Cosmic-ray propagation with DRAGON2

Dark side of
the Universe
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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 (first release: summer 2008)

- 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 (comprehensive documentation on arXiv:xxxx, will be released soon)

- 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:xxxx.xxxx
- C. Evoli, D. Gaggero et al., "CR propagation with DRAGON2: II. cross-section network" *in preparation*

The DRAGON project

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

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

all **relevant processes** are taken into account:
— spatial diffusion
— energy losses
— reacceleration
— advection
— spallation

each process is associated to a **position 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

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 entirely 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.

This approach is required by both theory and observations.

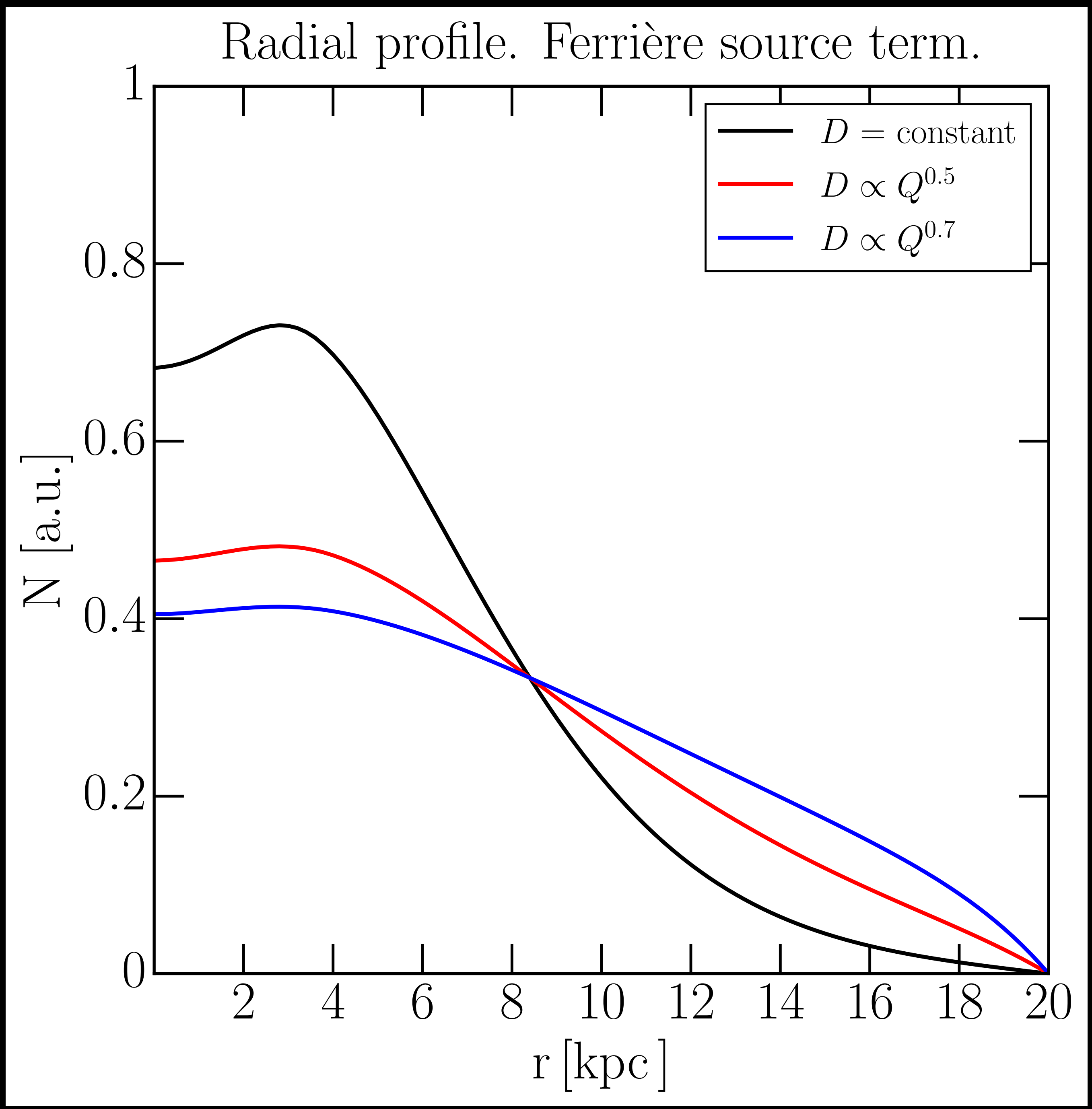
Theory: the presence of a **large scale Galactic magnetic field** breaks isotropy and introduces a **preferred direction**

Observations: data are in tension with conventional propagation models:

- **Gradient problem:** the radial profile of the gamma-ray emissivity along the galactic plane is flatter than predicted
- **Slope problem:** 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

-Gradient problem-



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

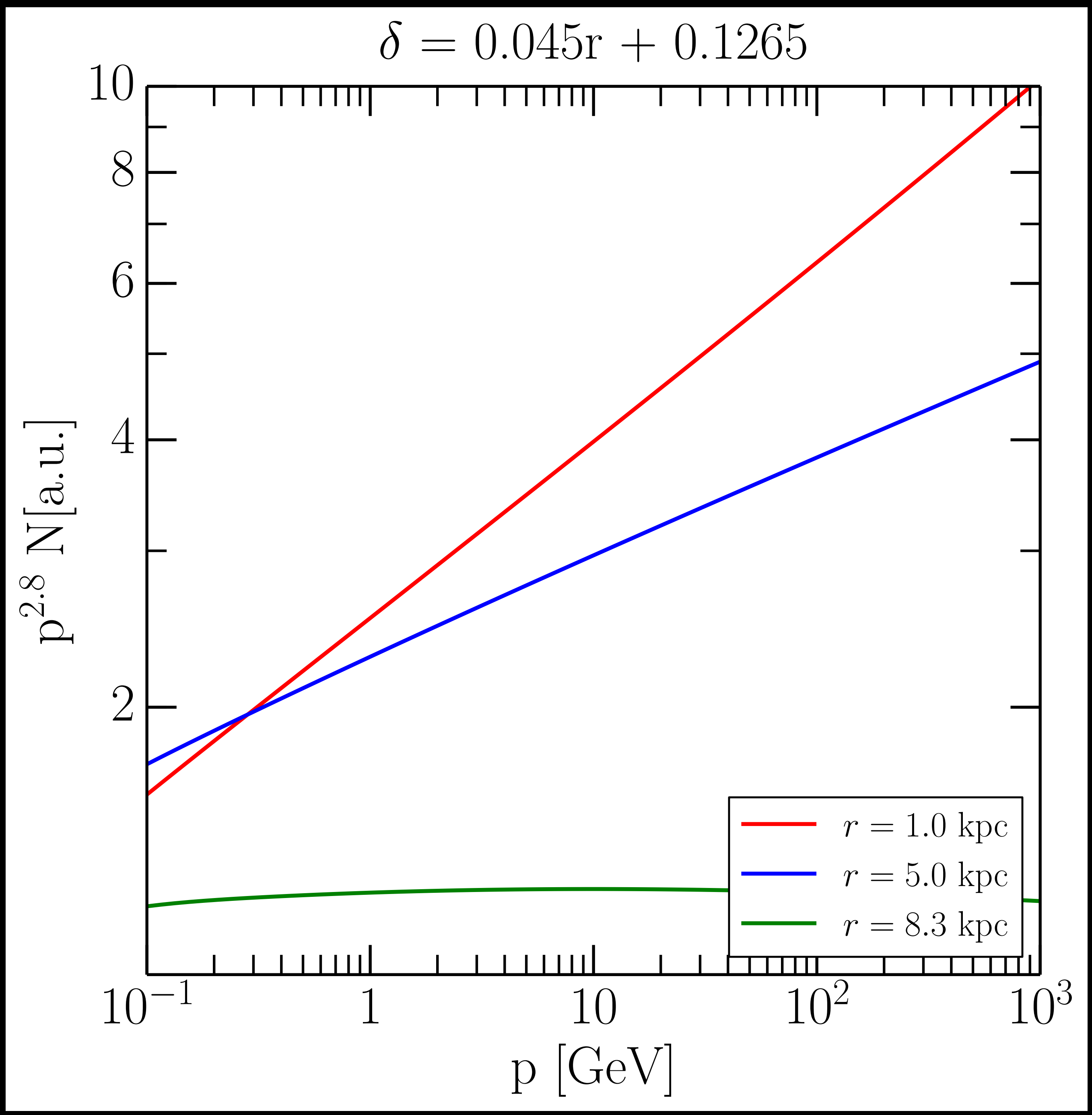
C.Evoli et al., PRL 108, 2012

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

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

spatial diffusion in DRAGON2

-Slope problem-



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-

Anisotropic diffusion can explain the hardening.

Galactic magnetic field: purely azimuthal with an out-of-plane component directed along z and confined within the bulge (2.9 kpc).

$$D_r = D_{0,\perp} \left(\frac{p}{p_0} \right)^{\delta_\perp}$$

$$D_z = D_{0,\perp} \left(\frac{p}{p_0} \right)^{\delta_\perp} + D_{0,\parallel} \exp\left(-\frac{r}{2.9\,\mathrm{kpc}} \right) \left(\frac{p}{p_0} \right)^{\delta_\parallel}$$

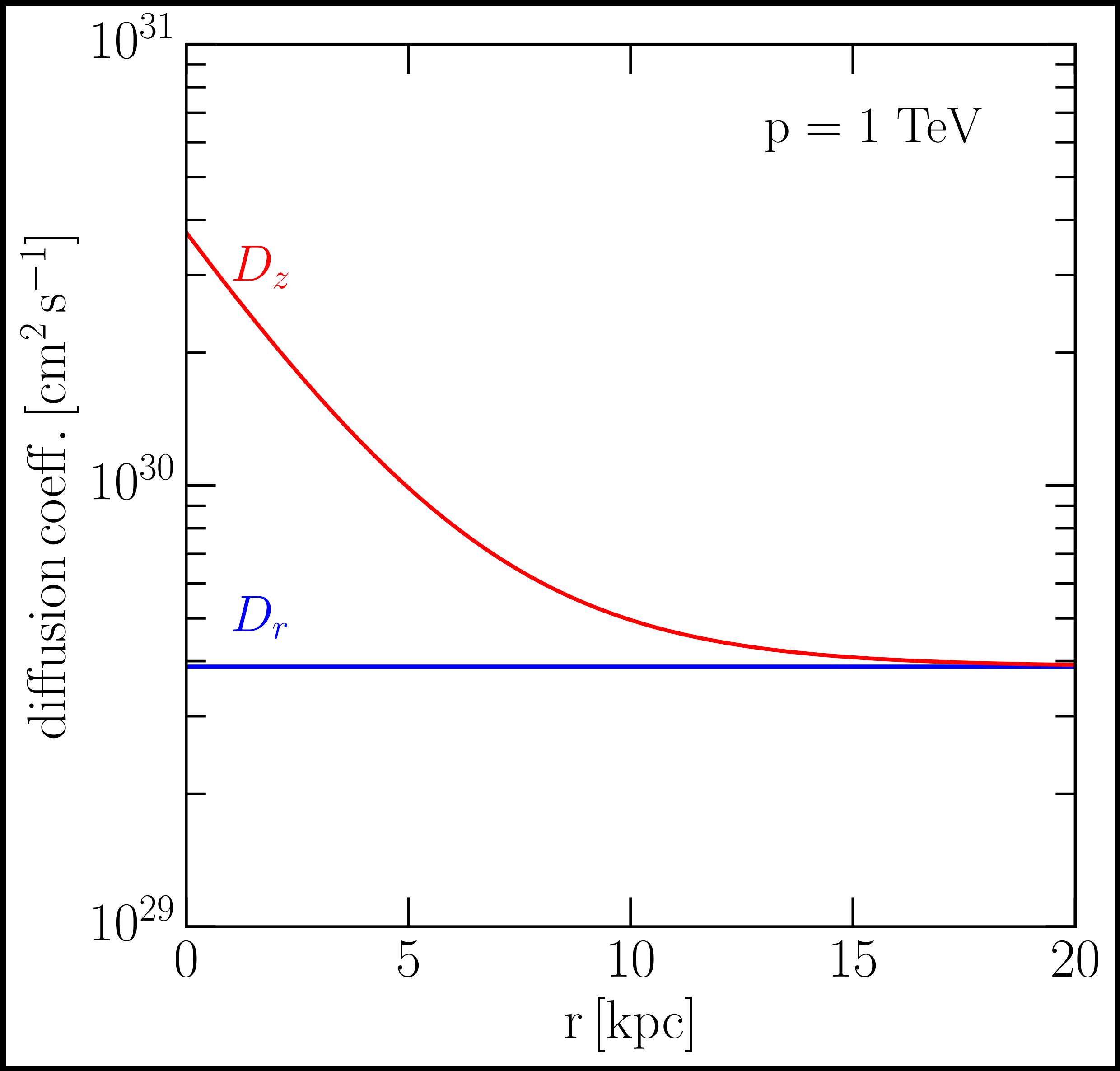
with $\delta_\perp = 0.5\,,\quad \delta_\parallel = 0.33$ and $D_{0,\parallel}/D_{0,\perp} = 30$

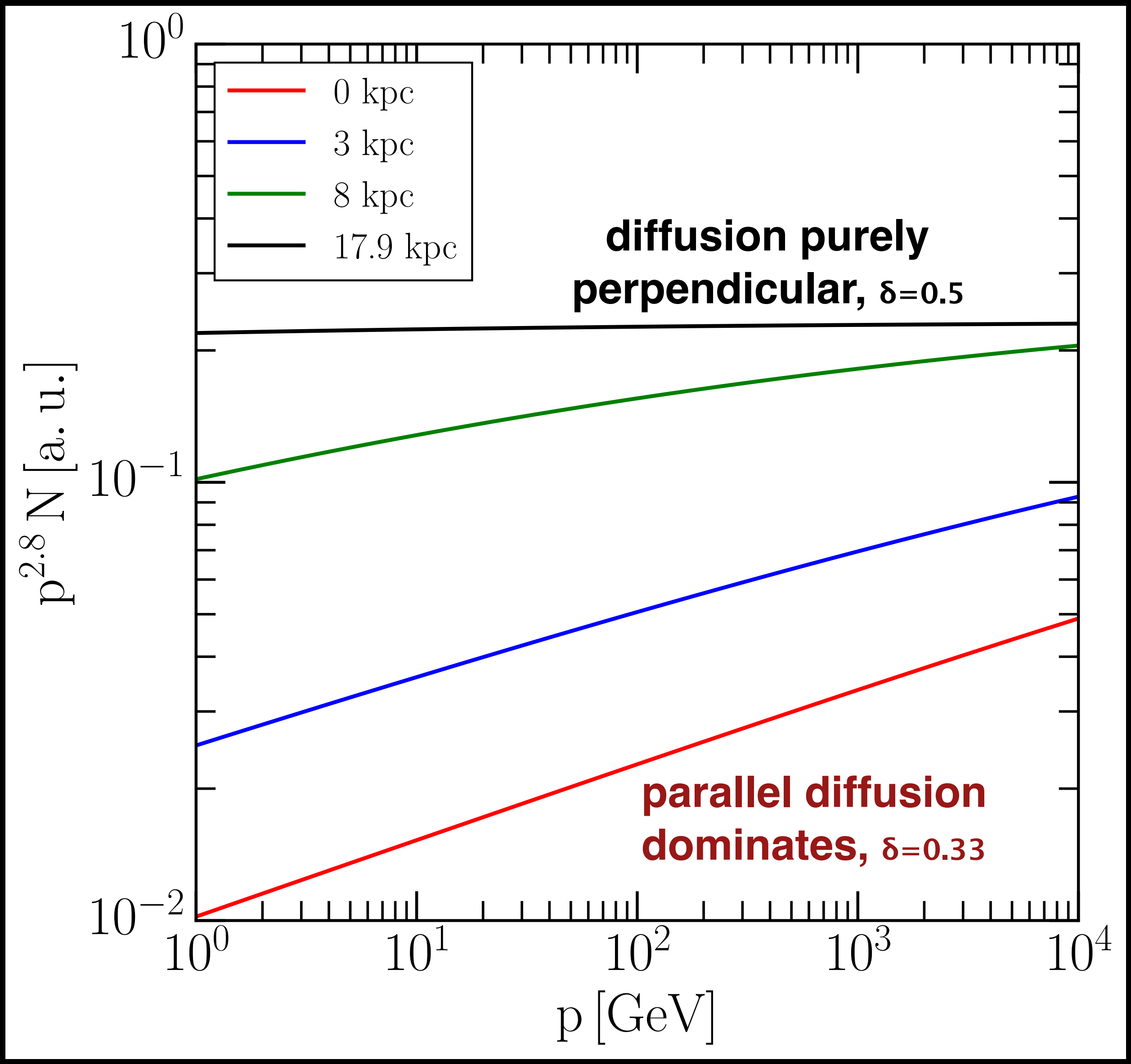
De Marco, Blasi. Stanev, JCAP 6 2007

spatial diffusion in DRAGON2

-Slope problem-

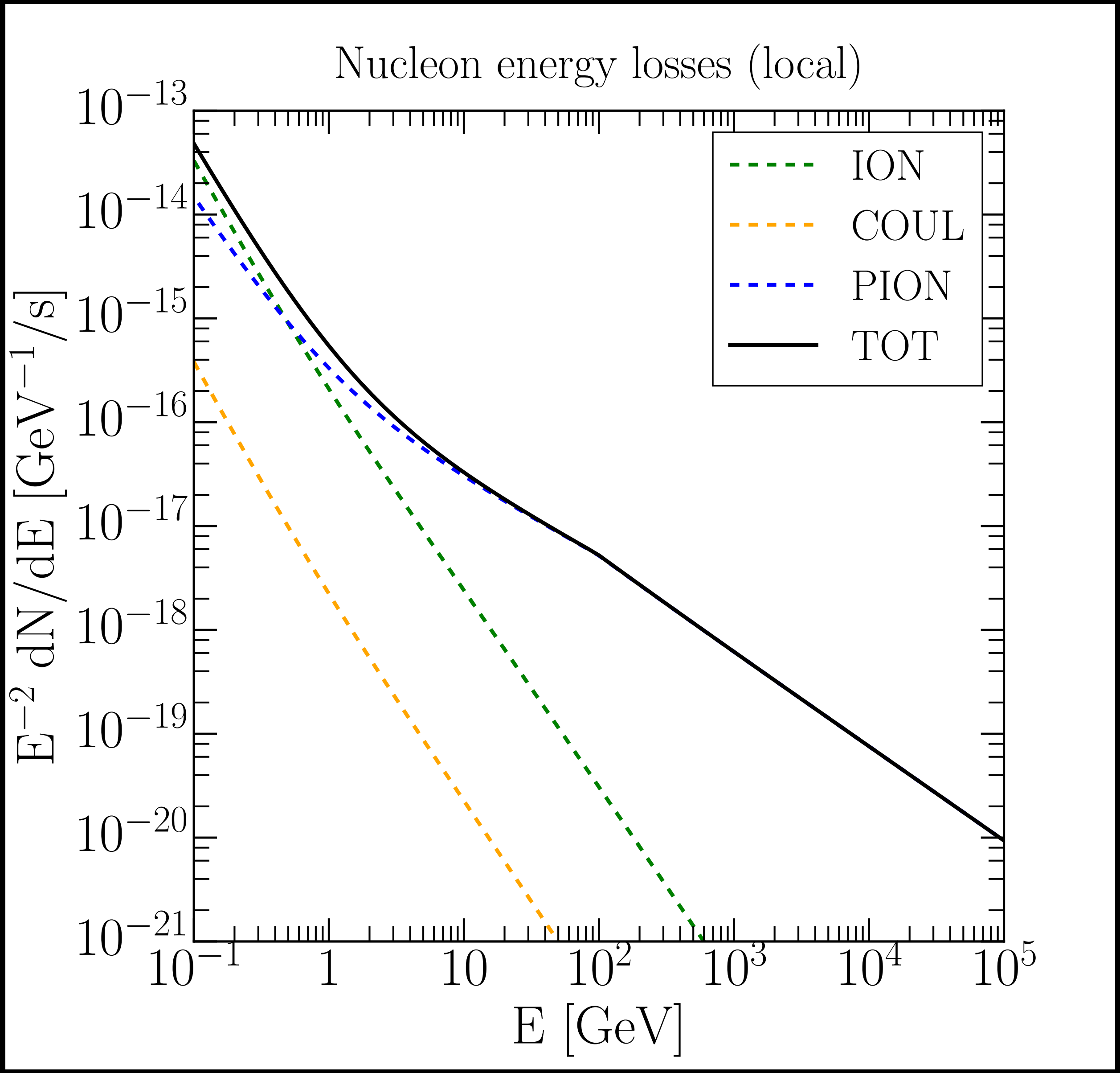
Anisotropic diffusion can explain the hardening.

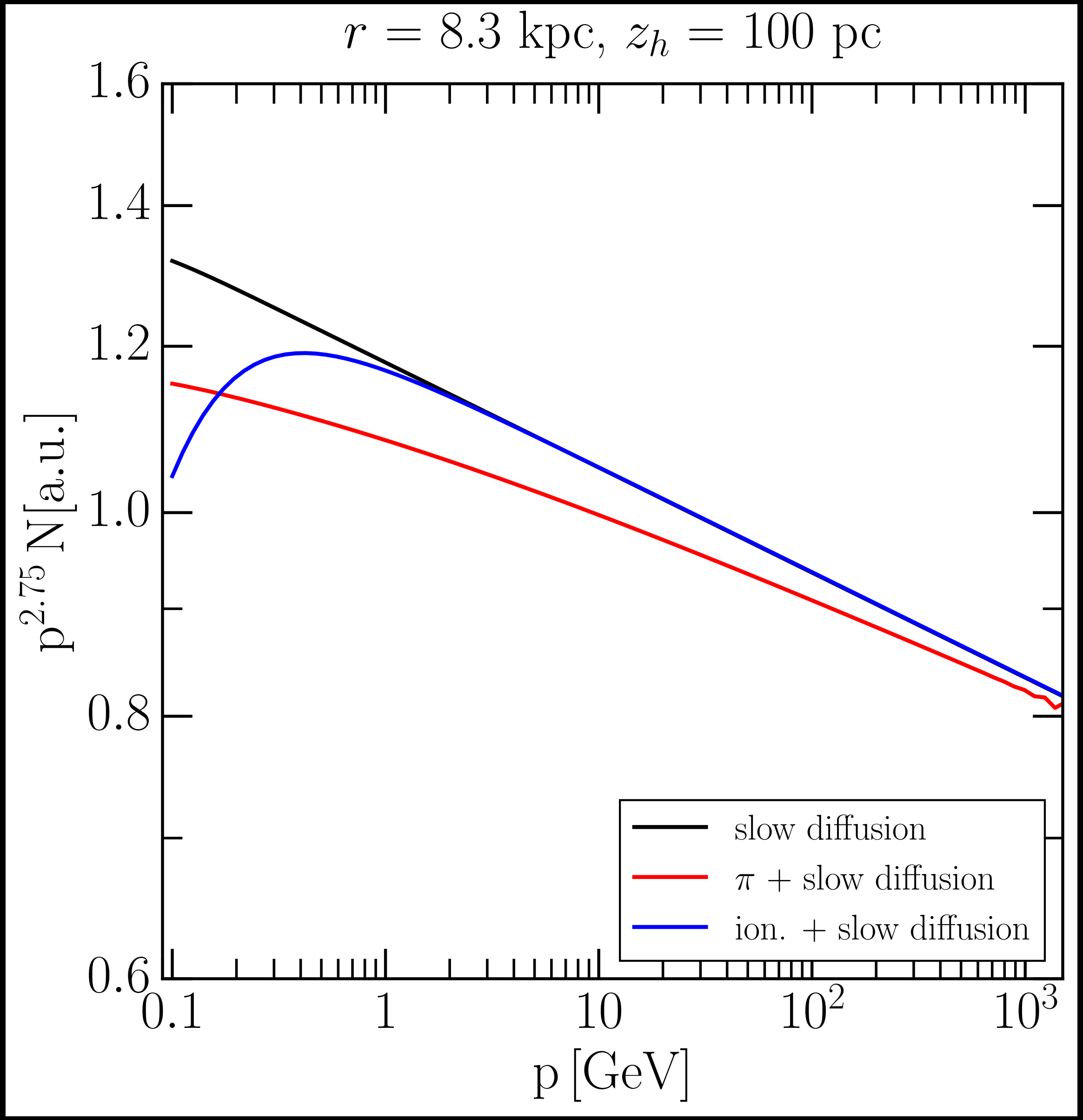




new ingredients in DRAGON2

DRAGON2 implements nuclear energy losses by pion production!



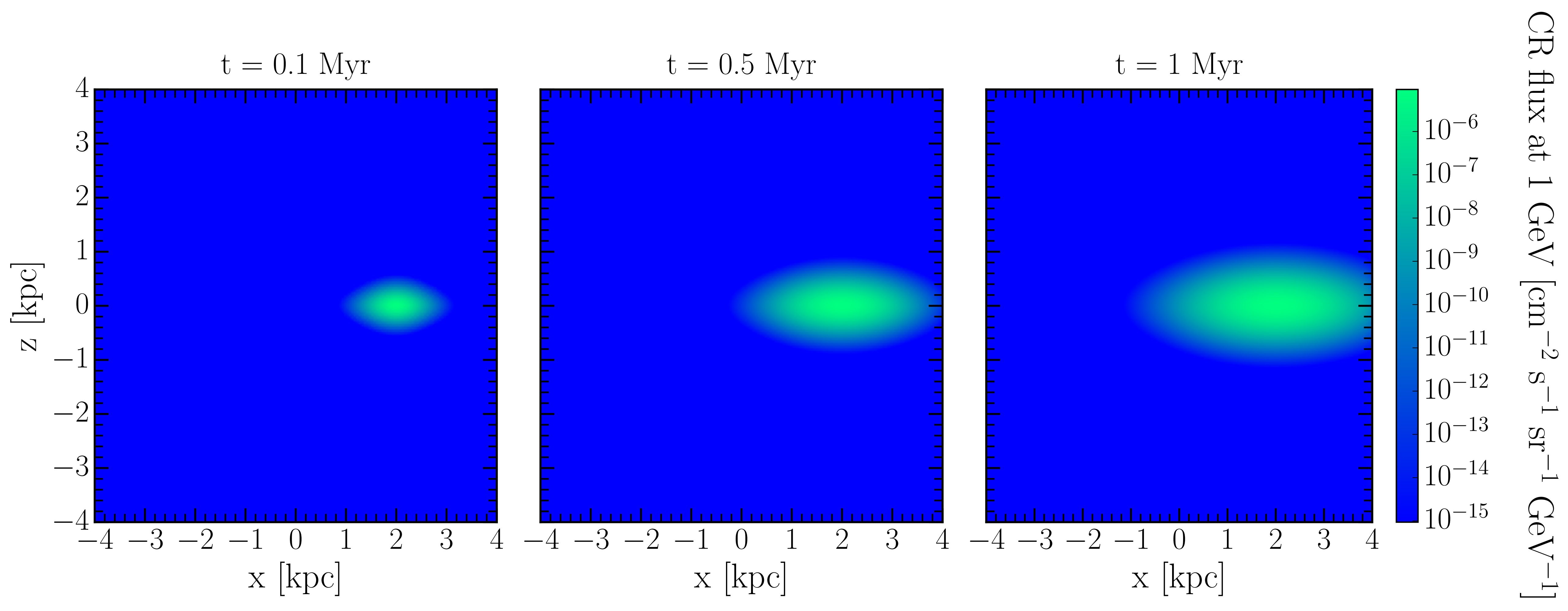


pion-production energy losses are relevant in the whole energy range → **They can affect the whole spectrum (especially if diffusion is slow)**

features of DRAGON2

-Anisotropic diffusion from a transient source-

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



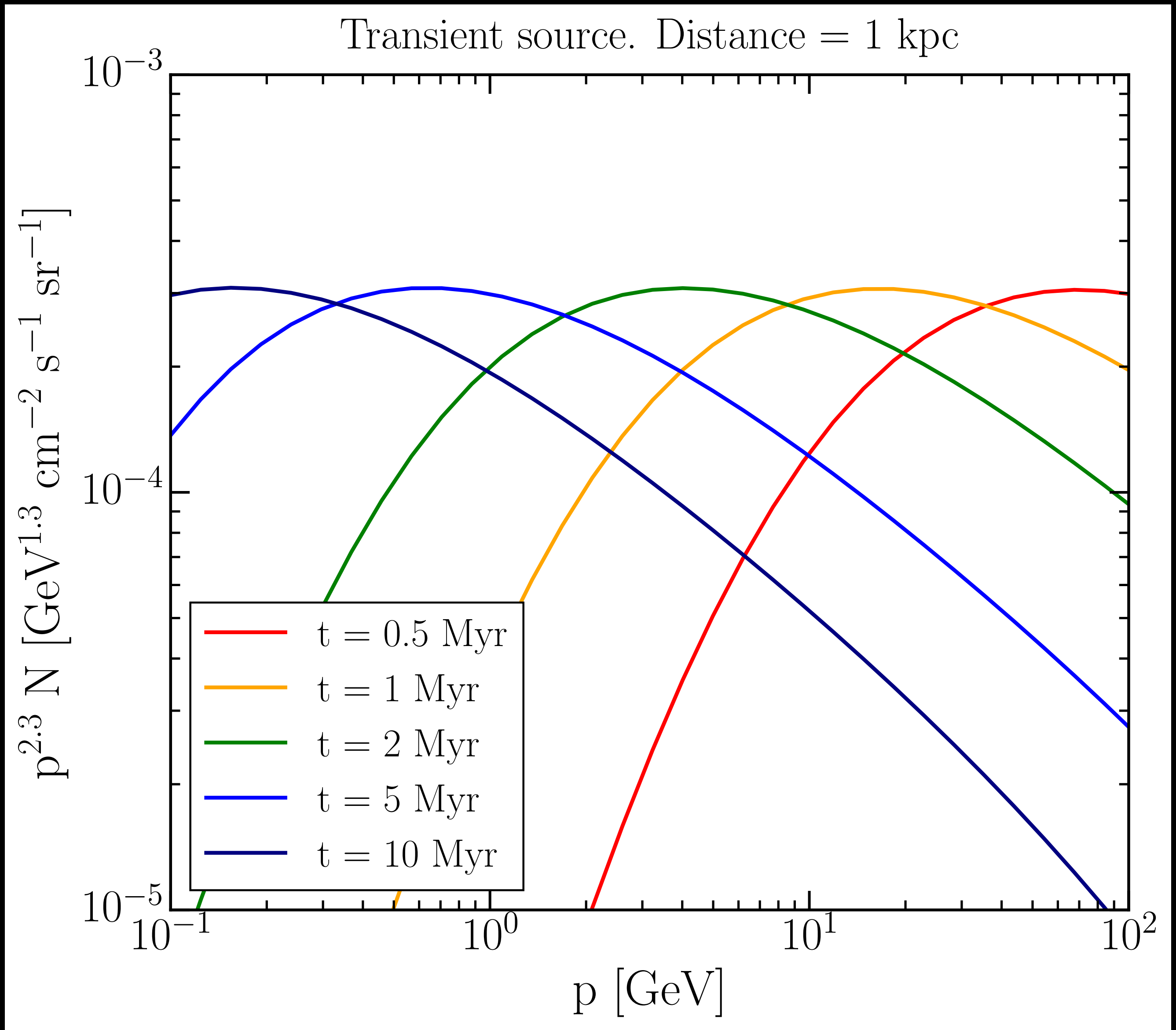
The signature of the anisotropic diffusion is clearly visible

features of DRAGON2

-Anisotropic diffusion from a transient source-

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

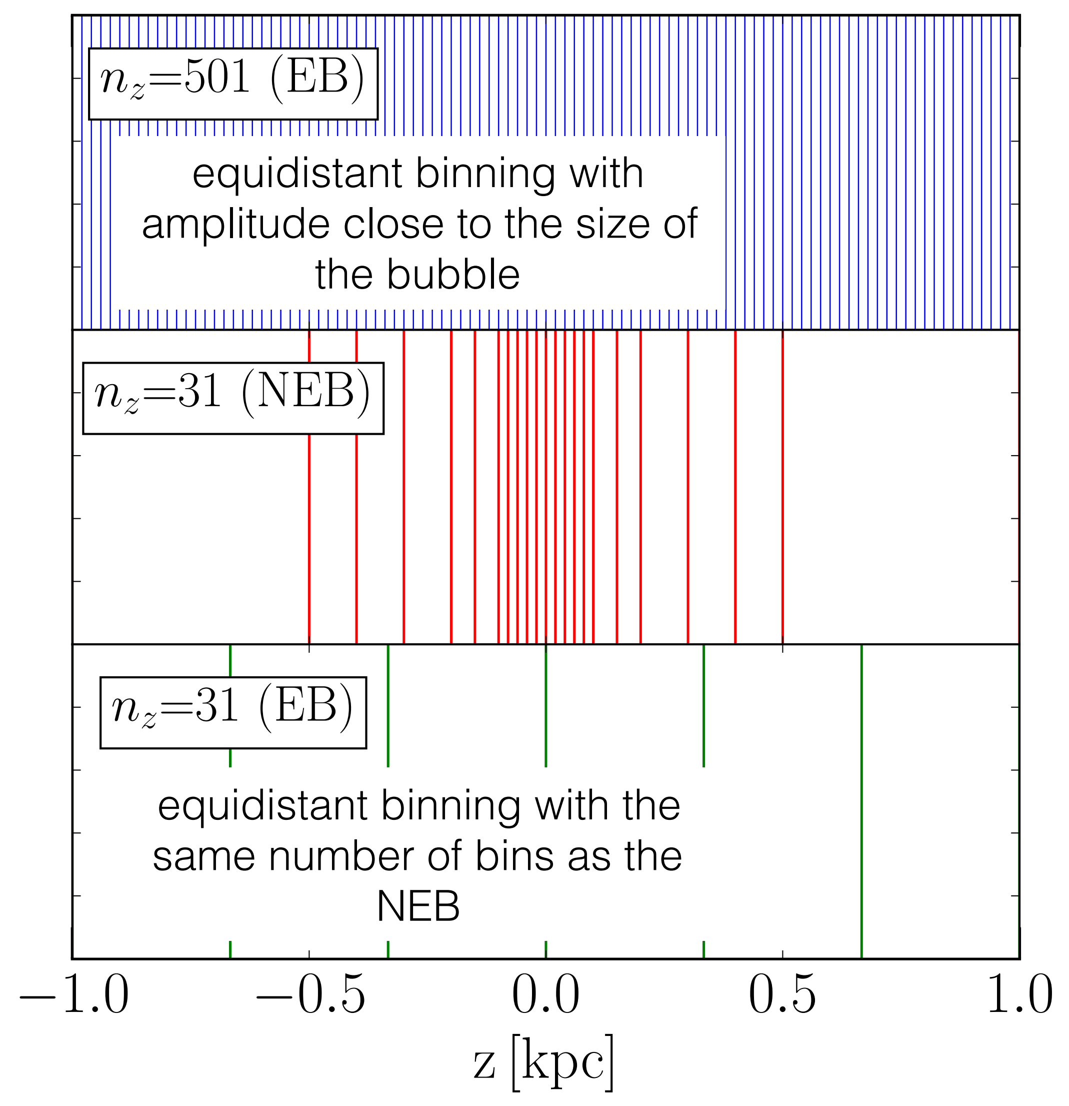
High-energy particles diffuse faster than low-energy ones:

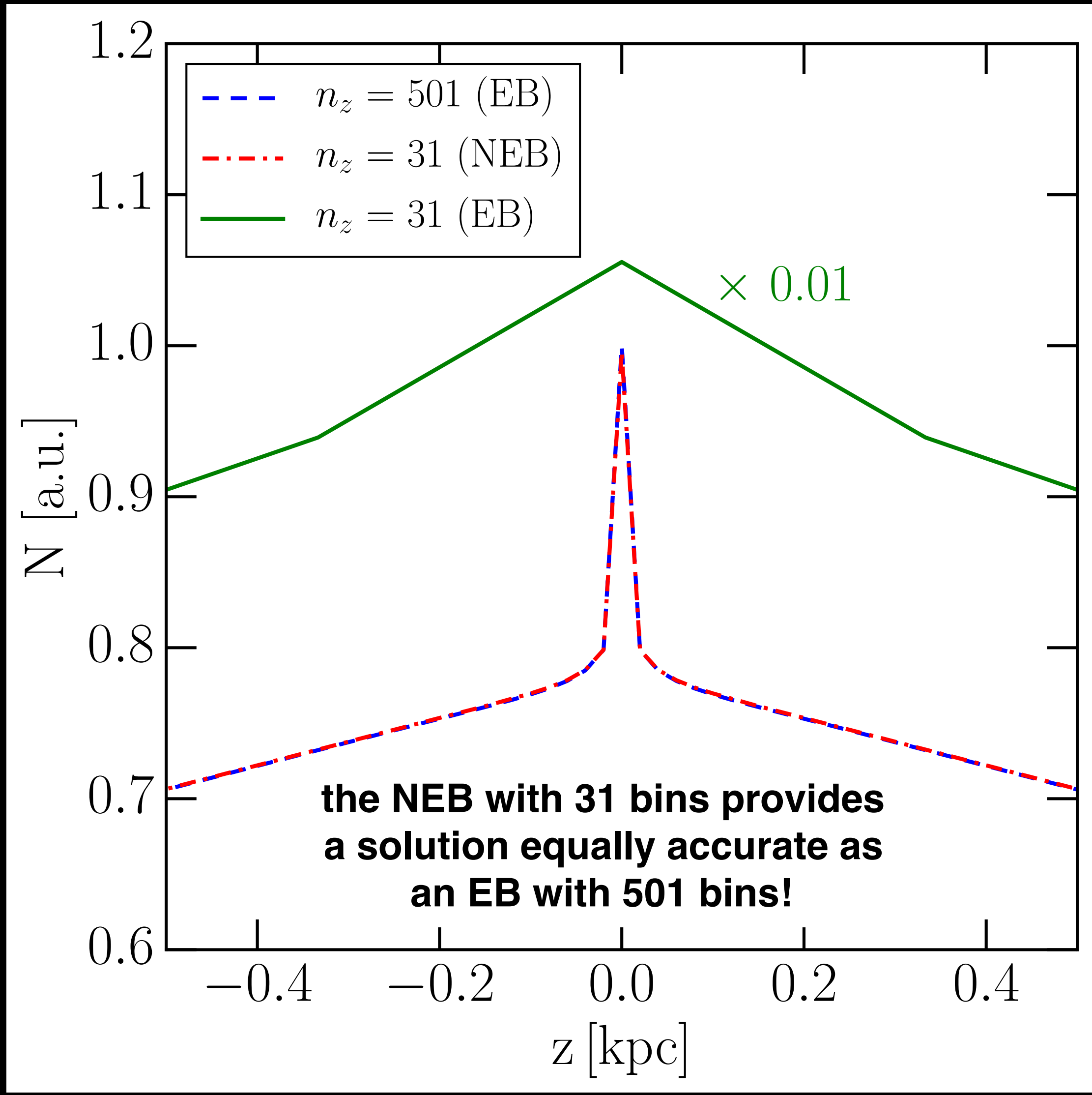
$$t_{\rm arrival} = \frac{1\,\mathrm{kpc}}{6D(p)}$$

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**)

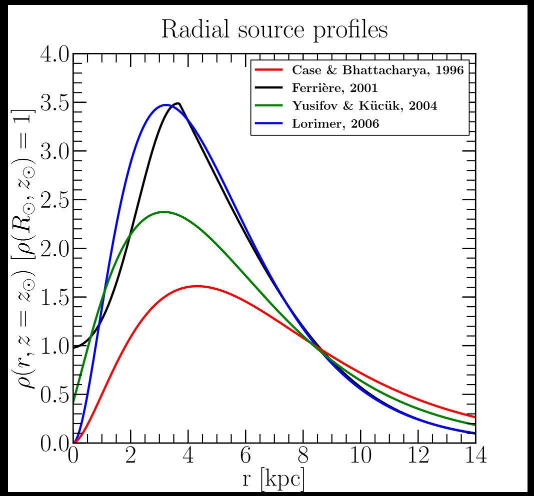




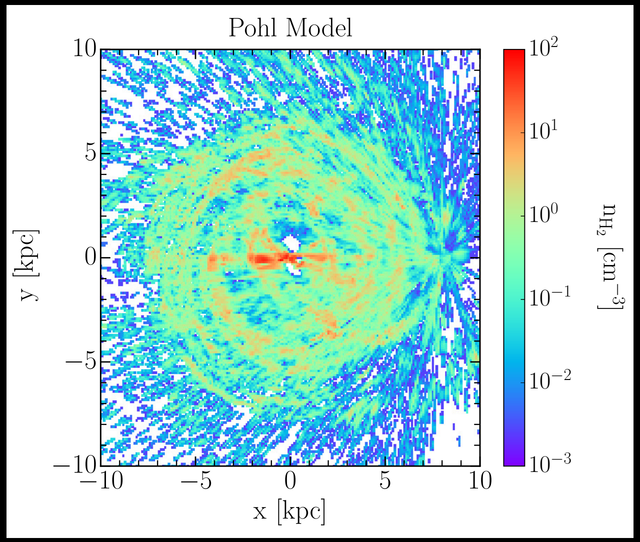
In some situations, using a NEB decreases sensibly the runtime!

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

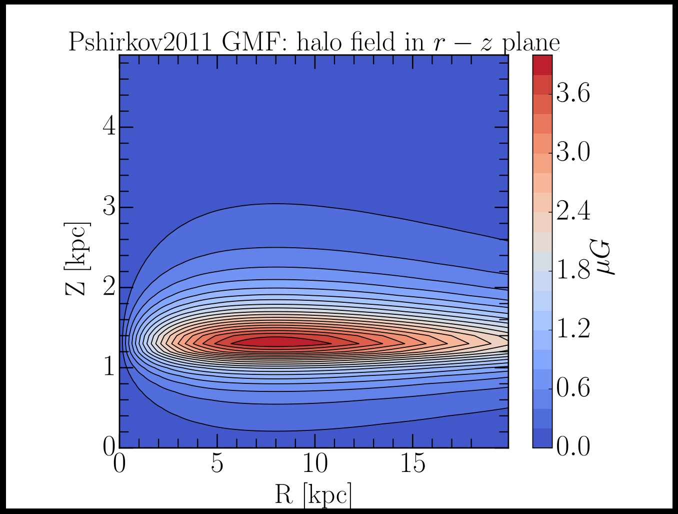
Source distribution
- Case1998
- Yusifov2004
- Lorimer2006
- Ferriere2001



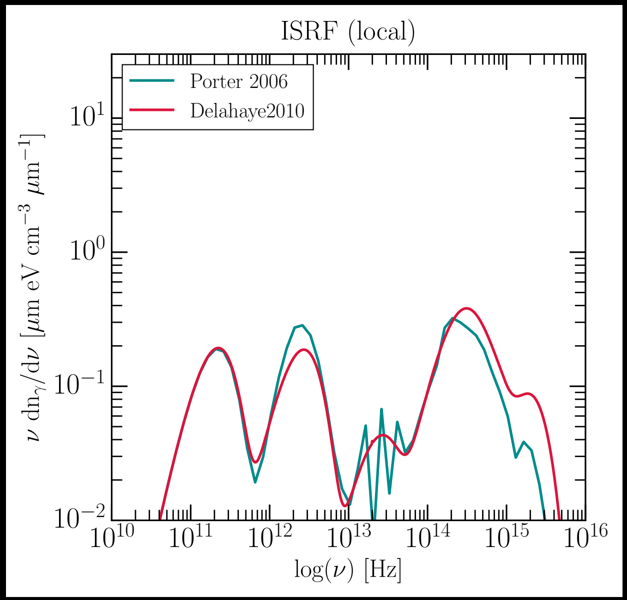
Interstellar gas distribution
- Atomic: Gordon1976, Nakanishi2003, Ferriere2007
- Molecular: Bronfman1988, Nakanishi2006, Ferriere2007, Pohl2008
- Ionized: Corders1991, NE2001



Magnetic field model
- Sun2007
- Pshirkov2011
- Jansson&Farrar2012



Interstellar radiation field model
- Porter2006
- Delahaye2010



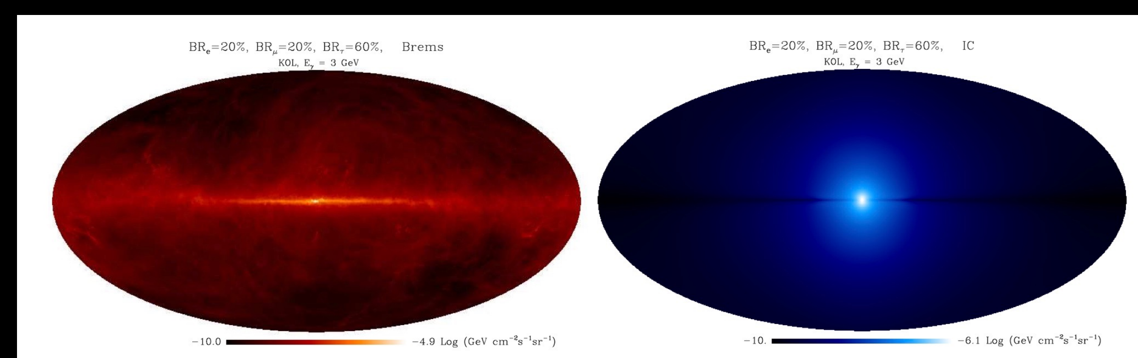
DRAGON2
in a broader context

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

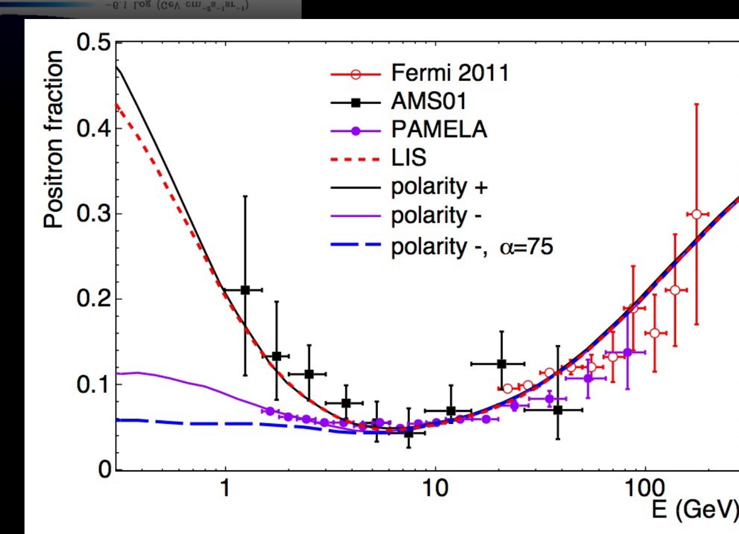


- synchrotron radiation

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

2) HelioProp

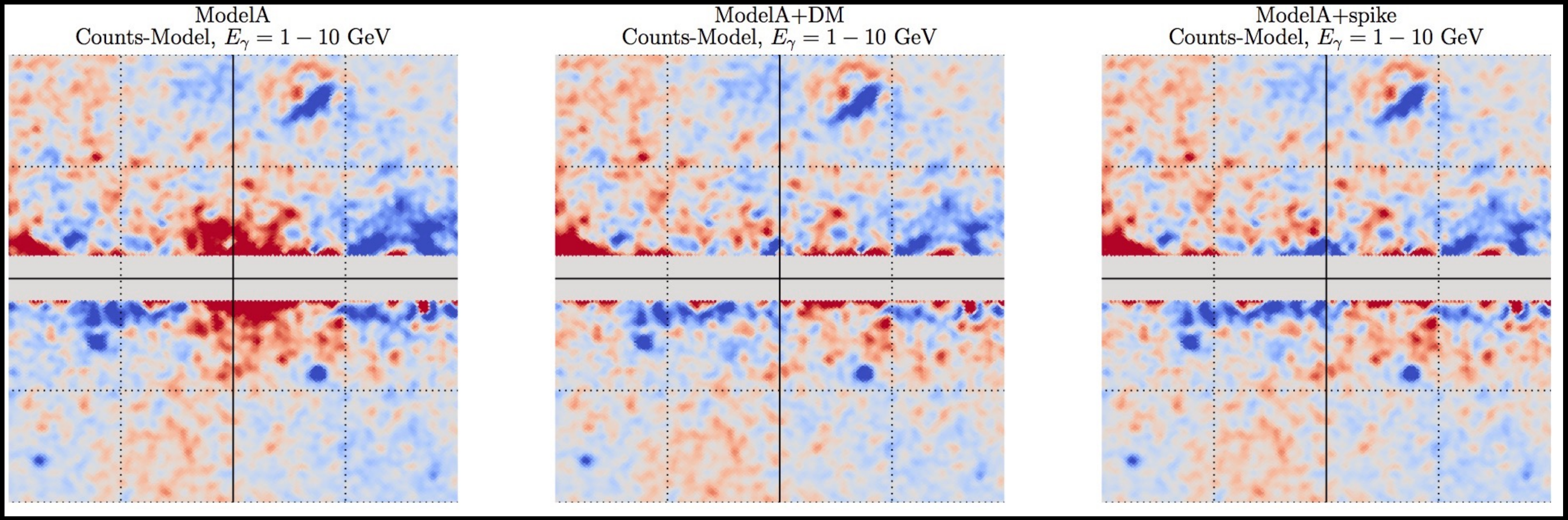
computes the diffusion-loss equation in the Heliosphere
allows to model charge-dependent solar modulation affecting CRs below few GeV



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 over a wide range of energies.

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!

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:

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