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Stefano Profumo

Santa Cruz Institute for Particle Physics

University of California, Santa Cruz

Astro-connections to lepton flavor and universality violation

COFI, San Juan, Puerto Rico

Friday, May 26, 2018

- **Lepton flavor physics with cosmic rays: (1) the positron excess**

- **Lepton flavor physics with cosmic rays: (2) DAMPE**

- **Dark matter and lepton flavor universality violation**

- **Lepton flavor physics with cosmic rays: (1) the positron excess**

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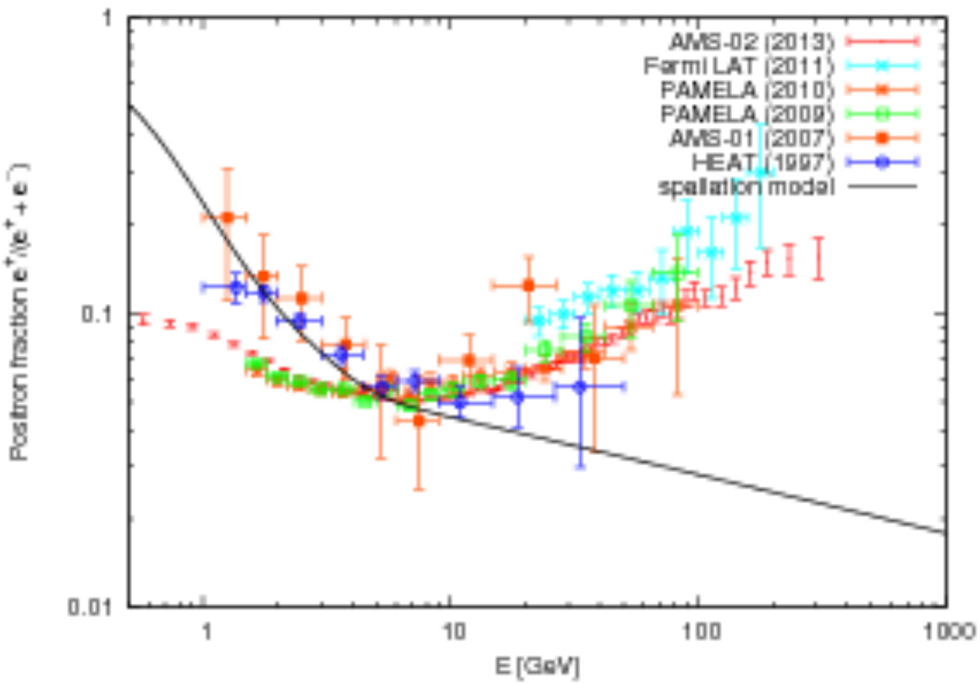
Most “famous” charged leptons in Astrophysics: Anomalous HE Positrons

Rising Positron Fraction with energy cut-off at Dark Matter particle mass, envisioned ~30 years ago, as smoking gun for Dark Matter searches

[Tylka 1989, Turner and Wilczek, 1990]

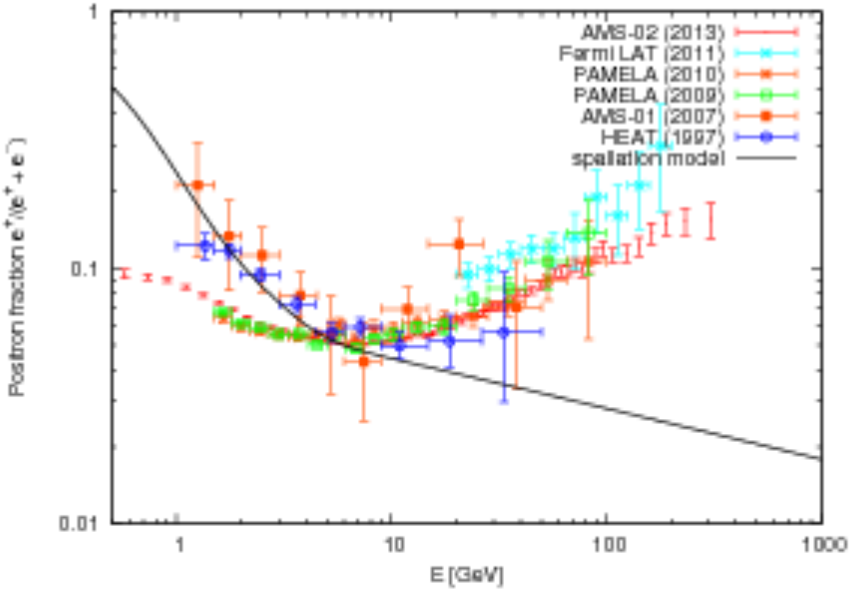
First hint of a rising positron fraction >20 year old!

- ✓ **HEAT 1997**
- ✓ **Pamela 2009**
- ✓ **Fermi 2010**
- ✓ **AMS 2013, 2015**



Decreasing positron fraction assumes **exclusive secondary origin**

[*Physics: D(E) ~ E^{δ}*]

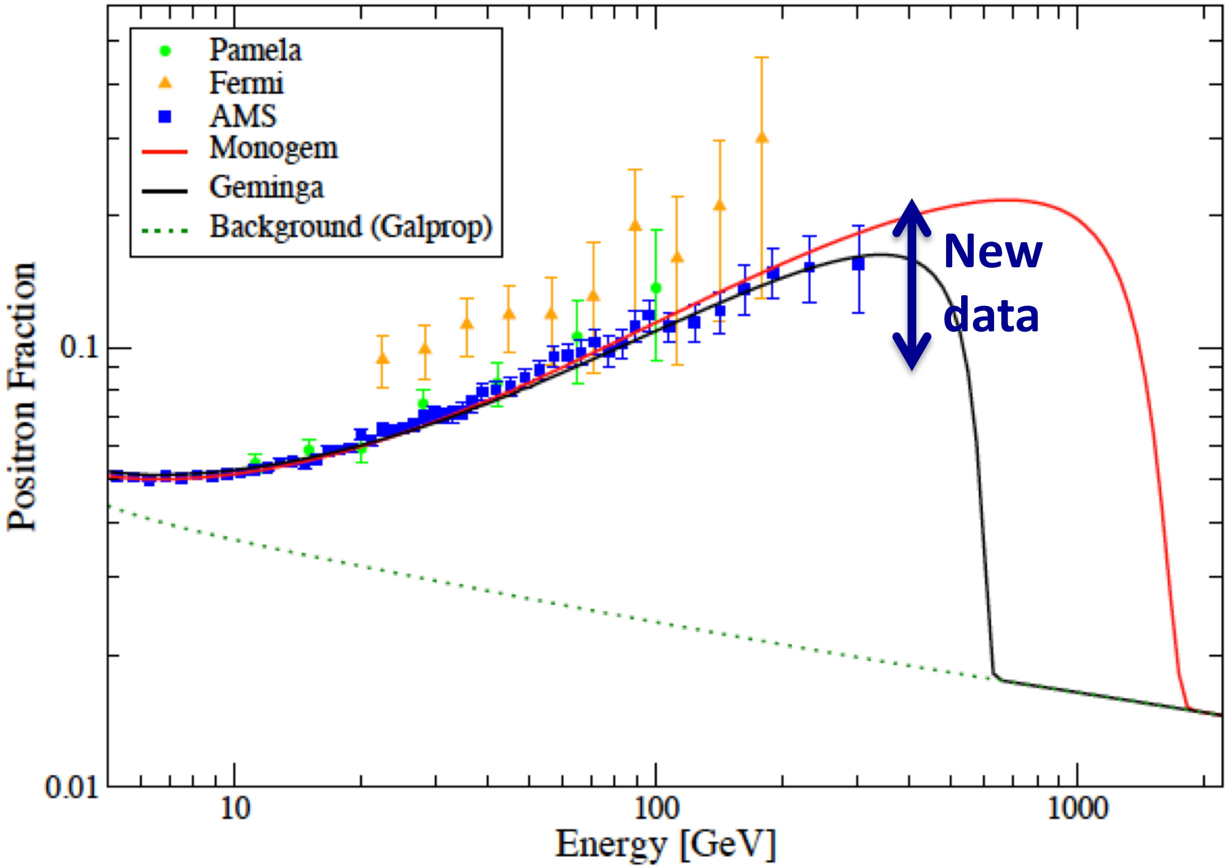


Hence **rising** fraction = **excess**

Caveats:

- in-source secondary **reacceleration** (**ruled out** by B/C)
- **primary** production (e.g. PSR)

PSRs work perfectly well



hardly any free parameter!

Linden and Profumo, **Astrophys.J. 772 (2013) 18**

Cutoff, in fact, is not a smoking gun for DM!

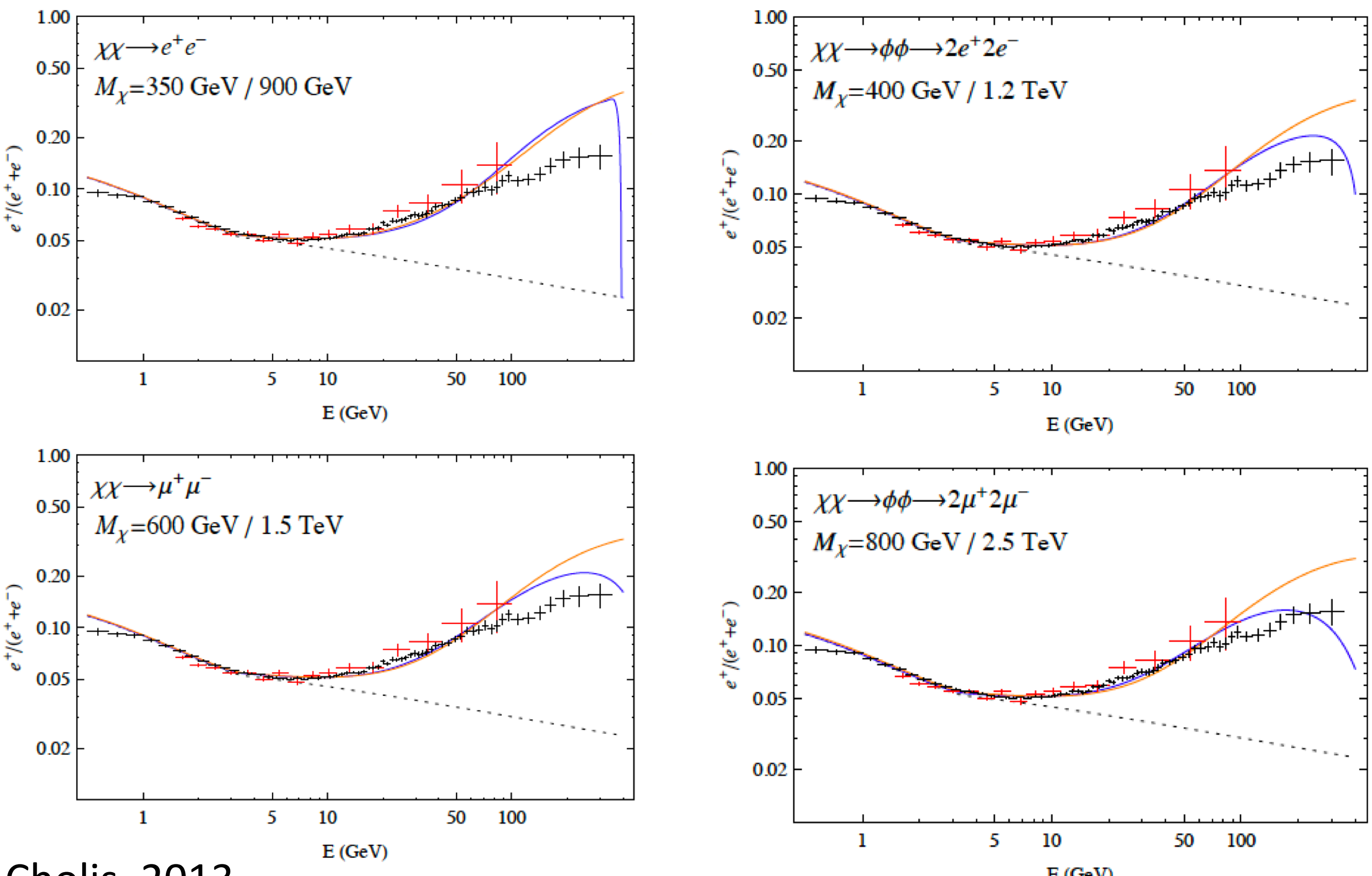
$$\frac{dE}{dt} = -bE^2 \qquad \int_{\infty}^{E_{max}} \frac{dE}{E^2} = -bT_{PSR} \qquad E_{max} = \frac{1}{bT_{PSR}}$$

Observing a cutoff will likely help pinpointing relevant PSR(s)

Known PSR OK

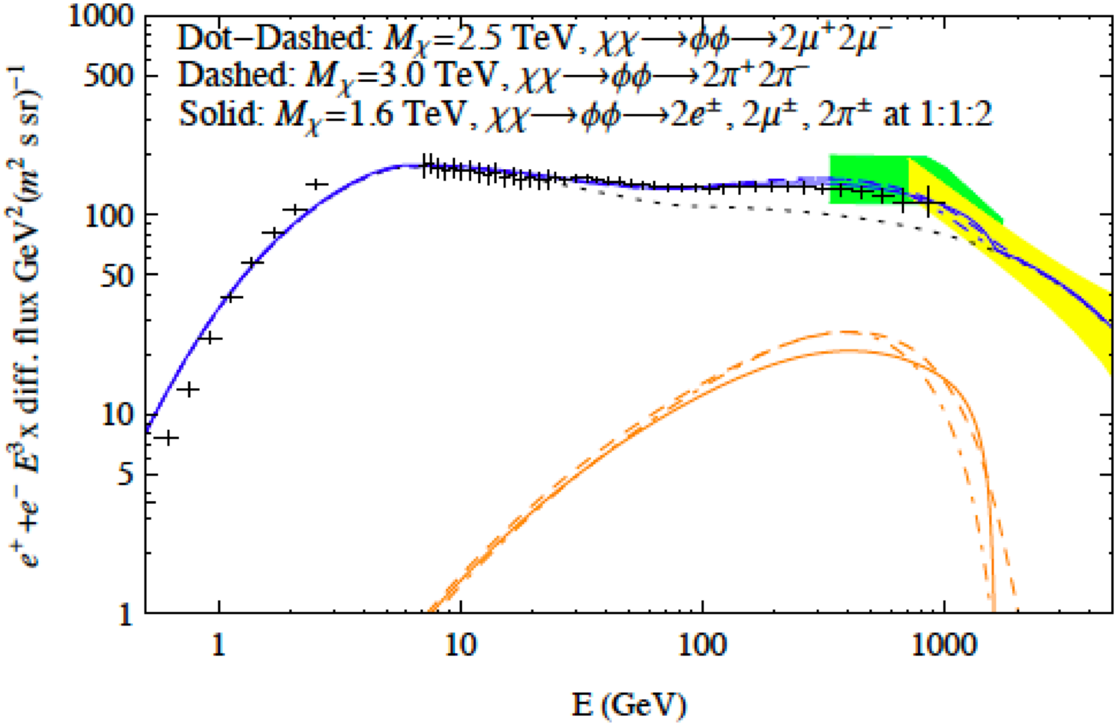
[new e.g. gamma-ray PSR also important, Gendelev+Profumo 2010]

If positrons come from DM annihilation, important implications for New Physics, flavor-related model building!



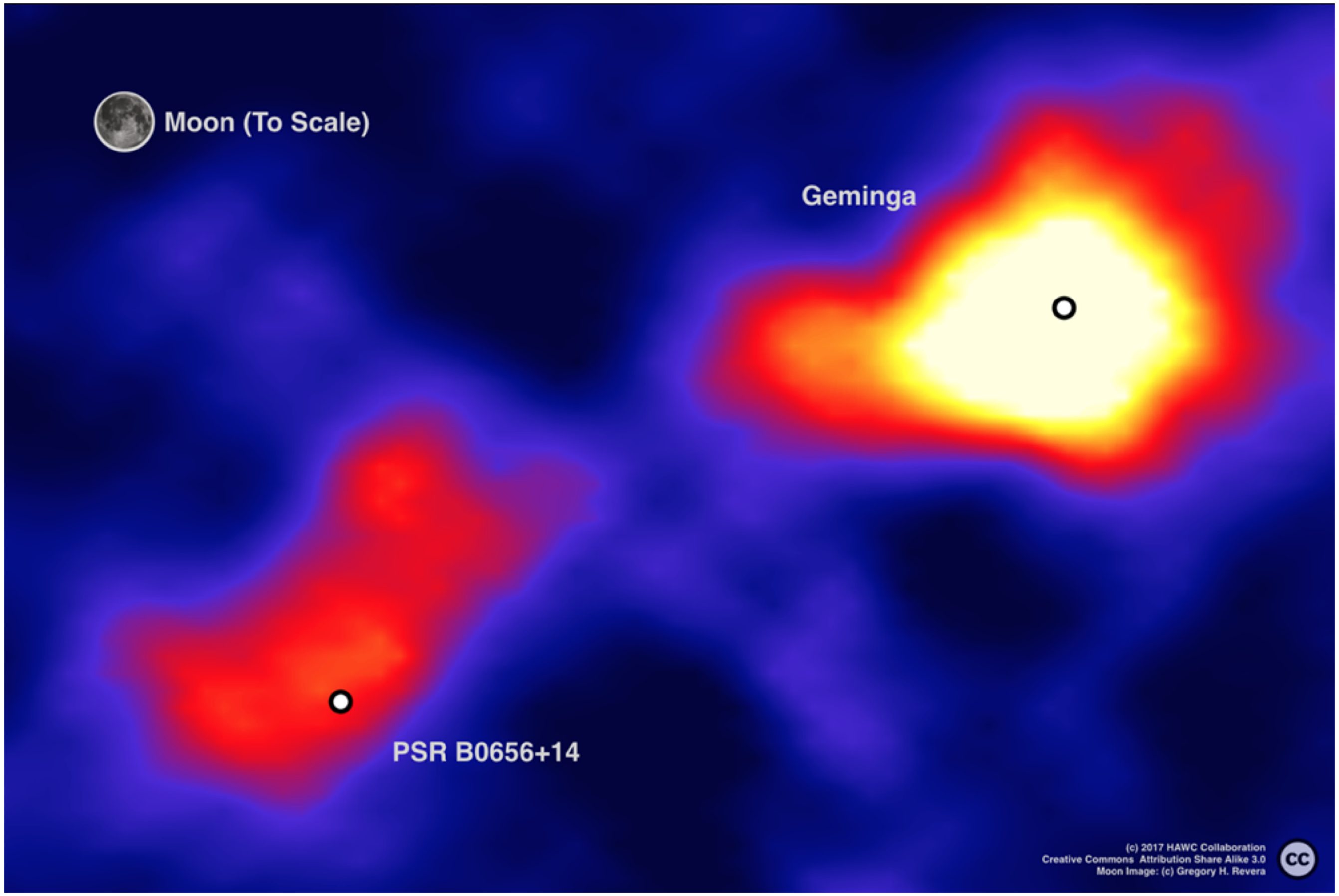
Hooper and Cholis, 2013

If positrons come from **DM annihilation**, important implications for **New Physics**, **flavor-related** model building!



Hooper and Cholis, 2013

While AMS continues to increase statistics, a new high-impact observational result appeared!


Moon (To Scale)
Geminga
PSR B0656+14
(c) 2017 HAWC Collaboration
Creative Commons Attribution Share Alike 3.0
Moon Image: (c) Gregory H. Revera
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PARTICLE ASTROPHYSICS

Extended gamma-ray sources around pulsars constrain the origin of the positron flux at Earth

A. U. Abeysekara,[1] A. Albert,[2] R. Alfaro,[3] C. Alvarez,[4] J. D. Álvarez,[5] R. Arceo,[4]
J. C. Arteaga-Velázquez,[5] D. Avila Rojas,[3] H. A. Ayala Solares,[6] A. S. Barber,[1]
N. Bautista-Elivar,[7] A. Becerril,[3] E. Belmont-Moreno,[3] S. Y. BenZvi,[8] D. Berley,[9] A. Bernal,[10]

demonstrate that these pulsars are indeed local sources of accelerated leptons, but the measured tera–electron volt emission profile constrains the diffusion of particles away from these sources to be much slower than previously assumed. We demonstrate that the leptons emitted by these objects are therefore unlikely to be the origin of the excess positrons, which may have a more exotic origin.

Astronomy®

Waukesha, WI

SUN & MOON | MERCURY & VI

Sun		Moon
RISE	6:16 AM	4:53 AM
SET	7:32 PM	3:59 PM

New pulsar result supports particle dark matter

The nature of dark matter remains elusive, but astronomers are now one step closer to the answer.

By Robert Naeye | Published: Thursday, November 16, 2017 physicsworld

Magazine

dark matter and energy

from dark matter after all

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NEWS SPACE 17 NOVEMBER 2017

Pulsars out for posit
leaving dark matter i

New modelling discounts a leading theory on ant
Andrew Masterson reports.

Sky-high observatory sheds light on origin of excess anti-matter

New study excludes nearby pulsars, points to dark matter as possible culprit

Chris Cesare, Miguel Mostafá, Gail McCormick
November 16, 2017

UNIVERSITY PARK, Pa. — The High-Altitude Water Cherenkov (HAWC) Observatory in Mexico, built and operated by an international team that

My key problem: (while writing numerous papers on the dark matter interpretation) I have a decade-old emotional attachment to the pulsar interpretation, that named names…

Dissecting Pamela (and ATIC) with Occam's Razor: existing, well-known Pulsars naturally account for the "anomalous" Cosmic-Ray Electron and Positron Data

Stefano Profumo[1,2]
[1] *Department of Physics, University of California, Santa Cruz, CA 95064, USA*
[2] *Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, CA 95064, USA*
(Dated: April 14, 2018)

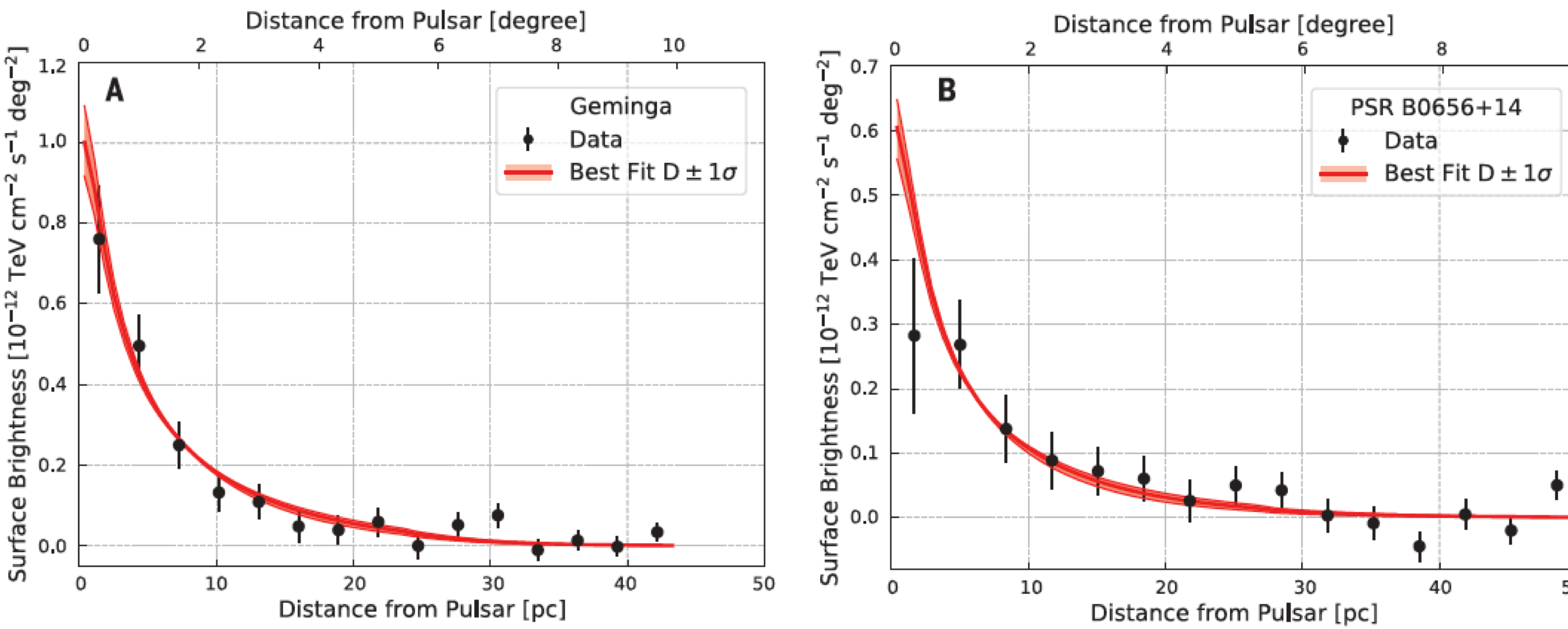
We argue that both the positron fraction measured by PAMELA and the peculiar spectral features reported in the total differential electron-positron flux measured by ATIC have a very natural explanation in electron-positron pairs produced by nearby pulsars. While this possibility was pointed

Name	Distance [kpc]	Age [yr]	$\dot{E}$ [ergs/s]	$E_{\rm out}$ [ST]	$E_{\rm out}$ [CCY]	$E_{\rm out}$ [HR]	$E_{\rm out}$ [ZC]	$f_{e^\pm}$	g
Geminga [J0633+1746]	0.16	3.42×10^5	3.2×10^{34}	0.360	0.344	0.013	0.053	0.005	0.70
Monogem [B0656+14]	0.29	1.11×10^5	3.8×10^{34}	0.084	0.456	0.004	0.372	0.015	0.14

spectral index of electron-positron pairs, and by (2) considering all known pulsars (as given in the ATNF catalogue). It appears unlikely that a single pulsar be responsible for both the PAMELA result and for the ATIC excess, although two sources are enough to naturally explain both of the experimental results. The PAMELA data favor mature pulsars (age $\sim 2 \times 10^6$ yr), with a distance of 0.8-1 kpc, or a younger and closer source like Geminga or the SNR Loop I. The ATIC data require a larger (and marginally unlikely) energy output, and favor an origin associated to powerful, more distant (1-2 kpc) and younger (age $\sim 5 \times 10^5$ yr) pulsars. We list several candidate pulsars that can

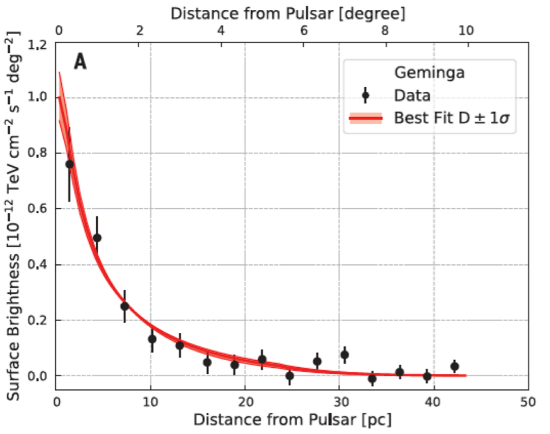
23 Dec 2008

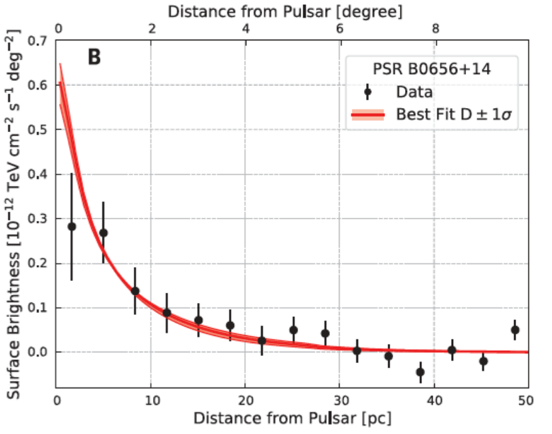
Key observational result: angular surface brightness



Gamma-ray energies as large as 20 TeV → e+e- as energetic as 100 TeV

100 TeV is deep in KN regime for starlight
→ only relevant photons: CMB





Gamma-ray energies as large as 20 TeV → e+e- as energetic as 100 TeV

$$E_\gamma^{\rm stars} \sim 1\,{\rm eV}, \qquad \gamma_e = \frac{10\ {\rm TeV}}{m_e} \sim 2{\times}10^7, \qquad E_\gamma \gg \frac{m_e}{\gamma_e} \sim 0.03\,{\rm eV}$$

100 TeV is deep in KN regime for star light
→ only relevant photons: CMB
→ Mean free path>>10 pc
→ Direct measurement of e+e- diffusion!

Inferred diffusion coefficients:

	Geminga	PSR B0656+14
D_{100} (diffusion coefficient of 100-TeV electrons from joint fit of two PWNe) ($\times 10^{27}$ square centimeters per second)	4.5 ± 1.2	4.5 ± 1.2
D_{100} (diffusion coefficient of 100-TeV electrons from individual fit of PWN) ($\times 10^{27}$ square centimeters per second)	$3.2^{+1.4}_{-1.0}$	15^{+49}_{-9}

…versus ISM diffusion coefficient (GALPROP, AMS-02…)

$$D_{100}^{\rm ISM} \simeq 3.86\times 10^{28} \left(\frac{E_e}{\rm GeV}\right)^{0.33} \ {\rm cm}^2/{\rm s} \rightarrow \ 1,720\times 10^{27}\ {\rm cm}^2/{\rm s}$$

…thus the inferred diffusion coefficient is 100-500 times larger than the ISM effective value!

(notice also the injected power in electrons is consistent with being a fraction of O(0.1) of spin-down power)

What does this mean?

Go back to electron transport

Transport model: diffusive (Brownian) motion + energy losses

$$\frac{\partial \psi}{\partial t} = \vec{\nabla} \cdot (D(\vec{x}, E)\vec{\nabla}\psi) + \frac{\partial}{\partial E}(P(E)\psi) + Q$$

This PDE has a known Green frunction

$$\psi(t, r, E) = \frac{N_o(E_o)P(E_o)}{\pi^{3/2}P(E)r_{\rm diff}^3} e^{-r^2/r_{\rm diff}^2}, \qquad r_{\rm diff}^2 = \int_E^{E_o} D(x)/P(x)dx.$$

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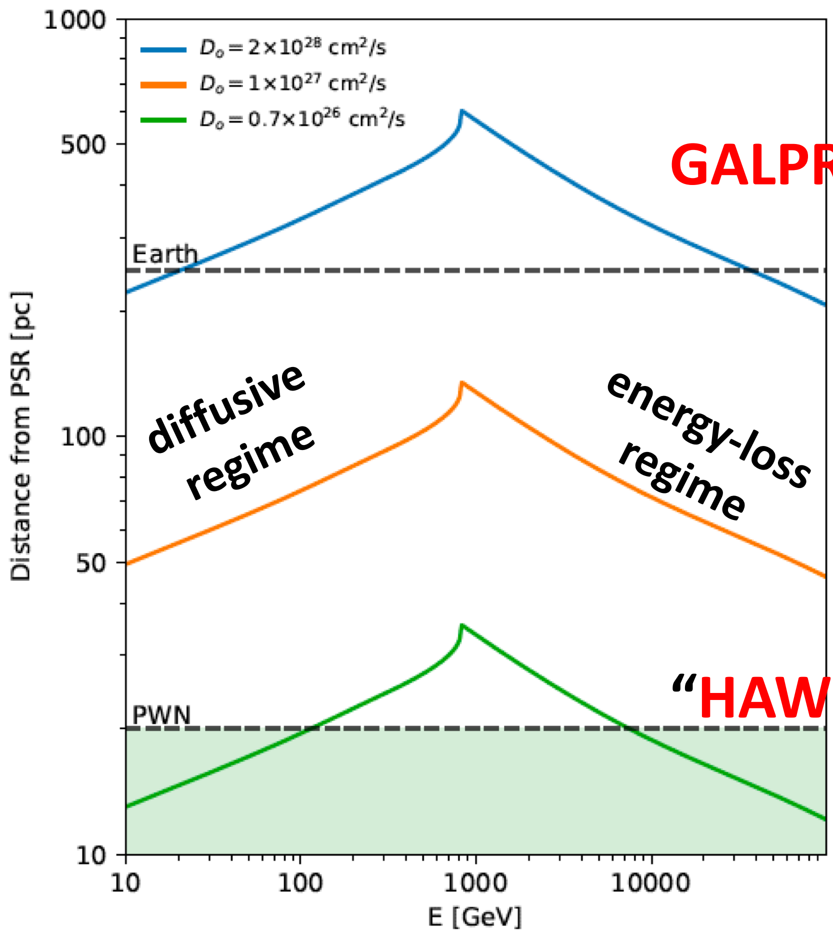
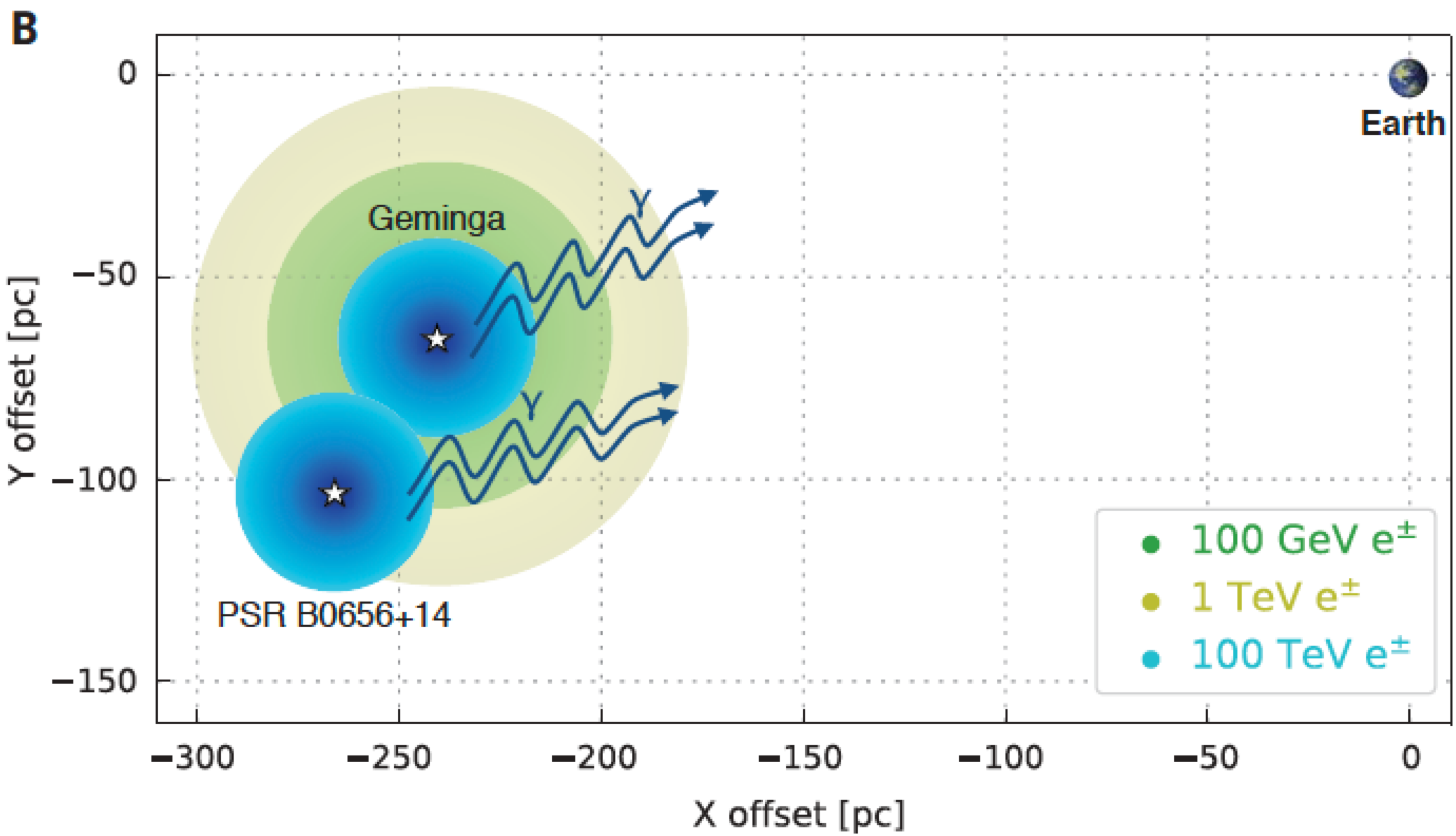
What is the diffusion radius for relevant electron energies?



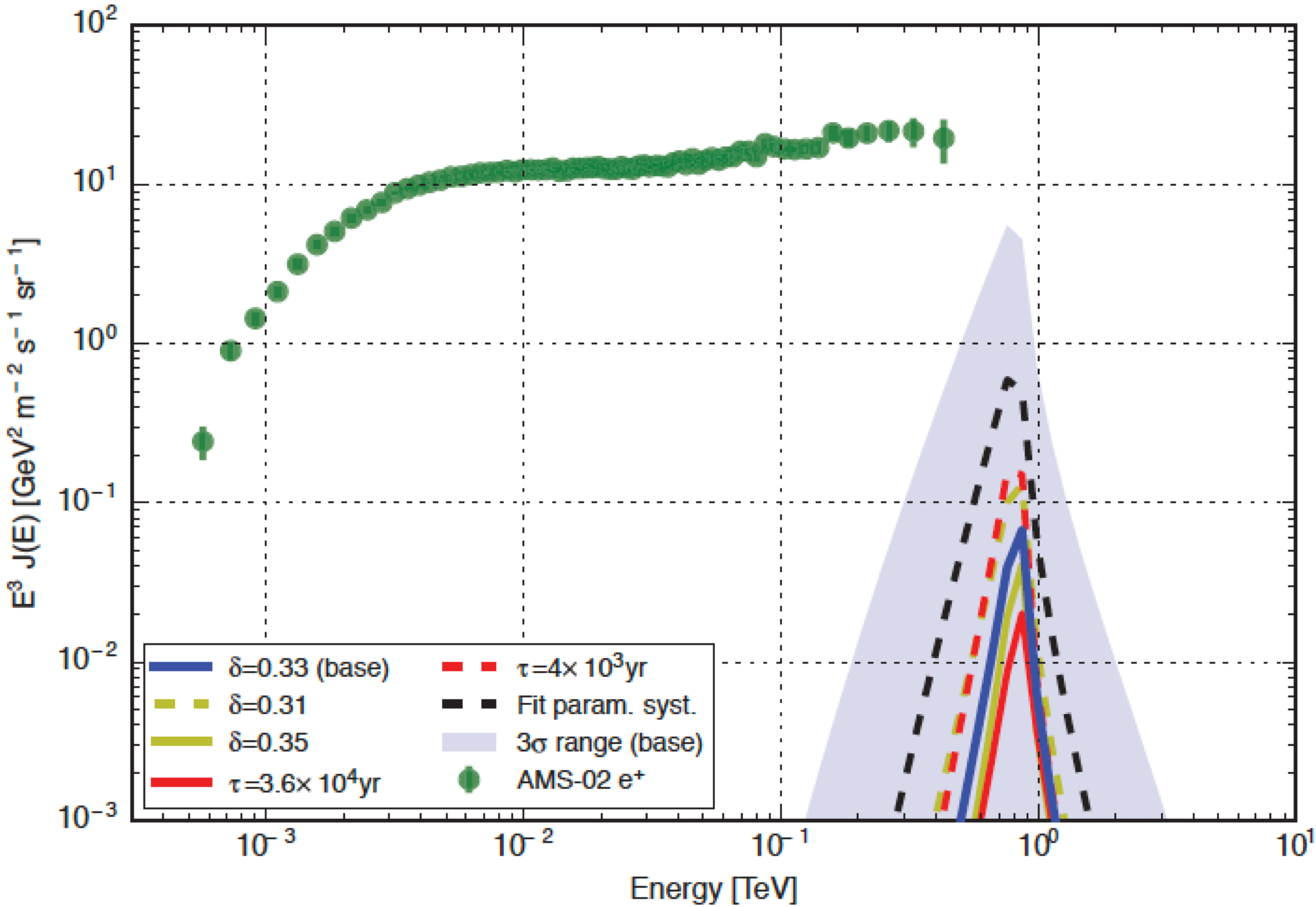
GALPROP-AMS Diff.Coeff.

“HAWC” Diff.Coeff.

*Profumo, Reynoso, Kaaz, Silverman 2018



* Abaysekara et al (HAWC Coll.) 2017



* Abaysekara et al (HAWC Coll.) 2017

Geminga and PSR B0656+14 are the oldest pulsars for which a tera–electron volt nebula has so far been detected. Under our assumption of isotropic and homogeneous diffusion, the dominant source of the positron flux above 10 GeV cannot be either Geminga or PSR B0656+14. Under the unlikely situation that the field is nearly

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NEWS SPACE 17 NOVEMBER 2017

Pulsars out for positron count, leaving dark matter in the frame

New modelling discounts a leading theory on antimatter particles hitting Earth. Andrew Masterson reports.

Is this conclusion **plausible**?

Very probably **NO**.
Two **key** arguments:

1. **Lifetime** of TeV electrons is **short**: $\tau_e \sim 3 \times 10^5 \text{ yr} \times (1 \text{ TeV}/E_e)$.

We observe directly CR electrons with energies >20 TeV

$$d \lesssim \sqrt{D\tau_e}$$

for HAWC Diff.Coeff., this means a source within 10-20 pc.
Such a source however **doesn't exist**!

* Profumo et al, Hooper and Linden 2017

Is this conclusion plausible?

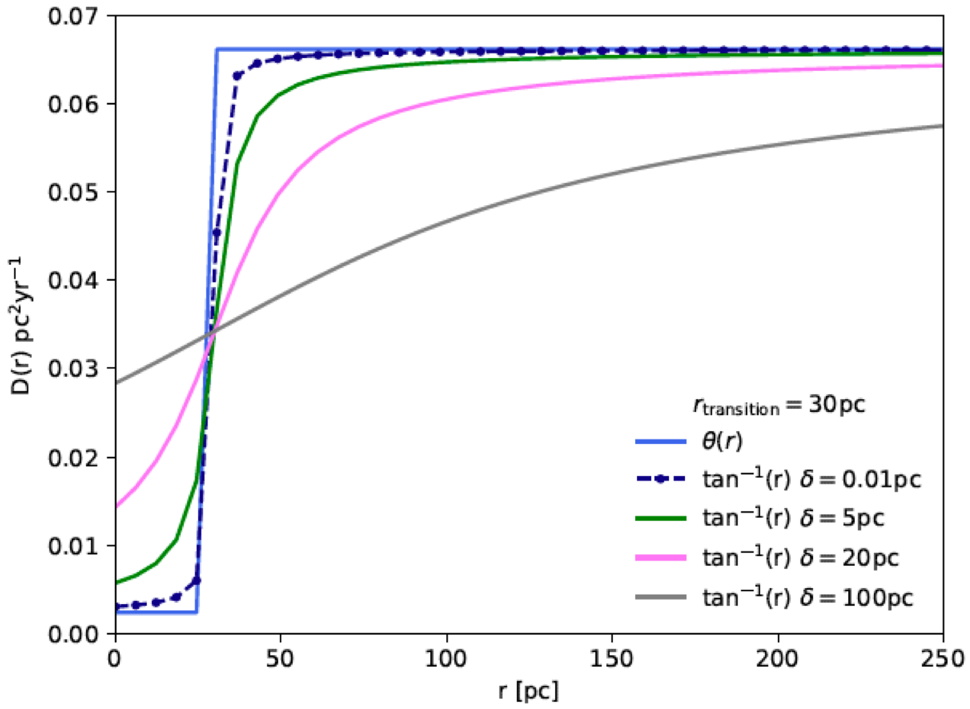
Very probably NO.
Two key arguments:

2. Models of CR emission predict inefficient diffusion near sources

Alfven waves generated by cosmic rays induce a net force that suppresses diffusion near the sites of cosmic-ray acceleration and, more generally, where cosmic-ray fluxes are larger

* Malkov et al 2012, Nava et al 2016, D'Angelo et al 2018

What happens to the local electron flux if indeed diffusion is not homogeneous?



$$D_\theta(r) = D_1\theta(r_T - r) + D_2\theta(r - r_T)$$

$$D_{\mathrm{T}}(r) = D_1 + \frac{(D_2 - D_1)}{\pi}\left(\tan^{-1}\left(\frac{\mathrm{r} - \mathrm{r_T}}{\delta}\right) + \frac{\pi}{2}\right)$$

*Profumo, Reynoso, Kaaz, Silverman 2018

What happens to the local electron flux if indeed diffusion is not homogeneous?

$$\frac{\partial f}{\partial t} = D \frac{\partial^2 f}{\partial x^2}$$

$$f(t,x) = \frac{1}{2\pi} \int_{-\infty}^{\infty} dx' f_o(x') \left\{ \frac{1}{\sqrt{4\pi D t}} e^{\frac{(x-x')^2}{4Dt}} \right\}$$

$$x = x_o + \eta \sqrt{2D\Delta t},$$

$$\Delta t \rightarrow \Delta u(E) \qquad\qquad \Delta u(E_i) = \int_{E_i+\Delta E}^{E_i} \frac{D(x)}{P(x)} dx,$$

*Profumo, Reynoso, Kaaz, Silverman 2018

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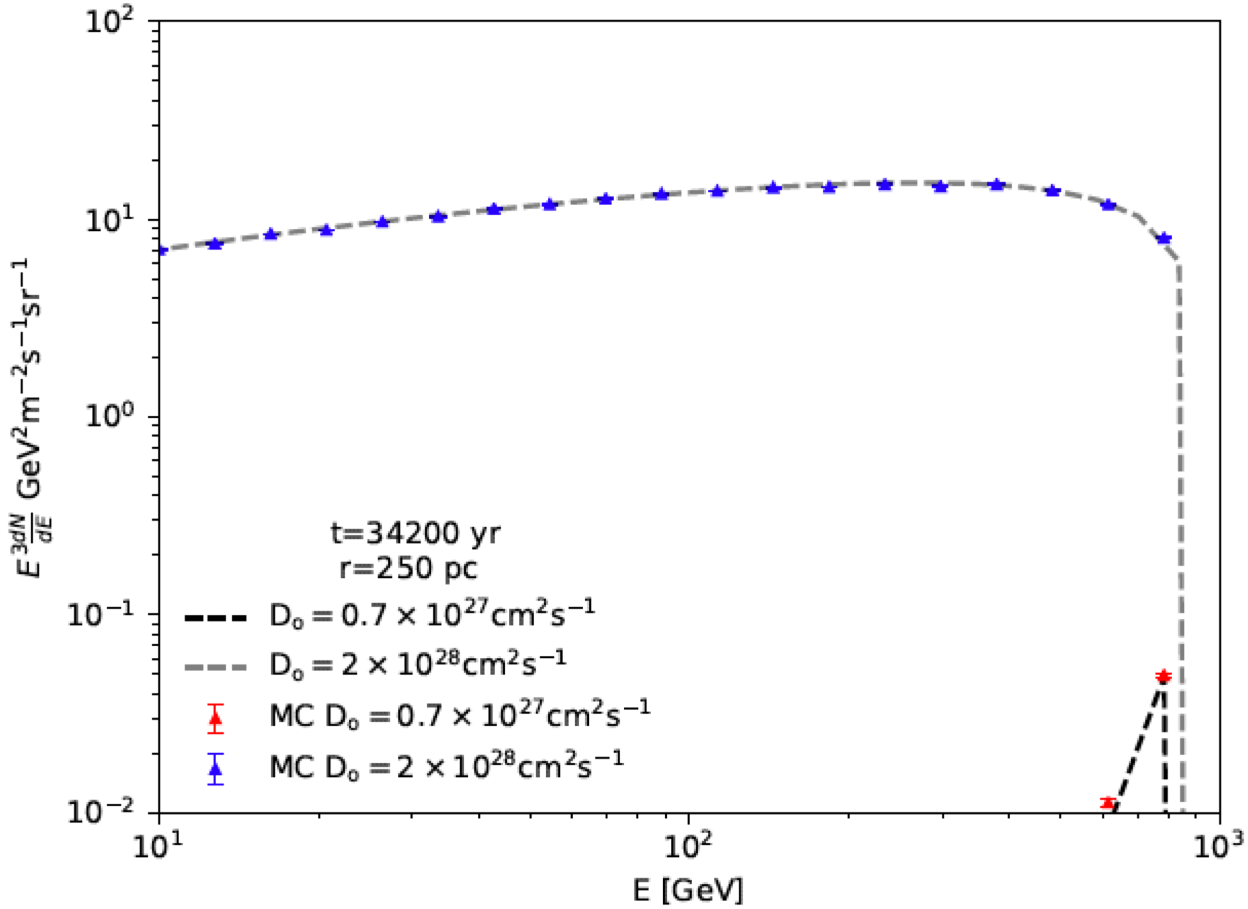

*Profumo, Reynoso, Kaaz, Silverman 2018

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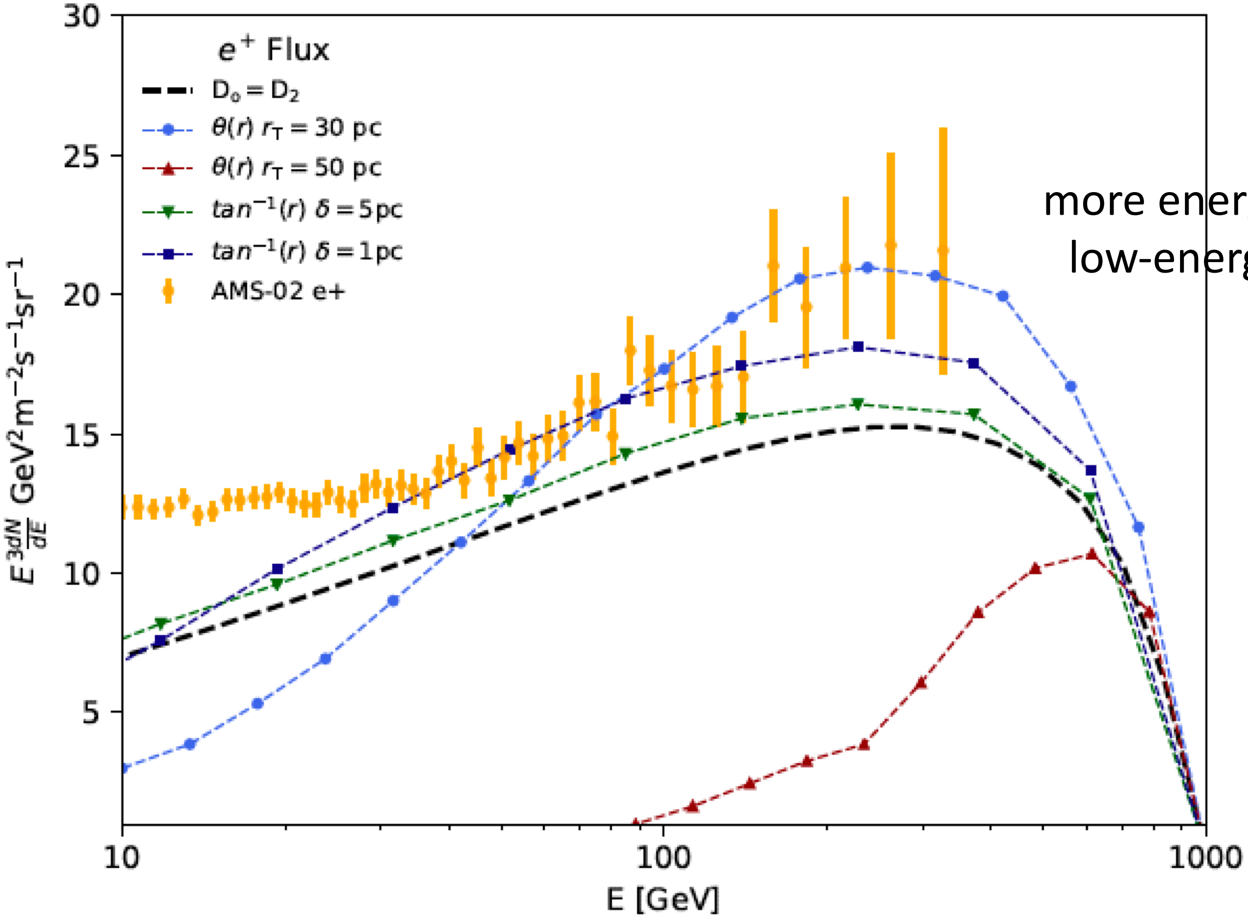

more energetic and less low-energy electrons!

*Profumo, Reynoso, Kaaz, Silverman 2018

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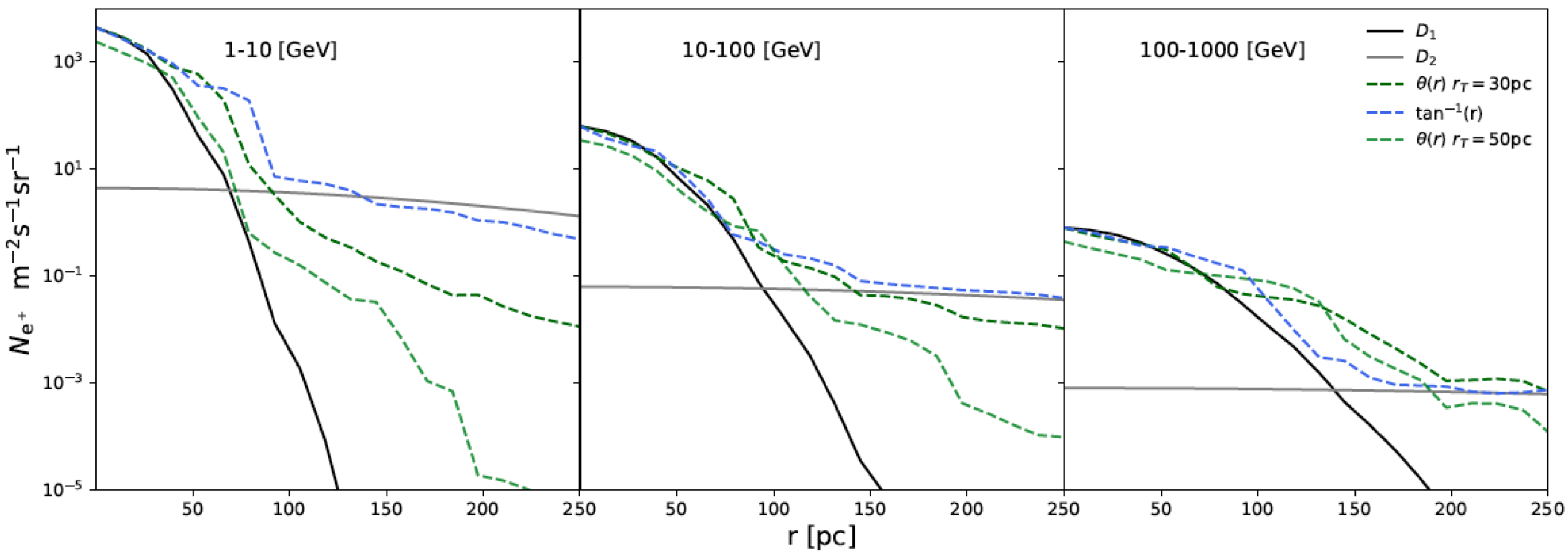

*Profumo, Reynoso, Kaaz, Silverman 2018

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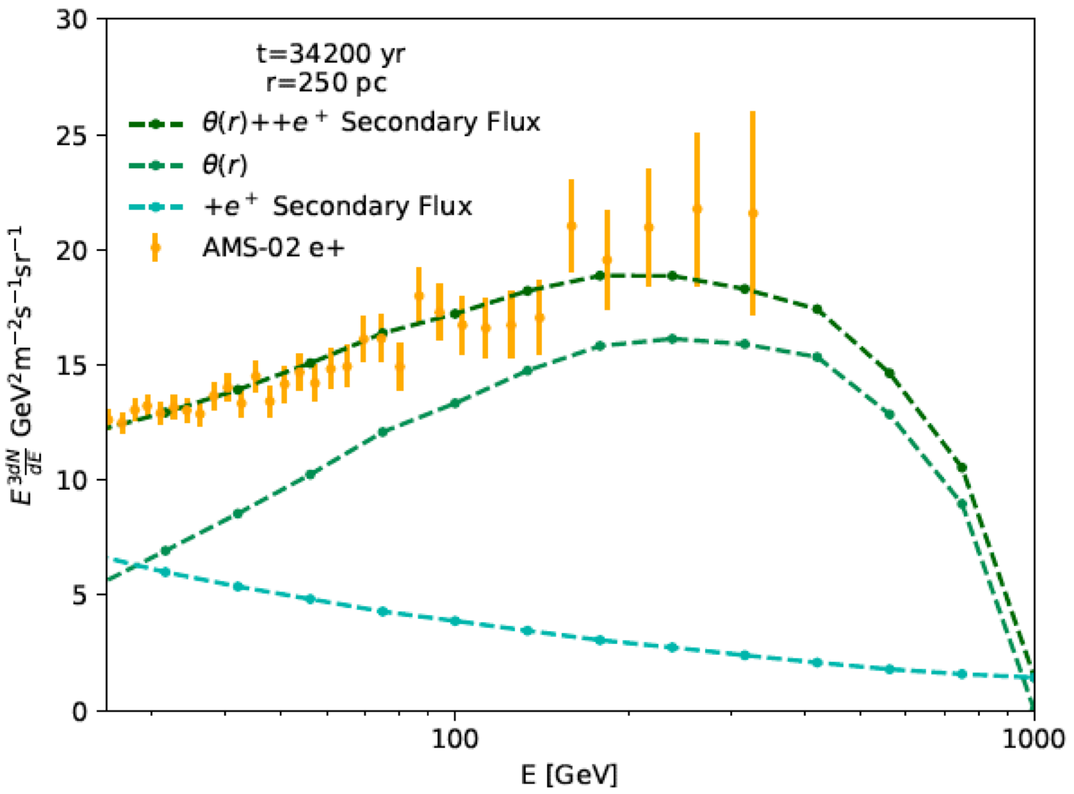


In reality: source time-dependence, additional contributions from other sources….

*Profumo, Reynoso, Kaaz, Silverman 2018

How can we test inhomogeneous diffusion?
Does it matter, globally on Galactic scales?

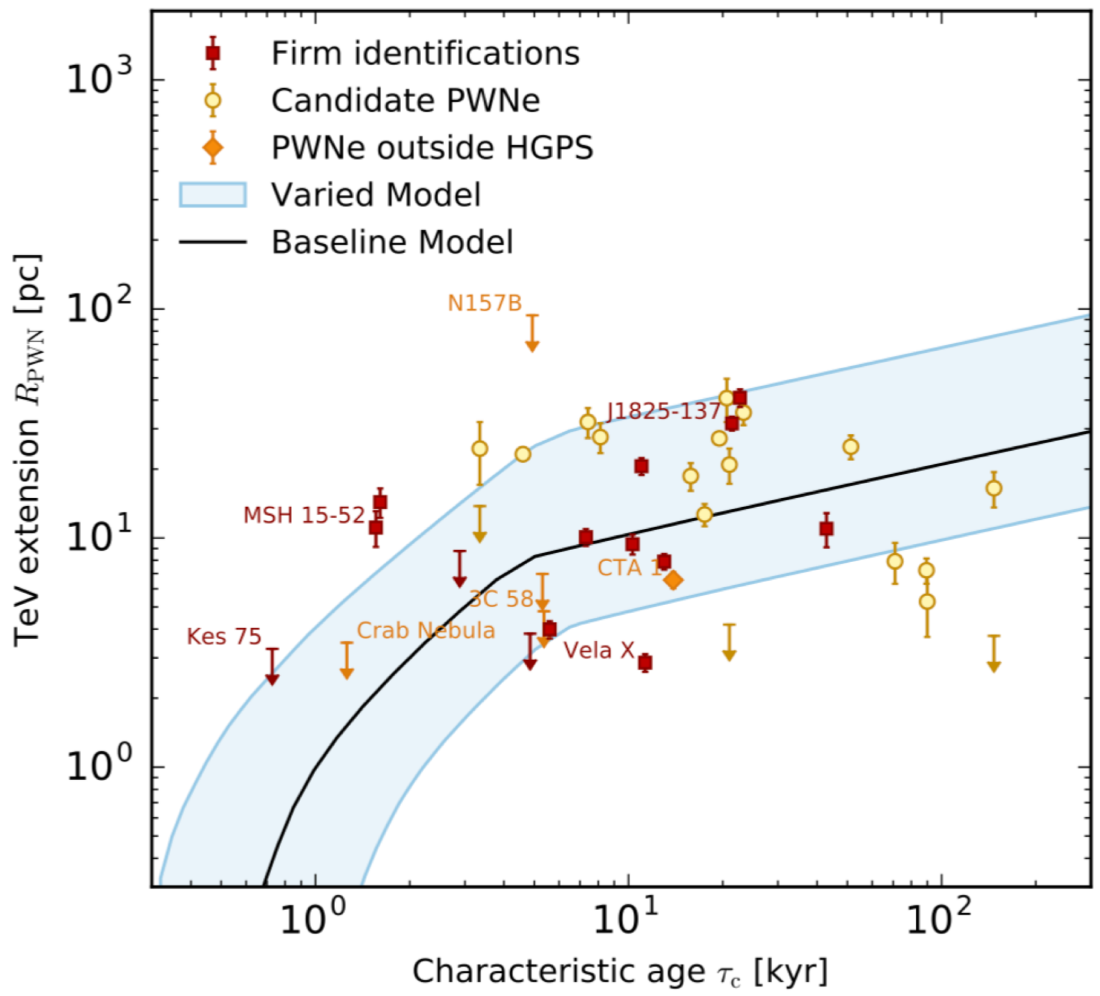
Estimate the volume of regions of inefficient diffusion

1. How big is a PWN as a function of time?

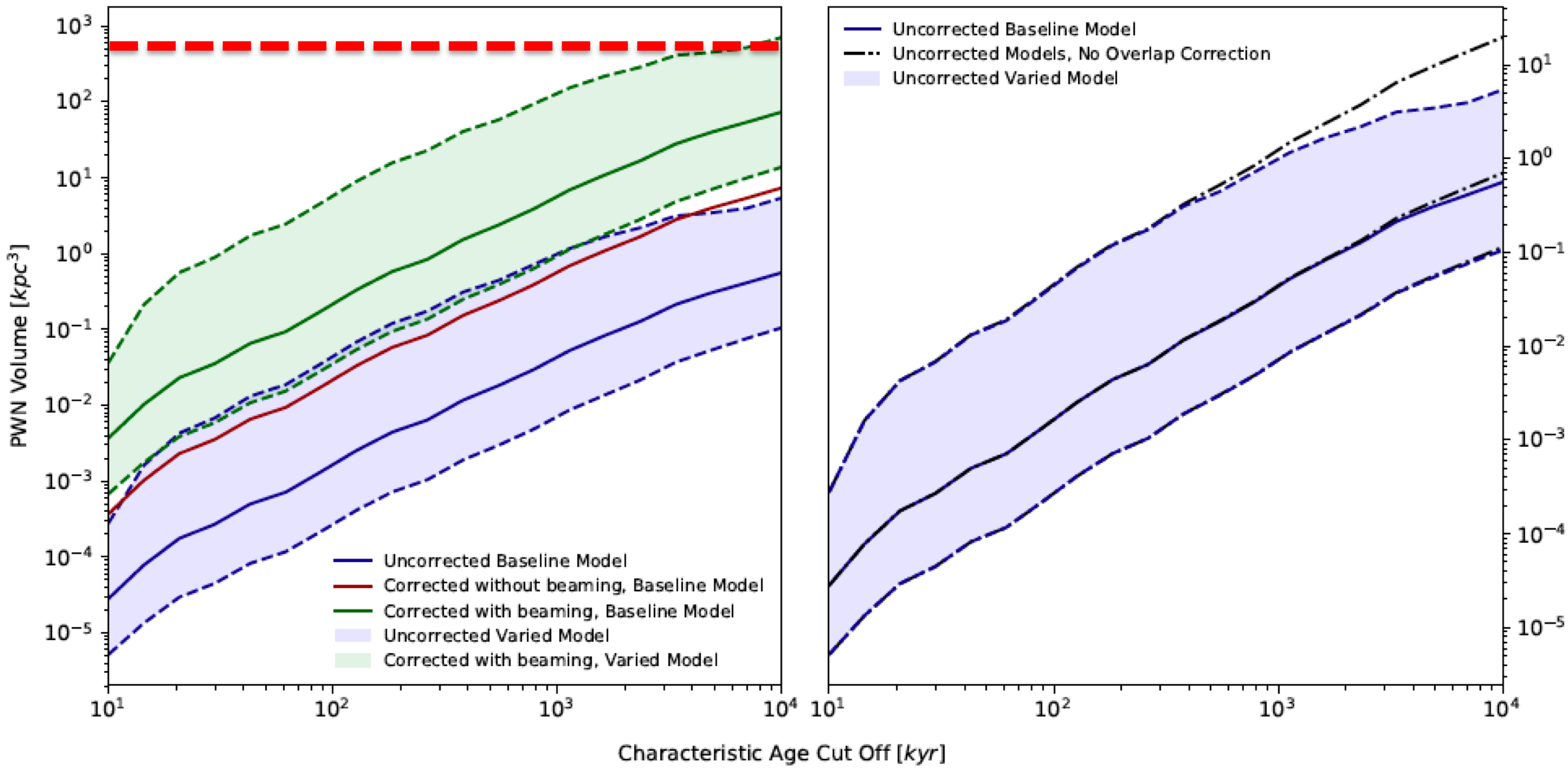
The population of TeV pulsar wind nebulae in the H.E.S.S. Galactic Plane Survey

H.E.S.S. Collaboration, H. Abdalla[1], A. Abramowski[2], F. Aharonian[3,4,5], F. Ait Benkhali[3], A.G. Akhperjanian[†6,5], T. Andersson[10], E.O. Angüner[7], M. Arrieta[15], P. Aubert[24], M. Backes[8], A. Balzer[9], M. Barnard[1], Y. Becherini[10], J. Becker Tjus[11], D. Berge[12], S. Bernhard[13], K. Bernlöhr[3], R. Blackwell[14], M. Böttcher[1], C. Boisson[15], J. Bolmont[16], P. Bordas[3], J. Bregeon[17], F. Brun[26], P. Brun[18], M. Bryan[9], T. Bulik[19], M. Capasso[29], J. Carr[20], S. Carrigan[‡,3], S. Casanova[21,3], M. Cerruti[16], N. Chakraborty[3], R. Chalme-Calvet[16], R.C.G. Chaves[17,22], A. Chen[23], J. Chevalier[24], M. Chrétien[16], S. Colafrancesco[23], G. Cologna[25], B. Condon[26], J. Conrad[27,28]

1. How big is a PWN as a function of time?



…but of course the sample is incomplete… (beaming+detectability)
…and we don't know when PWN run out of steam…



$$\langle V \rangle_{\rm ISM} \simeq 500\ {\rm kpc}^3 \left(\frac{R_h}{20\ {\rm kpc}}\right)^2 \left(\frac{z_h}{0.2\ {\rm kpc}}\right)$$

*Profumo, Reynoso, Kaaz, Silverman 2018

so, does this matter?
well, the time spent in inefficient diffusion pockets is potentially much larger than volume ratios!

$$\langle L \rangle \sim \sqrt{D \cdot t},$$

$$\frac{t_{\rm PWN}}{t_{\rm ISM}} \sim \left(\frac{\langle V \rangle_{\rm PWN}}{\langle V \rangle_{\rm ISM}} \right)^{2/3} \frac{D_{\rm ISM}}{D_{\rm PWN}} \sim 10^{-2} \left(\frac{\langle V \rangle_{\rm PWN}}{\langle V \rangle_{\rm ISM}} \right)^{2/3}$$

$$\langle V \rangle_{\rm PWN} \gtrsim 0.5 \ {\rm kpc}^3$$

*Profumo, Reynoso, Kaaz, Silverman 2018

…OK, but how can we test this?

if a large fraction of CR electrons are trapped in inefficient diffusion pockets, those pockets will be illuminated by energy-loss radiative processes (radio, IC, brems)

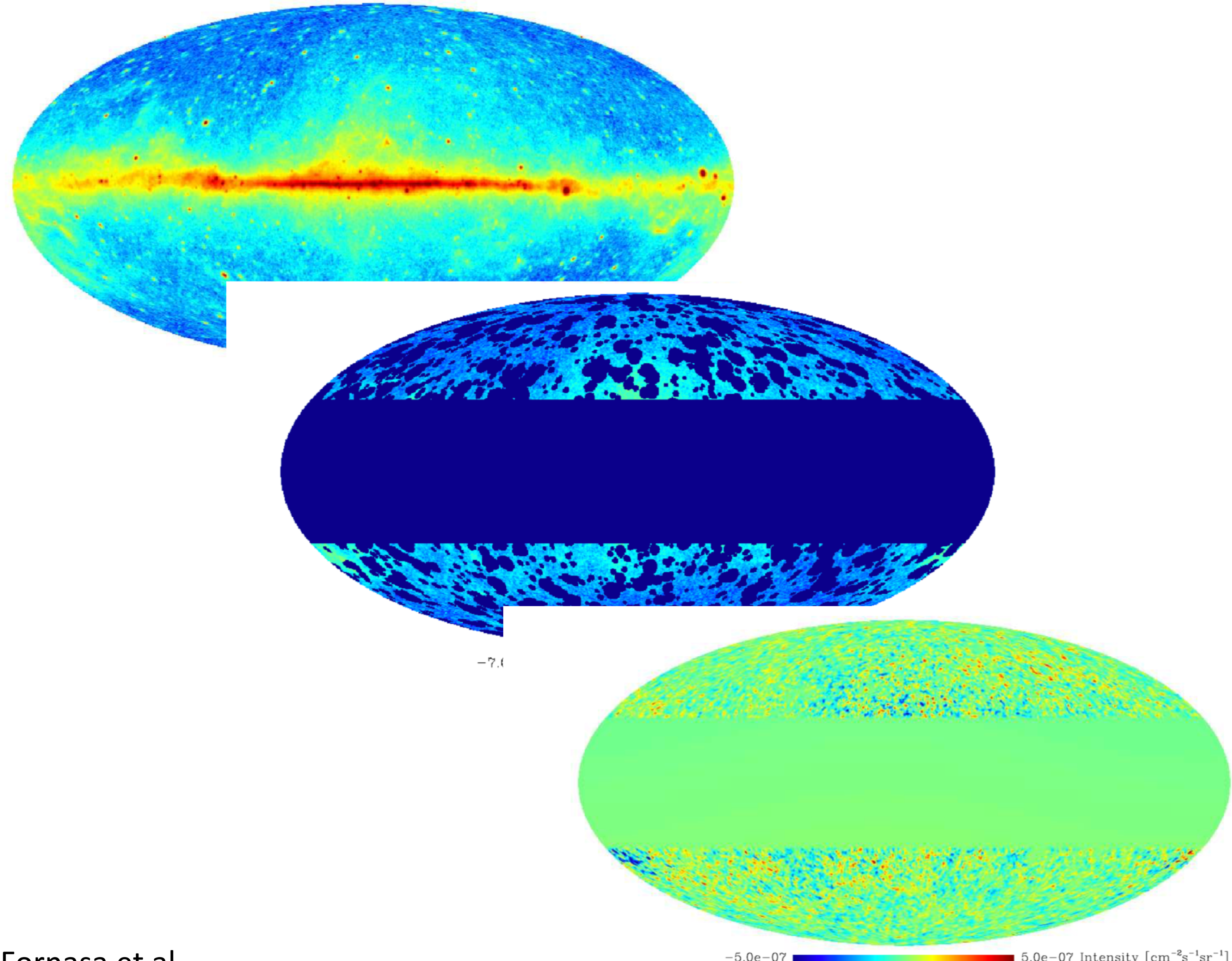
$$\theta \sim \frac{R_{\rm PWN}}{d_{\rm PWN}}$$

theta ranges from few degrees to 0.1 degrees

can use any frequency from radio (with additional B uncert.) to X-ray to gamma rays

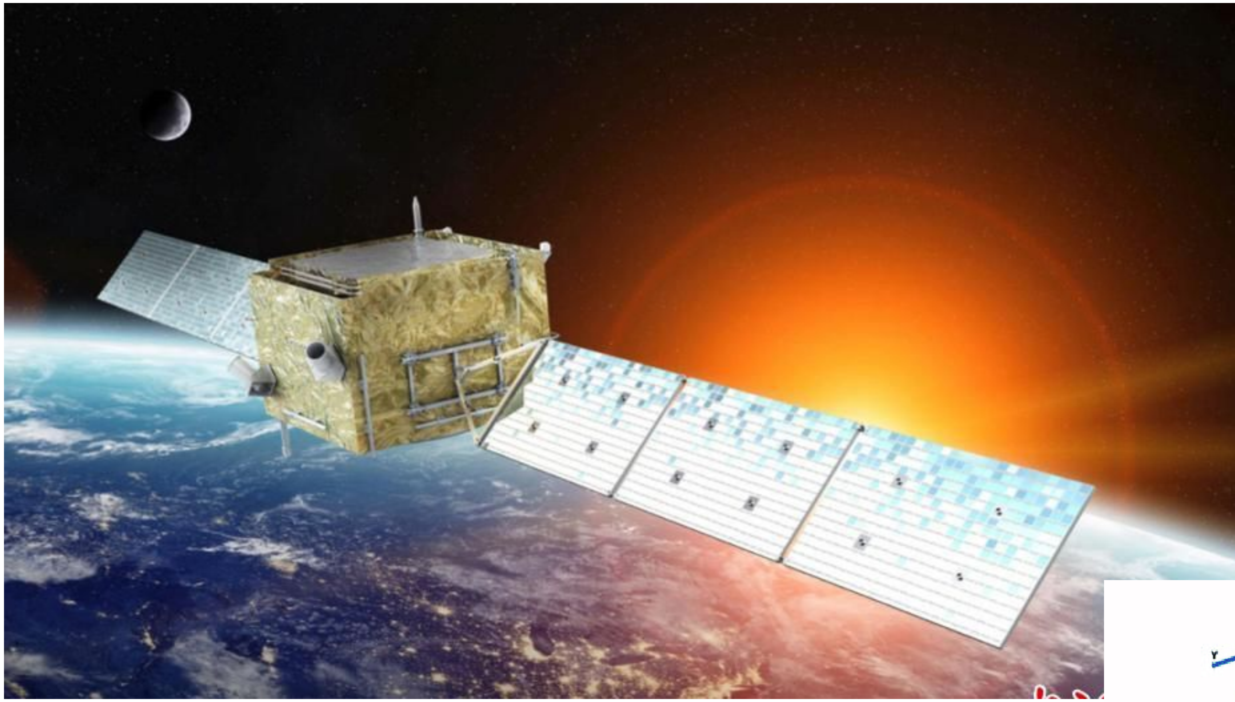
Can use simple angular power spectrum, or wavelet transforms, Poissonian noise analysis

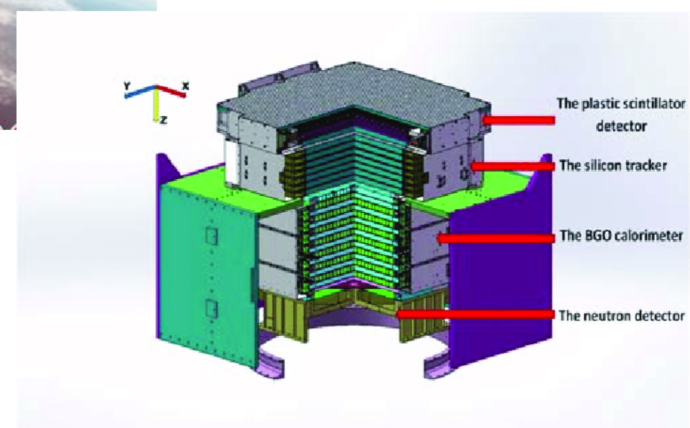
*Profumo, Reynoso, Kaaz, Silverman 2018



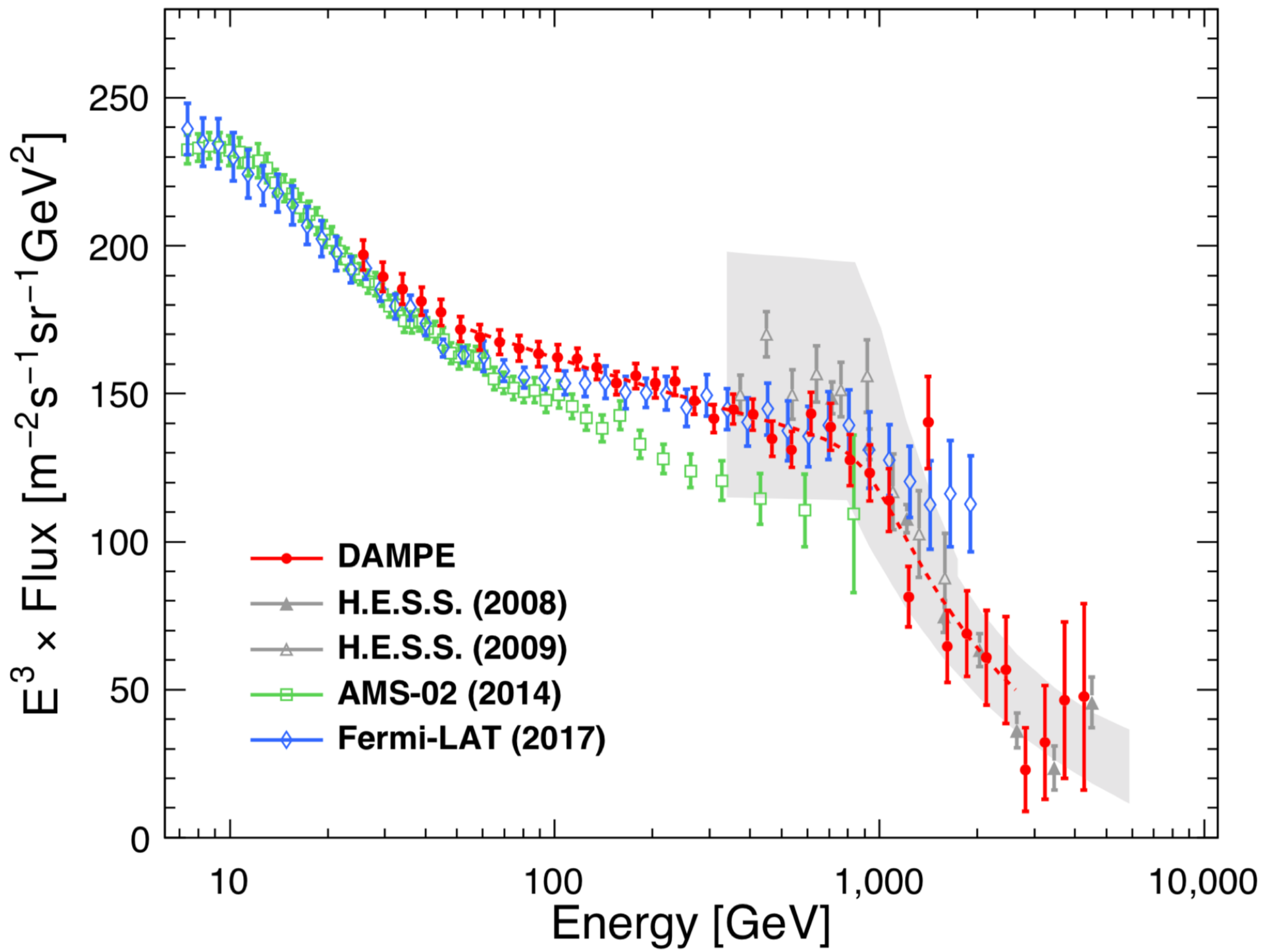
* Fornasa et al

- Lepton flavor physics with cosmic rays: (1) the positron excess
- **Lepton flavor physics with cosmic rays: (2) DAMPE**
- Dark matter and lepton flavor universality violation



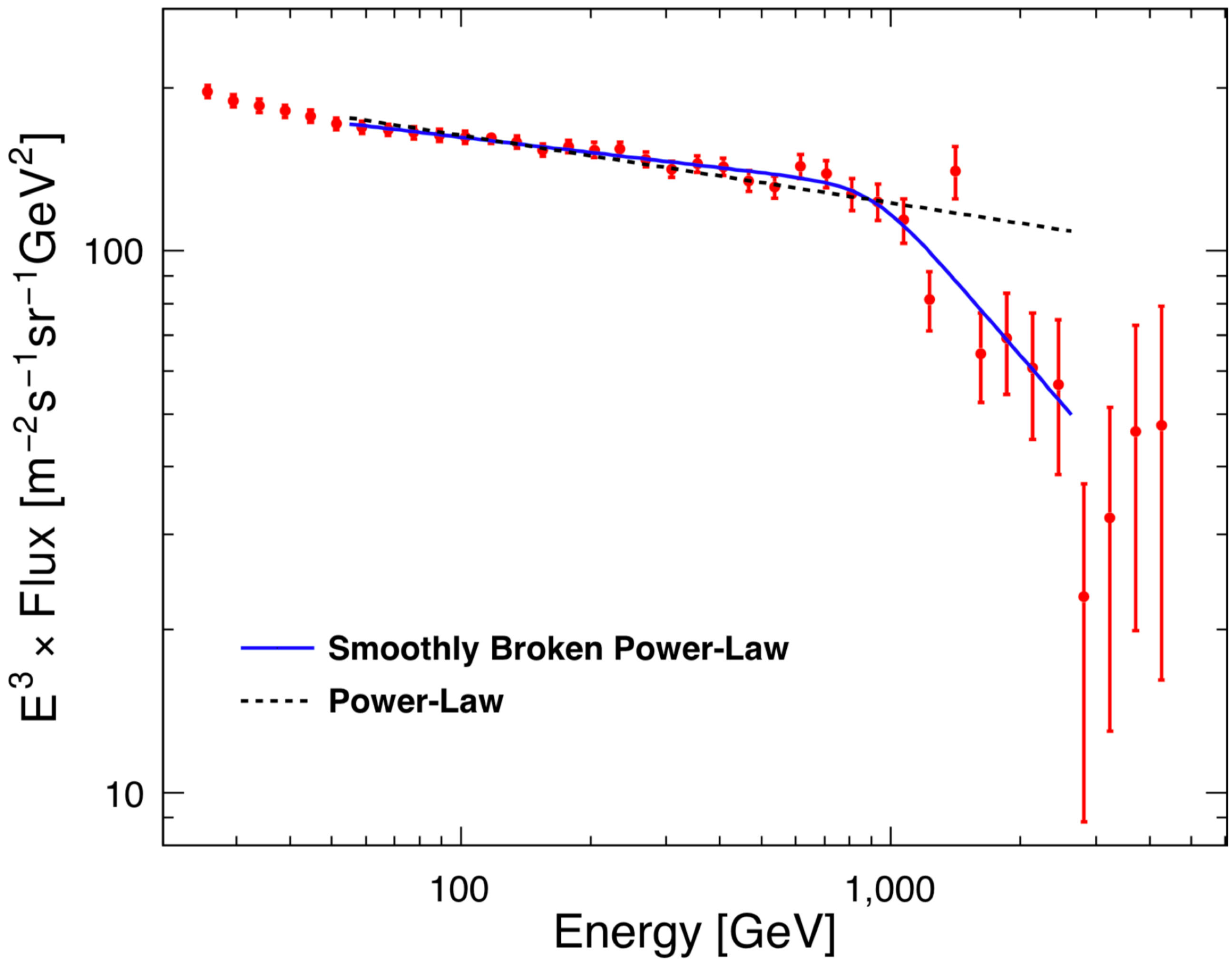


The Dark Matter Particle Explorer, or DAMPE, is a Chinese Academy of Sciences satellite launched on 17 December 2015



Key result: high-statistics measurement of HE CR electron+positron flux

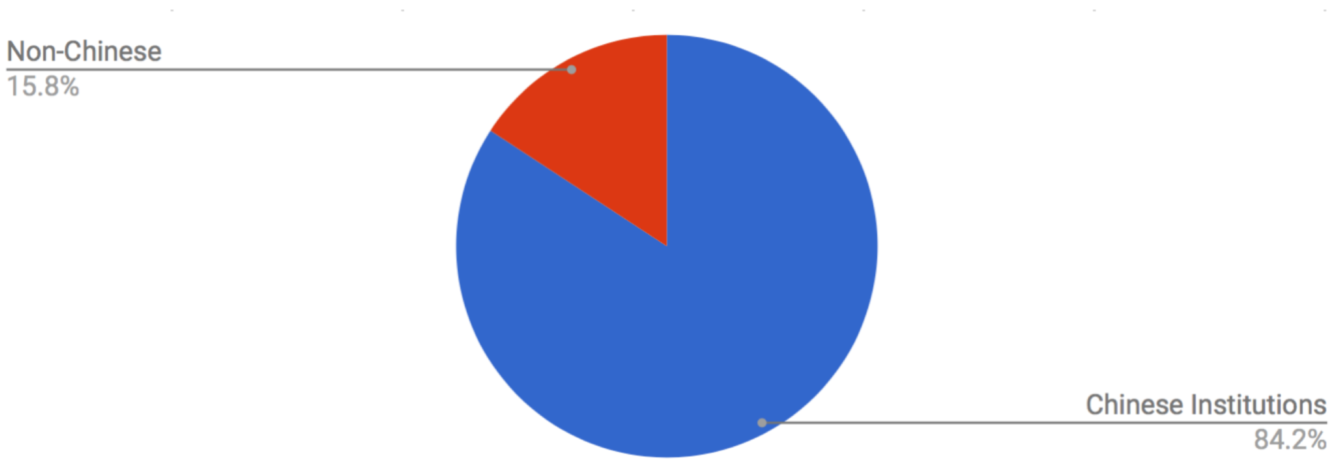
DAMPE Collaboration, Nature, December 2017



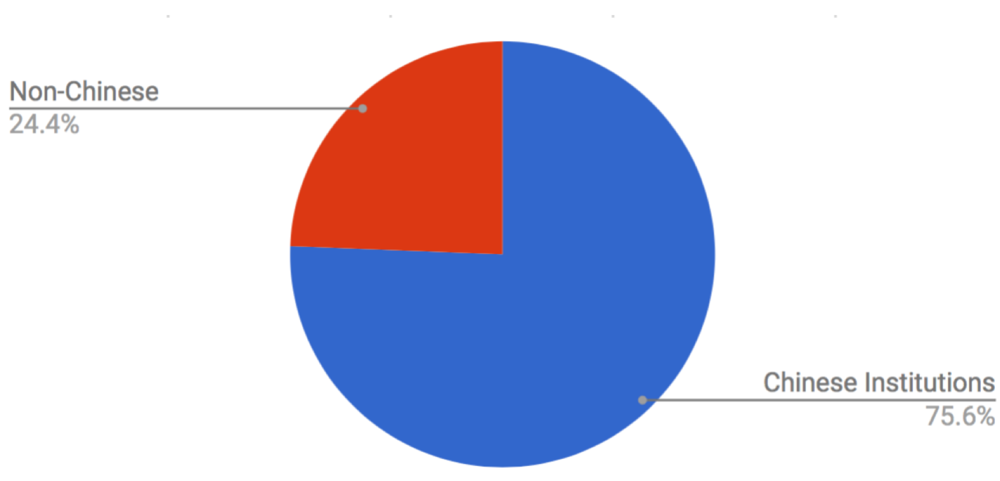
Key result: high-statistics measurement of HE CR electron+positron flux

DAMPE Collaboration, Nature, December 2017

…and prompted an interesting socio-nationalistic phenomenon



11/2017 cites (total=19)

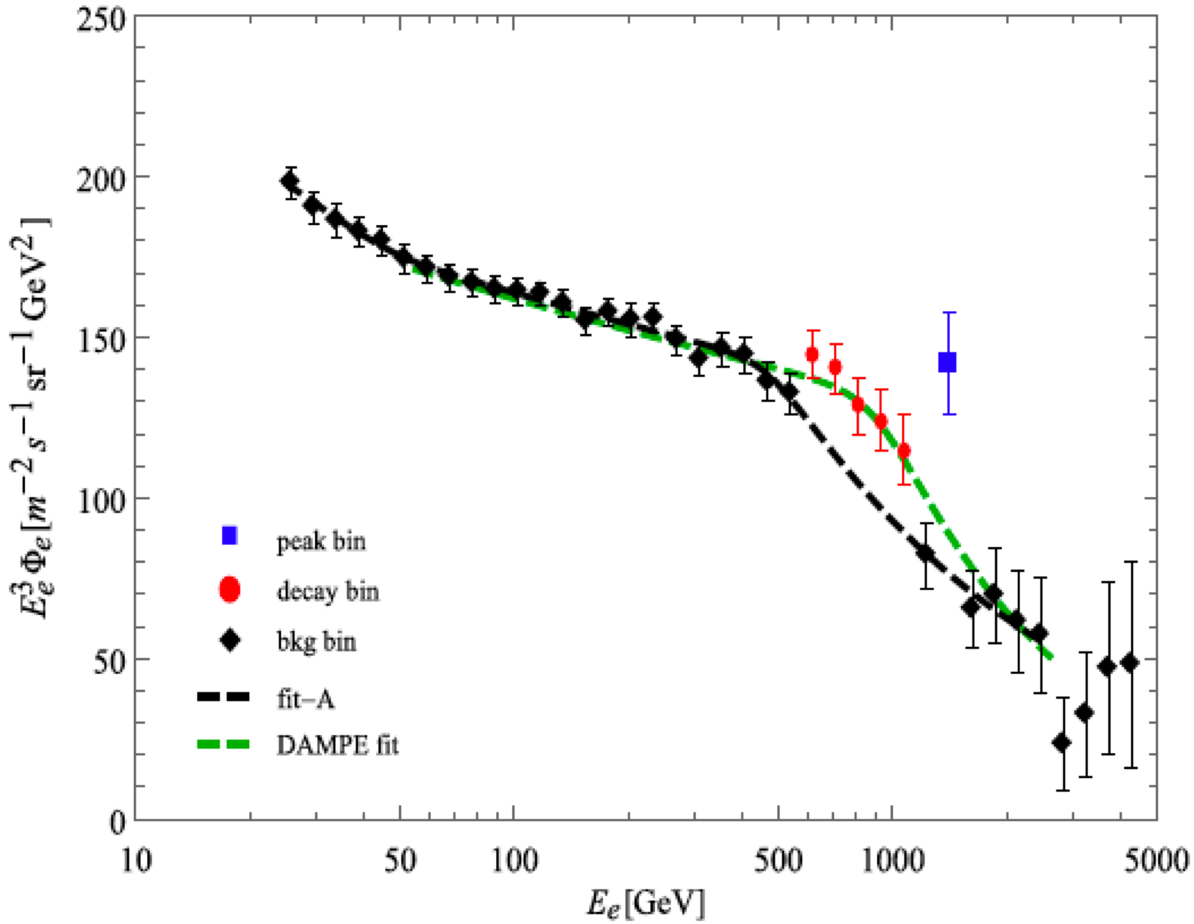


11+12/2017 cites (total=41)

Assume indeed there is a bump + line – so what?

Ge et al (2018) pretend there's a line+bump

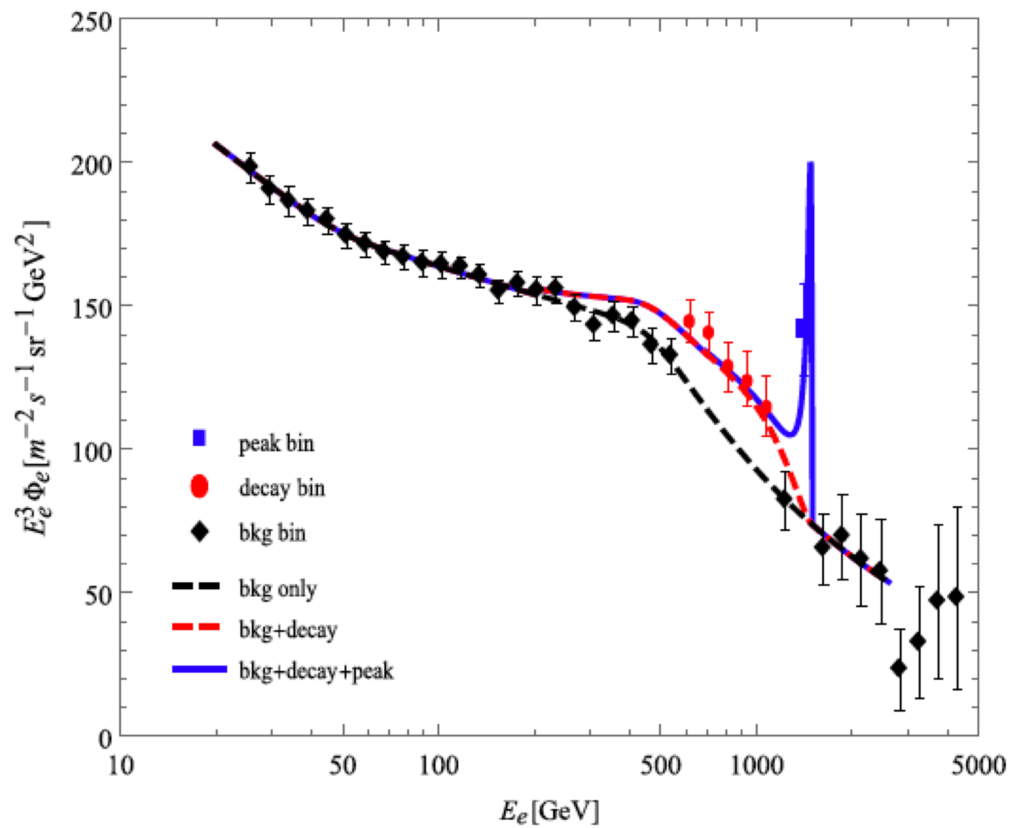
background: double-broken power law



Assume indeed there is a bump + line – so what?

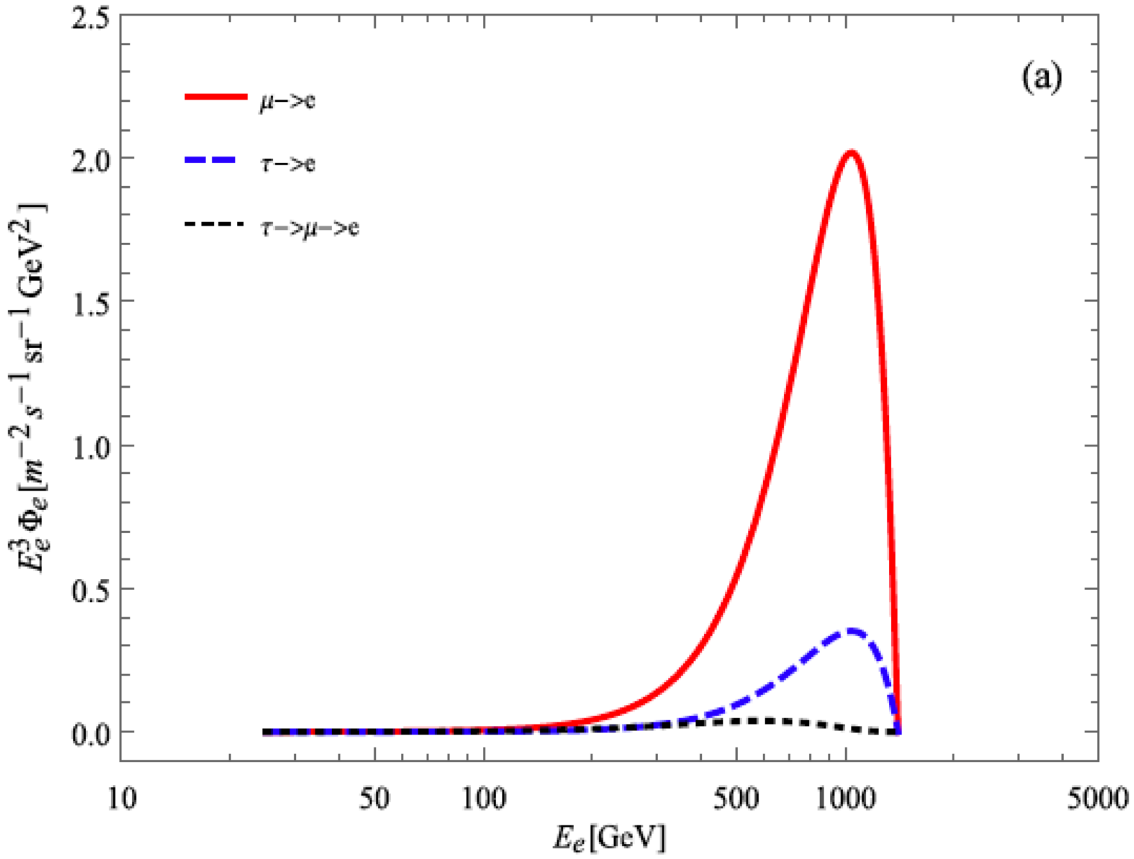
Ge et al (2018) pretend there's a line+bump

signal: lepto-philic 1.4 TeV DM annihilation in a nearby clump, with some non-flavor universal BR into e:μ:τ



Assume indeed there is a bump + line – so what?

τ decay produces much fewer and softer electrons than μ decay – hard to constrain/negligible:
use $N_e:N_\mu:N_\tau=1:y:0$, fit for y



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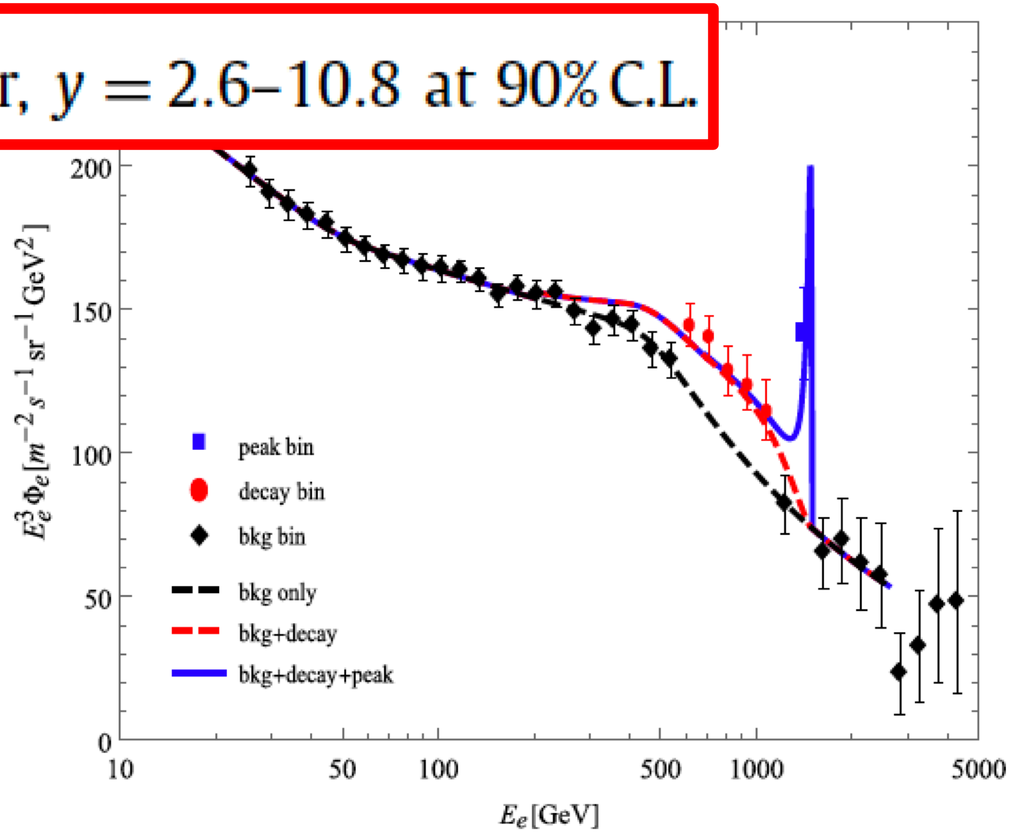
use $N_e:N_\mu:N_\tau=1:y:0$, fit for y

$$\boxed{y = 8.6^{+1.4}_{-2.5},\ \text{or},\ y = 2.6\text{–}10.8 \text{ at } 90\%\ \text{C.L.}}$$



Assume indeed there is a bump + line – so what?

What do we learn?

1. Flavor structure: e.g. implemented by Dirac fermion DM with scalar mediator,

$$\mathcal{L}_\chi \supset \lambda_j S_j \overline{\chi_L} \ell_{Rj} + \text{h.c.},$$

2. Distance to the clump fixed by width of the “line”, density distribution fixed by height of line

d ~ 200 pc, rs ~ 100 pc (we are partly within clump!)
[I think this clump would be ruled out by Fermi-LAT!]

- Lepton flavor physics with cosmic rays: (1) the positron excess

- Lepton flavor physics with cosmic rays: (2) DAMPE

- **Dark matter and lepton flavor universality violation**

Augment L_μ-L_τ Z' model for B anomalies with a DM particle

Dressing $L_\mu - L_\tau$ in Color

Wolfgang Altmannshofer,[1,*] Stefania Gori,[1,†] Maxim Pospelov,[1,2,‡] and Itay Yavin[1,3,§]

$$\mathcal{L}_{Z'} = -\frac{1}{4}(Z')_{\alpha\beta}(Z')^{\alpha\beta} + |D_\alpha \Phi|^2 + V(\Phi) + g' Z'_\alpha J^\alpha_{Z'} \ .$$

$$J^{\alpha\,(\mathrm{lep})}_{Z'} = Q_\ell\Big(\bar{\ell}_2\gamma^\alpha\ell_2 - \bar{\ell}_3\gamma^\alpha\ell_3 + \bar{\mu}_R\gamma^\alpha\mu_R - \bar{\tau}_R\gamma^\alpha\tau_R\Big)$$

$$\mathcal{L}_m = m_Q \bar{Q}_L \tilde{Q}_R + m_D \bar{\tilde{D}}_L D_R + m_U \bar{\tilde{U}}_L U_R \ + \ \mathrm{h.c.}$$

$$\begin{aligned}\mathcal{L}_{\mathrm{mix}} = \ & \Phi \bar{\tilde{D}}_R (Y_{Qb} b_L + Y_{Qs} s_L + Y_{Qd} d_L) \\ & + \Phi \bar{\tilde{U}}_R (Y_{Qt} t_L + Y_{Qc} c_L + Y_{Qu} u_L) \\ & + \Phi^\dagger \bar{\tilde{U}}_L (Y_{Ut} t_R + Y_{Uc} c_R + Y_{Uu} u_R) \\ & + \Phi^\dagger \bar{\tilde{D}}_L (Y_{Db} b_R + Y_{Ds} s_R + Y_{Dd} d_R) \ + \ \mathrm{h.c.}\end{aligned}$$

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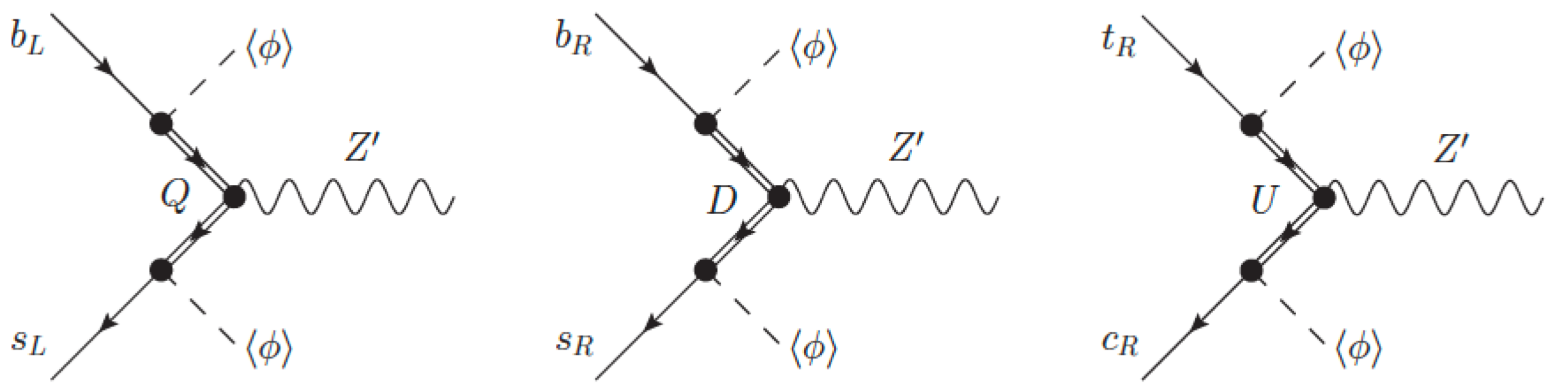

FIG. 1. Example diagrams in the high energy theory that lead to flavor-changing effective couplings of the Z' to SM quarks.

Augment L_μ-L_τ Z' model for B anomalies with a DM particle

Explaining Dark Matter and B Decay Anomalies with an $L_\mu - L_\tau$ Model

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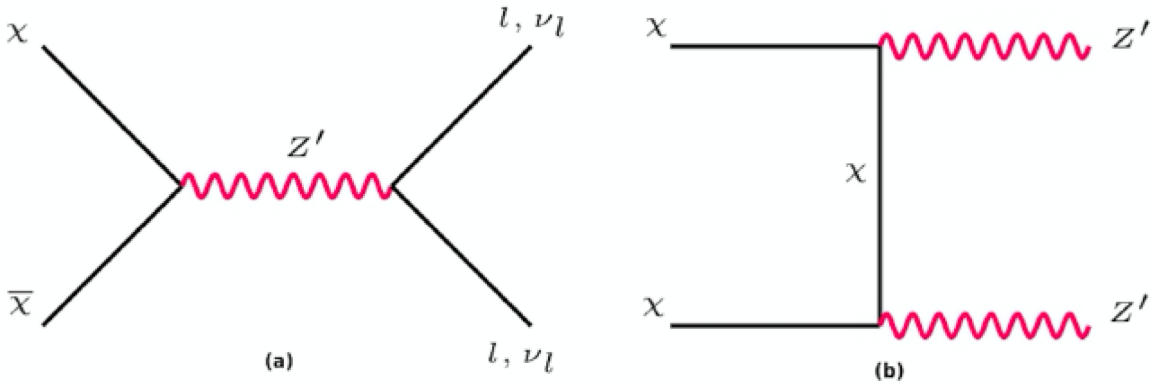
Wolfgang Altmannshofer[a], Stefania Gori[a], Stefano Profumo[b], Farinaldo S. Queiroz[c]

$$\mathcal{L}_{\text{fermions}} \supset q_\ell g' \left(\bar{\mu}\gamma_\alpha\mu - \bar{\tau}\gamma_\alpha\tau + \bar{\nu_\mu}\gamma_\alpha P_L \nu_\mu - \bar{\nu_\tau}\gamma_\alpha P_L \nu_\tau\right) Z'^\alpha$$

$$\mathcal{L}_{\text{dark}} \supset q_\chi\, g'\, \bar{\chi}\gamma_\alpha\chi Z'^\alpha$$

Consider ***$q_l = q_\chi$*** and ***$q_l >> q_\chi$*** limits; without loss of generality, set *$q_l = 1$*

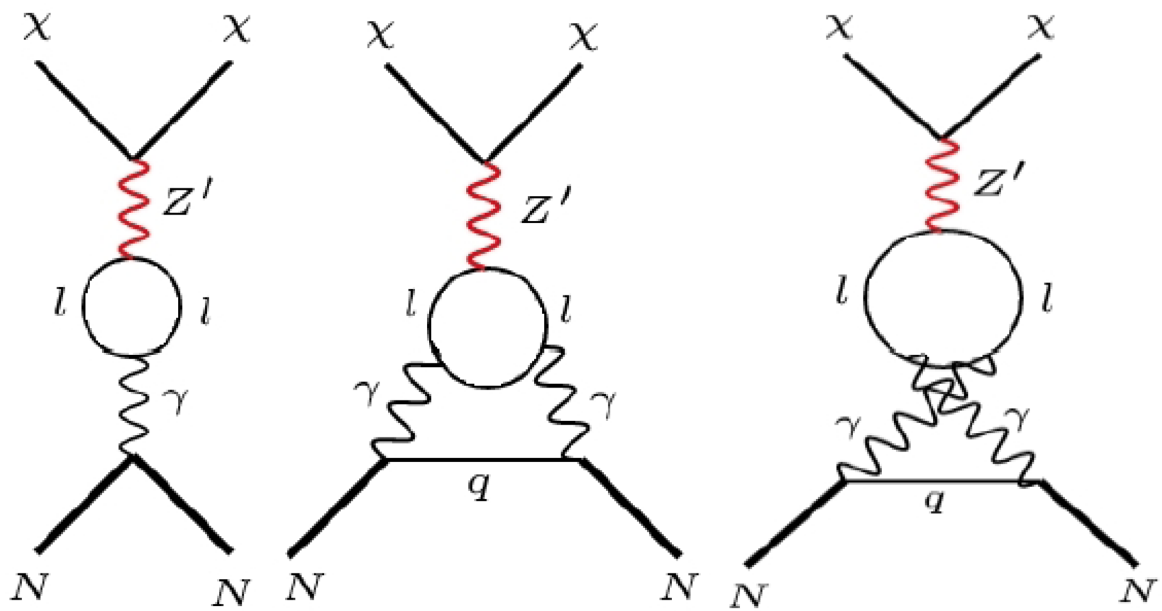
DM Phenomenology: indirect/relic density and direct detection



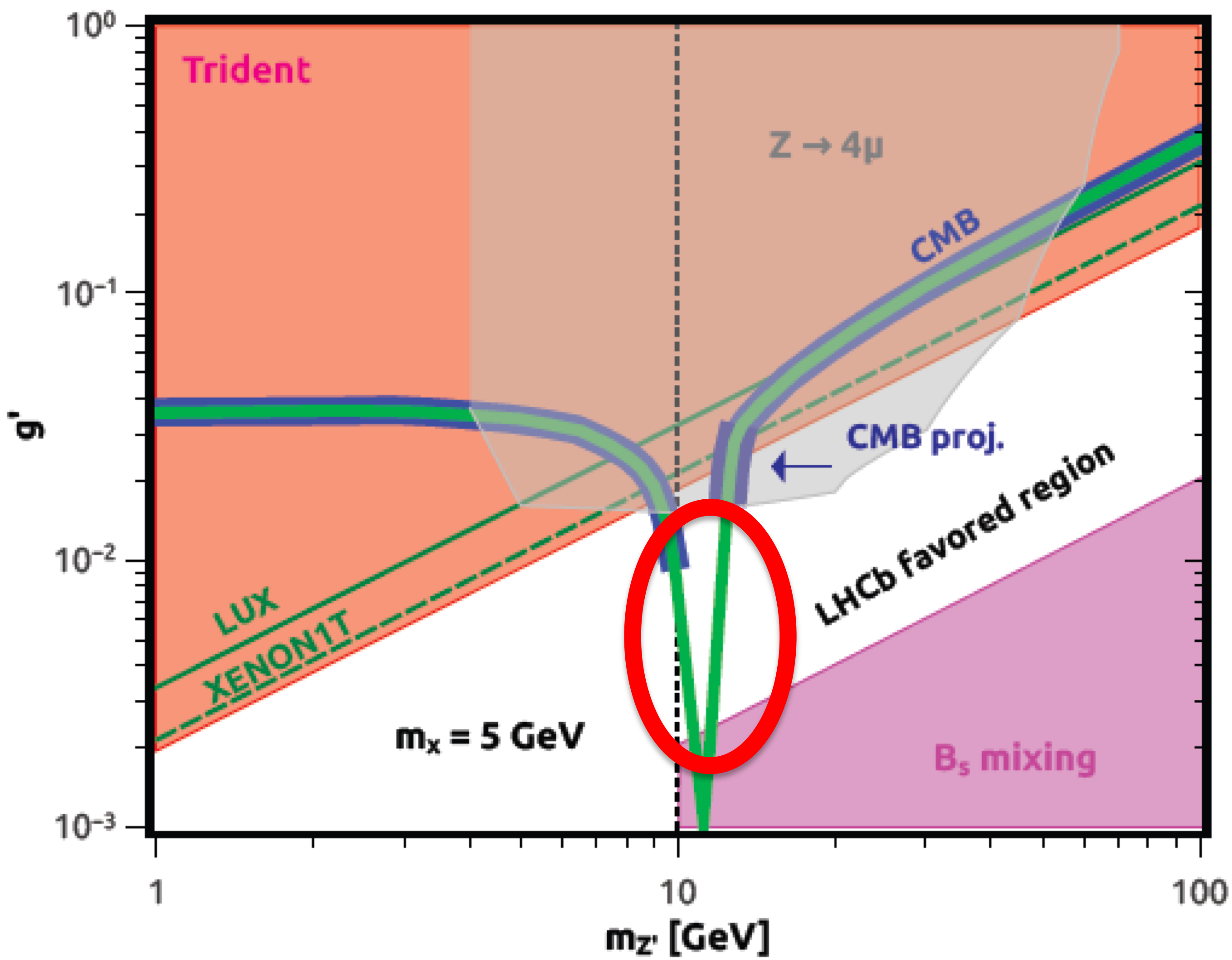
$$\sigma v \left(\chi\bar{\chi} \to \ell^+\ell^-\right) \approx \frac{q_\chi^2 q_\ell^2 g'^4}{2\pi} \frac{m_\chi^2}{\left(4m_\chi^2 - m_{Z'}^2\right)^2}$$

…expect 3 regimes depending on m_χ, $m_{Z'}$ hierarchy

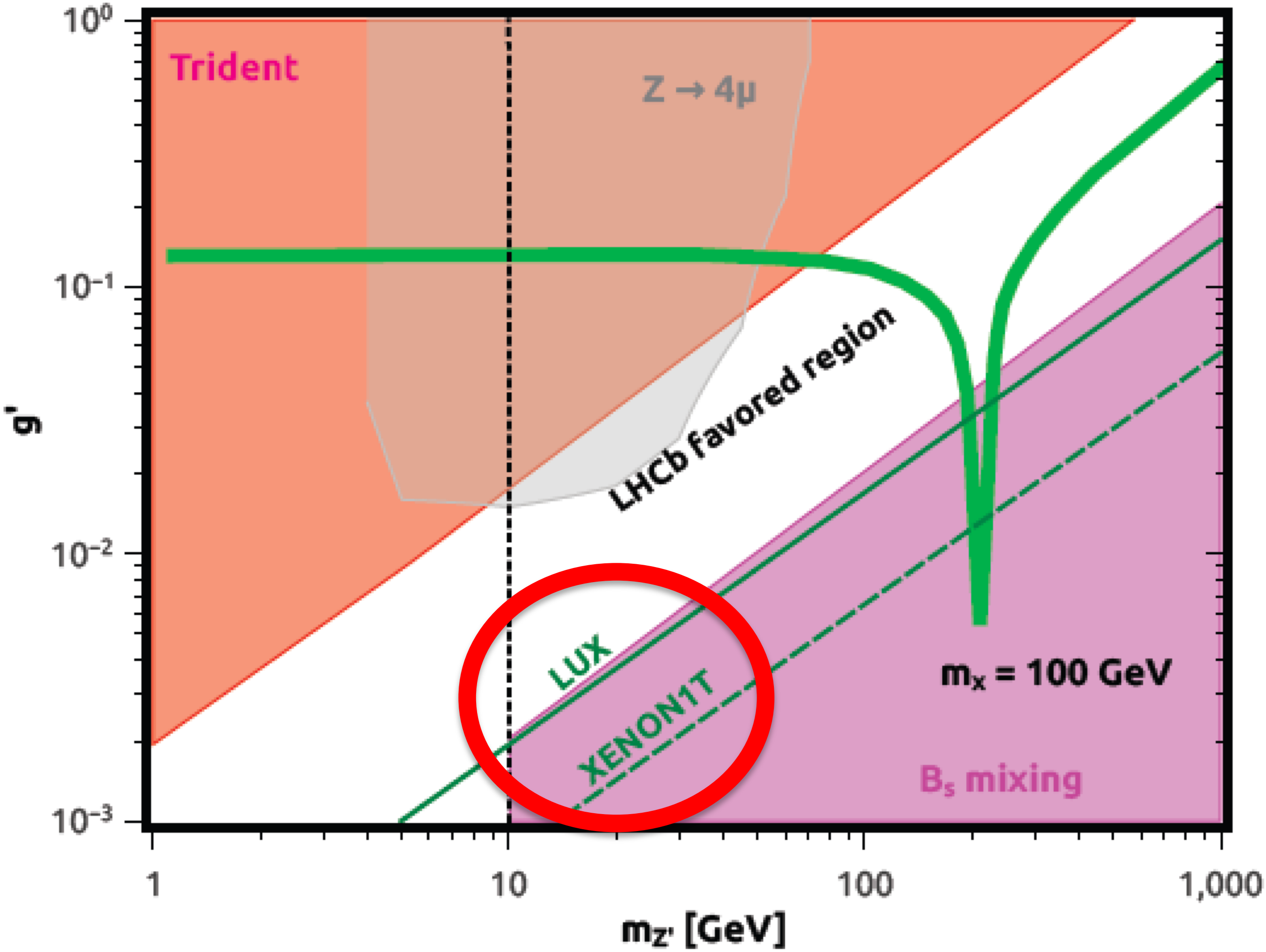
DM Phenomenology: indirect/relic density and direct detection



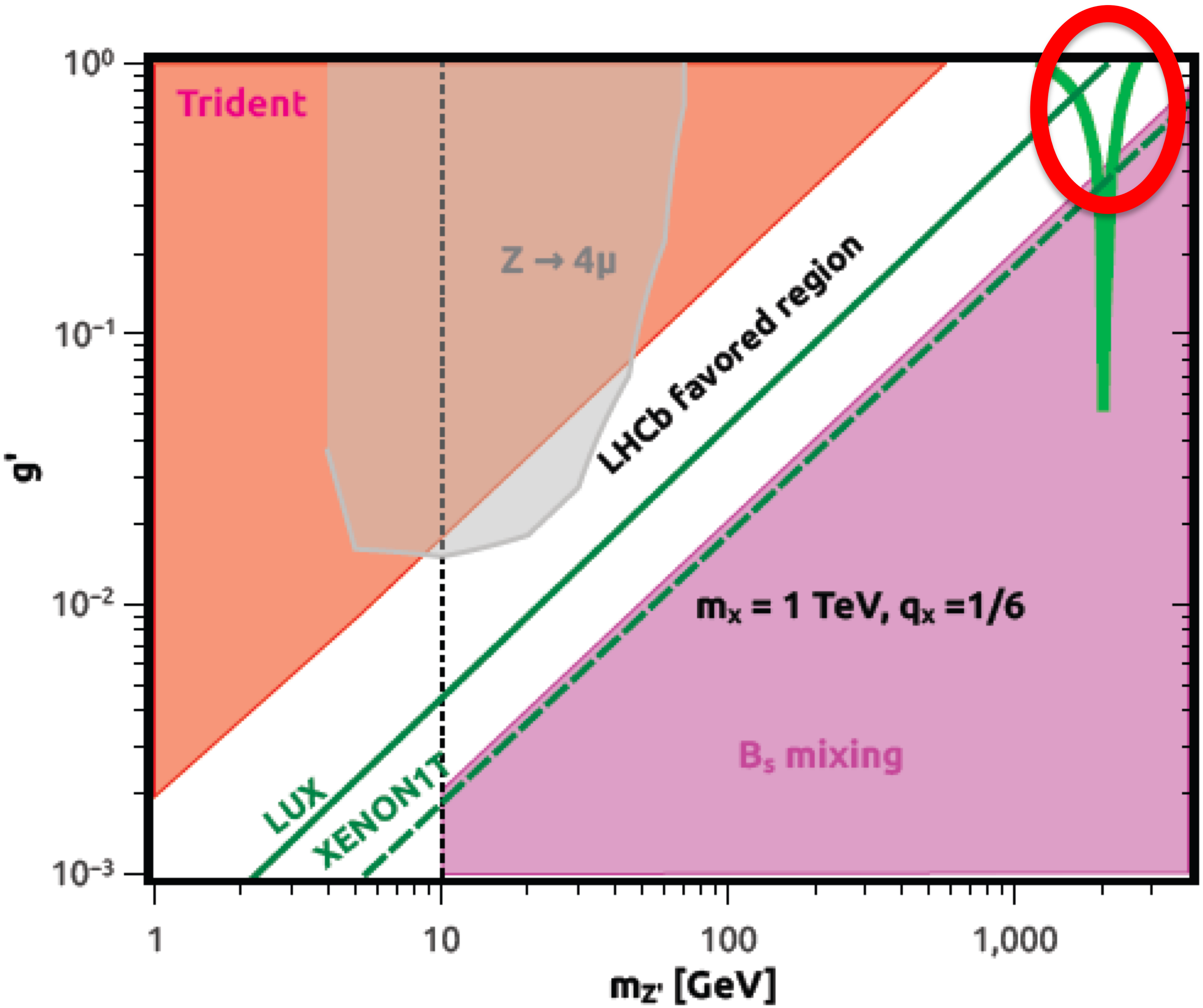
Light DM, large DM charge, q_χ =1



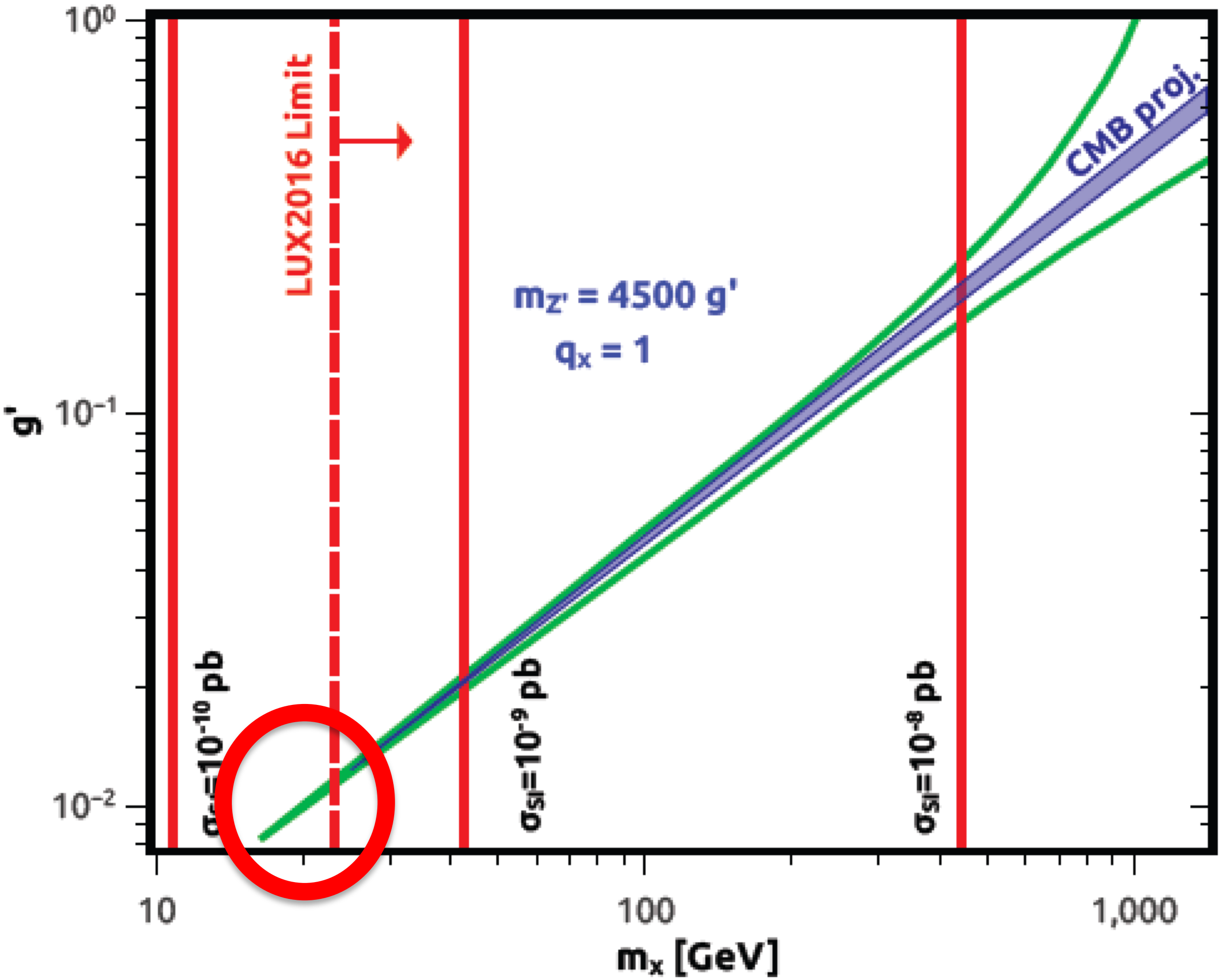
Heavy DM, large DM charge, q_χ =1: tough luck!



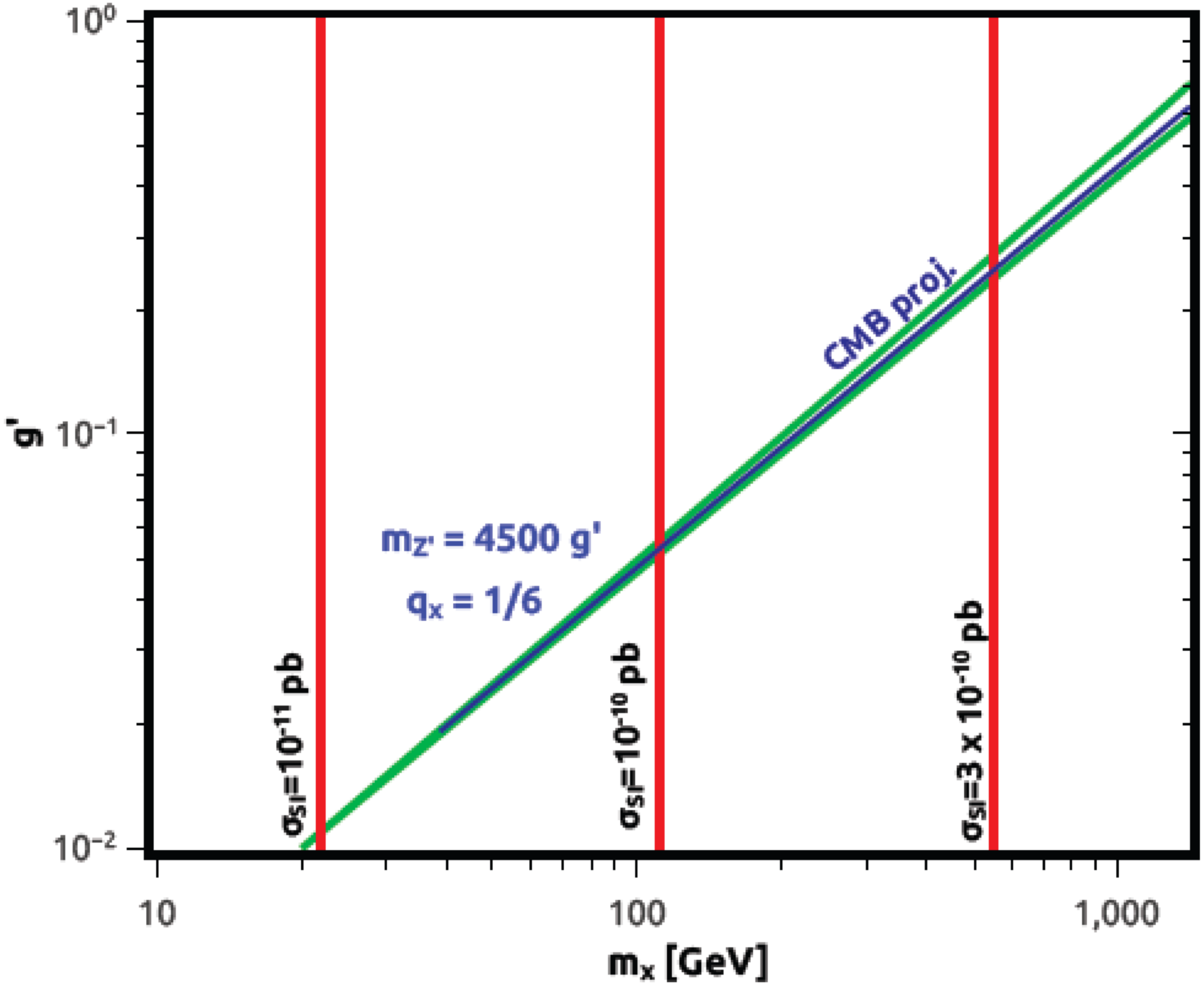
Even Heavier DM, smaller DM charge, q_χ =1/6: barely OK (for now)



Orthogonal view, large DM charge q_χ =1: ouch!



Orthogonal view, small DM charge q_χ =1/6



- **Lepton flavor physics with cosmic rays: (1) the positron excess**
  - ✓ ***nearby pulsars are the likely source of anomalous CR positrons***
  - ✓ ***if so, diffusion is not homogeneous; we know how to test it!***

- **Lepton flavor physics with cosmic rays: (2) DAMPE**
  - ✓ ***premature, but proof of principle of flavor physics model building from astro data!***

- **Dark matter and lepton flavor universality violation**
  - ✓ ***if Z' from L_μ-L_τ is the right explanation to B anomalies, and if Z' is the portal for DM, very predictive scenario, testable with direct detection***