HELMHOLTZ WEIZMANN
RESEARCH SCHOOL
MULTIMESSENGER ASTRONOMY

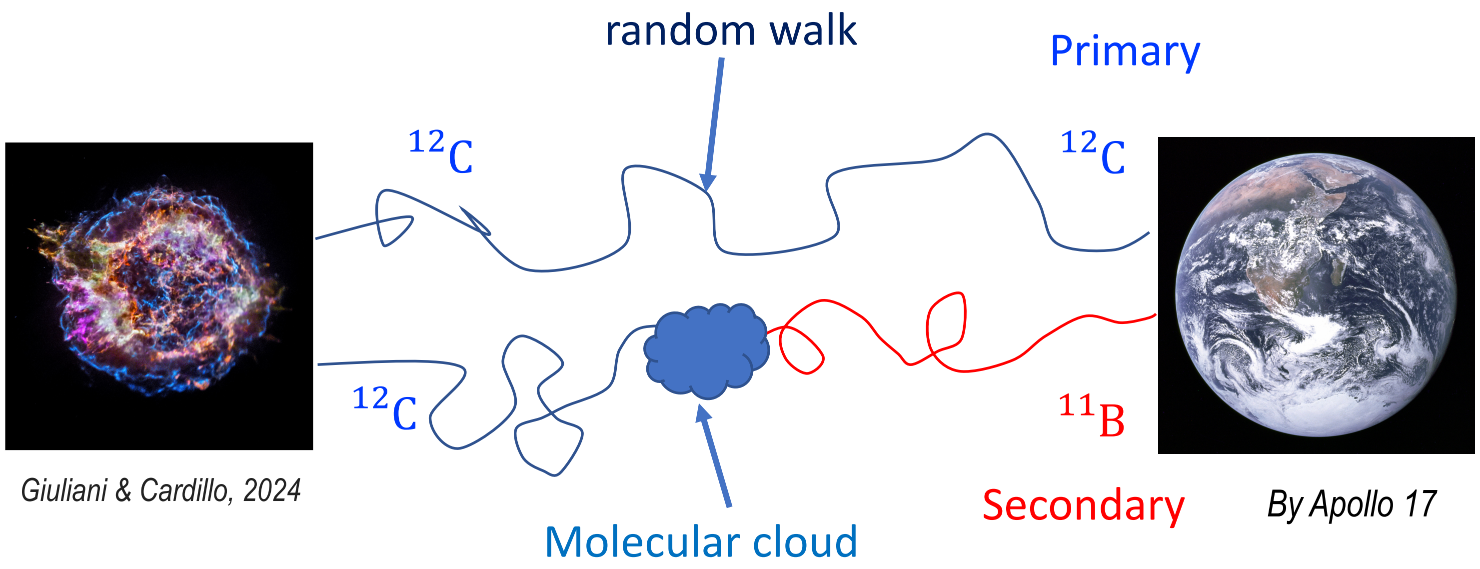
Galactic CR Transport in the Giant CGM Halo

Chao-Ming Li & Andrew M. Taylor

Symposium of UHE γ-rays from SNRs and the Origin of GCRs
Chengjiang, Yuxi, Yunnan province, China
26 Feb 2026 – 2 Mar 2026

General picture of Galactic CRs

Cosmic Rays(CR) are high-energy charged particles from outer space.



Acceleration at source

↓

Diffusion and Interaction

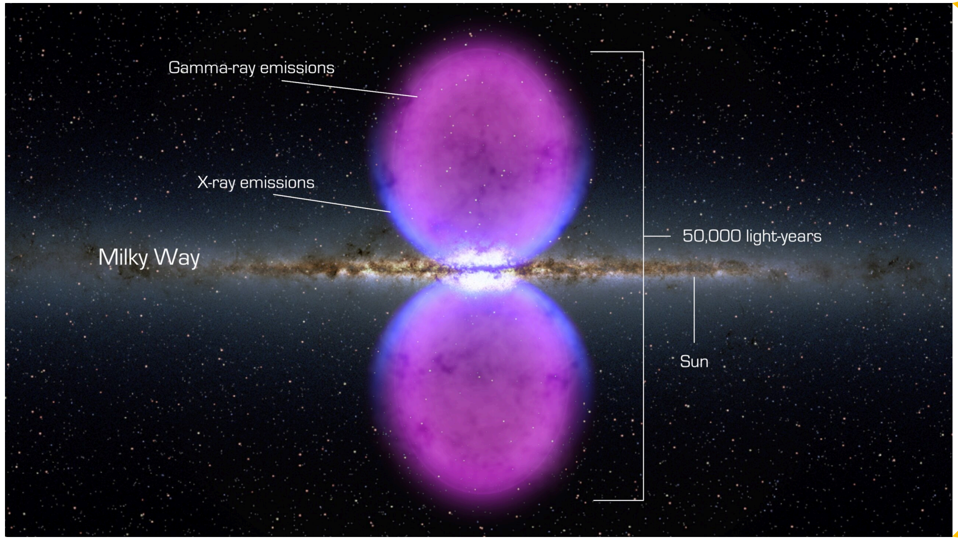
↓

Helio-sphere propagation

↓

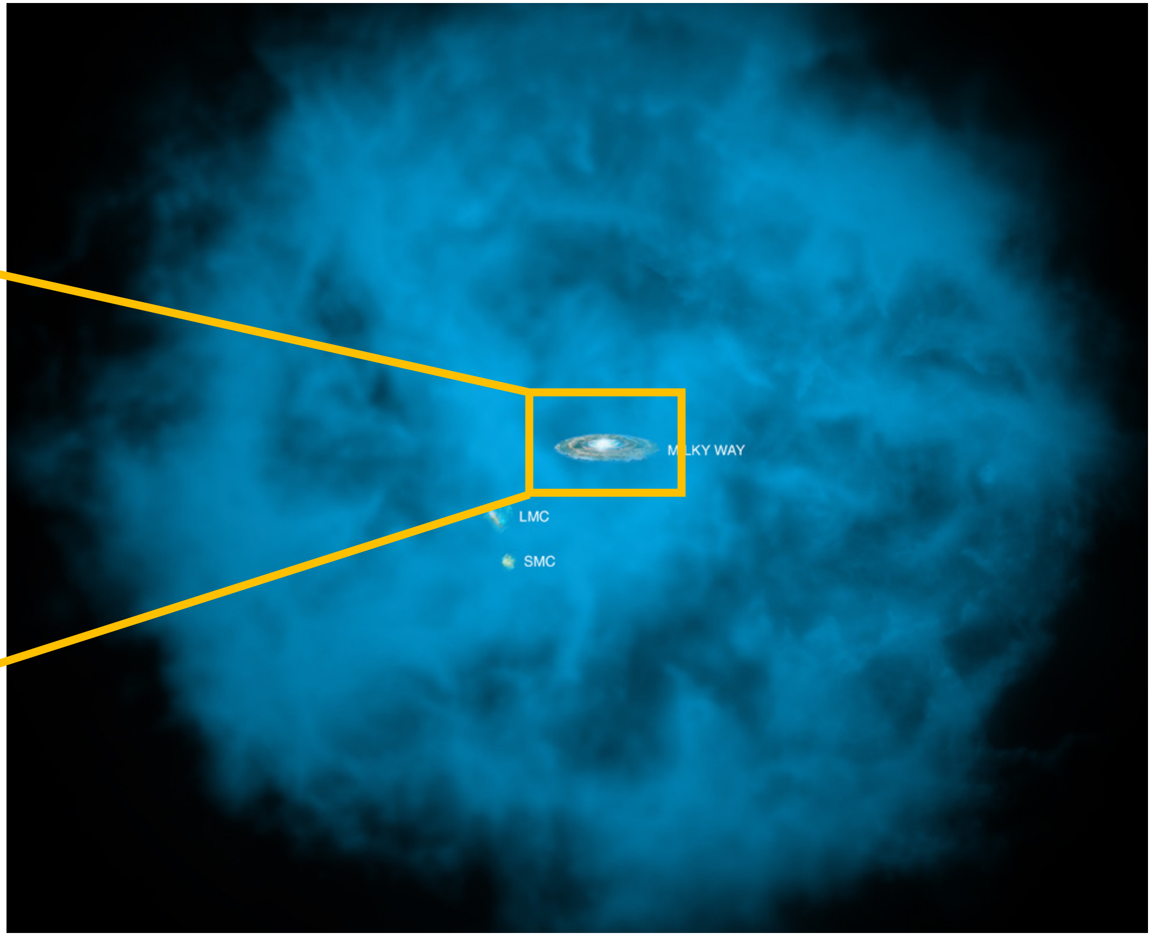
Detection at the Earth

The Milky Way: disk & halo structure



~40 kpc

The Milky Way disk and Fermi bubbles
By NASA's Goddard Space Flight Center



~ 500 kpc

The Circumgalactic Medium(CGM) halo extends to virial radius. *Gupta, A et al, 2012*

The Milky Way: mass distribution

Cautun et al 2020 with Gaia DR2:

Baryon Dark matter

Total mass of MW: $1\times10^{12}\ M_\odot = 1.6\times10^{11}\ M_\odot + 8.4\ \times10^{11} M_\odot$

Stellar mass: $5\times10^{10}\ M_\odot$

ISM mass: $1\times10^{10}\ M_\odot$

CGM mass: $1\times10^{11}\ M_\odot$ largest fraction! -> missing baryon problem

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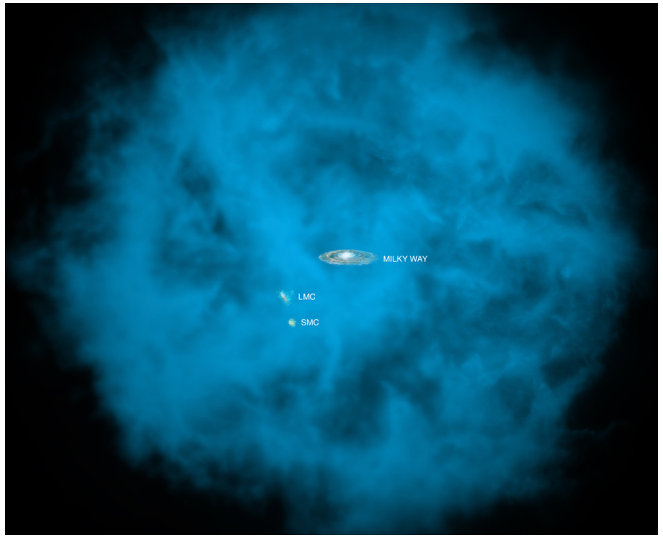
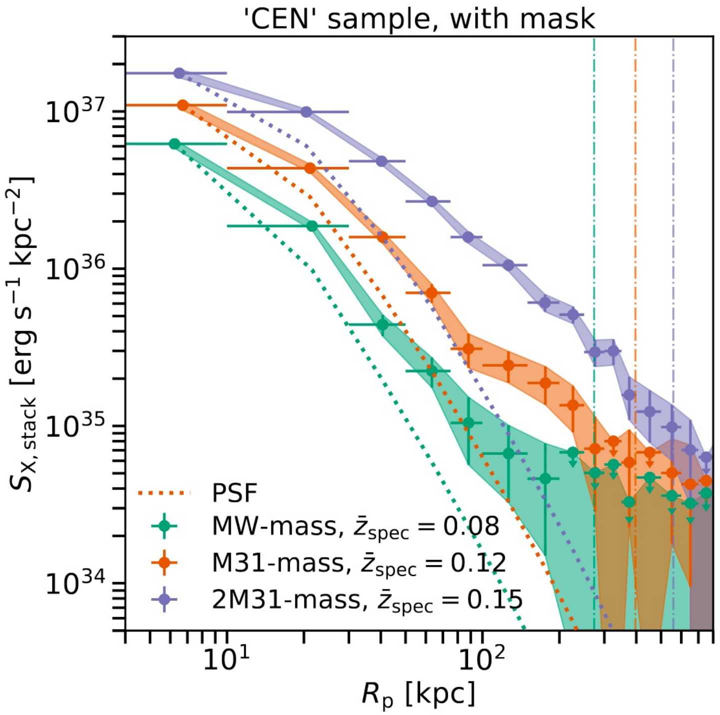


Gupta, A et al, 2012



eROSITA X-ray brightness profile of hot CGM

Zhang et al 2024

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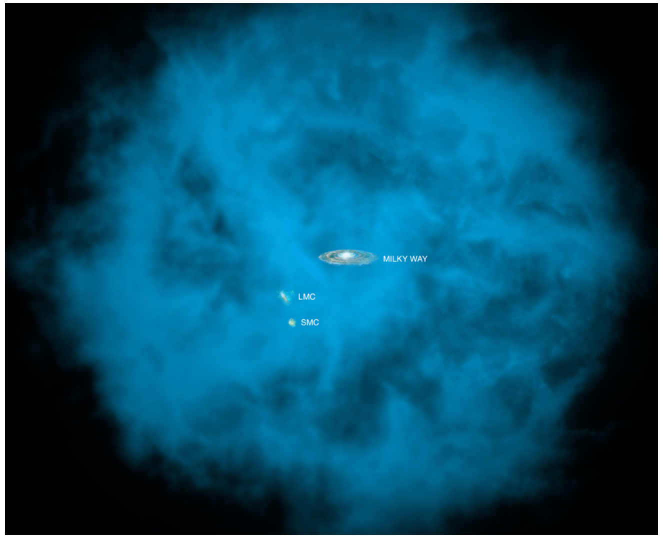

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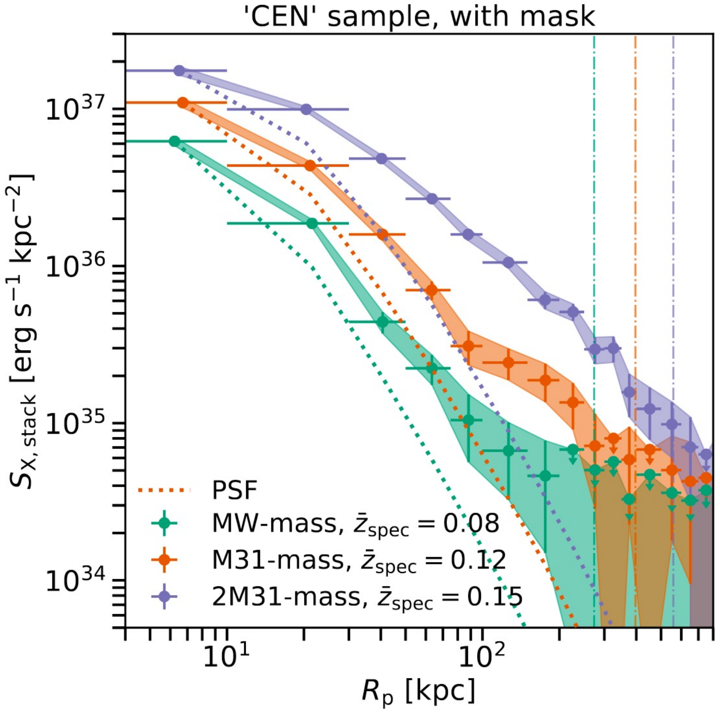

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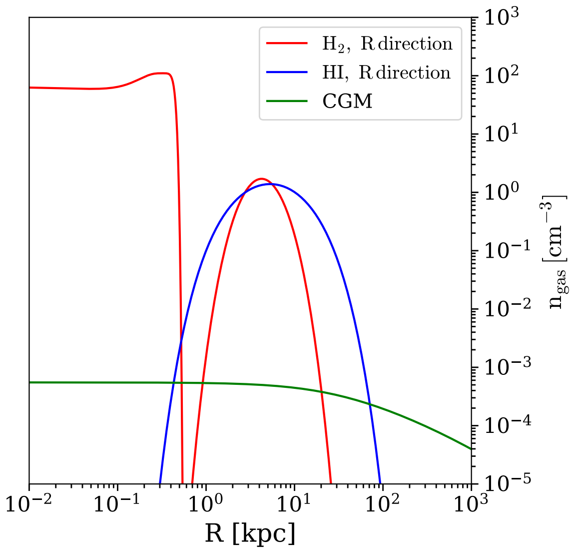
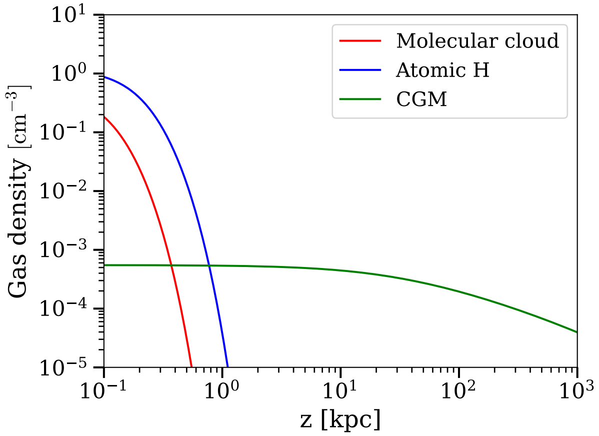




Density distribution of gas in galactic R(top) and z(bottom) direction.

Cosmic ray transport: small VS giant halo

CR transport equation: $$\frac{\partial n_i}{\partial t} = \nabla\left(D\nabla n_i\right) + \sum_j \frac{n_j}{\tau_j} - \frac{n_i}{\tau_i} + Q_{inj}$$

diffusion

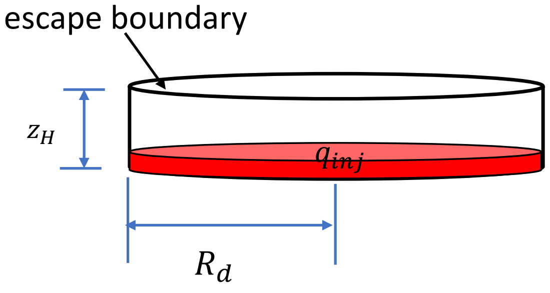
Spallation & decay

injection

Classical

Small halo:

$z_H \leq R_d$



Model setup

Cosmic ray transport: small VS giant halo

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diffusion

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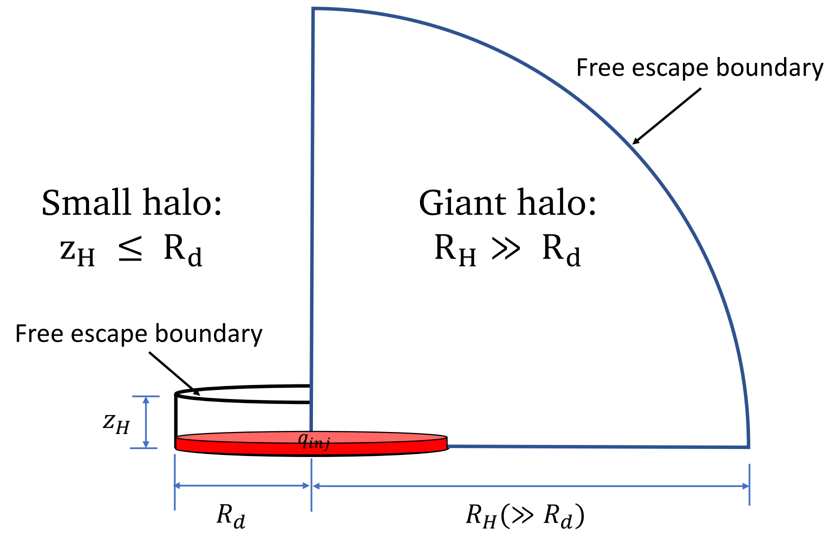

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diffusion

Spallation & decay

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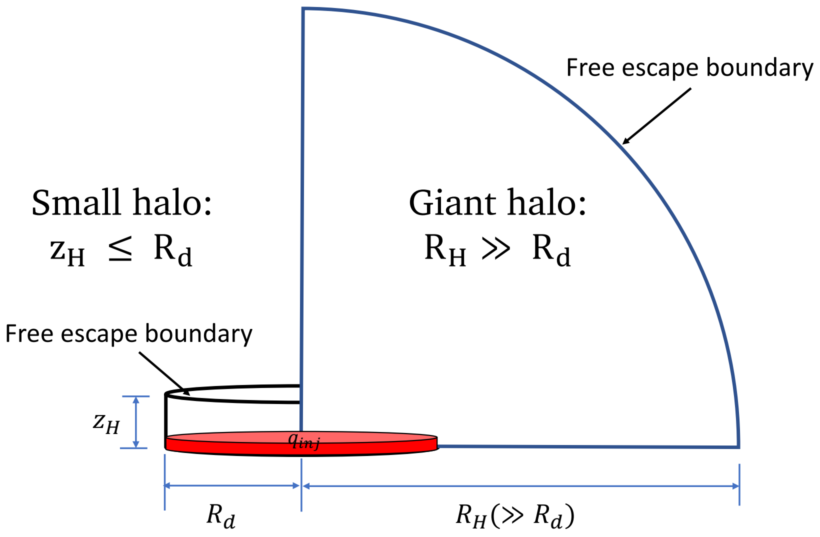
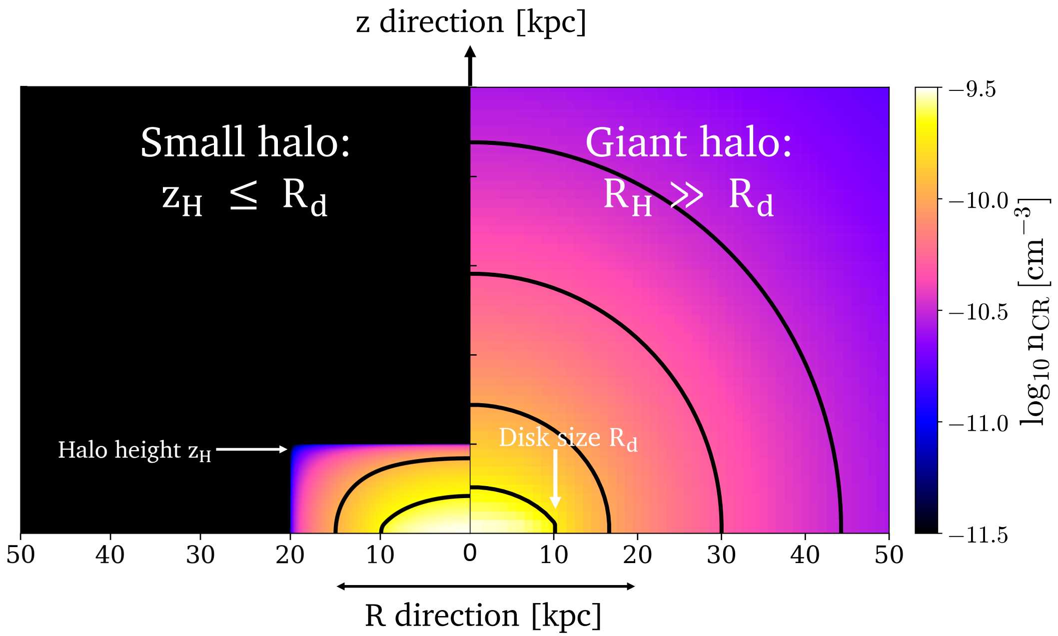


Model setup



Corresponding result of CR distribution

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diffusion

Spallation & decay

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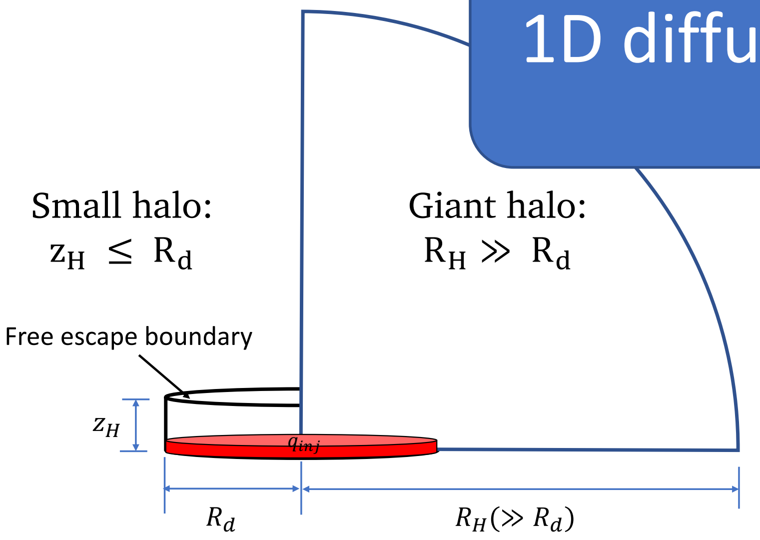
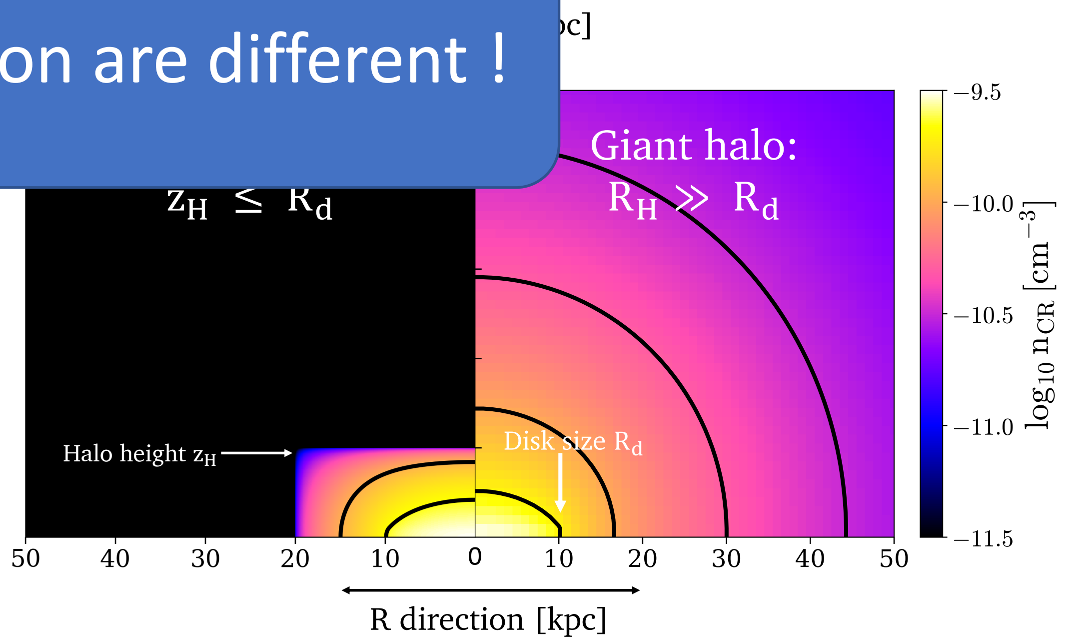
1D diffusion and 3D diffusion are different !



Model setup

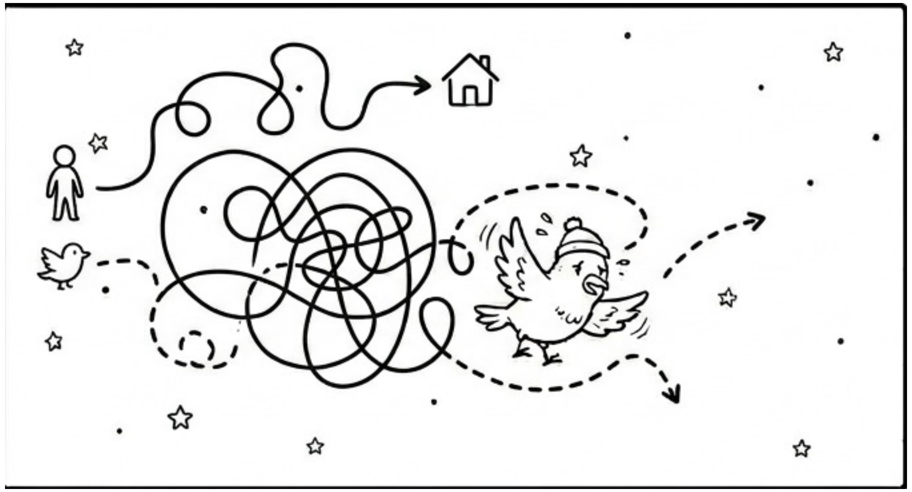


Corresponding result of CR distribution

Cosmic ray transport: random walk

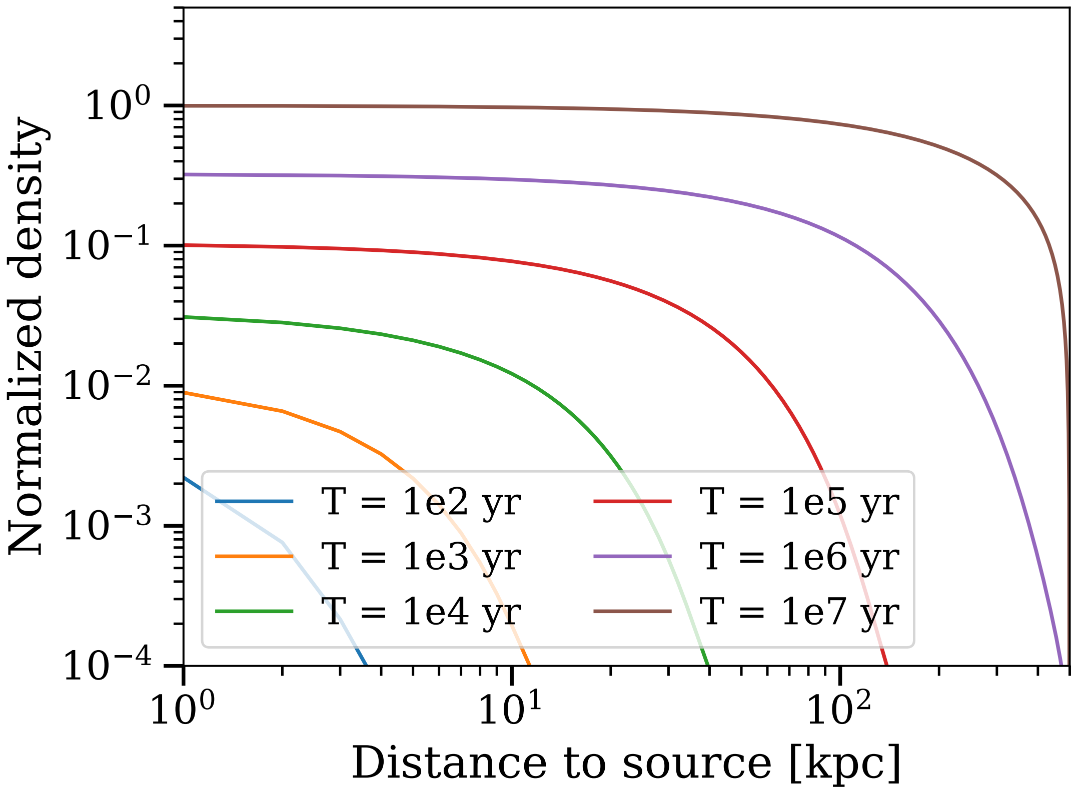
A drunk man will eventually find his way home,
but a drunk bird may get lost forever.

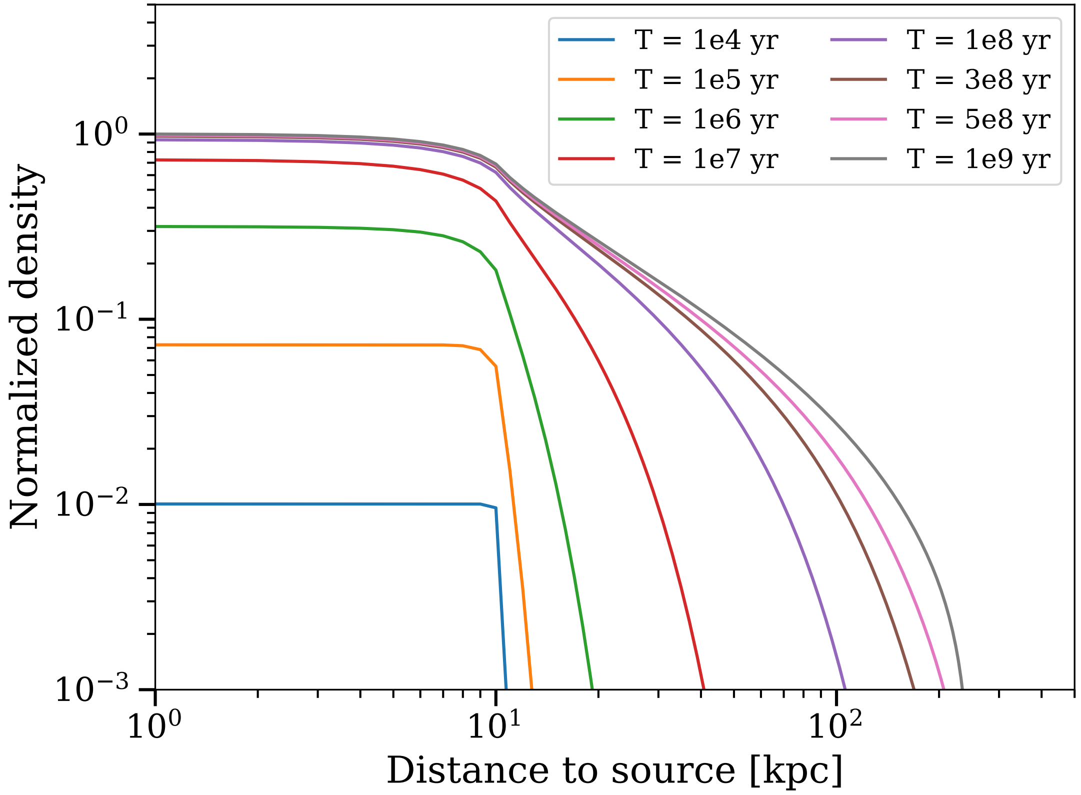
Shizuo Kakutani
(角谷静夫)



- 1D & 2D random walk is recurrent: particles can always return to the origin
- (≥)3D random walk is transient: there is a nonzero probability that particles never come back.

Cosmic ray transport: 1D VS 3D diffusion

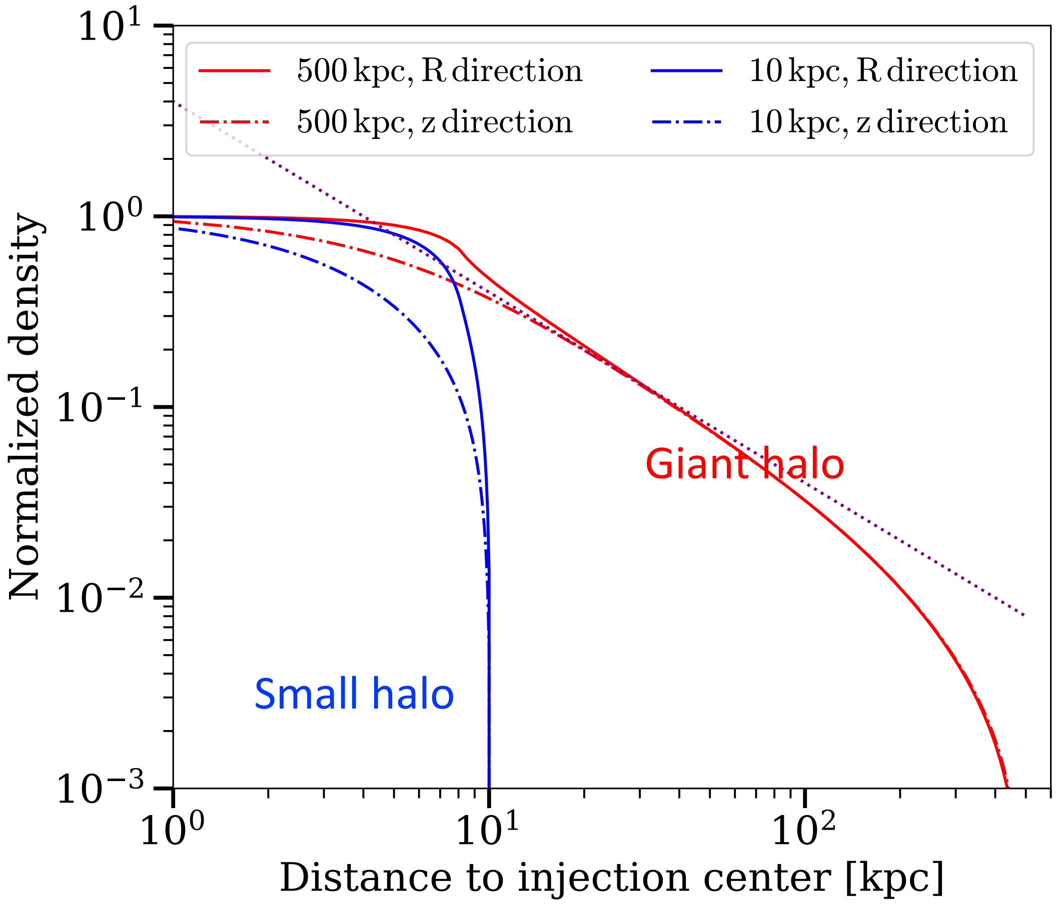


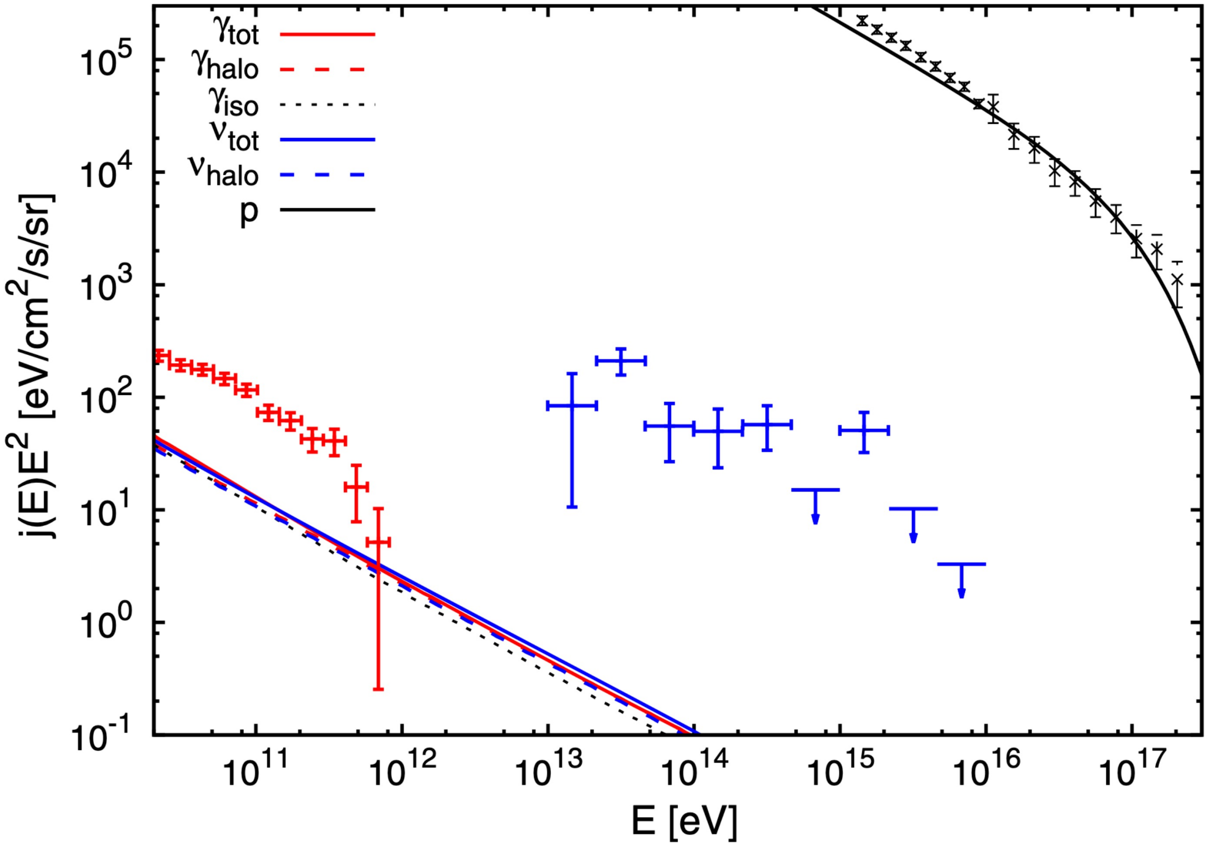


Particle distribution evolution with time for 1D(left) and 3D(right) diffusion(constant source).

- 1D & 2D diffusion can not get steady state,
- (≥)3D diffusion can get steady state.

Cosmic ray transport: small VS giant halo





Diffuse neutrino(blue) and gamma-ray(red) spectra

Kalashev & Troitsky 2016

- CR diffusion in the source region is similar to 1D, but in the giant halo is 3D, resulting a long $1/r$ tail.
- CRs in the halo contribute to diffuse gamma-ray and neutrino emission at a level comparable to those in the disk.

Cosmic ray transport: numerical solution

CR transport equation: $$\frac{\partial n_i}{\partial t} = \nabla\left(D\nabla n_i\right) + \sum_j \frac{n_j}{\tau_j} - \frac{n_i}{\tau_i} + Q_{inj}$$

diffusion

Spallation & decay

injection

Explicit scheme

Courant condition: $\Delta t < \frac{\Delta x^2}{D}$

Long CPU time !!!

CR transport simulation in giant halo is also great challenge for Galprop and DRAGON

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diffusion

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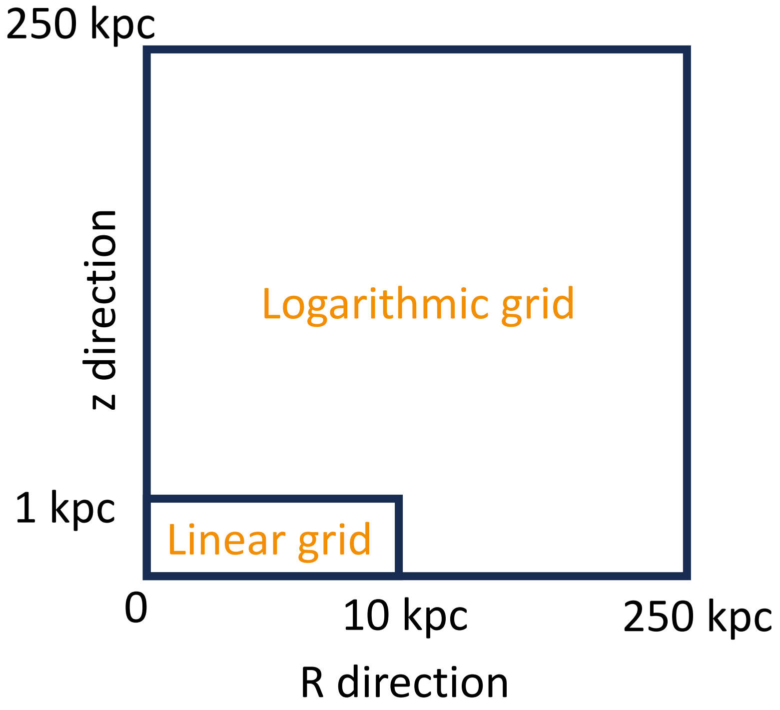
Simulation box



Explicit scheme

↓

Courant condition: $\Delta t < \frac{\Delta x^2}{D}$

↓

Long CPU time !!!

↓

Nonuniform spatial grid

CR transport simulation in giant halo is also great challenge for Galprop and DRAGON

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diffusion | Spallation & decay | injection

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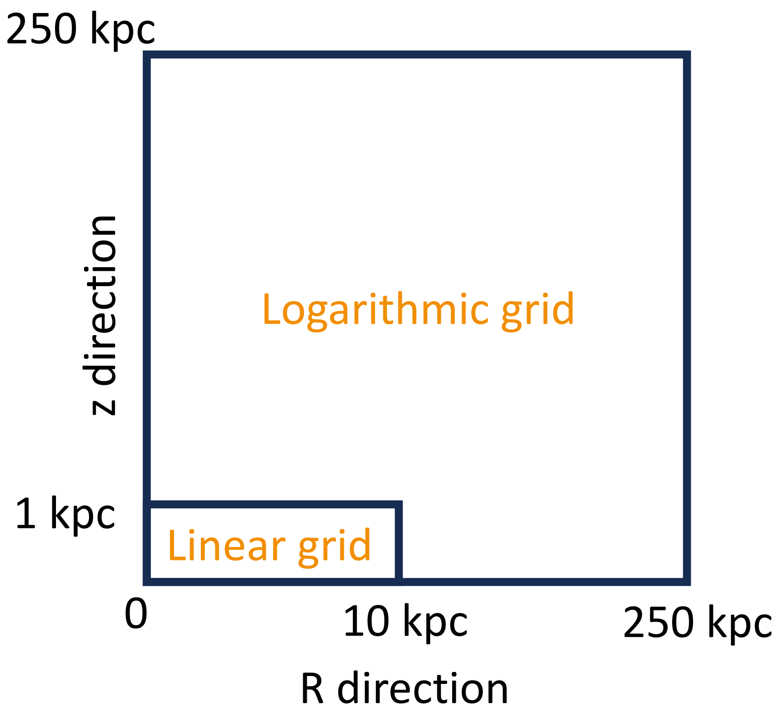

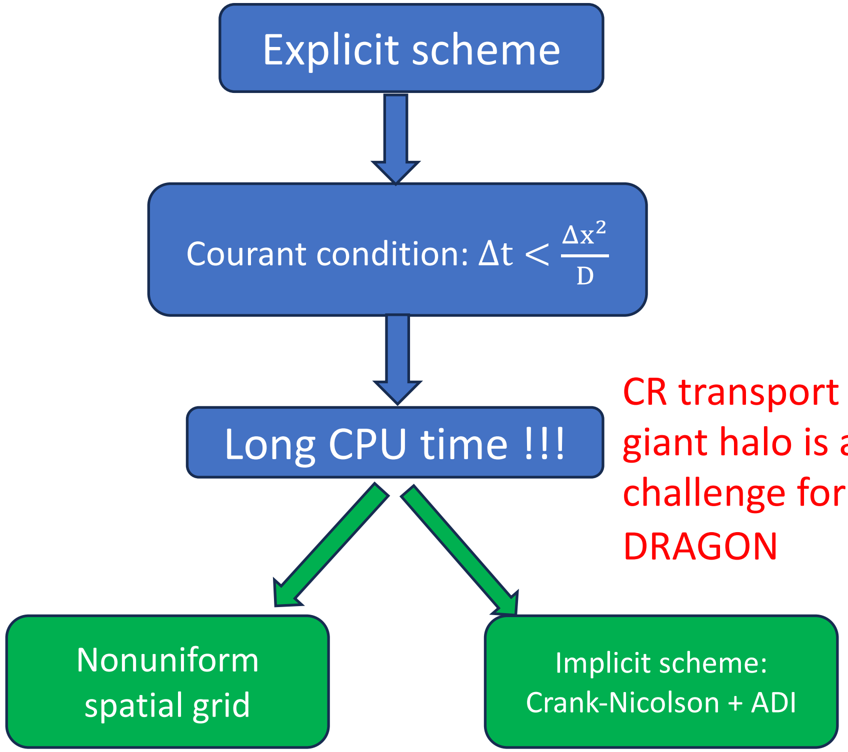

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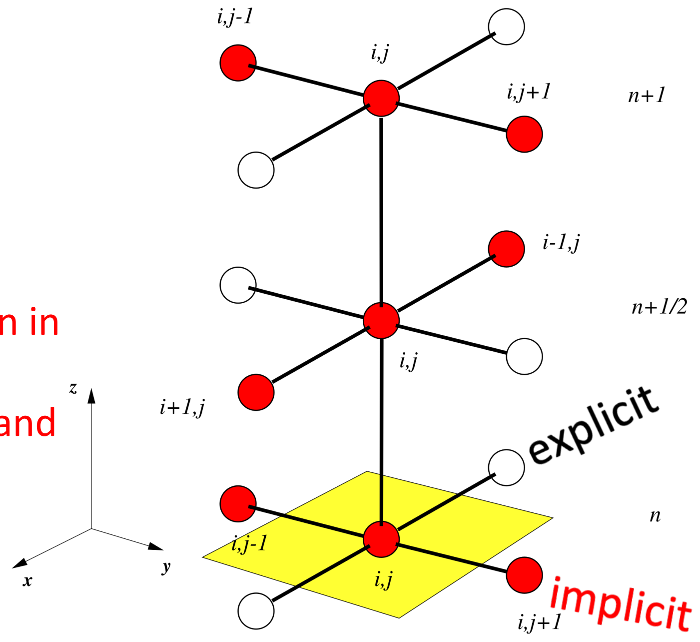
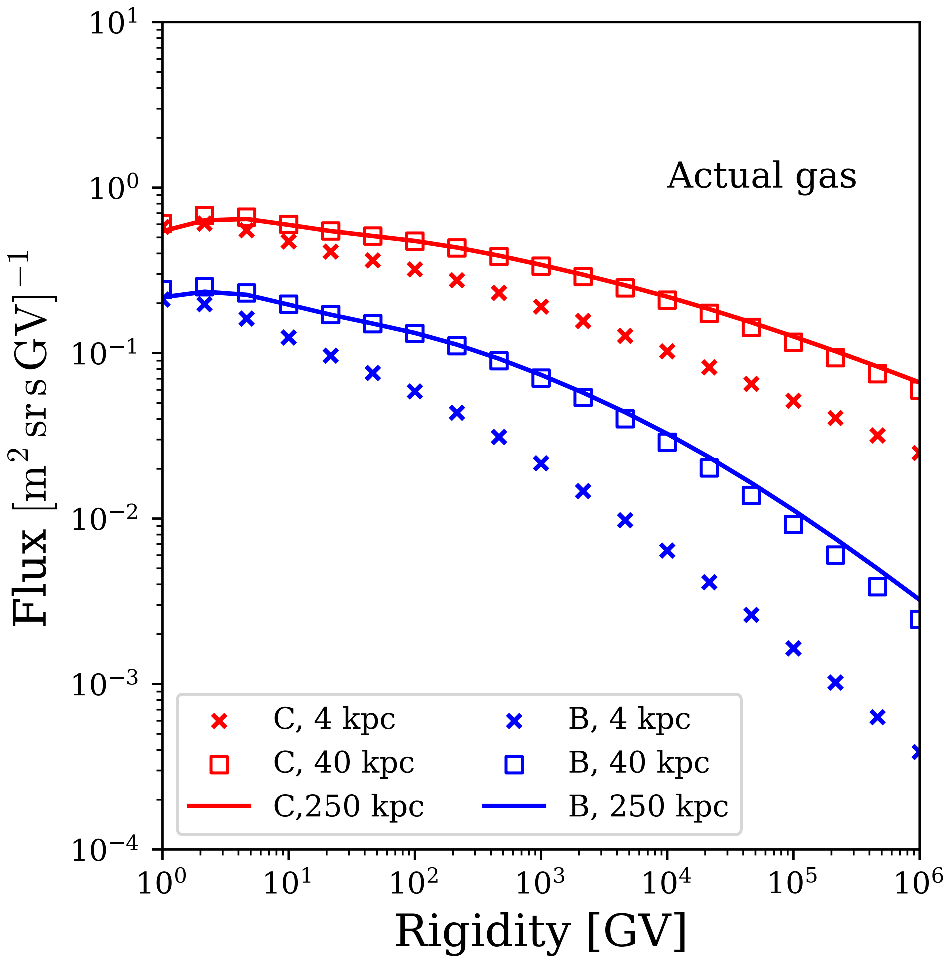


Alternating-direction implicit method
By Sidney.hy.li

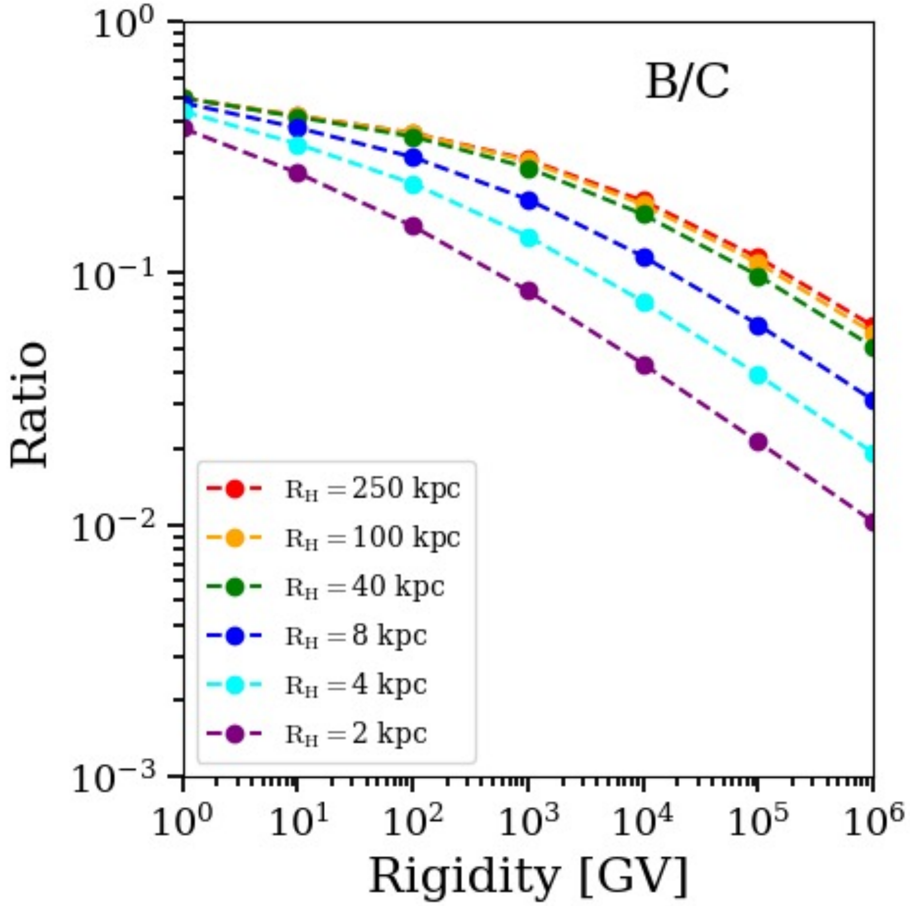
Cosmic ray transport: C and B spectra



Steady state B&C spectrum for different halo sizes

1. Boron slope steeper than Carbon slop by a factor of δ
2. When the halo size is large enough, it does not affect the inner region anymore.

Cosmic ray transport: B/C ratio & halo size



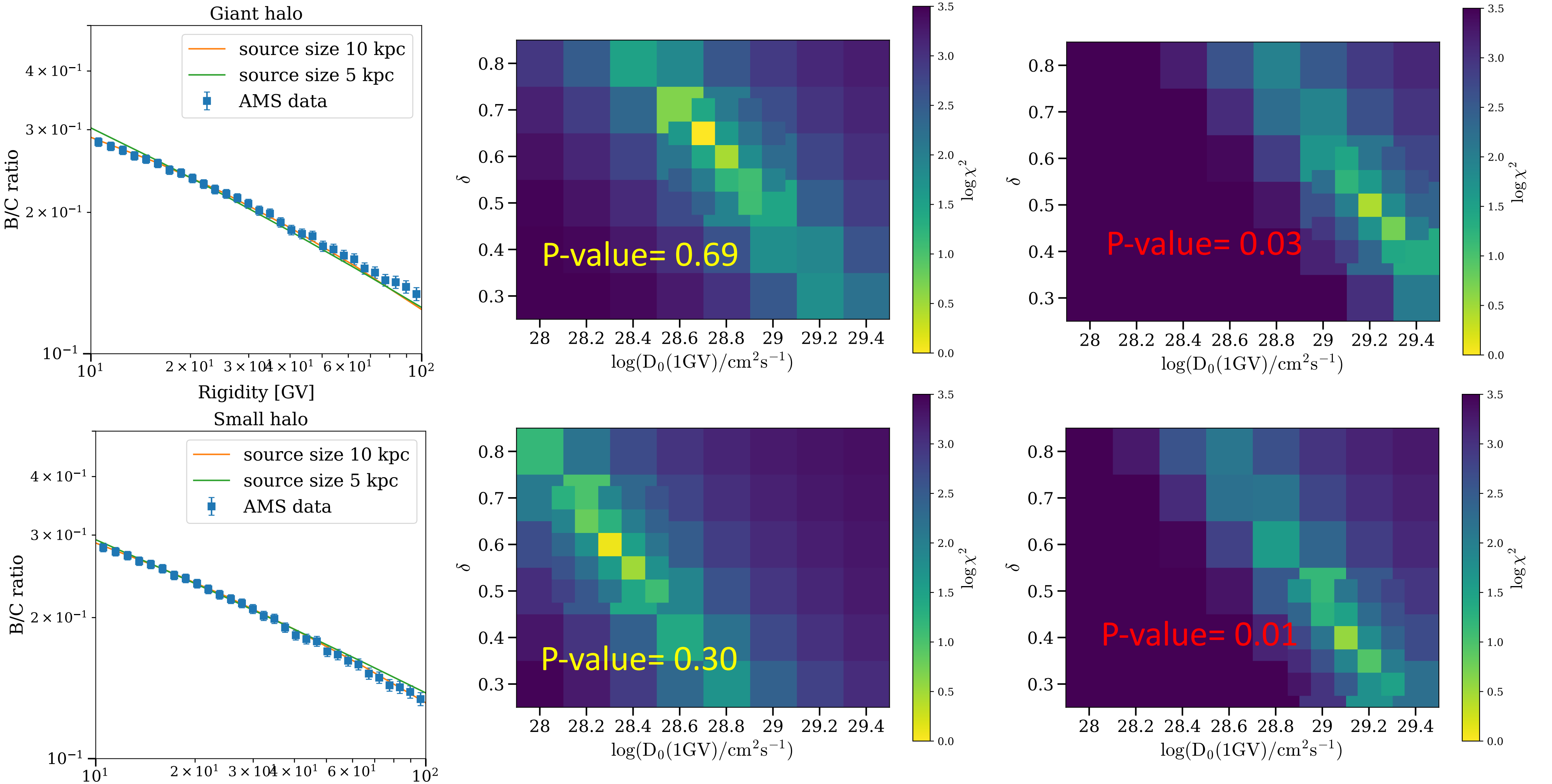
Steady state B/C ratio spectrum for different halo sizes with actual gas distribution

- Halo size affects both the slope and normalization.

Scan parameter space with nested grid

Giant halo

Small halo



Source size 10 kpc

Source size 5 kpc

- Both giant and small halo can fit the data
- Small source scenario is excluded

Summary:

1. CR diffusion in the source region is similar to 1D, but in the giant halo is 3D
2. When the halo is large enough, the halo size does not affect the CR distribution in the source region anymore.
3. Giant halo scenario can also explain the B/C ratio with reasonable diffusion coefficients

Future Perspective:

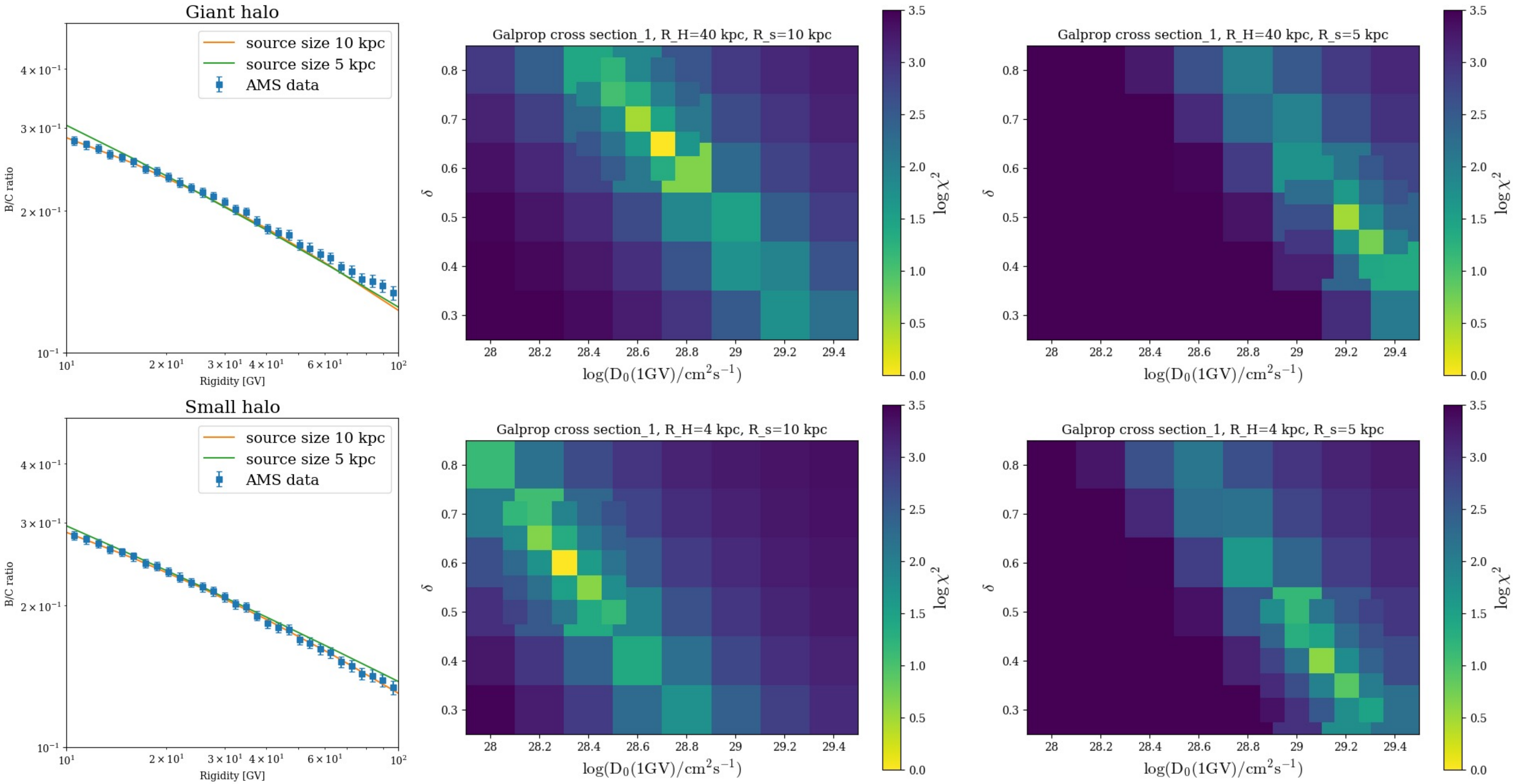
1. Include advection & reacceleration in simulation
2. Explain unstable secondary CRs(Beryllium)
3. Calculate the diffuse gamma-ray and neutrino emission from CGM halo

Backup slides

Fitting with Galprop cross sections

Giant halo

Small halo



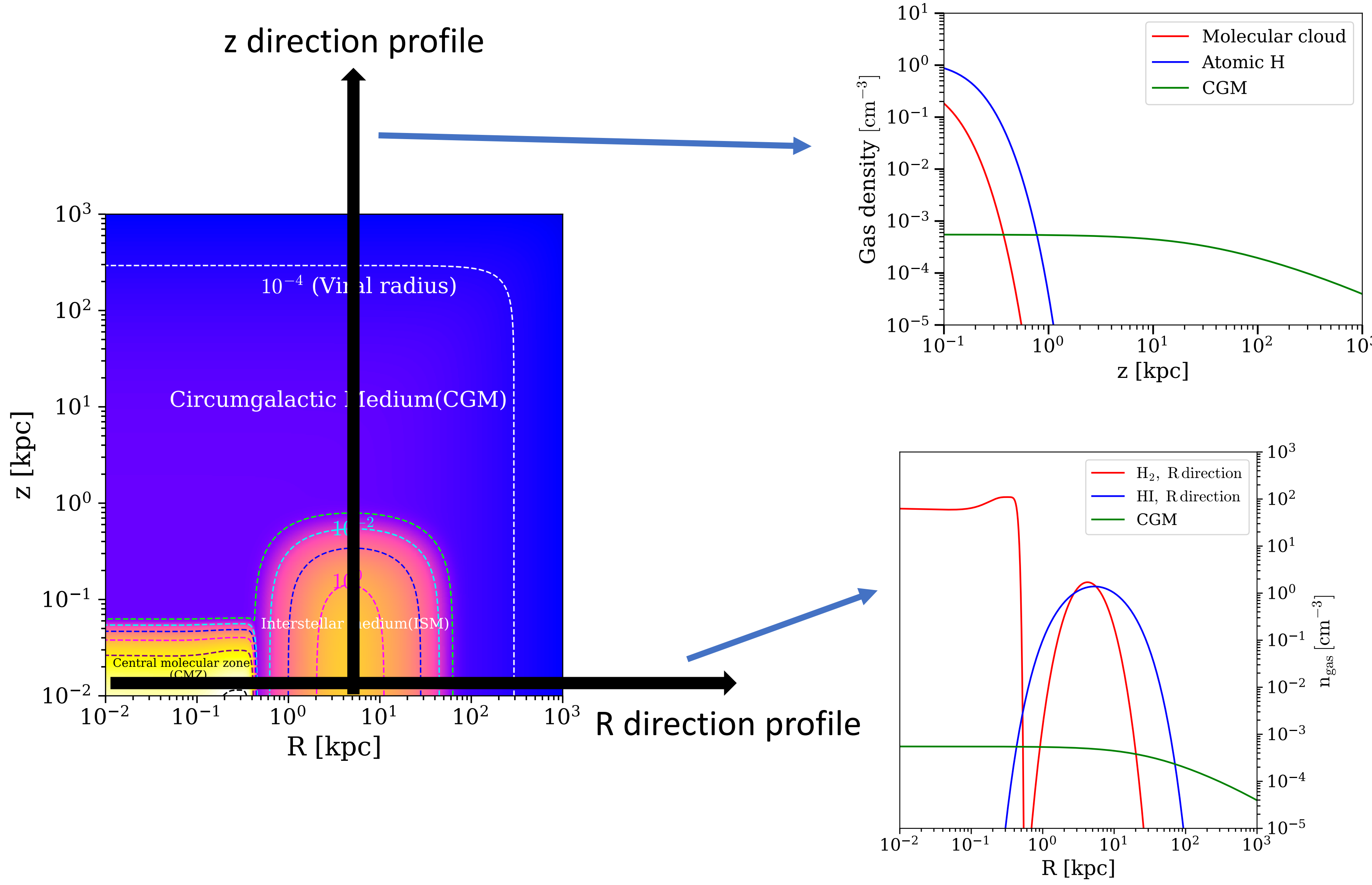
Best-fit results

Source size 10 kpc

Source size 5 kpc

Uncertainty in cross sections can change the best-fit diffusion coefficients a little

Cosmic ray transport: gas distribution



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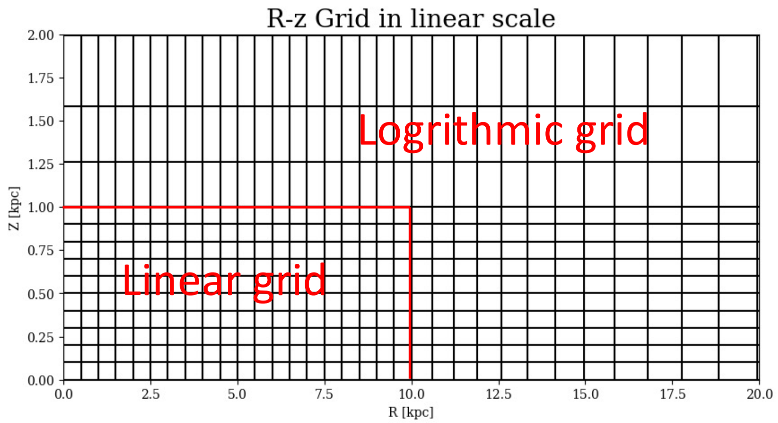
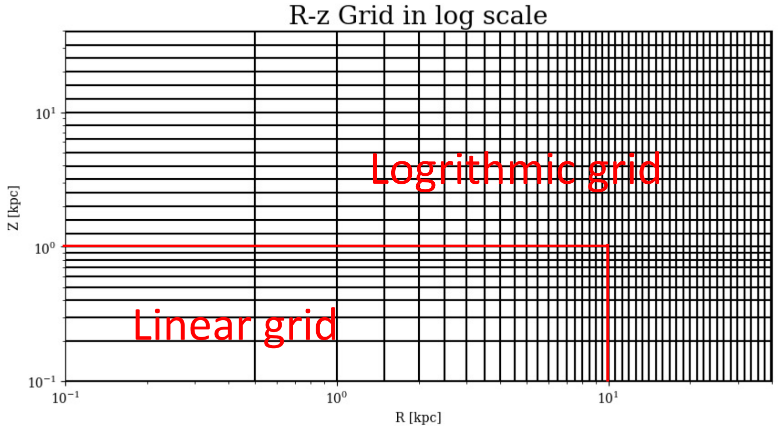
diffusion   Spallation   injection





Explicit scheme

↓

Courant condition: $\Delta t < \frac{\Delta x^2}{D}$

↓

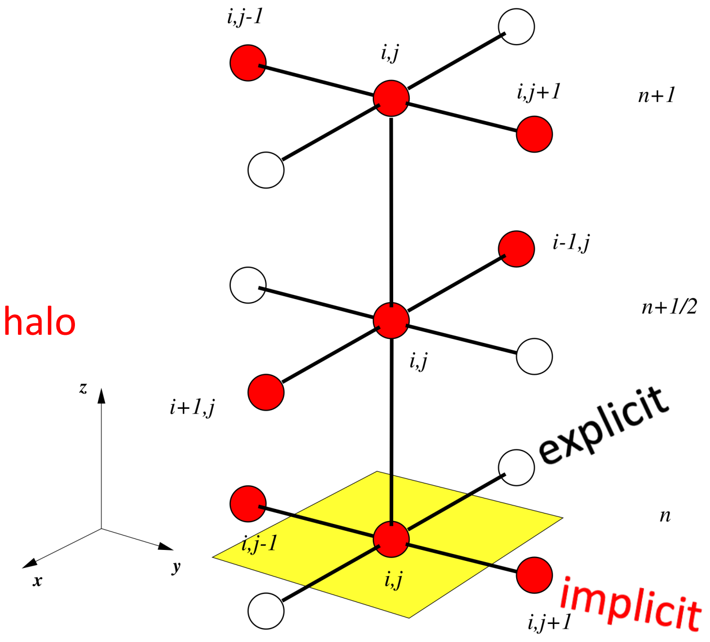
Long CPU time !!!

CR simulation in giant halo is also a challenge for Galprop and DRAGON

↙ ↘

Nonuniform spatial grid

Implicit scheme: Crank-Nicolson + ADI



Alternating-direction implicit method

By Sidney.hy.li

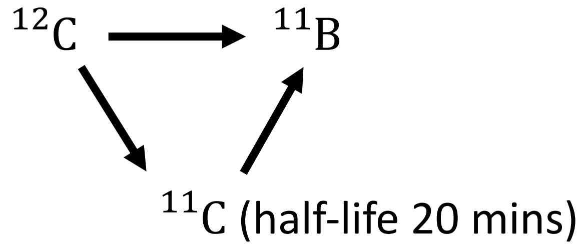
Cosmic ray transport: spallation

$$\frac{\partial n_i}{\partial t} = \nabla \cdot (D\nabla n_i) + \sum_j \frac{n_j}{\tau_j} - \frac{n_i}{\tau_i} + Q_{inj}$$

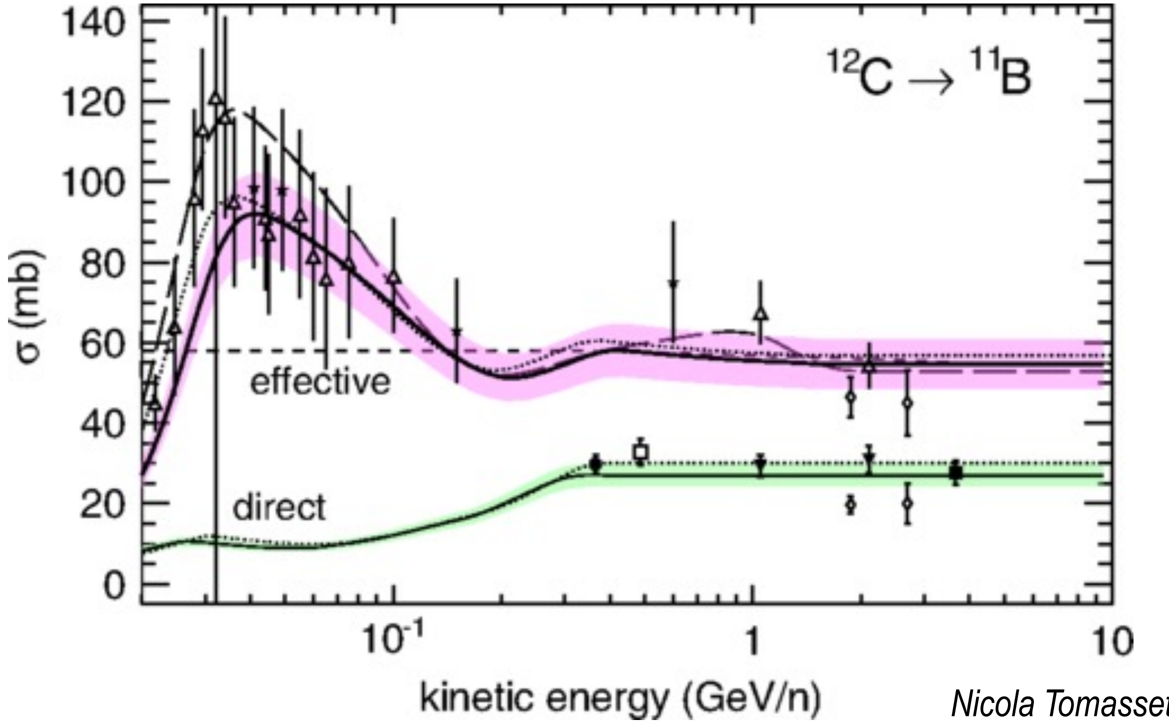
Cross section (mb)	EPOS-LHC	Galprop
$^{12}C \rightarrow {}^{11}B$	66.9	56.9
$^{12}C \rightarrow {}^{10}B$	8.5	12.3

The "*effective*" cross section accounts for the intermediate species

Intermediate species:

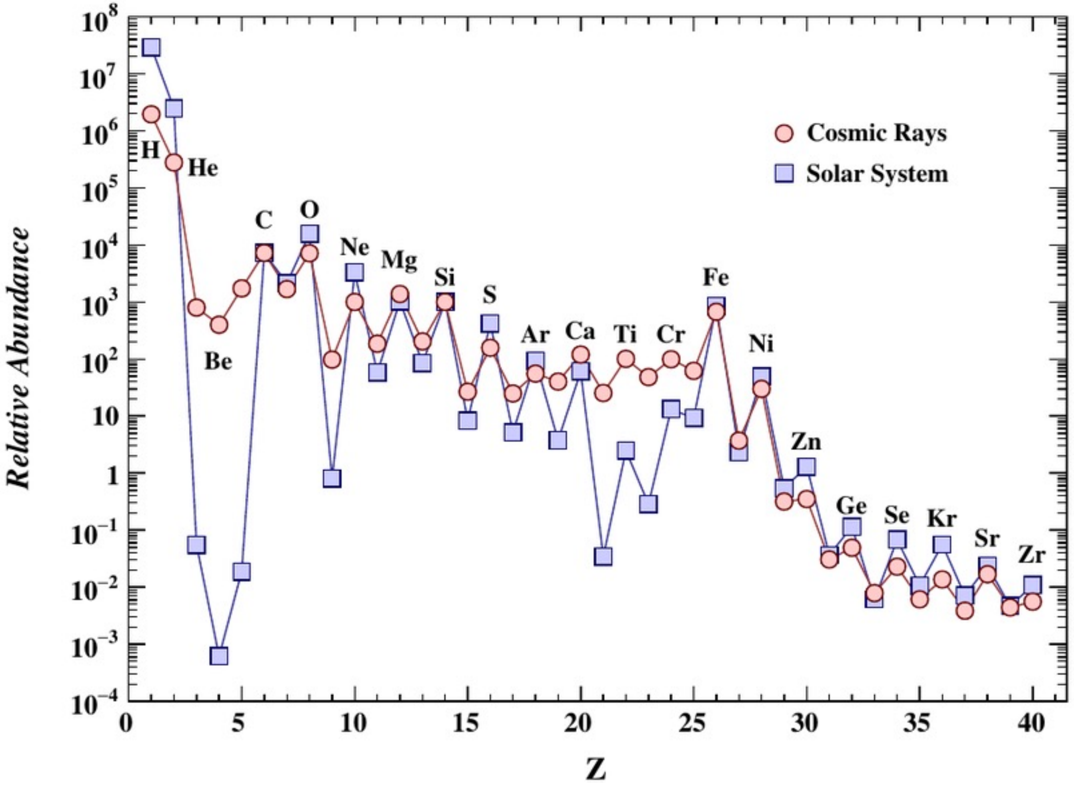


Cross sections still contribute a large fraction of uncertainties in the CR simulations.

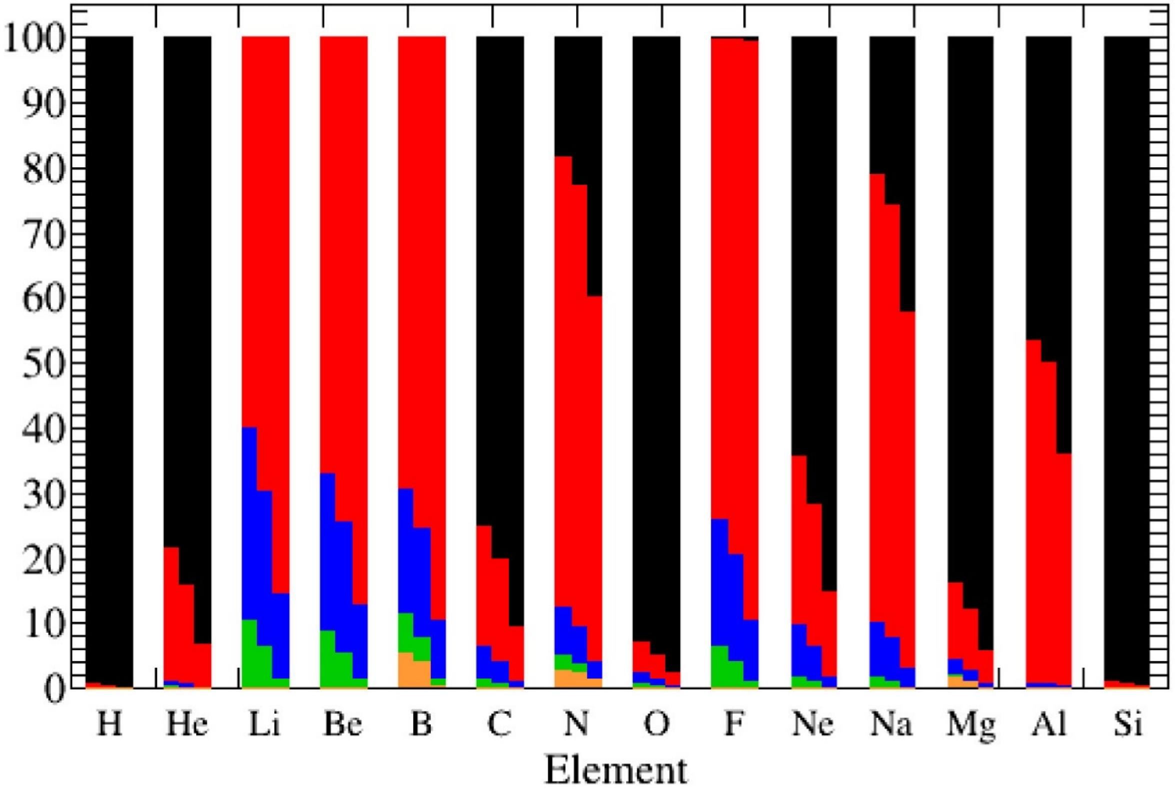


Nicola Tomassetti 2017

Cosmic ray abundance

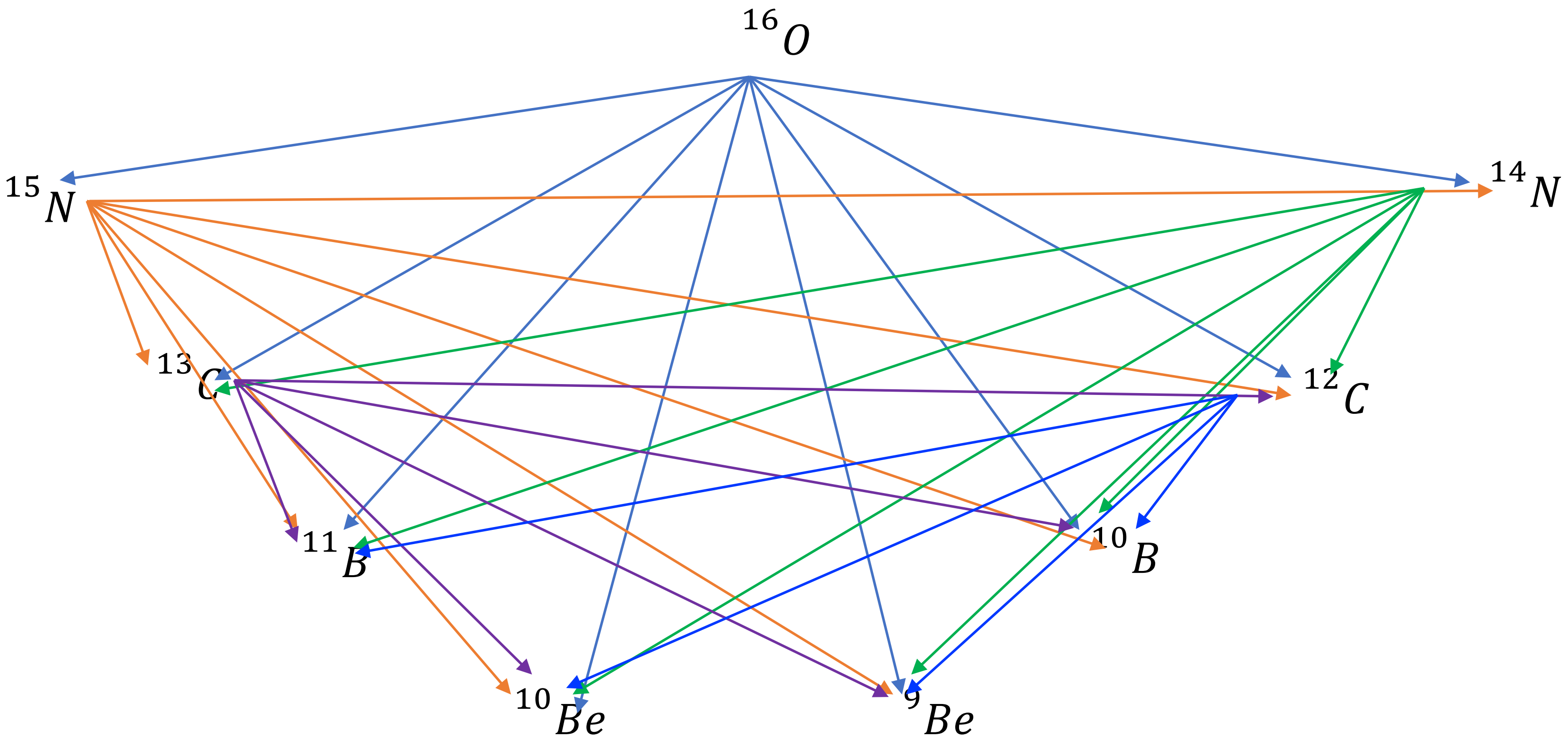


CR elemental abundance compared to the solar system. *Maggiora, Angelo, 2023*



Elemental fractional origins at 1, 10 and 100 GeV/n; primary (black); secondary(1,2,and > 2 steps in red, blue and green), radioactive(orange). *David Maurin 2019*

CR spallation network



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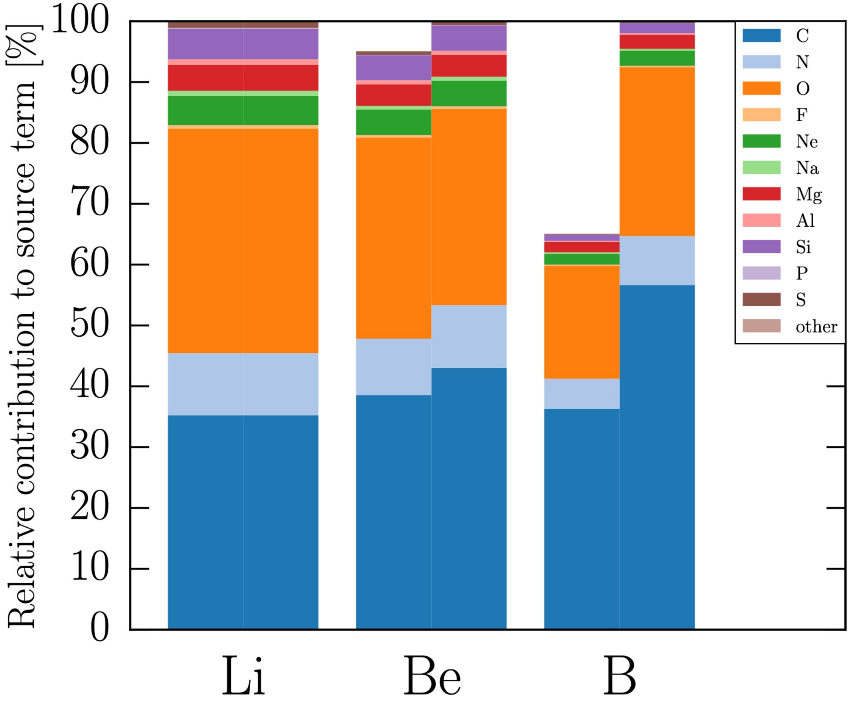


Fractional contribution to the secondary source term at 10 GeV/n

Evoli & Gaggero et al 2018

Cosmic ray propation: injection

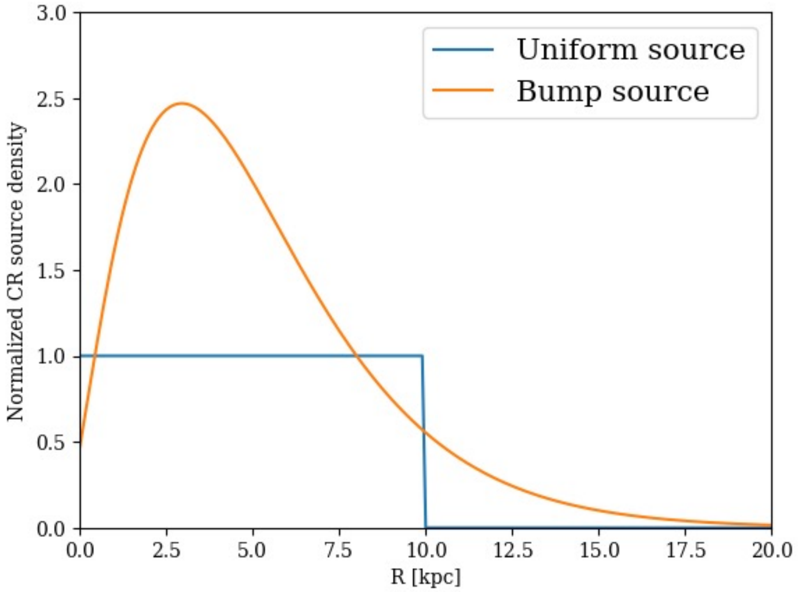
CR diffusion equation:

$$\frac{\partial n_i}{\partial t} = \nabla \cdot (D\nabla n_i) + \sum_j \frac{n_j}{\tau_j} - \frac{n_i}{\tau_i} + Q_{inj}$$

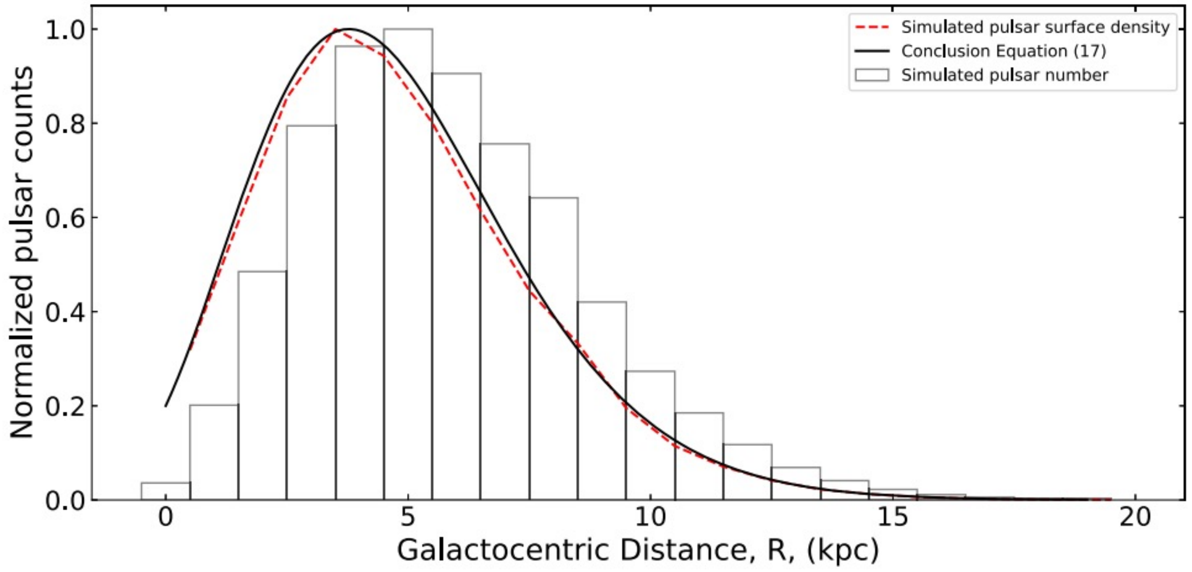
diffusion

decay

injection

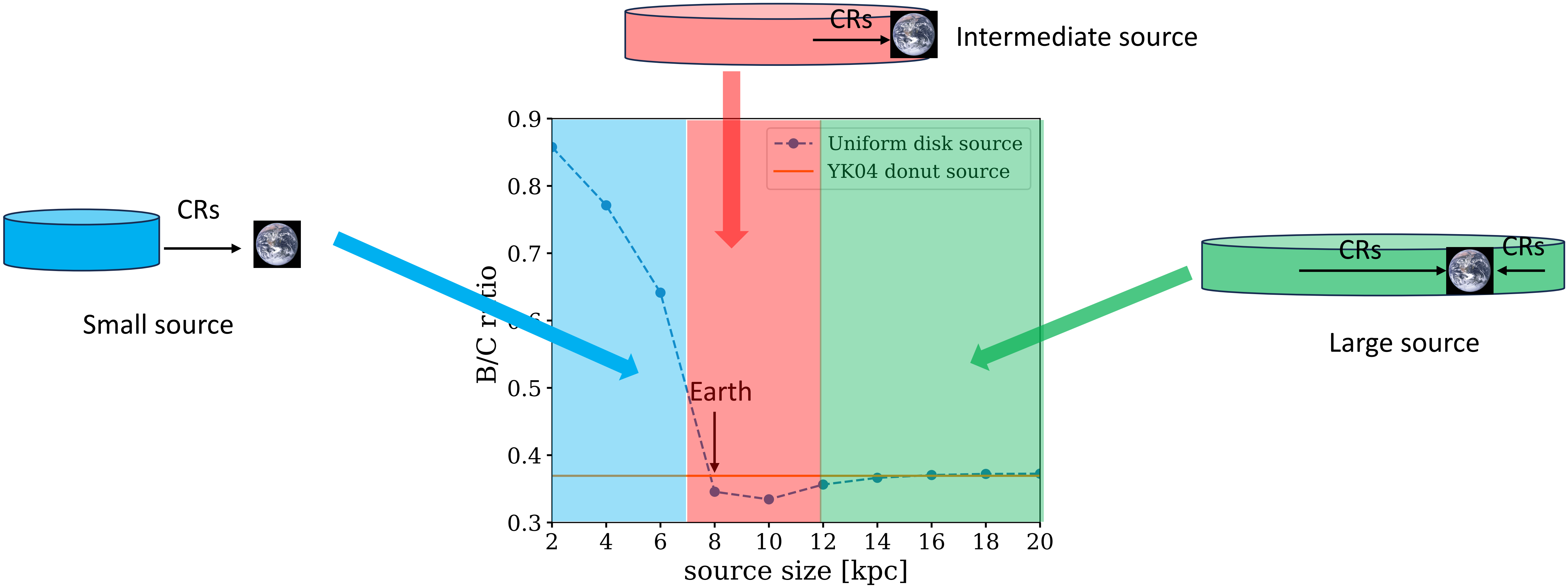


CR source distribution



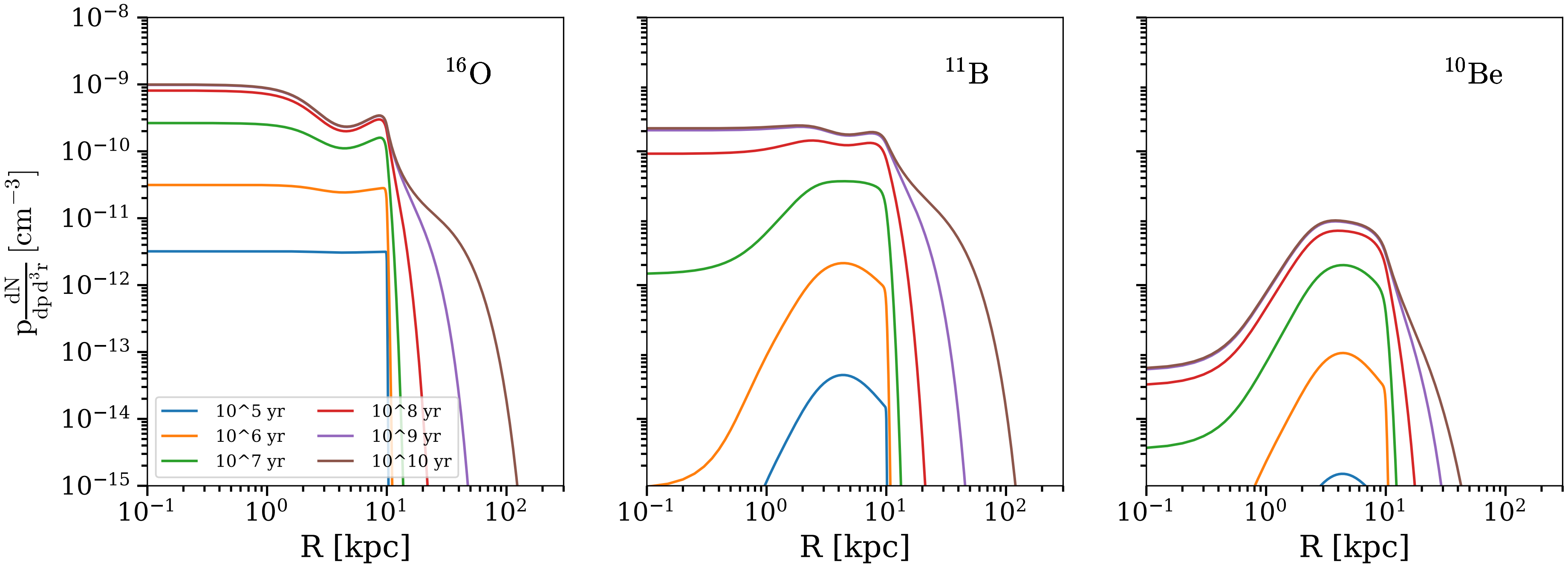
Pulsar distribution in the MW. *Xie et al 2024*

Cosmic ray transport: source injection



B/C ratio for different source distribution function.

Cosmic ray transport: density distribution with time



Density profile (in R direction) evolution with time for 3 species(@ 1 GV):

- ^{16}O (primary)
- ^{11}B (stable secondary)
- ^{10}Be (unstable secondary)

1. CRs get steady state at the source region first, then “leak” to farther distance.

2. CR distribution is shaped by the distribution of gas.