Cosmic-rays propagation in the ISM

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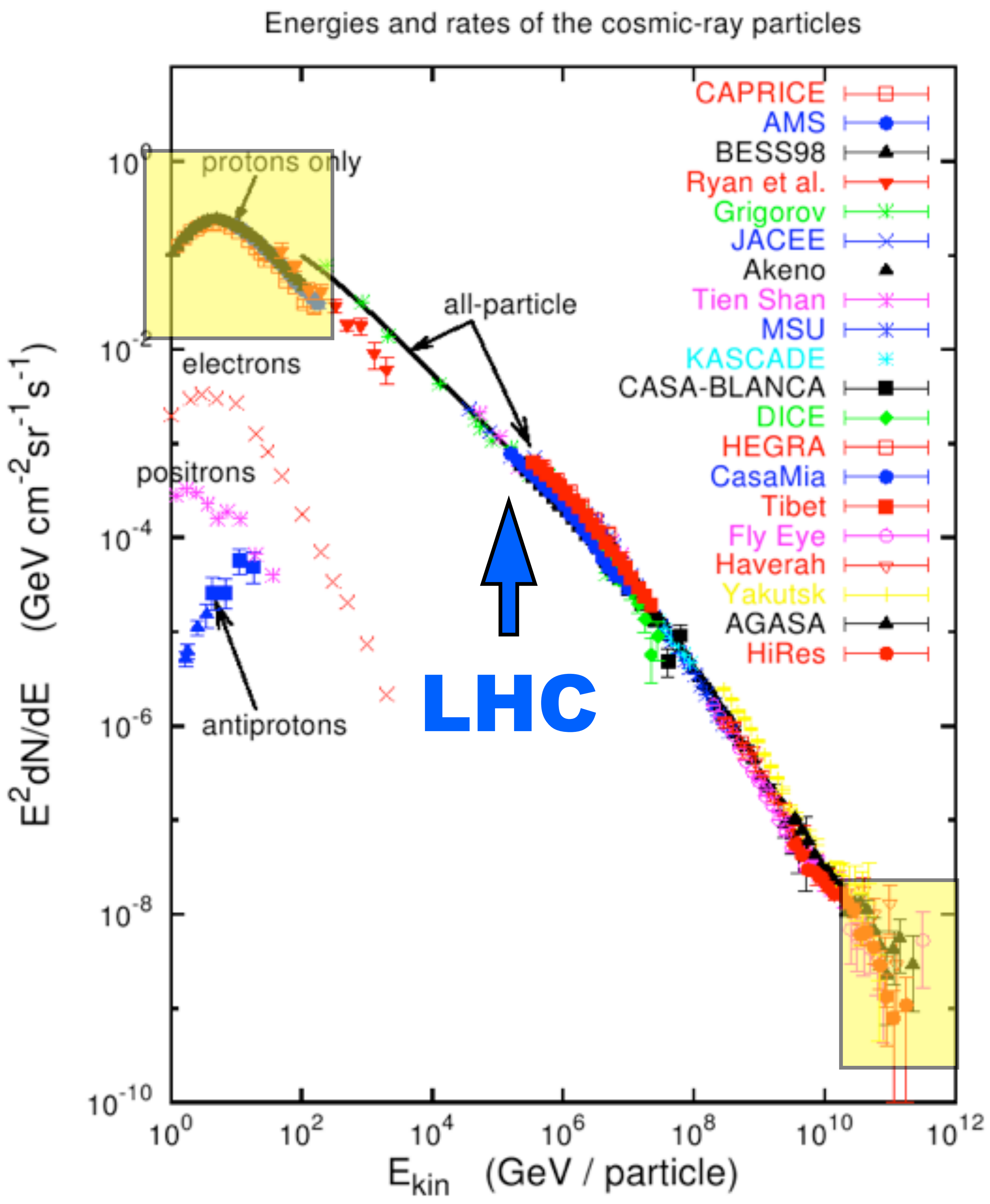
HELMHOLTZ
ASSOCIATION
Alliance for Astroparticle Physics

UH

Trieste | ICTP Workshop | 11th of October 2013

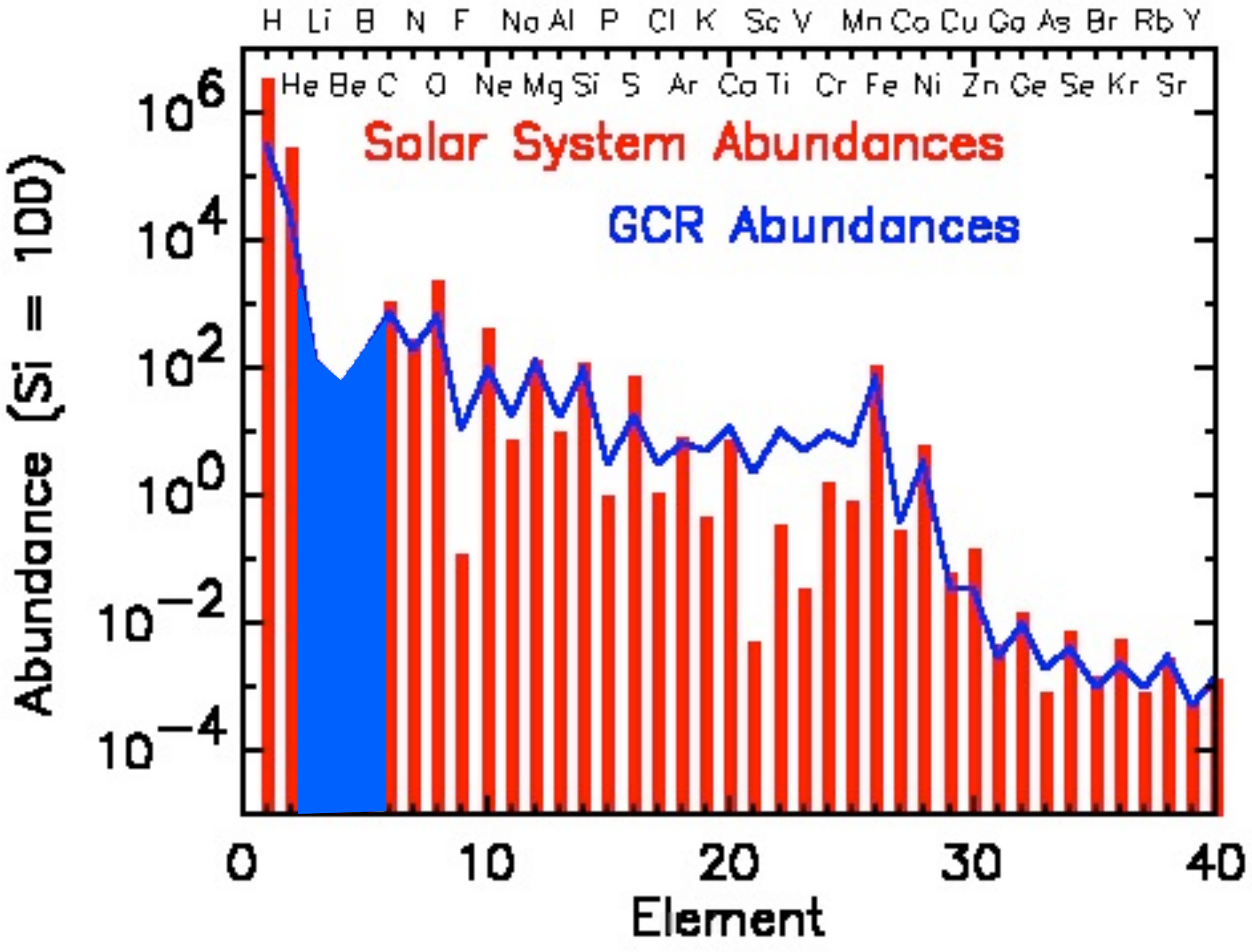
1/cm^2/s



1/km^2/century

$$L_{\rm SN} \sim R_{\rm SN} E_{\rm kin} \sim 3 \times 10^{41}\,{\rm erg/s}$$

Secondary / Primary



- **Primary** species are present in sources (CNO, Fe). Produced by stellar nucleosynthesis. Acceleration in SN shocks (≥10^4 yr).

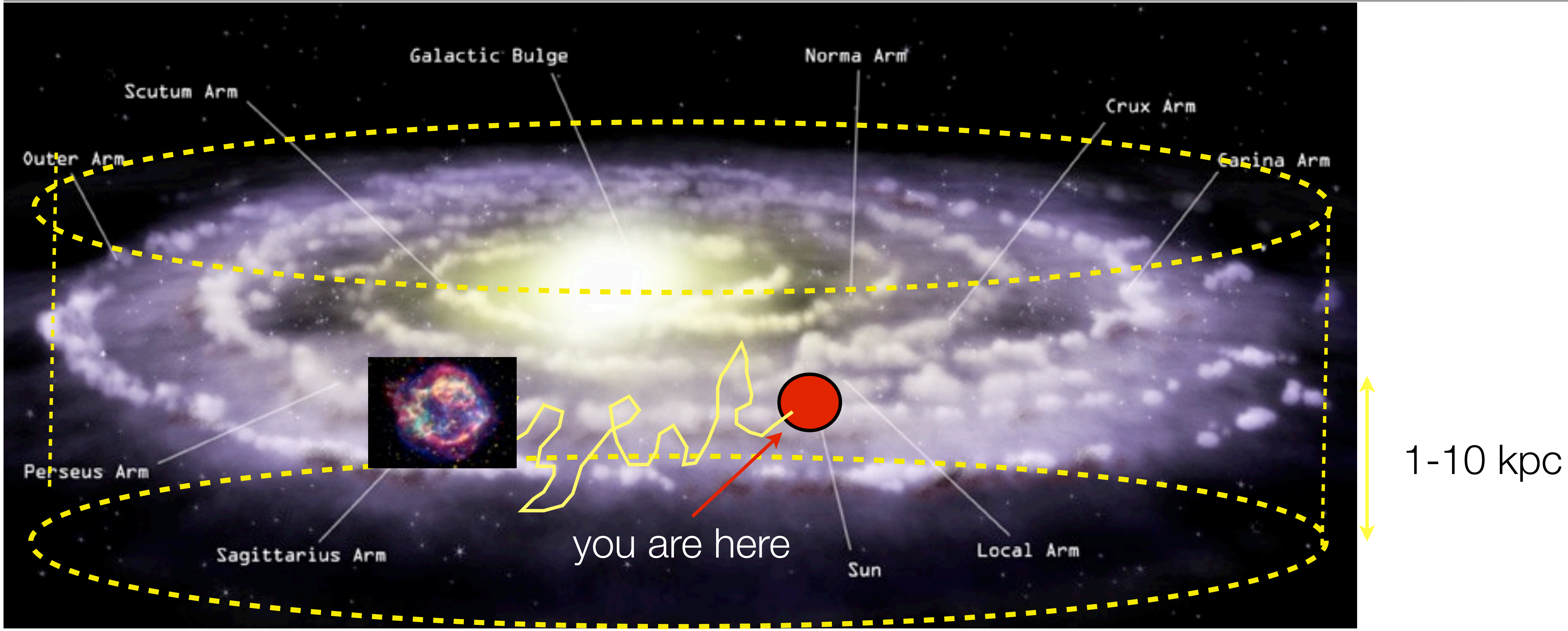
- **Secondary** species are absent of sources (LiBeB, SubFe). Produced during propagation of primaries.

In order to reproduce the measured abundances of stable nuclei, CRs should have traversed: ~10 g/cm^2 material:

$$L = \frac{\mathrm{grammage}}{n_{\mathrm{ISM}} m_p} \sim 10^4 \,\mathrm{kpc}$$

>> Galaxy size!

Galactic Propagation



CRs propagate into the **turbulent** Galactic magnetic field!
The *Larmor* radius of a CR is:

$$r_L(E) = \frac{E}{ZeB} \sim 1\,\mathrm{pc}\left(\frac{E}{10^{15}\,\mathrm{eV}}\right)\left(\frac{B}{1\,\mu\mathrm{G}}\right)^{-1}$$

for a magnetic field coherence length **~100 pc** ⇒ propagation is diffusive up to ~ **10^{16}-10^{17}** eV

CR Diffusion in the MW

The diffusion equation:

$$\frac{\partial N^i}{\partial t} - \nabla \cdot (D\nabla - v_c)N^i + \frac{\partial}{\partial p}\left(\dot{p} - \frac{p}{3}\nabla \cdot v_c\right)N^i - \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{N^i}{p^2} =$$

$$Q^i(p,r,z) + \sum_{j>i} c\beta n_{gas}(r,z)\sigma_{ij}N^j - c\beta n_{gas}\sigma_{in}(E_k)N^i$$

Source term:

- assumed to trace the SNR in the Galaxy
- assumed the same power-law everywhere

Ginzburg & Syrovatsky, 1964

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Spallation cross-section:

- appearance of nucleus i due to spallation of nucleus j

Ginzburg & Syrovatsky, 1964

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Spallation cross-section:

- appearance of nucleus i due to spallation of nucleus j
- total inelastic cross-section: disappearance of nucleus i

Ginzburg & Syrovatsky, 1964

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$$Q^i(p,r,z) + \sum_{j>i} c\beta n_{gas}(r,z)\sigma_{ij}N^j - c\beta n_{gas}\sigma_{in}(E_k)N^i$$

Diffusion tensor:

- $D(E) = D_0(\rho/\rho_0)^{\delta}\exp(z/z_t)$

Ginzburg & Syrovatsky, 1964

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$$Q^i(p,r,z) + \sum_{j>i} c\beta n_{gas}(r,z)\sigma_{ij}N^j - c\beta n_{gas}\sigma_{in}(E_k)N^i$$

Energy losses:

- ionization, Coulomb, synchrotron
- adiabatic convection

Ginzburg & Syrovatsky, 1964

CR Diffusion in the MW

The diffusion equation:

$$\frac{\partial N^i}{\partial t} - \nabla \cdot (D\nabla - v_c)N^i + \frac{\partial}{\partial p}\left(\dot{p} - \frac{p}{3}\nabla \cdot v_c\right)N^i - \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{N^i}{p^2} =$$

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Reacceleration:

- $D_{pp} \propto \frac{p^2 v_A^2}{D}$

Ginzburg & Syrovatsky, 1964

The ISM turbulence

S. Chandrasekhar, ApJ (1949)

- turbulence type:

$$\text{HD} \quad \text{vs} \quad \text{MHD}$$

- assuming constant energy flow (η) between eddies (of length k^{-1}):

$$\epsilon = f(\eta, k) \quad \text{vs} \quad \epsilon = f(\eta, k \cdot v_k/v_A)$$

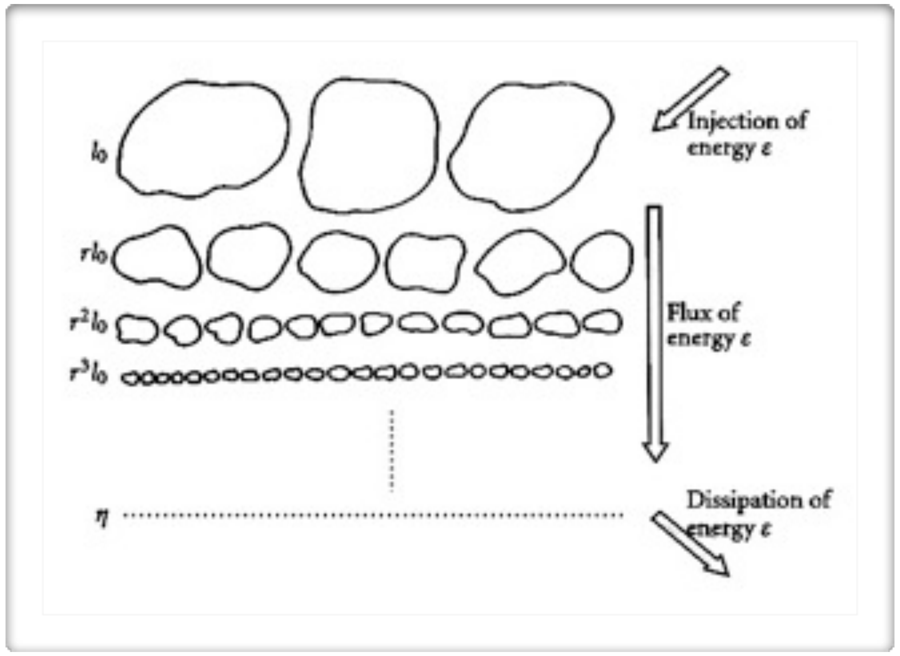
- a simple dimensional analysis gives for the energy spectrum:

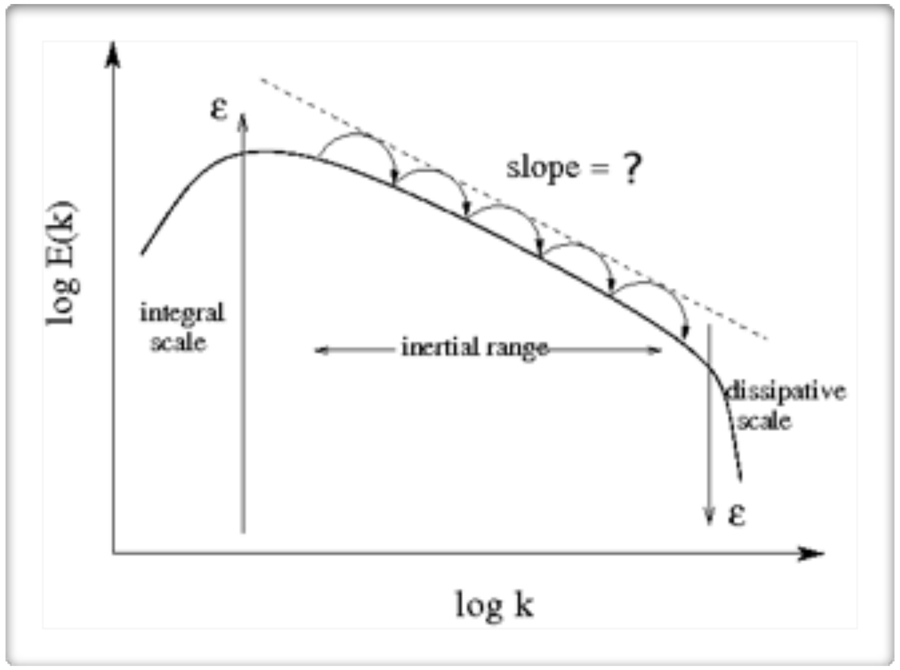
$$\epsilon \propto \eta^{2/3} k^{-5/3} \quad \text{vs} \quad \epsilon \propto \eta^{1/2} v_A^{1/2} k^{-3/2}$$

- finally, diffusion coefficient in QLT is given by:
  (i.e. imposing the resonance condition $r_L = 1/k$)

$$D = \rho^{2-5/3} = \rho^{1/3} \quad \text{vs} \quad D = \rho^{2-3/2} = \rho^{1/2}$$

“Kolmogorov” “Kraichnan”

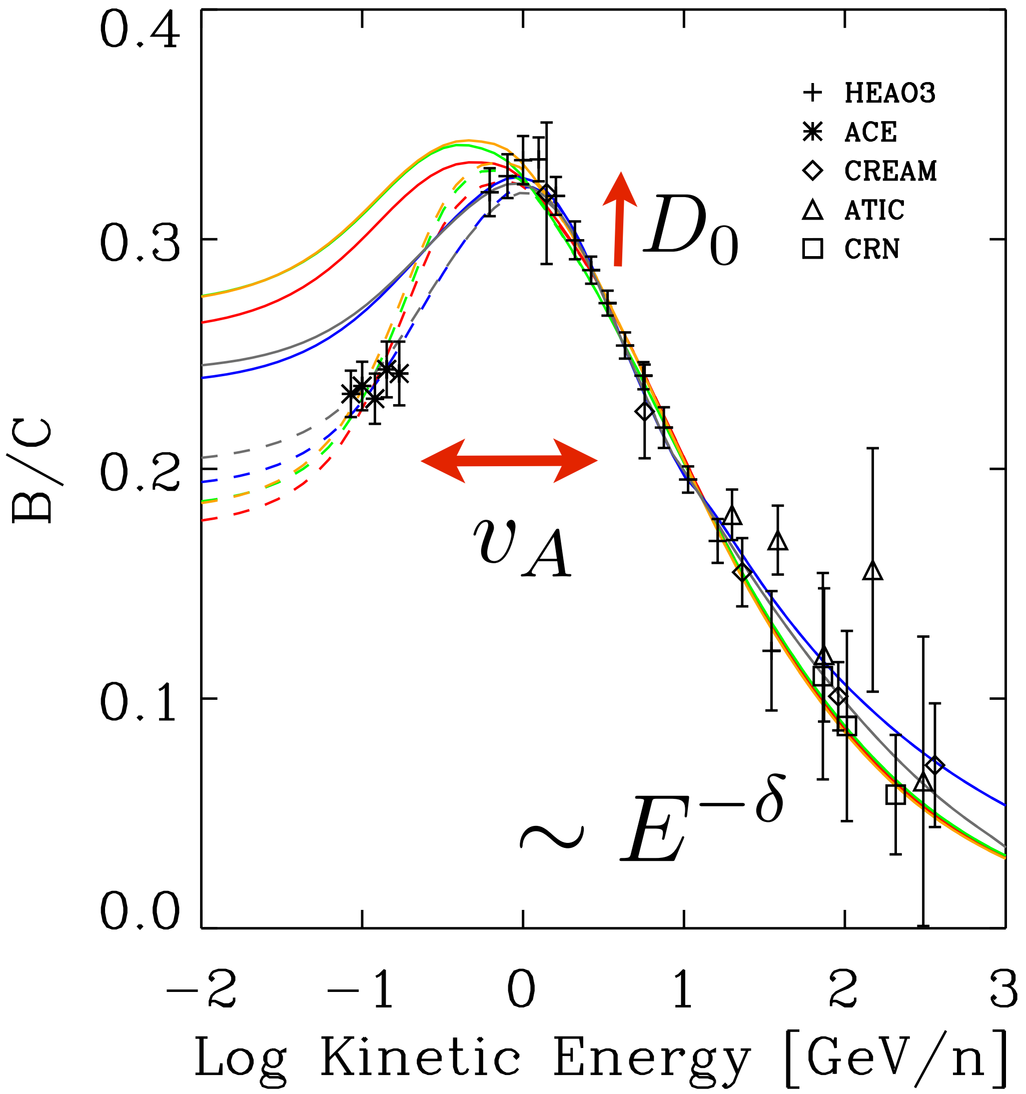




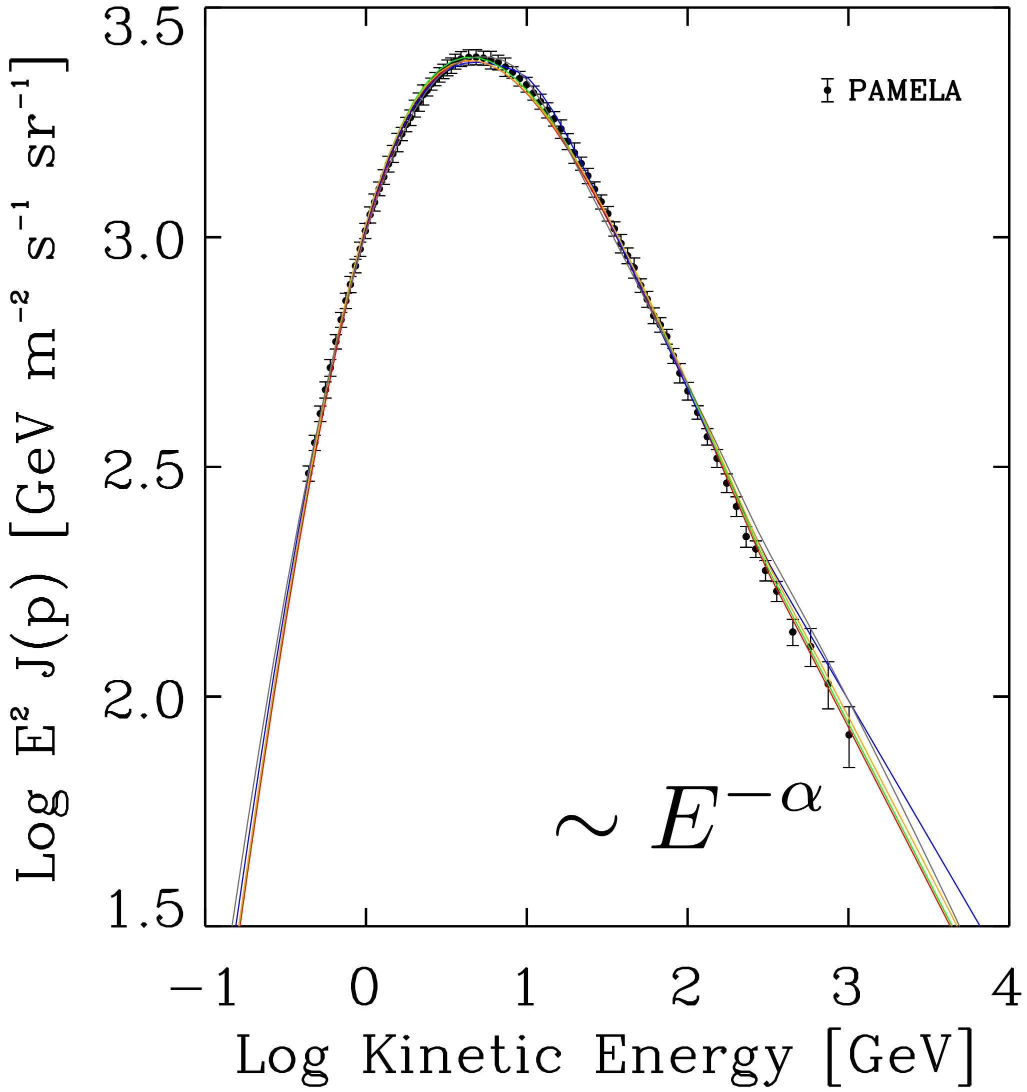
“Local” observables

CE, I.Cholis, D.Grasso, L.Maccione & P.Ullio, PRD, 2012, 1108.0664

Kolmogorov / Kraichnan



$\alpha \sim \gamma_p + \delta$



Is it possible being not-local?

- we can measure the anisotropy:

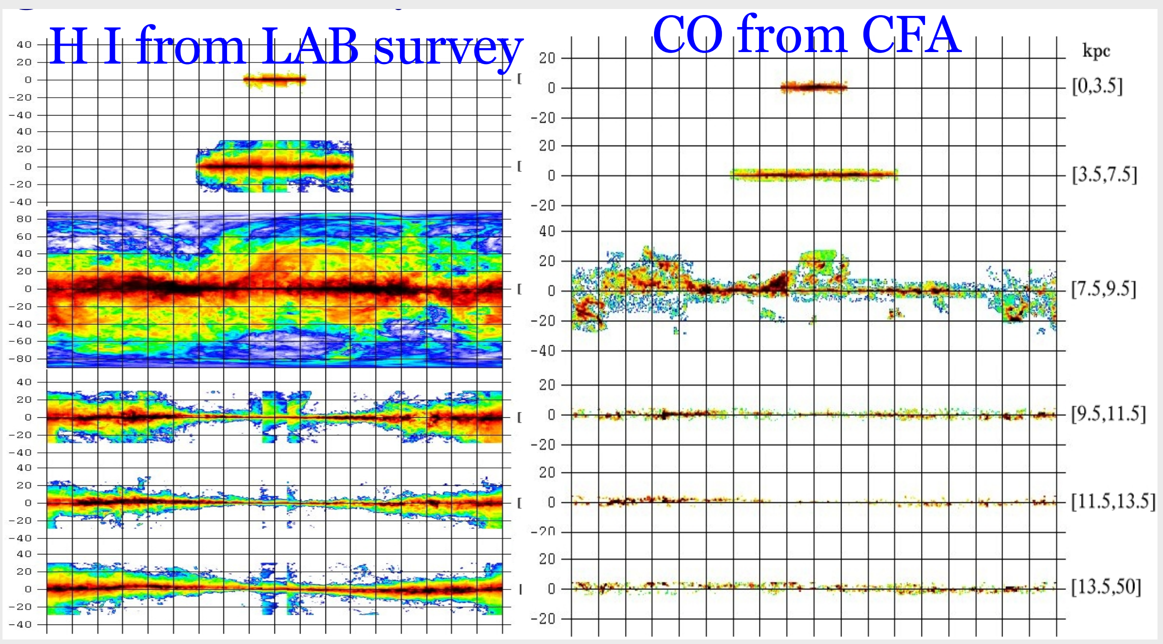
$$\delta \propto \nabla n_{\rm cr}$$

- we can observe diffuse emissions:

$$\phi_\gamma \propto \int_{los} n_{\rm cr} \cdot n_{\rm gas} \, dr$$

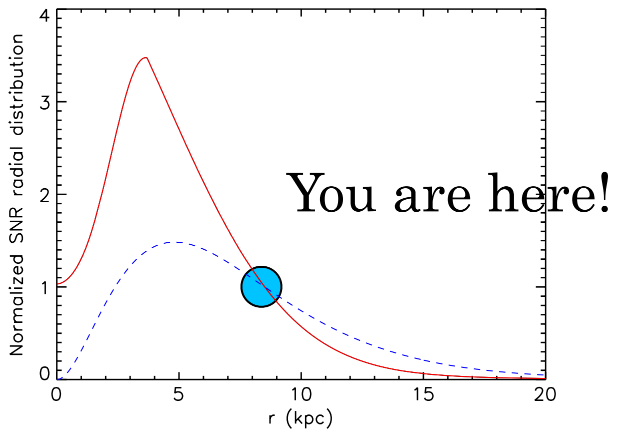
Atomic (HI):
Most massive component with a large filling factor, $z_{1/2}$ ~ 200 pc.

Molecular (H_2):
The most dense component, very clumpy, $z_{1/2}$ ~ 100 pc (derived from the **CO**!)



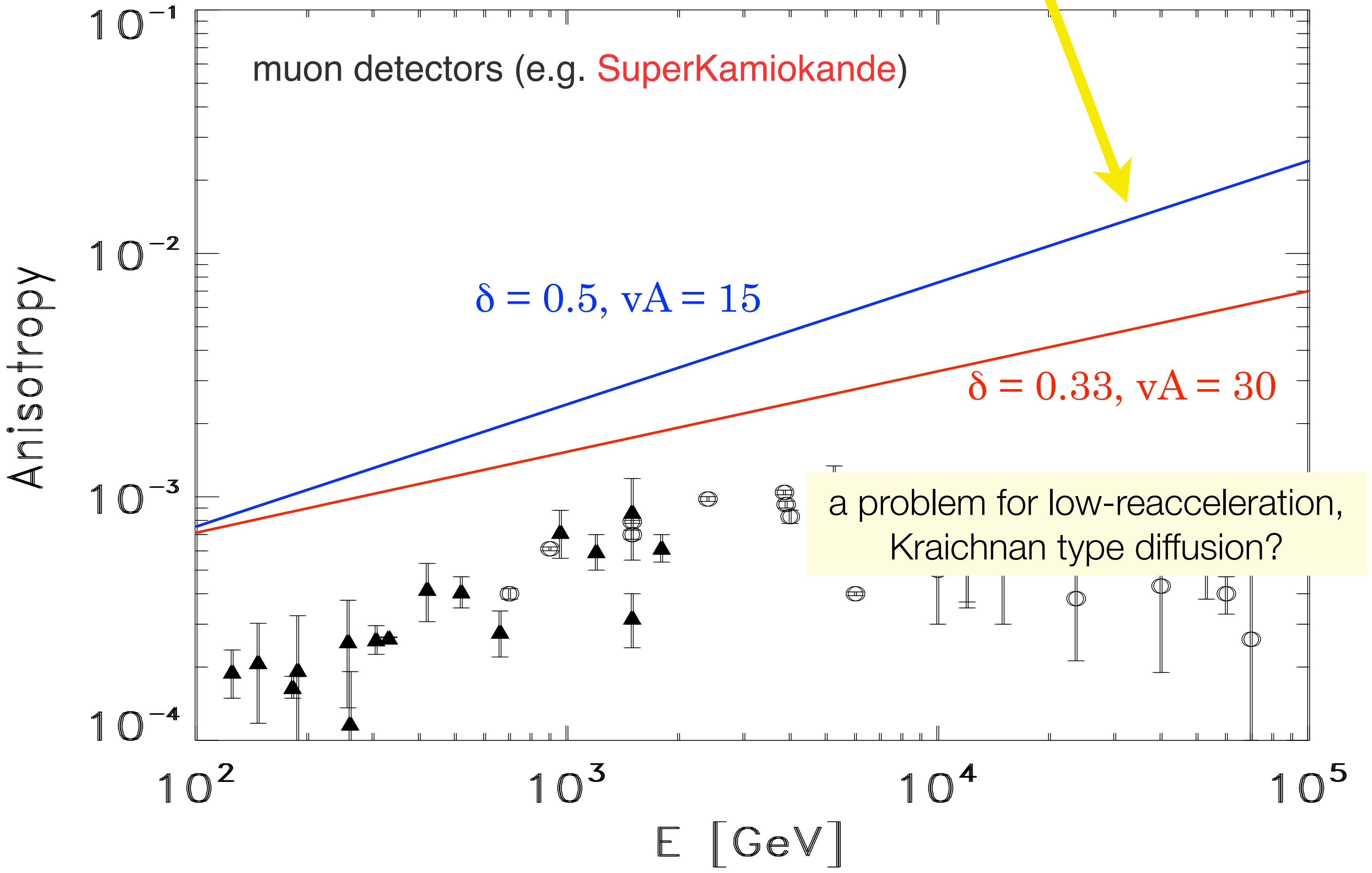
The *anisotropy* problem

Macro Collaboration, PRD, 2003; Super-Kamiokande Collaboration, PRD, 2007



Since CR sources are more abundant in the inner Galaxy, a dipole anisotropy is expected towards the Galactic center:

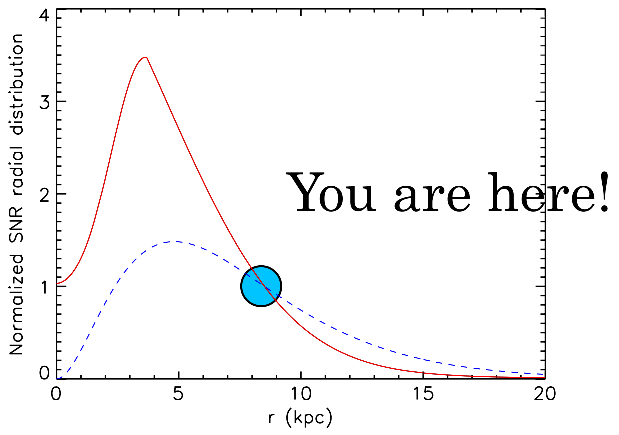
$$\delta_{\vec{x}} = \frac{3D(E)}{c}\frac{\nabla_{\vec{x}} n_{CR}(E,\vec{r},t)}{n_{CR}}$$



a problem for low-reacceleration, Kraichnan type diffusion?

The *anisotropy* problem

P. Blasi and E. Amato, JCAP, 2012



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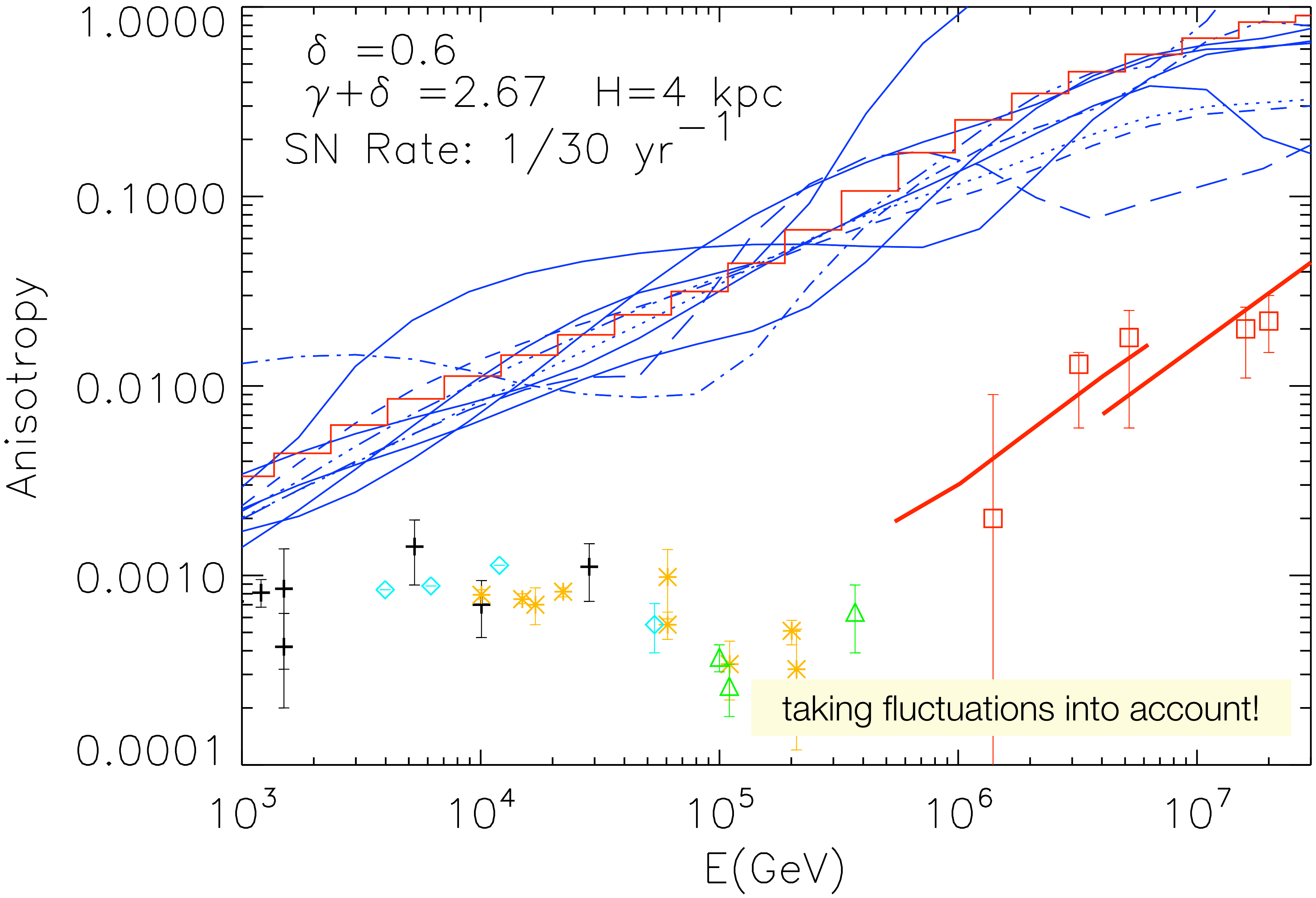
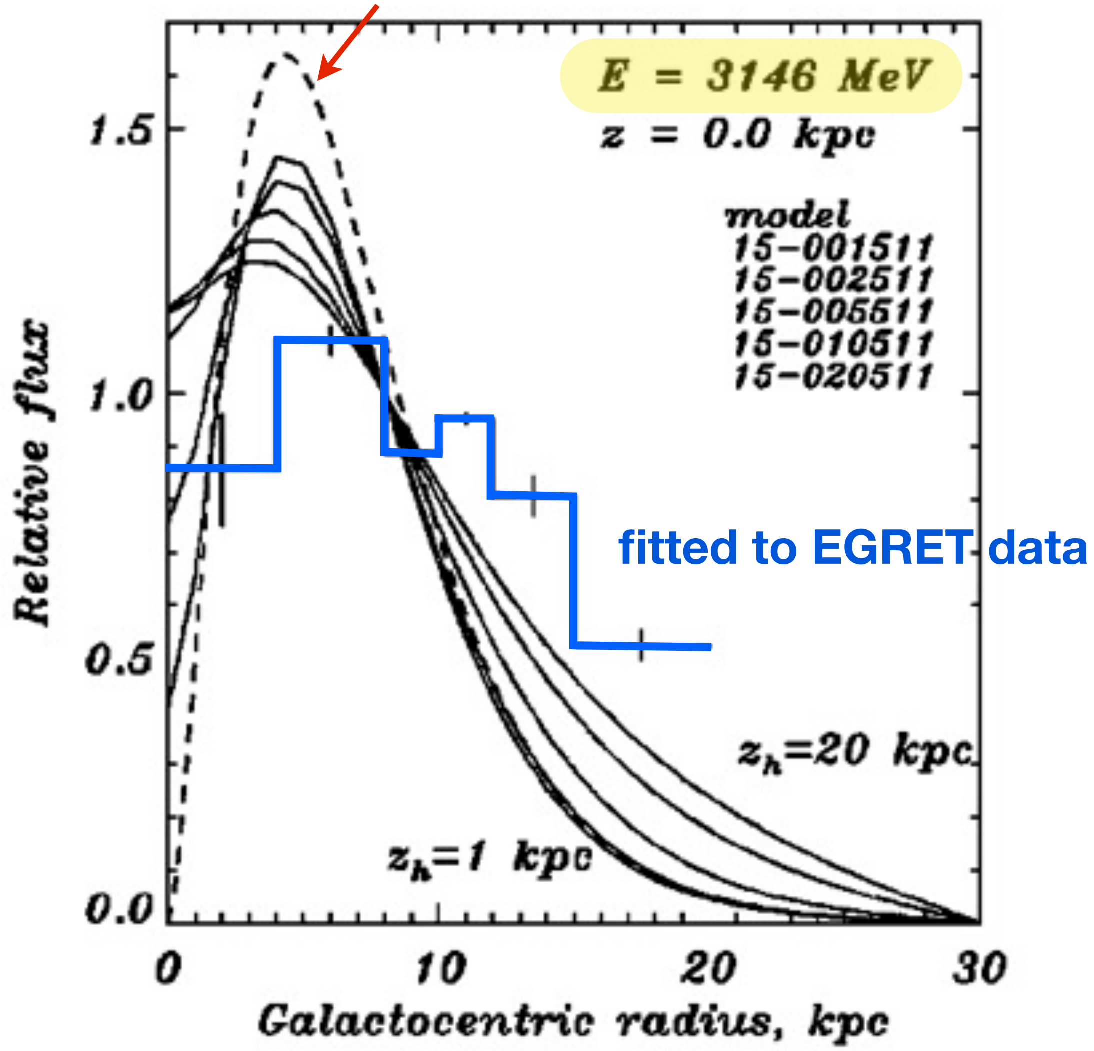


taking fluctuations into account!

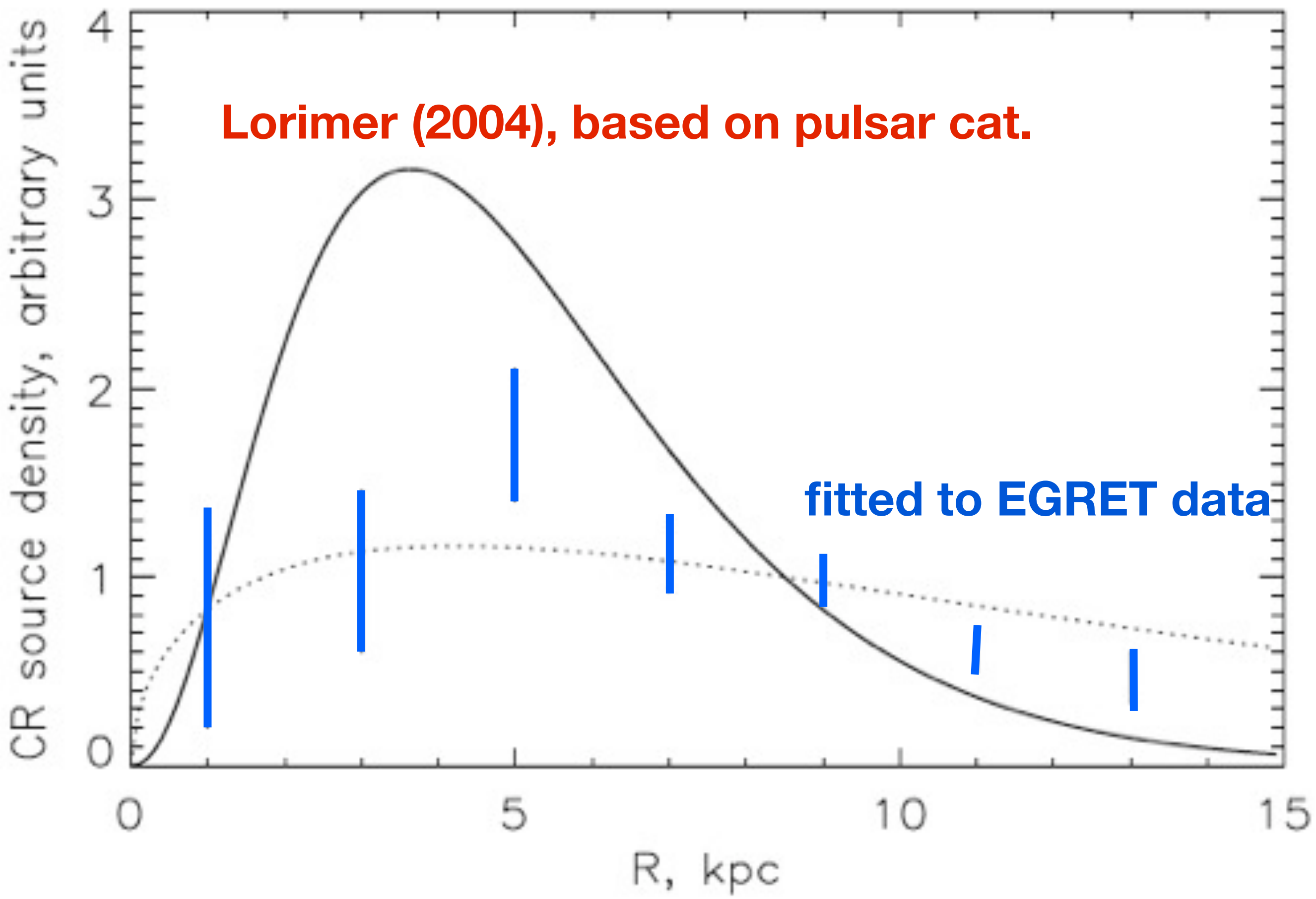
The *gradient* problem

Strong & Mattox, A&A, 1996; Strong et al., ApJ, 2000

Case & Bhattacharya (1996)



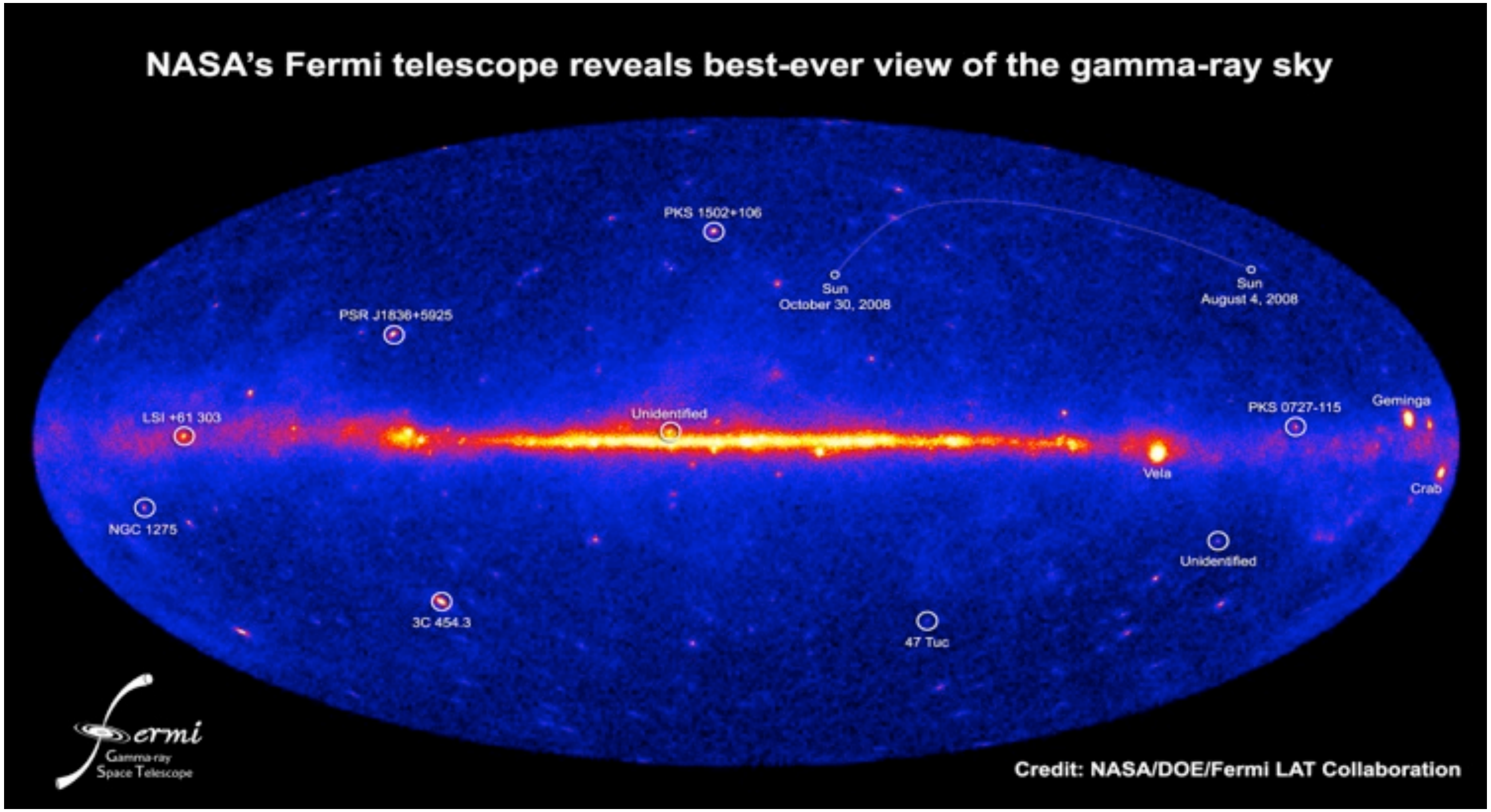
Lorimer (2004), based on pulsar cat.



- CR distribution inferred from gamma-ray data (method goes back to SAS-2/COS-B era) is **flatter** than that computed assuming the observed **SNR** (source) profile.

The *gradient* problem in the FERMI era

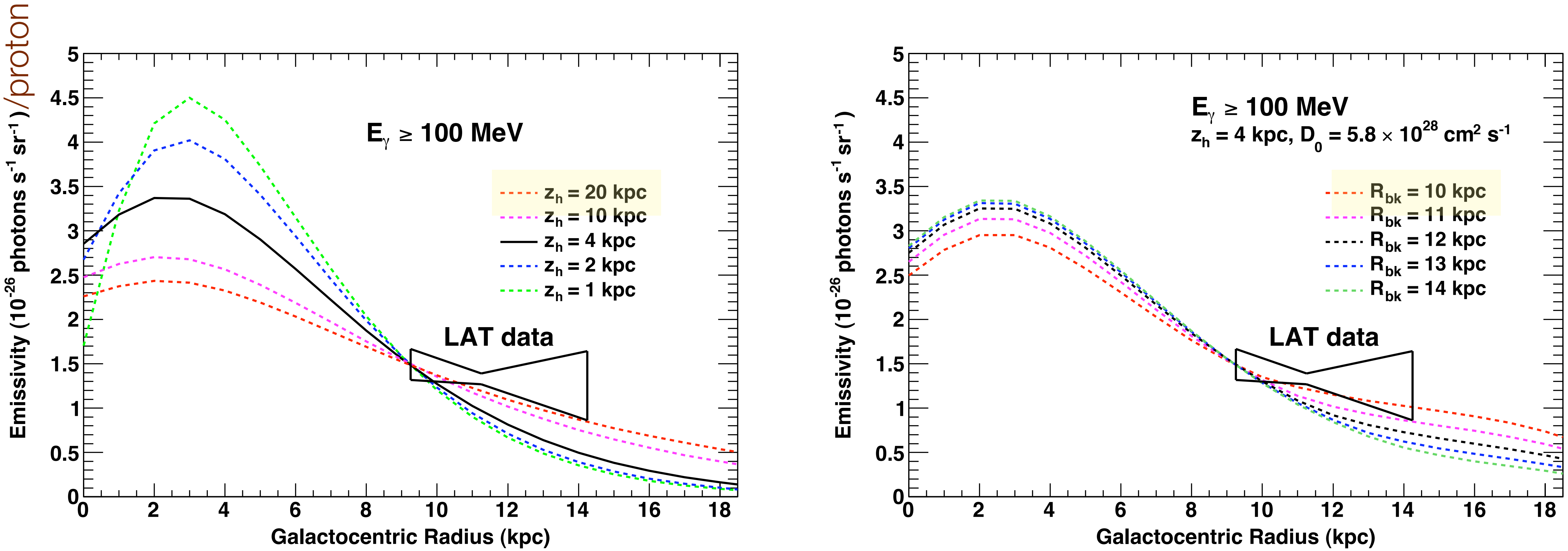
- The extremely accurate gamma ray maps that Fermi is providing are useful to trace the CR distribution throughout all the Galaxy!



Credit: NASA/DOE/Fermi LAT Collaboration

The *gradient* problem in the FERMI era

Fermi Collaboration, ApJ, 2011



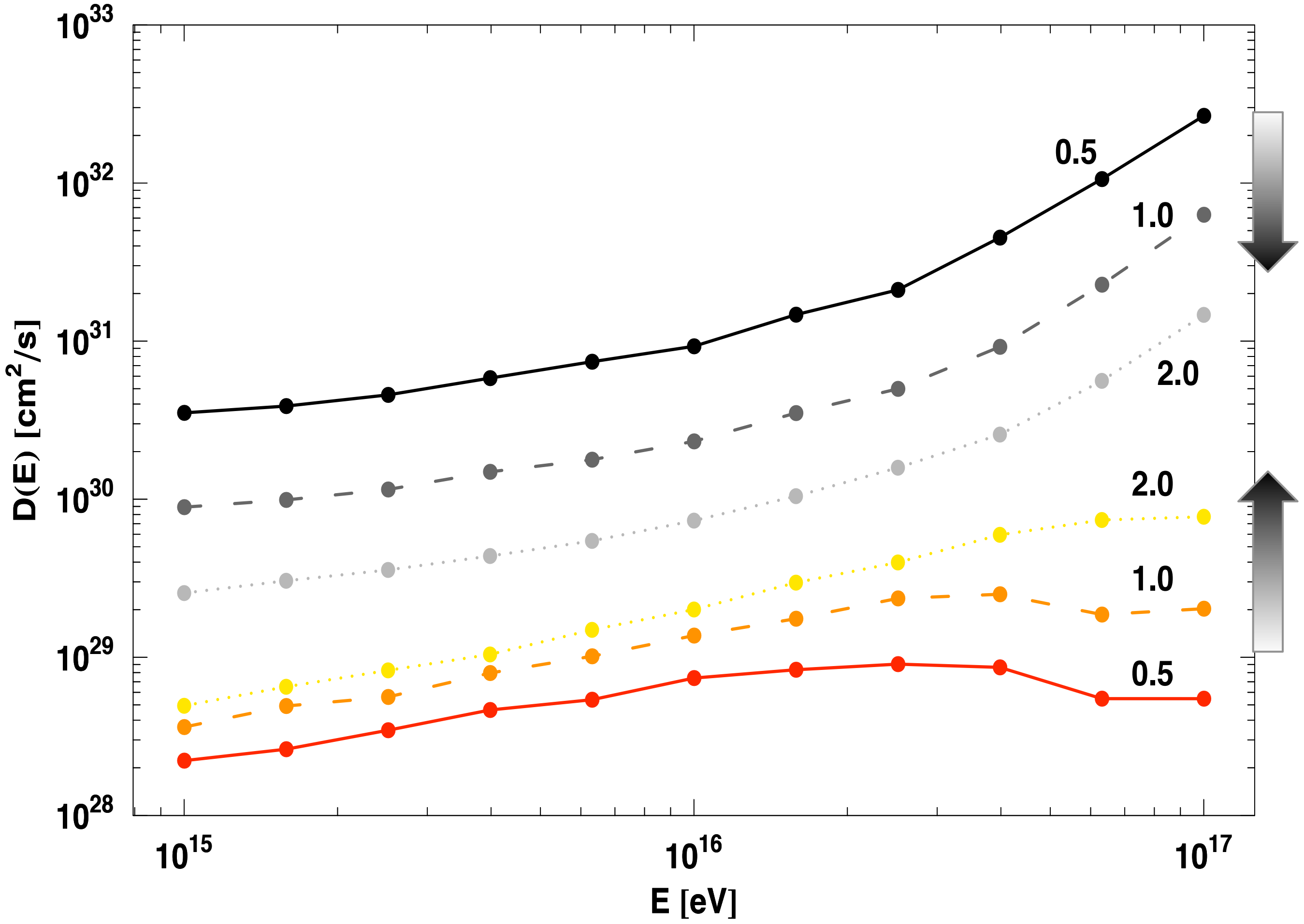
FERMI detected **more** γ's than a prediction based on SNR distribution and standard CR halo: more CR sources, more "dark gas" or larger CR halo?

A new approach

D. De Marco, P. Blasi & S. Todor, JCAP, 2007

- there are some regions in the **inner** Galaxy where a much higher density of CR sources – and hence turbulence – is present.

- According to both quasi-linear theory and numerical simulations:



Parallel diffusion coefficient **decreases** with increasing turbulence

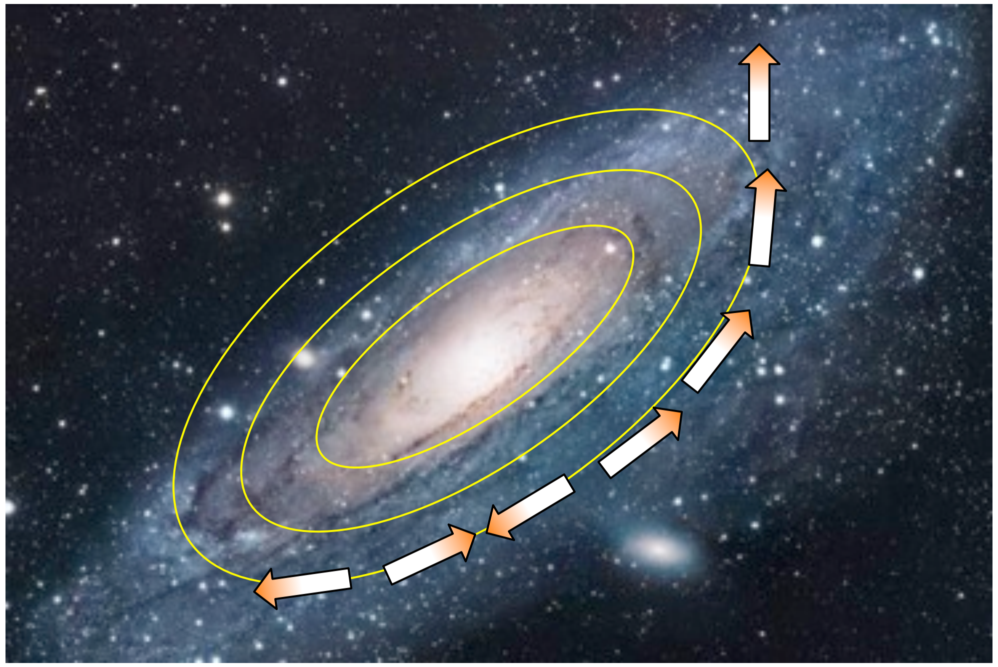
Perpendicular diffusion **increases** with increasing turbulence

Figure 3. Parallel and perpendicular diffusion coefficients as a function of energy for three levels of turbulence. The upper three lines are the parallel diffusion coefficients, while the bottom three represent the perpendicular one. The level of turbulence, $\delta B/B_0$ is given by the numbers attached to the lines.

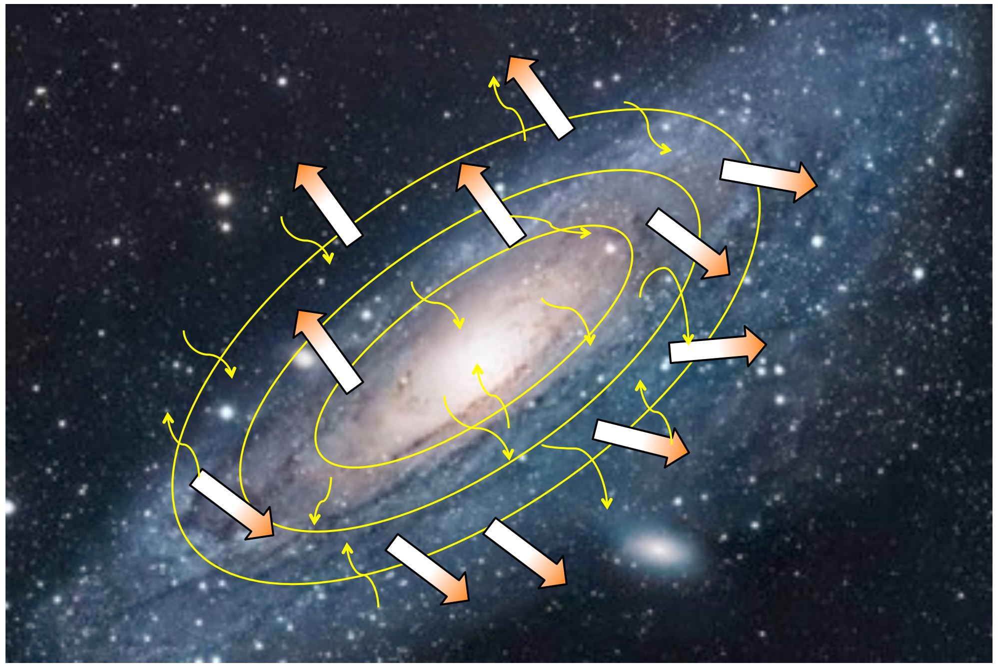
A new approach

- How do the diffusion coefficient depends on turbulence?

If the turbulent field is very low:



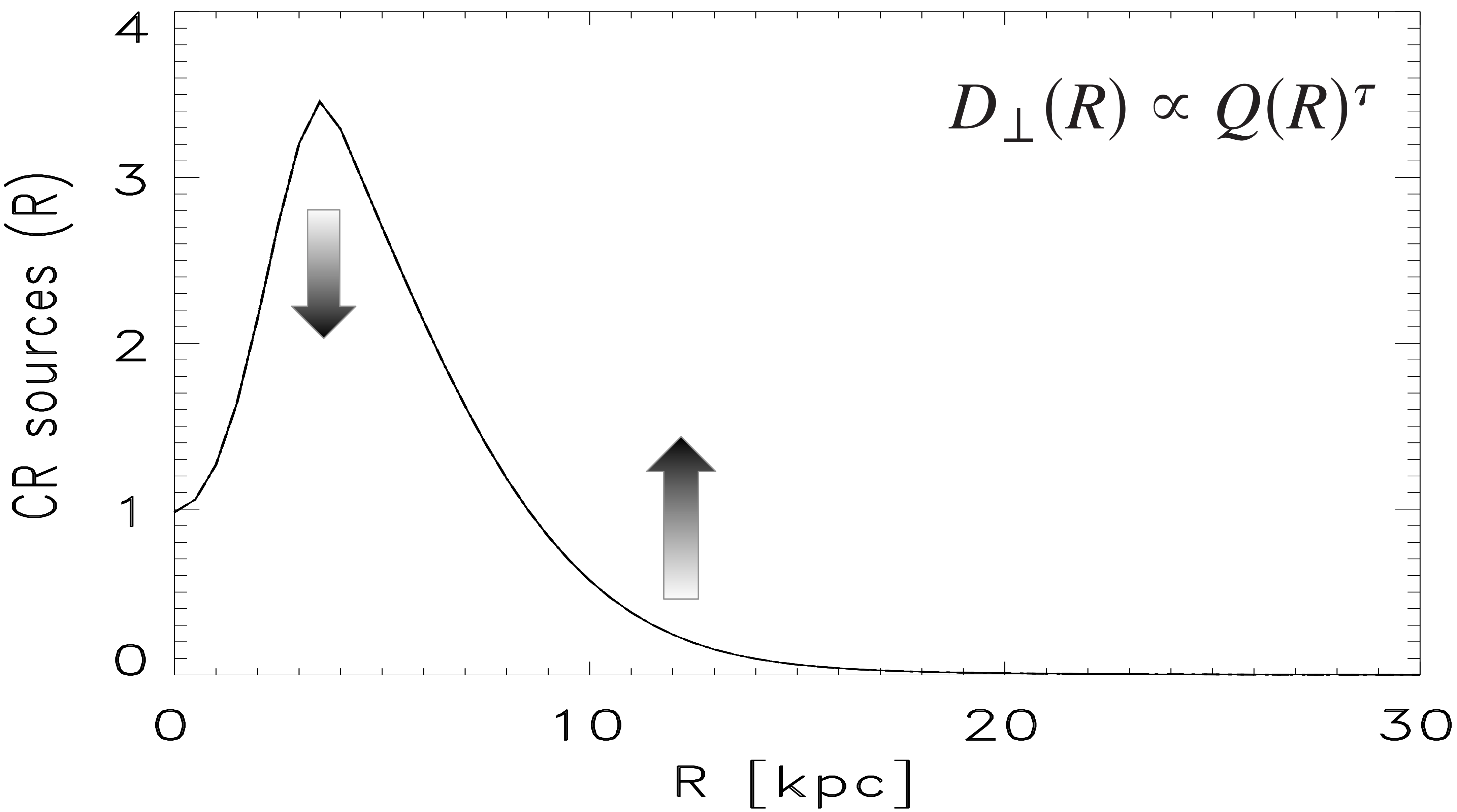
If the turbulent component is comparable to the regular field:



- In the inner galaxy, where turbulence is high, the parallel and perp. diffusion are similar values and the perpendicular escape is the dominant one:

$$\frac{T_{\parallel}}{T_{\perp}} \simeq \left(\frac{R_{\rm arm}}{H}\right)^{2} \frac{D_{\perp}}{D_{\parallel}} \simeq 4\times 10^{2}\left(\frac{H}{4\ {\rm kpc}}\right)^{-2} \frac{D_{\perp}}{D_{\parallel}}$$

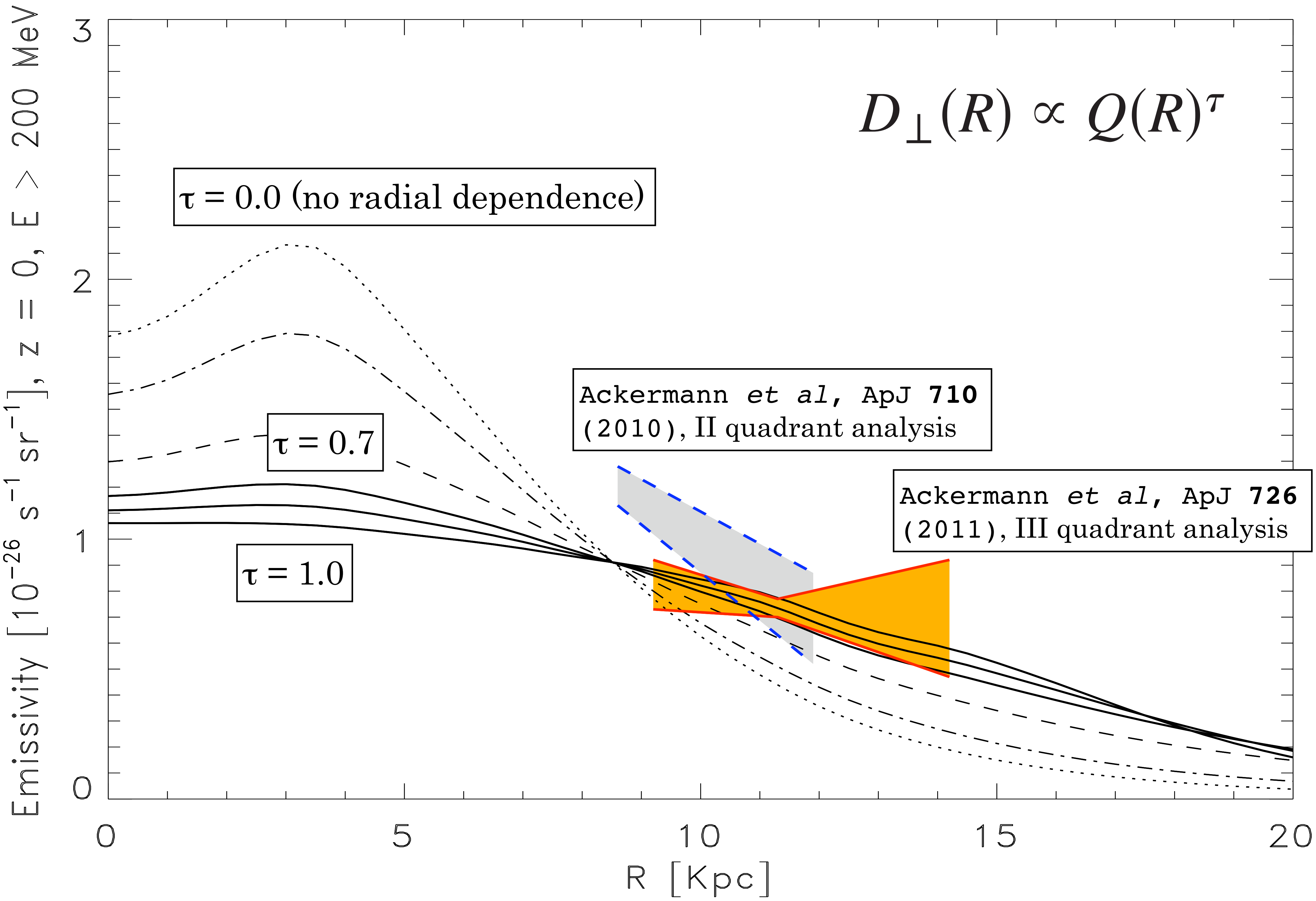
How to solve the gradient problem



- In the regions where CR sources are more abundant turbulence is higher then perpendicular escape is faster, more CR are removed.

Results

CE, D. Gaggero, D. Grasso & L. Maccione, PRL, 2012



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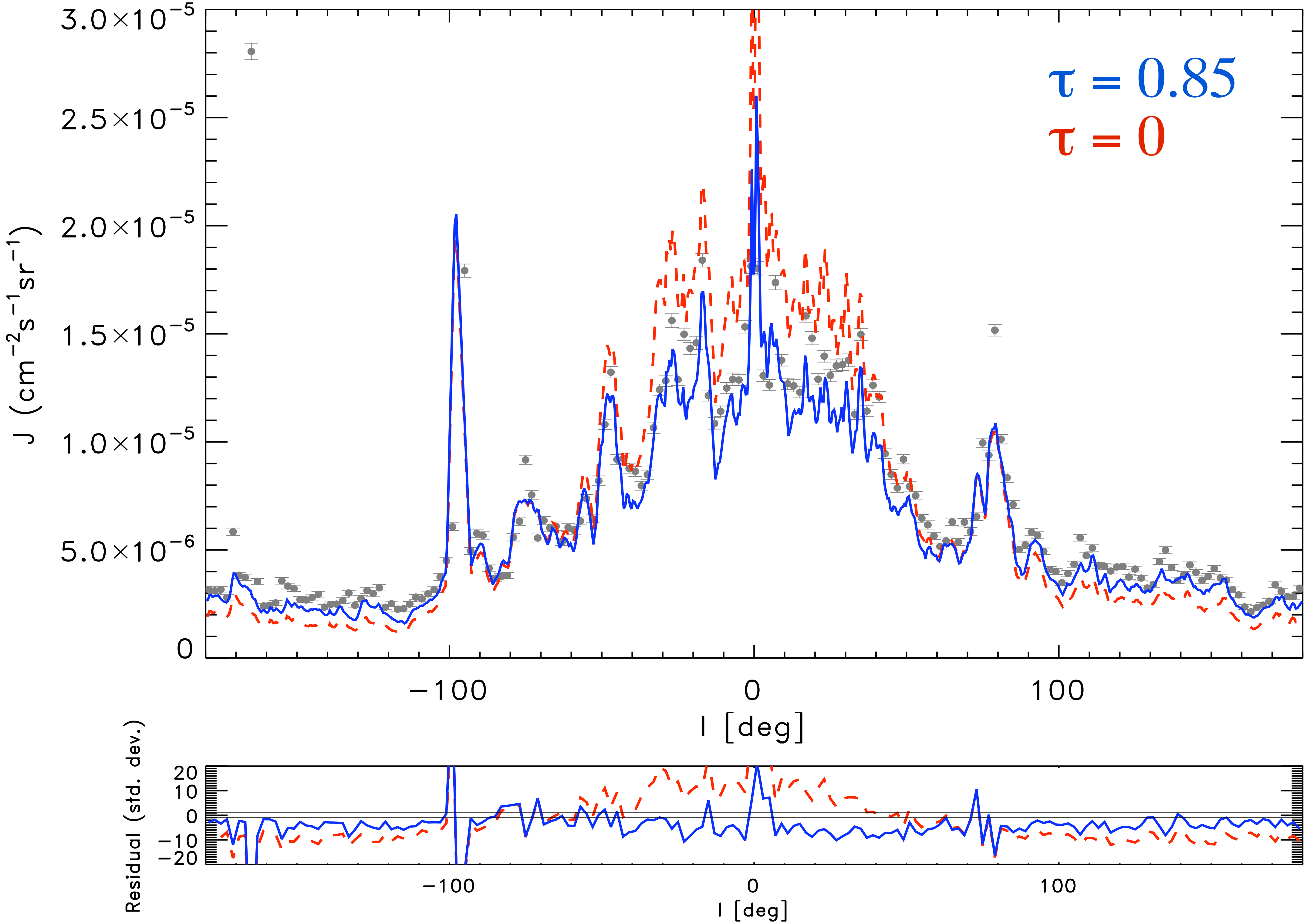
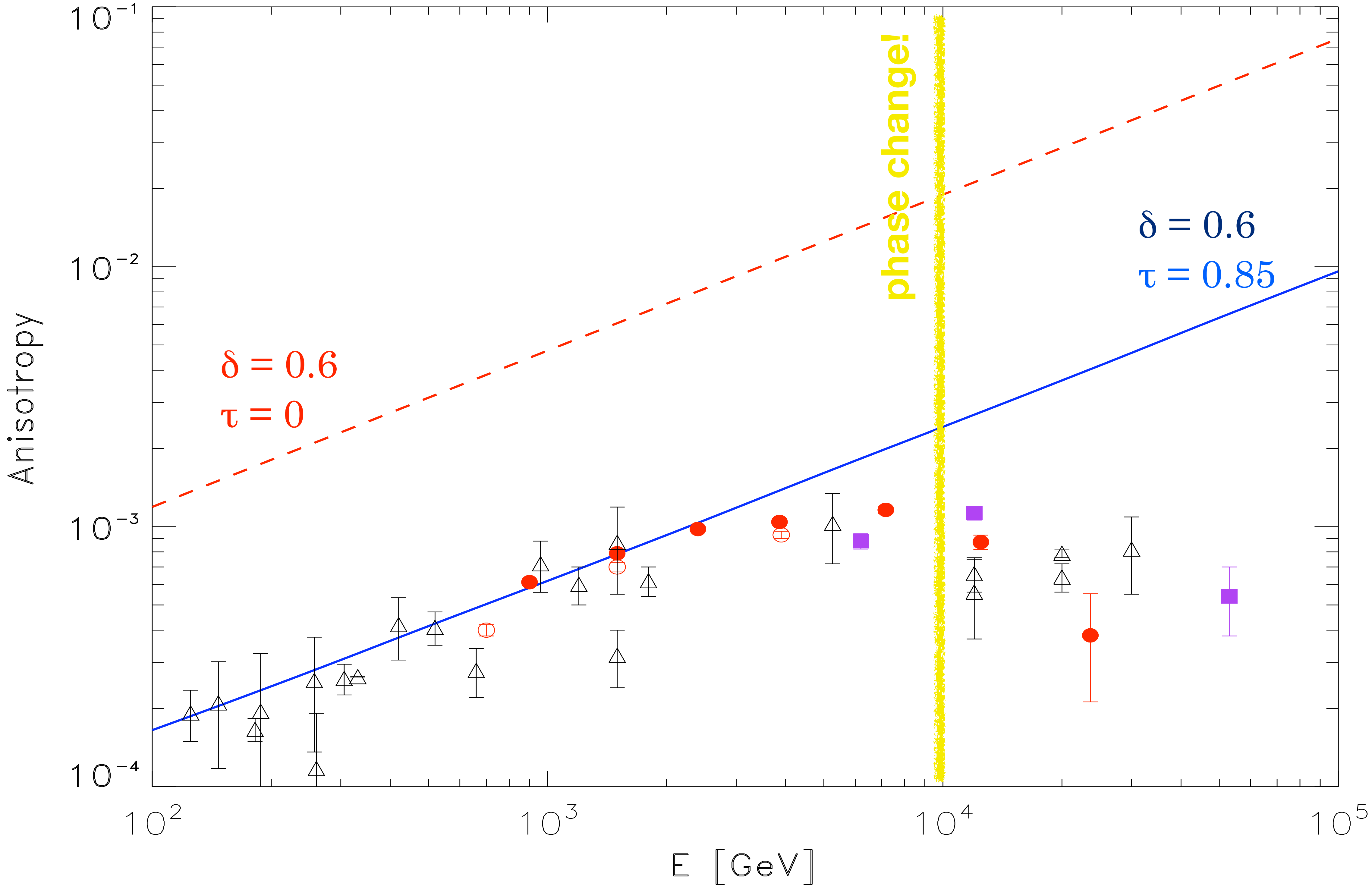


Anisotropy prediction

CE, D. Gaggero, D. Grasso & L. Maccione, PRL, 2012



Large Scale Anisotropy with IceCube / IceTop

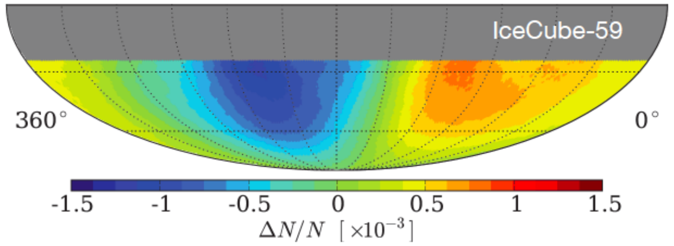
IceCube
muon bundles > 1 TeV

IceTop
CR showers > 100 TeV

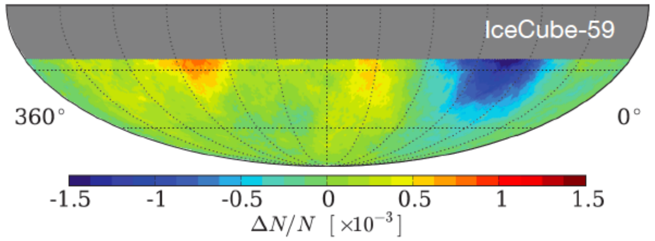
IceCube, ApJ 746, 33 (2012)

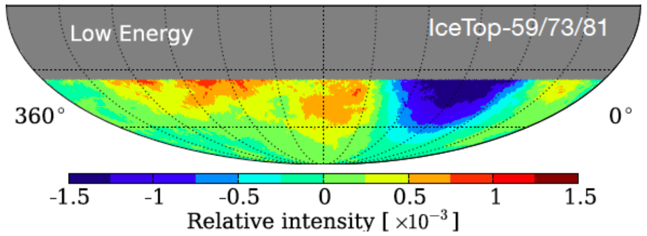
IceCube, ApJ 765, 55 (2013)

20 TeV

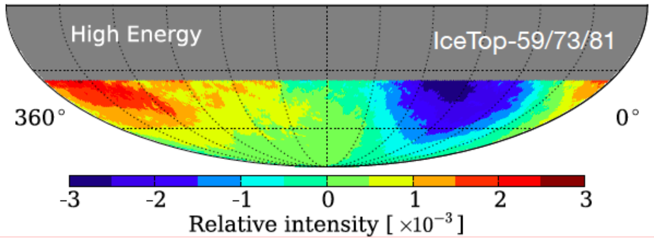


400 TeV

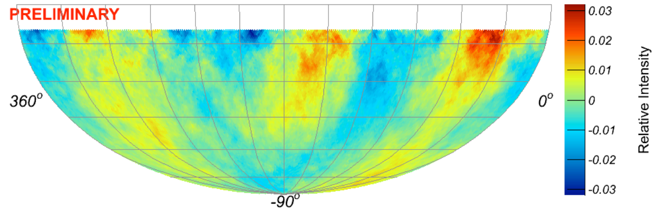




2 PeV



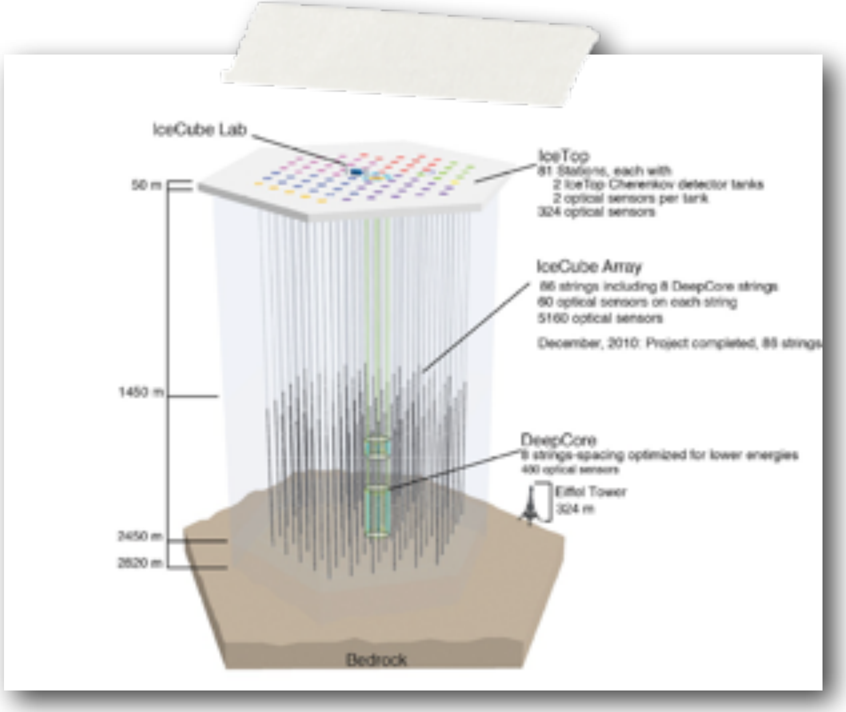
10 PeV



topology changes
between 20 - 400 TeV

anisotropy is not dipole

amplitude increases
with energy



Is it possible to move further from QLT?

H. Yan & A. Lazarian, ApJ, 2008

- particle's pitch angle follows the variation of the *turbulent* magnetic field due to conservation of the adiabatic invariant:

$$\frac{\Delta v_\parallel}{v_\perp} = \frac{\left\langle (B - B_0)^2 \right\rangle^{1/4}}{B_0^{1/2}}$$

- resonance function has a Gaussian broadening:

$$R_n^{\mathrm{NLT}}(k_\parallel v_\parallel - \omega \pm n\Omega) = \frac{\sqrt{\pi}}{k_\parallel \Delta v_\parallel} \exp\left[-\frac{(k_\parallel v\mu - \omega \pm n\Omega)^2}{k_\parallel^2 \Delta v_\parallel^2}\right]$$

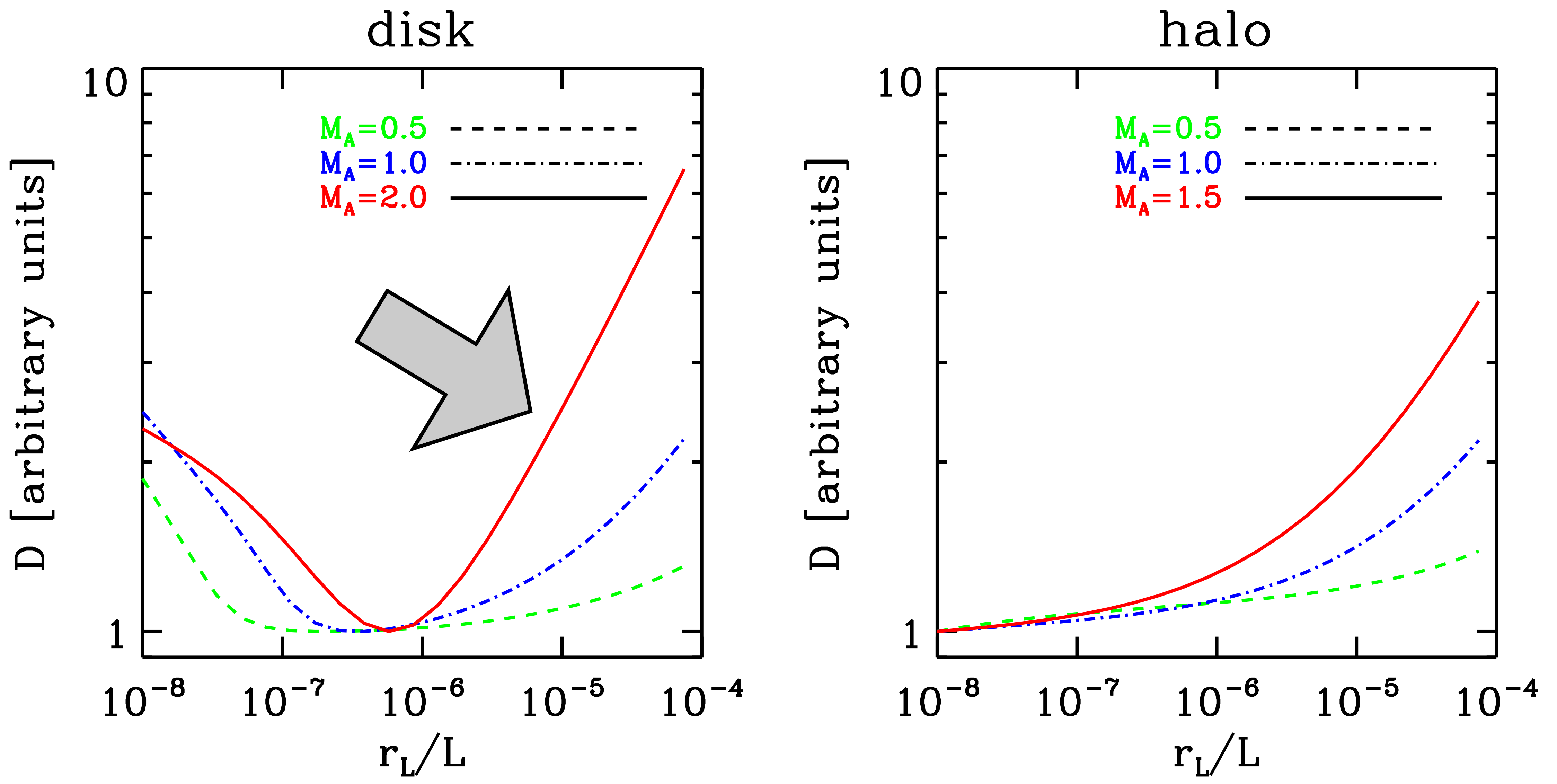
- damping mechanisms make diffusion environment-dependent:

$$D_{\mu\mu} = \frac{\Omega^2(1-\mu^2)}{B_0^2} \int d^3k \, R_n^{\mathrm{NLT}}(\mathbf{k}) \left[\frac{k_\parallel^2}{k^2} J_n'^2(w) I^F(\mathbf{k})\right]$$

Results (preliminary!)

halo = collisionless damping
disk += viscous damping

CE & H. Yan, *in preparation*



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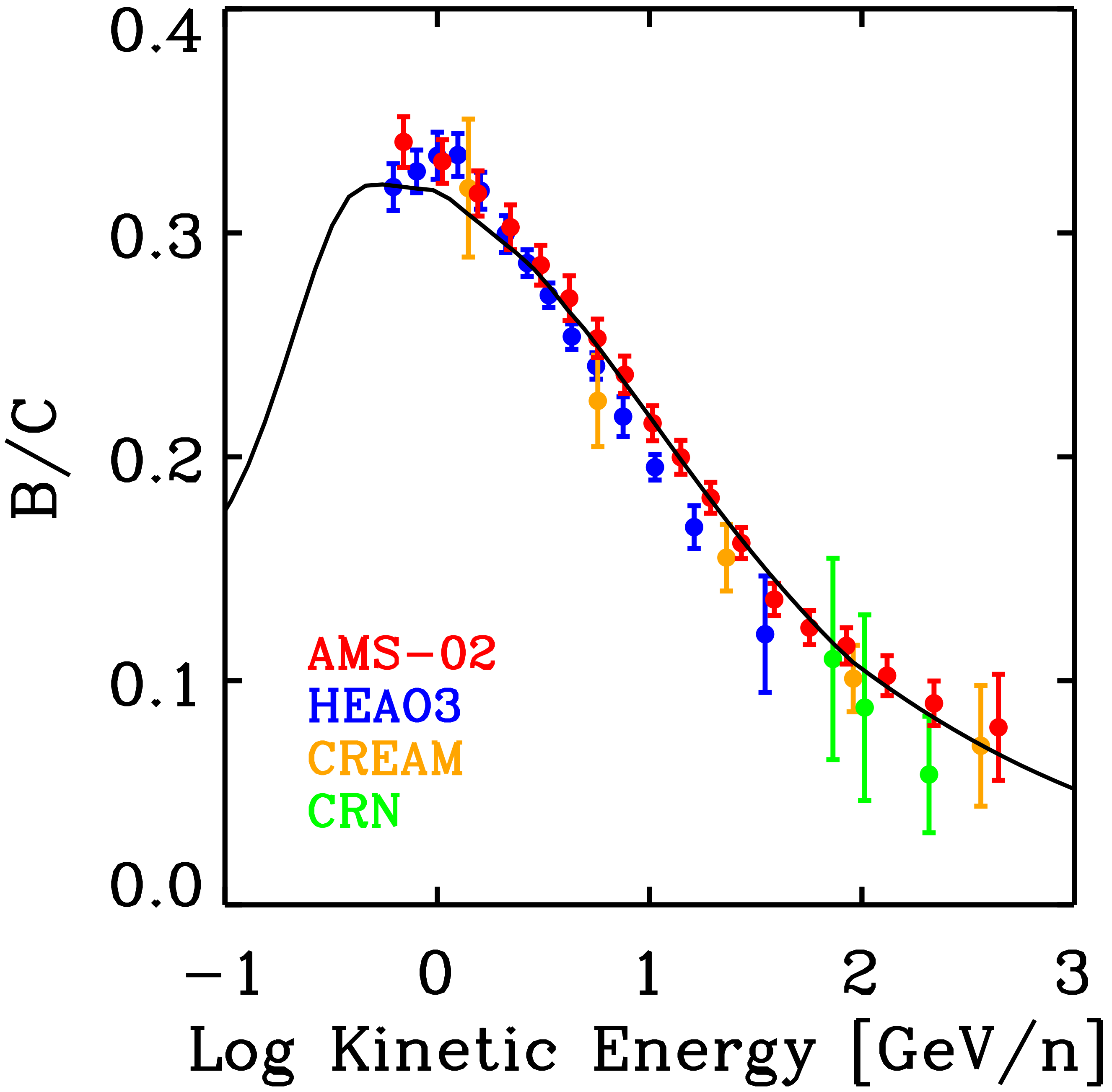


Figure 4. Comparison of our model with $M_A = 2$ for the disk and $M_A = 1$ in the halo and modulated with a 100 GV potential against B/C data. See Table 1 for a reference list of the experimental data.

Conclusions I

- A **position-dependent** perpendicular diffusion coefficient that traces regions of the Galaxy where turbulence is higher offers a natural explanation of not-local CR observations.
- Upcoming (**PLANCK**, LOFAR...) **synchrotron data** can further support this scenario.
- Future diffusion codes should take into account the complexity of the Galaxy, and allow full **3D** simulations, **anisotropic diffusion**, and realistic distributions of **sources**, gas, magnetic fields, especially in the local environments.

DRAGON

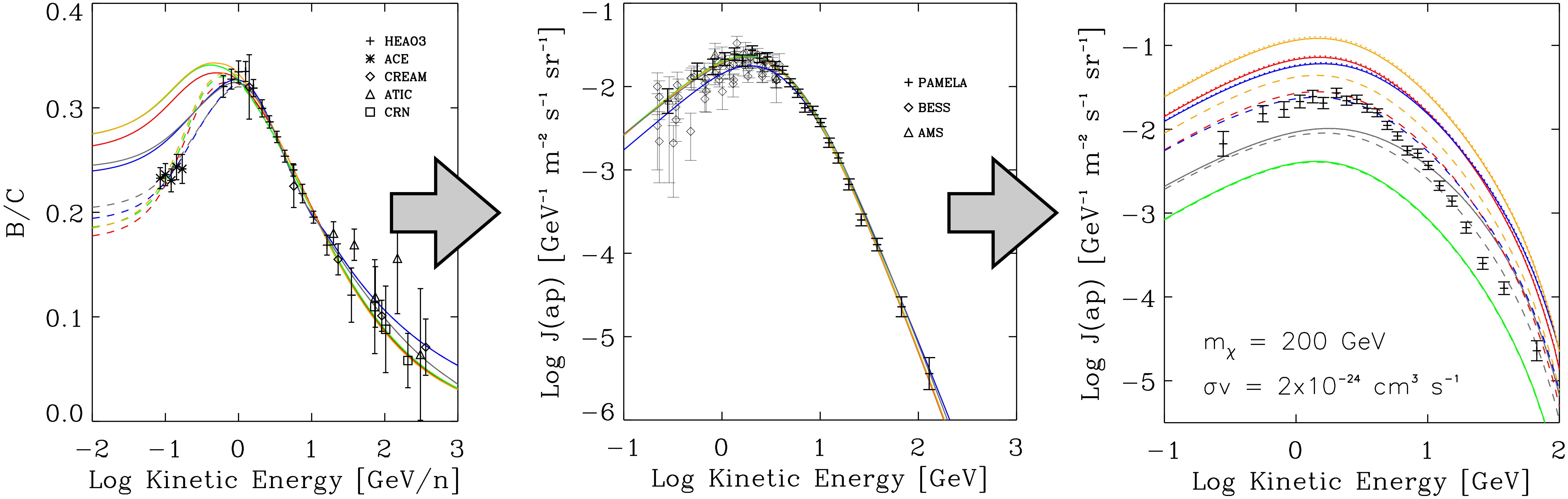
- solve the diffusion equation on a 3D (r,z,E) grid (now also 4D!)
- realistic distributions for sources and ISM
- different models for fragmentation cross sections
- position dependent, anisotropic diffusion
- independent injection spectra for each nuclear species
- speed and memory high-performances (full C++)
- public: http://dragon.hepforge.org

see Daniele’s talk!

Why should I care about it?

Playing with anti-protons from DM

CE, I.Cholis, D.Grasso, L.Maccione & P.Ullio, PRD, 2012, 1108.0664



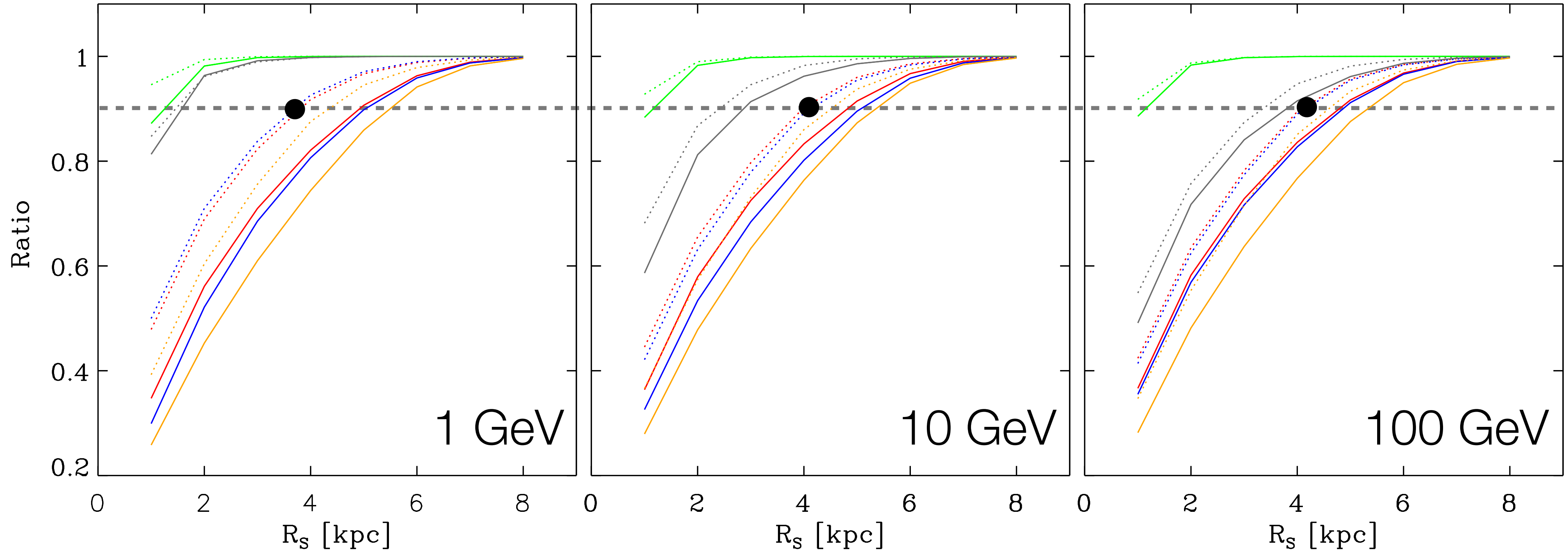
30%

~1 oom

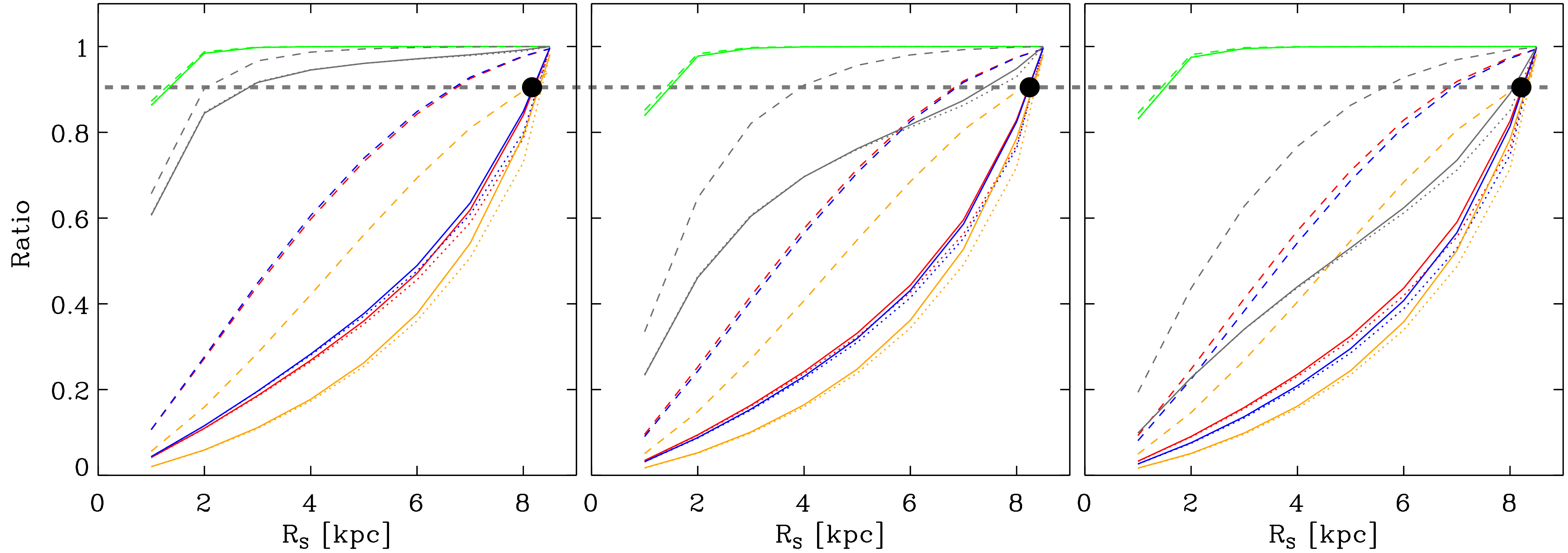
Model	z_t (kpc)	δ	$D_0(10^{28}$ cm^2/s)	η	v_A (km/s)	γ	dv_c/dz (km/s/kpc)	$\chi^2_{B/C}$	χ^2_p	Φ (GV)	$\chi^2_{\bar{p}}$	Color in Figs.
KRA	4	0.50	2.64	−0.39	14.2	2.35	0	0.6	0.47	0.67	0.59	Red
KOL	4	0.33	4.46	1.	36.	1.78/2.45	0	0.4	0.3	0.36	1.84	Blue
THN	0.5	0.50	0.31	−0.27	11.6	2.35	0	0.7	0.46	0.70	0.73	Green
THK	10	0.50	4.75	−0.15	14.1	2.35	0	0.7	0.55	0.69	0.62	Orange
CON	4	0.6	0.97	1.	38.1	1.62/2.35	50	0.4	0.53	0.21	1.32	Gray

It’s all about locality!

CE, I.Cholis, D.Grasso, L.Maccione & P.Ullio, PRD, 2012, 1108.0664



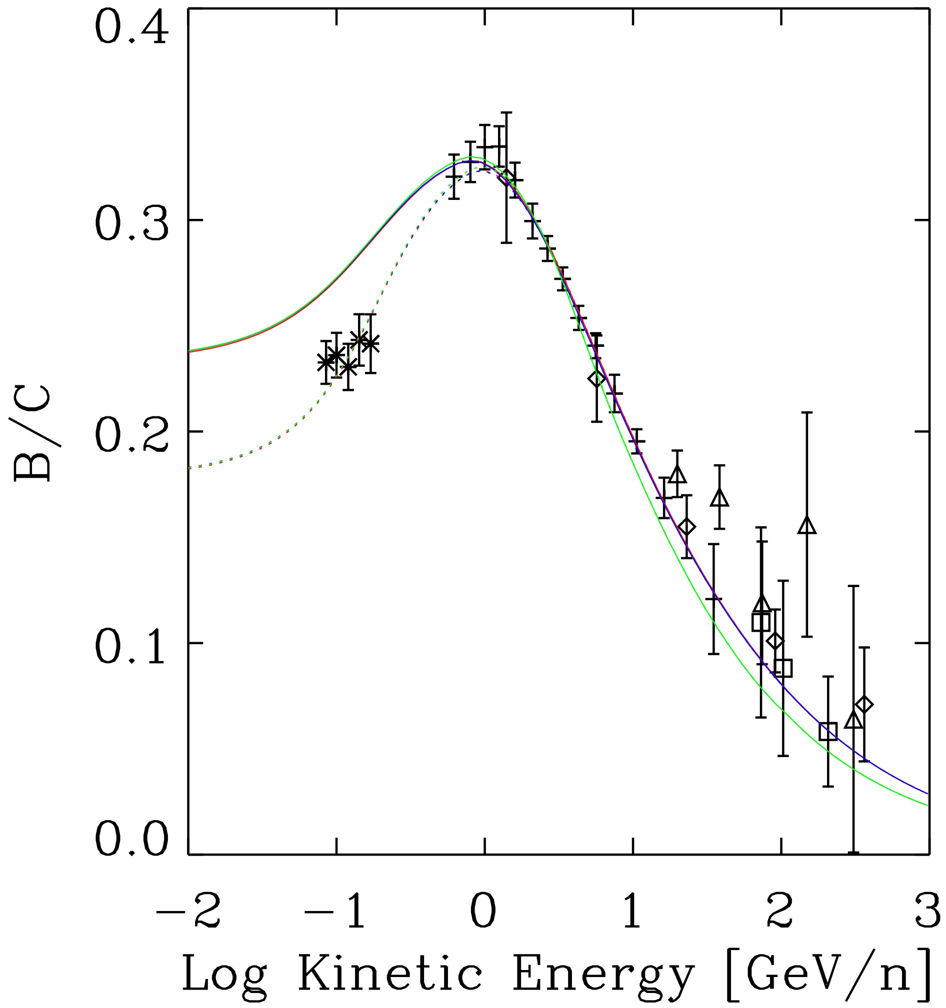
solid: primary protons
dotted: anti-protons

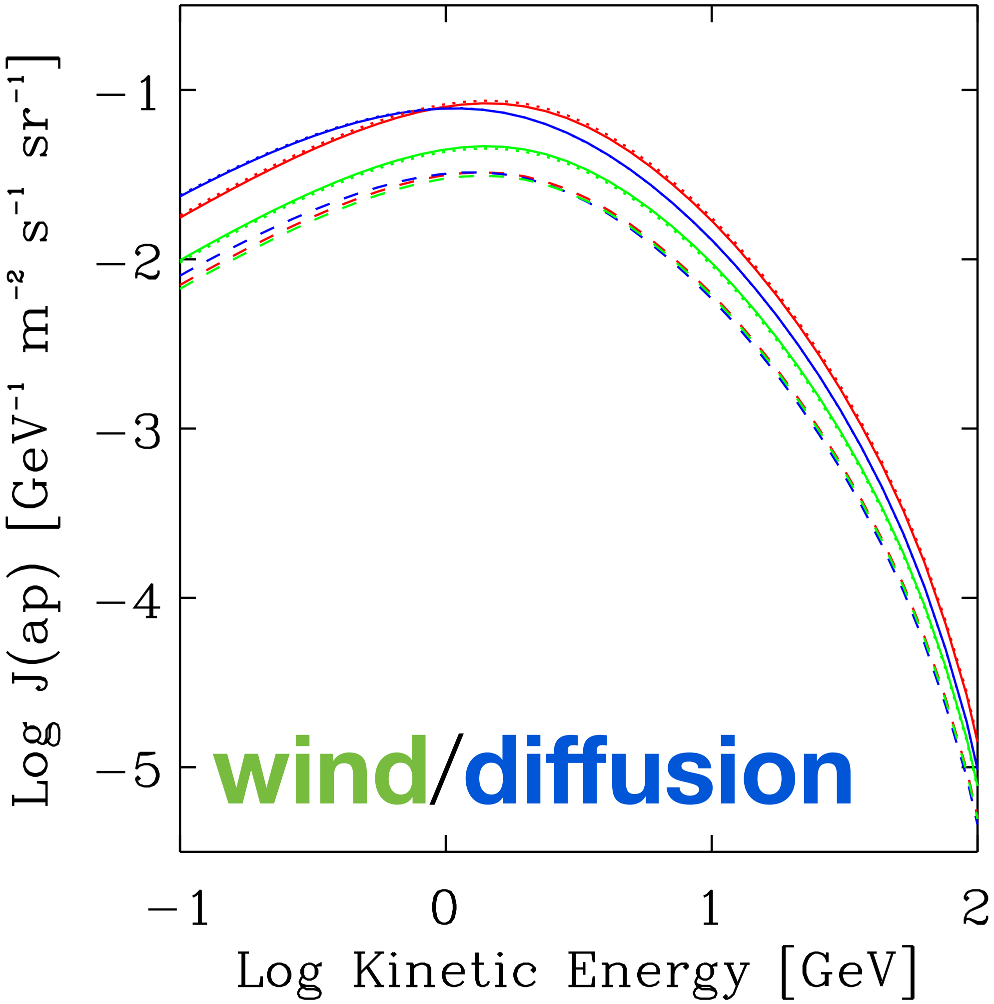


solid: cusped profile
dotted: cored profile

Unavoidable uncertainties?

CE, I.Cholis, D.Grasso, L.Maccione & P.Ullio, PRD, 2012, 1108.0664





multiwave/messenger is the solution!

Conclusions II

- If your CR source is the “galactic-center” do not trust too much “global models” that are “locally” tuned...
- ...or at least “put a warning” about uncertainties due to not-locality.
- A lot of work is still ahead for understanding ISM propagation **before** to be robust in DM searches with charged particles!