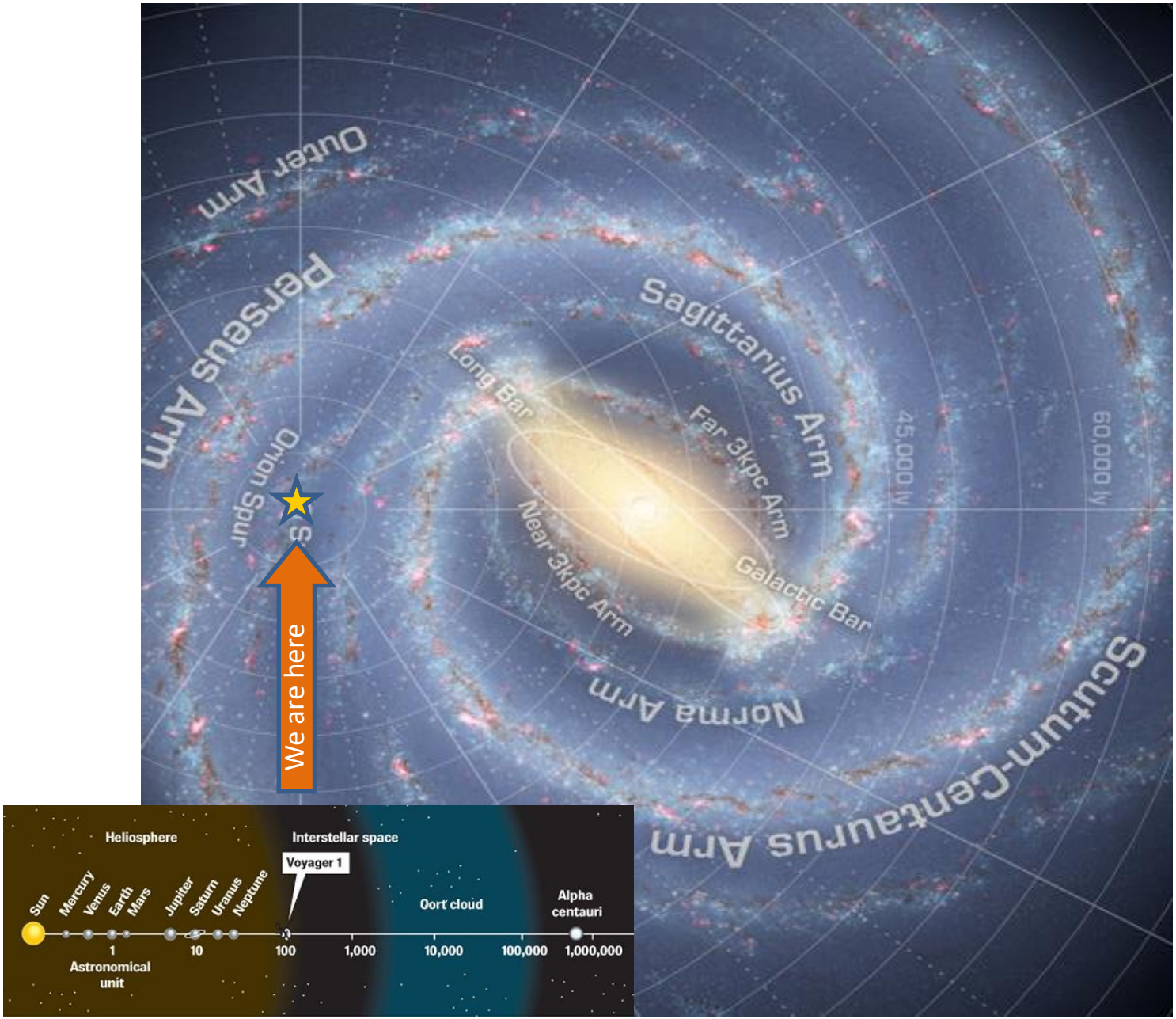


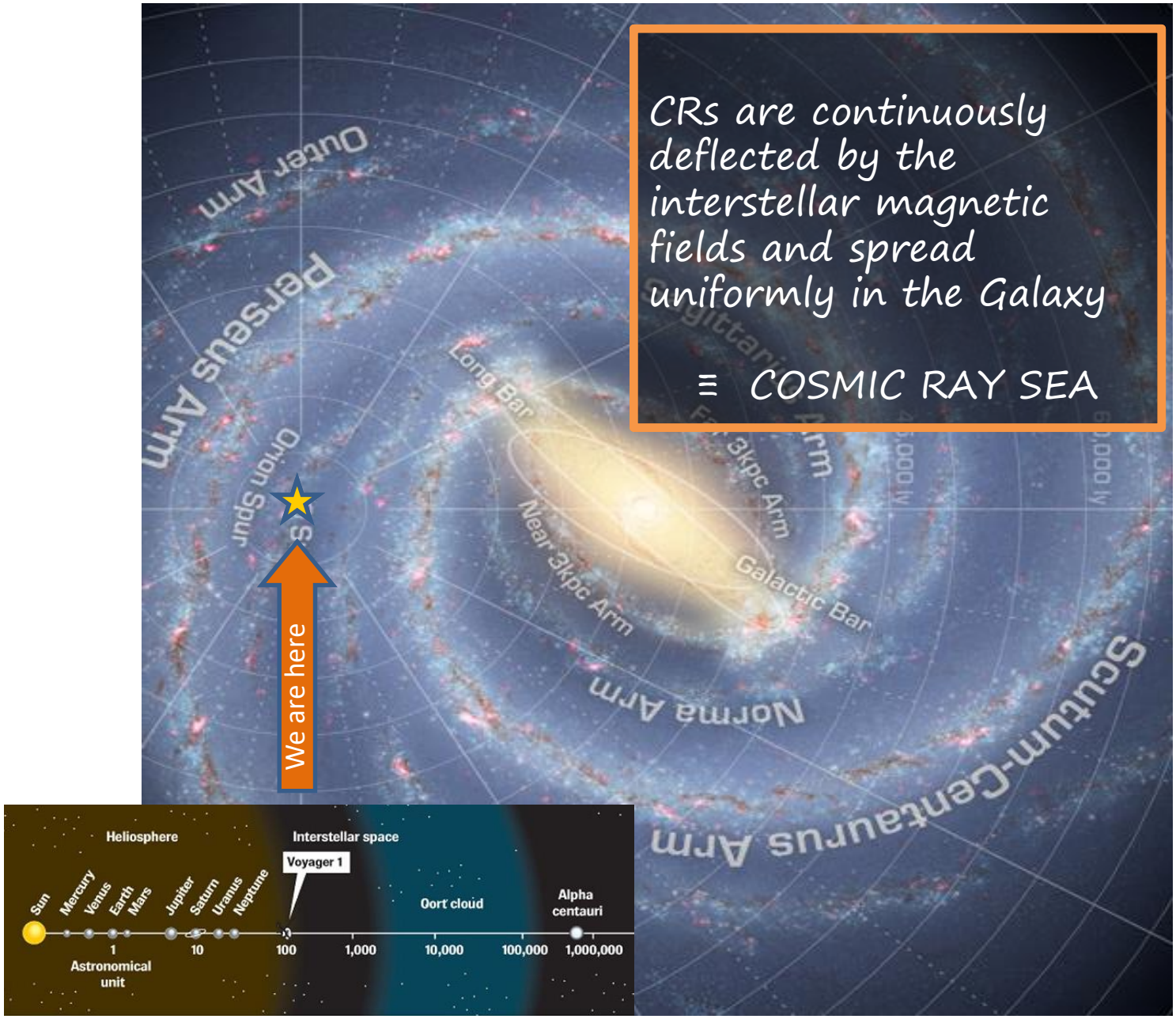
CR protons: the spectrum



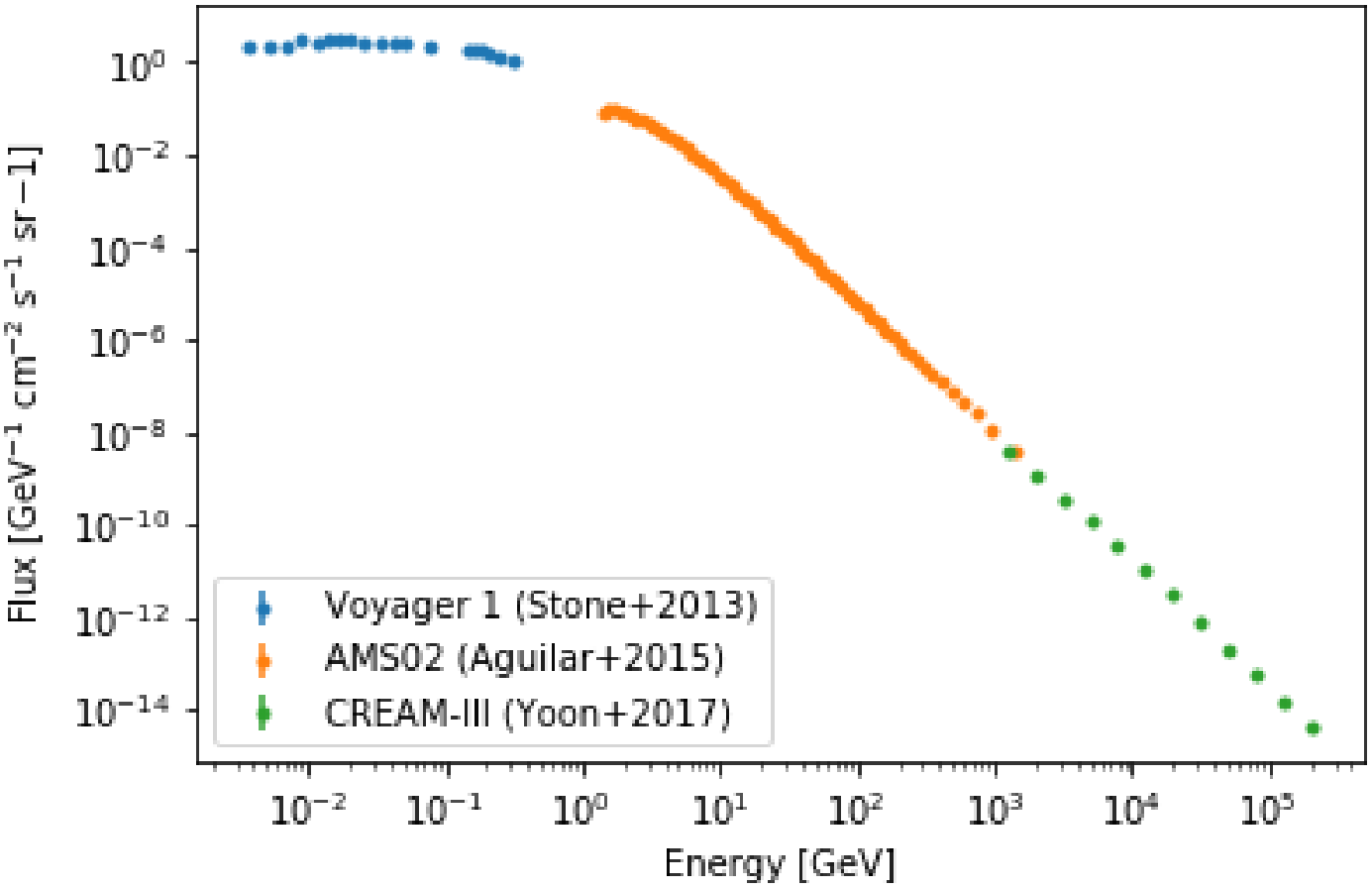
CR protons: the LOCAL spectrum




Outer Arm
Perseus Arm
Sagittarius Arm
Long Bar
Orion Spur
Far 3kpc Arm
45,000 ly
60,000 ly
Near 3kpc Arm
Galactic Bar
Norma Arm
Scutum-Centaurus Arm
We are here
Heliosphere
Interstellar space
Voyager 1
Sun
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
Oort cloud
Alpha centauri
1
10
100
1,000
10,000
100,000
1,000,000
Astronomical unit

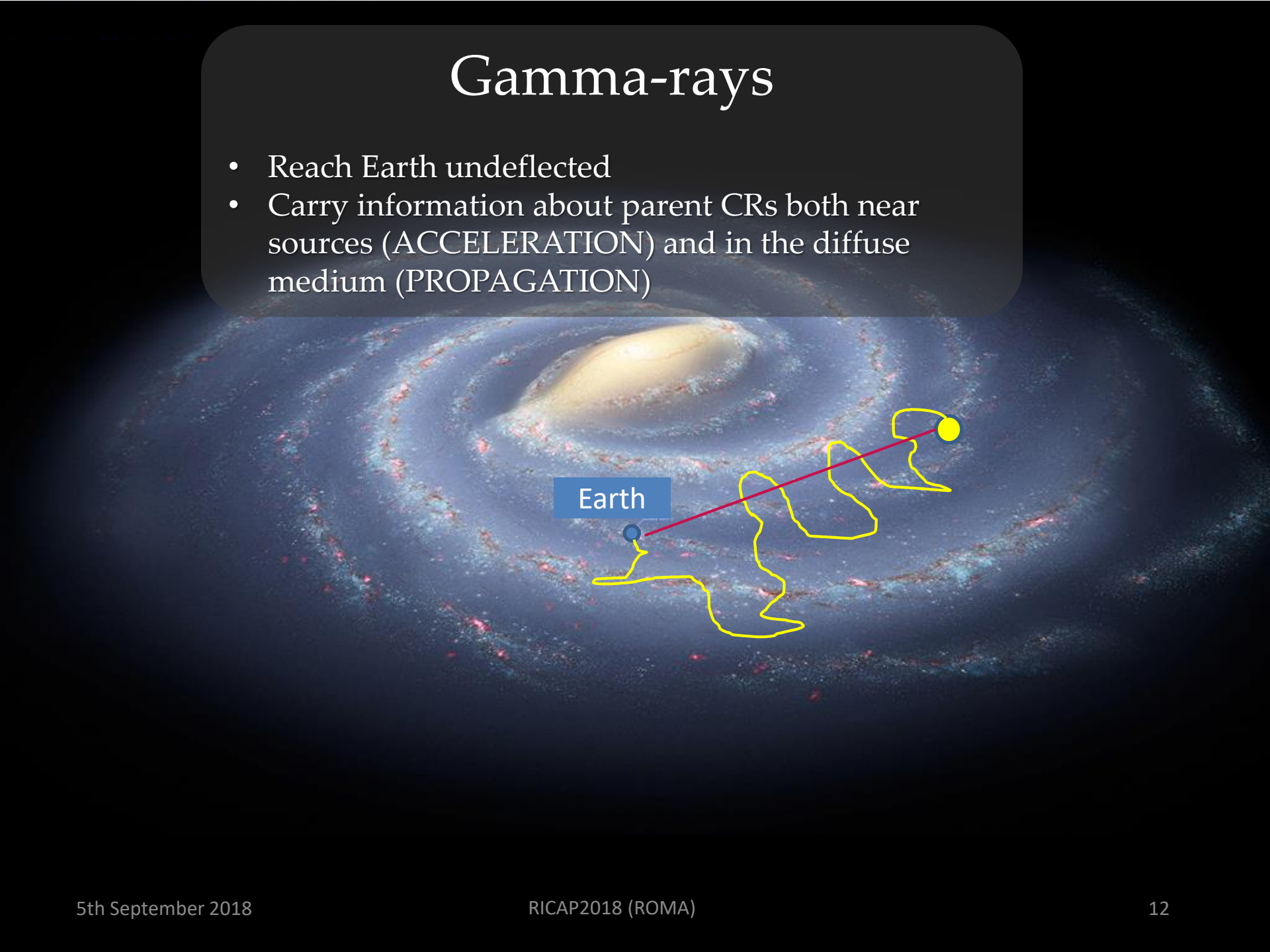

CRs are continuously deflected by the interstellar magnetic fields and spread uniformly in the Galaxy
≡ COSMIC RAY SEA
Outer Arm
Perseus Arm
Long Bar
Orion Spur
We are here
Near 3kpc Arm
3kpc Arm
Galactic Bar
Norma Arm
Scutum-Centaurus Arm
Heliosphere
Interstellar space
Voyager 1
Sun
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
Oort cloud
Alpha centauri
1
Astronomical unit
10
100
1,000
10,000
100,000
1,000,000

Is this the Cosmic Ray SEA?



Gamma-rays

- Reach Earth undeflected
- Carry information about parent CRs both near sources (ACCELERATION) and in the diffuse medium (PROPAGATION)



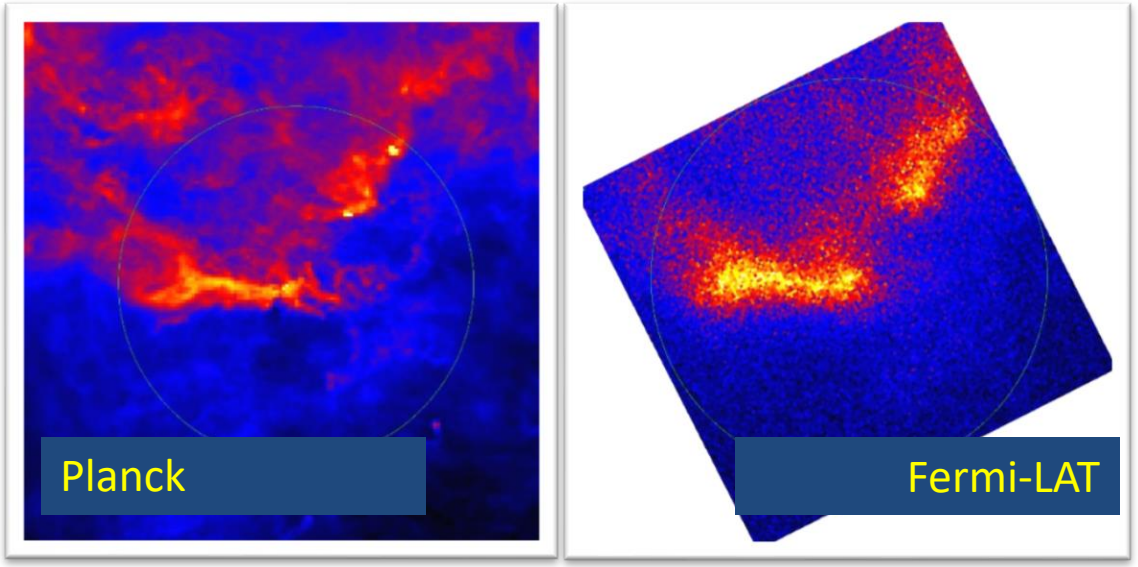
Cosmic Rays produce Gamma Rays

CR ISM

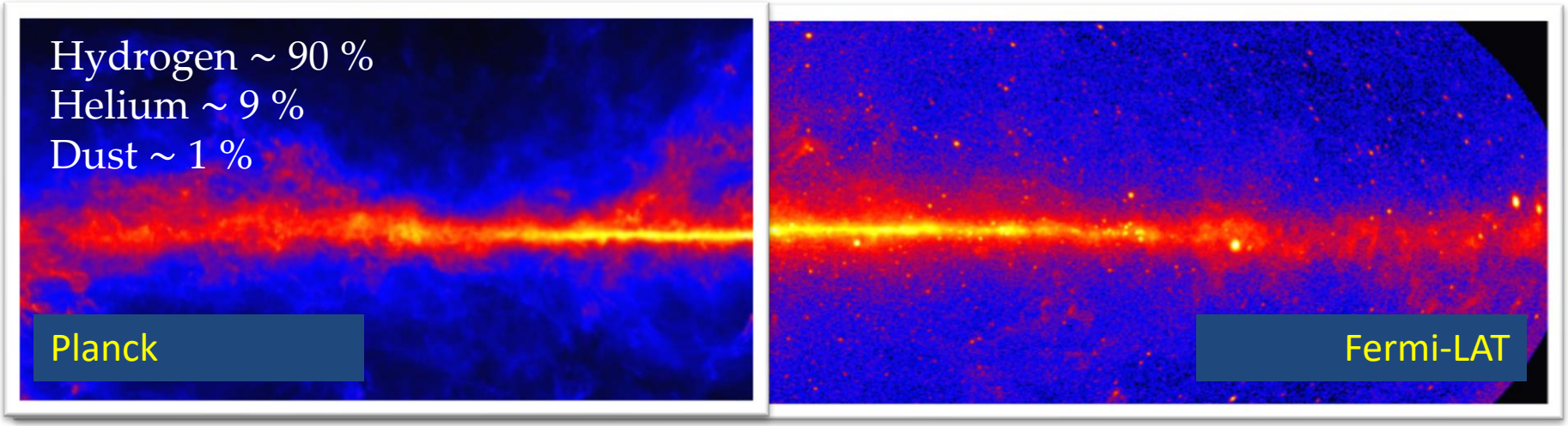
$$p + p \rightarrow \pi^0 \rightarrow 2\gamma$$

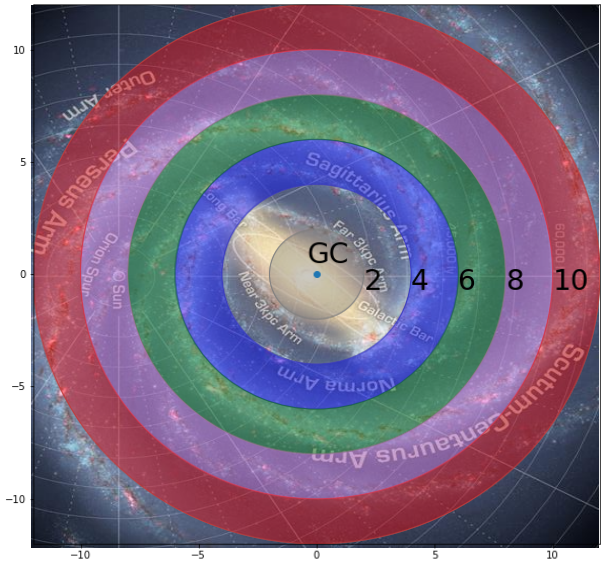
$$F_\gamma = \frac{dN_\gamma}{dE_\gamma\, dA\, dt\, d\Omega} = n_{col} \int dE_p \, \frac{d\sigma_{pp\rightarrow\gamma}}{dE_\gamma}\left(E_p, E_\gamma\right) F_p(E_p)$$

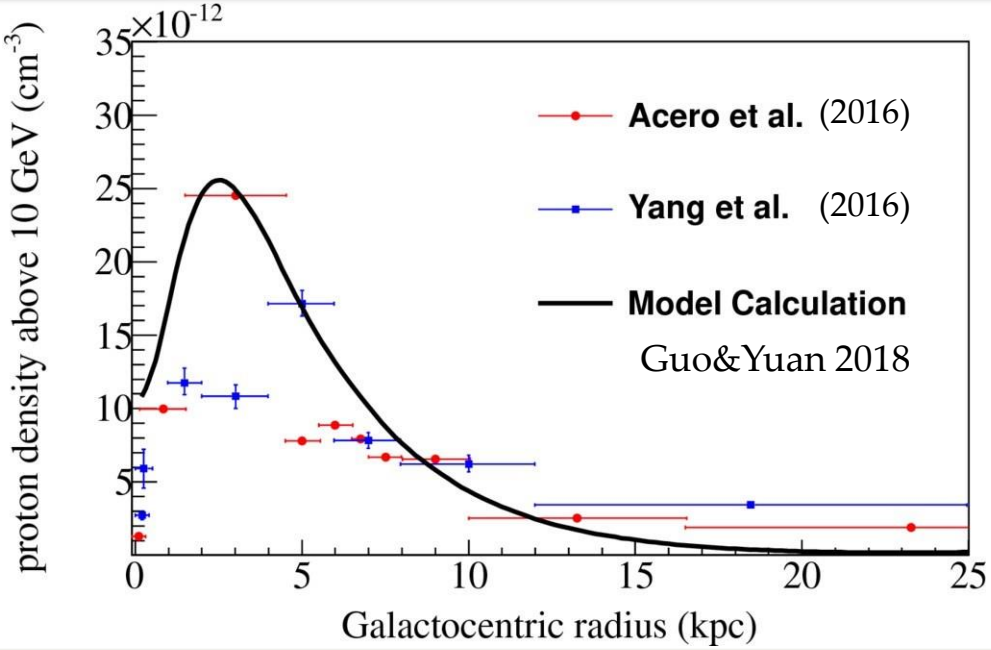
$$\left[n_{col} = \int n(r,l,b)\, dr \right]$$



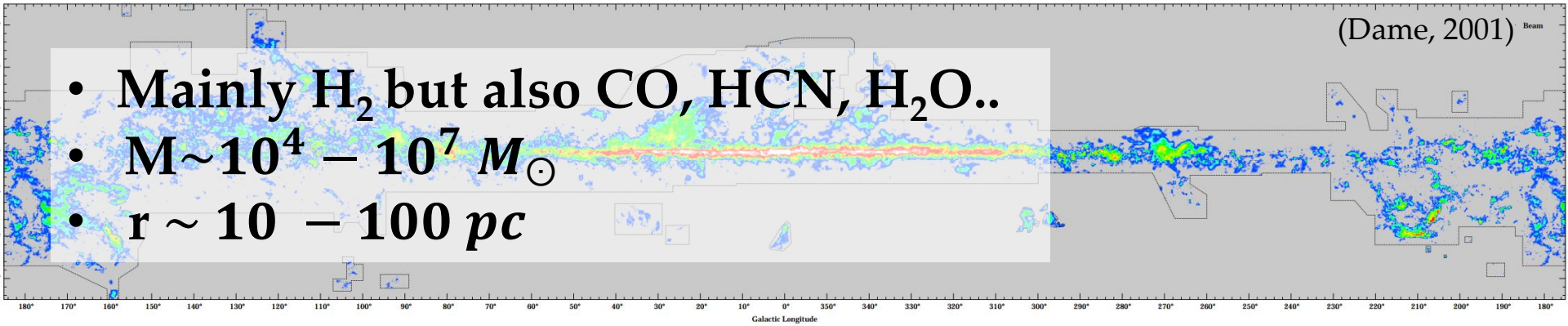
The interstellar medium







Molecular Clouds



- Mainly H_2 but also CO, HCN, H_2O..
- $M \sim 10^4 - 10^7\ M_\odot$
- $r \sim 10 - 100\ pc$

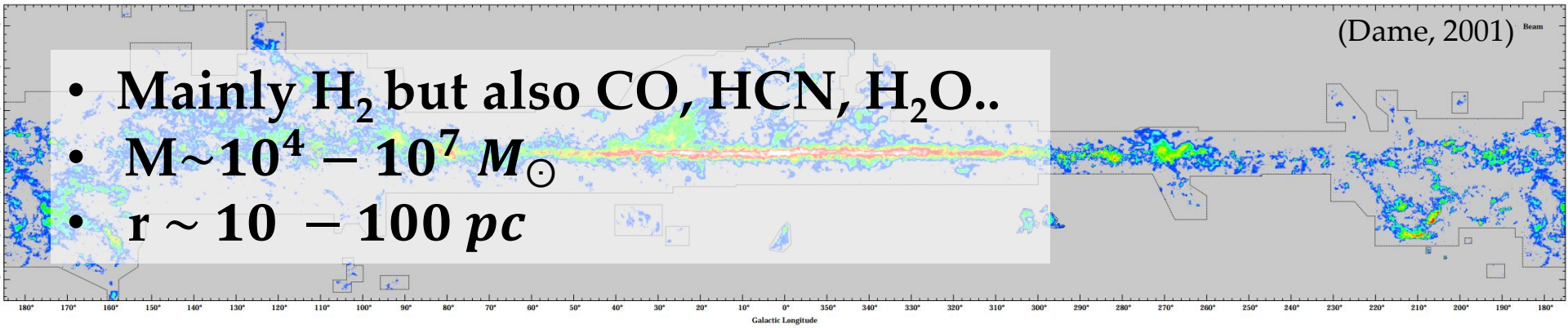
$$F_\gamma = n_{col} \int dE_p \frac{d\sigma_{pp\to\gamma}}{dE_\gamma}(E_p, E_\gamma) J(E_p)$$

$$F_{MC} \propto \frac{M_5}{d_{kpc}^2} \int dE_p \frac{d\sigma_{pp\to\gamma}}{dE_\gamma}(E_p, E_\gamma) J(E_p)$$

$$M_5 \equiv \frac{M}{10^5 M_\odot}$$

$$d_{kpc} \equiv \frac{\mathrm{d}}{1\ \mathrm{kpc}}$$

Molecular Clouds

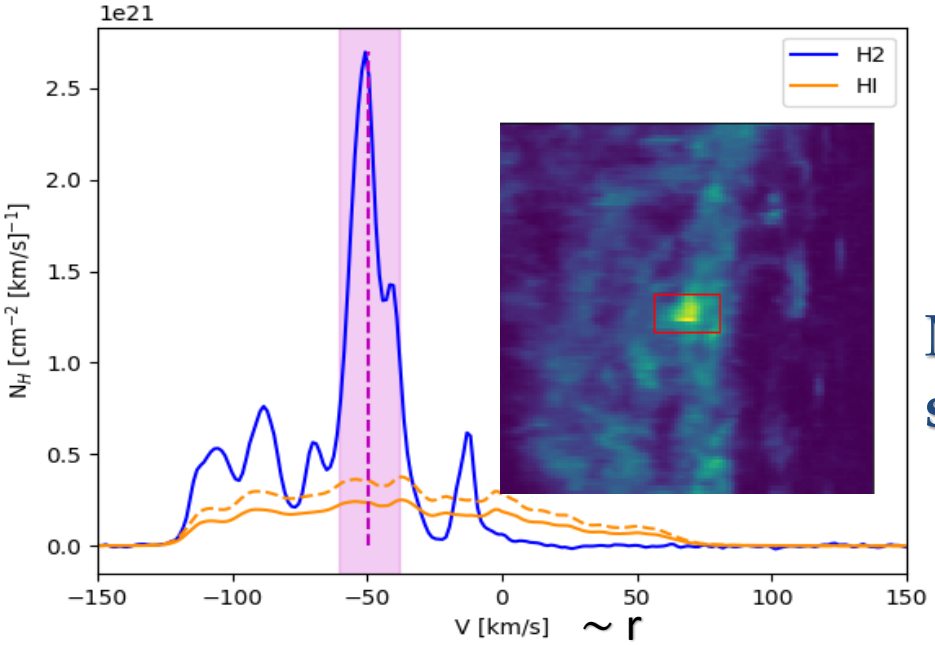


- Mainly H_2 but also CO, HCN, H_2O..
- M~$10^4 - 10^7\ M_\odot$
- r ~ $10 - 100\ pc$

$$F_{MC} \propto \frac{M_5}{d_{kpc}^2}$$

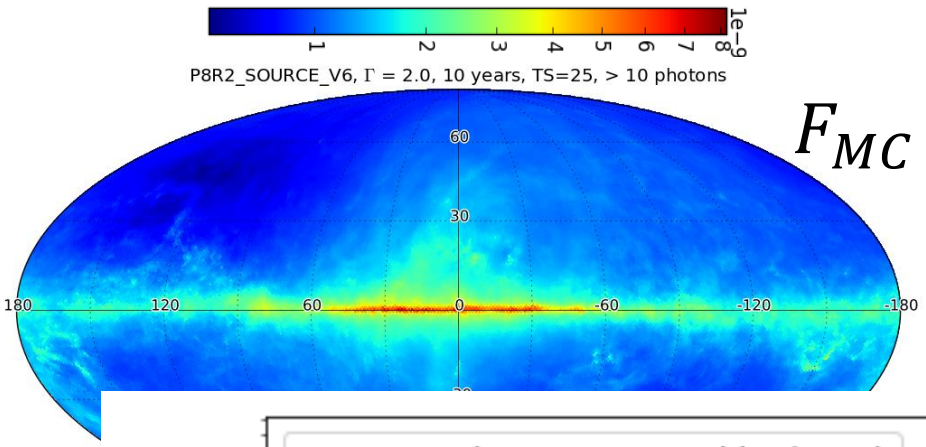
$$M_5 \equiv \frac{M}{10^5 M_\odot}$$

$$d_{kpc} \equiv \frac{\mathrm{d}}{1\ \mathrm{kpc}}$$

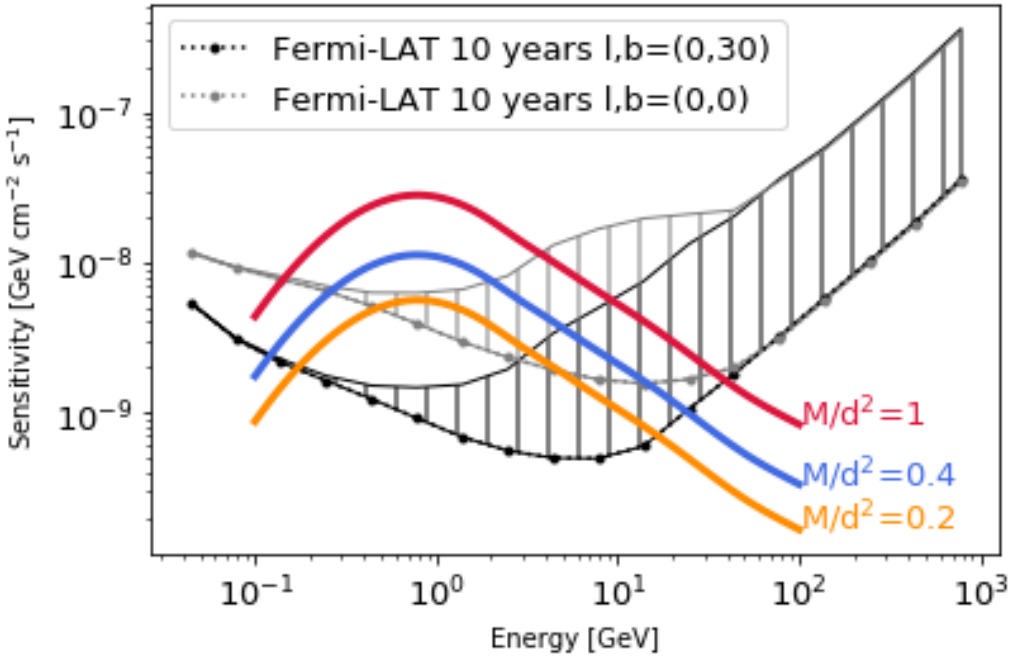


MCs allow to test **specific locations**

Molecular Clouds & Fermi-LAT



$$F_{MC} \propto \frac{\boldsymbol{M_5}}{\boldsymbol{d_{kpc}^2}} \int dE_p \, \frac{d\sigma}{dE_\gamma} F_p(\boldsymbol{E_p})$$



Assuming:

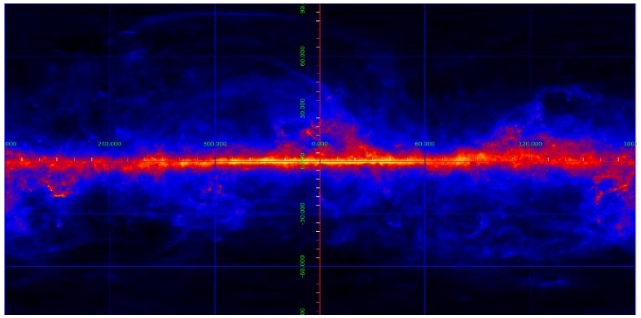
- $sens_{wide} \sim sens_{point} \frac{\sqrt{\sigma_{psf}^2+\sigma_r^2}}{\sigma_{psf}}$
- $F_p = F_{AMS} \sim E^{-2.8}$
- $\frac{d\sigma}{dE_\gamma}$ from Kafexhiu+2014

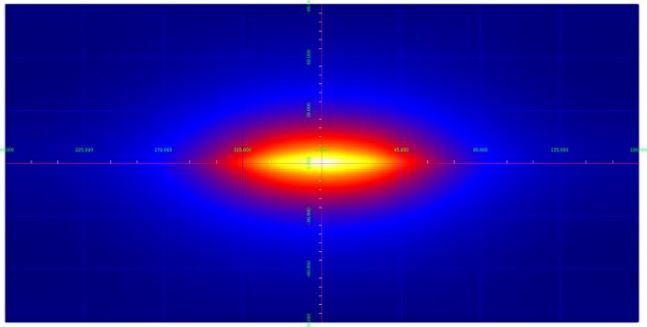
Molecular Clouds & Fermi-LAT

- 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





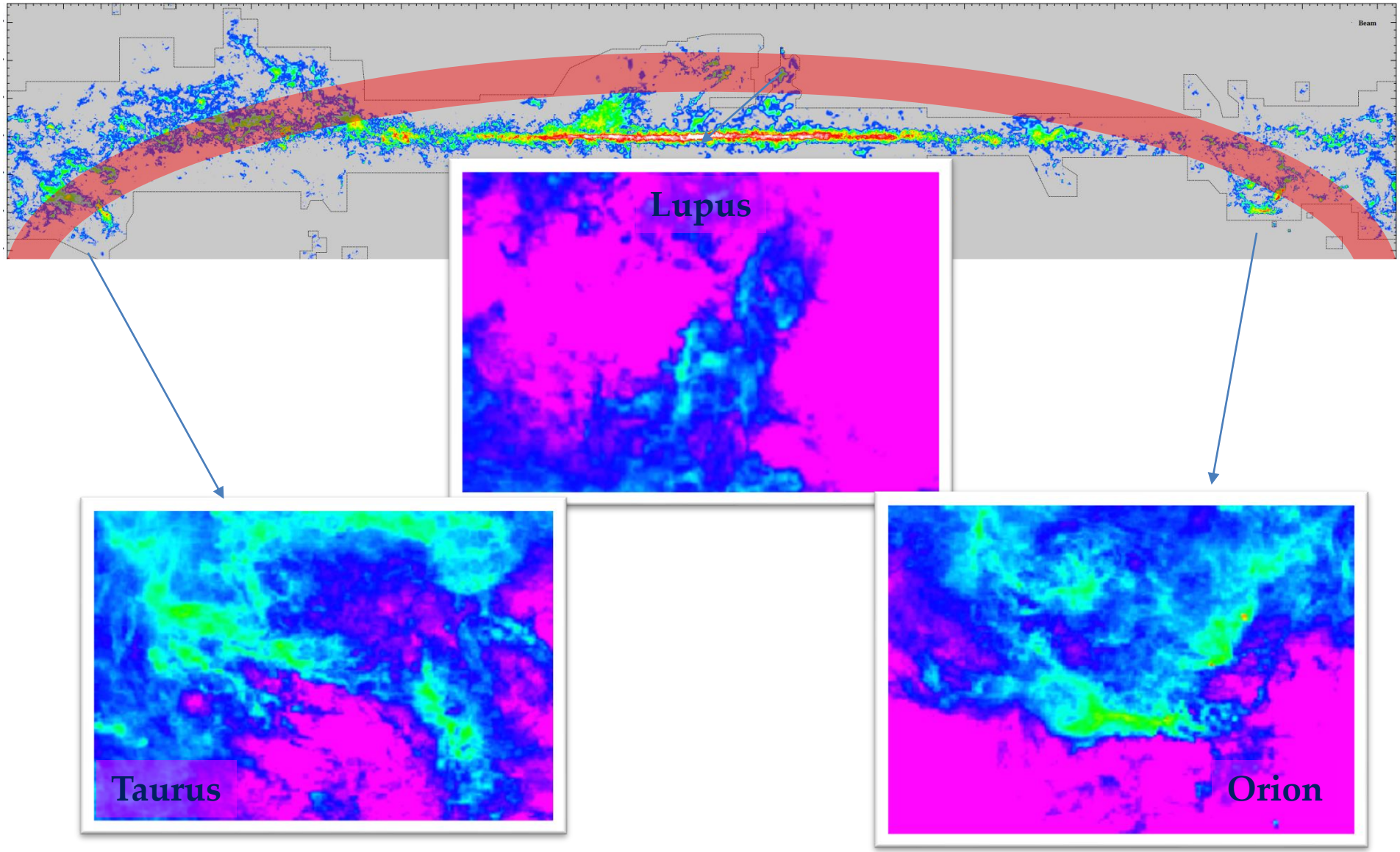
- Inverse Compton (galprop v54)

- Isotropic diffuse: computed by fitting a region of 30 degrees centered in l,b=(150,90)

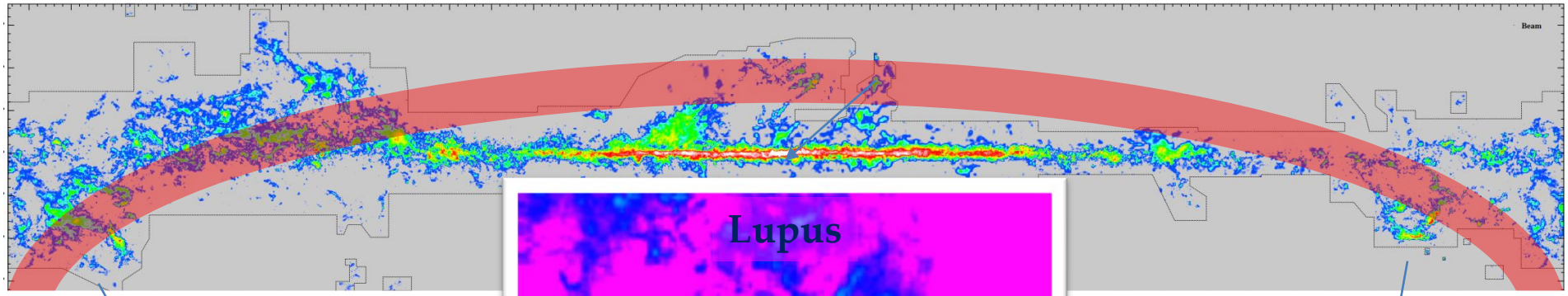
- Sources from 3FGL catalog

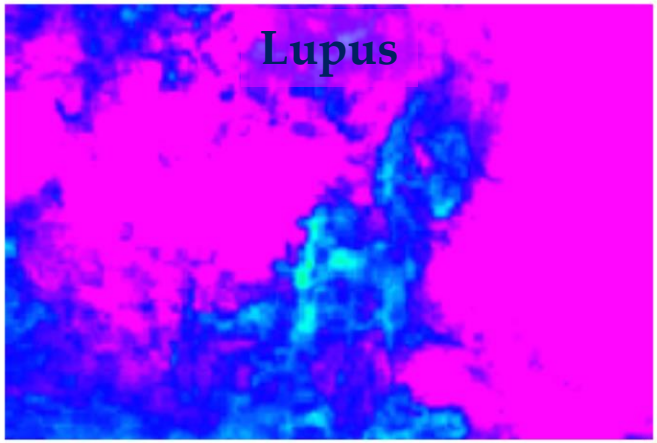
Gould Belt Clouds

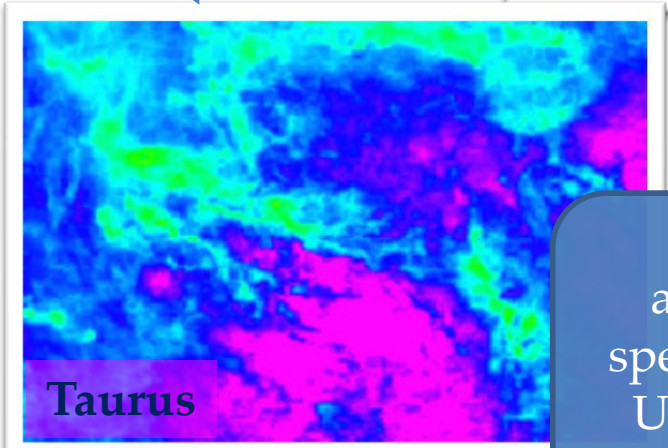
$\sim 200\ pc$



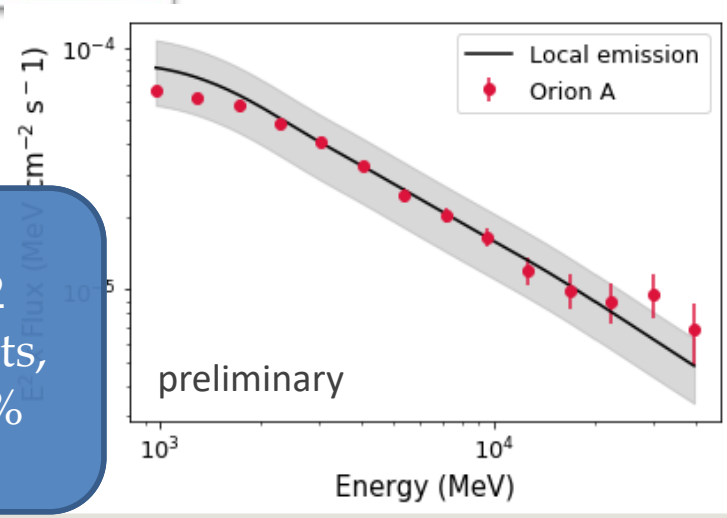
Gould Belt Clouds



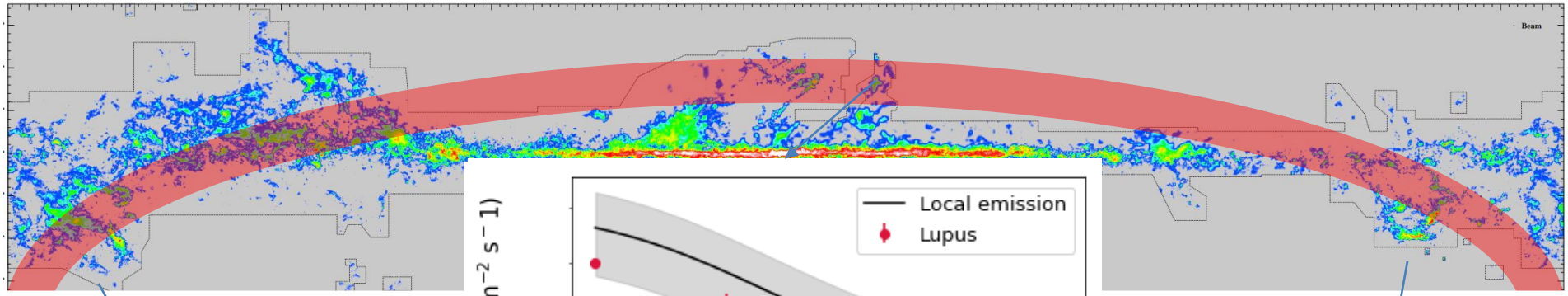


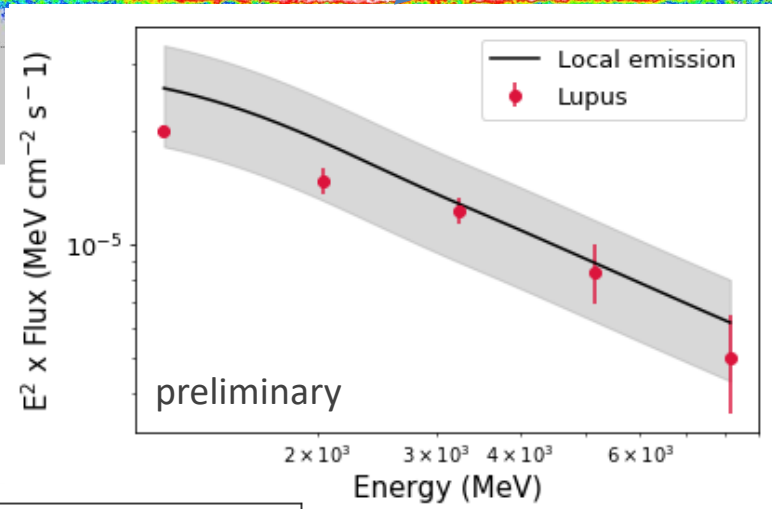


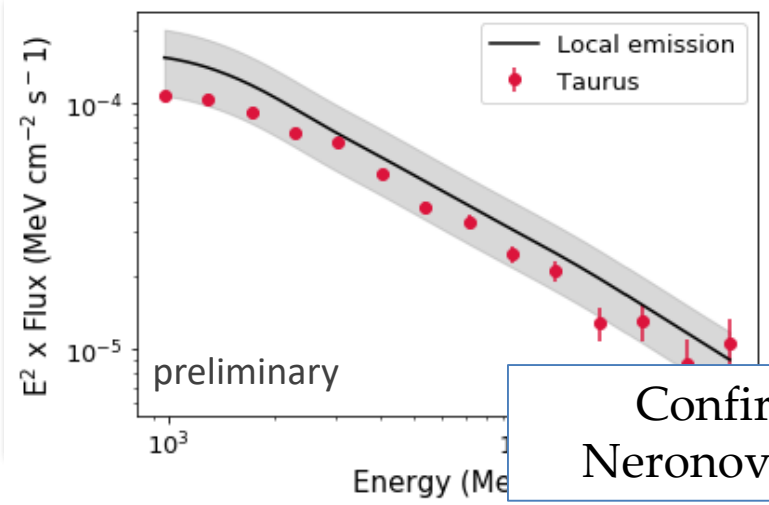
Expected flux assuming AMS02 spectrum for parents, Uncertainty of 30% due to X_{CO}

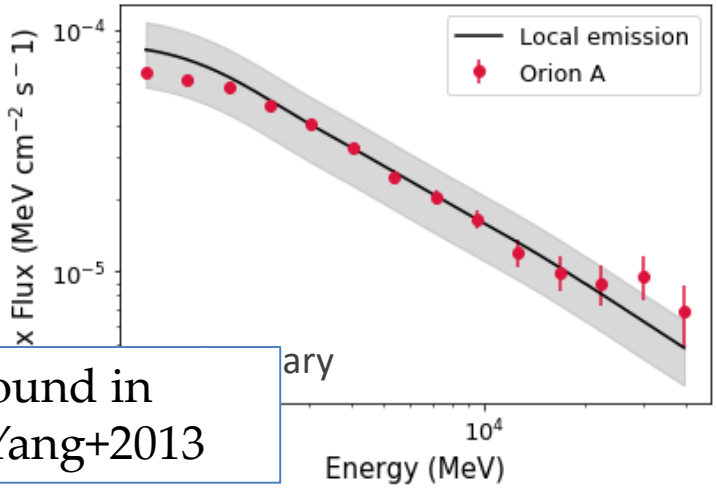


Gould Belt Clouds



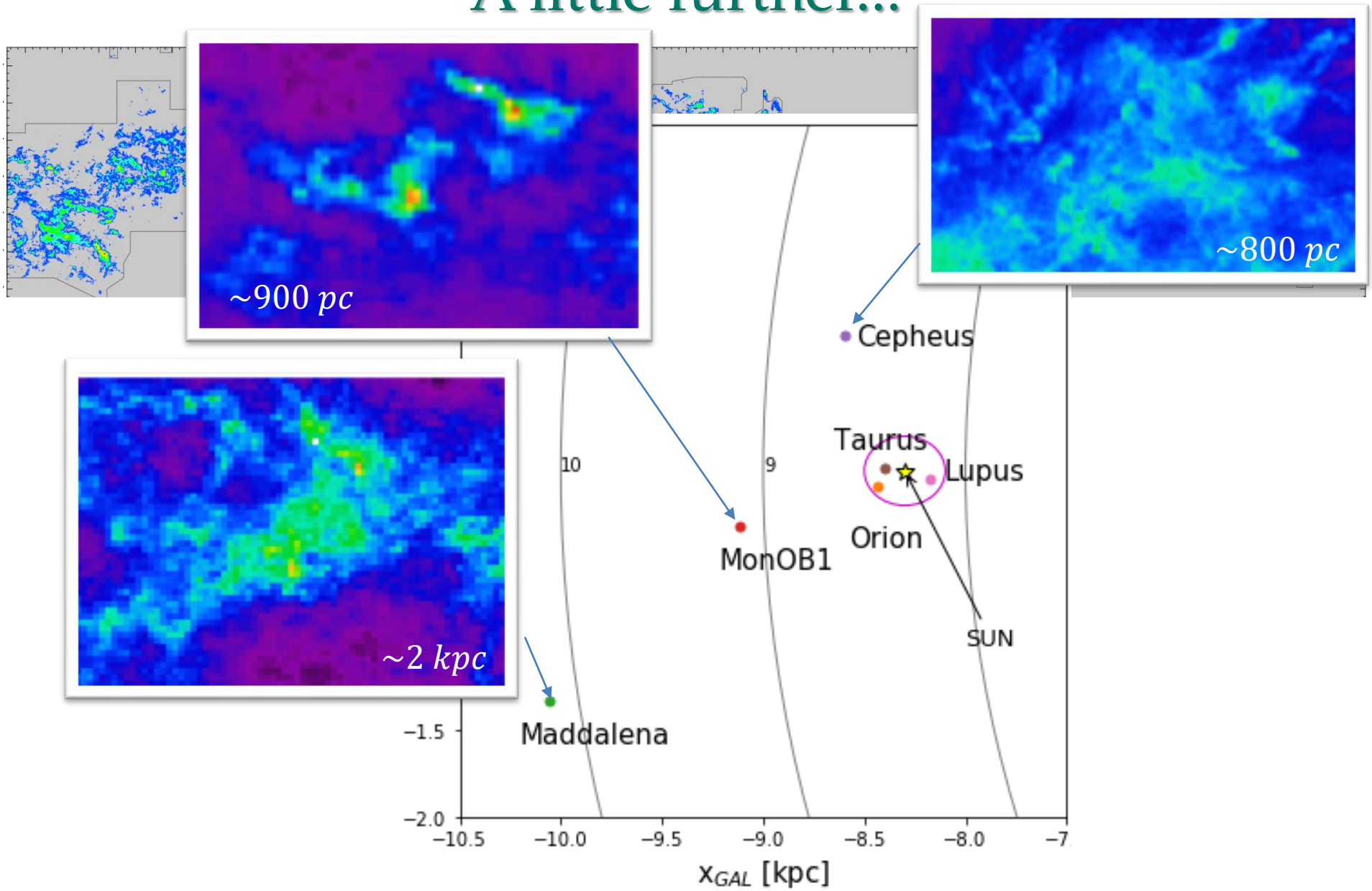




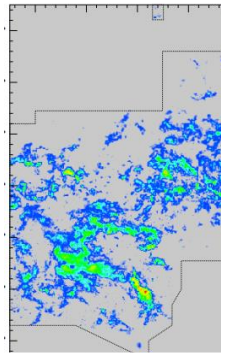


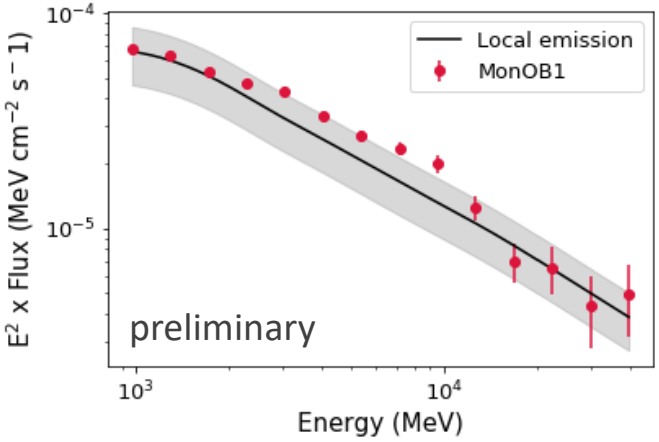
Confirmed what found in Neronov+ 2017 and Yang+2013

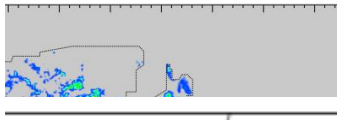
A little further...

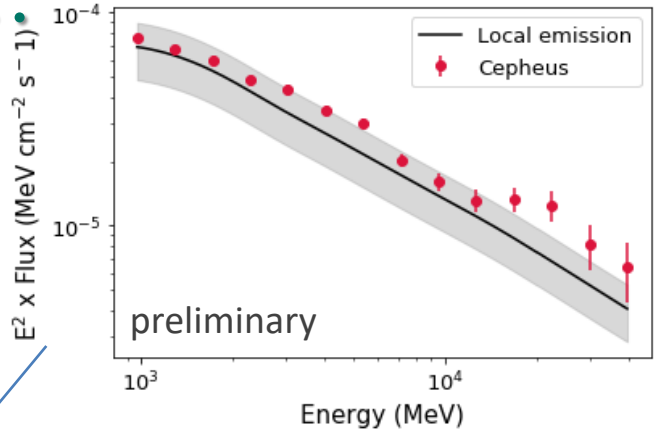


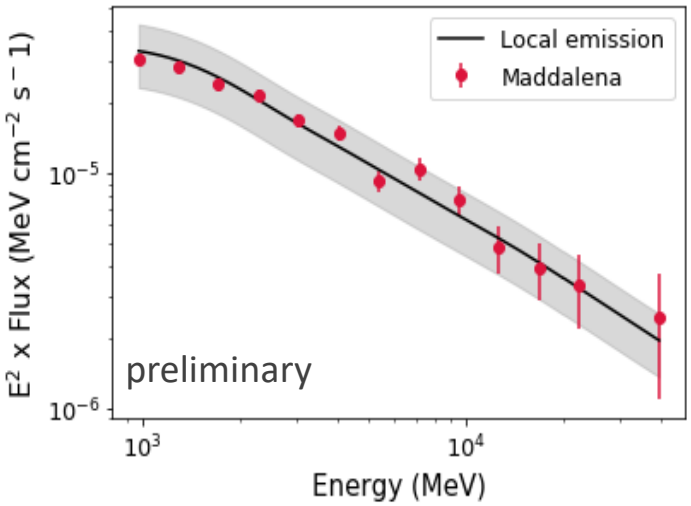
A little further…

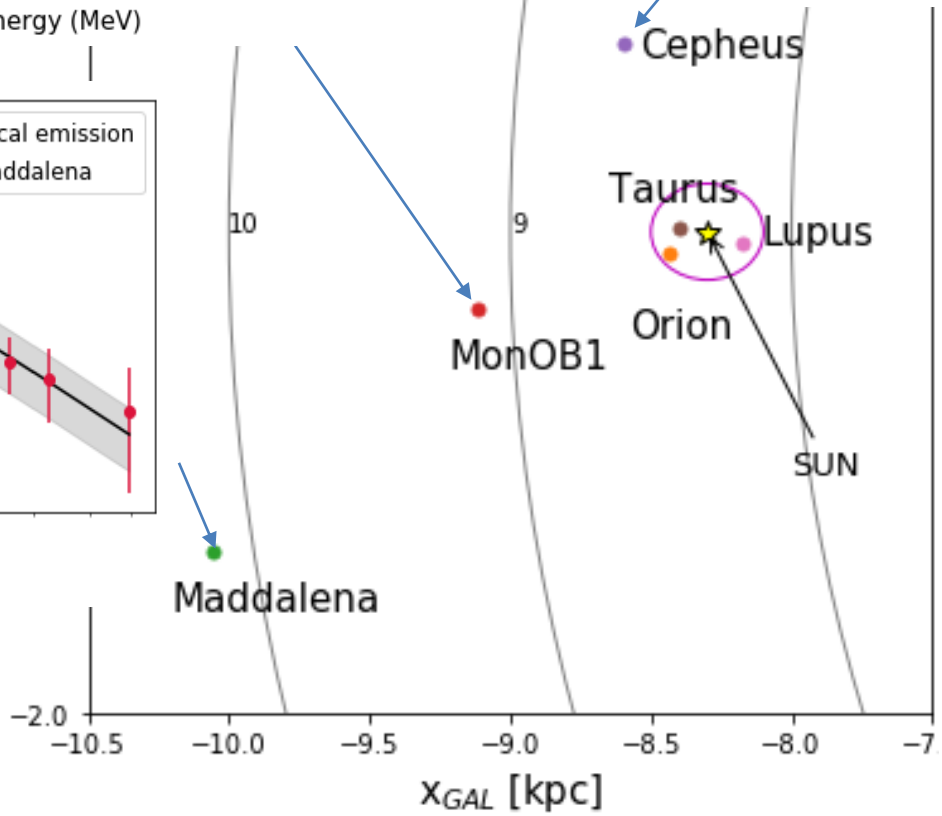




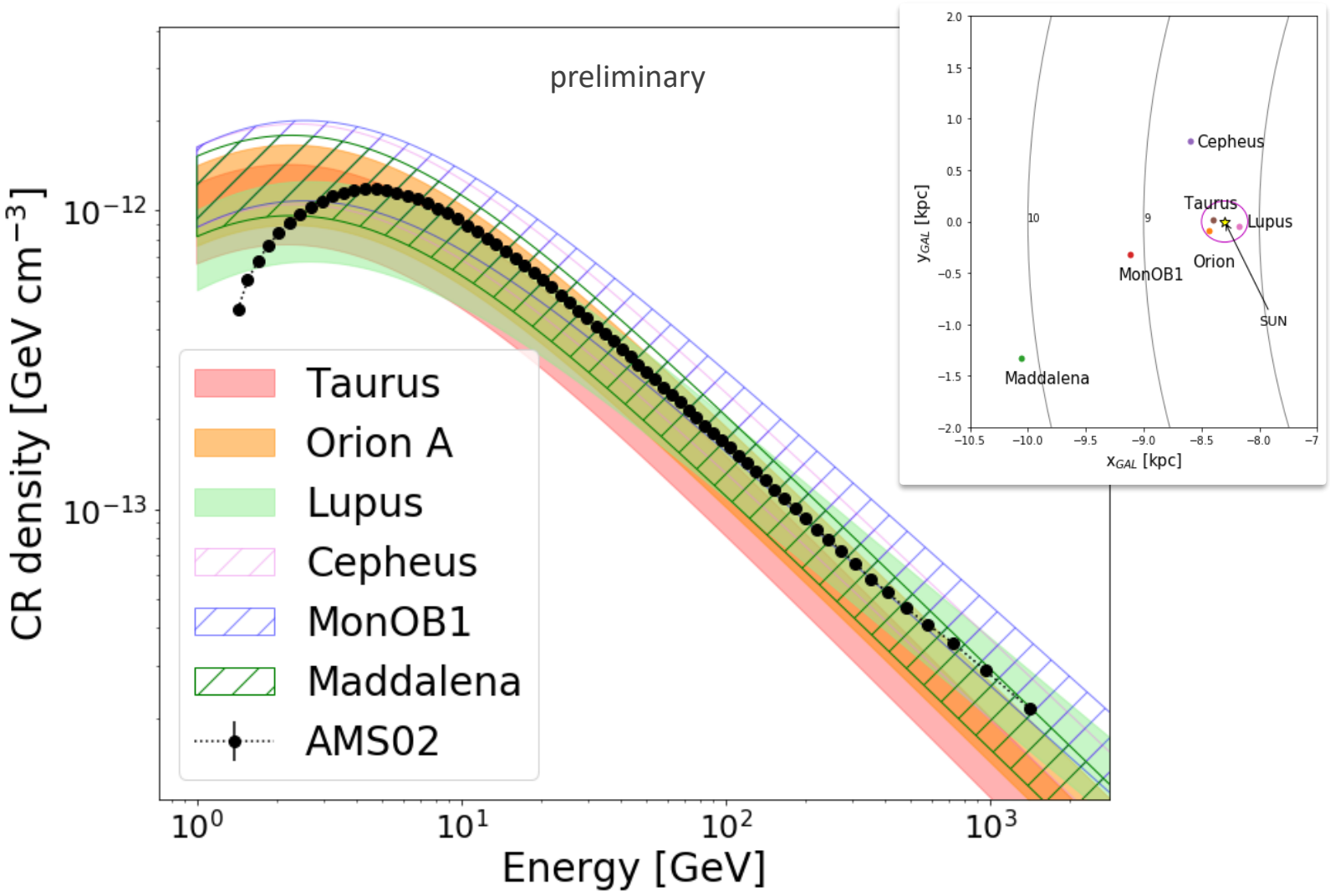




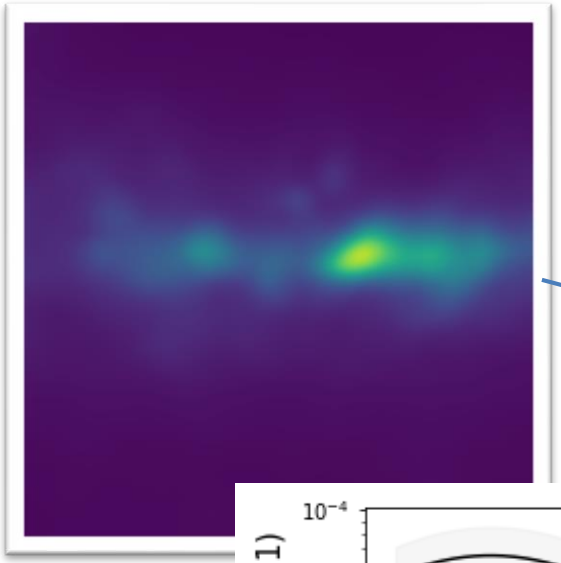


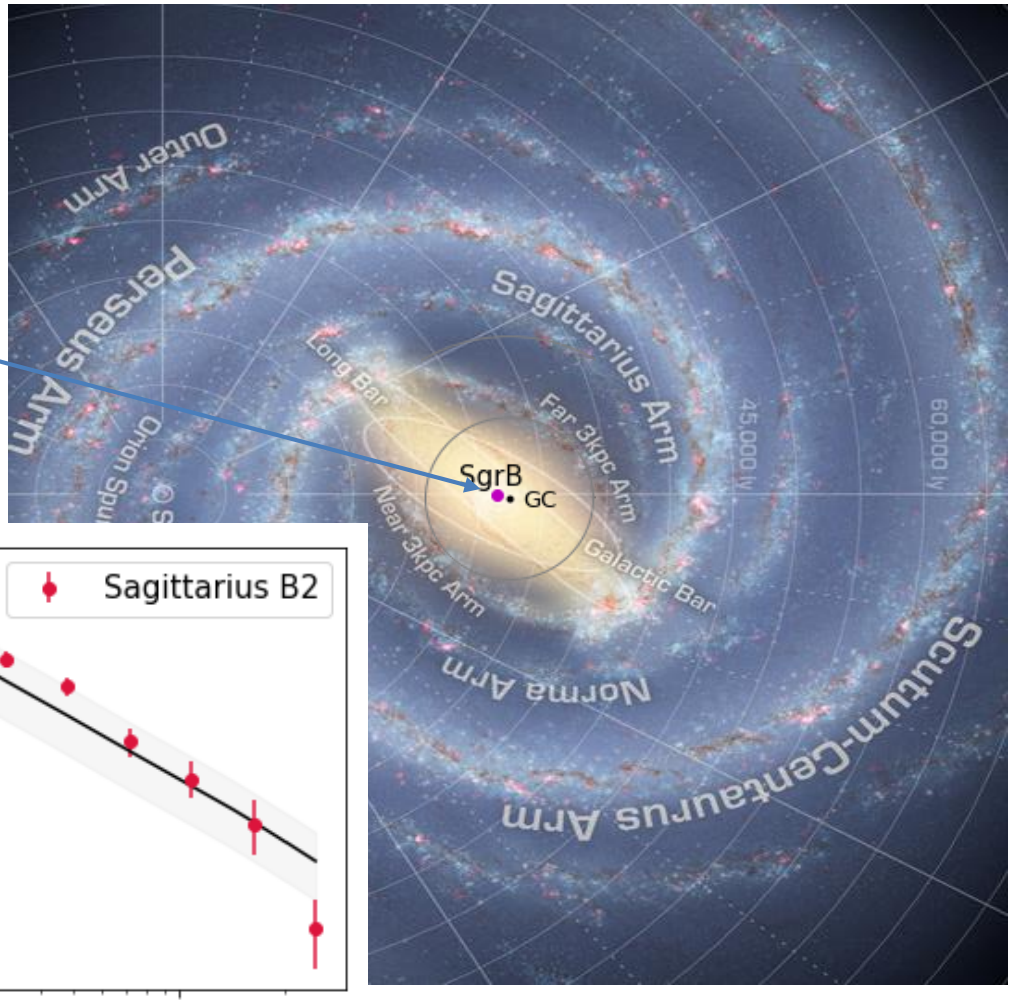


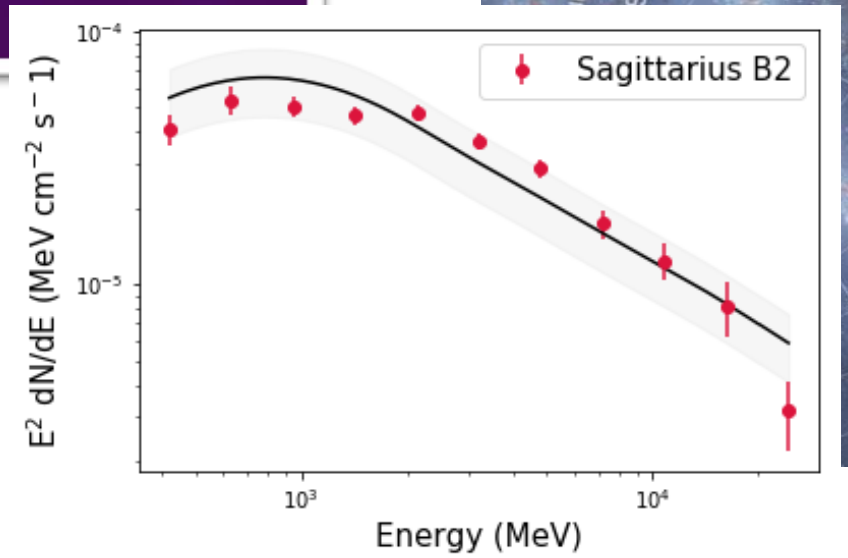
The local (few kpc) environment



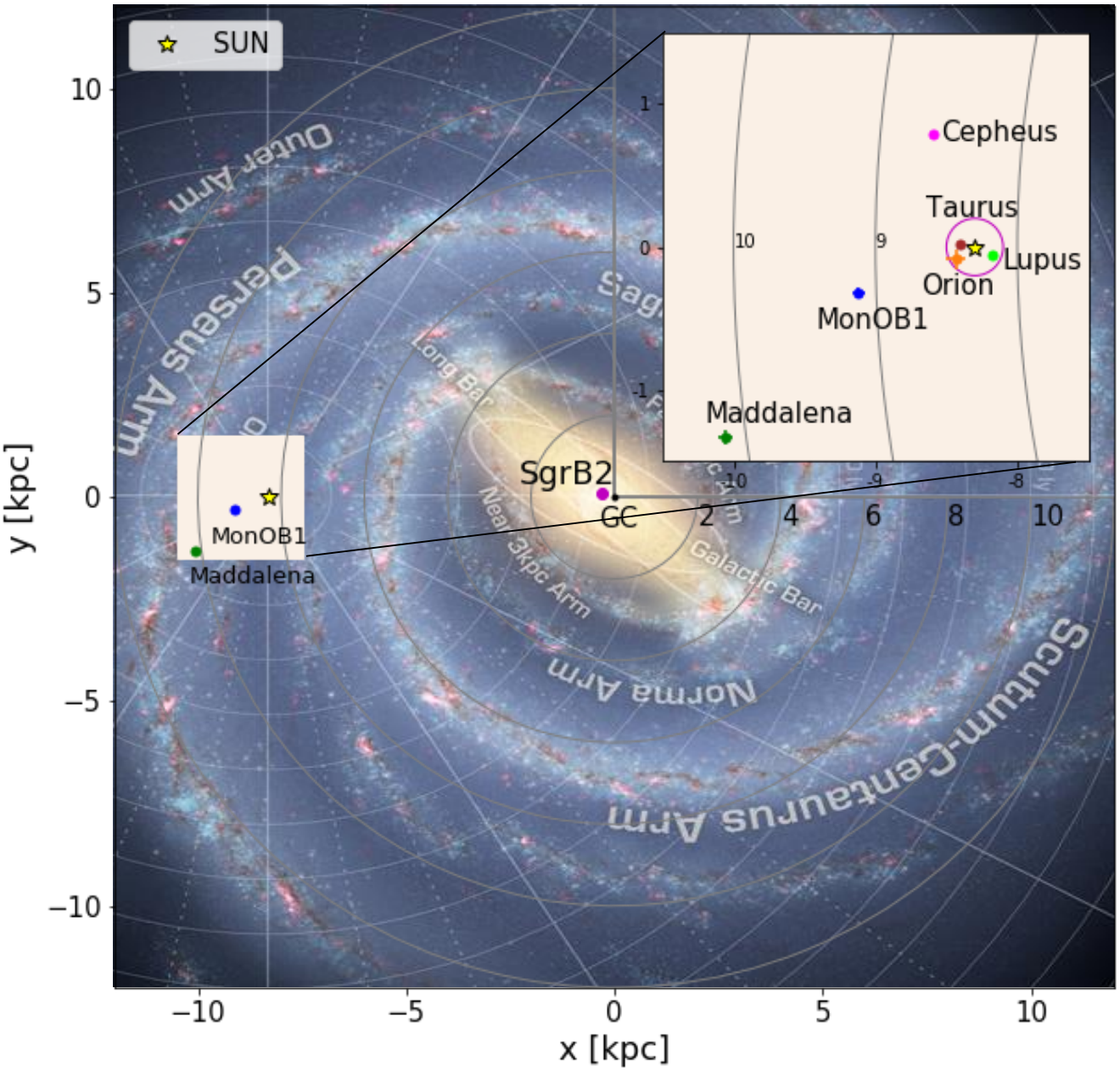
Close to the Galactic Center: SgrB2

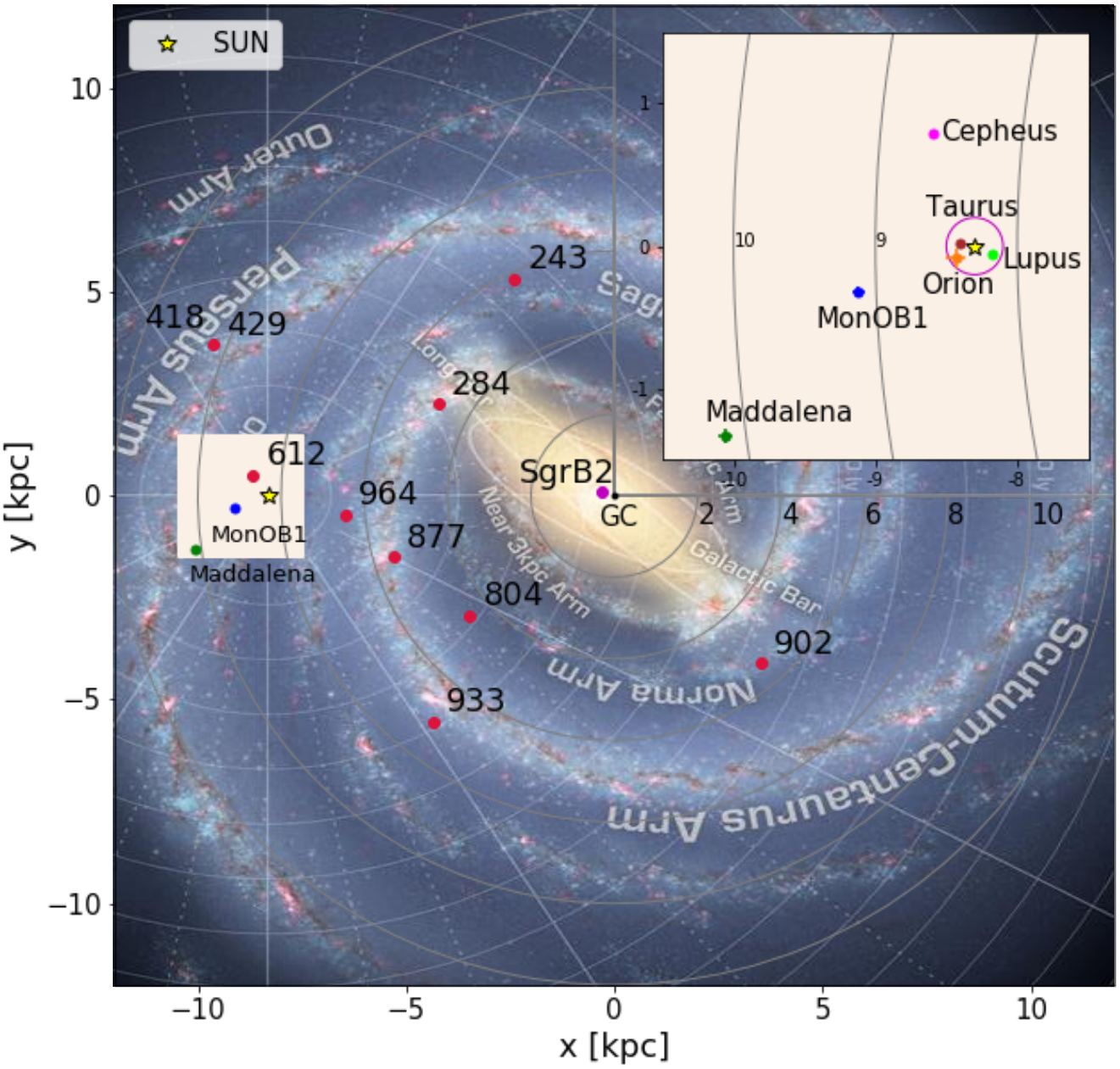


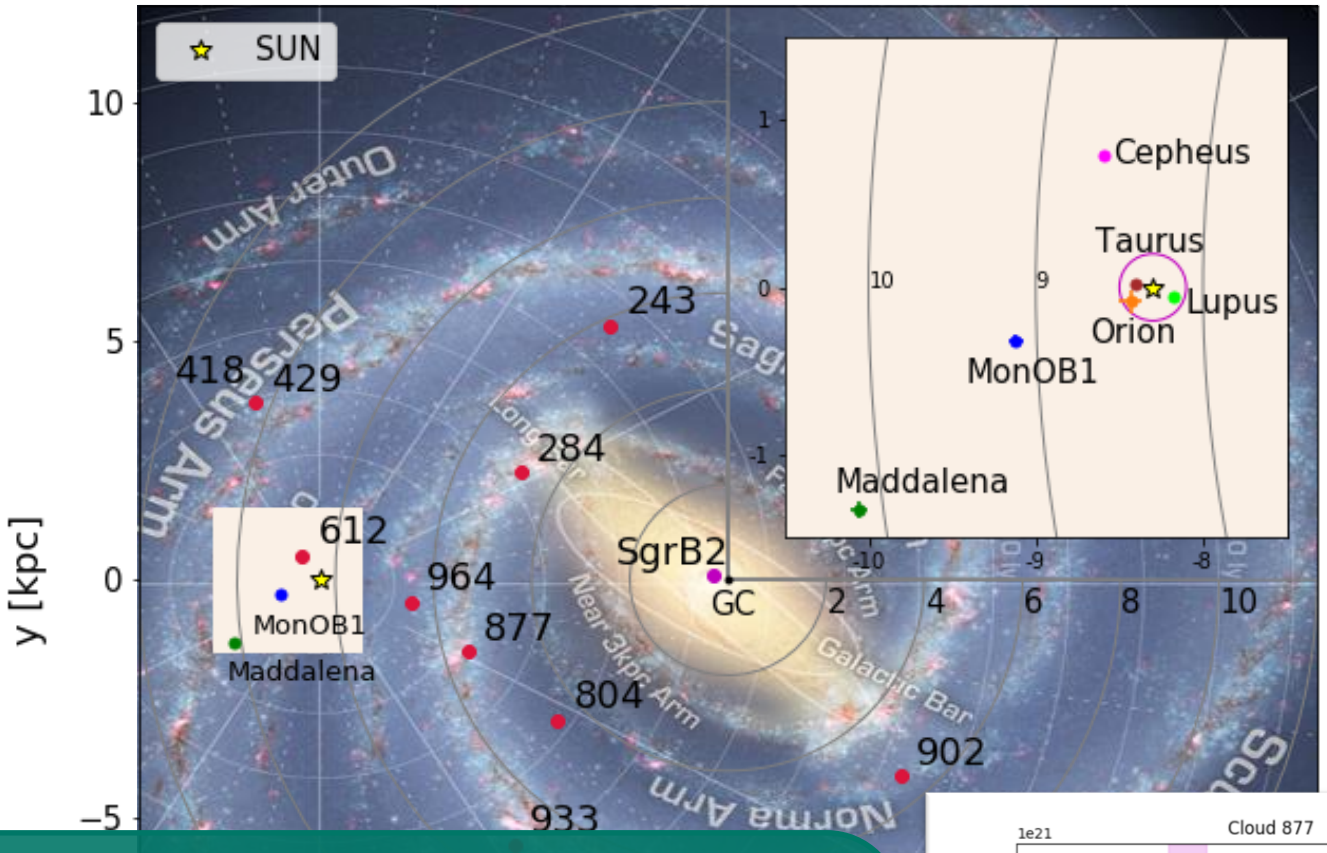


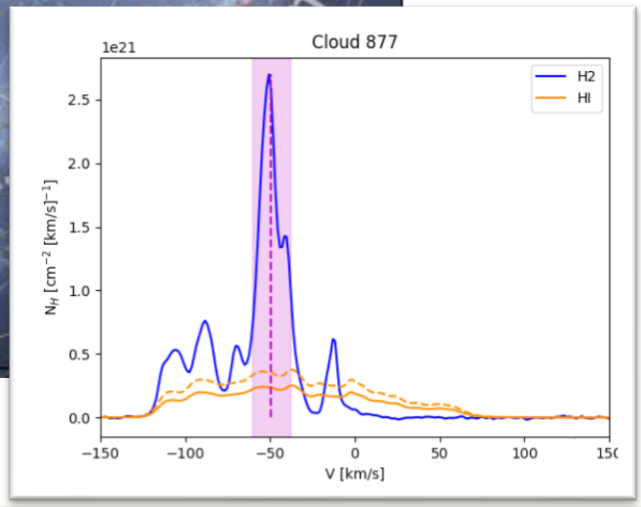


Yang+2014


SUN
Outer Arm
Perseus Arm
Sagi
Long Bar
SgrB2
GC
Near 3kpc Arm
Galactic Bar
Norma Arm
Scutum-Centaurus Arm
MonOB1
Maddalena
Cepheus
Taurus
Lupus
Orion
MonOB1
Maddalena
y [kpc]
x [kpc]
10
5
0
−5
−10
−10
−5
0
5
10


SUN
Outer Arm
Perseus Arm
Sagi
Near 3kpc Arm
Galactic Bar
Norma Arm
Scutum-Centaurus Arm
243
418
429
284
612
964
877
804
902
933
SgrB2
GC
MonOB1
Maddalena
Cepheus
Taurus
Lupus
Orion
y [kpc]
x [kpc]

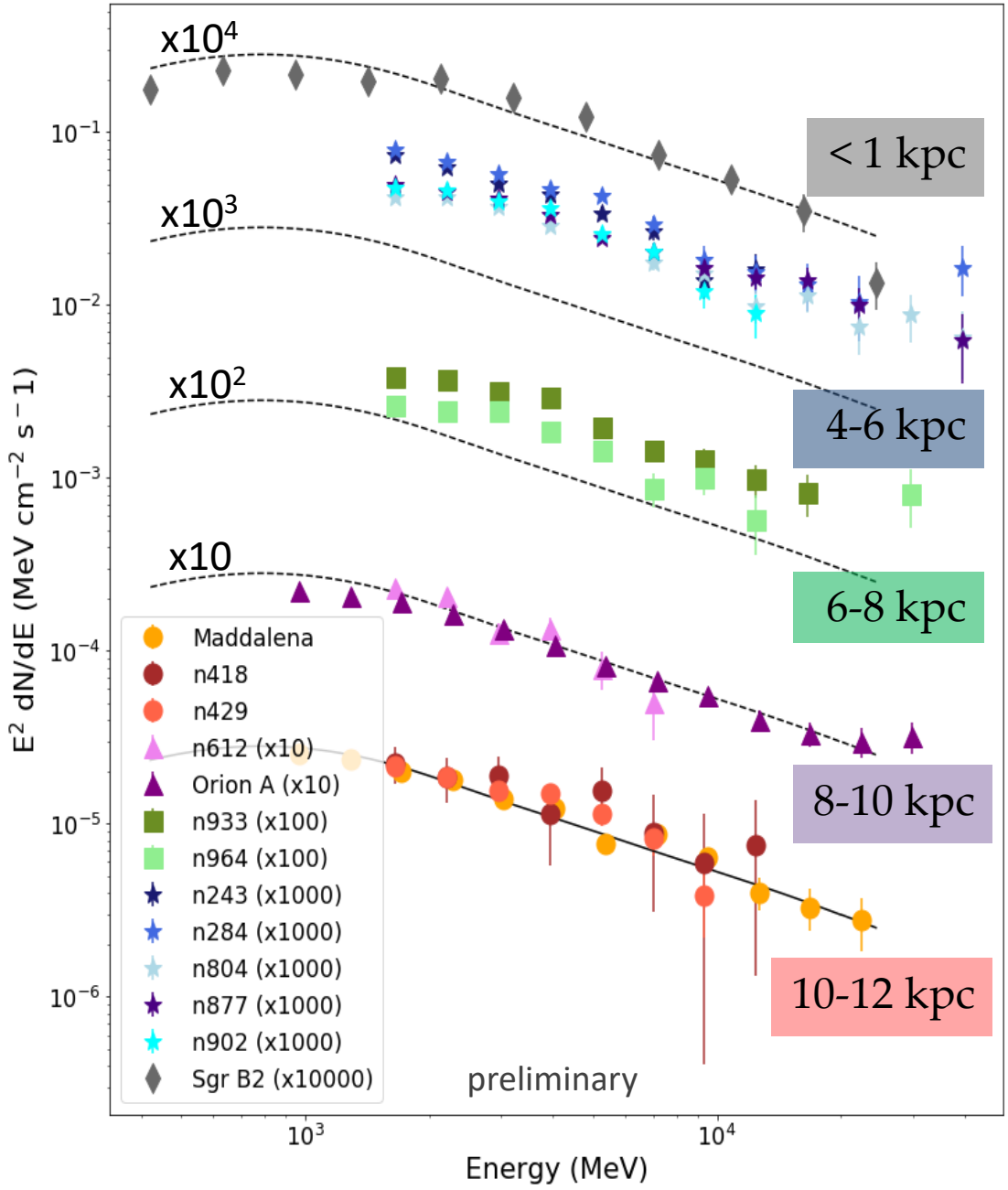


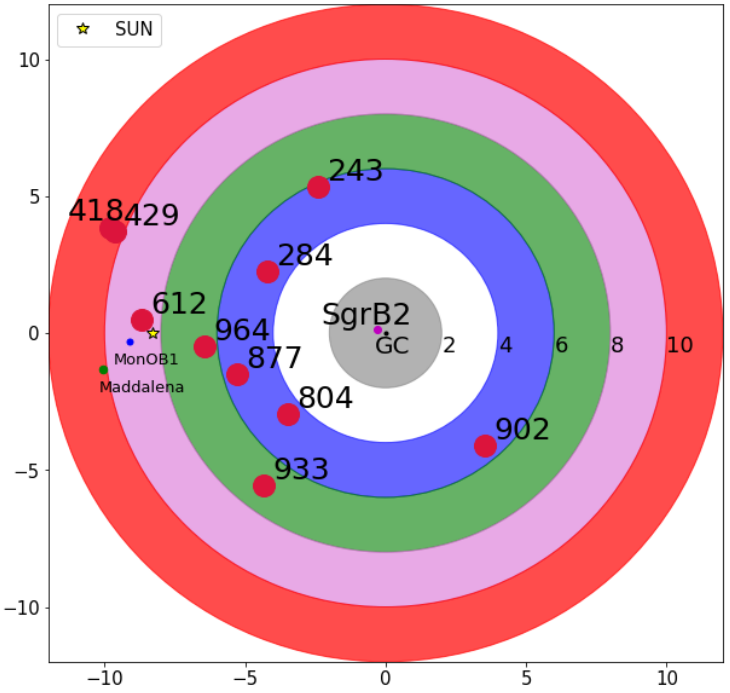


From Rice+2016 catalog (1064 clouds)

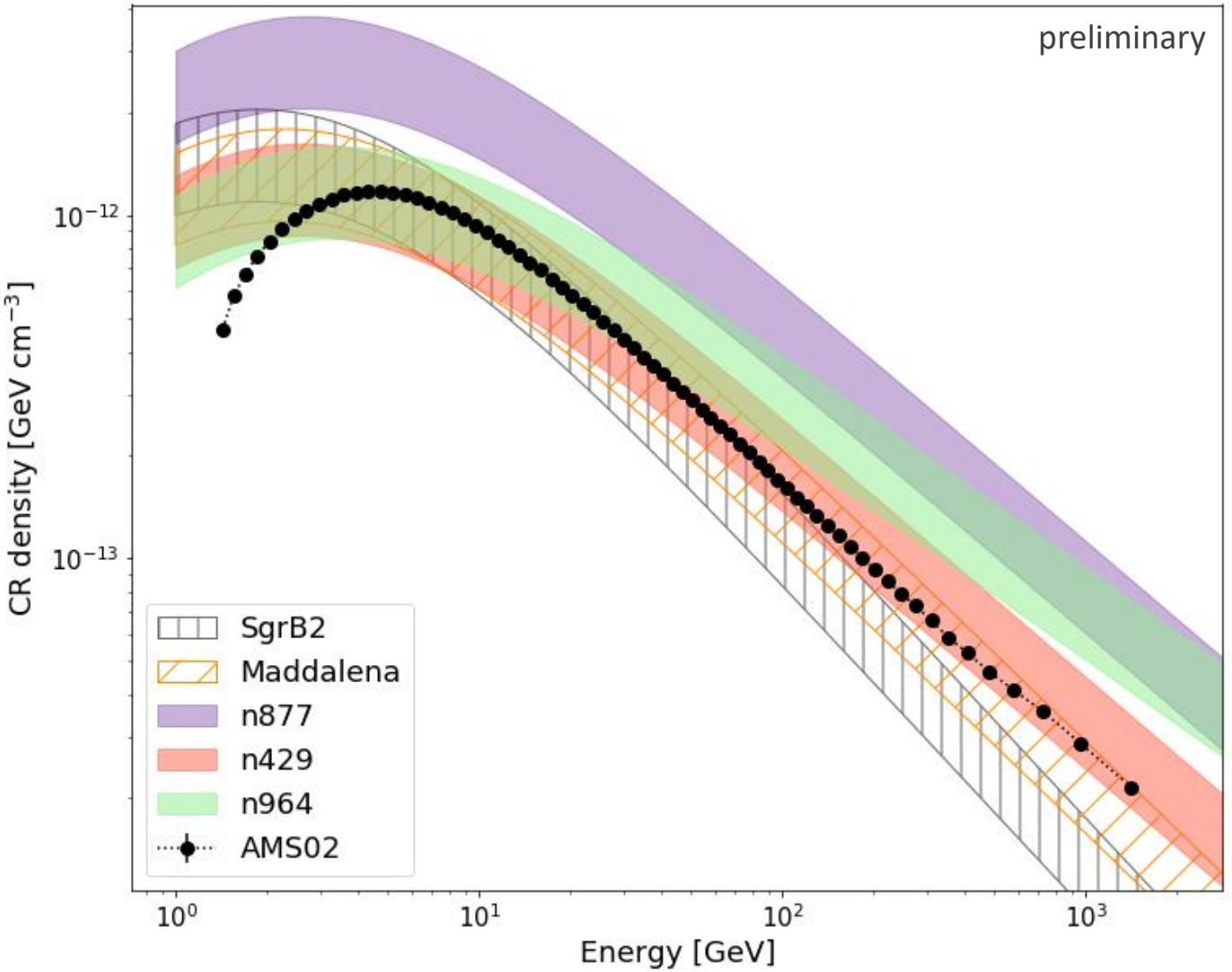
<u>10 CLOUDS</u>:

- $M_5/d_{kpc}^2 > 0.4$
- Dominant object in the LoS
- Different location in the Galaxy
- No overlapping with known γ-ray sources


x10^4
x10^3
x10^2
x10
< 1 kpc
4-6 kpc
6-8 kpc
8-10 kpc
10-12 kpc
Maddalena
n418
n429
n612 (x10)
Orion A (x10)
n933 (x100)
n964 (x100)
n243 (x1000)
n284 (x1000)
n804 (x1000)
n877 (x1000)
n902 (x1000)
Sgr B2 (x10000)
preliminary
E^2 dN/dE (MeV cm^-2 s^-1)
Energy (MeV)


SUN
SgrB2
GC
MonOB1
Maddalena
243
418
429
284
612
964
877
804
902
933
2
4
6
8
10

CR proton: derived spectra from MCs



4-6 kpc

6-8 kpc

10-12 kpc

Summary and Conclusions

- Molecular Clouds are the best way to derive CR properties in specific region 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;
- Improving instrument sensitivity will allow to widen the sample of clouds and have a complete tomography of the Milky Way.

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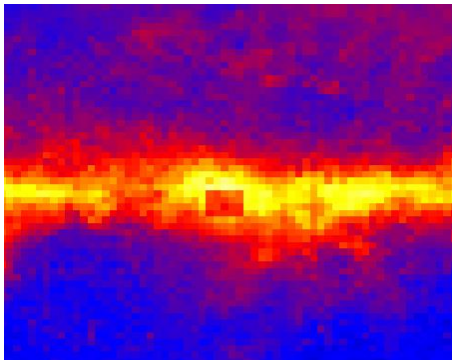
Grazie!

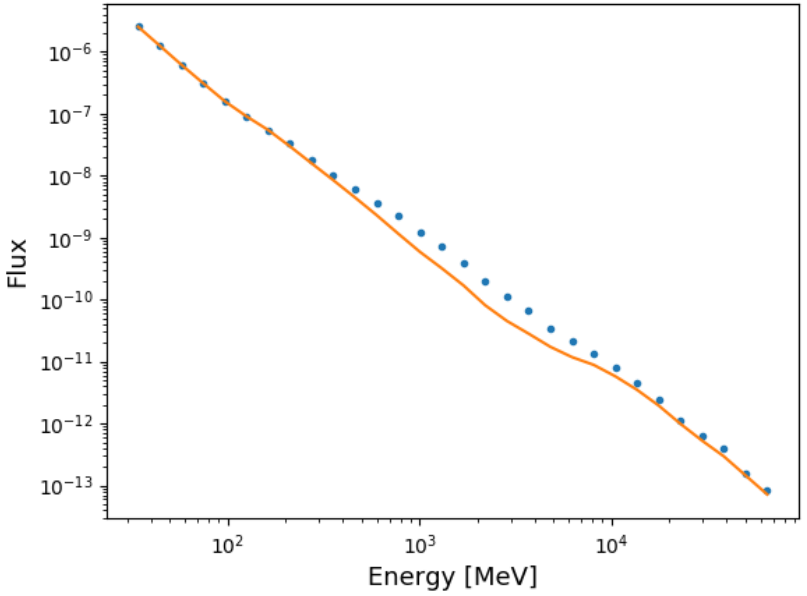
Analysis details: modeling the background

- 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 (galprop v54)
- Isotropic diffuse: computed by fitting a region of 30 degrees centered in l,b=(150,90)
- Sources from 3FGL



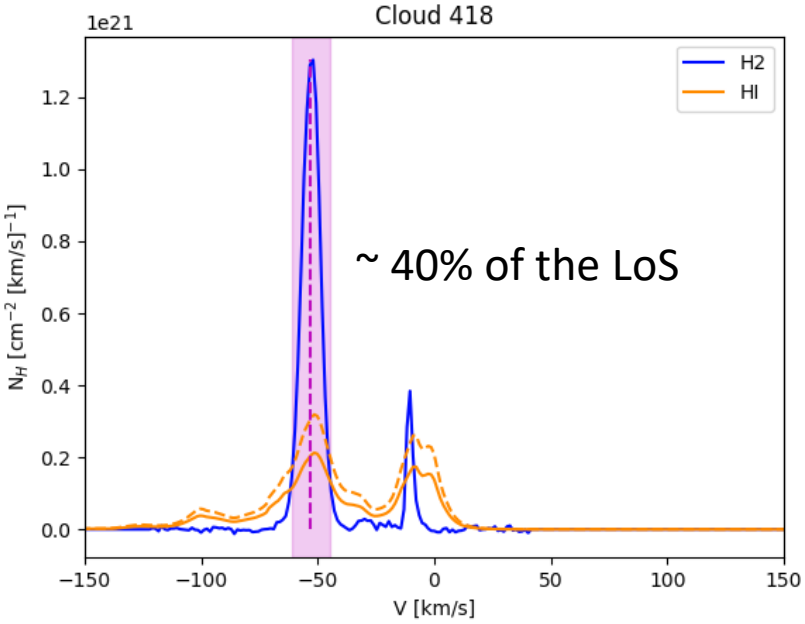
Cloud as boxes with:
-side 2r;
-cut in velocity range;
-centered in l,b;

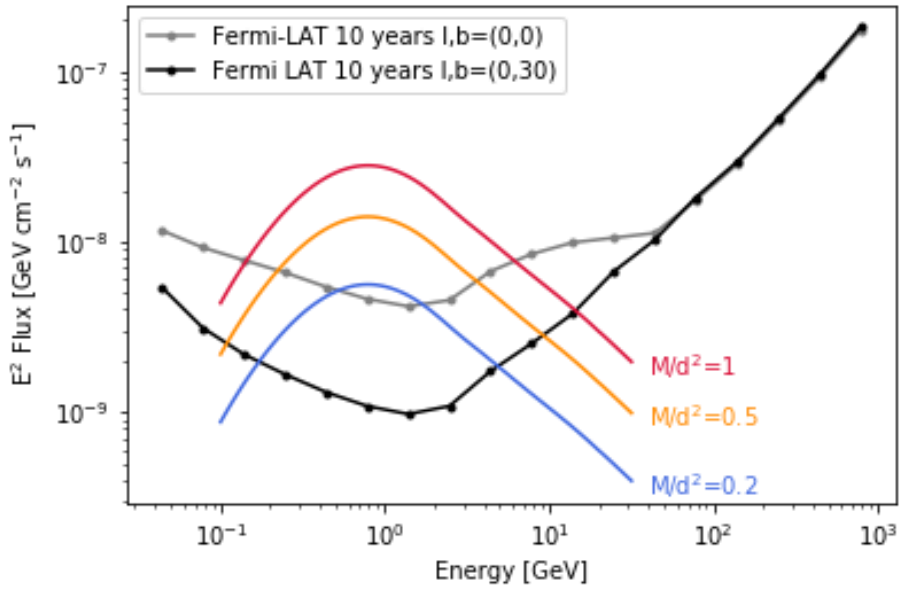
as given in Rice+2016

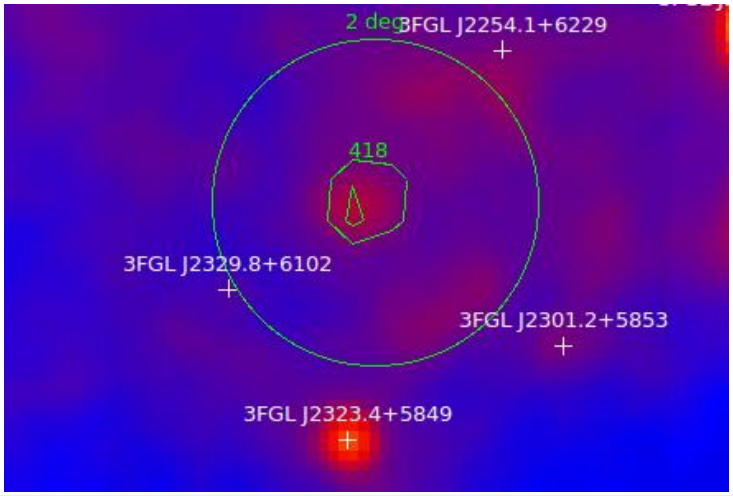


Analysis details: the selection of the MCs

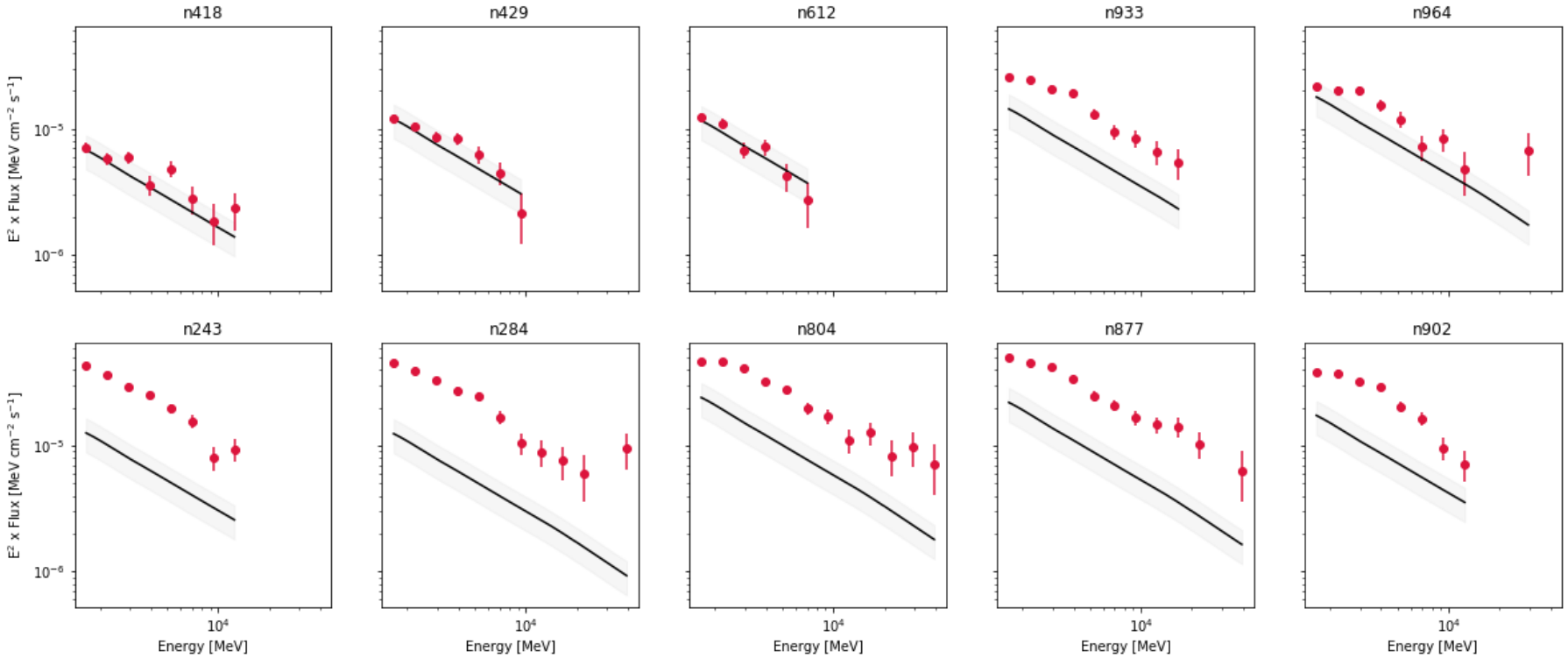
1) Large $\frac{M_5}{d_{kpc}^2}$
2) No 3FGL nor HESS sources overlapping, no brigth sources at < 2 degrees
3) Dominant object in the line of sight in term of gas (30-80% of the LoS).







Analysis details: all the spectra



Analysis details: residuals in term of TS