MAKING SENSE OF RECENT RESULTS FROM COSMIC RAY EXPERIMENTS

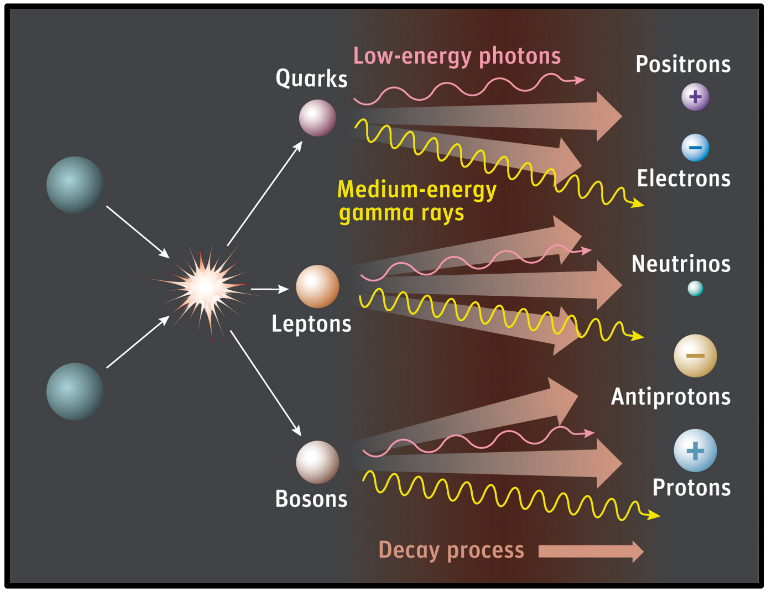
Dan Hooper – Fermilab and the University of Chicago

Fermilab LHC Physics Center (LPC) Forum

March 9, 2017

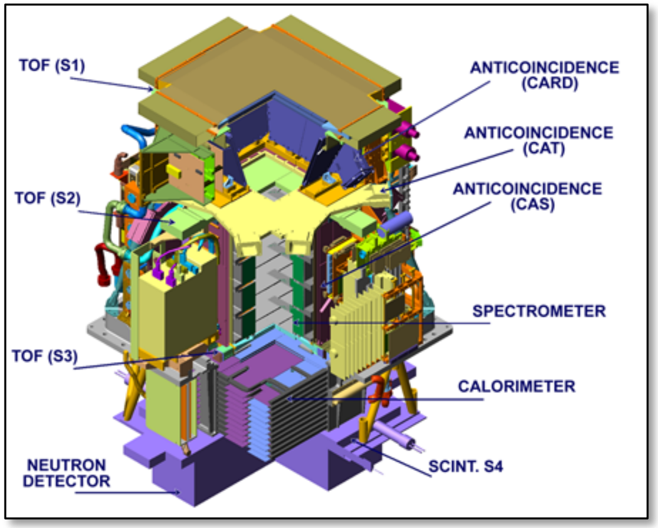
Dark Matter Searches With Cosmic-Ray Antimatter

- Astrophysical sources of cosmic rays generally produce much more matter (electrons, protons, nuclei) than antimatter (positrons, antiprotons, anti-nuclei)
- In contrast, dark matter annihilations and decays are predicted (in most models) to generate equal quantities of matter and antimatter
- Since the 1980s, it has been argued that searches for cosmic-ray antimatter could be used to constrain or discover annihilating or decaying dark matter (Silk, Srednicki 1984; Stecker, Rudaz, Walsh 1985; Ellis et al 1988; Kamionkowski and Turner 1991)



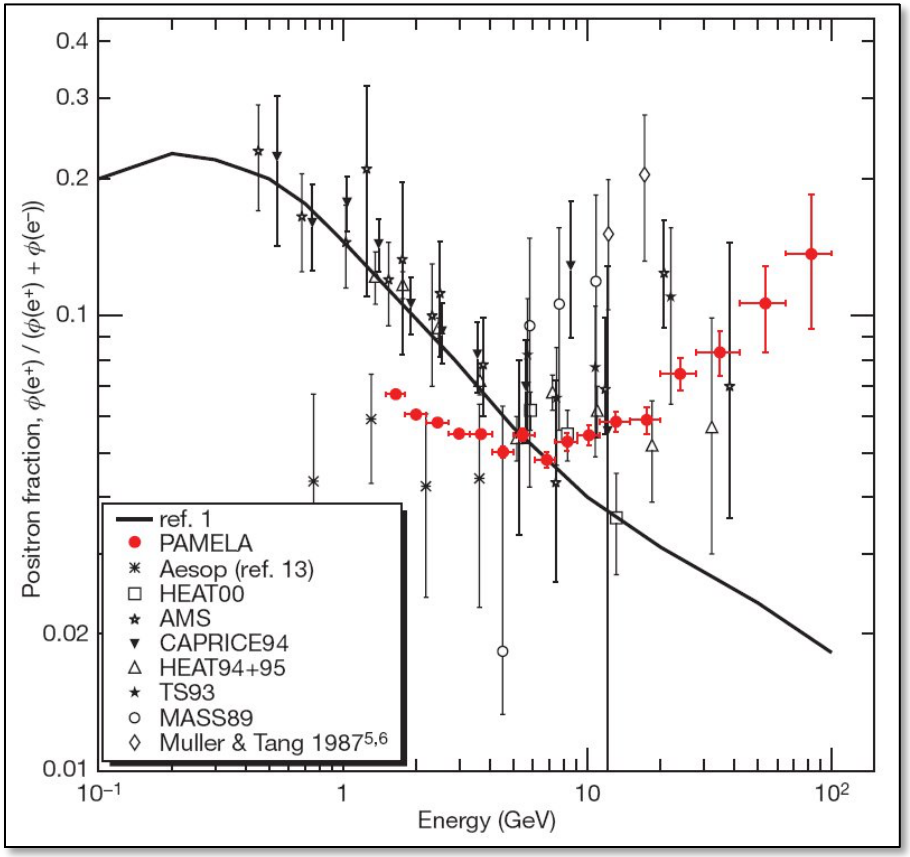
Modern Space-Based Cosmic Ray Detectors

- Experimental programs such as PAMELA and especially AMS-02 have the sensitivity required to potentially test a wide range of dark matter models
- These experiments can separate cosmic rays by mass and charge, and have produced high-precision measurements of the spectra of many cosmic ray species



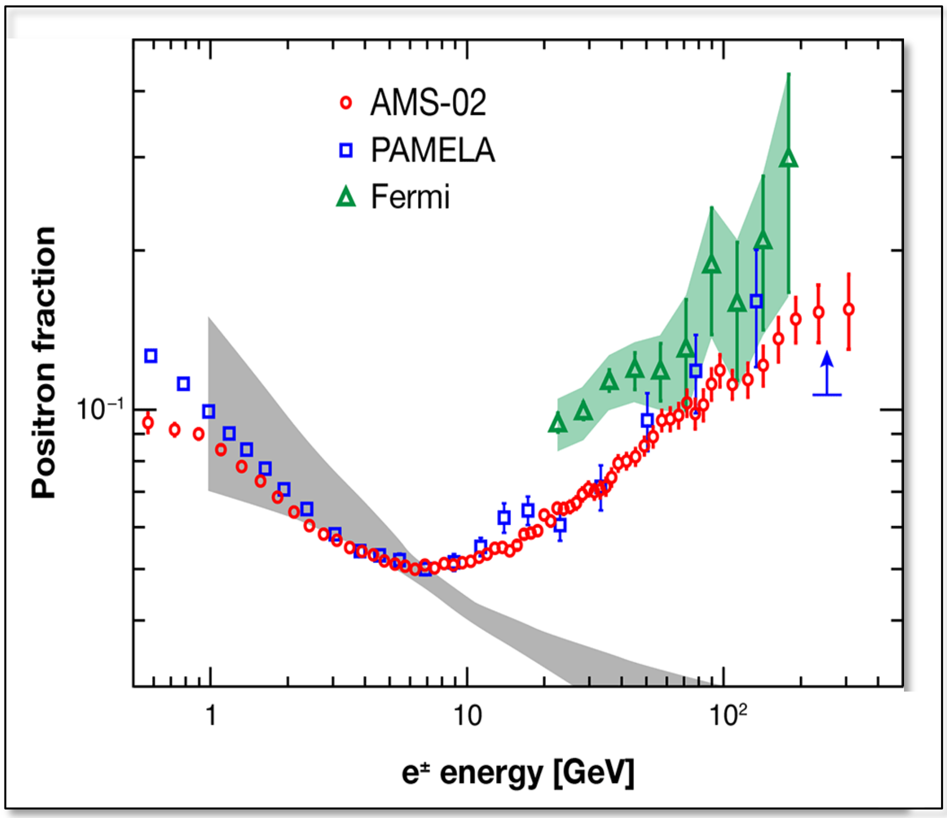
The PAMELA Positron Excess

- In 2008, the PAMELA Collaboration reported their measurement of the cosmic ray positron fraction, identifying an excess at energies above ~10 GeV (confirming earlier indications from HEAT and AMS-01)
- At the time, the reported spectrum could be fit by a wide range of annihilating dark matter models (~100 GeV to several TeV, annihilating to leptons or gauge bosons)
- This result generated an explosive response from the particle dark matter community (~1800 citations, the majority of which are about the implications for dark matter)



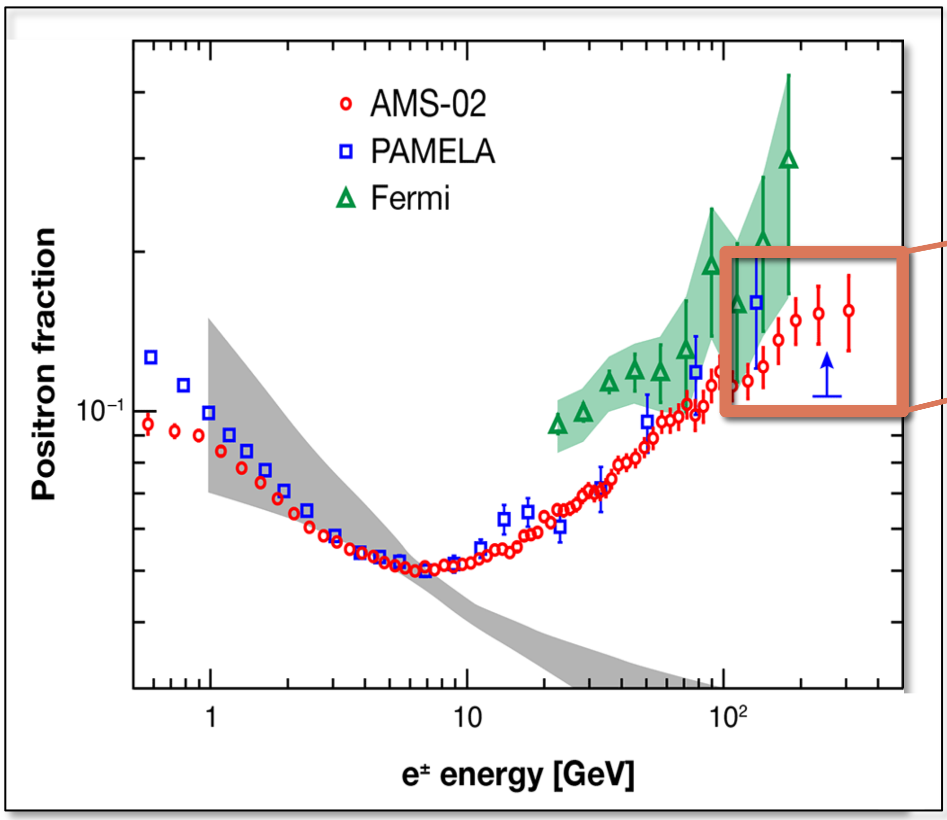
The Positron Fraction From AMS-02

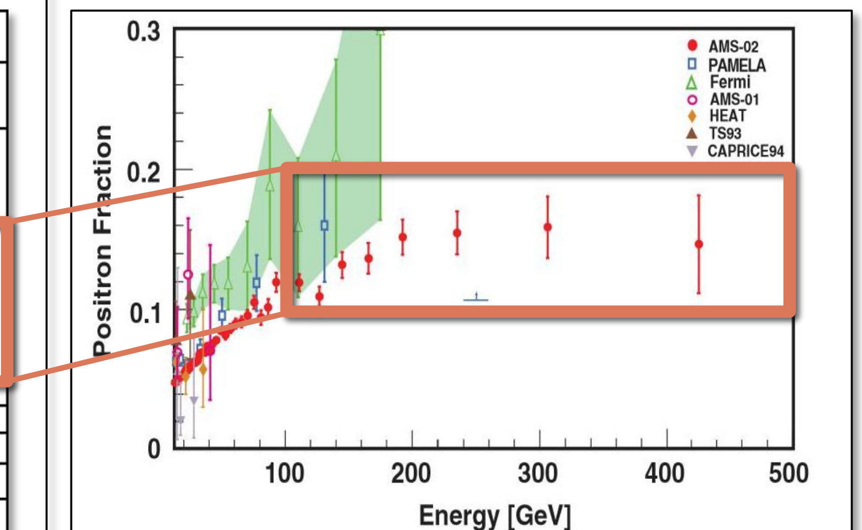
- In 2011, the AMS-02 experiment was deployed on the ISS
- Beginning in 2013, the AMS Collaboration has reported measurements of the positron fraction, confirming PAMELA's excess (also confirmed by Fermi), and extending this measurement to energies above ~400 GeV



The Positron Fraction From AMS-02

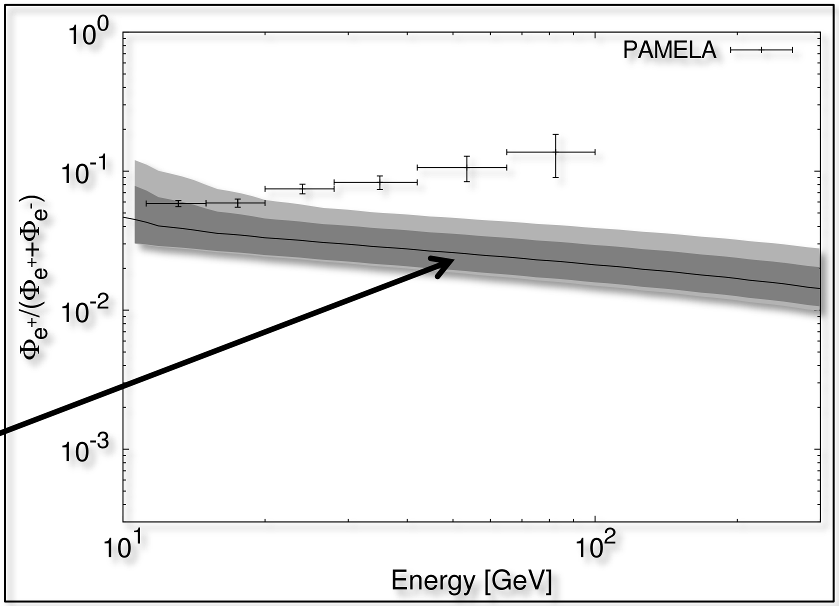
- In 2011, the AMS-02 experiment was deployed on the ISS
- Beginning in 2013, the AMS Collaboration has reported measurements of the positron fraction, confirming PAMELA's excess (also confirmed by Fermi), and extending this measurement to energies above ~400 GeV





Where Do The Positrons Come From?

- The anticipated background to the positron flux is generated by cosmic ray interactions with gas, yielding positrons through charged pion decay (*ie*. "*secondary" positrons*)
- The precise spectrum of these secondary positrons depends on the parameters of the cosmic-ray transport model (diffusion coefficients, boundary conditions, gas distributions, etc.), which are constrained by observations of other secondary-to-primary ratios (B/C, Ti/Fe, ^{9}Be/^{10}Be, etc.)
- For no empirically acceptable combination of these parameters is the positron fraction predicted to increase with energy
- Here is an example of a 2009 study that predicted the possible range of secondary positron fluxes (the uncertainties are smaller now, due to improved data)



M. Simet, DH, JCAP, arXiv:0904.2398

Where Do The Positrons Come From?

Three basic ideas have been proposed to generate the excess positrons:

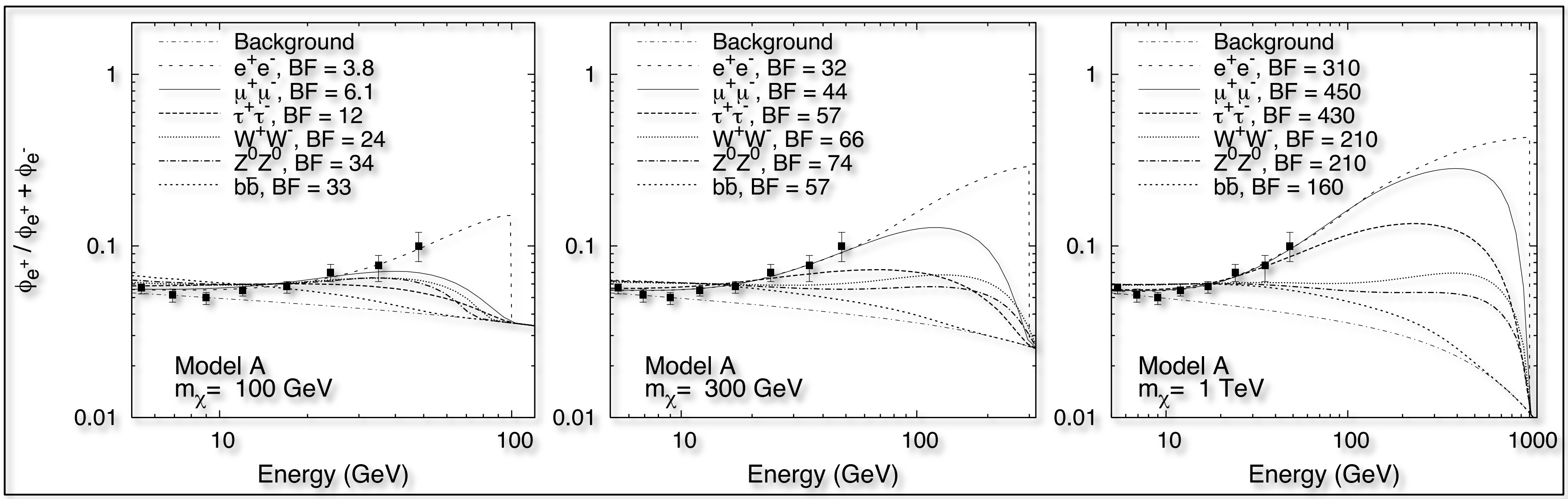
1) Annihilating or decaying dark matter particles

2) The acceleration of secondary positrons within the environments of cosmic-ray sources (*ie*. supernova remnants)

3) Nearby *primary* sources of high-energy positrons (*ie*. pulsars)

Annihilating Dark Matter and the Positron Excess

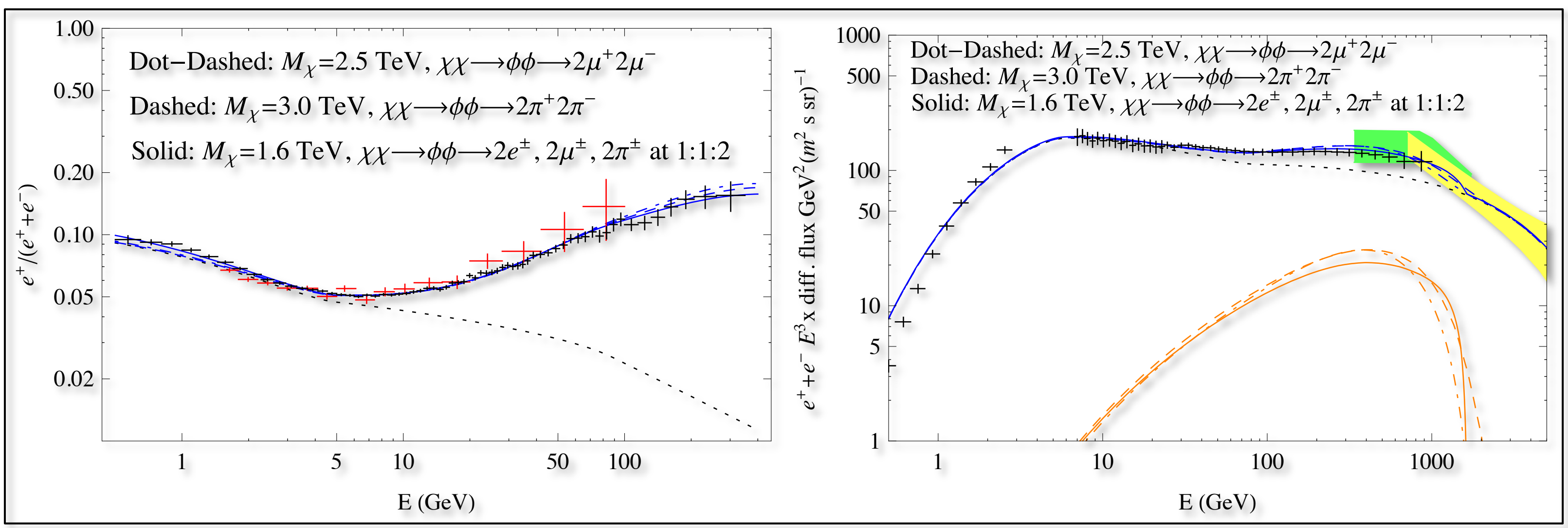
- When the PAMELA excess was first reported, it was possible to fit the data with a wide range of dark matter models
- Dark matter annihilating largely to leptons or gauge bosons could provide a good fit, with masses between ~100 GeV and a few TeV, and without necessarily requiring very large annihilation cross sections or boost factors



Cholis, Goodenough, DH, Simet, Weiner, PRD, arXiv:0809.1683

Annihilating Dark Matter and the Positron Excess

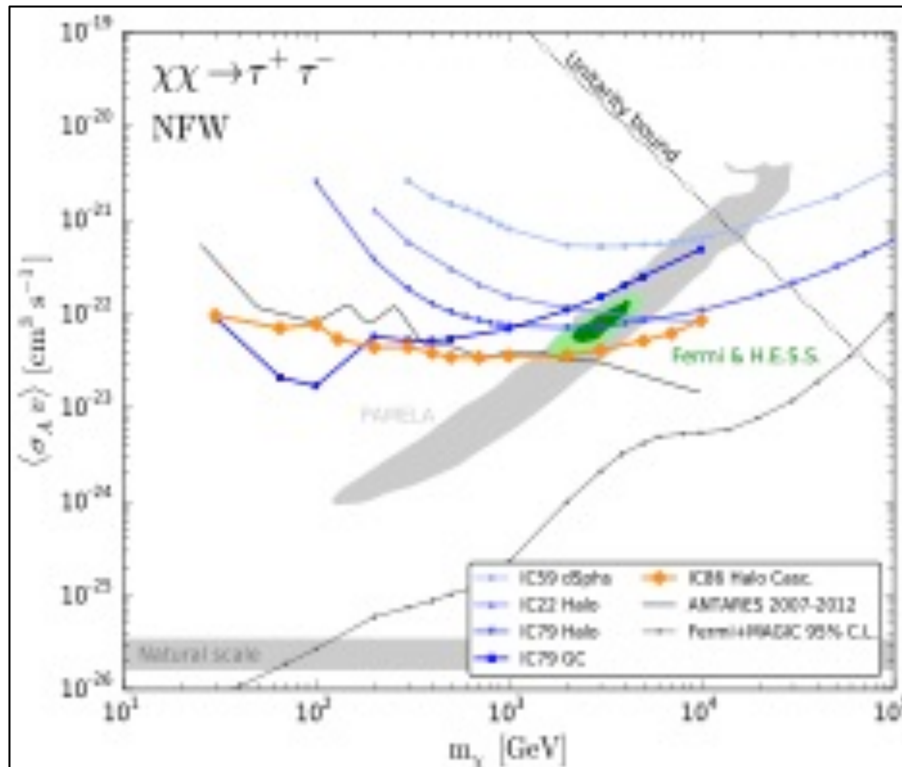
- With much more detailed measurements of the positron fraction from AMS (and of the electron+positron spectrum from Fermi and HESS), most of these dark matter models became incompatible with the data
- Dark matter models that *can* accommodate the data generally consist of a ~1-3 TeV particle that annihilates 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 and IceCube non-trivial to evade



Cholis, DH, PRD, arXiv:1304.1840

Annihilating Dark Matter and the Positron Excess

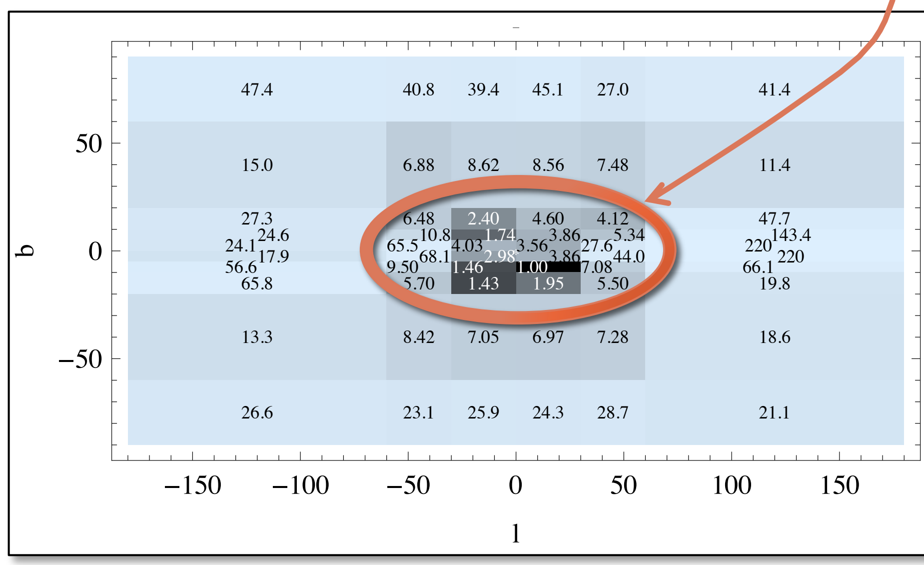
- Here is an example that makes clear why dark matter annihilating to tau leptons is ruled out (by both Fermi/HESS, and to a lesser extent IceCube)
- Annihilation channels to muons, electrons and charged pions are the only way to come even close to evading the gamma-ray constraints – and even then, there is some tension



IceCube Collaboration, EPJC, arXiv:1606.00209

Annihilating Dark Matter and the Positron Excess

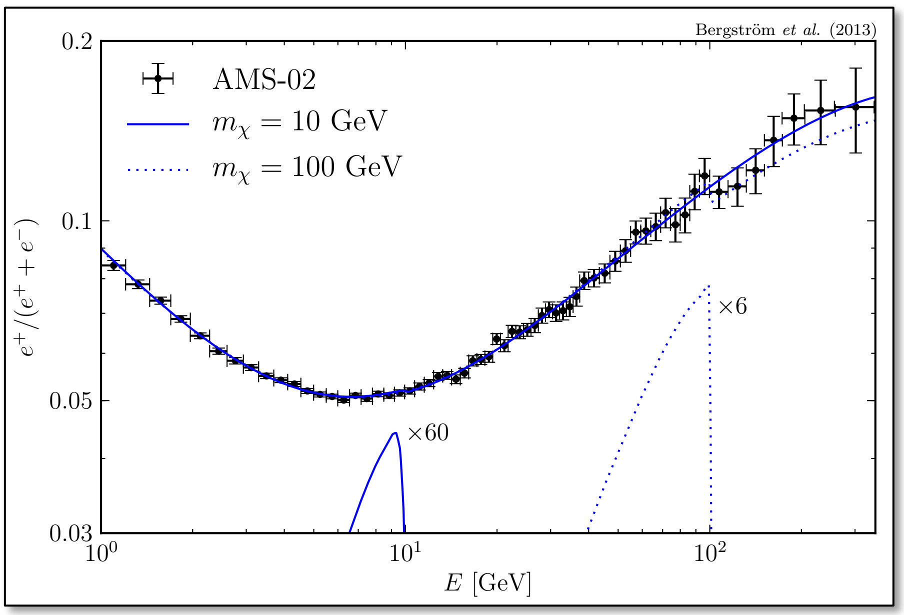
- Consider approximately the most favorable example: a 1.6 TeV dark matter candidate that annihilates to light intermediate particles which decay with branching fractions of 1:1:2 to electrons, muons and charged pions – this fits the positron data well for an annihilation cross section of $\sigma v \approx 6\times10^{-24}$ cm^3/s
- Fermi observations (especially from the Inner Galaxy) lead to a constraint of $\sigma v < 8.9\times10^{-25}$ cm^3/s (3σ CL) for this model
- If we vary the parameters associated with the ISM (gas distribution, radiation densities, etc.), we can reduce this constraint by a factor of ~2
- If the dark matter halo profile of the Milky Way is taken to have a large, flat-density core, we can reduce this constraint by a factor of ~3
- Taken together, such a scenario is just marginally consistent with the existing Fermi data

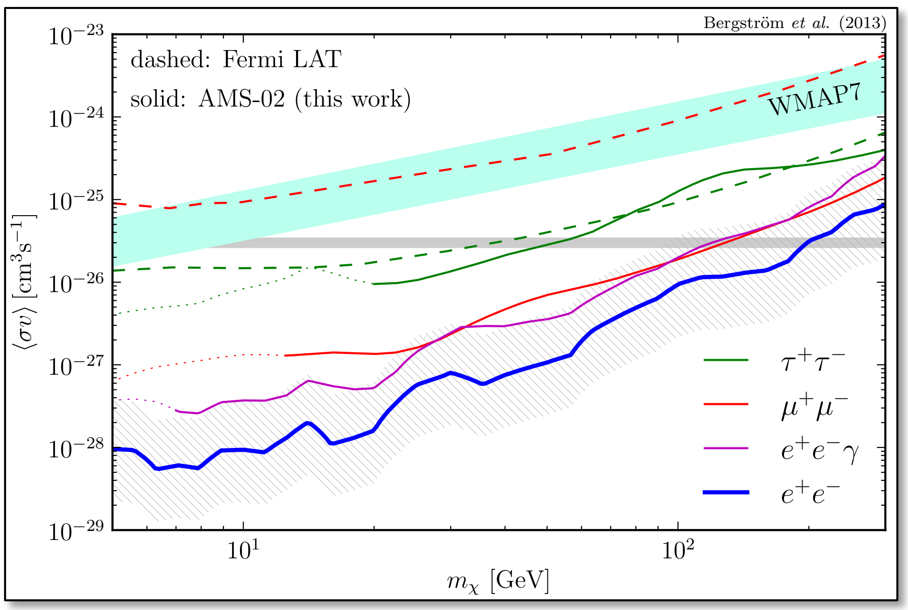


Tavakoli, Cholis, Evoli, Ullio, JCAP, arXiv:1308.4135

Constraining Annihilating Dark Matter With The Cosmic Ray Positron Fraction

- Regardless of what sources or mechanisms generate the positron excess, the *shape* of the positron fraction can be used to constrain annihilating dark matter models, especially for dark matter that annihilates significantly to charged leptons
- Annihilations to charged leptons yield a distinctive spectral feature, which is not seen in the measured positron fraction





Bergstrom, Bringmann, Cholis, DH, Weniger, PRL, arXiv:1306.3983

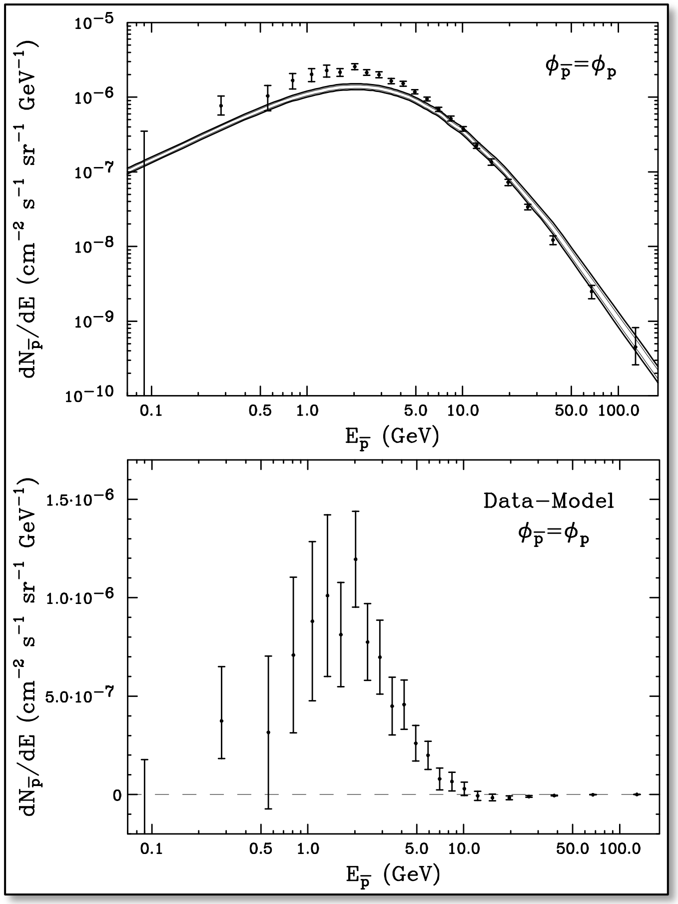
Sidebar: Annihilating Dark Matter And Cosmic-Ray Antiprotons

Dark matter searches using antiprotons are complementary to positron searches for a number of reasons

- Sensitive to different dark matter models (non-leptophillic models, etc.)
- Probe a large fraction of the Galactic Halo (not just the surrounding ~kpc)
- Compared to positrons, there is much less astrophysical production of cosmic-ray antiprotons ($\bar{p}/p \sim 10^{-4}$, rather than $e^+/e^- \sim 10^{-1}$)
- I'd argue that an antiproton excess could potentially be interpreted as a more robust detection of dark matter

Sidebar: Annihilating Dark Matter And Cosmic-Ray Antiprotons

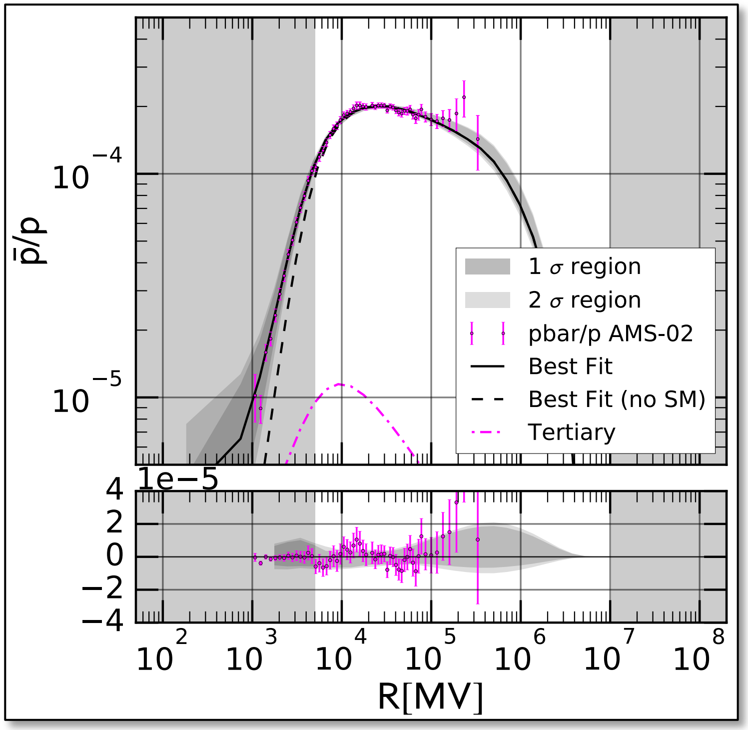
- In the PAMELA antiproton spectrum, there are hints of an excess (relative to standard secondary production), at ~3 GeV
- Limited statistics, and sizable systematic uncertainties, made it difficult to draw any strong conclusions



DH, Linden, Mertsch, JCAP, arXiv:1410.1527
Cuoco, Kramer, Korsmeier, arXiv:1610.03071
Cui, Yuan, Tsai, Fan, arXiv:1610.03840

Sidebar: Annihilating Dark Matter And Cosmic-Ray Antiprotons

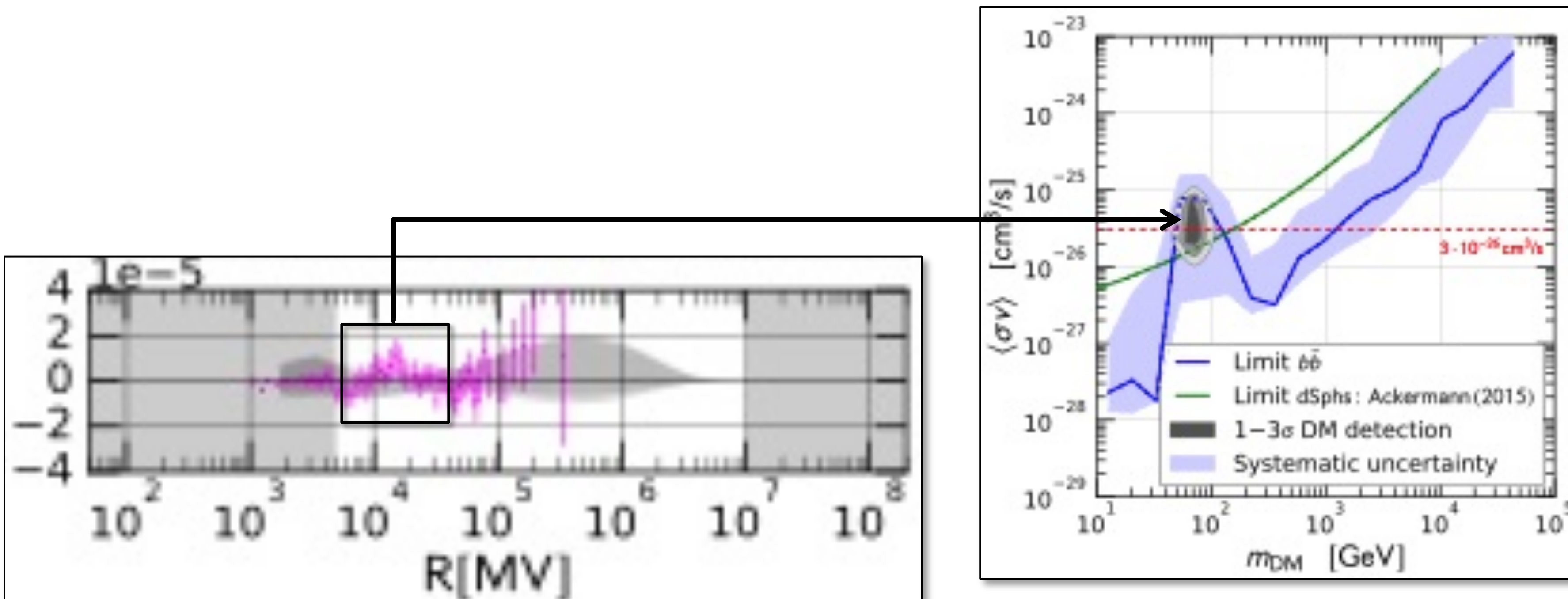
- Recently, a similar spectral feature has been identified in the AMS antiproton data
- This appears to be statistically robust ($\sim 8\sigma$), but systematic uncertainties associated with the antiproton production cross section and with the effects of solar modulation could very plausibly reduce the significance of this result



Cuoco, Kramer, Korsmeier, arXiv:1610.03071
Cui, Yuan, Tsai, Fan, arXiv:1610.03840

Sidebar: Annihilating Dark Matter And Cosmic-Ray Antiprotons

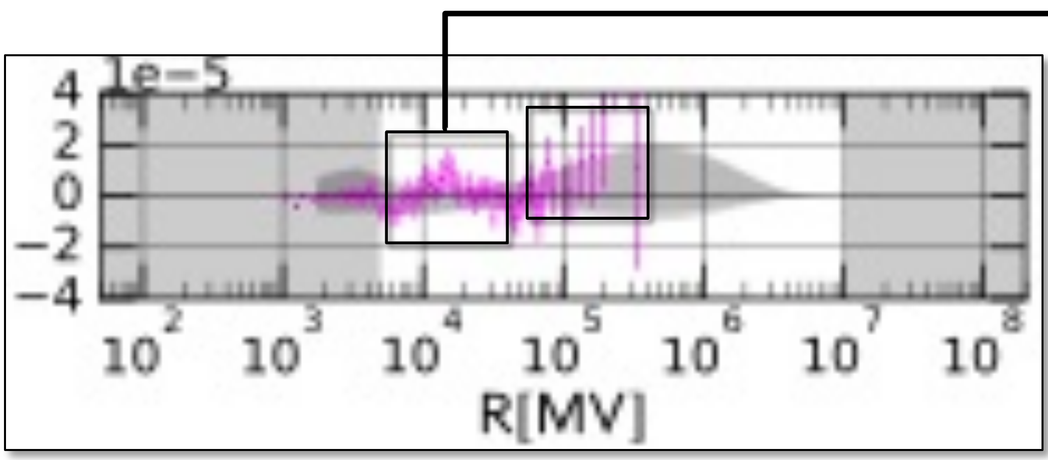
- The reported excess is well fit by a ~50-90 GeV dark matter particle (for $b\bar{b}$), in good agreement with the Galactic Center gamma-ray excess

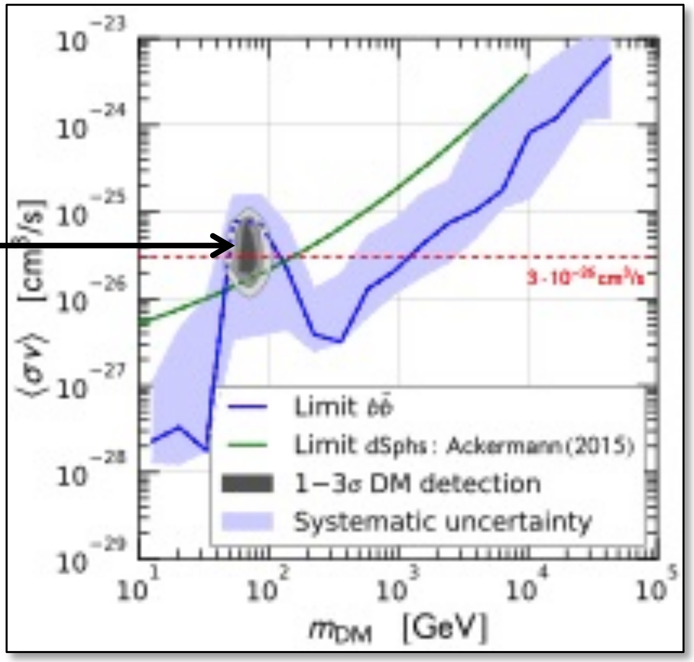


Cuoco, Kramer, Korsmeier, arXiv:1610.03071
Cui, Yuan, Tsai, Fan, arXiv:1610.03840

Sidebar: Annihilating Dark Matter And Cosmic-Ray Antiprotons

- The reported excess is well fit by a ~50-90 GeV dark matter particle (for $b\bar{b}$), in good agreement with the Galactic Center gamma-ray excess
- There is also a less significant ($\sim 3\sigma$) antiproton excess at energies above ~100 GeV – possibly heavier dark matter (or accelerated secondaries)
- I consider these both to be things to keep eye on, but perhaps not to get too excited about (just yet)

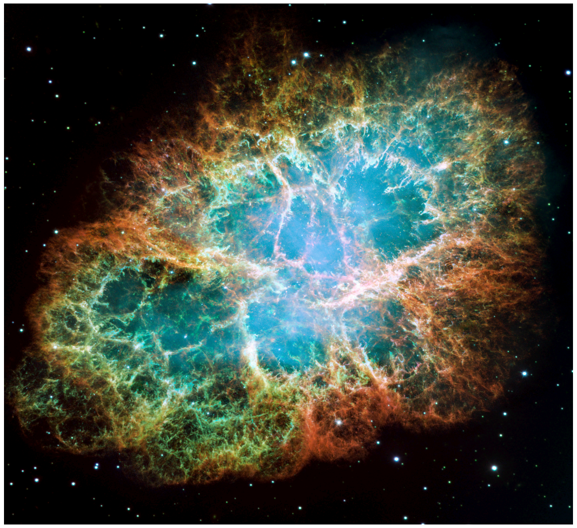


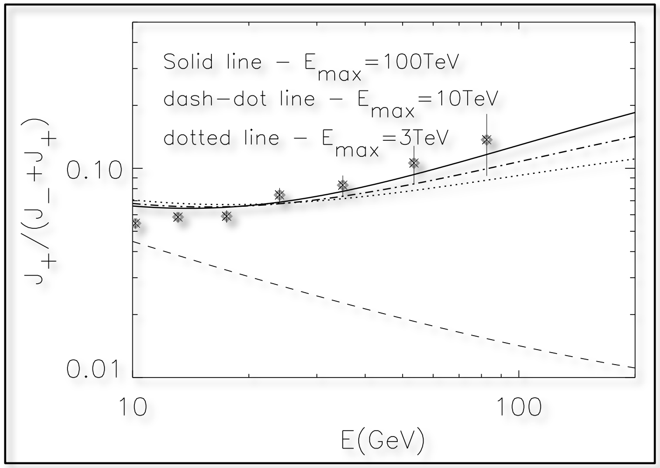


Cuoco, Kramer, Korsmeier, arXiv:1610.03071
Cui, Yuan, Tsai, Fan, arXiv:1610.03840

The Acceleration of Secondary Positrons in Supernova Remnants

- In 2009, Pasquale Blasi proposed that supernova remnants might generate secondary positrons, and then efficiently accelerate them before they escape into the surrounding environment
- To some extent this must occur, but it was difficult to estimate the degree – seemed likely to be a small effect, but not implausible that it could significantly contribute to the observed positron excess

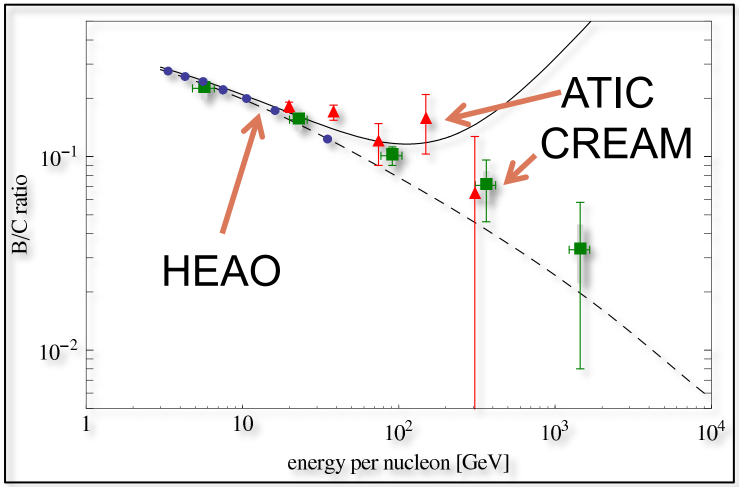


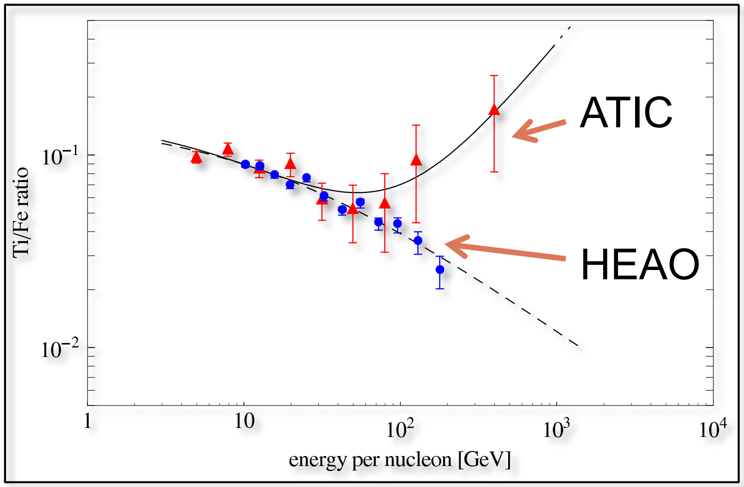


P. Blasi, PRL, arXiv:0903.2794

The Acceleration of Secondary Positrons in Supernova Remnants

- A few months later, Phillip Mertsch and Subir Sarkar pointed out that this scenario could be tested by measuring other secondary-to-primary ratios
- If secondary positrons were accelerated in supernova remnants, then secondary species of nuclei should be as well
- At the time, the evidence was inconclusive (and not particularly self-consistent)





Mertsch, Sarkar, PRL, arXiv:0905.3152

The Acceleration of Secondary Positrons in Supernova Remnants

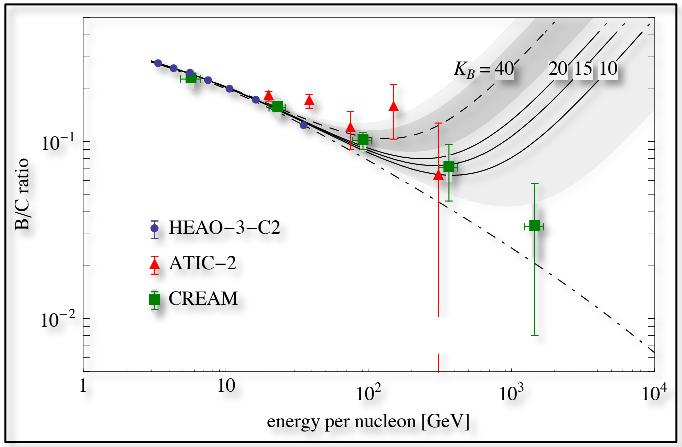
- The main uncertainty in the calculation of the acceleration of cosmic ray secondaries is the value of the parameter K_B, which appears in the expression for the diffusion coefficient near the shock front:

$$D_i^{\pm}(E) = \frac{K_B\, r_L(E)\, c}{3} = 3.3{\times}10^{22}\, K_B\, B^{-1}\, E\, Z_i^{-1} \mathrm{cm}^2\, \mathrm{s}^{-1}$$

- This quantity is related to the magnitude of the variations in the magnetic field strength near the shock, $K_B \sim (B/\delta B)^2$ – larger values allow for more efficient streaming
- For a value of $K_B \sim 40$, the entire positron excess could originate from positron acceleration in supernova remnants
- Although one generally expects K_B to be order unity, Blasi, Merstch and Sarkar have argued that significantly larger values are plausible

The Acceleration of Secondary Positrons in Supernova Remnants

- To test this scenario, measurements of other secondary-to-primary ratios are essential
- Although the boron-to-carbon (B/C) data was initially inconclusive, with new data from AMS it became clear that $K_B \sim 40$ is *not* compatible (values up to ~10 are consistent)

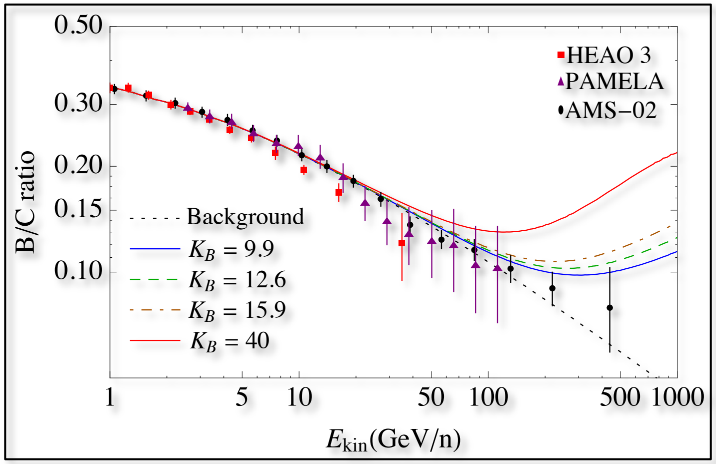


Ahlers, Mertsch, Sarkar, PRD, arXiv:0909.4060

Two Possible Caveats:

1) Supernova remnants with large K_B might be responsible for proton acceleration (and thus positrons), while those responsible for nuclei (and thus boron) might have smaller values

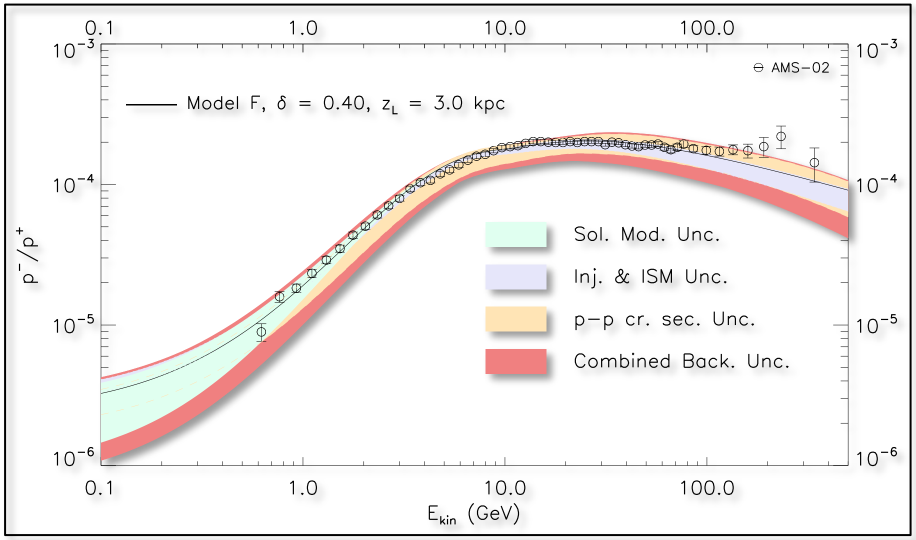
2) The quantitative results depend on the ISM model, and in particular on the energy dependence of the diffusion coefficient; consistency requires $\delta \sim 0.7$
(see Mertsch, Sarkar arXiv:1402.0855)



Cholis, DH, PRD, arXiv:1312.2952

The Acceleration of Secondary Positrons in Supernova Remnants

- To close these caveats, one can use the AMS measurement of the antiproton-to-proton ratio (unlike boron, antiprotons and positrons originate from the same proton primaries)
- The most challenging part of this calculation is the treatment of systematic uncertainties, including those associated with solar modulation, ISM transport, and the antiproton production cross section

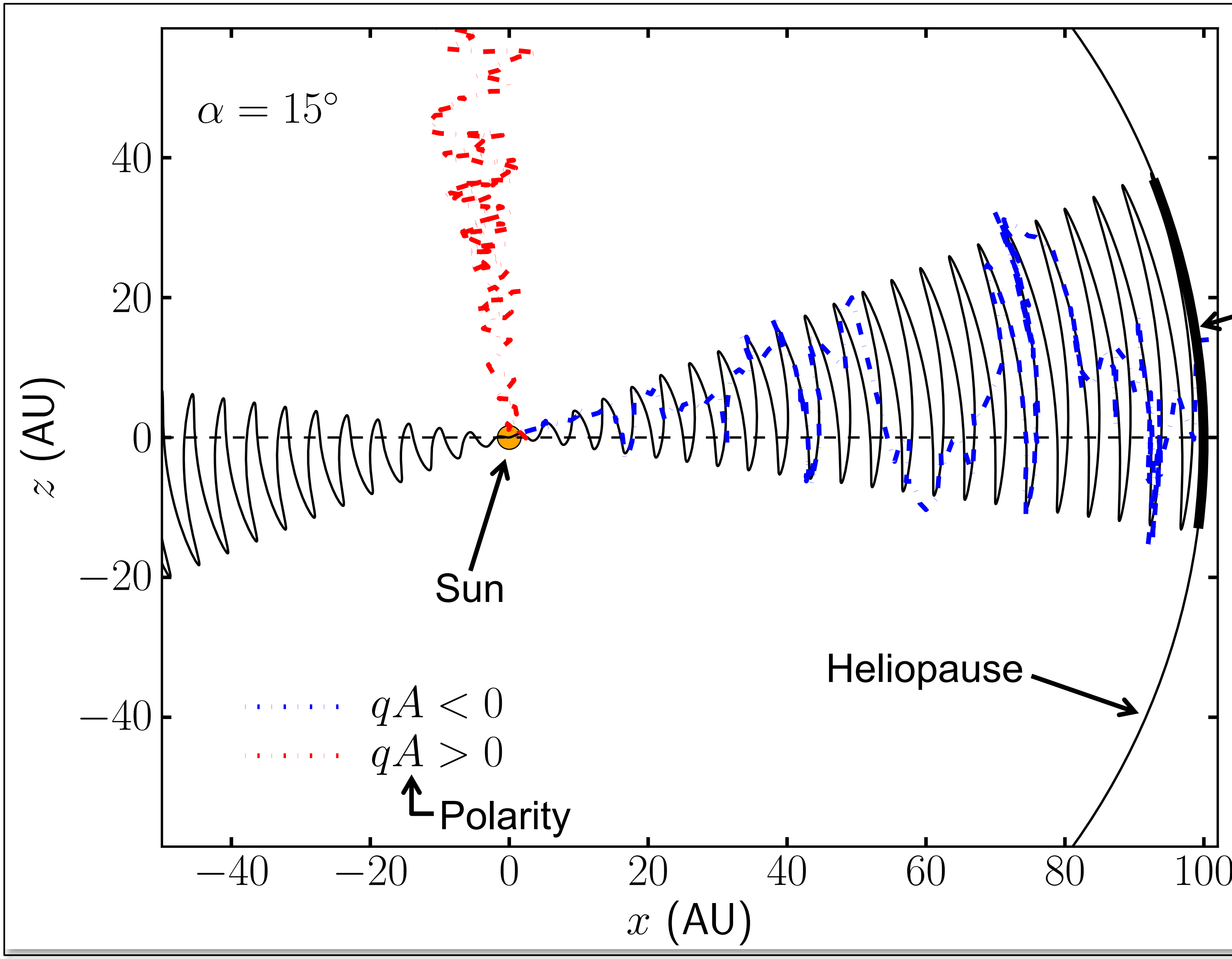


Cholis, DH, Linden, arXiv:1701.04406

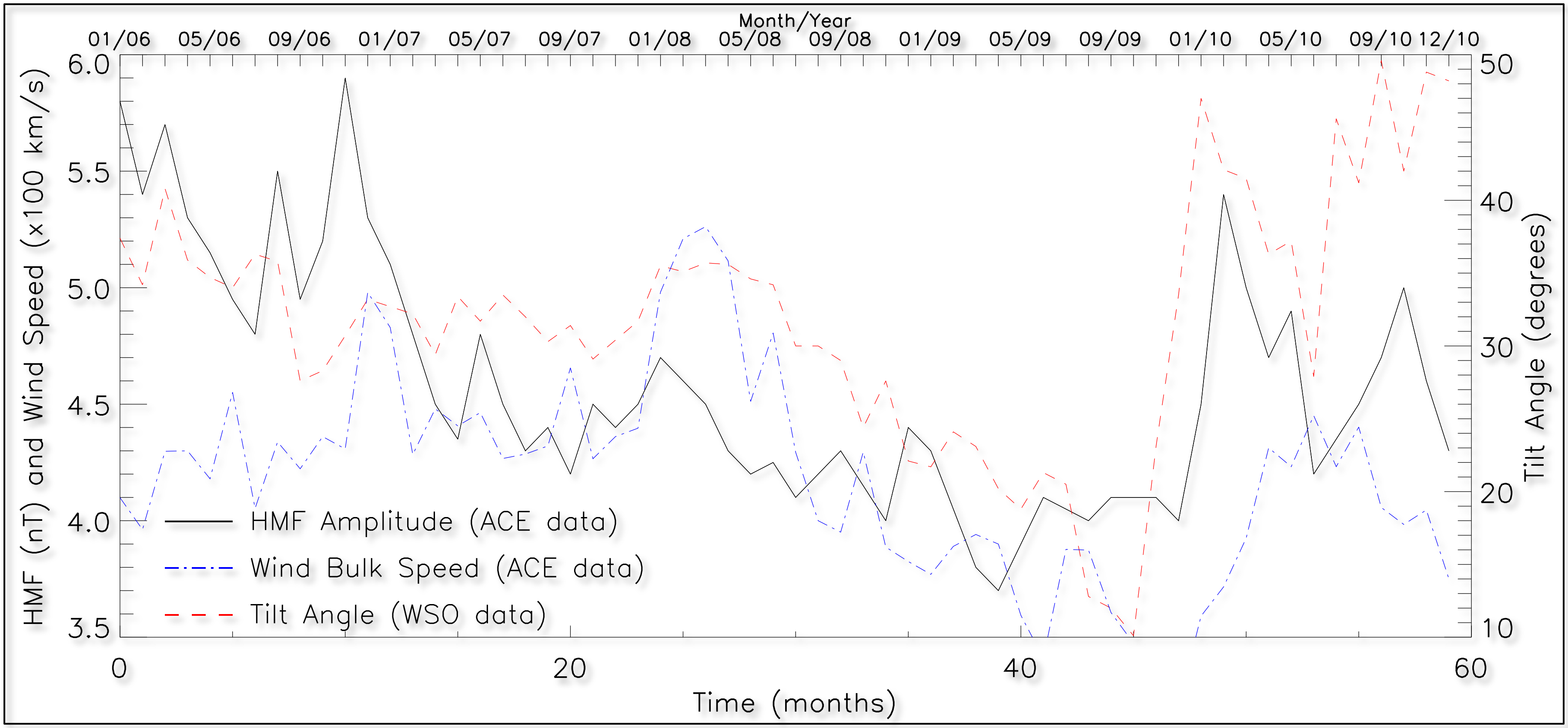
Solar Modulation

- At rigidities below ~10 GV, cosmic rays are very significant impacted by the effects of the solar wind and other heliospheric forces (*ie*. solar modulation)
- The effects of solar modulation varies with time, as well as with the rigidity and charge sign of the cosmic ray
- Only a few years ago, state-of-the-art studies would simply apply a single force-field potential, and perhaps fit the value of this quantity to the data
- We can now move significantly beyond this simple approach due to the following three factors:
  1) High statistics data from PAMELA and AMS, presented in time bins
  2) Recent Voyager 1 measurements of the cosmic ray spectrum beyond the boundaries of the Solar System (*ie*. beyond the heliopause)
  3) Measurements of various solar observables, and their correlation with the solar modulation potential (the polarity and magnitude of the heliospheric magnetic field, the bulk velocity of the solar wind, and the tilt angle of the heliospheric current sheet)

Cholis, DH, Linden, PRD, arXiv:1511.01507

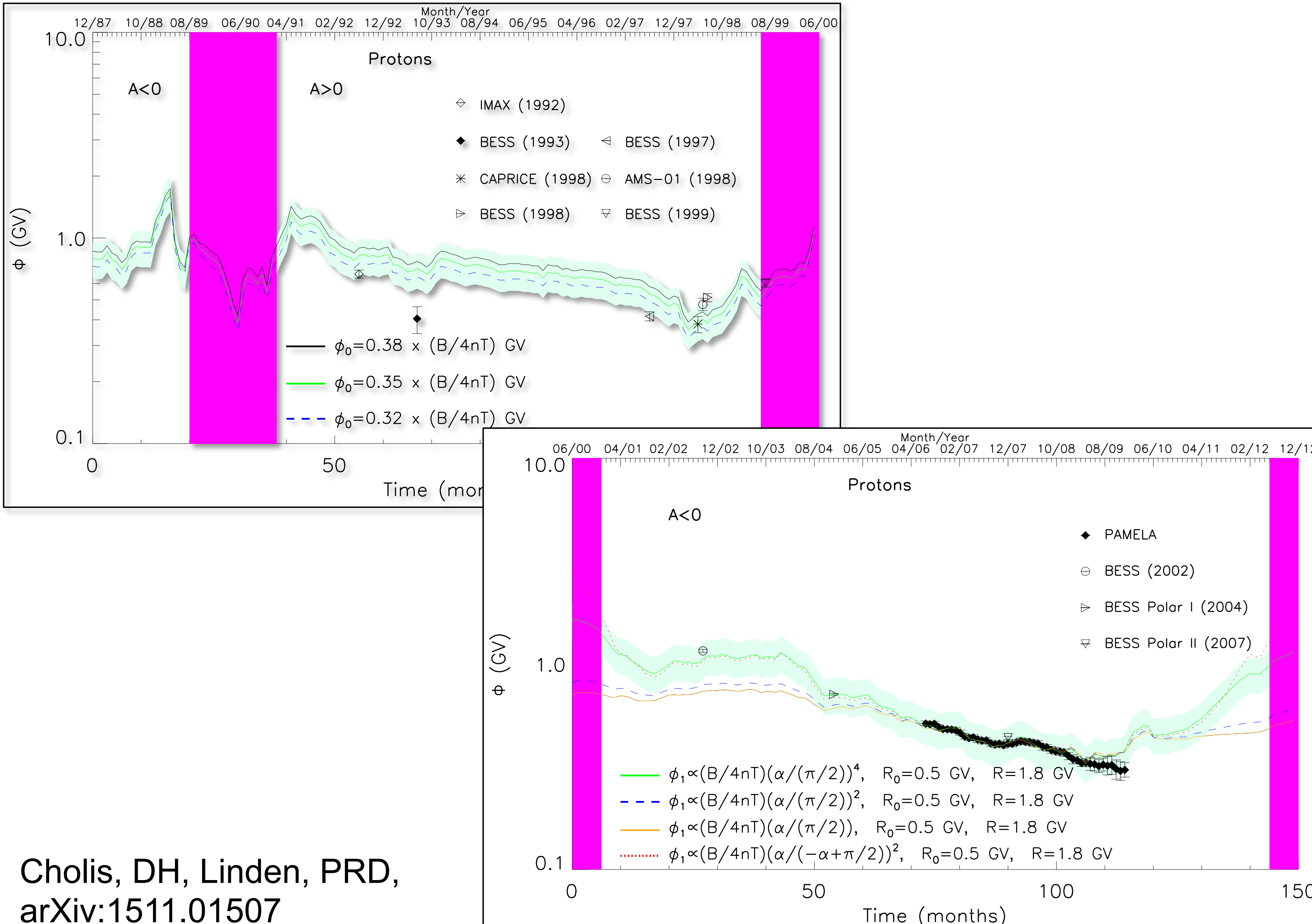


Cholis, DH, Linden, PRD, arXiv:1511.01507



$$\Phi(R,t) = \phi_0 \left(\frac{|B_{\rm tot}(t)|}{4\,{\rm nT}}\right) + \phi_1\, H(-qA(t)) \left(\frac{|B_{\rm tot}(t)|}{4\,{\rm nT}}\right) \left(\frac{1+(R/R_0)^2}{\beta(R/R_0)^3}\right) \left(\frac{\alpha(t)}{\pi/2}\right)^4$$

Cholis, DH, Linden, PRD, arXiv:1511.01507



Cholis, DH, Linden, PRD, arXiv:1511.01507

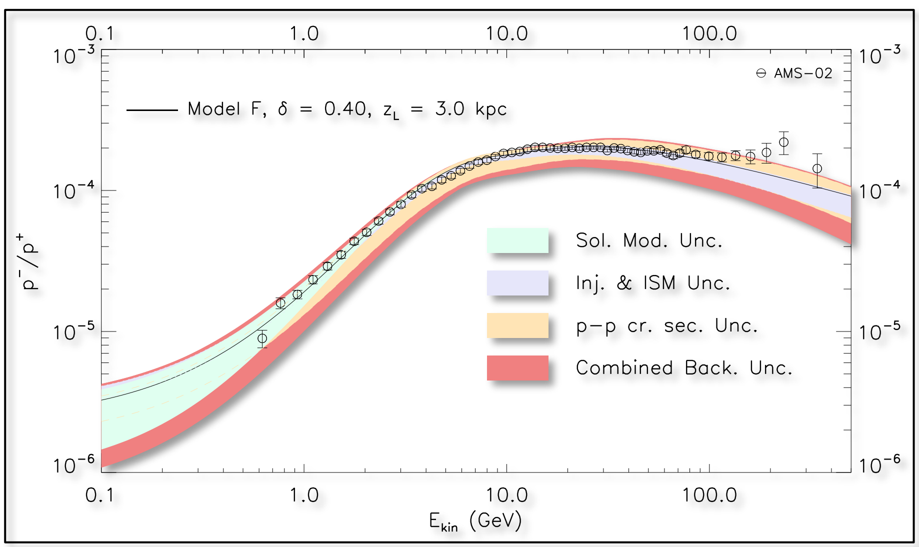
The Acceleration of Secondary Positrons

- To account for the systematic uncertainties, we:

1) Vary the parameters of our Solar Modulation model

2) Marginalize over a range of ISM transport models

3) Marginalize over the parameters of a logarithmic polynomial, which we use to rescale the antiproton production cross section (this flexibility is important)



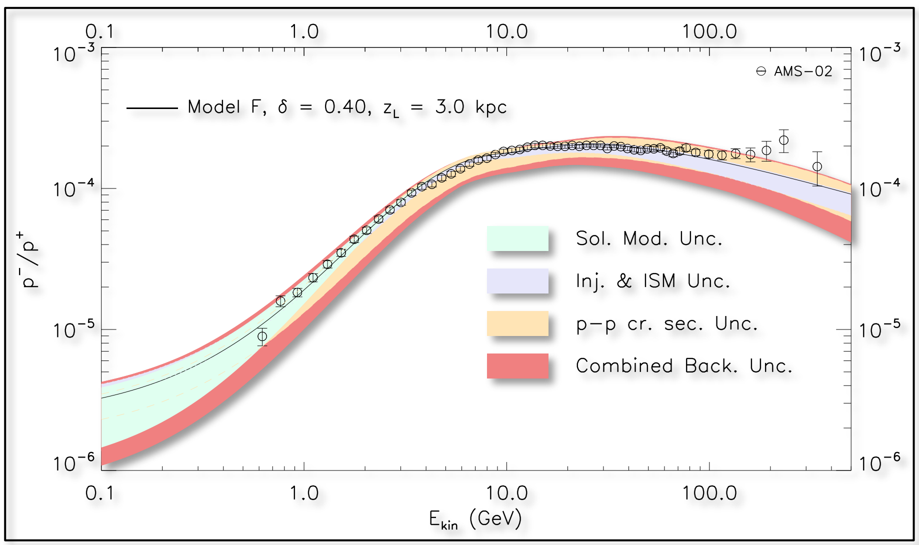
Cholis, DH, Linden, arXiv:1701.04406

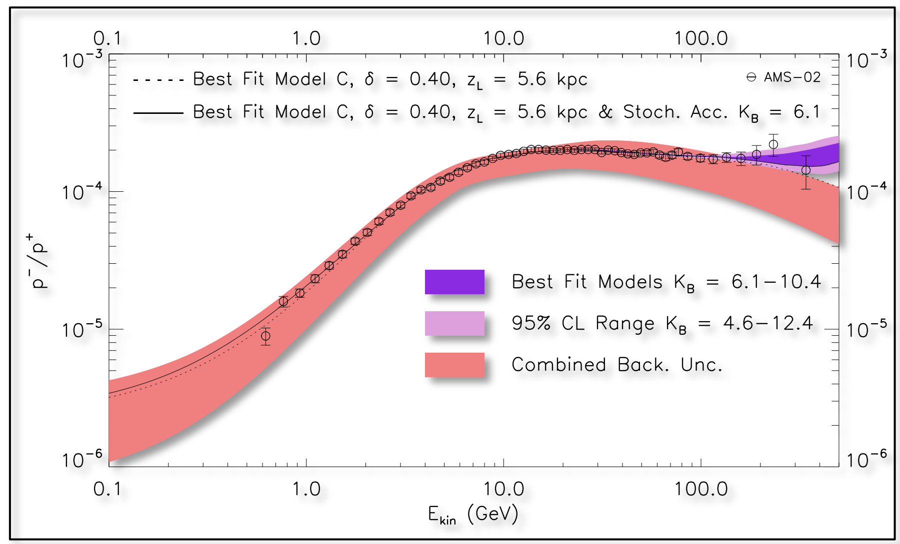
The Acceleration of Secondary Positrons

- To account for the systematic uncertainties, we:

1) Vary the parameters of our Solar Modulation model
2) Marginalize over a range of ISM transport models
3) Marginalize over the parameters of a logarithmic polynomial, which we use to rescale the antiproton production cross section (this flexibility is important)

- After taking these factors into account, we find that our fit prefers K_B~4.6-12.4 (95% CL), near the upper limits allowed by B/C measurements
- The absence of secondary acceleration (K_B=0) is disfavored at 3.2σ

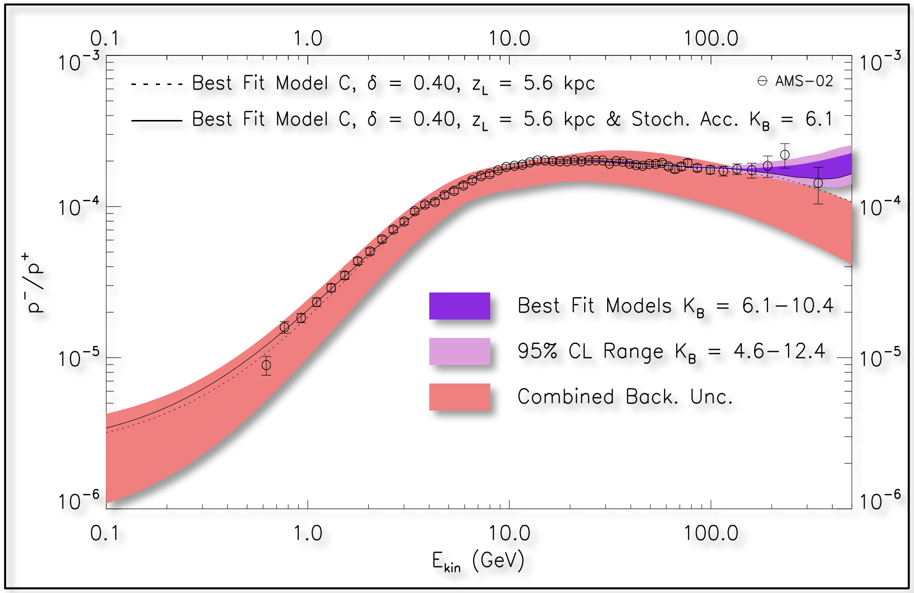


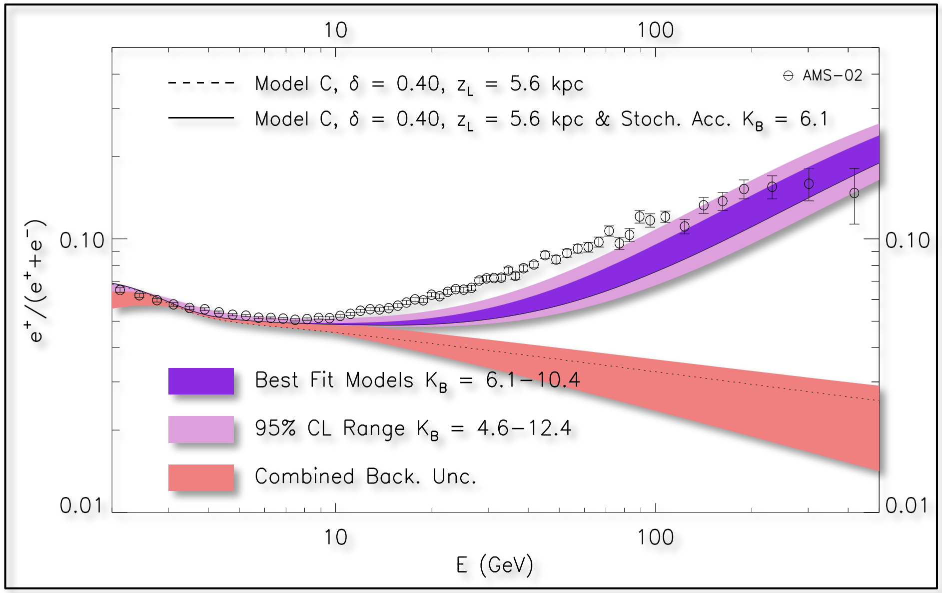


Cholis, DH, Linden, arXiv:1701.04406

The Acceleration of Secondary Positrons

- We can use the range of values favored by the antiproton measurement (K_B~6.1-10.4) to predict the contribution to the positron fraction
- This exercise suggests that a non-negligible fraction of the positron excess might originate from accelerated secondaries
- Since K_B is likely to be energy dependent, we can only rigorously predict the contribution to the positron flux at a few tens of GeV (at higher energy, other behavior is certainly possible)

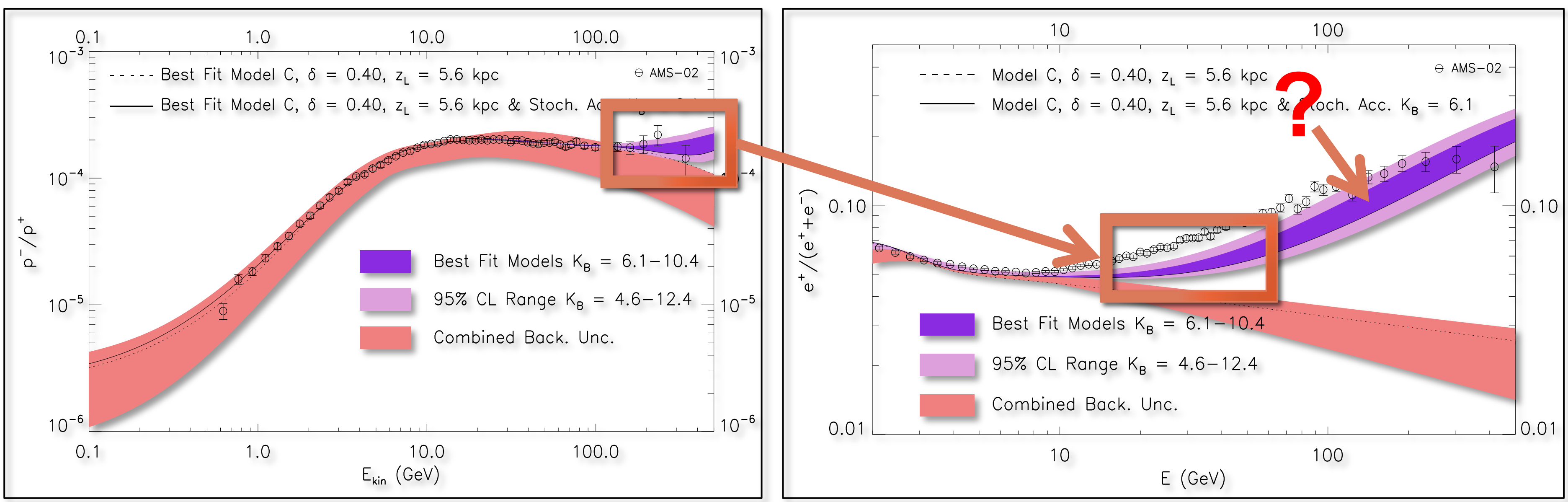




Cholis, DH, Linden, arXiv:1701.04406

The Acceleration of Secondary Positrons

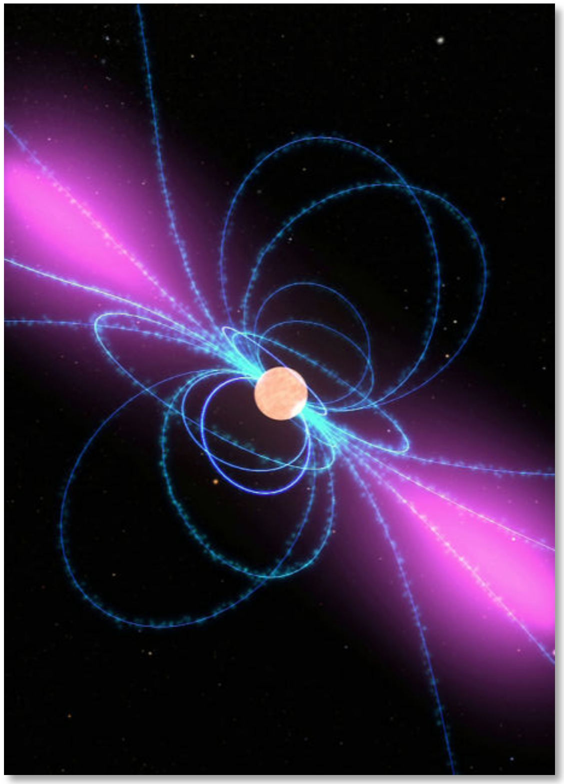
- We can use the range of values favored by the antiproton measurement (K_B~6.1-10.4) to predict the contribution to the positron fraction
- This exercise suggests that a non-negligible fraction of the positron excess might originate from accelerated secondaries
- Since K_B is likely to be energy dependent, we can only rigorously predict the contribution to the positron flux at a few tens of GeV (at higher energy, other behavior is certainly possible)



Cholis, DH, Linden, arXiv:1701.04406

Cosmic Ray Positrons From Pulsars

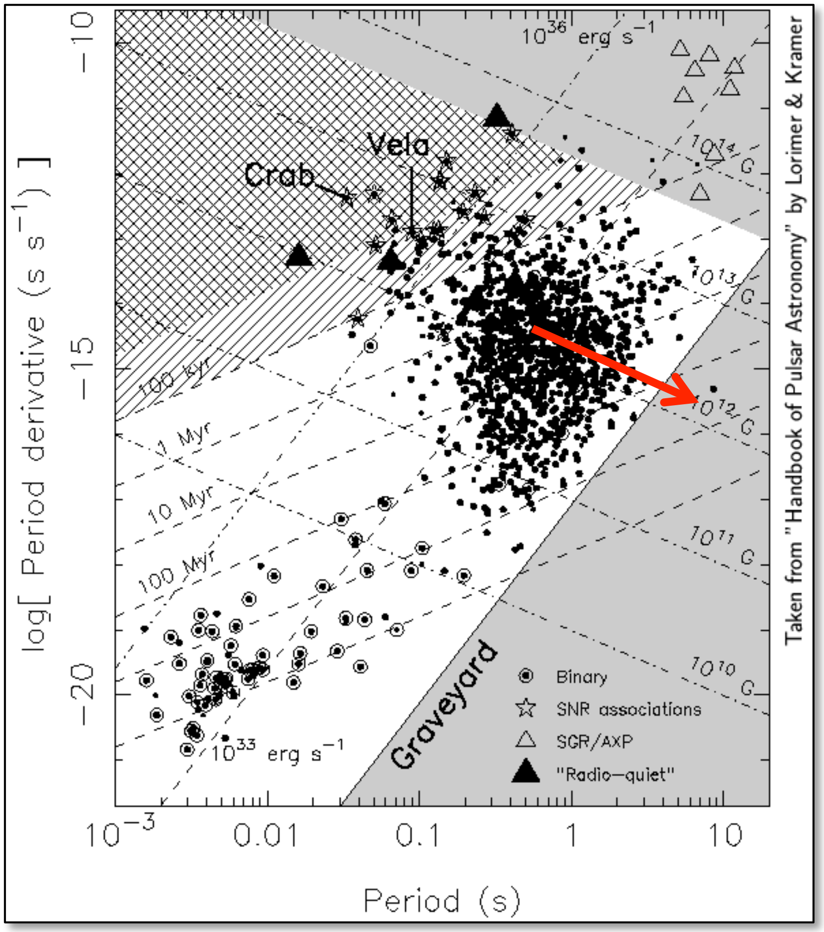
- Shortly after the PAMELA excess was reported, it was suggested that the positrons might originate from pulsars
- In my view, this has long been the most likely source of the positron excess



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 101

- 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 spindown evolution, and it power depends on the strength of its magnetic field (which transfers rotational kinetic energy into radiation via magnetic dipole braking)



Pulsars Emission Models

- There is considerable debate and research activity 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)

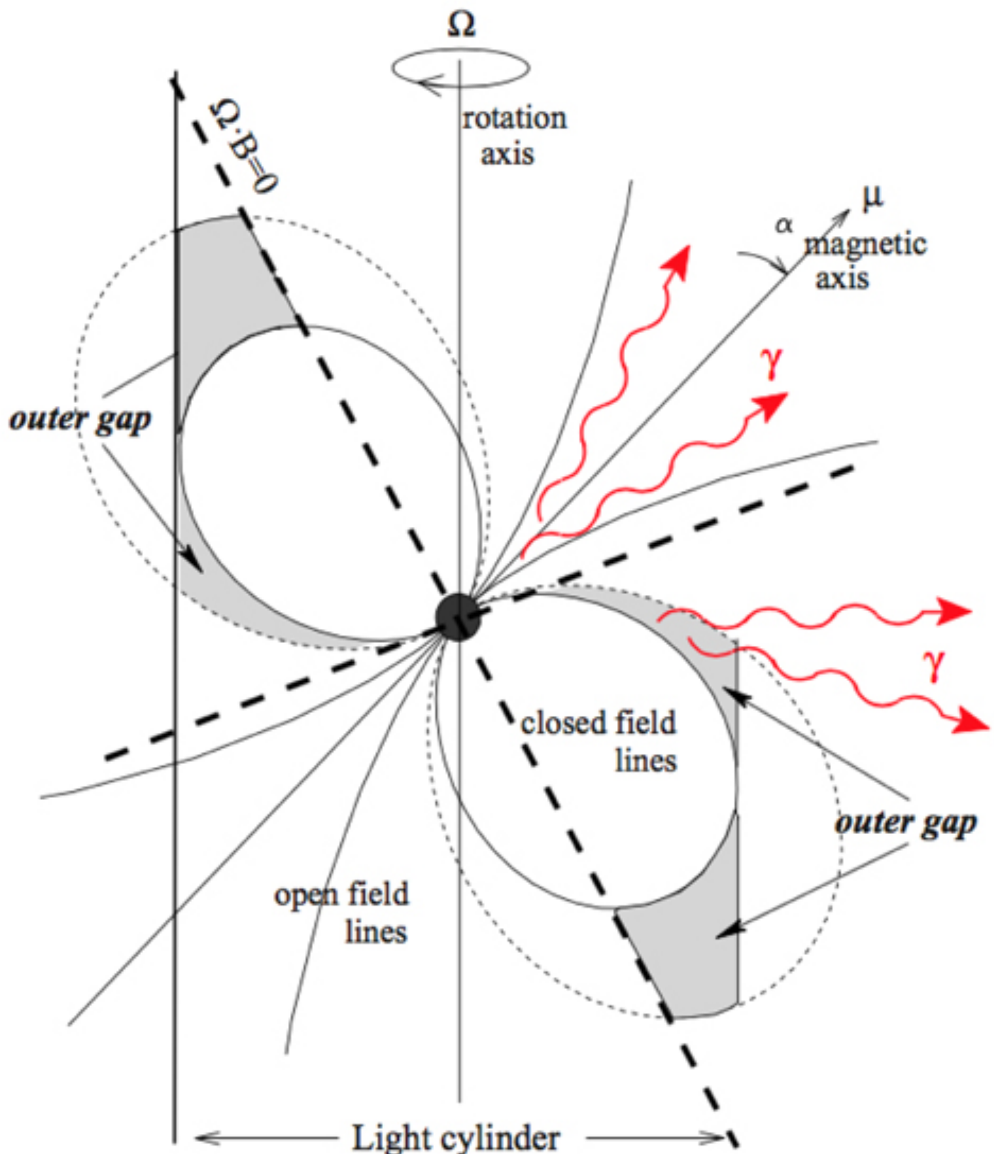
  -These electrons then induce electromagnetic cascades through the emission of curvature radiation

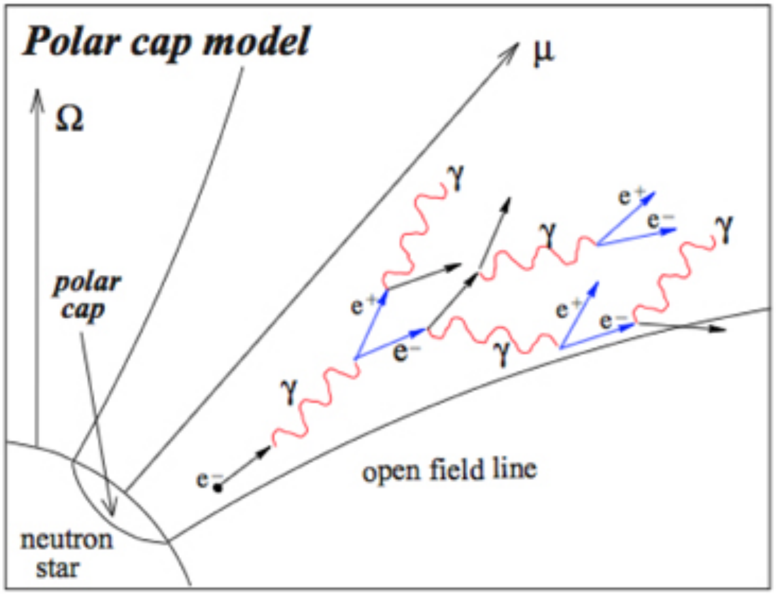
  -This results in the production of photons with energies above the threshold for pair production in the strong magnetic field

  -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%?

Pulsars Emission Models





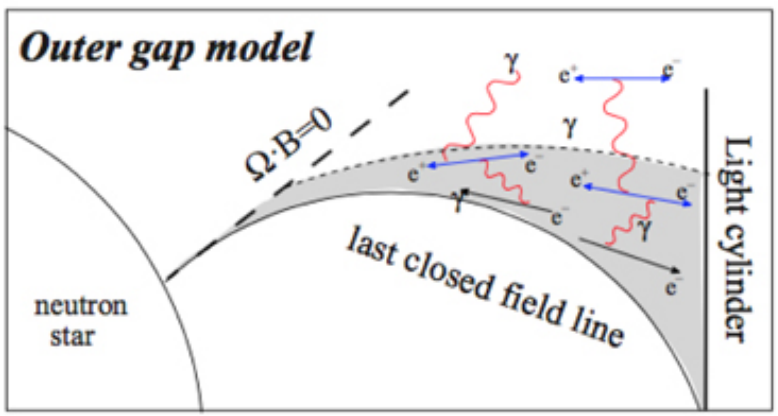


Image Credit: Yating, Kwong-Sang, Jumpei (2016)

Which Pulsars Contribute to the Positron Flux?

Consider the standard cosmic-ray transport equation:

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

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

Which Pulsars Contribute to the Positron Flux?

Consider the standard cosmic-ray transport equation:

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

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

$$L_{\rm dif}(E_e, t) \simeq 200\,\mathrm{pc}\left(\frac{35\,\mathrm{TeV}}{E_e}\right)^{0.3}\left(1-(1-E_e b t)^{0.6}\right)^{1/2}$$
$$\sim 40\,\mathrm{pc}\left(\frac{t}{10^5\,\mathrm{yr}}\right)\left(\frac{E_e}{100\,\mathrm{GeV}}\right)^{0.7}$$

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

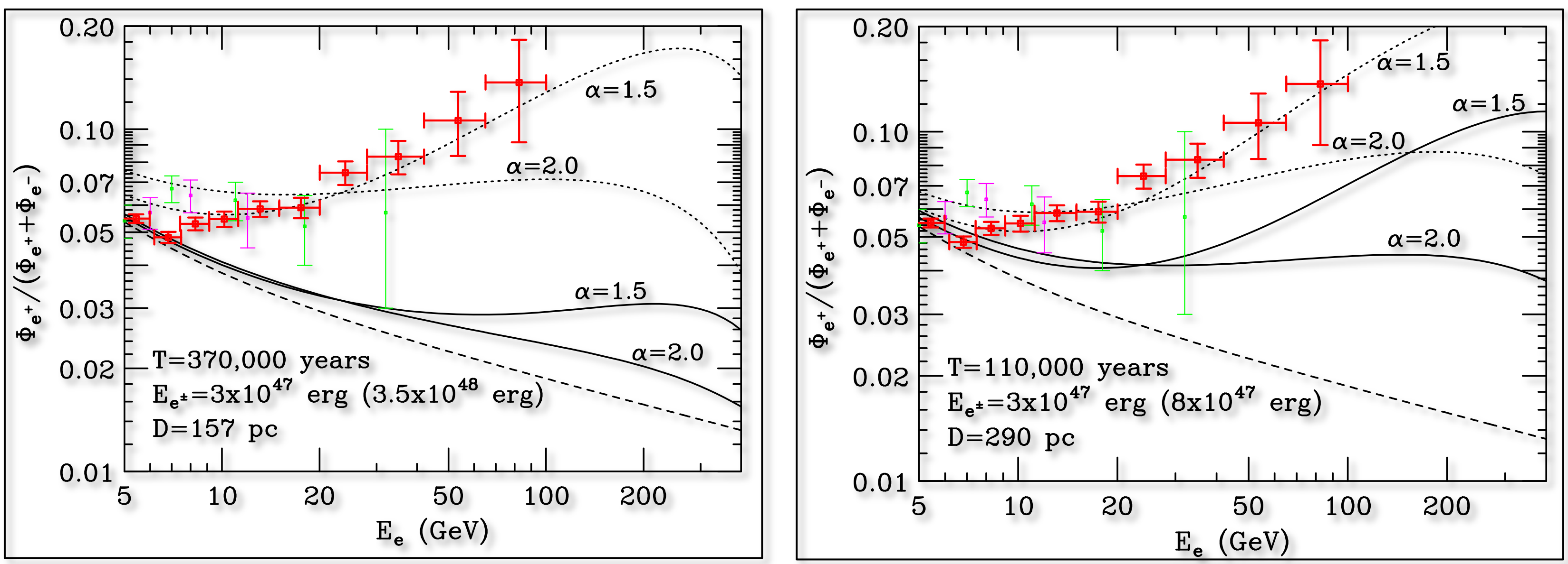
Cosmic Ray Positrons From Pulsars

- From these considerations, there are two known pulsars which appear to be 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

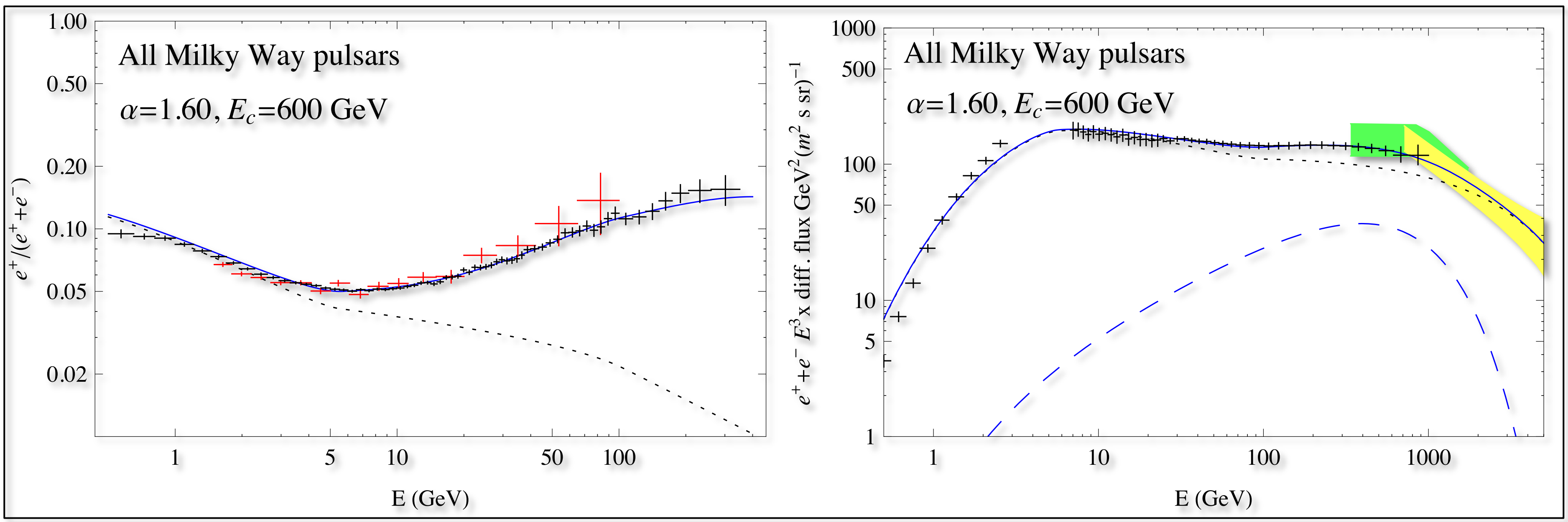
- If ~10% of the spindown power of these pulsars has been transferred into pairs, they could plausibly dominate the observed positron spectrum



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

Cosmic Ray Positrons From Pulsars

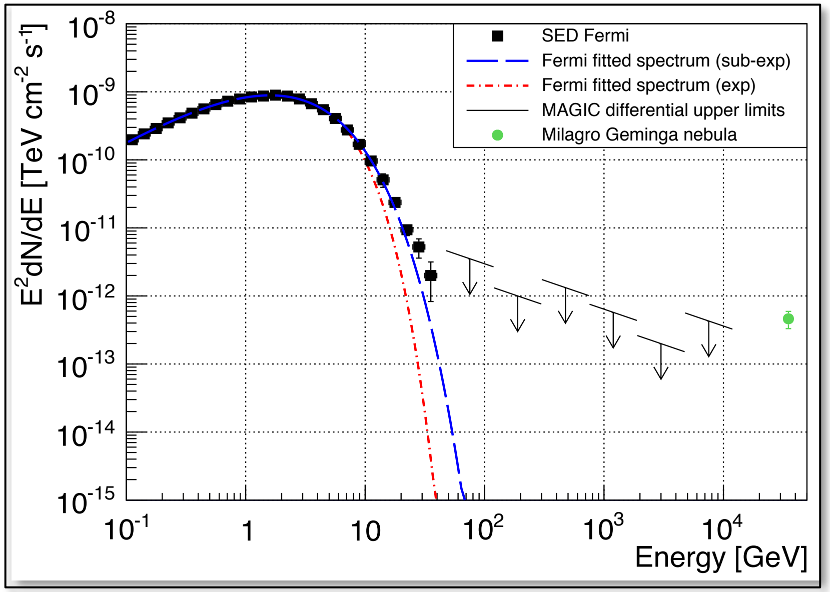
- The data from AMS, Fermi and HESS can be easily explained by these pulsars, although with non-negligible contributions from more distant Milky Way pulsars (which contribute most significantly at low energies)
- In the example shown below, all pulsars are assumed to inject 16% of their total spindown power into e^+e^- pairs
- The pulsar efficiency to pairs is the key parameter for this scenario, and was almost entirely unconstrained at the time



Cholis, DH, PRD, arXiv:1304.1840

Gamma-Ray Observations of Geminga

- At Fermi energies, Geminga is one of the brightest sources on the sky (second only to Vela), with a flux of $F \sim 7 \times 10^{-7}$ cm^{-2} s^{-1}, >1 GeV
- Geminga's GeV emission is highly pulsed, indicating that it originates from the pulsar itself (not from the surrounding nebula)



- MAGIC has also performed deep observations of Geminga, but have detected no emission at ~0.1-10 TeV energies

See Fermi 3FGL and 2PC catalogs;
MAGIC Collaboration, A&A, arXiv:1603.00730

Very High Energy Water Cherenkov Detectors

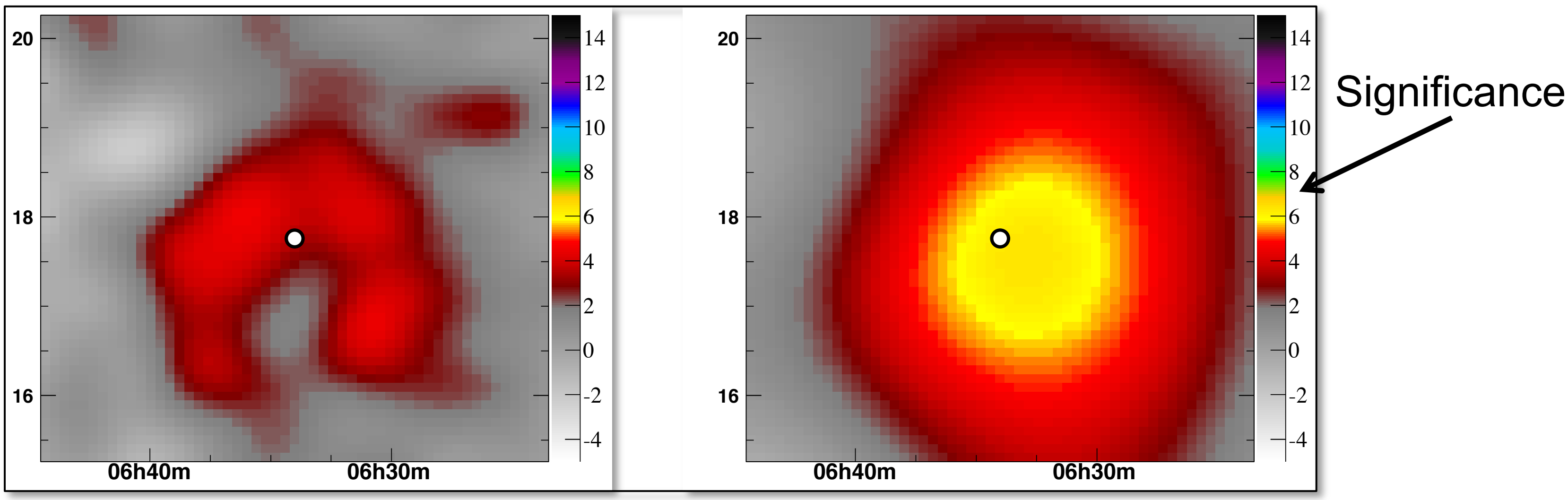
- The Milagro and HAWC experiments are ground-based gamma-ray and cosmic-ray detectors, located near Los Alamos and Puebla, Mexico, respectivley
- Unlike IACTs, these telescopes do not point – they observe most of the northern sky at all times
- The energy thresholds of these experiments are very high, in practice ranging from several TeV to tens of TeV.

Milagro

HAWC

VHE Gamma-Ray Observations of Geminga

- Milagro has also reported the detection of Geminga, although at a much higher energy of ~35 TeV
- If modeled as a point source, the significant of this detection is modest (3.5σ)
- But if modeled as a 1° Gaussian, this increases to 6.3σ
- The Milagro Collaboration regards this as a "definitive detection of extended emission" from Geminga, and report a full-width-half-max of $2.6^{+0.7}_{-0.9}$ degrees



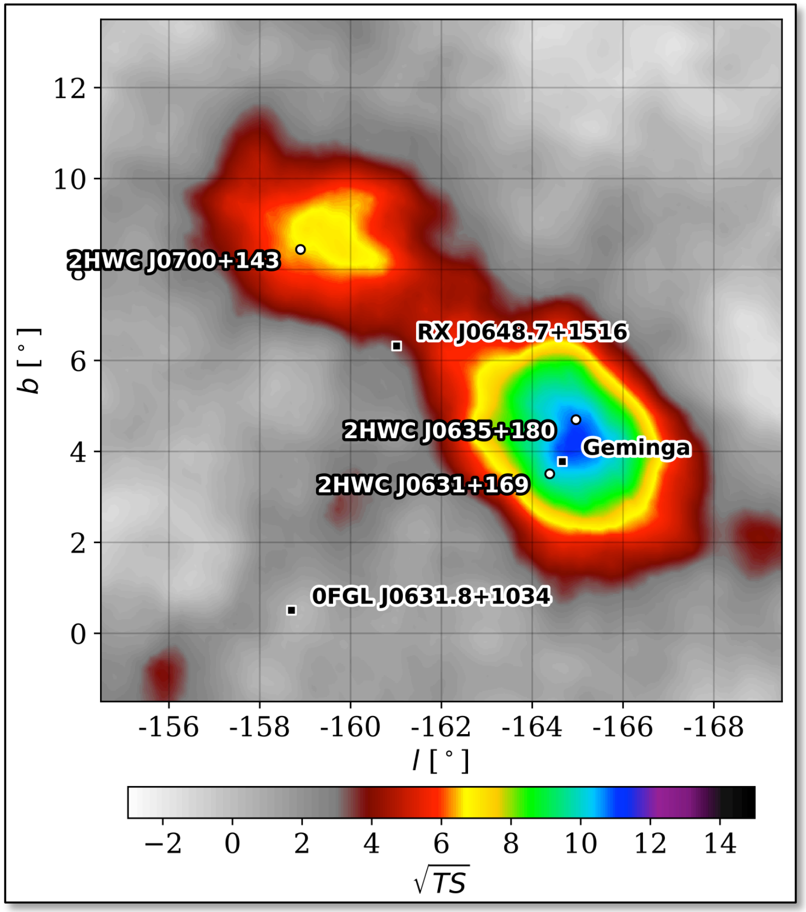
Modeled as a Point Source

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 Fermi
- The statistical significance of these results, and the quantity of spectral information, is much greater than that from Milagro

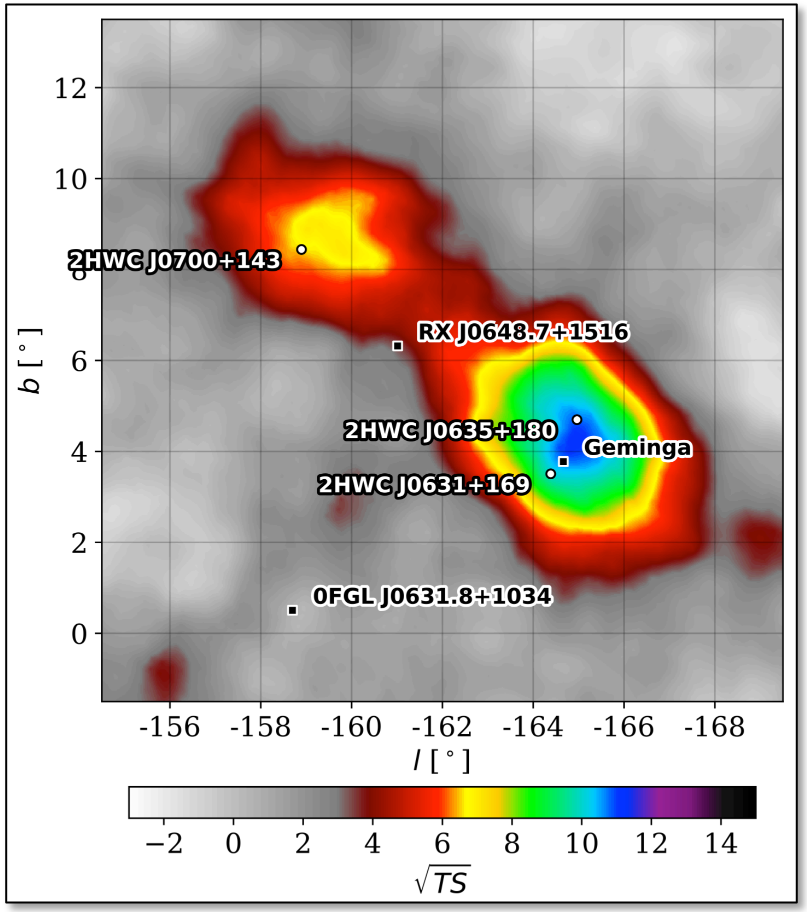


(Modeled as a 2° Radius Disk)

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 virtually certain to be responsible for this emission



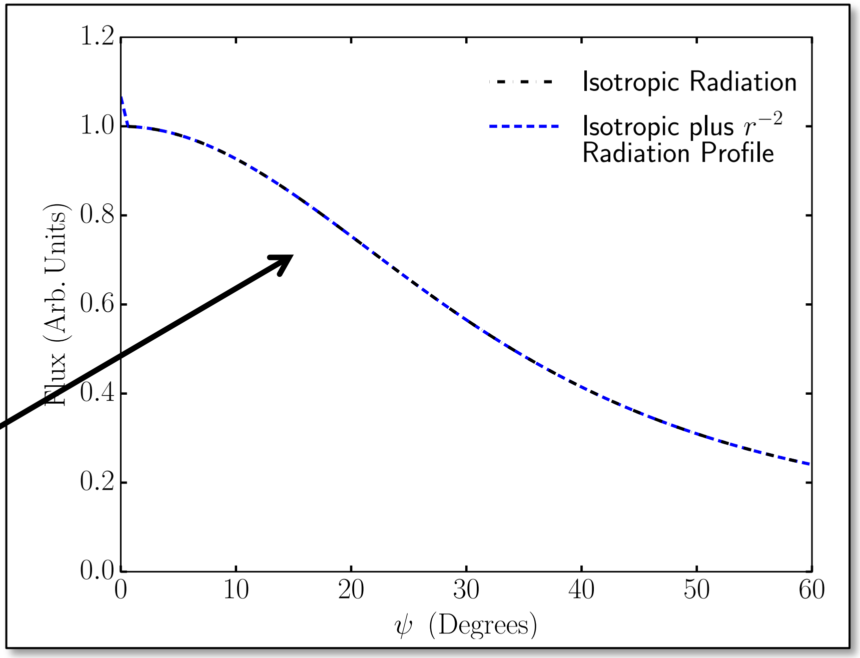
(Modeled as a 2° Radius Disk)

HAWC Collaboration, arXiv:1702.02992

Non-Standard Cosmic Ray Transport Around Geminga and B0656+14

- It is difficult to understand the observed spatial extension of this emission within the context of standard cosmic-ray transport
- For example, consider a ~35 TeV electron; this particle will lose its energy via ICS and synchrotron over a timescale of ~5000 years
- Over this length of time, the electron will diffuse ~120 parsecs
- The expected angular profile of the inverse Compton emission from Geminga is ~30°, not even close to the observed ~2° extension
- No plausible enhancement in the radiation density can substantively change this conclusion

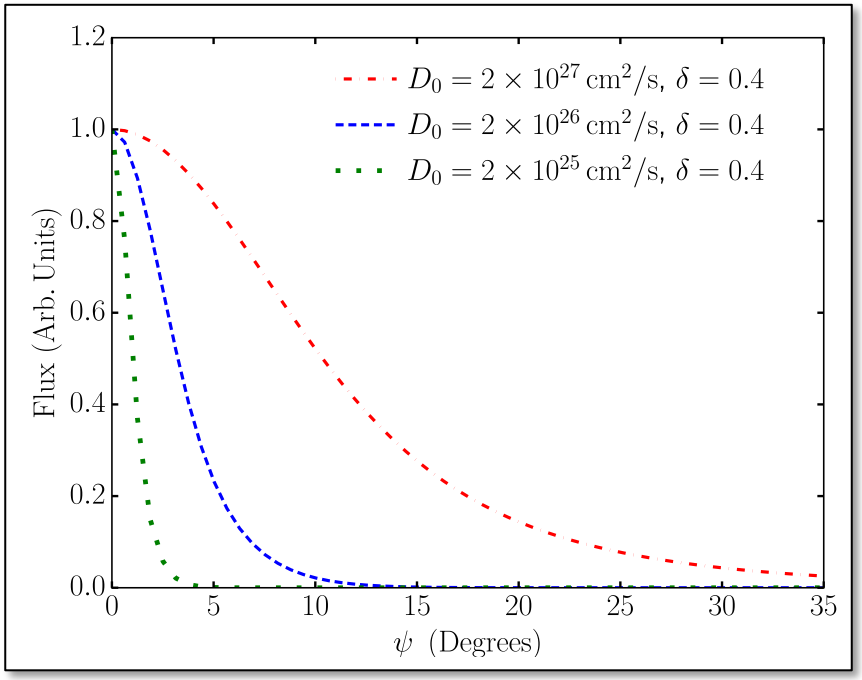
$$\Phi_\gamma(E_\gamma = E_e, \psi) \propto \int \dot{E}\, dt \int_{\rm los} \frac{dn_e}{dE_e}(E_e, r, t)\, \rho_{\rm rad}(r)\, dl$$



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

Non-Standard Cosmic Ray Transport Around Geminga and B0656+14

- In order for ~10-100 TeV electrons to diffuse only a few parsecs in an energy loss time, we must dramatically reduce the diffusion coefficient (by a factor of ~10^3 relative to that in the ISM) within the region surrounding these pulsars
- Physically, this means that particles frequently scatter within these environments, jumping from field line-to-field line (*ie*. taking very small steps in their random walk)



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

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

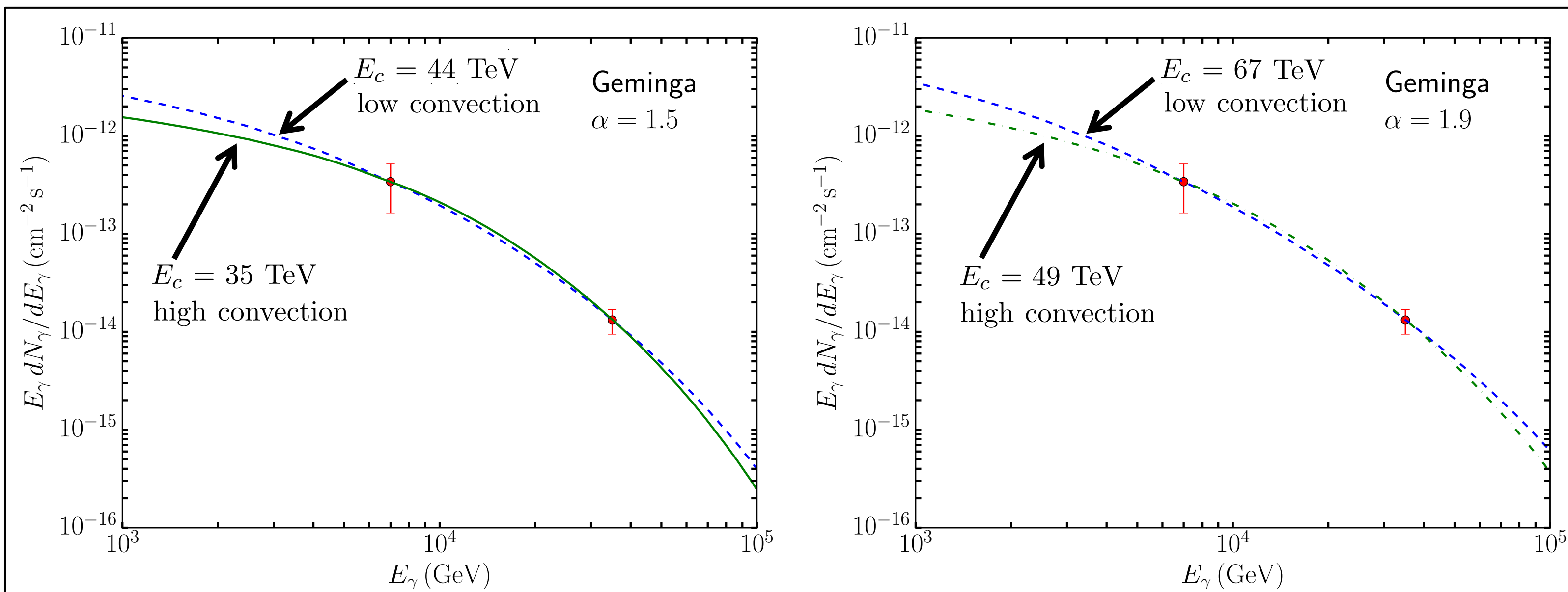
Main Idea: ***The surprising spatial extension of Geminga and B0656+14 allow us to measure the critically important (and until now highly uncertain) fraction of these pulsars' spindown power that goes into the production of energetic e^+e^- pairs***

- When a very high energy electron is injected into this environment, it emits the vast 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)

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

Implications of HAWC and Milagro for the Positron Excess

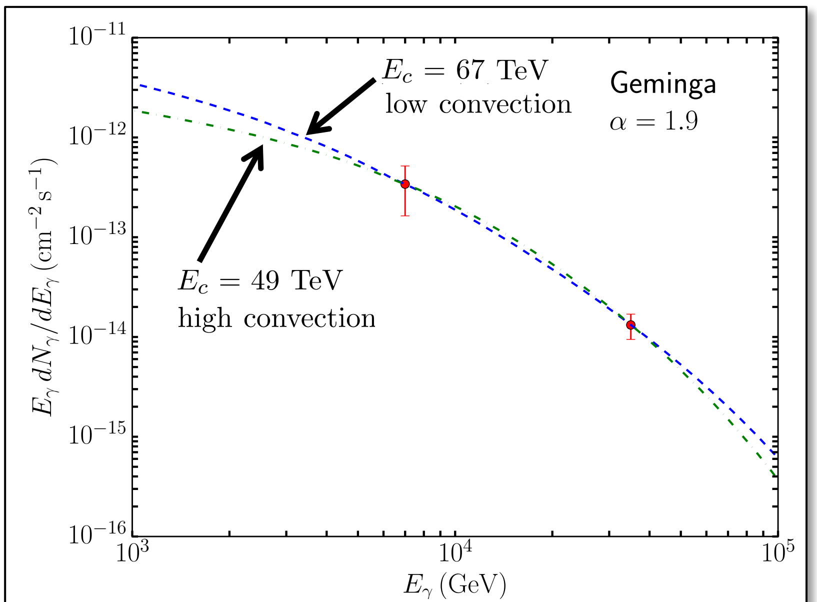
- For a given spectrum of injected pairs, we calculate the resulting ICS spectrum (including all Klein-Nishina corrections), and use this to constrain the normalization, spectral index (α), and energy cutoff (E_c)
- The VHE gamma-ray fluxes are best fit by α~1.5-2.0 and E_c~35-70 *TeV*
- In these best-fit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

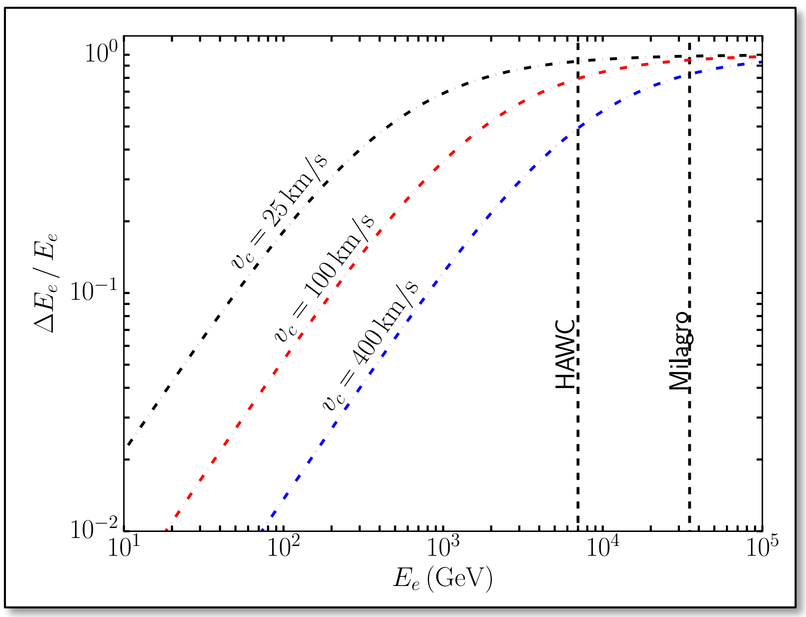


DH, I. Cholis, T. Linden, K. Feng, arXiv:1702.08436

The Role Of Convection

- For the very low diffusion coefficient that is required to explain the observed extension, it is mostly convective winds that allow lower energy electrons to escape the region surrounding Geminga
- The convection velocity impacts the shape of the gamma-ray spectrum
- 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 $v_c \sim 227$ *km/s* × (r_{region}/5 *pc*) while "*low convection*" refers to a tenth of this value

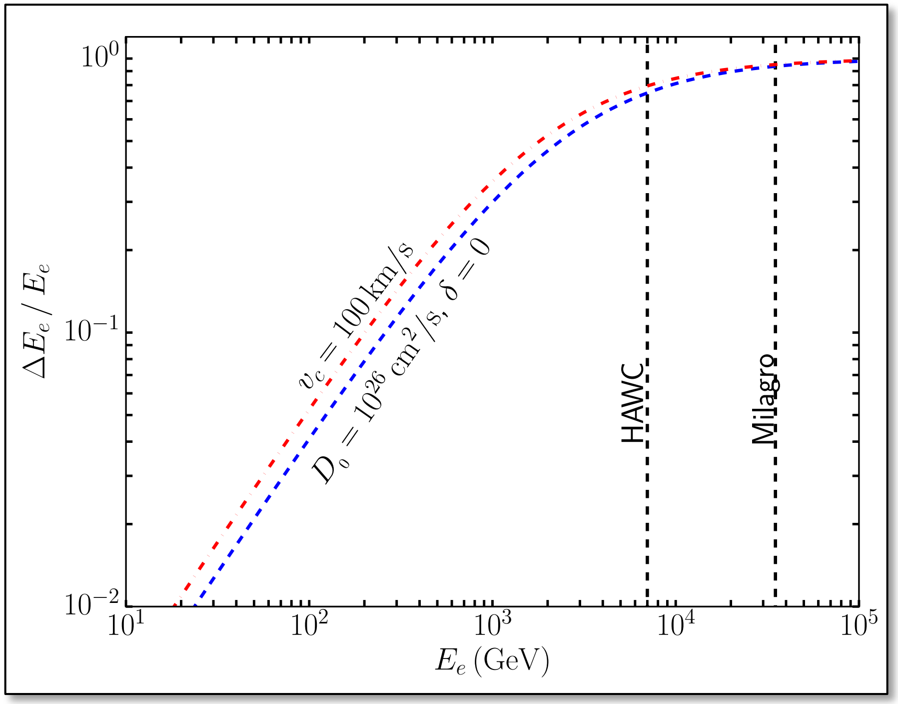




DH, I. Cholis, T. Linden, K. Feng, arXiv:1702.08436

The Role Of Convection

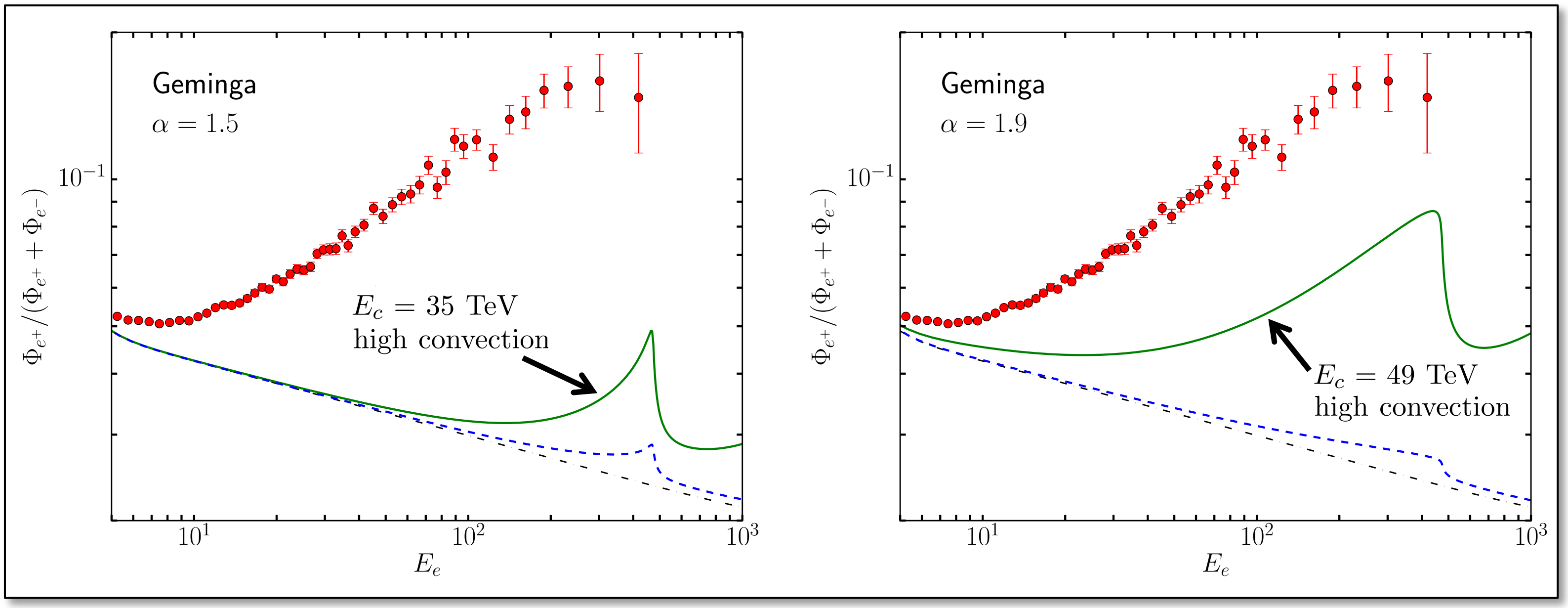
- One should keep in mind that convection in this context is largely indistinguishable from energy-independent diffusion (δ~o)
- I am happy to remain agnostic about the details of this mechanism
- Regardless, what the HAWC data tell us is that below ~10 TeV or so, electrons leave the region surrounding Geminga before they lose the majority of their energy



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

Implications of HAWC and Milagro for the Positron Excess

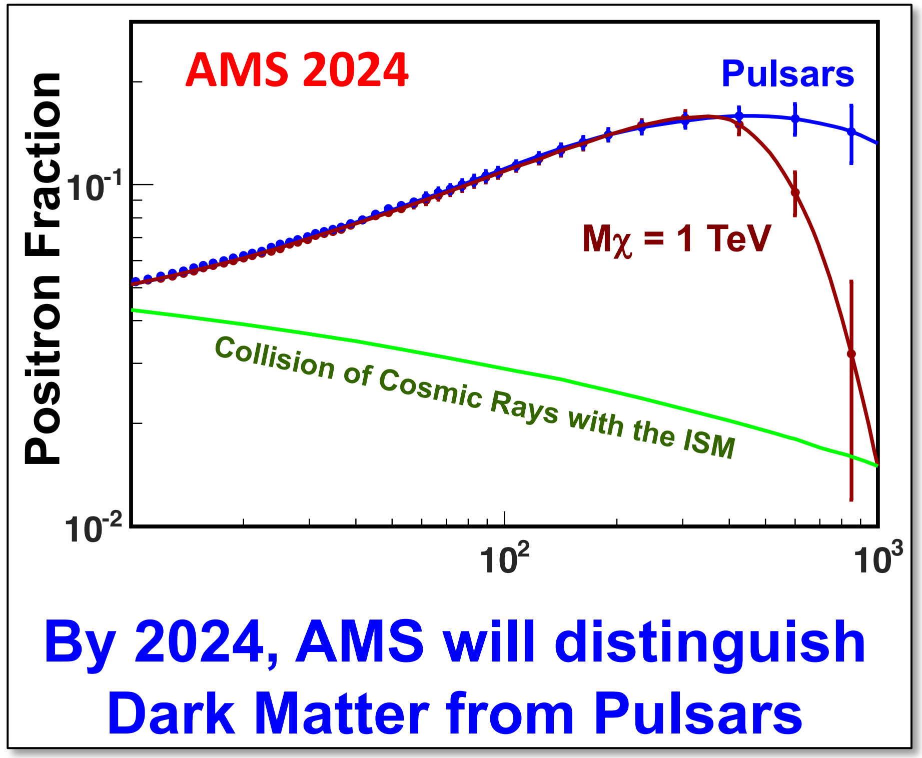
- We can now use this information to calculate the contribution from Geminga to the local positron flux
- Across the range of models that provide a good fit to the HAWC and Milagro data, Geminga contributes non-negligibly to the observed excess



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

A Note On Positron Spectral Features

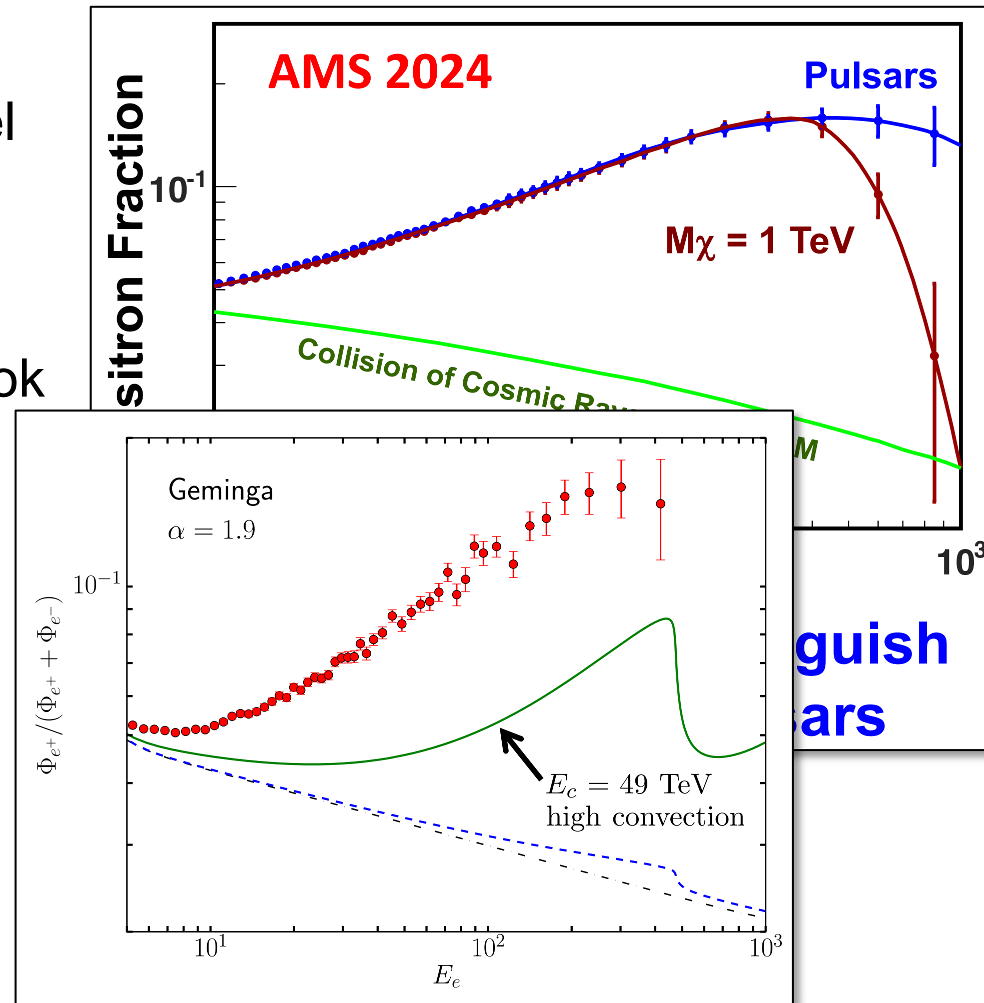
- A great deal is often made about "edges" and other spectral features that might appear in the positron spectrum
- Consider this plot, for example:
- First of all, this dark matter model doesn't make much sense – it is supposed to be from J. Kopp, PRD 88 (2013), but that paper doesn't show any spectra that look at all like this



From Talk by Sam Ting, Dec. 2016

A Note On Positron Spectral Features

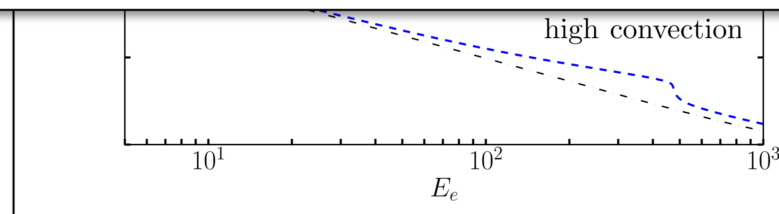
- A great deal is often made about “edges” and other spectral features that might appear in the positron spectrum
- Consider this plot, for example:
- First of all, this dark matter model doesn’t make much sense – it is supposed to be from J. Kopp, PRD 88 (2013), but that paper doesn’t show any spectra that look at all like this
- And secondly, a nearby pulsar could very plausibly generate an edge-like spectral feature
- Such an edge will appear at an energy of $E\sim 1/bt_{age}$, which for Geminga is at ~350-700 GeV (recall $dE/dt=-bE^2$)

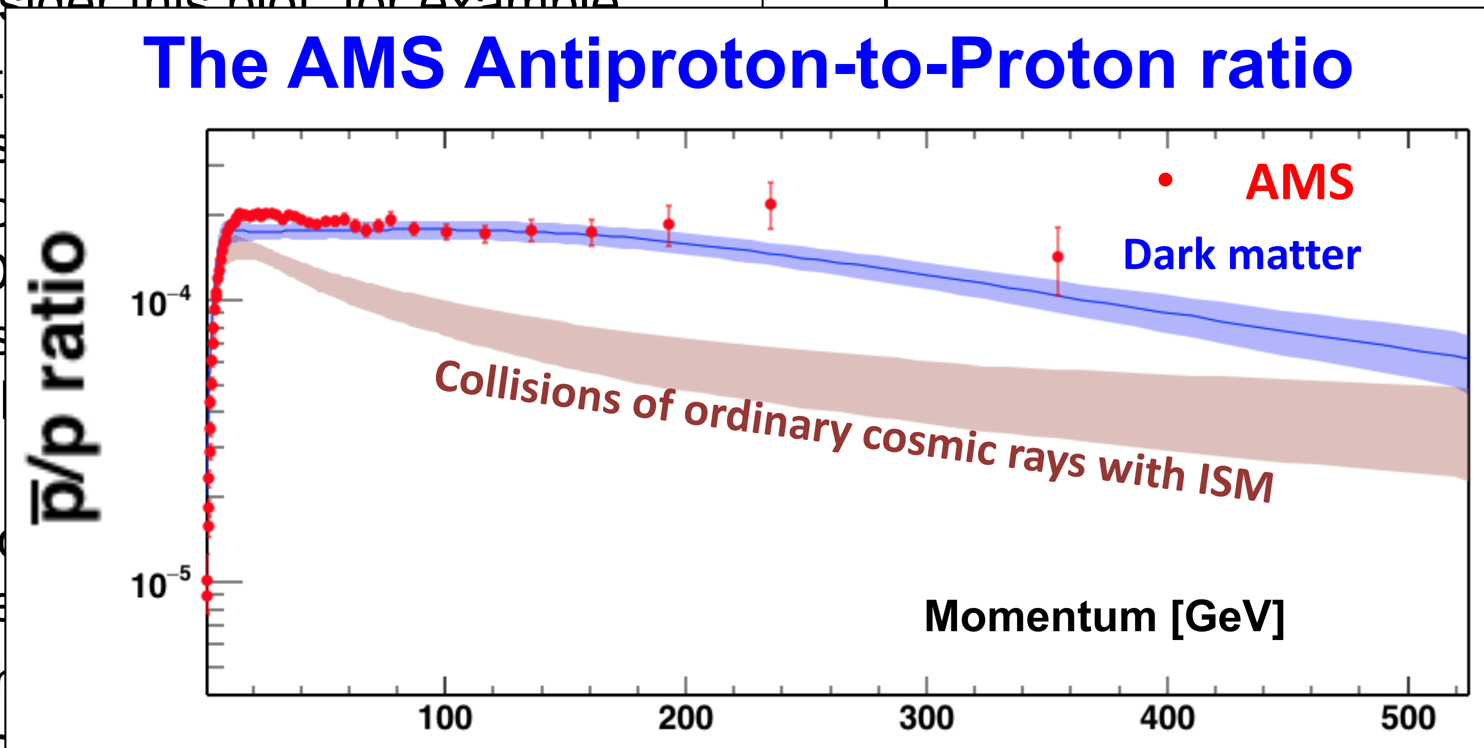


From Talk by Sam Ting, Dec. 2016

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:
- First does supp PRD does at all
- And coul edge
- Such ener Geminga is at ~350-700 GeV (recall dE/dt=-bE^2)





From Talk by Sam Ting, Dec. 2016

Some Caveats

The results of this calculation could easily be changed by an order one factor

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

Some Caveats

The results of this calculation could easily be changed by an order one factor

1) ICS vs synchrotron

- Some of the energy injected as e^+e^- pairs goes into synchrotron rather than ICS
- In our calculation, we adopted $B=3\ \mu G$, $\rho_{star}=0.60$ eV/cm^3, $\rho_{IR}=0.60$ eV/cm^3, and $\rho_{UV}=0.10$ eV/cm^3
- 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 results of this calculation could easily be changed by an order one factor

2) 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 (~3×10^5 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 $\tau \sim 10^4$ 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

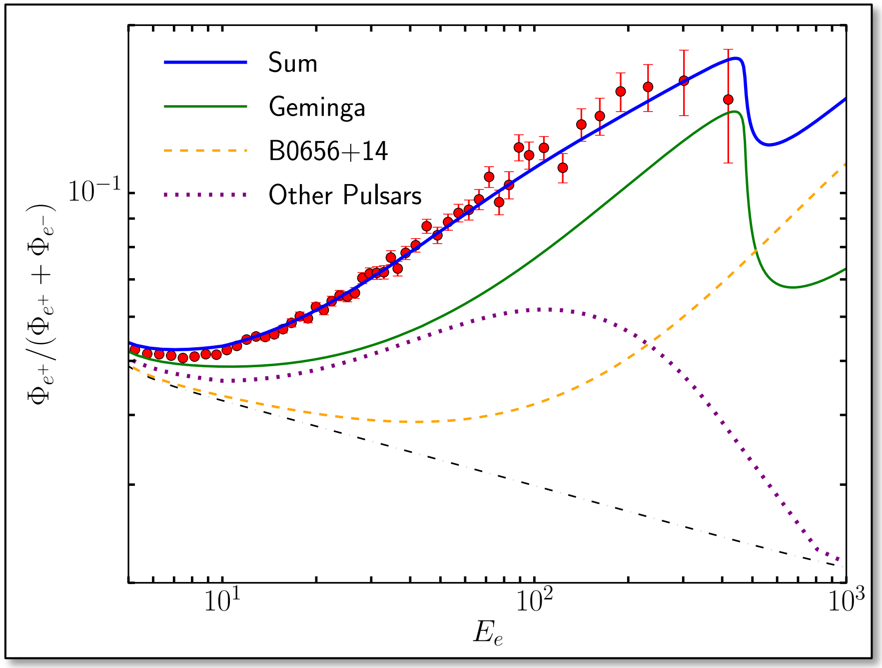
Positrons From Geminga, B0656+14, and More Distant Pulsars

- 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

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
- 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



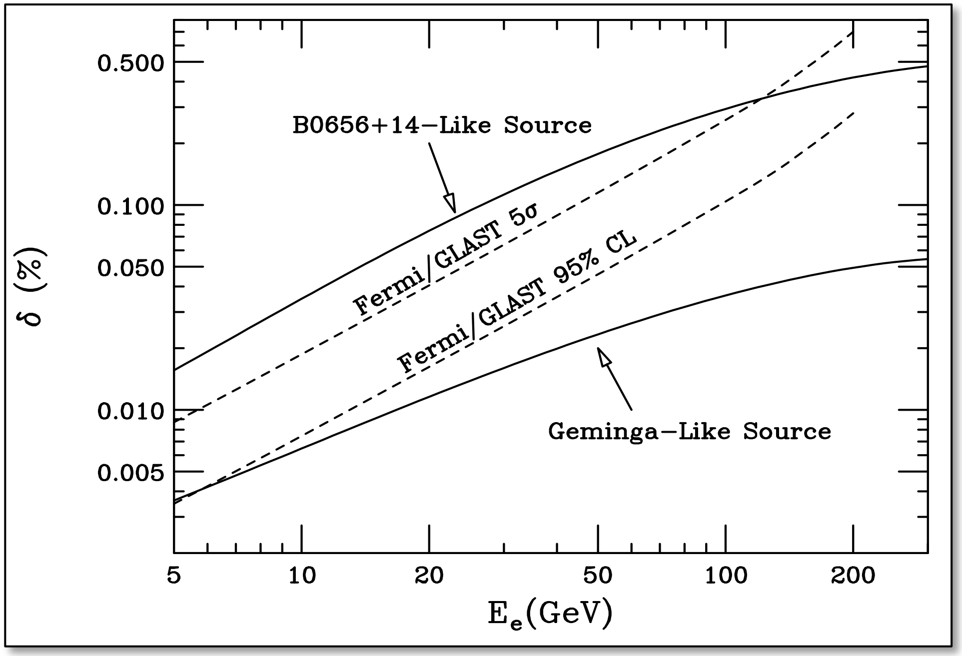
DH, I. Cholis, T. Linden, K. Feng, arXiv:1702.08436

Departures From Isotropy?

- If the local positron spectrum is dominated by Geminga and B0656+14, this to induce a small dipole anisotropy (at the level of ~10^{-3}, for electrons plus positrons)

$$\delta = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \frac{3K|\nabla(dN_e/dE_e)|}{c\,(dN_e/dE_e)}$$

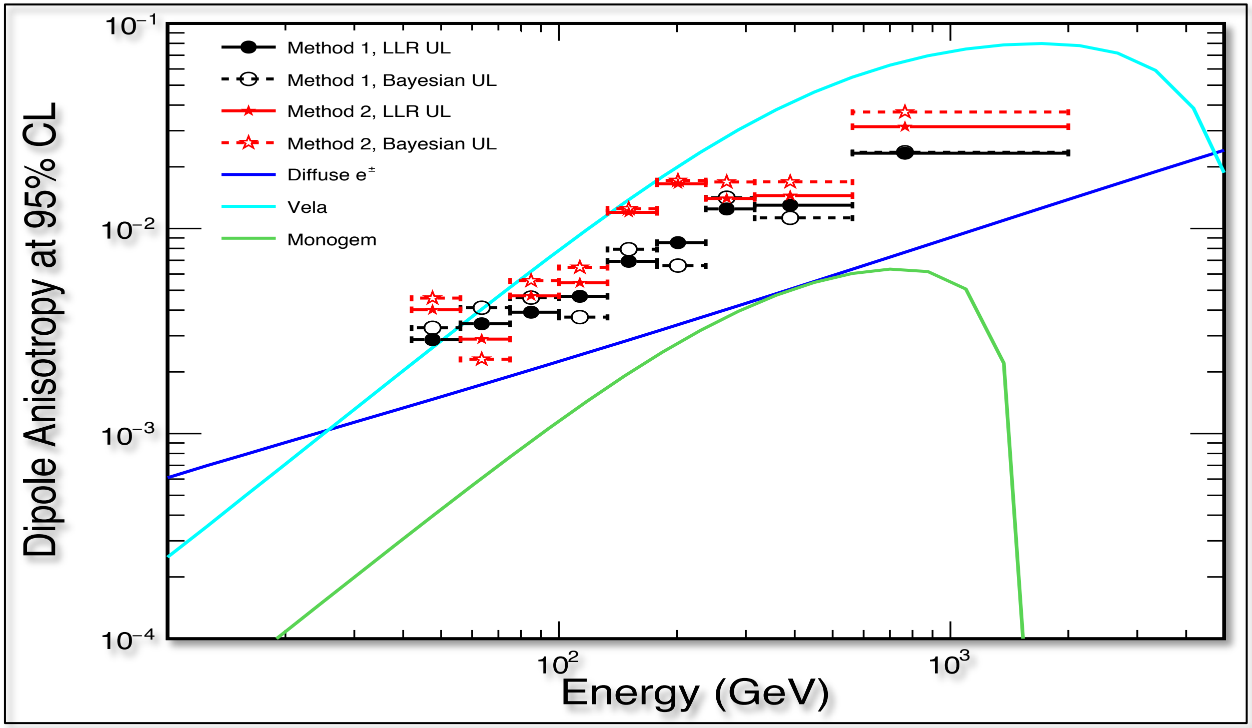
- From as early as 2008, it was projected that Fermi could be sensitive to such a scenario (although barely)
- AMS does not have nearly enough exposure to detect such a feature



DH, Blasi, Serpico, PRD, arXiv:0810.1527
(see also Buesching, et al., ApJ, arXiv:0804.0220)

Departures From Isotropy?

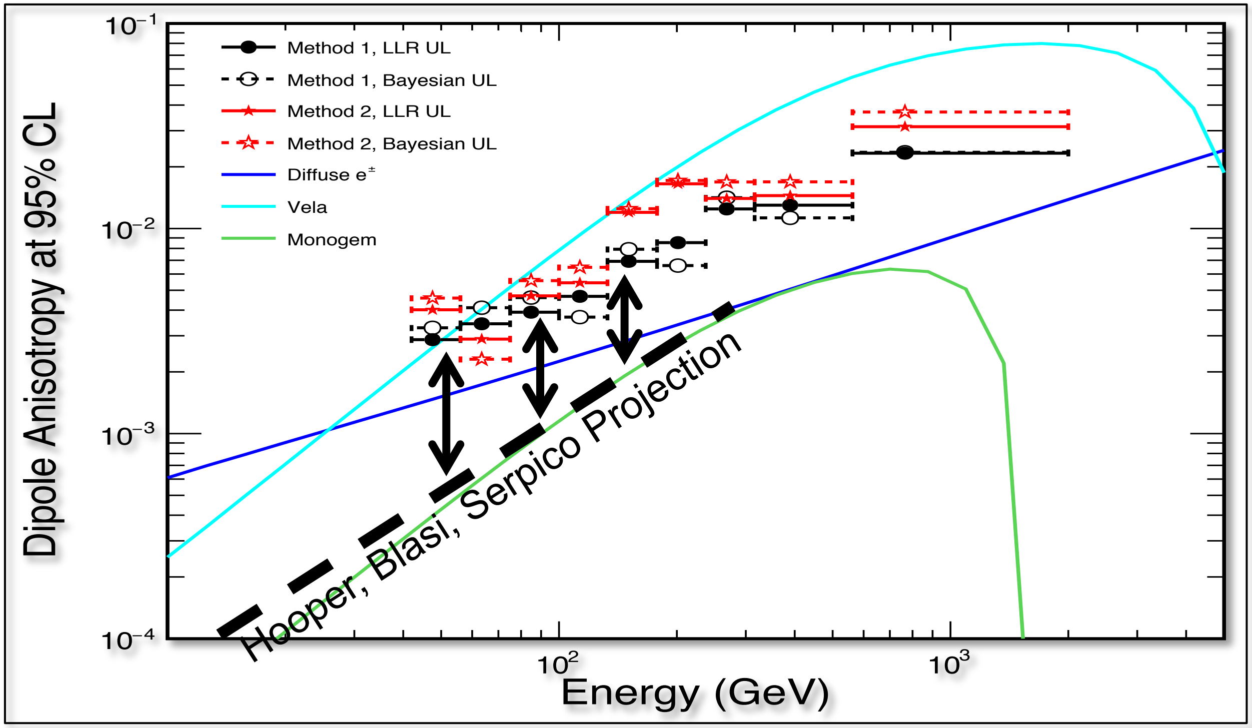
- The Fermi Collaboration has recently presented the results of an updated analysis searching for a dipole cosmic-ray anisotropy



Fermi Collaboration, arXiv:1703.01073
DH, Blasi, Serpico, PRD, arXiv:0810.1527
(see also Buesching, et al., ApJ, arXiv:0804.0220)

Departures From Isotropy?

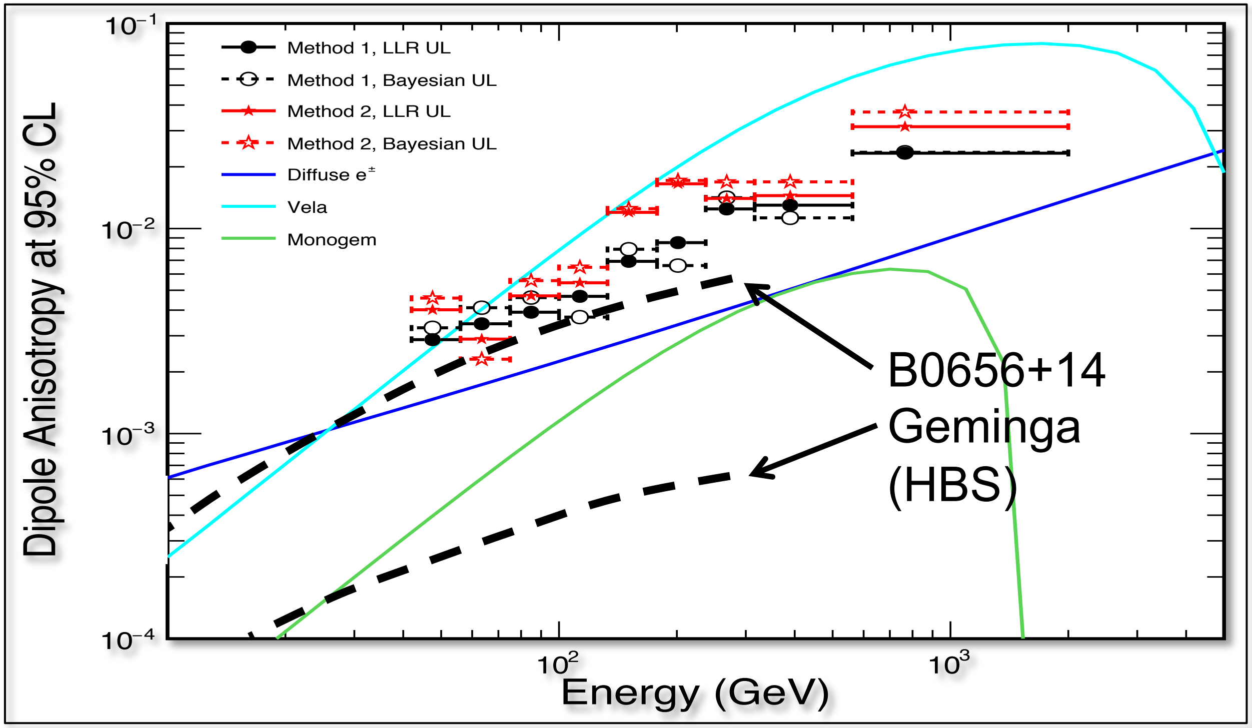
- The Fermi Collaboration has recently presented the results of an updated analysis searching for a dipole cosmic-ray anisotropy



Fermi Collaboration, arXiv:1703.01073
DH, Blasi, Serpico, PRD, arXiv:0810.1527
(see also Buesching, et al., ApJ, arXiv:0804.0220)

Departures From Isotropy?

- The Fermi Collaboration has recently presented the results of an updated analysis searching for a dipole cosmic-ray anisotropy



Fermi Collaboration, arXiv:1703.01073
DH, Blasi, Serpico, PRD, arXiv:0810.1527
(see also Buesching, et al., ApJ, arXiv:0804.0220)

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 (although some dark matter models may be able to accommodate the positron spectrum with only modest tension with Fermi)
- Recent measurements of the cosmic-ray antiproton spectrum by AMS provide some evidence ($\sim 3\sigma$) for the acceleration of cosmic-ray secondaries in supernova remnants – if confirmed, this would suggest that SNRs are responsible for a non-negligible fraction of the positron excess
- 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 allows us to deduce that pulsars generate an order one fraction of the positron excess, and plausibly 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.