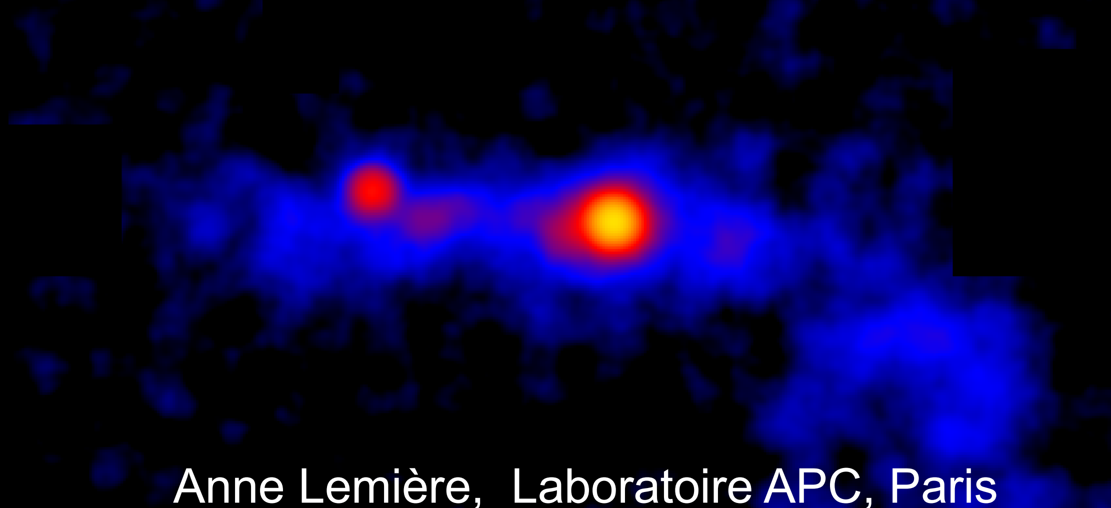
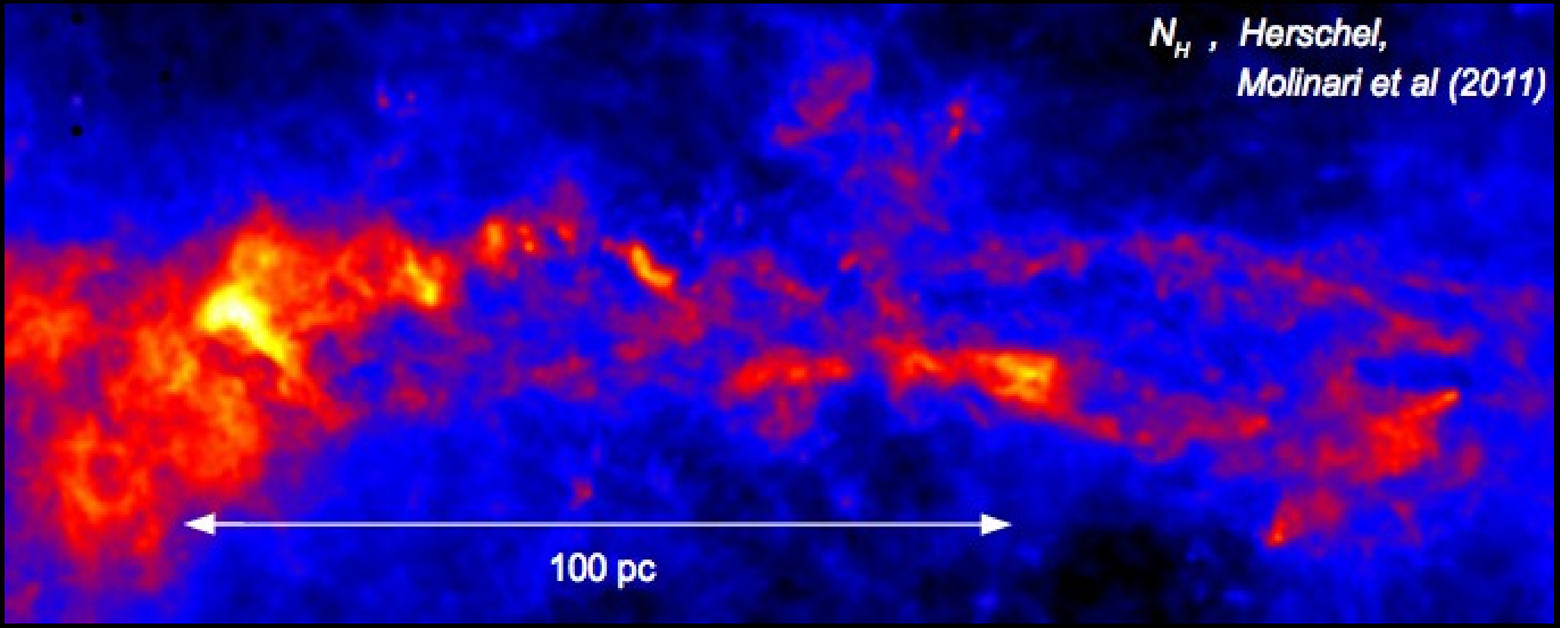
Searching for the sources of Galactic CRs

VHE CRs at the Galactic Center



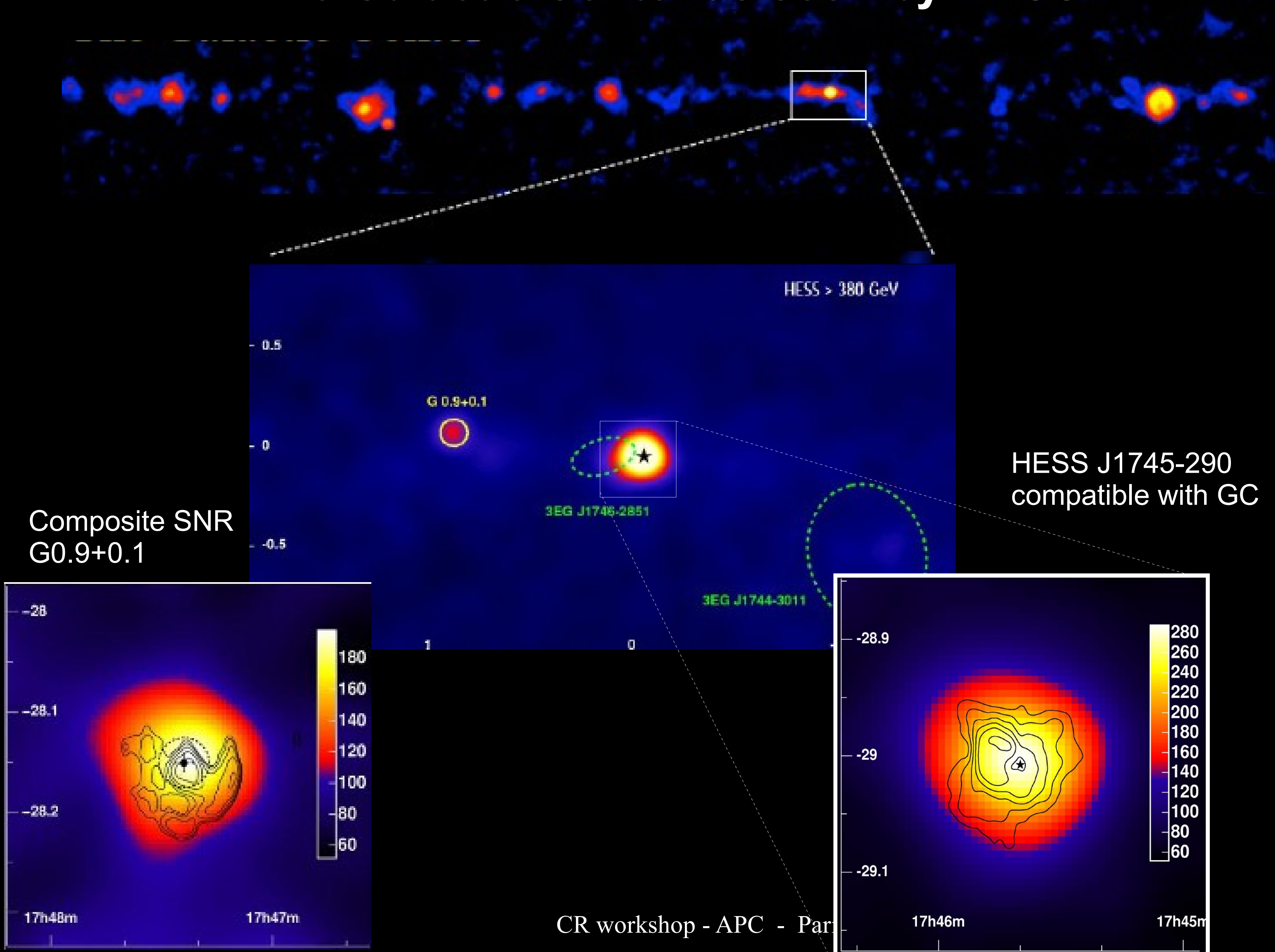
Anne Lemière, Laboratoire APC, Paris

Central 200 pc : The Galactic Center Ridge



- Super massive BH SgrA* : M~ 4.10^{6} M_{sun}
- 10% of the total molecular mass (CMZ) of the Galaxy.
- Large fraction of young massive star clusters located in the GC : 10% of massive star forming activity in the CMZ
- Many accelerators : Superbubles candidates,SNRs candidates, ect...

The Galactic Center as seen by HESS



HESS J1745-290 Spectrum

- Significant deviation from a power-law :

  spectral index ~ 2.2

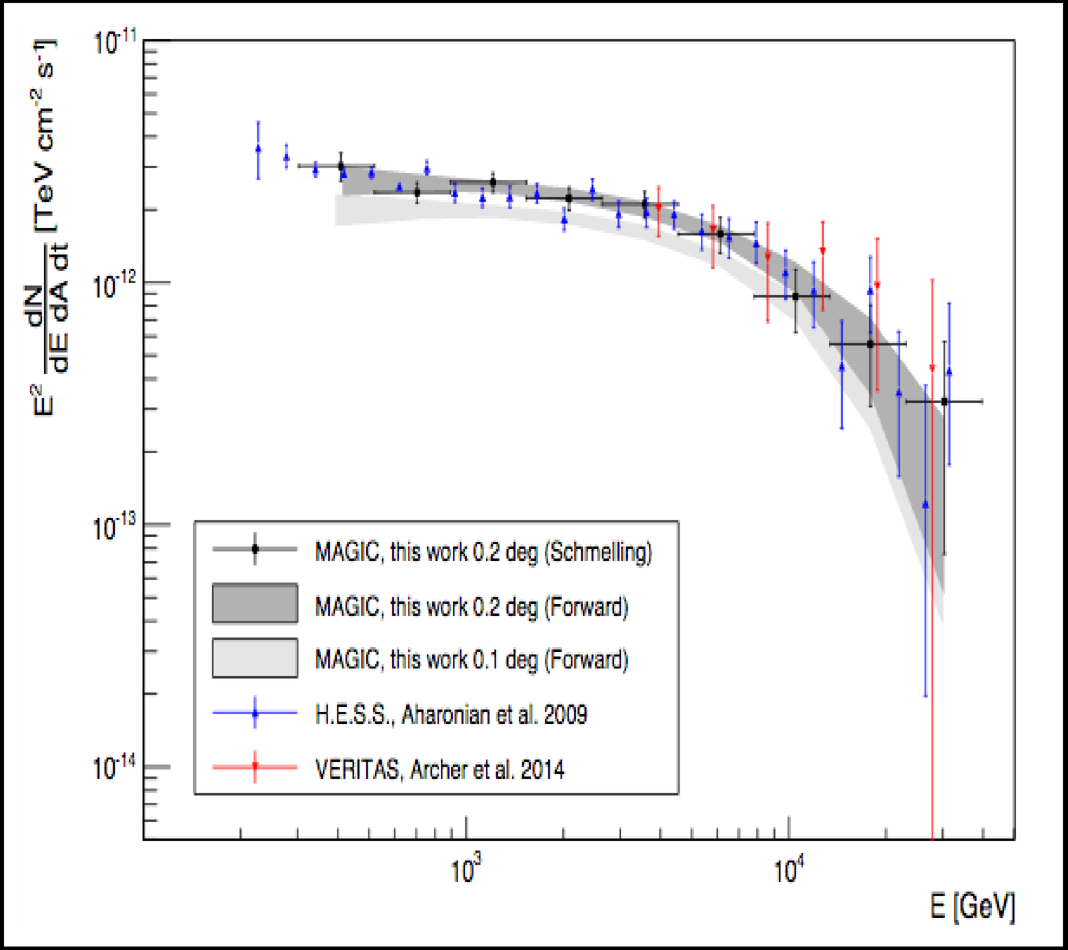
  exp cut-off at E~15 TeV

  F(1TeV) = 2.5 10^{-12} $cm^{-2}.s^{-1}.TeV^{-1}$

- Steady source :

no variation found despite simultaneous Chandra observations with X-ray flare (2005).

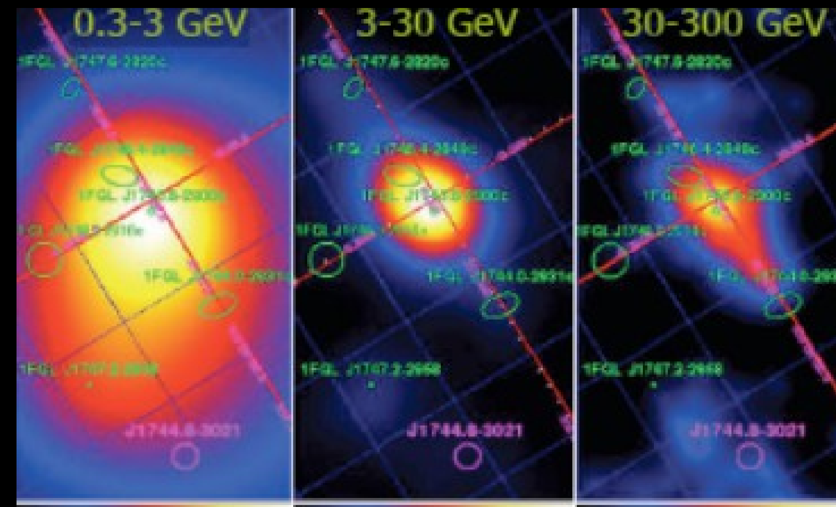
(factor 2 increase excluded at 99%CL)



FERMI LAT point source at the GC

One point-source at the GC : *(Chernyakov et al. 2011)*

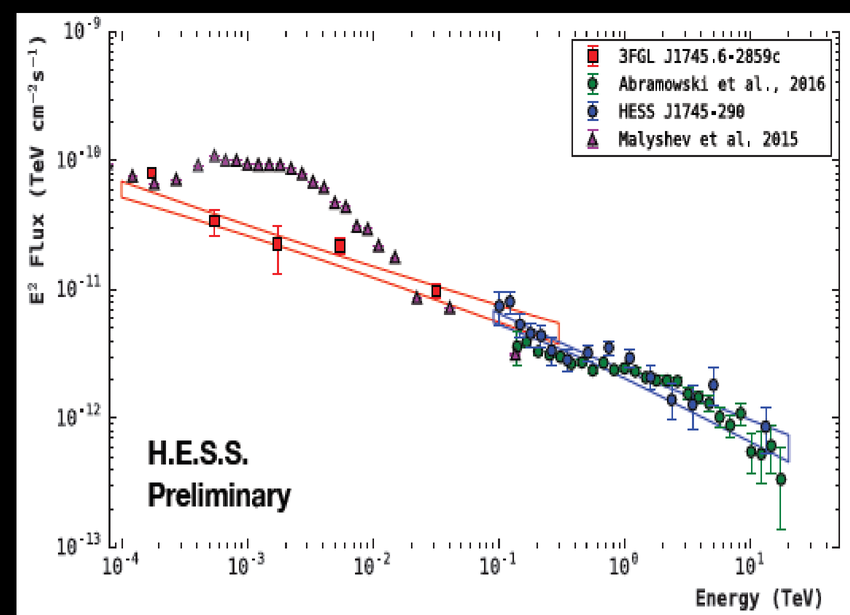
- Centroid seems to be consistent with SgrA* at high energy : 2' +- 1' offset in the 2FGL
  index1 = 2.2 (<5GeV)
  index2=2.7 (>5GeV)



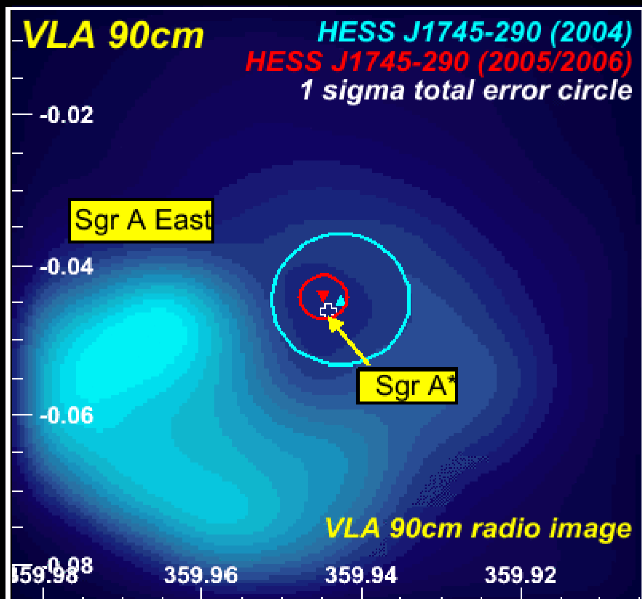
Two sources at the GC : *(Acero et al. 2015)*

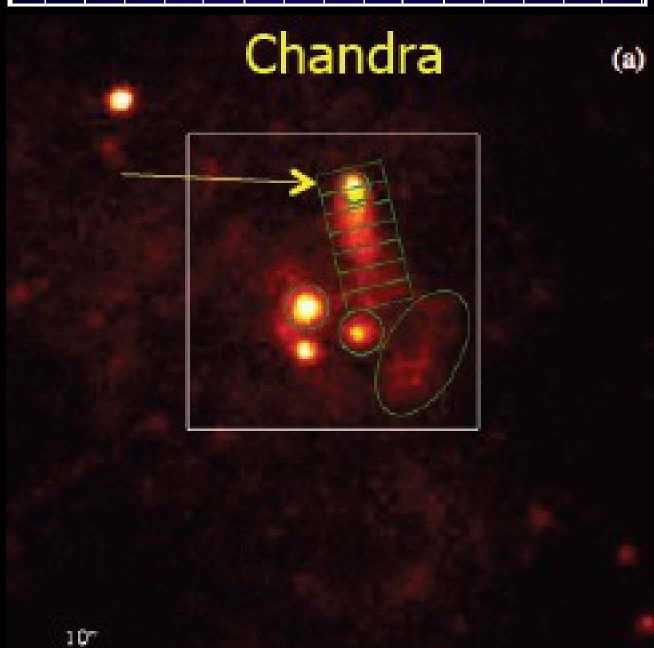
- 3FGL1745.6-2859c:
  compatible with GC PWL spectrum
  $\Gamma = 2.32 \pm 0.034$
  Flux(1-10 GeV)=$2.18 \pm 0.2\ 10^{-8}\ \gamma/cm^2/s$

- 3FGL J1745.3-2903c :
  second source at 6' for SgrA* with curved spectrum



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)

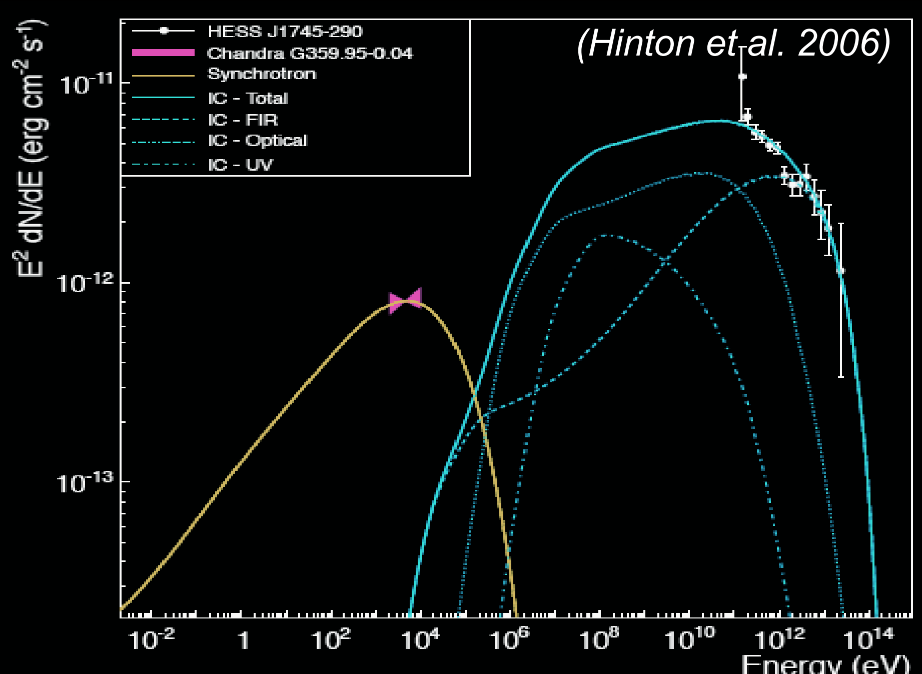
Nature of the emission ?

- Sgr A East SNR : excluded
- 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)

Nature of HESS J1745-290

Hadron scenario:

- Reflects the energy cut-off in the primary proton spectrum at Ep ~100 TeV
- diffusion of protons outside of the center: competition between injection and escape of protons



Leptonic scenario:

IC emission from very high energy electrons(up to 100TeV) of the PWN

Energetically possible given high local radiation field and if B~few 10 of μG *(Hinton et al. 2006)*

But recent magnetar measurement constrain B~100μG

The TeV Galactic Centre 10 years later

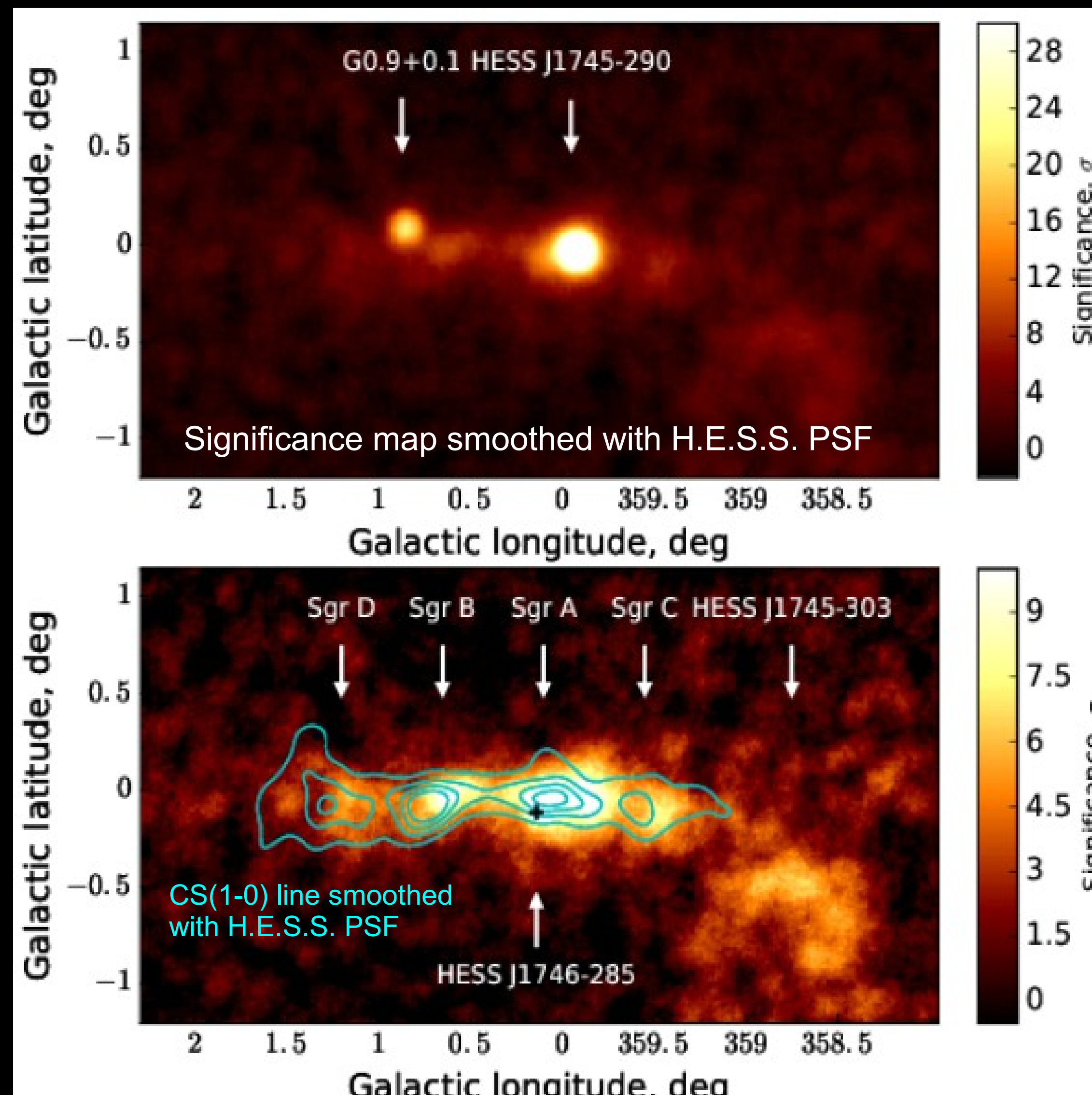
•**Dataset :** ~10 years H.E.S.S.I data set from 2004-2014 : 250 hours of livetime *HESS Collab: Abdalla et al. 2017*

•Diffuse emission correlated with dense gas tracer CS: ɣ produced through p-p collisions

• Diffuse emission spectrum : Γ=2.3 ± 0.1, L_γ (>4TeV)= 5.10^{34} erg/s

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° scale: diffusion of CR injected at the center ?



GC VHE diffuse emission components

Model

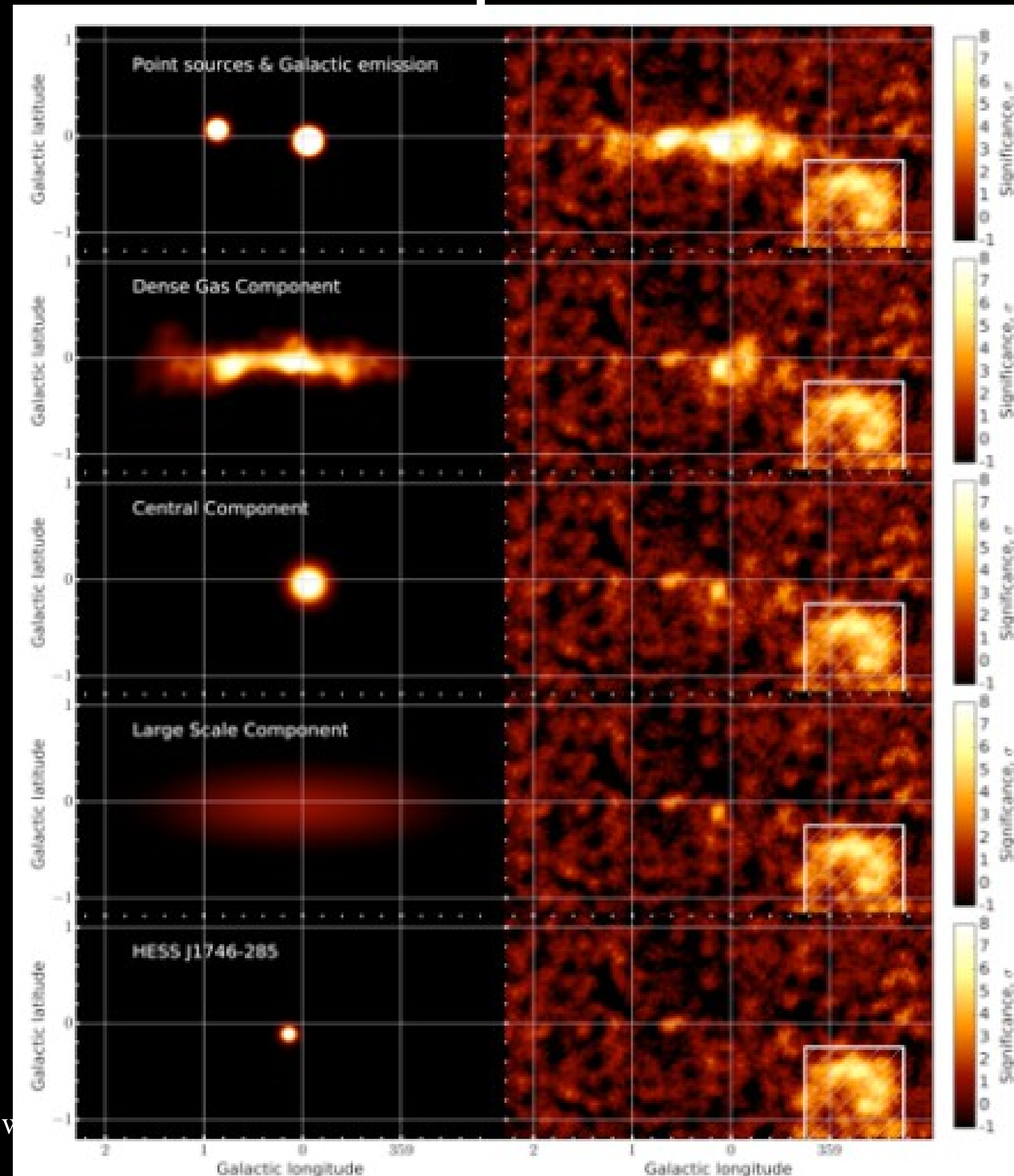
$a_1 S_1 \quad + \quad a_2 S_2 \; + \;$ OFF + GalDiff

$+ \; \alpha_{CR}$ (Gauss($\boldsymbol{\sigma x}$, $\boldsymbol{\sigma y}$) x CS) * PSF

$+ \quad \alpha_{CC}$ Central Compo($\boldsymbol{\sigma}$)

$+ \quad \boldsymbol{\alpha_{LS}}$ LargeScale($\boldsymbol{\sigma x}$,$\boldsymbol{\sigma y}$)

$+ \; a_3 S_3(l,b)$

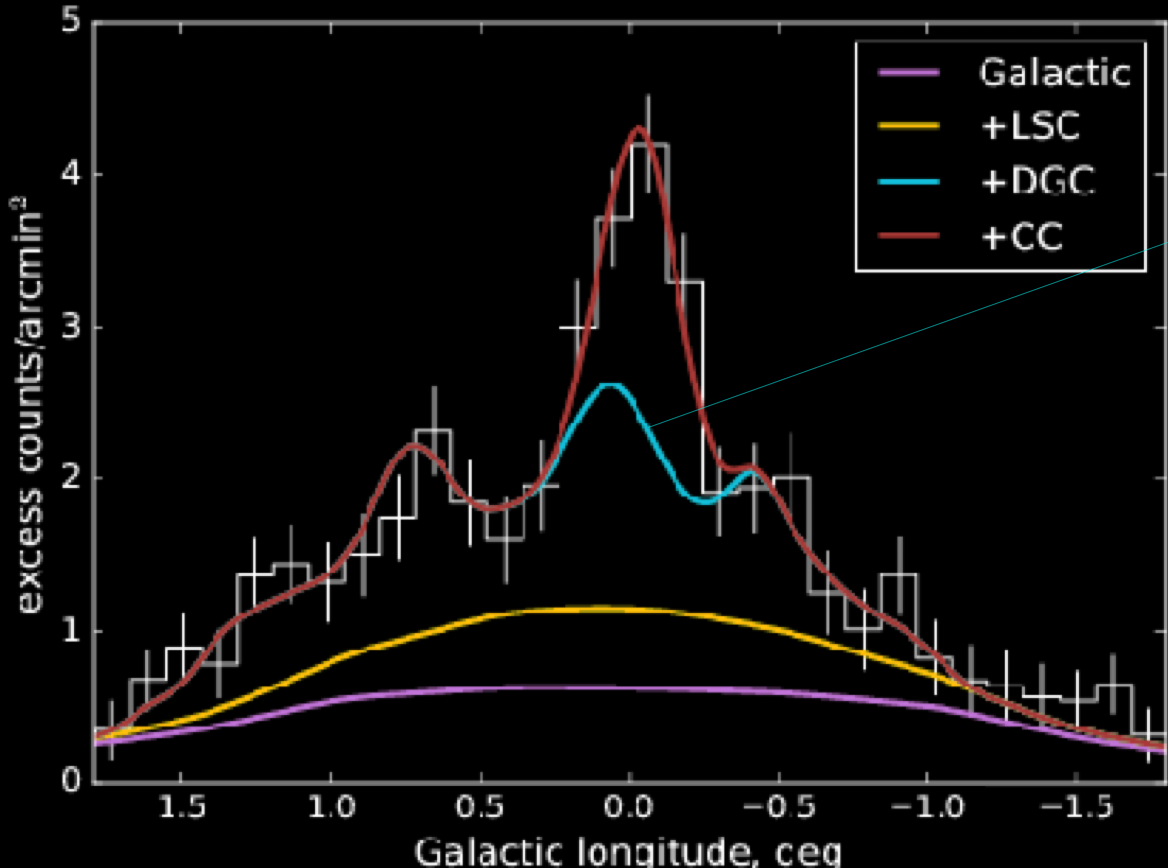


HESS Collab: Abdalla et al. 2017

GC VHE diffuse emission components

Longitude profile of the emission

HESS Collab: Abdalla et al. 2017



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

  → signature of protons interacting with the CMZ

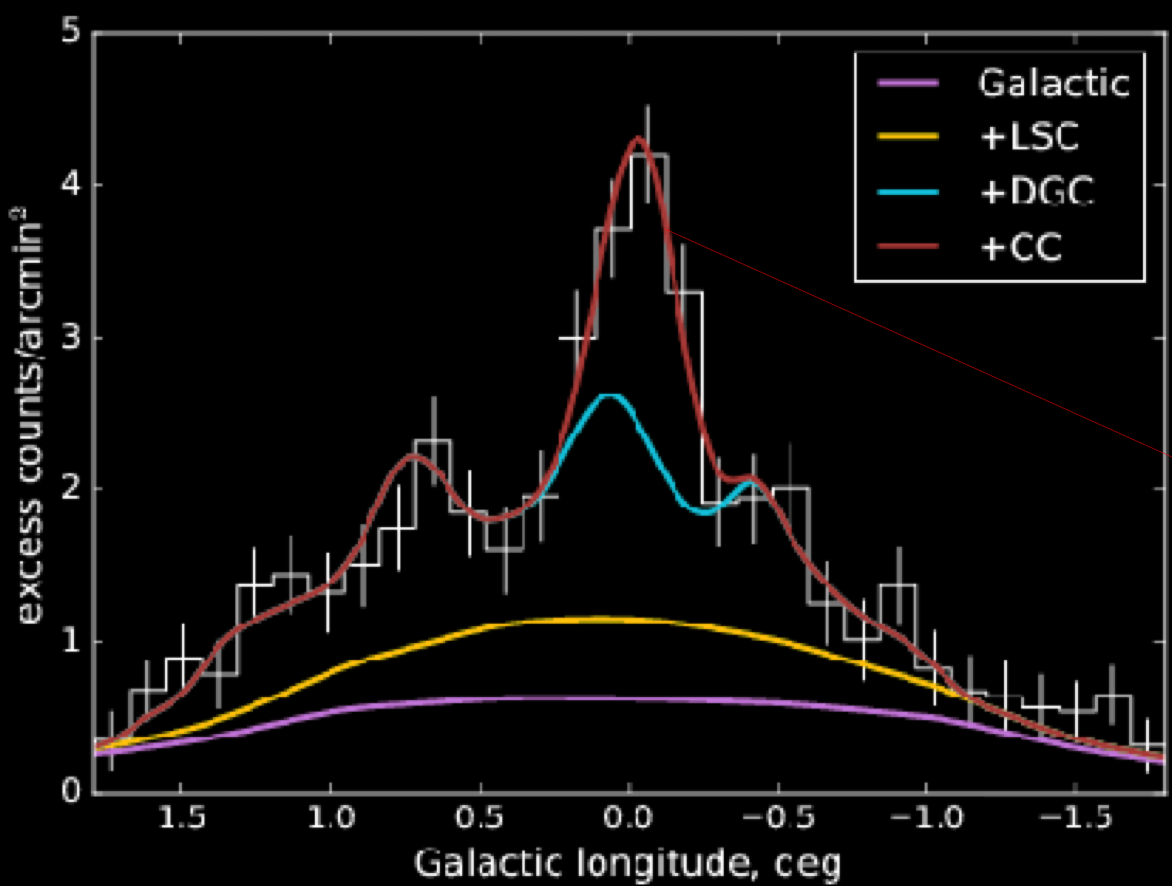
- CR gaussian extension of ~0.9° confirmed by 2D fit

  → CR distribution not homogeneous : enhancement near the center

GC VHE diffuse emission components

Longitude profile of the emission

HESS Collab: Abdalla et al. 2017



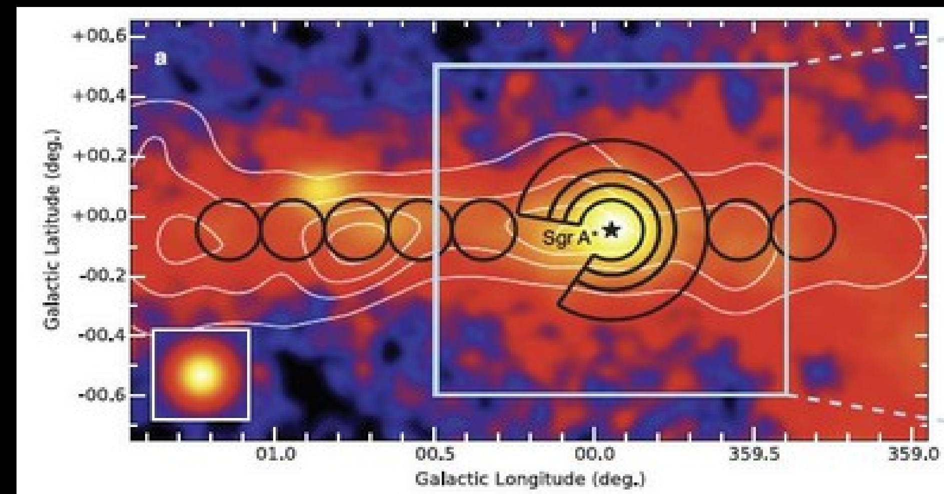
- Central component centered on the GC, 0.1°(or 14 pc) extension and 15% of the total ridge emission.

→ 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.

CR density profile integrated on the line of sight

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

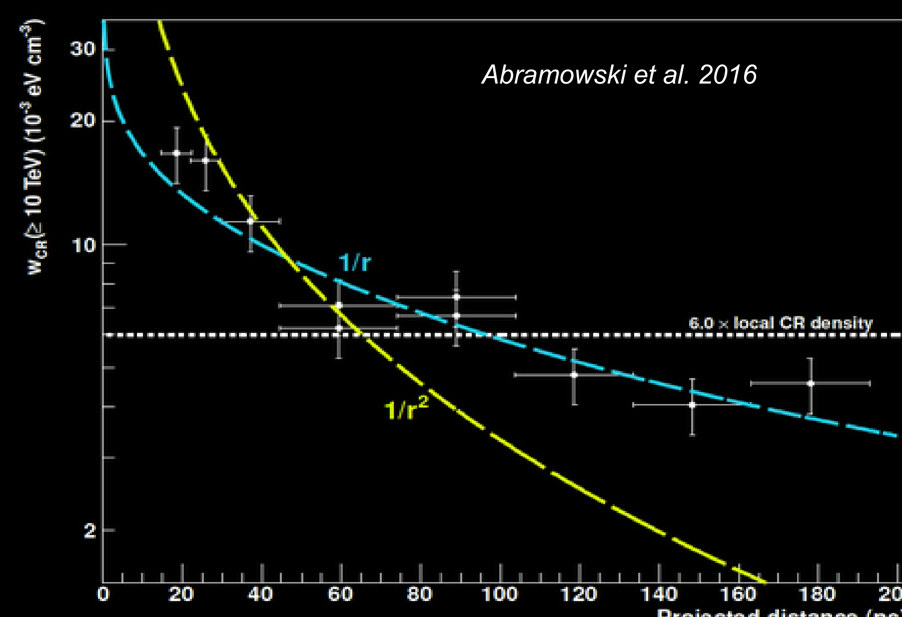


- Build CR density radial distributions :

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

  $1/r$ continuous injection and diffusive propagation

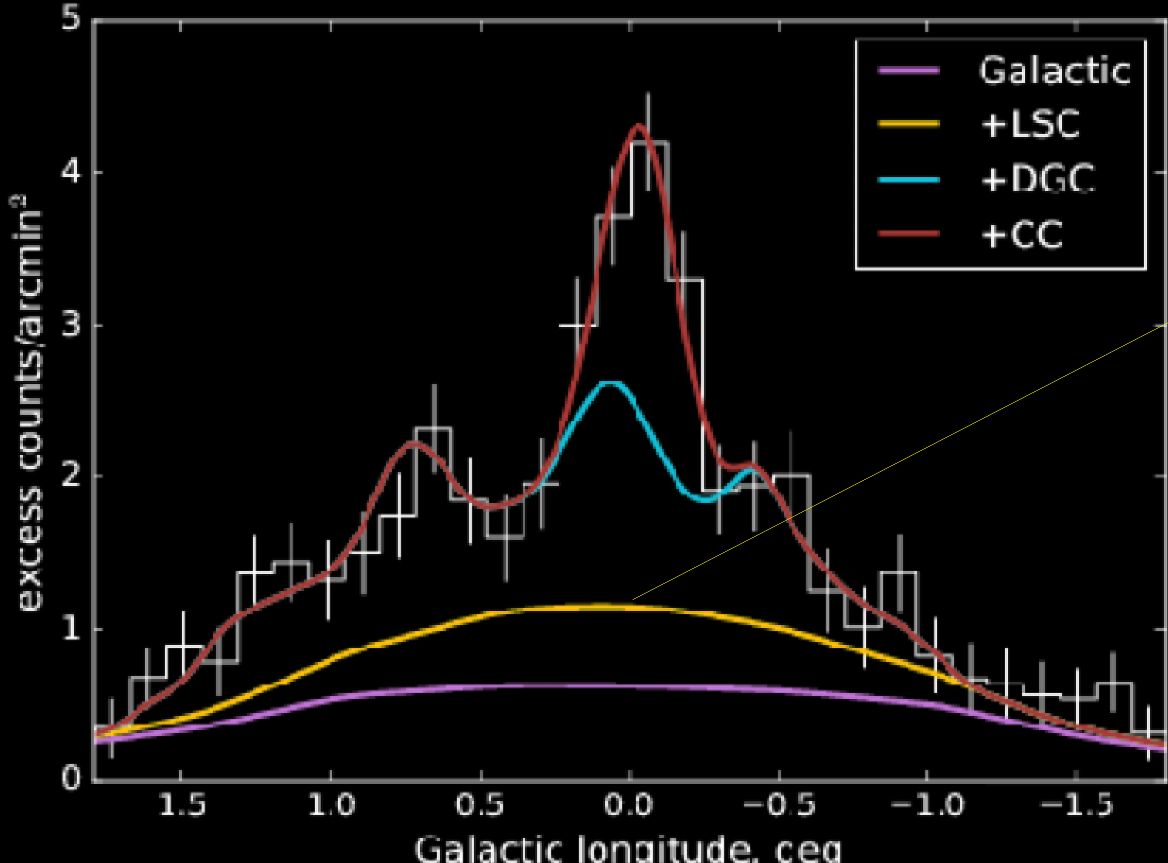
→ Homogeneous/Constant-Impulsive injection of CRs and diffusive propagation



GC VHE diffuse emission components

Longitude profile of the emission

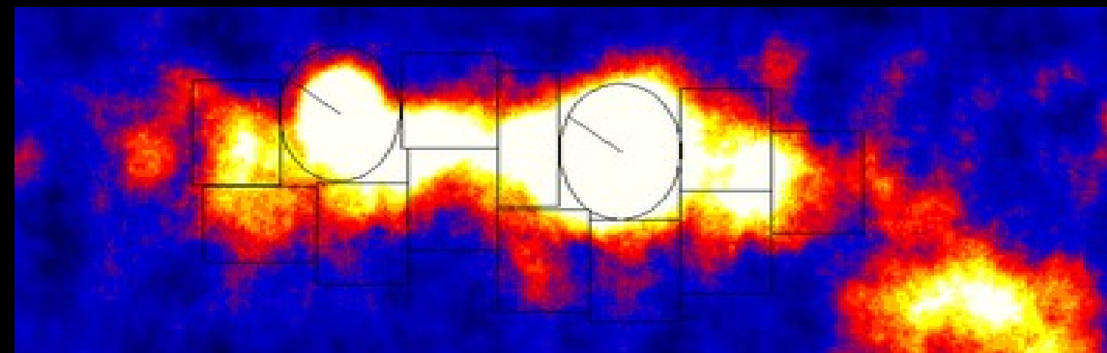
HESS Collab: Abdalla et al. 2017



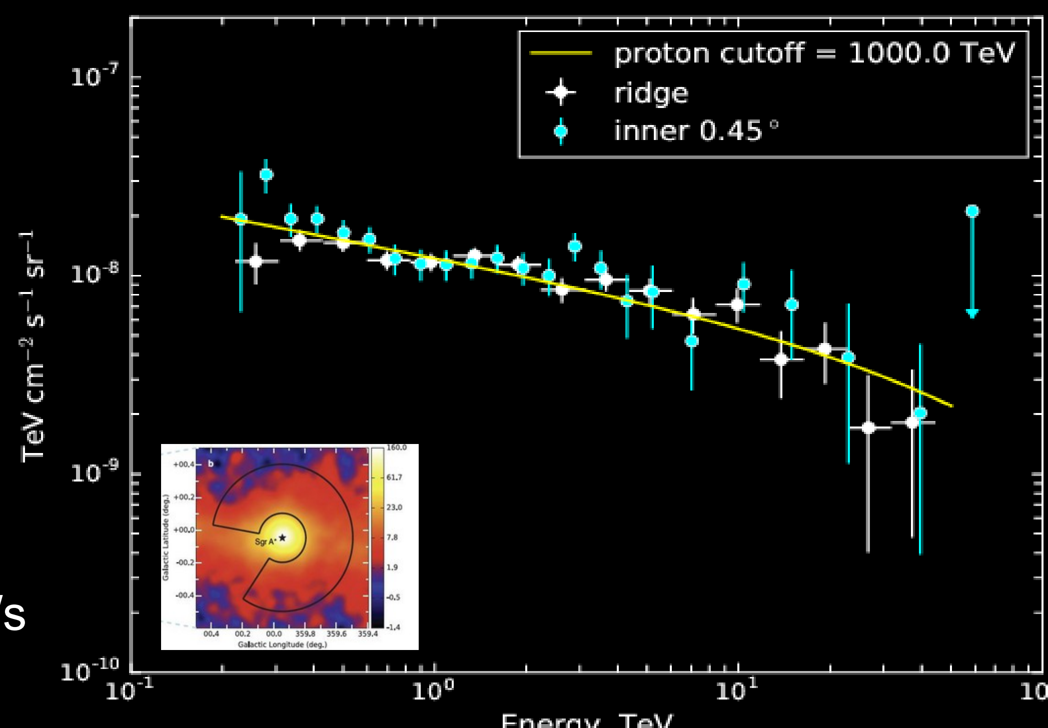
- A large scale component extending:
  - ±30 pc in latitude
  - ±150 pc in longitude
- Origin uncertain :
  - → Diffuse gas component not seen in tracers ?
  - → Unresolved TeV sources ?
  - → Diffuse features at high latitude ?

Spectrum of diffuse emission

HESS Collab ; Abramowski et al. 2016
Abdalla et al. 2017



- 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 :

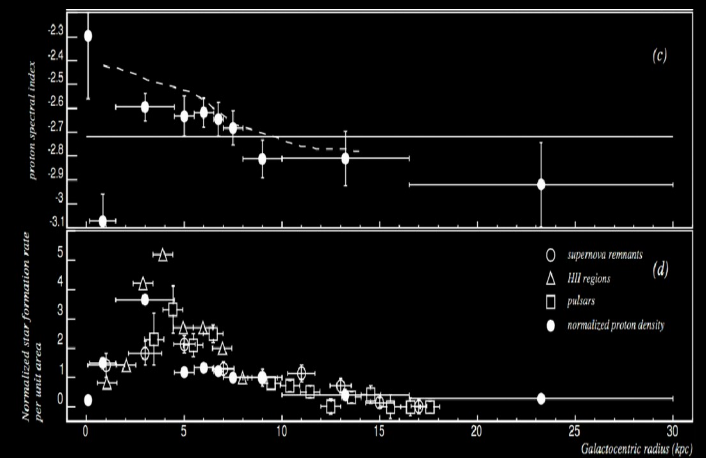
- extend to PeV energies : PeVatron !
- fill the entire CMZ

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

Is there an excess of CRs in the GC ?

Gaggero et al. 2017 :

Estimate the contribution of the CR large-scale population to the diffuse emission measured by H.E.S.S. and Fermi-LAT in the GC region

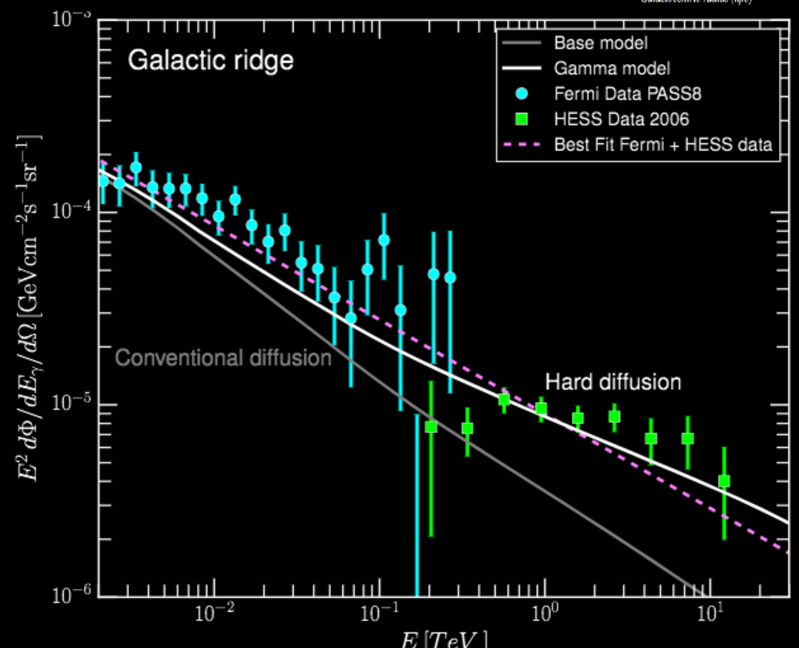


Relaxing the hypothesis of a uniform spectral index in the Galaxy :

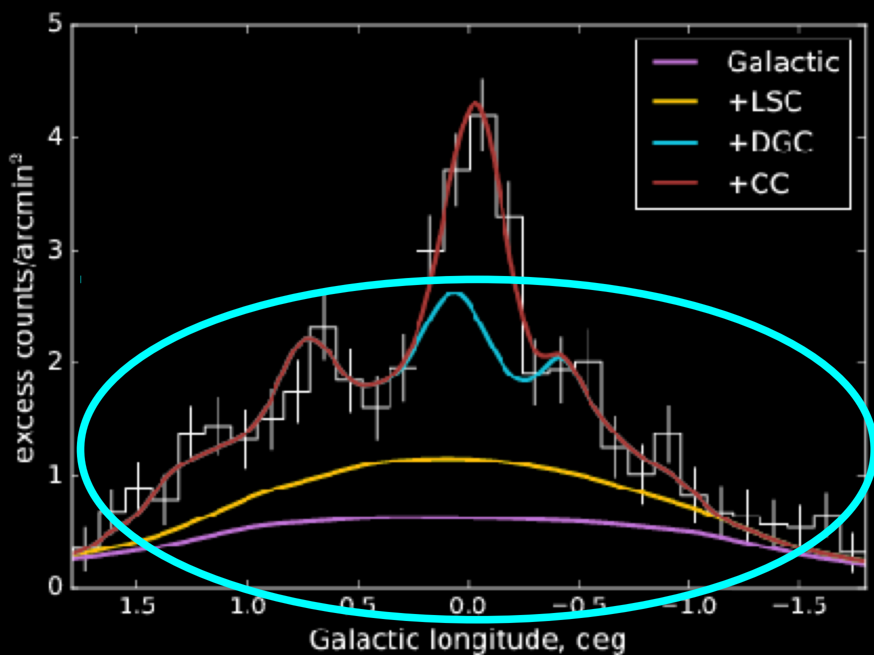
Scaling diffusion coefficient with rigidity and impose a linear dependence on the Galacto-centric radius

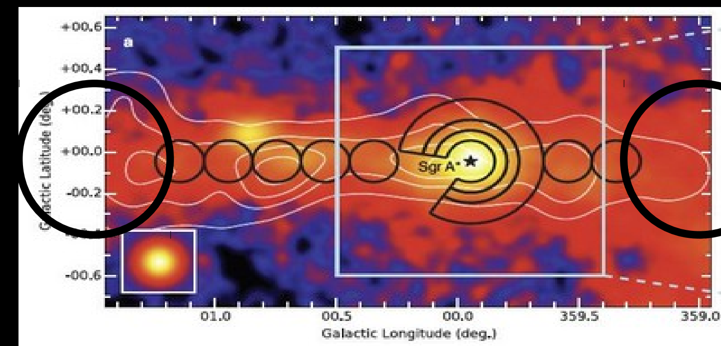
→ CR primary spectrum, gets harder approaching the GC

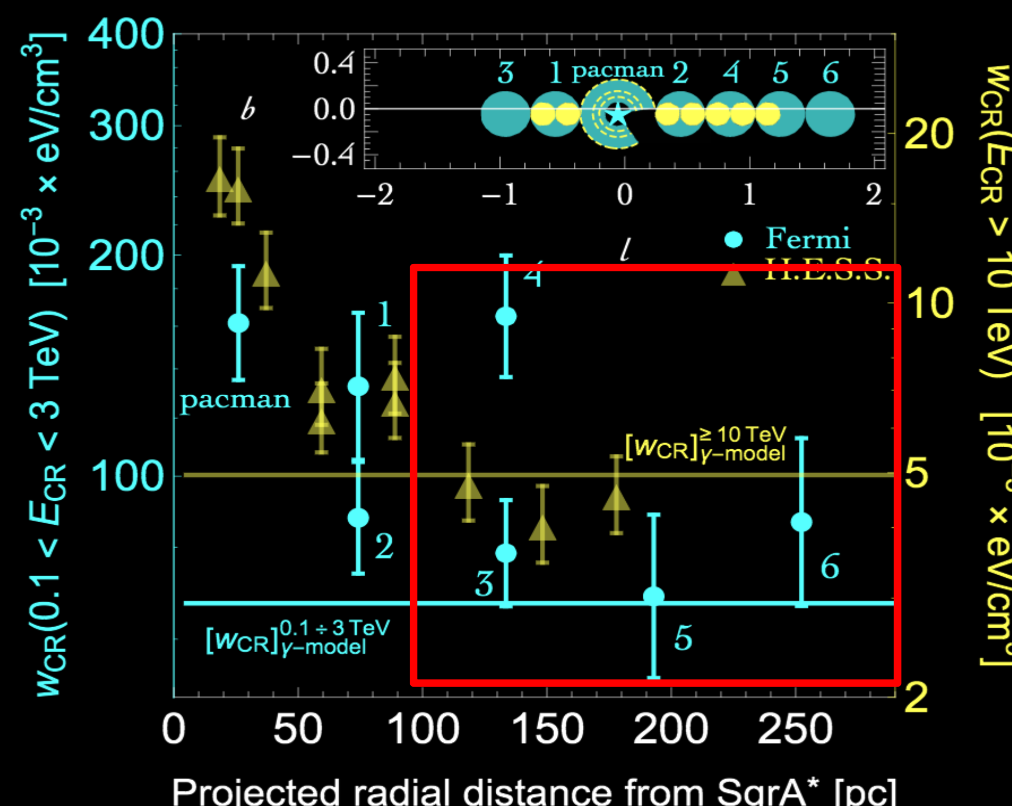
→ Harder gamma-ray diffuse emission toward the GC



Is there an exces of CRs in the GC ?





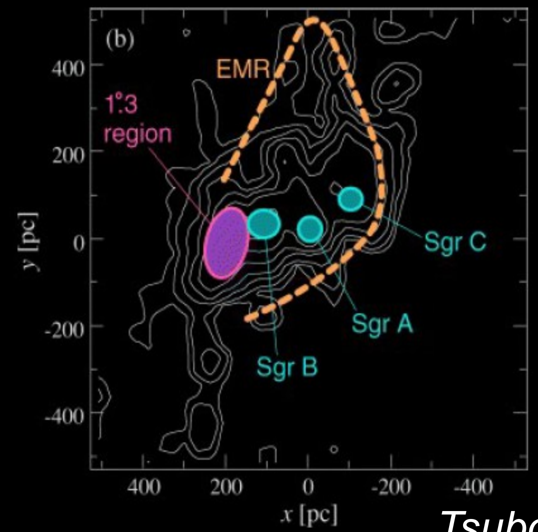


Gaggero et al. 2017 claim R>50 pc Galactic ridge emission can be reproduced by the interaction of diffuse steady state Galactic CR sea with the CMZ.

But what happens at larger longitudes ?

A deficit of gamma-ray emission at l=1.3°

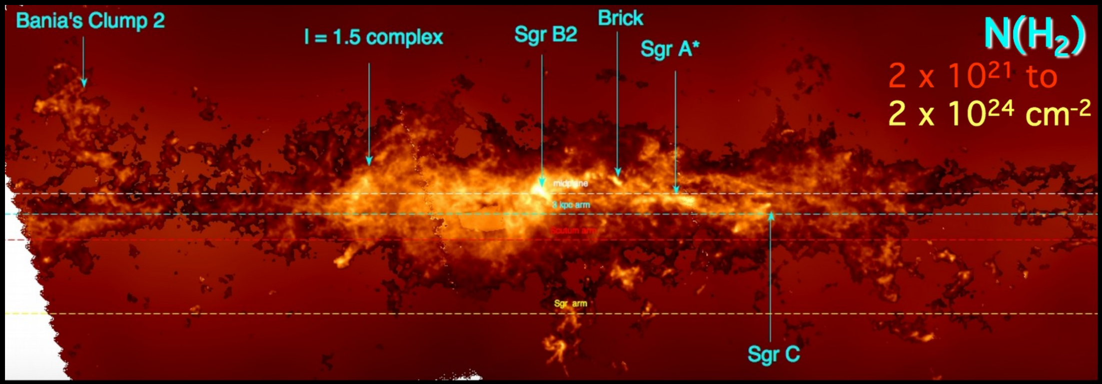
Sawad et al., 2004

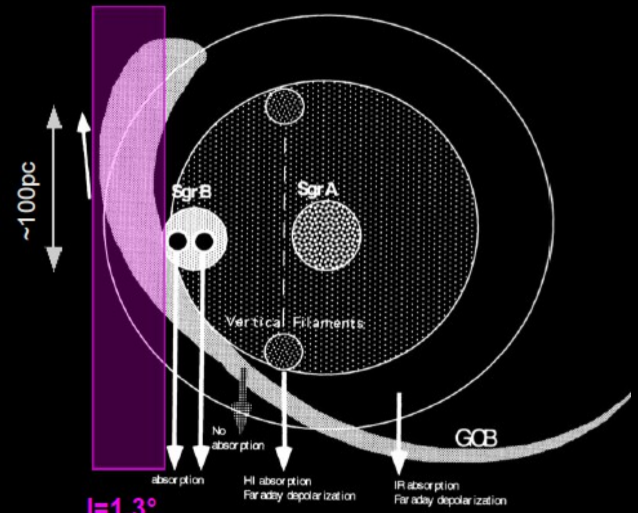


A face-on view of the CMZ :

- l=1.3° feature is the tangent point of a large arc of gas
- Gas is more distributed and spread along the line of sight

Tsuboi et al.,1999



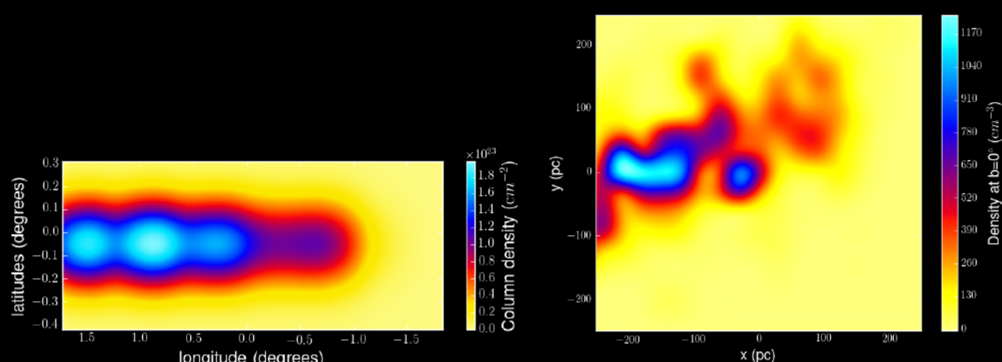


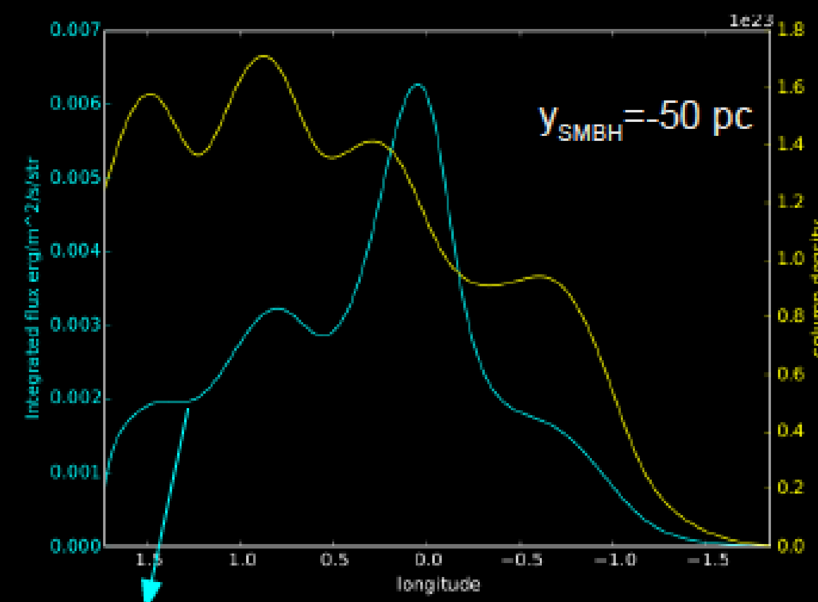
A stationary source at the center ?

Reproduce the TeV flux and morphology :

→ Test the 1/r CR profile in a 3D model using 3D CMZ + a stationary source at the GC

Jouvin et al.,2016





Gamma-ray profile

Gas column density

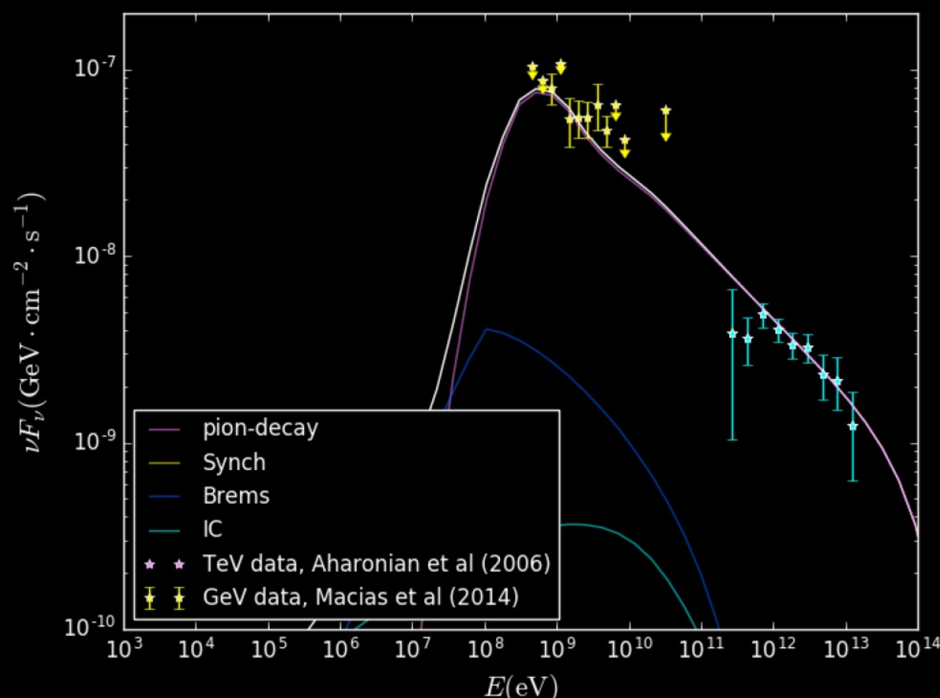
- Need acc power: 10^{38}erg/s during 10^{5} yrs
- 10% of SgrA* acc power at Bondi radius (10^{39}erg/s)
- Factor of 2 enhancement towards inner region is clearly visible
- Decrease at l=1.3° is there. Profile is broadly consistent with data

Impact of the SNRs in the CMZ

Hypothesis :The supernovae exploding every few thousand years in CMZ inject enough power:

- sustain the steady-state population of CRs required to generate non-thermal radio and TeV γ-ray emissior

Yoast-Hull et al. 2014, Macias et al 2015, Crocker et al. 2011



Jouvin phd 2017

One-zone stationary model :

Powerful wind advects particles out of the inner GC

→ *t_{advec} >> t_{rec} : constant CR density*

- high wind speeds v ~400-1000 km s^{-1}
- total power in non-thermal particles ~10^{39}erg s^{-1}
- smooth Injection index : 2.4
- unrealistic mater density(10cm^{-3}) or very large recurrence time (10^4 yrs) !

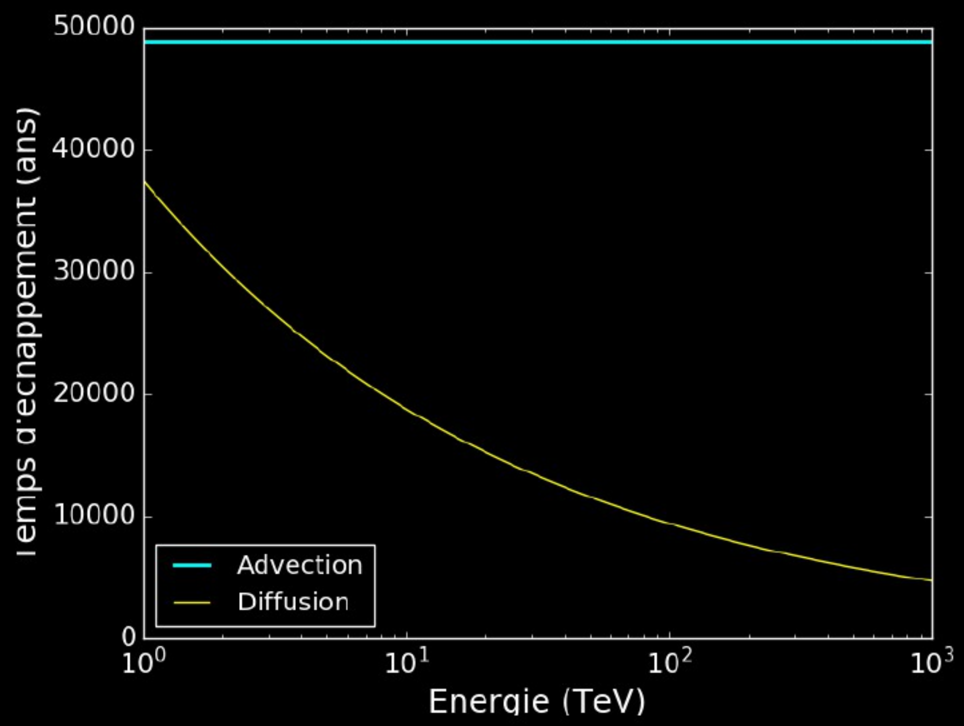
Impact of the SNRs in the CMZ

But escape by diffusion is much more efficient than advection in the very high energy domain

- Typical D_0=2 10^{29} cm^2s^{-1} and δ =0.3
- Wind v = 1000 $km.s^{-1}$

Need to take into account injection by SNRs as a function of time and particles diffusion in the CMZ.

Jouvin et al. 2017
Using code GAMERA (Hahn 2015).



Escape time of CRs as a function of energy by advection and using diffusion

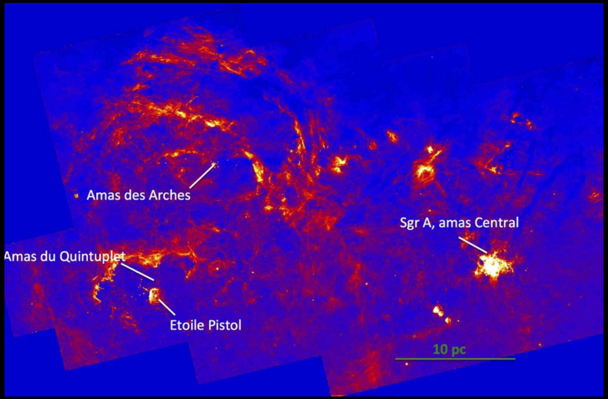
Impact of the SNRs in the CMZ

Model :

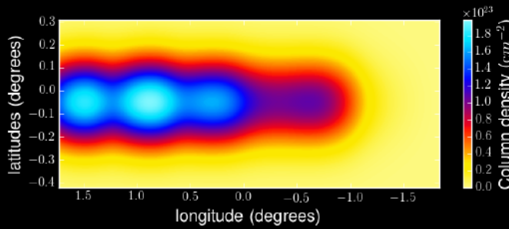
Jouvin et al. 2016

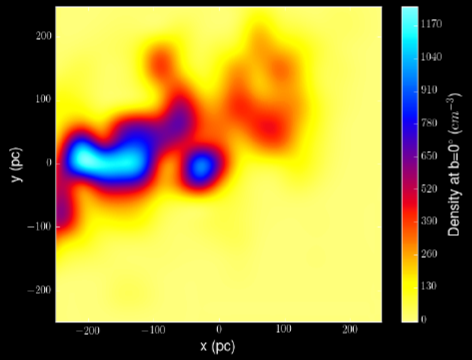
3D box : 500 pc * 500 pc * 50 pc

- Impulsive injection
- Realistic spatial distribution of SNRs:
    - uniform distribution in the CMZ (SNR rate ~ 4 10^{-4} yrs^{-1})
    - 3 majors star formation clusters toward CMZ centre :
        - Arches (excluded, too young)
        - Quintuplet , Central: SNR rate ~ 8 10^{-5} yrs^{-1}
          (Estimated from cluster mass+IMF)



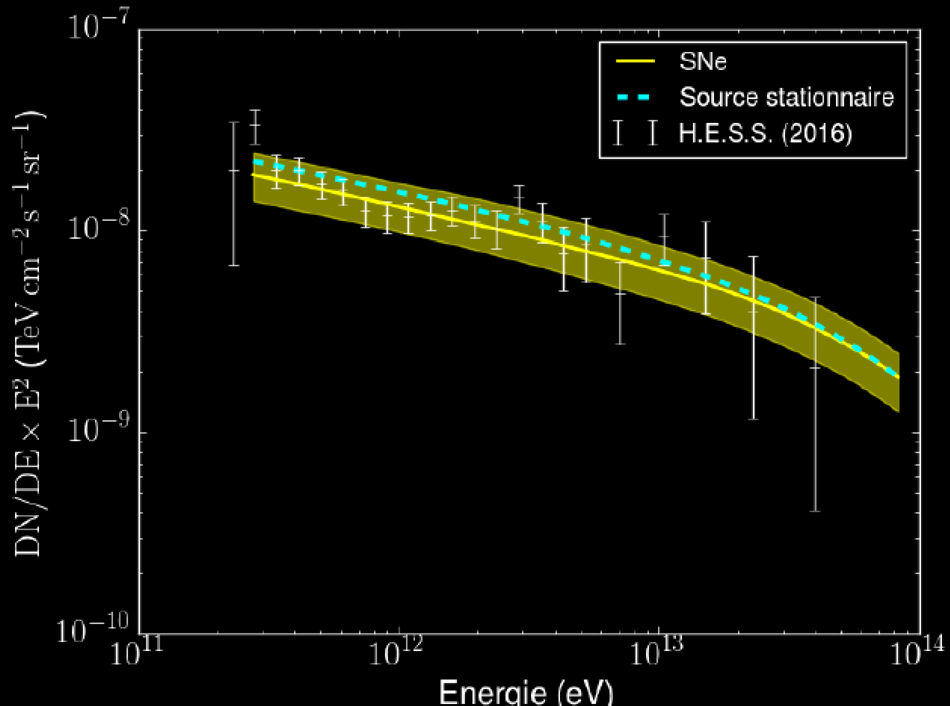
- 3D CMZ matter distribution (M_{tot}=4 10^{7} M_{sol})
- Diffusion D_0 (10 TeV) = 2 .10^{29} cm^2s^{-1}



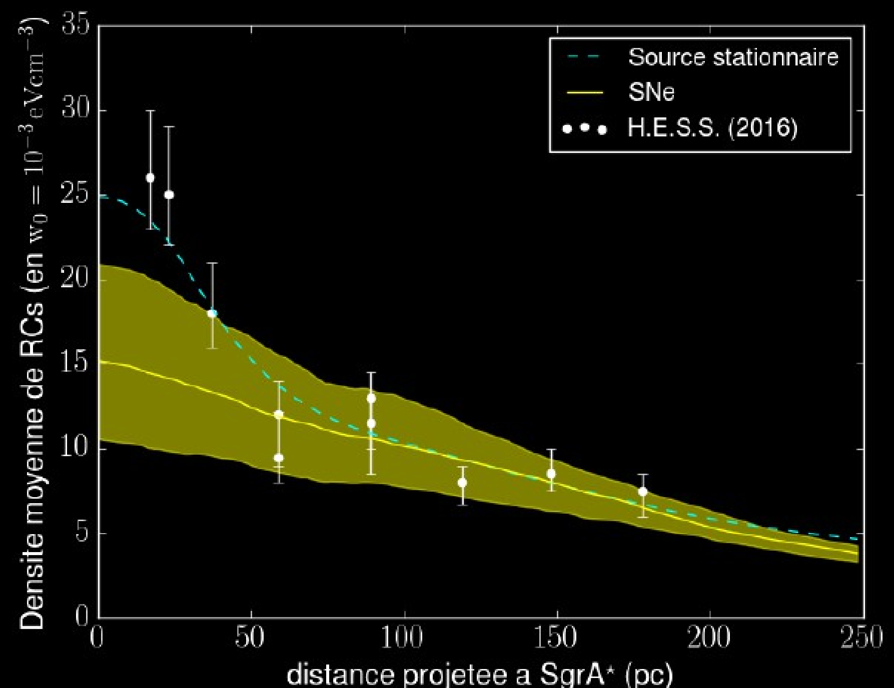


Impact of the SNRs in the CMZ

Jouvin et al.,2017



Median and dispersion of 100 generated spectra for different spatial and temporal configurations.



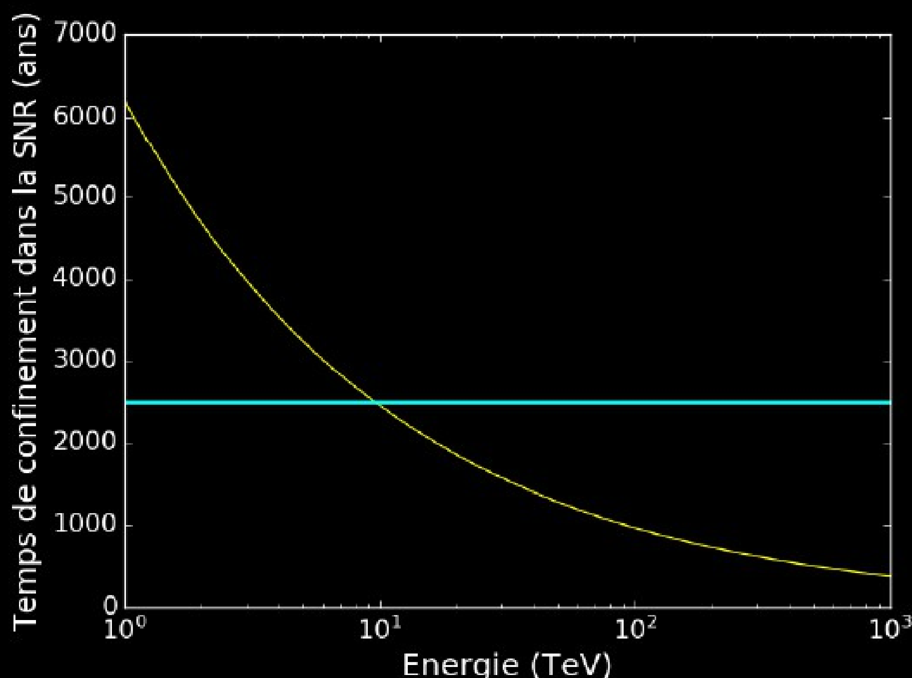
Average and dispersion of CR density profile for -0.1°<b<0.1°.

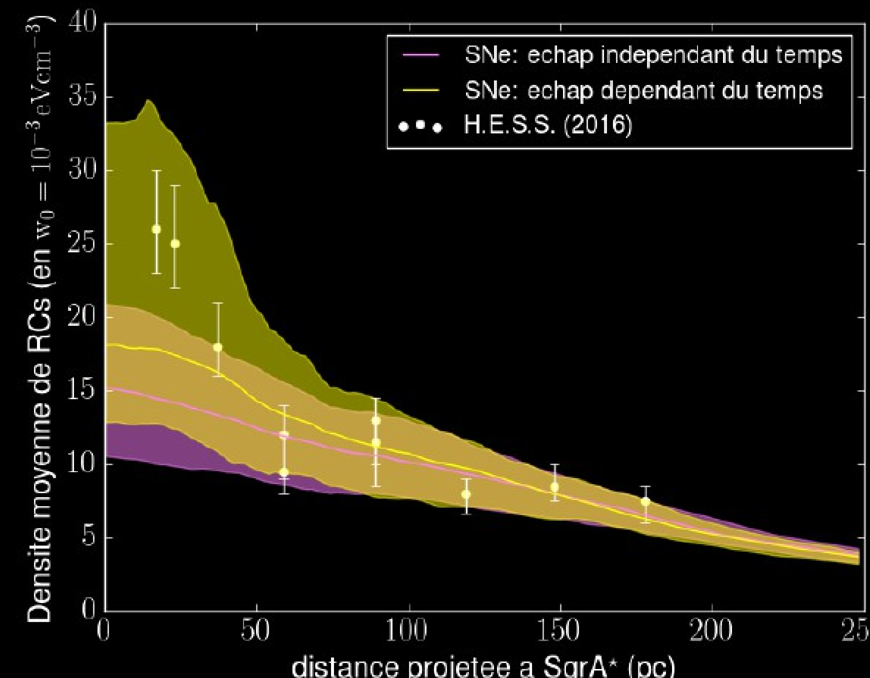
→ In order to not overproduce the HESS flux, the model need a very limited efficiency of CR acceleration by SNRs in the CMZ.

→ The reproduced CR density profile increases toward the center, but fail to reproduce the strong gradient in the central 30pc.

Time-dependant injection from the SNRs in the CMZ

Jouvin et al.,2018





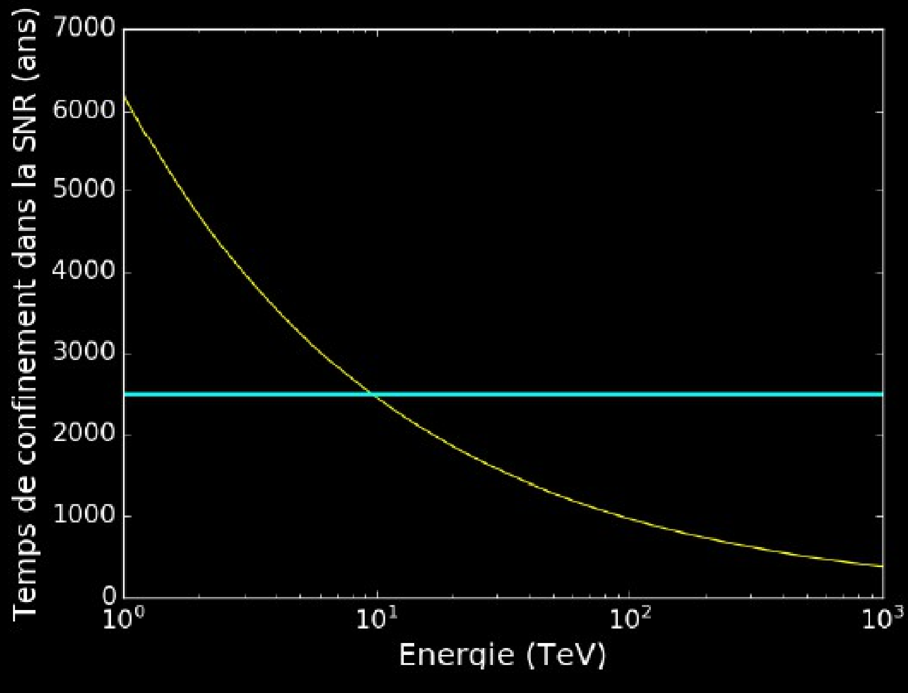
Taking into account the time dependent escape of CRs during Sedov-phase :

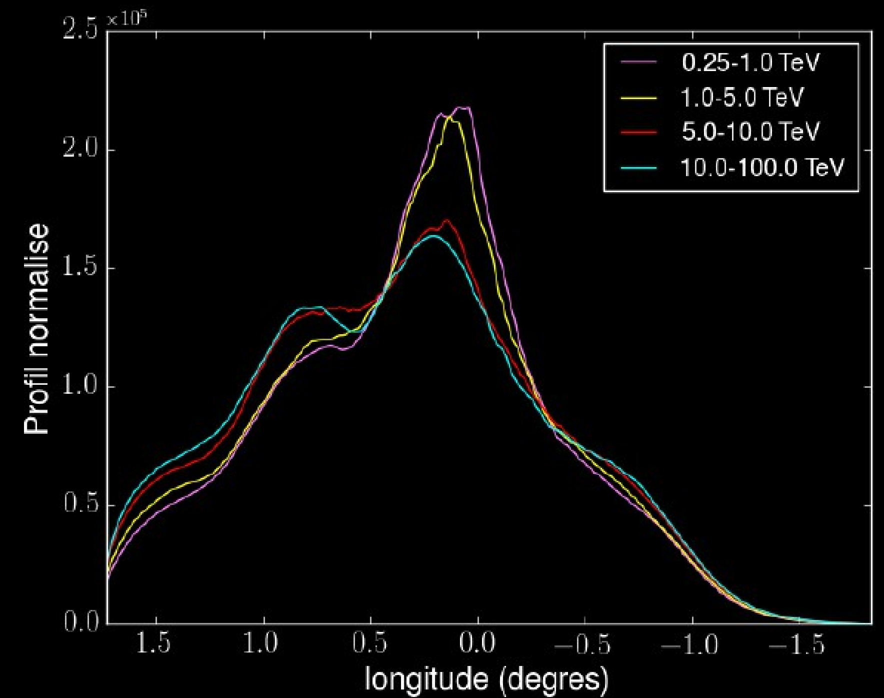
→ For lower E the confinement time starts to be larger than the recurrence time : the injection behaves like a constant injector at the center.

→ 1/r gradient in the CR profile is now reproduced

Time-dependant injection from the SNRs in the CMZ

Jouvin et al.,2018





Confinement time of CRs in the SNR as a function of CR energy compared with the SN recurrence time.

Energy dependent morphology of the gamma-ray profile

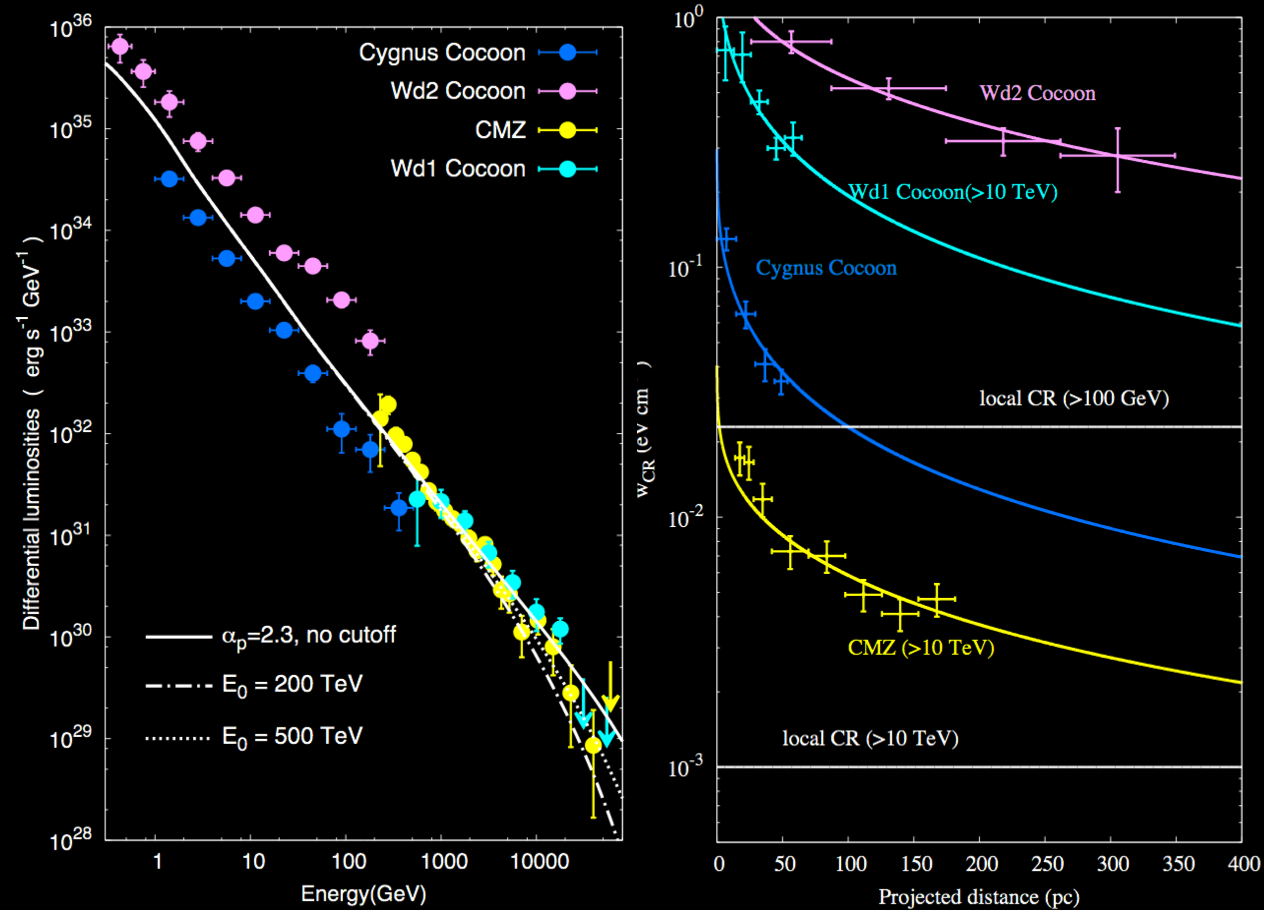
Massive Stars as Major Factories of Galactic CRs ?

Constancy of the energy and radial distribution of the CR density derived around the prominent galactic clusters:

- Westerlund 2
- Cygnus Cocoon
- Westerlund 1
- Ultracompact clusters in the GC

Distinct signature of continuous injection of CRs and their diffusion through ISM.

Population of young massive stars can provide production of CRs at a rate of up to 10^{41} erg/s, which is sufficient to support the flux of Galactic CRs without invoking other source populations.



Aharonian et al. 2018

Conclusions

- HESS observations have shown that PeV protons fill the entire CMZ and emit gamma-rays.
- HESS see a local excess of VHE CRs in the CMZ : need a local source
- We observe a radial gradient of CRs in the CMZ compatible with the shape expected if CR are accelerated by a steady source at the GC
- The contribution of SNRs can hardly be neglected

A lot of open questions :

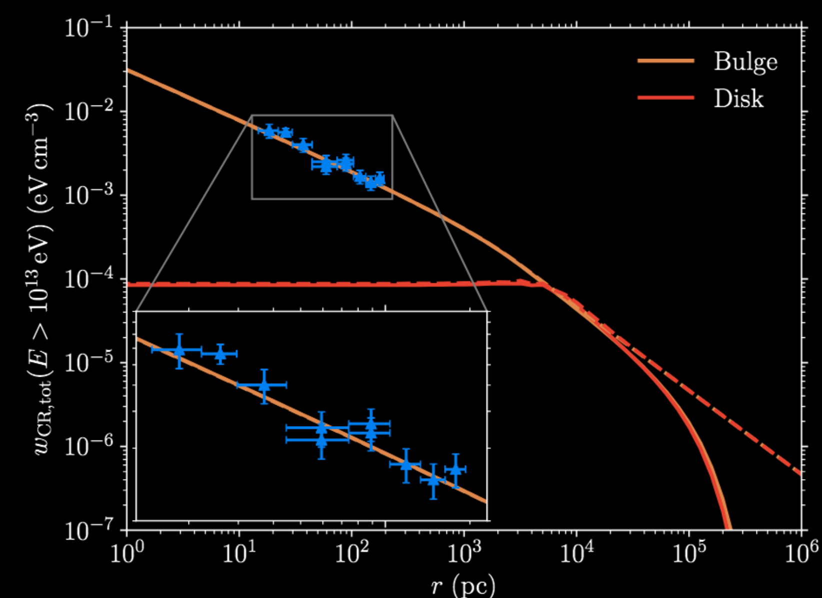
- Which relation with the central point-source ?
- Which connection with the Fermi bubbles ?
- Why don't we see emission from the SNRs (very high rate)
- What is the contribution of all the 30 PWN detected by Chandra in the central 30pc ?
- ...

Millisecond Pulsars as Pevatron at the GC ?

Guépin et al. 2018

The spatial and spectral dependences of the gamma ray diffuse emission observed by H.E.S.S. :

A population of ~$10^4 - 10^5$ millisecond pulsars above the cosmic-ray luminosity 10^{34}erg s−1, with moderate acceleration efficiency.

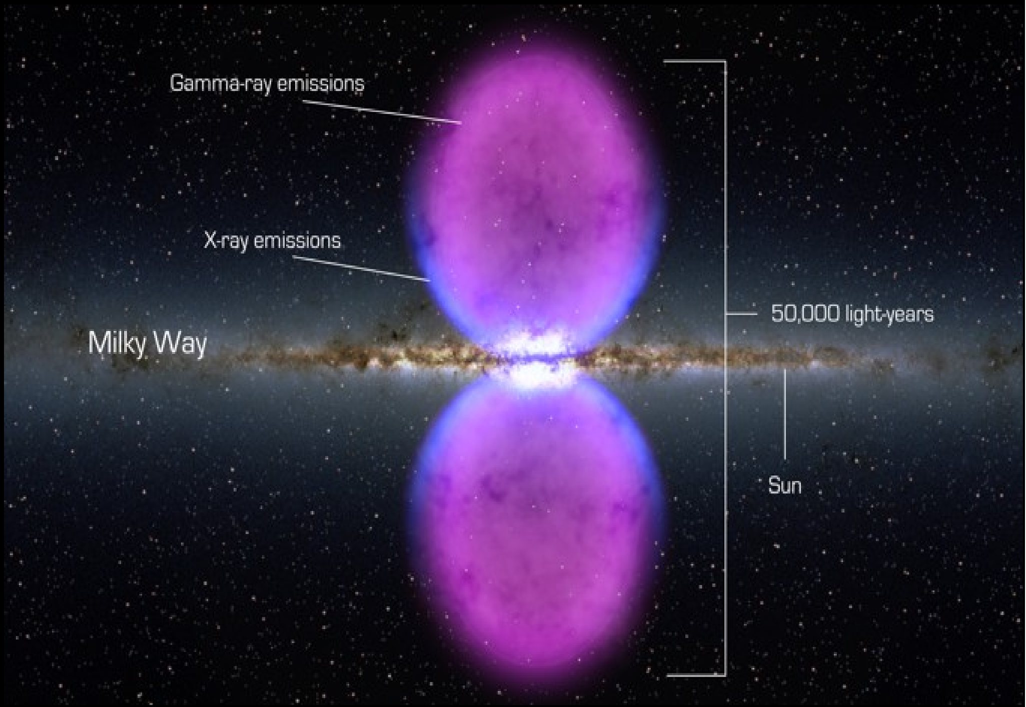


Total cosmic-ray density profiles for the bulge and disk populations of MSP

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 !

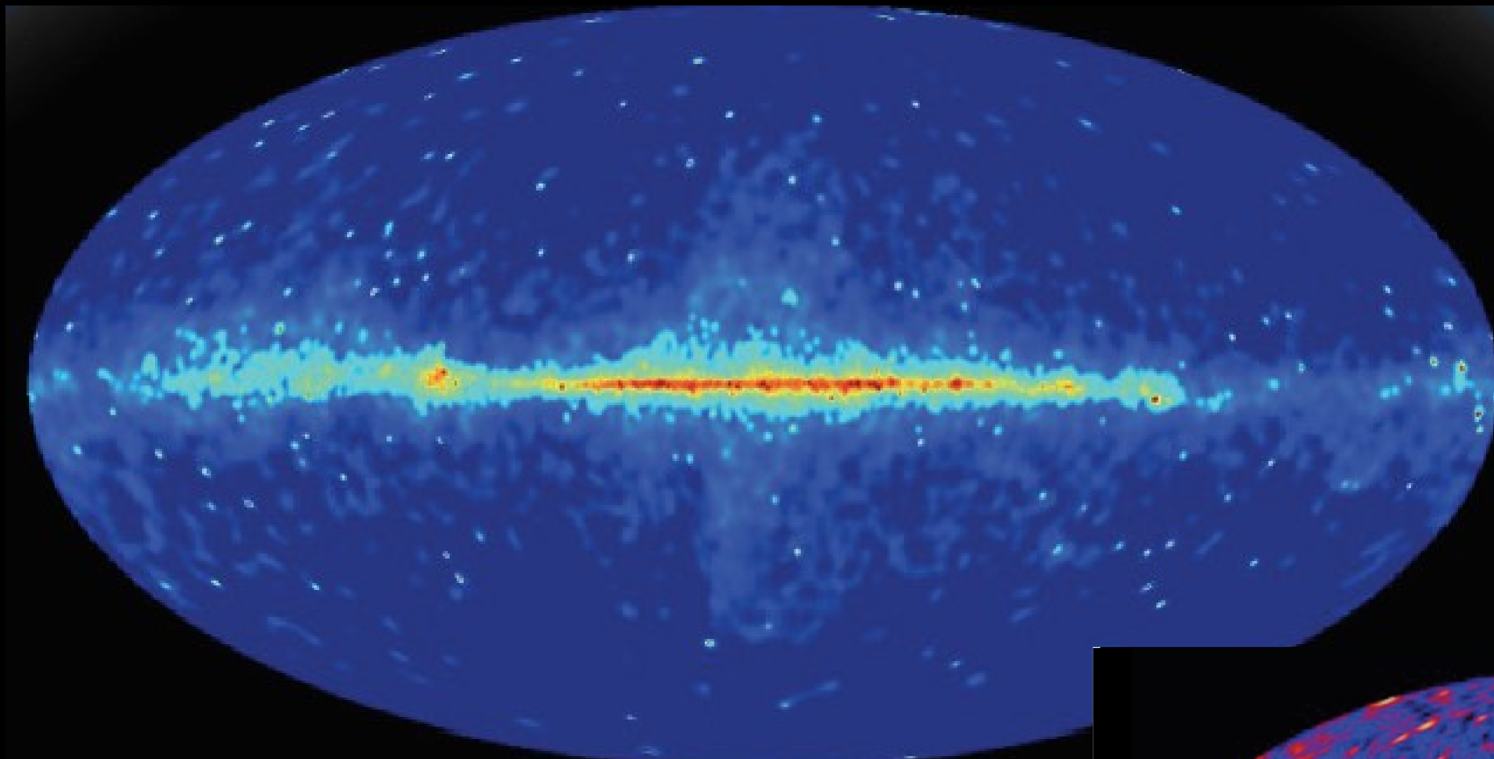


• Possible role of the supermassive black hole :

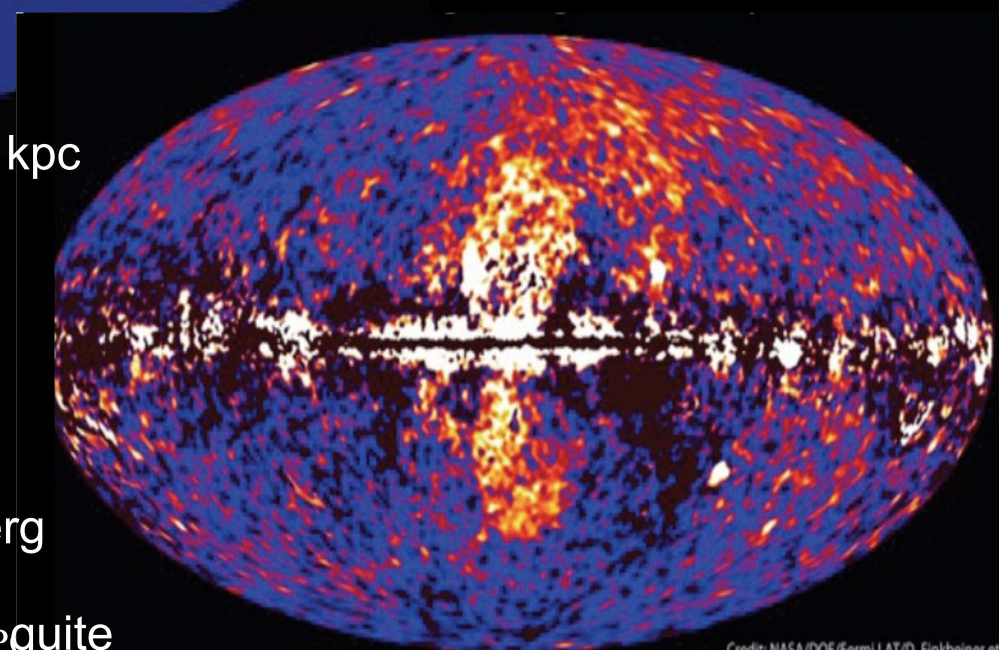
→ intense AGN phase at high luminosity accompanied by jets or outflows a few millions years ago
→ recurrent (every 10^4-10^5 years) accretion of stars captured by the black hole.

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 .

Fermi bubbles



E>10 GeV



- Large **gamma**-ray structures extending up to 10 kpc above and below the Galactic plane

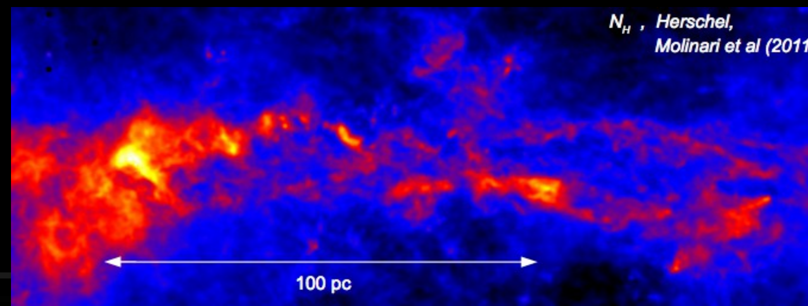
- Detected above a few GeV

- Hard spectrum extending up to at least 100 GeV.

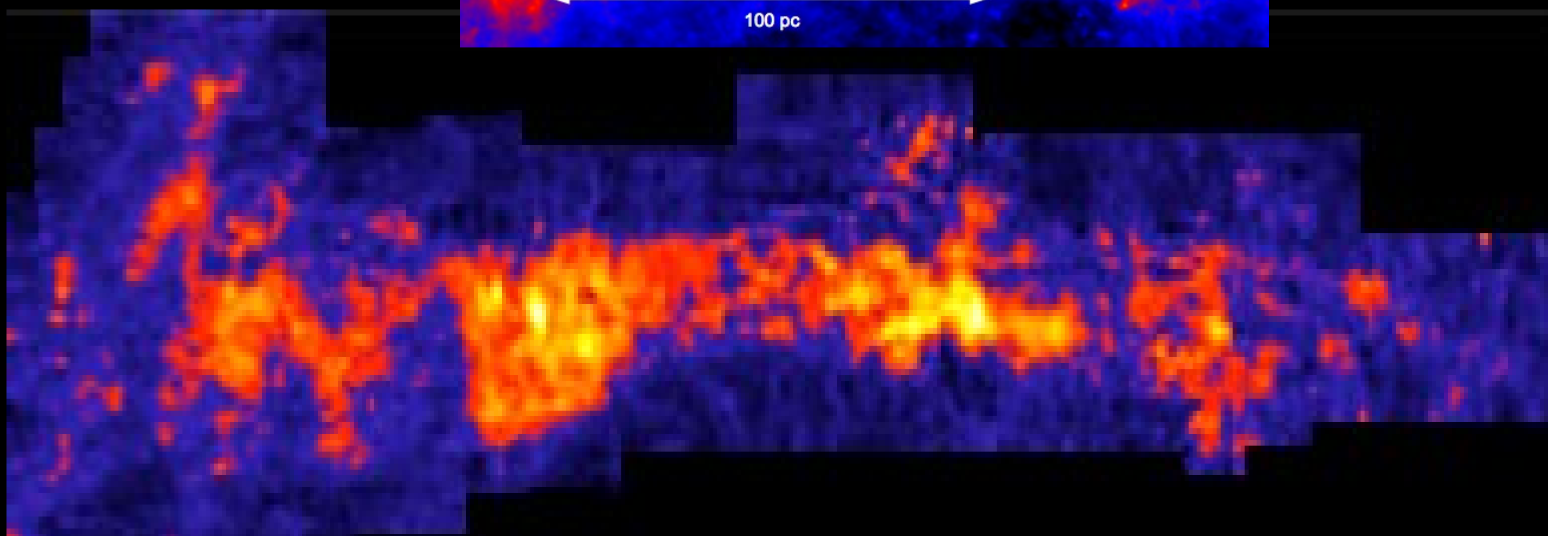
- Estimated energy content is of the order of 10^{55} erg

→ Mechanism providing such a large energy input quite uncertain.

Tracers of dense gas



Molinari et al 2011
Total NH



Tsuboi et al
1998
CS

- CS is an effective tracer of dense gas, but suffers from self-absorption in very dense regions (Full CMZ : (-1. 5°< l < 1. 5°))

- HCN has similar density distribution than CS (Full CMZ)

- Molinari et al (2011) total **NH** map (-0. 8°< l < 0. 8°) :
  Dust temperature and column density maps deduced from multi-frequencies **Herschel** observations : total gas column density is deduced multiplying by a constant gas-to-dust ratio.

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^{3yrs} for low energies (diffusive motion)

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