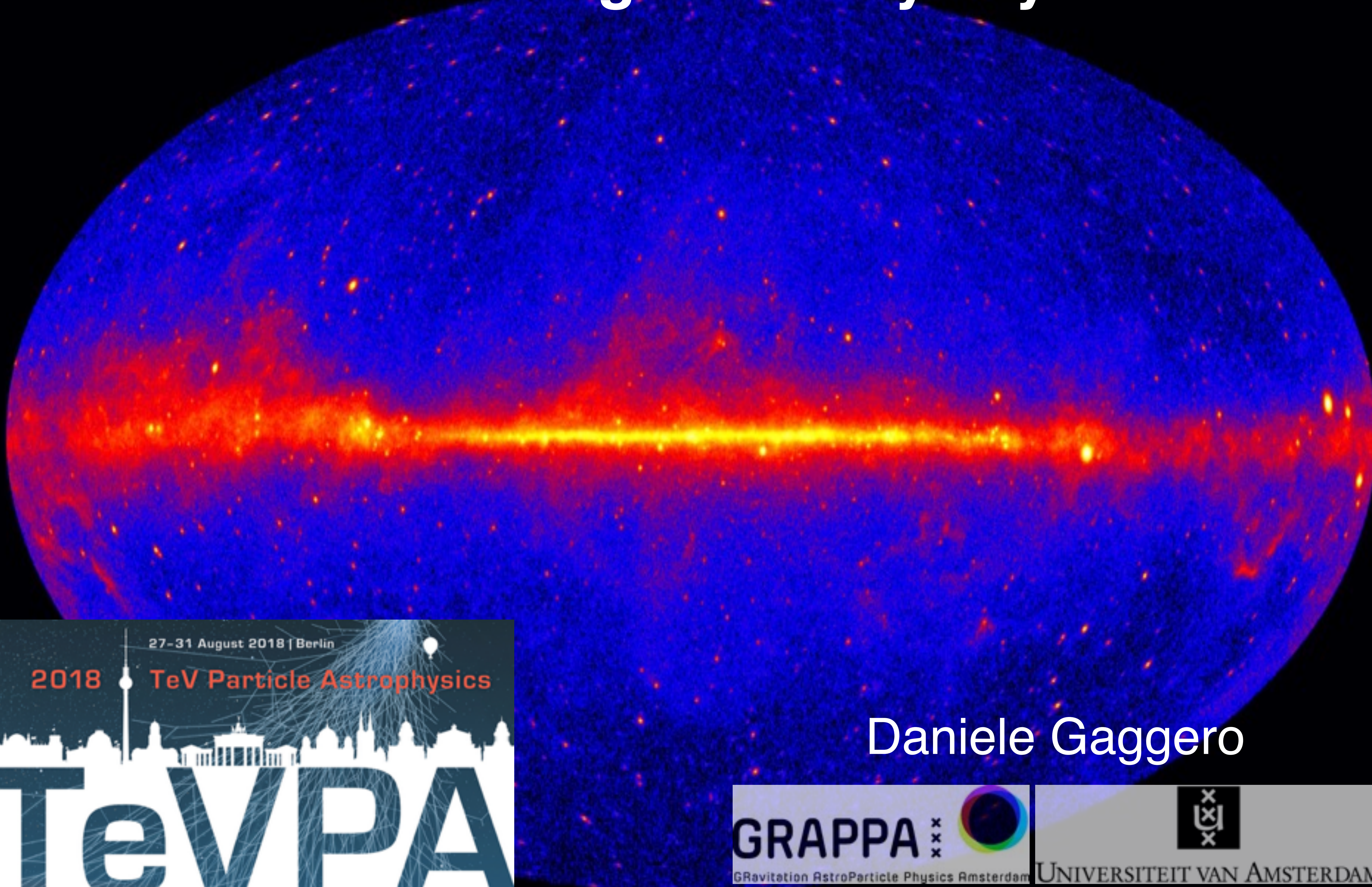
Learning the physics of CR transport from the gamma-ray sky

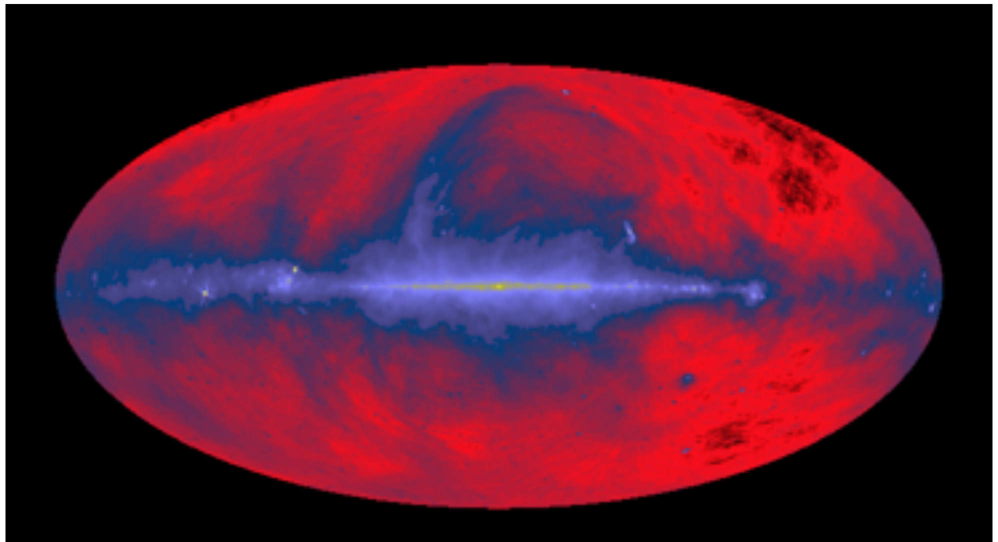


27-31 August 2018 | Berlin
2018 TeV Particle Astrophysics
TeVPA

Daniele Gaggero

GRAPPA
GRavitation AstroParticle Physics Amsterdam
UNIVERSITEIT VAN AMSTERDAM

Non-thermal emission from CRs

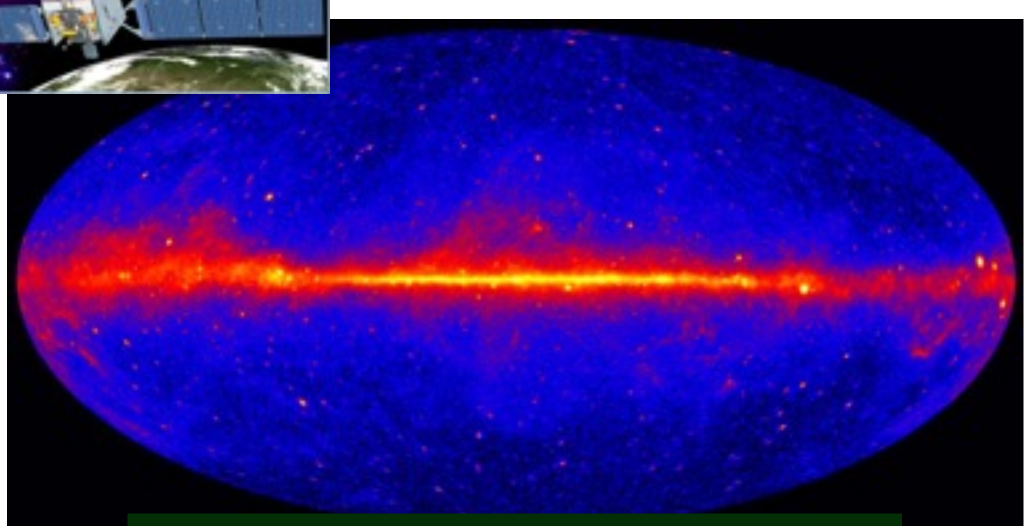


Planck (2009-2013): GHz - THz radio sky

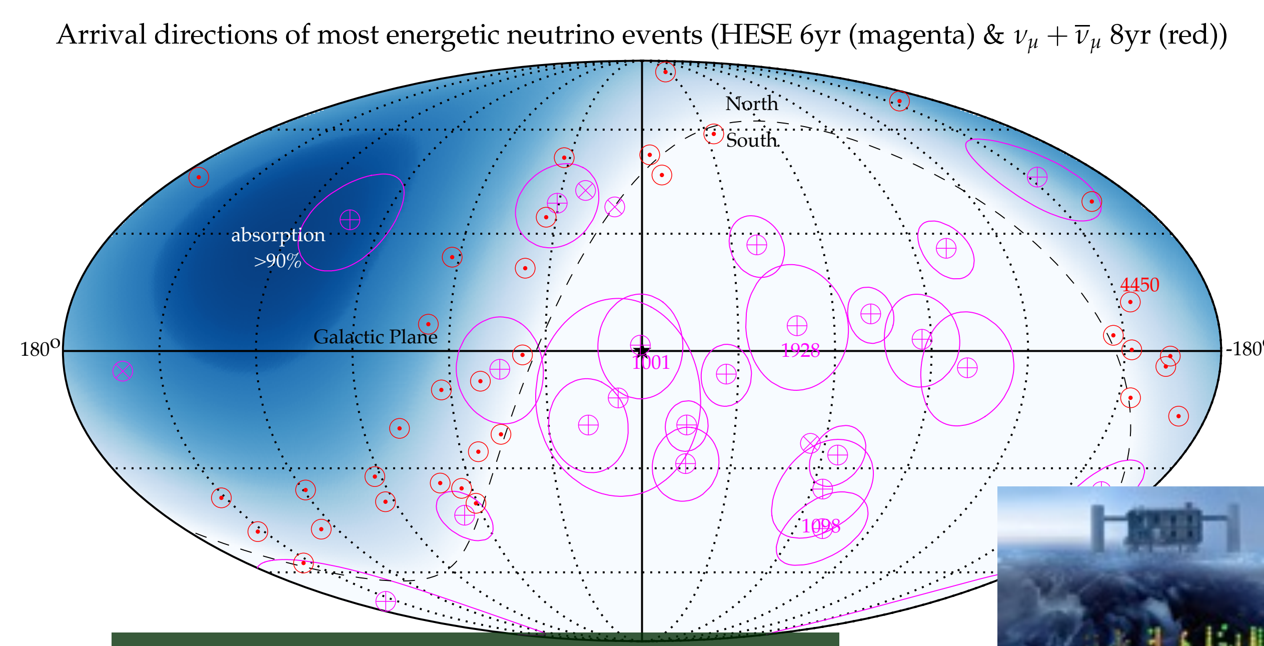
Non-thermal emission from CRs is crucial to understand their properties.

Observations cover **> 20 orders of magnitude** in energy, from ~100 MHz radio waves to PeV neutrinos

Future data will come from experiments such as
- SKA (radio domain, 50 MHz -> 14 GHz)
- e-ASTROGAM? AMEGO? (MeV γ-ray domain)
- CTA, HAWC (TeV γ-ray domain)
- LHAASO, HERD (TeV to PeV CRs and γ-rays)
- Icecube, Km3NET (neutrinos)
- Dampe, CALET, ISS-CREAM (TeV charged CRs)



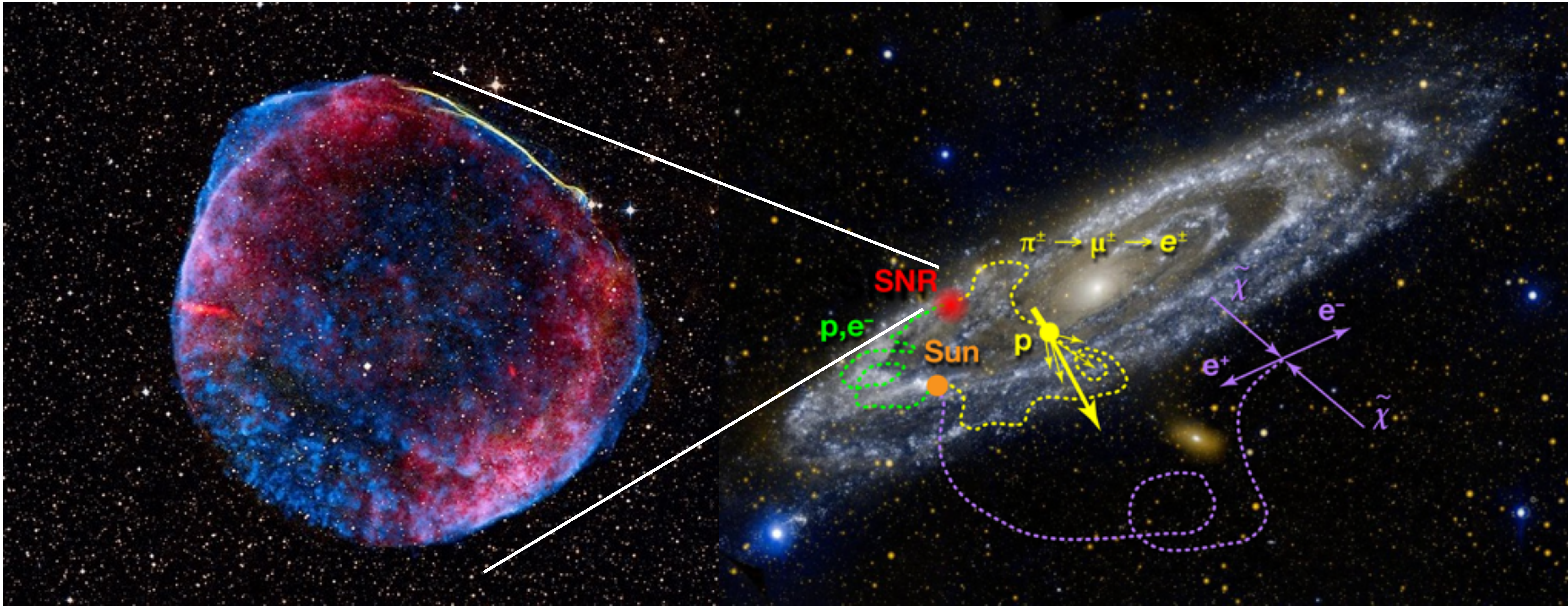
Fermi-LAT (2008 - ongoing): ~0.3 - ~300 GeV γ-ray sky



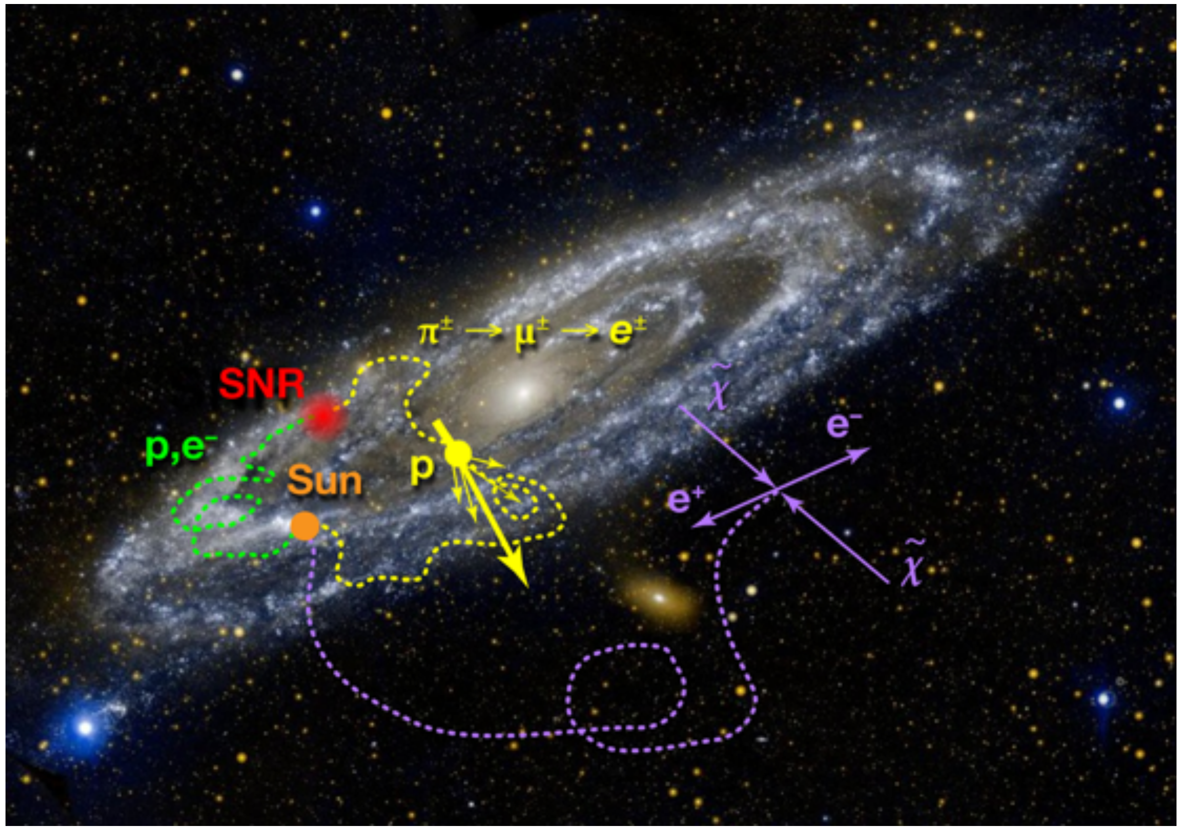
IceCube (2013- ongoing): TeV - PeV neutrino sky

The key questions

1) Where do CRs come from?
2) How do they propagate in (different region of) the Galaxy? What is the mechanism of confinement?
3) Can they reveal hints of new physics?



Phenomenology of CR transport



Physical processes that affect CR transport in the Galaxy:
[Ginzburg&Syrovatskii 1964; Berezinskii et al. 1990]

- **Primary CR production**
- **Secondary CR production** via spallation
- *Rigidity-dependent* **diffusion**
- *Rigidity-independent* **advection**
- Possibly, stochastic **II order Fermi acceleration** (*reacceleration*)
- **Energy losses**

$$\nabla \cdot (\vec{J}_i - \vec{v}_w N_i) + \frac{\partial}{\partial p}\left[p^2 D_{pp} \frac{\partial}{\partial p}\left(\frac{N_i}{p^2}\right)\right] - \frac{\partial}{\partial p}\left[\dot{p} N_i - \frac{p}{3}\left(\vec{\nabla}\cdot\vec{v}_w\right) N_i\right] =$$

$$Q + \sum_{i<j}\left(c\beta n_{\rm gas}\,\sigma_{j\to i} + \frac{1}{\gamma\tau_{j\to i}}\right) N_j - \left(c\beta n_{\rm gas}\,\sigma_i + \frac{1}{\gamma\tau_i}\right) N_i$$

$$J_i = -D_{ij}\nabla_j N$$

The numerical (phenomenological) approach

$$\nabla \cdot (\vec{J}_i - \vec{v}_w N_i) + \frac{\partial}{\partial p}\left[p^2 D_{pp} \frac{\partial}{\partial p}\left(\frac{N_i}{p^2}\right)\right] - \frac{\partial}{\partial p}\left[\dot{p} N_i - \frac{p}{3}\left(\vec{\nabla} \cdot \vec{v}_w\right) N_i\right] =$$

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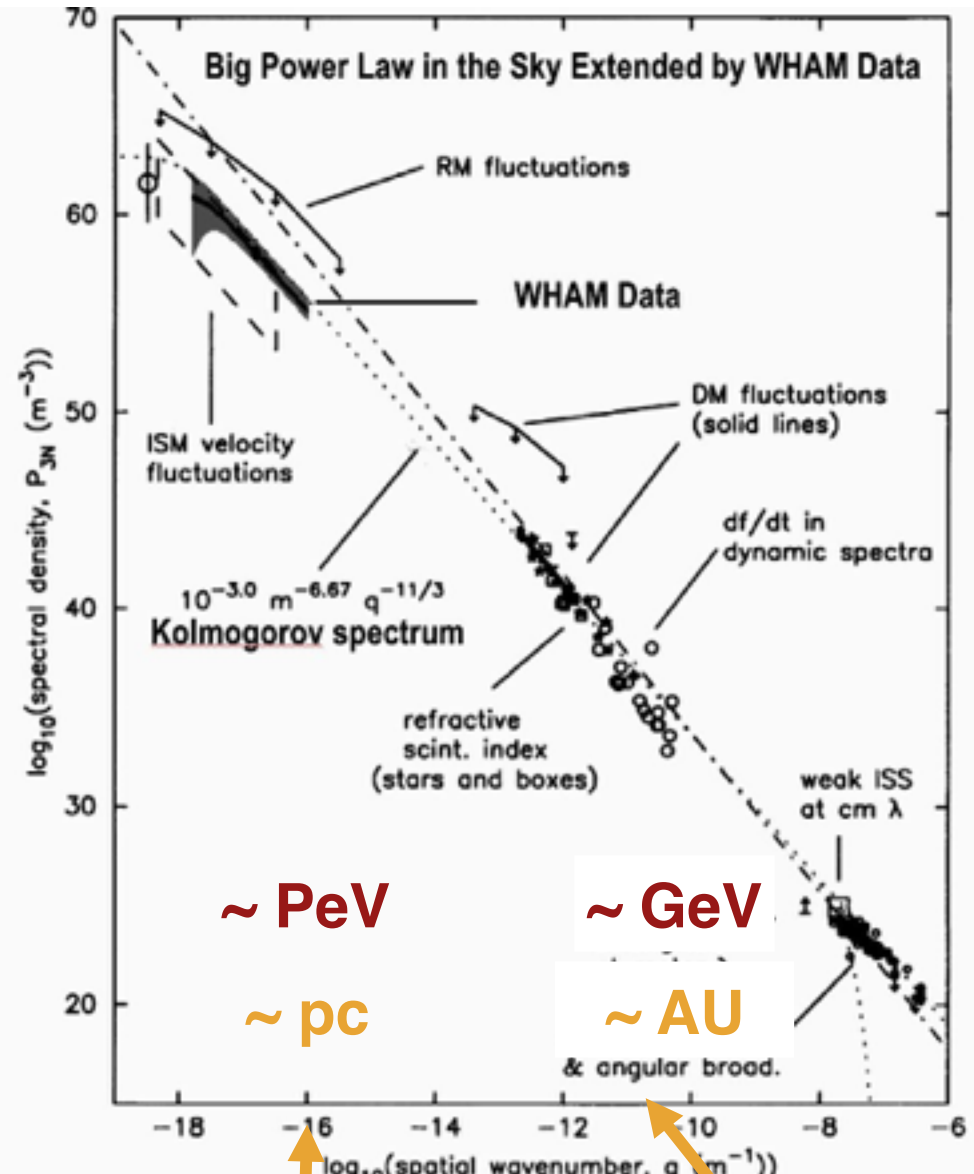
- **Solve the CR transport equation** for all the relevant species (heavy and light nuclei, leptons, antiparticles…)

- Compute the **non-thermal emission over 20 orders of magnitude**, from ~100 MHz radio waves (synchrotron emission) to GeV-TeV γ-rays and neutrinos [see R. Kissmann's, T. Porter's talks]

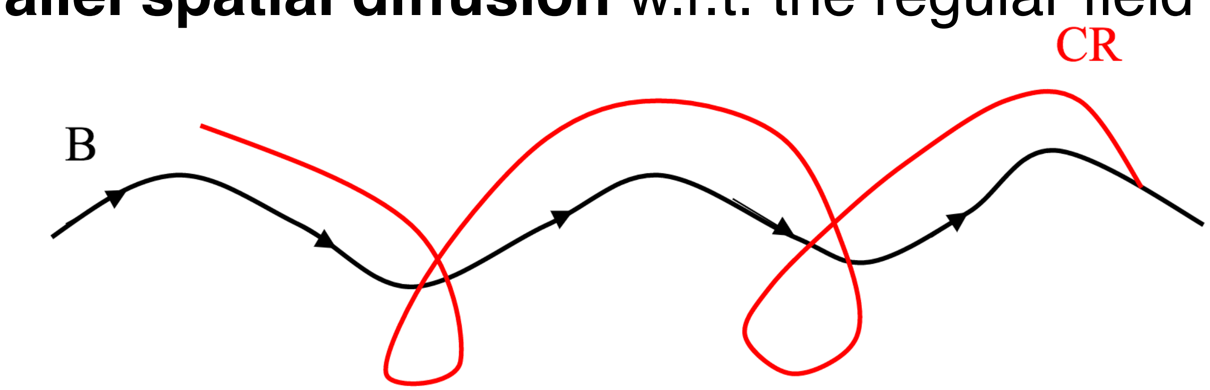
The theory behind CR diffusion

Guideline: resonant pitch-angle scattering on Alfvénic turbulence

[Morrison 1957; Jokipii ApJ **146** 1966; Jokipii&Parker PRL **21** 1968]



- The ISM is **magnetized** and **turbulent** over a wide inertial range; energy injection at large scales (~100 pc), e.g. by supernova explosions or other mechanisms
- **Pitch-angle scattering:** a resonant interaction between Alfvén waves and charged CRs
- Whenever a CR interacts with an Alfvén wave, if the **resonance condition** is satisfied, changes randomly the pitch angle: This stochastic process eventually results in a mostly **parallel spatial diffusion** w.r.t. the regular field



$$D_{\parallel} = \frac{1}{3} c^2 \tau_s \approx \frac{1}{3} \frac{c^2}{\Omega_g} \mathcal{F}(k)^{-1} = \frac{1}{3} R_L c \, \mathcal{F}(k)^{-1}$$

$[I(k_{res})\, k_{res}]/B^2$

Bohm diffusion coefficient D_B

The theory behind CR diffusion

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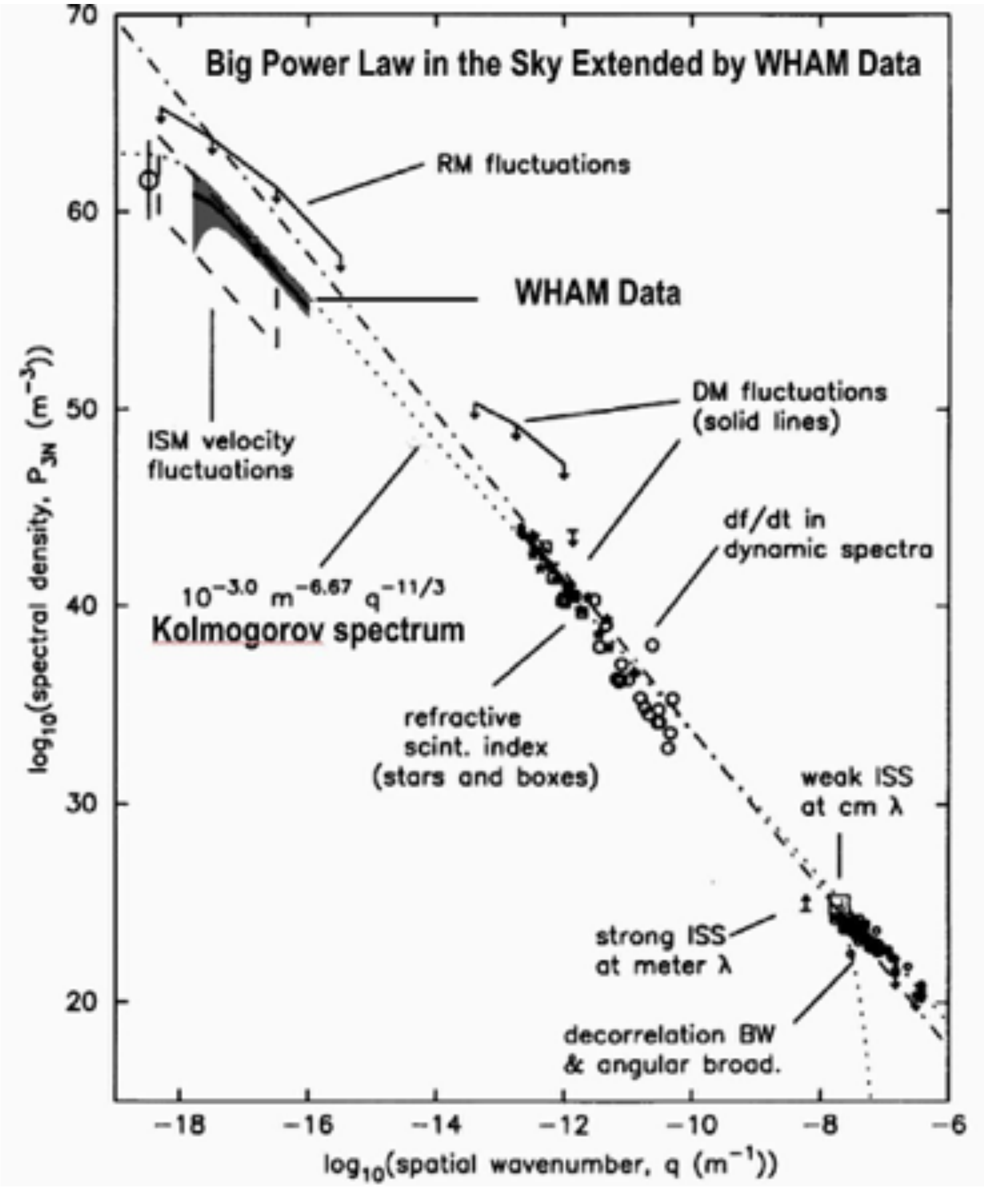


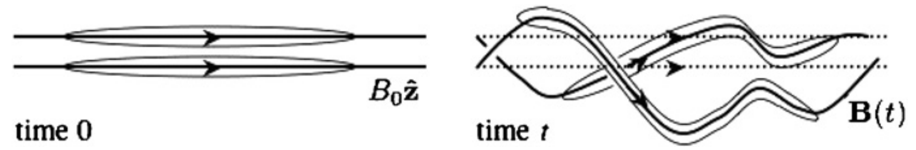


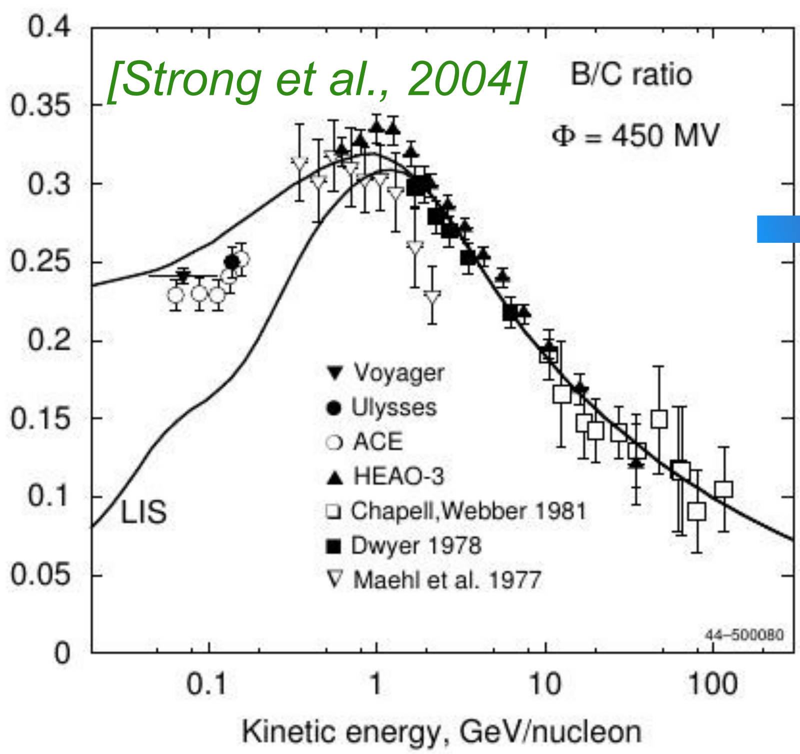
Figure 7. Lagrangian mixing of passive fields: fluctuations develop small scales across, but not along the exact field lines.

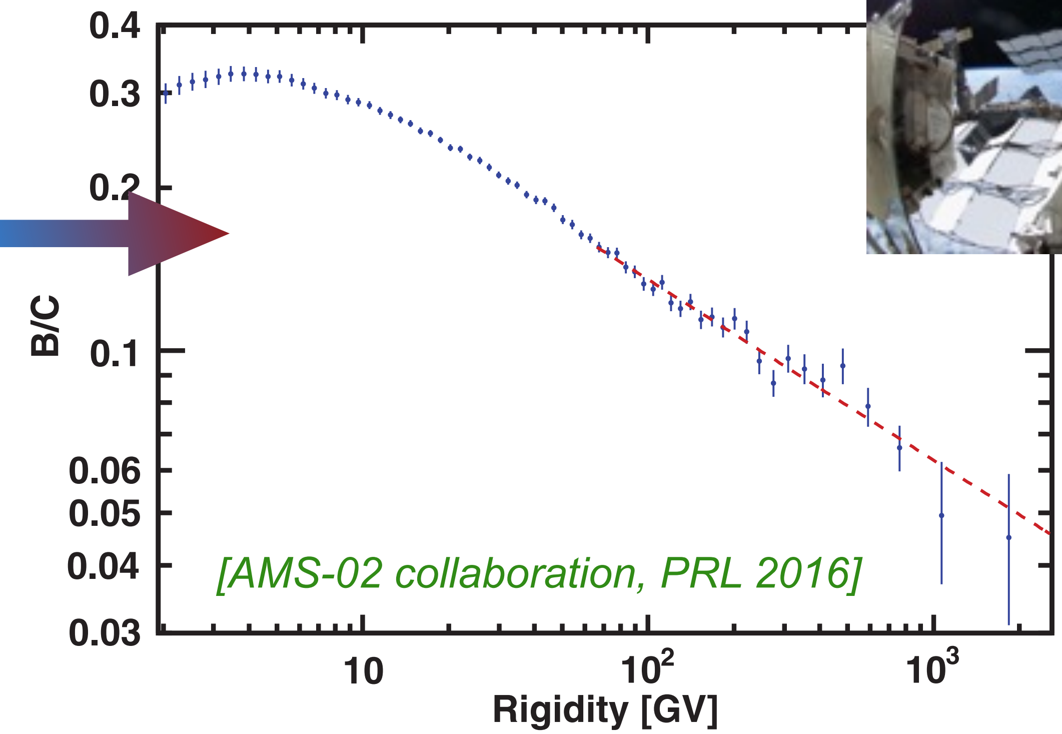
The real picture is much more complicated:

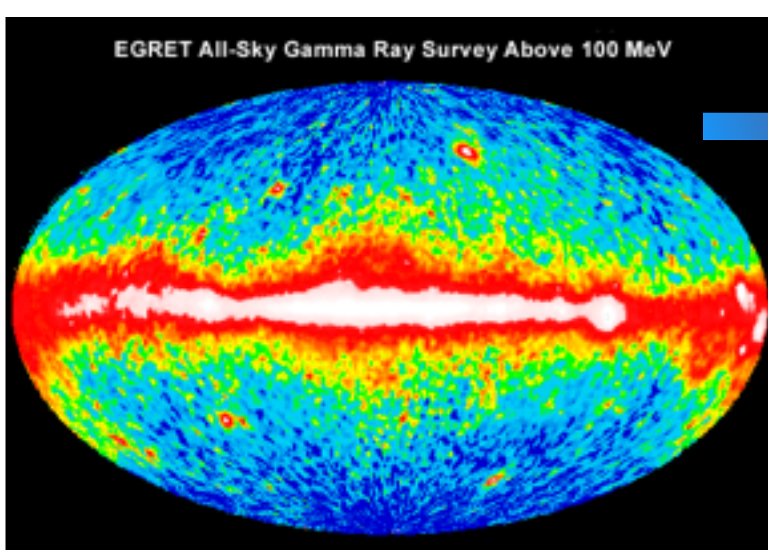
- **Non-linear effects at small scales.** If CRs stream faster than the Alfvén speed, they can amplify waves (naturally of the correct shape for scattering) through the *resonant streaming instability* [Wentzel 1974; Skilling 1975; Cesarsky 1980; Farmer&Goldreich 2003]
- **Pitch-angle scattering is not an efficient confinement mechanism if Alfvénic turbulence is anisotropic.** [Chandran 2000, Yan&Lazarian 2002]

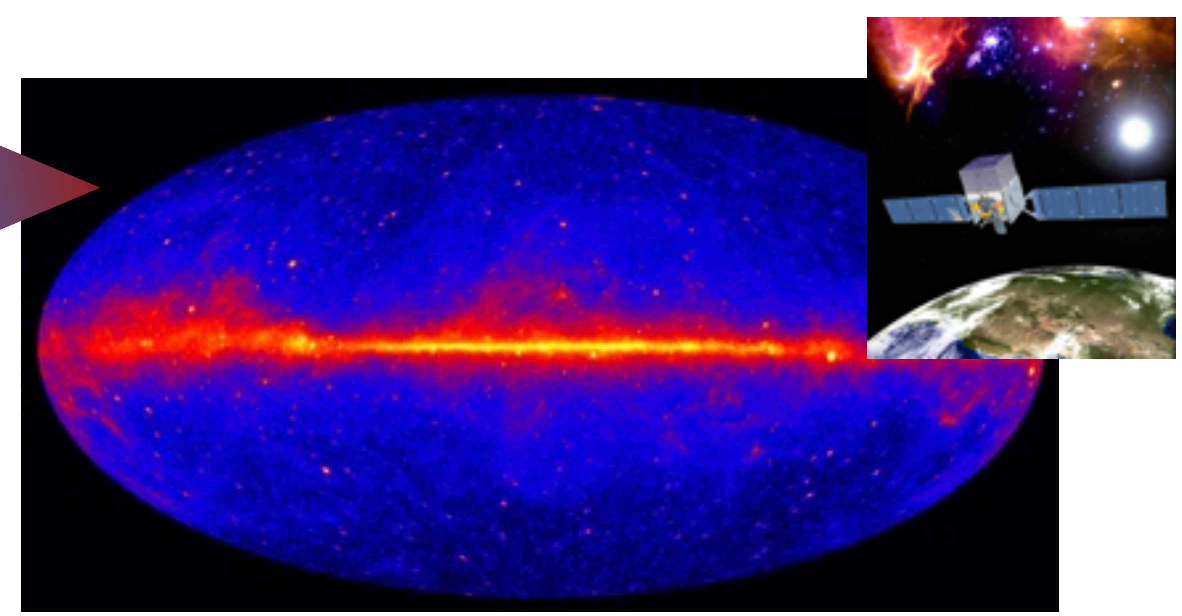
Achievements in the CR field

A new precision era in CR and gamma-ray physics
1990s -> 2010s

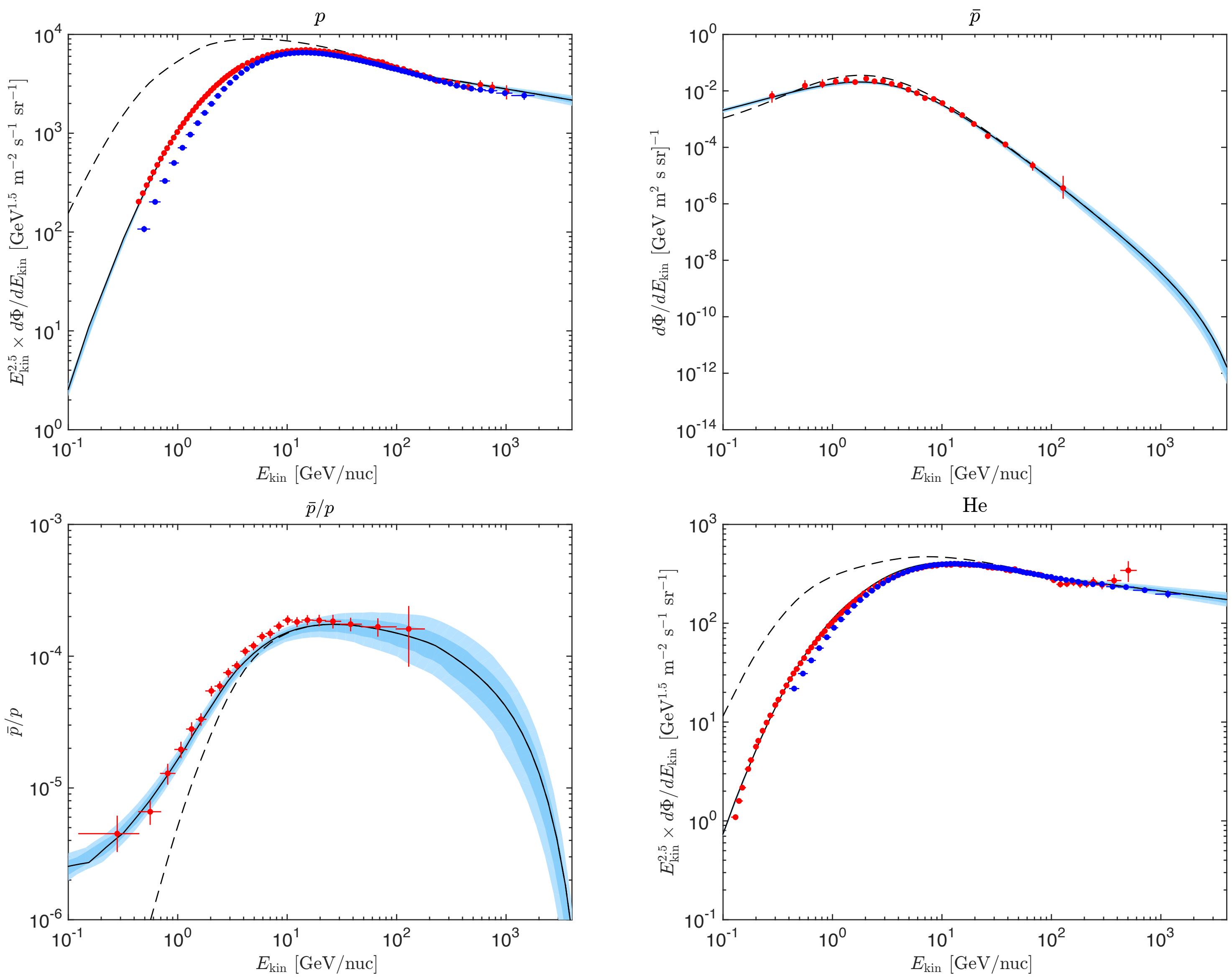




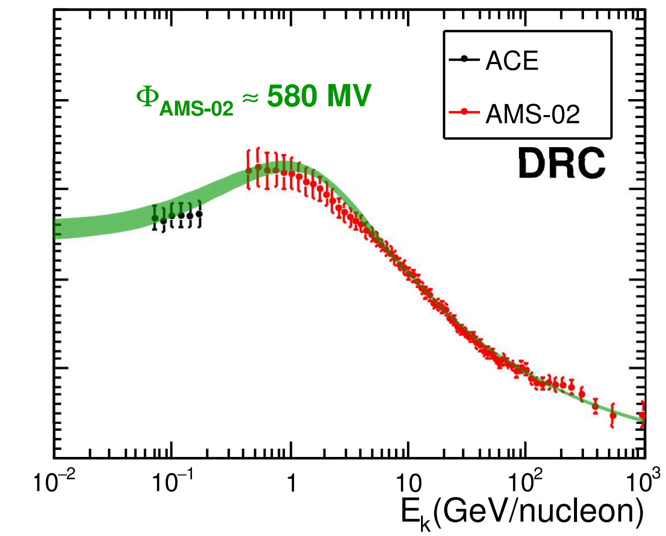


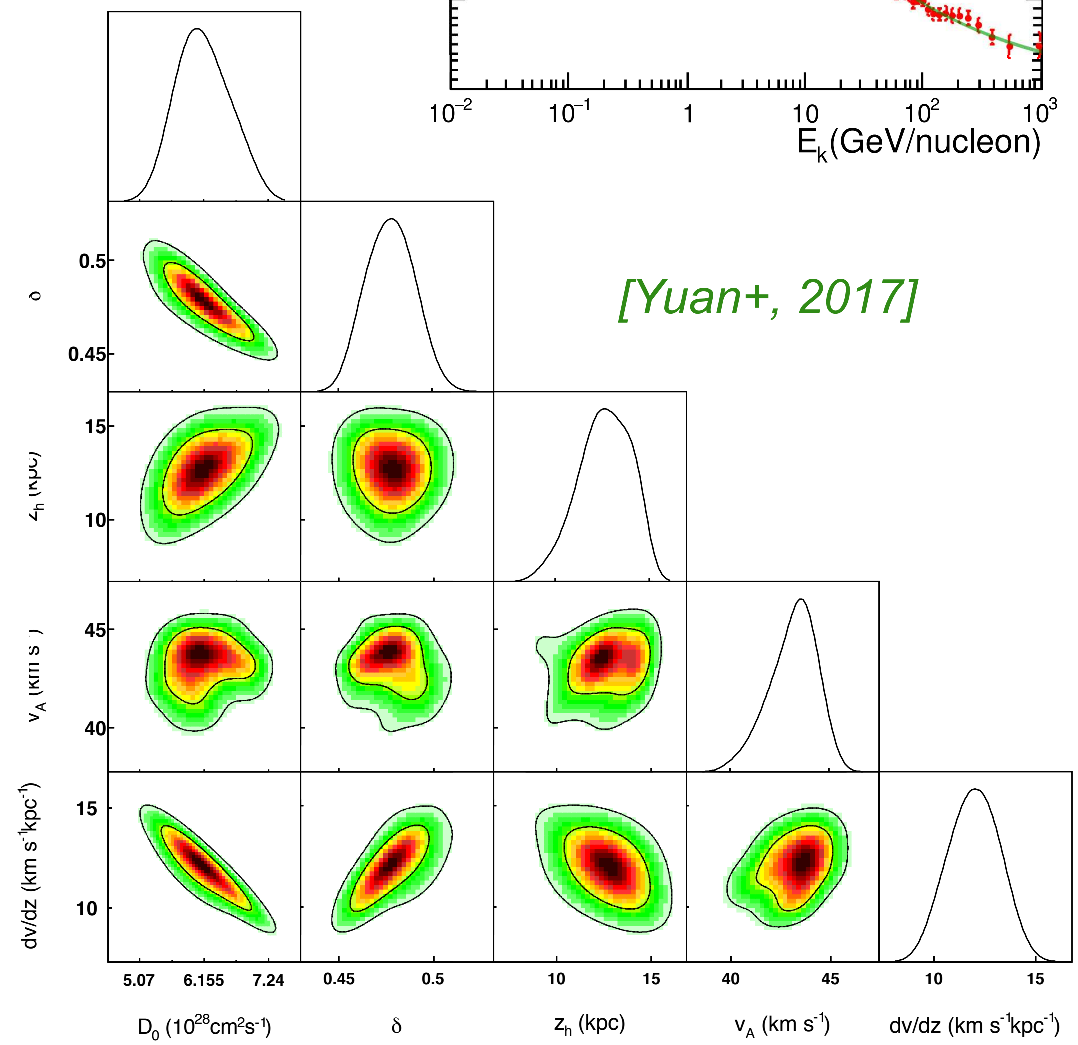


The power of multi-channel phenomenological analyses:
The "conventional scenarios" seem to work for many channels



[Johanneson+, 2016]

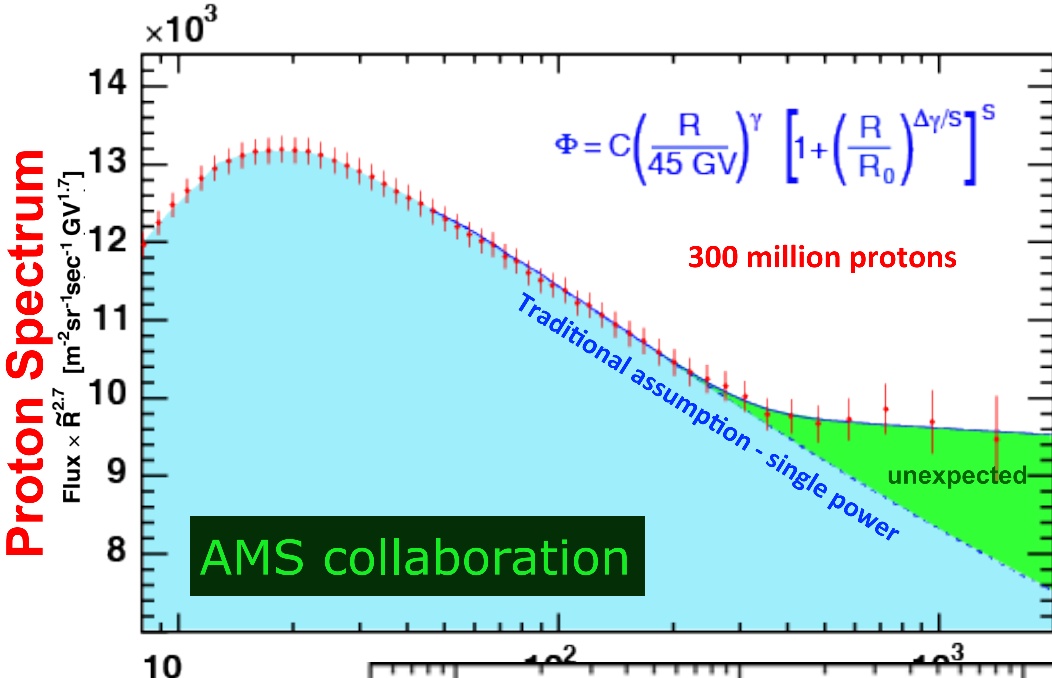


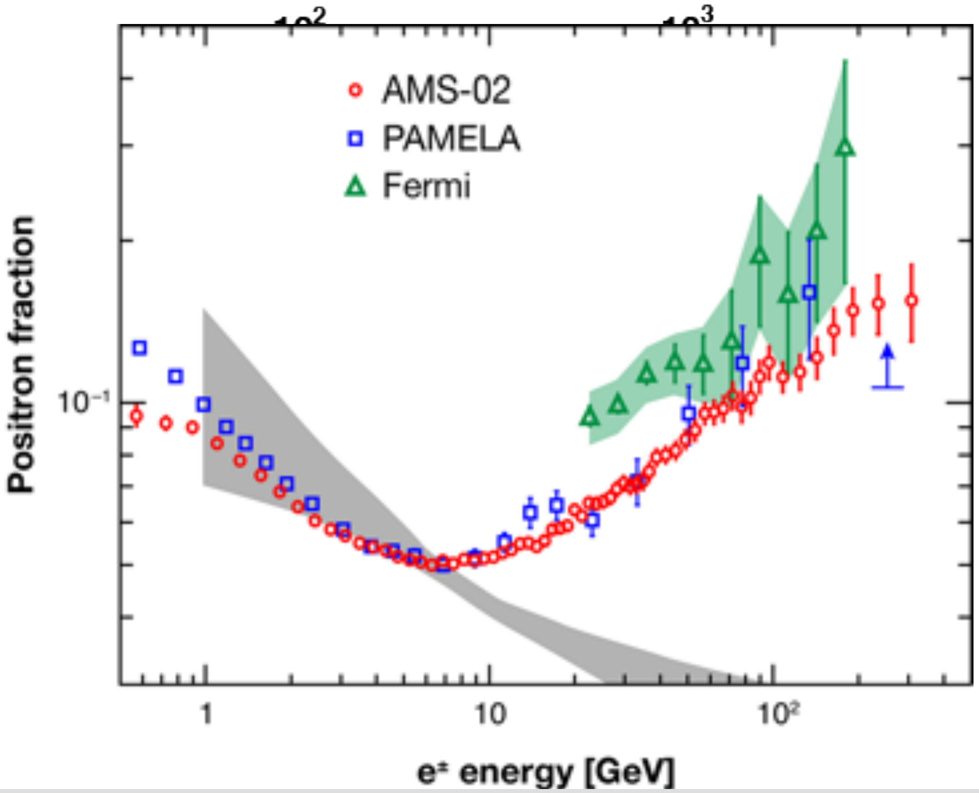


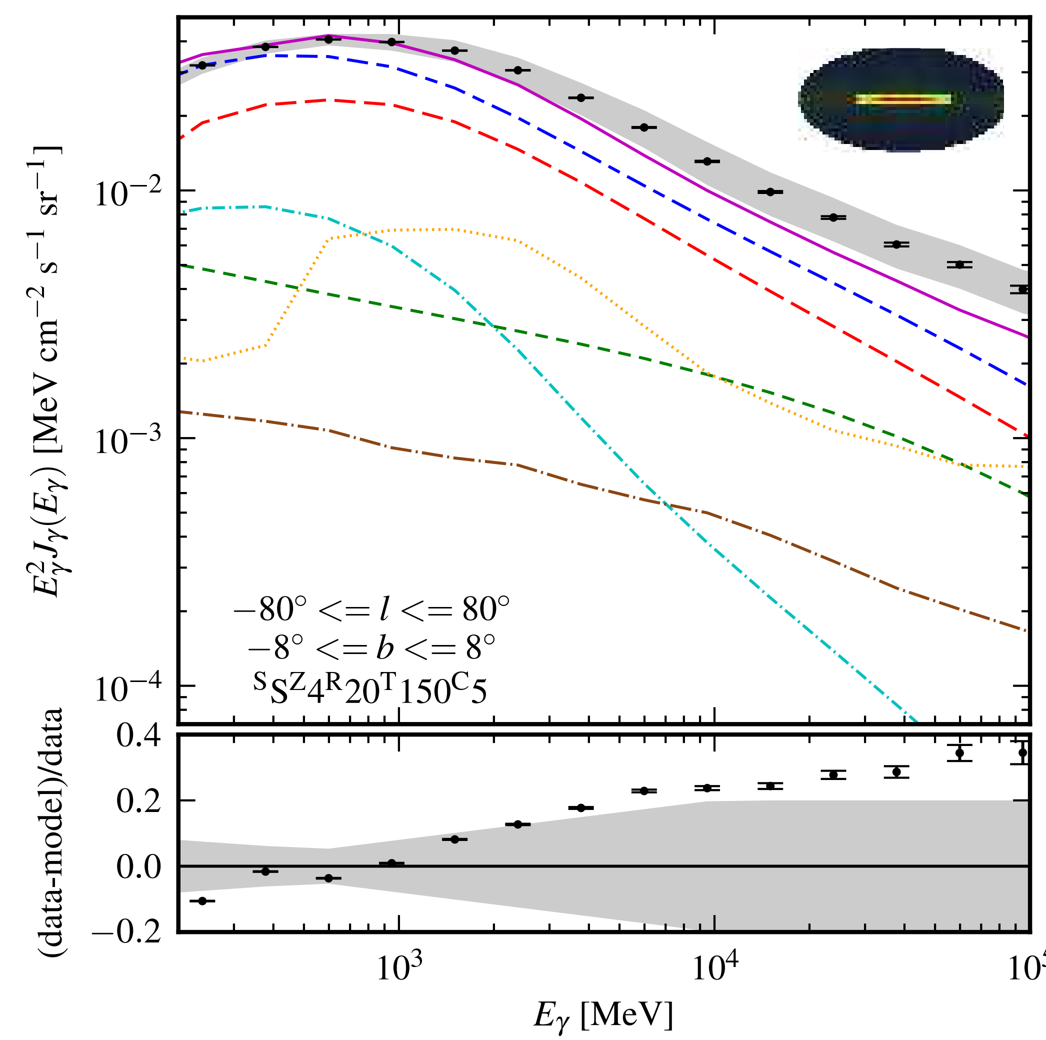
[Yuan+, 2017]

However, we have anomalies!

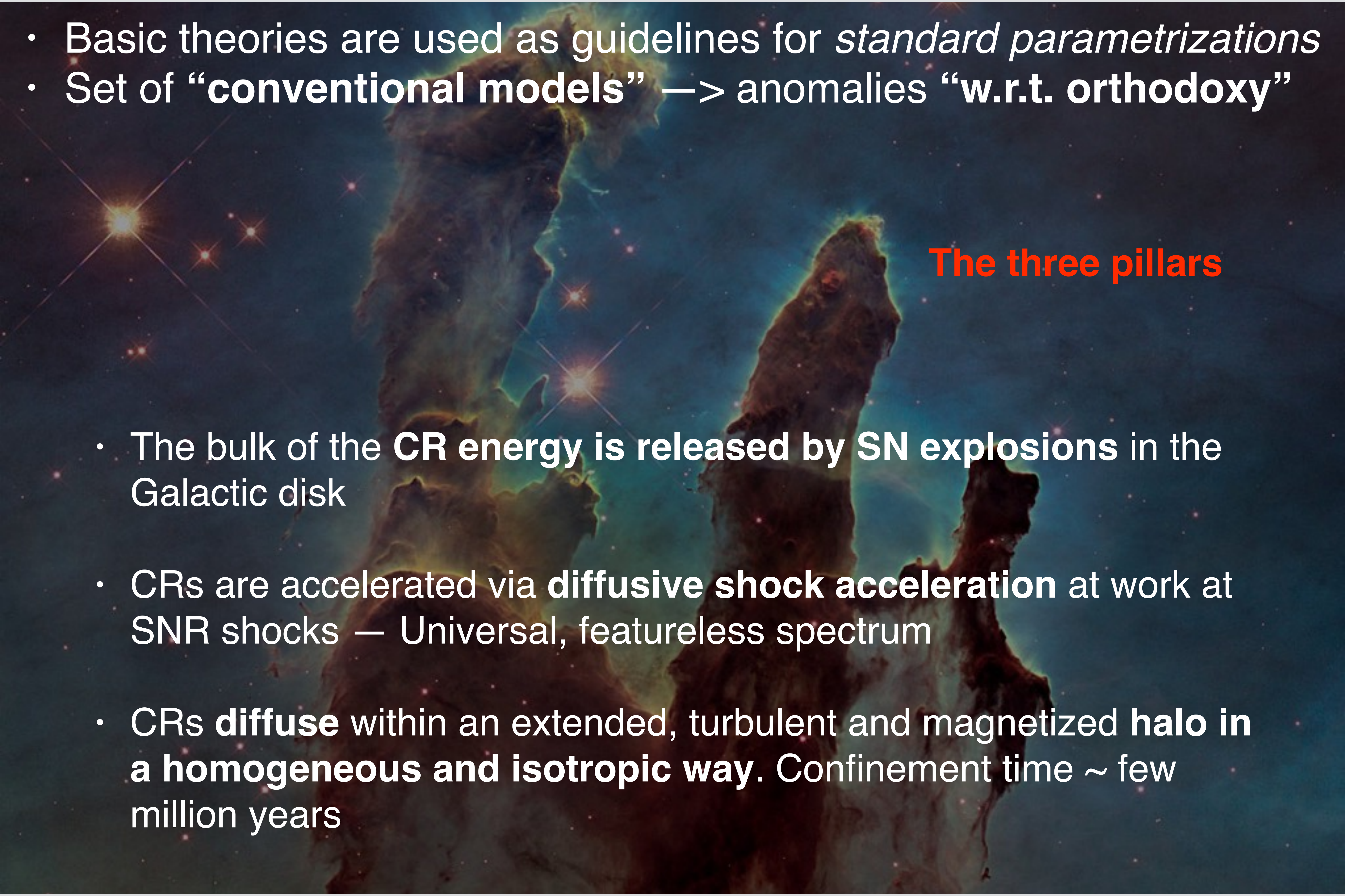
… however, there are also **relevant anomalies** to be explained







Anomalies with respect to what?



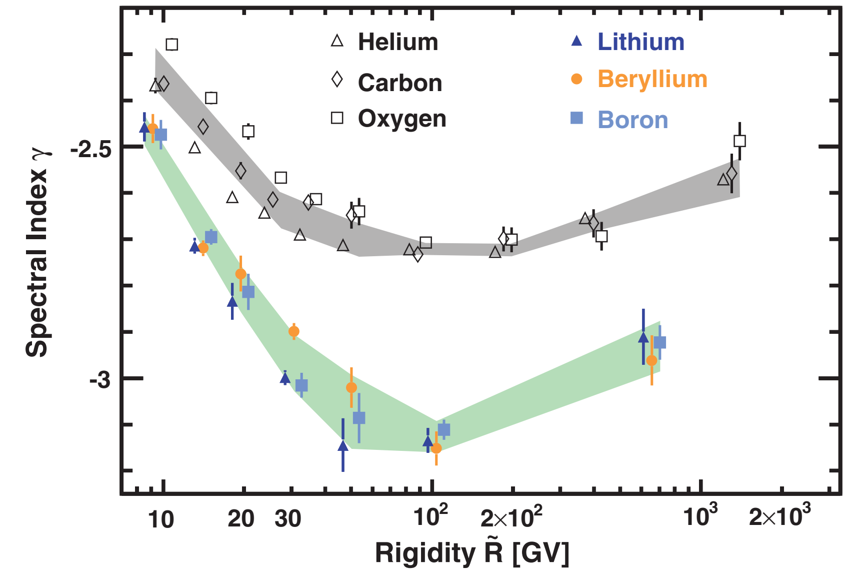
- Basic theories are used as guidelines for *standard parametrizations*
- Set of **“conventional models”** —> anomalies **“w.r.t. orthodoxy”**

The three pillars

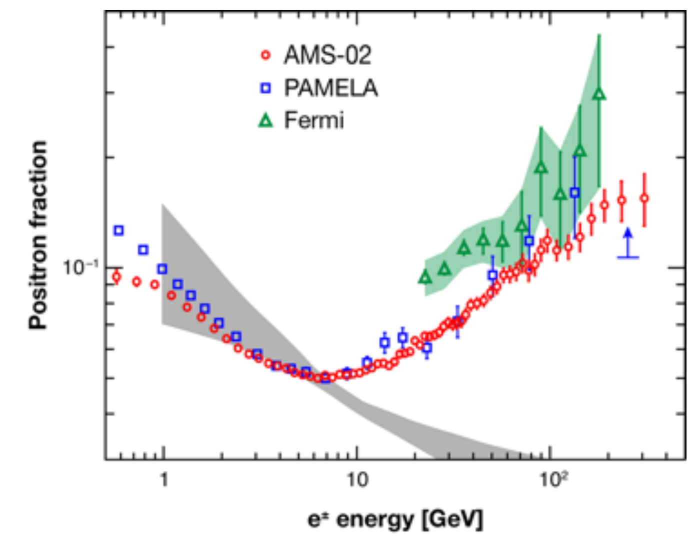
- The bulk of the **CR energy is released by SN explosions** in the Galactic disk
- CRs are accelerated via **diffusive shock acceleration** at work at SNR shocks — Universal, featureless spectrum
- CRs **diffuse** within an extended, turbulent and magnetized **halo in a homogeneous and isotropic way**. Confinement time ~ few million years

List of anomalies: Charged CRs

- **Spectral hardening** in primary and secondary species at ~200 GV

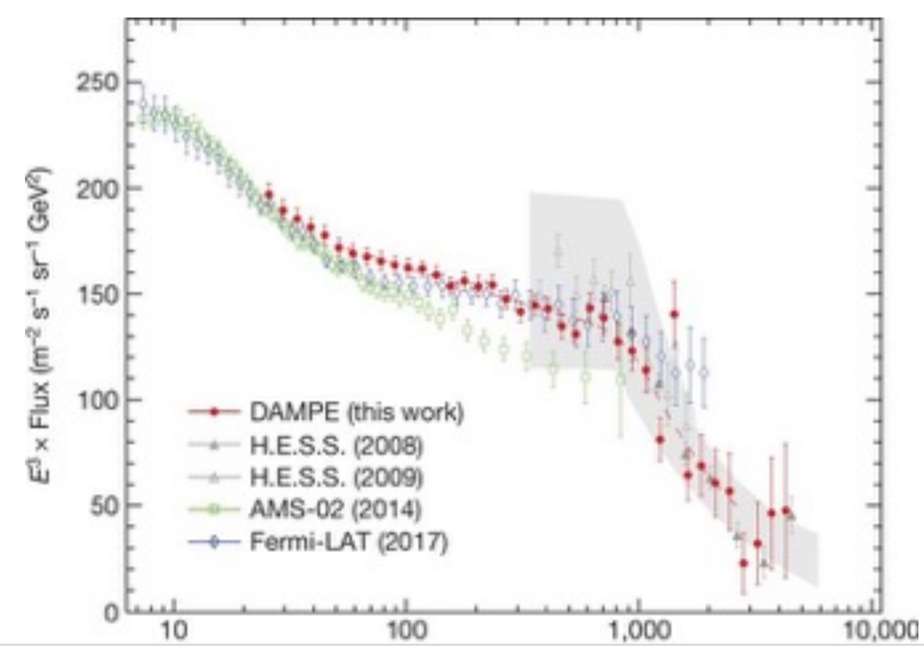


☆ Probably a transport effect.
☆ Different transport properties in the disk and in the halo? [Tomassetti 2015]
☆ Transition from self-generated to pre-existing turbulence? [Blasi, Amato, Serpico, PRL 2012; Aloisio, Blasi, Serpico 2015]



- **Positron excess**

☆ A population of leptonic accelerators (e.g. pulsars?) [Aharonian&Atoyan 1995; Hooper+ 2009, Grasso+ 2009; Yuan+ 2018]
☆ DM interpretation challenged by many constraints (e.g. CMB) [1502.01589]
☆ Anomalous transport properties? Change of paradigm in CR propagation? [P. Lipari arXiv:1707.02504]
☆ [review arXiv:1802.00636]



- Low- and high-energy **electrons**?
- Low- and high-energy **antiprotons**?

List of anomalies: Gamma rays

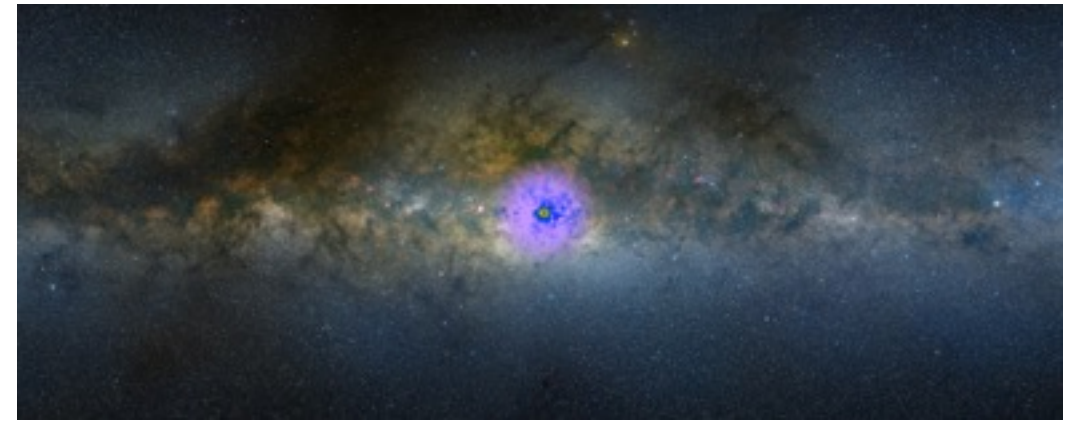
- **“GeV extended emission from the inner Galaxy”**

☆ *millisecond pulsars?* [Lee+ 2016, Bartels+ 2016]

☆ *molecular clouds?* [De Boer+ 2017]

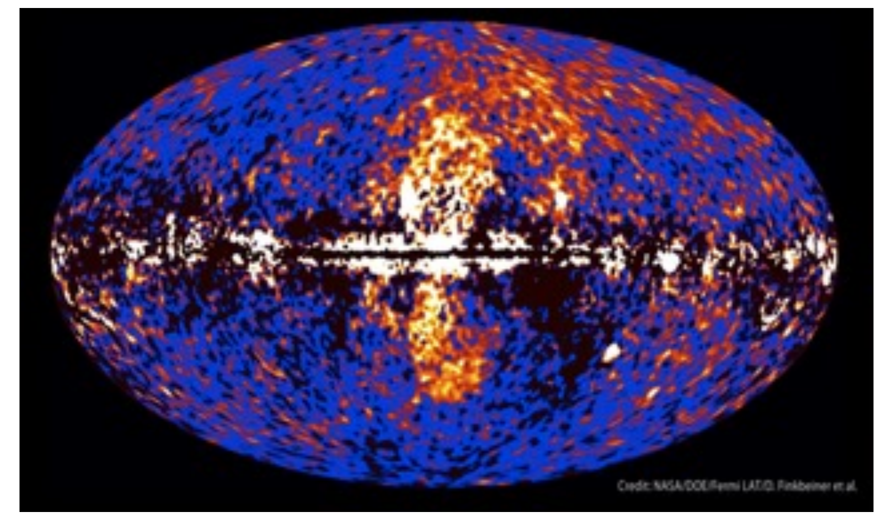
☆ *dark matter?* [Hooper&Goodenough 2011, Daylan+ PDU 2016, many others…]

[see D. Hooper, E. Storm’s, T. Edwards talks]



- **Fermi Bubbles**

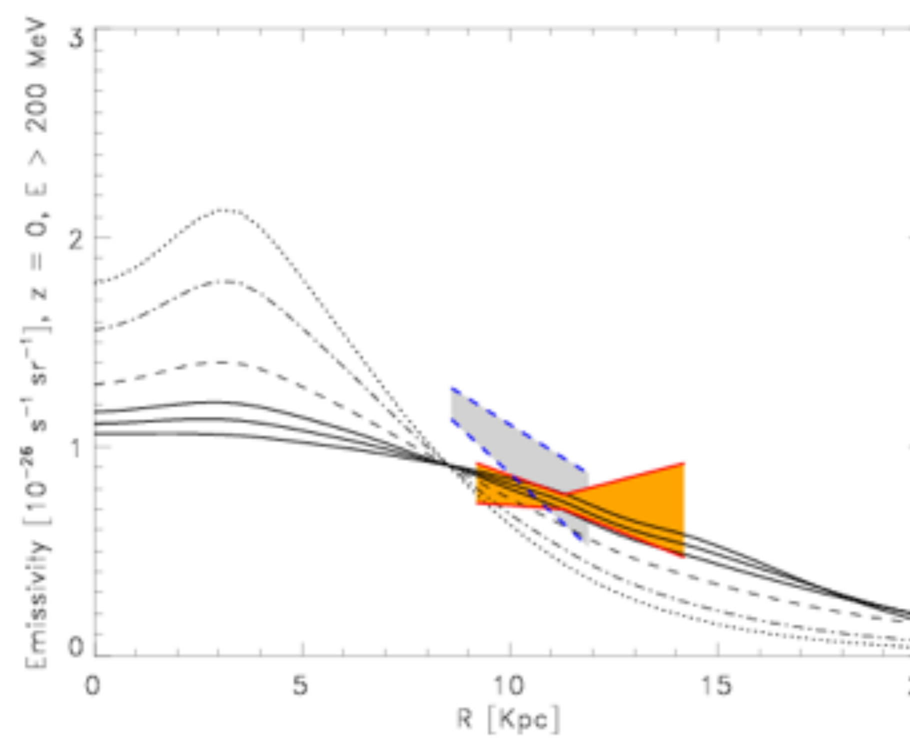
[see K. Yang’s, L. Yang’s, D. Malyshev’s talks]



- **Progressive hardening** in the proton spectrum towards the inner Galaxy

- **Gradient problem**

[Strong+ 2004, Evoli+ 2012]



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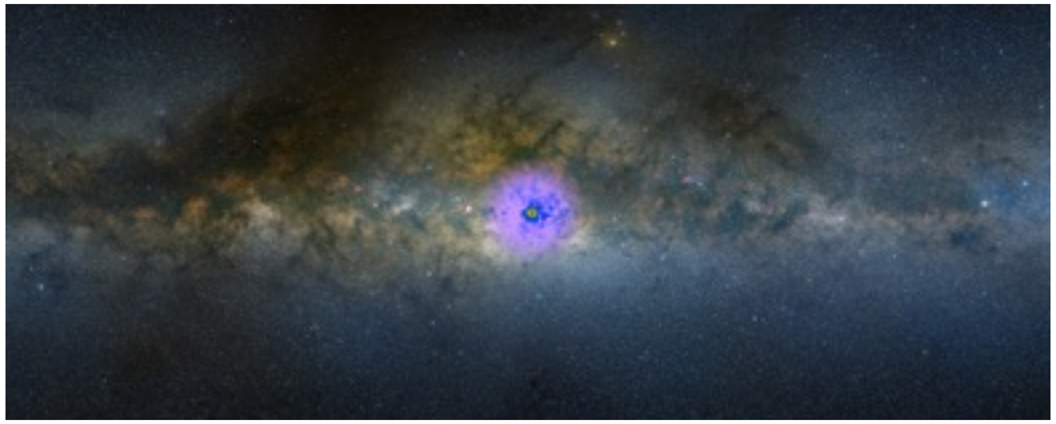

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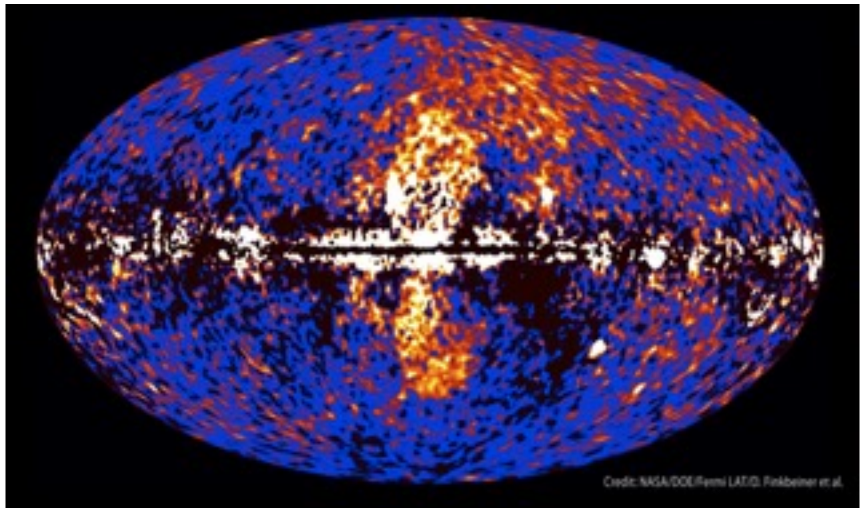

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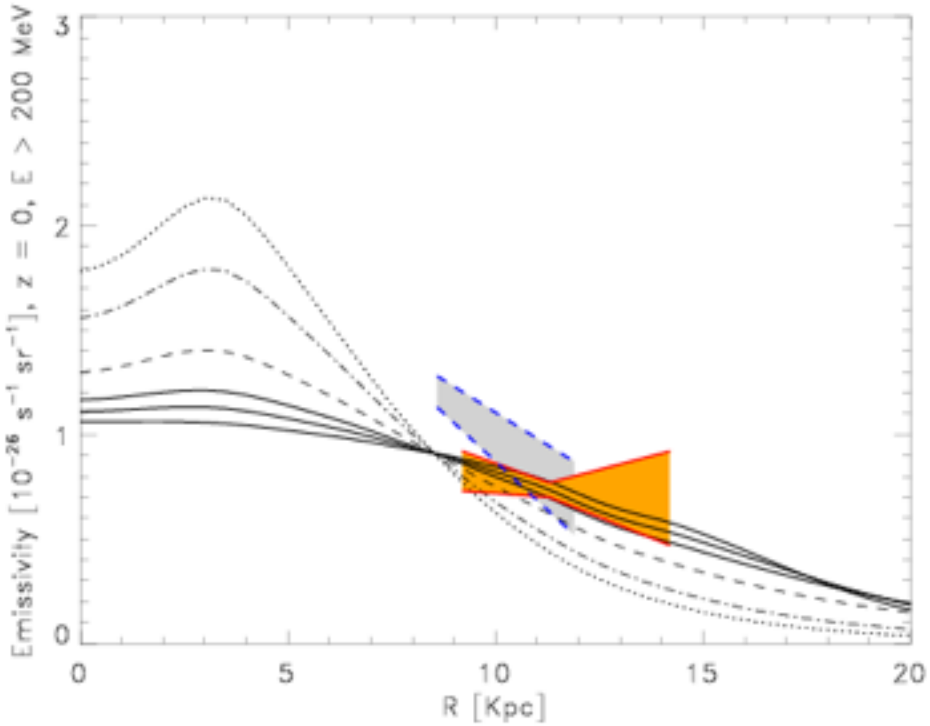


Spectral hardening from gamma-ray data

- A progressive **CR hardening in the inner Galaxy** inferred from gamma-ray data can be interpreted as a progressively harder scaling of the diffusion coefficient as first noticed in [Gaggero et al., PRD 2015, arXiv:1411.7623]

- Confirmed by the Fermi-LAT collaboration via a **template-fitting procedure** based on:
  - ☆ Ring decomposition for the gas distribution
  - ☆ Model for the IC emission,
  - ☆ Catalogs of point and extended sources

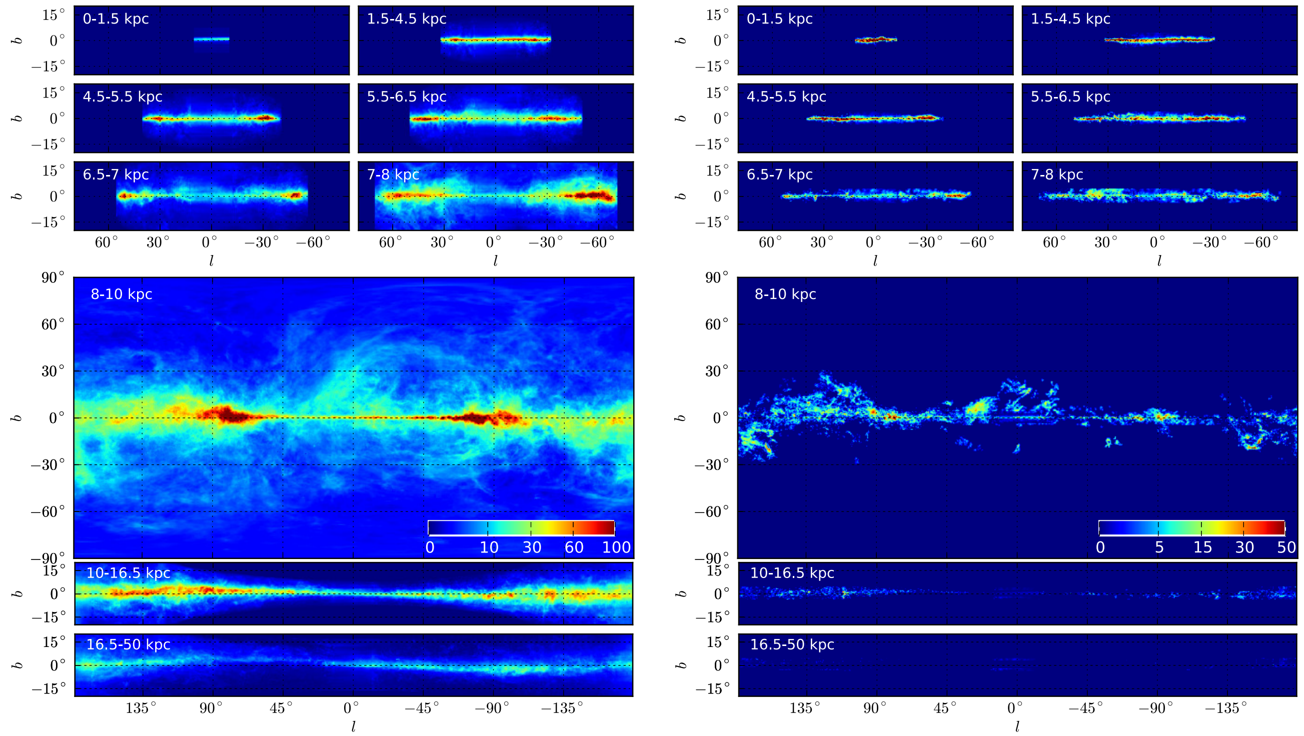
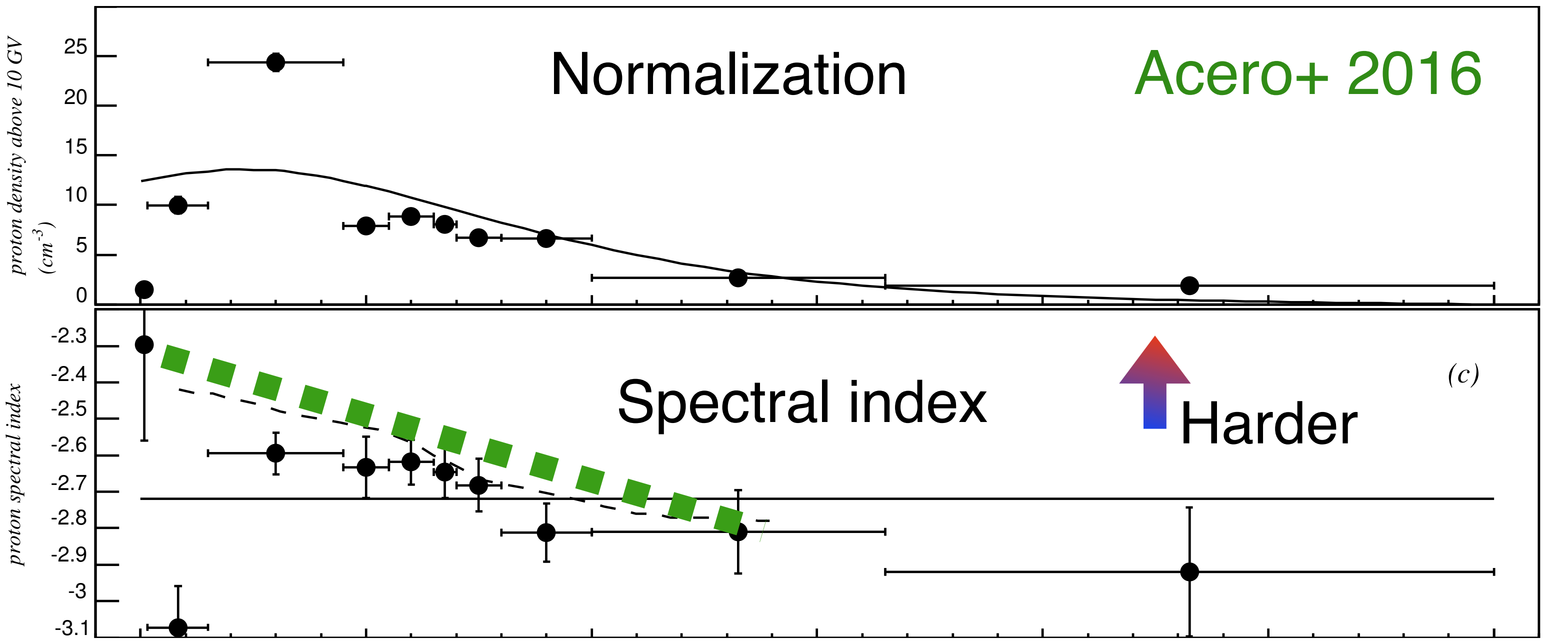


Fig. 3.— Galactocentric annuli of $N_{\rm H\,I}$ in 10^{20} cm^{-2} (left) and $W(\rm CO)$ in K km s^{-1} (right), displayed in Galactic plate carrée projection with bin size of 0°.125 × 0°.125. The square root color scaling saturates at 100×10^{20} cm^{-2} for $N_{\rm H\,I}$ and at 50 K km s^{-1} for $W(\rm CO)$. The Galactocentric boundaries for each annulus are written in each panel.



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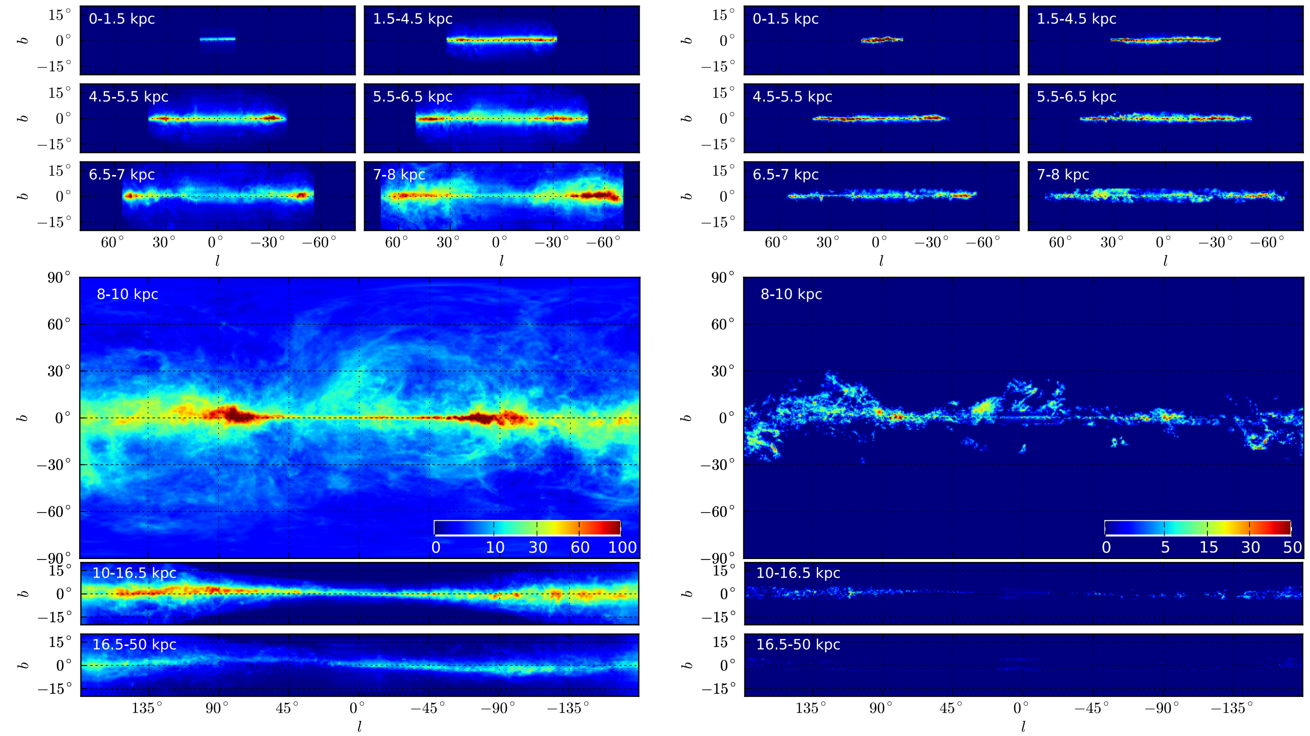

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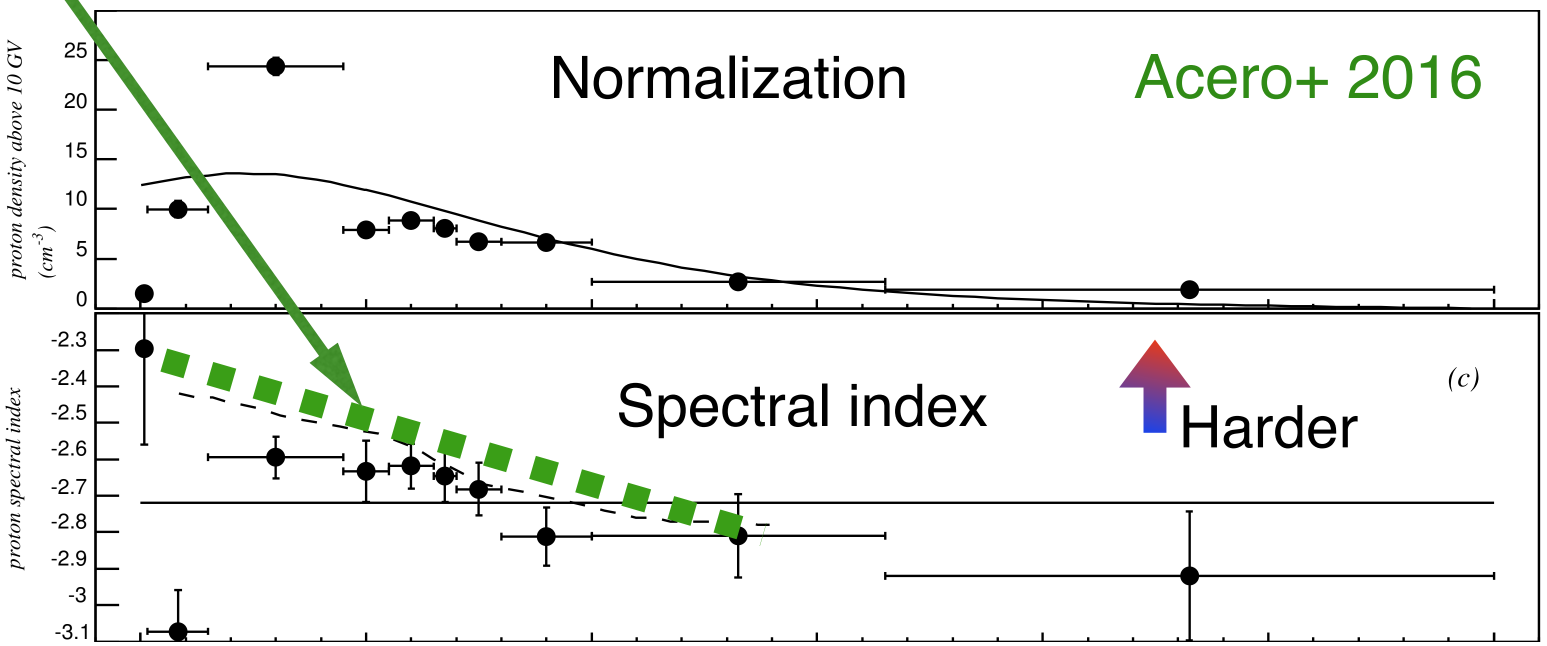
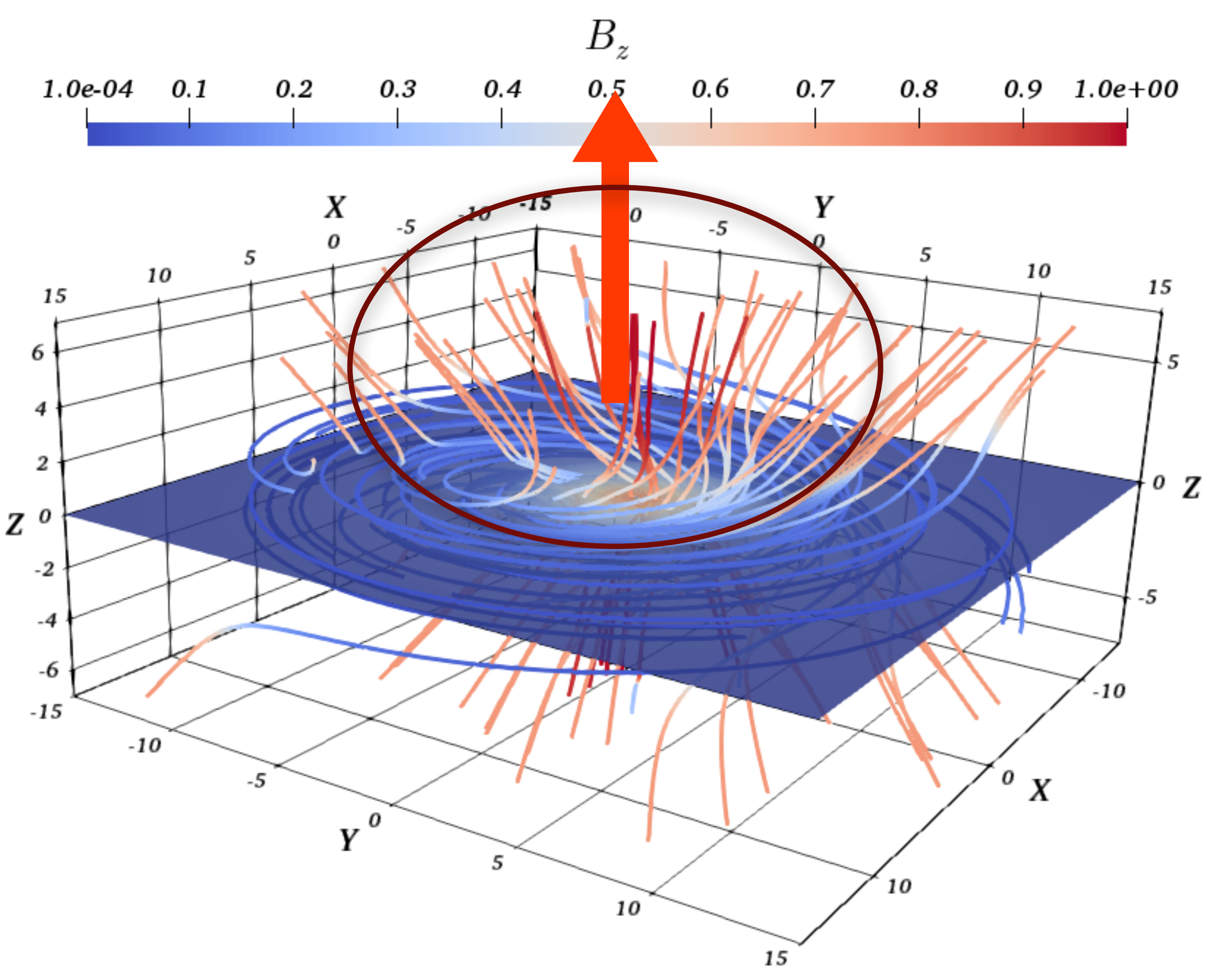


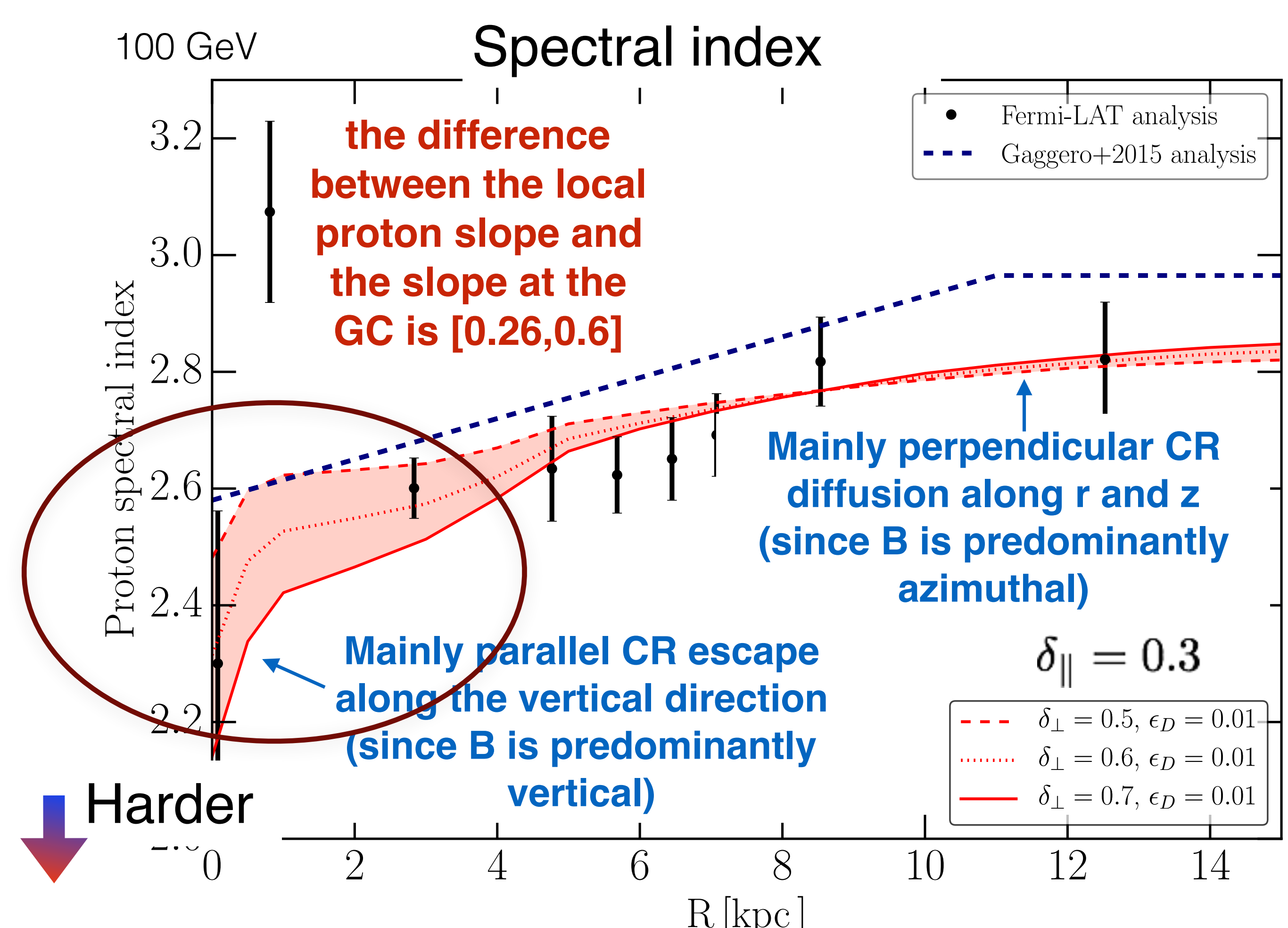
Is this a potential **signature of anisotropic CR transport?**

$$D_{ij} \equiv D_\perp \delta_{ij} + (D_\parallel - D_\perp) b_i b_j \, , \qquad b_i \equiv \frac{B_i}{|\mathbf{B}|} \, ,$$

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





S.S. Cerri, **DG**, et al., JCAP 2017

Physical interpretations (I)

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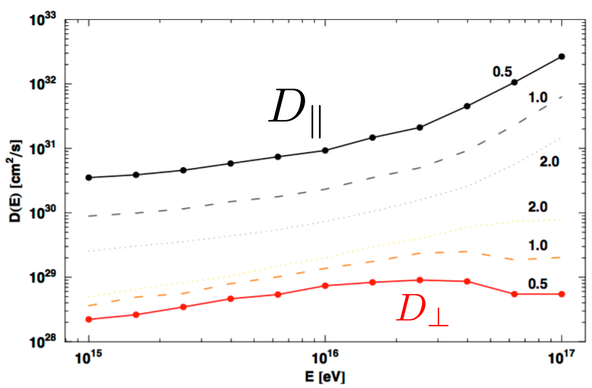
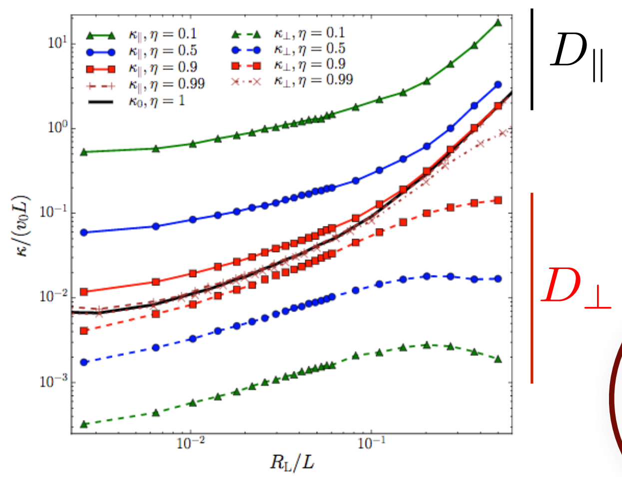
Enhanced parallel escape in the vertical direction in the inner Galaxy

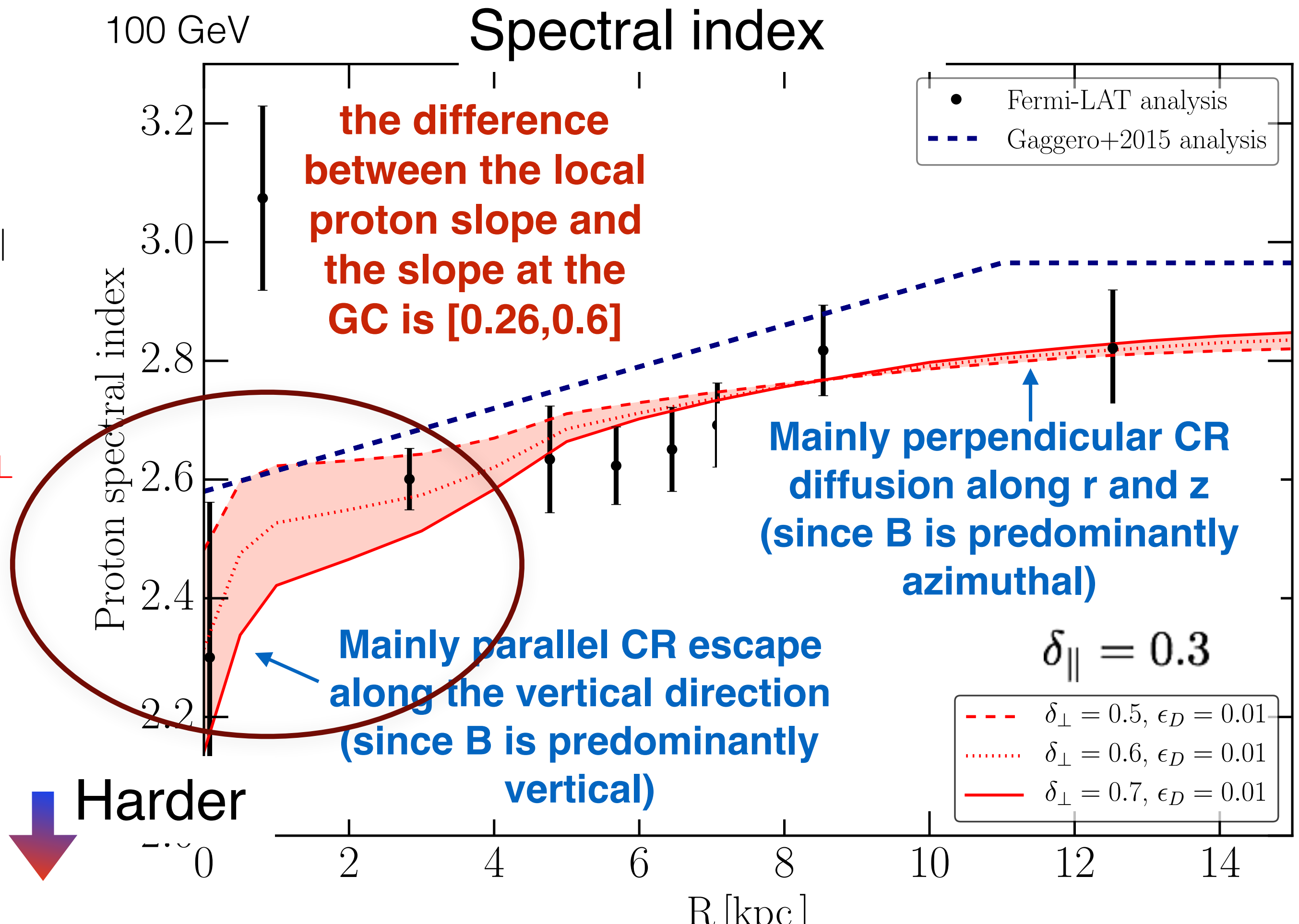
Different scalings of parallel and perpendicular diffusion coefficients



De Marco, Blasi, Stanev, JCAP 6 2007



Snodin et al. ,MNRAS 457 (2016)



S.S. Cerri, **DG**, et al., JCAP 2017

Physical interpretations (II)

Alternative explanation for the progressive hardening based on CR self confinement

Growth-damping balance of self-generated magnetic turbulence

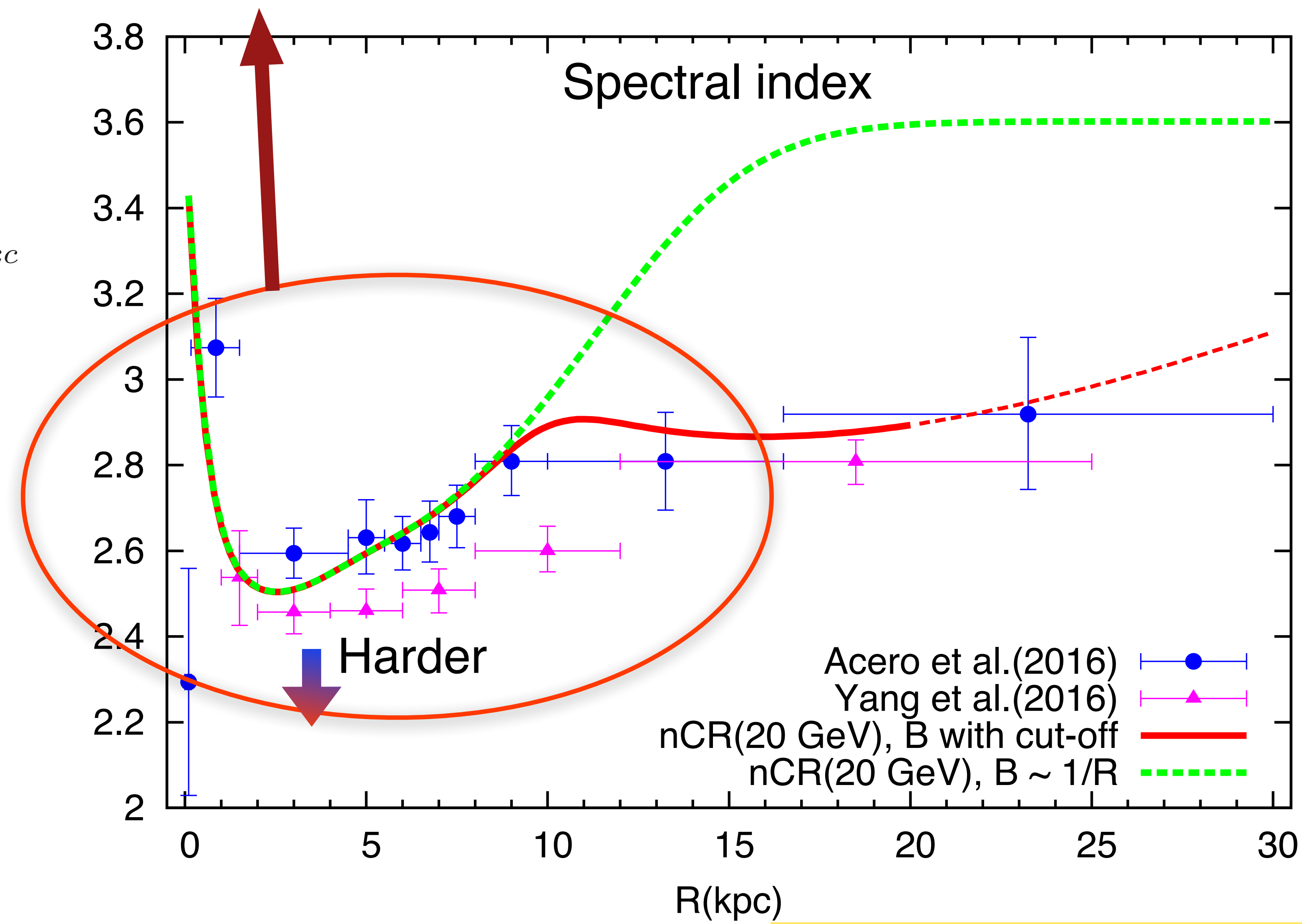
$$\frac{\partial}{\partial k}\left[D_{kk}\frac{\partial W}{\partial k}\right] + \Gamma_{\rm CR} W = q_W(k).$$

$$\Gamma_{\rm cr}(k) = \frac{16\pi^2}{3}\frac{v_{\rm A}}{k\,W(k)B_0^2}\left[p^4 v(p)\frac{\partial f}{\partial z}\right]_{p=qB_0/kc}$$

$$D_{kk} = C_{\rm K} v_{\rm A} k^{7/2} W(k)^{1/2}$$

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

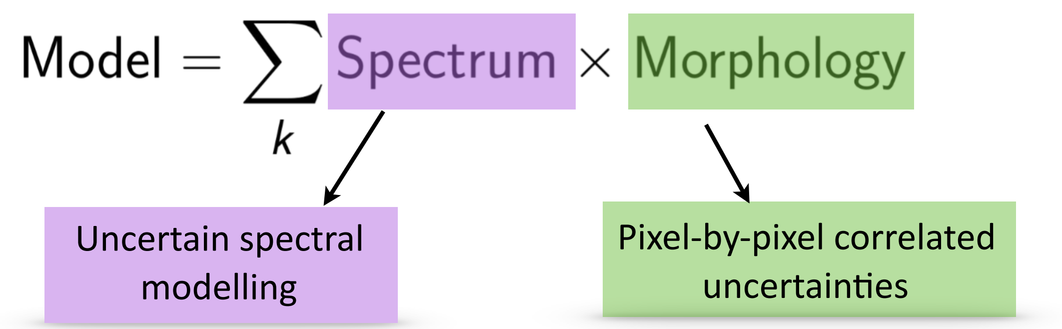
this effect only holds for E < ~50 GeV!



Recchia, Blasi, Morlino 2016

A new analysis with SkyFACT

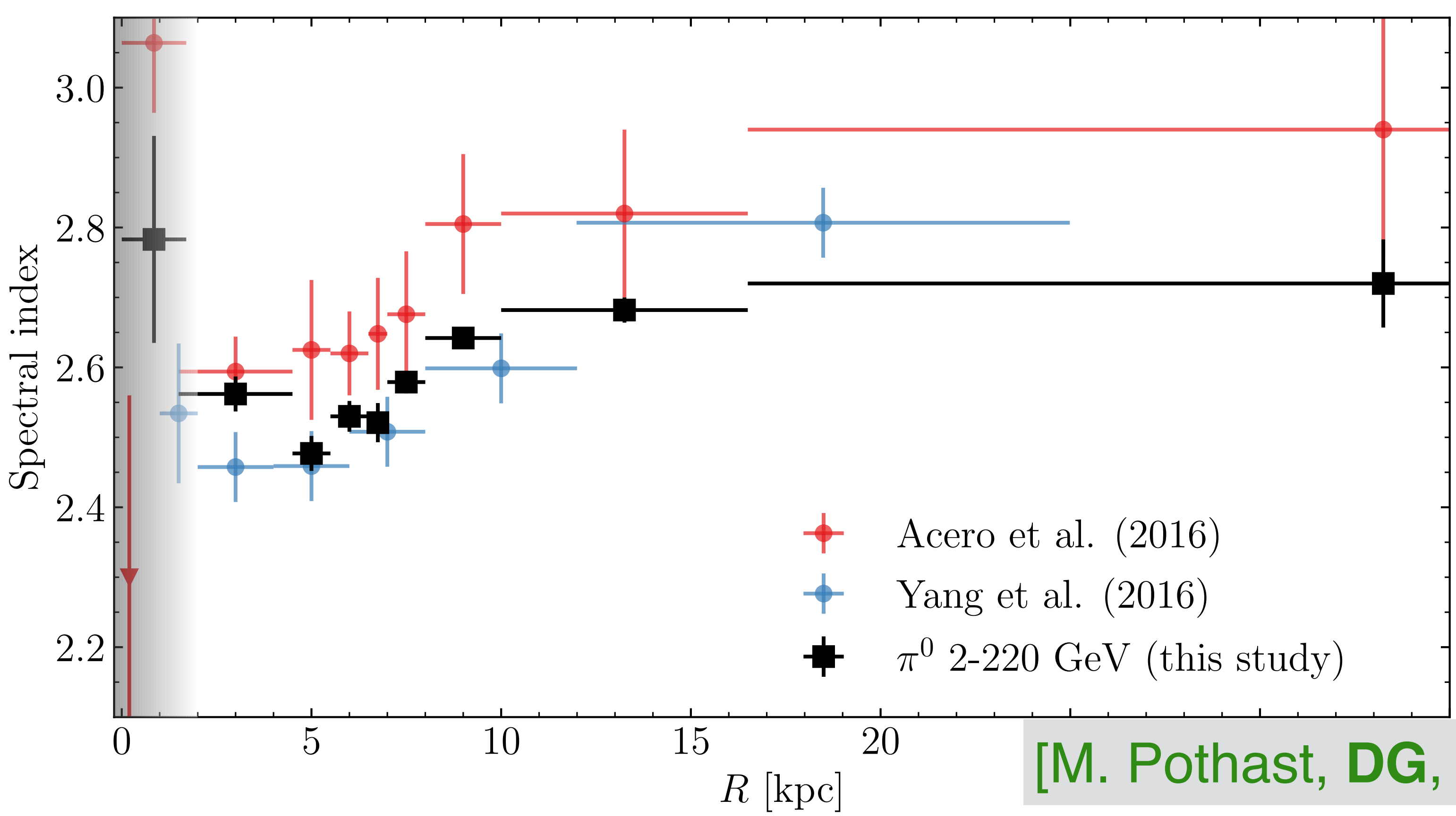
- Adaptive template-fitting analysis
- **Spectral trend confirmed outside the Galactic bulge**
- Unclear behavior at very low radii!
- High-energy fits show same trend!



$$\phi_{pb} = \sum_k T_p^{(k)} \tau_p^{(k)} \cdot S_b^{(k)} \sigma_b^{(k)} \cdot \nu^{(k)}$$

$$\ln \mathcal{L} = \ln \mathcal{L}_{\mathrm{P}} + \ln \mathcal{L}_{\mathrm{R}}(\lambda, \lambda', \lambda'', \eta, \eta')$$

Penalized Poisson likelihood with regularisation conditions



Components	Notes
IGRB	Fixed isotropic template, 25% spectral freedom.
3FGL PSC	Fixed positions, 5% spectral freedom, 30% freedom on normalizations.
Extended Sources	Free spectra and templates, mild spatial smoothing.
Fermi bubbles	Fixed template, 1% spectral freedom
ICS	Factor of 3 spatial freedom, 25% spectral freedom, strong spatial smoothing.
Gas rings	30% spatial freedom, 25% spectral freeom, mild spatial smoothing.

[M. Pothast, **DG**, E. Storm, C. Weniger, arXiv:1807.04554]

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Model $= \sum_k$ Spectrum $\times$ Morphology

Spectrum → Uncertain spectral modelling

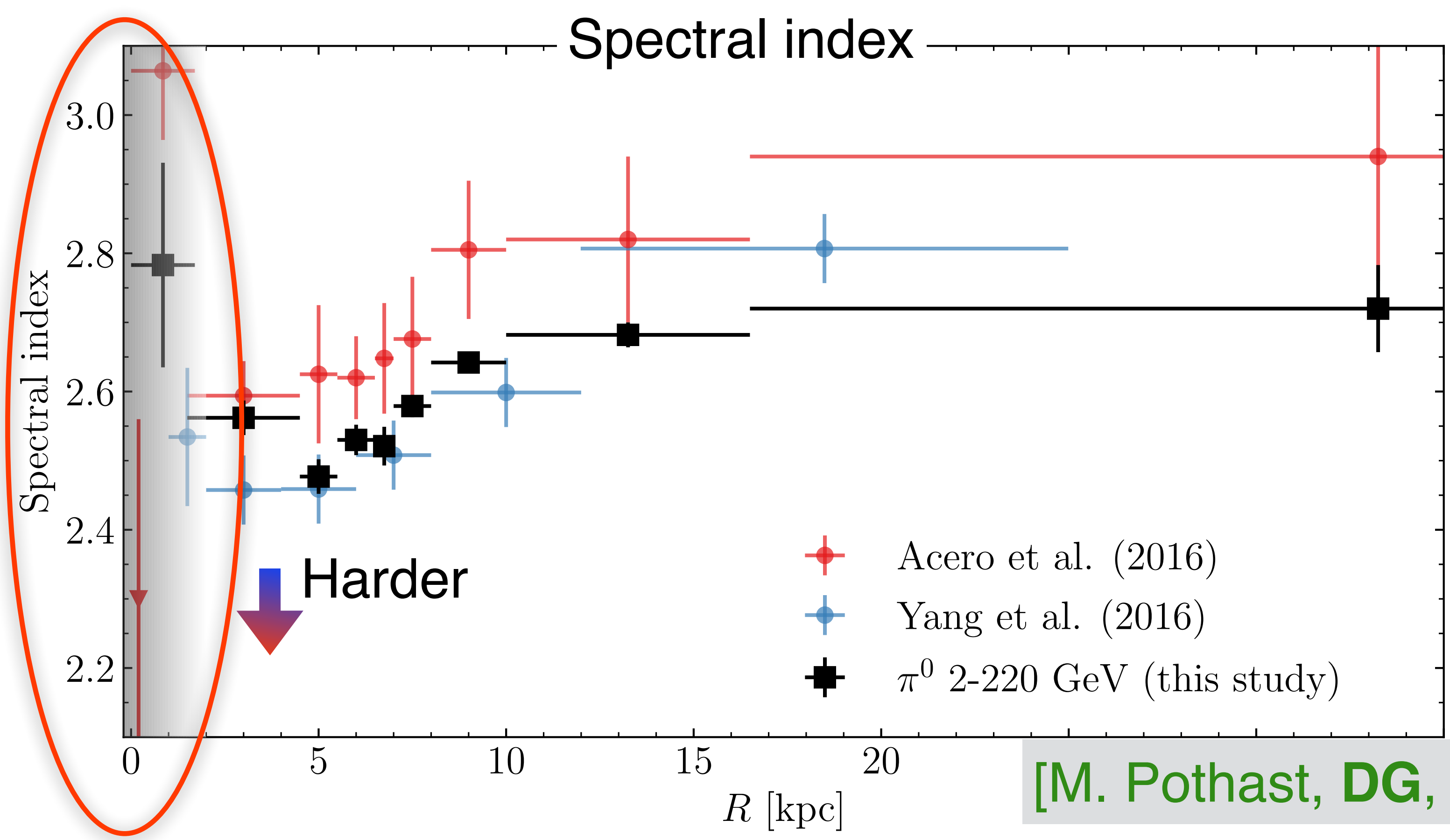
Morphology → Pixel-by-pixel correlated uncertainties

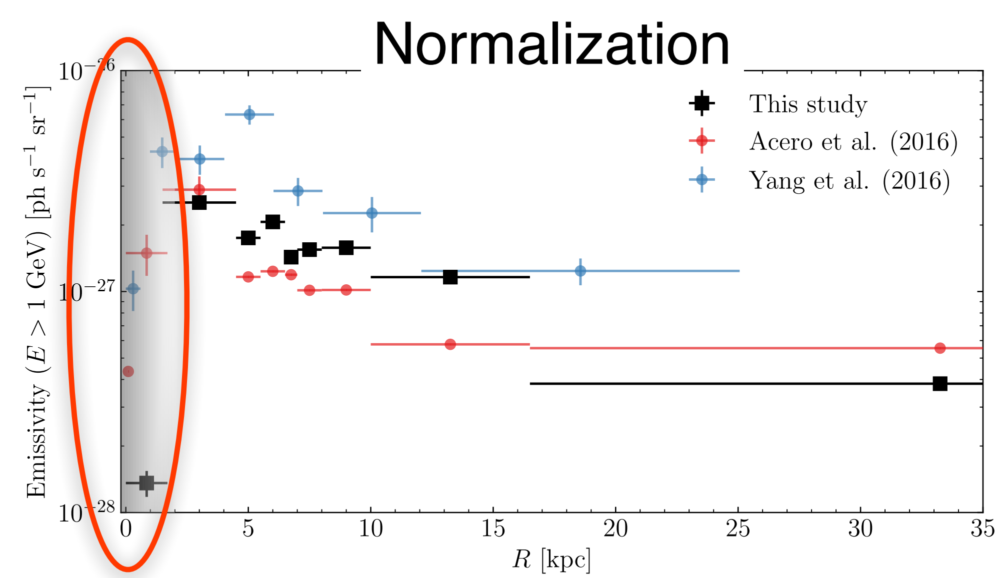
$$\phi_{pb} = \sum_k T_p^{(k)} \tau_p^{(k)} \cdot S_b^{(k)} \sigma_b^{(k)} \cdot \nu^{(k)}$$

$$\ln \mathcal{L} = \ln \mathcal{L}_{\mathrm{P}} + \ln \mathcal{L}_{\mathrm{R}}(\lambda, \lambda', \lambda'', \eta, \eta')$$

Penalized Poisson likelihood with regularisation conditions

[E. Storm, C. Weniger, F. Calore, arXiv:1705.04065]

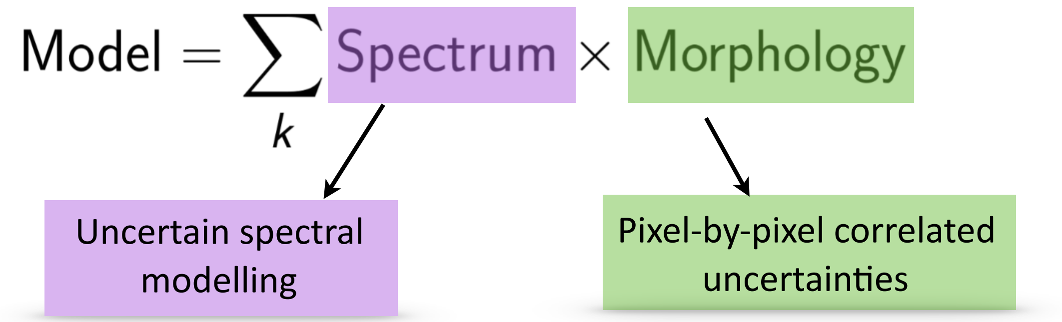




[M. Pothast, **DG**, E. Storm, C. Weniger, arXiv:1807.04554]

A new analysis with SkyFACT

- Adaptive template-fitting analysis
- Spectral trend confirmed outside the Galactic bulge
- Unclear behavior at very low radii!
- **High-energy power-law fits show same trend!**



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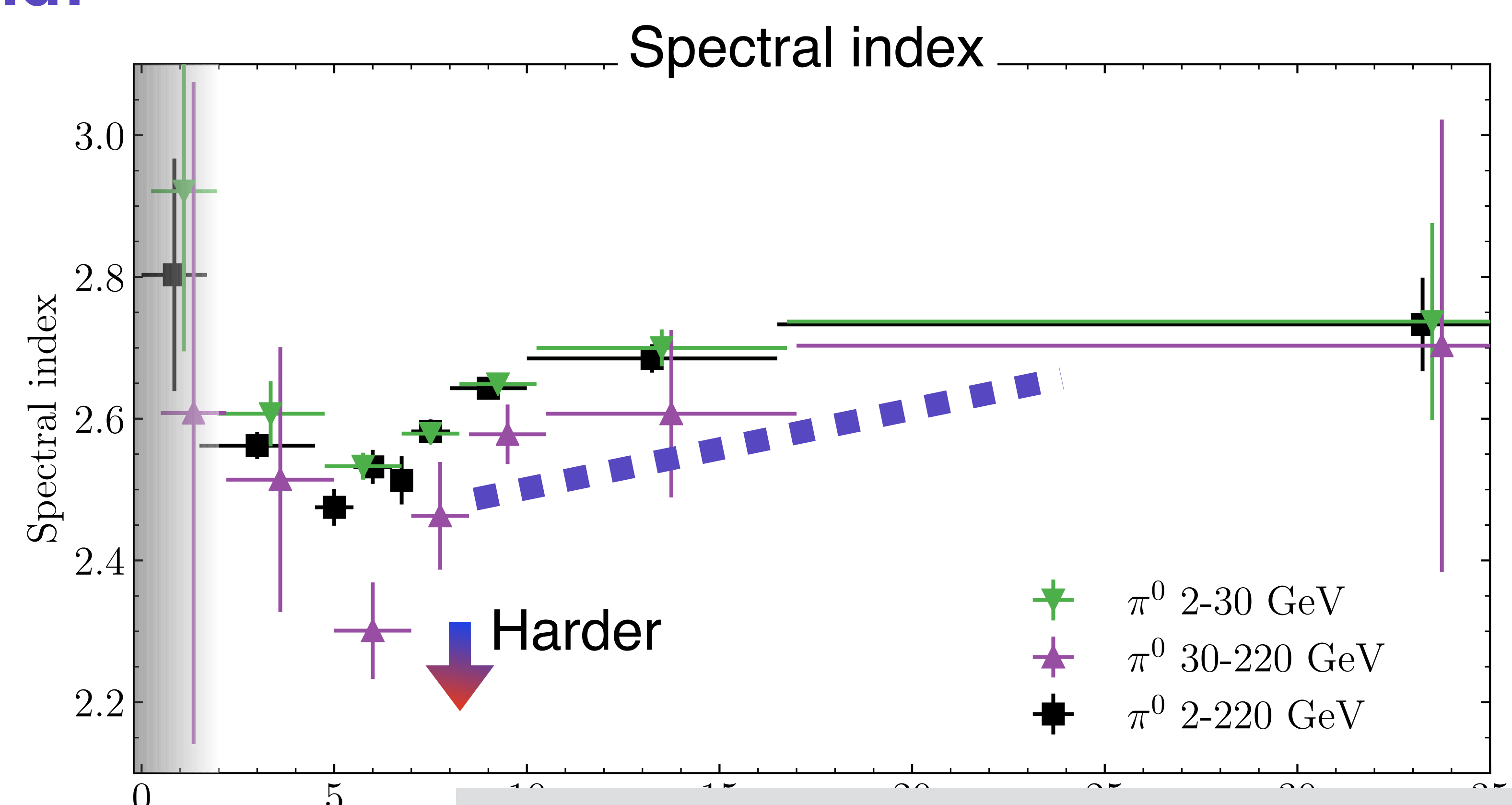
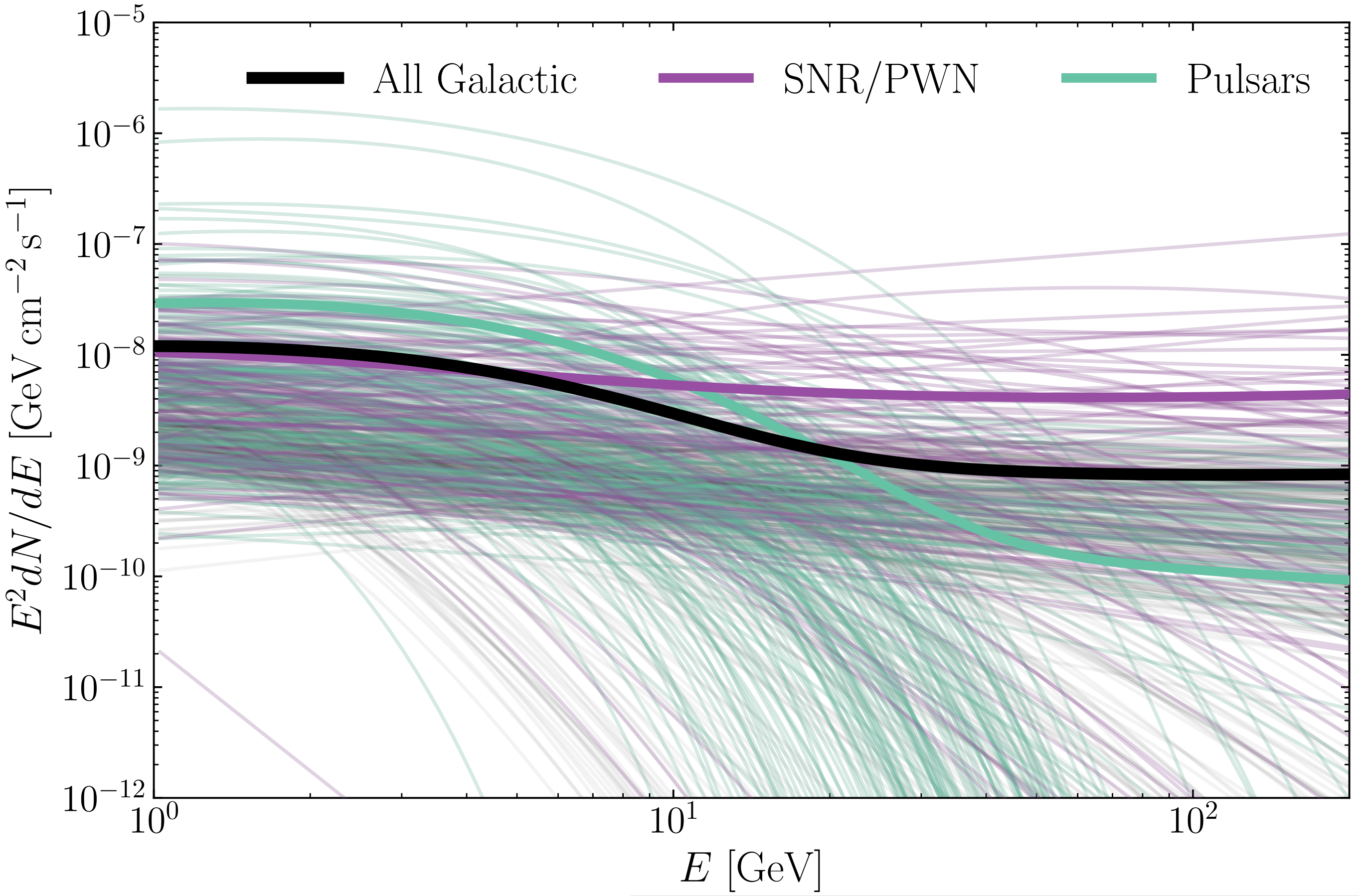
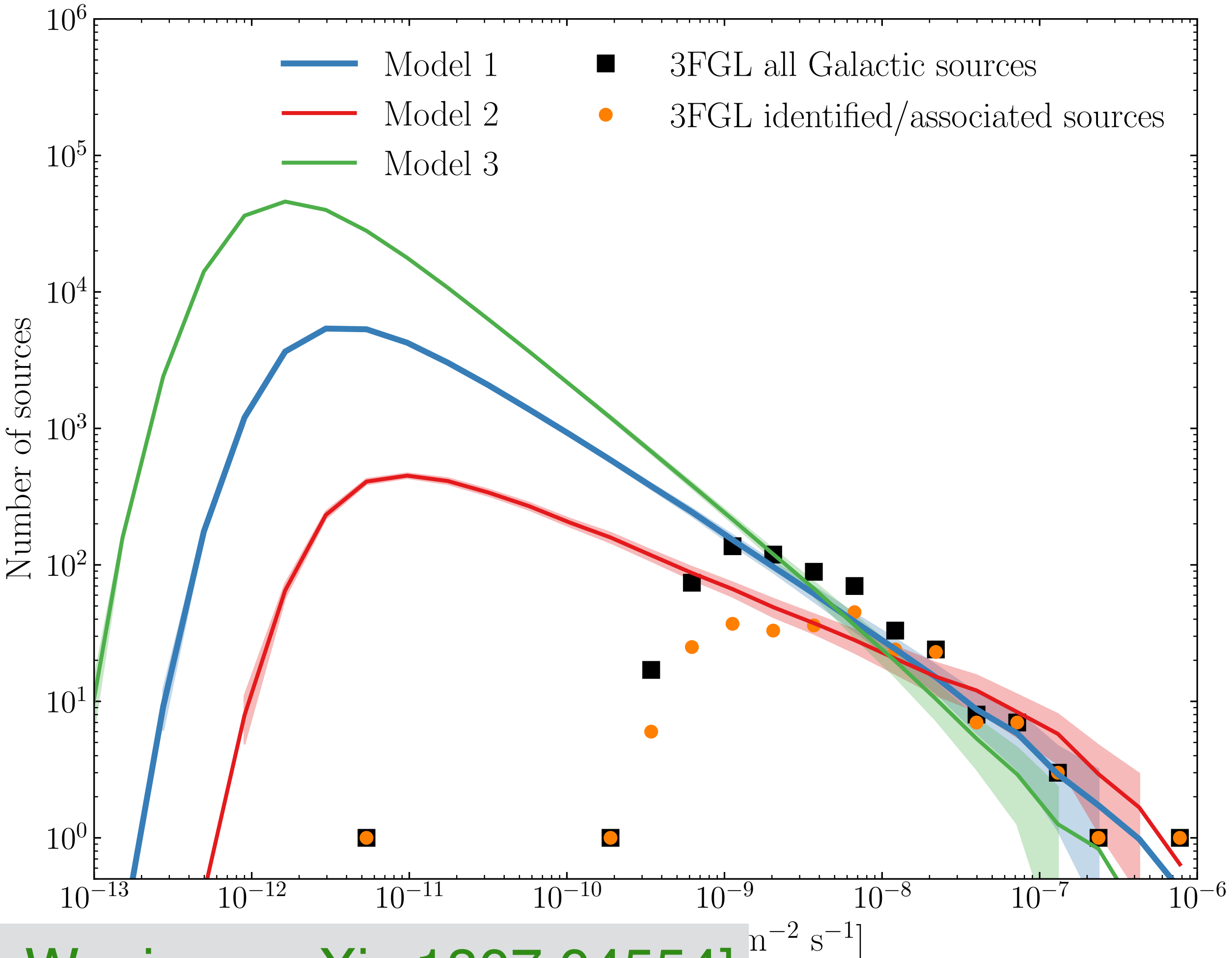


[M. Pothast, **DG**, E. Storm, C. Weniger, arXiv:1807.04554]

The role of unresolved sources

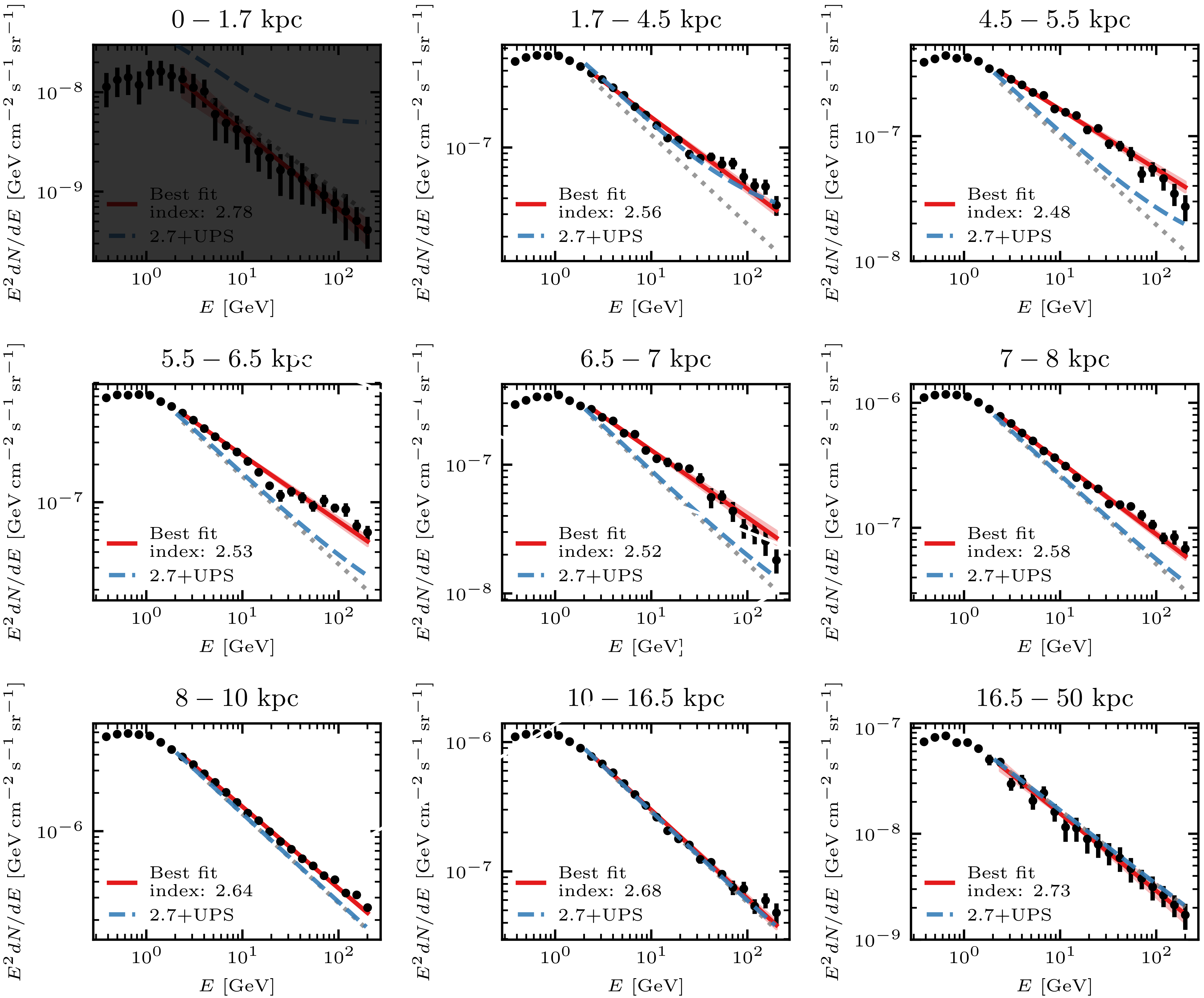
- Unresolved point sources could in principle mimic the spectra trend
- We set up a MC simulation based on the spectra and luminosity function of resolved sources. Strong uncertainties on the low-luminosity cutoff!
- **Unresolved sources do not play a major role outside the Galactic bulge**





[M. Pothast, **DG**, E. Storm, C. Weniger, arXiv:1807.04554]

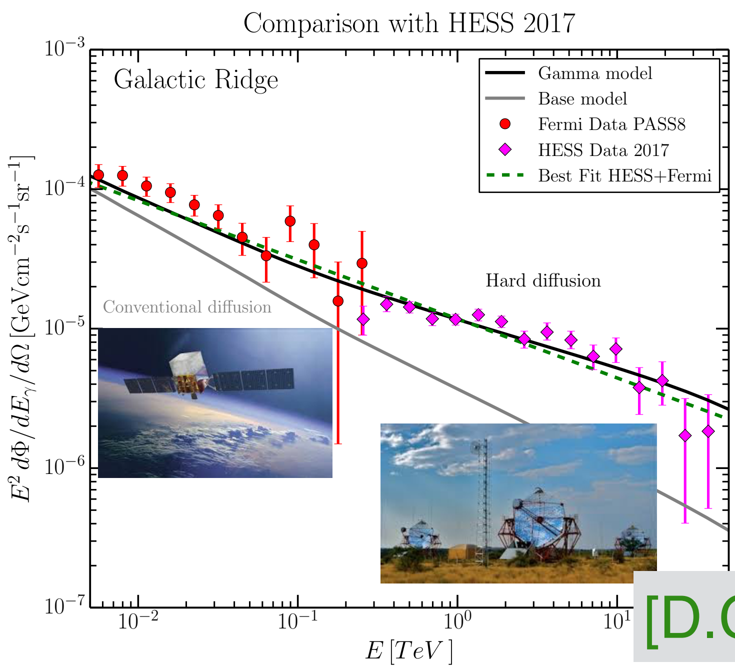
Unresolved sources do not play a major role outside the Galactic bulge

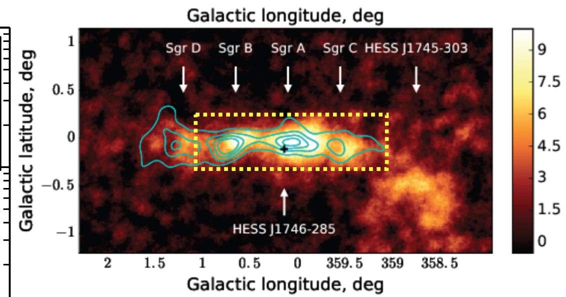


[M. Pothast, **DG**, E. Storm, C. Weniger, arXiv:1807.04554]

Future prospects: The TeV sky

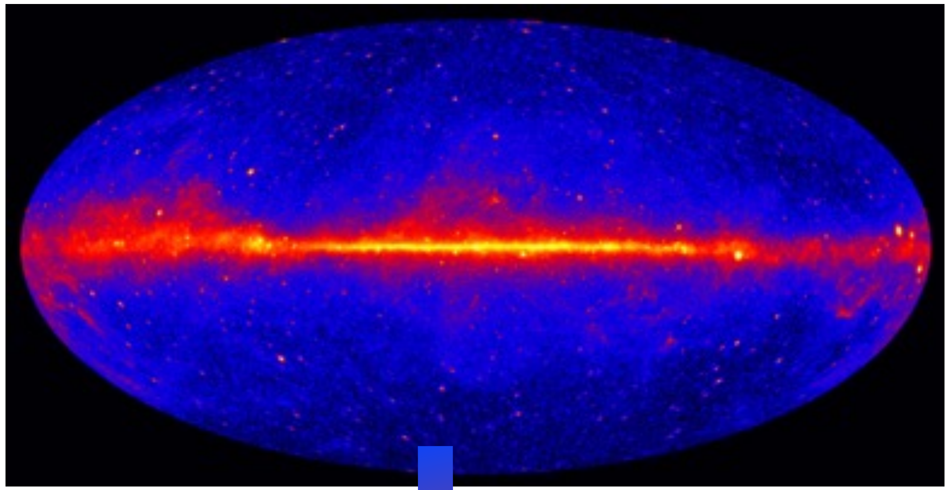
- “Hard CR sea” in the inner Galaxy explains TeV emission from the Galactic ridge?



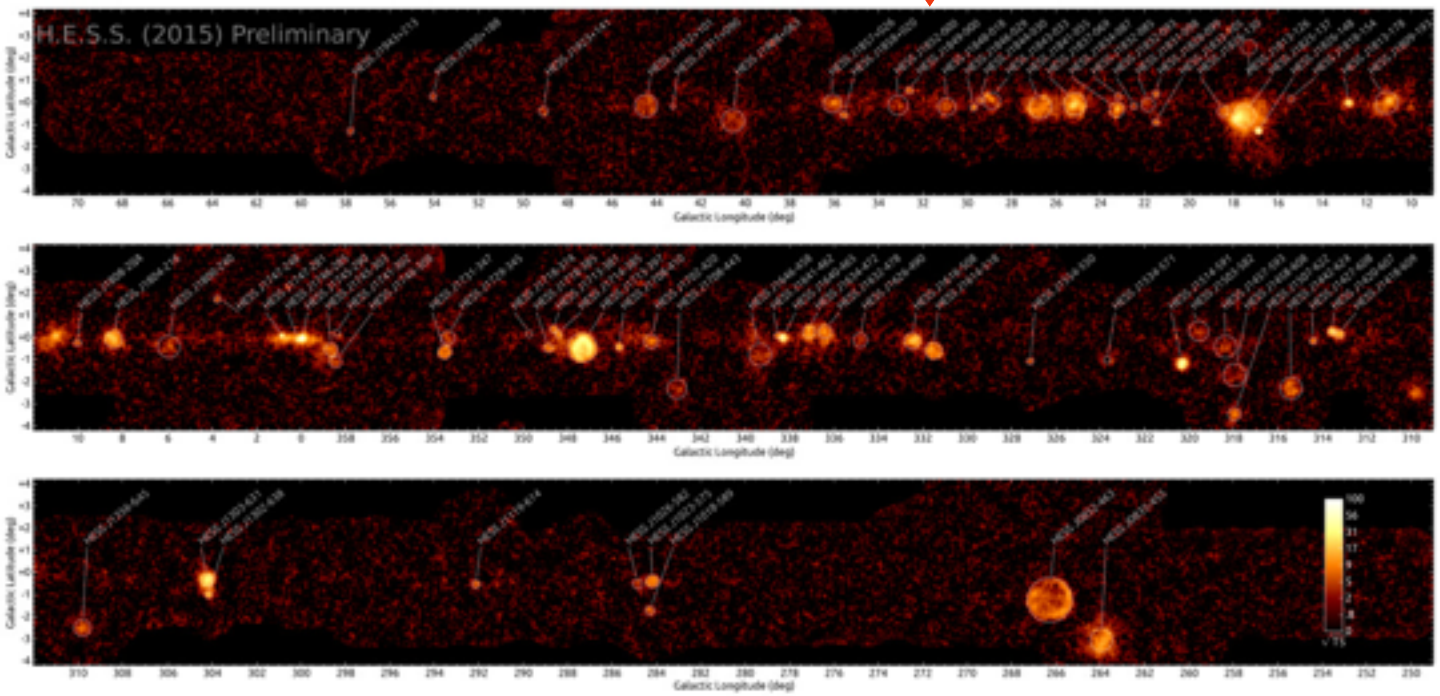


PASS8 Fermi-LAT 470 weeks of data extracted with the v10r0p5 Fermi tool. Point sources from the 3FGL catalogue subtracted.

[D.Gaggero+ PRL 2017]



- Looking forward to the diffuse TeV emission map from future experiments (HAWC, CTA)
- The presence of a spectral trend in the very high energy can reveal a lot of information about the physics



Take-home message and outlook

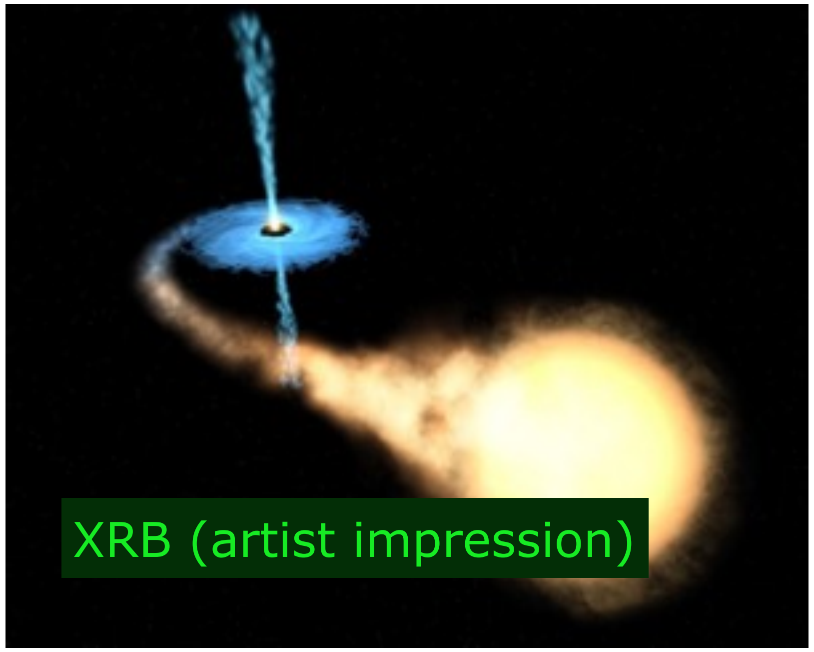
- We are still far from fully understanding the physics of cosmic rays and their mechanisms of confinement
- We have great data, and a lot of anomalies to explain, both in the charged CR spectra and in the non-thermal emission
- Gamma-ray data can reveal CR spectral properties in different regions of the Galaxy. They can shed light on the physics of CR transport
- Looking forward to the TeV gamma-ray diffuse skymaps

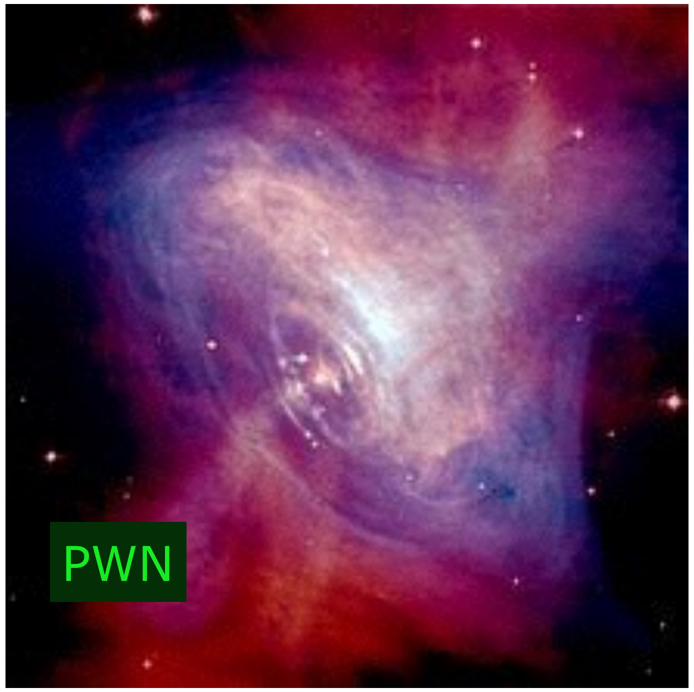
Thank you !

Backup Slides

Phenomenology of CR sources

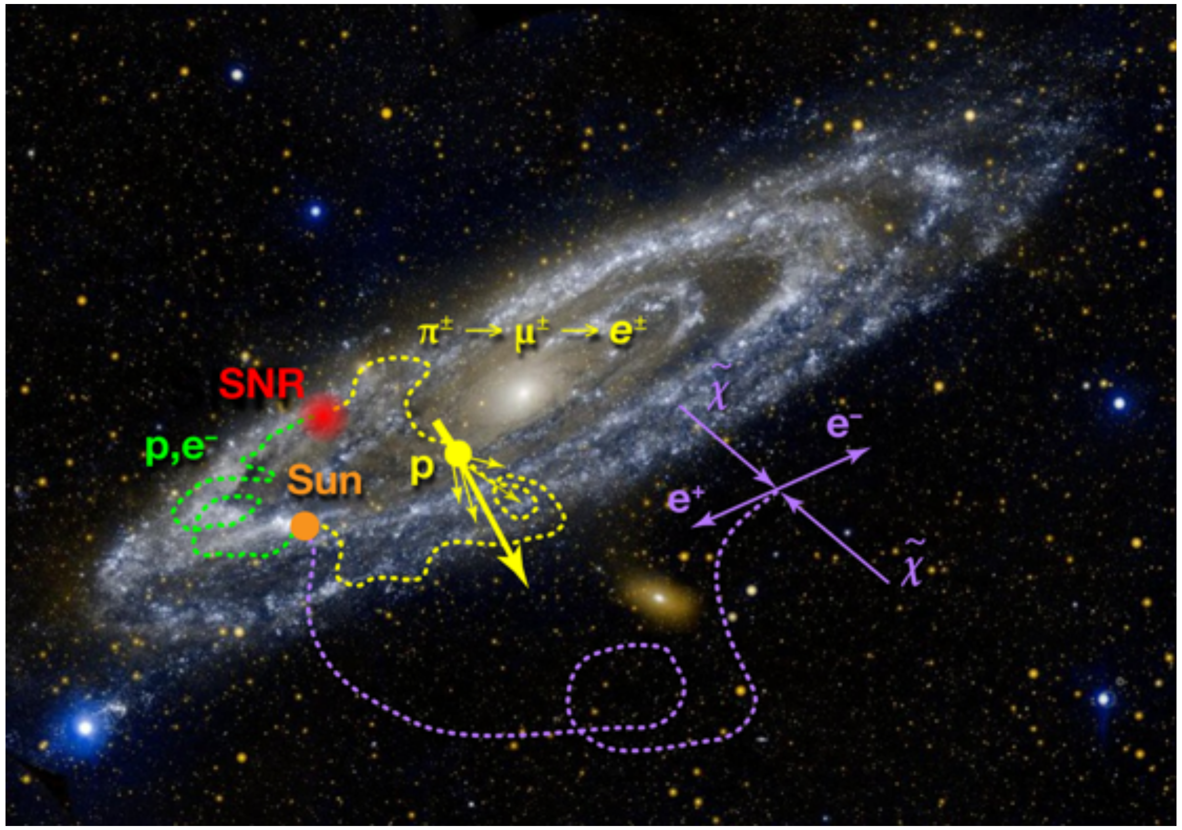
1) based on **DSA** at non-relativistic shocks (e.g. SNRs, superbubbles)
   [Blandford & Ostriker 1978; Bell 1978; Axford et al. 1977; Krymskii 1977]
2) based on (transient or steady-state) accretion-powered relativistic **jet acceleration** (XRBs on the Galactic scale, GRBs and AGNs on larger scales)
3) based on other (leptonic) processes (PWNs)





Shock waves are ubiquitous: They are powerful heating machines and particle accelerators

Phenomenology of CR transport



Physical processes that affect CR transport in the Galaxy:
[Ginzburg&Syrovatskii 1964; Berezinskii et al. 1990]

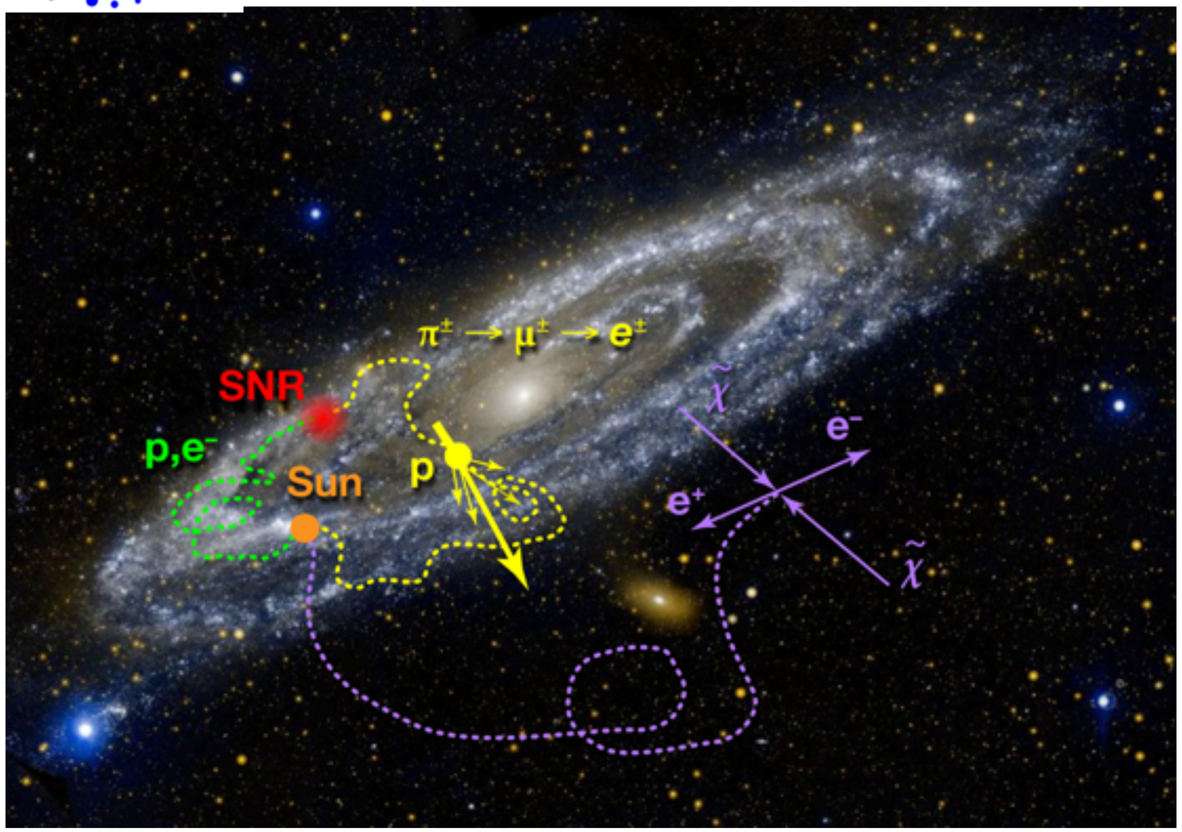
- **Primary CR production**
- **Secondary CR production** via spallation
- *Rigidity-dependent* **diffusion**
- *Rigidity-independent* **advection**
- Possibly, stochastic **II order Fermi acceleration** (*reacceleration*)
- **Energy losses**

$$\nabla \cdot (\vec{J}_i - \vec{v}_w N_i) + \frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\left(\frac{N_i}{p^2}\right)\right] - \frac{\partial}{\partial p}\left[\dot{p}N_i - \frac{p}{3}\left(\vec{\nabla}\cdot\vec{v}_w\right)N_i\right] =$$

$$Q + \sum_{i<j}\left(c\beta n_{\rm gas}\,\sigma_{j\to i} + \frac{1}{\gamma\tau_{j\to i}}\right)N_j - \left(c\beta n_{\rm gas}\,\sigma_i + \frac{1}{\gamma\tau_i}\right)N_i$$

$$J_i = -D_{ij}\nabla_j N$$

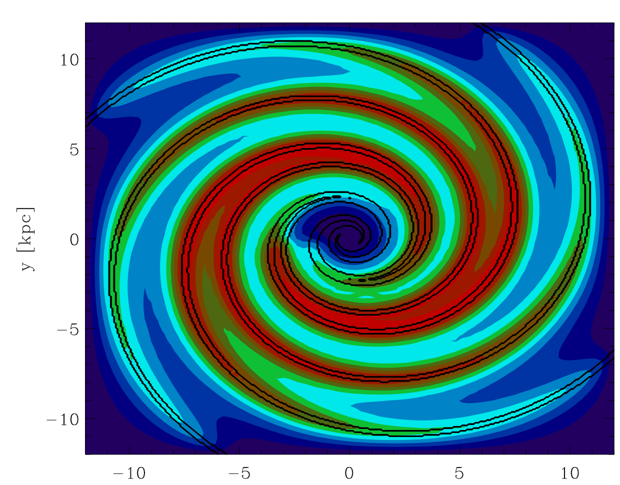
The DRAGON project

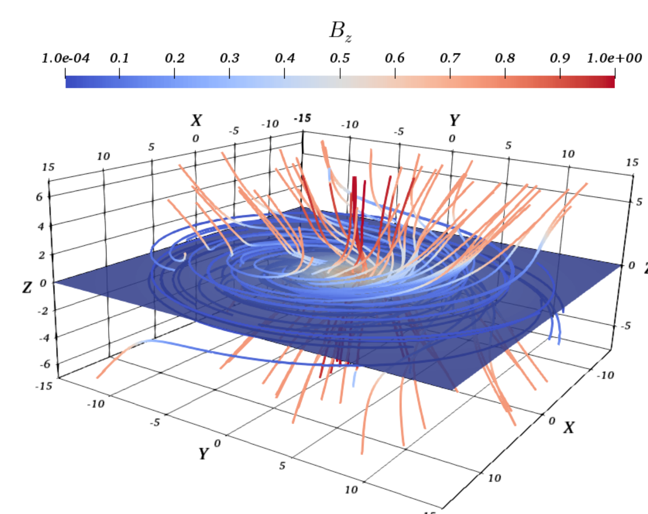


C. Evoli, **DG**, D. Grasso, L. Maccione, JCAP 2008 (DRAGON 1)
DG, C. Evoli, *et al.*, **PRL** 2013 (DRAGON3D)
C. Evoli, **DG**, *et al.*, JCAP 2016 (DRAGON 2)
C. Evoli, **DG**, *et al.*, 2017 (DRAGON 2 xsec)

DRAGON implements fully-tested **2D and 3D *inhomogeneous*** isotropic diffusion, and **2D *anisotropic*** diffusion

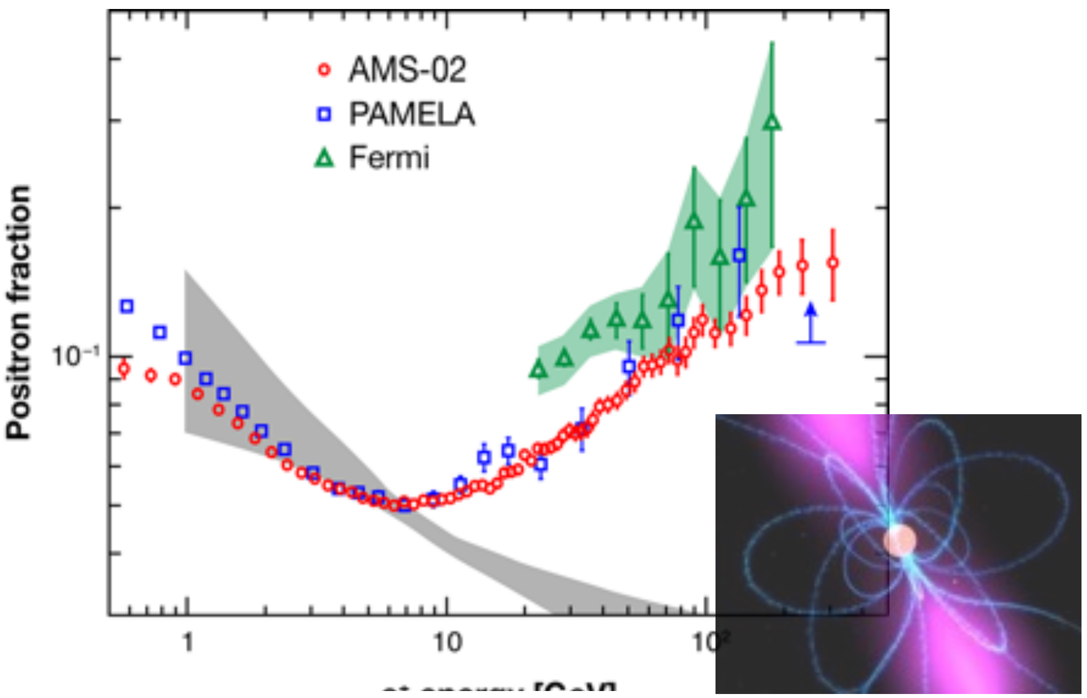
- Possibility to study **transients,** moving sources, 3D structures
- Possibility to study **different transport regimes** in different regions of the Galaxy
- Possibility to account for both astrophysical and beyond-standard-model processes



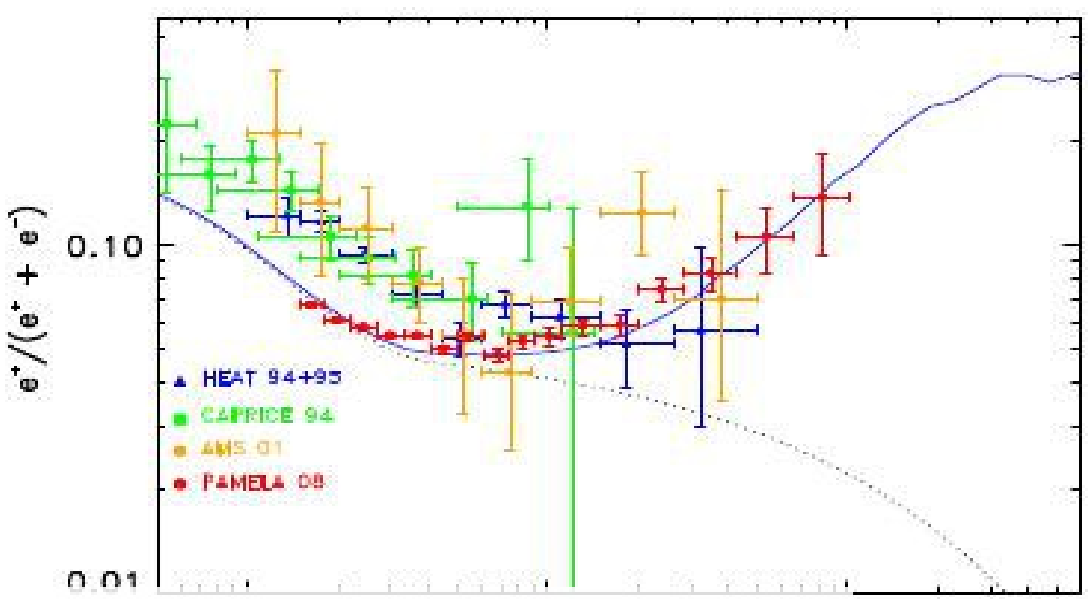


Selected highlights

The mysterious high-energy positron excess and the pulsar hypothesis



— In conventional scenarios, positrons are **secondary products** of CR spallation on interstellar gas, and their spectrum is expected to be steeper than the electron one (in general, secondary-to-primary ratios are expected to decline with increasing rigidity)



— A large excess in high-energy positrons detected by PAMELA and later AMS
— A signature of a **new class of sources** at work?

D. Grasso, **DG**, et al., APP 2009
G. Di Bernardo, **DG**, et al., APP 2011
DG, L. Maccione et al., PRD 2013

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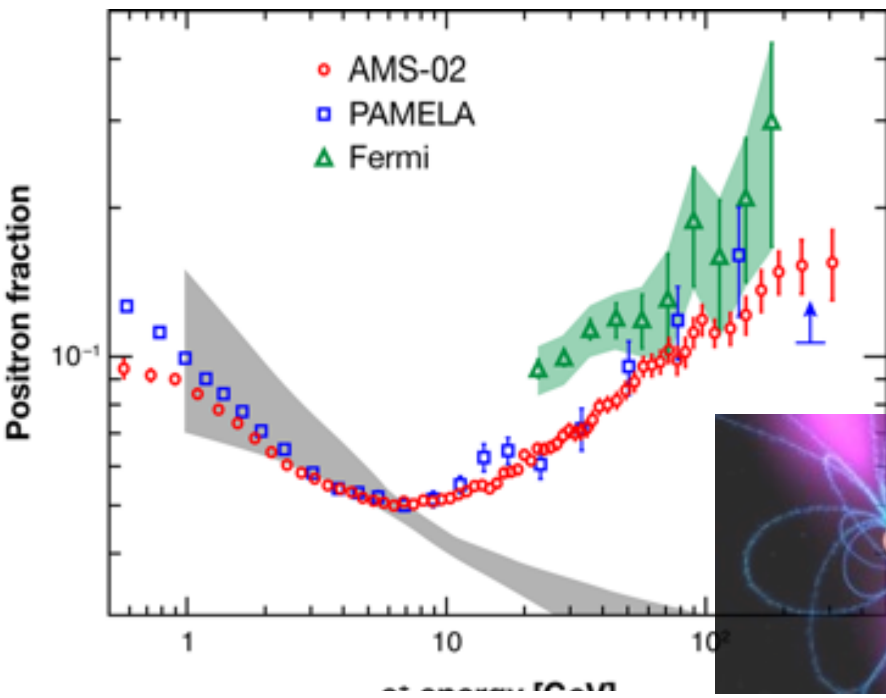

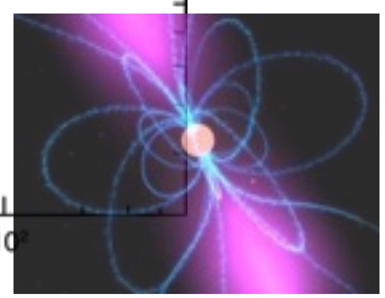

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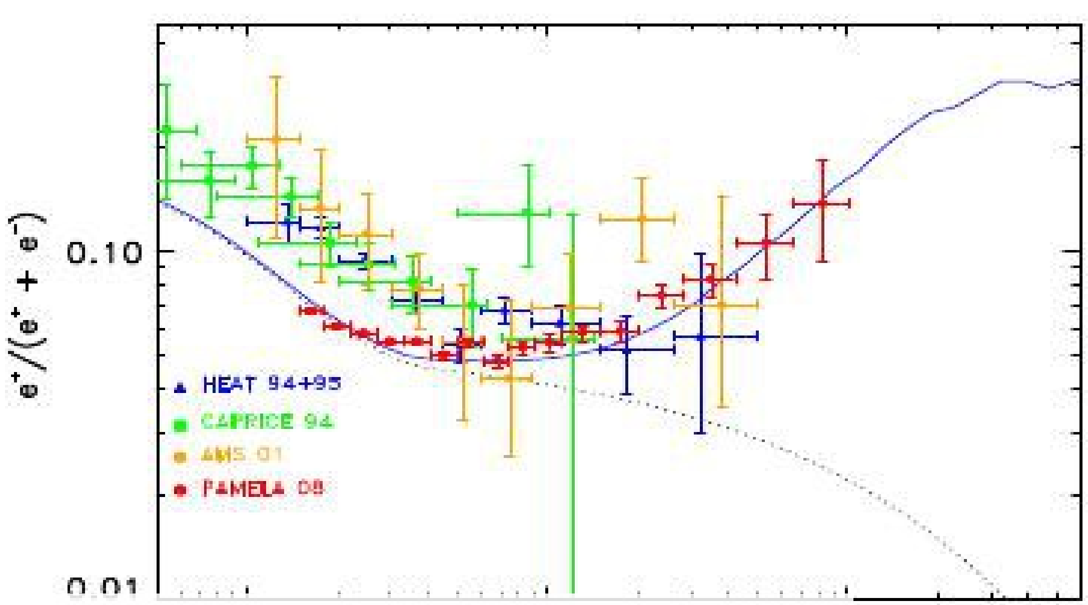

1. Energy budget OK
2. spectrum is fitted to the data (—> *provides info on acceleration mechanism*)
3. Predictions for anisotropy
4. Numerical frameworks allow to show that **all channels work consistently taking into account a comprehensive catalogue of pulsars**

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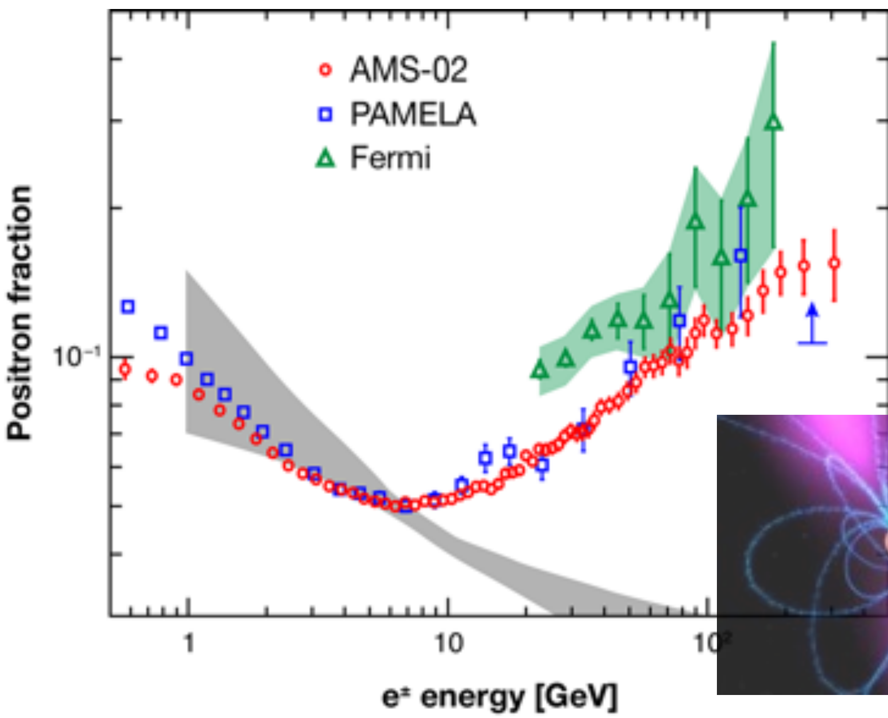

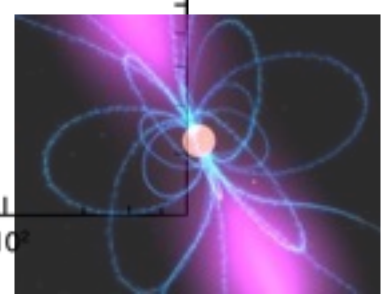

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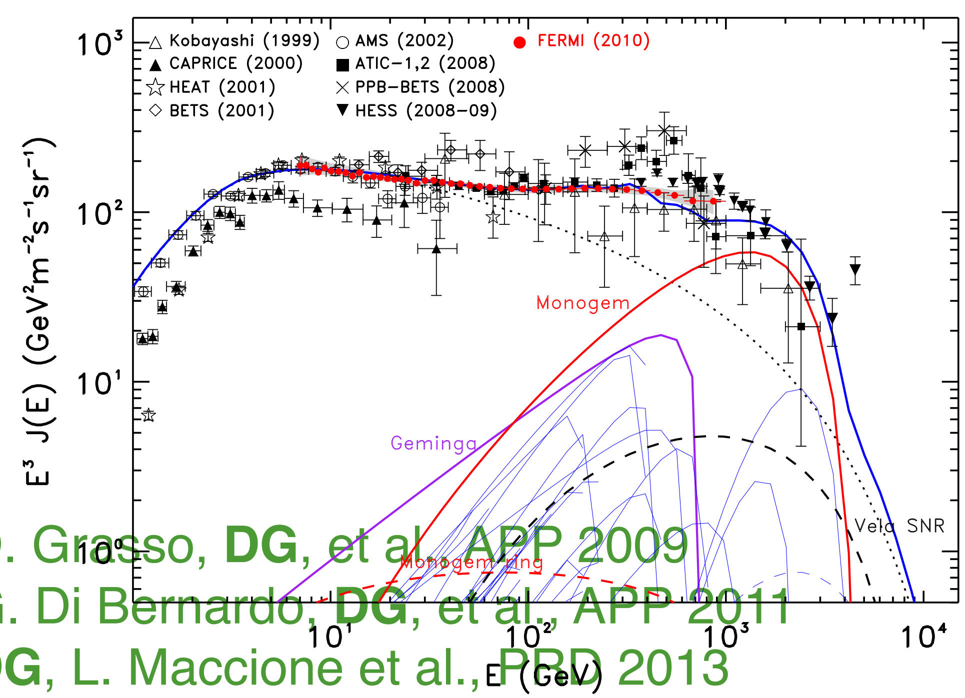

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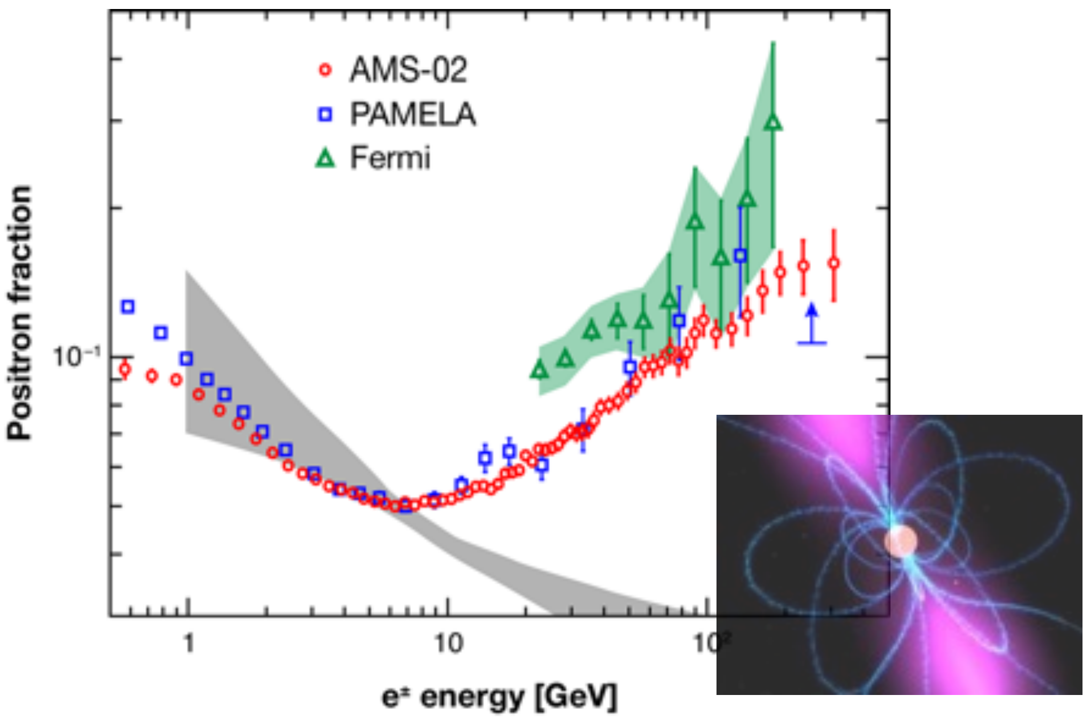

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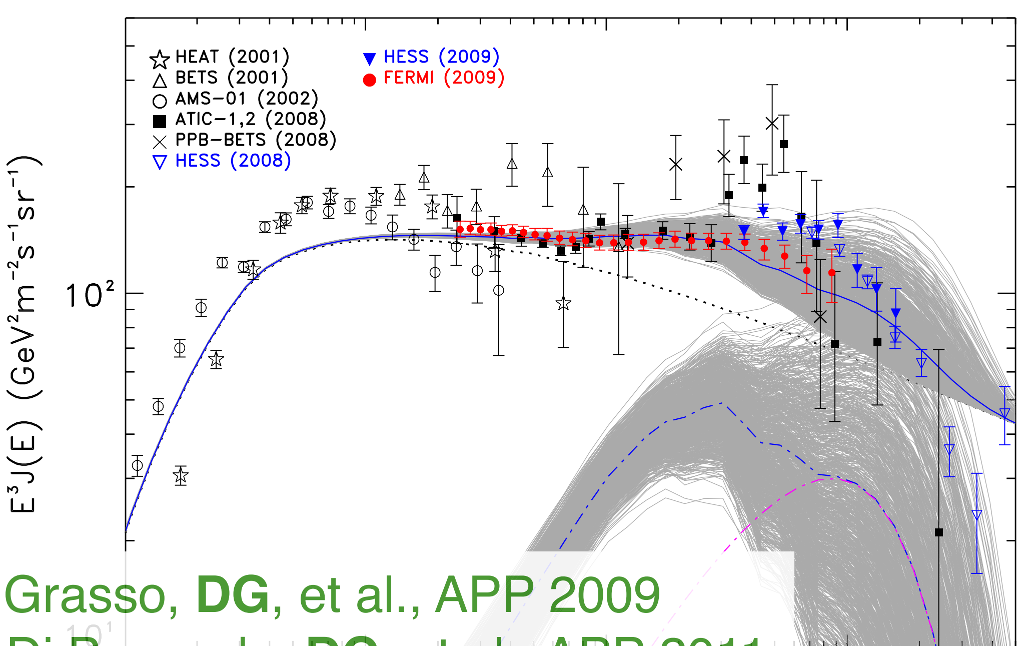

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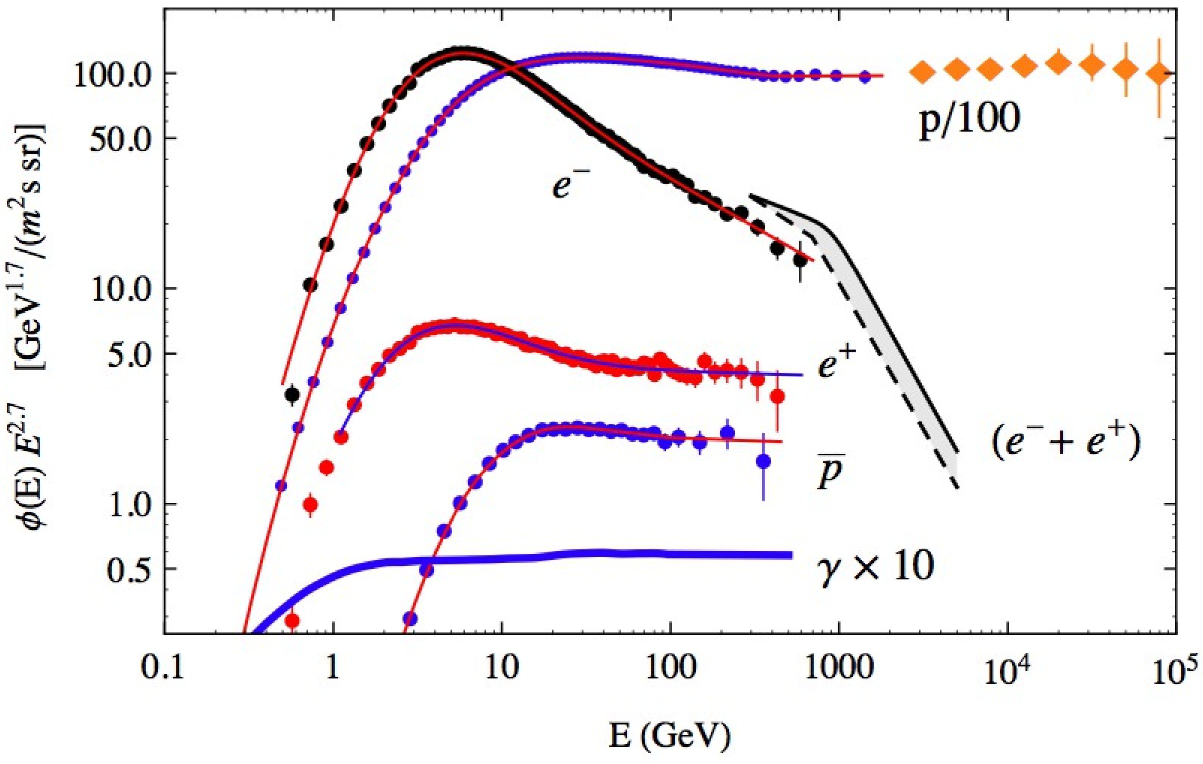
Alternative ideas?

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

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

Selected highlights

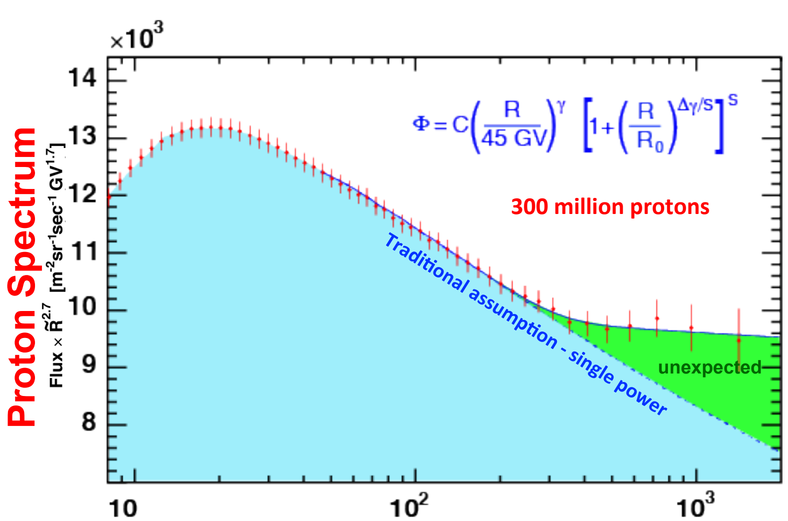
The high-energy hardening in local CR data

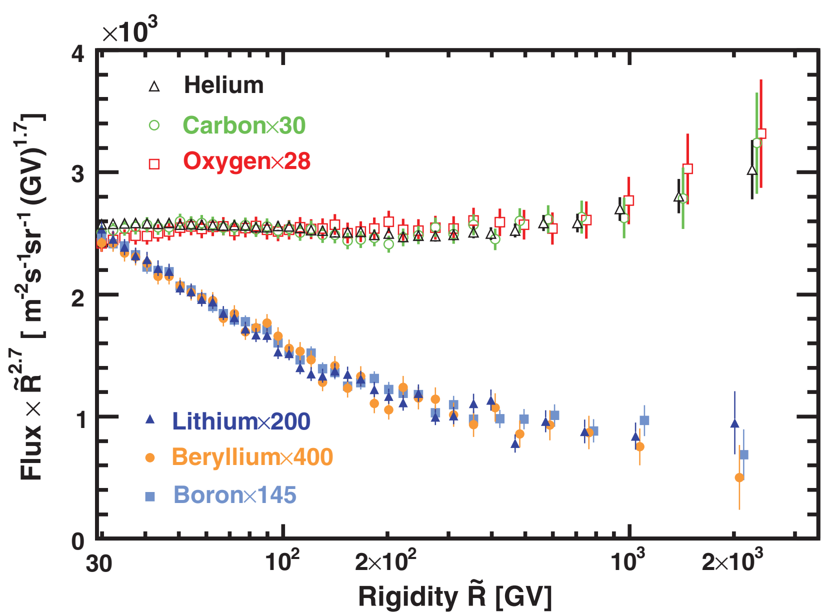
An important discovery by PAMELA:
proton and He spectral breaks at ~200 GV

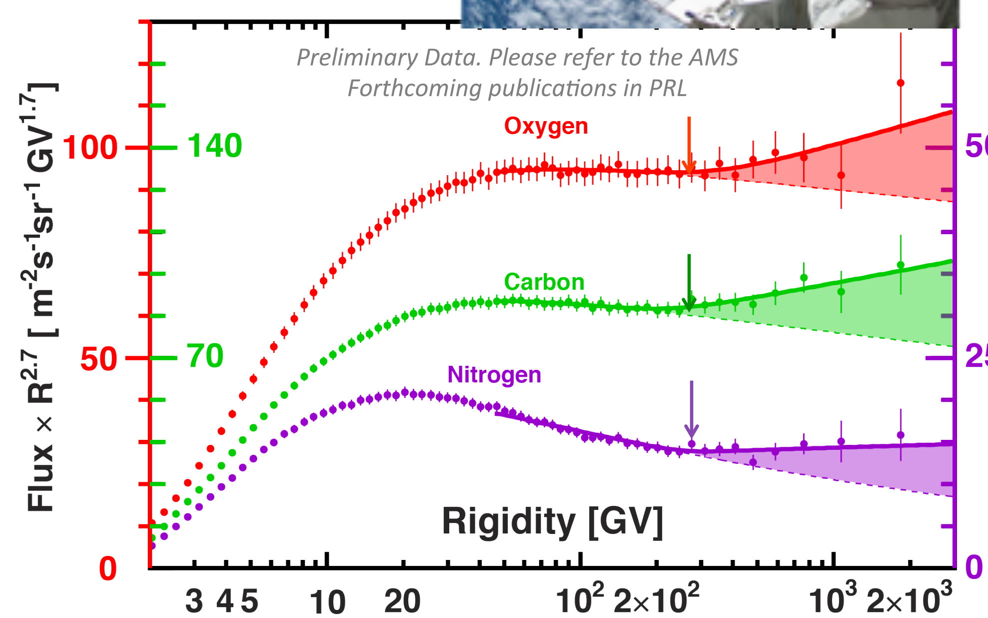

PAMELA Measurements of Cosmic-Ray Proton and Helium Spectra
O. Adriani[1,2], G. C. Barbarino[3,4], G. A. Bazilevskaya[5], R. Bellotti[6,7], M. Boezio[8], E. A. Bogomolov[9], L. Bonechi[1,2], M. Bongi[2], V. Bo...
+ See all authors and affiliations
Science 01 Apr 2011:
Vol. 332, Issue 6025, pp. 69-72
DOI: 10.1126/science.1199172

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*



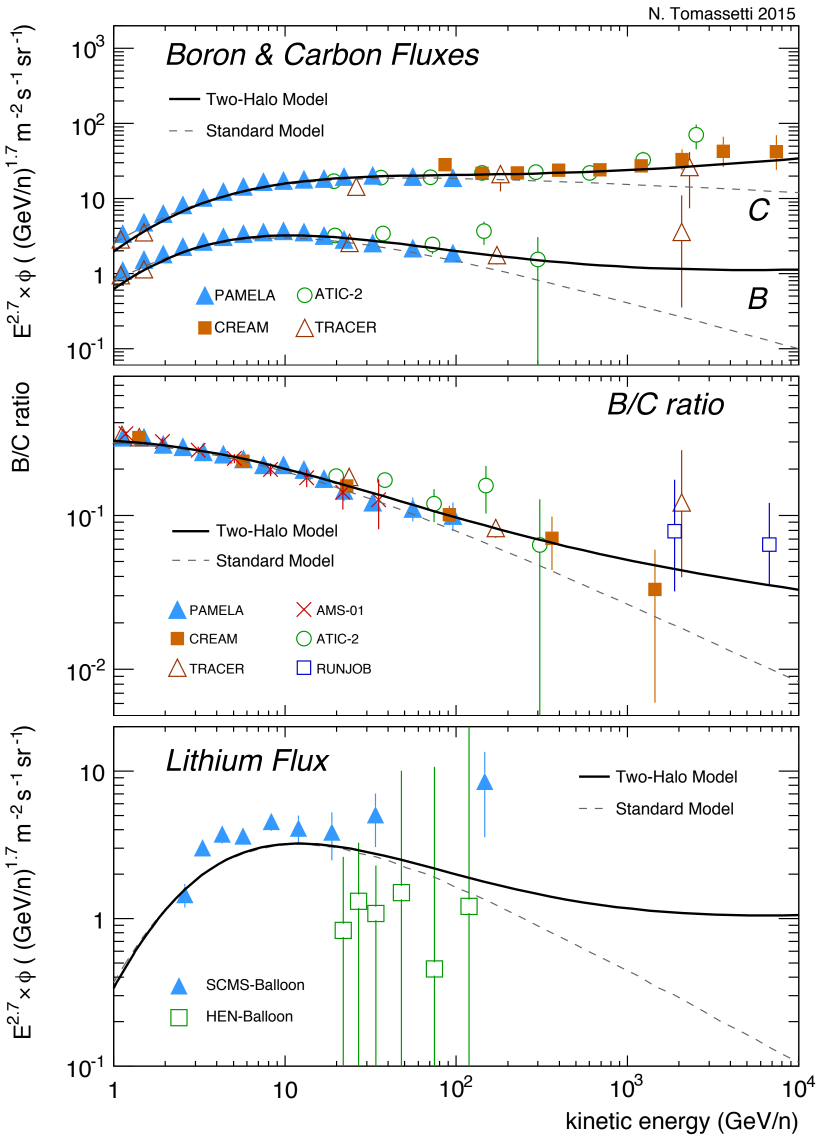




The high-energy hardening in local CR data

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]*
- Non-linear DSA? *[Ptuskin et al., ApJ 2013]*
- The fingerprint of a **local supernova event**? *[Kachelriess et al., PRL 2015; Tomassetti&Donato ApJ 2015; Tomassetti ApJL 2015]*



A transport effect?

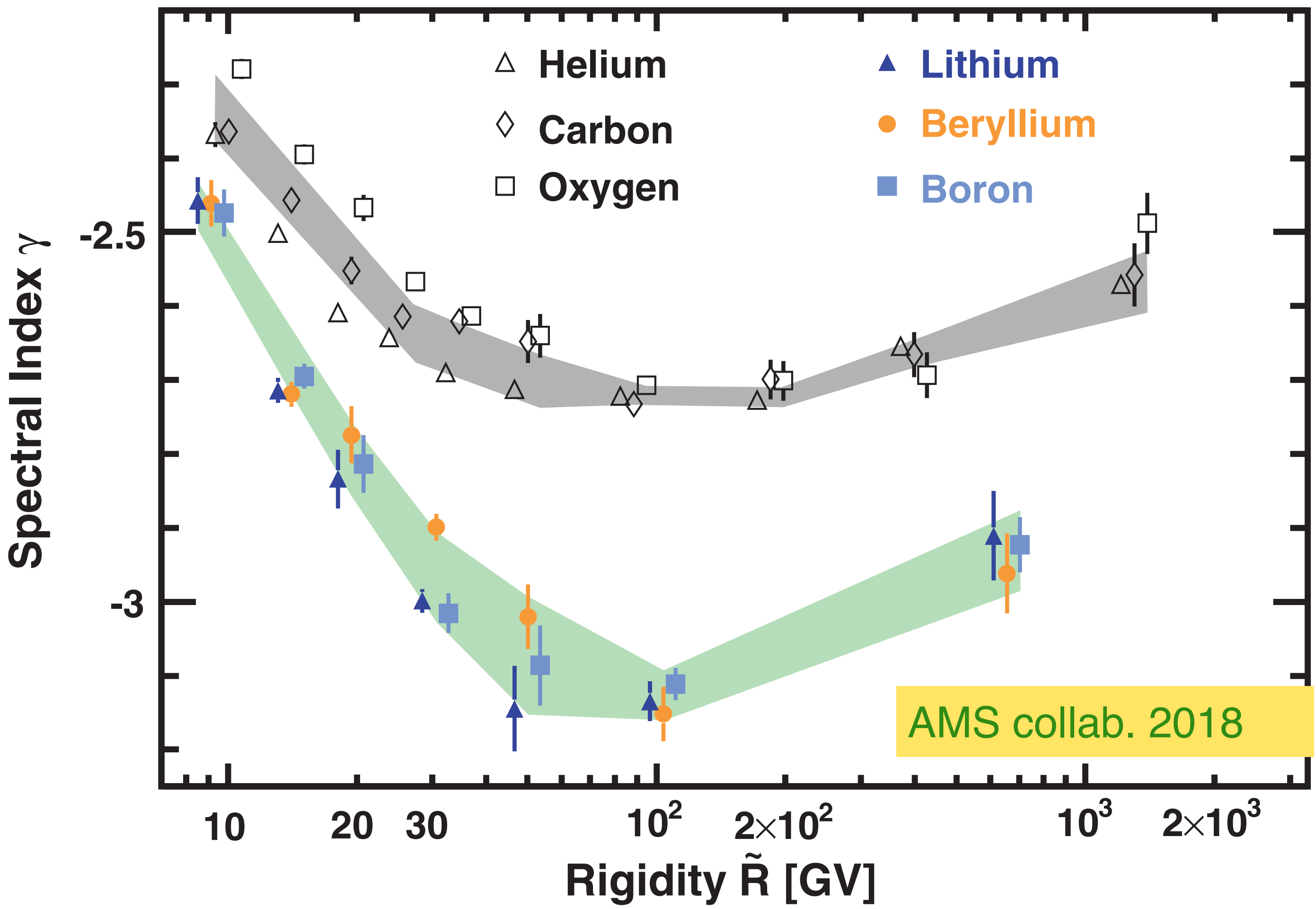
- **Different transport properties** in the disk w.r.t. the halo? *[Tomassetti, PRD 2015]*
- A possible **transition between different transport regimes**?
  - *low energies*: propagation in self-generated (via streaming instability) turbulence
  - *high energies*: propagation in pre-exisiting turbulence *[Farmer&Goldreich 2004; Blasi, Amato, Serpico, PRL 2012; Aloisio, Blasi, Serpico 2015]*

Selected highlights

- **How can we tell the difference?** 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; break in Li, Be, B is more pronounced*



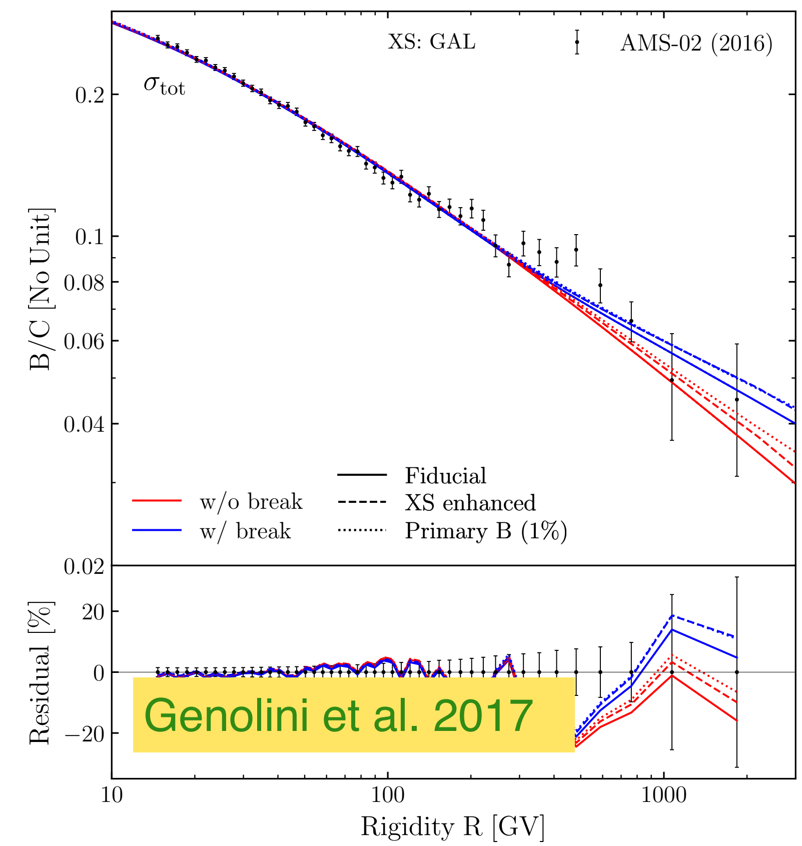
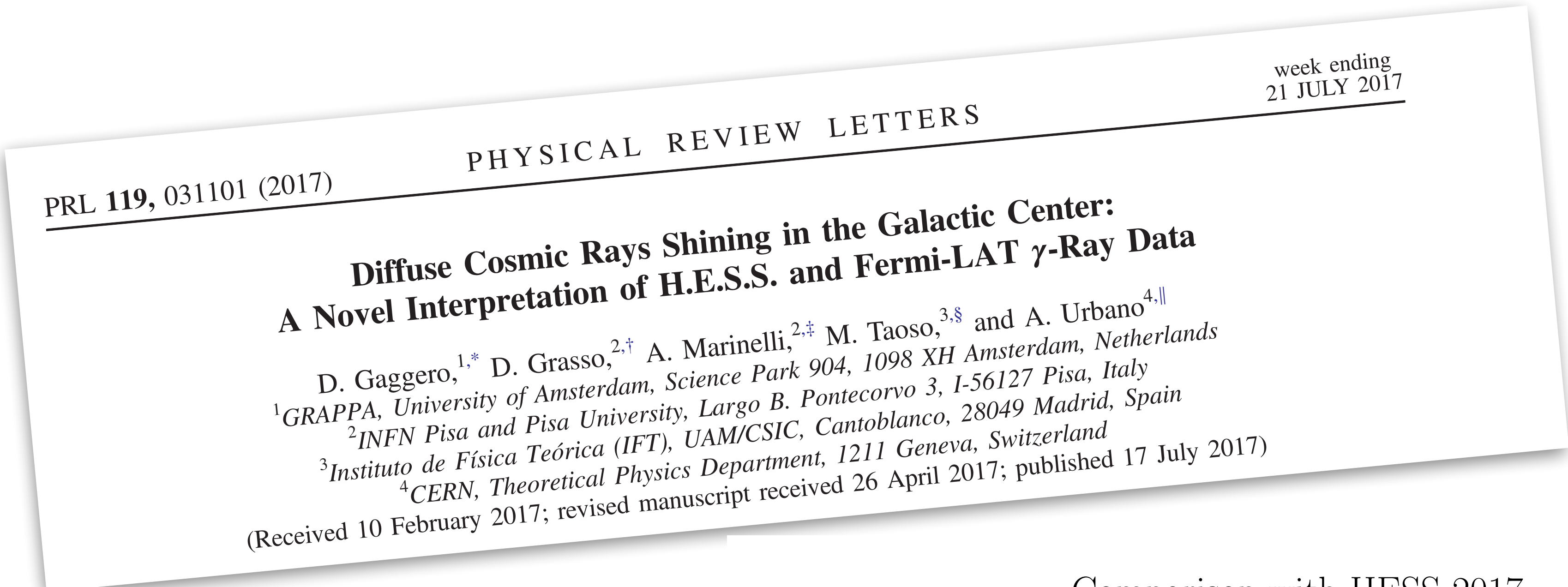


FIG. 2: Best fits and residuals with (blue) and without (red) the break using GALPROP cross sections and σ_{tot}, for the different models considered in the text.

Selected highlights

"Hard diffusion" in the inner Galaxy explains it all?


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,‖]

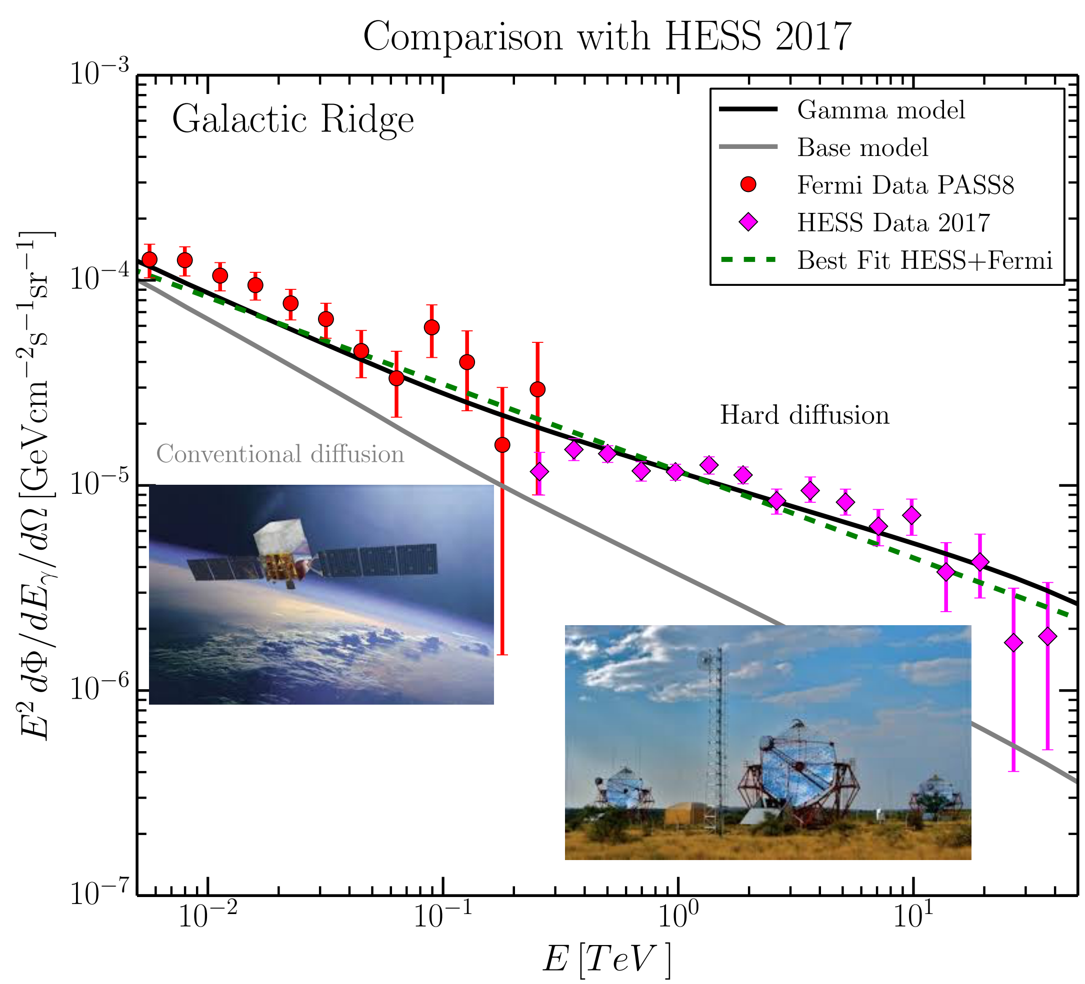
[1]*GRAPPA, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, Netherlands*
[2]*INFN Pisa and Pisa University, Largo B. Pontecorvo 3, I-56127 Pisa, Italy*
[3]*Instituto de Física Teórica (IFT), UAM/CSIC, Cantoblanco, 28049 Madrid, Spain*
[4]*CERN, Theoretical Physics Department, 1211 Geneva, Switzerland*

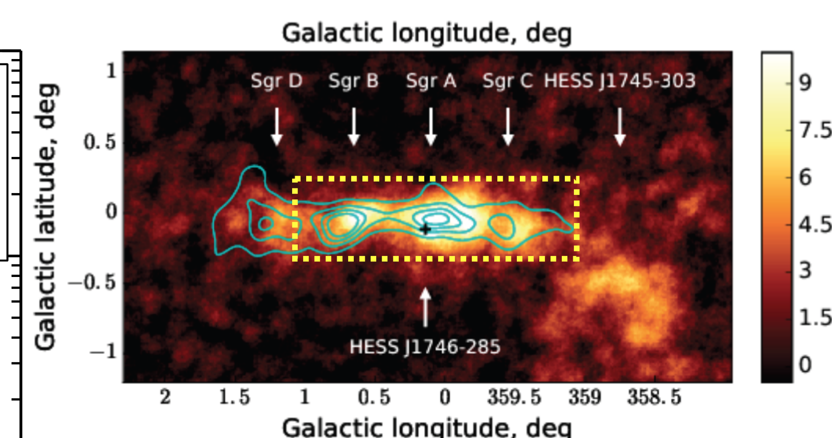
(Received 10 February 2017; revised manuscript received 26 April 2017; published 17 July 2017)

DG, D. Grasso *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



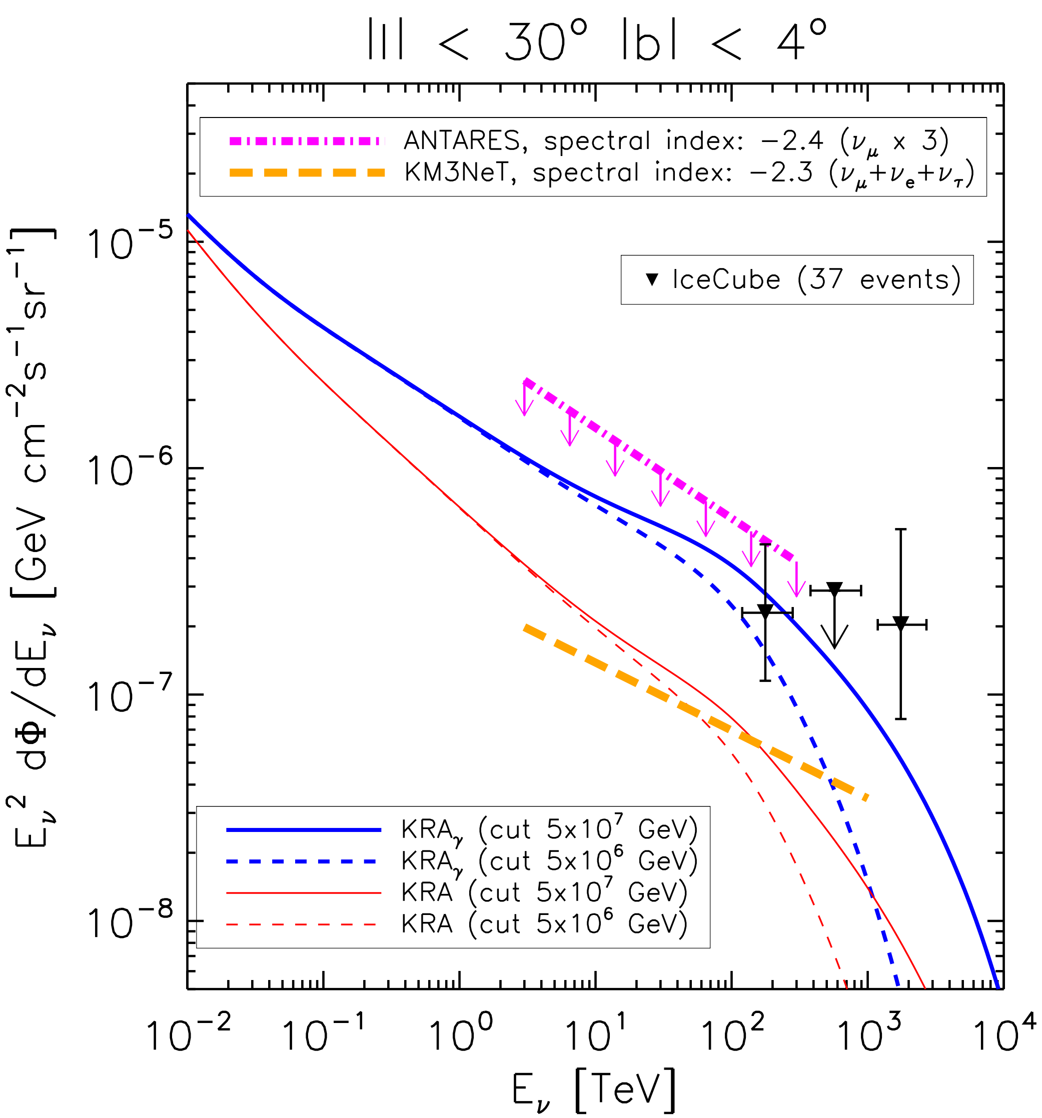


PASS8 Fermi-LAT 470 weeks of data extracted with the v10r0p5 Fermi tool. Point sources from the 3FGL catalogue subtracted.

This implies a **non-negligible Galactic component in IceCube data**

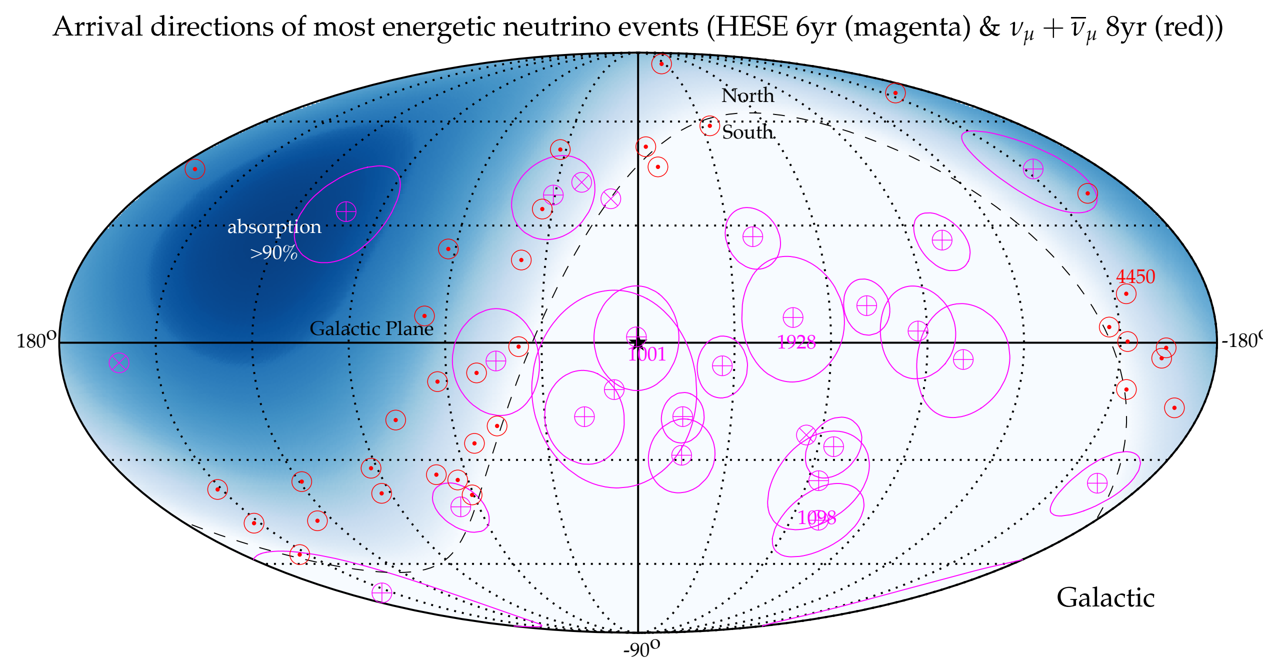
A testable prediction with KM3Net

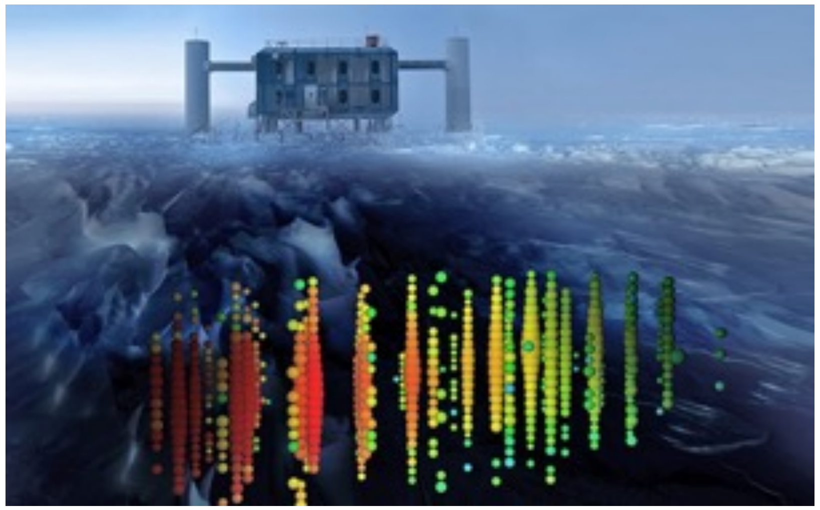
Joint IceCube+ANTARES analysis is ongoing



DG et al., ApjL, 2016

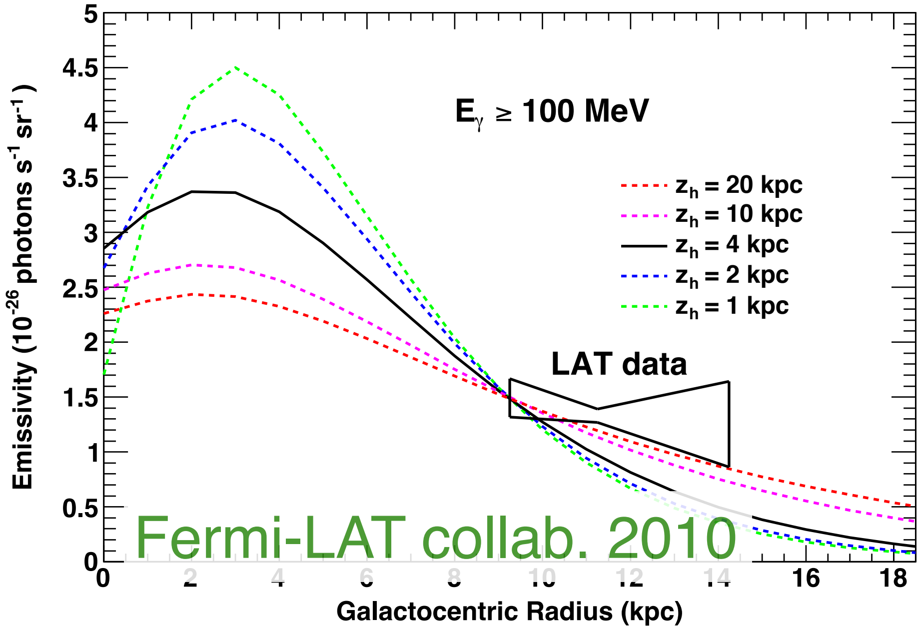
IceCube collaboration

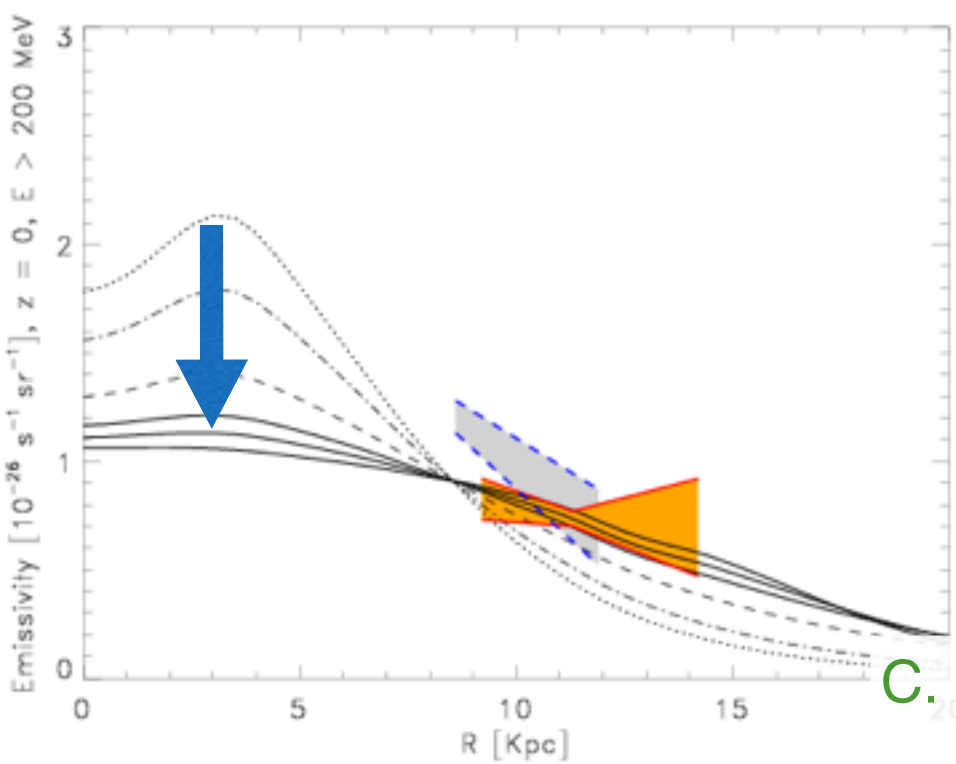




A glimpse on the gradient and anisotropy problem

The gradient problem and anisotropic, inhomogeneous diffusion





— γ-rays —> proton flux across the Galaxy is much flatter than what predicted under conventional assumptions

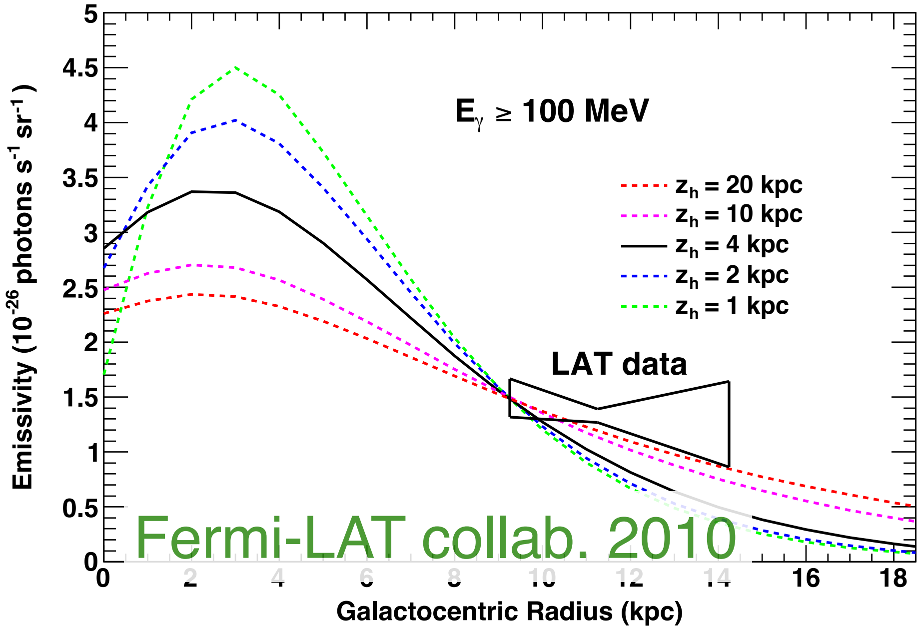
— We **solved this long-standing puzzle** together with the well-known *anisotropy problem* by implementing **enhanced perpendicular escape** along the vertical direction in regions with more CR sources

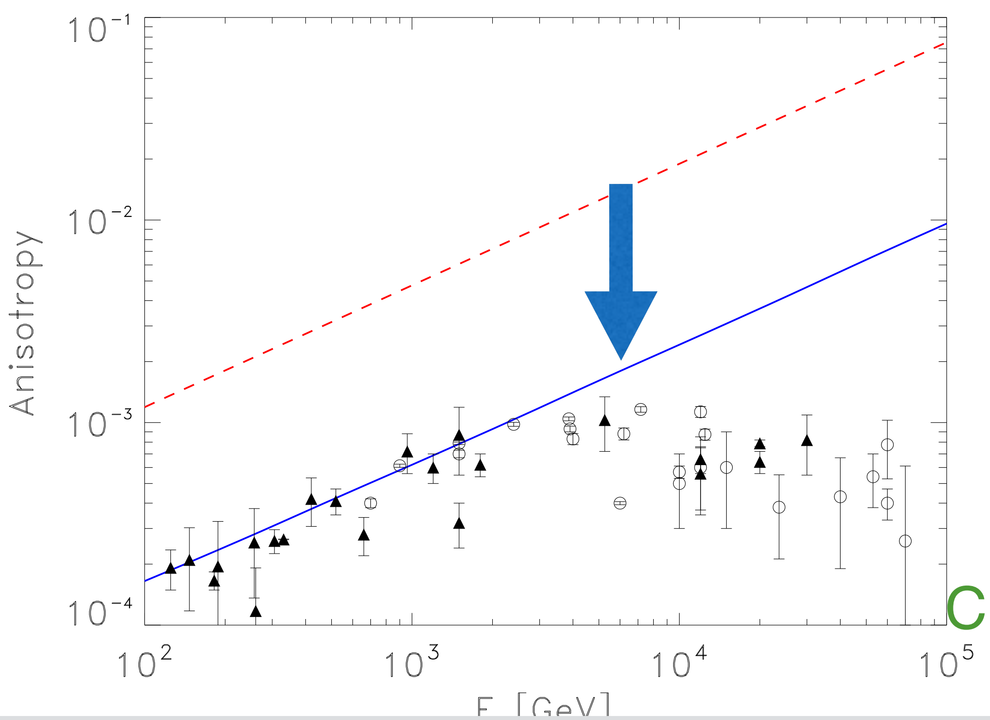
— another **evidence** inferred from gamma-ray data of **inhomogeneous diffusion** across the Galaxy?

C. Evoli, **DG,** D. Grasso et al., **PRL** 2013

A glimpse on the gradient and anisotropy problem

The gradient problem and anisotropic, inhomogeneous diffusion





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— We **solved this long-standing puzzle** together with the well-known *anisotropy problem* by implementing **enhanced perpendicular escape** along the vertical direction in regions with more CR sources

— another **evidence** inferred from gamma-ray data of **inhomogeneous diffusion** across the Galaxy?

C. Evoli, **DG,** D. Grasso et al., **PRL** 2013