The Galactic Centre as a powerful Pevatron

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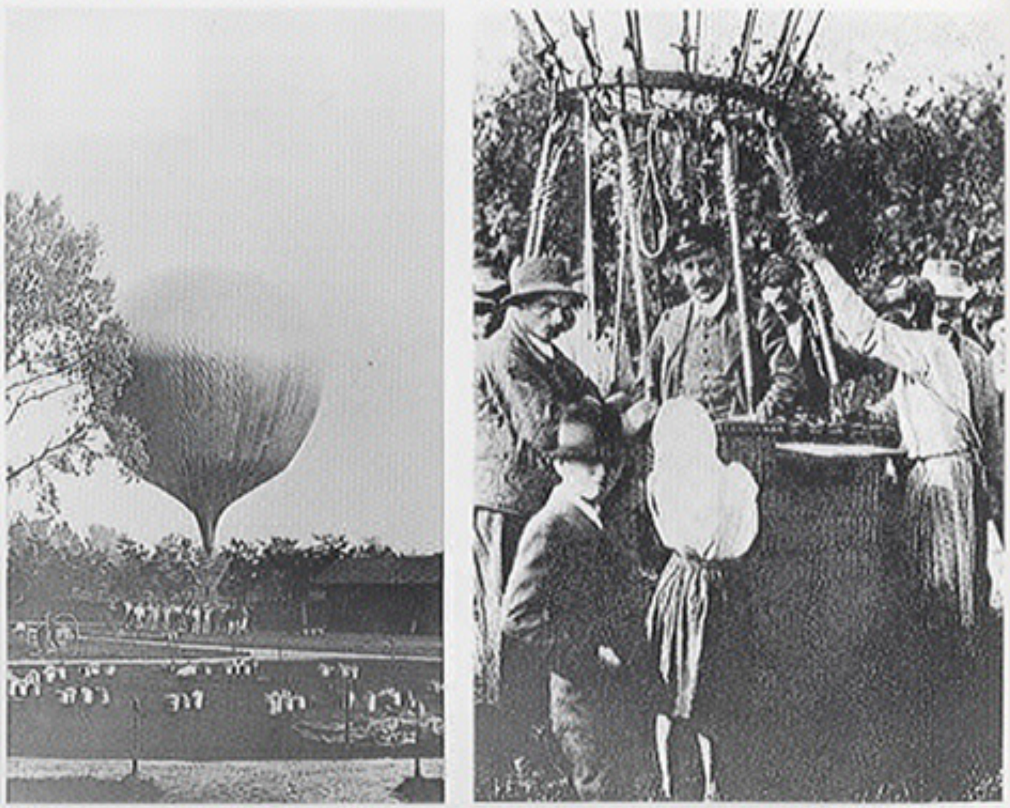
Presentation outlines

1. The Origin of Cosmic Rays and high-energies gamma-ray astronomy
2. Galactic Center region at high energies
3. Galactic Centre as a powerful Pevatron
4. Next steps and future with CTA
5. Summary and outlook

1. The Origin of Cosmic Rays and high-energies gamma-ray astronomy

The Origin of Cosmic-rays

- High energy cosmic particles continuously arriving on Earth, discovered by V. Hess in 1912



(*a*) (*b*)

Figure 1.3. The balloon flights of Victor F. Hess. (*a*) Preparation for one of his flights in the period 1911–12. (*b*) Hess after one of the successful balloon flights in which the increase in ionisation with altitude through the atmosphere was discovered. (From Y. Sekido and H. Elliot (eds) (1985). *Early history of cosmic ray studies*, Dordrecht: D. Reidel Publishing Company.)

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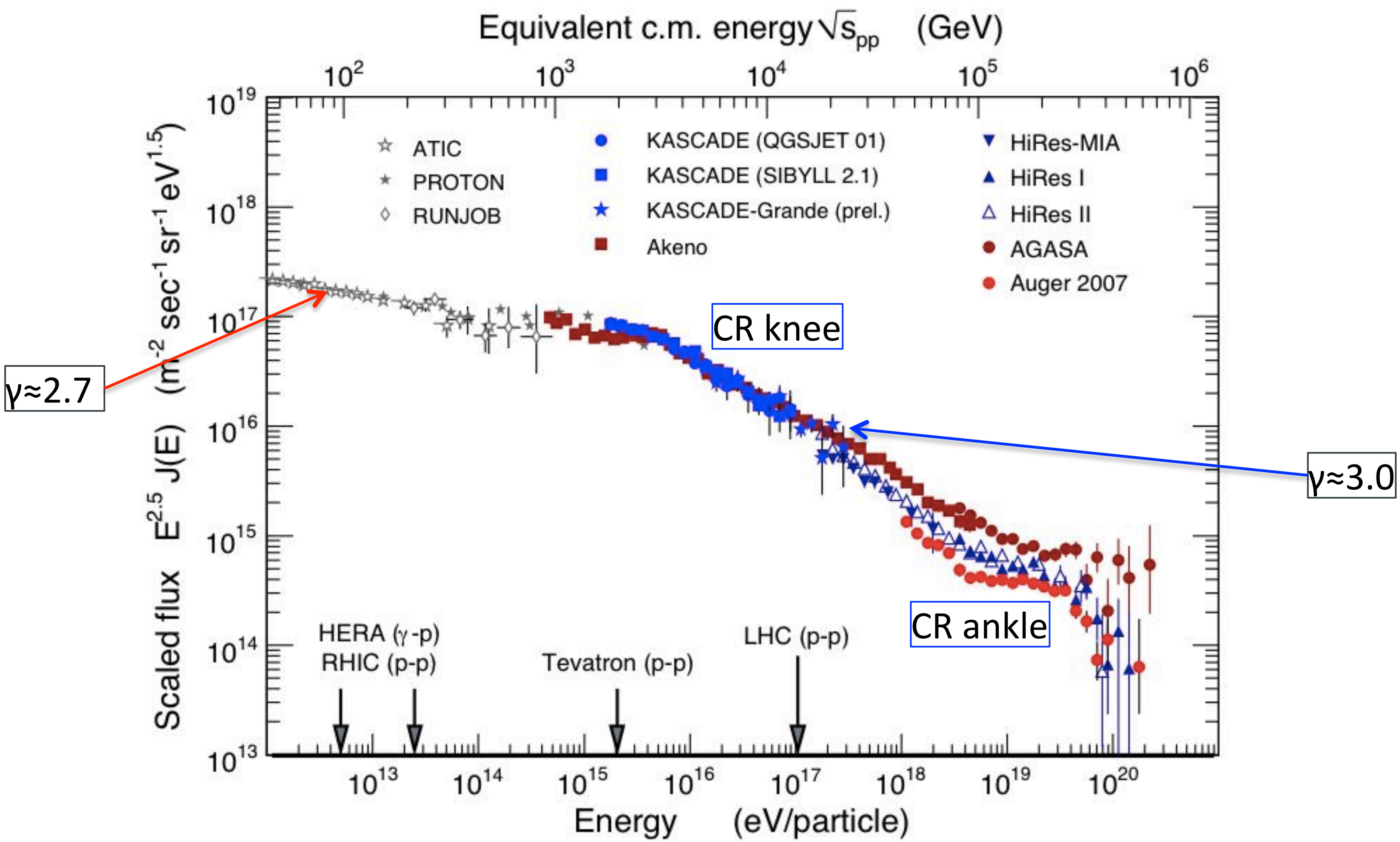
- 89% protons, 9% helium, 1% electrons and extremely **isotopic** up to very high energies
- the spectrum is (ALMOST) a single power law -> CR knee at few **PeVs** + ankle at 10 EeV



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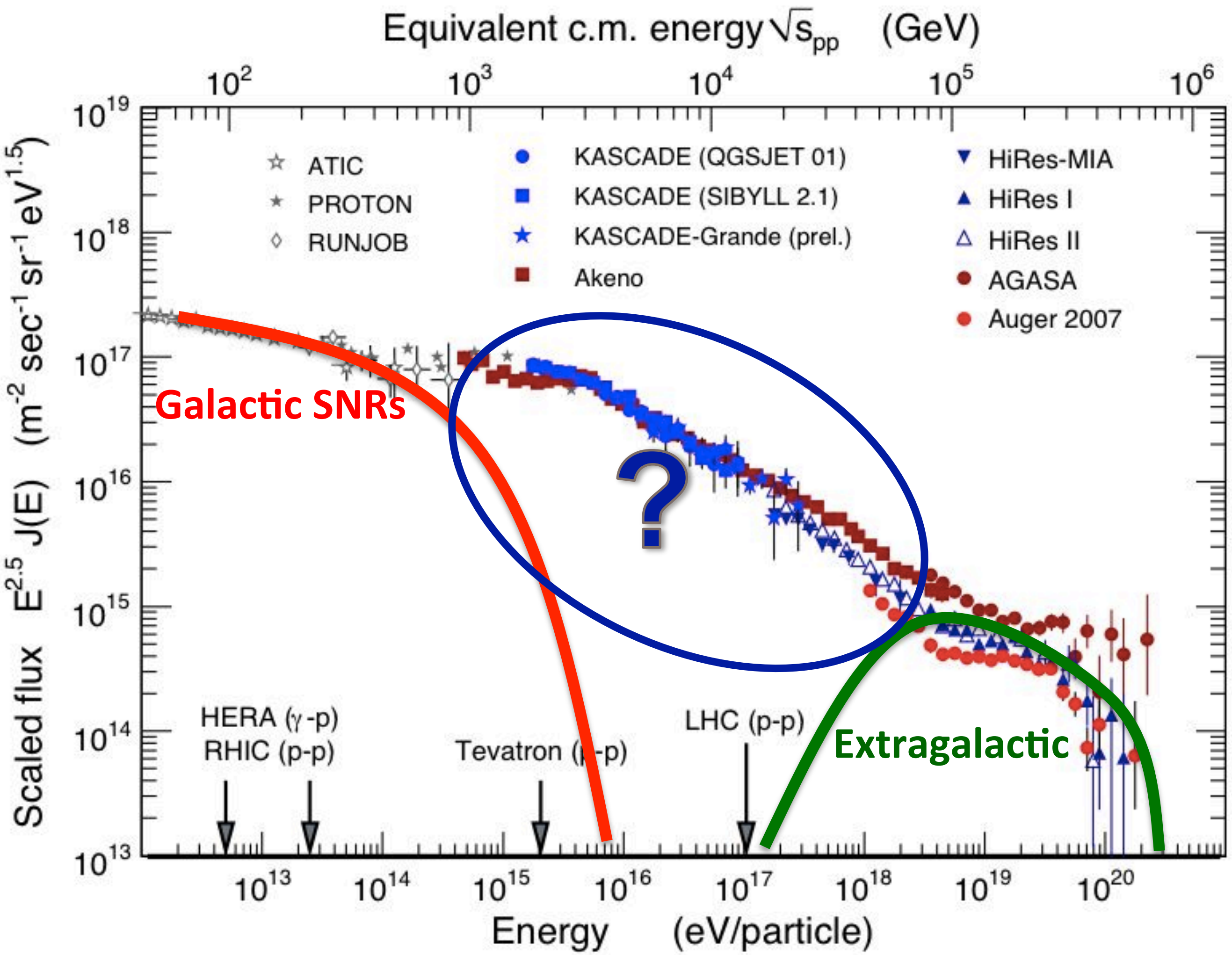

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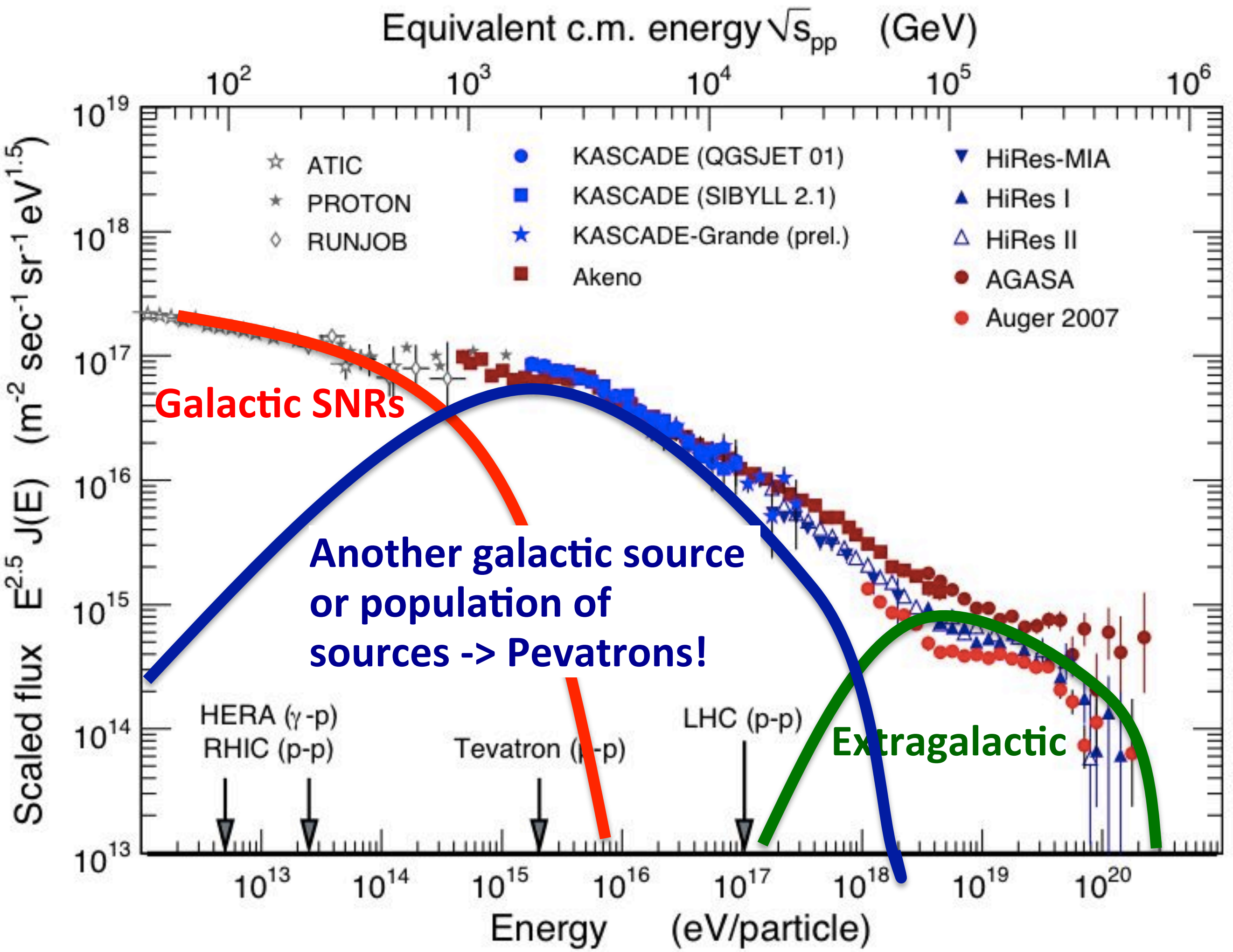

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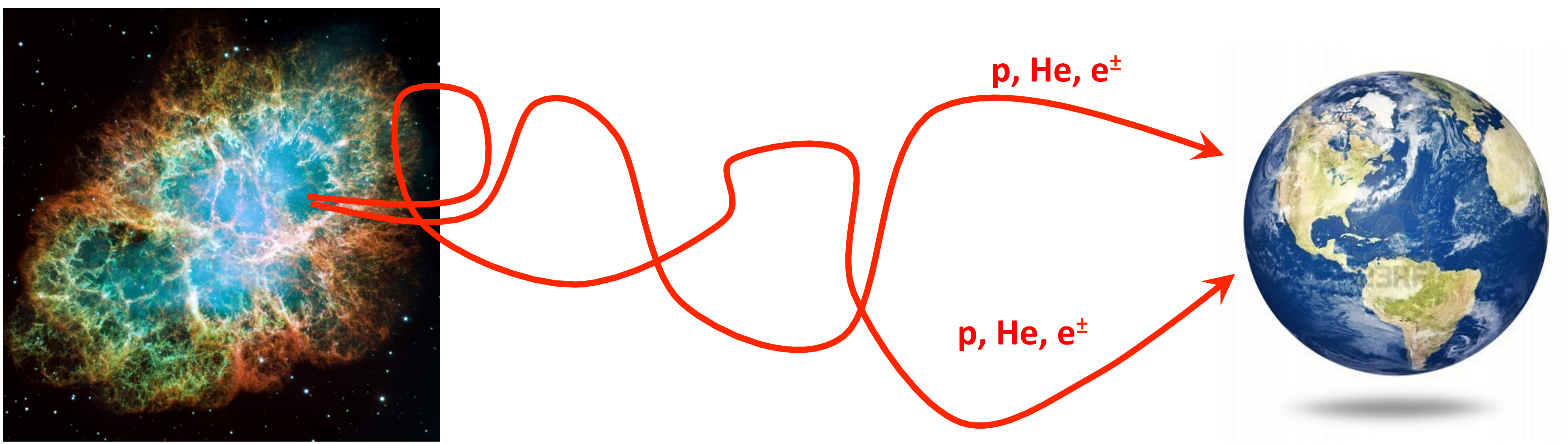

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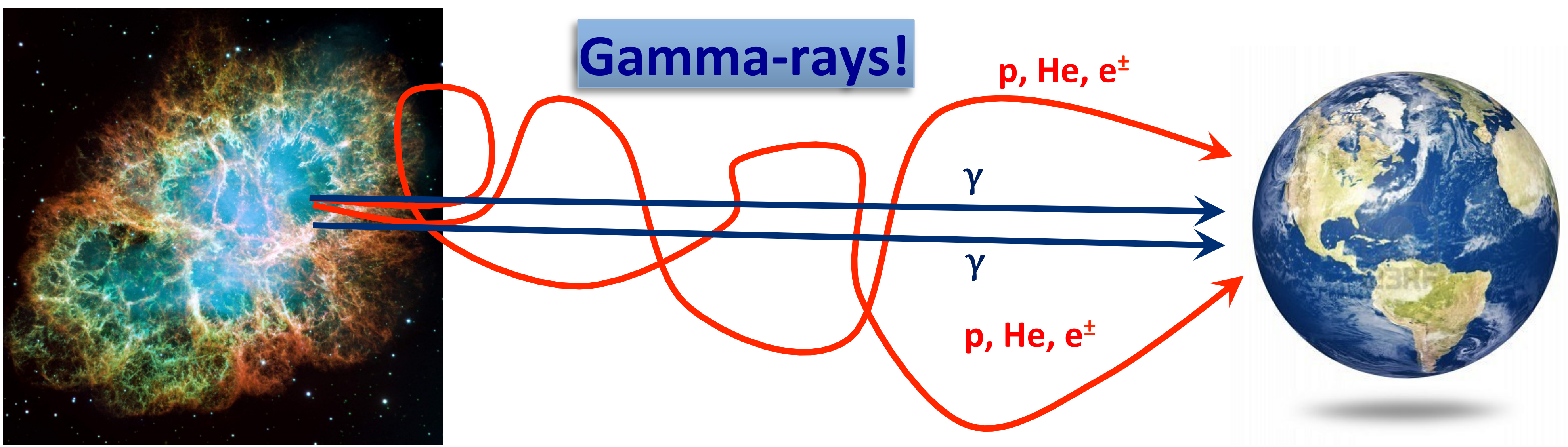
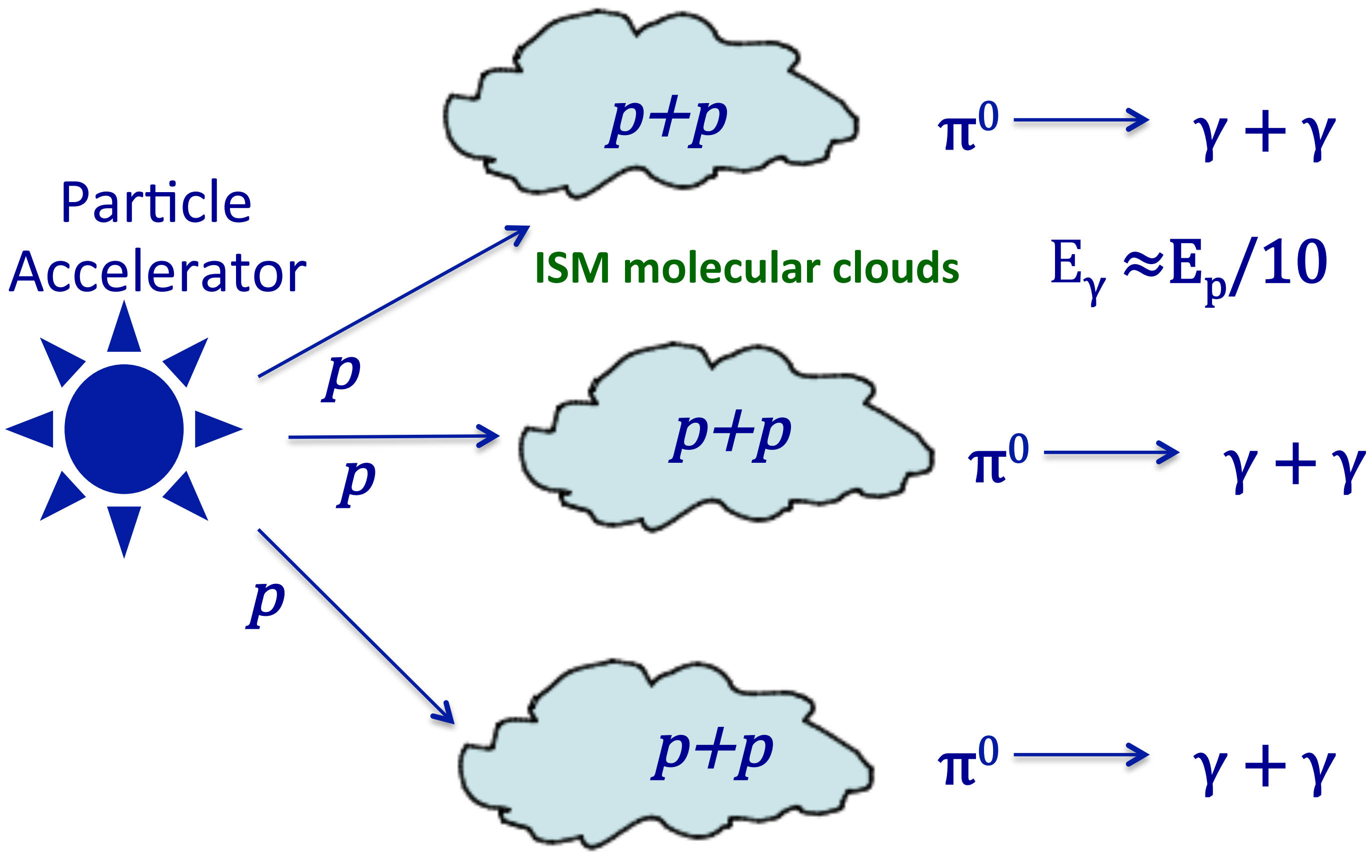
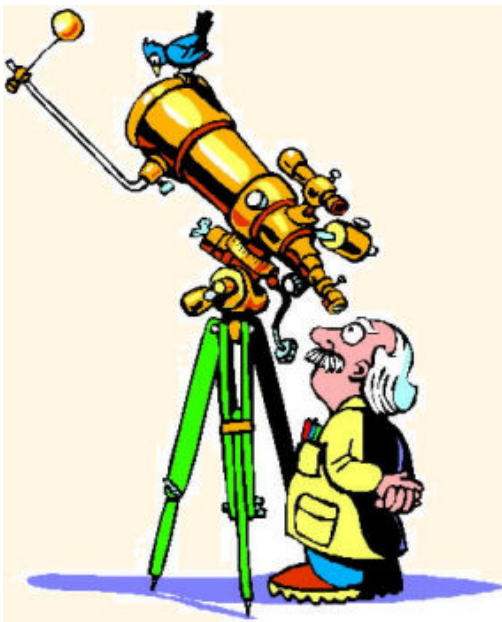


How to catch a Pevatron?

- **Gamma-ray observations is the most powerful tool to detect PeVatrons**
- **We use molecular clouds as a cosmic-ray barometer**

- $E_\gamma \approx E_p/10$ **=> need TeV gamma-rays to identify PeV protons**





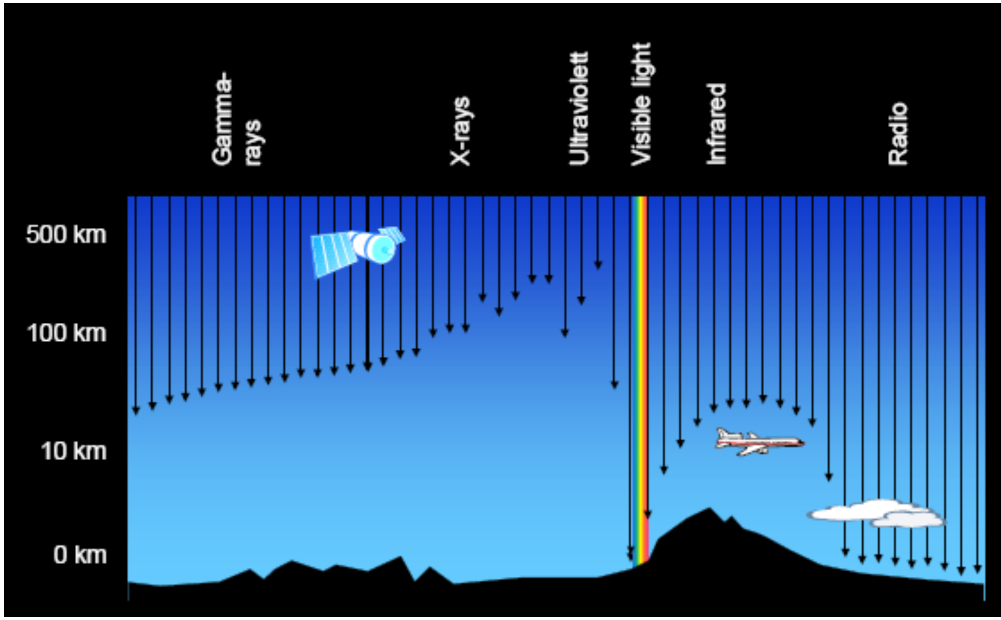
Very high energy gamma-ray astronomy

- **Gamma-ray production by non-thermal processes**
  - Hadronic processes (accelerated protons): pion decay
  - Leptonic processes (accelerated electrons): Synchrotron radiation, Bremstrahlung and inverse Compton
  - Self-annihilation or decay of large mass particles (dark matter)

$$pp \rightarrow \pi^0 + \ldots \rightarrow \gamma\gamma$$
$$p + \text{nucleus} \rightarrow \pi^0 + \ldots \rightarrow \gamma\gamma$$

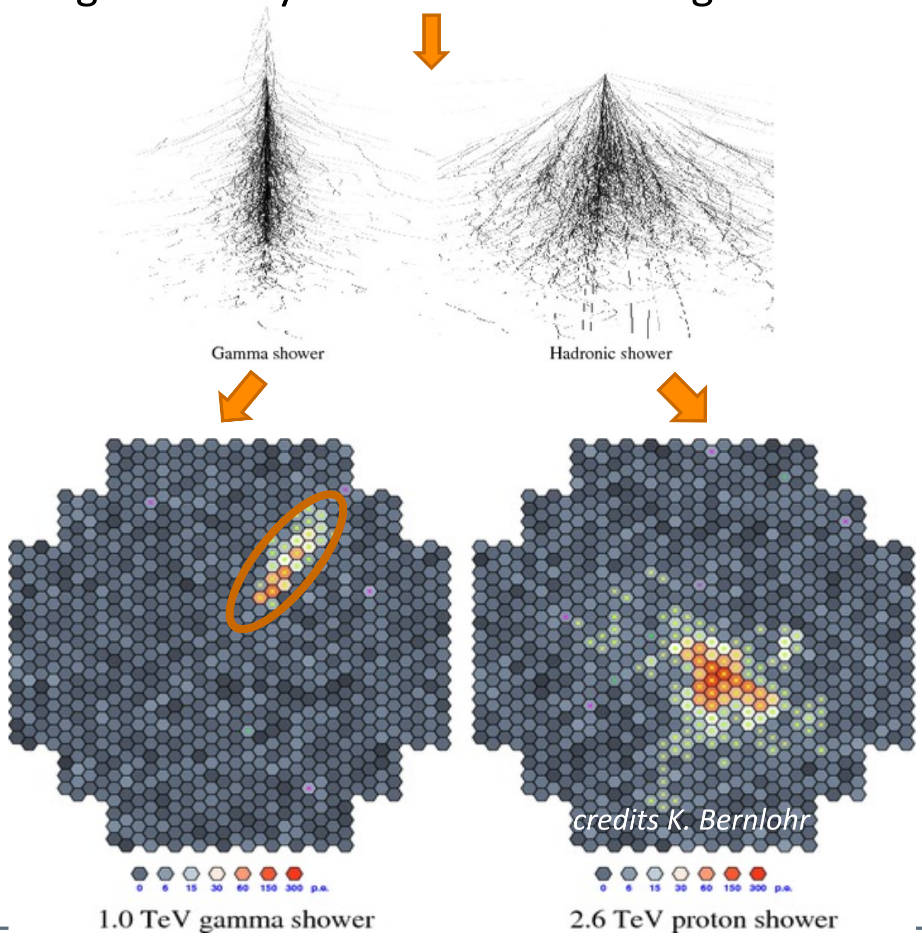
$$e^{\pm} \xrightarrow{\text{Synchrotron}} \gamma$$
$$e^{\pm} \xrightarrow{\text{Bremsstrahlung}} \gamma$$
$$e^{\pm} \xrightarrow{\text{Inverse Compton}} \gamma$$

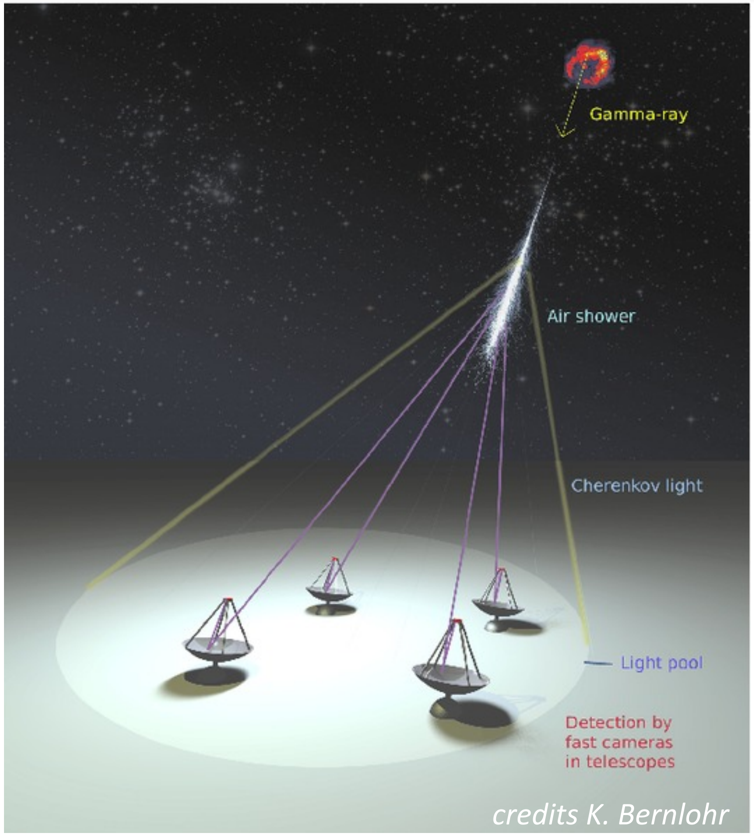
- **Detection:**
  - Gamma-rays interact with the atmosphere
  - Satellites detection up to ~100 GeV (Fermi)
  - Above 100 GeV : ground based Cherenkov telescopes (indirect detection)



Imaging Atmospheric Cherenkov Telescopes technique

- Interaction of gamma-rays in the atmosphere
- Particles shower developpement : **Cherenkov light emission** in cone of angle α ~ 1.0˚
- **Discrimination** between showers initiated by hadrons and gamma-rays based on their image on the cameras





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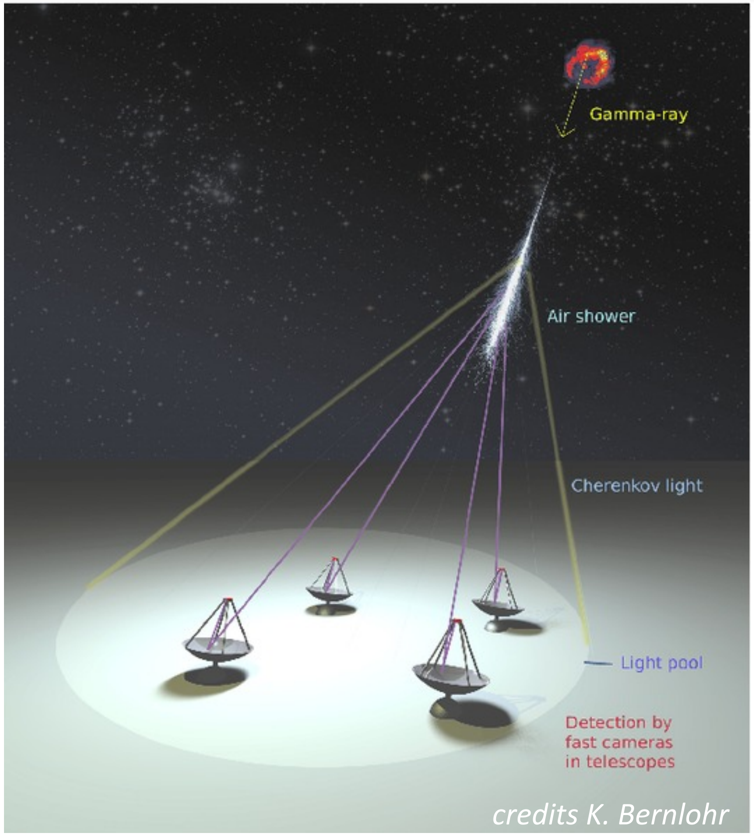
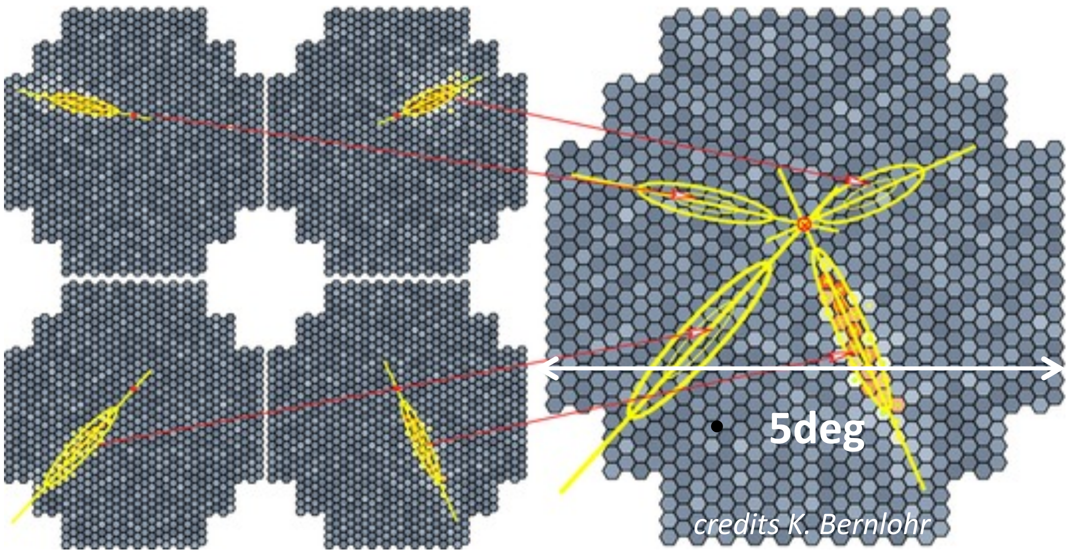
- **Stereoscopic** technique improves primary particle direction reconstruction (also improves hadron discrimination)



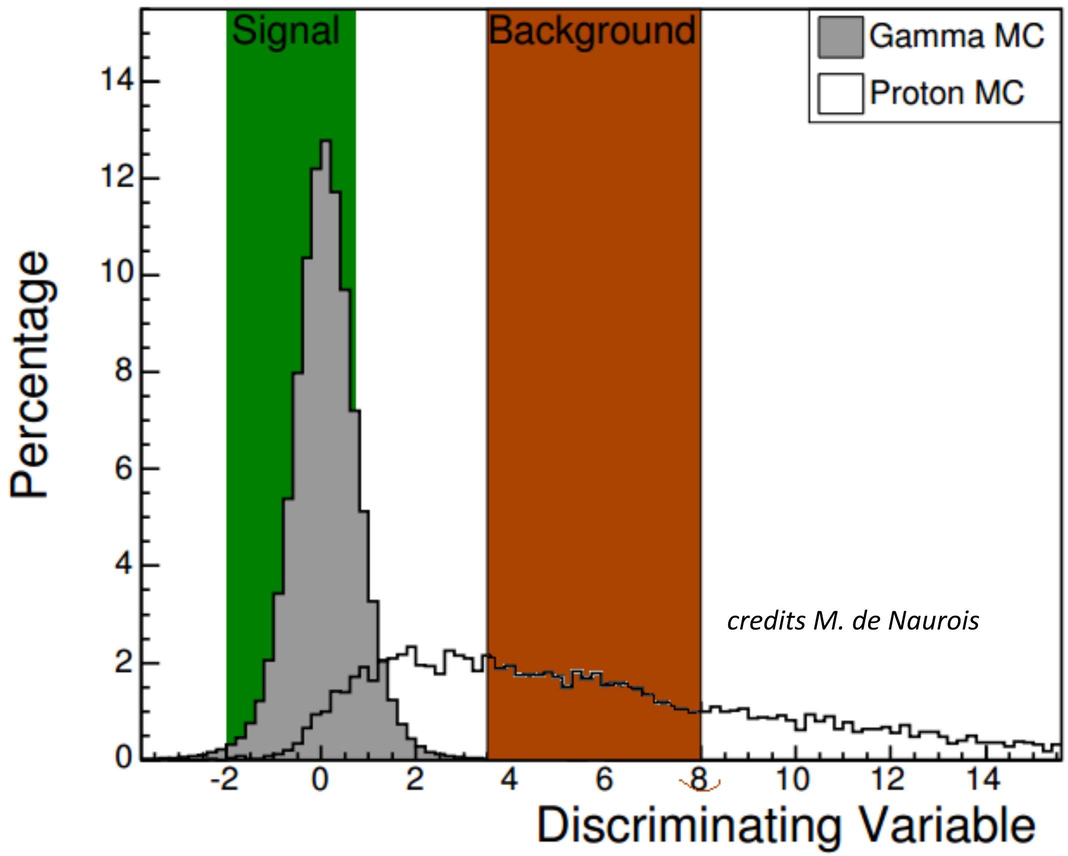


Data analysis in a nutshell : reconstruction and discrimination gamma/hadrons

- Semi-analytical « **Model** » analysis:
  - comparison of the recorded showers in the camera, with calculated shower images from a model of the Cherenkov light distribution in electromagnetic showers.

- A maximum-likelihood procedure allows to recover the best parameters of any shower:
  - Energy
  - Direction
  - Impact parameter
  - Primary interaction depth

- Discriminating variable to select gamma-like events



The current IACT world

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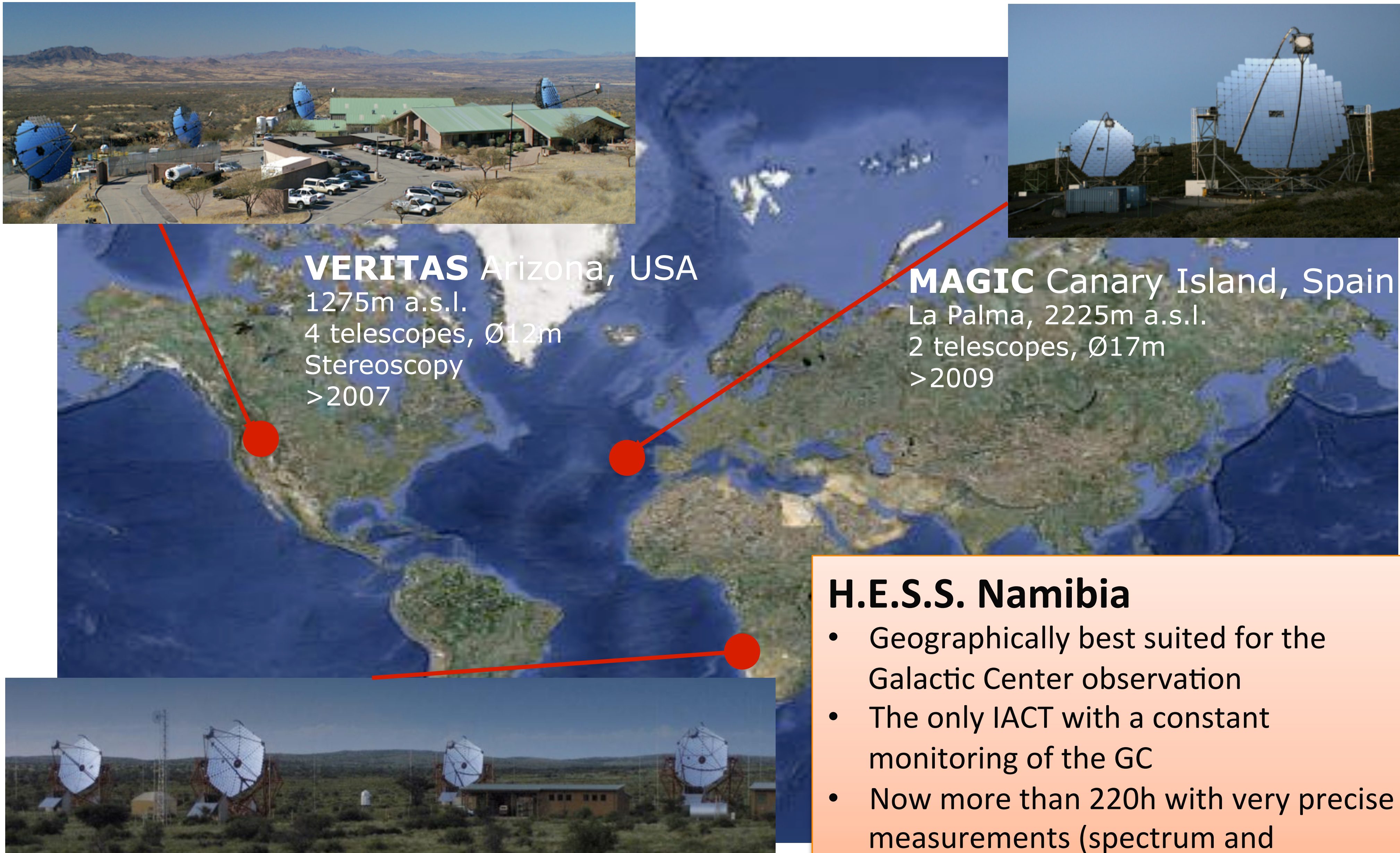

H.E.S.S. Namibia

- Geographically best suited for the Galactic Center observation
- The only IACT with a constant monitoring of the GC
- Now more than 220h with very precise measurements (spectrum and position)

The H.E.S.S. telescope array
H.E.S.S.-phase 1: 2003-2012

Array of four Imaging Atmospheric Cherenkov Telescopes
located in Namibia (1800m a.s.l.)

- 12 m diameter telescopes : 107 m^2 each
- Observations on moonless nights, ~1000h/year
- Field of view of 5° in diameter
- Stereoscopic reconstruction

- Angular resolution < 0.1°/γ
- Energy threshold (zenith) ~ 200 GeV
- Energy resolution ~ 15%

The H.E.S.S. telescope array
H.E.S.S.-phase 2: 2012

Array of FIVE Imaging Atmospheric Cherenkov Telescopes

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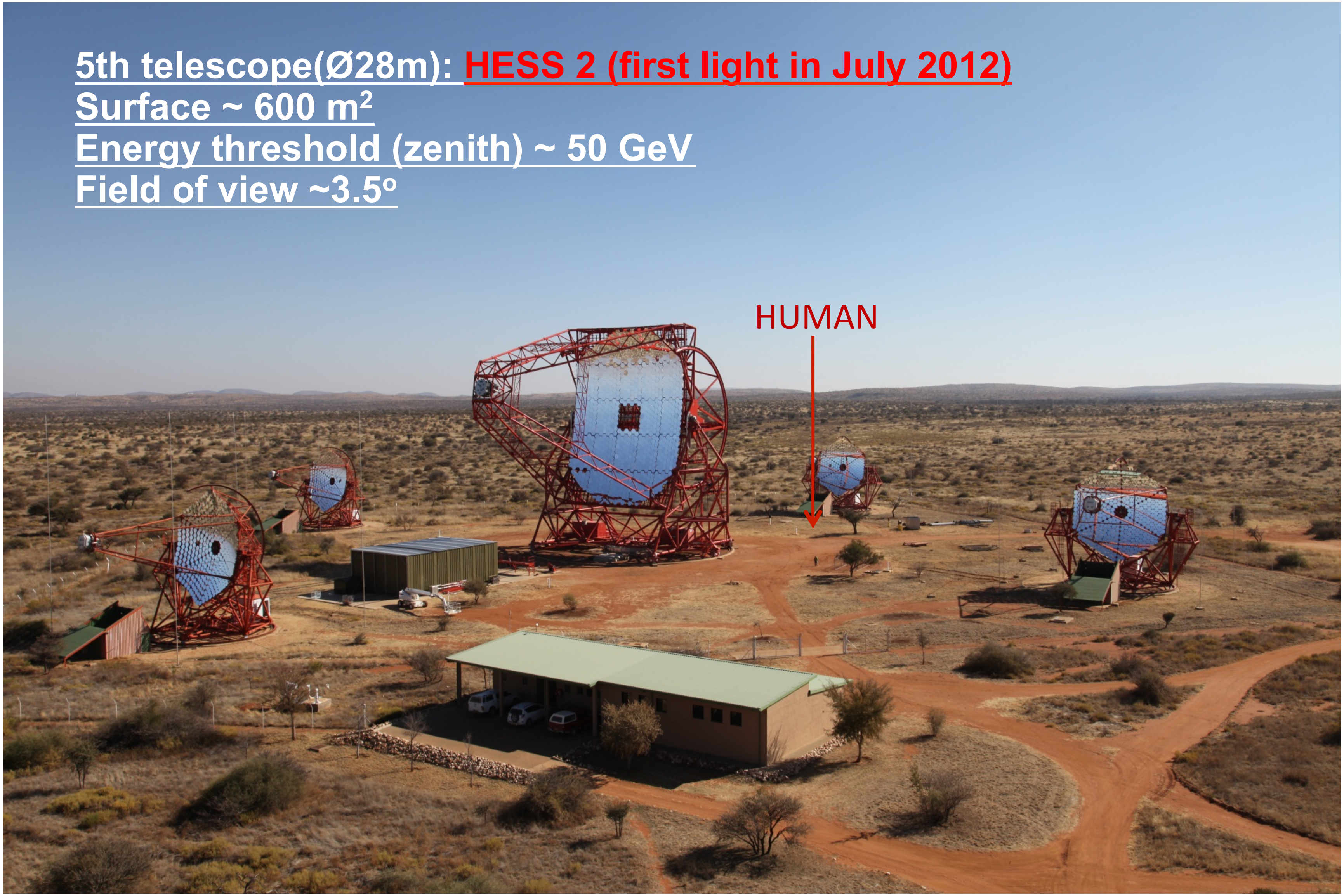
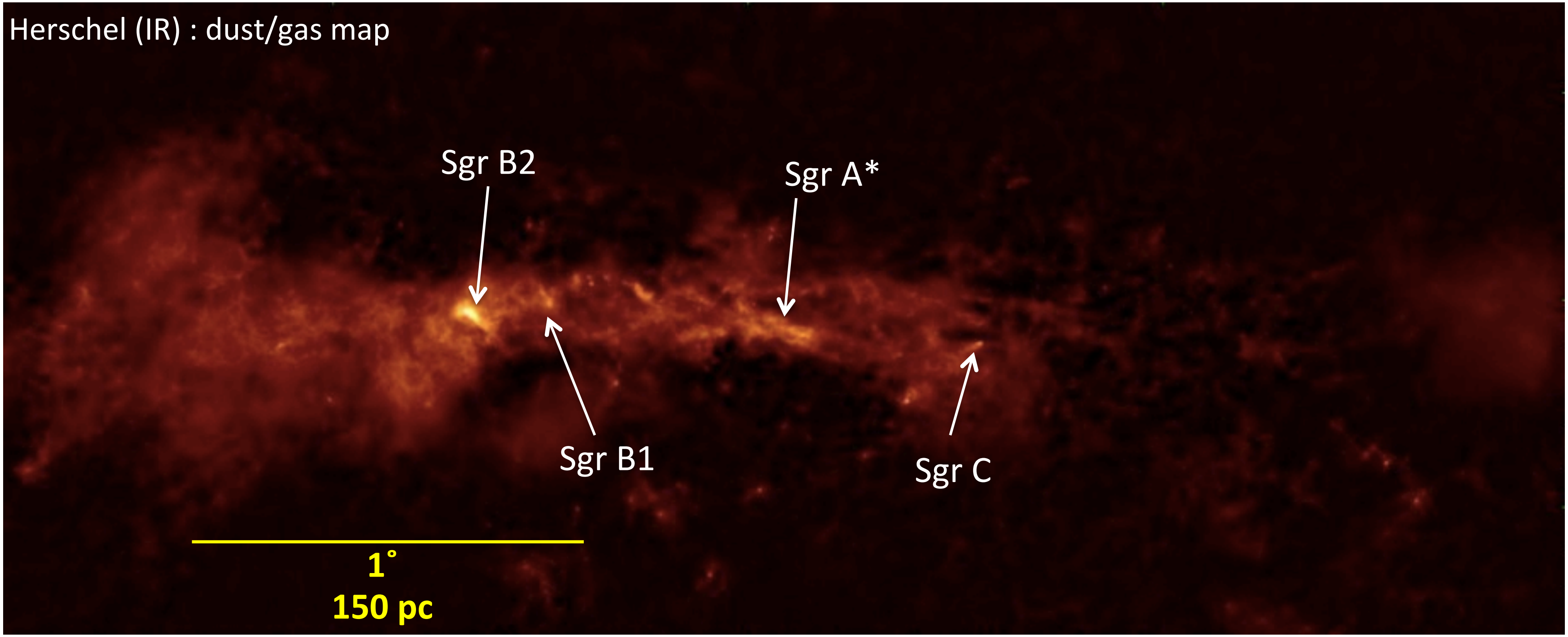


2. Galactic Center region at high energies

The Galactic Center region

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



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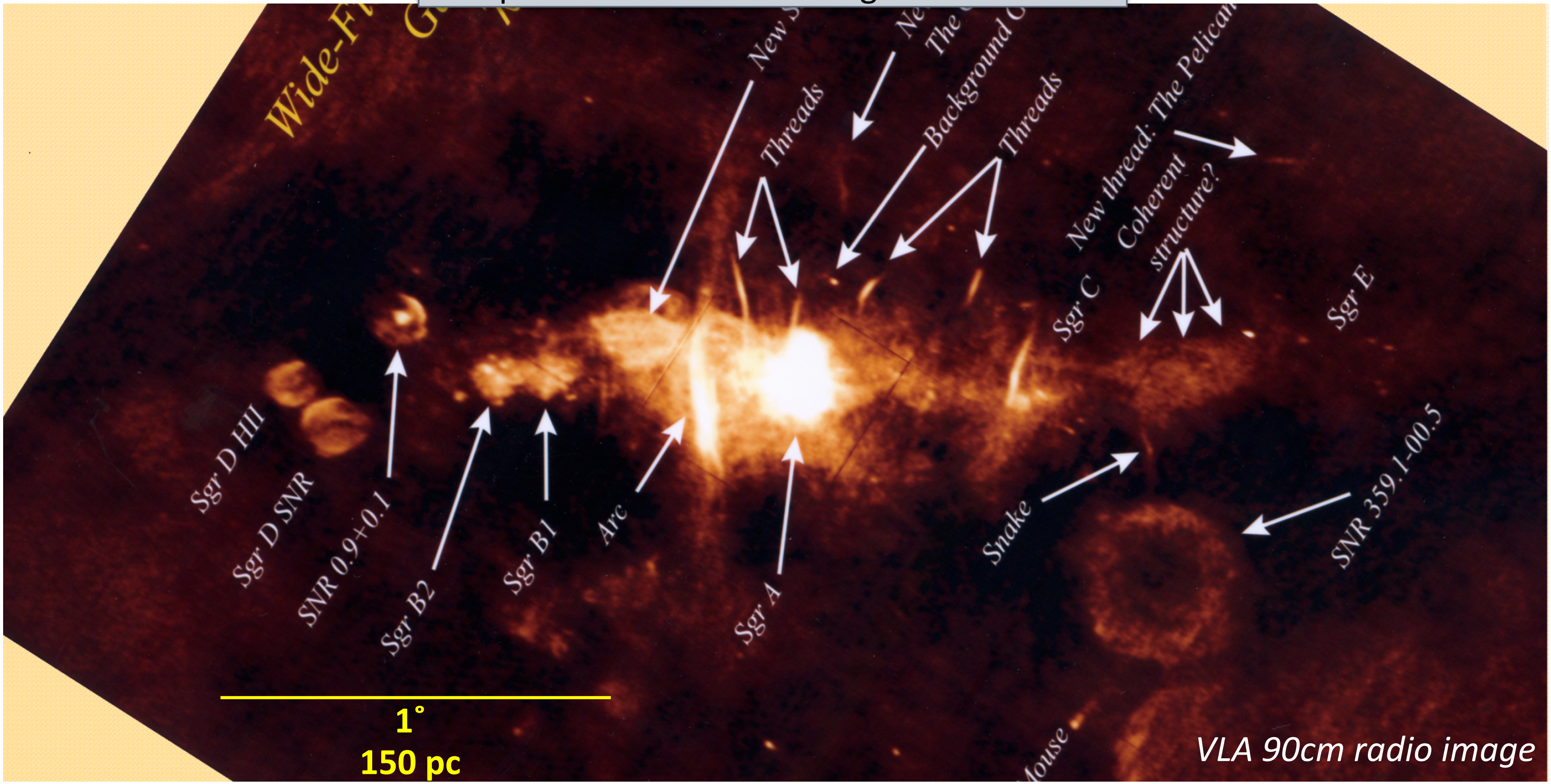
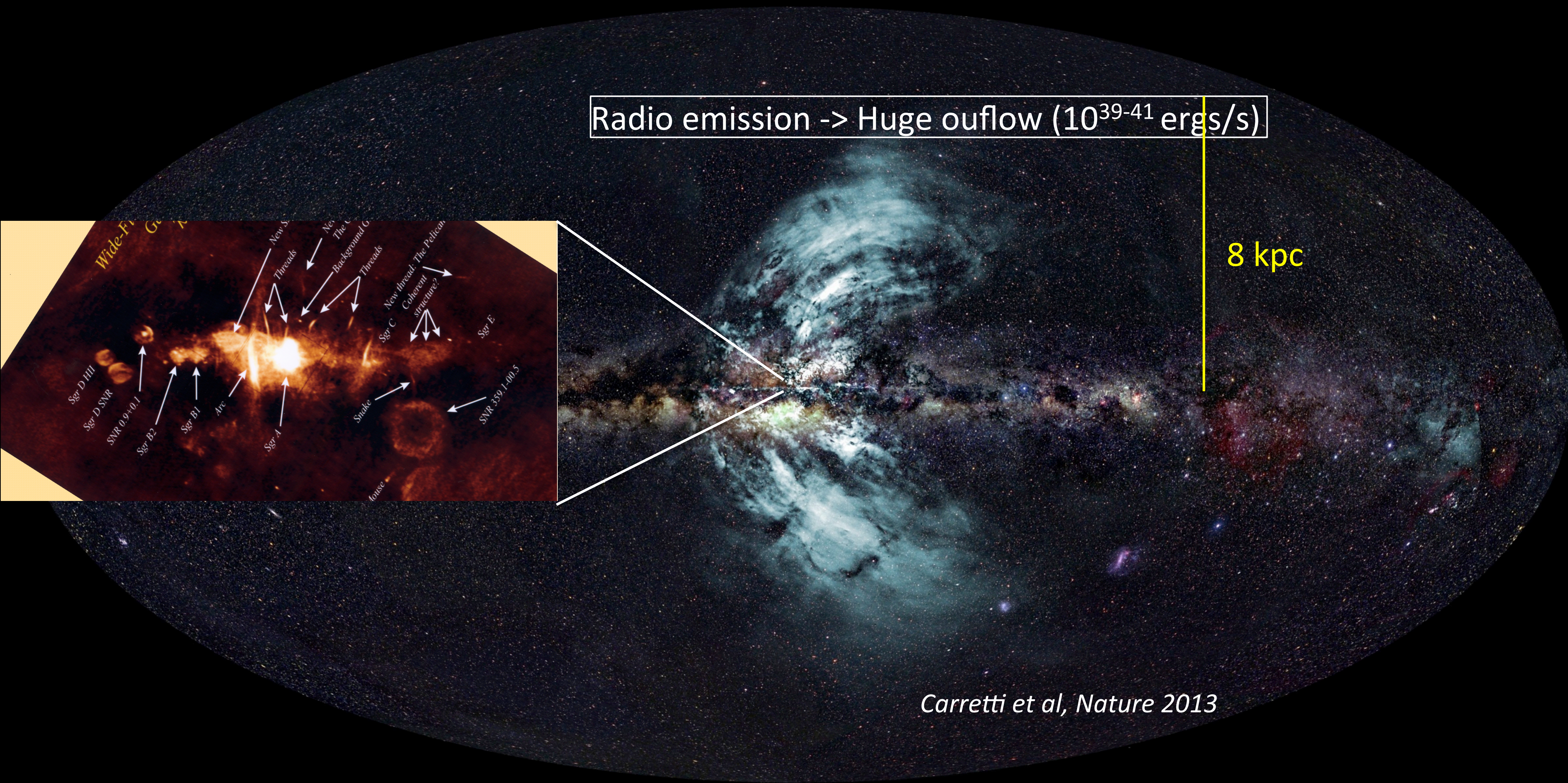
- CR accelerators: SNRs, magnetic filaments, supermassive black hole Sgr A*



Past activities of the Galactic Center

> 10^5 years timescale



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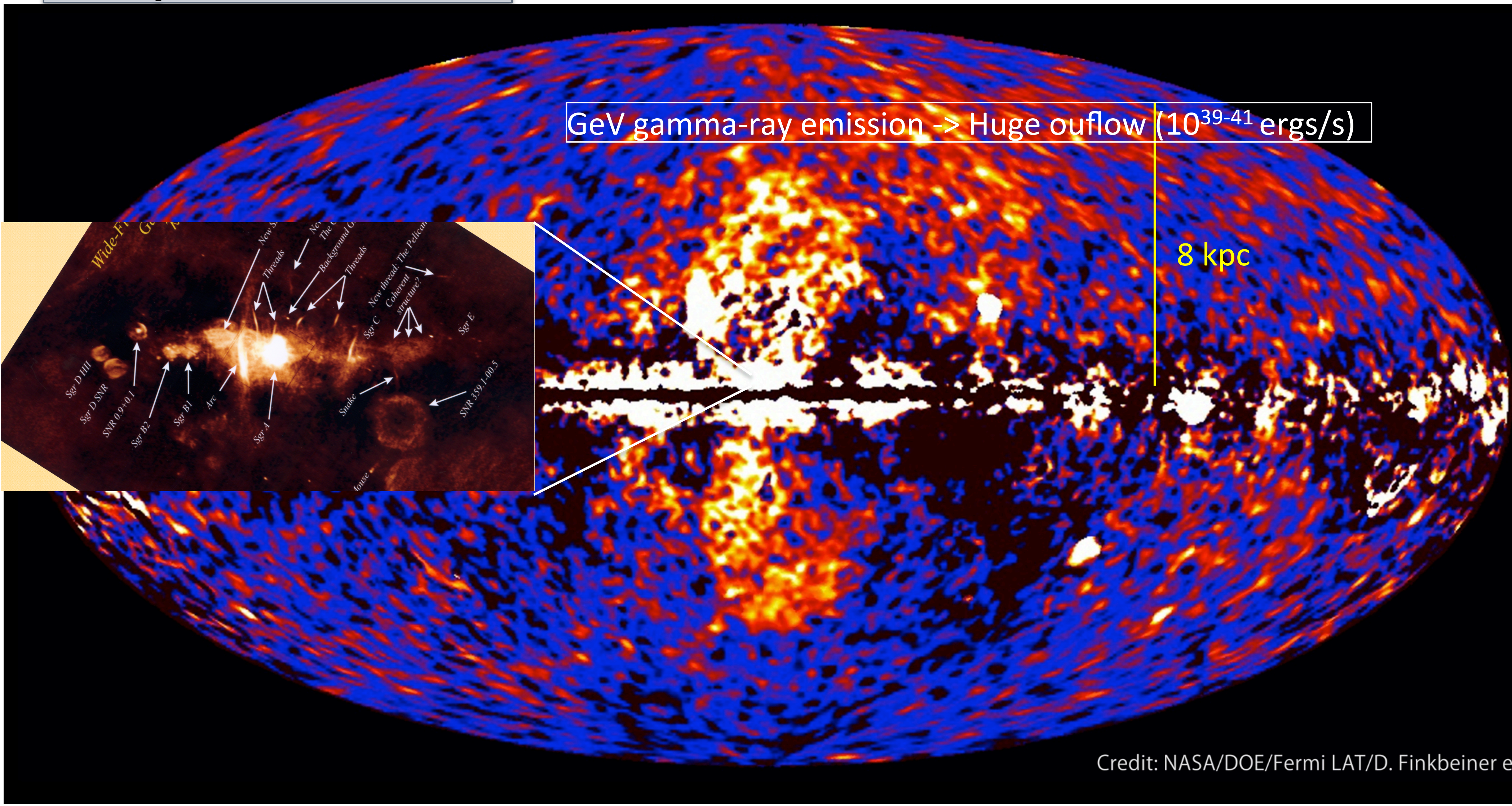

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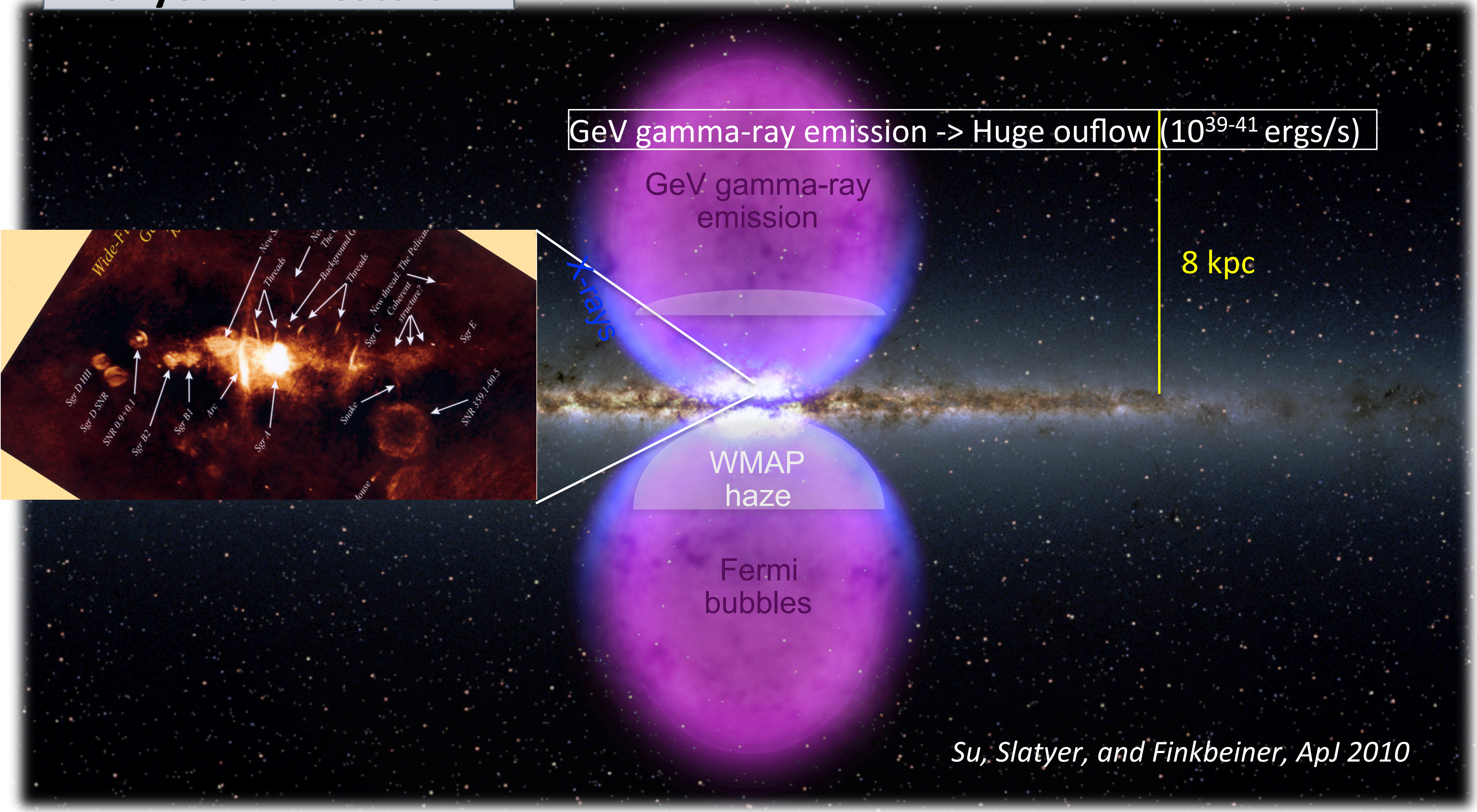

Su, Slatyer, and Finkbeiner, ApJ 2010

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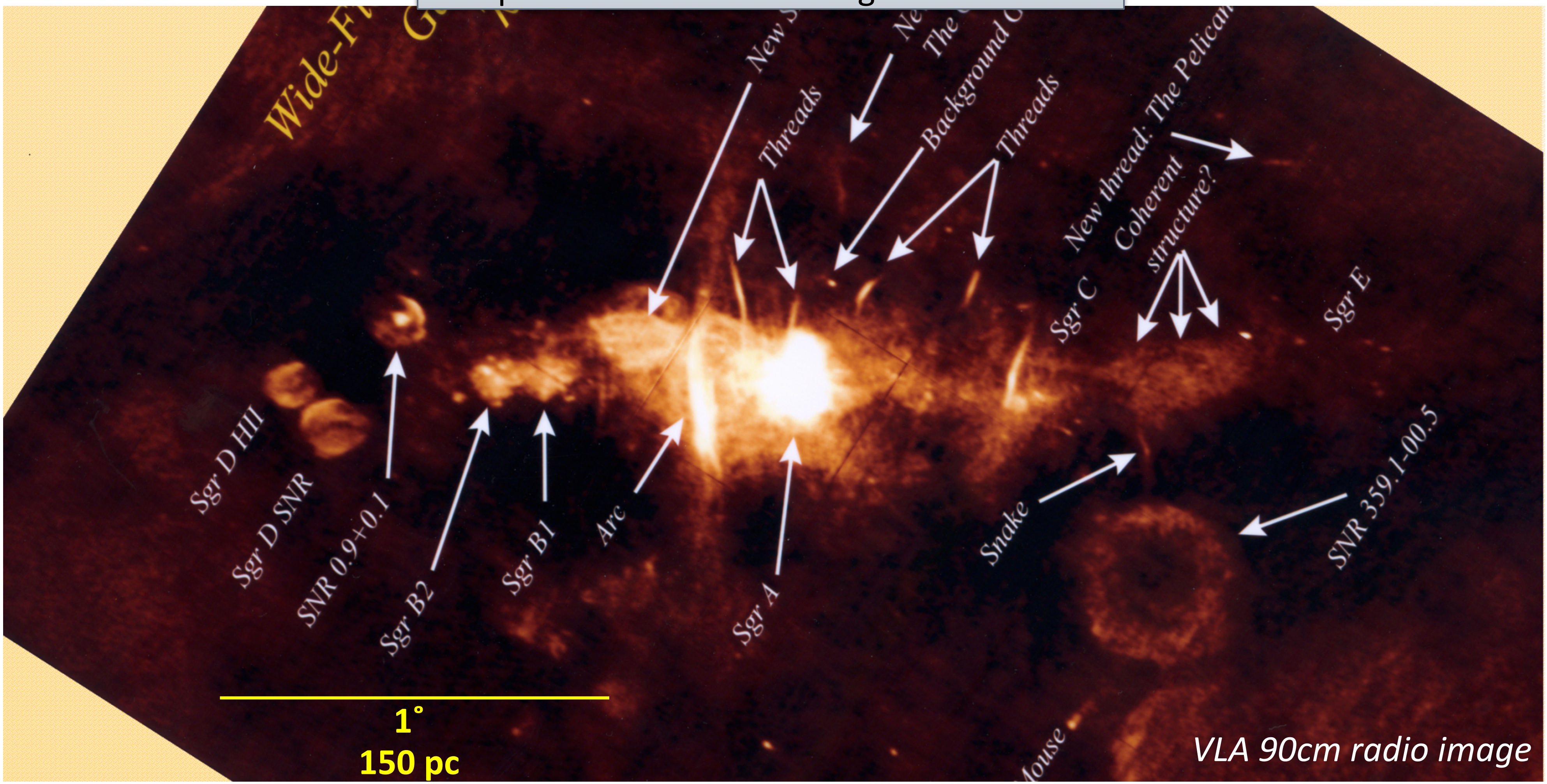
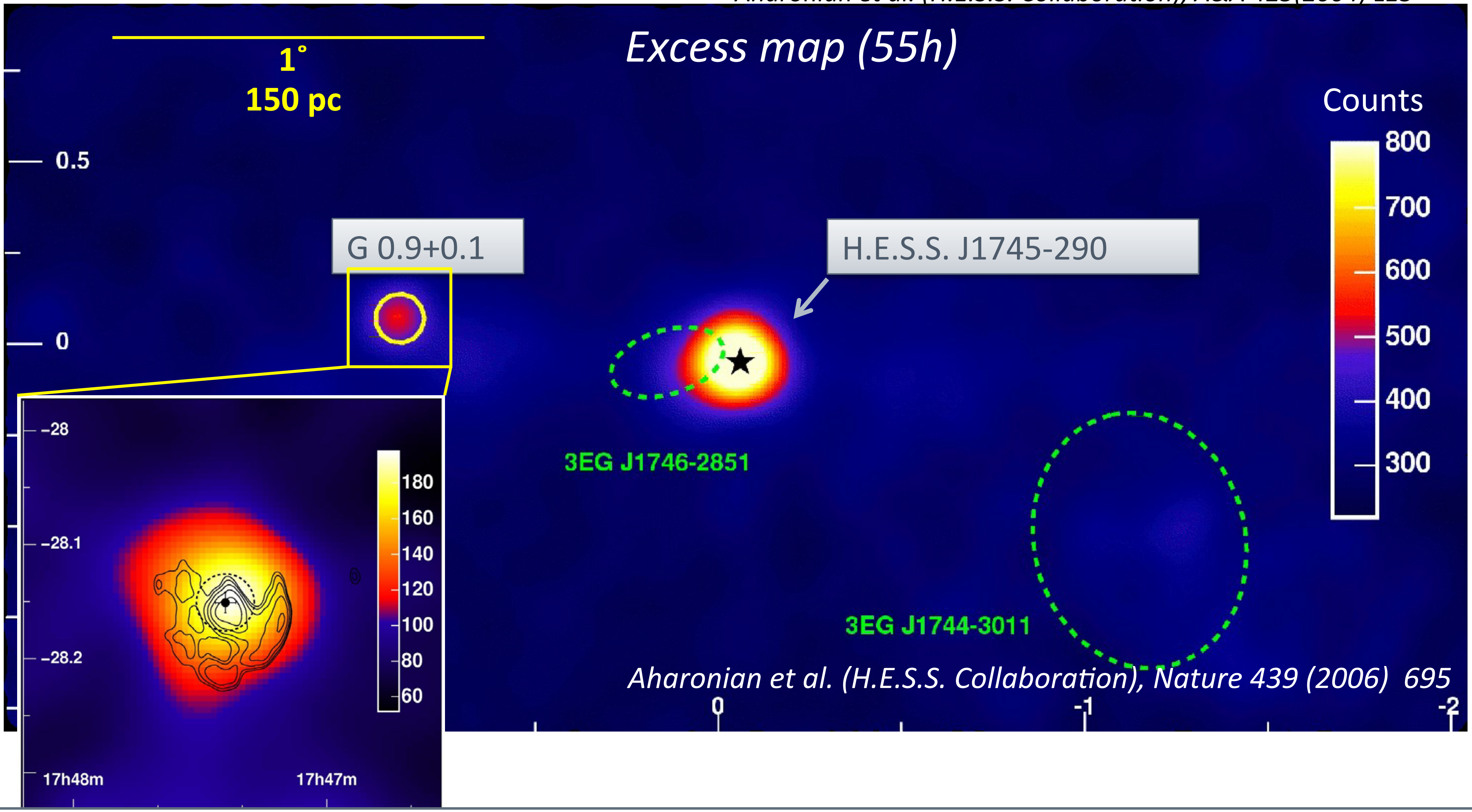


The Galactic Center region in gamma-rays: H.E.S.S. 2003-2005

Two bright point-like sources:
- G 0.9+0.1 : SNR/PWN association
-HESS J1745-290 : unidentified source

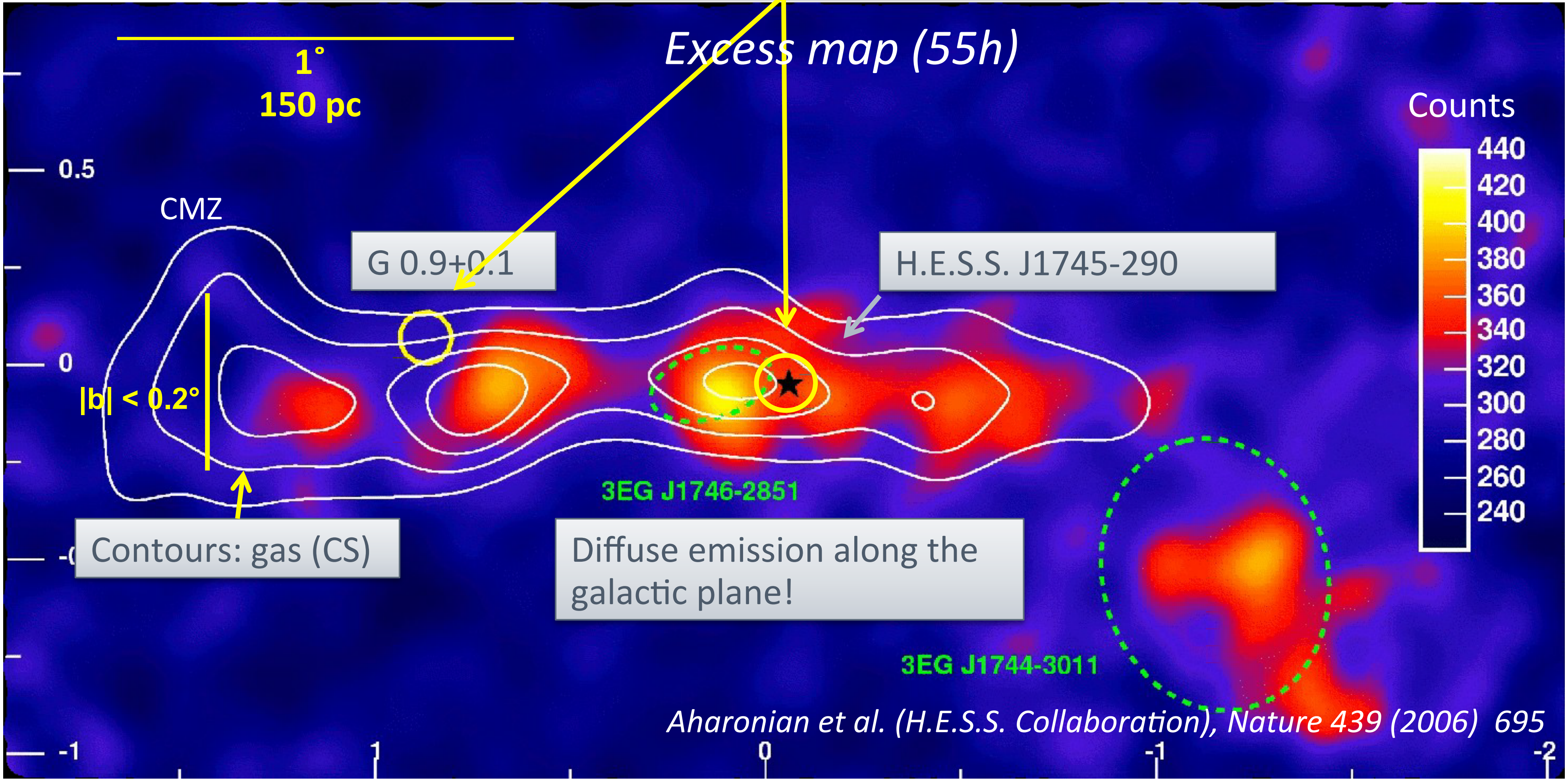
Aharonian et al. (H.E.S.S. Collaboration), A&A 425(2004) L13



Aharonian et al. (H.E.S.S. Collaboration), Nature 439 (2006) 695

The Galactic Center diffuse emission with H.E.S.S.: 2003-2005

- Search for much fainter emission
- Subtraction of the two bright sources
- Correlation of emission with molecular clouds of the Central Molecular Zone (CMZ) => hadronic origin of emission



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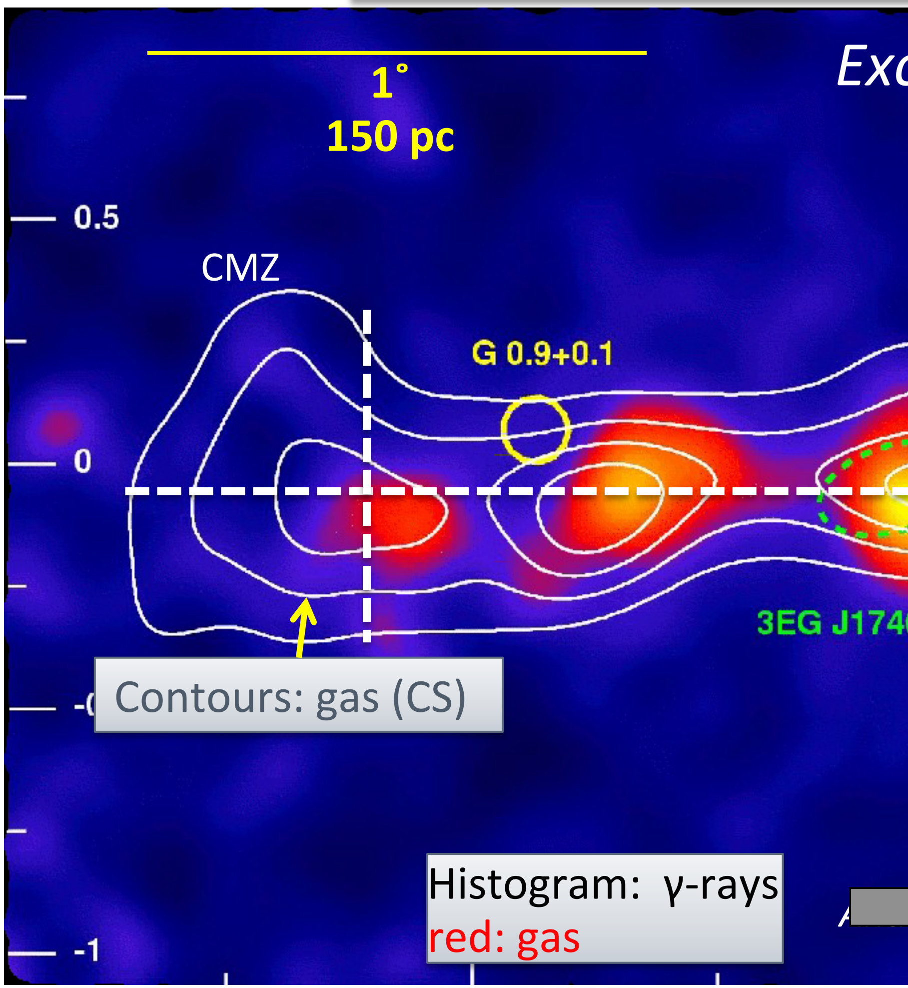
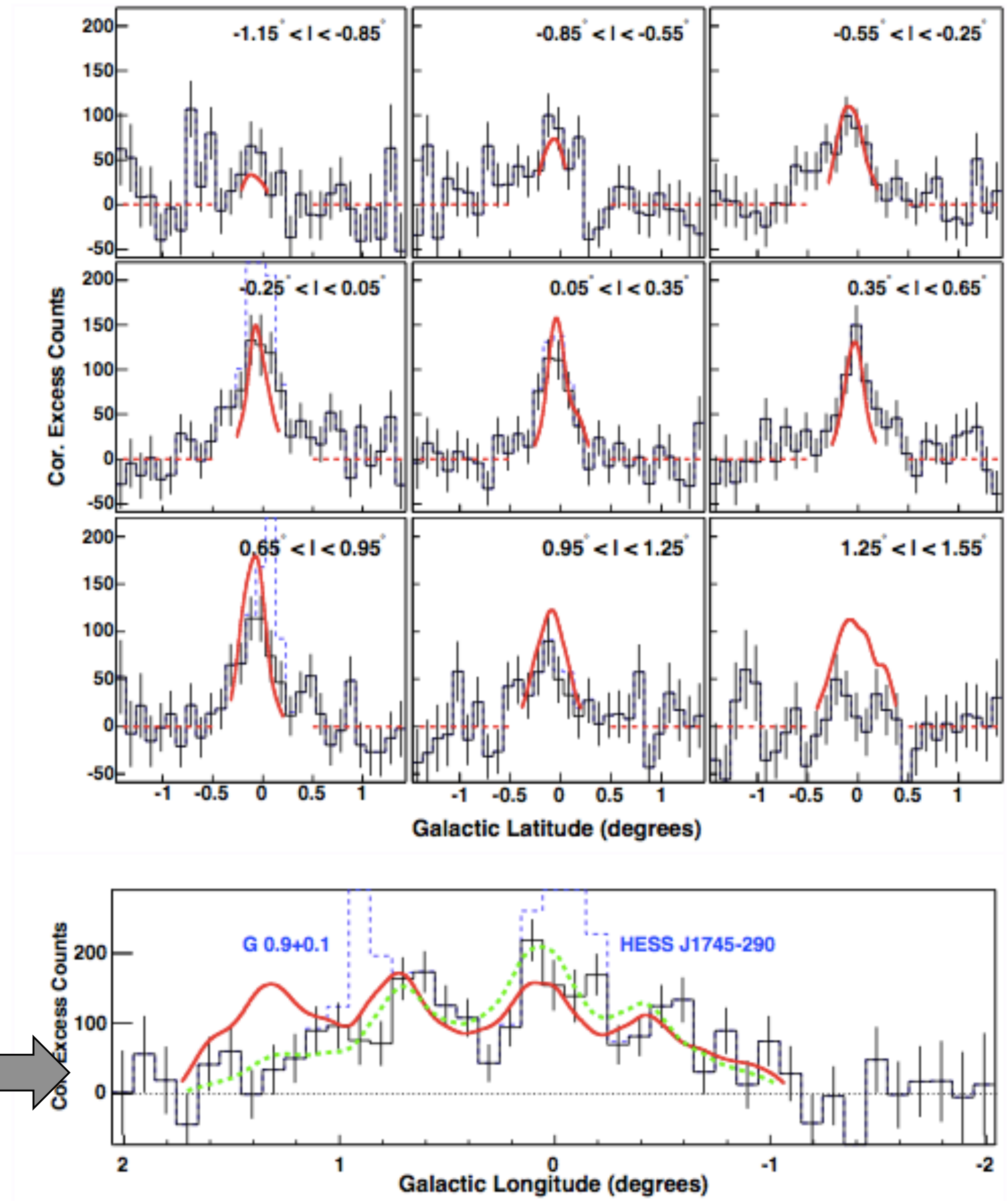
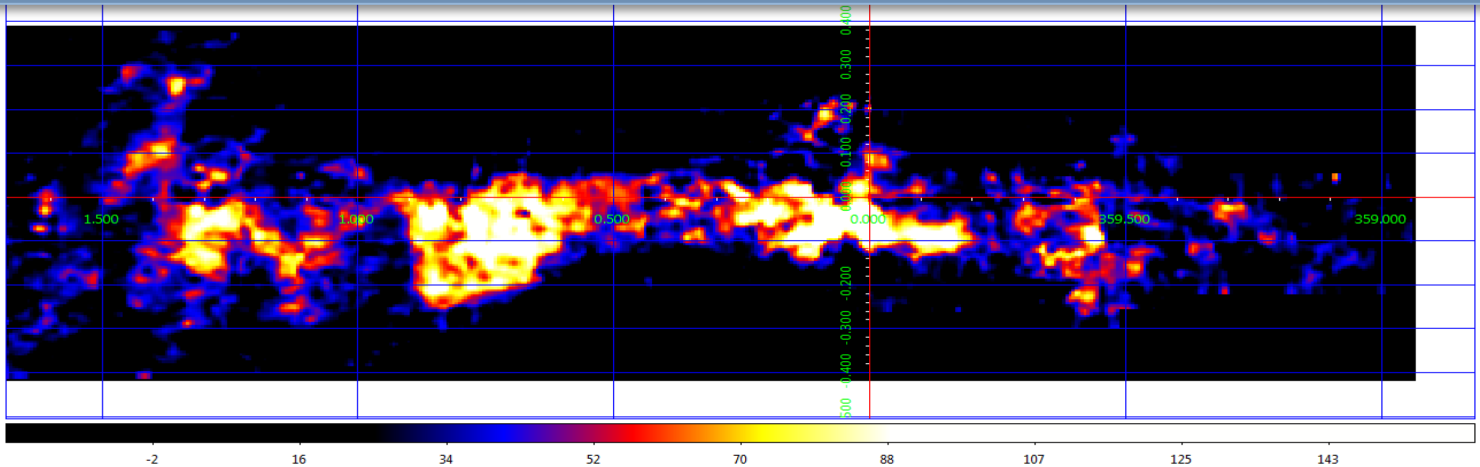




TeV diffuse emission X gas tracers

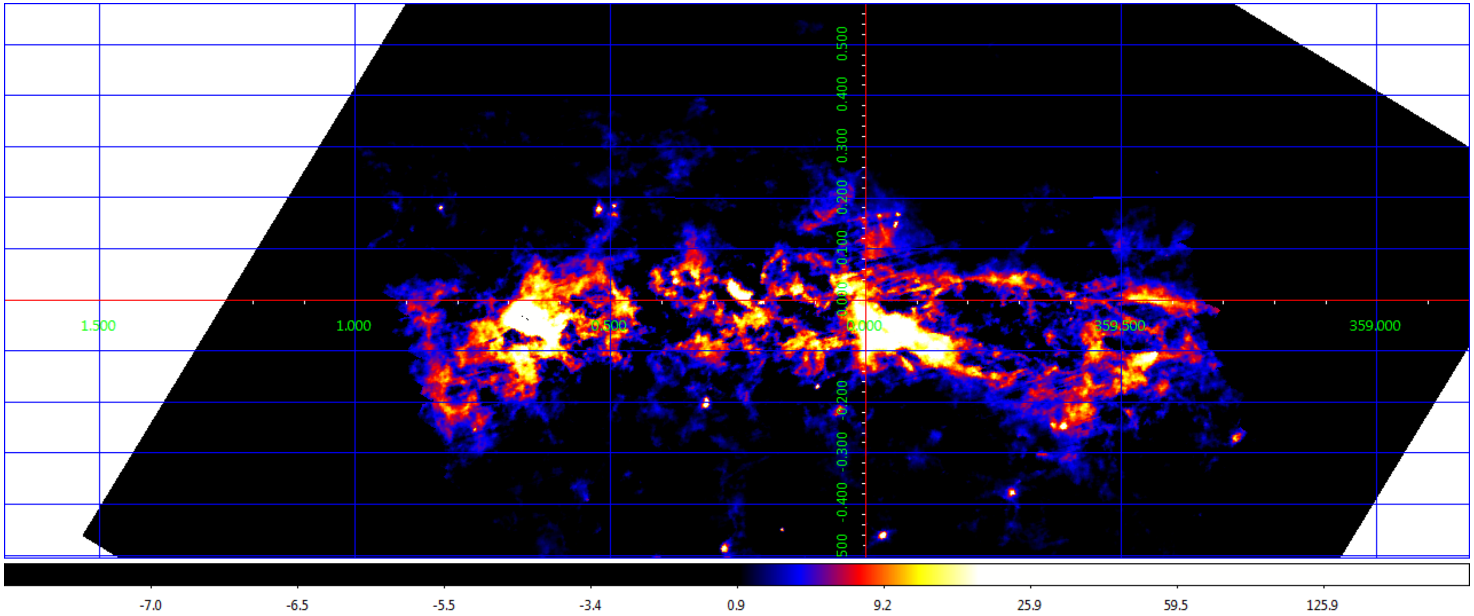
CS map

- Intensity proportional to gas density



HERSCHEL multifrequency

- Gas density N_H found by multiplying by a dust-to-gas ratio



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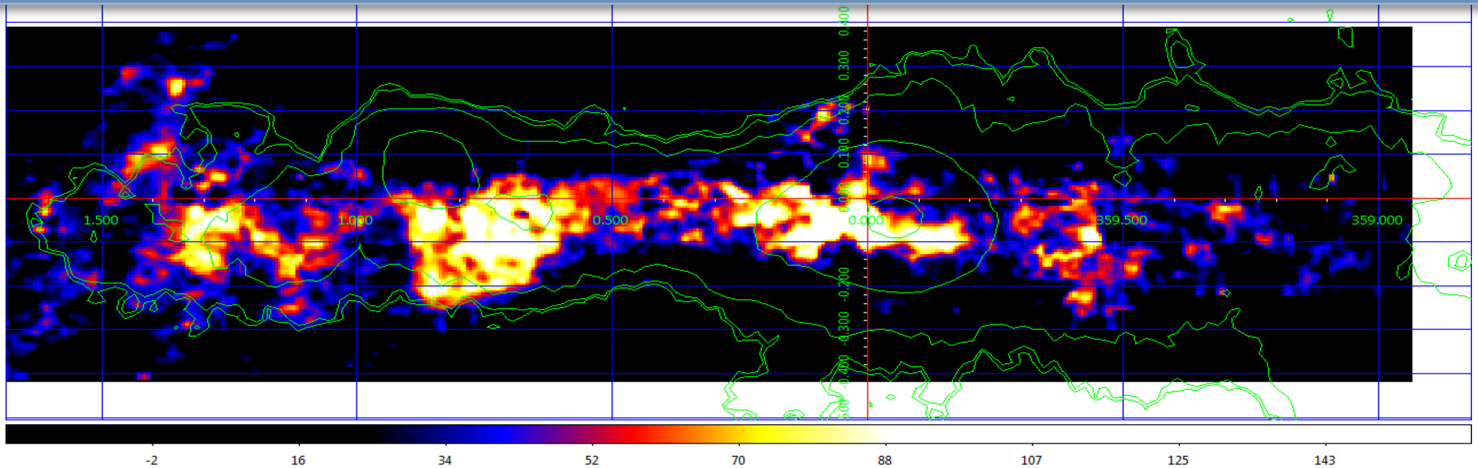

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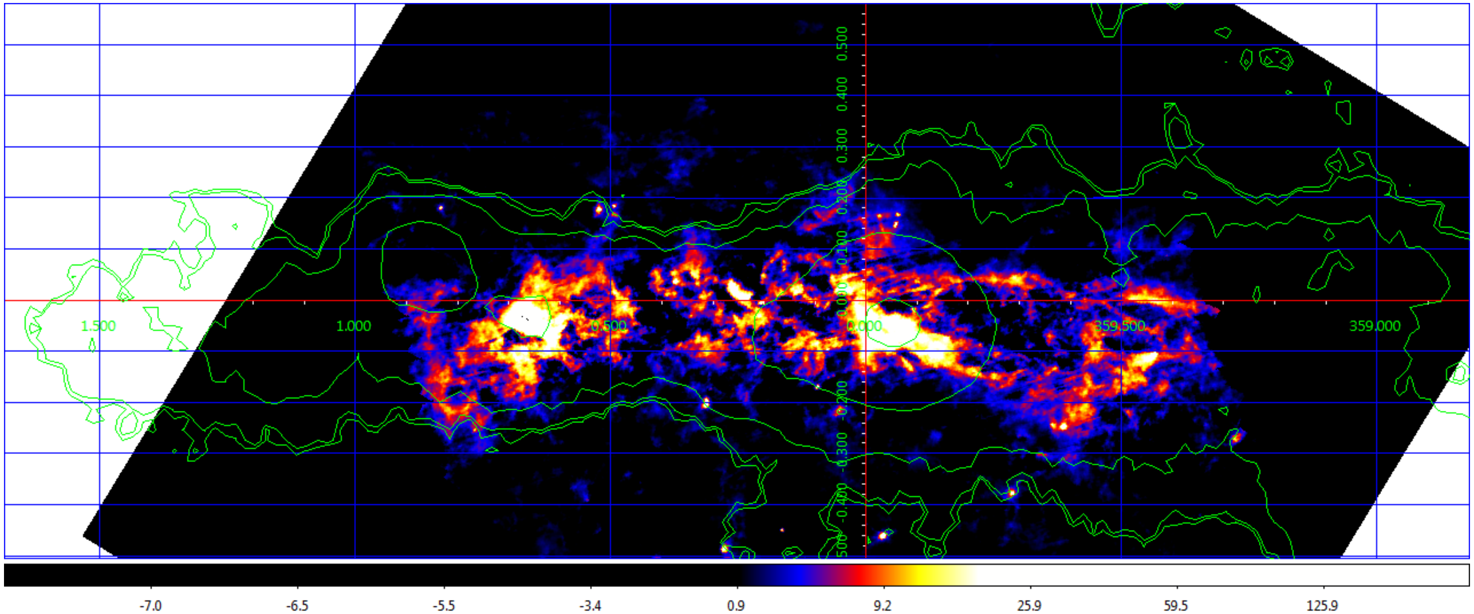
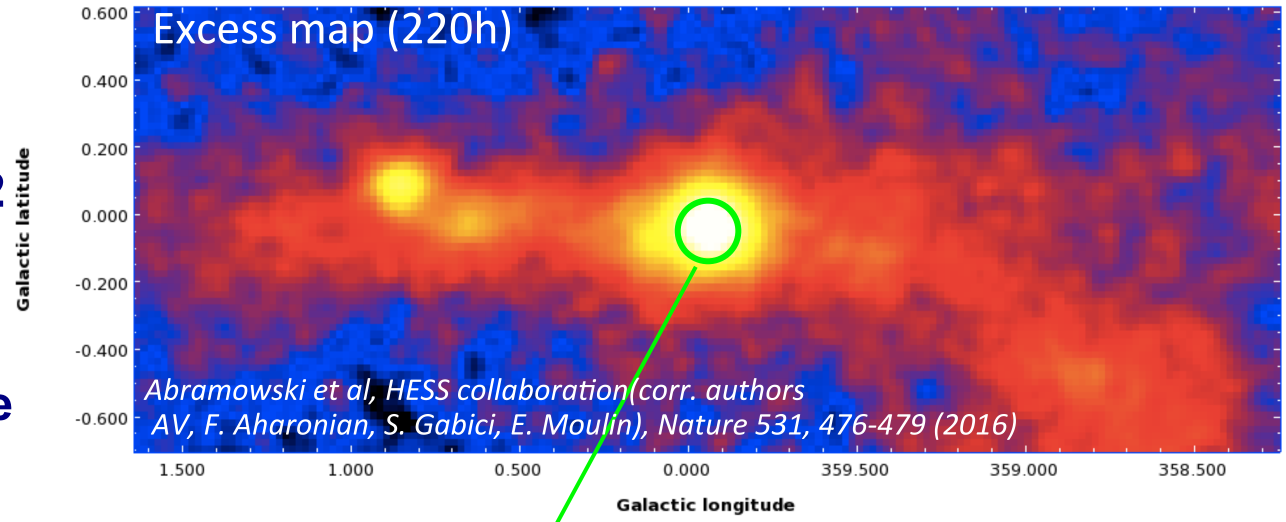


- ➢ **TeV emission well correlated to gas density => pp emission processes**
- ➢ **Use of different tracers => systematical uncertainty evaluation**

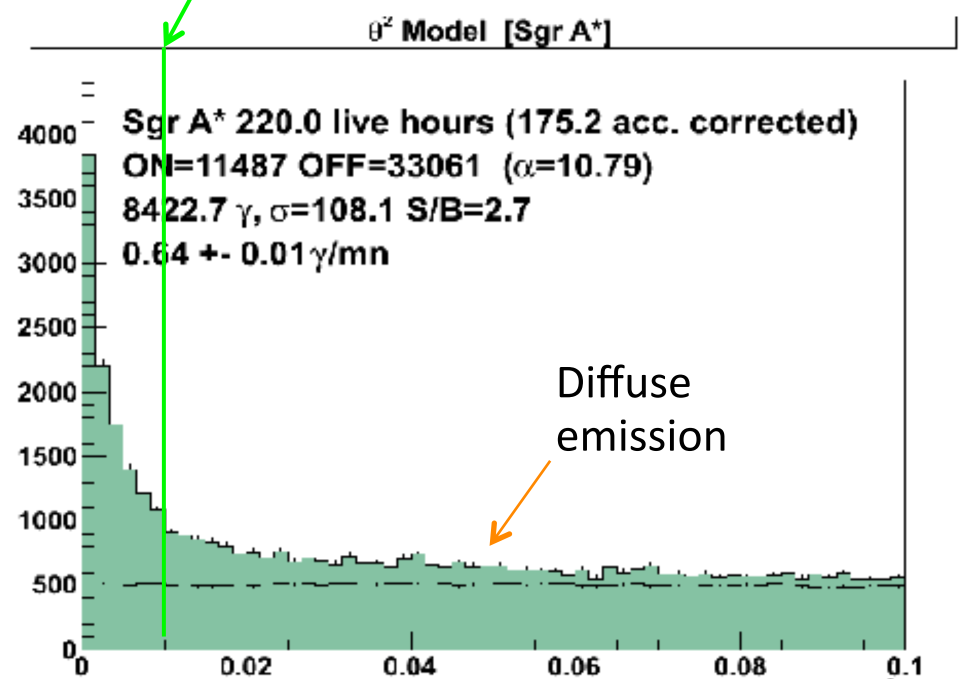
3. Galactic Centre as a powerful Pevatron

Data analysis of GC region: 2003-2012 (all HESS-I dataset)

- **Full dataset analysed : 2003-2012**
- **Diffuse emission excluded, G0.9 excluded, HESS J1745-303 excluded, for background estimate**



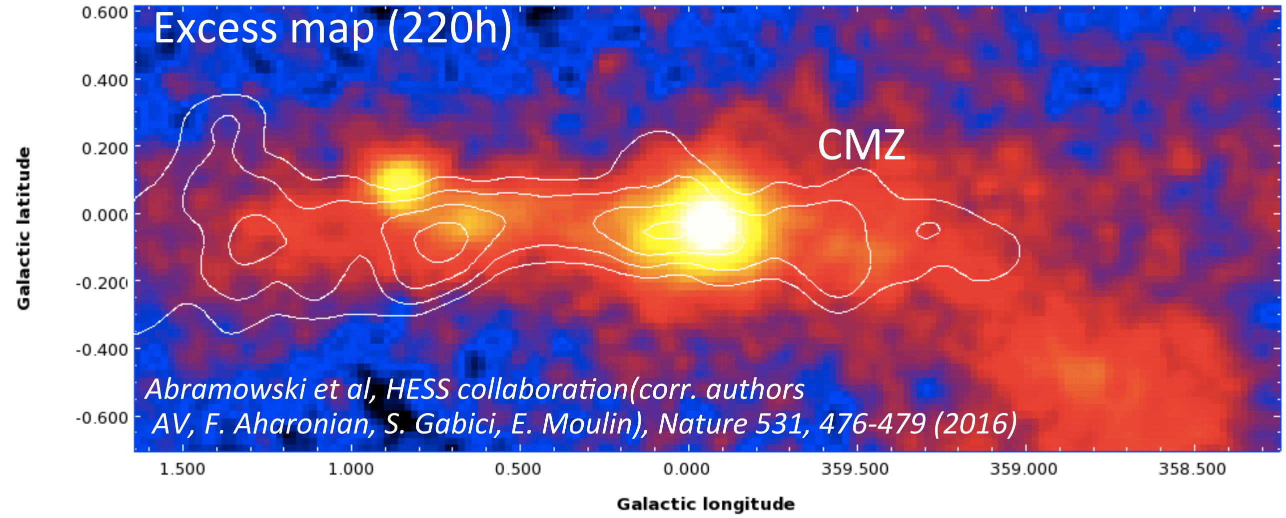
Year	$\theta_z^{(1)}$ [°]	$T_{obs}^{(2)}$ [h]	gamma-ray excess $^{(3)}$	Significance $^{(4)}$ [σ]
2004	21.8	48.5	2075.2	53.4
2005	28.8	68.6	2594.6	60.8
2006	18.7	28.7	1056.8	38.0
2007	11.2	11.4	399.8	24.6
2008	15.3	13.2	567.0	27.3
2009	17.8	4.4	123.7	12.8
2010	10.8	8.3	294.9	21.0
2011	33.6	10.1	267.9	18.5
2012	21.4	26.8	1078.2	38.8
All	22.6	220.0	8422.7	108.1



θ^2_{cut} = 0.01(point-like source)

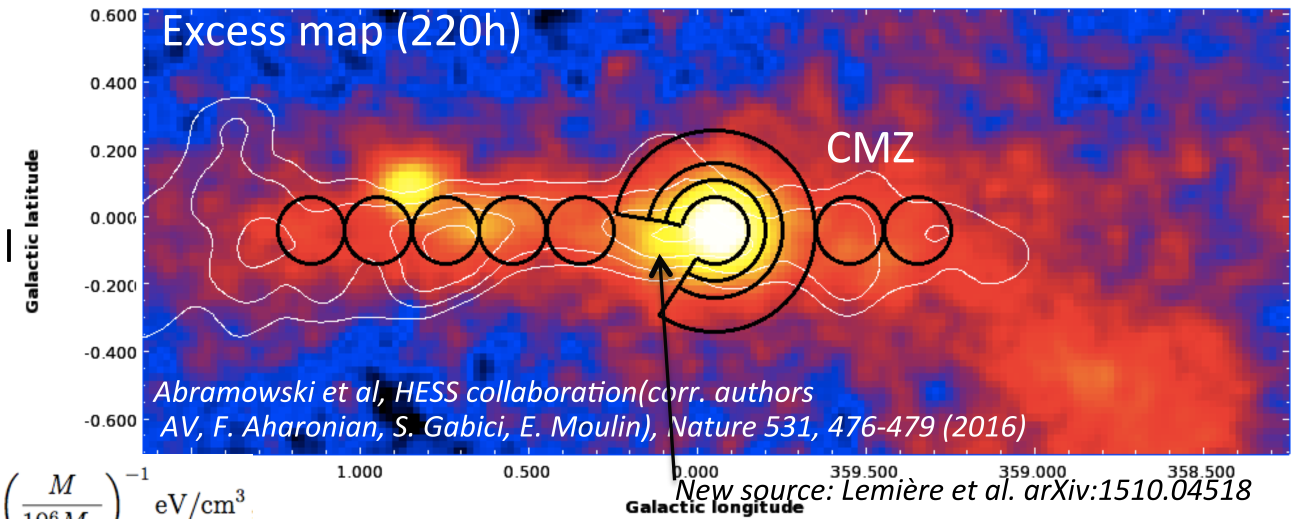
Cosmic-ray energy density distribution

- Correlation with molecular clouds => pp interaction target mass (M)

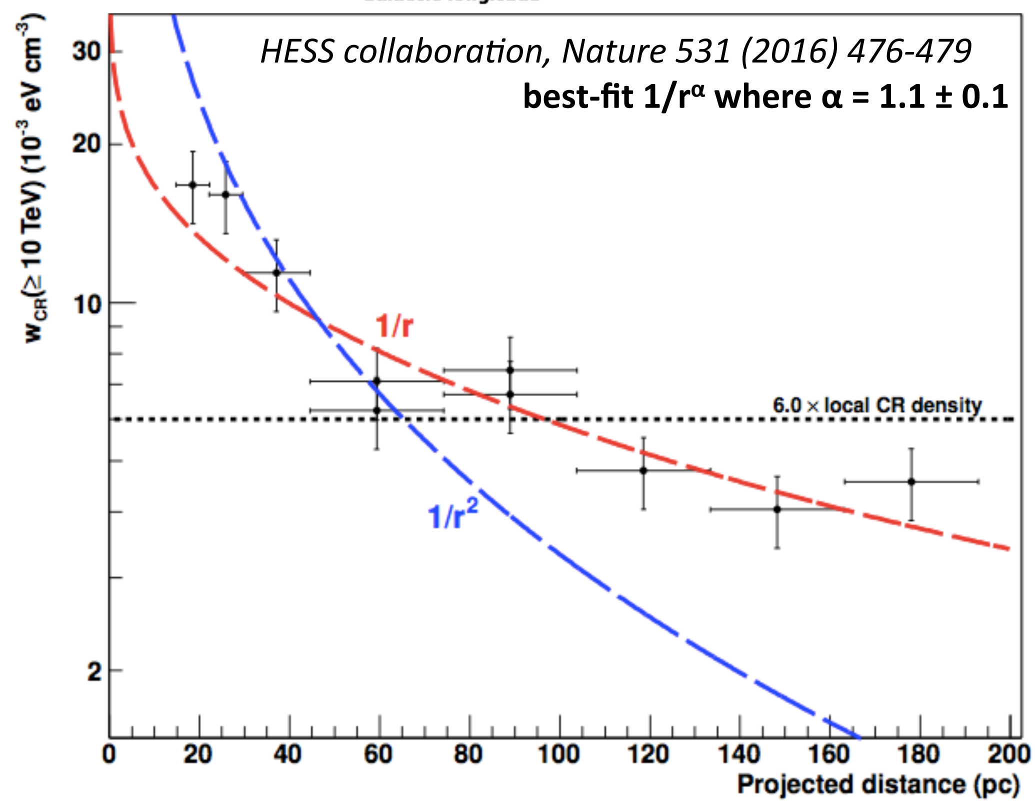


Cosmic-ray energy density distribution

- Correlation with molecular clouds => pp interaction target mass (M)
- Gamma-ray luminosity (L) in several regions
- => CR energy density ∝ L/M



$$w_{\rm CR}(\geq 10E_\gamma) = \frac{W_p(\geq 10E_\gamma)}{V} \sim 1.8\times 10^{-2}\left(\frac{\eta_N}{1.5}\right)^{-1}\left(\frac{L_\gamma(\geq E_\gamma)}{10^{34}\mathrm{erg/s}}\right)\left(\frac{M}{10^6 M_\odot}\right)^{-1}\ \mathrm{eV/cm^3}$$



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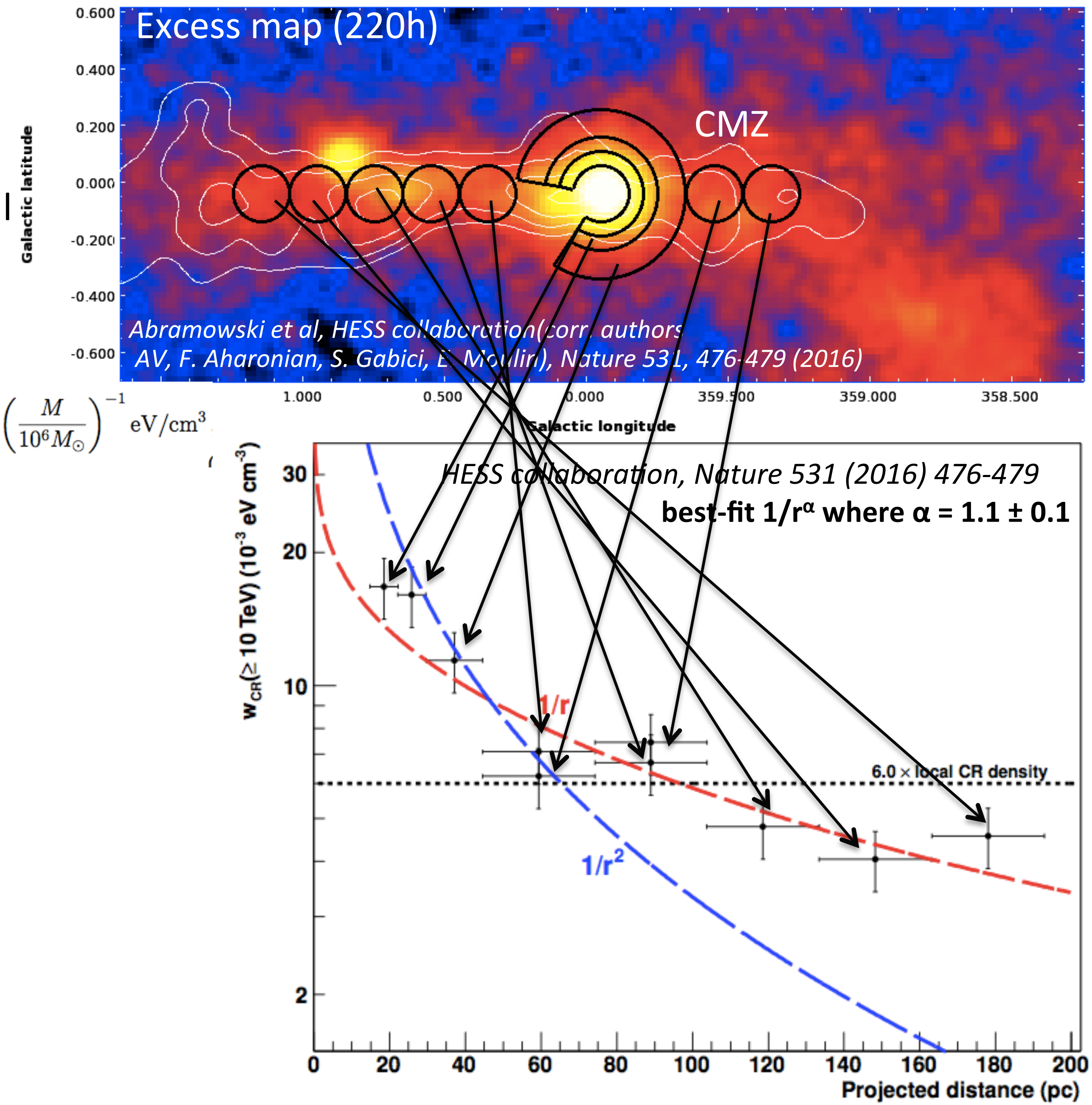

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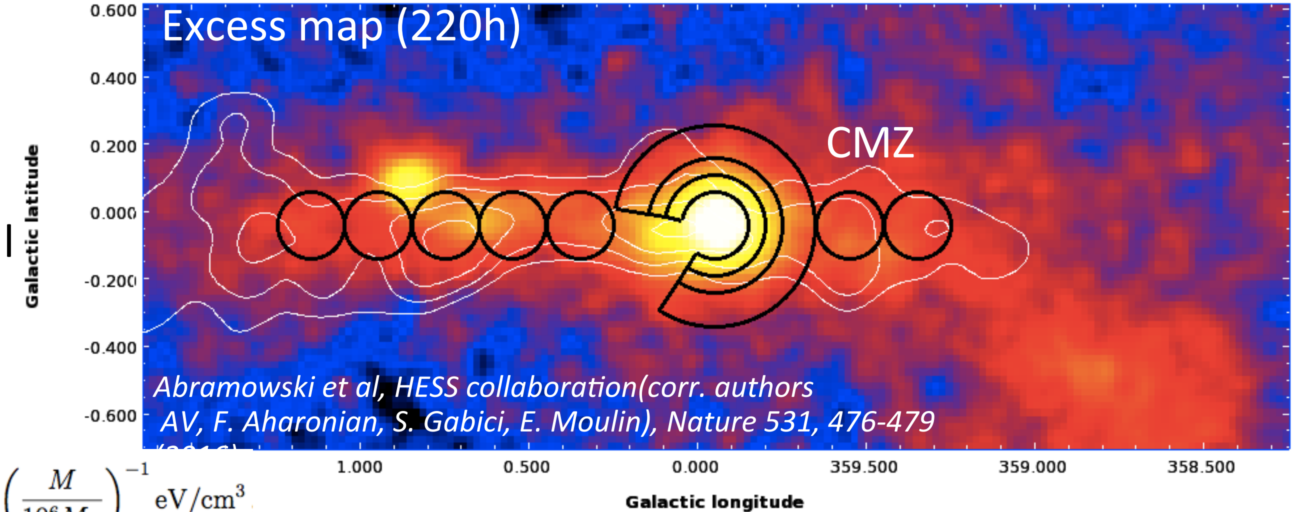

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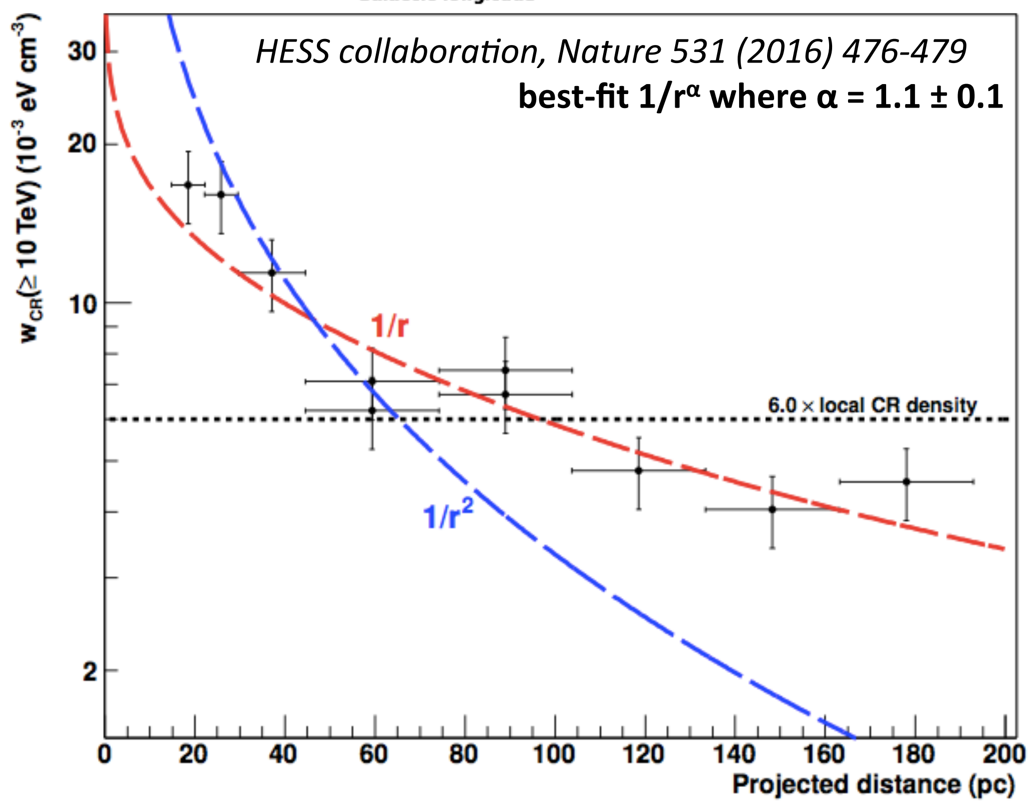

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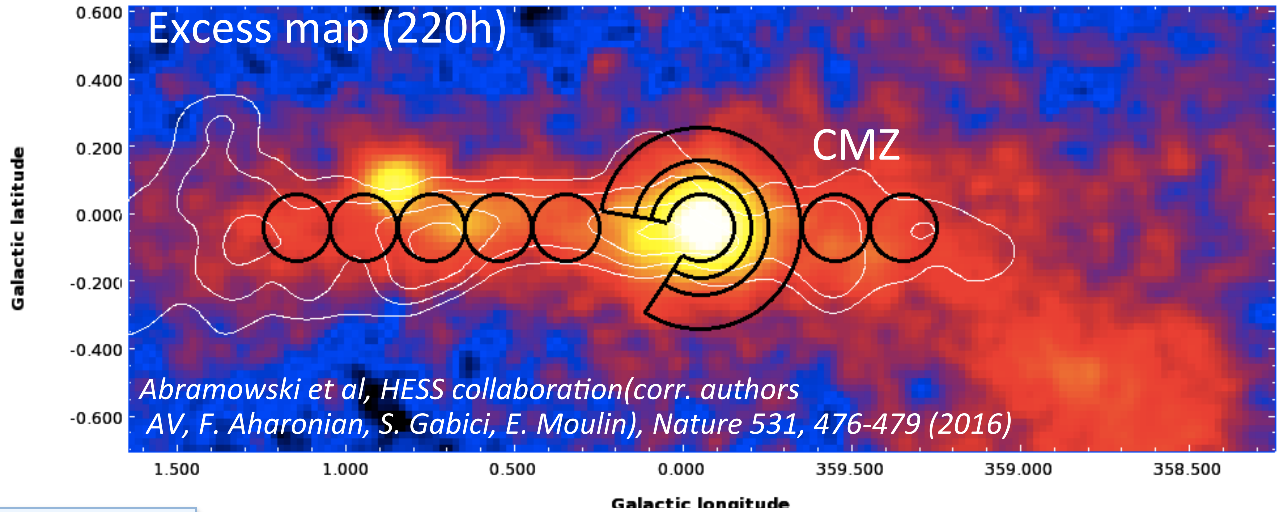
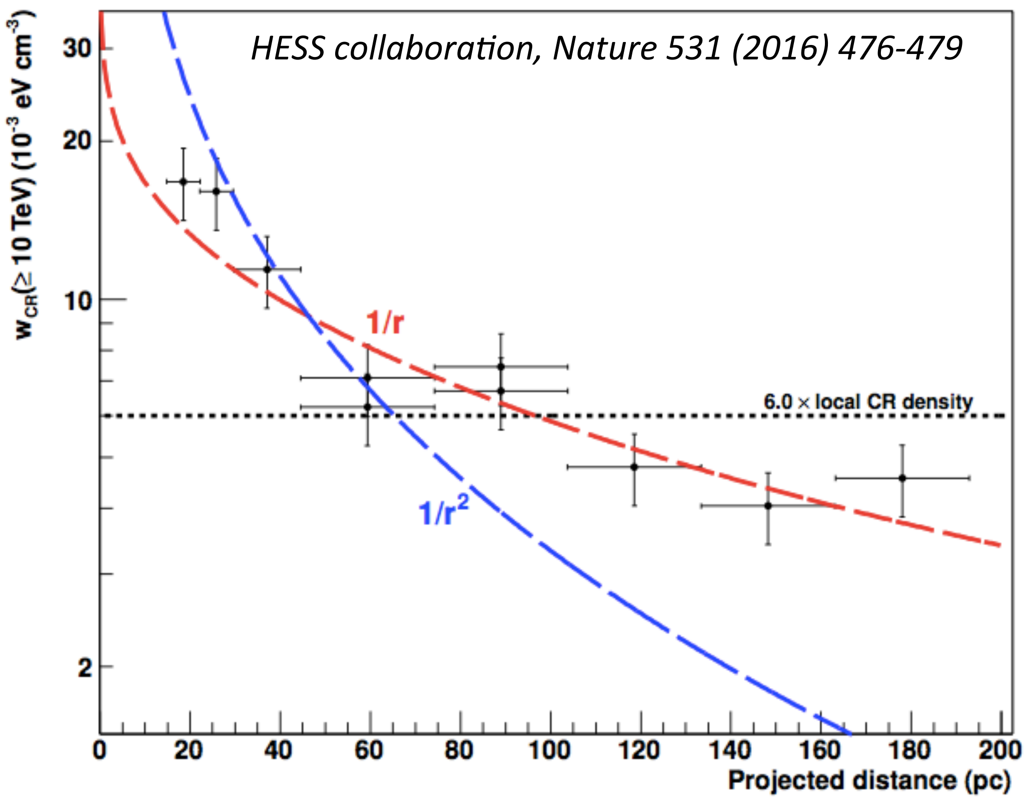


CR density radial distributions meanings:

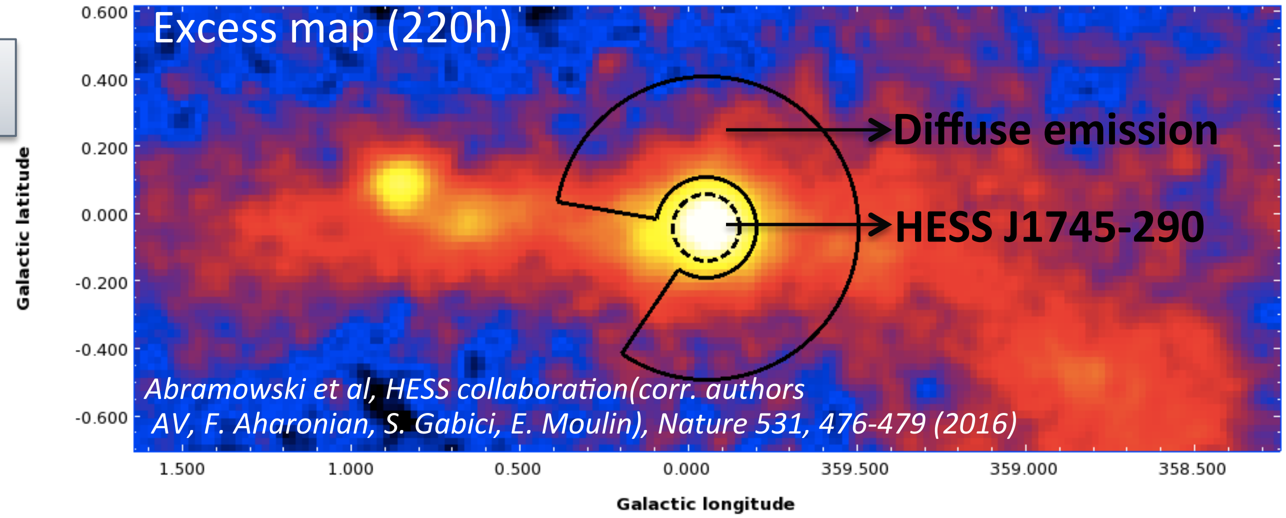
- **Homogeneous/Constant**
  - Impulsive injection of CRs and diffusive propagation
- **$1/r^2$**
  - Wind-driven or ballistic propagation
- **1/r**
  - continuous injection and diffusive propagation



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

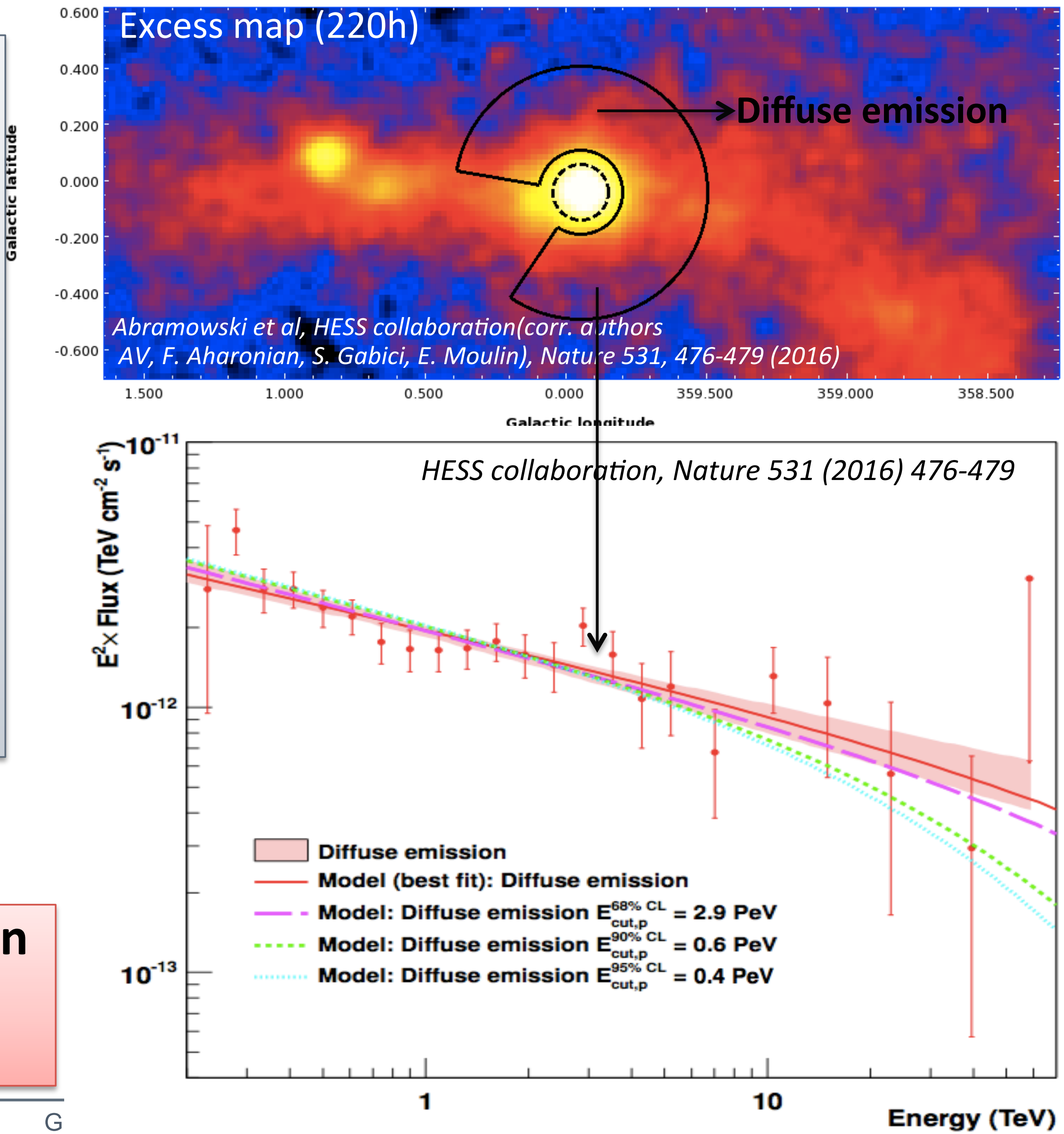
Diffuse gamma-ray emission and injection spectra

- Spectrum diffuse emission extracted from large ring $[r_{in}, r_{out}] = [0.15^o, 0.45^o]$



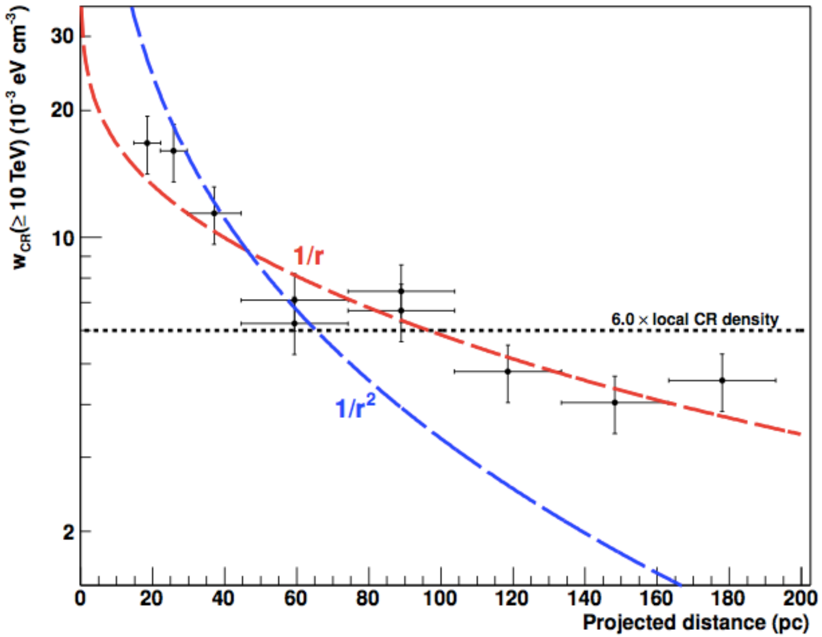
Diffuse gamma-ray emission and injection spectra

- Spectrum diffuse emission extracted from large ring $[r_{in}, r_{out}] = [0.15^{o}, 0.45^{o}]$
- Spectrum of diffuse emission: power-law with index 2.3 extending up to 50 TeV without energy cut-off
- Solve transport equation of protons injected at the center of the Galaxy and fit to HESS data
- Parent proton injection spectrum should extend to PeV energies
    - quasi-continuous injection lasting over ~10^{4} years
    - total CR power injected at the GC ~10^{38} erg/s

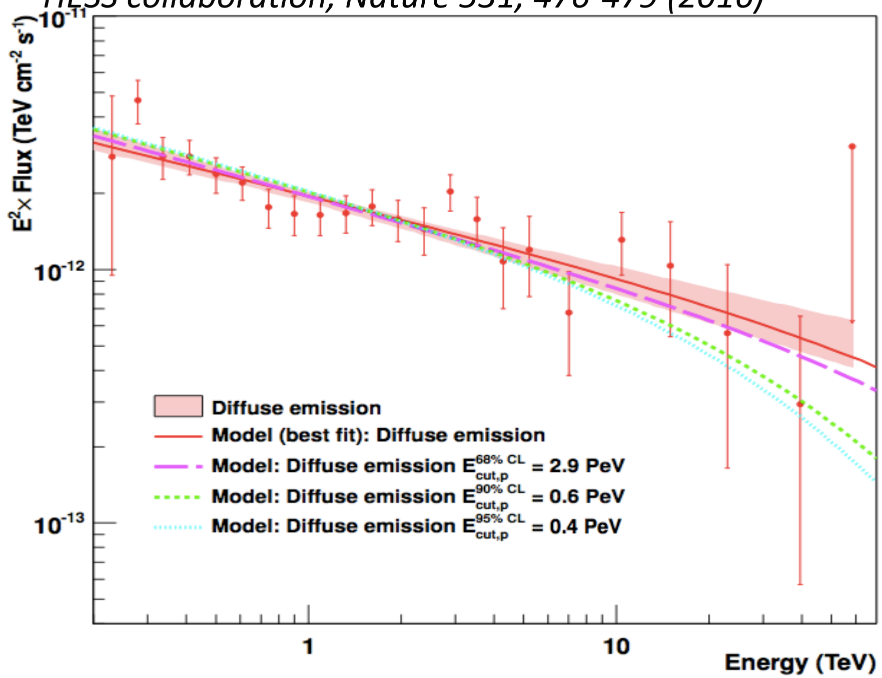


First robust detection of a cosmic Galactic PeVatron!

Galactic Centre as a powerful Pevatron



HESS collaboration, Nature 531, 476-479 (2016)



- Given the location (< 10 pc), the maximum acceleration energy (~PeV), the continuous power and age of the accelerator only the **SMBH Sgr A*** is a viable couterpart

- A significant fraction of accretion in Sgr A* is released through acceleration of particles to ultrahigh energies

- SgrA* has been more active in the past (Ponti et al. 2010/12, Terrier et al. 2010) => **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")**

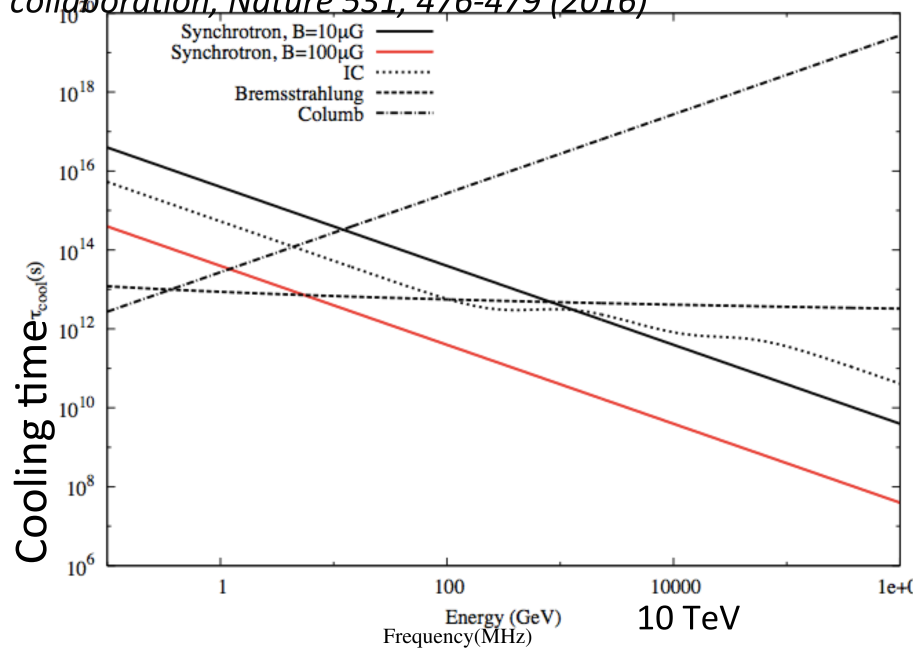
- Possible origin of two large scale structures : **Fermi Bubbles** observed by Fermi-LAT (Su et al. 2010, Crocker & Aharonian 2010) and isotropic flux of the **extraterrestrial neutrinos** discovered recently by IceCube (Taylor et al. 2014)

Multi-TeV γ-rays of leptonic origin?

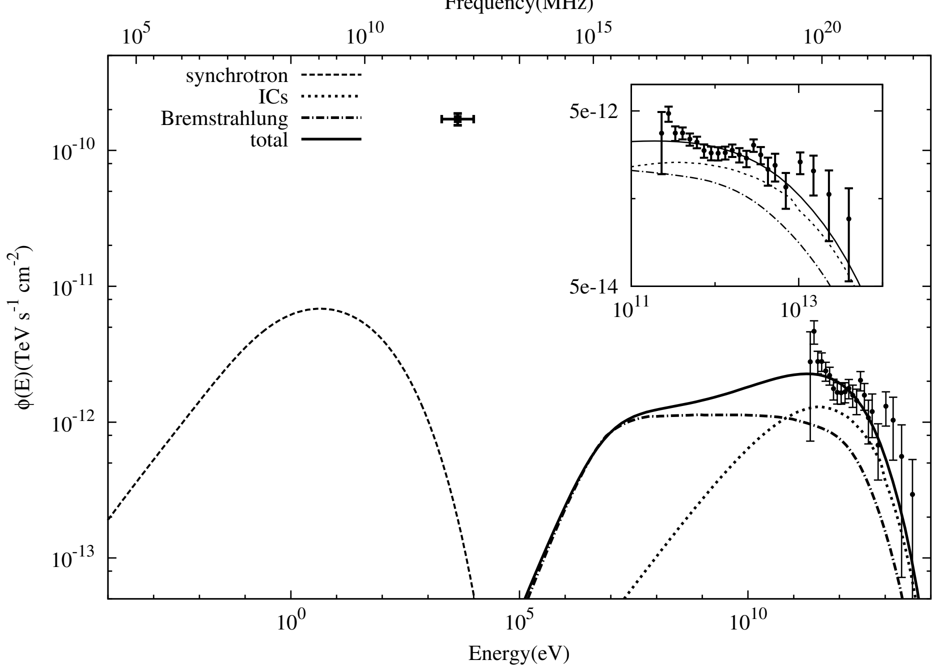
Leptonic origin needs to address these questions:

1. whether the accelerator could be sufficiently effective to boost the energy of electrons up to ≥ 100 TeV under the severe radiative losses in the GC;
2. whether these electrons can escape the sites of their production and propagate over distances of tens of parsecs;
3. whether they can explain the observed hard spectrum of multi-TeV γ-rays.

HESS collaboration, Nature 531, 476-479 (2016)



Synchrotron losses makes a leptonic origin extremely unlikely => it implies very small propagation distances and spectral break



Alternative accelerators

Possible alternative sources for the Pevatron include:

1. Supernova remnants

2. Stellar clusters

3. Magnetic radio filaments (Yusef-Zadeh 2013)

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For very young SNRs: $E_{max} \approx 10^{14}(B/100\ \mu\mathrm{G})(u_s/10000\ \mathrm{km\,s^{-1}})^2(\Delta t_{\mathrm{PeV}}/\mathrm{yr})\ \mathrm{eV}$

but $\Delta t_{\mathrm{PeV}} \sim O(10\text{-}100\ \mathrm{yrs})$ → Not enough time for a (quasi) continuous injection

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2. Stellar clusters

- Central stellar cluster located within 1 pc of the GC (size ~ 0.4 pc)
- Need SNRs to reach PeV energies
- Number of supernovas needed

in the past 1000 yr -> n $\sim 10(t_{\mathrm{PeV}}/100\,\mathrm{yr})(t_{\mathrm{inj}}/1000\,\mathrm{yr})^{-1}$ → Absurd amount for such a small region (0.4 pc)

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3. Magnetic radio filaments (Yusef-Zadeh 2013)

- Acceleration of electrons in elongated radio filaments (though no explanation how)
- Gamma-ray production through non thermal Bremstrahlung

→

- Need of fine-tuning distribution of magnetic filaments (1/r)
- Injection rate to fill the CMZ ~10^{41} ergs/s => extremely high (= total proton luminosity of the Galaxy)

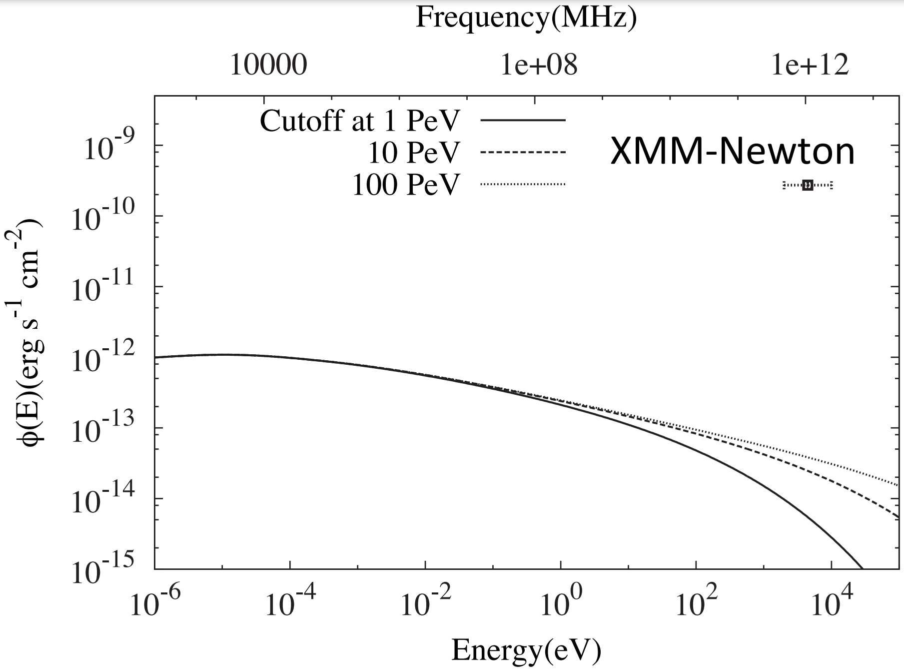
All these alternative sources fail to match the following three requirements:

i) the accelerator has to be located in the inner ~10 pc of the Galaxy,
ii) the accelerator(s) has(have) to be continuous over a timescale of at least thousands of years
iii) the acceleration has to proceed up to PeV energies.

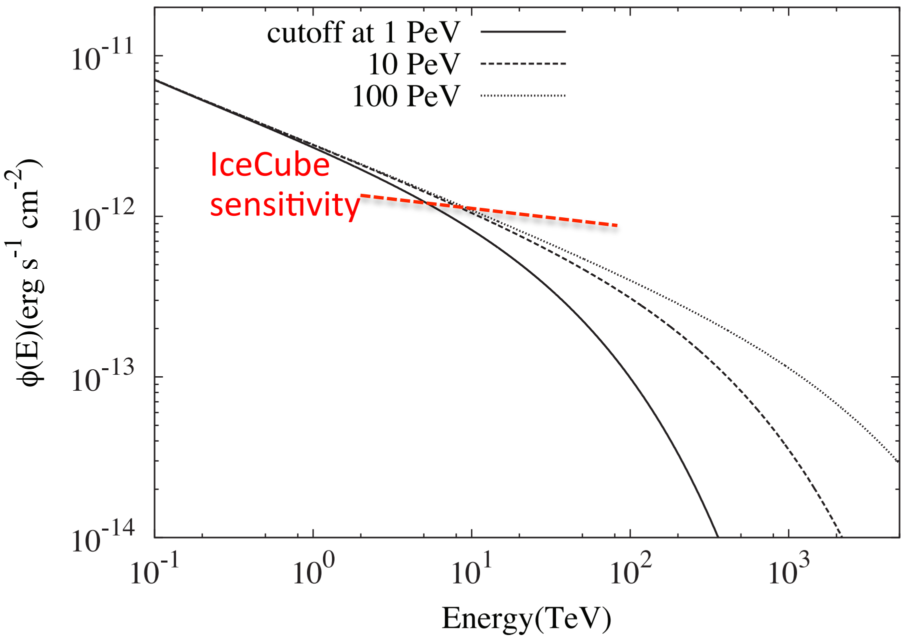
Multiwavelength and multi-messenger signatures of PeVatrons

HESS collaboration, Nature 531, 476-479 (2016)

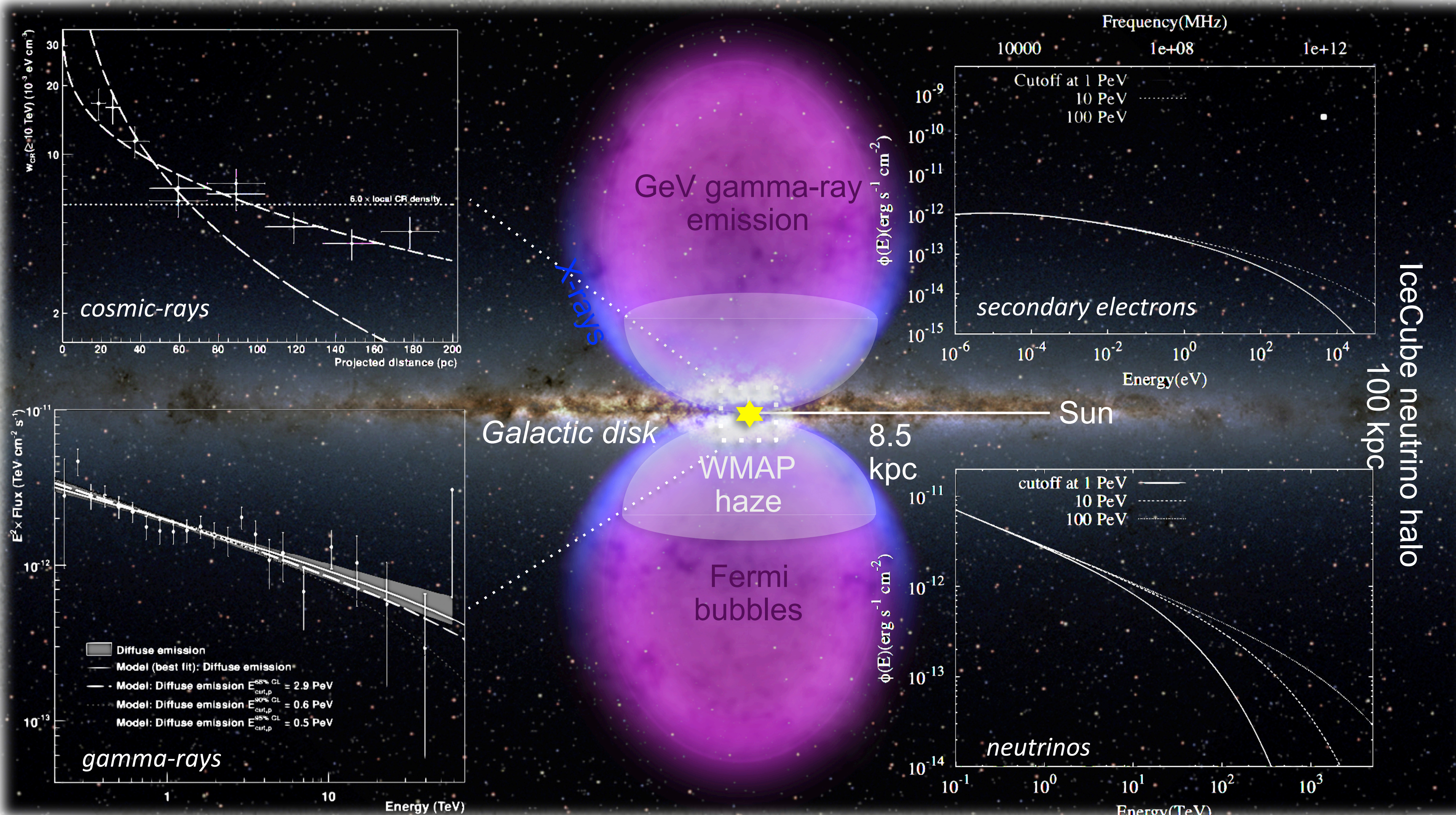
- Secondary electrons from charged pion => synchrotron emission in X-rays
- Too faint when compared to diffuse(thermal) emission detected by XMM-Newton



- Neutrinos are equally produced in pion decays
- Expected neutrino flux from GC Pevatron is close to km3-scale detectors (such as IceCube or KM3Net) detection sensitivity



Galactic Centre as a powerful Pevatron



Abramowski et al, HESS collaboration(corr. authors AV, F. Aharonian, S. Gabici, E. Moulin), Nature 531, 476-479 (2016)

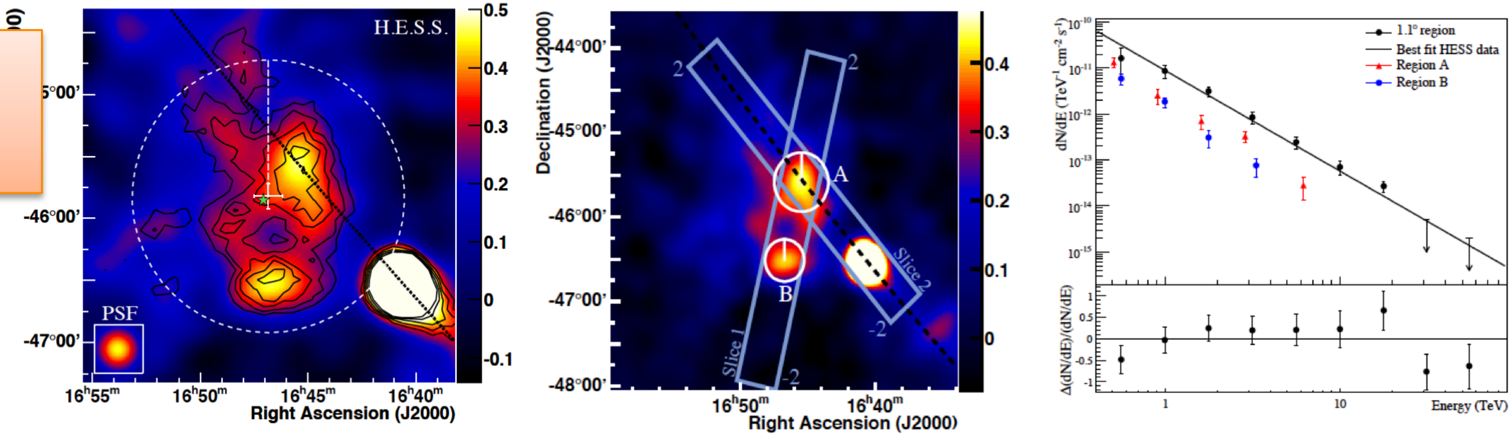
4. Next steps and future with CTA

Next steps: other Pevatrons with H.E.S.S. ?

➢ Although the GC Pevatron could potentially explain all PeV CRs, other sources, such as SNRs or superbubbles are still possible

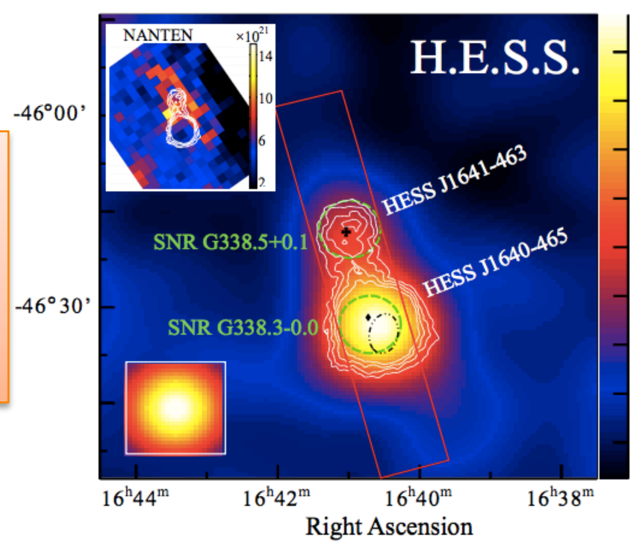
Westerlund 1
- hard powerlaw index
- superbubble candidate

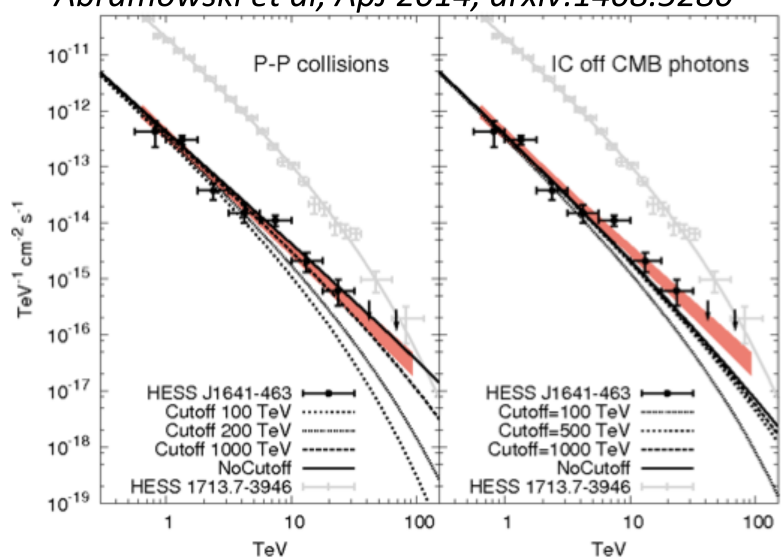
Abramowski et al , A&A 2012, arxiv: 1111.2043



HESS J1641-463
- hard powerlaw index up to 20 TeV
- hadronic or leptonic origin disputed

Abramowski et al, ApJ 2014, arxiv:1408.5280





Next steps: H.E.S.S. Inner Galaxy Survey (high latitude survey)

- Key Science Project for the last years of H.E.S.S.
- 1000h on high latitudes (~0.5°-5°)

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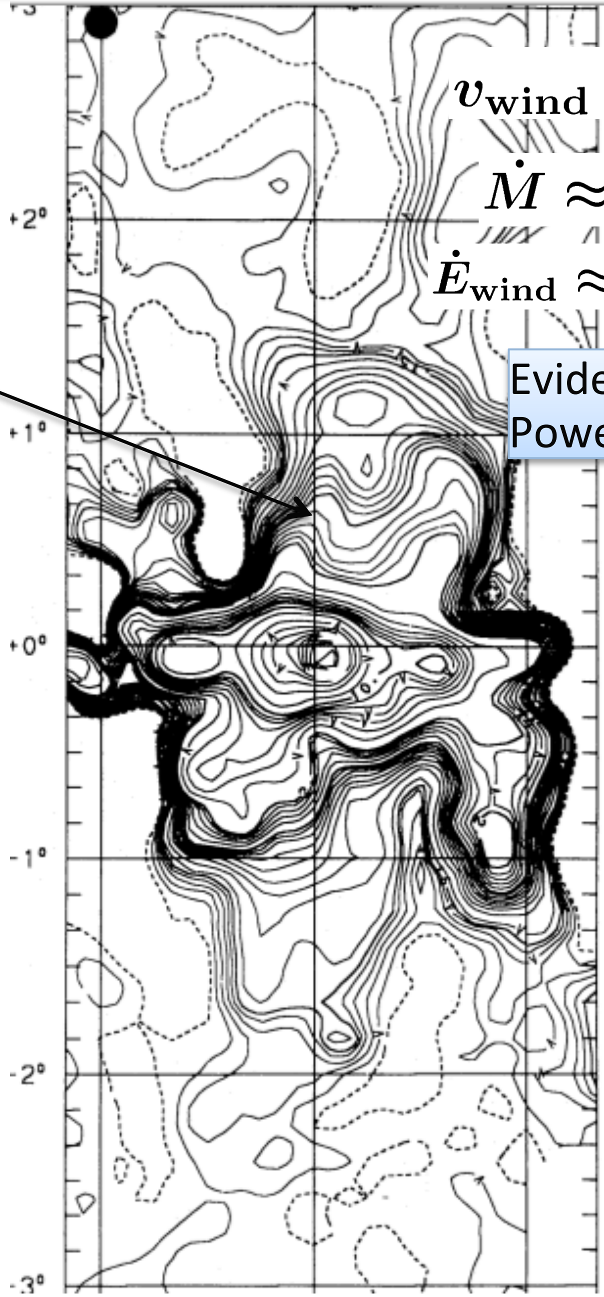
Search for :

- Outflows

Radio Lobe



$$v_{\rm wind} \approx 500 \ {\rm km\ s^{-1}}$$

$$\dot{M} \approx 0.1 \ M_\odot \ {\rm yr^{-1}}$$

$$\dot{E}_{\rm wind} \approx 3 \times 10^{40} \ {\rm erg\ s^{-1}}$$

Evidence of Centrally Powered Escape?

2.7 GHz radio data (unsharp mask, 9.4`) Pohl, Reich & Schlickeiser 1992

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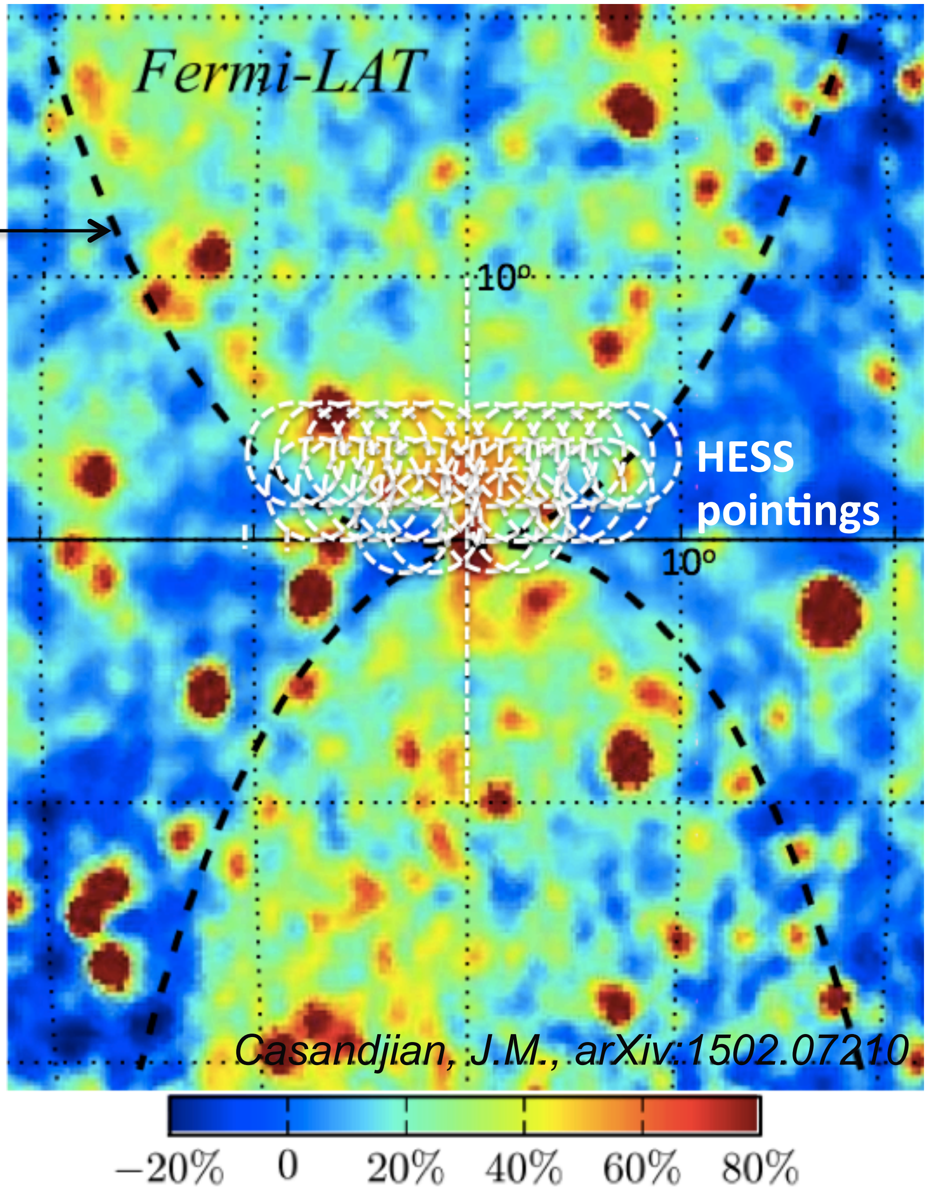
Fermi Bubbles inner 10° edge



Search for :

- Outflows
- Link with the Fermi bubbles

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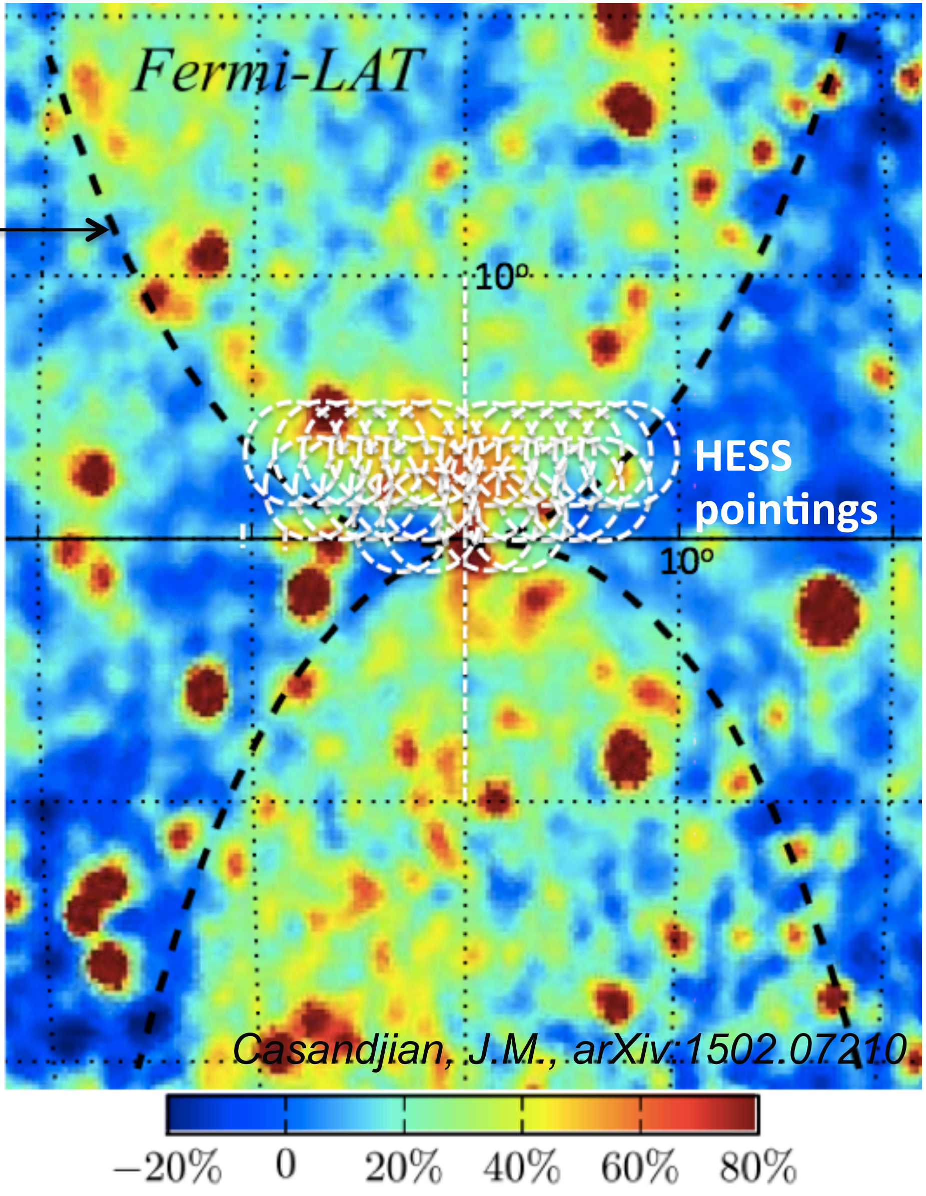


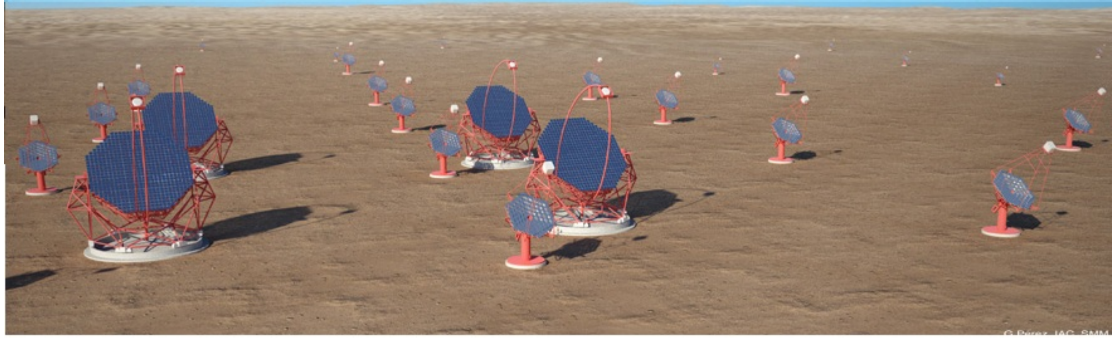
Search for :

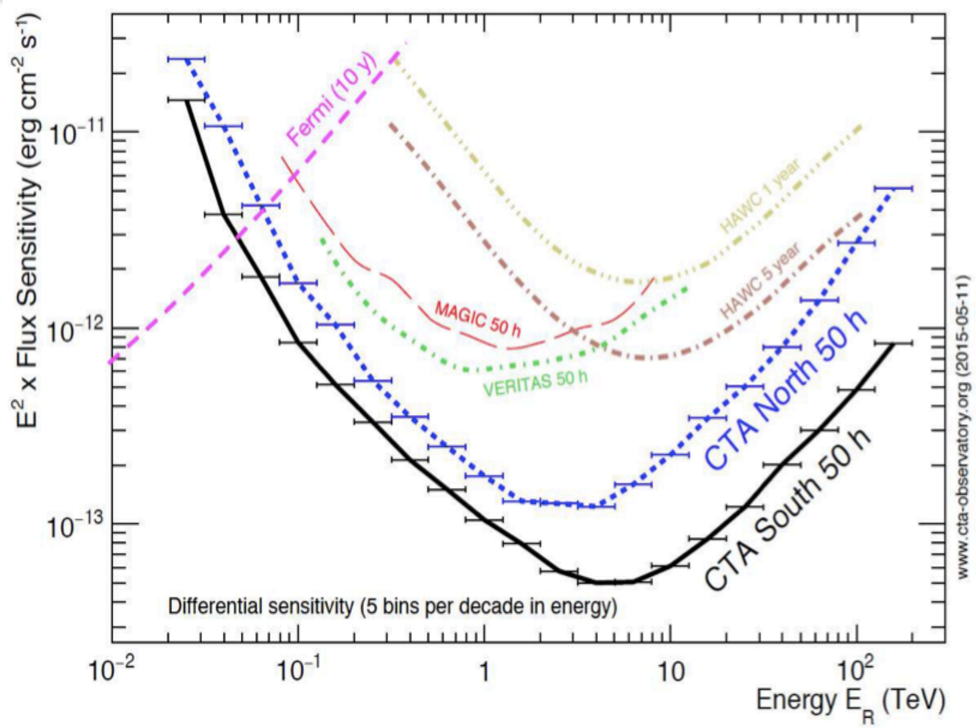
- Outflows
- Link with the Fermi bubbles
- Dark matter from GC halo
- Dark matter clumps
- Diffuse emissions far from the plane

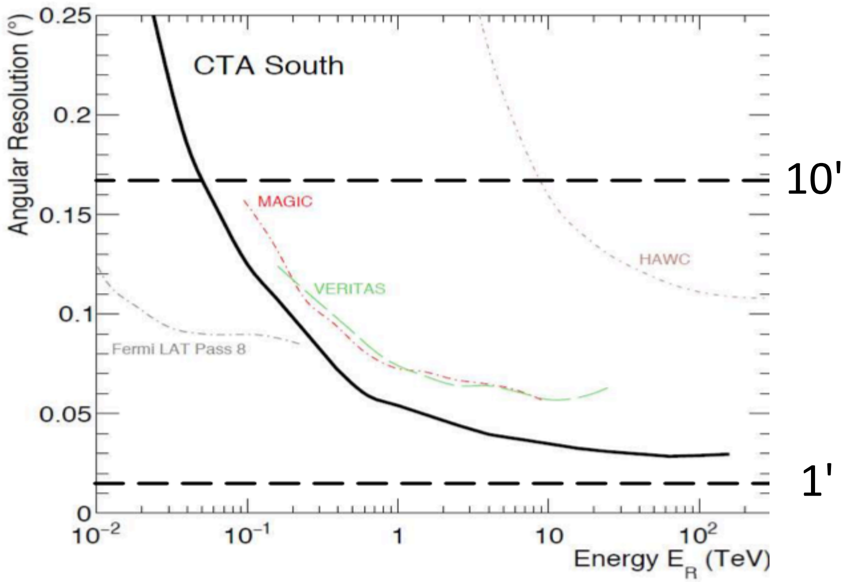
Pathfinder for CTA

CTA : Cherenkov Telescope Array

- Factor 10 better flux sensitivity
- Larger energy coverage, field of view and twice better angular and energy resolution

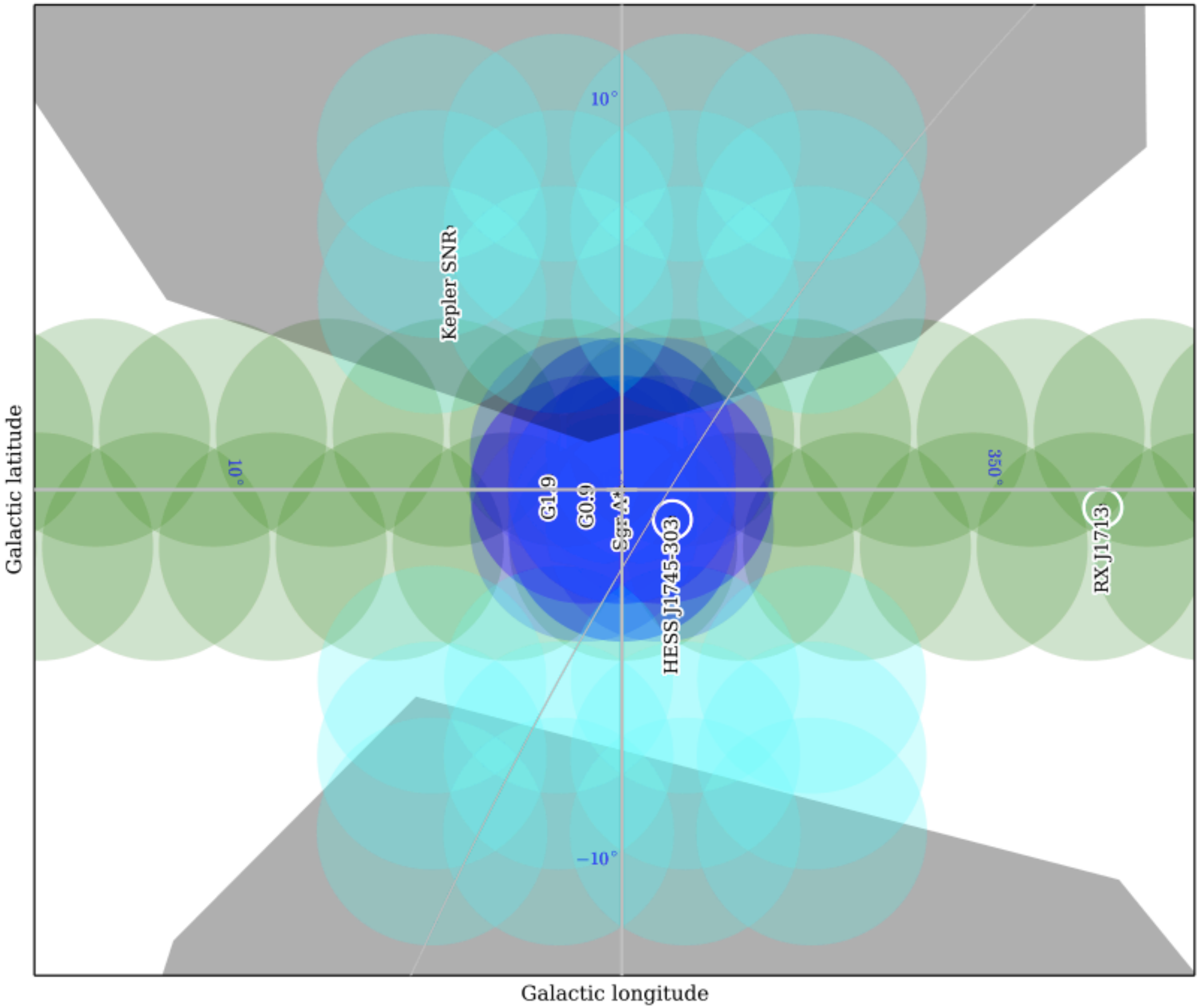






Future with CTA

Galactic Centre Key Science Project [825 h]



- **Large field of view** => more detailed view of the Diffuse VHE emission (new sources, outflows, etc)
- Improved PSF (r68~0.02˚-0.03 ˚), pointing accuracy (3”) and sensitivity => **resolve GC source** (e.g.: 0.5‘ (0.01 ˚); size of circumnuclear disk; distinguish Sgr A* and PWN
- **Search for a possible time dependent component =>** Sgr A* MWL observations with IR/ X-ray instruments and improved sensitivity to flux variation for flares (typically 1h)
- **Search for long term flux evolution** => Expected if energetic protons accelerated during past periods of increased activity of Sgr A*

Summary and outlook

- Gamma-ray observations is the most powerful tool to detect PeVatrons. H.E.S.S.-I Dataset 2003-2012: 220 hours

- First measurement of radial CR density distribution => central CR accelerator within 10 pc and continuously injecting CRs for >> 1kyrs

- Spectrum of diffuse emission extending up to 50 TeV without energy cut-off, proton injection spectrum => **First robust detection of cosmic PeVatron**
  - quasi-continuous injection lasting over ~10^4 years
  - total CR power injected at the GC ~10^{38} erg/s

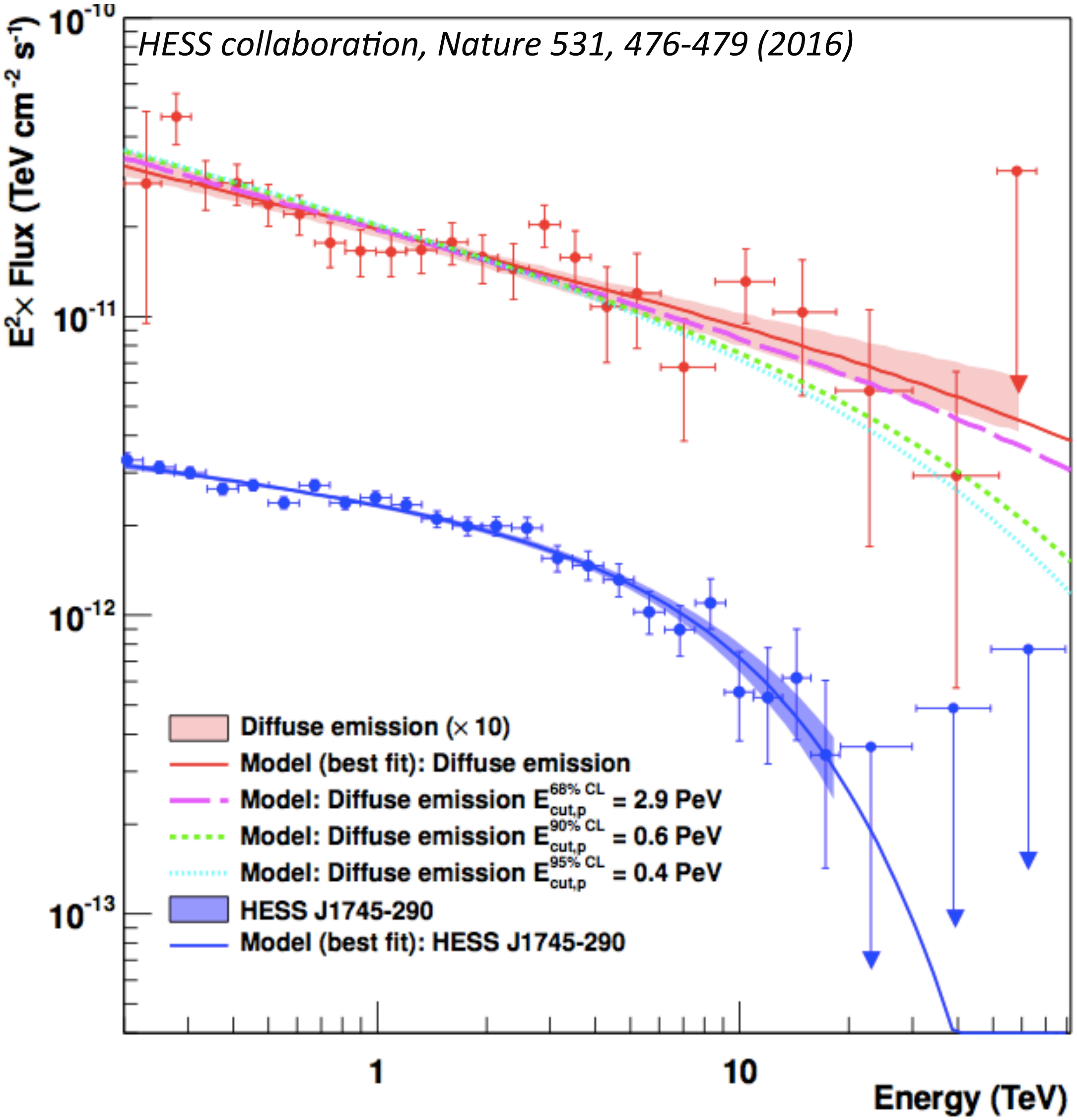
- Only SMBH Sgr A* can sustain such acceleration power in the central 10 pc:
  - significant fraction of accretion in Sgr A* is released through acceleration of particles to ultrahigh energies;
  - SgrA* has been more active in the past => GC PeVatron can explain the fluxes of galactic CRs above 100 TeV to a few PeV (region of the "knee") , Fermi Bubbles and extraterrestrial neutrinos
  - Connection between Pevatron and HESS J1745-290 possible with γ absorption in IR field

- Paper published: Abramowski et al, HESS collaboration(corr. authors AV, F. Aharonian, S. Gabici, E. Moulin), Nature 531, 476-479 (2016)
- Last years of HESS operation and first years of CTA will hopefully bring a revolution to the field

Backup slides

Connexion between the Pevatron and HESS J1745-290

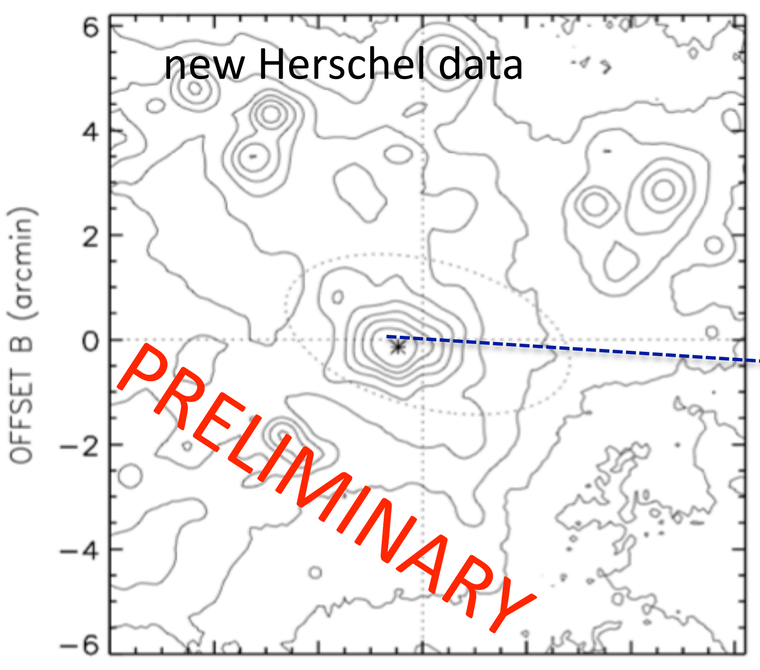
- HESS J1745-290 **has significant deviation from a power-law with spectral index ~ 2.1 and exponential cut-off at energy ~ 11 TeV**(compatible with previous analyses: Aharonian et al. (HESS coll.) A&A 503 (2009) 817)

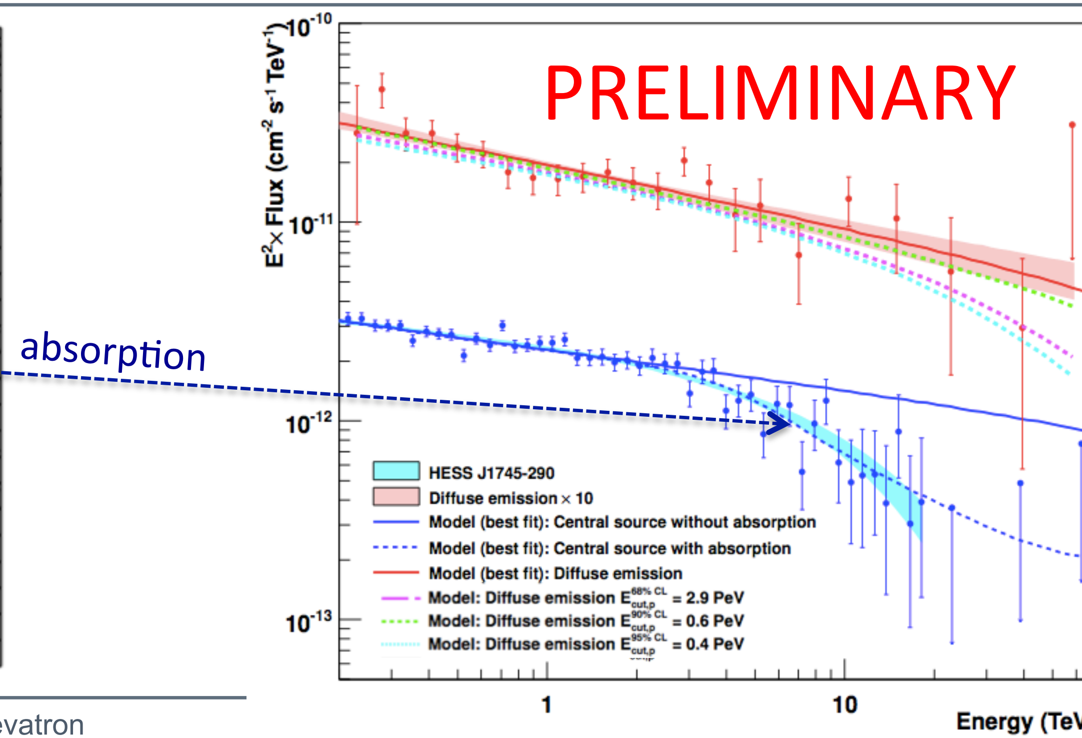


Connexion between the Pevatron and HESS J1745-290

- HESS J1745-290 **has significant deviation from a power-law with spectral index ~ 2.1** <u>and exponential cut-off</u> **at energy ~ 11 TeV**
- If they are not connected, HESS J1745-290 could be explained by: Sgr A*, PWN ou Dark Matter
- if HESS J1745-290 is linked to PeVatron the energy cut-off in the central source could be explained from:
  - photon absorption on the infrared radiation field

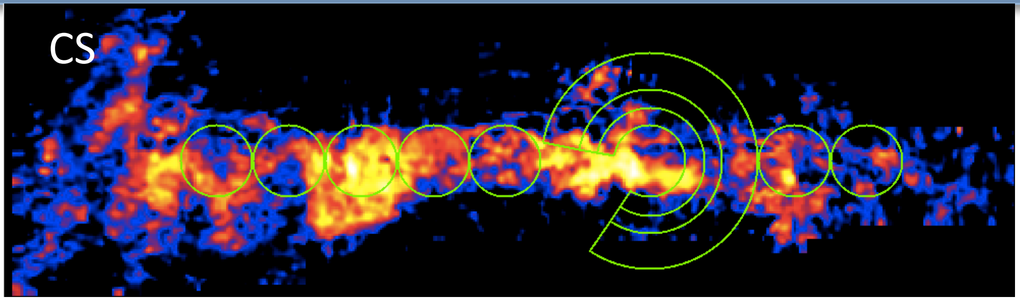
  and/or
  - difference in gamma-ray emission timescales due to energy dependent diffusion coefficient: 10 yrs for high energies (ballistic motion) and 10^3 for low energies (diffusive motion) => a decrease in luminosity in timescales O(10 yr) would generate a cut-off
- Using new Herschel data we show that absoprtion is a viable option (F. Aharonian, S. Gabici, E. Moulin, R. Tuffs, and AV in preparation)

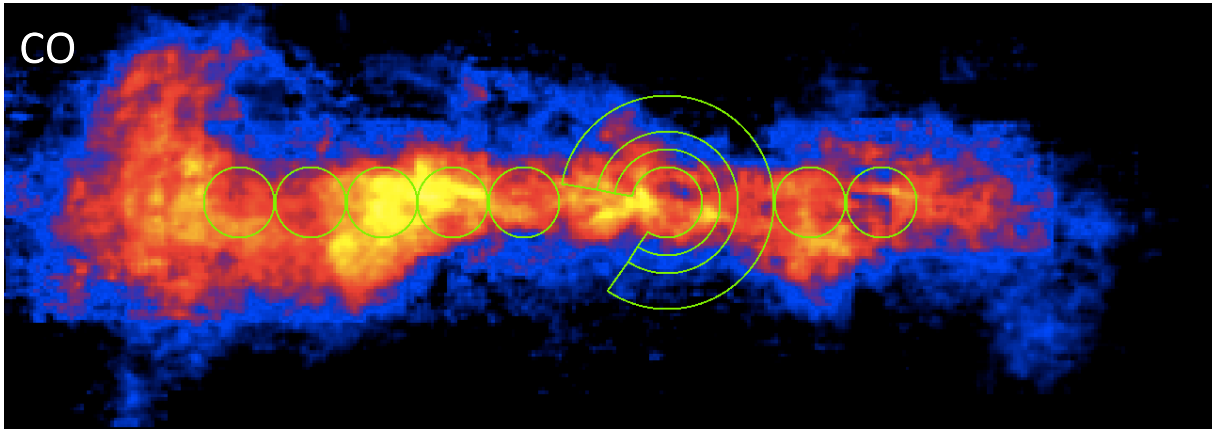




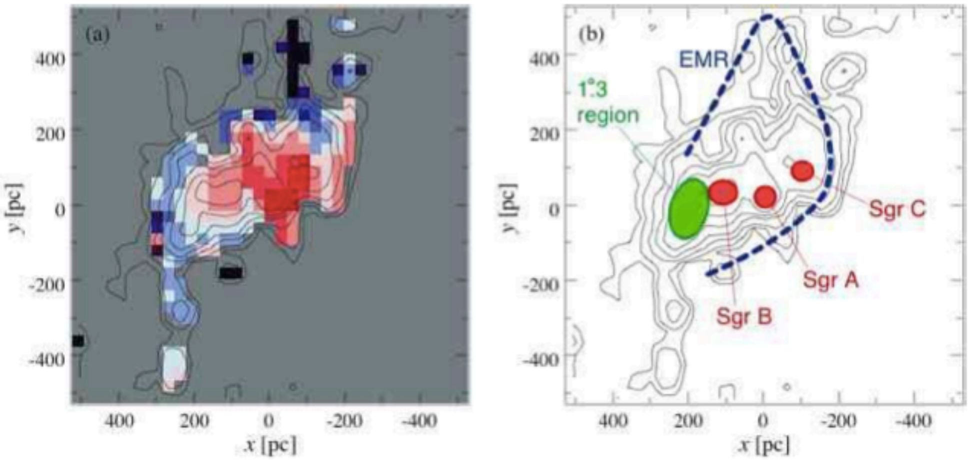
Gas distribution in the CMZ

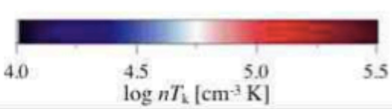
- Several tracers used to check systematical uncertainty
- CMZ has a coherent structure => 3D distribution of gas affects mildly the CR density calculation (~10%)





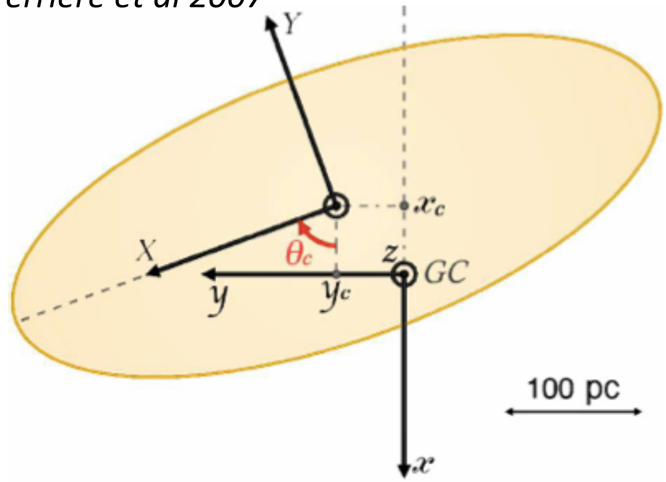
Sawada et al 2004





Face-on view of CMZ: OH/CO ratio (OH absorbs 18cm emission)

Ferriere et al 2007



Fermi-LAT GeV excess : some caveats

- It has been long known that the Fermi diffuse models under-predict the data in the inner Galaxy for energies above a few GeV.
- The Fermi collaboration itself "do not recommend using this model for analyses of spatially extended sources in the region defined in Fig. 1"

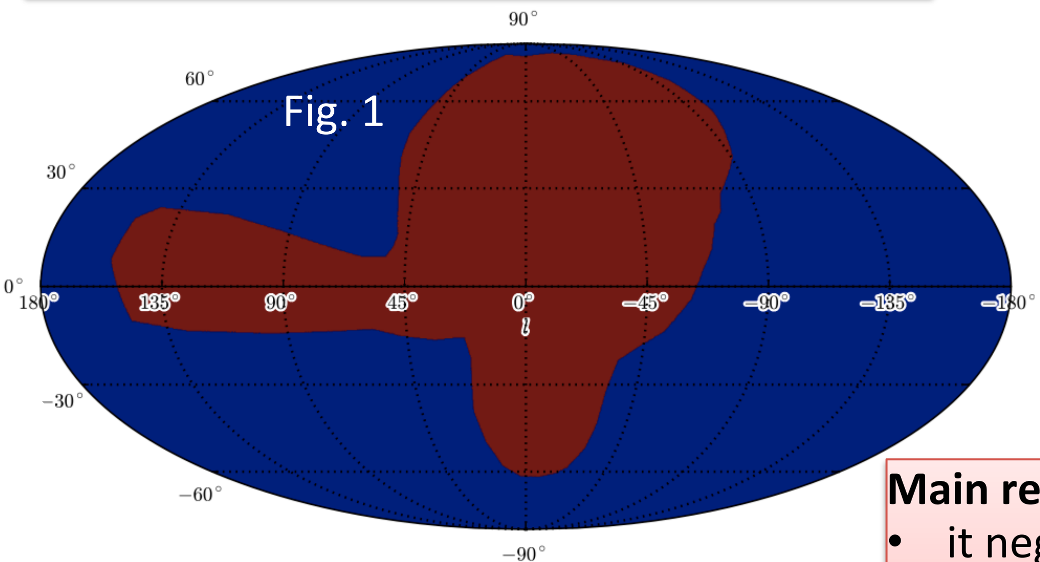
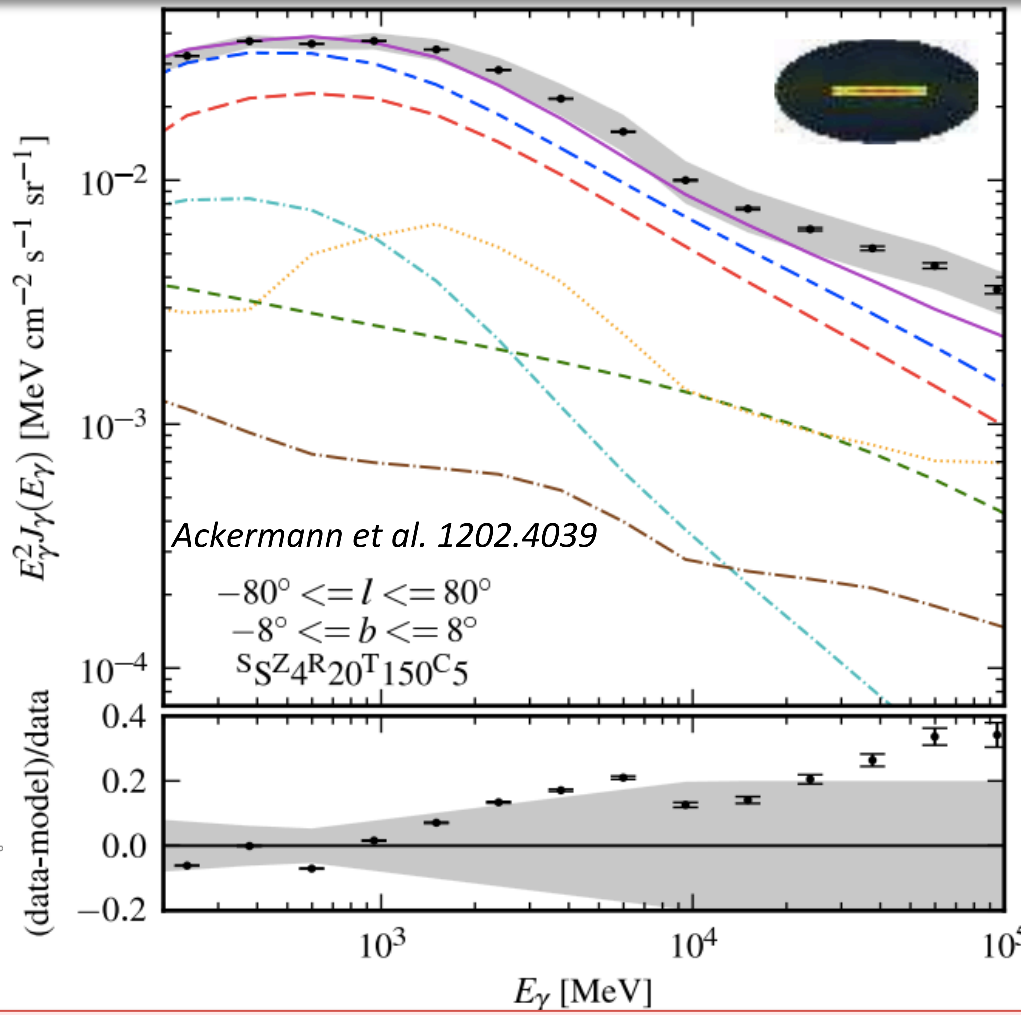


Fig. 1

http://fermi.gsfc.nasa.gov/ssc/data/access/lat/Model_details/FSSC_model_diffus_reprocessed_v12.pdf



Main reasons:
- it neglects the possibility of a significantly enhanced cosmic-ray abundance in the inner Galaxy
- inverse-Compton template strongly depends on inputs: source distribution, diffusive halo geometry and source spectrum

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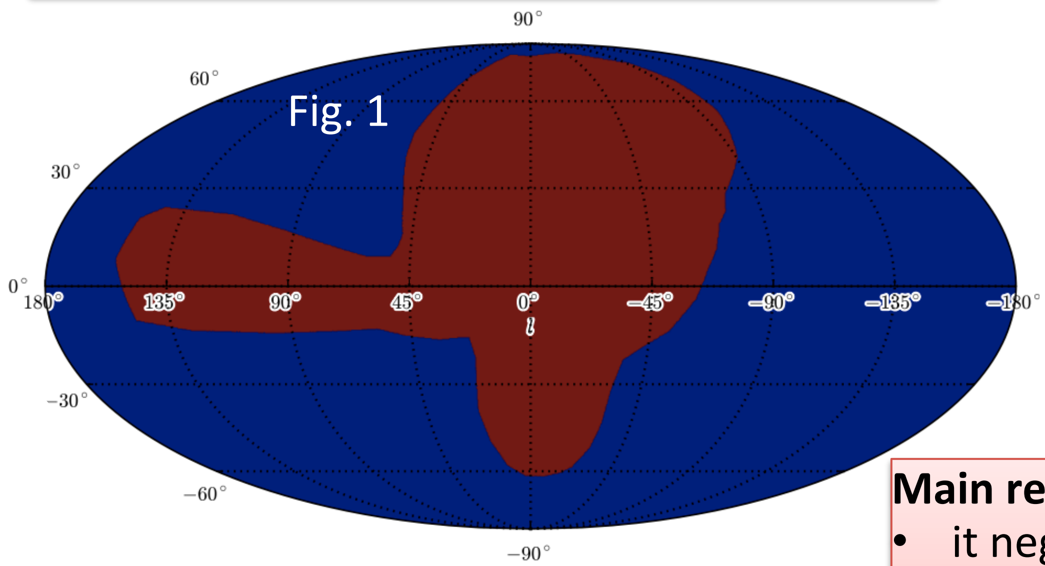
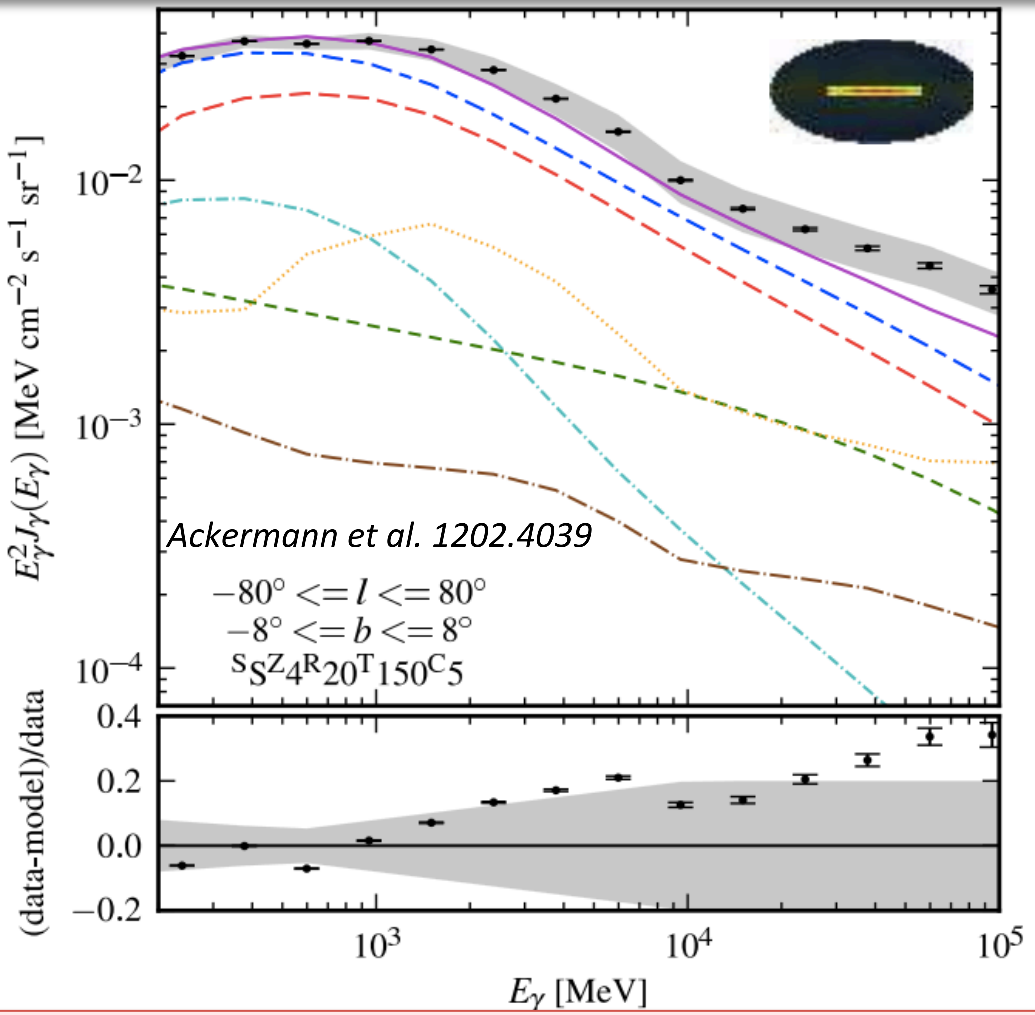


http://fermi.gsfc.nasa.gov/ssc/data/access/lat/Model_details/FSSC_model_diffus_reprocessed_v12.pdf



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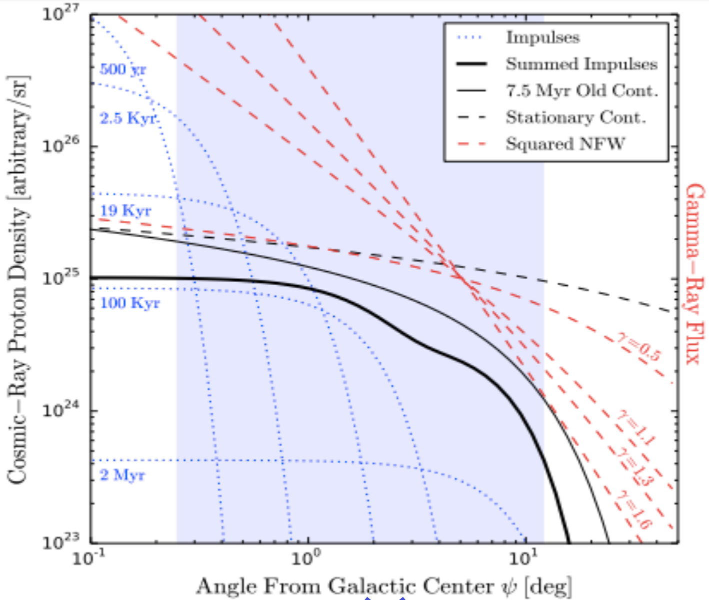
Fermi-LAT GeV excess : proton accelerator

- **The convolution of the proton distribution and the warm ionized gas gives the right radial distribution**



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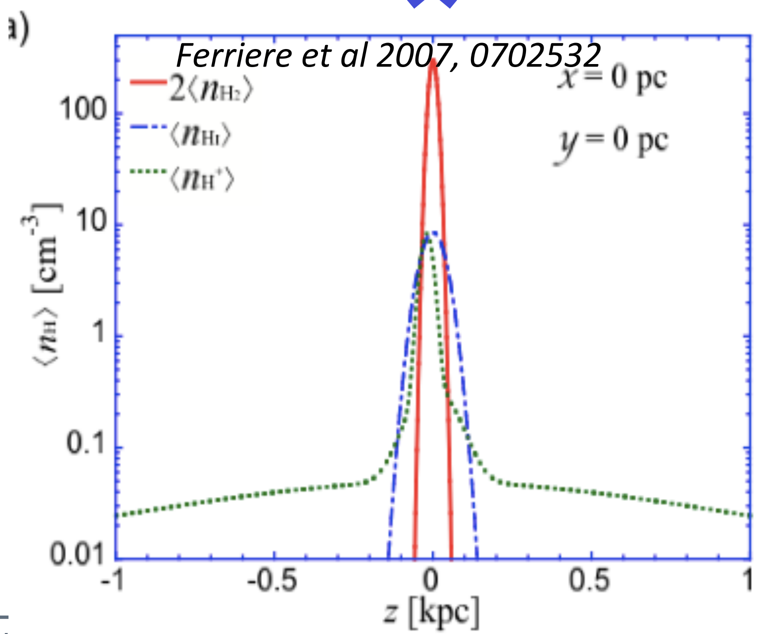
Ferriere et al 2007, 0702532



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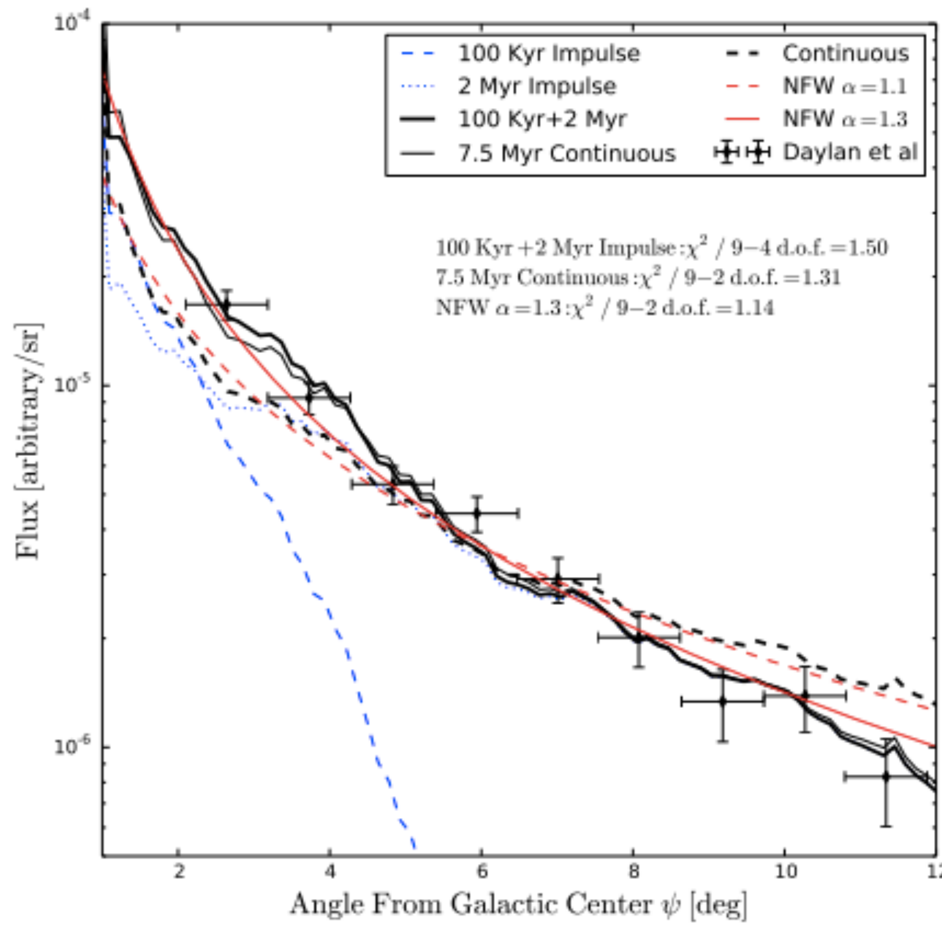
Carlson & Profumo, 1405.7685

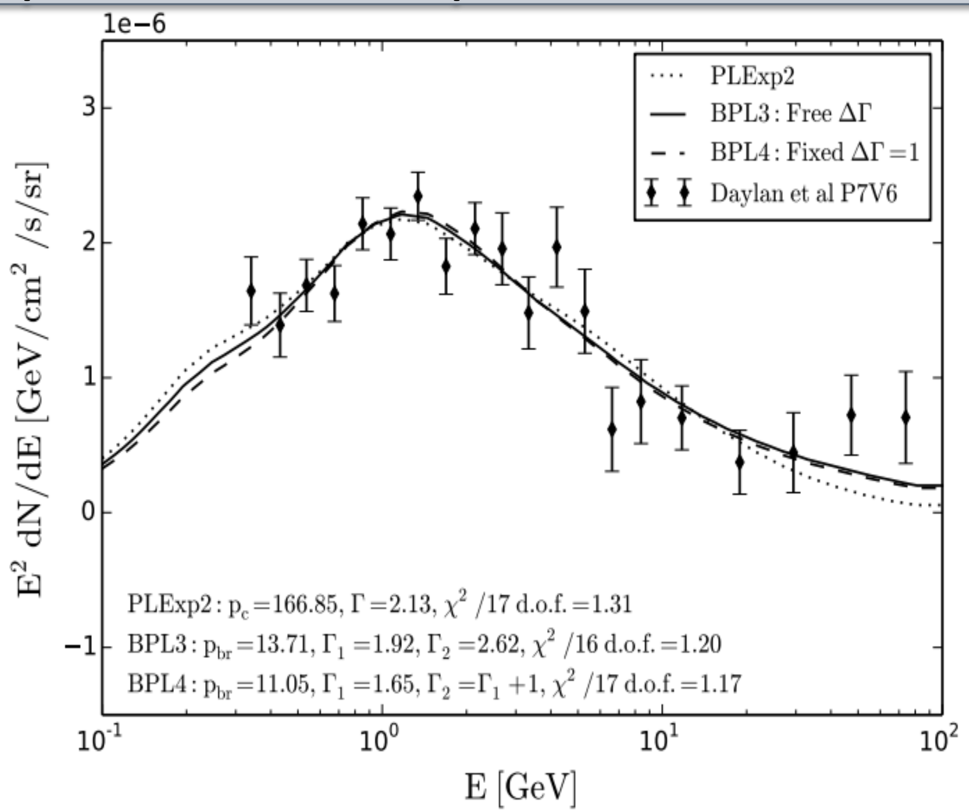


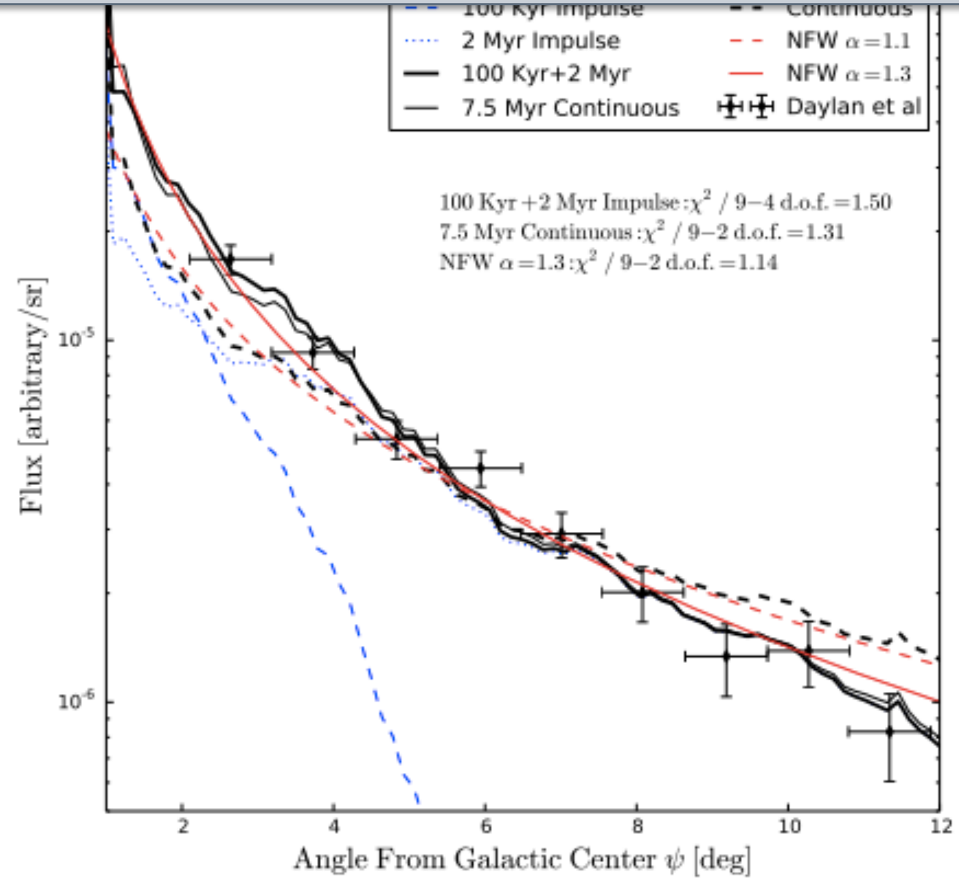
Fermi-LAT GeV excess : proton accelerator

- The convolution of the proton distribution and the warm ionized gas gives the right radial distribution

Carlson & Profumo, 1405.7685

- The excess spectrum can be fitted with a proton injection spectrum with a broken power-law
- Interestingly the gamma-ray spectrum from pion decays of an initial proton spectrum with a E^{-2} power-law has a bump at ~ 1 GeV

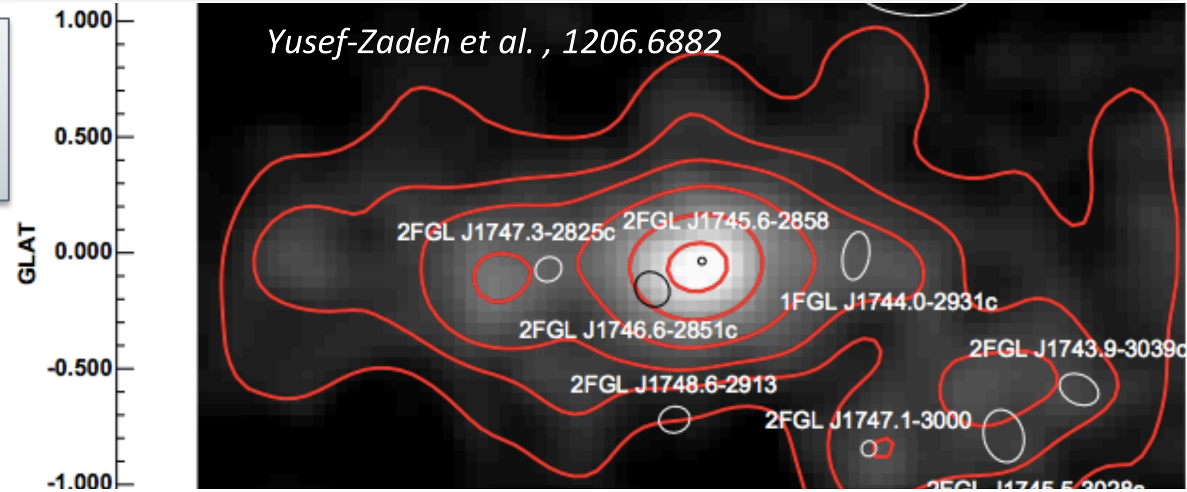


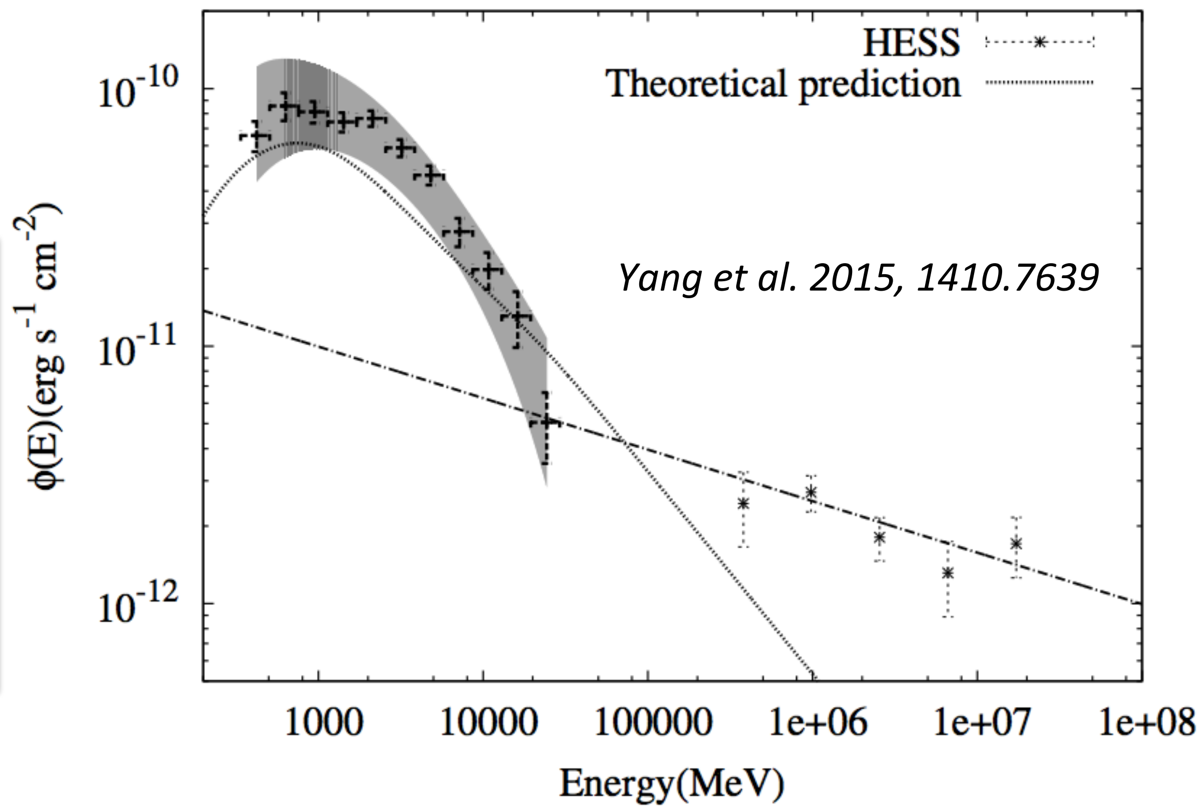


Proton injection power needed:
10^{38} ergs/s (> 100 MeV)

Galactic Ridge at GeV

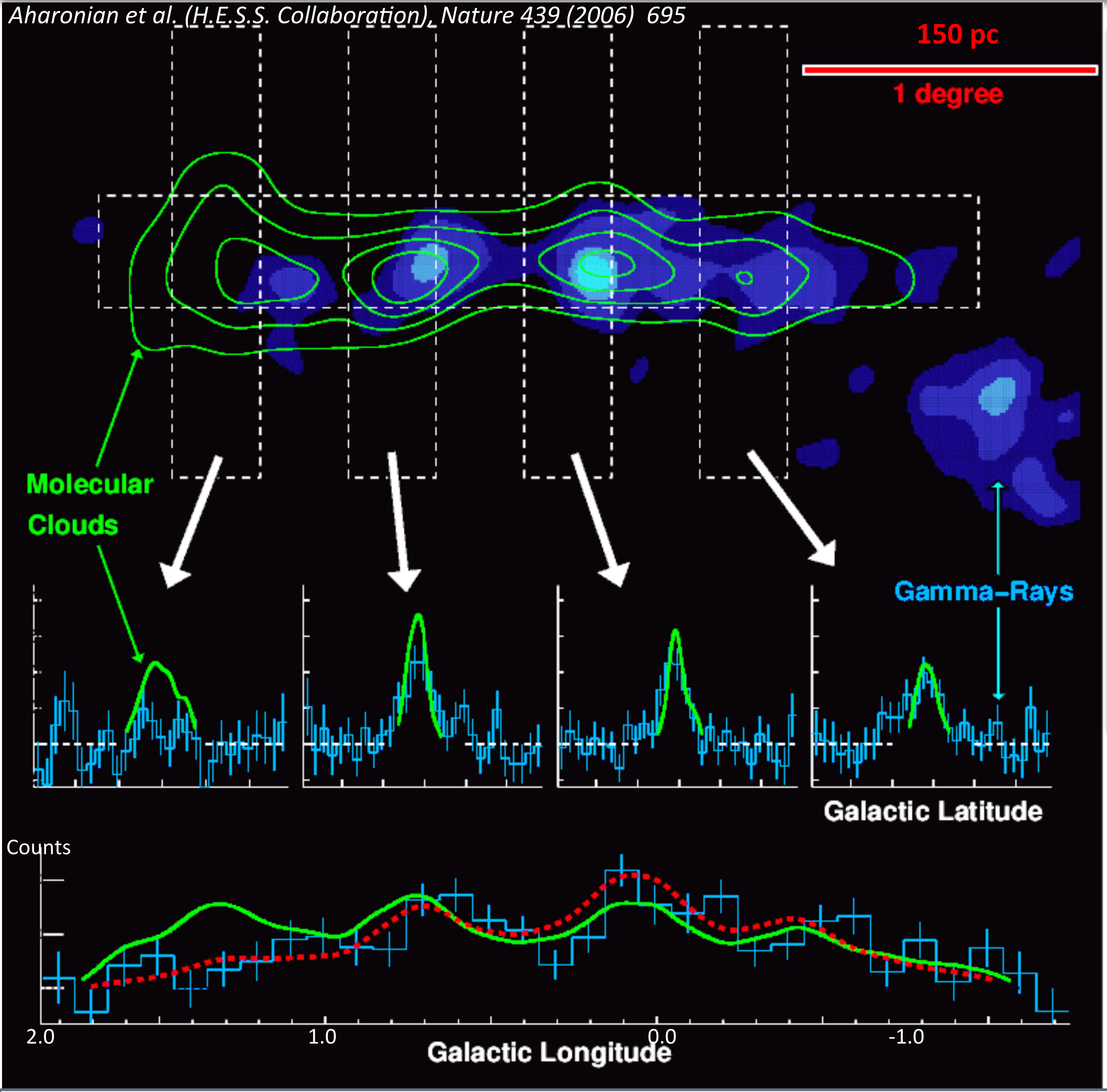
Fermi map and contours at 1-300 GeV:
- 2FGL J1745-2858 : coincident with the HESS source





- Sgr B2 region spectrum well below the expected emission from the « sea of CRs»
- Beyond ~25 pc of the central proton accelerator gamma-rays below 10 GeV will be dominated by « isotropic » diffuse component

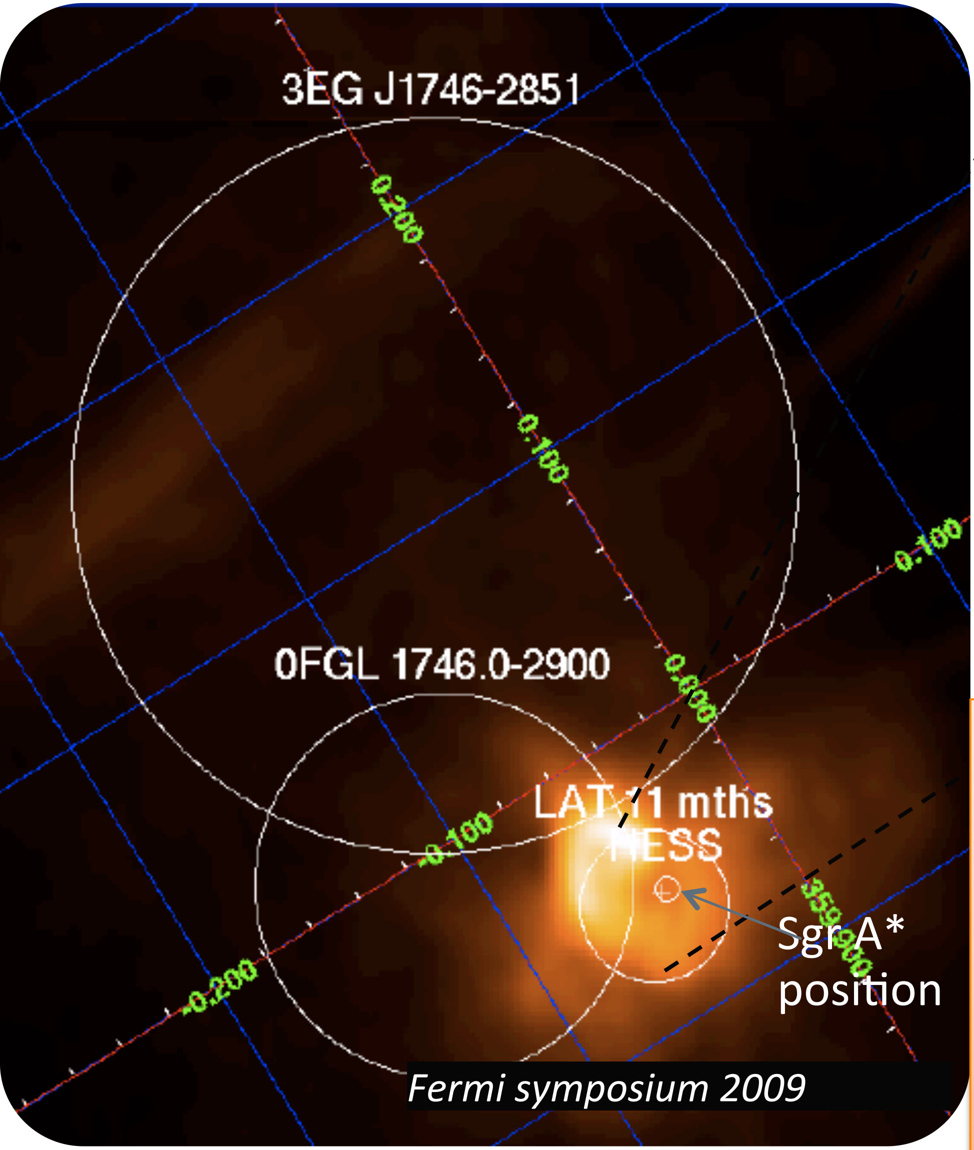
The Galactic Center diffuse emission with H.E.S.S.



- Diffuse emission associated with giant molecular clouds (CS maps as tracers) => hadronic interaction
- CR energy density higher than the local CR density by an order of magnitude
- Lack of TeV emission at b>1.0º => CR gradient necessary to explain emission

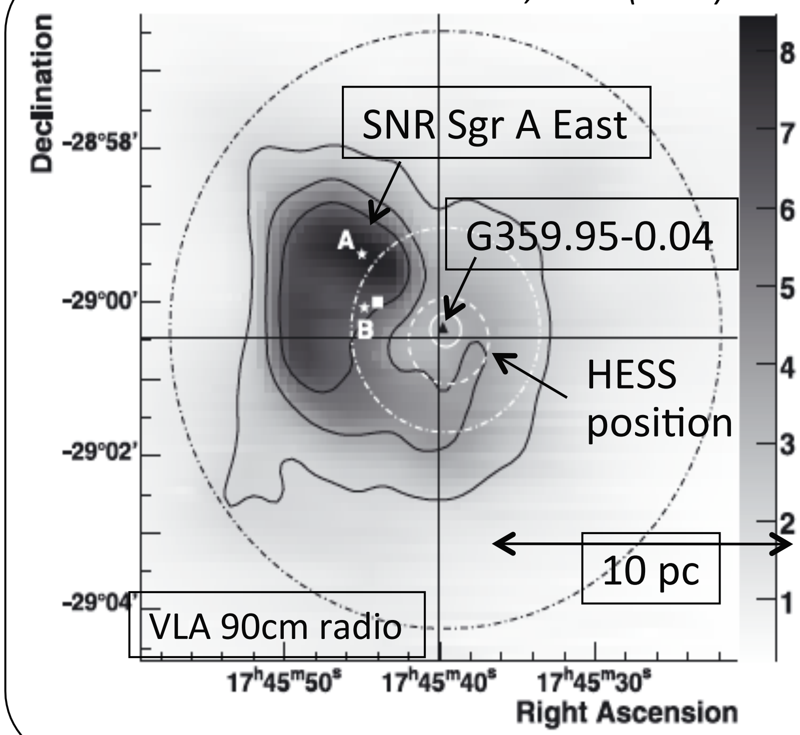
The HESS J1745-290 central source position

HESS improved pointing analysis : 30''->6''



Fermi symposium 2009

HESS coll. MNRAS 402, 1877 (2010)



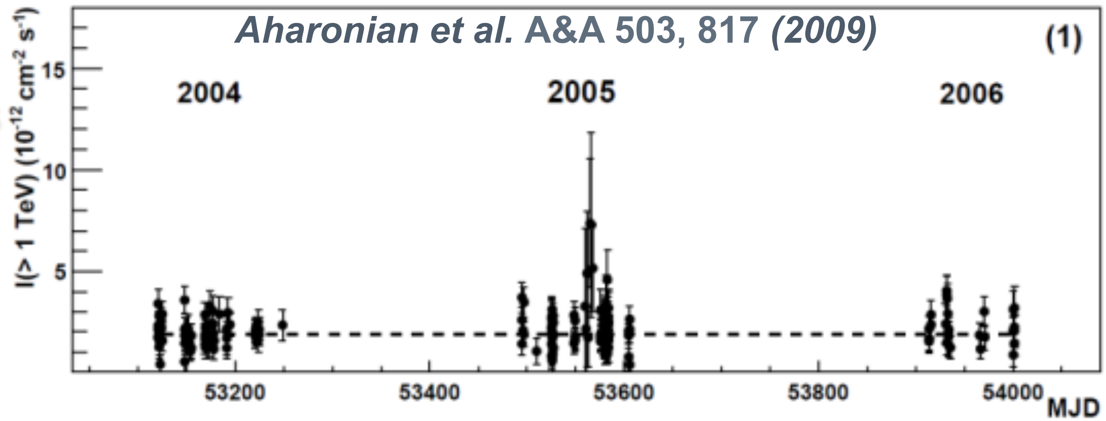
- position:
  l=359°56'41.1''± 6.4''± 6''
  b=-0°2'39.2'' ± 5.9'' ±6''
- centroid emission located at 7''±12'' from Sgr A*
- Sgr A East excluded at the 7σ C.L.
- G359.95-0.04 and Srg A* still inside error bars (8.7'' from Sgr A*)

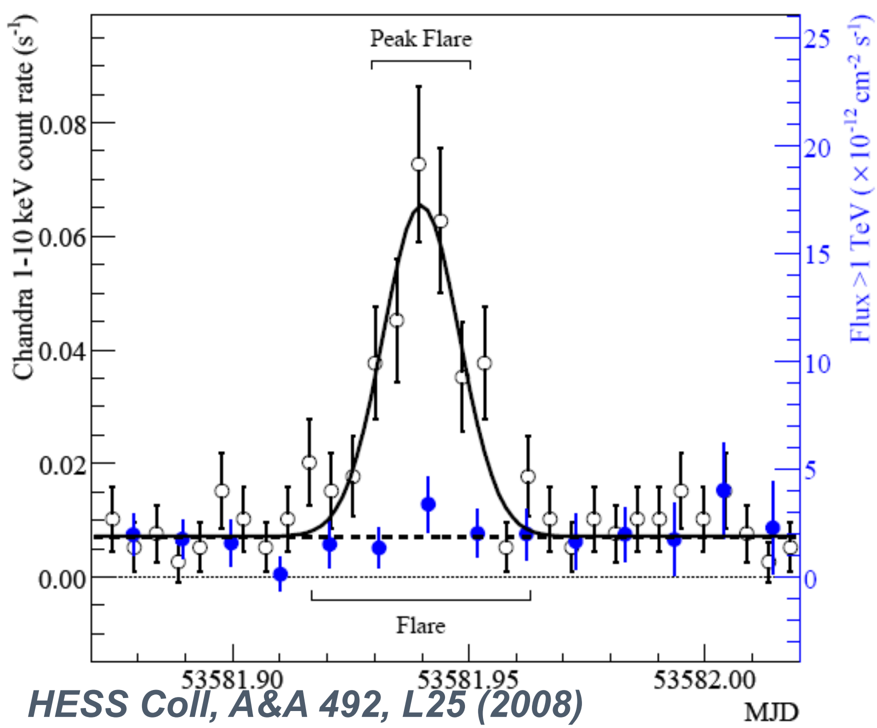
The J1745-290 GC central source variability

- No signs variability in VHE light curve observed based on 93 hours of data

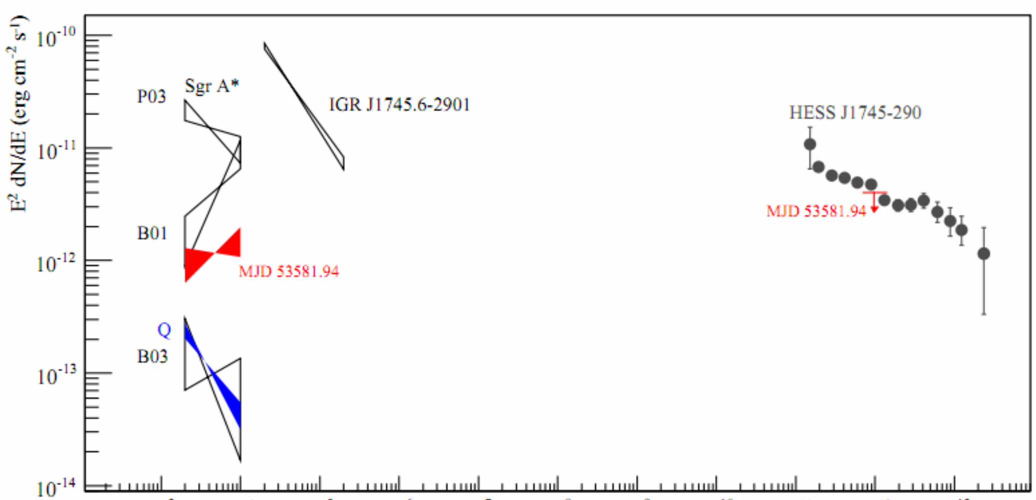
- Simultaneous HESS and Chandra observations in 2005
- X-ray flare detected
  - 1-10 keV
  - 1600s duration
  - 9x quiescent level
- No increase of gamma flux >1 TeV (factor 2 increase excluded at 99%CL)

=> disfavours scenarios where keV and TeV emission are associated with the same parent population (or mechanism)





HESS Coll, A&A 492, L25 (2008)



CTA improvements on Galactic Center

- Large field of view=> more detailed view of the Diffuse VHE emission
  - Resolving new, previously undetectable sources
  - Studying the interaction of the central source with neighbouring clouds
  - outflows
- Improved PSF (r68~0.02˚-0.03 ˚), Improved pointing accuracy (3”) and sensitivity:
  - **Try to resolve GC source** (e.g.: 0.5‘ (0.01 ˚) size of circum-nuclear disk)
  - **distinguish Sgr A* and PWN**
  - If TeV emission produced by hadrons, emission should be extended (0.5')
- **Search for a possible time dependent component**
  - Sgr A* MWL observations with IR/ X-ray instruments
  - Improved sensitivity to flux variation for flares (typically 1h)
- Search for long term flux evolution
  - Expected if energetic protons accelerated during past periods of increased activity of Sgr A*