The Galactic Center seen at very high energies

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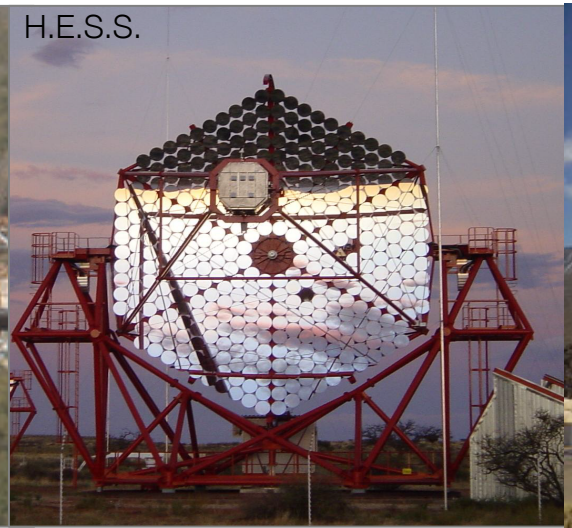
July 23-29
ICISE
Exploring the Dark Universe
2017

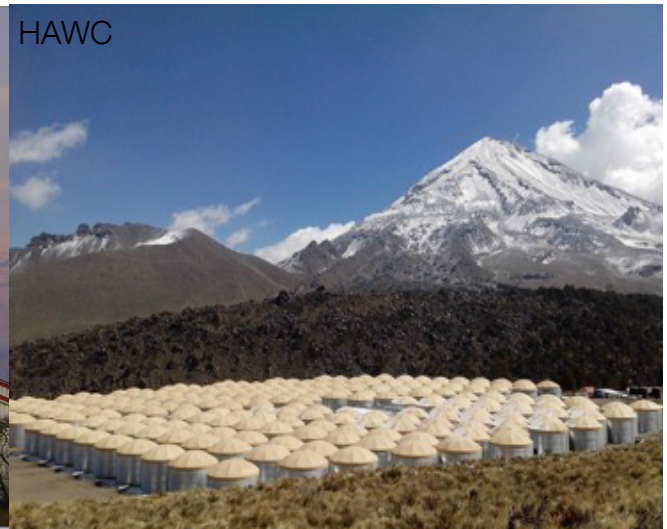
CEA - Saclay

Why VHE gamma rays ?

- Effectively *produced* through electromagnetic and hadronic interaction at the sources or in their vicinity
  - inverse Compton of electrons/positrons off ambient photons
  - inelastic collisions of protons/nuclei with gas
  - dark matter annihilation
- Effectively photon-by-photon *detected* by ground-based instruments with $> 10^5$ m^2 effective detection area

- … but effectively interact with matter, radiation and B-field
  → information could arrive with some distortion

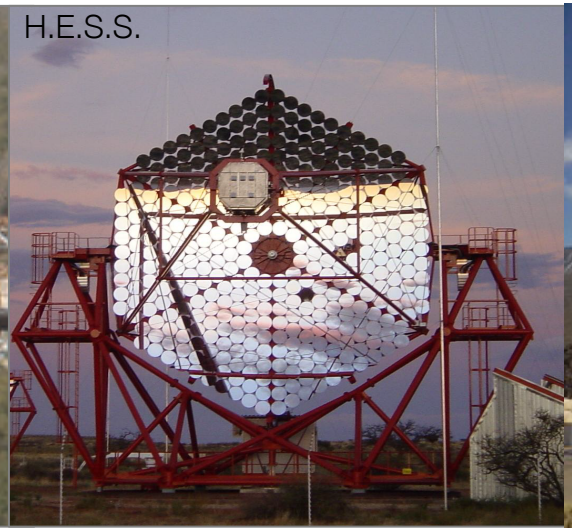


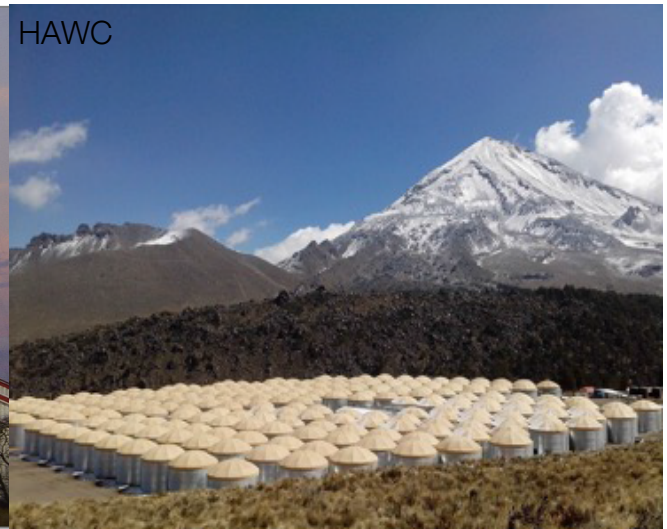


Why VHE gamma rays ?

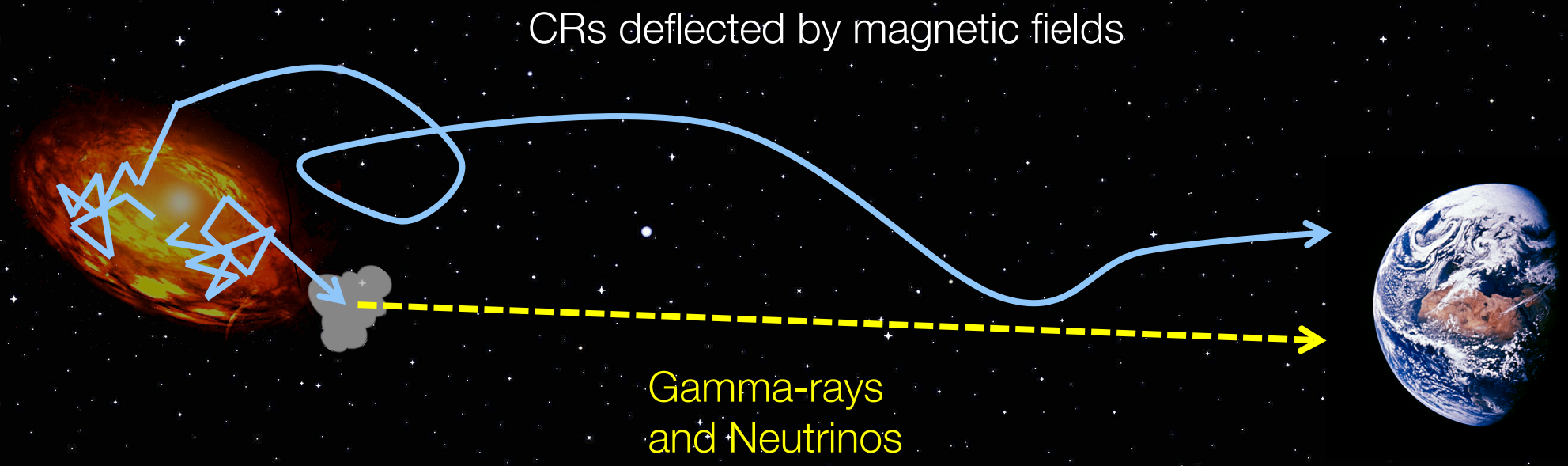
- Effectively *produced* through electromagnetic and hadronic interaction at the sources or in their vicinity
- Effectively *detected* by ground-based instruments
- … but effectively interact with matter, radiation and B-field: information could arrive with some distortion

→ provide unambiguous proof of particle acceleration beyond TeV energies
→ provide mapping of acceleration/propagation/creation sites
→ provide direct tracer of relativistic proton populations





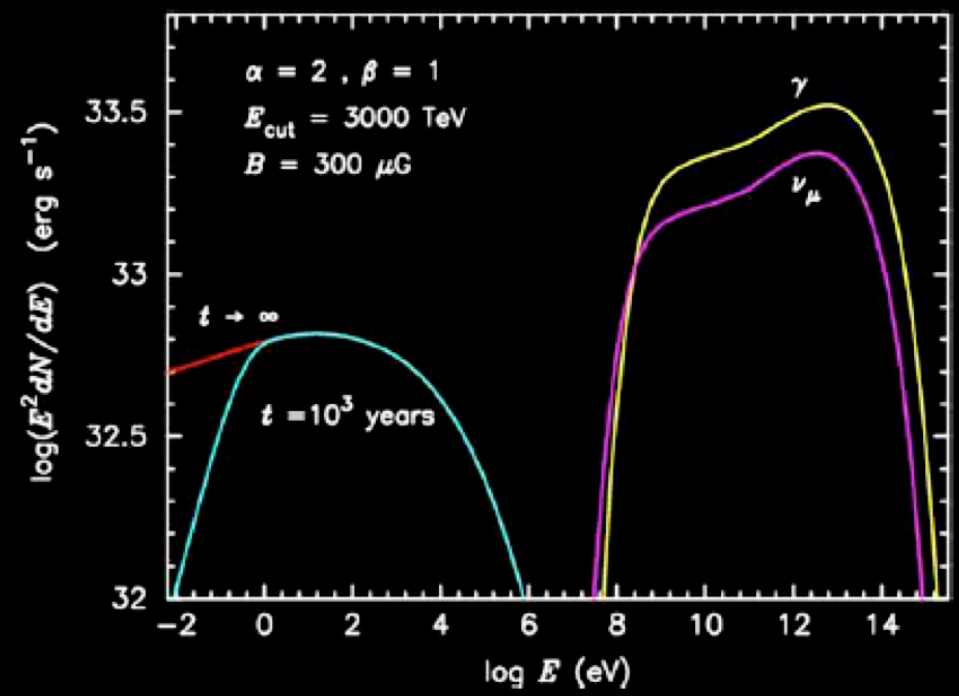
Gamma-rays from *pp* interaction

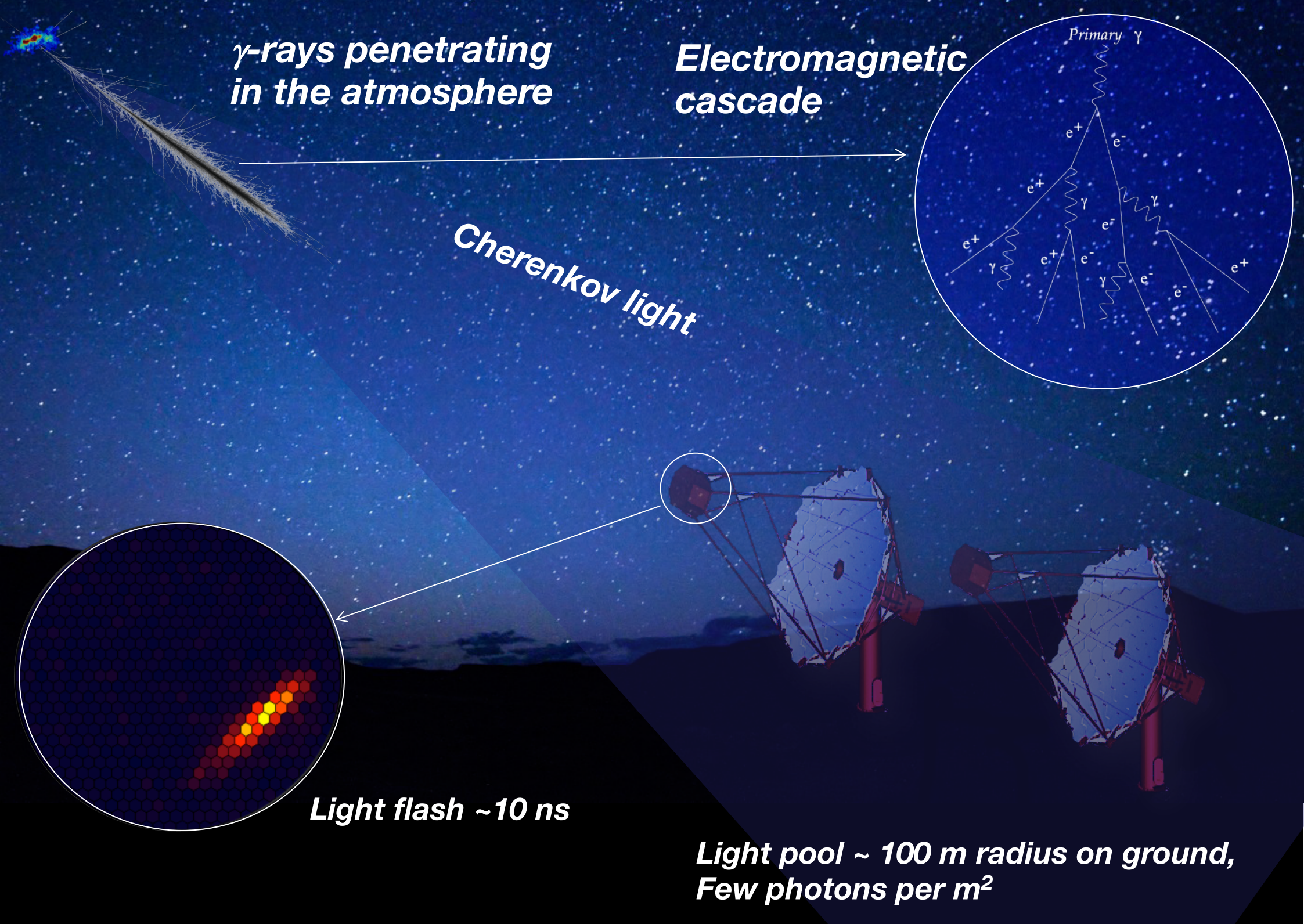


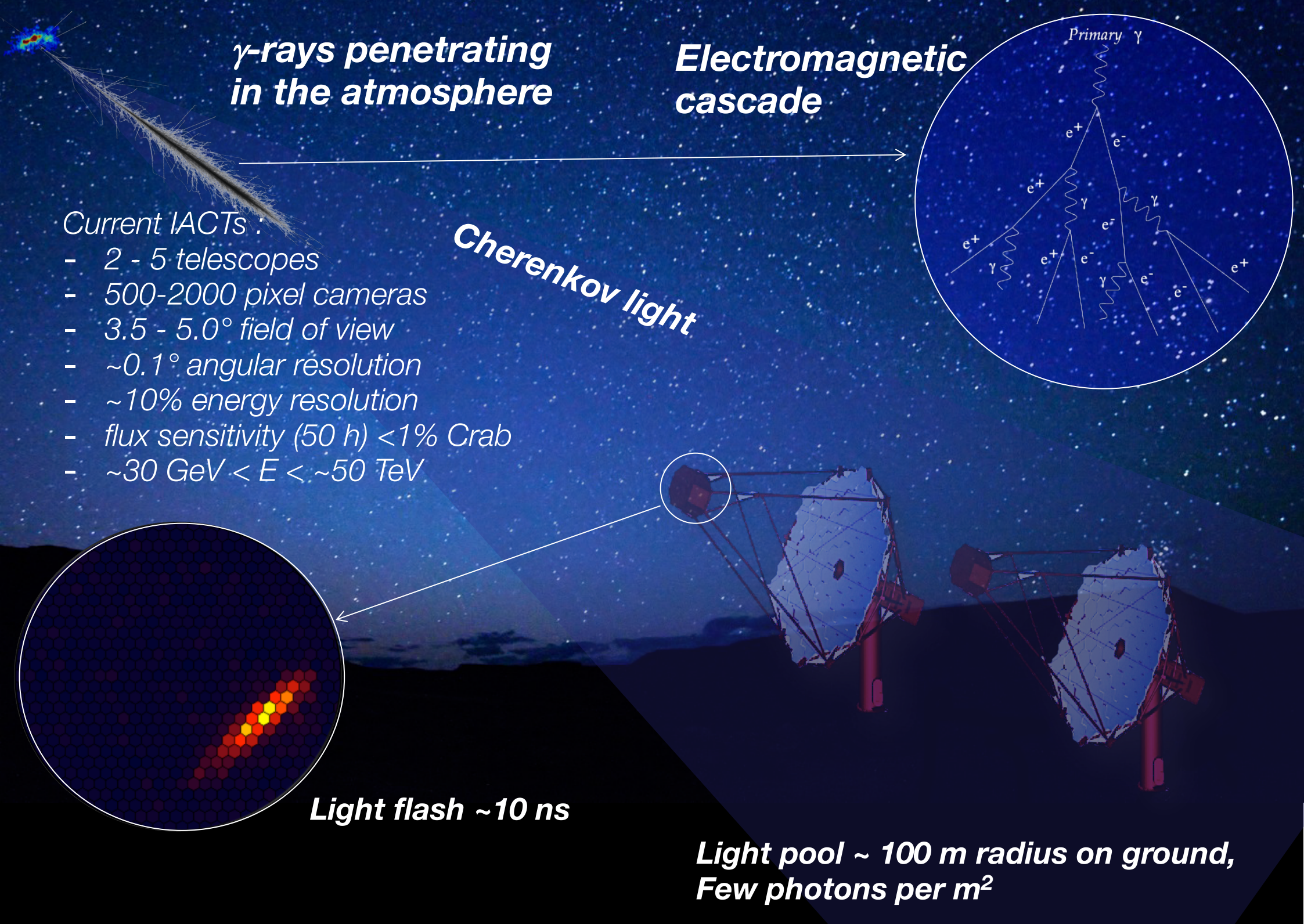
$$p + p_{ISM} \rightarrow \pi + X$$

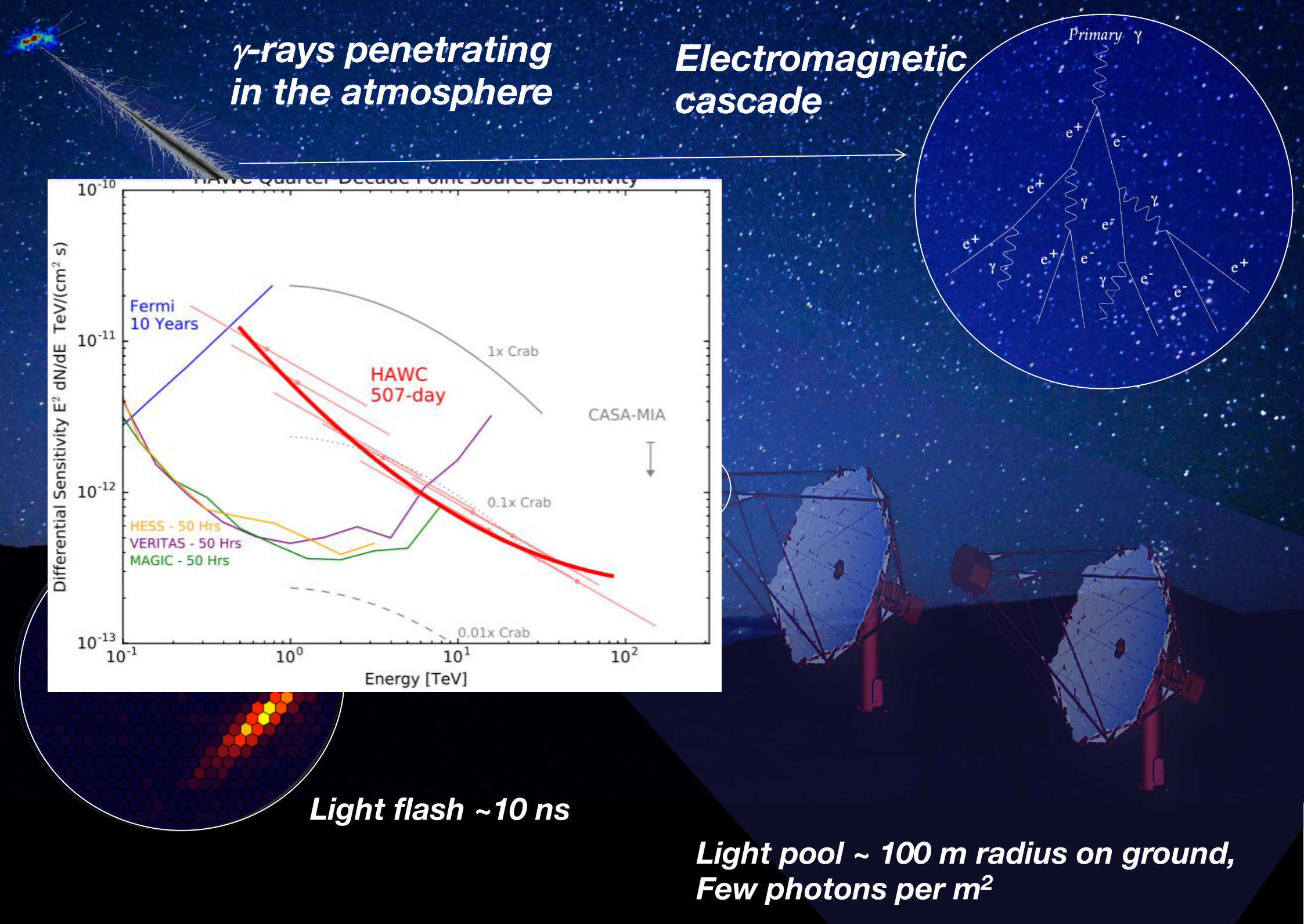
$$\pi^0 \rightarrow \gamma + \gamma$$
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu$$

Molecular gas clouds illuminated by cosmic rays
→ Gamma-rays and gas are spatially correlated

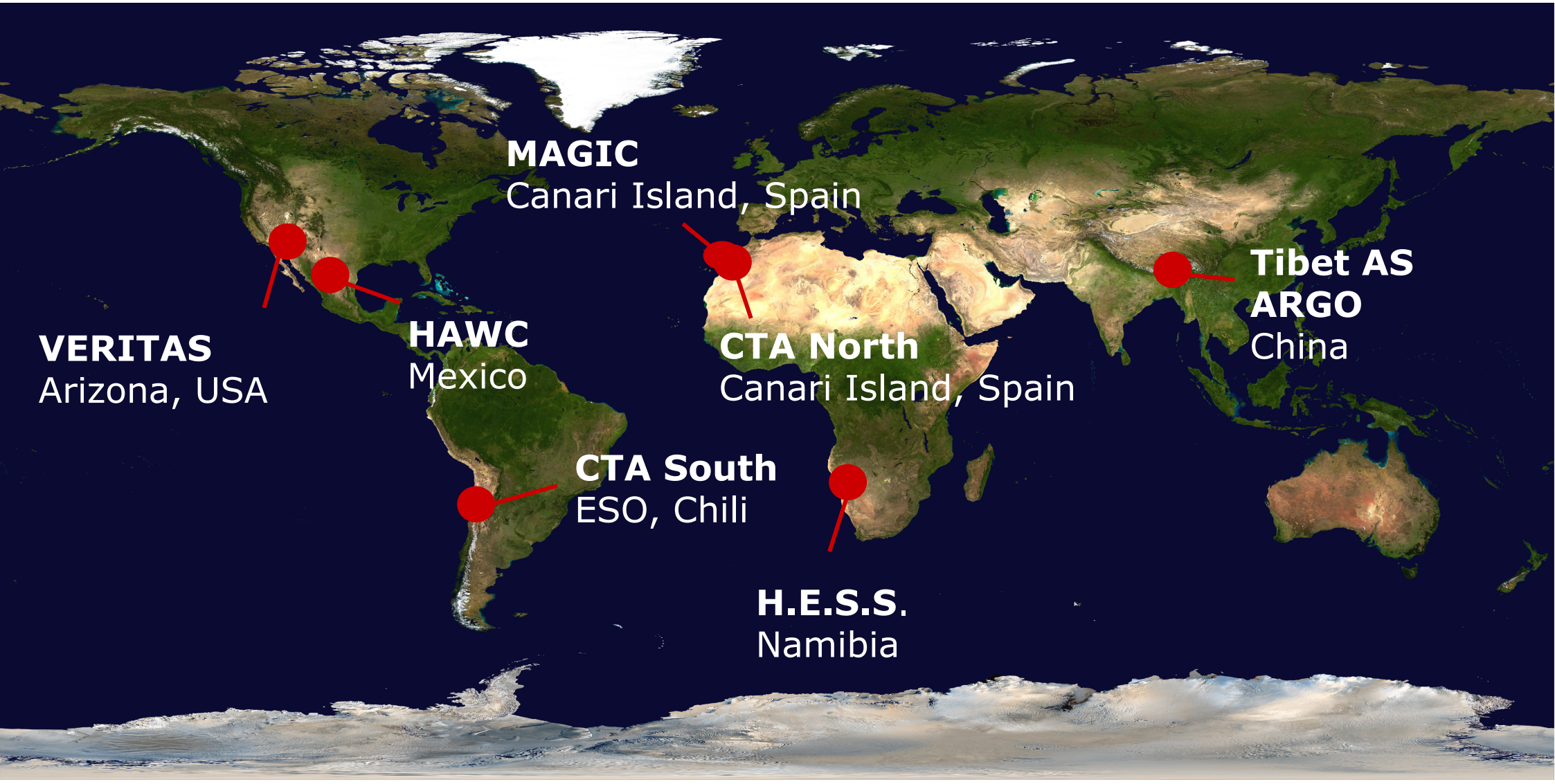



γ-rays penetrating in the atmosphere
Electromagnetic cascade
Primary γ
Cherenkov light
Light flash ~10 ns
Light pool ~ 100 m radius on ground,
Few photons per m²


γ-rays penetrating in the atmosphere
Electromagnetic cascade
Primary γ
Cherenkov light
Current IACTs :
- 2 - 5 telescopes
- 500-2000 pixel cameras
- 3.5 - 5.0° field of view
- ~0.1° angular resolution
- ~10% energy resolution
- flux sensitivity (50 h) <1% Crab
- ~30 GeV < E < ~50 TeV
Light flash ~10 ns
Light pool ~ 100 m radius on ground,
Few photons per m²

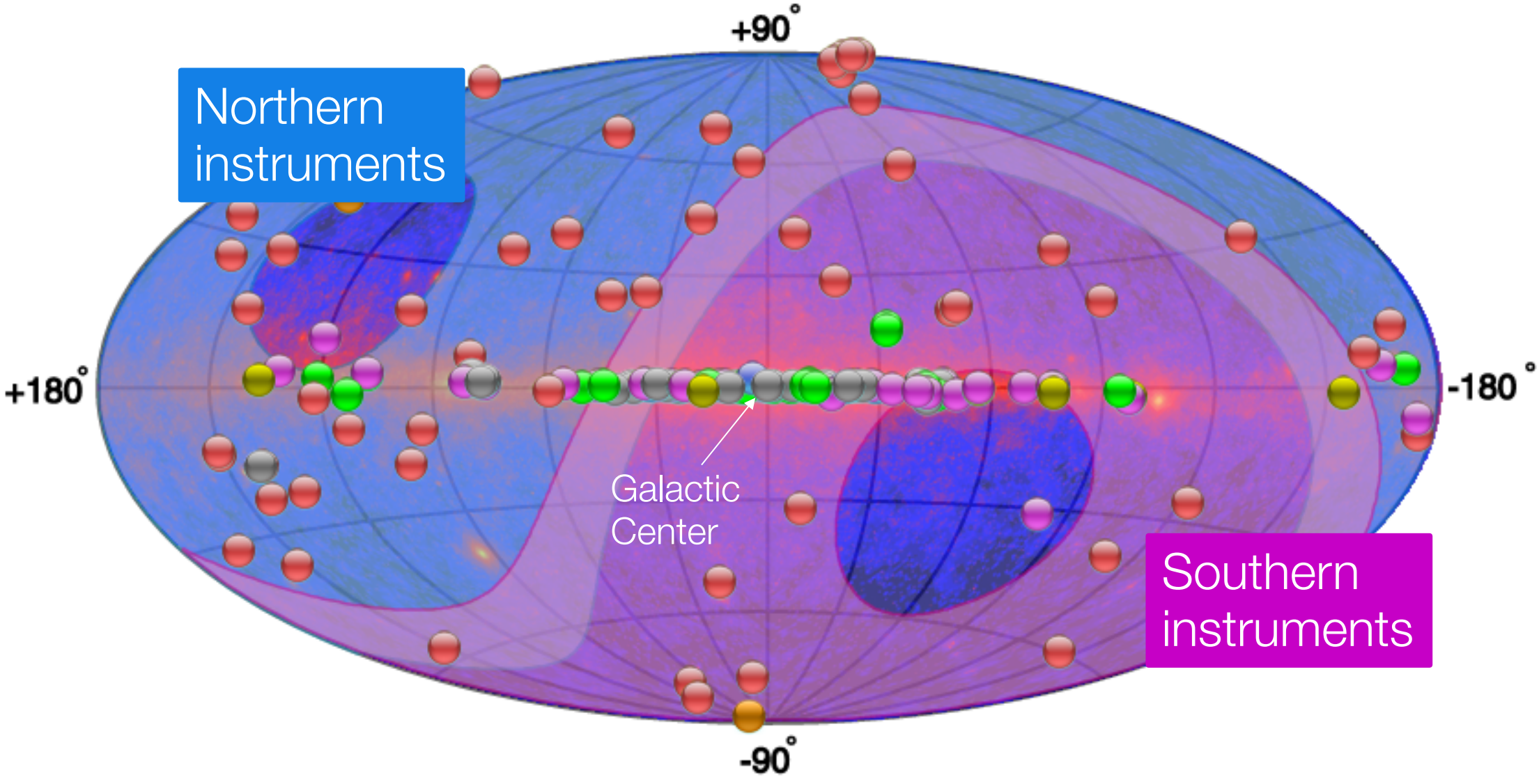

γ-rays penetrating in the atmosphere
Electromagnetic cascade
Primary γ
e+
e-
γ
HAWC Quarter-Decade Point Source Sensitivity
Differential Sensitivity E² dN/dE TeV/(cm² s)
Energy [TeV]
Fermi 10 Years
HAWC 507-day
1x Crab
0.1x Crab
0.01x Crab
CASA-MIA
HESS - 50 Hrs
VERITAS - 50 Hrs
MAGIC - 50 Hrs
Light flash ~10 ns
Light pool ~ 100 m radius on ground,
Few photons per m²

Ground-based Cherenkov Telescopes

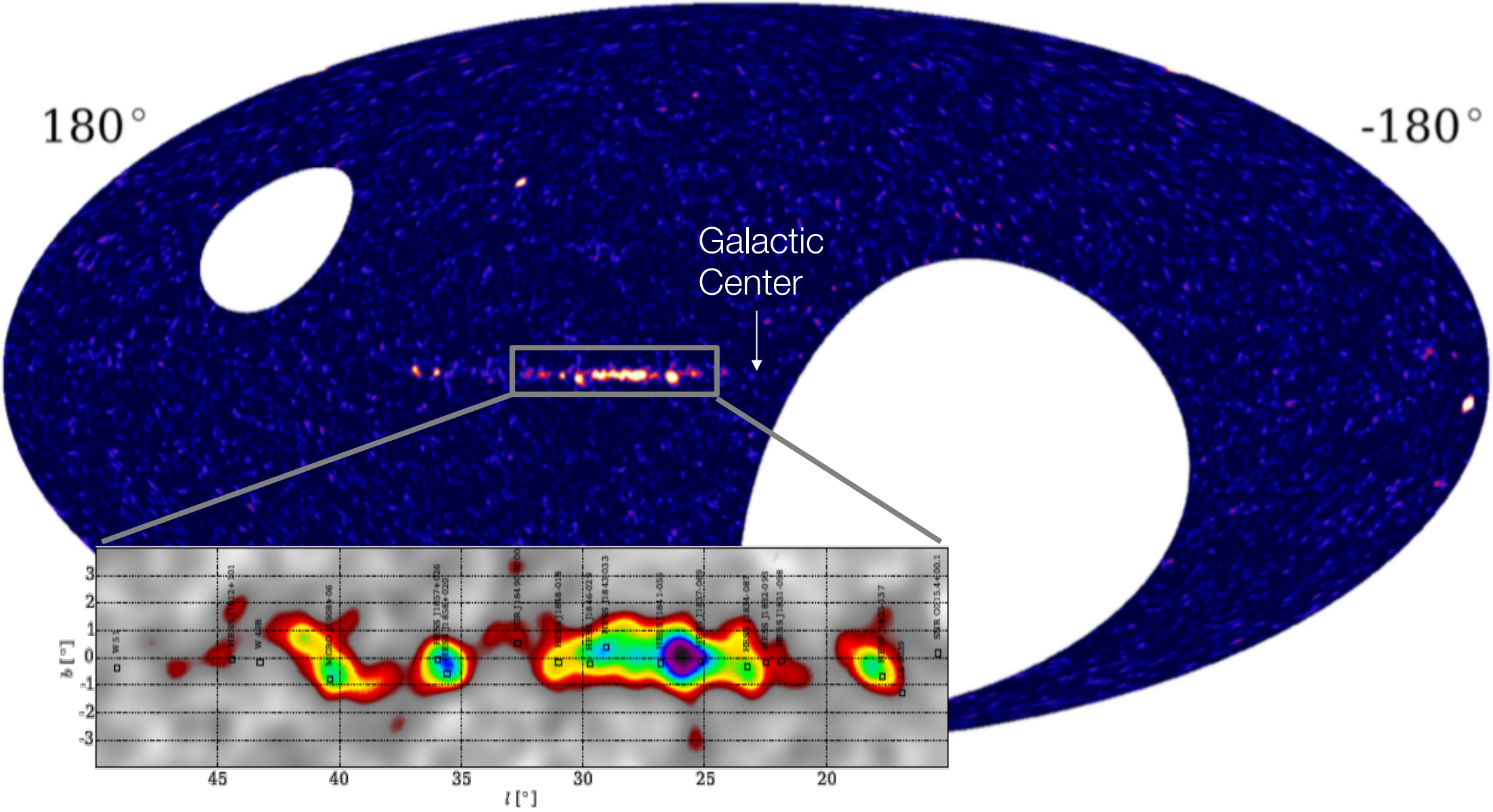


> Telescope locations in both hemispheres is crucial

Sky coverage



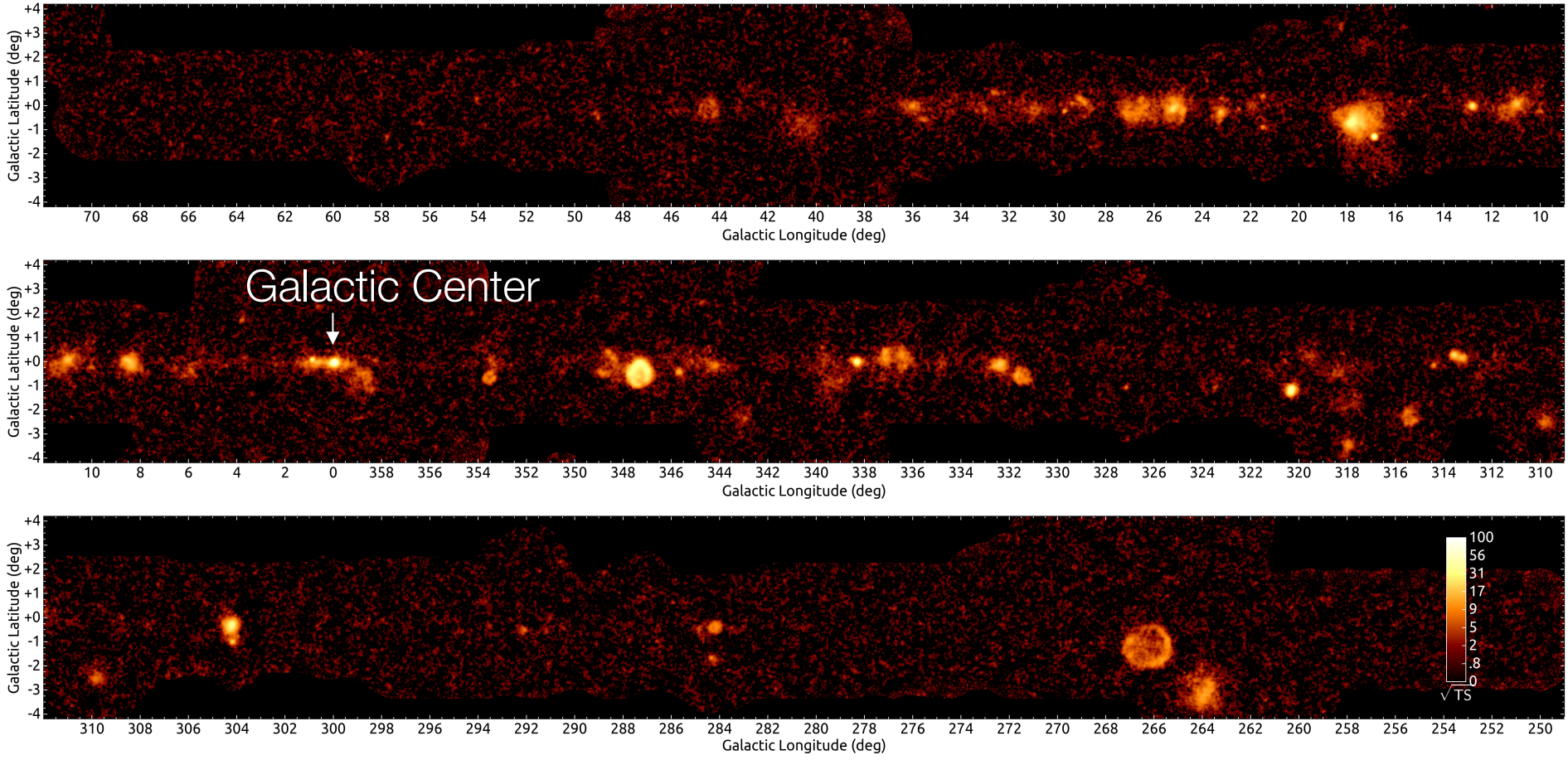
HAWC's view of the TeV sky



HAWC Collaboration: A.U. Abeysekara et al., Astrophys. J. 817, 3 (2016)

The H.E.S.S. Galactic plane survey

- Almost 2700 hours of pointed observations taken on the galactic plane by H.E.S.S.
- Coverage to at least 10% Crab Flux
- Much better in most places



Donath et al (H.E.S.S. coll.) Gamma 2016

> First systematic catalog of Galactic TeV sources with E > 200 GeV : 78 sources detected

The Galactic Center region

Extremely complex and energetic region at all wavelenghts

Due to the location of H.E.S.S., it is an excellent target for observations

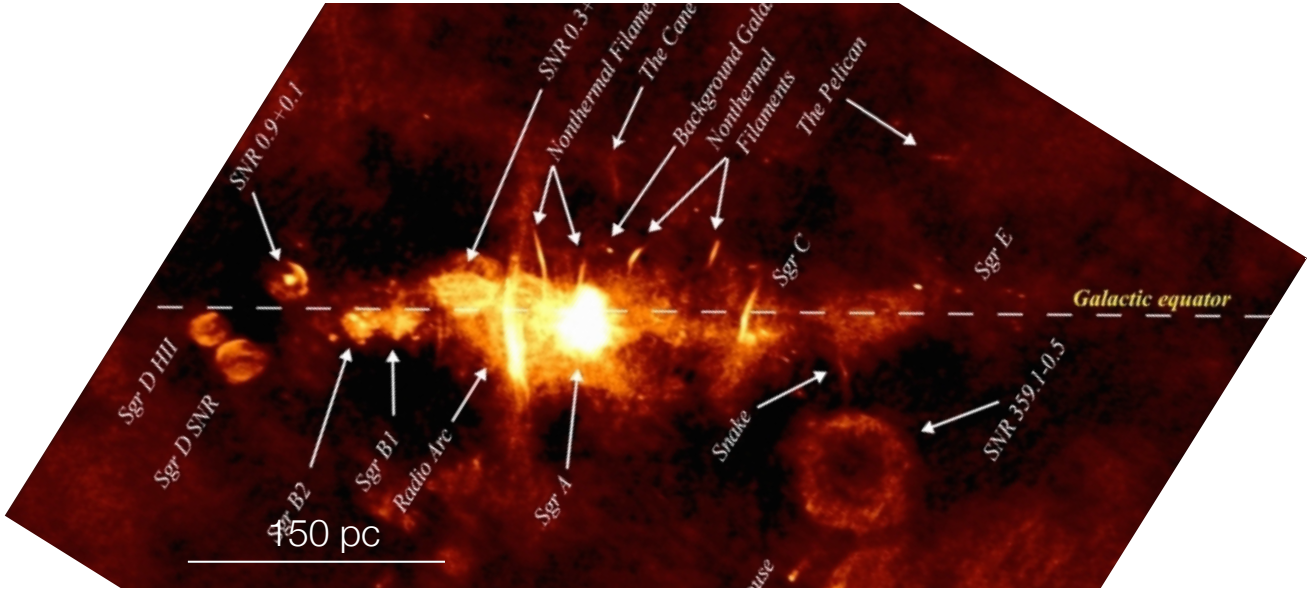
VHE emission first discovered in 2004

Diffuse emission

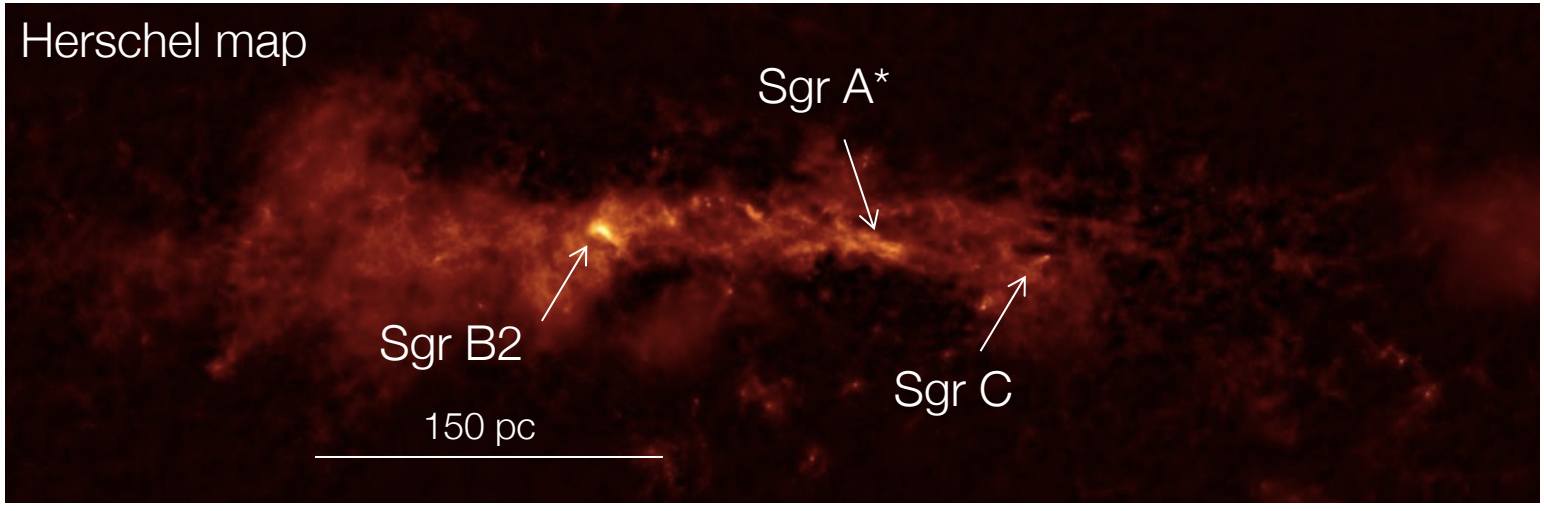
Target for dark matter search

The Galactic Centre region

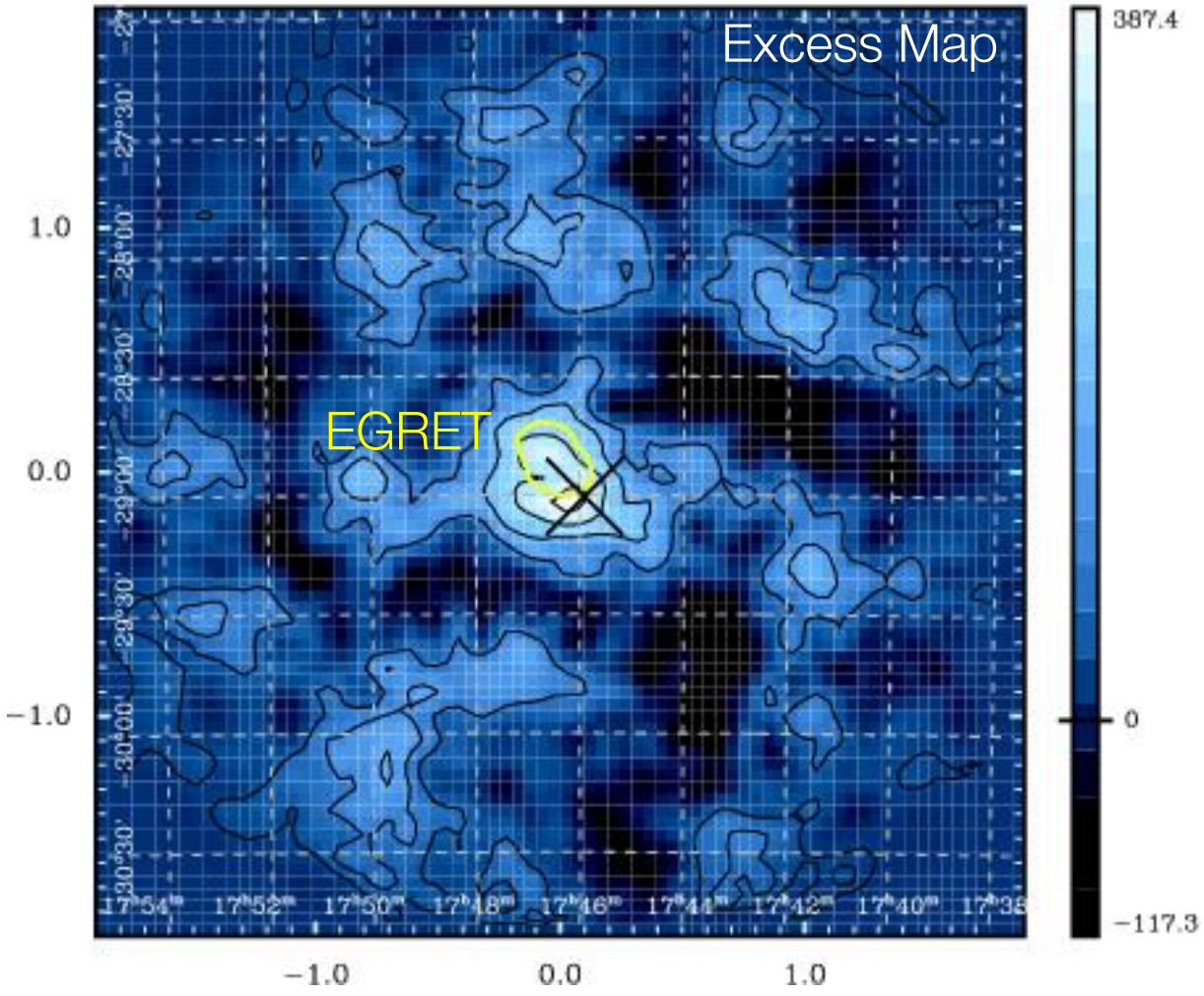
- *90cm radio map*
  - multiple SNRs (e.g. G 0.9, G 1.9,...)
  - multiple PWNe (e.g. Mouse)
  - Central Radio lobes (central ±1°) and arc features



- Central Molecular Zone (CMZ):
  - giant molecular clouds: ~10% of all the gas of the Galaxy



The GC region seen in 2004 by Whipple

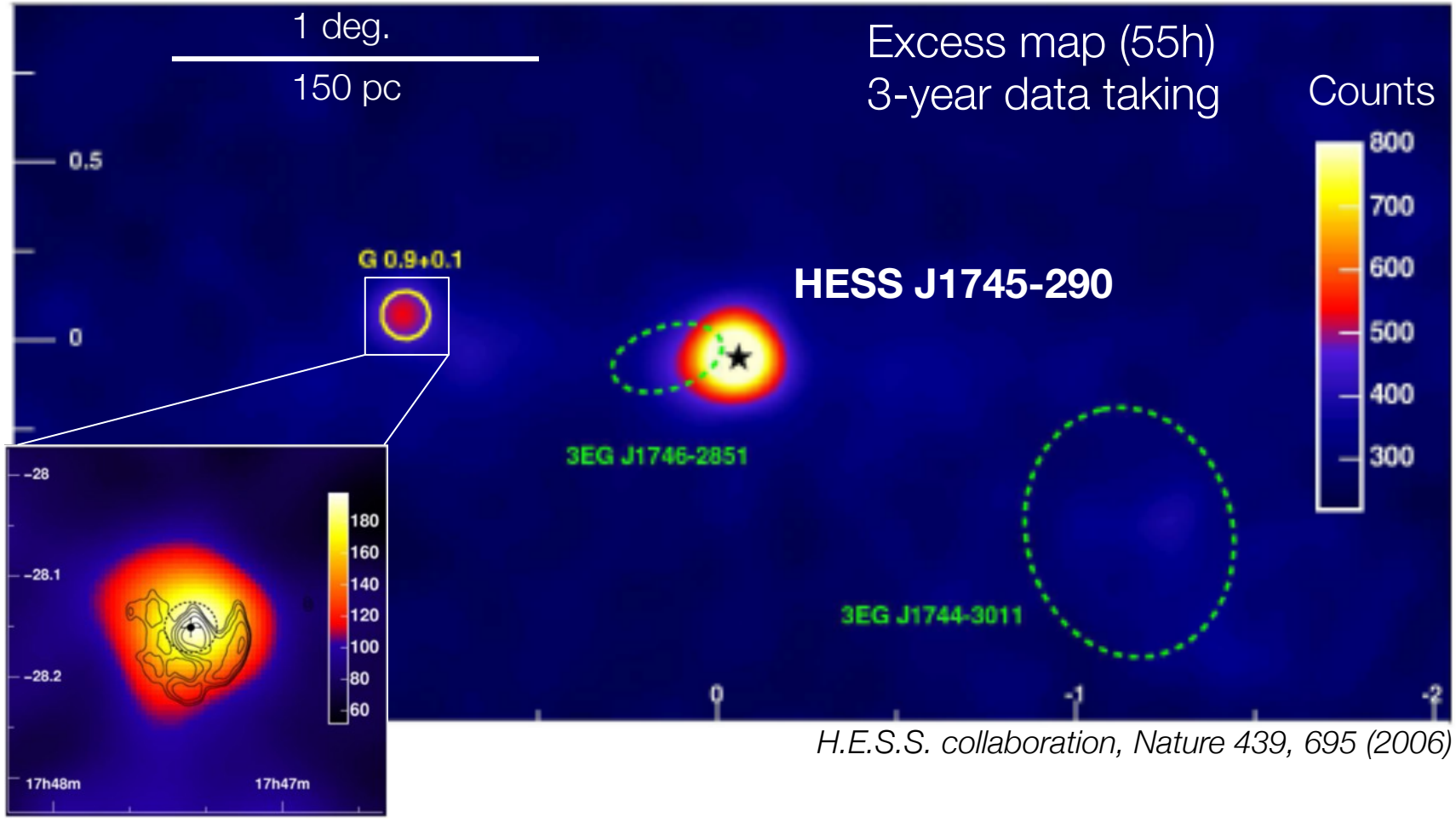


- *26 hours*
- *Single telescope observations*

The GC region seen by H.E.S.S. in 2005

Two bright pointlike sources

- HESS J1745-290 : still unidentified
- G 0.9+01: SNR/PWN association



H.E.S.S. collaboration, Nature 439, 695 (2006)

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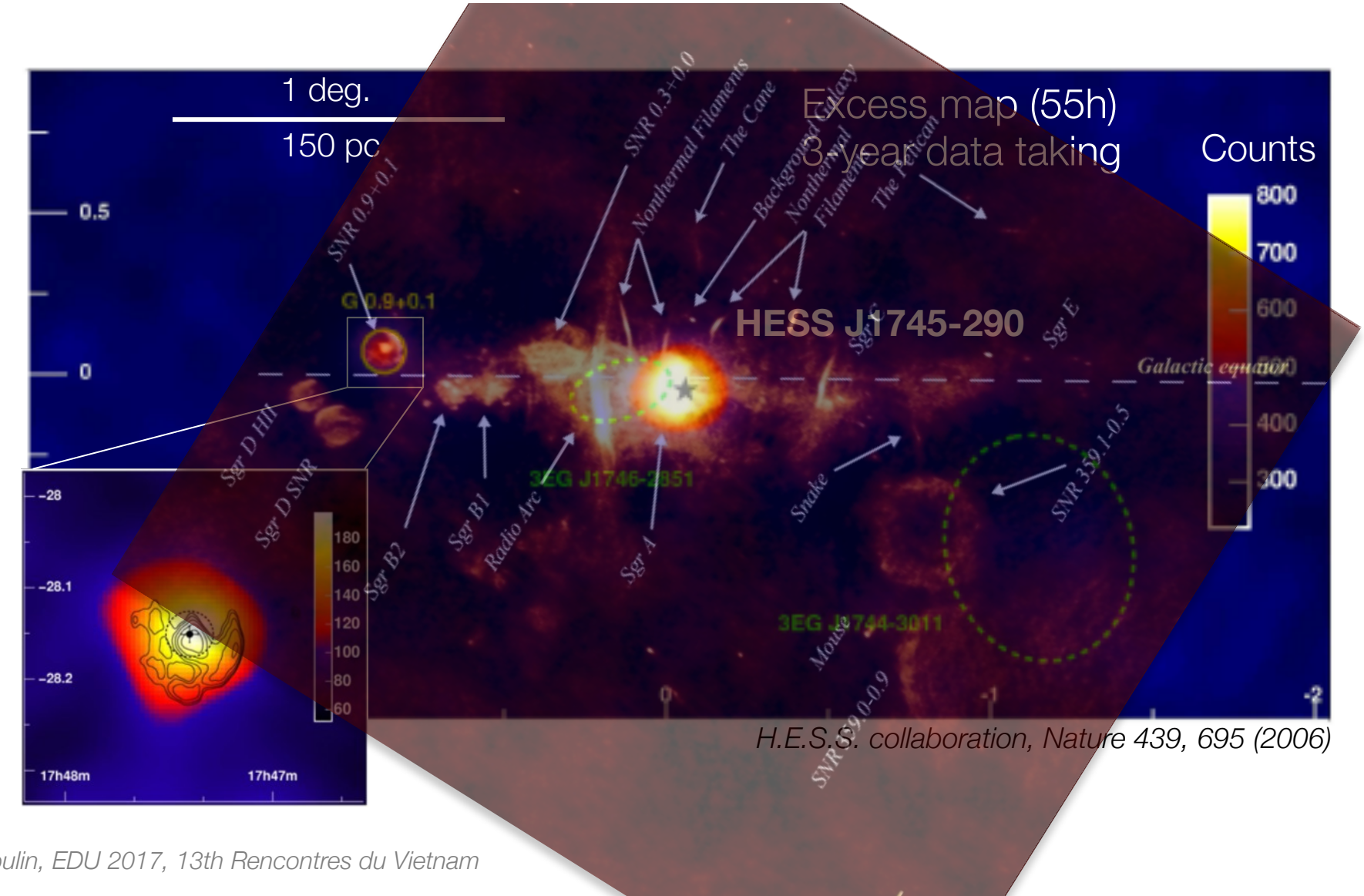
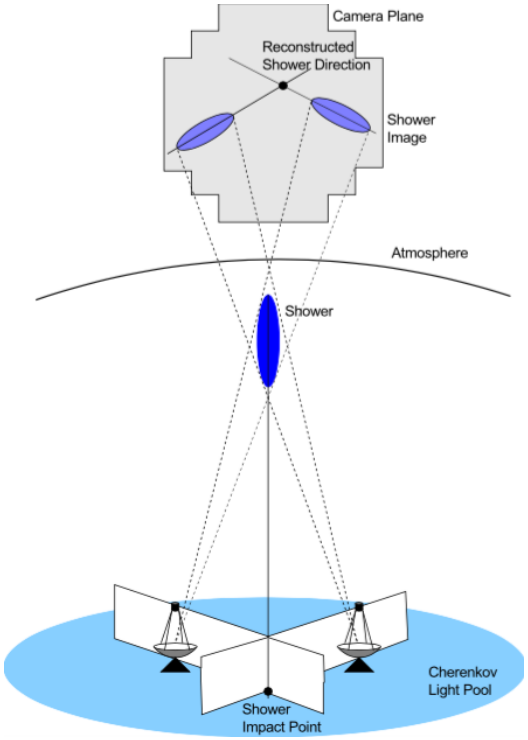


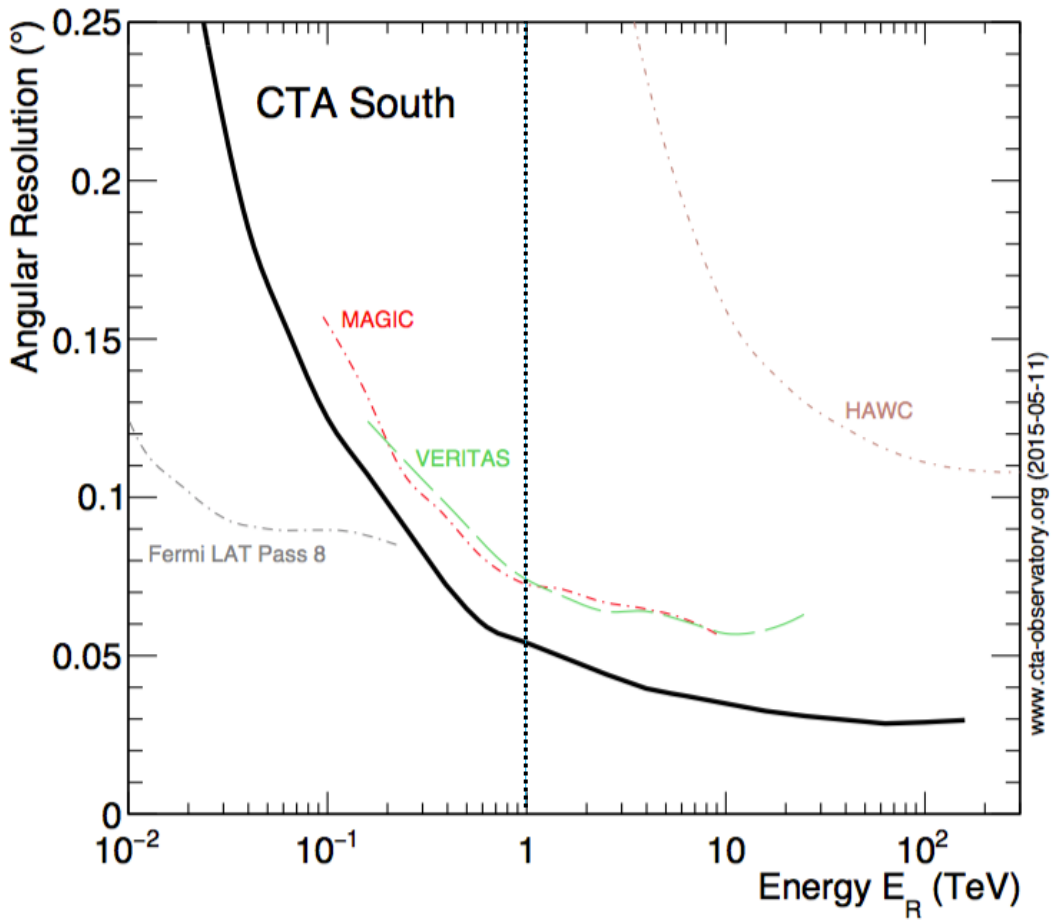
H.E.S.S. collaboration, Nature 439, 695 (2006)

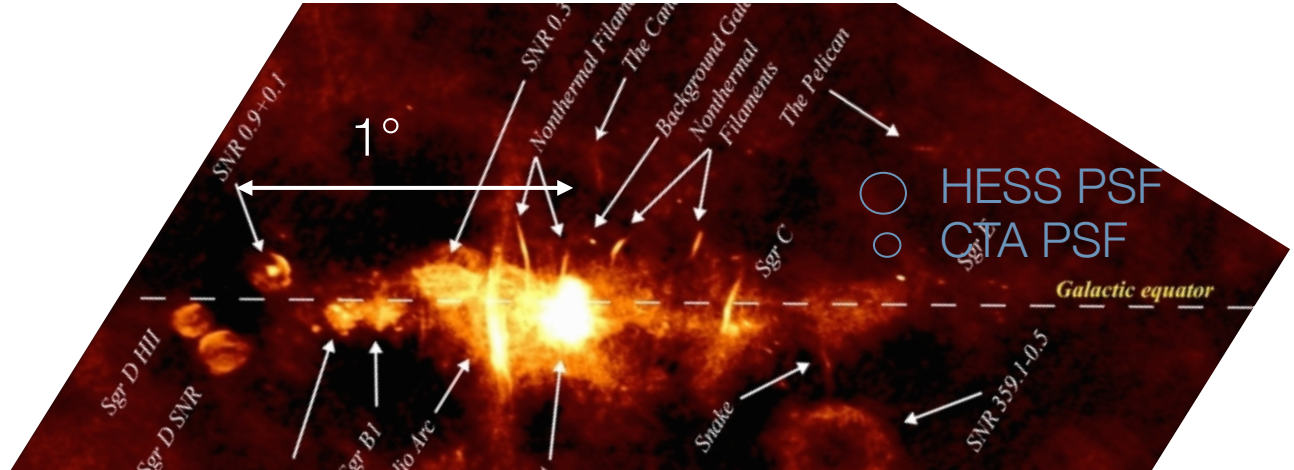
Angular resolution

Strongly energy-dependent

- H.E.S.S. ~5’ @ 1 TeV
- CTA: ~3’ @ 1 TeV
- shower fluctuations:
  ultimate limit ~20” @ 1 TeV





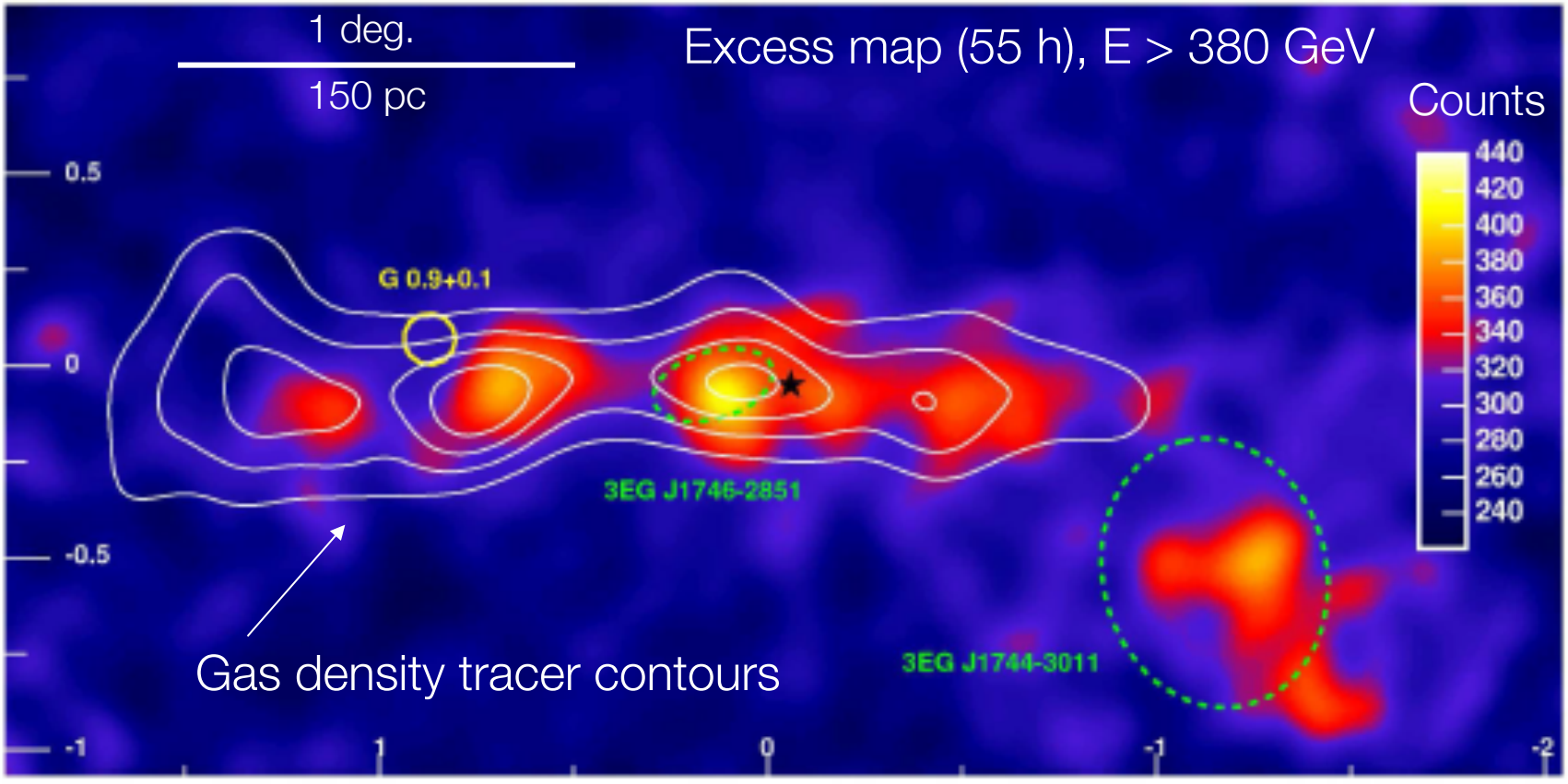


Source idenfication is limited from VHE angular resolution

VHE morphology of the ridge emission

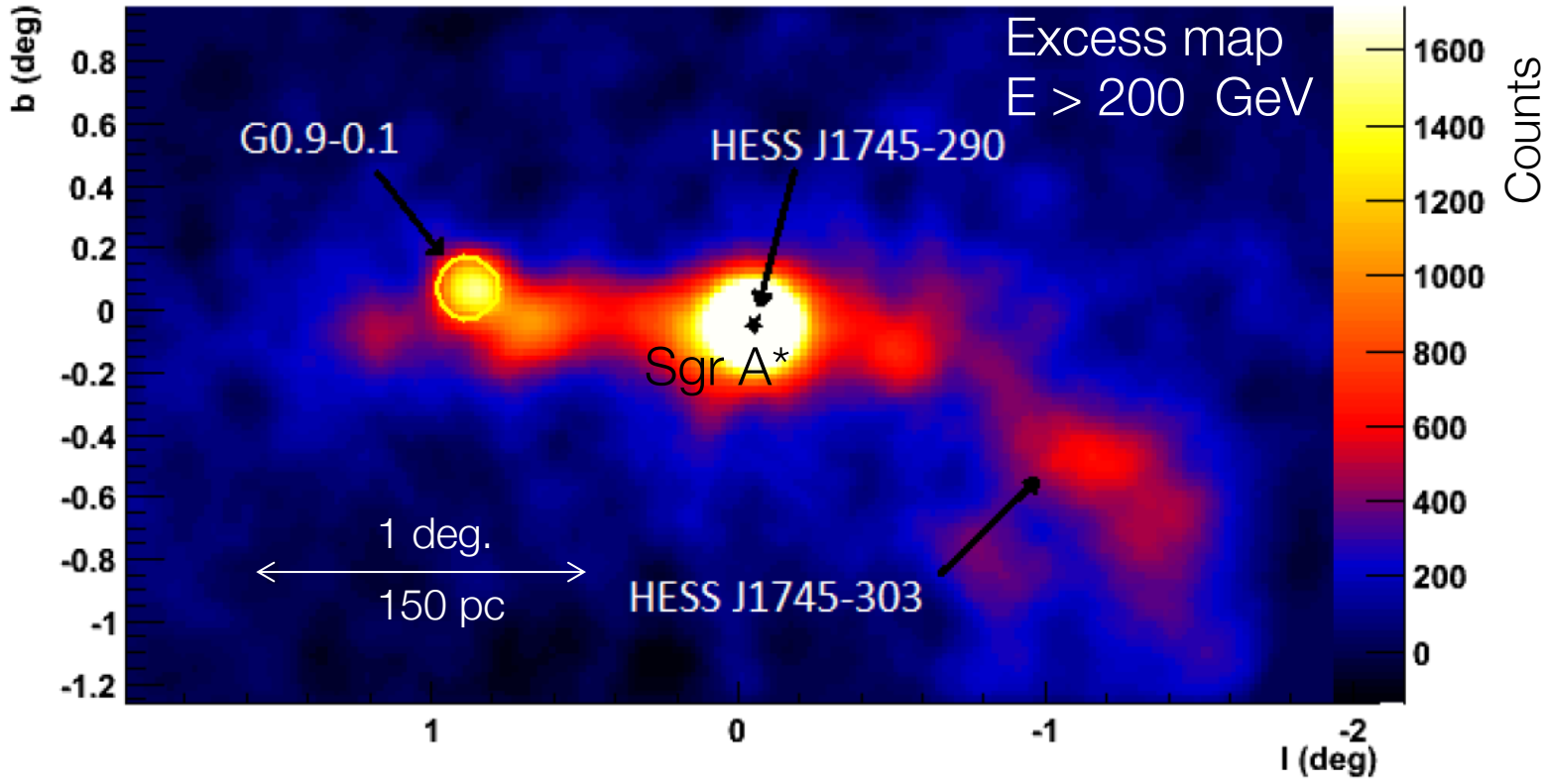
Substraction of the two pointlikes sources: look for fainter emissions…

- Diffuse emission spatially correlated with the distribution of molecular gas of the Central Molecular Zone (CMZ)
  → hadronic origin of the emission



H.E.S.S. collaboration, Nature 439, 695 (2006)

The GC region seen in 2016



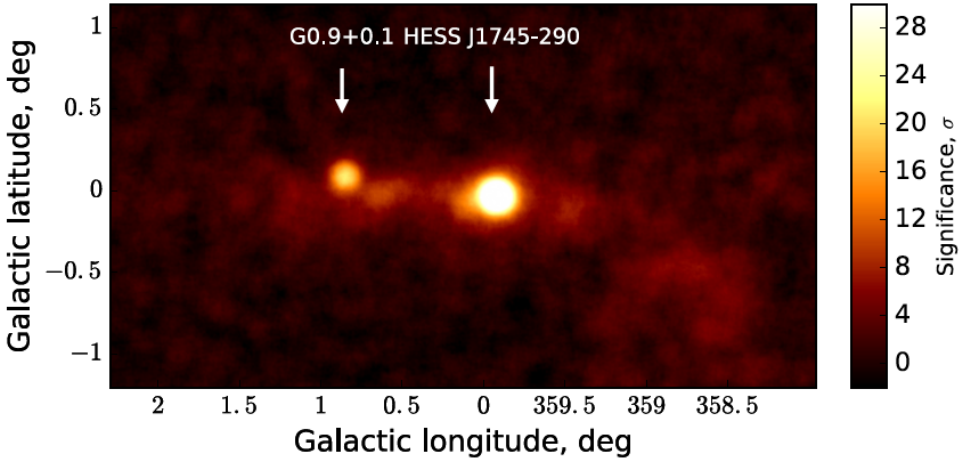
- **Regular observations of the GC region have now been made with the H.E.S.S. array for over 10 years : >220 hours of observation available**
- **New data analysis techniques have greatly improved the angular resolution and sensitivity**

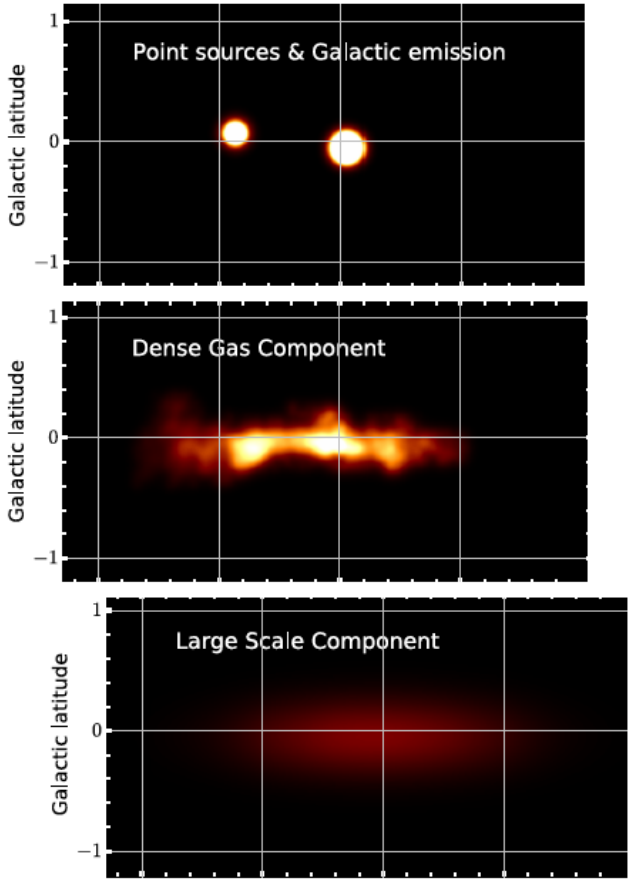
→ Excellent dataset for the study of CR acceleration in this region

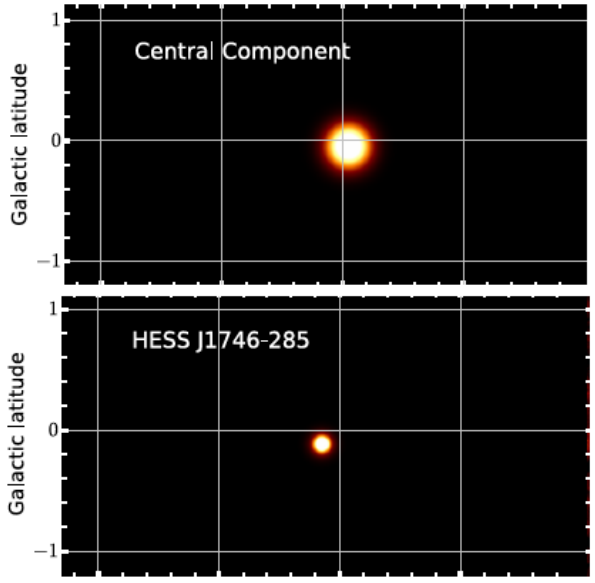
→ Take a closer look at the morphology of diffuse emission

→ We can also extend to analysis further into the high energy (statistics limited) regime

Breakdown GC ridge emission into components





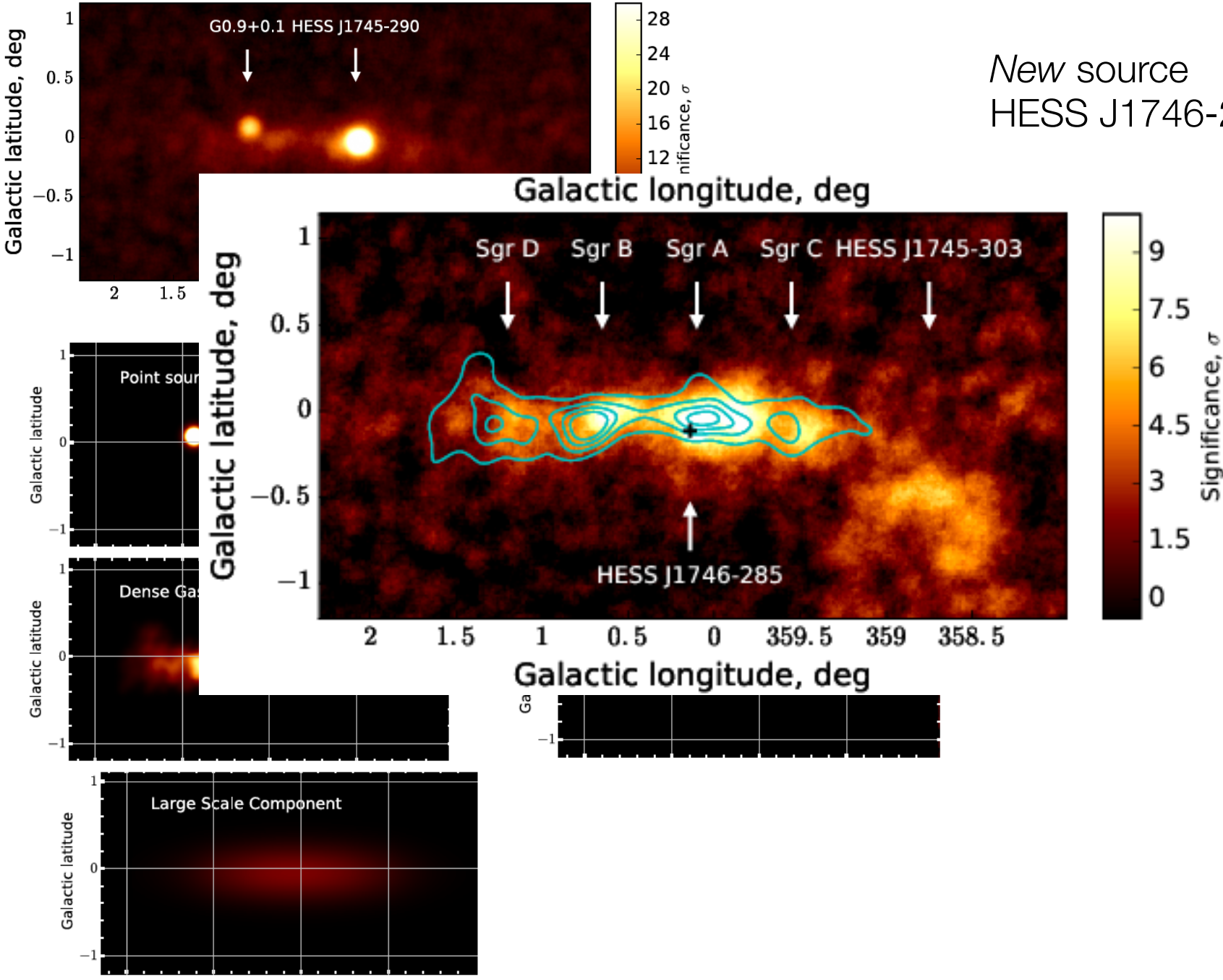


New source
HESS J1746-285

- Good spatial coincidence with PWN G0.13-0.11 seen in X rays
- The 'arc source' seen in IR/radio

H.E.S.S. Coll. arXiv:1706.04535

Breakdown GC ridge emission into components



New source
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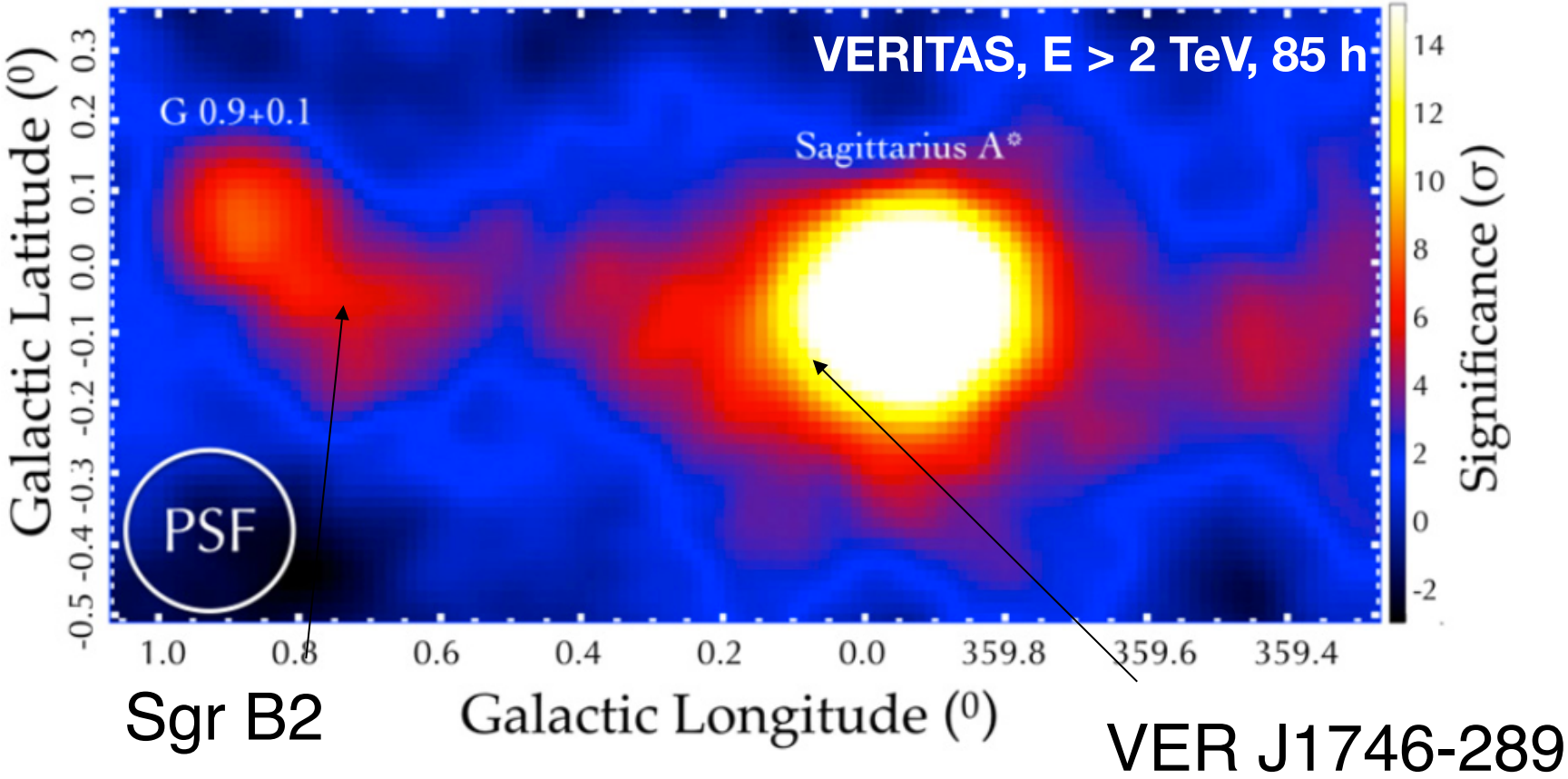
The GC seen by VERITAS in 2016

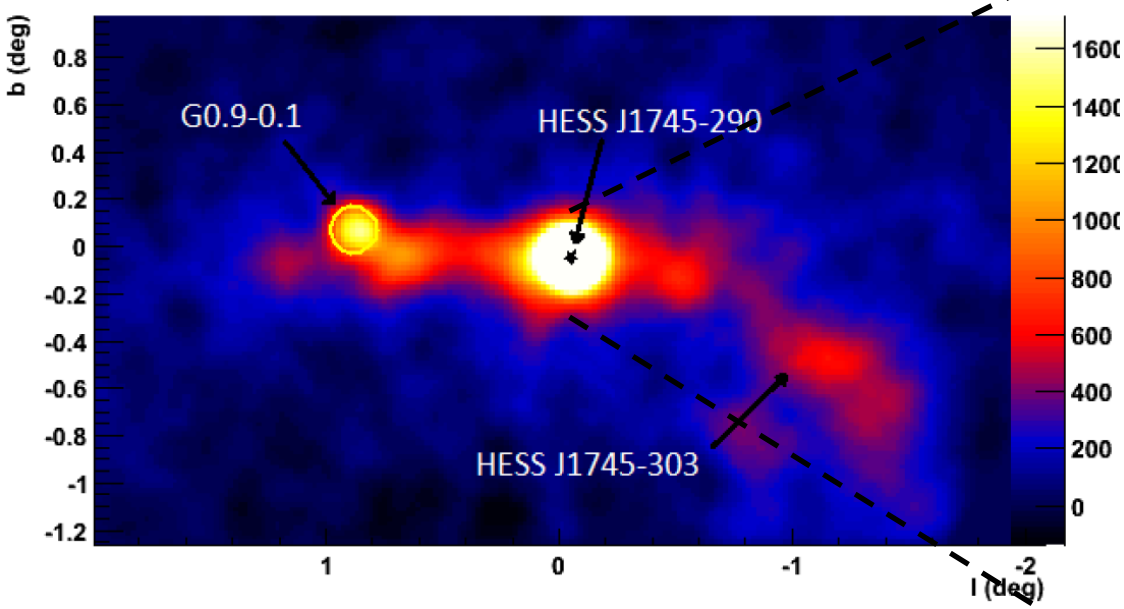
A. Archer et al. (VERITAS coll.) Astrophys.J. 821, 129 (2016)

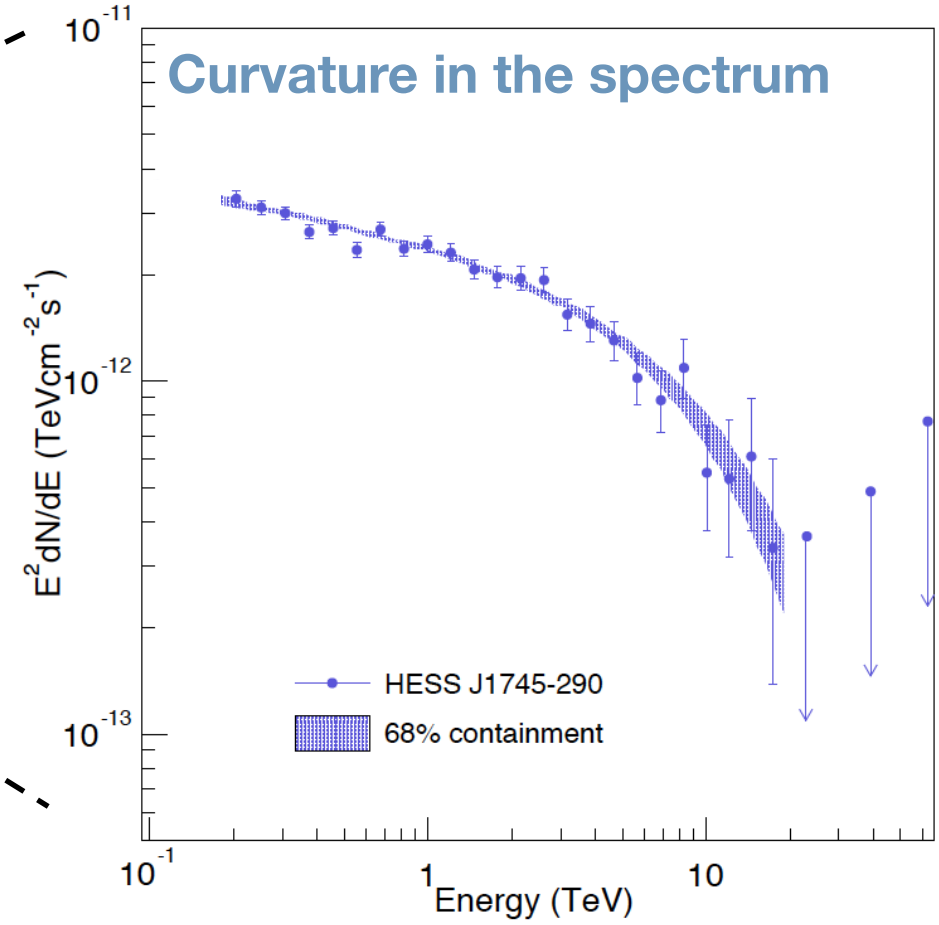


- High energy threshold from large zenith angle observations
- Morphology of the ridge seen by H.E.S.S. generally confirmed
- Evidence for emission from Sgr B2
- New source VER J1746-289

The central source HESS J1745-290

2004-2013 H.E.S.S. dataset



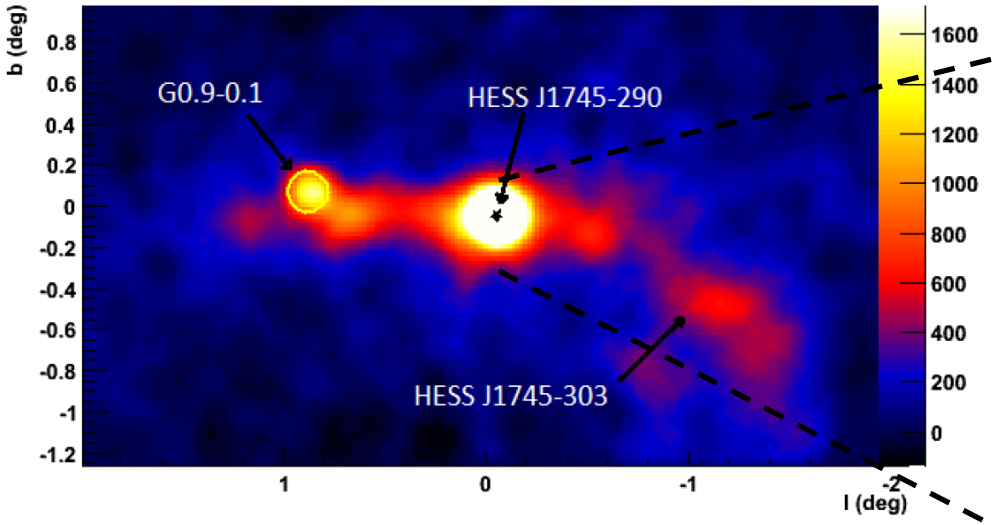


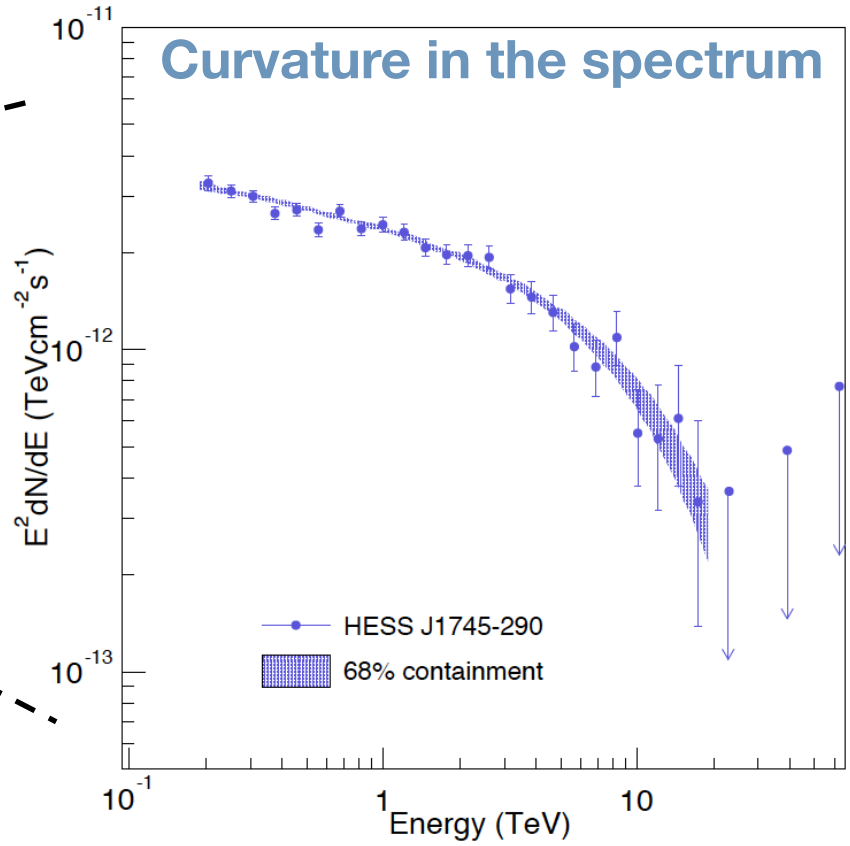
– strong emission: >10% of Crab flux (>1 TeV)
– point like source
– constant flux: ~1 gamma/min

- **Significant deviation from a pure power law**
- **No time variability so far from tens of minutes to daily time scales**
- **Can be well described by a power law with an exponenetial cut off at 10 TeV**

The central source HESS J1745-290

2004-2013 H.E.S.S. dataset





Counterparts :

(i) a CR source accelerating high energy protons in the vicinity of Sgr A* which produces VHE gamma rays interacton in the ISM

(ii) a pulsar wind nebula G359.95 0.04

(iii) a spike of annihilating DM particles

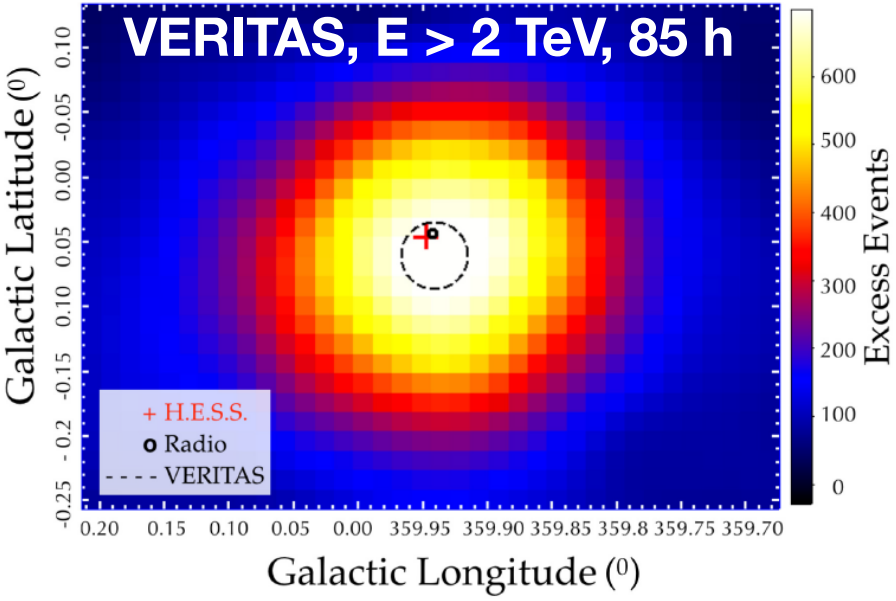
Exponential power law

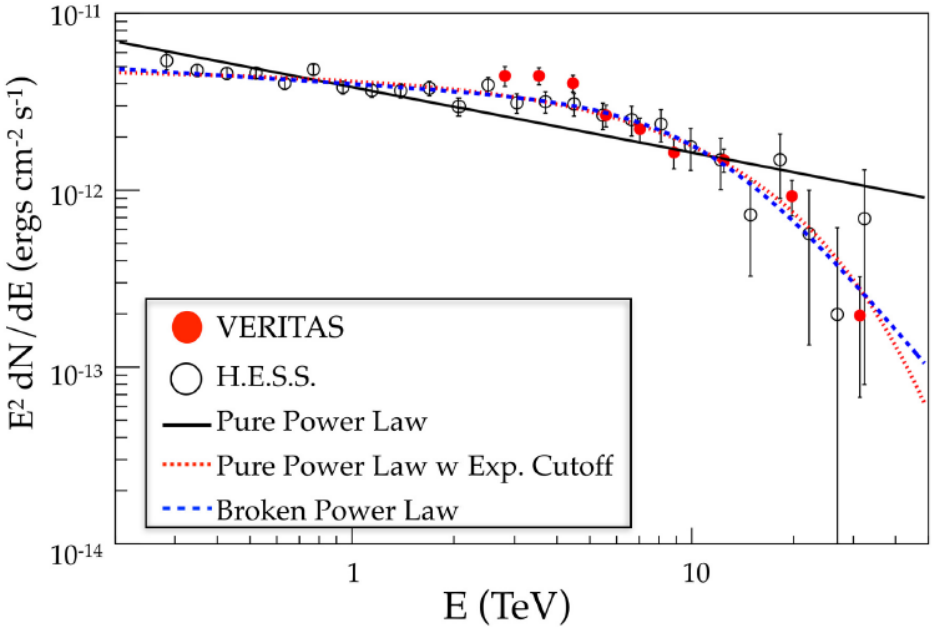
$dN/dE = \Phi_0 E^{-\Gamma_0} . \exp(-E/E_{cut})$

- **$\Phi_0 = (2.55 \pm 0.04_{stat} \pm 0.37_{syst})$ x 10^{-12} TeV^{-1} cm^{-2} s^{-1},**
- **$\Gamma_0 = 2.14 \pm 0.02_{stat} \pm 0.10_{syst}$**
- **$E_{cut} = (10.7 \pm 2.0_{stat} \pm 2.1_{syst})$ TeV**

Origin of HESS J1745-290 ?

A. Archer et al. (VERITAS coll.) Astrophys.J. 821, 129 (2016)





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- **(ii) a pulsar wind nebula G359.95 0.04**
- **(iii) a spike of annihilating DM particles**

VERITAS and H.E.S.S. results agree very well

Origin of HESS J1745-290

How to go further with VHE gamma-rays:
→ Spectral shape in the energy cut-off region

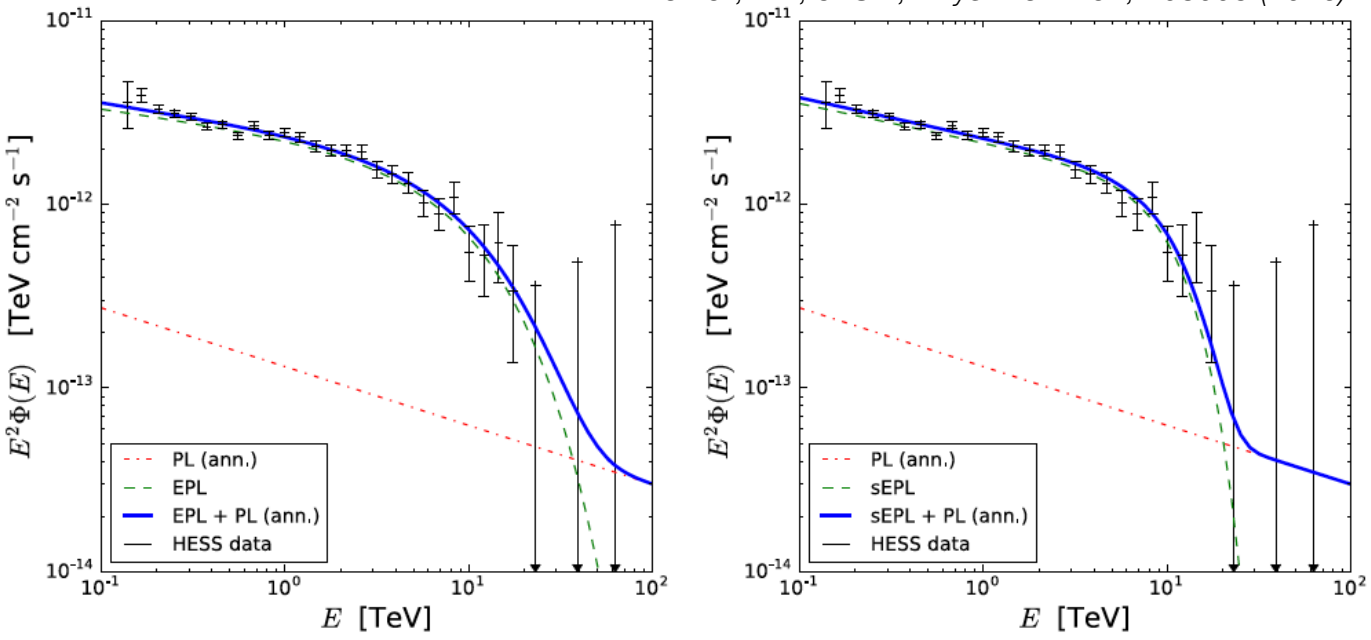
> A template gamma-ray spectrum for the proton-induced emission is a power law with an exponential energy cutoff

> The DM-induced spectrum template can be interpreted by a power law with superexponential energy cutoff

- **Data can be well described by both EPL and a SEPL spectral templates**

- **Present statistics is not sufficient to significantly discrimintate among the two templates**

A. Belikov, EM, J. Silk, Phys. Rev. D94, 103005 (2016)

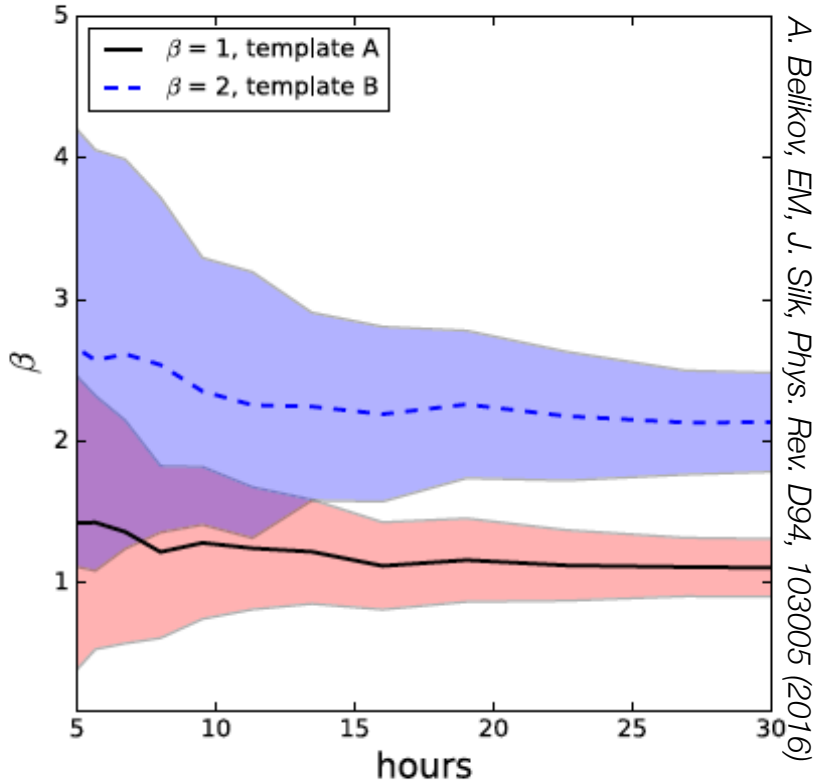


HESS J1745-290: prospects with CTA

- about 1-order-of-magnitude increase in sensitivity in the TeV regime
- a factor of 2 to 3 improvement in angular resolution compared to current instruments: 0.03°(68%) above 1 TeV
- energy resolution from about 20% at 100 GeV to better than 5% at 10 TeV

→ Generating mock spectral CTA data from EPL and a SEPL spectral templates

CTA should be able to reliably distinguish SEPL from EPL models in about 20 hours of observation time



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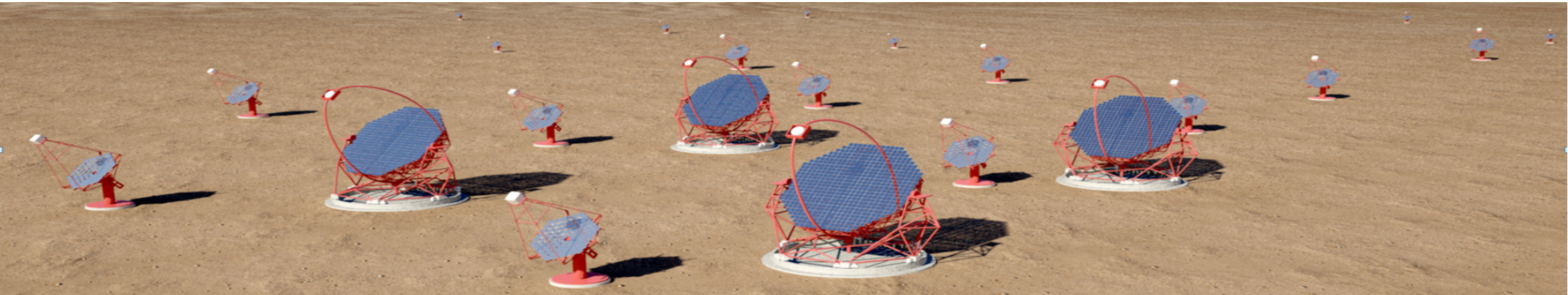
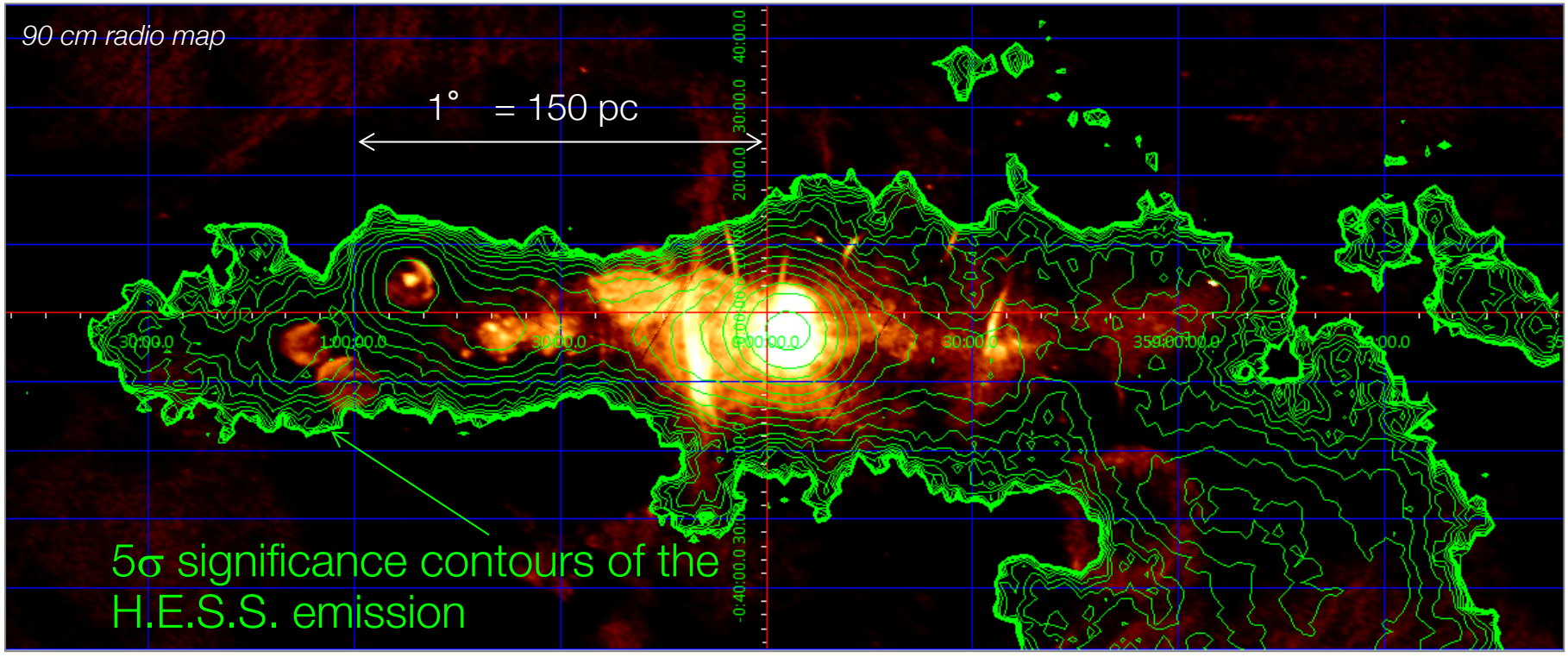


10-year GC observations with H.E.S.S.

Complex and structured emissions
Gas clouds illuminated by cosmic-ray source(s)

Dark matter halo emission?
Launch of Fermi bubbles?



- Largest H.E.S.S. dataset from a regular monitoring over 10 years
  - More than 1000 hours of observations : ~150000 gamma
- Most detailed map in VHE astronomy
  - Location in the Southern hemisphere is crucial

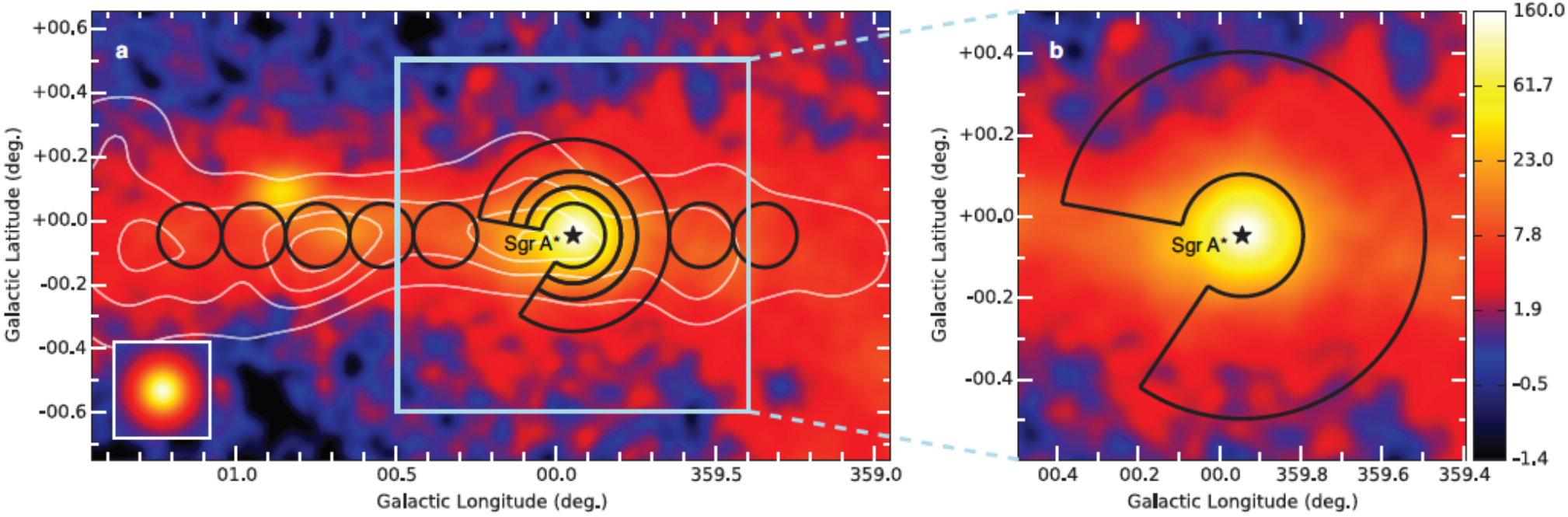
→ High-accuracy spectral and spatial measurements

Diffuse emission and CR transport

Diffuse emission correlated with molecular cloud distribution

→ the ratio of the TeV flux to the gas density provides the CR density

HESS collaboration, Nature 531, 476 (2016)



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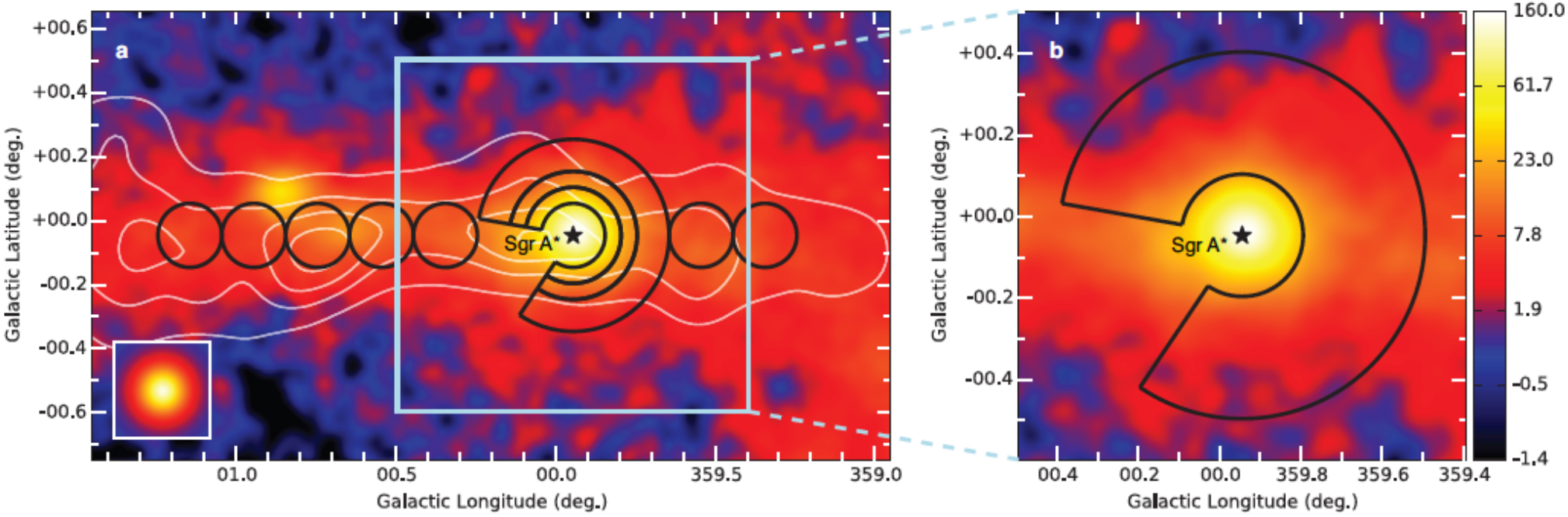

- Gamma-ray luminosity measurement in several regions
- Use of cloud mass measurements gas density from CS (CO, HCN)

CR energy density proportional to L_γ/M :

$$w_{\rm CR}(\geq 10E_\gamma) = \frac{W_p(\geq 10E_\gamma)}{V} \sim 1.8\times10^{-2}\left(\frac{L_\gamma(\geq E_\gamma)}{10^{34}{\rm erg/s}}\right)\left(\frac{M}{10^6 M_\odot}\right)^{-1}{\rm eV/cm^3}$$

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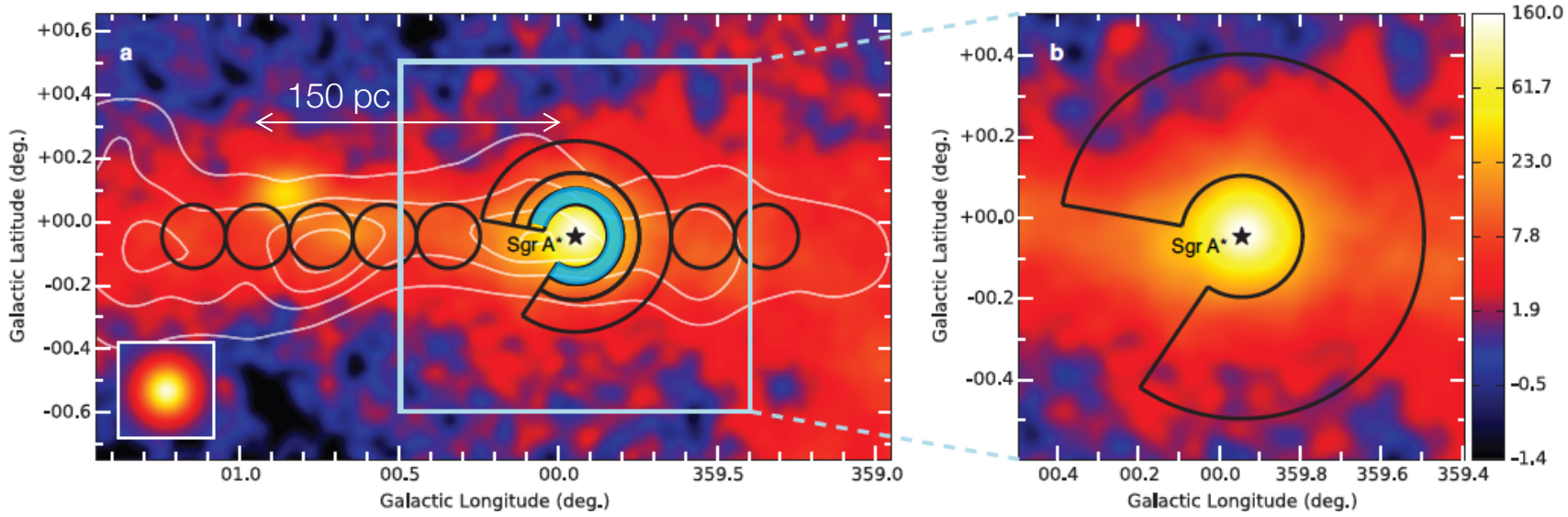

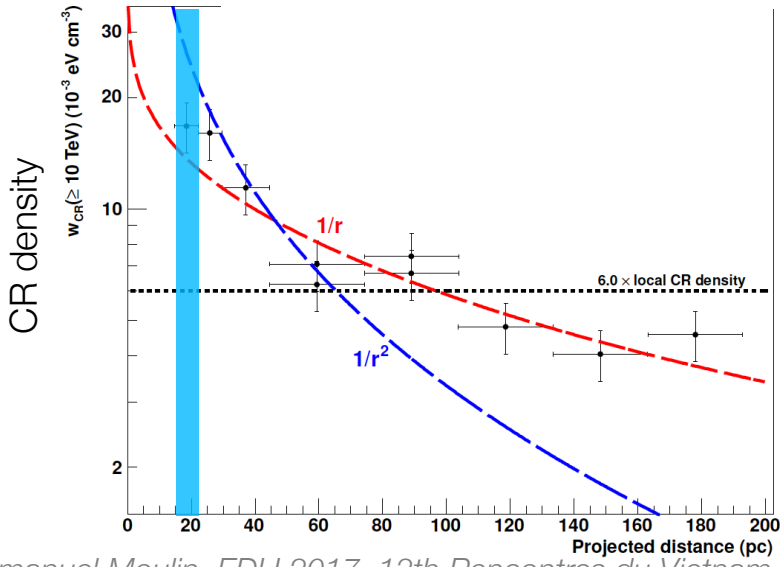

Measurement of CR density in the inner 200 pc of the Milky Way

→ Localization of the accelerator in the central 10 parsecs

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Diffuse emission correlated with molecular cloud distribution

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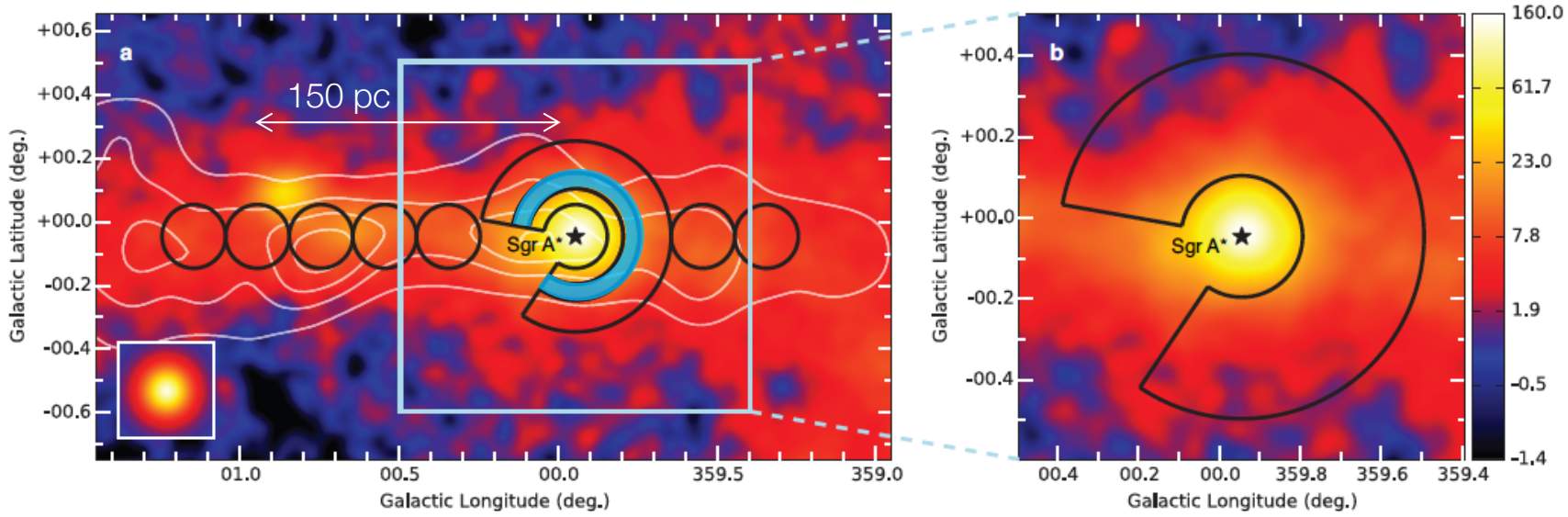

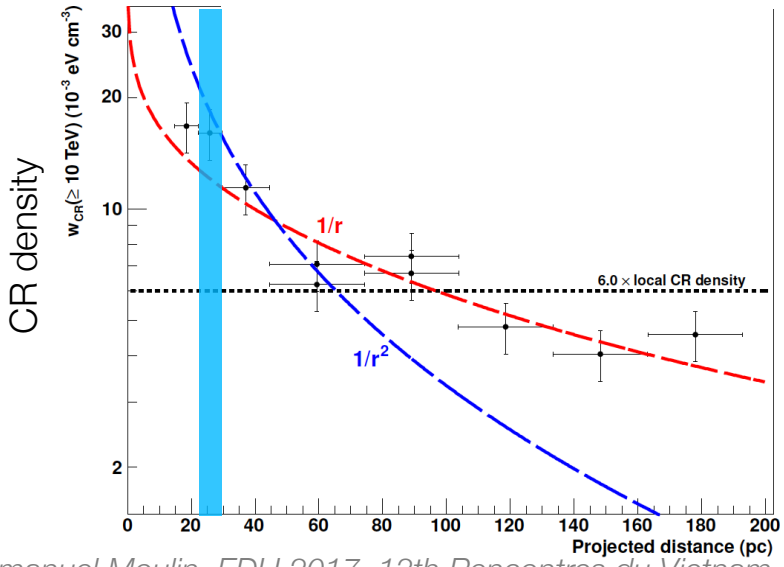

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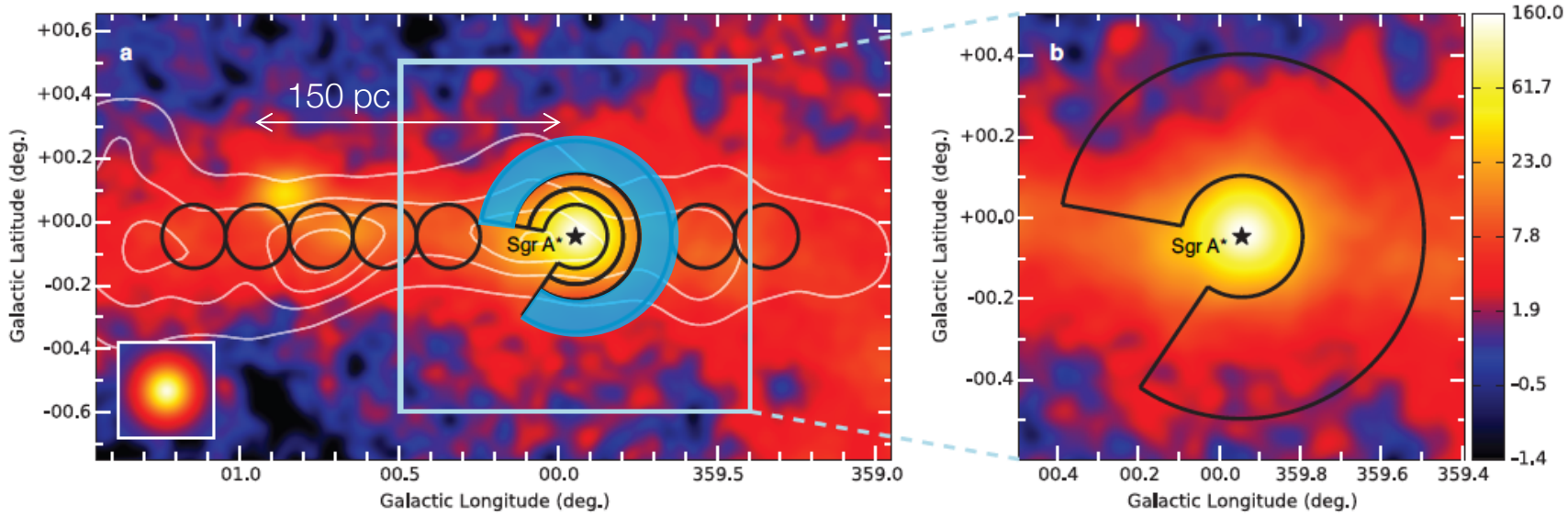

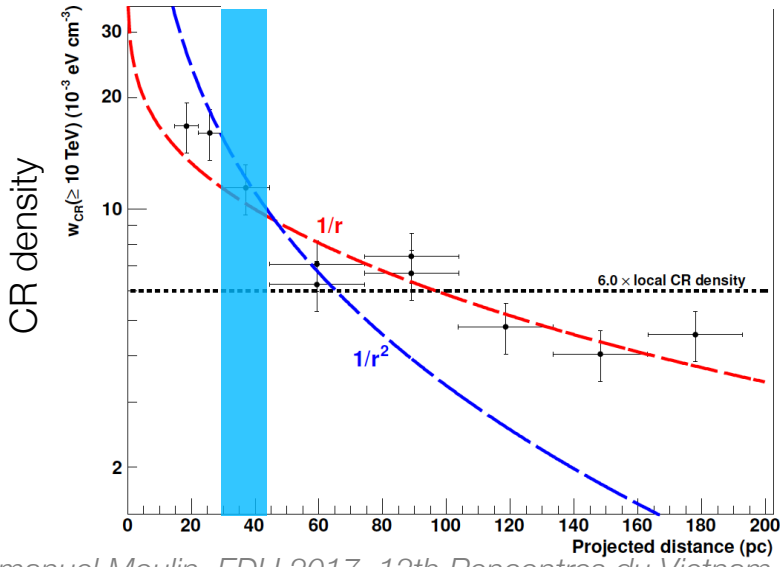

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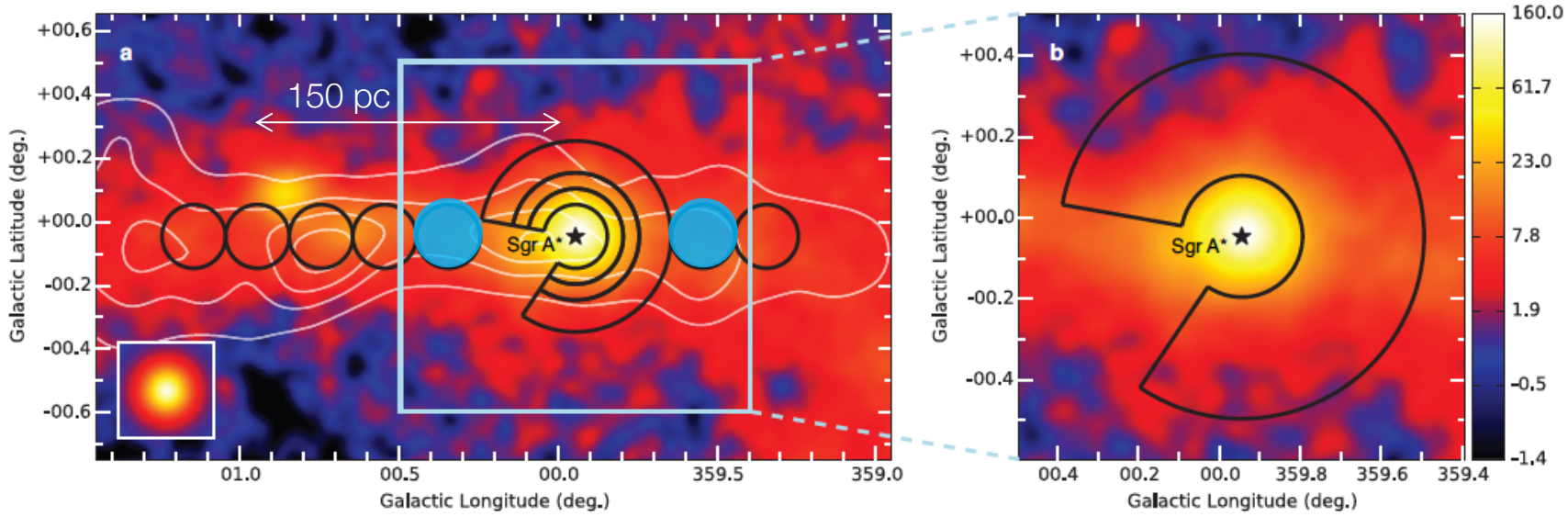

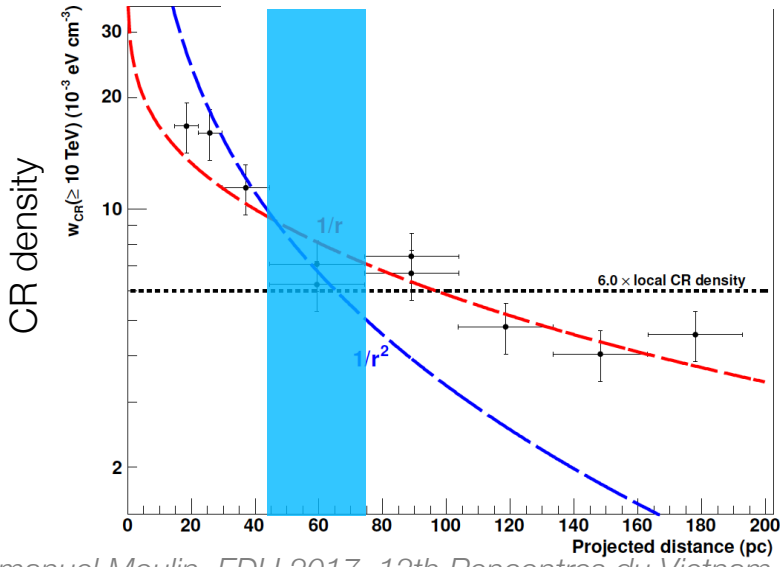

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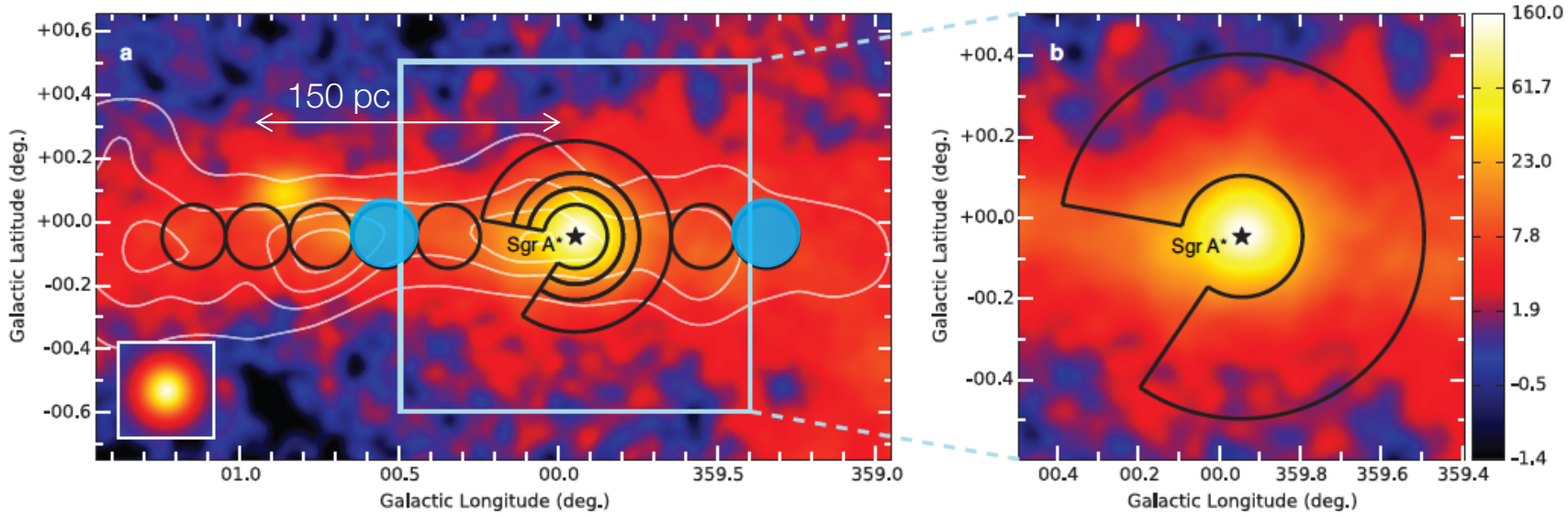

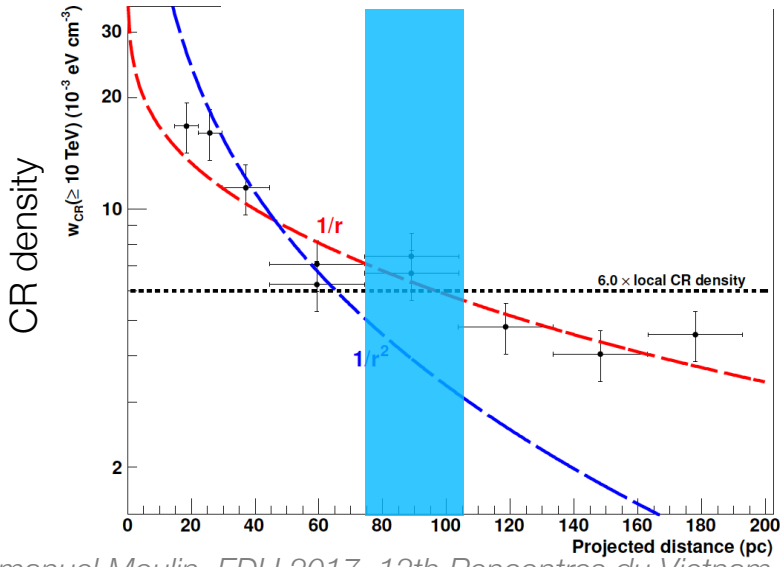

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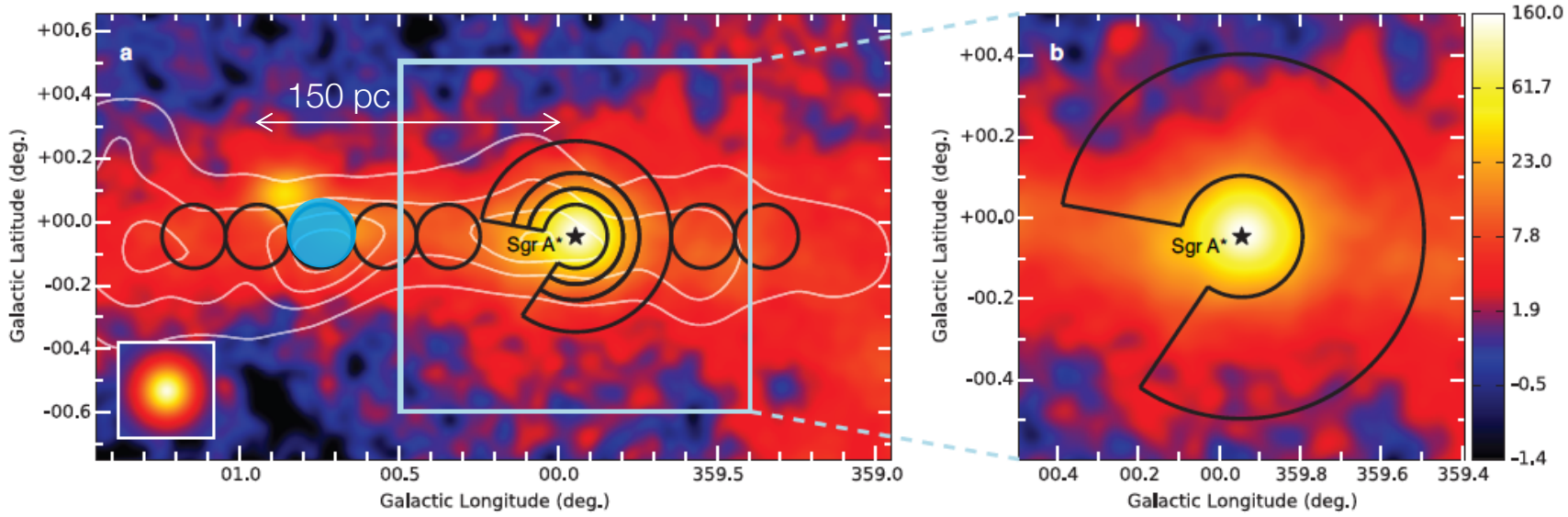

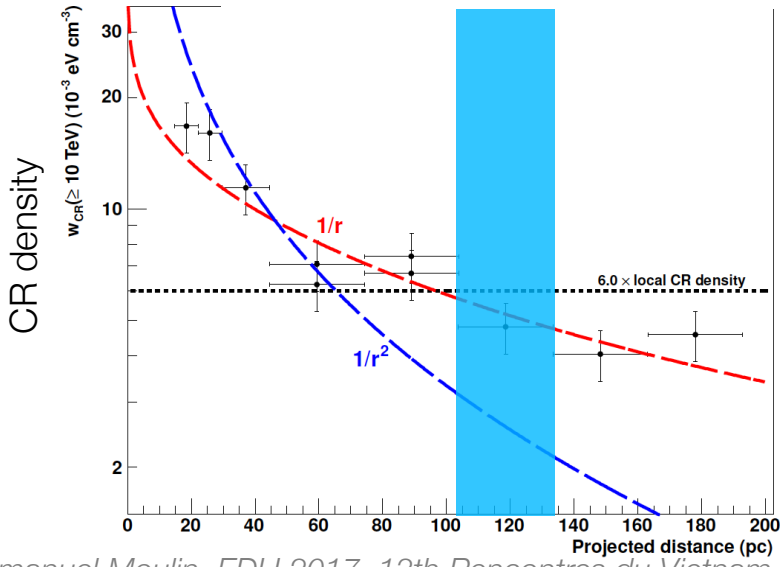

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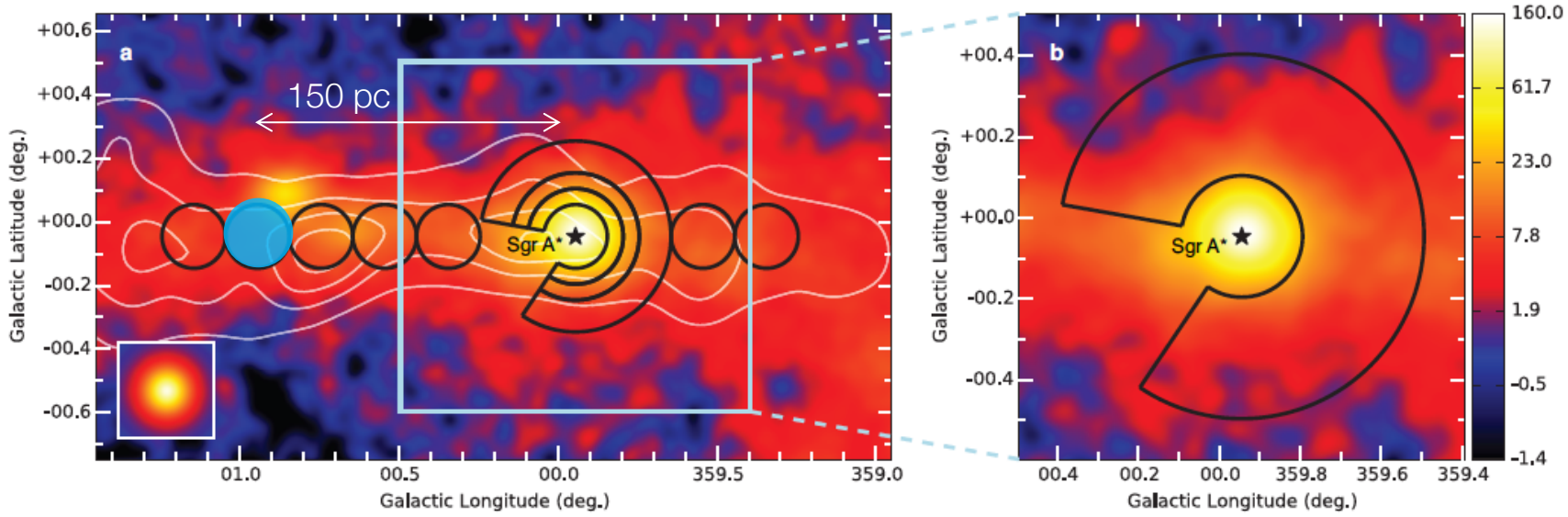

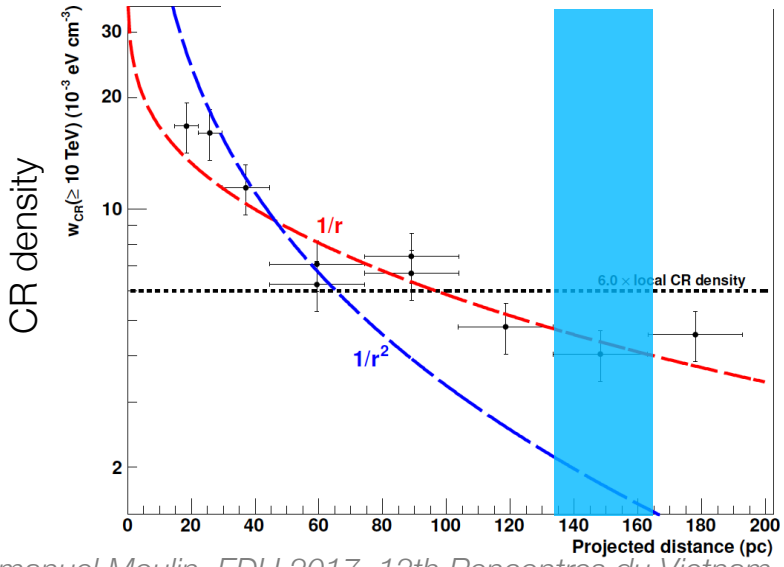

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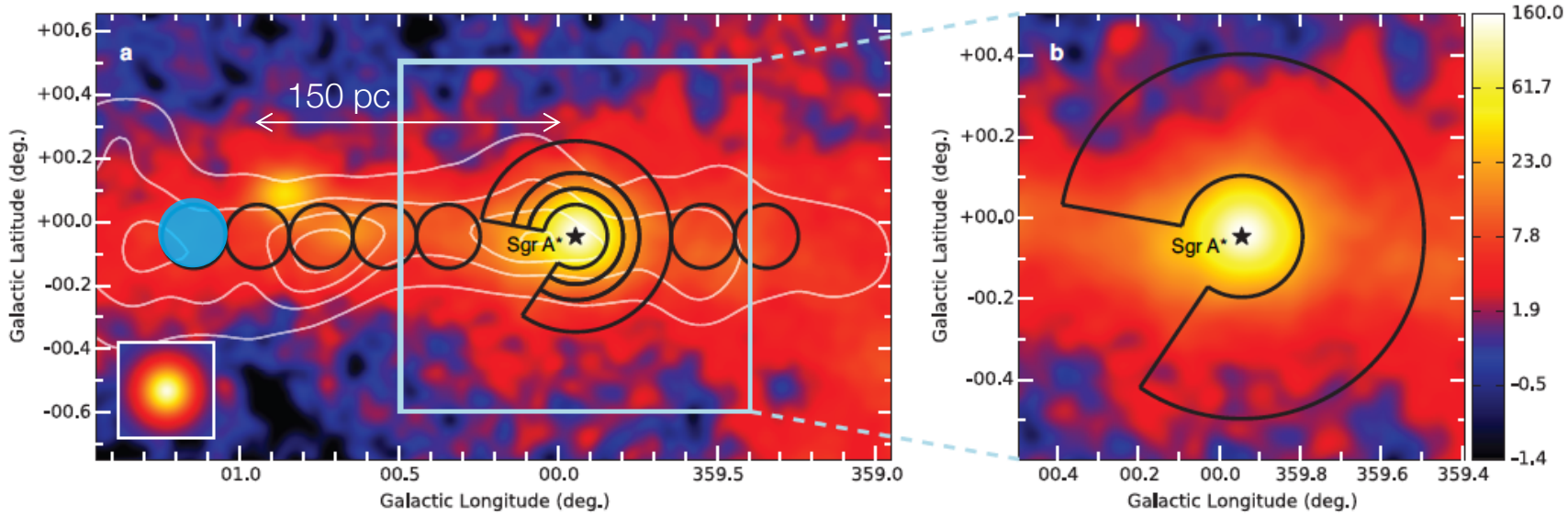

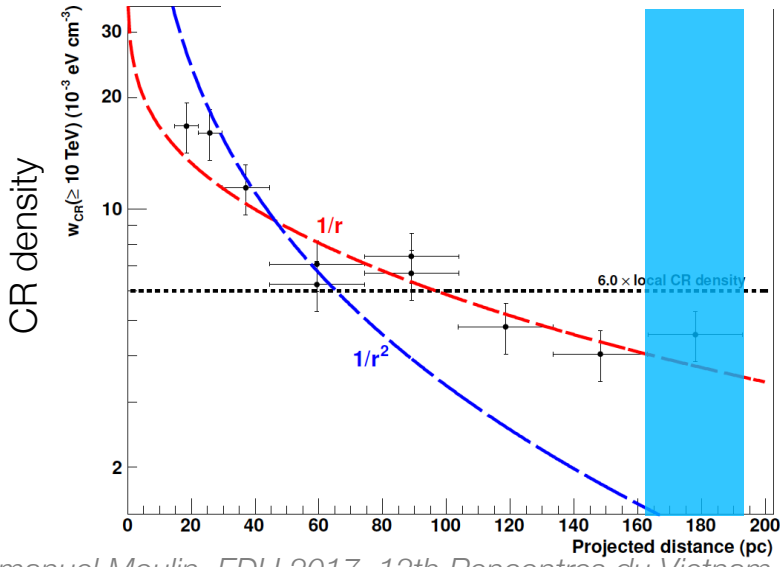

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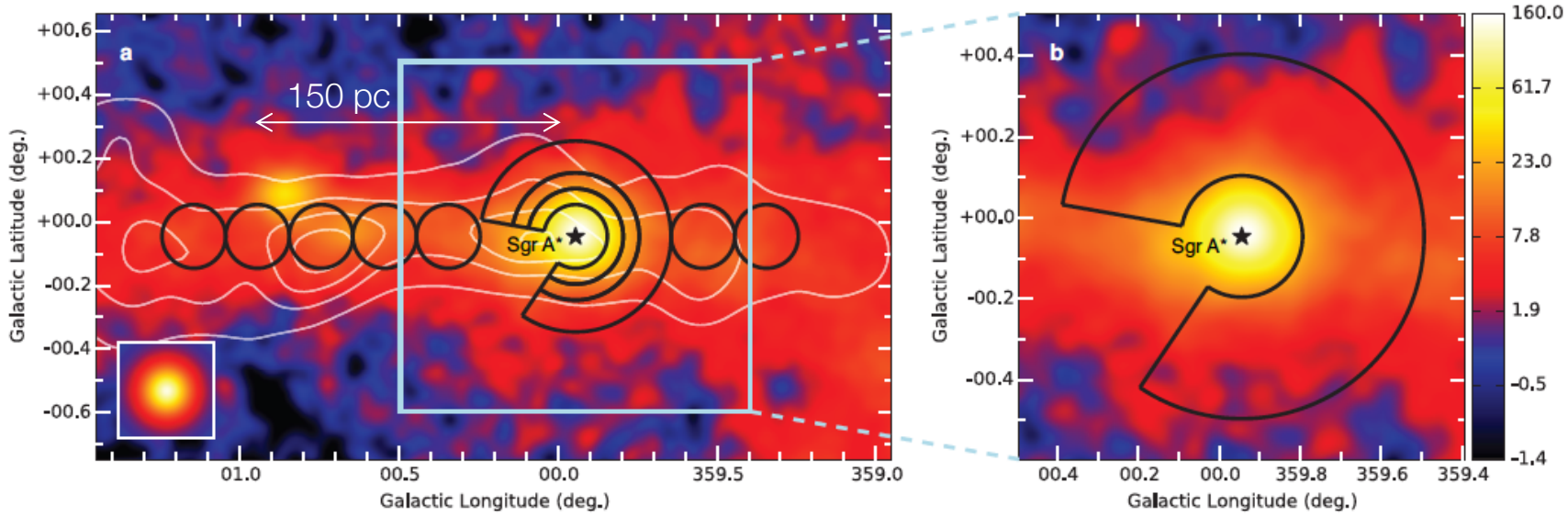
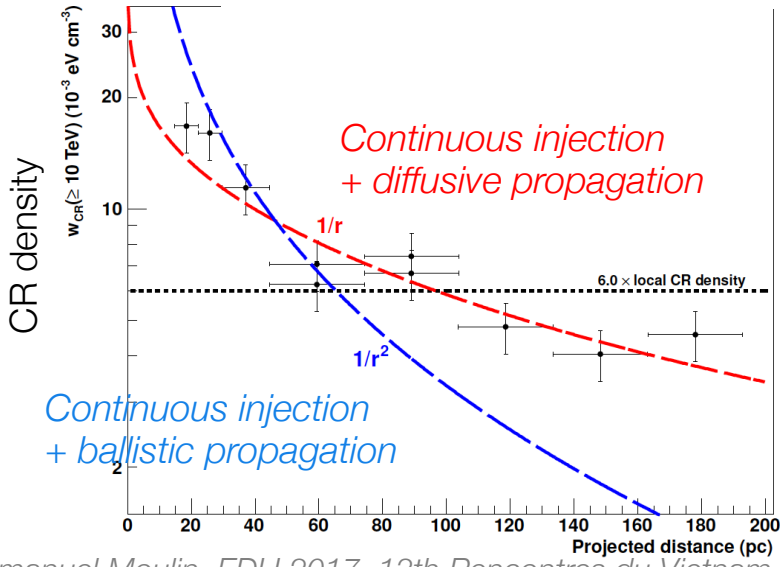




CR density radial distributions :

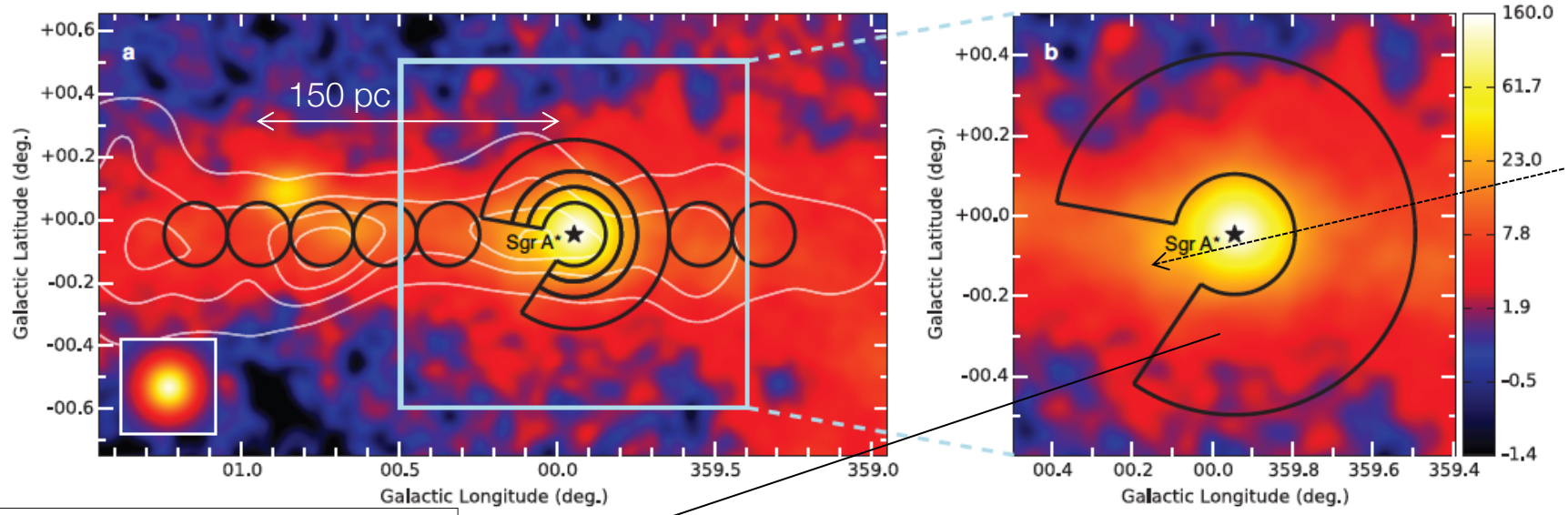
- *Homogeneous/constant: impulsive injection of CRs and diffusive propagation*
- *$1/r^2$: wind-driven or ballistic propagation*
- *1/r : continuous injection and diffusive propagation*

Central accelerator located within 10 pc and injecting CRs continuously over more than 1000 years

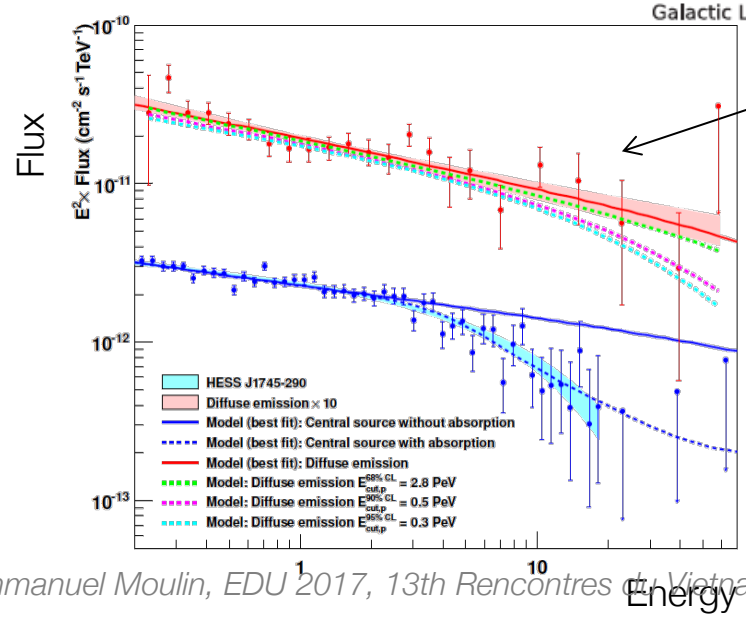
Diffuse emission: CR injection spectrum

Diffuse emission correlated with molecular cloud distribution

→ the ratio of the TeV flux to the gas density provides the CR density



Excluded Source : "Arc source"



Gamma-ray spectrum measured up to 50 TeV

- power law with index 2.3 with no energy cut-off

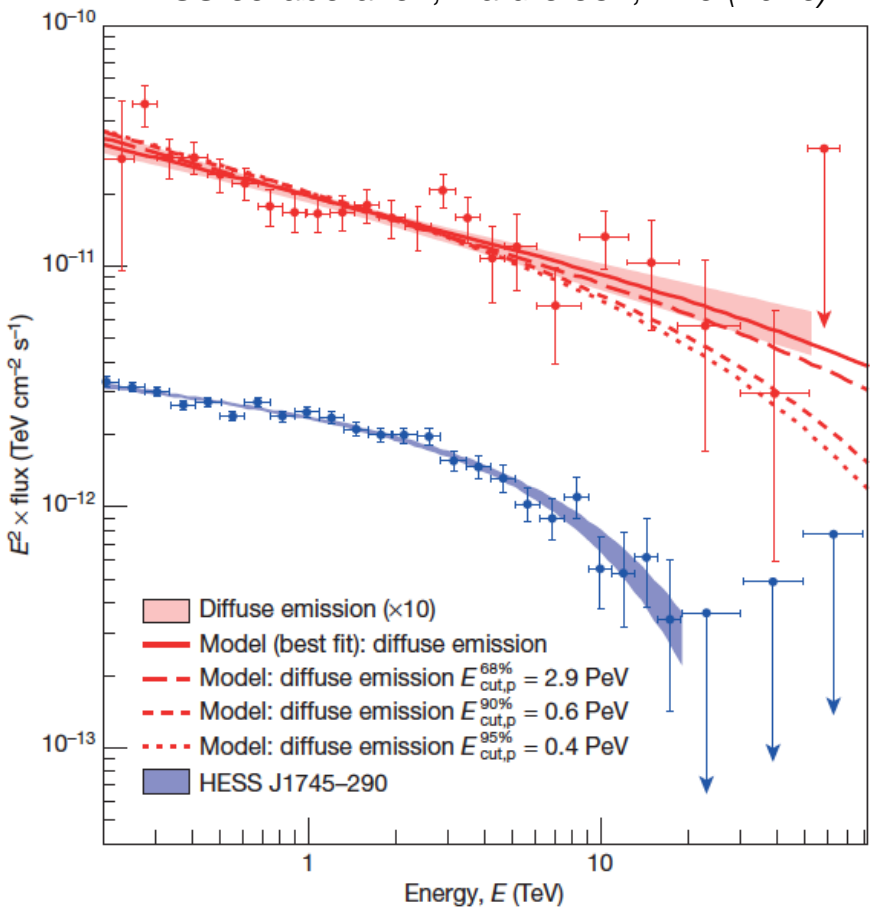
→ Parent proton spectrum should extend at least to PeV energies

Diffuse emission: CR injection spectrum

Spectrum diffuse emission extracted from large ring around Sgr A*

- Spectrum of diffuse emission: power-law with index 2.3 extending up to 50 TeV without energy cut-off

HESS collaboration, Nature 531, 476 (2016)



Diffuse emission: CR injection spectrum

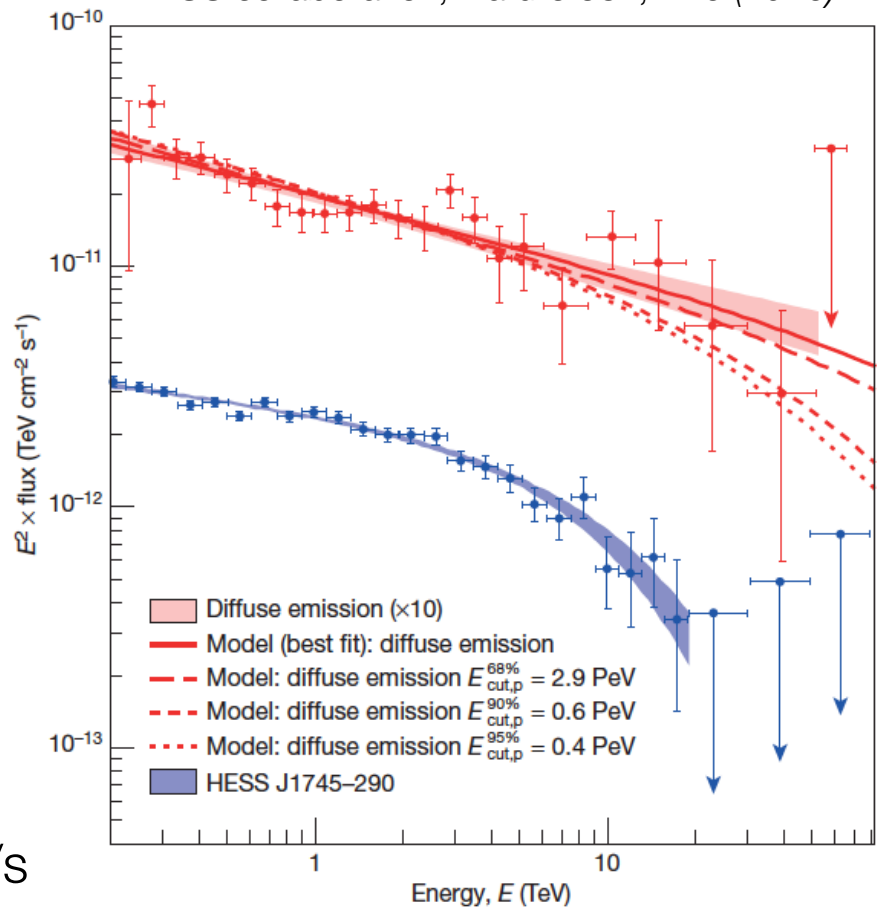
Spectrum diffuse emission extracted from large ring around Sgr A*

- Spectrum of diffuse emission: power-law with index 2.3 extending up to 50 TeV without energy cut-off

→ **Parent proton injection spectrum should extend to PeV energies**

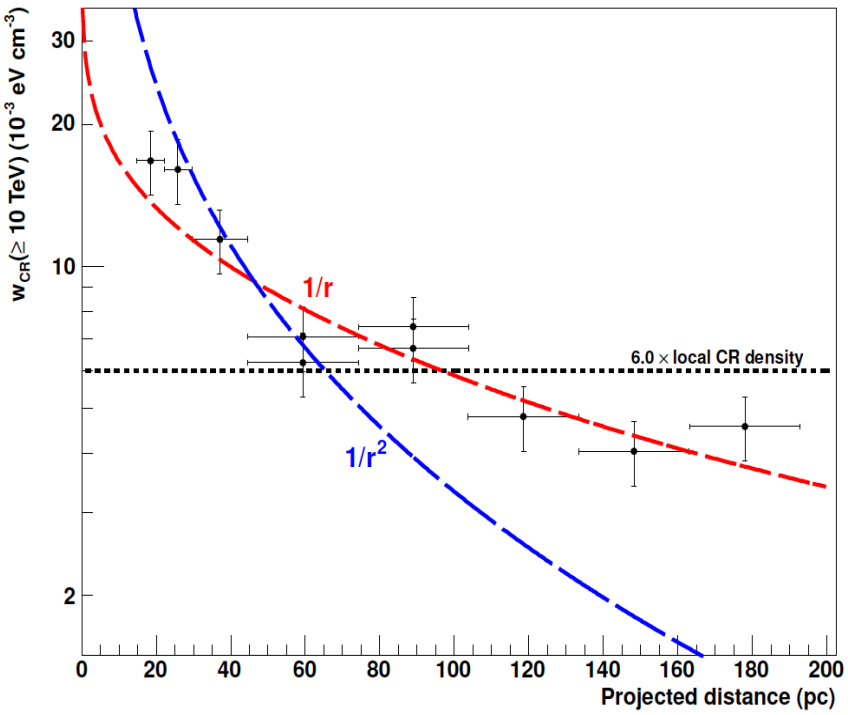
- quasi-continuous injection lasting over > 10^3 years
- total CR power injected at the GC ~10^{38} erg/s

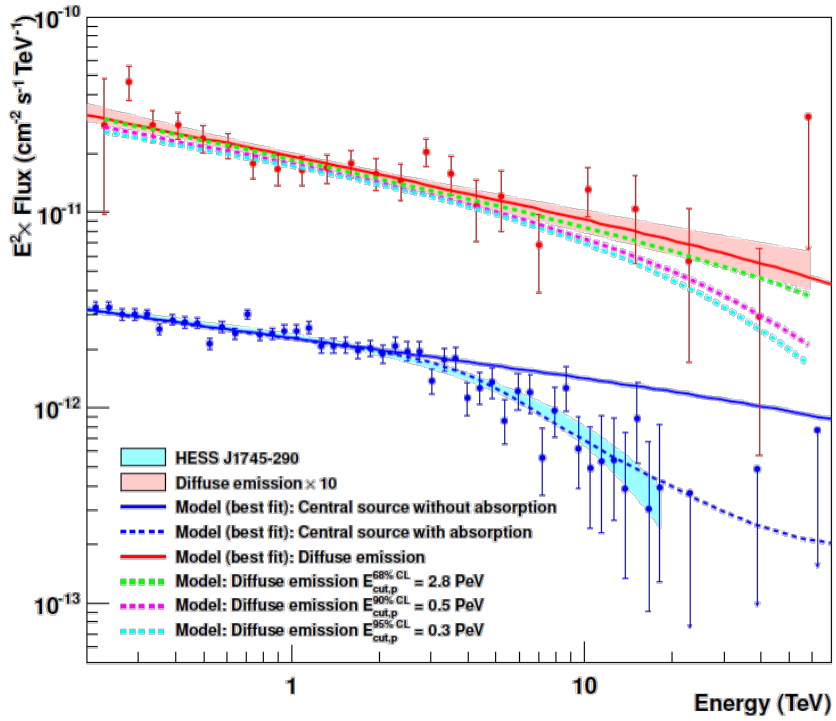
HESS collaboration, Nature 531, 476 (2016)



First robust detection of a cosmic PeVatron

Cosmic PeVatron counterpart: SMBH Sgr A*





- Given the location (<10 pc), accelerated enegies (PeV), continuous (kyrs) injection power of the accelerator → SMBH Sgr A* is a viable couterpart
- A significant fraction of accretion in Sgr A* is released through acceleration of high-energy particles
- Sgr A* may have been more active in the past :

  if injection power ≥ 10^{39} erg/s, GC PeVatron can explain the fluxes of Galactic CRs above 100 TeV to a few PeV (region of the “knee”)

A privileged region for DM search

- The inner region of the Milky Way halo harbors a large amount of dark matter
- Given its proximity, it is one of the most promising targets to look for DM

- … GC region is a crowded environment at VHE : pointlike sources (PWN, SNR, Unidentified sources) and diffuse emission(s)

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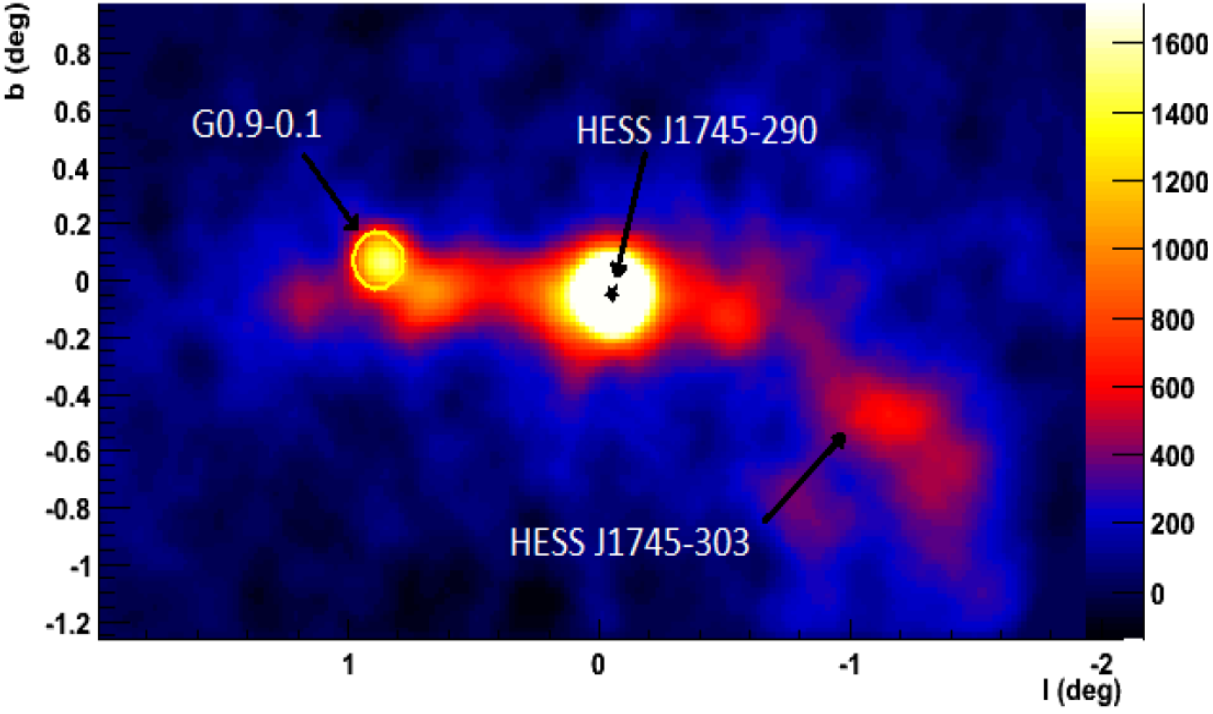
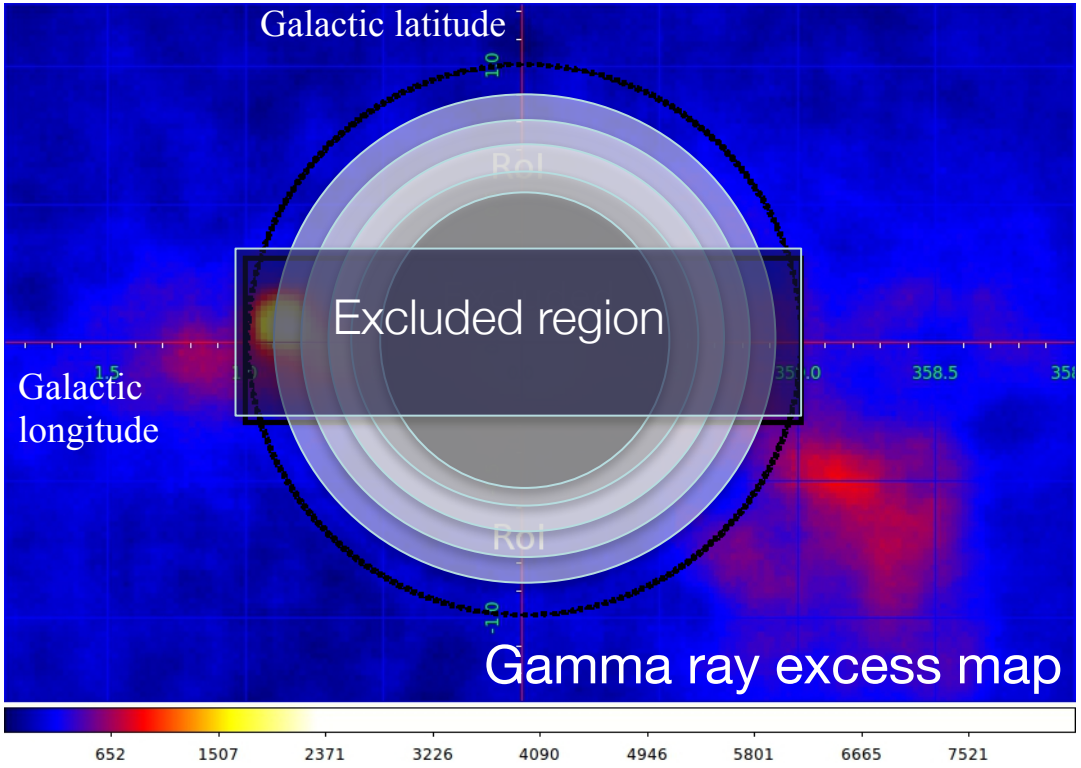


- 10-year observations with H.E.S.S. 1 toward the GC

- Gamma-ray statistics : 254 h compared to 112 h as used in 2011/2013 analyses

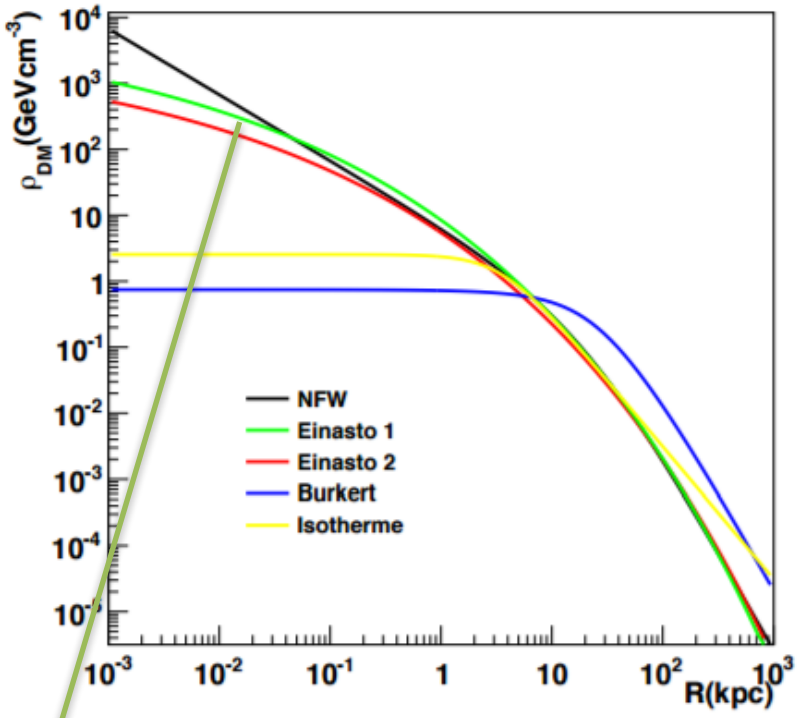
DM search in the GC : regions of interest

- The inner region of the Milky Way halo harbors a large amount of dark matter (DM).
- Given its proximity, it is one of the most promising targets to look for DM
- 10-year observations with H.E.S.S. 1 provides a valuable dataset for that



- Excluded region ±0.3° : dominated by astrophysical sources and diffuse emission
- Does not require standard astrophysical emission modelling in the region of interest
- Whole region of Interest: 1° in radius
  → divided in 7 sub-regions of 0.1°: spatial binning

DM distribution in the GC region



$$\rho_{\mathrm{Ein1}}(r) = \rho_s \exp\left[\frac{-2}{\alpha}\left(\left(\frac{r}{r_s}\right)^{\alpha} - 1\right)\right]$$

parametrized with

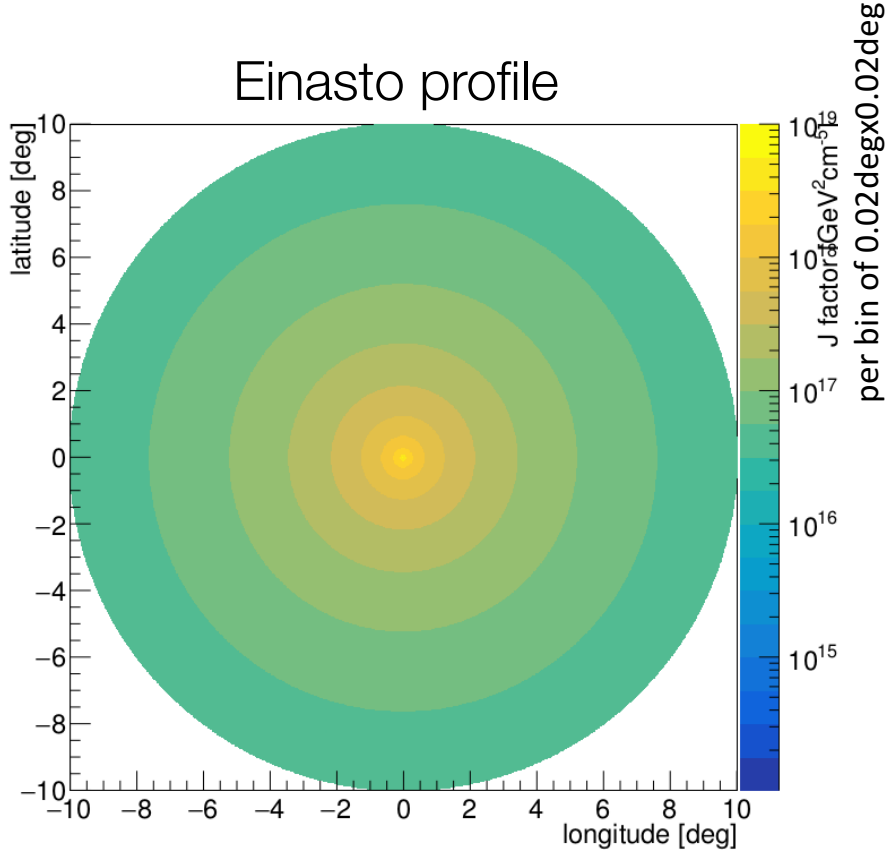
$\alpha = 0.17$

$r_s = 21\ \mathrm{kpc}$

$\rho_s = 0.07\ \mathrm{GeVcm}^{-3}$

as used in HESS GC 2011, 2013 papers

We assume cusped DM density profiles, e.g. the Einasto, NFW, …



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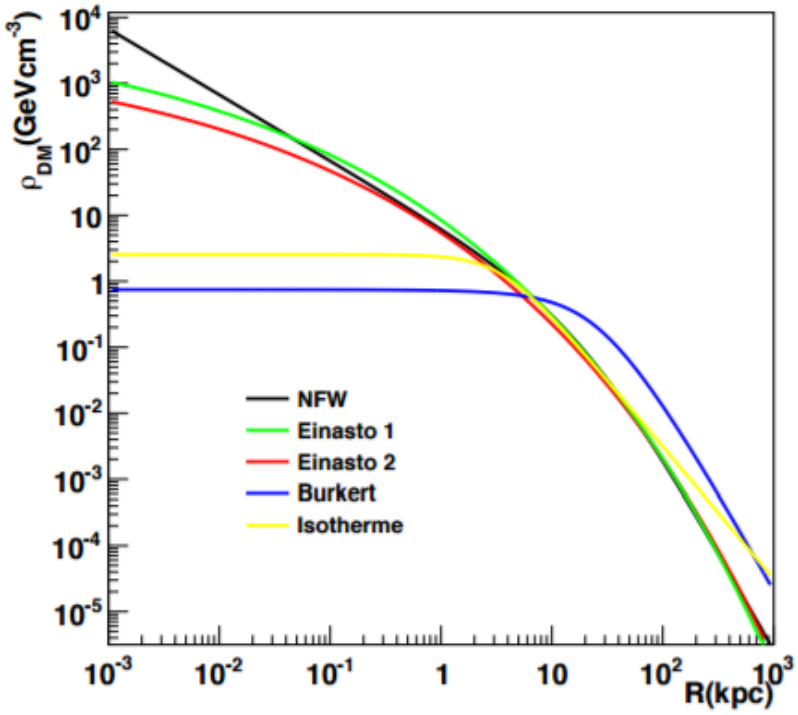

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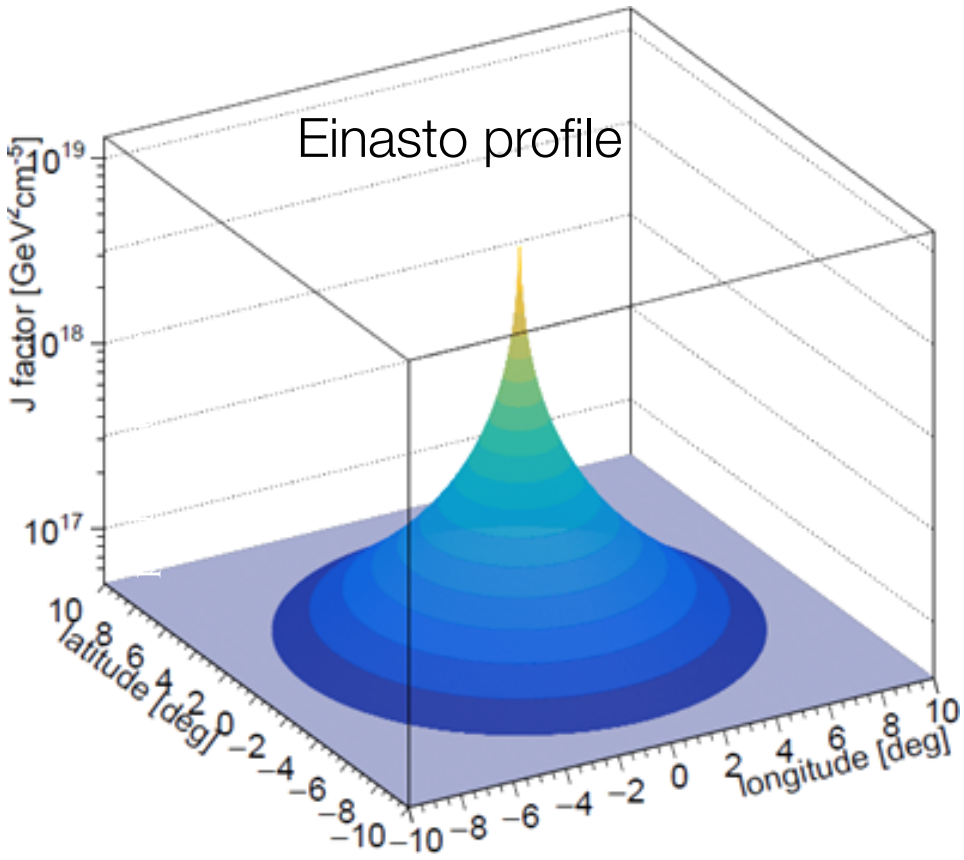
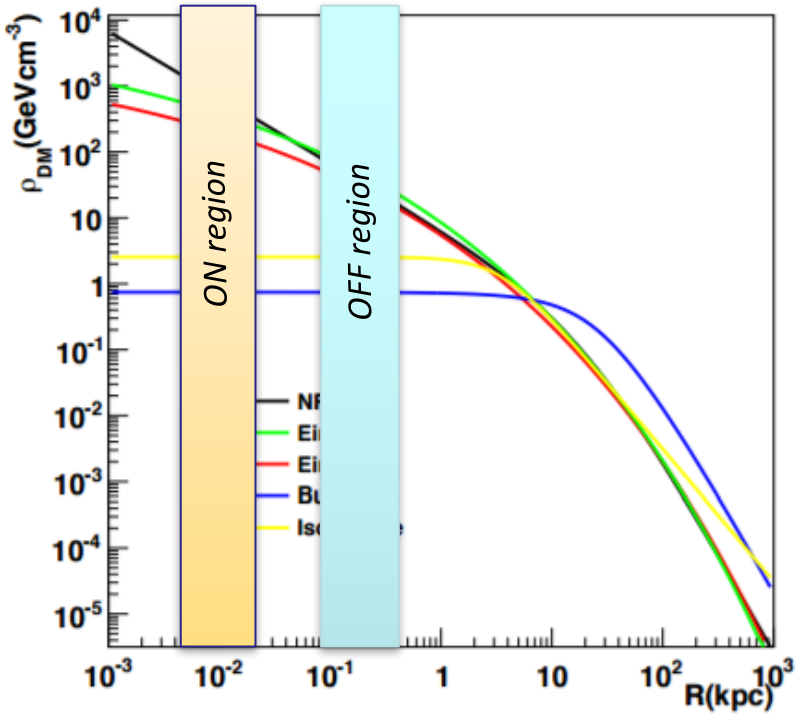


Spatial information can be used to discriminate from the isotropic residual background

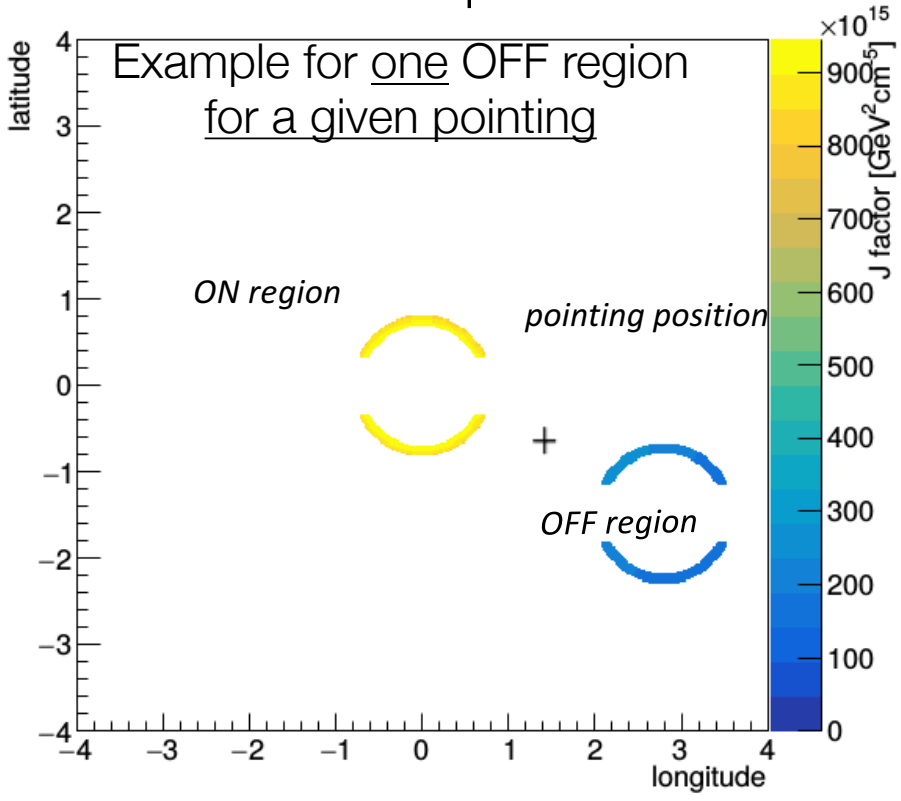
Background measurement



- **Significant DM gradient between ON and OFF regions**

We assume cusped DM density profiles, e.g. the Einasto, NFW, …

Einasto profile



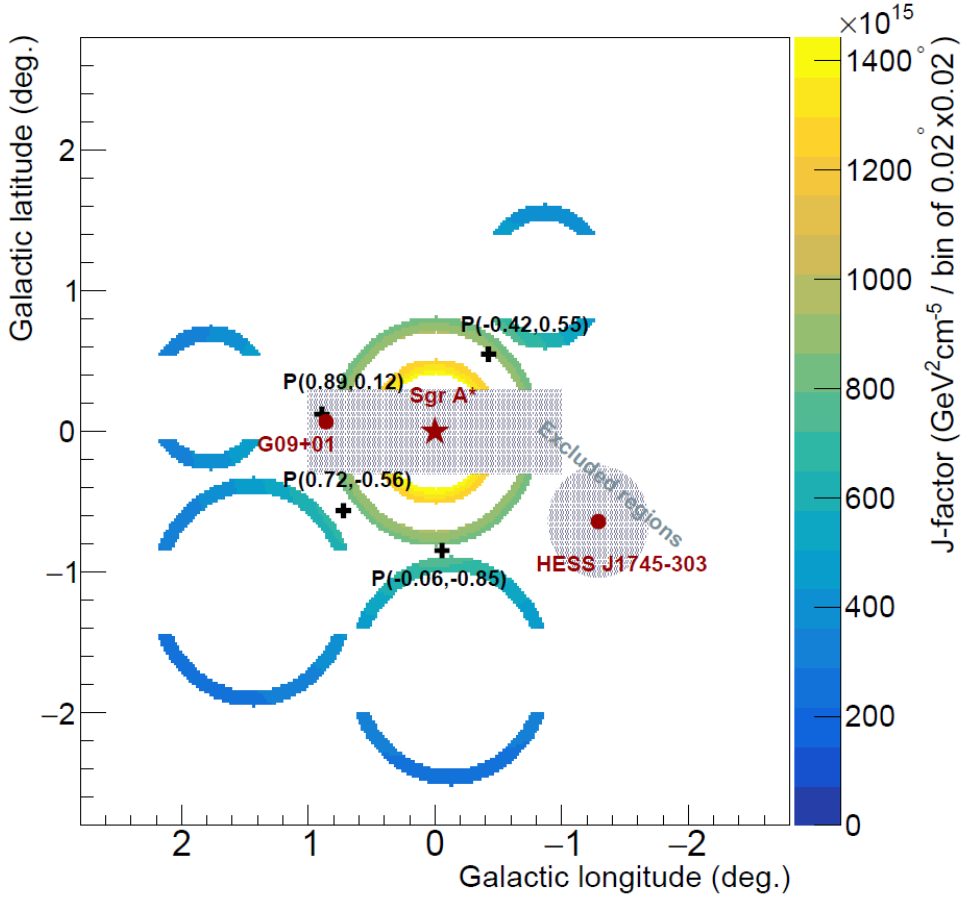
Background measurement

- Given the possible complex emission in the GC, optmiized background measurement technique is required

- OFF regions are chosen symmetrically to ON regions with respect to the pointing position in the same observational field of view
  → same observational/instrumental conditions for signal and background measurement

- Procedure is done for each observation run and each ROI

→ same acceptance in ON and OFF region
→ strong dark matter gradient that improves the limits



Dark matter search in the GC

- 2D likelihood analysis with spectral and spatial information of signal and background
- Likelihood-ratio test statistics
- No significant excess if found in any of the 7 ROIs

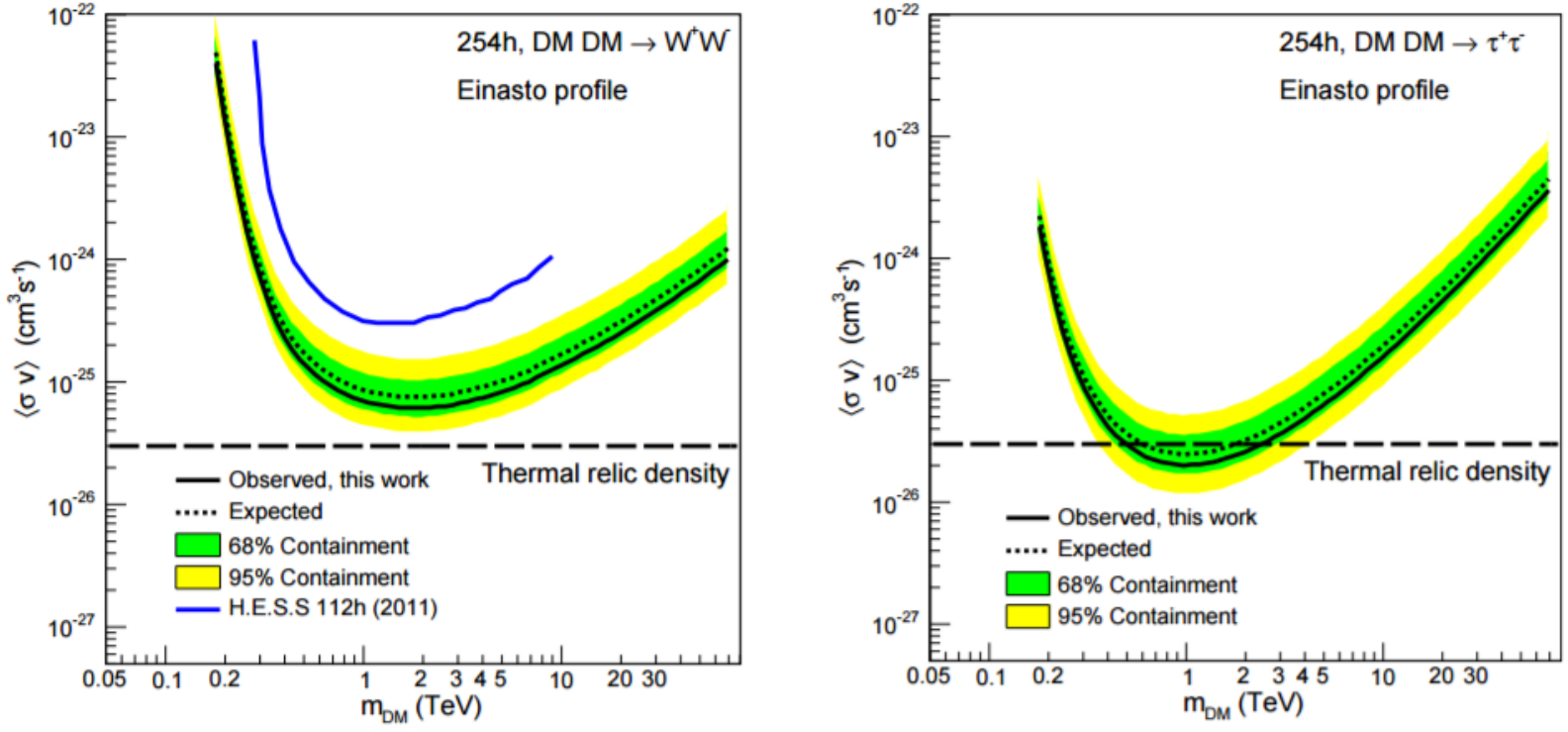
  → Upper limits derived on the annihilation cross section

TS = 2.71
for a 95% CL limit

Constraints on the DM continuum signal

- 2D likelihood analysis with spectral and spatial information of signal and background
- No significant excess if found in any of the 7 ROIs
  → Upper limits derived through a likelyhood ration test statistics

Continuum emission ("Secondary photons") → from fragmentation of quarks/massive gauge bosons (via π_0 decay)



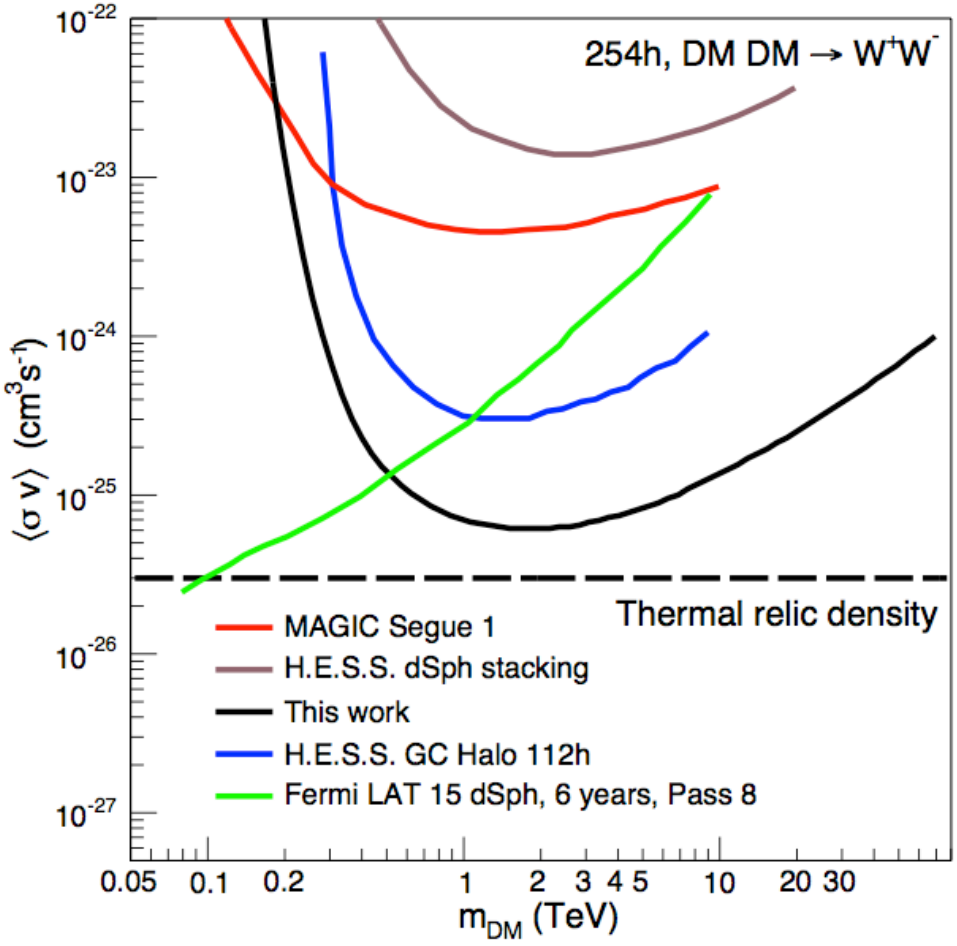
H.E.S.S. Coll., Phys. Rev. Lett. 117, 111301 (2016)

For the Einasto profile, strongest limits so far in the TeV mass range:

- in the WW channel: 6×10^{-26} cm^3 s^{-1} at 1.5 TeV
- in the ττ channel: 2×10^{-26} cm^3

Constraints on the DM continuum signal

H.E.S.S. Collaboration, Phys. Rev. Lett. 117, 111301 (2016)



- For the Einasto profile, strongest limits so far in the TeV mass range:

  → in the W^+W^- channel: 6×10^{-26} cm^3 s^{-1} at 1.5 TeV

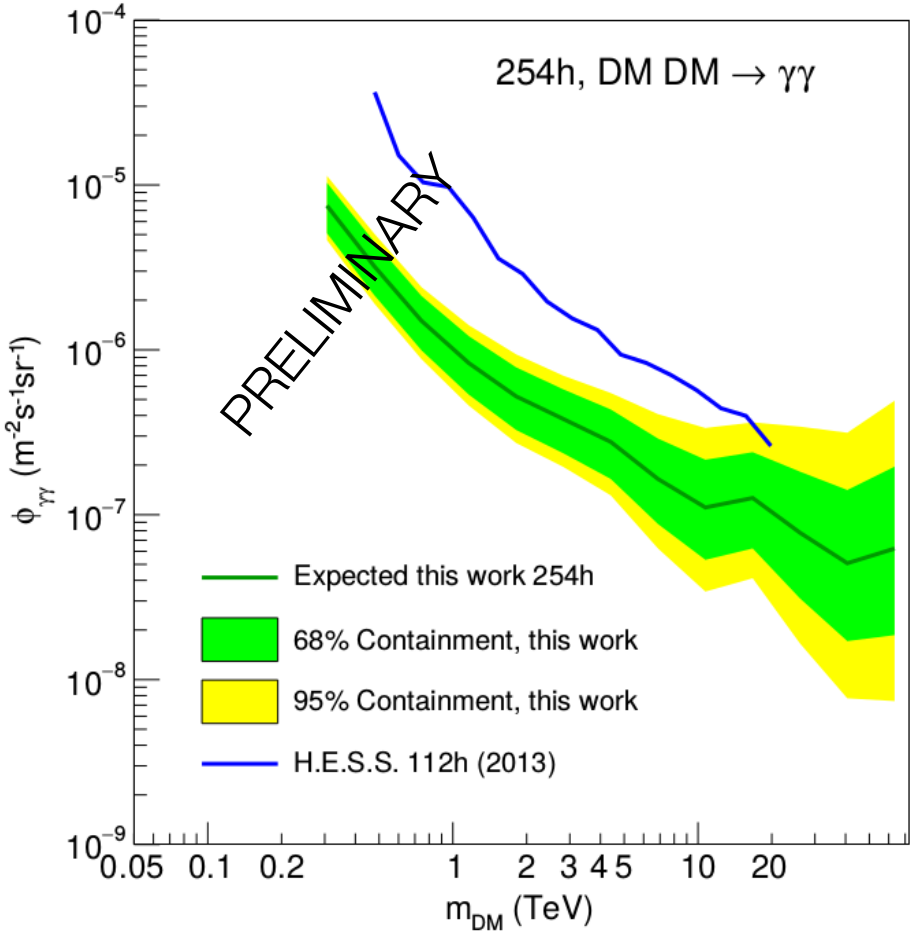
- They well complement the Fermi-LAT limits down to about 300 GeV

- *Full H.E.S.S.-II array observations within the inner Galaxy Survey programme with pointings up to 3° in Galactic latitudes started in 2015*

Constraints on the DM line signal

- 2D likelihood analysis with spectral and spatial information of signal and background
- No significant excess if found in any of the 7 ROIs
  → Upper limits derived through a likelihood ratio test statistics

Gamma-ray lines
→ from two-body annihilation into photons
→ forbidden at tree-level, generically suppressed by $O(\alpha^2)$



E. Moulin et al. (H.E.S.S. Coll.), ICRC 2017

- Improvement of a factor about 8 observed @ 1 TeV on the mean expected limits
- Improvement from the analysis: exclusion regions, 2D binned likelihood analysis approach, improved raw data danalysis, higher statistics

Constraints on the DM line signal (2)

- 2D likelihood analysis with spectral and spatial information of signal and background
- No significant excess if found in any of the 7 ROIs
  → Upper limits derived through a likelyhood ration test statistics

Gamma-ray lines
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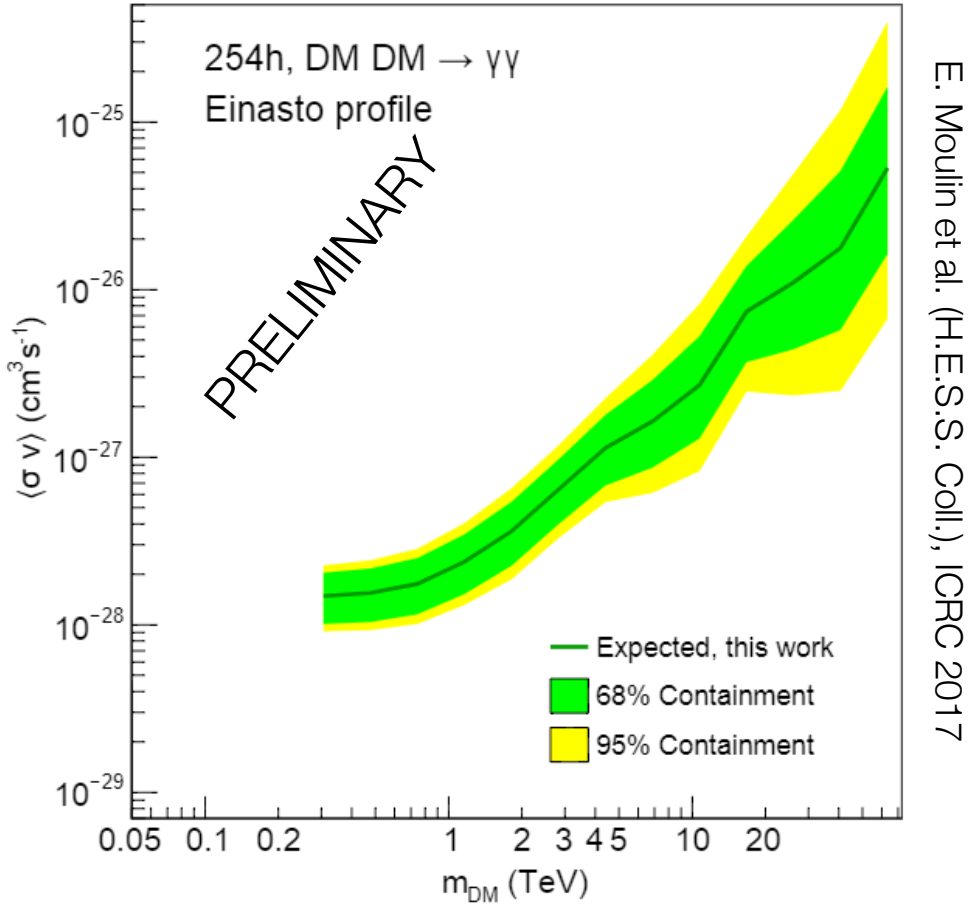
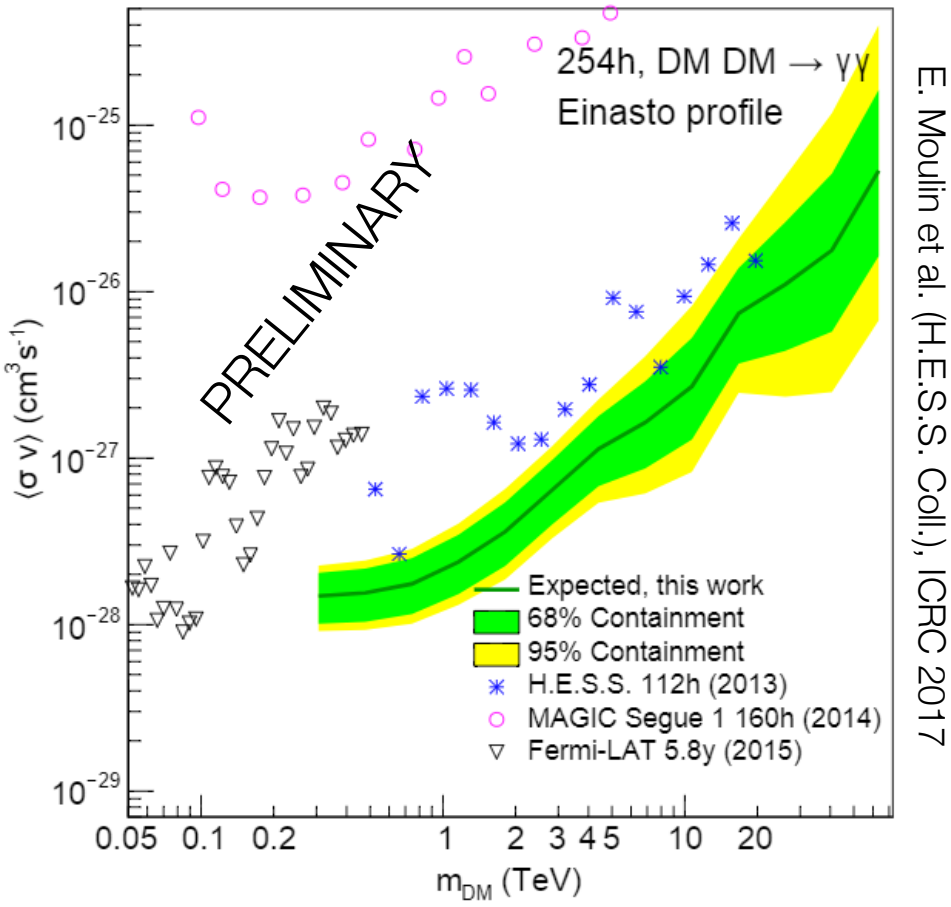


E. Moulin et al. (H.E.S.S. Coll.), ICRC 2017

- Best sensitivity $2\times10^{-28}\,cm^3s^{-1}$ @1TeV
- Mass range extended down to 300 GeV and up to 70 TeV

Constraints on the DM line signal (3)

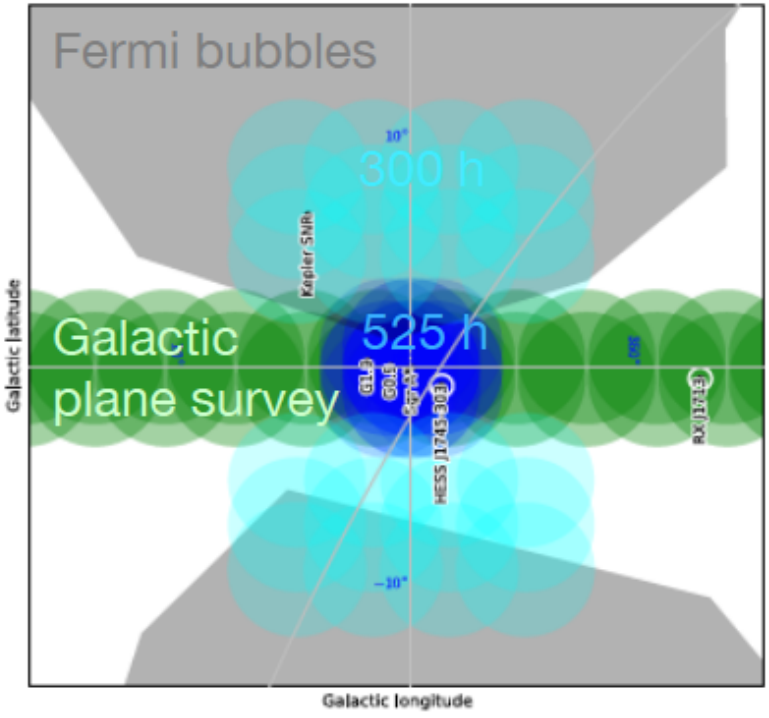
- 2D likelihood analysis with spectral and spatial information of signal and background
- No significant excess if found in any of the 7 ROIs
  → Upper limits derived through a likelyhood ration test statistics

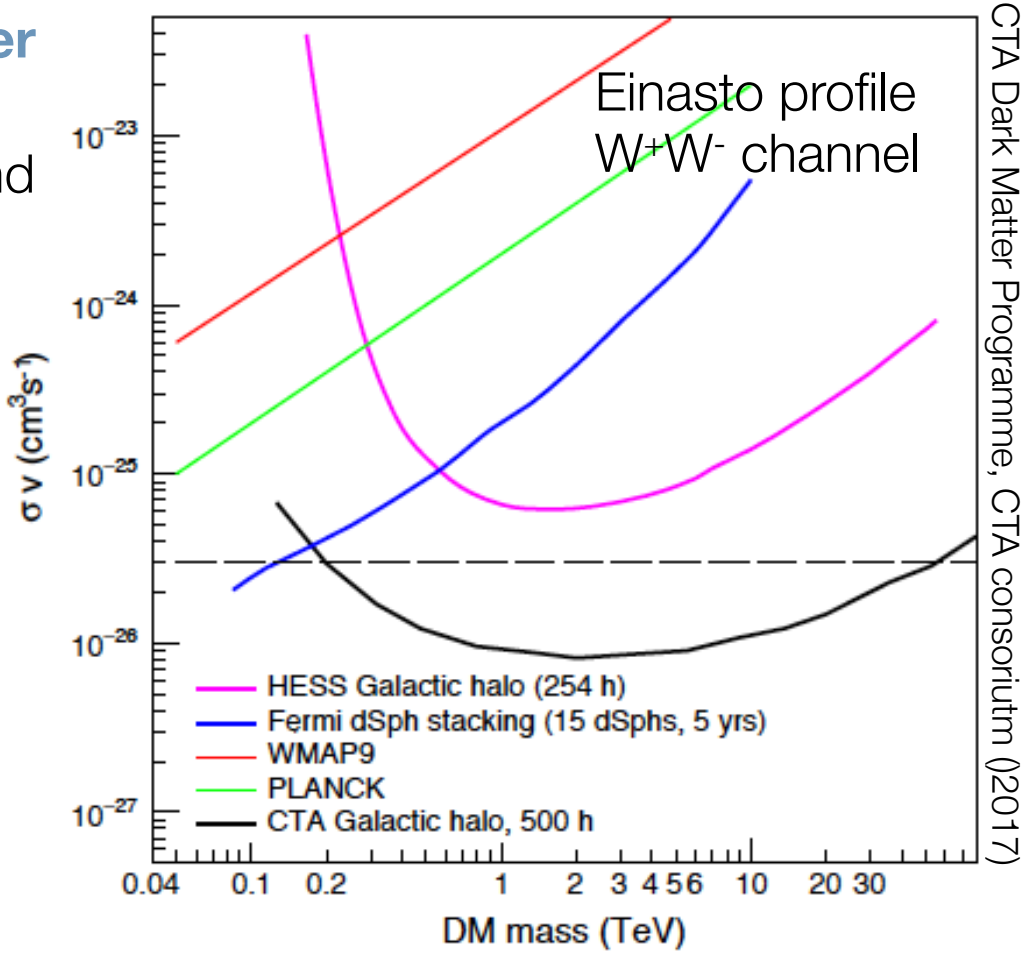


- Best sensitivity $2\times10^{-28}cm^3s^{-1}$ @1TeV
- Mass range extended down to 300 GeV and up to 70 TeV
- Fermi-LAT limits surpassed of a factor about 6 @300 GeV

Dark matter at the GC halo with CTA

- **Priority target in the CTA Dark Matter programme**
  - Fair balance between brightness and robustness





- **CTA is a unique player for TeV dark matter with great discovery possibility**

Summary and outlook

- The Galactic Centre is an interesting and very complex region in VHE gamma-rays
  - Large dataset and improved analysis from the H.E.S.S. observations over more than 10 years has allowed a deep analysis of this region
  - Spectral and spatial morphology of the diffuse emission detected suggests a continuous injection of cosmic rays from the central source
    - strongly suggests that SMBH Sgr A* is a hadronic cosmic-ray accelerator
    - *first* Galactic Pevatron discovered

- GC is one the most important target for dark matter detection
  - It provides the strongest dark matter contraints in the TeV dark matter mass range

- The H.E.S.S. Inner Galaxy Survey started in 2015 will allow to significantly the photon statistics in the inner 5 degrees of the GC

- The inner Galactic halo region is the priority target in the CTA KSP dark matter programme