Cosmic-rays propagation in the ISM

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HELMHOLTZ | ASSOCIATION
Alliance for Astroparticle Physics

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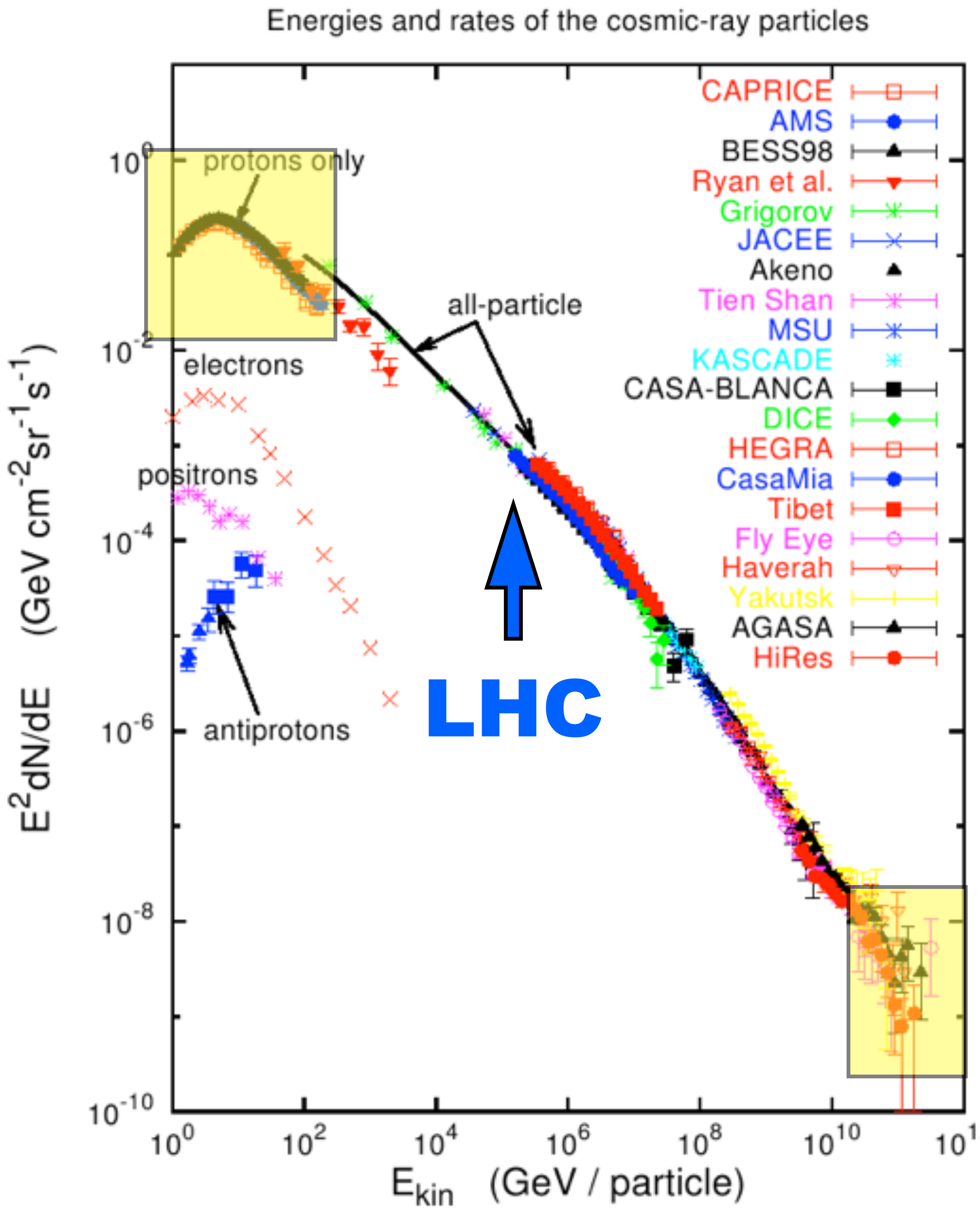
Geneva | SUGAR15 | 22th of January 2015

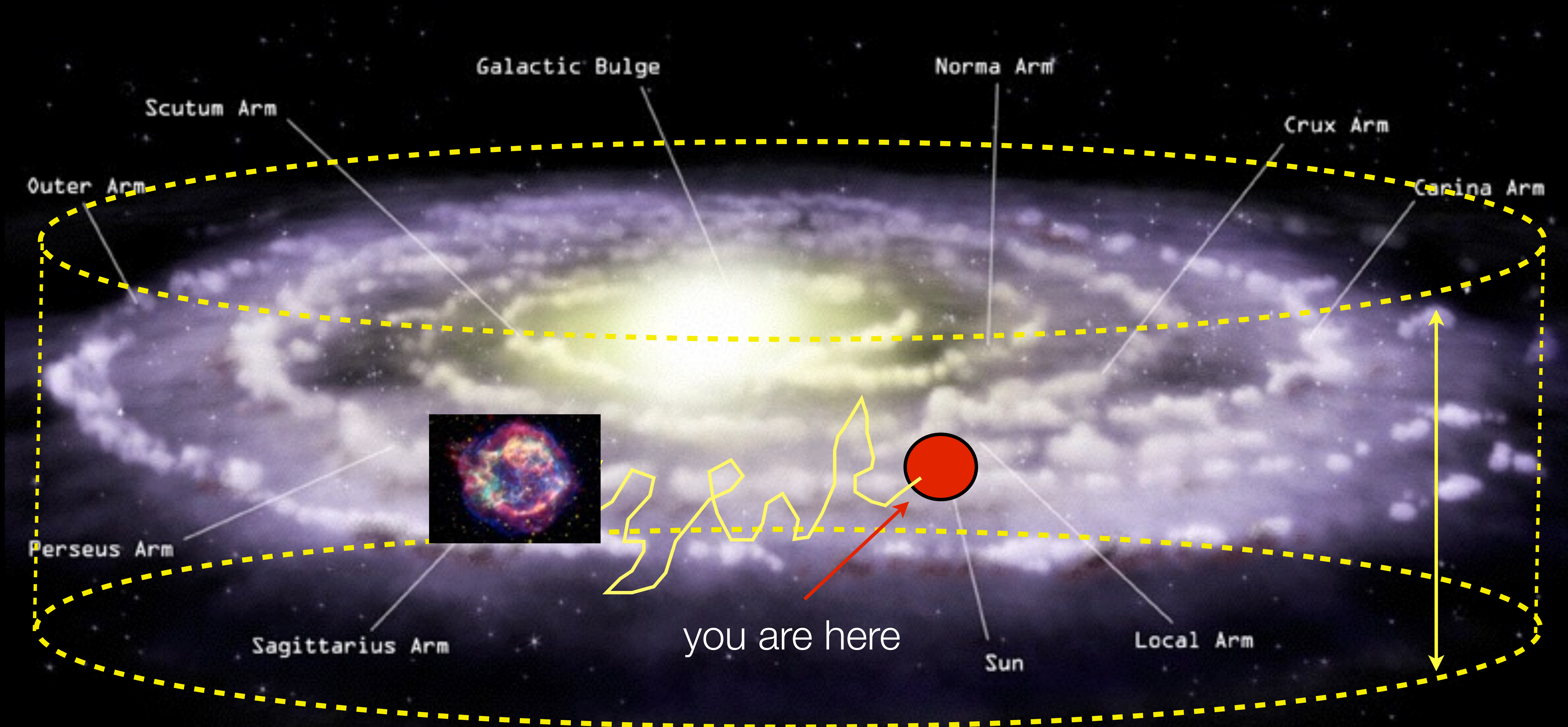
1/cm^2/s



1/km^2/century

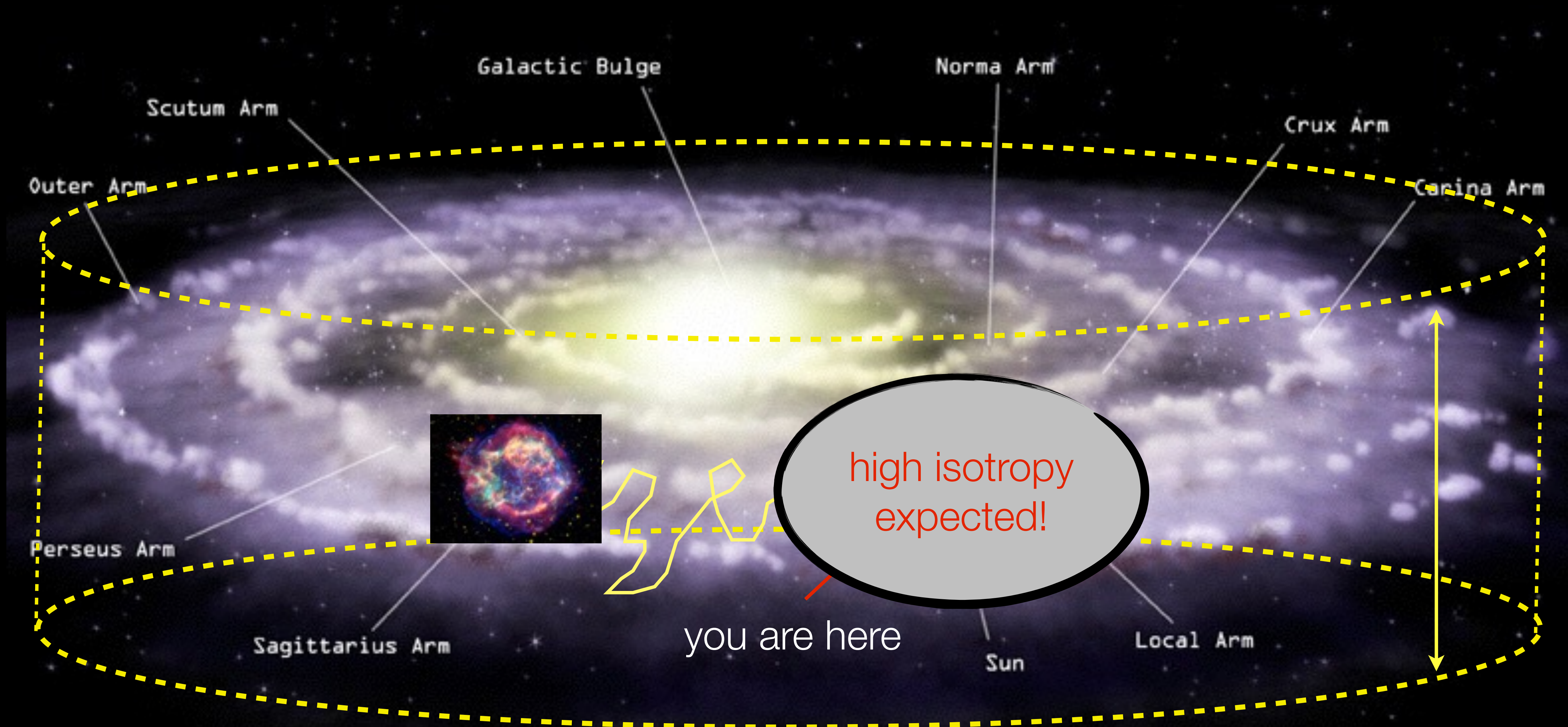
$$L_{\rm SN} \sim R_{\rm SN} E_{\rm kin} \sim 3 \times 10^{41}\,{\rm erg/s}$$

Galactic Propagation



L = 1-10 kpc

Galactic Propagation



L = 1-10 kpc

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
- 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

CR Diffusion in the MW

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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:

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

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

Reacceleration:

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

Ginzburg & Syrovatsky, 1964

Outline

Diffusion is (almost) constant, isotropic, symmetric.

is diffusion really constant?

is diffusion really isotropic?

is diffusion really symmetric?

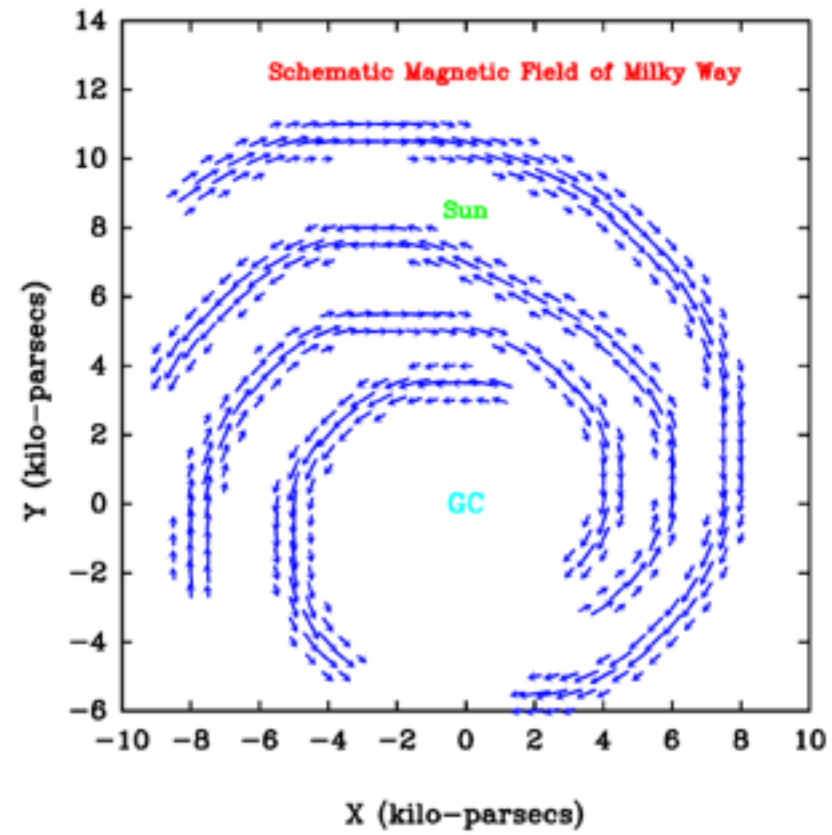
Galactic CR diffusion from “first principle”

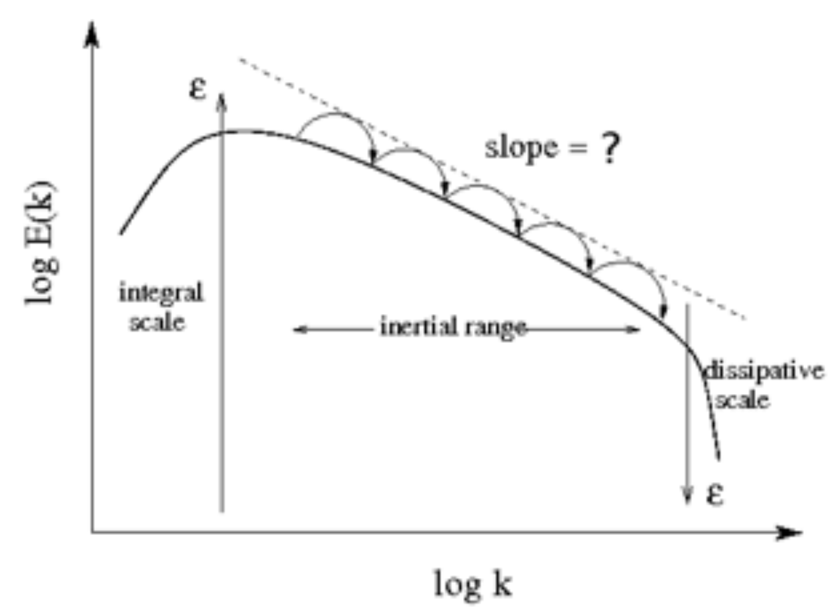
Assumptions:

- GCR diffuse in the ISM turbulent magnetic field
- The turbulent field can be modeled with a Kolmogorov isotropic power-spectrum
- The turbulent field amplitude is a small fluctuation with respect to the regular component
- Resonant interaction wave-particle

It follows:

$$D = D_0 \rho^{\delta}$$





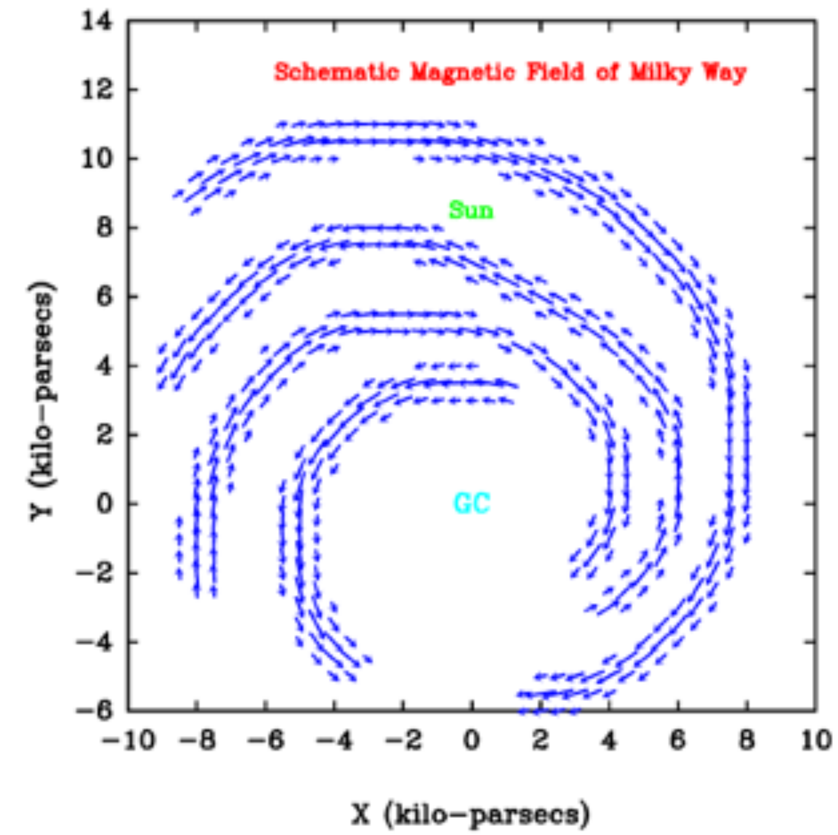
Galactic CR diffusion from “first principle”

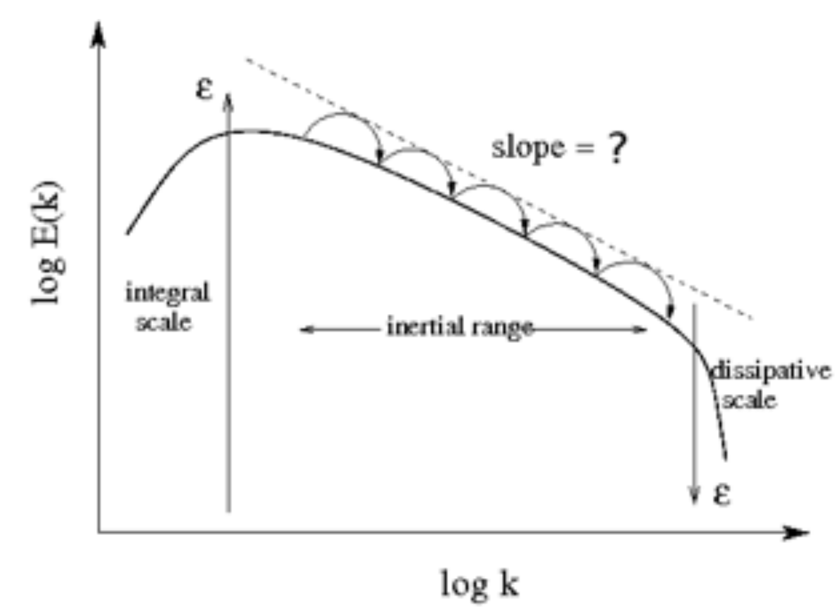
Assumptions:

- ~~GCR diffuse in the ISM turbulent magnetic field~~
  see Blasi, Amato & Serpico, PRL, 2012
- ~~The turbulent field can be modeled with a Kolmogorov isotropic power-spectrum~~
  see GS95, Cho & Lazarian, PRL, 2002
- ~~The turbulent field amplitude is a small fluctuation with respect to the regular component~~
  see Planck intermediate results. XIX. (A&A sub.)
- ~~Resonant interaction wave-particle~~
  see Yan & Lazarian, PRL, 2002

It follows:

$$D = D_0 \rho^{\delta}$$

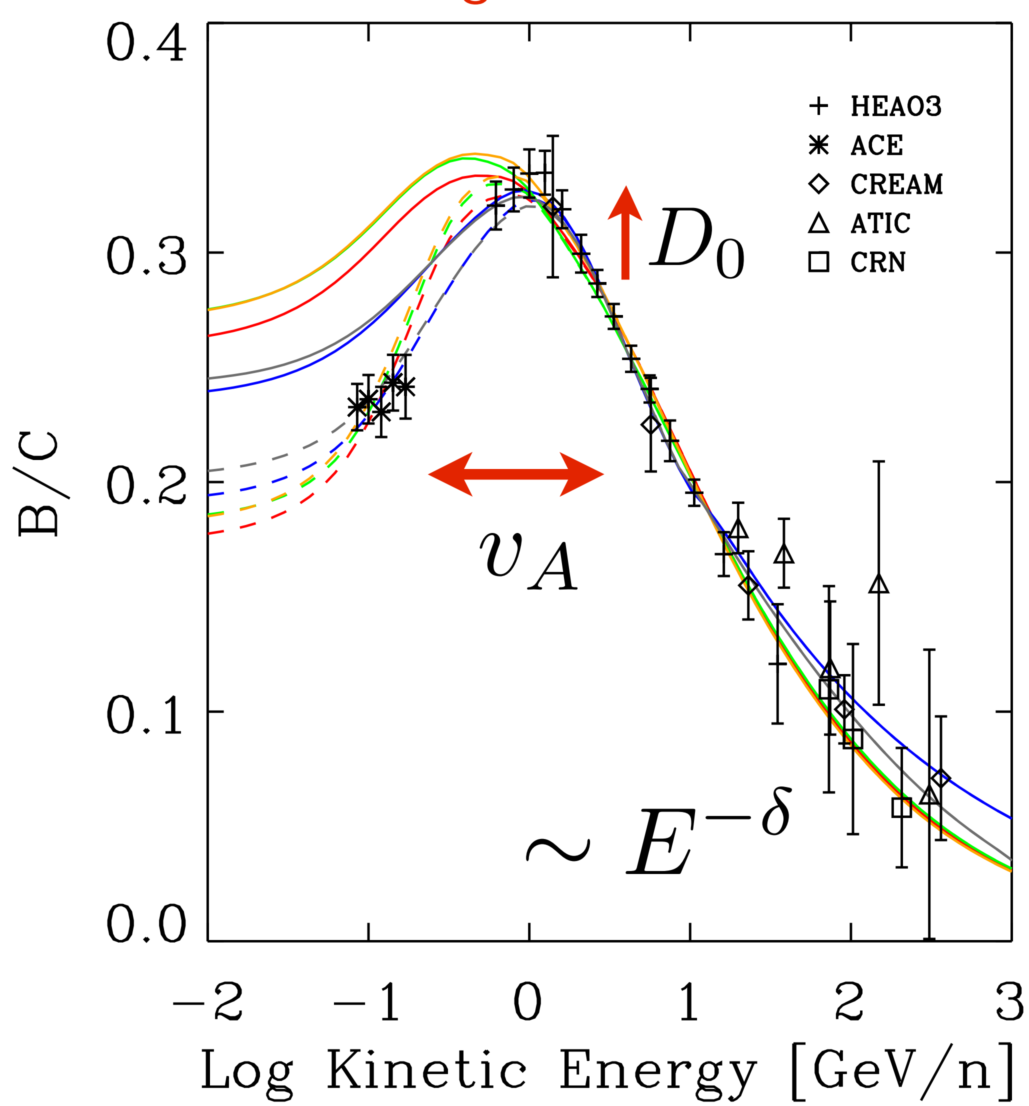




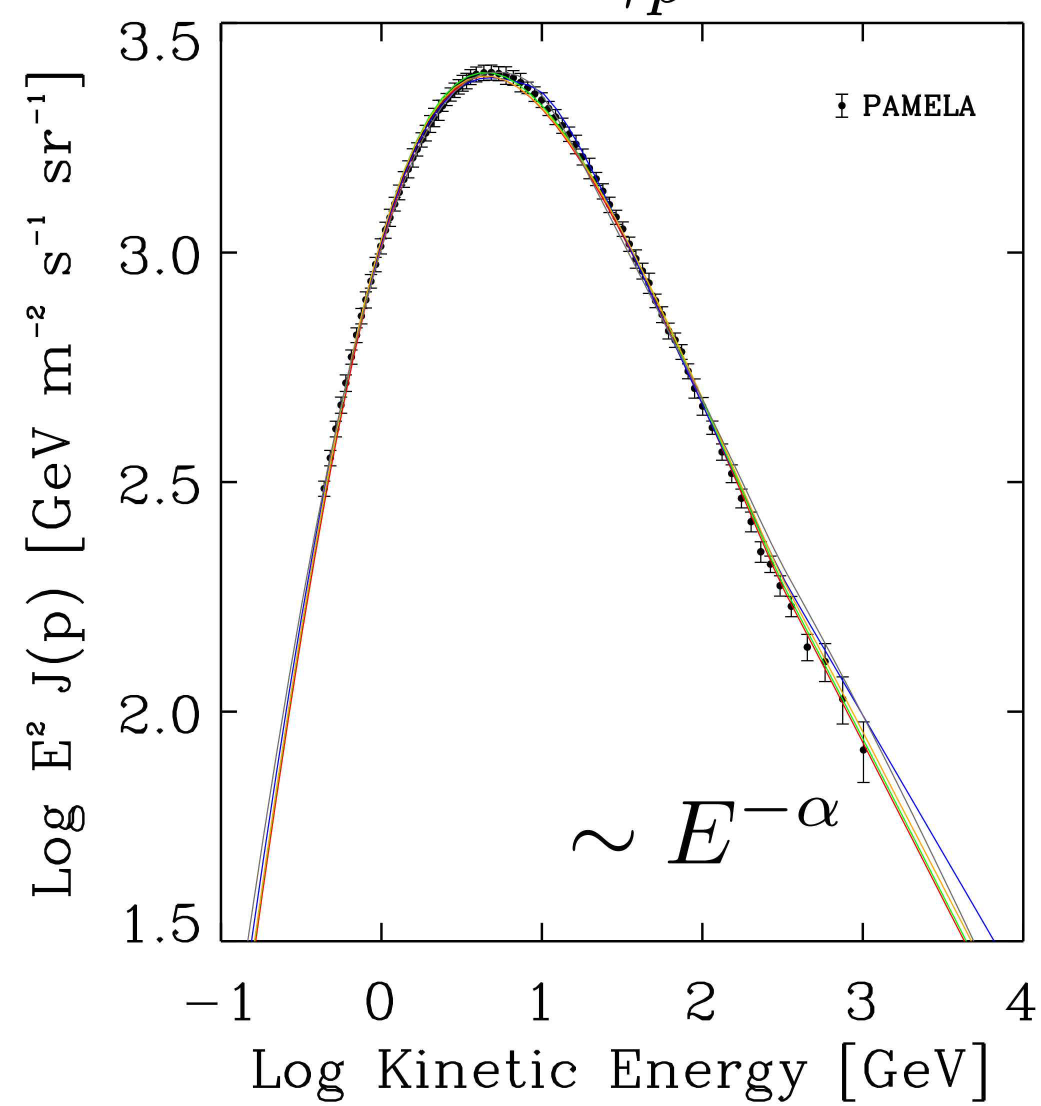
Reproduce all the “local” observables

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

Kolmogorov / Kraichnan



$\alpha \sim \gamma_p + \delta$

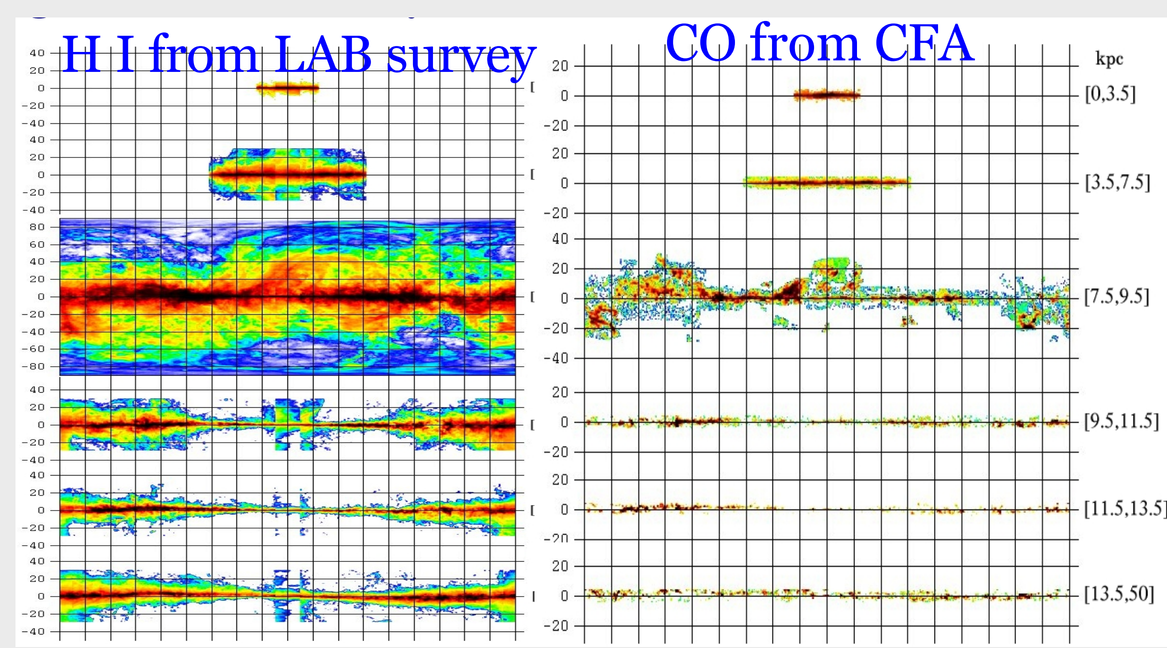


Is it possible being not-local?

- 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**!)



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Diffusion in not-linear theory (NLT)

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:

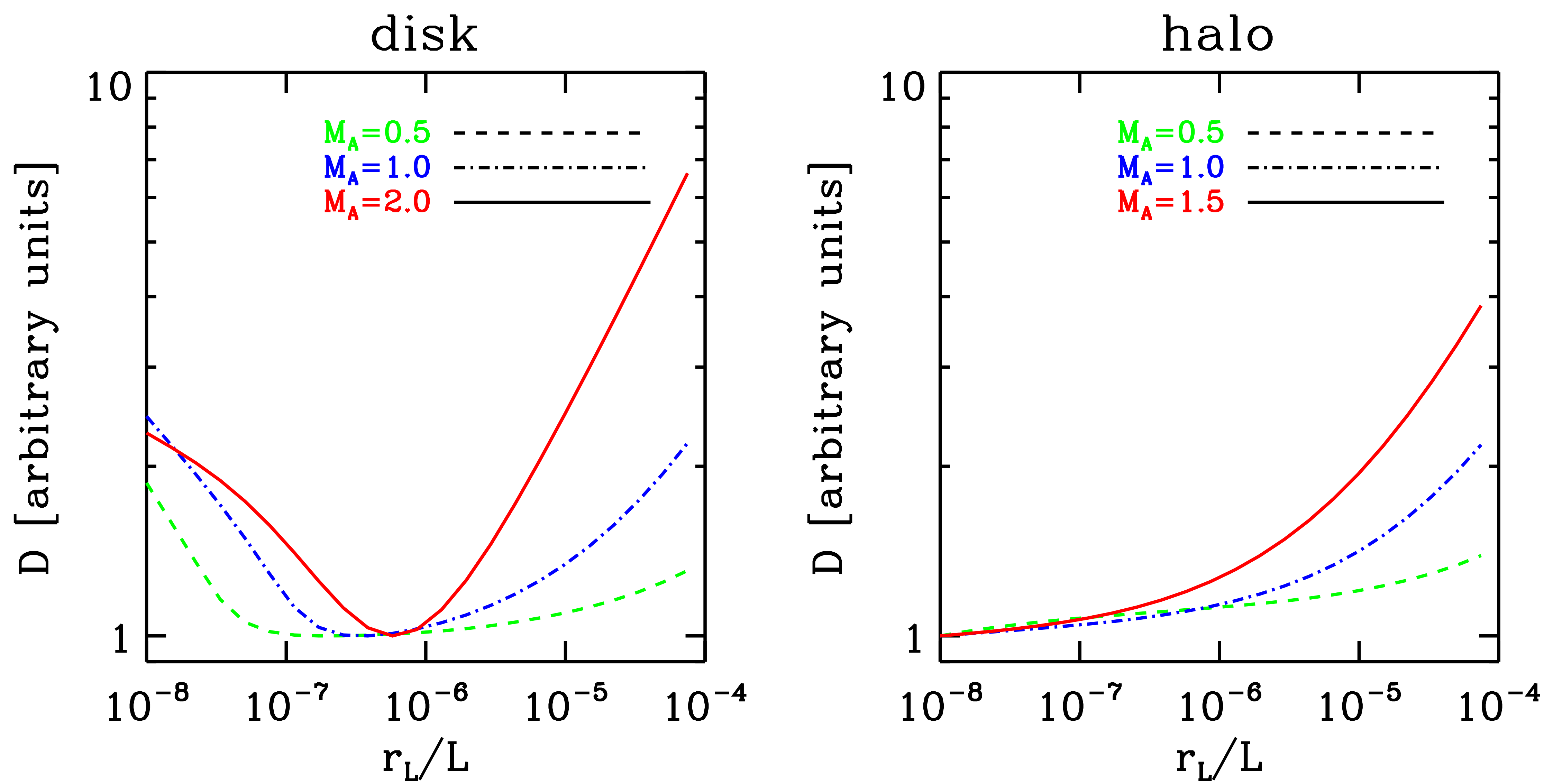
$$R_n^{\rm NLT}(k_{\parallel} v_{\parallel} - \omega \pm n\Omega) = \frac{\sqrt{\pi}}{k_{\parallel}\Delta v_{\parallel}} \exp\left[-\frac{(k_{\parallel} v\mu - \omega \pm n\Omega)^2}{k_{\parallel}^2 \Delta v_{\parallel}^2}\right]$$

- damping mechanisms make diffusion environment-dependent:

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

Diffusion in NLT is environment dependent

CE & H. Yan, ApJ, 2014

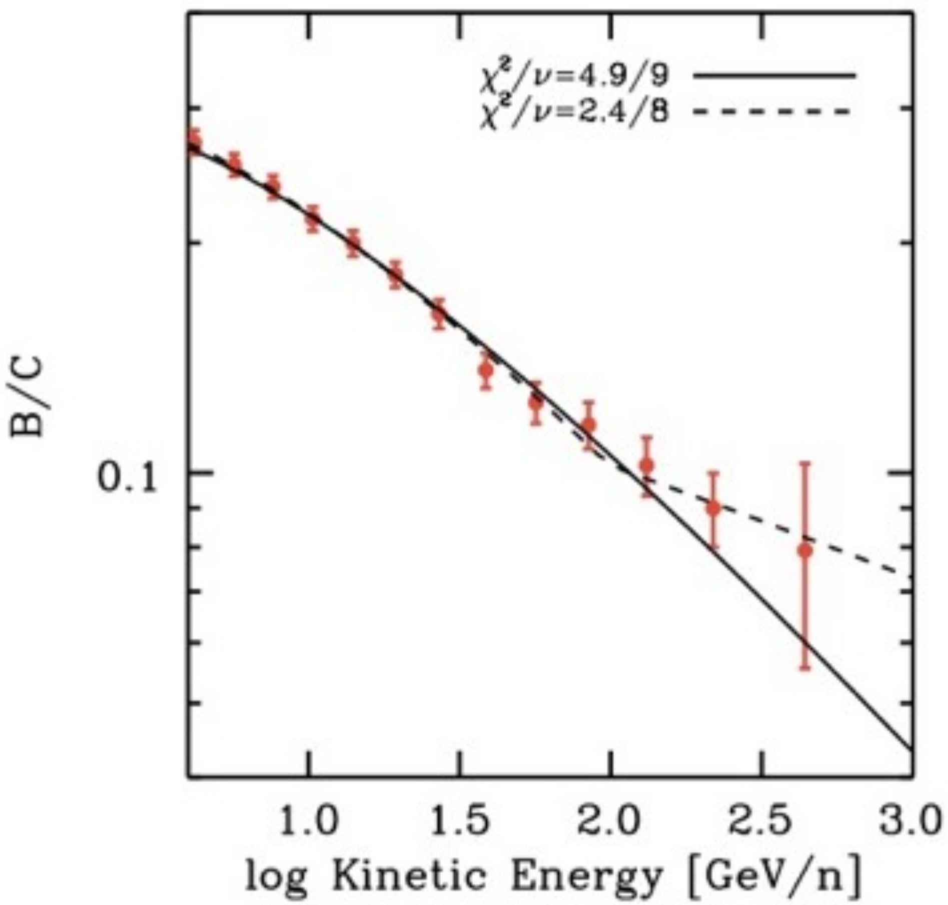


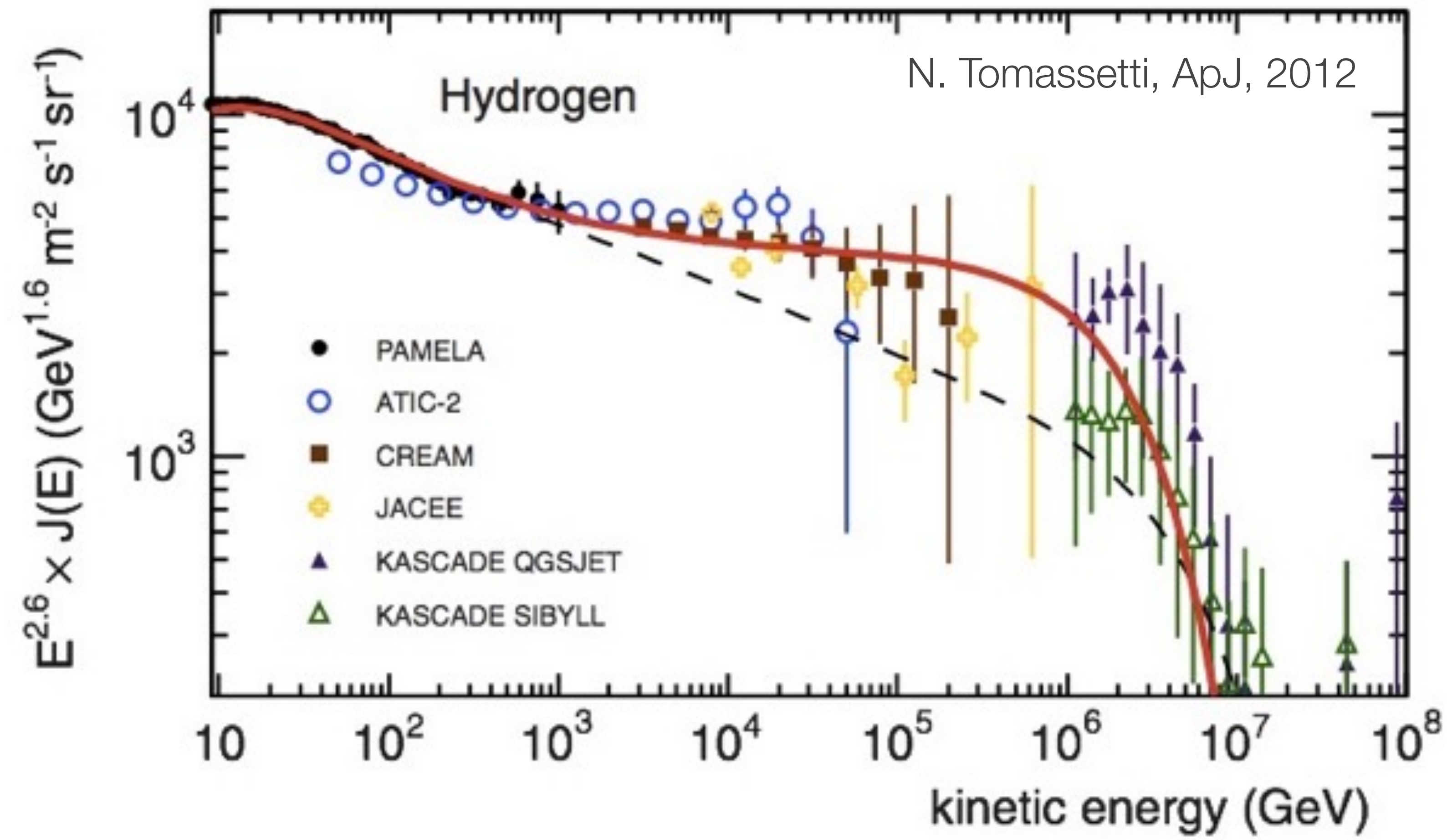
halo = collisionless damping

disk = collisionless + viscous damping

Diffusion in the halo different than in the disk

CE & H. Yan, ApJ, 2014, N. Tomassetti, ApJ, 2012





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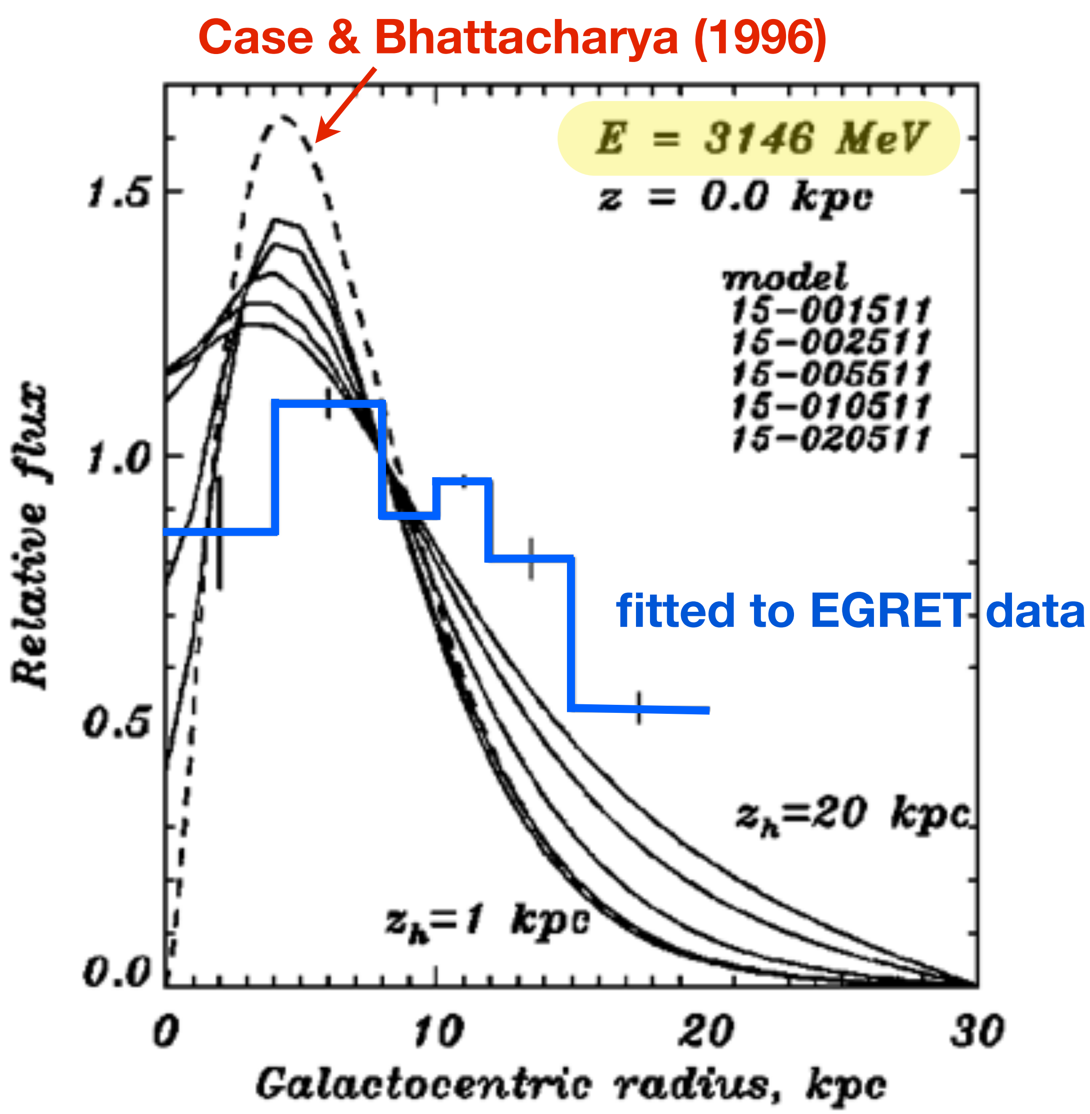
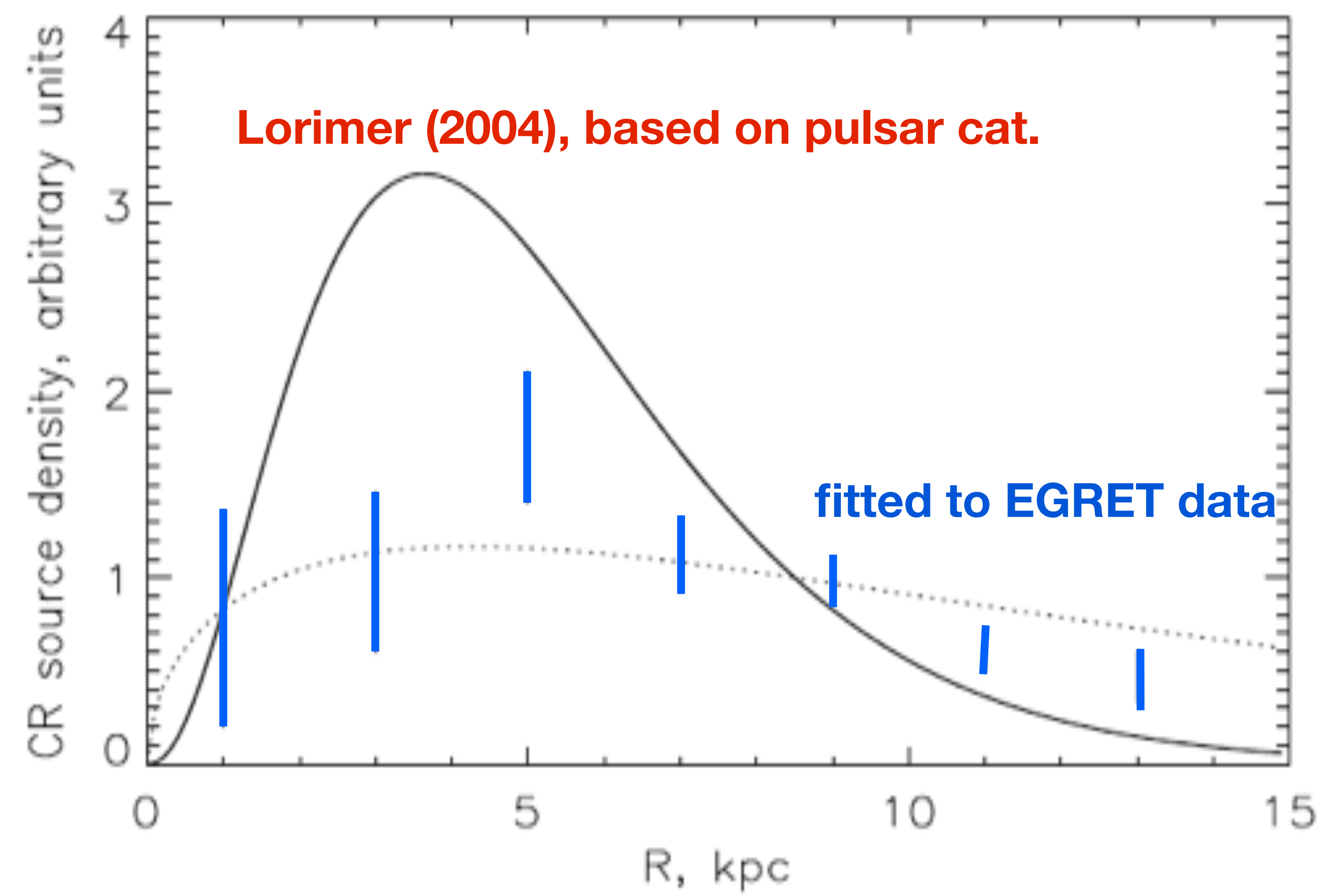
The *gradient* problem

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

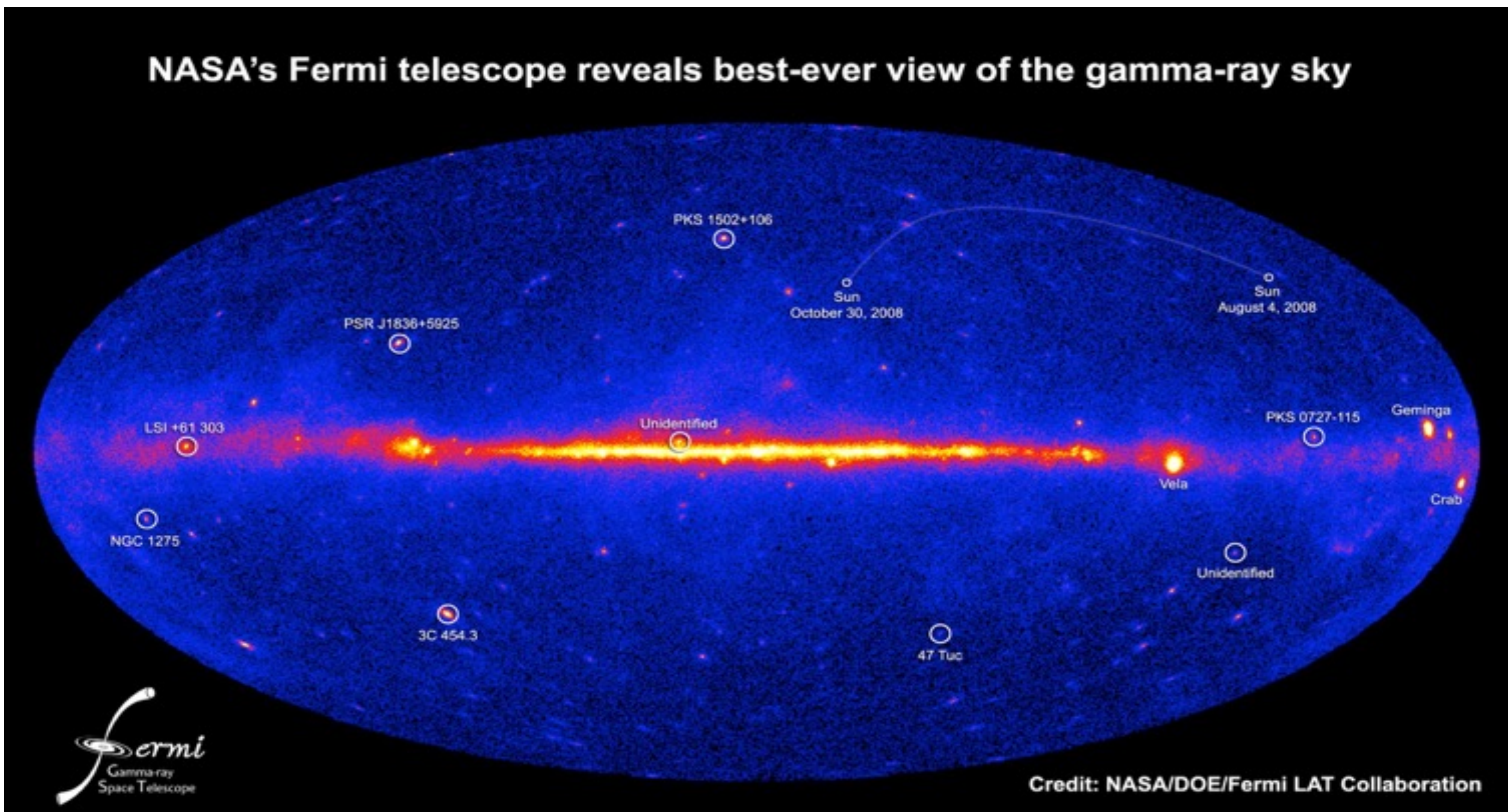




- CR distribution inferred from gamma-ray data (method goes back to SAS-2/COS-B era) is **flatter** than that computed assuming the observed **SNR** (source) profile.

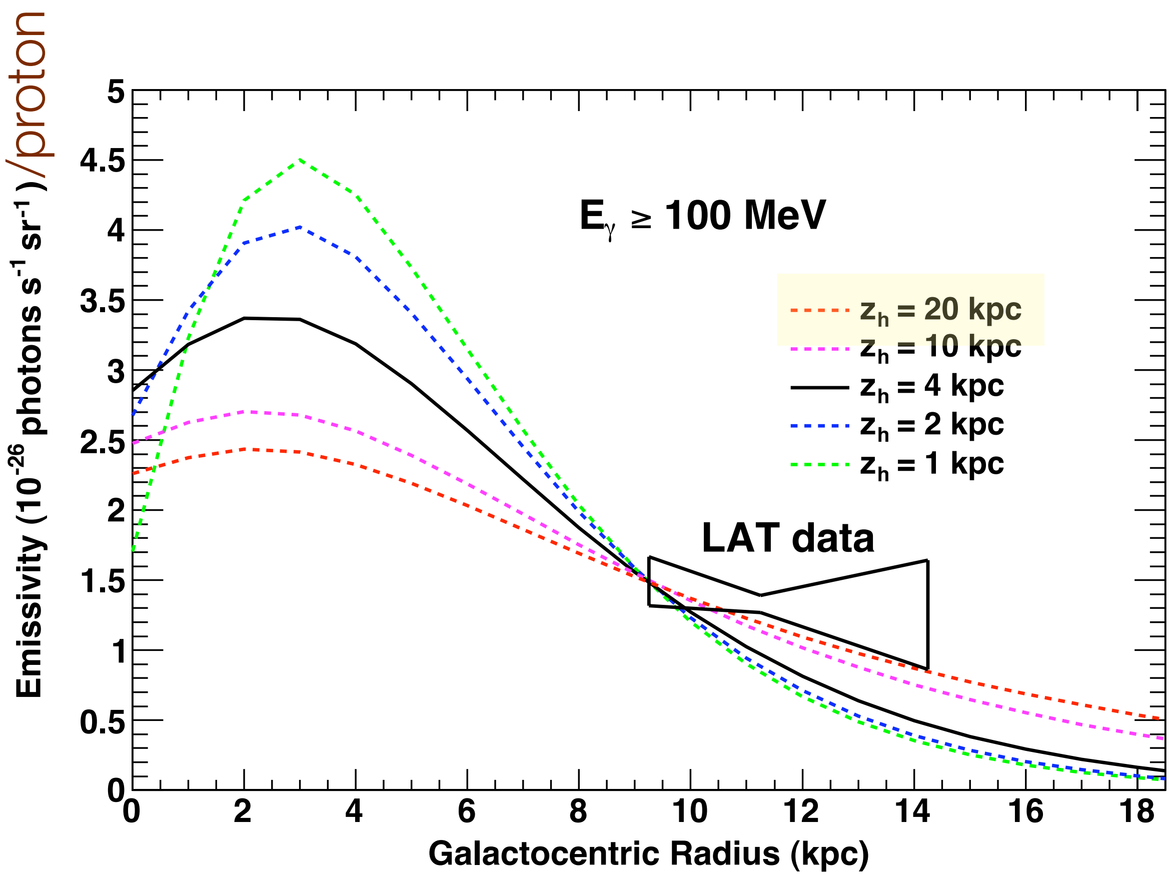
The *gradient* problem in the FERMI era

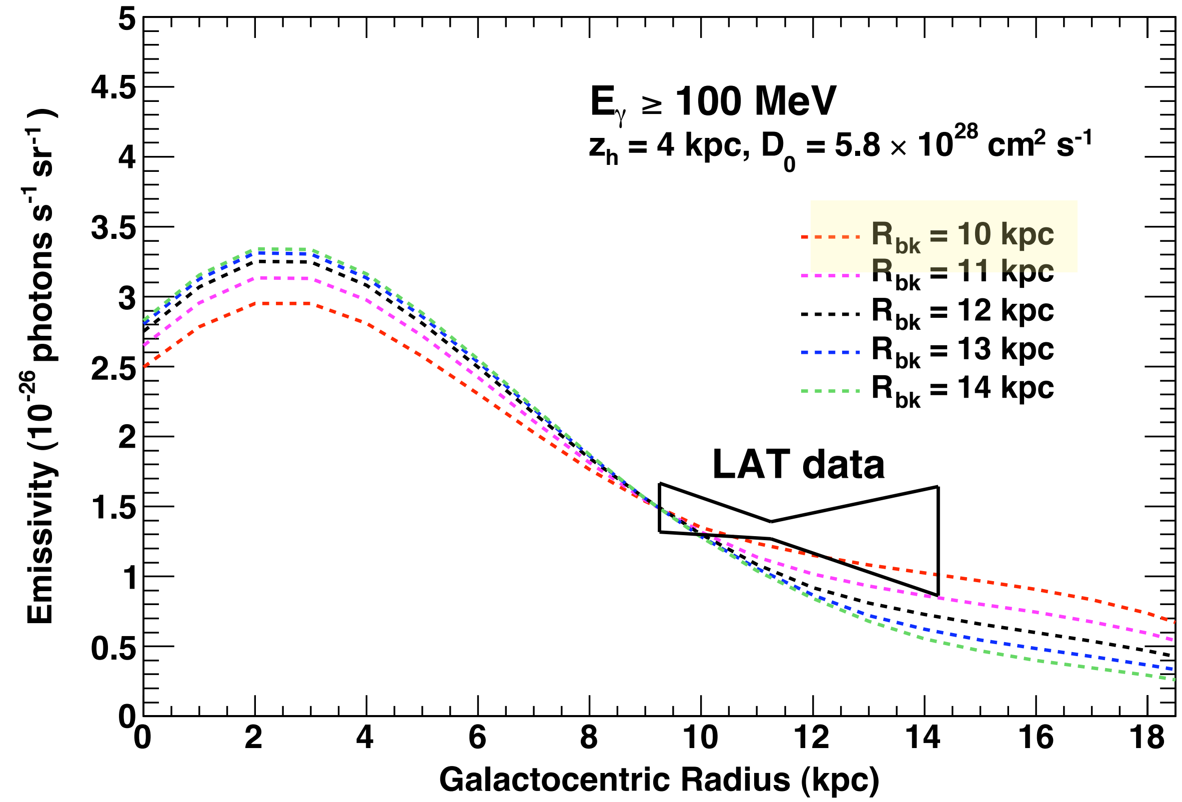
- The extremely accurate gamma ray maps that Fermi is providing are useful to trace the CR distribution throughout all the Galaxy!



The *gradient* problem in the FERMI era

Fermi Collaboration, ApJ, 2011



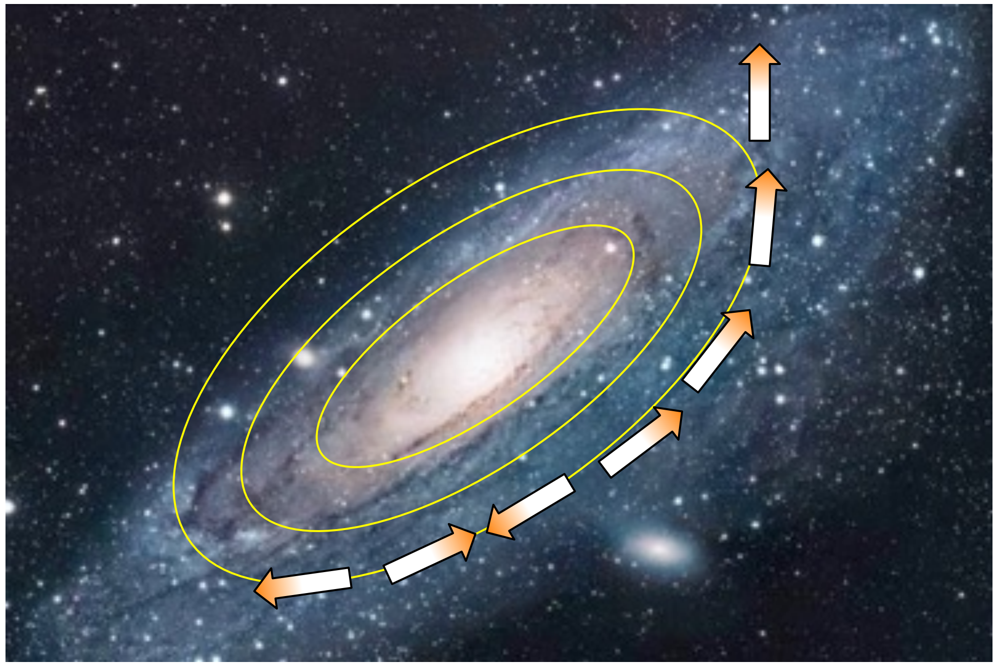


FERMI detected **more** γ's than a prediction based on SNR distribution and standard CR halo
possible explanations: more CR sources, more "dark gas" or larger CR halo?

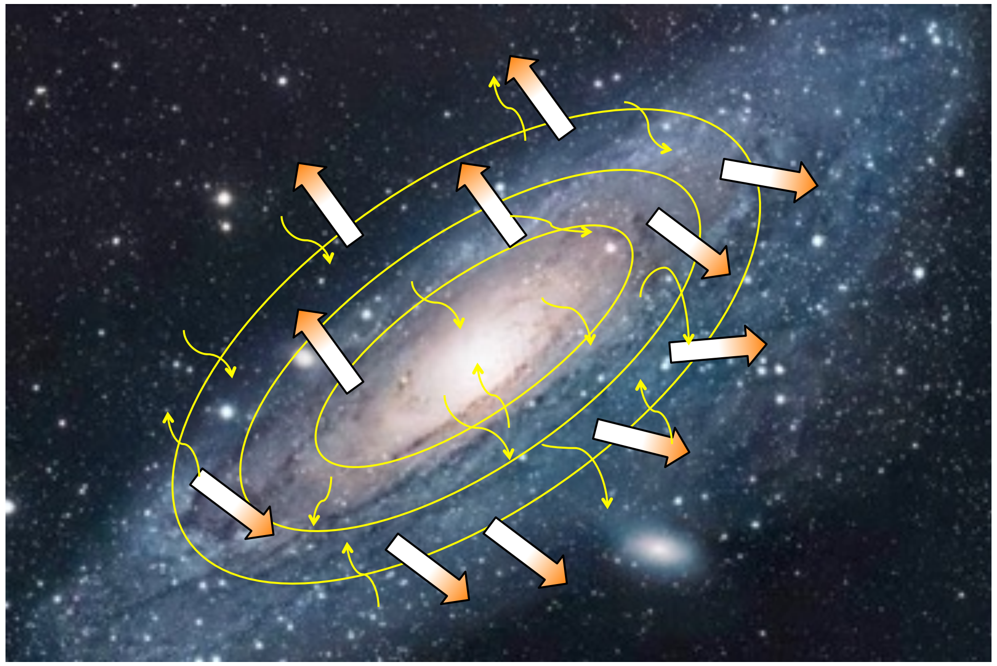
A new approach

- How do the diffusion coefficient depends on turbulence?

If the turbulent field is very low:



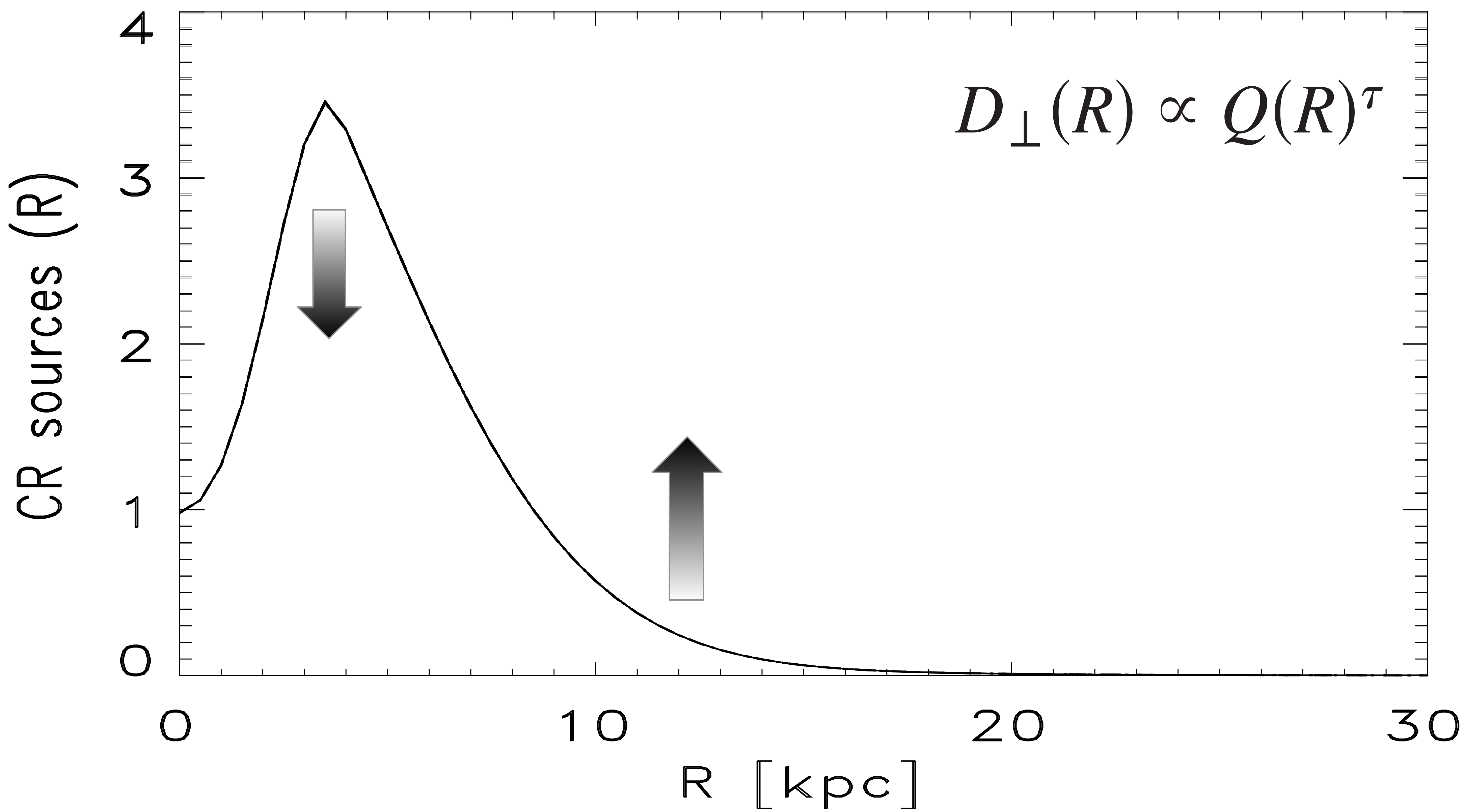
If the turbulent component is comparable to the regular field:



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

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

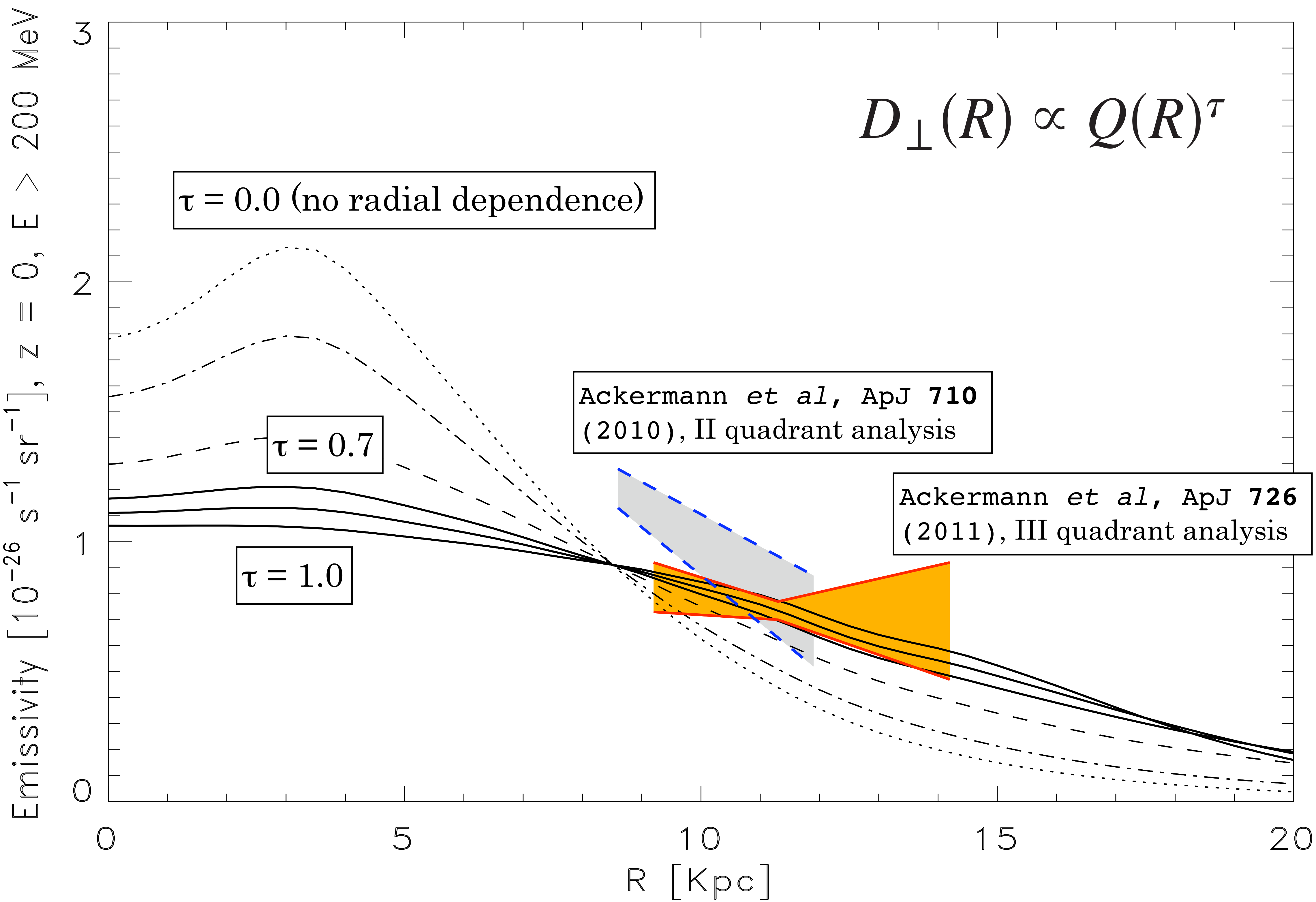
How to solve the gradient problem



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

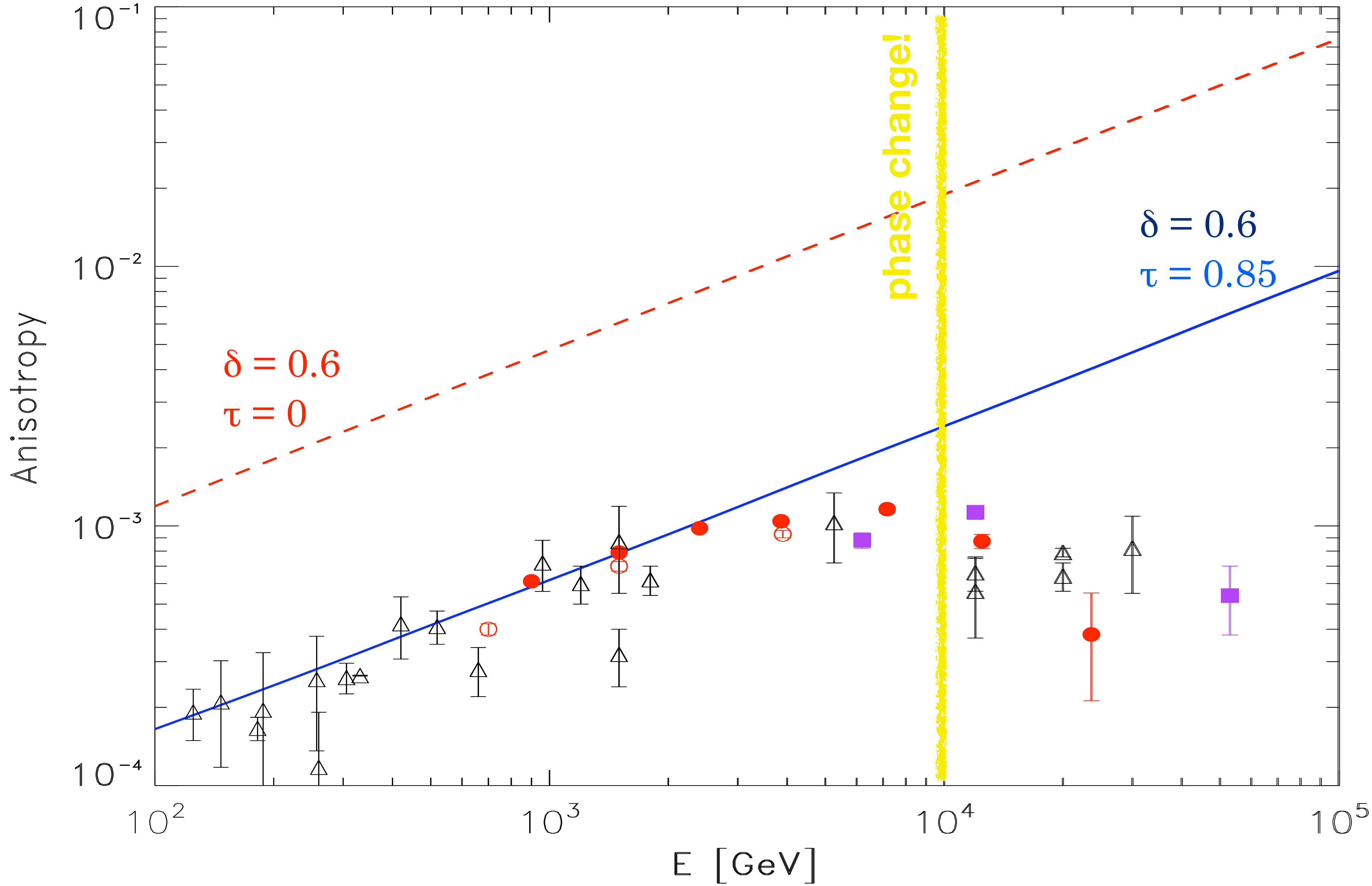
Results

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



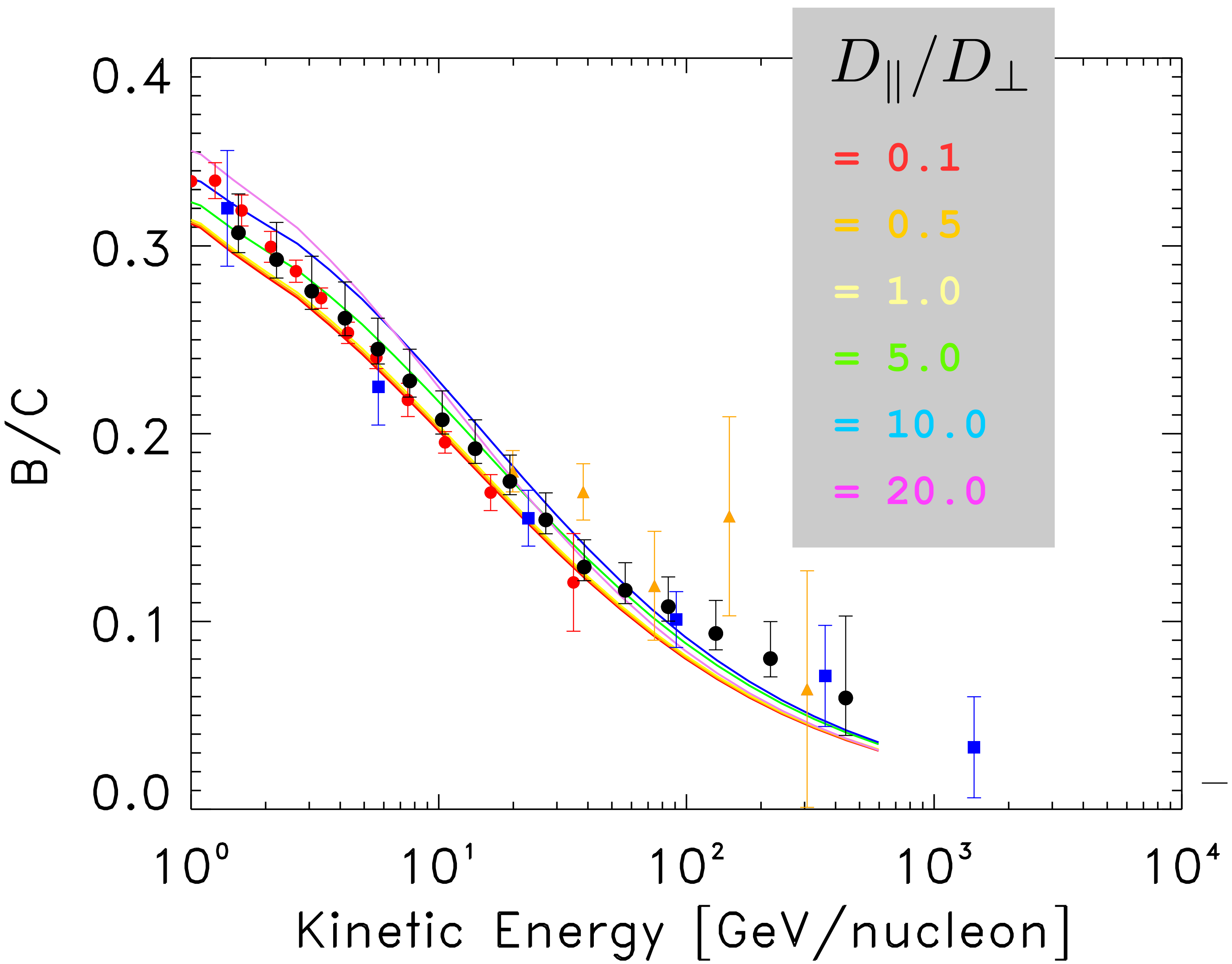
Anisotropy prediction

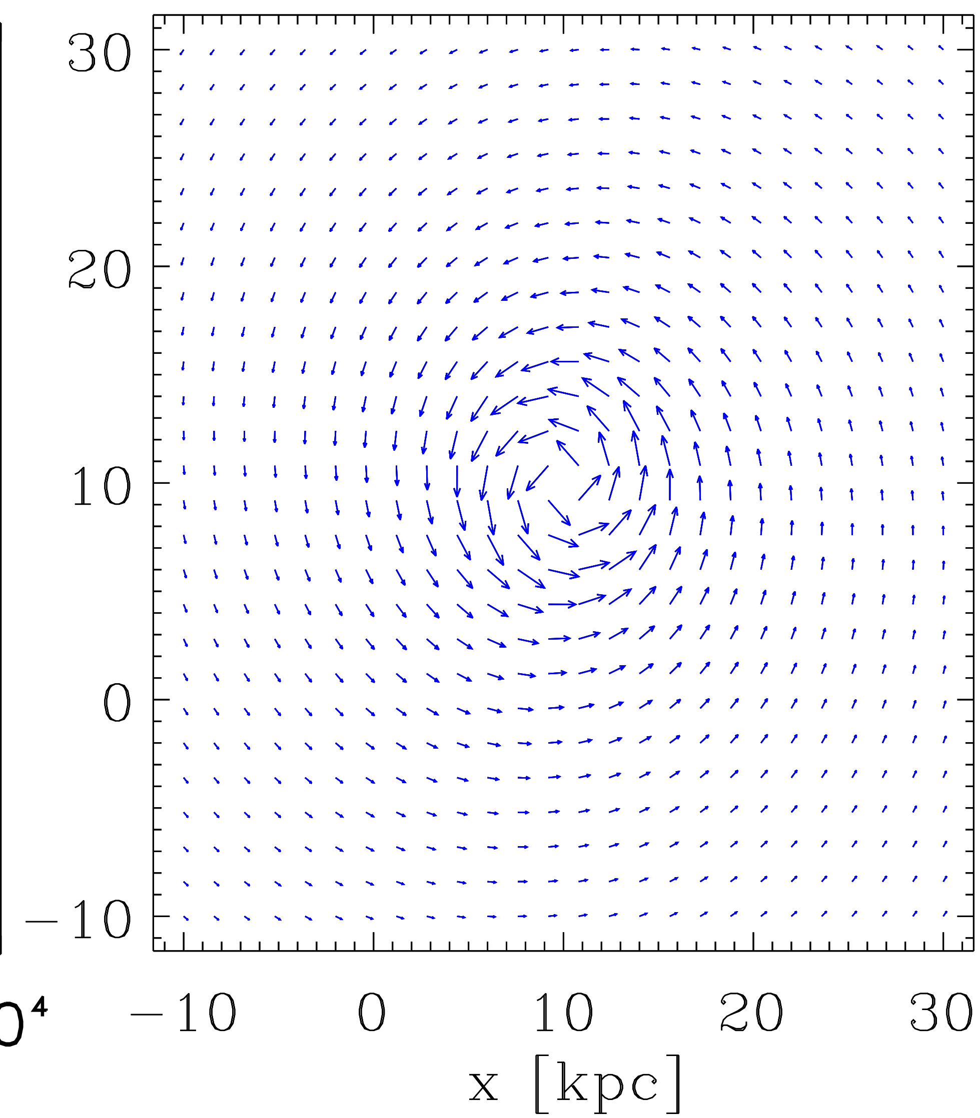
CE, D. Gaggero, D. Grasso & L. Maccione, PRL, 2012



A full anisotropic model

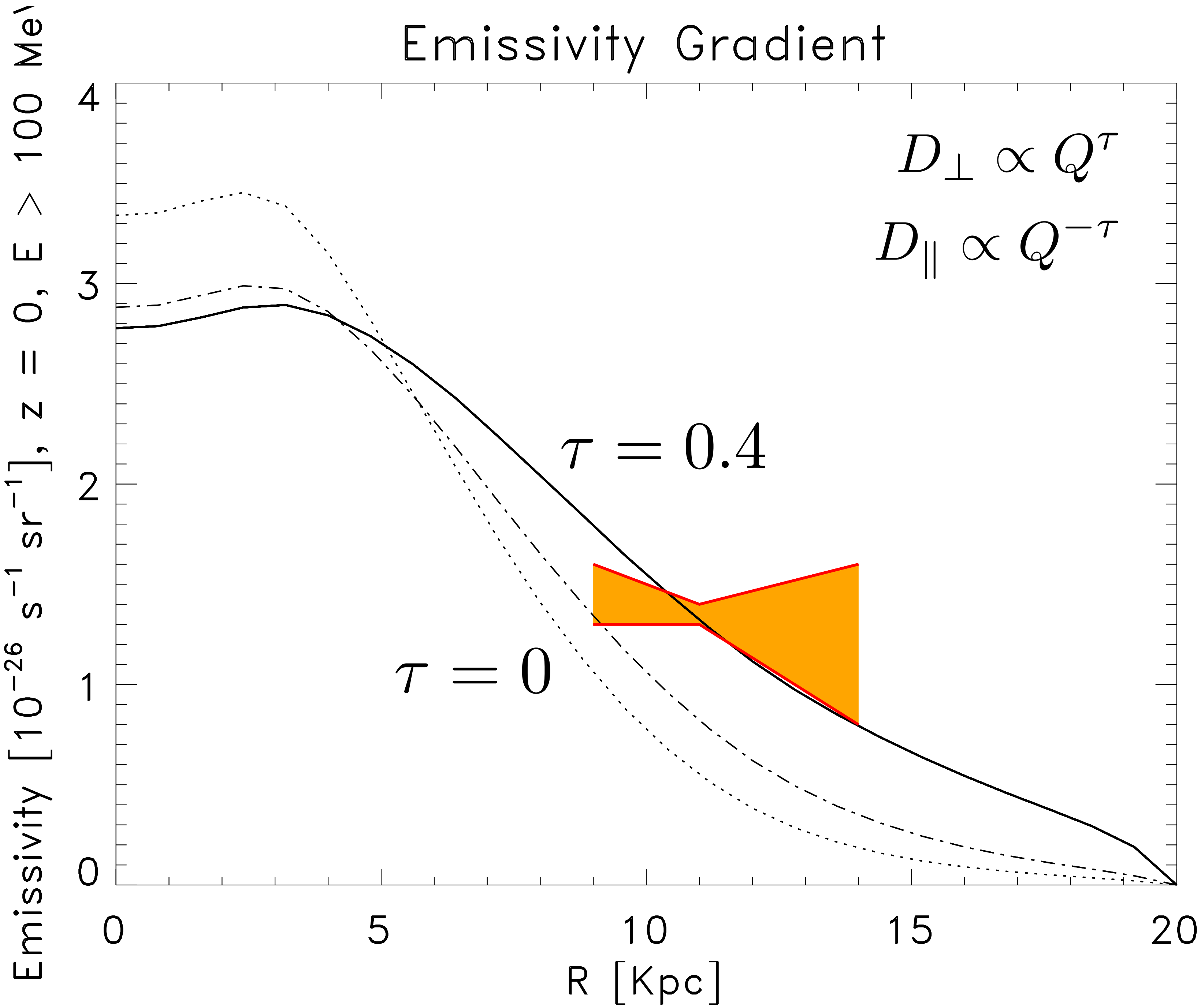
D. Gaggero, **CE** et al., *in preparation*





Now in 3D! (without glasses)

D. Gaggero, **CE** et al., *in preparation*



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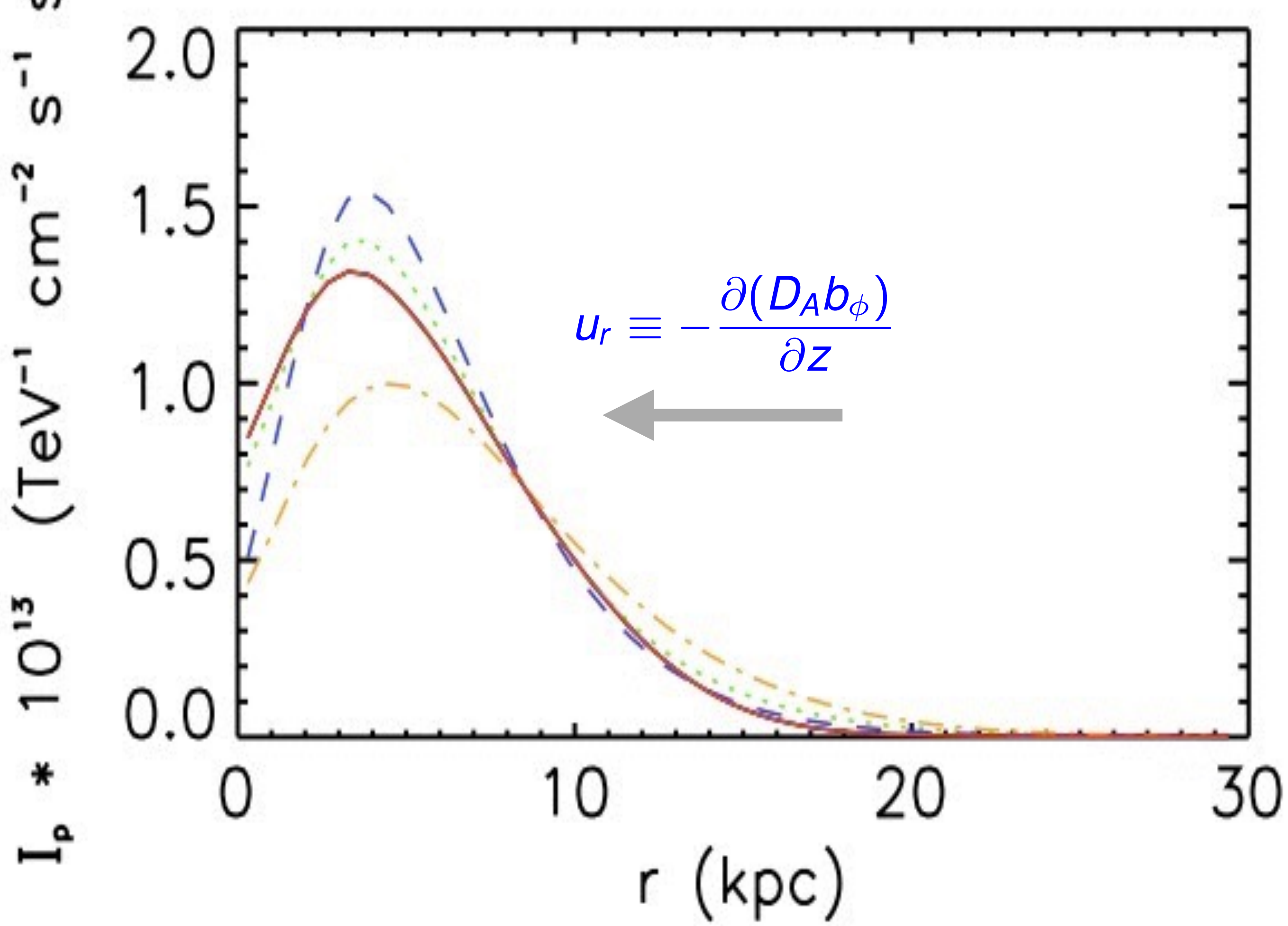
Diffusion as a tensor

CE, D. Grasso & L. Maccione, JCAP, 2007, J. Candia, JCAP, 2005

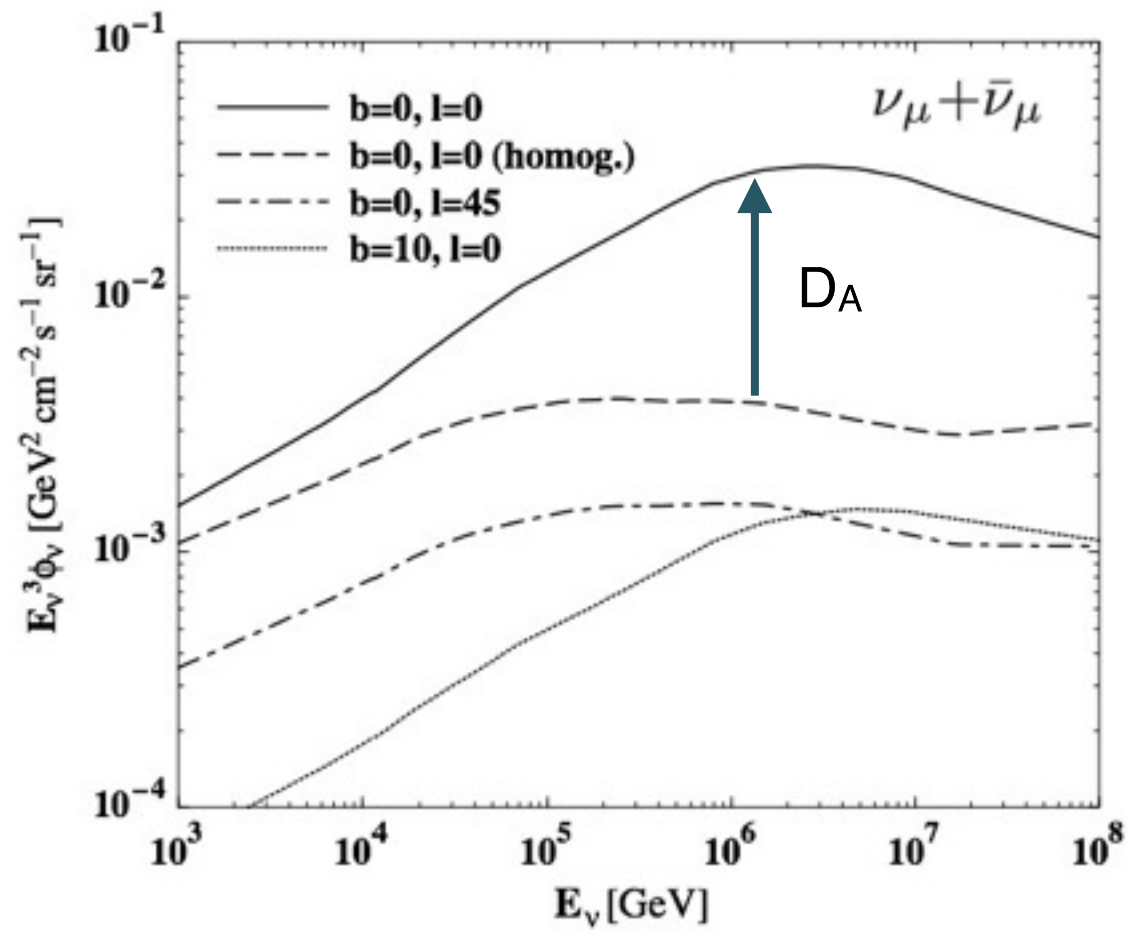
$$D_{ij} = (D_{\parallel} - D_{\perp}) b_i b_j + D_{\perp} \delta_{ij} + D_A \epsilon_{ijk} b_k$$

$\mathbf{b} = \mathbf{B_0}/|\mathbf{B_0}|$

Proton distributions at **1 PeV** for different level of turbulence

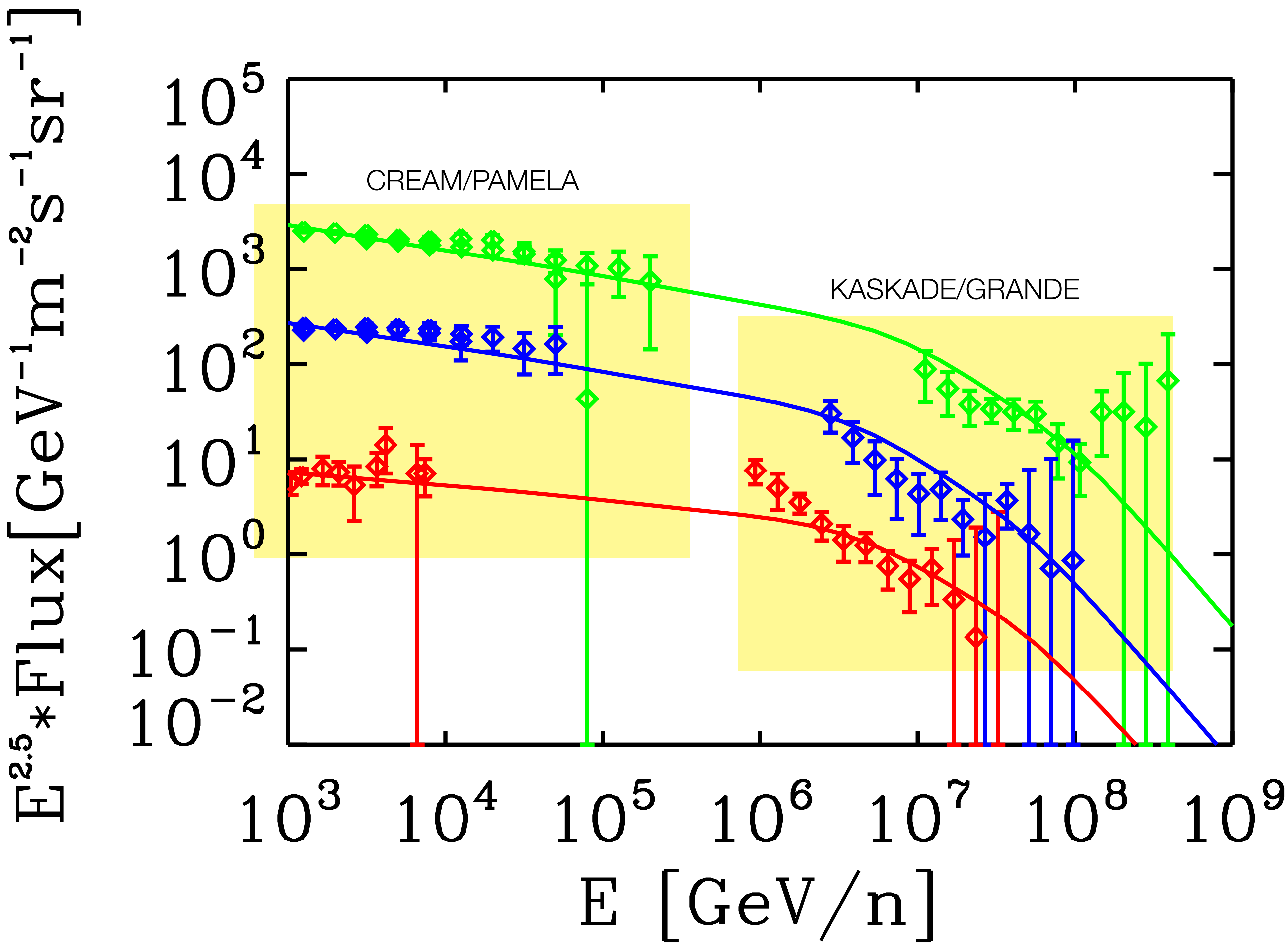


Neutrino fluxes from the GC region



The neutrino galactic diffuse emission

in preparation



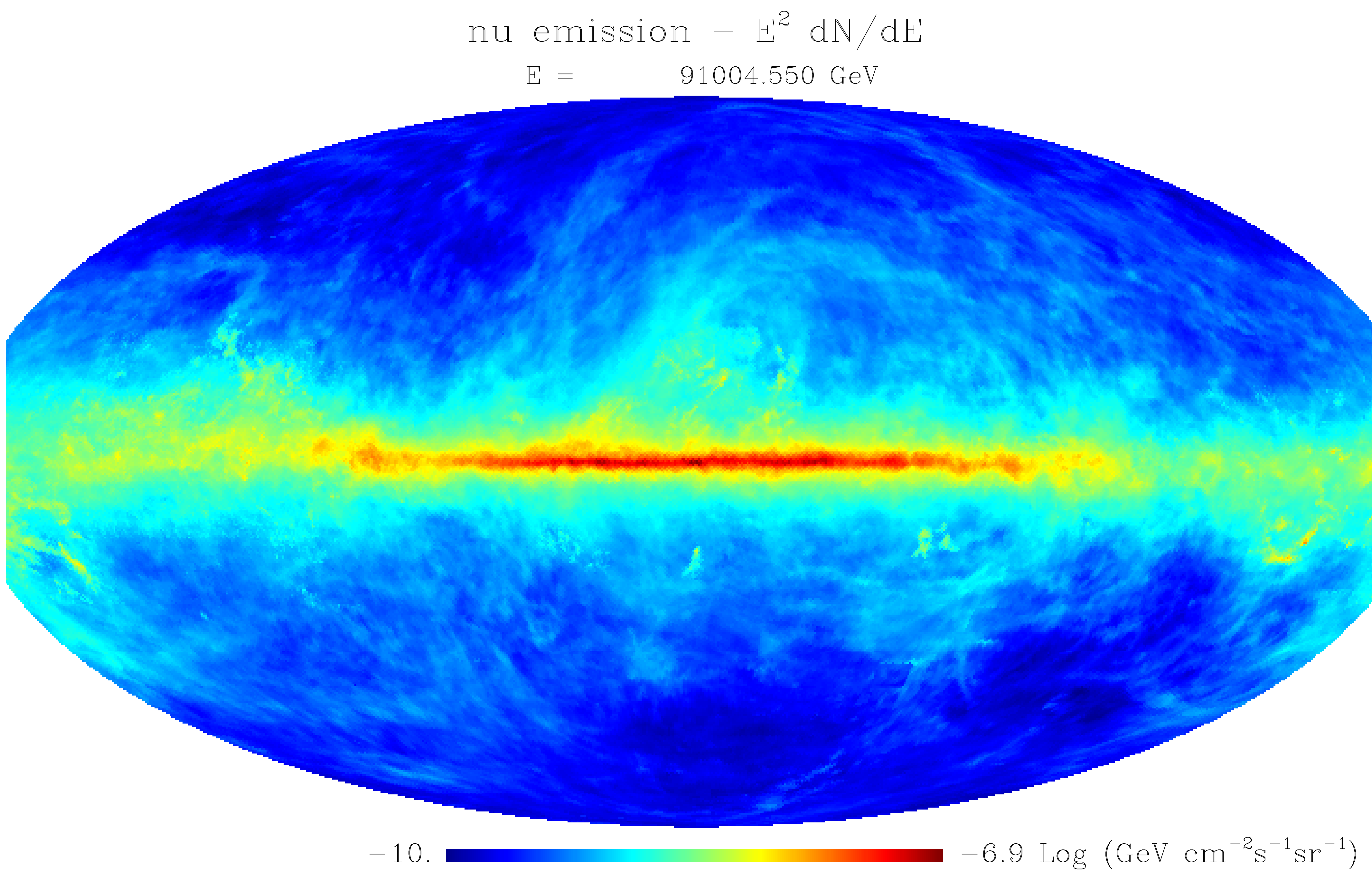
H

He

C

The neutrino galactic diffuse emission

in preparation



Conclusions

- Describing the Galaxy as a simple homogenous box where CR diffuse uniformly is insufficient to grasp the real conditions of the ISM, and moreover shades the profound link with diffusion at the microscopic level.

- A “phenomenological” **position-dependent** perpendicular diffusion coefficient that traces regions of the Galaxy where turbulence is higher offers a natural explanation of not-local CR observations.

- Future diffusion models 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://www.dragonproject.org