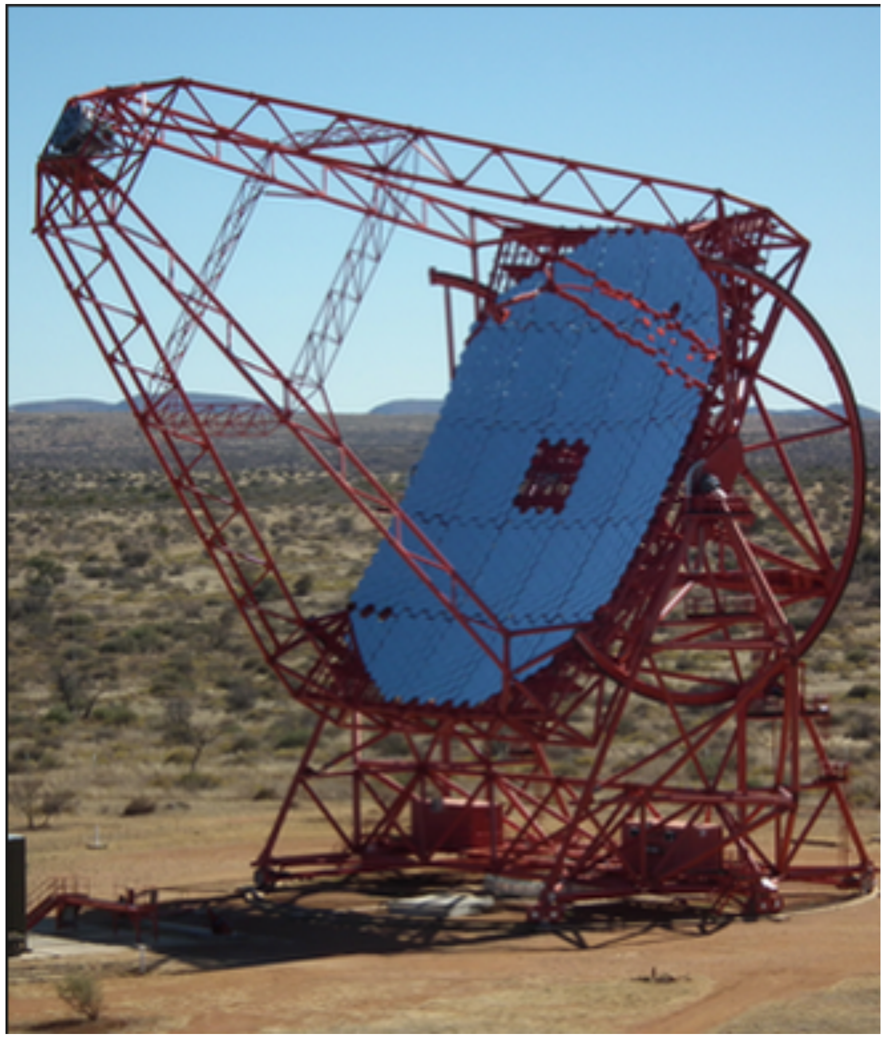
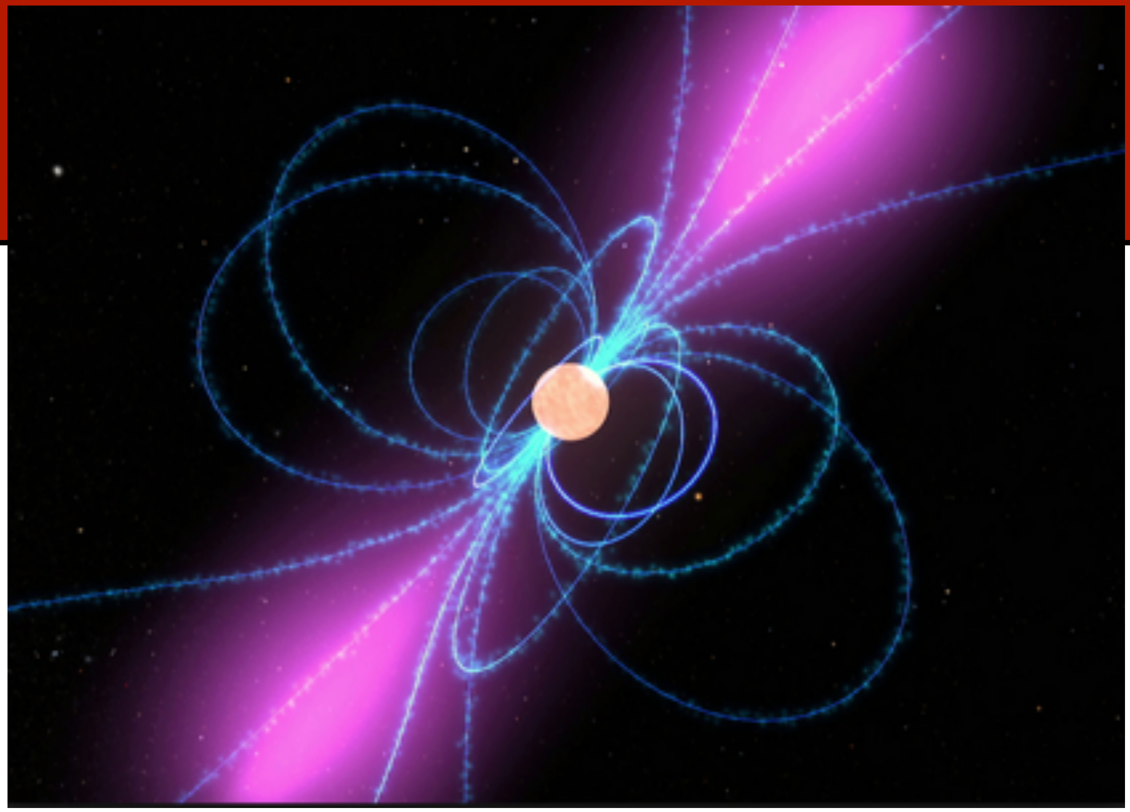
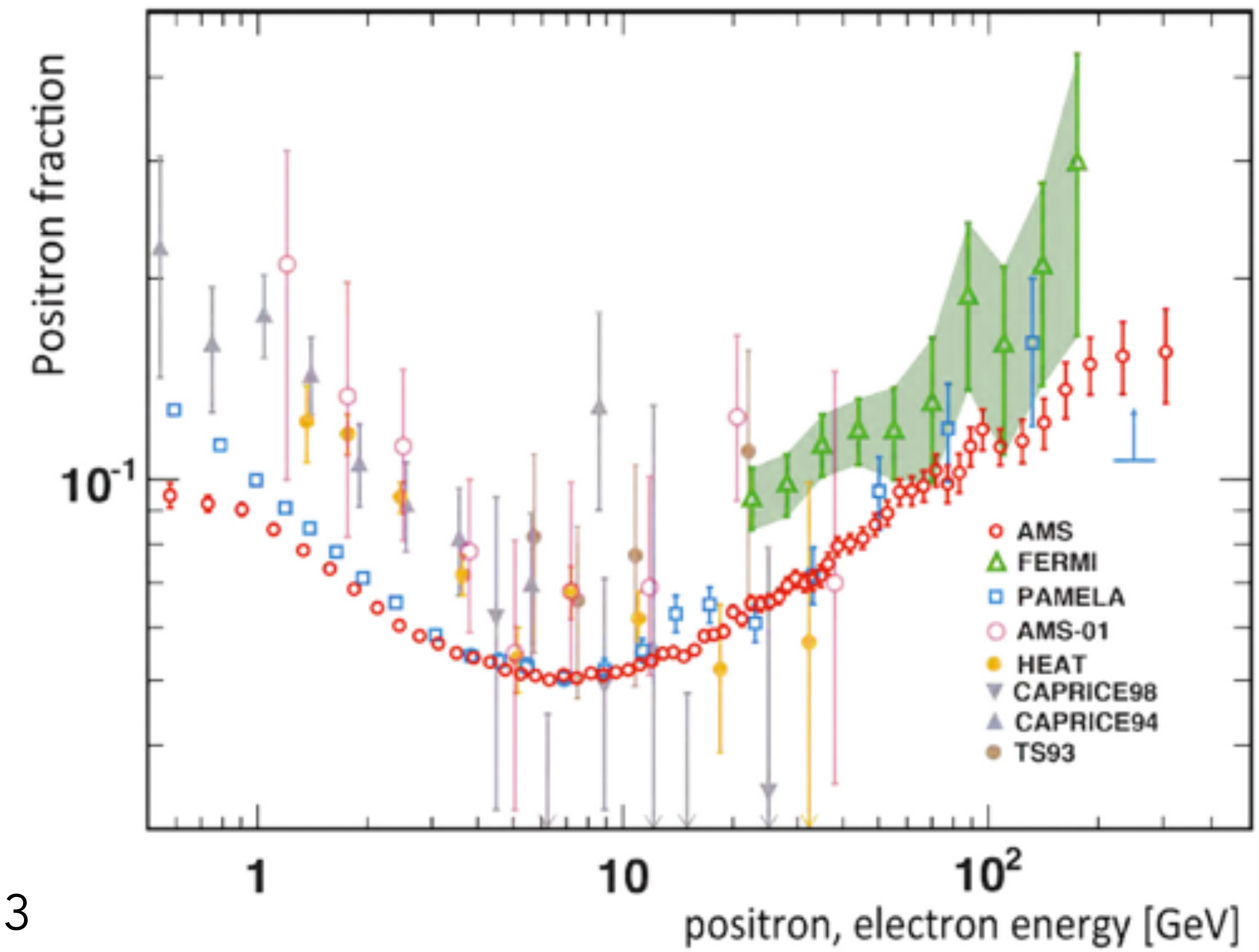
Modeling the Positron Excess: Pulsars, Anisotropies, and ACTs







Tim Linden
UC - Santa Cruz

with Stefano Profumo

UC, Santa Cruz - CosmoClub April 22, 2013

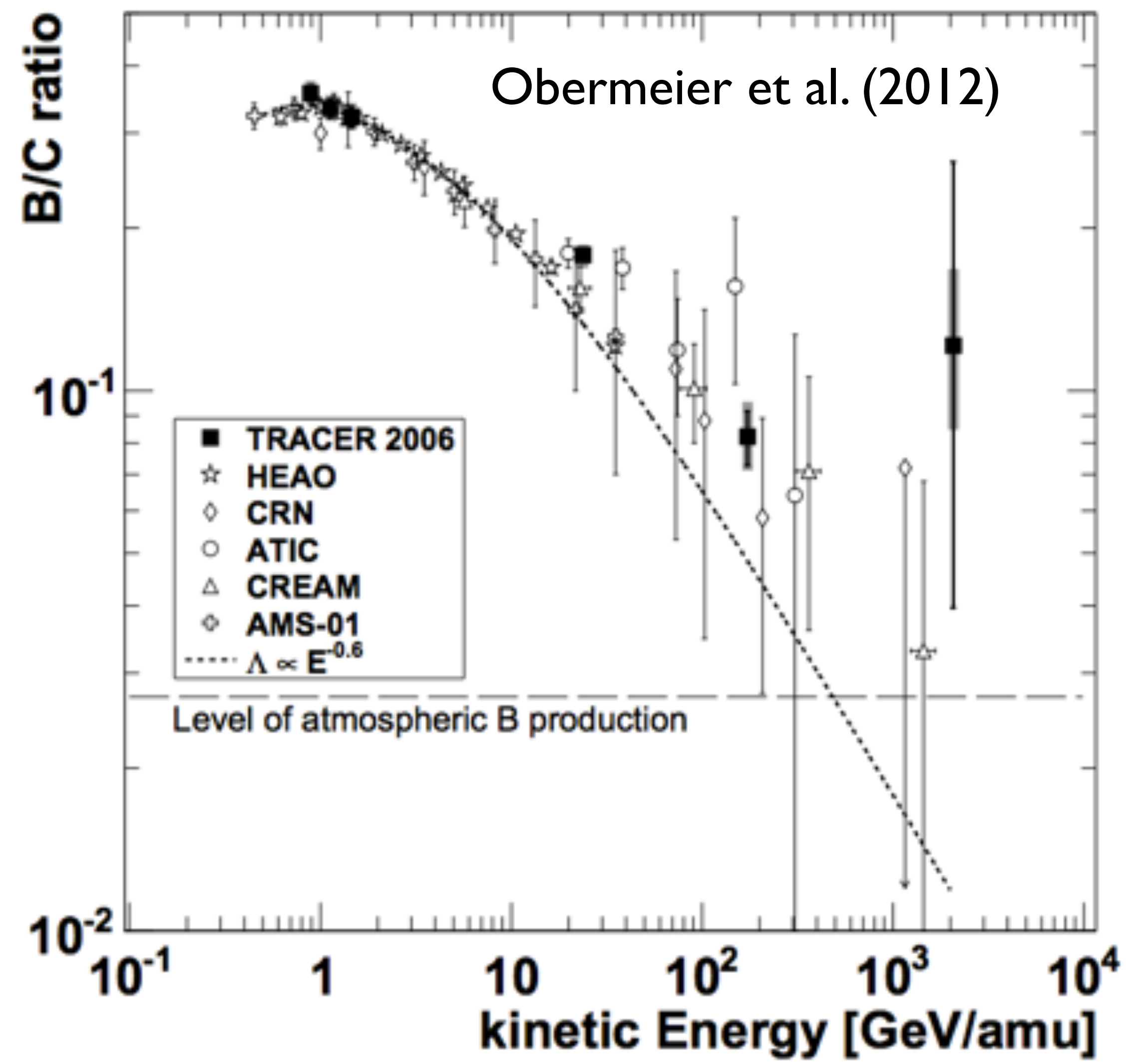
Cosmic-Ray Physics

- Cosmic-Ray Abundances are among the most indirect handles on cosmic-ray physics (they isotropize quickly in the interstellar medium - we don't know where they come from)

- However their fluxes (and especially the ratio of fluxes from different cosmic-ray species tell us both about their injection, and about how charged particles diffuse throughout the galaxy)

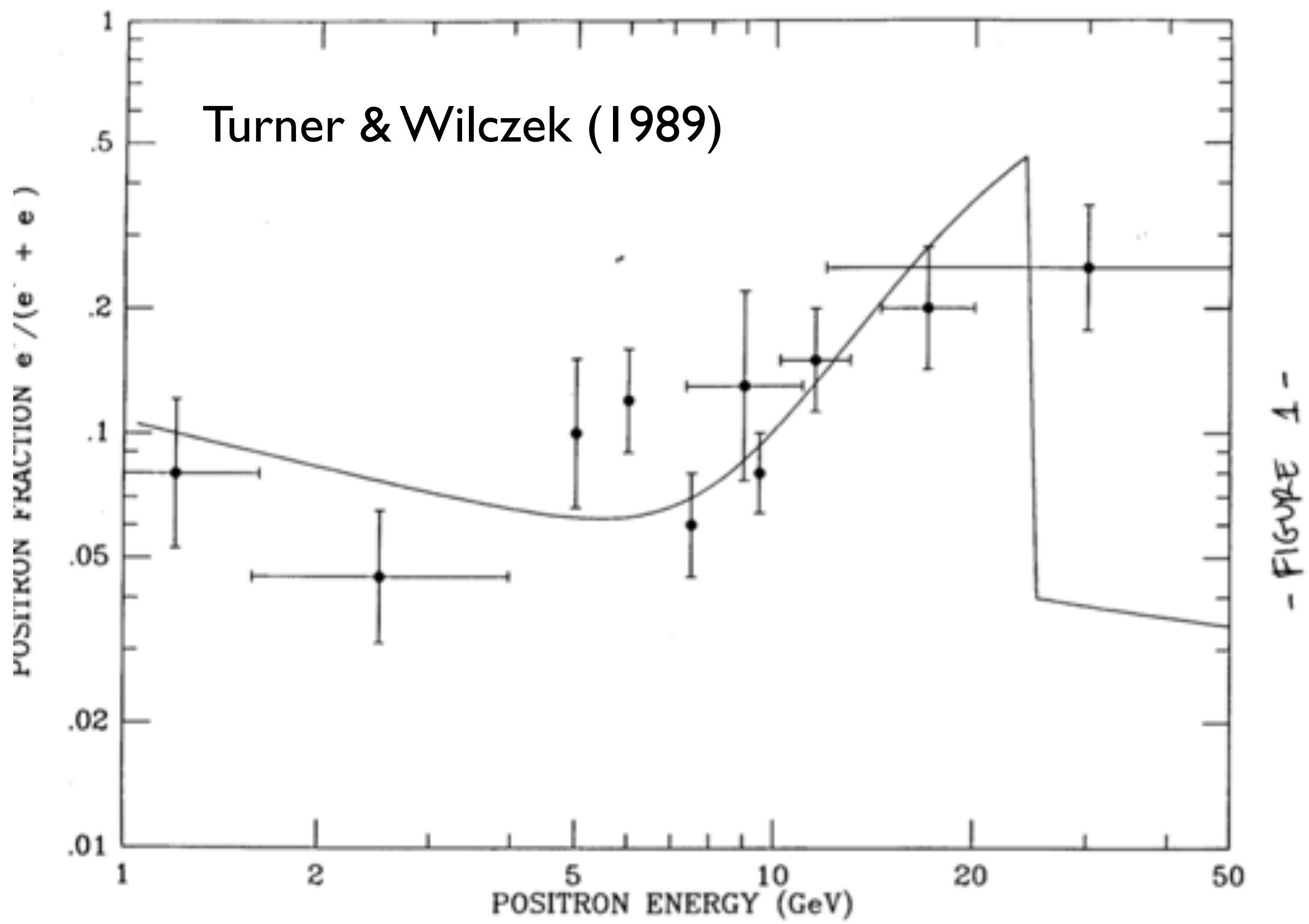
- Example - Boron is not produced in Supernovae, but is instead a byproduct of Carbon spallation (carbon atoms hitting gas in the ISM)

- Tells us how long a given carbon atom has propagated through ISM



Why is the Positron Fraction Interesting?

- Astrophysical Shocks (1st Order Fermi Acceleration) primarily accelerate matter, and not antimatter



- Some secondary production of anti-matter
  - e.g. p + p -> e^+ + e^- + jets
  - Ratio of antimatter secondaries to primary particles should fall at higher energies

- Some sources (e.g. dark matter) may produce **primary** particle/anti-particle pairs in equal numbers. This could create a rise, or bump in the positron fraction at a specific energy

Definition of Positron Fraction

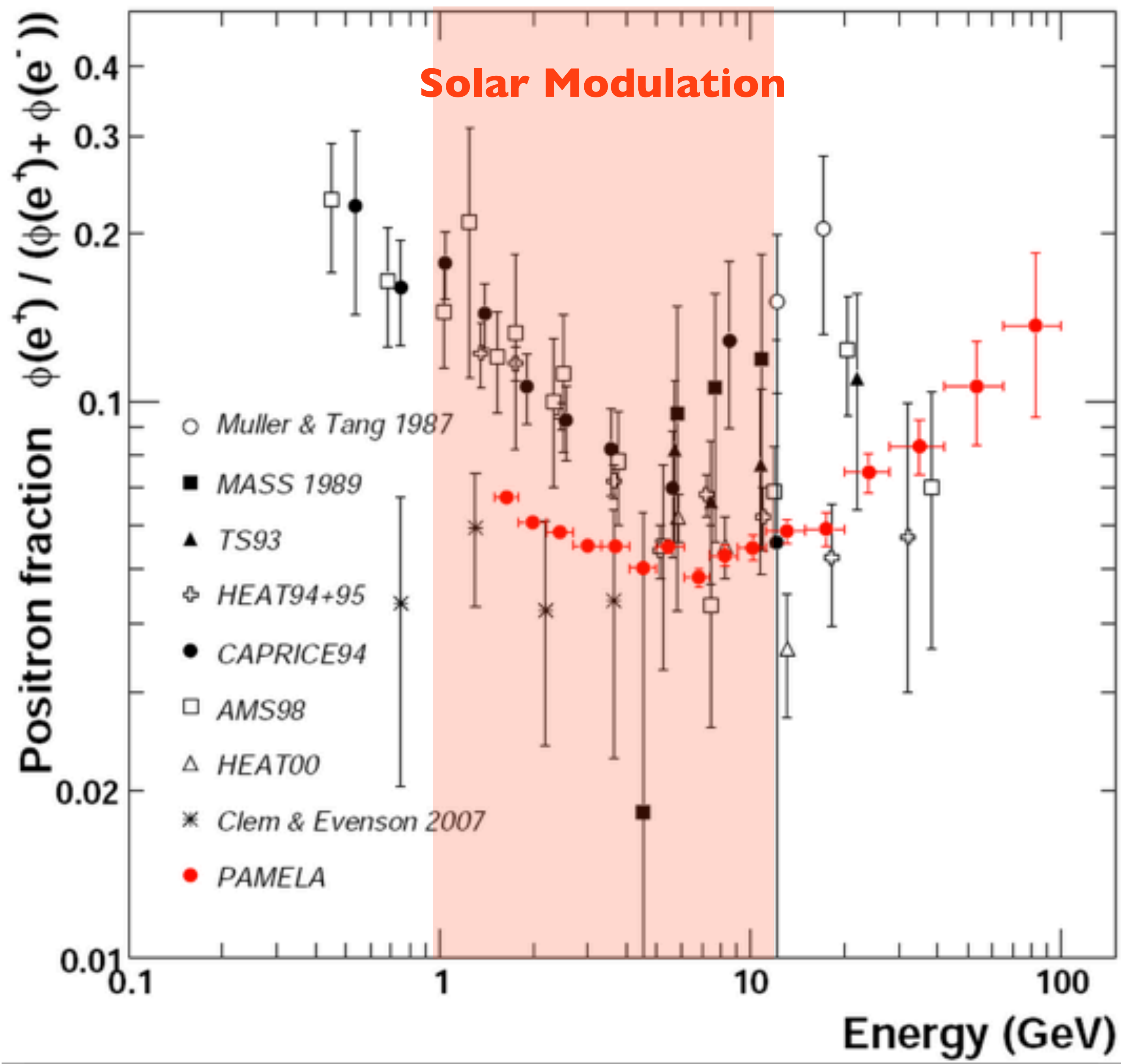
$$\frac{\phi_{e^+}}{\phi_{e^+} + \phi_{e^-}}$$

- A Positron fraction of 0 would indicate that all leptons are made through first order Fermi Accerleration of matter (e.g. in supernova remnants)
- A Positron fraction of 0.5 would indicate equipartition injection of matter and anti-matter (e.g. by dark matter)
- Any positron fraction greater than 0.5 would signal something truly odd

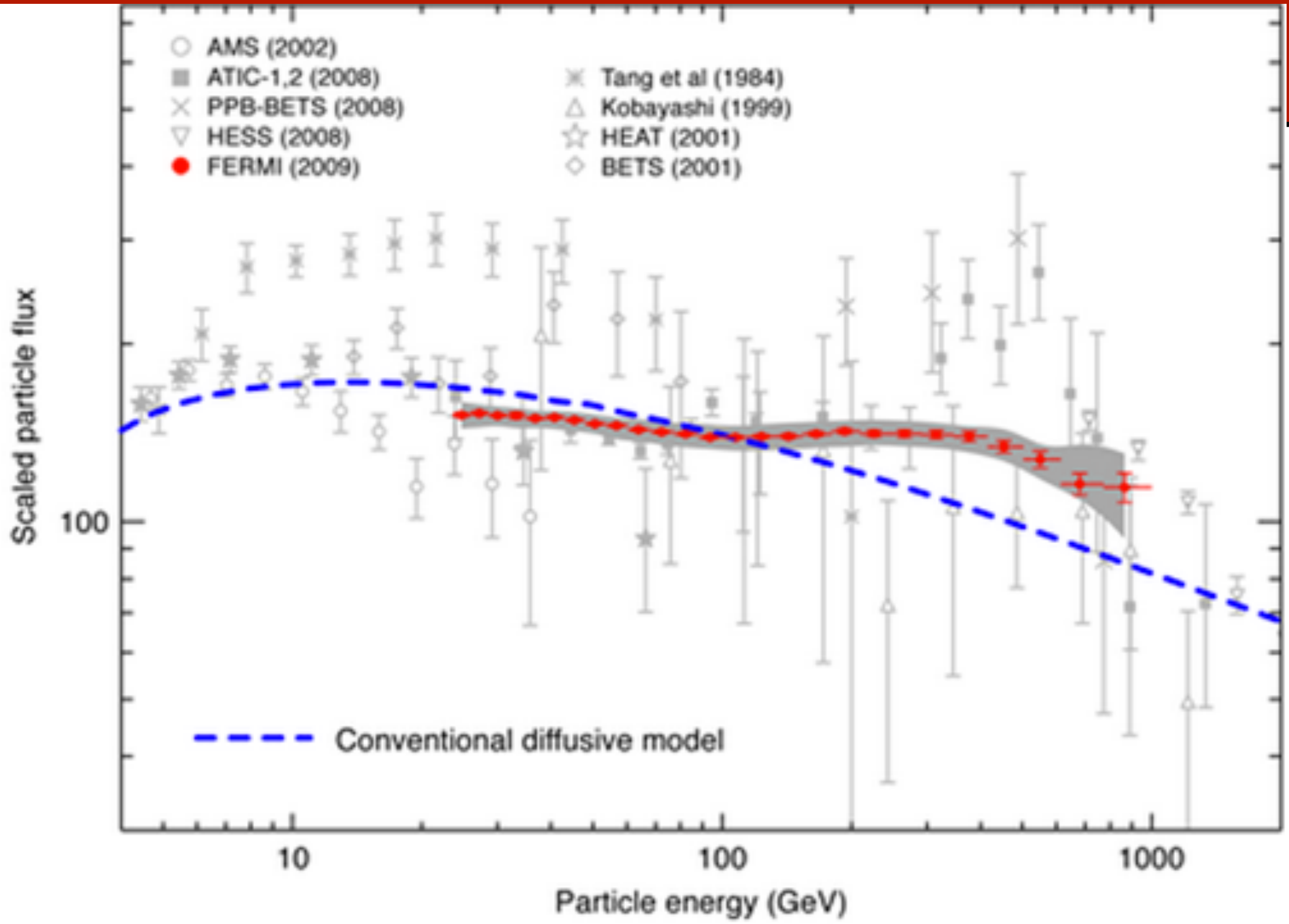
A Rising Positron Fraction in PAMELA?

- PAMELA satellite (2006 - Present) has observed cosmic-rays, using a magnetic field to differentiate between particles and anti-particles

- Found a surprising increase in the positron fraction above 10 GeV



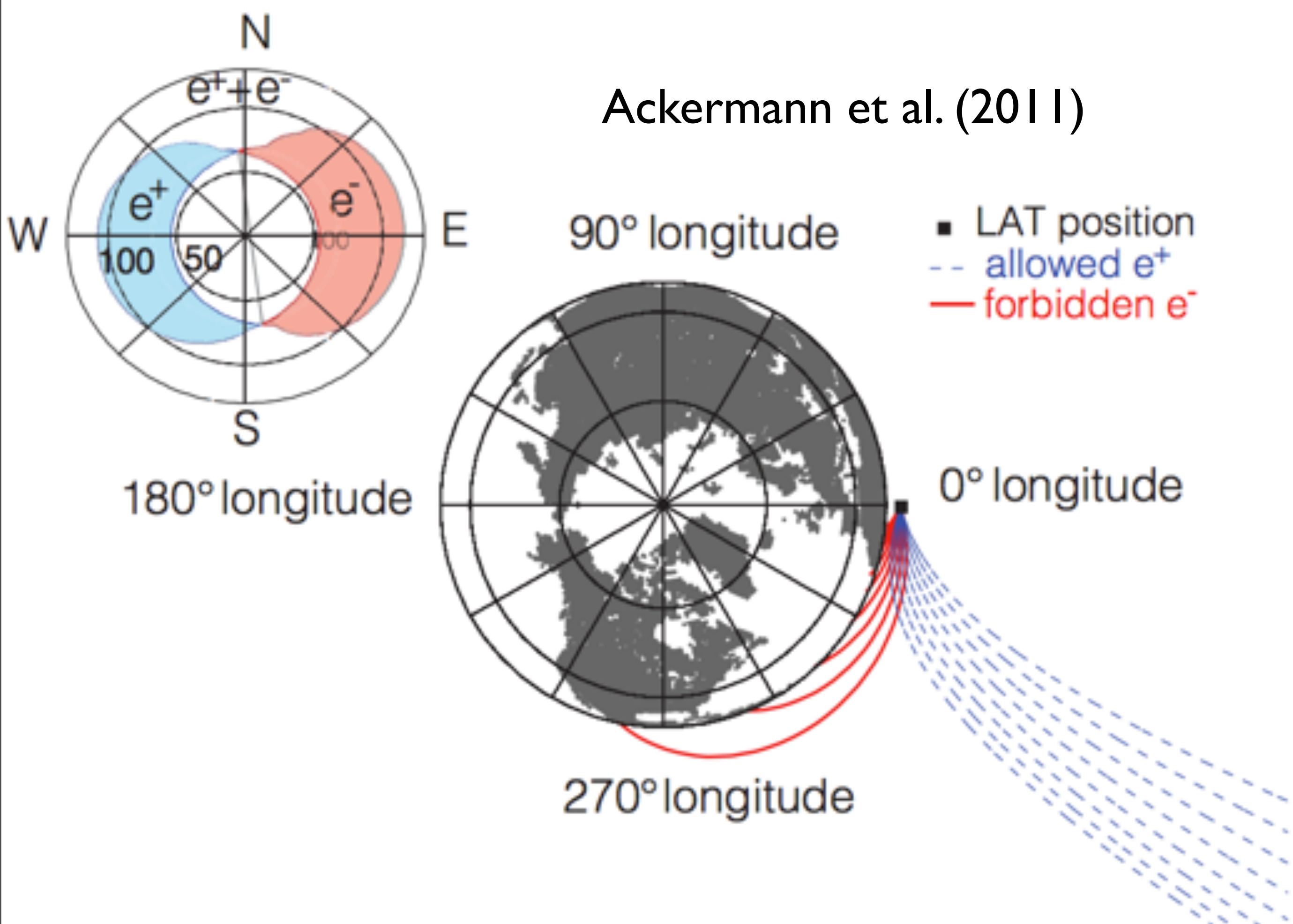
The Fermi e^+e^- Spectrum



- The Fermi-LAT telescope can also detect cosmic-ray electrons, which produce showers equivalent to γ-rays and also produce a signal while moving through the anti-coincidence detector

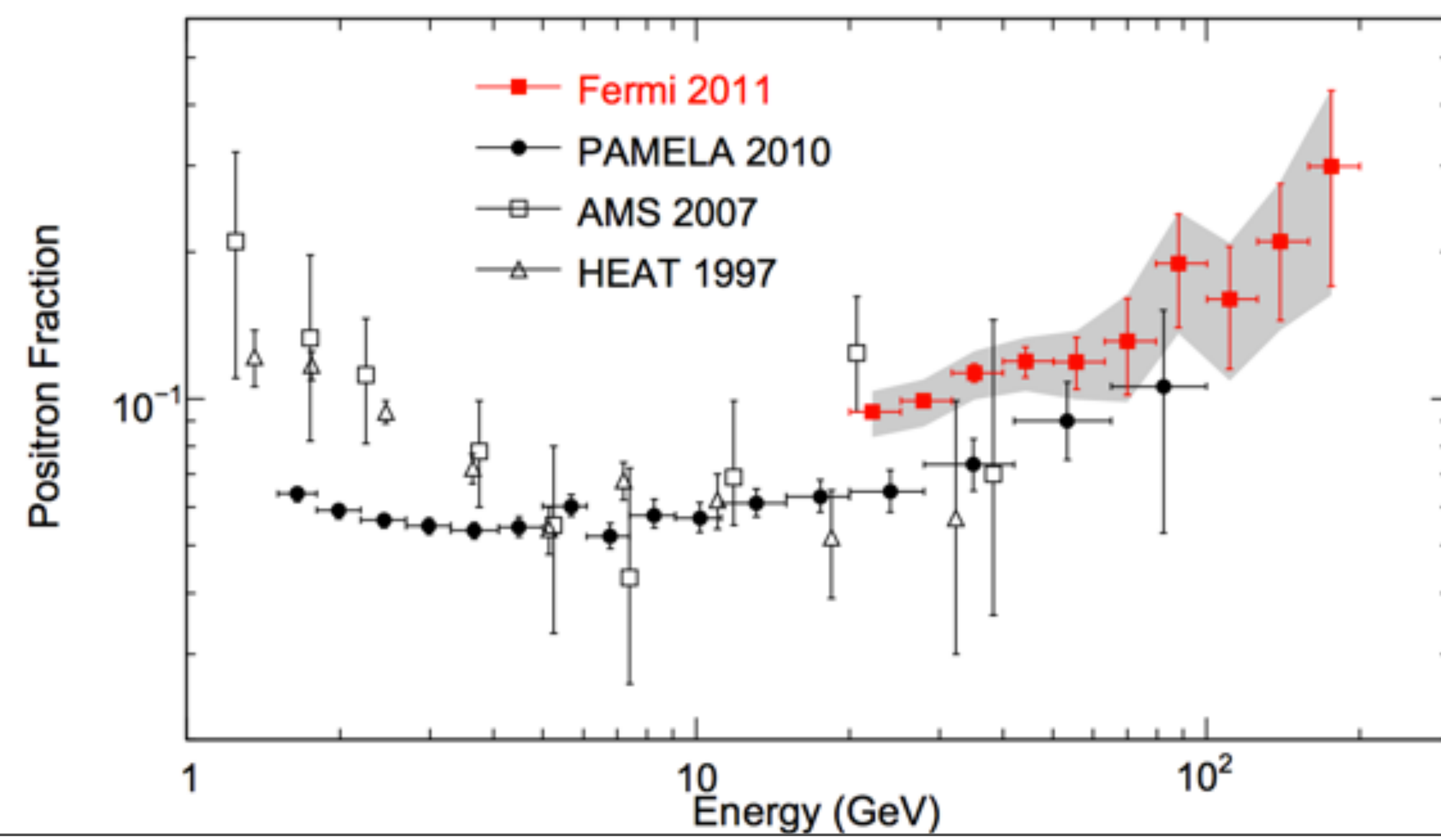
- The Fermi-LAT found a hardening of the primary electron spectrum in the energy range of 20-1000 GeV, compared to conventional diffusion models

Fermi-LAT Positron Fraction

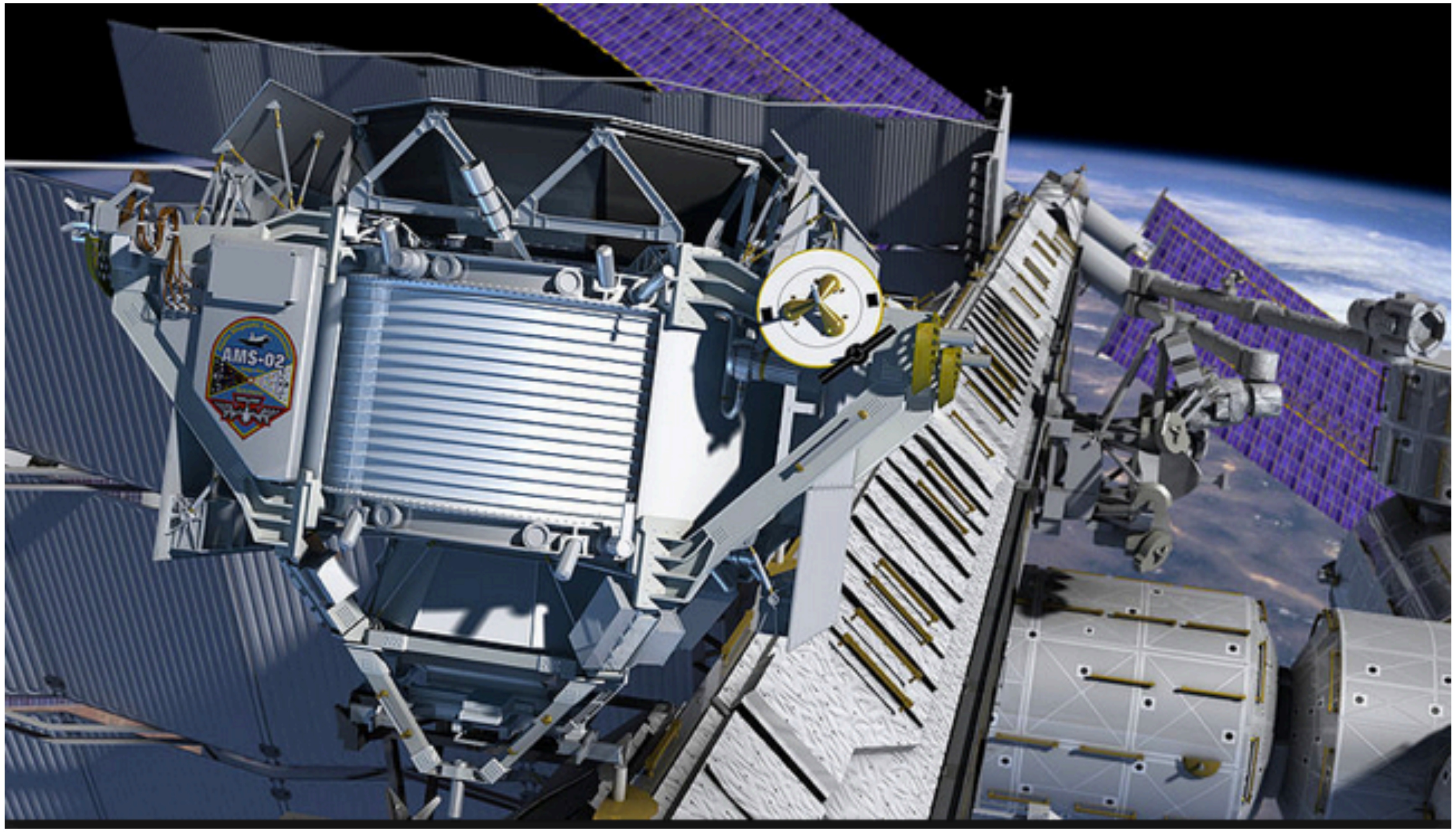


- While the Fermi-LAT has no magnetic field, the Earth's magnetic field can create "zones of exclusion" where either positrons or electrons are prohibited from hitting the instrument

- Using these regions, the positron fraction was independently calculated, in good agreement with the PAMELA data



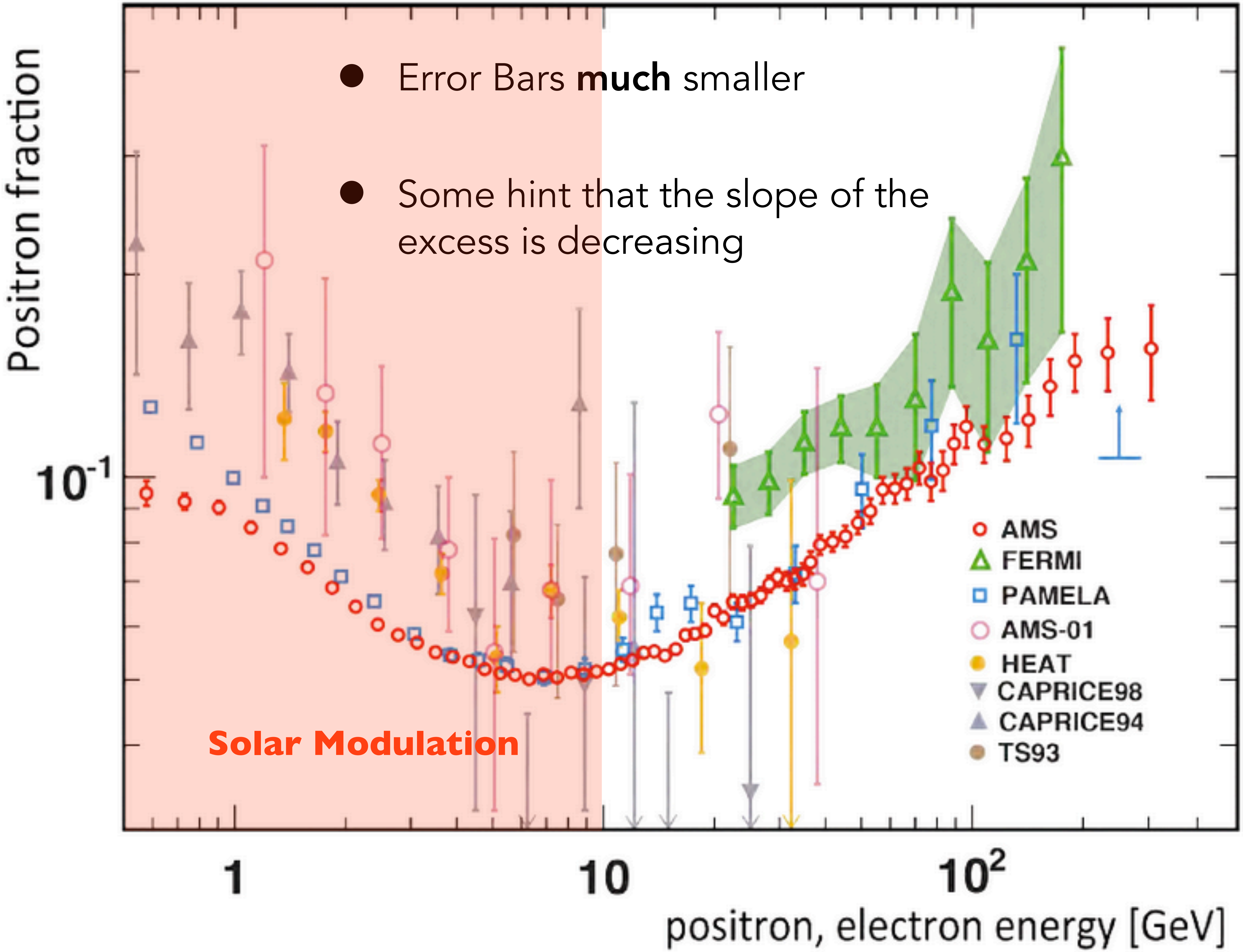
The Alpha Magnetic Spectrometer (AMS-02)



- Charged particle detector (with magnetic field), placed on board the International Space Station
- Much large effective area than PAMELA, and better magnetics allow superior discrimination

AMS-02 Measurement of the Positron Excess

- Error Bars **much** smaller
- Some hint that the slope of the excess is decreasing

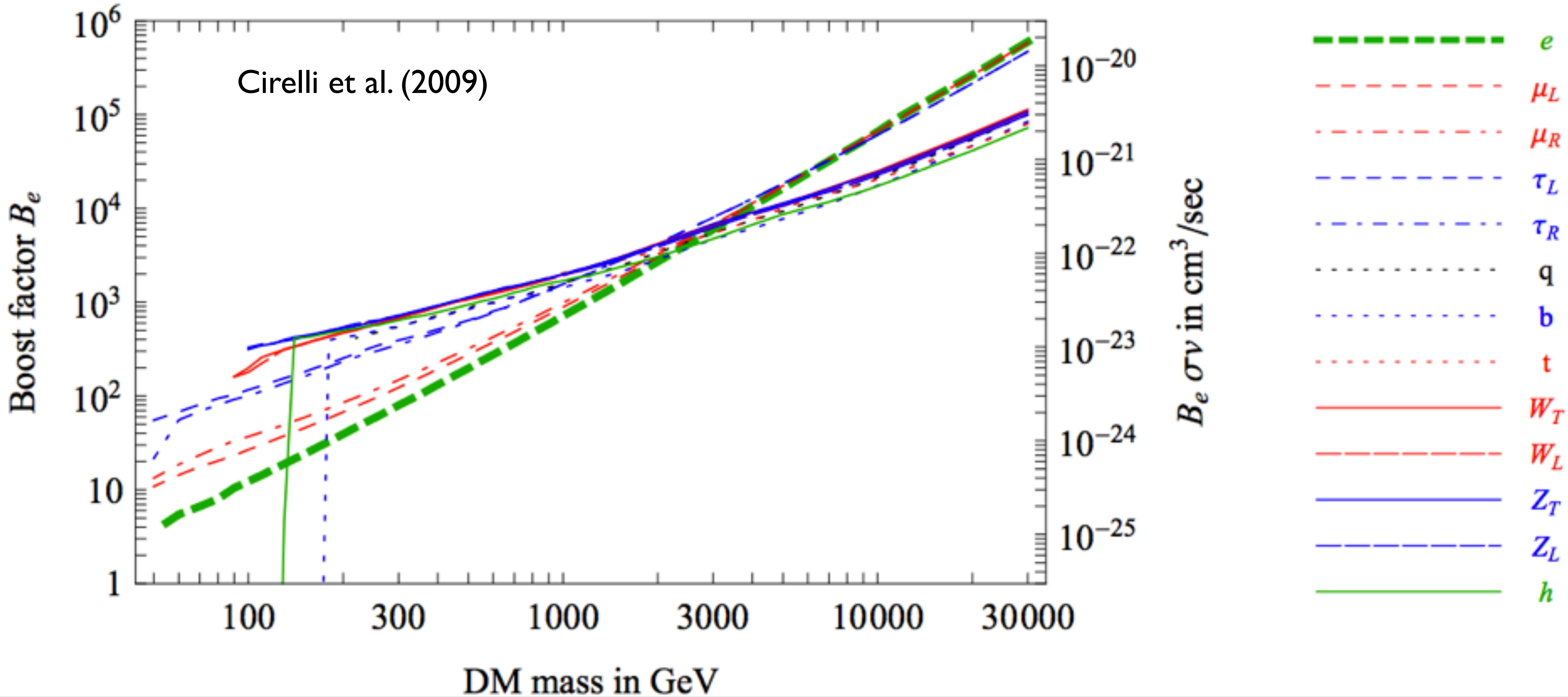


Current State of Measurements

- Three independent experiments verify the existence of a rising positron spectra at energies between 10-300 GeV
- This is impossible to replicate with Fermi acceleration and diffusion of cosmic-ray leptons
- What models can produce a rising positron spectrum?

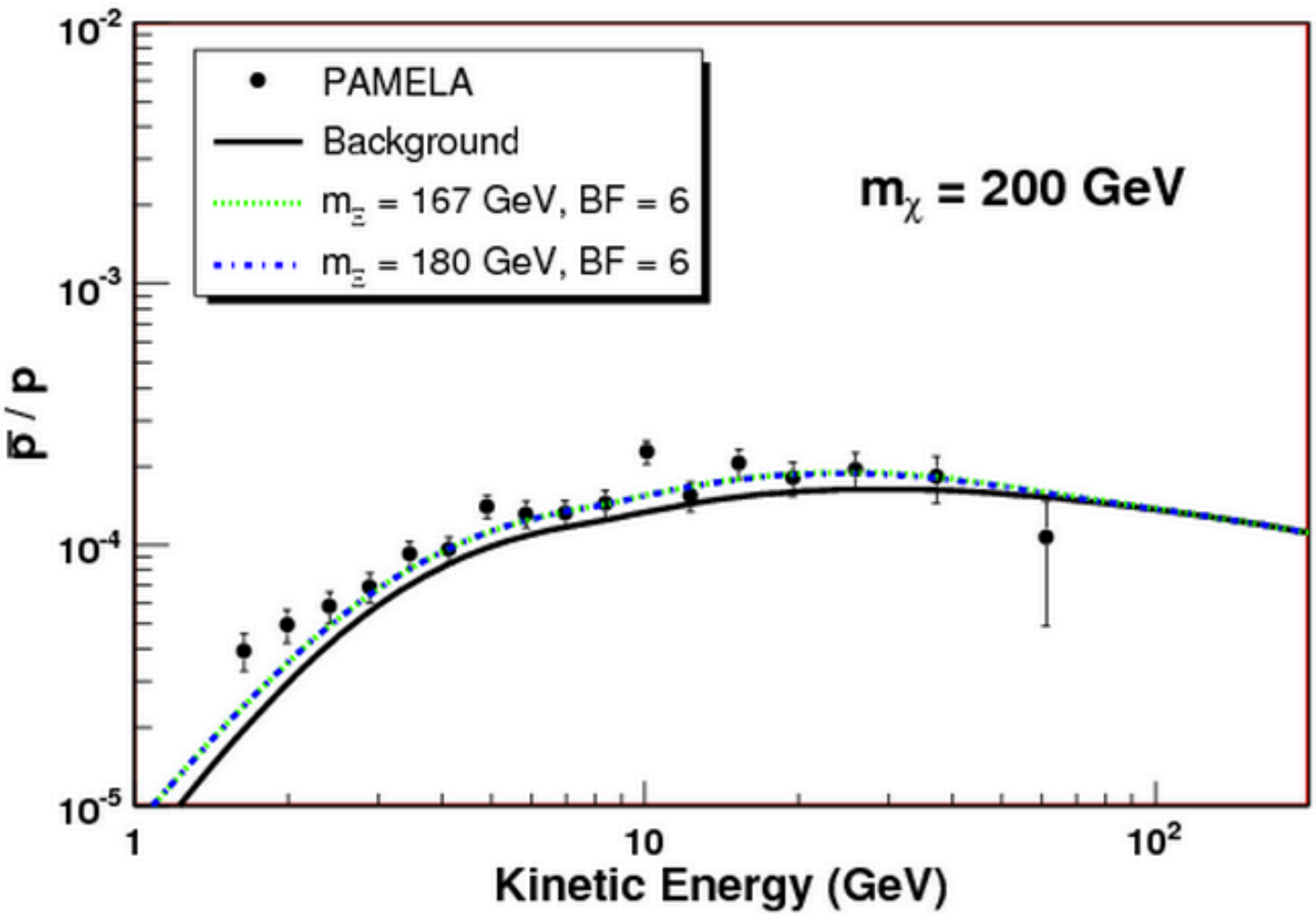
Dark Matter Models of the Positron Excess

- Many many models (> 800 papers)
- A few standard features:
  - High Mass (~300 GeV - 10 TeV)
  - Large Cross-section (100-1000 above thermal cross-section)



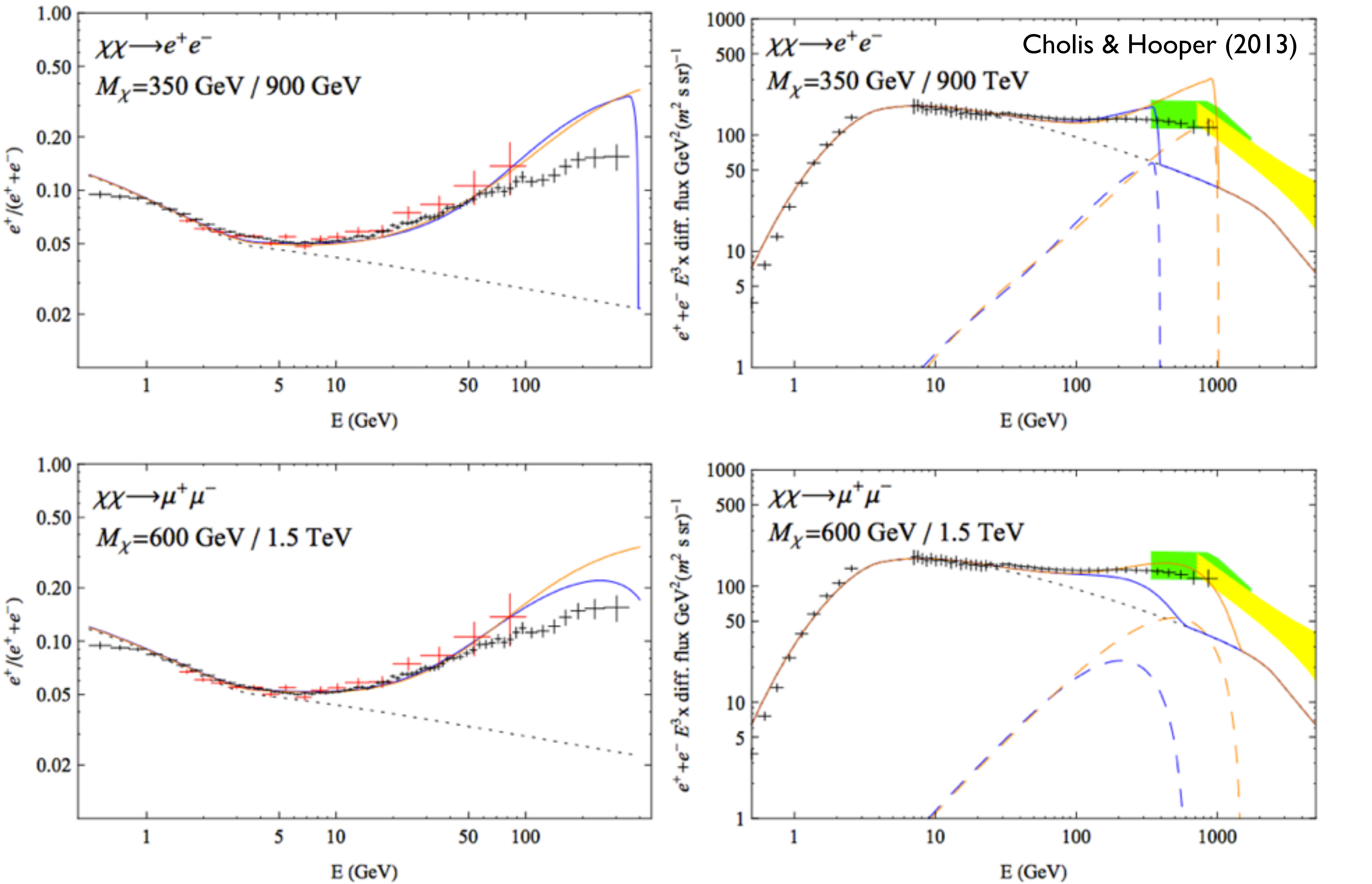
Dark Matter Models of the Positron Excess

- Many many models (> 800 papers)
- A few standard features:
  - Leptonic Final States (Strong constraints on the antiproton/proton ratio)



Dark Matter Models of the Positron Excess

- New Restrictions from AMS-02 Data



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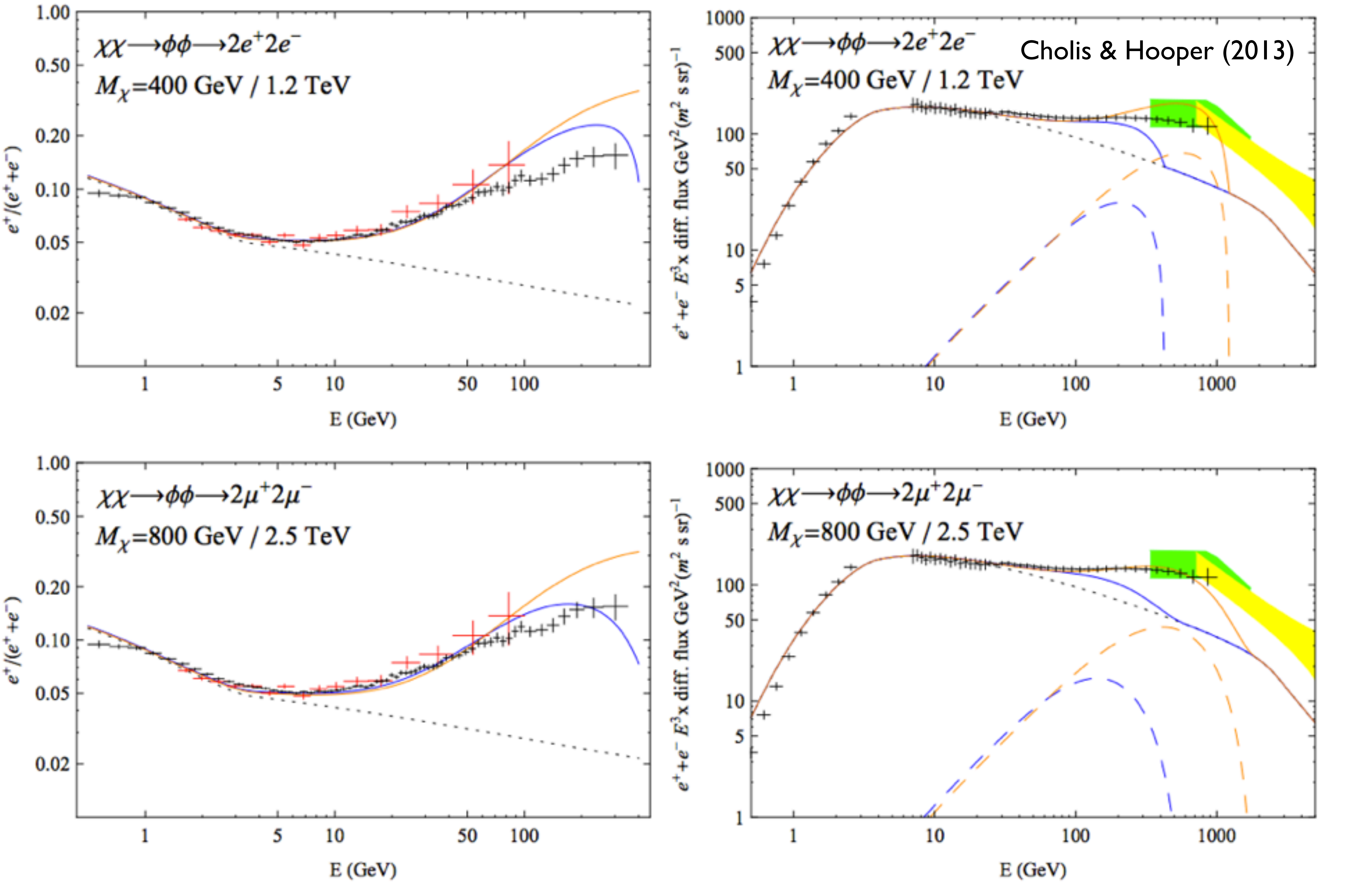

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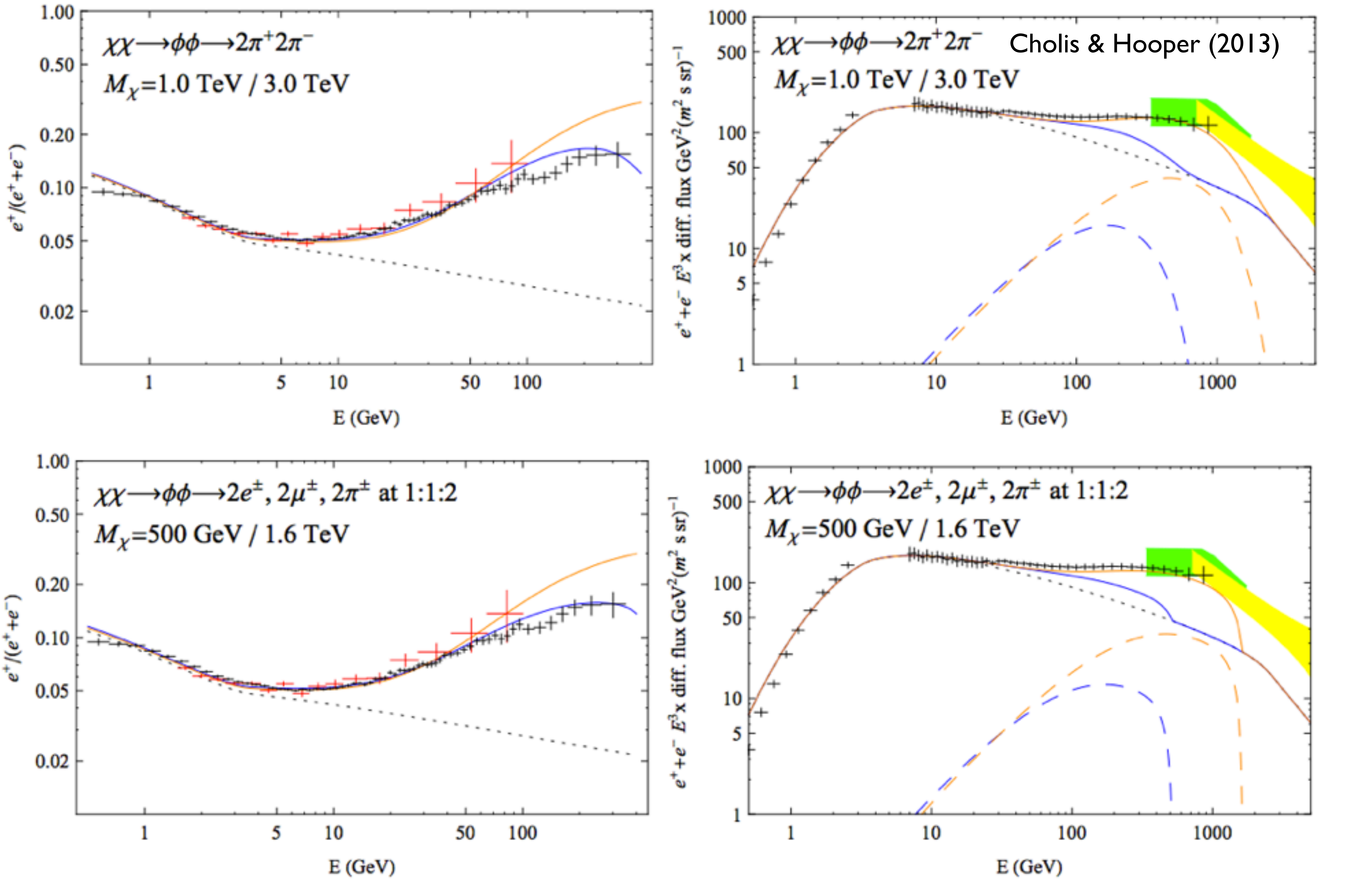
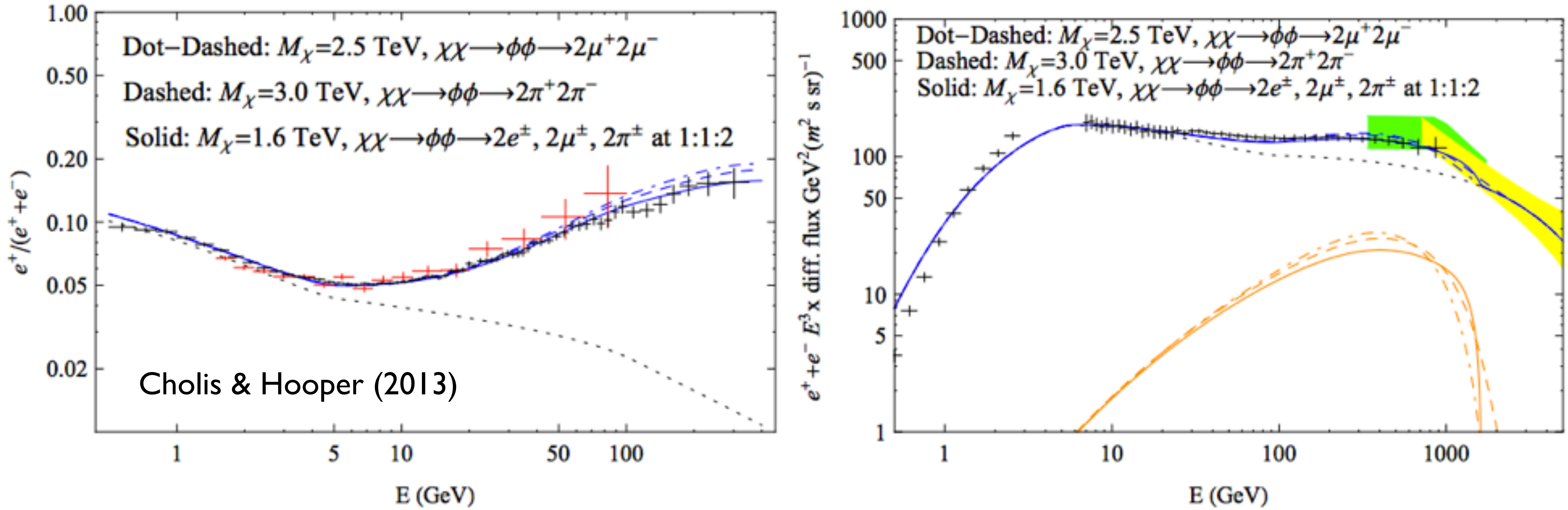


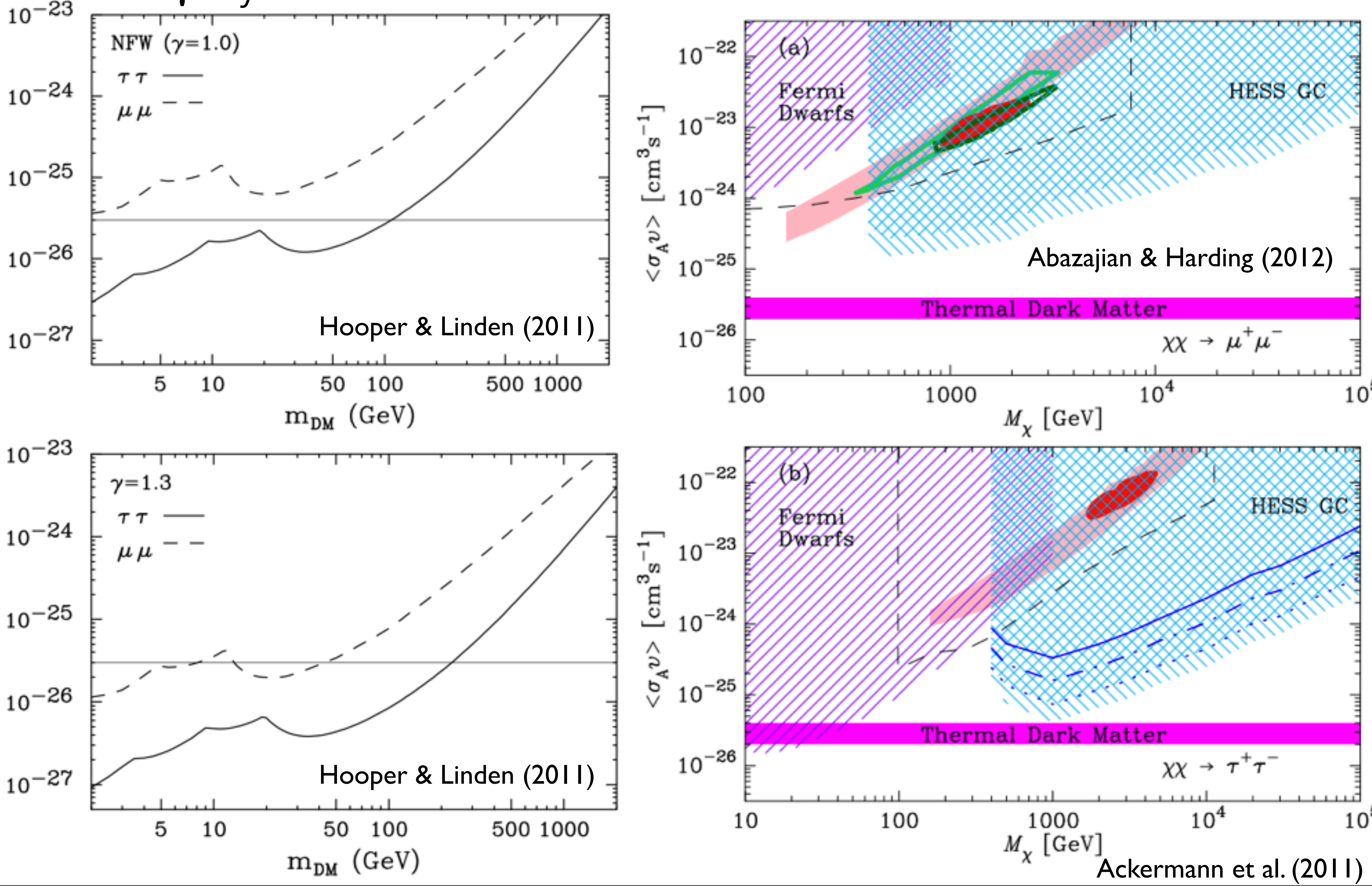
Dark Matter Models of the Positron Excess



- However, many of these exclusions can be fixed with careful choices of diffusion parameters, and a new spectral break in the primary electron spectrum

Limits from Gamma-Ray Studies

- Much stronger constraints can be placed on certain pathways, using limits from γ-ray observations



Limits from Gamma-Ray Studies

- Note: These limits can be avoided in many scenarios (e.g. annihilation through a light mediator into electrons)

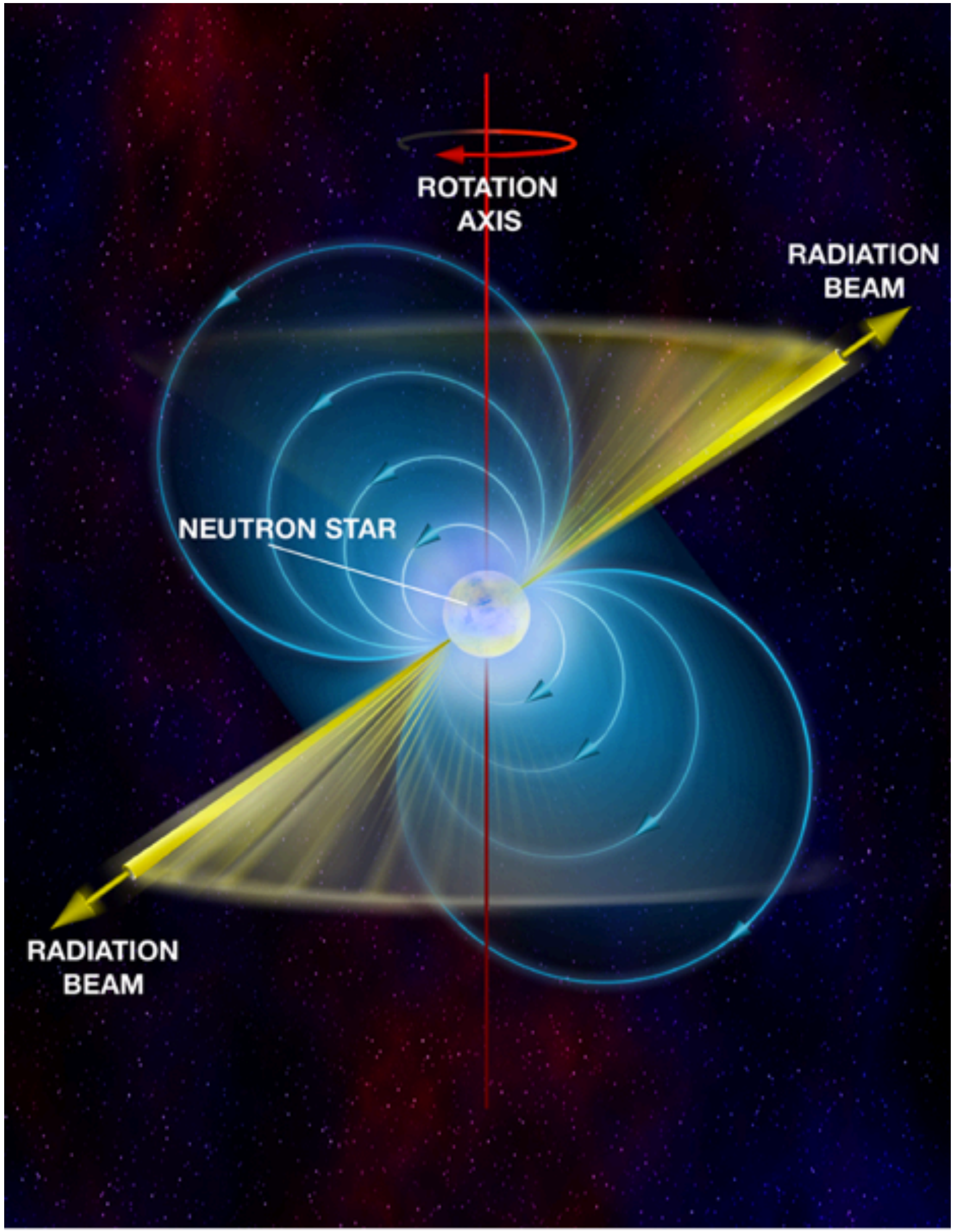
- Dark Matter Explanations for the positron excess are still possible **(and interesting!)**

- **If you make a stronger constraint, the world gives you a more creative theorist**

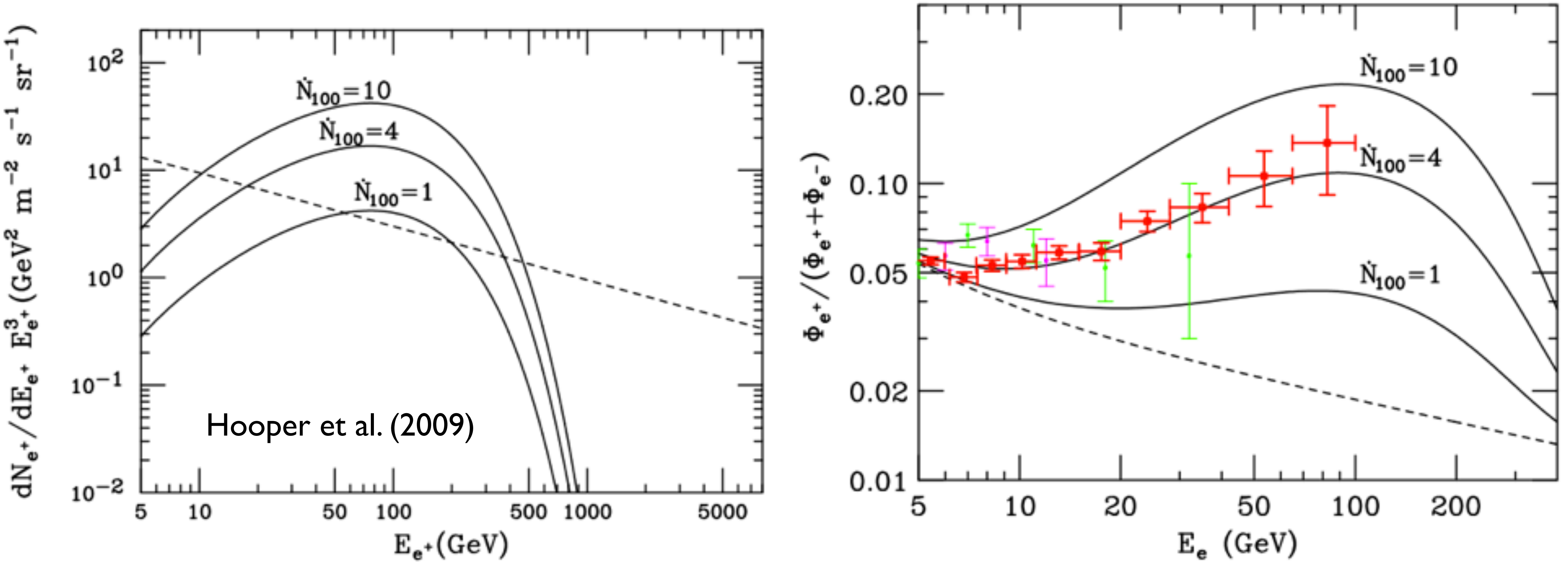
Pulsar Models of the Positron Excess

- Pulsars are a **guaranteed** source of primary positrons in the galaxy

- Stefano Profumo- "Occam's Razor implies that pulsar explanations should be considered first."

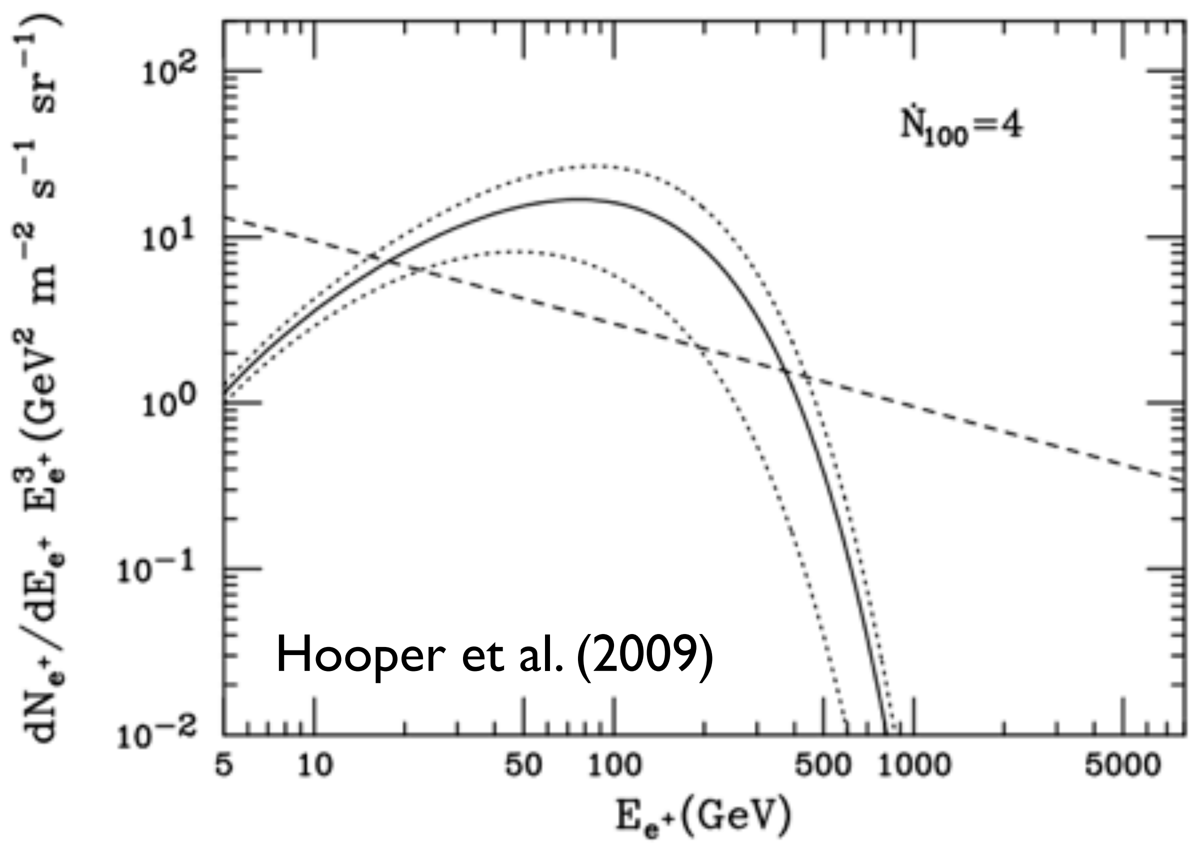


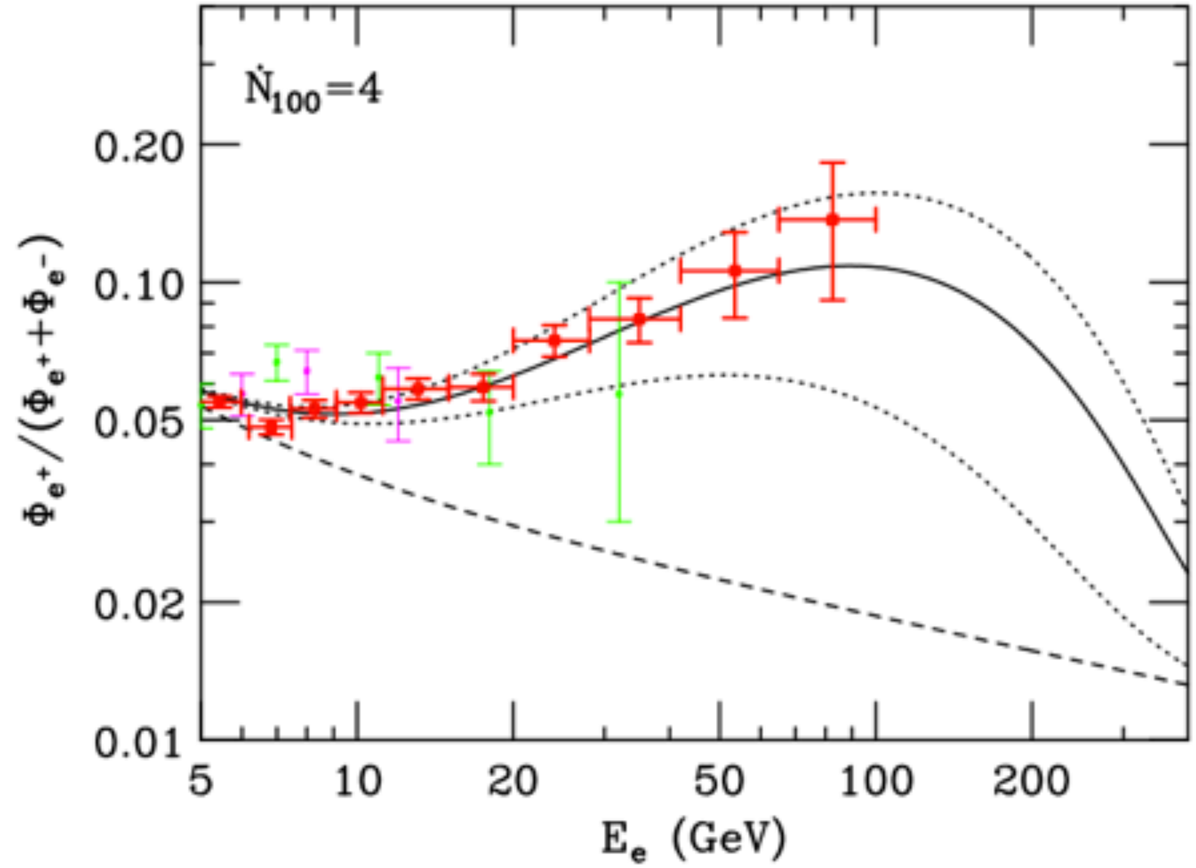
Galactic Pulsar Models



- A galactic population of pulsars can also fit the positron excess, given a birth-rate of a few pulsars/century

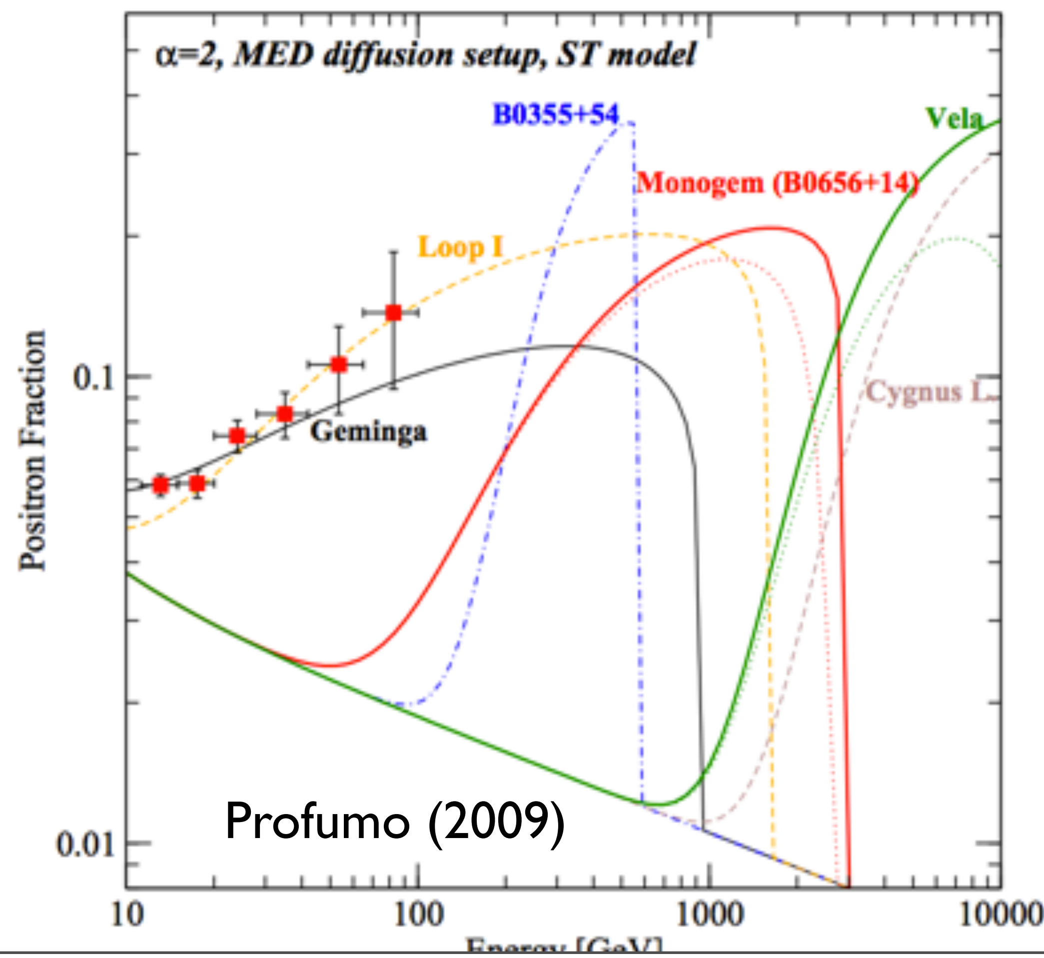
Local Pulsar Models



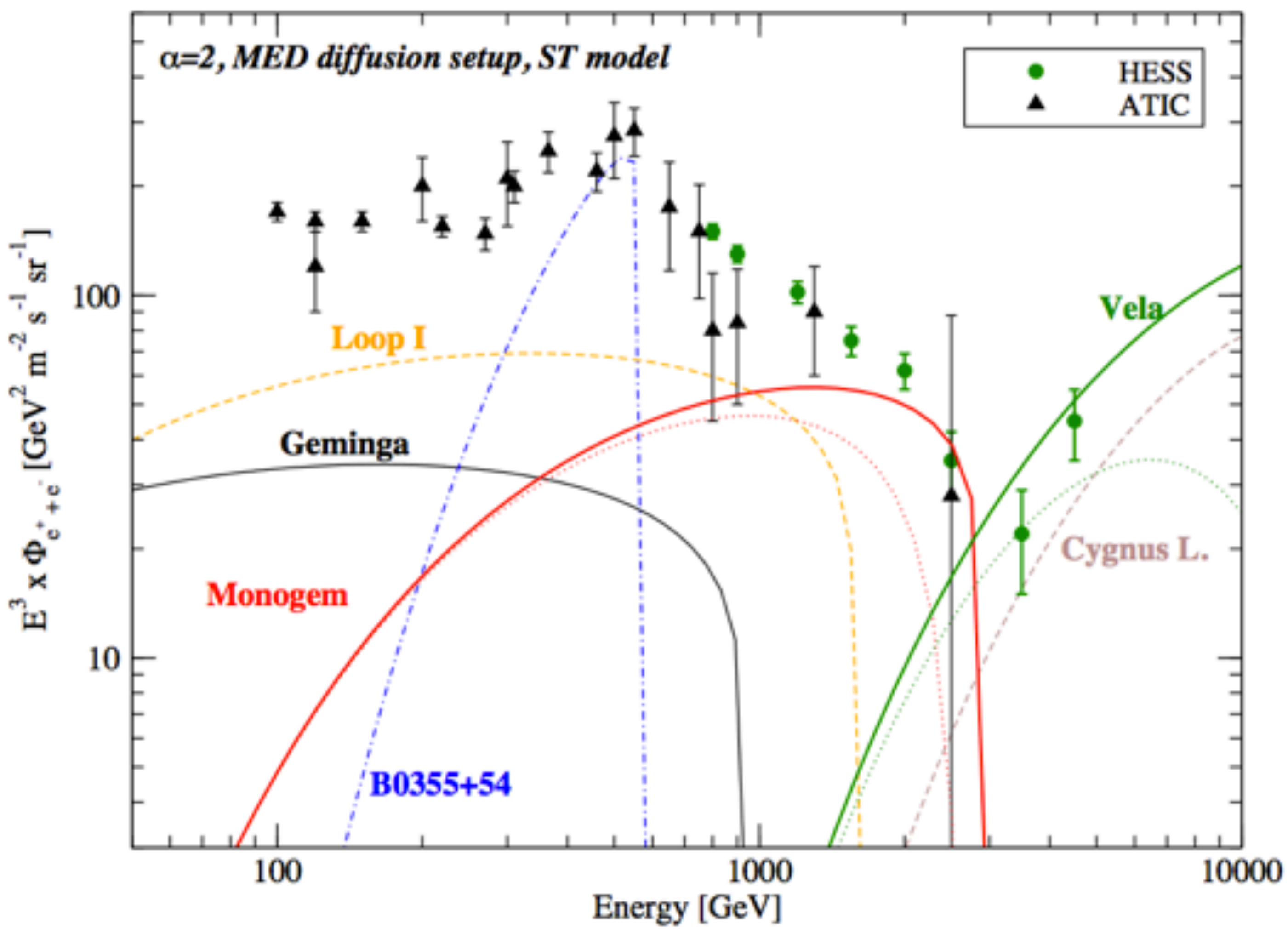


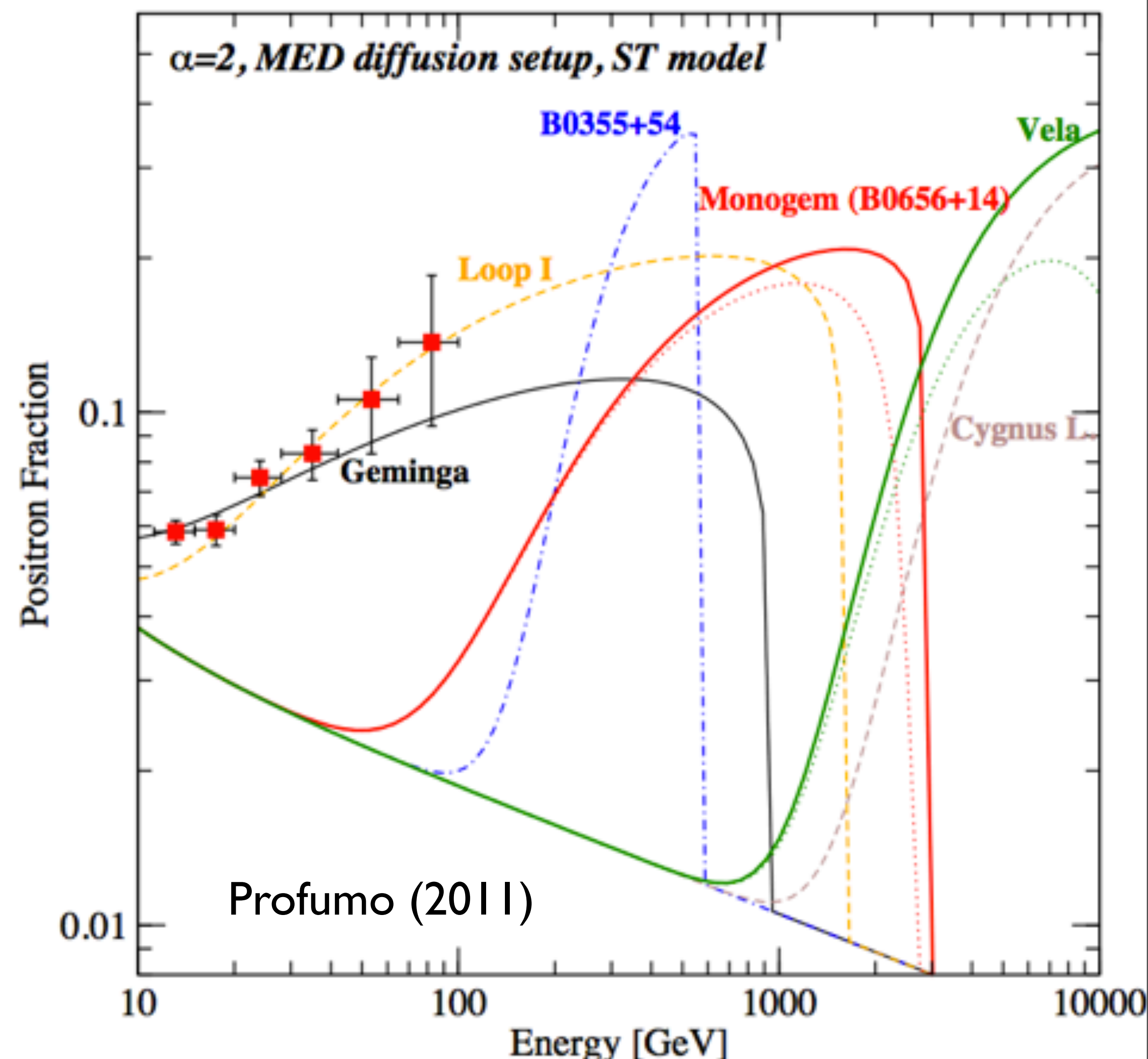
- However, this signal may be significantly enhanced by nearby sources

- Or may be composed almost entirely by one nearby source!



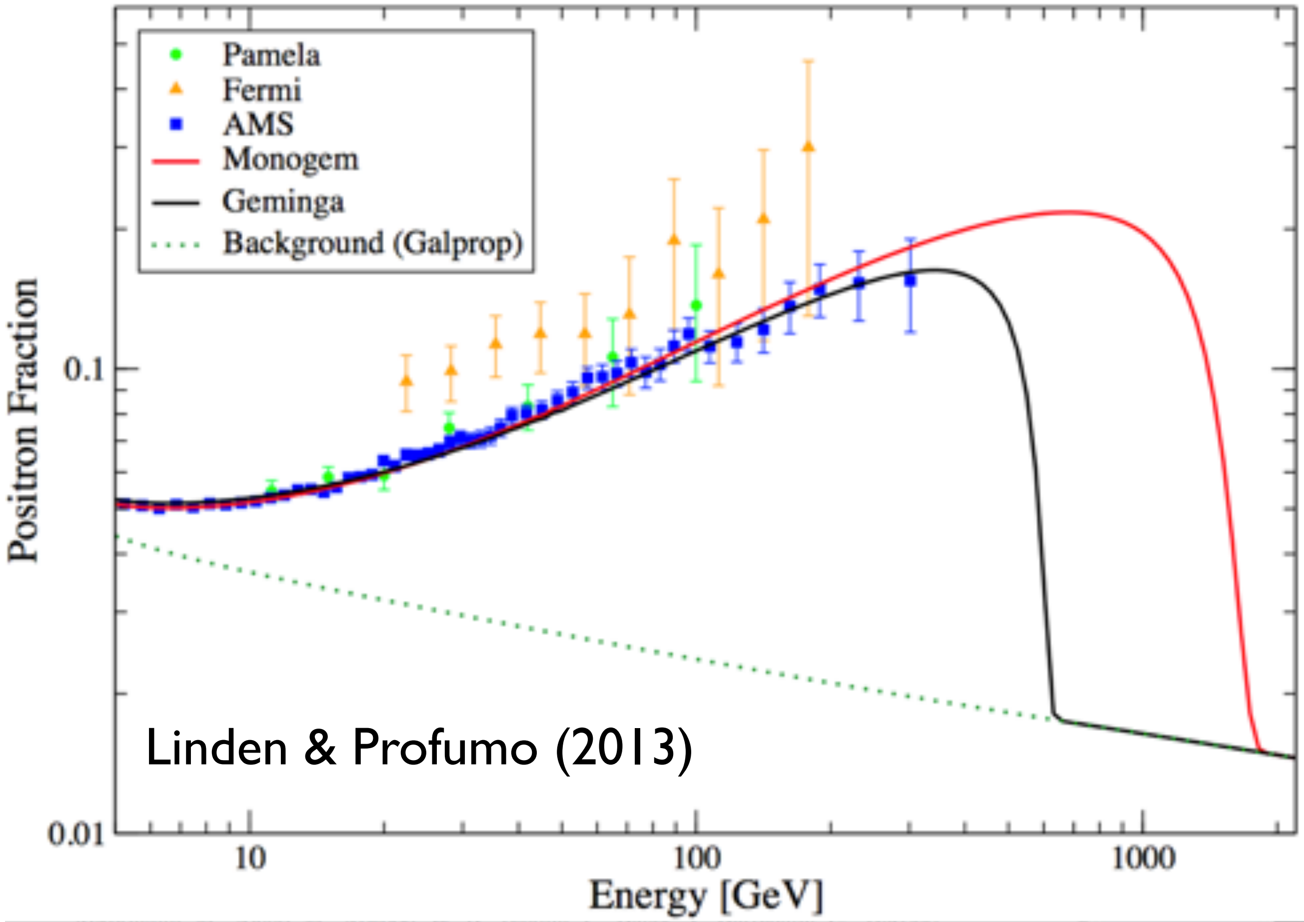
Likely Local Pulsars

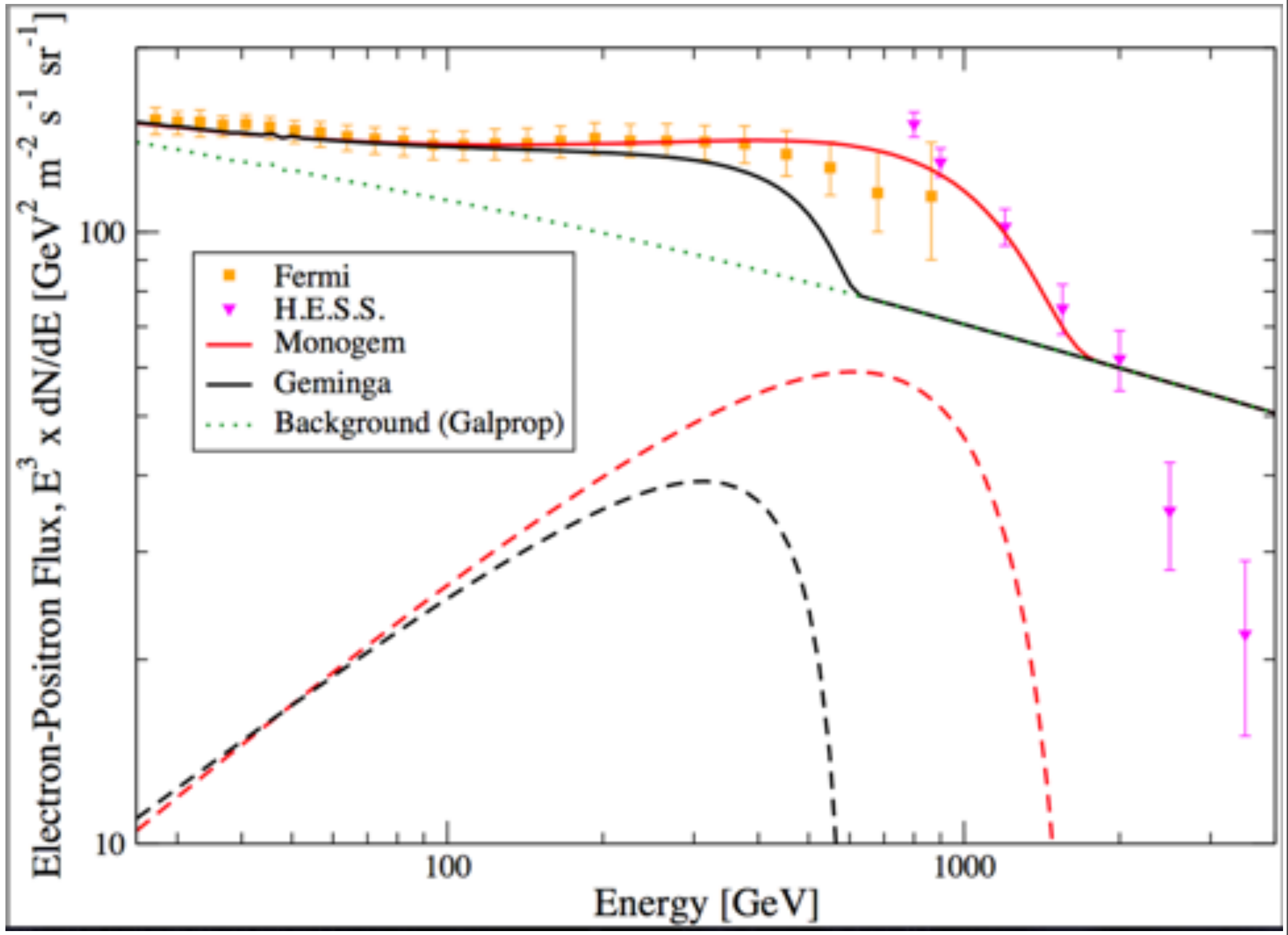




- A number of nearby pulsars are likely candidates (including Geminga, B0355+54, Monogem, Cynus I, Vela)
- Also, confirmation of radio-quiet, gamma-ray pulsars!

Pulsars Remain Good fits to AMS-02





- Models of the Monogem and Geminga Pulsars continue to fit the data extremely well

- This certainly provides the **simplest** model which is consistent with all current data

e^+e^- Production from Pulsars

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

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

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

- We assume a “burst-like” injection of electrons, near the time the pulsar was formed
- The electron spectrum takes the form of a power-law, with an exponential cutoff
- The total energy is given by ηW_0, which is the spin-down energy multiplied by an efficiency for electron/positron creation

The Geminga and Monogem Pulsars

- Values for this study:

  - Geminga age is set to 3.42×10^5 yr, Monogem to 1.11×10^5 yr
  - Geminga distance set to 0.15 kpc, Monogem to 0.29 kpc
  - We find the best fitting $\Upsilon = 1.9$ for Geminga and $\Upsilon = 1.95$ for Monogem
  - And we calculate a best fitting $\eta W_0 = 2 \times 10^{49}$ for Geminga and $\eta W_0 = 8.6 \times 10^{48}$ for Monogem
  - For both pulsars we assume $E_{cut} = 2$ TeV, though this parameter is relatively unimportant so long as $E_{cut} >$ AMS energy threshold

Diffusion Calculation of Pulsar Anisotropies

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

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

- The anisotropy , Δ , can then be calculated as above. δ is the index of the diffusion coefficient, d is the distance to the candidate pulsar, and T the time from the electron injection, E_{loss} is the energy loss time, and N_{psr}/N_{tot} gives the fraction of electrons stemming from the pulsar

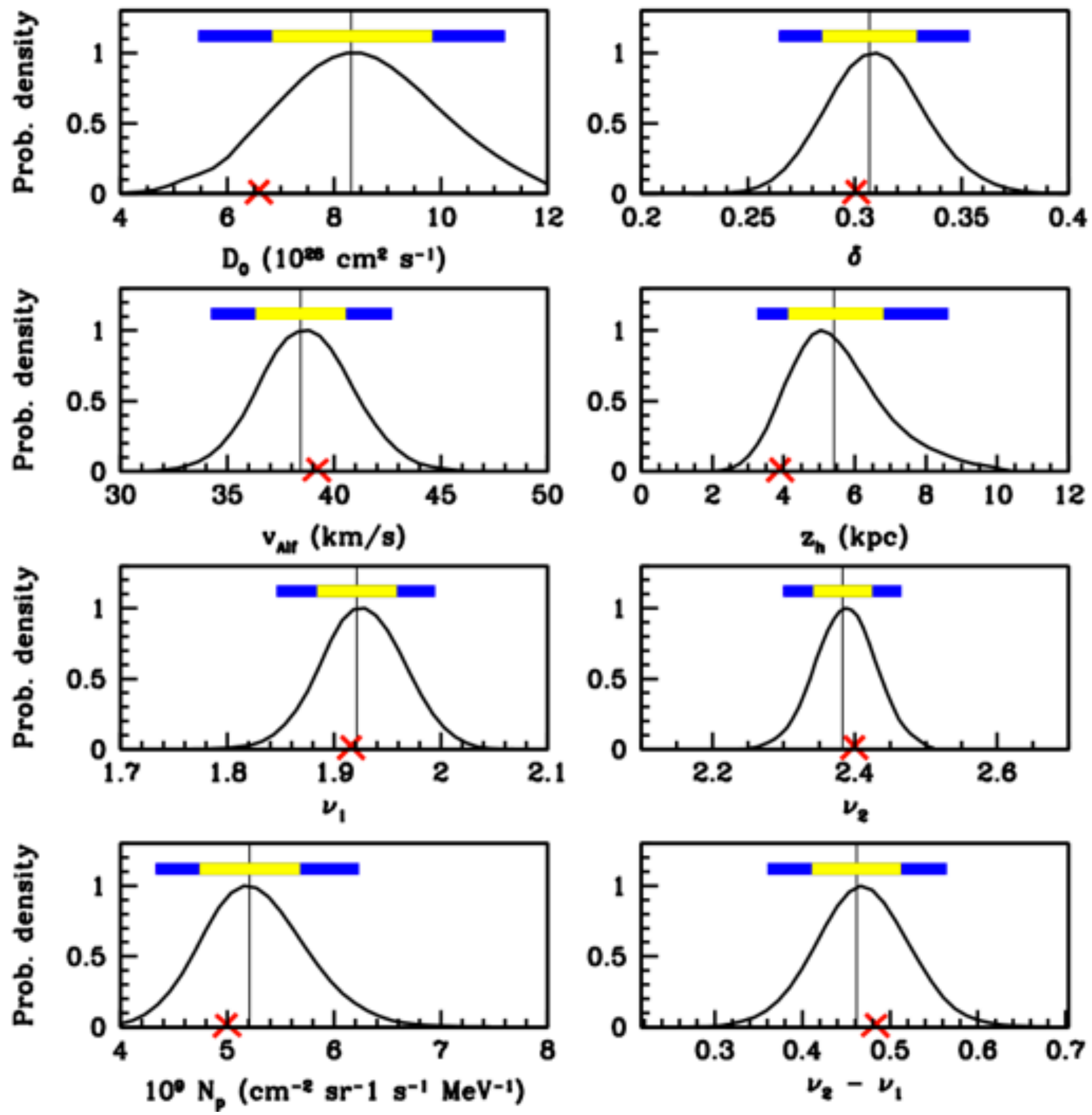
Diffusion Calculation of Pulsar Anisotropies

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

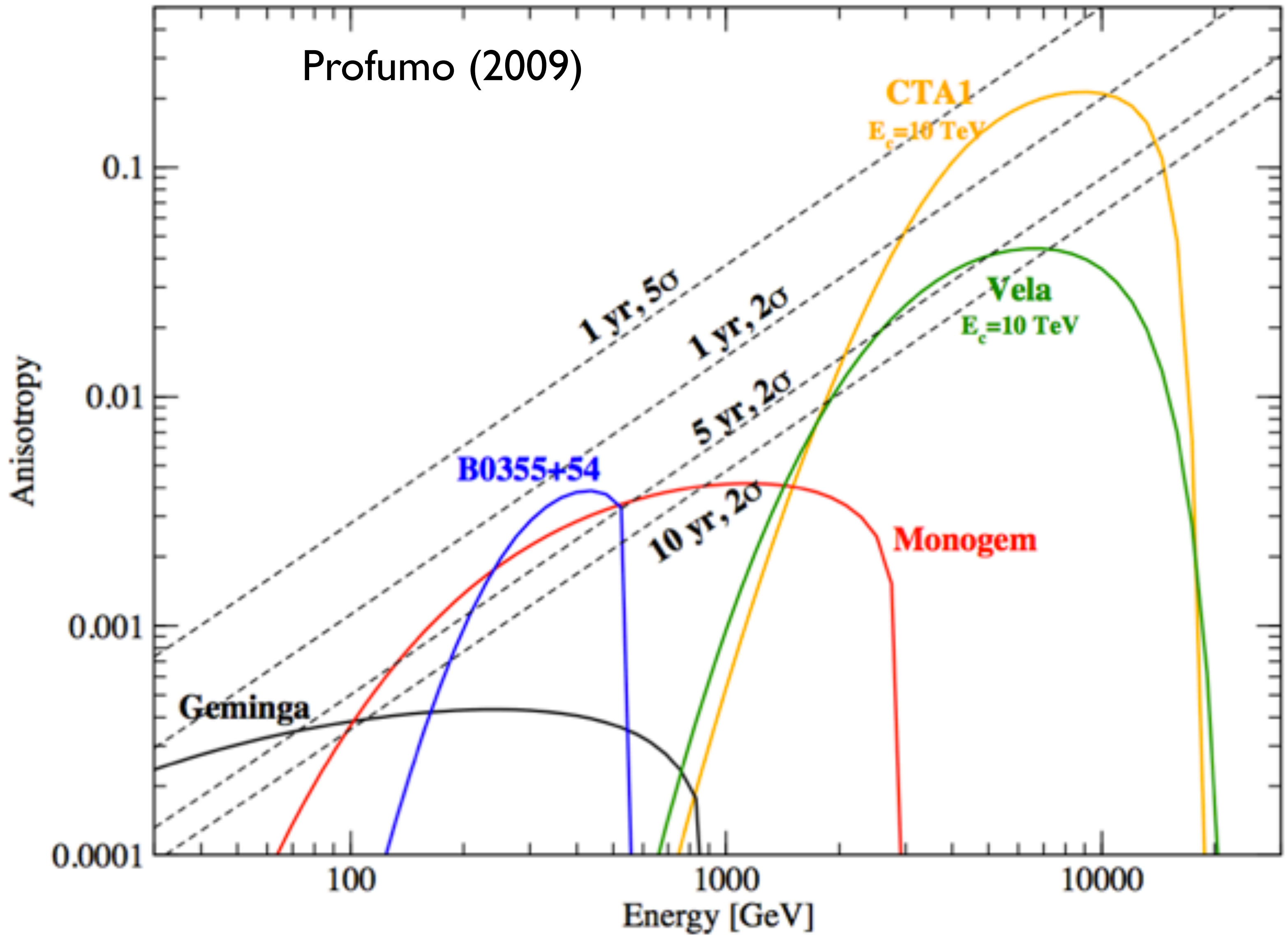
- If I want a 2σ detection of anisotropy, I need the following to hold

Galprop Diffusion Model

- In our work, we take the best fitting Bayesian model for cosmic-ray propagation (Trotta et al. 2012)
- Specifically, we adopt:
    - $D_0 = 8.32 \times 10^{28}$ cm^2 s^{-1}
    - δ=0.31

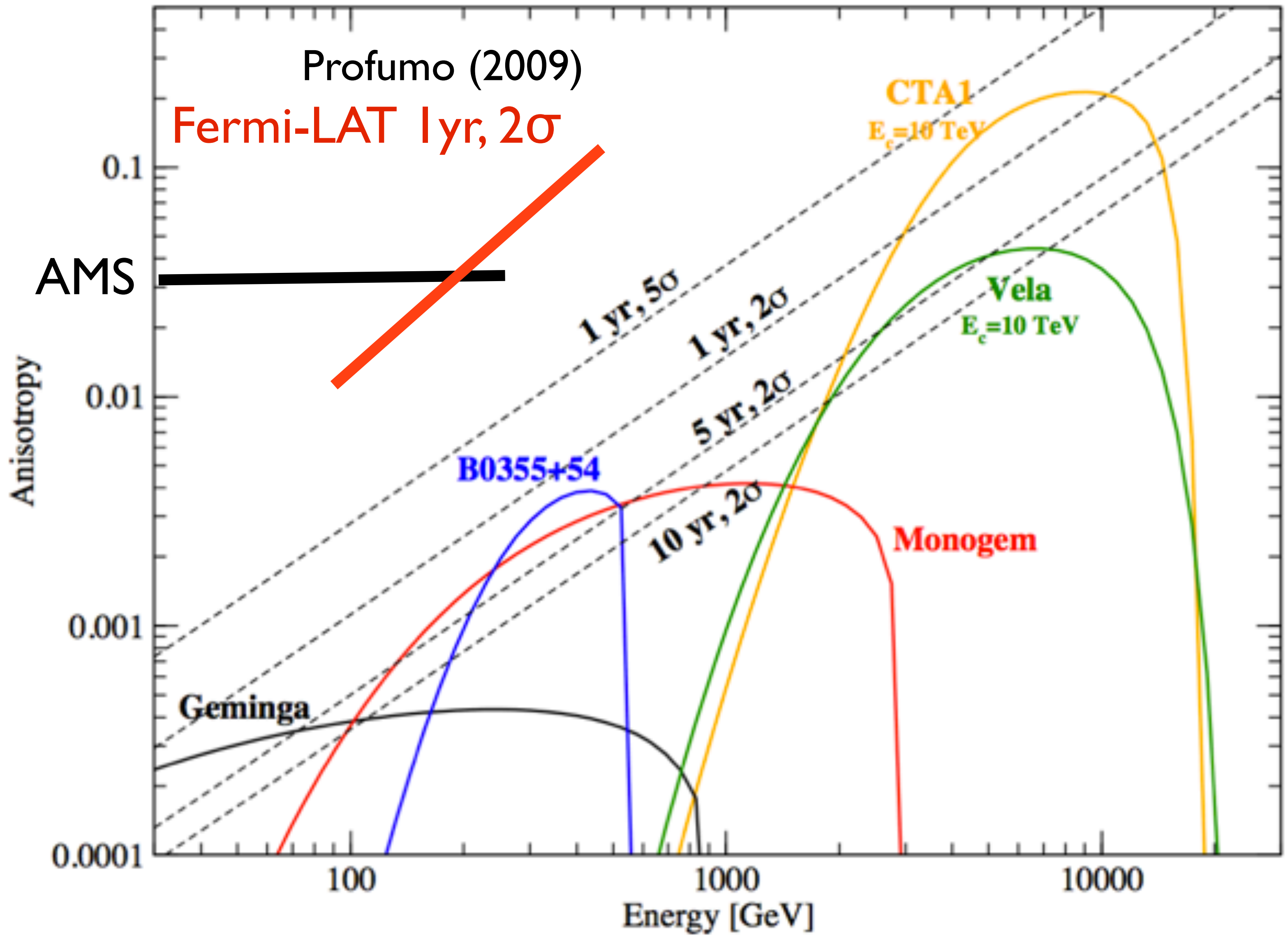


Anisotropies from Local Pulsars



- The anisotropy for various pulsar had been previously calculated by Profumo (2009) , who found that anisotropies from several nearby pulsars would be detectable by the Fermi-LAT

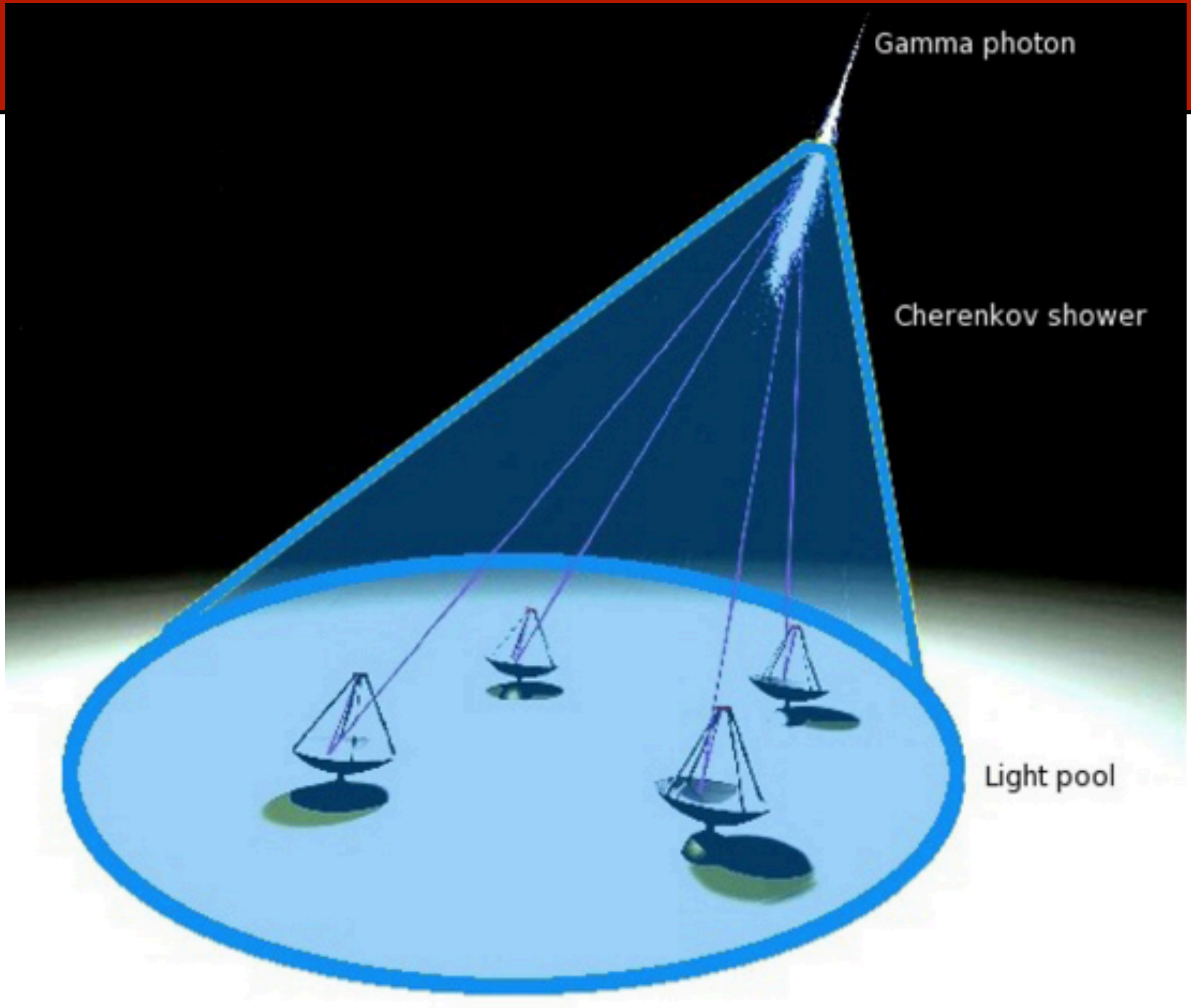
Anisotropies from Local Pulsars



- However, current Fermi-LAT (and AMS-02) limits fail to rule out pulsar signals by approximately an order of magnitude

ACTs

- Atmospheric Cherenkov Telescopes have a extraordinarily large effective area, which is the key component in determining any electron anisotropy



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.

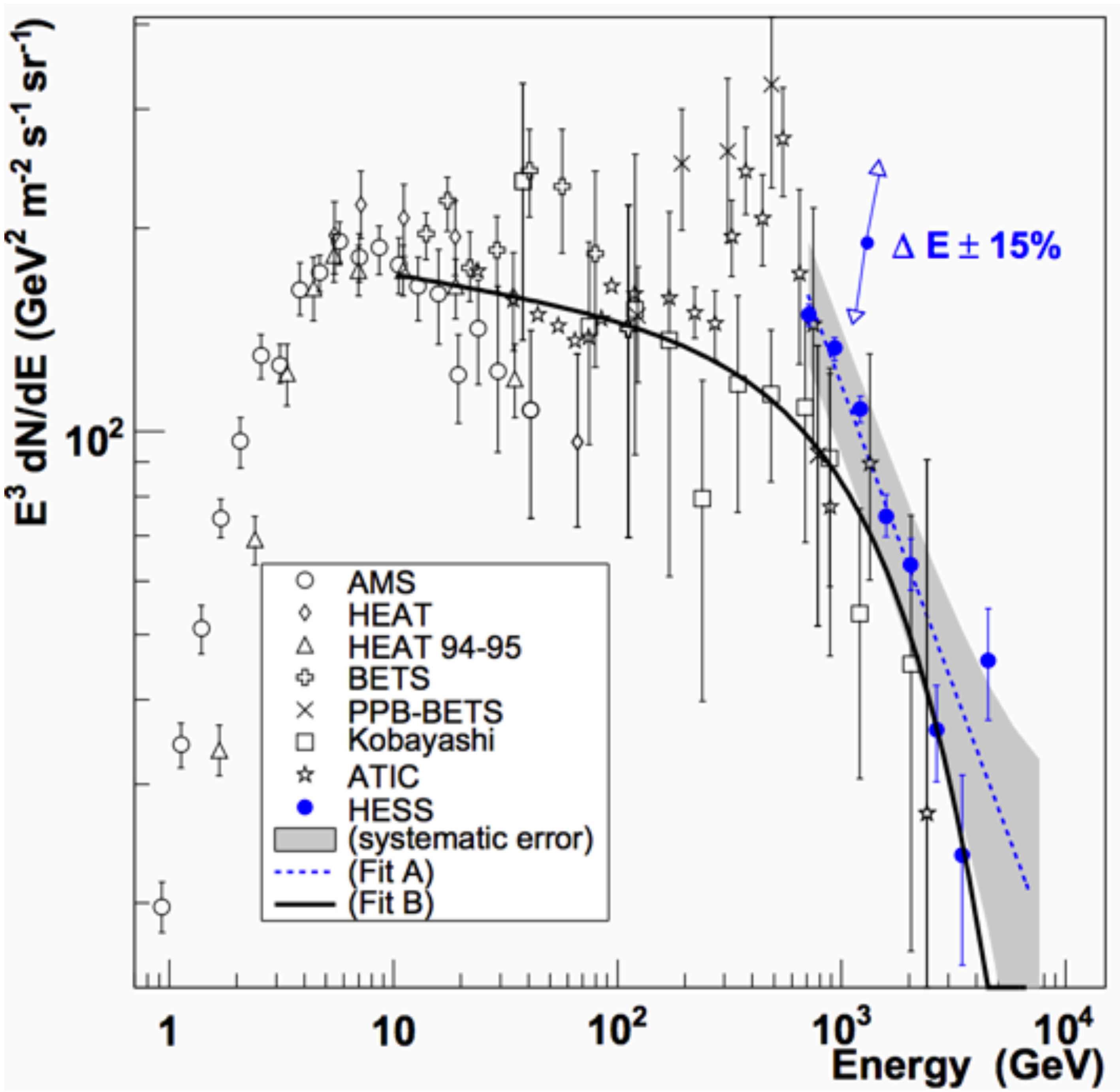
Effective Area ~ 5×10^4 m^2
Angular Acceptance ~ 0.002 sr
Total Observation Time ~ 5000h

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

Detection of Electron Showers with ACTs

- Electron Shower Proceeds Almost Identically to a Gamma-Ray Shower -- but electrons much more prevalent
- H.E.S.S. can accurately determine the electron spectrum at energies up to nearly 10 TeV

Aharonian et al. (2009)



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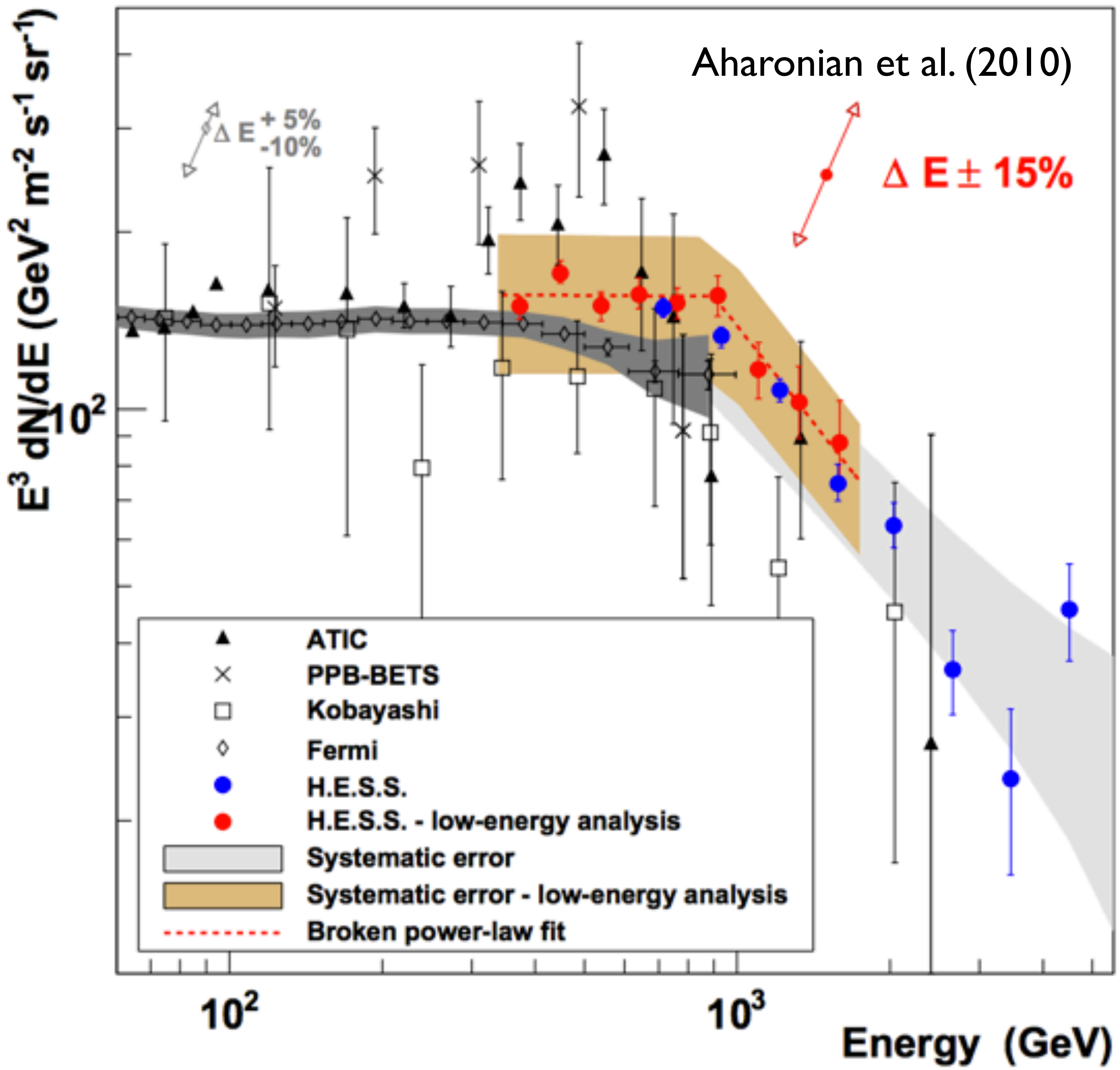
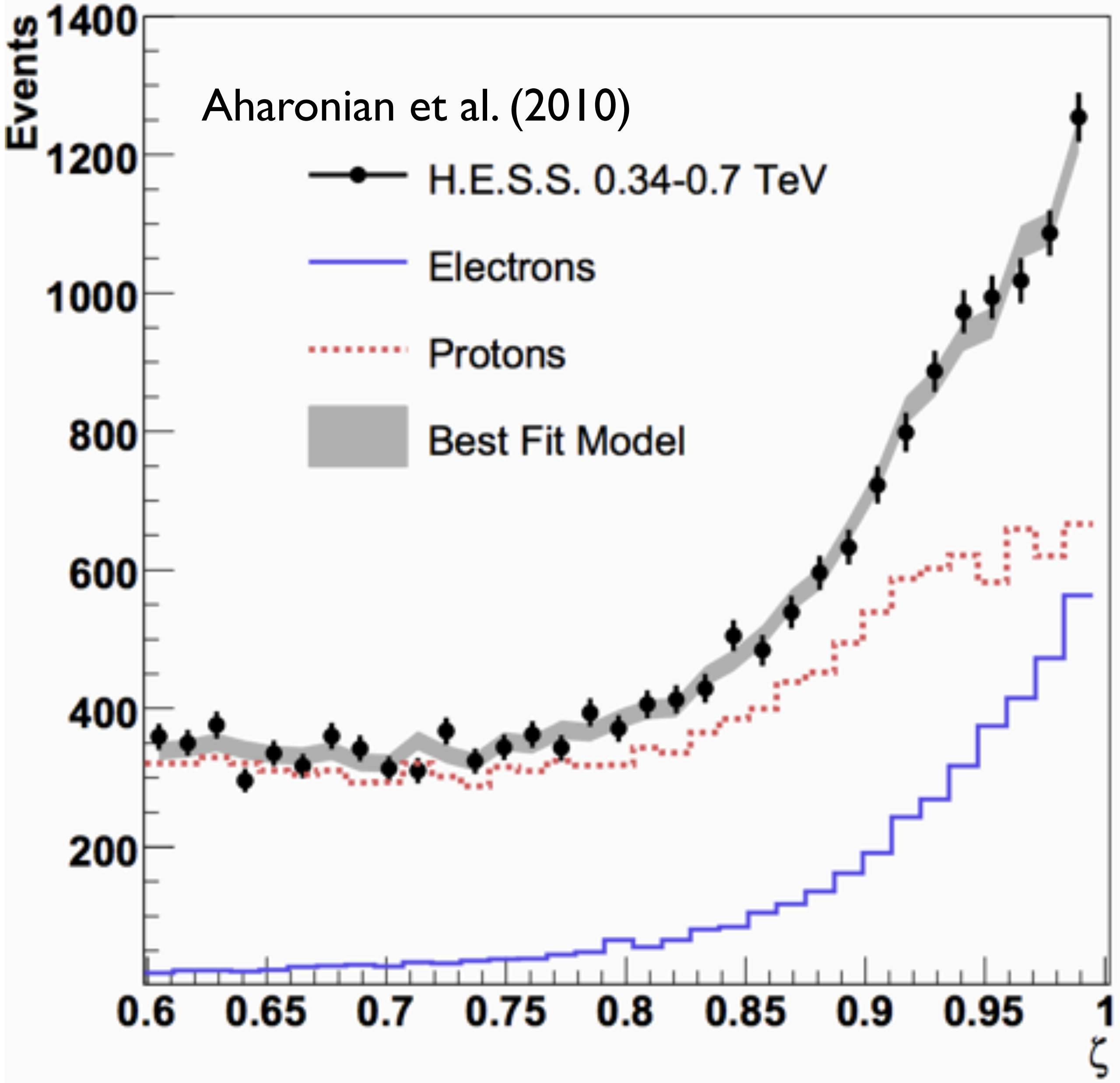
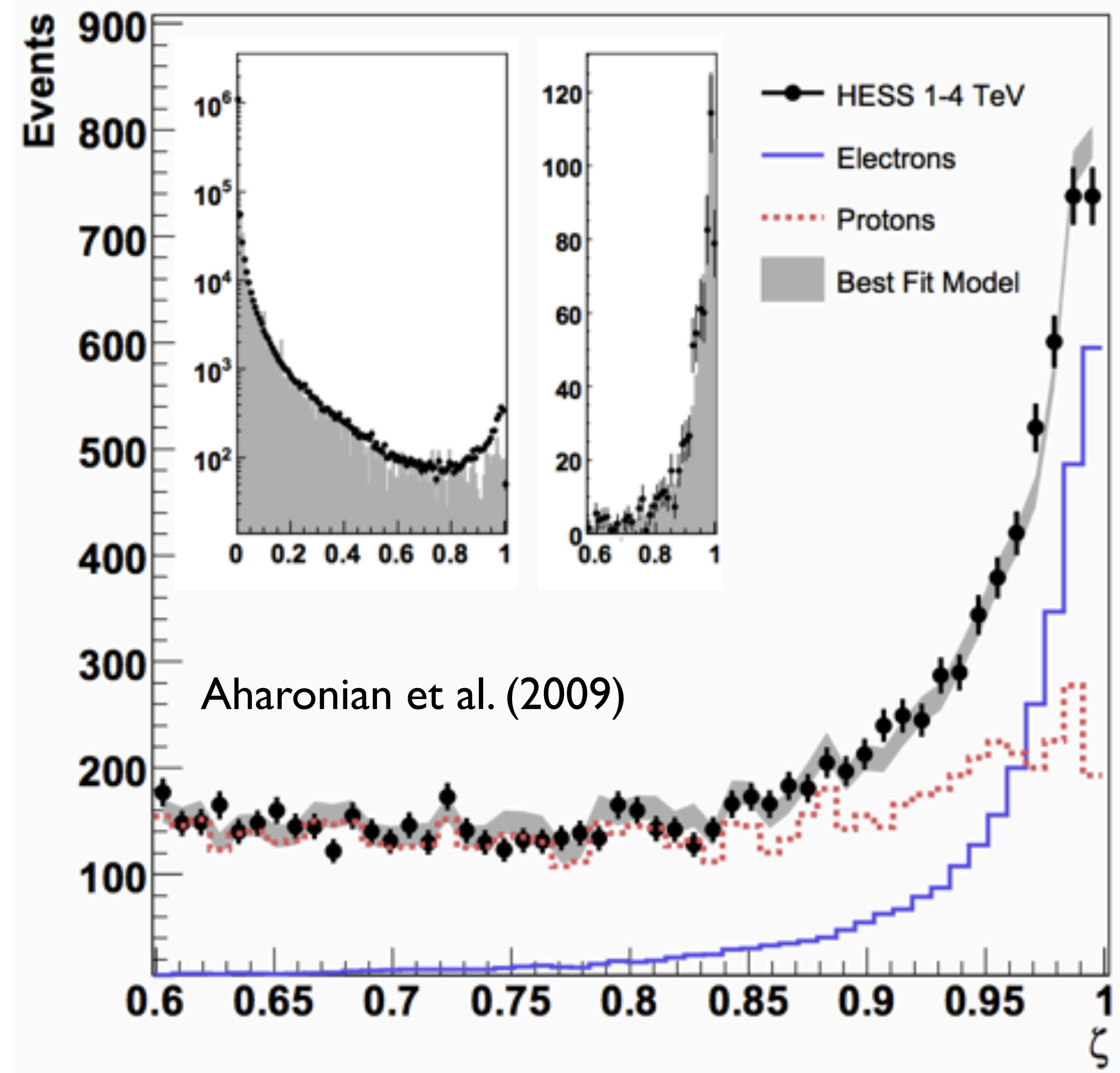


Errors from Hadronic Rejection

- Biggest systematic error stems from proton mis-identification.
- Proton flux ~ 10,000 x the Electron Flux
- Fortunately, the showers from proton interactions are hadronic, and not electromagnetic, allows ACTs to distinguish between proton and electron events

Errors from Hadronic Rejection





- The parameter ς has been created in order to calculate the "electron-ness" of the shower, with 0 < ς < 1 providing the confidence that the shower is electromagnetic

- At high values of ς electrons can become dominant, or at least a large portion of the signal

In Anisotropy Searches, These Errors are Statistical!

- Instead of asking the question “what is the anisotropy of the electron spectrum observed by an ACT” -- we ask “what is the anisotropy of the total cosmic-ray spectrum observed by an ACT”
- Protons (as well as electrons that do not stem from the pulsar) are known to be highly isotropized
- We can still make a cut (on ς) so that cosmic-ray electrons produce a dominant portion of the total signal
- To translate this back into a measurement of the total electron anisotropy, we must include the systematic errors from proton misidentification, but we can detect a signal without systematic errors

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

In Anisotropy Searches, These Errors are Statistical!

- Example: With a cut of $\varsigma > 0.9$, H.E.S.S. identified 2600 electrons, and 2470 protons in 239h of livetime

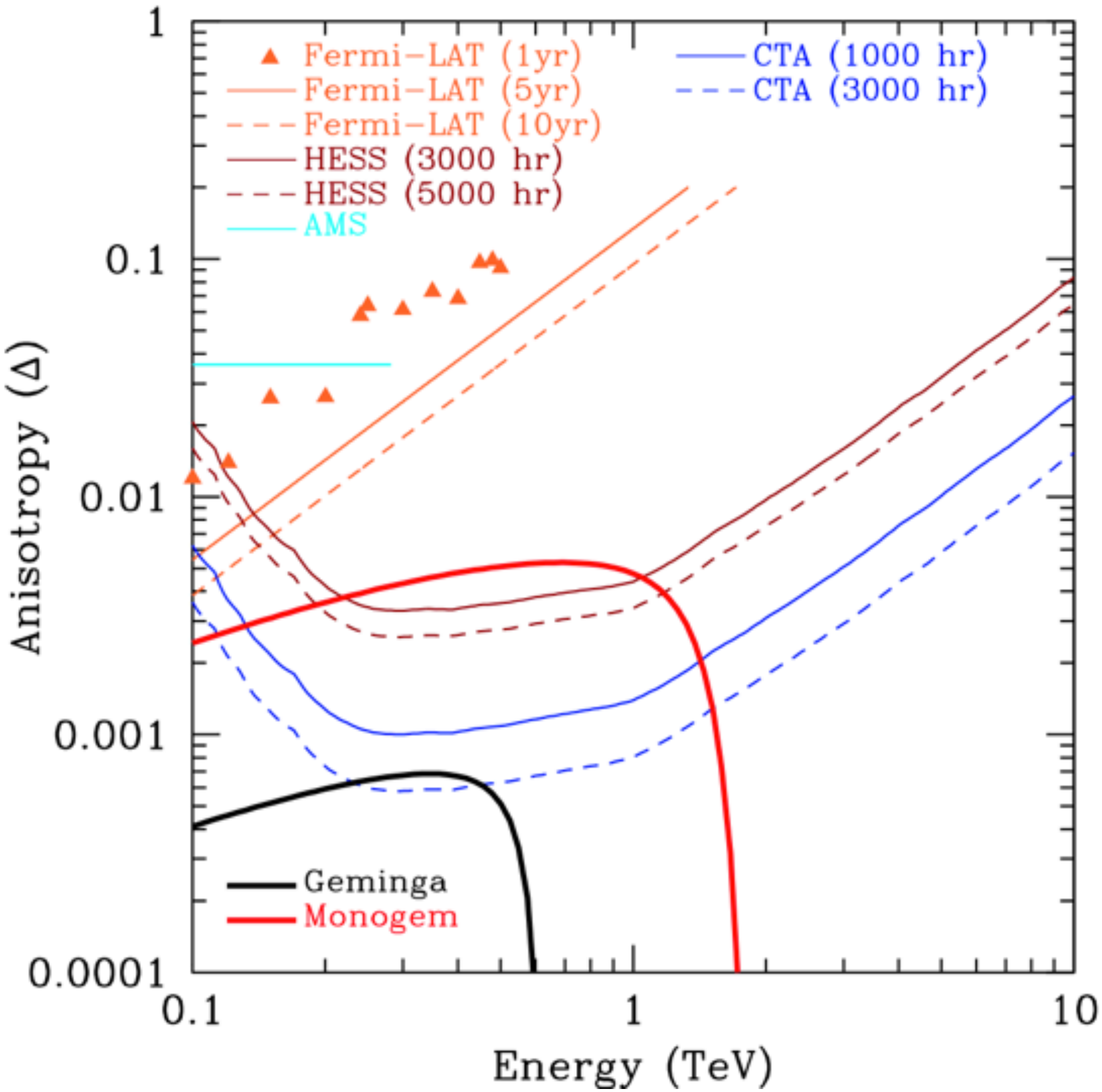
- This implies the observation of 54400 electrons and 52100 protons with 5000h livetime

- Thus, we only need a pulsar to produce 460 more forward electrons compared to backwards electrons (for a 2σ) detection-- which means a single pulsar producing 100% of the total signal with a 0.5% anisotropy

Limits on Anisotropies with H.E.S.S.

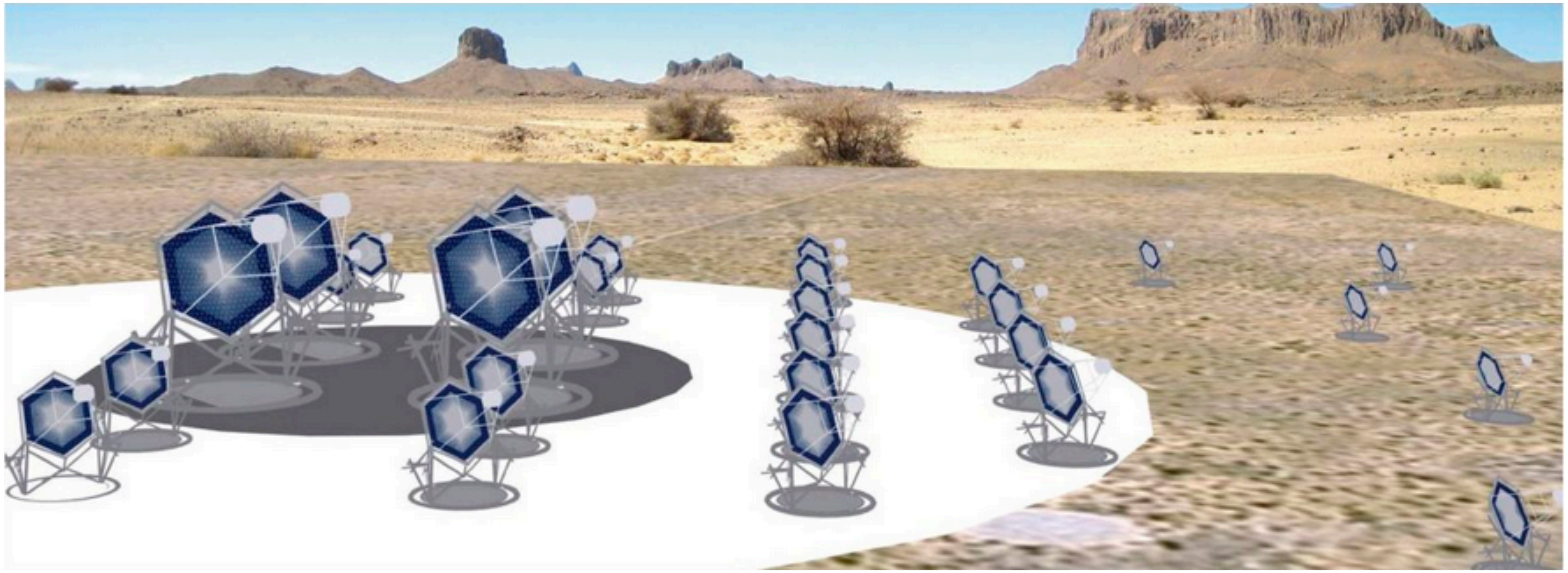
- The limits from H.E.S.S. are superior to those from the Fermi-LAT and AMS-02 by more than an order of magnitude, and run to significantly higher energies

- Current H.E.S.S. data may be sufficient to detect anisotropies from Monogem, but not Geminga (due primarily to its greater age)



Linden & Profumo (2013)

The Cherenkov Telescope Array

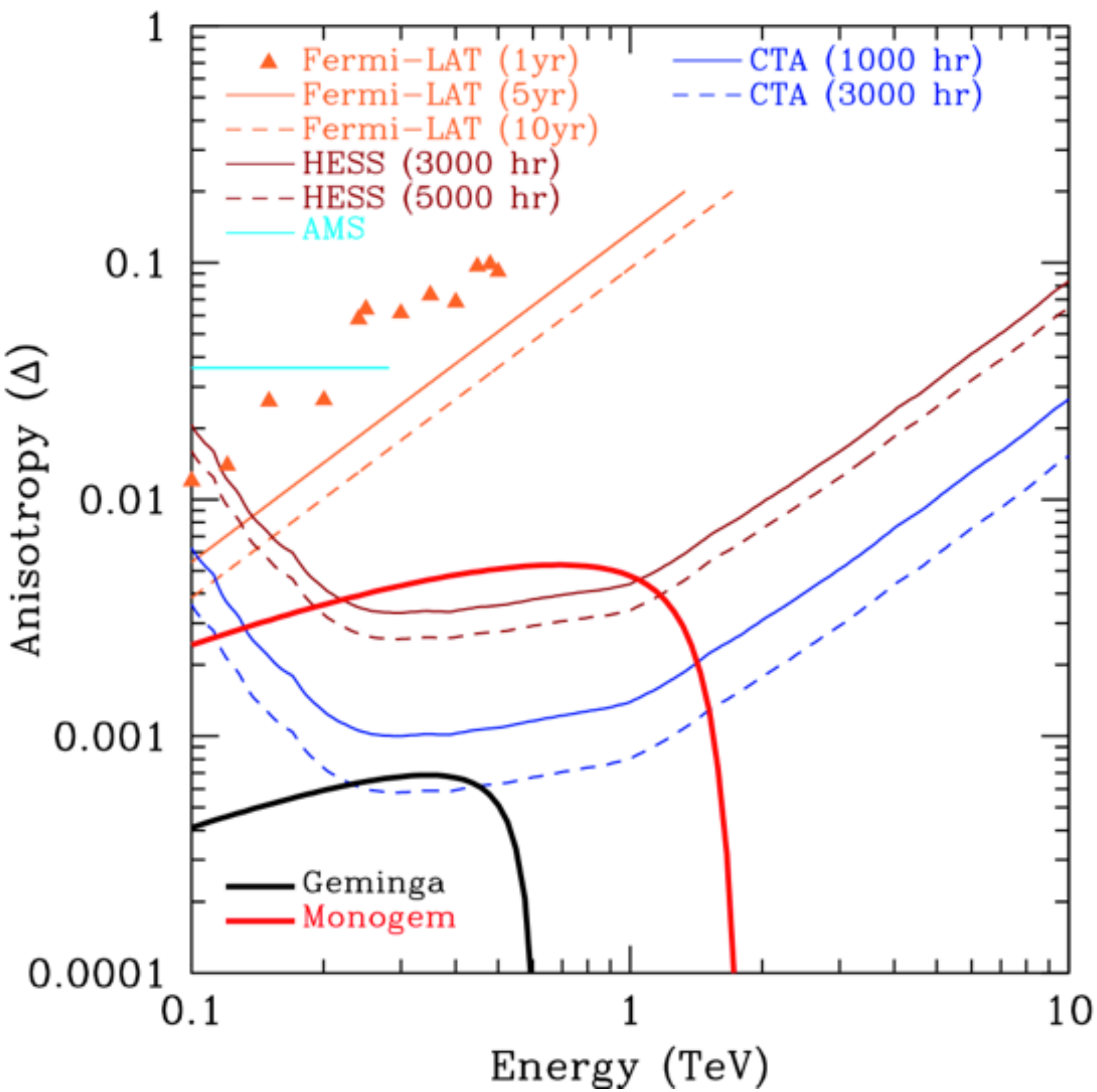


- Upcoming ACT (2017-2018) with a much larger effective area, and better hadronic rejection than H.E.S.S.
- In this paper, it is simply modeled as a machine with a 10x larger effective area, and a 2x better hadronic rejection

Limits with the Cherenkov Telescope Array

- CTA observations will be able to detect anisotropies which are an order of magnitude below current H.E.S.S. limits

- May be able to detect pulsars with fairly weak anisotropies (e.g. Geminga)



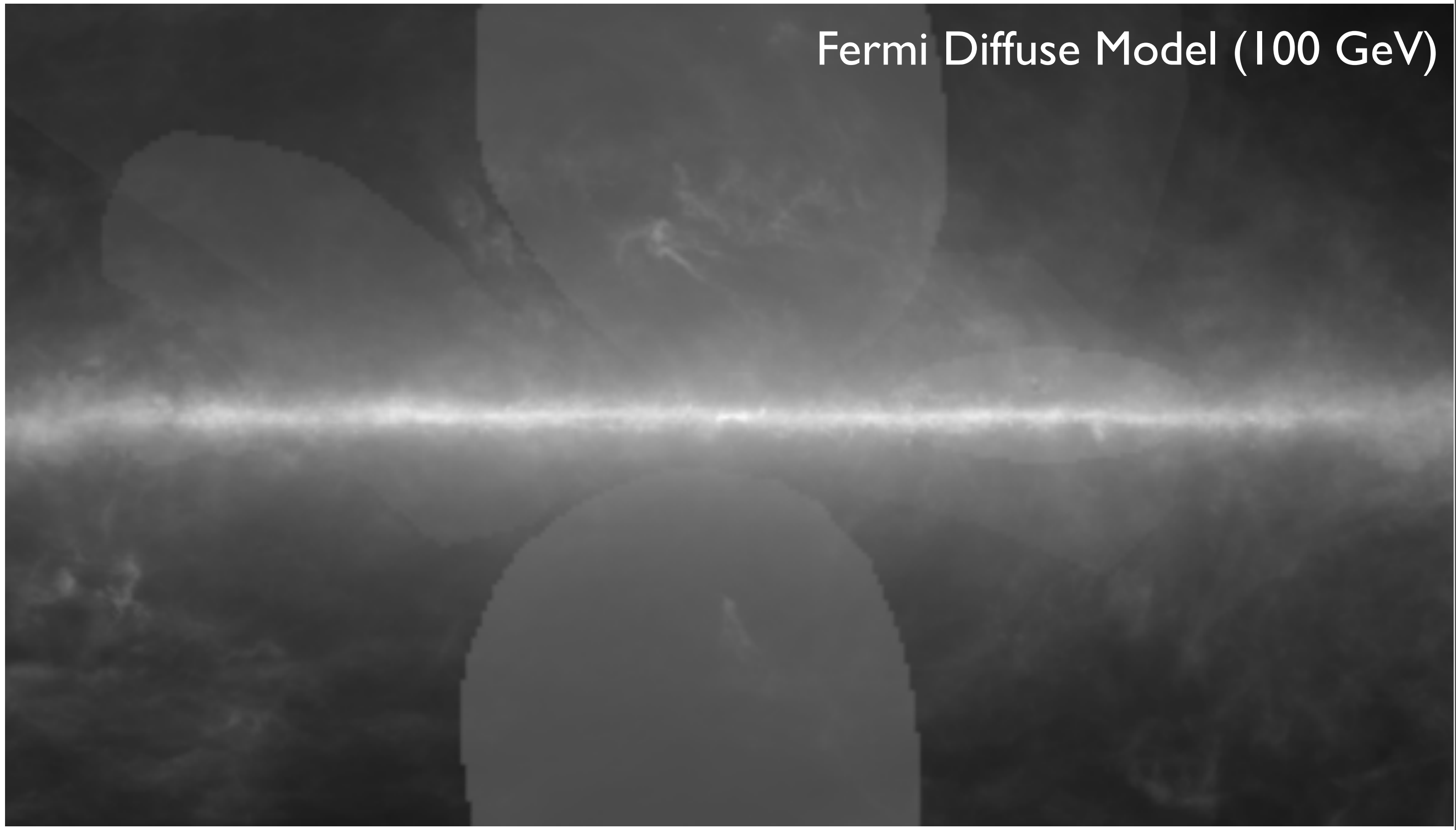
Uncertainties from Gamma-Rays

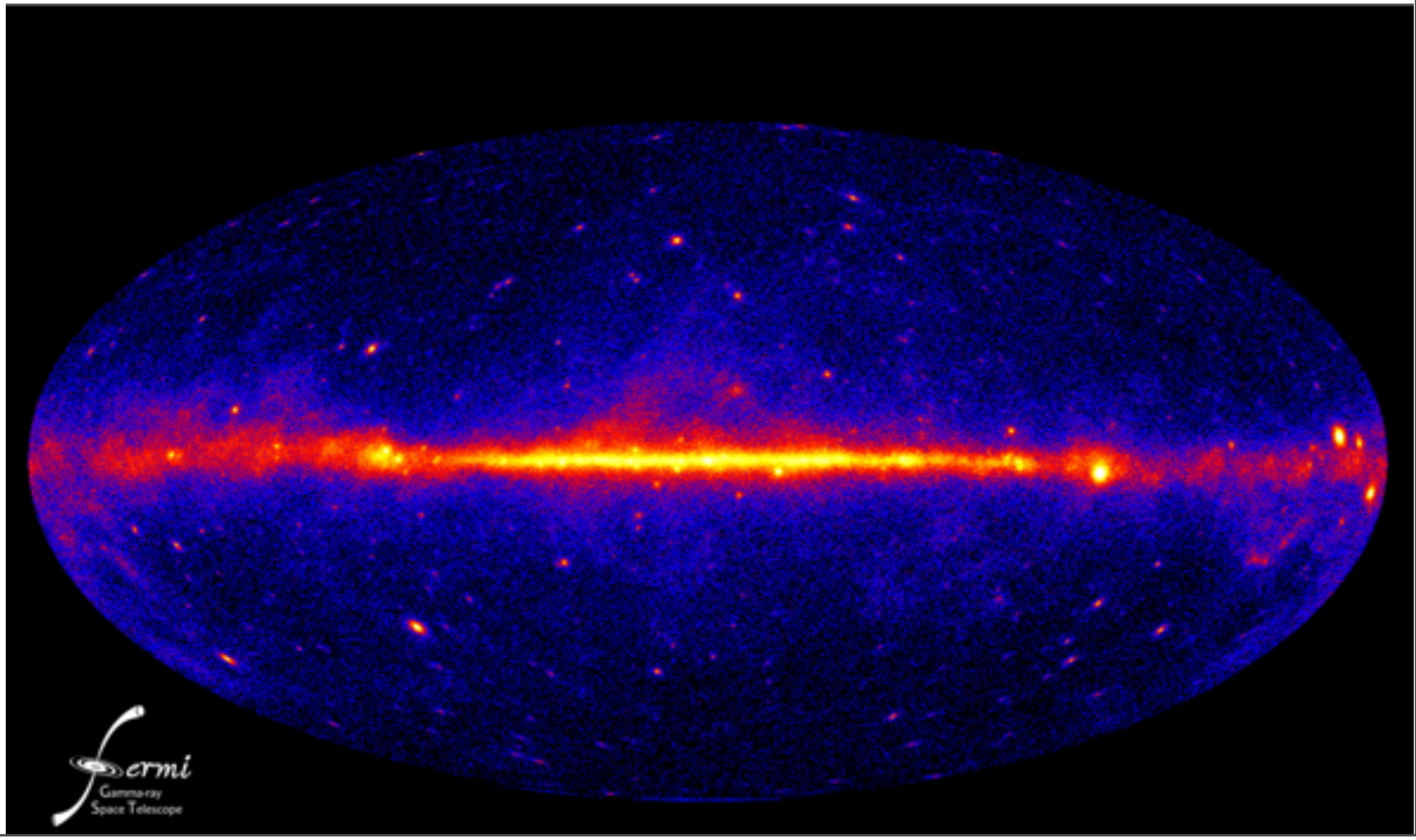
- Gamma-Rays are another possible source of error
  - Can’t be separated from electrons, because both showers are electromagnetic
- Extragalactic Gamma-Ray Background is not particularly important
  - Highly subdominant (factor of 250)
  - Highly isotropic (will be a statistical background, like protons)
- Diffuse Galactic Gamma-Rays are important
  - Moderately subdominant (factor of 60 if $|b| > 5^{o}$)
  - **.However, anisotropies can be order 1**

Comparison with the Fermi-LAT Diffuse Emission

- However, 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





Conclusions

- Pulsars remain the most reasonable mechanism for producing the primary positron injection spectrum observed by PAMELA, Fermi-LAT and AMS-02
- Models show that the e^+e^- observed at the solar position may be dominated by a few, nearby pulsar sources
- These pulsars may have an appreciable anisotropy - though far below the current limits set by the Fermi-LAT and AMS-02
- The large effective area of ACTs makes them optimal instruments for such a study
- Current ACT data would likely be able to detect anisotropies from Monogem, the CTA would be necessary to detect anisotropies from Geminga