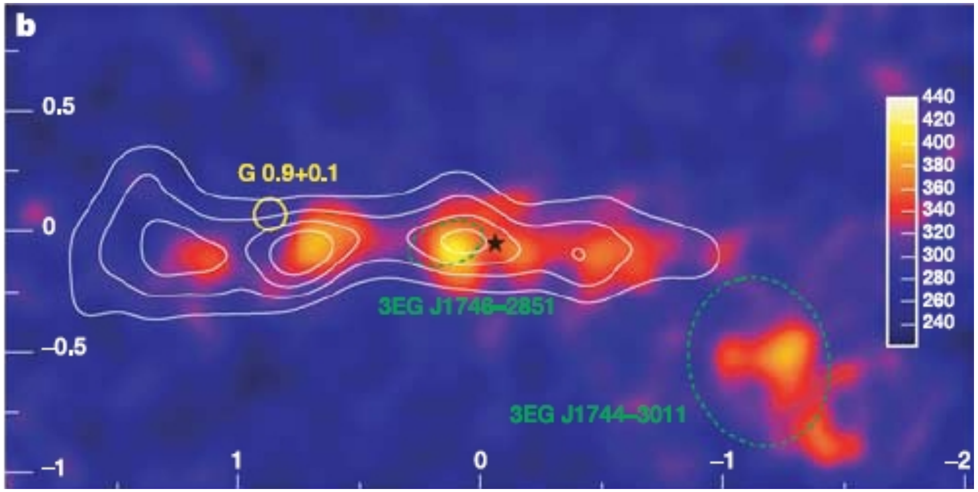
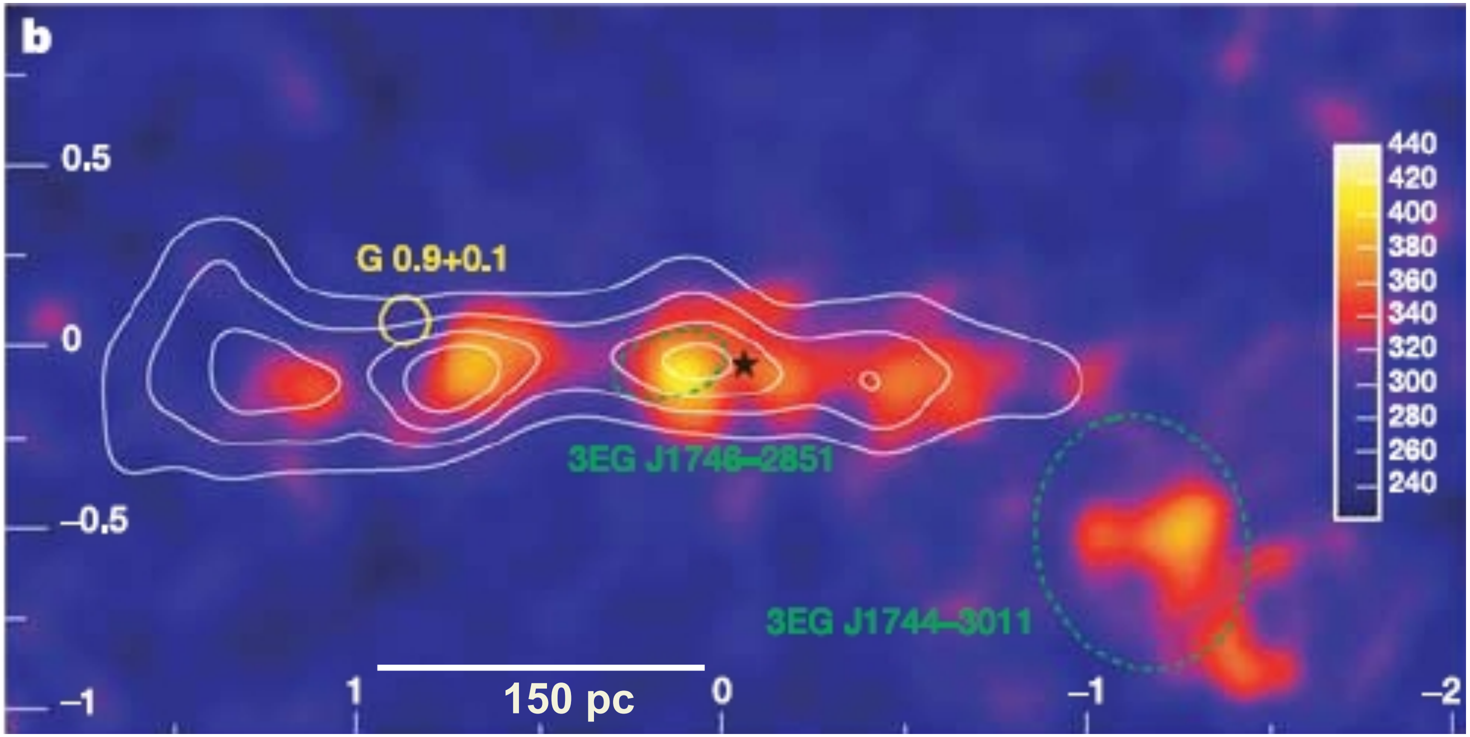
# EXCESS OF VHE COSMIC RAYS IN THE CENTRAL 100 PC OF THE MILKY WAY

**Jouvin L., Lemière A. and Terrier R.**



# Excess of VHE cosmic rays (CRs)

***γ-ray count map***



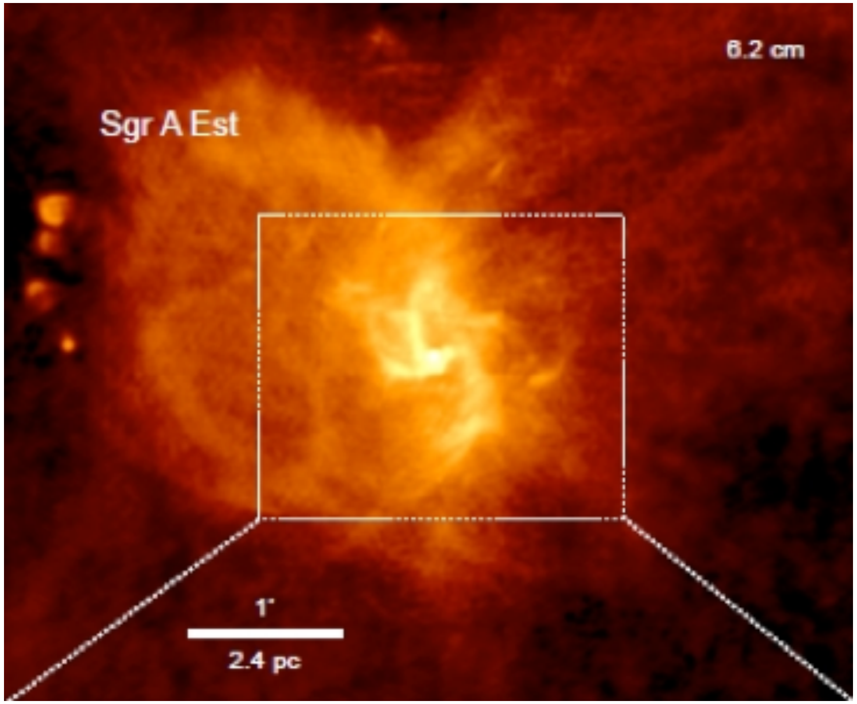

**Credits: H.E.S.S. collaboration**
**Aharonian et al., 2006**

After subtracting the brightest TeV sources:

***-> diffuse hadronic emission***

***-> CRs energy density: 3-9 times higher than the local one and harder spectrum (Γ=2.3)***

# A unique accelerator in the central pc?



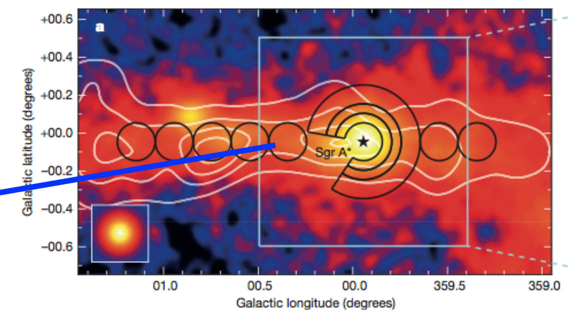

Credits: F. Yusef-Zadeh

SgrA East :
- Supernovae remnant
- situated at ~ 2 pc from SgrA*
- explosion ~ 10 000 years

➔ ***Impulsive injection***

Flat CR profile ➔ now excluded

# CR profile

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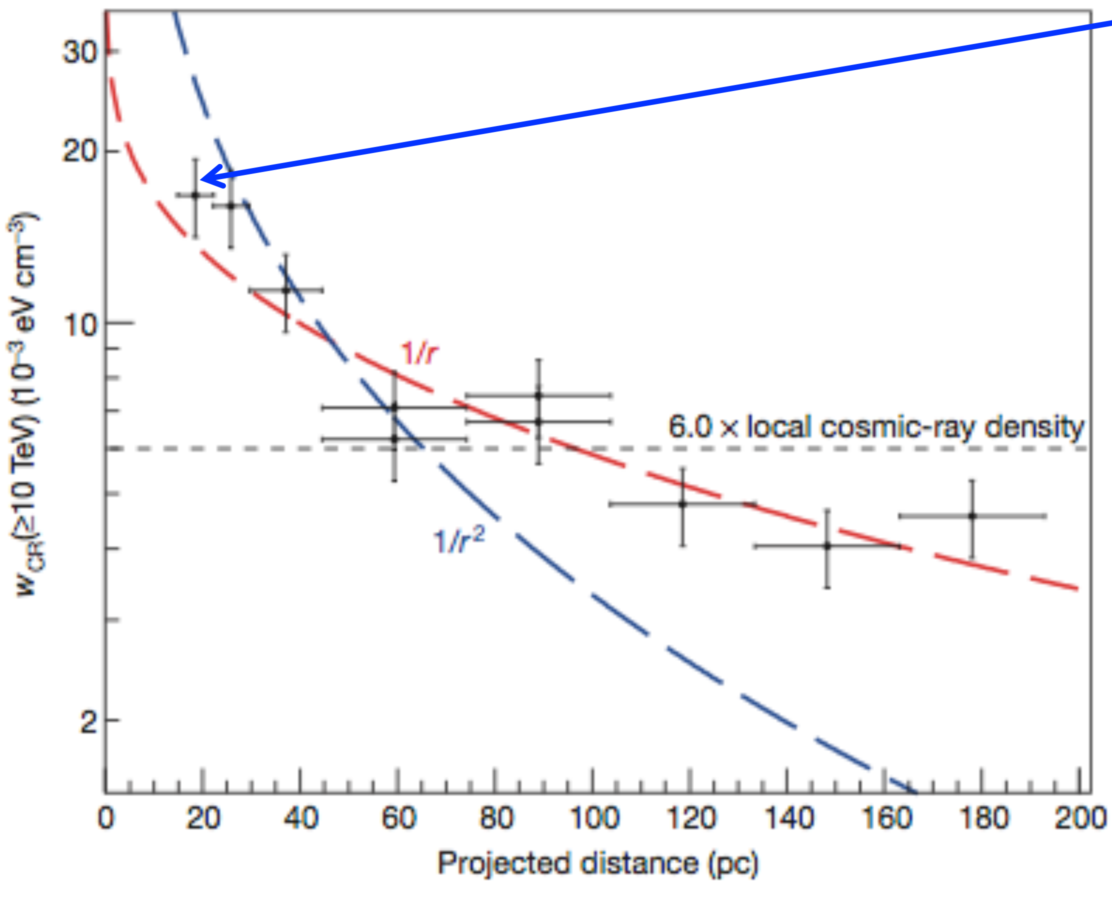
Abramowski **et al., 2016**

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Abramowski **et al., 2006**

- Peaked toward the center
- Compatible with an 1/r profile as the one produced by a **stationary source** at the center

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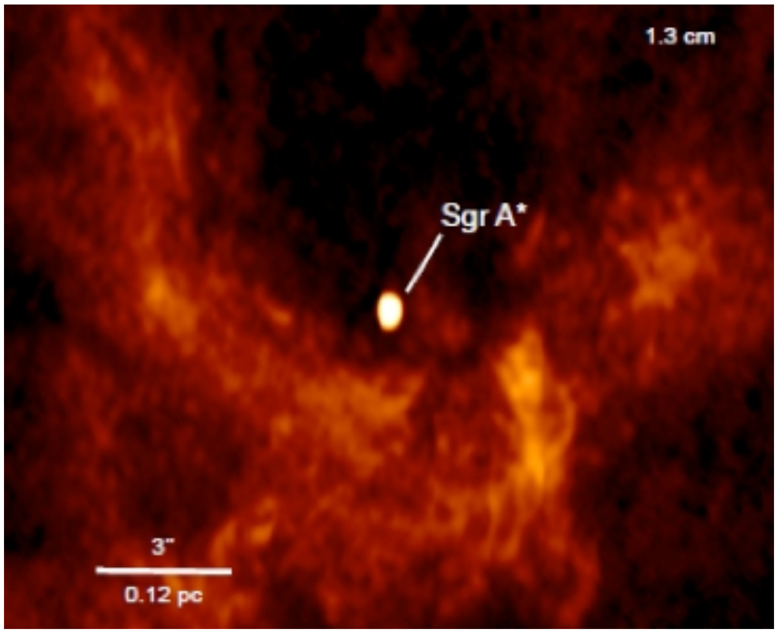


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SgrA*:

Super Massive black hole

- **M :** $4*10^6$ $M_{sun}$

(Ghez et al. (2000) and Gillesen et al. (2009))

Extremely faint nowadays

- $L_{Eddigton}$ : $10^{44}$ erg
- $L_{bolometriqe}$ : $10^{36}$ erg

Radiatively inneficient accretion flow -> powerful outflow evacuating the matter where CR acceleration is possible

- Dissipated power: $10^{39}$ $ergs^{-1}$ (Wang et al , 2013)

H.E.S.S: total CRs rays flux ≈ $10^{50}$ erg

BH: 10% of the accretion power to CR acceleration

→ ***Stationary injection***

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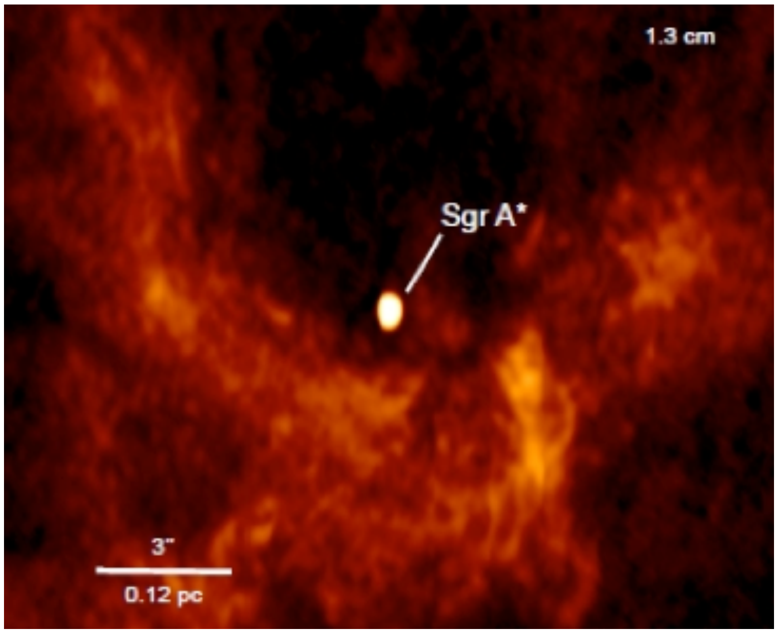


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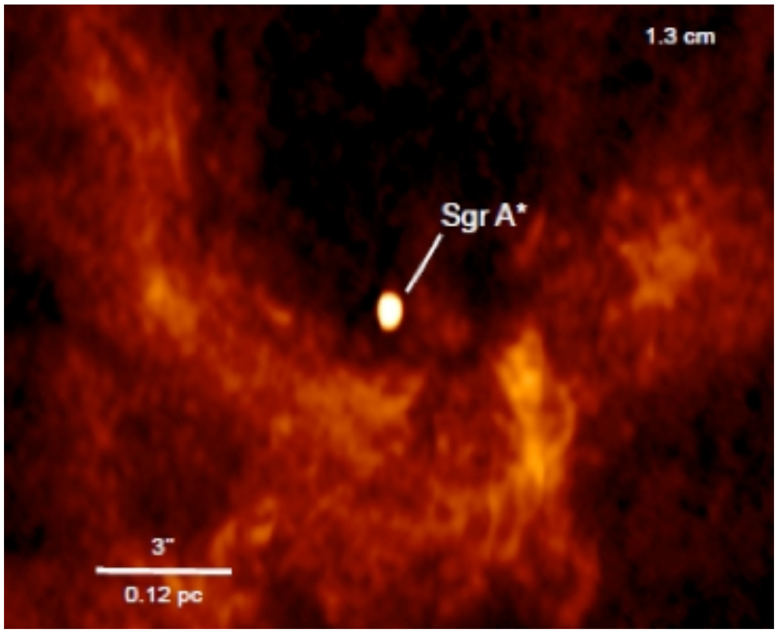


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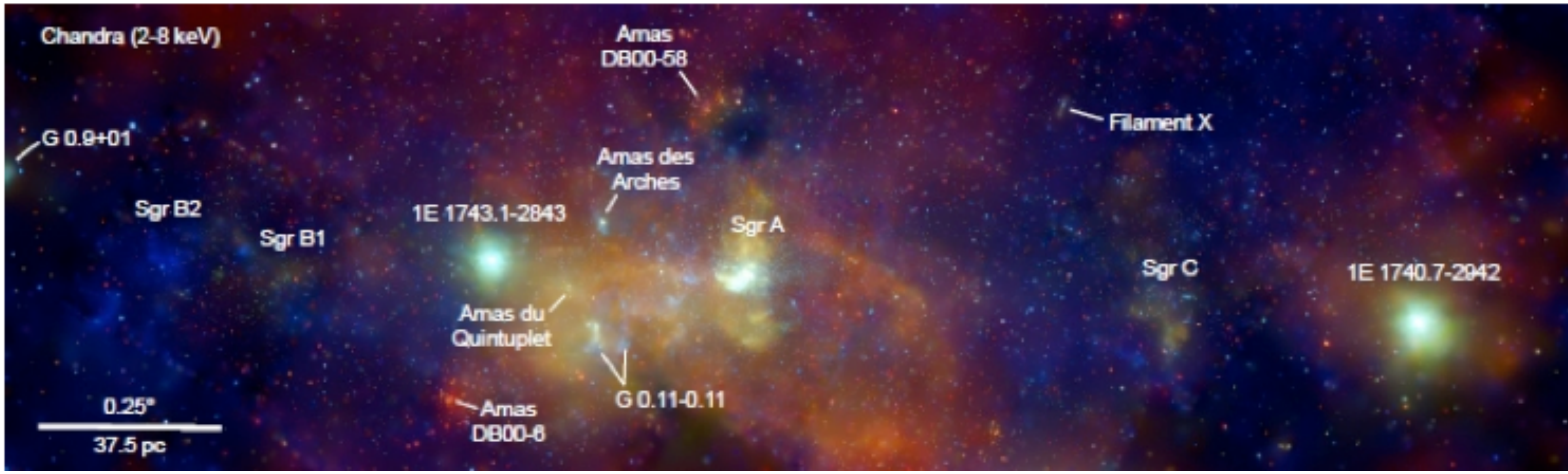
# Multiple CR impulsive injections

Galactic Center: 2% of the Galaxy's massive star formation
➔ high massive star formation
➔ high SN rate: $10^{-3}$-$10^{-4}$ $yrs^{-1}$ (Crocker et al (2011), Ponti et al (2015)) but large uncertainties
➔ central value of Crocker et al (2011): 1 SN per 2500 years

*What is the impact of this SN on the VHE emission in the GC?*

# Spatial distribution of the SN in the GC




Credits: M. Muno

- Thermal emission concentrated in the central part of the GC
- Three compact and massive cluster in the GC: the Quintuplet (3-5 Myrs), the Arches (2-3 Myrs) and the Central Cluster (4-6 Myrs)
- Several independant observations shown the presence of a high number of isolated stars (Mauerhan, 2010)

# SNe modelisation: One zone steady state model

# Advection vs diffusion

**Advection:**

- perpendicular wind of speed v

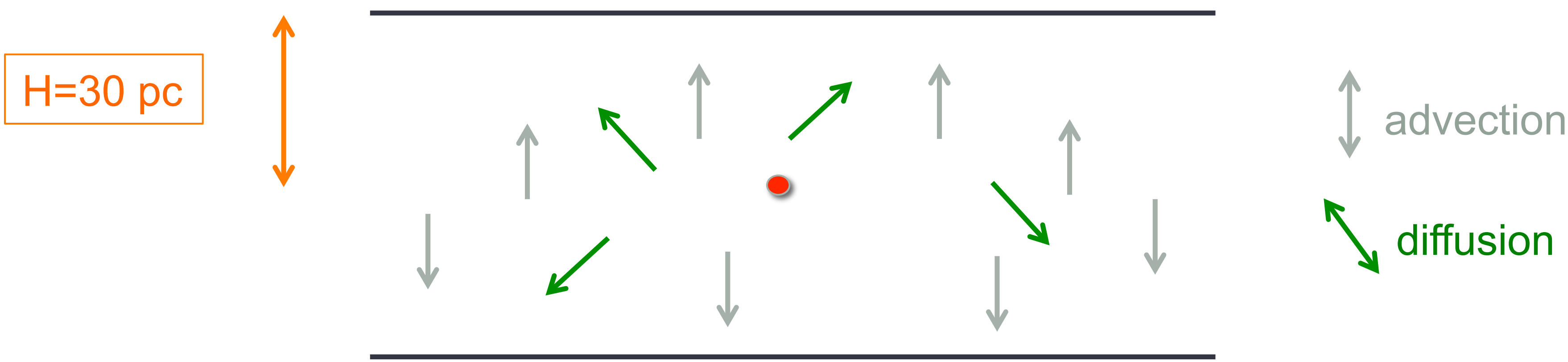
(yoast-hull (2014), Crocker et al (2011))

- v=1000 km/s
- **$\tau_{adv}$ = H/v** ➔ $\tau_{adv}$ =30 000 yrs

**Diffusion:**

- along the magnetic field lines
- $D=D_{10TeV}$ (E/10 TeV)$^{0.3}$
- **$D_{10TeV}=2\times10^{29}$ m$^2$s$^{-1}$**
- **$\tau_{diff}$ = H$^2$/D** ➔At 1 Tev, $\tau_{diff}$ =600 yrs

Diffusion more competitive than advection

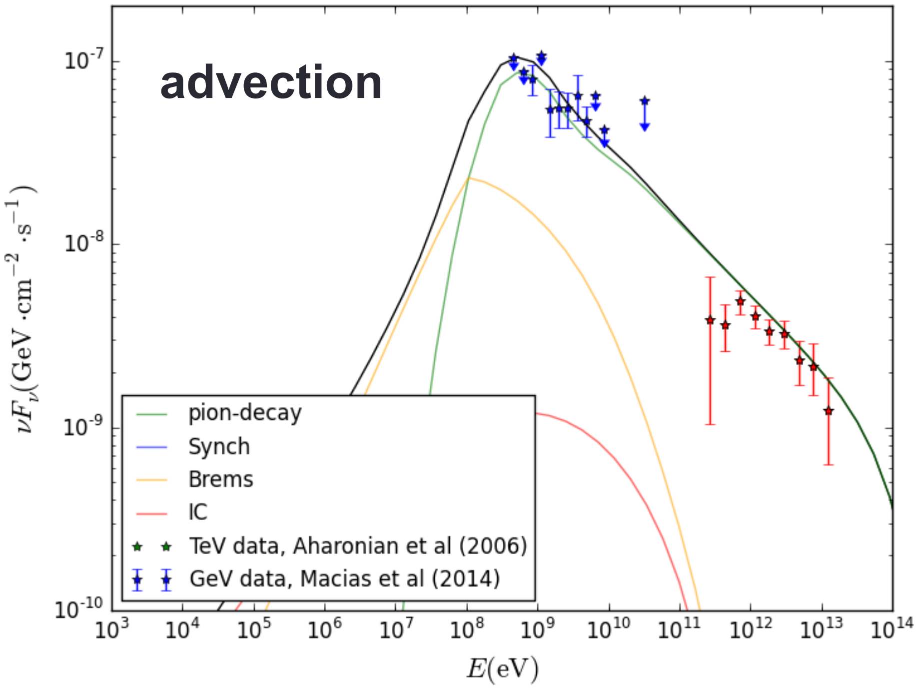


# Spectral energy distribution

GAMERA (Hahn, 2015) solves the following kinetic equation: $\frac{\delta N}{\delta t} = \frac{\delta}{\delta \gamma}(PN) - \frac{N}{\tau} + Q$

power-law injection: $Q=Q_0E^{-p}$

SED



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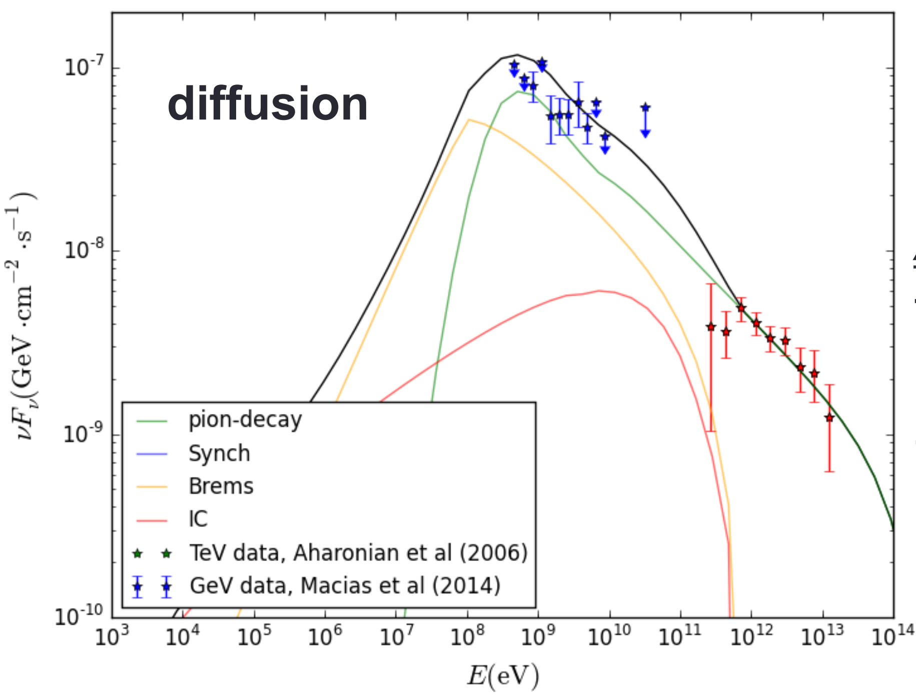


*Advection:*

$t_{SN}$=1e4 yrs

p=2.45

$\tau_{adv}$ =30 000 yrs

*Diffusion:*

$t_{SN}$= 2e3 yrs

p=2.15

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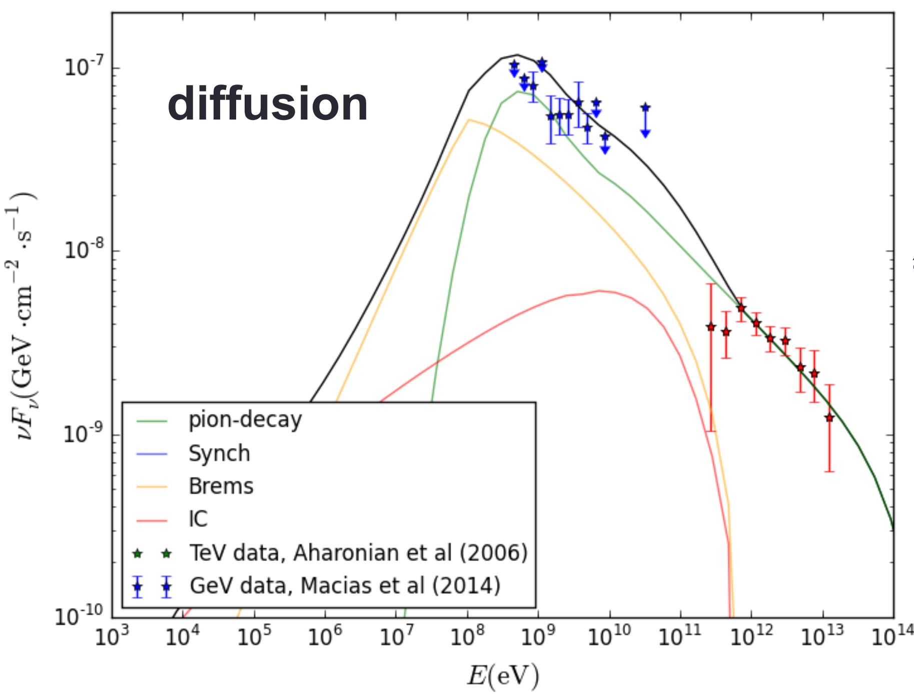


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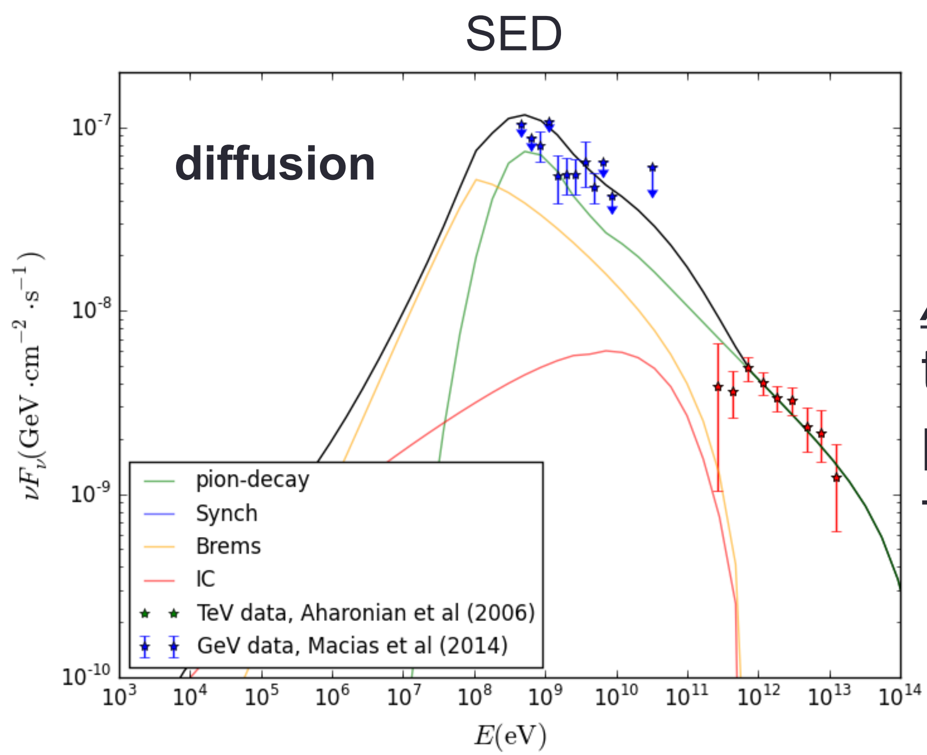


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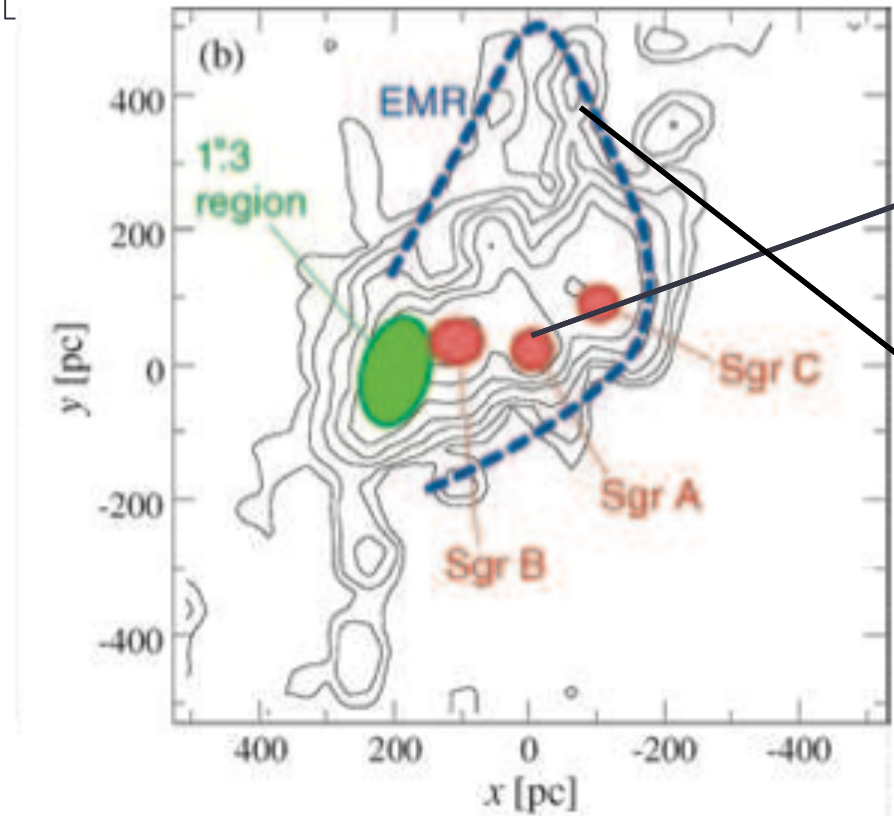
**$\tau_{diff} < t_{SN}$ : stationary state assumption incorrect**

# A simple time dependent 3D model of CR injection and gamma-ray production

# 3D matter distribution

**Sawada et al (2004)**

- No kinematical model
- ***OH/CO ratio carries information on the position of the gas along the line of sight relative to the continuum source***
- $M_{tot}=40\times10^6\ M_{sun}$, $(1.2\text{-}6.4\ 10^7\ M_{sun})$
- Exponential decay along the lattitude (Ferriere K et al. 2007)




Well known gas structure in the center

Larger spread along the line of sight

# CR diffusion

- ➢ <u>Injection:</u> Power law Q= $\mathbf{N_o E^{-2}}$

- ➢ <u>Propagation:</u> Transport equation

$D=D_{10TeV}\,(E/10\ \text{TeV})^{0.3}$, $\mathbf{D_{10TeV}=2\times10^{29}\ m^2s^{-1}}$ (interstellar medium value):

High diffusion coefficient ➔Neglecting the convection ➔ diffusion equation

$$\frac{\partial f}{\partial t} + \cancel{(\vec{u}\cdot\vec{\nabla})}f + \vec{\nabla}\vec{J} = Q$$

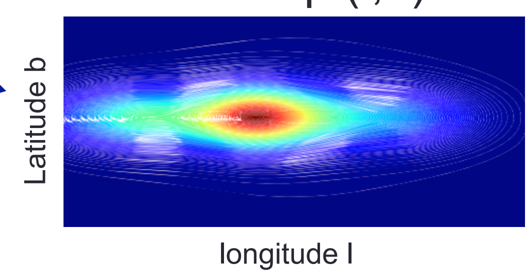
$$\vec{J} = -D\vec{\nabla}f$$

- Two solutions: impulsive (SNRs) and stationary (SgrA*)

- ➢ $E_{CR}$: 1 TeV to 1 PeV

Integration along the line of sight

2D map (l,b)



# Profile of the 3D emission and comparaison with H.E.S.S. data

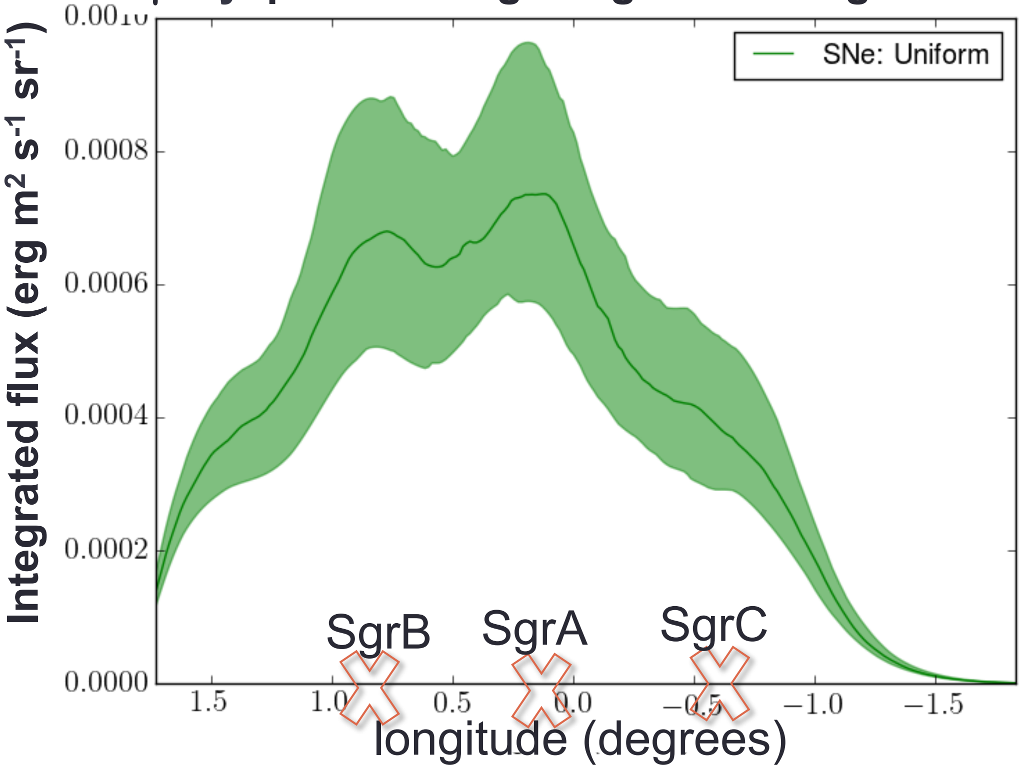
# Gamma ray profile for the SNRs filling the GC

- Recurrence time: 2500 years,
- Sources spatial distribution:

1)homogeneous cylinder

2)homogeneous cylinder + concentration of the SNs in the two clusters: Quintuplet and Central

**γ-ray profile along the galactic longitude**




- Profile highly dependent on each SNs spatial and temporal distribution
- Rather flat CR profile ➔ γ-ray emission peaked on the molecular clouds
- More realistic distribution of SNRs (with the two clusters): makes the distribution peaked toward the GC

***100 temporal and spatial distributions***

***Solid line: median of the γ ray profiles + spread around this median***

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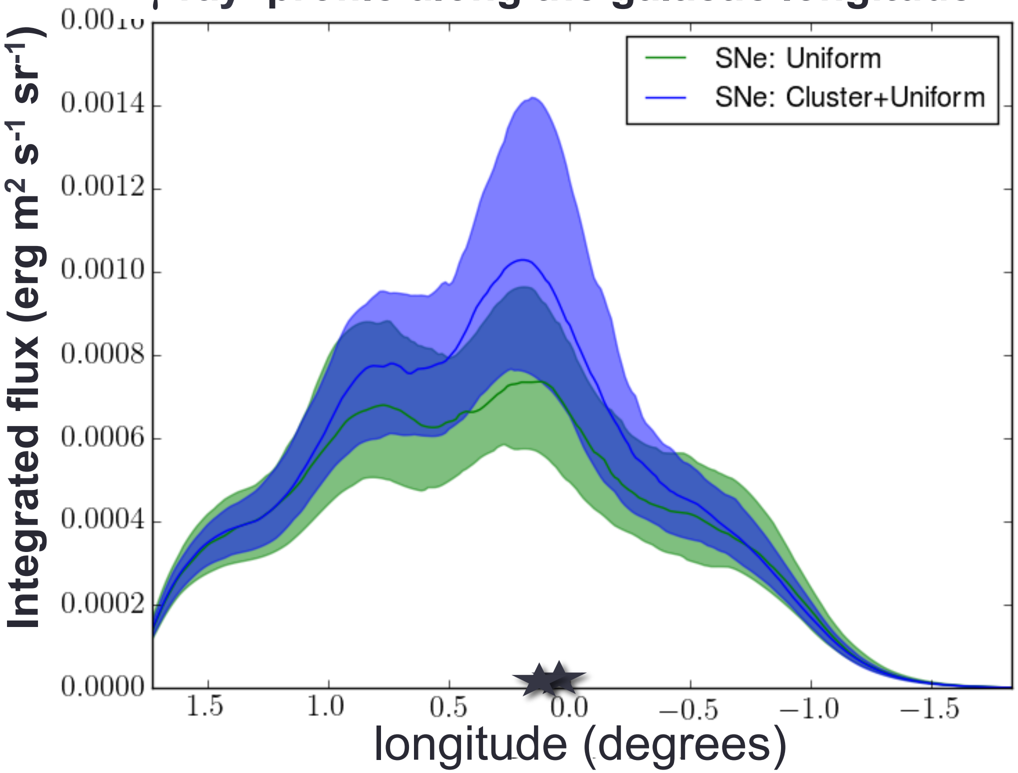


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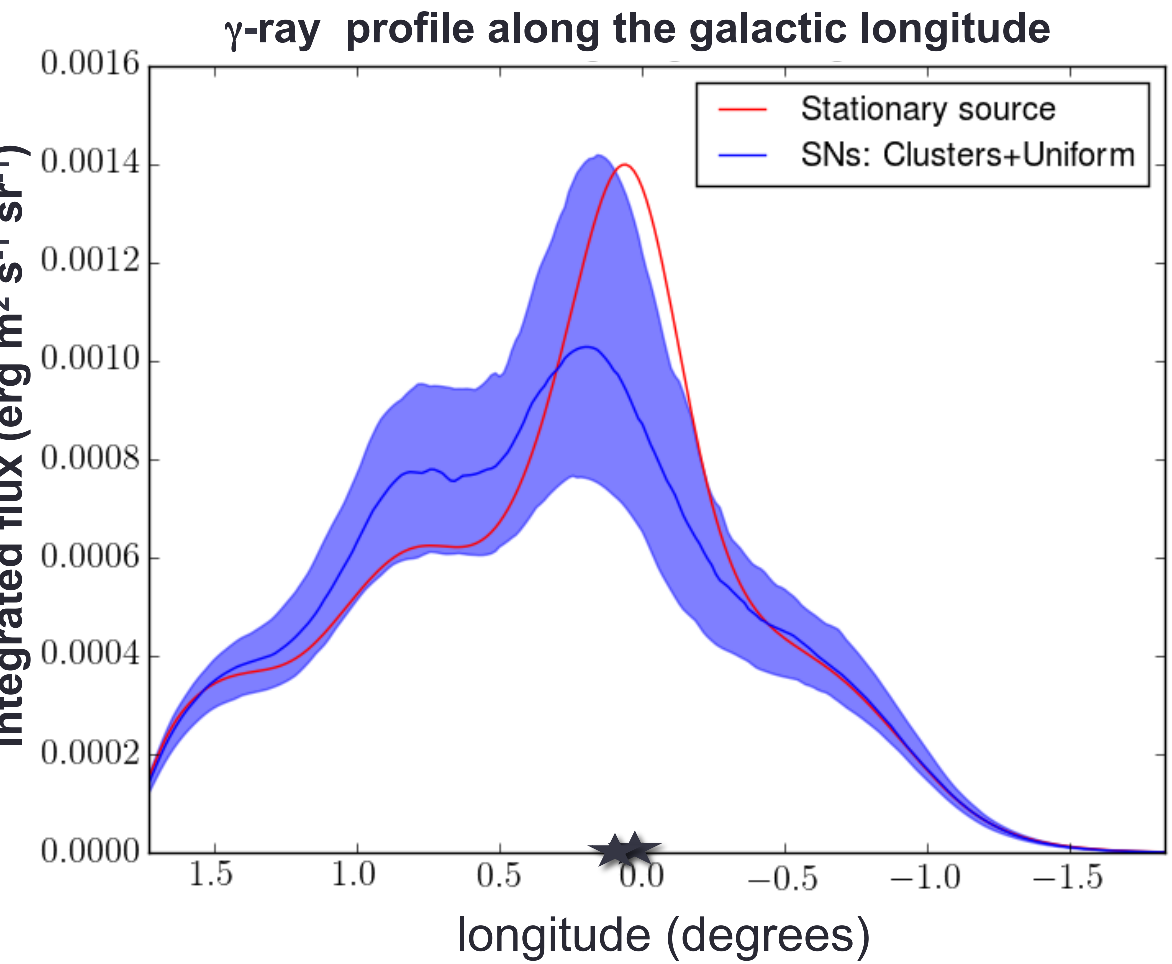
# γ-rays: spatial distribution




**Stationary source:**

- Profile more peaked toward the source
- Profile decreases at large distances due to a more spread ISM

**SNs filling the GC region**

- Taking into account the central clusters makes the distribution peaked toward the GC

***SNs:100 temporal and spatial distributions***

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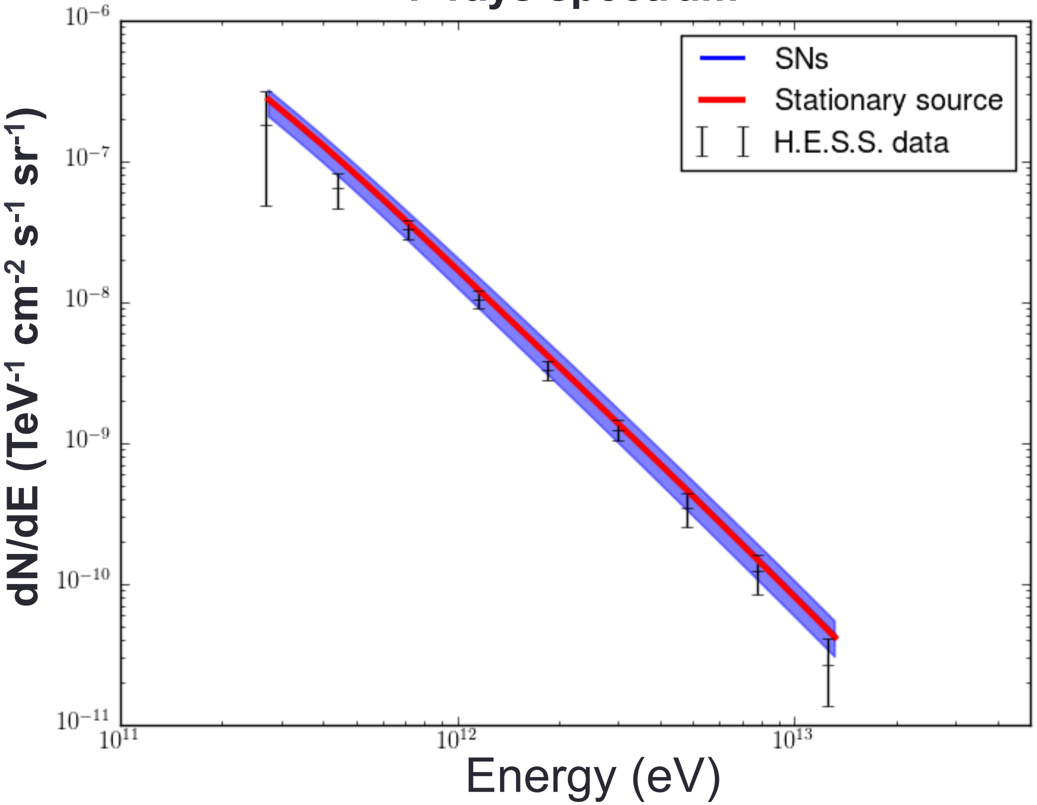
# γ-rays: spectral distribution

- Spectrum of the region: 0.8°< l < 0.8° and 0.3°< b < 0.3°
- Both models, stationary source at the center or SNRs, can reproduce the H.E.S.S. total flux

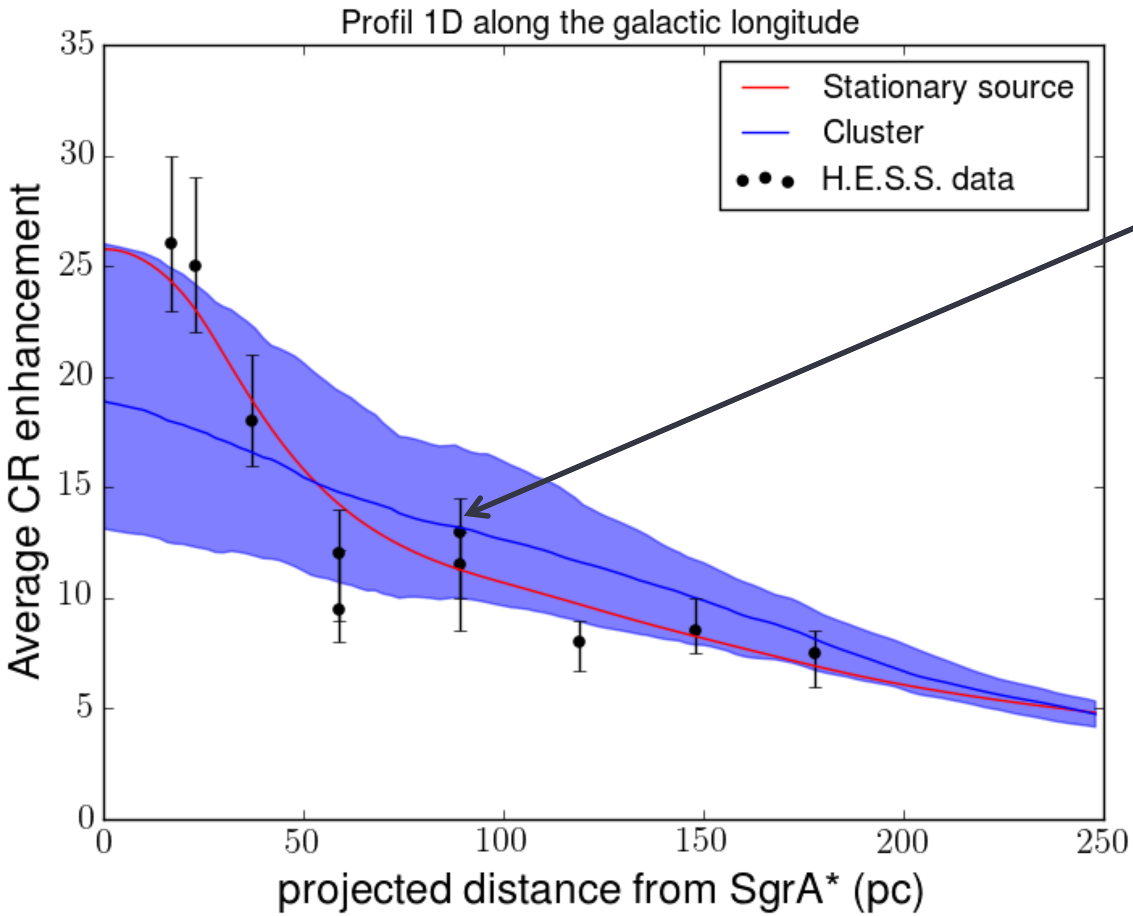
**ϒ-rays spectrum**

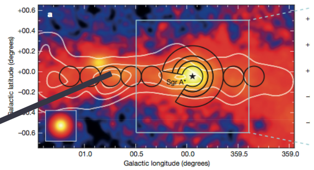



| Model Parameters | Values |
|---|---|
| Spectral index of the proton spectrum | 2 |
| Emin for the injected proton | 1 TeV |
| Emax for the injected proton | 1 PeV |
| Box size | 500 pc × 500 pc × 50 pc |
| Total mass | $4 \times 10^7\ M_\odot$ |
| Do (10 TeV) | $2 \times 10^{29}\ \mathrm{cm^2 s^{-1}}$ |
| Spectral index of the diffusion coefficient (d) | 0.3 |
| Power for CR acceleration | $1.5 \times 10^{38}\ \mathrm{erg\,s^{-1}}$ (Stationary source) |
| $E_{SN}$ | $10^{51}$ erg (Impulsive source) |
| Efficiency for CR acceleration | 2% (Impulsive source) |
| SN recurrence time | 2500 yrs (Impulsive source) |

***SNs:100 temporal and spatial distributions***
***Solid line: median of the γ ray profiles + spread around this median***

# CR density profile



**Credits: H.E.S.S. collaboration**
Abramowski **et al., 2016**

**SNs:**

- Produce also a CR density gradient
- Significant contribution of the SNRs at the center not to exclude
- At distance >50pc: both model can explain the data

***SNs:100 temporal and spatial distributions***
***Solid line: median of the γ ray profiles + spread around this median***

# Conclusion

- CR and γ-rays profile: peak toward the GC

- **SNRs contribution can not be neglected:**
  - High SN rate
  - Already re(over)produce the total flux
    -> SNR efficiency?
  - With a realistic spatial distribution -> gradient of CR density toward the center but seems difficult for the SNs to reproduce all the VHE emission at the center

- Single stationary accelerator at the center as proposed by Abramowski et al., 2016:
  - fit very well the H.E.S.S. data point (spectral and spatial distribution)

- ***Not possible to conclude that <u>SgrA</u>* is the only source responsible for all the VHE emission observed with H.E.S.S. in the GC knowing the significant contribution of the SNe***

# Backup slides

Advection

$$L_\gamma = 3.4\times10^{35}\, erg\, s^{-1} \left(\frac{\eta}{10\%}\right)\left(\frac{E_k}{10^{51} erg}\right)\left(\frac{\tau_{SN}}{10^4\ yrs}\right)^{-1}\left(\frac{H}{30\,pc}\right) \times \left(\frac{v}{10^3\ km/s}\right)^{-1}\left(\frac{n}{100\,cm^{-3}}\right)$$

Diffusion

$$L_\gamma(10TeV) = 3.2\times10^{35}\, erg\, s^{-1} \left(\frac{\eta}{10\%}\right)\left(\frac{E_k}{10^{51}\ erg}\right)\left(\frac{\tau_{SN}}{2\times10^3\ yrs}\right)^{-1} \times \left(\frac{H}{30\,pc}\right)^2\left(\frac{D_o}{2\times10^{29}\ cm^2 s{-1}}\right)^{-1}\left(\frac{n}{100\,cm^{-3}}\right)$$

Aharonian et al (2006): Lγ=3.5e35 erg $s^{-1}$

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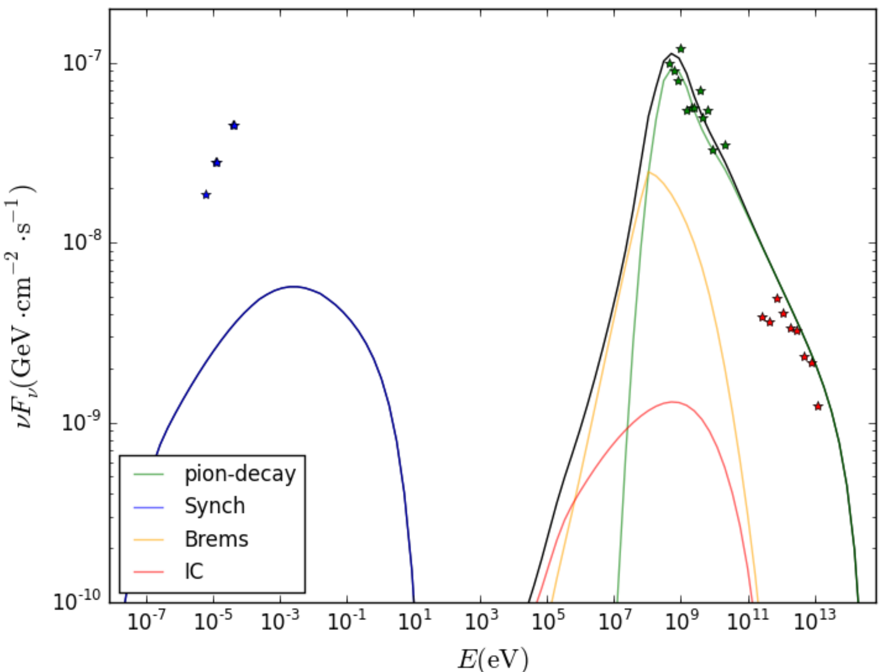


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