The Galactic Centre Above 10 TeV

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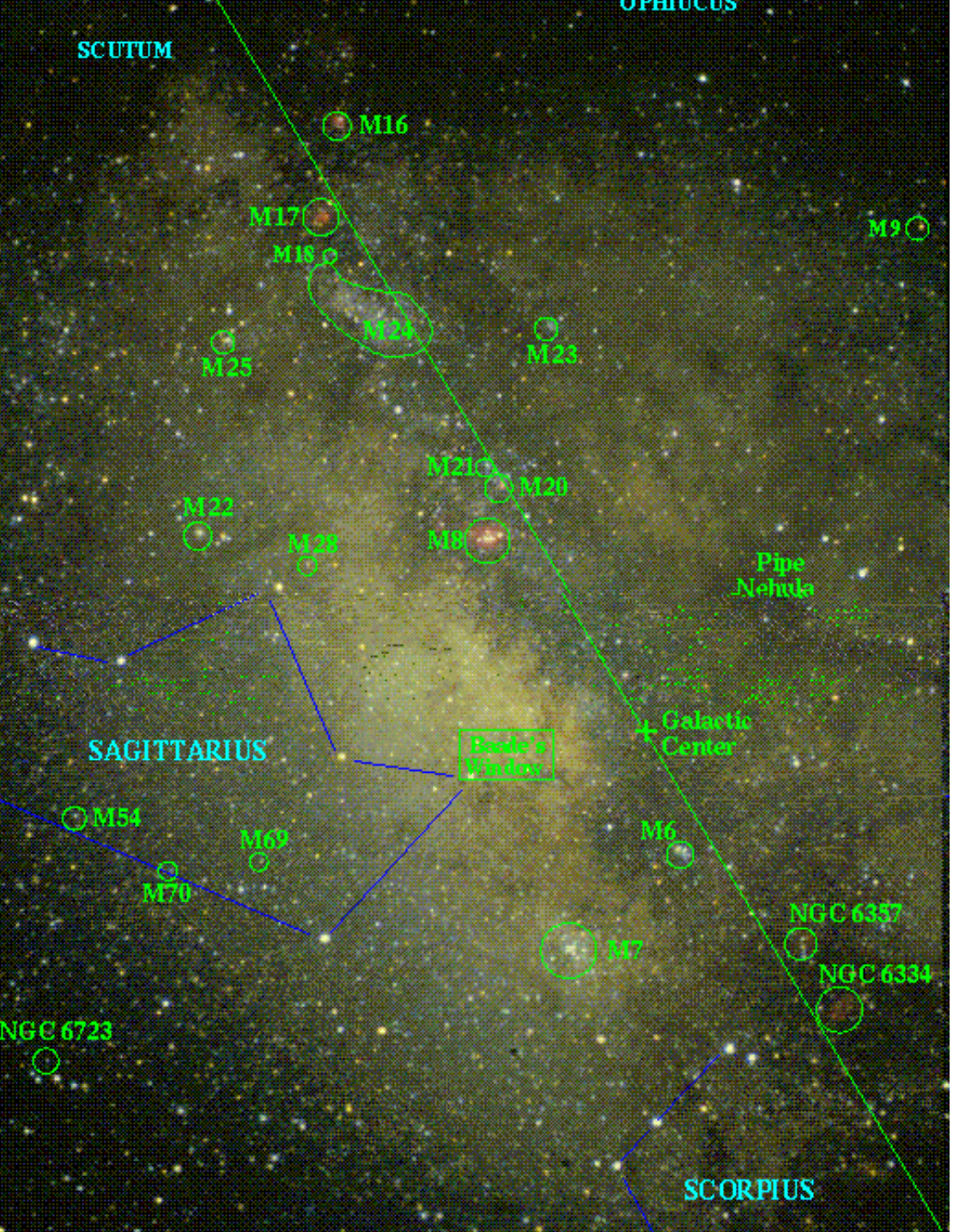
Slide attribution - just in case somebody is in the audience…

- I have stolen material from talks available on line by:

1. Dermer and Attoyan
2. Andrea Goldwurm
3. HESS Collaboration



GC at Optical Wavelengths

- We can observe the GC at radio, sub-millimeter, infrared, X-ray and γ-ray wavelengths

Credit: UCLA Galactic Center Group

GC - NIR

- From NIR monitoring with VLA and Keck of stars in close orbits (periods ~ few decades), it is now conclusively determined that:

1. the distance to the GC, R_0, is ~ 8 kpc
2. at the dynamical GC there is a 3.7 10^6 solar mass black hole $\Longrightarrow$

$$L_{Edd} = \frac{4\pi G M m_H}{\sigma_T} = 5\times10^{44}\left(\frac{M_{BH}}{4\times10^6 M_o}\right) ergs\ s^{-1}$$

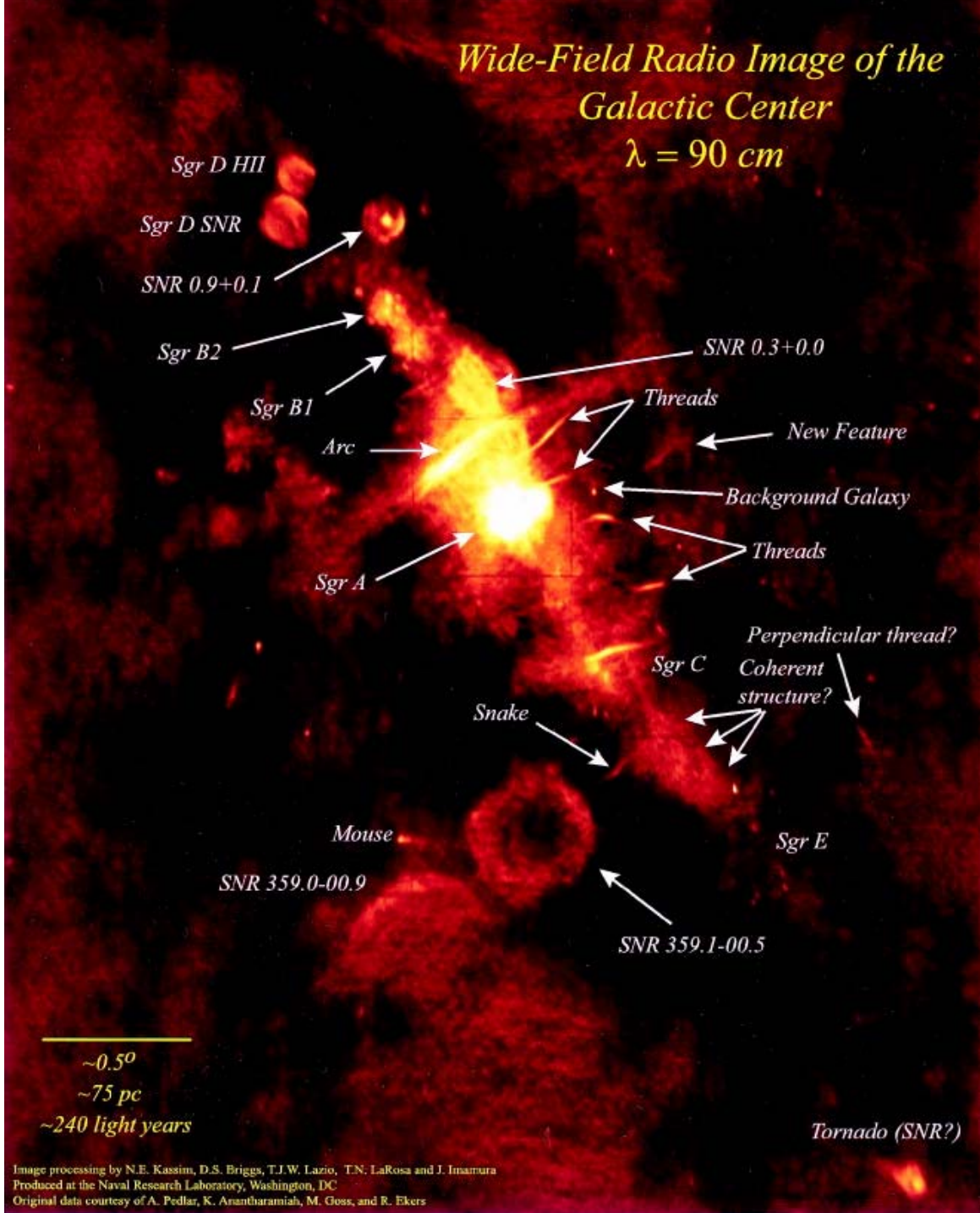
$$r_S = \frac{2GM}{c^2} = 1.2\times10^{12}\left(\frac{M_{BH}}{4\times10^6 M_o}\right) cm \approx 0.08\mathrm{AU}$$

Radio Zoom

Galactic Center Region at 90 cm ~ 300 pc

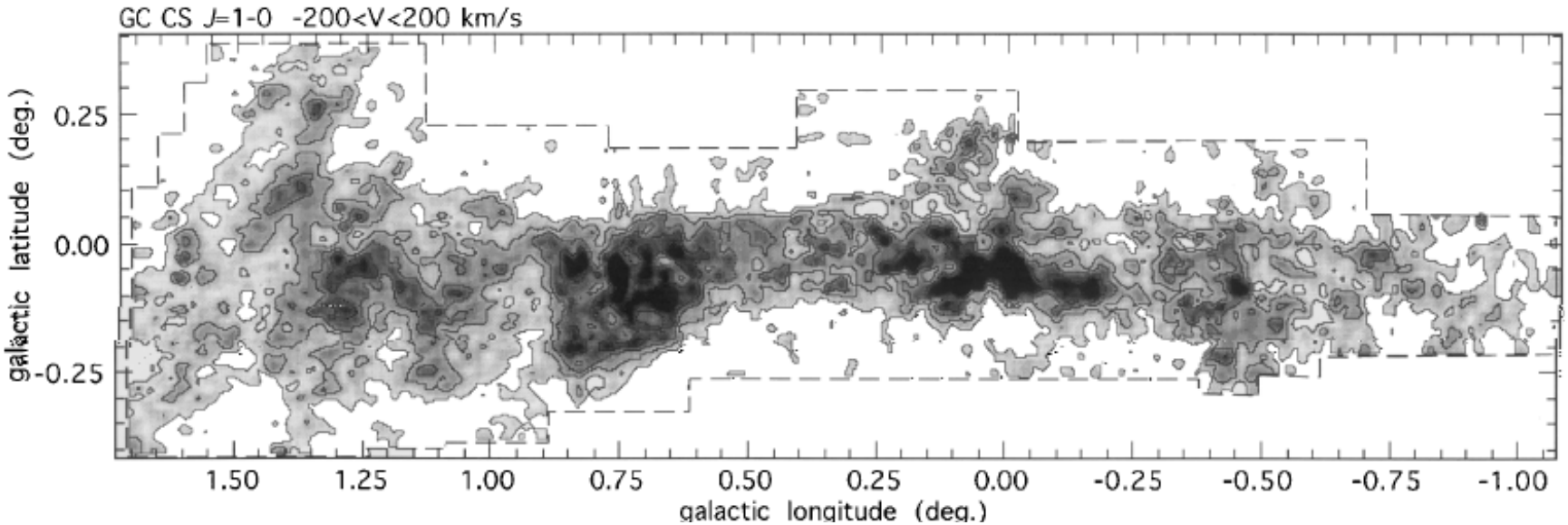
- Nonthermal radio-emitting filaments
- Large scale magnetic fields and relativistic electrons
- SNRs, HII regions
- Poloidal magnetic field within ~100 pc of nucleus
- Sgr A: compact radio sources at nucleus of Milky Way

LaRosa et al. (2000)



Credit: Dermer and Atoyan

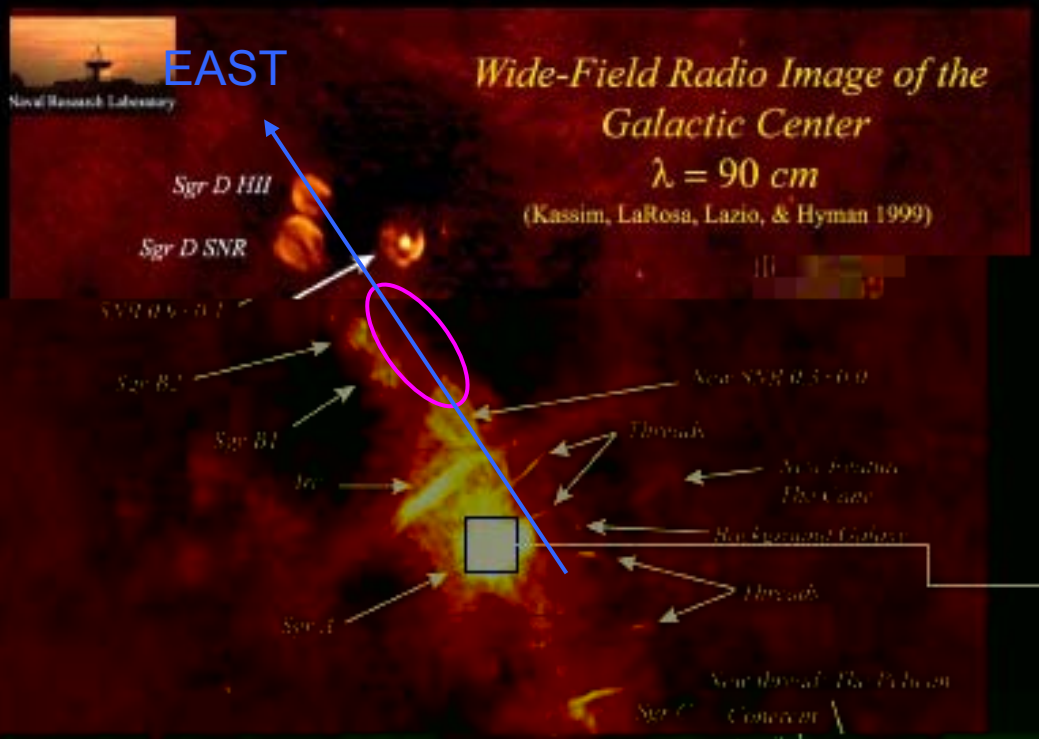
Gas Density Through GC



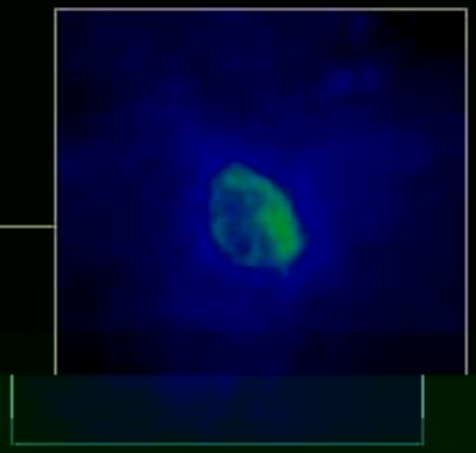
Tsuboi (1999)

- Molecular line observations trace gas density and show up central molecular zone of giant molecular cloud complexes bound in tight orbits (~100 pc) around Sgr A - these contain ~ 10% of the Galaxy's molecular gas (3-8 10^7 solar mass) in densities of $n_{H2} \sim 10^4$ cm^{-3}

The Galactic Centre



- The central 2° = 300 pc
  - GC Region
  - Central 50 pc = Sgr A



- Radio emission of the Sgr A complex is dominated by the SNR Sgr A East

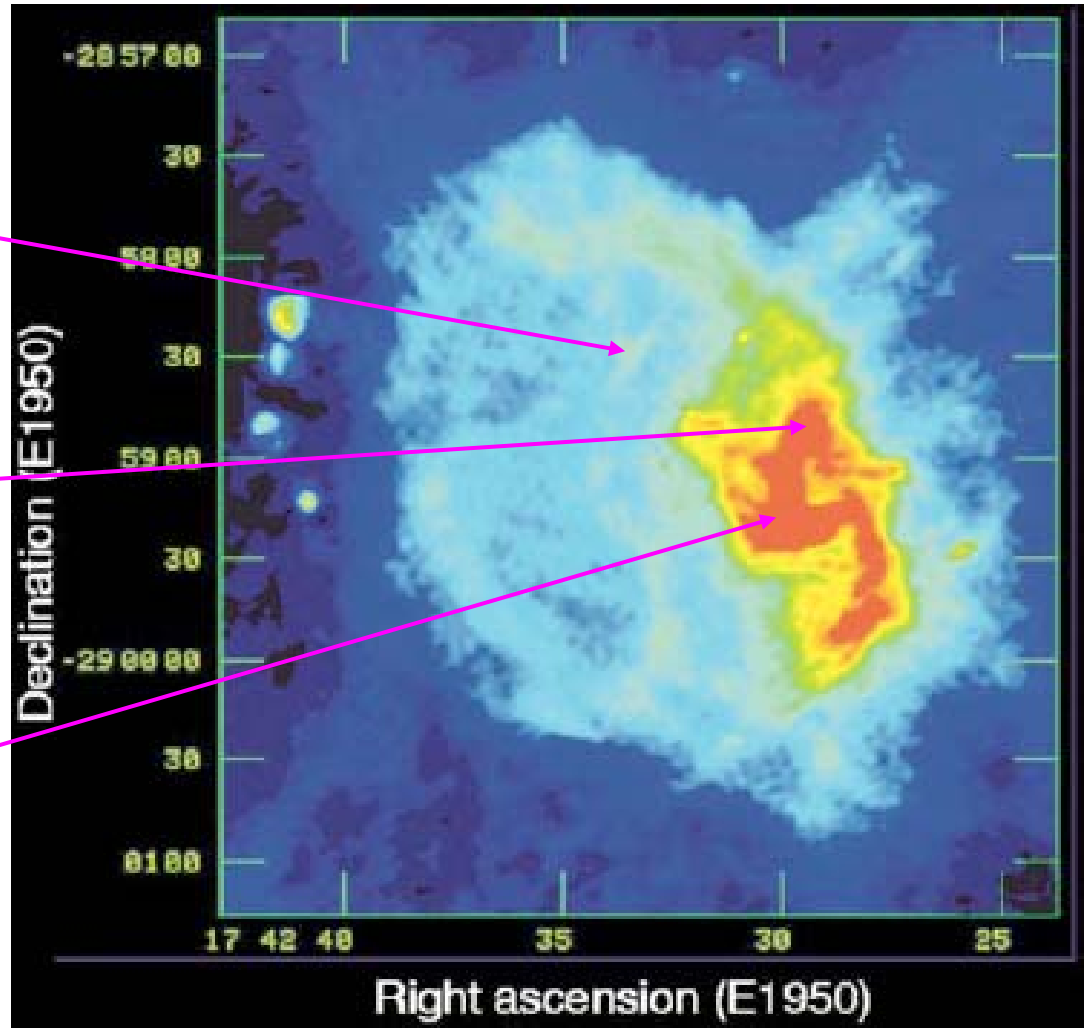
Credit: HESS Collaboration

Sgr A Resolved: Radio Features of Inner 10 pc (4′×3′, or 9.3×7 pc)

Sgr A East (blue): extremely energetic (≈10^{52} ergs) region occurring ≈ 50,000 yrs ago from chain of SNRs, a GRB, or star swallowed by BH. Diffuse X-ray emission.

Sgr A West (red): Gas and dust streamers ionized by stars and spiraling around the Galactic center, possibly feeding the nucleus.

Sgr A*: A bright compact radio source at intersection of the arms of the Sgr A West, coincident with Gal dynamical centre



6 cm VLA radio of Sgr A East and Sgr A West

(Yusef-Zadeh, Melia, & Wandle 2000)

Other components:

1. cluster of evolved and young stars
2. dusty molecular ring (circumnuclear disk)
3. ionized gas streamers

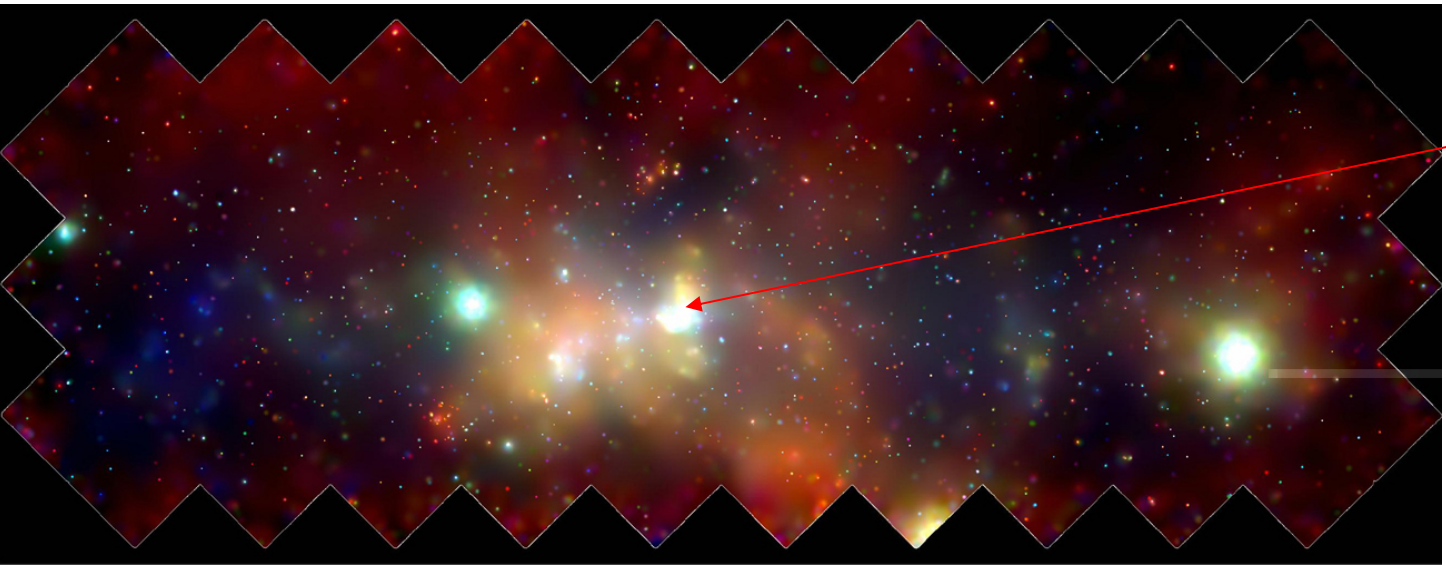
Credit: Dermer and Atoyan

Sgr A* in Radio

- GC contains bright radio source, Sgr A*, first identified in the 1970s and coincident with dynamical centre of Galaxy…~ 1 Jy and variable (tens of days)
- @ 3mm size: $\lesssim$ 1 AU ~ 20 R_{Sch}…emission associated with accretion disk

GC in X-rays

Chandra GC Survey



GC in X-rays:

- Point sources: few bright (X-ray Binaries), several transients, many weak PS
- Complex diffuse emission (continuum and lines) peaking towards Sgr A but with a structured 6.4 keV component associated with MCs (fluorescence due to a bright X-ray flare of Sgr A*?)
- Shell SNR (**Sgr A East**), Plerion SNR (composite G09+01), star clusters (Arches), Non-Thermal-Filaments, …

Sgr A* in X-rays

- In soft and hard X-rays, Sgr A* is observed to have two states:

1. quiescent: X-ray emission from an extended region, 0.6 arcseconds, or 7×10^{16} cm $\approx 10^5\ r_S$ with

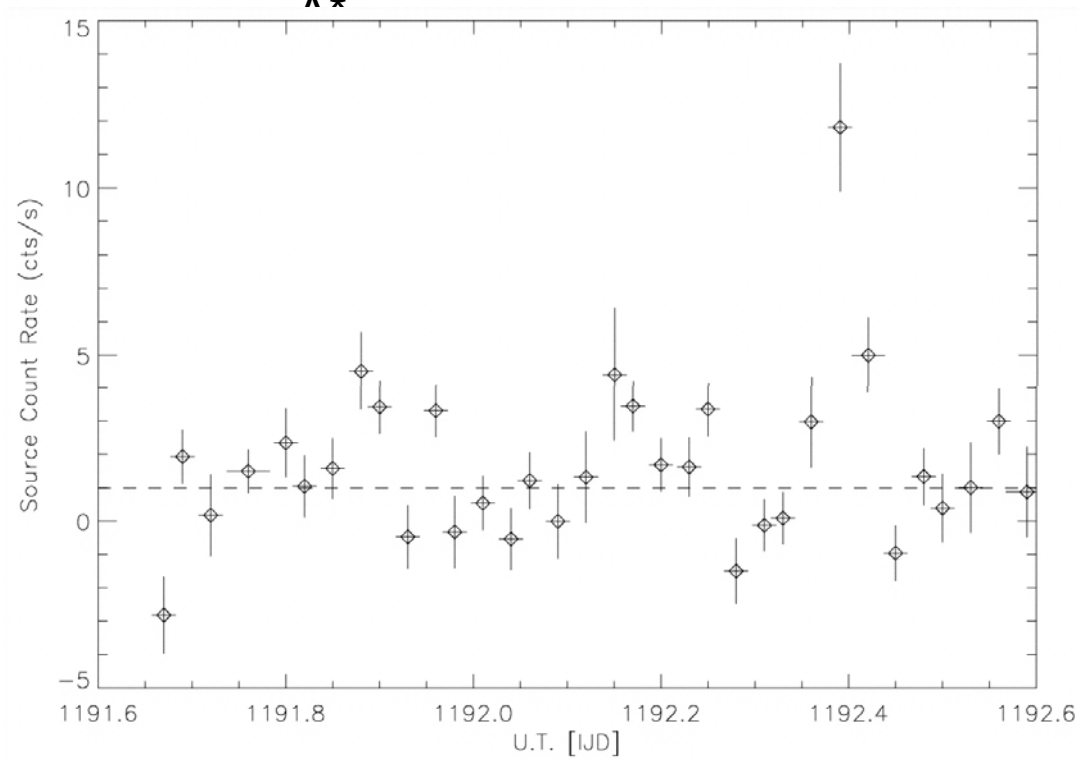
$$L \approx \text{few} \times 10^{33} \text{ ergs s}^{-1}$$

2. X-ray flares: in both soft and hard X-rays – rise times of 10s of minutes $\Longrightarrow$ emission from inner 10's of r_S

Credit: Dermer and Atoyan

Flaring Hard X-ray Emission from the Direction of Sgr A*

INTEGRAL observations of flaring 20-40 keV emission within 0.9′ of Sgr A*



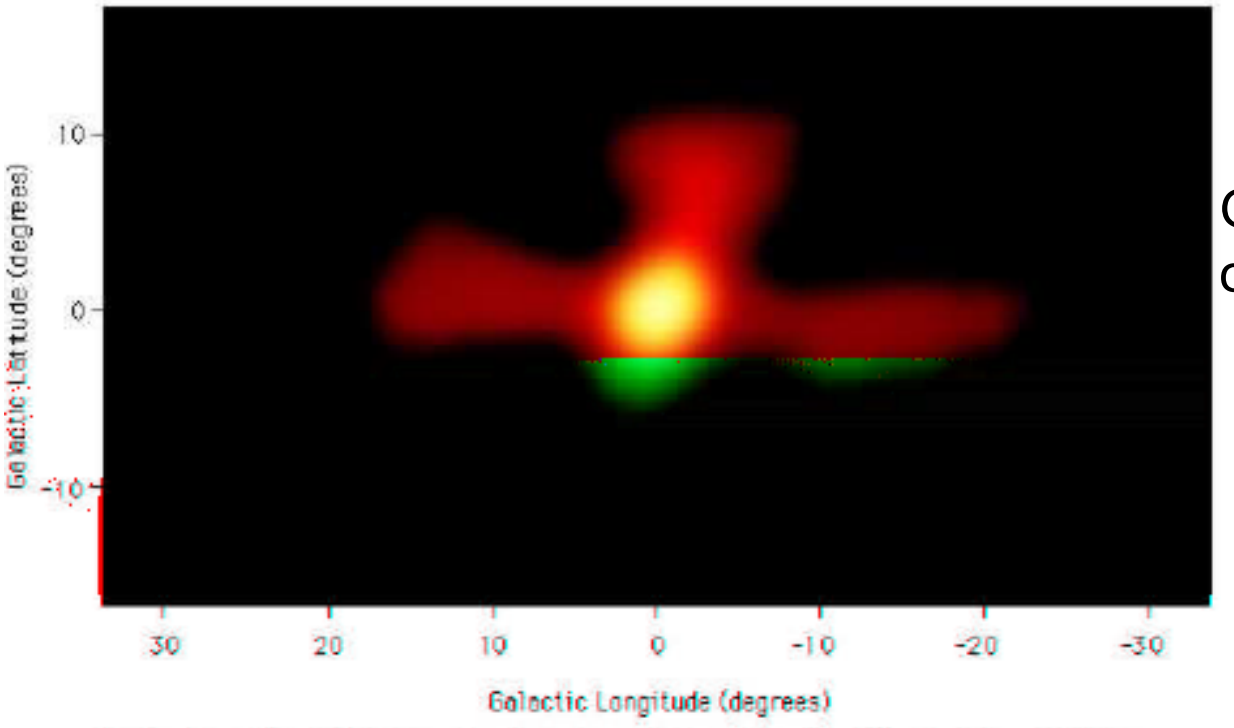
Flare lasts < 40 minutes

$$1\, r_s = 40\, lt - s$$

Bélanger et al. (2004)

Soft Gamma-Rays

- 511 keV emission detected since 1970s
- Emission traces Galactic bulge
- Point-like contribution to bulge is neither excluded or confirmed

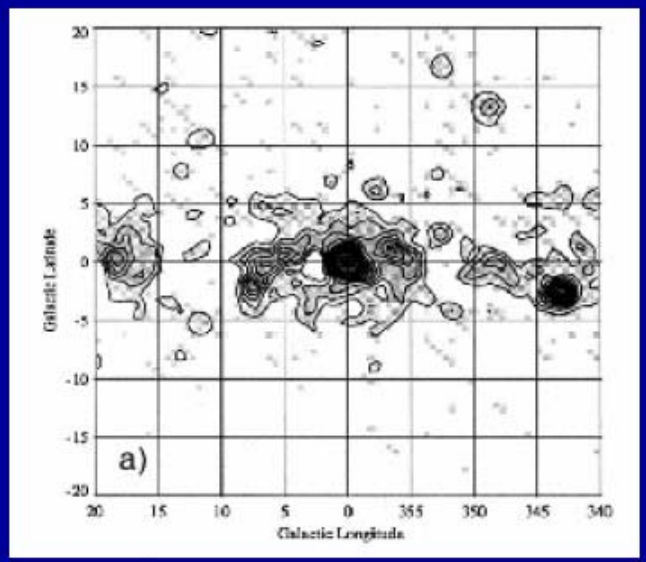


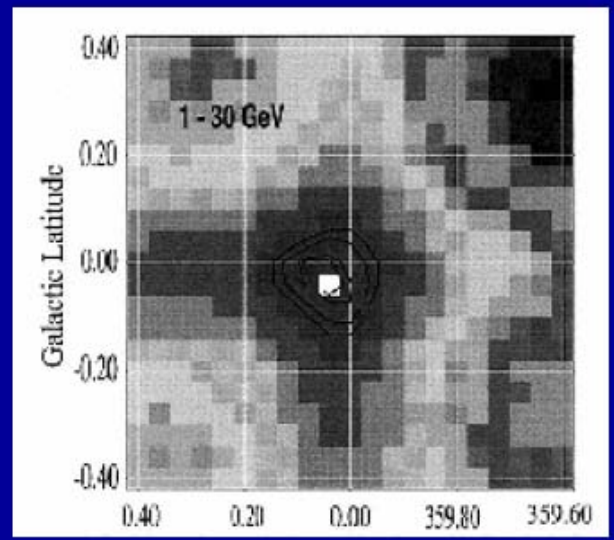
GRO/OSSE 511 keV observations

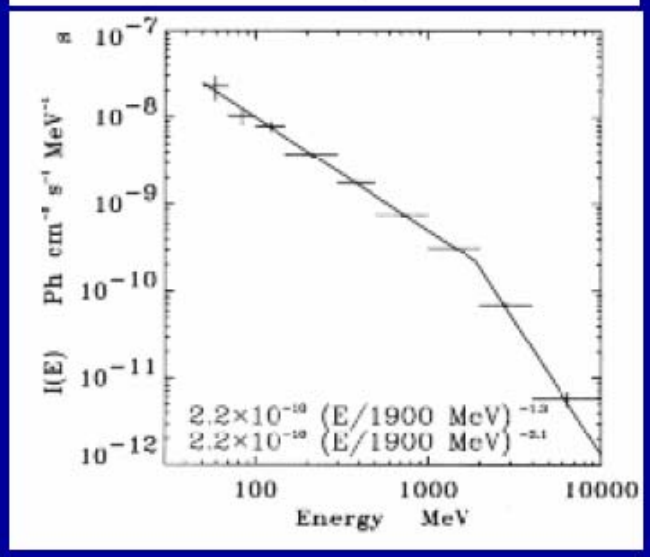
History of HE Detections of GC

- HE γ-ray emission (30 MeV+) detected since 1970s (Cos-B, SAS-2)
- EGRET detected a source (3 EG J1746-2851) marginally consistent with the position of Sgr A*
- Later analysis (Dingus and Hooper, Pohl) showed that this source is not coincident with Sgr A*

GRO/EGRET Source at the GC







- 2EG J1746-2852 ~ point source at ~ 0.2° from Sgr A* but compatible with it
- L (>100 MeV) = 2.2 10^{37} erg s^{-1}
- Broken power-law (α_1= 1.3 α_2 = 3.1 E_b = 1900 MeV)
- 3EG catalogue : smaller error box (0.12°) less compatible with Sgr A but .. confused region !

(Mayer-Hasselwander et al 98, Hartman et al 99)

Credit: Goldwurm

EGRET GC Source

- The identity of the EGRET source cannot be determined observationally because of the number of HE, candidate sources within PSF
- Lesson: meed excellent angular resolution to pick between candidate source for HE emission in this very crowded region

~TeV Observations of GC

- In 2004, definite detections of the GC at ~TeV energy was reported by:

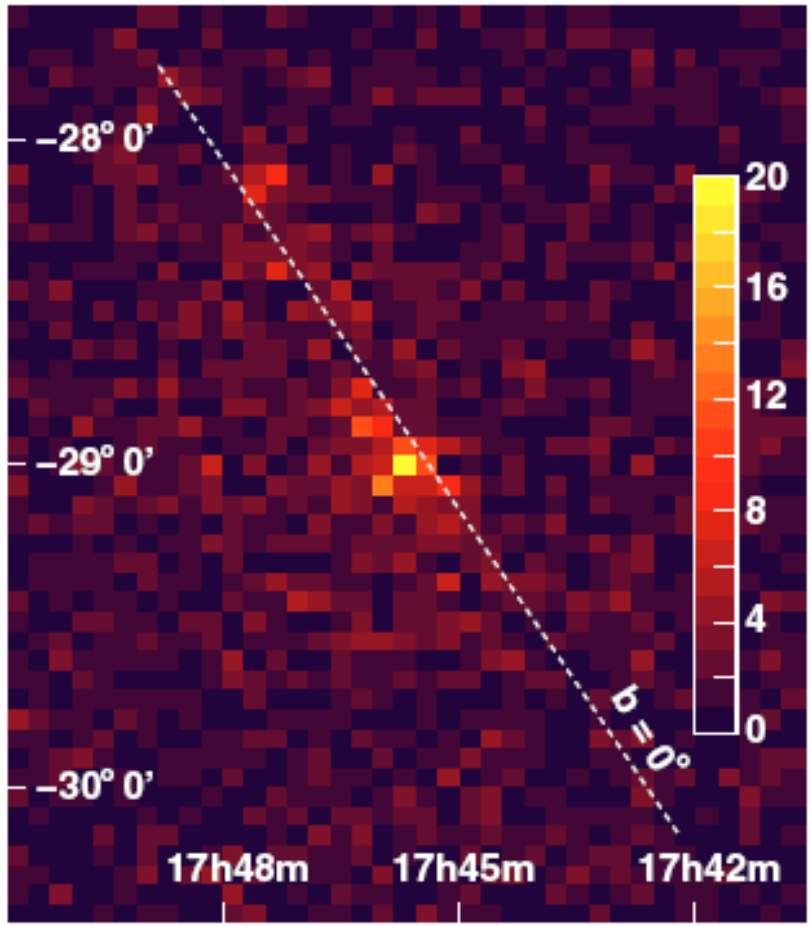
1. CANGAROO (Tsuchiya et al. 2004)
2. Whipple (Kosack et al. 2004)
3. HESS (Aharonian et al. 2004)

- Observation of GC with MAGIC has since been reported (Albert et al. 2006)

HESS Observation of GC

Aharonian et al. 2004

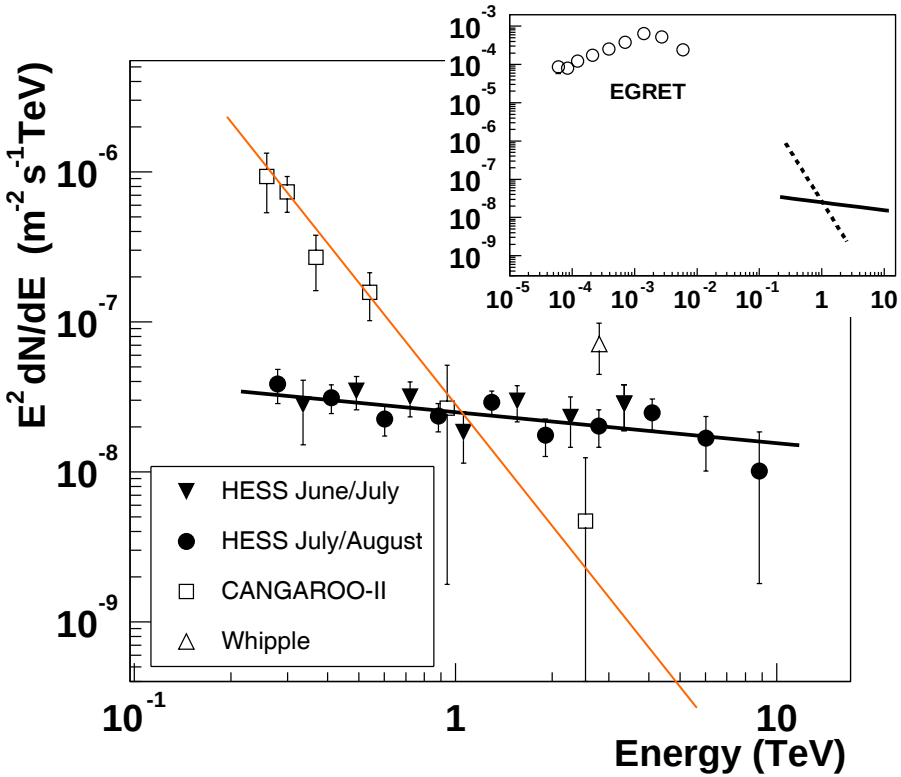
- Consistent with point source, σ < 3 arcmin ~ 7 pc
- Located within 1 arcmin of Sgr A* -- also consistent with Sgr A East SNR



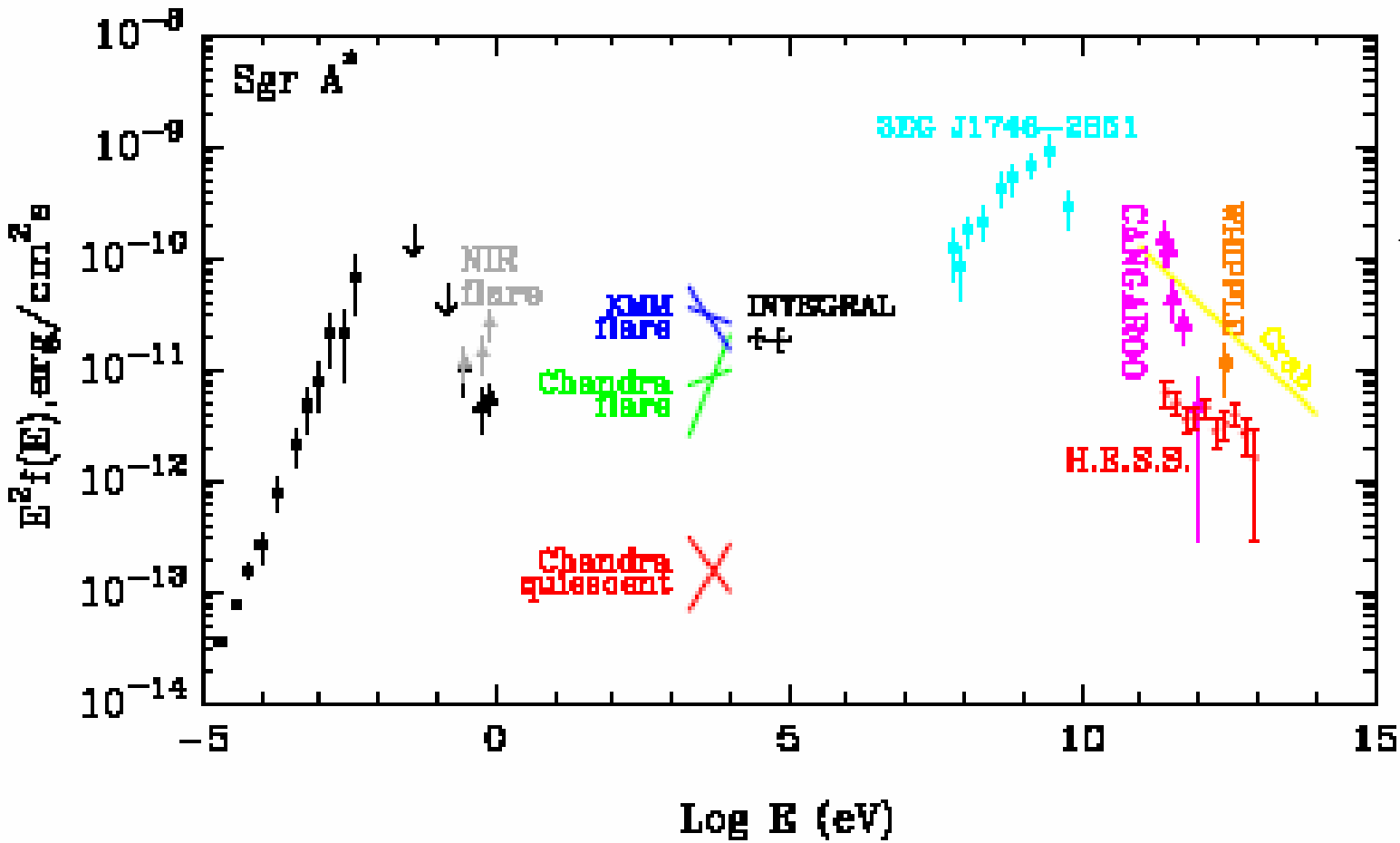
HESS Observation of GC contd

- Hard spectrum:

  -2.25 ± 0.04(stat.) ± 0.10(syst.)
- This spectrum confirmed by MAGIC which found -2.2 ± 0.2
- Data consistent with steady source



Multiwavelength Observations of GC: Synthesis from Aharonian and Neronov (2004)



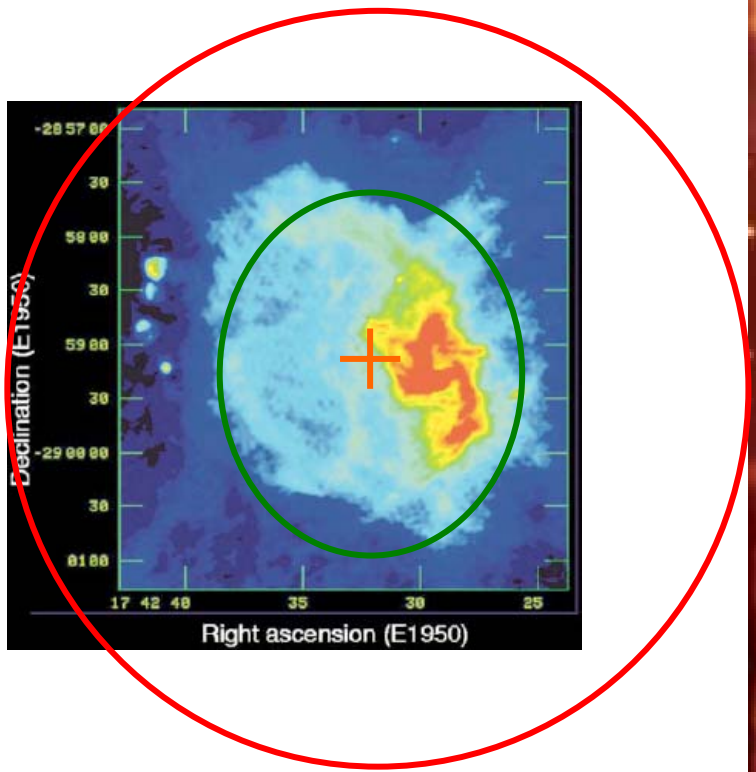
$\sim 10^{36}$ ergs s^{-1}

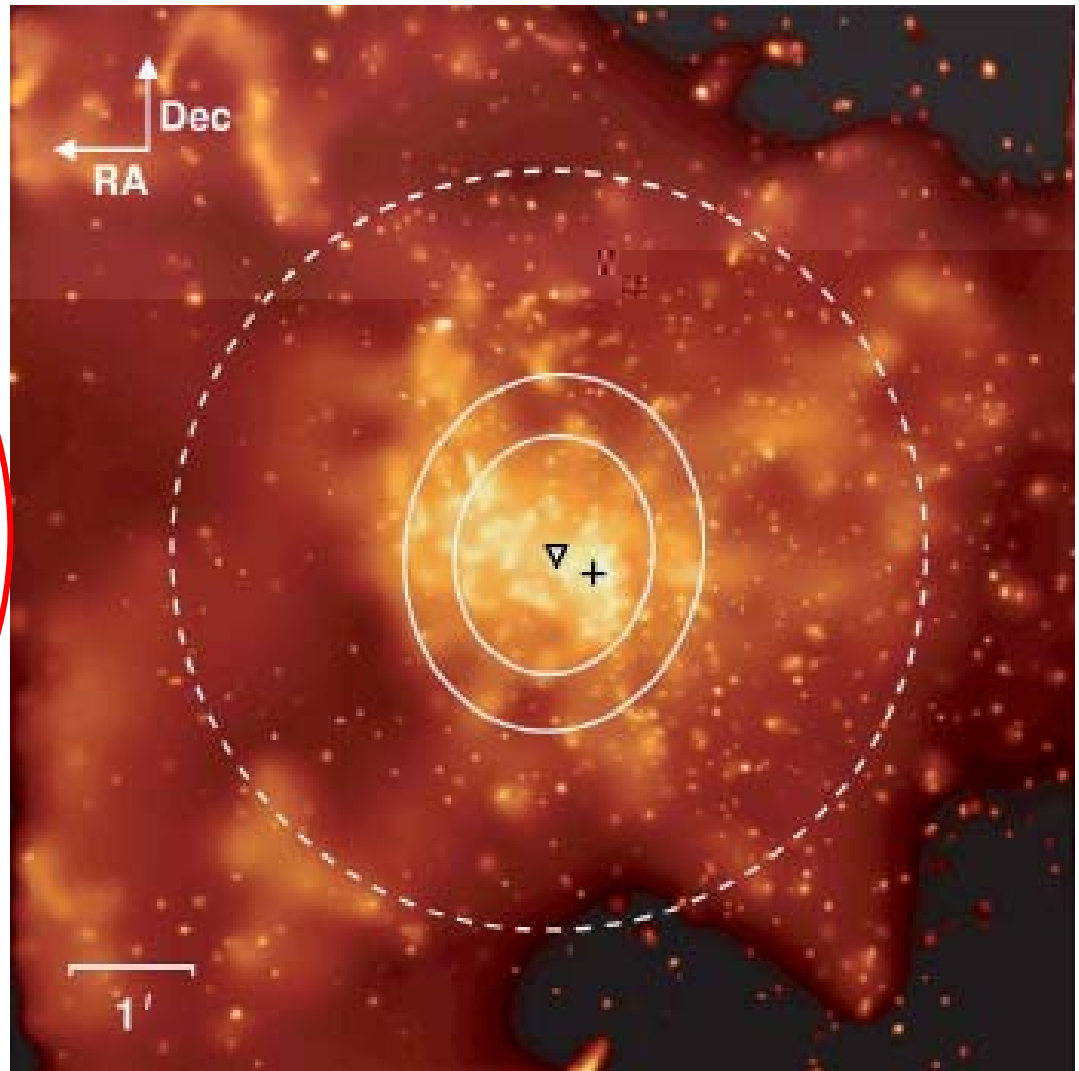
Note that Sgr A* is underluminous at all wavelengths by many orders of magnitude: $L_{SgrA^*} \sim 3\times10^{-10}\ L_{Edd}$

What is the TeV Source at the GC?

Many ideas – overview presented in Aharonian and Neronov (2005)

Source Localization





Dark Matter Annihilation

- Seems to be disfavoured: a flat spectrum (as observed) extending up to $\gtrsim$ 20 TeV is difficult to reconcile with DM models which tend to turn-over below 10 TeV (given masses of DM candidates) – see
- A sub-dominant contribution cannot be ruled out however:

Hadronic Models

- General comment: efficiency of process is determined by ratio of radiative loss time to diffusive/advective escape time – diffusion highly uncertain in GC environment (A&N 2005)
- p's might be accelerated in/at

1. Sgr A*:
   i. shocks in the accretion disk
   ii. stochastically accelerated (2nd order Fermi) in MHD turbulence (Liu et al. 2004)
   iii. in jet from tidally-disrupted star (Lu et al. 2006)
2. shocks associated with Sgr A East SNR (Crocker et al. 2005)

γ's from pp Collisions

p's might interact

i. close to the BH horizon (inefficient: A&N 2005)

ii. in dense gas at larger radii (A&N 2005, Ballantyne et al. 2006) – out to a few pc

γ's from pγ Collisions

- Requires p's accelerated to 10^{18} eV+ in shocks/high B fields at ~10 r_s (A&N 2005), interact with IR γ's here
- VHE γ's + 2ndary e's cascade in IR γ background/B field down to ~TeV
- inefficient

Sample of Leptonic Scenarios

- Generically invoke HE e's IC scattering IR γ's with e's accelerated by/at
- strong, ordered **E**/**B** fields close to BH horizon (A&N 2005)
- winds associated with winds off massive stars (Quataert & Loeb 2005)
- the termination shock of the subrelativistic wind from the central part of the advection-dominated accretion flow onto the GC black hole – cf. pulsar wind nebulae (Atoyan & Dermer 2005)

Utility of Higher Energy GC Observations – See Cut-off?

- Phenomenologically, no evidence for cut-off in HESS spectrum
- Generically, leptonic models are pushed to accelerate electrons to required energy because of synchrotron losses
- Need to exercise care in interpreting any observed cut-off at 10 TeV+ energies…

γ-γ Attenuation

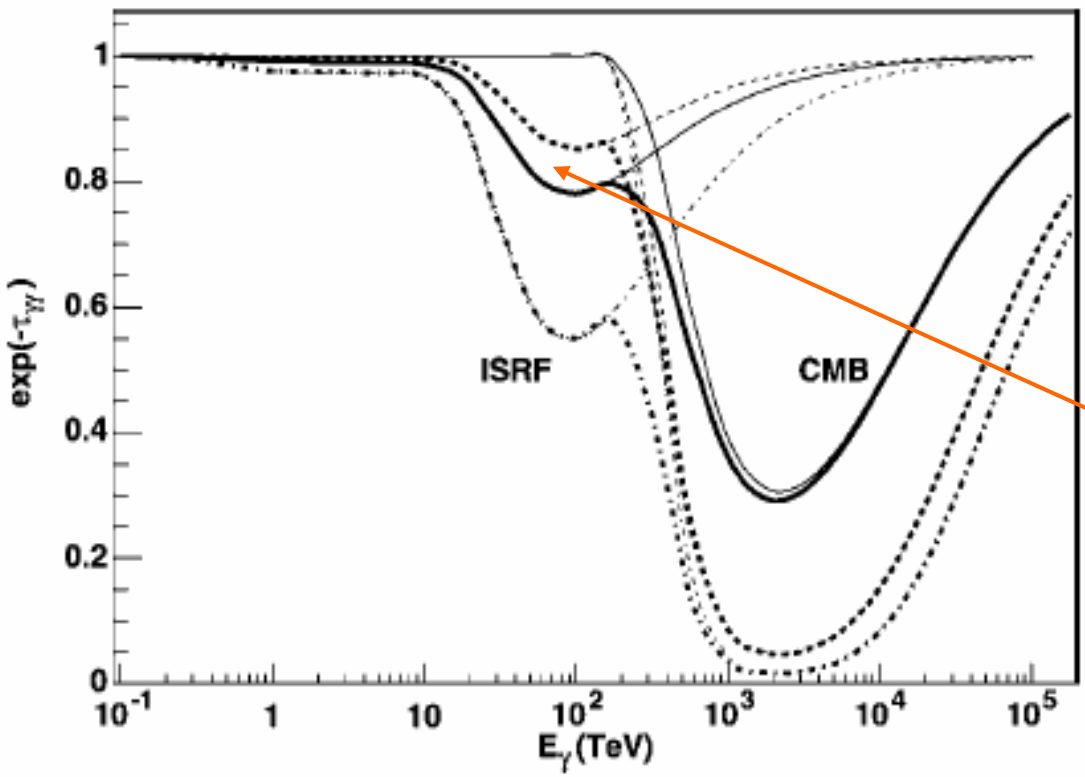


FIG. 3.—Transmittance of VHE γ-rays as a function of γ-ray energy. *Solid lines*, $(R, z, \alpha) = (0$ kpc, 0 kpc, $0^\circ)$ $(L = 8.5$ kpc); *dashed lines*, $(R, z, \alpha) = (20$ kpc, 0 kpc, $90^\circ)$ $(L = 21.8$ kpc); *dash-dotted lines*, $(R, z, \alpha) = (20$ kpc, 0 kpc, $180^\circ)$ $(L = 28.5$ kpc). Thick lines give the total transmittance curve including the ISRF and CMB. The leftmost thin lines give the transmittance for the ISRF only, and the rightmost thin lines that for the CMB only.

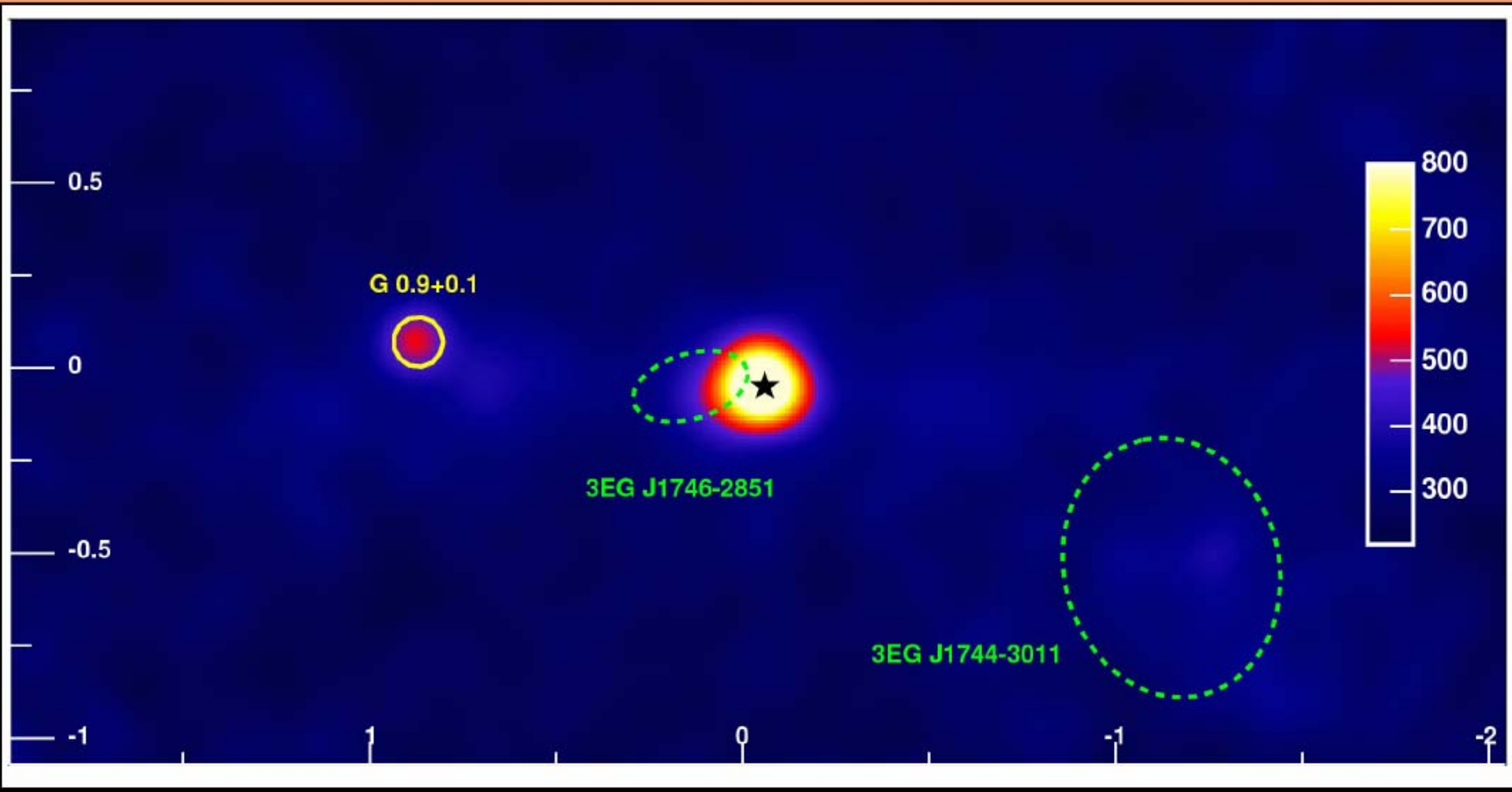
Moskalenko, Porter and Strong

Getting significant attenuation at $\gtrsim 40$ TeV for GC γ's

Need to somehow distinguish between intrinsic and absorption cut-offs

Diffuse Emission

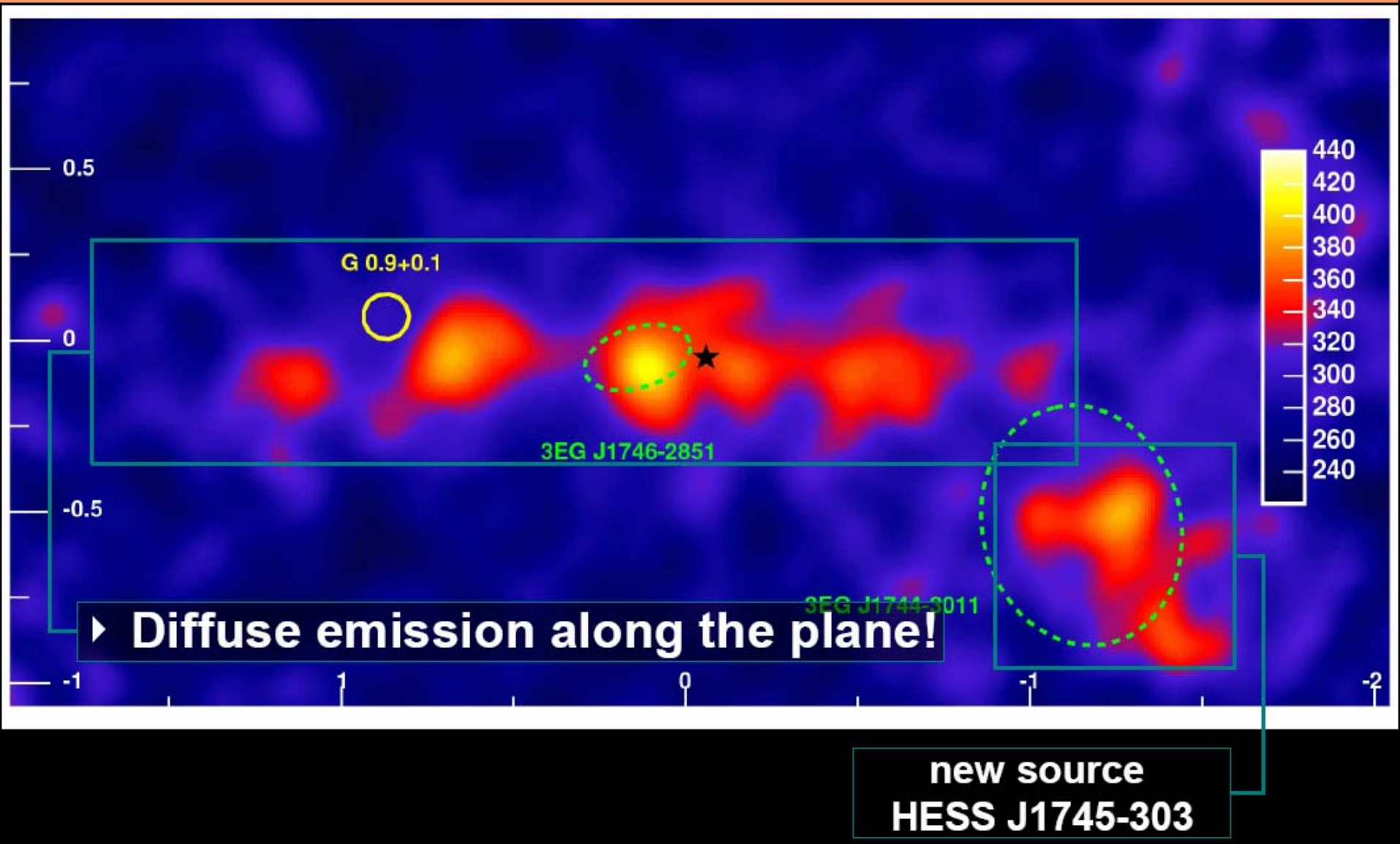
Diffuse γs in H.E.S.S. data?



- 50 hour H.E.S.S. Observation of GC in 2005
- Need to subtract the two bright sources

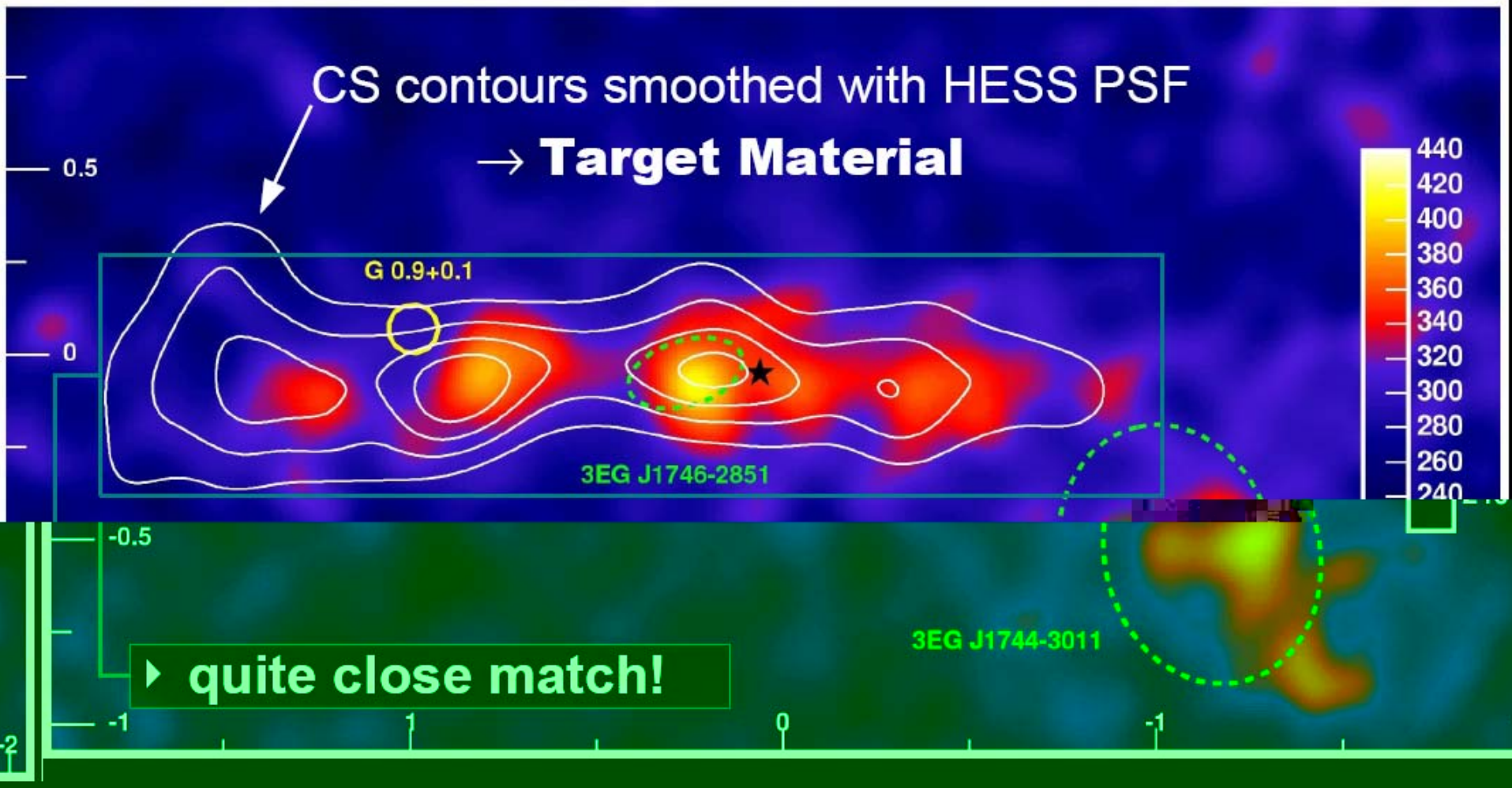
Credit: HESS Collab

Residuals after source subtraction



Credit: HESS Collab

CS contours over H.E.S.S. map



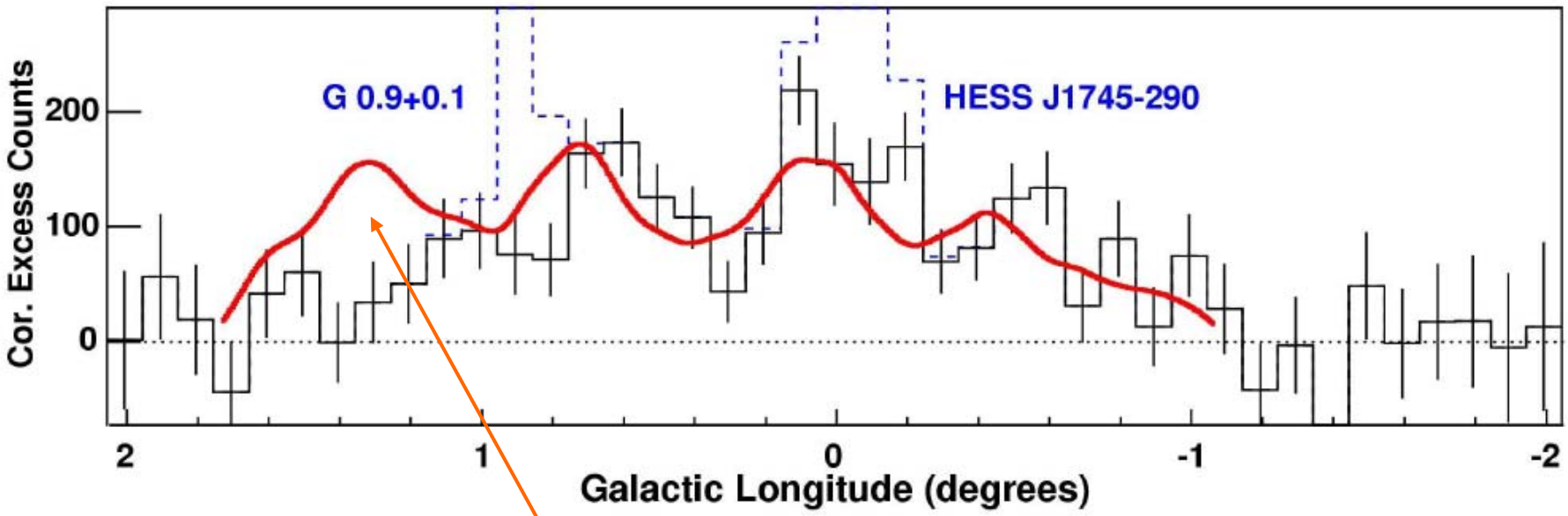
- quite close match!

Credit: HESS Collab

Explaining Emission

- HESS collaboration, noting correlation between γ-rays and molecular density, posit hadronic collisions as source of emission – implies 10^{50} ergs in CR hadrons through the CMZ
- Yusef-Zadeh et al. noting independent correlation between Fe Kα line emission and γ-rays suggest origin in IC scattering of IR background by primary electrons

Longitudinal Slice



- Reasonable agreement overall but
  - Deficit around l = 1.3°

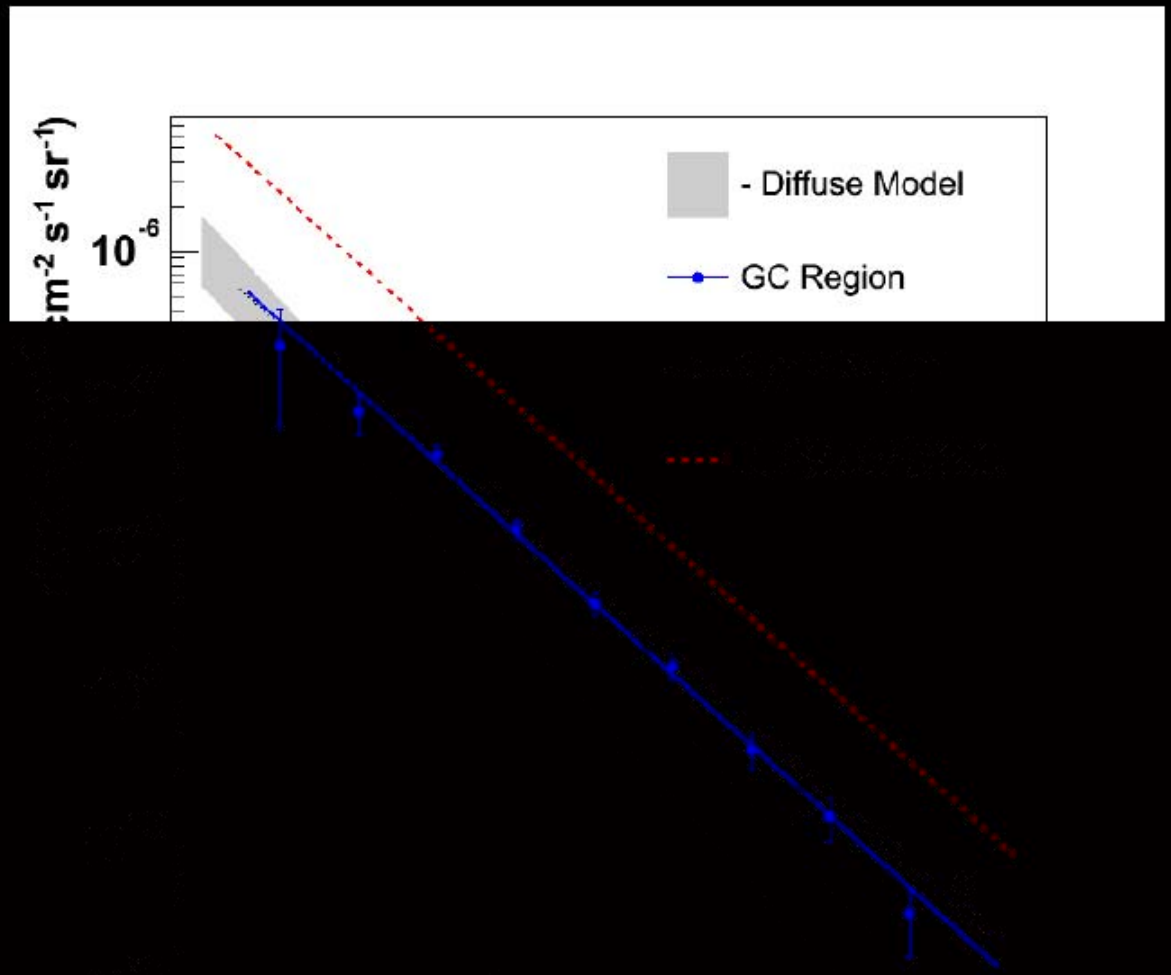
Credit: HESS Collab

Interpreting γ-ray/gas Correlation

- HESS Collaboration suggests that break-down of correlation at angular scales ~ 1° suggests NSS scenario where CR hadrons injected at central source
- Assuming diffusion coefficient typical for Galactic disk, viz., 10^{30} cm^2s^{-1} @ TeV, diffusion time to 1° is ~10^4 years – close to some estimates of age of Sgr A East SNR

Energy Spectrum

- The Galactic Centre Source:

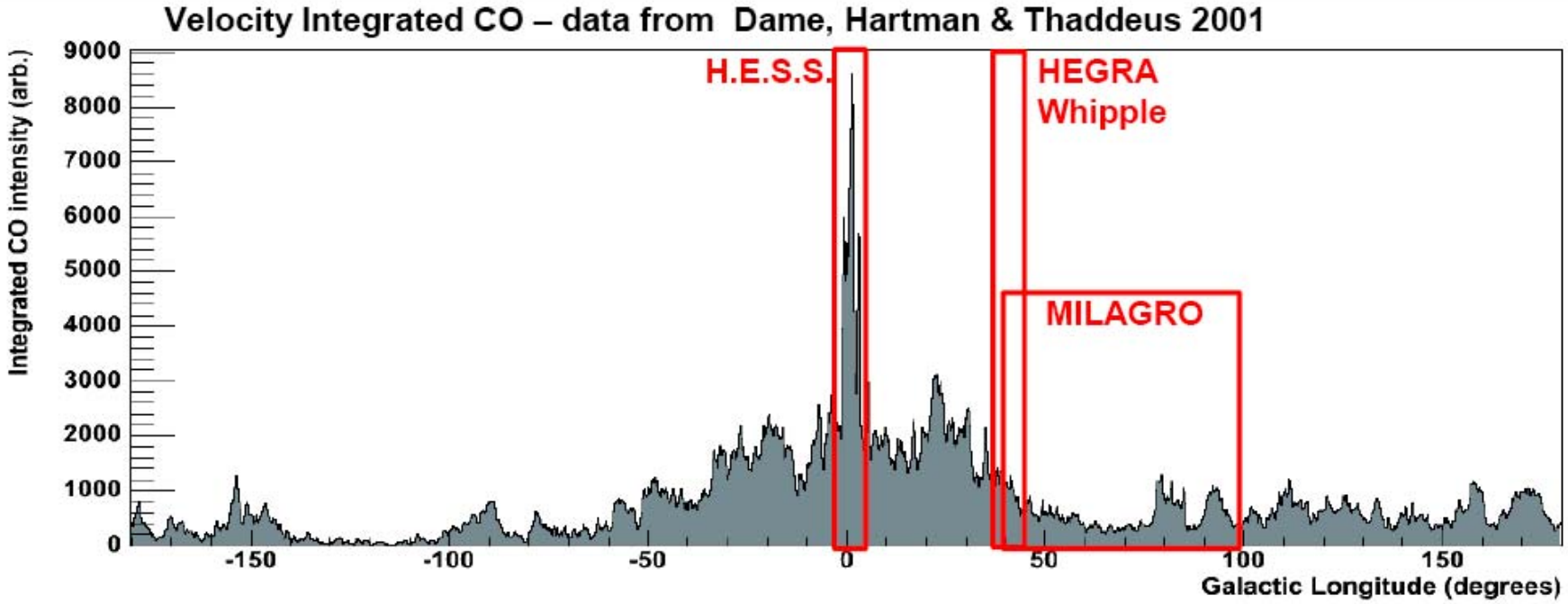


Credit: HESS Collab

Couple of Points Concerning SPIN

- Spectrum much harder than would be produced by local CR population interacting in GC gas
- On the one hand, the fact that the SPIN of the diffuse emission and the GC point source are so similar might argue for a common accelerator (at Sgr A*, Sgr A East?)
- On the other hand, the fact that the spectral index of the diffuse emission does not vary across the region poses some problems for a model invoking diffusion: why doesn't the SPIN flatten at large distances?

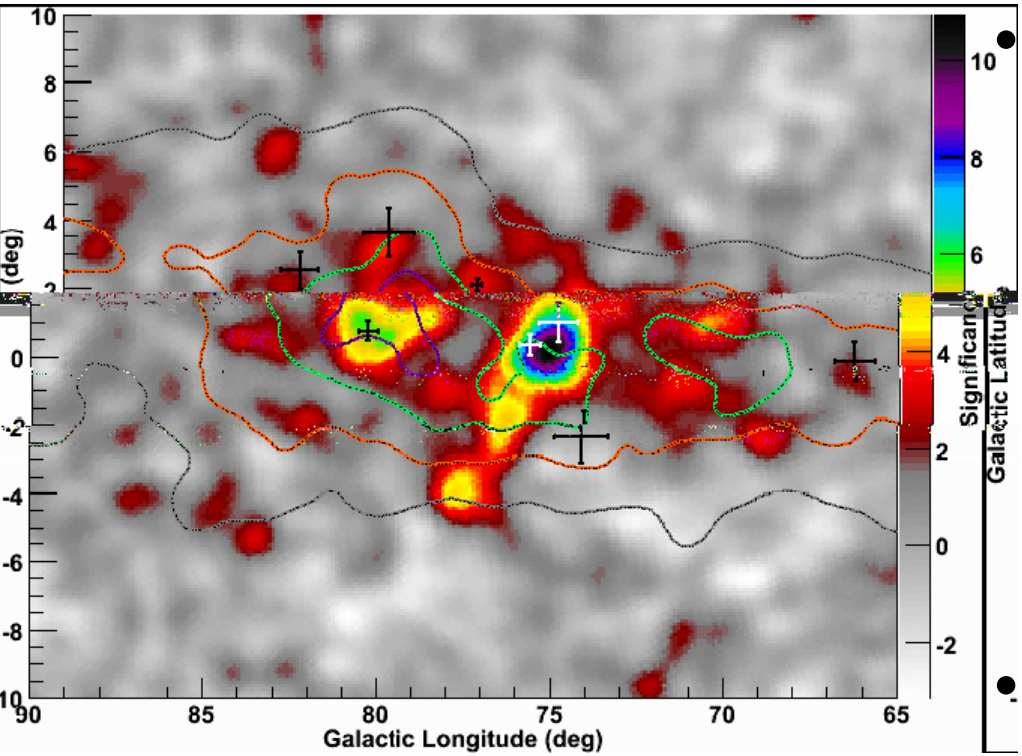
Molecular Material in the Galaxy



- Atomic component is rather uniform but
- Molecular part (traced by CO) is strongly peaked along the plane and in the GC region
- assume π°-decay @TeV: CR interaction with gas

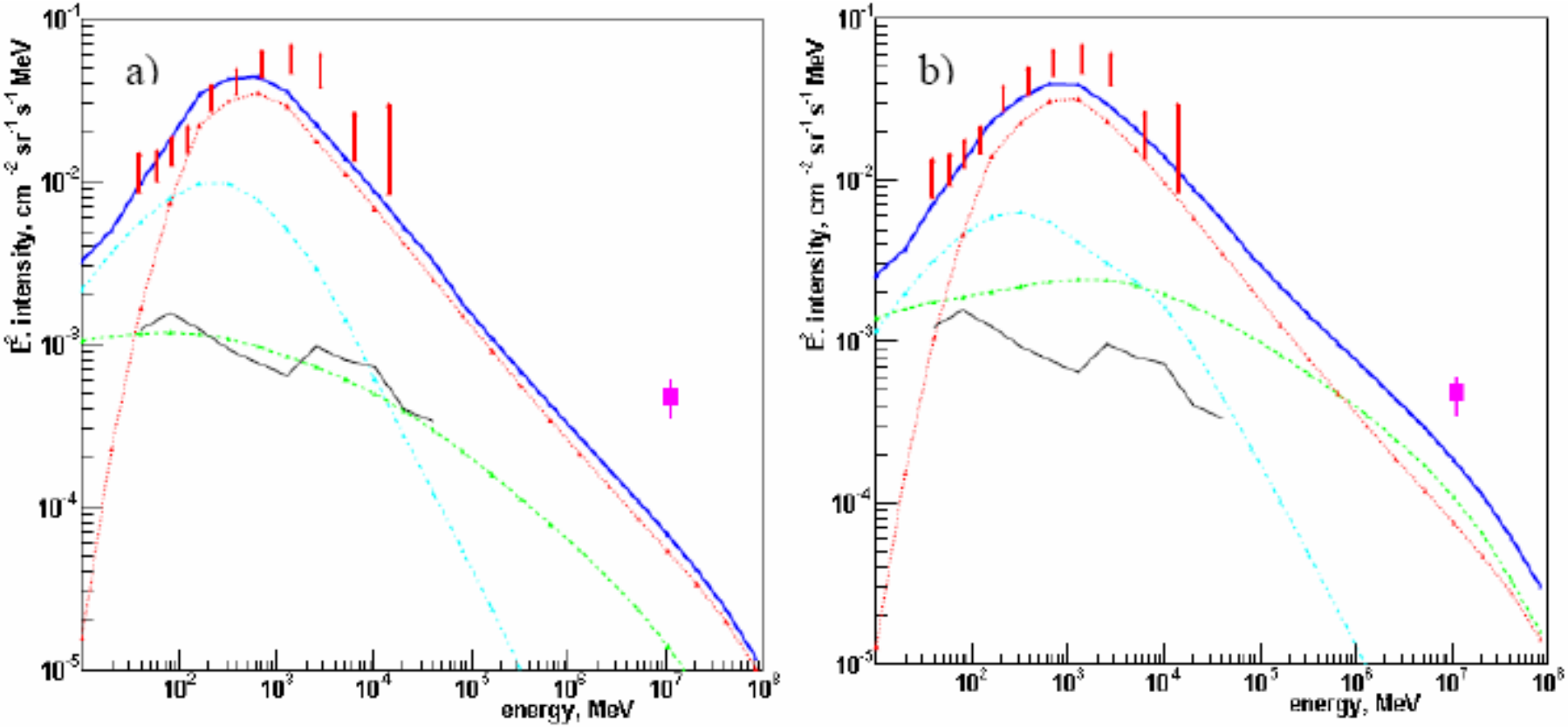
Credit: HESS Collab

Millagro Detects Large-scale, Diffuse Emission at 10 TeV



- **The Cygnus Region of the Galaxy as seen in TeV gamma rays…angular resolution is ~0.5° for individual photons**
- **astro-ph/0611691, Abdo et al. (Milagro collab)**

Diffuse Emission to 10 TeV: ‘TeV Excess’?



Spectrum of the diffuse emission from the Cygnus Region of the Galactic Plane.

astro-ph/0611691, Abdo et al. (Milagro collab)

Cosmic Ray Anisotropy Towards GC

Evidence for EHE CR Anisotropy

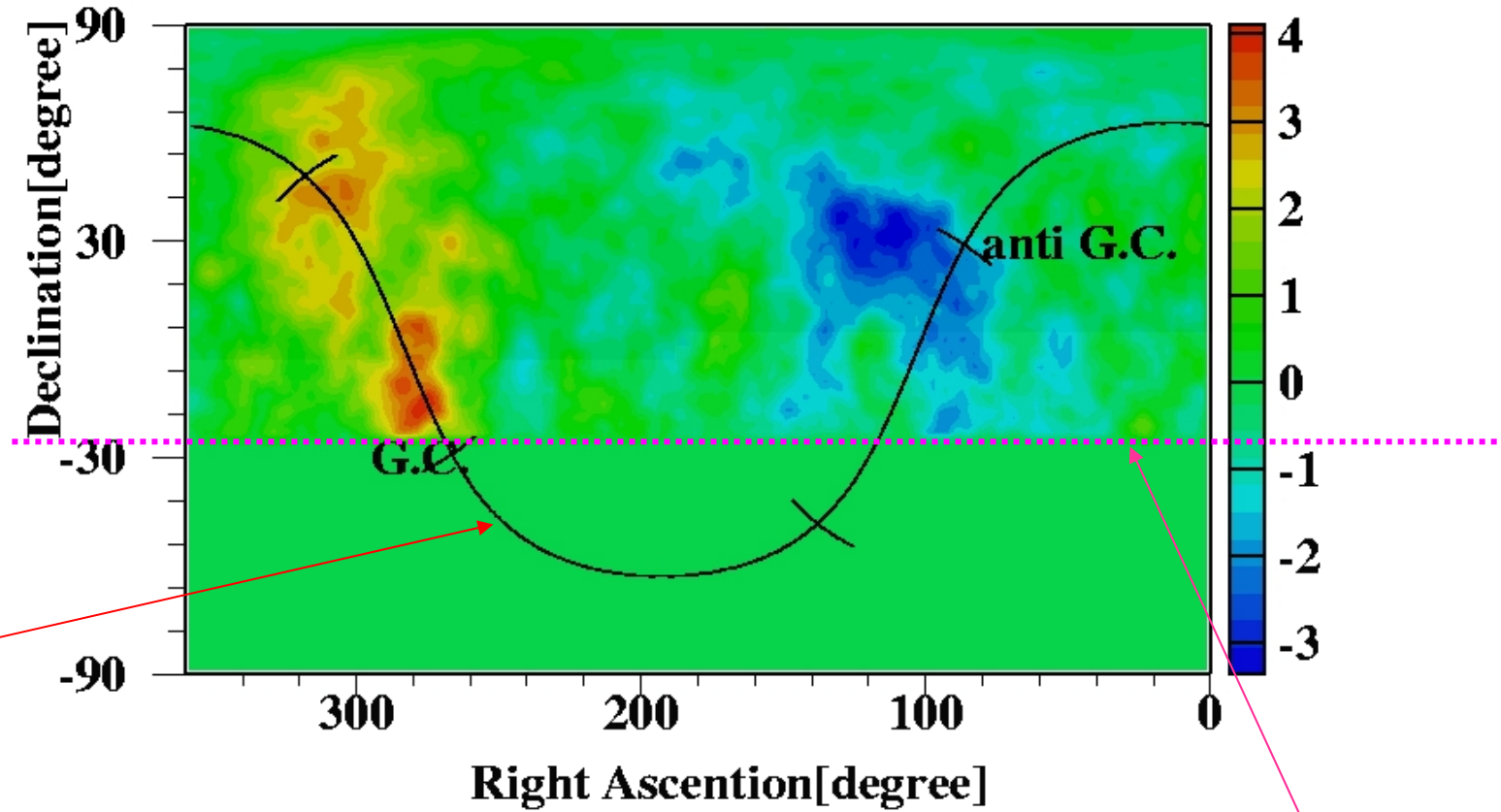
- **AGASA:** found ~25 % over-abundance towards the **GC** over a 20 degree diameter circle for

  $17.9 < \log[\, E/eV \,] < 18.3$

  Data taken over a 20 year period. 200 000 $>10^{17}$ eV CR showers. **4.5 σ** result. (Hayashida et al. 1999)

- **SUGAR** data (1968-1979): **point source** near GC. 4000 events within *a priori* restricted energy range. **2.6 σ** result. (Bellido et al. 2001)

AGASA CR Sky

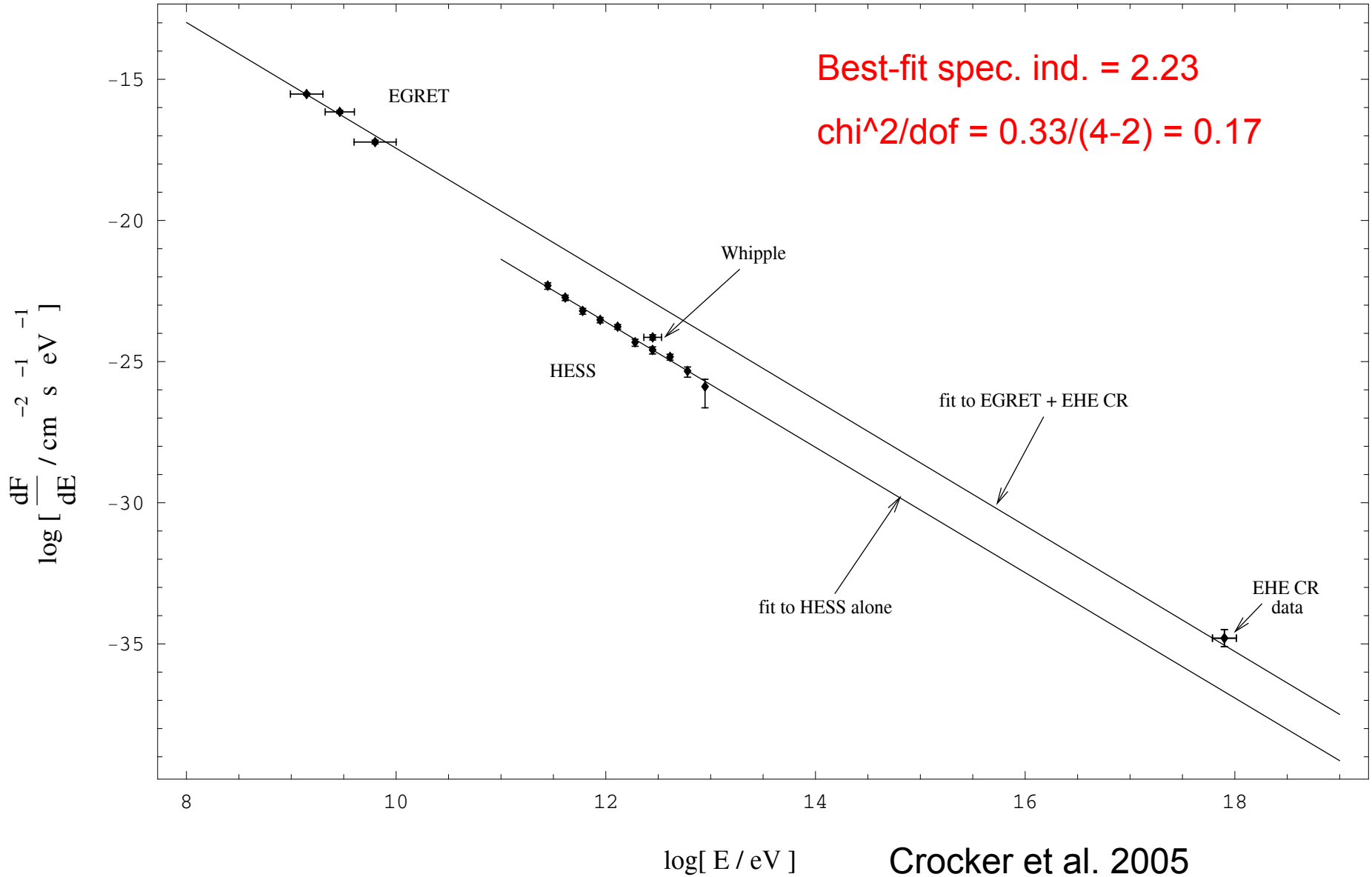


Galactic Plane

Instrument horizon

Hayashida et al. 1999

Chi-squared Fitting to Combined Data



Crocker et al. 2005

AUGER: Nothing Obvious at GC

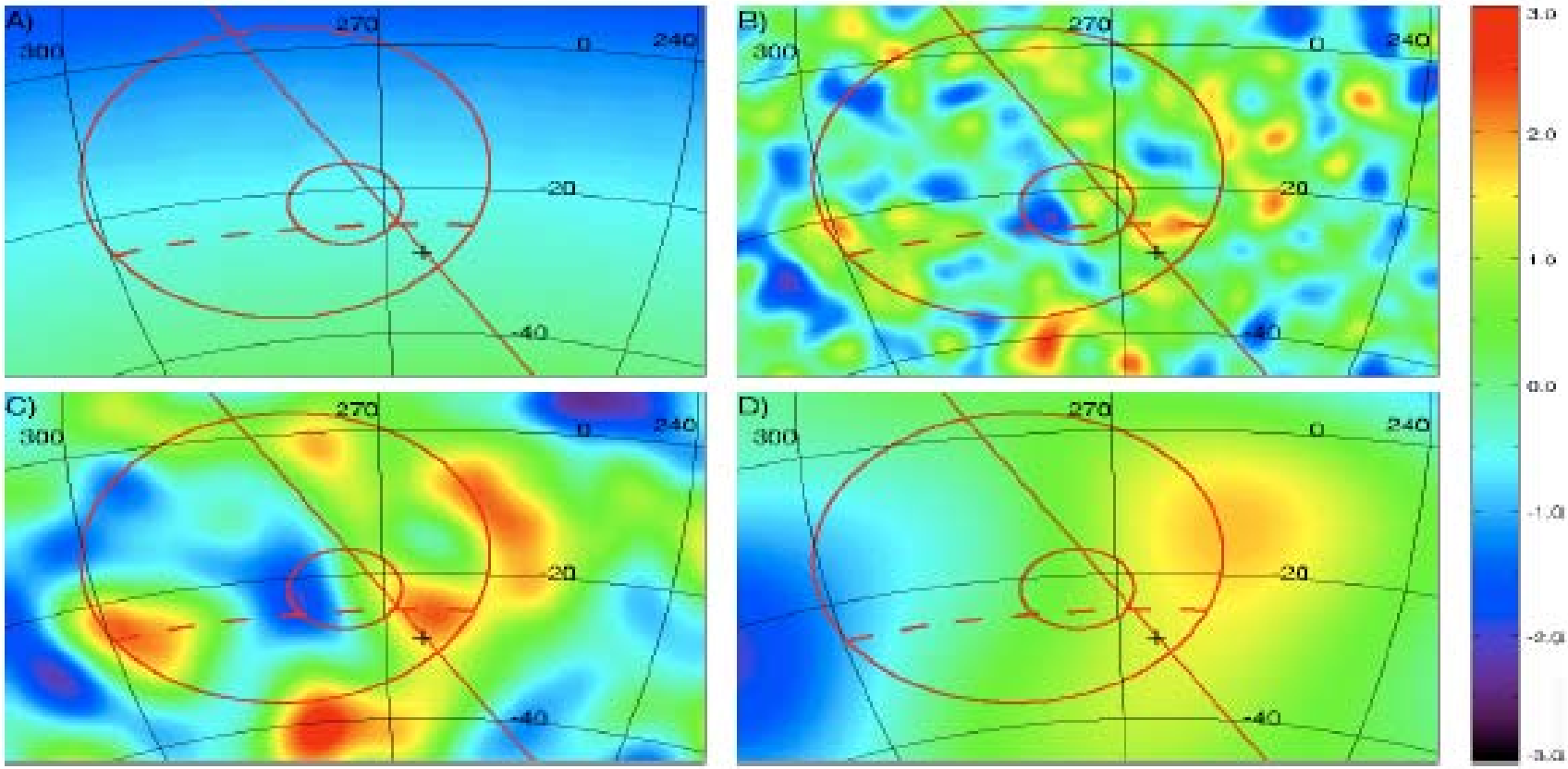


Figure 1. Lambert projections of the galactic centre region, GC (cross), galactic plane (solid line), regions of excess of AGASA and SUGAR (circles), AGASA f.o.v. limit (dashed line). A) coverage map (same color scale as the significance maps, but in a range [0-1.0]). B) significance map in the range [0.8-3.2] EeV smoothed using the individual pointing resolution of the events and a 1.5° filter (Auger like excess), C) same smoothed at 3.7° (SUGAR like excess), D) in the range [1.0-2.5] EeV smoothed at 13.3° (AGASA like excess).

Letessier-Selvon, 29th ICRC 2005