Cosmic Ray propation in the Milky Way halo

MMS Annual meeting

Chaoming Li

03.06.2025

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General picture of galactic CRs

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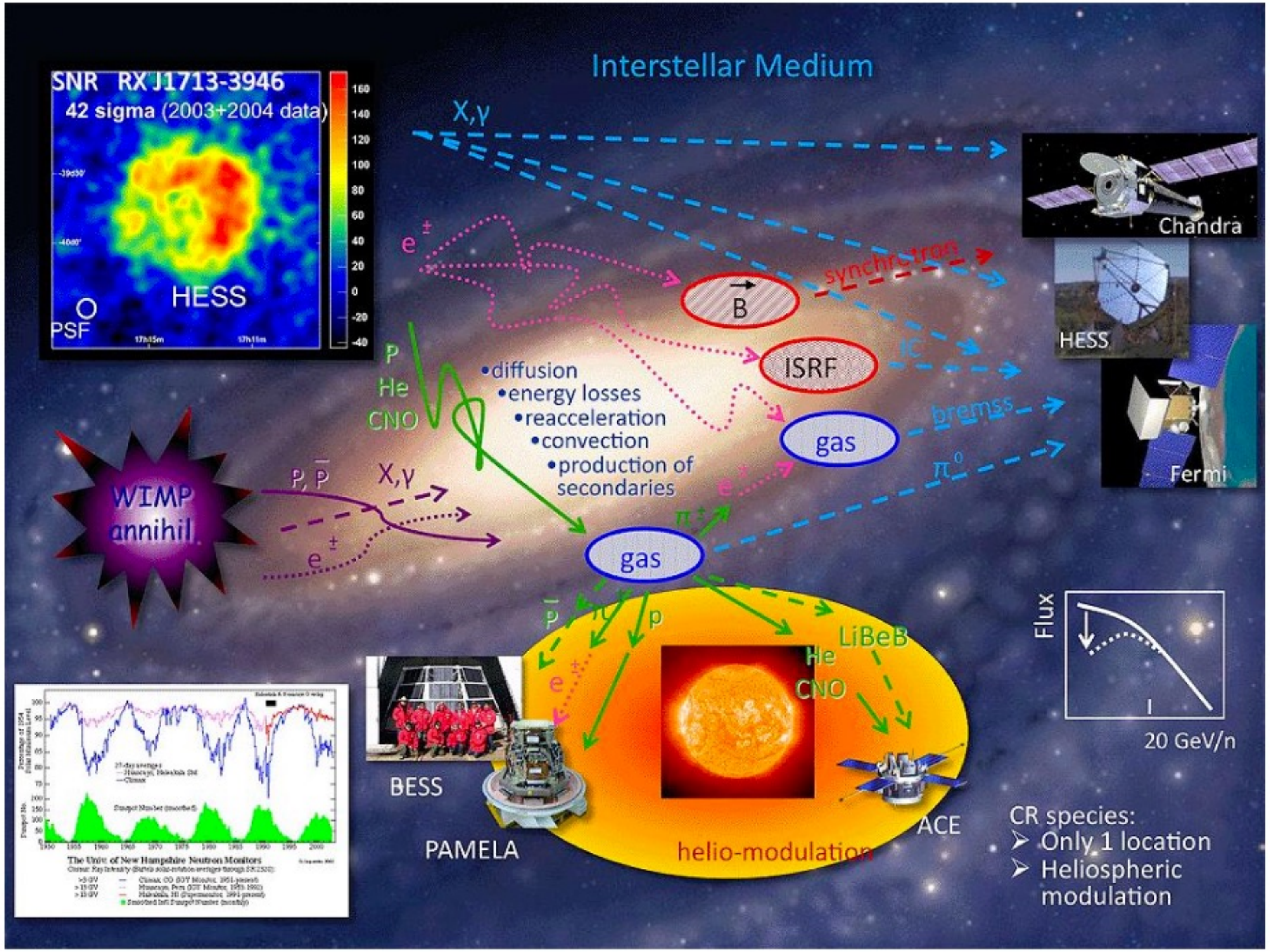
Cosmic Rays(CR) are high-energy charged particles from outer space.



Acceleration at source

↓

Diffusion and Interaction

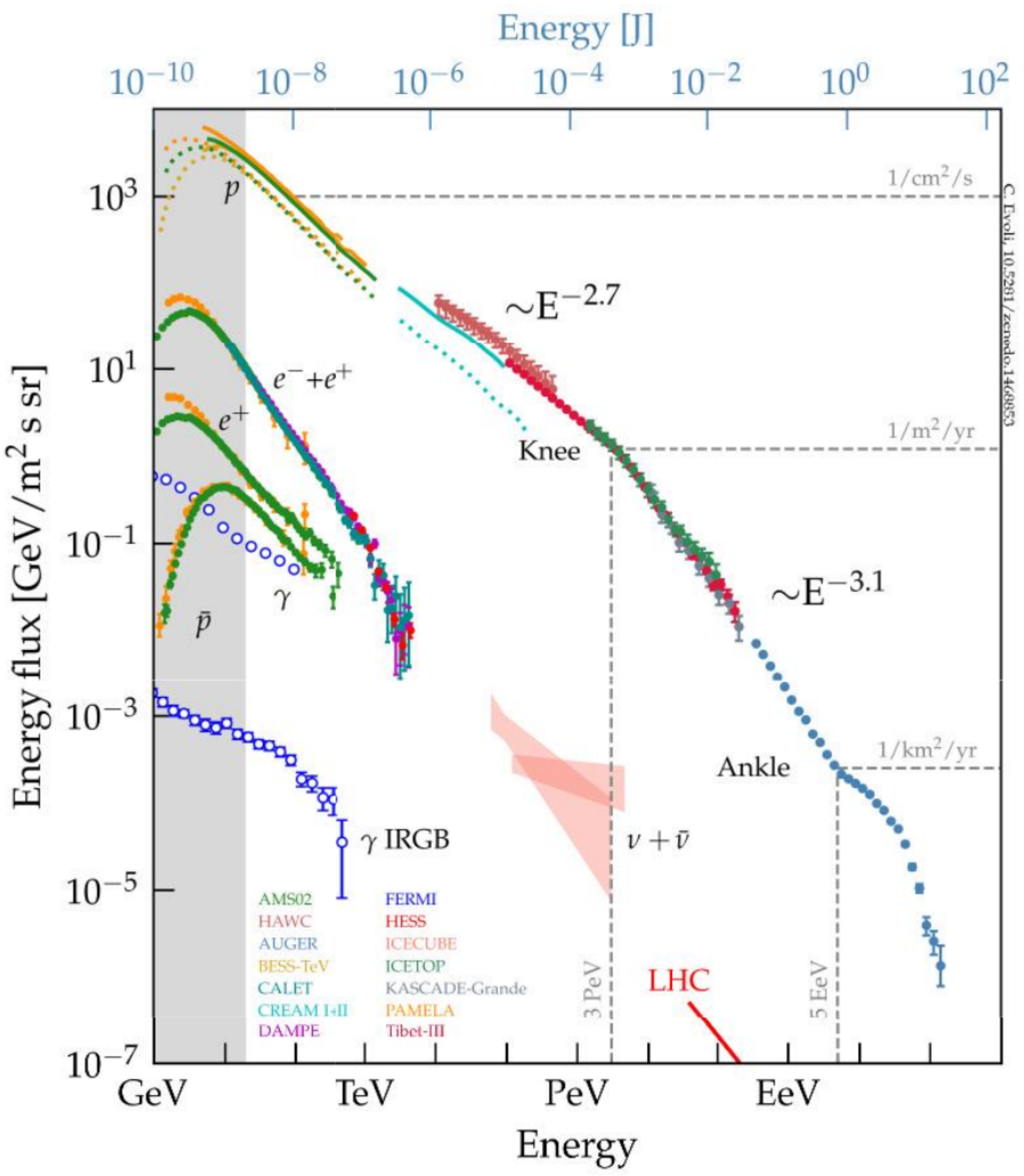
↓

Helio-sphere propagation

↓

Detection at the Earth

Cosmic ray energy spectrum



CR energy spectrum.@ Evoli Varmelo 2018

Spectral Energy Distribution(SED) features:

- Power-law in different energy bins
- CRs with energy below the ”knee” originate from the Milky Way
- CRs above the “ankle” originate from other galaxies

Galaxy halo

Halo gas lies between the virial radius($\sim 250\ kpc$) and disk ($26.8\times2.6\ kpc^2$)

ΛCDM fraction

Baryon Dark matter

Mass distribution of the MW galaxy:

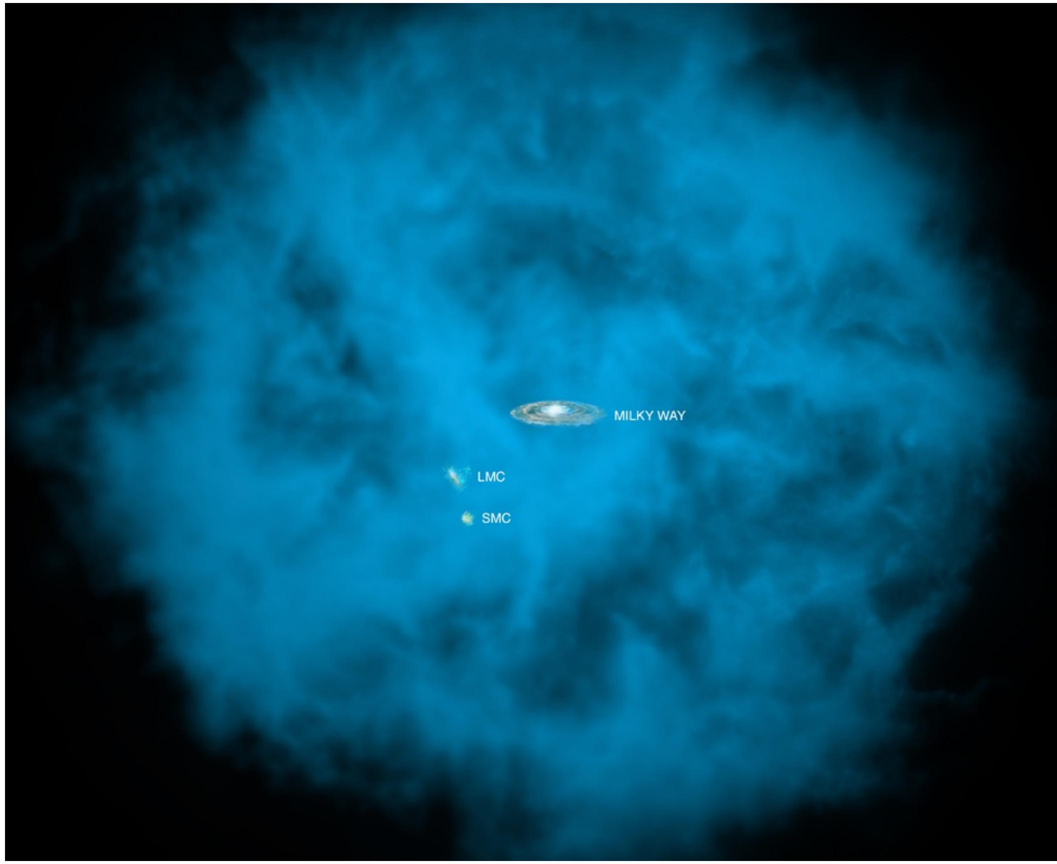
Total mass: $10^{12}\ M_\odot = 1.6\times10^{11}\ M_\odot + 8.4\times10^{11} M_\odot$

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

Interstellar medium mass: $1\times10^{10}\ M_\odot$ ← Disk

Circumgalactic medium mass: $1\times10^{11}\ M_\odot$ ← halo

(data from Cautun et al 2020)



The Milky Way galaxy disk and its gaseous halo. The Large Magellanic Cloud and Small Magellanic Cloud are also shown. (Gupta, A et al, 2012)

Cosmic ray propation: diffusion(random walk)

CR diffusion equation:

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

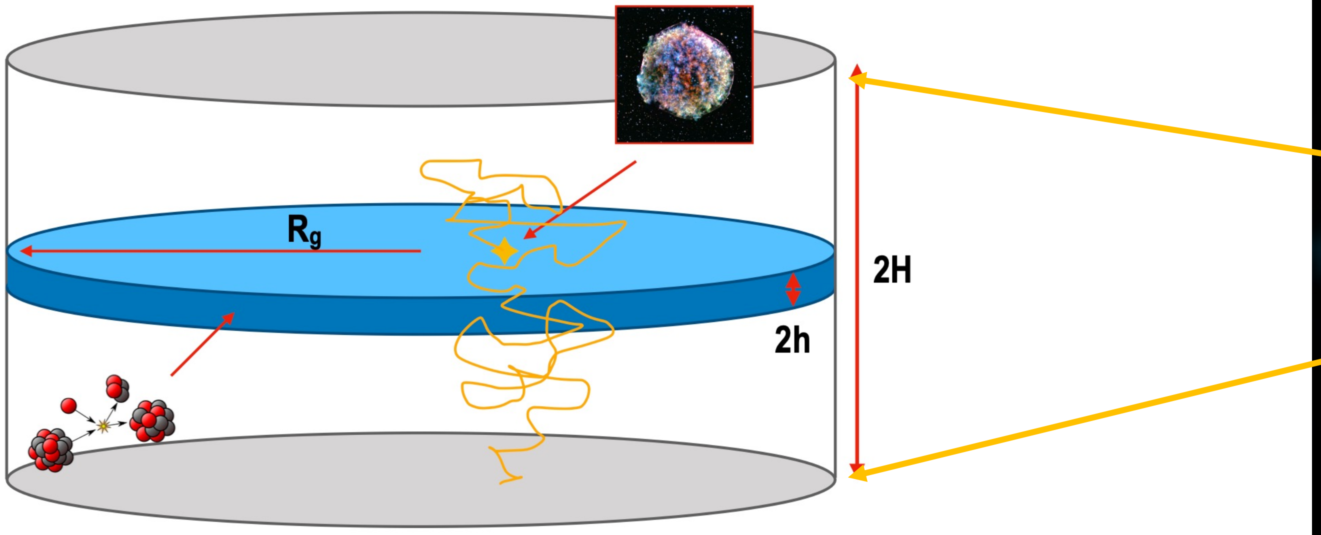
diffusion

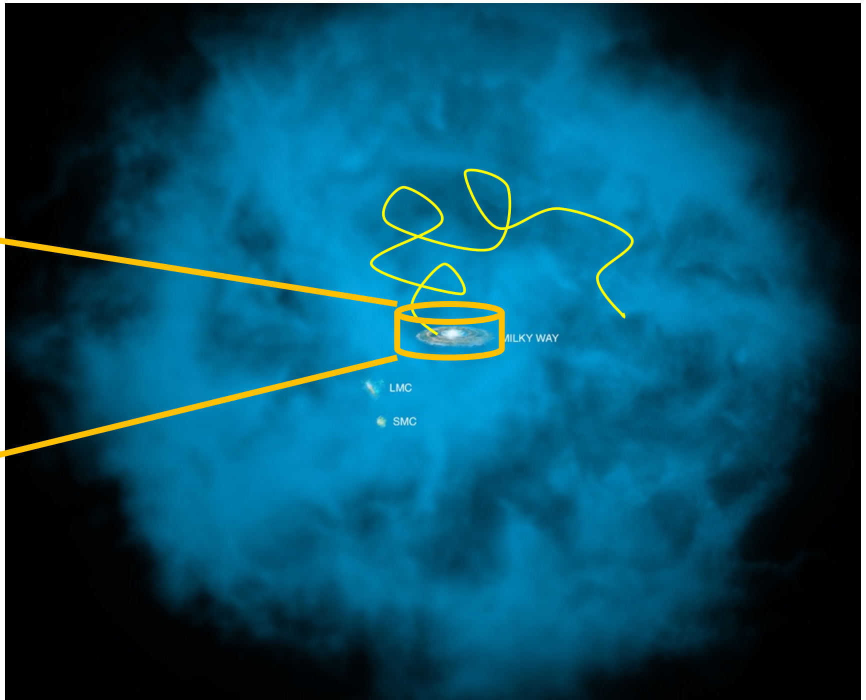
decay

injection

1D model

3D model





@Evoli lectures

Cosmic ray propation: decay

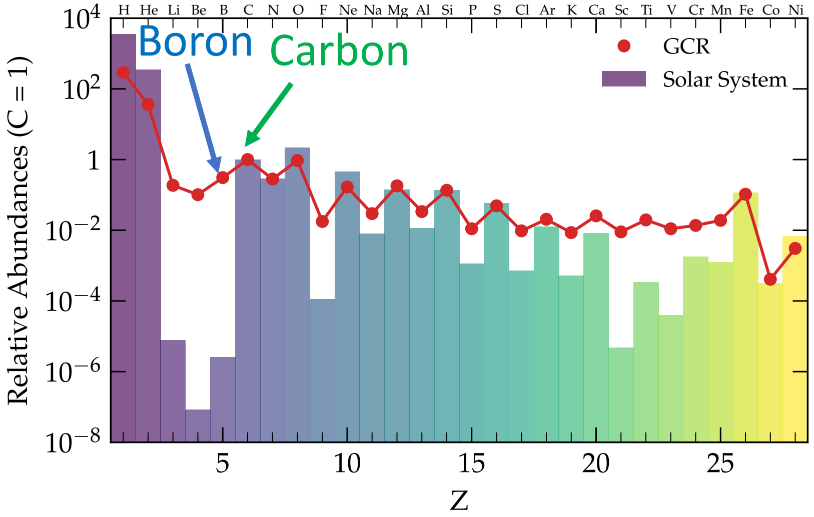
CR diffusion equation:

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

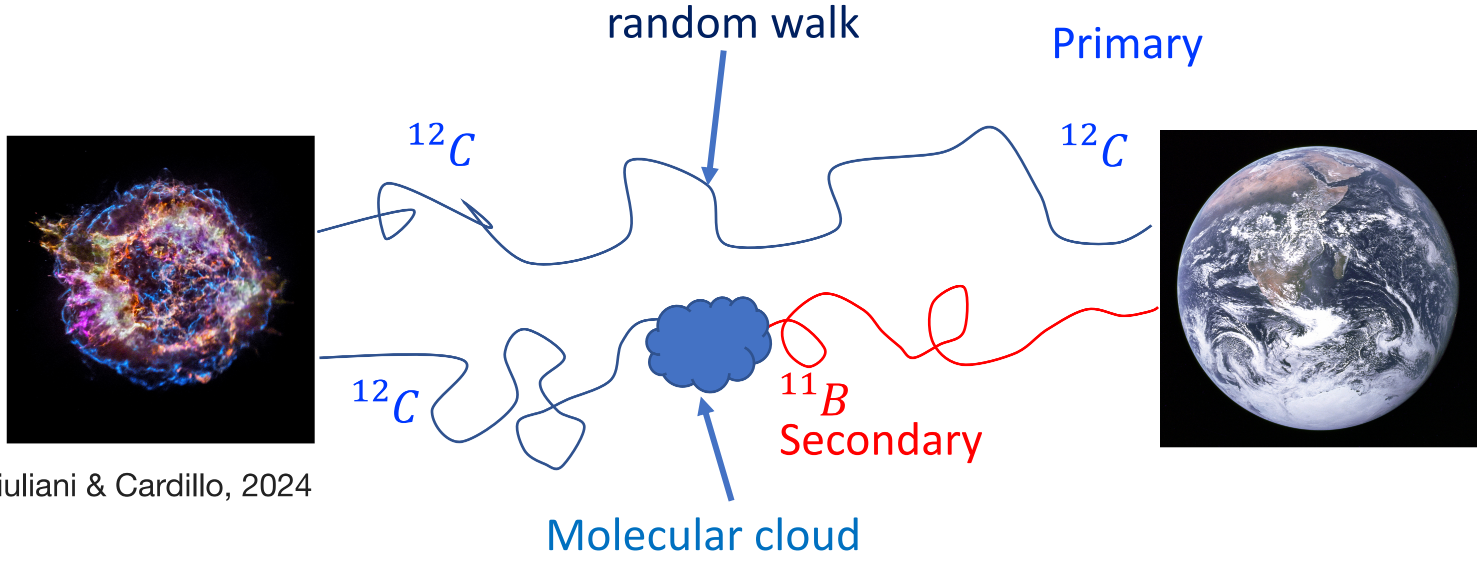
diffusion

decay

injection



CR elemental abundance compared to the solar system. Fig link



Giuliani & Cardillo, 2024

Decay timescale: $\tau = \frac{1}{n_p c \sigma}$

Where n_p is target proton density,
c is speed of light,
σ is cross section

Nuclear reactions:
$$\begin{cases} C + p \rightarrow B \\ C + p \rightarrow Be \\ B + p \rightarrow Be \\ \dots \end{cases}$$

Cosmic ray propation: target gas distribution

The Milky Way galaxy:

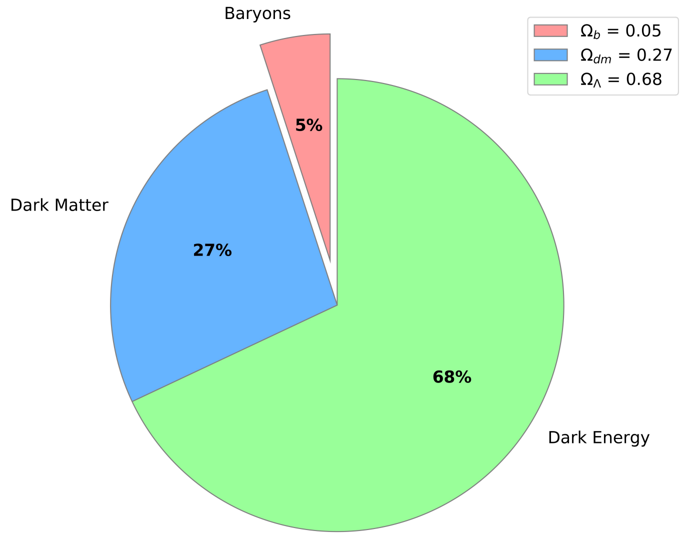
Baryon ↓ Dark matter ↓

Total mass: $10^{12}\ M_\odot = 1.6\times10^{11}\ M_\odot + 8.4\times10^{11} M_\odot$

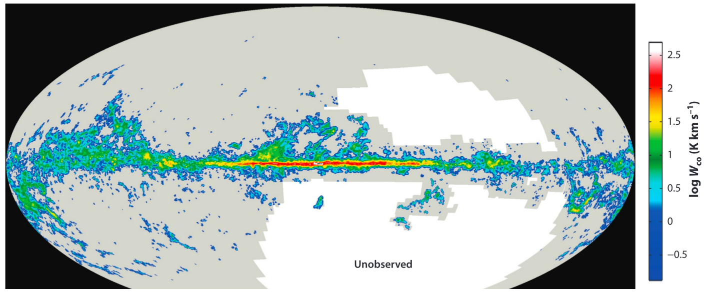
Stellar mass: $5\times10^{10}\ M_\odot$

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

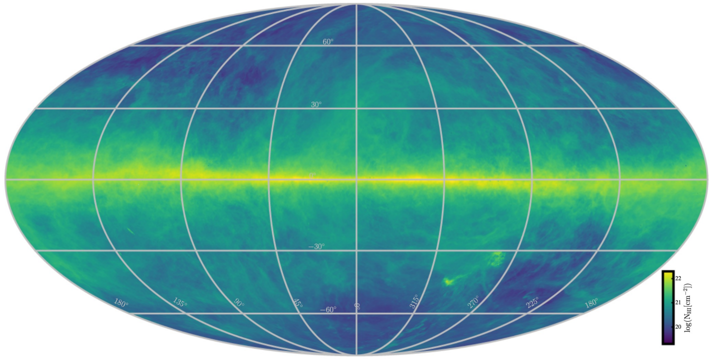
CGM mass: $1\times10^{11}\ M_\odot$



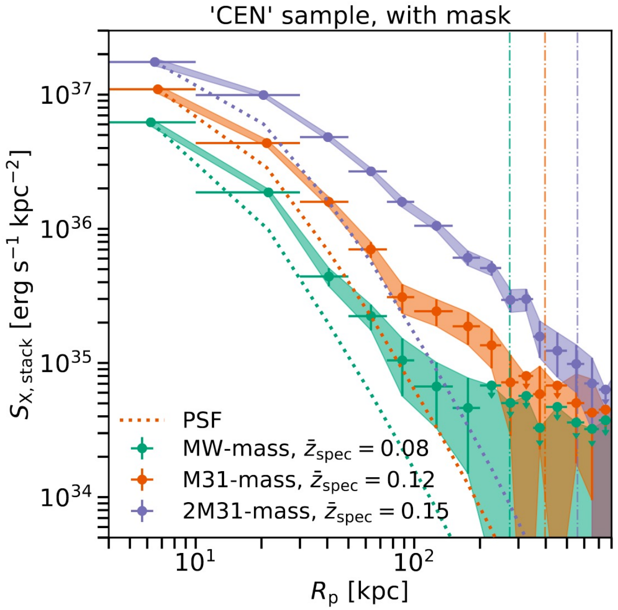
ΛCDM cosmology (Planck Collaboration et al. 2013)



CO emission of the MW (Heyer & Dame, 2015)



Column density of HI gas (HI4PI Collaboration 2016)



Mean X-ray brightness profile of galaxies' halo. (Zhang et al 2024)

Cosmic ray propation: cross section

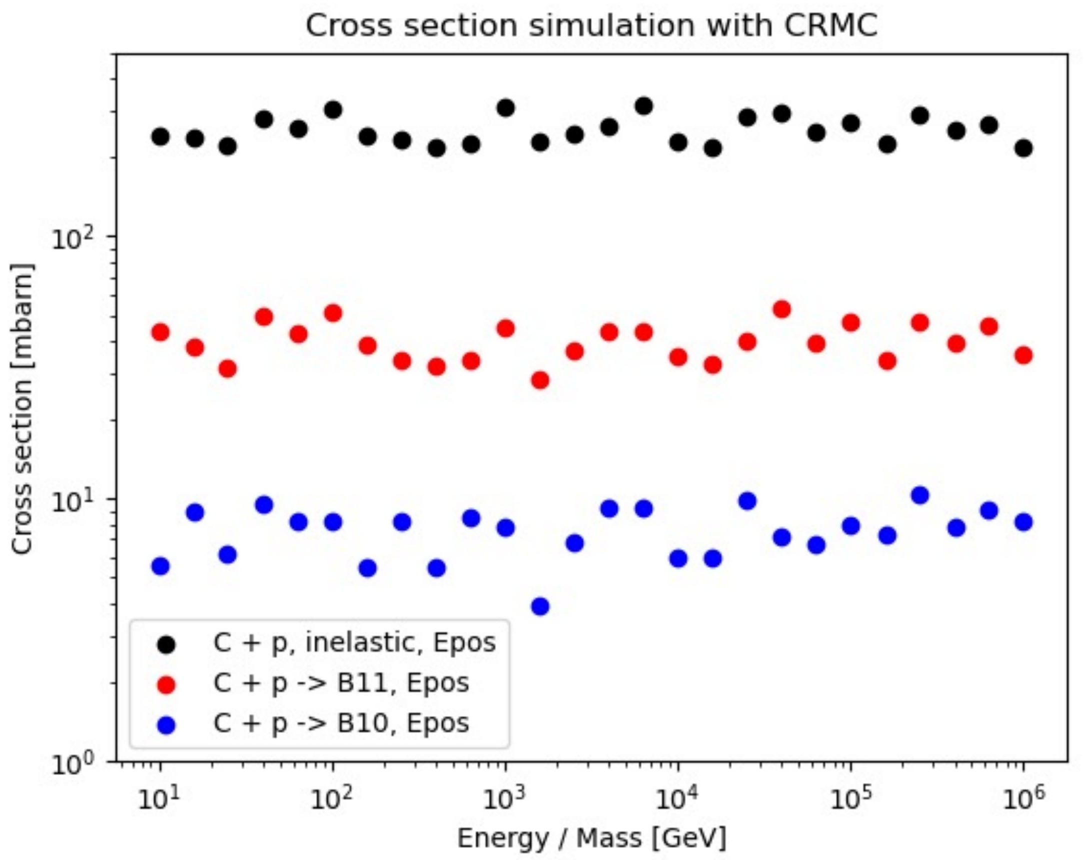
$$^{12}C + p \rightarrow \begin{cases} ^{11}B \\ ^{10}B \\ \ldots \end{cases}$$

$$^{11}B + p \rightarrow \ldots$$

$$^{10}B + p \rightarrow \ldots$$

Compare with other models:

QGSJet, Siblly, DPMJet……



Cross section of $^{12}C + p$ with 1000 EposLHC-R events.

Cosmic ray propation: injection

CR diffusion equation:

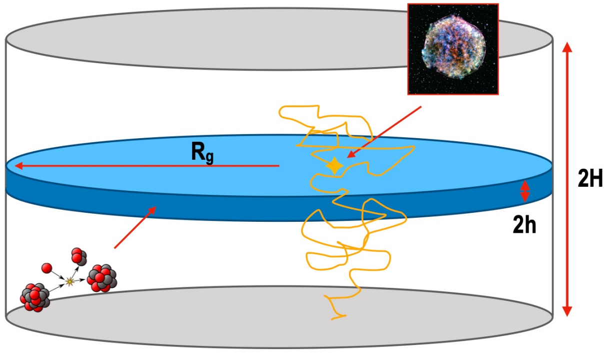
$$\frac{\partial n_i}{\partial t} = \nabla \cdot (D \nabla n_i) + \sum_j \frac{n_j}{\tau_j} - \frac{n_i}{\tau_i} + Q_{inj}$$

diffusion

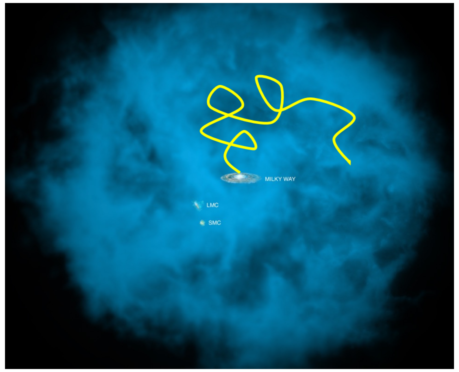
decay

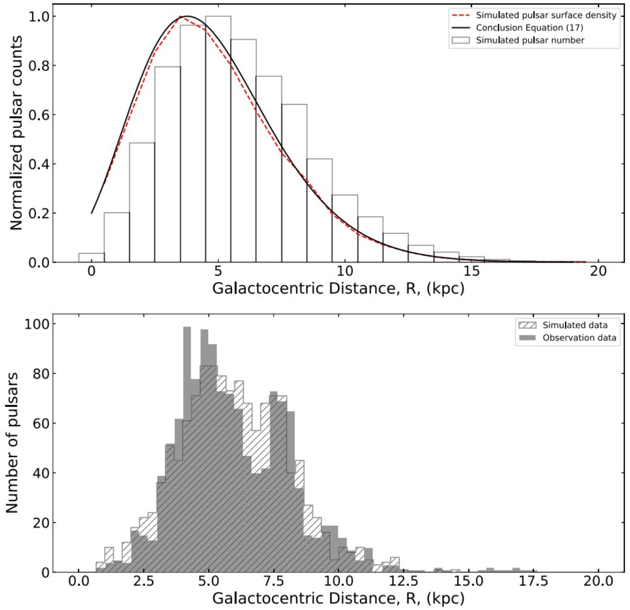
injection

1D



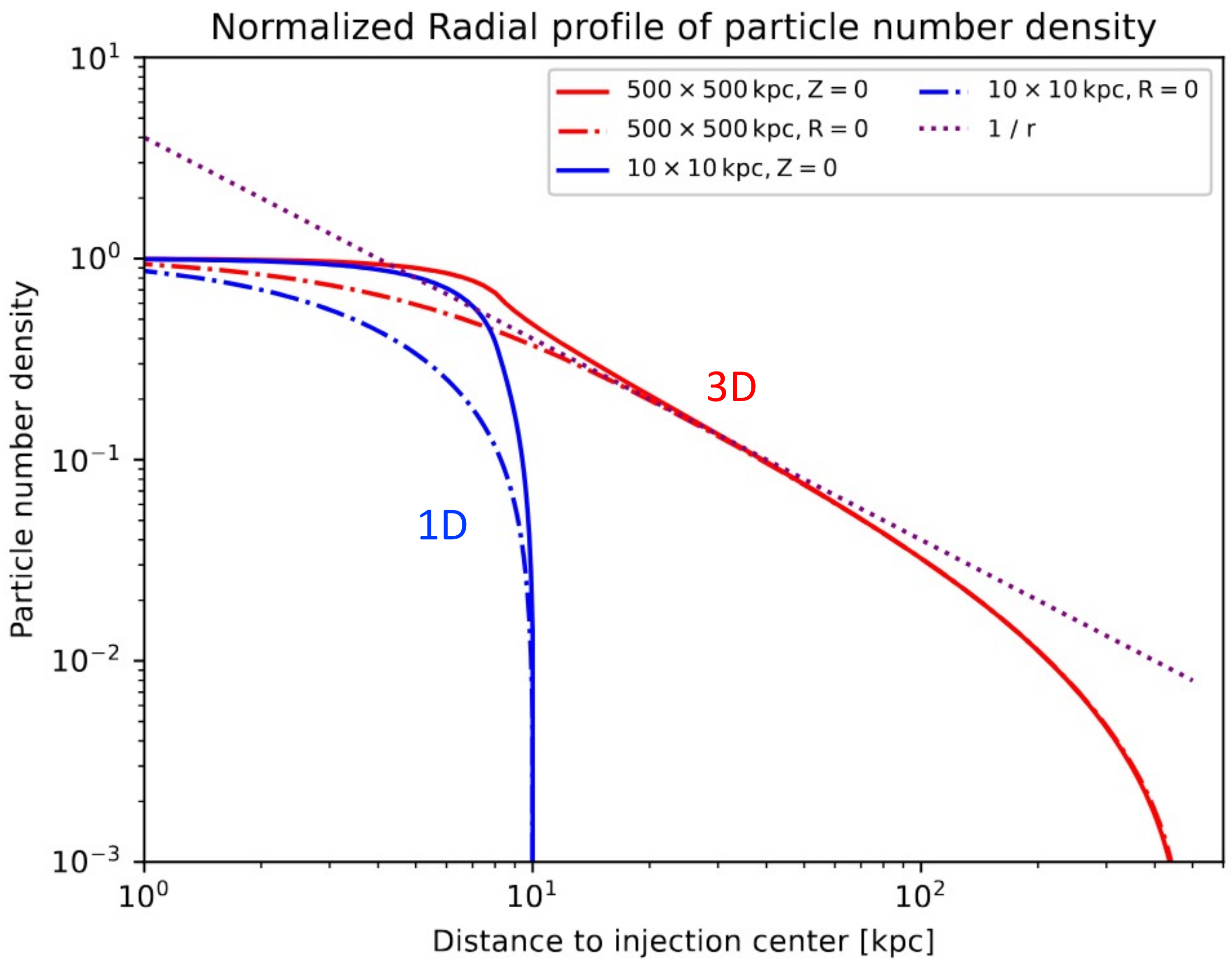
3D





Pulsar distribution in the MW. (Xie et al 2024)

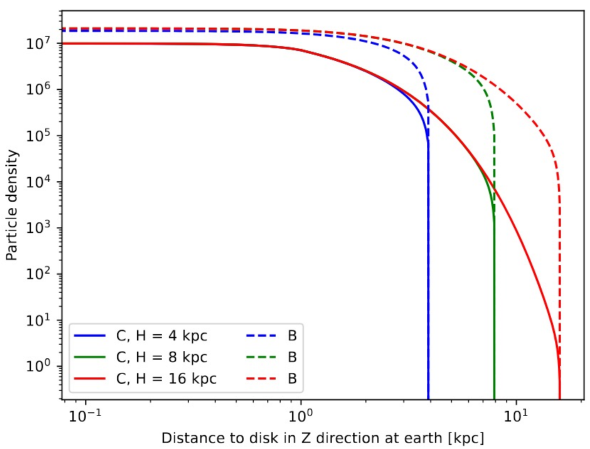
Diffusion model of cosmic rays: 1D VS 3D



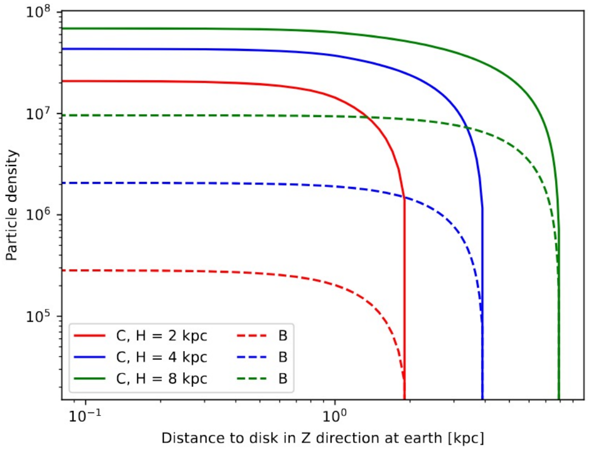
With a flat disk injection:

3D diffusion has long tail (1/r) and thus can extend to further distance(halo region)

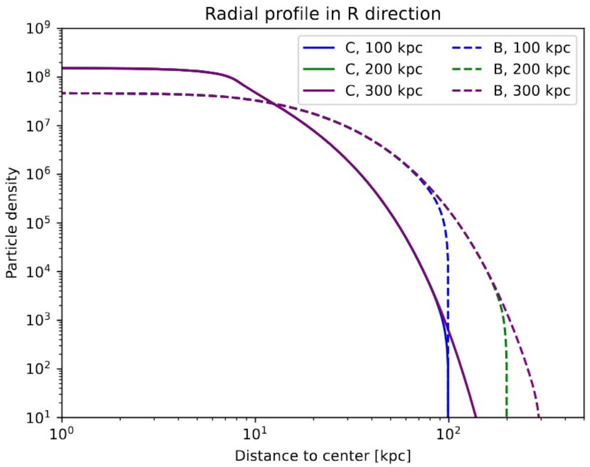
Diffusion model, boundary condition



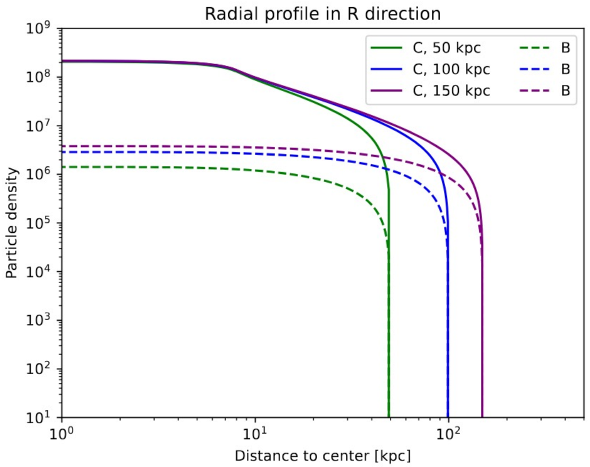
(a) 1D decay dominant



(a) 1D diffusion dominant



(a) 3D decay dominant



(a) 3D diffusion dominant

R_B: boundary distance

$\sqrt{D\tau}$: diffusion distance before decay

- $R_B \ll \sqrt{D\tau}$: diffusion dominant, the boundary dictates the distribution of CRs
- $R_B \gg \sqrt{D\tau}$: decay dominant, the boundary only influence the nearby distribution

Summary:

1. CRs can escape to halo region due to 3D diffusion

2. Halo gas can produce more target protons than ISM

3. Gas density and cross sections are vital quantities that dictate the propagation of CRs

To do list:

1. Compare my results with observation (AMS-02)

2. Add more terms in the diffusion equation: advection, anisotropic diffusion, more CR nuclei… …

3. Estimate the gamma-ray and neutrino emission from galaxy halo