TeV Proton Transport in the Galactic Centre:
Issues and Implications

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With help from…

– F. Melia, S. Liu, and R. Crocker

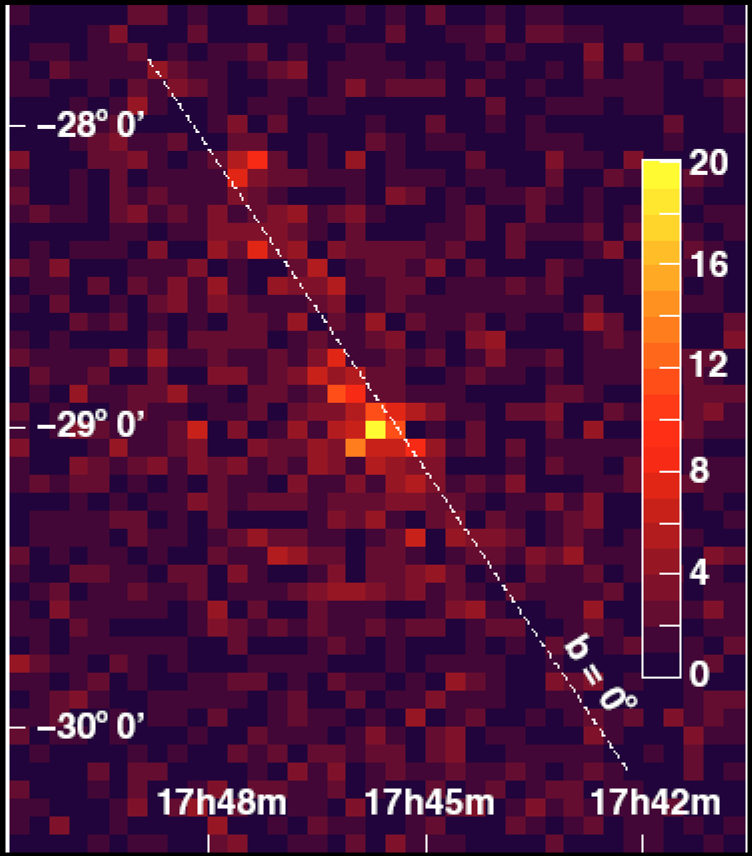
Ballantyne, D.R. et al., 2007, ApJ, 657, L13.

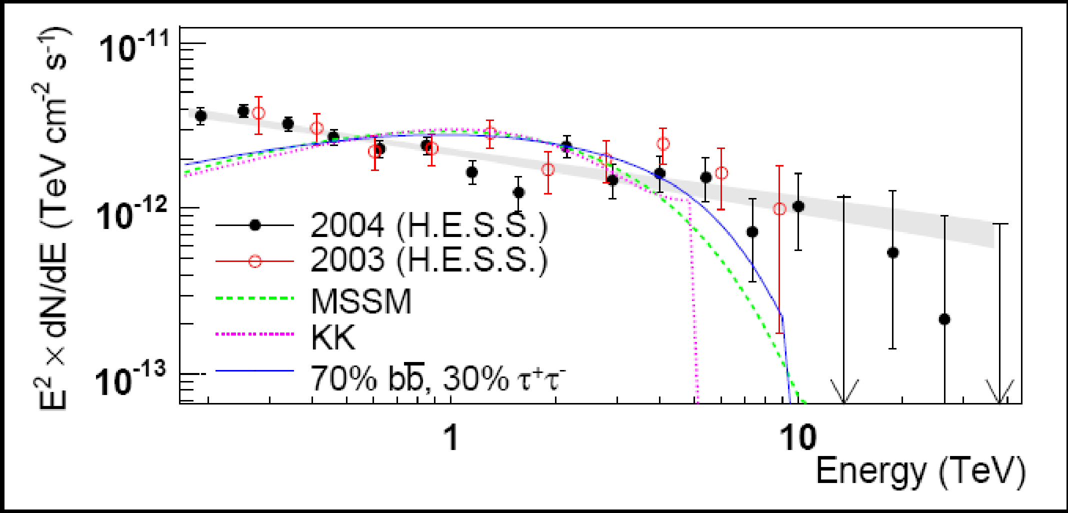
Crocker, R.M. et al., 2007, ApJ, 664, L95.

– M. Schumann and B. Ford

Ballantyne, D.R. et al., 2011, MNRAS, 410 1521.

HESS Detection of the Galactic Center



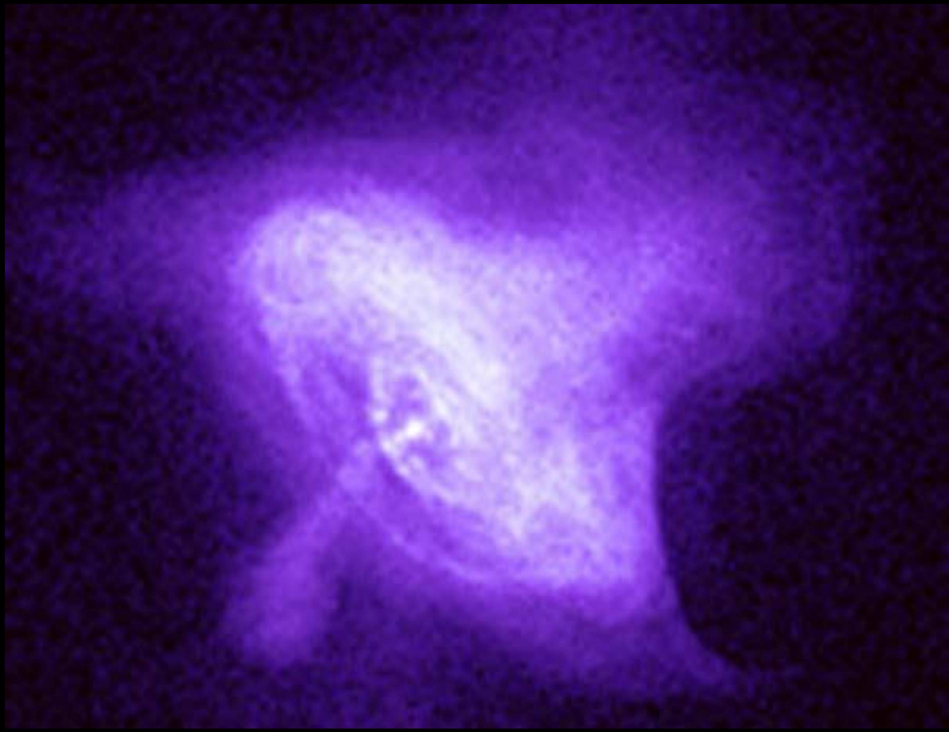


Aharonian et al. (2004)
Aharonian et al. (2006b)
Acero et al. (2010)

- Observed photon index of 2.25+/- 0.10
- Flux (> 1 TeV) = (1.87 +/- 0.30) × 10^{-8} m^{-2} s^{-1}
- Source is coincident within 13” of Sgr A*; rms size must be less than 1.3’ (3 pc)

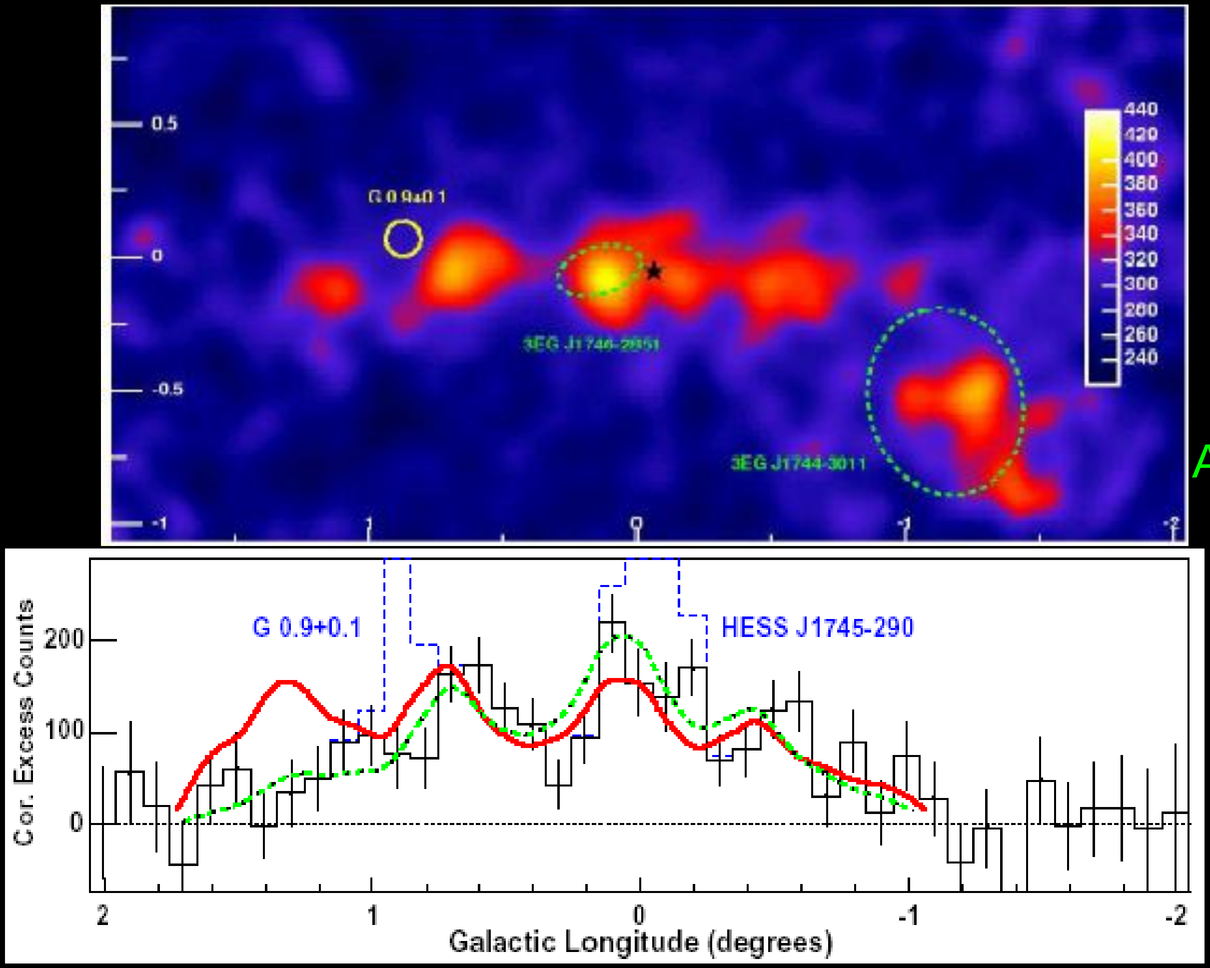
How to produce TeV γ-rays?

- Annihilation of dark matter particles
  - problems fitting the data
    (Profumo 2005; Aharonian et al. 2006b)
- Inverse Compton off of TeV electrons
  - e^- accelerated in nearby pulsar wind nebula
  - high photon energy density in Galactic Center
  - decent fits can be obtained
    (Hinton & Aharonian 2007)
- Interaction of TeV protons with ambient H
  - $pp \rightarrow pp\pi^0\pi^\pm$
  - $\pi^0 \rightarrow \gamma\gamma$



Crab pulsar wind nebula in X-rays (Chandra)

Evidence for the Hadronic Model



Aharonian et al. (2006a)

- Implies that very high energy protons have been accelerated within the Galactic center environment

Can Sgr A* be the Source of the TeV protons?

- Sgr A* is a very low luminosity black hole
- accreting at $\approx 10^{-9}\ L_{Edd}$
- Stochastic acceleration can occur in a magnetically-dominated region close to BH
- TeV protons will be generated (Liu et al. 2006)
- these protons will random-walk outwards into the surroundings to interact with the ambient gas

Proton Transport

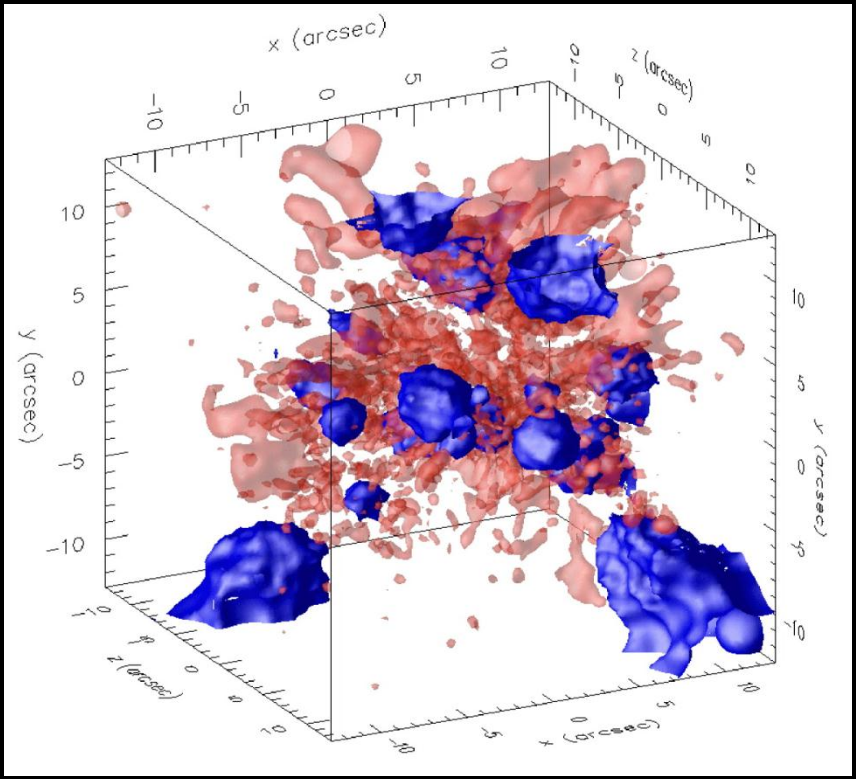
- The motion of relativistic protons in the ISM is subject only to the Lorentz force:

$$\frac{d\boldsymbol{v}}{dt} = \frac{(\boldsymbol{v} \times \boldsymbol{\Omega})}{\gamma}$$

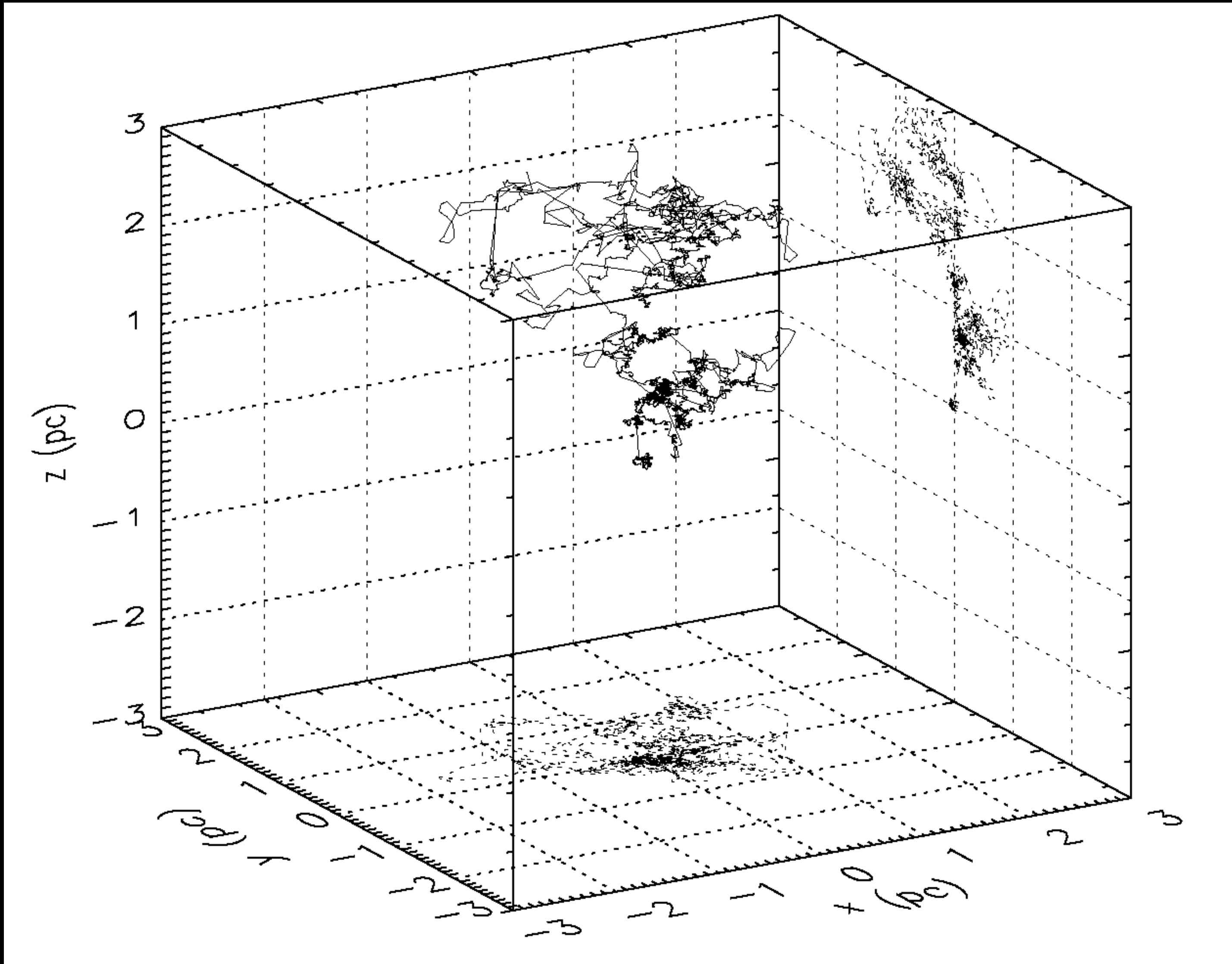
where $\boldsymbol{\Omega} = \dfrac{e\boldsymbol{B}}{mc}$

- Thus, given a description for **B**(x,y,z) in the computational volume, the trajectory of the proton can be calculated exactly.
- Assume **B**(x,y,z) is produced by Kolmogorov turbulence with a magnitude proportional to gas density and assuming equipartition (Giacolone & Jokipii 1994).
- Calculate trajectories in a 6 pc × 6 pc × 6 pc cube consisting of 10^6 equally spaced cells centered on the Galactic Center.

- This volume contains stellar wind gas and a high-density CND
  - Inner radius 1.2 pc
  - thickness 1 pc
- $\langle n_{sw} \rangle = 121\ \mathrm{cm}^{-3}$
  $\langle B \rangle = 3\ \mathrm{mG}$
- $\langle n_{CND} \rangle = 2\times10^{5}\ \mathrm{cm}^{-3}$
  $\langle B \rangle = 0.35\ \mathrm{mG}$
- 250,020 p trajectories calculated with energies b/w 1-100 TeV

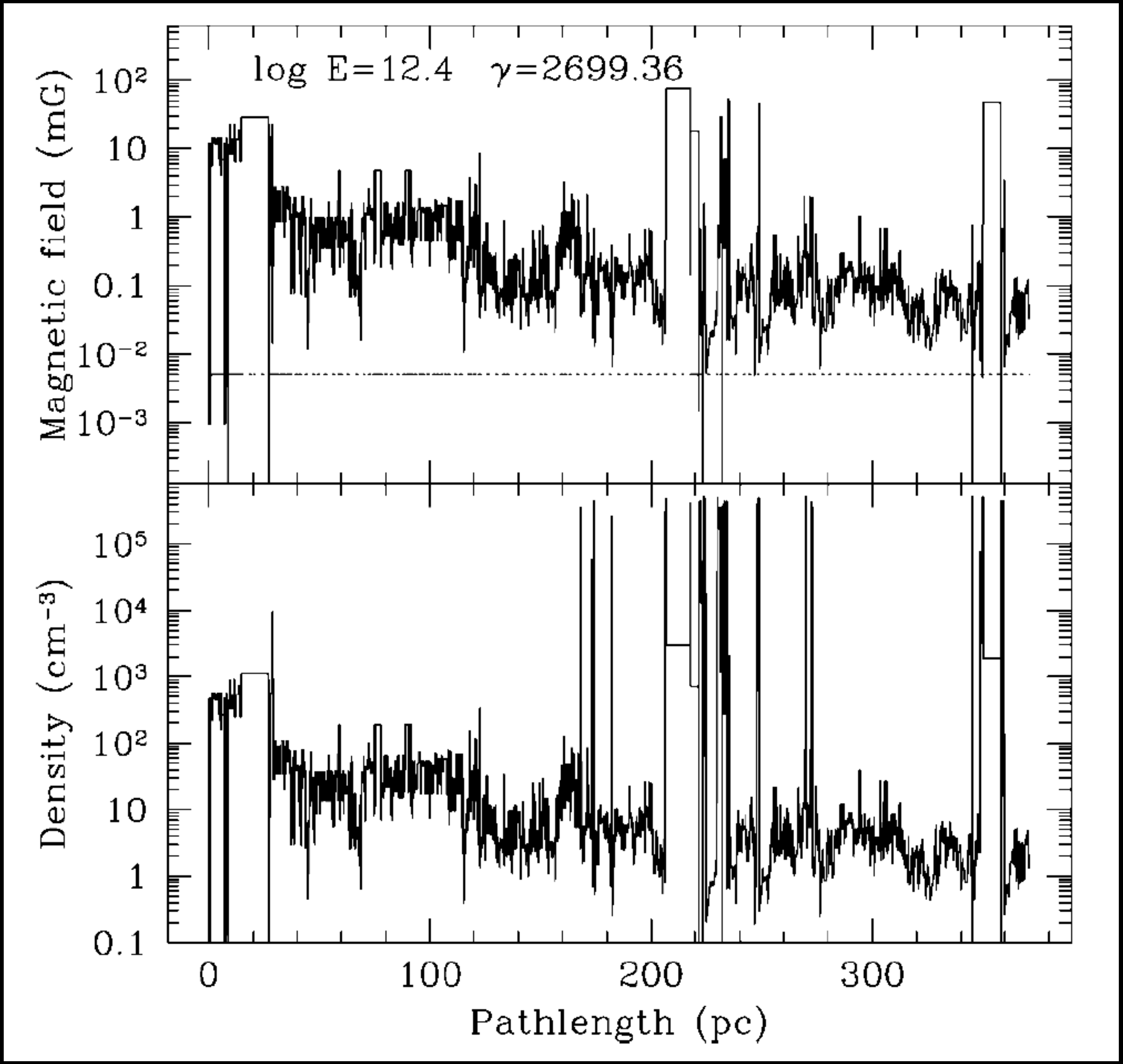


Rockefeller et al. (2004)



Ballantyne et al. (2007)

• Example trajectory of a log(E/eV) = 12.4 proton from injection at Sgr A* until it escapes at z=3



Ballantyne et al. (2007)

- The particle traveled for 1,211 years and traversed 371.3 pc

Computing the π^0 Production Rate and γ-ray Emissivity

- $\sigma_{pp} \approx$ 40-60 mbarns in this energy range
- Consider the protons in 21 energy bins:
  - log (E/eV) = 12,12.1,…,13.9,14
- We followed each proton and for each cell with density > 3000 cm^{-3} compute

$$d\tau = \overline{n_H}\sigma_{pp}(E)dl$$

- The fraction of protons at energy E that undergo pp scattering in each volume element is then

$$f(E) = 1 - e^{-\left(\int d\tau\right)/N}$$

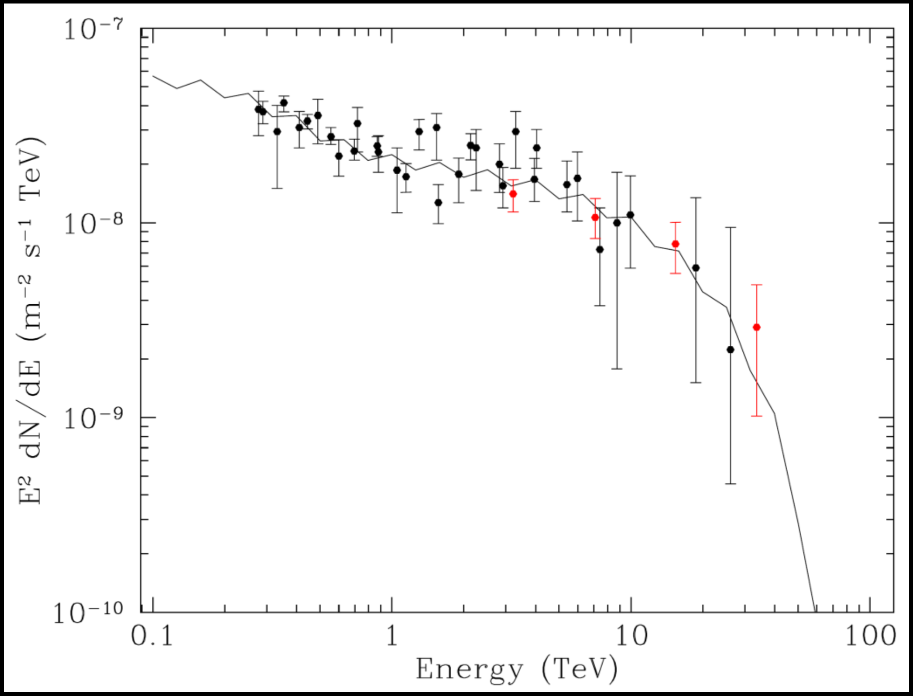
- Assume a power-law proton spectrum injected by Sgr A*

$$\frac{dn}{dE_{\mathrm{inj}}} = K\left(\frac{E}{E_{\mathrm{min}}}\right)^{-\alpha}$$

- We calculate the expected γ-ray spectrum for different values of *K* and α and compare with the observed HESS 0.1-40 TeV data
  - γ-rays at a given energy are preferentially produce by protons with ~10× greater energy

Results

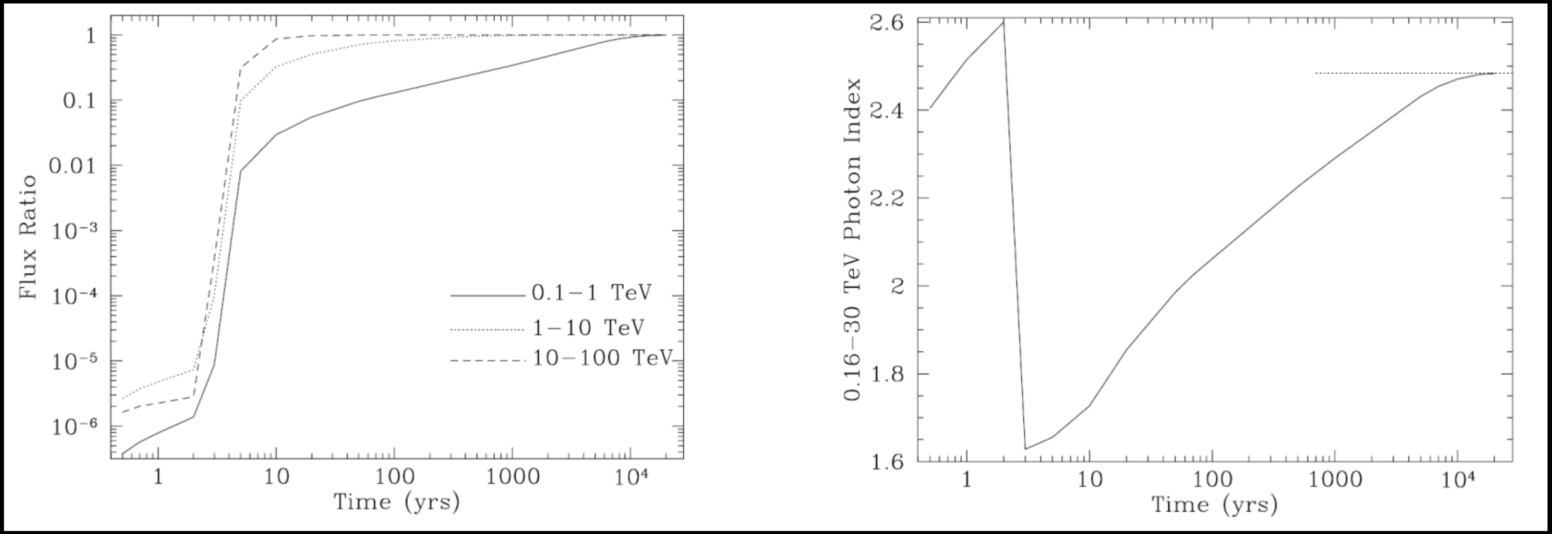
- Best fit:
  - 1-40 TeV energy in protons: 5×10^{45} ergs
  - α=0.75
- α significantly harder than observed photon-index
- higher energy protons escape easier w/o interacting with disk so need harder spectrum
- 30% of the protons interact with the disk
- the remainder can escape and perhaps contribute to the ridge emission



Ballantyne et al. (2007) with VERITAS points (Beilicke 2011)

Time Dependence

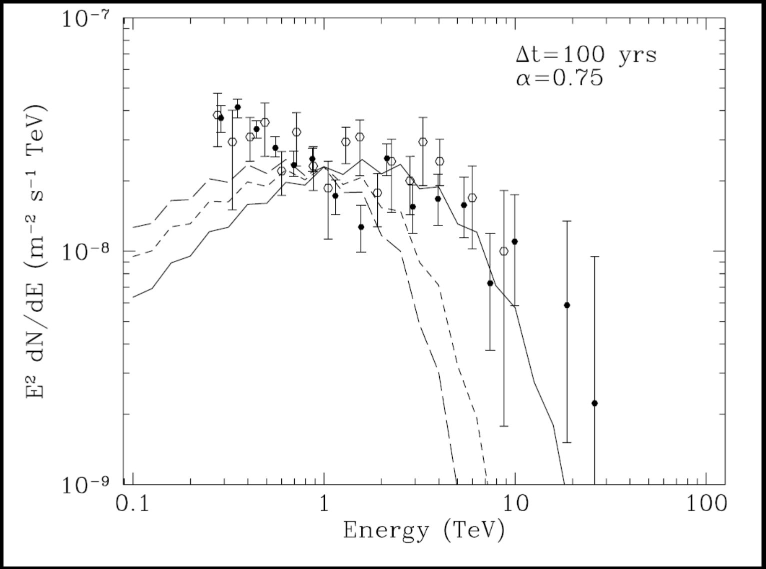
- This unique framework allows for an investigation of the spectral and flux evolution of the TeV source
- Consider two scenarios:
  - Ignition of constant particle acceleration at some t=0
  - A burst of particle acceleration lasting Δt years

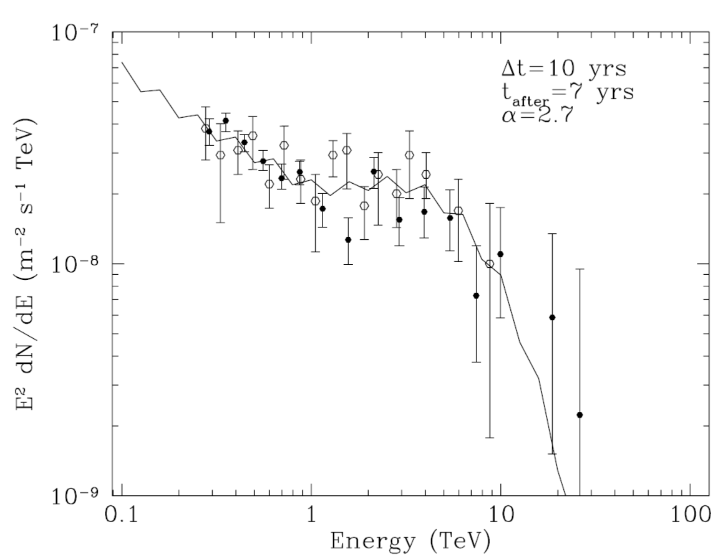


Ballantyne et al. (2011)

- >10 TeV protons interact first after ~10 yrs
- Any flare will not be observed in the 1-10 TeV band for over a century
  - Null result for coordinated X-ray/TeV observations (Aharonian et al. 2008) not surprising.
- $>10^4$ yrs needed to reach flux and spectral shape
  - Still 1000x less than estimated lifetime of the CND (Montero-Castano et al. 2009)

10, 50 & 100 yrs after burst ->



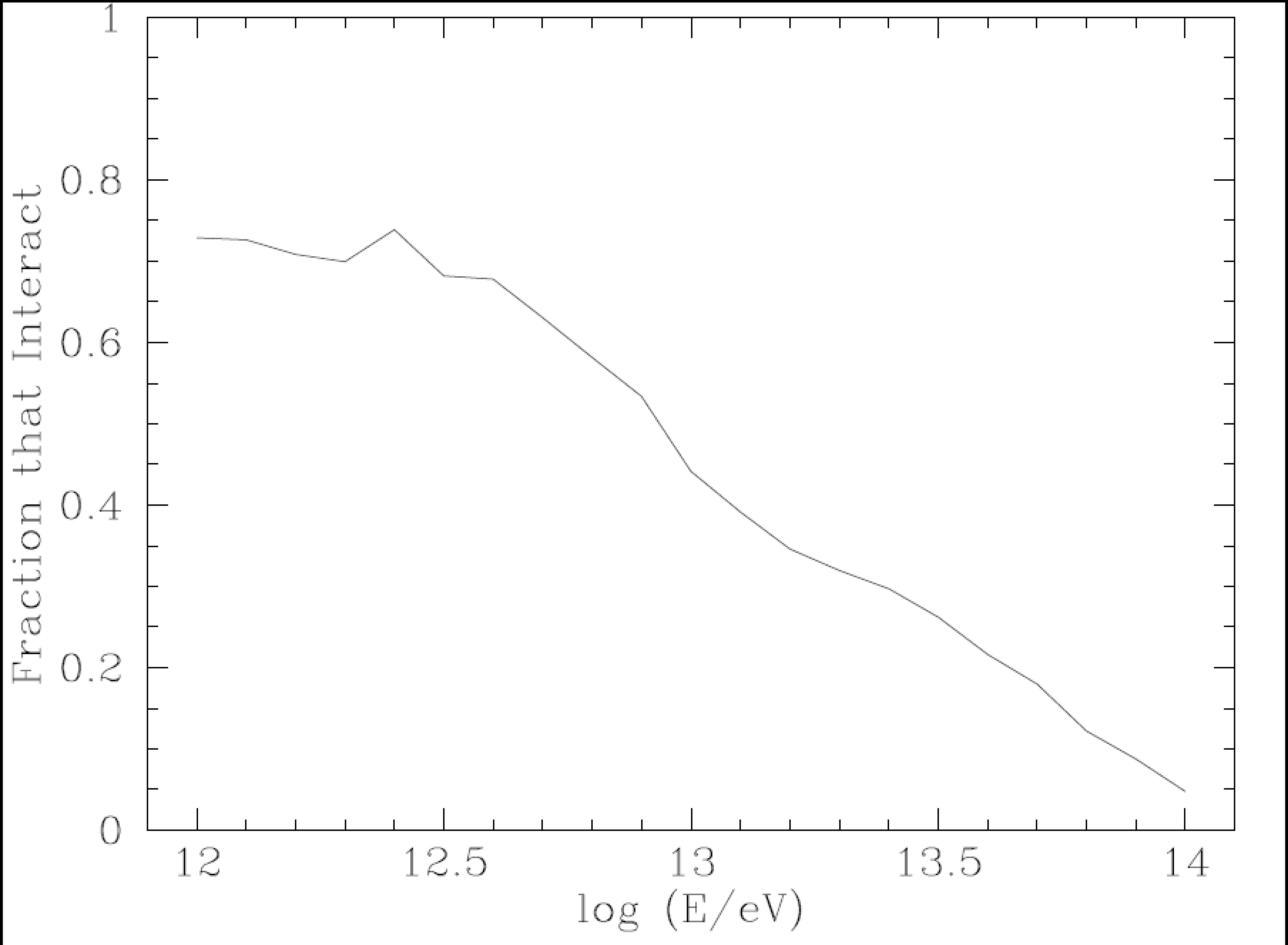


Ballantyne et al. (2011)

- For bursts, the rapid diffusion of the high-energy protons, makes it difficult to obtain correct spectral shape
  - Independent of α
  - Rules out connection with period of increased X-ray activity >~ 100 yrs ago
- BUT, can obtain a decent fit with α=2.7 if observed only a few years after a short burst
  - Proton luminosities must be larger ($10^{39\text{-}40}$ erg/s)
  - Implies the particle acceleration could be important in reducing radiative efficiency of Sgr A* (10^{-3} to 10^{-4} M-dot$_{\mathrm{Bondi}}$)
  - Numerous events could continuously energize TeV spectrum
    - Could show variability on ~10yr timescales, esp. at > 10 TeV

Geometry Matters

- Steady-state results show a steepening of 1.5 from initial proton spectrum to observed gamma-ray spectral index
  - very different from homogeneous diffusion with either Kolmogorov or Bohm turbulence
- Fraction of interacting protons strongly energy dependent
  - ~73% at log(E/eV)=12-12.4
  - 44% at log(E/eV)=13
  - 5% at log(E/eV)=14


Fraction that Interact
1
0.8
0.6
0.4
0.2
0
12
12.5
13
13.5
14
log (E/eV)

Issues & Implications

- Results depend on
  - Geometrical model of CND
  - Magnetic field
    - Equipartition assumption
    - Strength
    - Scaling w/ density
  - Form of turbulence?
  - Computationally prohibitive for proton E < 1 TeV

- Modeling of hadronic production of TeV photons in an inhomogenous environment cannot rely solely on the diffusion equation.

Conclusions & Future Work

- Protons accelerated at Sgr A* can explain the observed HESS source using the molecular circumnuclear disk as target material.
- The same proton source can also account for the observed GHz radio emission from this region using the stellar winds as target material.
- Is the very hard injected proton spectrum viable?
- The inhomogeneous and anisotropic medium results in an observed γ-ray spectral index very different from the input p spectrum.
- Can obtain softer proton spectrum if source is being constantly re-energized by short bursts of acceleration.
- Model predicts variability at > 10 TeV on ~ 10yrs timescales