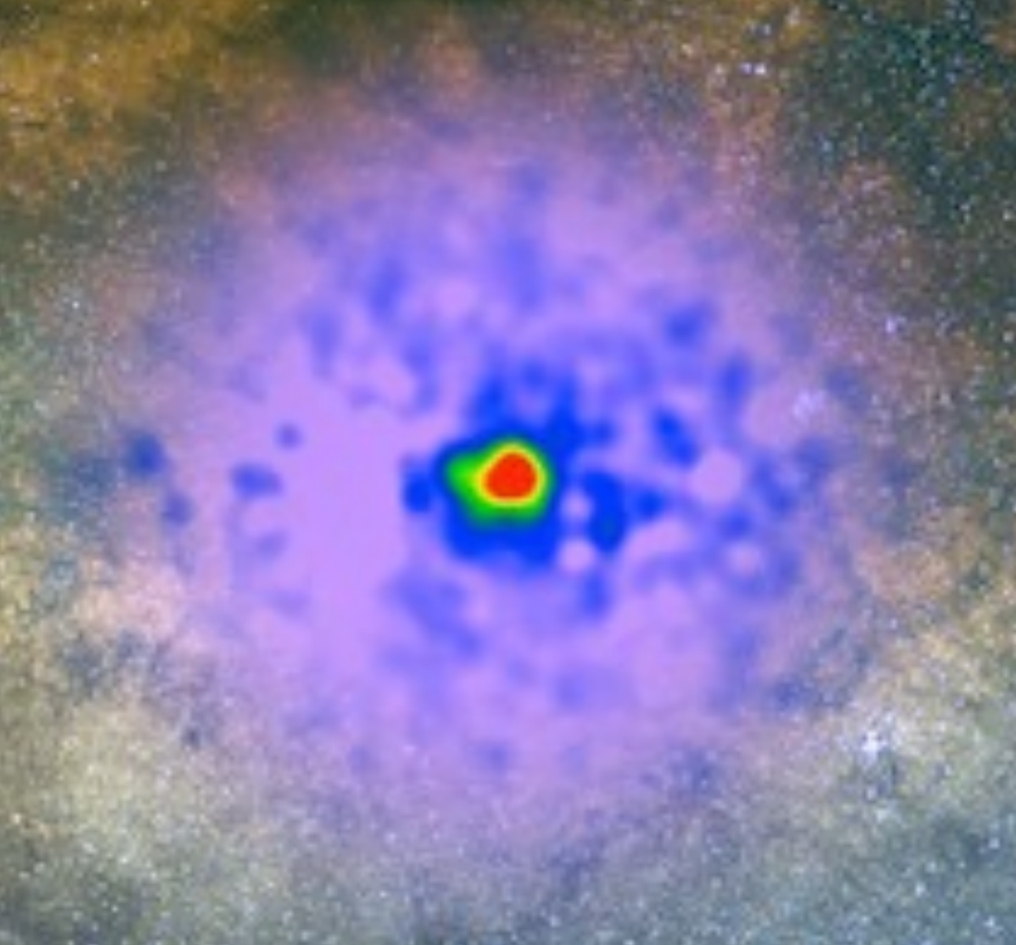
Cosmic-ray and gamma-ray anomalies and their interpretations



Daniele Gaggero

GRAPPA
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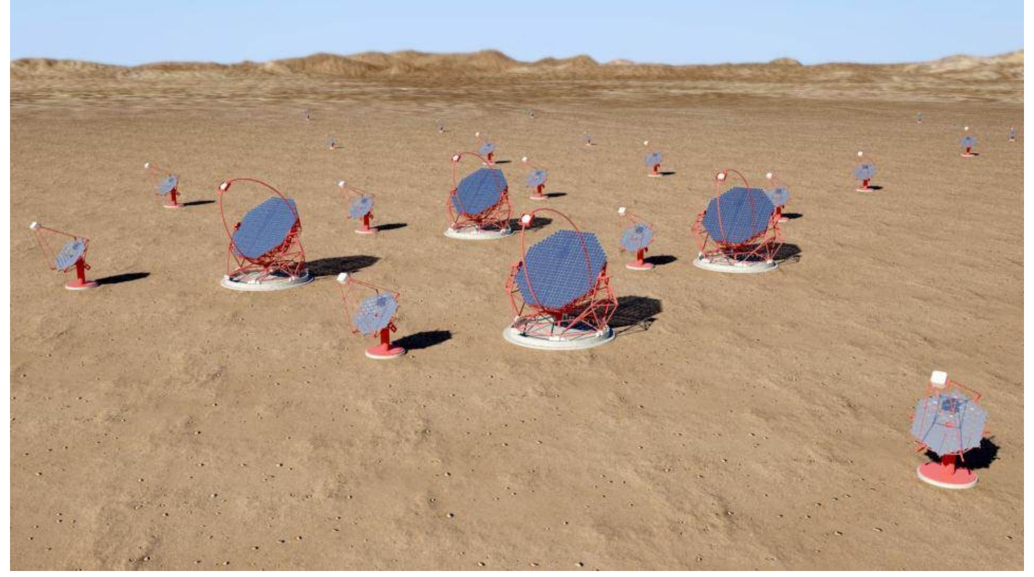
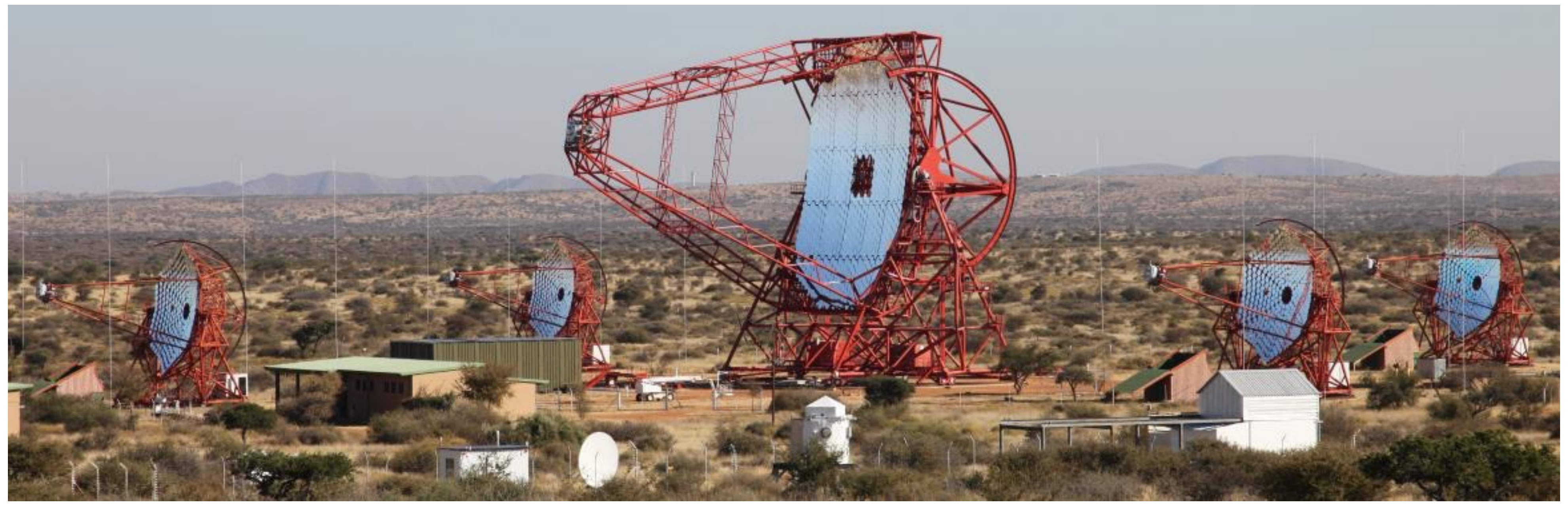
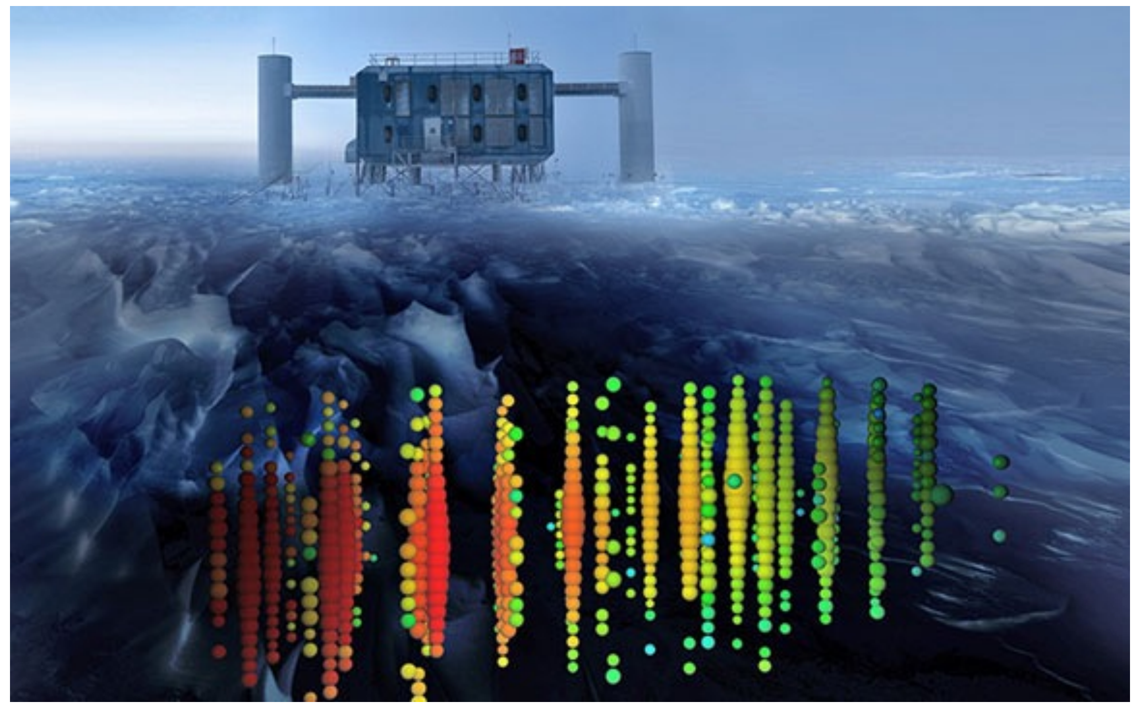
TeV PARTICLE ASTROPHYSICS
TeVPA 2017
AUGUST 7-11
COLUMBUS, OH

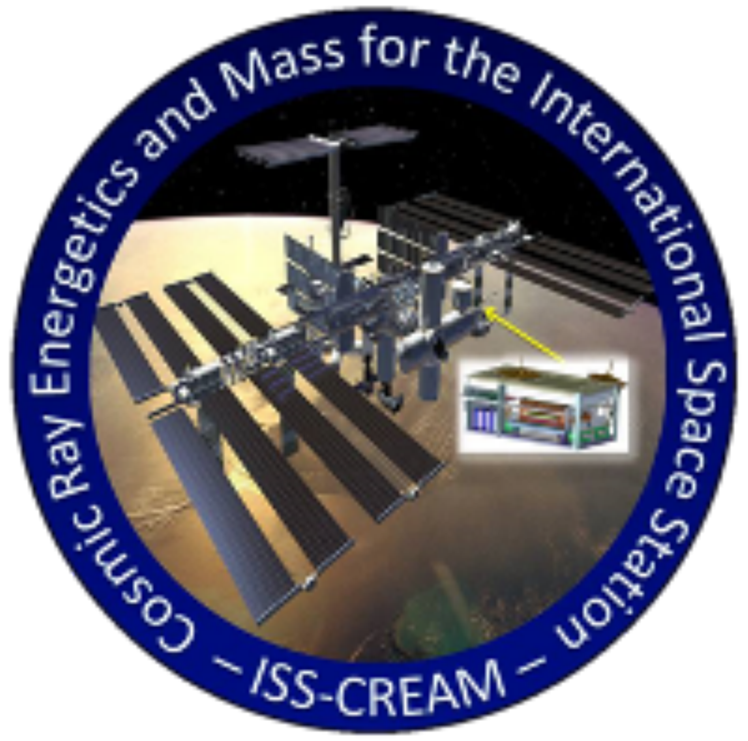
Columbus, OH
August 9th, 2017

A new epoch of precision measurements

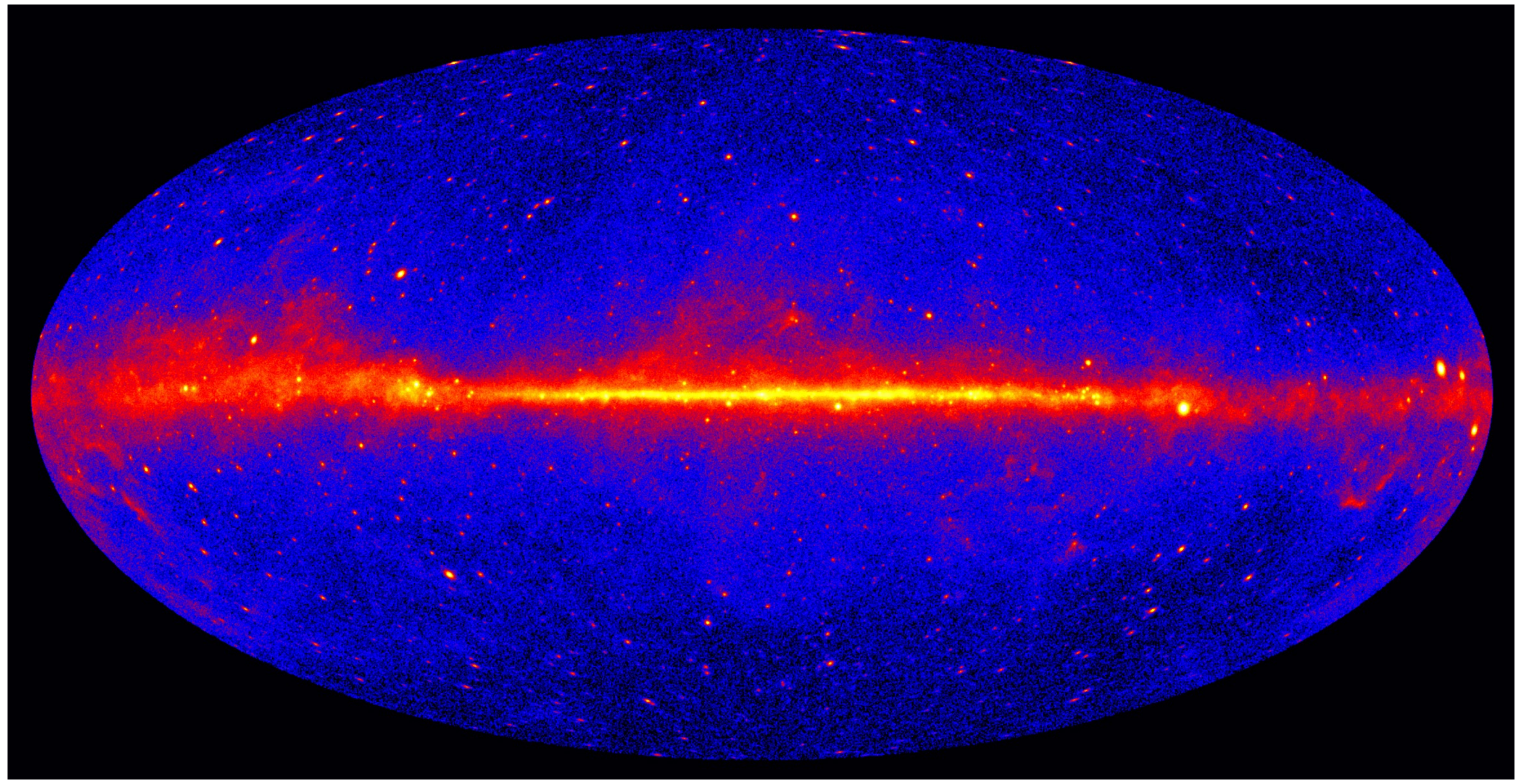


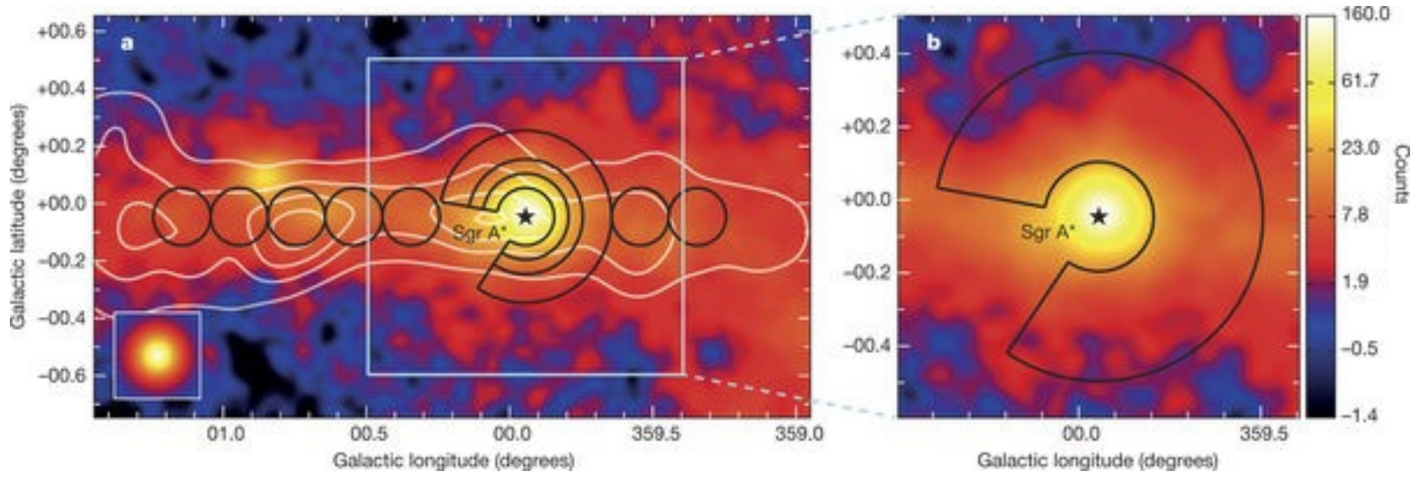


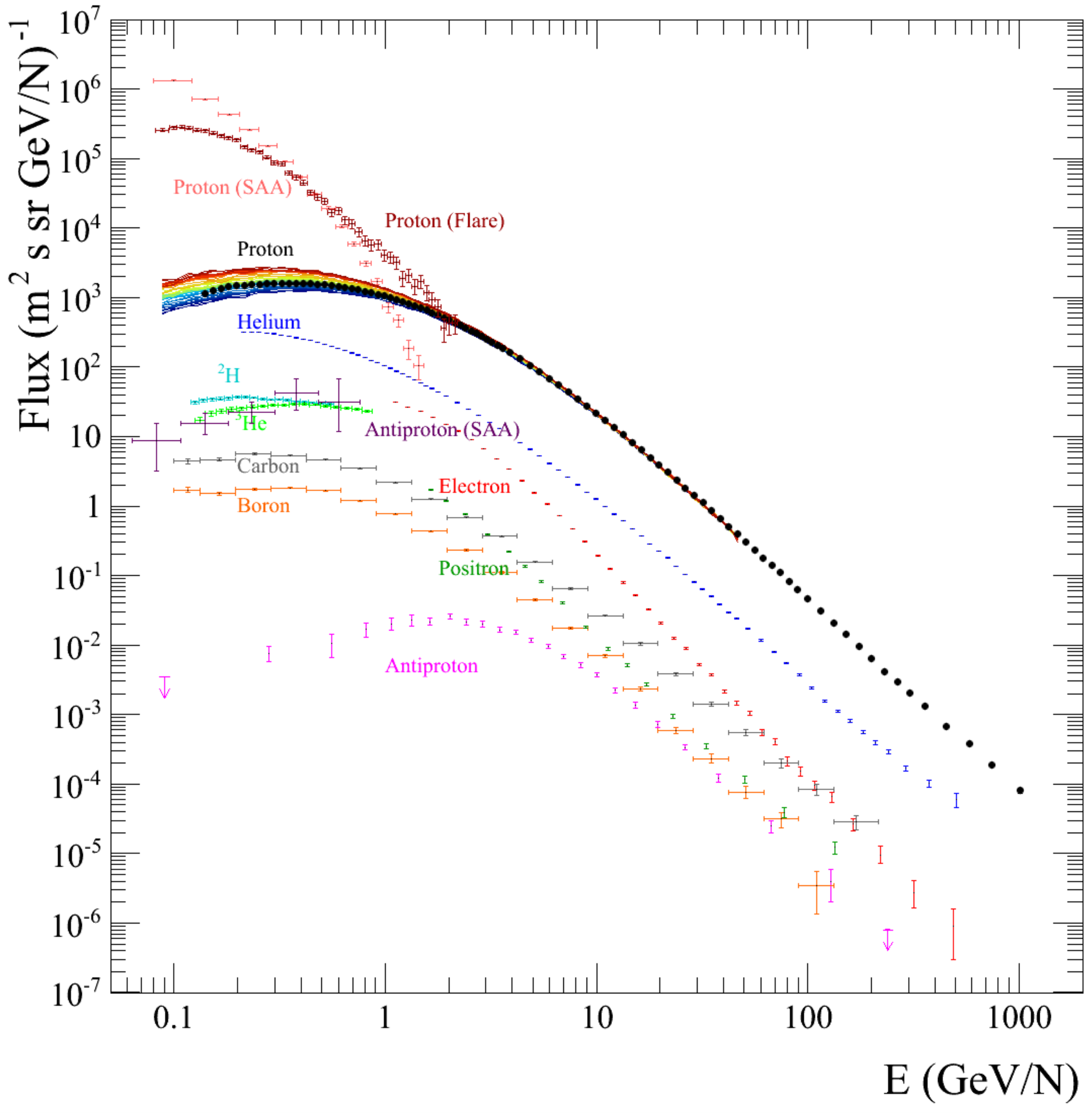


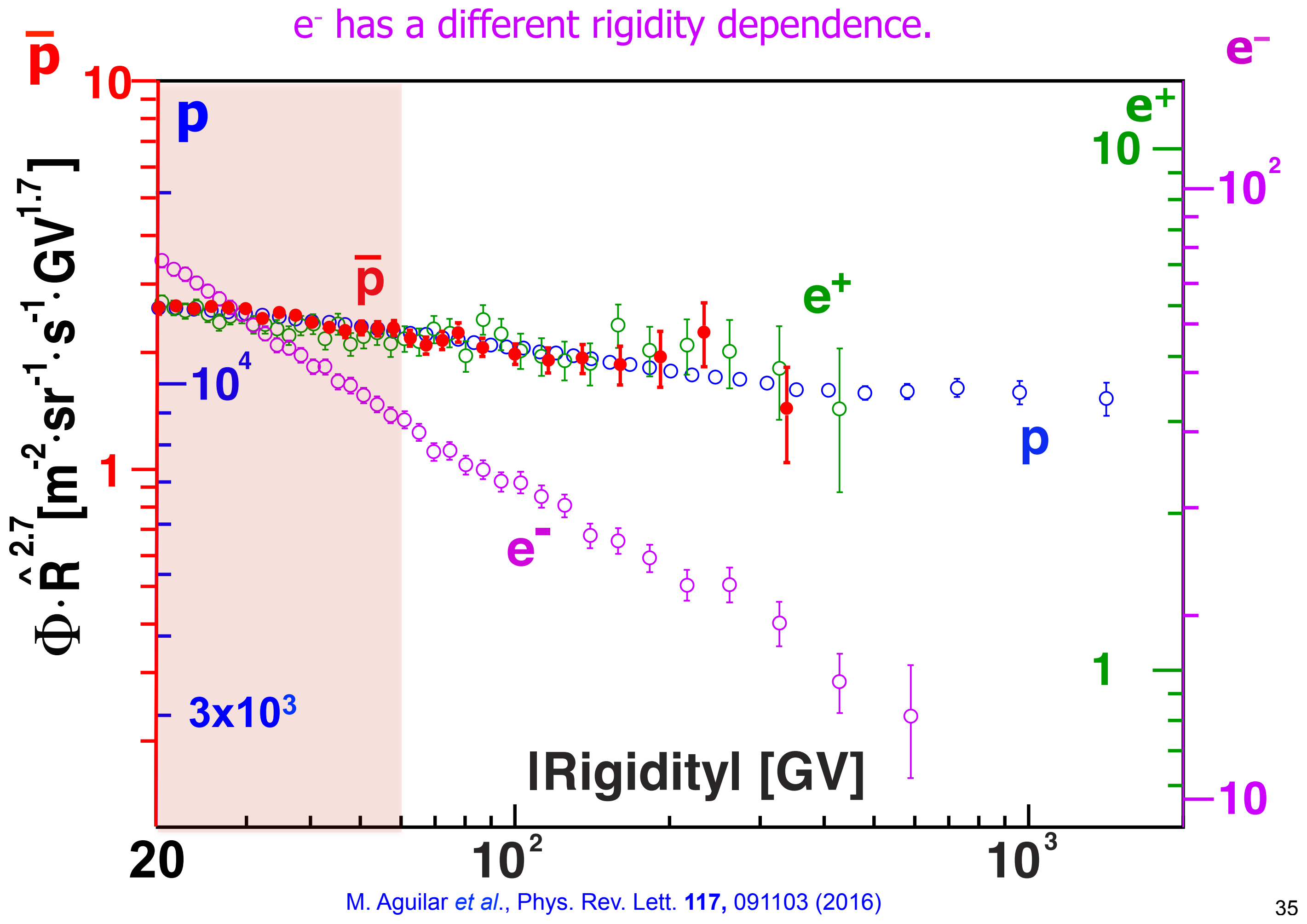


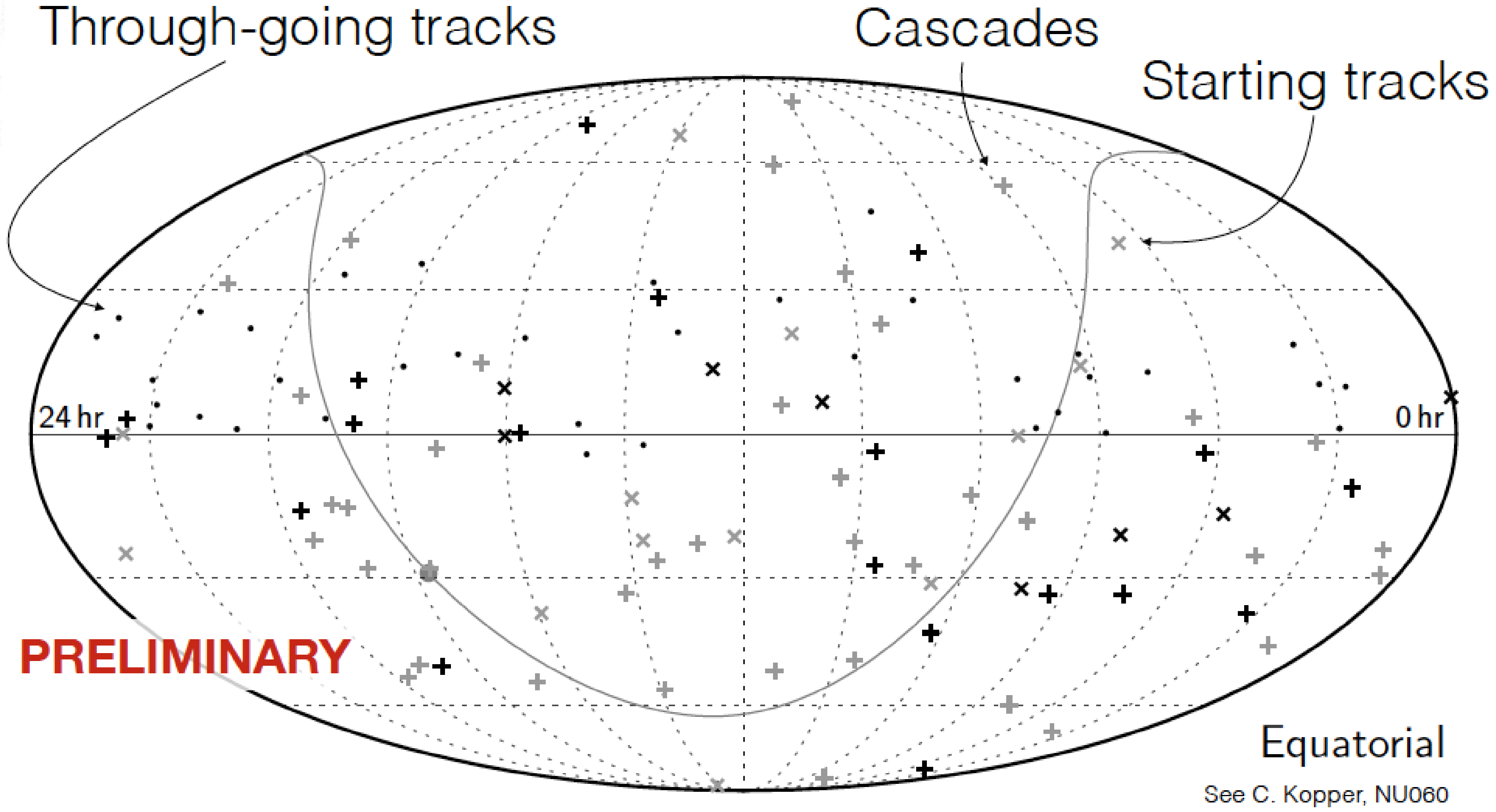
A new epoch of precision measurements

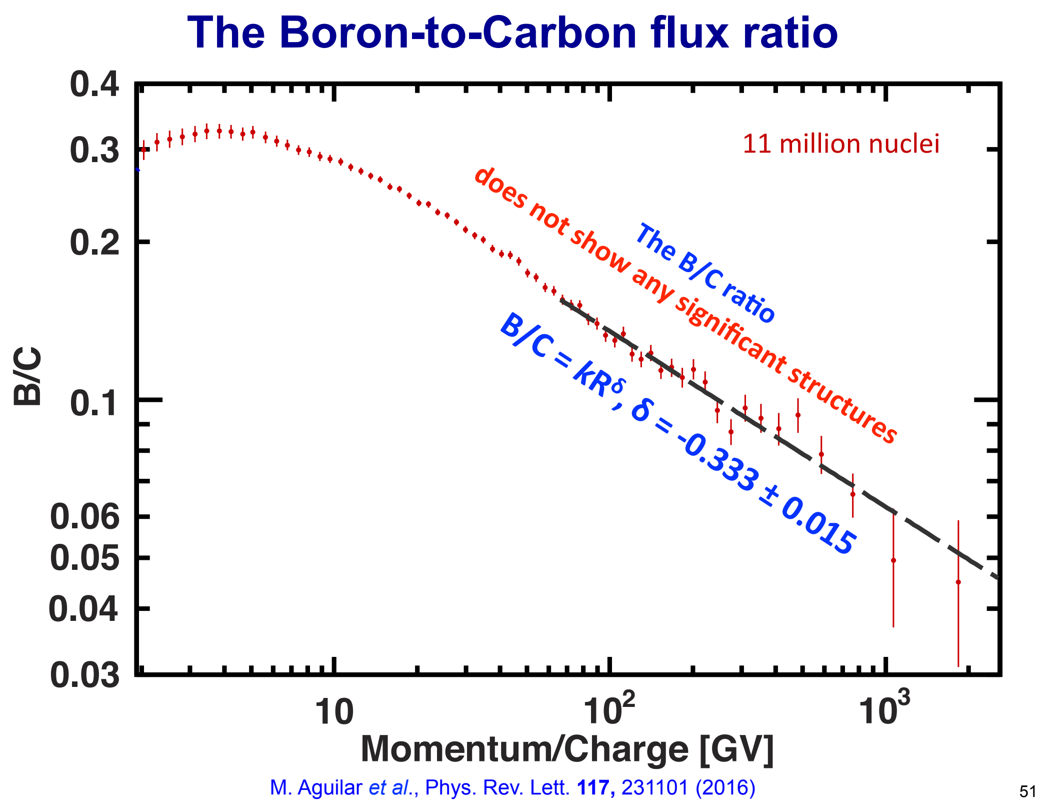








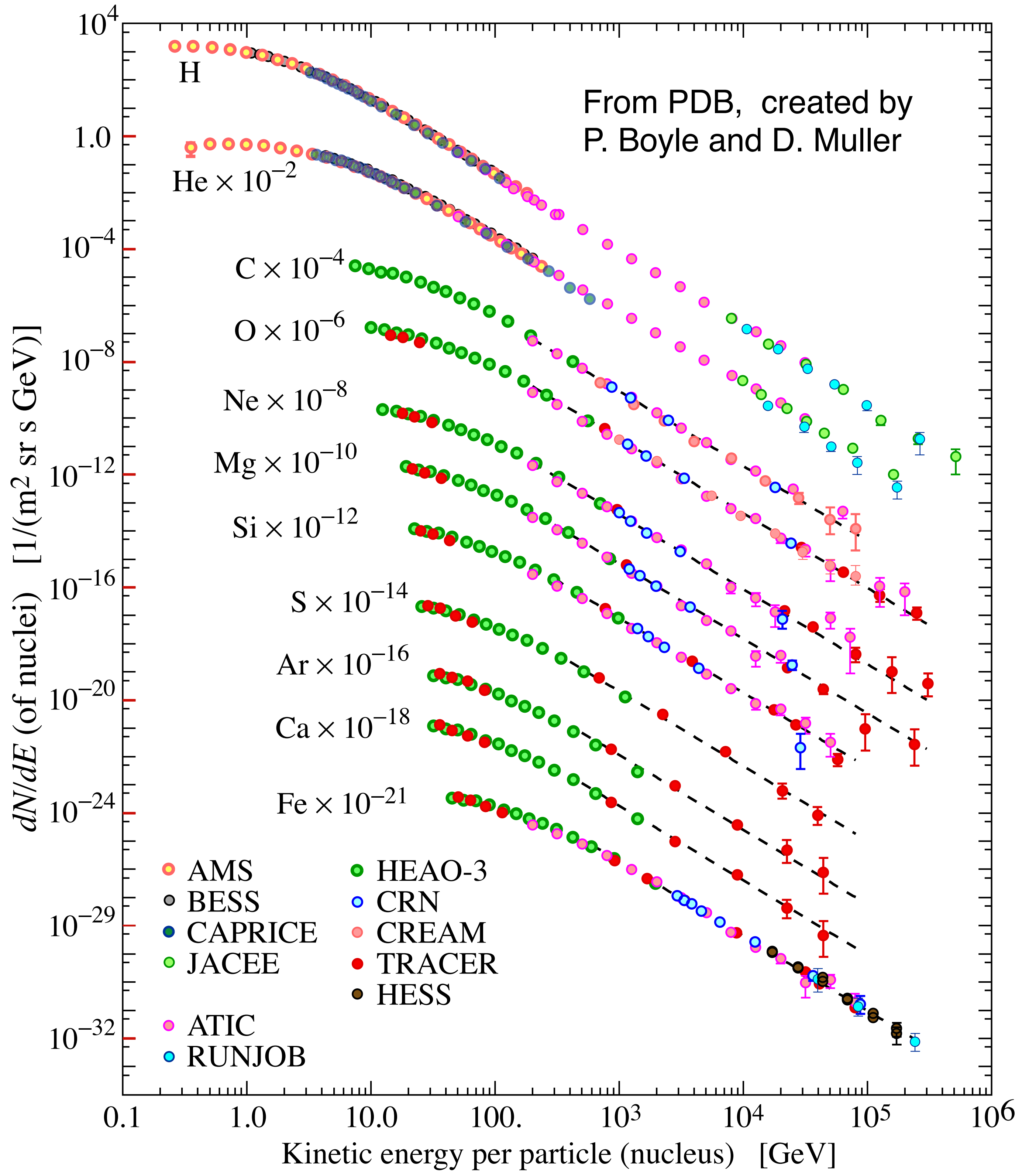




Anomalies with respect to what?

…with respect to *theoretical predictions*? what do theories predict?

- **CR acceleration:** diffusive shock acceleration theory *["Bobalski": Bell 1978, Ostriker&Blandford 1978, Axford et al. 1977, Krimskii 1977]*
- **CR transport:** QLT of resonant pitch-angle scattering on Alfvén waves *[Jokipii 1966, Ginzburg&Syrovarskii 1964, …]*
  - CRs diffuse in the ISM on small fluctuations in the magnetic field;
  - turbulent field can be modeled by a Kolmogorov isotropic power spectrum

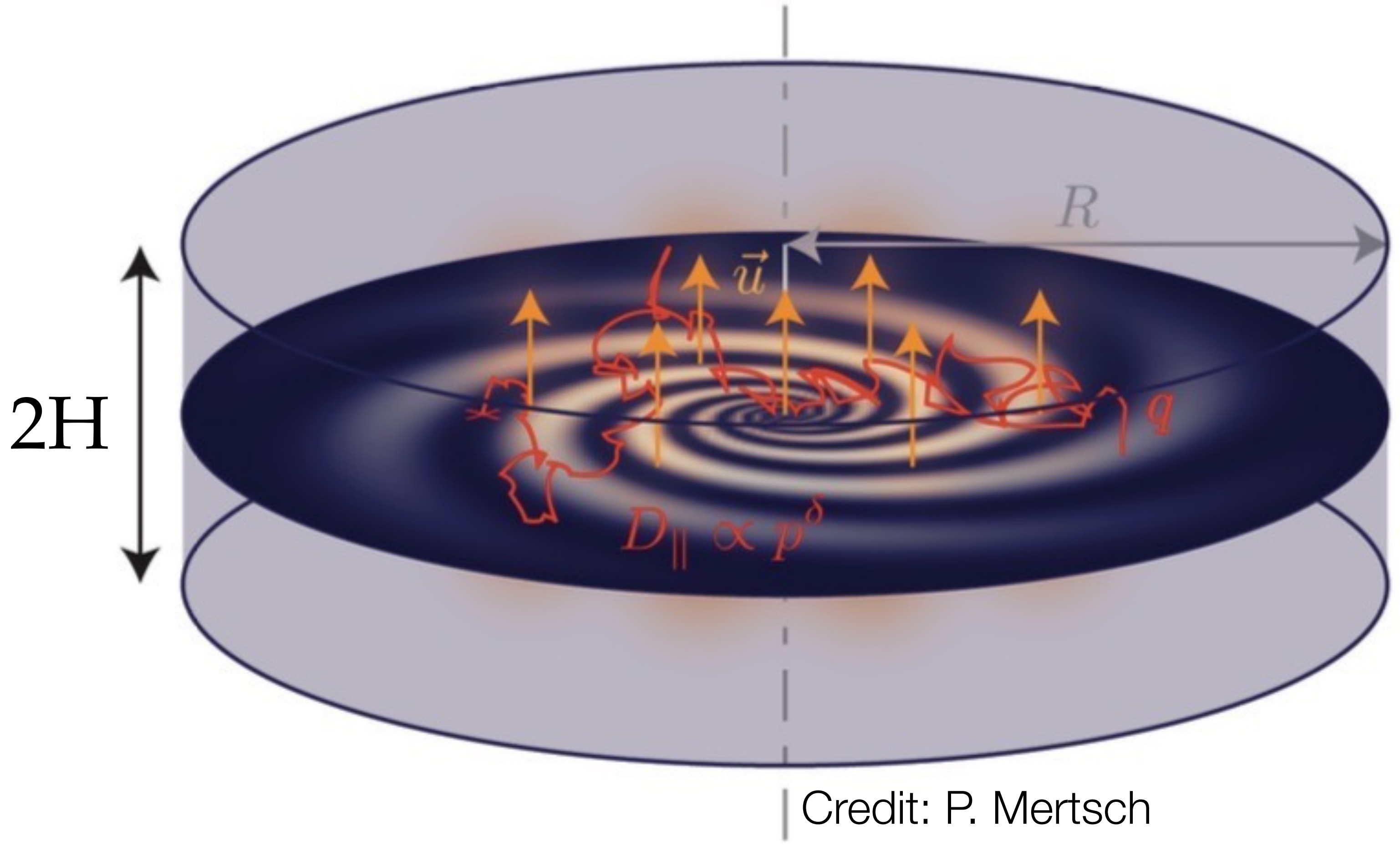


- in their simplest form they *predict featureless and universal* spectra
- key aspects: *self-similarity of DSA theory, Kolmogorov turbulence…*
- **adequate to pre-PAMELA data**

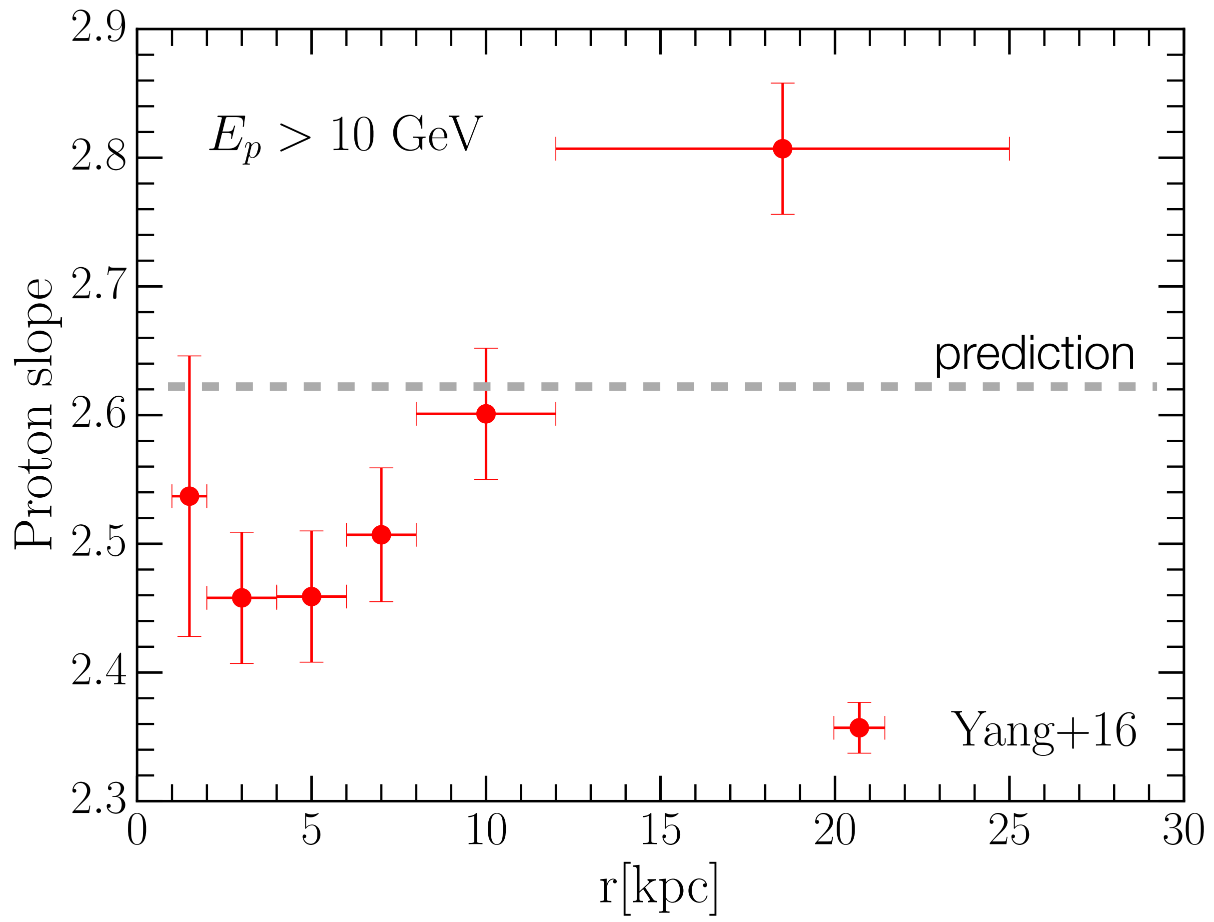
Anomalies with respect to what?

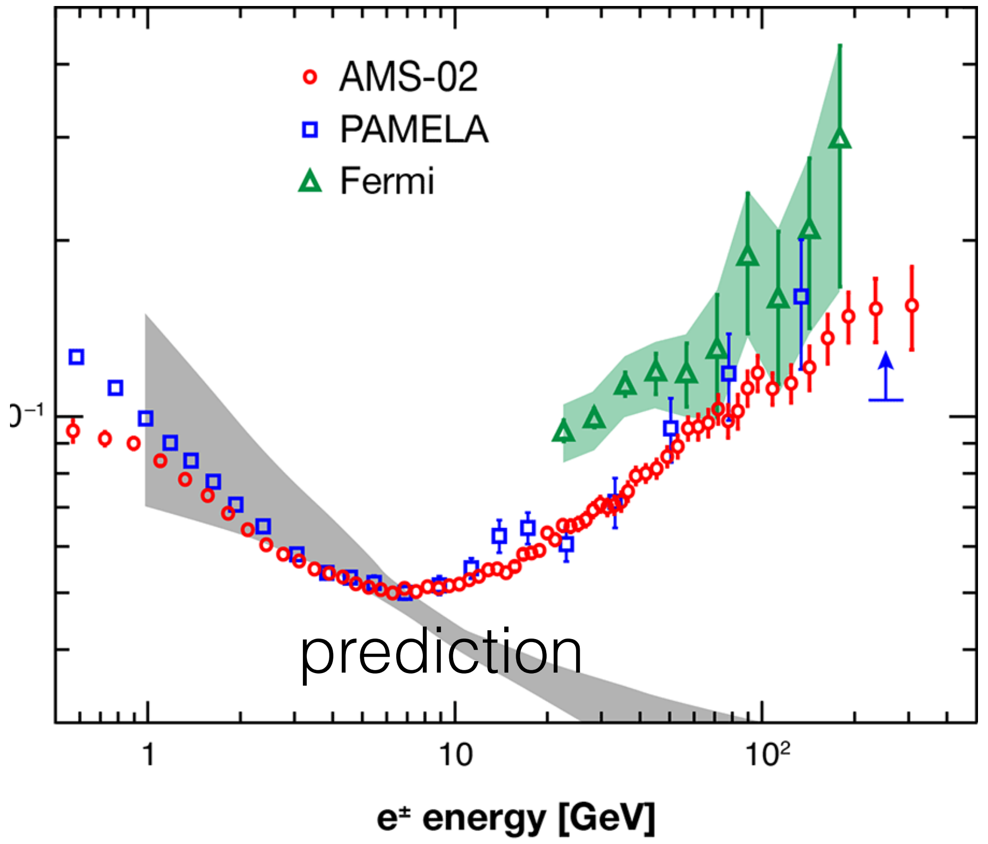
- basic theories used as guidelines for *standard parametrizations* implemented in numerical codes
- set of "conventional models" —> anomalies "w.r.t. conventional model predictions"

$$\frac{\partial \psi}{\partial t} = q(\vec{r}, p) + \vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi - \vec{V} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left[\dot{p} \psi - \frac{p}{3} (\vec{\nabla} \cdot \vec{V}) \psi \right] - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi$$



Credit: P. Mertsch





usually standard scenarios are defined by:

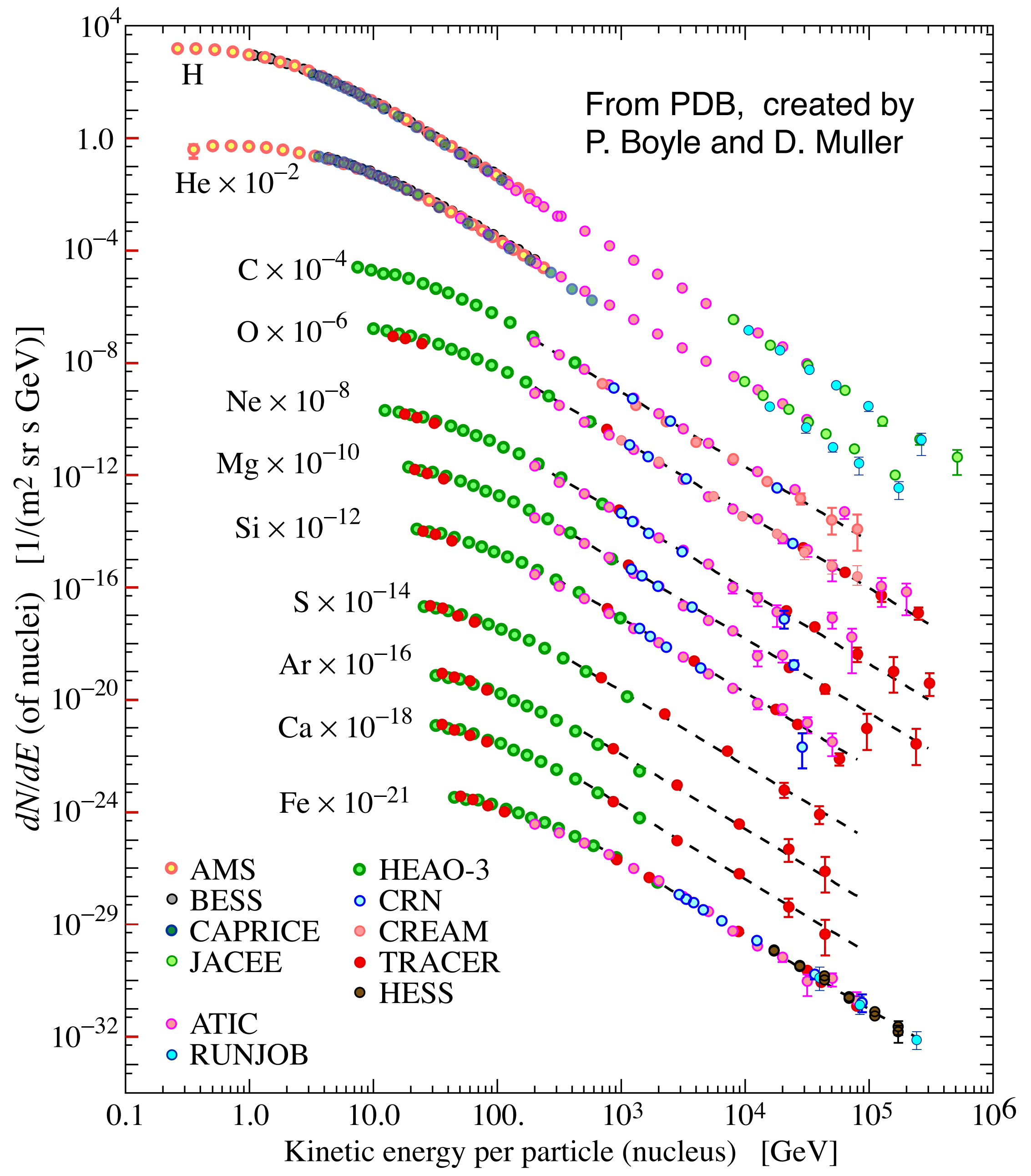
- one source class (SNRs), universal featureless source spectrum *(but sometimes breaks are introduced)*
- isotropic, homogeneous diffusion *(is it compatible with QLT?)*

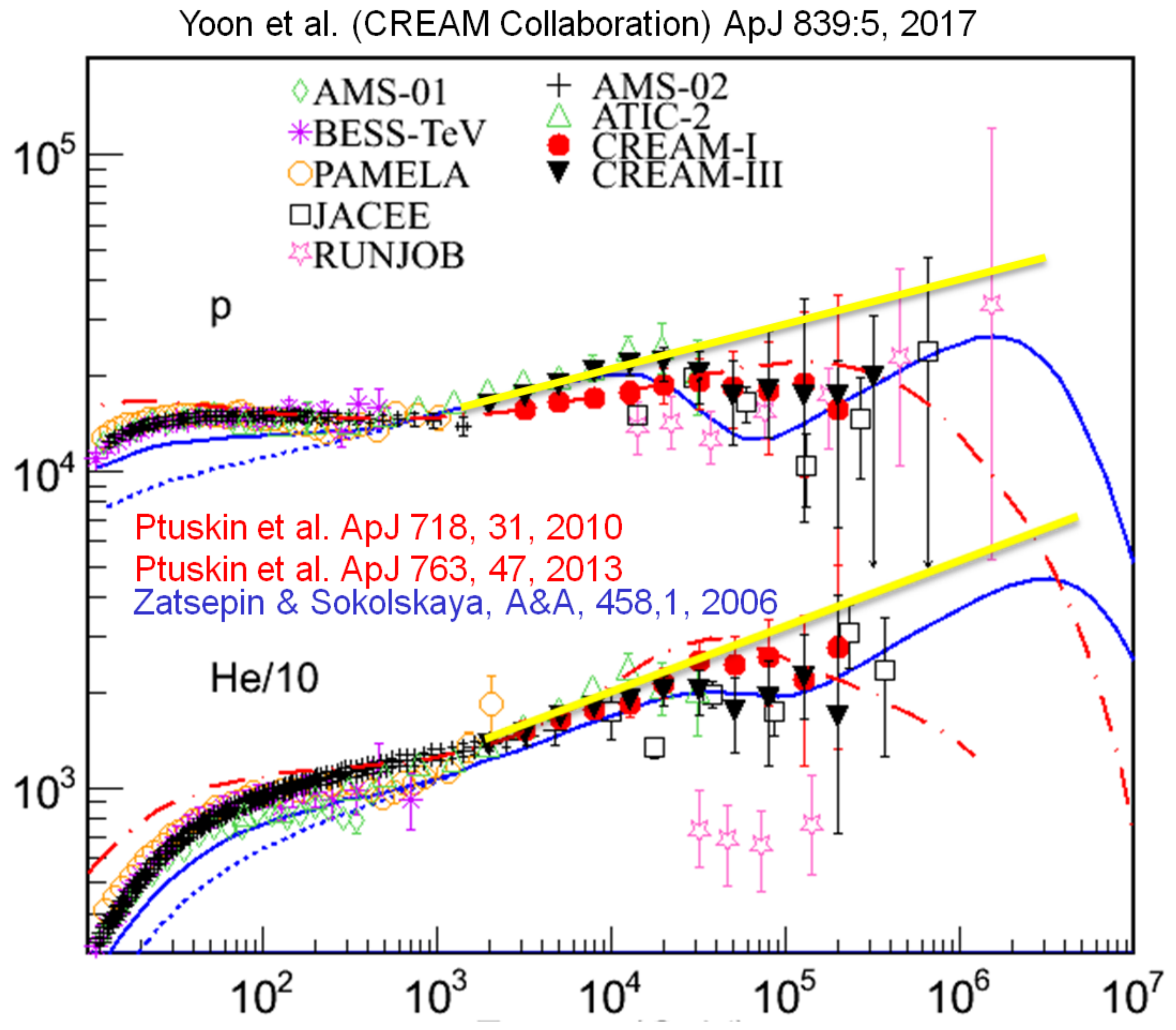
Anomalies with respect to what?

- a *much more complicated theoretical picture is expected*

(different acceleration mechanisms in different classes of sources; anisotropic and inhomogeneous transport; non linearities and CR self-confinement…)

- the data and their anomalies offer now the opportunity to investigate the impact of more complicated theoretical pictures





… let's go and look for spectral features!

Part 1: charged CR anomalies

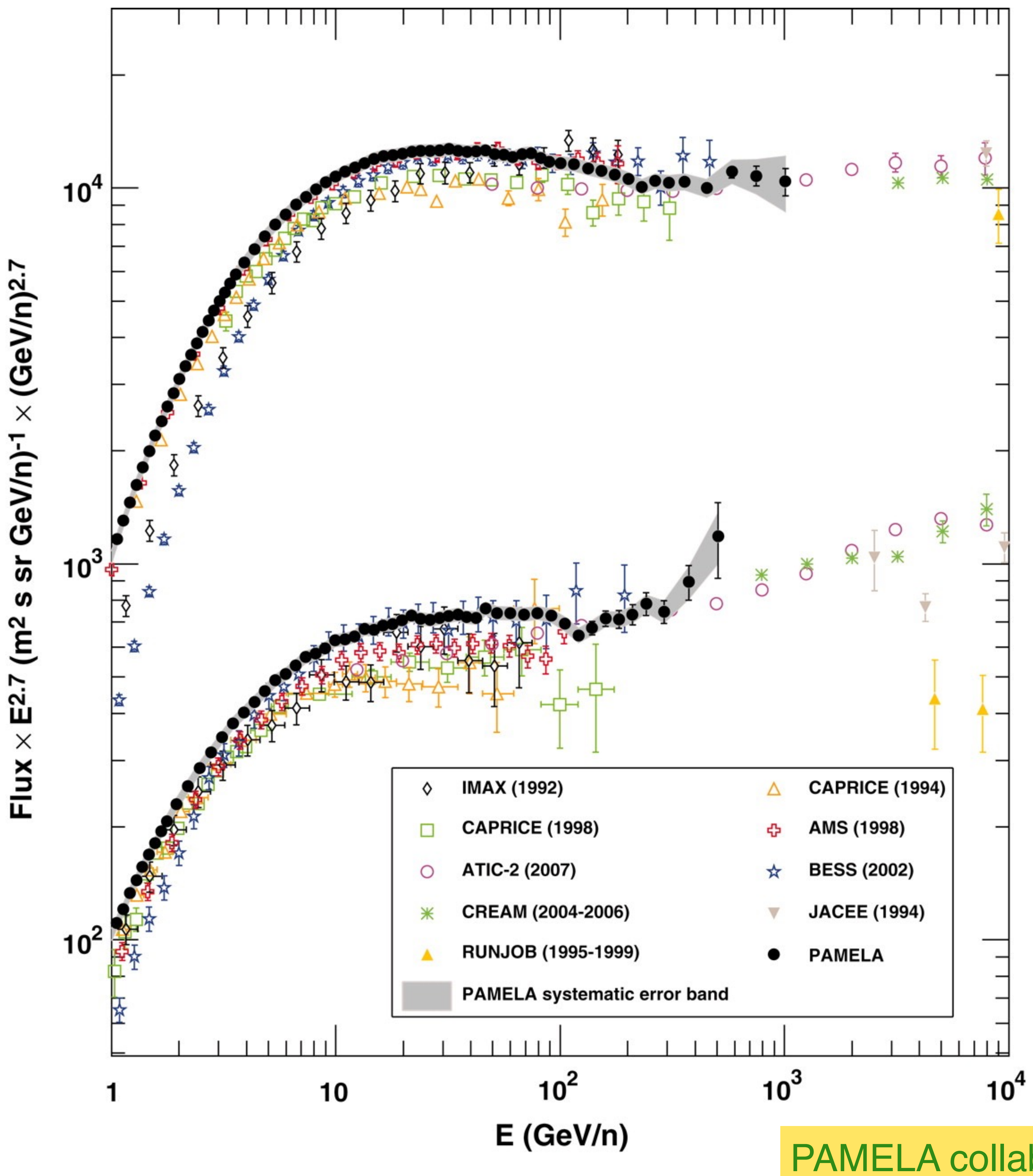
CR anomalies: Spectral features in p, He

An important discovery by PAMELA: proton and He spectral breaks at ~200 GV


PAMELA Measurements of Cosmic-Ray Proton and Helium Spectra

O. Adriani[1,2], G. C. Barbarino[3,4], G. A. Bazilevskaya[5], R. Bellotti[6,7], M. Boezio[8], E. A. Bogomolov[9], L. Bonechi[1,2], M. Bongi[2], V. Bo...
+ See all authors and affiliations

Science 01 Apr 2011:
Vol. 332, Issue 6025, pp. 69-72
DOI: 10.1126/science.1199172



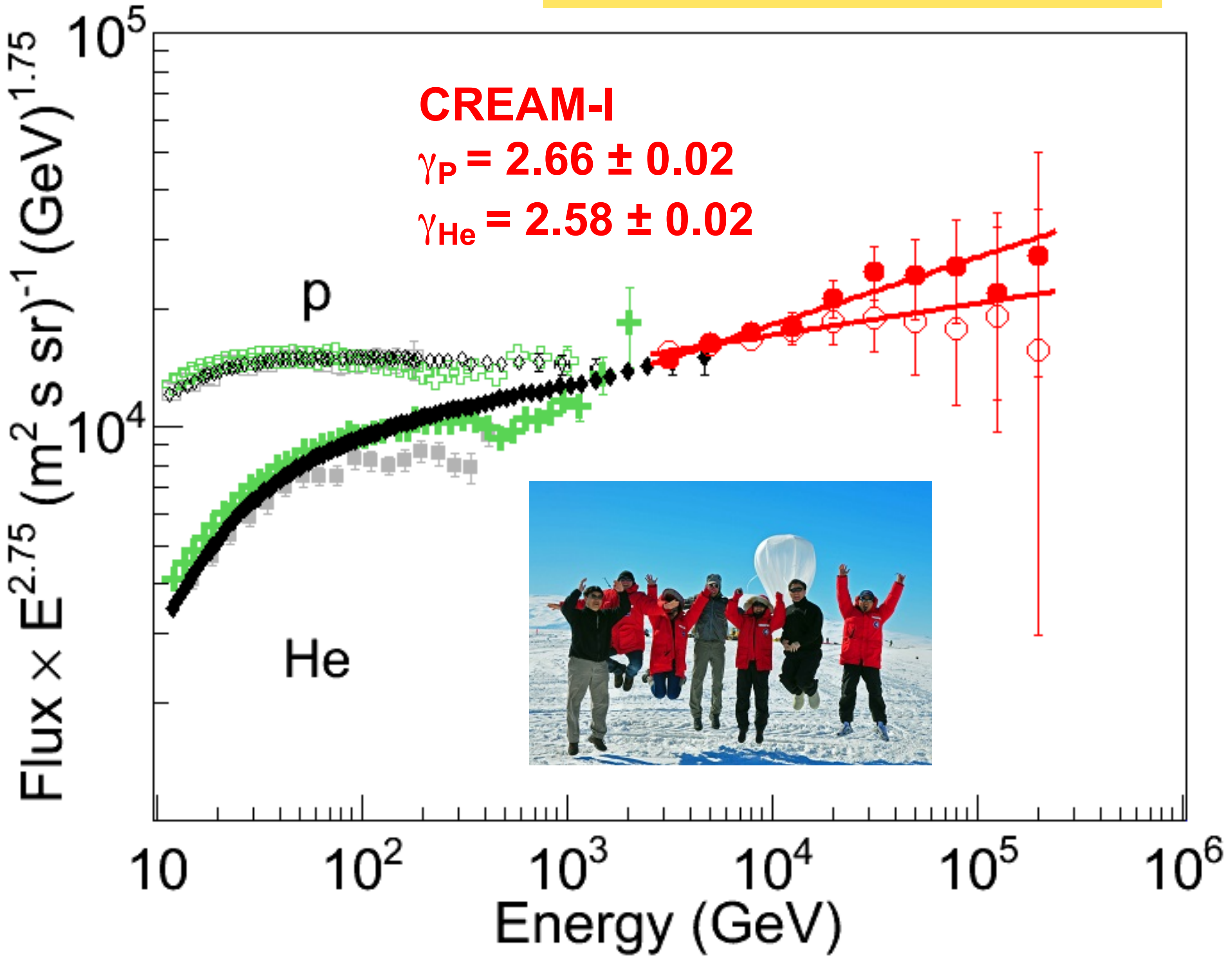
PAMELA collaboration, 2011

CR anomalies: Spectral features in p, He

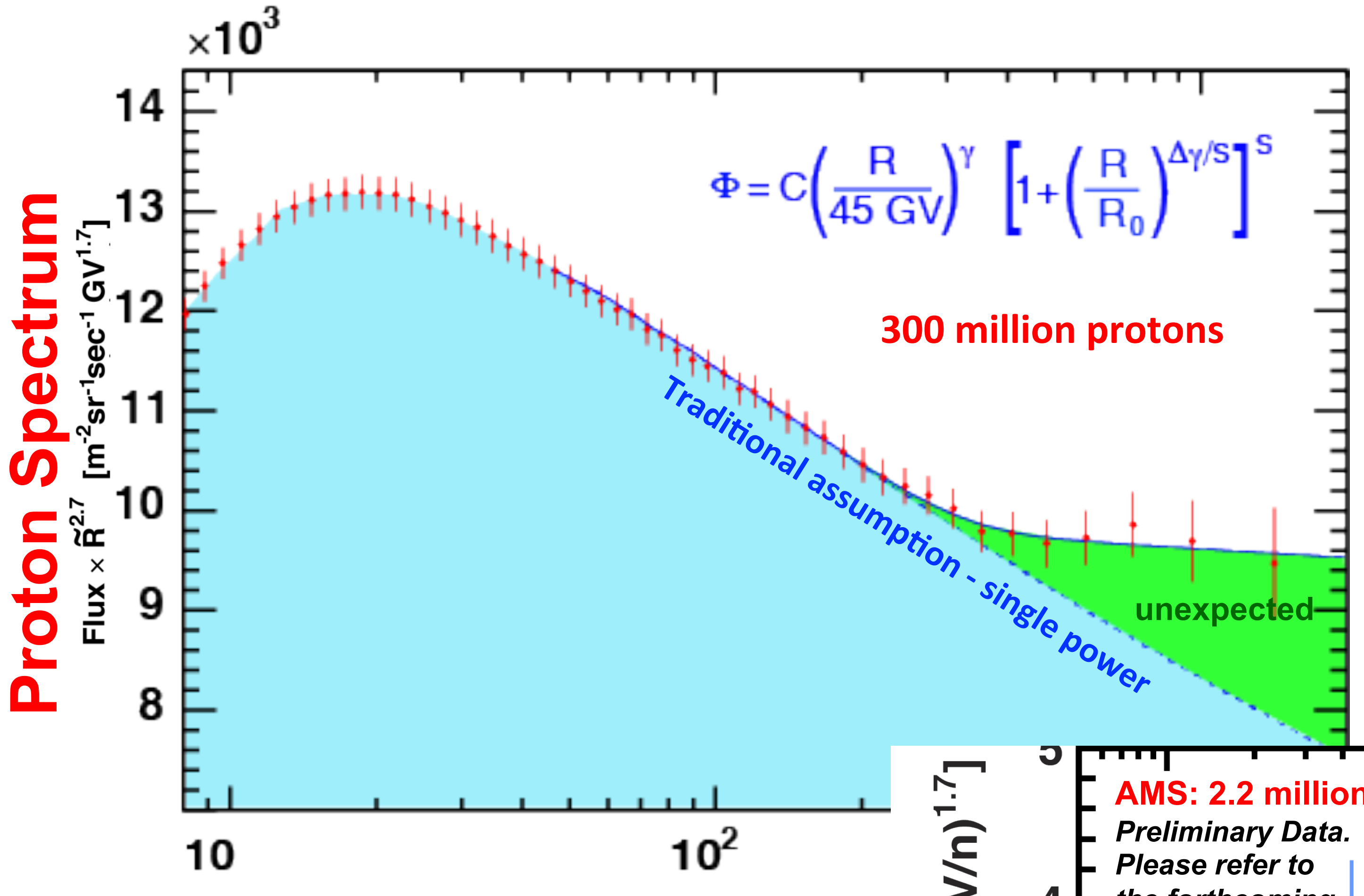
Confirmed by AMS with higher accuracy. It's a smooth feature

- present in Li, C, N, O as well [preliminary]
- *Compatible with higher energy data*

[Ahn et al., ApJ **714**, *L89*, 2010]



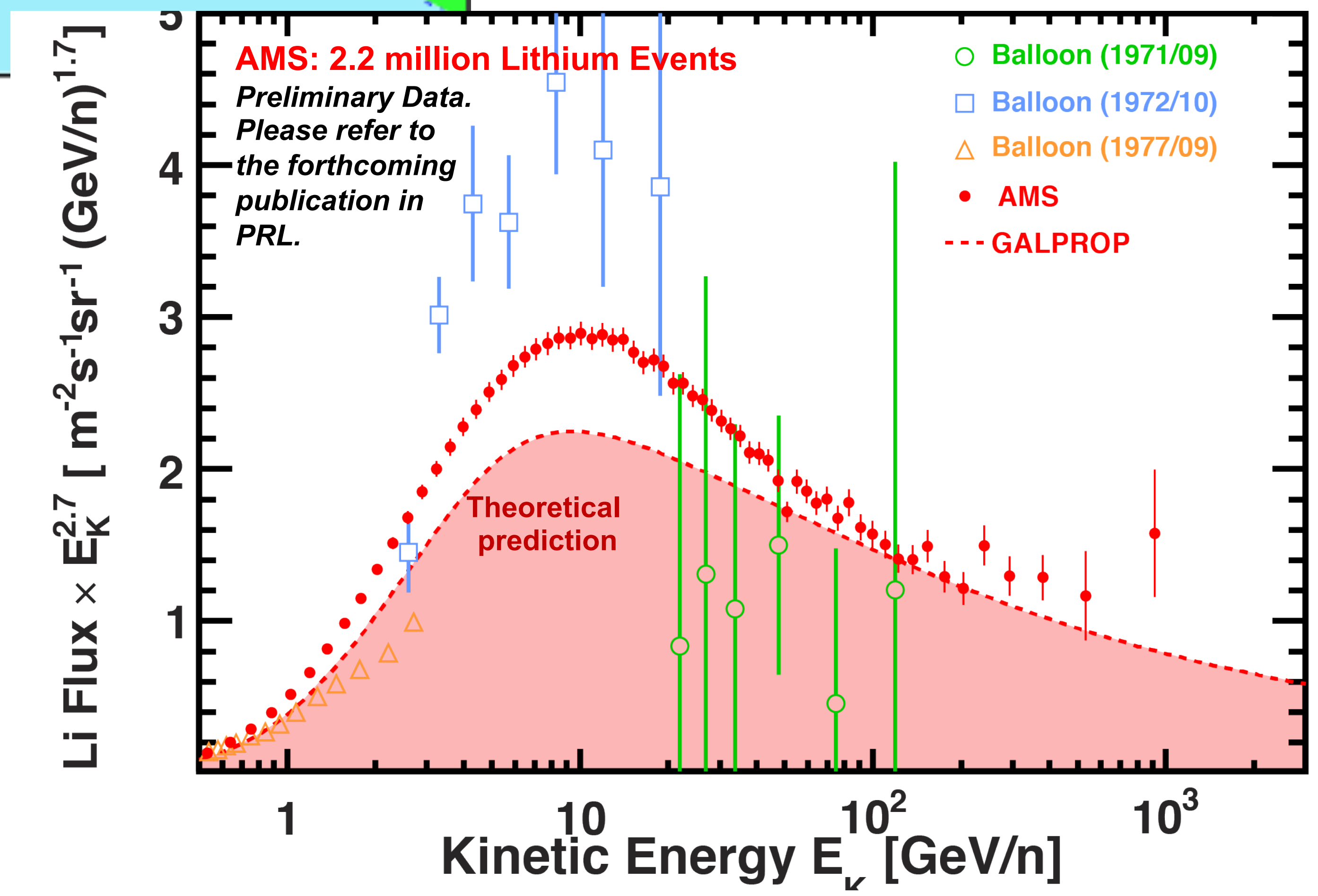
from **CREAM collaboration**

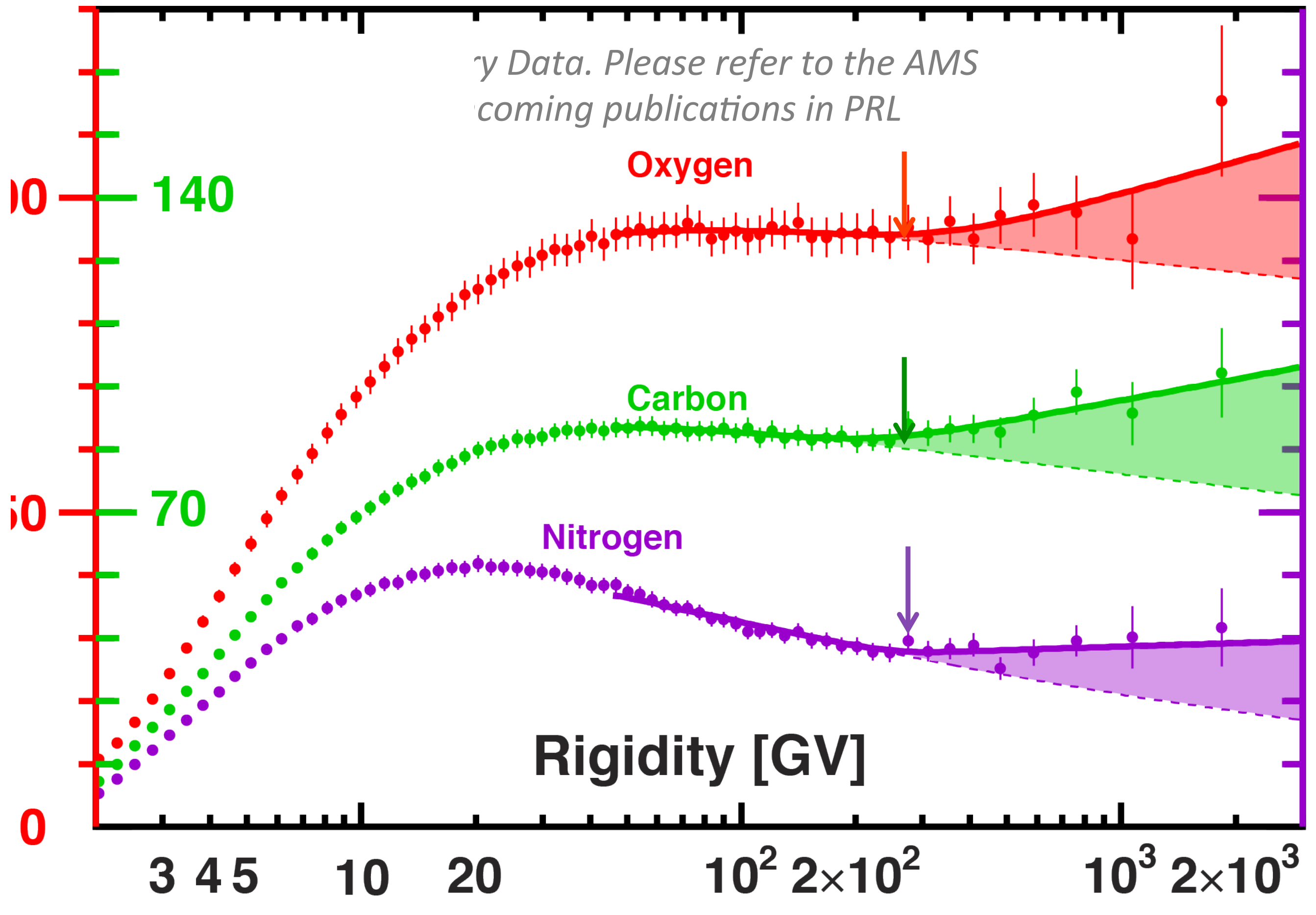


from **AMS collaboration**, ICRC highlight talk, 2017

see M. Heil talk

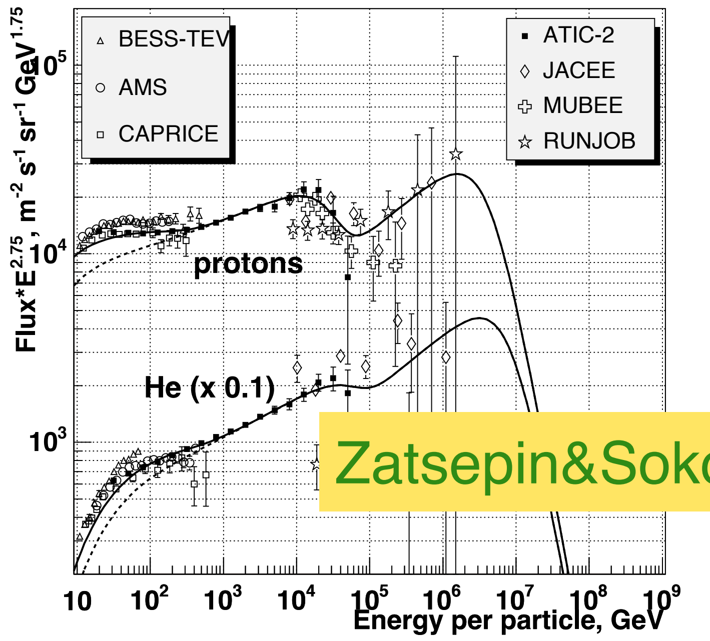
see also J. Tjus talk
see also V. Bindi talk





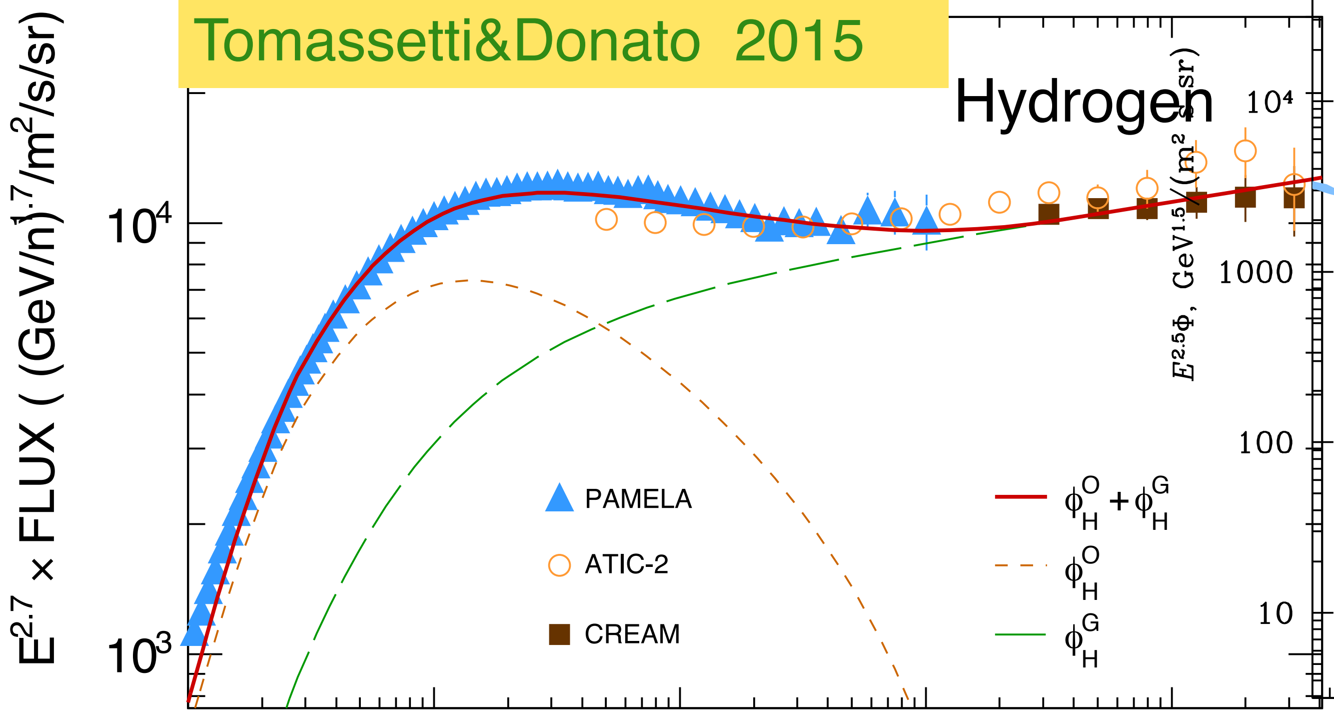
Proton/He break: A source effect?

- A new population of sources kicking in? *[Zatsepin&Sokolskaya 2008, pre-AMS]*
- Possible role of superbubbles? *[Ohira et al., PRD 2016; Parizot et al., A&A 2004, pre-AMS]*

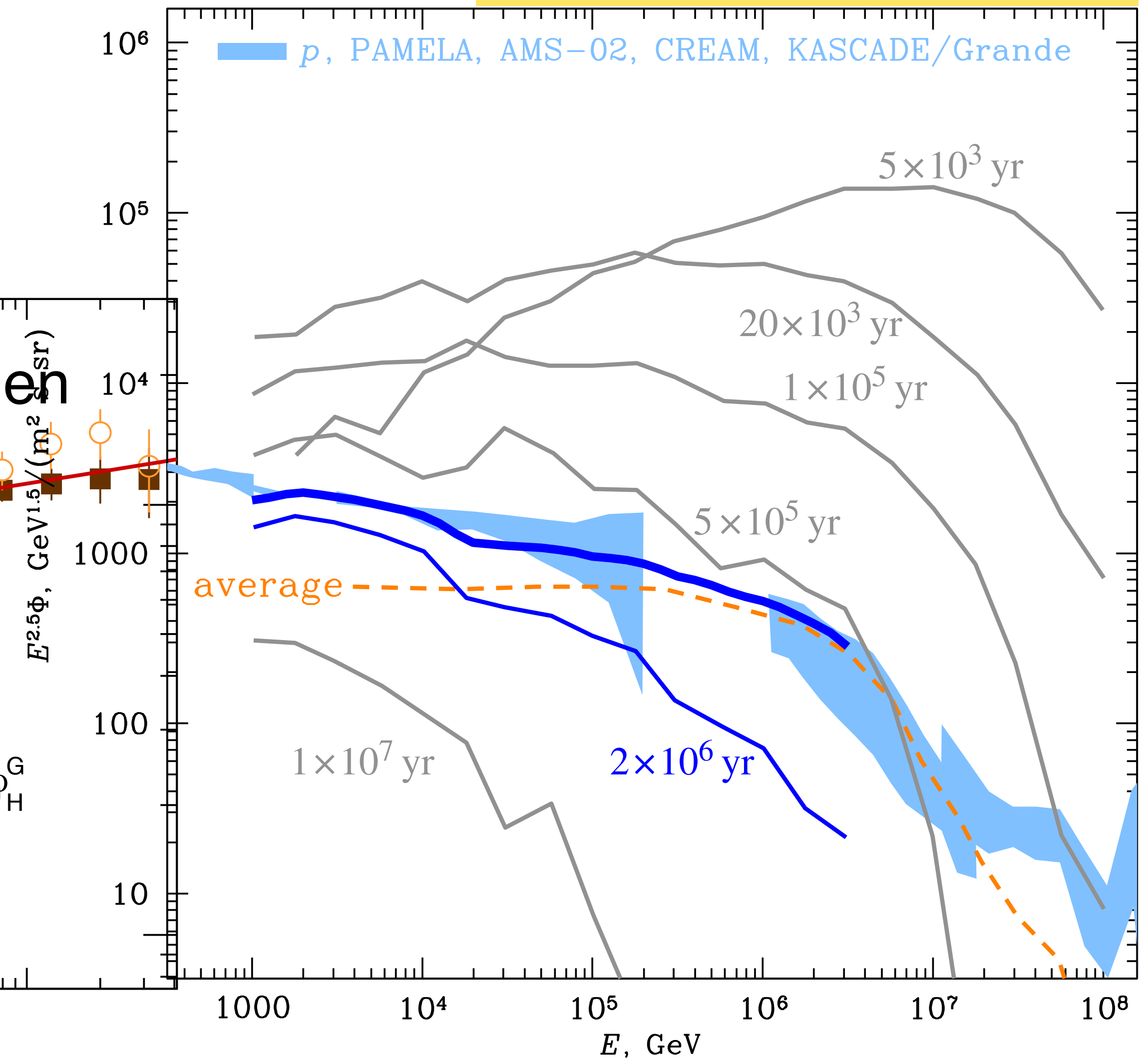


Zatsepin&Sokolskaya 2008

- Non-linear DSA? *[Ptuskin et al., ApJ 2013]*



Tomassetti&Donato 2015



Kachelriess, Neronov, Semikoz, PRL 2015

- The fingerprint of a local supernova event (*below the break*)? *[Kachelriess et al., PRL 2015; Tomassetti&Donato ApJ 2015; Tomassetti ApJL 2015]*

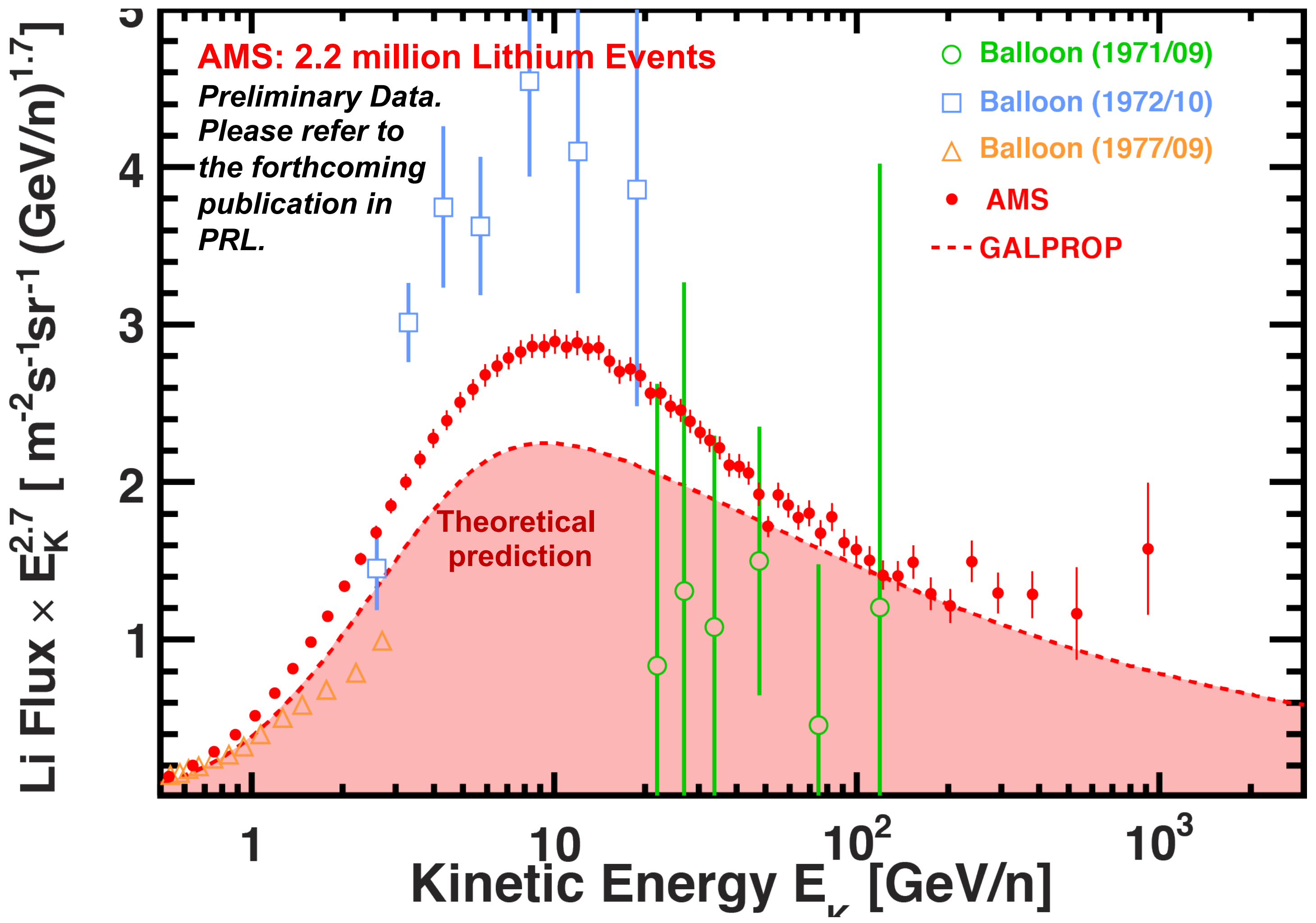
- How likely is such a relevant local fluctuation? *the probability seems to be low [Genolini et al., A&A 2017]*

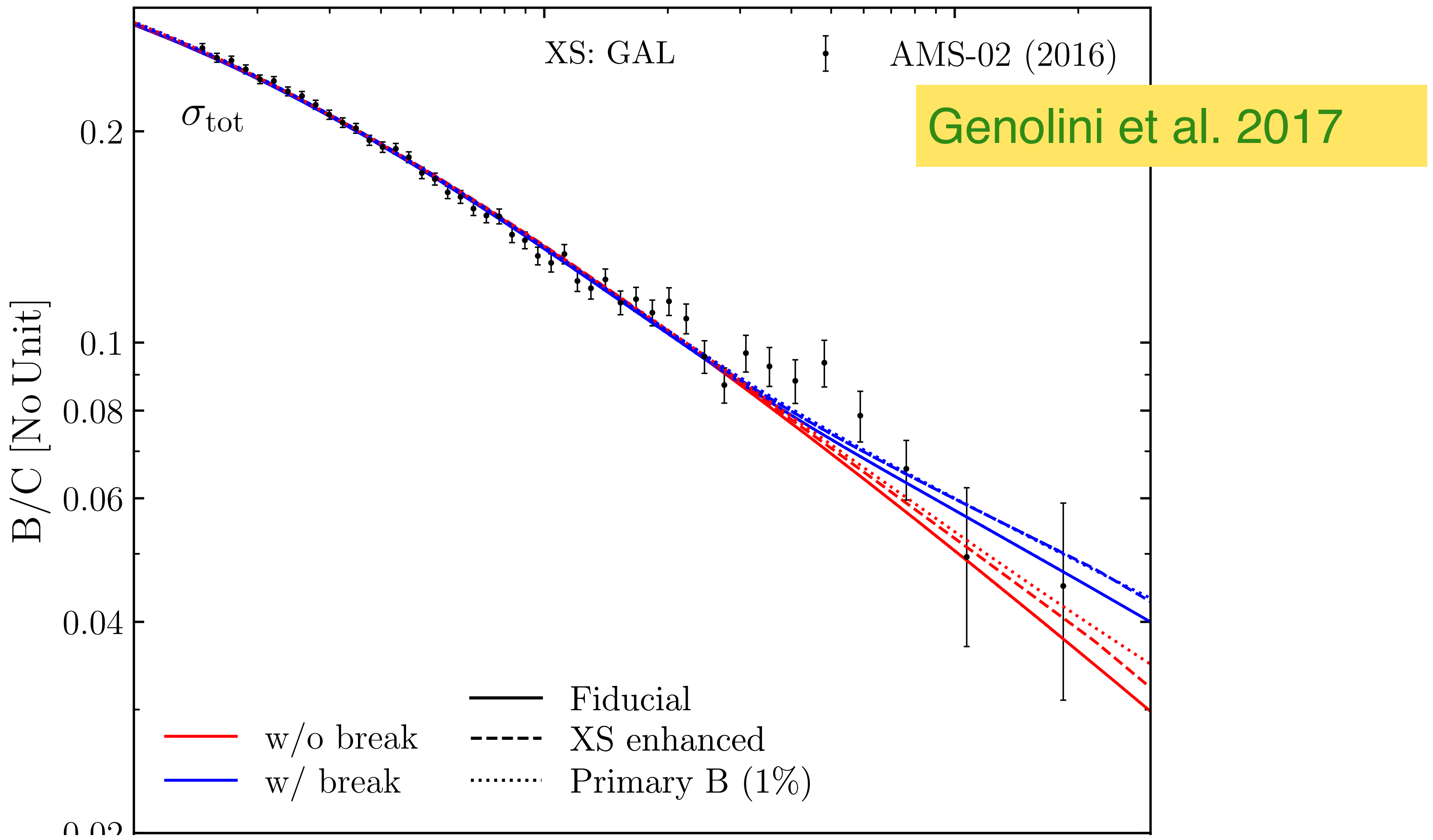
Models	PAMELA		AMS02	
Model	50GeV $p\,(\Psi > \langle\Psi\rangle + 3\sigma)$ $p\,(\Psi < \langle\Psi\rangle - 3\sigma)$	1TeV $p\,(\Psi > \langle\Psi\rangle + 3\sigma)$ $p\,(\Psi < \langle\Psi\rangle - 3\sigma)$	50GeV $p\,(\Psi > \langle\Psi\rangle + 3\sigma)$ $p\,(\Psi < \langle\Psi\rangle - 3\sigma)$	1TeV $p\,(\Psi > \langle\Psi\rangle + 3\sigma)$ $p\,(\Psi < \langle\Psi\rangle - 3\sigma)$
MIN	0.15 0.13	0.083 $< 10^{-6}$	0.28 0.63	0.26 0.51
MED	0.047 $< 10^{-6}$	0.014 $< 10^{-6}$	0.16 0.26	0.12 0.0025
MAX	0.009 $< 10^{-6}$	0.0018 $< 10^{-6}$	0.045	0.016

Genolini et al., A&A 2017

Proton/He break: A Transport effect?

- Is the break due to transport? secondary spectra and secondary/primary ratios such as B/C are crucial observables *[Genolini et al., 2017]*





- source effects: secondaries inherit the primary feature: *B/C should be featureless*

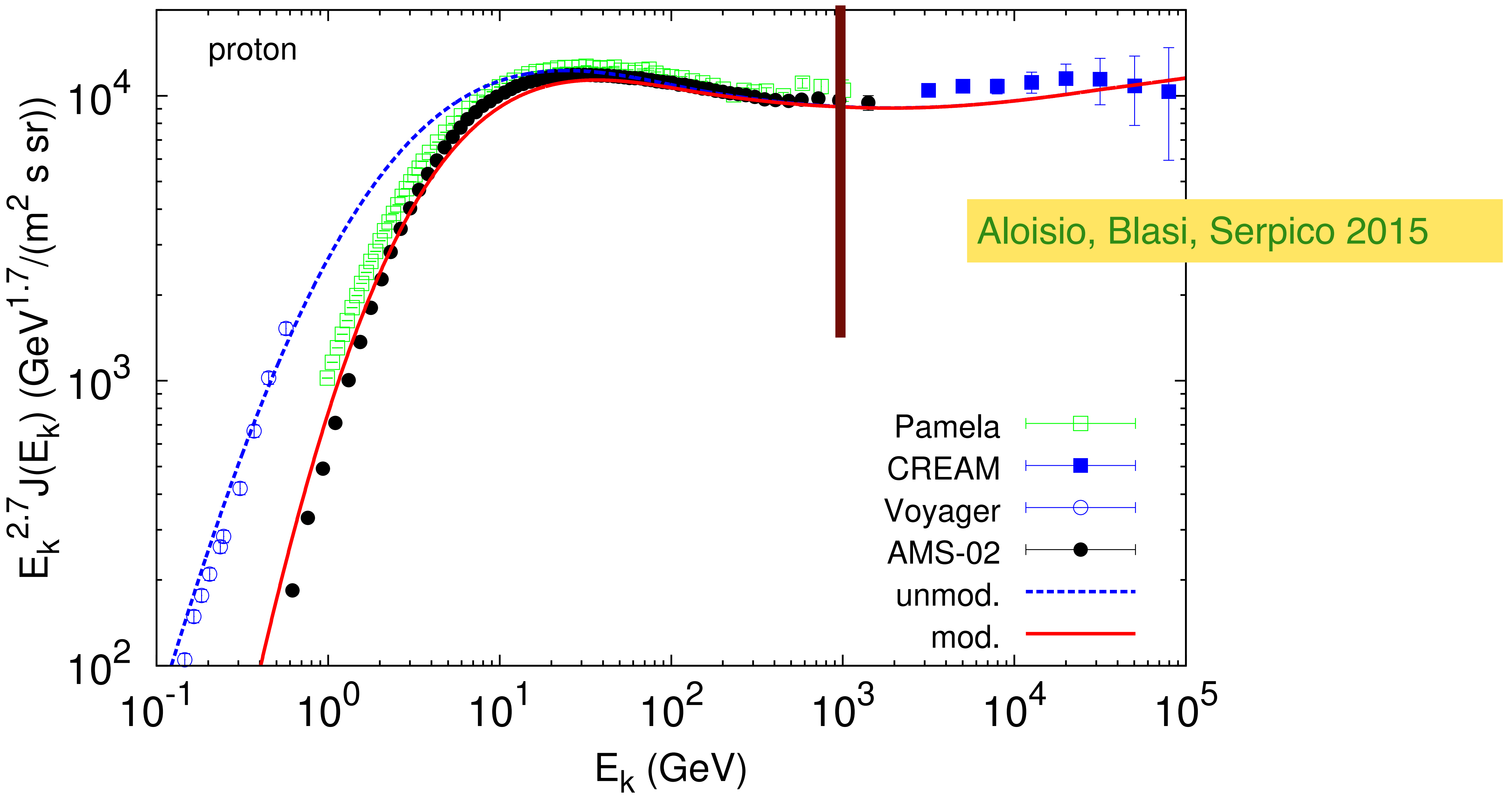
(secondaries originate from spallation, which preserve E/A; E/A is proportional to the rigidity)

- transport effect: secondaries inherit the primary feature and get a further hardening due to propagation: *B/C should show a break; Lithium should show a more pronounced break*

Proton/He break: A Transport effect?

- Different transport properties in the disk w.r.t. the halo? *[Tomassetti, PRD 2015]*
- A possible transition between different transport regimes?
    - *low energies*: propagation in self-generated (via streaming instability) turbulence
    - *high energies*: propagation in pre-exisiting turbulence *[Blasi, Amato, Serpico, PRL 2012; Aloisio, Blasi, Serpico 2015]*

$$E_{\rm tr} = 228\ {\rm GeV} \left(\frac{R_{d,10}^2 H_3^{-1/3}}{\xi_{0.1} E_{51} \mathcal{R}_{30}} \right)^{\frac{3}{2(\gamma_p - 4)}} B_{0,\mu}^{\frac{2\gamma_p - 5}{2(\gamma_p - 4)}},$$

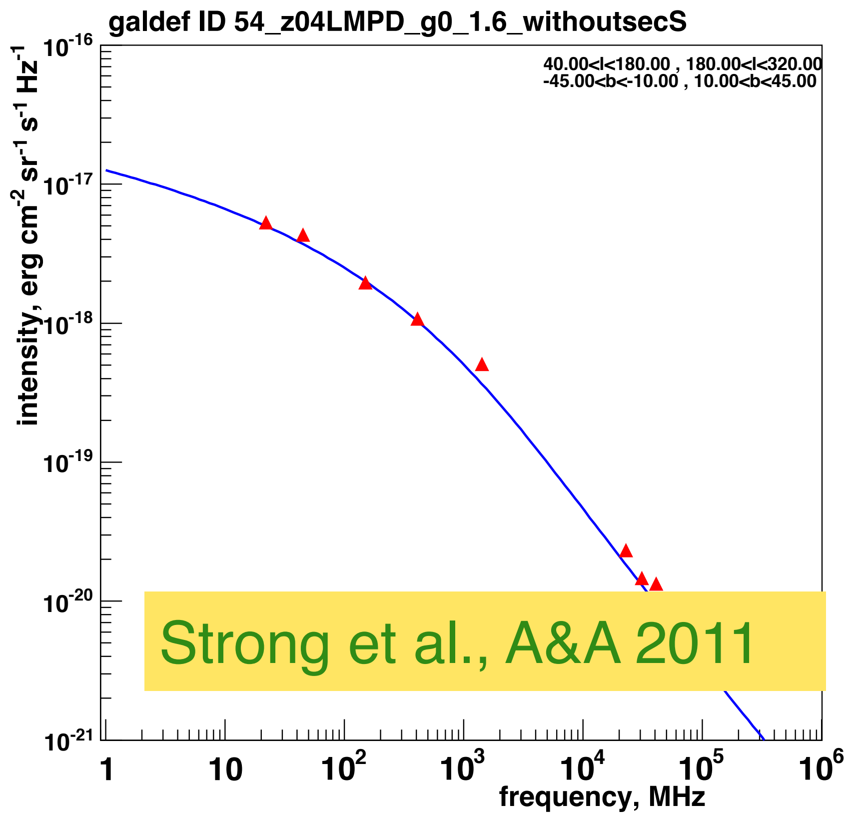


CR anomalies: Leptons (low and high energy)

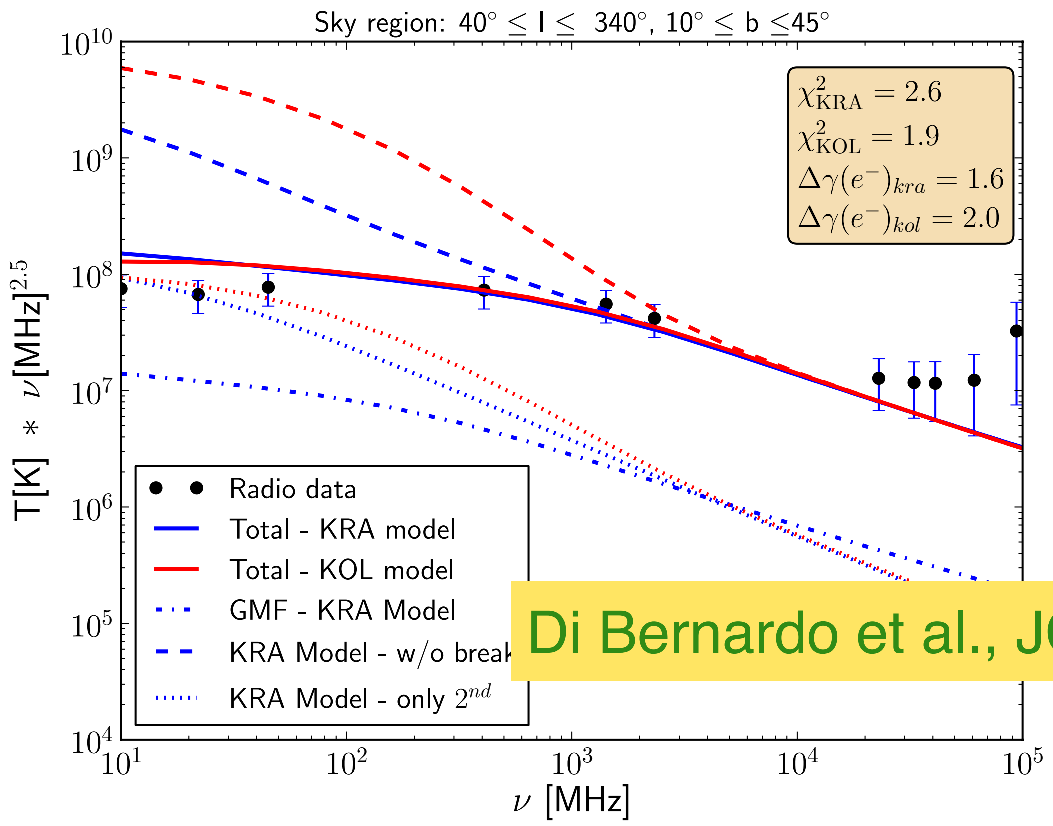
Many issues under debate!

- *Low-energy behavior*: spectral break at few GeV; confirmed by synchrotron data (see E. Orlando talk)

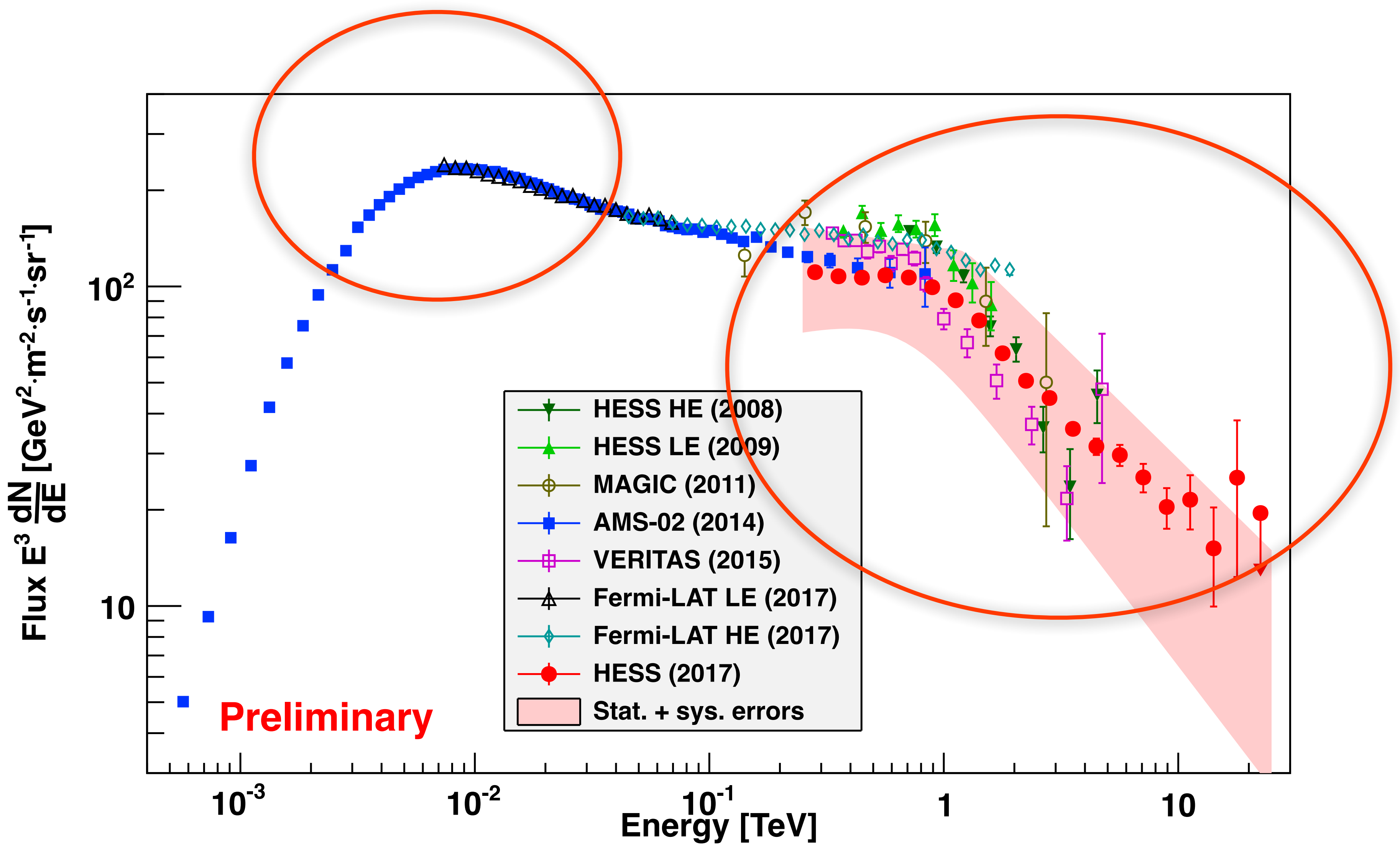
often overlooked



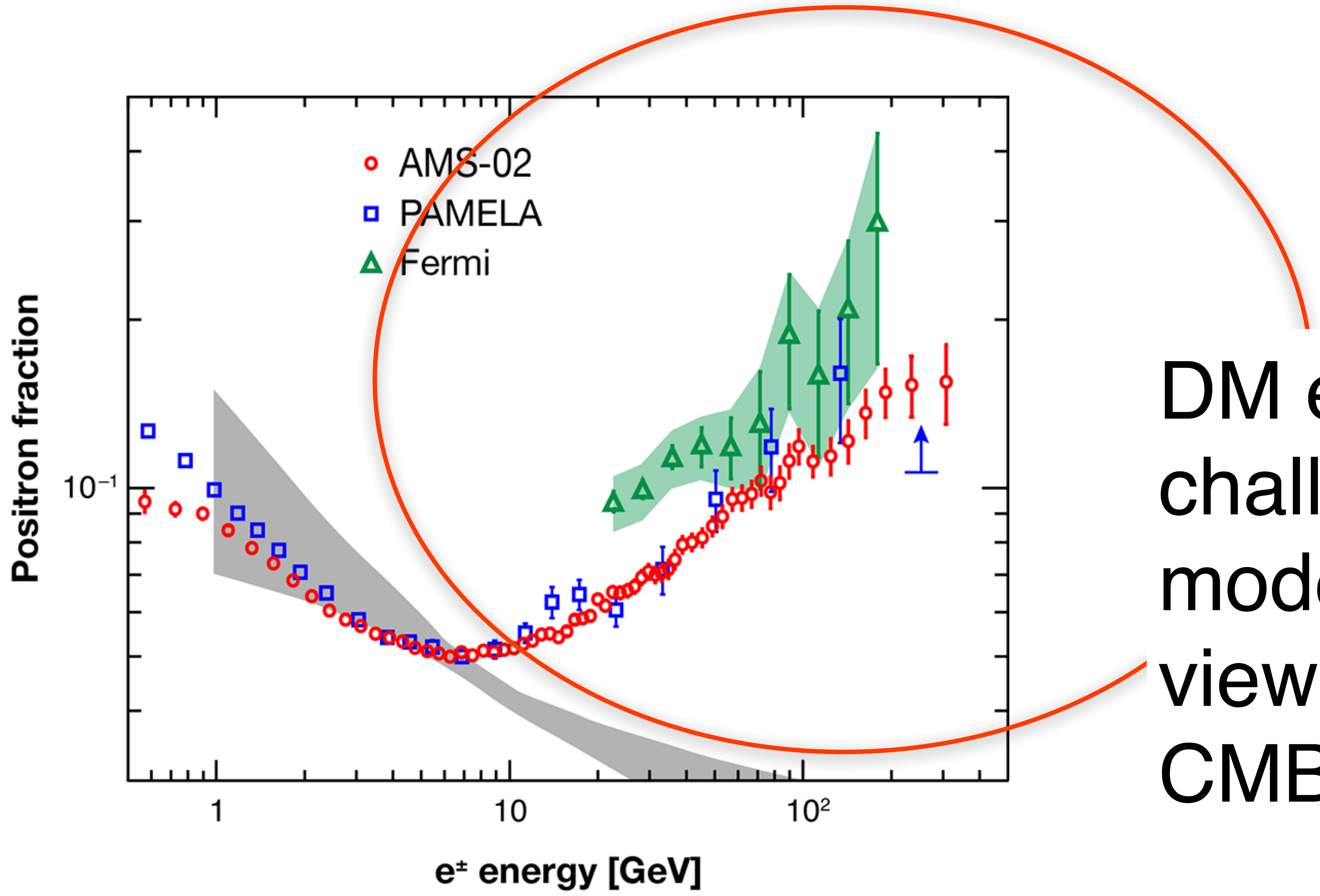
Strong et al., A&A 2011



Di Bernardo et al., JCAP 2013



- *High-energy behavior*: sharp break
- *Primary positron source?* Pulsar wind nebula are a natural candidate; acceleration mechanism different from DSA: spectrum harder than E^{-2}



DM explanations challenging from model-building point of view; in tension with CMB constaints

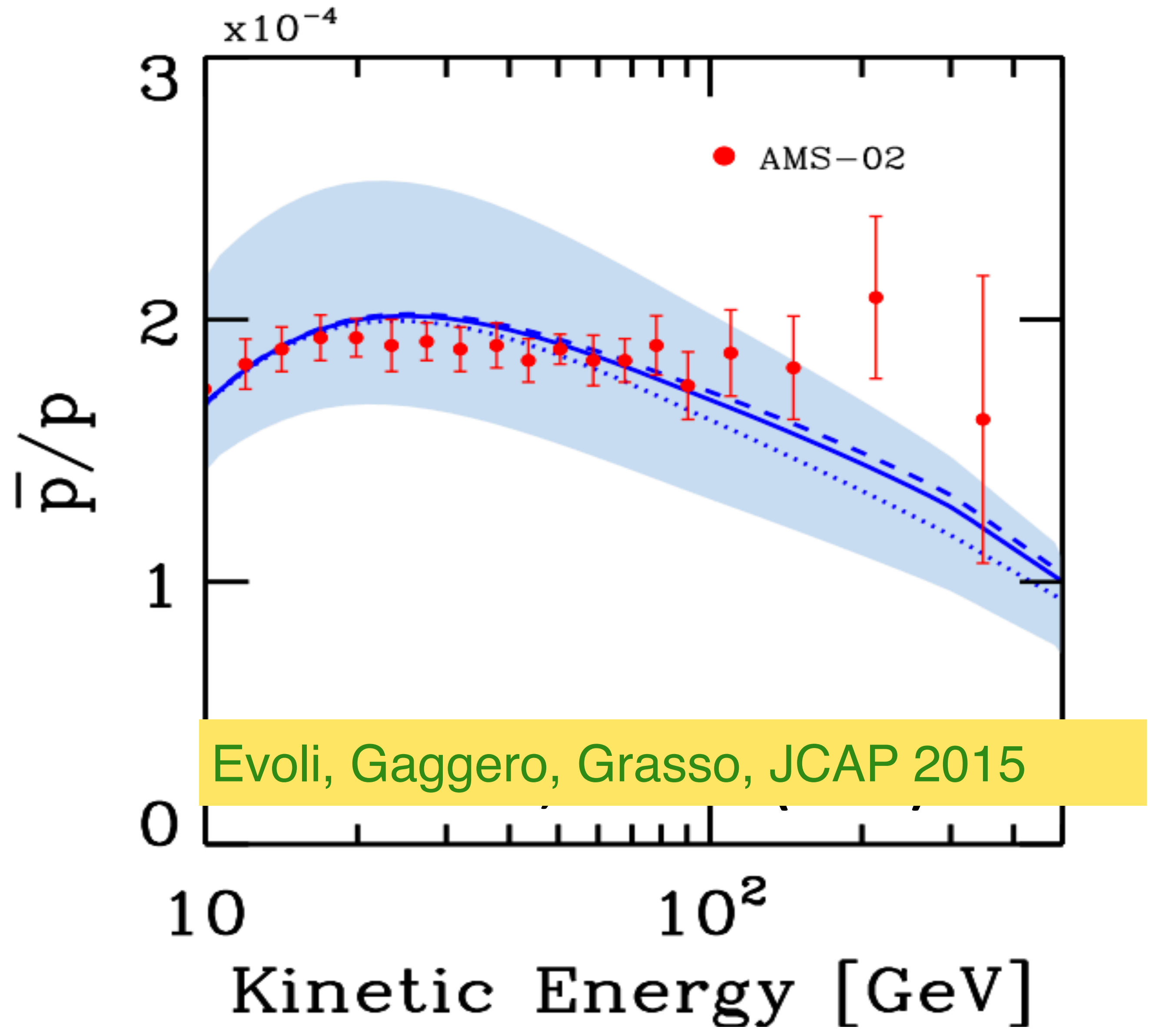
CR anomalies: Antiprotons

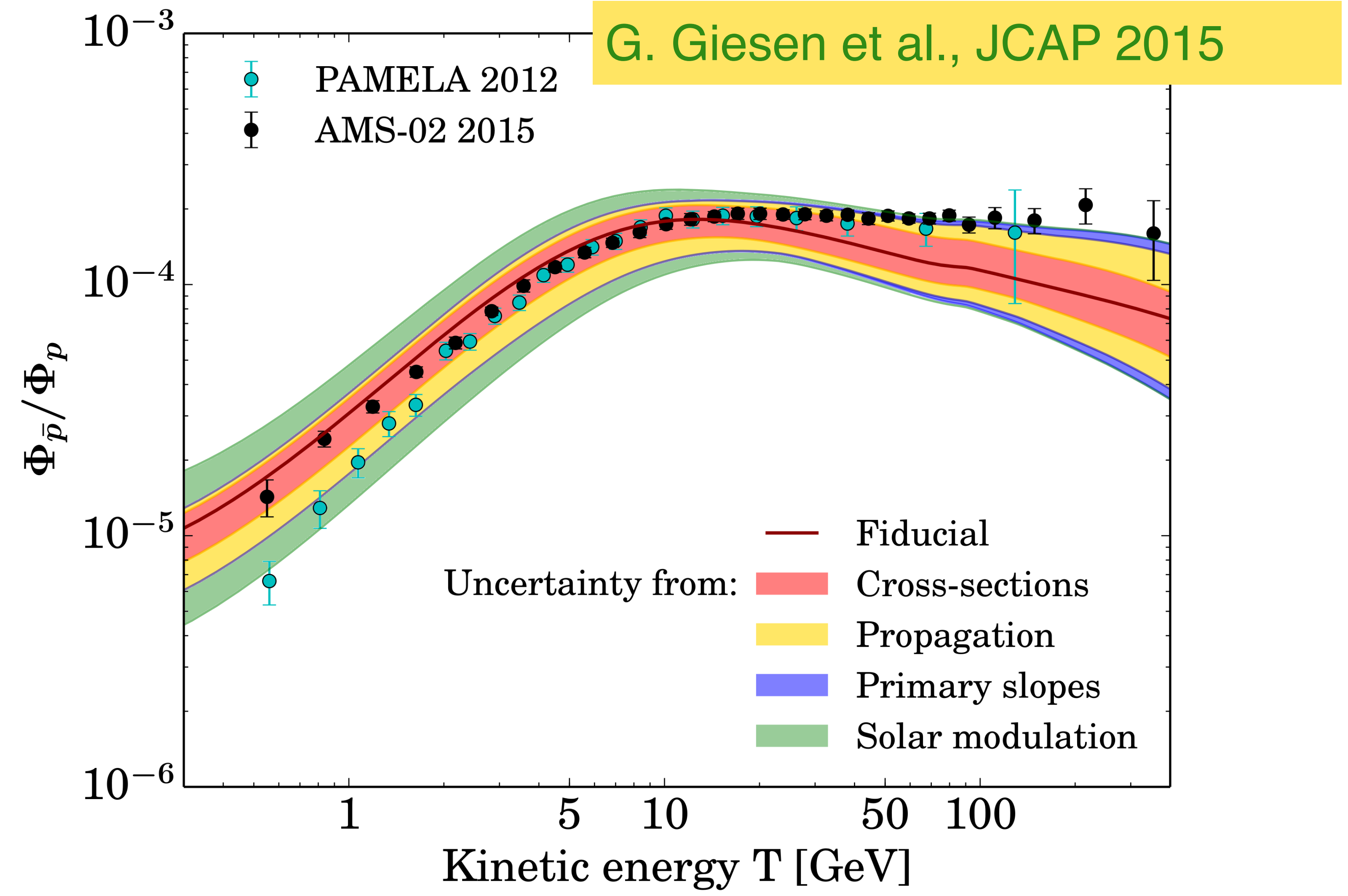
Crucial observable for DM studies

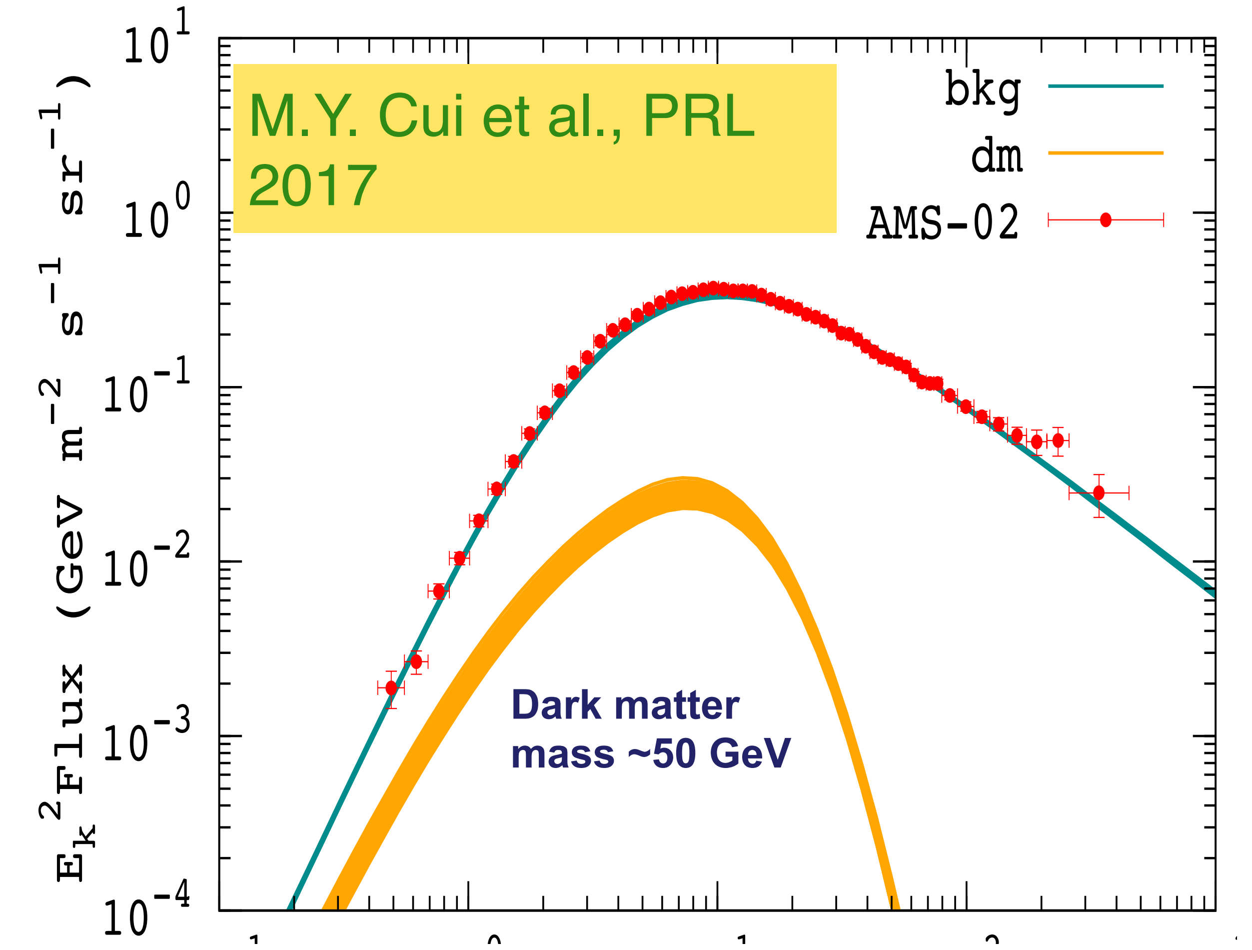
- *High energy*: Is there really an anomaly? Currently just a ~2σ hint

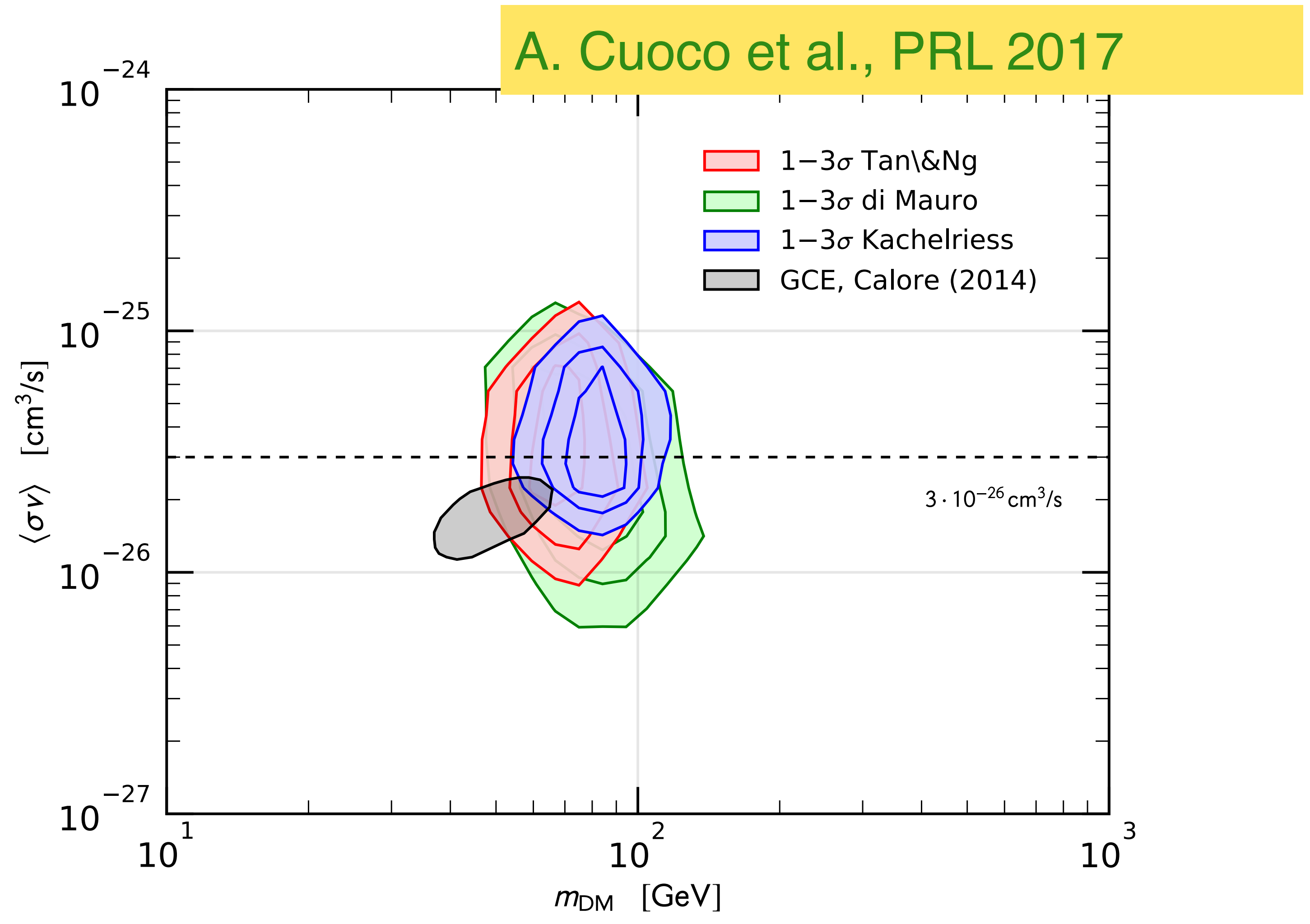
- *Low energy:* Is there a feature possibly correlated to the GeV gamma-ray excess, and possibly originating from DM annihilation?

  Further investigation is needed.
  - Different choices of background parametrization?





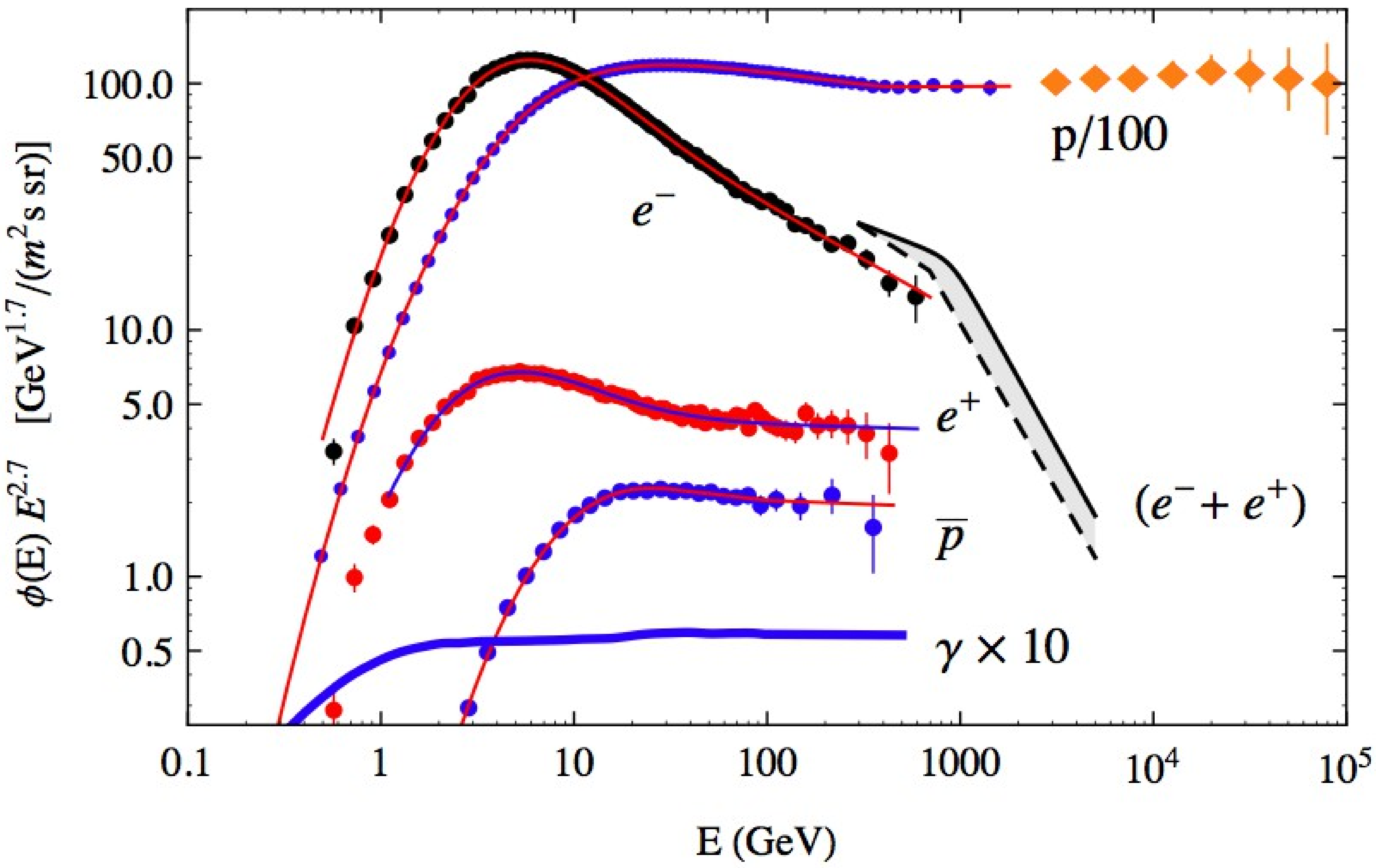




An interesting coincidence

AMS02 p e^- e^+ $\bar{p}$

CREAM p data



P. Lipari, ICRC 2017

Conventional propagation scenario:

A1. Very long lifetime for cosmic rays

A2. Difference between electron and proton spectra shaped by propagation effects

A3. New hard source of positrons is required

A4. Secondary nuclei generated in interstellar space

Alternative propagation scenario:

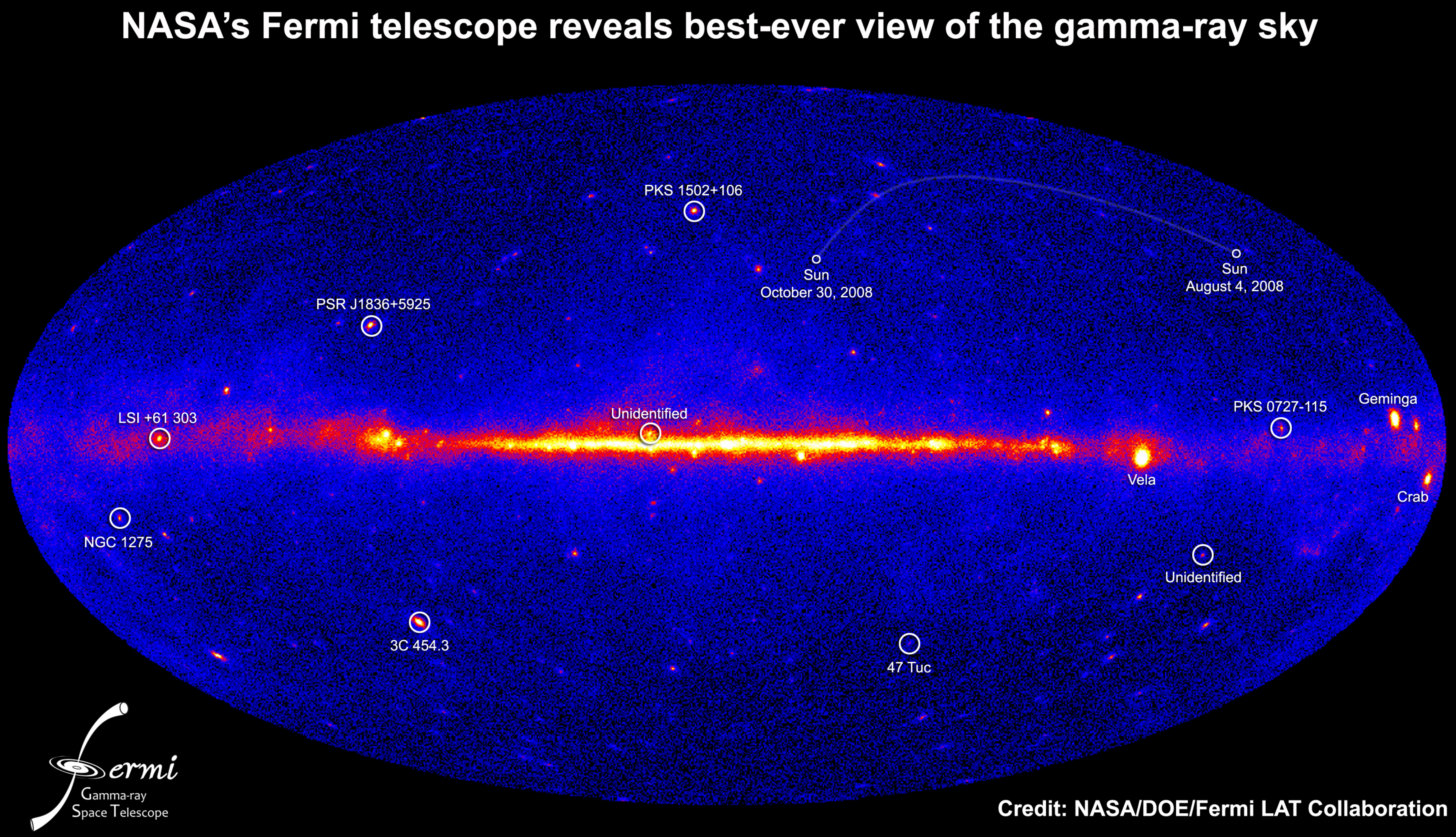
B1. Short lifetime for cosmic rays

B2. Difference between electron and proton spectra generated in the accelerators

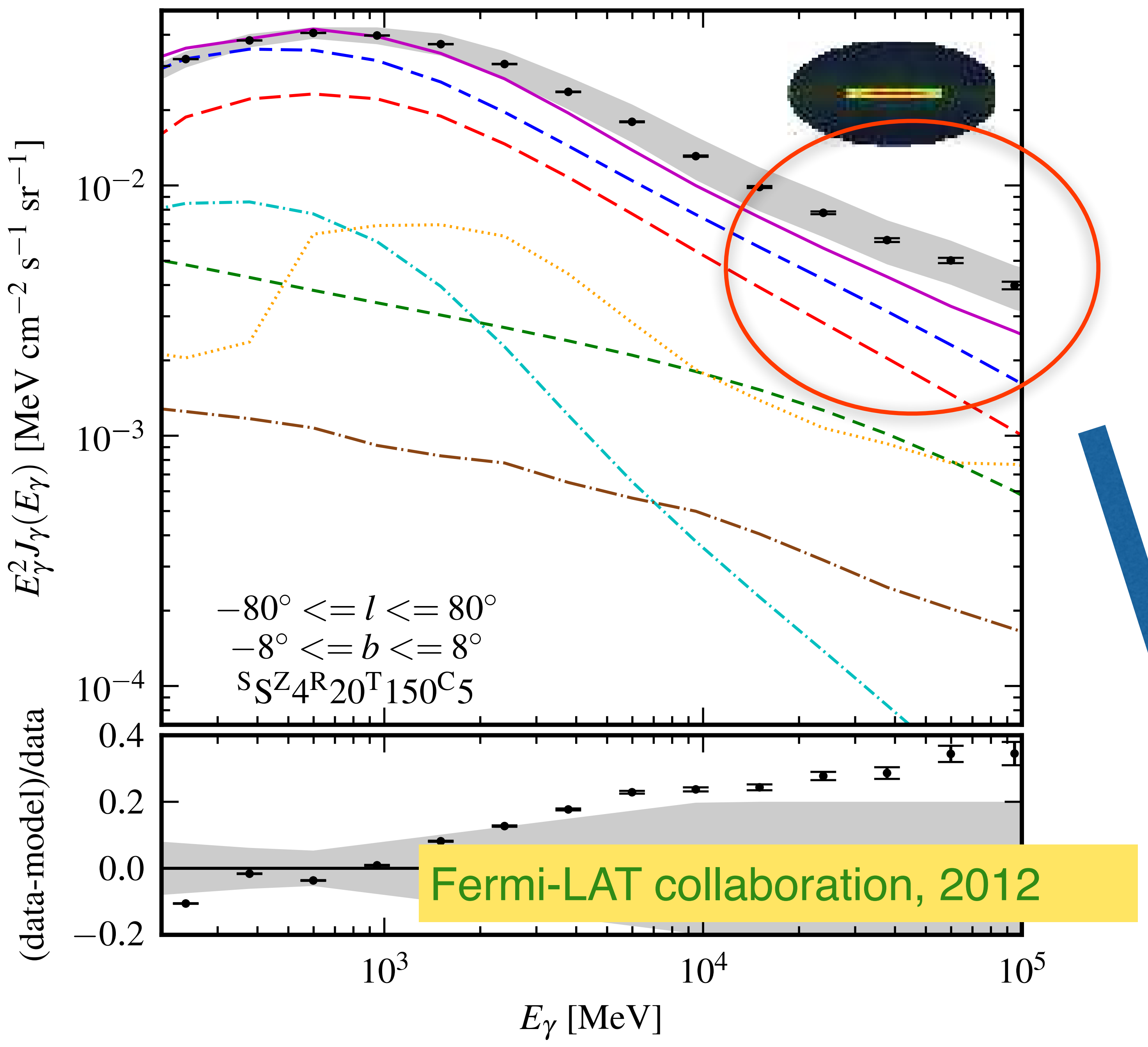
B3. antiprotons and positrons of secondary origin

B4. Most secondary nuclei generated in/close to accelerators

Part 2: anomalies inferred from γ-rays



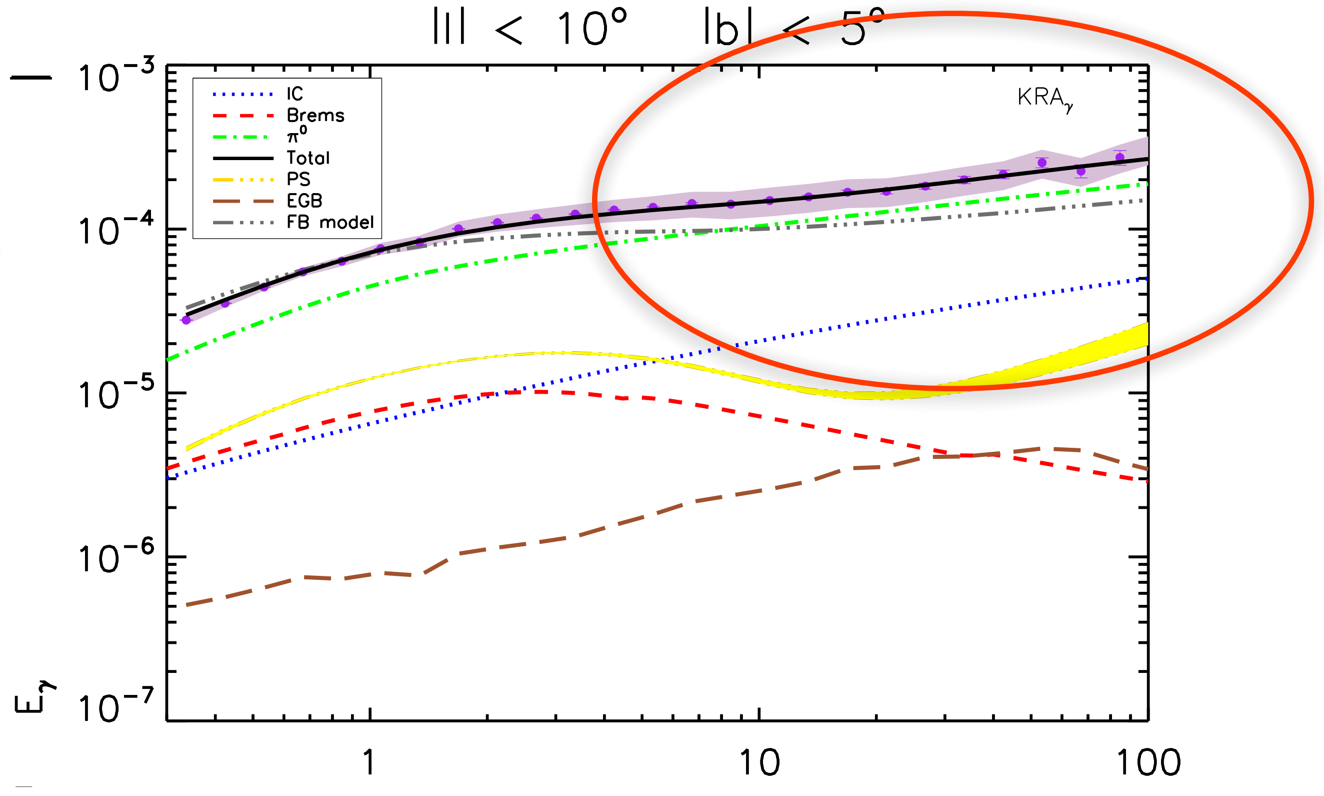
γ-ray anomalies: hardening & gradient

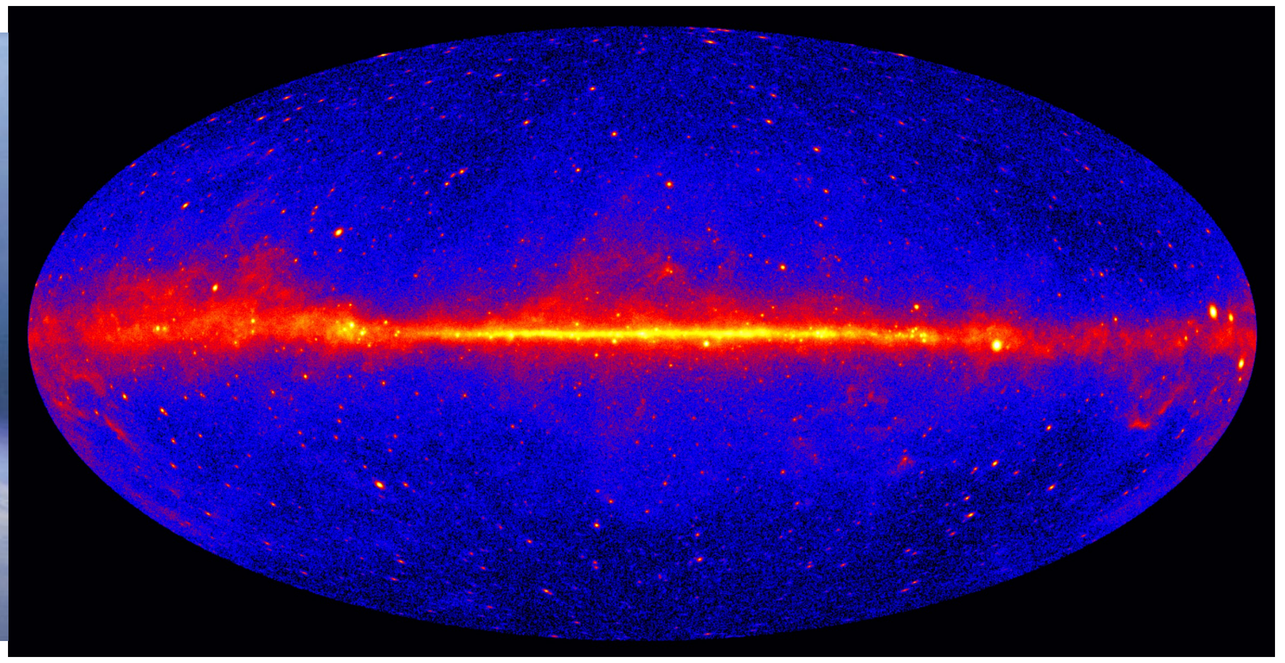


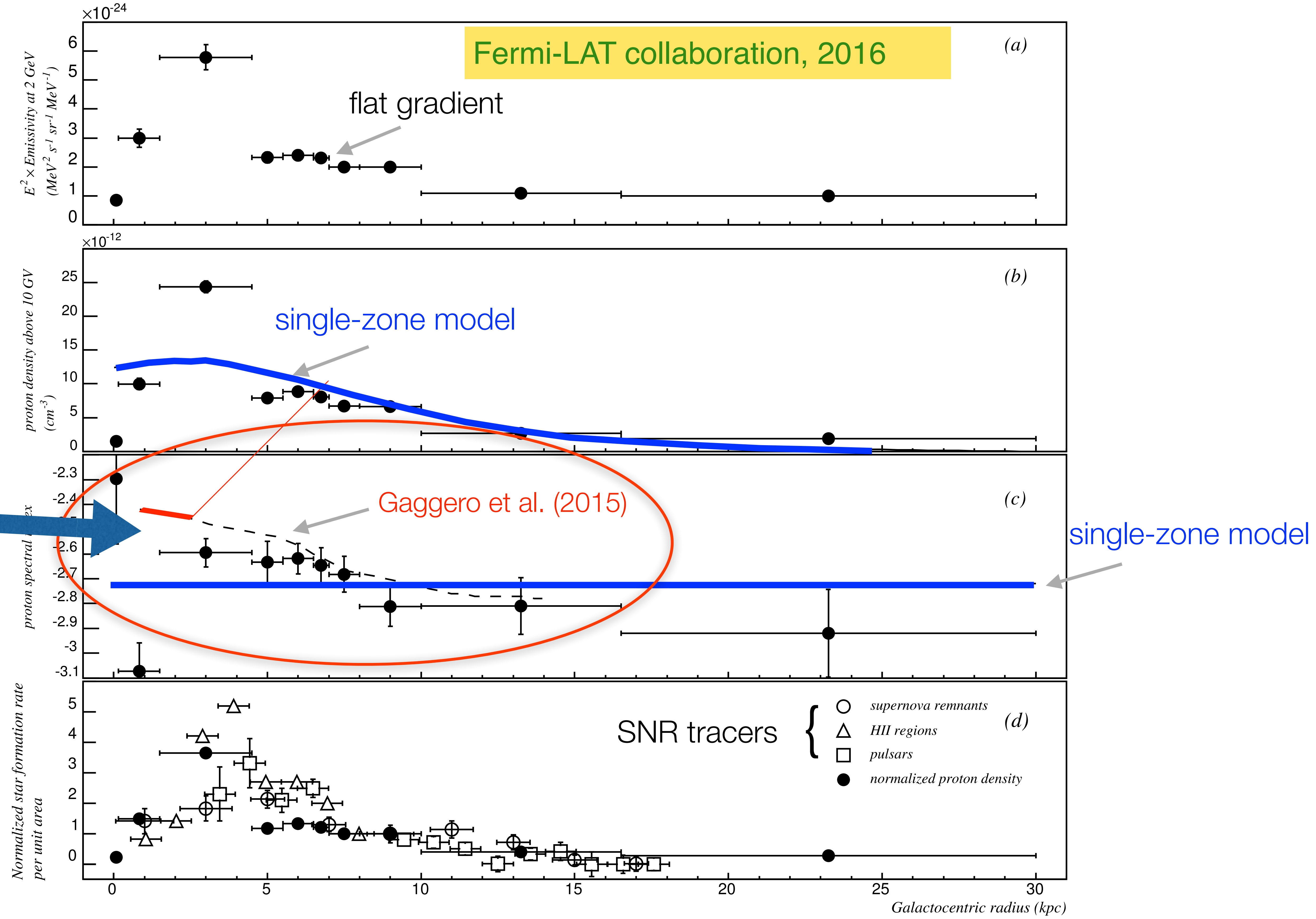
A CR hardening in the inner Galaxy?

$$D(\rho) = D_0 \beta^\eta \left(\frac{\rho}{\rho_0}\right)^{\delta(r)}$$

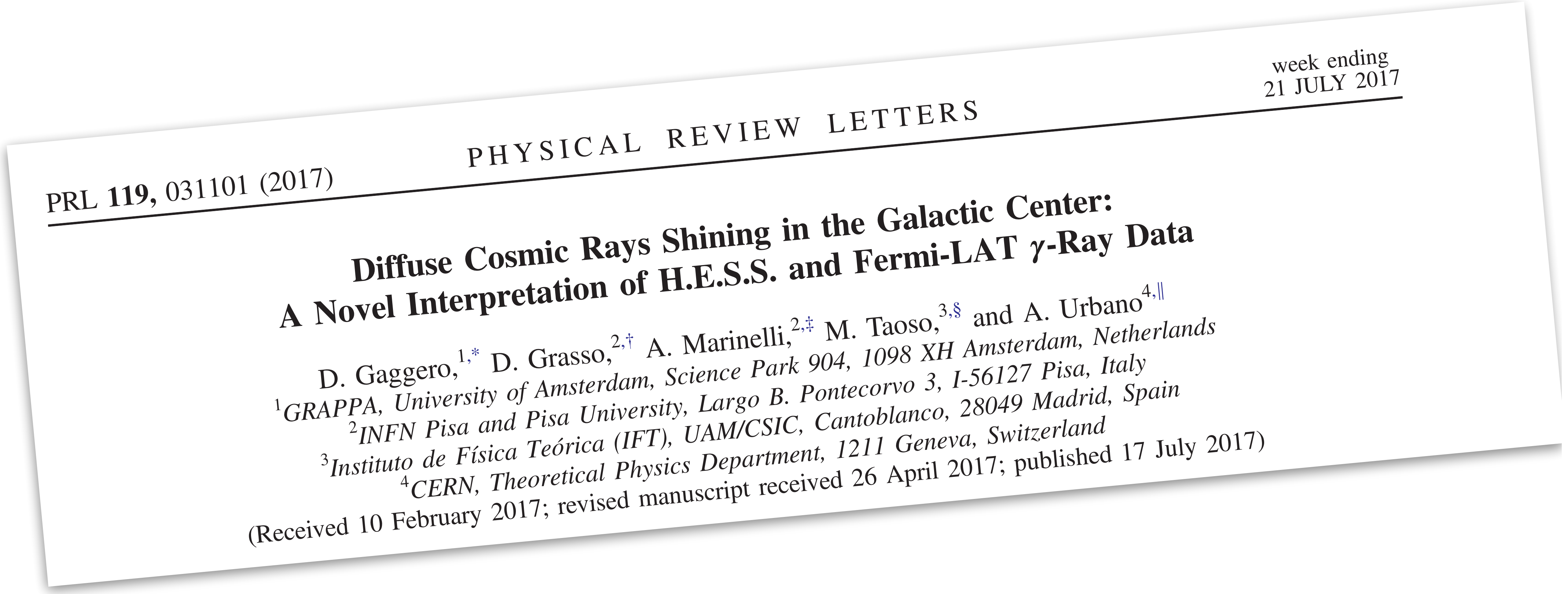
$$\delta(r) = ar + b$$







γ-ray anomalies: GeV-TeV connections



PRL 119, 031101 (2017) PHYSICAL REVIEW LETTERS week ending 21 JULY 2017

Diffuse Cosmic Rays Shining in the Galactic Center: A Novel Interpretation of H.E.S.S. and Fermi-LAT γ-Ray Data

D. Gaggero,[1,*] D. Grasso,[2,†] A. Marinelli,[2,‡] M. Taoso,[3,§] and A. Urbano[4,∥]
[1]GRAPPA, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, Netherlands
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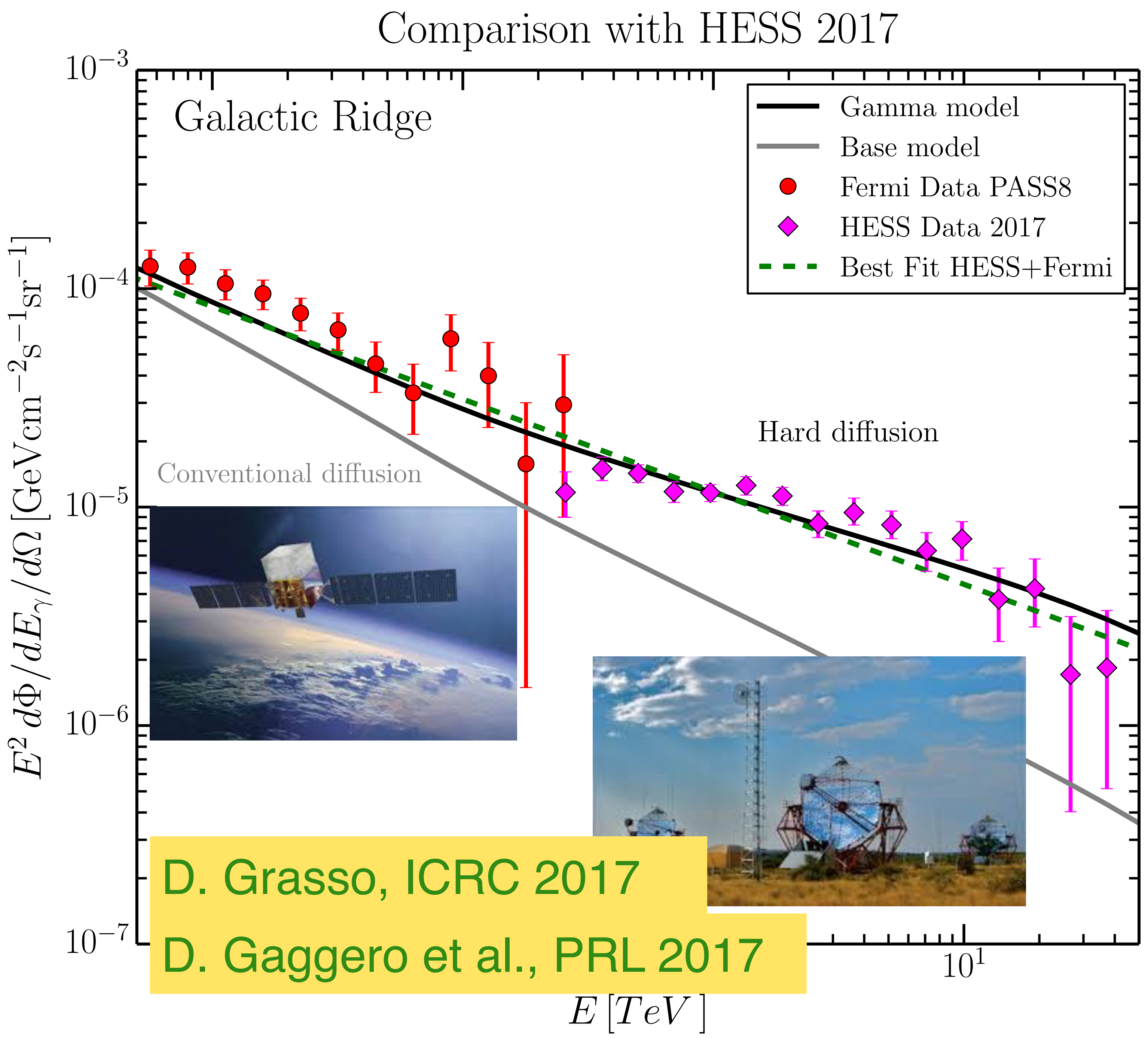
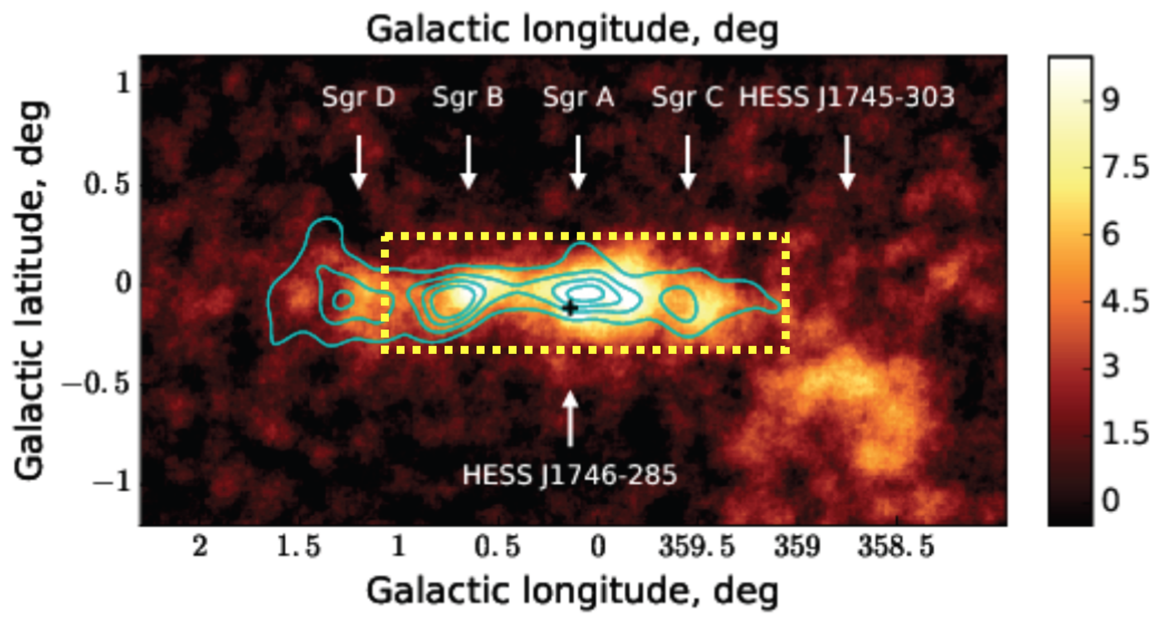
[4]CERN, Theoretical Physics Department, 1211 Geneva, Switzerland
(Received 10 February 2017; revised manuscript received 26 April 2017; published 17 July 2017)



D. Grasso, ICRC 2017

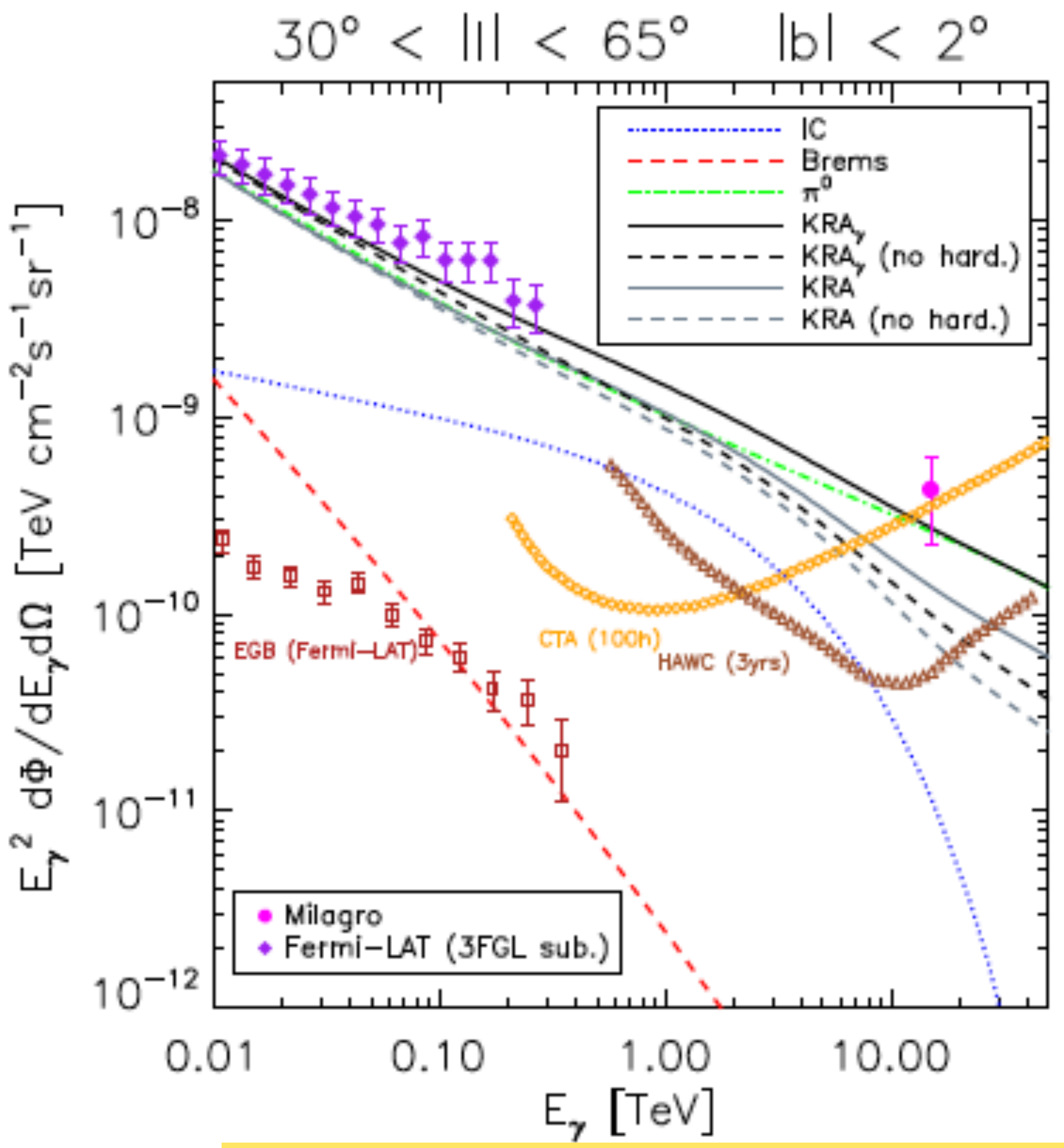
D. Gaggero et al., PRL 2017



Under the assumptions that:

1) the proton break at ~200 GV is present all through the Galaxy,
2) the diffusion coefficient has a harder rigidity dependence, as suggested by Fermi-LAT data

See also T. Linden talk for leptonic models!



D. Gaggero et al., ApjL, 2016

CR hardening in the inner Galaxy. Explanation I: Non-linear physics?

Recchia, Blasi, Morlino 2016

CR transport equation

$$\frac{\partial f}{\partial t} + v_A \frac{\partial f}{\partial z} = \frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right]$$

Diffusion coefficient as a function of magnetic turbulence

$$D(p,z,t) = \frac{r_L v}{3}\frac{1}{\mathcal{F}(k,z,t)}\bigg|_{k=1/r_L}$$

$$\frac{\partial B^2}{B_0^2} = \int \mathcal{F}(k)\frac{dk}{k}$$

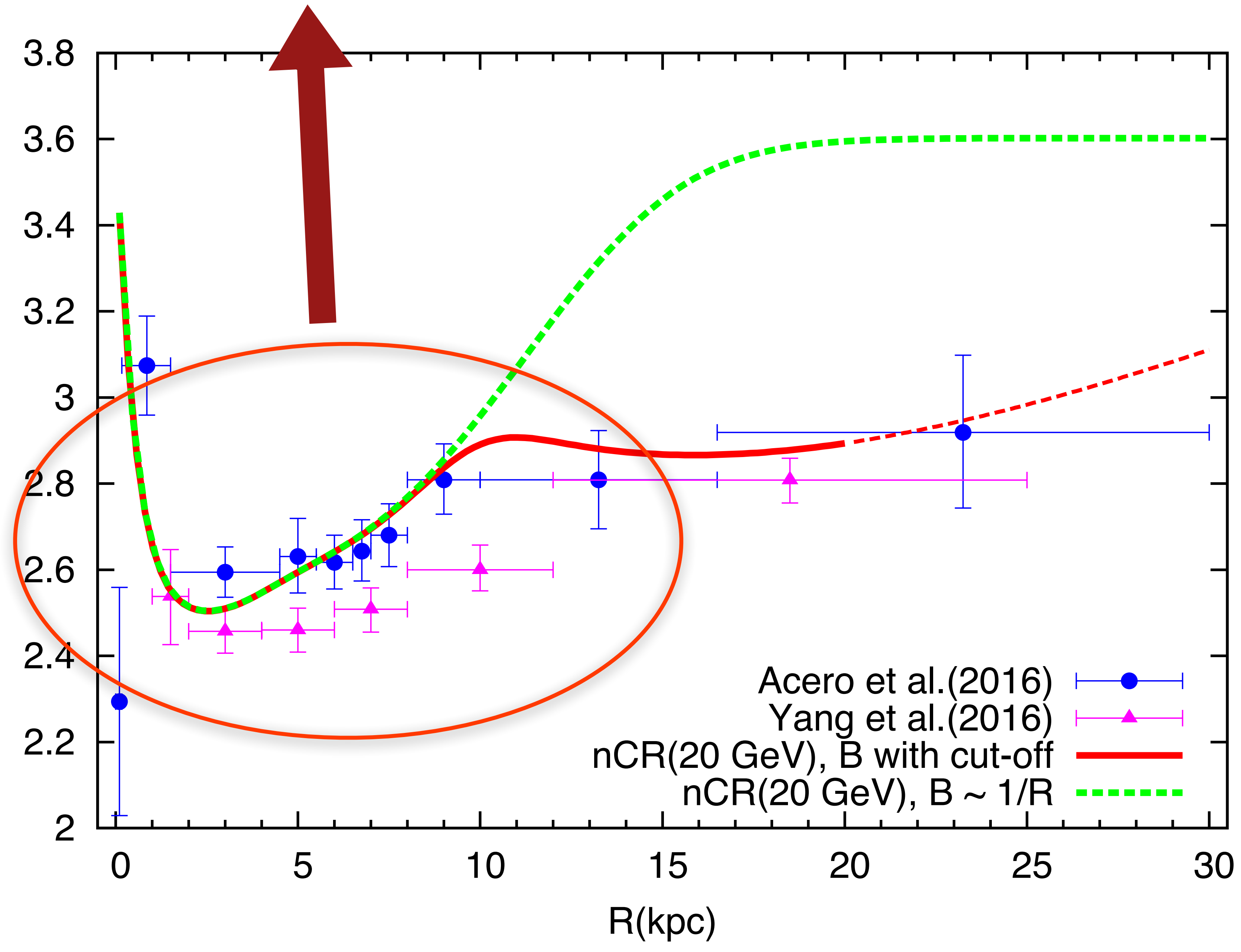
Growth-damping balance of self-generated magnetic turbulence

$$\frac{\partial \mathcal{F}}{\partial t} + v_A \frac{\partial \mathcal{F}}{\partial z} = (\Gamma_{\rm CR} - \Gamma_D)\,\mathcal{F} + Q_w$$

growth rate $\Gamma_{\rm CR} = \frac{16\pi}{3}\frac{v_A}{\mathcal{F}B_0^2}\left[p^4 v \nabla f\right]\Big|_{p=p_{\rm res}}$

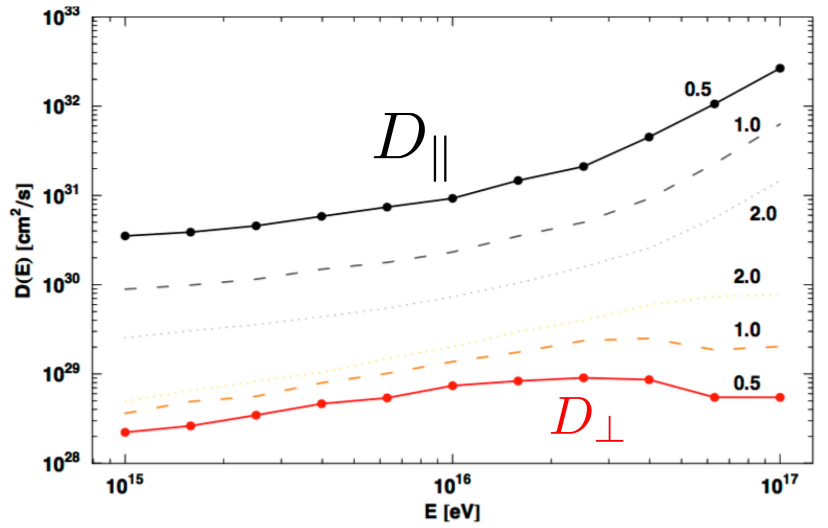
Stronger CR gradients
—> more effective self-confinement
—> low diffusion coefficient
—> advection takes over at larger energies
—> propagated spectrum closer to the inj. one

this effect only holds for E < ~50 GeV!

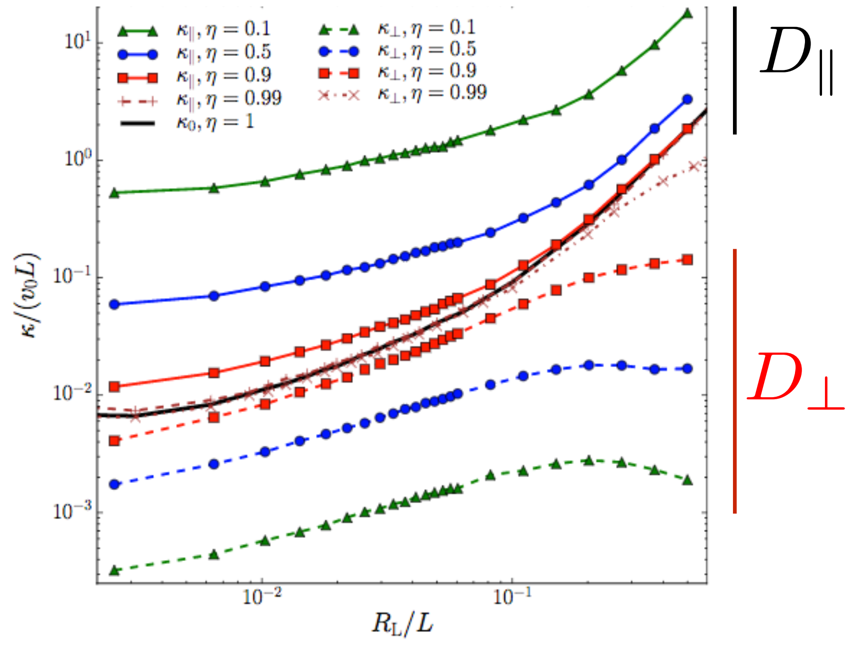


CR hardening in the inner Galaxy. Explanation II: Anisotropic transport

GeV-TeV CR transport is expected to be highly anisotropic (resonant scale: 1 - 1000 AU, QLT holds)



De Marco, Blasi, Stanev, JCAP 6 2007

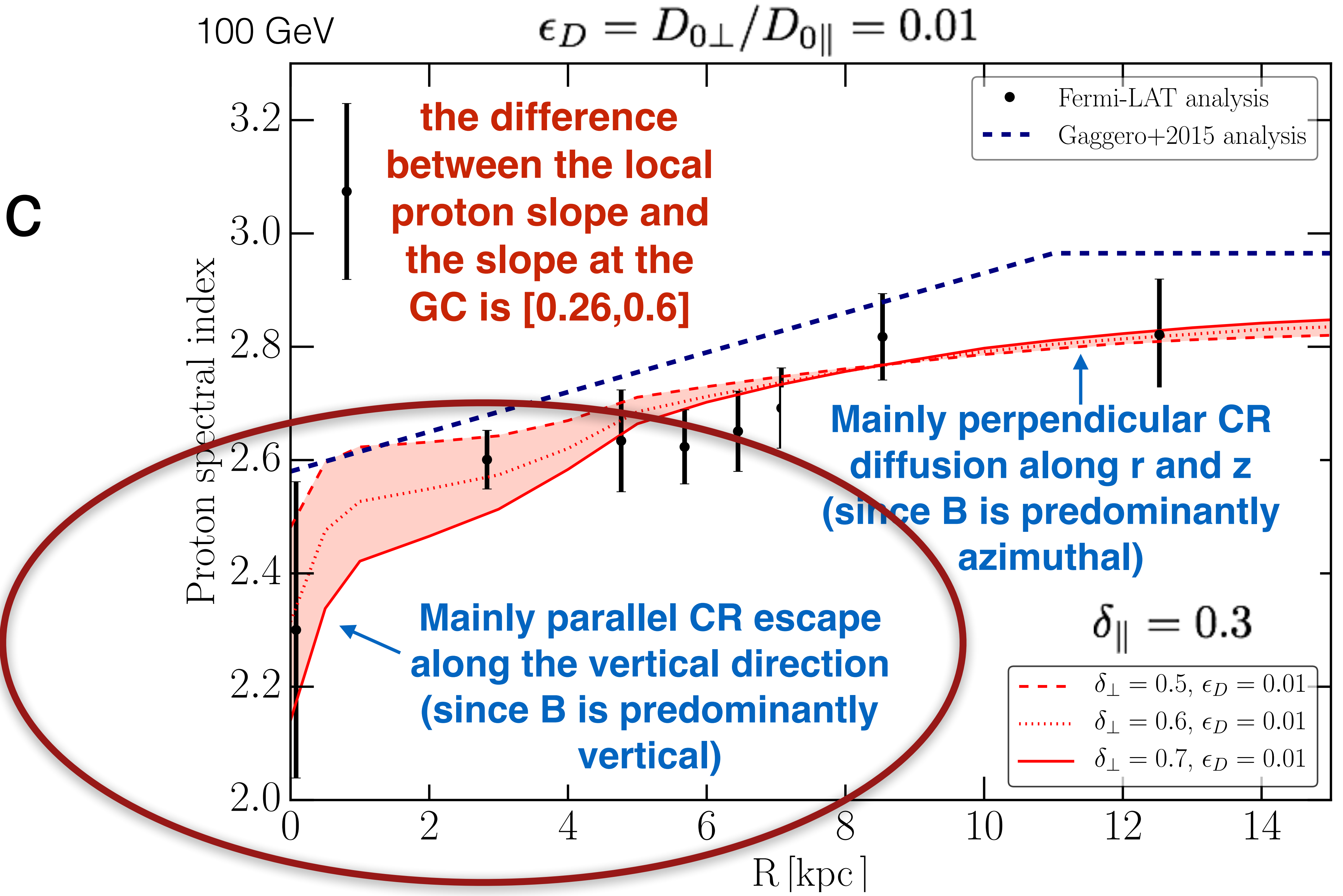


Snodin et al. ,MNRAS 457 (2016)

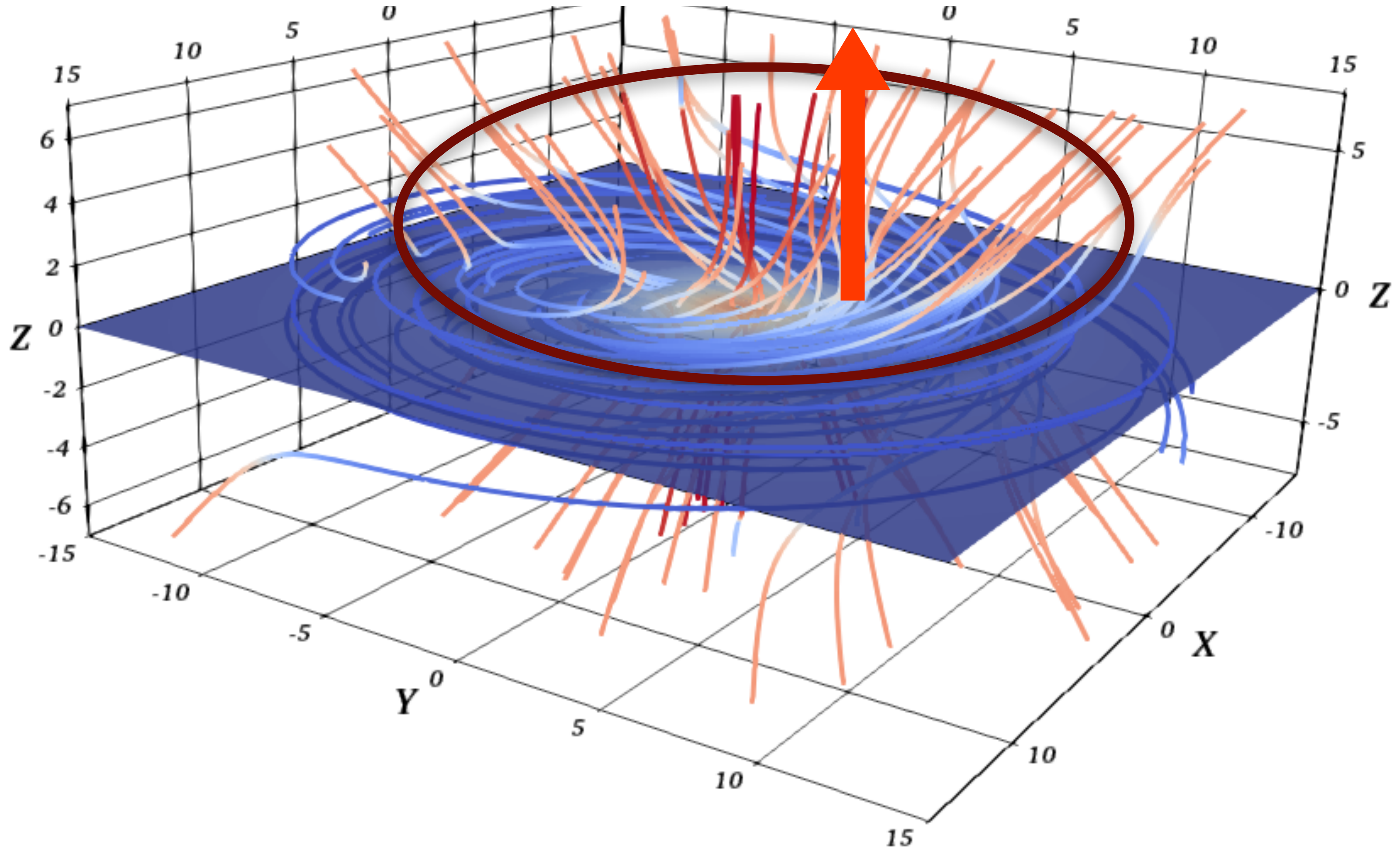
Different scalings of parallel and perpendicular diffusion

DRAGON2

S.S. Cerri, D. Gaggero, A. Vittino, C. Evoli, D. Grasso, 2017

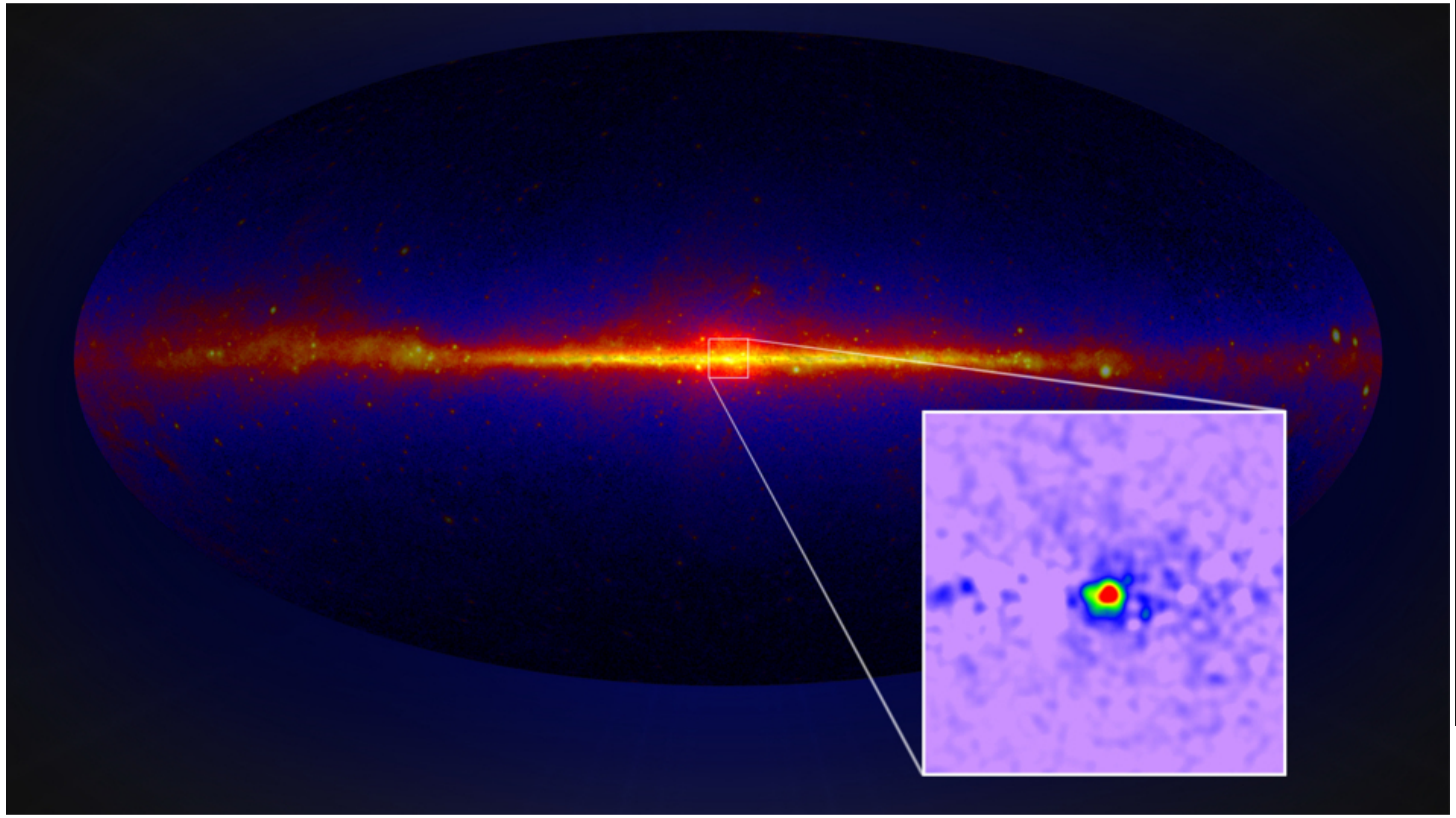


Improved modeling of large-scale topology of the Galactic magnetic field: poloidal component in the inner Galaxy

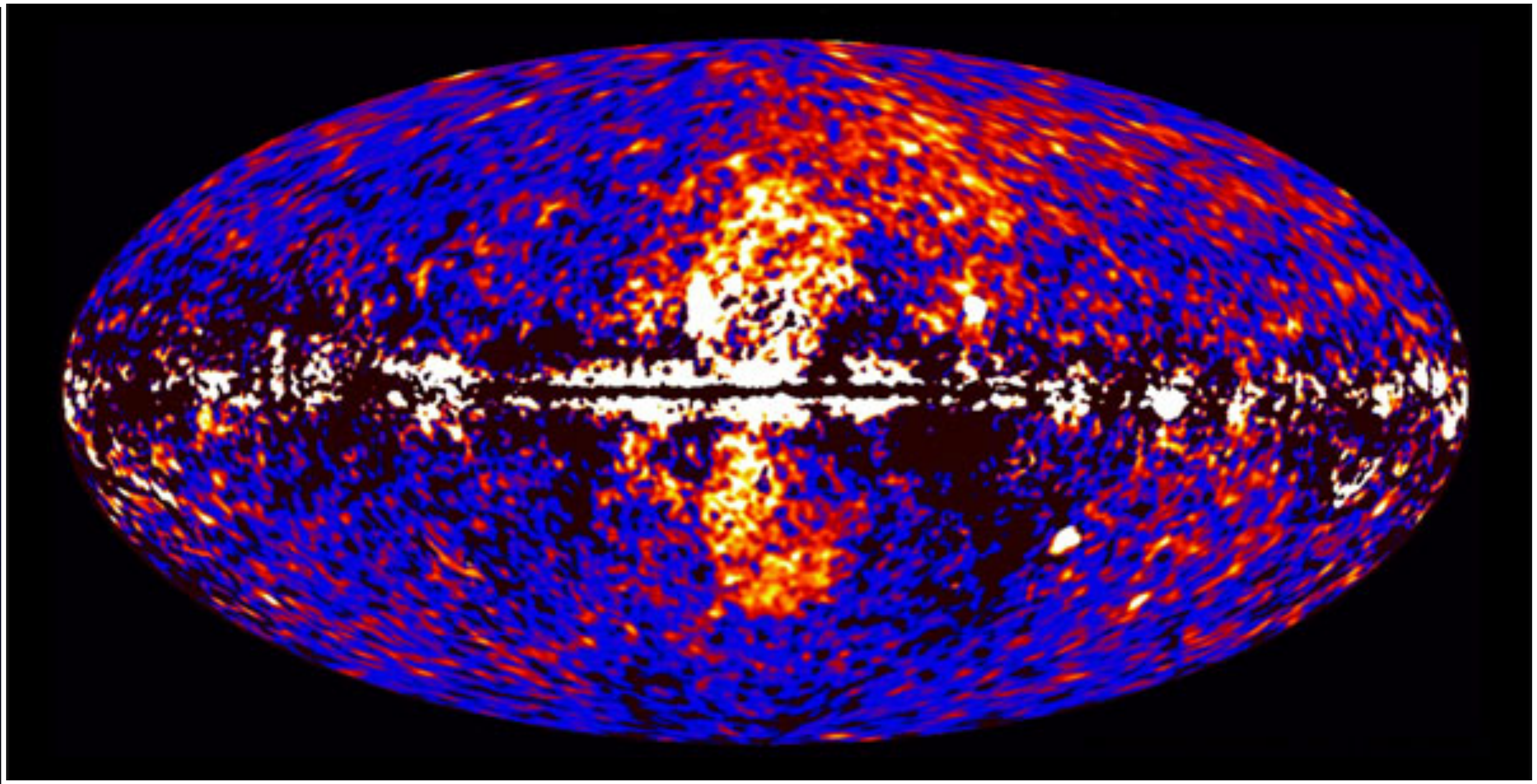


Enhanced parallel escape in the vertical direction in the inner Galaxy

γ-ray anomalies: The giant monsters in the sky

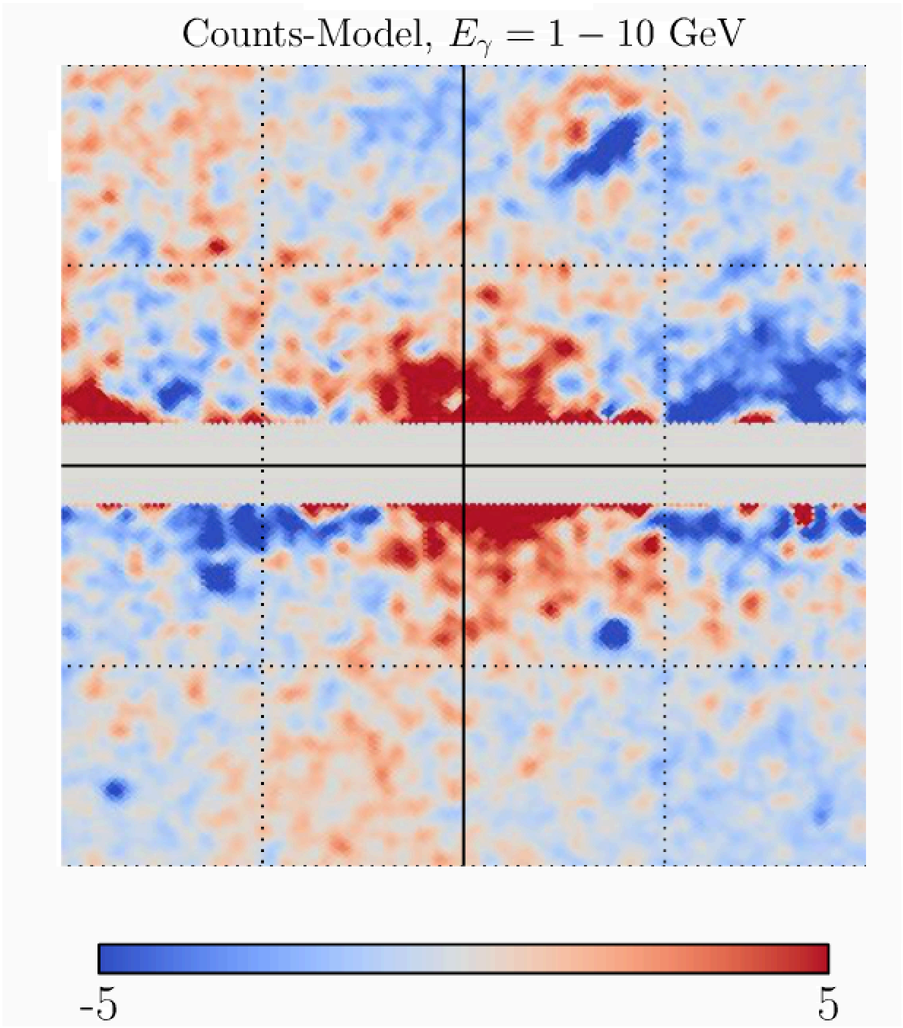


GeV excess



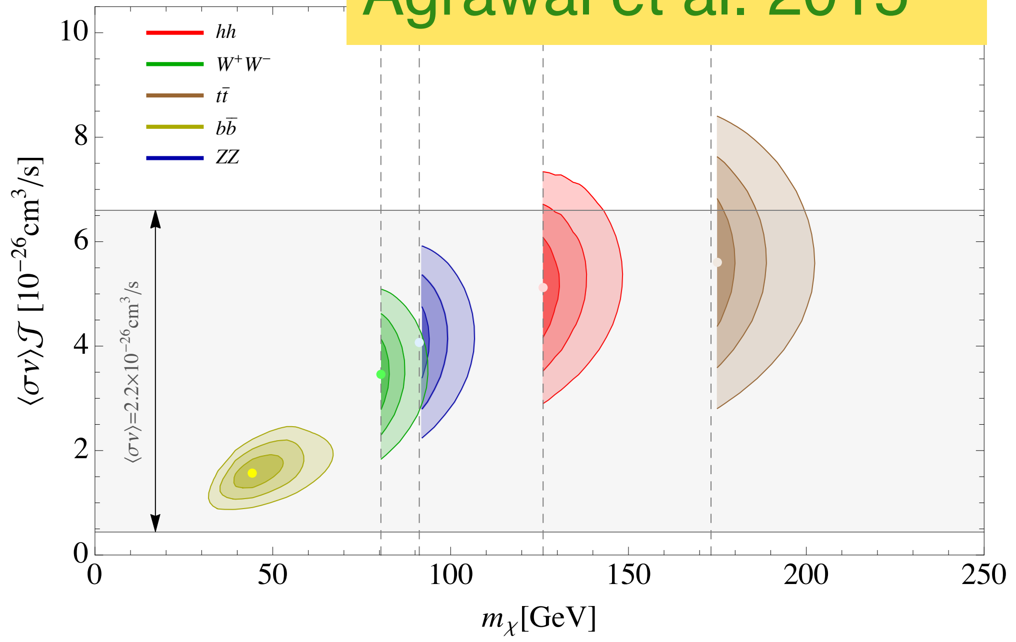
Fermi bubbles

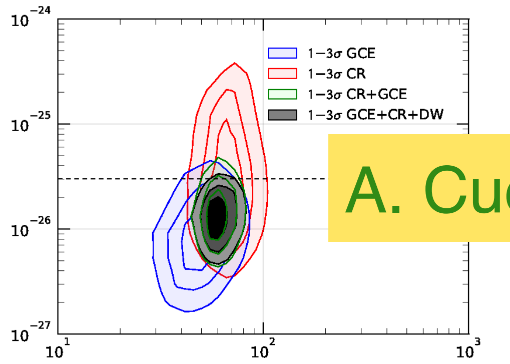
γ-ray anomalies: The giant monsters in the sky



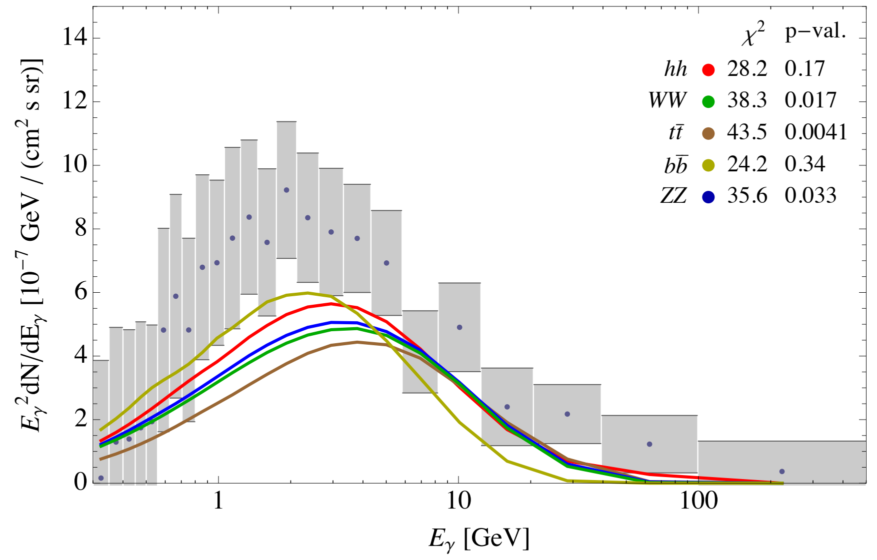
- **DM interpretation**
multichannel studies are needed
(tension with dwarf galaxy constraints?
connections with antiprotons)

Agrawal et al. 2015





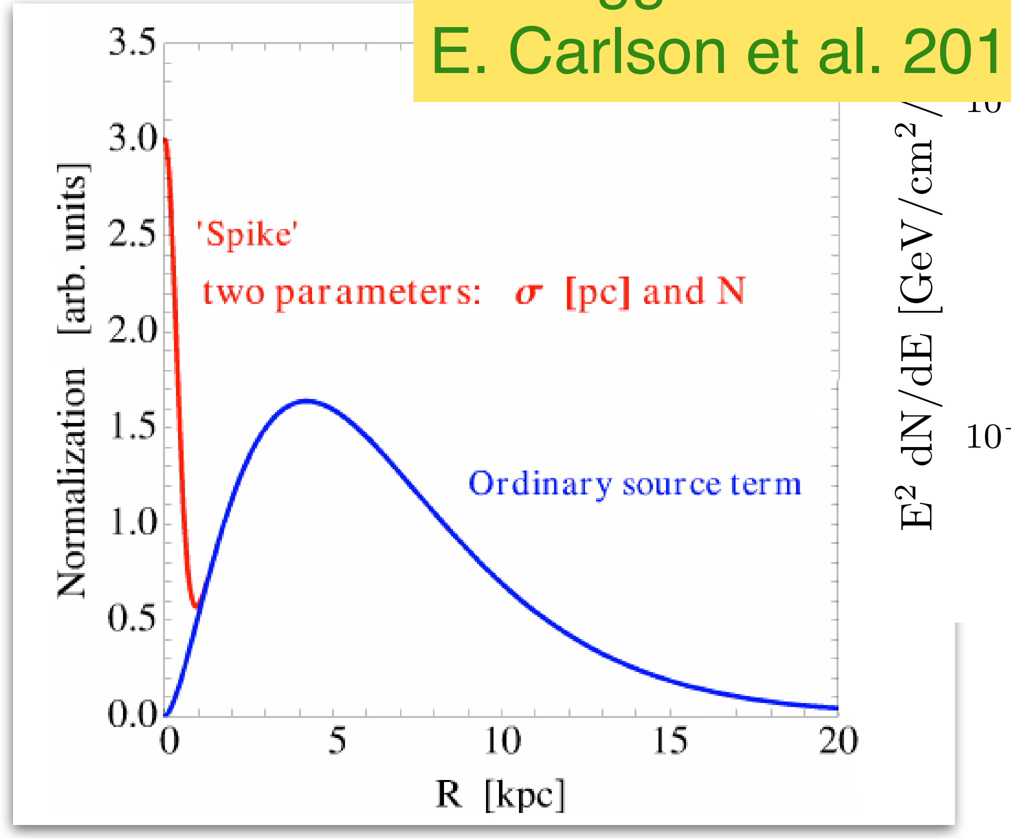
A. Cuoco et al. 2017

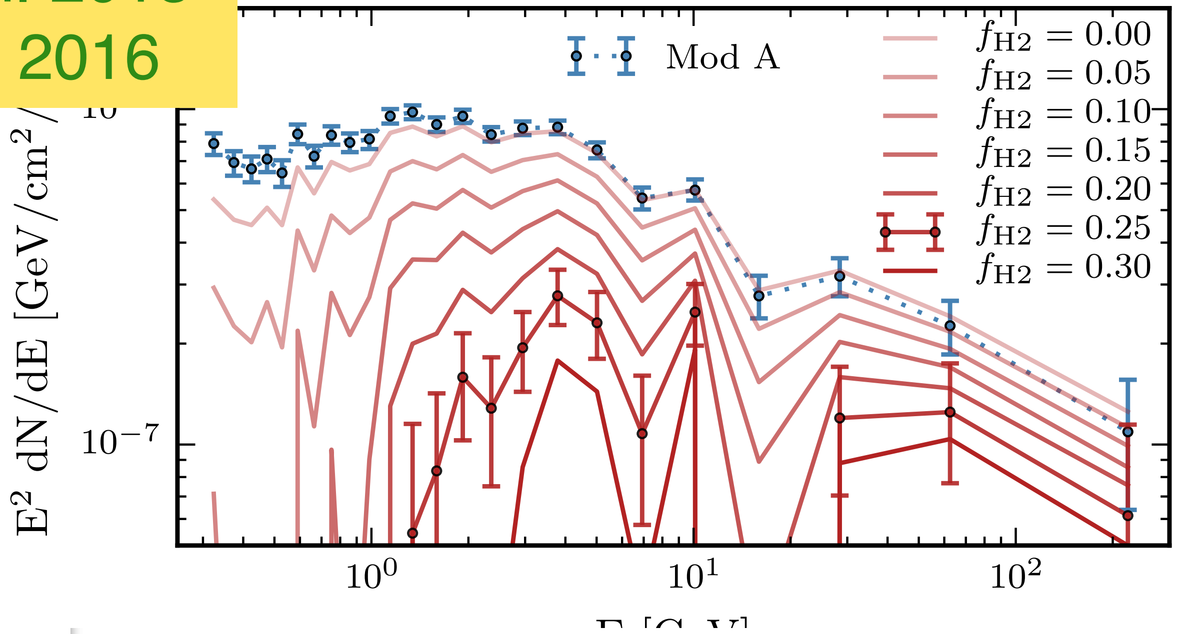


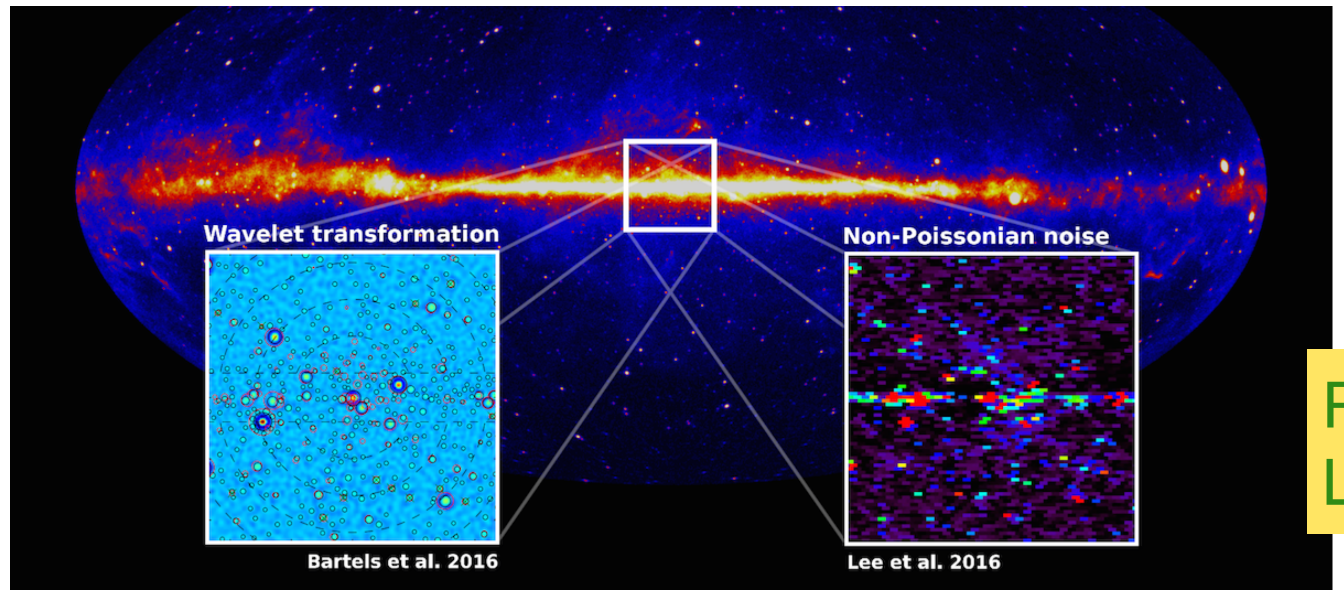
- **MSP interpretation**
suggested by wavelet analyses
connection with 511 keV signal (see R. Bartels talk)

- **Is it really an excess?**

D. Gaggero et al. 2015
E. Carlson et al. 2016







R. Bartels et al. 2016
Lee et al. 2016

- **X-ray shape?**
(see O. Macias talk)

- **Alternative interpretation**
in terms of CR interacting with MCs

De Boer et al. 2017

Conclusions

- The CR and gamma-ray data finally offer the unique opportunity to move beyond a simplistic picture of CR acceleration and propagation
- Anomalies exist in all channels
- A lot of exciting work for theorists and phenomenologists working on CR transport codes
- Dark matter detection claims are still under debate. Astrophysical interpretations seem to be preferred in all cases. A solid detection in several independent channels is needed.
- Looking forward to more data both in low-energy (e-ASTROGAM) and high-energy (CTA, HAWC, CALET, HERD, … …) domain

Thank you for your attention!

Backup slides