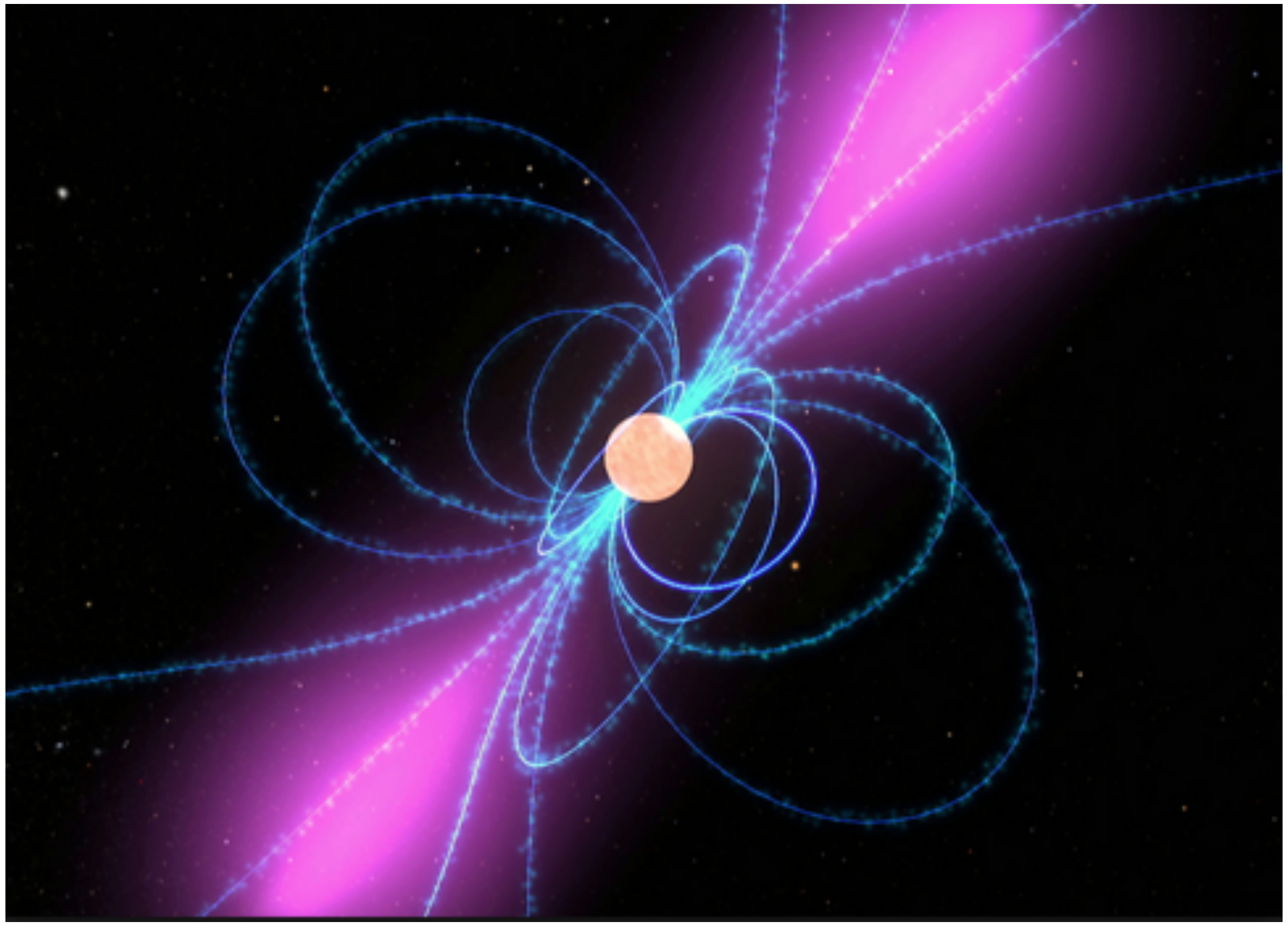
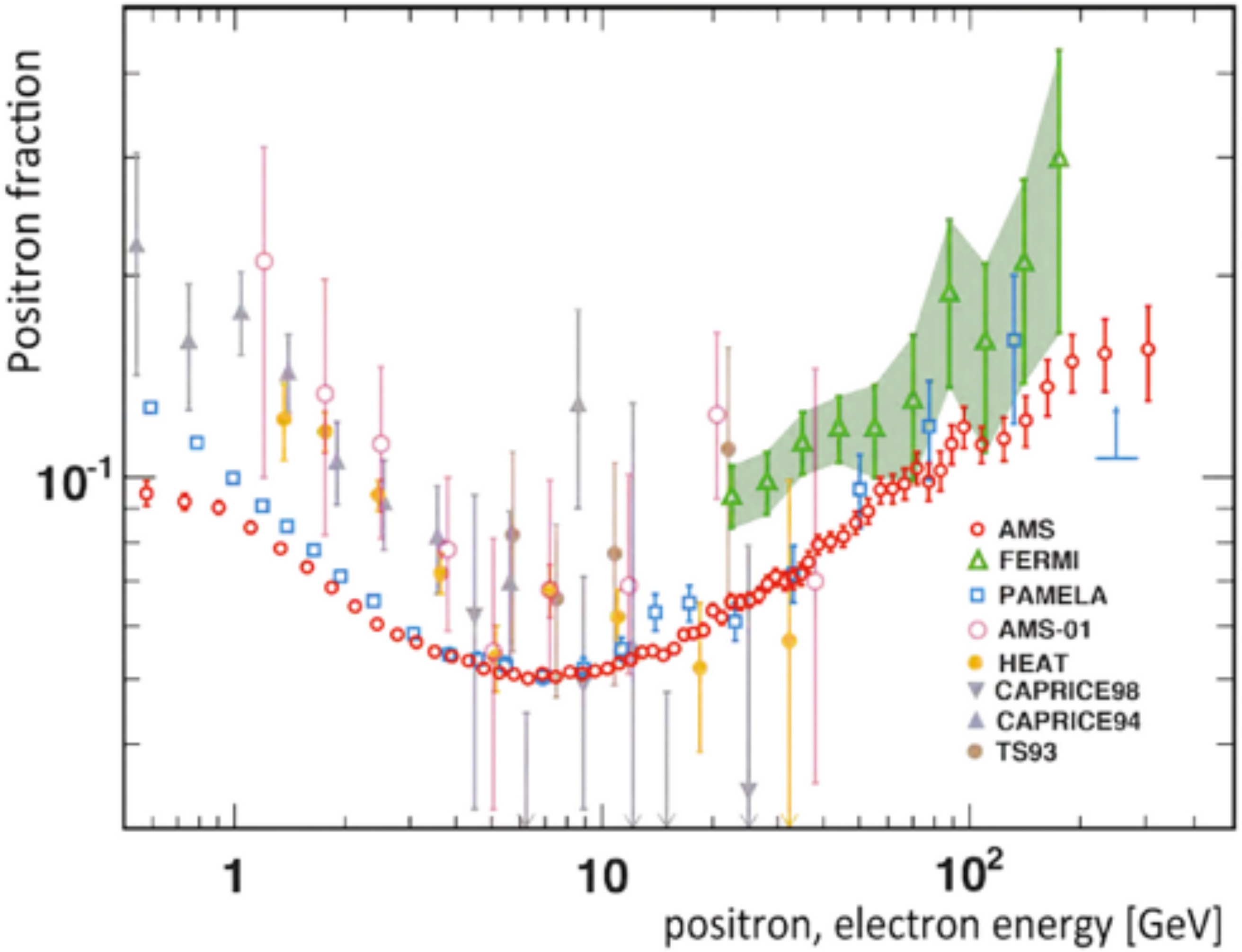
The Production of Positrons by Pulsars





Tim Linden

Einstein/KICP Postdoctoral Fellow
University of Chicago

Debates on the Nature of Dark Matter

Cambridge, MA

5/22/14

Why Do We Study the Positron Fraction?

$$\frac{\phi_{e^+}}{\phi_{e^+} + \phi_{e^-}}$$

- Observations of the positron fraction eliminates many of the uncertainties intrinsic to models of absolute fluxes

- Uncertainties like: Diffusion Constant, Alfven Velocity, Magnetic Field Strength should all be charge-independent

The Astrophysical Positron Fraction

$$\Phi_E \propto \left(\frac{dN}{dE}\right)_{inj} \tau(E)$$

$$\frac{\phi_{e^+}}{\phi_{e^+} + \phi_{e^-}}$$

$$\left(\frac{dN}{dE}\right)_{inj,pri} = E^{-\gamma}$$

Protons $\tau_{diff} \propto E^{-\delta}$

Leptons $\tau(E) \approx \left(\frac{\tau_{loss}}{\sqrt{D(E)\tau_{loss}}}\right) \propto E^{-\alpha/2-\delta/2}$

The Astrophysical Positron Fraction

$$\Phi_E \propto \left(\frac{dN}{dE}\right)_{inj} \tau(E)$$

$$\frac{\phi_{e^+}}{\phi_{e^+} + \phi_{e^-}}$$

σ_{pp} is velocity independent
and most protons don’t interact →

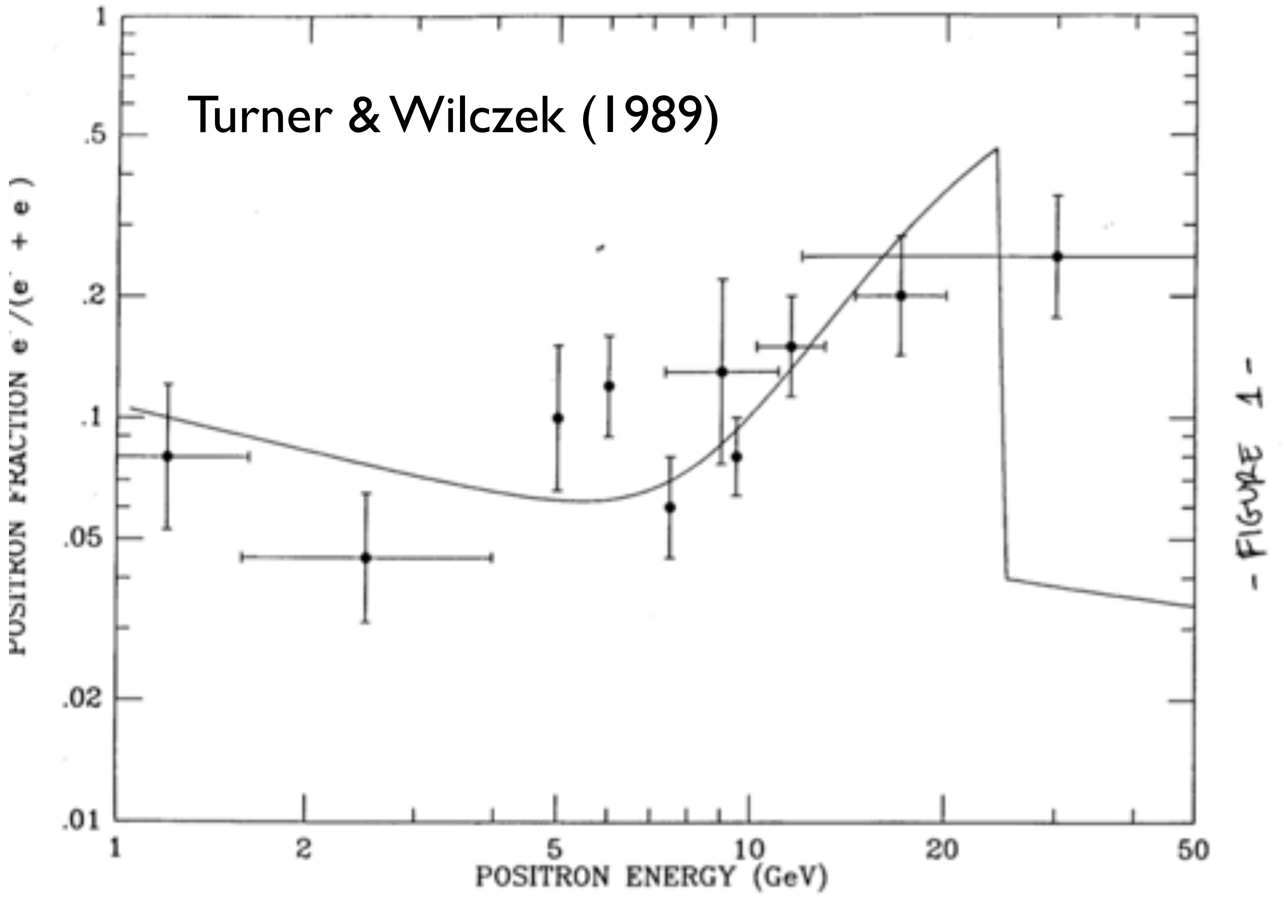
$$\left(\frac{dN}{dE}\right)_{inj,sec} = E^{-\gamma-\delta}$$

$$\tau(E) \approx \left(\frac{\tau_{loss}}{\sqrt{D(E)\tau_{loss}}}\right) \propto E^{-\alpha/2-\delta/2}$$

$$\frac{\Phi_+}{\Phi_+ + \Phi_-} \approx \frac{\Phi_+}{\Phi_-} \propto E^{-\delta}$$

“Debates on the Nature of Dark Matter” ??

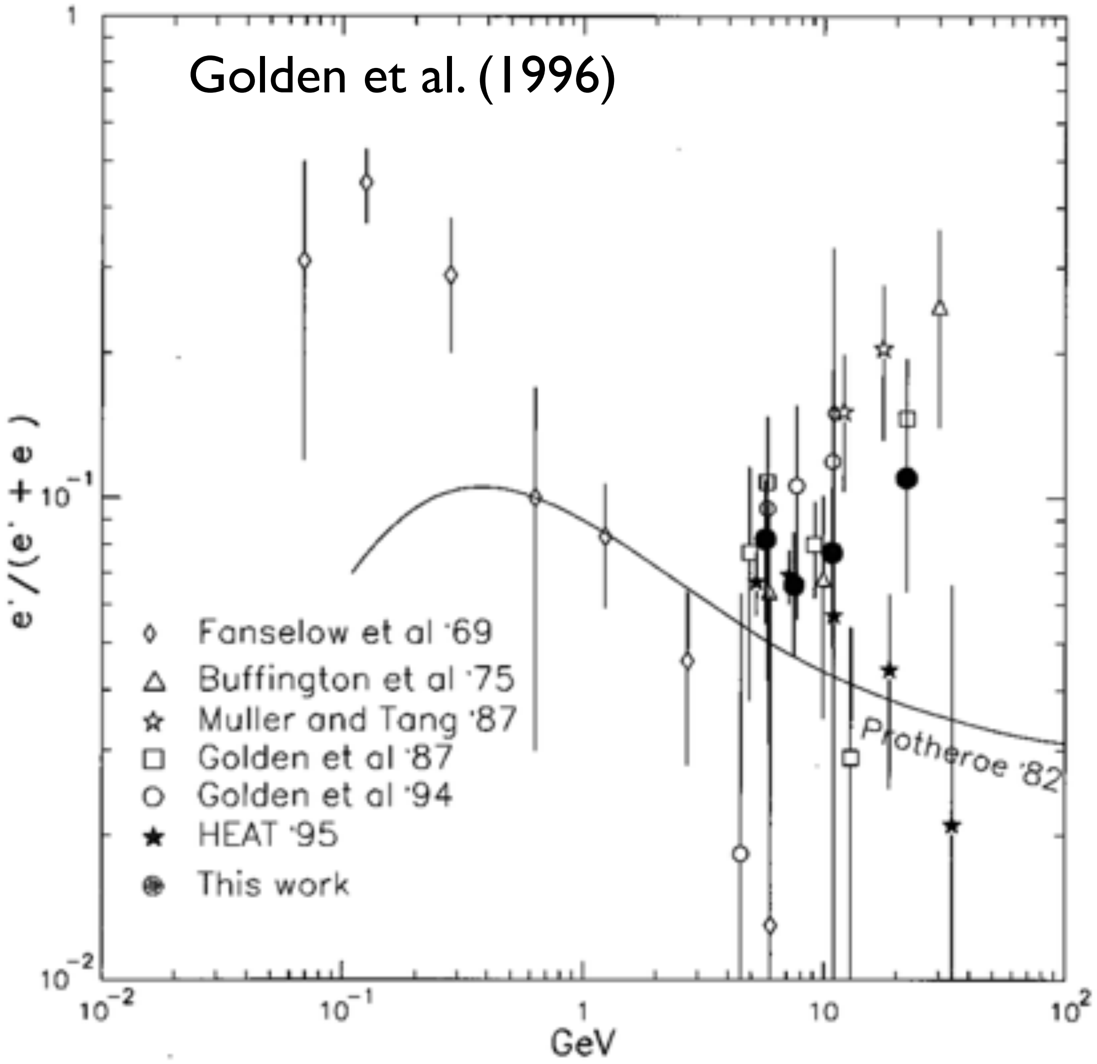
- **A bump in the positron fraction could be a signal of dark matter annihilation!**

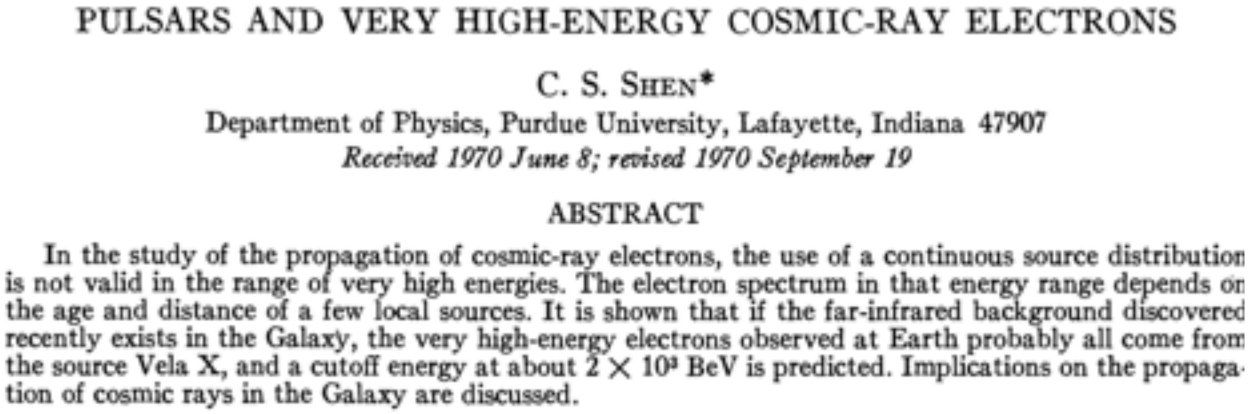

Turner & Wilczek (1989)

- **Note: Dark matter models predict a <u>sharp cutoff</u> at the mass of the dark matter particle**

Observations of the Rising Positron Fraction

- **Several hints towards a rising positron fraction from very early experiments**
- **Even before then, crazy theorists produced pulsar and dark matter models**


Golden et al. (1996)


PULSARS AND VERY HIGH-ENERGY COSMIC-RAY ELECTRONS

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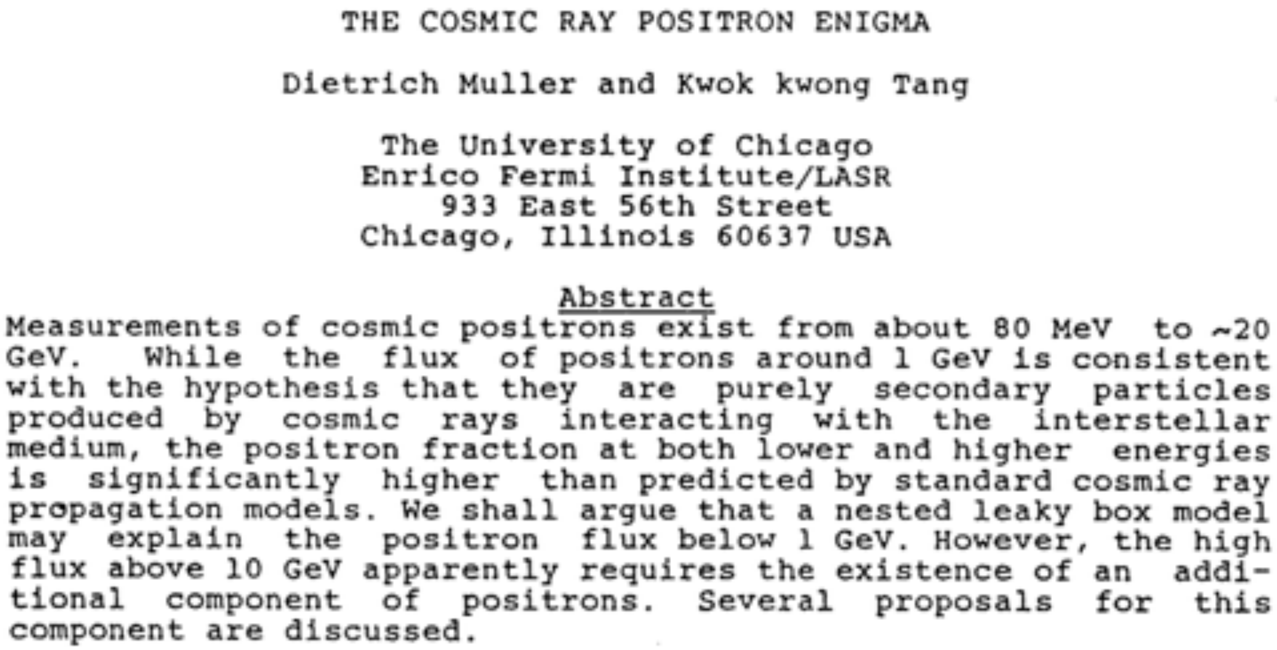
Received 1970 June 8; revised 1970 September 19

ABSTRACT

In the study of the propagation of cosmic-ray electrons, the use of a continuous source distribution is not valid in the range of very high energies. The electron spectrum in that energy range depends on the age and distance of a few local sources. It is shown that if the far-infrared background discovered recently exists in the Galaxy, the very high-energy electrons observed at Earth probably all come from the source Vela X, and a cutoff energy at about 2 × 10^3 BeV is predicted. Implications on the propagation of cosmic rays in the Galaxy are discussed.


THE COSMIC RAY POSITRON ENIGMA

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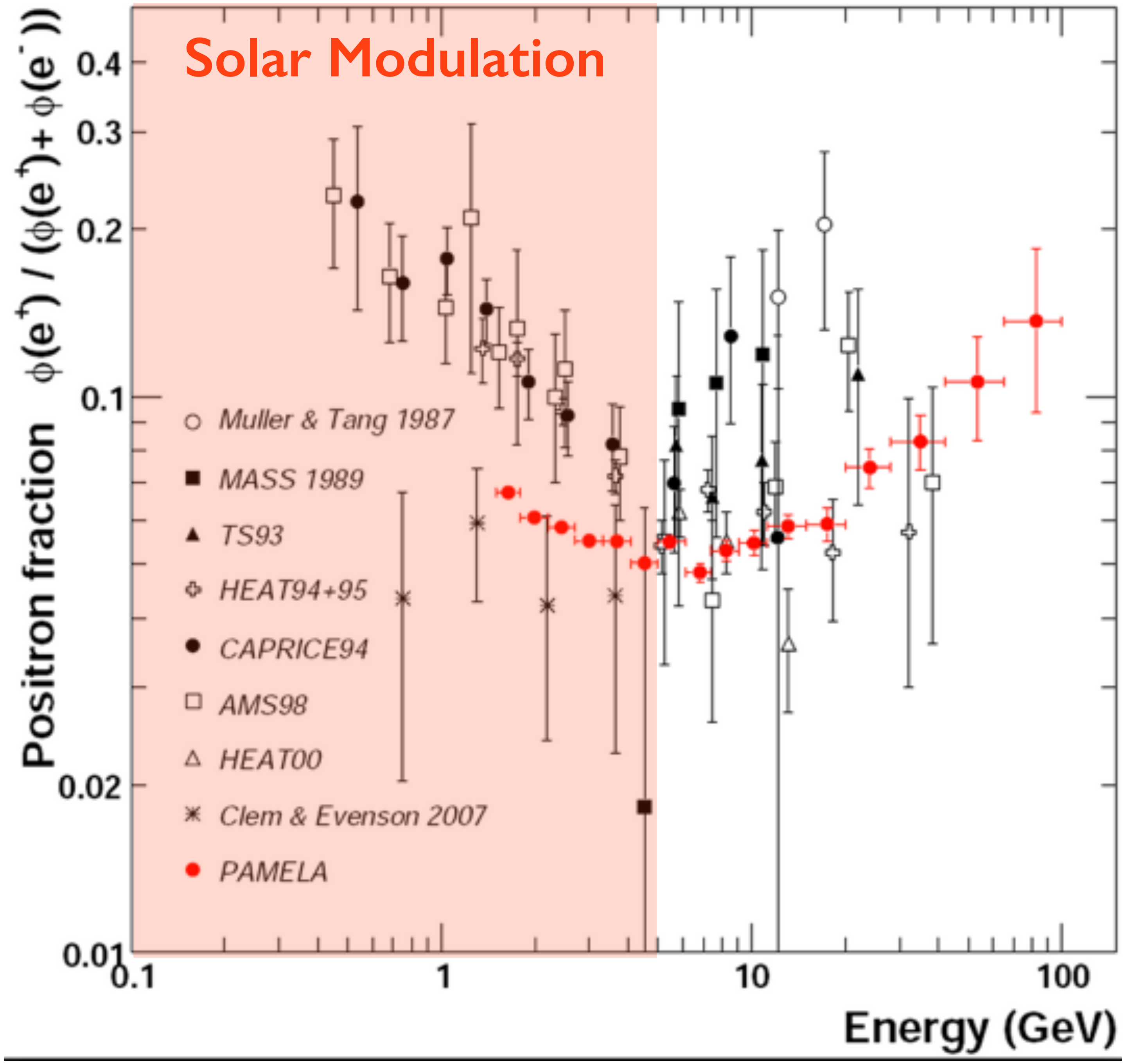
933 East 56th Street
Chicago, Illinois 60637 USA

Abstract

Measurements of cosmic positrons exist from about 80 MeV to ~20 GeV. While the flux of positrons around 1 GeV is consistent with the hypothesis that they are purely secondary particles produced by cosmic rays interacting with the interstellar medium, the positron fraction at both lower and higher energies is significantly higher than predicted by standard cosmic ray propagation models. We shall argue that a nested leaky box model may explain the positron flux below 1 GeV. However, the high flux above 10 GeV apparently requires the existence of an additional component of positrons. Several proposals for this component are discussed.

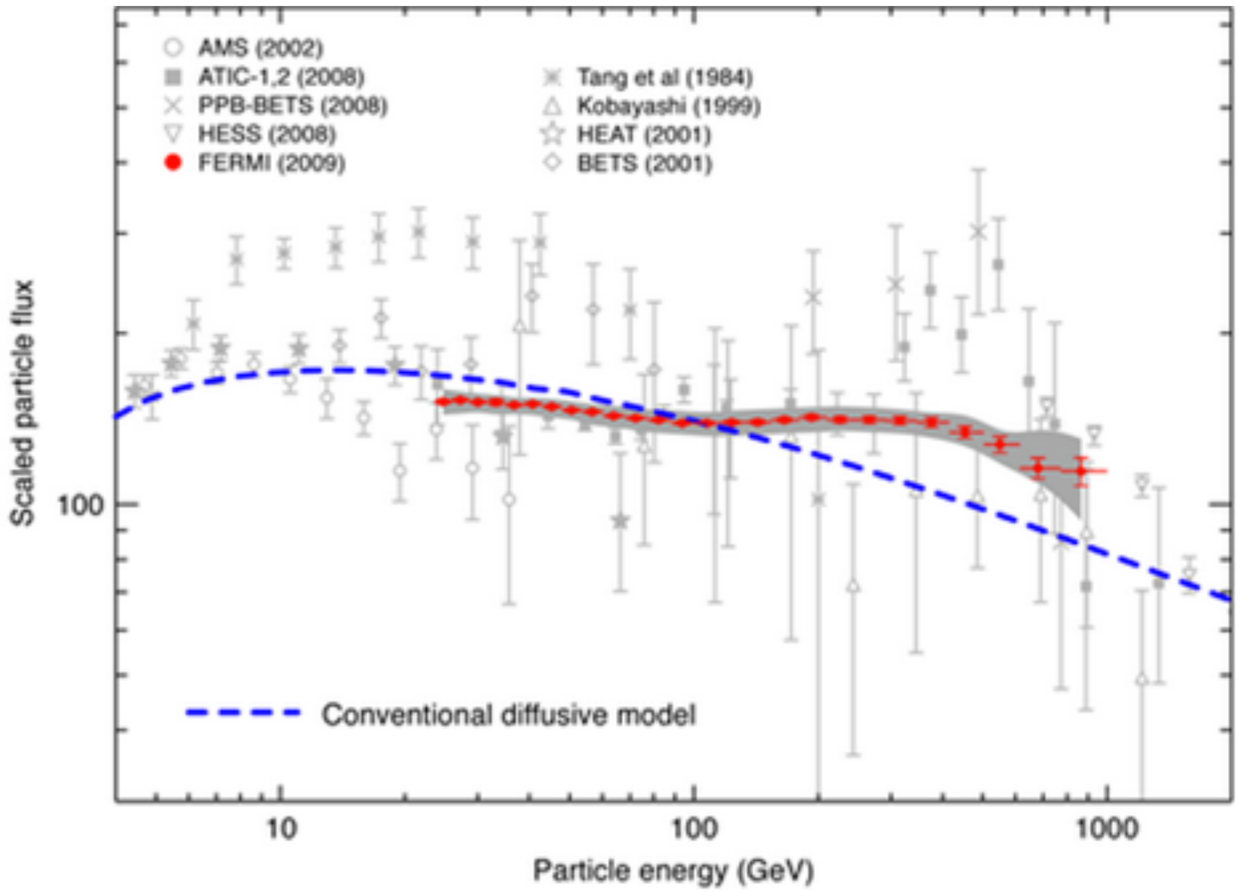
Observations of the Rising Positron Fraction

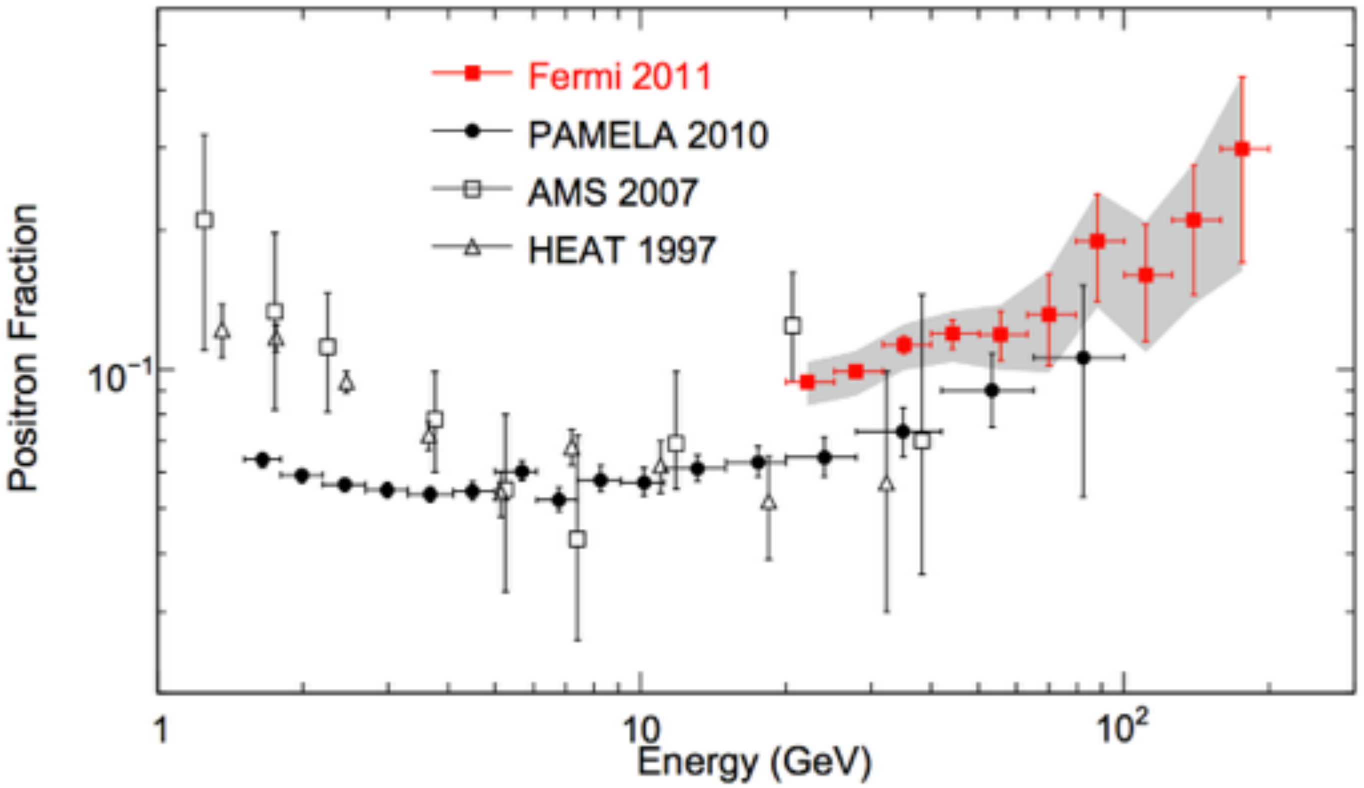
- **PAMELA observations provided strong evidence that the rising positron fraction was real**



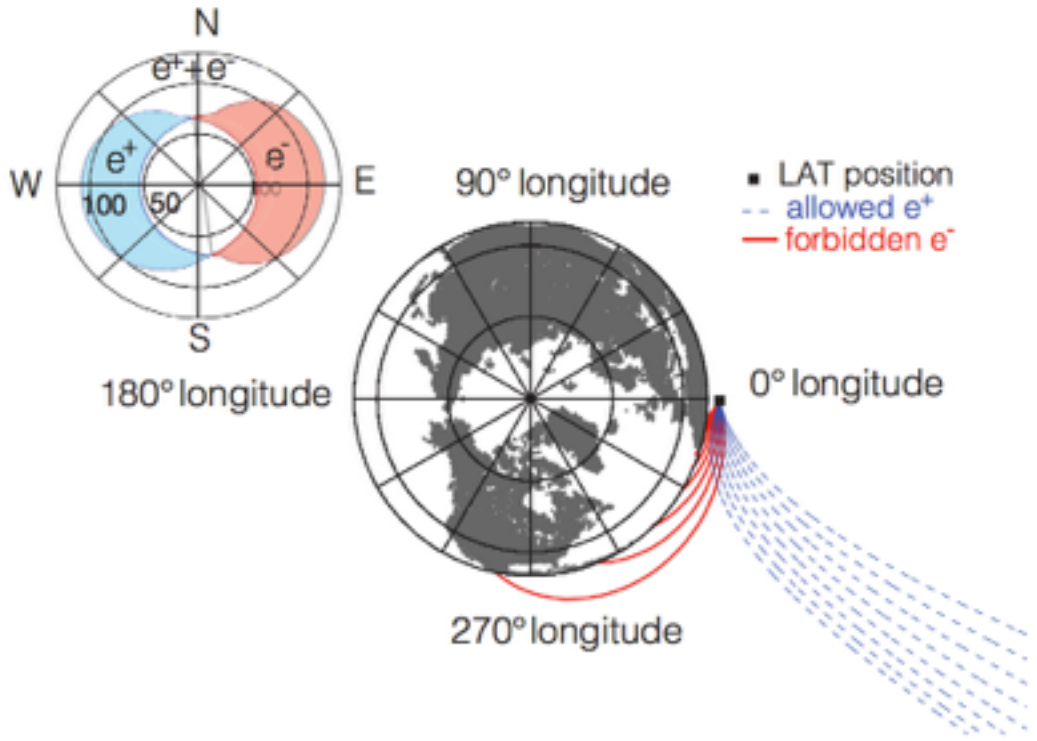
- **Positron fraction continues to rise <u>(potentially at a steepening pace)</u> up to the maximum energy threshold of the PAMELA satellite**

Observations of the Rising Positron Fraction

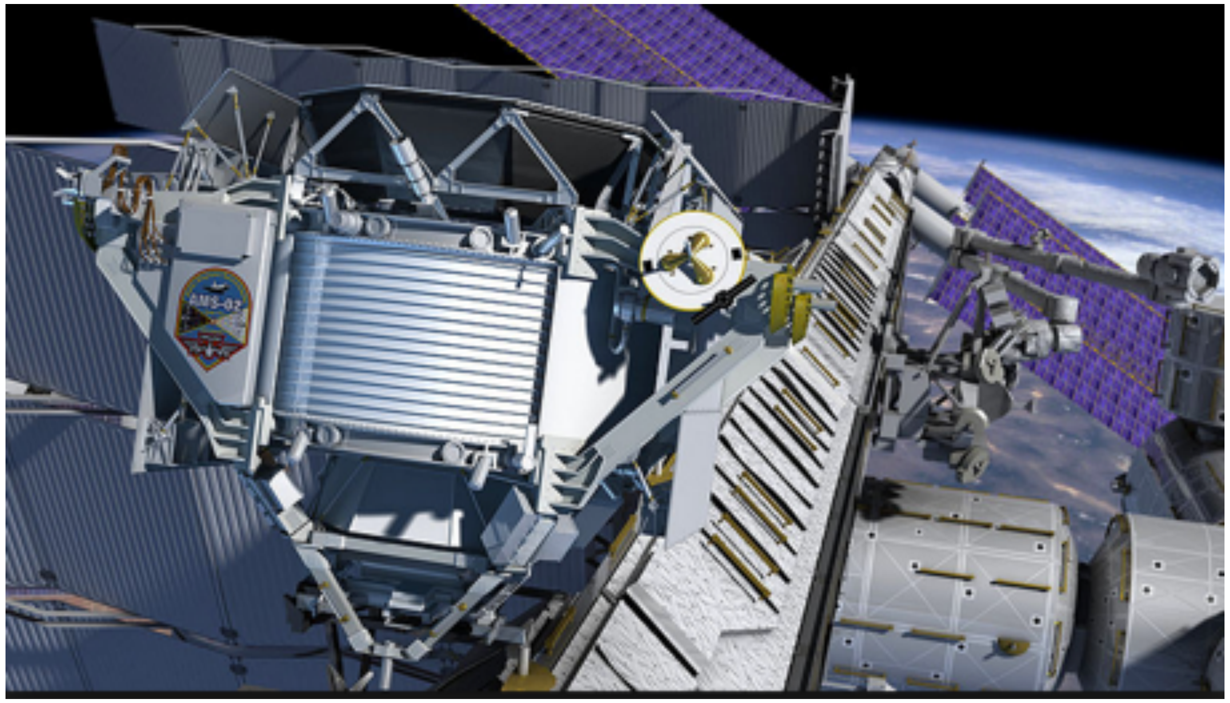


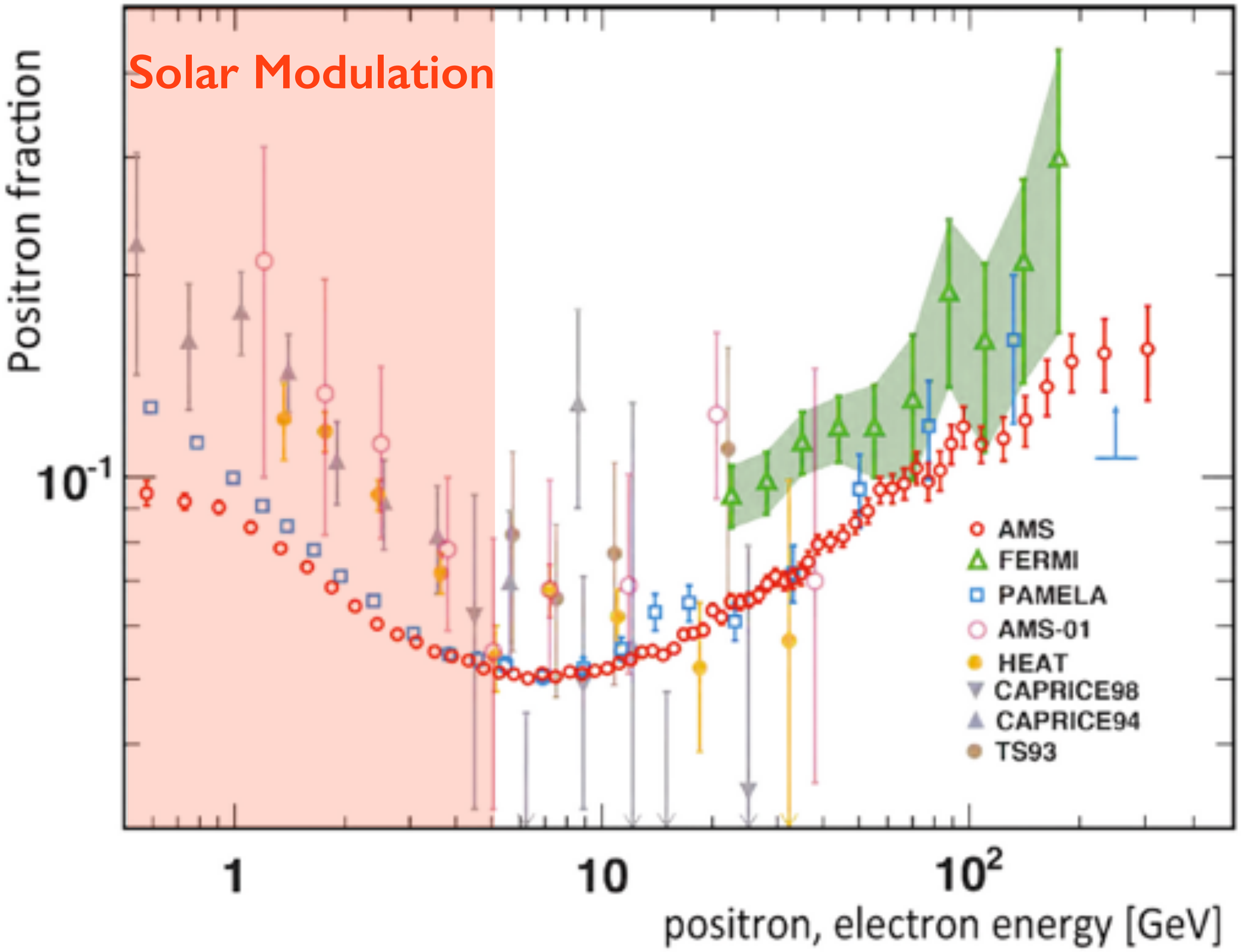


- **Positron fraction continues to rise <u>(potentially with a steepening slope)</u> up to the maximum energy threshold of the PAMELA satellite**



Observations of the Rising Positron Fraction

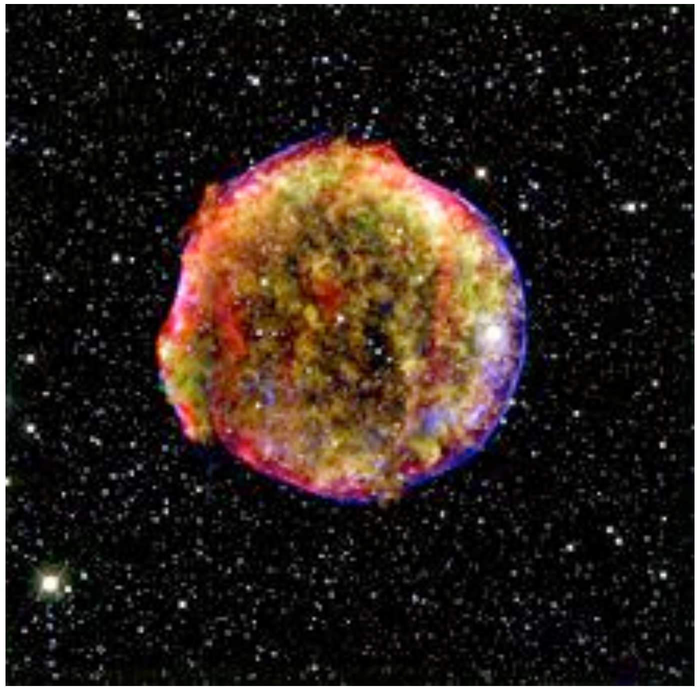




- **AMS-02 corroborated these results with greatly improved statistical precision**
- **Found some evidence for a softening positron spectrum at higher energies**

Interpretations of the Current Data

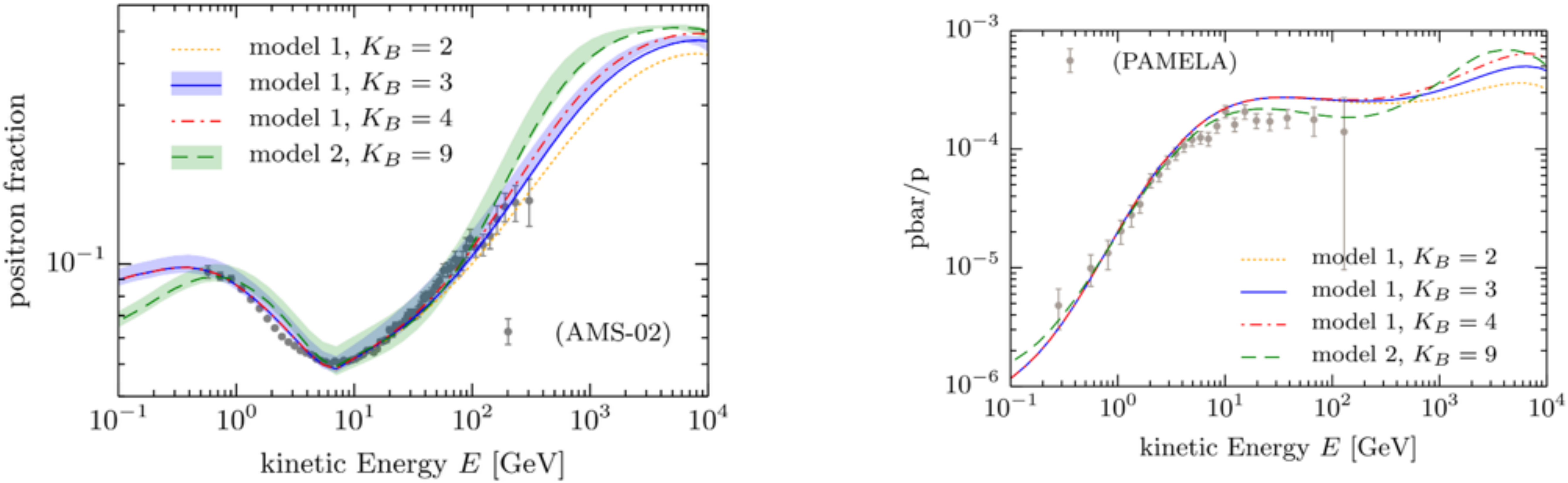
PWN



SNR

DM

Secondary Production and Acceleration in SNR

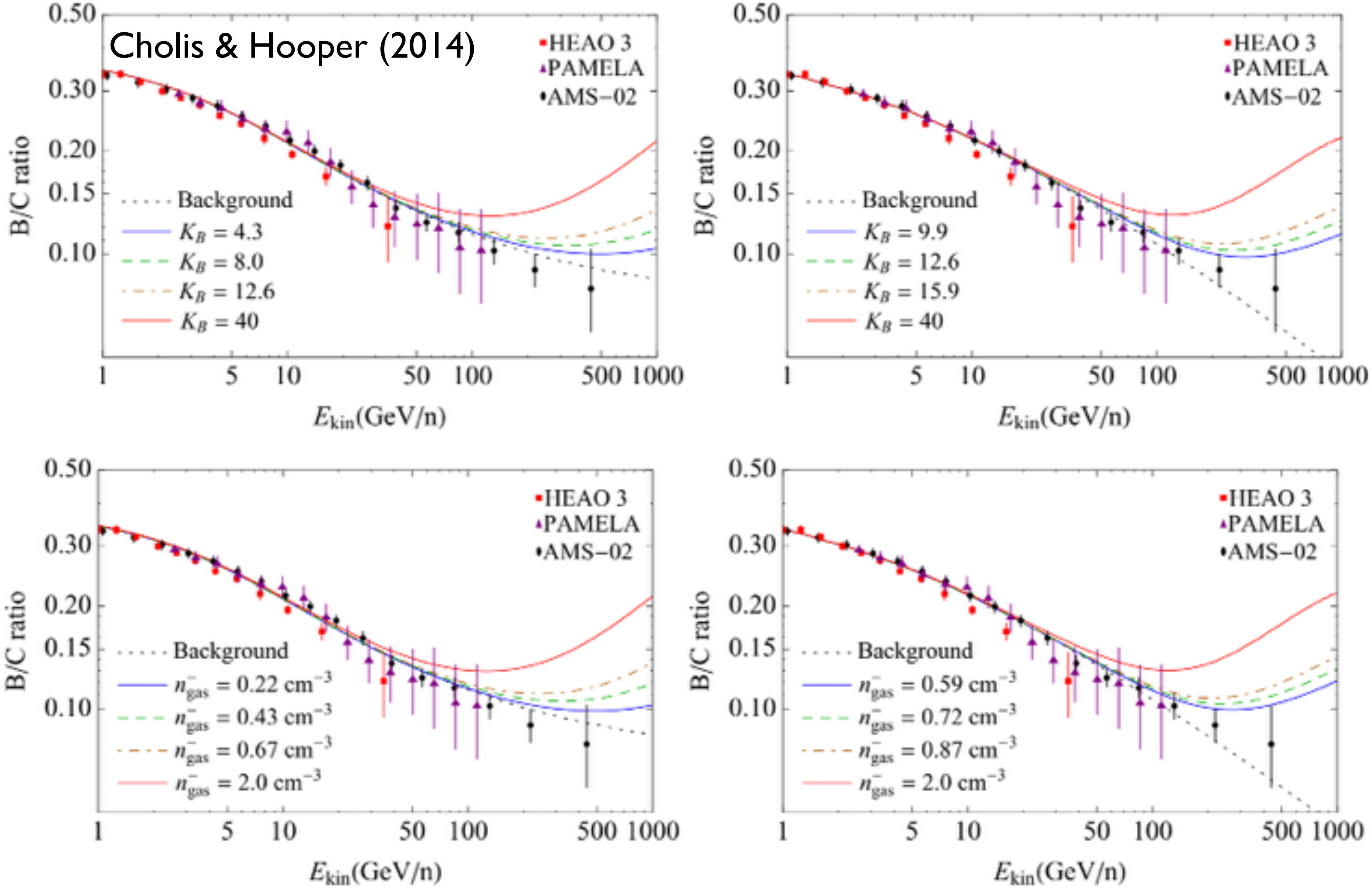


- **One possible “secondary production” channel involves the production of secondary e^+ and e^- in SNR.**

- **This requires that protons are confined within SNR for a sufficient time in order to undergo a pp collision**

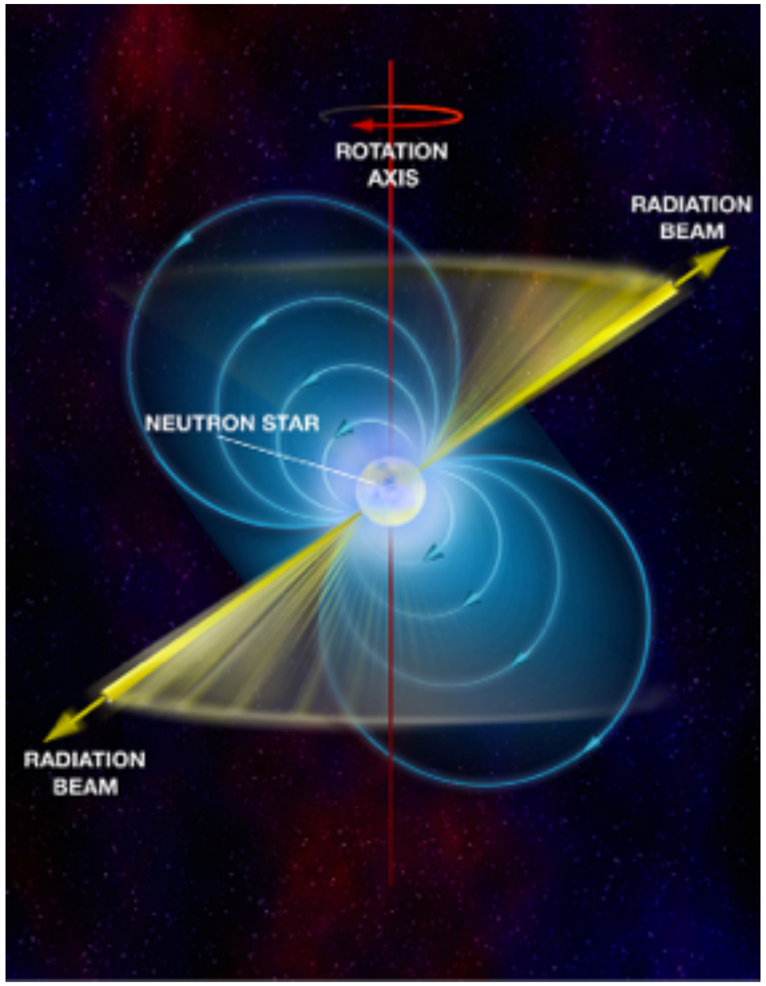
- **Predicts that the positron fraction will continue to rise at very high energies**

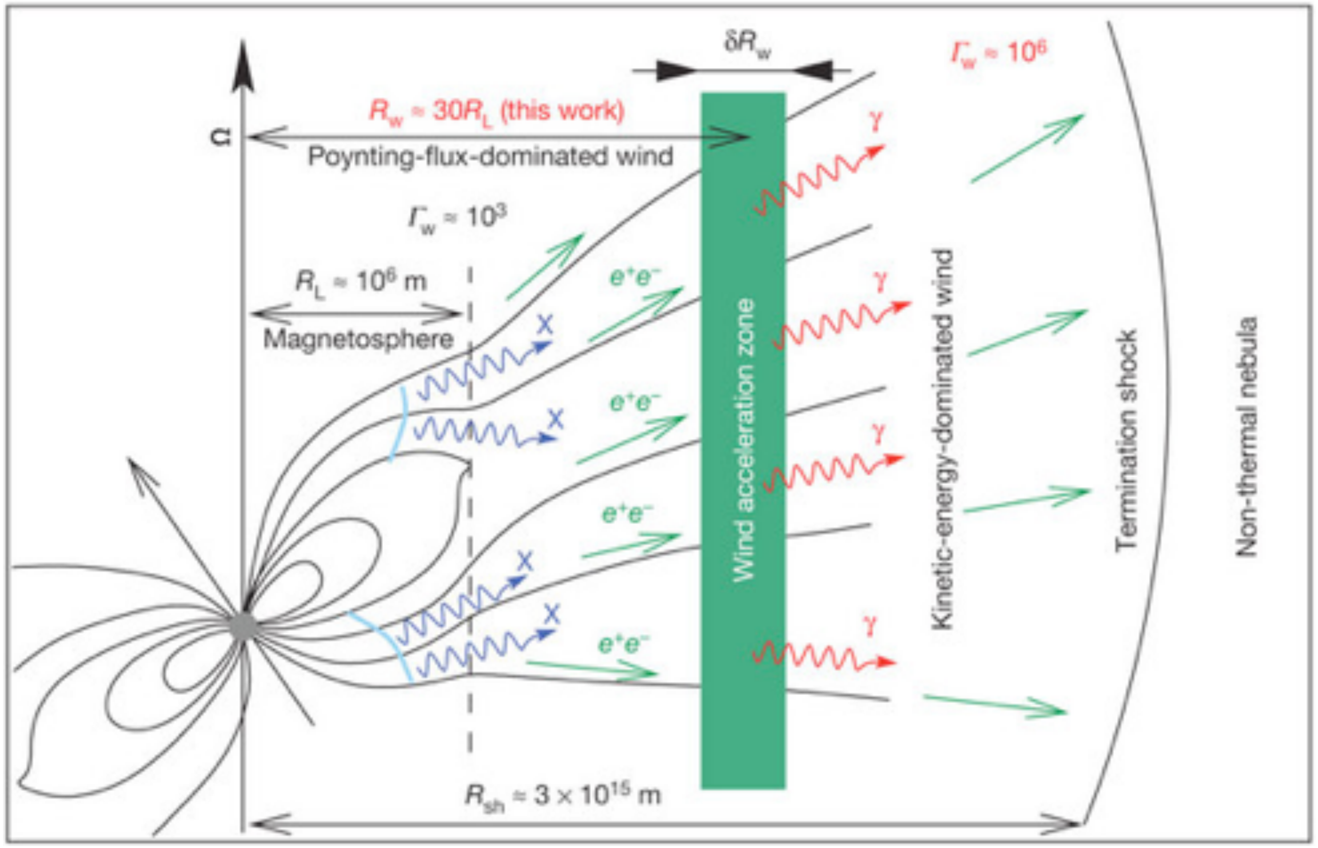
Secondary Production and Acceleration in SNR

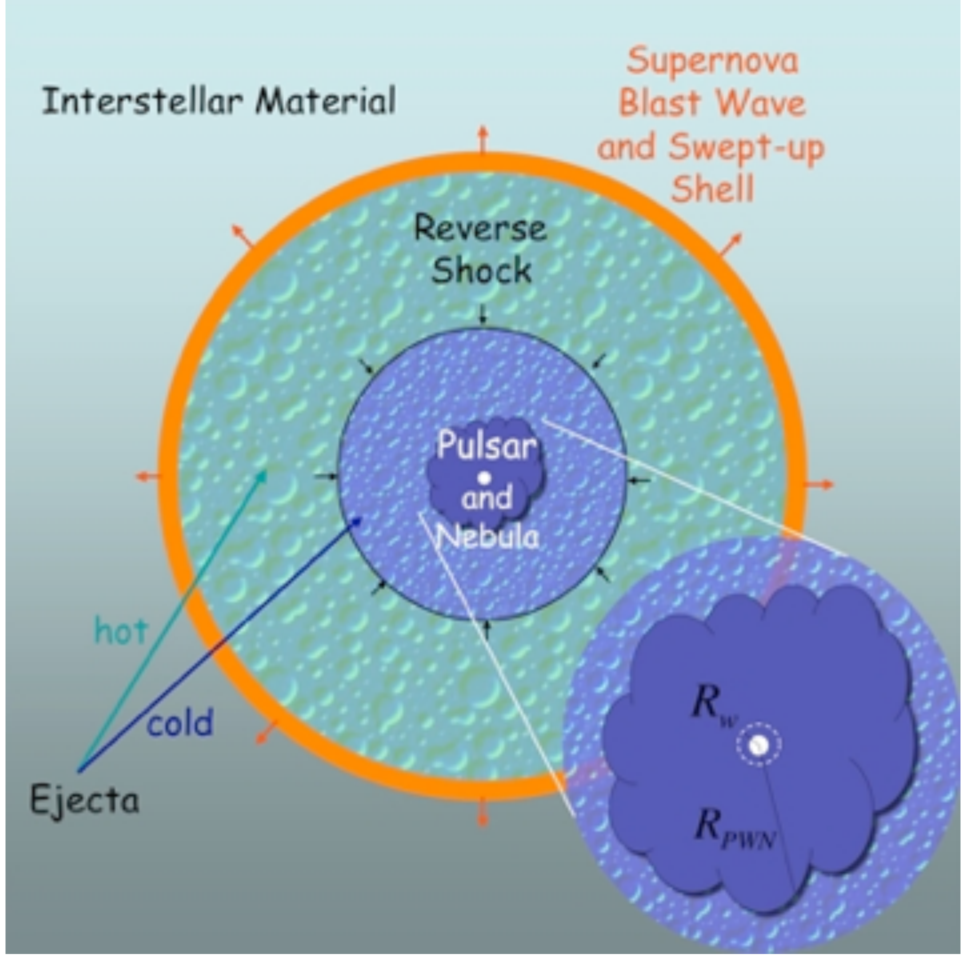

Cholis & Hooper (2014)

- **However, SNR secondary production would also create secondary production of B/C, which is at odds with current observations**

The Pulsar Interpretation

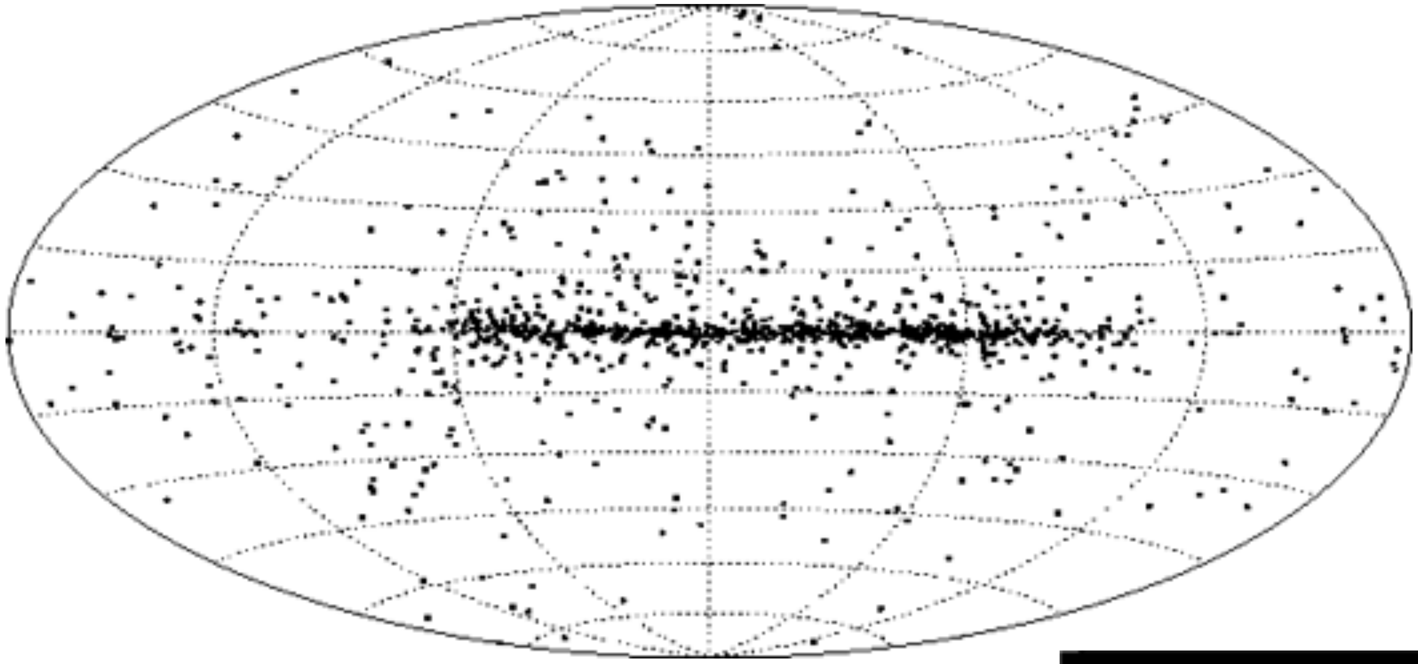


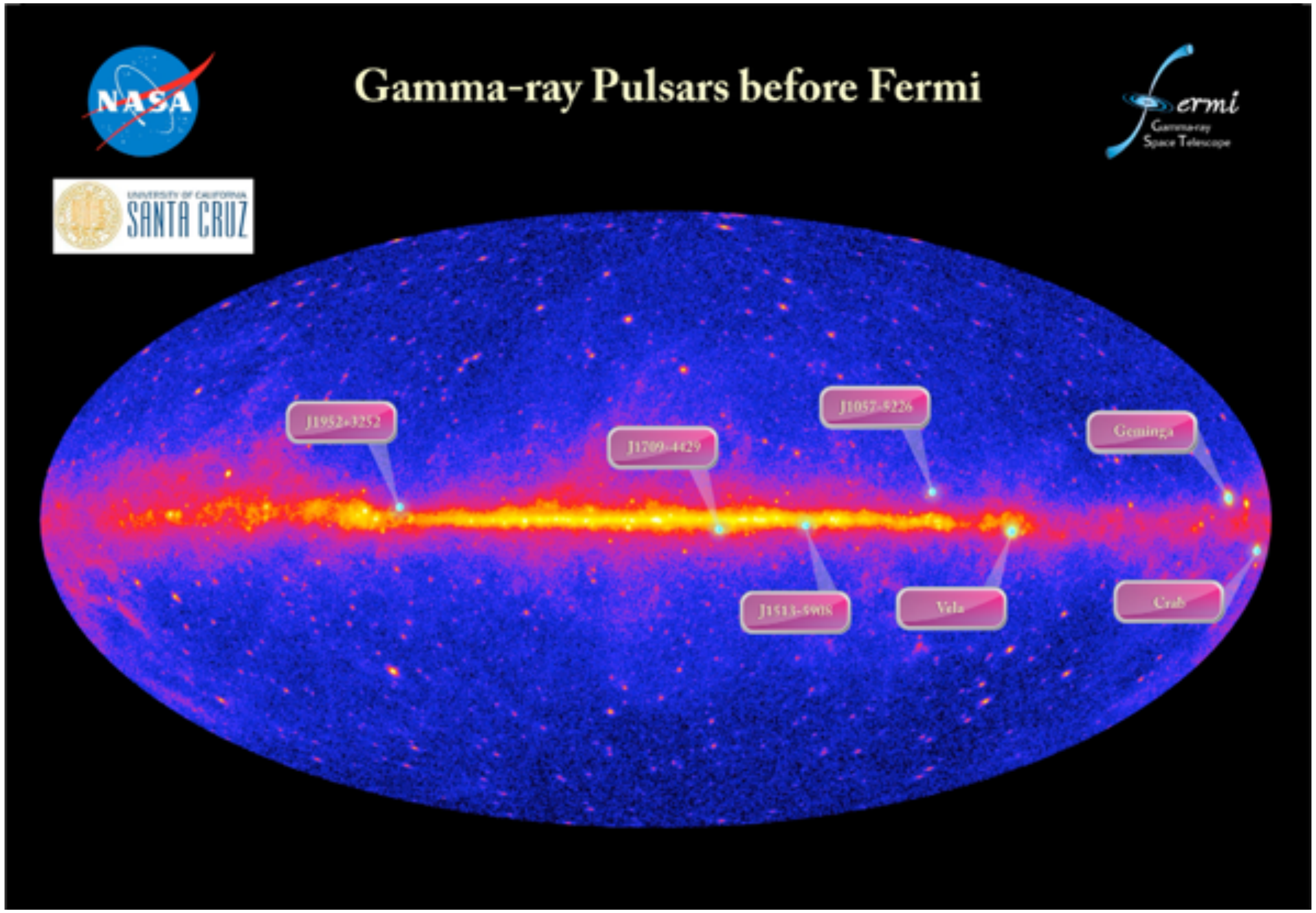




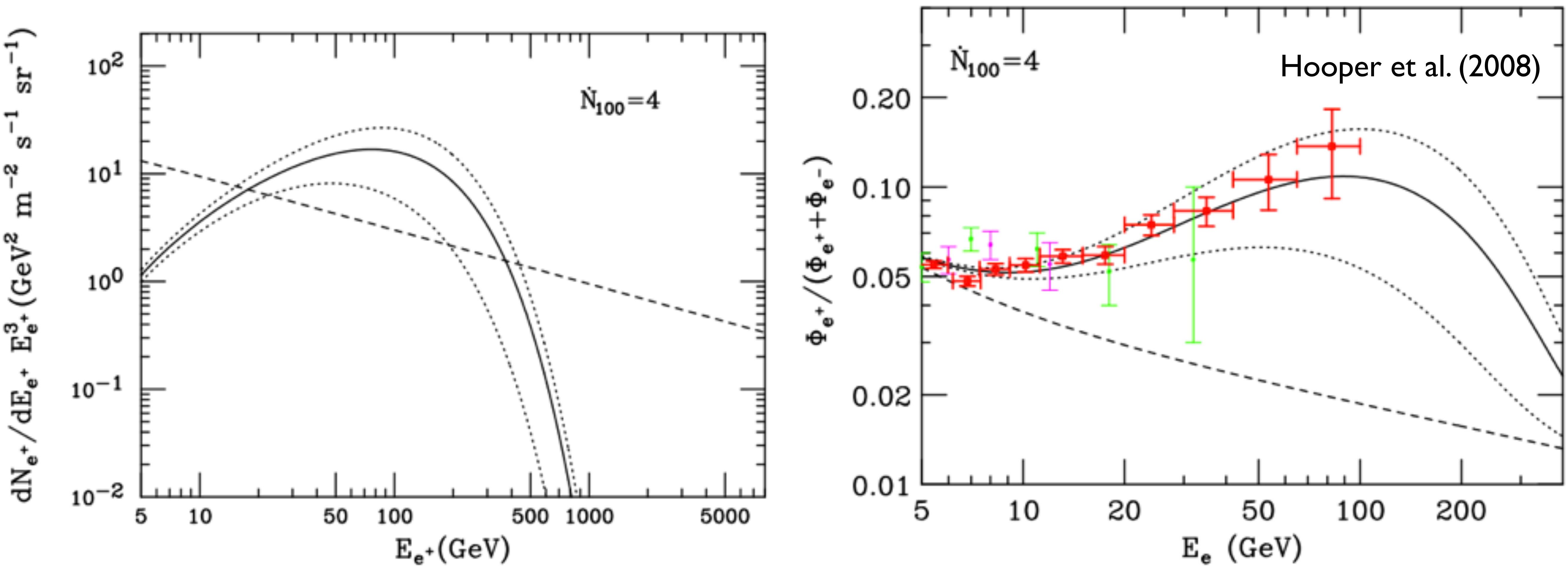
- Pulsars can produce e+e- pairs and then accelerate them to high energy

Global Pulsars vs. Local Pulsars





Global Pulsar Properties

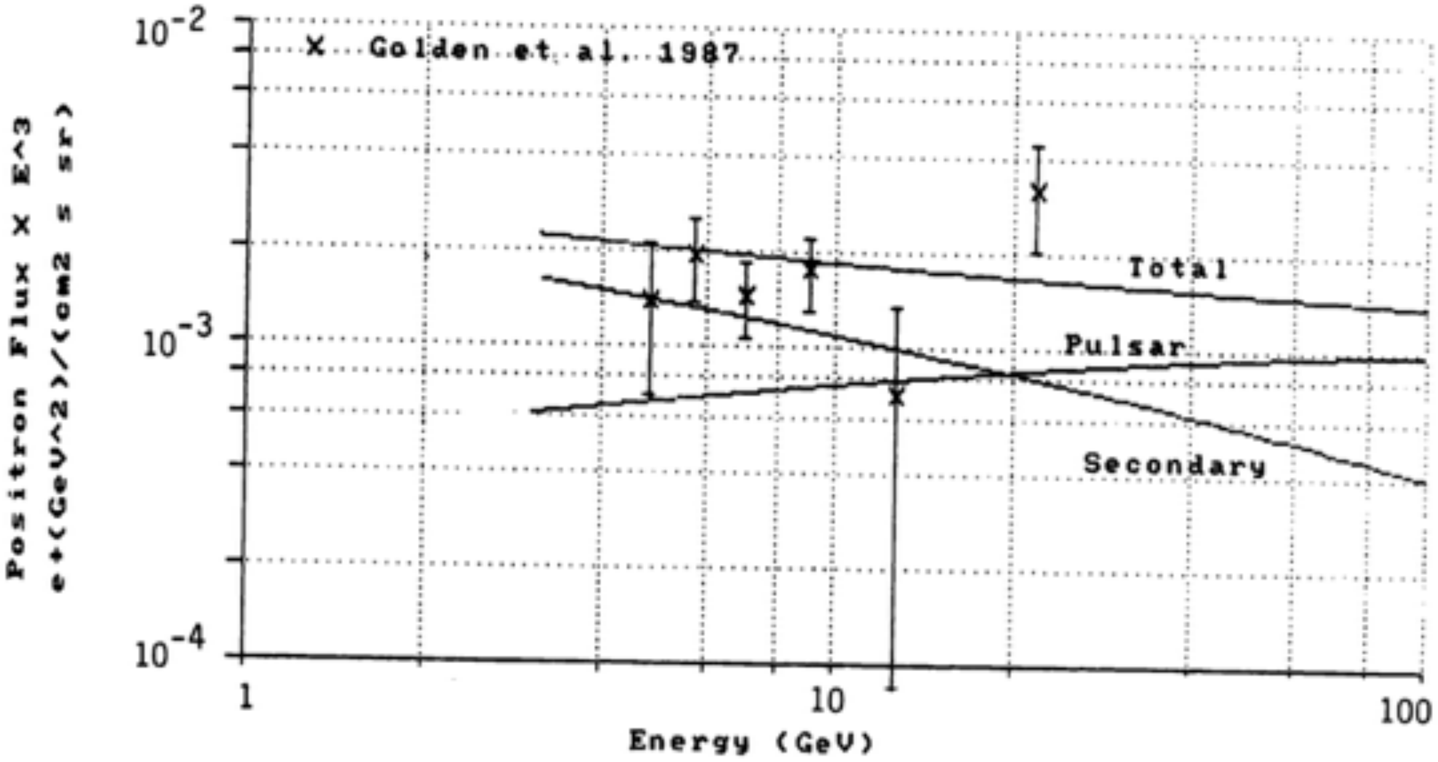


Hooper et al. (2008)

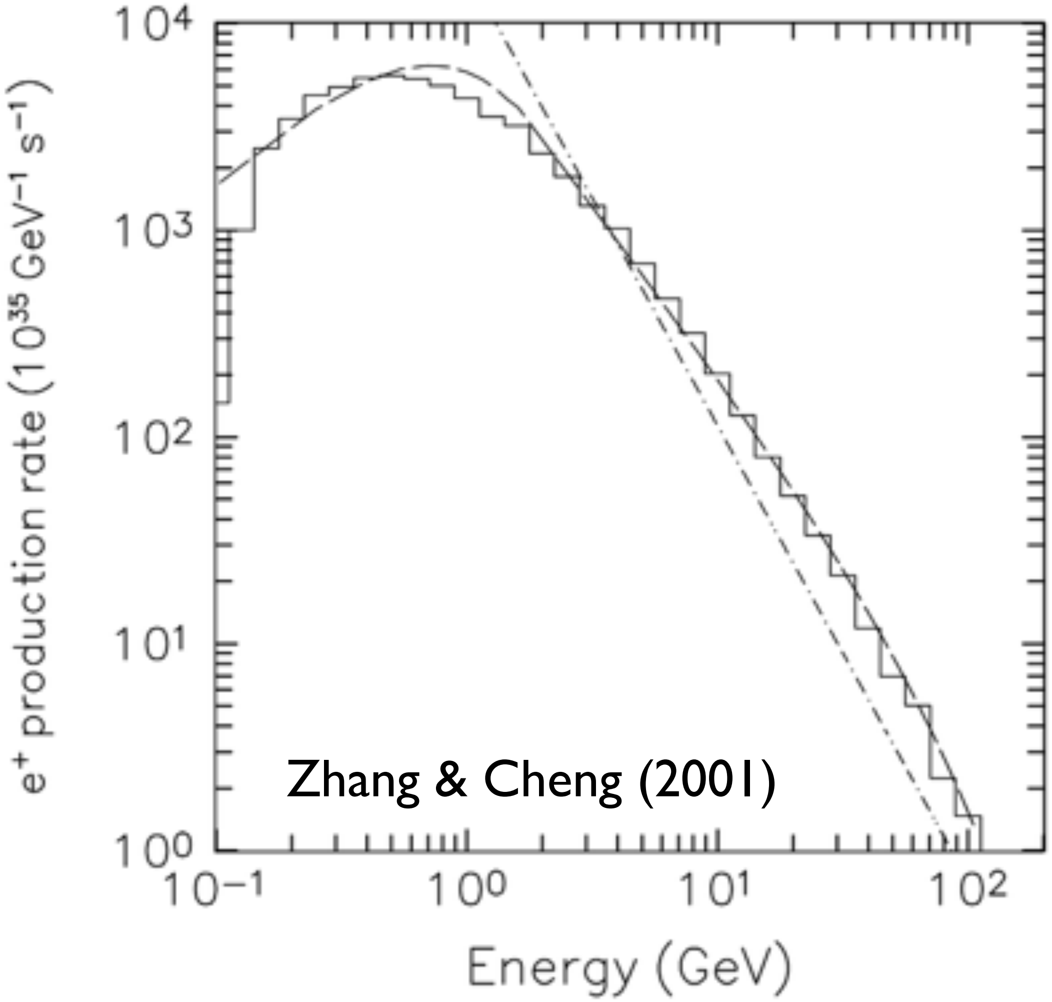
- **For galactic emission, we can compare the total power with that expected from the supernova rate**

- **For a rate of approximately 4 SNR/century**

Global Pulsar Properties



Harding & Ramaty (1987)



Zhang & Cheng (2001)

$$\Phi_\gamma(E) = 2.4 \times 10^{-7}\ E^{-2.2}\ \mathrm{ph\ cm^{-2} s^{-1} GeV^{-1}}$$

$$Q_+(E) = 8.6 \times 10^{39}\ b_{30} f_+ B_{12}^{-0.7} \left(\frac{t_{max}}{10^4 yr}\right)^{.15}\ E^{-2.2}\ \mathrm{s^{-1} GeV^{-1}}$$

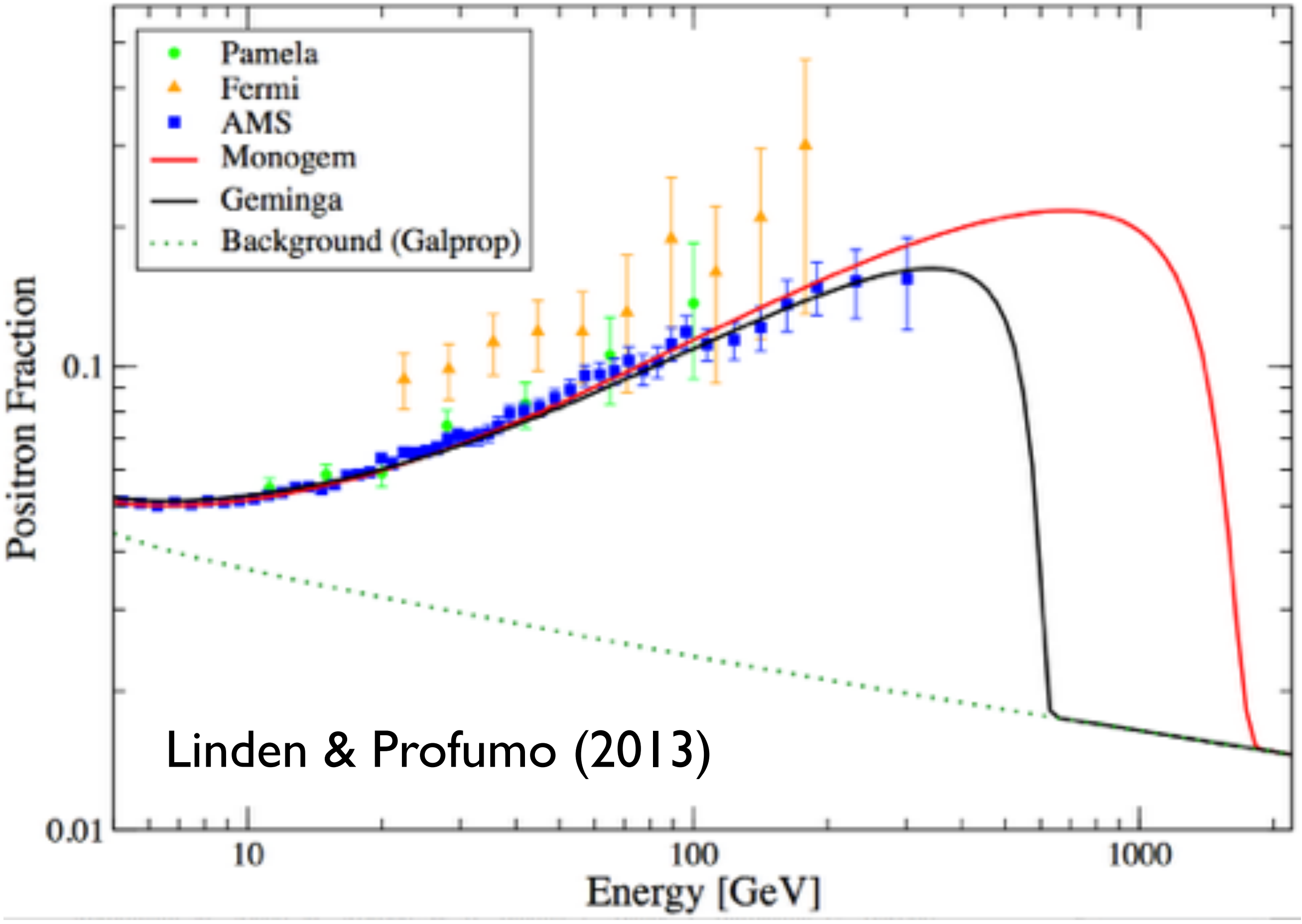
- **The spectrum of injected cosmic-rays is also, to some extent, a prediction**

Local Pulsar Properties

$$Q(\vec{r}, t, E) = Q(E))\delta^3(\vec{r})\delta(t))$$

$$Q(E) = Q_0 E^{-\gamma} \exp\left(E/E_{\mathrm{cut}}\right)$$

$$\int_0^\infty Q(E) E \mathrm{d}E = \eta W_0$$



Linden & Profumo (2013)

- **<u>Assume:</u>**
  - **Delta-Function injection rate**
  - **Power-Law + Exp. Cutoff e^+e^- Injection Spectrum**
  - **Total Lepton Energy corresponding to the spindown energy multiplied by an efficiency for e^+e^- production**

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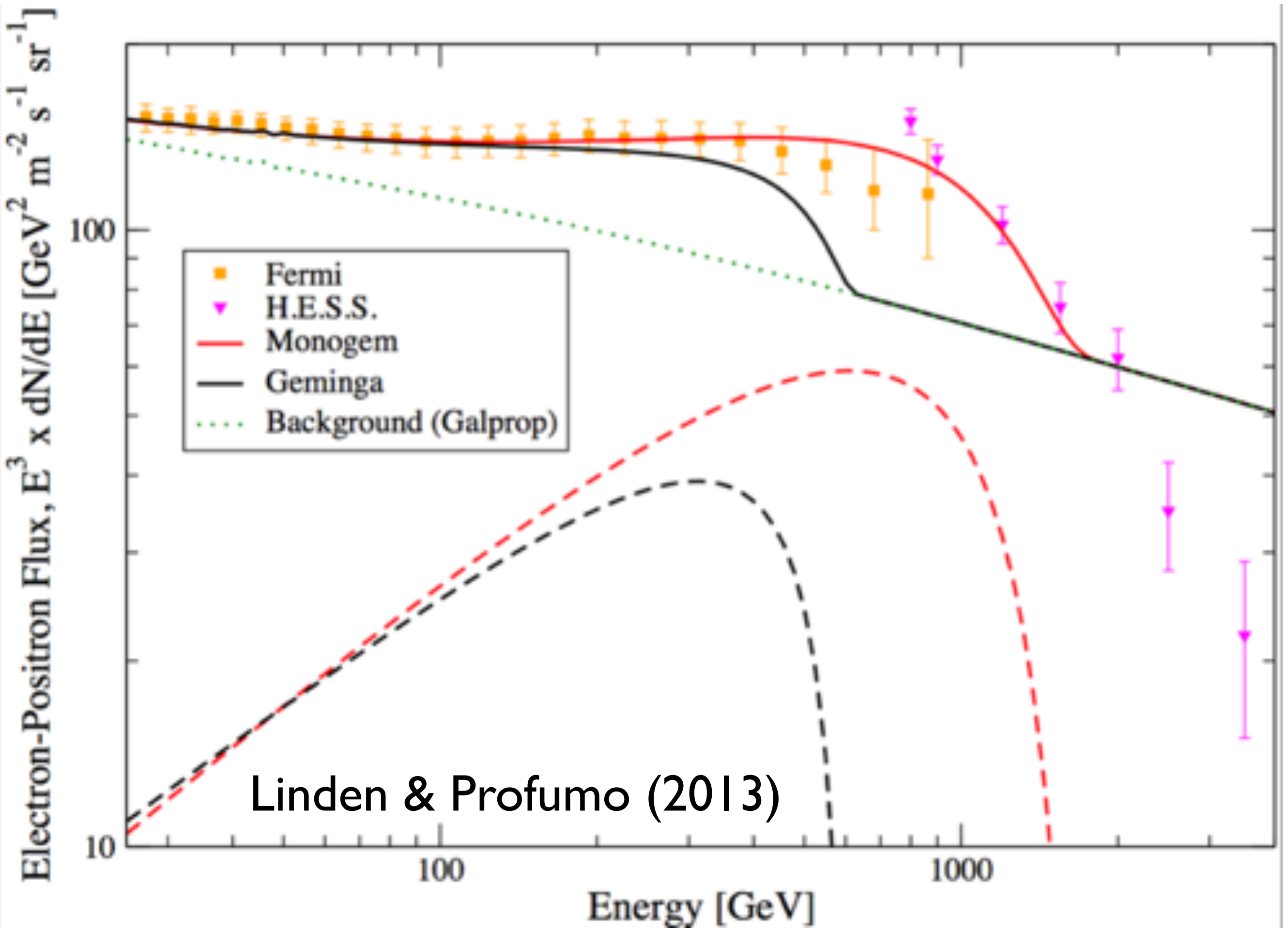

Linden & Profumo (2013)

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  - **Delta-Function injection rate**
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Bayesian Prior

- Most appear to believe the pulsar interpretation, but this is mostly a statement of how reasonable the pulsar interpretation appears

- It's not an unreasonable claim, pulsars are a good fit to the data

- This should make us 80%, 90%, 95% certain of the pulsar interpretation….

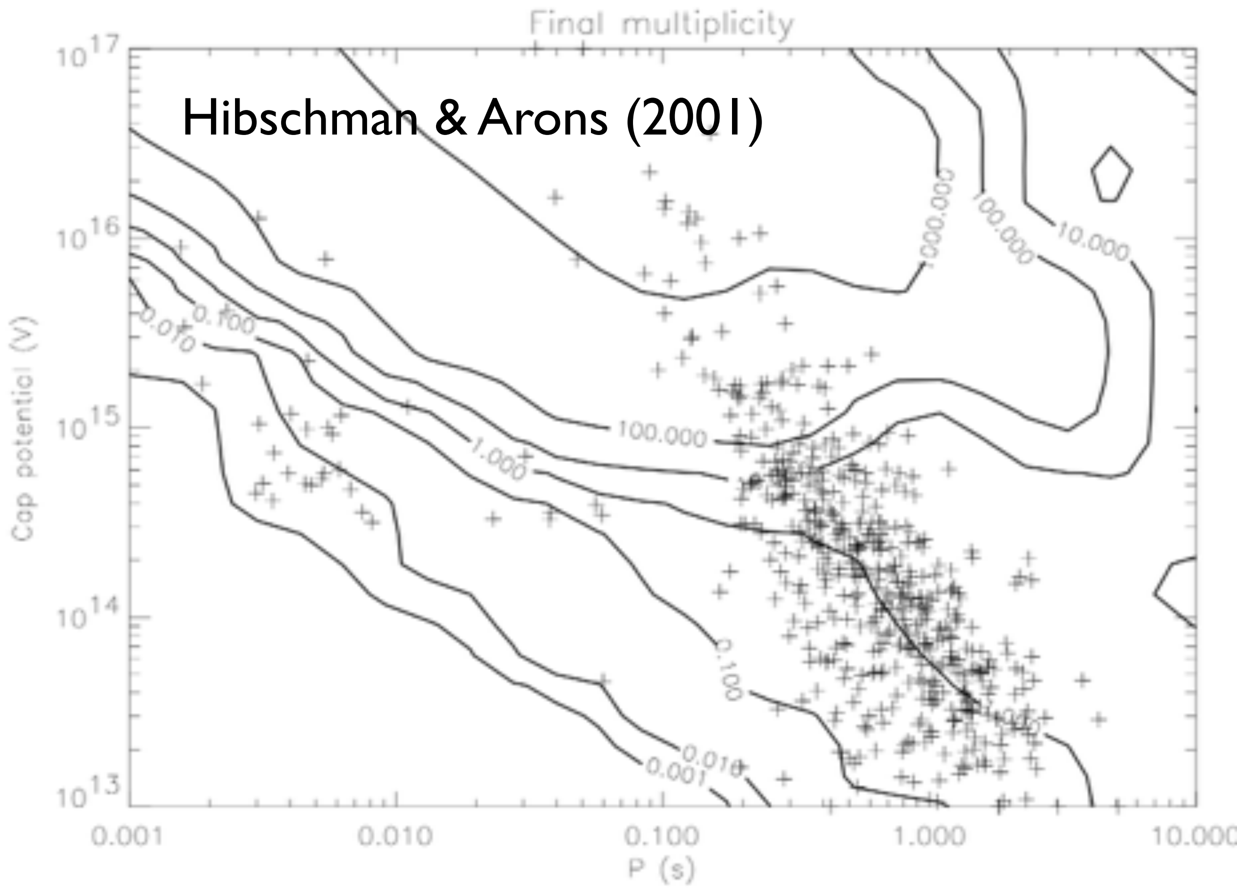
- How do we move past that?

Theoretical Uncertainties

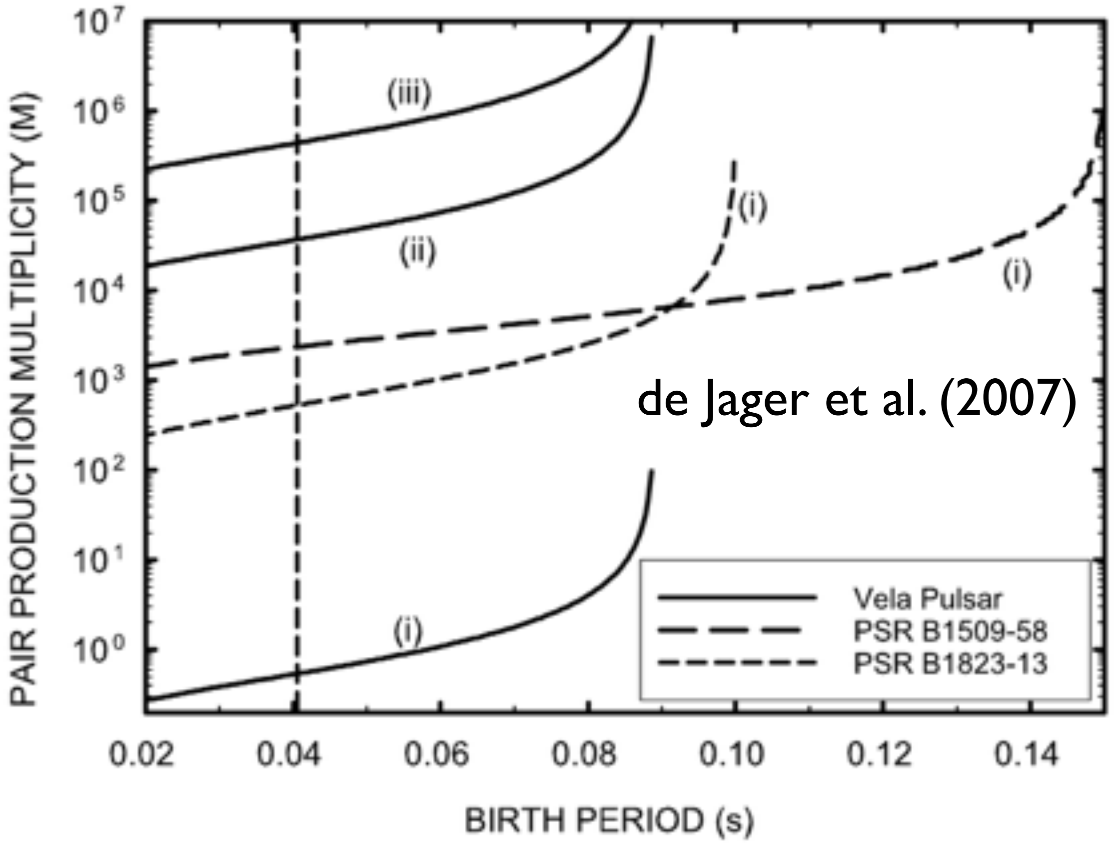
And before we say 99% sure…

Some pulsar emission models predict very low pair-multiplicity, which would be unable to drive a high positron fraction

Recent γ-ray observations by Pierbattista et al. (2014) and de Jager et al. (2007) indicate that high multiplicity models are preferred



Hibschman & Arons (2001)

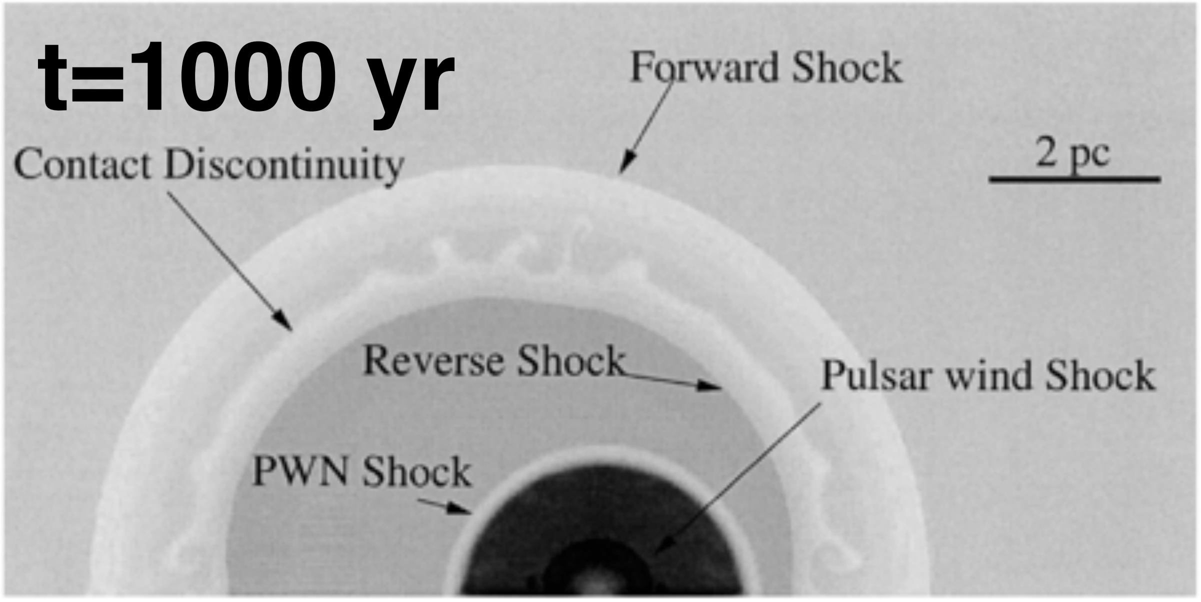


de Jager et al. (2007)

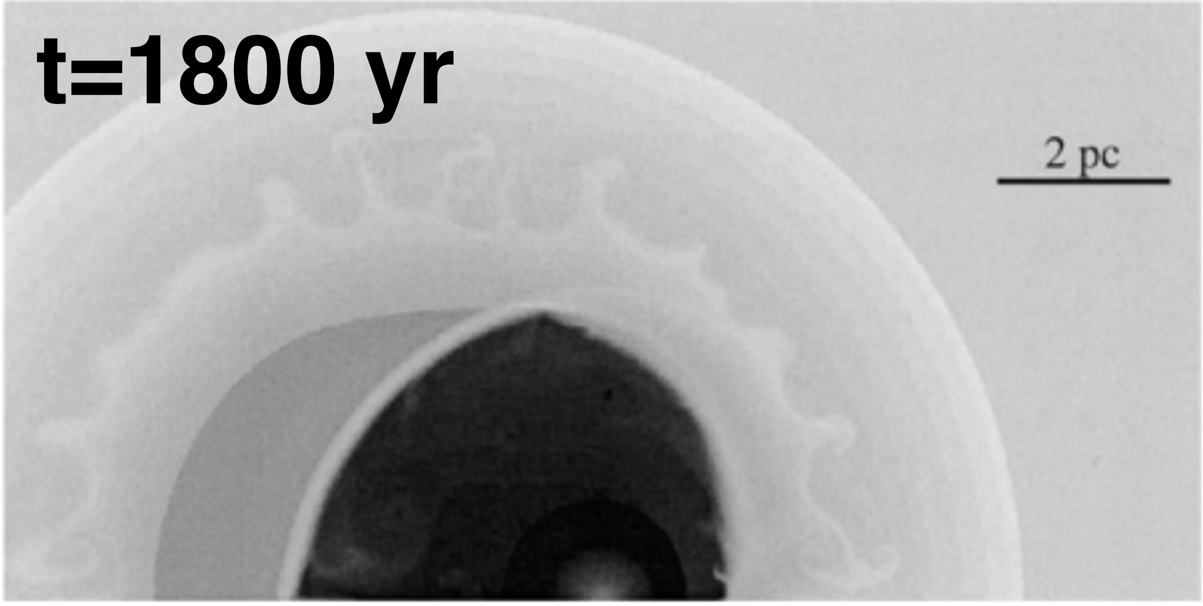
Theoretical Uncertainties

And before we say 99% sure…

- **It is not entirely clear how e^+e^- formed in the PWN escape into the surrounding medium**



van der Swalue et al. (2004)

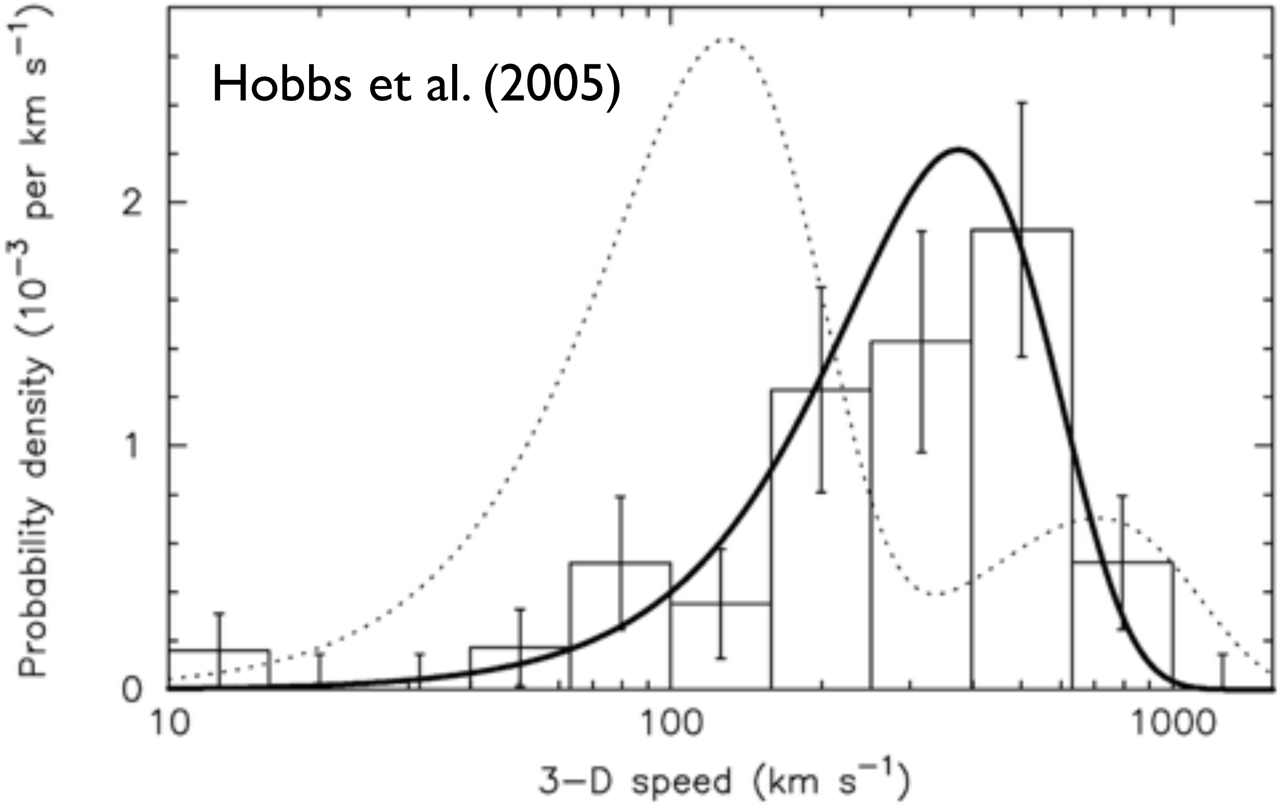


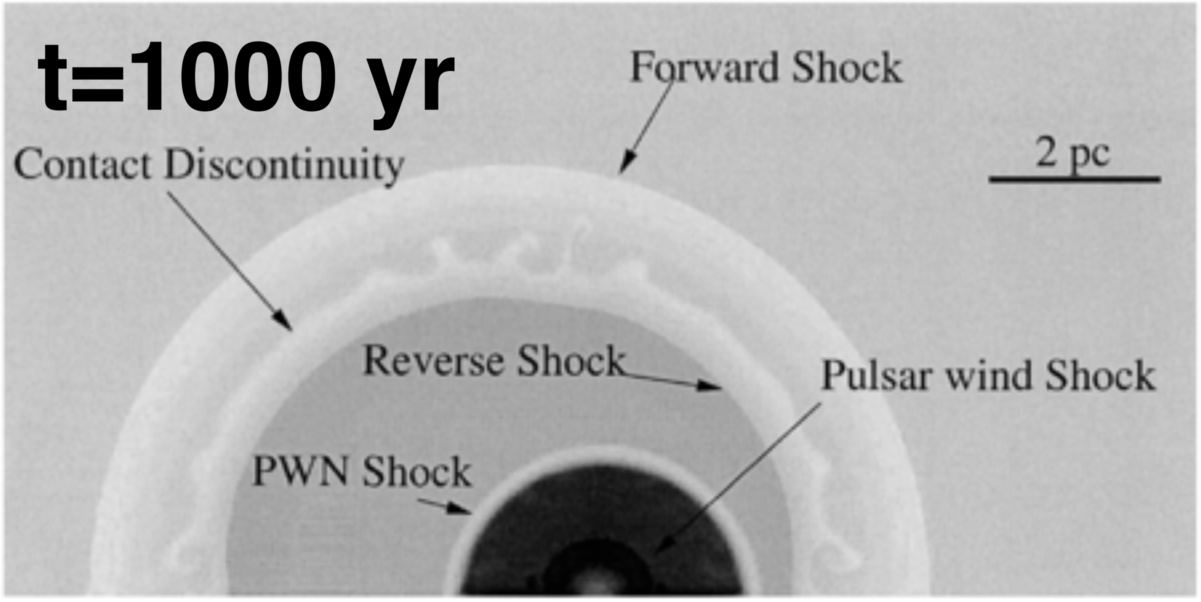
$$t_B = 1.3\times10^4\ yr\left(\frac{E}{100GeV}\right)^{-1}\left(\frac{B}{100\mu G}\right)^{-2}$$

Theoretical Uncertainties

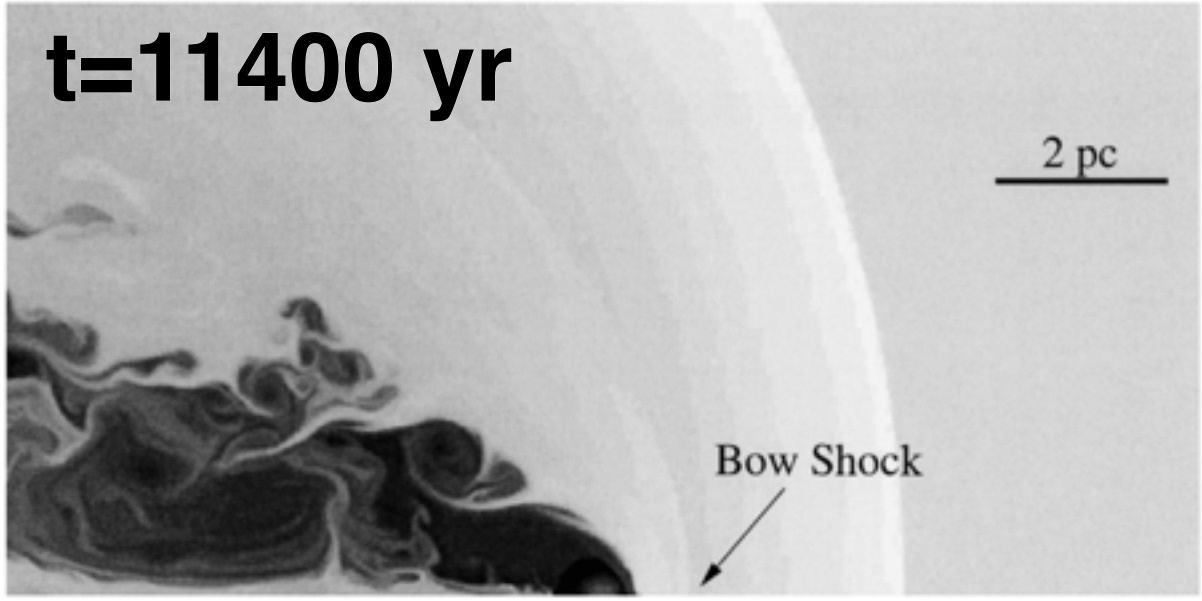
And before we say 99% sure…

- **Need to think about ‘bow shock’ PWN, where the pulsar is escaping from the reverse shock of the SNR**


Hobbs et al. (2005)



van der Swalue et al. (2004)



- **But this can make energetics more annoying**

Going Beyond the Bayesian Prior

- “Wiggles” in the cosmic-ray lepton flux
- Anisotropies in the Cosmic-Ray Lepton Spectrum
- Synchrotron Polarization in PWN

Wiggles in the Lepton Spectrum

- **Diffusion scales mildly with energy, while energy loss scales strongly with energy (for ICS and synchrotron)**

$$D(E) \propto E^{0.31 \pm 0.02}$$

Trotta et al. (2009)

$$d(t) = \sqrt{6Dt}$$

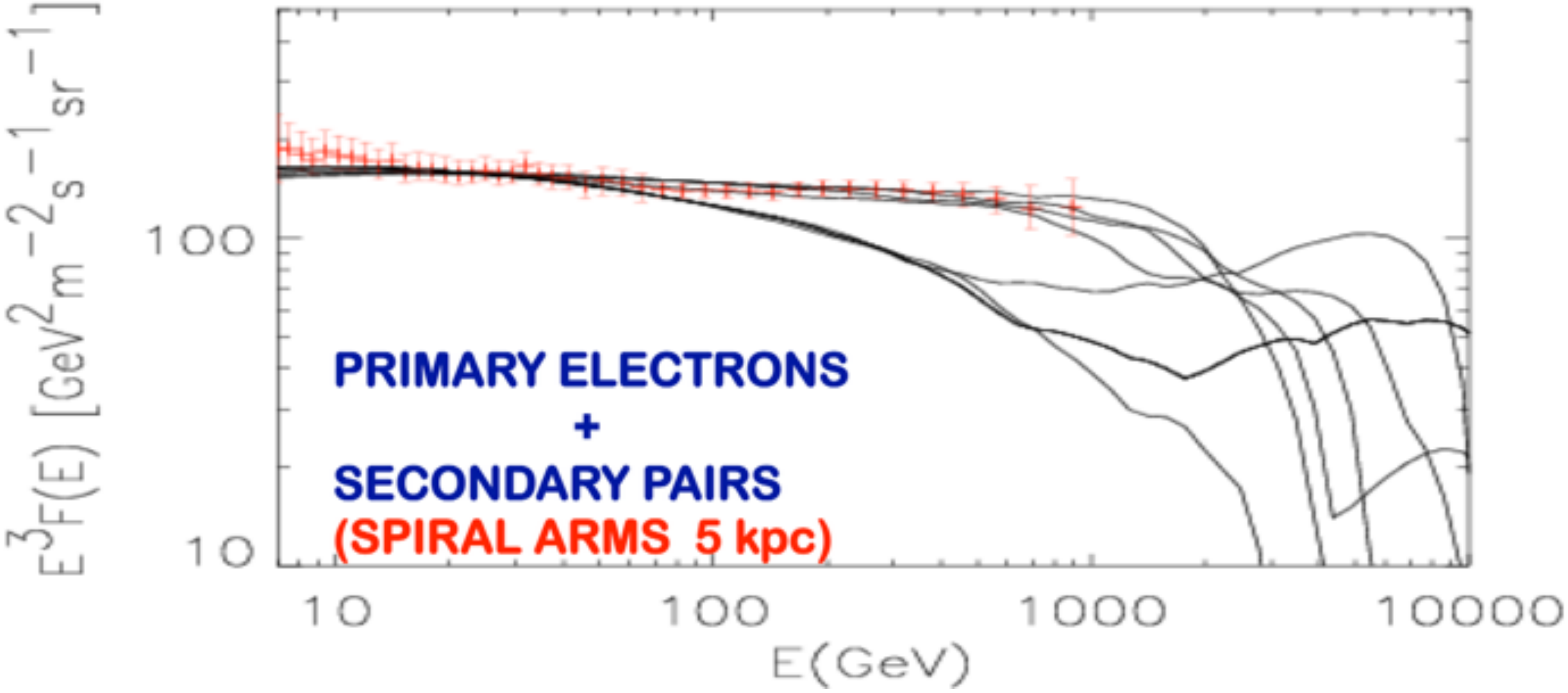
$$t_{loss}(E) \propto E^{-1}$$

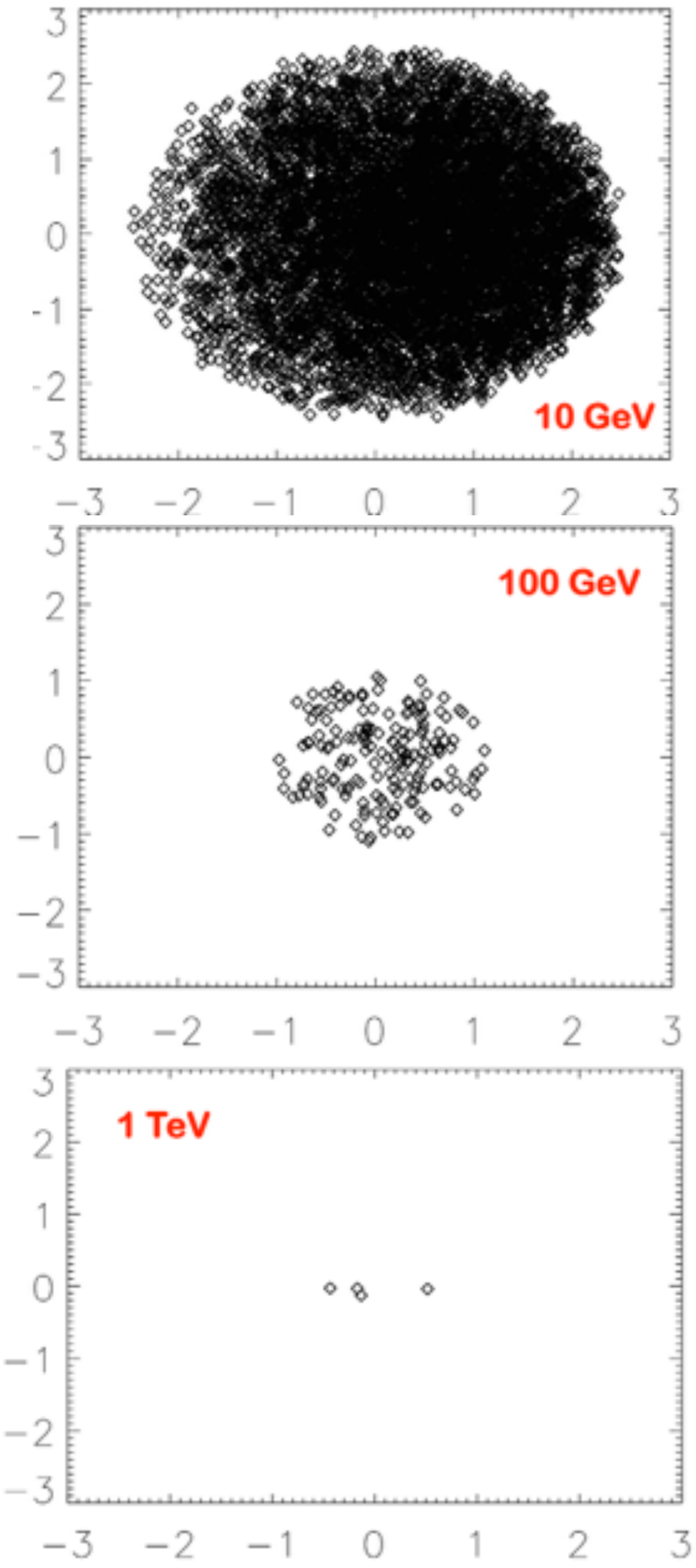
- **Implies that high energy leptons were produces closer to the solar position, compared to low energy leptons**

Wiggles in the Lepton Spectrum

- Do we expect the cosmic-ray electron spectrum to continue to be smooth up to high energies?

- The diffusion distance in one energy loss time at 1 TeV is ~300 pc, should be affected by local sources

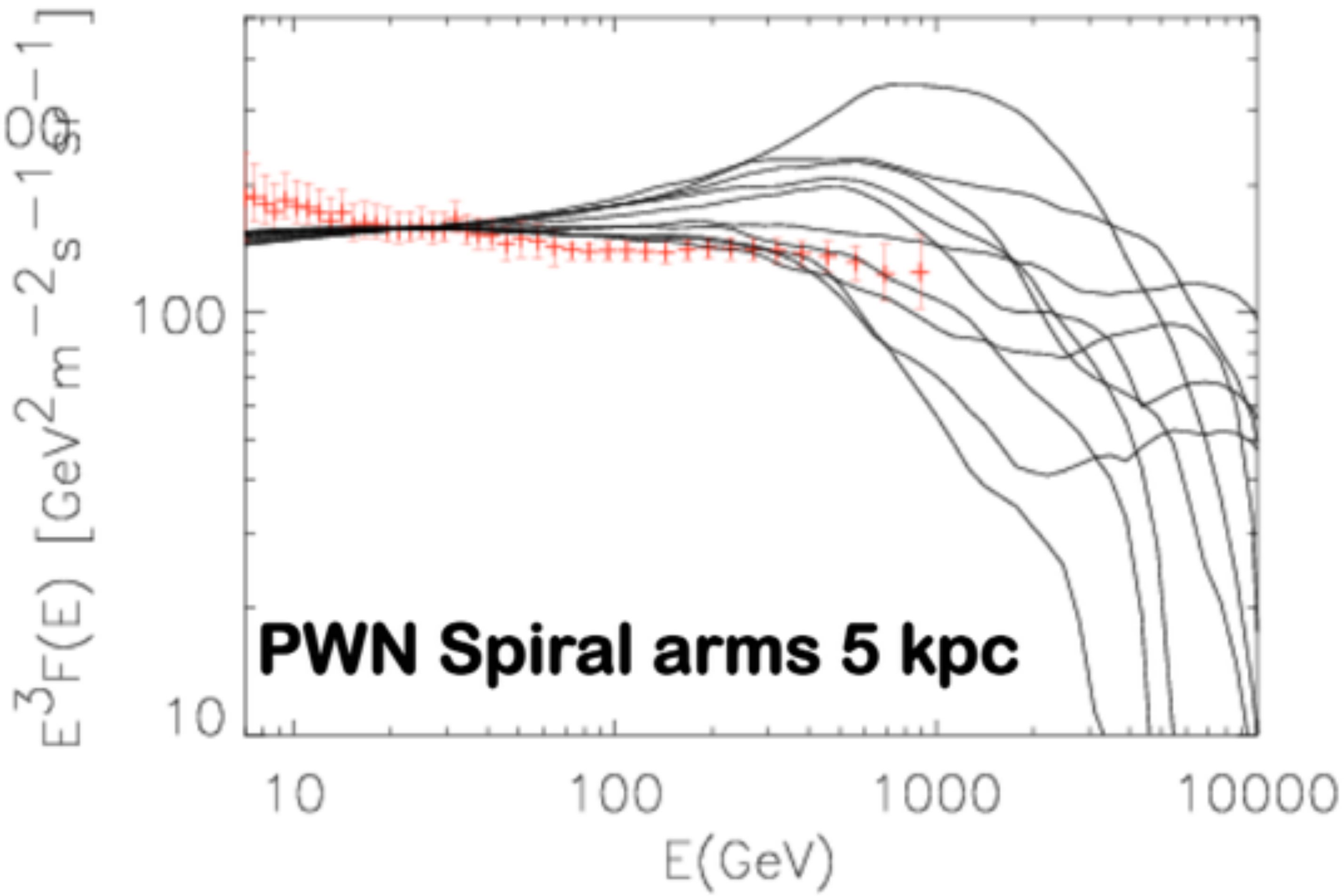


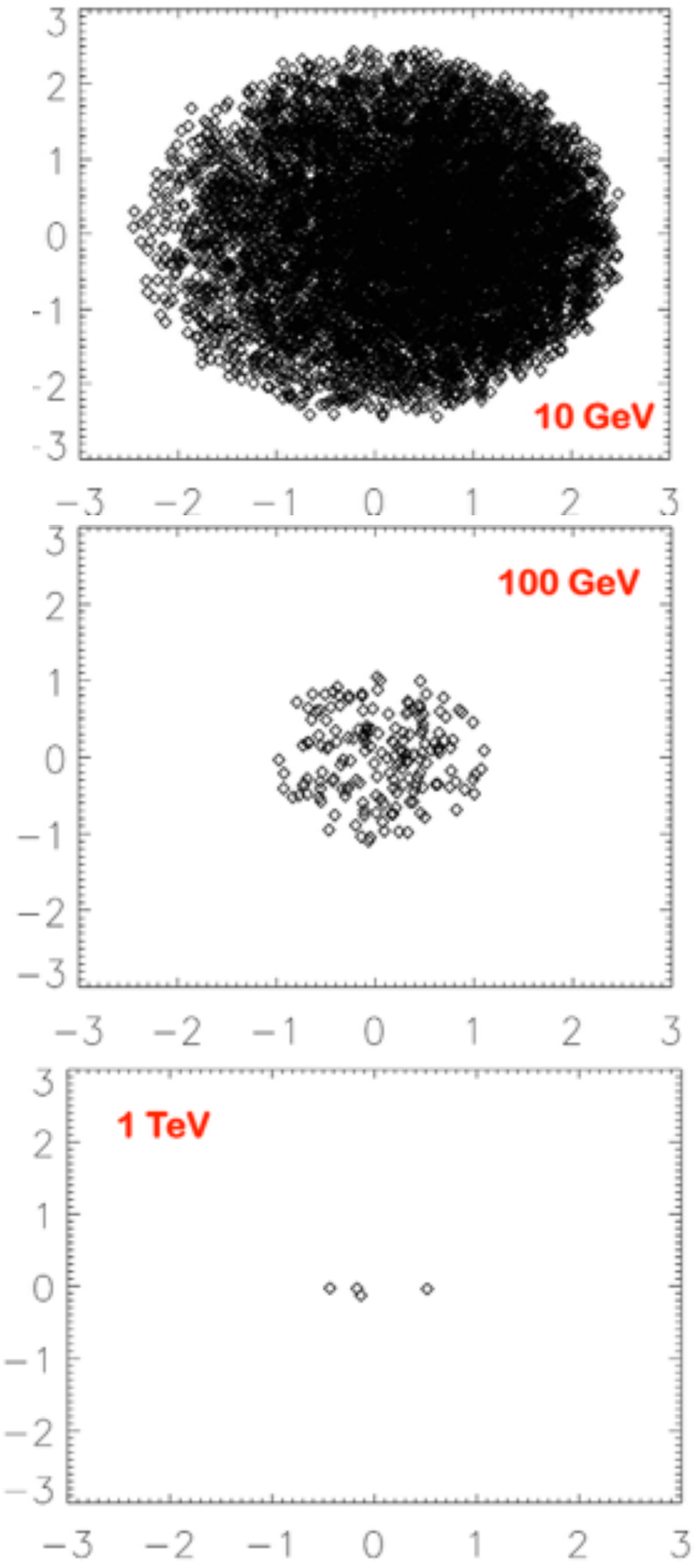


Blasi & Amato (2010)

Wiggles in the Lepton Spectrum

- **While this will greatly affect the expected lepton flux from nearby primary sources, it will not affect either secondary production or dark matter production of e^+e^-**





Blasi & Amato (2010)

Cosmic-Ray Lepton Anisotropies

$$\Delta = \frac{N_f - N_b}{N_f + N_b}$$

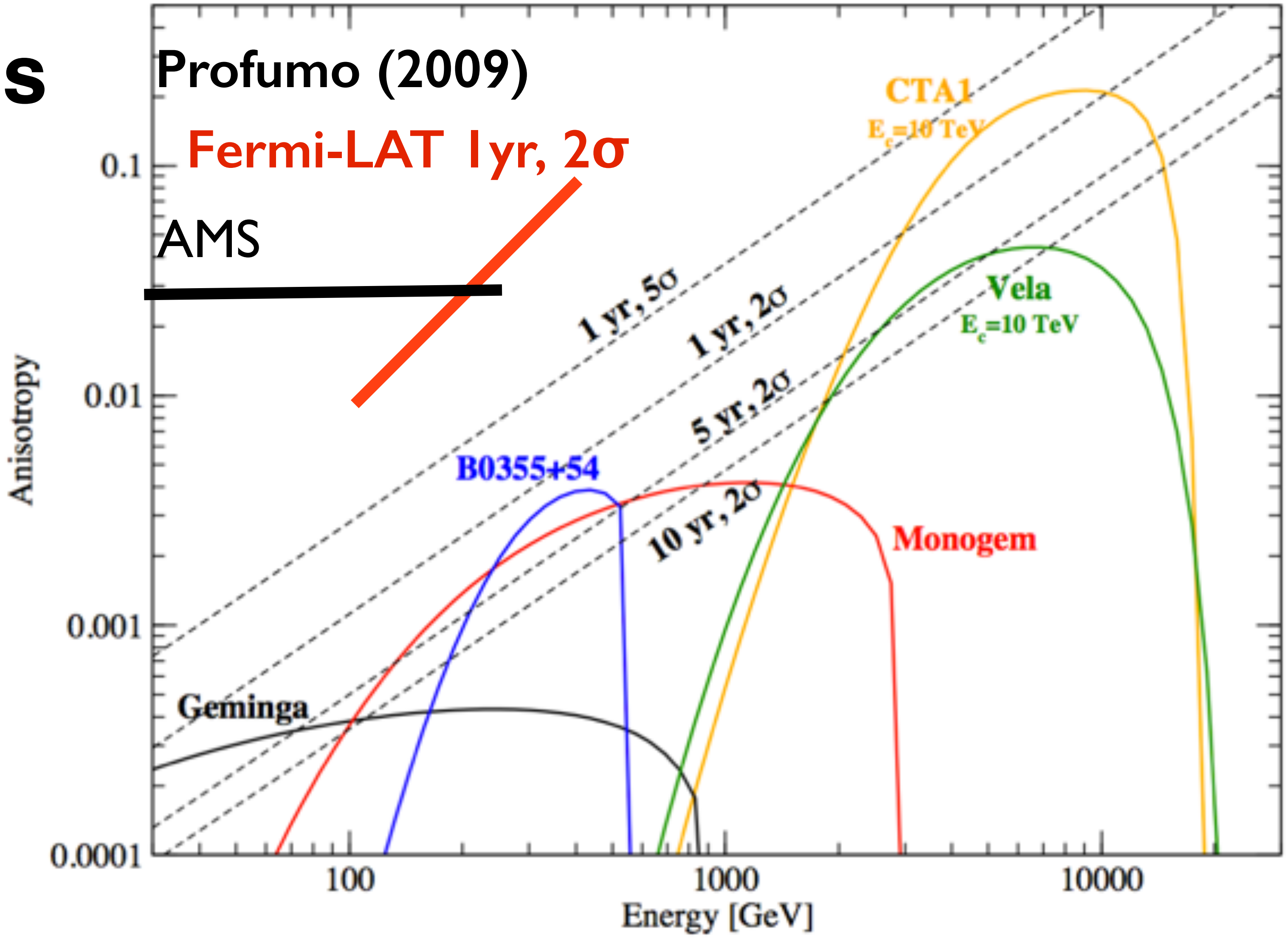
$$\Delta = \frac{3}{2c}\frac{d}{T}\frac{(1-\delta)E/E_{\rm loss}}{1-(1-E/E_{\rm loss})^{1-\delta}}\frac{N_{\rm psr}(E)}{N_{\rm tot}(E)}$$

$$\Delta > 2\frac{\sqrt{N_{avg}}}{N_{avg}}$$

- **You can look for anisotropies in the positron flux, stemming from this stochastic distribution**

Lepton Anisotropies

- **Fermi-LAT observations should place strong constraints on the lepton anisotropy**

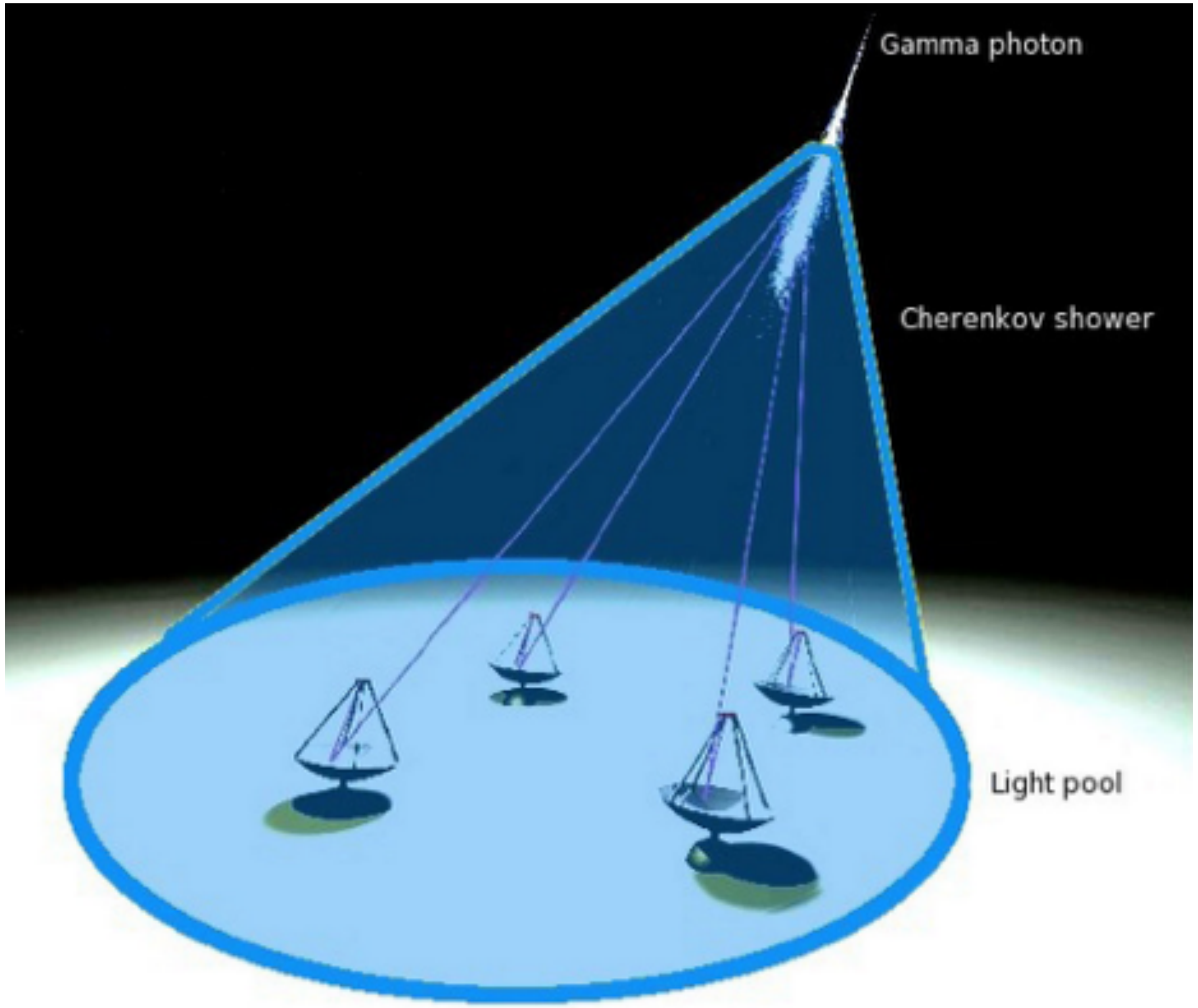


- **However, current constraints fall below theoretical predictions**

- **Either a sign that the measurement is difficult, or that there is some residual anisotropy preventing limits from becoming stronger**

Observations with ACTs?

- **ACTs have a large effective area, which their sensitivity for anisotropy searches**



Fermi-LAT

Effective Area ~ 1 m^2
Angular Acceptance ~ 2 sr
Total Observation Time ~ 5 yr

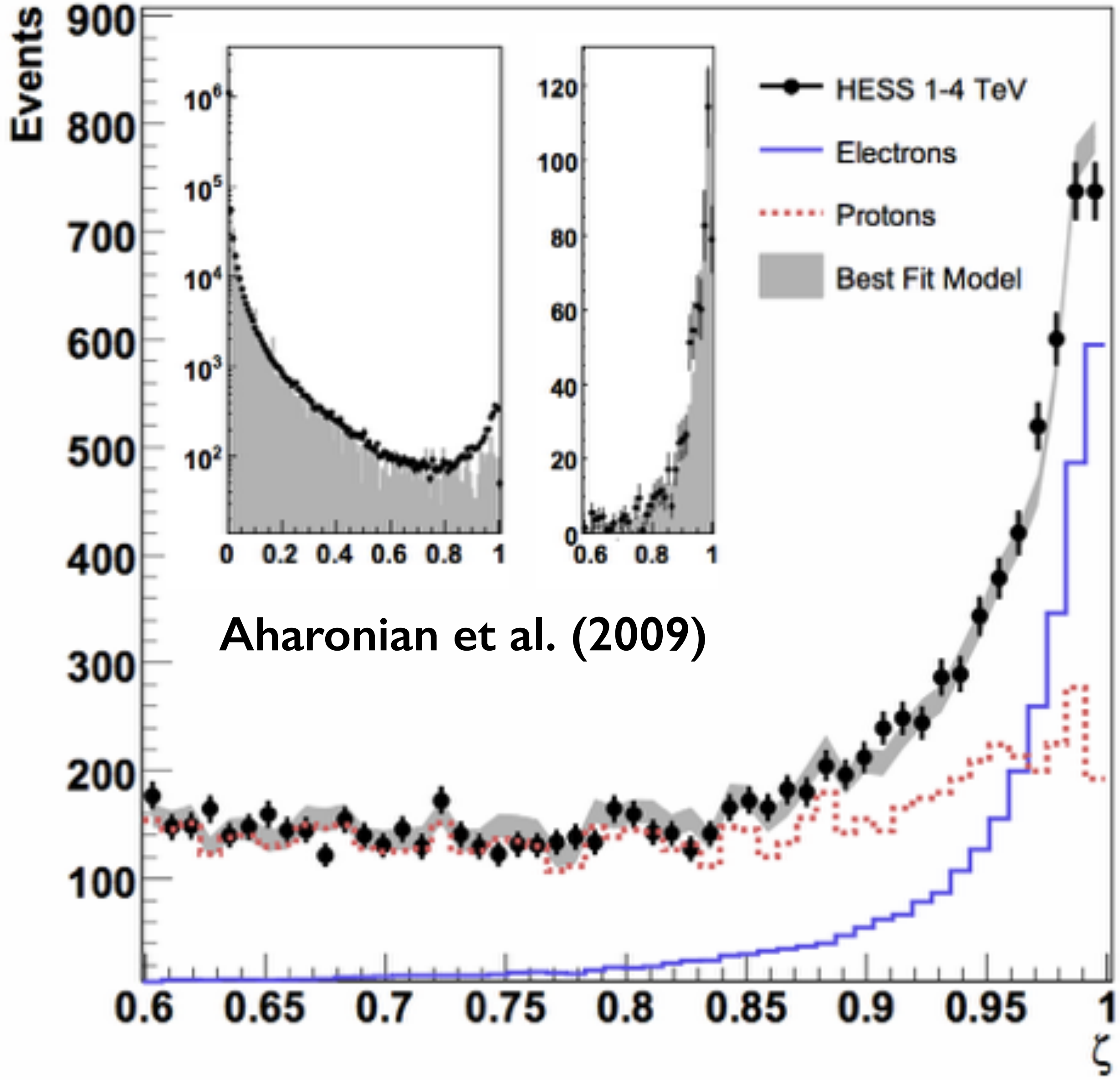
Effective Acceptance ~ 3.2×10^8 m^2 sr s

H.E.S.S.

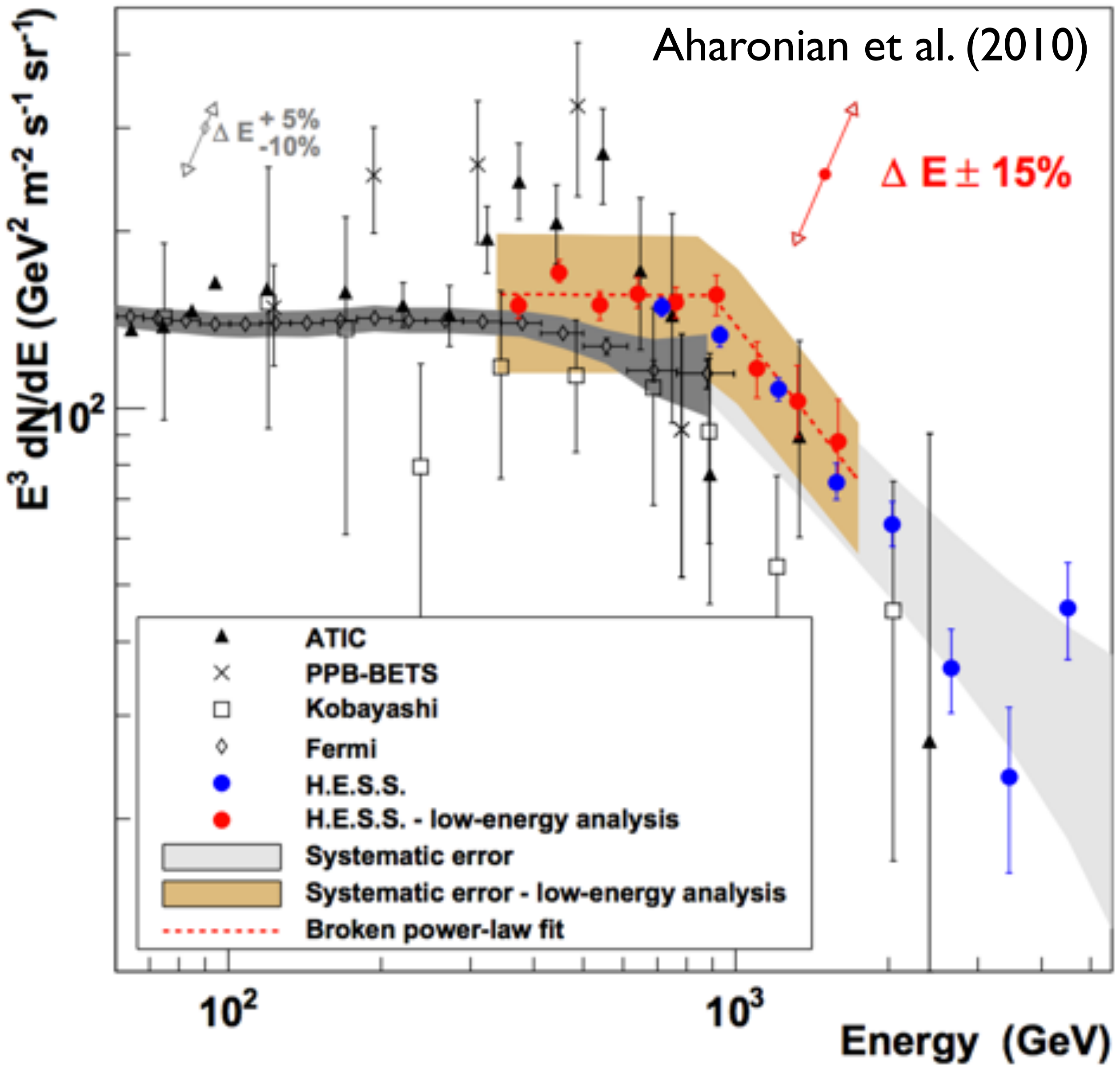
Effective Area ~ 5×10^4 m^2
Angular Acceptance ~ 0.002 sr
Total Observation Time ~ 5000h

Effective Acceptance ~ 1.8×10^9 m^2 sr s

Observations with ACTs?



Aharonian et al. (2009)



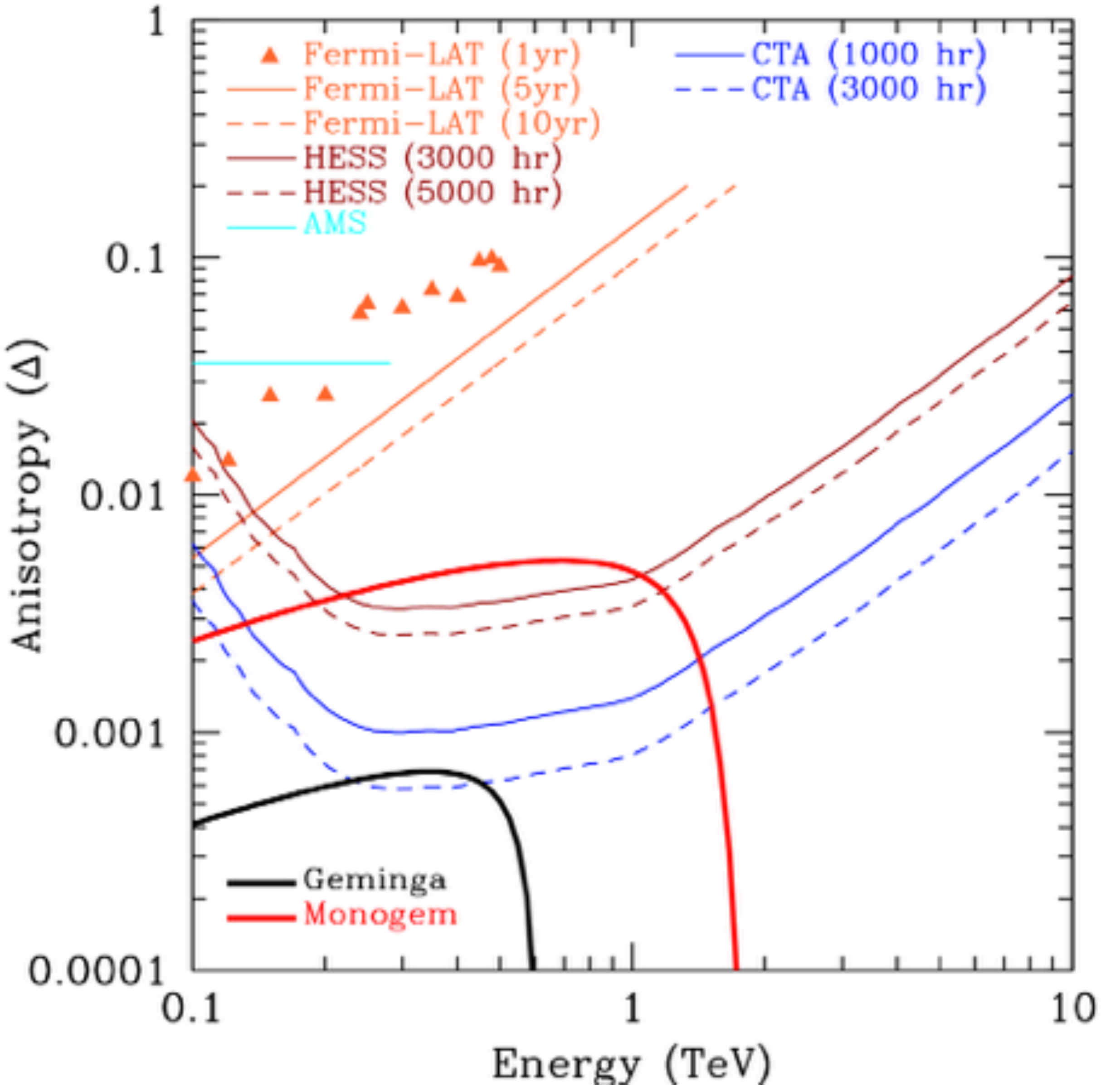
Aharonian et al. (2010)

- **However, ACTs do not have great Hadronic Rejection**
- **Also, the Energy Reconstruction and Effective Area of ACTs is highly uncertain**

Observations with ACTs?

- **The largest uncertainties don't matter for anisotropy searches**
    - **Overall effective area cancels**
    - **Energy Reconstruction can be ignored**

$$N_{tot} = (N_{psr} + N_{\gamma}) + (N_{e,iso} + N_p)$$



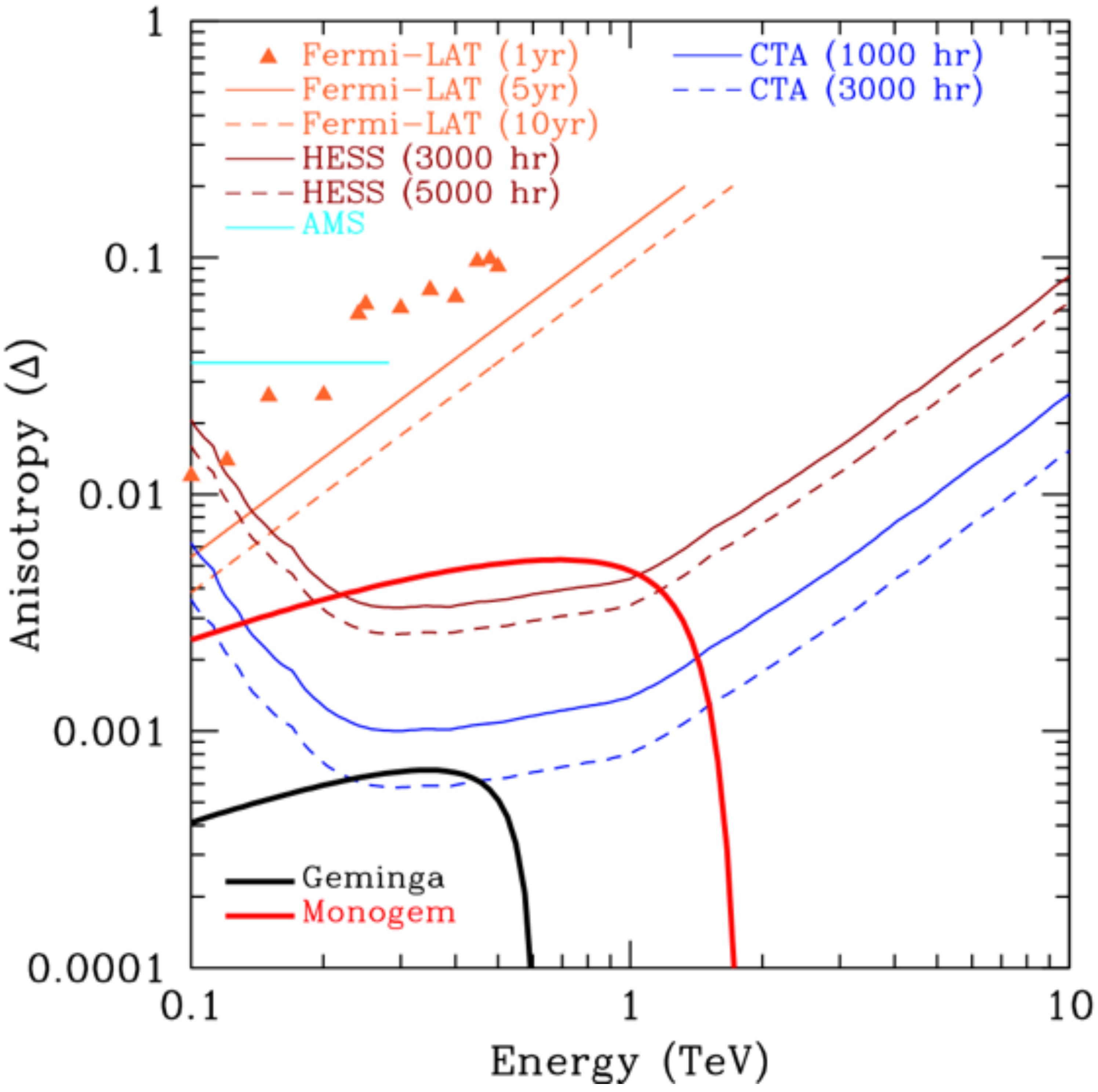
Linden & Profumo (2013)

$$\Delta = \frac{N_f - N_b}{N_f + N_b} = \frac{N_{psr,f} - N_{psr,b}}{N_{psr,f} + N_{psr,b} + 2(N_{e,iso} + N_p)}$$

- **While Hadronic rejection does matter, the hadronic background is highly isotropic (at the level 10^{-4}), this creates a statistical uncertainty**

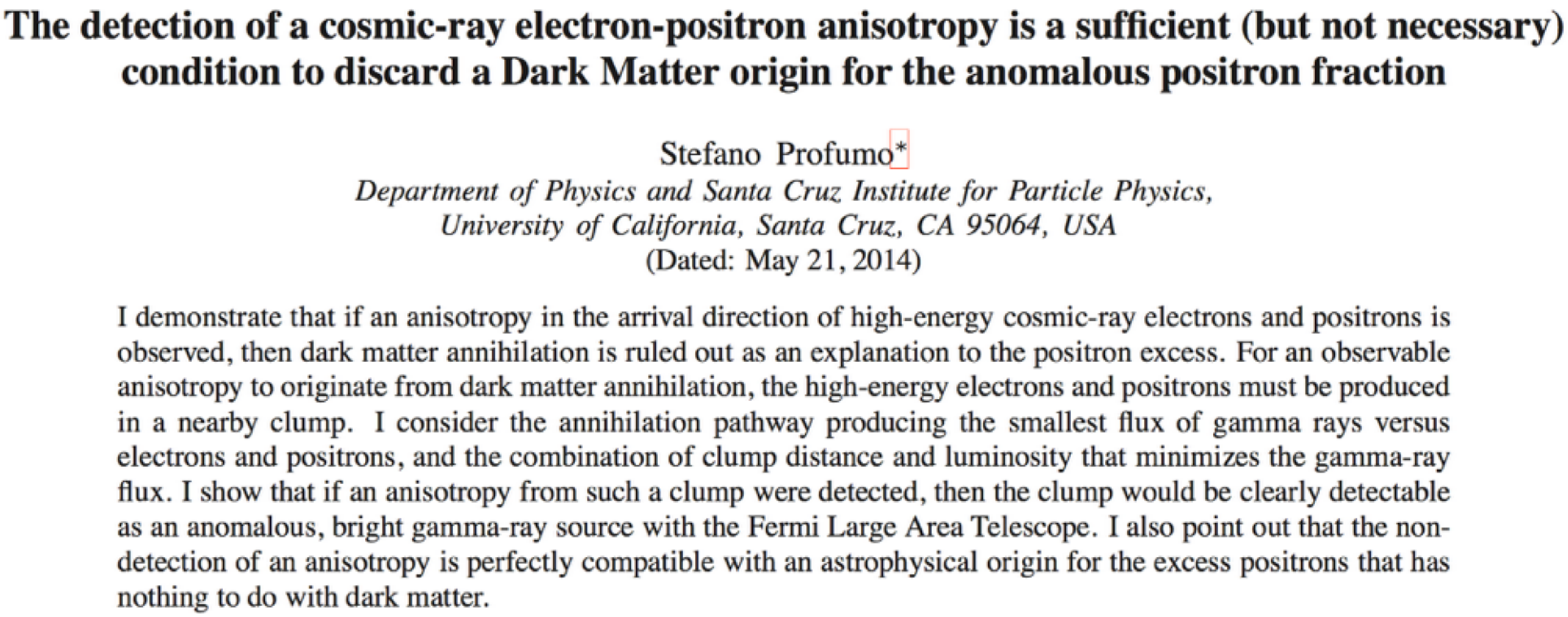
Observations with ACTs?

These observations are available for free!



Linden & Profumo (2013)

Observations with ACTs?



The detection of a cosmic-ray electron-positron anisotropy is a sufficient (but not necessary) condition to discard a Dark Matter origin for the anomalous positron fraction

Stefano Profumo*
Department of Physics and Santa Cruz Institute for Particle Physics,
University of California, Santa Cruz, CA 95064, USA

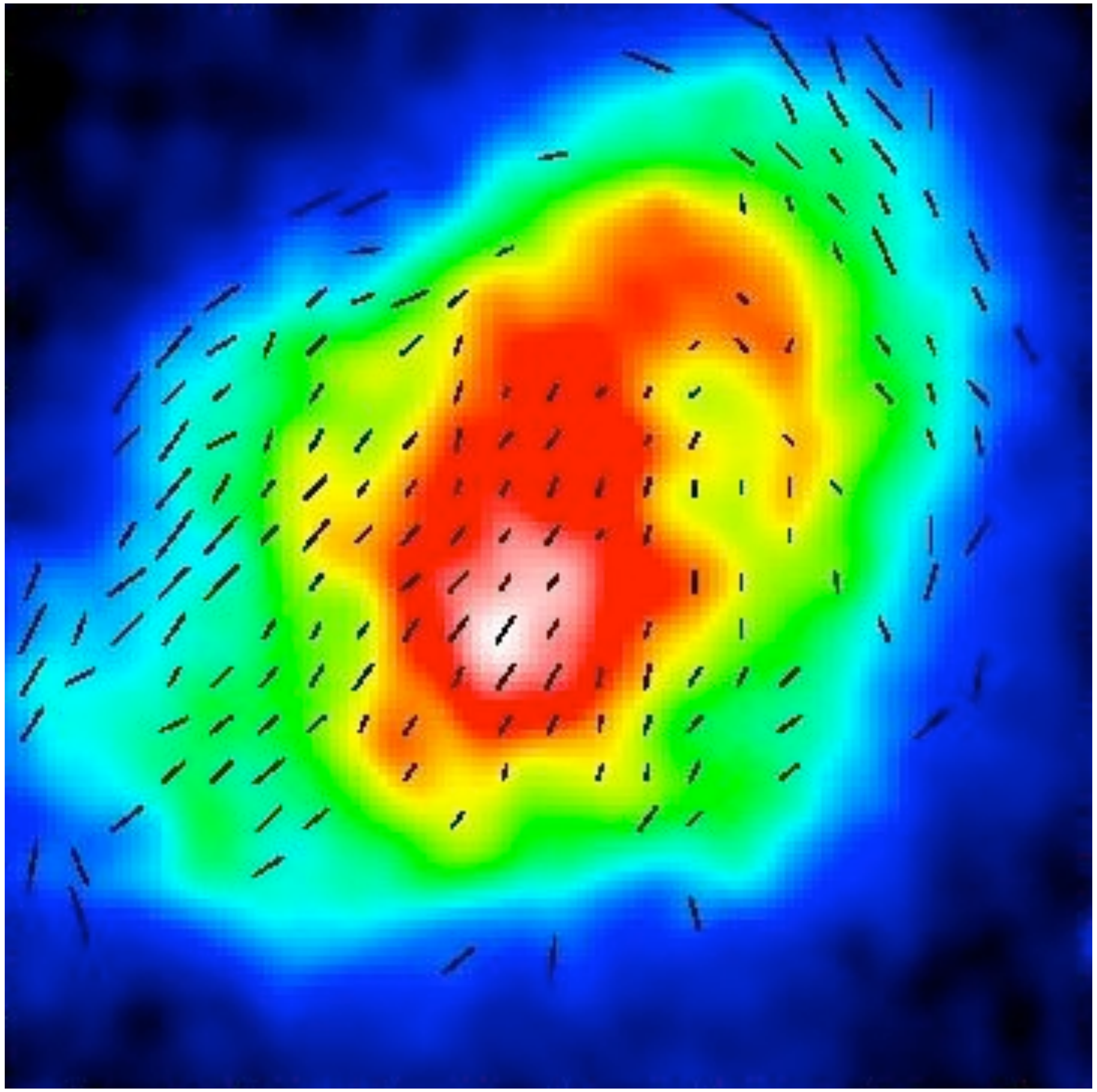
(Dated: May 21, 2014)

I demonstrate that if an anisotropy in the arrival direction of high-energy cosmic-ray electrons and positrons is observed, then dark matter annihilation is ruled out as an explanation to the positron excess. For an observable anisotropy to originate from dark matter annihilation, the high-energy electrons and positrons must be produced in a nearby clump. I consider the annihilation pathway producing the smallest flux of gamma rays versus electrons and positrons, and the combination of clump distance and luminosity that minimizes the gamma-ray flux. I show that if an anisotropy from such a clump were detected, then the clump would be clearly detectable as an anomalous, bright gamma-ray source with the Fermi Large Area Telescope. I also point out that the non-detection of an anisotropy is perfectly compatible with an astrophysical origin for the excess positrons that has nothing to do with dark matter.

Circular Polarization Observations

$$\left(\frac{V}{I}\right) = \frac{4}{\sqrt{3}}\frac{b(\gamma)}{a(\gamma)}cot(\theta)\sqrt{\frac{qB_0 sin(\theta)}{2\pi m_e c f}}$$

- **e^+e^- moving through an ordered magnetic field produce both linearly and circularly polarized synchrotron radiation**



Crab Linear Polarization

Circular Polarization Observations

$$\left(\frac{V}{I}\right) = \frac{4}{\sqrt{3}}\frac{b(\gamma)}{a(\gamma)}cot(\theta)\sqrt{\frac{qB_0 sin(\theta)}{2\pi m_e c f}}$$

- **Unfortunately, both linear and circular polarization can be reduced by environments**
  - **Continuous Electron Spectra (both)**
  - **Disordered Magnetic Fields (both)**
  - **Faraday Rotation (linear)**
  - **Presence of Positrons! (circular only)**

Circular Polarization Observations

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- **An alternative method comes from observations of circular polarization in PWN**

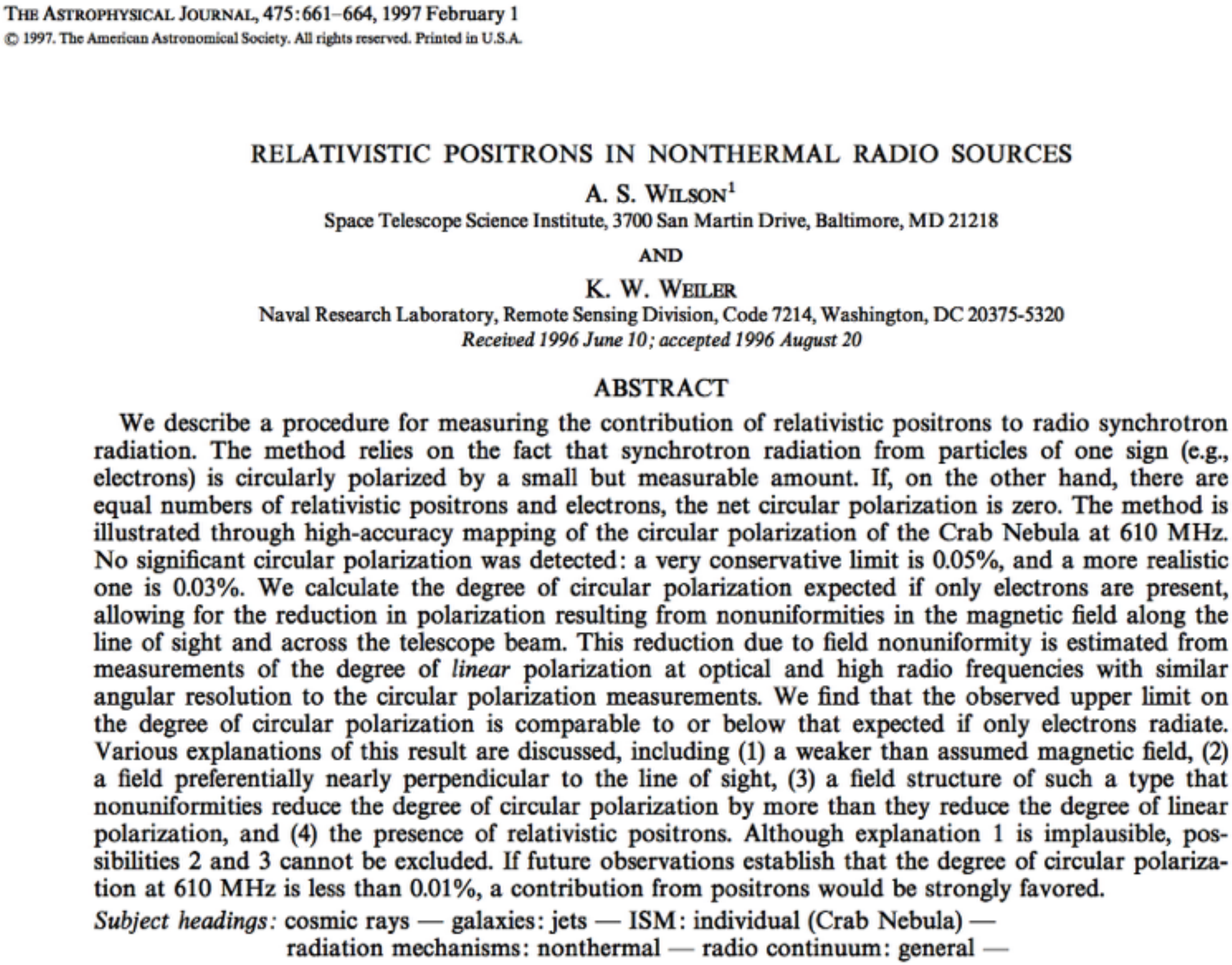
- **PWN are linearly polarized, which implies that they should be circularly polarized as well**

- **However, the contribution of positrons and electrons to circular polarization cancel**

- **An observation of circular polarization in PWN would place an upper limit on the positron fraction**

Circular Polarization Observations

To my scientific intrigue and professional disappointment…….



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RELATIVISTIC POSITRONS IN NONTHERMAL RADIO SOURCES

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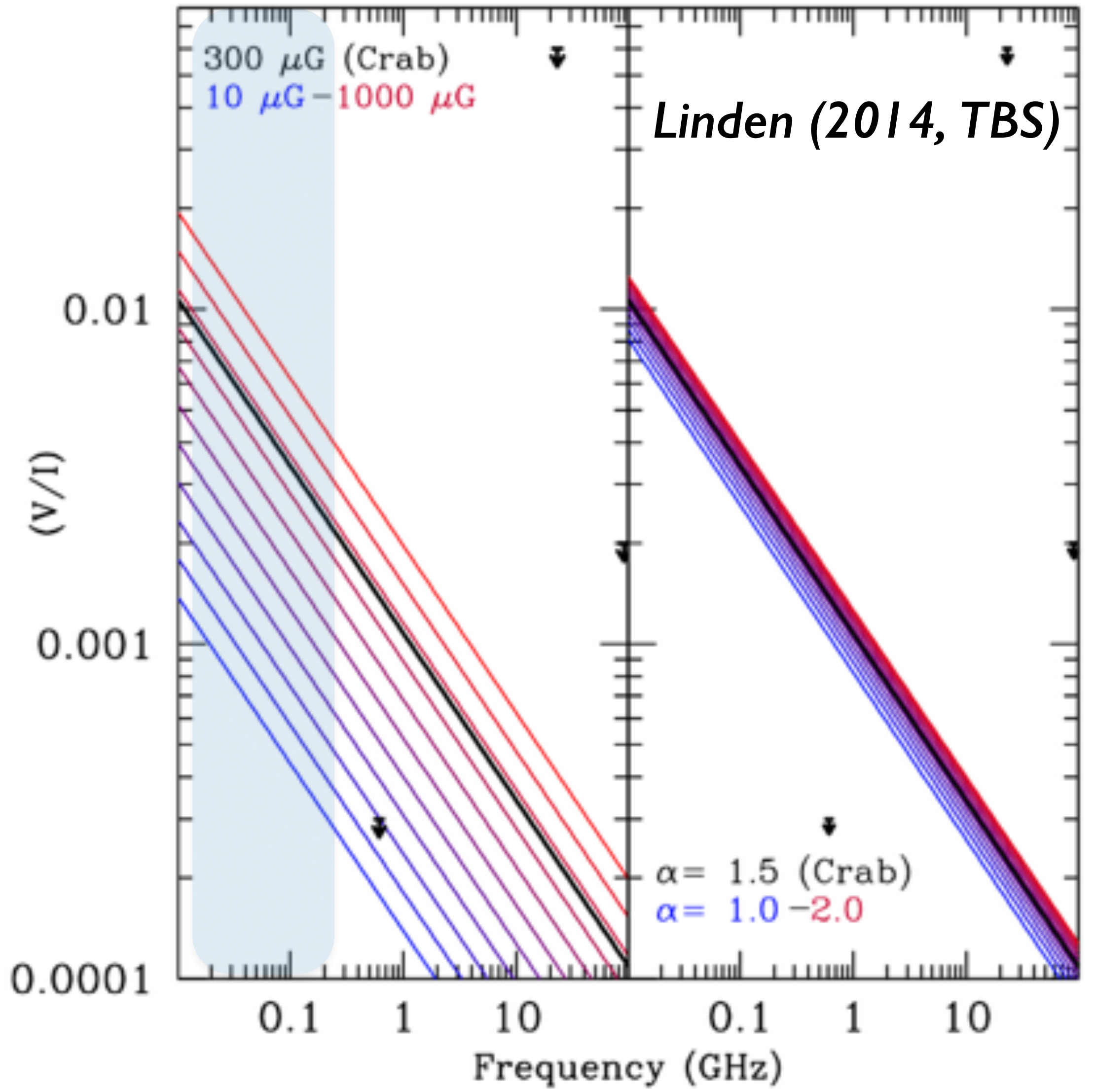
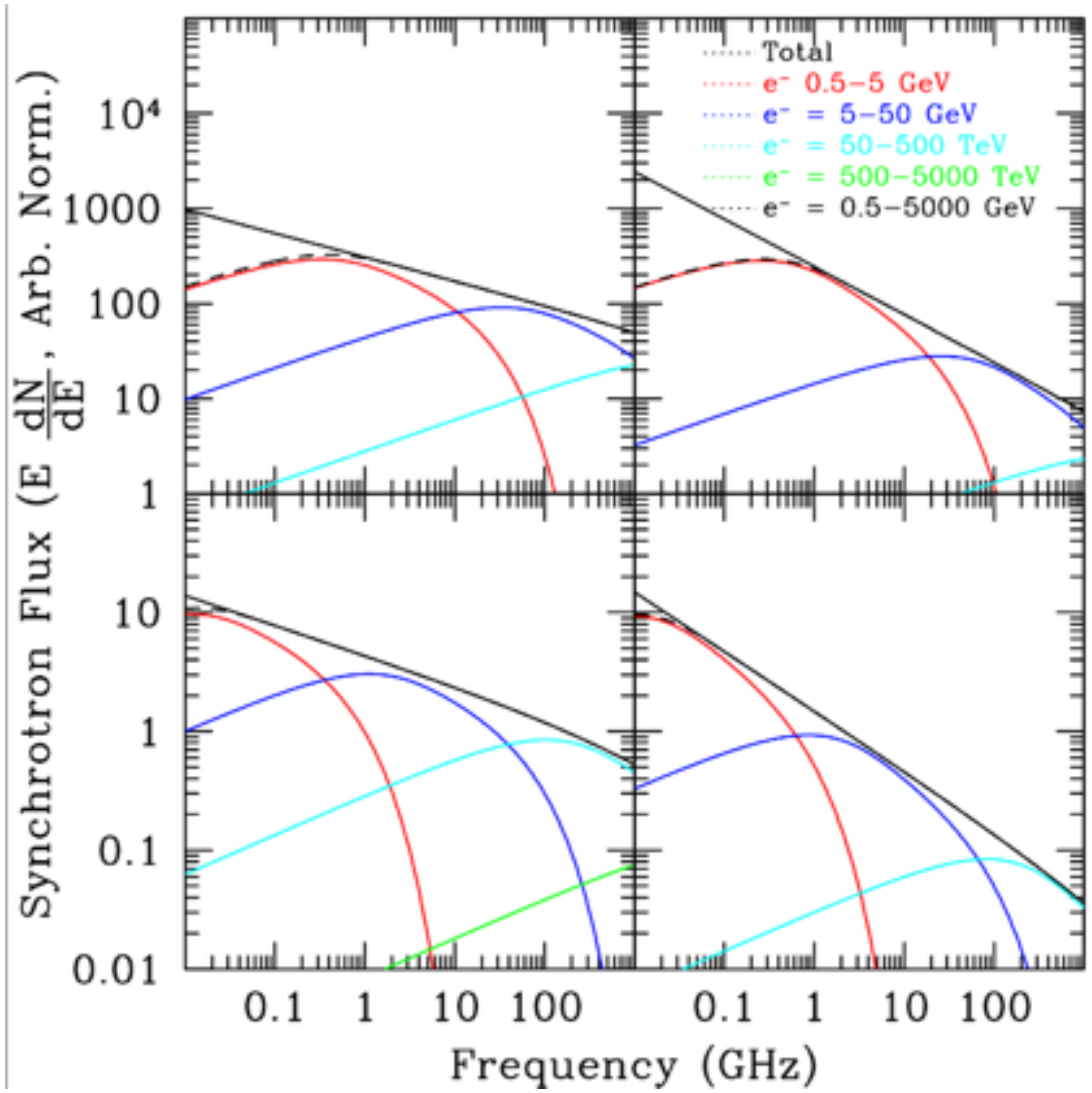
ABSTRACT

We describe a procedure for measuring the contribution of relativistic positrons to radio synchrotron radiation. The method relies on the fact that synchrotron radiation from particles of one sign (e.g., electrons) is circularly polarized by a small but measurable amount. If, on the other hand, there are equal numbers of relativistic positrons and electrons, the net circular polarization is zero. The method is illustrated through high-accuracy mapping of the circular polarization of the Crab Nebula at 610 MHz. No significant circular polarization was detected: a very conservative limit is 0.05%, and a more realistic one is 0.03%. We calculate the degree of circular polarization expected if only electrons are present, allowing for the reduction in polarization resulting from nonuniformities in the magnetic field along the line of sight and across the telescope beam. This reduction due to field nonuniformity is estimated from measurements of the degree of *linear* polarization at optical and high radio frequencies with similar angular resolution to the circular polarization measurements. We find that the observed upper limit on the degree of circular polarization is comparable to or below that expected if only electrons radiate. Various explanations of this result are discussed, including (1) a weaker than assumed magnetic field, (2) a field preferentially nearly perpendicular to the line of sight, (3) a field structure of such a type that nonuniformities reduce the degree of circular polarization by more than they reduce the degree of linear polarization, and (4) the presence of relativistic positrons. Although explanation 1 is implausible, possibilities 2 and 3 cannot be excluded. If future observations establish that the degree of circular polarization at 610 MHz is less than 0.01%, a contribution from positrons would be strongly favored.

Subject headings: cosmic rays — galaxies: jets — ISM: individual (Crab Nebula) —
radiation mechanisms: nonthermal — radio continuum: general —

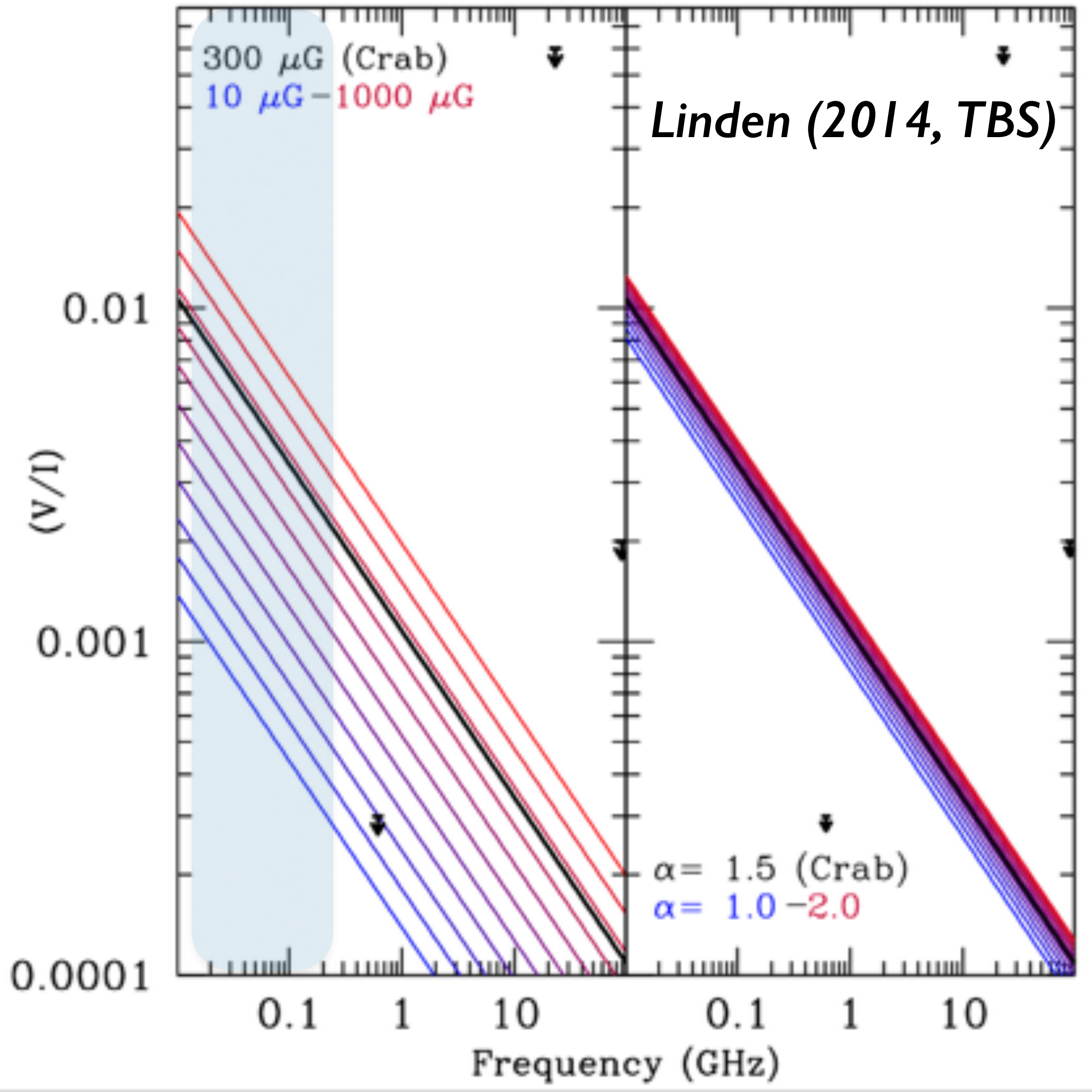
Circular Polarization Observations

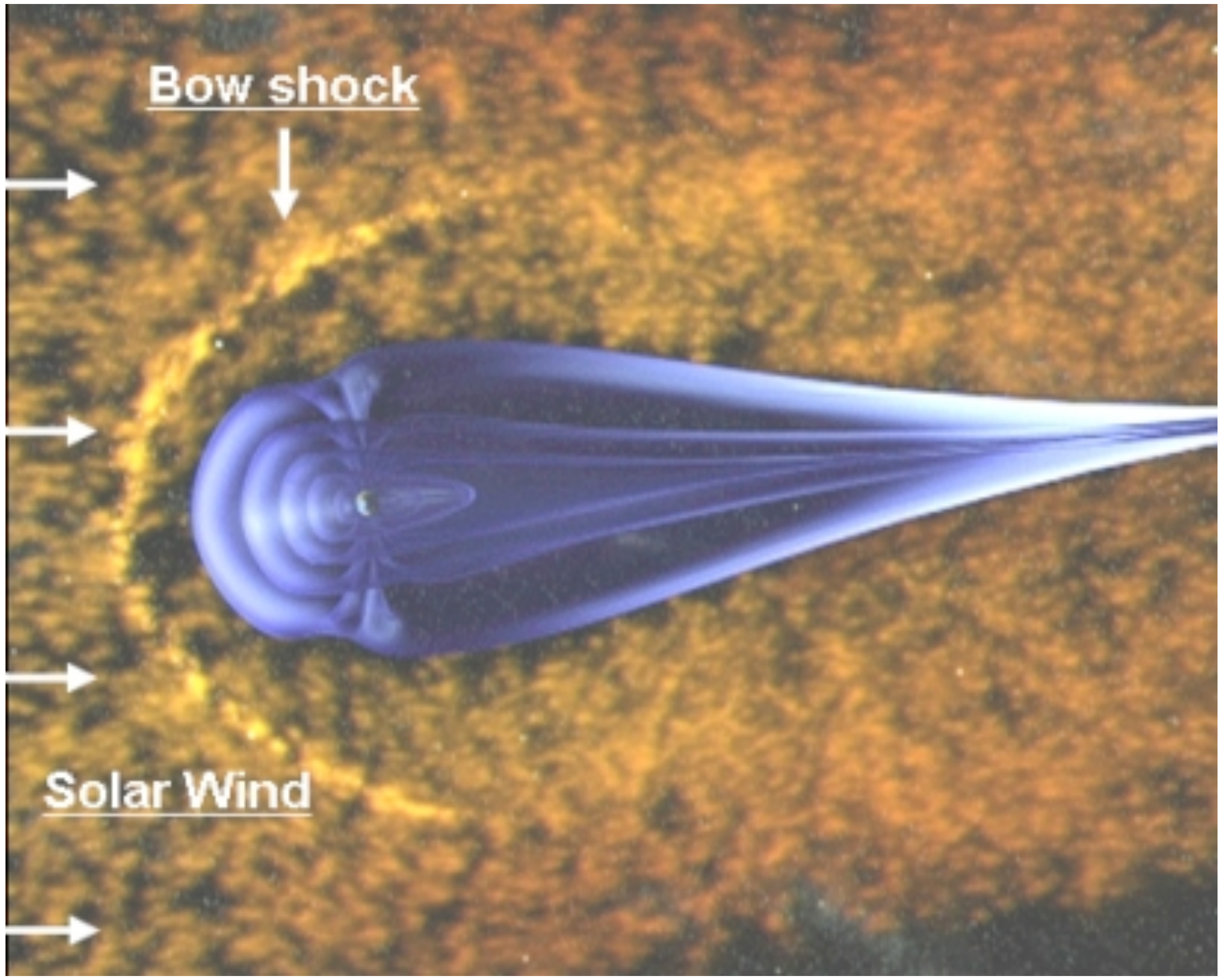

Linden (2014, TBS)



- In the case that PWN emission is dominated by an e⁻ component, detectable levels of circular polarization are expected at low frequencies
- This circular polarization can be probed by current radio interferometers, such as LOFAR

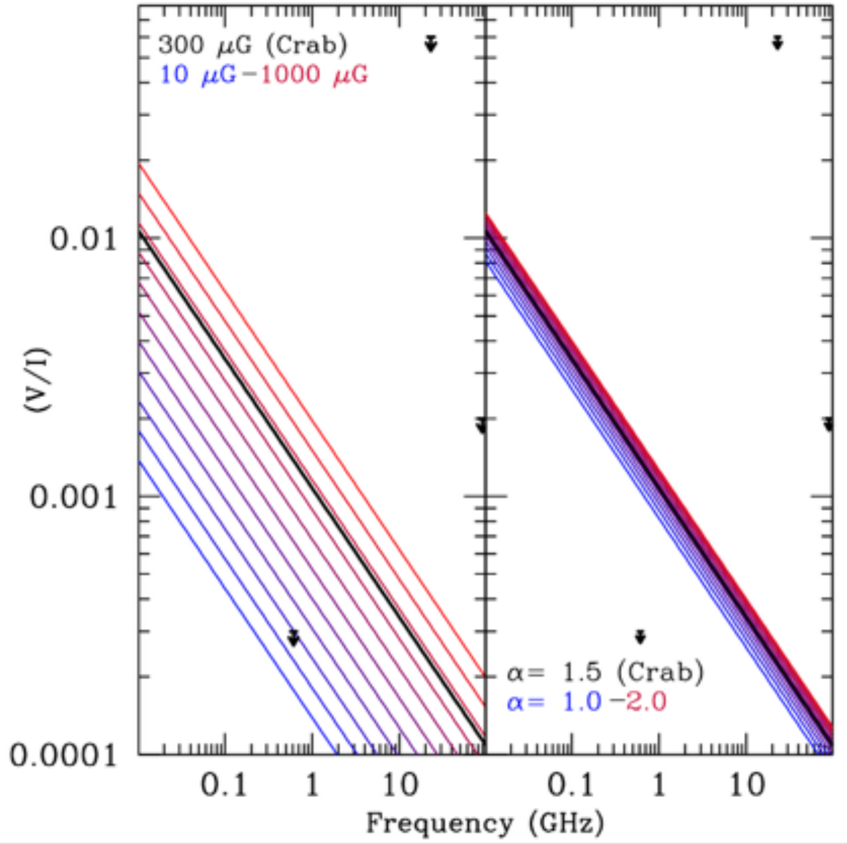
Circular Polarization Observations

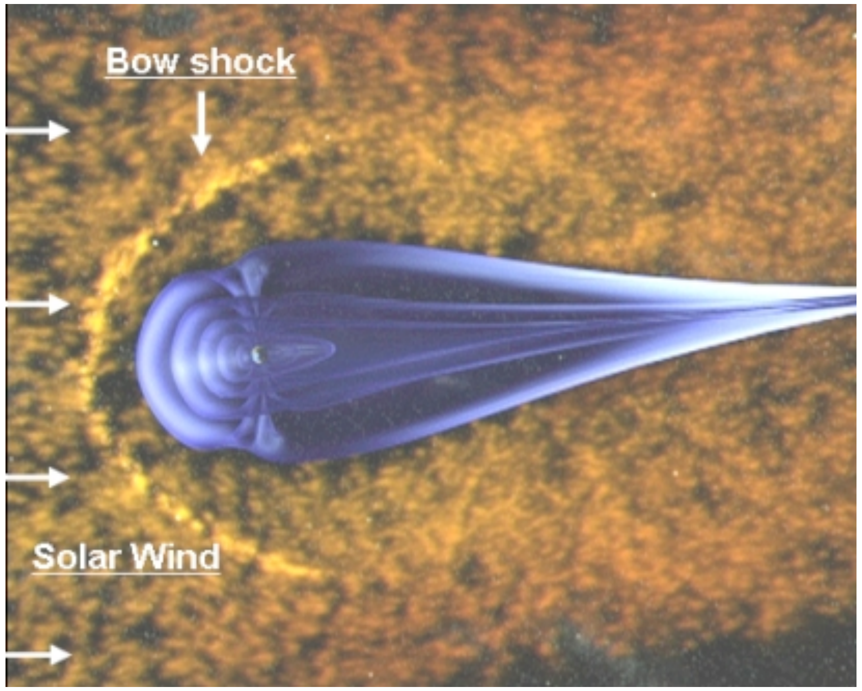




- **In addition to probing the Crab PWN, we can study “mature” bow-shock PWN, such as G189.22+2.90**

In Bow Shock PWN





- The flux in the bow shock is proportional to the magnetic field strength times the flux of high energy leptons

- The energy spectrum of the bow shock is proportional to the magnetic field strength convolved with the energy spectrum of positrons

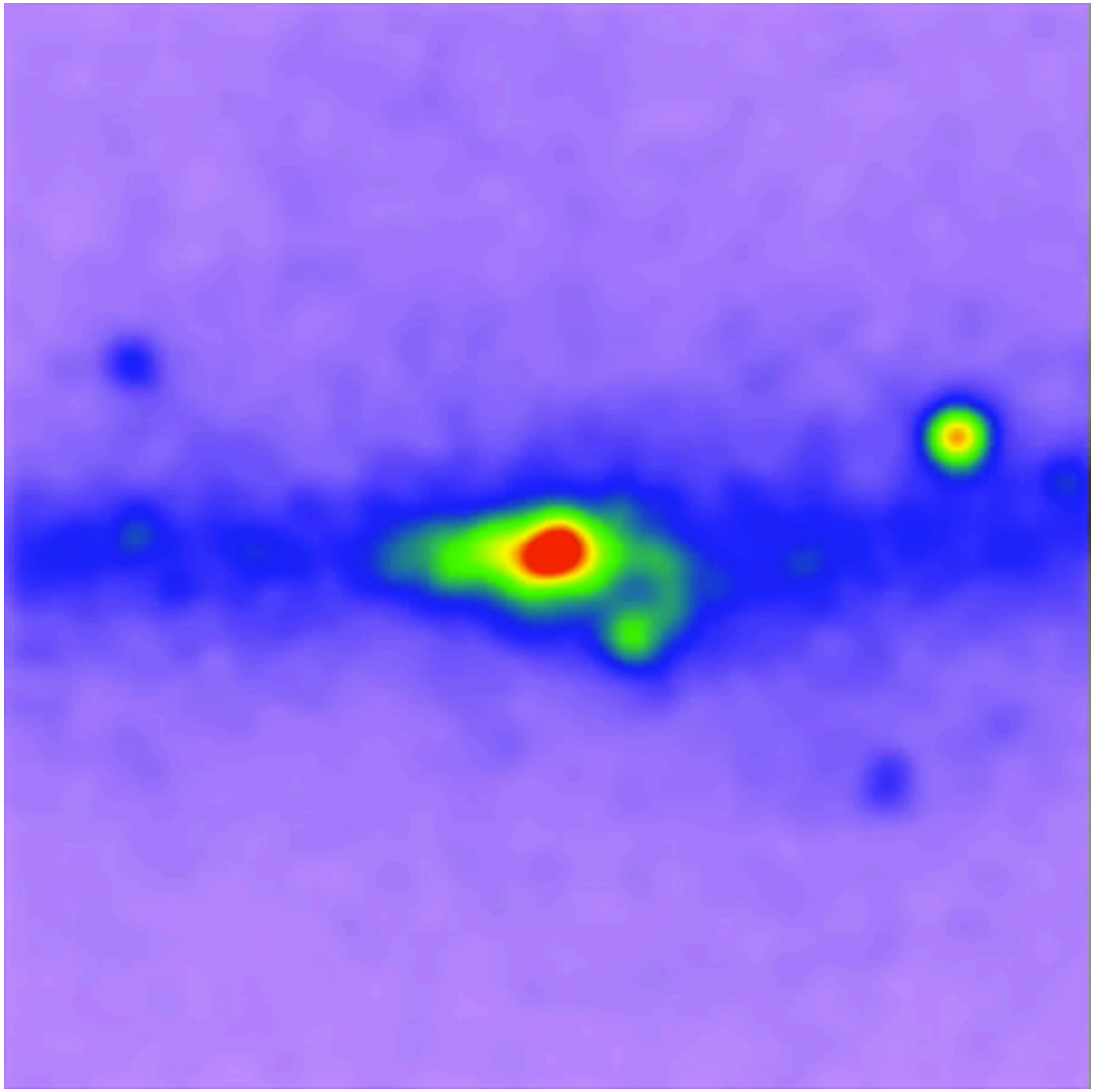
- The circular polarization is proportional to the magnetic field strength times the lepton flux times the difference between the positron and electron fluxes

Conclusions

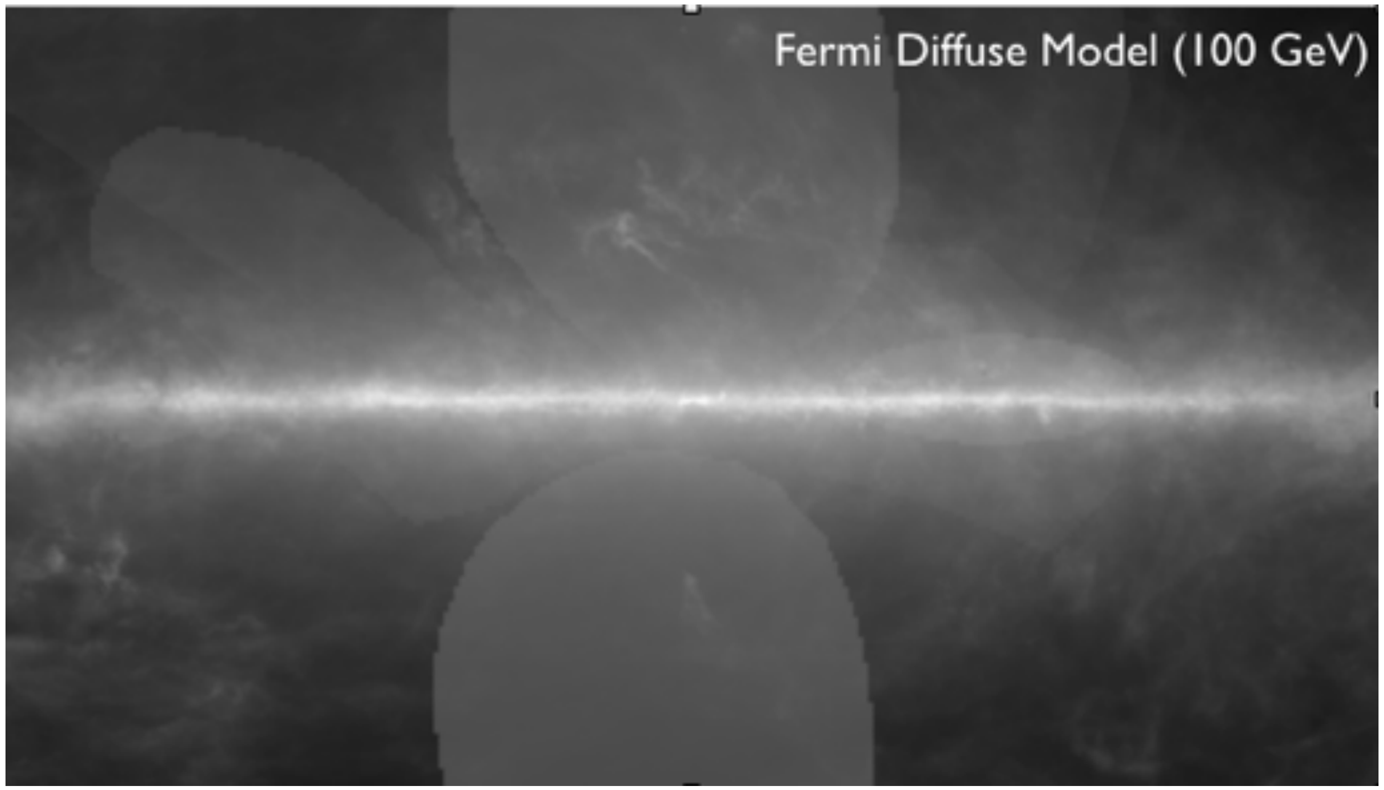
- The rising pulsar fraction is an enticing signal, which could be due to dark matter annihilation (and is thus being discussed here).
- However, pulsars are an obvious source of e^+e^- pairs
- There are several present experiments with the capability to directly test this pulsar interpretation, and either rule out or confirm the pulsar interpretation
- These experiments are cheap (free?) and are important to confirm an important result

Dark Matter

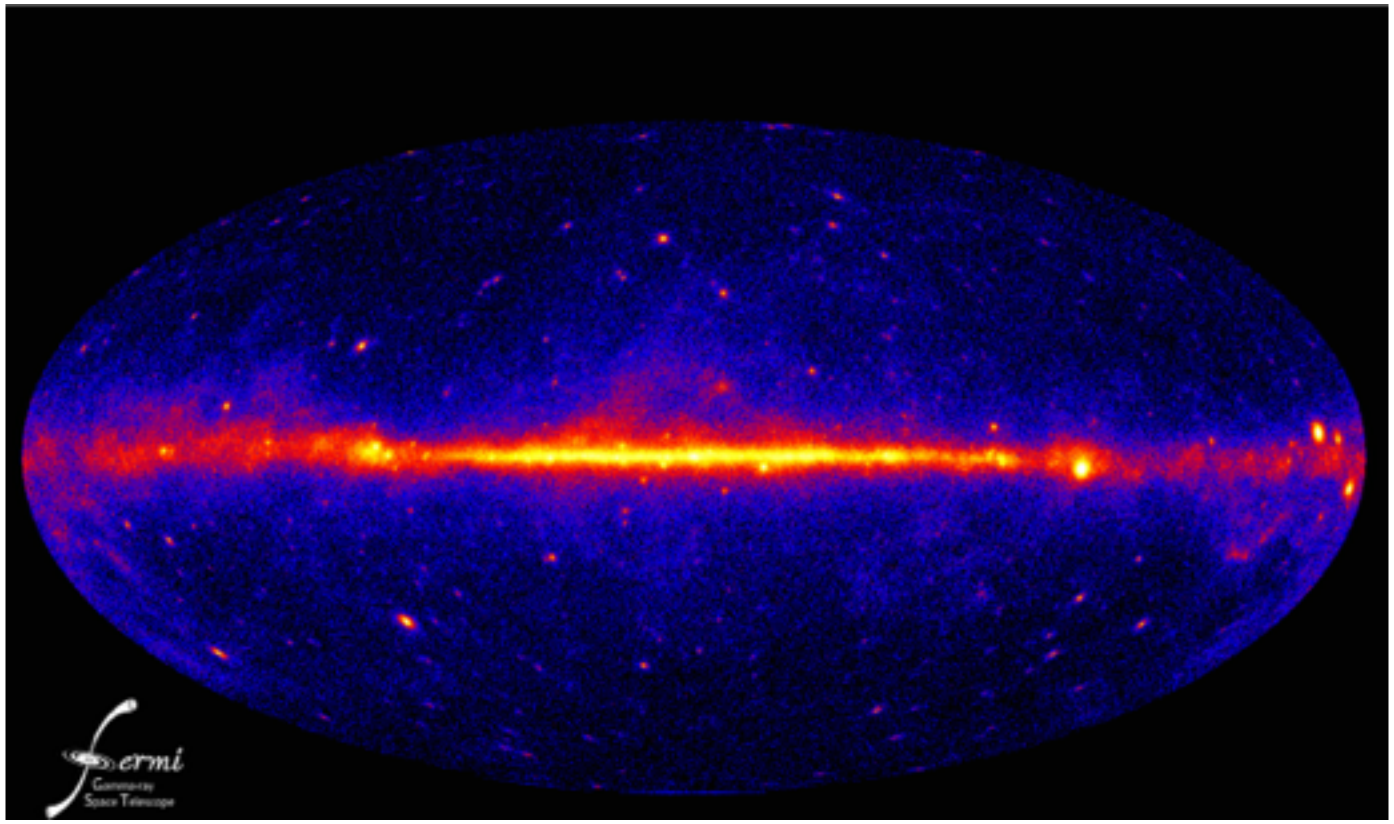
- **Wait - you actually talked about what you were assigned to talk about?**



Untangling Anisotropies from Gamma-Rays



- The Fermi-LAT can detect gamma-rays at energies ~500 GeV, and is able to differentiate gamma-rays and electrons



- A Template Analysis which removes the component correlating to the Fermi-LAT diffuse gamma-ray sky will remove this contamination

Beryllium 10/9 Ratio