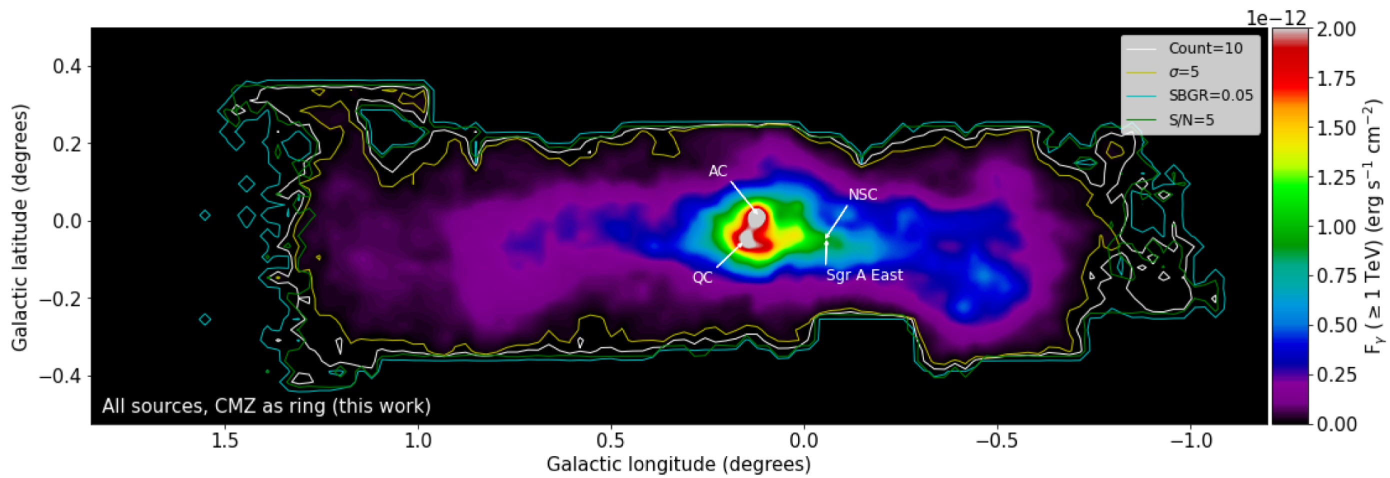
Reproducing the Multiwavelength Galactic Center Gamma-Ray Emission with a Composite PeVatron and Realistic Cosmic-Ray Dynamics



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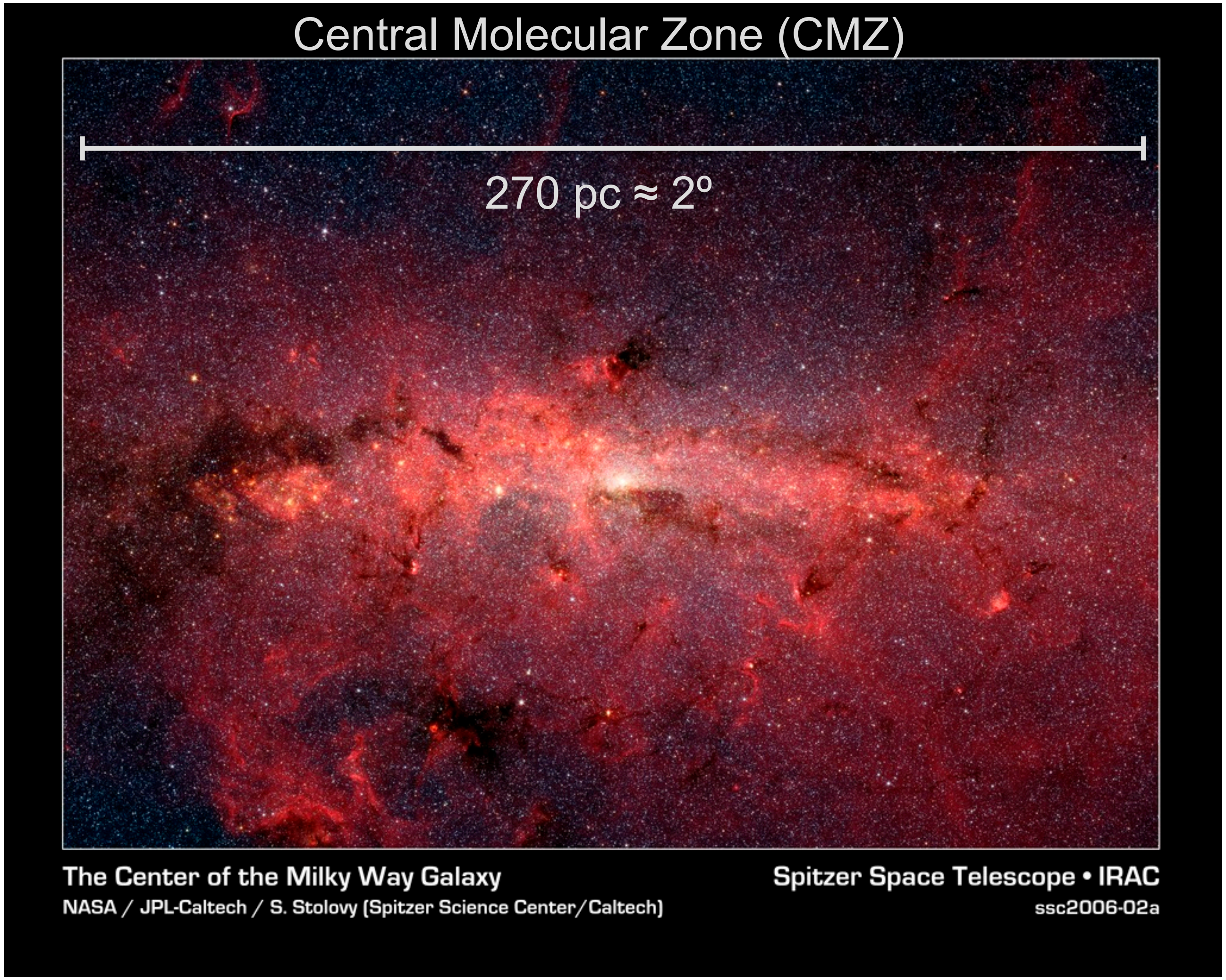
The Central Molecular Zone

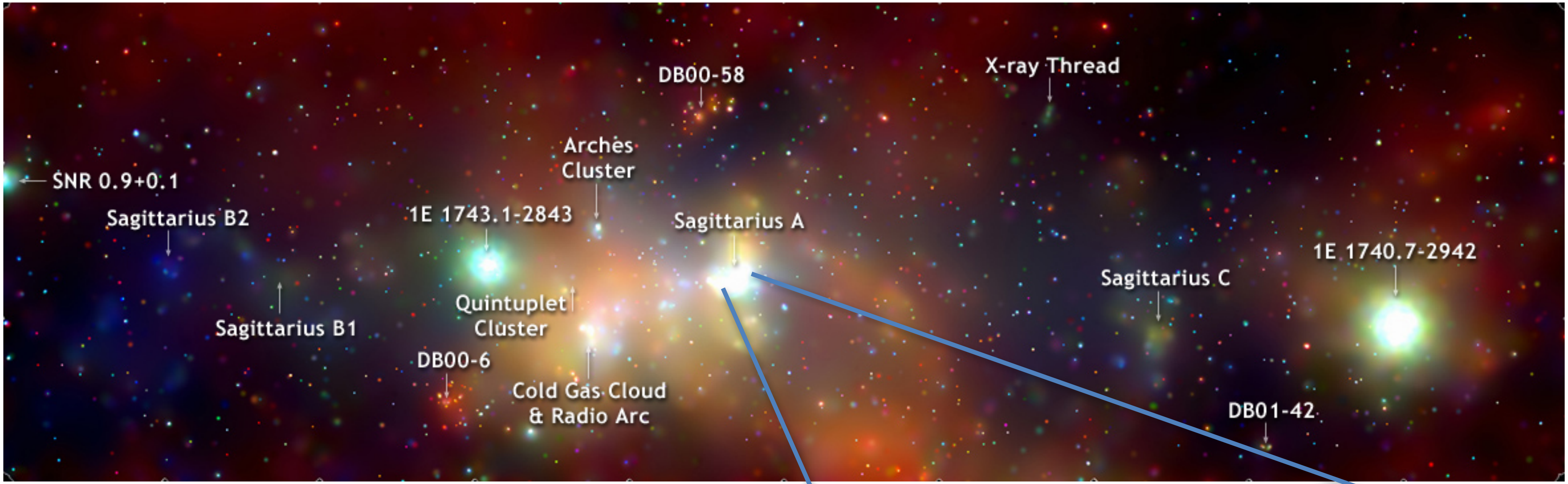


60 million solar masses of gas

Radius ~ 100 pc around Galactic Center

Densest gas region in the Galaxy

Young stellar clusters: Nuclear, Arches and Quintuplet



Chandra X-ray Observatory

1 pc ≈ 30”

VLT / MPE

10 million solar masses in stars

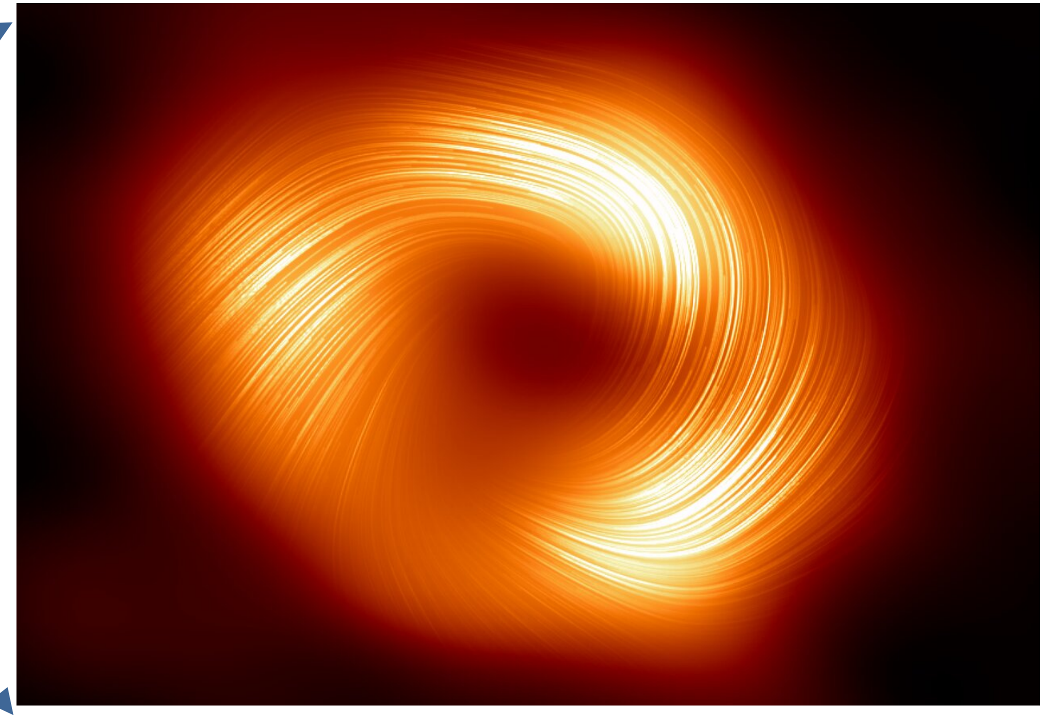
Radius ~ few pc

Densest star clusters in the Galaxy

Many young, massive stars, with strong winds, likely cosmic ray sources

Sgr A*, the super-massive black hole

VLT / MPE



Event Horizon Telescope

VLT / MPE

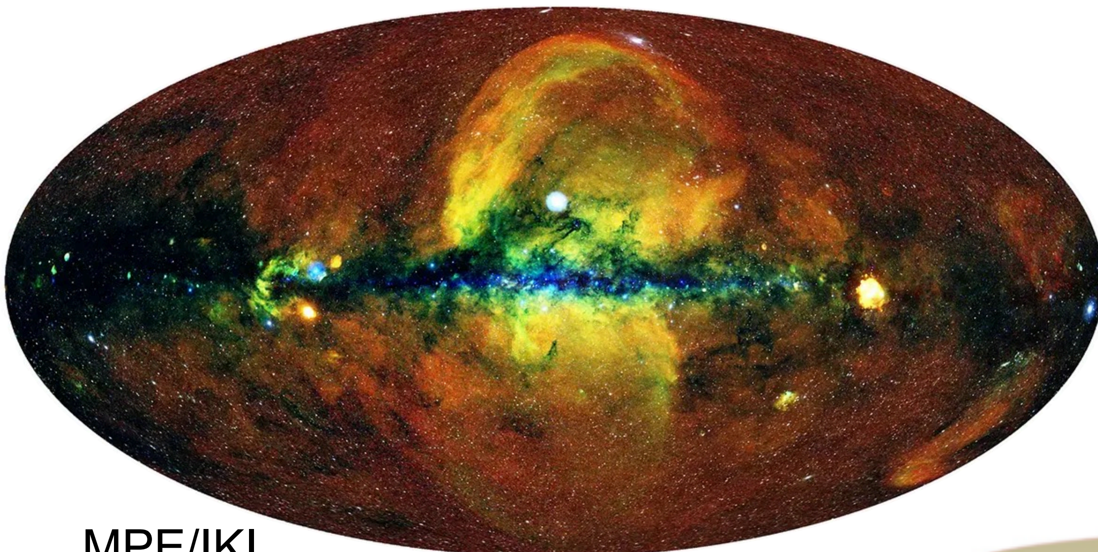
4 million solar masses

Only known massive black hole in the Galaxy

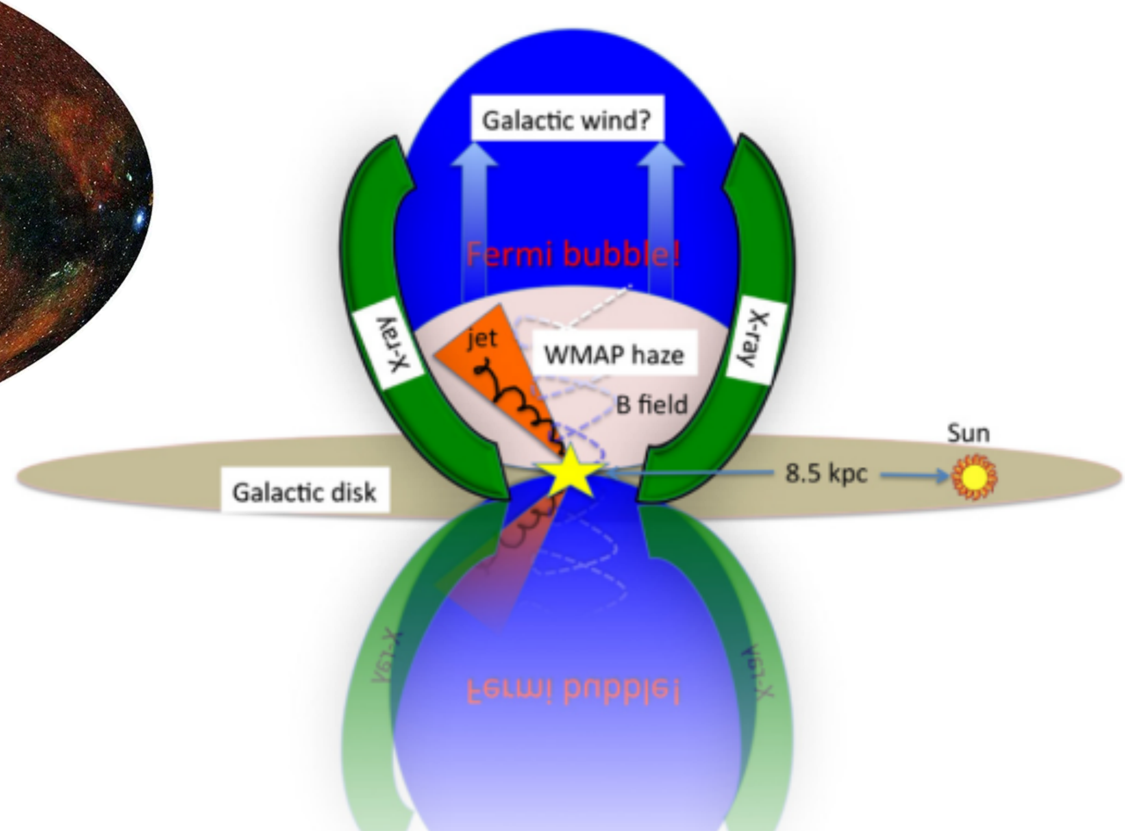
Likely a source of cosmic rays

Fermi bubbles

Fermi bubbles are interpreted as a wind from the Galactic centre, either from black hole or stellar activity.

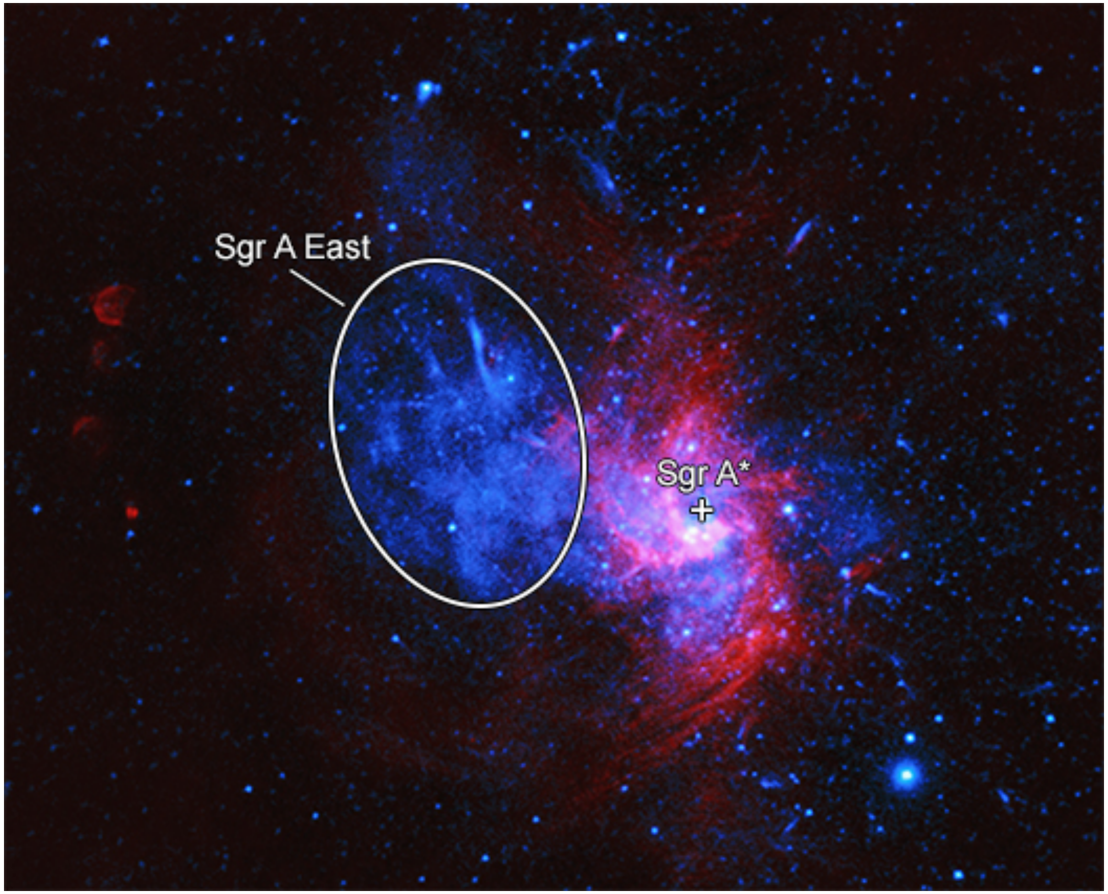


MPE/IKI



Su et al., 2010

Supernova remnants



X-ray: NASA/CXC/Nanjing Univ./P. Zhou et al. Radio: NSF/NRAO/VLA

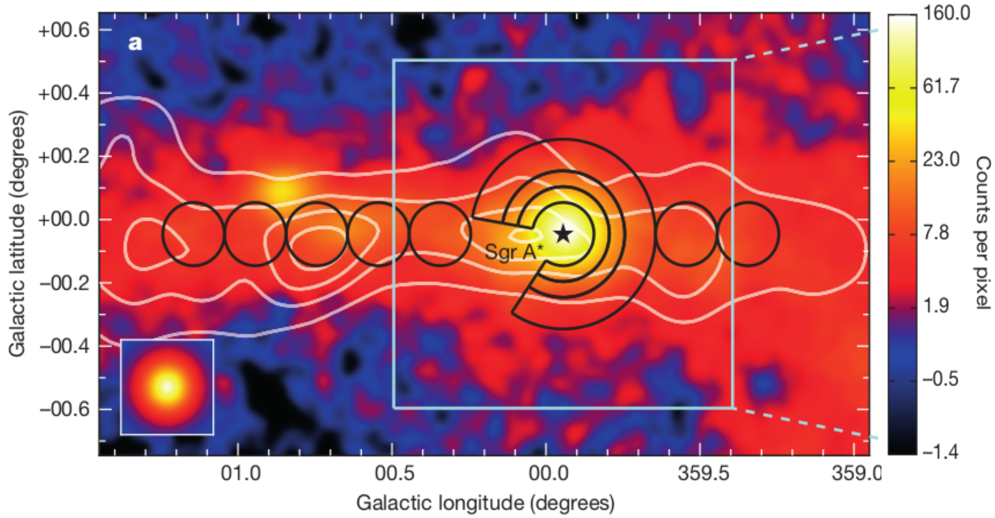
Sgr A East is likely a supernova remnant in central 10 pc

Exploded ~2000 yr ago, with an energy ~ 10^{51} erg (Rockefeller+ 2005, Fryer+ 2006)

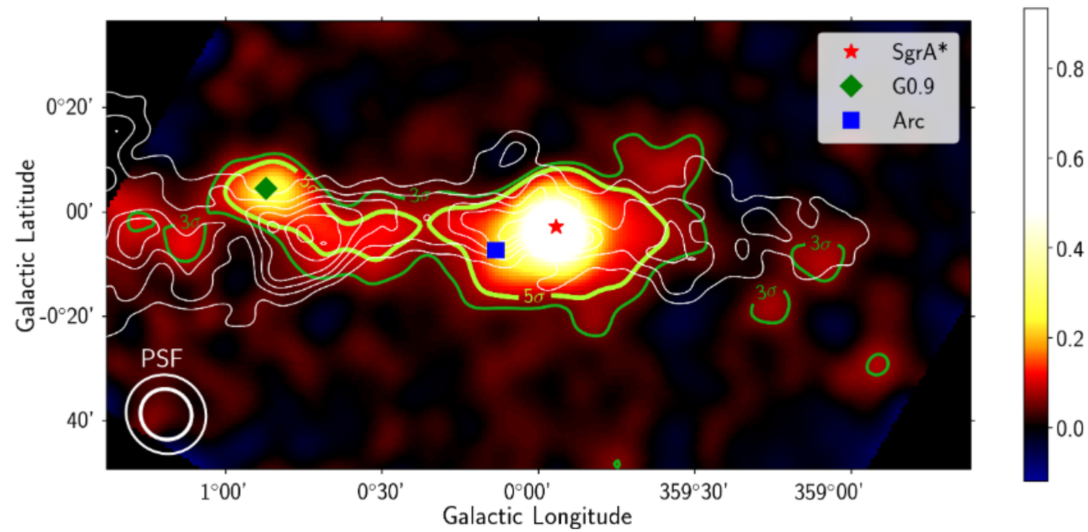
Impulsive source of cosmic rays!

Diffuse VHE γ-rays from the Galactic Center

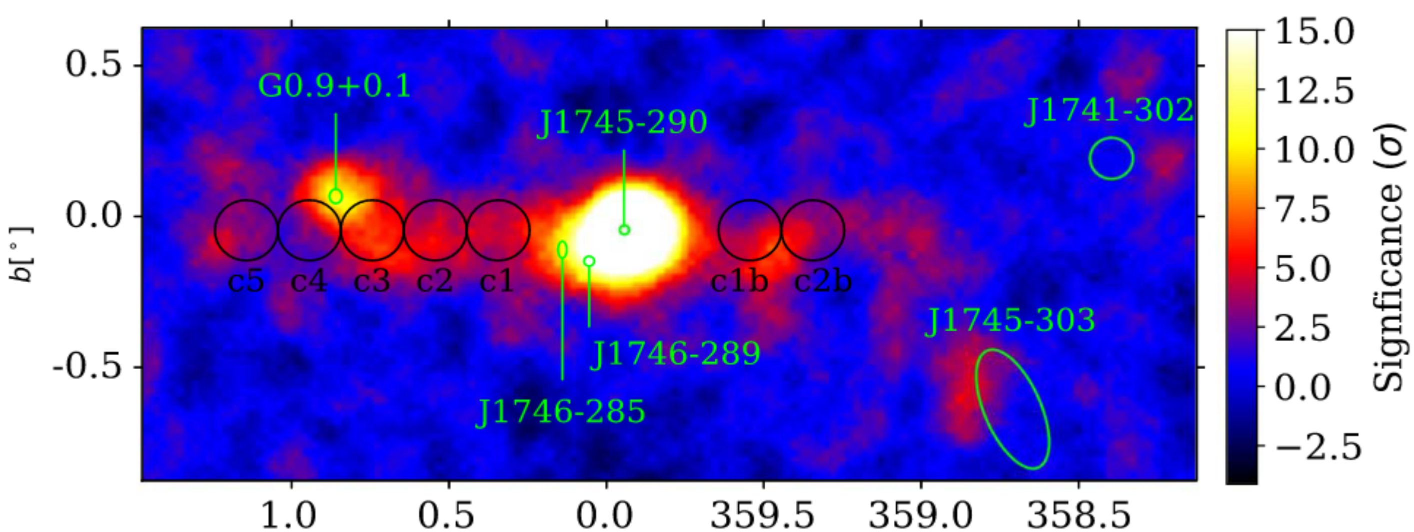
HESS, MAGIC, and VERITAS have observed diffuse very high energy γ-ray emission (0.1–100 TeV) correlated with the Central Molecular Zone.



HESS Collaboration 2016



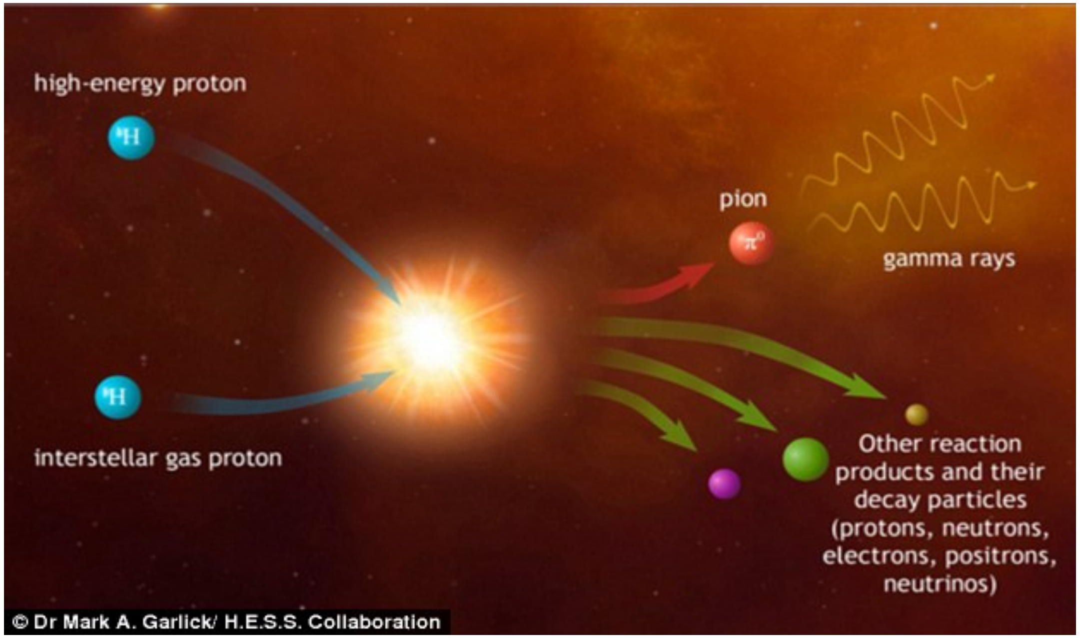
MAGIC Collaboration 2020



Adam et al. 2021

How are the γ-rays generated?

Interaction between cosmic-ray protons and ambient-gas protons



$$p + p \rightarrow p + p + \pi^0 + \pi^+ + \pi^-$$

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

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

Neutral pions (π^0) produced on the collision, which decay in gamma rays

$$L_\gamma \propto w_{cr} \ n_{gas}$$

L_γ : γ-ray luminosity
w_{cr} : Cosmic-ray energy density
n_{gas} : Ambient gas particle density

Observed cosmic-ray density profile favours diffusion

Single burst-like event

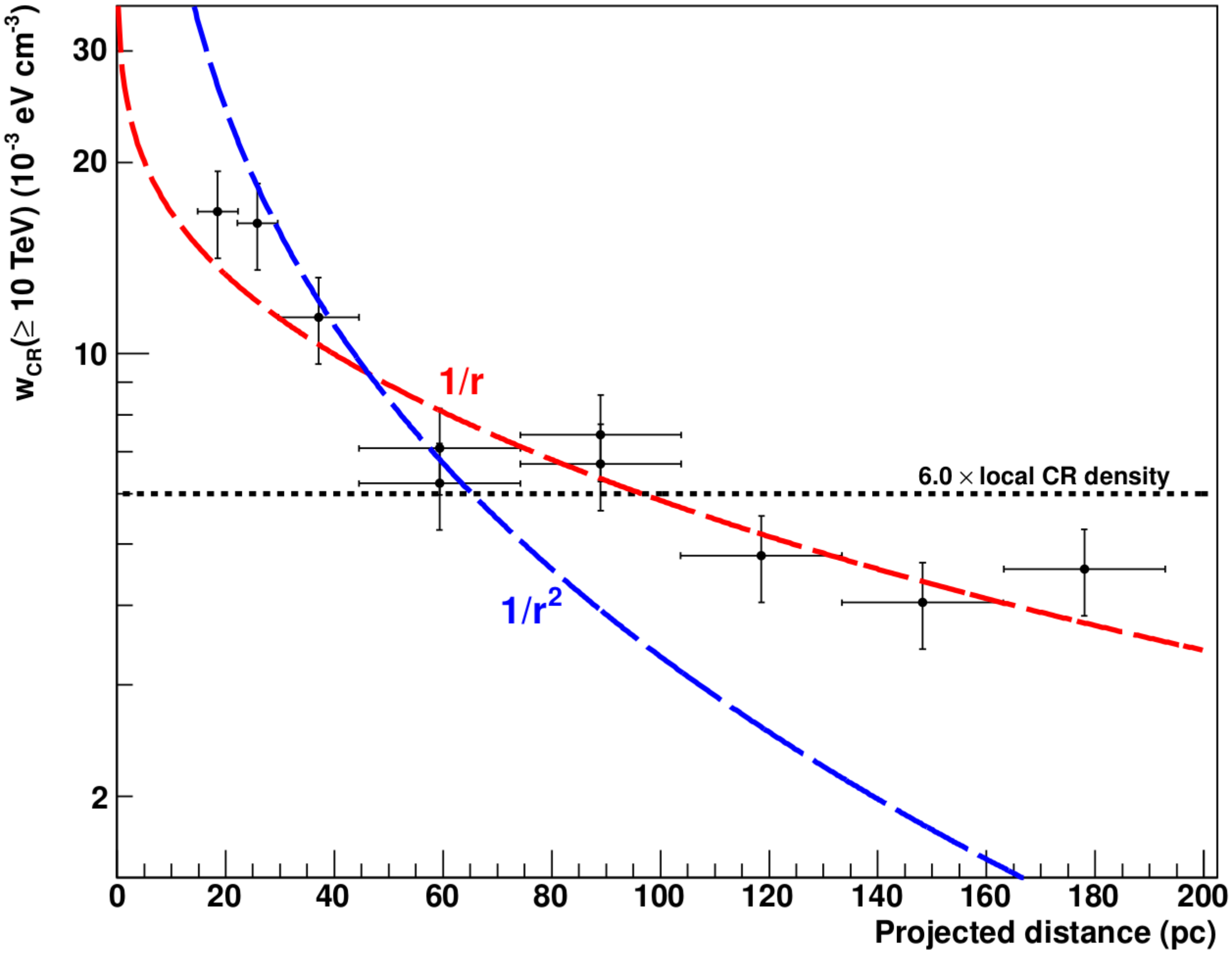
$$\omega_{CR} \propto Uniform$$

Continuous injection from a central source, with advection

$$\omega_{CR} \propto \frac{1}{r^2}$$

Continuous injection from a central source, no advection

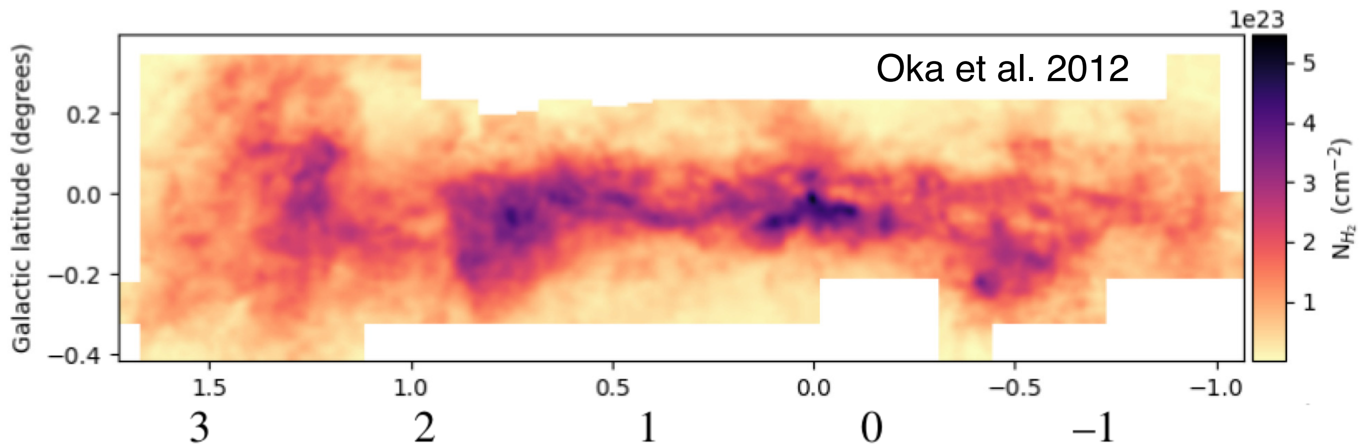
$$\omega_{CR} \propto \frac{1}{r}$$



HESS Collaboration 2016

Our synthetic gamma ray maps

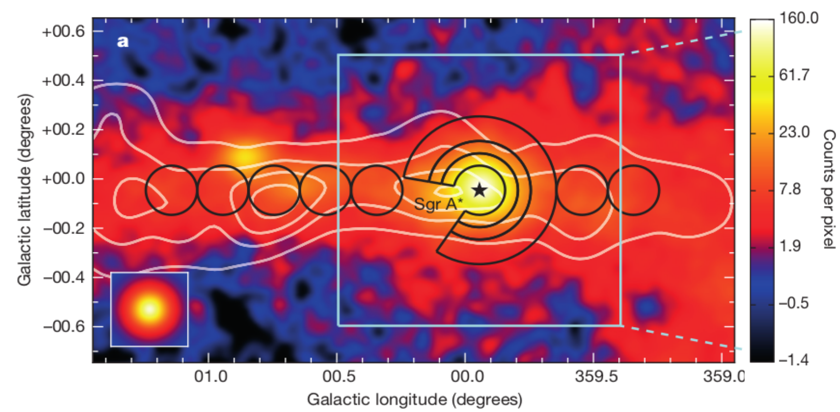
We compute synthetic γ-ray maps from cosmic-ray theoretical models and the observed gas to reproduce current observations.



+

$$\frac{\partial f(\vec{r},p,t)}{\partial t} = \underbrace{\nabla\cdot(D_{xx}\cdot\nabla f)}_{Diffusion} - \underbrace{u\cdot\nabla f}_{Advection} - \underbrace{\frac{\partial}{\partial p}\left(\left(\frac{dp}{dt}\right)f\right)}_{Energy\ loss} + \underbrace{Q(\vec{r},p,t)}_{Source}$$

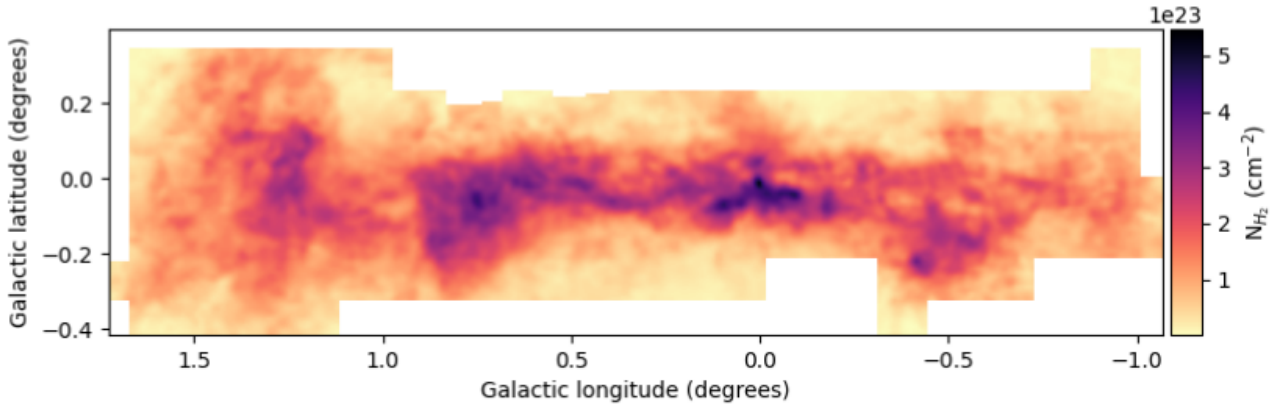
=

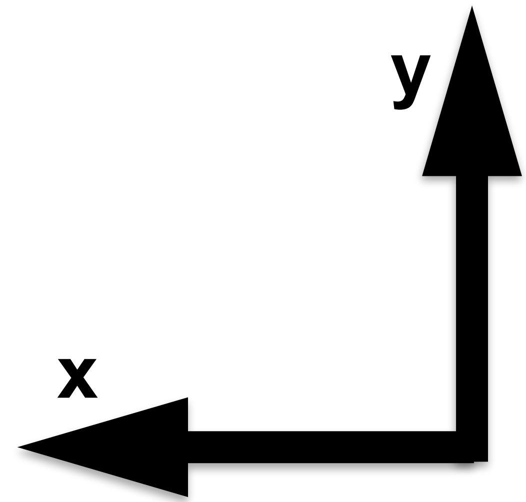


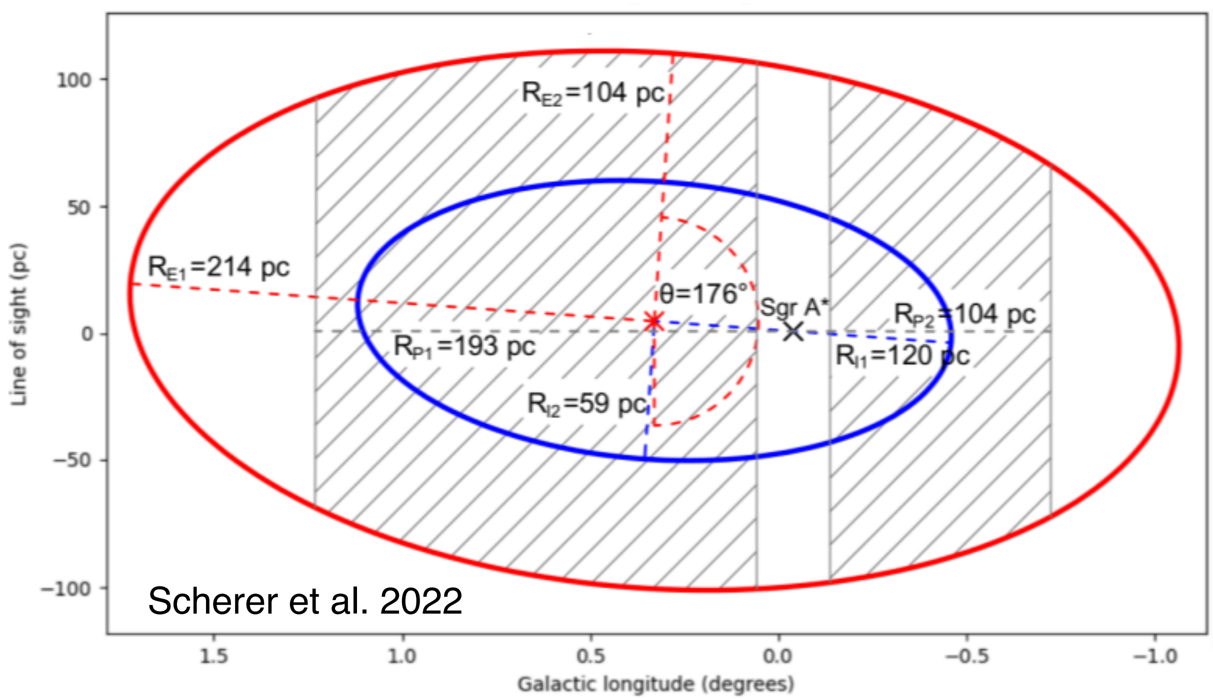
HESS Collaboration 2016

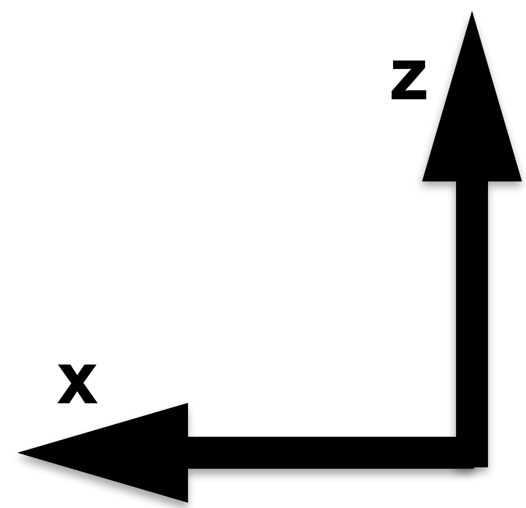
Central molecular zone geometry

- Convert Oka+ (2012) CO map into total gas column density
- Model the 3D gas distribution either with or without an inner cavity, using Kruijssen+ (2015) geometry









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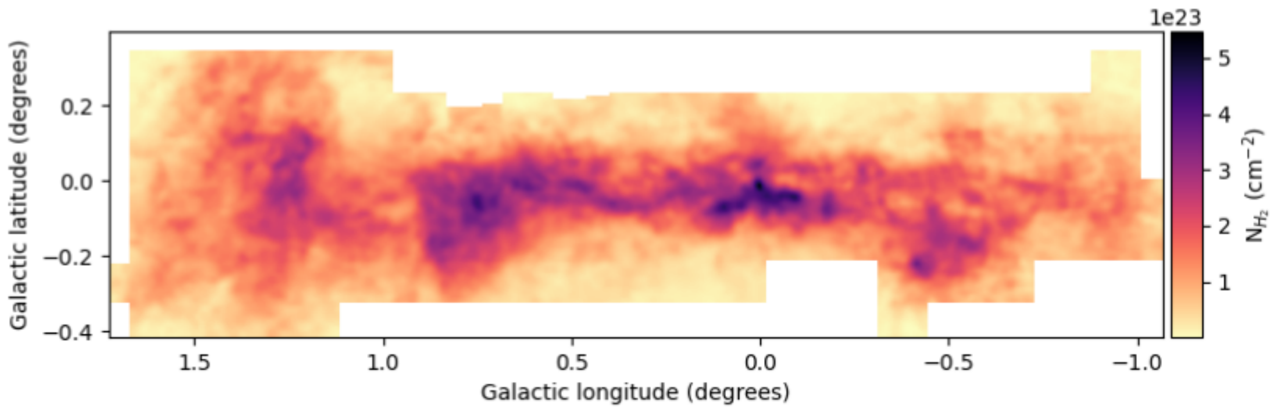

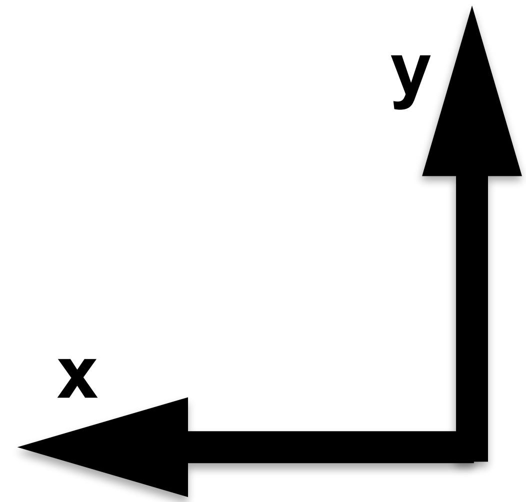

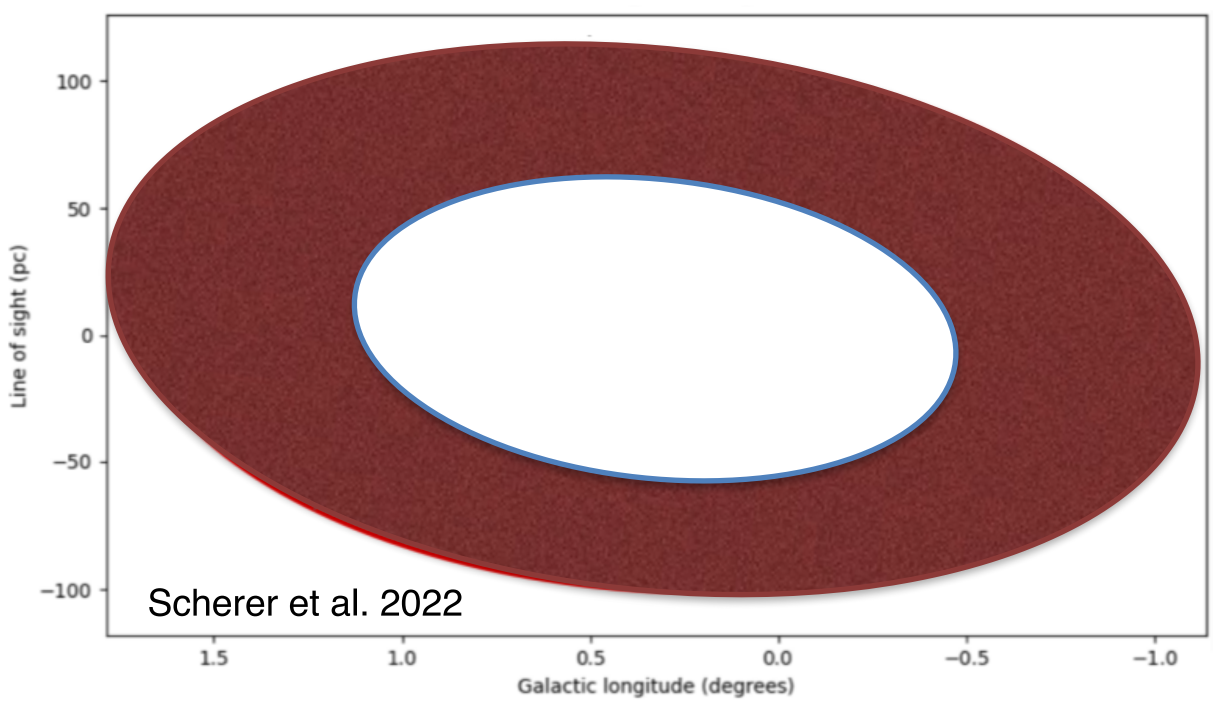

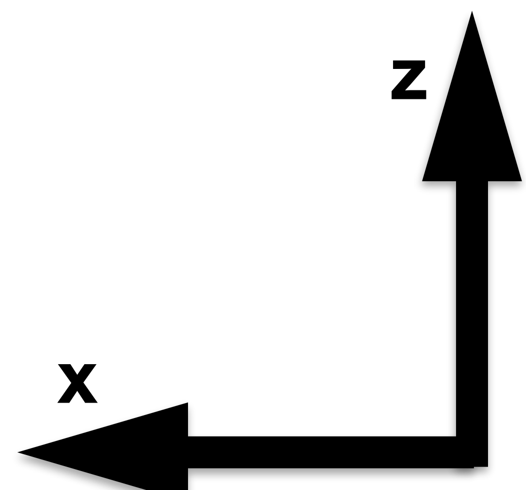

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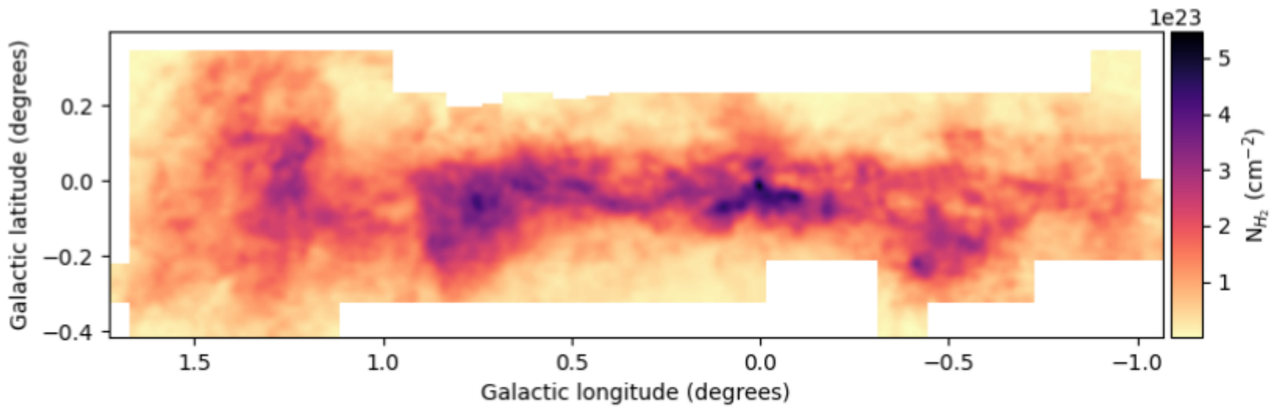
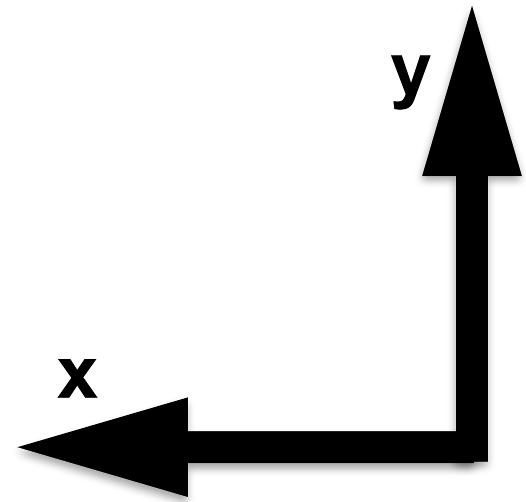
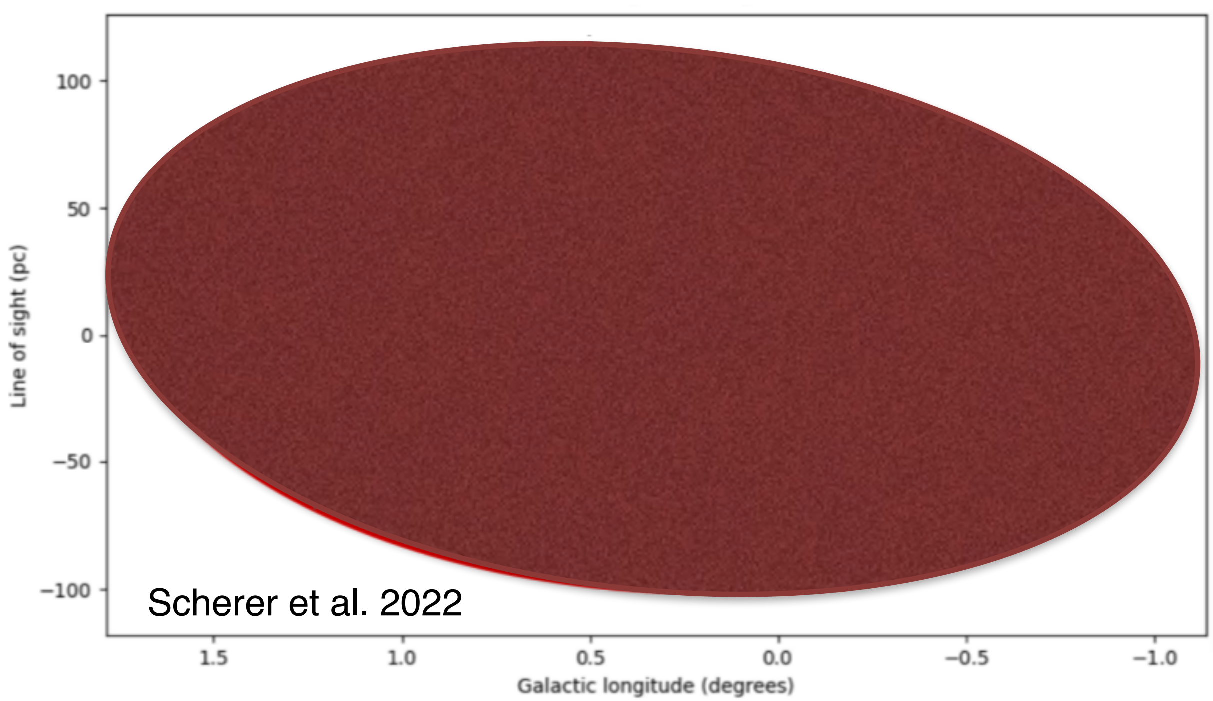
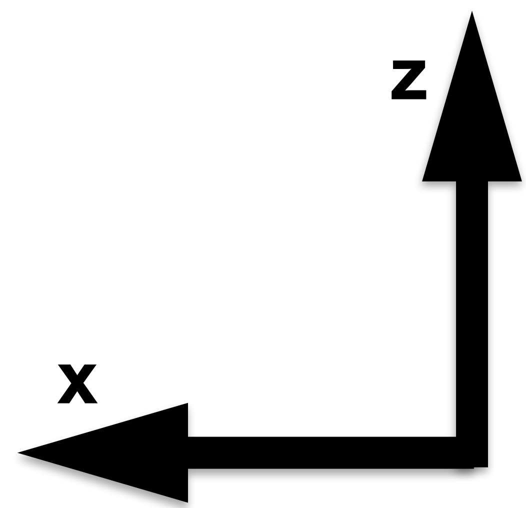






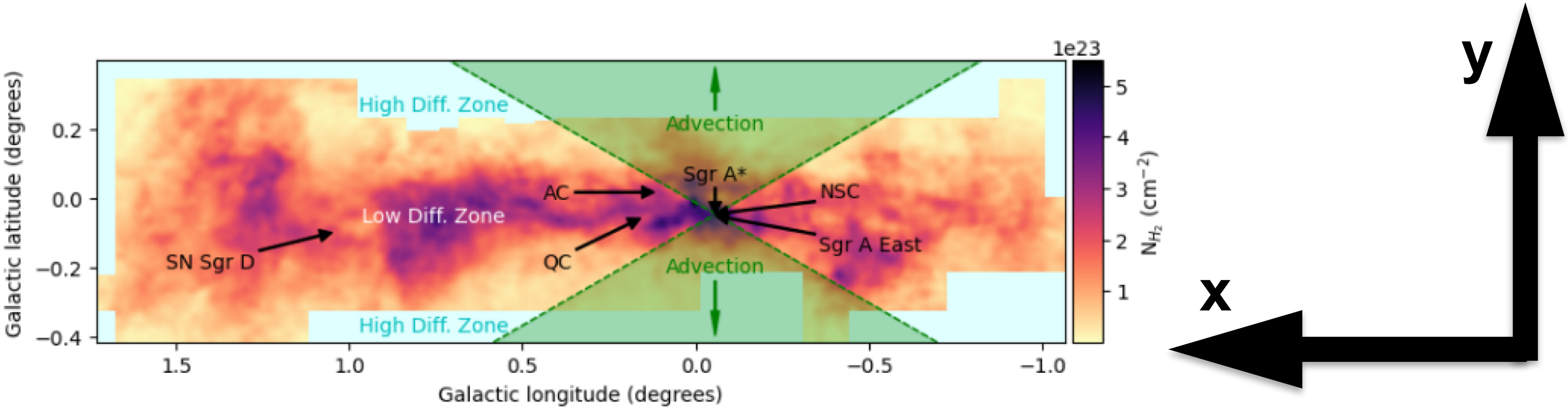


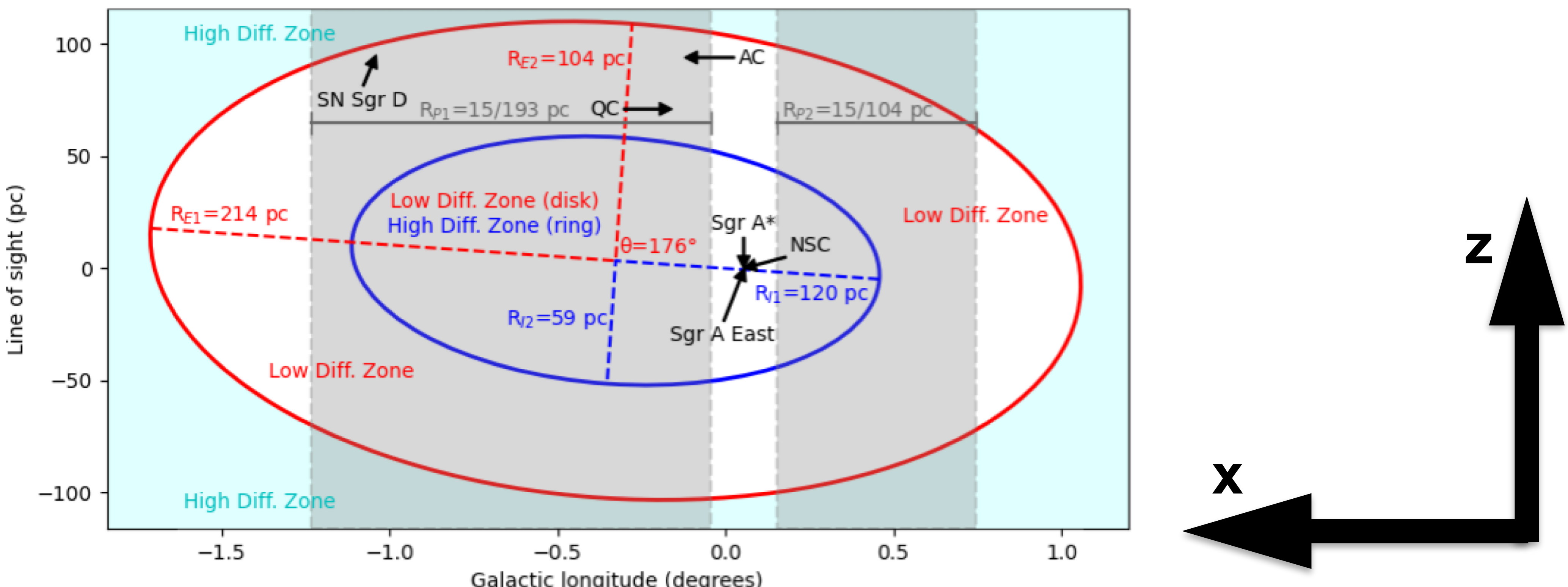
Cosmic-ray dynamics and sources

$$\frac{\partial f(\vec{r},p,t)}{\partial t} = \underbrace{\nabla \cdot (D_{xx} \cdot \nabla f)}_{Diffusion} - \underbrace{u \cdot \nabla f}_{Advection} - \underbrace{\frac{\partial}{\partial p}\left(\left(\frac{dp}{dt}\right) f\right)}_{Energy\ loss} + \underbrace{Q(\vec{r},p,t)}_{Source}$$

- CR energies of 1 PeV
- Isotropic diffusion, low value appropriate for high gas density
- Bipolar advection
- Cooling negligible for dynamics, but produces gamma rays
- Continuous injection from stellar clusters, powered by stellar winds
- Impulsive injection from supernovae
- Run model for a million years

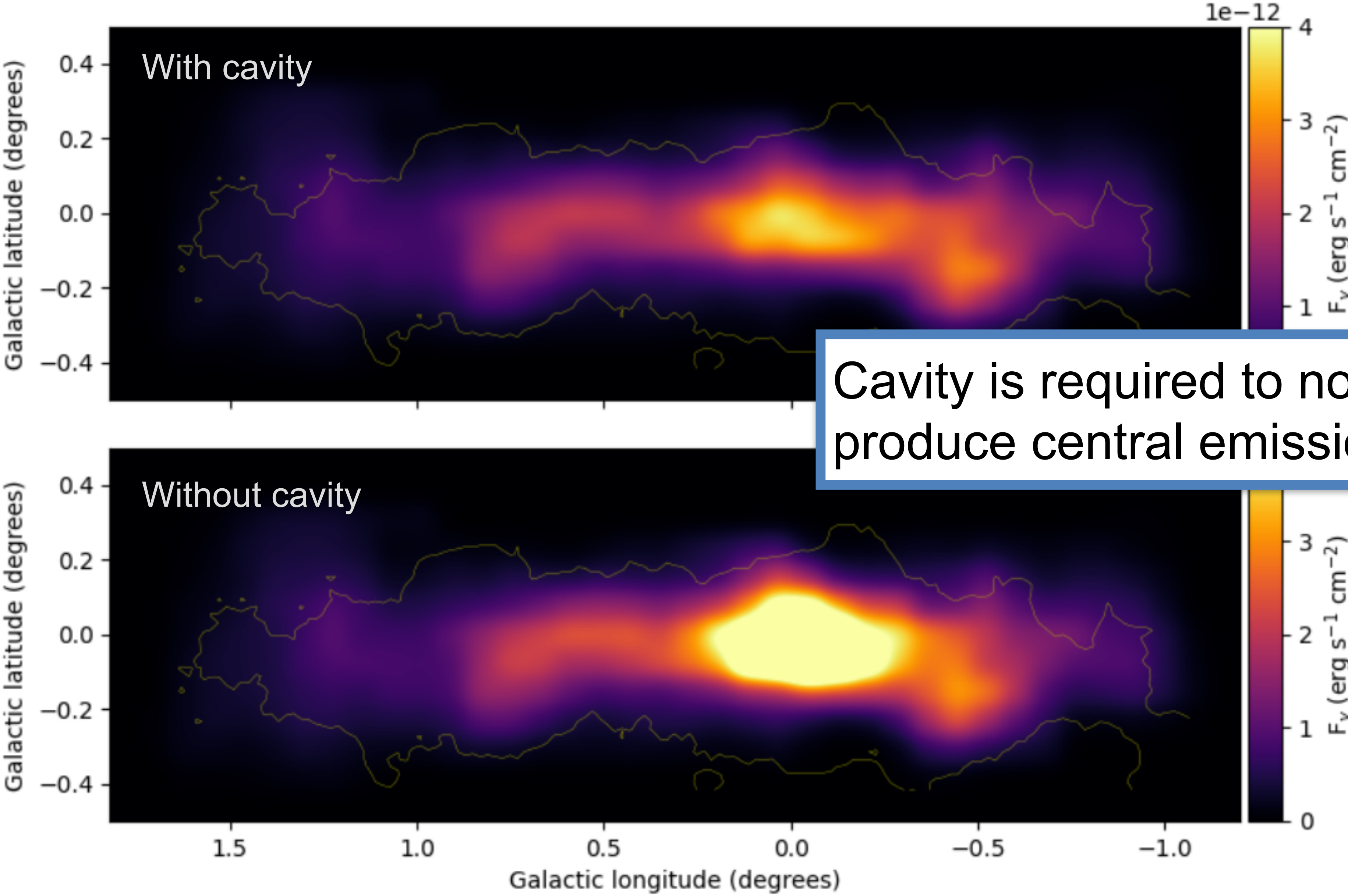
Differential diffusion, polar advection and CR sources





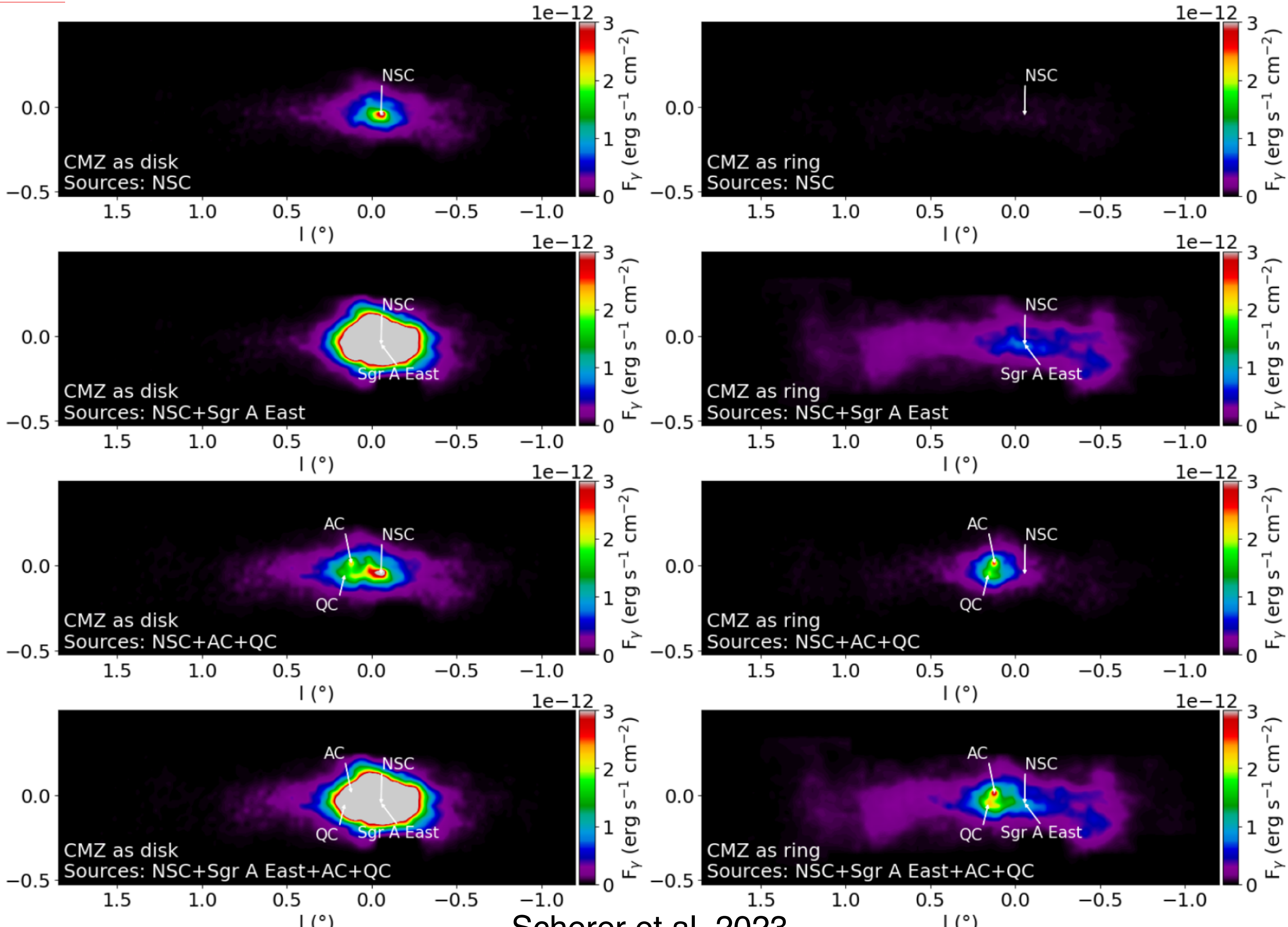
Scherer et al. 2023

Resulting γ-ray maps



Cavity is required to not over-produce central emission.

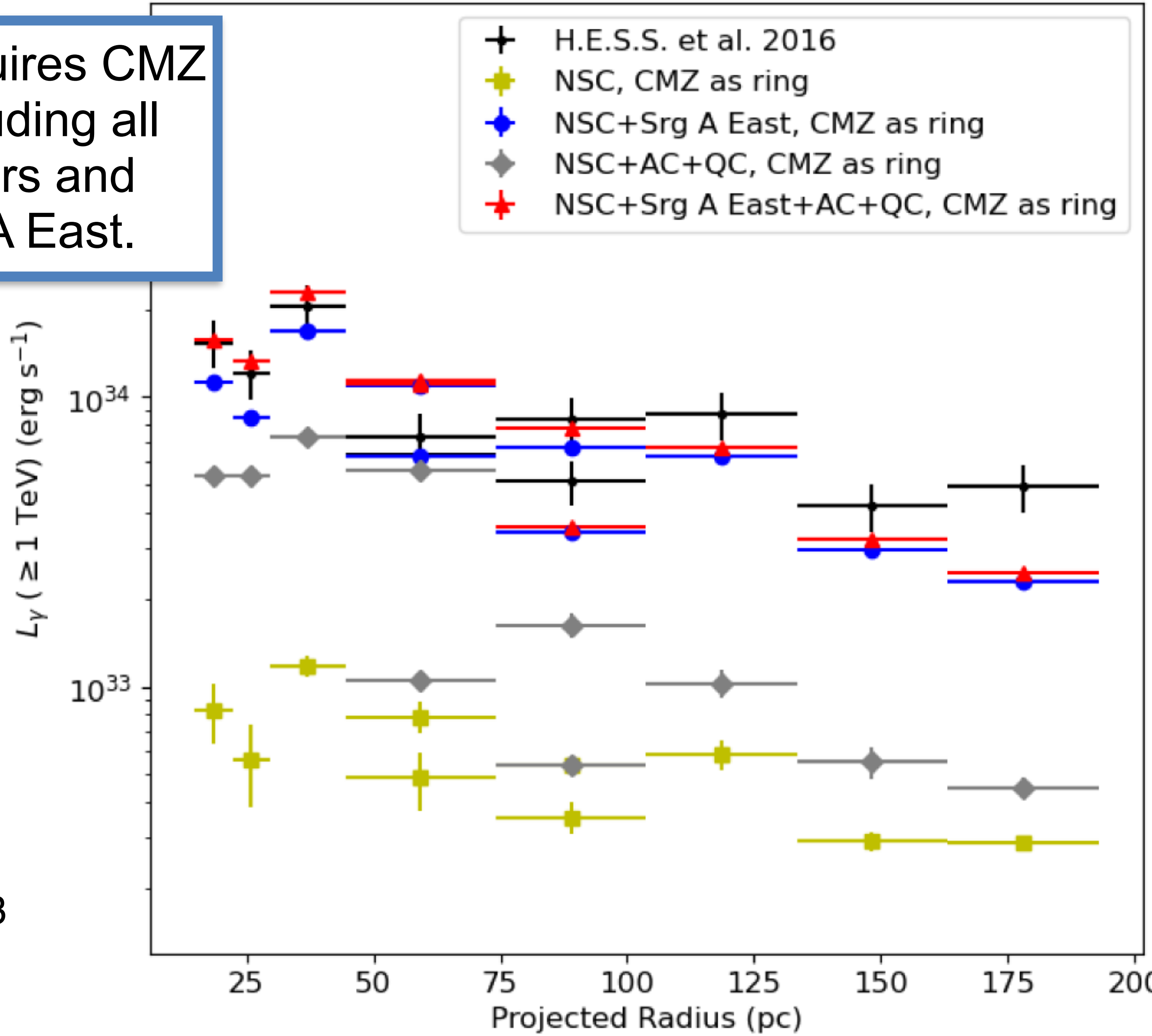
Scherer et al. 2022



Scherer et al. 2023

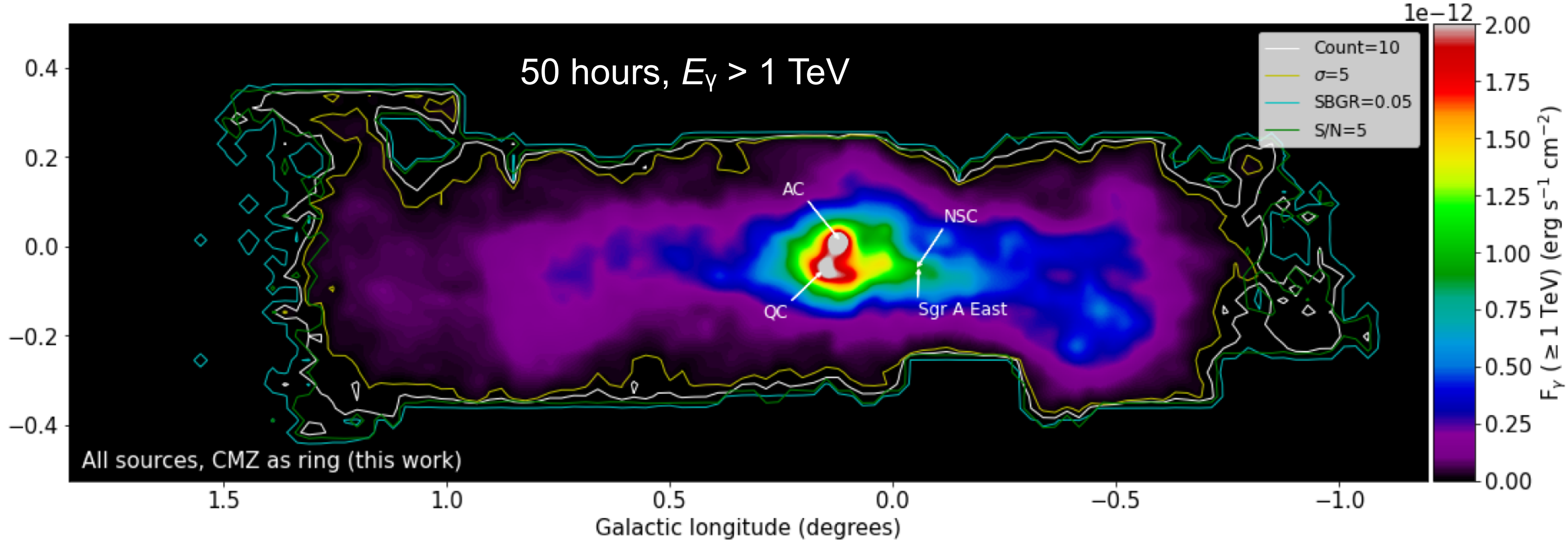
Quantitative comparison to HESS data

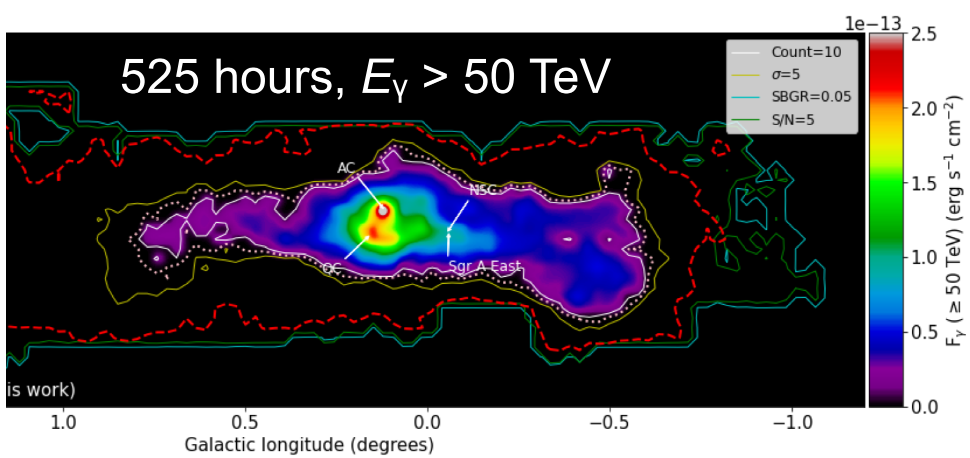
Best match requires CMZ cavity, plus including all three star clusters and supernova Sgr A East.



Scherer et al. 2023

Best model at CTA resolution

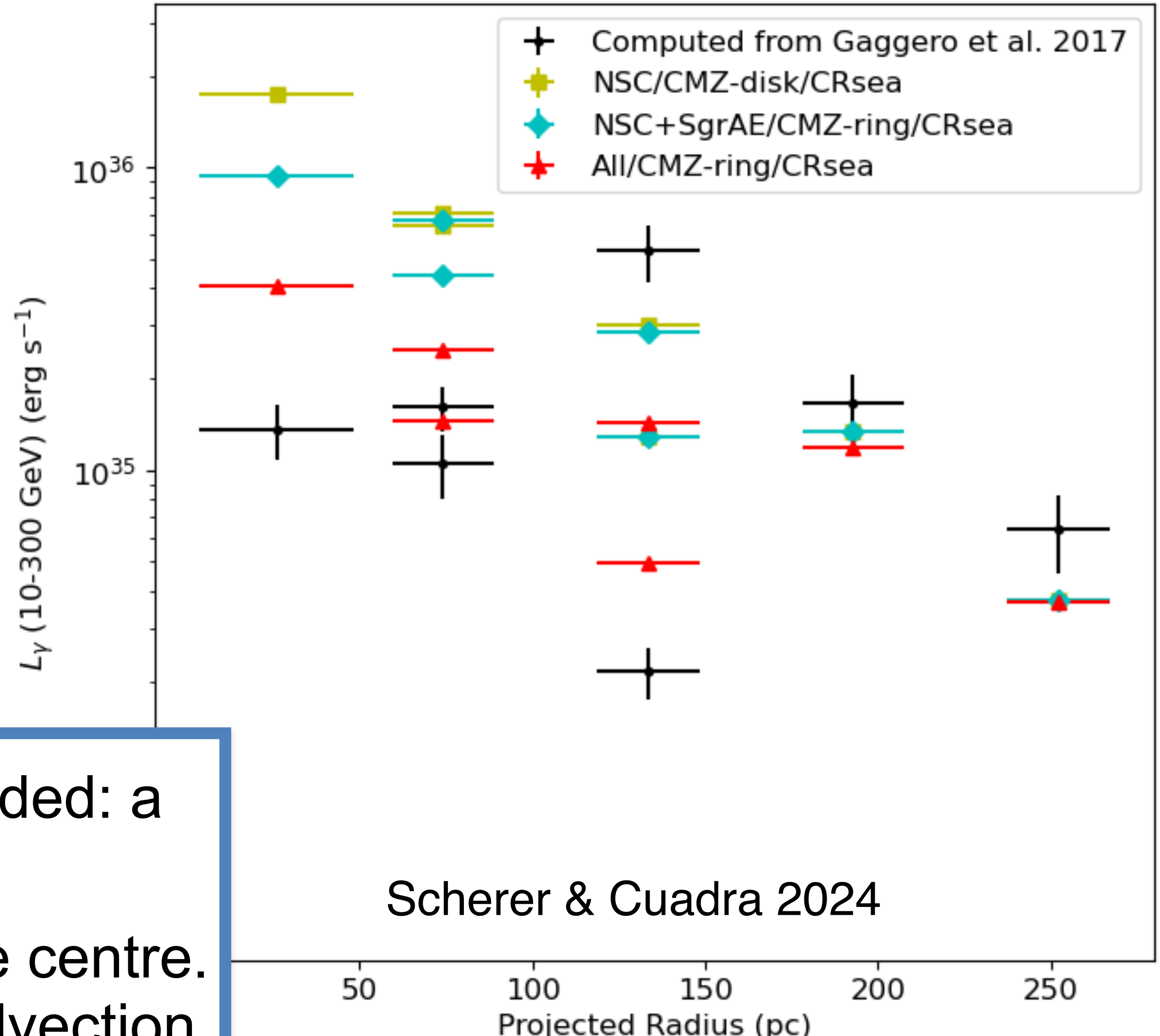




CTA will clearly resolve clusters, and even detect PeVatron there!

Scherer et al. 2023

Comparison to Fermi-LAT data



Scherer & Cuadra 2024

Additional ingredient needed: a Galactic CR “sea”.

Also, too much flux at the centre. Perhaps needs higher advection.

Conclusions

- We developed a Montecarlo model of CR diffusion that includes well-motivated gas distribution, CR sources (star clusters and SN) and dynamics (polar advection and differential diffusion).
- Fiducial model reproduces HESS γ-ray observations without tuning if central molecular zone has inner cavity.
- CTA will resolve sources, and confirm PeVatron nature of stellar clusters without massive black hole.
- Same model matches Fermi data outside central region, if a Galactic CR sea is included.

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