DRAGON2 : A novel code for Cosmic-Ray transport in the Galaxy

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Cosmic rays origin - Beyond the standard models
San Vito di Cadore, 18-24 September 2016

The DRAGON project (2008 - ongoing)

Important support, contribution, feedback from: **Iris Gebauer** and the KIT team (**Matthias Weinreuter**, **Simon Kunz**, **Florian Keller**), **Antonio Marinelli** (INFN Pisa), **M.Nicola Mazziotta** (INFN Bari), **Piero Ullio** (SISSA, Trieste), **Alfredo Urbano** (CERN), **Marco Taoso** (UAM), **Mauro Valli** (SISSA, Trieste)

Major contribution from Luca Maccione to the first version

The DRAGON project (2008 - ongoing)

DRAGON1 (2008 - still maintained)

https://github.com/cosmicrays/DRAGON

- **C. Evoli, D. Gaggero, D. Grasso, L. Maccione**, "Cosmic ray nuclei, antiprotons and gamma rays in the galaxy: a new diffusion model" JCAP issue 10 id 018 (2008)
- **G. Di Bernardo, C. Evoli, D. Gaggero, D. Grasso, L. Maccione**, "Unified interpretation of cosmic ray nuclei and antiproton recent measurements", APP 34 (2010)
- **C. Evoli, D. Gaggero, D. Grasso, L. Maccione,** "Common Solution to the Cosmic Ray Anisotropy and Gradient Problems", PRL 108, 21 (2012)
- **D. Gaggero, L. Maccione, G. Di Bernardo, C. Evoli, D. Grasso**, "Three-Dimensional Model of Cosmic-Ray Lepton Propagation Reproduces Data from the Alpha Magnetic Spectrometer on the International Space Station", PRL 111, 2 (2013)
- **D. Gaggero, A. Urbano, M. Valli, P. Ullio**, "Gamma-ray sky points to radial gradients in cosmic-ray transport", PRD (2014)

DRAGON2 (2016 - in development)

- **C. Evoli, D. Gaggero, A. Vittino, G. Di Bernardo, M. Di Mauro, A. Ligorini, P. Ullio, D. Grasso,** "CR propagation with DRAGON2: I. numerical solver and astrophysical ingredients" arXiv:1607.07886, submitted to JCAP
- **C. Evoli, D. Gaggero et al.**, "CR propagation with DRAGON2: II. cross-section network" in preparation
- **S.S. Cerri, A. Vittino, D. Gaggero et al.** "Anisotropic CR propagation with DRAGON2", in preparation

The DRAGON project

aim: **modeling CR transport in the Galaxy in the most general way**

spatial diffusion — advection — reacceleration — energy losses — source

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

each process is associated to a **position and rigidity dependent** operator

+

state-of-the art, updated models for the astrophysical distributions of sources, interstellar gas, radiation field, magnetic field

DRAGON2
new features, a complete documentation

C.Evoli et al. arXiv:1607.07886

The new code will be released soon as a fully open-source package
a light version of the code with the new solver will be available online in a very short time

The solver was **mostly rewritten** and **new technical solutions** have been considered for **each operator**

Main features

- **Position-dependent** and **anisotropic** spatial diffusion
- **New numerical approach** for reacceleration, advection and energy losses (new discretization schemes, new boundary conditions)
- **New physical ingredients** (e.g. pion production energy losses)
- Possibility to use a **non-equidistant spatial grid** and of propagating **transient sources**

spatial diffusion in DRAGON2

The user can implement a general, non-separable expression of the parallel and perpendicular diffusion coefficients. A variable normalization and rigidity scaling of the diffusion coefficient can be considered.

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

This approach is required by both theory and observations.

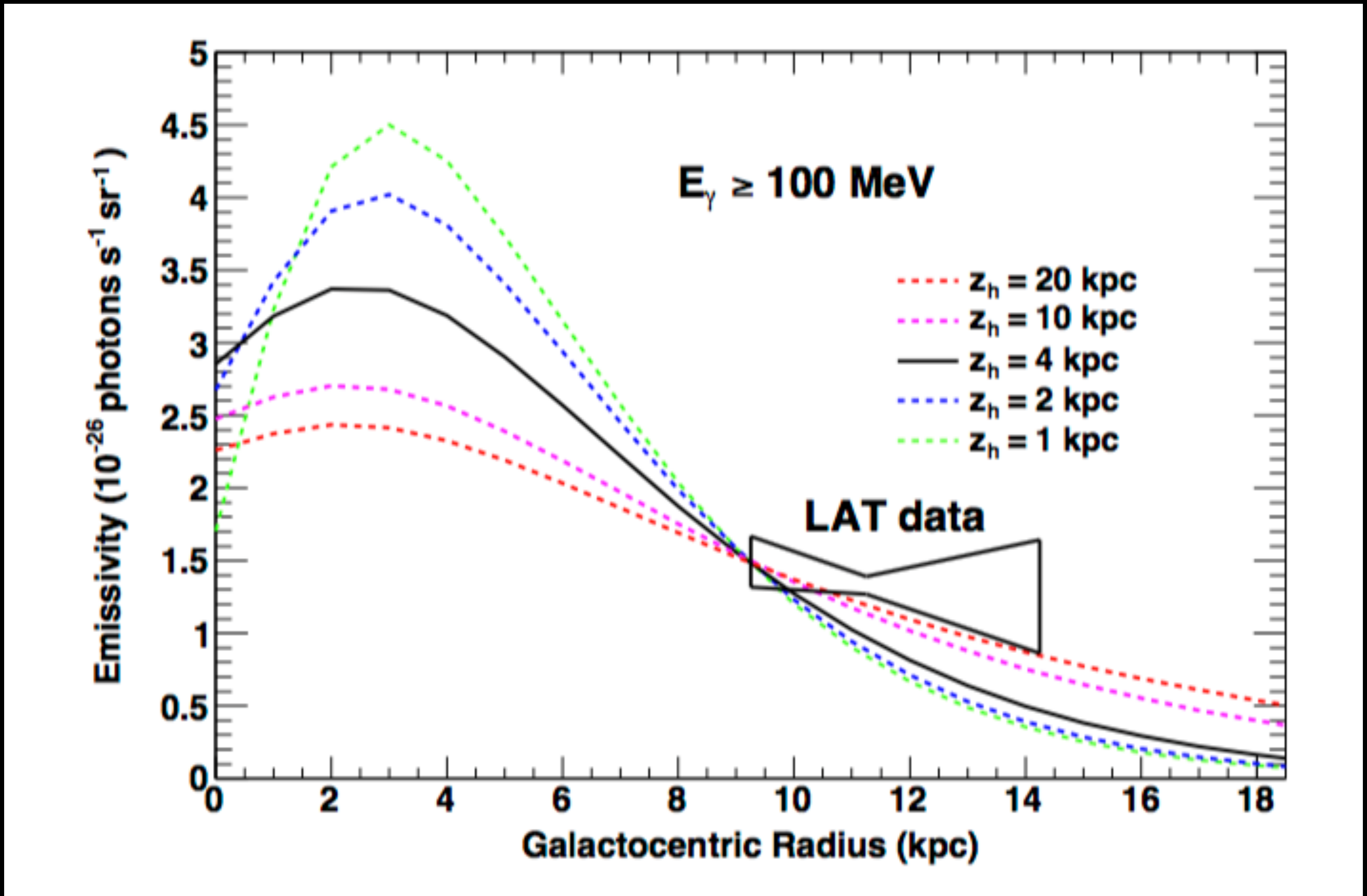
- **Theory:** the presence of a **large scale Galactic magnetic field** breaks isotropy and introduces a **preferred direction**

- **Observations:** data are in **tension** with **homogeneous propagation models**

spatial diffusion in DRAGON2

-Gradient problem-

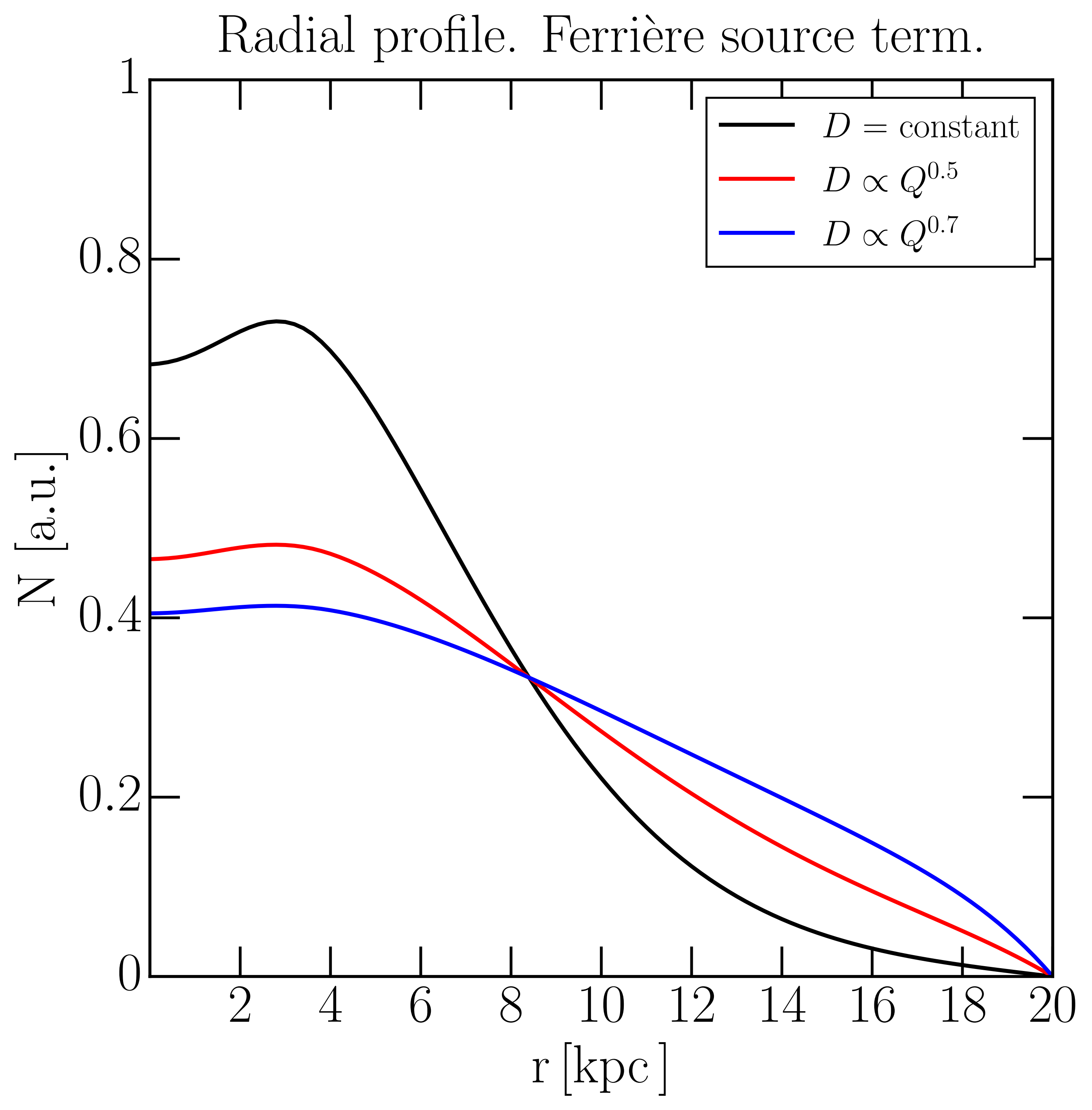
M.Ackermann et al. (Fermi-LAT Coll.), ApJ 726, 2010



the **radial profile** of the **gamma-ray emissivity** along the galactic plane is **flatter than predicted** on the basis of SNR catalogues

spatial diffusion in DRAGON2

-Gradient problem-



inhomogenous diffusion coefficient correlated with the turbulent strength of the magnetic field (to the CR source density)

C.Evoli et al., PRL 108, 2012

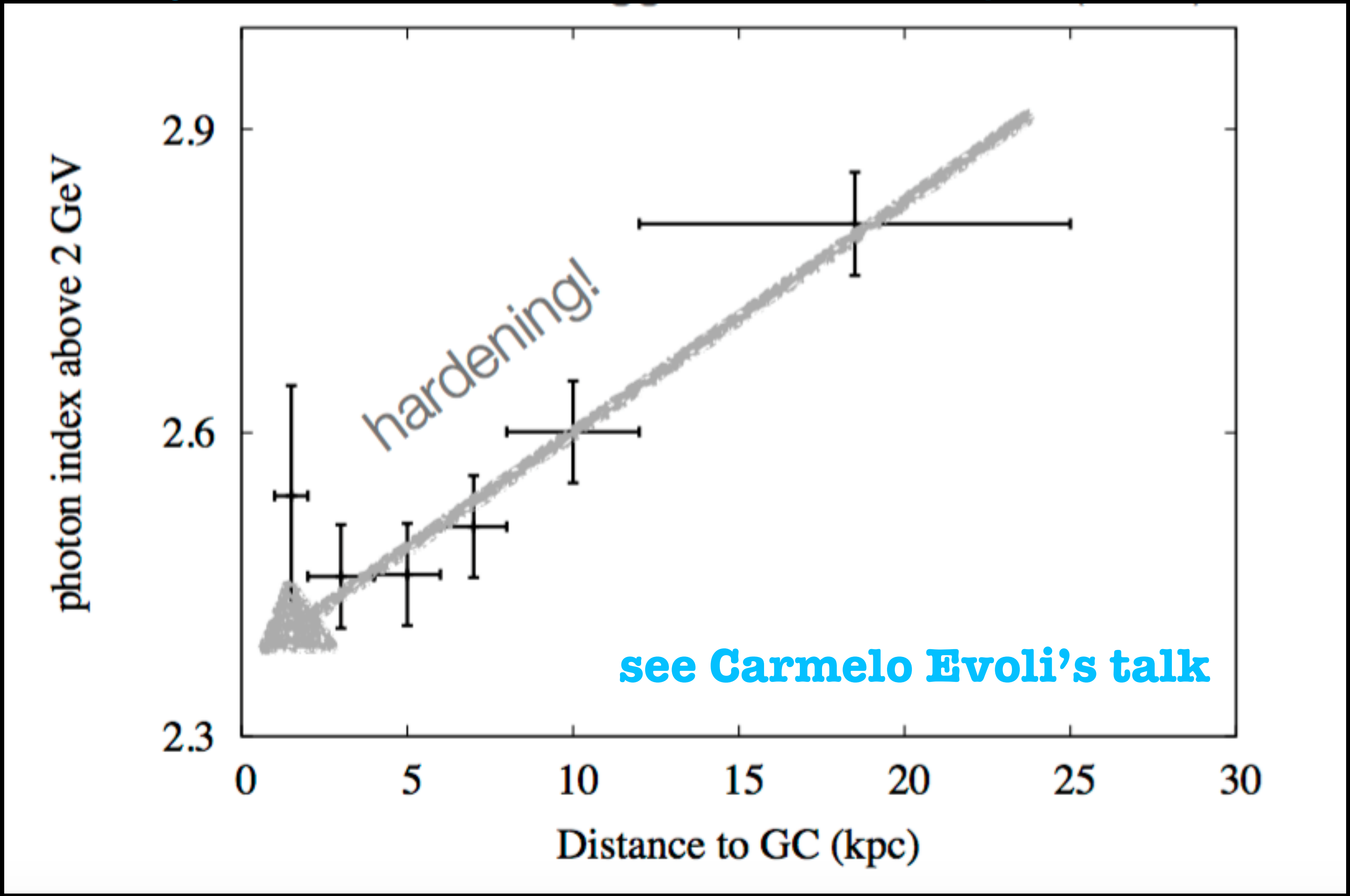
$$D \propto Q(r)^{\tau}$$

the CR density profile flattens and the gradient problem is solved!

spatial diffusion in DRAGON2

-Slope problem-

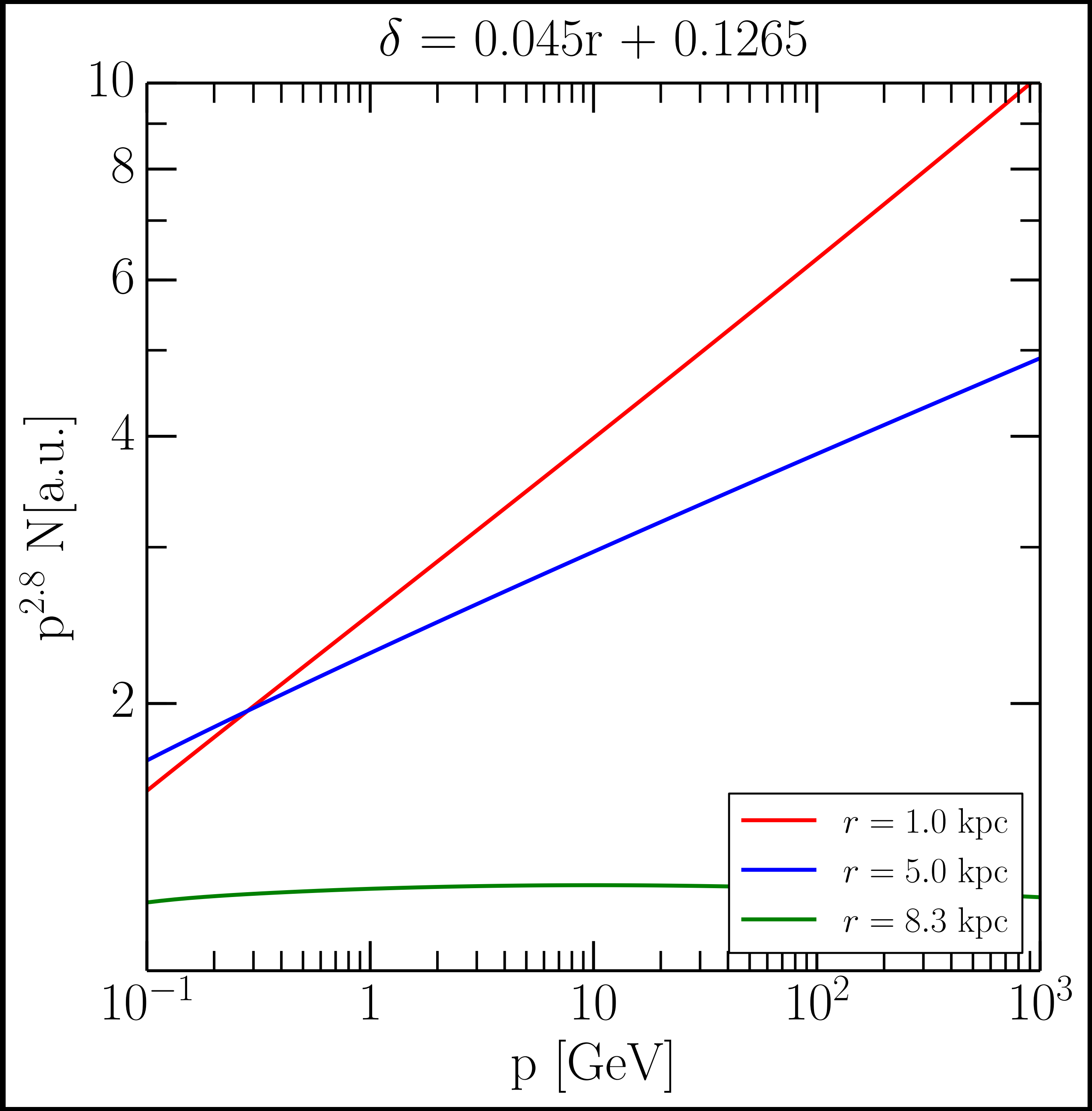
C. Yang et al., PRD 93, 2016, Acero et al. (Fermi Coll.) ApJS 223 26 (2016)



gamma-ray spectra in the inner Galactic plane point towards an **hardening of CR spectra** towards the **center of the Galaxy**

spatial diffusion in DRAGON2

-Slope problem-



Progressively harder scaling of the diffusion coefficient with rigidity

D.Gaggero et al., PRD 91, 2015

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

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

the CR spectrum hardens towards the center and the slope problem is solved!

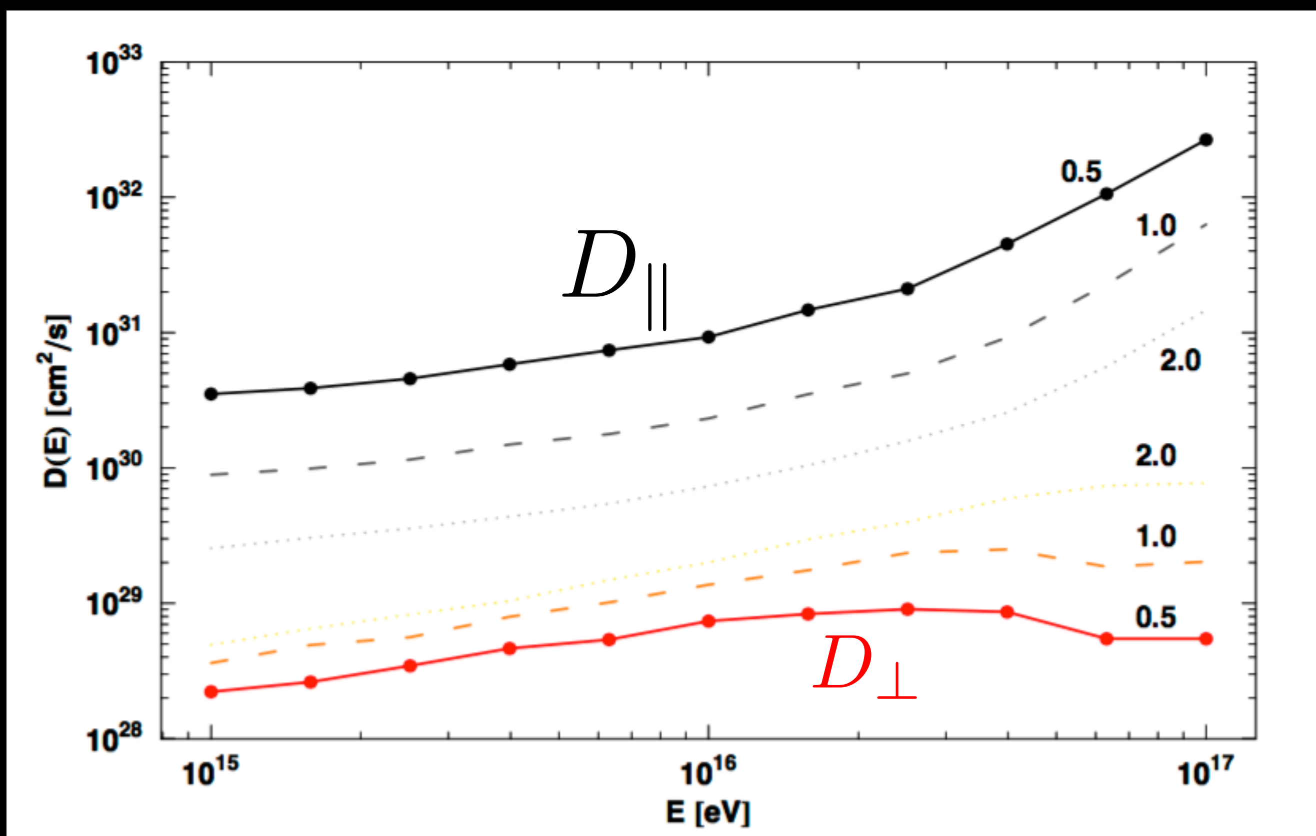
spatial diffusion in DRAGON2

-Slope problem-

S.S. Cerri, A. Vittino,
D. Gaggero et al.,
in preparation

Anisotropic diffusion can explain the hardening.

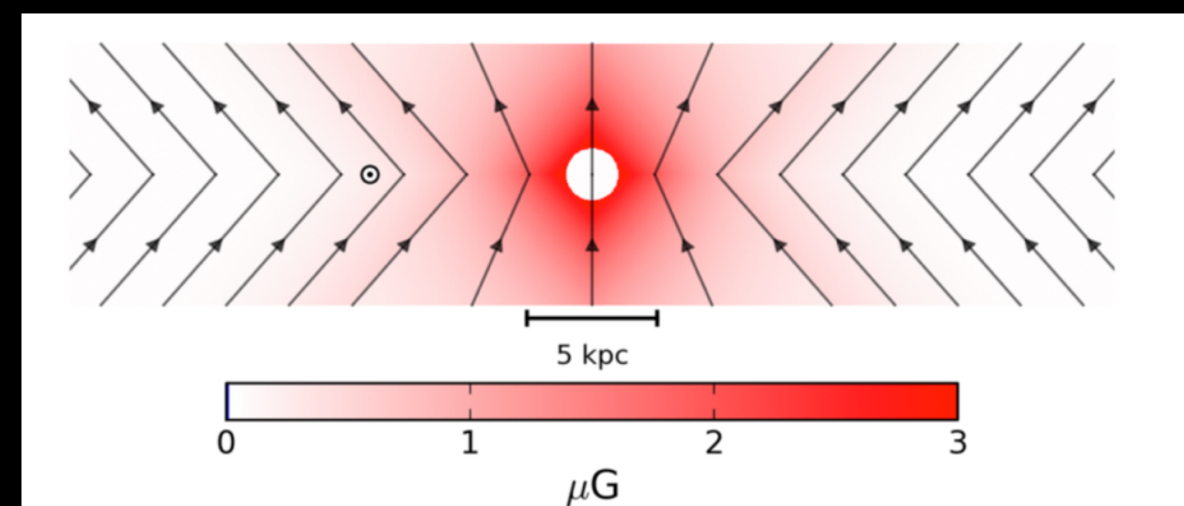
$$D_{ij} = D_\perp \delta_{ij} + (D_\parallel - D_\perp) b_i b_j$$



De Marco, Blasi. Stanev, JCAP 6 2007

$$D_\parallel \propto E^{1/3}$$
$$D_\perp \propto E^{0.5 \div 0.6}$$

Out-of-plane component of the GMF in the inner Galaxy



Jansson and Farrar 2012

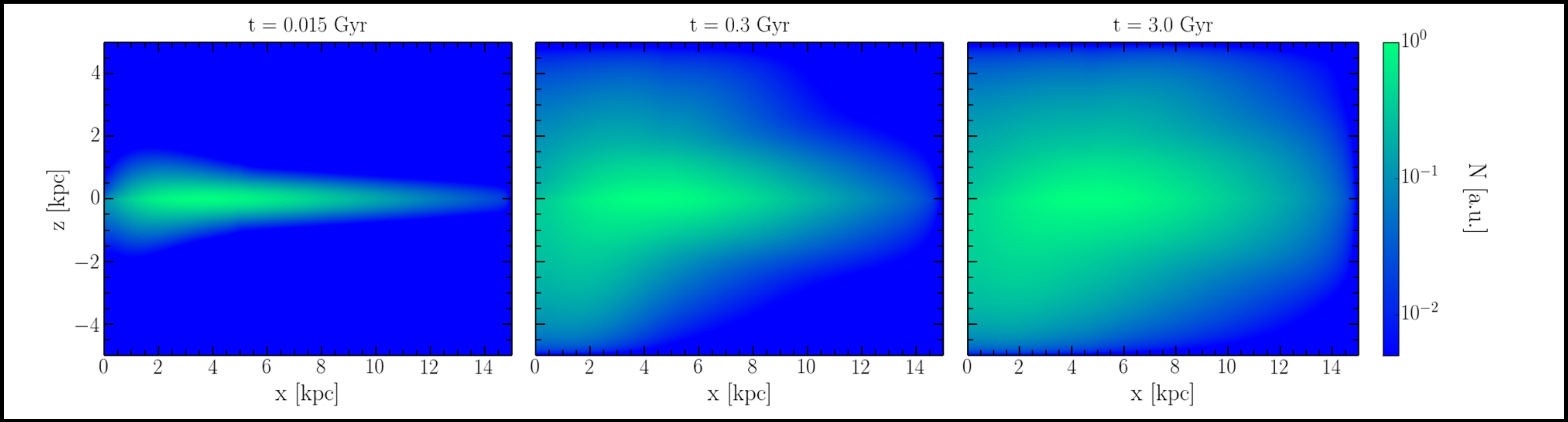
Are we seeing parallel escape of CRs in the inner Galaxy?

spatial diffusion in DRAGON2

-Slope problem-

Anisotropic diffusion can explain the hardening.

S.S. Cerri, A. Vittino, D. Gaggero et al., in preparation

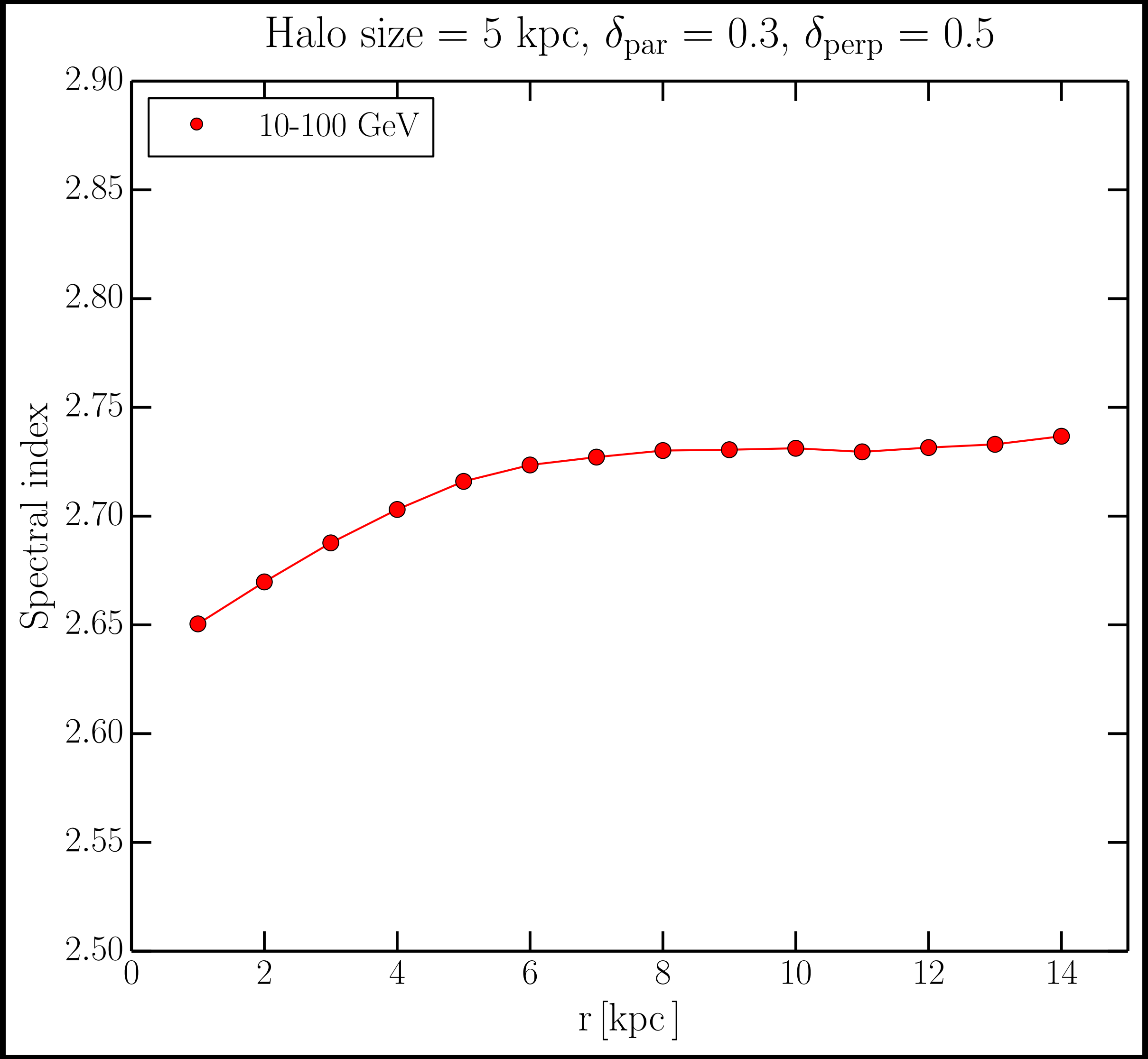


spatial diffusion in DRAGON2

-Slope problem-

Anisotropic diffusion can explain the hardening.

S.S. Cerri, A. Vittino, D. Gaggero et al., in preparation



The shape of the spectral index profile depends on the features of the parallel and perpendicular transports, the Galactic magnetic field, the degree of turbulence, the size of the halo …

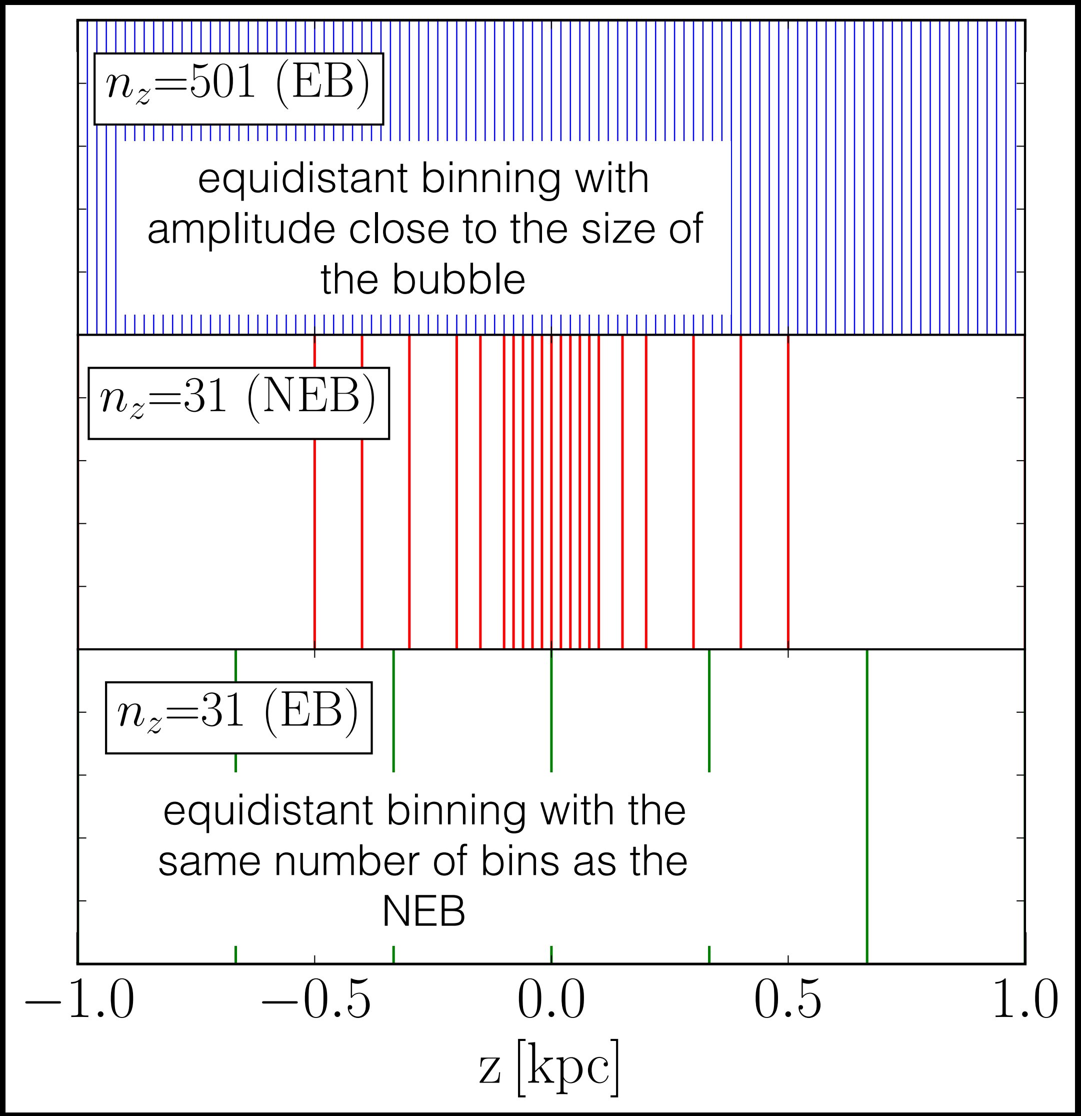
Is there a way to explain the hardening inferred from gamma-ray data within this picture?

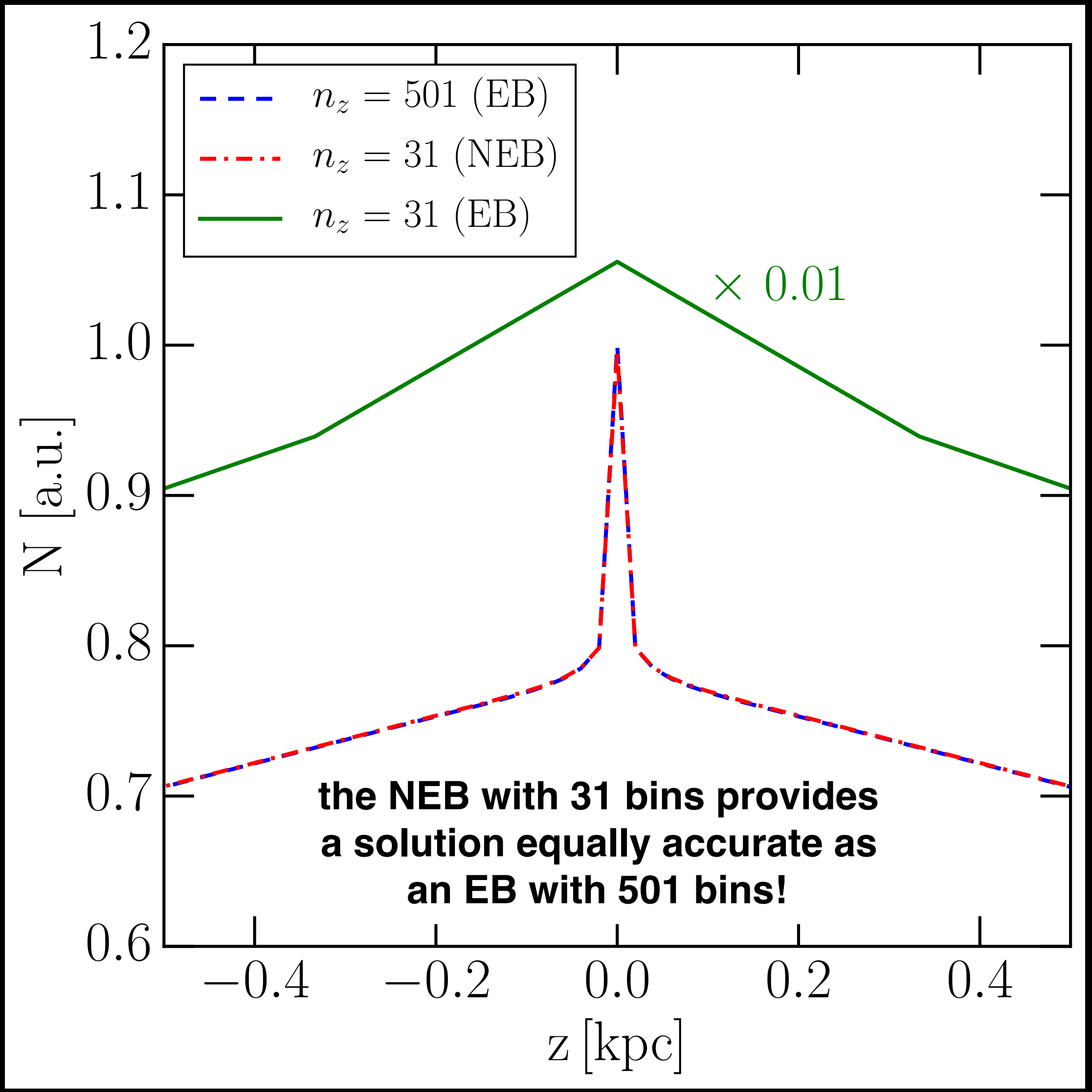
other features of DRAGON2

other features of DRAGON2

-Use of a non-equidistant binning-

A non-equidistant binning (NEB) is useful to model CRs that are **confined in a very compact region**. This might occur if a CR source is within or close to a region where the diffusion coefficient drops (**local bubble**)



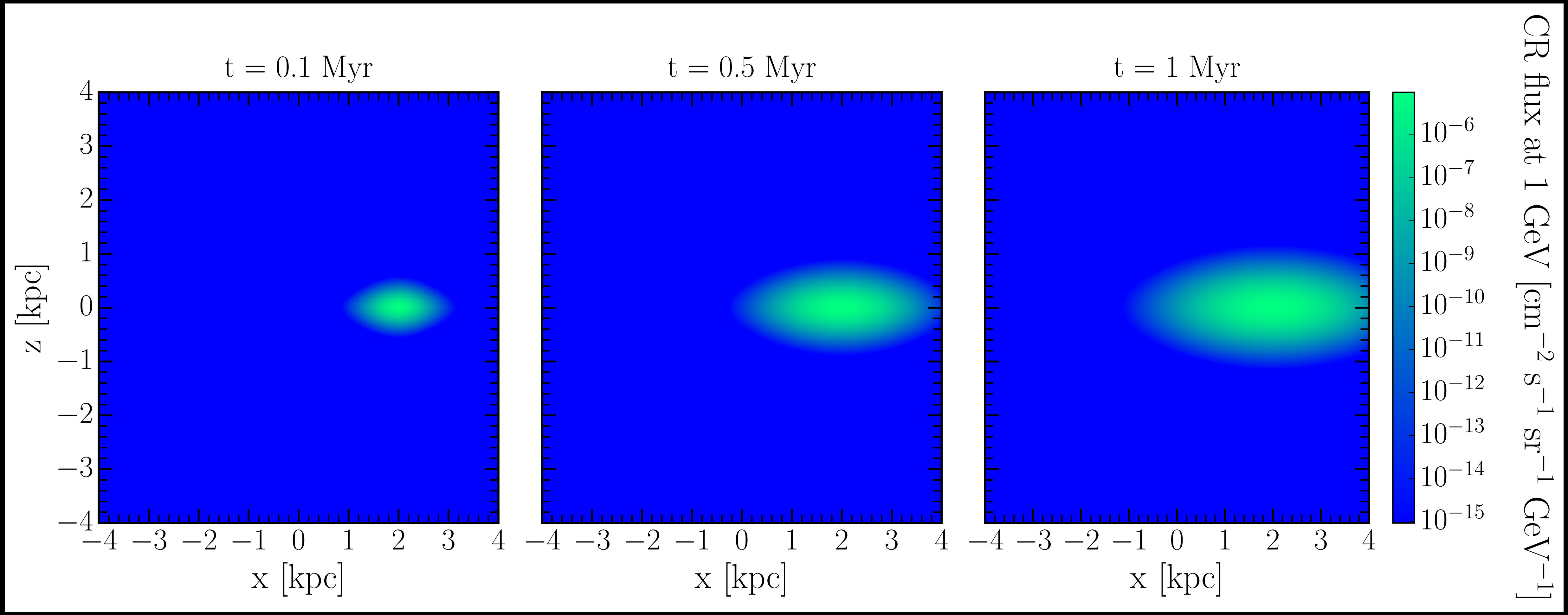


In some situations, using a NEB decreases sensibly the runtime!

other features of DRAGON2

-Possibility to model transient sources-

Point-like source **active for 0.05 Myr**.
Diffusion across the galactic plane dominates over the vertical one



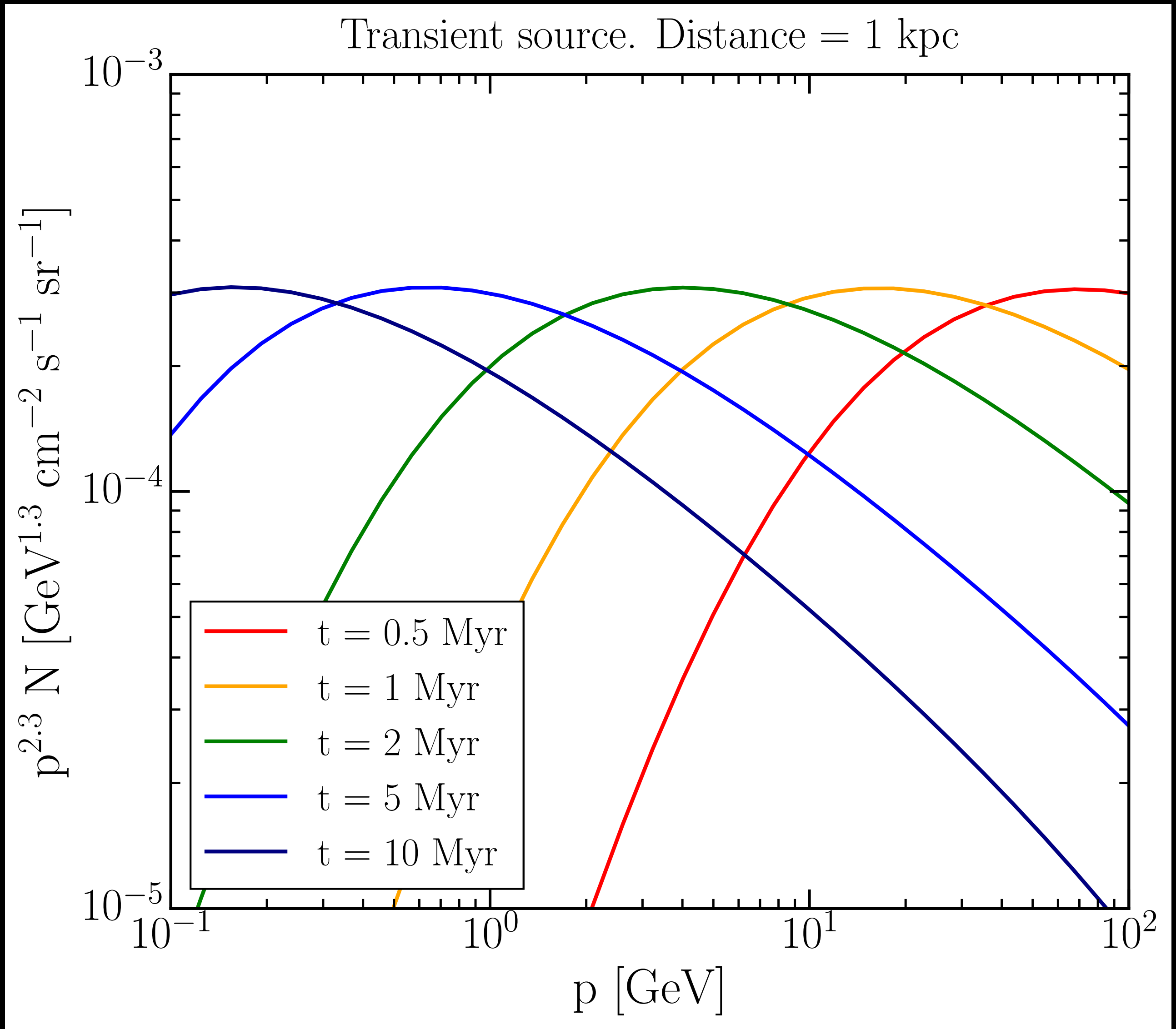
The signature of the anisotropic diffusion is clearly visible

other features of DRAGON2

-Possibility to model transient sources-

Point-like source **active for 0.05 Myr**.
Diffusion across the galactic plane dominates over the vertical one

spectrum evolution at 1kpc from the source



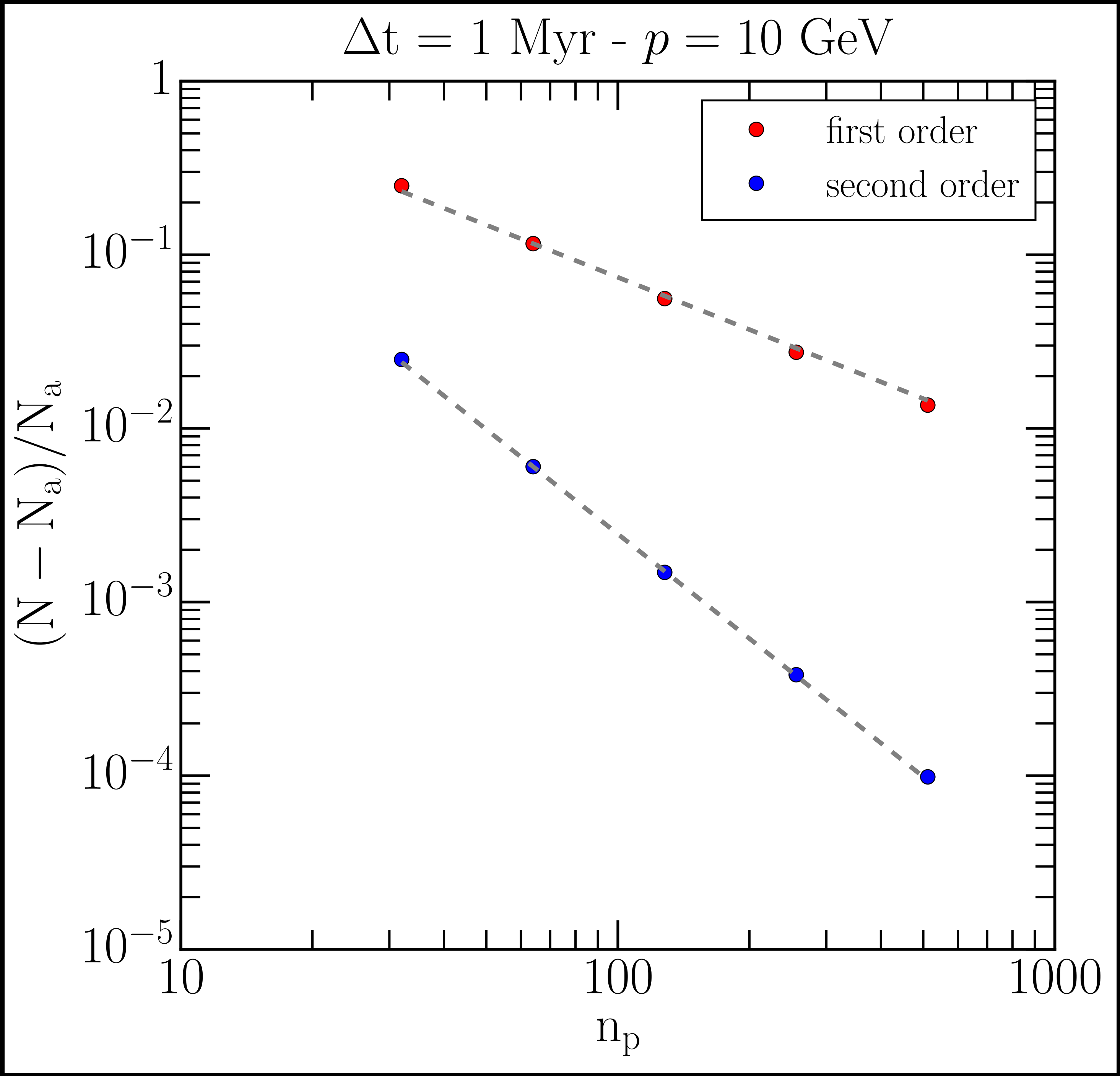
Different timescales associated to the diffusion at **different rigidities** can be seen clearly

High-energy particles diffuse faster than low-energy ones:

$$t_{\text{arrival}} = \frac{1\ \text{kpc}}{6D(p)}$$

other features of DRAGON2

-2nd order discretization scheme for energy losses-

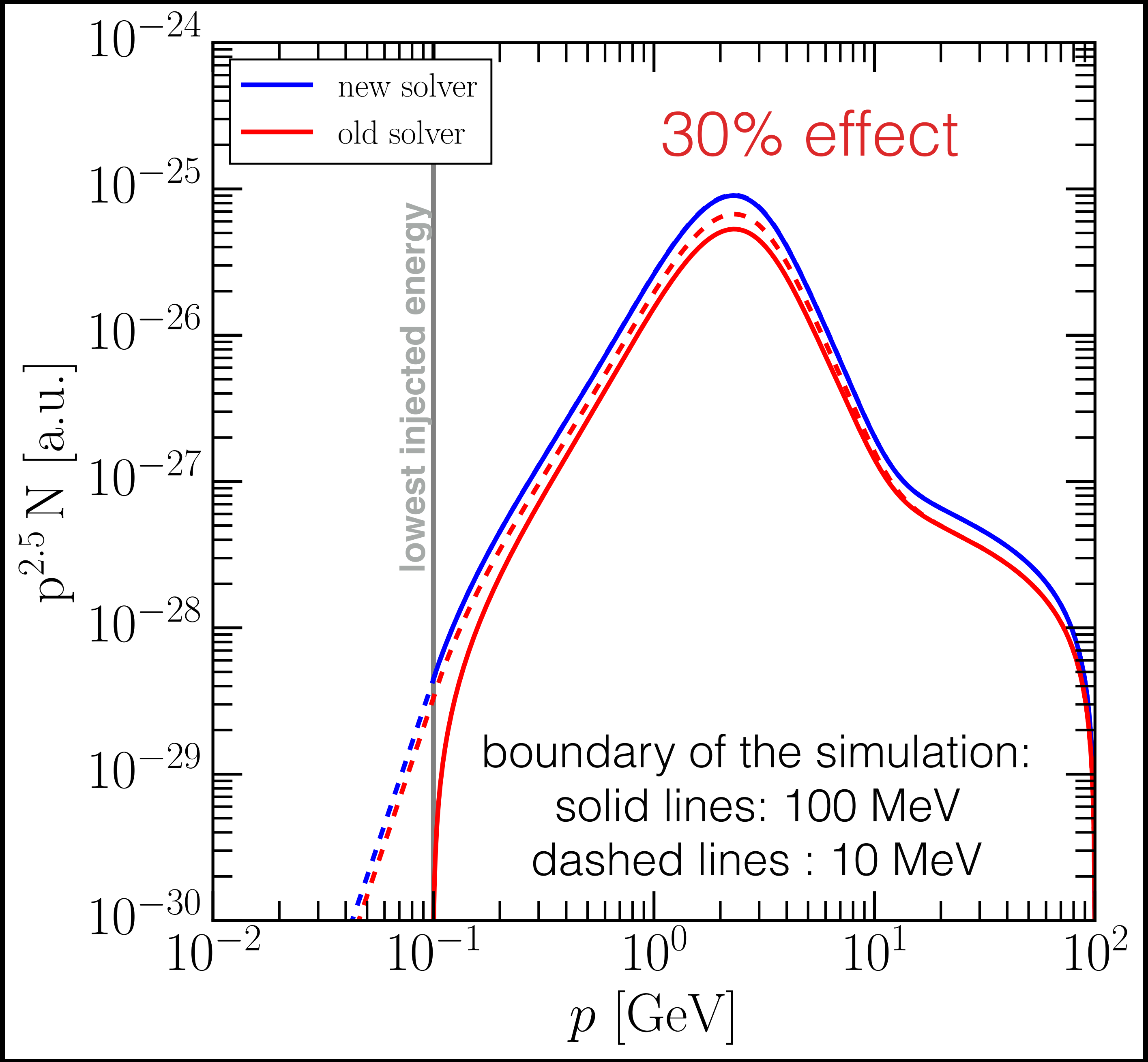


We implement a 2nd order discretisation scheme for the energy loss operator as done in the PICARD code Kissmann AP 55, 2014

We gain one order of magnitude in accuracy without increasing the number of iterations!

other features of DRAGON2

-new treatment of reacceleration-



We use new boundary conditions in the treatment of momentum diffusion:

$$N(p = p_{\max}) = 0, \quad \left(\frac{d}{dp}\frac{N}{p^2}\right)_{p_{\min}} = 0$$

With the new solver the condition $p_{min} = p_{min}$ (injection) can be imposed without loss of accuracy!

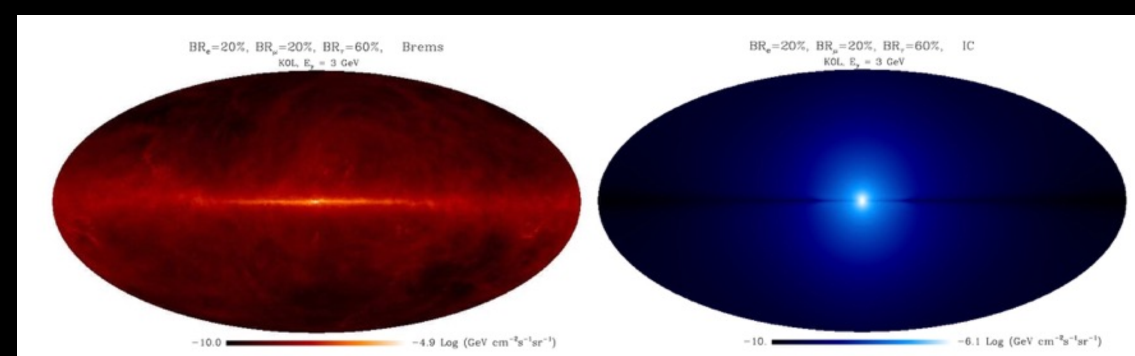
DRAGON2
in a broader context

DRAGON2 is part of a **suite of numerical packages** that cover all the relevant processes in Astroparticle physics from MeV to PeV scale!

1) HeSky

- models gamma-ray diffuse emission from GeV to TeV due to:

- Inverse Compton scattering
- Bremsstrahlung
- Pion decay

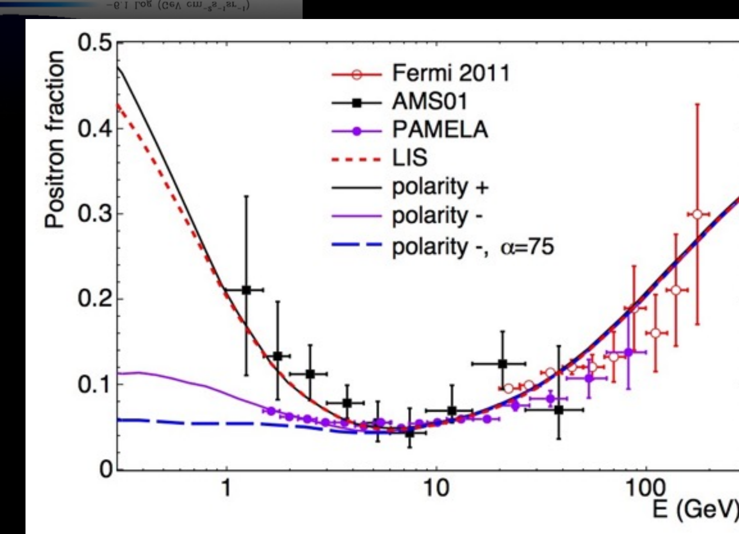


- synchrotron radiation

- diffuse neutrino emission due to pion decay up to PeV energy

2) HelioProp

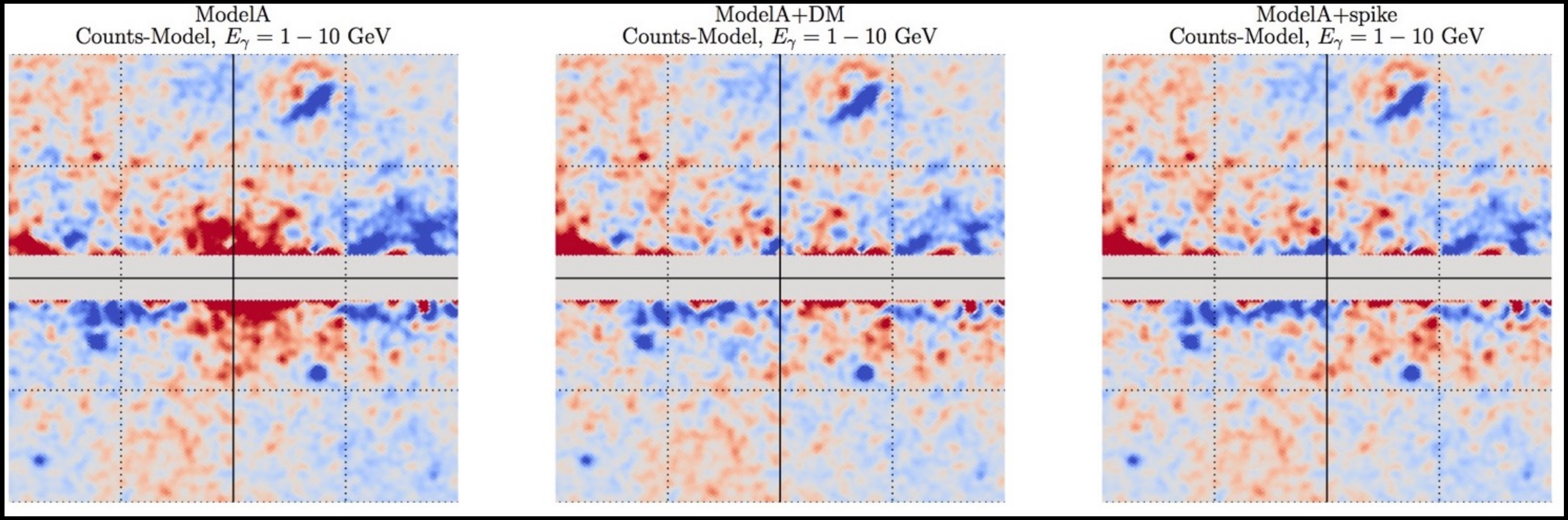
computes the diffusion-loss equation in the Heliosphere
allows to model charge-dependent solar modulation affecting CRs below few GeV



DRAGON2
and the Dark Matter community

The new features in DRAGON2 are very useful for the community interested in indirect DM detection!

Example: the inner Galaxy gamma-ray excess



a careful assessment of the astrophysical background is needed to characterize the excess

D.Gaggero et al., JCAP, 2015 (also Carlson, Profumo, 2015)

with a more realistic modeling of the source distribution in the GC region the excess is reabsorbed!

To better investigate that, models including advection, anisotropic diffusion, and exploiting the non-equidistant binning are needed!

Conclusions and forthcoming work

We have presented DRAGON2,
the new version of the DRAGON code.

The novel features of DRAGON2 make it suitable to be used to model a wide range of processes in CR physics and compete with the upcoming more precise measurements.

The complete suite of tools (DRAGON2, HeSky and HELIOPROP) provide an invaluable instrument to study both CR physics and dark matter indirect detection in a multi-messenger and consistent way

Next steps of the DRAGON project:

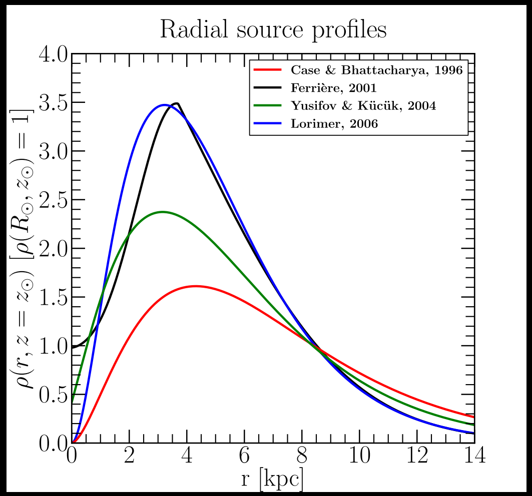
- Public release of a light version of the code with the new solver (very soon!)
- Dedicated papers on cross-sections network and anisotropic diffusion
- Release of the full version of the code, that will be followed by HeSky and Helioprop


Thank you for your attention!

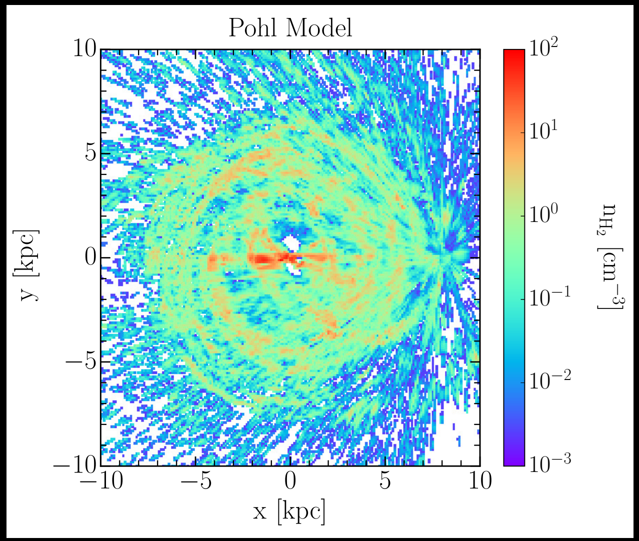
Backup slides

DRAGON2
state-of-the-art models for the astrophysical ingredients

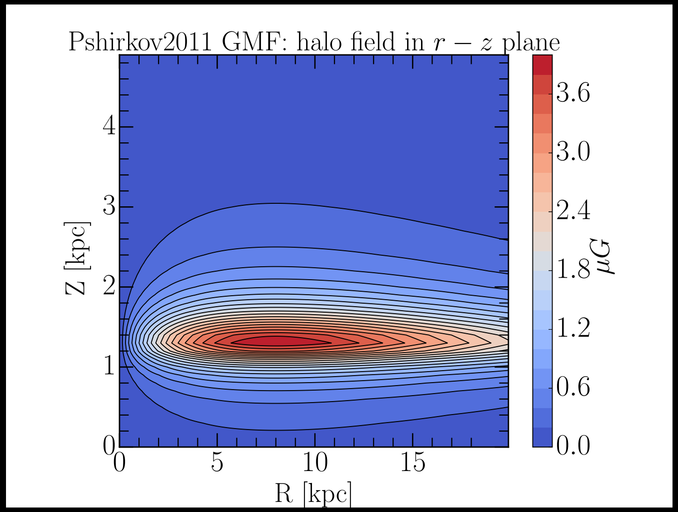
Source distribution
- Case1998
- Yusifov2004
- Lorimer2006
- Ferriere2001



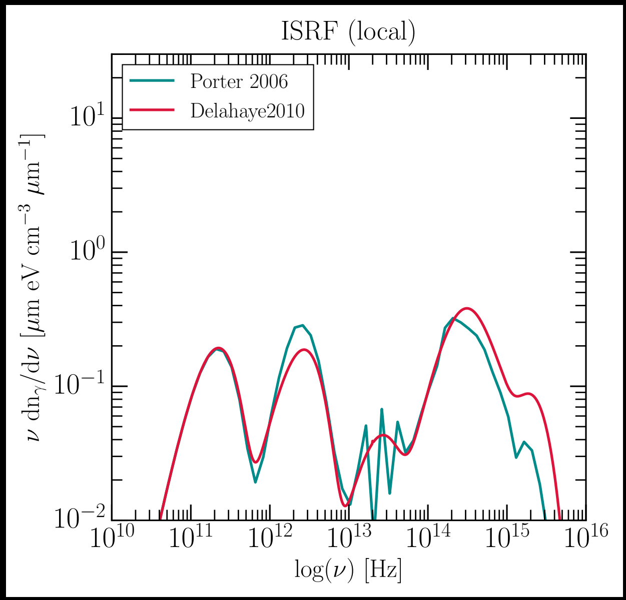
Interstellar gas distribution
- Atomic: Gordon1976, Nakanishi2003, Ferriere2007
- Molecular: Bronfman1988, Nakanishi2006, Ferriere2007, Pohl2008
- Ionized: Corders1991, NE2001



Magnetic field model
- Sun2007
- Pshirkov2011
- Jansson&Farrar2012



Interstellar radiation field model
- Porter2006
- Delahaye2010



DRAGON2
numerical tests

for each operator:

— we derive an analytical solution

— we consider the relevant timescales

— we choose the timestep of the simulation

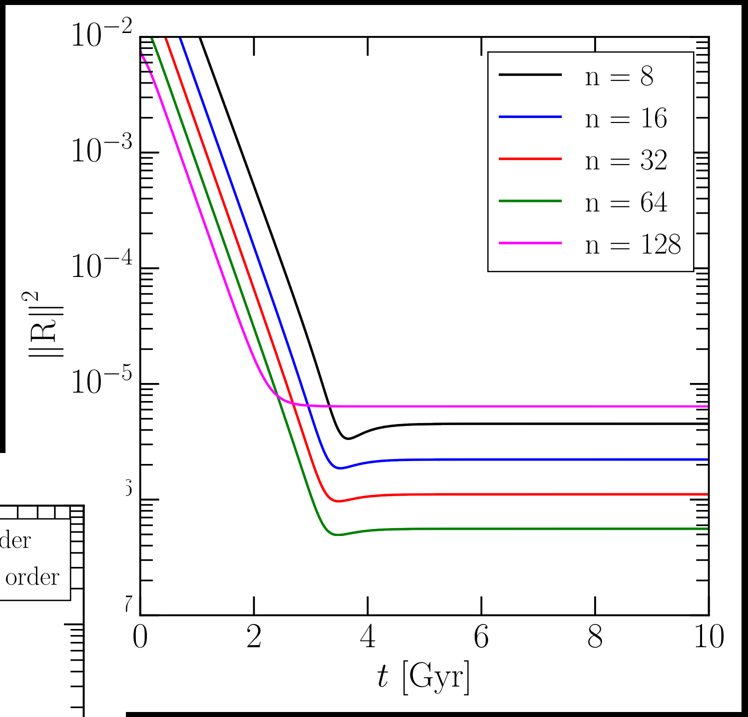
— we run the solver until convergence is reached (for the single operator, it is enough to look at the residual)

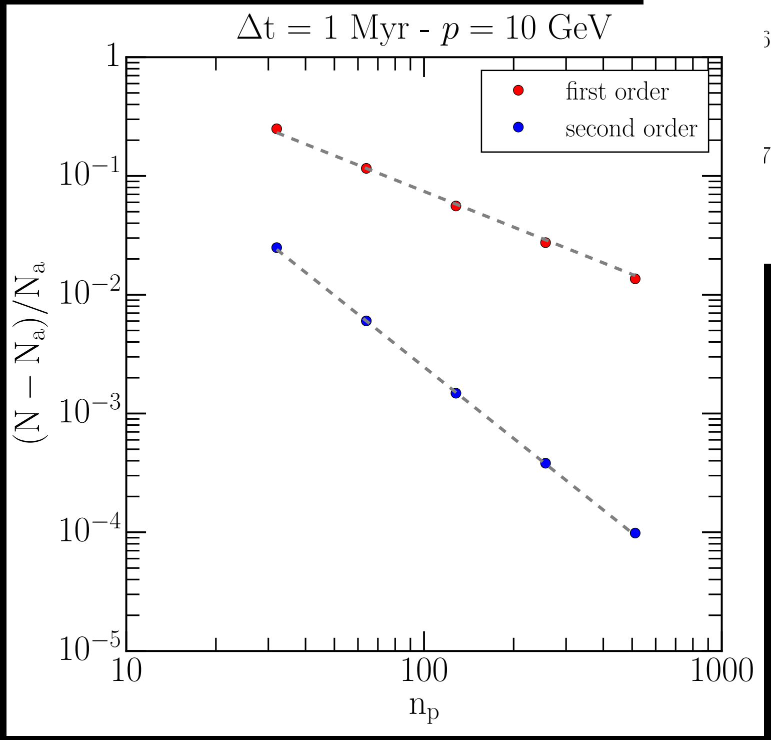
— we compare numerical and analytical solutions for different choices of the grid size

$$N_a(x,y,z) = \cos\left(\frac{\pi x}{2L_x}\right)\cos\left(\frac{\pi y}{2L_y}\right)\cos\left(\frac{\pi z}{2L_z}\right).$$

In order to satisfy Eq. B.4, the source term must take the following form:

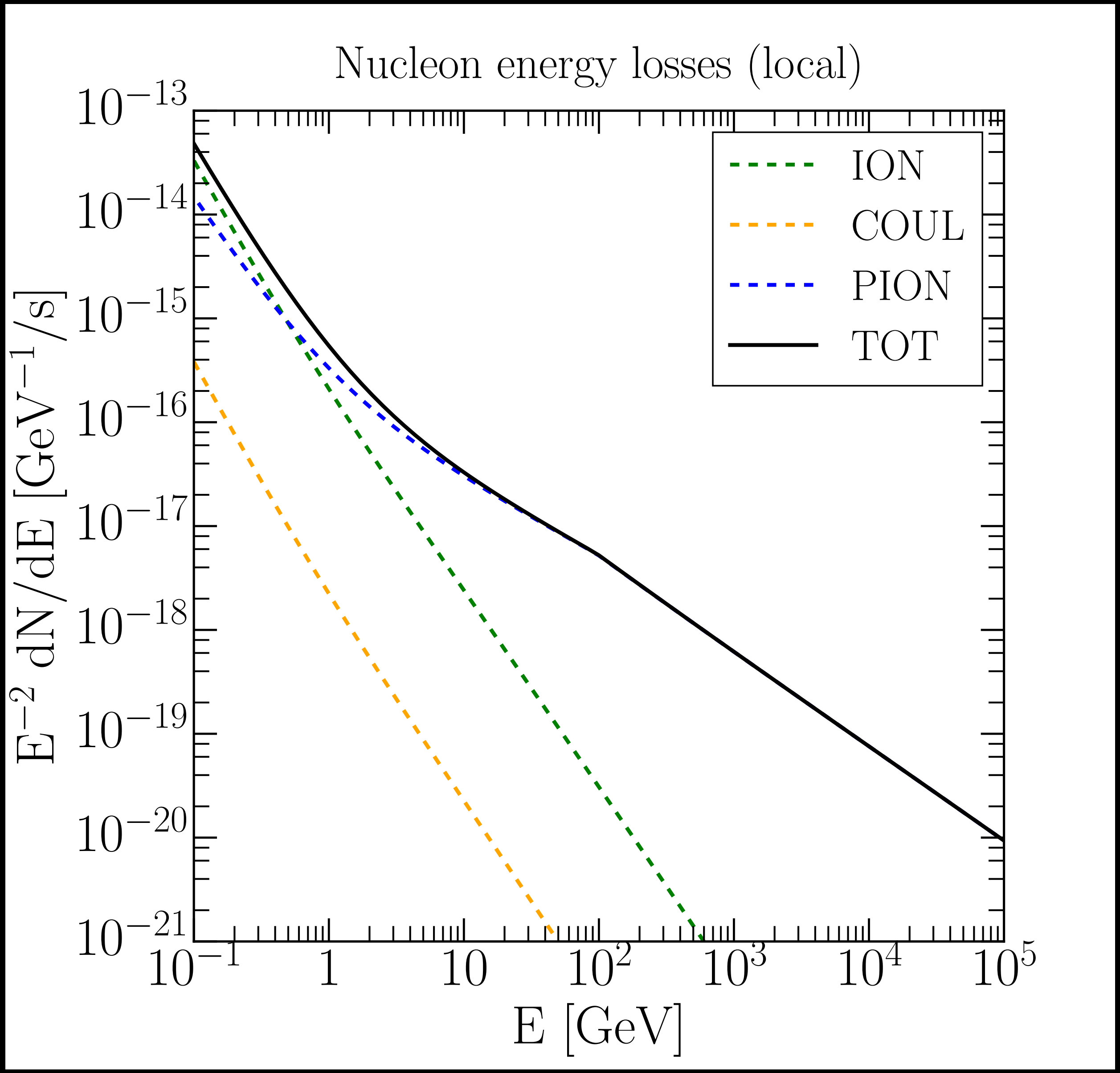
$$Q(x,y,z) = \frac{\pi^2}{4}\left(\frac{D_{xx}}{L_x^2}+\frac{D_{yy}}{L_y^2}+\frac{D_{zz}}{L_z^2}\right)\cos\left(\frac{\pi x}{2L_x}\right)\cos\left(\frac{\pi y}{2L_y}\right)\cos\left(\frac{\pi z}{2L_z}\right)$$

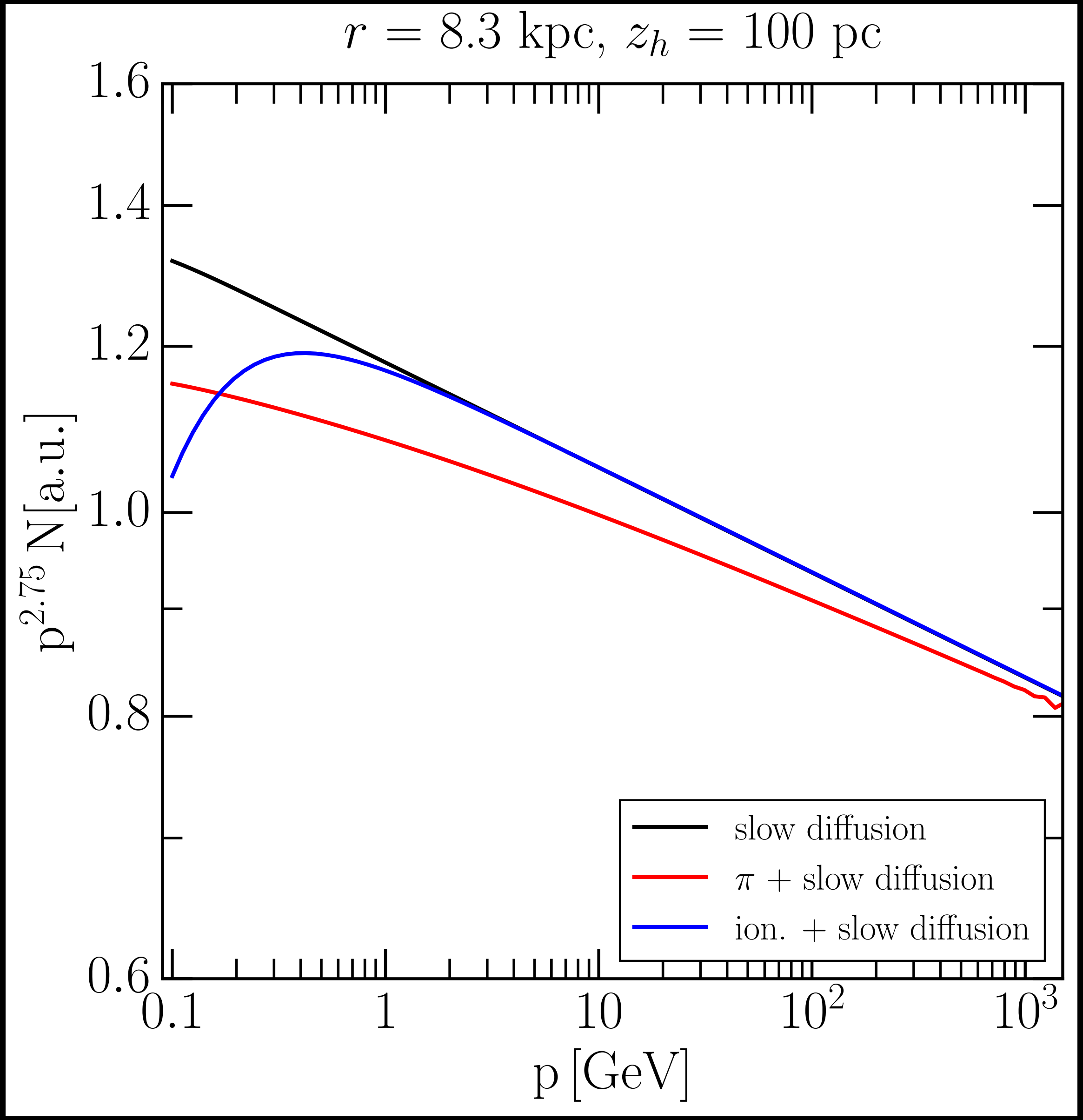




new ingredients in DRAGON2

DRAGON2 implements nuclear energy losses by pion production!





pion-production energy losses are relevant in the whole energy range → **They can affect the whole spectrum (especially if diffusion is slow)**