NEARBY PULSARS AND THE COSMIC RAY POSITRON EXCESS

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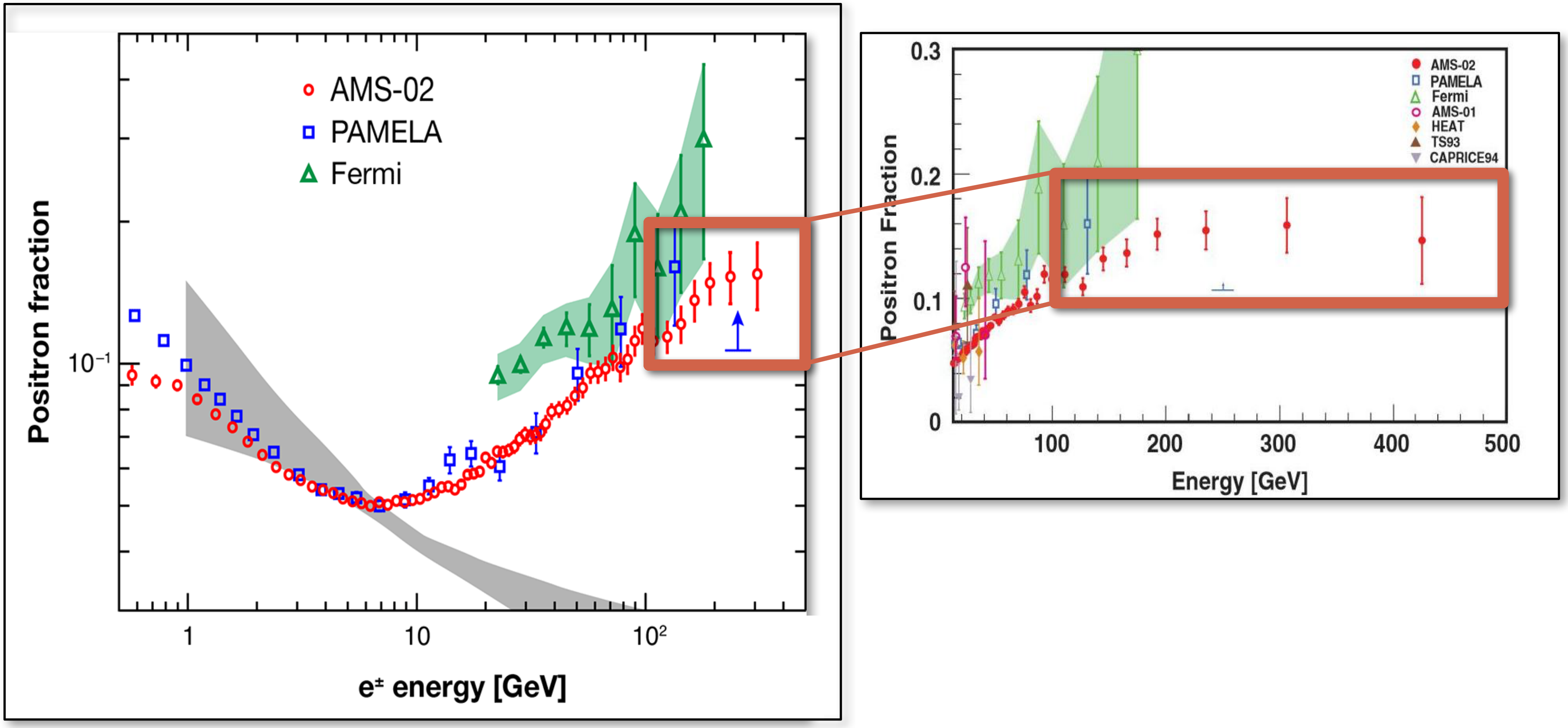
(Based on work with Ilias Cholis, Ke Feng and Tim Linden)

The Cosmic Ray Positron Excess

- In 2008, PAMELA reported a surprisingly large quantity of positrons in the cosmic ray spectrum, now confirmed with much greater precision by AMS

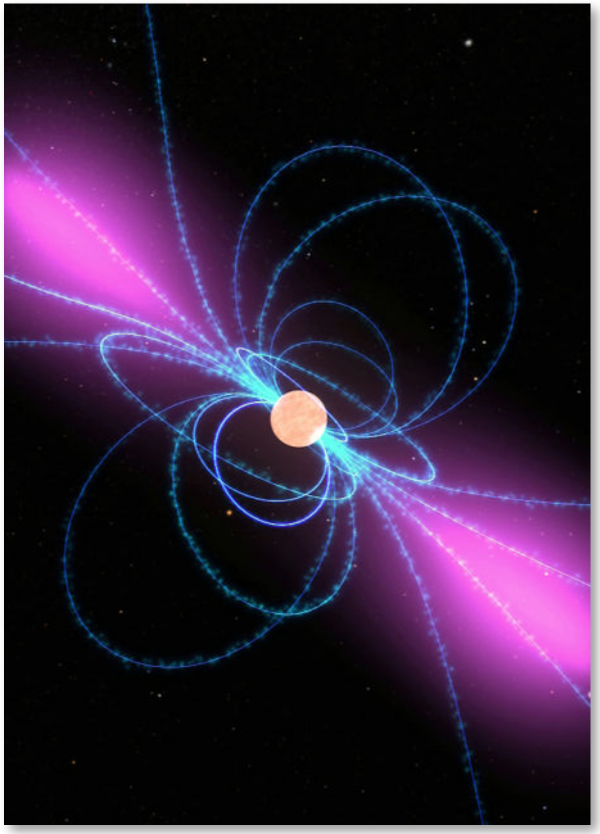


Where Do The Excess Positrons Come From?

- The main contribution to the positron flux was anticipated to be that generated by cosmic ray interactions with gas in the ISM, yielding positrons through charged pion decay (*ie*. "*secondary" positrons*); this cannot account for the observed positrons
- Instead, three basic ideas have been proposed to account for the excess positrons:

1) Annihilating or decaying dark matter particles
2) The acceleration of secondary positrons within cosmic-ray sources (*ie*. supernova remnants)
3) Nearby *primary* sources of high-energy positrons (*ie*. pulsars)

Cosmic Ray Positrons From Pulsars



- Shortly after the PAMELA excess was reported, it was suggested that the positrons might originate from pulsars
- Pulsars are rapidly spinning neutron stars, which gradually convert their rotational kinetic energy into radio, X-ray, and gamma-ray emission, and into e^+e^- pairs
- Newly formed pulsars typically exhibit periods on the order of ~0.01-0.1 second, although most observed pulsars have higher periods (between ~0.1 and a few seconds)
- The rate of a pulsar’s spin-down evolution (and power) depends on the strength of its magnetic field (which transfers rotational kinetic energy into radiation via magnetic dipole braking)

DH, Blasi, Serpico, PRD, arXiv:0810.1527;
Yuksel, Kistler, PRL, arXiv:0810.2784
(see also Zhang, Cheng, A&A, 2001; Grimani, A&A, 2007)

Pulsars Emission Models

- Considerable research activity has been directed toward understanding exactly how pulsars generate their observed emission
- There are a number of basic elements that are found across a wide range of proposed models:
  - -Electrons are accelerated by the strong magnetic fields, somewhere in the magnetosphere (the location is model dependent)
  - -These electrons then induce electromagnetic cascades through the emission of curvature radiation
  - -This results in the production of photons with energies above the threshold for pair production in the strong magnetic field
  - -These electrons and positrons then escape the magnetosphere through open field lines, or after reaching the pulsar wind

- There is no consensus on what fraction of a pulsar’s power is likely to go into the production of energetic e^+e^- pairs
- As high as ~20-30% of the energy budget? Or perhaps ~0.01%?

Which Pulsars Contribute to the Positron Flux?

Consider the standard cosmic-ray transport equation:

$$\frac{\partial}{\partial t}\frac{dn_e}{dE_e}(E_e,r,t) = \vec{\bigtriangledown}\cdot\left[D(E_e)\vec{\bigtriangledown}\frac{dn_e}{dE_e}(E_e,r,t)\right] + \frac{\partial}{\partial E_e}\left[\frac{dE_e}{dt}(r)\,\frac{dn_e}{dE_e}(E_e,r,t)\right] + \delta(r)Q(E_e,t)$$

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Diffusion: $D(E_e) \; = \; D_0 E_e^{\delta}$

Energy Losses:
(ICS, Synchrotron)

$$-\frac{dE_e}{dt}(r) = \sum_i \frac{4}{3}\sigma_T\rho_i(r)S_i(E_e)\left(\frac{E_e}{m_e}\right)^2 + \frac{4}{3}\sigma_T\rho_{\rm mag}(r)\left(\frac{E_e}{m_e}\right)^2$$
$$\equiv b(E_e,r)\left(\frac{E_e}{\rm GeV}\right)^2$$

Injection Spectrum: $Q(E_e,t) = \delta(t)Q_0E^{-\alpha}\exp(-E_e/E_c)$
(burst-like approximation)

Which Pulsars Contribute to the Positron Flux?

The solution to this equation is as follows:

$$\frac{dn_e}{dE_e}(E_e, r, t) = \frac{Q_0\, E_0^{2-\alpha}}{8\pi^{3/2} E_e^2\, L_{\rm dif}^3(E_e, t)} \exp\left[\frac{-E_0}{E_c}\right] \exp\left[\frac{-r^2}{4L_{\rm dif}^2(E_e, t)}\right]$$

where

$$L_{\rm dif}(E_e, t) \equiv \left[\frac{D_0}{b(E_e/{\rm GeV})^{1-\delta}(1-\delta)}\left(1-(1-E_e b t)^{1-\delta}\right)\right]^{1/2}$$

The sources that make the maximum contribution to the local positron flux are those located at a distance of $r \sim 2.4\, L_{\rm dif}$, which for ISM-like diffusion parameters yields:

$$r \sim 2.4\, L_{\rm dif} \sim 100\,{\rm pc} \left(\frac{t}{10^5\,{\rm yr}}\right)\left(\frac{E_e}{100\,{\rm GeV}}\right)^{0.7}$$

Conclusion: The pulsars which contribute most to the local positron flux are ~10^5 years old and are located at a distance of ~100 pc

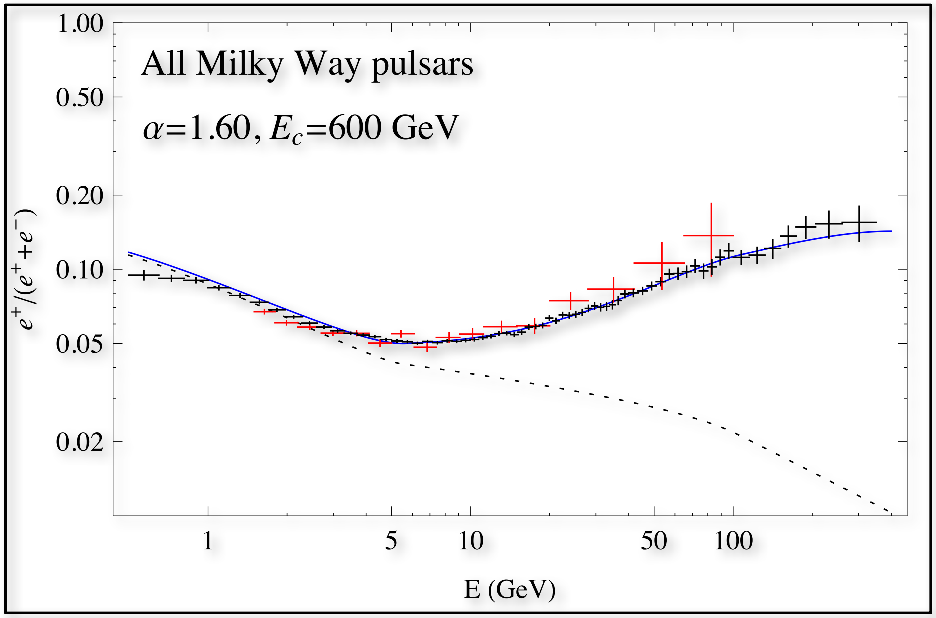
Cosmic Ray Positrons From Pulsars

- From these considerations, there are two known pulsars which stand out as the strongest potential sources of ~100 GeV cosmic-ray positrons:

  Geminga, age~370,000 yrs, distance~250 pc

  B0656+14 (*ie*. monogem), age~110,000 yrs, distance~280 pc

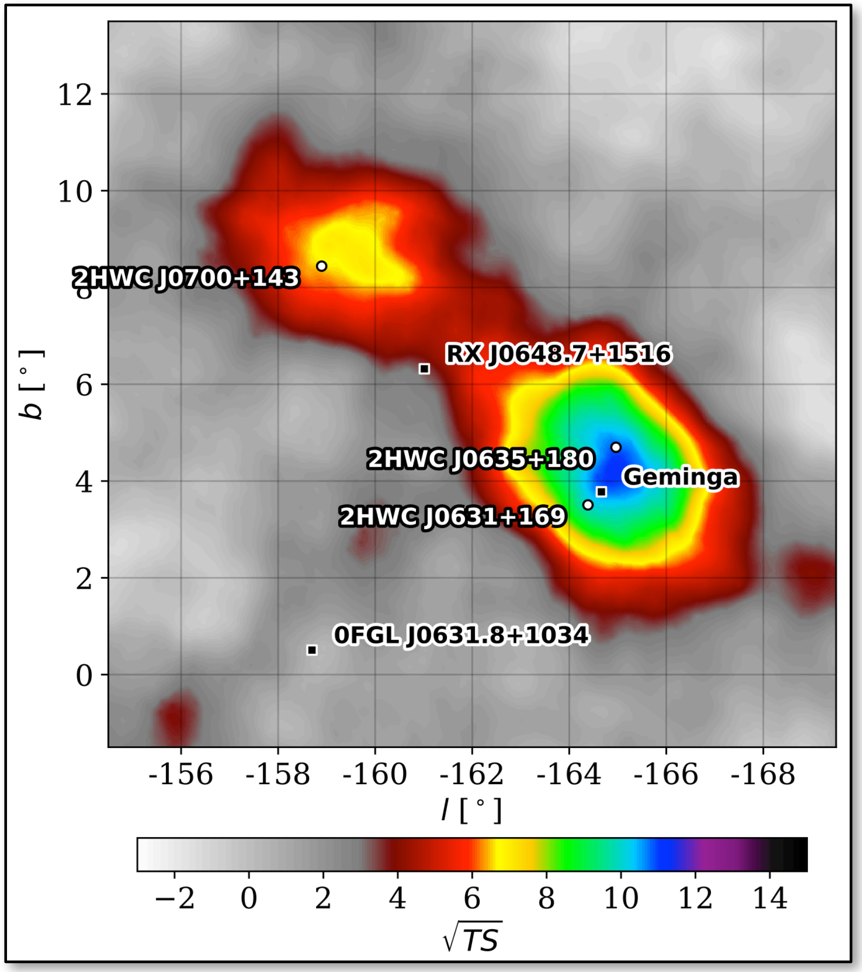
- If ~10-20% of the spin-down power of these pulsars is transferred into pairs, they could plausibly dominate the observed positron spectrum



DH, Blasi, Serpico, PRD, arXiv:0810.1527;
Yuksel, Kistler, PRL, arXiv:0810.2784;
Cholis, DH, PRD, arXiv:1304.1840

VHE Gamma-Ray Observations of Geminga

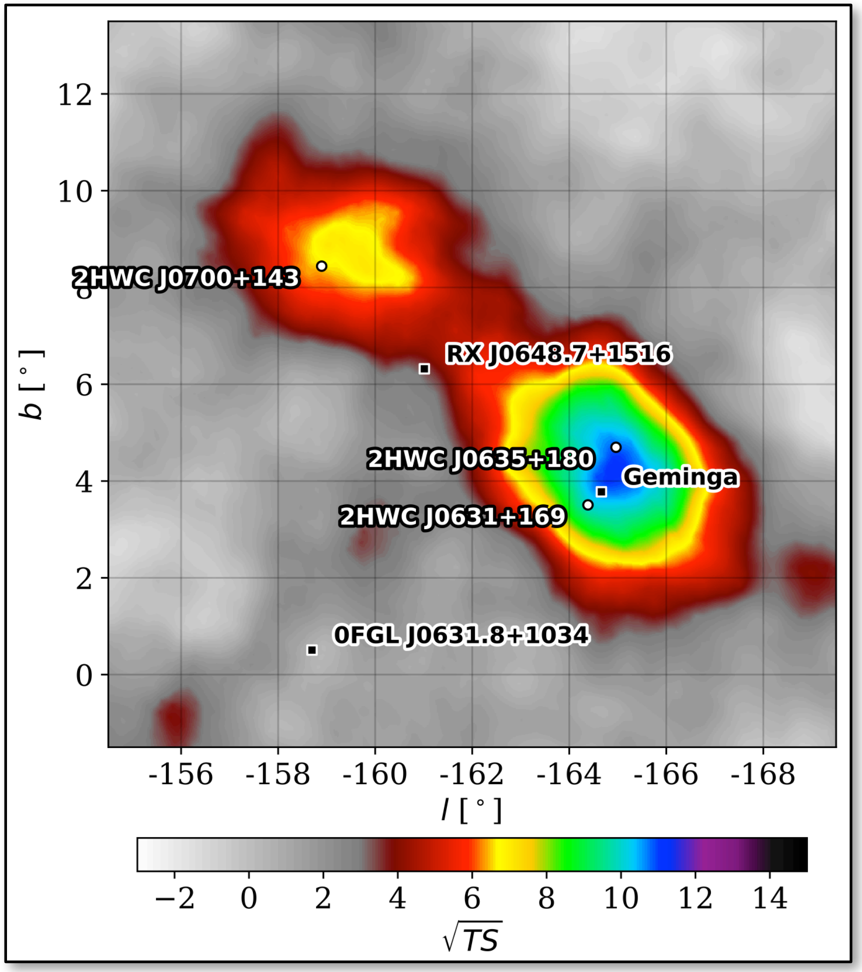
- Milagro detected VHE emission from Geminga and reported the “definitive detection of extended emission” from this source, with a full-width-half-max of $2.6^{+0.7}_{-0.9}$ degrees
- Very recently, the HAWC Collaboration confirmed Milagro’s detection of Geminga, and its spatial extension, finding a radius of ~2°
- Furthermore, HAWC also reports ~2° extended emission from the pulsar B0656+14 (2HWC J0700+143), not detected by Milagro (or by Fermi)



HAWC Collaboration, arXiv:1702.02992

What Produces These Gamma Rays?

- The spatial extension of this emission indicates that the observed gamma rays ***do not originate from the pulsar itself***, but from a surrounding region several parsecs in extent
- The only diffuse emission mechanisms that can produce such high-energy photons are inverse Compton scattering and pion production
- A pion production origin would require an implausibly large quantity of ~10^2 TeV protons (>10^{46} erg), which would have to somehow be confined to the region for >10^5 years
- In light of these considerations, inverse Compton scattering is almost certainly responsible for this emission



HAWC Collaboration, arXiv:1702.02992

HAWC Measurements Are Essential To Solving The Mystery Of The Positron Excess

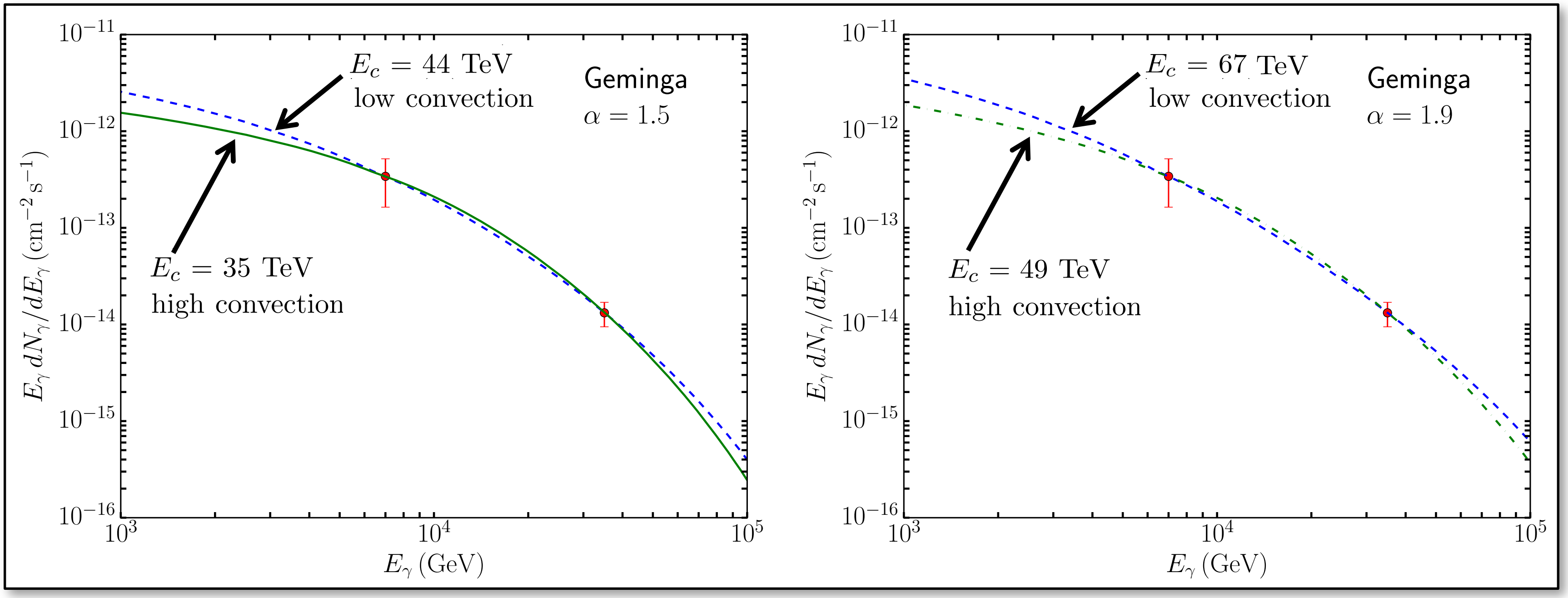
- When a very high energy electron is injected into this environment, it emits the majority of its energy as Inverse Compton emission (along with a similar, but likely smaller quantity as synchrotron)
- The results of HAWC (and Milagro) thus provide us with a direct measurement of the energy that Geminga and B0656+14 are currently injecting into very high-energy e^+e^- pairs (as well as information pertaining to the spectral shape of these pairs)

Main Idea: ***The spatial extension of Geminga and B0656+14 allow us to measure the critically important (and until now highly uncertain) fraction of these pulsars' spindown power that goes into the production of energetic e^+e^- pairs***

DH, I. Cholis, T. Linden, K. Feng, arXiv:1702.08436

Implications of HAWC and Milagro for the Positron Excess

- For a given spectrum of injected pairs, we calculate the resulting ICS spectrum (including all Klein-Nishina corrections), and use this to constrain the normalization, spectral index (α), and energy cutoff (E_c) of the injected spectrum of e^+e^- pairs
- The VHE gamma-ray fluxes are best fit by α~1.5-2.0 and E_c~35-70 TeV
- In these best-fit models, between 7-29% of Geminga's current spindown power goes into e^+e^- pairs – ***similar to that required to generate the positron excess!***



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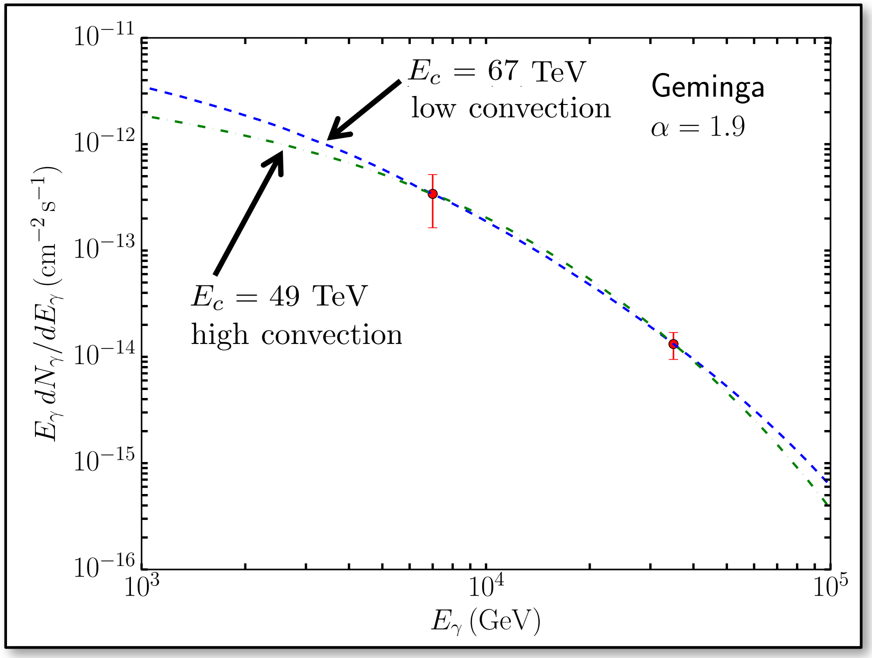
The Role Of Convection

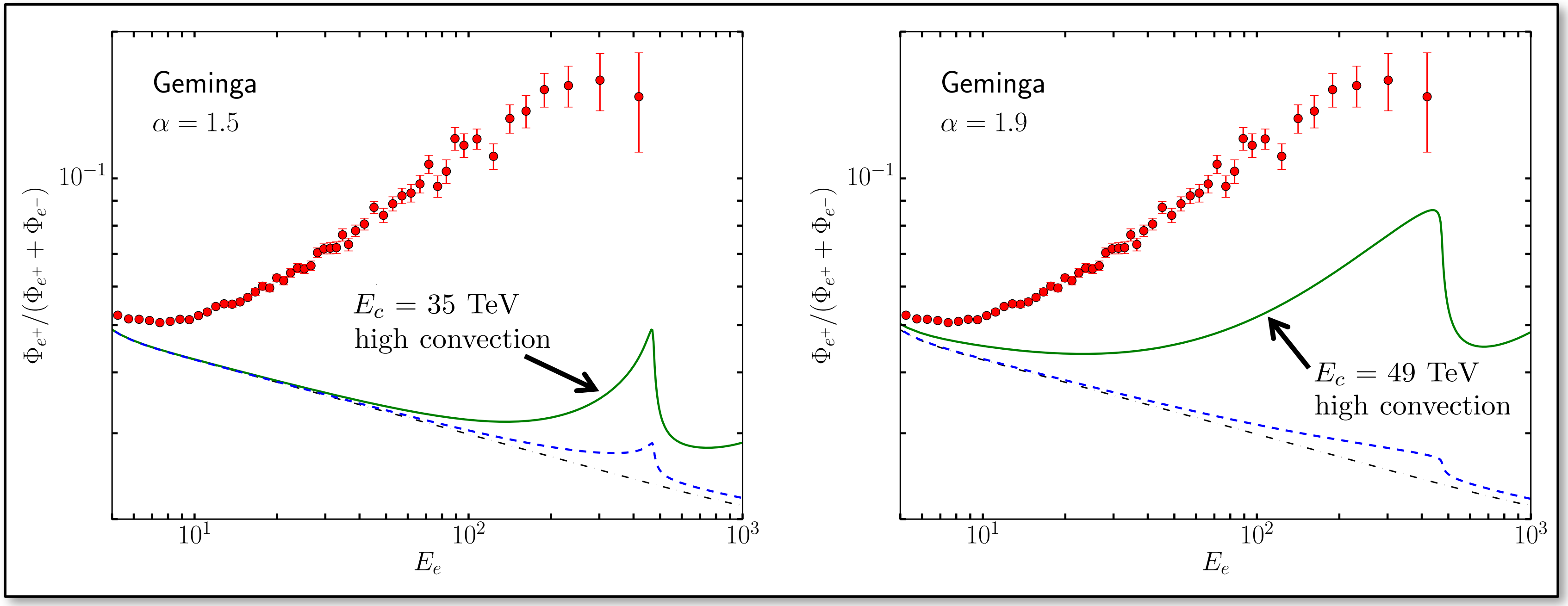
- The angular extension of the emission observed by HAWC indicates that diffusion is inefficient for VHE electrons/positrons in the parsecs surrounding these pulsars
- Lower energy leptons cool more slowly, and are likely to escape this region, perhaps via convection or through energy-independent diffusion
- We remain agnostic about how exactly this occurs, and simply parameterize the combination of these effects by a convection velocity
- This quantity impacts the shape of the gamma-ray spectrum, and when we take into account the spectral slope reported by HAWC (-2.23±0.08), we find that a sizable convection velocity is required, *v_c~100-500 km/s*
- In these plots, "*high convection*" refers to v_c~230 km/s × (r_{region}/5 pc) – *focus your attention on these curves*



DH, I. Cholis, T. Linden, K. Feng, arXiv:1702.08436

Implications of HAWC and Milagro for the Positron Excess

- We can now use this information to calculate the contribution from Geminga to the local positron flux
- Across the range of models that provide a good fit to the HAWC and Milagro data, Geminga contributes non-negligibly to the observed excess



DH, I. Cholis, T. Linden, K. Feng, arXiv:1702.08436

Main Uncertainties

ICS vs Synchrotron

- The fraction of energy in e^+e^- pairs goes into synchrotron rather than ICS is an uncertainty in our calculations (we adopted what we think are reasonable parameters: $B=3\ \mu G$, $\rho_{star}=0.60$ eV/cm^3, $\rho_{IR}=0.60$ eV/cm^3, and $\rho_{UV}=0.10$ eV/cm^3)
- Over a reasonable range of these parameters, we could plausibly change the net result by up to a factor of roughly ~2 (either way)

The Time Profile of Geminga's Emission

- HAWC and Milagro measure the energy in ICS today, and thus are sensitive to the pairs that were injected over the past ~10^4 years
- In contrast, the positrons reaching the Solar System today were injected much longer ago, when the pulsar was young (~10^5 years ago)
- In our calculation, we adopt the standard magnetic dipole braking model with a spindown timescale of 10^4 years
- By varying our choice of this parameter, we could plausibly change the net result by an order one factor

DH, I. Cholis, T. Linden, K. Feng, arXiv:1702.08436

Positrons From Geminga, B0656+14, and Other, More Distant Pulsars

- We have the most information about Geminga, and there is still an order one uncertainty as to its contribution to the local positron flux
- Larger uncertainties apply to B0656+14 and other pulsars
- That being said, can make a reasonable estimate for the total contribution

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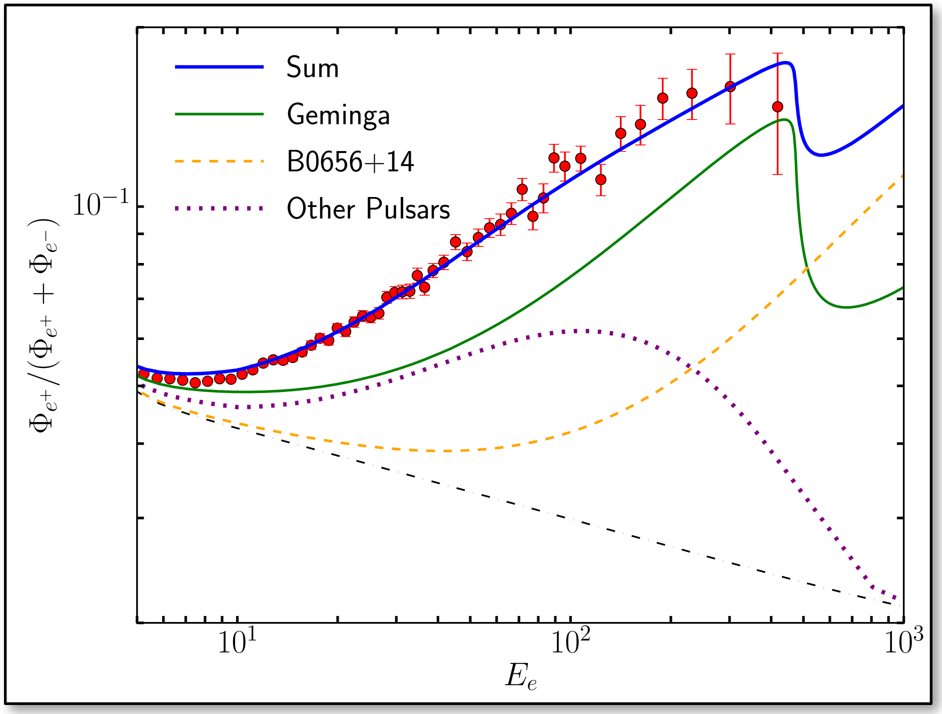
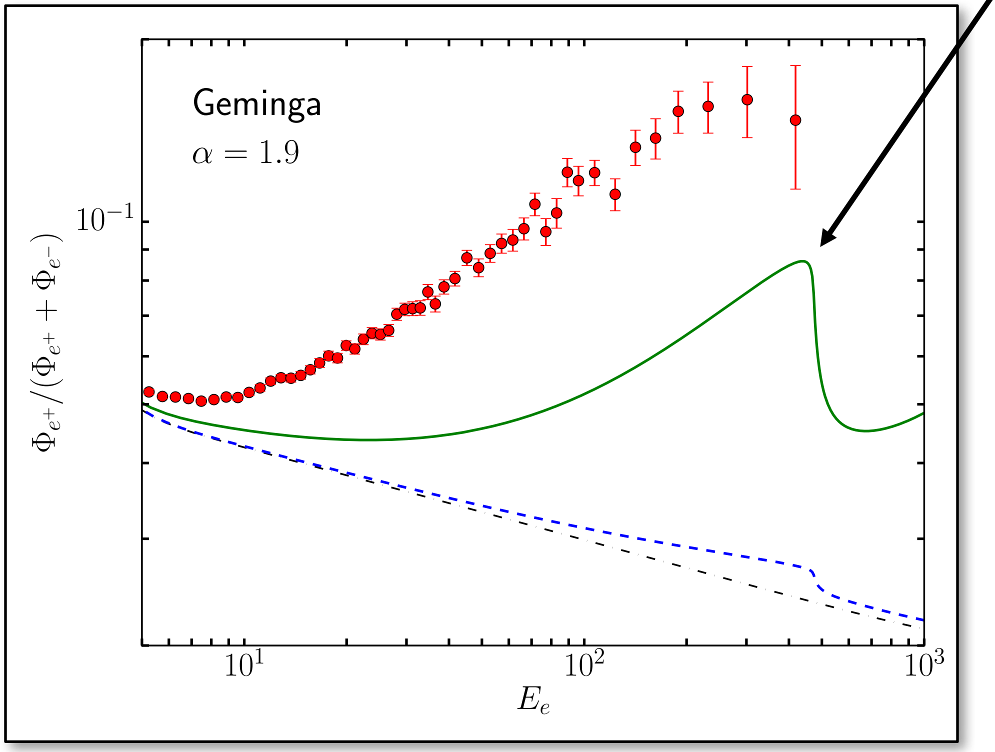
- In this figure, we have assumed that all pulsars inject e^+e^- pairs with the same efficiency and spectrum as Geminga, and adopted $\tau \sim 4.3 \times 10^3$ years and a birth rate of 2 new pulsars per century throughout the Milky Way (adopting the Lorimer *et al.* spatial distribution)
- These assumptions might not be precisely correct, but this shows that ***pulsars very plausibly generate the entire excess, and very likely provide the dominant contribution***



DH, I. Cholis, T. Linden, K. Feng, arXiv:1702.08436

A Note On Positron Spectral Features

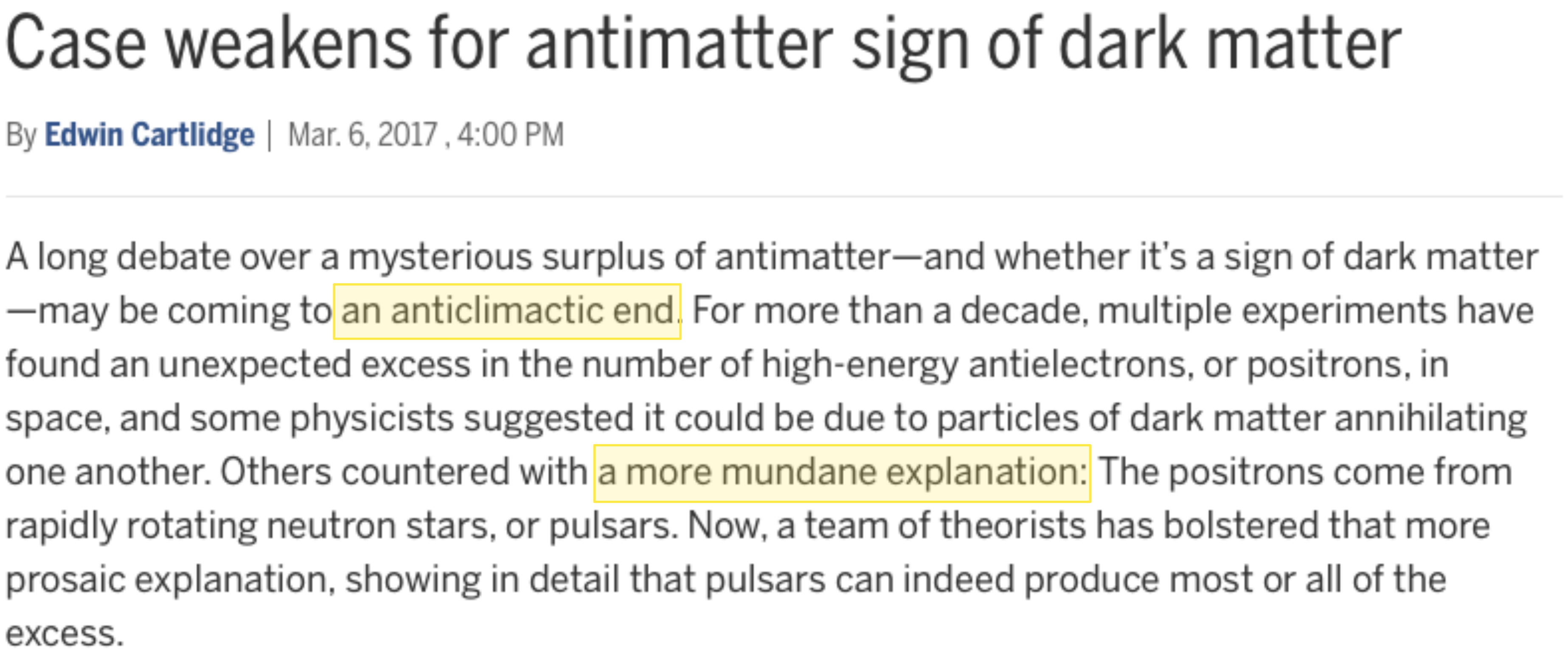
- A great deal is often made about “edges” and other spectral features that might appear in the positron spectrum; such features are sometimes called a “smoking gun” for dark matter annihilation or decay
- In fact, a nearby pulsar could very plausibly generate an edge-like feature, at an energy of $E \sim 1/bt_{age}$ (which for Geminga is at ~350-700 GeV)



Summary

- Recent observations of Geminga and B0656+14 by HAWC provide a determination of the flux of very high-energy e^+e^- pairs that is currently being injected by these pulsars; equivalent to ~7-29% of the total current spindown power
- The is a critical quantity, and was previously almost entirely unknown
- This new information indicates that pulsars generate an order one fraction of the positron excess, and are very likely to be responsible for the majority (or entirety) of this signal
- There is still room in the uncertainties for other contributions to the positron flux (*i.e.* dark matter or secondary acceleration), but it is now reasonably clear that pulsars are the main source of the observed positron excess

Personally, I think this is a very exciting result … regardless of what Science Magazine has to say about it;)



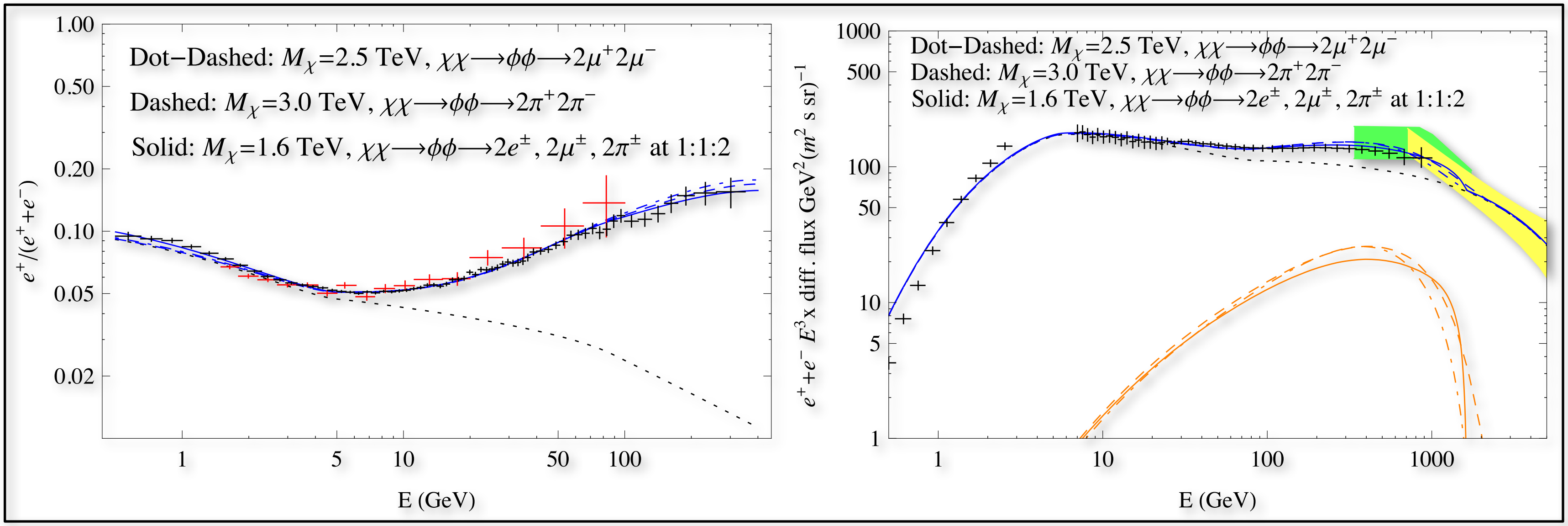
Case weakens for antimatter sign of dark matter

By **Edwin Cartlidge** | Mar. 6, 2017 , 4:00 PM

A long debate over a mysterious surplus of antimatter—and whether it's a sign of dark matter—may be coming to an anticlimactic end. For more than a decade, multiple experiments have found an unexpected excess in the number of high-energy antielectrons, or positrons, in space, and some physicists suggested it could be due to particles of dark matter annihilating one another. Others countered with a more mundane explanation: The positrons come from rapidly rotating neutron stars, or pulsars. Now, a team of theorists has bolstered that more prosaic explanation, showing in detail that pulsars can indeed produce most or all of the excess.

Annihilating Dark Matter and the Positron Excess

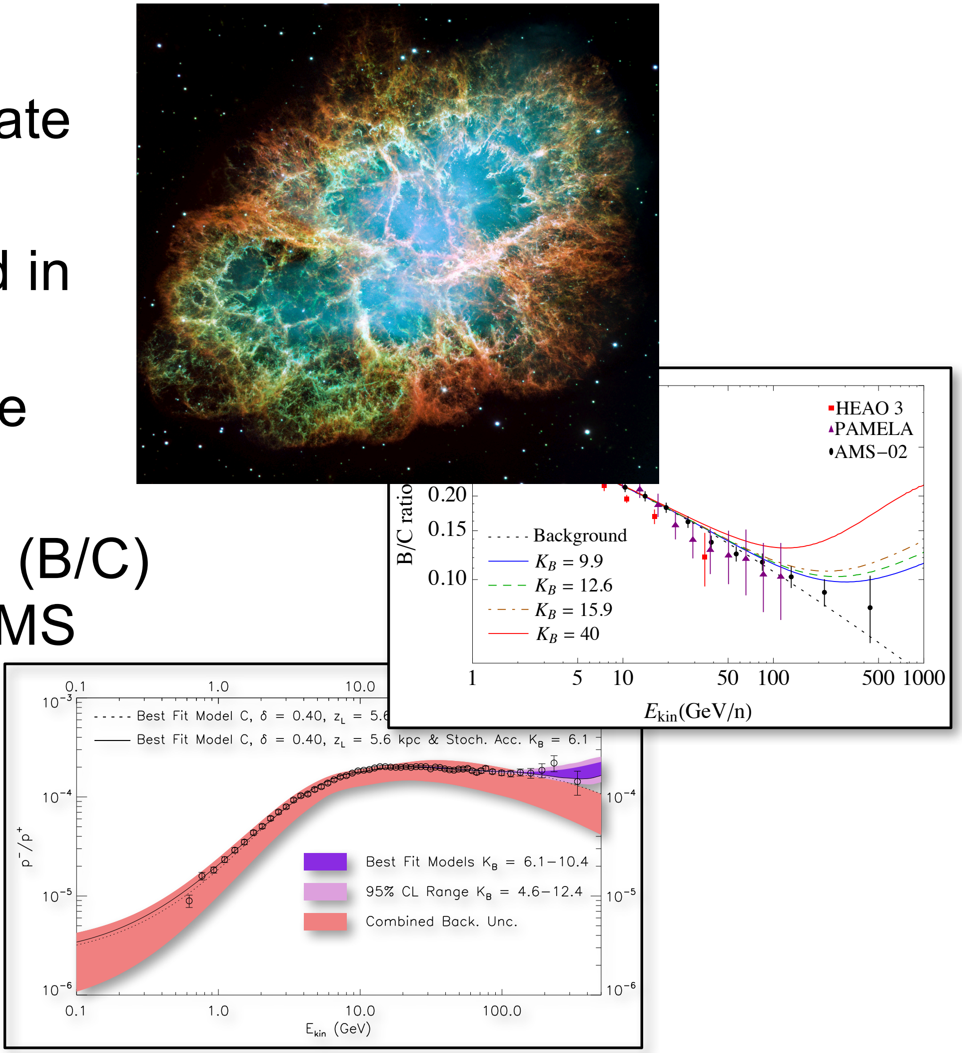
- In light of the detailed measurements of the positron fraction from AMS (and of the electron+positron spectrum from Fermi and HESS), few dark matter models can accommodate the data
- Dark matter models that *can* accommodate the data generally consist of a ~1-3 TeV particle that annihilates to unstable intermediate states, which then decay to electrons, muons and/or charged pions
- Large annihilation cross sections are also required (~10^{-24} to $3\text{x}10^{-23}$ cm^3/s), making constraints from Fermi difficult to evade



Cholis, DH, PRD, arXiv:1304.1840

The Acceleration of Secondary Positrons in Supernova Remnants

- Supernova remnants could generate secondary positrons and then accelerate them before they escape into the ISM
- If secondary positrons are accelerated in supernova remnants, then secondary antiprotons and boron nuclei should be accelerated as well
- Measurements of the boron-to-carbon (B/C) and antiproton-to-proton ratios from AMS indicate that secondary acceleration cannot account for the entirety of the positron excess, but may contribute non-negligibly



P. Blasi, PRL, arXiv:0903.2794; Mertsch, Sarkar, PRL, arXiv:0905.3152; Cholis, DH, PRD, arXiv:1312.2952; Cholis, DH, Linden, arXiv:1701.04406