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Lessons from HAWC PWNe observations

1st Workshop on Gamma-Ray Pulsars

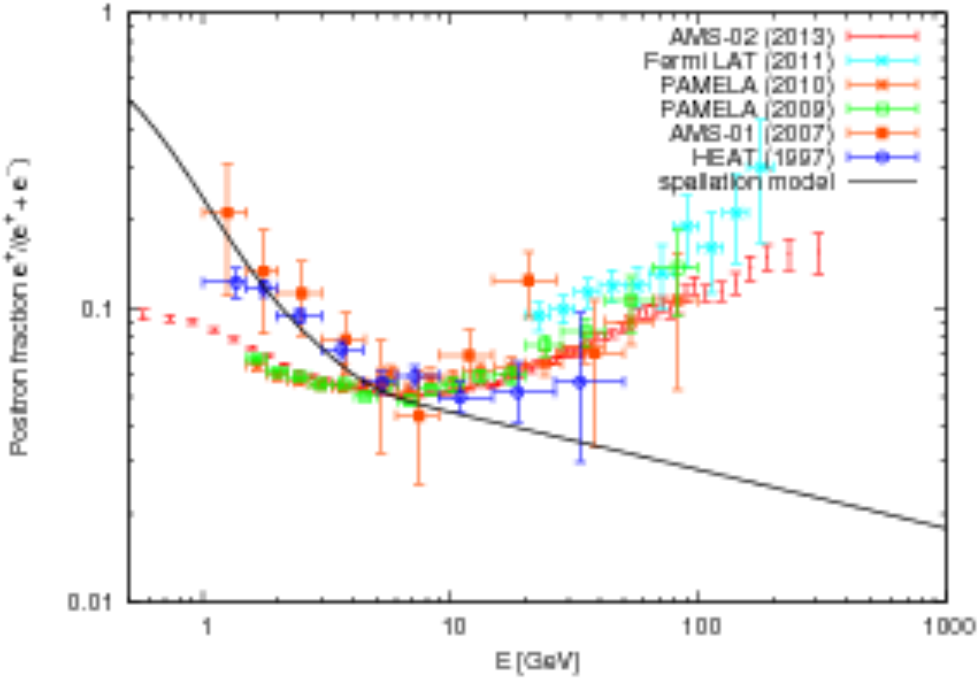
December 3, 2020

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

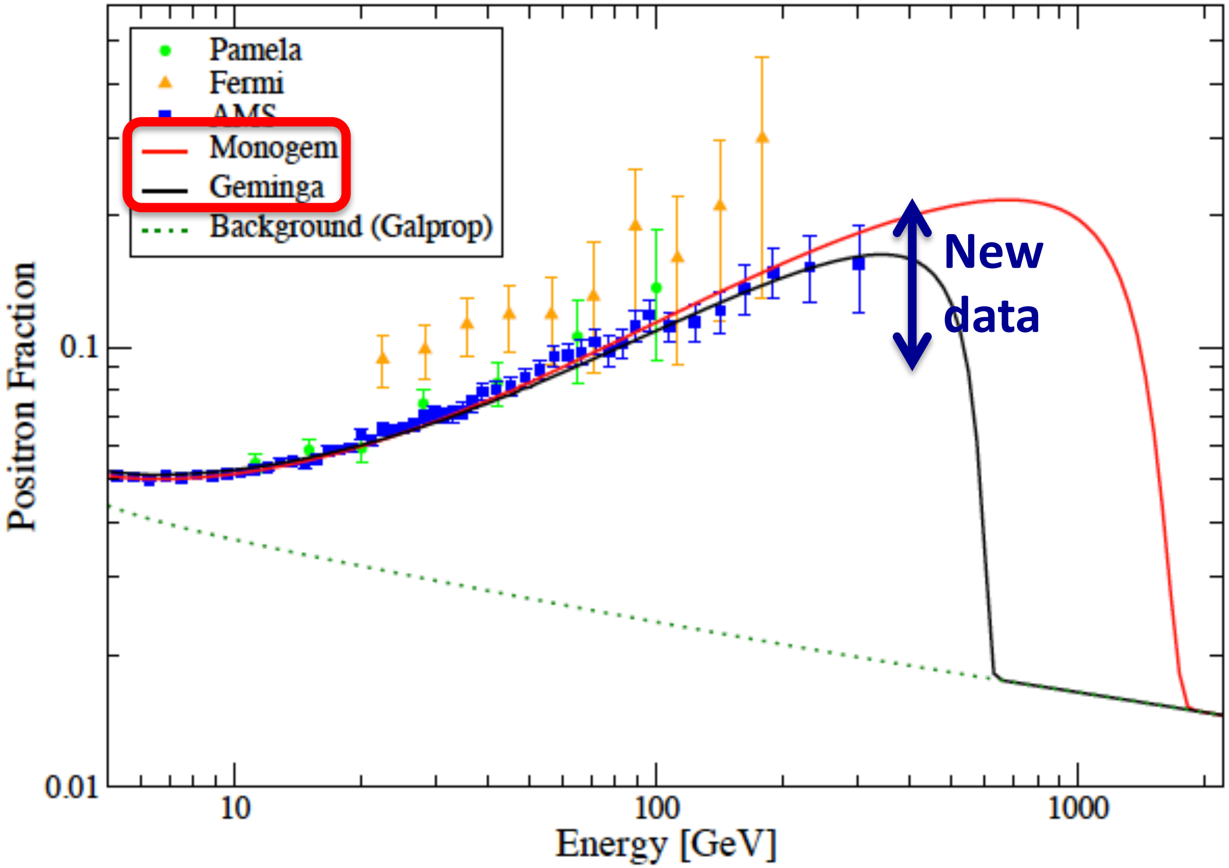
[Tylka 1989, Turner and Wilczek, 1990]

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

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

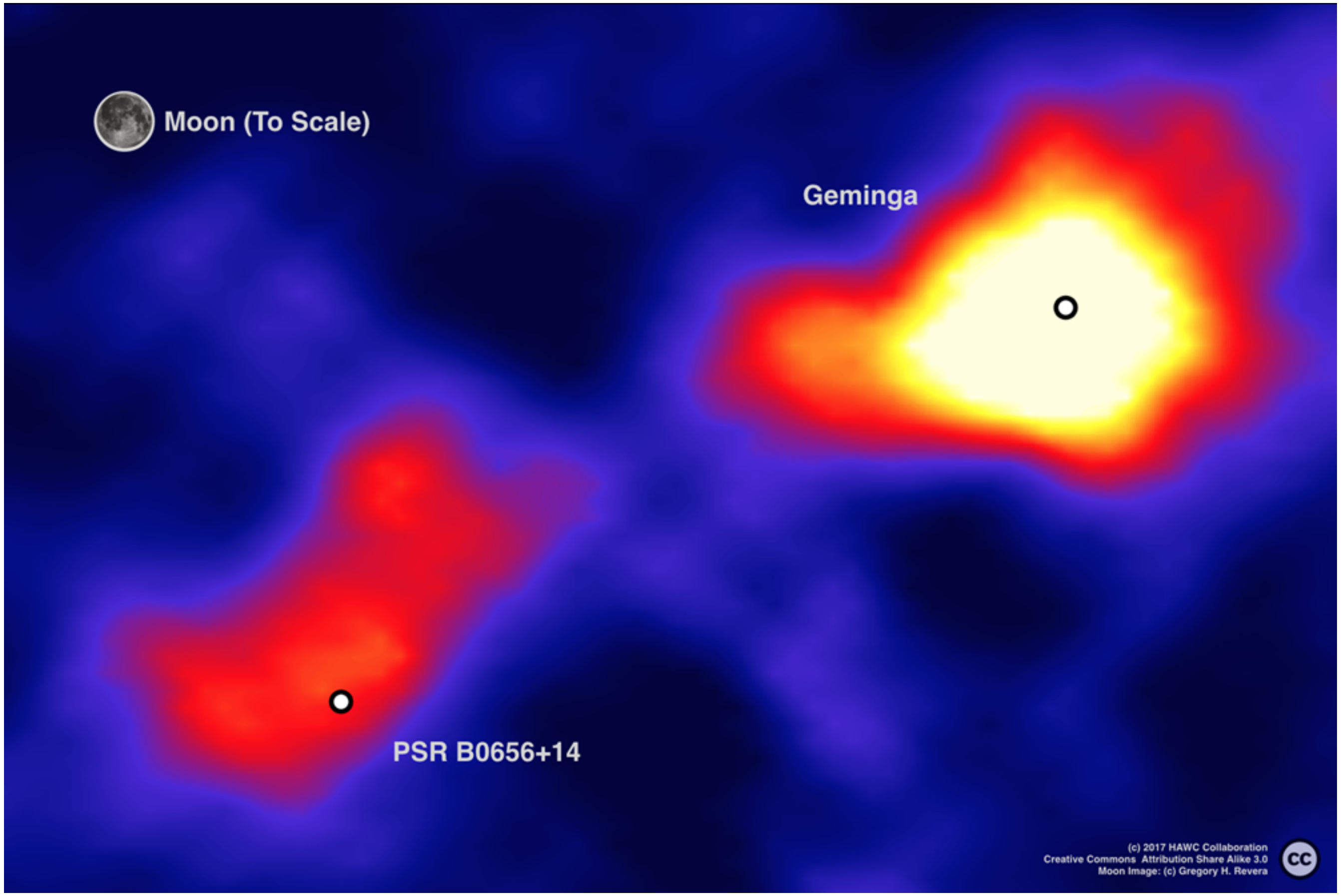


PSRs work perfectly well



only one (not-so) free parameter!

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



* Abeysekara et al 2017

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.

* Abeysekara et al 2017

Astronomy®

Waukesha, WI

SUN & MOON | MERCURY & VI

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

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Home / News / **New pulsar result supports particle dark matter**

1.6K

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

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]

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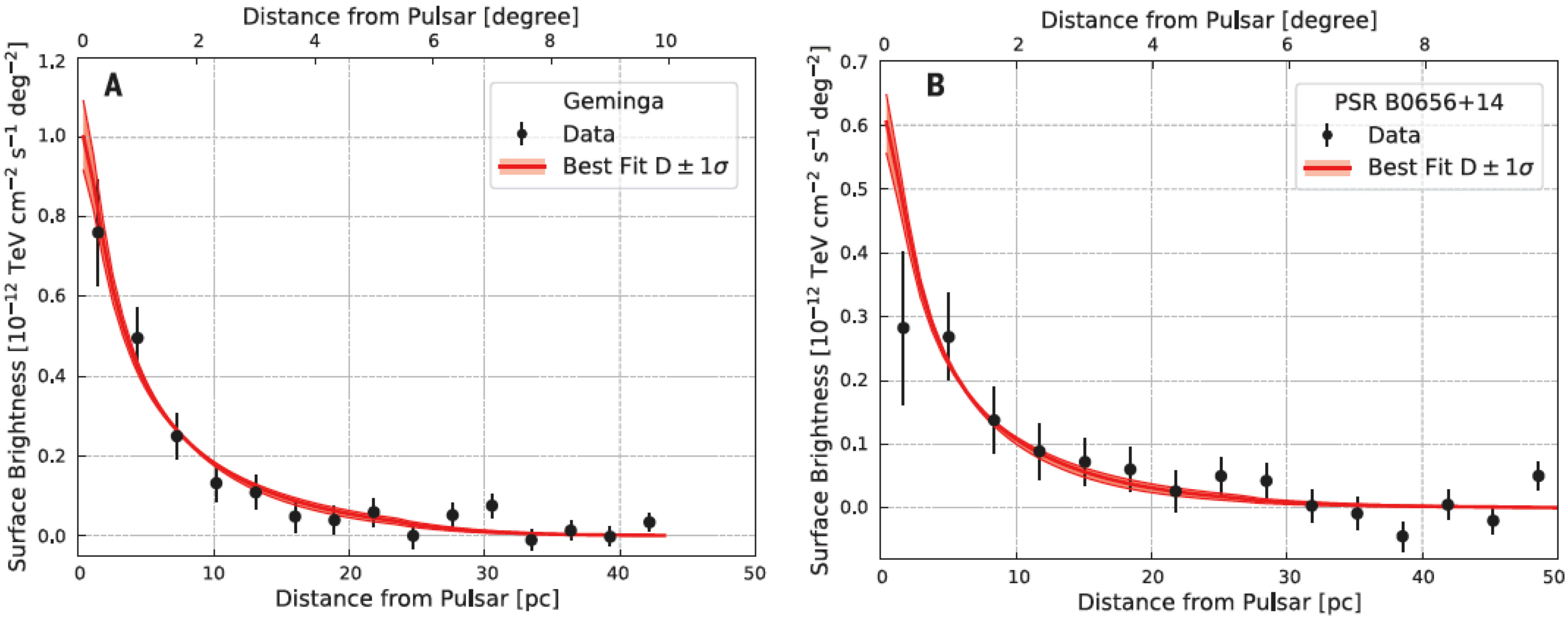
(Dated: April 14, 2018)

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_{out} [ST]	E_{out} [CCY]	E_{out} [HR]	E_{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

simple theoretical models for estimating the energy output, the diffusion setup and the injection 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

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

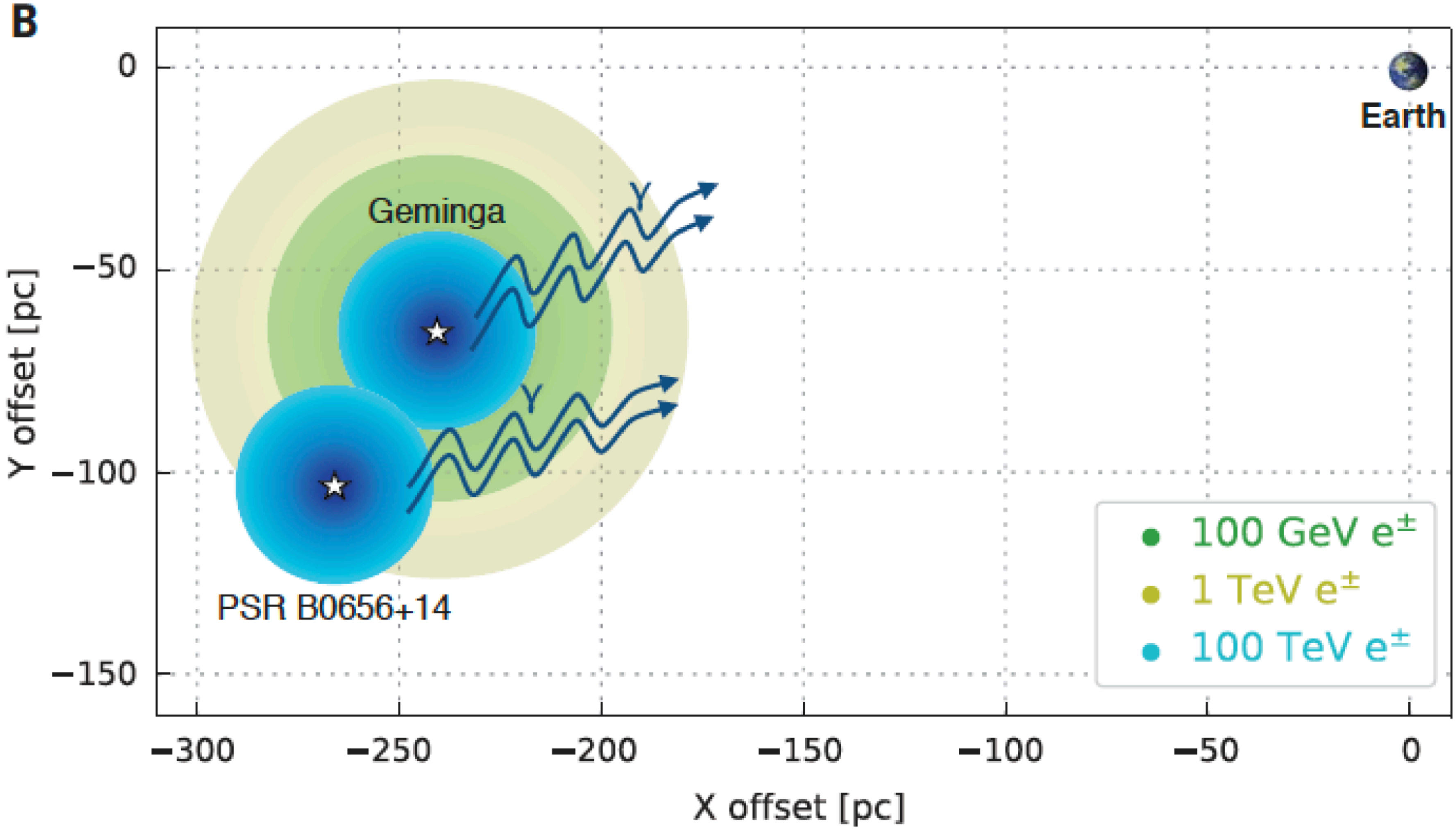
Inferred diffusion coefficients:

	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}

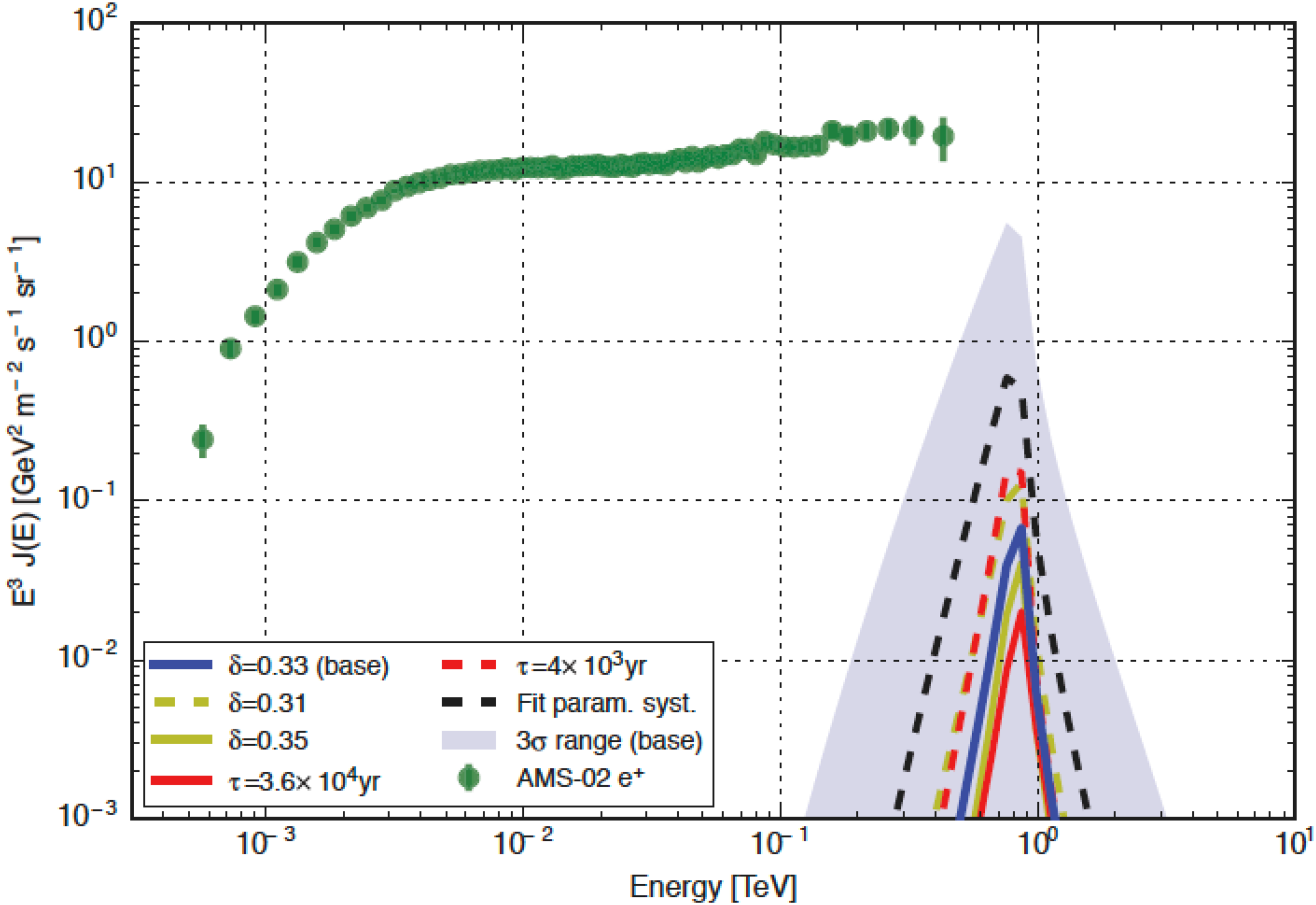
…versus ISM diffusion coefficient (GALPROP, AMS-02…)

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

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



* Abaysekara et al (HAWC Coll.) 2017



* Abaysekara et al (HAWC Coll.) 2017

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, 2018; Hooper and Linden 2017

Is this conclusion plausible?

Very probably NO.
Two key arguments:

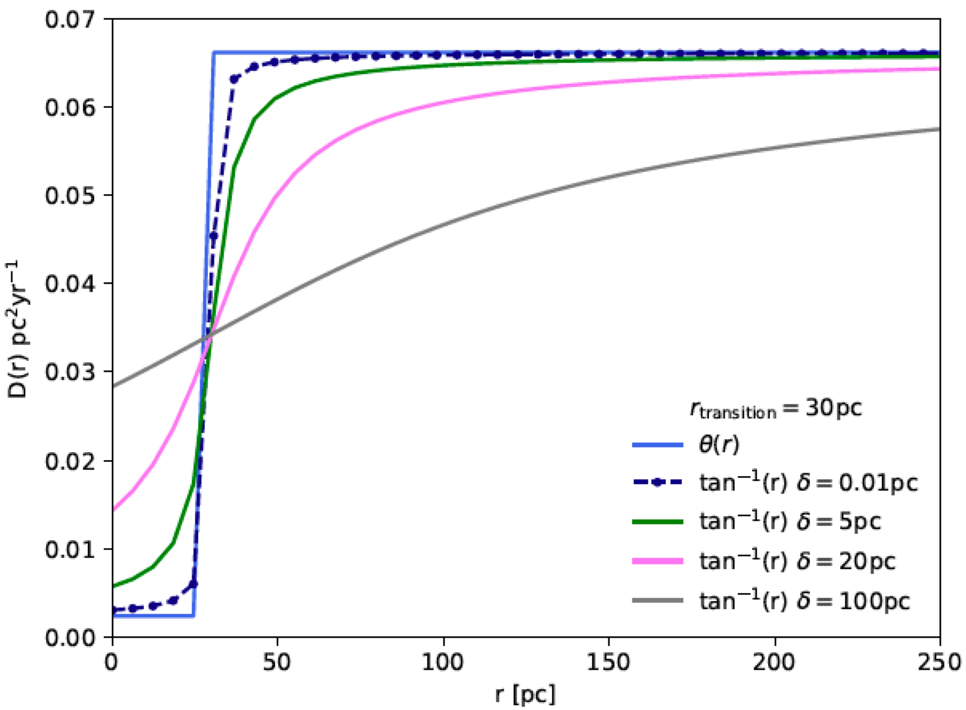
2. Models of CR emission predict inefficient diffusion near sources

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;
A few other possibilities (see e.g. **Evoli**'s talk)

- ▷ $L \downarrow \quad D_{||} \downarrow$ (Lopez-Coto, Giacinti, MNRAS 479, 2018)
- ▷ $k_{\rm res} W(k_{\rm res}) \uparrow \quad D_{||} \downarrow$
- ▷ Pressure gradients by not-resonant instability (Schroer et al., arXiv:2011.02238)

* 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 PRD 2018

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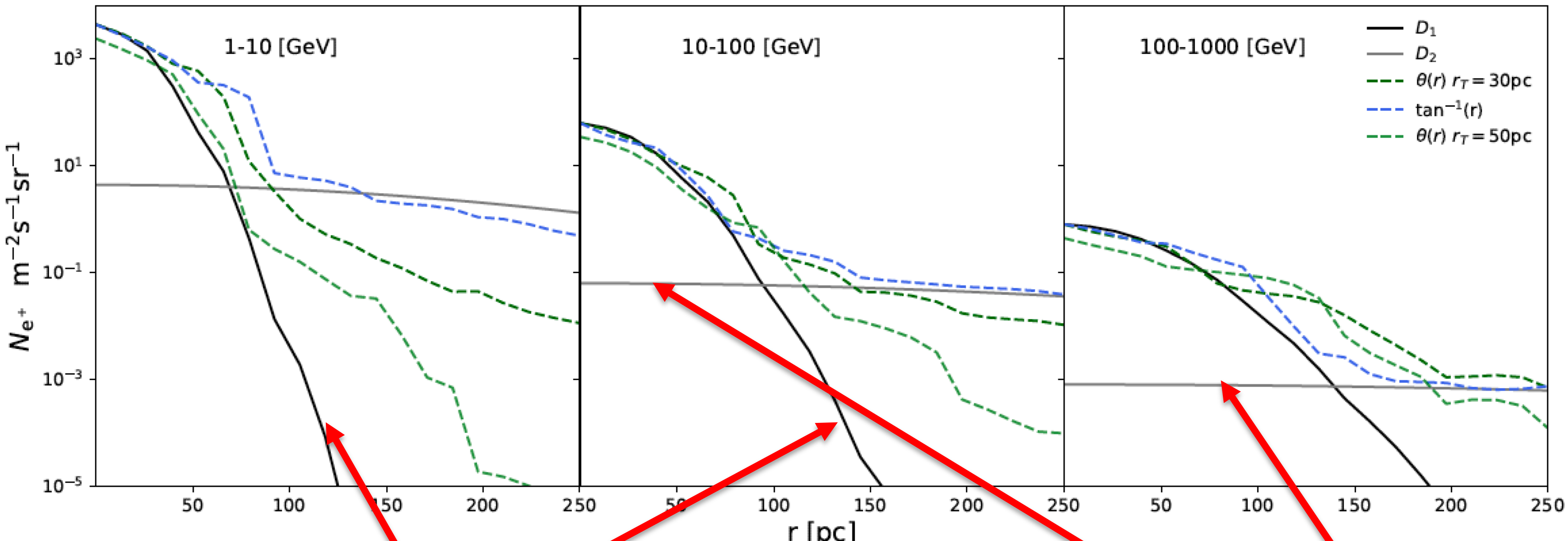
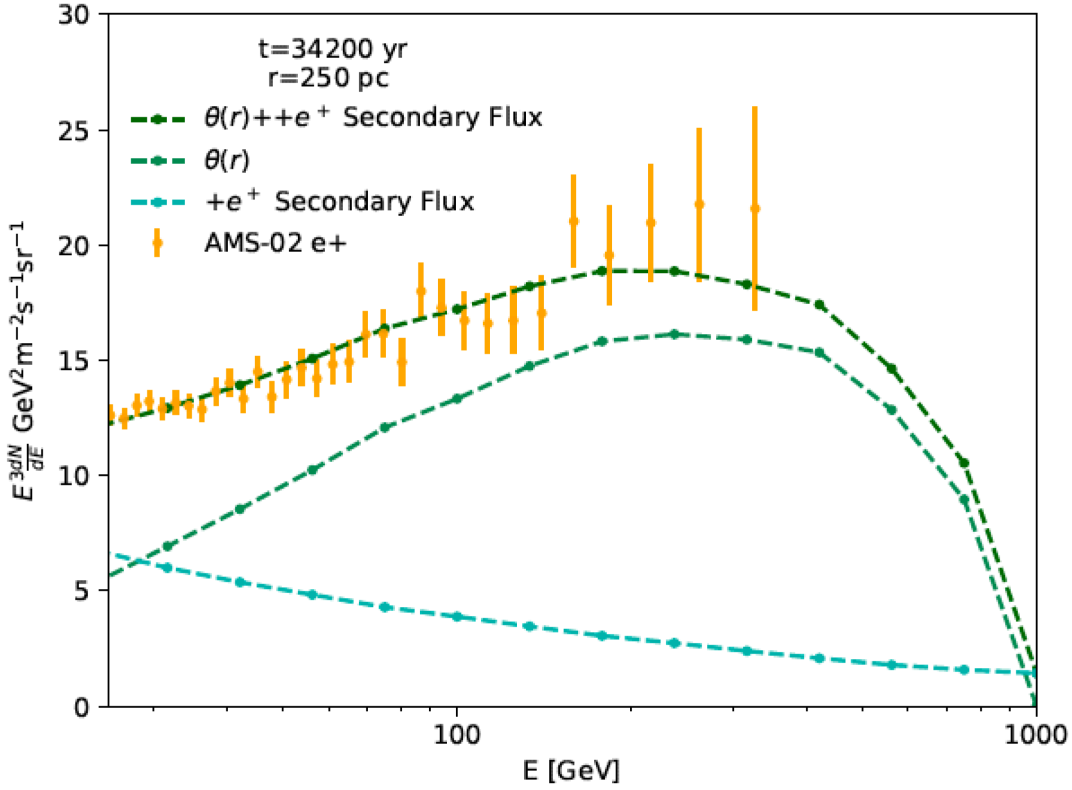


"HAWC" (inefficient) diffusion

"GALPROP" (efficient) diffusion

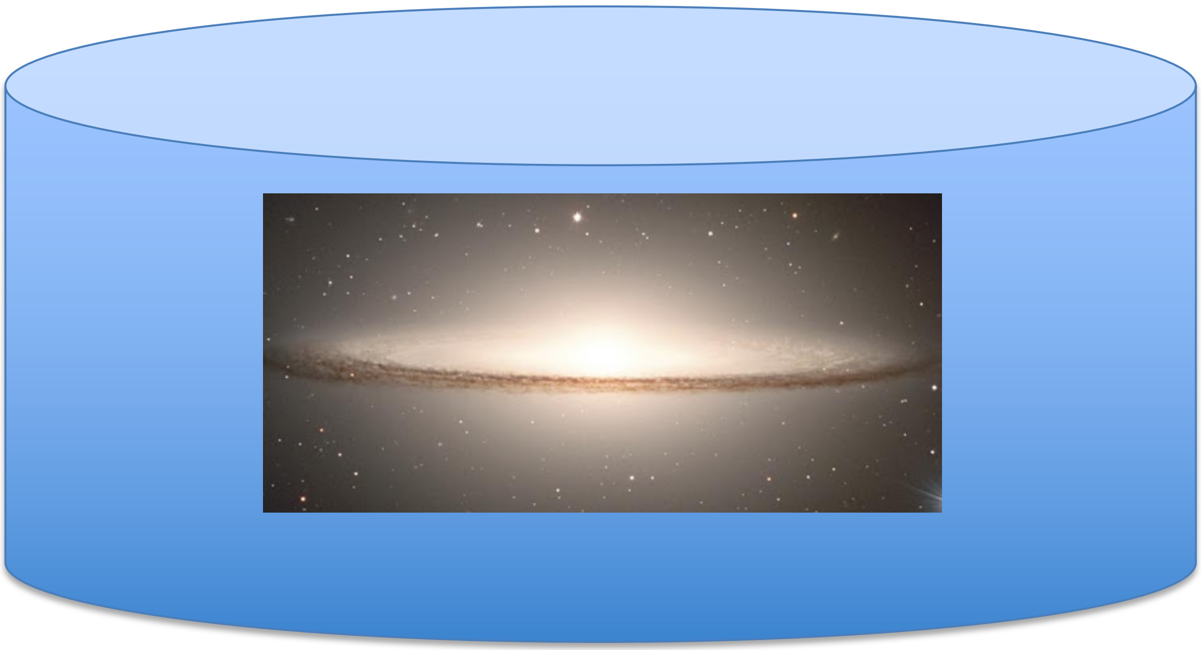
*Profumo, Reynoso, Kaaz, Silverman PRD 2018

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

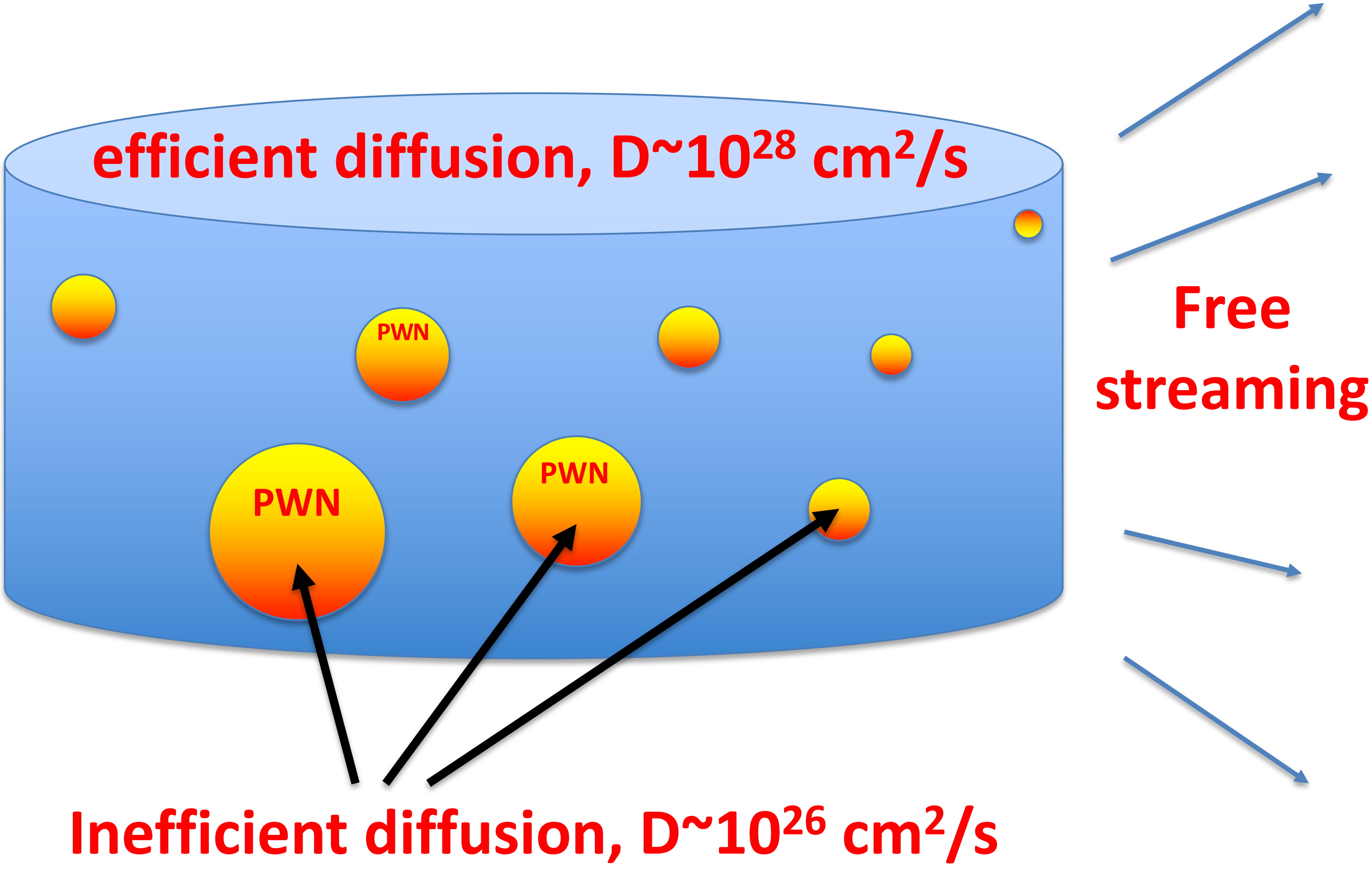


*Profumo, Reynoso, Kaaz, Silverman PRD 2018

“Swiss Cheese” Galactic Cosmic-Ray Diffusion



“Swiss Cheese” Galactic Cosmic-Ray Diffusion



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

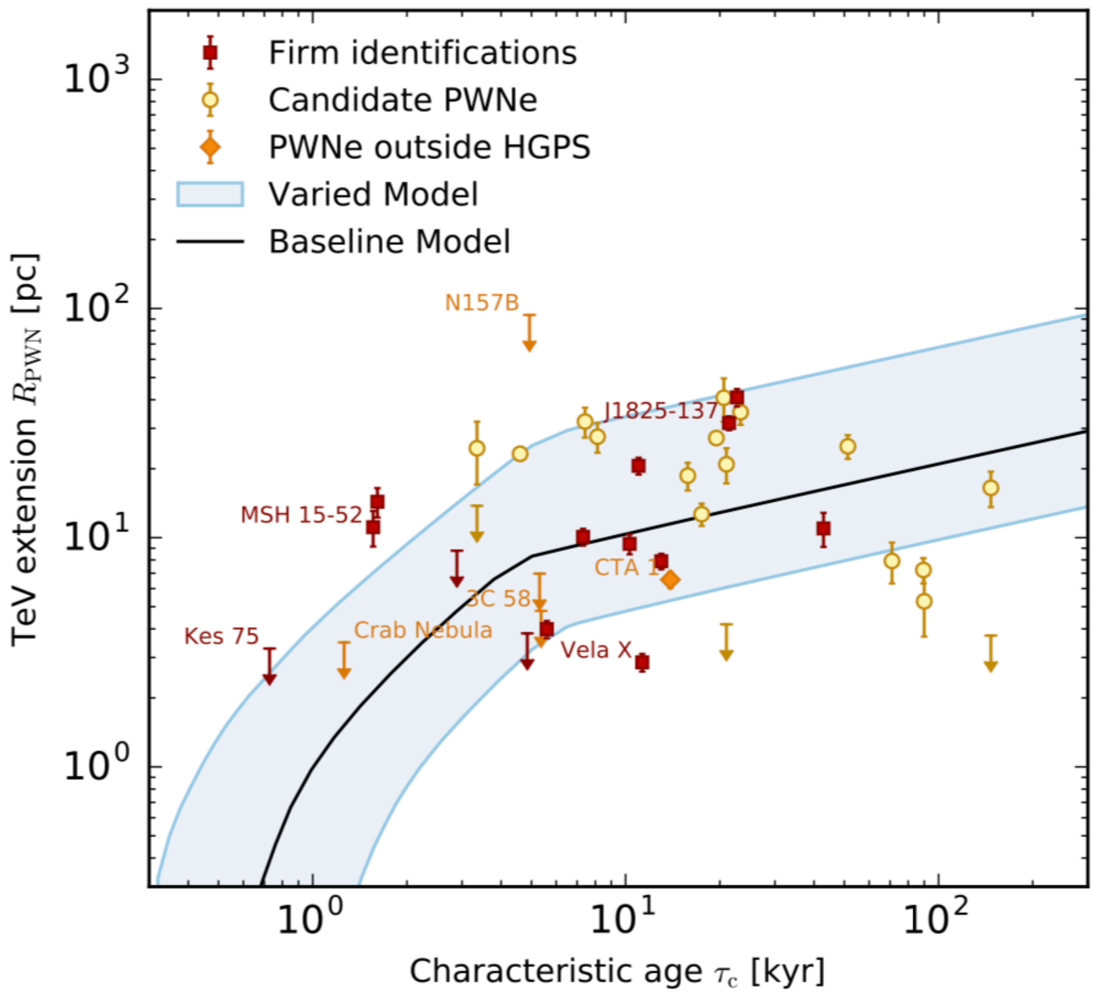
Estimate the **volume** of regions of inefficient diffusion

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

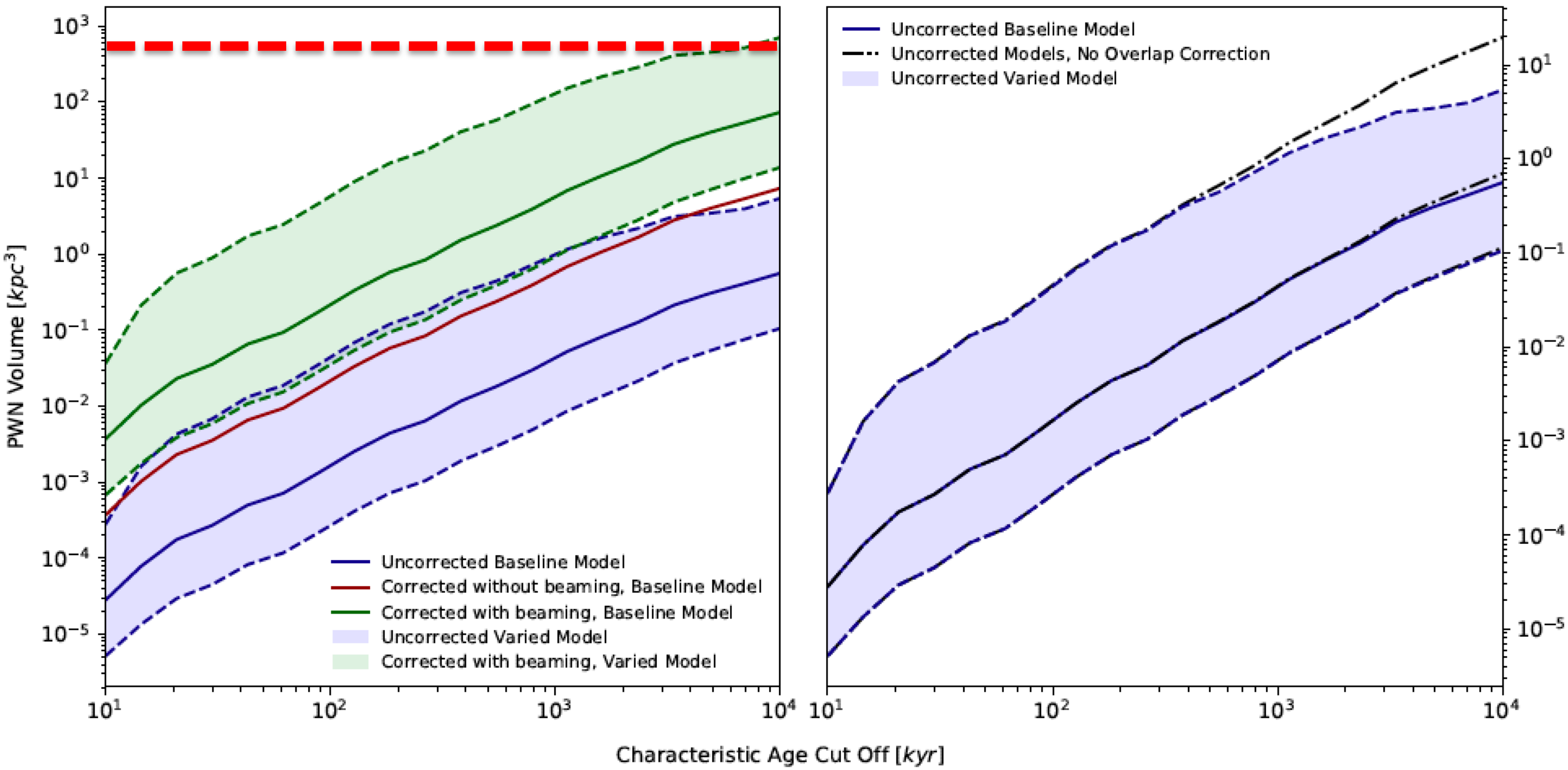
H.E.S.S. Collaboration, H. Abdalla[1], A. Abramowski[2], F. Aharonian[3,4,5], F. Ait Benkhali[3], A.G. Akhperjanian[†6,5], T. Andersson[10], E.O. Angüner[7], M. Arrieta[15], P. Aubert[24], M. Backes[8], A. Balzer[9], M. Barnard[1], Y. Becherini[10], J. Becker Tjus[11], D. Berge[12], S. Bernhard[13], 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]

* Abdalla et al 2017



* Abdalla et al 2017

…but of course the (ATNF) 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!

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

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

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

Thus, t_{PWN} ~ t_{ISM} and cosmic rays should illuminate bubbles of inefficient diffusion!

*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)

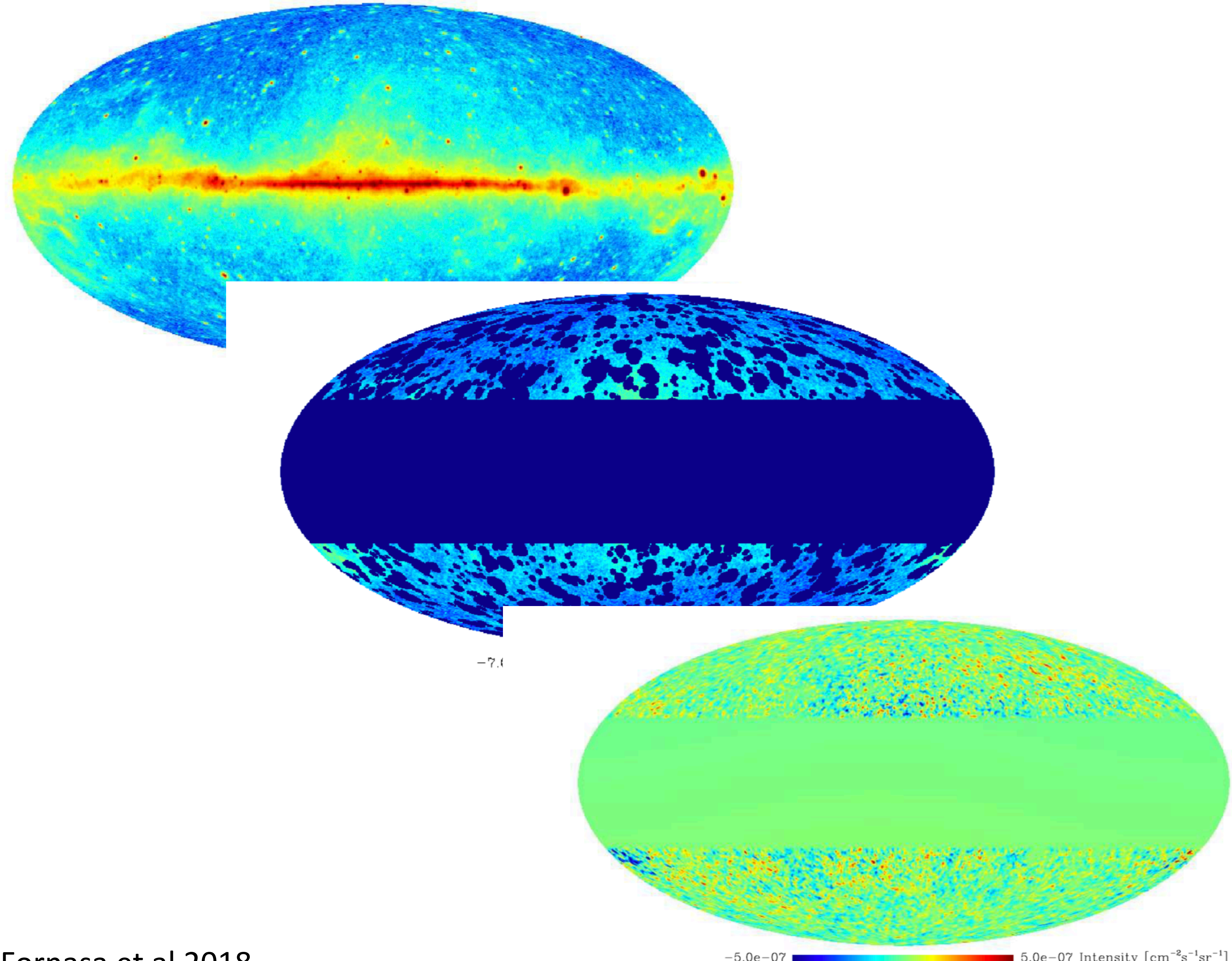
$$\theta \sim \frac{R_{\rm PWN}}{d_{\rm PWN}}$$

theta ranges from few degrees to 0.1 degrees

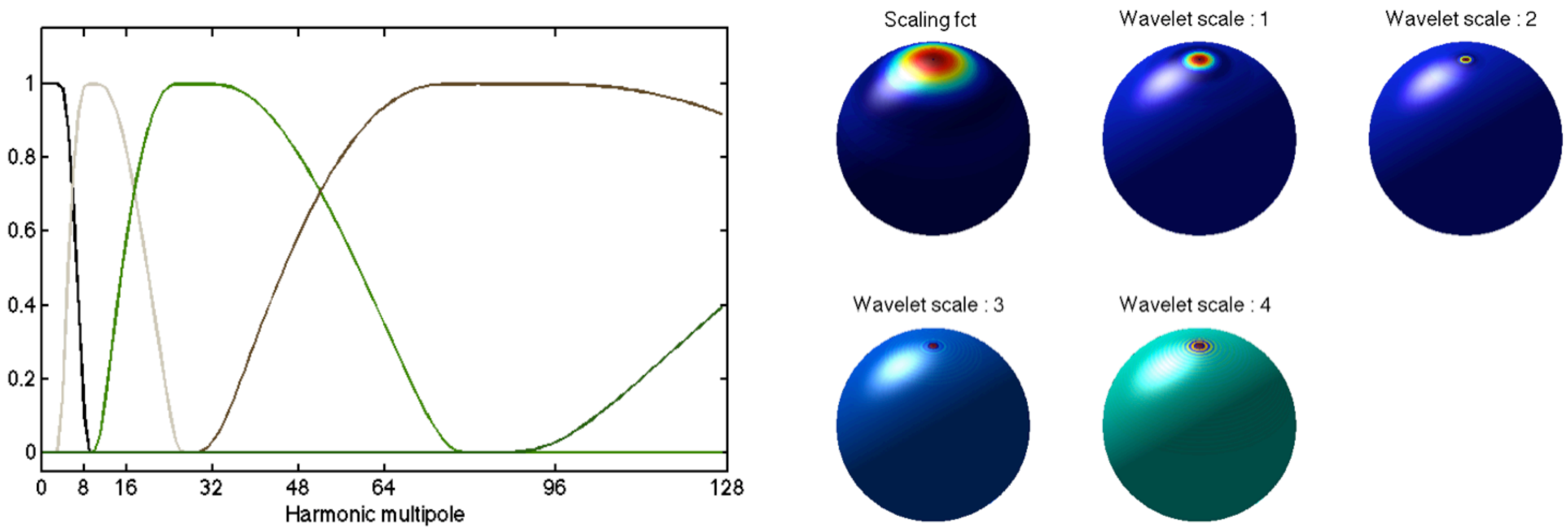
can use any frequency from radio (with additional B uncert.) to X-ray to gamma rays

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

*Profumo, Reynoso, Kaaz, Silverman 2018

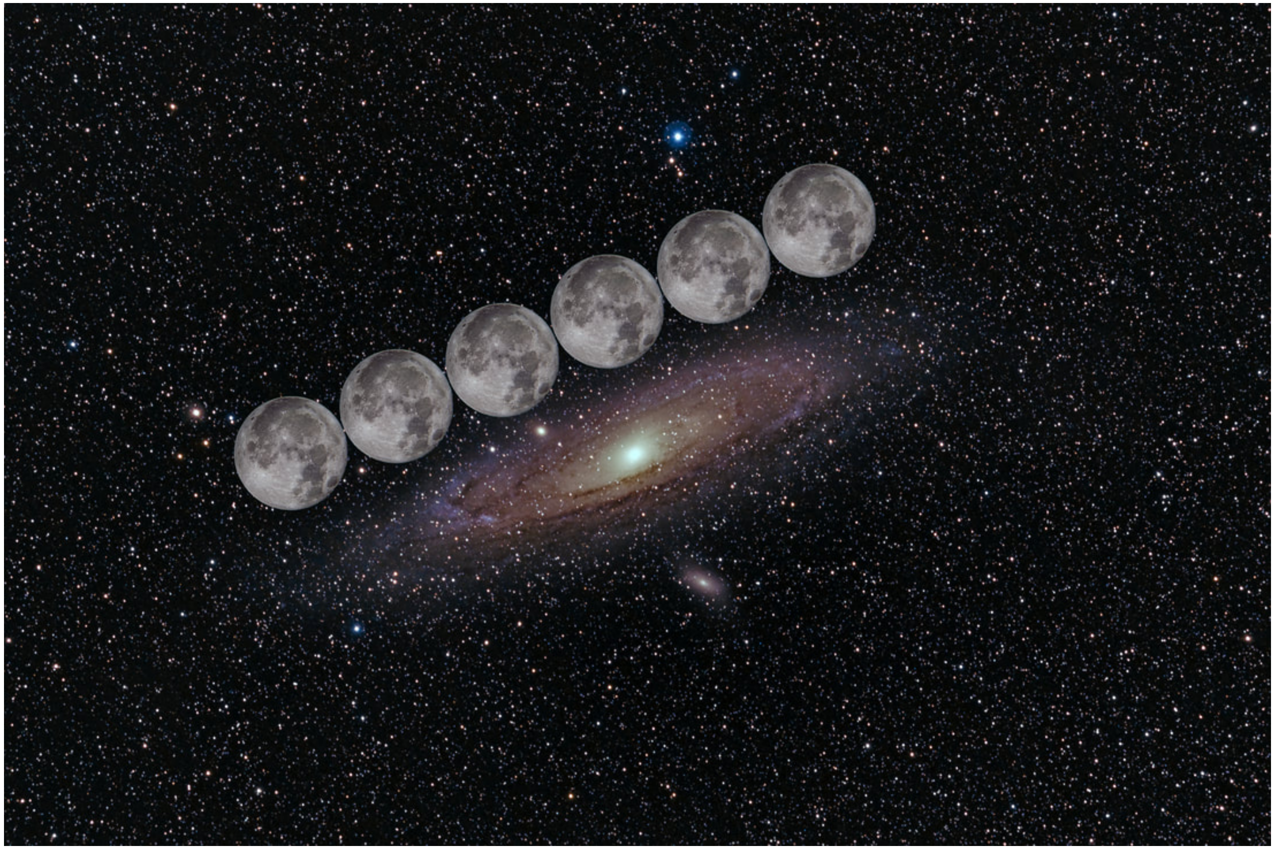


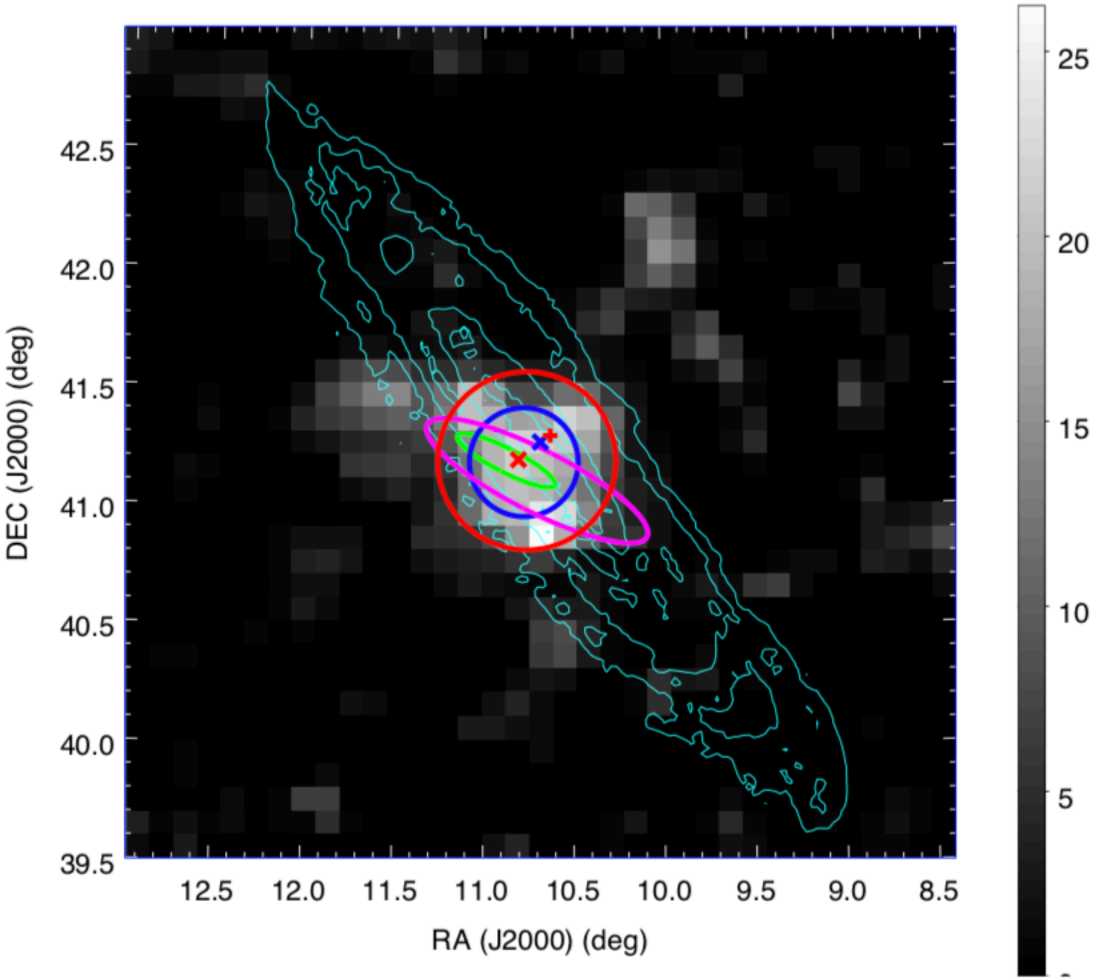
* Fornasa et al 2018



1
0.8
0.6
0.4
0.2
0
0
8
16
32
48
64
96
128
Harmonic multipole
Scaling fct
Wavelet scale : 1
Wavelet scale : 2
Wavelet scale : 3
Wavelet scale : 4

Where else can we test the "Swiss Cheese" Hypothesis?





Ackermann et al 2017

FERMI-LAT OBSERVATIONS OF γ-RAY EMISSION TOWARDS THE OUTER HALO OF M31

CHRISTOPHER M. KARWIN[†], SIMONA MURGIA[‡], AND SHELDON CAMPBELL[¶]
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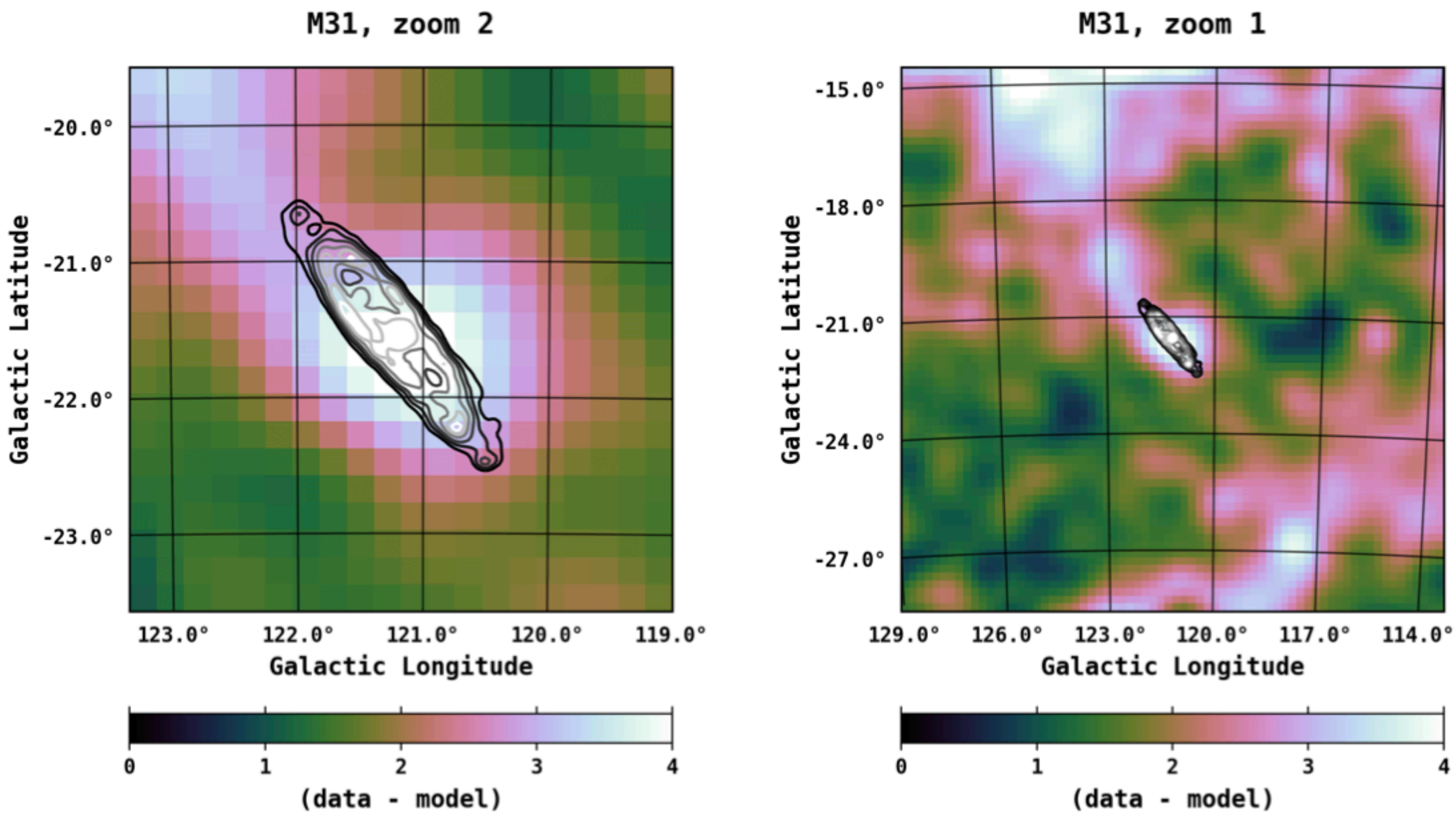
Accepted for publication in The Astrophysical Journal



Karwin et al 2019

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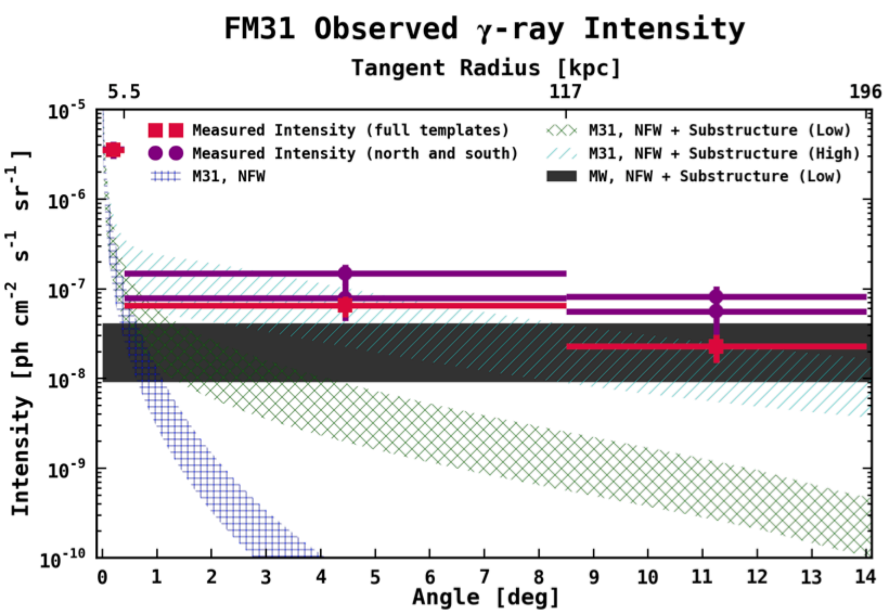

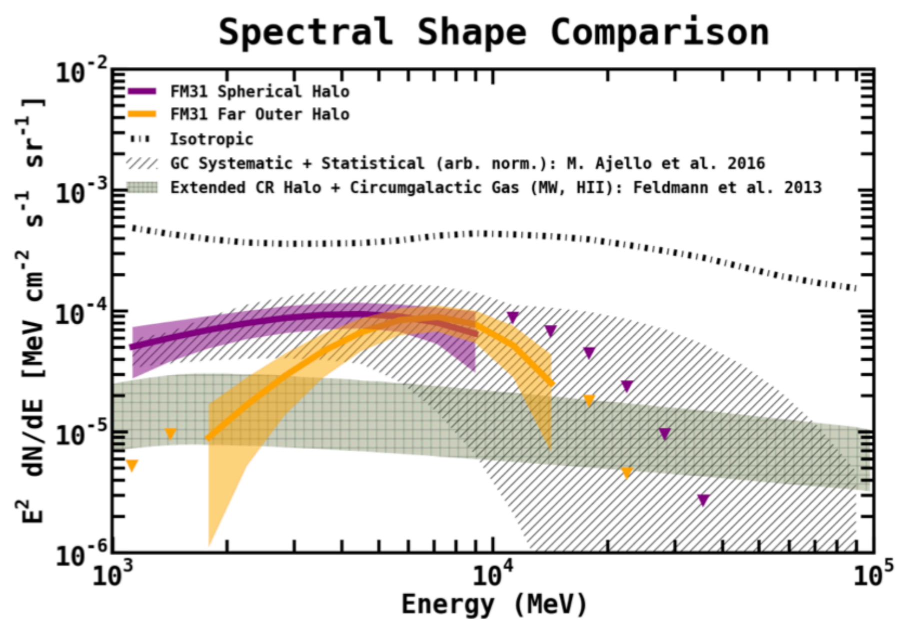

Karwin et al 2019

Cosmic-ray transport and gamma-ray emission in M31

Audrey Do[1], Matthew Duong[1], Alex McDaniel[1,2,3⋆],
Collin O'Connor[1], Stefano Profumo,[1,2]†, Justine Rafael[1], Connor Sweeney[1],
and Washington Vera III[1]
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[3] *Department of Physics and Astronomy, Kinard Lab of Physics, Clemson, SC 29634-0978, USA*

(CRE1): Benchmark diffusion scenario, with CRE injected at the very center of M31

(CRE2): Benchmark diffusion scenario, with CRE injected in star-forming regions

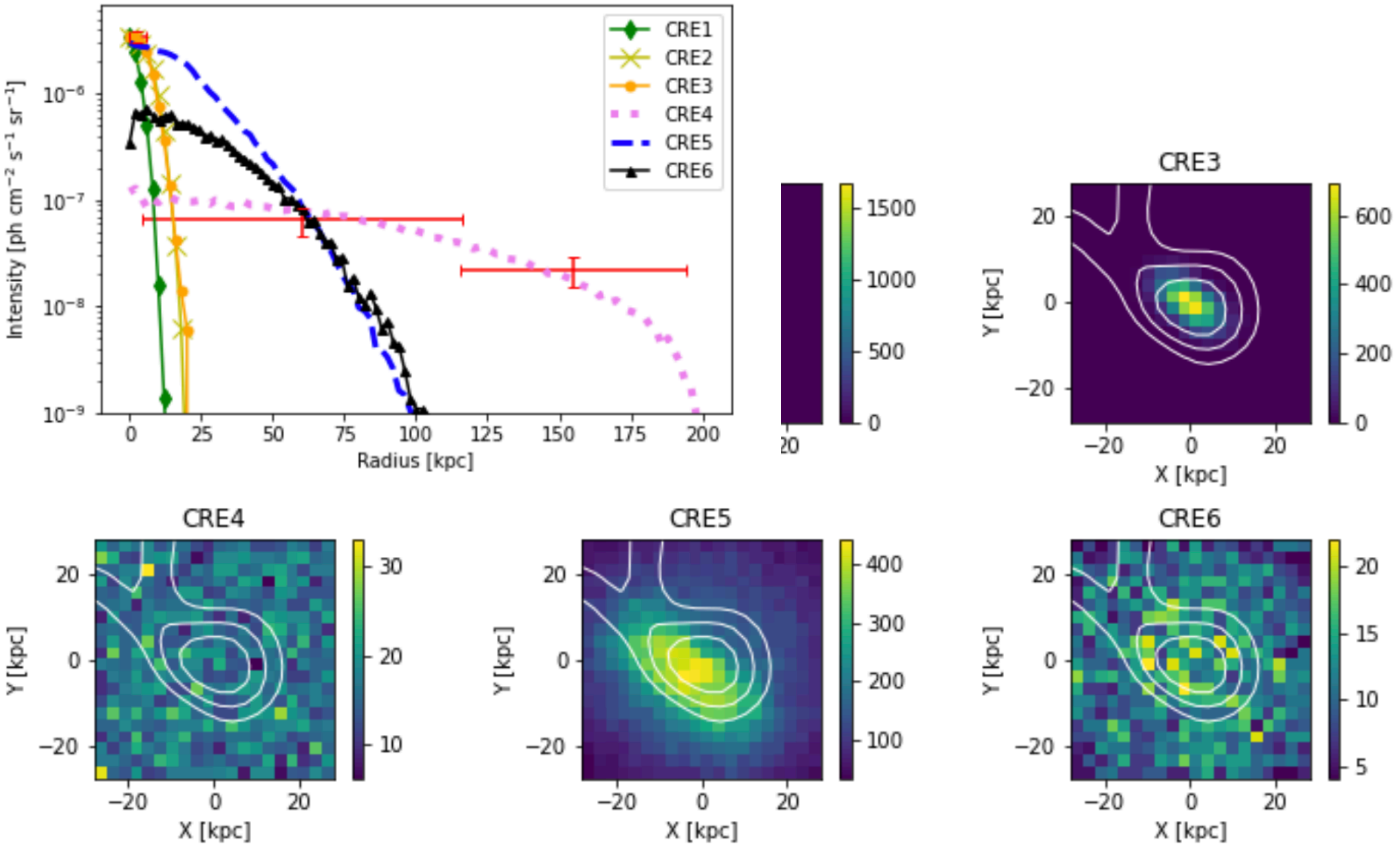
(CRE3): Benchmark diffusion scenario, with CRE injected at the location of mature synthetic pulsar locations

(CRE4): Constant diffusion scenario, with CRE injected at the very center of M31

(CRE5): Gradual diffusion scenario, with CRE injected at the very center of M31

(CRE6): "Swiss cheese" diffusion scenario, with CRE injected at the location of mature synthetic pulsar locations

Do et al 2020, to appear



Do et al 2020, to appear

Cosmic-ray transport and gamma-ray emission in M31

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[3] *Department of Physics and Astronomy, Kinard Lab of Physics, Clemson, SC 29634-0978, USA*

(CRP1): Benchmark diffusion scenario, with CRP injected at the very center of M31

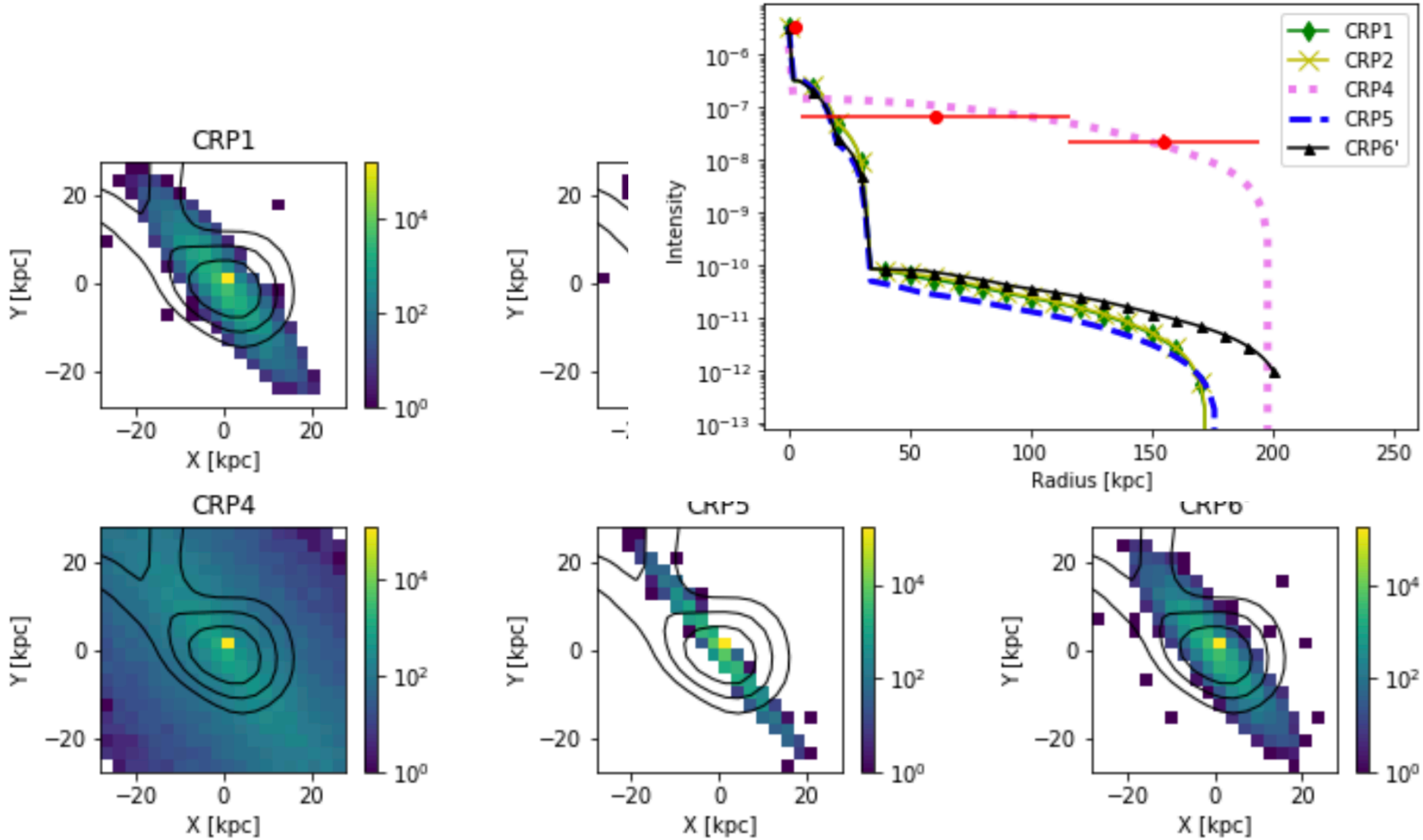
(CRP2): Benchmark diffusion scenario, with CRP injected in star-forming regions

(CRP4): Constant diffusion scenario, with CRP injected at the very center of M31

(CRP5): Inhomogeneous diffusion scenario, with $D_2/D_1 = 55$, with CRP injected at the very center of M31

(CRP6'): "Swiss cheese" diffusion scenario, but with CRP injected in star-forming regions

Do et al 2020, to appear



Do et al 2020, to appear

- No physical reason for galactic cosmic-ray diffusion to be spatially homogeneous
- Circumstantial evidence for pockets of inefficient diffusion from HAWC PWNe observations
- Testable in the Milky Way
- Potentially indirectly testable in outer galaxies (M31)
- Important implications for diffuse gamma-ray emission models