THE ORIGIN OF THE COSMIC POSITRON & ELECTRON EXCESS AND BEYOND

Cosmic Ray Anisotropy Workshop
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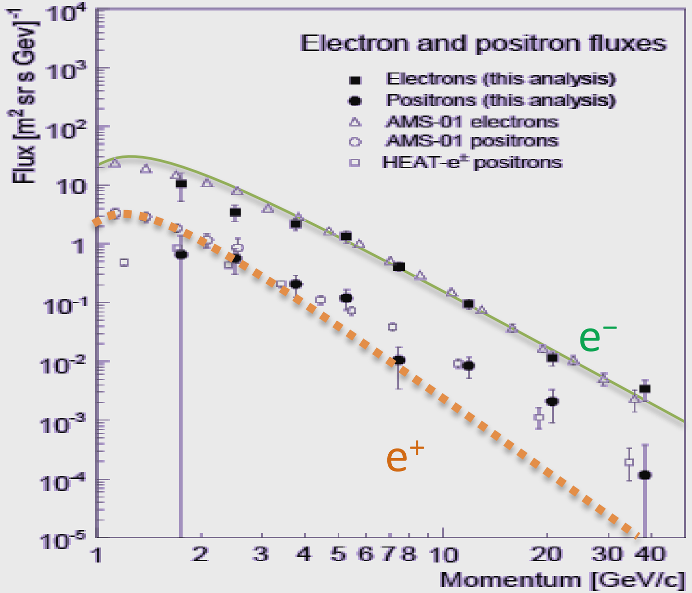
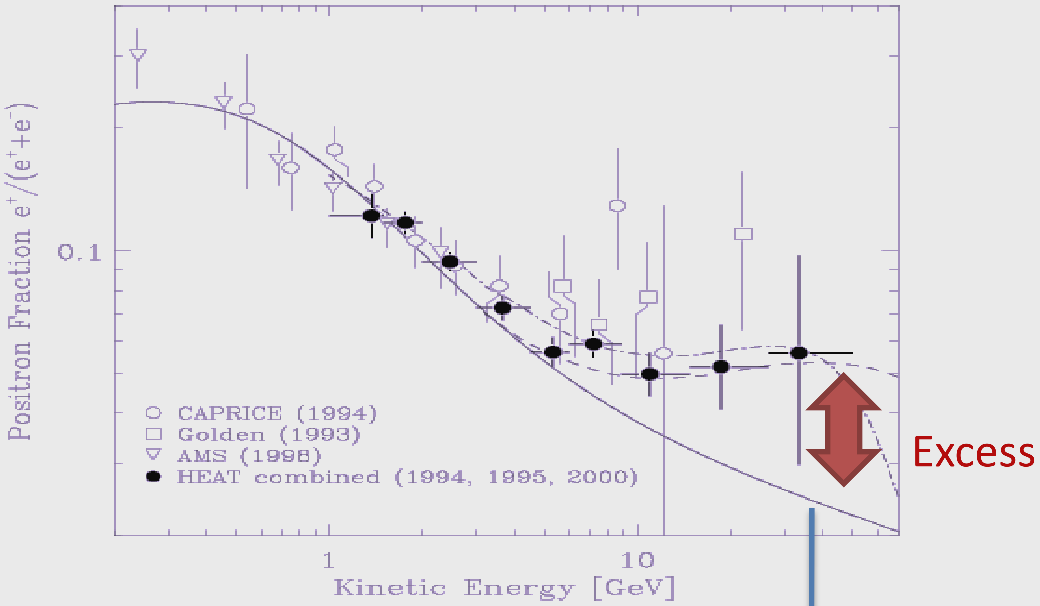
H. Yüksel, M.D. Kistler & T. Stanev, Phys. Rev. Lett. 103, 051101, 2009
M.D. Kistler & H. Yüksel (arXiv:0912.0264)

Spectra of Electrons & Positrons (Summer 2008)

Primary Sources: e^- accelerated in supernova remnants

Secondary Sources: $e^\pm$ from collisions between cosmic rays & ISM protons

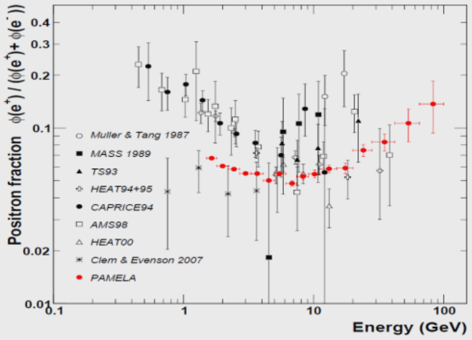


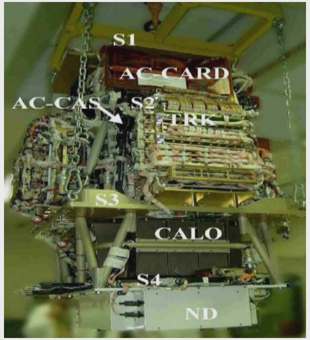


Model Prediction: $e^+/(e^- + e^+)$

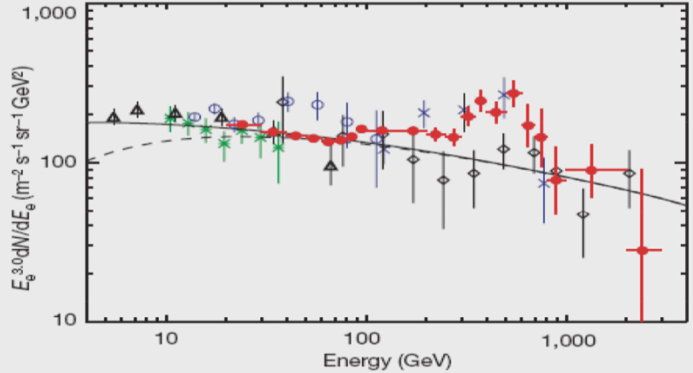
Past & Future Observations of Cosmic Electrons/Positrons

PAMELA

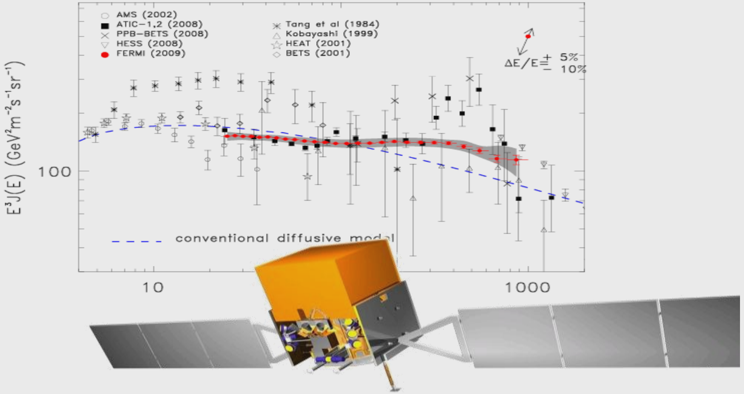




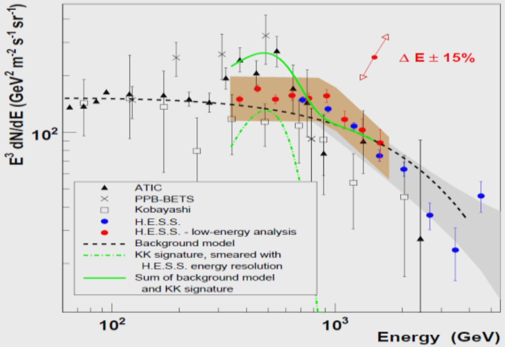
ATIC

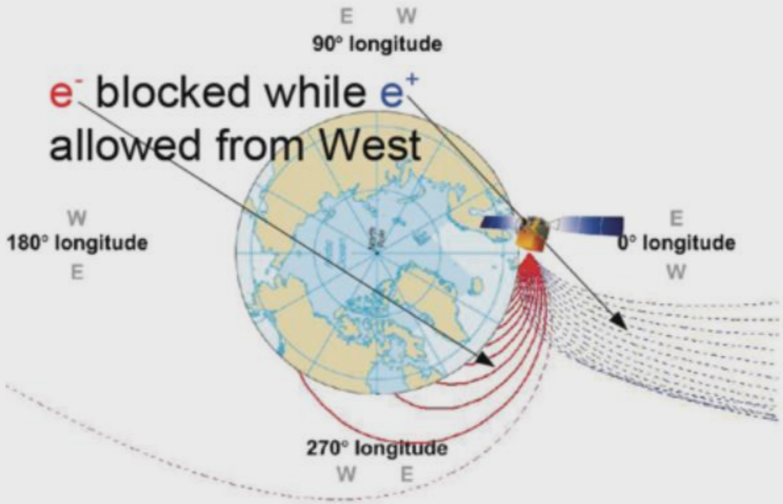


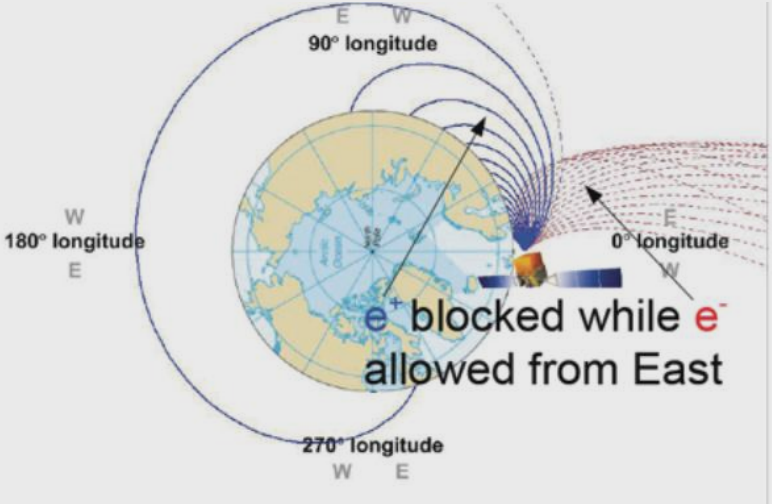
Fermi



HESS




E W
90° longitude
e- blocked while e+
allowed from West
W
180° longitude
E
E
0° longitude
W
270° longitude
W E


E W
90° longitude
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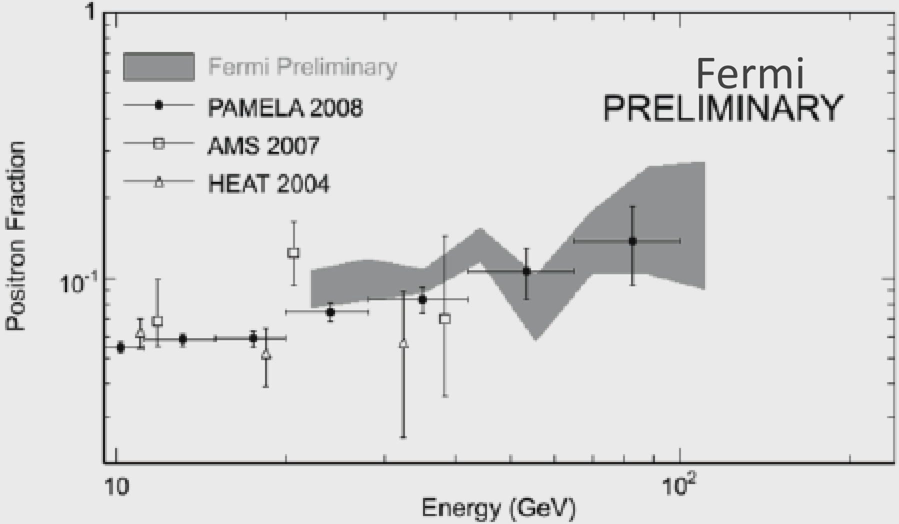
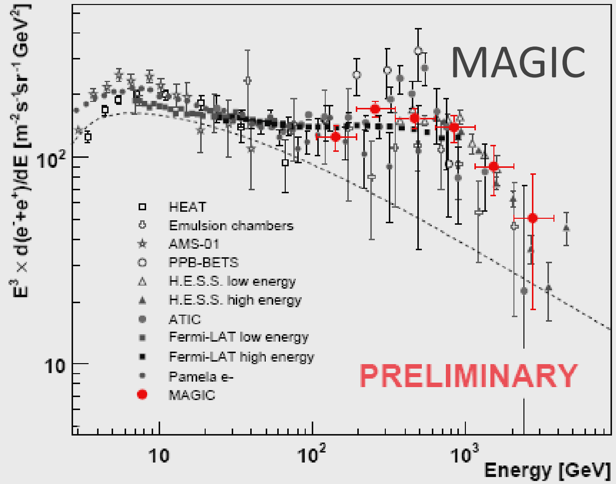
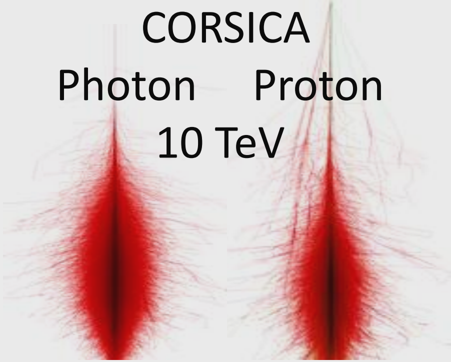
e+ blocked while e-
allowed from East
270° longitude
W E

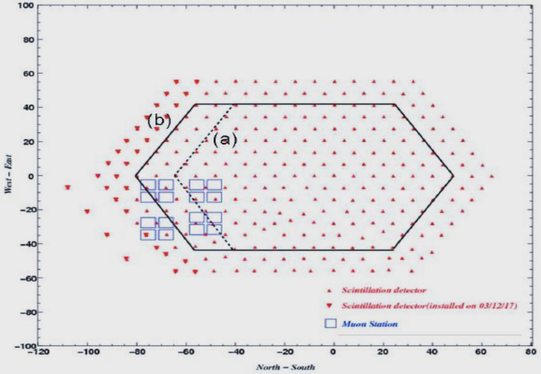

Fermi Preliminary
PAMELA 2008
AMS 2007
HEAT 2004
Fermi
PRELIMINARY
Positron Fraction
1
10-1
10
10²
Energy (GeV)


MAGIC
E³ × d(e⁻+e⁺)/dE [m⁻²s⁻¹sr⁻¹GeV²]
10²
10
HEAT
Emulsion chambers
AMS-01
PPB-BETS
H.E.S.S. low energy
H.E.S.S. high energy
ATIC
Fermi-LAT low energy
Fermi-LAT high energy
Pamela e-
MAGIC
PRELIMINARY
10
10²
10³
Energy [GeV]

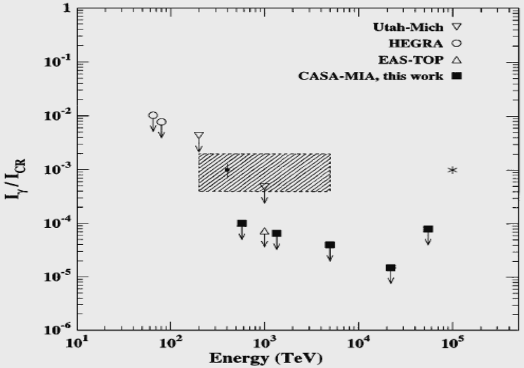
Diffuse Gamma Ray Limits (>100TeV)



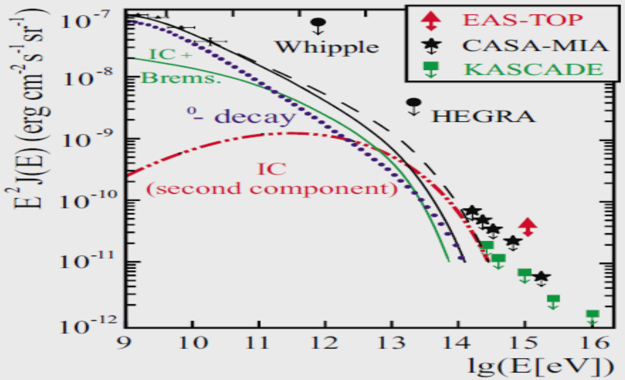
- Muon poor fraction of the showers observed yields upper limits on diffuse gamma ray flux contributions to UHECR fluxes



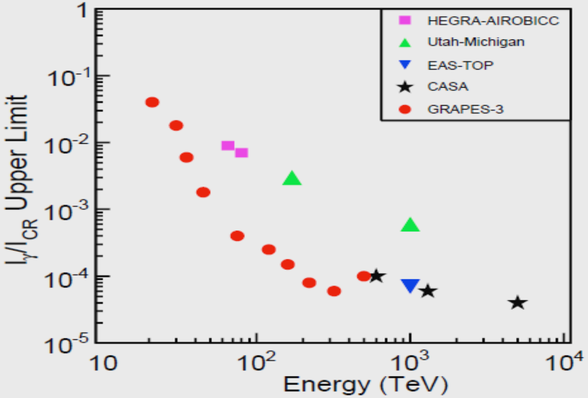
Casa-Mia



KASCADE



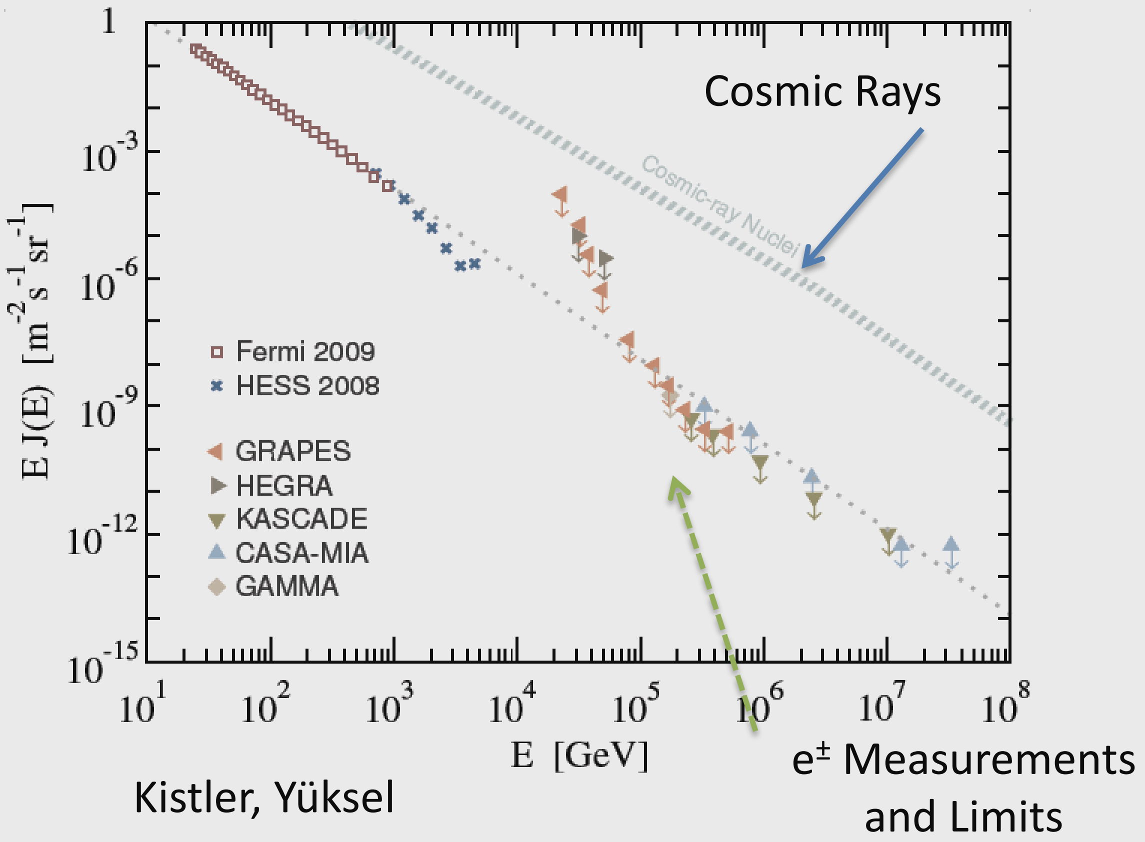
GRAPES



Cosmic Ray "Protons + Nuclei" vs. Cosmic $e^{\pm}$ Spectrum

- Published limits on gamma ray intensity are derived ignoring any plausible $e^{\pm}$ contribution
- Both gamma and $e^{\pm}$ will initiate an electromagnetic cascade & shower
- Cannot differ more than one interaction length, while shower starting point already fluctuates even more

→ **Limits on diffuse gamma ray fluxes are applicable to $e^{\pm}$ fluxes as well**



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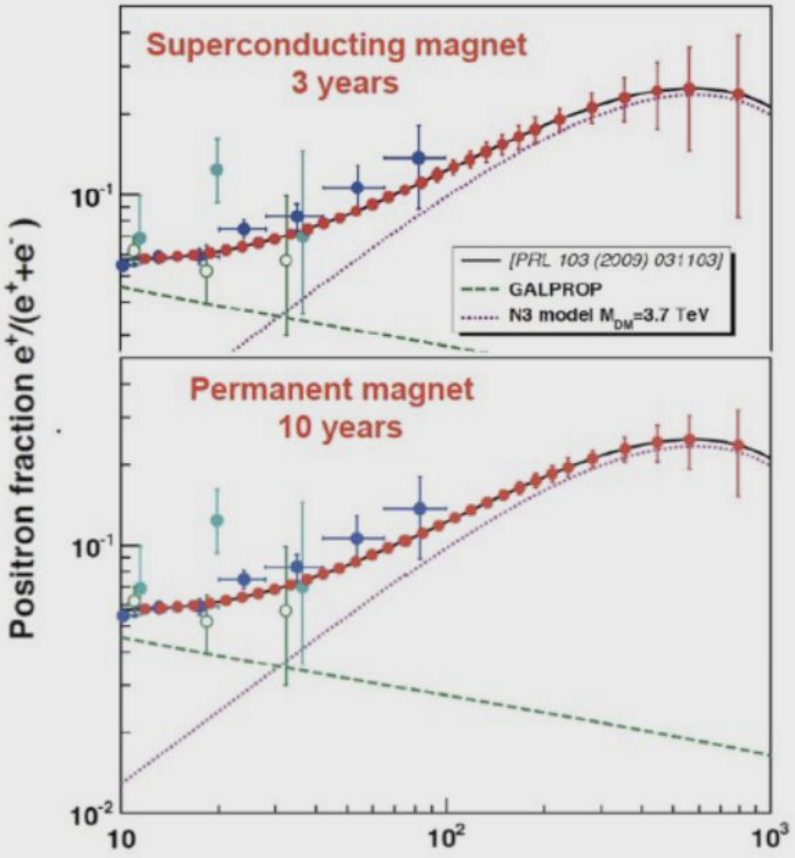
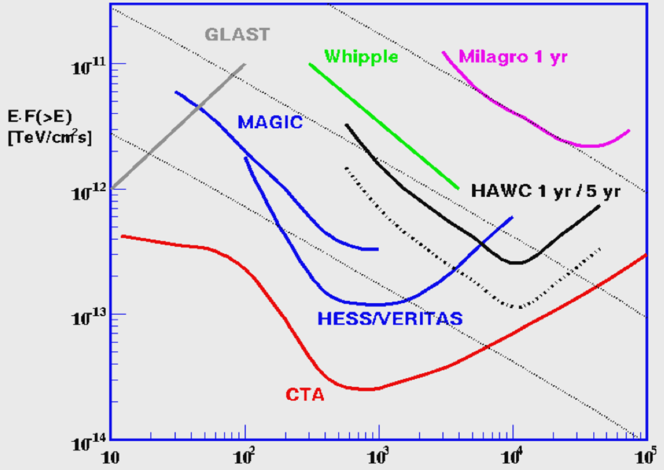
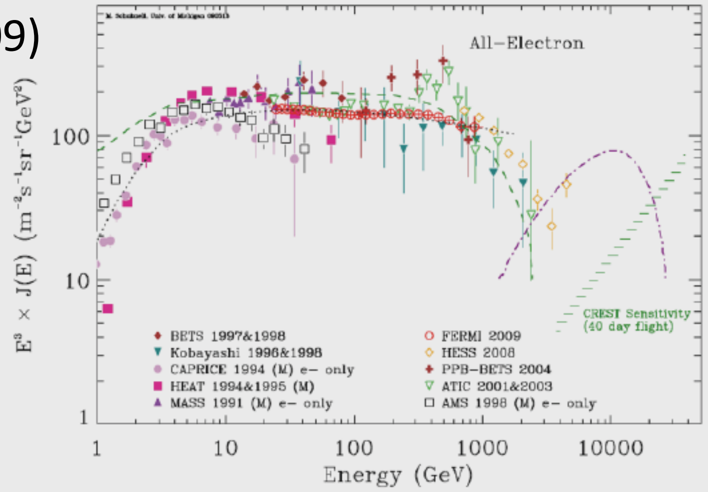
AMS-02 now up!



HAWC sensitivity for2π sr



Crest (2009)

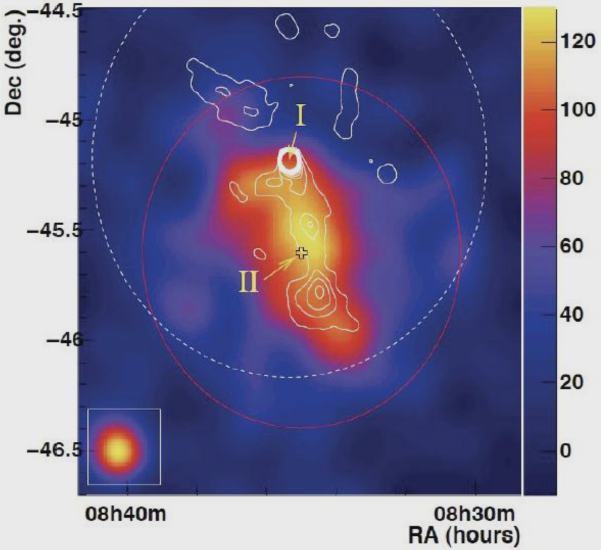


Nearby TeV Gamma Ray Sources

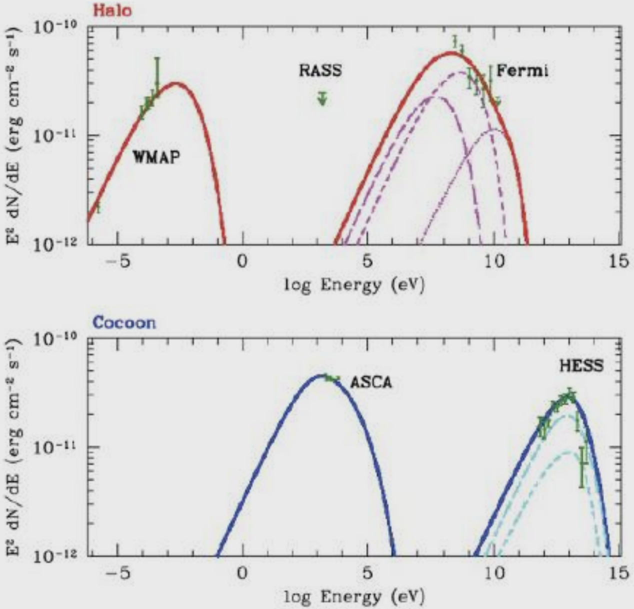
Vela X

11k year, 290 pc

Hess 2006



Two distinct electron/positron populations:



Electron spectrum consistent with E^{-2} with exponential cutoff at ~70 TeV

~10^{46} erg in TeV electrons seen

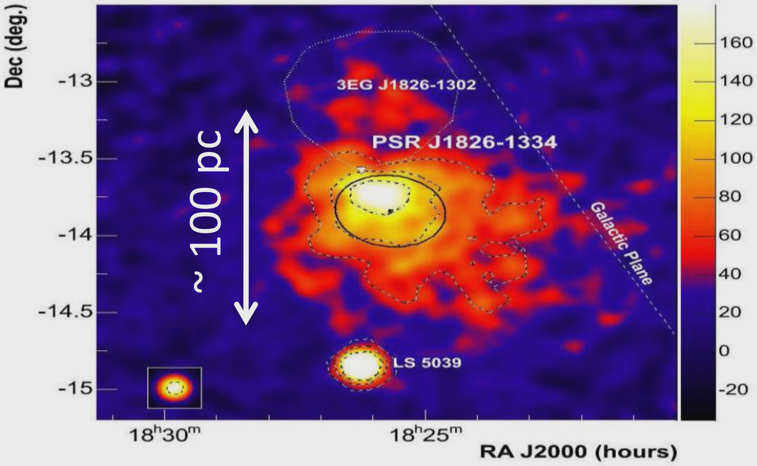
Radio implies electron spectrum of form $E^{-1.8}$, cutoff at ~100 GeV

~4 x 10^{48} erg in radio population

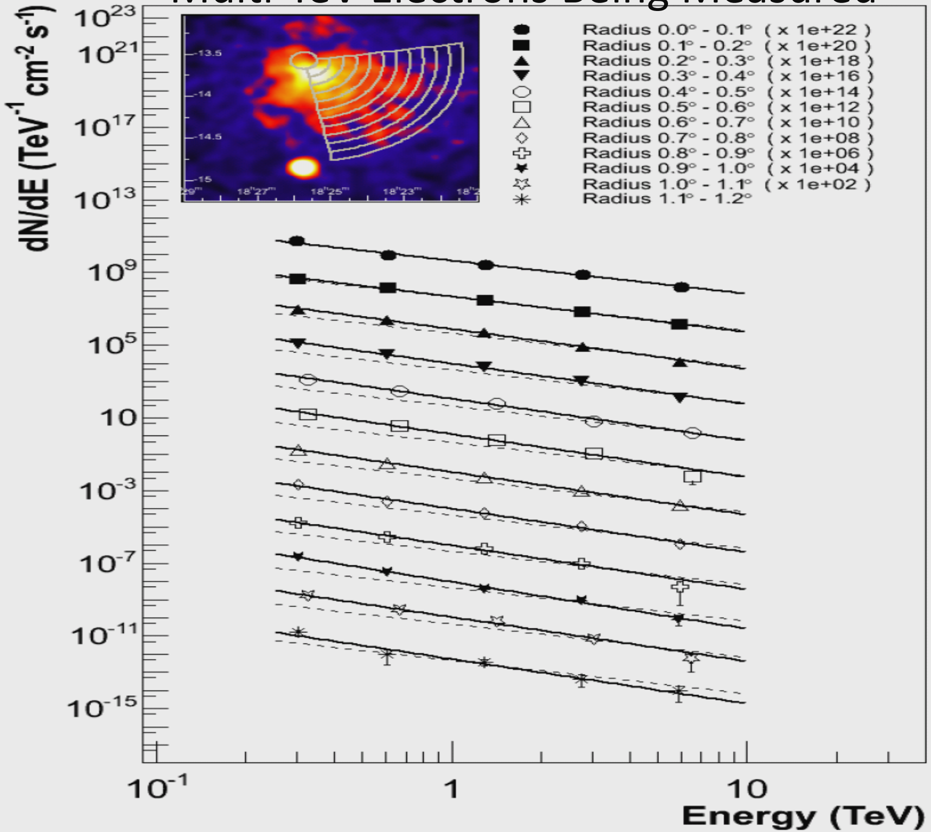
More Distant PWN by HESS

HESS J1825-137, Aharonian et al.

Distance ~ 3.9 ± 0.4 kpc
Age ~ 21,400 year
Energy > 10^{48} erg



Multi-TeV Electrons Being Measured

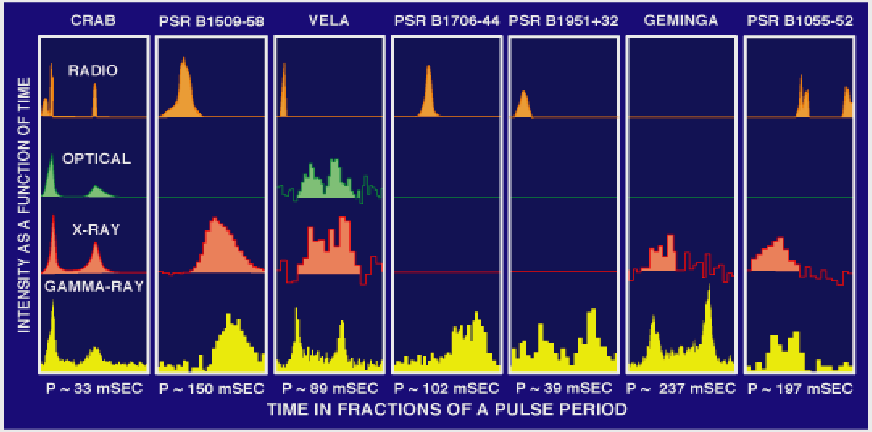


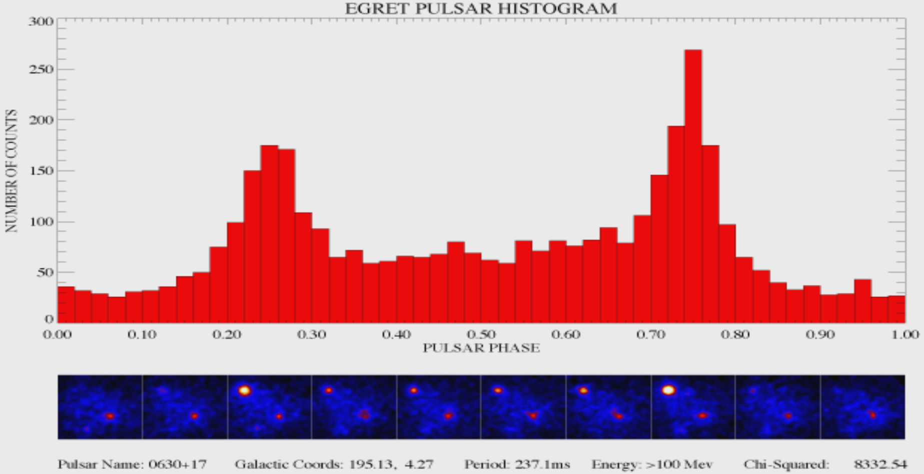
Geminga:

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

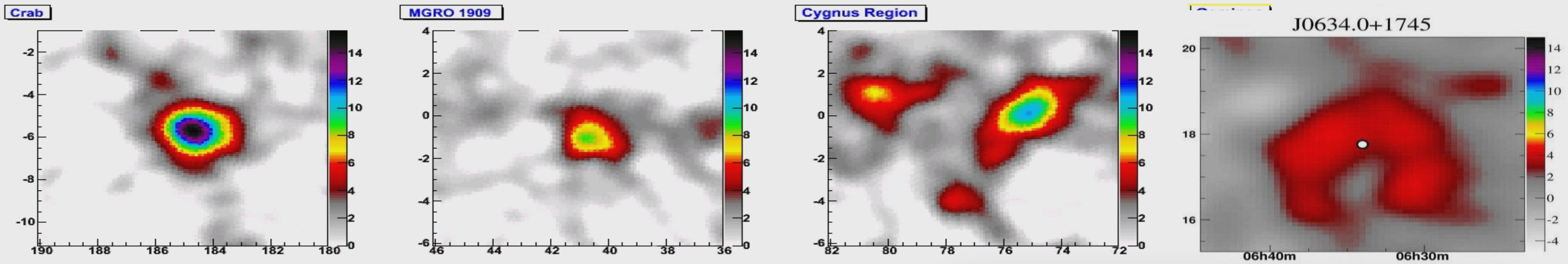
$$r_G \sim 250^{+120}_{-62}\ \mathrm{pc}$$
$$t_G \sim 3 \times 10^5\ \mathrm{yr}$$

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

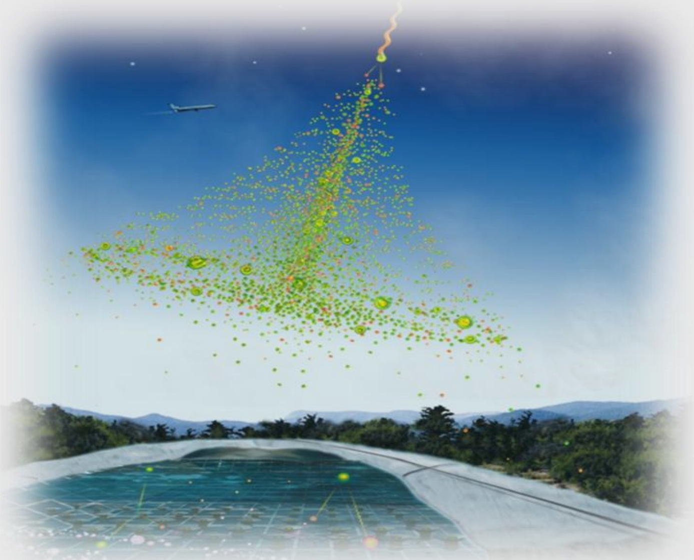


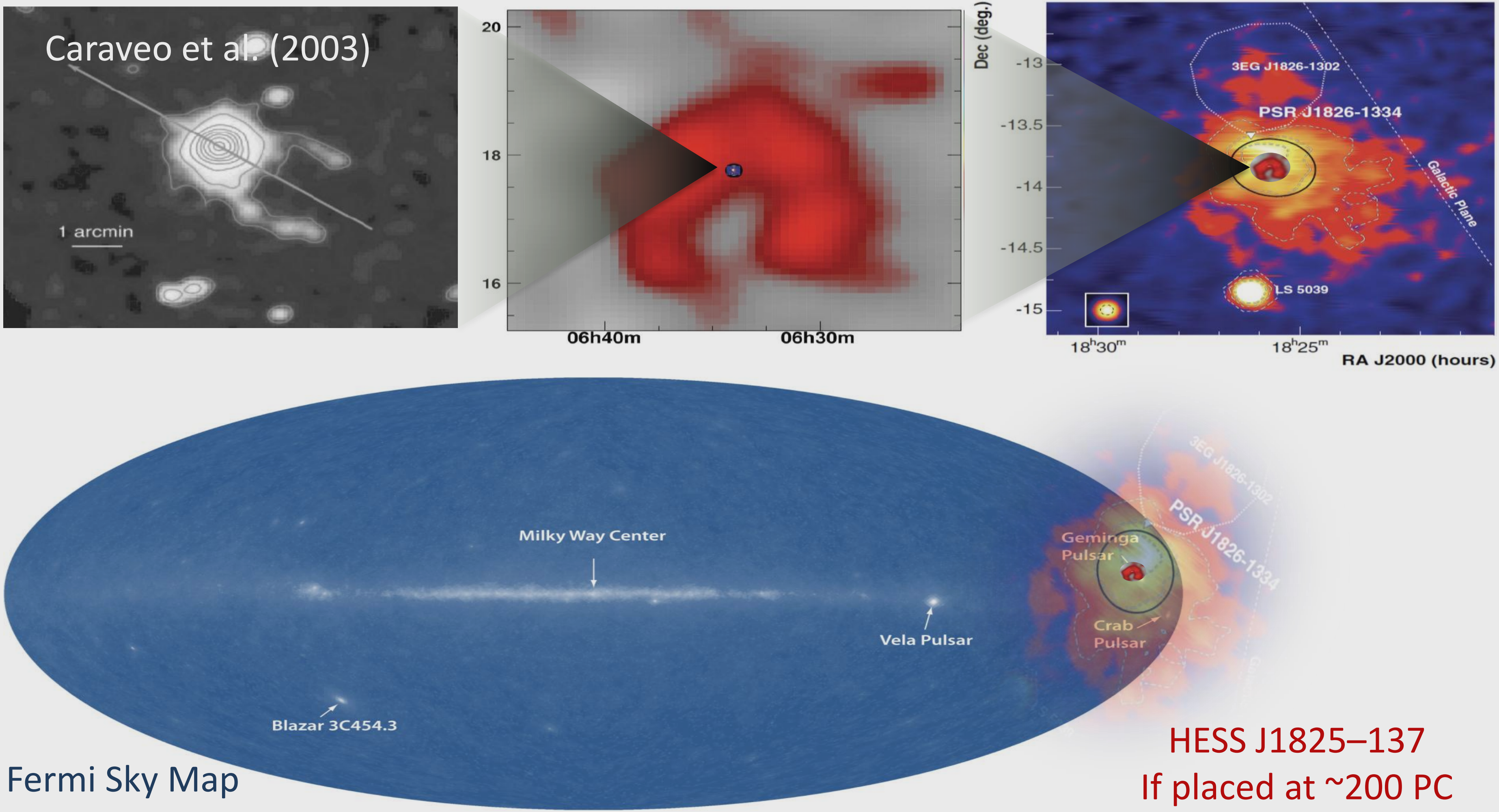


Milagro Galactic Plane Survey



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





Caraveo et al. (2003)

Fermi Sky Map

HESS J1825–137
If placed at ~200 PC

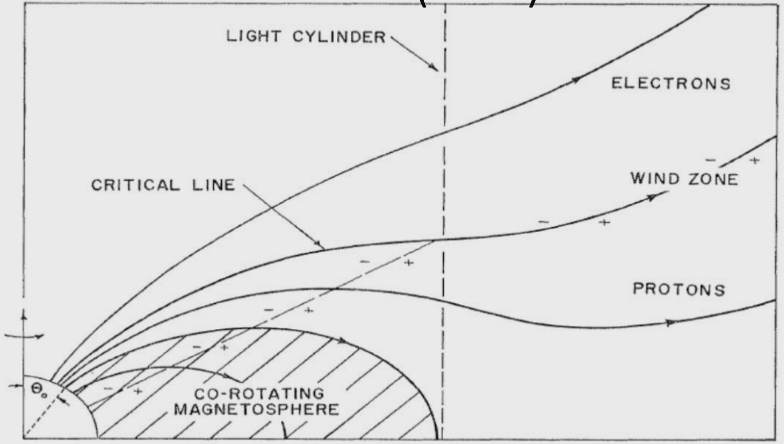
Implications of TeV Gamma Rays from Geminga

- 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 leptonic 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

From TeV Gamma Ray sources to Cosmic Electrons/Positron Fluxes

Pulsar Wind

Goldreich & Julian (1969)



Goldreich Julian Current:

$$\dot{N}_{\rm GJ} \simeq B\,\Omega^2\,R^3/ec$$

Pair production multiplicity:

$$\mathcal{M} = \dot{N}_{e^\pm}/\dot{N}_{\rm GJ}$$

could be > 10^4 as shown for some other sources

100 TeV electrons are needed to produce > 20 TeV gamma rays

The age of Geminga: $t_G \sim 3 \times 10^5\,\mathrm{yr}$

is much larger than the IC cooling time on CMB: $\tau_{IC} \sim 10^4 (100\,\mathrm{TeV}/E_e)\,\mathrm{yr}$

Fresh Pair Production at the source

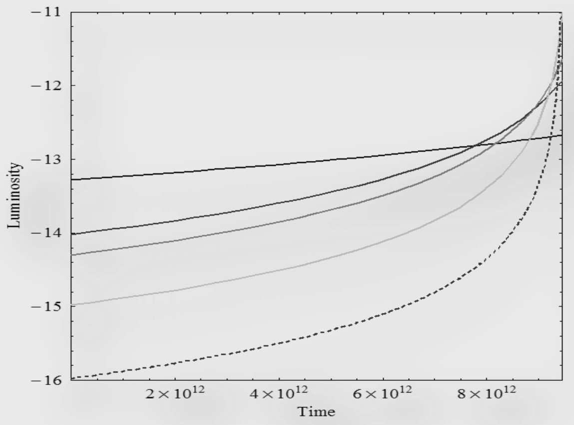
Blast from the Past

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 electrons and positrons by Geminga:

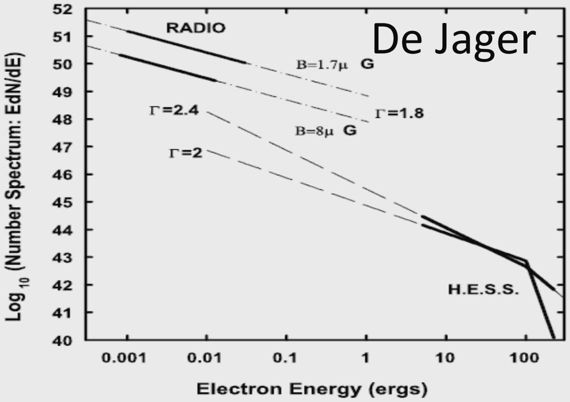
$$\mathcal{L}_e(t) = \frac{\mathcal{E}_G}{t_G} \frac{(1+(t_G-t)/t_0)^{-2}}{\int^{t_G} dt'(1+(t_G-t')/t_0)^{-2}}$$

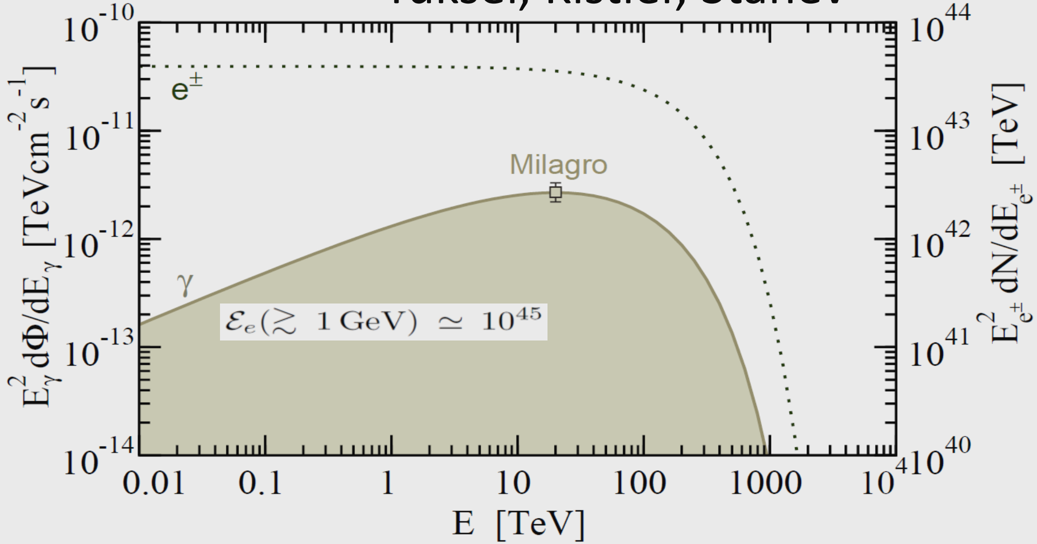
$$\dot{N}_0 = \mathcal{L}_e(t)\left(m_e c^2 \int_{\gamma_{min}} \gamma^{-\alpha+1} e^{-\gamma/\gamma_{max}} d\gamma\right)$$



Geminga was much stronger in the past and dominated the TeV sky:
Multi-GeV positrons are reaching us today from that time

TeV Gamma Rays from Geminga





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

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

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

$$\alpha = 2$$

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

Diffusion According to Syrovatsky

$$\frac{\partial n}{\partial t} = \frac{D(E)}{r^2}\frac{\partial}{\partial r} r^2 \frac{\partial n}{\partial r} + \frac{\partial}{\partial E}[b(E)\,n] + Q$$

$$Q(r,t,E_g) = \delta(r)\,\delta(t)\,dN/dE_g$$

$$n_S(r,t,E) = \frac{e^{-r^2/r_{dif}^2}}{\pi^{3/2}\,r_{dif}^3}\frac{dN}{dE_g}\frac{dE_g}{dE}$$

$$\lambda(E,t) = \int_0^t dt'\,D[E(t')] = \int_E^{E_g} dE'\,\frac{D(E')}{b(E')}$$

$$r_{dif}(E,t) = 2\sqrt{\lambda(E,t)}$$

Energy Losses

$$b(E) = -dE/dt$$

$$b(E) = b_2 E^2 \qquad b_2 \simeq 5 \times 10^{-16}\ \mathrm{s}^{-1}\ \mathrm{GeV}^{-1}$$

$$\int_E^{E_g} -dE/b(E) = t$$

$$1/E = 1/E_g + b_2 t \qquad dE_g/dE = (E_g/E)^2$$

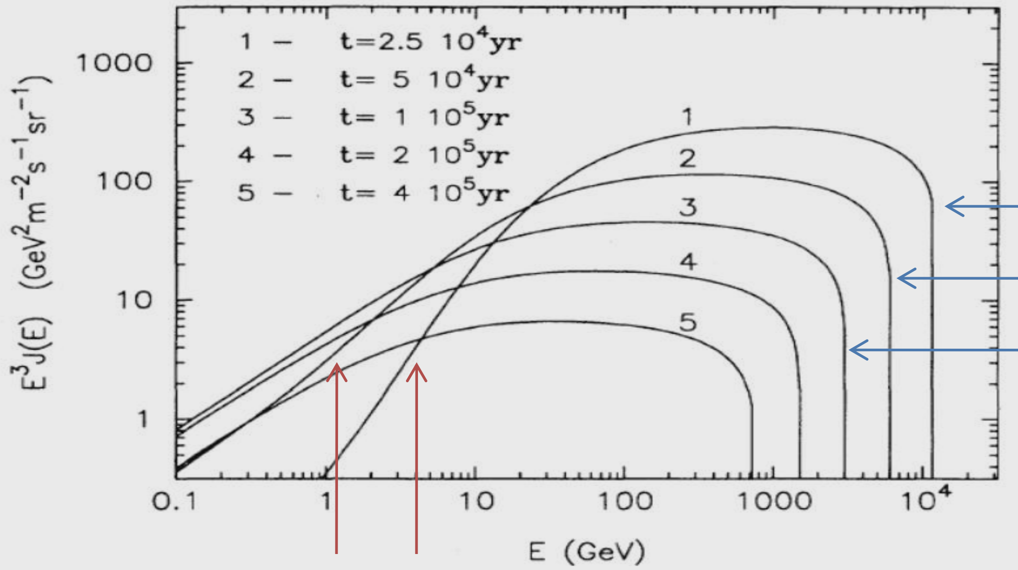
Local Particle Density

$$Q(r, t, E_g) = \quad \delta(r)\,\delta(t)\,d\dot{N}/dE_g$$

$$n_\odot(E) = \int_0^t dt'\,\dot{n}(r, t', E) \qquad J_\odot = (c/4\pi)\,n_\odot$$

Time-Dependent Propagation from a Burst

Atoyan, Aharonian & Volk (1995)



Age and
Energy Loss Rate

Distance and
Diffusion Parameterization

- Due to severe energy losses, very high energy particles cannot travel too far: 100 TeV particles cannot reach from distances larger than ~ kpc
- Contributions proportional to $\sim 1/r^3$
- Only a few nearby sources such as Geminga, Vela X, Vela SN remnant could contribute in very high energy regime

- For "very small t" and/or "very high E", v_{dif} could exceed speed of light:

$$E_g \sim E \qquad v_{dif}(t) = r_{dif}(t)/t \simeq 2\sqrt{D(E)}/t.$$

- Diffusion According to Jüttner: motivated by similarity between Maxwell distribution and diffusion equation (e.g. review by Dunkel et al. 2007, Cubero et al. 2007, Aloisio et al. 2008)

$$n_J(r,t,E) = \frac{\theta(1-\xi)}{4\pi(ct)^3}\frac{e^{-\alpha/\sqrt{1-\xi^2}}}{(1-\xi^2)^2}\frac{\alpha}{K_1(\alpha)}\frac{dN}{dE_g}\frac{dE_g}{dE}$$

$$\alpha(E,t) = c^2t^2/(2\lambda(E,t)) \qquad \xi(r,t) = r/ct \qquad K_1 \text{ is the modified Bessel function}$$

- Superluminal velocities (v > c) are forbidden, smooth transition to Diffusive regime at "large t" and/or "small E"

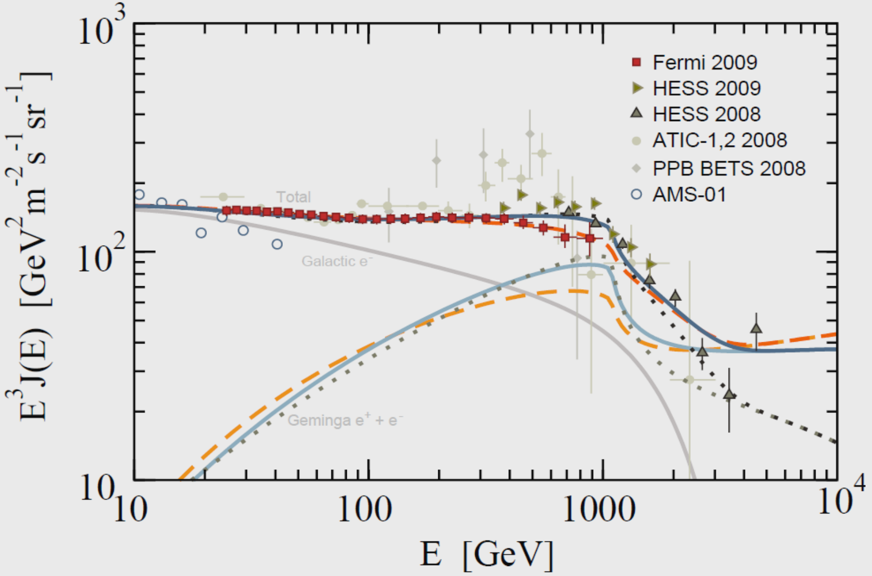
Positron Excess by Geminga

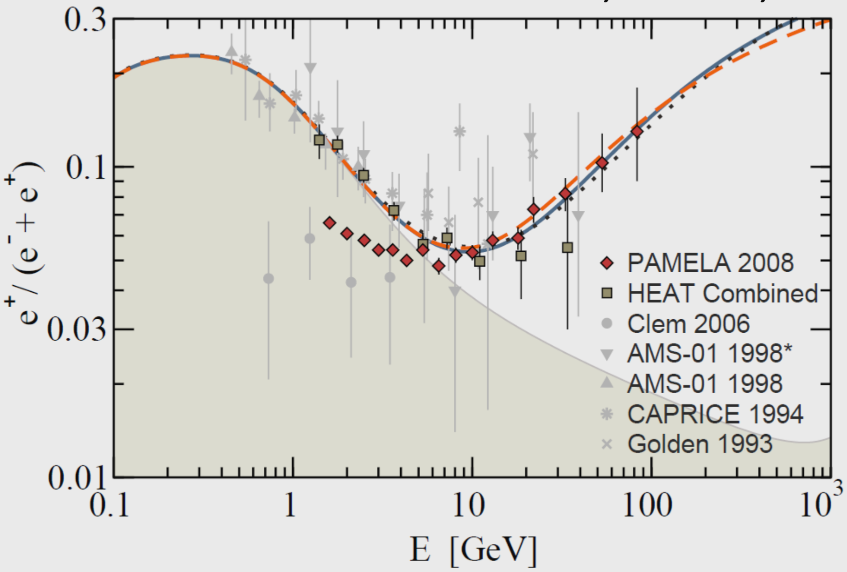
Dotted, Solid, Dashed lines correspond to $t_G = 3 \times 10^5$ yr

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

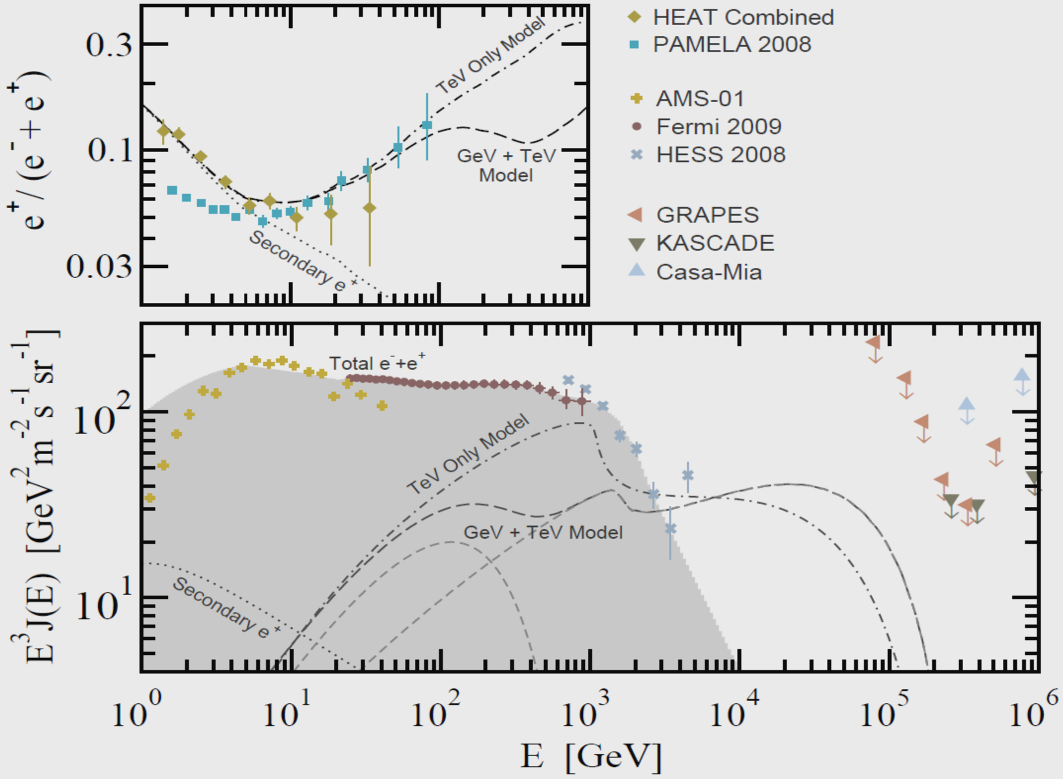
$$r_G = 150 \to 250\ \mathrm{pc},\ 220\ \mathrm{pc},\ 250 \to 200\ \mathrm{pc}$$

Yuksel, Kistler, Stanev

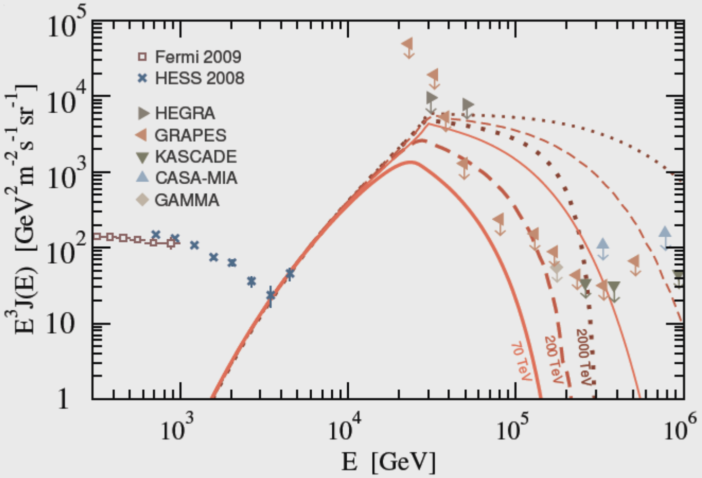




A source with two distinct electron/positron populations:



A nearby young source like Vela X dominating > 10TeV?



Kistler, Yüksel

Concluding Remarks

- Gamma ray data implies production of large quantities of positrons by nearby astrophysical sources that can account for the observed excess
- Diffuse gamma rays limits are applicable to CR $e^{\pm}$
  - Past observations already yield strong limits which can be improved even further
- If there is a positive signal in >10TeV Region:
  - Astrophysical sources: possibly very strong anisotropy
  - Or particle theorists may need to come up with even more exotic dark matter models
- If no detection or stronger limits >10TeV Region:
  - Further constraining the parameters of astrophysical scenarios which are suggested to explain positron excess