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Investigation of CR distributions using gamma-rays

Ruizhi Yang
USTC
In collaboration with Liu Bing, Li Guangxing, Sun Xiaona, et.al

Outlines

- Large scale distributions
- Implication to CR propagation models
- Small scale inhomogeneity

Propagation of GCRs

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- **Diffusion in an extended halo**

- **Primary injection spectrum (e.g, from DSA)**

  $Q(E) \sim E^{-\Upsilon}$

- **Confinement time (leaky box or diffusion model)**

  $\tau(E) \sim E^{-\delta}$

- **Steady state primary spectrum**

  $N(E) \sim Q(E)\tau(E) \sim E^{-(\Upsilon+\delta)}$

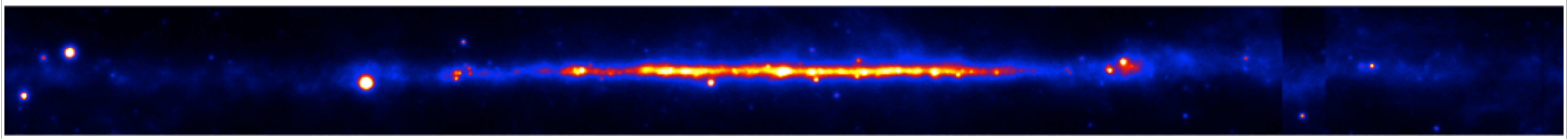
- **Steady state secondary spectrum**

  $N(E) \sim Q(E)\tau^2(E) \sim E^{-(\Upsilon+2\delta)}$

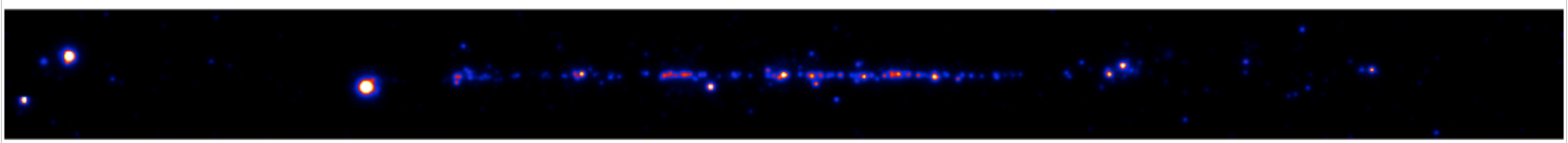
- **Secondary/primary ratio** $\sim E^{-\delta}$ (B/C observations)

Diffuse gamma-rays

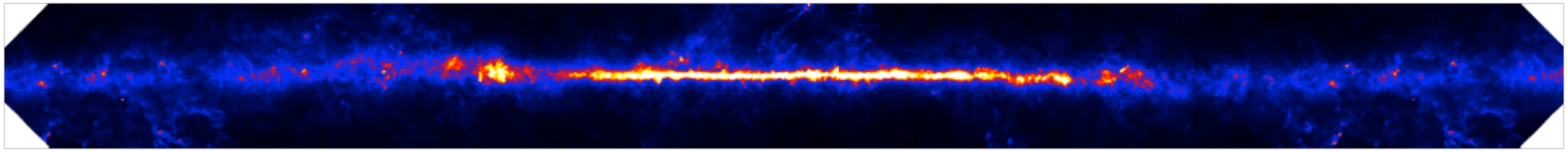
Gamma-ray counts map



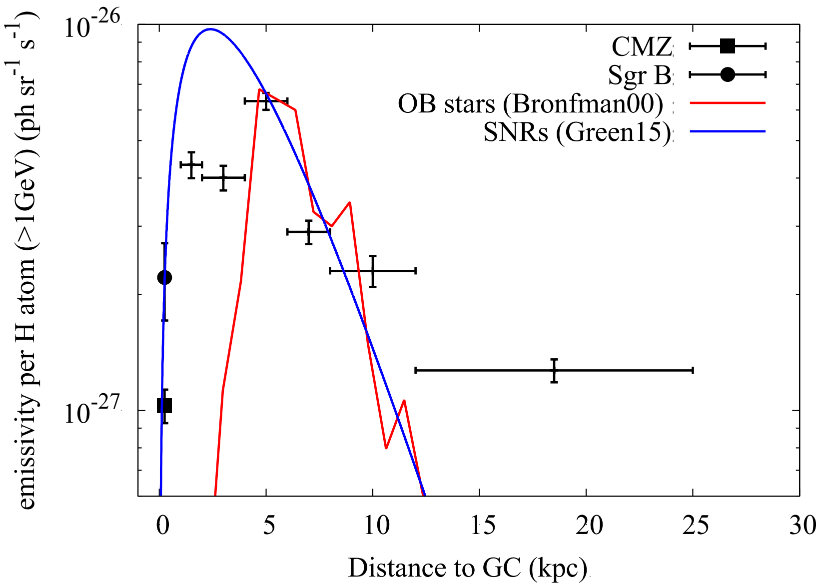
Point source contribution

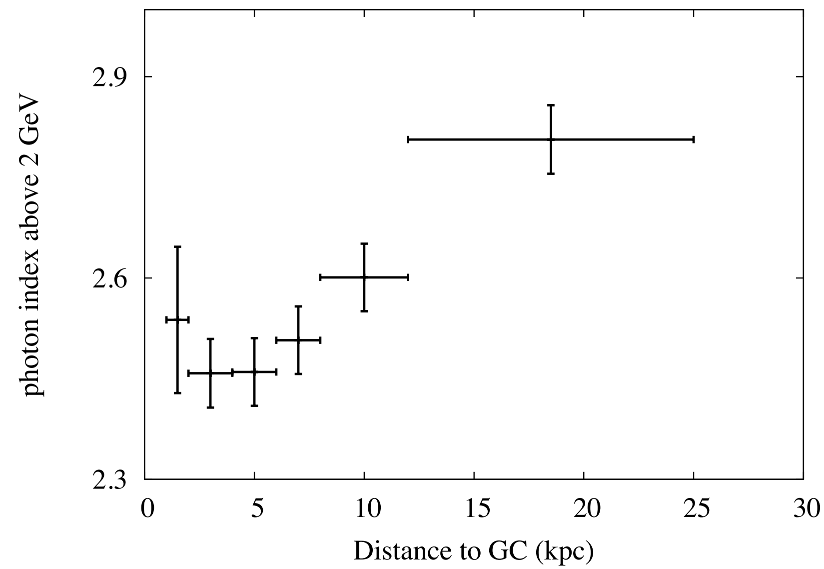


Dust opacity map (gas column)



CR Radial distributions



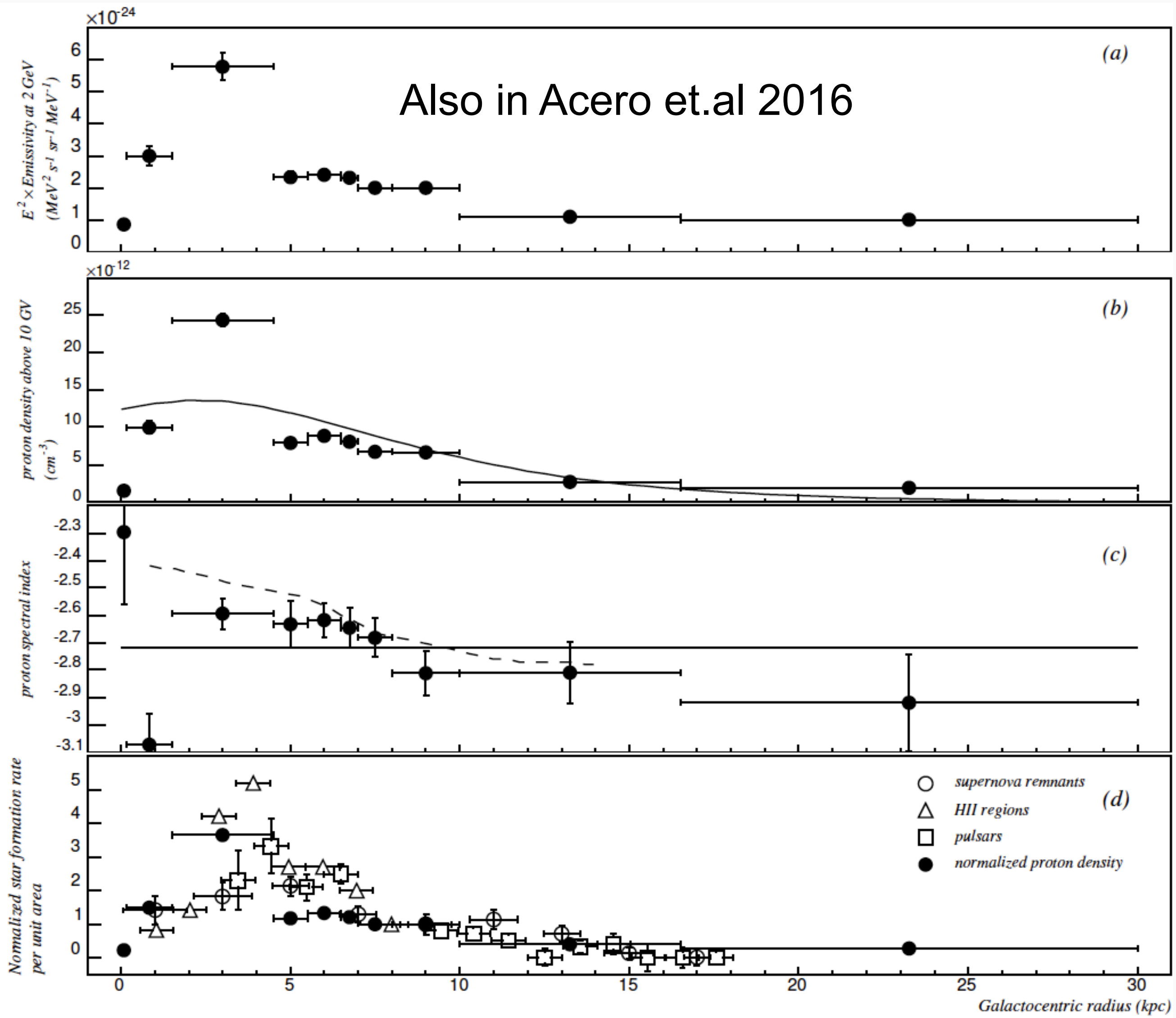


Yang et.al 2016

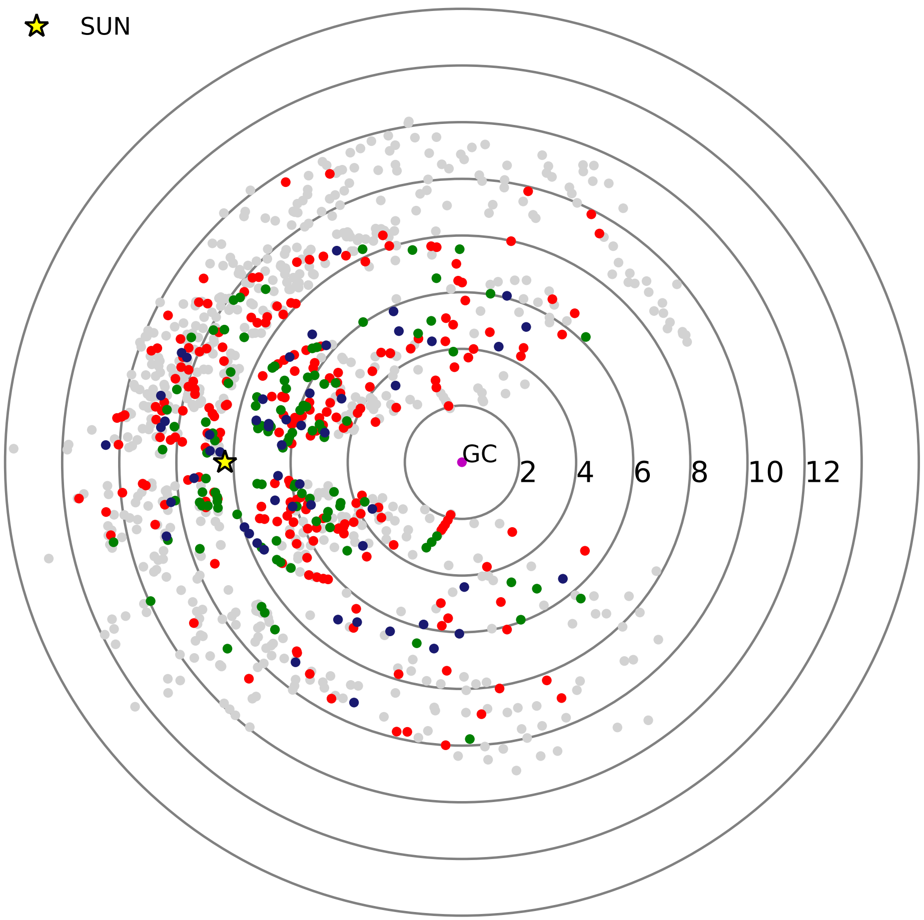
Inhomogeneity in large scale, both in spectra and in densities:

- Softening towards outer Galaxy
- Peak of density at 4-6 kpc ring

CR Radial distributions



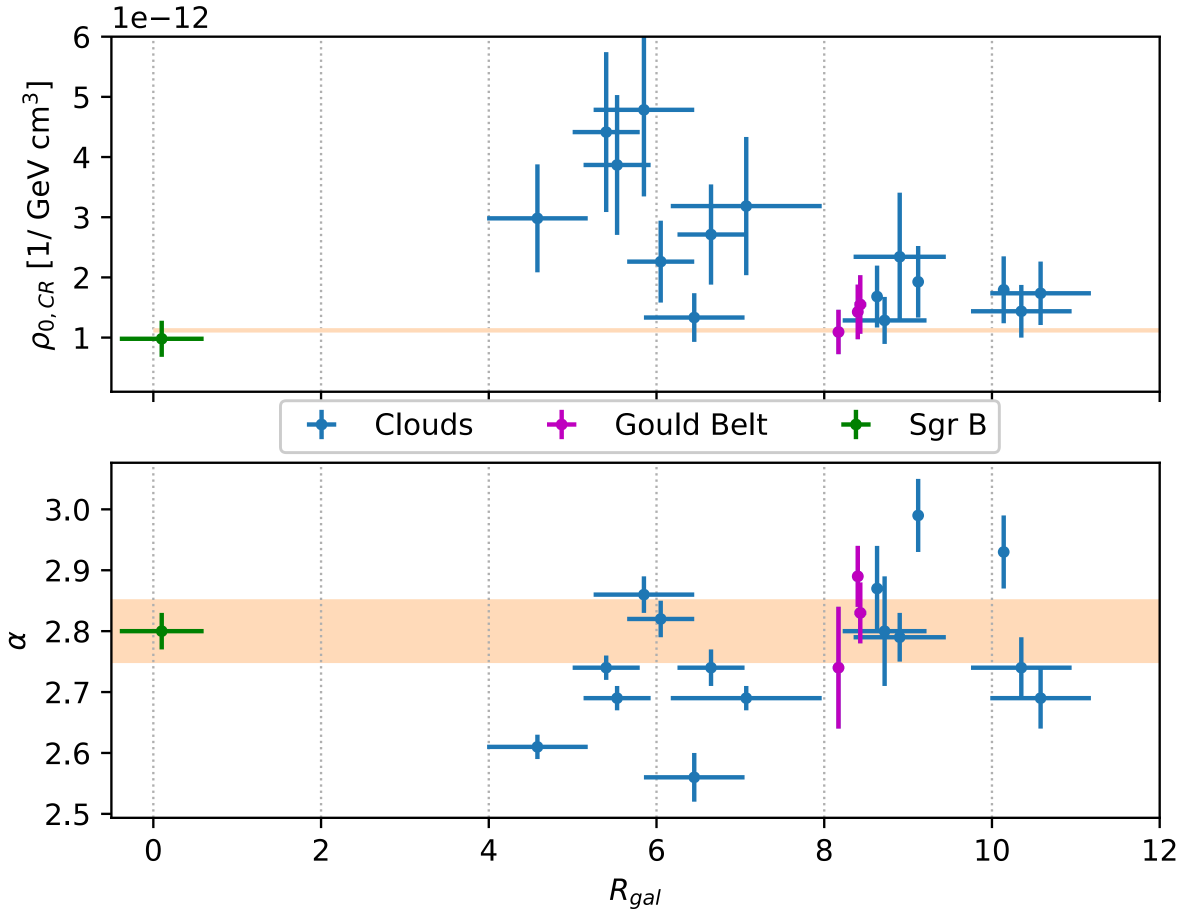
distant GMCs



Aharonian et.al 2019

- Rice et.al (2016) have identified thousands of Molecular Clouds in the Galaxy
- Possible to measure CR density in each position of the Galaxy.

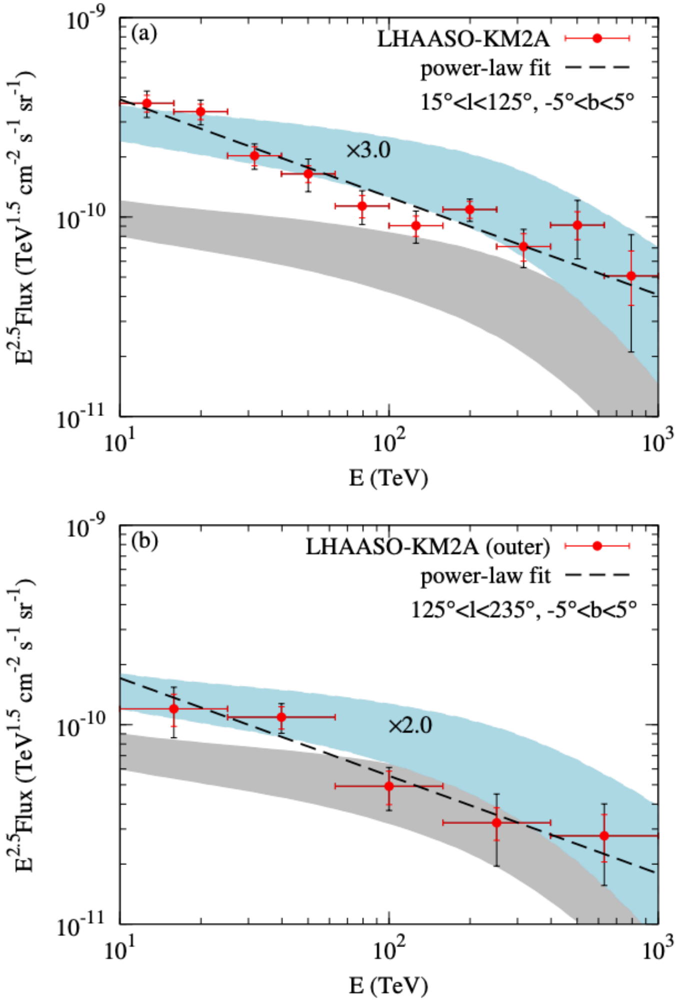
Distant GMCs

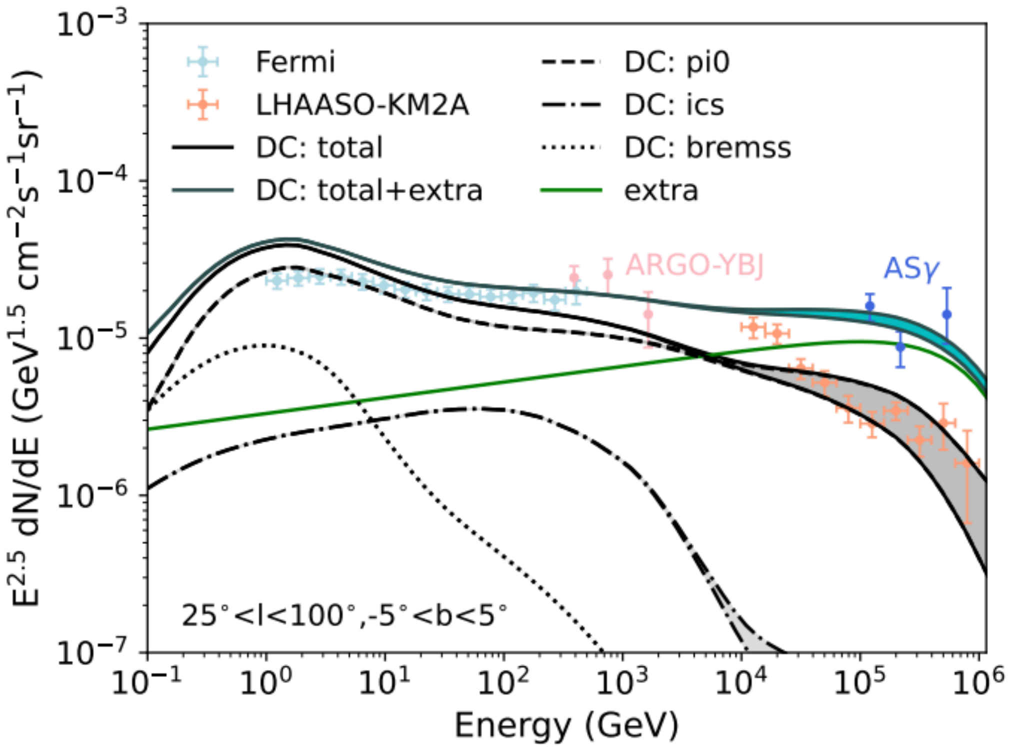


Aharonian et.al 2019

- Also reveal similar picture

LHAASO Results





Zhang et.al 2023

A new component?

A hard component associated with HII gas?

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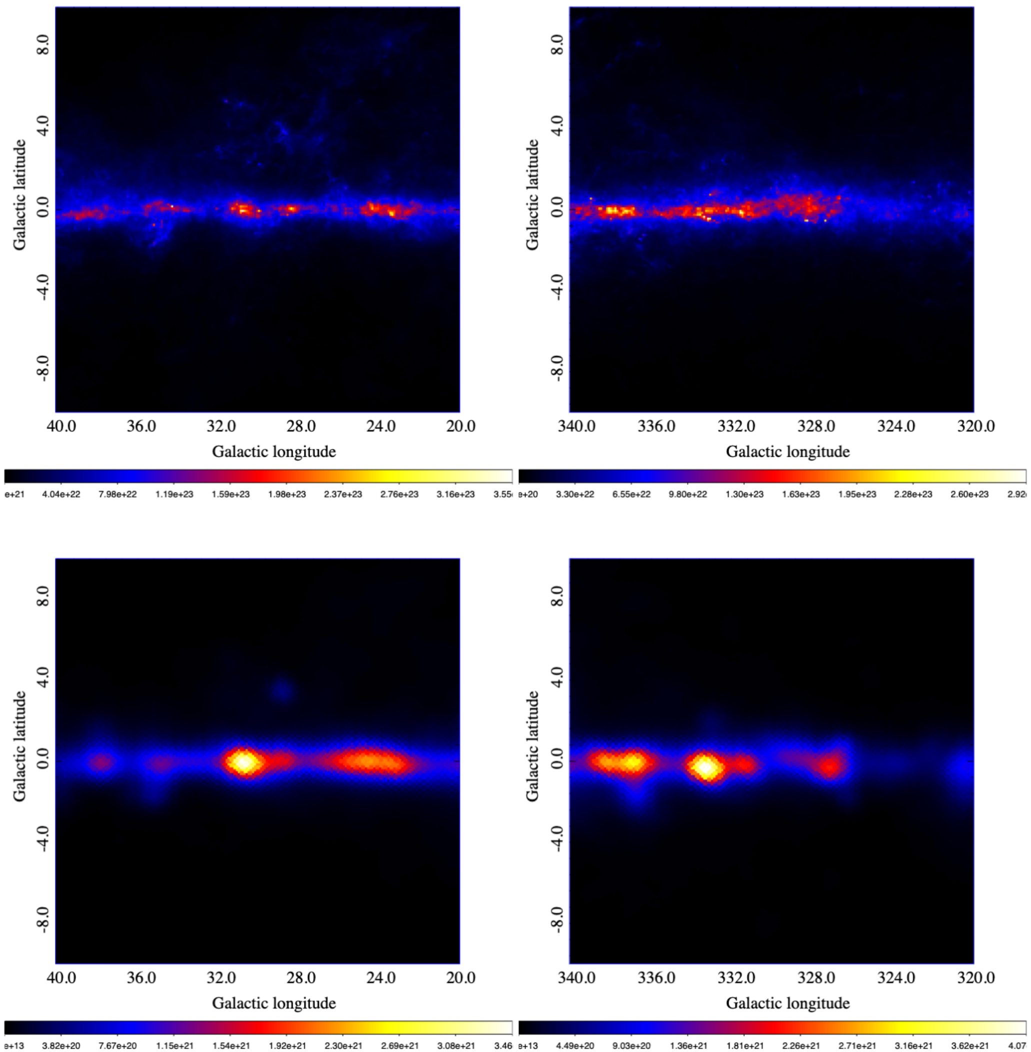
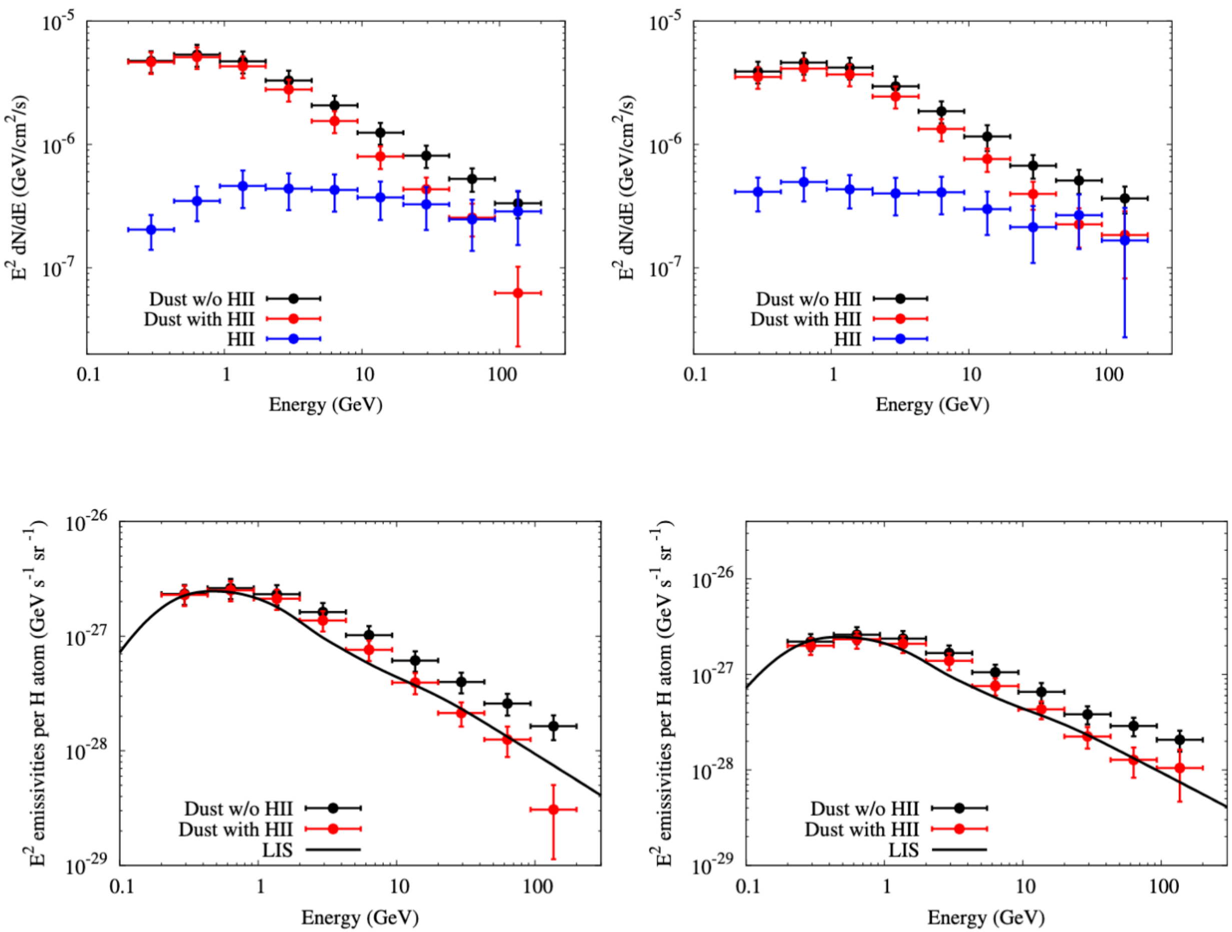


Liu et.al A&A 659, A101 (2022)

- HII gas were ignored in former modeling
- HII can trace star forming activity, may related to CR sources (such as cocoons near YMCs).
- Different Morphology in HII and total gas column can be used to separate different component

A hard component associated with HII gas?

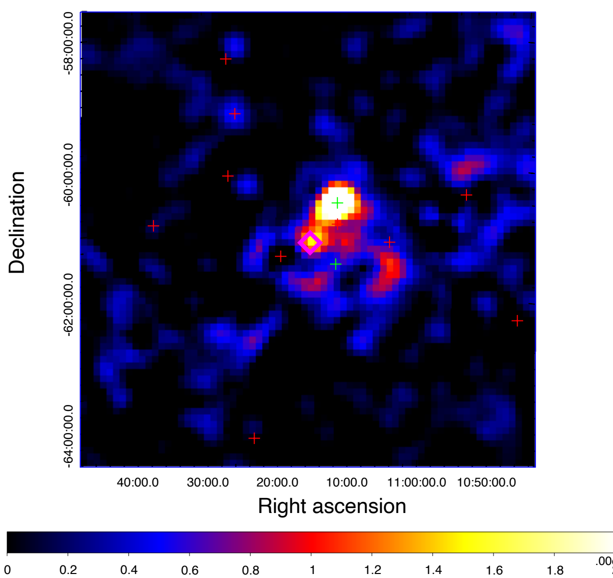


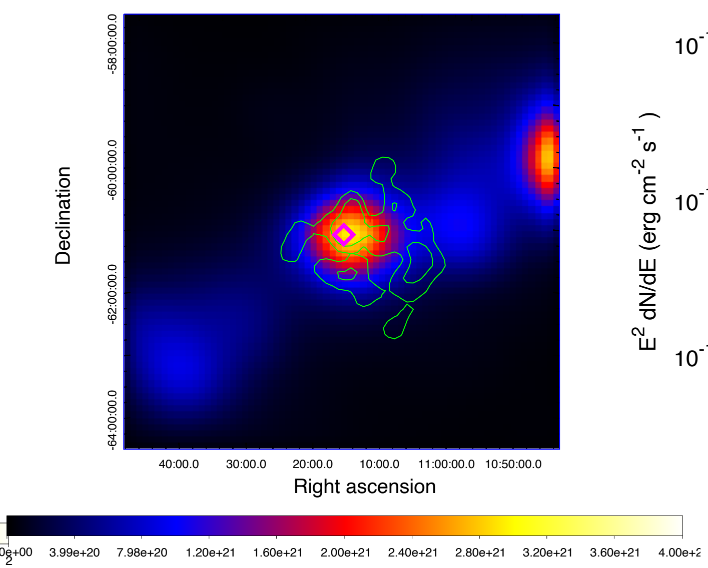
- After considering HII component the CR distributions looks “more homogeneous”
- The former inhomogeneity is simply due to the mixing of “true” diffuse (sea) component with hard “source” (island) regions

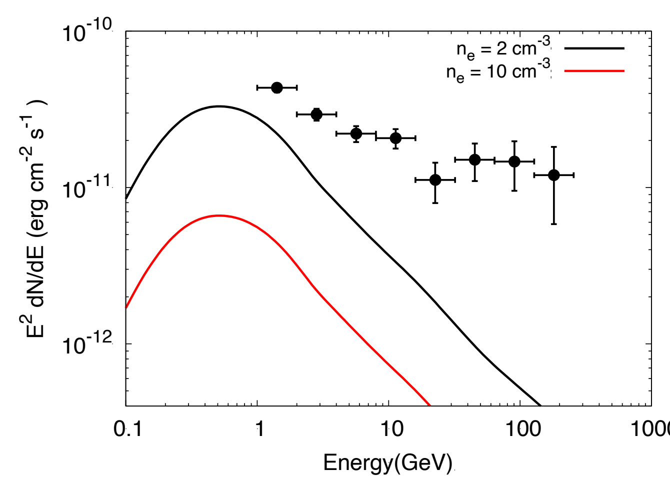
Liu et.al A&A 659, A101 (2022)

Possible sources related to those HII region

The HII regions are linked naturally to the young massive star clusters (YMCs). Below is the case for NGC 3603. left :gamma, middle: HII







CR cocoon/bubble near accelerator

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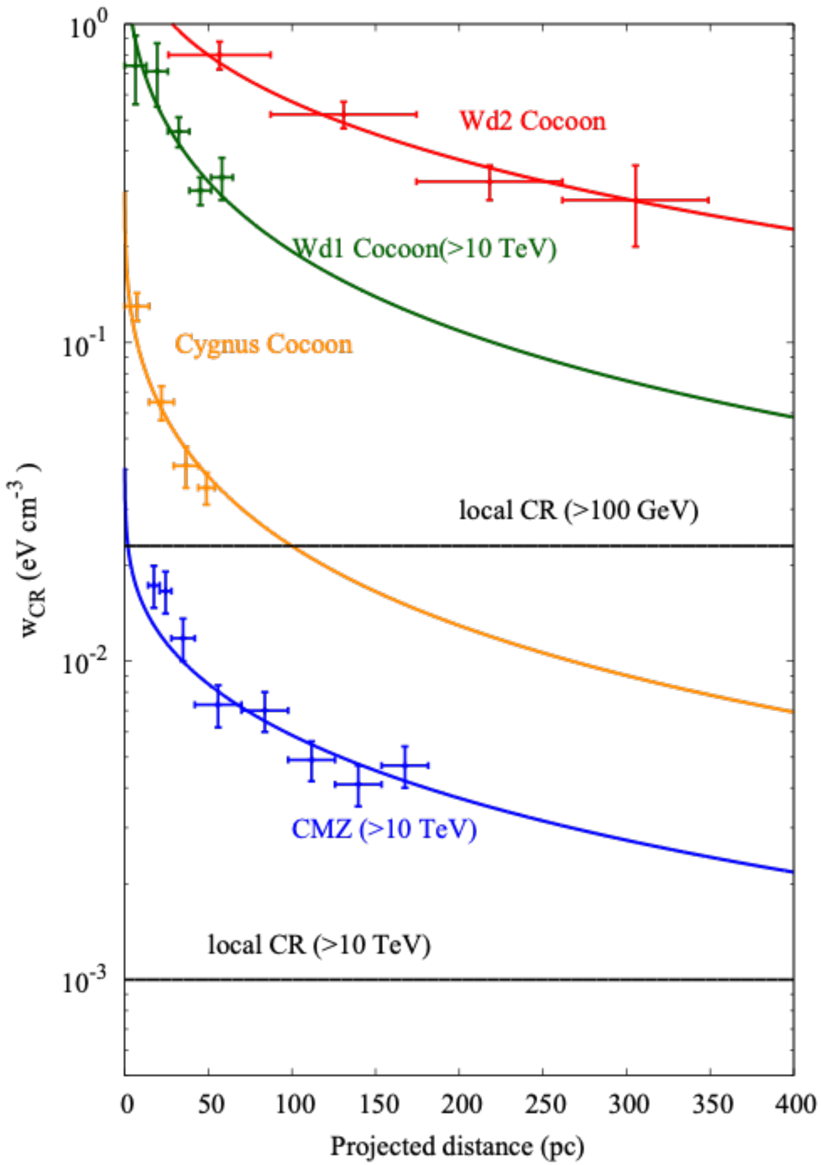

- CR distribution derived by gamma-ray profile and gas distributions
- All four sources (Wd1, Wd2, Cygnus cocoon, GC) show 1/r distribution of CRs
- In diffusion, 1/r profile implies a continuous injection (in the lifetime of clusters)
- The limited age and wind power reveal a rather small D(E), 100 times smaller than the ISM value

Aharonian et.al 2019

An extreame example : LHAASO Cygnus bubble

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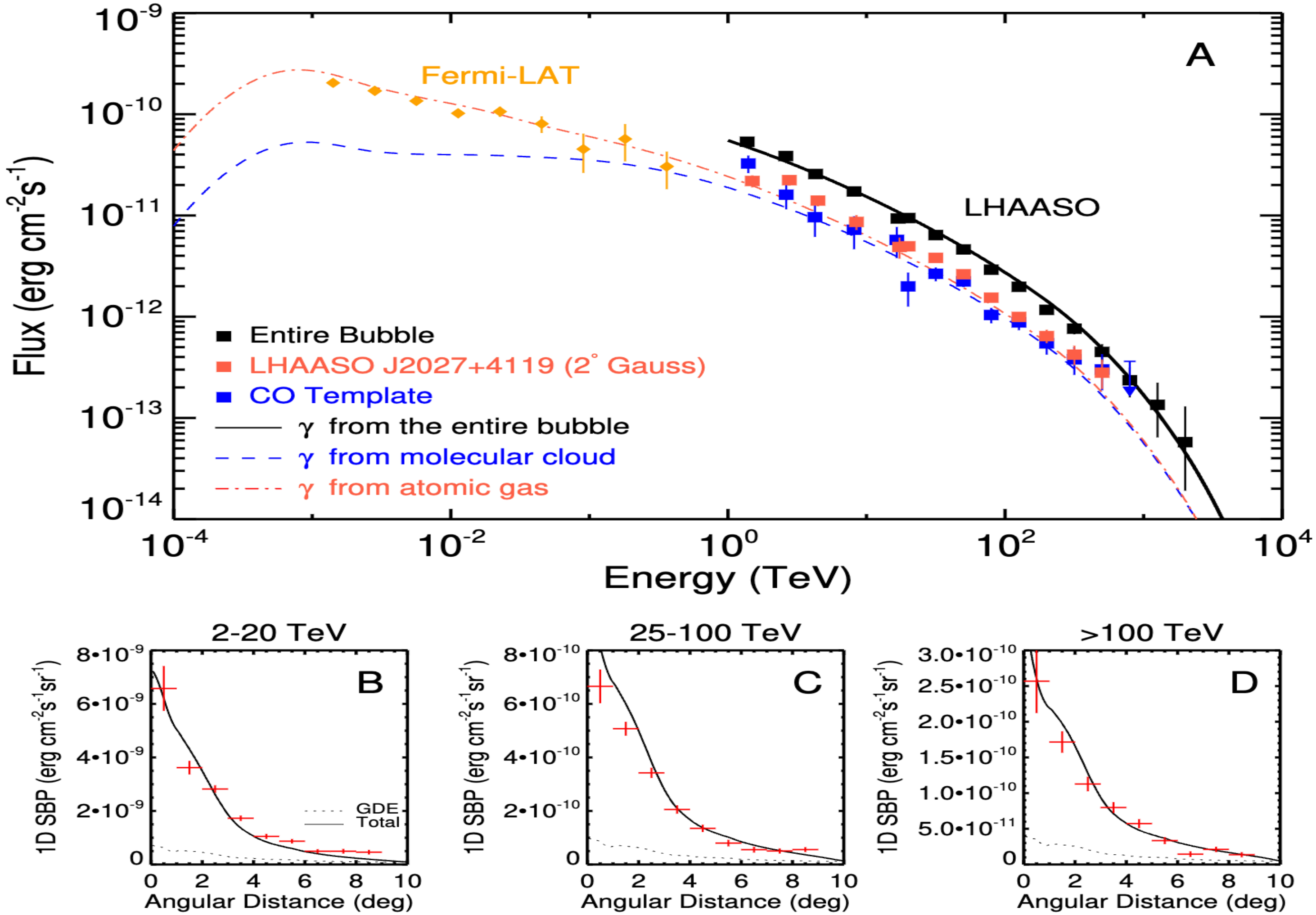

a size of more than 150 pc

Slow diffusion (also) in pulsar Halos

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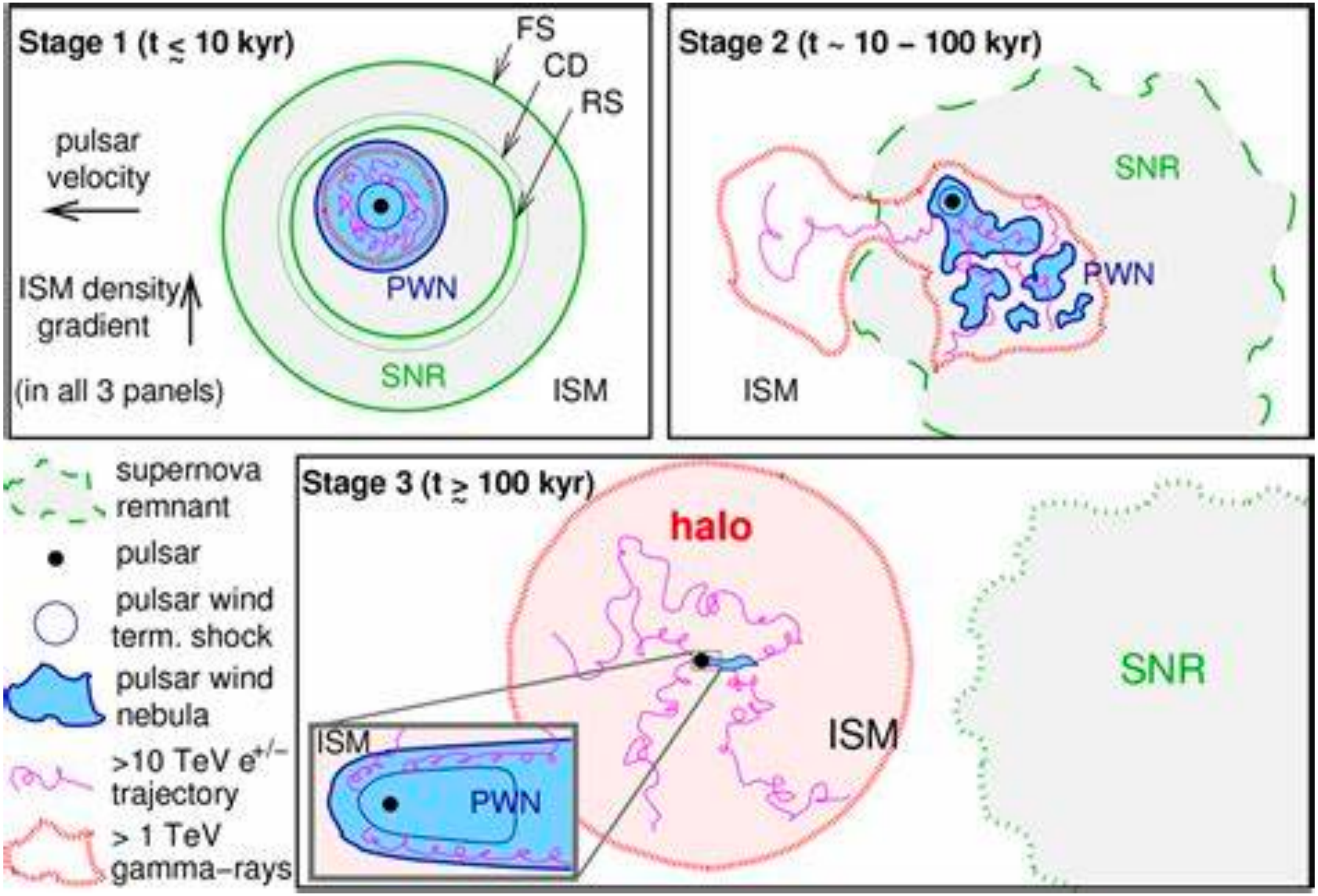

Self confinement near CR sources

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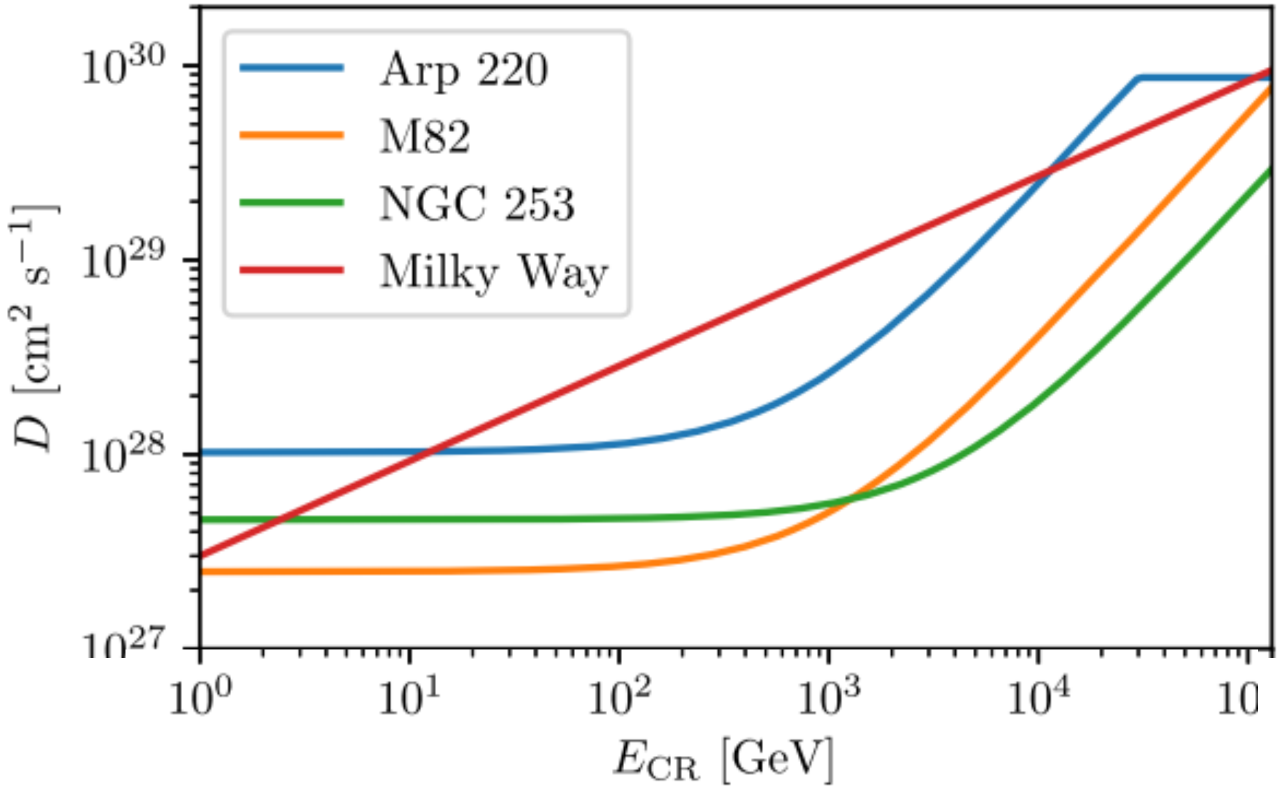
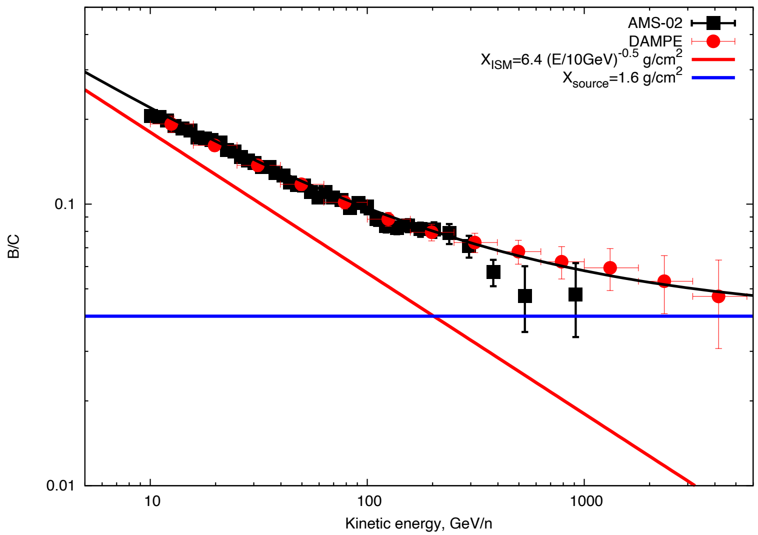
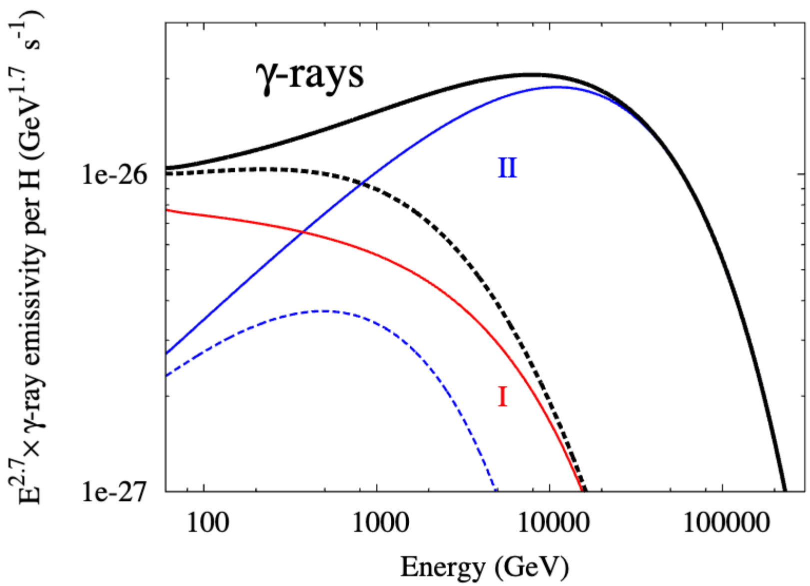
- Possible energy independent escape from Source regions (normal assumption if CR streaming dominate the magnetic turbulence, e.g. Krumholz 2019)



Slow diffusion region near source

- A natural explanation for the hardening of B/C ratio ?
- An extra component in diffuse emission





Grammage inside cocoon/bubble: X=m_H*n_H*c*T, T~L**2/D, L :size of cocoon

X~1.5 g/cm^2*(l/50pc)**2*(2e26 cm^2/s/D)

See also   Yang & Aharonian 2020   PhysRevD.100.063020

Also Sun et.al 2307.02372

Possible link to dynamical structures

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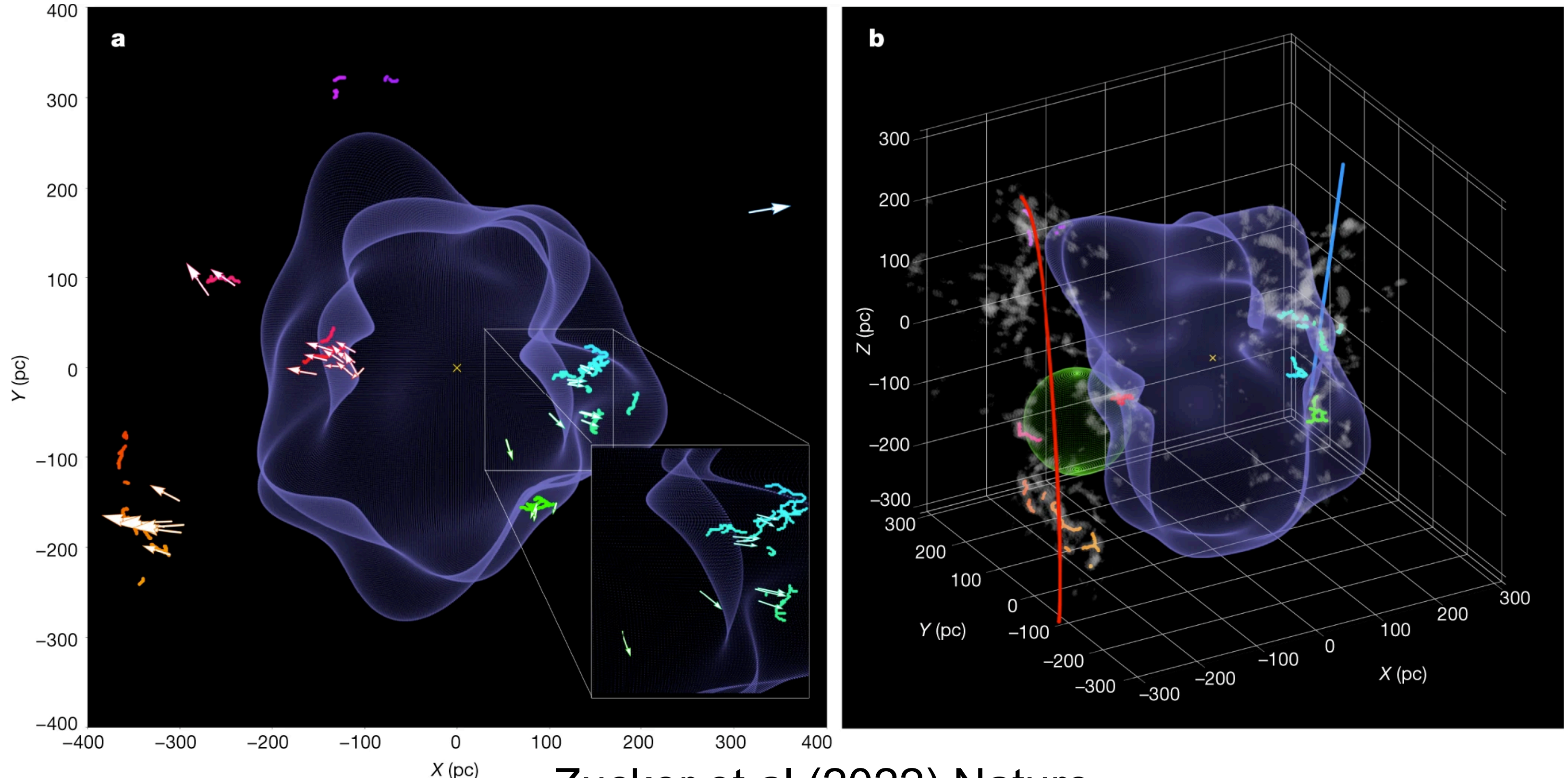
- hard Gamma-ray emissions associated with HII region
- related to CR cocoons/bubbles near YMC.
- Slow diffusion therein and produce additional secondaries. (similar to two-zone Halo-disk model)

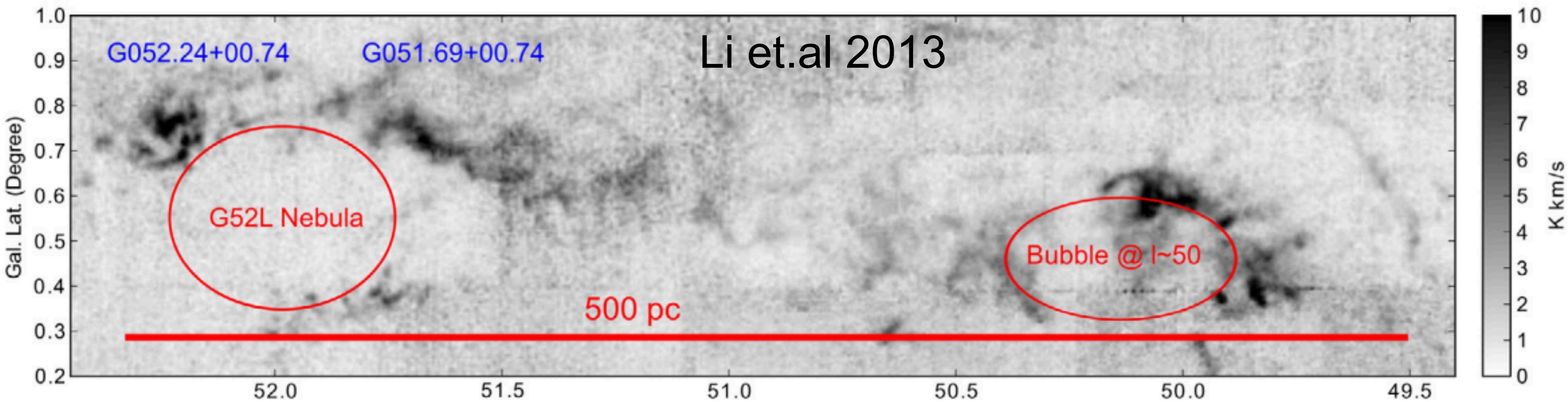
Are these CR cocoons coincide with the gas structures dubbed as Super bubbles ?

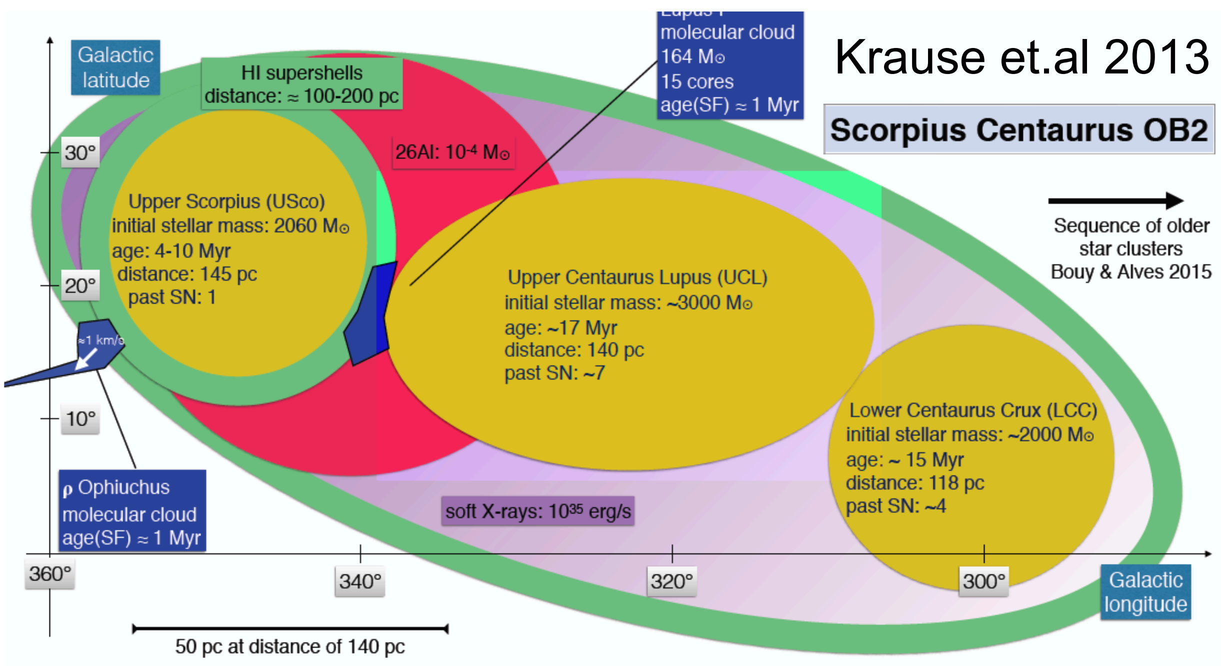


Zucker et.al (2022) Nature

Possible link to dynamical structures

Molecular clouds are formed in the boundary of these super bubbles.





Would be interesting target for LHAASO.

VHE CR will hit them earlier than low energy CRs, very hard spectrum expected.

Alternative scenario

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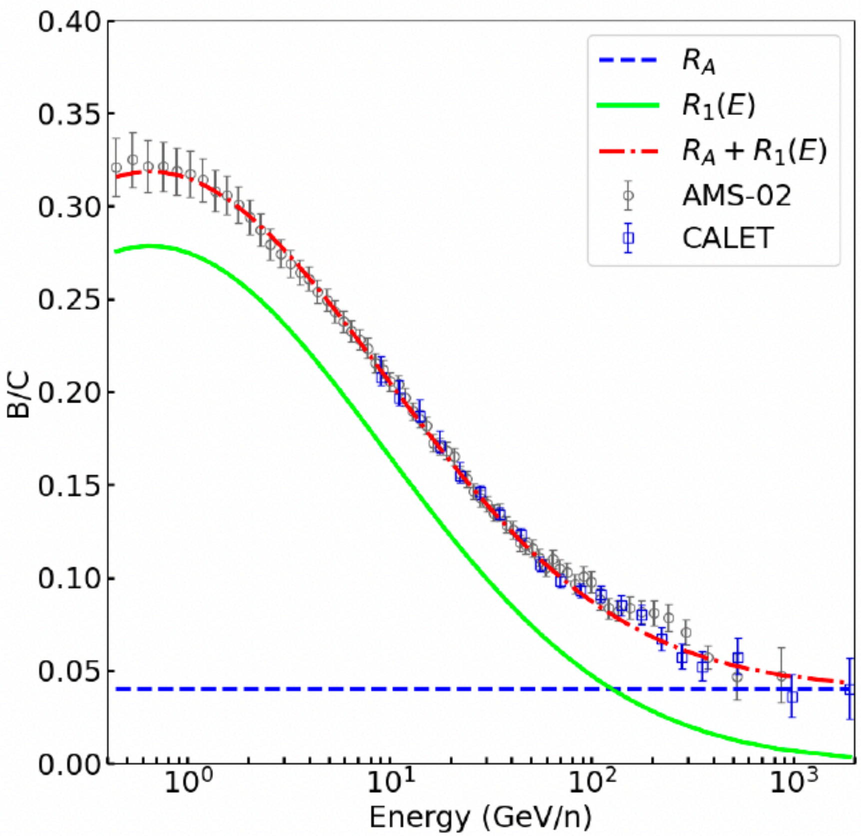

Cowsik 2023

- Energy independent diffusion in the ISM
- Energy dependent diffusion near source

Future： IACTs in LHAASO site (LACT)

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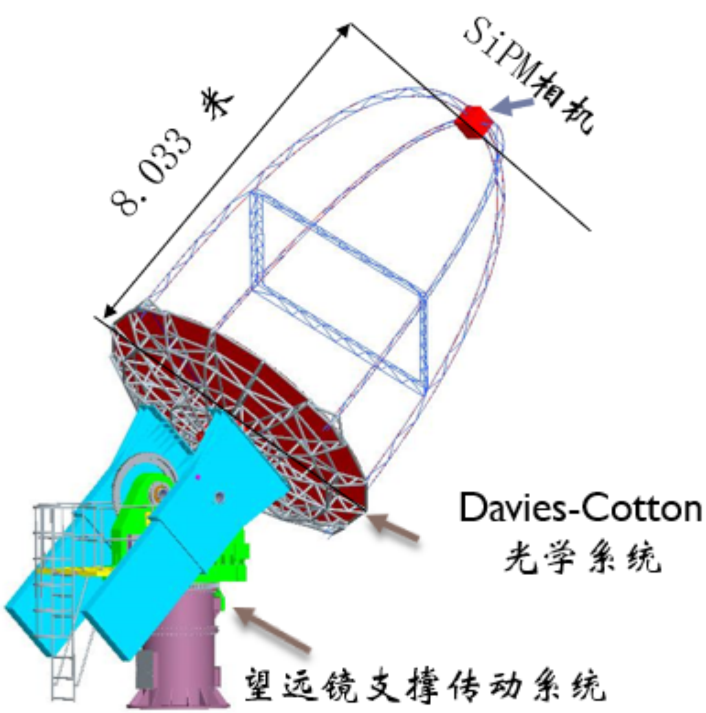

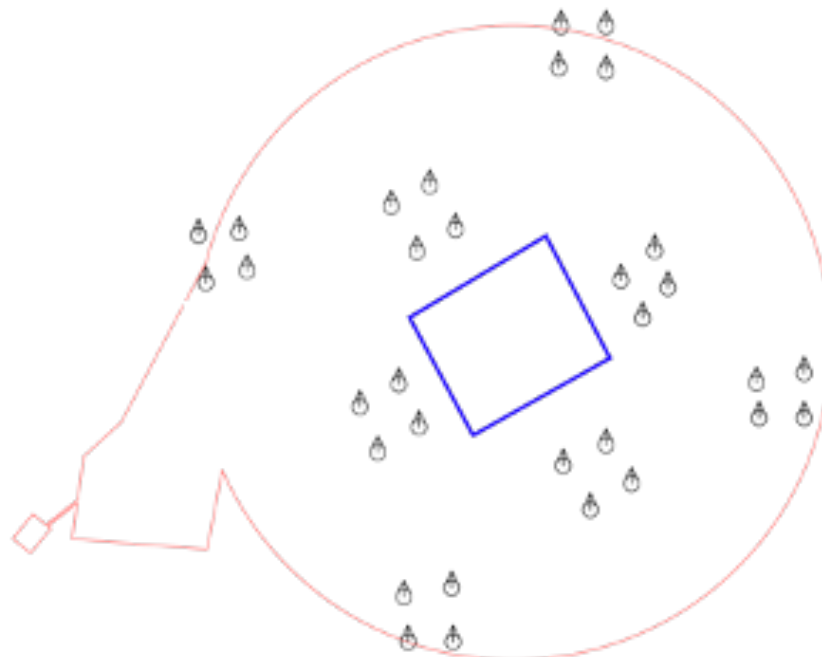

6m telescopes

8 X 4 arrays in LHAASO site

Prototype nearly finished

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First light soon!

Predicted sensitivities

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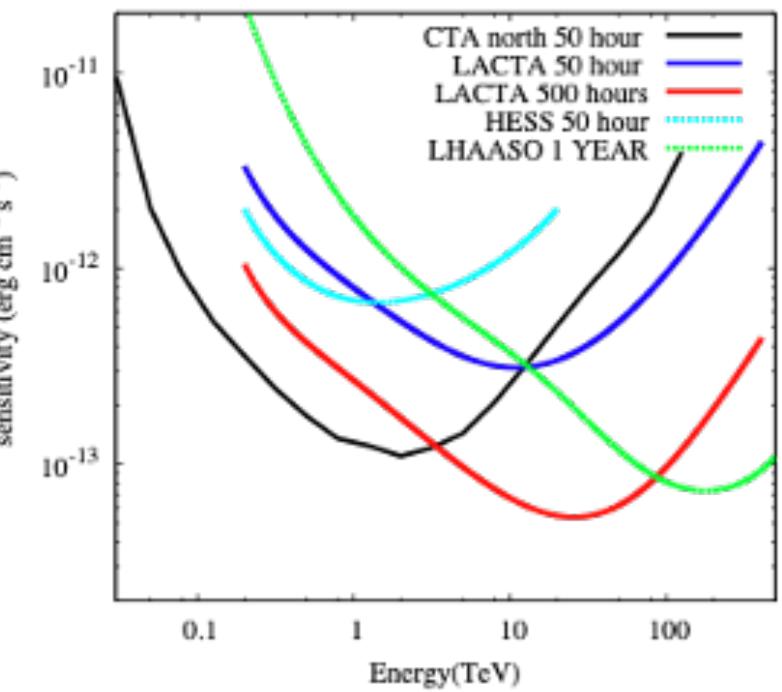
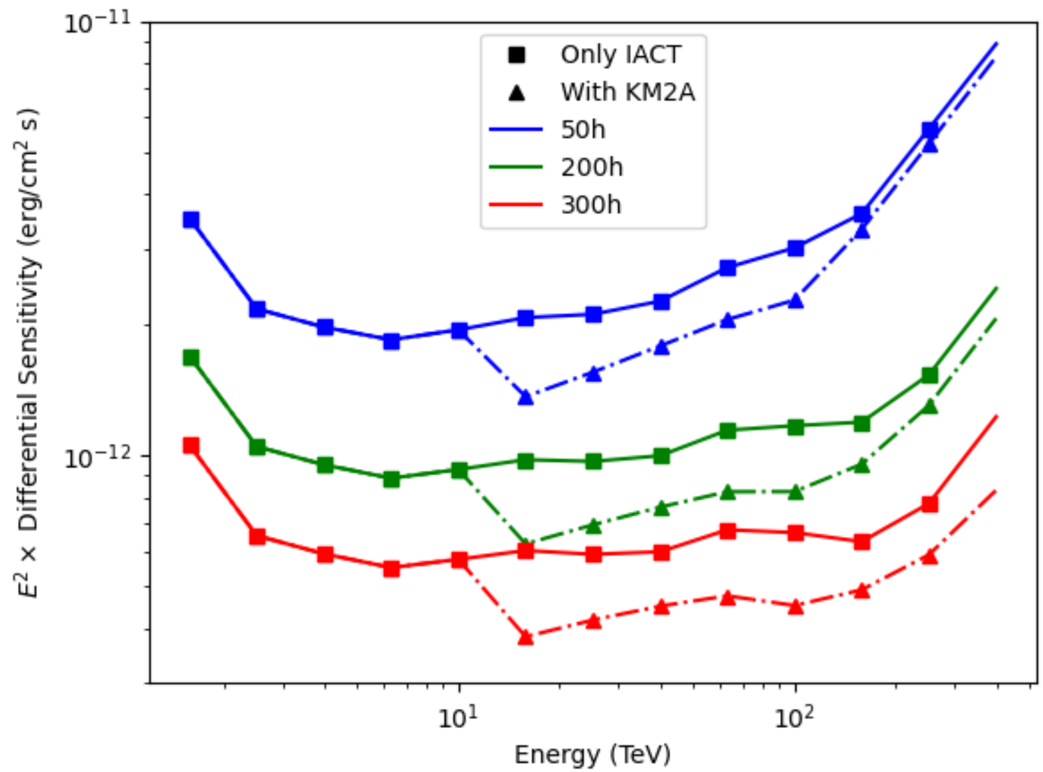
Synergy with LHAASO
Detailed morphology study of PeVatrons, TeV halo, PWN…
* Joint reconstruction with LHAASO cab further improve the sensitivity





Inhomogeneity in small scale

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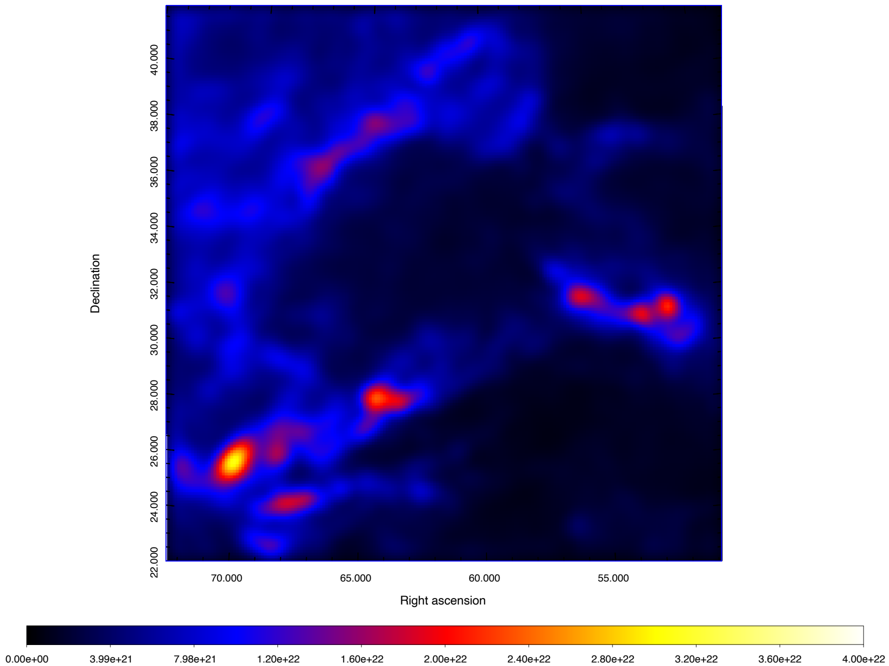
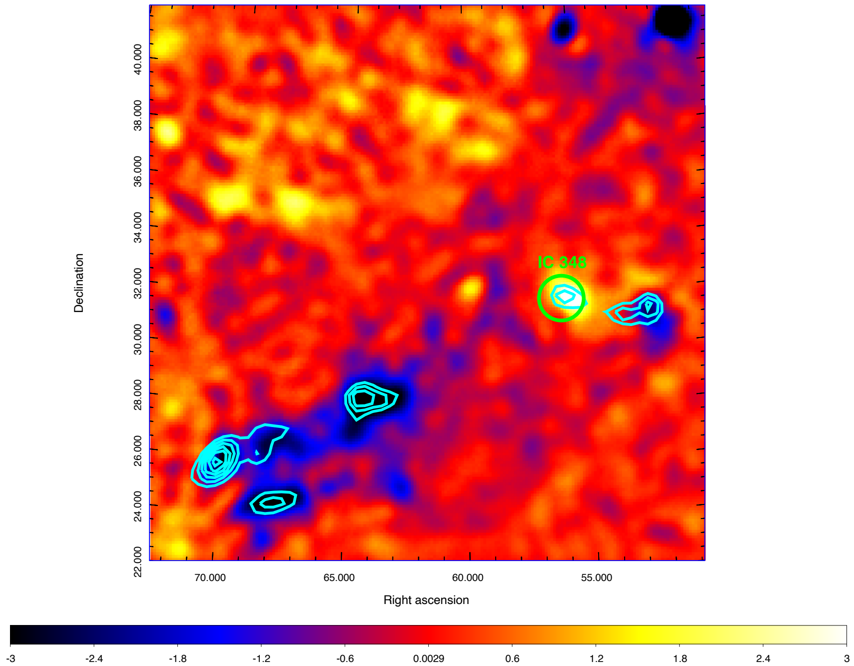
- Taurus-Perseus region
- low gamma-ray emissivities in Highest density regions



Dust opacity (gas distribution)



gamma residual (CR density)

Inhomogeneity in small scale

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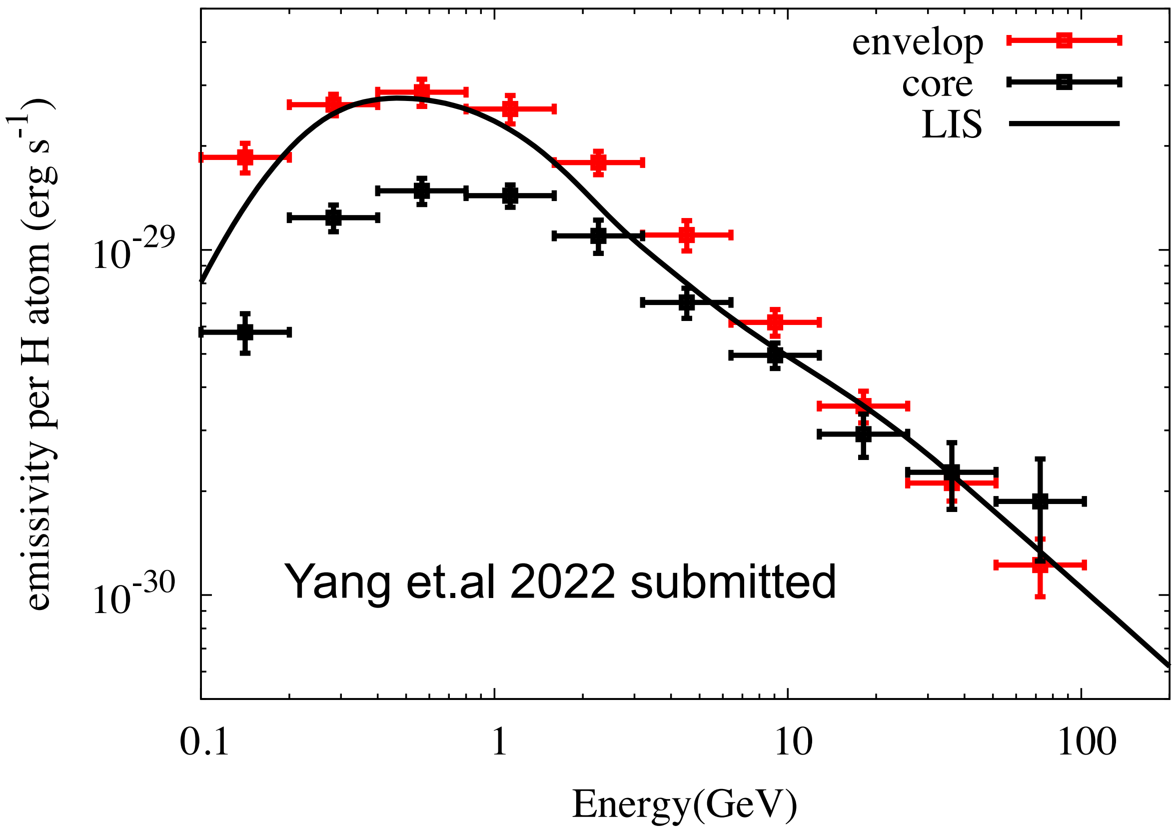
- LECR cannot penetrate into clumps.
- Lower Ionization rate therein?



Smaller ionization rate?

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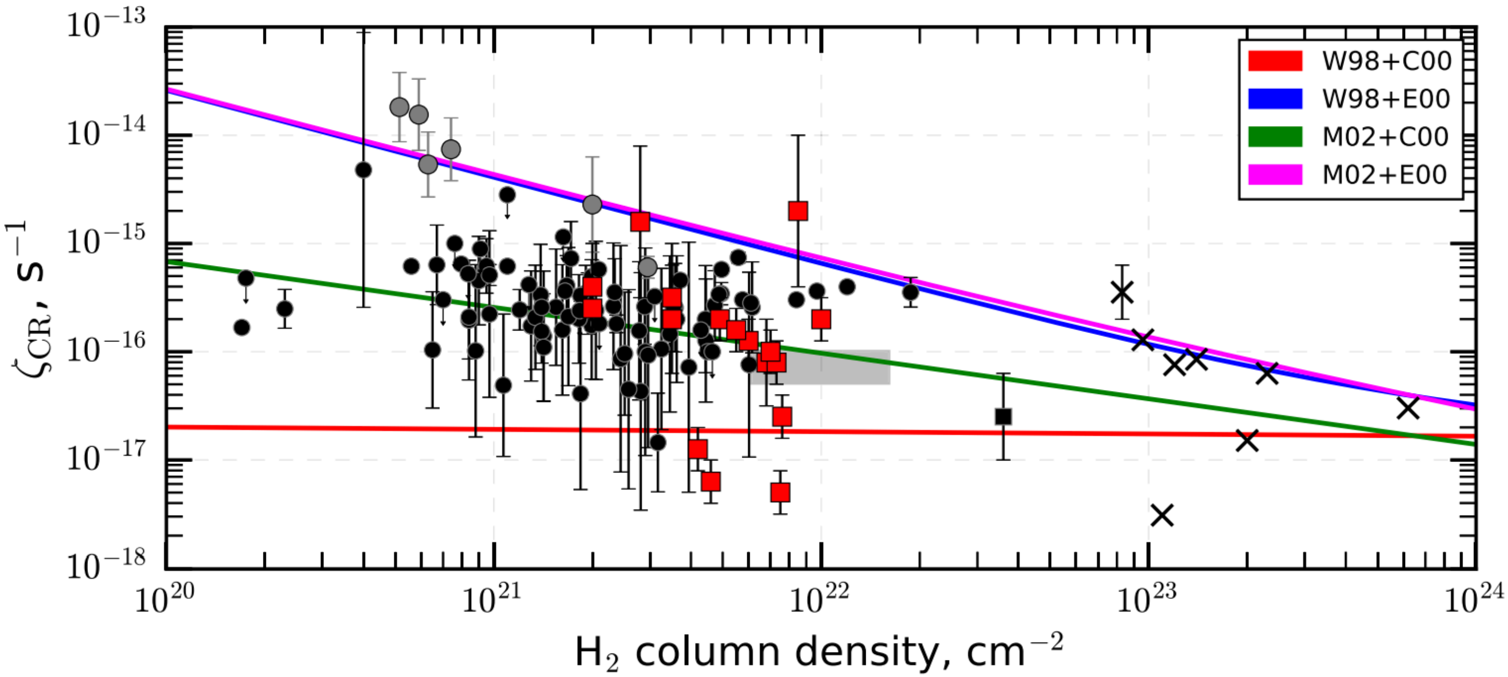
NAL, 868:40 (13pp), 2018 November 20 Albertsson, Kauffmann, &



bserved sources with measured H_2 column densities and ζ_{CR}. The symbols specify the type of object in the observations as follows:

Slower diffusion inside clumps

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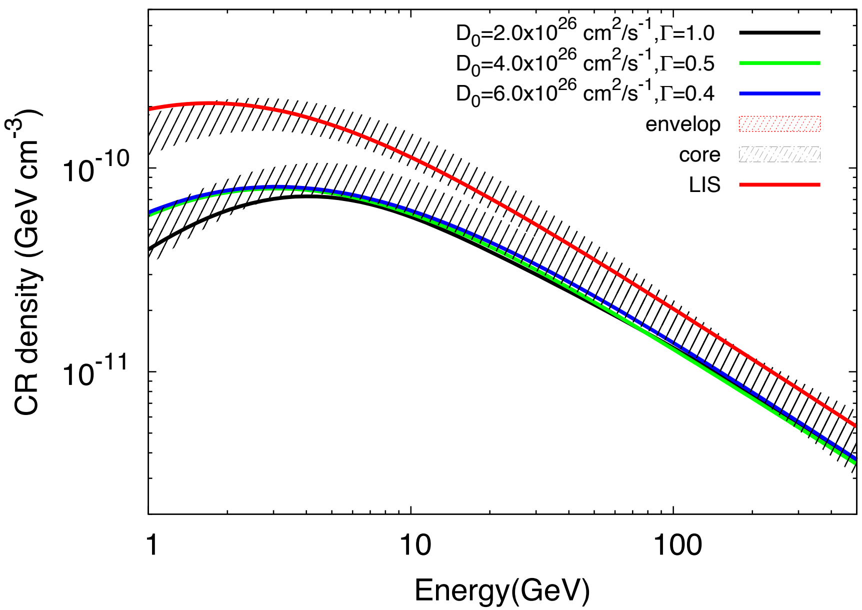
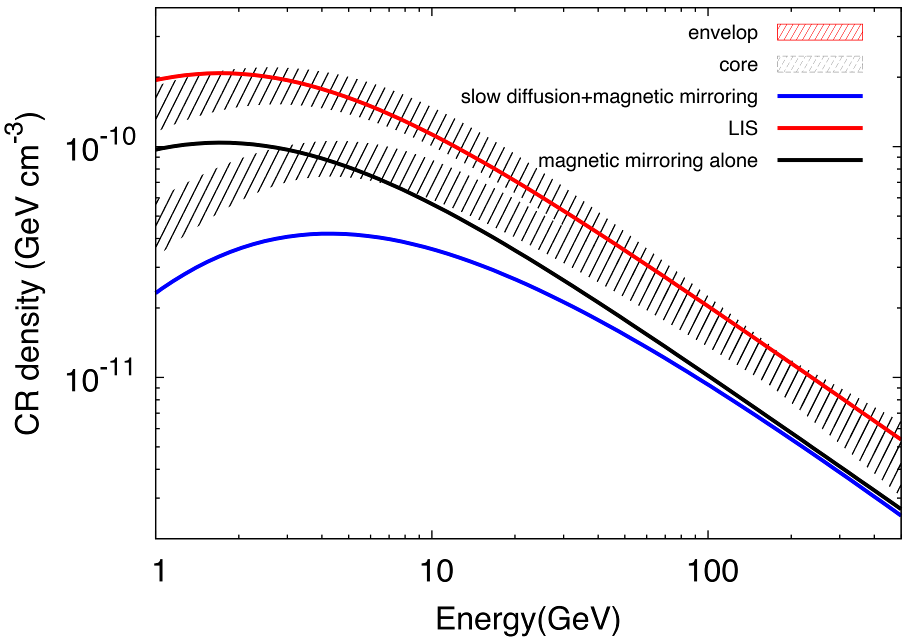




Also 100 times smaller than ISM in GeV

Magnetic mirroring can hardly explain

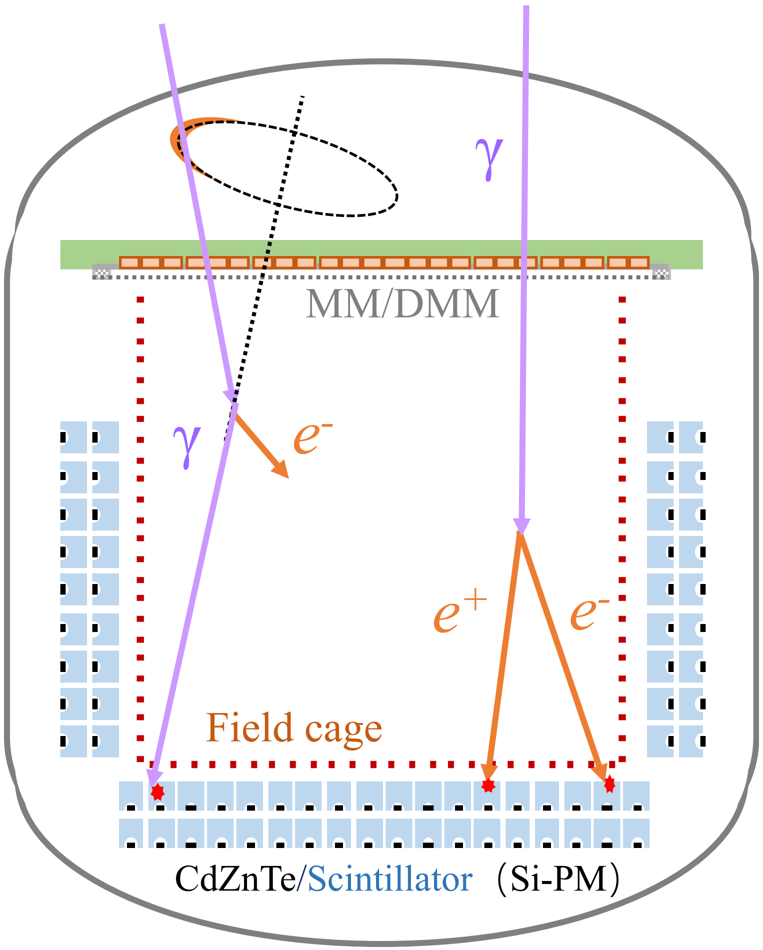
Nature Astronomy *7, 351–358 (2023)*

MeGaT: a high resolution MeV Gamma Telescope using TPC and CZT detectors

High Precision Telescope for MeV Gamma Rays

Design and goals

- 50cm cubic TPC, 3-5 bar, weight ~ 1400 kg
- Resistive-Micromegas (or double-MM) gas amplification.
- Collection on x-y strips, 0.8 mm pitch .
- CdZnTe/Scintillator +Si-PM for energy measurement .
- Energy region: 0.1MeV -1GeV .
- Resolution: 1.2° @MeV, 0.5 ° @100 MeV.



MeGaT sensitivities

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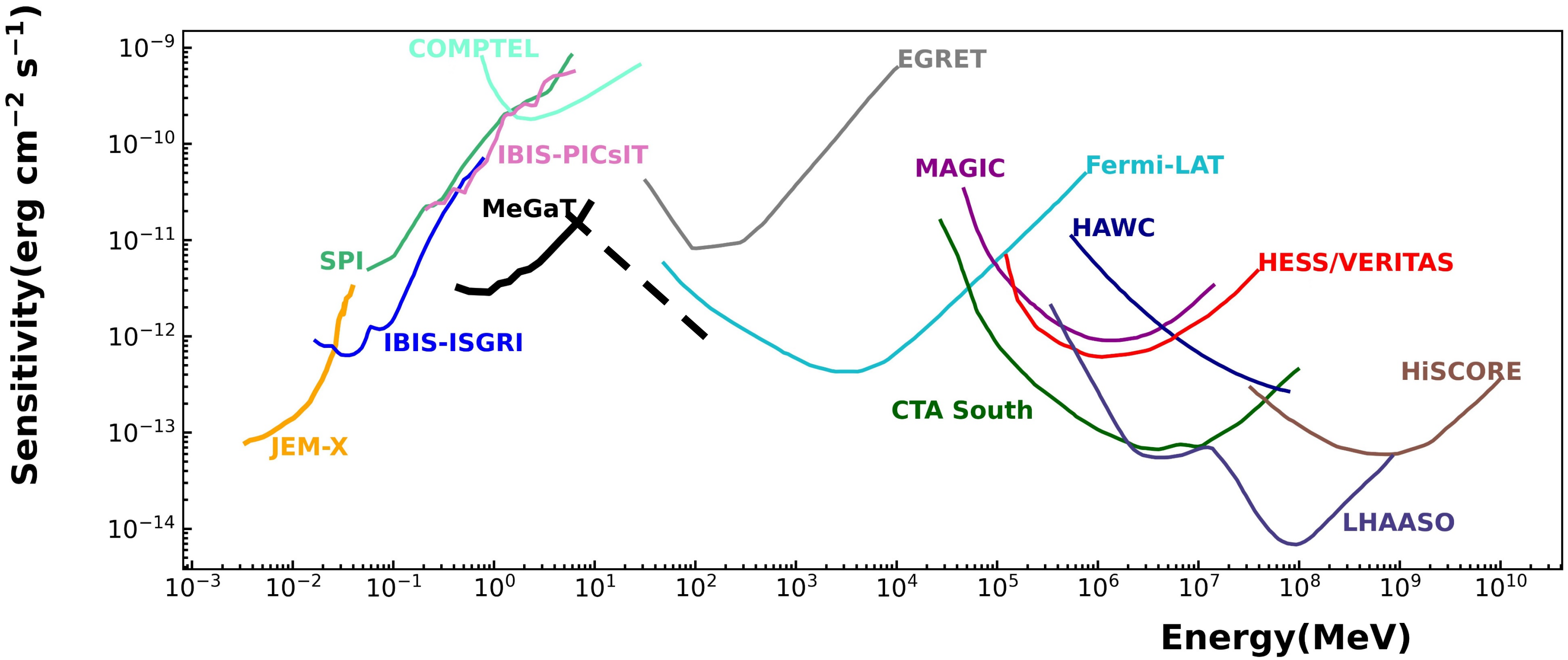
—— Very preliminary simulation result without pair conversion

- - - Rough estimation by taking pair into account

Four identical 50cm cubic detection vessels



Perfect performance on spatial and energy resolution are required for the TPC and calorimeter

Conclusion

- Gamma-ray observations bring new hints for CR propagation.
- Slow diffusion near source region.
- Slow diffusion in dense molecular clumps.