NEARBY PULSARS AND THE COSMIC RAY POSITRON EXCESS

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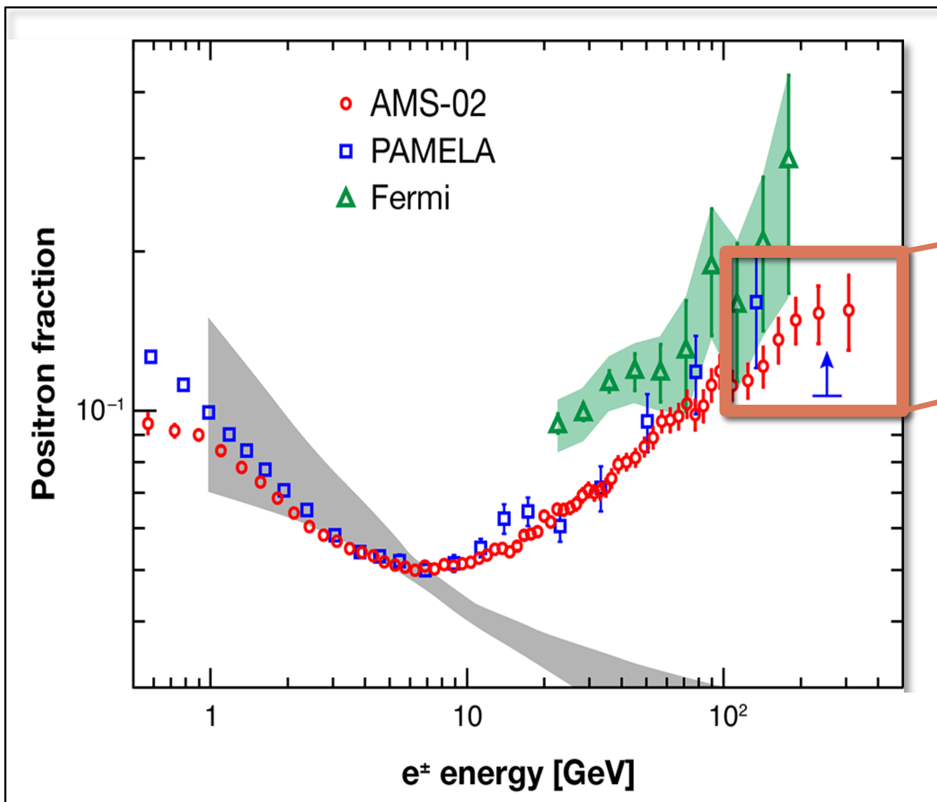
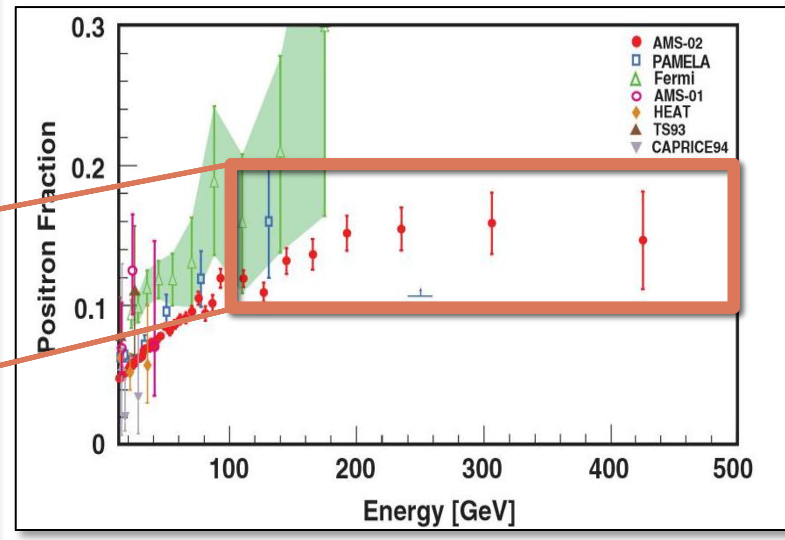
The Cosmic Ray Positron Excess

- In 2008, PAMELA reported a surprisingly large quantity of positrons in the cosmic ray spectrum, now confirmed with much greater precision by AMS
- This result generated an explosive response from the particle dark matter community (~1800 citations, the majority of which focus on the implications for dark matter)





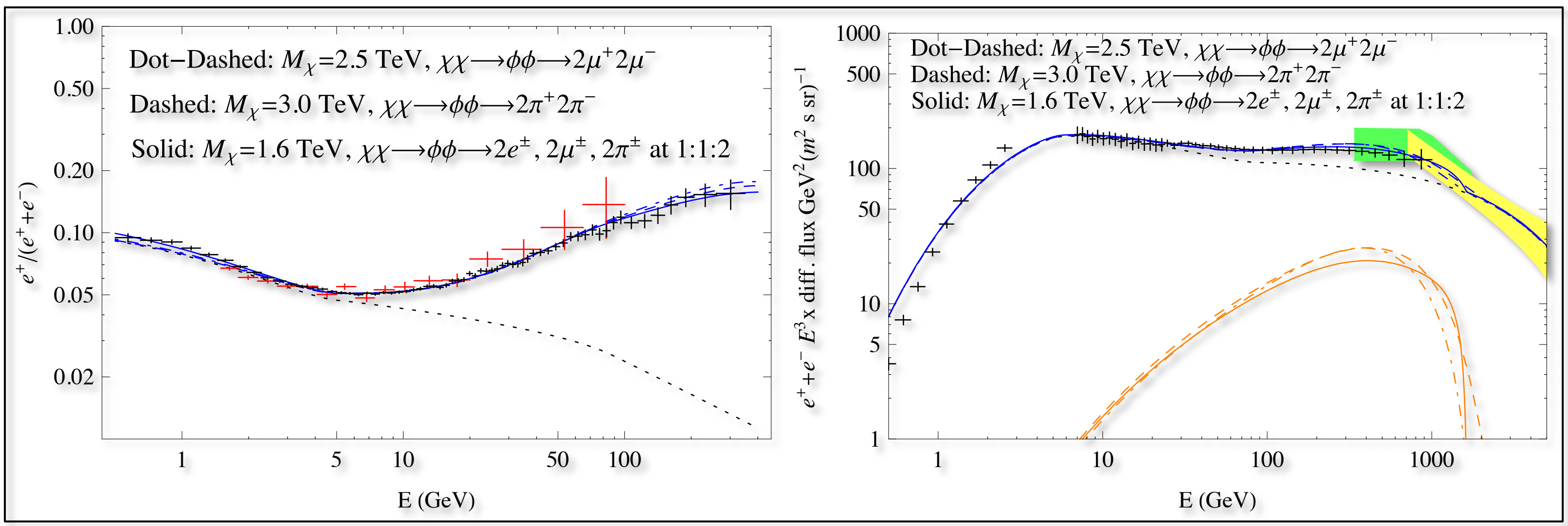
Where Do The Positrons Come From?

- The anticipated background to the positron flux is 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)

Annihilating Dark Matter and the Positron Excess

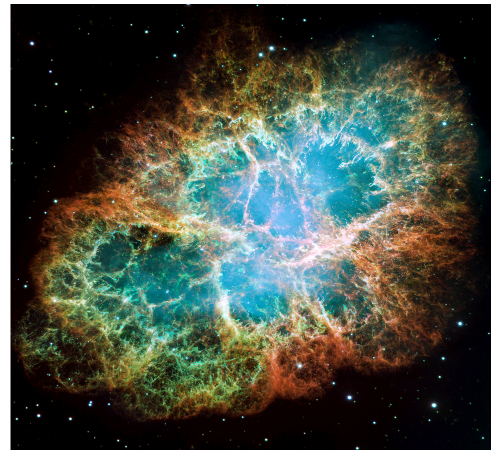
- In light of the detailed measurements of the positron fraction from AMS (and of the electron+positron spectrum from Fermi and HESS), few dark matter models can accommodate the data
- Dark matter models that *can* accommodate the data generally consist of a ~1-3 TeV particle that annihilates to unstable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

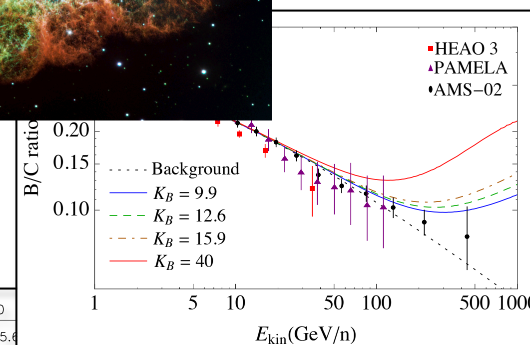


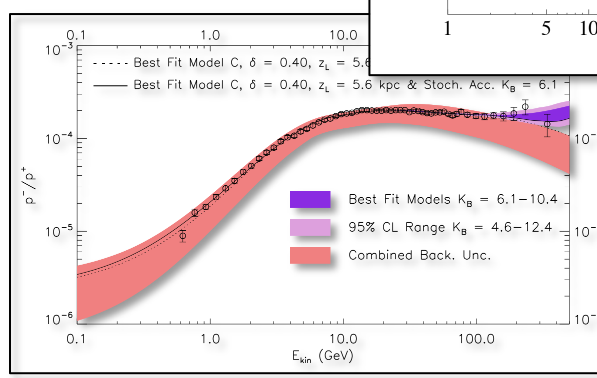
Cholis, DH, PRD, arXiv:1304.1840

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



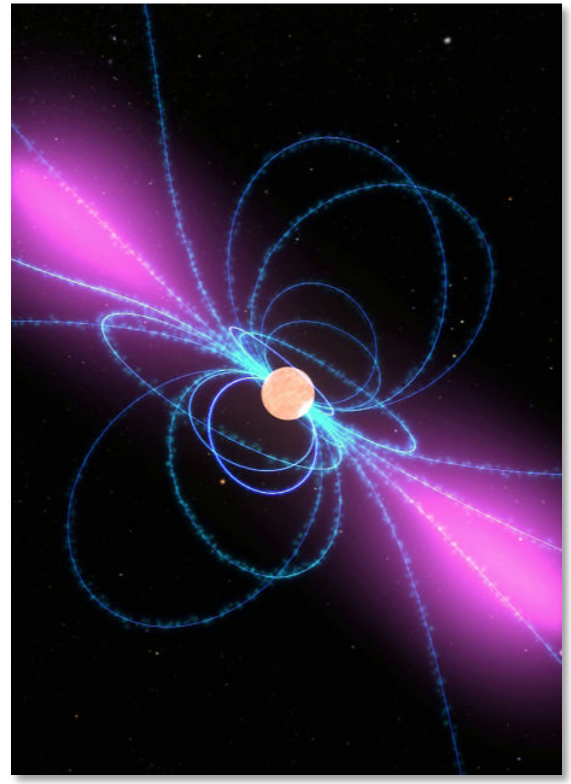




P. Blasi, PRL, arXiv:0903.2794; Mertsch, Sarkar, PRL, arXiv:0905.3152; Cholis, DH, PRD, arXiv:1312.2952; Cholis, DH, Linden, arXiv:1701.04406

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 it 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 focused on 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: (burst-like approximation)

$$Q(E_e,t) = \delta(t)Q_0 E^{-\alpha}\exp(-E_e/E_c)$$

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

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

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

Taking the derivative of this solution with respect to r and setting it to zero, we find that a given pulsar will contribute the most to the local positron flux if it is located at a distance of $r{\sim}2.4\, L_{\rm dif}$

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

Which Pulsars Contribute to the Positron Flux?

For parameters appropriate for the ISM: $(D_0 \simeq 2 \times 10^{28}\ \mathrm{cm^2/s},\ \delta \simeq 0.4,\ b = 1.8 \times 10^{-16}\ \mathrm{GeV/s})$.

$$L_{\rm dif}(E_e, t) \simeq 200\,\mathrm{pc}\left(\frac{35\,\mathrm{TeV}}{E_e}\right)^{0.3}\left(1-(1-E_e b t)^{0.6}\right)^{1/2}$$

$$\sim 40\,\mathrm{pc}\left(\frac{t}{10^5\,\mathrm{yr}}\right)\left(\frac{E_e}{100\,\mathrm{GeV}}\right)^{0.7}$$

Thus the pulsars that contribute to the most to the local positron flux (those for which $r \sim 2.4\, L_{\rm dif}$) are those that are roughly ~10^5 years old *and* that located at a distance of roughly ~100 pc

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

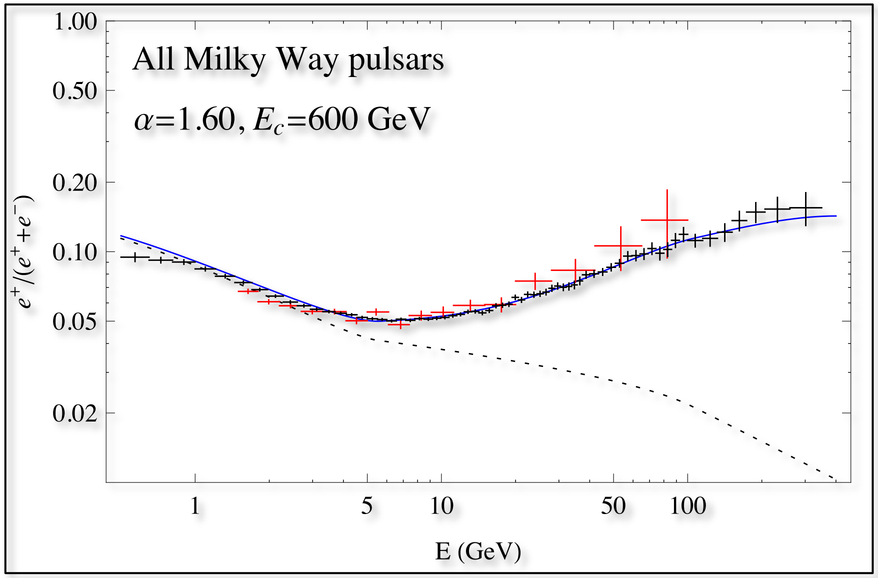
Cosmic Ray Positrons From Pulsars

- 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



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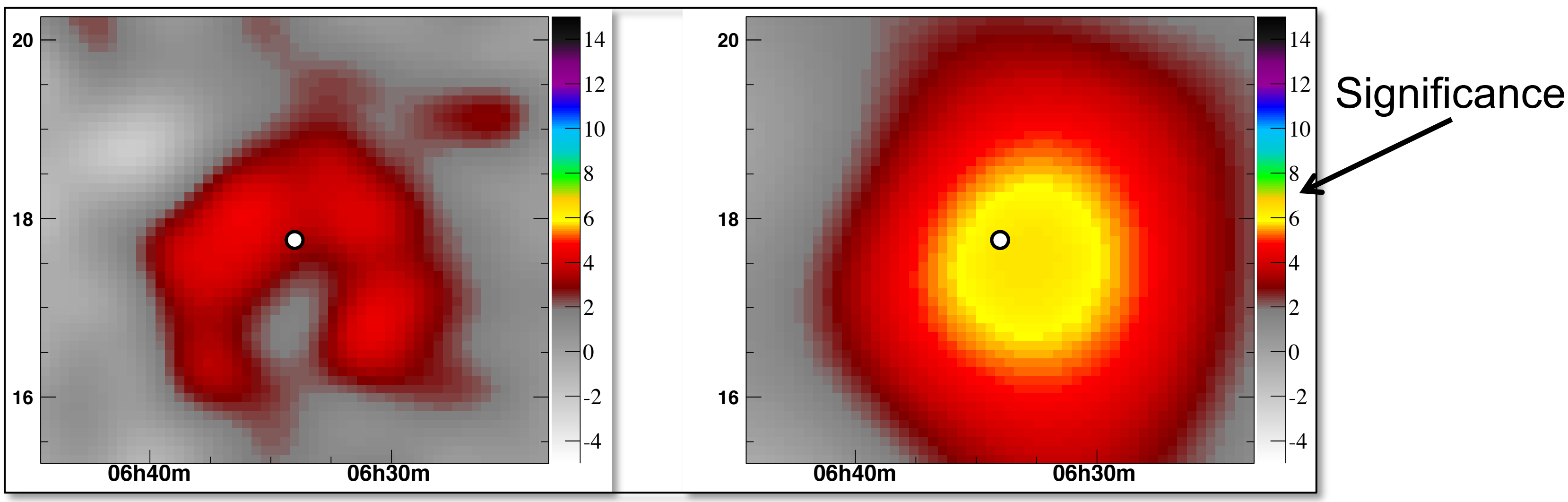
VHE Gamma-Ray Observations of Geminga

- Milagro has reported the detection of Geminga at an energy of ~35 TeV
- They also report the "definitive detection of extended emission" from Geminga, with a full-width-half-max of $2.6^{+0.7}_{-0.9}$ degrees



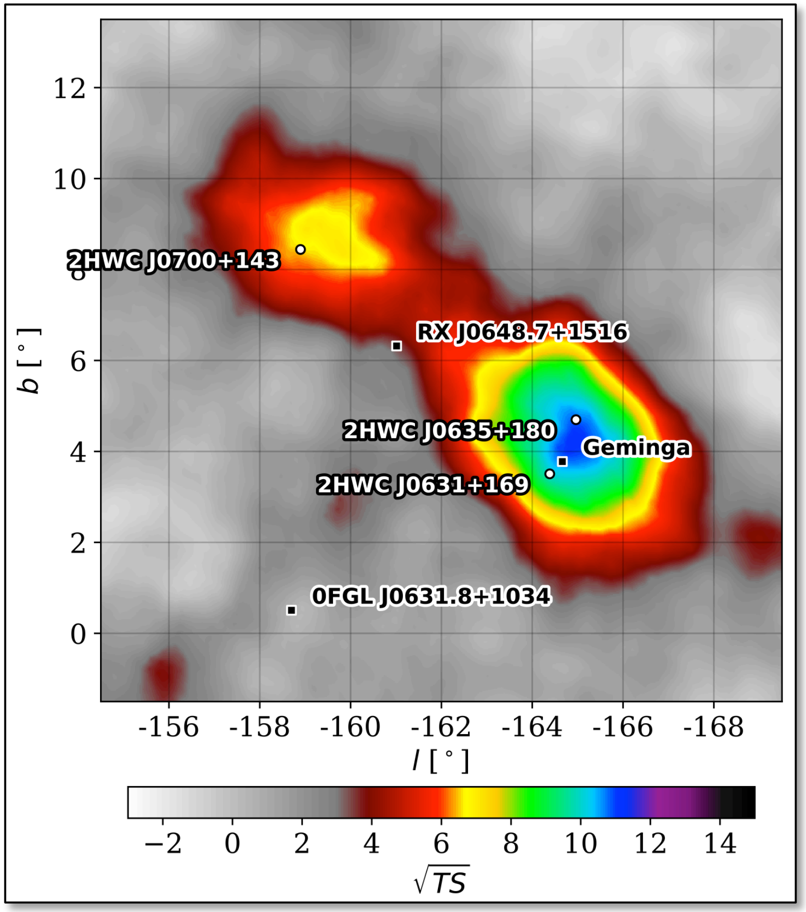
Modeled as a Point Source

Modeled as a 1° Gaussian

Milagro Collaboration, ApJ, arXiv:0904.1018

VHE Gamma-Ray Observations of Geminga

- Very recently, the HAWC Collaboration confirmed Milagro's detection of Geminga, and its spatial extension, in this case at ~7 TeV
- HAWC reports an extension of radius ~2°, similar to that reported by Milagro
- Furthermore, HAWC also detects ~2° extended emission from the pulsar B0656+14 (2HWC J0700+143), not detected by Milagro (or by Fermi)

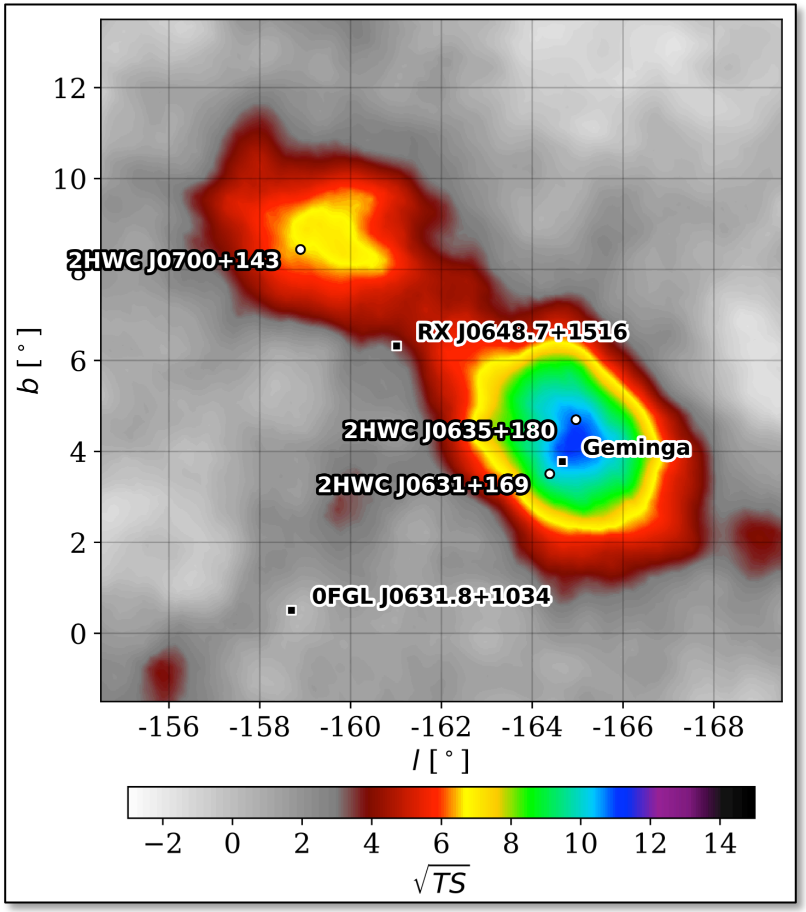


(Modeled as a 2° Radius Disk)

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 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
- Inverse Compton scattering is almost certainly responsible for this emission



(Modeled as a 2° Radius Disk)

HAWC Collaboration, arXiv:1702.02992

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

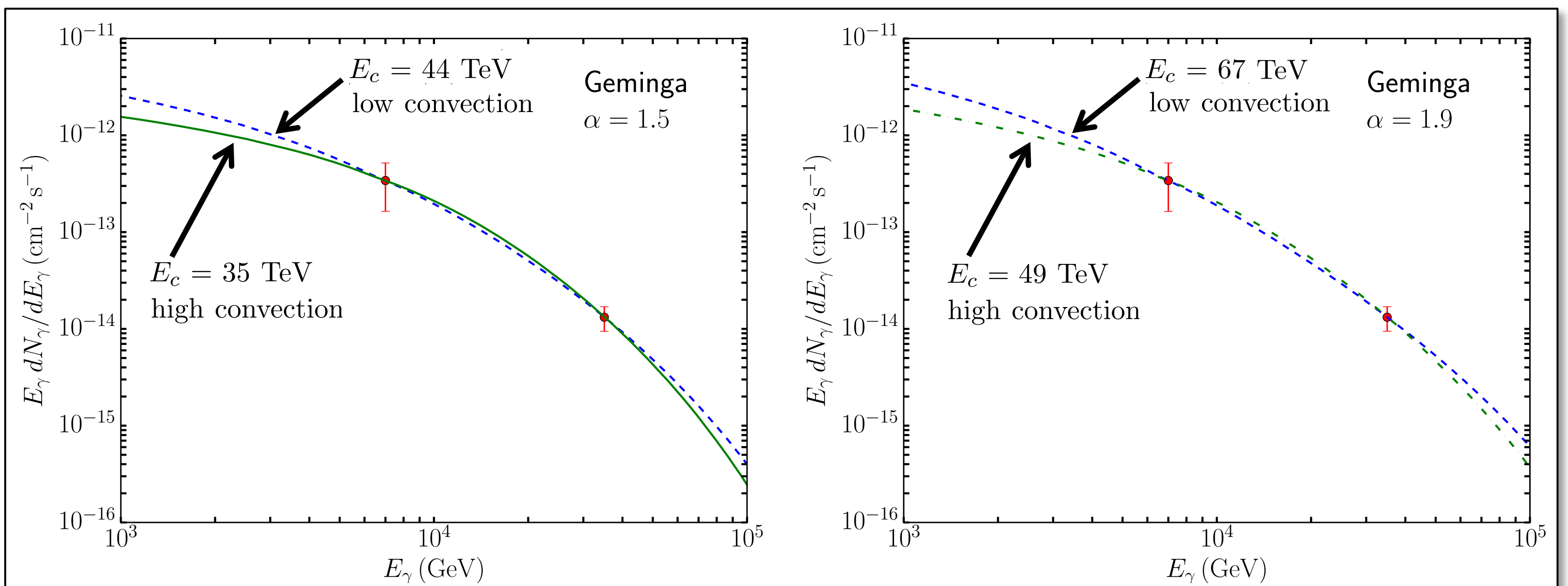
- When a very high energy electron is injected into this environment, it emits the majority of its energy as Inverse Compton emission (along with a similar quantity as synchrotron)
- The results of HAWC and Milagro thus provide us with a direct measurement of the energy that Geminga and B0656+14 are 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)
- 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 for the positron excess!*



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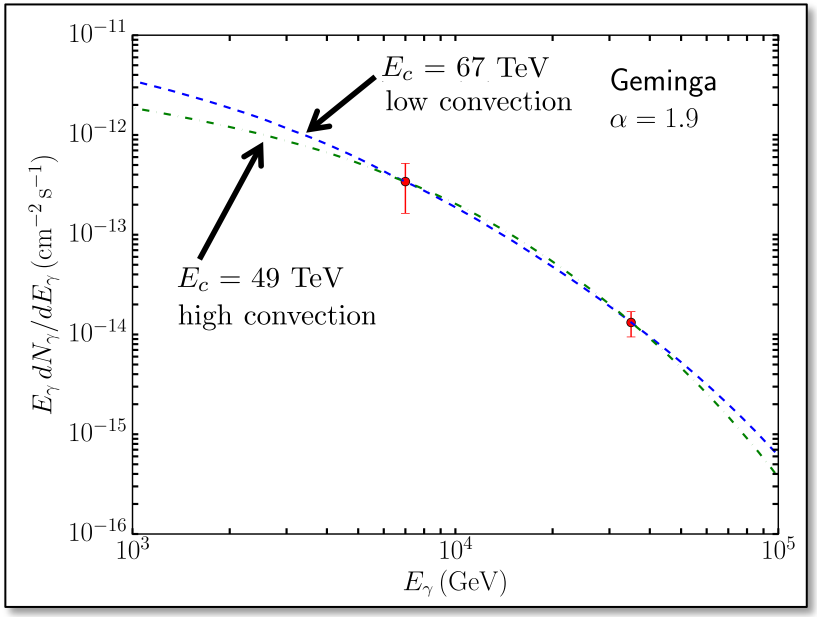
The Role Of Convection

- For the low degree of diffusion that is required to explain the observed extension, it is a combination of convection and energy-independent diffusion ($\delta \sim 0$) that enables lower energy electrons to escape the region surrounding Geminga – we parameterize the combination of these effects by a convection velocity
- The convection velocity impacts the shape of the gamma-ray spectrum, and when we take into account the slope reported by HAWC (-2.23±0.08), we find that a sizable convection velocity is required $v_c \sim 100\text{-}500$ km/s
- In these plots, "*high convection*" refers to $v_c \sim 230$ km/s $\times$ (r_{region}/5 pc) – *focus on these curves*



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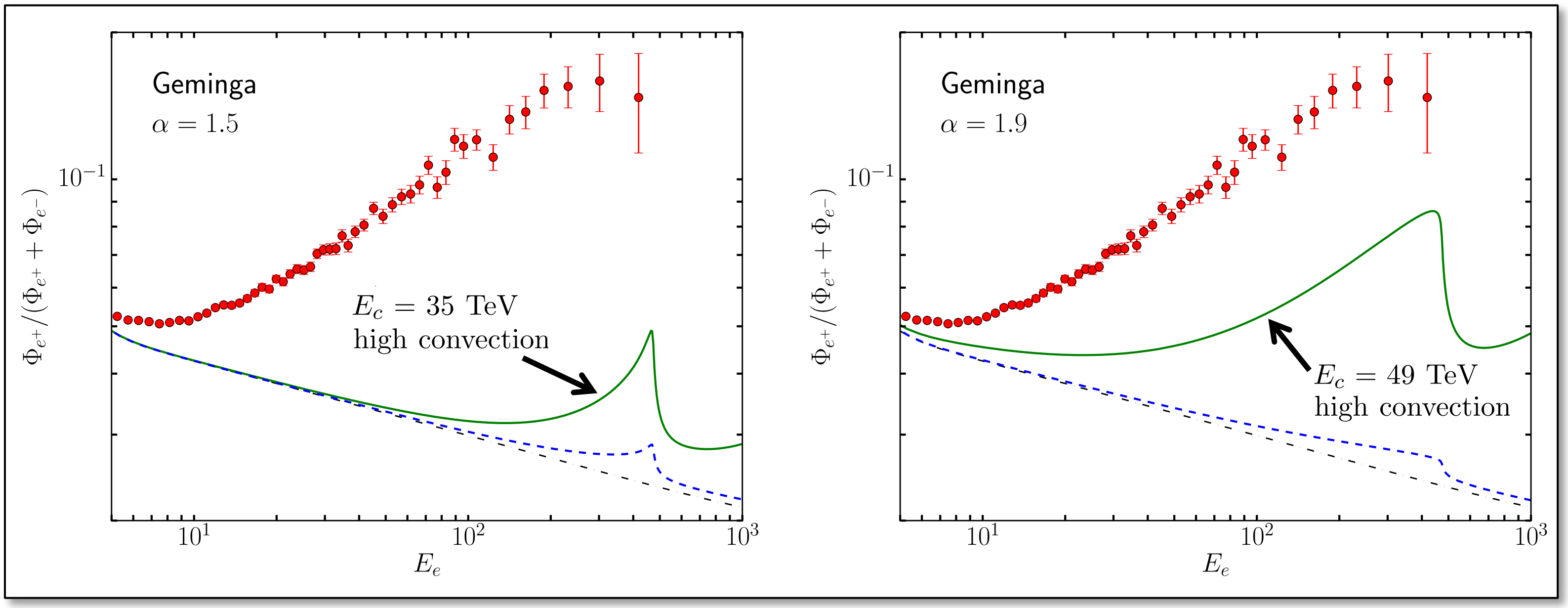
Implications of HAWC and Milagro for the Positron Excess

- 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

Some Caveats

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

Some Caveats

ICS vs synchrotron

- Some of the energy injected as e^+e^- pairs goes into synchrotron rather than ICS
- In our calculation, we adopted what we think are reasonable parameters (B=3 μG, ρ_{star}=0.60 eV/cm³, ρ_{IR}=0.60 eV/cm³, and ρ_{UV}=0.10 eV/cm³)
- If we had adopted a larger value of B, or smaller values of ρ_{star}, ρ_{IR} or ρ_{UV}, the contribution to the positron excess would increase (and vice versa)
- Over a reasonable range of these parameters, we could plausibly change the net result by up to a factor of roughly ~2 (either way)

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

Some Caveats

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 in the past ~10^4 years
- In contrast, the positrons reaching the Solar System today were injected much longer ago, when the pulsar was young (~$3\text{x}10^5$ years ago)
- Geminga's rotation was faster and its spindown power higher when young:

$$\dot{E} = -\frac{8\pi^4 B^2 R^6}{3c^3 P(t)^4}$$

- In our calculation, we adopt the standard magnetic dipole braking model with τ~10^4 years:

$$P(t) = P_0 \left(1 + \frac{t}{\tau}\right)^{1/2} \qquad \tau = \frac{3c^3 I P_0^2}{4\pi^2 B^2 R^6} \approx 9.1 \times 10^3 \,\text{years} \left(\frac{P_0}{0.040\,\text{sec}}\right)^2$$

- By varying our choice of τ, 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 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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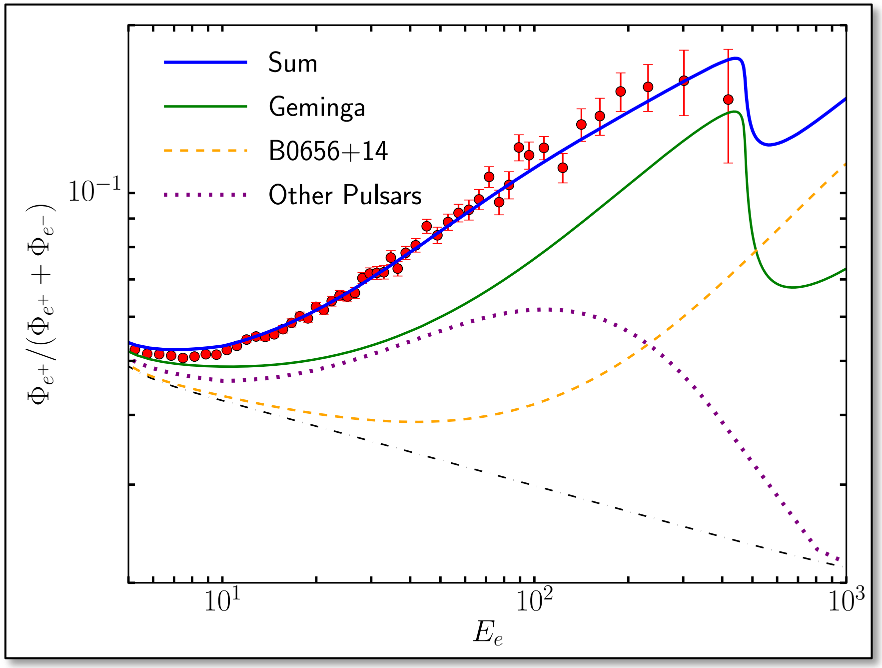
- That being said, can make a reasonable estimate for the total contribution
- In this figure, we have assumed that all pulsars inject e^+e^- pairs with the same efficiency and spectrum as Geminga, and adopted $\tau \sim 4.3\times10^3$ years and a birth rate of 2 new pulsars per century throughout the Milky Way (adopting the Lorimer *et al.* spatial distribution)
- These assumptions might not be precisely correct, but this shows that pulsars could very plausibly generate the entire excess, and likely provide the dominant contribution



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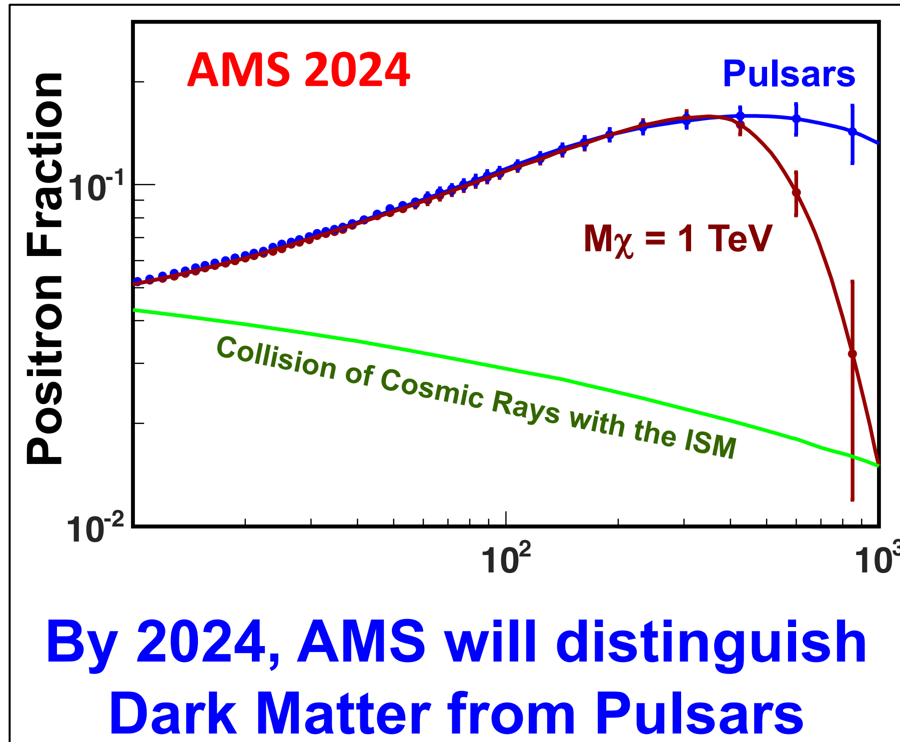
A Note On Positron Spectral Features

- A great deal is often made about “edges” and other spectral features that might appear in the positron spectrum
- Consider this plot, for example:

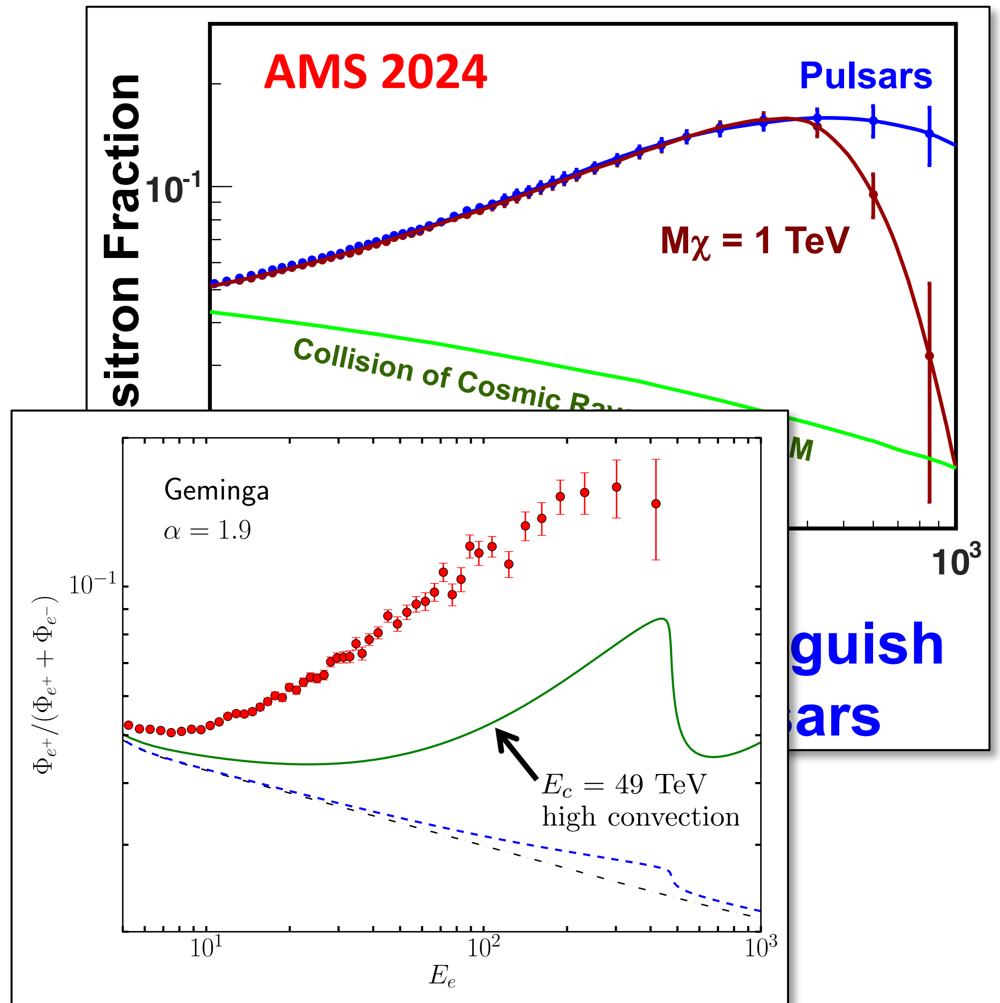


Sam’s words, not mine

From Talk by Sam Ting, Dec. 2016

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
- Consider this plot, for example:
- A nearby pulsar could very plausibly generate an edge-like feature
- In fact, such an edge *will* appear at an energy of $E \sim 1/bt_{age}$, which for Geminga is at ~350-700 GeV ($dE/dt = -bE^2$)



- Model based on J. Kopp PRD88, 2013

From Talk by Sam Ting, Dec. 2016

Summary

- Measurements from AMS-02 (as well as Fermi, HAWC) have revolutionized our understanding of cosmic rays in the Milky Way
- The PAMELA positron excess received a great deal of attention due to the possibility that it might be generated by annihilating dark matter – this no longer looks likely
- 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 sources – this efficiency factor was previously almost entirely unknown
- This new information implies that pulsars generate an order one fraction of the positron excess, and could very plausibly be responsible for the entirety of this signal

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.