Multi-year observations of the Galactic Center region with the MAGIC telescopes

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Galactic Center (GC) — a complex astrophysical region

Galactic Center – a unique astrophysical region with a high concentration of various types sources.

20cm, 1.1mm, IR

Features a number of sources (gas clouds, supernovae remnants) as resolved in radio.

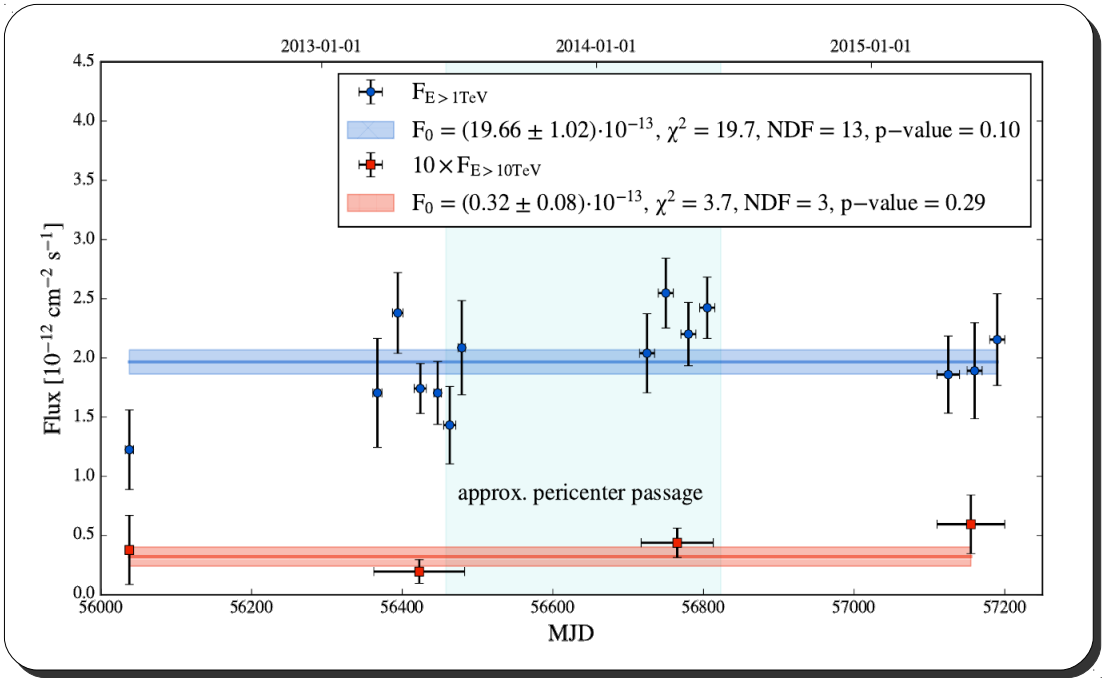
The dominant source – Sgr A*, associated with the central SMBH.

All of this is contained in a small ~1 deg region, comparable to the MAGIC FoV.

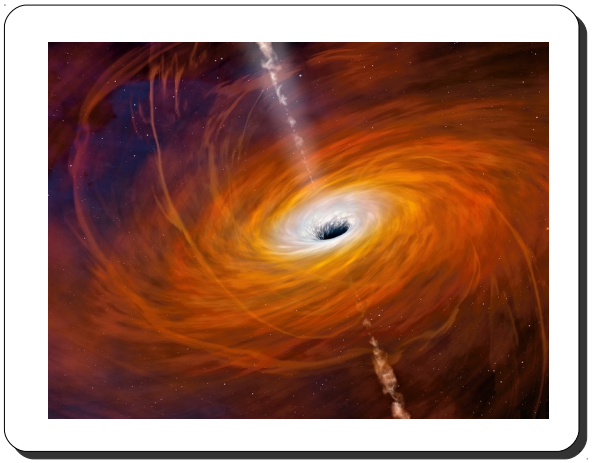
The central black hole — Sgr A*

The central black hole is, perhaps, the most intriguing source in the region.

→ Strong gravity, accretion of matter, particle acceleration, winds...



Sgr A* TeV light curve (Ahnen+ '17)



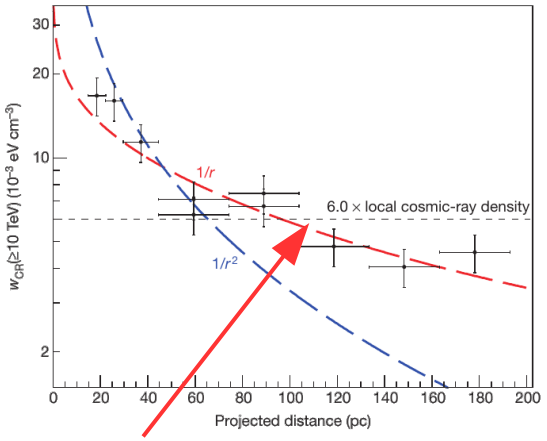
Artist's image capturing the most important black hole features – accretion disk and jet.

Still, no variability observed (in gamma-rays), the spectrum is broadly consistent with a range of emission models.
Uncertain influence on the surrounding gas (i.e. the high-energy appearance)

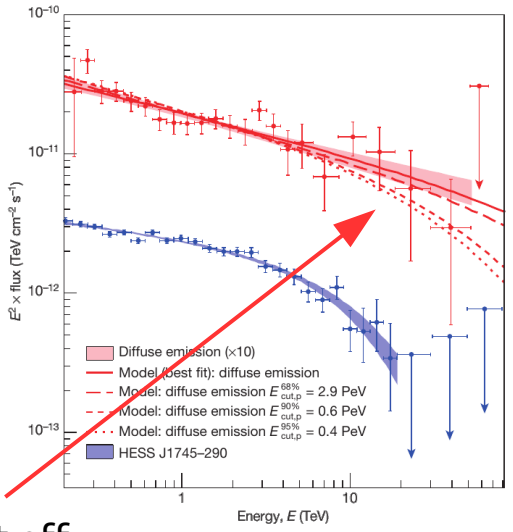
A pevatron in the Galactic Center

Recently the interest to the Galactic Center has increased with the discovery of a potential pevatron there, likely associated with the SMBH.

H.E.S.S. (Abramowski+ '16)



Consistent with the point-like source



No cut-off

If confirmed, this provides an important milestone to the
1) identification of the galactic pevatrons
2) investigation of the CR propagation in the Galaxy

Alternative explanations proposed (Gaggero+ '17) underline the importance of the large scale CR sea for the firm interpretation.

However, one of the main ingredients is the gas distribution in the central ~200 pc from the black hole.

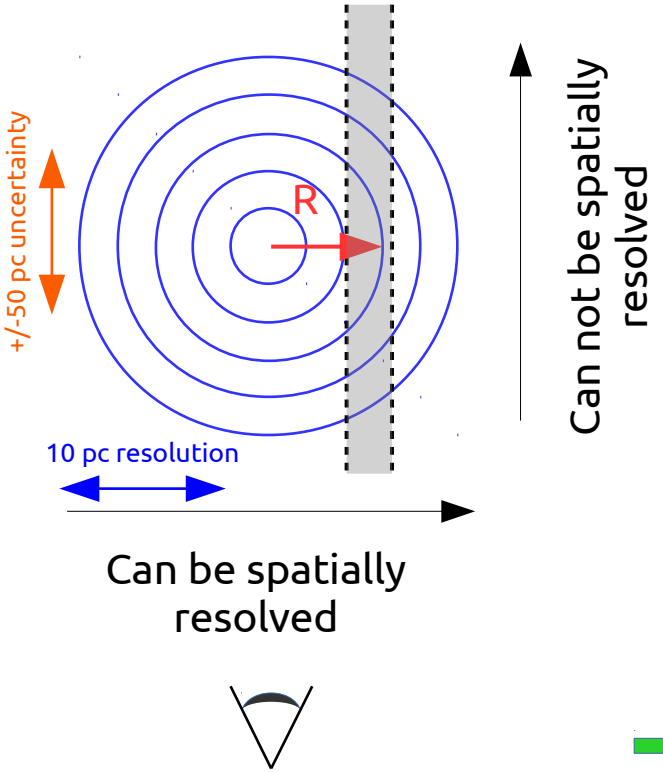
And it is particularly difficult to get.

Towards the 3D model of the Galactic Center

The gamma-ray emission observed is the result of interaction of the GC cosmic ray population with the underlying gas.

In fact we see only its projection

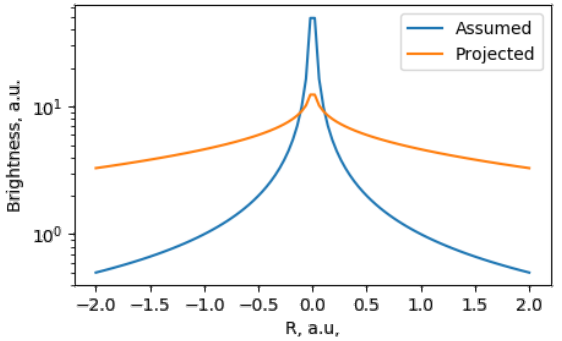
$\int \rho(r) w_{CR}(r) dr$



Let's illustrate the projection effect:

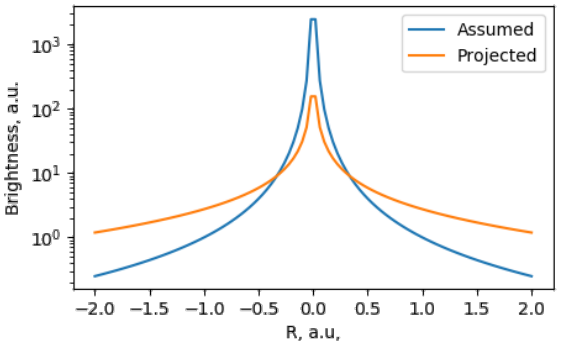
Profile 1/r

→ Projected ~$\sinh^{-1}(c/r)$



Profile 1/r^2

→ Projected ~$\tan^{-1}(c/r)/r$



→ The full 3D model (and calculations) are required to account for projection effect.

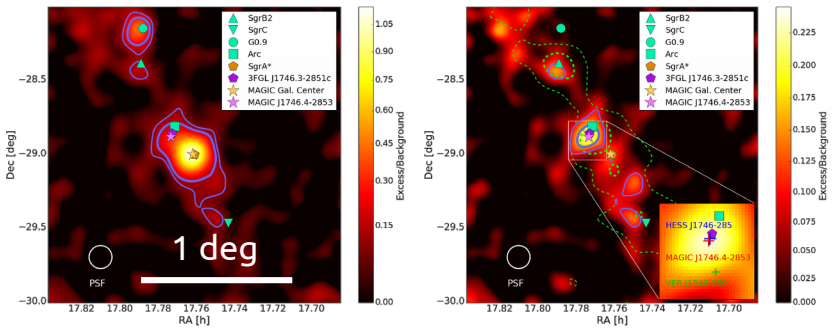
MAGIC observations of the Galactic Center region

The goal of this work was to use available ~5 years of MAGIC observations to provide an independent study of the galactic center diffuse emission CR profile.

MAGIC

Telescopes: two D=17m, F/D=1.03
Site: Observatorio del Roque de Los Muchachos (Canary Islands)
Energy range: 40 GeV – above 50 TeV
Sensitivity: 0.6% Crab units (integral)

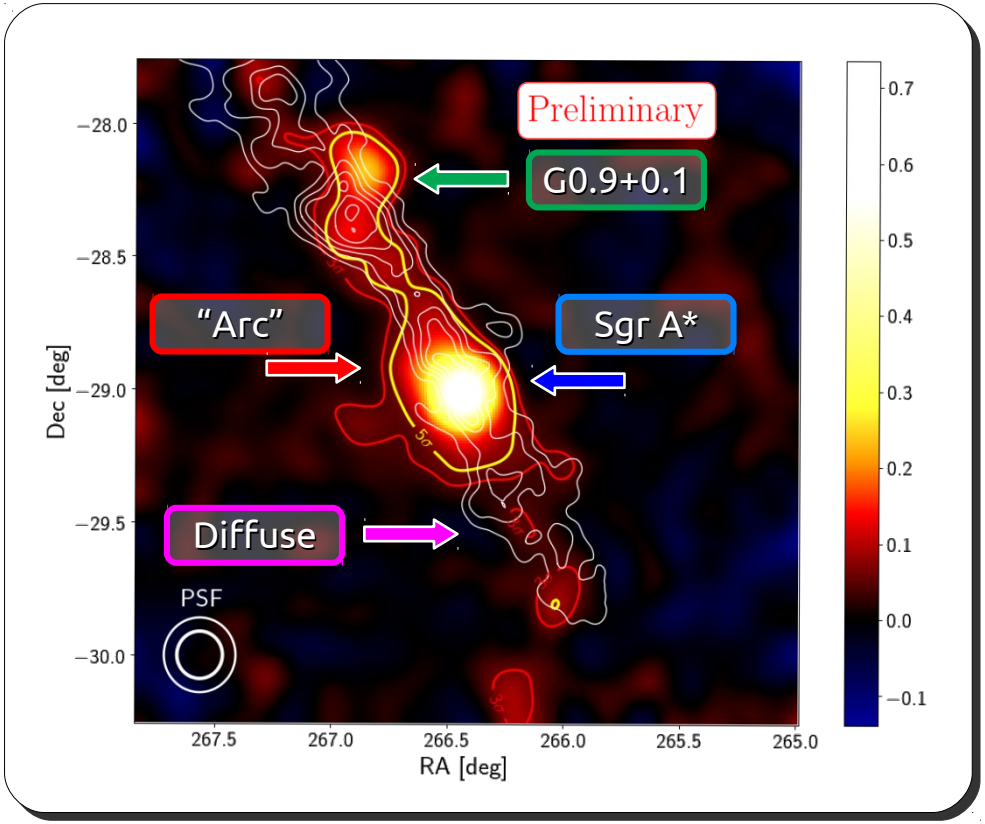
MAGIC (Ahnen+ '16)



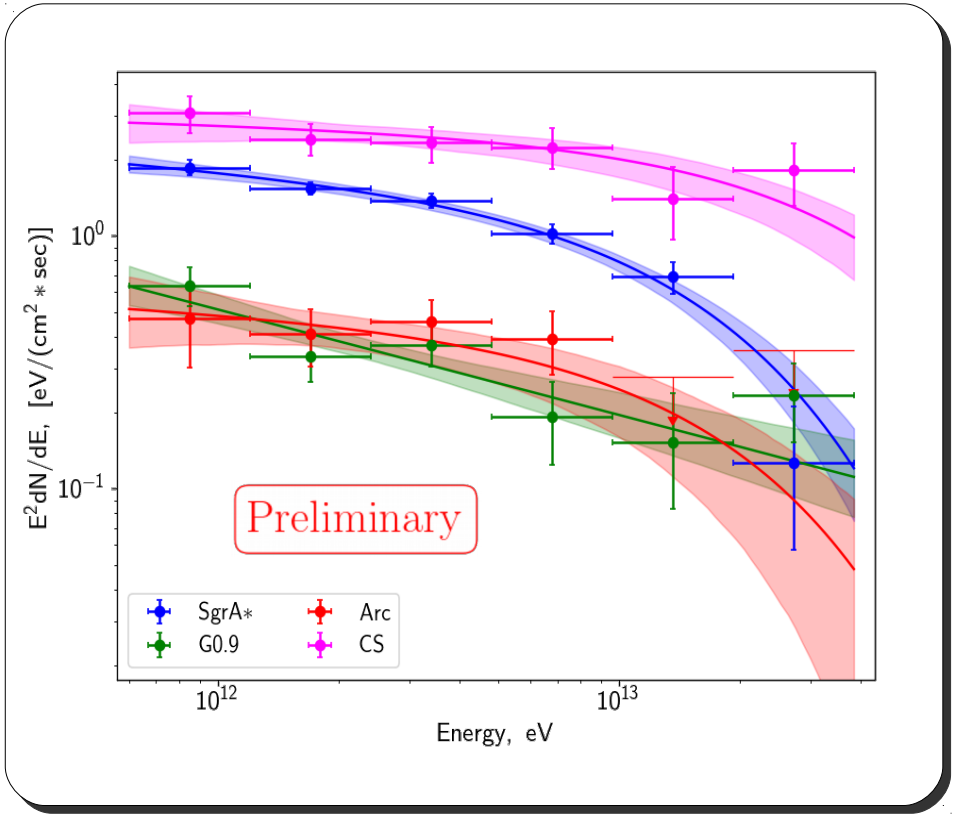
Data and tools

Large zenith angle (~60 deg) observations
Collection area A_{eff} ~ 0.2 km^2
100 hr of total exposure
Atmosphere transmission real-time corrections (LIDAR system)
Analysis with the new MAGIC 2D likelihood analysis package (SkyPrism).

MAGIC view of Gal. Center region



Sky map above 1 TeV.



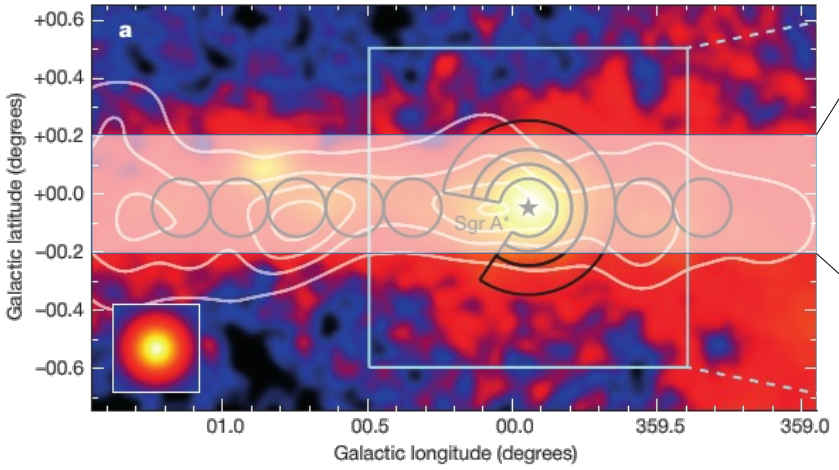
Spectra of the detected sources, obtained from the 2D likelihood fit.

The diffuse component spectrum is best described with power law with cut-off.
The spectrum of the "Arc" (Archer+ '16, Ahnen+ '17, Abdalla+ '17) is consistent with Γ~2.2 power law.

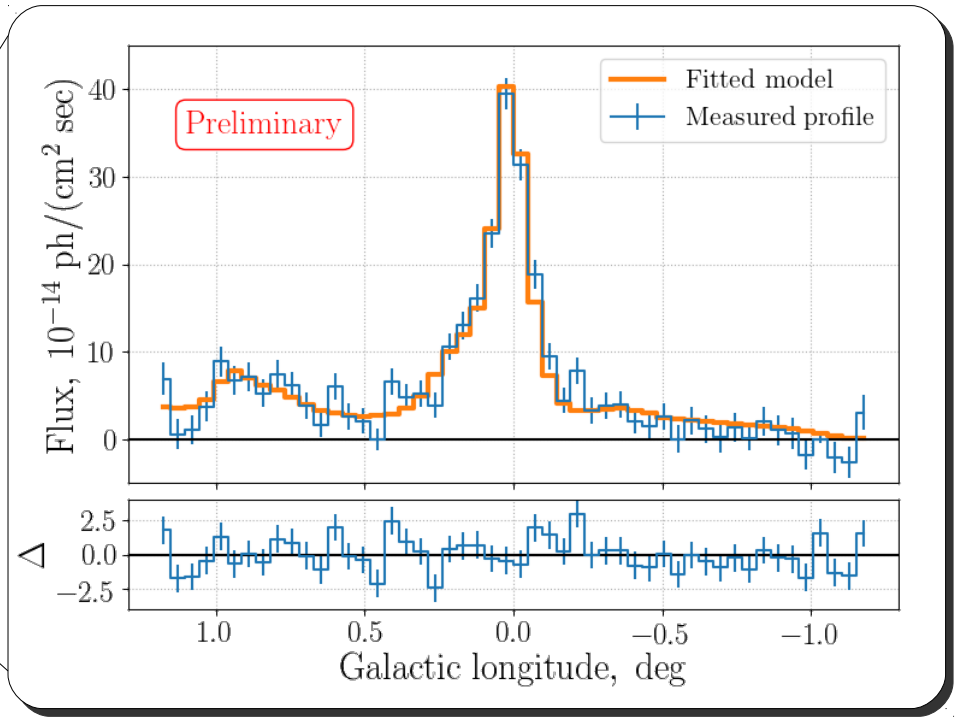
Galactic plane brightness scan

To search for the peaked CR profile presence, we constructed the brightness scan of the galactic plane in the [-0.2;0.2] deg range above 1.2 TeV.

The scan contains bulk of the HESS regions + Arc, G0.9 and Sgr A* sources.



Abramowski+ ‘16



x^2 = 72/46 d.o.f. (p-value = 0.01)

Model provides a reasonable description of the data.
Still, high x^2 value indicates that something is missing in the fit.

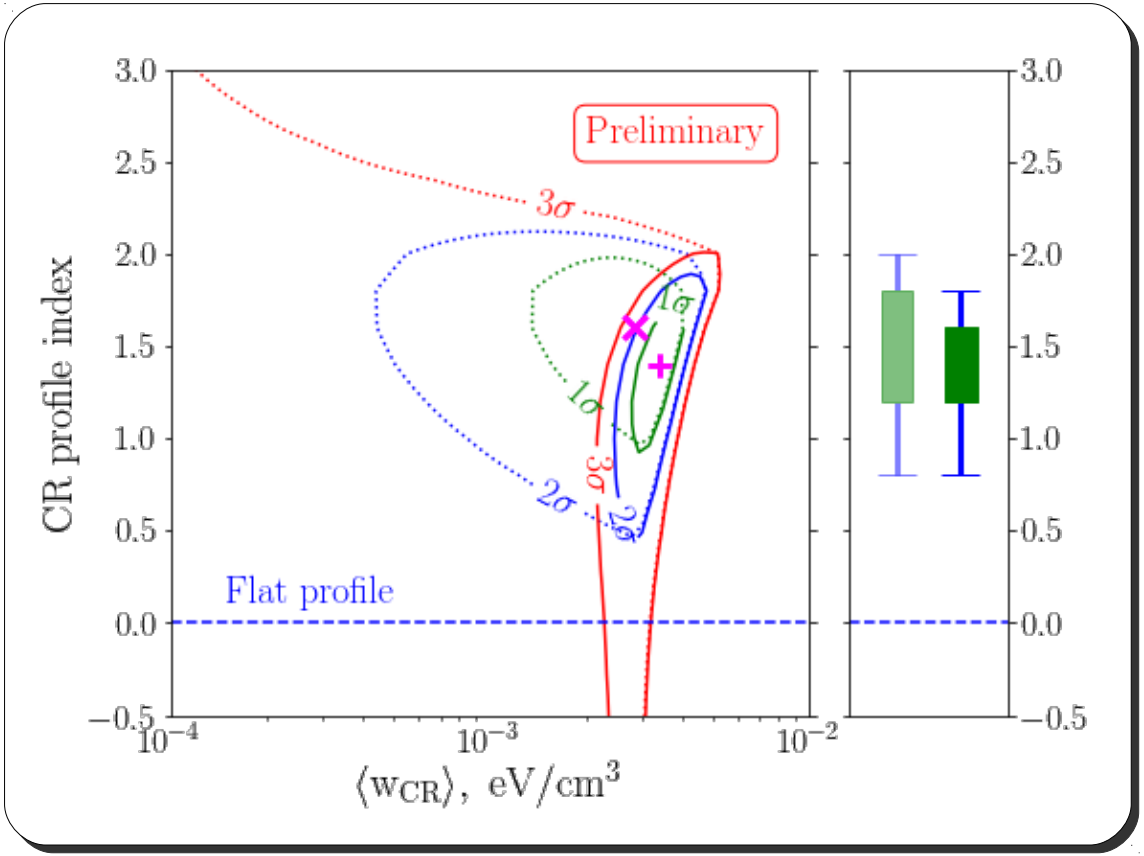
Search for the peaked CR population

Missing component – CR radial profile. Here we searched for ~$1/R^{\alpha}$ type profiles.

Diffuse emission map – CS emission scaled with the "projected" version of cosmic ray profile.

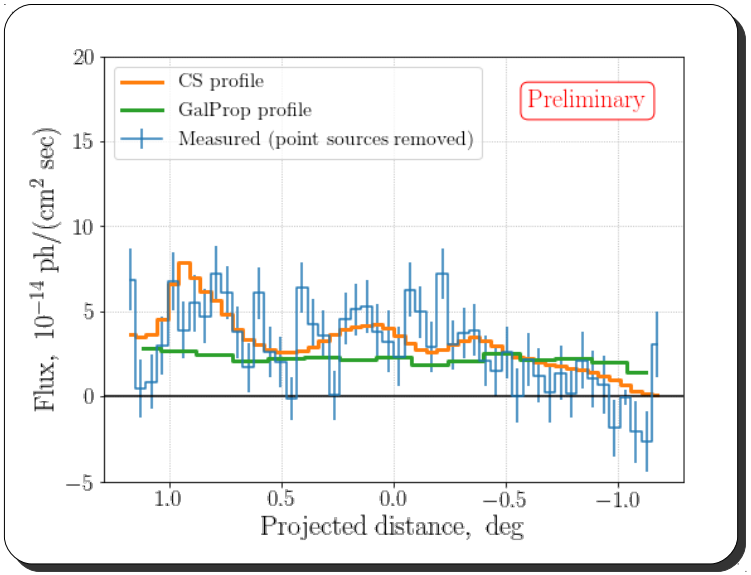
Tested two assumptions:
(1) there is only peaked CR profile;
(2) peaked profile is on top of the uniform one (similar to Gaggero+ '17)

Average CR density is obtained with the gas mass estimates computed from Tsuboi+ '99 data.



MAGIC data prefer the peaked CR profile with index ~1.2-1.5.

Cosmic ray profile in the Gal. Center region



Observations are also consistent with the $1/r^2$ + const profile

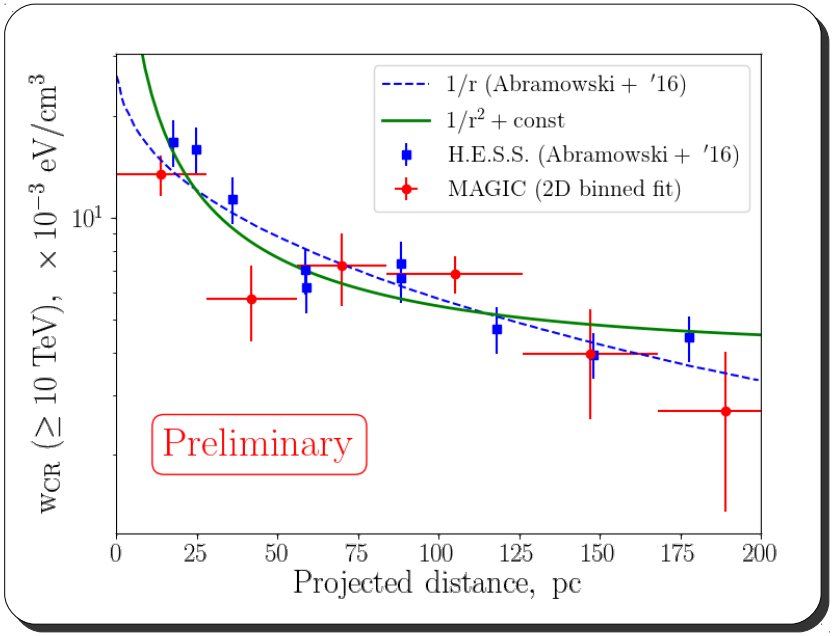
➡ CR advection in wind is not excluded.

Still, these measurements are affected by strong systematics (unknown line of sight gas distribution)

Data above 1.2 TeV support an assumption that CR distribution is not flat.

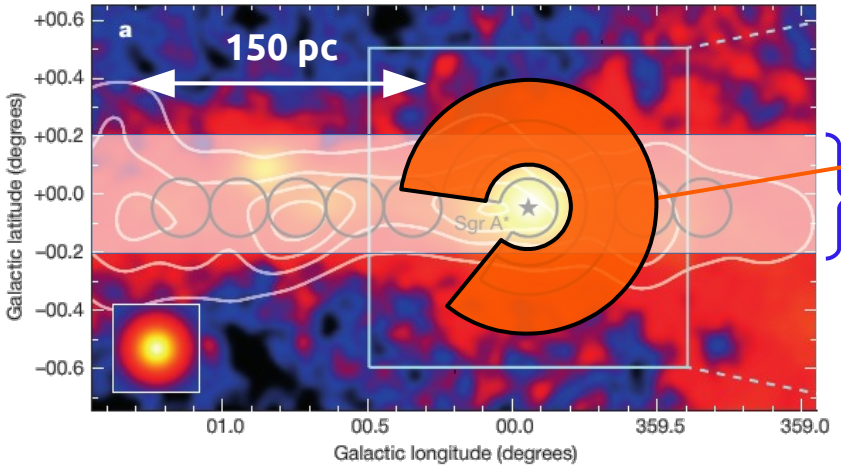
Mismatch with the GalProp-predicted profile, which (assumes that CR source distribution follows SNRs)

➡ Additional source(s) in the GC region.
PeVatron?

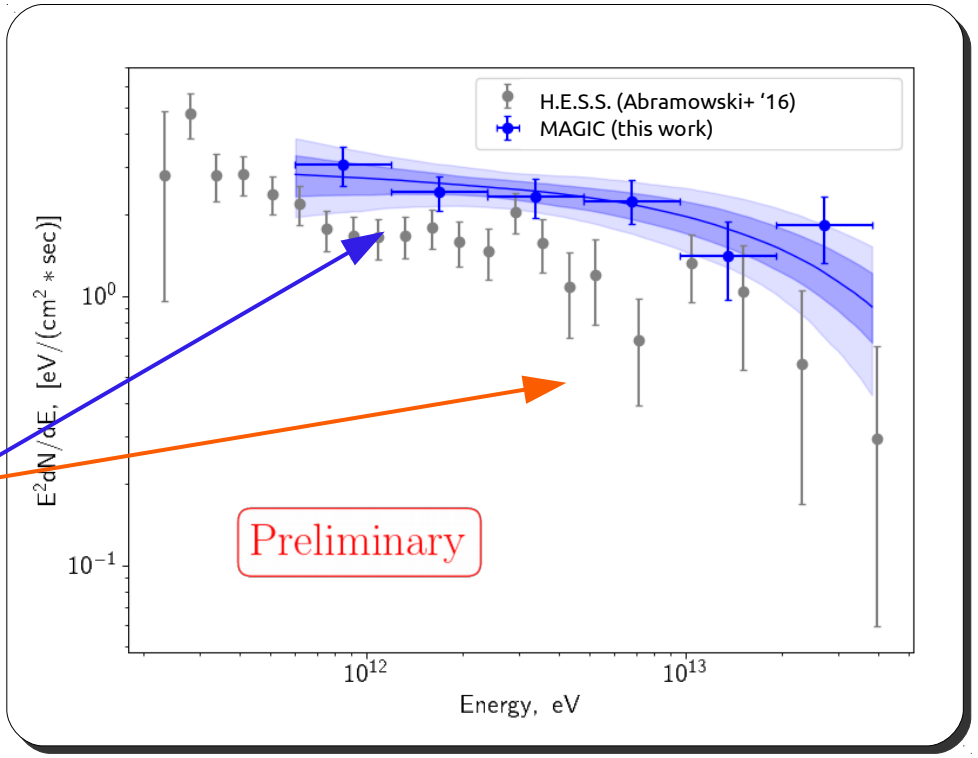


Cut-off in the diffuse emission component

- 2D likelihood fit including also “Arc”, G0.9+0.1, Sgr A* + residual background.
- Parameters are estimated via the MCMC sampling of the parameter space.
- Cut-off energy is marginalized over the rest of parameters.



Abramowski+ ‘16

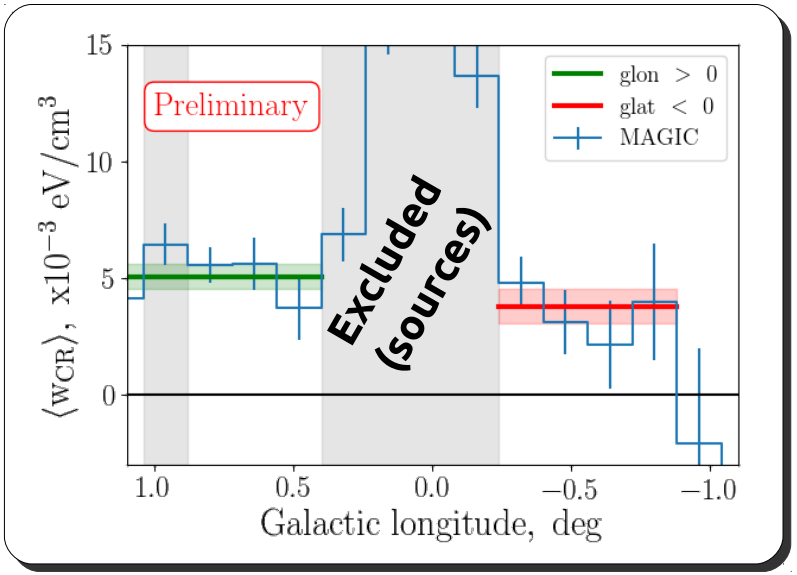


$$E_{cut} = 43\,^{+23}_{-15}\ (68\%)\ ^{+49}_{-25}\ (95\%)\ \text{TeV}$$

Cosmic ray population in the galactic plane cuts off before PeV energies.

$t_{pp} \sim 10^8$ yr $(1/n\ \text{cm}^{-3})$ → Other sources of cooling? Non-symmetric diffusion?

Cosmic ray density asymmetry

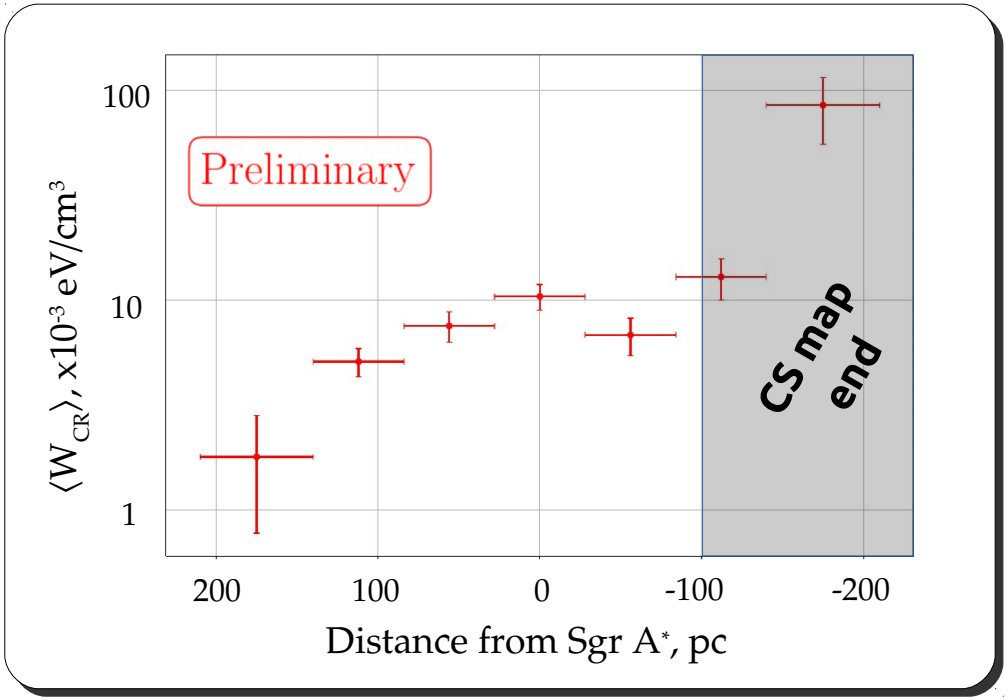


Longitudinal scan of the Gal.Plane brightness does not suggest a significant asymmetry.

Left: (5.08 +/- 0.52) x 10^{-3} eV/cm^3

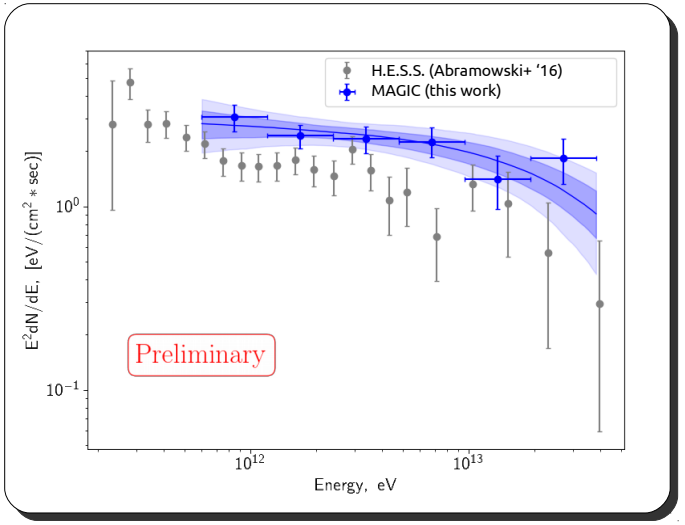
Right: (3.81 +/- 0.75) x 10^{-3} eV/cm^3

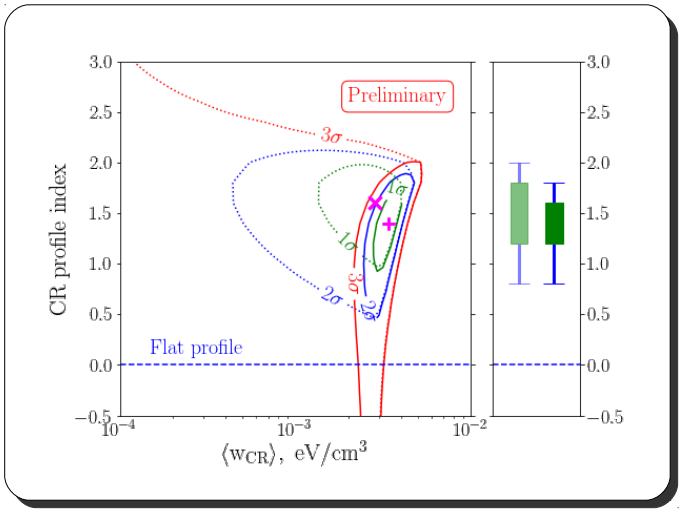
Similar picture arises from the 2D likelihood fit in radial bins (non-symmetric)



No significant asymmetry seen.

Summary





Deep MAGIC observations detect the variety of sources in the Galactic Center region.

Galactic Center (Sgr A*) TeV emission is stable on the ~5 year time scale.

Observations suggest an extension of the VHE "Arc" source - inconsistent with the PWN assumption.

Data >1 TeV suggest the radial scaling of the CR profile, similar to that found in Abramowski+ '16. There is no evidence for its asymmetry.

These measurements are consistent with the $1/r^2$ (or similar) CR profile in presence of the more diffuse "sea".

Cosmic ray spectrum of the Galactic Plane cuts off at ~400 TeV (i.e. below PeV); non-symmetric diffusion?

Uncertainties in the gas line-of-sight distribution may further weaken a hypothesis of the CR source in Gal.Center.

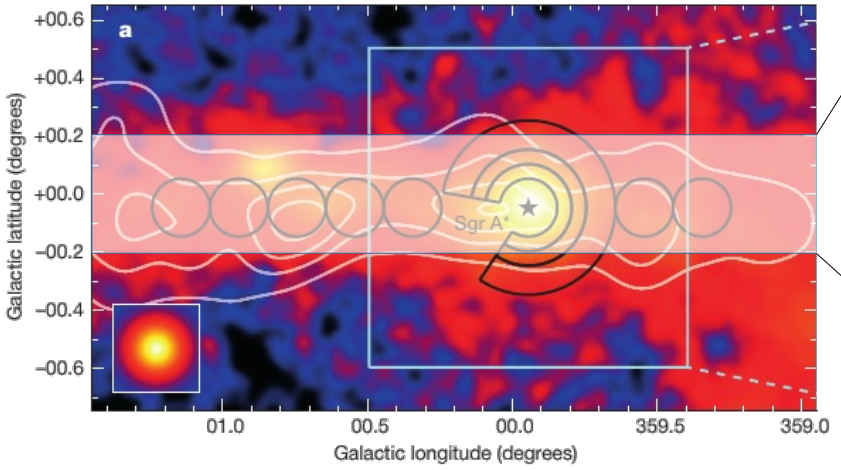
Deep observations (also with CTA) of the outer 1-2 deg Galactic Plane regions may clarify this issue.

Back up

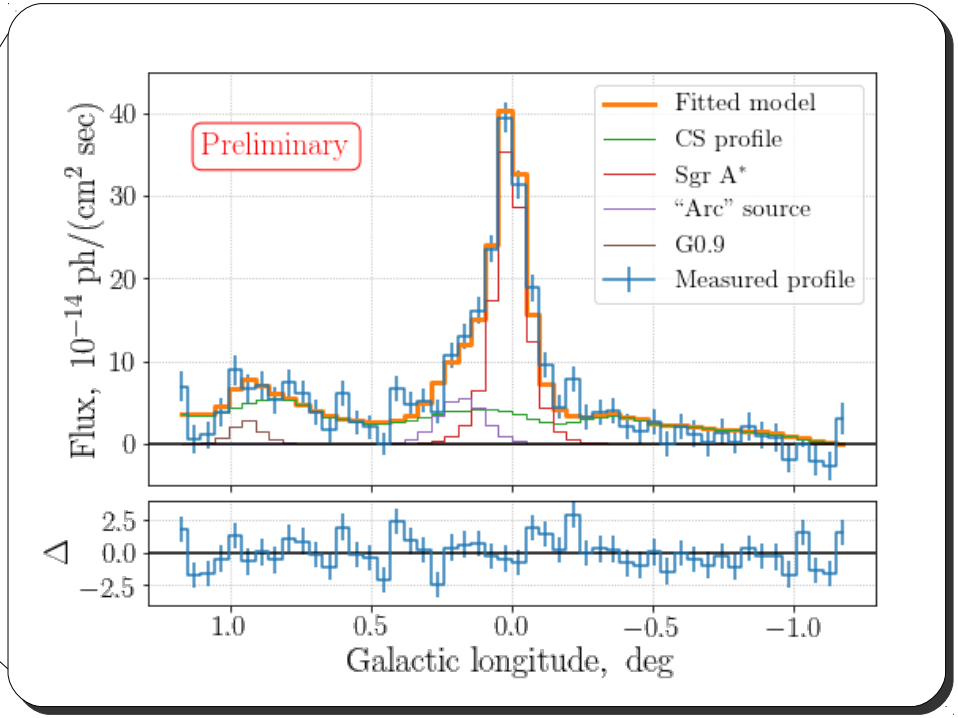
Galactic plane brightness scan

To search for the peaked CR profile presence, we constructed the brightness scan of the galactic plane in the [-0.2;0.2] deg range above 1.2 TeV.

The scan contains bulk of the HESS regions + Arc, G0.9 and Sgr A* sources.



Abramowski+ '16



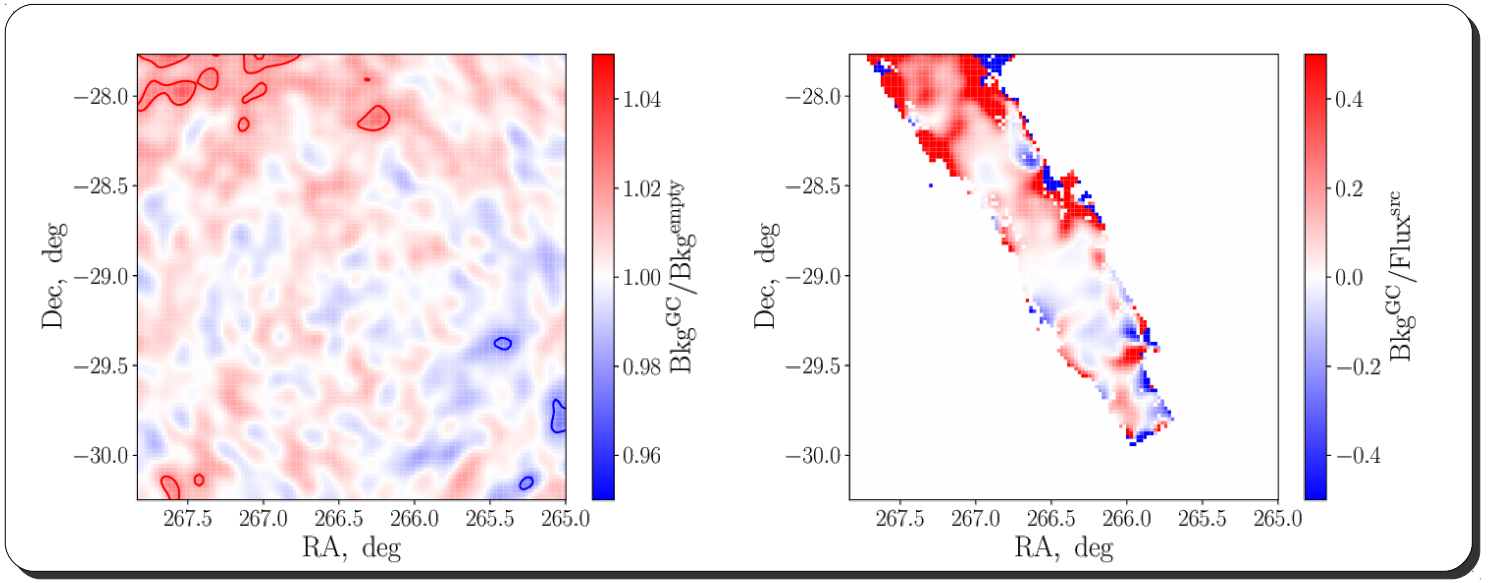
x^2 = 72/46 d.o.f.
(p-value = 0.01)

➡ Model provides a reasonable description of the data.
Still, high x^2 value indicates that something is missing in the fit.

Background model: a key to extended source analysis

The background model was computed from the same observations (blind wobble map).

The accuracy of the map estimated with MC simulations, assuming known diffuse and point-like sources in the region (Sgr A*, “Arc” source, G0.9+0.1, diffuse)



Estimated background bias map. Contours: +/- 2%

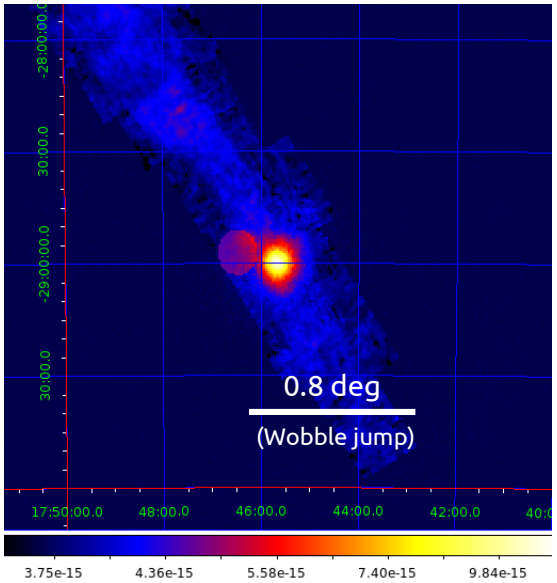
The same, but converted to units of the diffuse emission flux.

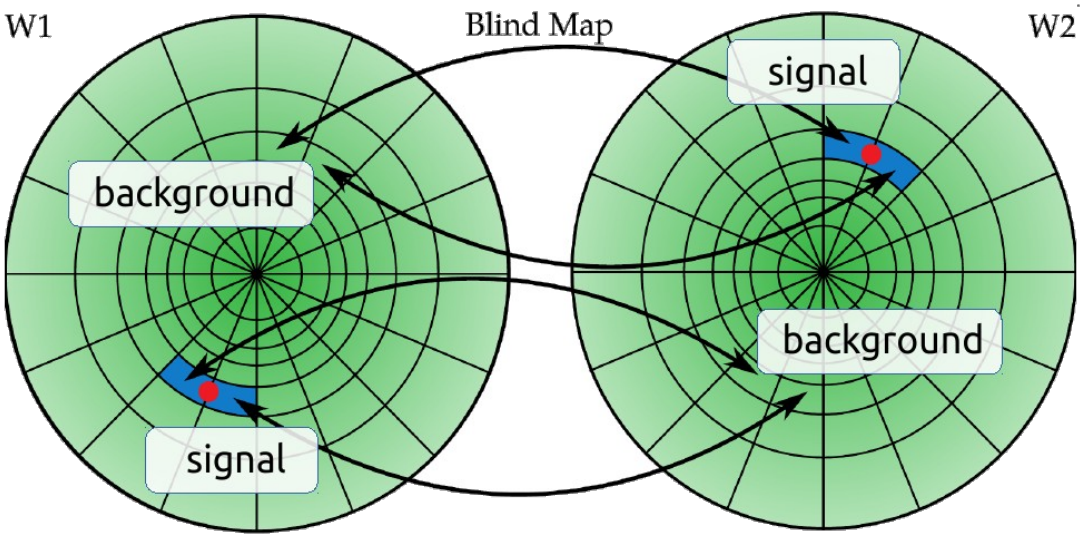
→ Very good control of the background bias.

Background model construction

Accurate background model – key to any extended source analysis.

Complication: GC extension is so big that our standard background estimation methods fail.
Solution: use an improved blind map, capable of excluding source region from the calculation.





Standard blind map would be biased with respect to the extended Galactic plane.

Background model construction

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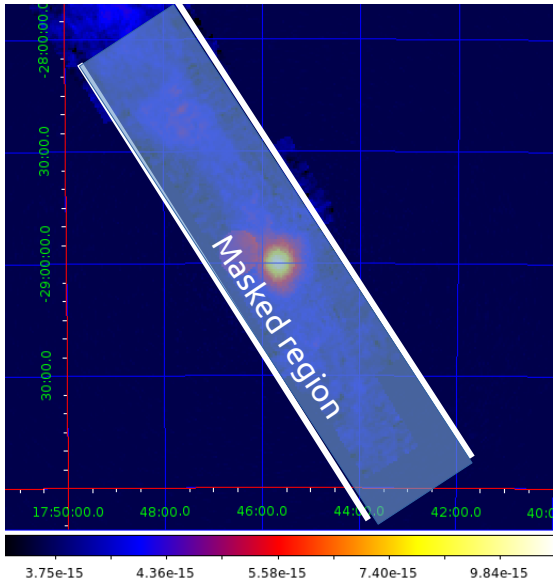
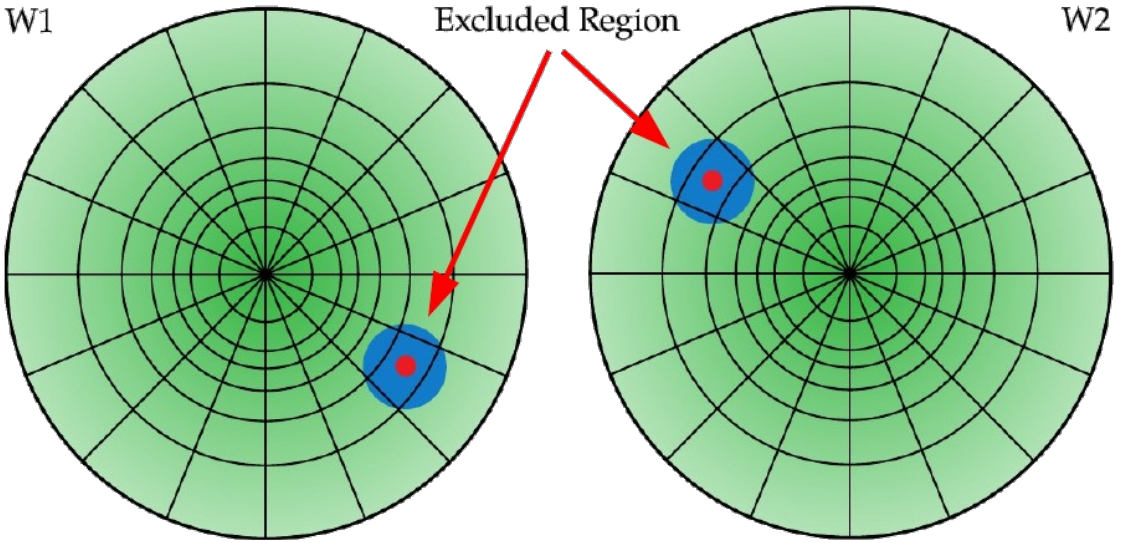
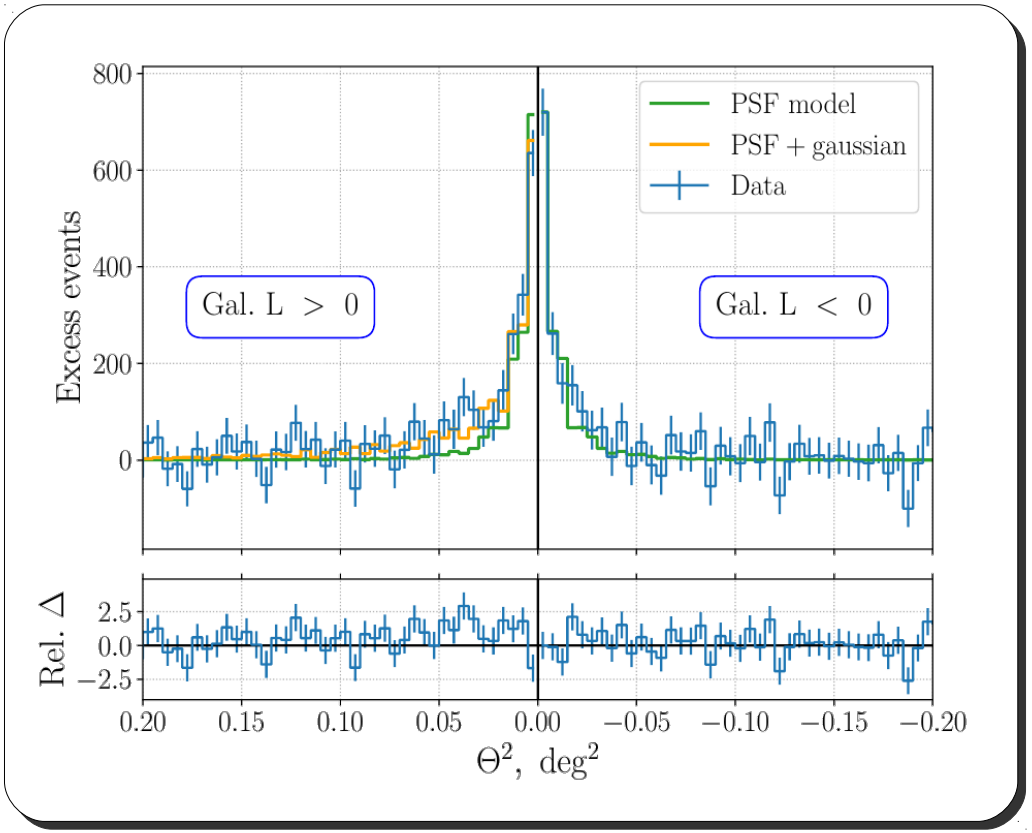




The improved blind map explicitly excludes Galactic Plane from background.

Central source extension



The apparent extension of the central source may indicate the presence of the CR “halo”, as suggested in Abdalla+ ‘17.

We tested for the presence of the “halo” with the 2D PSF model, precomputed with SkyPrism.

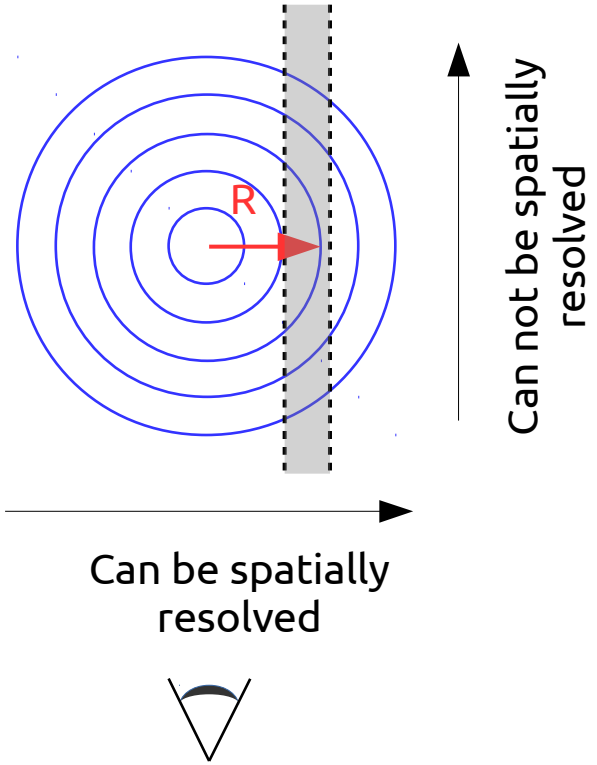
MAGIC sees no indications for such extension (chi2 = 39.2 / 39 d.o.f.), though the derived flux upper limit is above the estimates of Abdalla+ ‘17.

Towards the 3D model of the Galactic Center

The gamma-ray emission observed is the result of interaction of the GC cosmic ray population with the underlying gas.

In fact we see only its projection

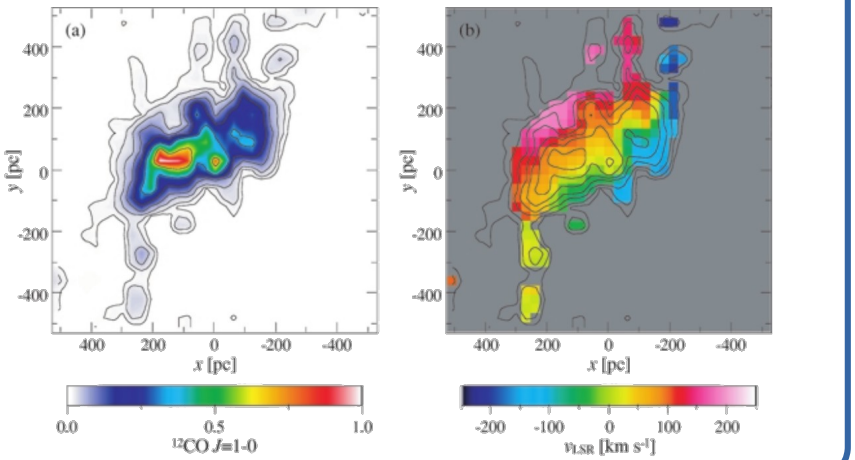
$$\int \rho(r) w_{CR}(r) dr$$



In radio band several detailed scans of the GC region were performed (e.g. Tsuboi+ '99, McQuinn+ '02, Sawada+ '04, Tsuboi+ '12); however the line of sight distance could not be derived there.

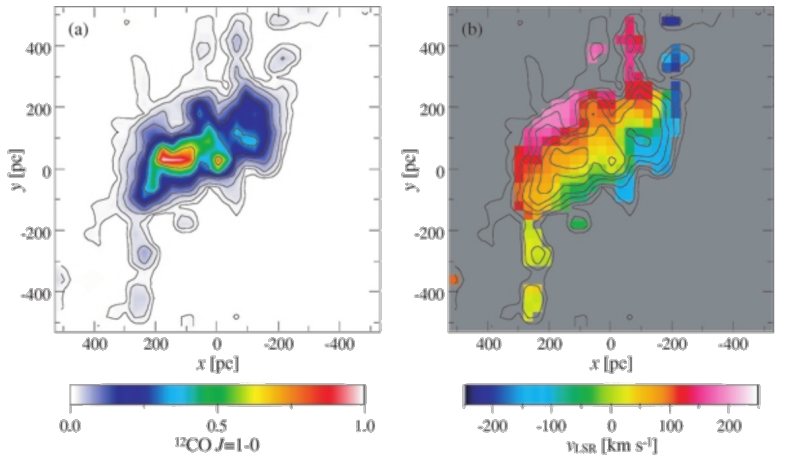
Still, using the absorption in several spectral lines + some simplifying assumptions, this issue can be resolved to a certain degree.

Sawada+ '04

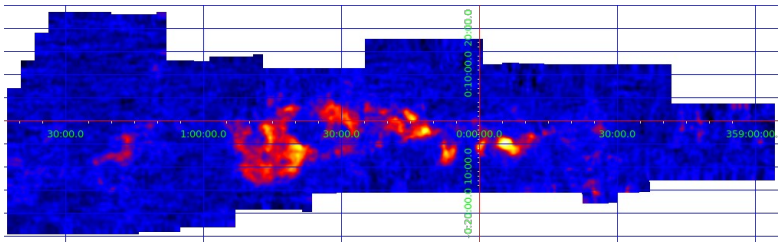


Towards the 3D model of the Galactic Center

Sawada+ ‘04



Tsuboi+ ‘99



The radial velocity-resolved maps show the gas (l,b) distribution as a function of v.

Combining this information one can reconstruct the full 3D gas distribution and predict its appearance for various $w_{CR}(r)$ density profiles.

Our modeling