Title: The origin of the cosmic ray positron/electron excesses in light of the recent observations

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Abstract: The spectra of cosmic ray electrons and positrons should have contributions from known sources such as particles accelerated in supernova remnants and from the cosmic rays interactions. Besides these guaranteed contributions, any evidence for an additional component may carry hints of a new phenomenon. Most recently PAMELA and ATIC experiments hinted an overabundance of these particles as compared to model expectations and generated much interest on astrophysical and exotic explanations. I will first examine the implications of the recent detection of extended, multi-TeV gamma-ray emission from Geminga pulsar wind nebula, which reveals the existence of an ancient/nearby cosmic ray accelerator that can also plausibly account for the observed excess. Next, I will focus on a possibility that these particles might be produced through dark matter decays/annihilations within the halo of our Galaxy. I will conclude by reviewing implications of these scenarios for several categories of upcoming Gamma Ray/Neutrino observatories including Fermi and IceCube.

THE ORIGIN OF THE COSMIC

# POSITRON & ELECTRON EXCESSES

IN LIGHT OF THE RECENT OBSERVATIONS

New Lights on Dark Matter
Perimeter Institute
June 11-13, 2009

Hasan Yüksel
Bartol Research Institute
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*in collaboration with M.D. Kistler & T. Stanev*

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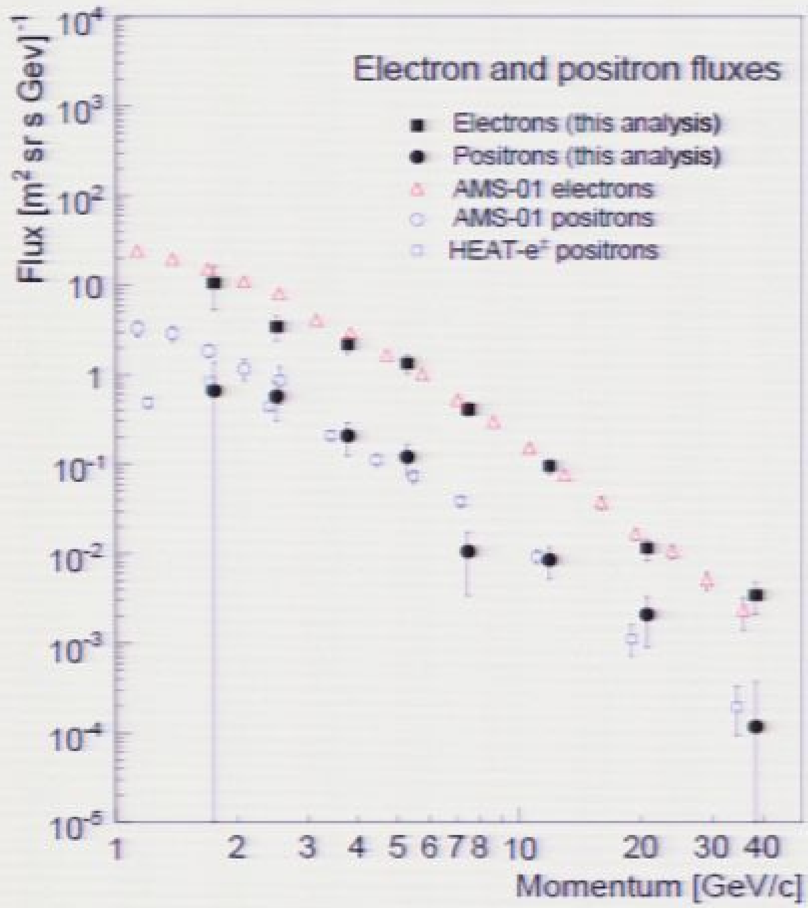
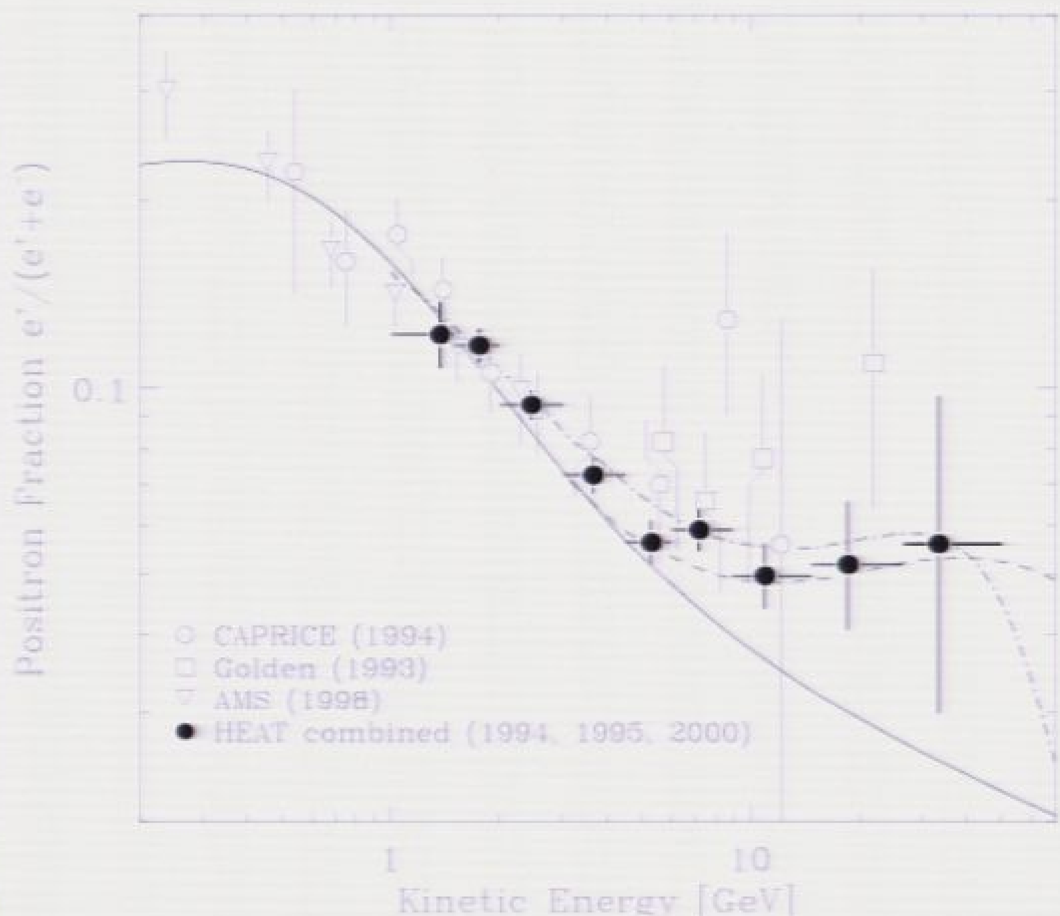
# Introduction

# Spectra of Electrons & Positrons

Primary Sources: $e^-$ accelerated in supernova remnants
Secondary Sources: $e^\pm$ from collisions between cosmic rays & ISM protons

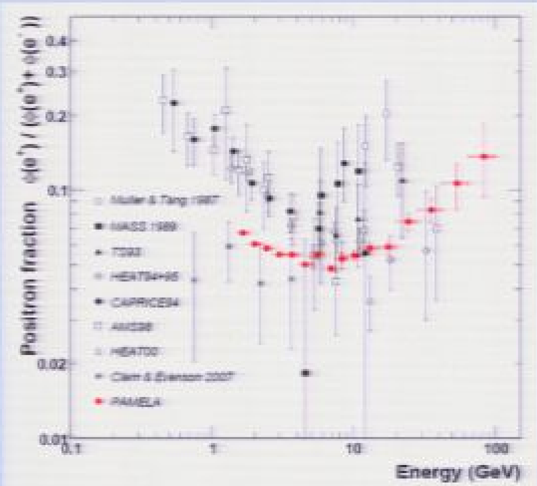




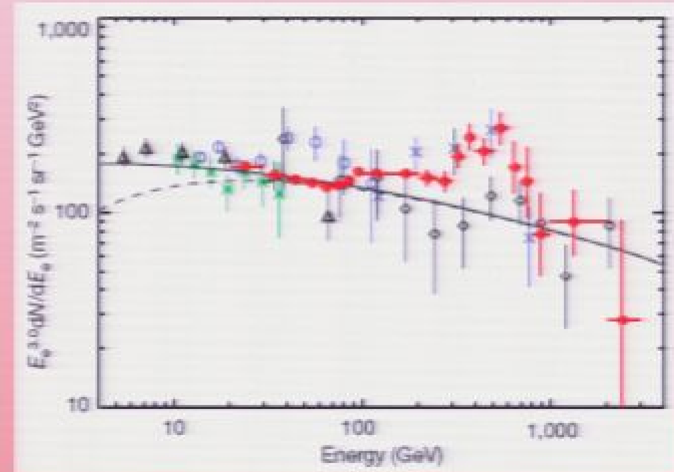

Strong Moskalenko Ptuskin

# PAMELA

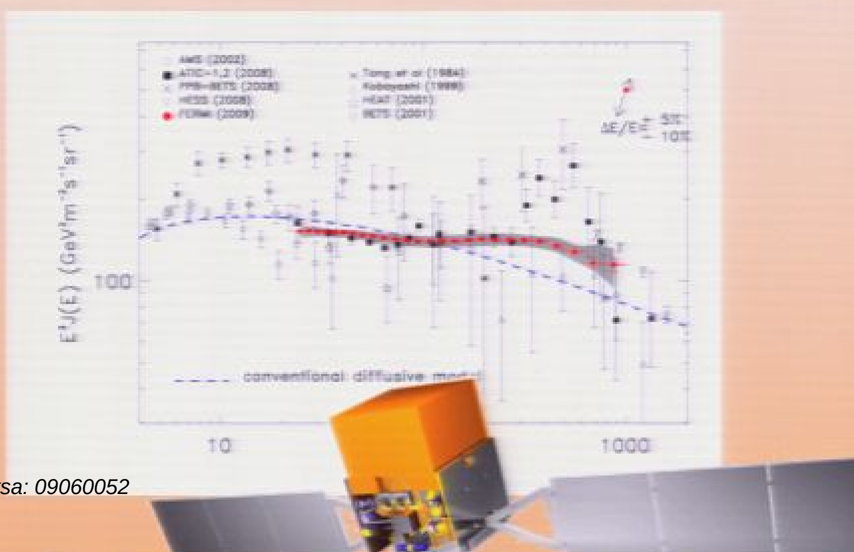




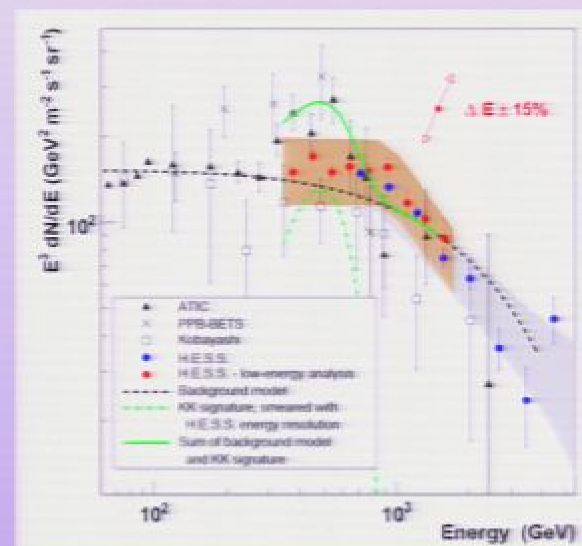
# ATIC

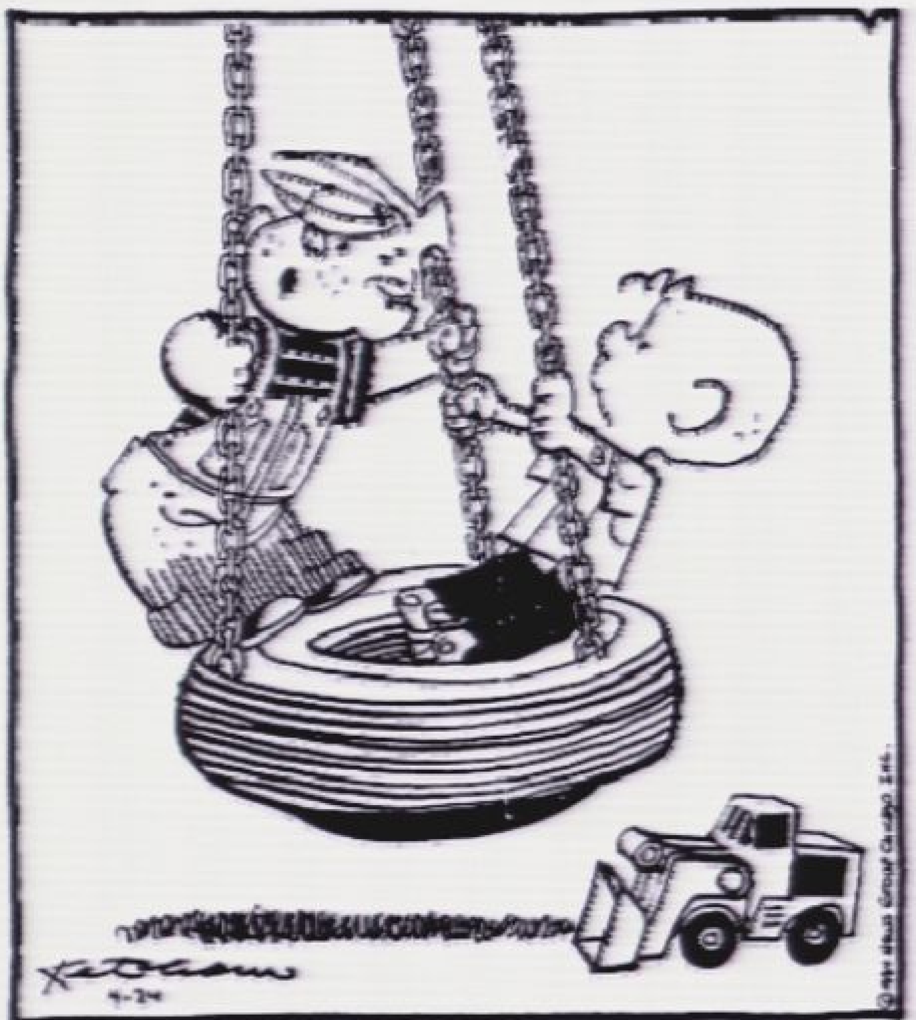



# Fermi




# Hess

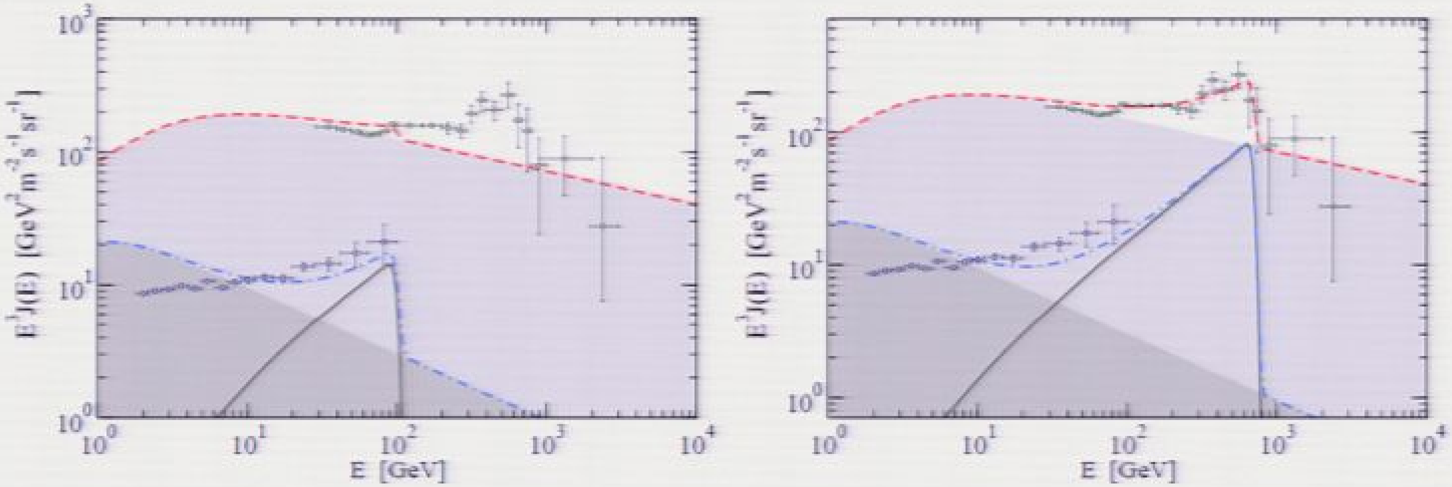




"LOTS OF THINGS ARE INVISIBLE, BUT WE DON'T KNOW HOW MANY BECAUSE WE CAN'T **SEE** THEM."

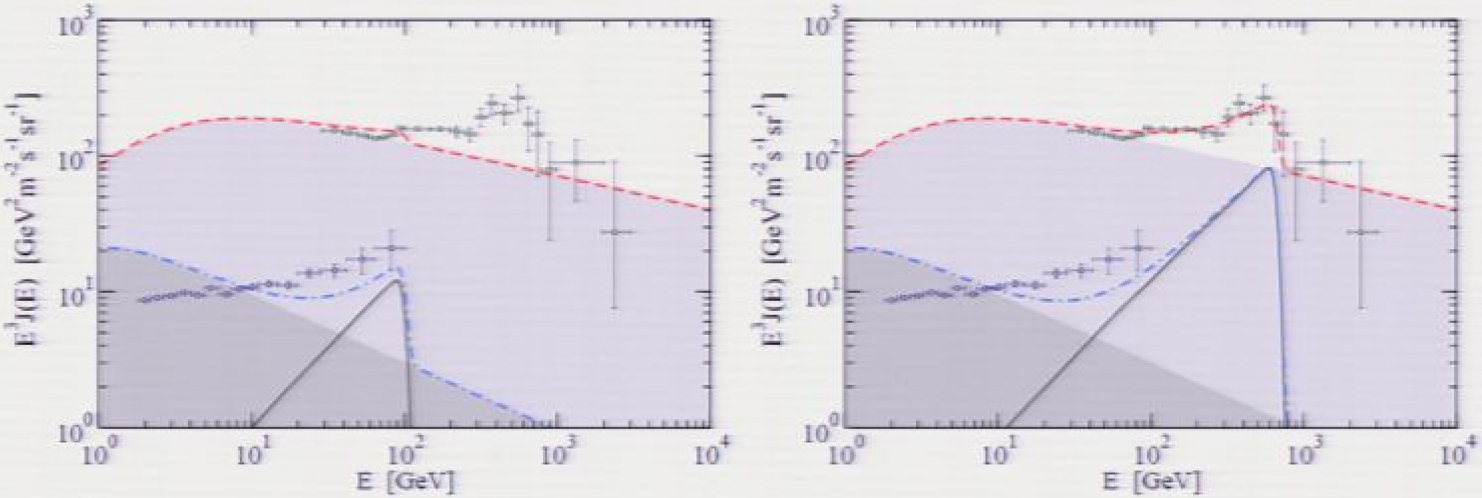
- What to look for:
  - Annihilating dark matter
  - Decaying dark matter

- Where to look at:
  - $\gamma$-rays from Galactic Center, Galactic Halo, Dwarf Satellites, Nearby Galaxies, Cosmic sources
  - $\nu$'s from the Sun, Galactic Halo
  - Anti-particle spectrum measured in solar neighborhood

$\chi\chi \rightarrow e^+e^-$ $m_\chi \sim 0.1\text{–}0.7$ TeV $f_B\langle\sigma v\rangle \sim 10^{-24}\ \mathrm{cm^3/s}$




$\chi \rightarrow e^+e^-\nu$ $m_\chi \sim 0.3\text{–}2$ TeV $\tau \sim 10^{27}$ s

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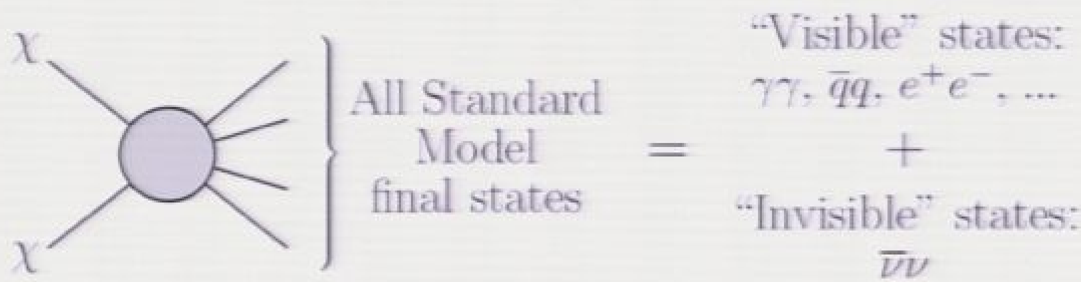
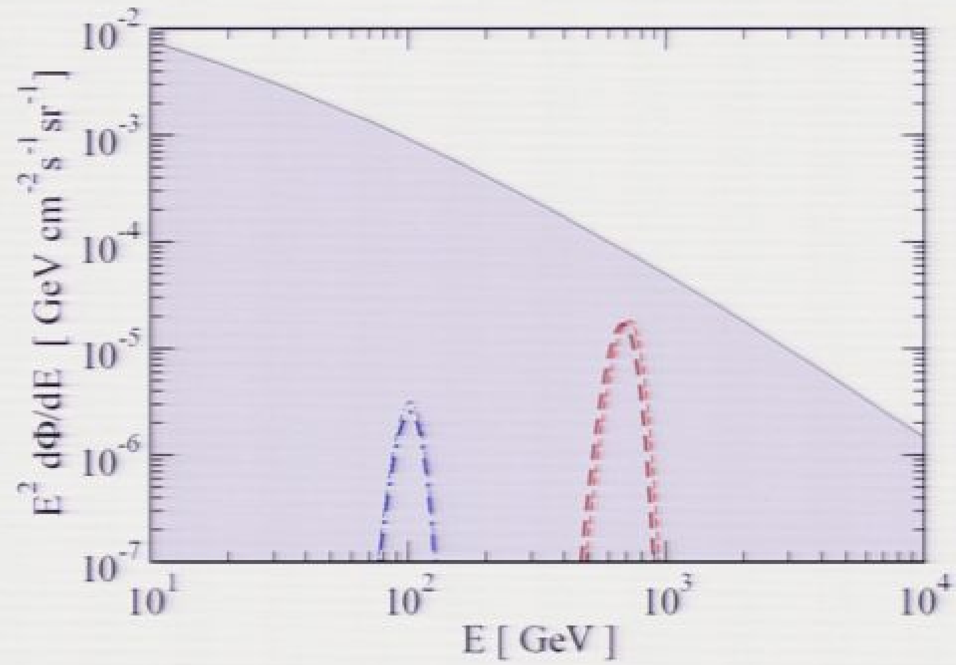
# Neutrino Limits on the DM Annihilation Cross Section

- Stringent upper limit on total annihilation cross section can be obtained by assuming only neutrinos are produced in final states (worst case, least visible)
- Anything else will eventually produce much more visible gamma rays (leading to a stronger limit)





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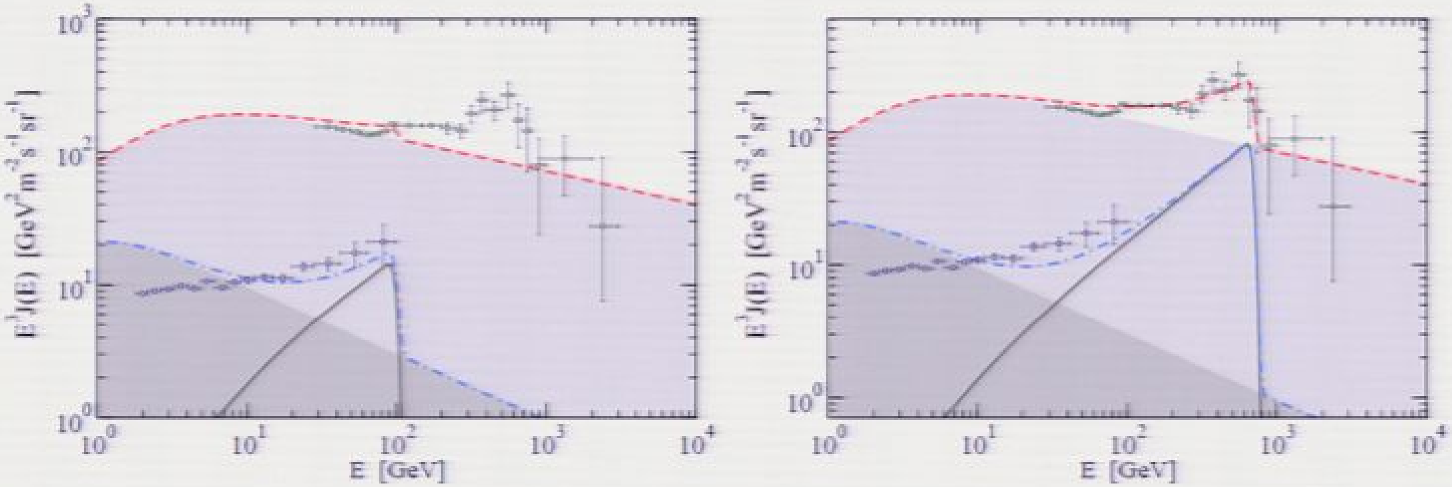


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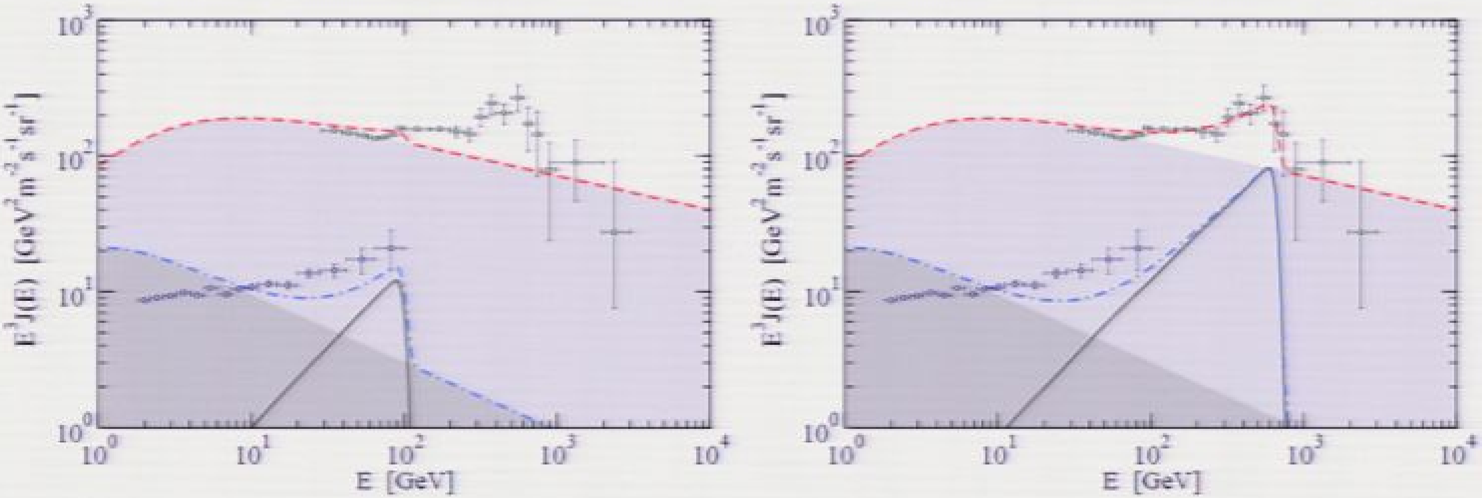


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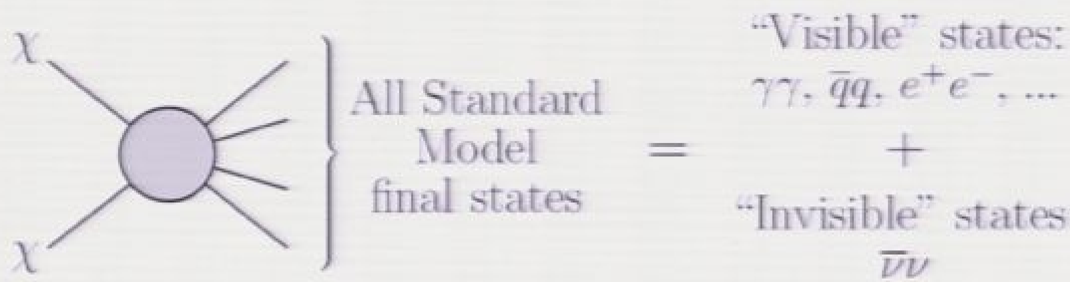


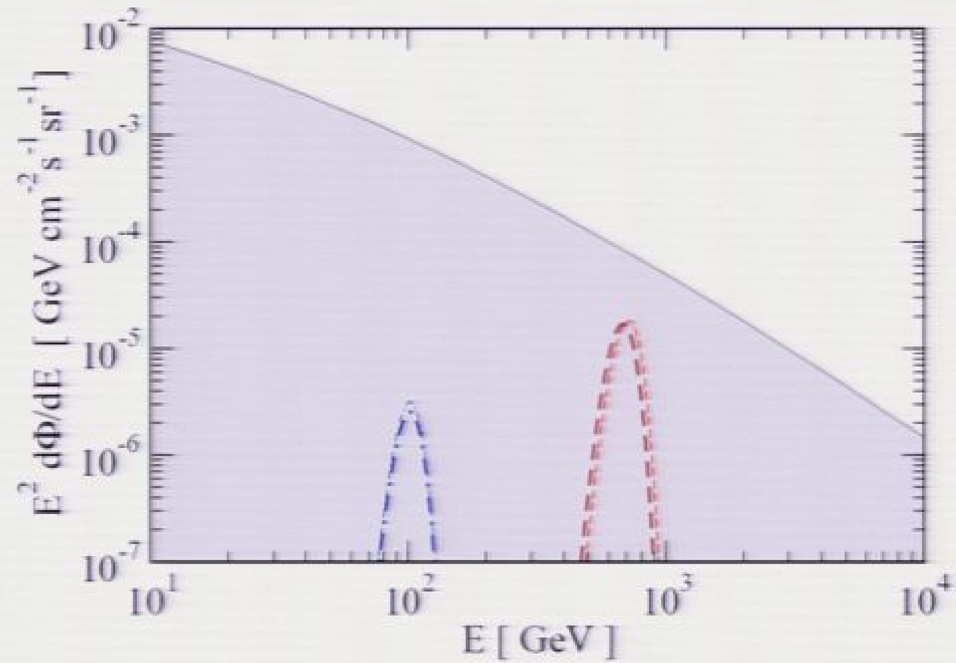






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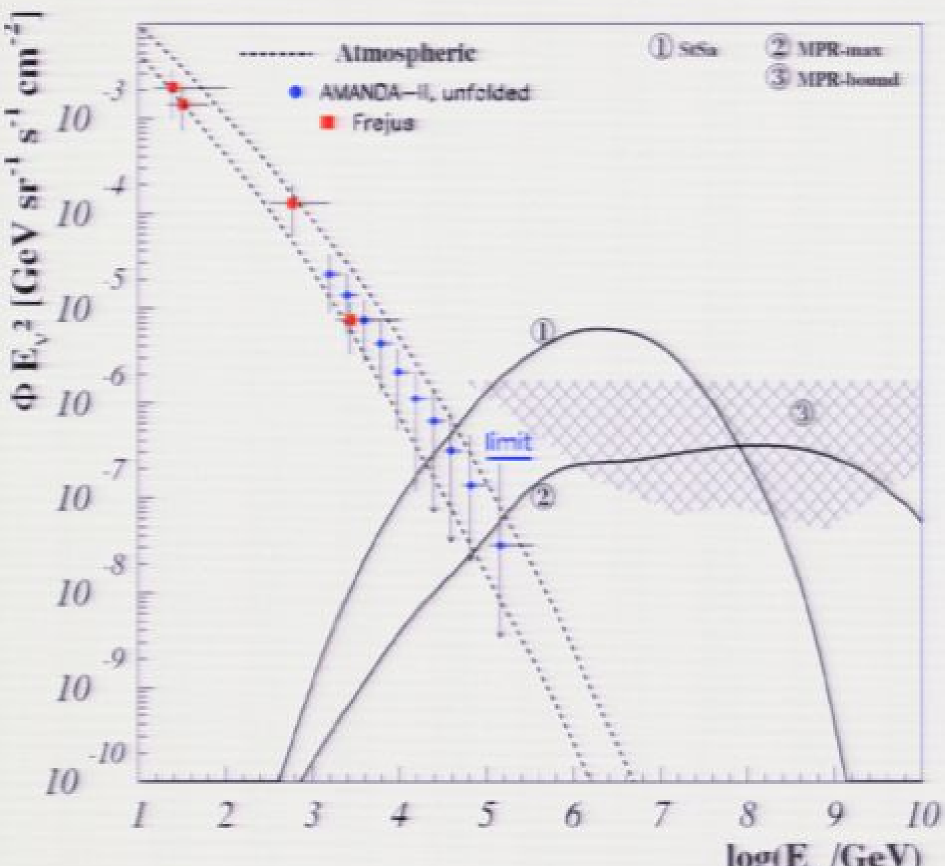
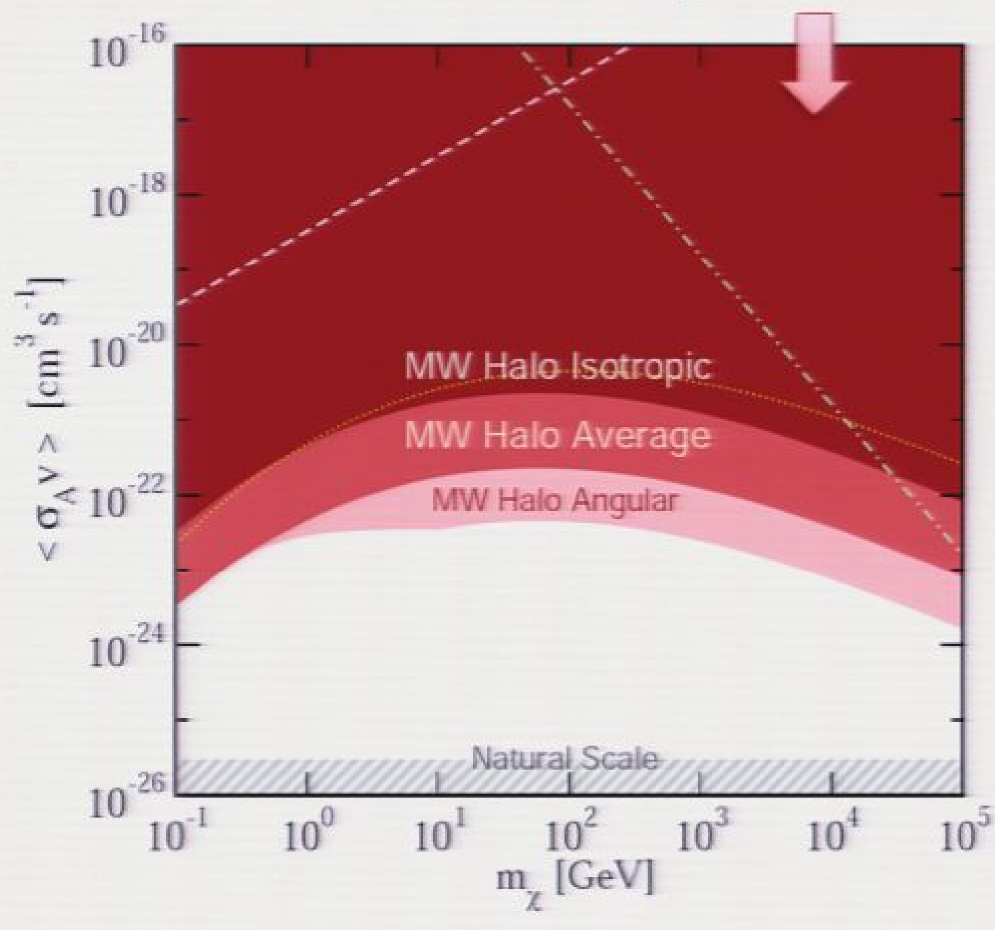
# Compare to Atmospheric Nu Flux




"Even Neutrinos are overproduced"




Yuksel, Horiuchi, Beacom, Ando

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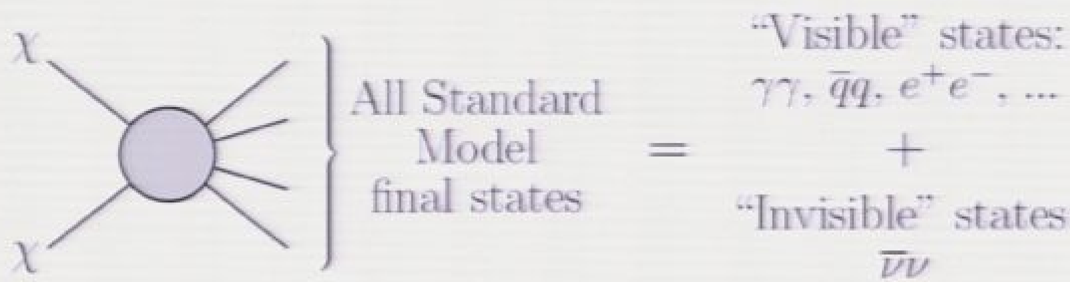


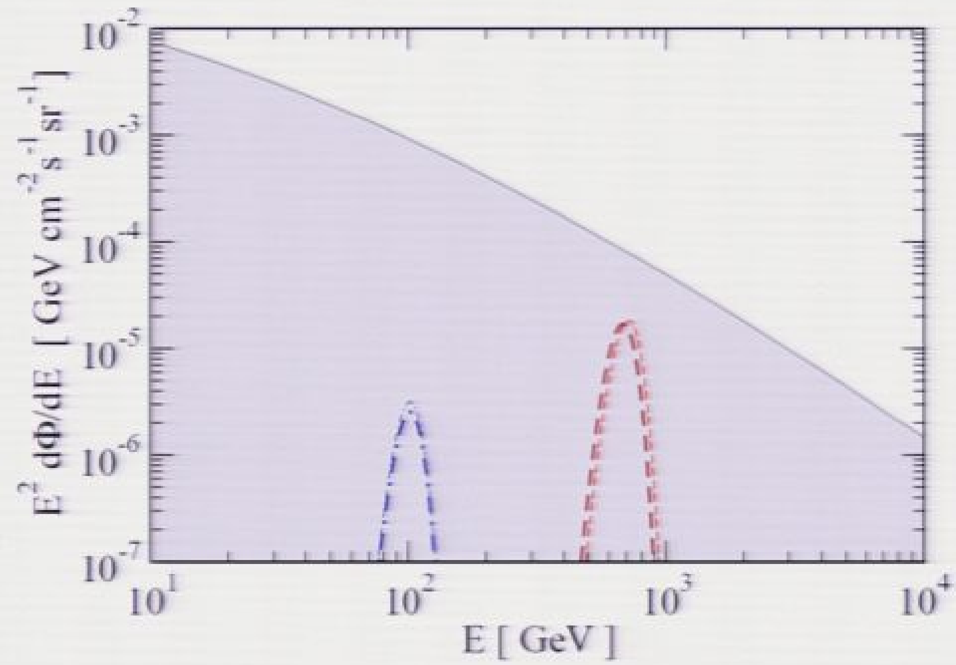


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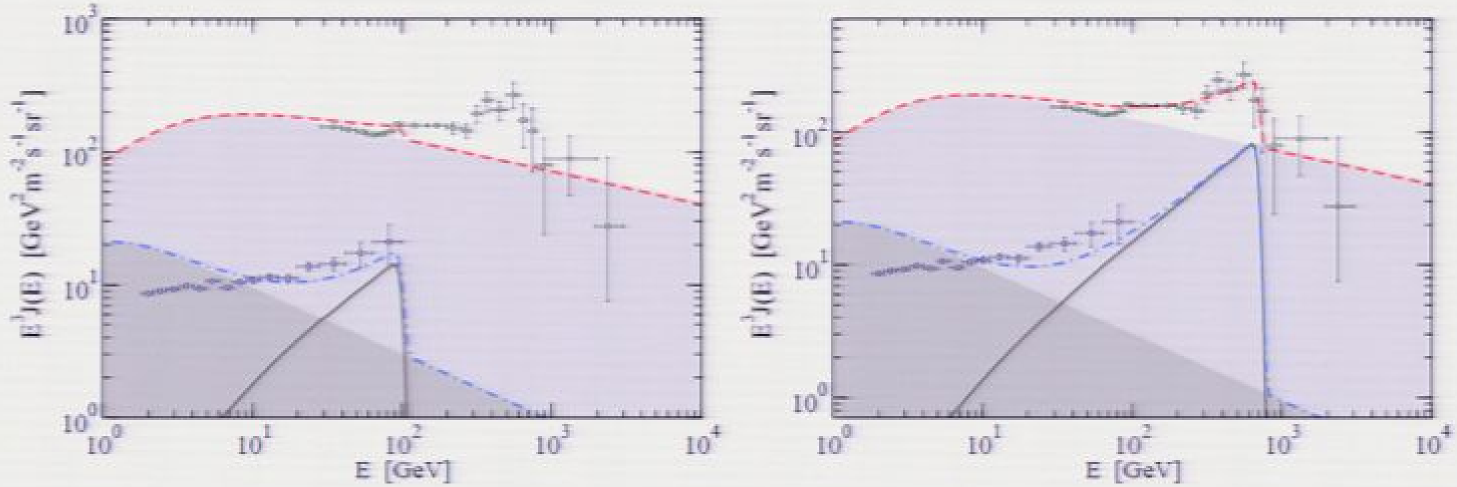


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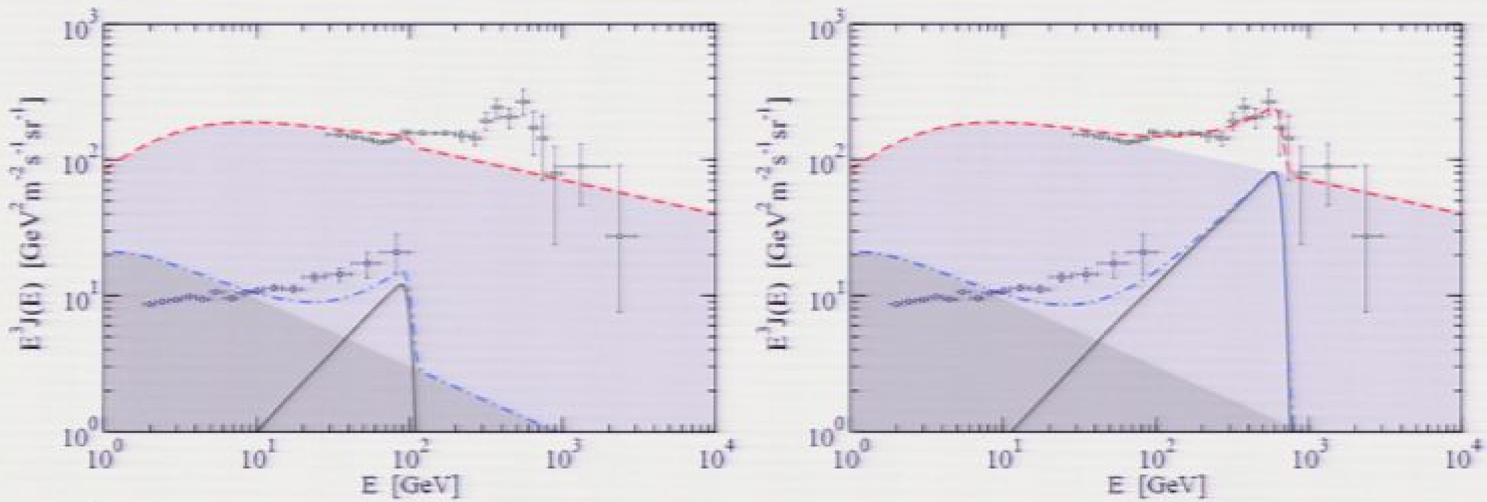


Gogoladze, Khalid, Shafi, Yuksel

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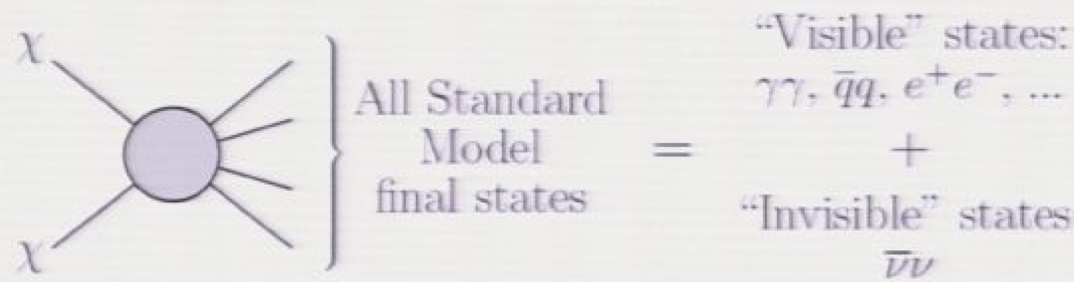


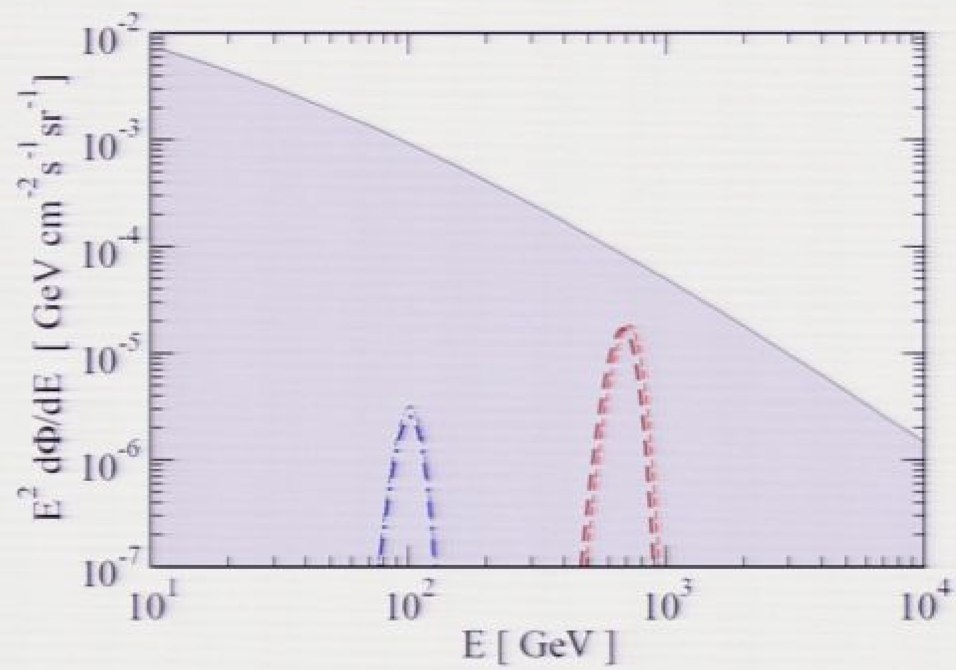






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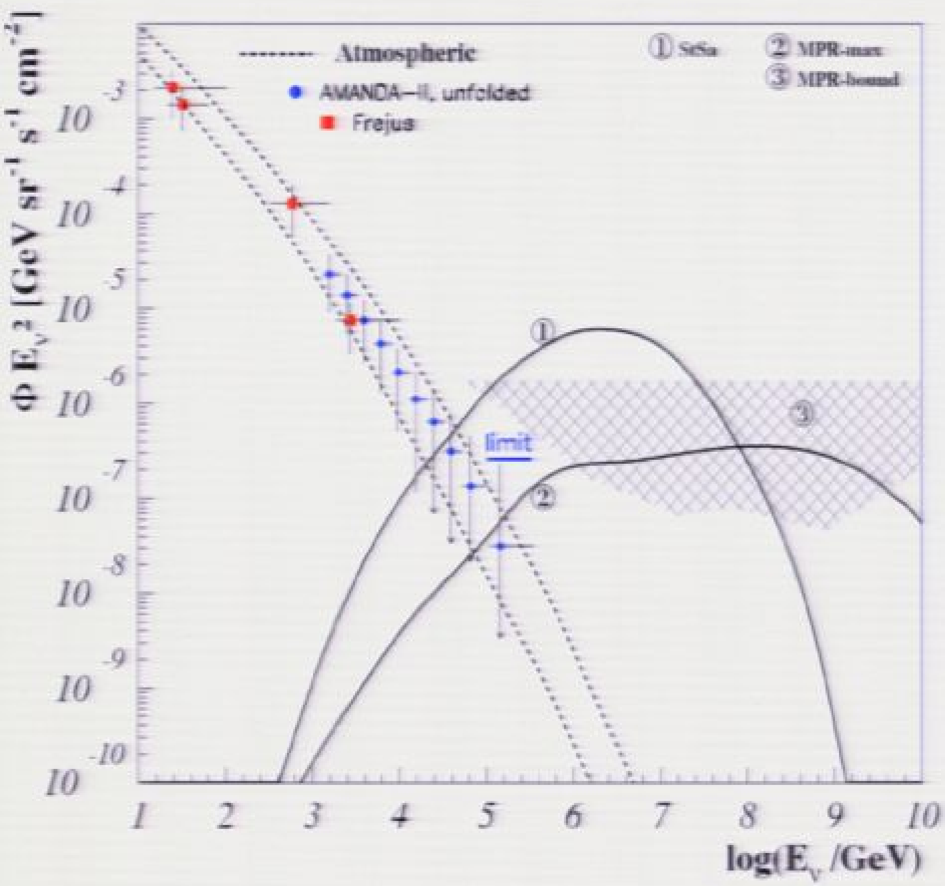


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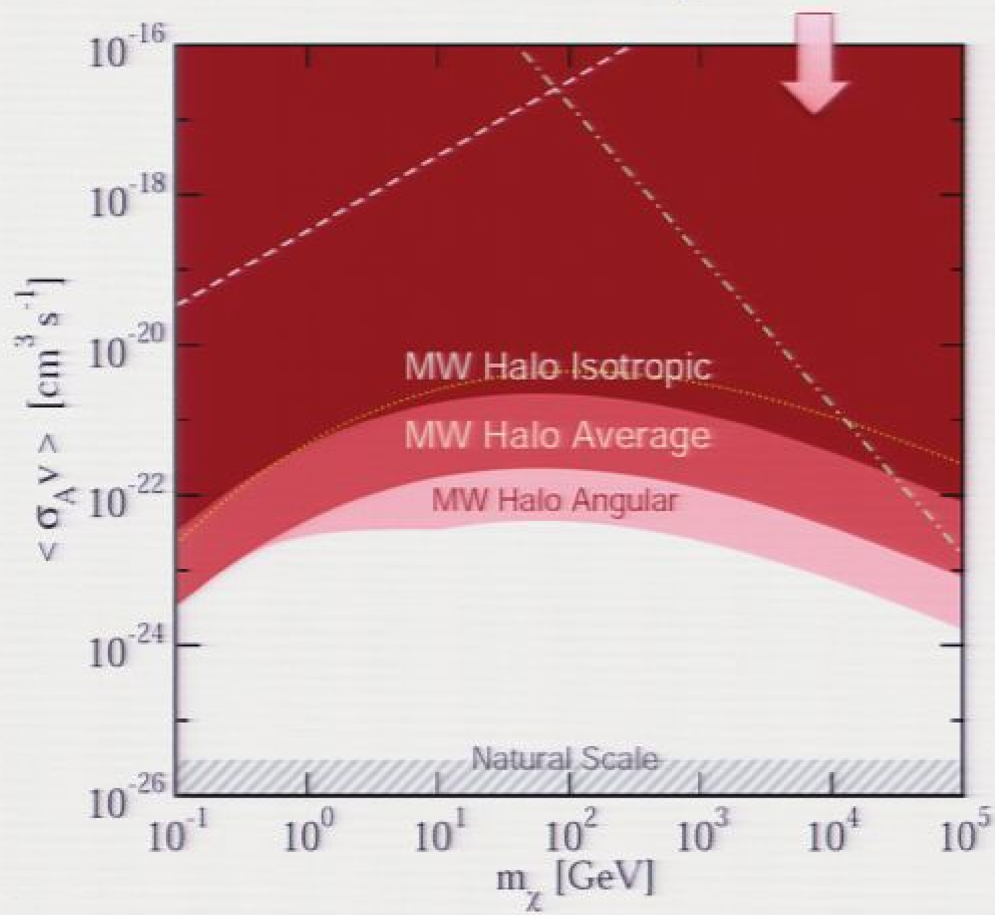


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# The Gamma-ray Source Next Door

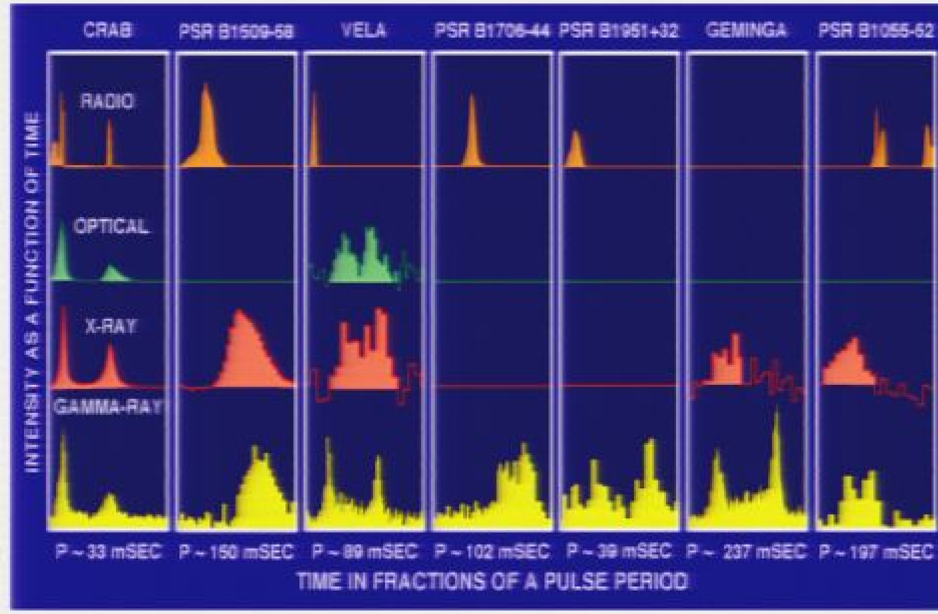
# Geminga:

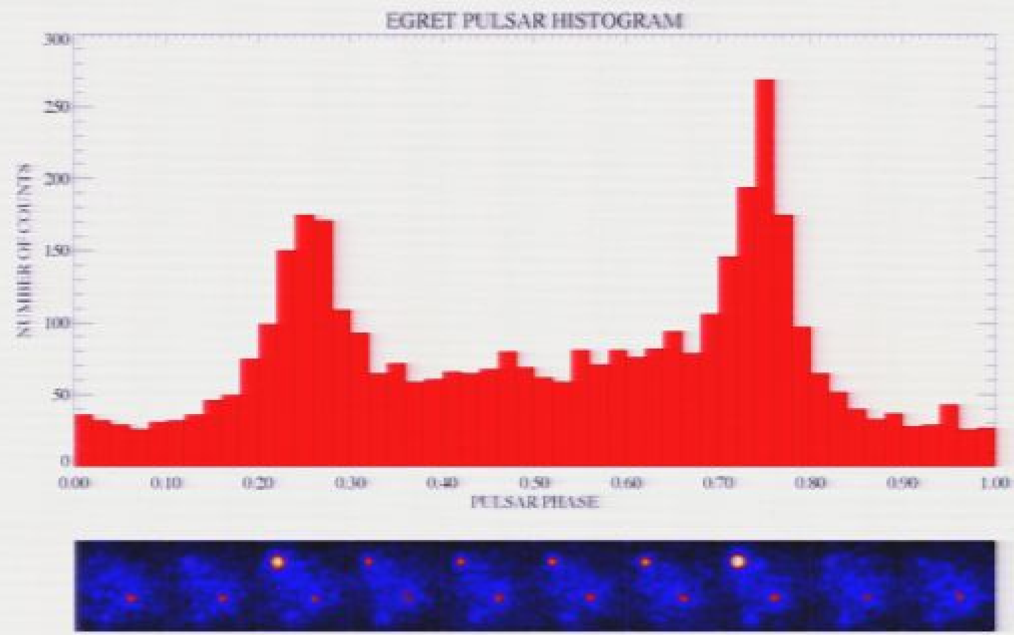
- Radio quite
- First pulsar to be discovered through gamma rays
- Until recently, no evidence of a high energy activity beyond immediate neighborhood

$$r_G \sim 250^{+120}_{-62}\ \mathrm{pc}$$

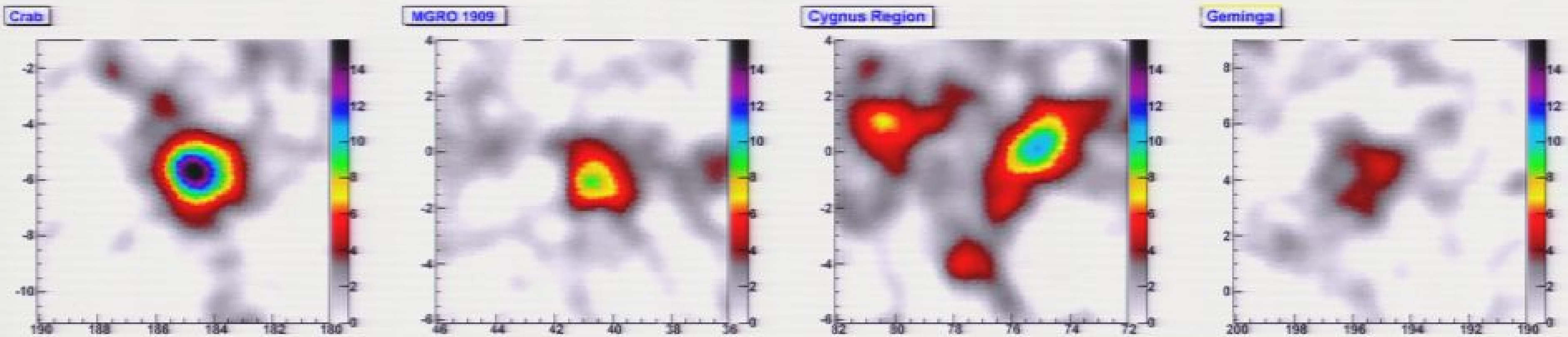
$$t_G \sim 3 \times 10^5\ \mathrm{yr}$$

- Displacement of up to ~100 pc since its birth is possible

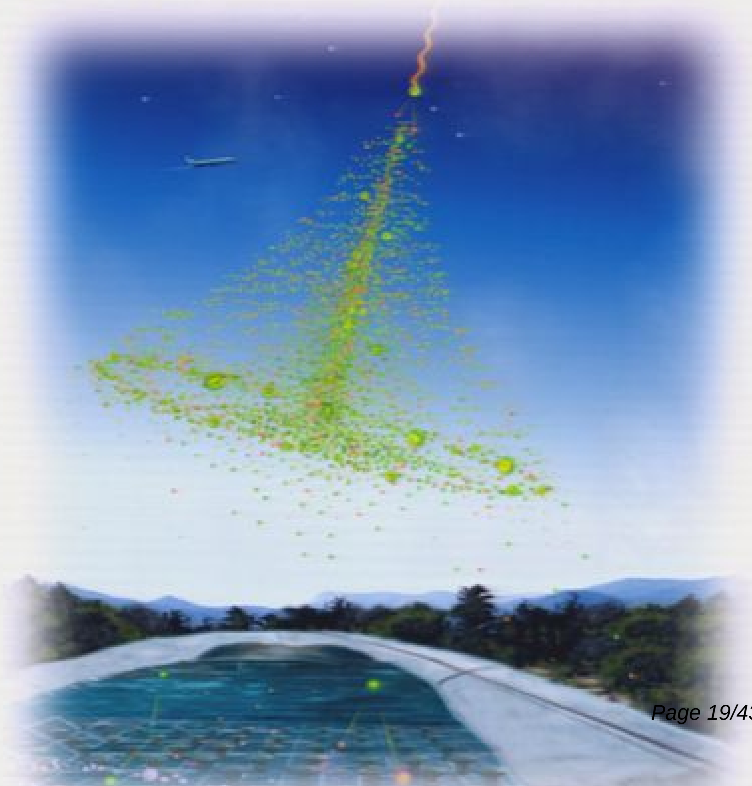


# Milagro Galactic Plane Survey




| Object | Location (l, b) | Flux[c] at 20 TeV $\times 10^{-15}$ $TeV^{-1}cm^{-2}s^{-1}$ | Extent Diameter (deg) |
|---|---|---|---|
| Crab | 184.5, −5.7 | $10.9 \pm 1.2$ | - |
| MGRO J2019+37 | 75.0, 0.2 | $8.7 \pm 1.4$ | $1.1^\circ \pm 0.5^\circ$ [d] |
| MGRO J1908+06 | 40.4, −1.0 | $8.8 \pm 2.4$ | $< 2.6^\circ (90\% CL)$ |
| MGRO J2031+41 | 80.3, 1.1 | $9.8 \pm 2.9$ | $3.0^\circ \pm 0.9^\circ$ |
| C1 | 77.5, −3.9 | $3.1 \pm 0.6$ | $< 2.0^\circ (90\% CL)$ |
| C2 | 76.1, −1.7 | $3.4 \pm 0.8$ | [e] |
| C3 | 195.7, 4.1 | $6.9 \pm 1.6$ | $2.8^\circ \pm 0.8^\circ$ |
| C4 | 105.8, 2.0 | $4.0 \pm 1.3$ | $3.4^\circ \pm 1.7^\circ$ |



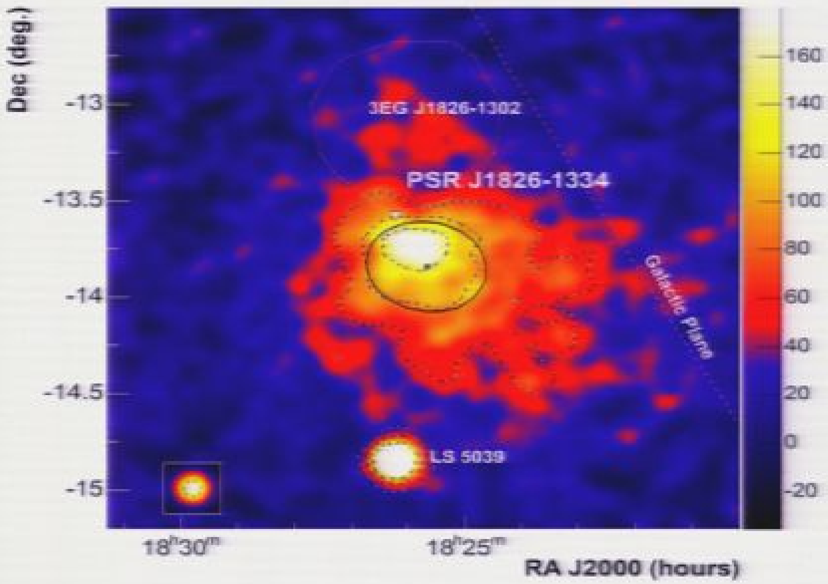
# Immediate Implications:

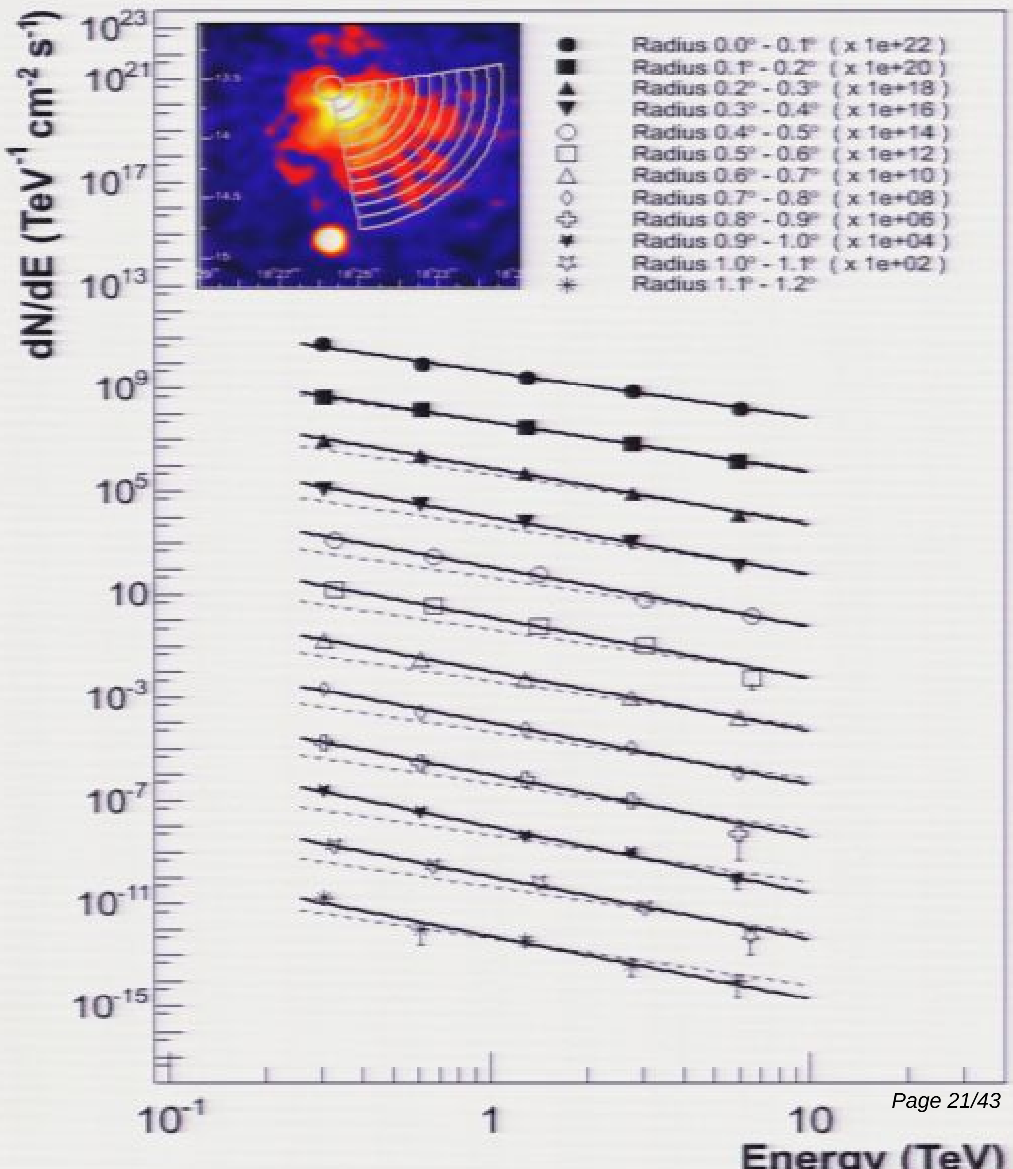
- Milagro detection puts Geminga among growing class of TeV PWNe
- Detection of TeV gamma rays indicates the existence of a nearby cosmic ray accelerator:
  - If gamma rays have a <u>leptonic</u> origin, the source is young & close enough to make a significant contribution to CR electrons & positrons

– We can go beyond simply assuming pulsar's are responsible for the observed positron/electron excess

# More Distant PWN by HESS

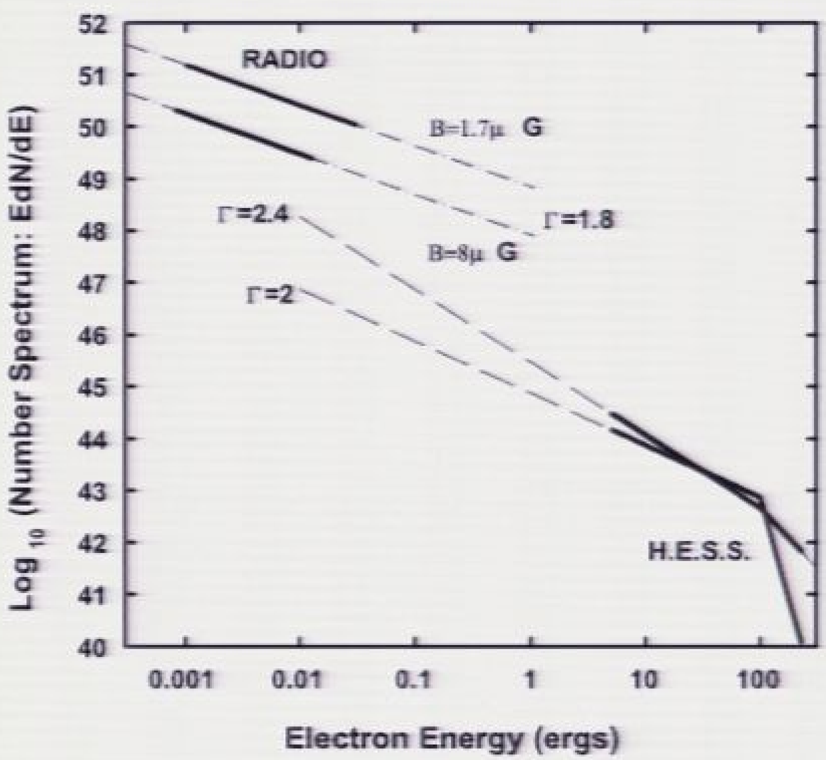
HESS J1825-137, Aharonian et al.



# A Generic Leptonic Model

- The age of Geminga is already much larger than the IC cooling time on CMB photons of the > 100 TeV electrons needed to produce > 20 TeV gamma rays --> Fresh Pair Production




$$\gamma_{max} = E_{max}/(m_e c^2)$$

$$dN/d\gamma = N_0 \gamma^{-\alpha} e^{-\gamma/\gamma_{max}}$$

$$E_{min} = 1 \text{ GeV}, E_{max} = 200 \text{ TeV}$$

$$\alpha = 2$$

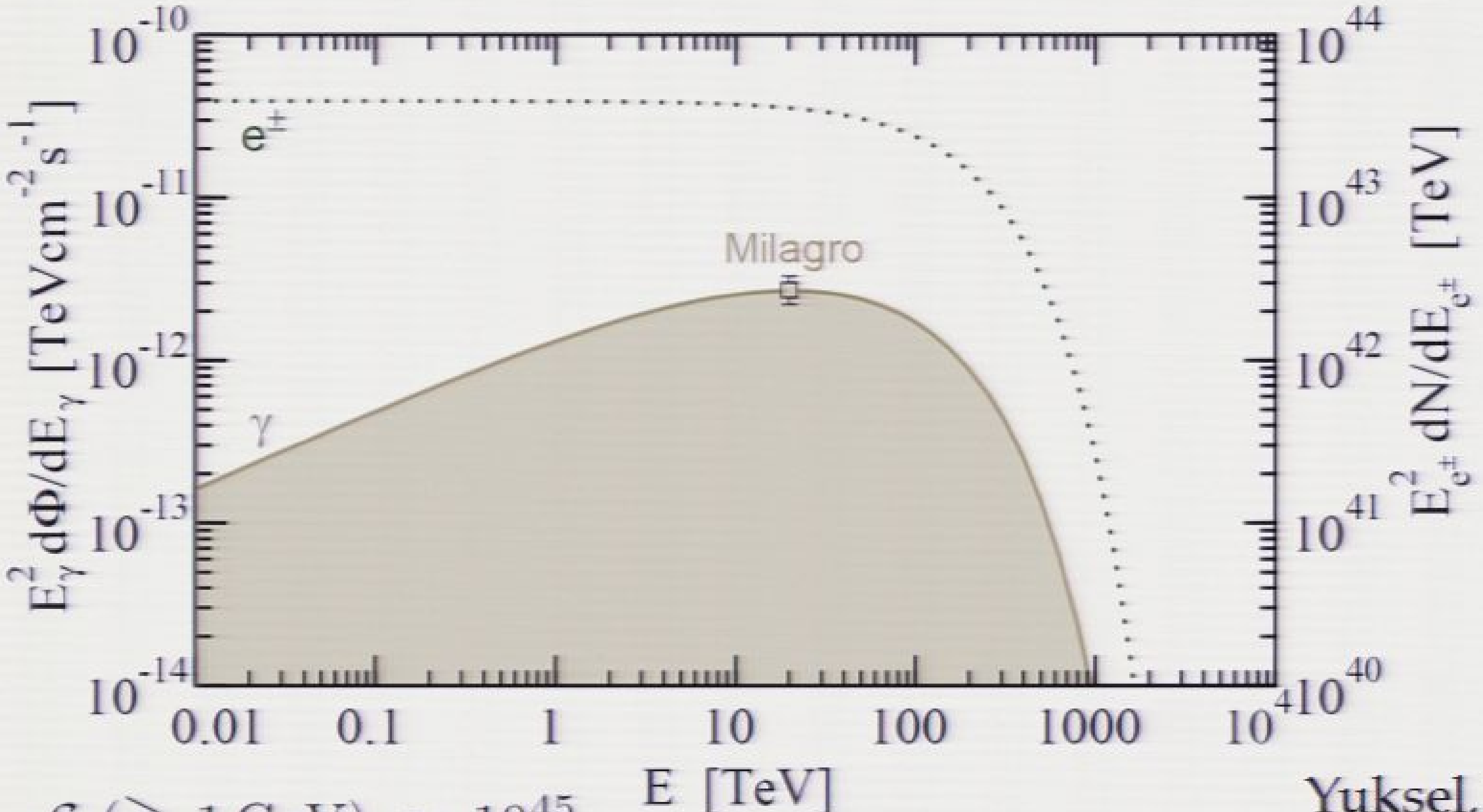




De Jager

# IC Gamma Rays from Geminga

$$\frac{d\Phi}{dE_\gamma} = \frac{c}{4\pi r_G^2}\int d\gamma \int dE_{ph}\frac{dN}{d\gamma}\, n_{ph}(E_{ph})\,\sigma_{KN}(\gamma, E_{ph}, E_\gamma)$$




$\mathcal{E}_e(\gtrsim 1\,\mathrm{GeV}) \simeq 10^{45}$

Yuksel, Kistler, Stanev

# Back of the Envelope Estimates

Observed TeV Gamma Ray Luminosity around Geminga: ~$3 \times 10^{32}$ erg/s

The particle flux with the Goldreich-Julian density from Geminga: ~ $10^{32}$ /s

For a pure electron flow:

$\alpha = 2.$ E:[ 1 GeV - 1000 TeV ] dN/dE ~ $10^{32}$ GeV/s $E^{-2}$

Energy(>1GeV): ~ $2\ 10^{30}$ erg/s Energy(>10TeV): ~$5 \times 10^{29}$ erg/s

Pair multiplicity should be > 200 even if all particles > 10 TeV are confined

In reality, it is harder to confine such high energy particles, so:

Pair multiplicity as large as 10000 (as inferred for younger TeV PWN) could be possible without exceeding pulsar spin down power of ~$3 \times 10^{34}$ erg/s

# IC Gamma Rays from Geminga

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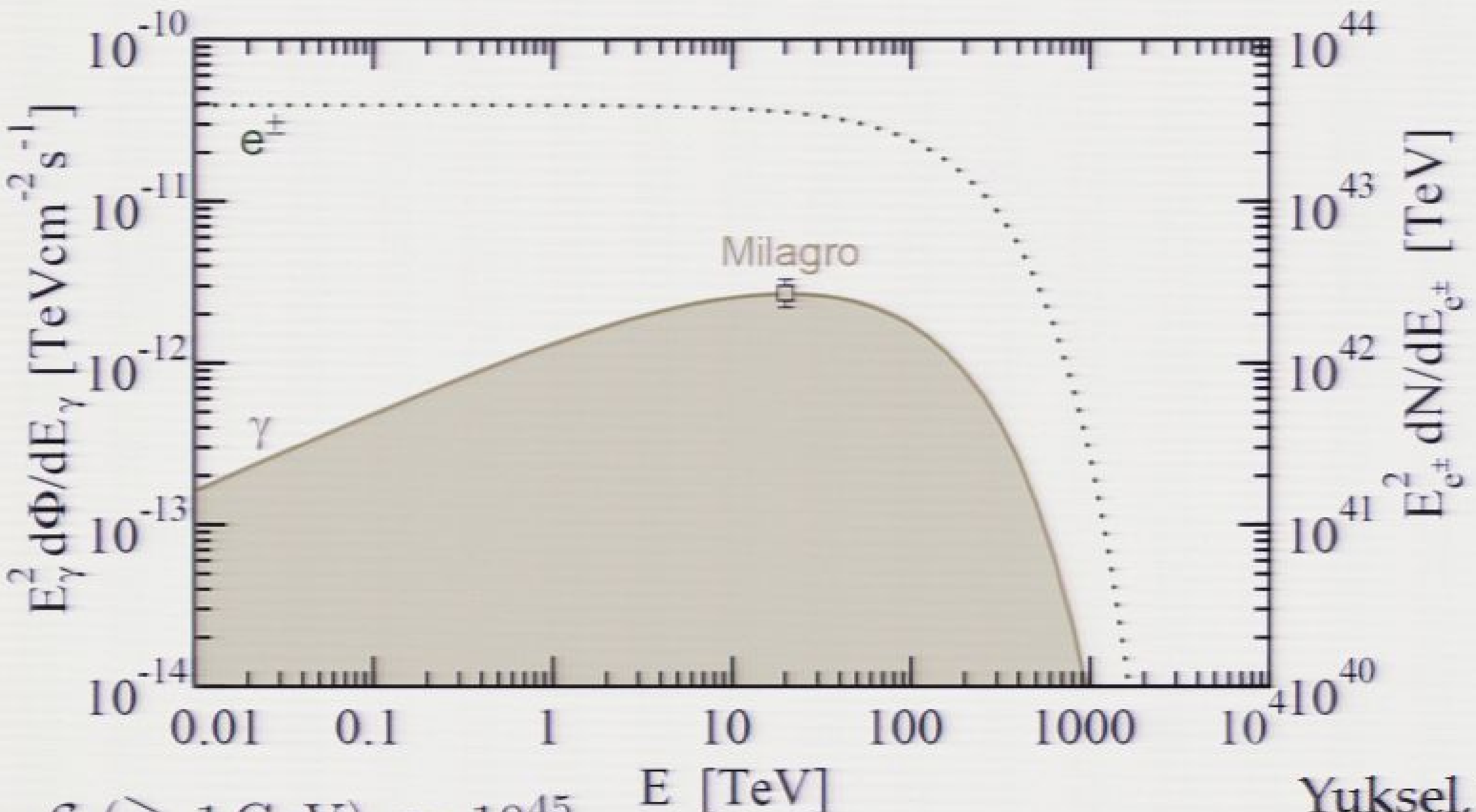


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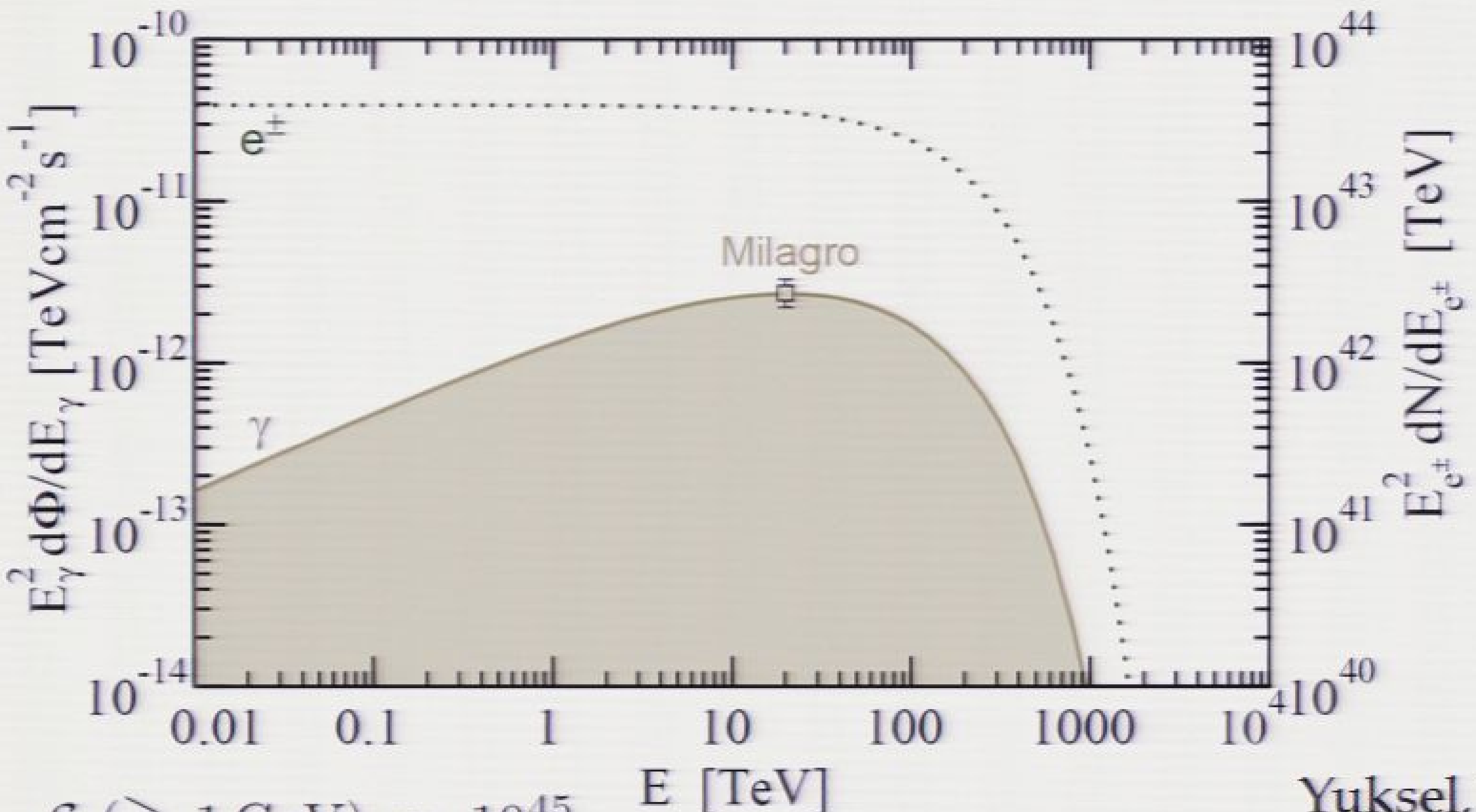


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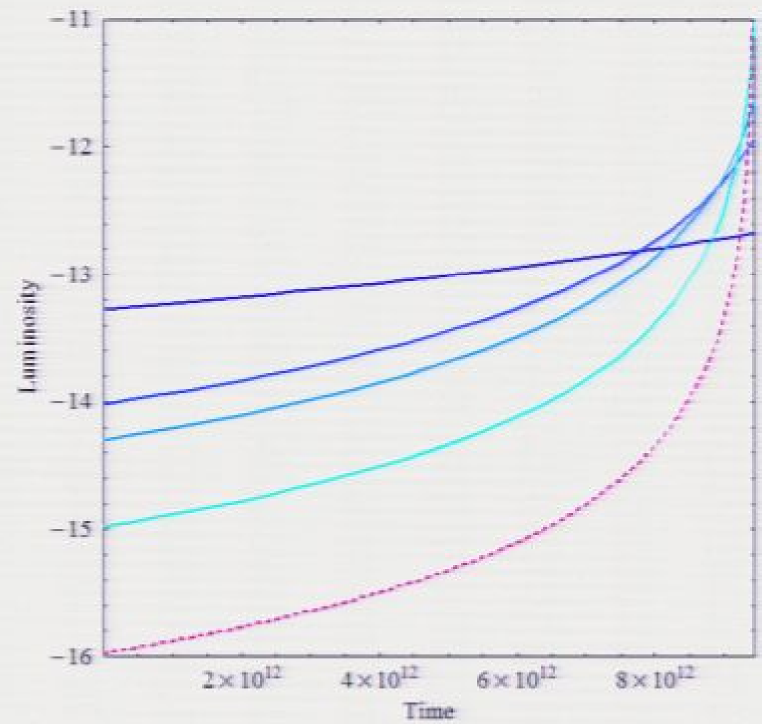
# The Origin of Positron Excess

# Local Positrons from a Nearby Continuously Emitting Source

Assuming breaking via magnetic dipole radiation:
Pulsar spin down luminosity evolves as $\propto (1+t/t_0)^{-\frac{n+1}{n-1}}$

The injection rate of relativistic e-e+ by Geminga:

$$\mathcal{L}_e(t) = \frac{\mathcal{E}_G}{t_G} \frac{(1+(t_G-t)/t_0)^{-2}}{\int^{t_G} dt'(1+(t_G-t')/t_0)^{-2}}$$




Geminga was much stronger in the past and dominated the TeV sky: Multi-GeV positrons may still be reaching us today

# Positron Injection to ISM & Diffusion

$$\boxed{\frac{\partial n}{\partial t} = \frac{\mathcal{D}(\gamma)}{r^2}\frac{\partial}{\partial r}r^2\frac{\partial n}{\partial r} + \frac{\partial}{\partial \gamma}[\ell(\gamma)\, n] + Q(\gamma)}$$

$$\mathcal{D}(\gamma) = \mathcal{D}_0(1+\gamma/\gamma_*)^\delta \quad \ell(\gamma) = \ell_0\gamma^2 \qquad \ell_0 \simeq 5\times 10^{-20}\,\mathrm{s}^{-1}$$

$$Q(\gamma) = dN/d\gamma\,\delta(r)\,\delta(t-t_G)$$

Atoyan, Aharonian, Volk, 1995

$$\boxed{n(r,t,\gamma) = \frac{dN/d\gamma}{\pi^{3/2}\,r^3}\frac{(r/r_d(t,\gamma))^3\,e^{-(r/r_d(t,\gamma))^2}}{(1-\ell_0\,t\,\gamma)^{2-\alpha}}}$$

$$r_d(t,\gamma) \simeq 2\left(\mathcal{D}(\gamma)\,t\,[1-(1-\gamma/\gamma_c)^{1-\delta}]/[(1-\delta)\gamma/\gamma_c]\right)^{1/2}$$

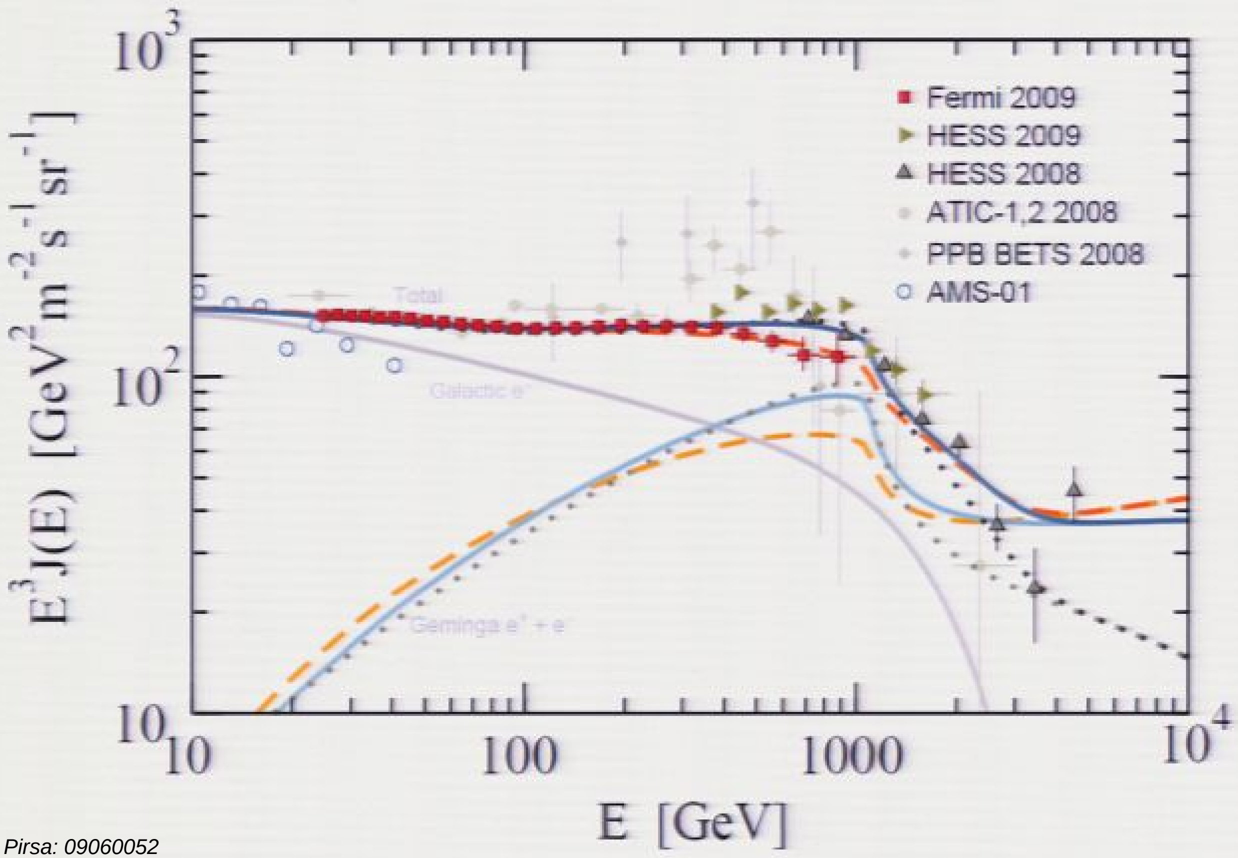
For $t_G \sim 3\times 10^5\,\mathrm{yr}$, $\mathcal{D}_0 \simeq 4\times 10^{27}\ \mathrm{cm^2 s^{-1}}$, and $\delta = 0.4$ (intermediate between $\delta = 1/3$ and $1/2$ [28]), the diffusion radius is $r_d \simeq 150, 175, 250$ pc for $E = 2, 10, 50$ GeV

# Geminga Contributions

Dotted, Solid, Dashed lines correspond to $t_G = 3 \times 10^5$ yr

$\mathcal{E}_G = 1, 2, 3 \times 10^{48}$ erg $\quad \delta = 0.4, 0.5, 0.6$

$r_G = 150 \rightarrow 250$ pc, 220 pc, $250 \rightarrow 200$ pc

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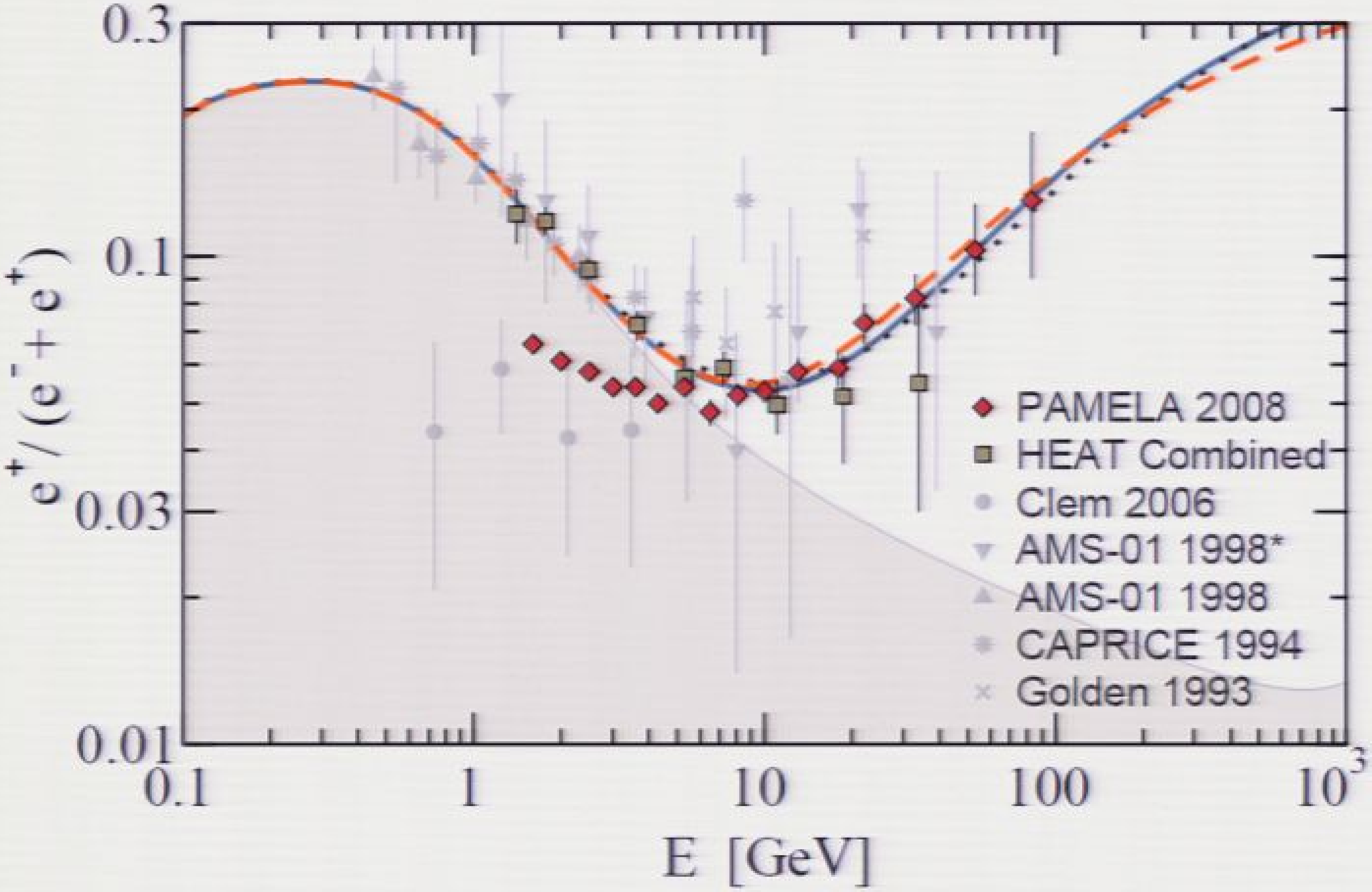
# Accounting for Positron Excess?

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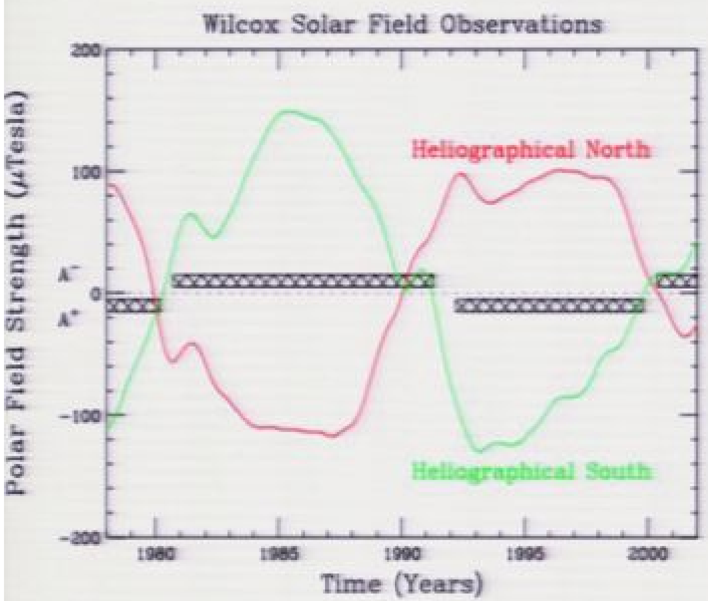
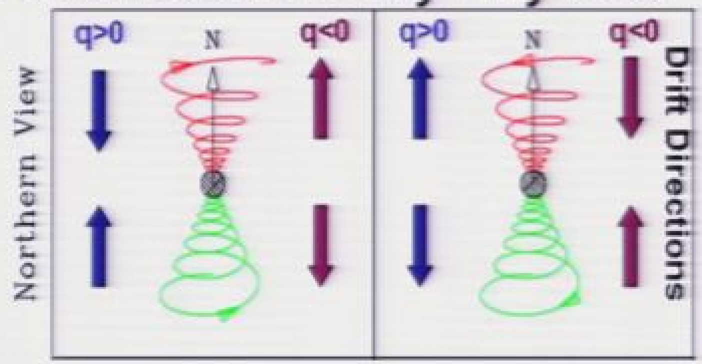
See also Bouleras (1998) Atoyan et al (1995), Hooper et al (2008) , Profumo (2008) and many others

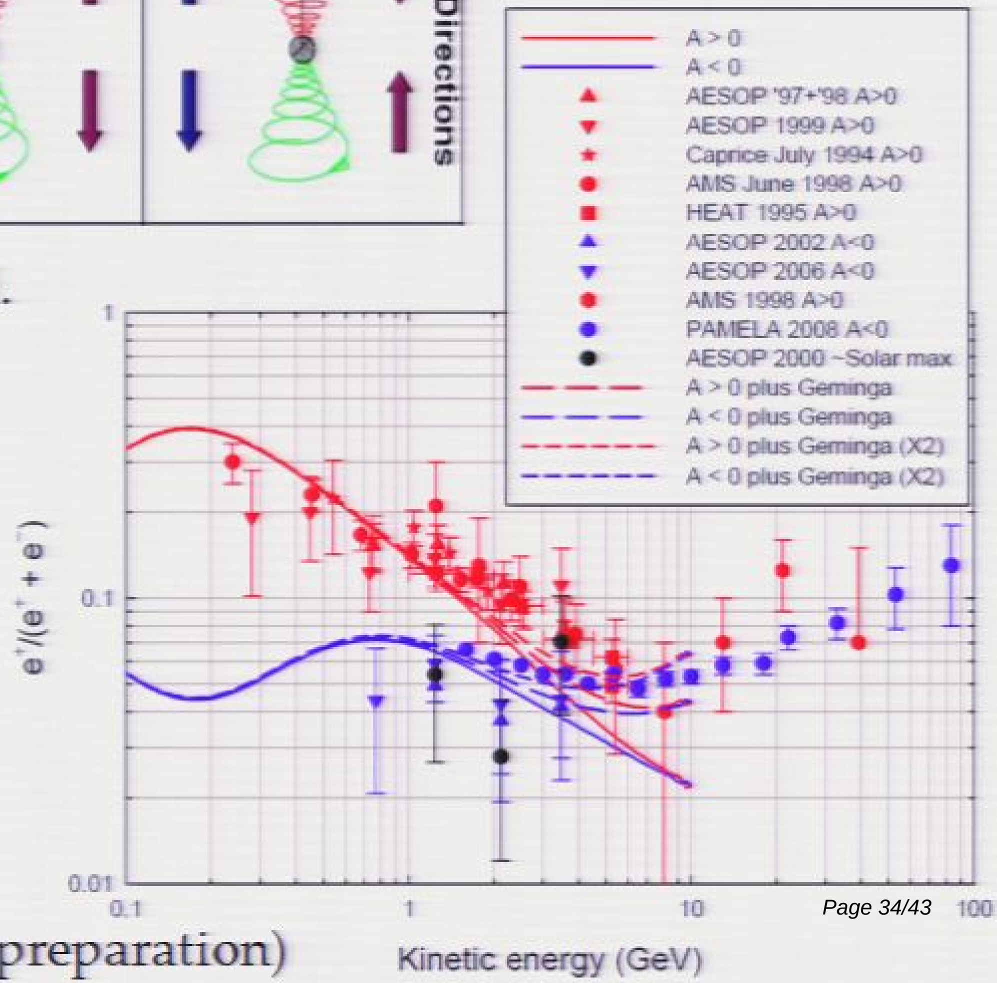
# Charge Sign Dependent Solar Modulation

Reversals of the solar magnetic field occurs every 11 years.



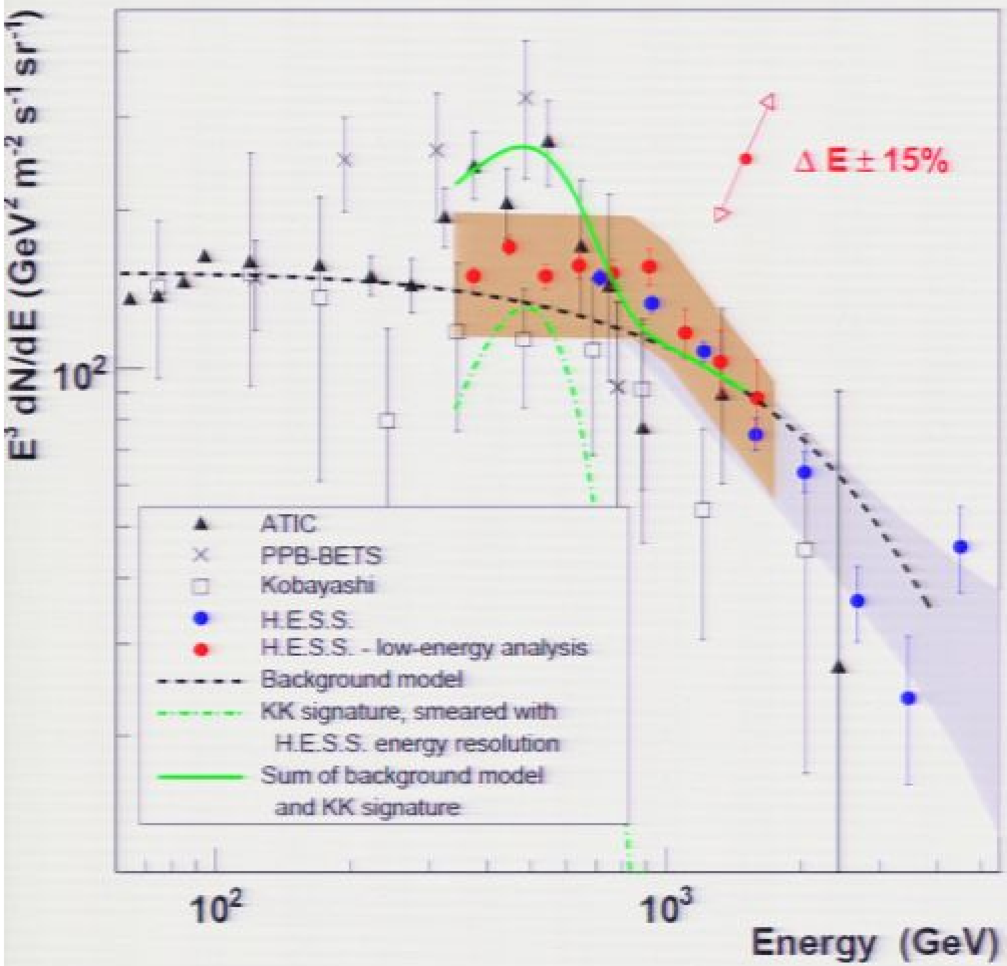

Clem et al.

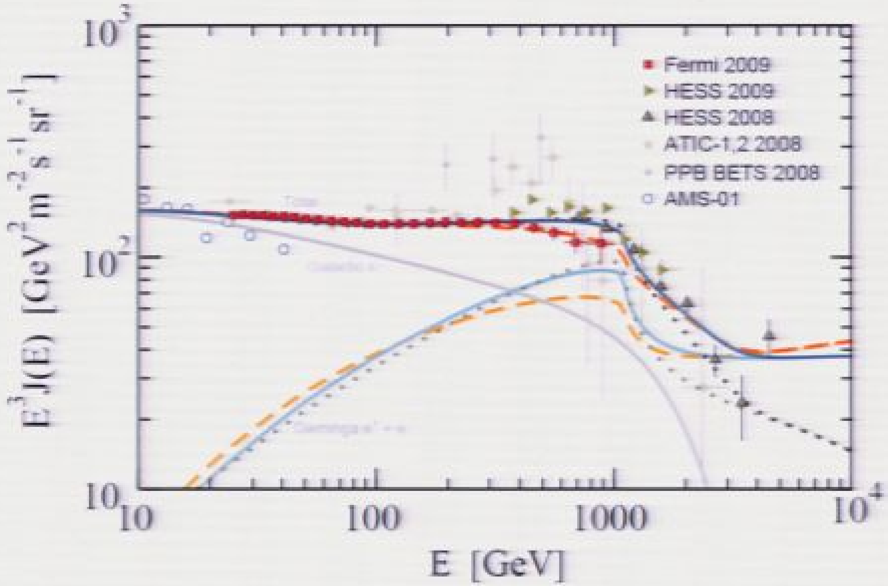



Burger et al. (in preparation)

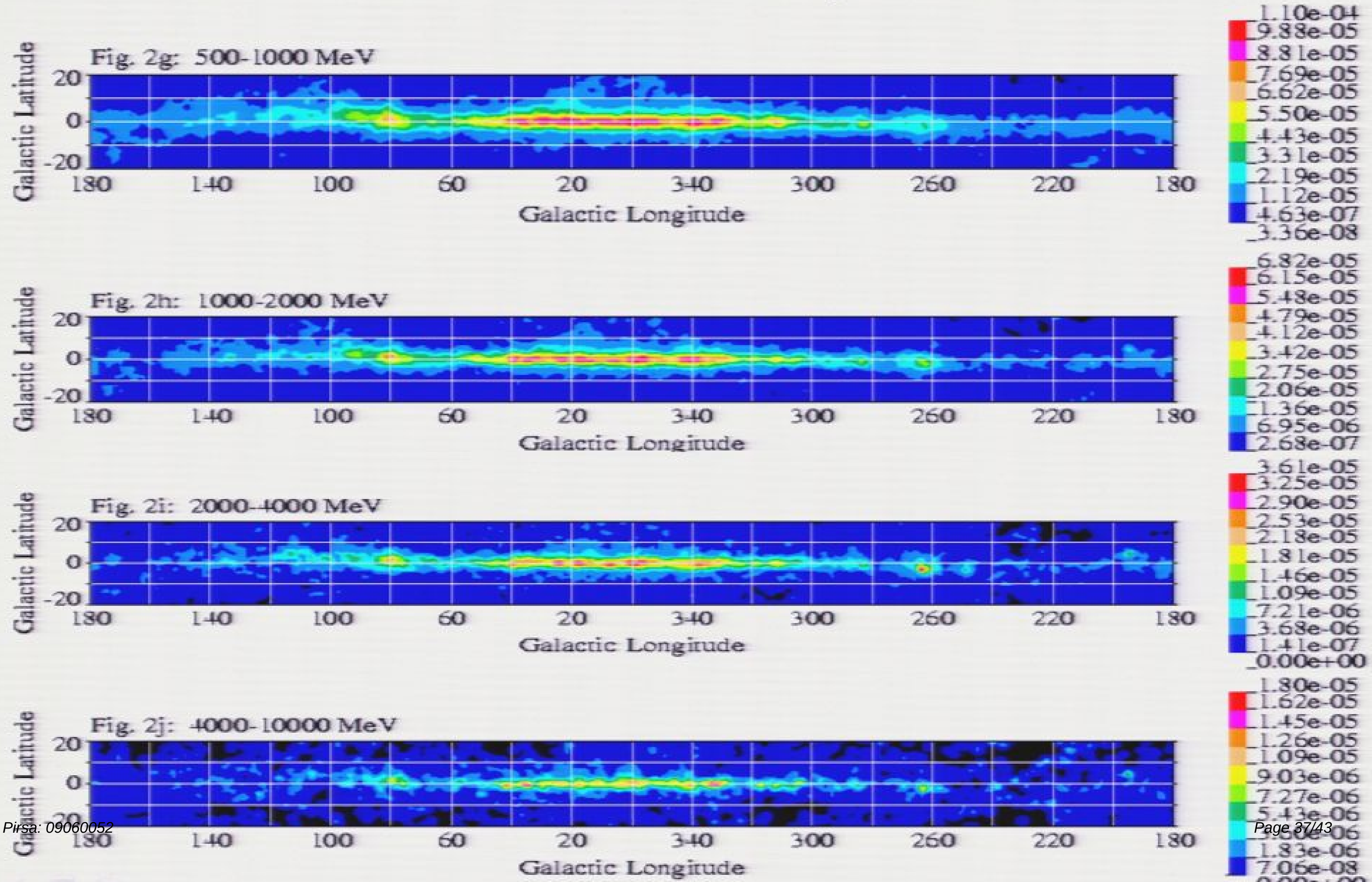
# Future Implications

# Multi TeV Energies

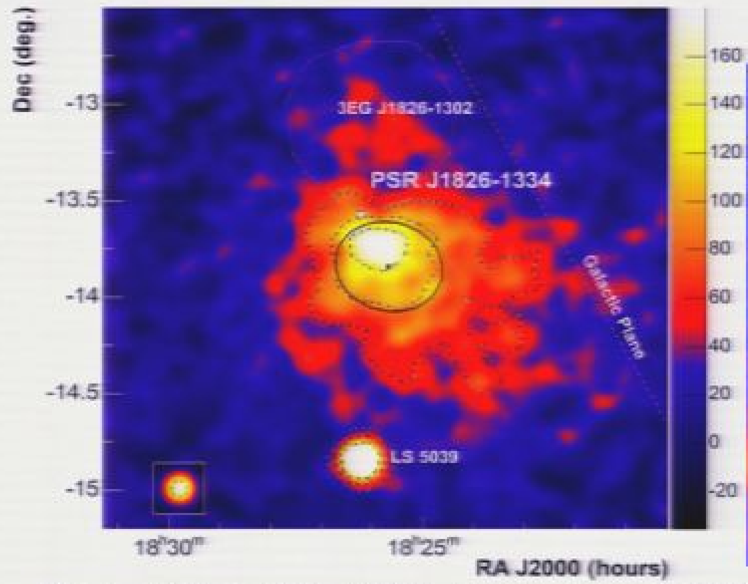


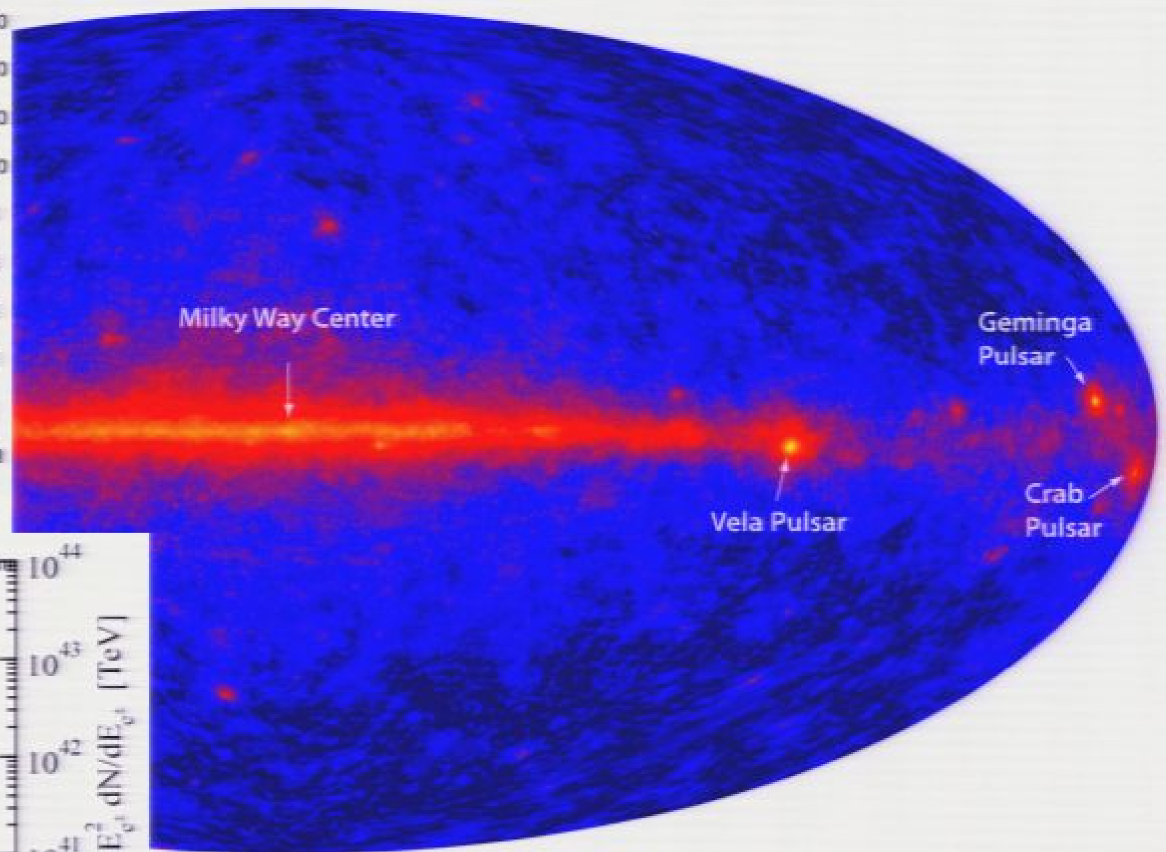



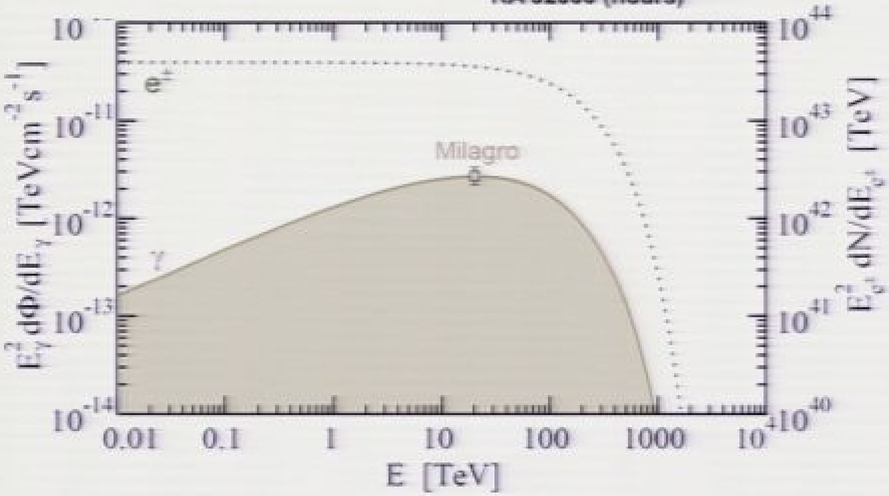

# Galactic Plane by EGRET



# Fermi Prospects



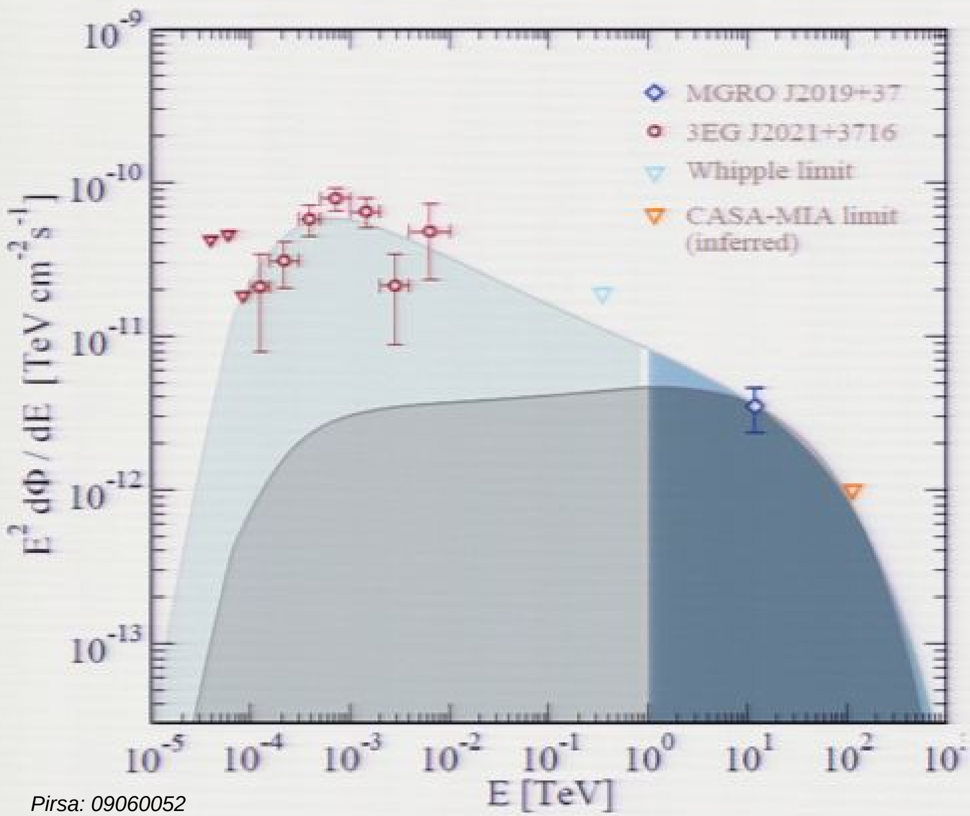


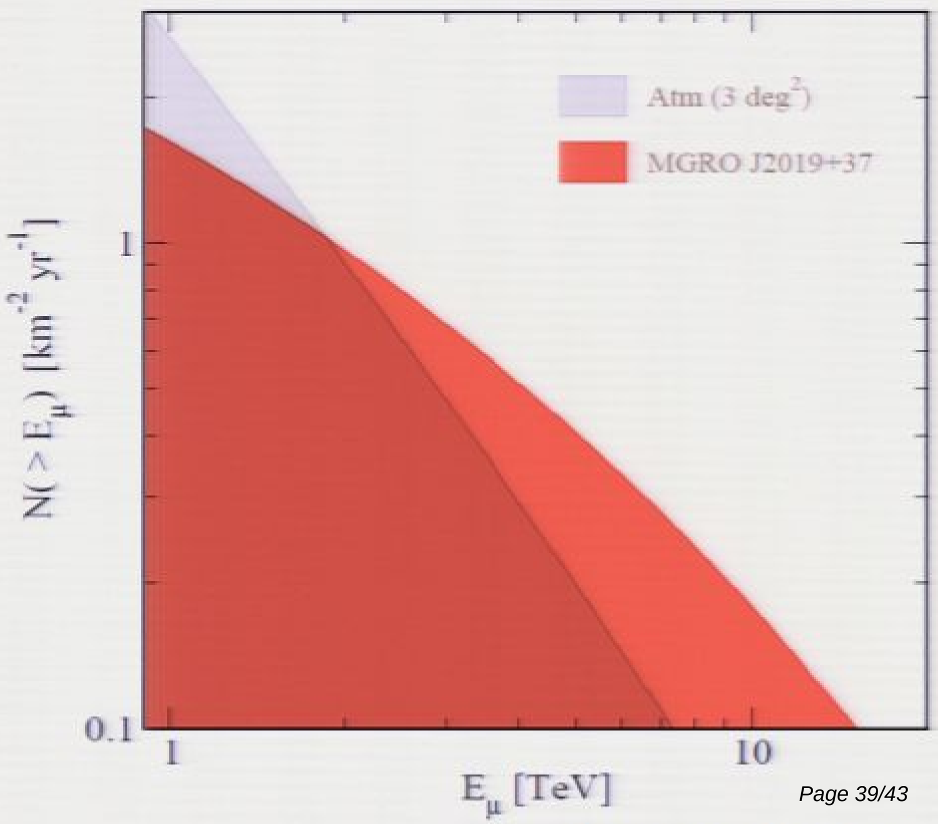

More observations will be needed to pin-down the total energy and how it is distributed both in energy and spatially.

# Hadronic Alternative: TeV Neutrinos

If a nucleonic wind carry away much of the spin down energy of pulsar, gamma rays may be produced via decay of neutral pions from hadronic scattering

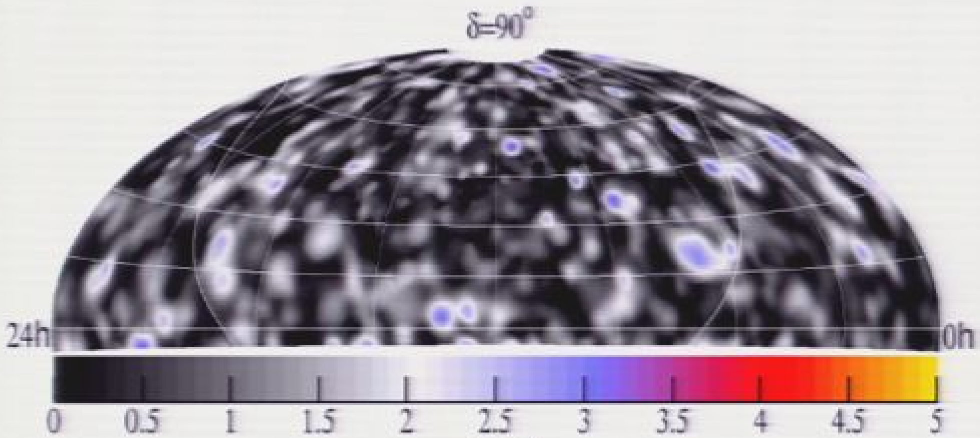
➔ >1 Neutrino-induced muon in IceCube

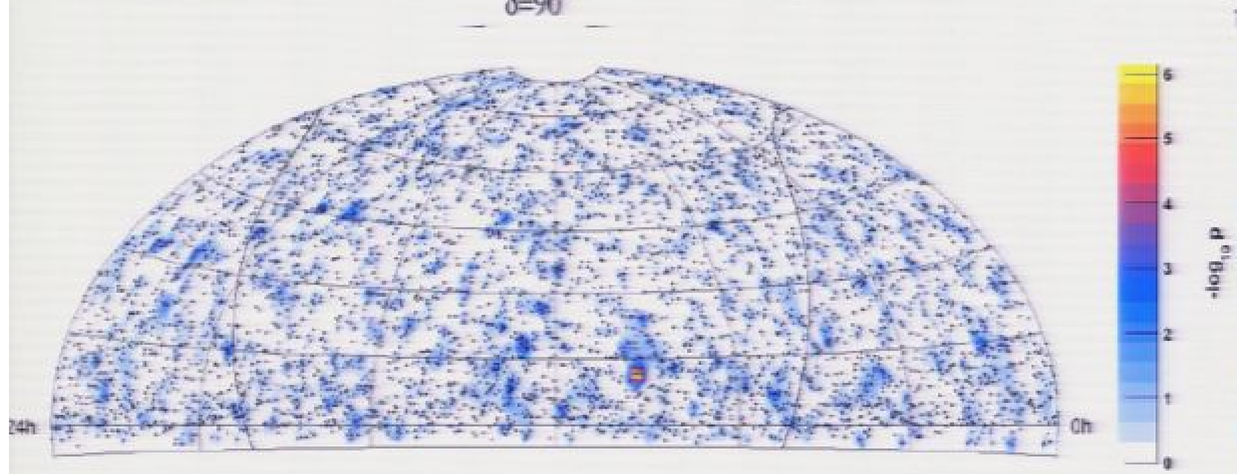



Beacom, Kistler

# Amanda-II Hot Spot?




| Candidate | $\delta(^\circ)$ | $\alpha(h)$ | $\Phi_{90}$ | $p$ | $\Psi(^\circ)$ |
|---|---|---|---|---|---|
| 3C 273 | 2.05 | 12.49 | 8.71 | 0.086 | 2.1 |
| SS 433 | 4.98 | 19.19 | 3.21 | 0.64 | 2.2 |
| GRS 1915+105 | 10.95 | 19.25 | 7.76 | 0.11 | 2.3 |
| M87 | 12.39 | 12.51 | 4.49 | 0.43 | 2.3 |
| PKS 0528+134 | 13.53 | 5.52 | 3.26 | 0.64 | 2.3 |
| 3C 454.3 | 16.15 | 22.90 | 2.58 | 0.73 | 2.3 |
| Geminga | 17.77 | 6.57 | 12.77 | 0.0086 | 2.3 |
| Crab Nebula | 22.01 | 5.58 | 9.27 | 0.10 | 2.3 |
| GRO J0422+32 | 32.91 | 4.36 | 2.75 | 0.76 | 2.2 |
| Cyg X-1 | 35.20 | 19.97 | 4.00 | 0.57 | 2.1 |
| MGRO J2019+37 | 36.83 | 20.32 | 9.67 | 0.077 | 2.1 |
| 4C 38.41 | 38.14 | 16.59 | 2.20 | 0.85 | 2.1 |
| Mrk 421 | 38.21 | 11.07 | 2.54 | 0.82 | 2.1 |
| Mrk 501 | 39.76 | 16.90 | 7.28 | 0.22 | 2.0 |
| Cyg A | 40.73 | 19.99 | 9.24 | 0.095 | 2.0 |
| Cyg X-3 | 40.96 | 20.54 | 6.59 | 0.29 | 2.0 |
| Cyg OB2 | 41.32 | 20.55 | 6.39 | 0.30 | 2.0 |
| NGC 1275 | 41.51 | 3.33 | 4.50 | 0.47 | 2.0 |
| BL Lac | 42.28 | 22.05 | 5.13 | 0.38 | 2.0 |
| H 1426+428 | 42.68 | 14.48 | 5.68 | 0.36 | 2.0 |
| 3C66A | 43.04 | 2.38 | 8.06 | 0.18 | 2.0 |
| XTE J1118+480 | 48.04 | 11.30 | 5.17 | 0.50 | 1.8 |
| 1ES 2344+514 | 51.71 | 23.78 | 5.74 | 0.44 | 1.7 |
| Cas A | 58.82 | 23.39 | 3.83 | 0.67 | 1.6 |
| LS I +61 303 | 61.23 | 2.68 | 14.74 | 0.034 | 1.5 |
| 1ES 1959+650 | 65.15 | 20.0 | 6.76 | 0.44 | 1.5 |

# Help is on the Way

- More data should become available soon:
  - GeV Gamma Rays: Fermi (GLAST)
  - TeV Gamma Rays: Hess, Veritas, Future ACTs
  - Positrons/Electrons: PAMELA, ATIC, Fermi, HESS, AMS?
  - Neutrinos: IceCube, Super-K ...
- Which may result in:
  - Developing more detailed models, including time & spatial evolution in the source & Galaxy
  - Unraveling positron/electron excess?
  - Learning more about Dark Matter
  - Discovering First TeV neutrino source?

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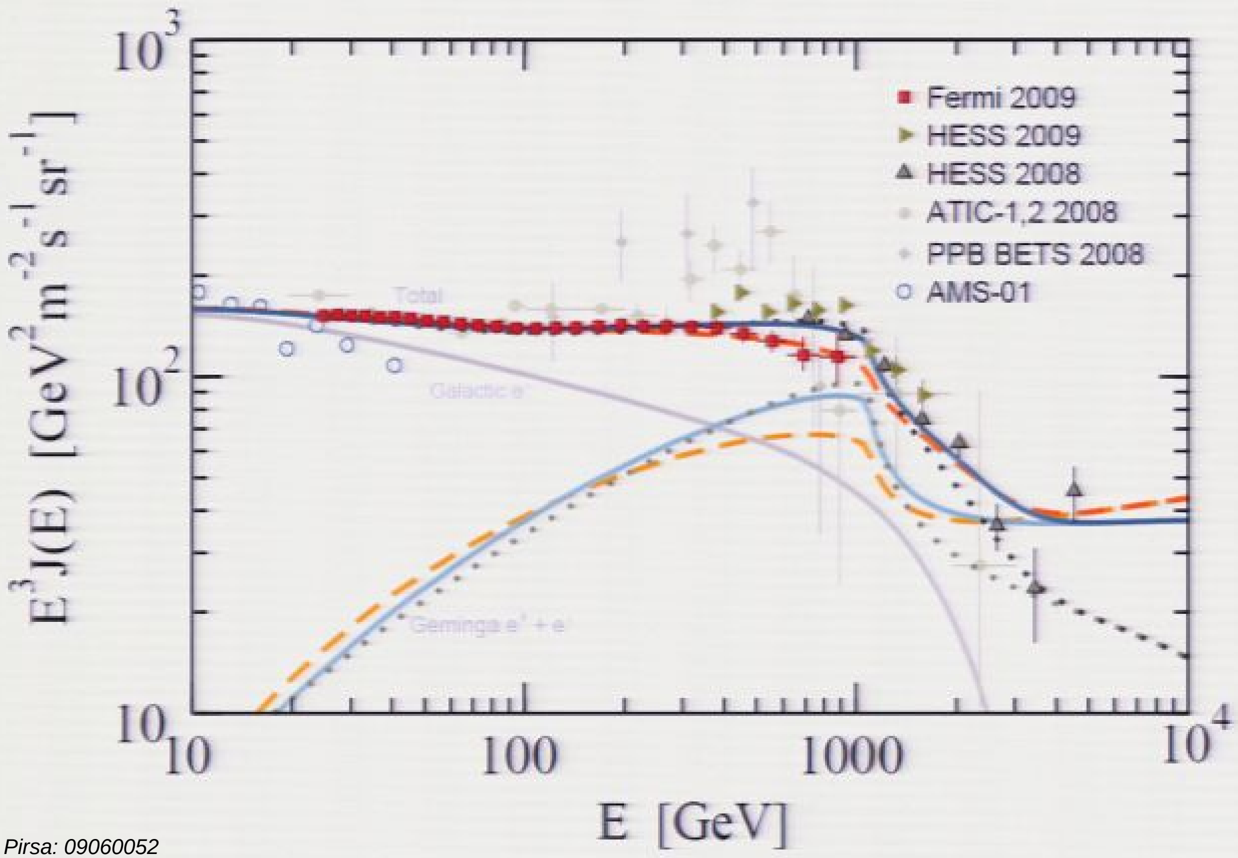
# Geminga Contributions

Dotted, Solid, Dashed lines correspond to $t_G = 3 \times 10^5$ yr

$\mathcal{E}_G = 1, 2, 3 \times 10^{48}$ erg $\quad \delta = 0.4, 0.5, 0.6$

$r_G = 150 \rightarrow 250$ pc, 220 pc, $250 \rightarrow 200$ pc




Yuksel, Kistler, Stanev