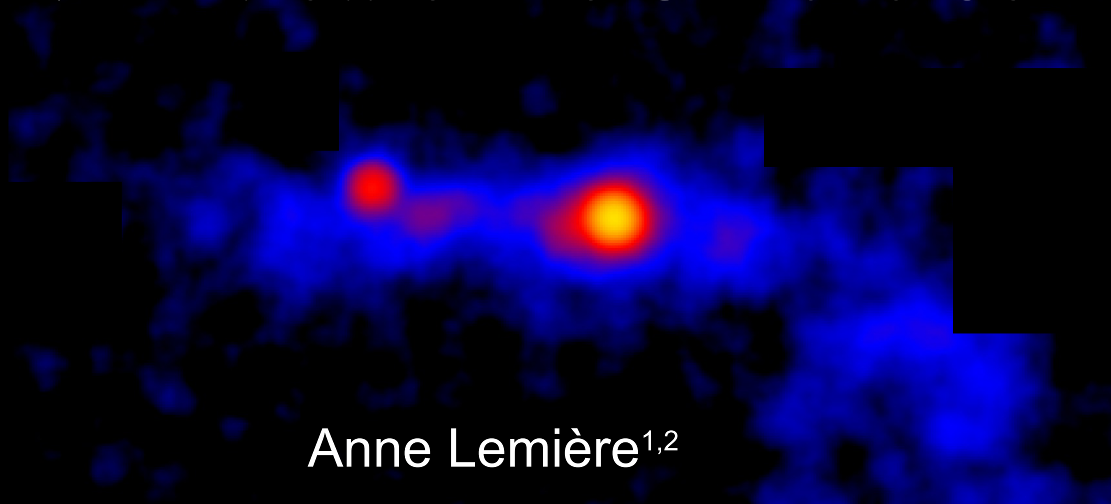
2nd HONEST workshop
PeVatrons and their environments

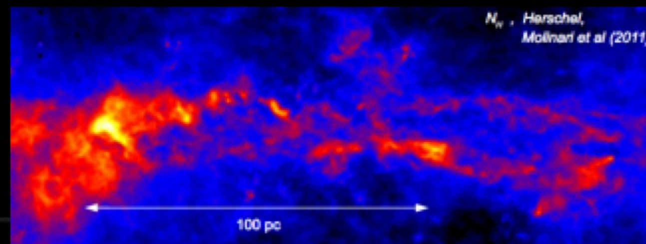
VHE view of the Galactic Centre



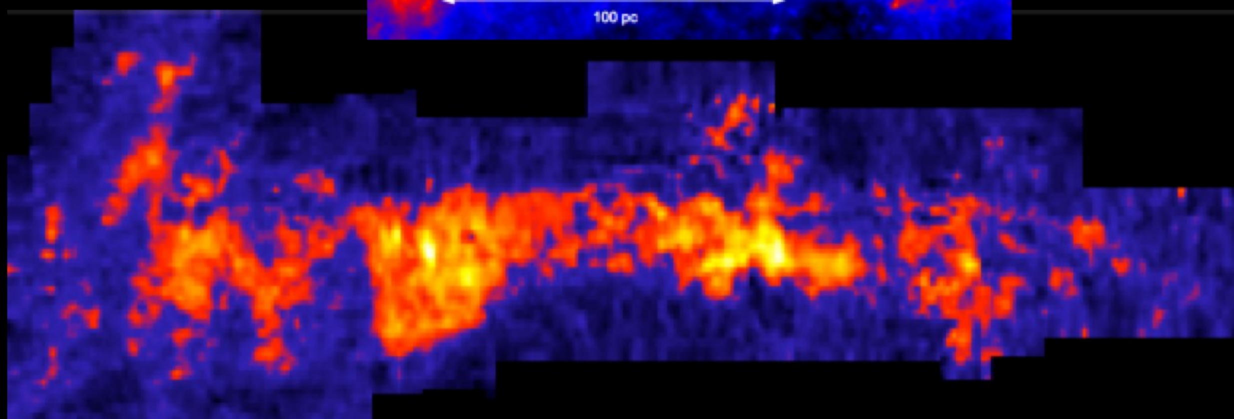
Anne Lemière[1,2]

1 : Laboratory APC, Paris . 2 : Laboratory IAFE, Buenos Aires

Central 200 pc : The Galactic Center Ridge



Molinari et al 2011
Total NH



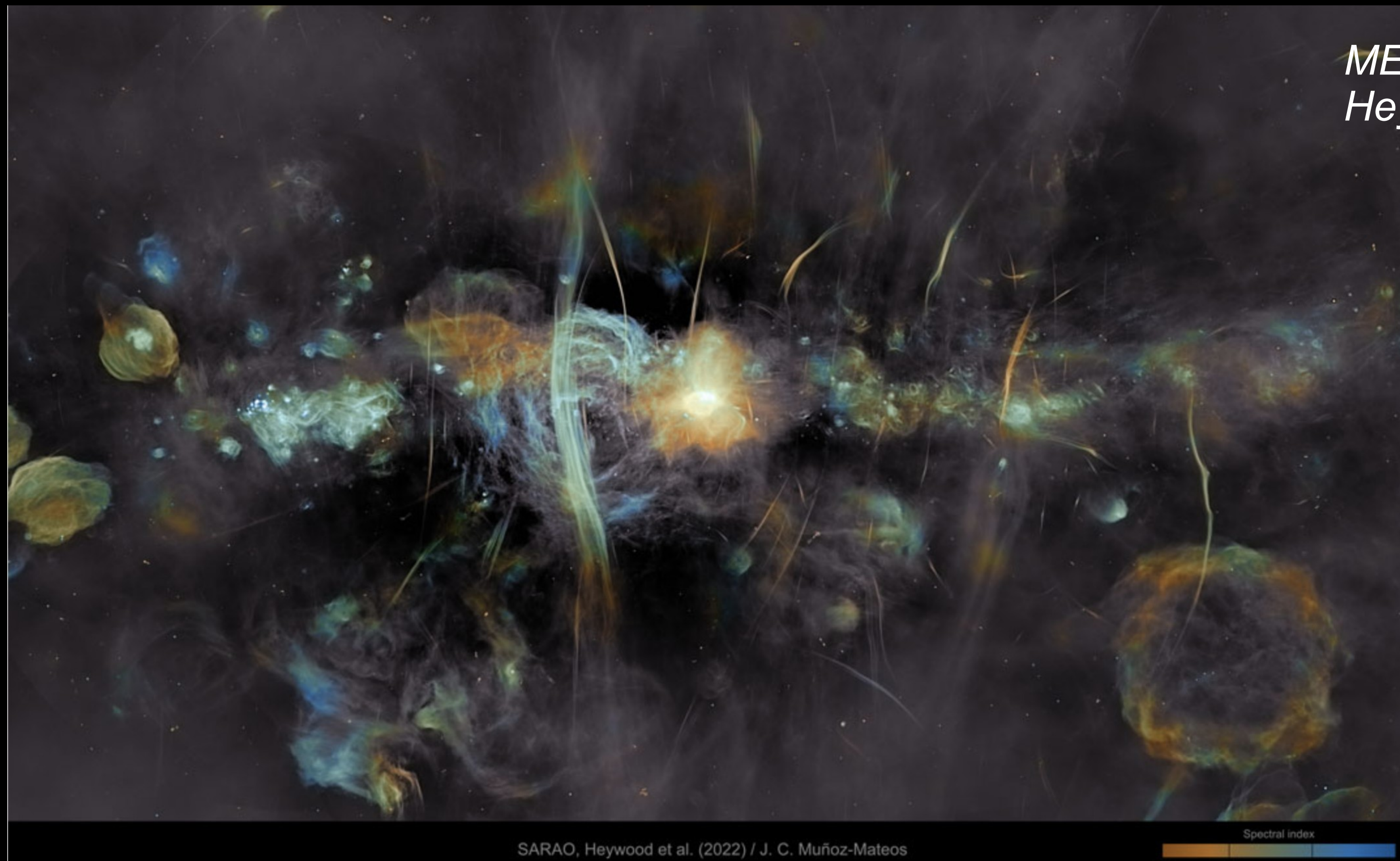
Tsuboi et al
1998
CS

- 10% of the total molecular mass of the Galaxy in 10^{-6} of its volume !

  Central Molecular Zone (CMZ) contains up to 5 10^{7} Mo of molecular matter in form of massive molecular clouds ($n>10^{4}$ cm^{-3}) and a diffuse molecular component (100 cm^{-3})

- Large fraction of young massive star clusters located in the GC: 10% of massive star forming activity in the CMZ

Central 200 pc : The Galactic Center Ridge



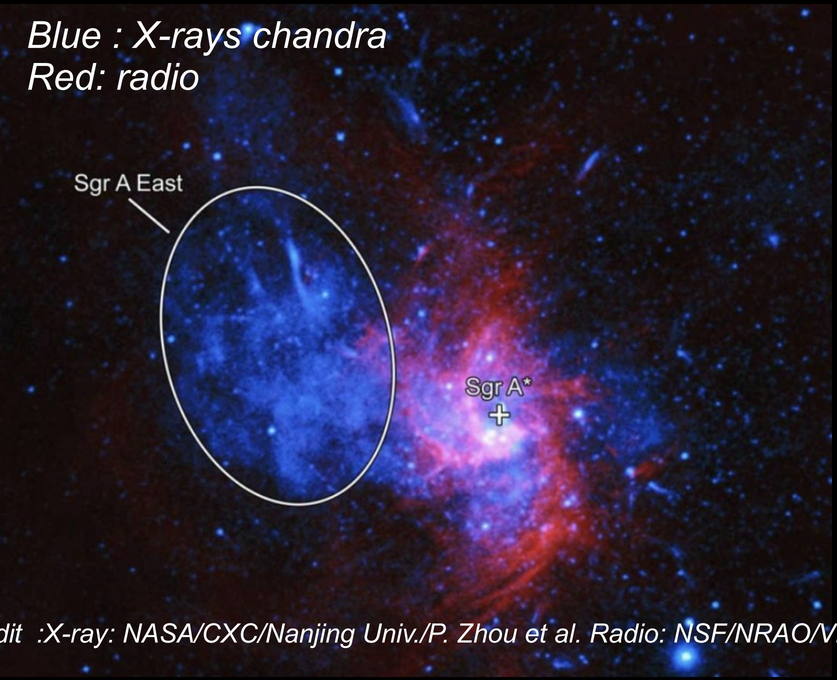
MEERKAT
Heywood et al. 2022

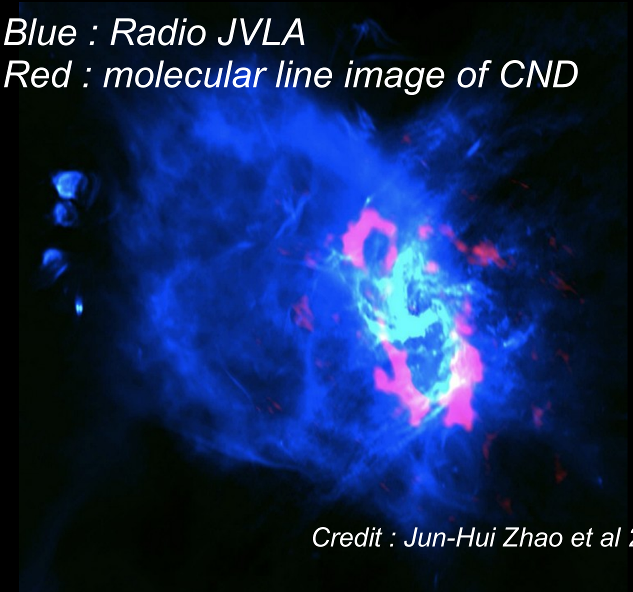
- Many extended objects such as SNRs, non-thermal filaments, pulsar wind nebulae, massive star clusters, etc.

- Magnetic field :

→ Powerful poloidal magnetic field B>50 μG, possibly B ~ mG *(Ferriere et al. 2011)*.
→ Huge amount of magnetic energy, E ~10^{55} erg, stored in the central 300 pc.

The Galactic Center





- Sgr A east:
  bright and compact mixed morphology SNR (radio shell & thermal X-ray core).
  (Sakano et al (2004), Park et al (2005),Koyama et al (2007))

- SgrA* : M~ 4.10^6 M_{sun}
  (Ghez et al. (2000) and Gillesen et al. (2009))
  - remarkably faint : L $=10^{33}$ erg/s
  - subject to frequent X-ray flares (not at TeV)

- The mini-spiral of ionized gas falling into or orbiting the Center
- The circumnuclear disk (CND)

- A Pulsar Wind nebula :
  PWN G359.95-0.04 at only 7'' (0.3pc) of SgrA*
  (Hinton et al. 2007)

GC observed by IACTs

- H.E.S.S.(2004,2006,2016,2018,2022)

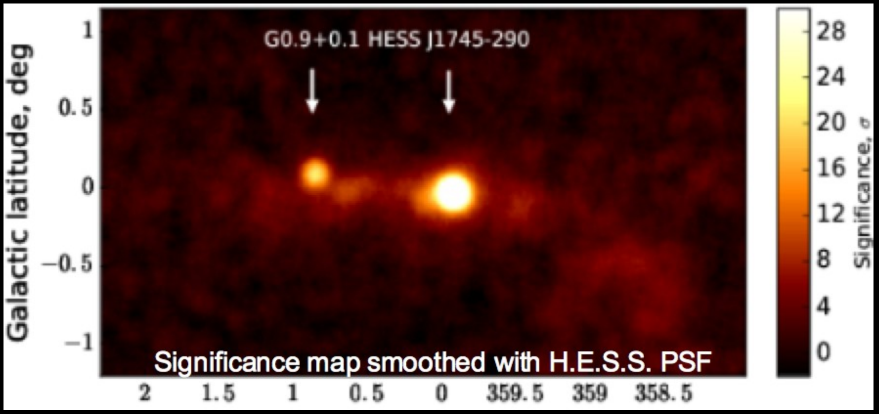
2004 : first clear GC TeV source detection-Spectrum with photon index ~2.2,

2006 : first detection of Diffuse Emission

2016 : Detect a Pevatron candidate

2018 : Full morphological strudy and total ridge spectrum extraction (250 hours of livetime)

2022 : 12 years of H.E.S.S. data (CT1-4) total livetime of > 350 hours. First 3D analysis.

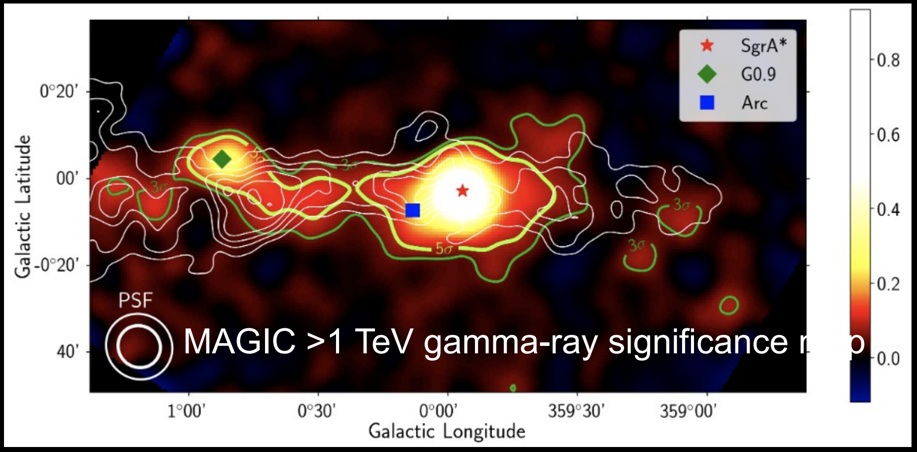


- MAGIC (2006,2016,2020)

2006 :confirms H.E.S.S. detection of HESS J1745-290

2016 : Detect diffuse emission

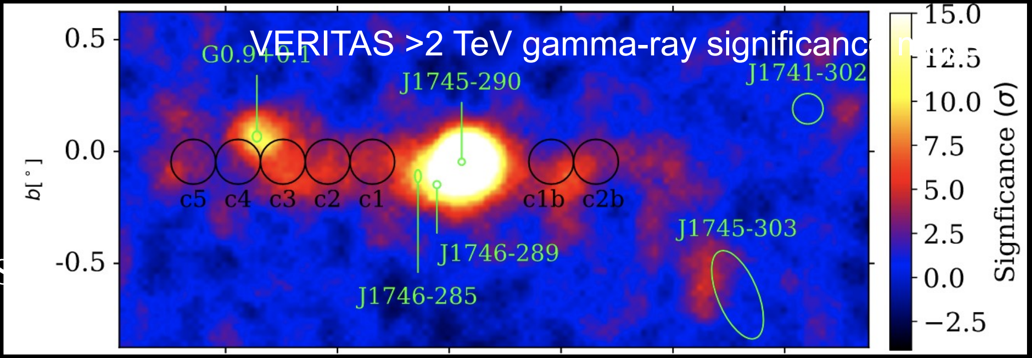
2020 : 100 hr (2012- 2017), derive spectra of individual sources and diffuse emission



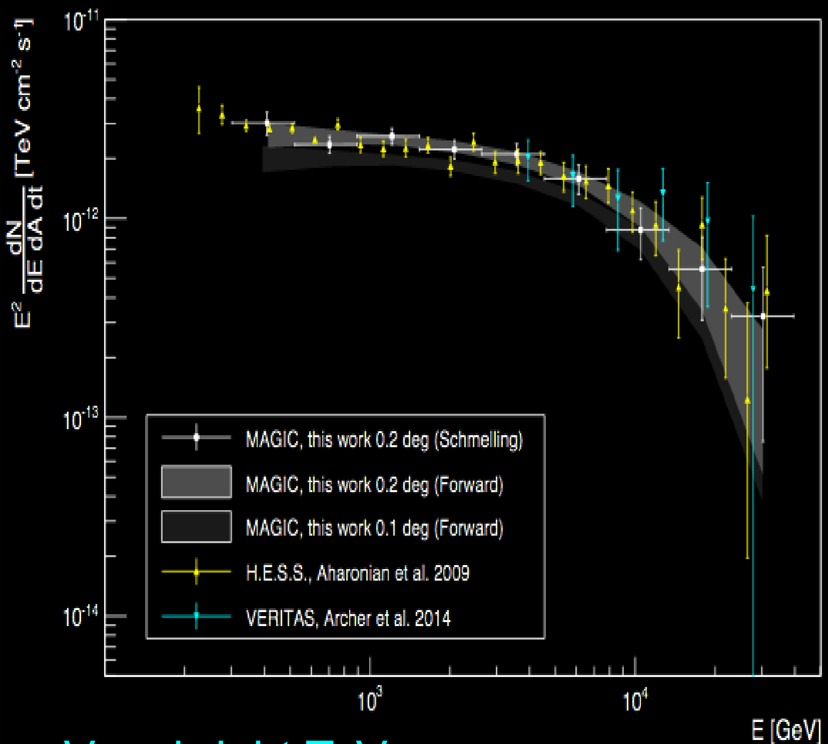
VERITAS (2011,2016, 2021)

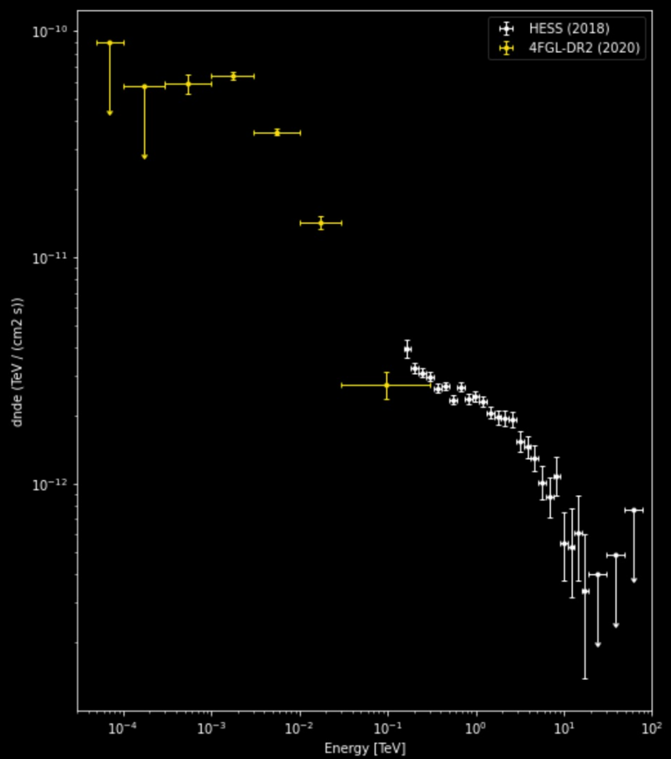
2016 : Diffuse emission detection (80 hrs)

2021 : 125 hrs (2010-2018)



HESS J1745-290 Spectrum





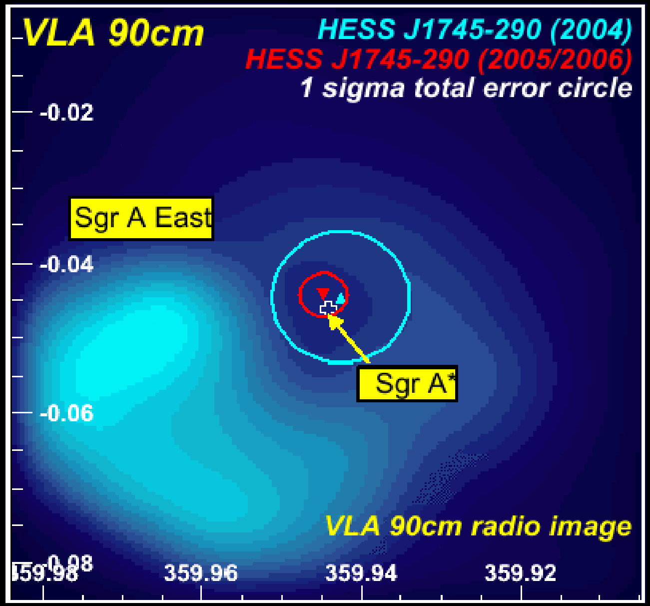
Very bright TeV source :

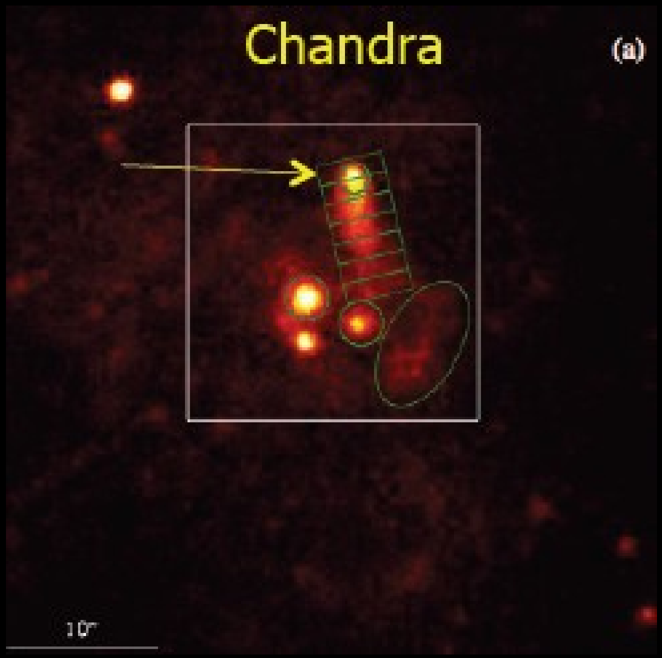
- L(>1TeV) ~ 8 × 10 ^{34} erg s−1
- Significant deviation from a power-law :
  - Spectral index ~ 2.2
  - Exp cut-off at E~15 TeV
- No variability

FERMI counterpart confirmed : (*Cafardo et al. 2021*)

- 4FGL J1745.6−2859
- centroid of the emission approaches Sgr A*'s location as the energy increases.
- L (>0.1 GeV) ~ 2.6 × 10 ^{36} erg s−1
- Log Parabola shape
- No variability

Counterparts for HESS J1745-290





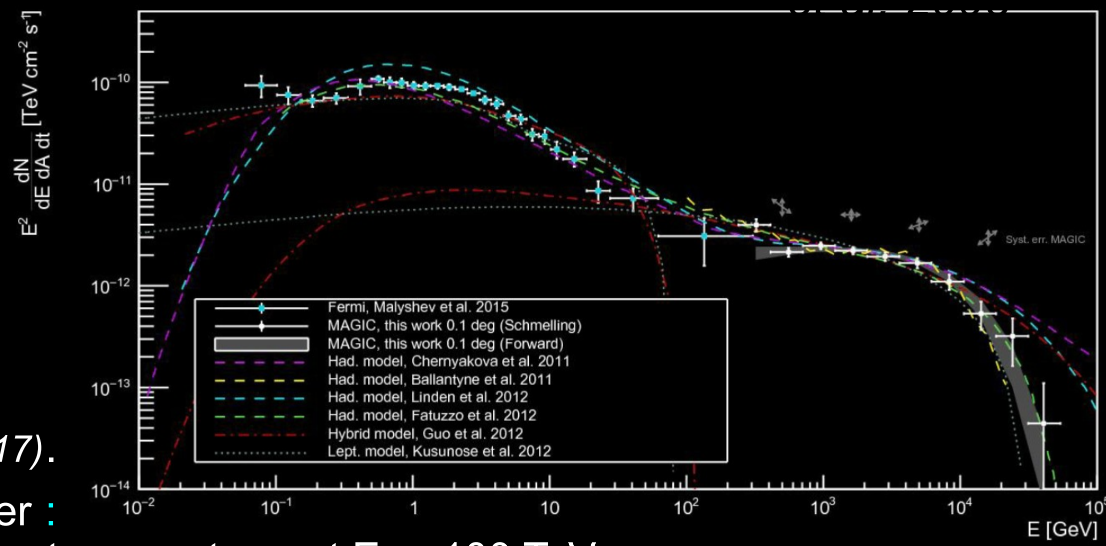
HESS collab. 2010 :

- Maximal source extension <1.3' (95% CL) i.e. < 3pc
  Excludes Sgr A East as a plausible counterpart
- Source within 6'' of Sgr A* (after pointing accuracy improvements)

Nature of the emission ?

- Sgr A* :
  TeV particles accelerated in the vicinity of the SMBH, diffuse and interact with the dense circum-nuclear disk.
- The PWN G359.95-0.04 at only 7'' (0.3pc) of SgrA* (Hinton et al. 2006)

A counterpart for HESS J1745-290 : SgrA * ?



- Proton acceleration at the chocs
  in the accretion flow, close to SgrA* :
  - pp interaction in the flow matter *(Aharonian et al. 2005)*
  - diffusion at larger distance, pp interaction with the CND *(Chernyakova et al. 2011, Linden et al. 2012 , Ballantyne et al. 2017)*.

  The energy cut-off in the TeV spectrum can either :
  - Reflect the energy cut-off in the primary proton spectrum at Ep ~100 TeV
  - Be due to photon-meson absorption on local mm-IR photons
  - Reflect the diffusion of protons outside of the center: competition between injection and escape of protons as function of energy

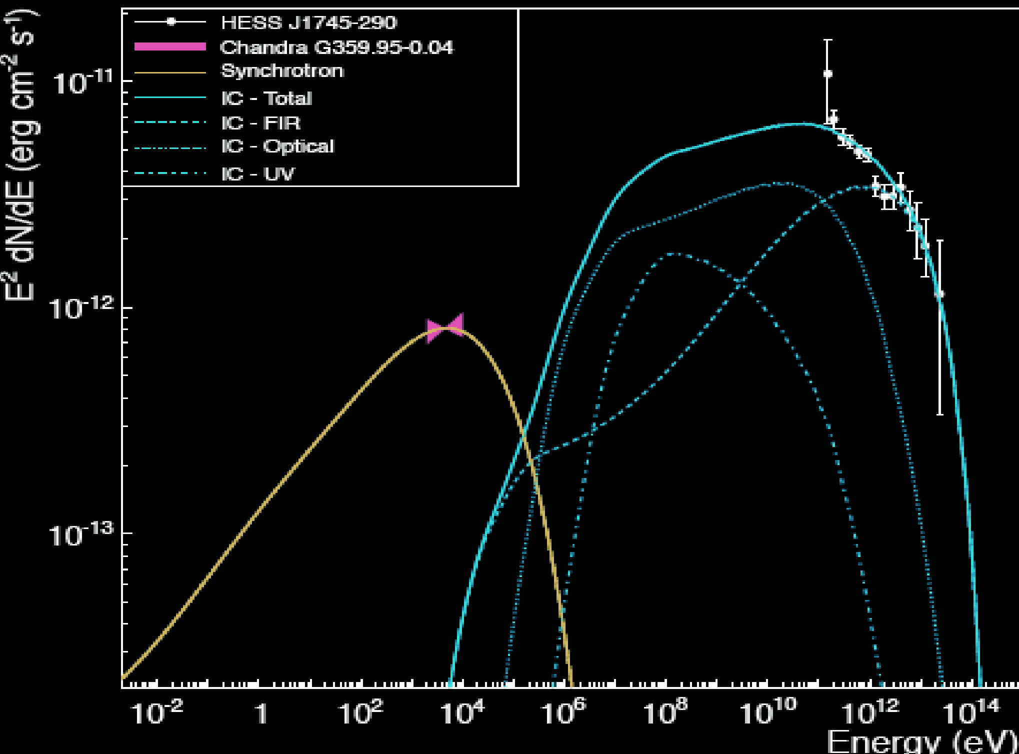
- Electrons accelerated :

  IR flares accumulated close to SgrA* + IC on photon field from stars and dust (Kusunose et al. 2012)

  → reproduce FERMI data but not VHE harderning

- Hybrid models (Guo et al. 2014) : protons + seconday electrons

A counterpart for HESS J1745-290 : PWN G359.95-0.04 ?



Hinton et al. 2007

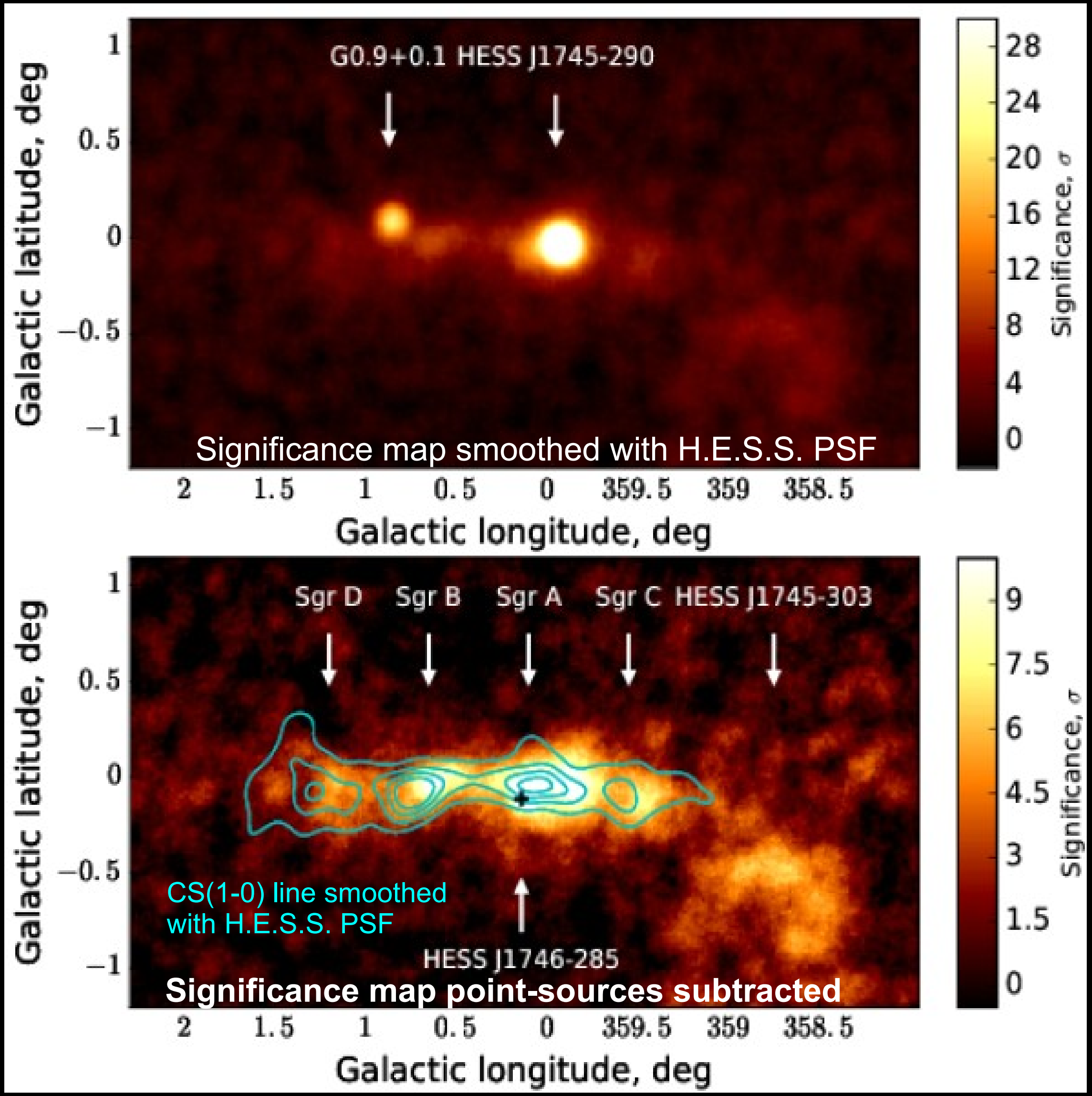
- IC emission from VHE electrons (up to 100 TeV) of the PWN
- Strong cooling effect due to IC of electrons within the strong field of radiation in the GC.
- Energetically possible given high local radiation field and if B~few 10 of μG (Hinton et al. 2007)
- But recent magnetar measurement constrain B~100 of μG *(Kennea et al. 2013,Eatough et al. 2013, Mori et al. 2015)*
- *Reproduce X-ray and TeV if the PWN in at a distance of 1 pc from the GC (Kistler et al. 2015)*

•*But Fail to reproduce FERMI data*

Galactic Center Diffuse Emission

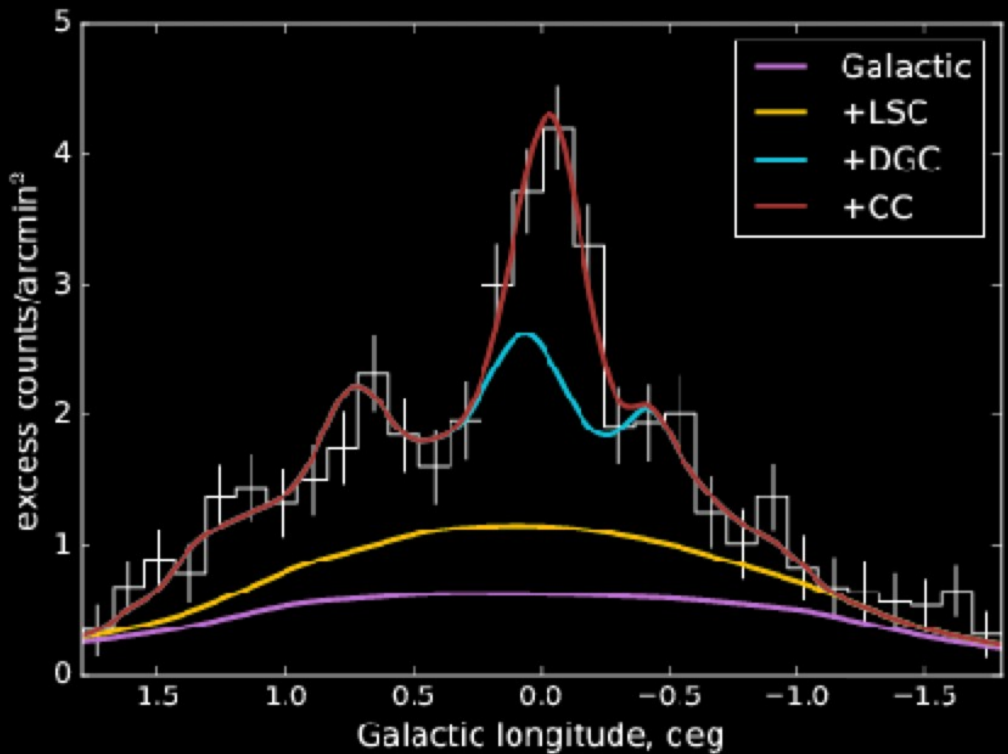
Dataset : ~10 years H.E.S.S.I data set from 2004-2014 : 250 hours of livetime

- Diffuse emission correlated with dense gas tracer CS: ɣ produced through p-p collisions
- Diffuse emission spectrum :
  L_{γ}(>4TeV)= 5.10^{34} erg/s
  10^{49} erg in CR protons (4-40 TeV)
  diffusion time to reach such large distances > 10^{4} years
- Not compatible with spectrum expected from local CR
  → Existence of a local cosmic-ray accelerator
- Deficit of emission at l =1.3° suggest gradient of cosmic-ray on 0.8-1°

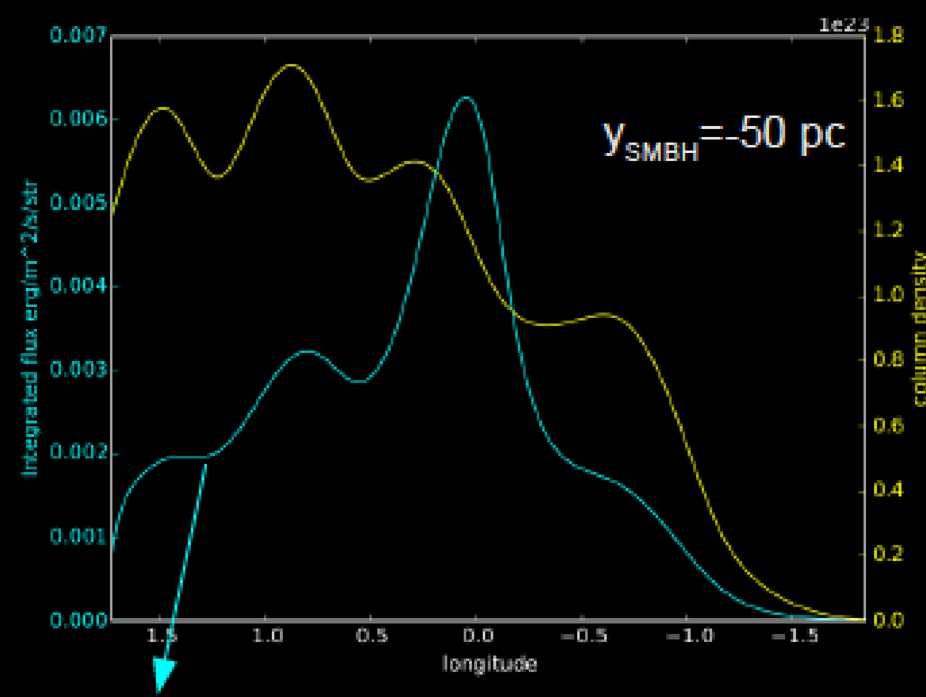


GC VHE diffuse emission components

Longitude profile of the emission : HESS Data



Longitude profile of the simulated gamma-ray emission

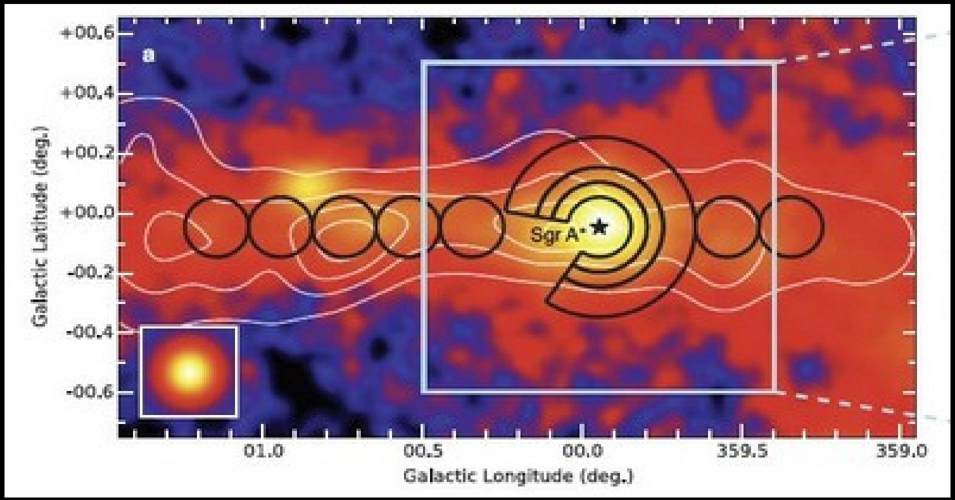


Gamma-ray profile

3D model by Léa Jouvin (AP

CR density profile integrated on the line of sight

- Compute Gamma-ray luminosity L in several regions
- Derive CR energy density : L / M

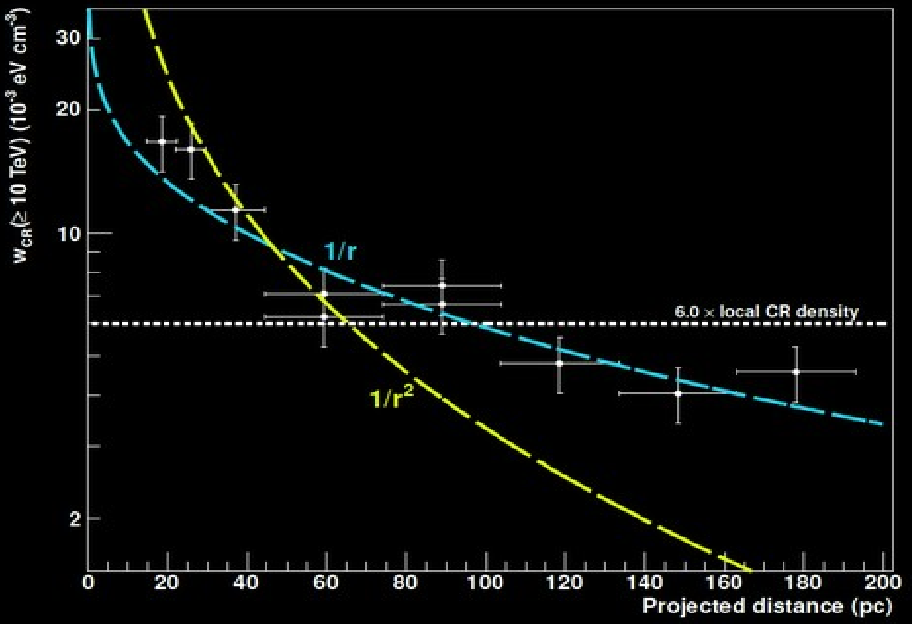


- Build CR density radial distributions :

  $1/r^2$ Wind-driven or ballistic propagation

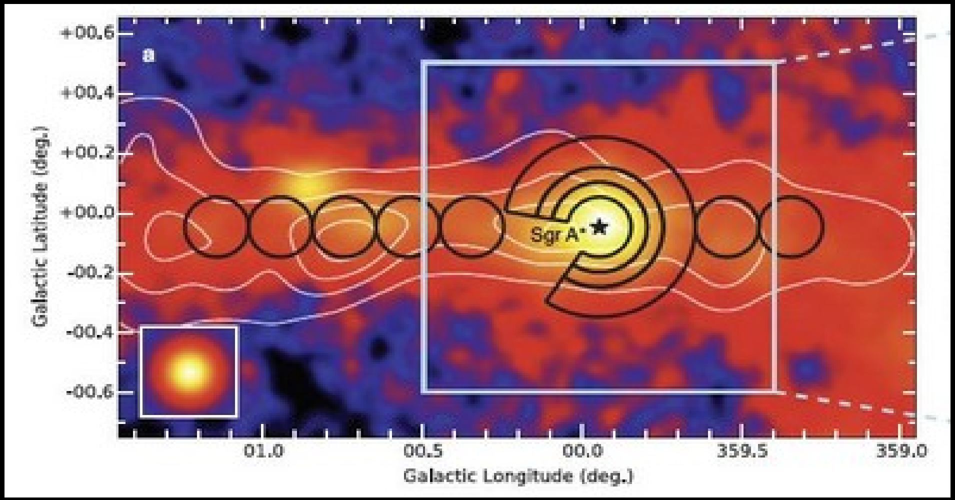
  $1/r$ continuous injection and diffusive propagation

→ Homogeneous/Constant-Impulsive injection of CRs and diffusive propagation



HESS Collab 2016

CR density profile integrated on the line of sight



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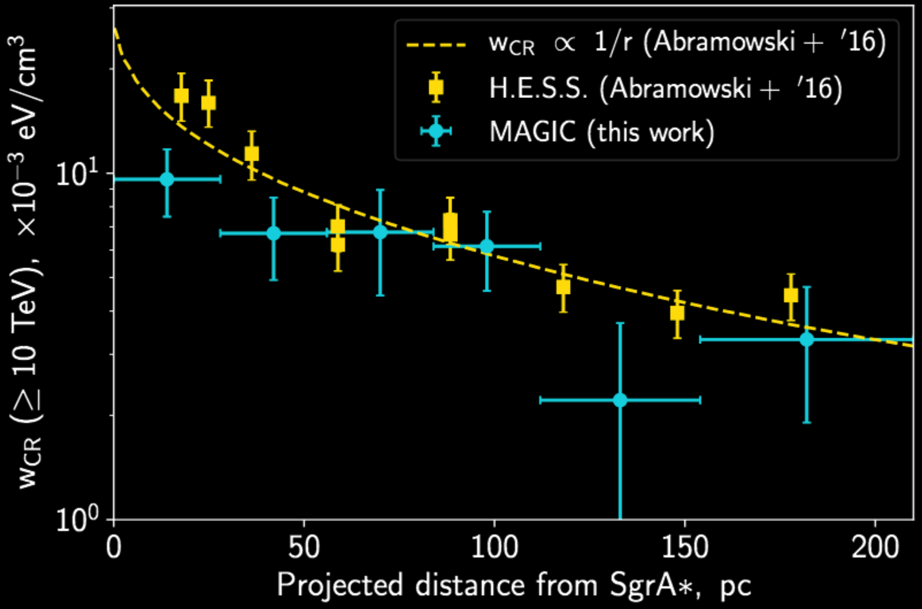
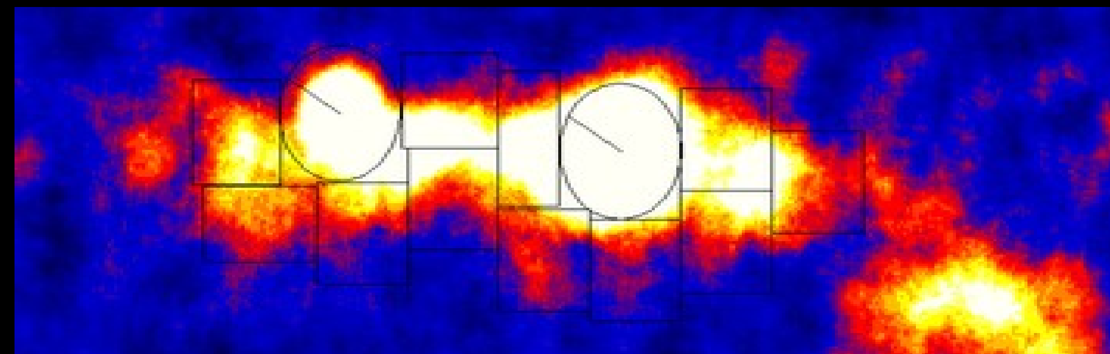


MAGIC Collab 2020

Spectrum of the diffuse emission

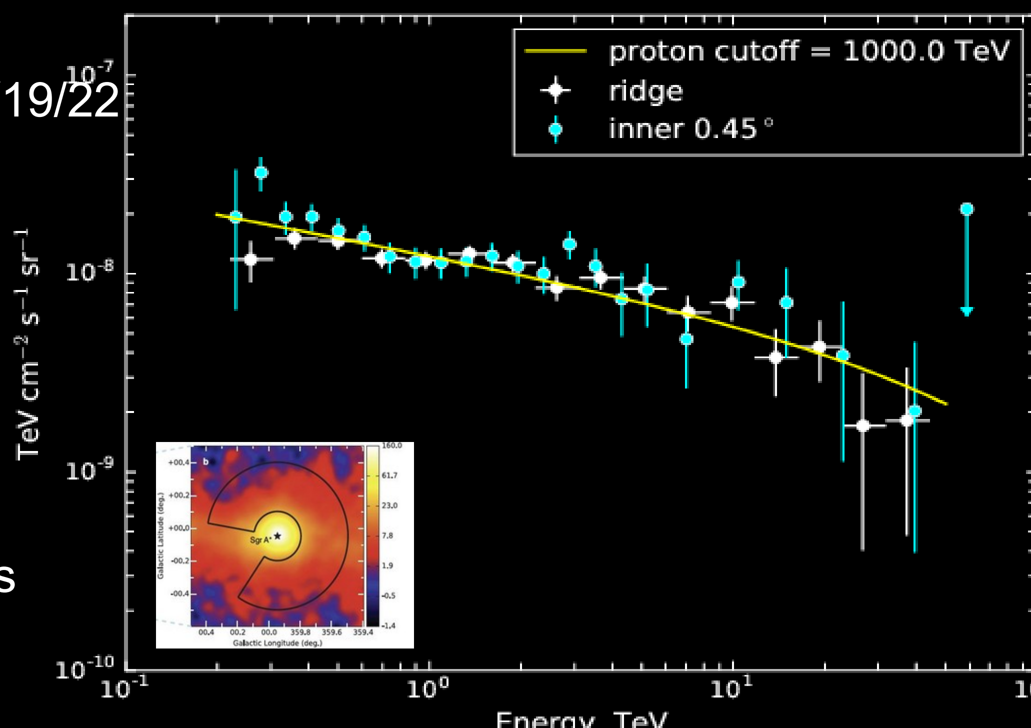


- Power-law with index 2.3 compatible with previous spectrum
- Spectrum extending up to 50 TeV without any detected energy cut-off

Parent proton injection spectrum should :

- extend to PeV energies : PeVatron !
- fill the entire CMZ

9/19/22

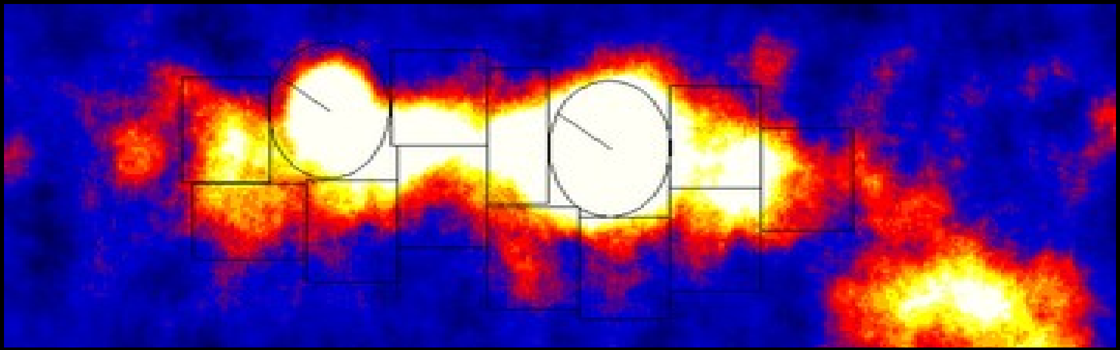


- Quasi-continuous injection lasting over $\sim 10^4$ years
- Total CR power injected at the GC $\sim 10^{38}$ erg/s

HESS Collab 2016

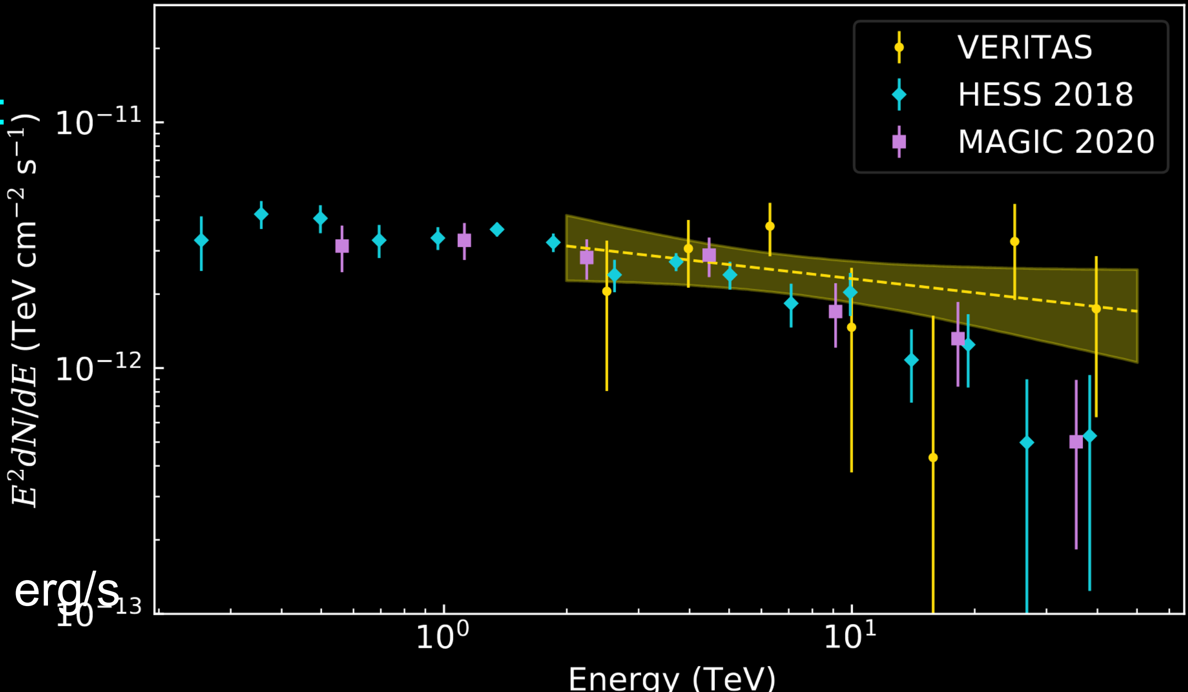
Spectrum of the diffuse emission

- Power-law with index 2.3 compatible with previous spectrum
- Spectrum extending up to 50 TeV without any detected energy cut-off



Parent proton injection spectrum should :

- extend to PeV energies : PeVatron !
- fill the entire CMZ



- Quasi-continuous injection lasting over ~10^4 years
- Total CR power injected at the GC ~10^{38} erg/s

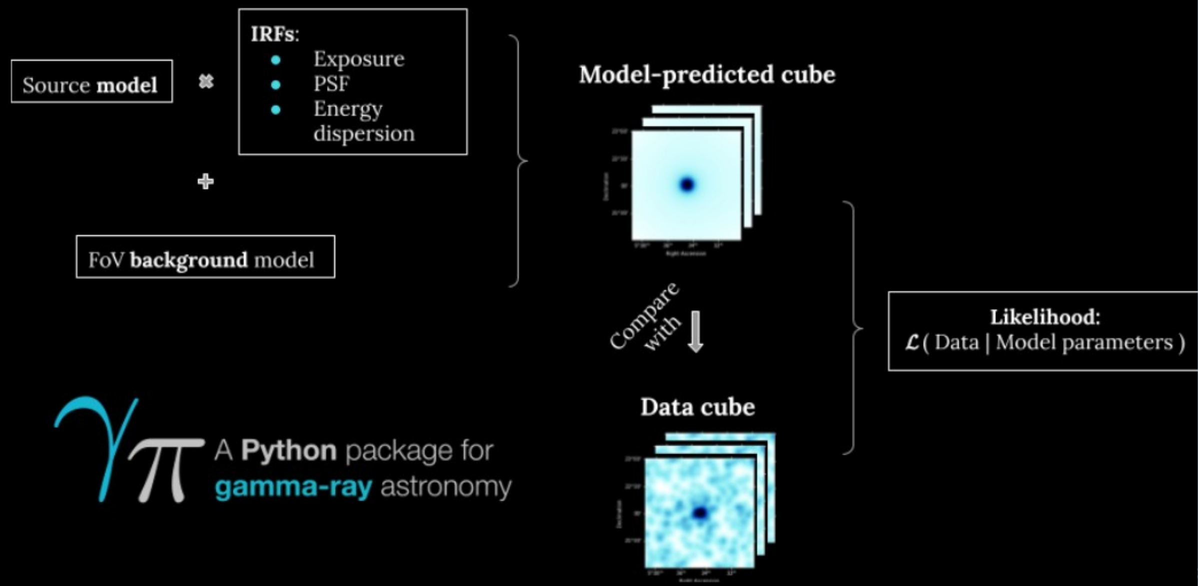
VERITAS Collab 2021

Spectral-morphological 3D likelihood analysis

Revisiting the Galactic center region with a spectro-morphological analysis

- 12 years of H.E.S.S. data (CT1-4)
- Maximum zenith angle of 40°
- 1161 runs (total livetime of ~ 540 hours
- Fit of a 6° x 4° region
- Energy band : 0.4 TeV - 100 TeV

data cube = spatial binning (2D) × spectral binning (1D)



Spectral-morphological 3D likelihood analysis

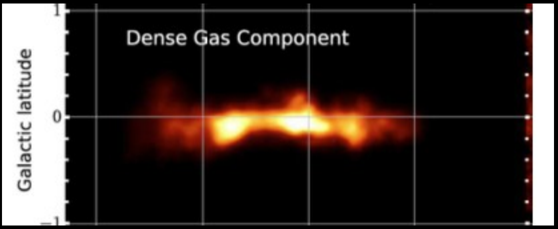
Sources Model

- HESS J1745–290
- HESS J1747–281: PWN G0.9+0.1
- HESS J1746–285: Arc source
- HESS J1741–302: Unidentified source

Diffuse emissions:

➡ Central Molecular Zone (CMZ)

CS map * CR Gauss



➡ Central component (Gauss 0.1°)

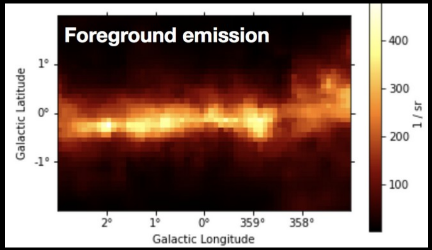
➡ Foreground galactic emission:

2D template extracted

from HERMES calculation of the CR

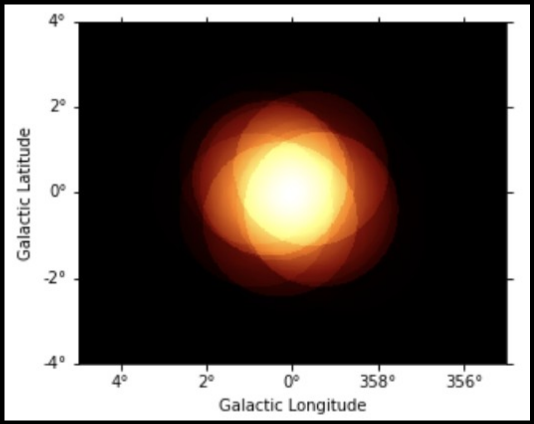
sea interacting with the

CO gas excluding the CMZ.



Background Model

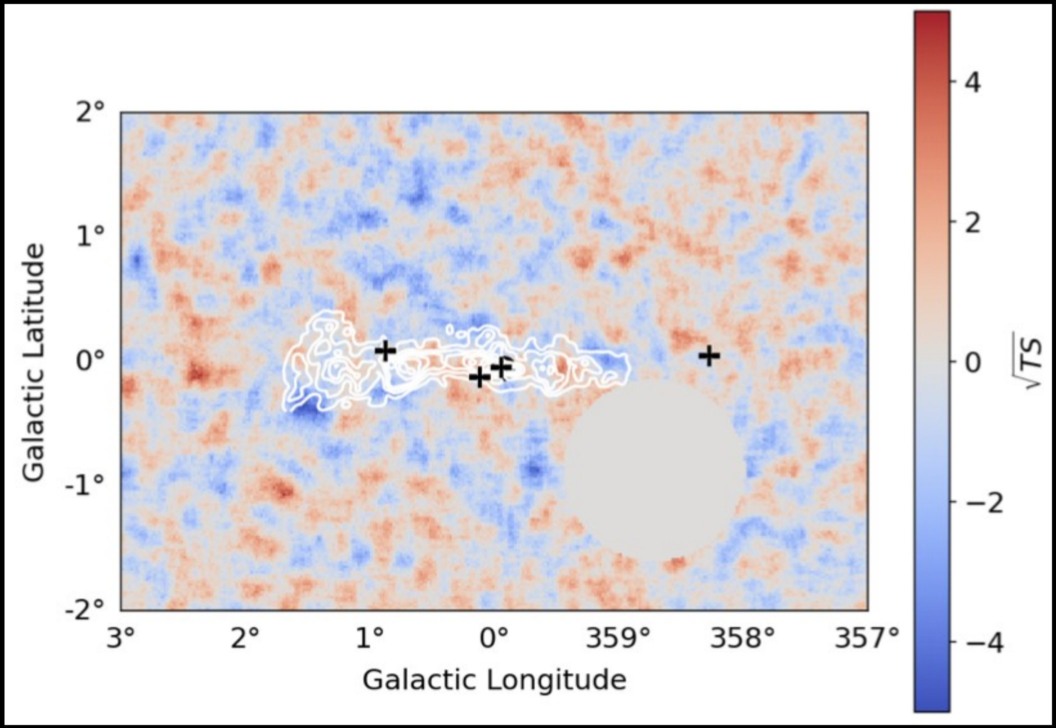
- Background models are created using observation runs on empty regions (high galactic latitudes)
- Events are projected in arrays of observational parameters
- The model is interpolated for each run

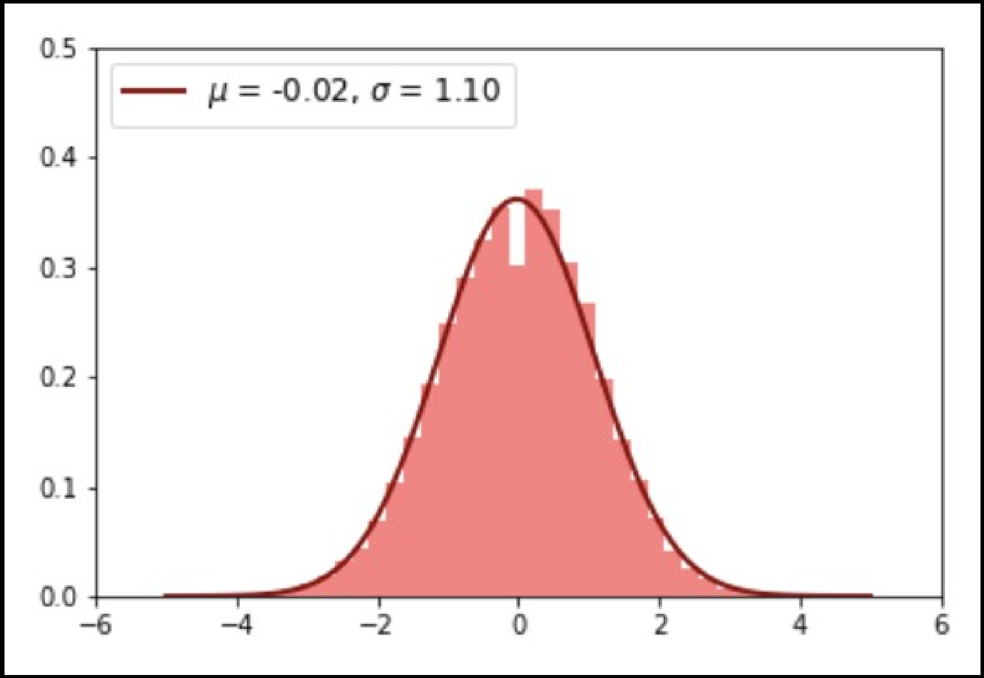


Dundovic et al. 21

Spectral-morphological 3D likelihood analysis

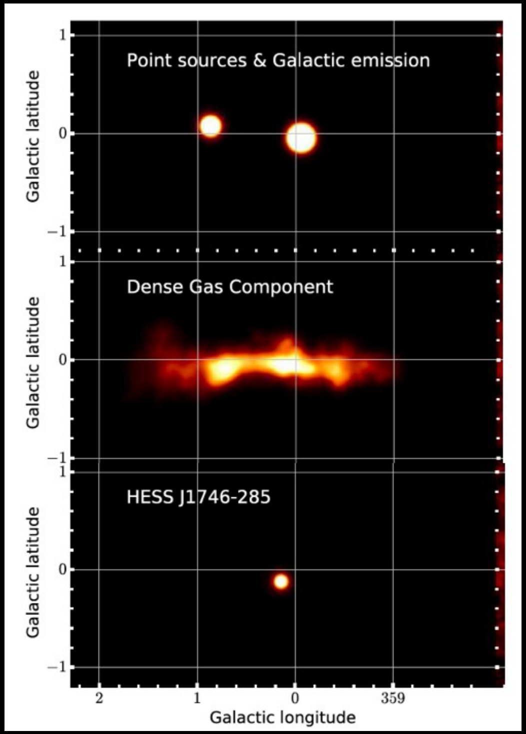
The entire region is well modeled





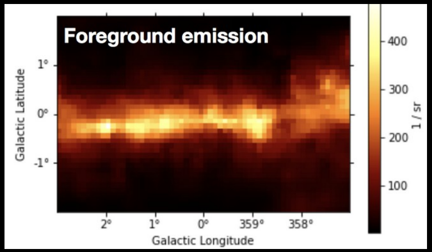
Devin et al. 2022

Spectral-morphological 3D likelihood analysis



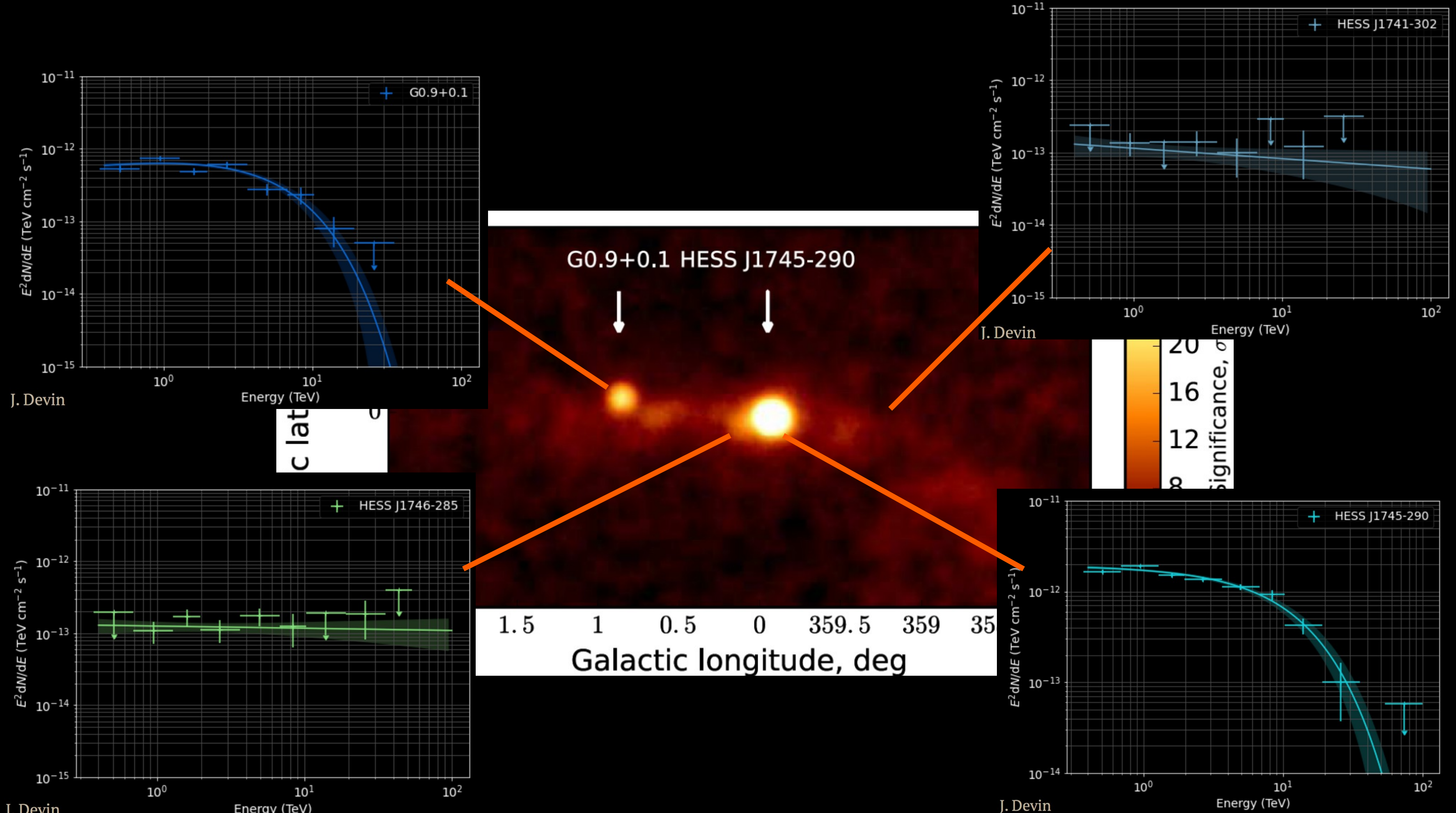
Central component detected at the level of Delta TS = 138.8

Foreground large scale emission detected at the level of Delta TS = 198.4



- 3D analysis confirm the strong gradient of gamma-ray emission toward the GC and the enhancement of gamma-ray emission in the central parts of the CMZ with respect to the edge of the CMZ.
- 3D analysis detect firmly a large scale diffuse component along the Galactic plane that follow the foreground distribution of matter.
- Each of the components of the model has its own spectrum parameters fitted.

Extract intrinsic spectra of TeV point-sources in the GC



Devin et al. 2022

Conclusion

• An excess of energetic protons fills the entire CMZ and we observe a radial gradient of these CRs in the CMZ expected if CR are accelerated at the GC.

Still a lot of open questions :

- Which relation with the central point-source ?
- Which connection with the Fermi bubbles ?
- Why don't we see emission from the SNRs (very high rate !)
- What is the contribution of all the 30 PWN detected by Chandra in the central 30pc ?
- Ect.…

GammaPy Open Software allows to perform spectro-morphological analysis of TeV data:

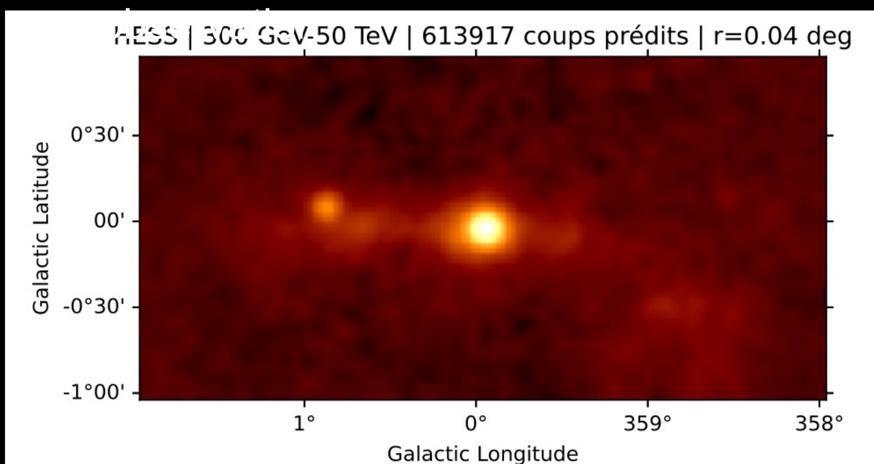
→ allows to separate sources and diffuse emission properly

→ allows to study in details the spectra of all components of the diffuse emission

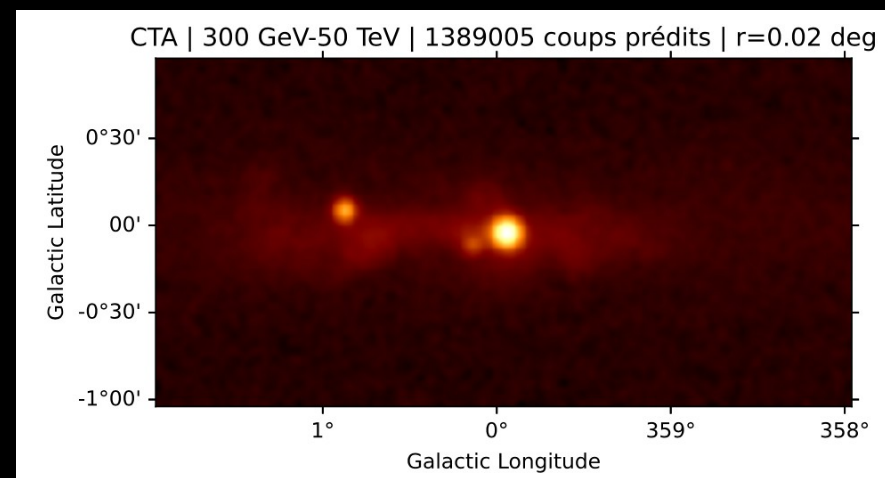
Analysis ongoing to derive the intrinsic spectrum of the CMZ

The GC with CTA

HESS excess map for 350 hours of

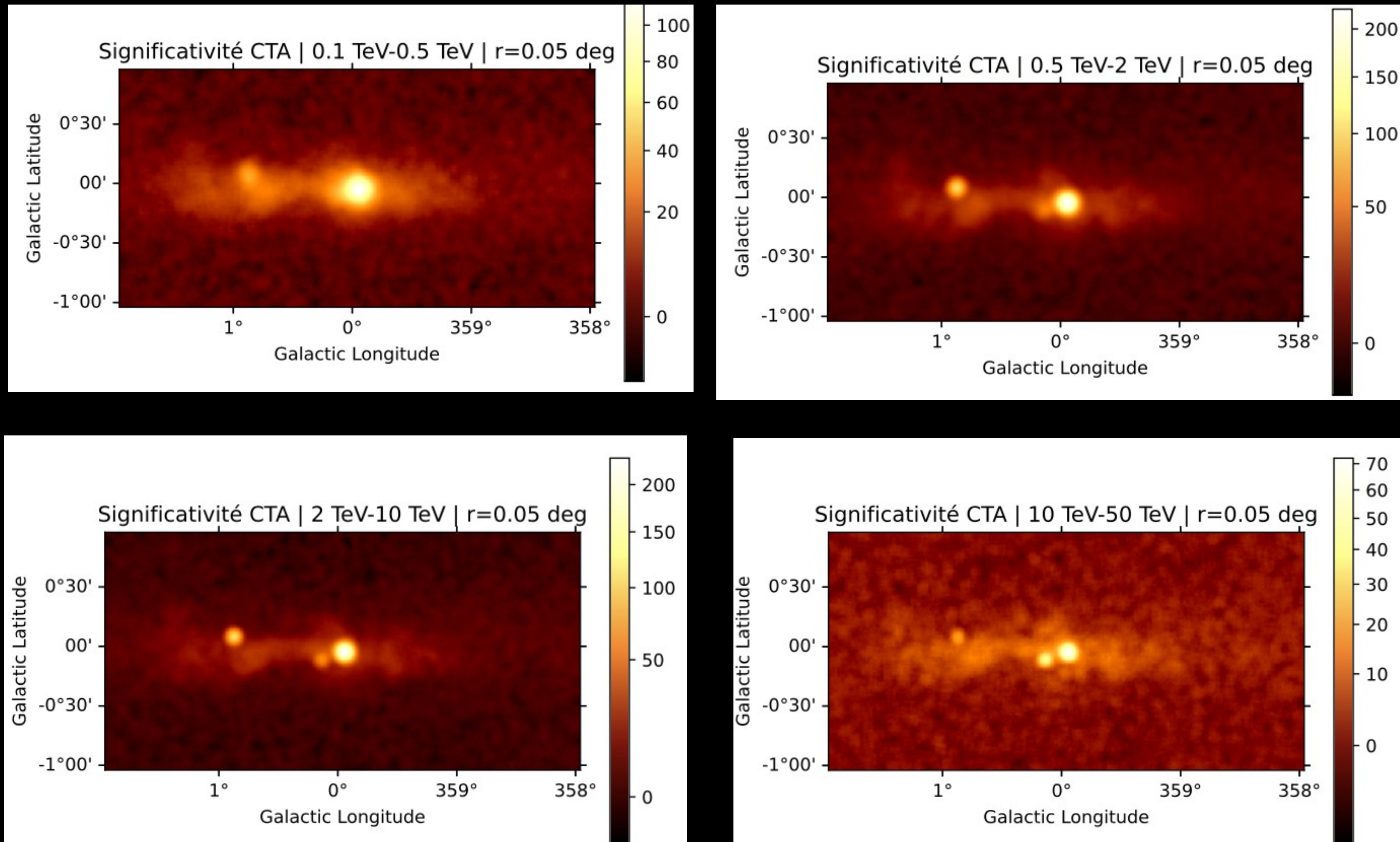


Simulation of the best HESS model for CTA IRFS, for 350 hrs of observations



Zouari phd Thesis 2022/23

The GC with CTA



Zouari phd Thesis 2022/23

Long term variability of HESS J1745-290 ?

Main technical problems :

•Time dependent systematic effects, due to variable observation time and change of instruments, and atmospheric conditions.

• Difficulty to estimate the background level in the region, since a diffuse emission dominates most of the central few degrees

Solutions :

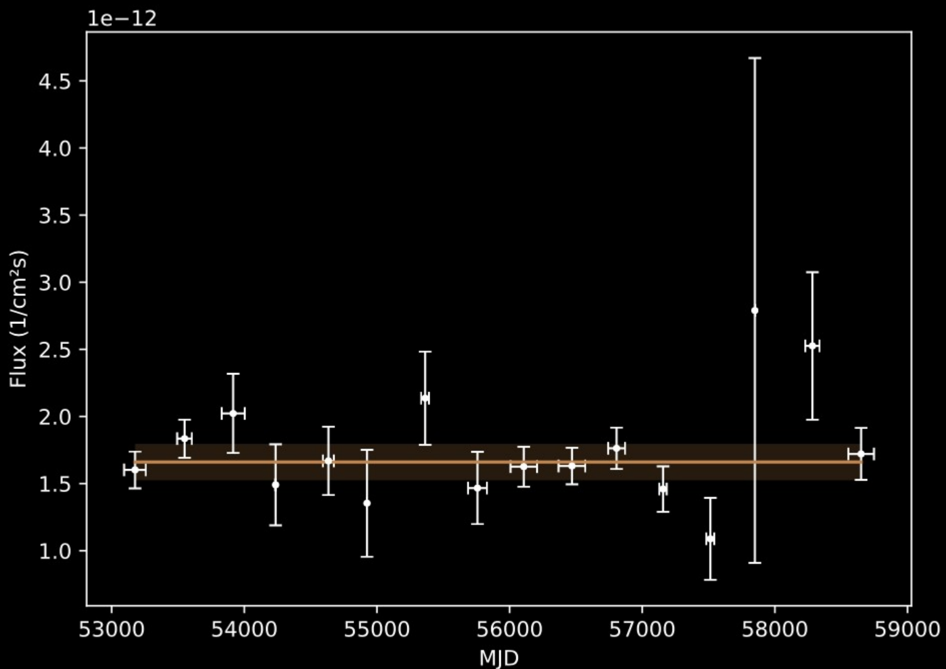
• We use the diffuse emission to calibrate the central point source (time dependent systematic effects that impact both in a similar way should thus be removed)

• Need to rely on background modeling instead of direct estimation

⇒ The spectral-morphological 3D analysis allows for both

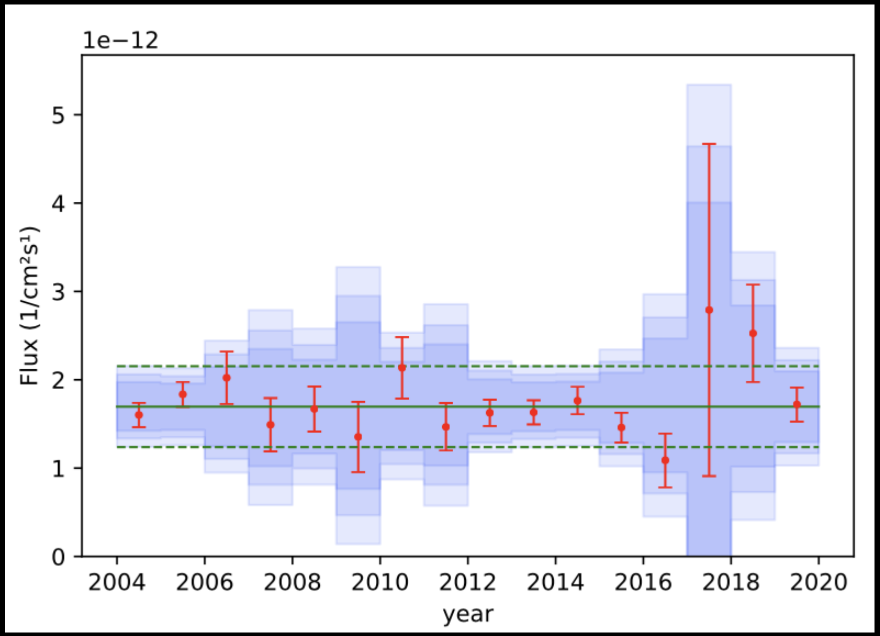
Time variability of HESS J1745-290

Light curve of HESS J1745-290 re-normalized by the diffuse emission

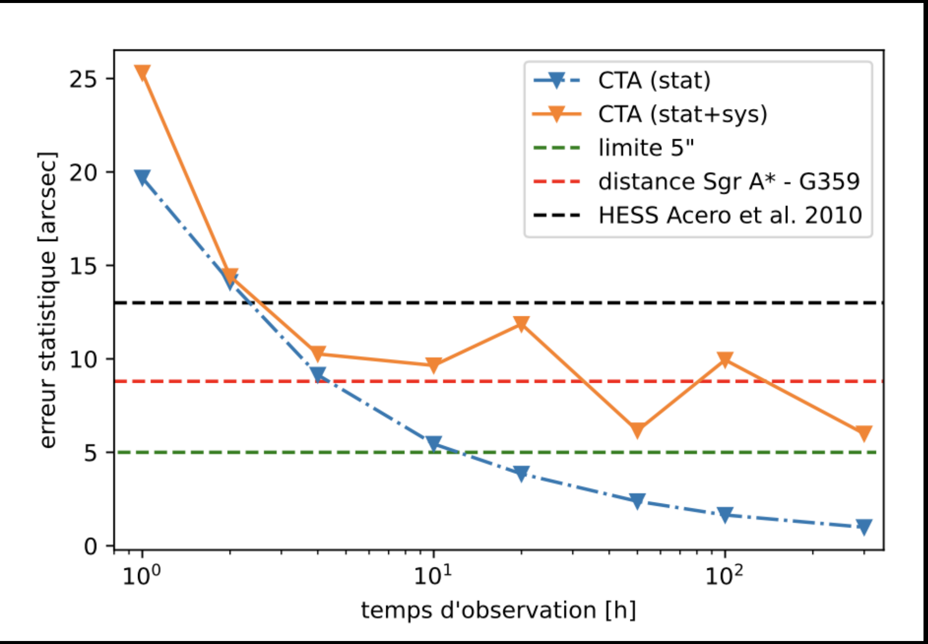


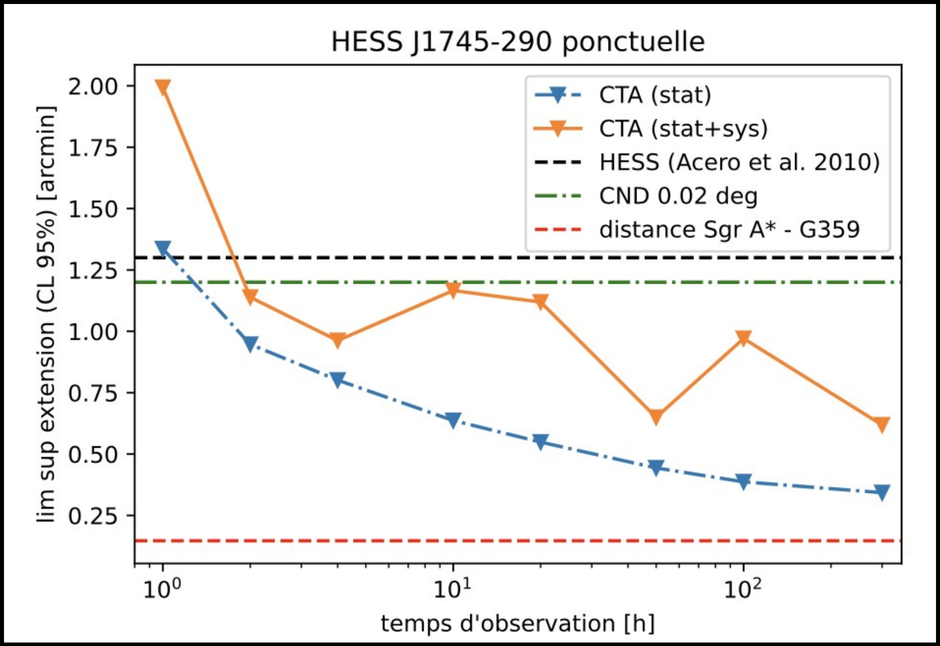
→ Best fit is a constant model, preferred to linear variation model

Sensitivity curve : 3σ post-trial fluctuation range for a constant HESS J1745-290 source

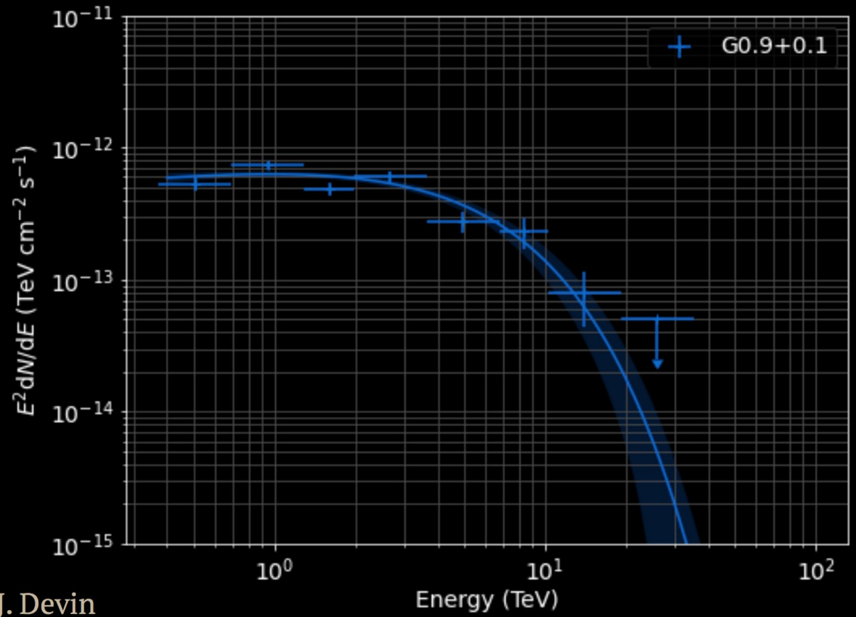


→ Test sensitivity to erratic variation : Smallest detectable yearly deviation from a 16-year average is~30%


CTA (stat)
CTA (stat+sys)
limite 5"
distance Sgr A* - G359
HESS Acero et al. 2010
erreur statistique [arcsec]
temps d'observation [h]

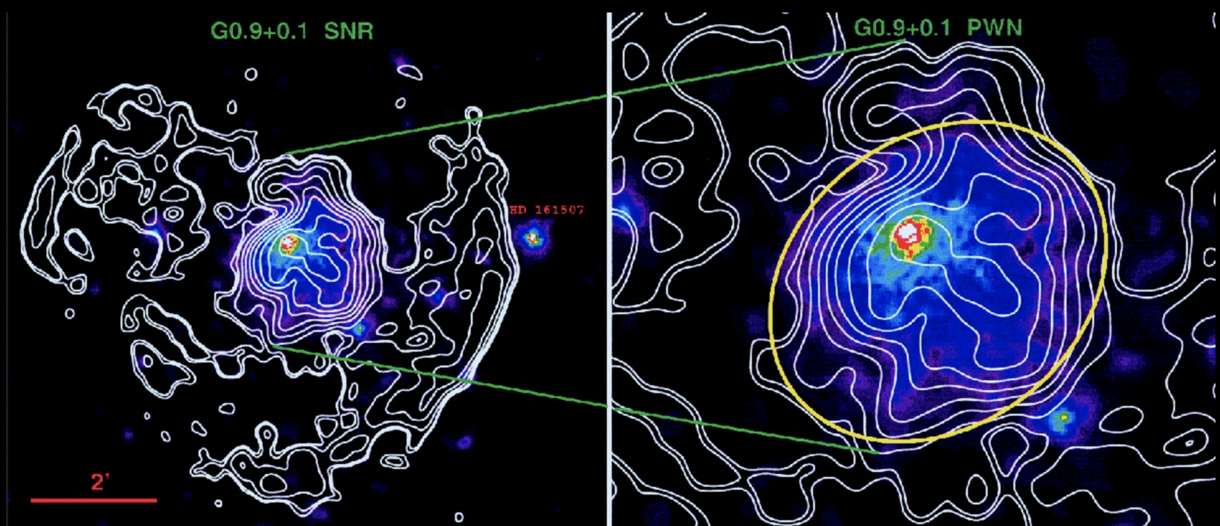

HESS J1745-290 ponctuelle
CTA (stat)
CTA (stat+sys)
HESS (Acero et al. 2010)
CND 0.02 deg
distance Sgr A* - G359
lim sup extension (CL 95%) [arcmin]
temps d'observation [h]

Extract intrinsic spectra of TeV point-sources in the GC



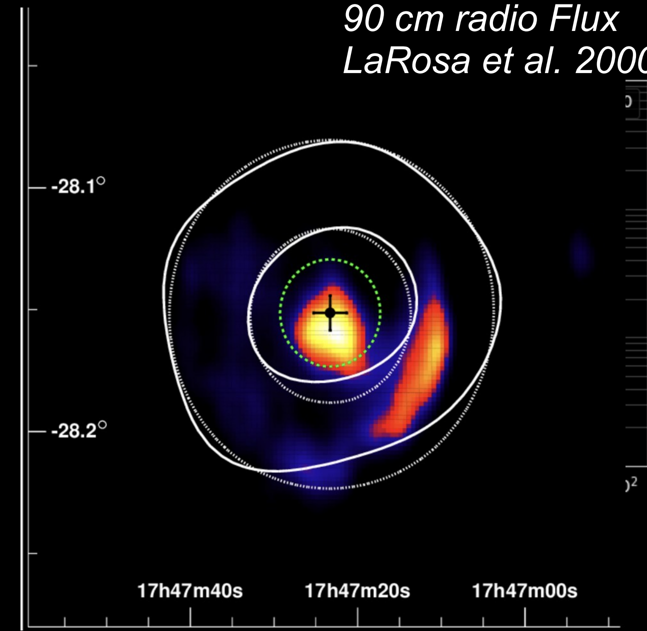
SNR G0.9+0.1

- TeV source associated with the young 3kyrs PWN observed in radio and X-ray
- Hard index (1.8)
- Exponential cutoff at 4.5 TeV significantly detected (> 5 sigma)

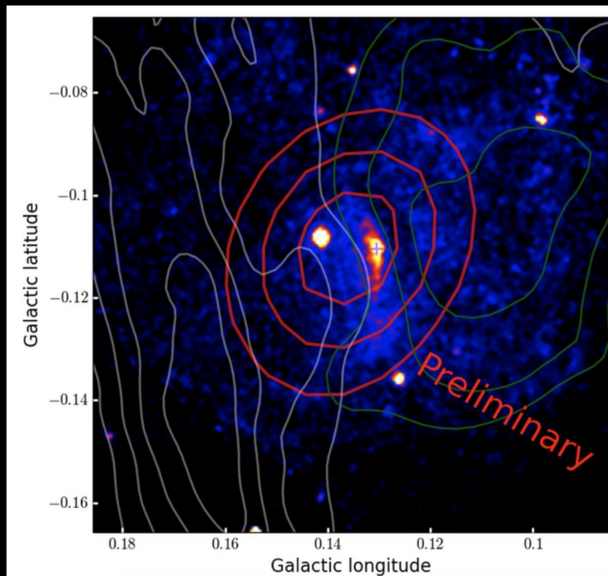


XMM-EPIC *Porquet et al. 2002*

90 cm radio Flux
LaRosa et al. 2000

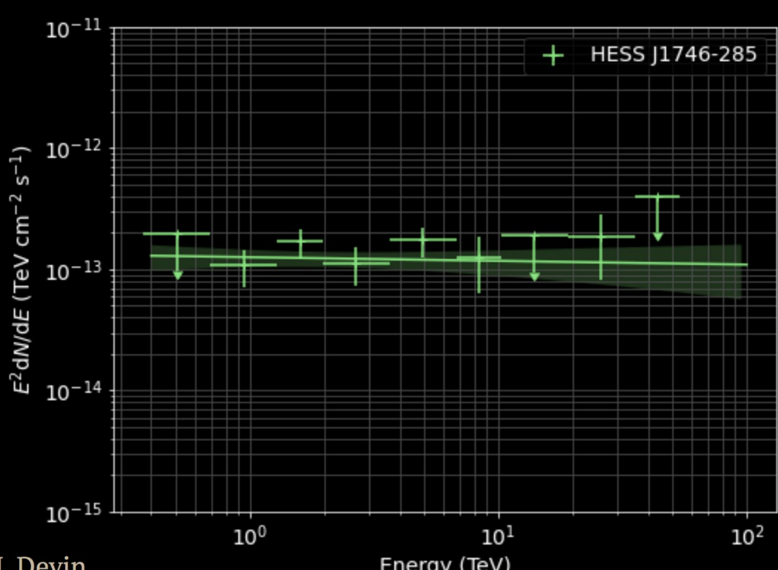


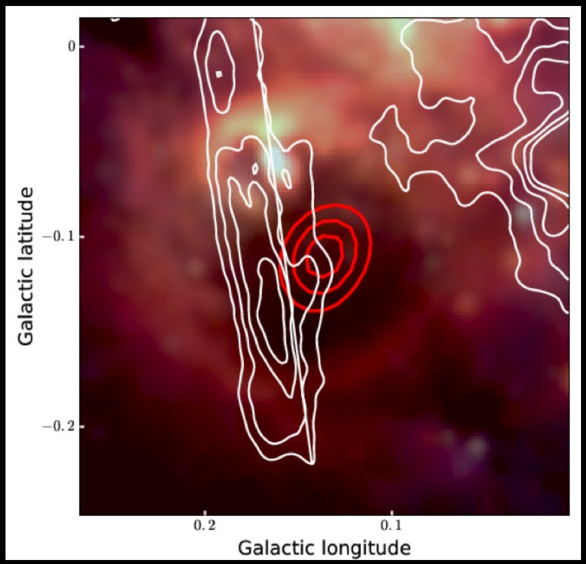
Extract intrinsic spectra of TeV point-sources in the GC



Arc Source

- Position compatible with the soft (3.2±0.3) Fermi source 1FHLJ1746.3-2851
- Lies in the low density Radio-Arc Bubble : an IR cavity field with soft plasma
- Coincident with X-ray filament G0.13-0.11
- Close to the non-thermal filaments of the Radio Arc





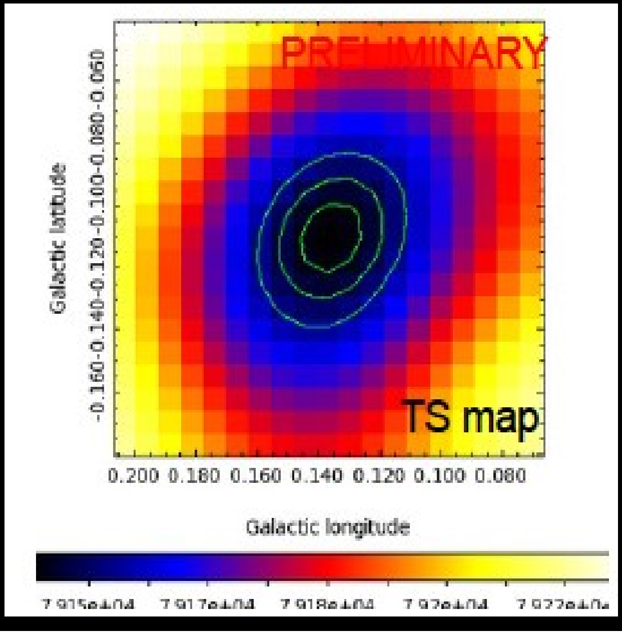
J. Devin

The VHE radio Arc source HESS J1746-285

A new source is detected at more than 6σ :

- compatible with a point-source

- lying at Galactic position : l = 0.14° ±0.013°
  b = -0.114° ±0.02°

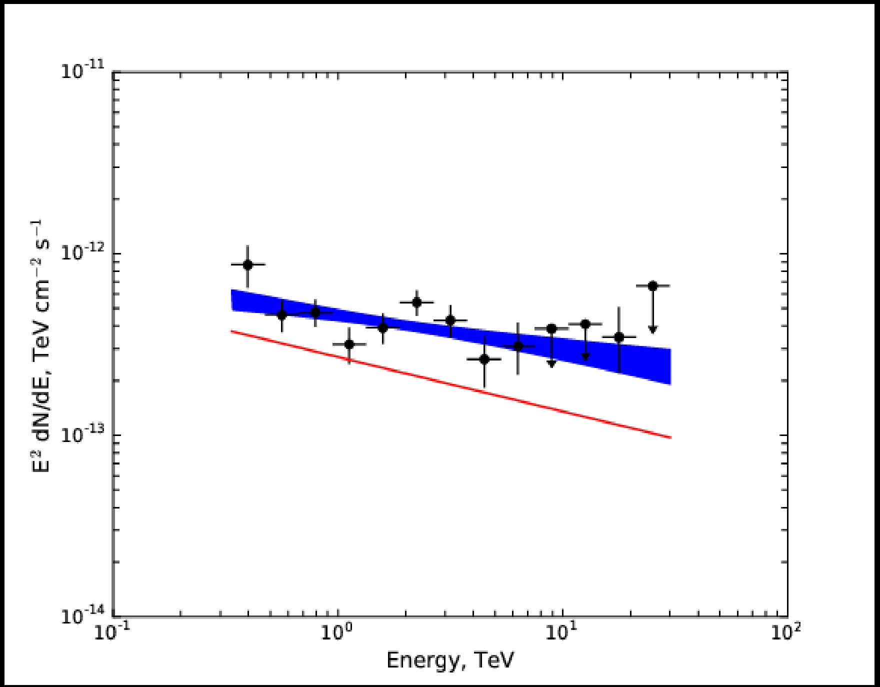


- *Intrinsic* spectrum :

F(1TeV) = (1.8±0.33)$10^{-13}cm^{-2}s^{-1}TeV^{-1}$

index = 2.19±0.16

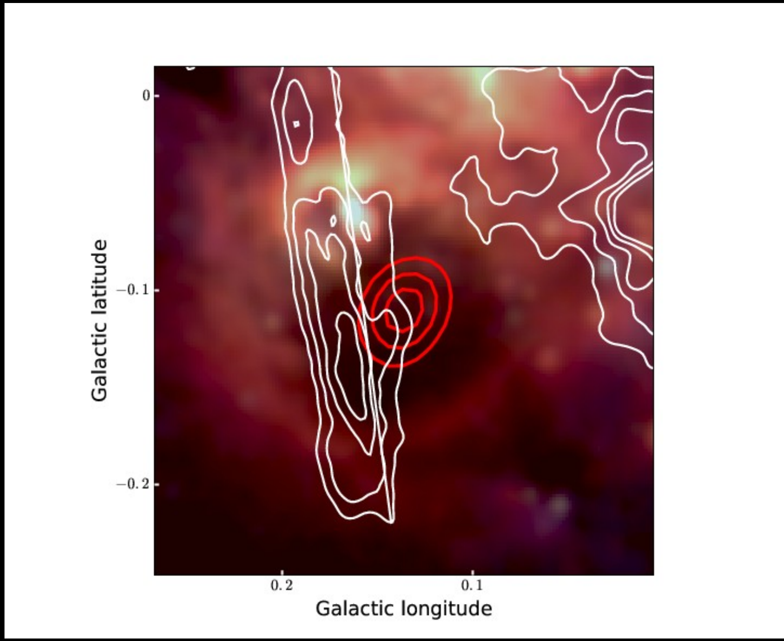
luminosity of L = 2-3 10^{33}erg s^{-1} at 8 kpc

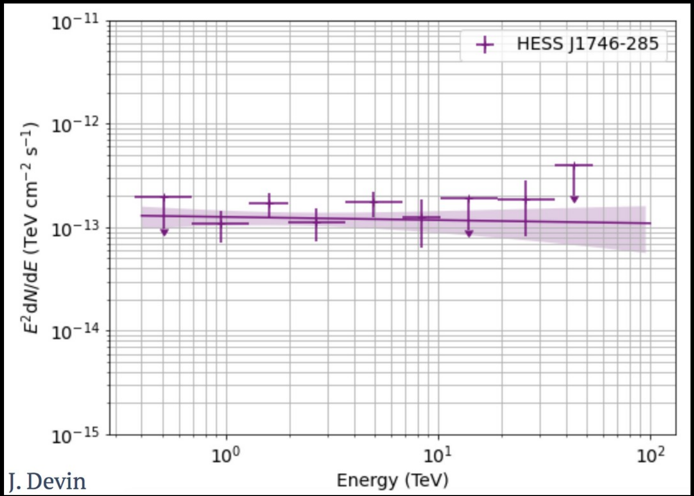


The VHE radio arc source HESS J1746-285

A new point-source is detected at more than 6σ :
Index = 2.19±0.16
L = 2-3 10^{33}erg s^{-1} at 8 kpc

- Position compatible with the soft (3.2±0.3) Fermi source 1FHLJ1746.3-2851
- Lies in the low density Radio-Arc Bubble : an IR cavity field with soft plasma
- Coincident with X-ray filament G0.13-0.11
  - L(2-10 keV)= 3 10^{33} erg/s, Γ_X ~1.4-2.5
  - A PWN in high B field?
    Interaction NTFs /MC : B~100-1000 μG
    X-ray synchrotron lifetime : l~40" → B<300μG
    L_X / L_γ ~ 1, in the range of observed Galactic PWNe



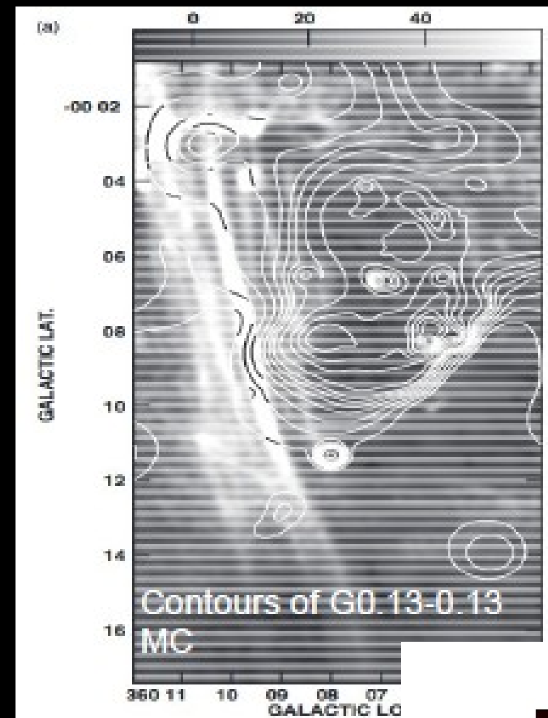


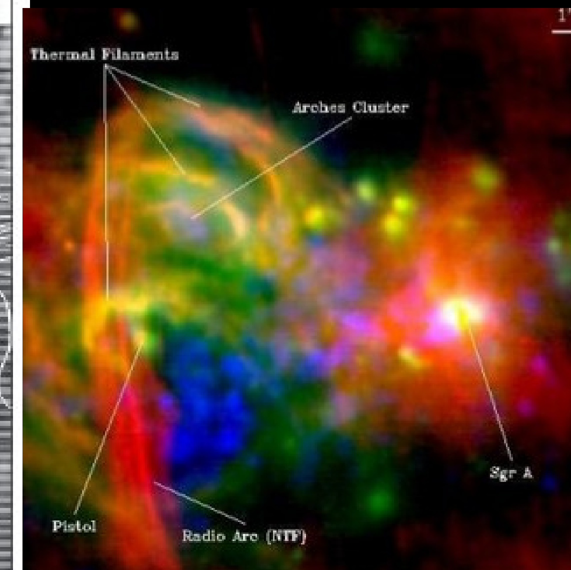
The VHE radio Arc source HESS J1746-285

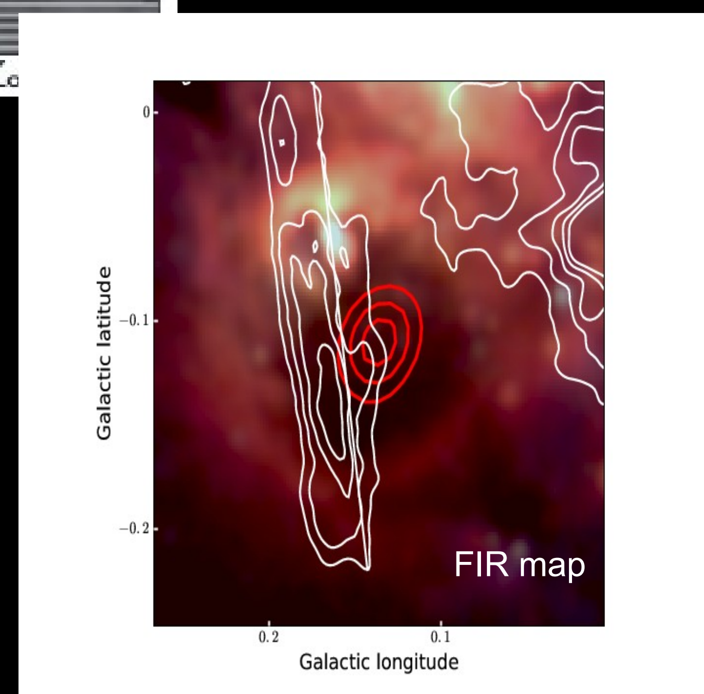
- Close to the non-thermal filaments of the Radio Arc :
  bright linear filaments perpendicular to the Galactic plane near l = 0.2°,
  high magnetic field (>50μG) expected.

- Lies just next to the dense molecular cloud called G0.13-0.13 believed to be expanding into this Radio Arc.

- Lies in the low density Radio-Arc Bubble :
  An IR cavity field with soft plasma (kT~1 keV)



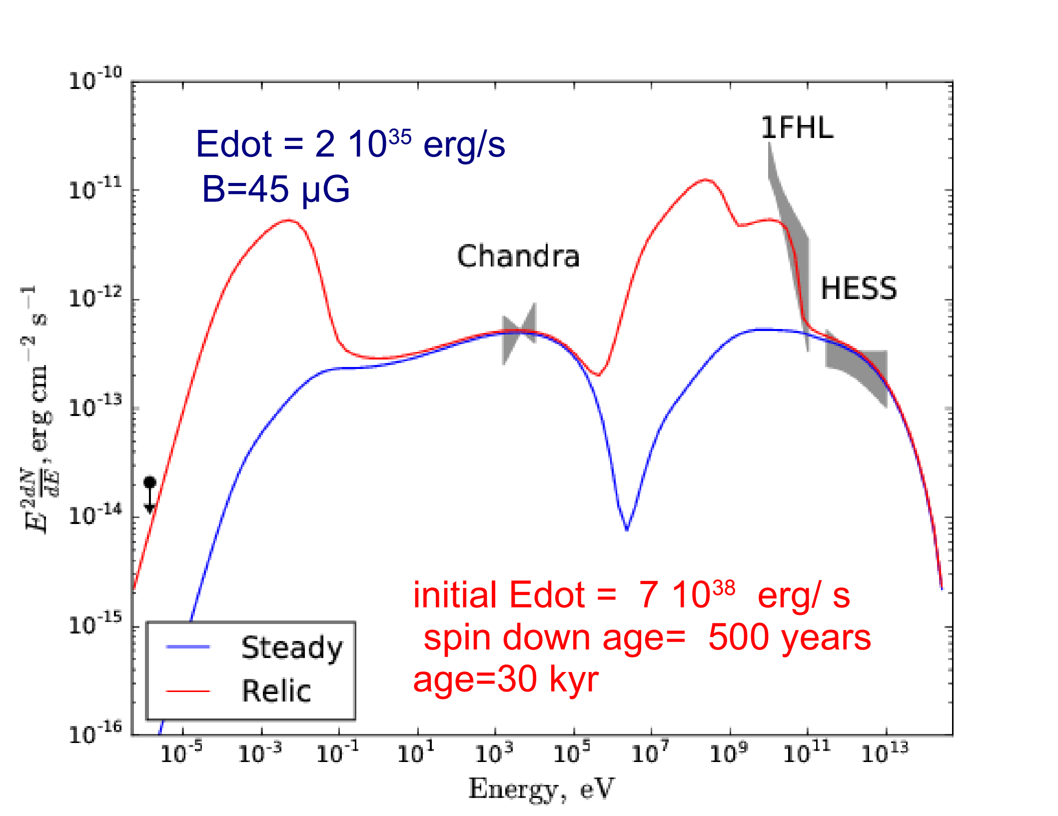




Is **HESSJ1746-285** associated with the X-ray PWN ?

Local fields energy density :
IR radiation ~ 50 eV/cm^3
Optical radiation ~ 250 eV/cm^3.

Large radiation densities:
evolution of the nebula driven by IC losses
→ can explain the hard X- ray spectrum observed by Chandra .

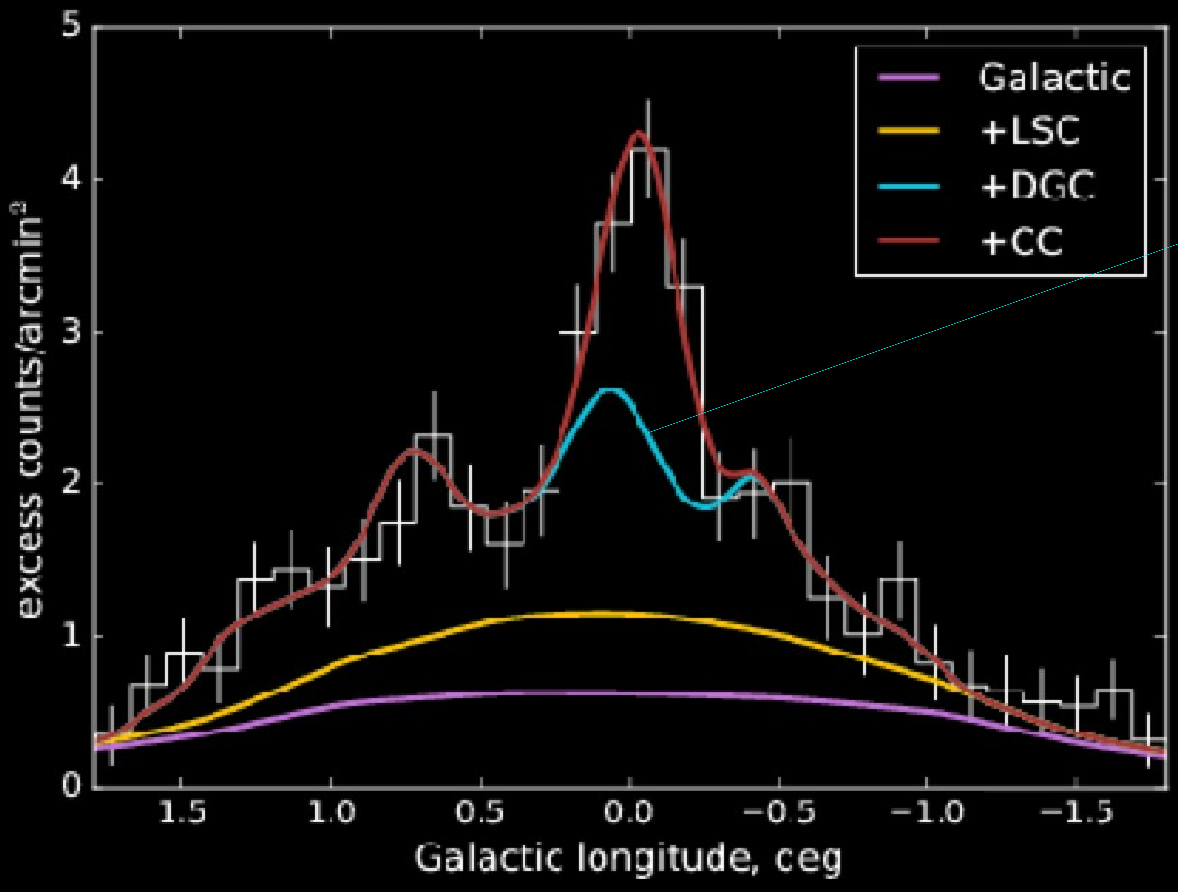


Compute the spectrum radiated by electrons injected by the putative pulsar as a function of time taking into account pulsar braking and energy dependent losses

GAMERA package to compute the time evolution of the electron population (Hahn 2015)

GC VHE diffuse emission components

Longitude profile of the emission



- Half of GC ridge emission is distributed like dense gas tracers

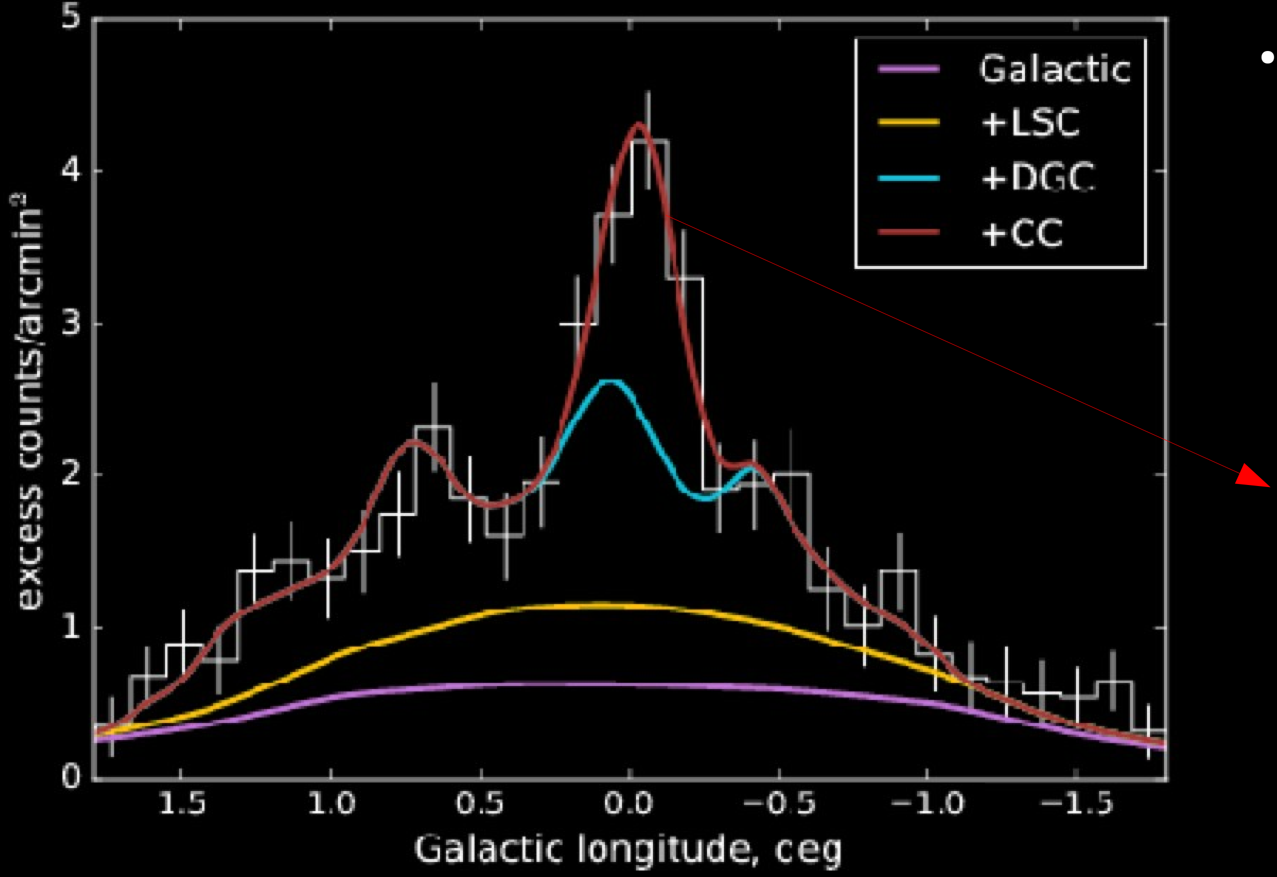
  → signature of protons interacting with the CMZ

- CR gaussian extension of ~0.9° confirmed by 2D fit

  → CR distribution not homogeneous : enhancement near the center

GC VHE diffuse emission components

Longitude profile of the emission

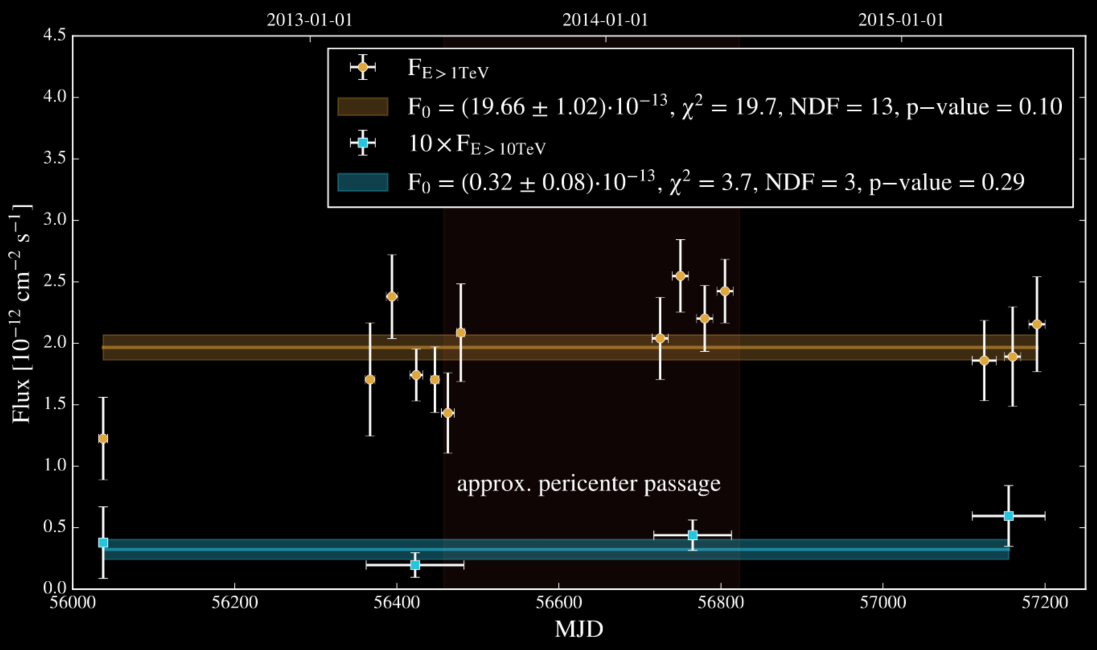


- Central component centered on the GC, 0.1°(or 14 pc) extension and 15% of the total ridge emission.

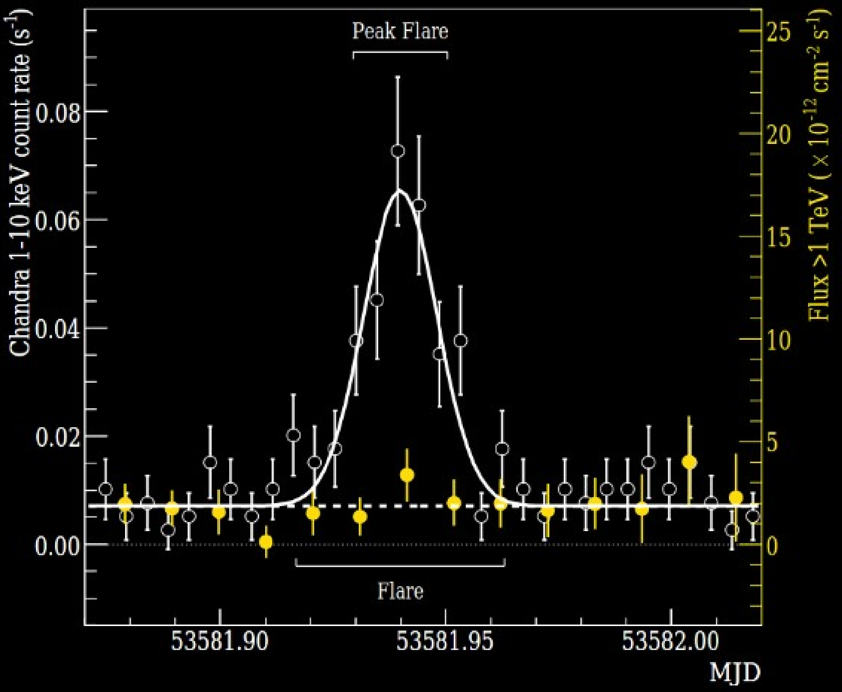
  → Signature of a radial gradient of CRs in the CMZ., profile expected when a stationary source of CRs is present.

  → Evidence that a fraction of CRs pervading the CMZ is accelerated at the GC, possibly around the SMBH itself.

Fast variability of HESS J1745-290 ?



MAGIC collab 2016



HESS collab 2008

Observations of Sagittarius A* during the pericenter passage of the G2 object with MAGIC.

Gillessen et al. (2012) reported the VLT infrared detection of a gas cloud with an estimated mass (~ 10−5 M) on a highly eccentric orbit towards SgrB2. Pericenter passage in mid-2013 at a distance of about 3100 Schwarzschild radii from SgrA*

Result of a simultaneous H.E.S.S.-Chandra observation of SgrA*/HESS

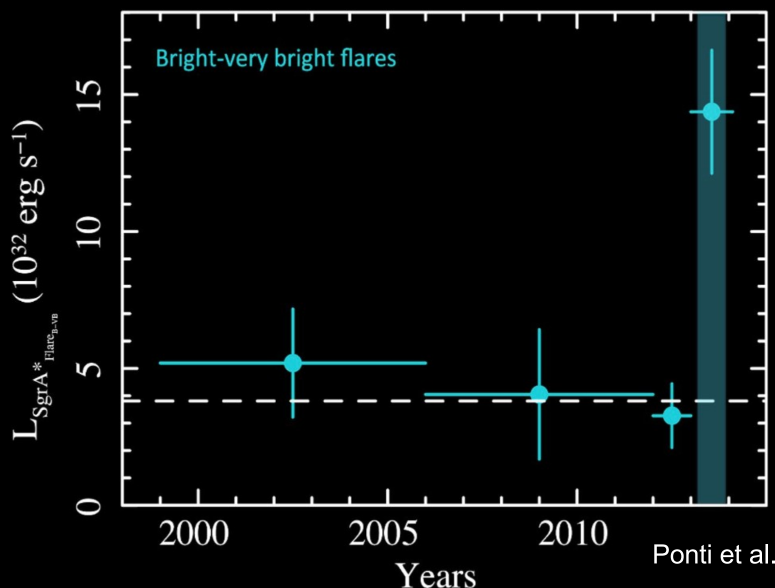
So far no similar variability has been found for HESS J1745-290

Long term variability of HESS J1745-290 ?

• X-ray and NIR flares from SgrA* are regular but their overall properties seem to vary over the years (Ponti et al. 2015, Andrés et al. 2020).

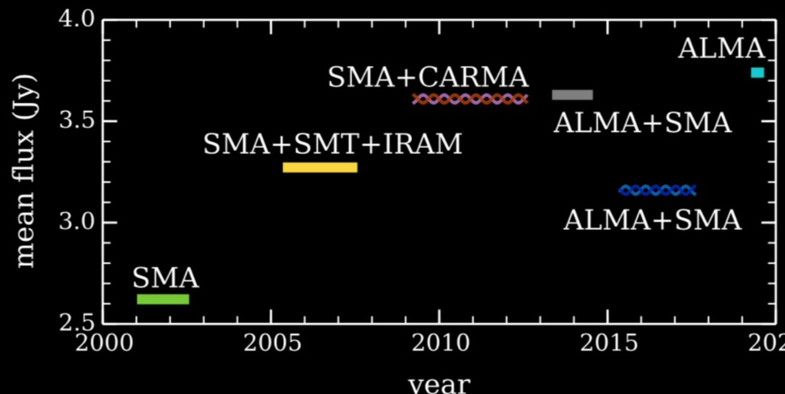
• Recent study (Murchikova & Witzel 2021) of submm observations of SgrA*show an evolution of mean fluxes for different epochs, interpreted as variations of the accretion rate.

• The accretion flow isn't a constant process nearby objects can influence it and thus high energy emissions in 2012-2013 the near passage of a gas cloud motivated searches for an evolution of the emission from SgrA*



Ponti et al. 2015

Evolution of the luminosity emitted as "bright flares" by SgrA*,the red period shows the G2 passage.

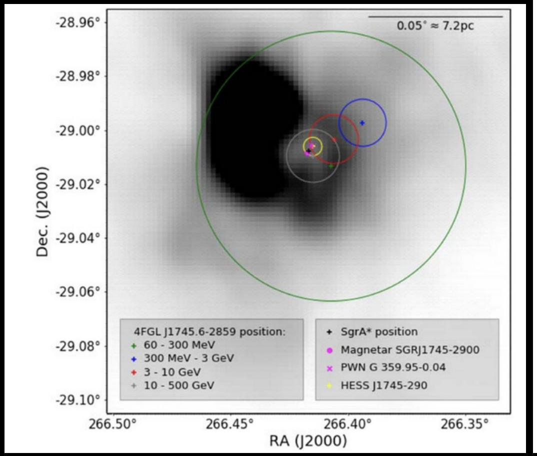


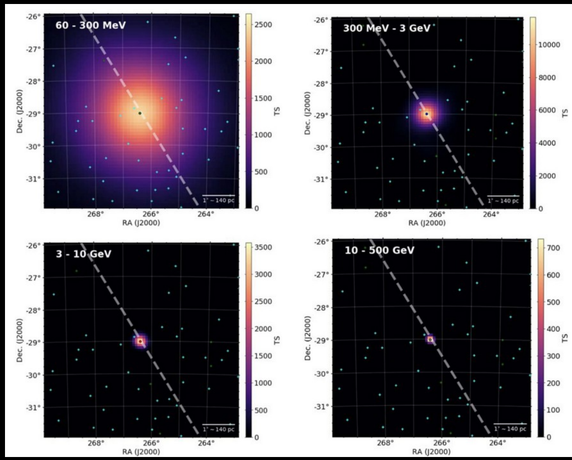
From Murchikova & Witzel 2021

FERMI LAT source at the GC

Two sources at the GC in the 3rd Cat :
(Acero et al. 2015)

- 3FGL1745.6-2859c:
  compatible with GC PWL spectrum
- 3FGL J1745.3-2903c :
  second source at 6' for SgrA* with curved spectrum

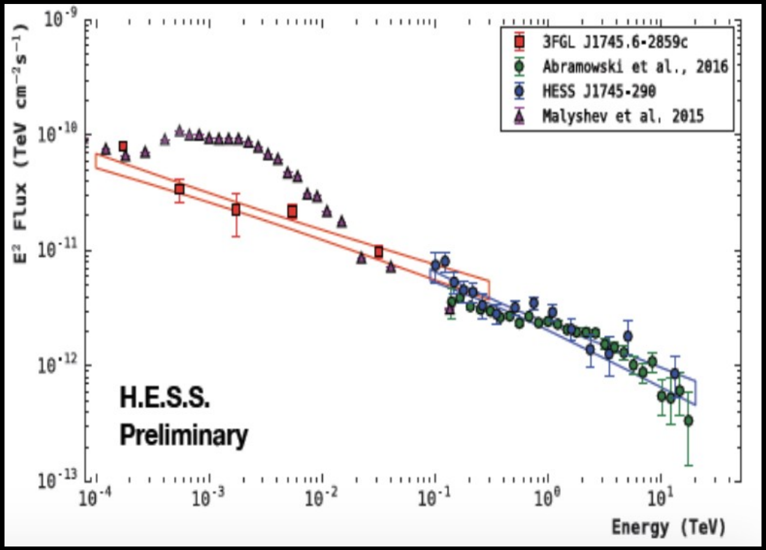




Cafardo et al. 2021

GC counterpart confirmed in recent analysis (*Cafardo et al. 2021*):

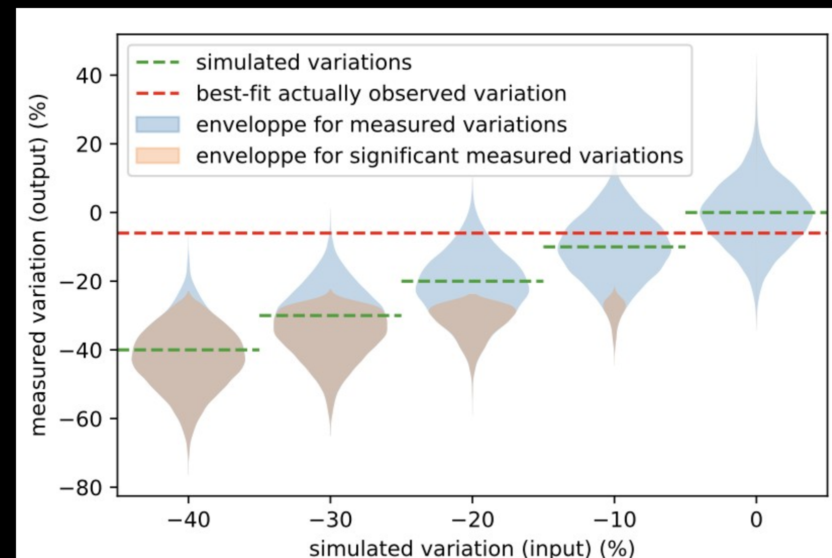
- 3FGL1745.6-2859c → 4FGL J1745.6−2859
- 11 yr of Fermi data
- centroid of the emission approaches Sgr A*'s location as the energy increases
- Luminosity =(2.61 ± 0.05) × 10 ^{36} erg s−1



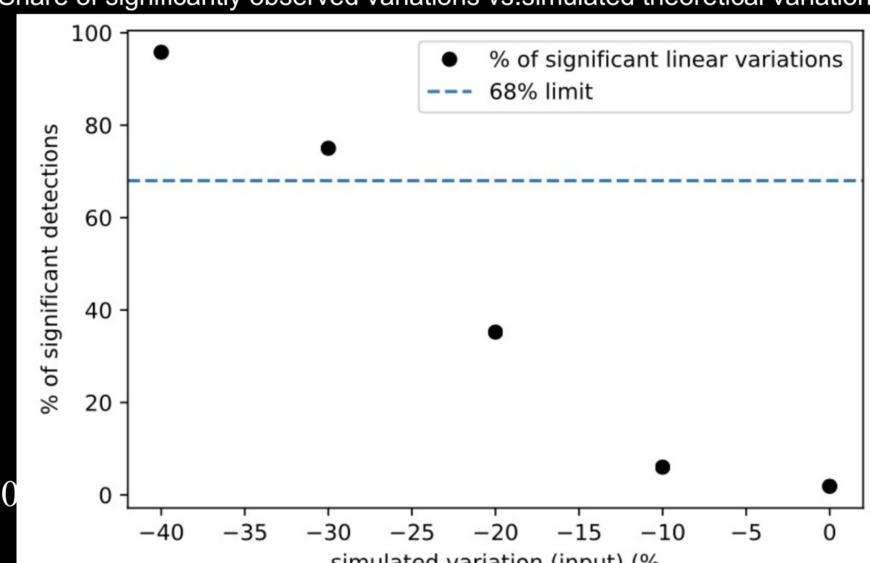
Sensitivity to linear variations

→intrinsic linear variation of>29%over 16 years should be significantlydetected, hence it can be ruled out

Results of simulations with 5 different simulated theoretical variations, and the measured variations, divided betweenwhether the variation were significantly observed



Share of significantly observed variations vs.simulated theoretical variation



Which link with the central point-source ?

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

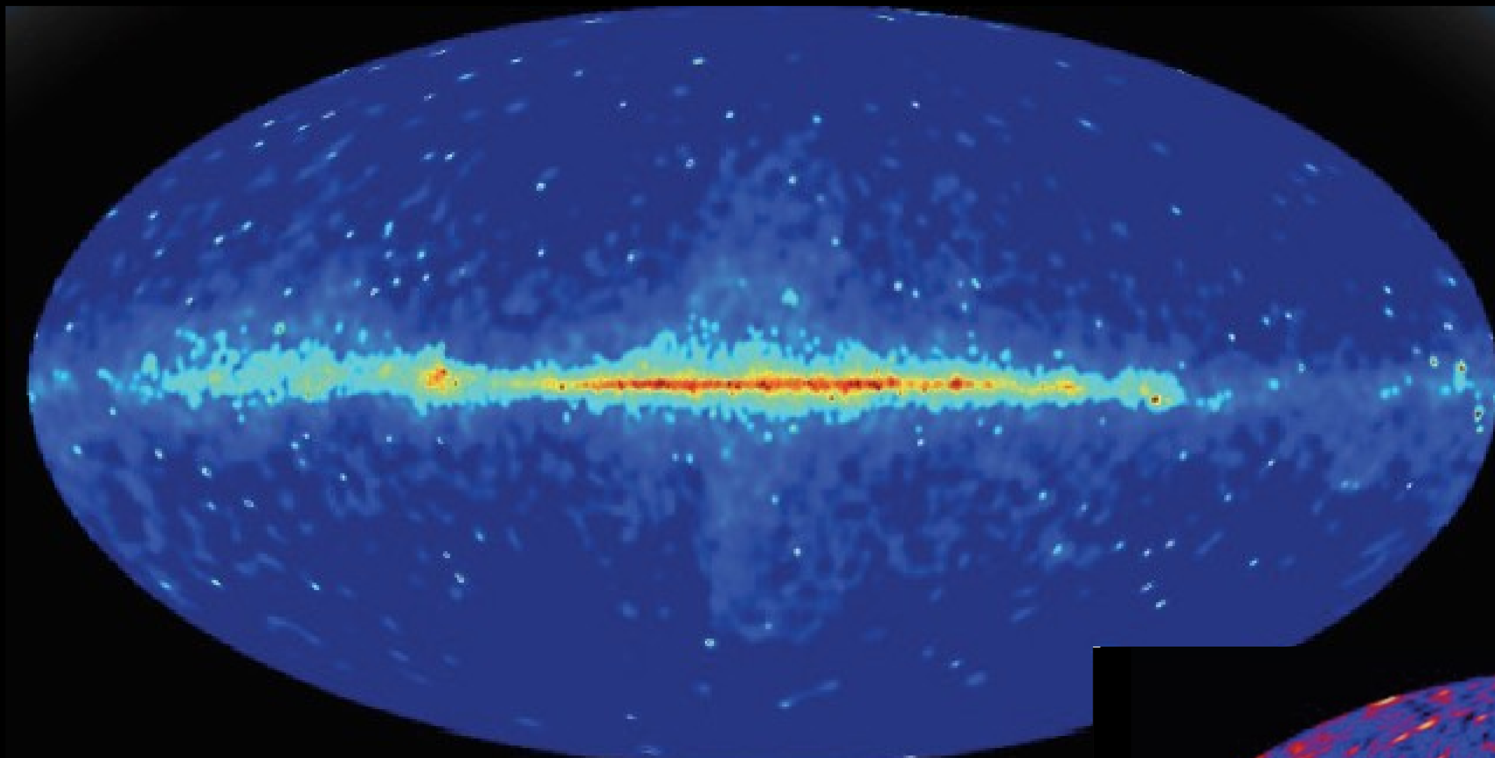
- difference in gamma-ray emission timescales due to energy dependent diffusion coefficient:

  10 yrs for high energies (ballistic motion)

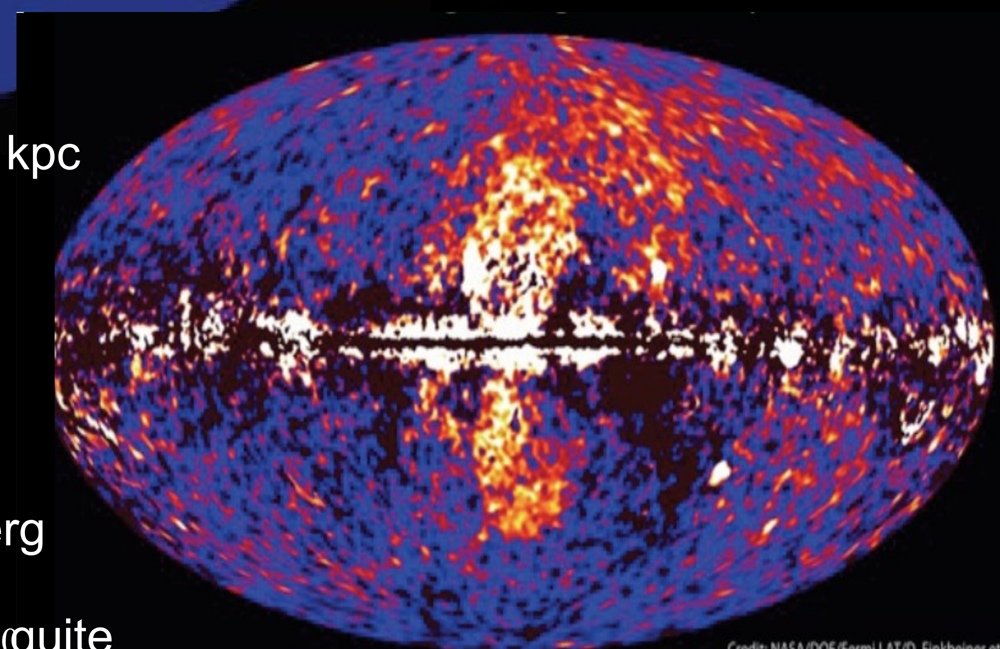
  10^3 for low energies (diffusive motion)

  a decrease in luminosity in timescales of ~10 yrs would generate a cut-off

Fermi bubbles



E>10 GeV



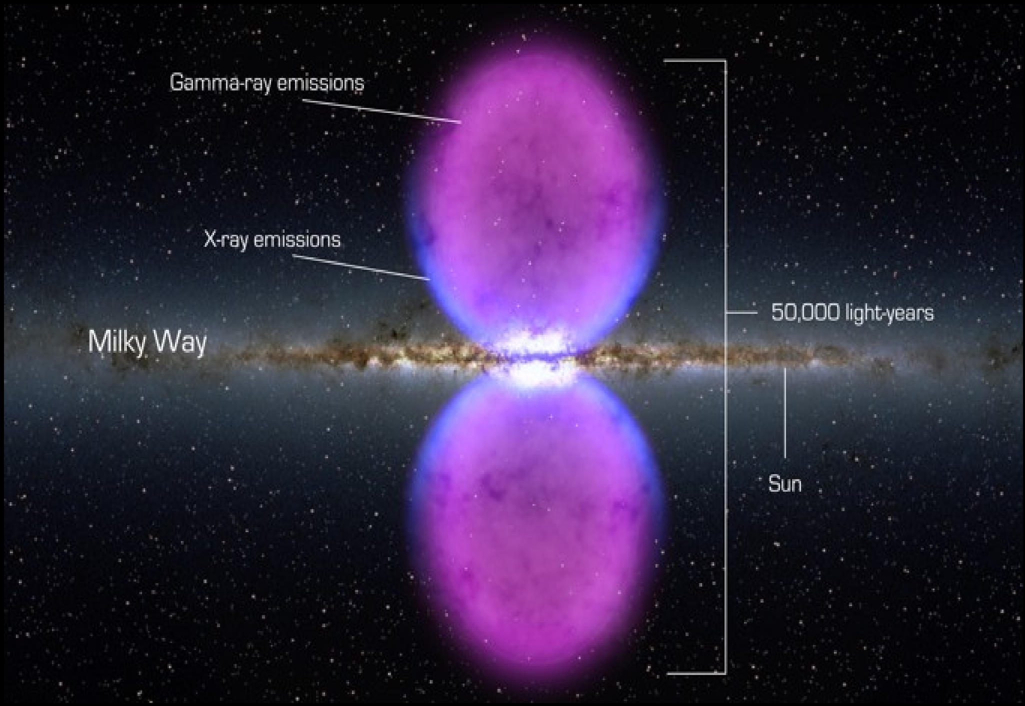
- Large **gamma**-ray structures extending up to 10 kpc above and below the Galactic plane
- Detected above a few GeV
- Hard spectrum extending up to at least 100 GeV.
- Estimated energy content is of the order of 10^{55} erg

→ Mechanism providing such a large energy input quite uncertain.

The Fermi Bubbles: main hypothesis

• The sustained star formation activity in the GC region can provide the required energy.

→ integrating a constant injection of 10^39 erg/s of SNR energy converted to cosmic rays.
→ but the particles have to be confined on extremely long timescales !

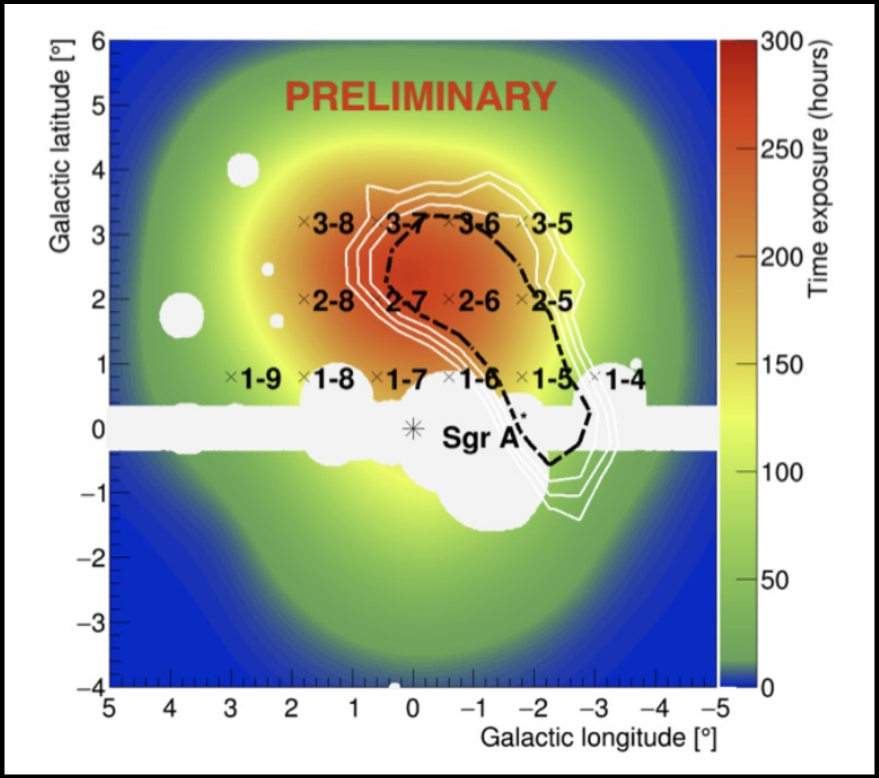


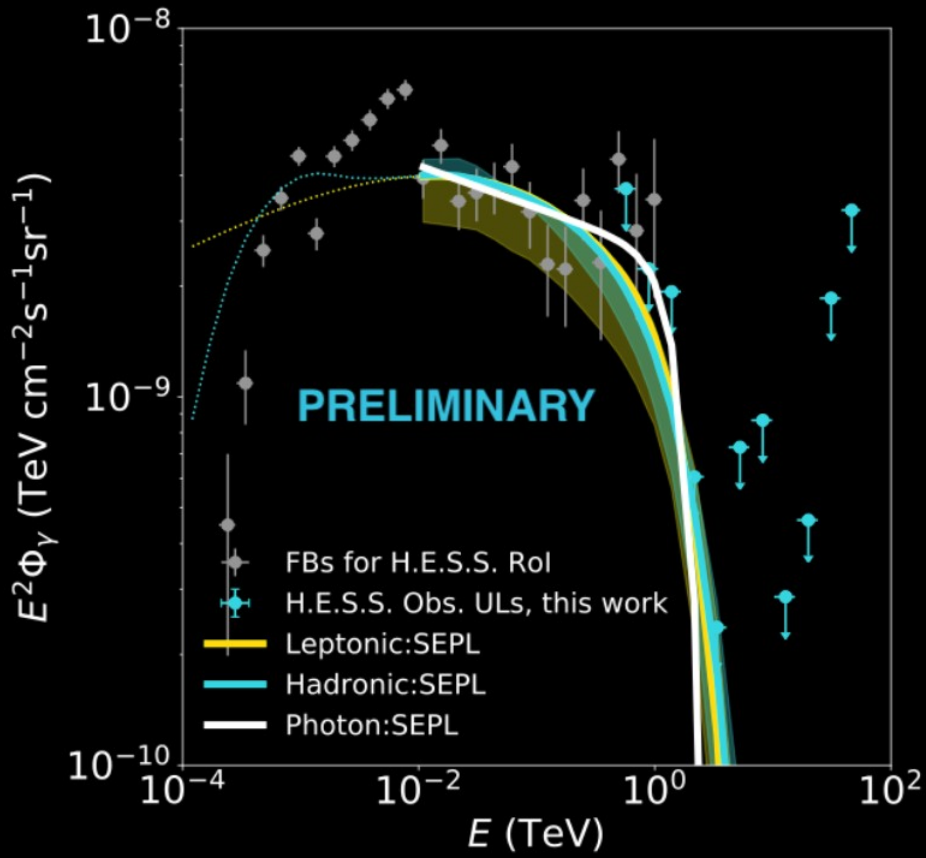
• Possible role of the supermassive black hole :

→ intense AGN phase at high luminosity accompanied by jets or outflows a few millions years ago
→ recurrent (every 10^4-10^5 years) accretion of stars captured by the black hole.

GeV-TeV connection is a key to resolve this problem :
If we determine whether the SMBH does accelerate multi-TeV particles
It will help to prove or disprove the hypothesis of a past AGN phase of Sgr A* as the origin of the large Fermi bubbles .

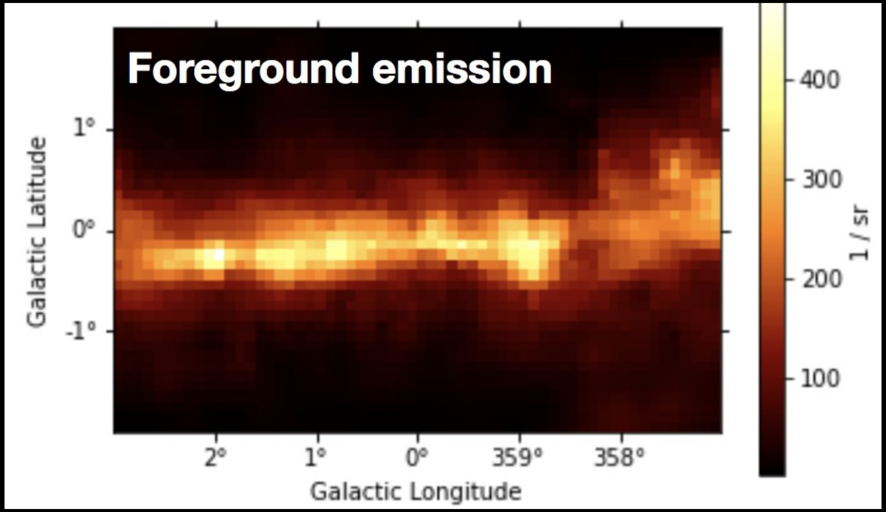
Search for TeV emission from the Fermi Bubbles at low Galactic latitudes with H.E.S.S. inner Galaxy survey observations





HESS Collab. ICRC 2021

Large Scale emission component



Foreground galactic emission: modeled by the cosmic-ray sea interacting with the CO gas (excluding the region of the CMZ) [Fornieri et al. 20, Remy et al. 18]

2D template computed with the HERMES code [Dundovic et al. 21] using either a constant or an inhomogeneous cosmic-ray density

Large-scale emission model (not a measure of the Galactic diffuse emission) which encompasses also residual emission e.g. from unresolved sources, inverse Compton, etc.