On the distribution of Cosmic Rays in the Galactic Center region: new insights from H.E.S.S.

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On behalf of the H.E.S.S. collaboration

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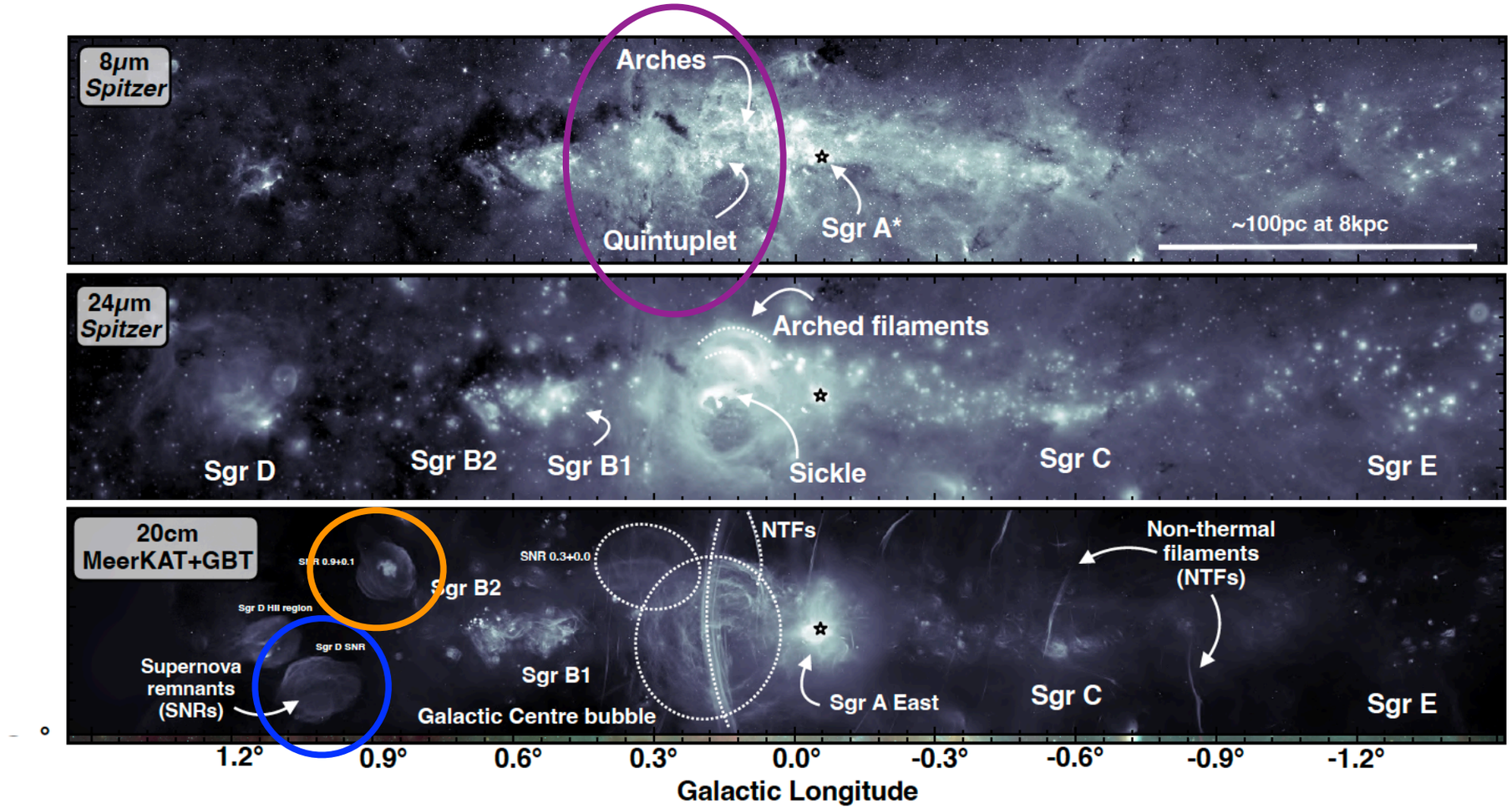
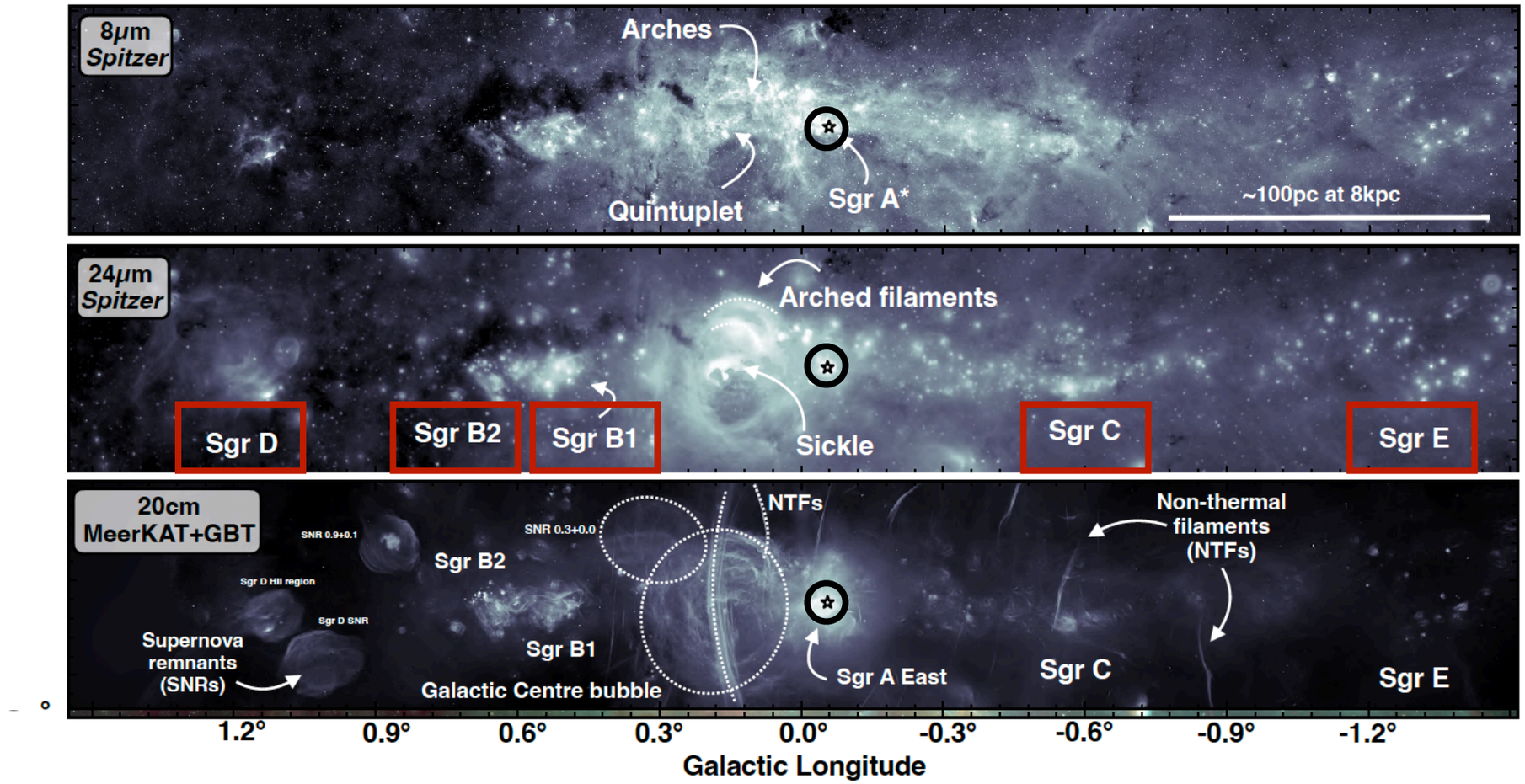
TeV Particle Astrophysics 2024, Chicago

The Galactic Center region



- One of the richest region in the Milky Way: **Massive Stellar Clusters**, **Pulsar Wind Nebulae (PWNe)**, **Supernova Remnants**, etc.

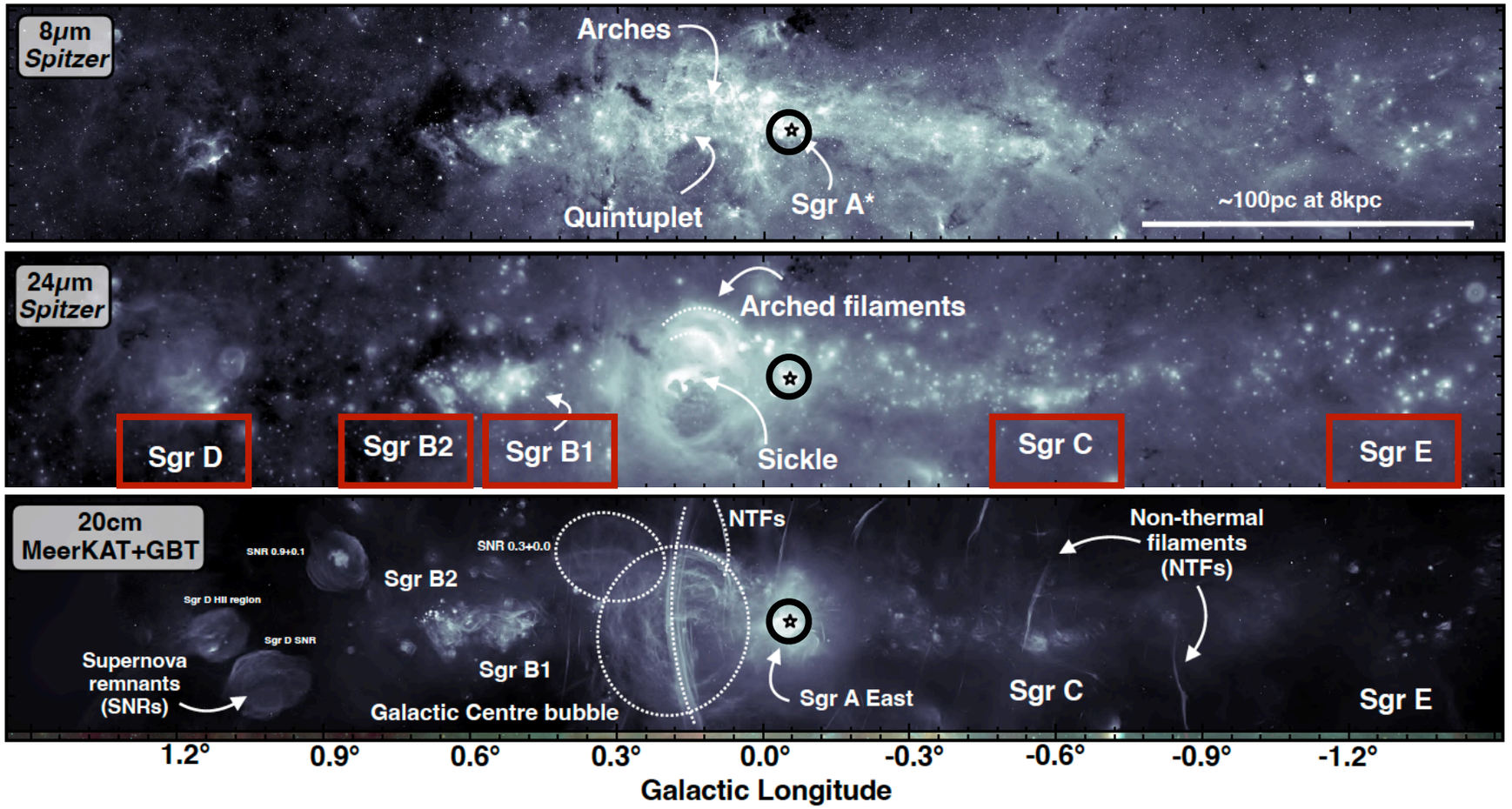
The Galactic Center region

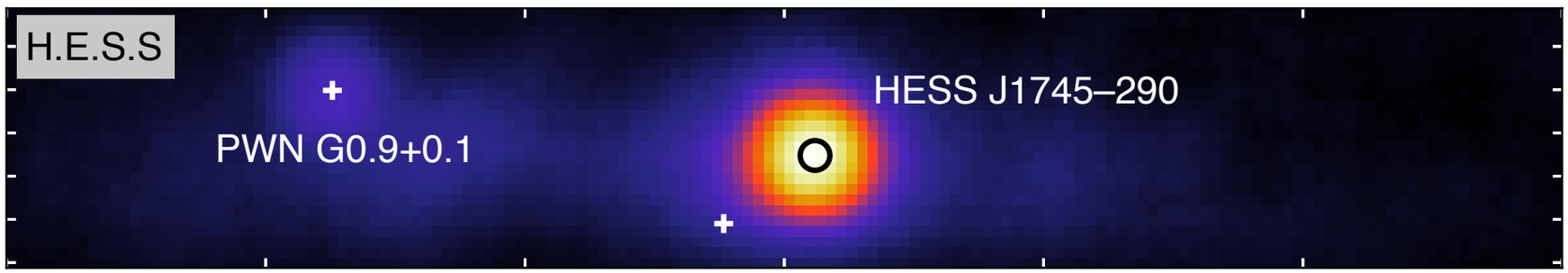


- One of the richest region in the Milky Way: **Massive Stellar Clusters**, **Pulsar Wind Nebulae (PWNe)**, **Supernova Remnants**, etc.

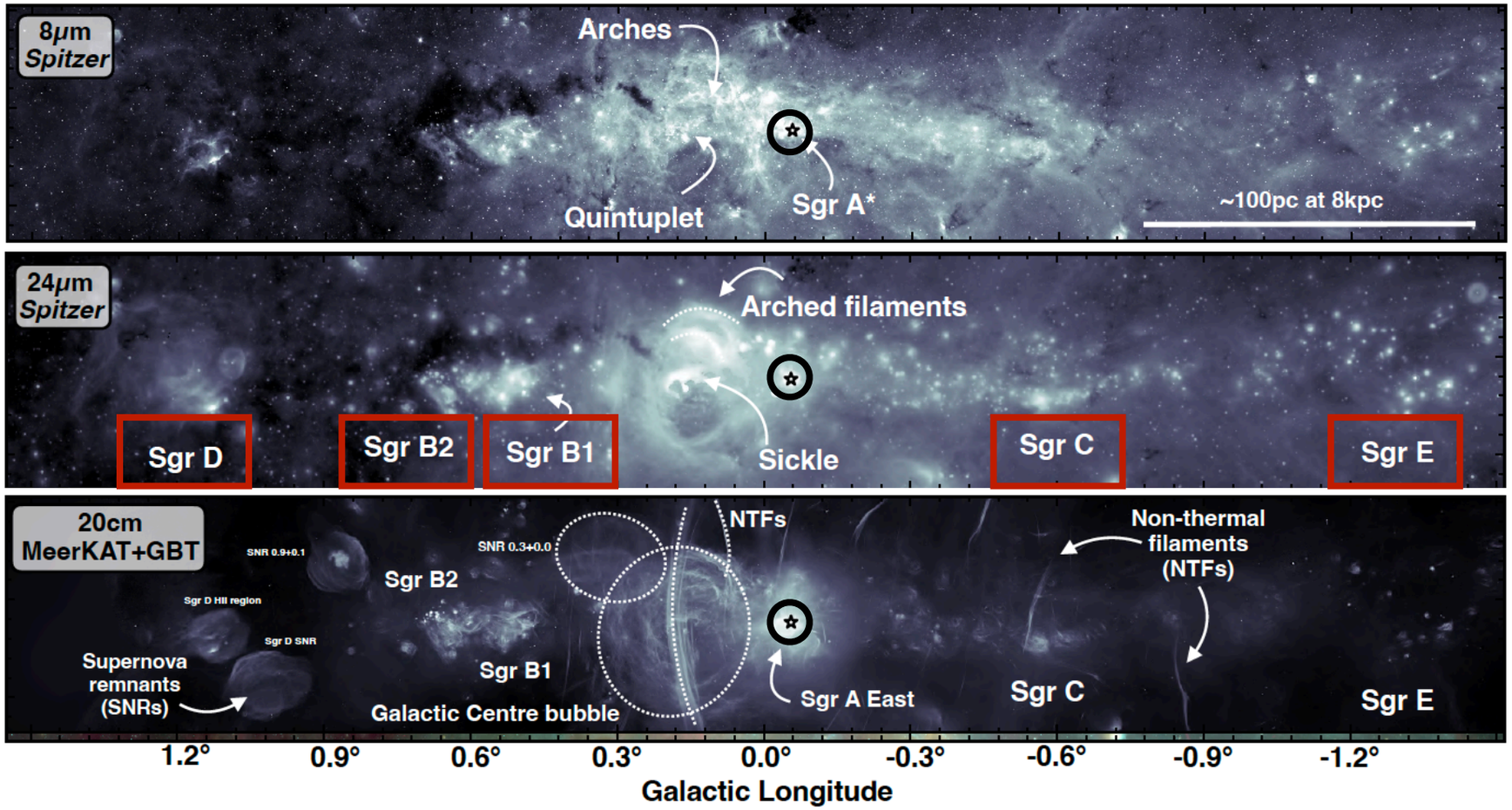
- The **supermassive black hole Sgr A*** is surrounded by dense molecular complexes shaping the **so-called Central Molecular Zone (CMZ)**

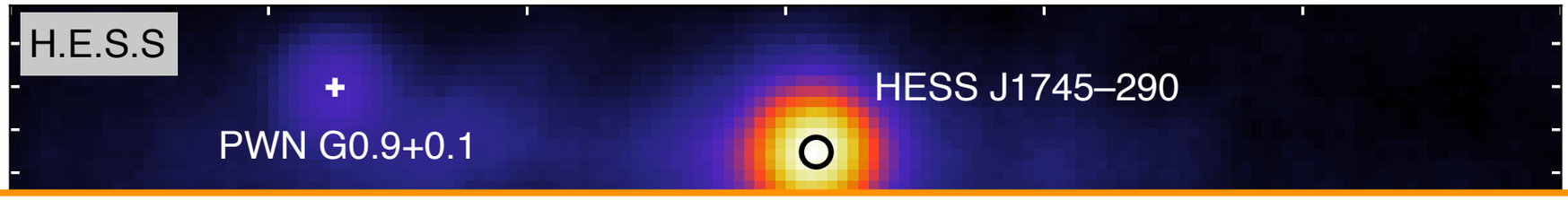
The Galactic Center region



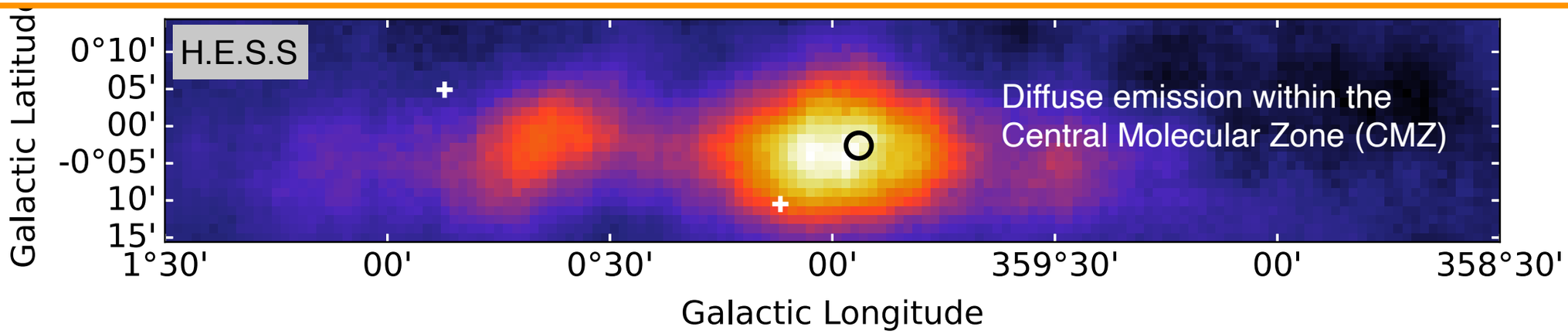


The Galactic Center region



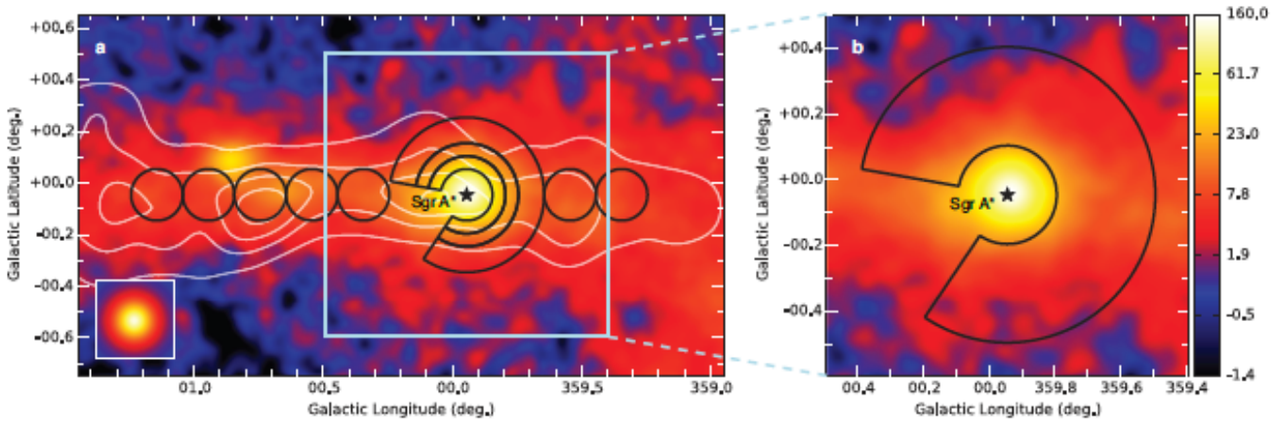


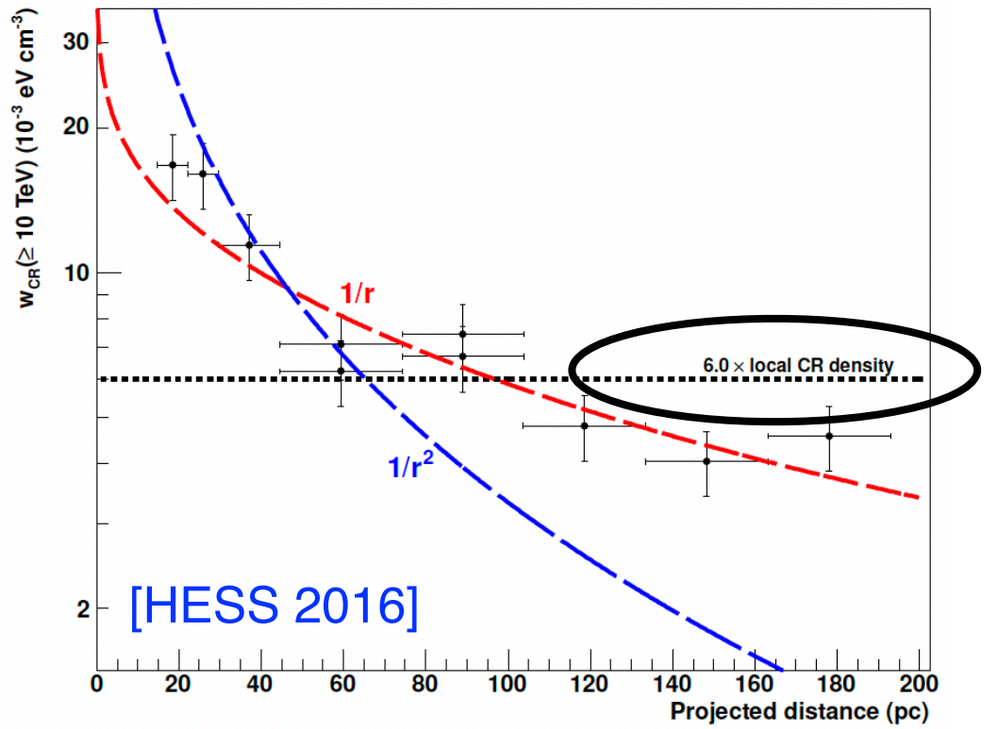
We know that gamma rays follow the gas distribution modulo a cosmic-ray (CR) gradient



Context: Gamma-ray morphology of the CMZ

- H.E.S.S. excess map:





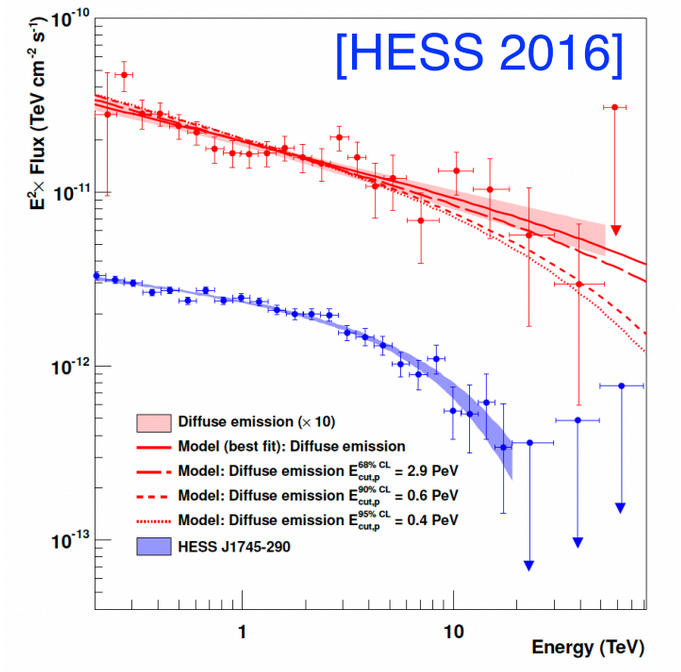
➡ **Excess of cosmic rays** (CRs) near the Galactic Center with a 1/r density profile:

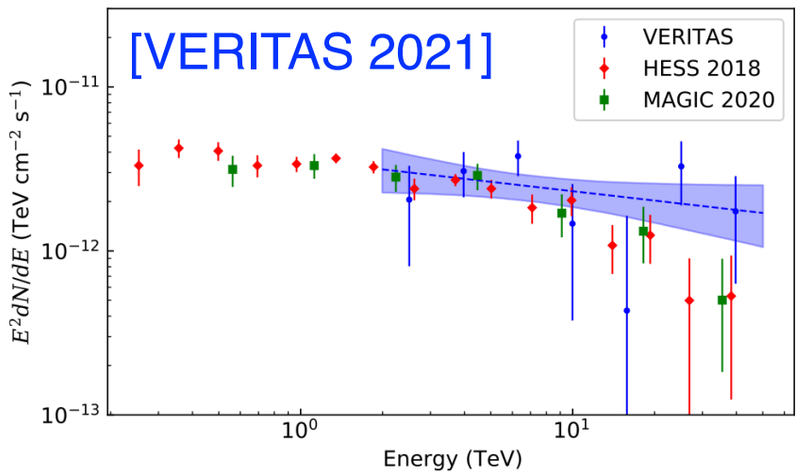
$$W_{\rm CR} \propto \frac{1}{r}$$ [HESS 2016, MAGIC 2020]

Indication of a continuous injection (steady source) of CRs near the Galactic center and diffusion through the Central Molecular Zone

Context: Gamma-ray spectrum of the CMZ

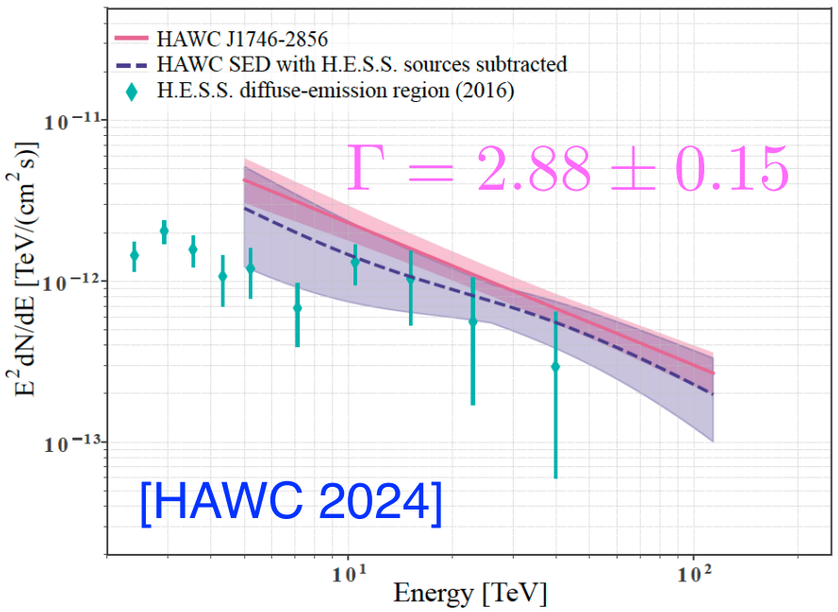
- No significant curvature detected:





A potential PeVatron at the Galactic Center

- But **hint for a spectral transition**: $E_{\rm cut} \sim 18$ TeV (@ 2 sigma) [MAGIC 2020]



What can we say with a more detailed analysis?

Can we better measure the H.E.S.S. spectrum?

Aim

General Question:

What is the distribution and spectrum of CRs in the inner 200 pc?
Where and how particles are injected?

Revisiting the diffuse emission at the Galactic center with more statistics and a **3D likelihood approach** (gammapy: simultaneous fit in latitude, longitude and energy)

1. **Do we have a steady source at the Galactic Center?**
   - ➡ Test of a possible deviation from a 1/r profile
   - ➡ Spectral variations across the CMZ?

2. **Spectral distribution of the diffused and injected CRs?**
   - ➡ First intrinsic gamma-ray spectrum of the CMZ

   (and then modeling of the corresponding parent population)

+ First intrinsic gamma-ray spectrum of the H.E.S.S. sources in the region

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What is the distribution and spectrum of CRs in the inner 200 pc?
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↑

Simultaneous spectro-morphological fits of the components

What's new?

1. **Do we have a steady source at the Galactic Center?**
   - ➡ Test of a possible deviation from a 1/r profile ⟵ 3D gas template *(l, b, z)*
   - ➡ Spectral variations across the CMZ?

2. **Spectral distribution of the diffused and injected CRs?**
   - ➡ **First intrinsic** gamma-ray spectrum of the CMZ

   (and then modeling of the corresponding parent population)

+ **First intrinsic** gamma-ray spectrum of the H.E.S.S. sources in the region

H.E.S.S. telescopes and observations

Namibia, Khomas Highland

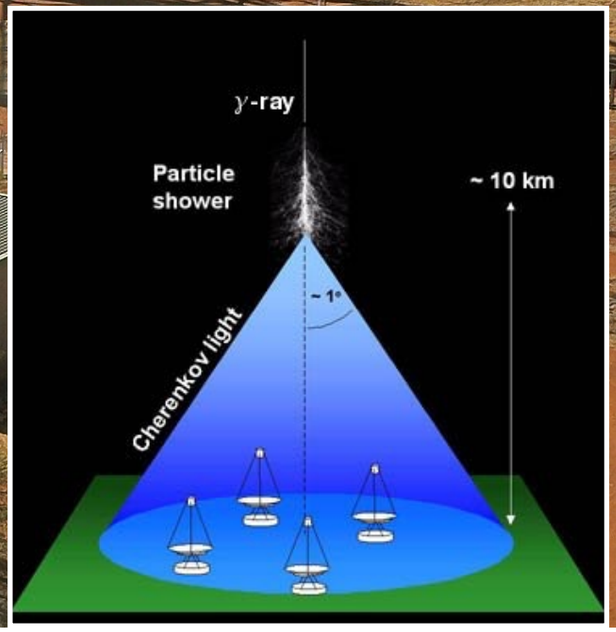
CT5

CT3

CT4

CT2

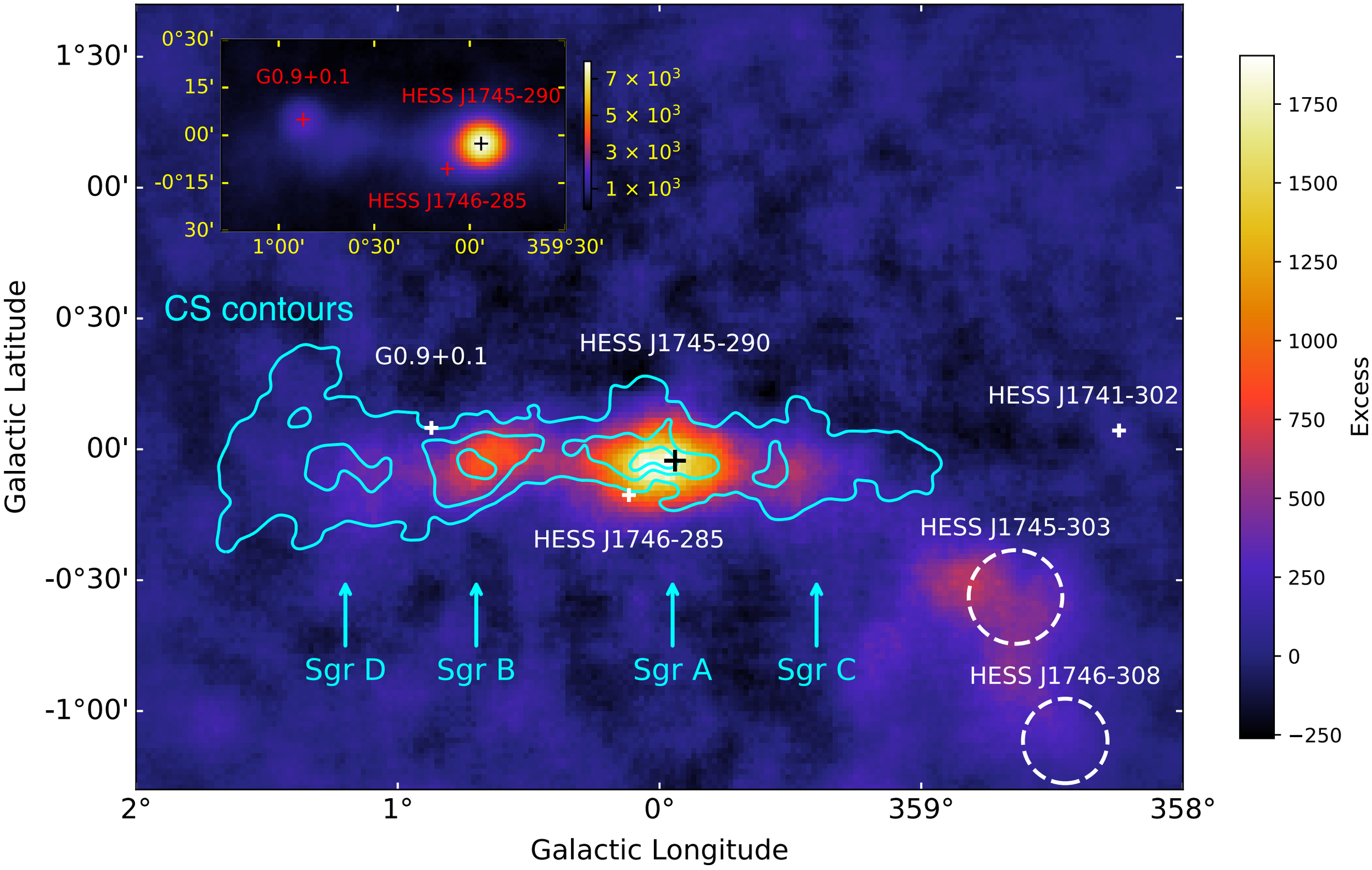
CT1



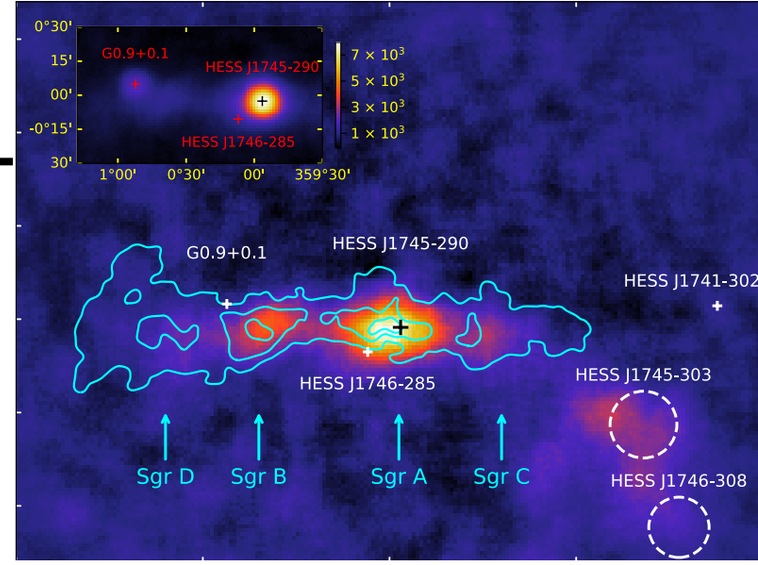
Observations:

- 16 years with CT1–4
- Zenith angle z_{max} = 40°, < z > = 18°
- $Offset_{max}$ = 2° (to the camera center)
- 6° x 4°, **0.4 —100 TeV**

H.E.S.S. excess map



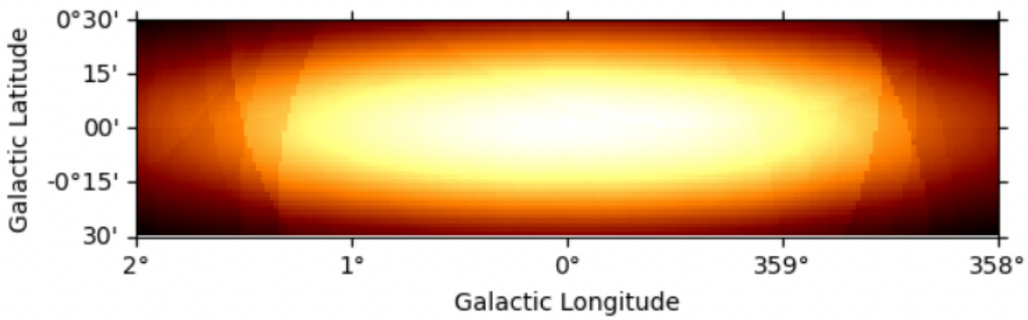
Model components in 3D (*l*, *b*, *E*)



- **4 point sources:** HESS J1745–290, G0.9+0.1, HESS J1746–285, HESS J1741–302 with an associated spectrum

- **Hadronic background component:** re-scaled normalization in each energy bin
  ➡ introducing nuisance parameters on the background

- **Large-scale emission:** Gaussian extent in latitude with an associated spectrum

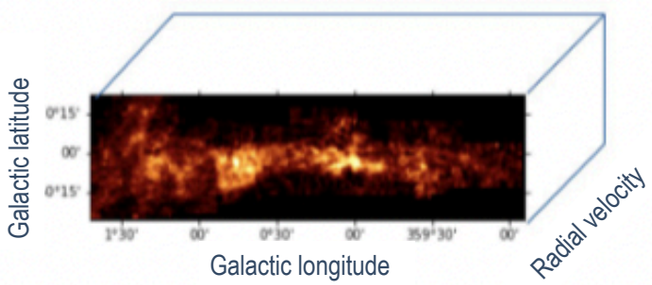


- **Template for the CRs in the CMZ:** need a gas distribution and a CR distribution (3D reprojected into 2D)

Template for the Cosmic Rays in the CMZ

[Tsuboi et al. 1999]

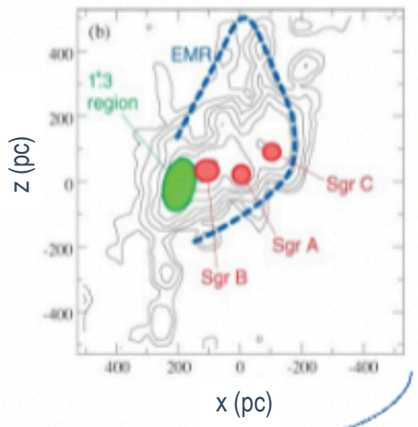
3D CS map *(l, b, v)*



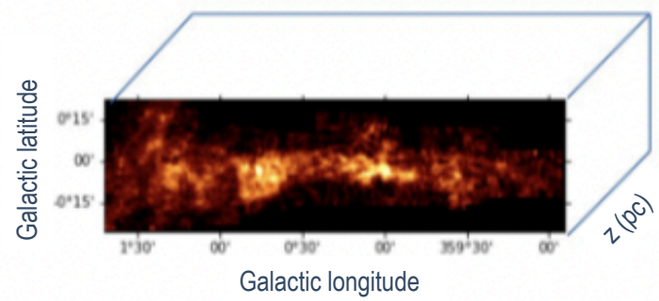
+

[Sawada et al. 2001]

2D map *(l, z)* CO

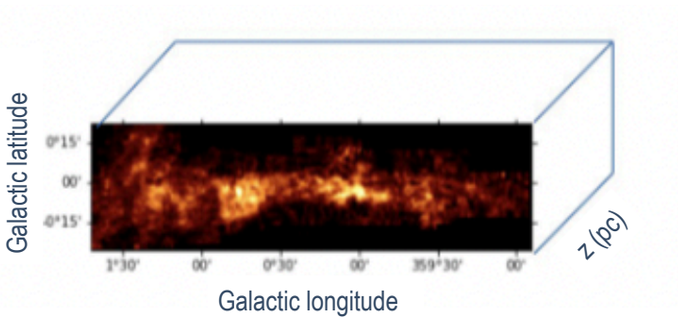


3D CS map *(l, b, **z**)*



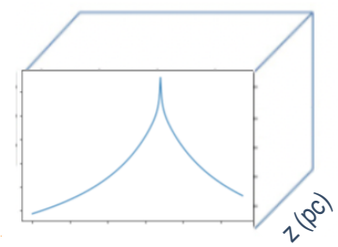
- Assume that CS and CO velocity distributions are similar
- Distribute CS emission along the l.o.s. for each bin in longitude
- Same distribution assumed at each latitude

3D CS map *(l, b, z)*

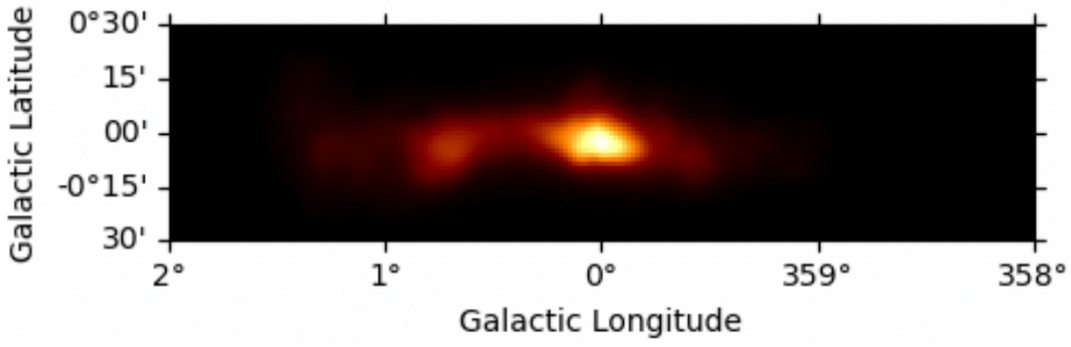


X

1/r *(l, b, z)*



Projected in 2D *(l, b)*



modeled with an associated spectrum

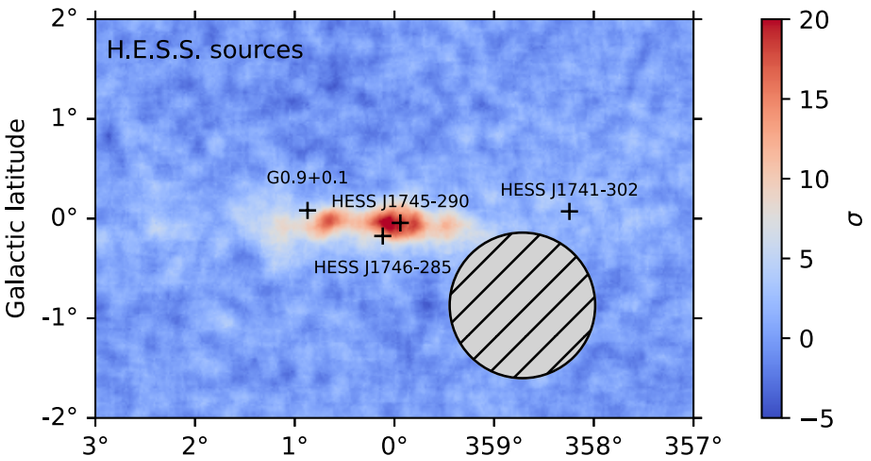
I. Importance of the large-scale emission in the analysis

- Position of the HESS sources and large-scale component extent fitted simultaneously with their spectrum

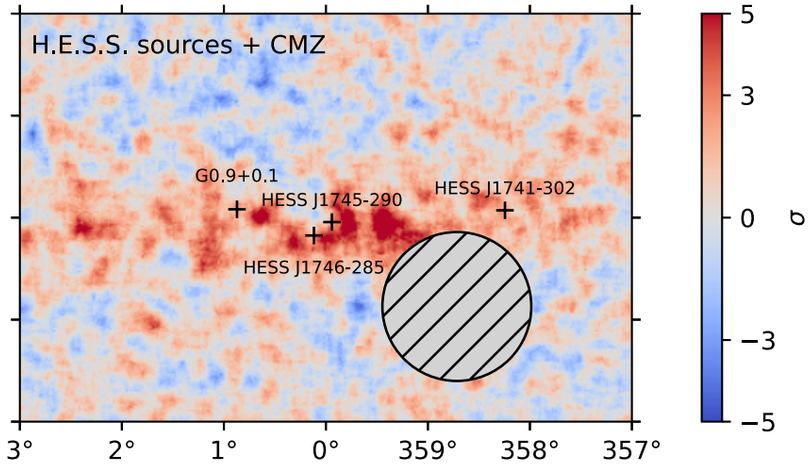
- Residual significance maps:

$$\sigma_{\mathrm{LSC}} = 0.32^\circ \pm 0.02^\circ$$

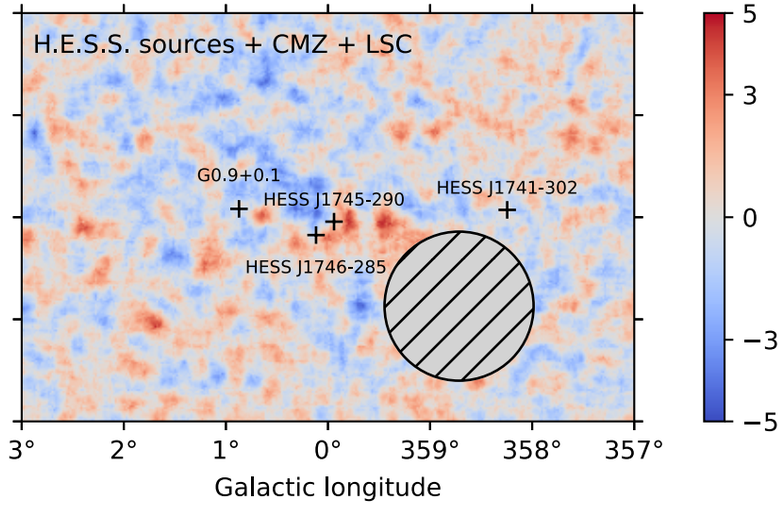
Background + HESS sources subtracted



+ CMZ subtracted



+ large-scale component subtracted



➡ The large-scale component is needed to properly model the region

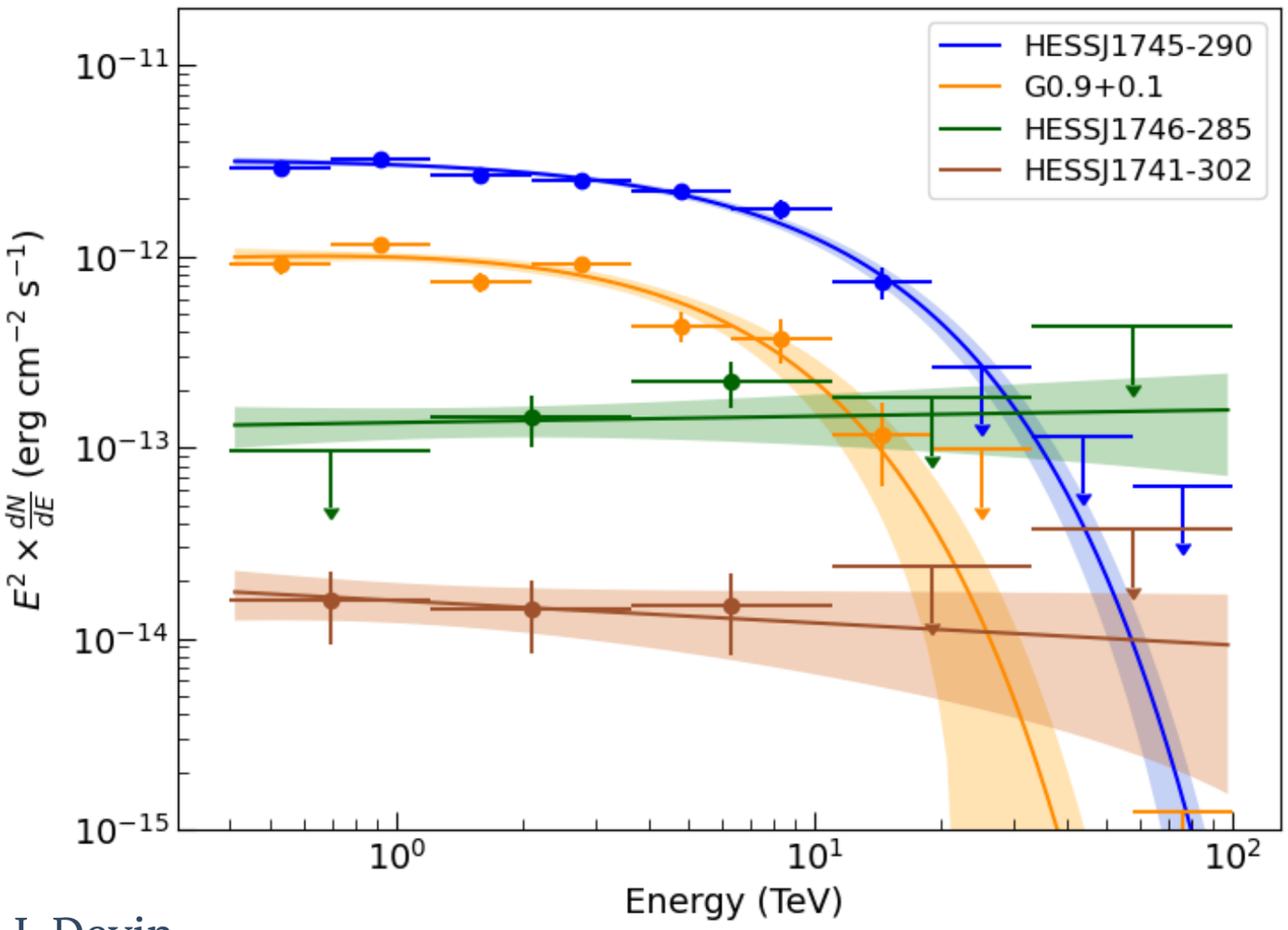
Data indicate that a curvature is needed in the large-scale component

➡ LogParabola model used (source of systematic uncertainty that does not change our conclusion)

II. Best-fit spectrum of the H.E.S.S. sources

Spectral shapes: $\frac{dN}{dE} = N_0 \left(\frac{E}{1\,\mathrm{TeV}} \right)^{-\Gamma}$ Or $\frac{dN}{dE} = N_0 \left(\frac{E}{1\,\mathrm{TeV}} \right)^{-\Gamma} \exp\left(\frac{-\mathrm{E}}{\mathrm{E_{cut}}} \right)$

Source	N_0 ($\mathrm{TeV^{-1}\ cm^{-2}\ s^{-1}}$)	Γ	E_{cut} (TeV)
HESS J1745−290	$(2.09 \pm 0.05_{\mathrm{stat}} \pm 0.49_{\mathrm{syst}}) \times 10^{-12}$	$1.98 \pm 0.05_{\mathrm{stat}} \pm 0.08_{\mathrm{syst}}$	$9.69 \pm 1.16_{\mathrm{stat}} \pm 0.95_{\mathrm{syst}}$
G0.9+0.1	$(7.54 \pm 0.72_{\mathrm{stat}} \pm 1.78_{\mathrm{syst}}) \times 10^{-13}$	$1.87 \pm 0.15_{\mathrm{stat}} \pm 0.13_{\mathrm{syst}}$	$5.03 \pm 1.68_{\mathrm{stat}} \pm 0.91_{\mathrm{syst}}$
HESS J1746−285	$(8.42 \pm 1.58_{\mathrm{stat}} \pm 1.93_{\mathrm{syst}}) \times 10^{-14}$	$1.97 \pm 0.12_{\mathrm{stat}} \pm 0.11_{\mathrm{syst}}$	–
HESS J1741−302	$(9.85 \pm 2.34_{\mathrm{stat}} \pm 2.78_{\mathrm{syst}}) \times 10^{-14}$	$2.12 \pm 0.18_{\mathrm{stat}} \pm 0.11_{\mathrm{syst}}$	–



➡ Spectra consistent with previous results

➡ Significant cutoff in the pulsar wind nebula G0.9+0.1 detected

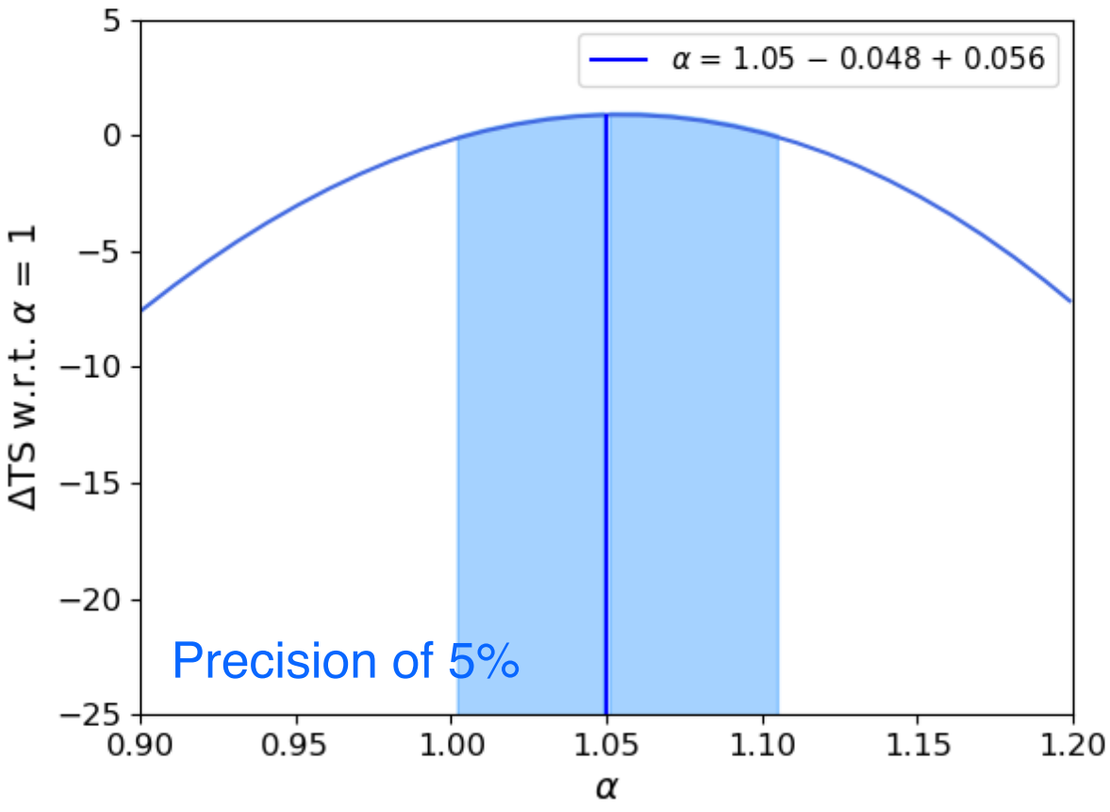
III. A continuous source at the Galactic Center?

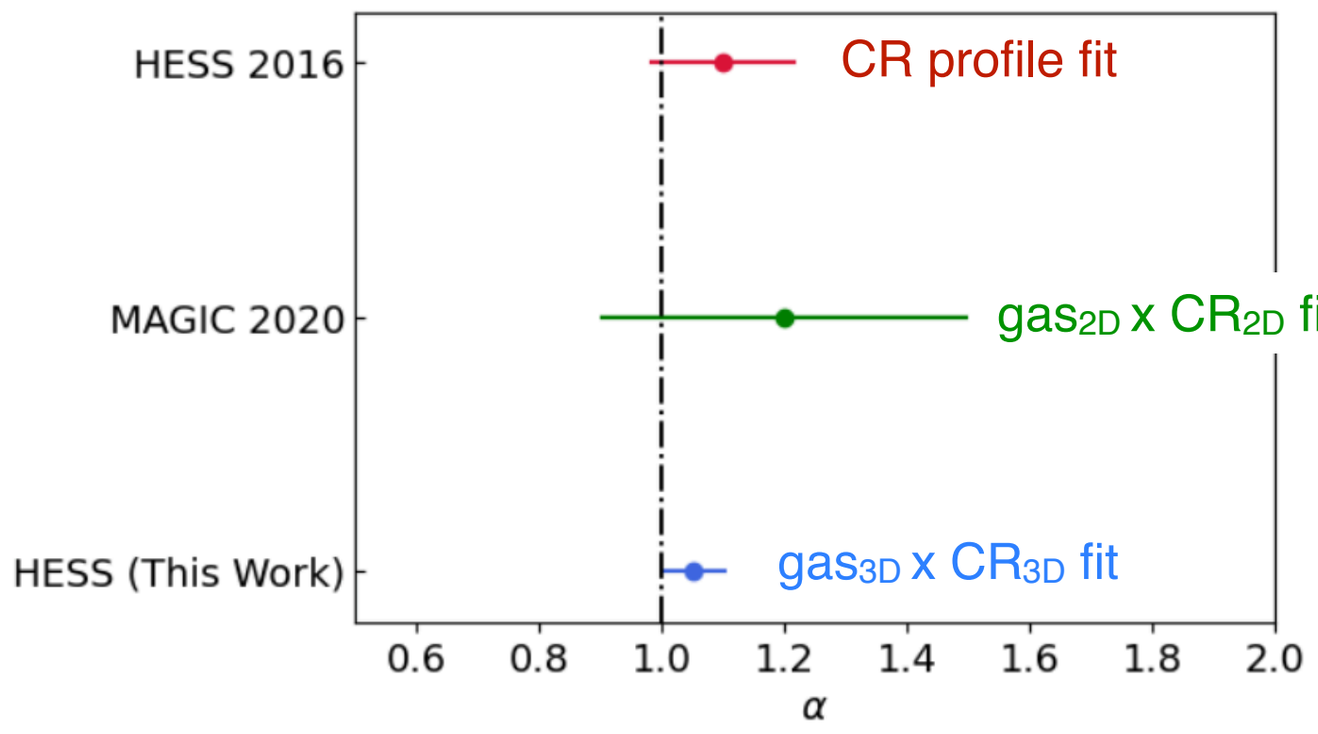
1. Test of a possible deviation from a 1/r profile

$$W_{\rm CR} \propto \frac{1}{r^{\alpha}}$$

3D template *(x, y, z)* reprojected in 2D for the fit:

$$S(x,y) = A \int \rho_{gas}(x,y,z)\, \rho_{CR}(x,y,z)\, dz$$





$$\alpha = 1.050^{+0.056}_{-0.048}$$

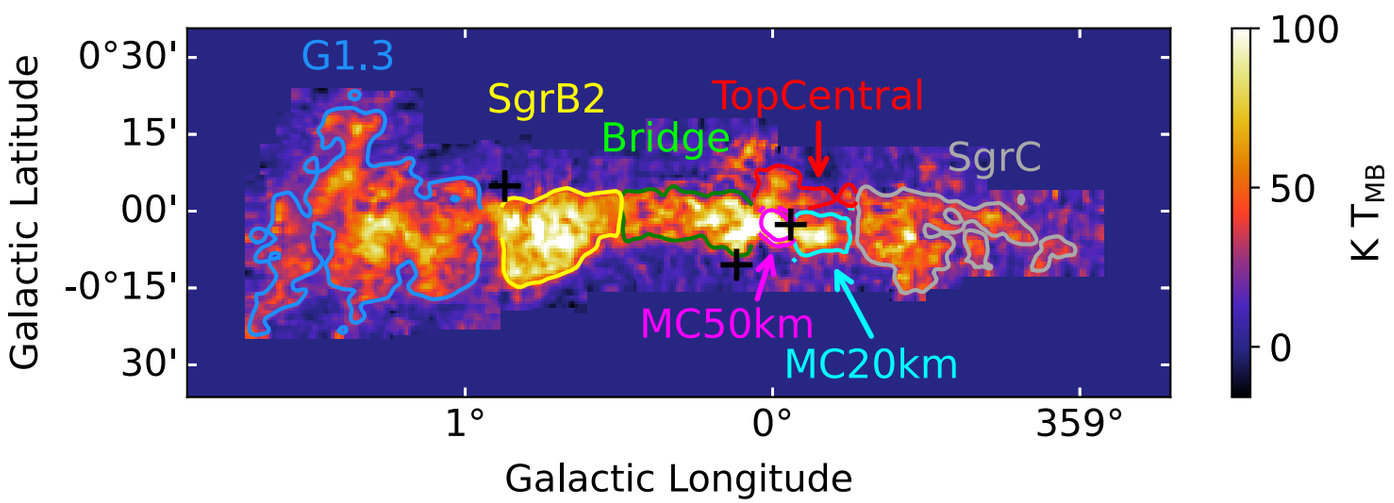
➡ Morphology fully compatible with a stationary source at the Galactic Center

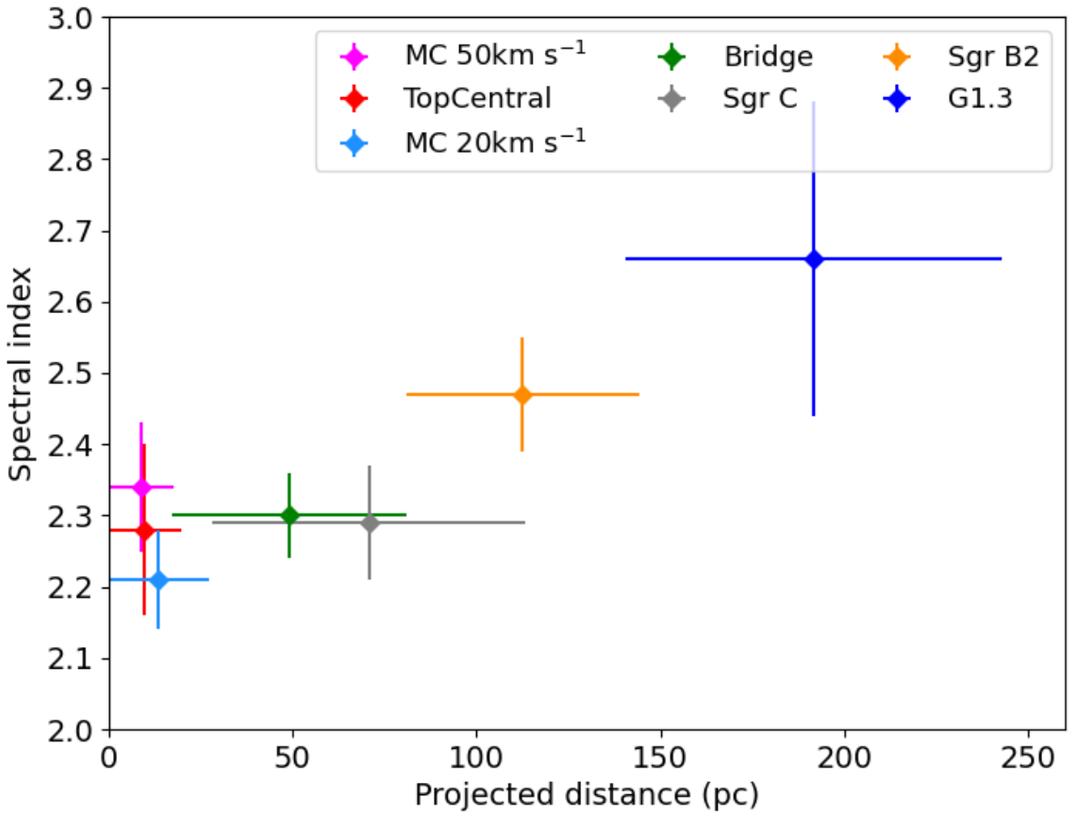
III. A continuous source at the Galactic Center?

2. Spectral variations across the CMZ?

Fit of the spectrum of each cloud (2D template) simultaneously with the other components:

$$\frac{dN}{dE} = N_0 \left(\frac{E}{1\,\mathrm{TeV}} \right)^{-\Gamma}$$

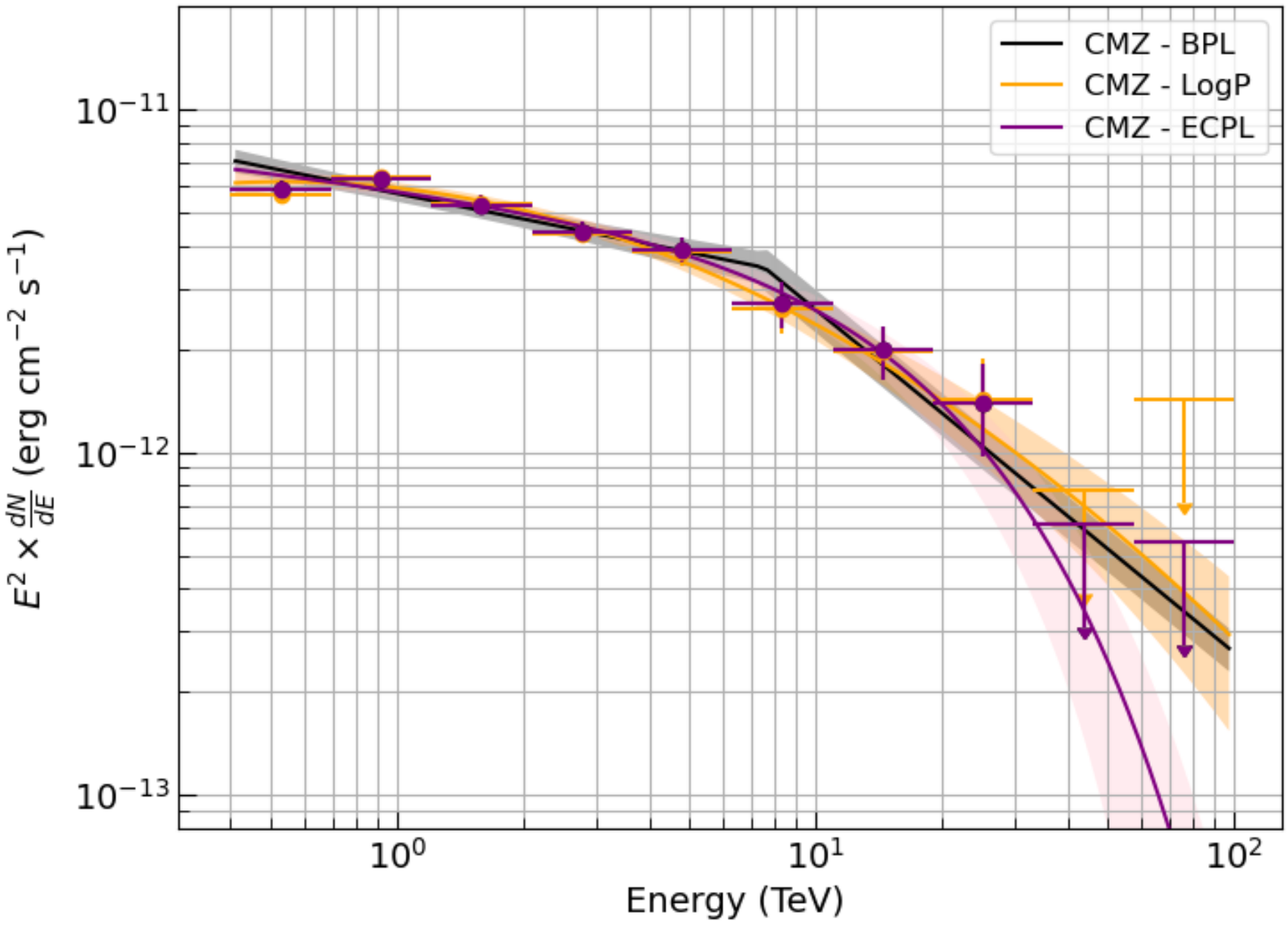




➡ No evidence for a deviation from a steady-source injection model

IV. Gamma-ray spectrum within the CMZ

Model	N_0 (TeV^{-1} cm^{-2} s^{-1})	Γ or α	β	E_b or E_{cut} (TeV)	ΔTS
PL	$(3.57 \pm 0.14 \pm 0.76_{syst}) \times 10^{-12}$	$2.34 \pm 0.04 \pm 0.19_{syst}$	–	–	0
BPL	$(3.79 \pm 0.12 \pm 0.50_{syst}) \times 10^{-12}$	$2.25 \pm 0.05 \pm 0.11_{syst}$	3 (fixed)	$7.55 \pm 0.33 \pm 0.45_{syst}$	10.3
LogP	$(3.68 \pm 0.13 \pm 0.65_{syst}) \times 10^{-12}$	$2.14 \pm 0.06 \pm 0.10_{syst}$	$0.11 \pm 0.03 \pm 0.20_{syst}$	–	12.8
ECPL	$(3.78 \pm 0.17 \pm 0.78_{syst}) \times 10^{-12}$	$2.14 \pm 0.06 \pm 0.12_{syst}$	–	$18.63 \pm 5.80 \pm 3.40_{syst}$	13.2



➡ Significant (> 3 sigma) curvature in the CMZ gamma-ray spectrum

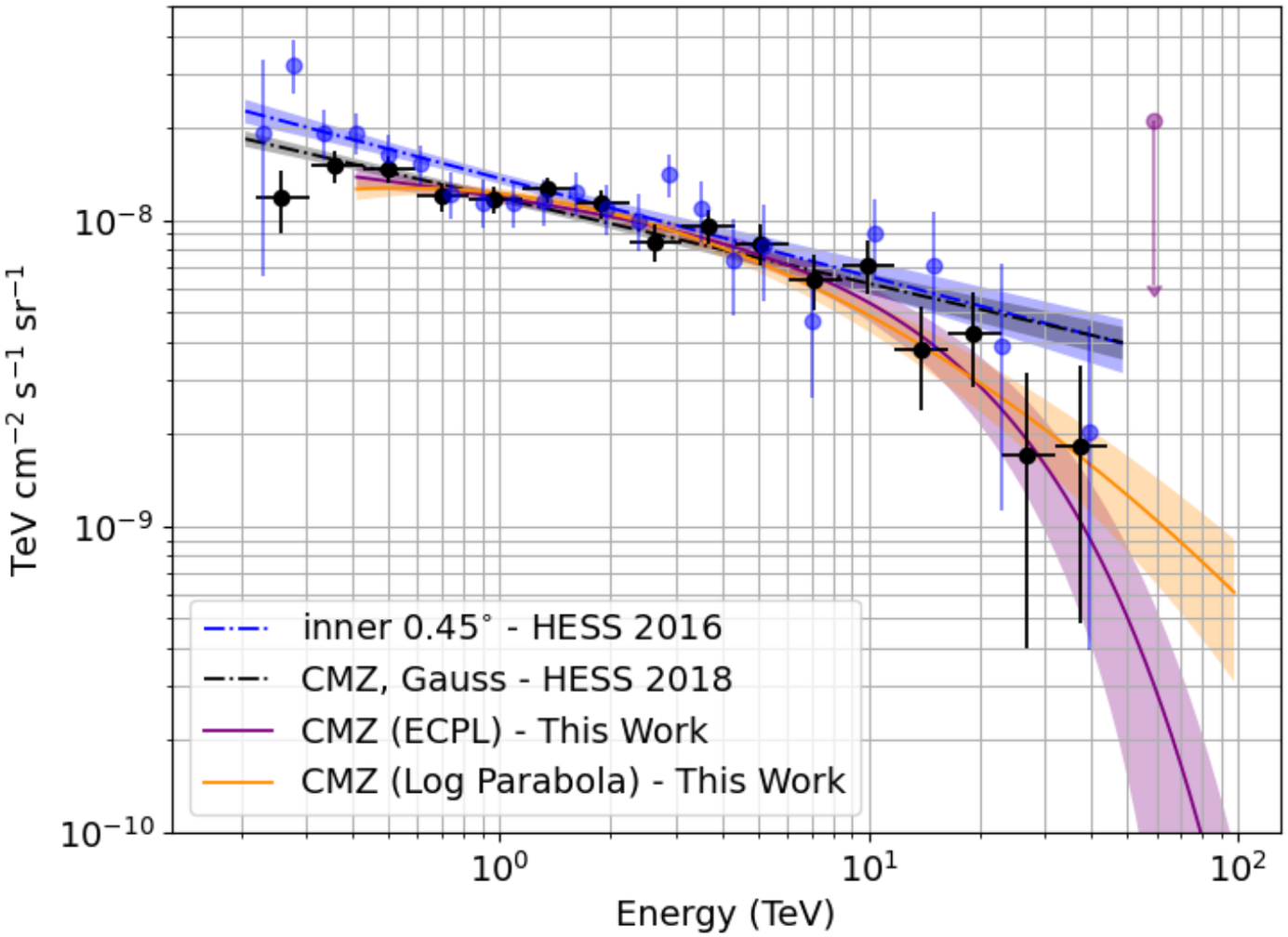
Cannot distinguish between models: similar up to ~ 40 TeV

Comparison with previous H.E.S.S. results

More detailed analysis with simultaneous spectro-morphological fits of the different components

➡ **better modeling of the systematic uncertainties** related to the large-scale component and to the hadronic background

+ enhanced statistics allow the detection of a spectral transition around 10—20 TeV

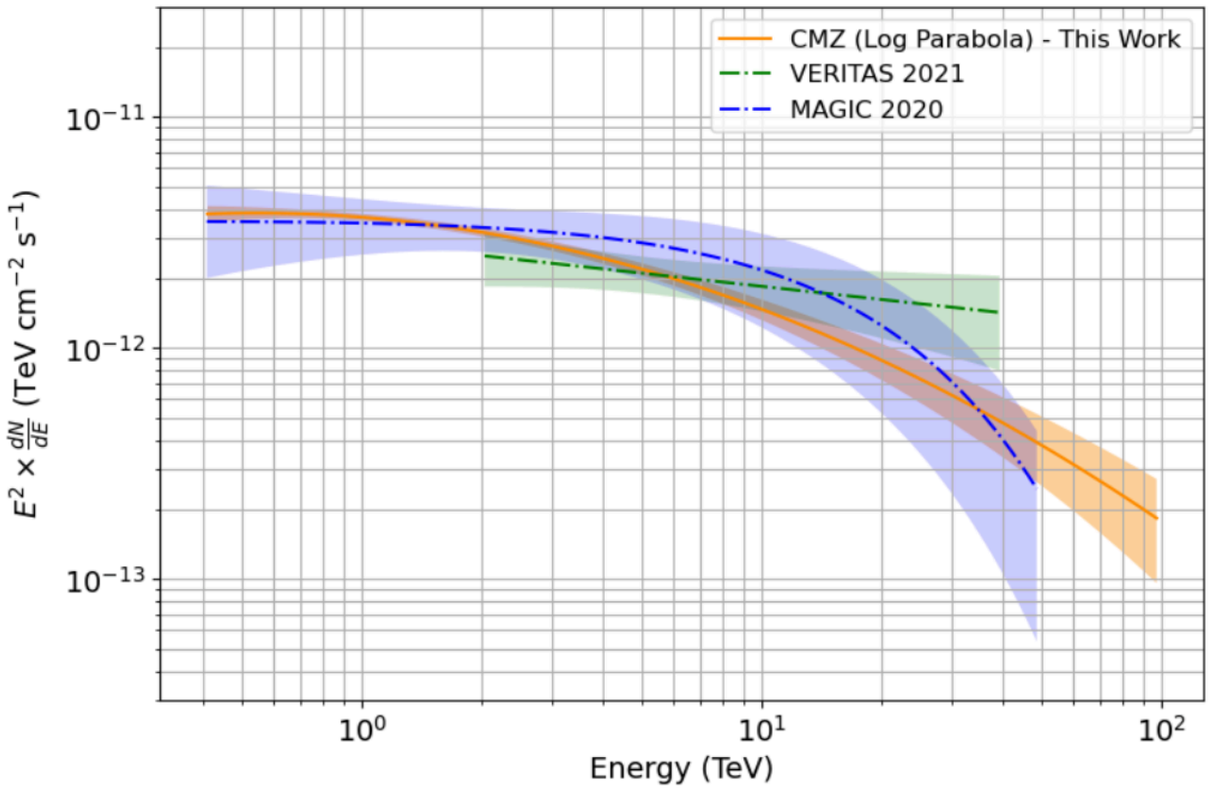


Related to the accelerator itself?
To propagation effects?
To a contribution from multiple sources? …

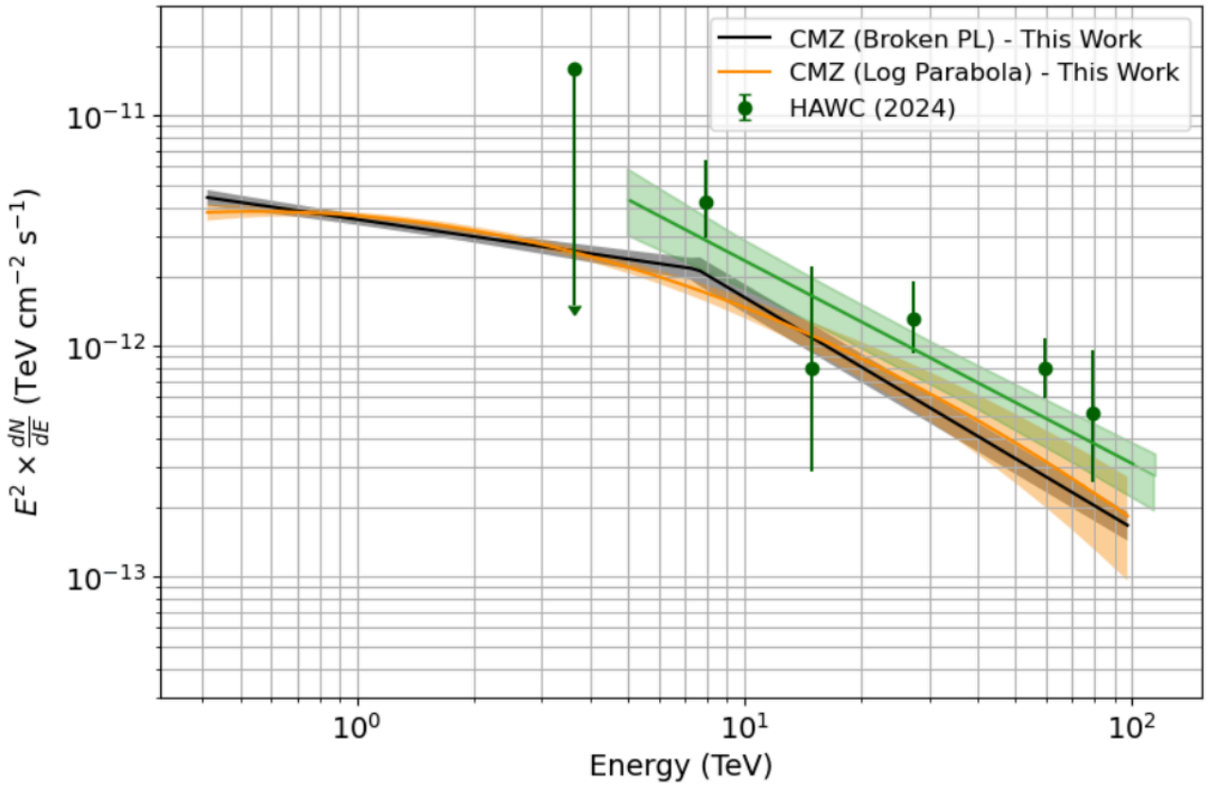
(Consistent with previous results)

Comparison with other experiments

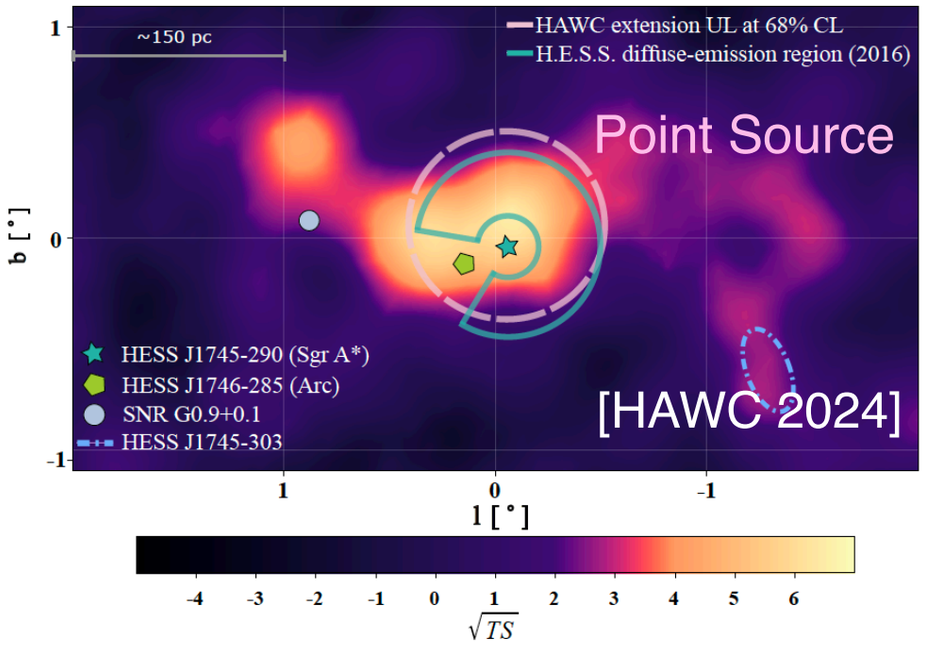
Consistent with the hint from MAGIC:



And recent results from HAWC:



Enhanced statistics above 10—20 TeV with better angular resolution (Cherenkov Telescope Array) and joint fit analysis (larger lever arm) would help



Conclusions

We revisit the gamma-ray diffuse emission at the Galactic Center with more statistics and a 3D likelihood approach:

- Spatial and Spectral distributions within the CMZ are **fully compatible with a continuous injection scenario**
  - ➡ Best-fit radial index: $\alpha = 1.050^{+0.056}_{-0.048}$
  - ➡ No spectral variations across the CMZ

- **Curvature in the CMZ spectrum** and first intrinsic spectrum of the 4 HESS sources (**significant cutoff in G0.9+0.1 detected**):