cosmic-ray propagation with DRAGON2

TeVPa 2016

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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 (2008 - still maintained): some relevant literature

- 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**

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

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

the equation is solved for all species in a time-dependent way, until convergence is reached

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

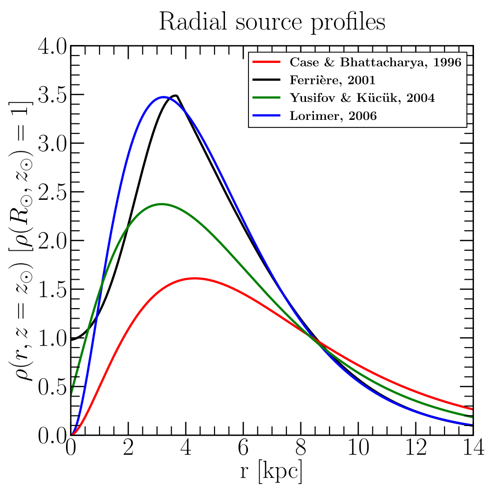
all the aspects of the code, all the details on the numerical schemes, boundary conditions, convergence, accuracy **are fully documented in detail**

Main features

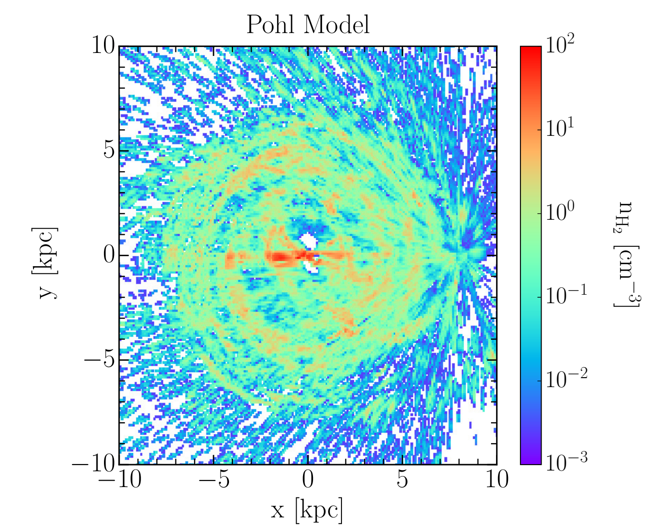
- **Position-dependent (non-separable)** and **anisotropic** spatial diffusion (fully tested); all operators are general and position-dependent
- **New numerical approach** for reacceleration, advection and energy losses (new discretization schemes, new boundary conditions), careful testing
- **New physical ingredients** (e.g. pion production energy losses)
- Possibility to use a **non-equidistant spatial grid** and of propagating **transient sources**

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

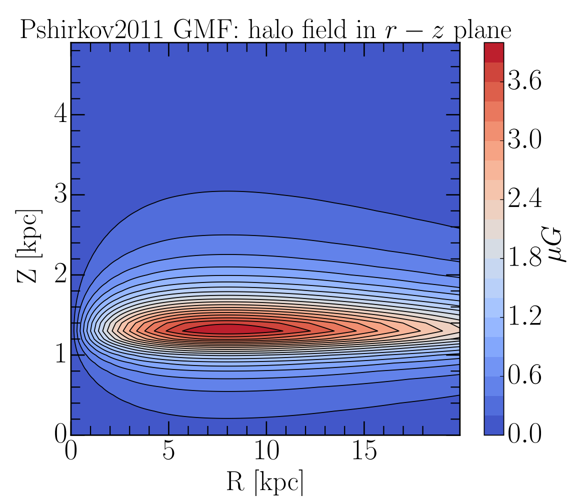
Source distribution
- Case1998
- Yusifov2004
- Lorimer2006
- Ferriere2001



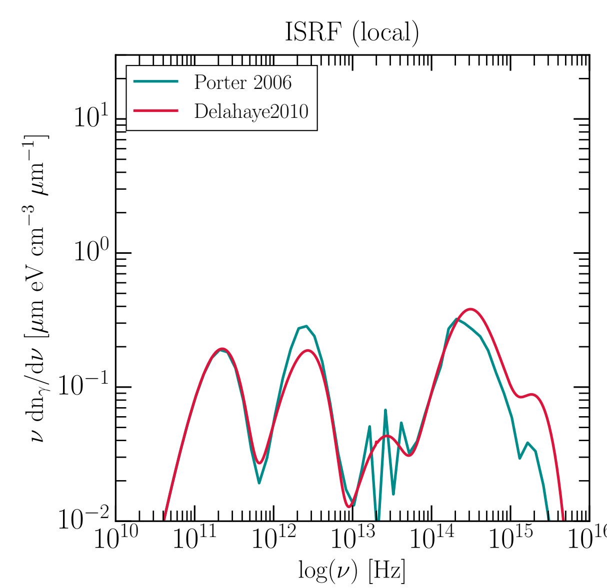
Interstellar gas distribution
- Atomic: Gordon1976, Nakanishi2003, Ferriere2007
- Molecular: Bronfman1988, Nakanishi2006, Ferriere2007, Pohl2008
- Ionized: Corders1991, NE2001



Magnetic field model
- Sun2007
- Pshirkov2011
- Jansson&Farrar2012



Interstellar radiation field model
- Porter2006
- Delahaye2010
- looking forward for new models!



new ingredients 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:

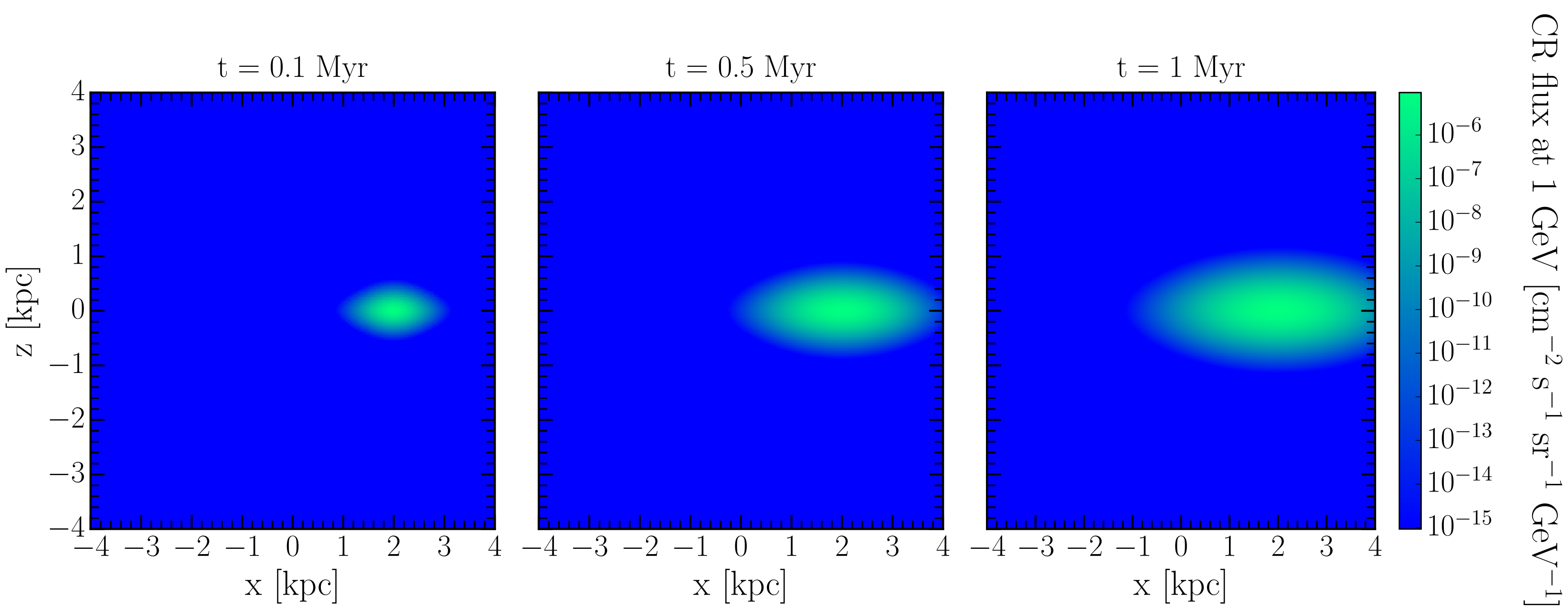
- **Gradient problem:** the radial profile of the gamma-ray emissivity along the galactic plane is flatter than predicted

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

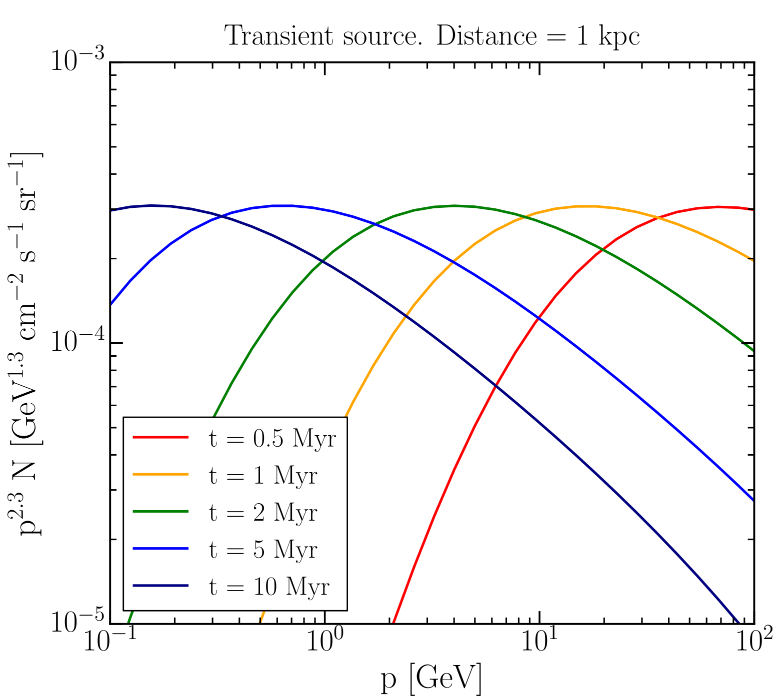
new ingredients in DRAGON2

DRAGON2 can simulate anisotropic propagation 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!



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

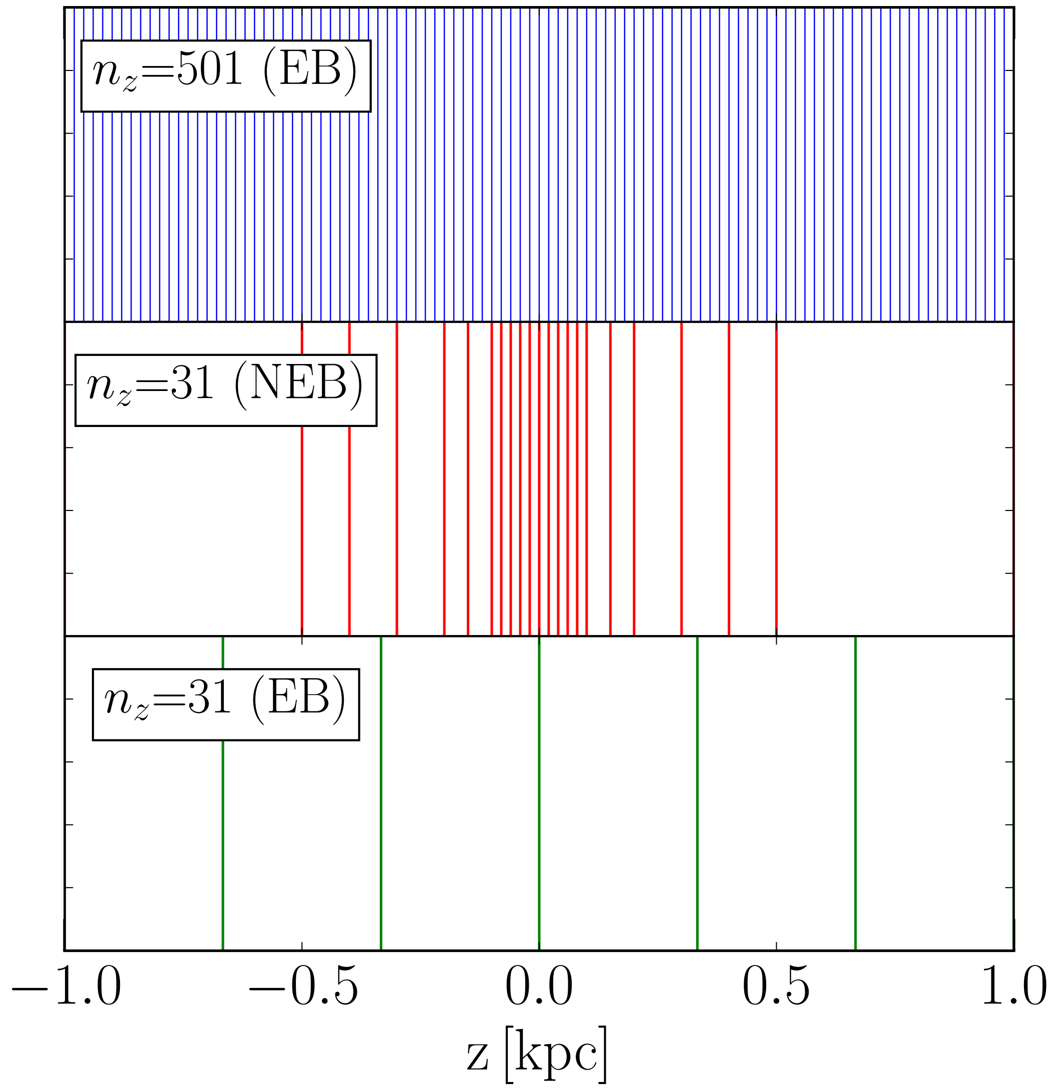
High-energy particles diffuse faster than low-energy ones

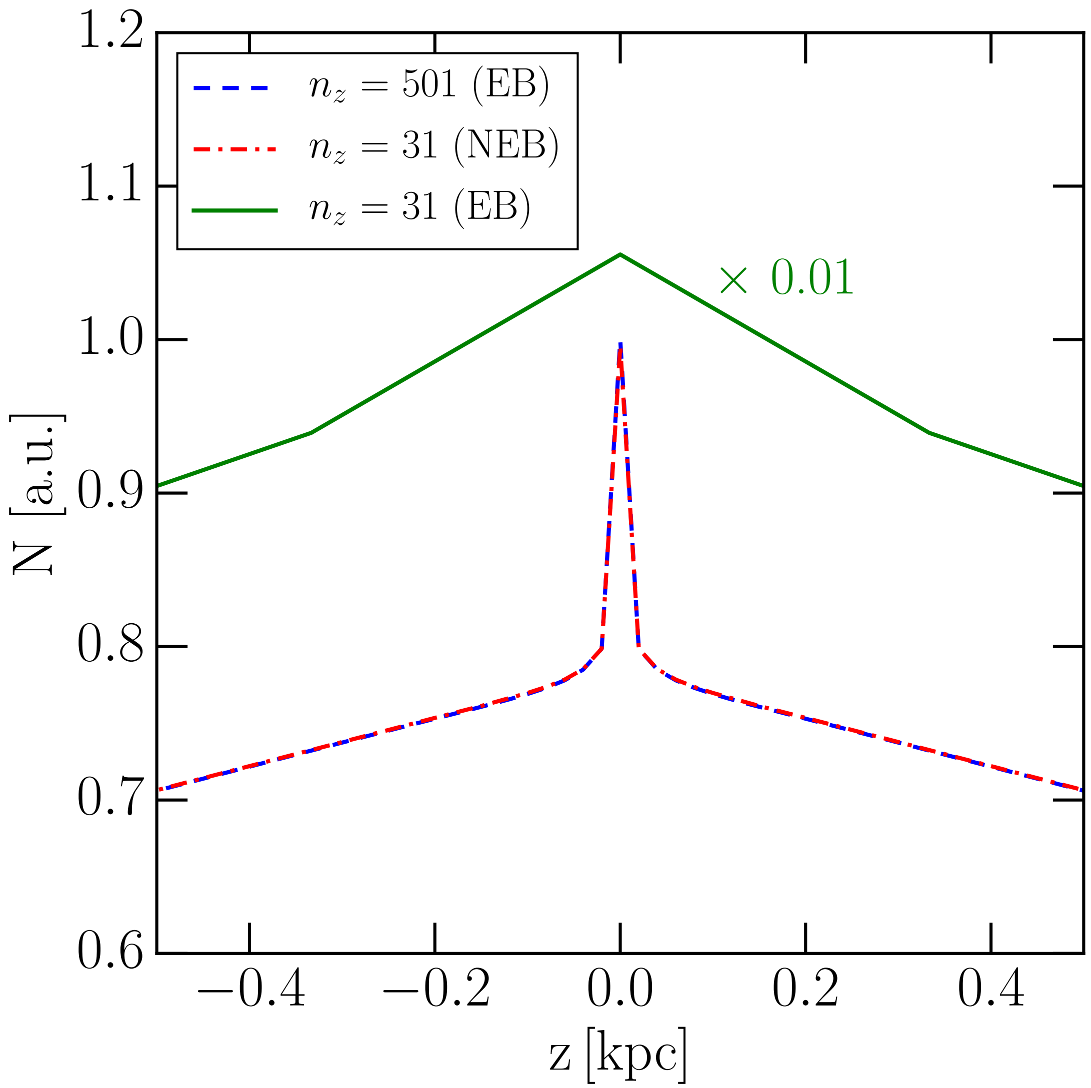
$$t_{\text{arrival}} = \frac{1\,\text{kpc}}{6D(p)}$$

new ingredients in DRAGON2

DRAGON2 exploits a fully tested non-equidistant binning for better performance

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**)



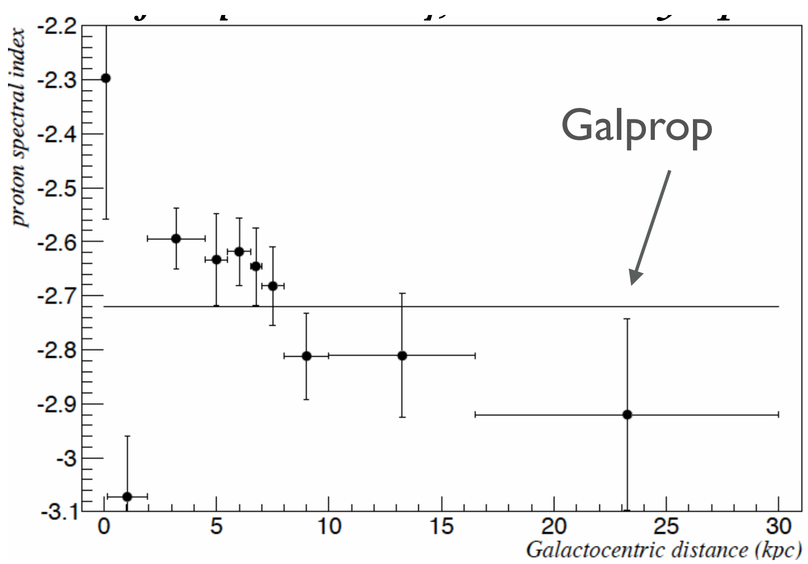


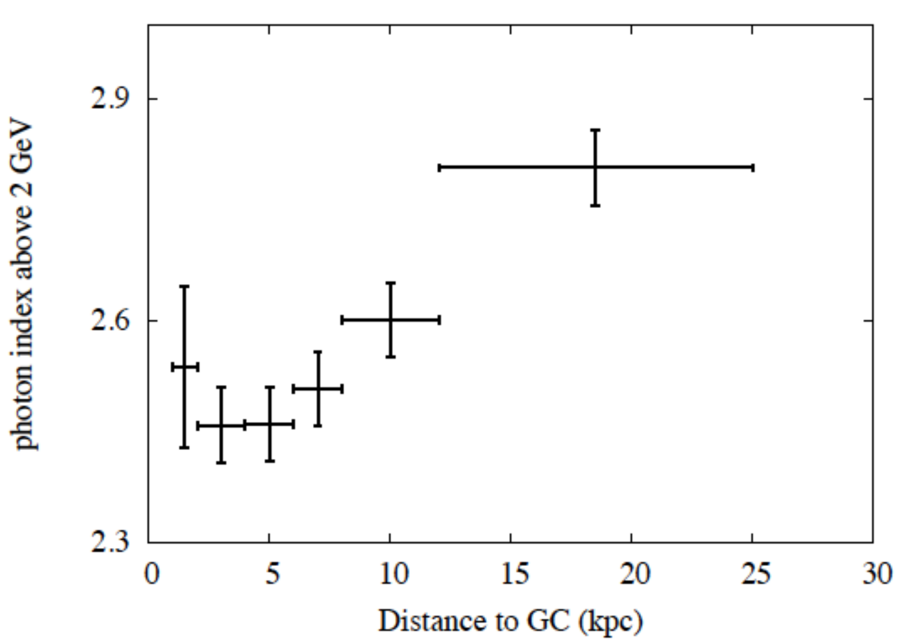
In many situations, NEB decreases the runtime in a significant way!

an application of DRAGON2

The slope problem in gamma-ray data

The gamma-ray data are a very important tracer of the CR distribution across the Galaxy
Fermi-LAT data are crucial to test and constrain CR propagation models!





A **progressively harder slope of the proton spectrum** towards the inner Galaxy has been recently inferred from Fermi-LAT gamma-ray data [*Fermi collab. 2016; Yang et al. 2016*]:
see also Carmelo Evoli's talk!

This result is in tension with conventional GALPROP-based predictions

A serious challenge for CR propagation models based on homogeneous diffusion!

an application of DRAGON2

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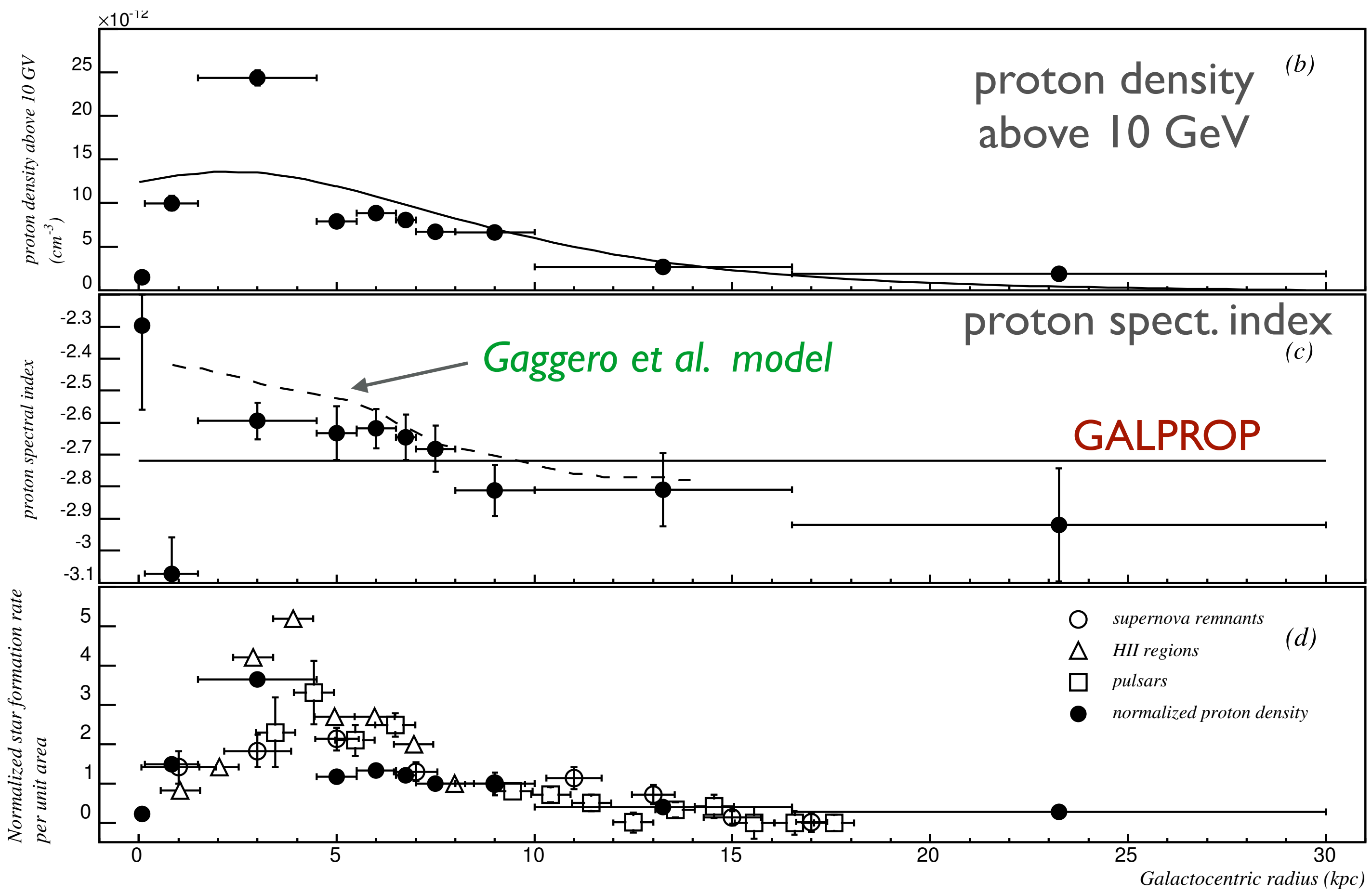

This effect may be the hint of a harder scaling of the diffusion coefficient with rigidity

[*D.Gaggero et al., PRD 91, 2015*]

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

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

an application of DRAGON2

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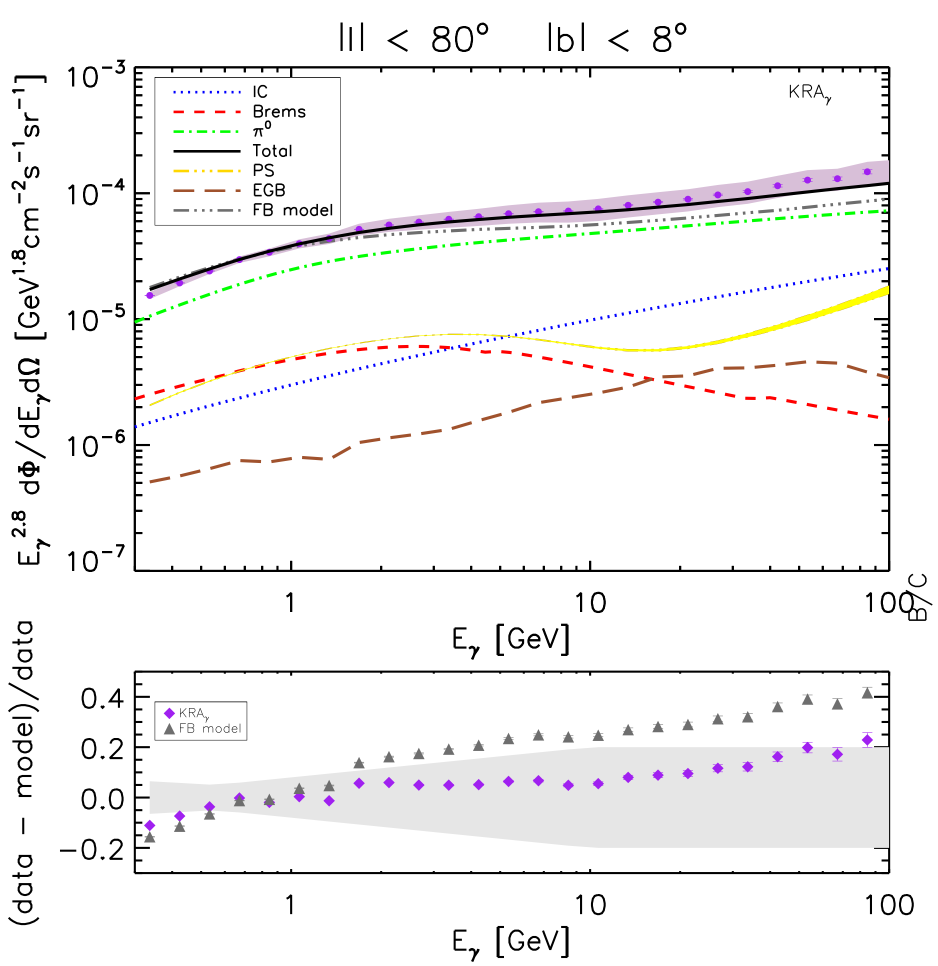

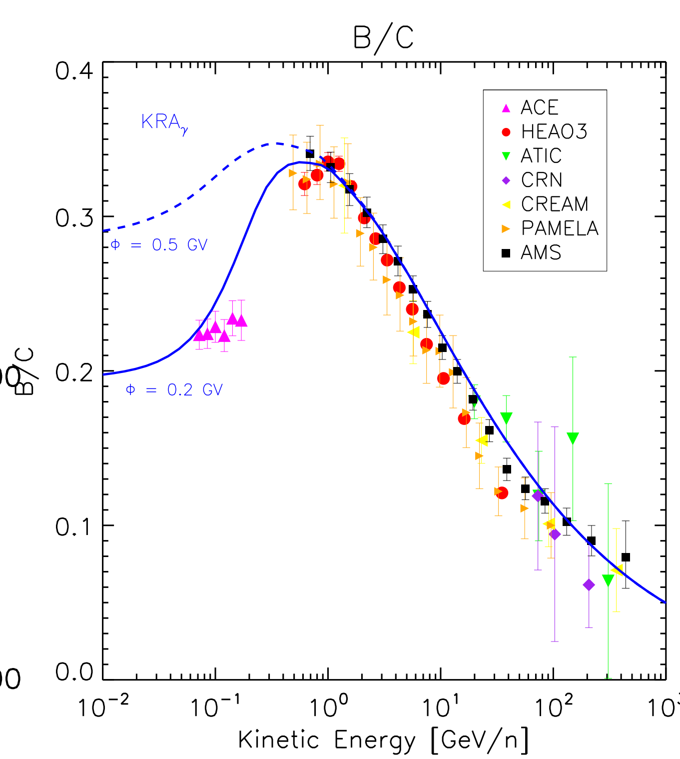

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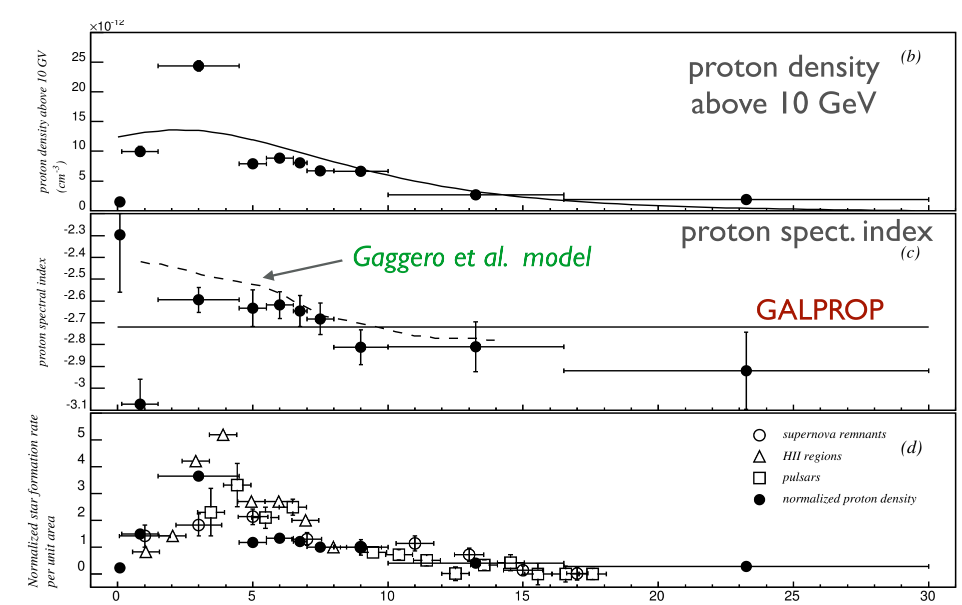

an application of DRAGON2

The slope problem in gamma-ray data

The gamma-ray data are a very important tracer of the CR distribution across the Galaxy
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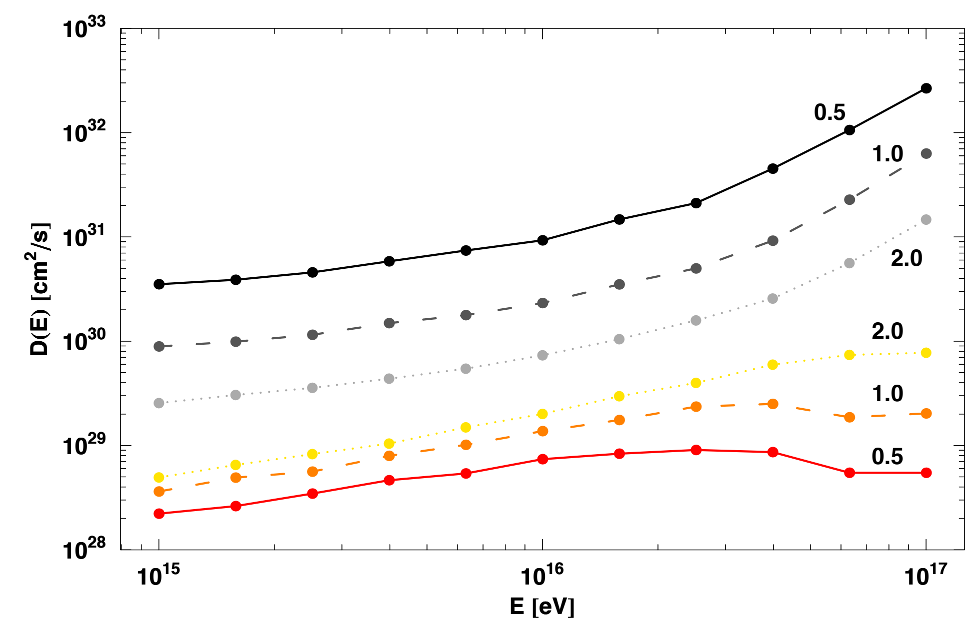
Why a harder diffusion in the inner Galaxy?

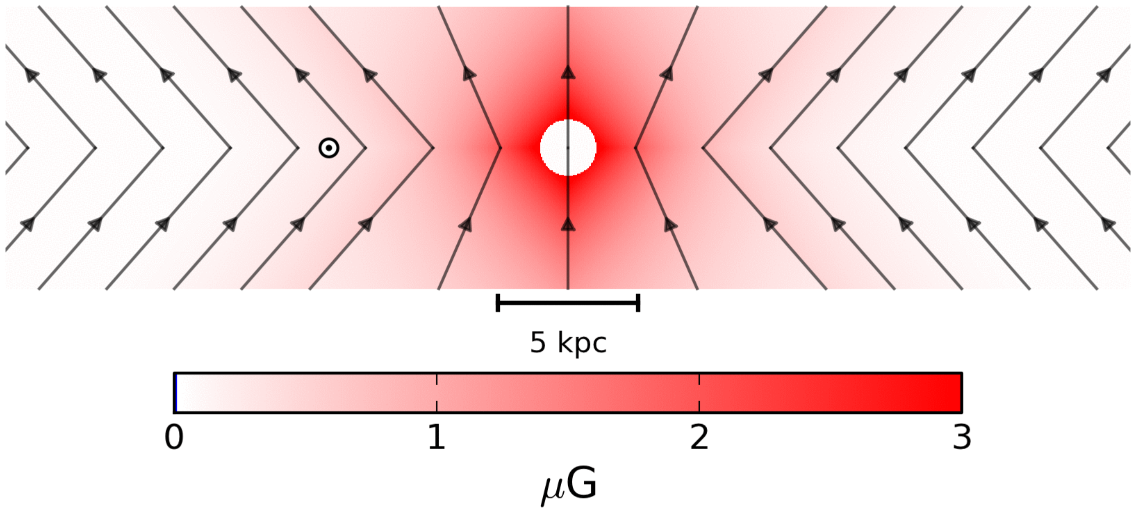
parallel diffusion: $\delta \sim 0.3$
perpendicular diffusion: $\delta \sim 0.5$
[De Marco, Blasi, Stanev, 2007]

out-of-plane Galactic magnetic field component in the inner Galaxy
[Jansson and Farrar, 2012]

—> are we seeing parallel escape of CRs in the inner Galaxy? <—

[*Cerri, Vittino et al., in preparation*]





an application of DRAGON2

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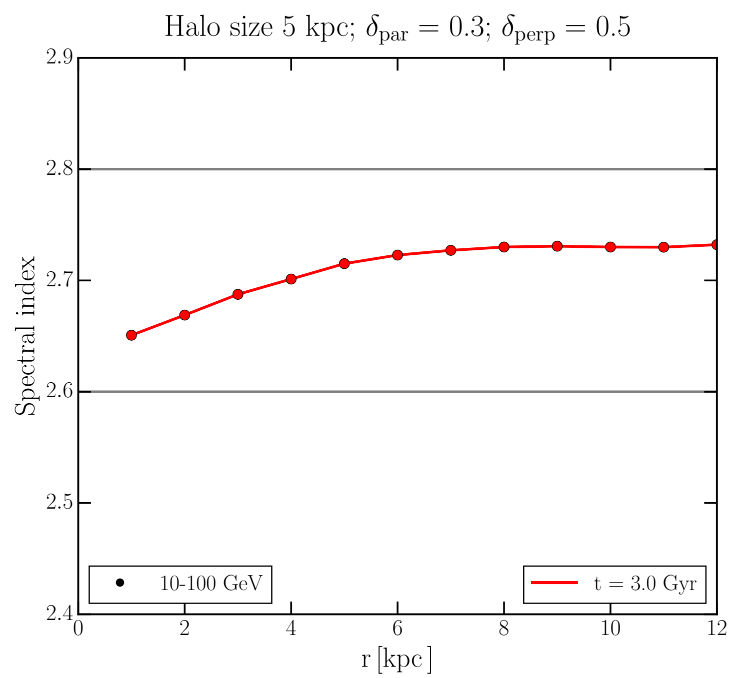

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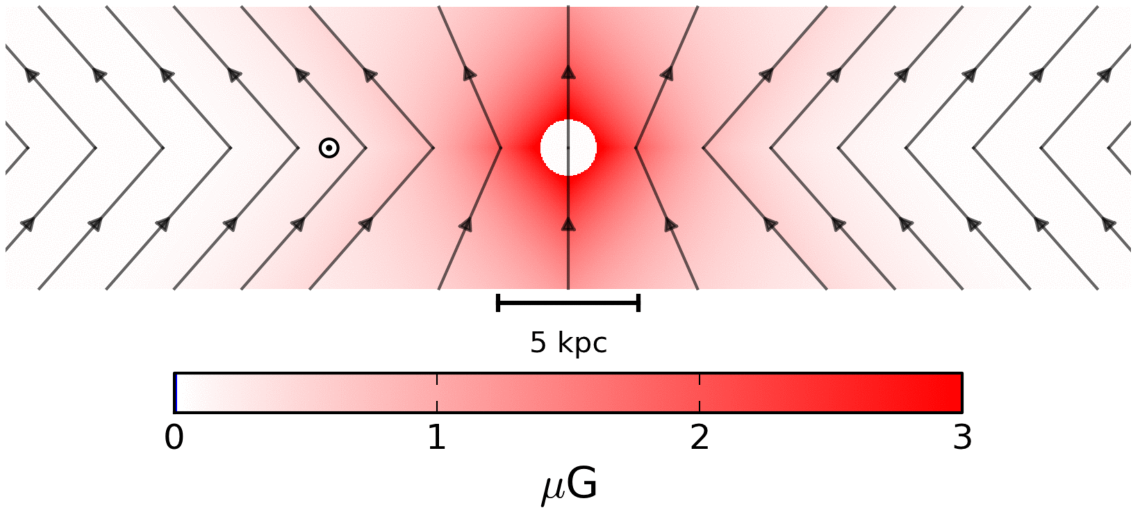

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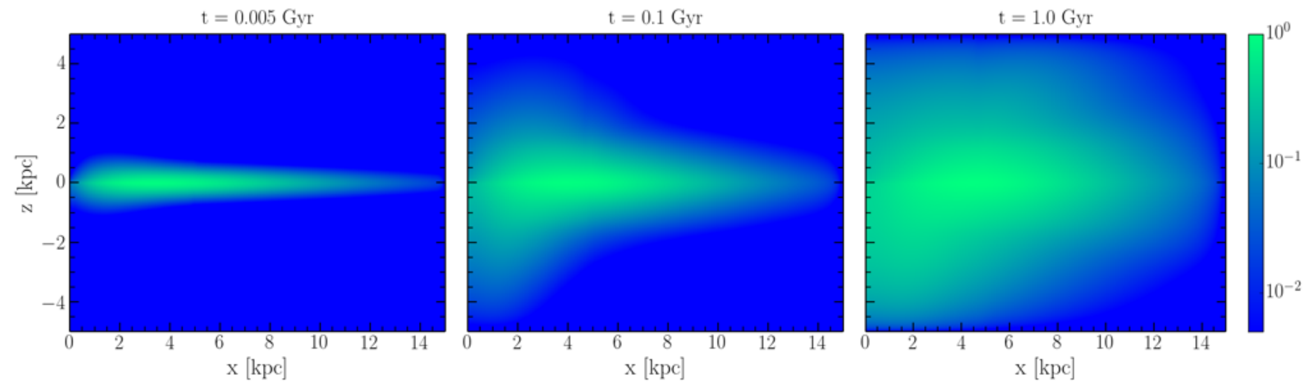

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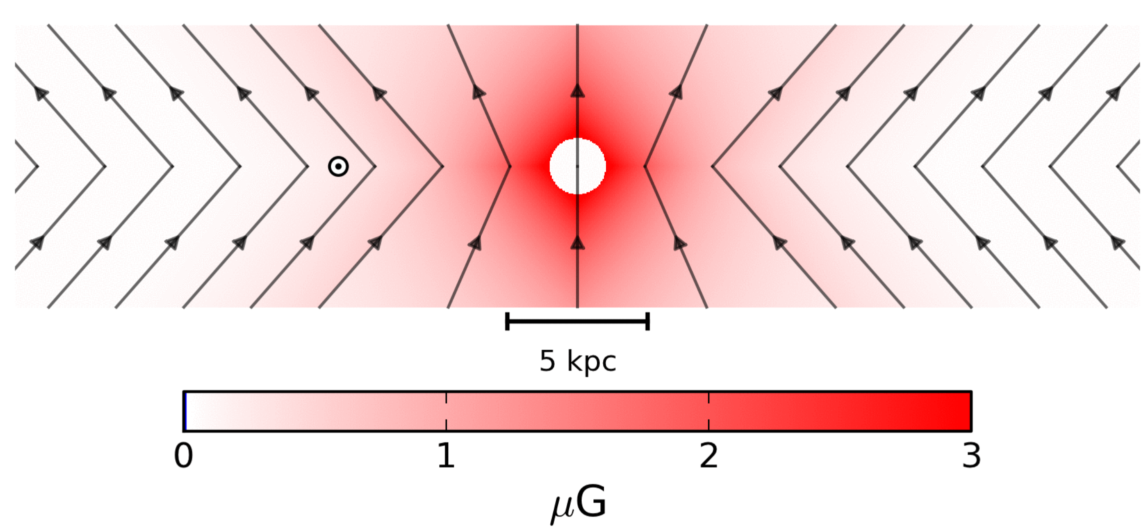

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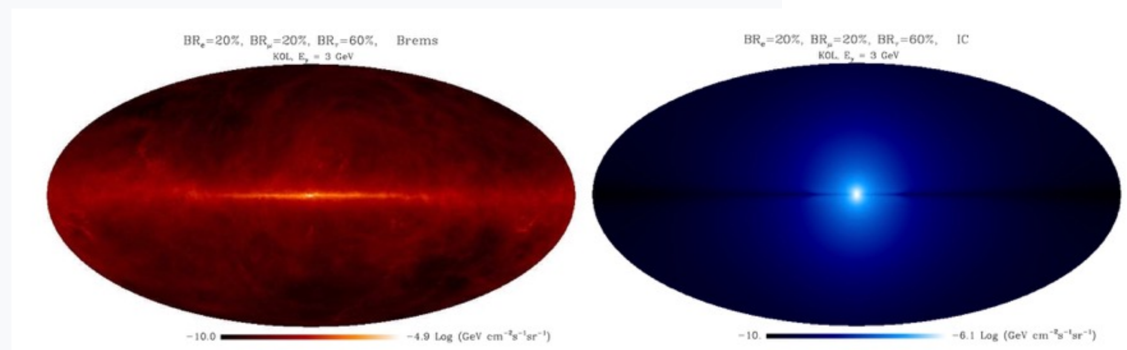
DRAGON2 in a broader context

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

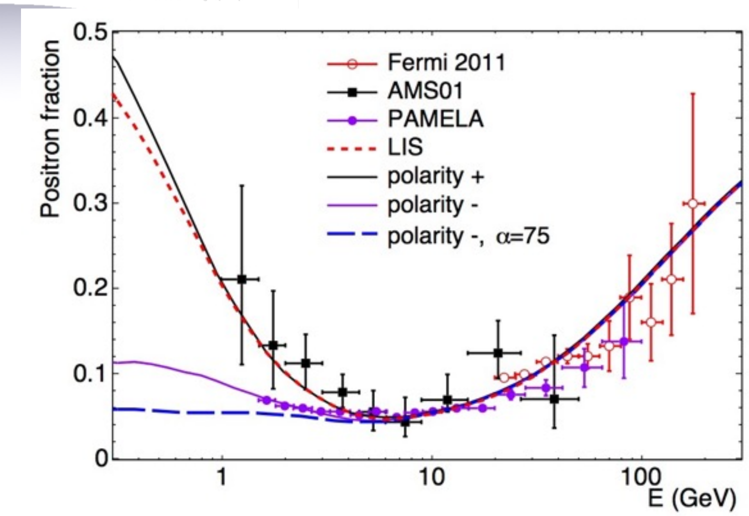


- synchrotron radiation

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

2) HelioProp

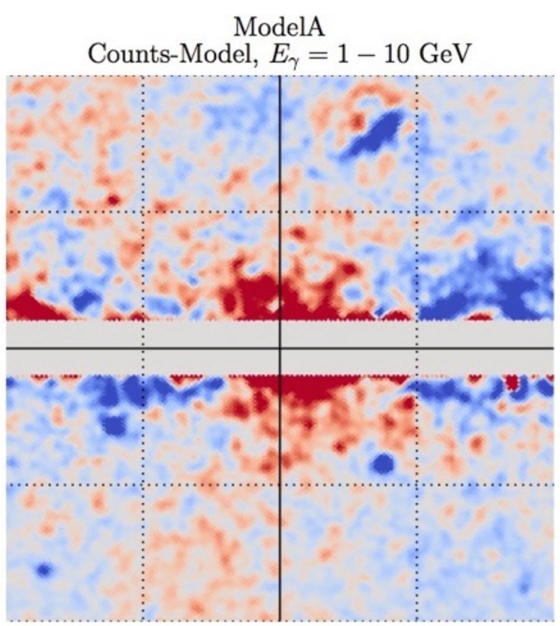
computes the diffusion-loss equation in the Heliosphere allows to model charge-dependent solar modulation affecting CRs below few GeV

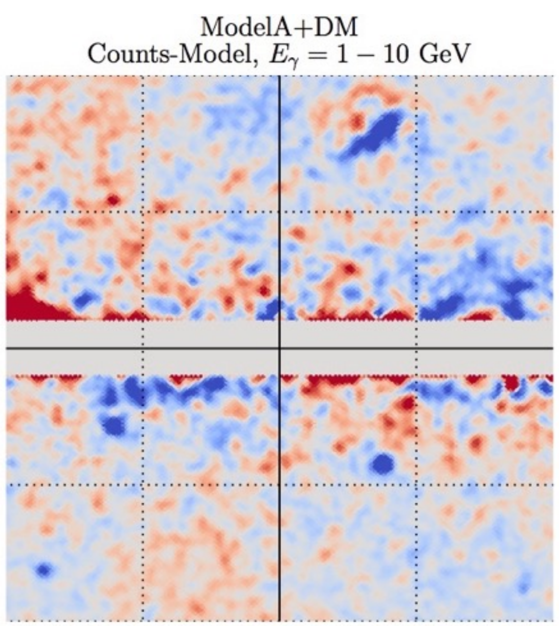


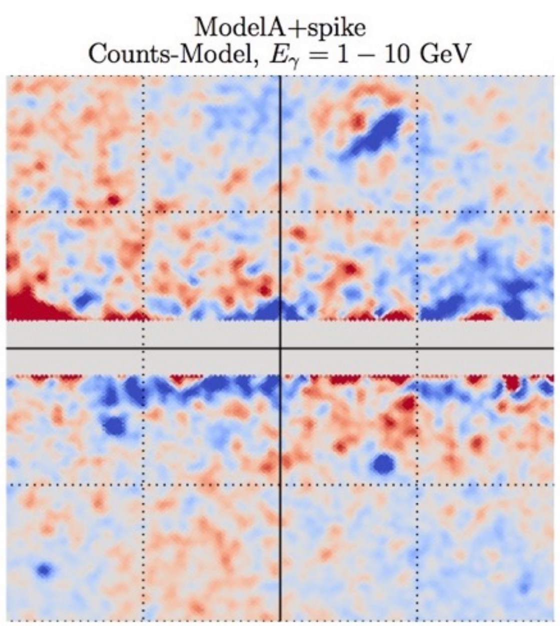
DRAGON2 and the dark matter community

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

Example: the Galactic bulge emission







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

[D.Gaggero et al., JCAP, 2015, E.Carlson et al. 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 future 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 a comprehensive set of instruments 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, followed by **HeSky** and **Helioprop**

Thank you for your attention!

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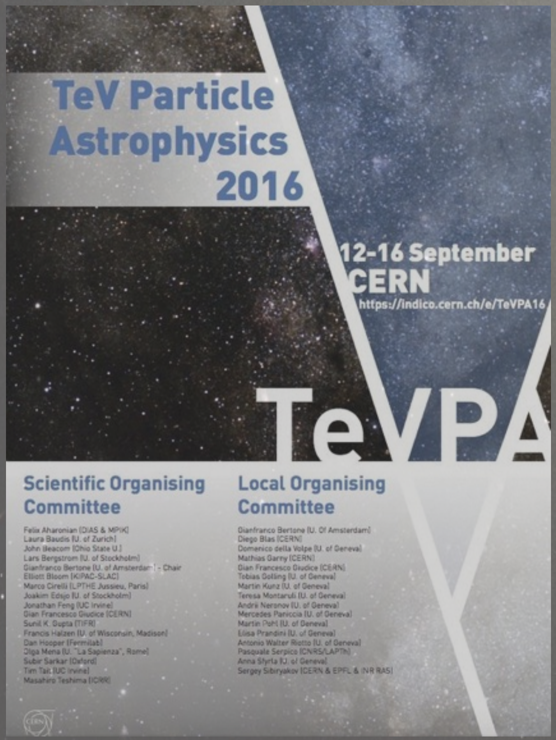

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DRAGON2

new features, a complete documentation

		GALPROP	PICARD	DRAGON2
spatial diffusion	- inhomogeneous	✗	✓	✓
	- anisotropic	✗	✓	✓
	- not-separable	✗	✗	✓
re-acceleration	- inhomogeneous	✗	✓	✓
	- not-separable	✗	✗	✓
advection	- spatially variable in (x,y)	✗	?	✓
	- spatially variable in z	✓	✓	✓
rhs	- inhomogeneous losses	✓	✓	✓
	- inhomogeneous sources	✓	✓	✓

DRAGON2
numerical tests

for each operator:

— we derive an analytical solution

— we consider the relevant timescales

— we choose the timestep of the simulation

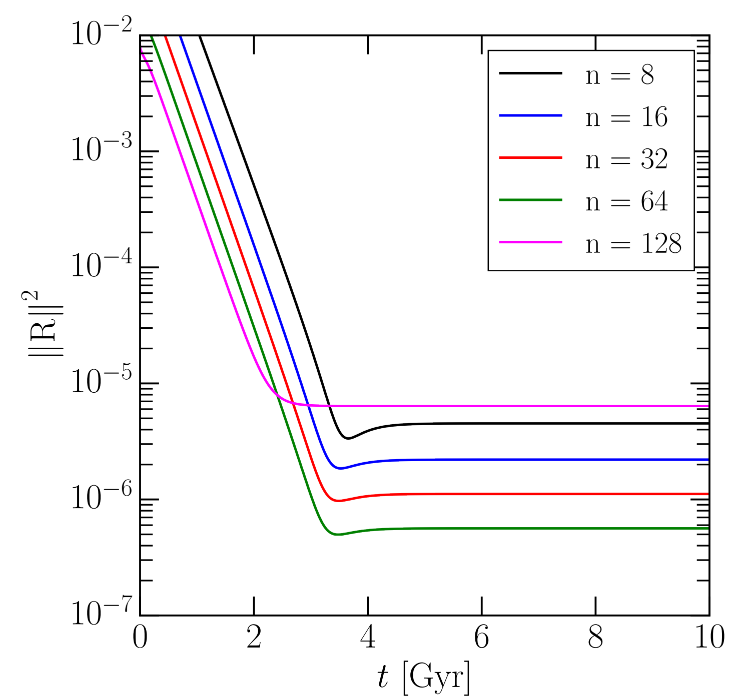
— we run the solver until convergence is reached (for the single operator, it is enough to look at the residual)

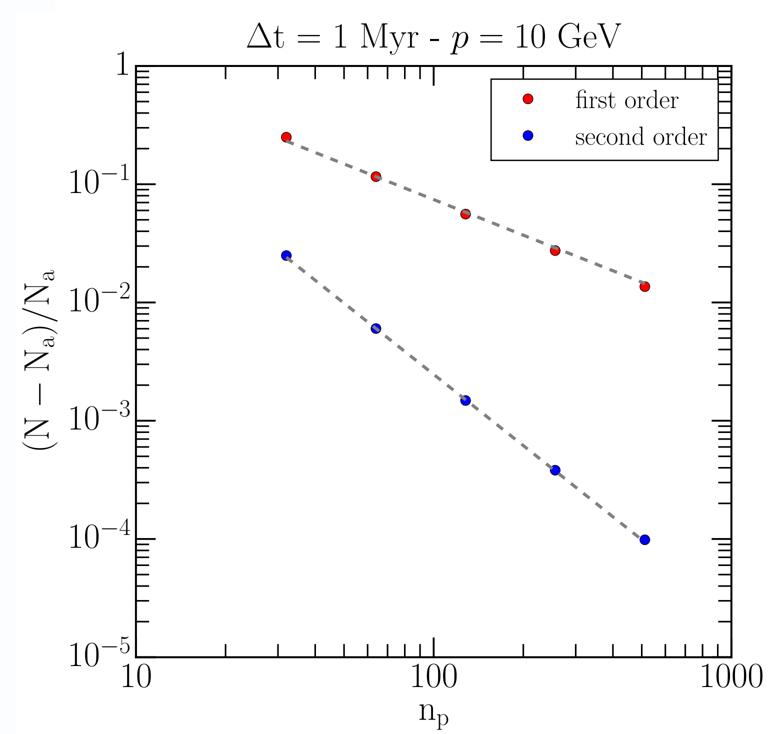
— we compare numerical and analytical solutions for different choices of the grid size

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

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

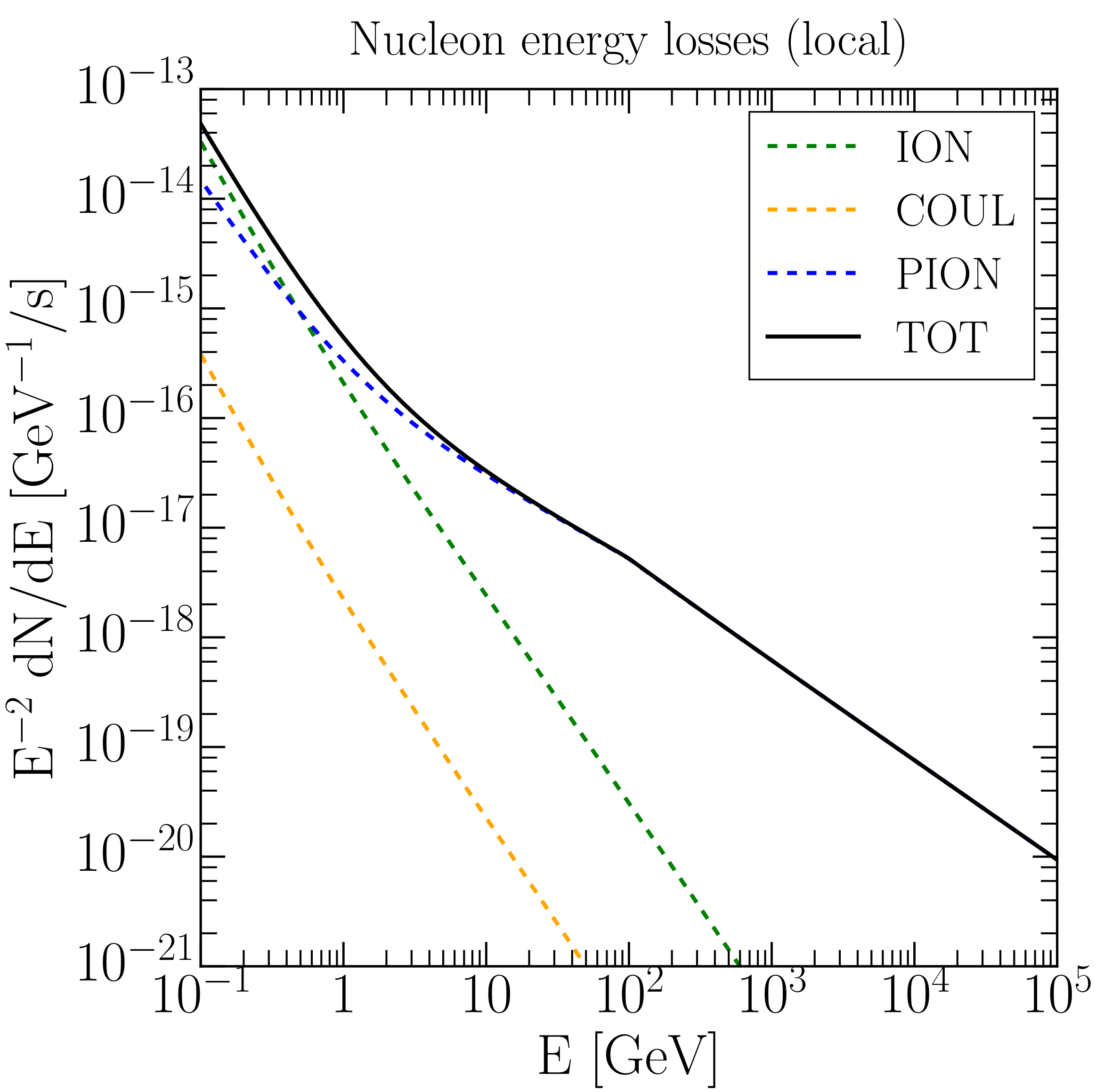
$$Q(x,y,z) = \frac{\pi^2}{4}\left(\frac{D_{xx}}{L_x^2} + \frac{D_{yy}}{L_y^2} + \frac{D_{zz}}{L_z^2}\right)\cos\left(\frac{\pi x}{2L_x}\right)\cos\left(\frac{\pi y}{2L_y}\right)\cos\left(\frac{\pi z}{2L_z}\right)$$

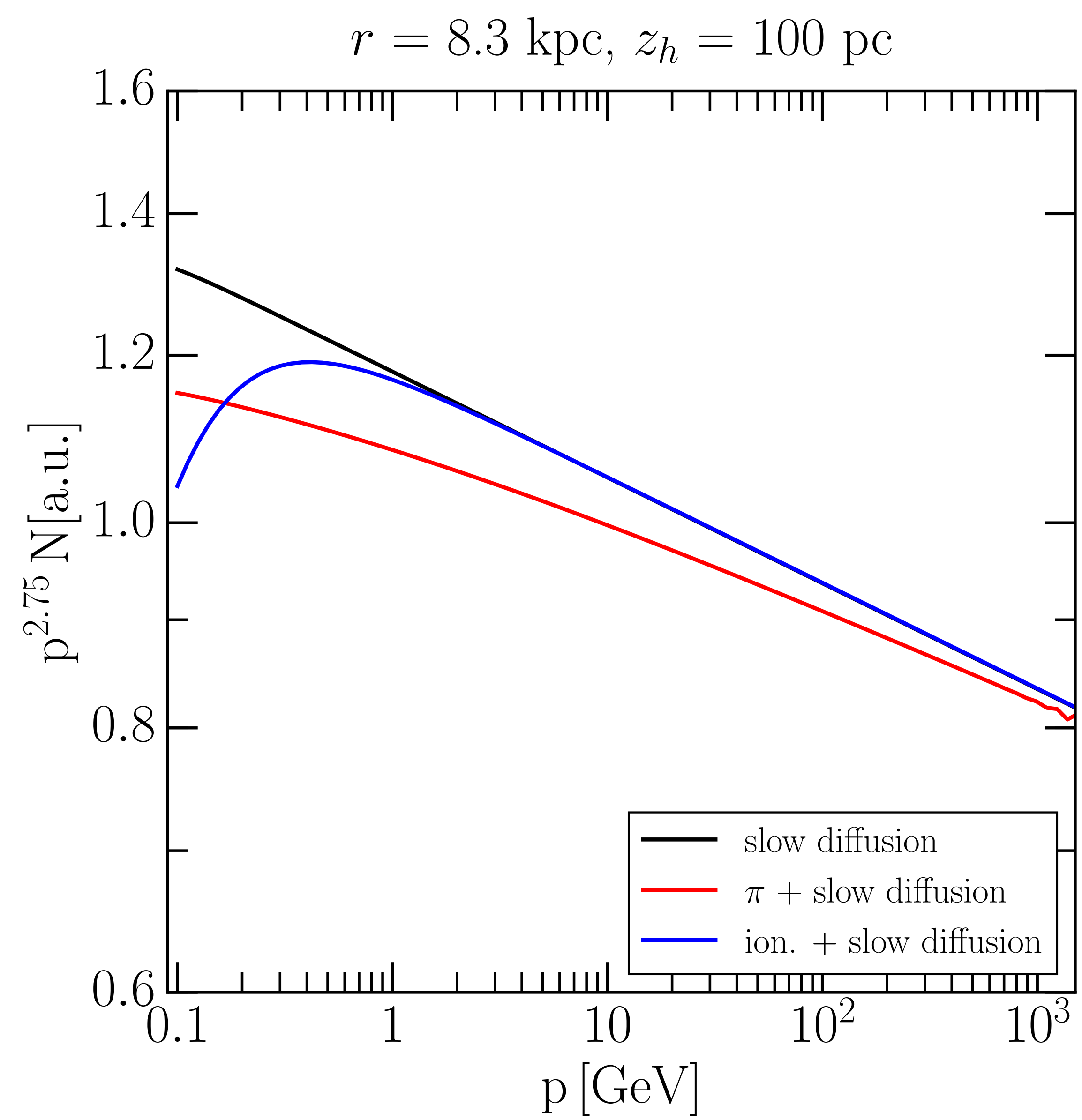




new ingredients in DRAGON2

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)