# Modeling the Galactic center gamma-ray emission with more realistic cosmic-ray dynamics

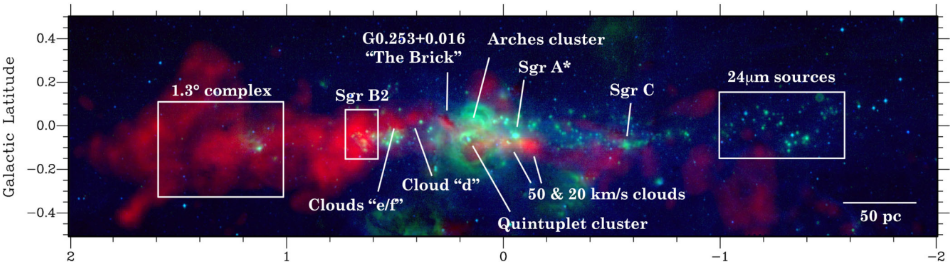
**Andrés Scherer**
**Universidad de Santiago de Chile**

Collaborators: Jorge Cuadra, Franz Bauer and Cristóbal Espinoza

CTAO Science Symposiumg
Bologna, April 17, 2024

# Center of the Milky Way

Central few hundred parsecs show a compact and luminous region designated the central molecular zone (CMZ)




Credit: Kruijssen et al. (2014)

- Densest and most massive molecular clouds
- Extremely elevated turbulence and strong magnetic field
- Clusters of young and massive stars and supernova explosions
- Supermassive black hole (Sgr A*)

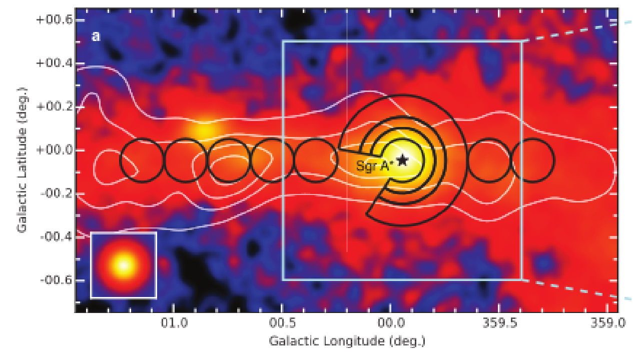
# Gamma-rays from the Galactic center

HESS (1 - 100 TeV) observed a extended emission correlated with the CMZ morphology.

Hadronic interactions are the most accepted scenario to produce it.

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

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



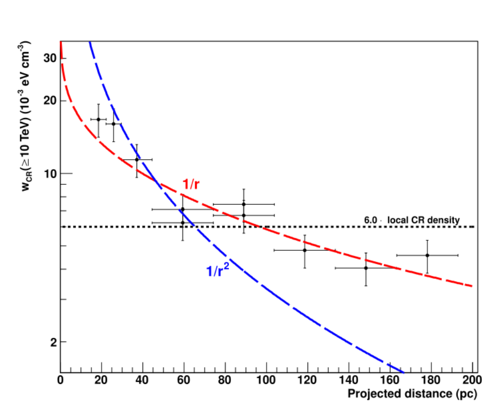

Credit: H.E.S.S. Collaboration et al. 2016

$E_\gamma \approx 0.1 E_p$ $\Rightarrow$ Cosmic-ray protons could have 1 PeV of energy

$L_\gamma \propto w_{cr}\ n_{gas}$ $\Rightarrow$ Cosmic-ray protons could be traced from gamma-rays

# Cosmic-ray traced from gamma-rays

HESS computed the average $w_{cr}$ on the line of sight from $N_{gas}$.




Credit: H.E.S.S. Collaboration et al. 2016

Cosmic rays are coherent with:

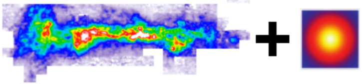
- Central source
- Continuous injection
- Transport dominated by diffusion

We focus this presentation on the impact of assuming a more realistic scenario for both cosmic rays and ambient gas.

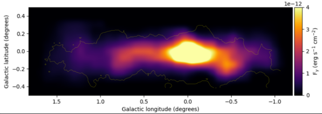
# Methodology

We compute synthetic gamma-ray maps from a cosmic-ray model and the observed gas

$$\frac{\partial \psi(\vec{r},p,t)}{\partial t} = \vec{\nabla} \cdot D\vec{\nabla}\psi - \vec{\nabla} \cdot \vec{V}\psi - \frac{\partial}{\partial p}\left(\frac{dp}{dt}\psi\right) + Q(\vec{r},p,t) \; + $$

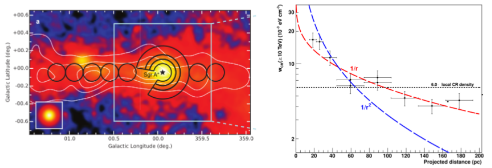


$=$




Next, we compare the maps with observed $L_\gamma$ and inferred $w_{cr}$

$\simeq$

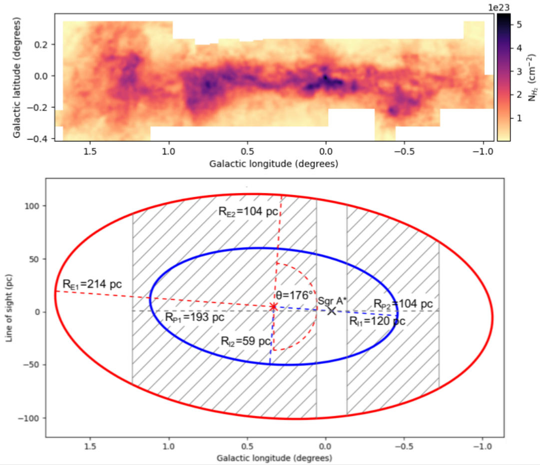



Finally, maps are converted to gamma-ray observed by CTA

# Modeling the CMZ 3D morphology

We explore the influence of the CMZ line-of-sight distribution. Several possibilities: spiral arms, elliptical ring, open stream, bar-like structure, torus with an inner disk, etc.

- $H_2$ column density computed from CO (J=3-2)
- Modeling as either an elliptical ring or an elliptical disk, constrained by current 3D models
- Gas distributed uniformly along the line of sight
- Simplified cosmic-ray transport

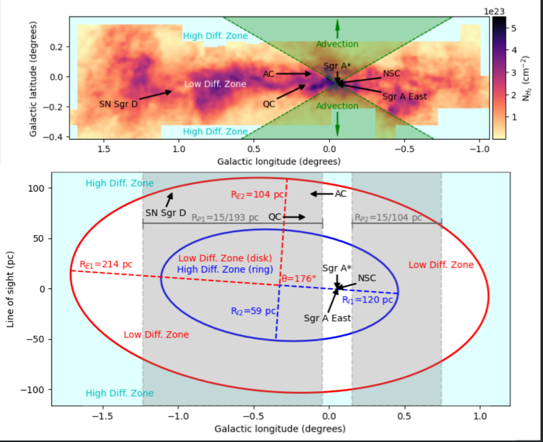



Scherer et al. 2022

# Modeling cosmic-ray transport in the CMZ

We verify if more realistic cosmic-ray dynamics are consistent with current gamma-ray observations.

- High density areas should have a diffusion two orders of magnitude lower
- Outflow velocities of the Fermi Bubbles suggest a advective transport
- Computed for both previous gas distributions

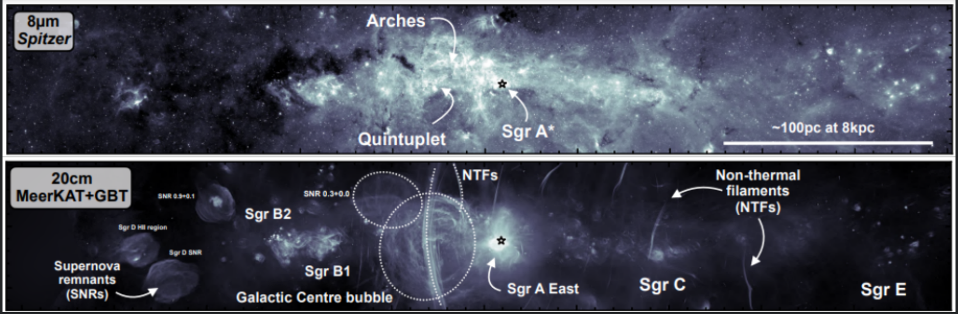



Scherer et al. 2023

# Cosmic-ray sources

In the Galactic center, Sgr A* would be our first option, but it is inactive. Therefore, we selected sources considering:

- Injection rates derived from their observed kinetic energies
- Low uncertainty on whether they are within the CMZ



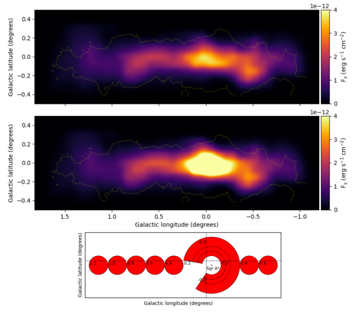

Credit: Henshaw et al. 2022

Potential sources: Clusters of massive stars (NSC, AC and QC) and SN Sgr A East

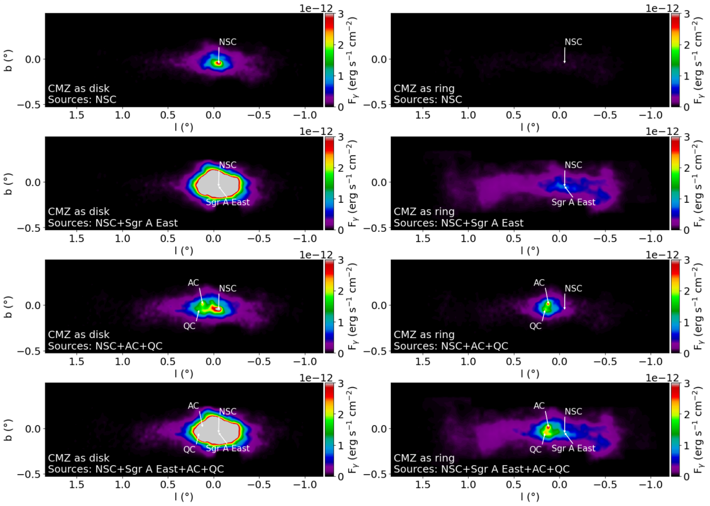
# Gamma-ray maps

We developed gamma-ray synthetic maps to different:

- Gas geometries
- Cosmic-ray dynamics
- Sources
- Angular resolutions




Scherer et al. 2022

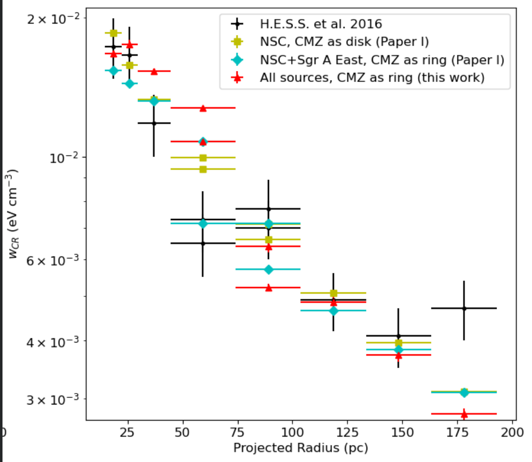



Scherer et al. 2023

# Radial profiles projected from Sgr A*

We contrast all models with current observations and selected the satisfactory models

- CMZ: Disk
  CR dynamics: Simplified
  CR source: NSC
- CMZ: Ring
  CR dynamics: Simplified
  CR source: NSC+SN Sgr A East
- CMZ: Ring
  CR dynamics: More realistic
  CR source: NSC+AC+QC+SN Sgr A East

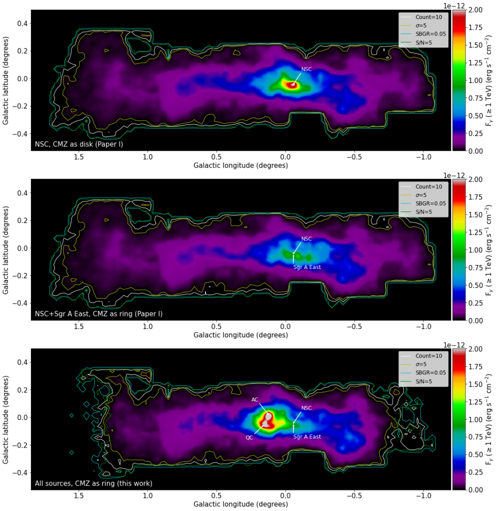



Scherer et al. 2023

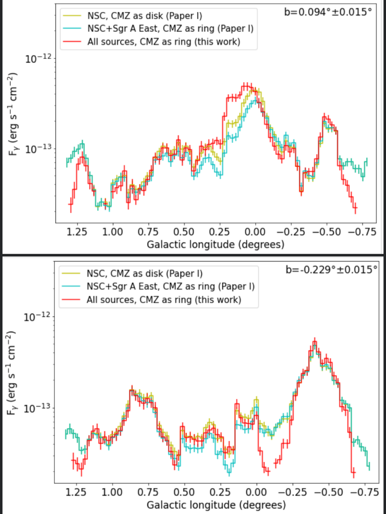
These three models are similar and fit the current observations...

# Gamma-ray maps as observed by CTA

...but they predict different observable features when imaged by CTA



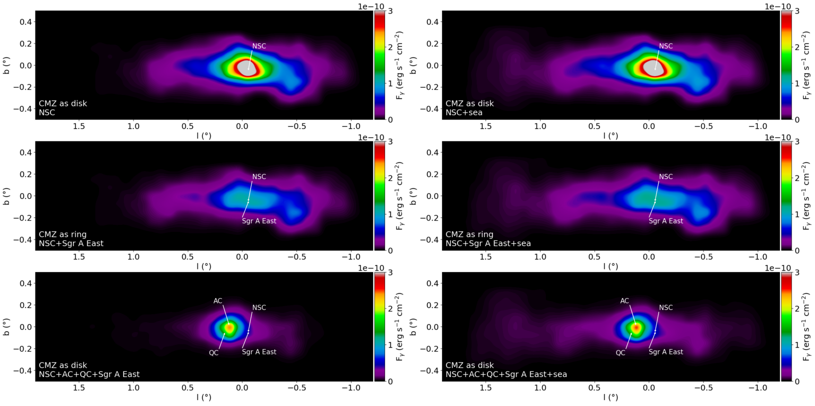

Scherer et al. 2023




Scherer et al. 2023

# Other gamma-ray energy bands

We contrast our satisfactory models with Fermi LAT observations

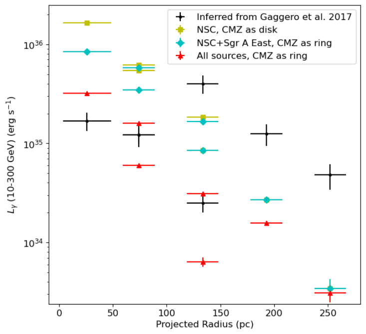


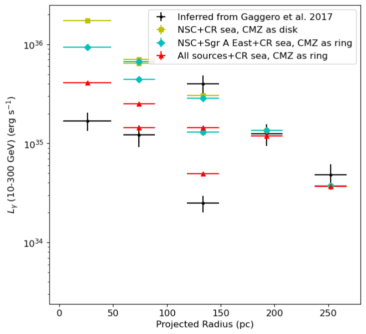

Scherer et al. 2024 (in Preparation)

Also, we studied the isotropic Galactic cosmic-ray component (CR sea) inside the CMZ

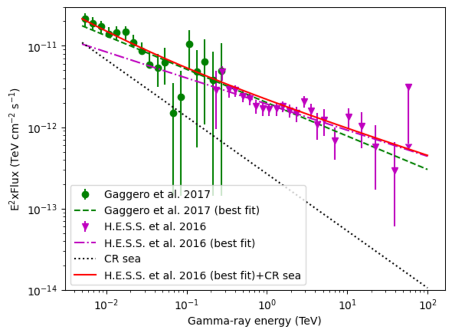
# Radial profiles projected from Sgr A*

We contrast our satisfactory models with Fermi LAT observations




Scherer et al. 2024 (in Preparation)




Scherer et al. 2024 (in Preparation)

More realistic cosmic-ray dynamics and a CR sea similar to the one observed in the Solar system reproduces better the current observations

# Conclusions

- More realistic cosmic-ray dynamics reproduce both HESS and Fermi LAT observations
- This transport suggests that the CMZ presents an inner cavity and that the Galactic center PeVatron can be reproduced by the four sources
- CTA will constrain the effects of differential diffusion, polar advection, cosmic-ray sources, and the CMZ morphology.
- Cosmic-ray sea within the CMZ is similar to the one in the Solar system

Future works:

- Reproduce the emission created by leptons (sources and hadronic interactions)
- Explore the cosmic-ray contribution from the expected neutron star population