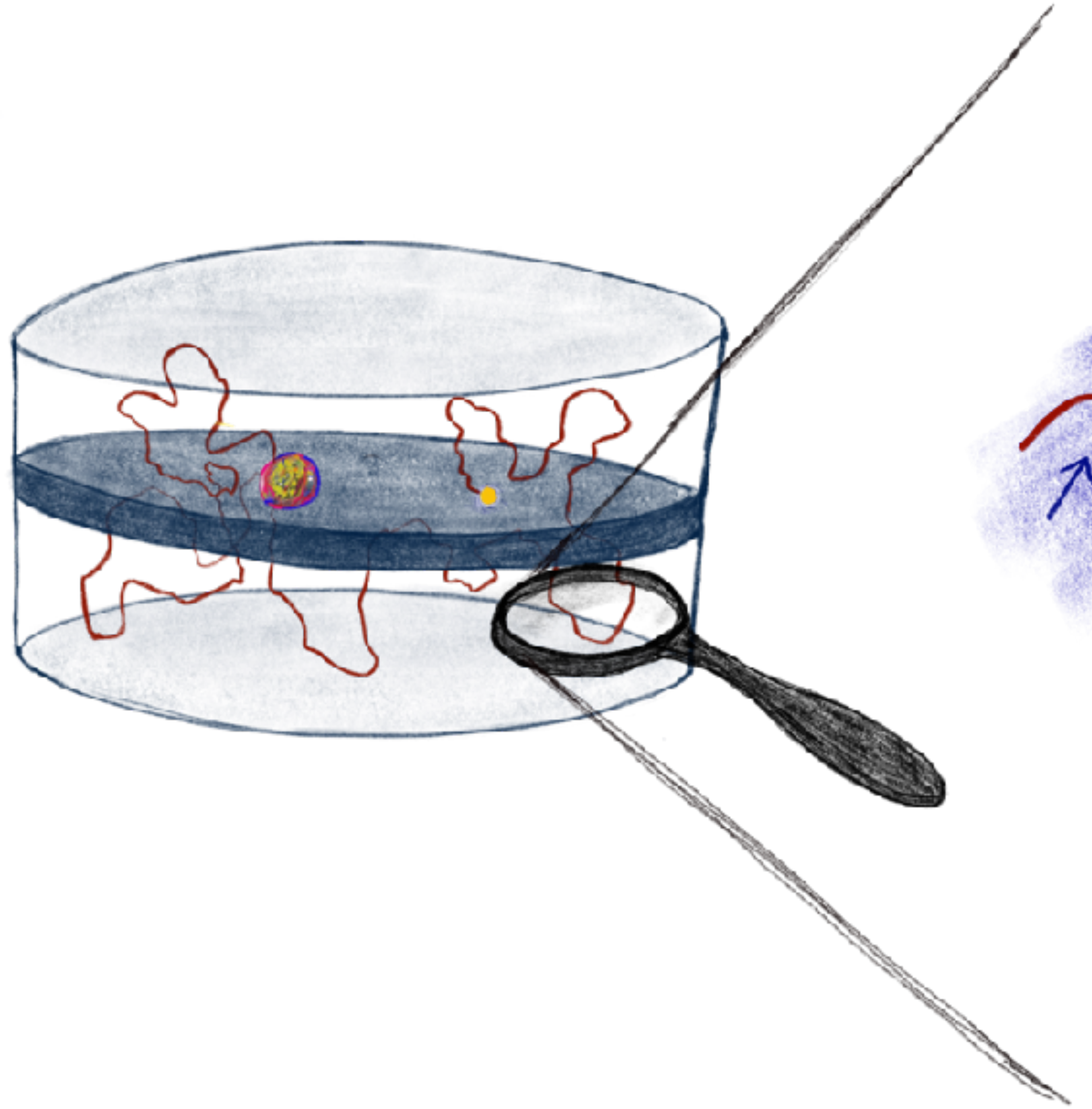
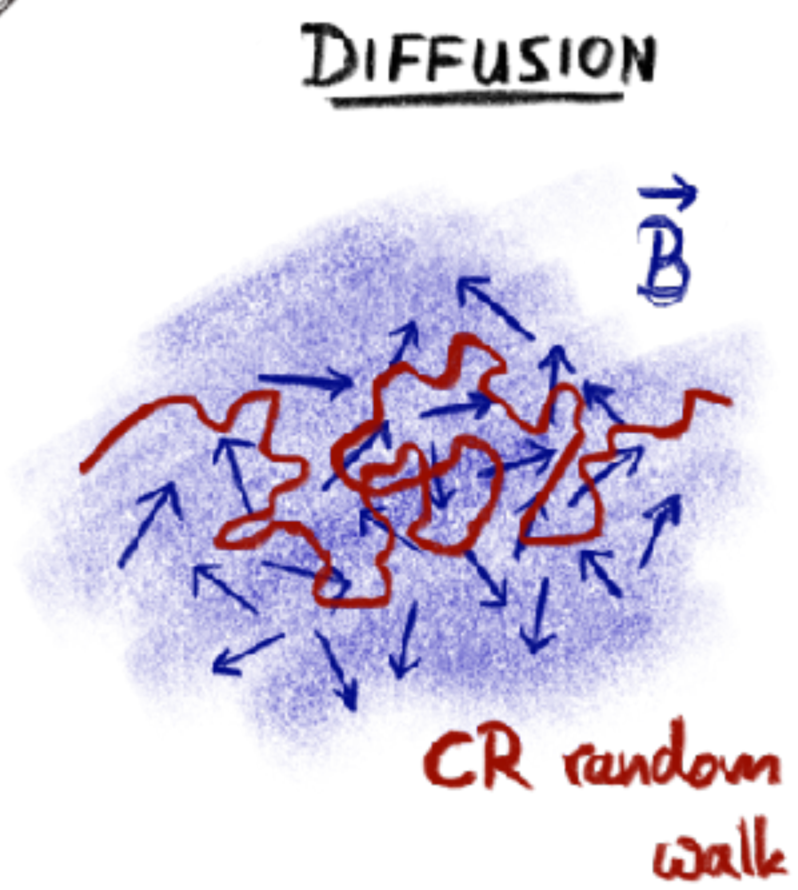
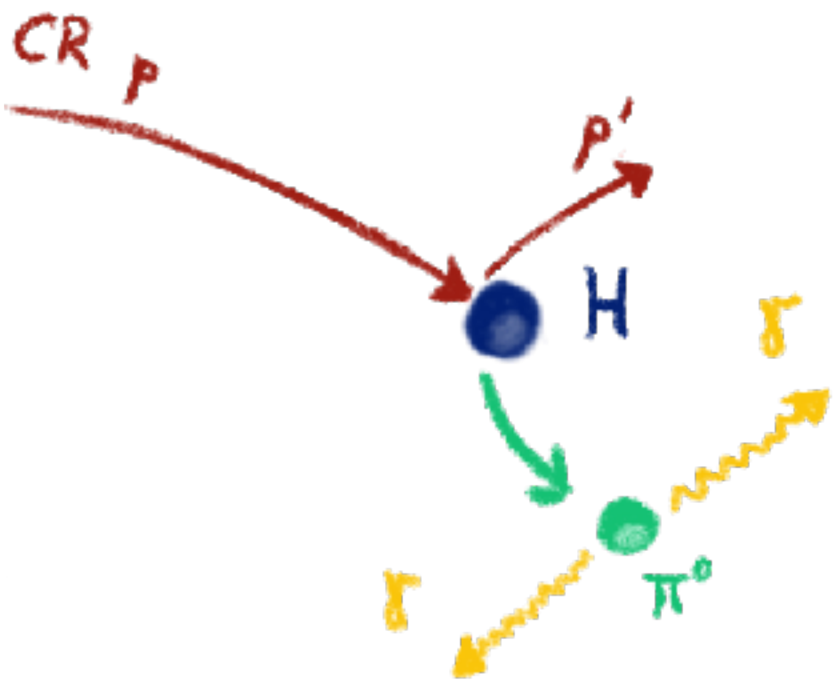
Michael Korsmeier - 2022/11/21

Oskar Klein centre

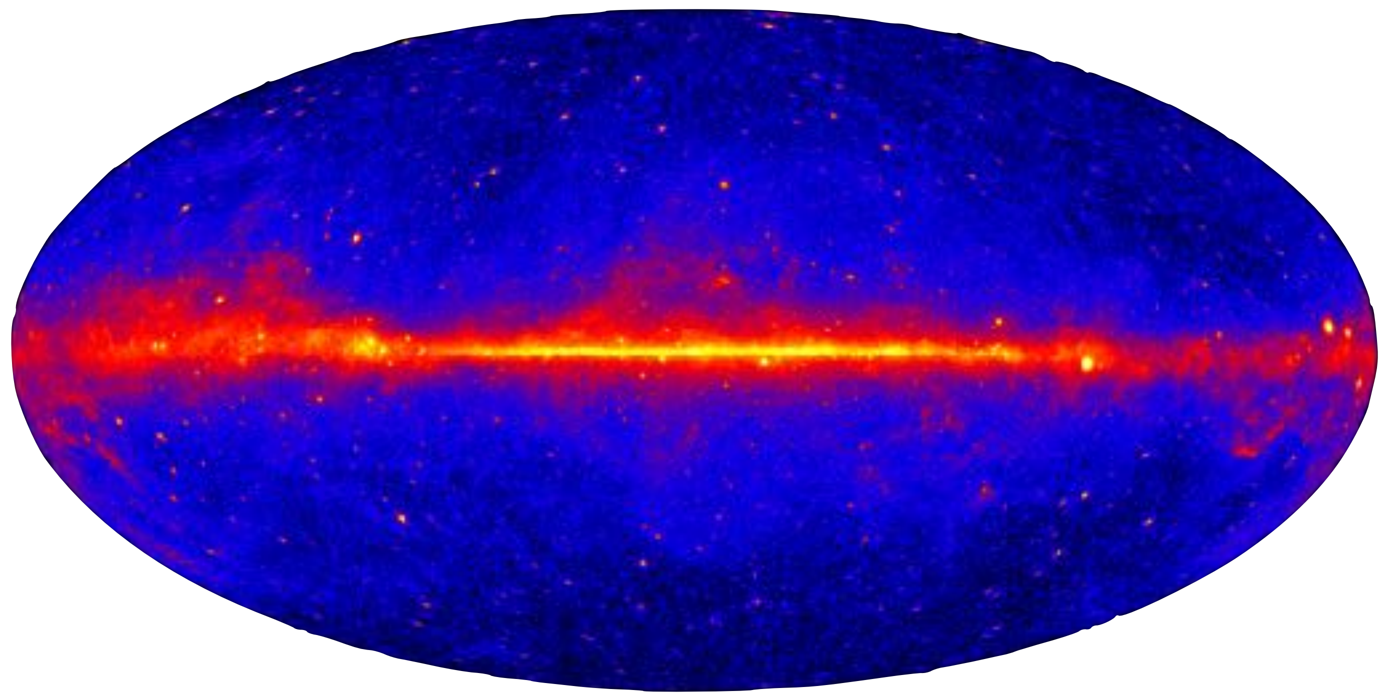
Stockholm University







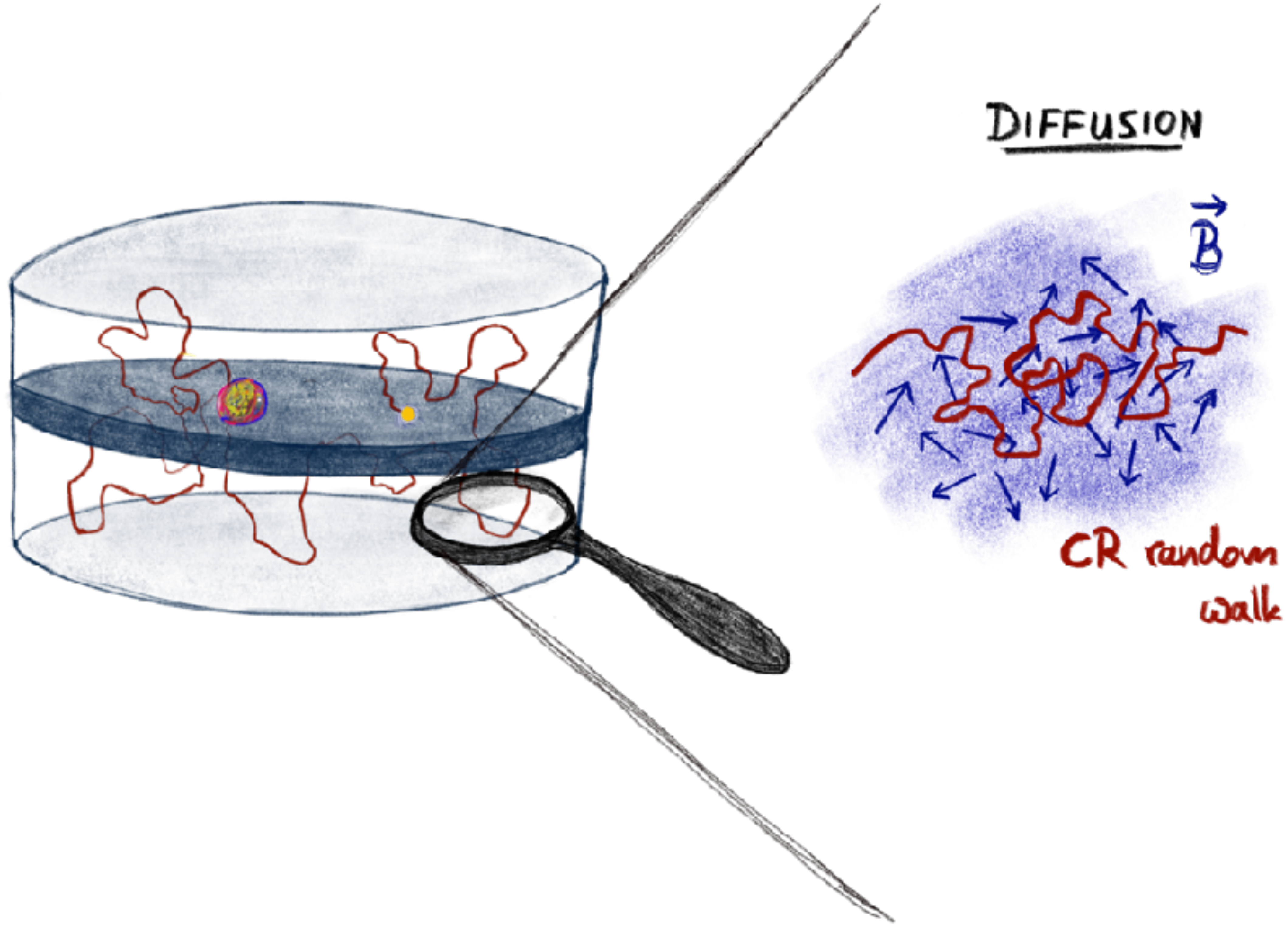
Fermi-LAT: Gamma-Ray Sky

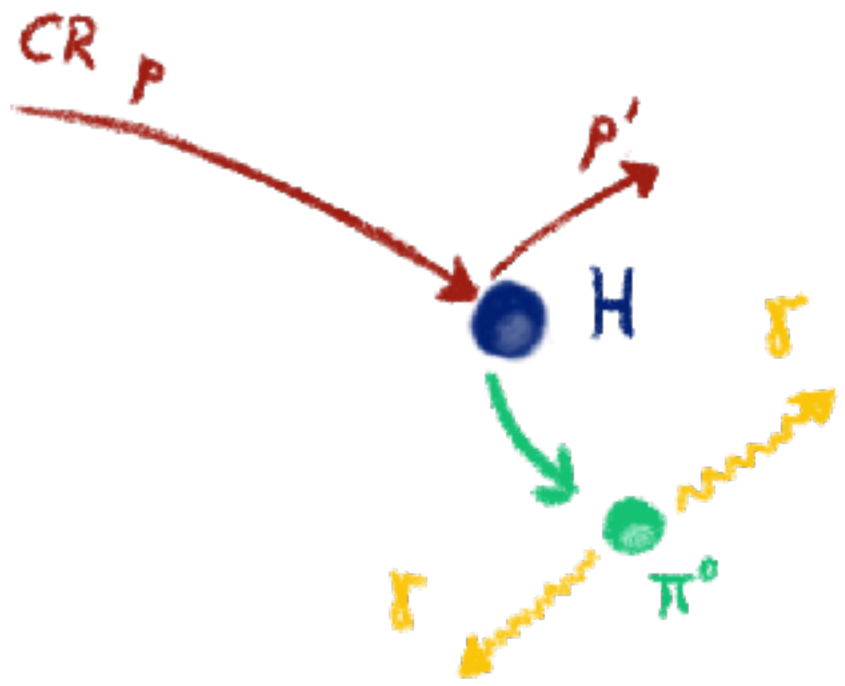


Cosmic Rays

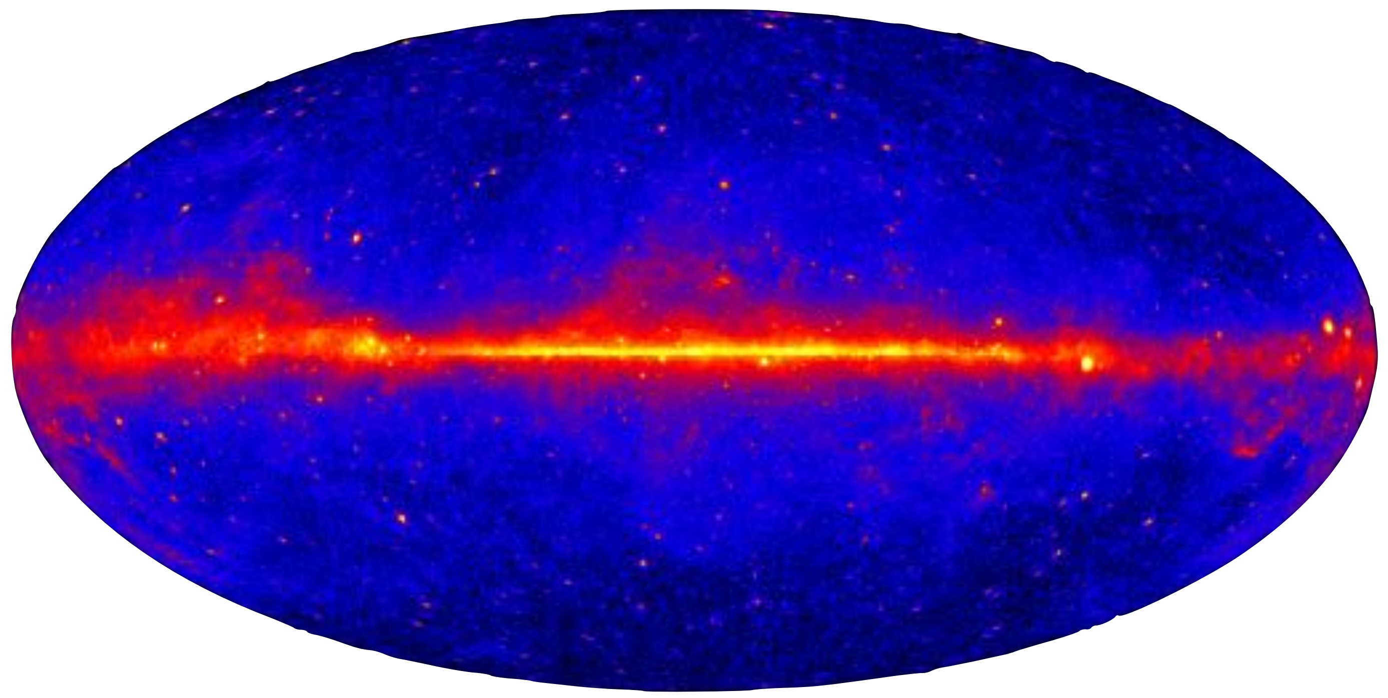
Studying our local Galactic Environment with Charged Particles

Michael Korsmeier - 2022/11/21 2022/12/05





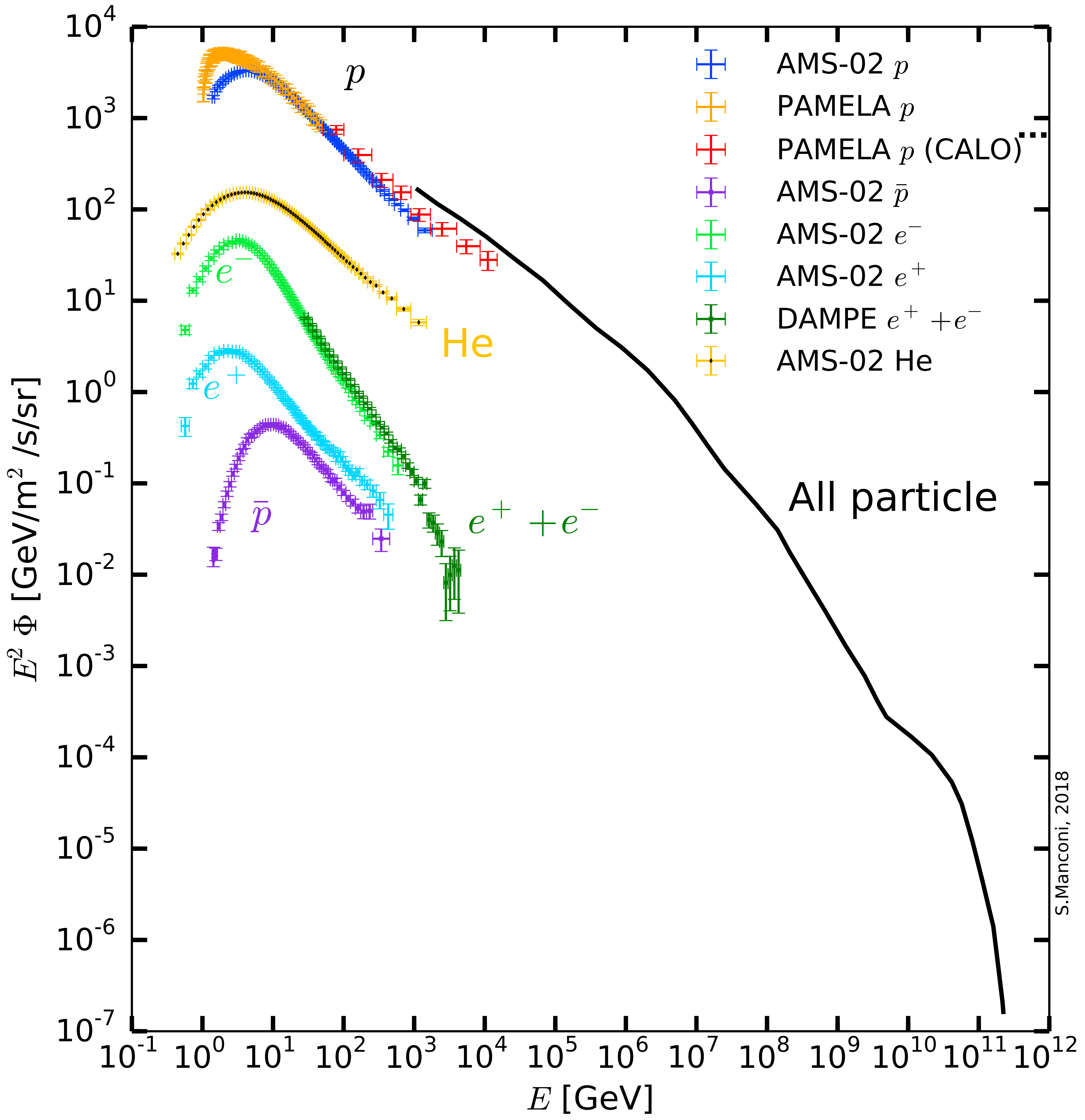
Fermi-LAT: Gamma-Ray Sky



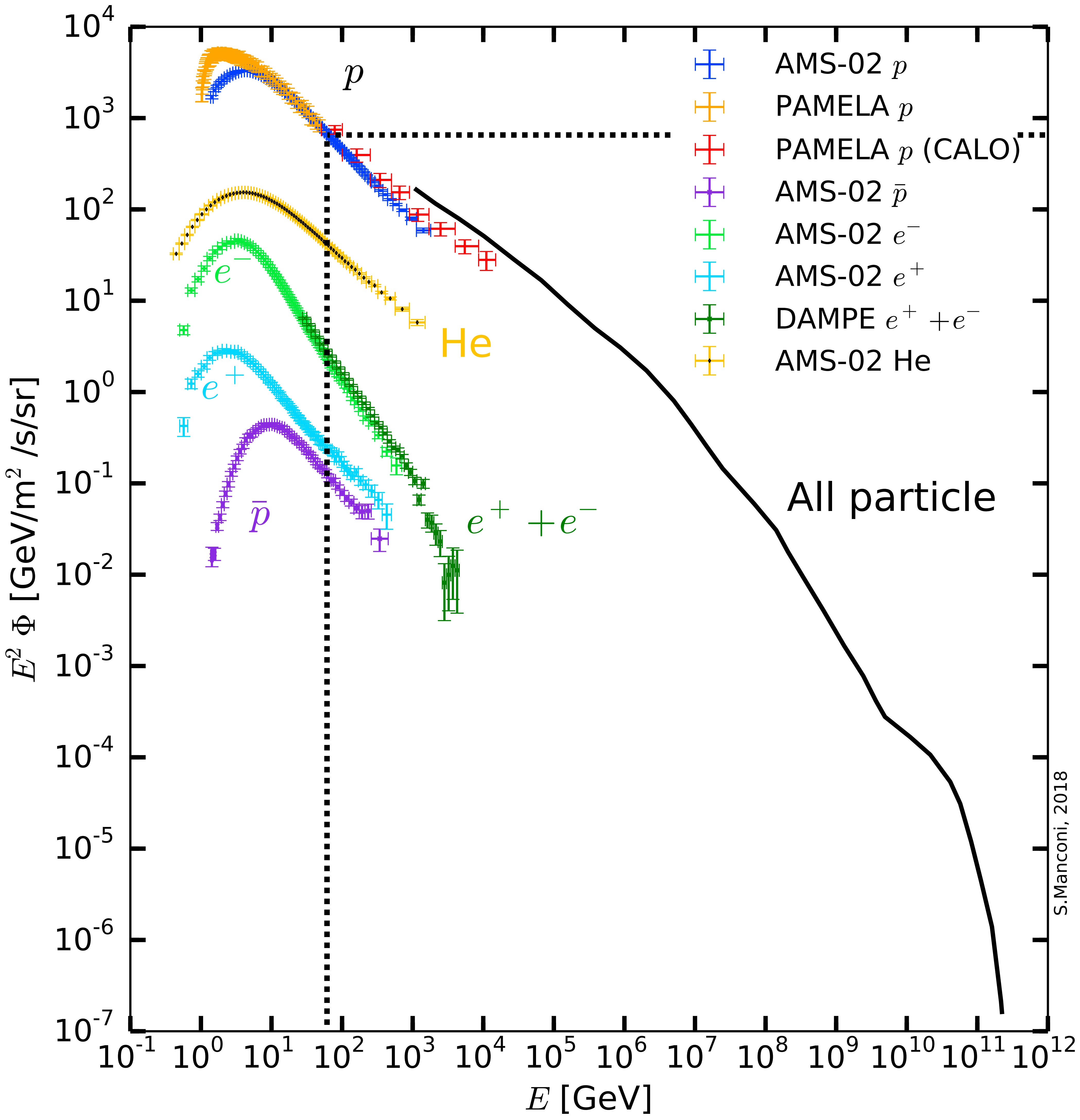
Cosmic Rays

Studying our local Galactic Environment with Charged Particles

The Cosmic-Ray Spectrum

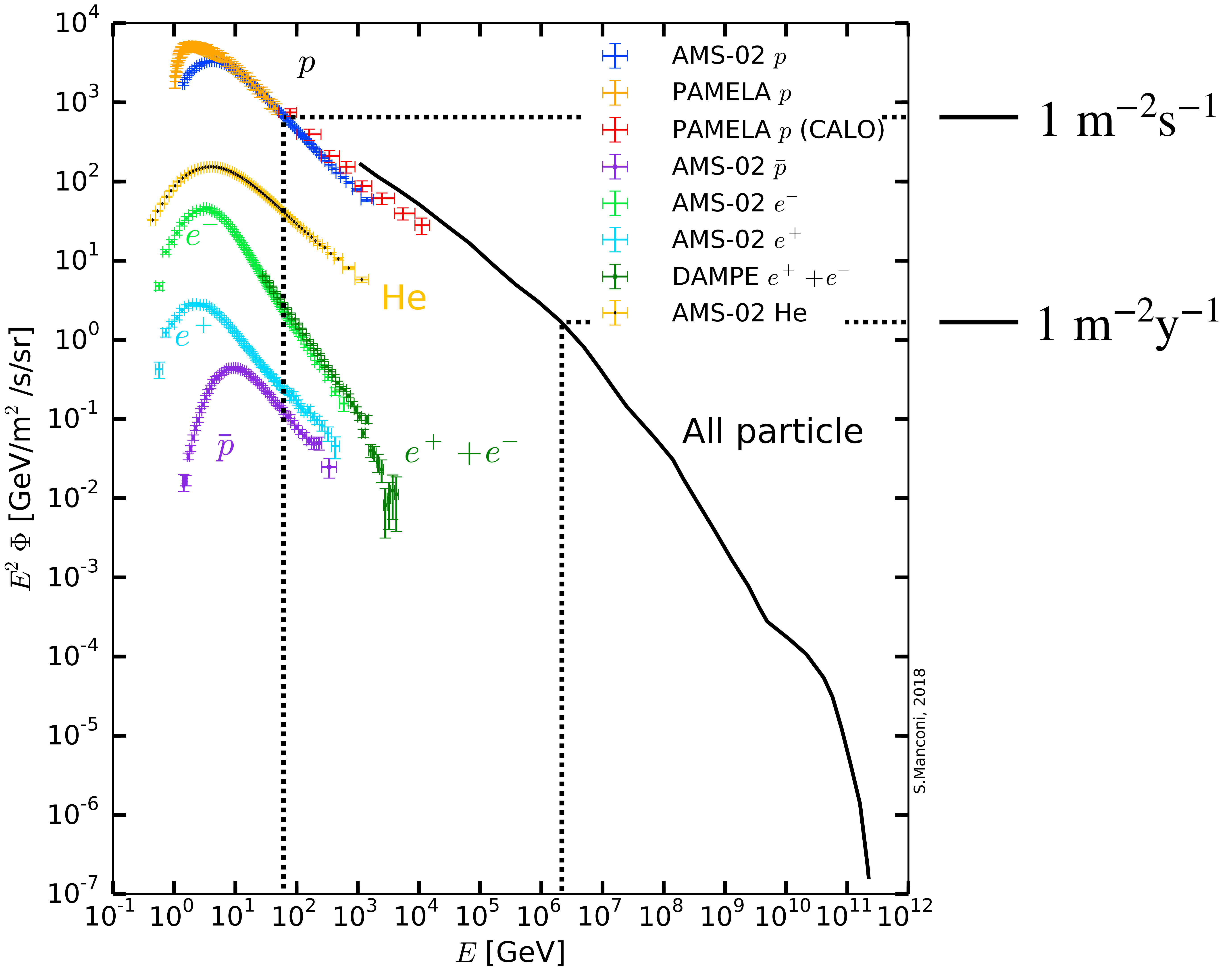


The Cosmic-Ray Spectrum

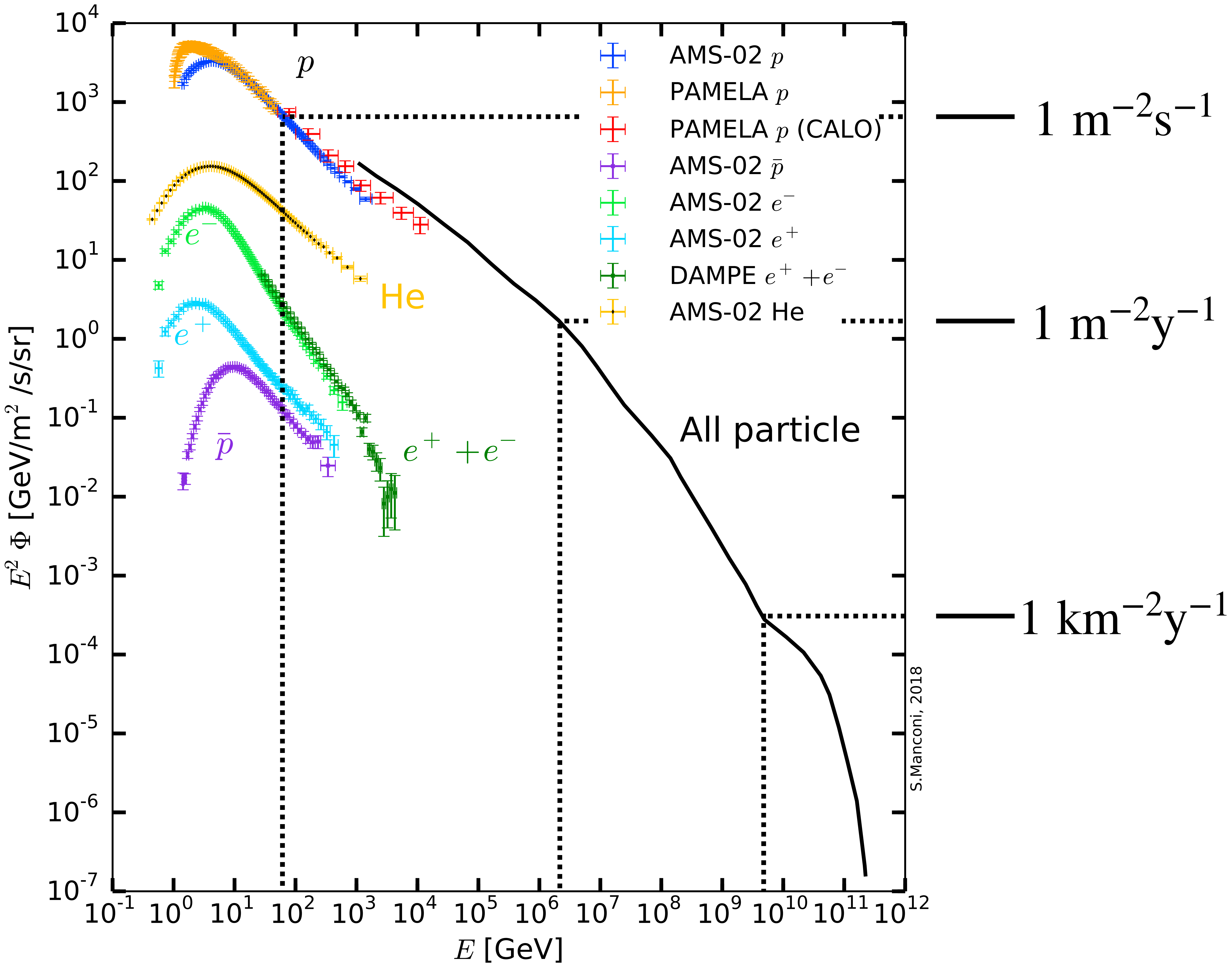


$1\ \mathrm{m}^{-2}\mathrm{s}^{-1}$

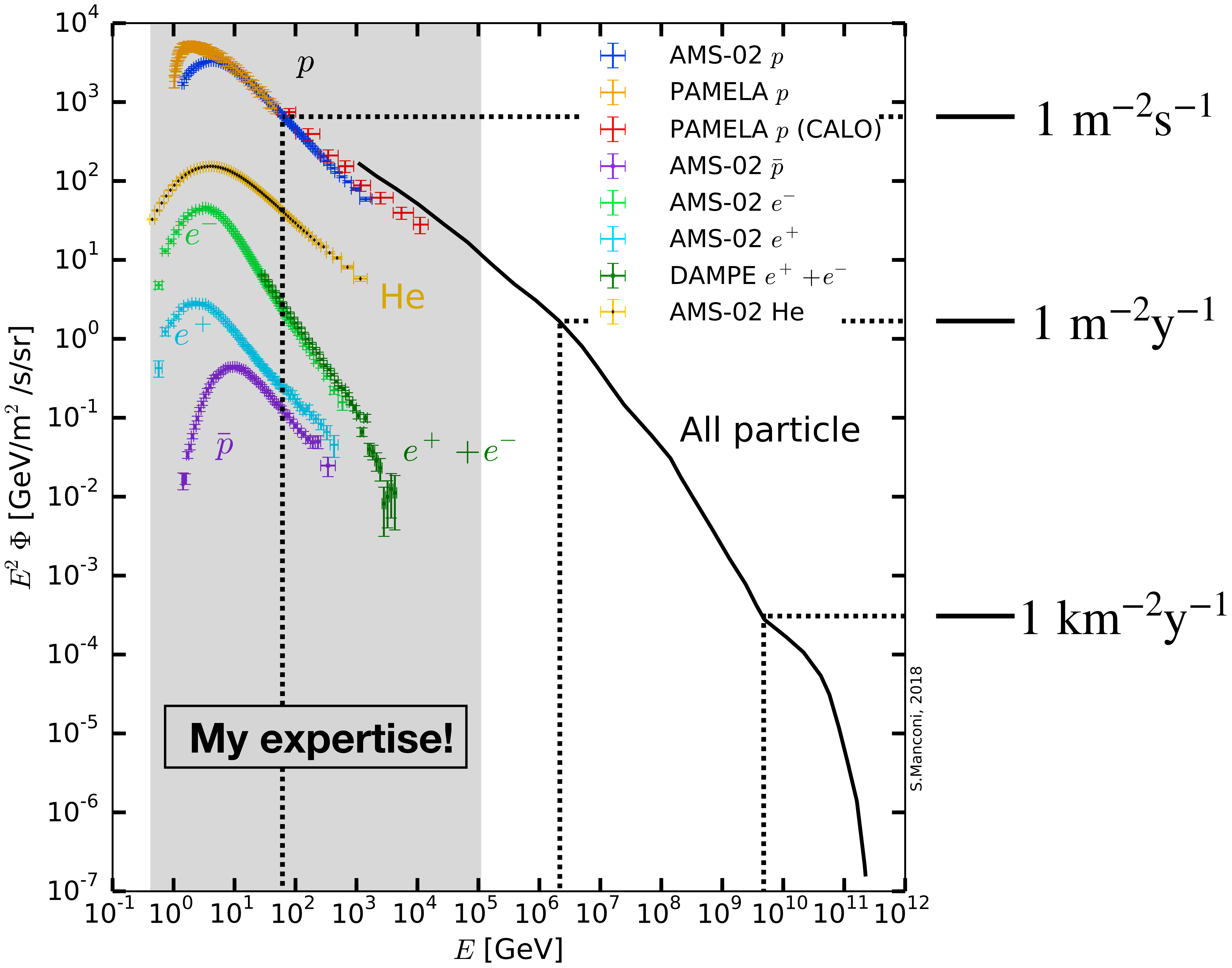
The Cosmic-Ray Spectrum



The Cosmic-Ray Spectrum

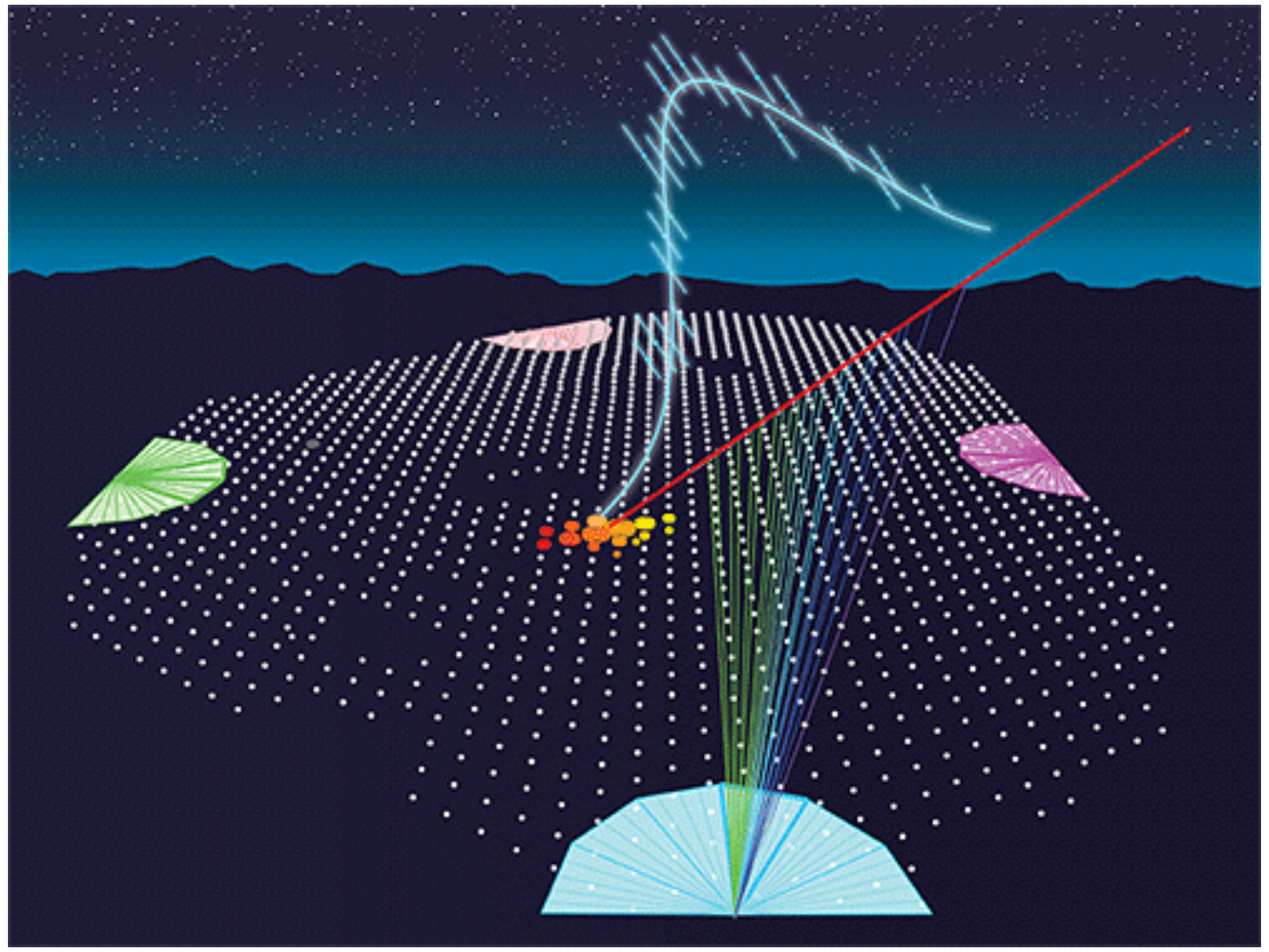


The Cosmic-Ray Spectrum



Detection Strategies Today

https://home.cern/news/news/experiments/ams-decade-cosmic-discoveries

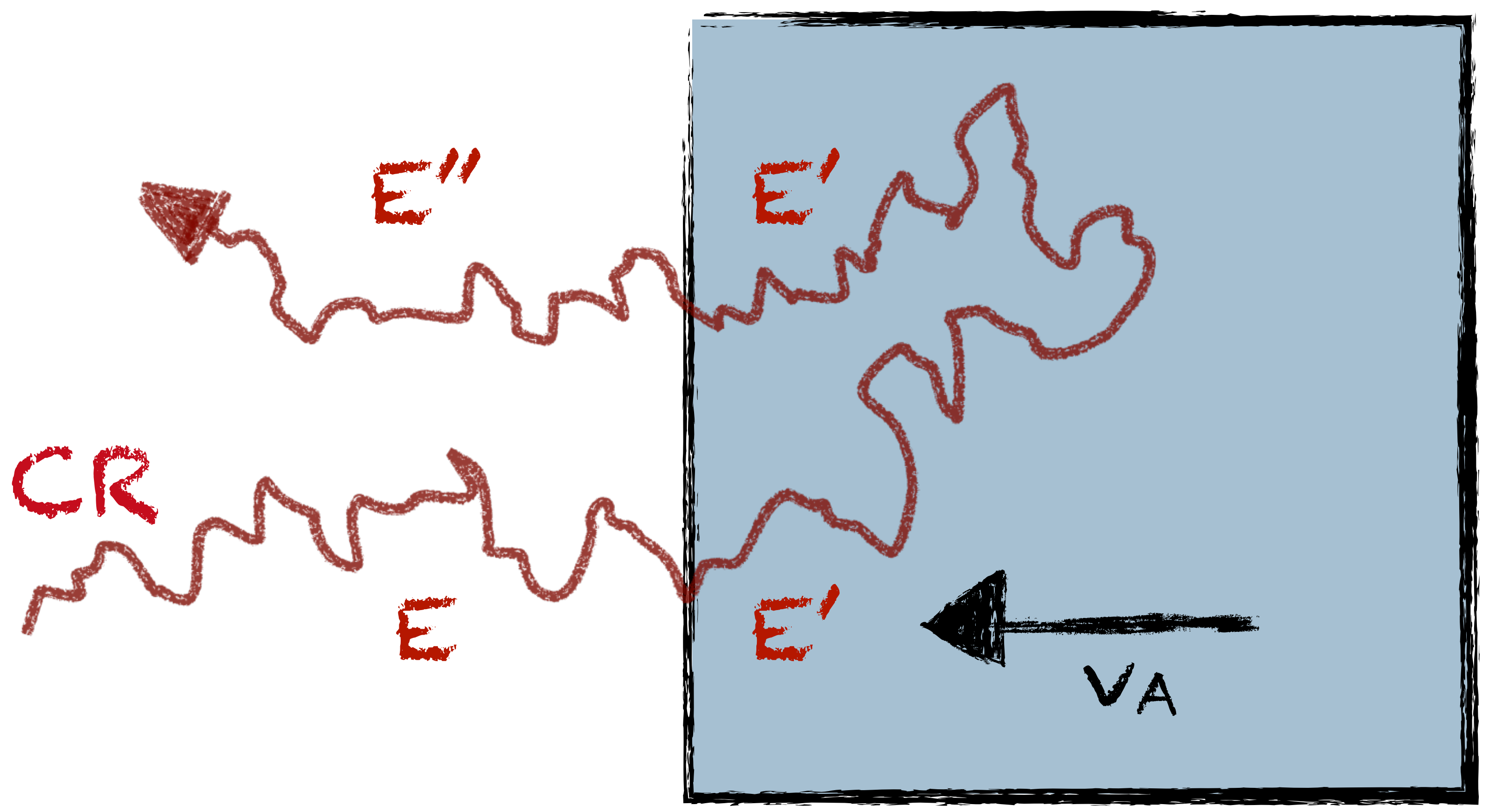


https://physics.aps.org/articles/v9/125

- Modern particle detectors in space (spectrometers, calorimeters, …)
- Individual particle identification

- Air Shower observation (water-Cherenkov detectors, fluorescence telescopes)
- Very large energies

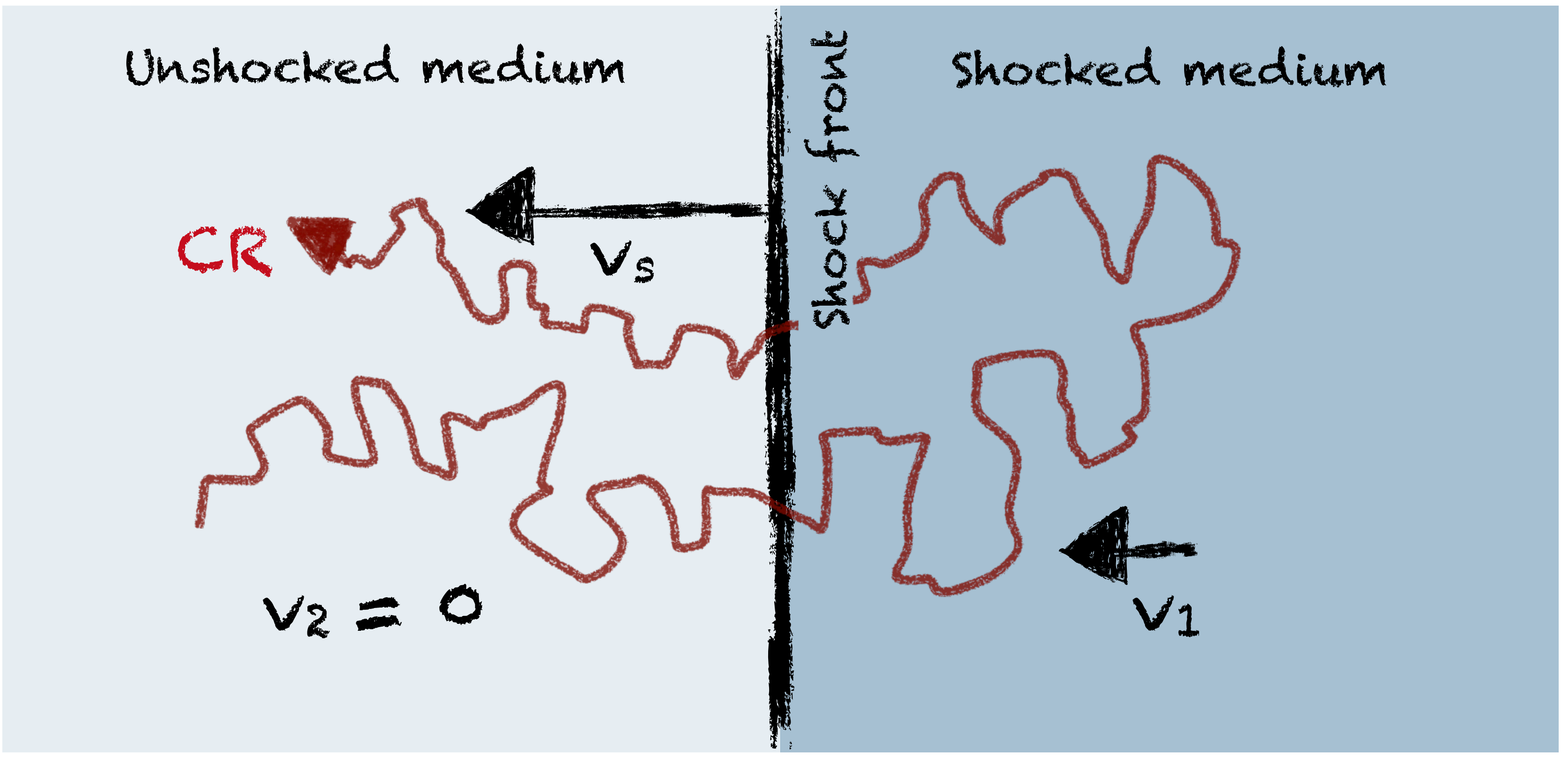
Acceleration Mechanism



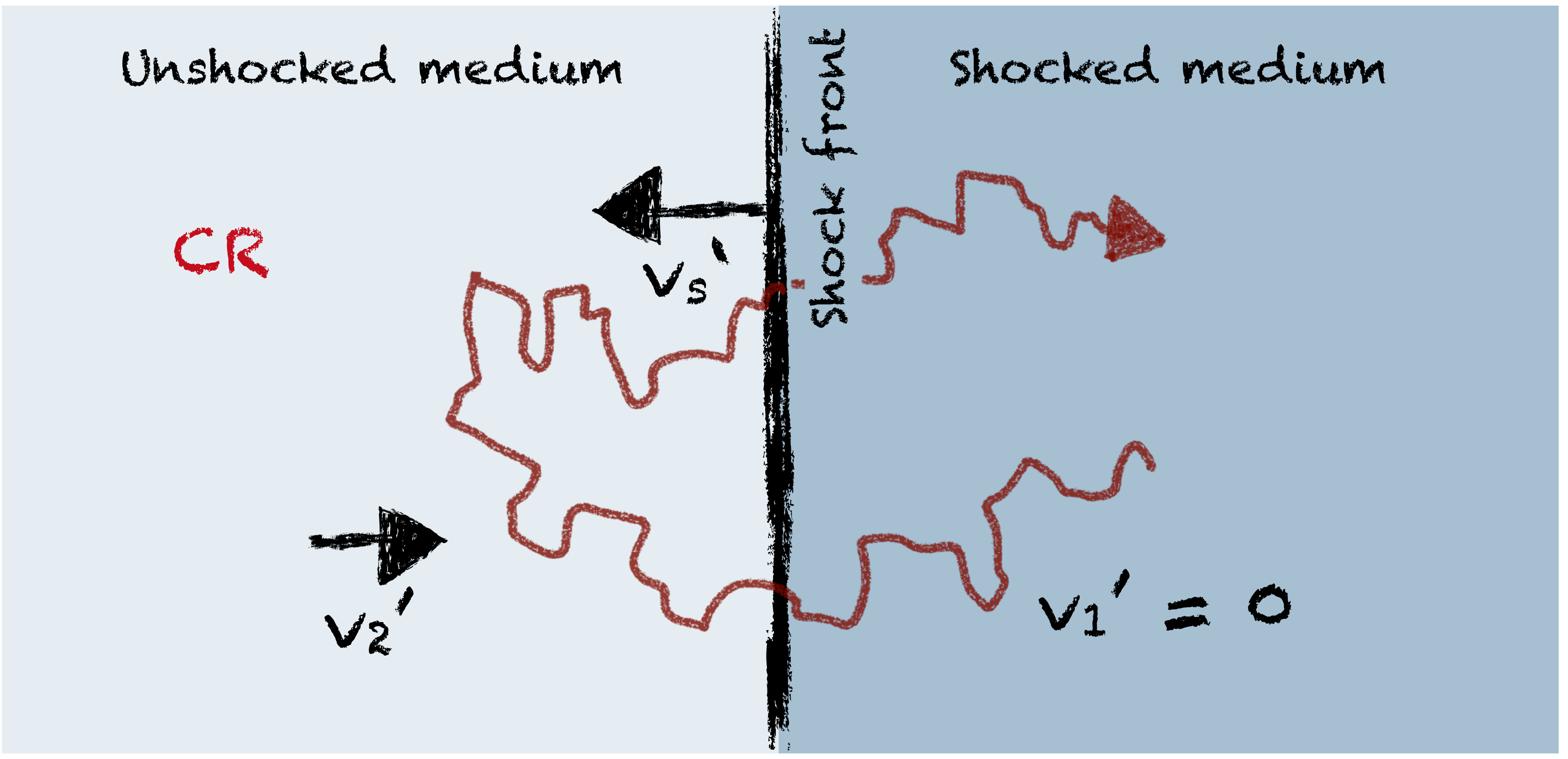
- Cosmic Rays gain energy from head-on collisions with Alfvèn waves (2nd order Fermi acceleration)
  $$\left\langle \frac{\Delta E}{E} \right\rangle \sim \beta_A^2$$ $\rightarrow$ not efficient enough

Acceleration Mechanism

Observer from the **unshocked** medium



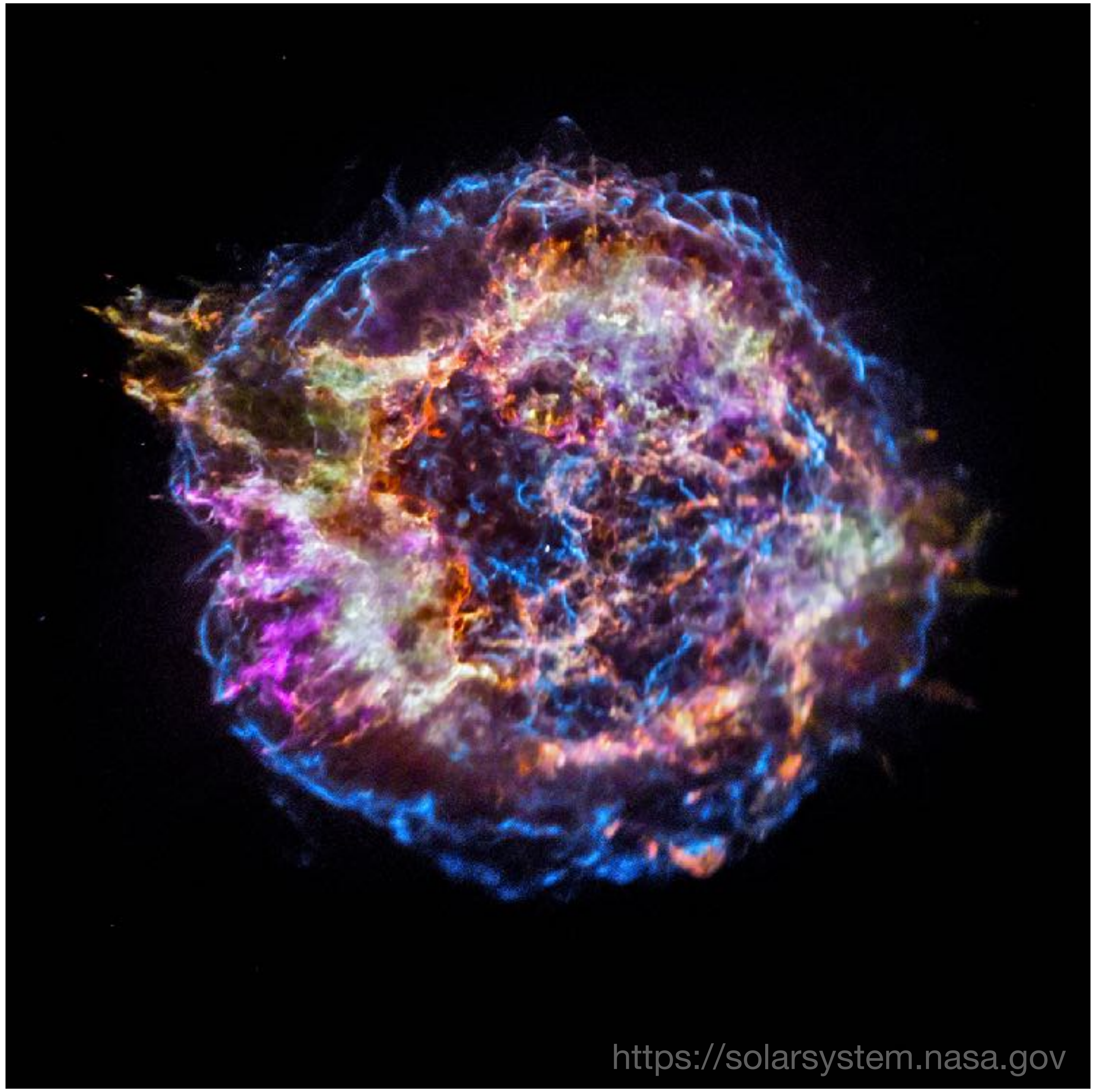
Observer from the **shocked** medium



- Cosmic Rays gain energy from head-on collisions with Alfvèn waves
(2nd order Fermi acceleration)
$$\left\langle \frac{\Delta E}{E} \right\rangle \sim \beta_A^2 \quad \rightarrow \text{ not efficient enough}$$

- At every crossing of the shock front the CR gains energy
(Fermi shock-acceleration)
$$\left\langle \frac{\Delta E}{E} \right\rangle \sim \beta \quad \rightarrow \text{ explains observations}$$

Acceleration Mechanism



- Cosmic Rays gain energy from head-on collisions with Alfvèn waves (2nd order Fermi acceleration)

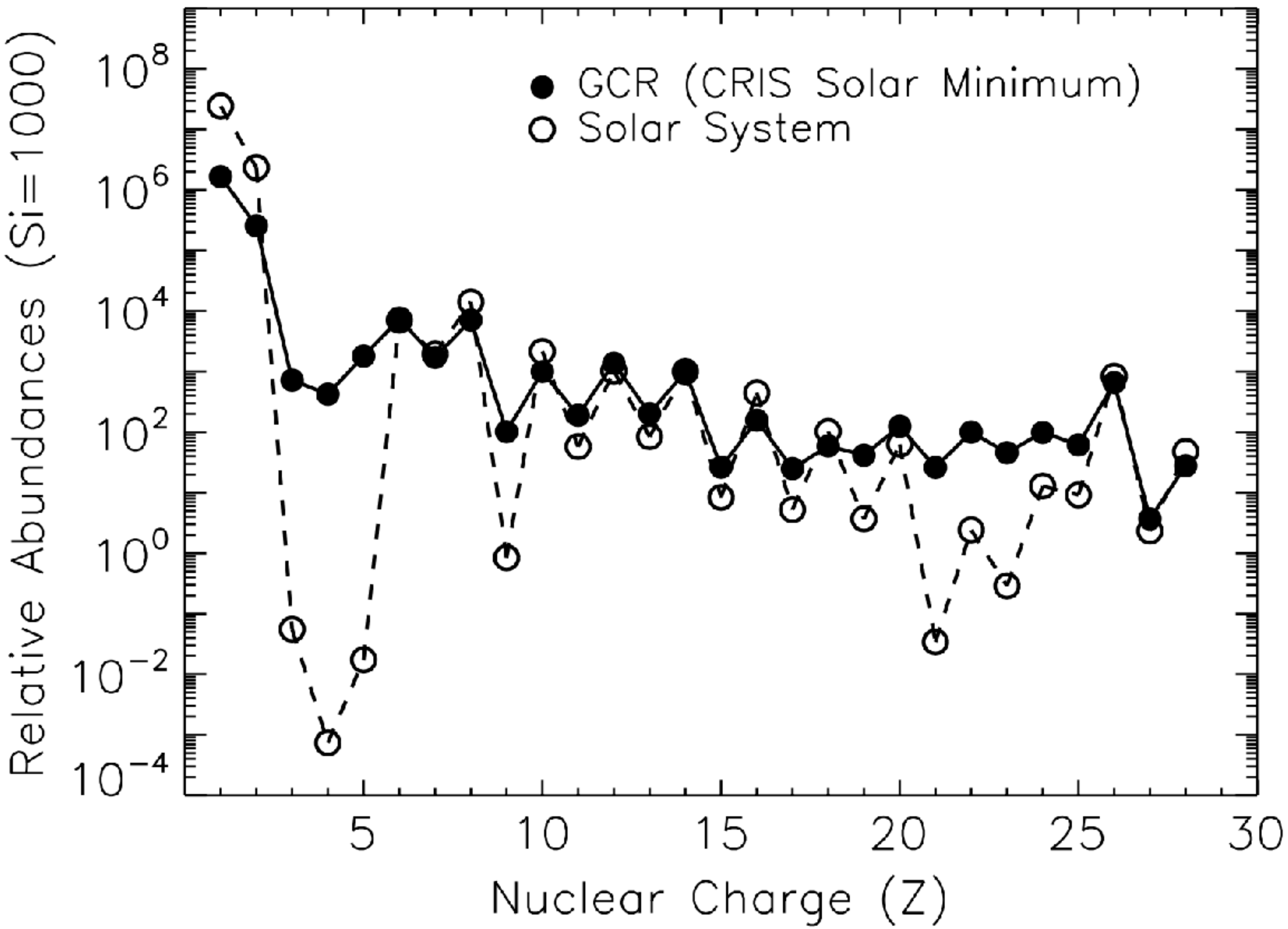
  $$\left\langle \frac{\Delta E}{E} \right\rangle \sim \beta_A^2 \qquad \rightarrow \text{not efficient enough}$$

- At every crossing of the shock front the CR gains energy (Fermi shock-acceleration)

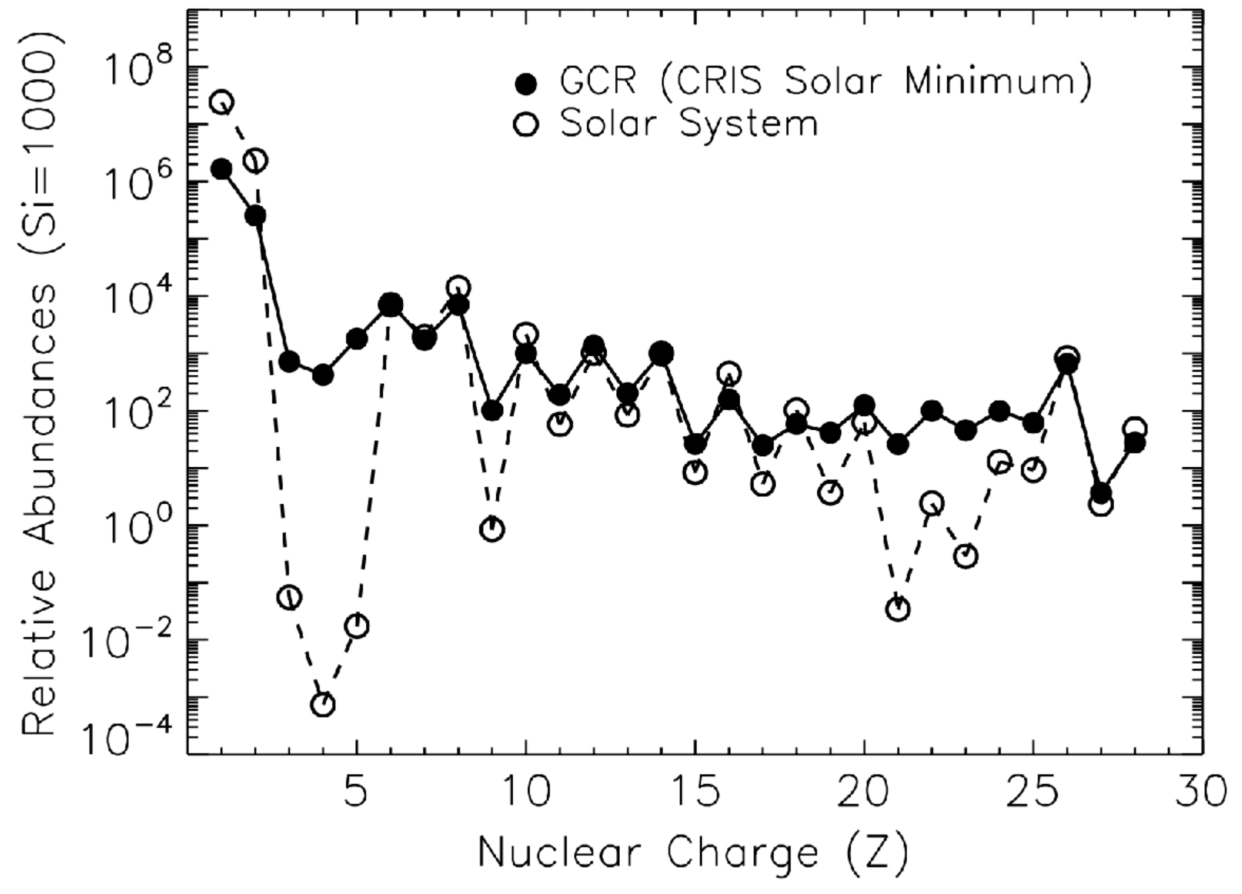
  $$\left\langle \frac{\Delta E}{E} \right\rangle \sim \beta \qquad \rightarrow \text{explains observations}$$

- Shock fronts are observed at SNRs
- CRs accelerated by SNRs are called **primaries**

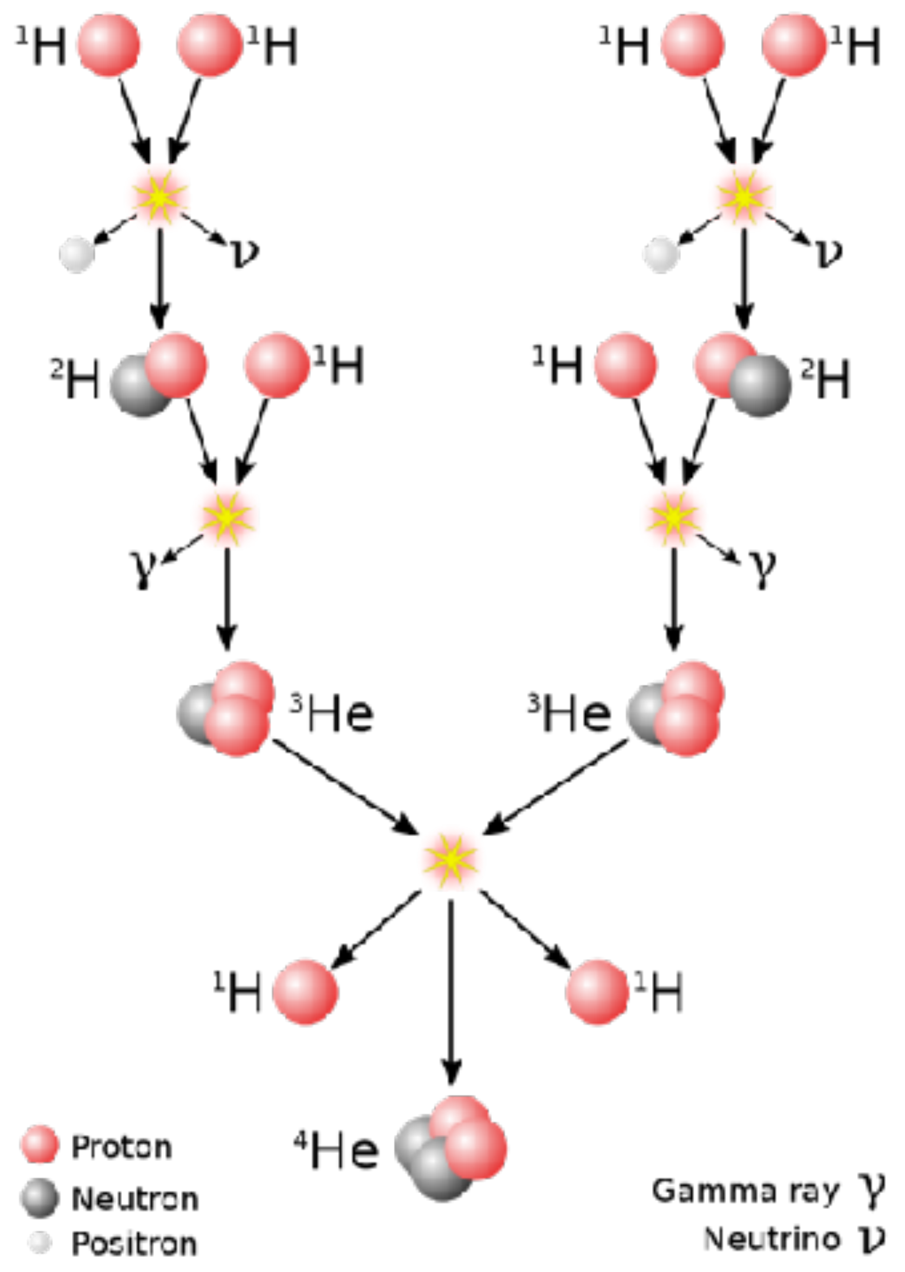
Primary and Secondary Cosmic Rays



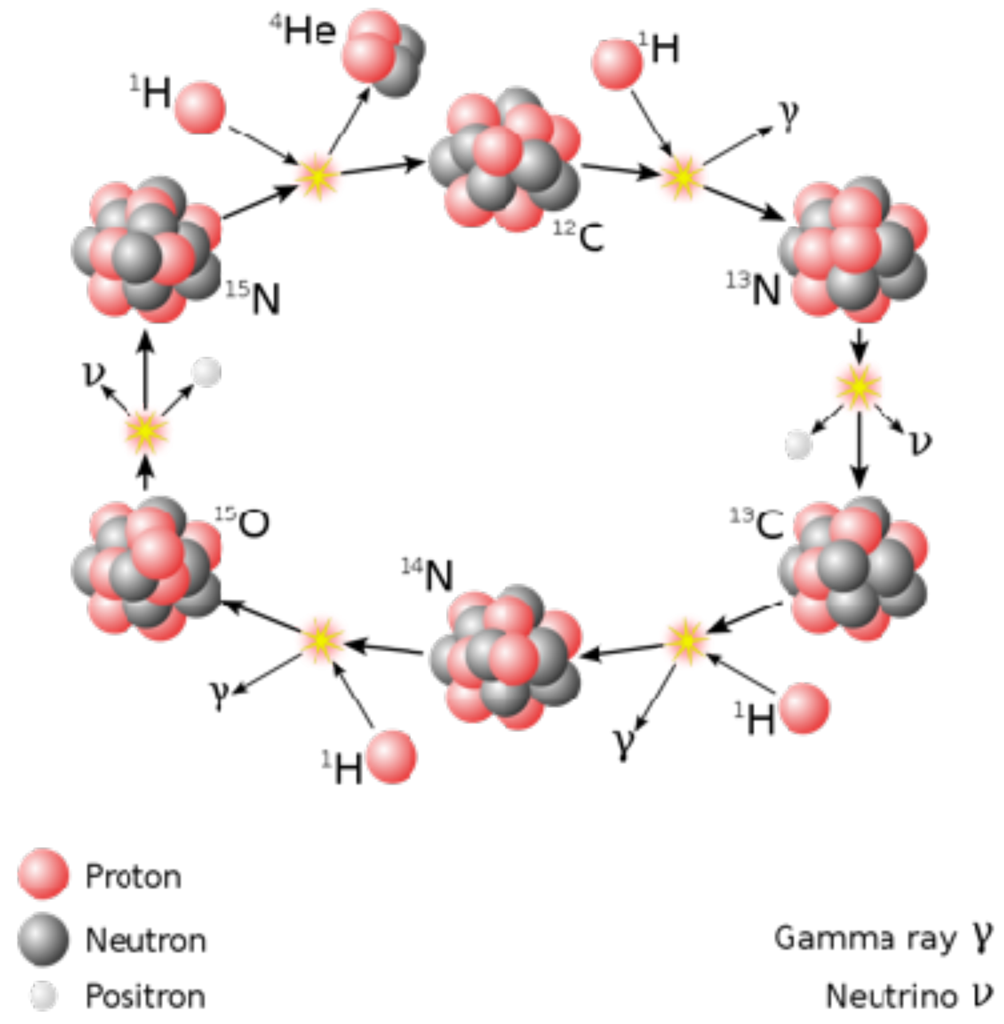
Primary and Secondary Cosmic Rays



Sun-like Stars



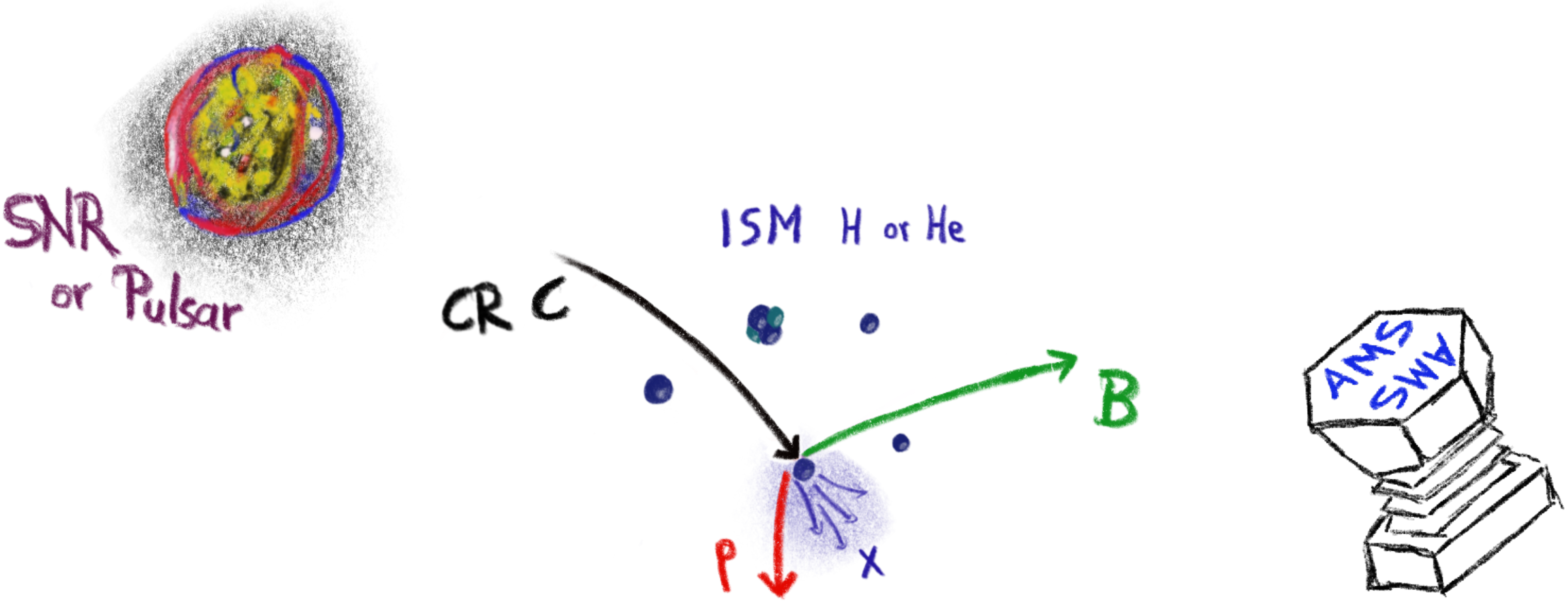
Heavier Stars



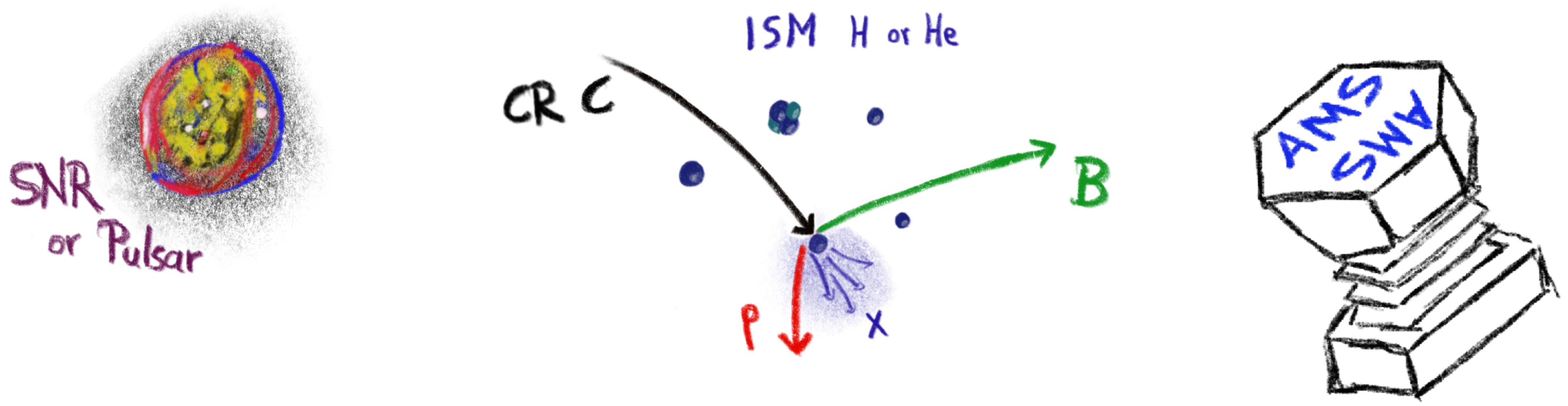
[Wikipedia]

- The **secondaries** (like Li, Be, and B) are not produced by nuclear fusion in stars
- **Secondaries** are produced during CR propagation

Gramage



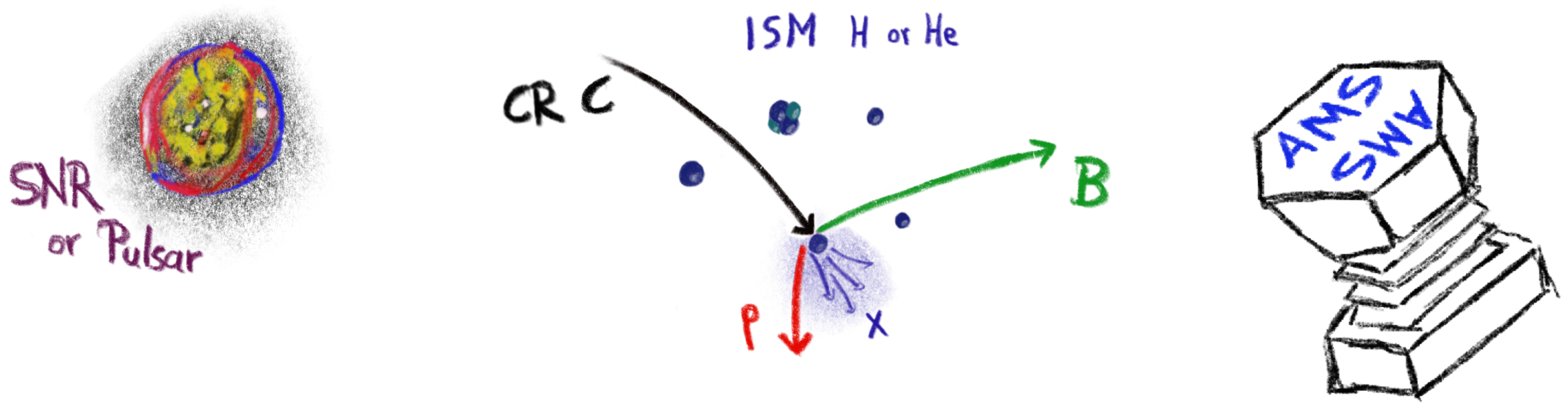
Gramage



$$\frac{dN_\mathrm{C}}{d\ell} = -\frac{N_\mathrm{C}}{\lambda_\mathrm{int}}$$

$$\frac{dN_\mathrm{B}}{d\ell} = -\frac{N_\mathrm{B}}{\lambda_\mathrm{int}} + \frac{N_\mathrm{C}}{\lambda_{\mathrm{C}\to\mathrm{B}}}$$

Gramage

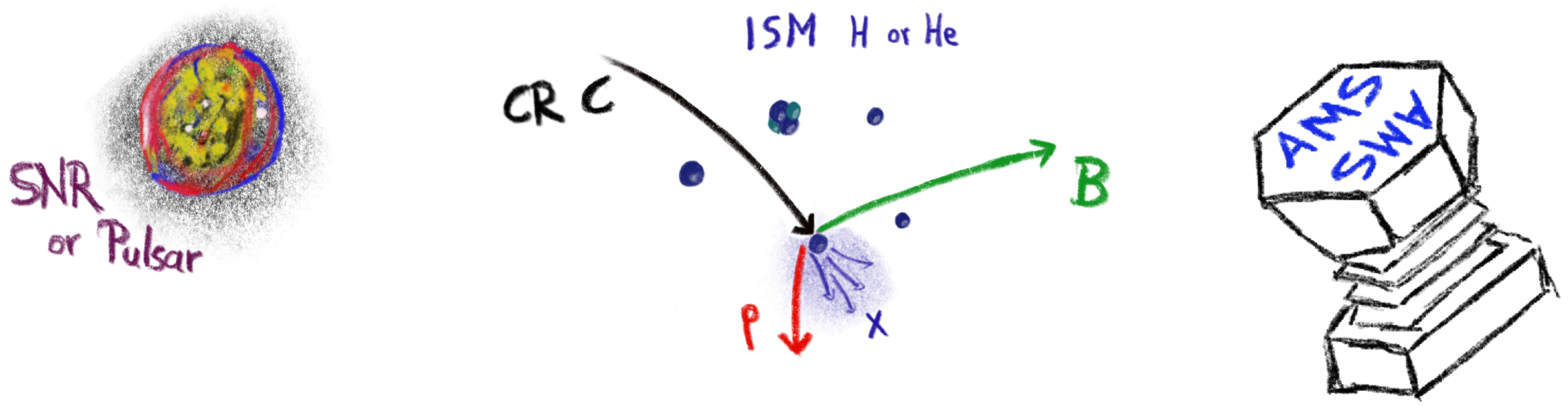


$$X = \ell \cdot \rho$$

$$\frac{dN_{\mathrm{C}}}{dX} = -\frac{\sigma_{\mathrm{inel,C}}}{m_p} N_{\mathrm{C}}$$

$$\frac{dN_{\mathrm{B}}}{dX} = -\frac{\sigma_{\mathrm{inel,B}}}{m_p} N_{\mathrm{B}} + \frac{\sigma_{\mathrm{C}\to\mathrm{B}}}{m_p} N_{\mathrm{C}}$$

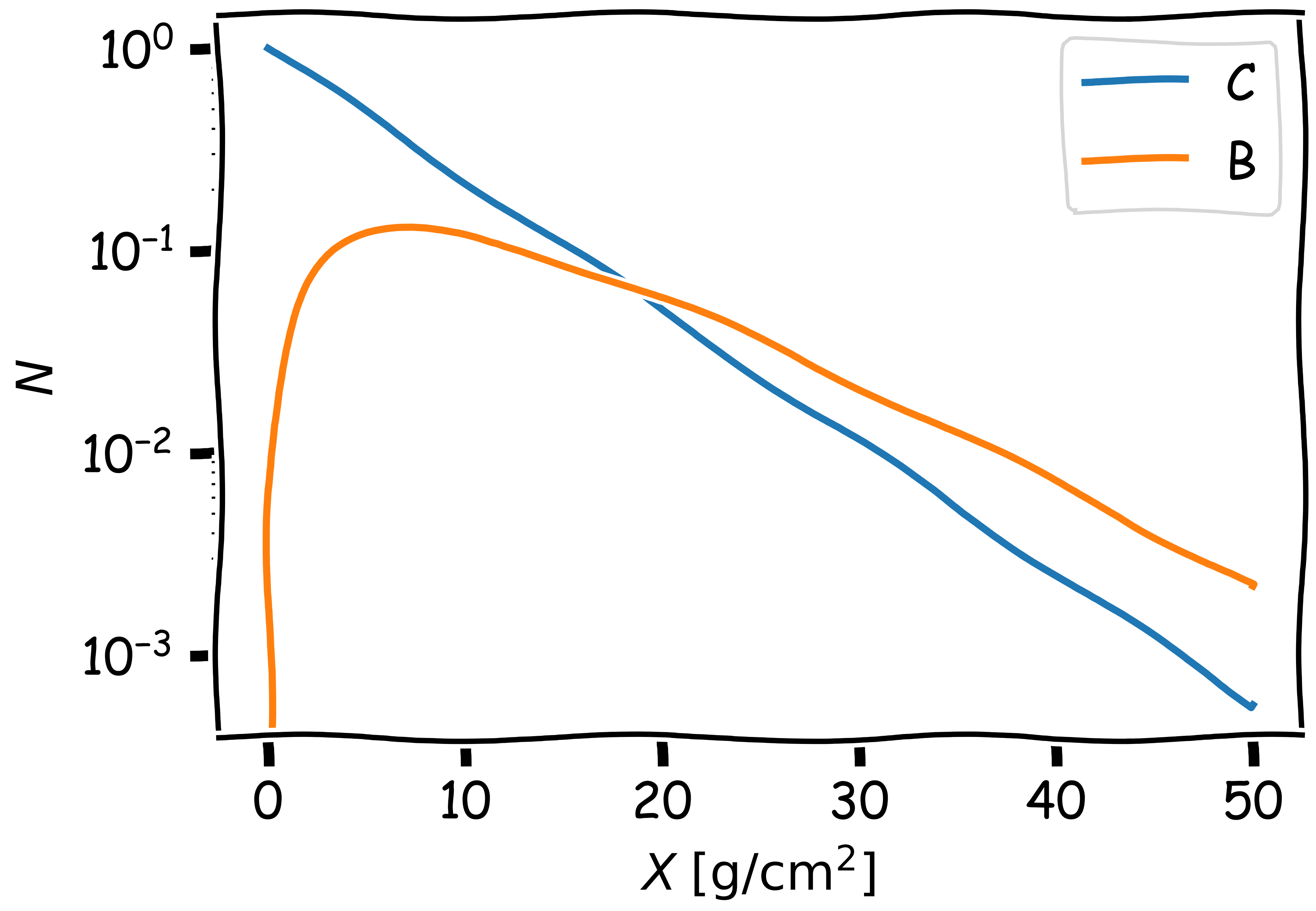
Gramage



$$X = \ell \cdot \rho$$

$$N_\mathrm{C} = N_0 \exp\left(- \frac{\sigma_\mathrm{inel,C}}{m_p} X \right)$$

$$\frac{N_\mathrm{B}}{N_\mathrm{C}} = \frac{\sigma_\mathrm{C \to B}}{\sigma_\mathrm{inel,C} - \sigma_\mathrm{inel,B}} \left[\exp\left(\frac{\sigma_\mathrm{inel,C} - \sigma_\mathrm{inel,B}}{m_p} X \right) - 1 \right]$$

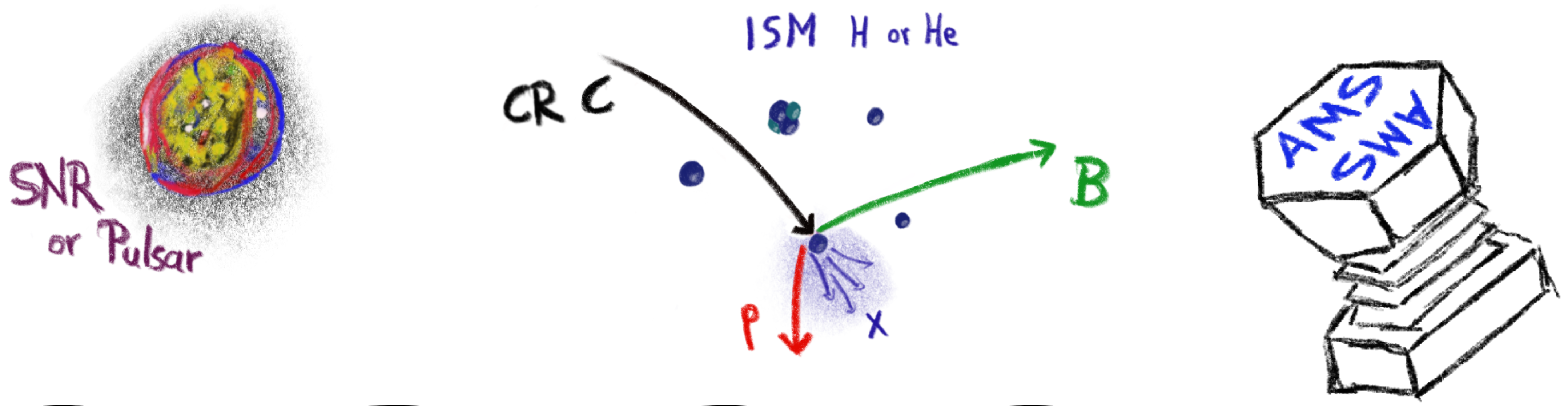


$$\sigma_\mathrm{C,inel} \sim 250 \text{ mb}$$

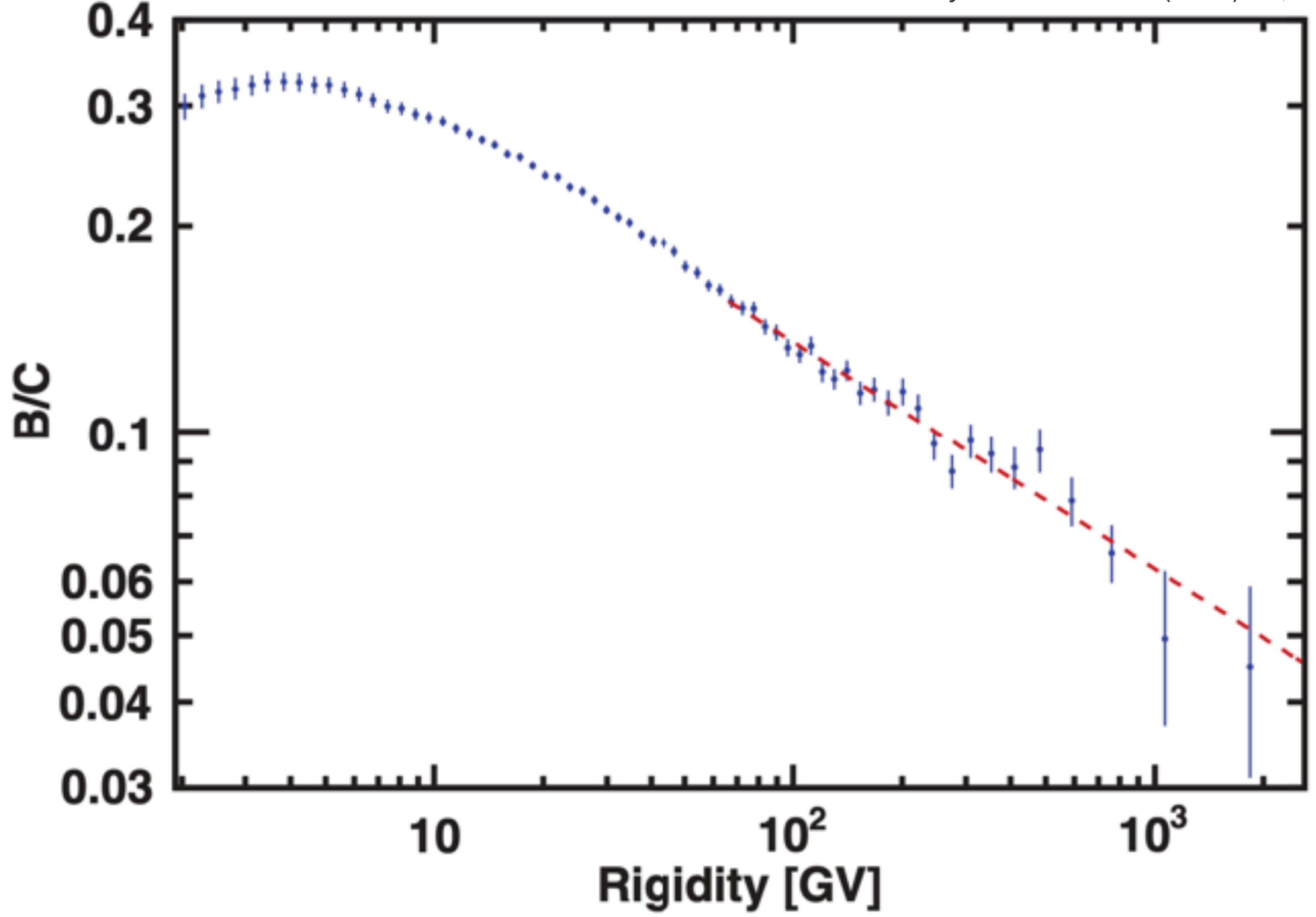
$$\sigma_\mathrm{B,inel} \sim 220 \text{ mb}$$

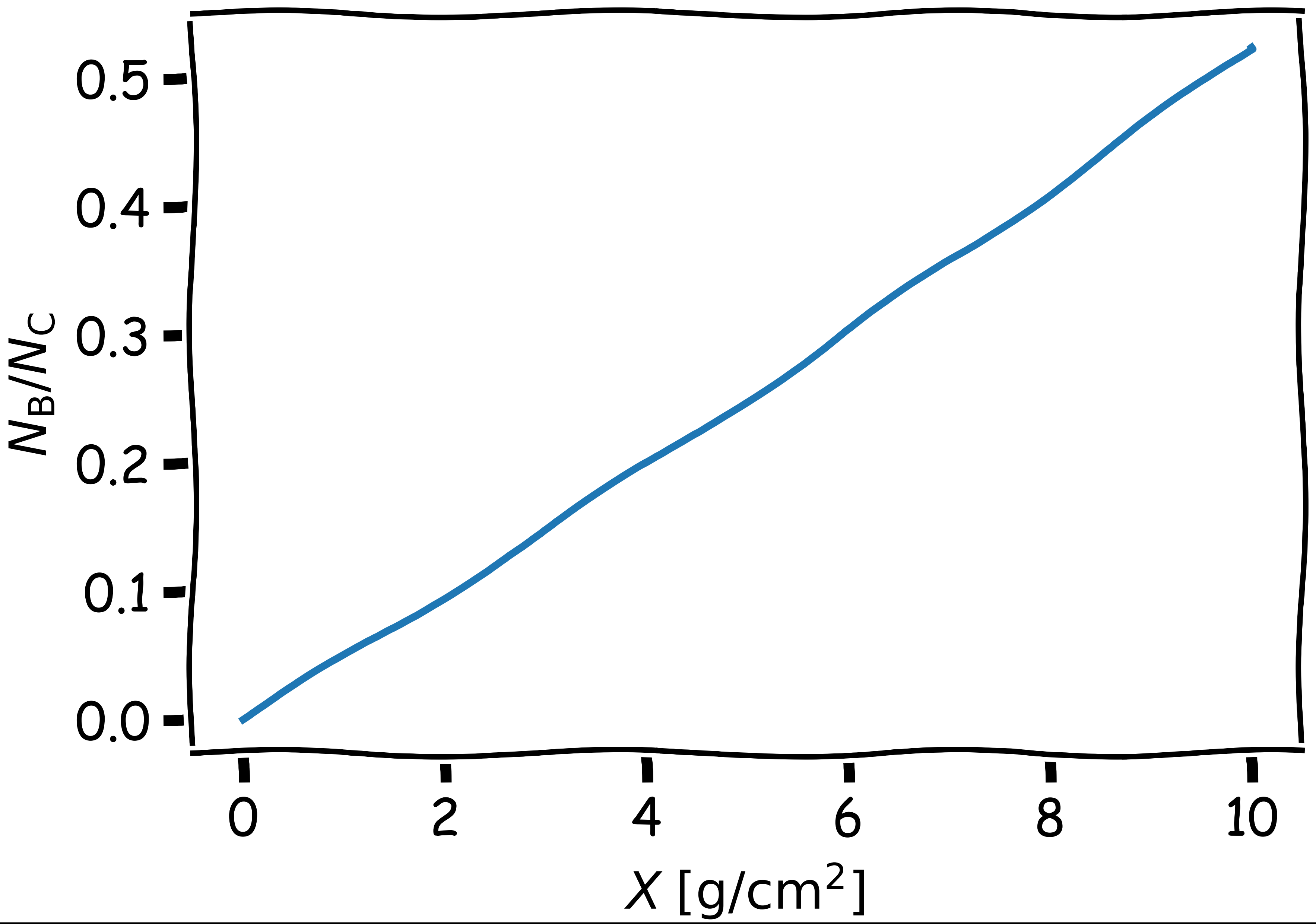
$$\sigma_\mathrm{C \to B} \sim 80 \text{ mb}$$

Gramage



Phys.Rev.Lett. 117 (2016) 23,

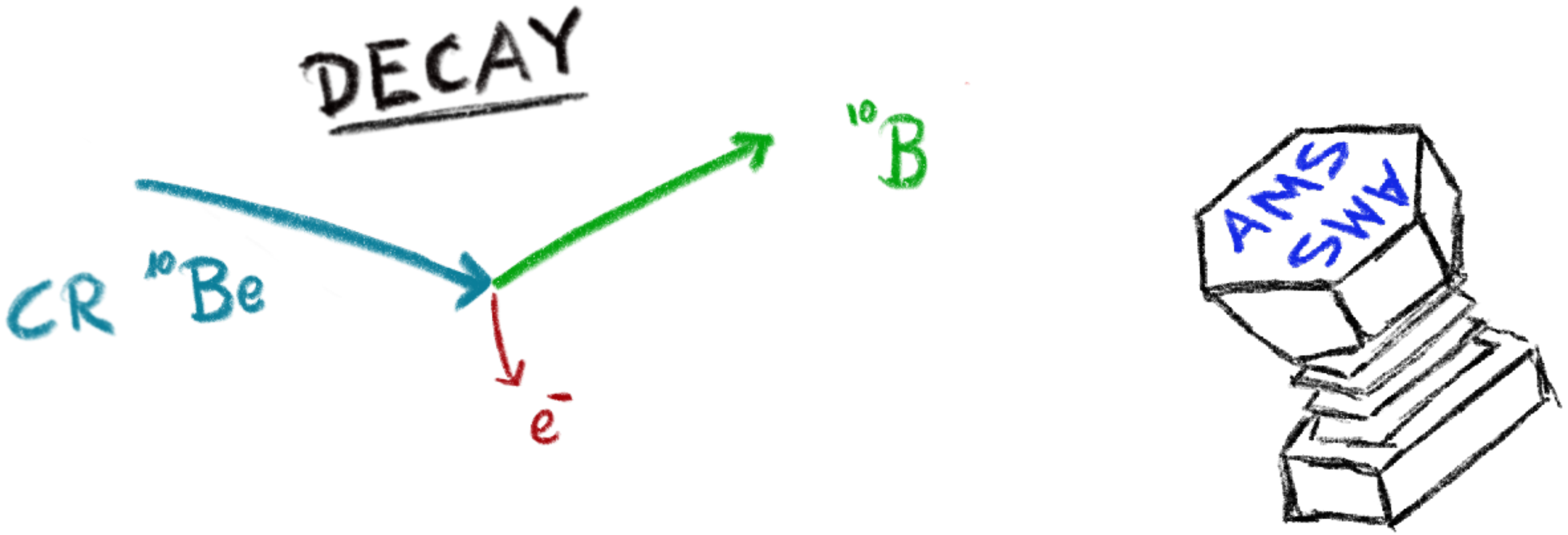




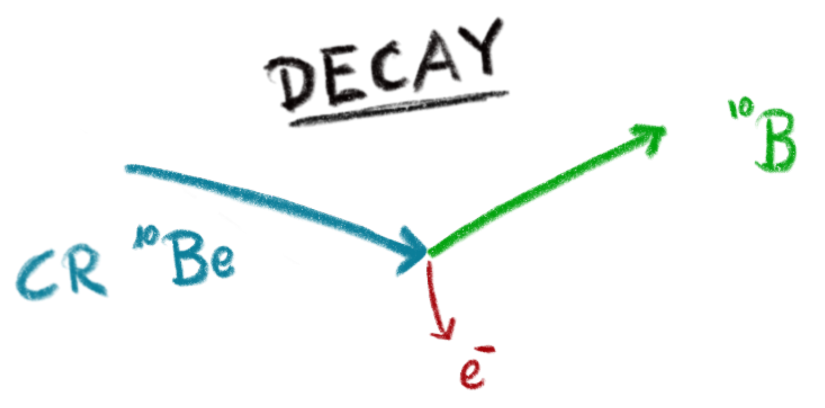
$$B/C \sim 0.3 \qquad\qquad (\text{at } 10\,\text{GV})$$
$$X_{10\,\text{GeV}} \sim 6 \text{ g/cm}^2$$
$$X_{\text{Galactic disc}} \sim 2 \times 10^{-3} \text{ g/cm}^2$$

CRs traverse the Galactic disc for a few thousand times → diffusion!

Cosmic-Ray Clocks



Cosmic-Ray Clocks

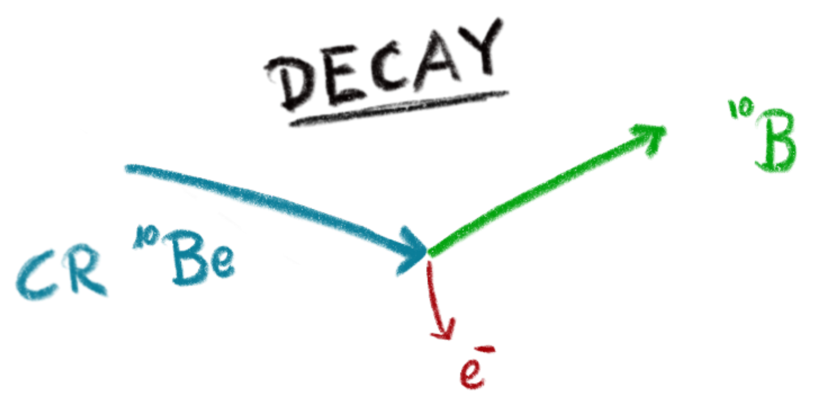


The Leaky Box Model

$$\frac{dN_{^9\mathrm{Be}}}{dt} = -\frac{N_{^9\mathrm{Be}}}{t_{\mathrm{esc}}} - \frac{N_{^9\mathrm{Be}}}{t_{\mathrm{int},9}} + Q_9$$

$$\frac{dN_{^{10}\mathrm{Be}}}{dt} = -\frac{N_{^{10}\mathrm{Be}}}{t_{\mathrm{esc}}} - \frac{N_{^{10}\mathrm{Be}}}{t_{\mathrm{int},10}} - \frac{N_{^{10}\mathrm{Be}}}{t_{\mathrm{dec},10}} + Q_{10}$$

Cosmic-Ray Clocks

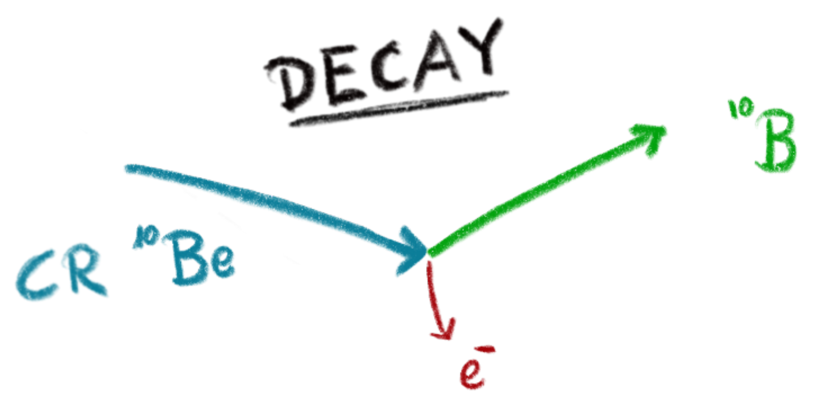


The Leaky Box Model

$$0 = -\frac{N_{^9\mathrm{Be}}}{t_{\mathrm{esc}}} - \frac{N_{^9\mathrm{Be}}}{t_{\mathrm{int},9}} + \frac{N_{\mathrm{CNO}}}{t_{\mathrm{CNO}\to{}^9\mathrm{Be}}}$$

$$0 = -\frac{N_{^{10}\mathrm{Be}}}{t_{\mathrm{esc}}} - \frac{N_{^{10}\mathrm{Be}}}{t_{\mathrm{int},10}} - \frac{N_{^{10}\mathrm{Be}}}{t_{\mathrm{dec},10}} + \frac{N_{\mathrm{CNO}}}{t_{\mathrm{CNO}\to{}^{10}\mathrm{Be}}}$$

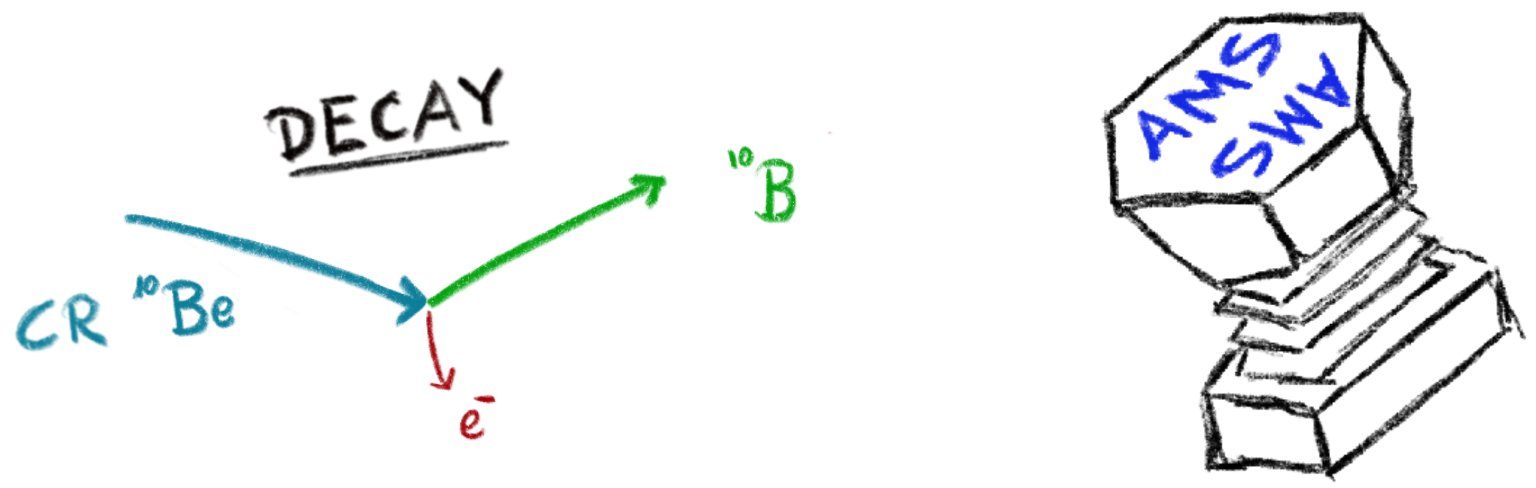
Cosmic-Ray Clocks



The Leaky Box Model

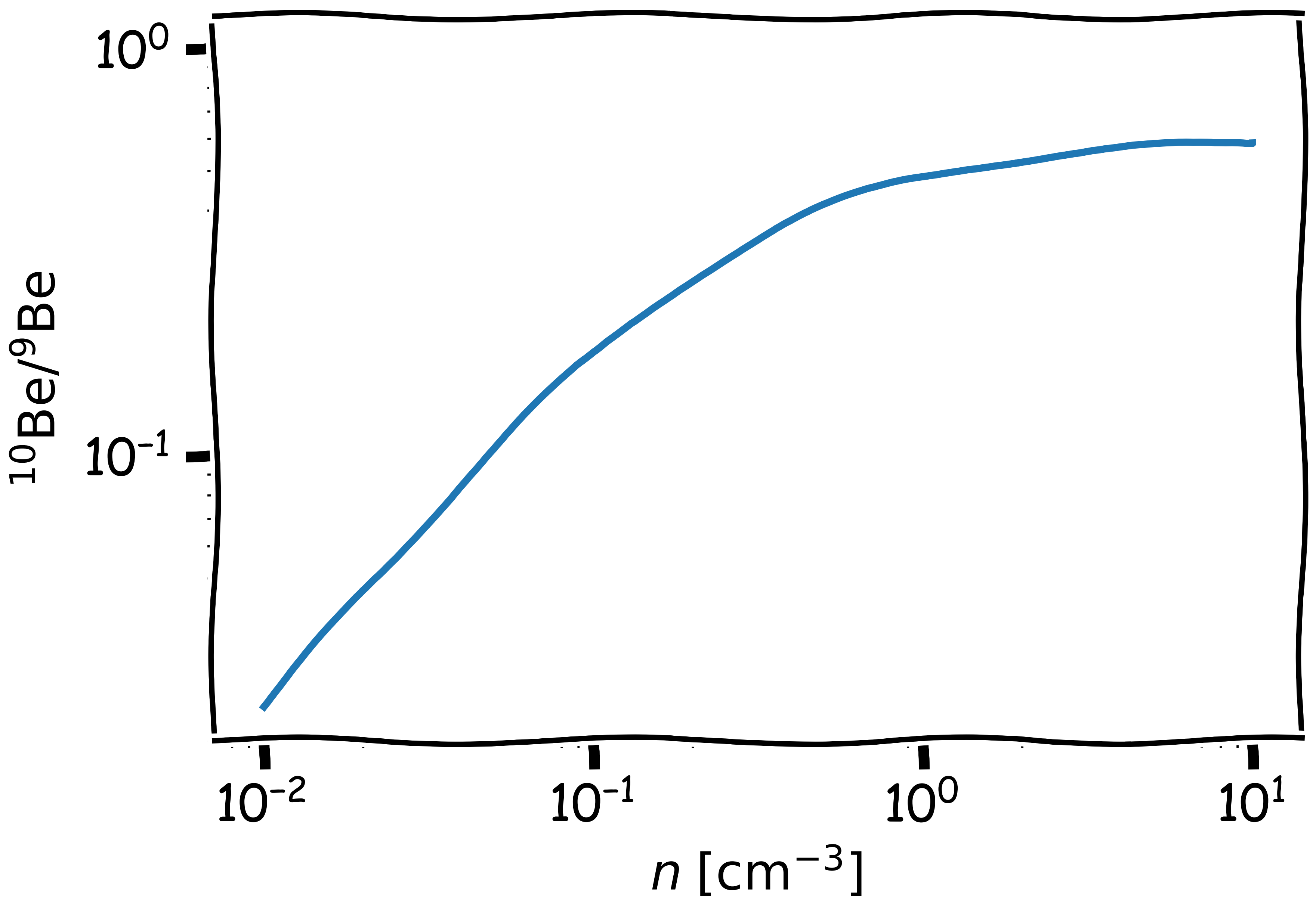
$$\frac{N_{^{10}\mathrm{Be}}}{N_{^{9}\mathrm{Be}}} = \frac{\sigma_{\mathrm{CNO}\to{}^{10}\mathrm{Be}}}{\sigma_{\mathrm{CNO}\to{}^{9}\mathrm{Be}}} \frac{\frac{1}{t_{\mathrm{esc}}} + \frac{1}{t_{\mathrm{int},9}}}{\frac{1}{t_{\mathrm{esc}}} + \frac{1}{t_{\mathrm{int},10}} + \frac{1}{t_{\mathrm{dec},10}}}$$

Cosmic-Ray Clocks

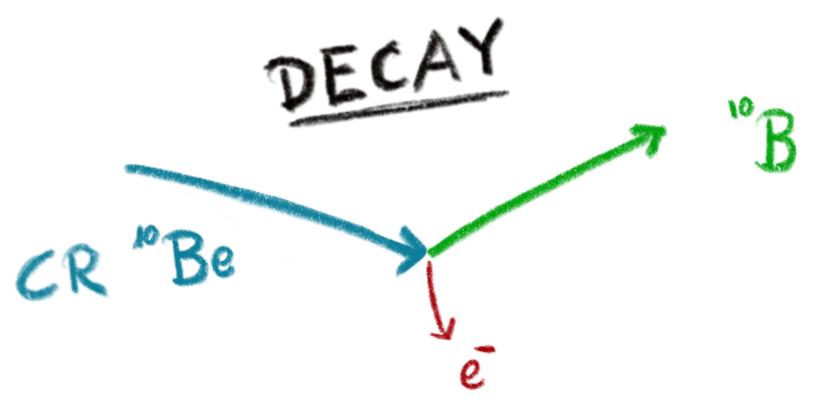


The Leaky Box Model

$$\frac{N_{^{10}\mathrm{Be}}}{N_{^{9}\mathrm{Be}}} = \frac{\sigma_{\mathrm{CNO}\to{}^{10}\mathrm{Be}}}{\sigma_{\mathrm{CNO}\to{}^{9}\mathrm{Be}}} \frac{\frac{v\,m_p\,n}{X} + v\,n\,\sigma_9}{\frac{v\,m_p\,n}{X} + v\,n\,\sigma_{10} + \frac{1}{\gamma\tau_{\mathrm{dec},10}}}$$

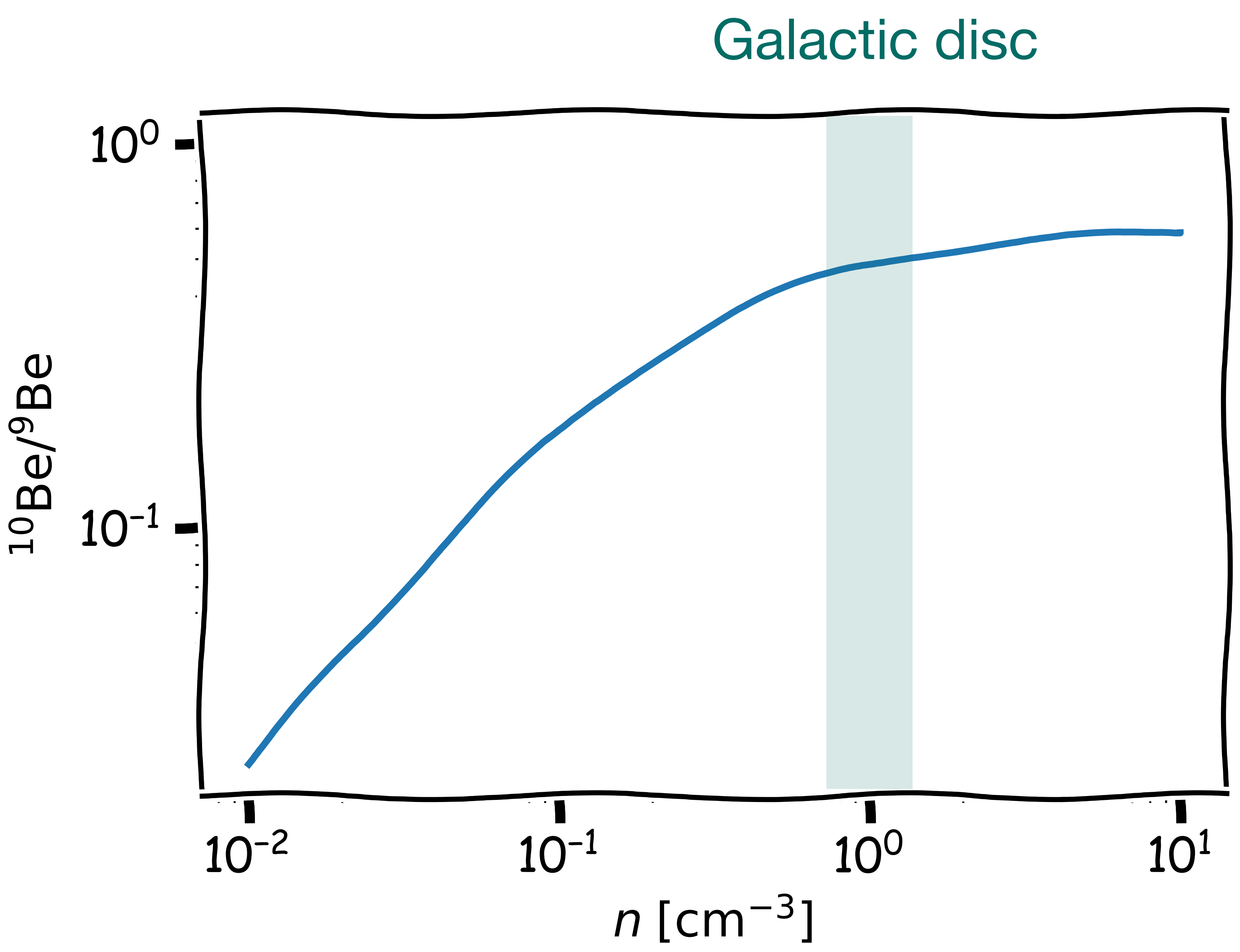


Cosmic-Ray Clocks

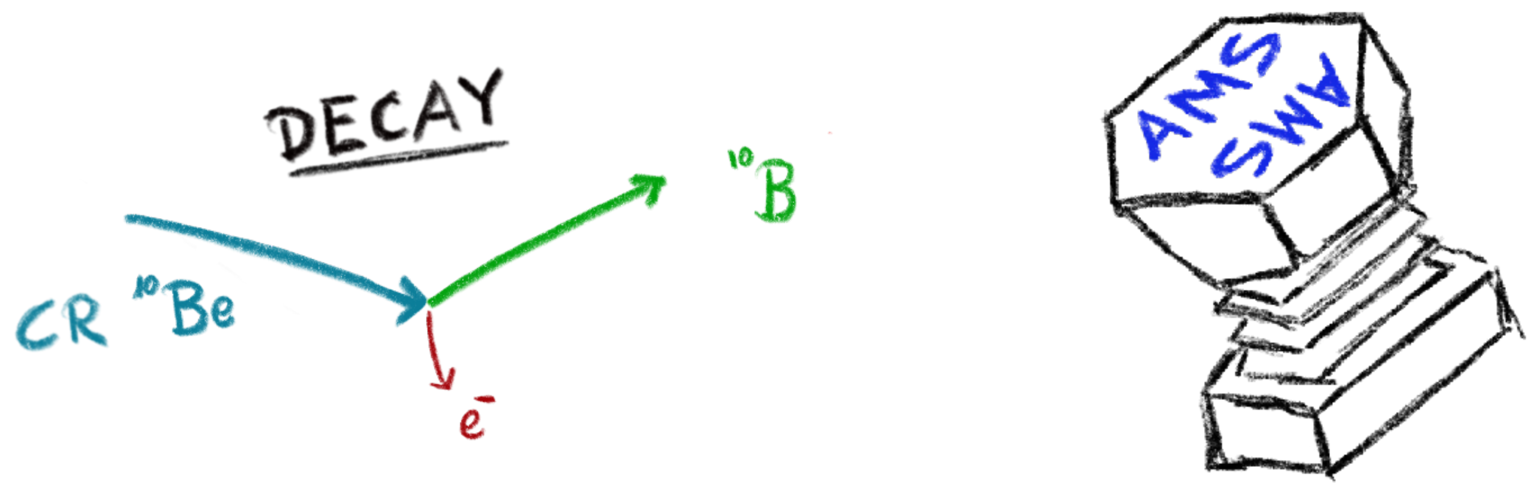


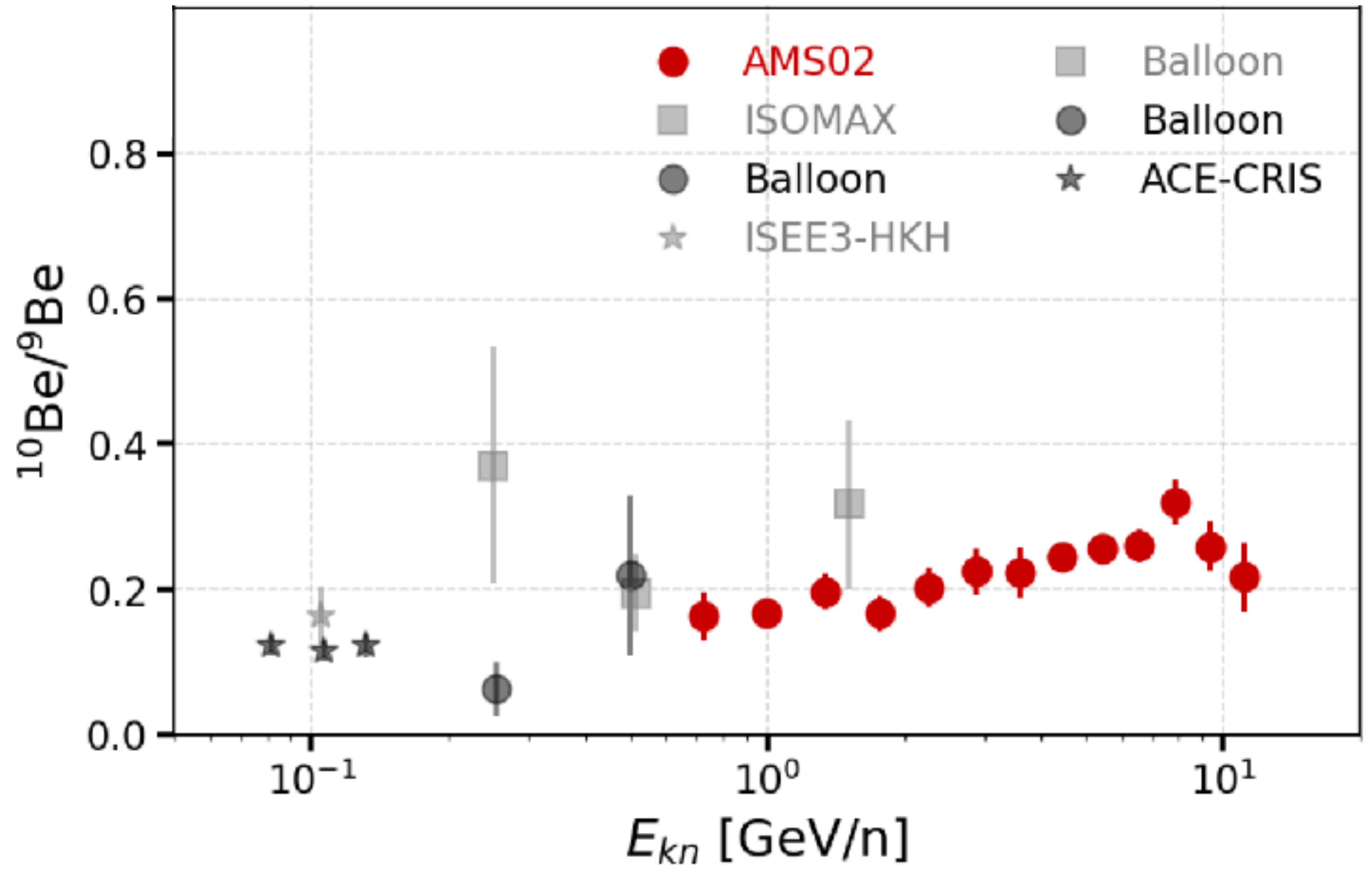
The Leaky Box Model

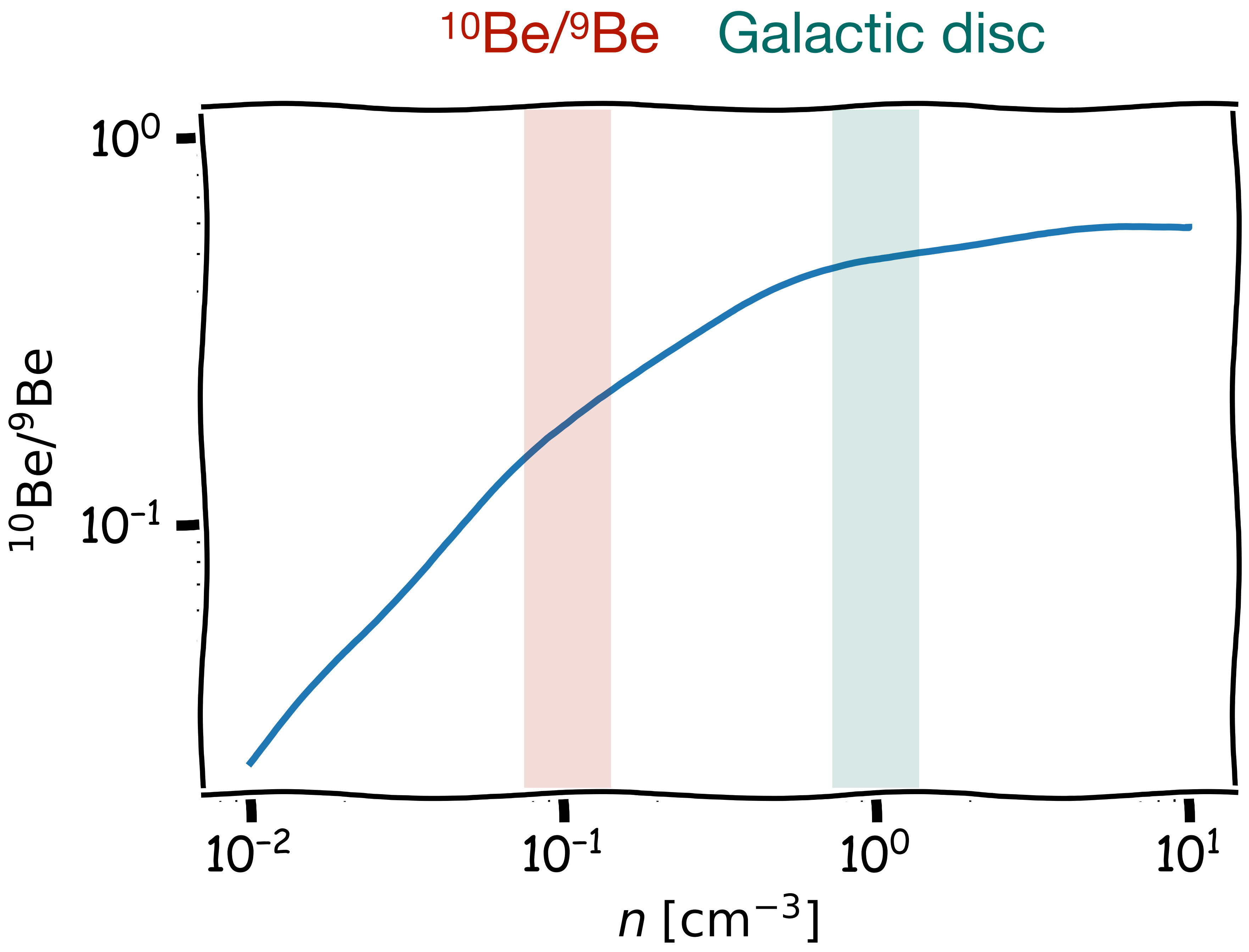
$$\frac{N_{^{10}\mathrm{Be}}}{N_{^{9}\mathrm{Be}}} = \frac{\sigma_{\mathrm{CNO}\to{}^{10}\mathrm{Be}}}{\sigma_{\mathrm{CNO}\to{}^{9}\mathrm{Be}}} \frac{\dfrac{v\, m_p\, n}{X} + v\, n\, \sigma_9}{\dfrac{v\, m_p\, n}{X} + v\, n\, \sigma_{10} + \dfrac{1}{\gamma \tau_{\mathrm{dec},10}}}$$



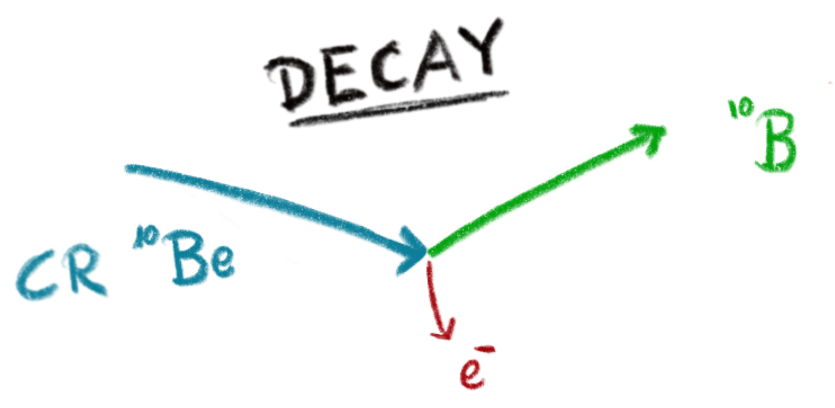
Cosmic-Ray Clocks

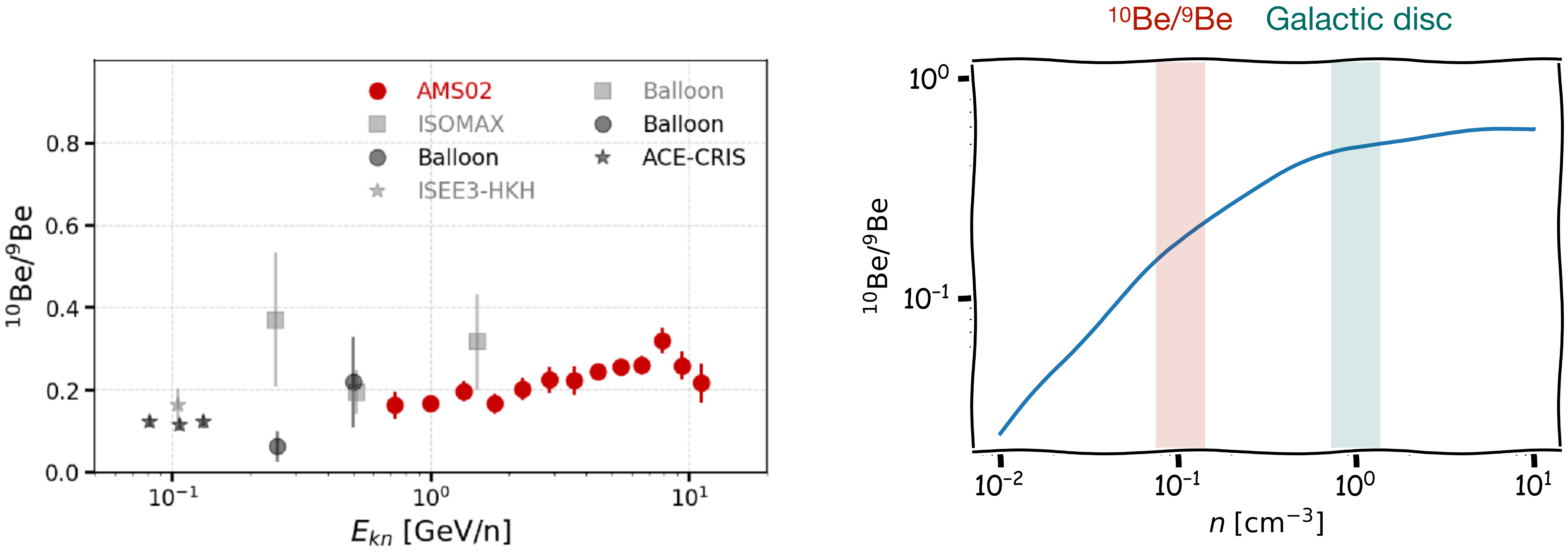






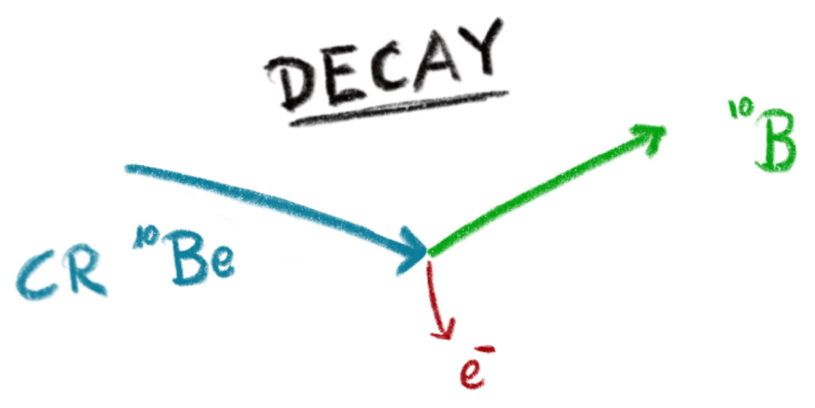
Cosmic-Ray Clocks

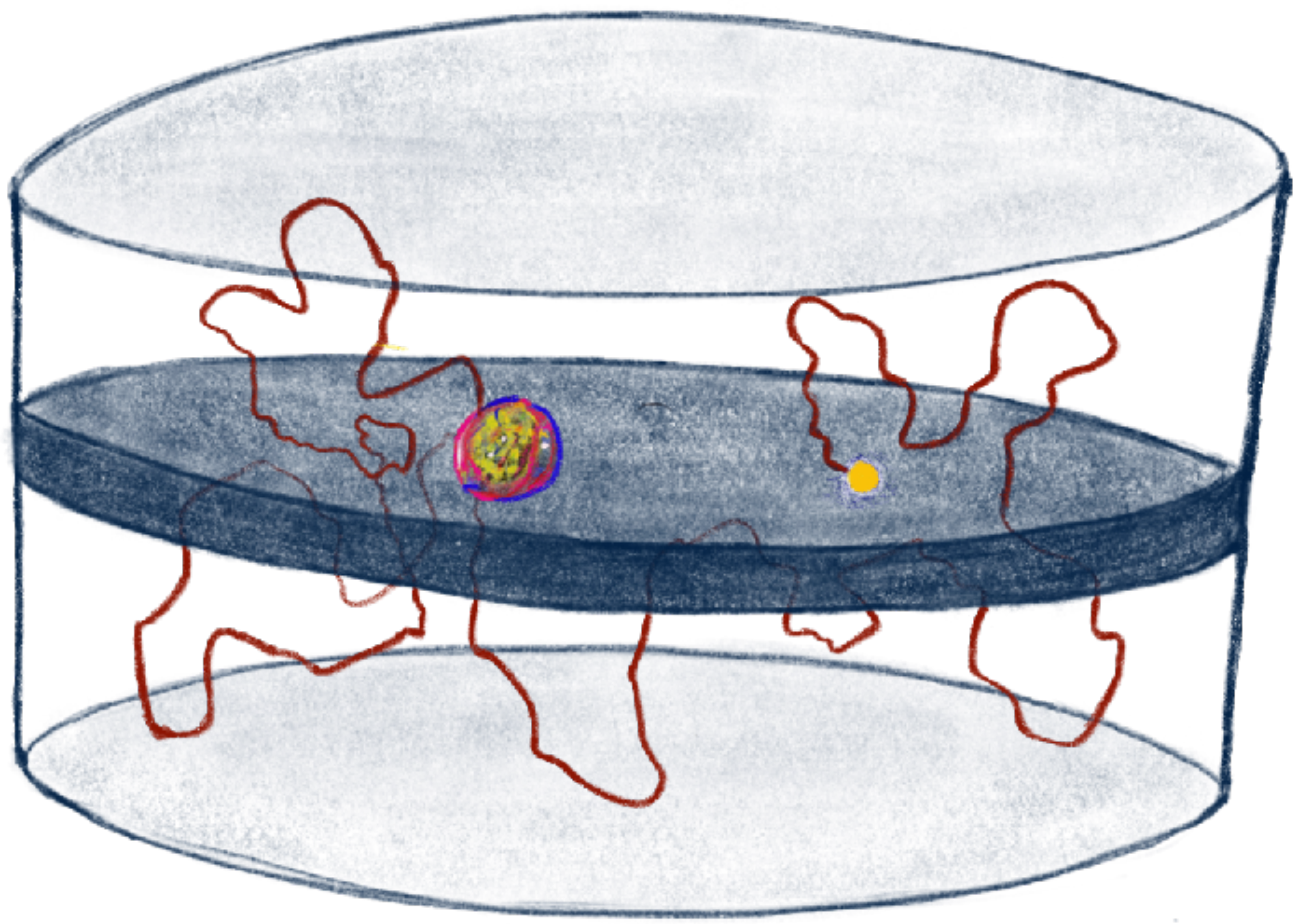




CRs spend a significant time outside the Galactic disc!

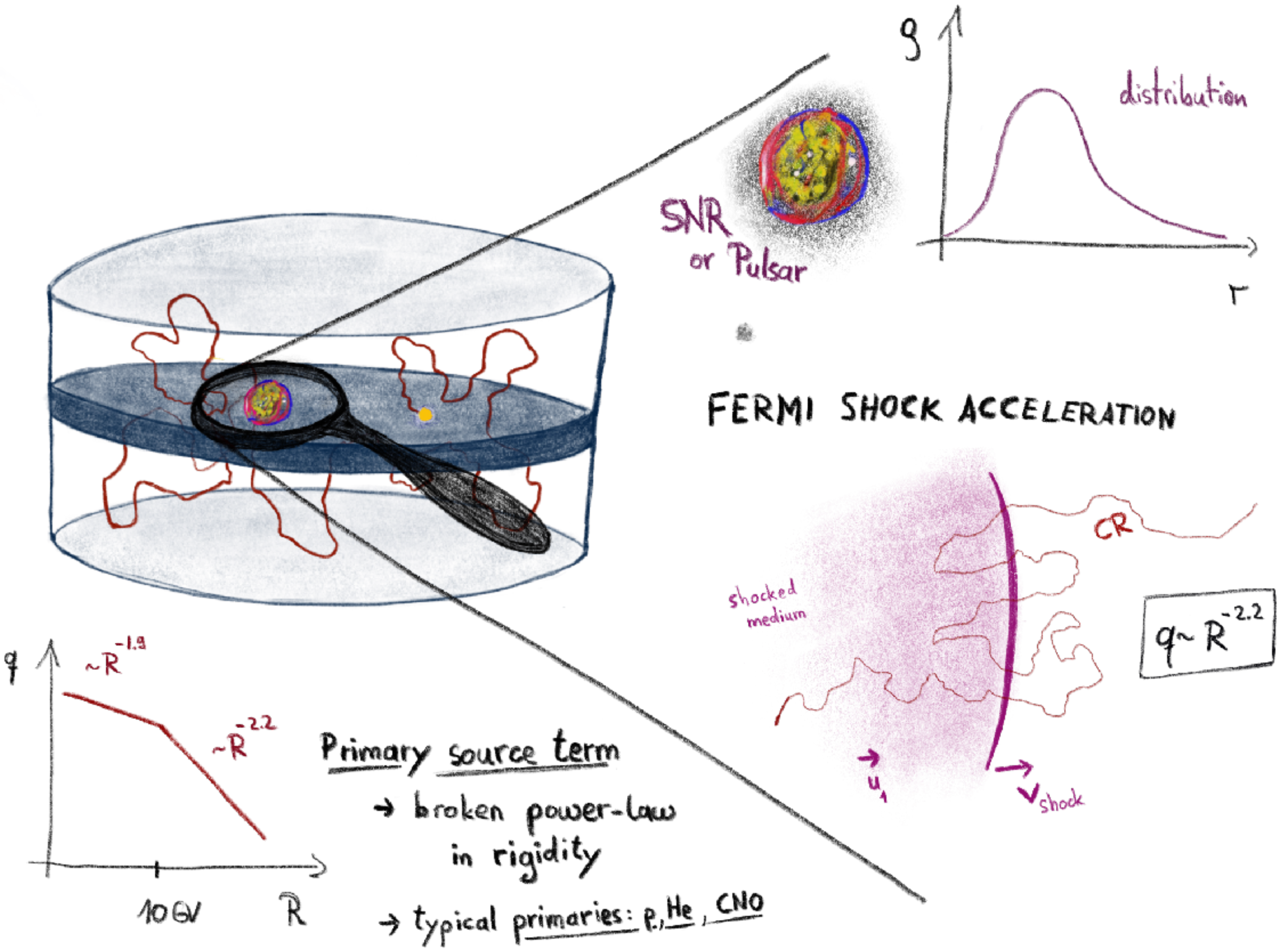
Cosmic-Ray Clocks



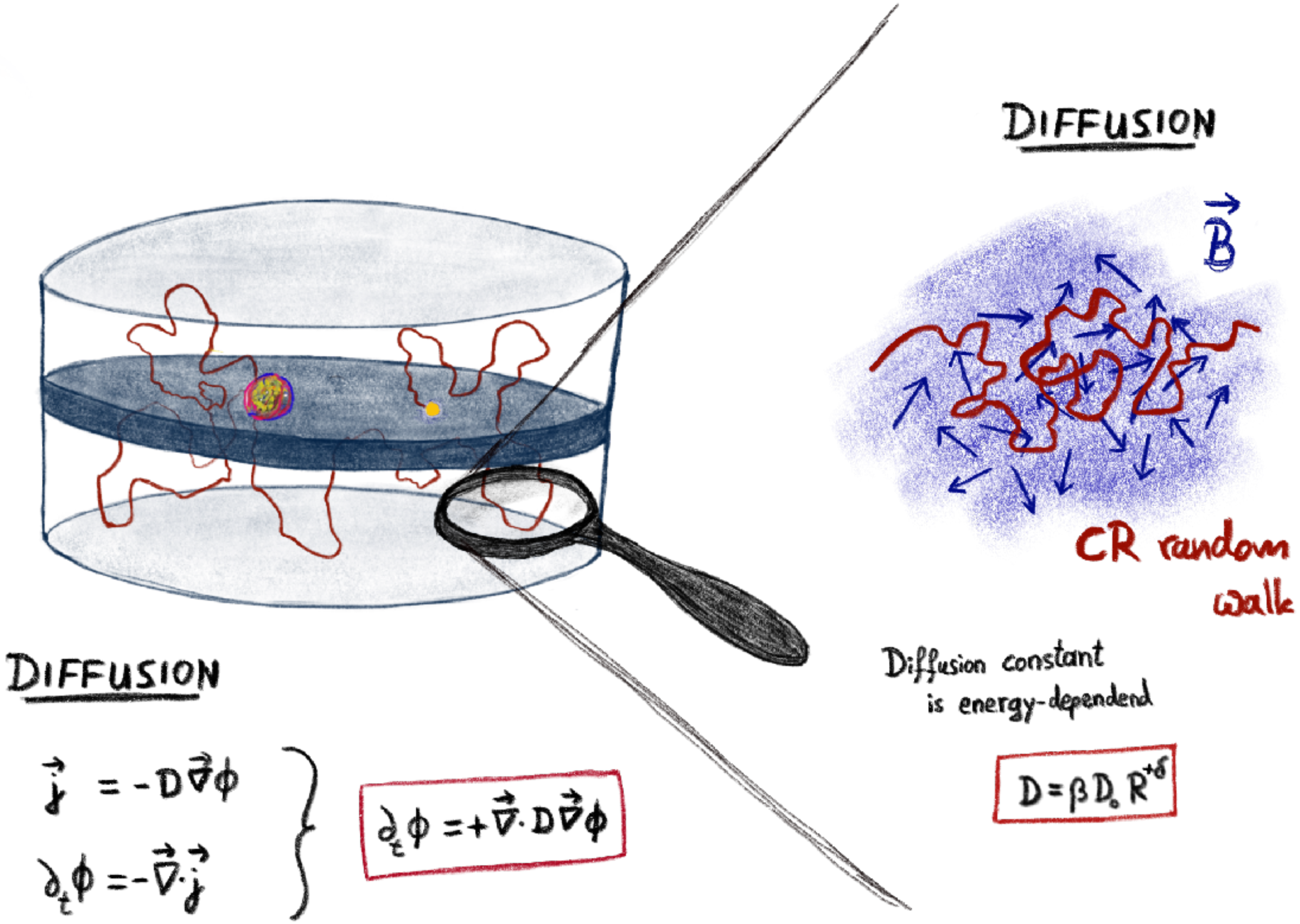


CRs spend a significant time outside the Galactic disc!

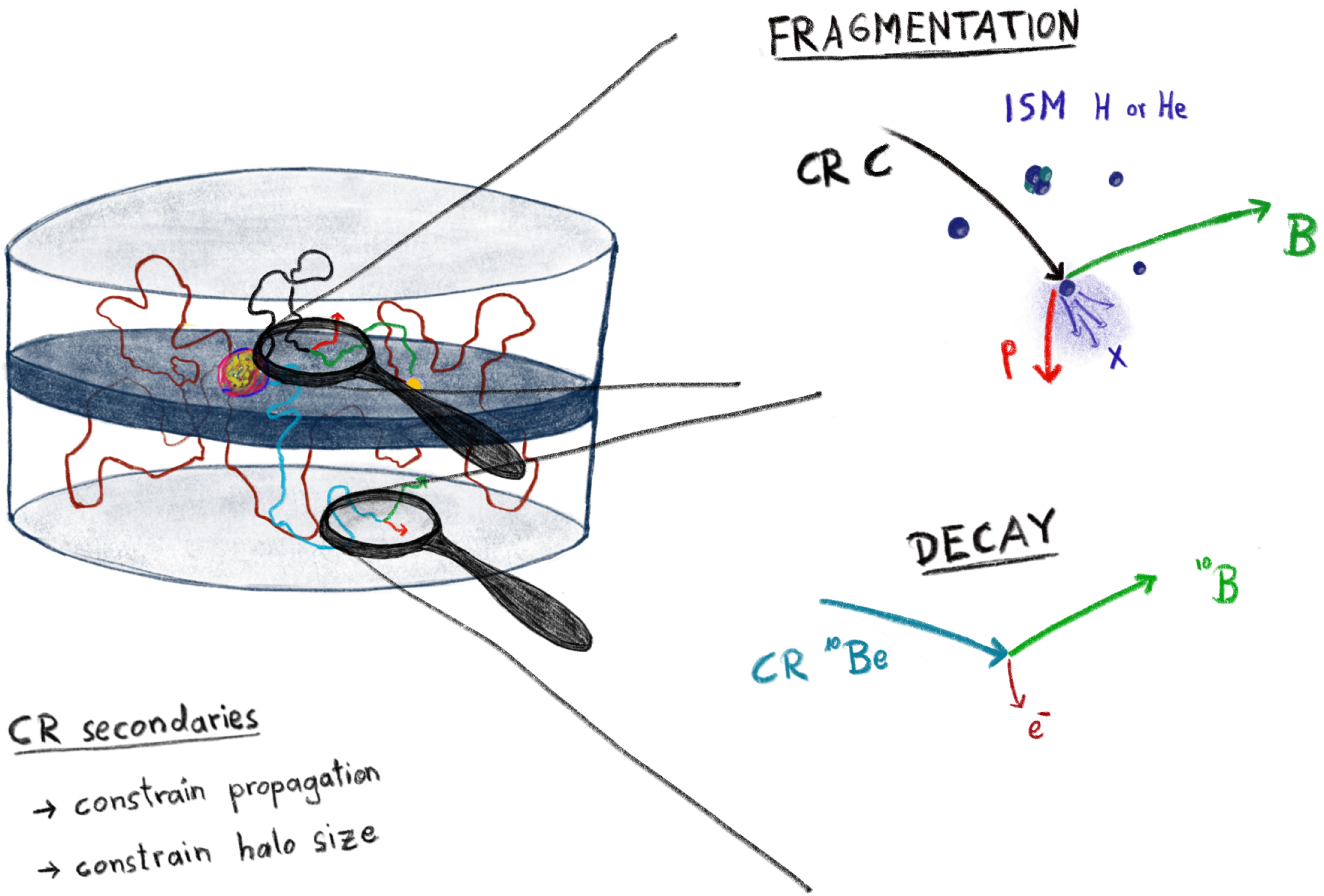
Modeling Cosmic-Ray Propagation



Modeling Cosmic-Ray Propagation



Modeling Cosmic-Ray Propagation



Diffusion Equation of Cosmic Rays

$\frac{d\psi_i}{dt} = q_i(\boldsymbol{x}, p)$	Source term
$+\nabla D_{xx} \nabla \psi_i$	Diffusion
$-\nabla \boldsymbol{V} \psi_i + \frac{\partial}{\partial p}\left(\frac{p}{3} \nabla \cdot \boldsymbol{V} \psi_i\right)$	Convection
$-\frac{\partial}{\partial p}\left(\frac{dp}{dt} \psi_i\right)$	Energy losses
$-\frac{\psi_i}{\tau_f} - \frac{\psi_i}{\tau_r}$	Fragmentation and decay
$+\frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi_i$	Reacceleration

Diffusion Equation of Cosmic Rays

$$\frac{d\psi_i}{dt} = q_i(\boldsymbol{x}, p)$$ Source term

$$+\nabla D_{xx} \nabla \psi_i$$ Diffusion

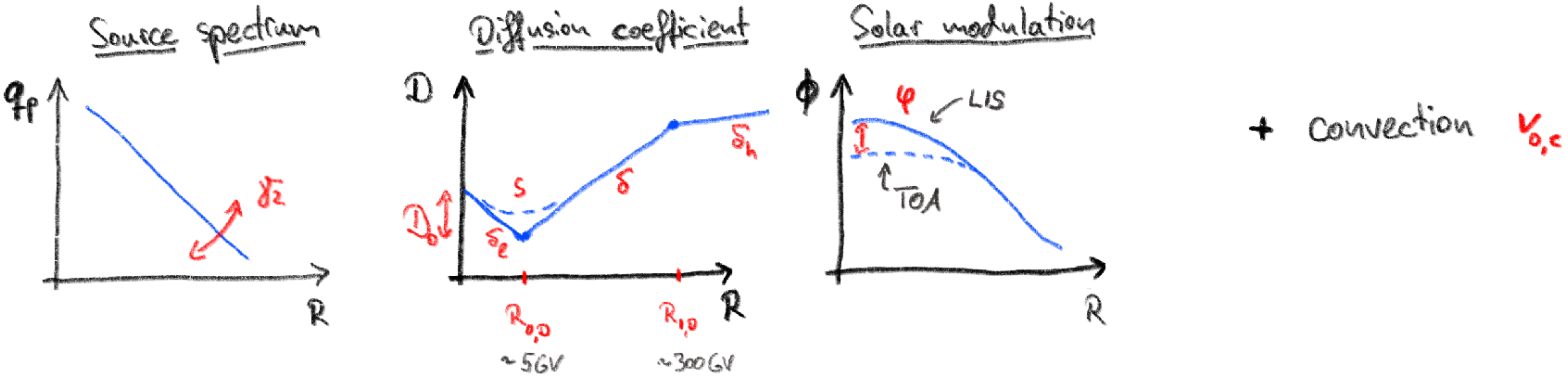
$$-\frac{\psi_i}{\tau_f} - \frac{\psi_i}{\tau_r}$$ Fragmentation and decay

$$+\frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi_i$$ Reacceleration

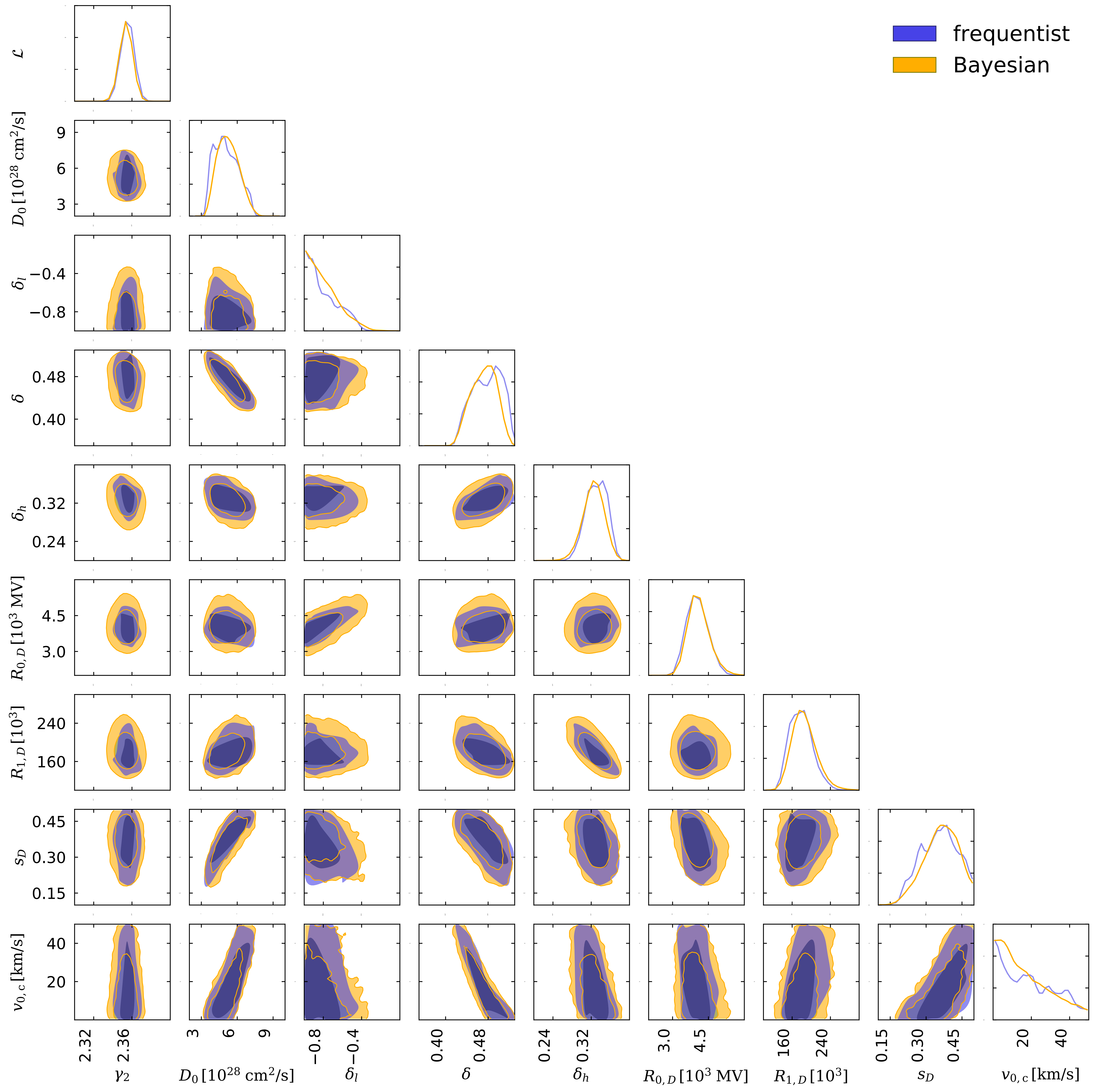
CR propagation is described by **diffusion equations**.

We use the **GALPROP** code to solve them.

Specific fit setup

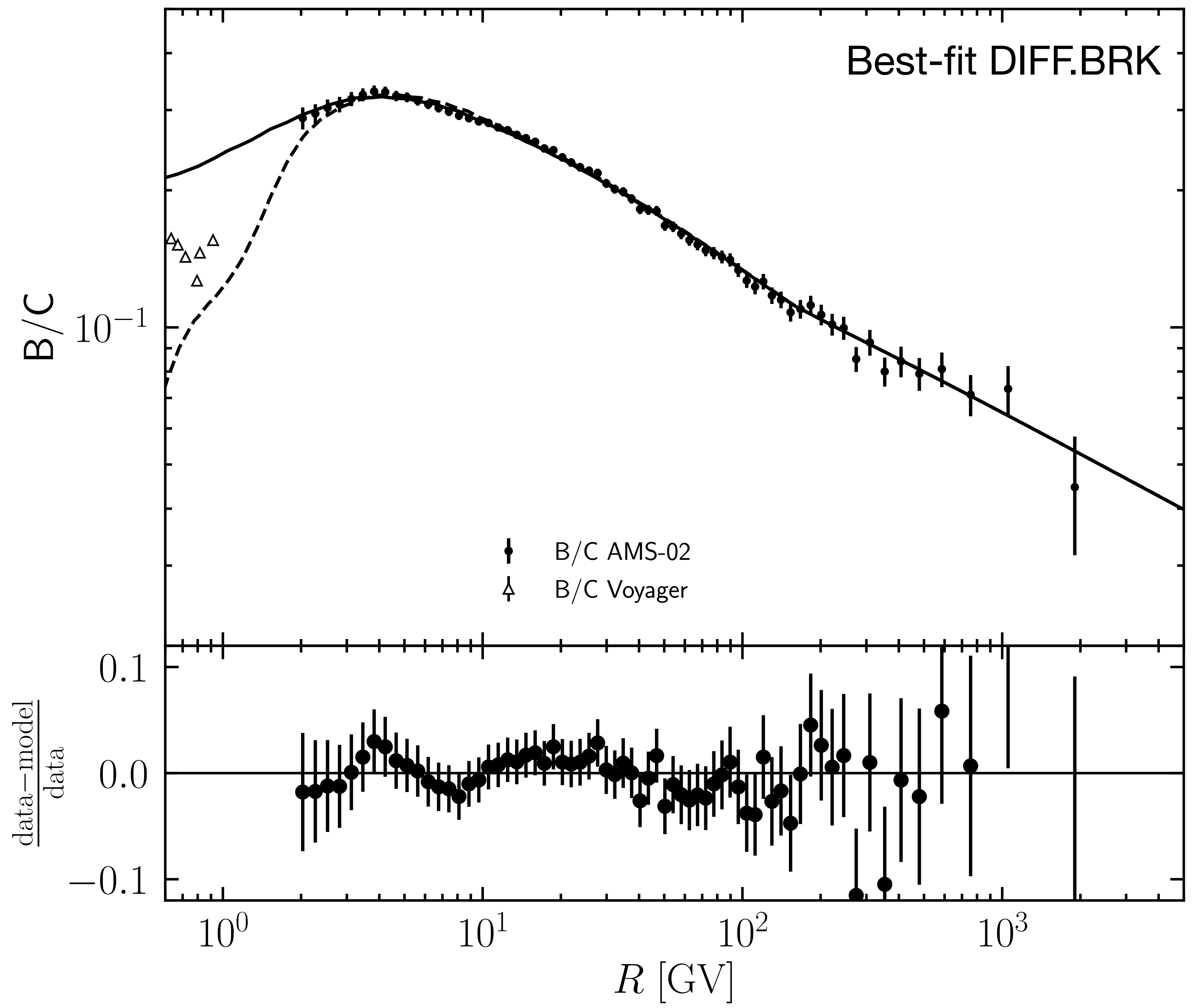


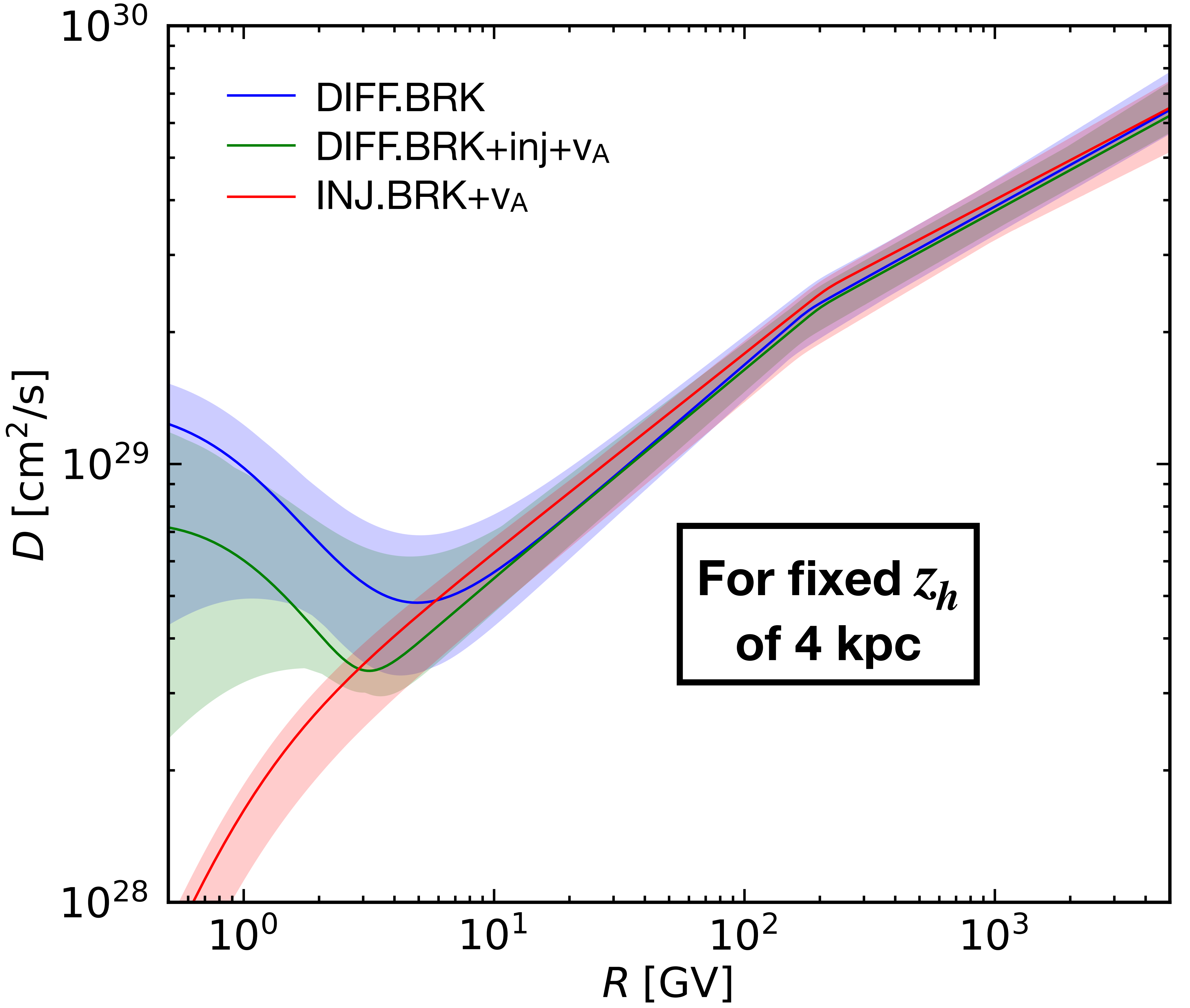
Monte Carlo Scans



Next to the parameters shown here we include nuisance parameters to consider systematic uncertainties for example in the fragmentation cross sections.

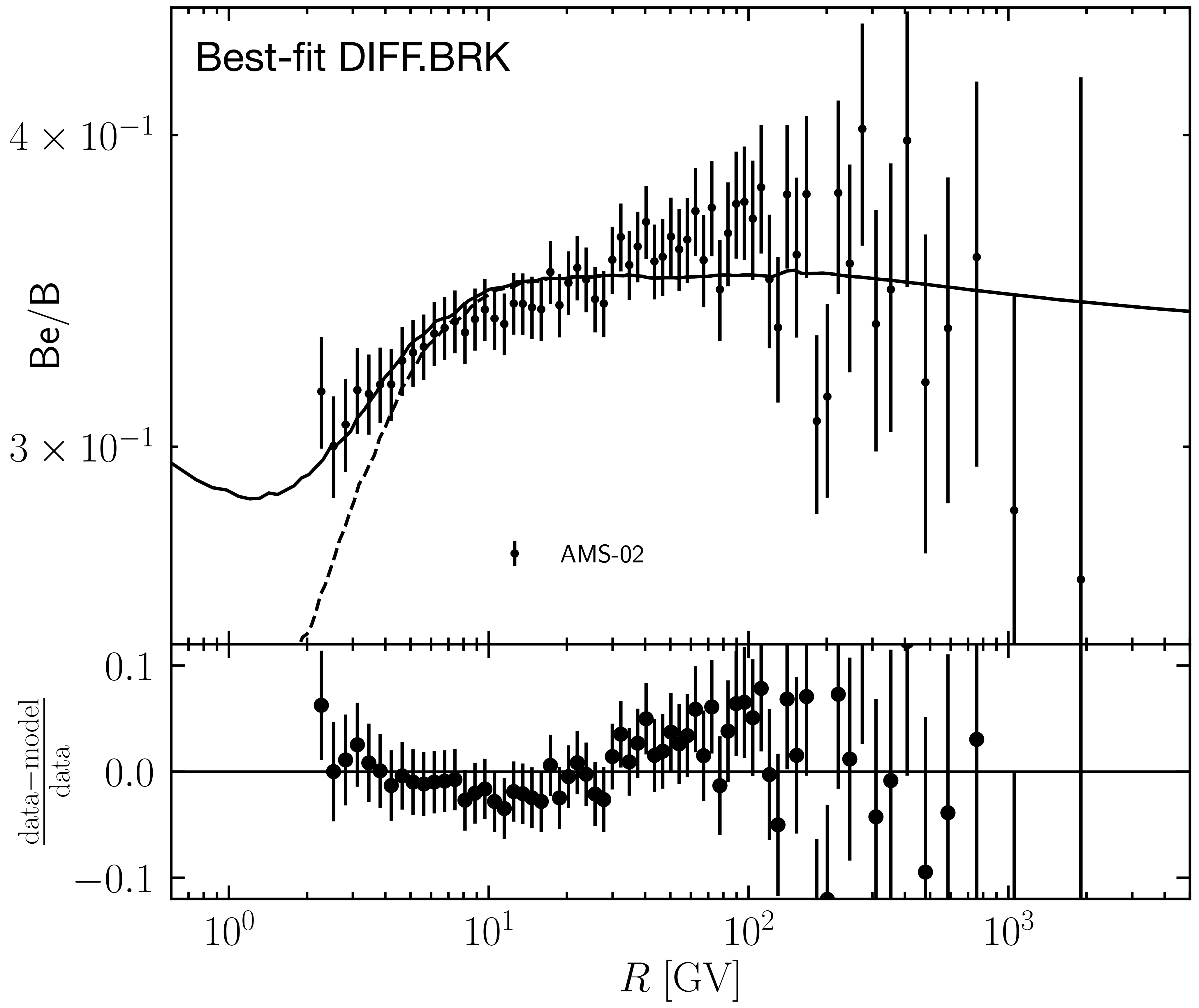
Secondary-to-Primary ratios constrain propagation

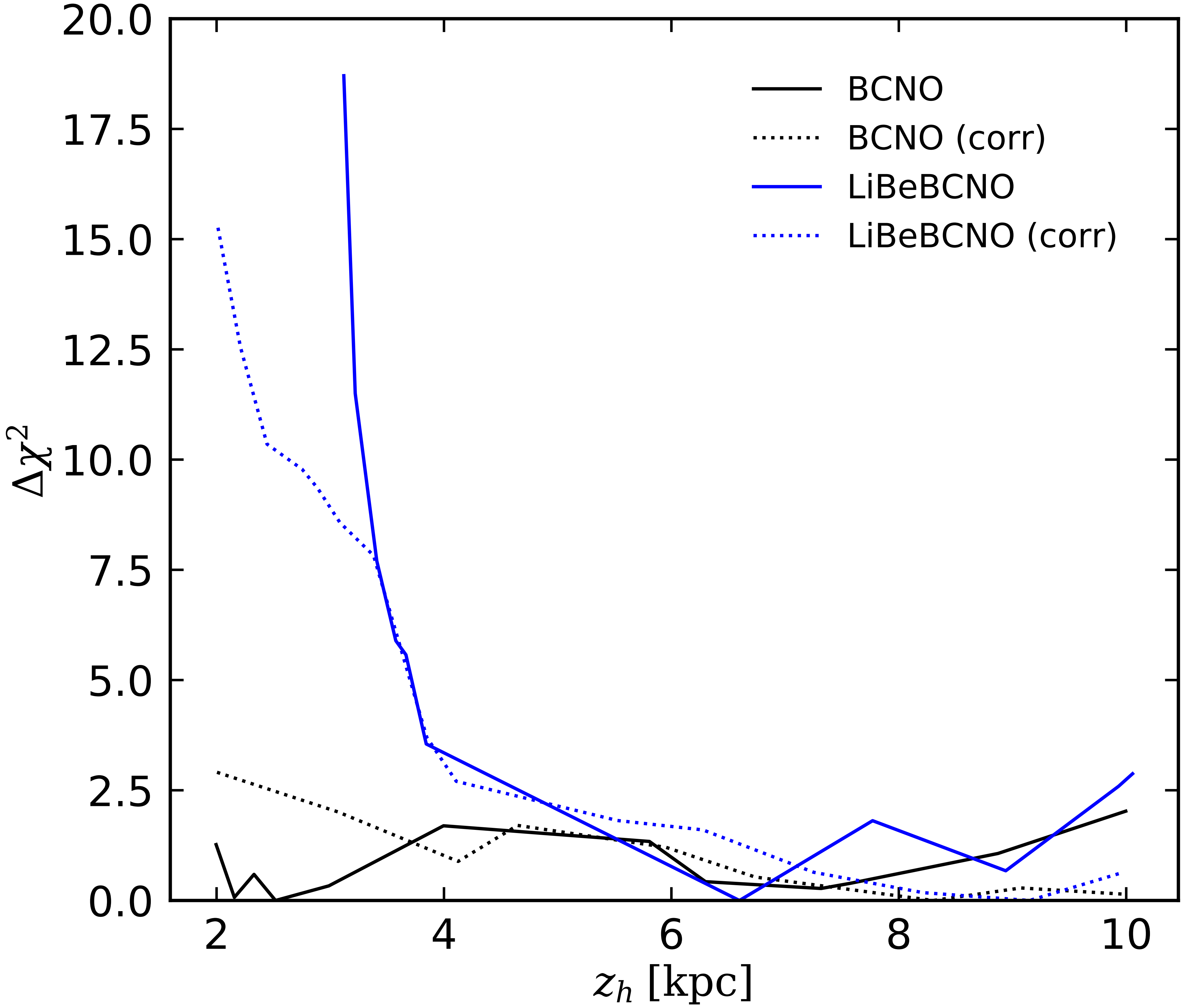




[MK, Cuoco, 2021]

Cosmic-Ray Clocks constrain the Halo Size



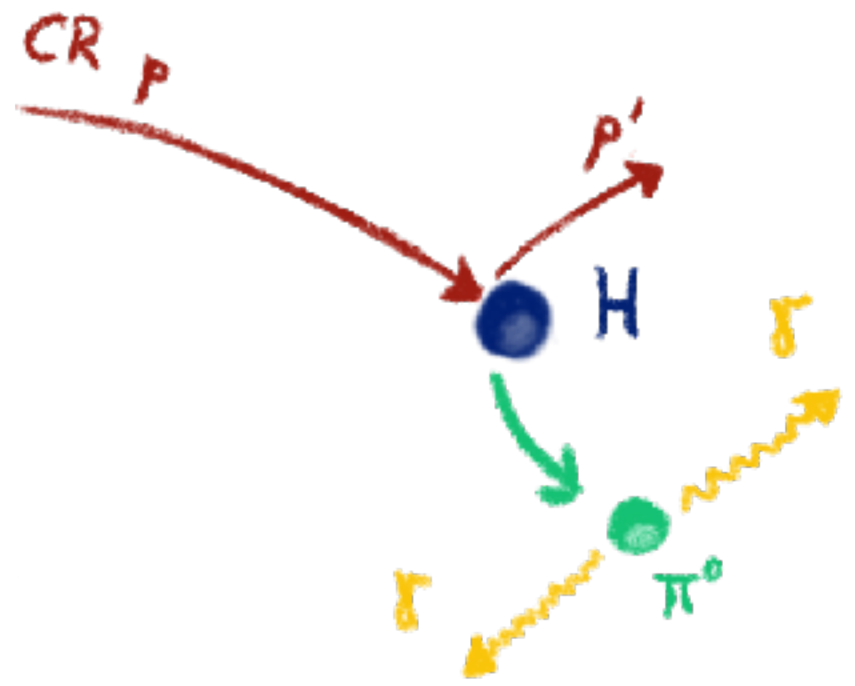


[MK, Cuoco, 2021]

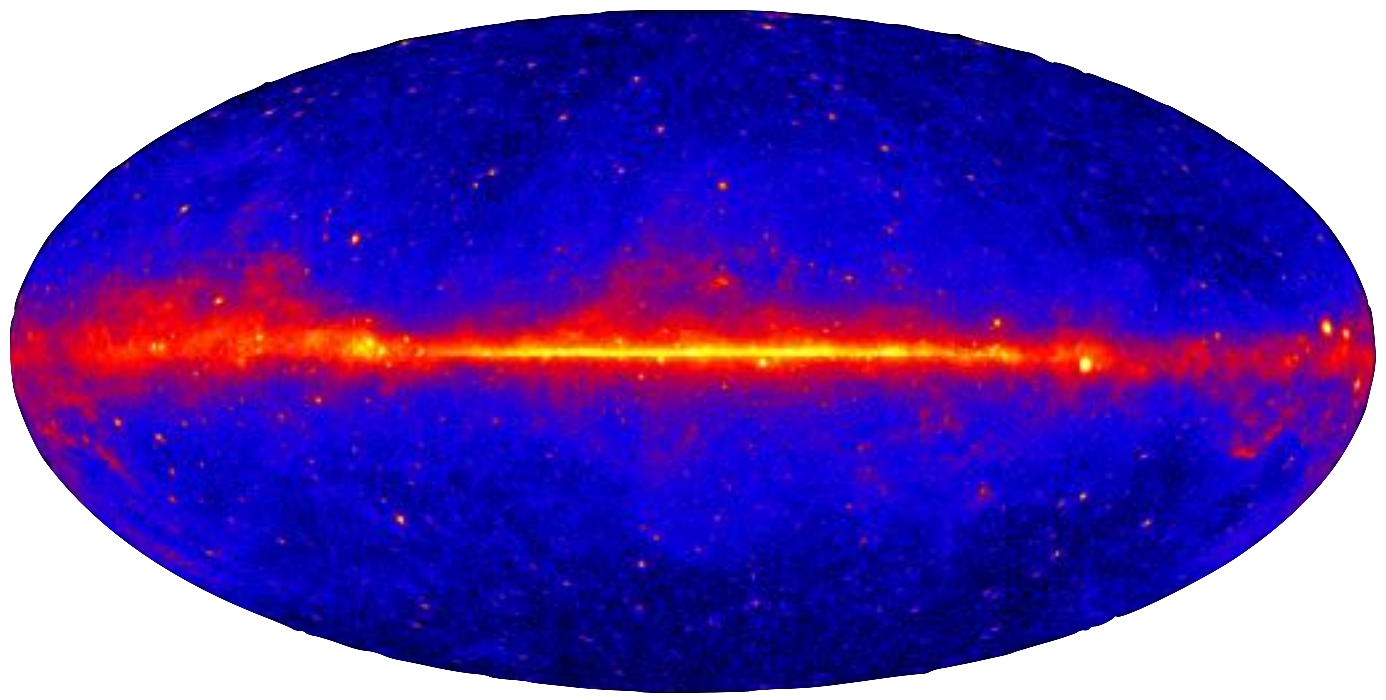
Part II

Connection of Cosmic Rays and Gamma-Rays

[arXiv: 2208.11704]



Fermi-LAT: Gamma-Ray Sky



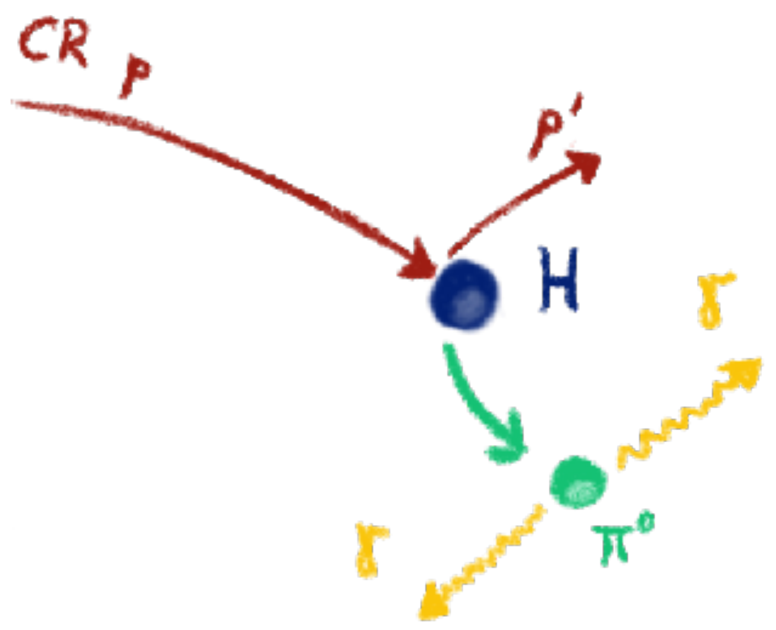
Weighing the Local Interstellar Medium using Gamma Rays and Dust

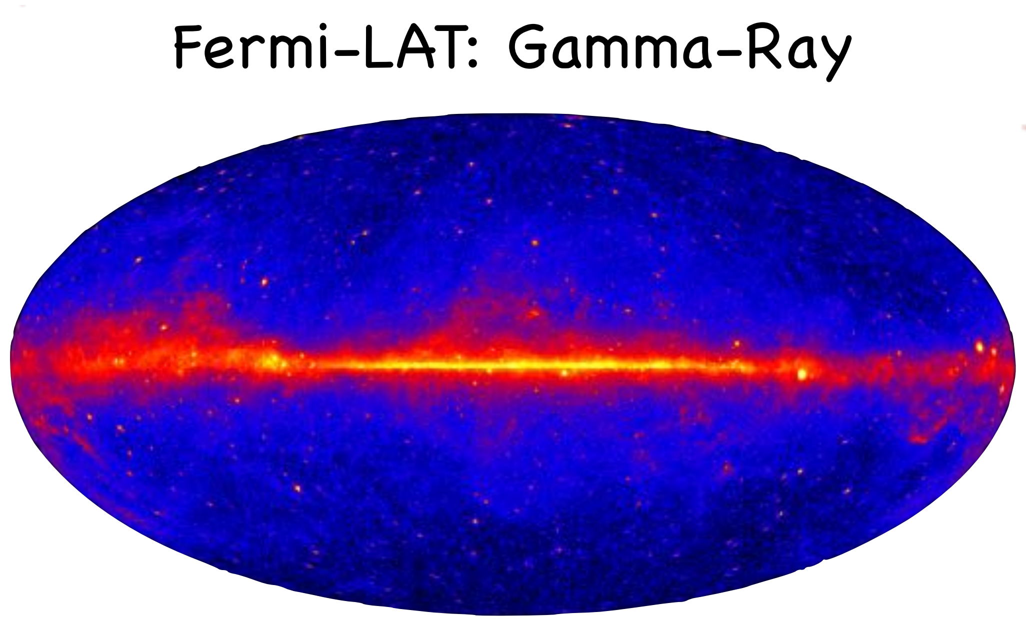
Axel Widmark,[1,*] Michael Korsmeier,[2,†] and Tim Linden[2,‡]

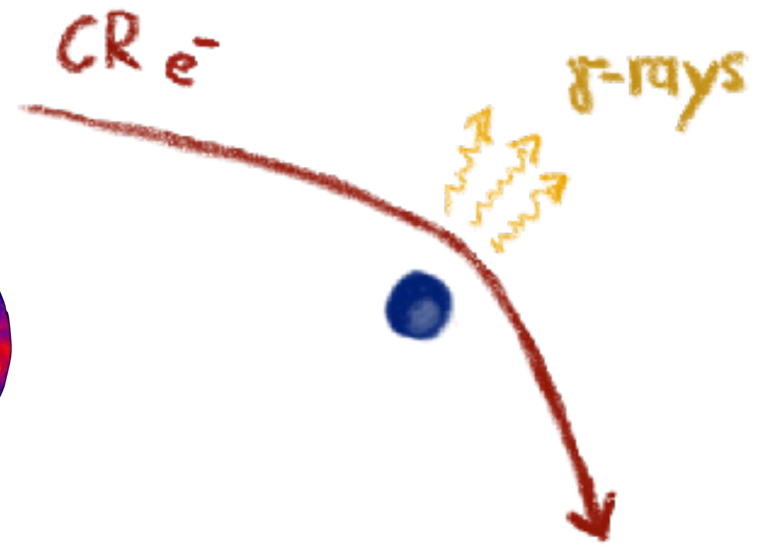
[1] *Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen, Jagtvej 128, 2200 Copenhagen N, Denmark*
[2] *Stockholm University and The Oskar Klein Centre for Cosmoparticle Physics, Alba Nova, 10691 Stockholm, Sweden*

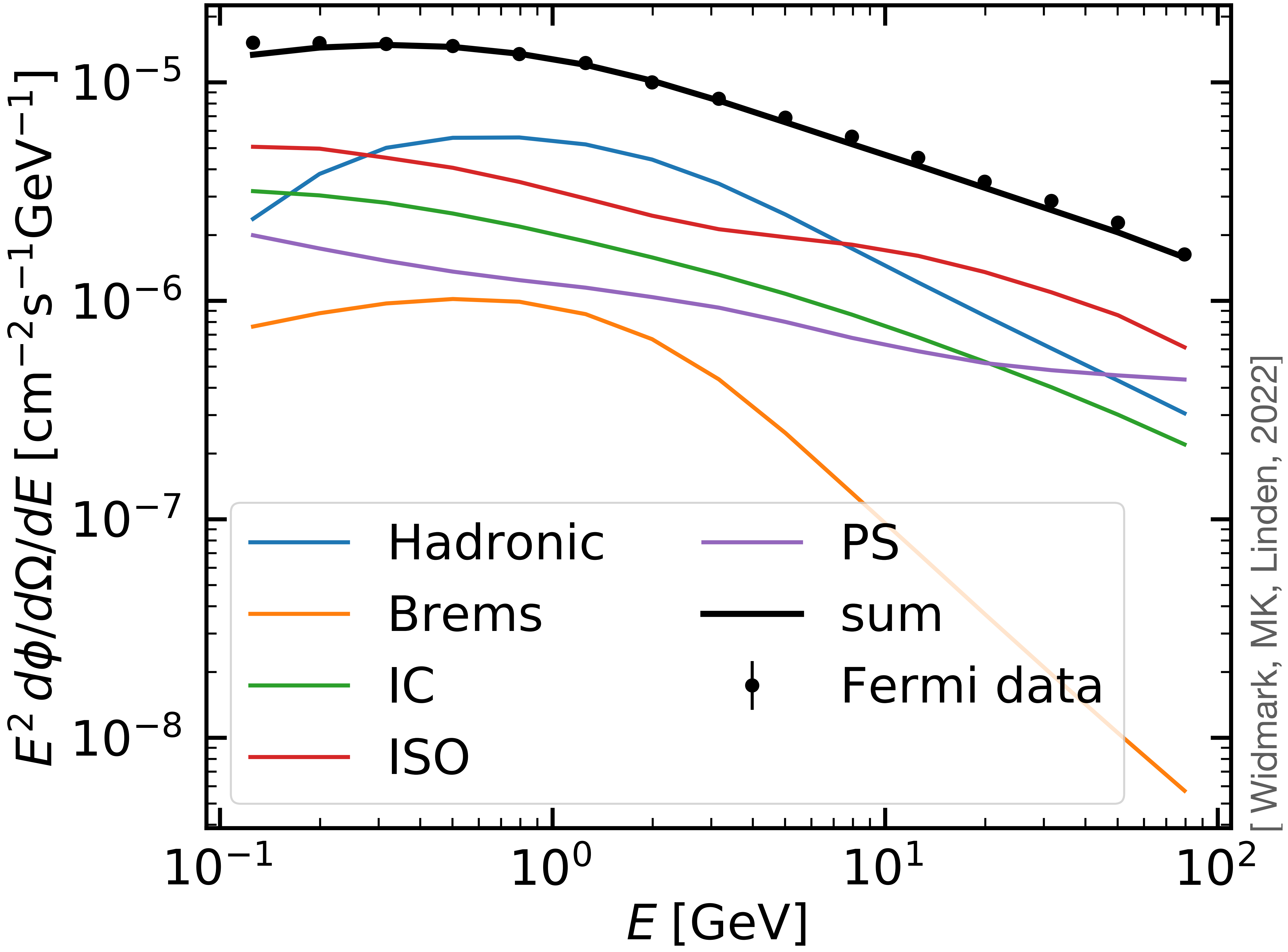
Cold gas forms a significant mass fraction of the Milky Way disk, but is its most uncertain baryonic component. The density and distribution of cold gas is of critical importance for Milky Way dynamics, as well as models of stellar and galactic evolution. Previous studies have used correlations between gas and dust to obtain high-resolution measurements of cold gas, but with large normalization uncertainties. We present a novel approach that uses *Fermi*-LAT γ-ray data to measure the total gas density, achieving a similar precision as previous works, but with independent systematic uncertainties. Notably, our results have sufficient precision to distinguish between the tension in current world-leading experiments.

Sources of Gamma-Rays





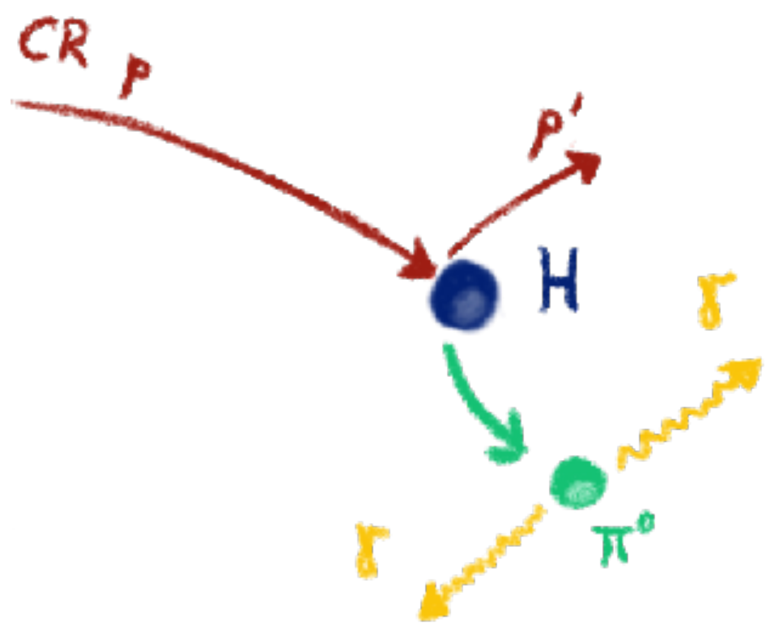


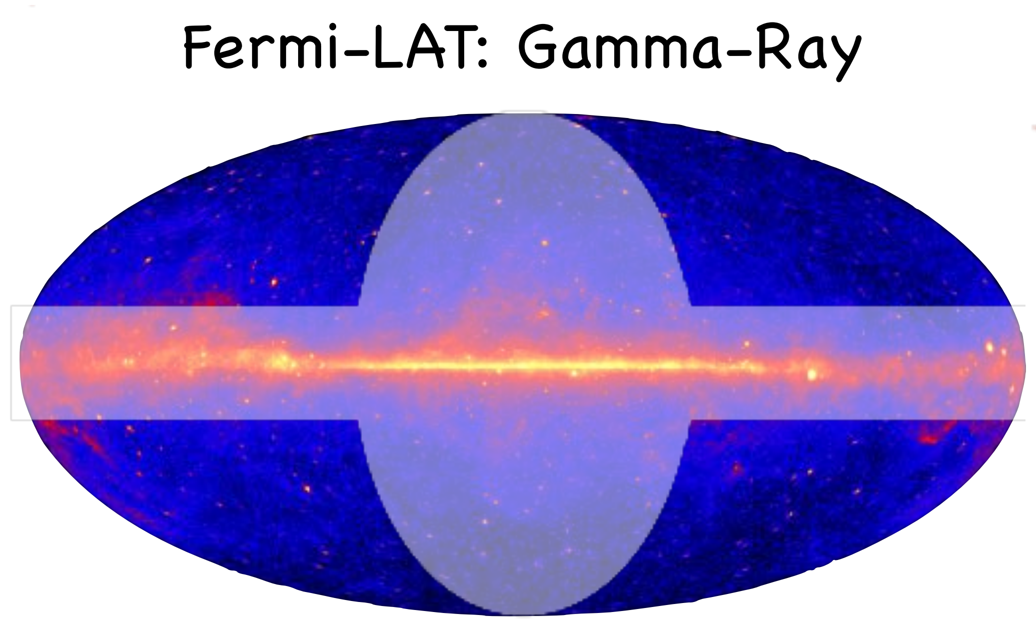


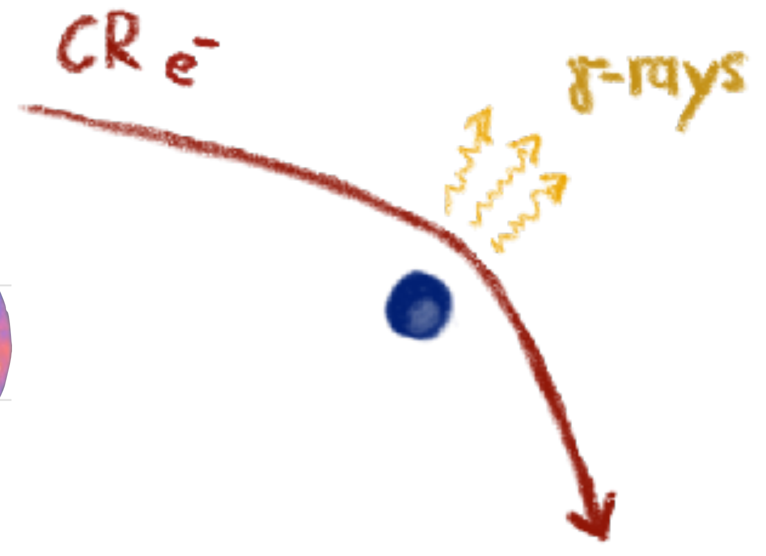
[Widmark, MK, Linden, 2022]

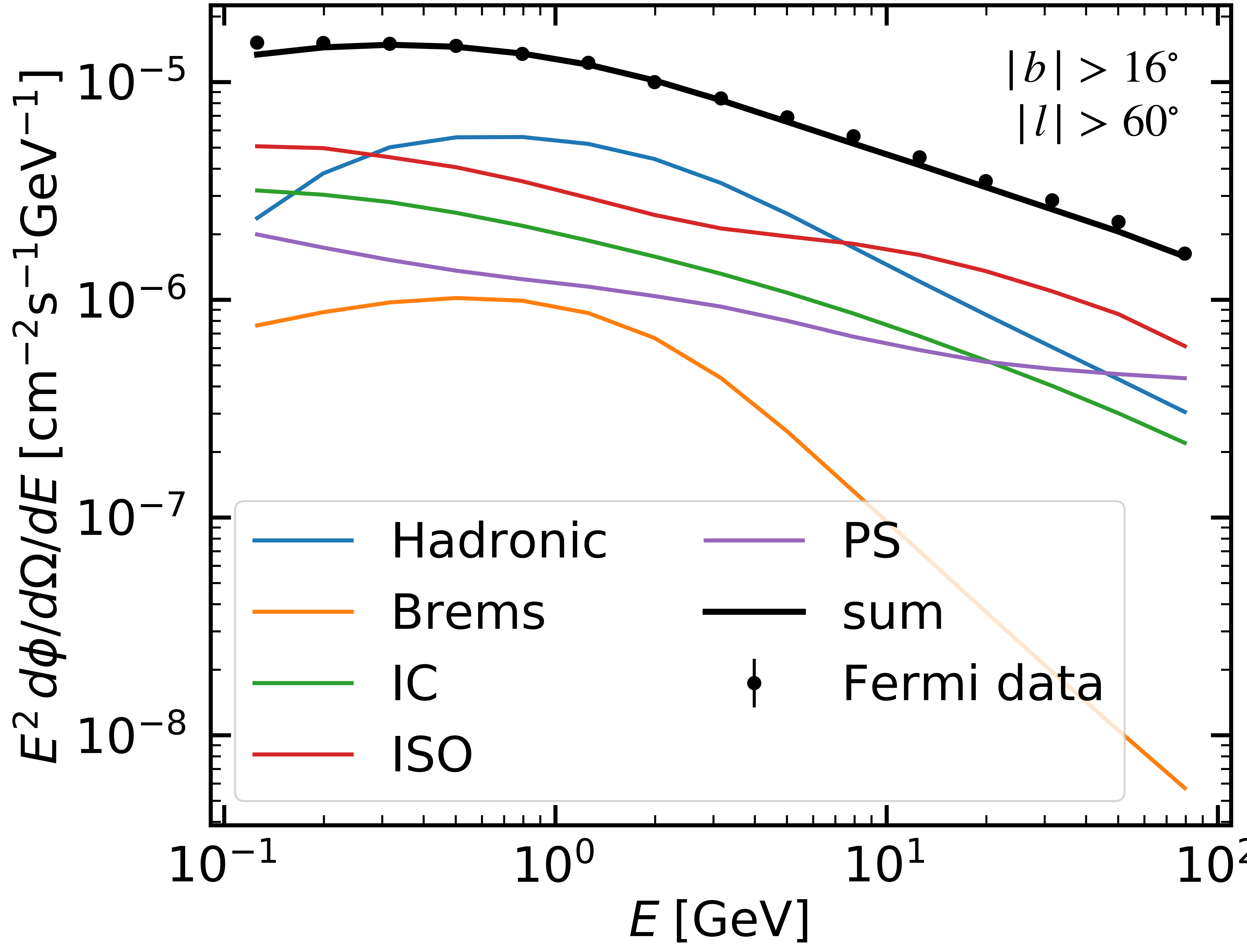
- Hadronic interactions ($\pi^0 \rightarrow \gamma\gamma$)
- Bremsstrahlung ($e^- + p \rightarrow e^{-'} + \gamma$)
- Inverse Compton ($e^- + \gamma \rightarrow e^- + \gamma$)
- Point sources (blazers, pulsars, SNR, …)
- Isotropic (mostly unresolved point sources)

Sources of Gamma-Rays





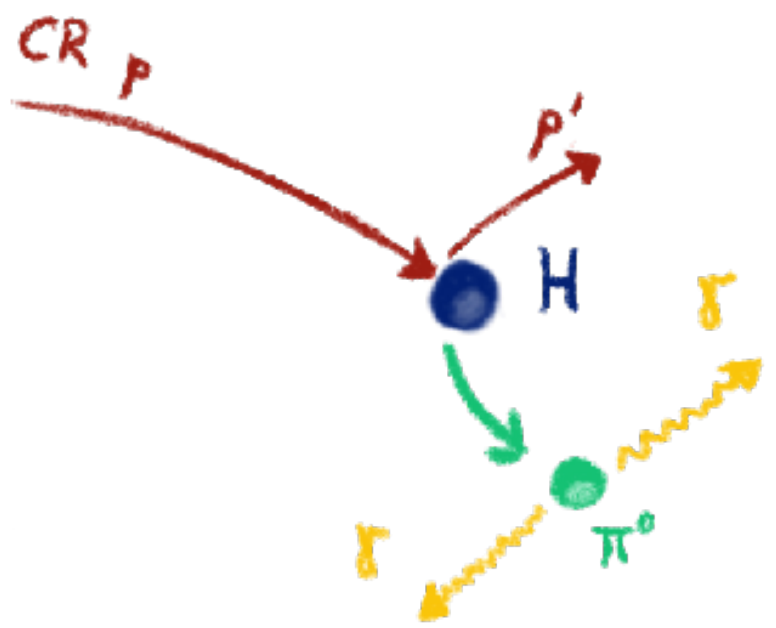


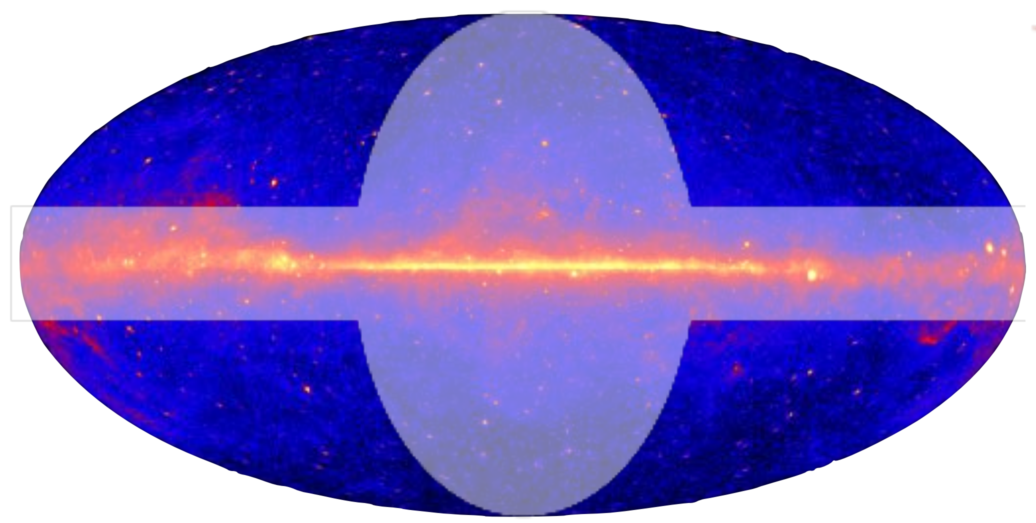


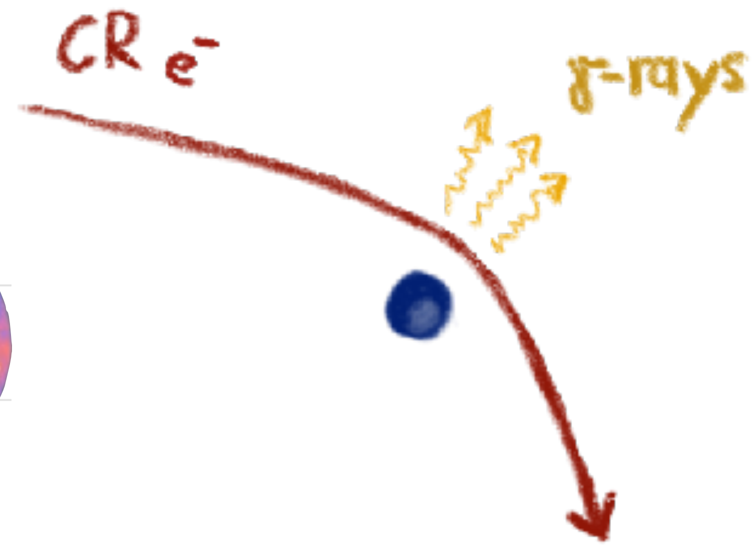
[Widmark, MK, Linden, 2022]

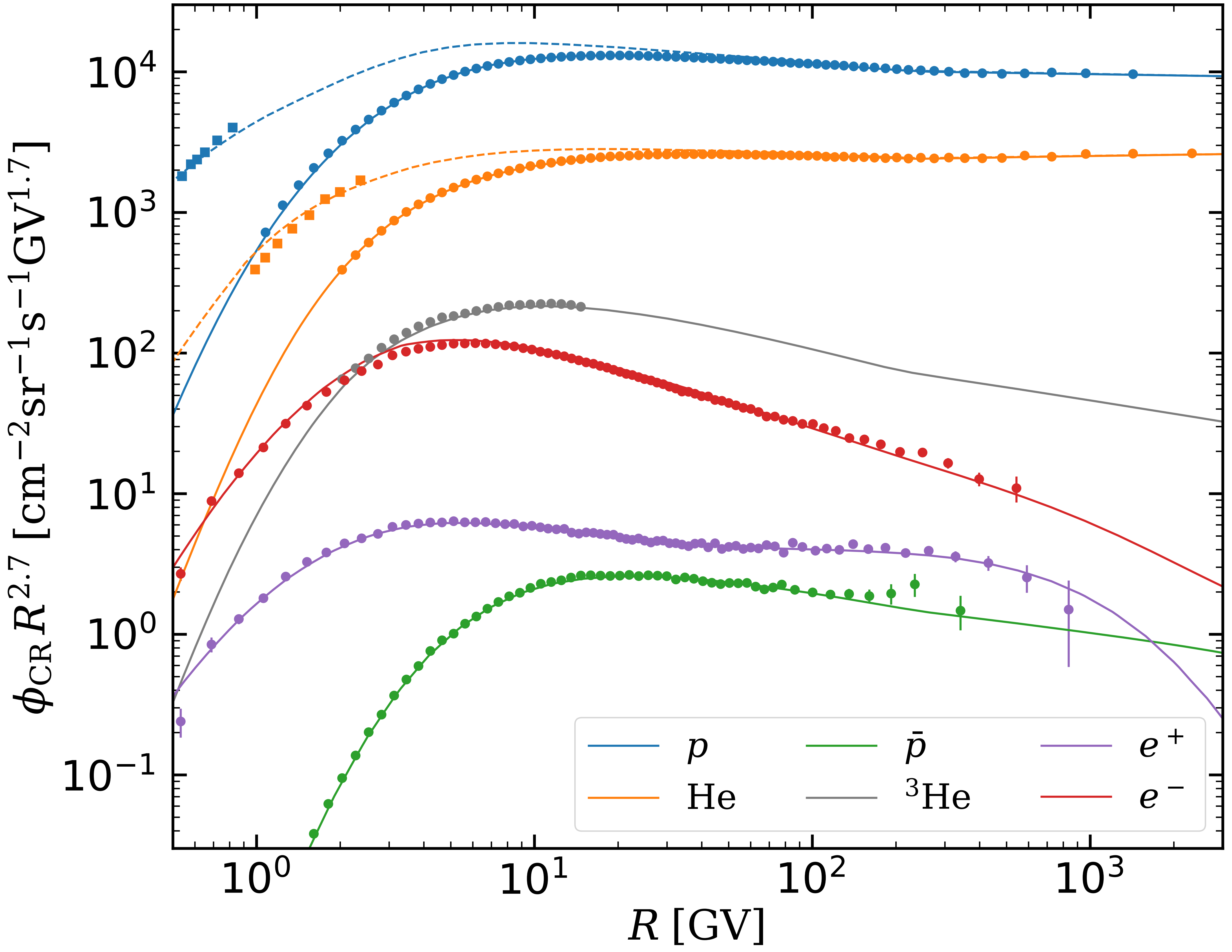
- Hadronic interactions ($\pi^0 \rightarrow \gamma\gamma$)
- Bremsstrahlung ($e^- + p \rightarrow e^{-\prime} + \gamma$)
- Inverse Compton ($e^- + \gamma \rightarrow e^- + \gamma$)
- Point sources (blazers, pulsars, SNR, …)
- Isotropic (mostly unresolved point sources)

Connection to Gas Maps









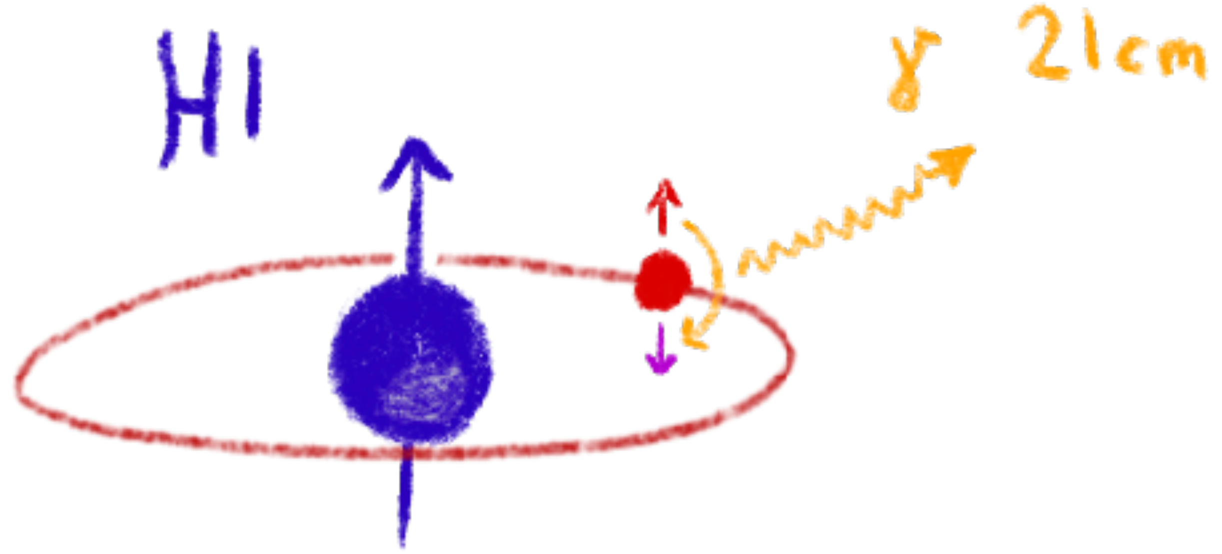
[Widmark, MK, Linden, 2022]

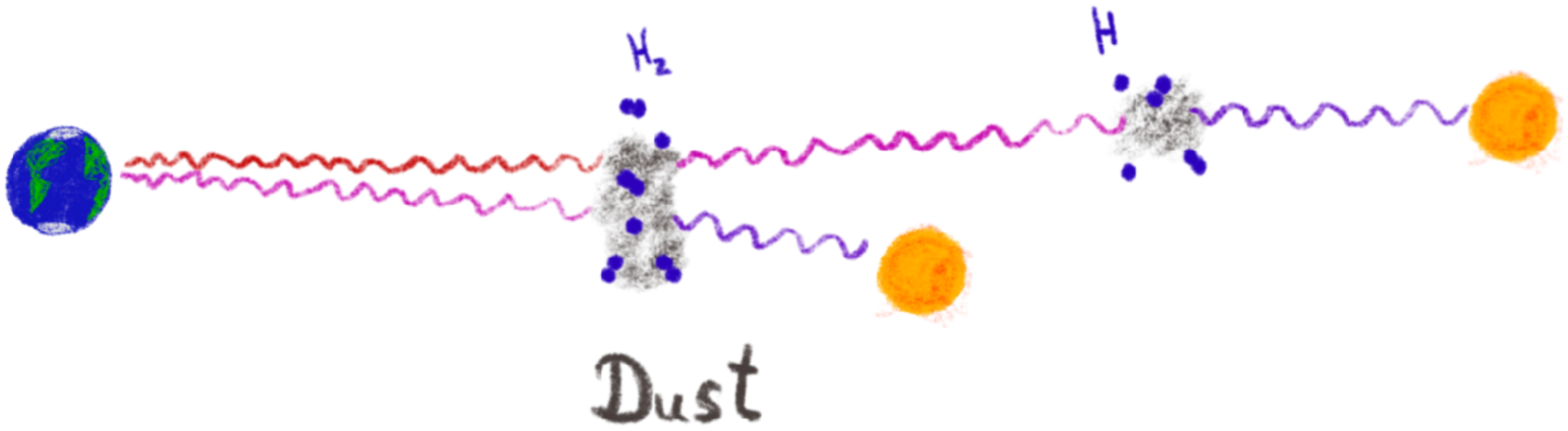
$$\epsilon^{ij}(E_\gamma, \boldsymbol{x}) = \int \mathrm{d}E_i \frac{\mathrm{d}\phi^i_{\rm CR}}{\mathrm{d}E_i}(E_i, \boldsymbol{x}) \frac{\mathrm{d}\sigma_{ij\to\gamma}}{\mathrm{d}E_\gamma}(E_i, E_\gamma)$$

$$\frac{\mathrm{d}^2\phi^{ij}_\gamma}{\mathrm{d}\Omega \mathrm{d}E_\gamma}(E_\gamma, \theta, \phi) = \int_{\rm l.o.s.} \mathrm{d}\ell \rho_j(\boldsymbol{x}) \epsilon^{ij}(E_\gamma, \boldsymbol{x})$$

Gas Tracers

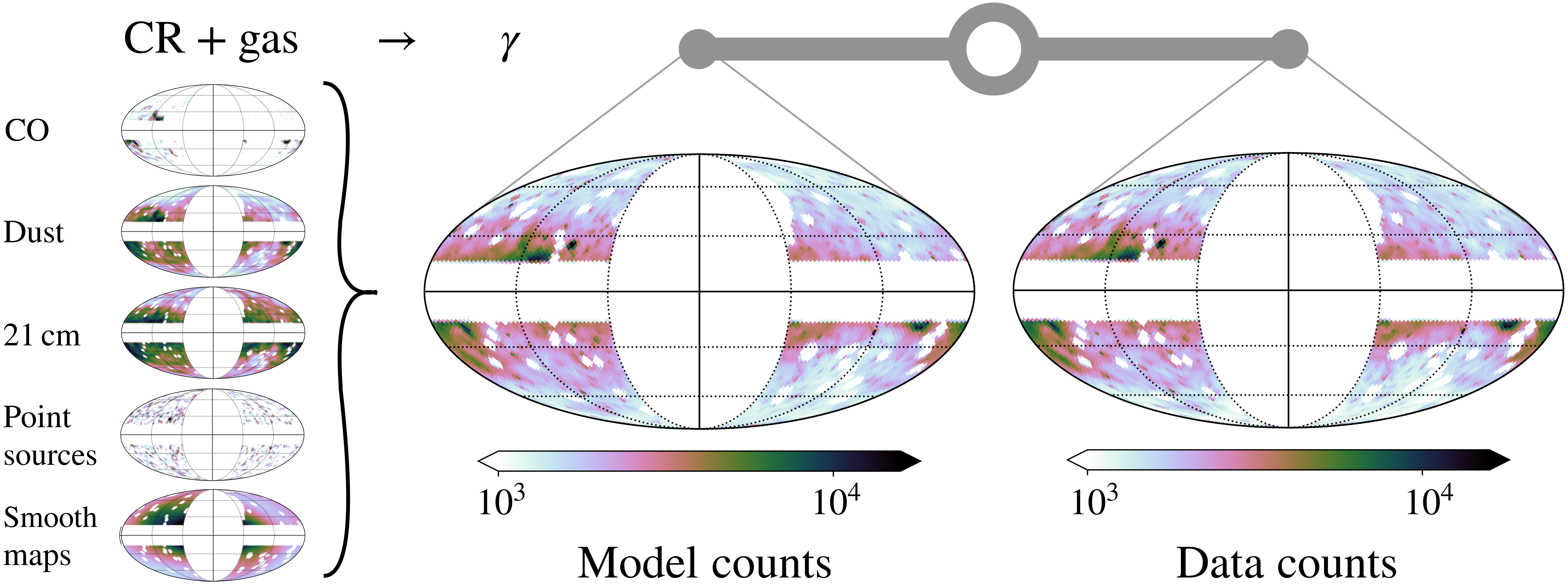
		CO H_2	CNM H_2	CNM HI	WNM HI
Model A	CO	✓			
	Dust		✓	✓	
	21 cm			✓	✓
Model B	CO	✓			
	Dust		✓	✓	
	f_{WNM}				✓



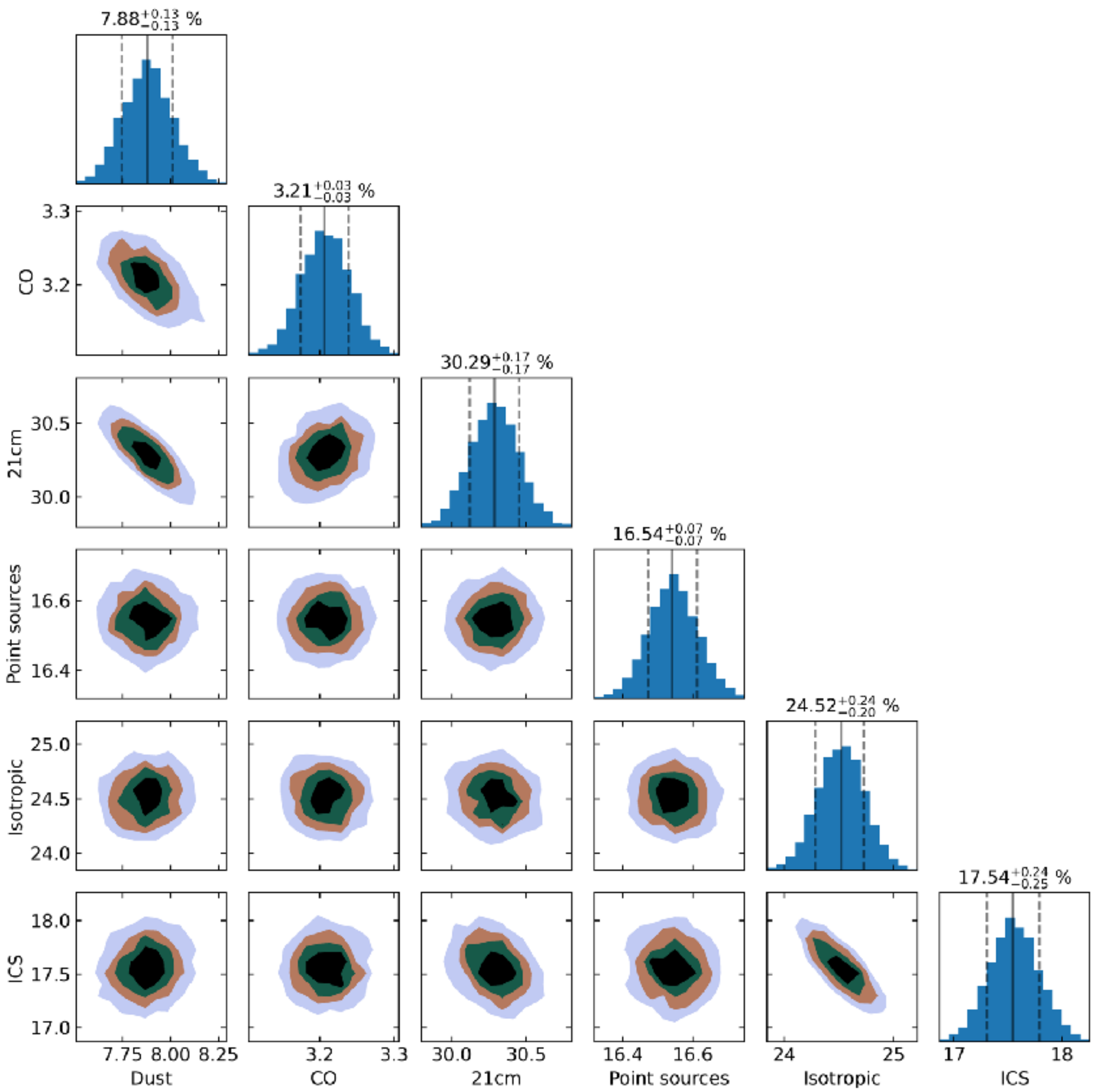


[Widmark, MK, Linden, 2022]

Connection to Gas Maps

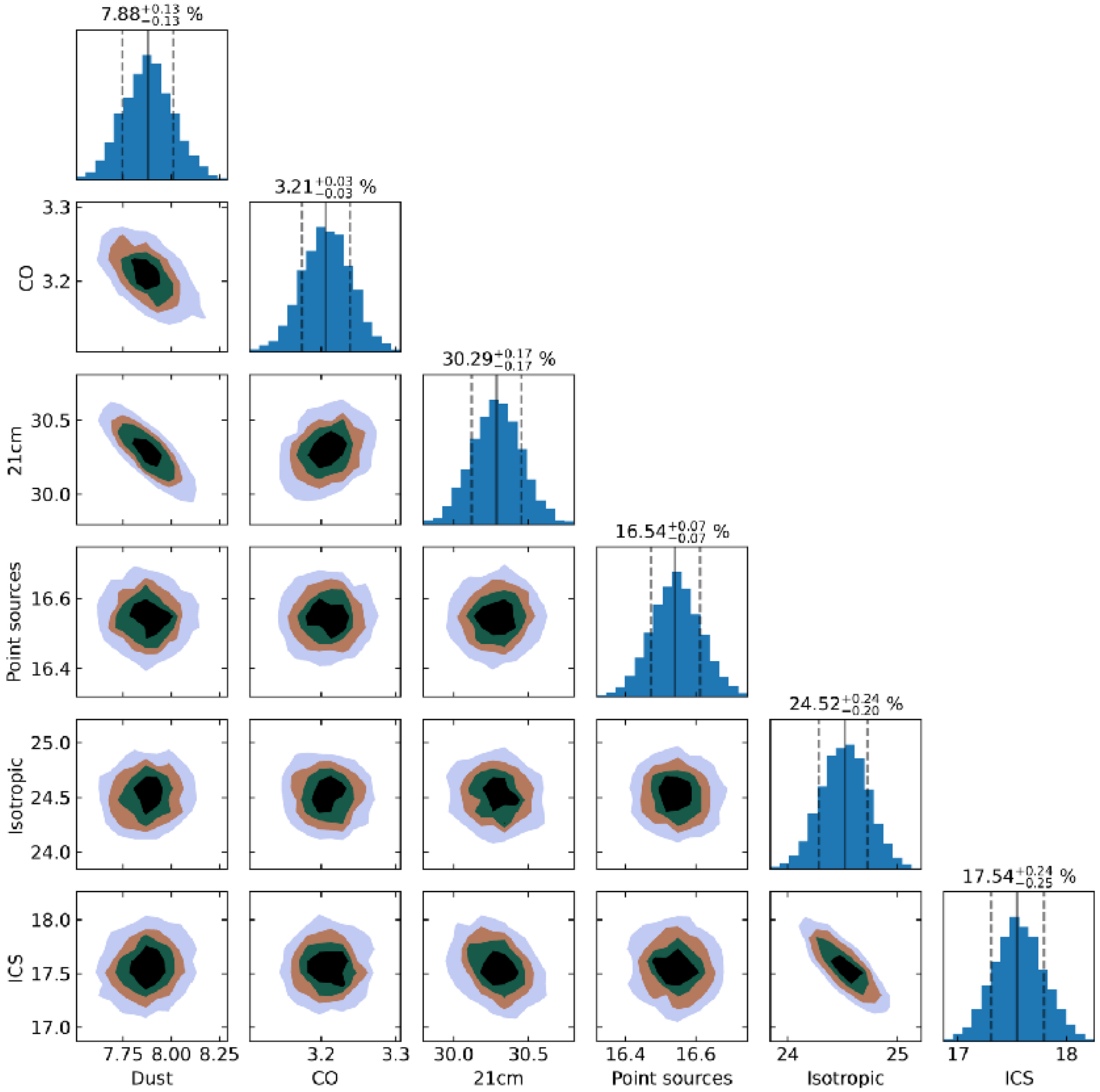


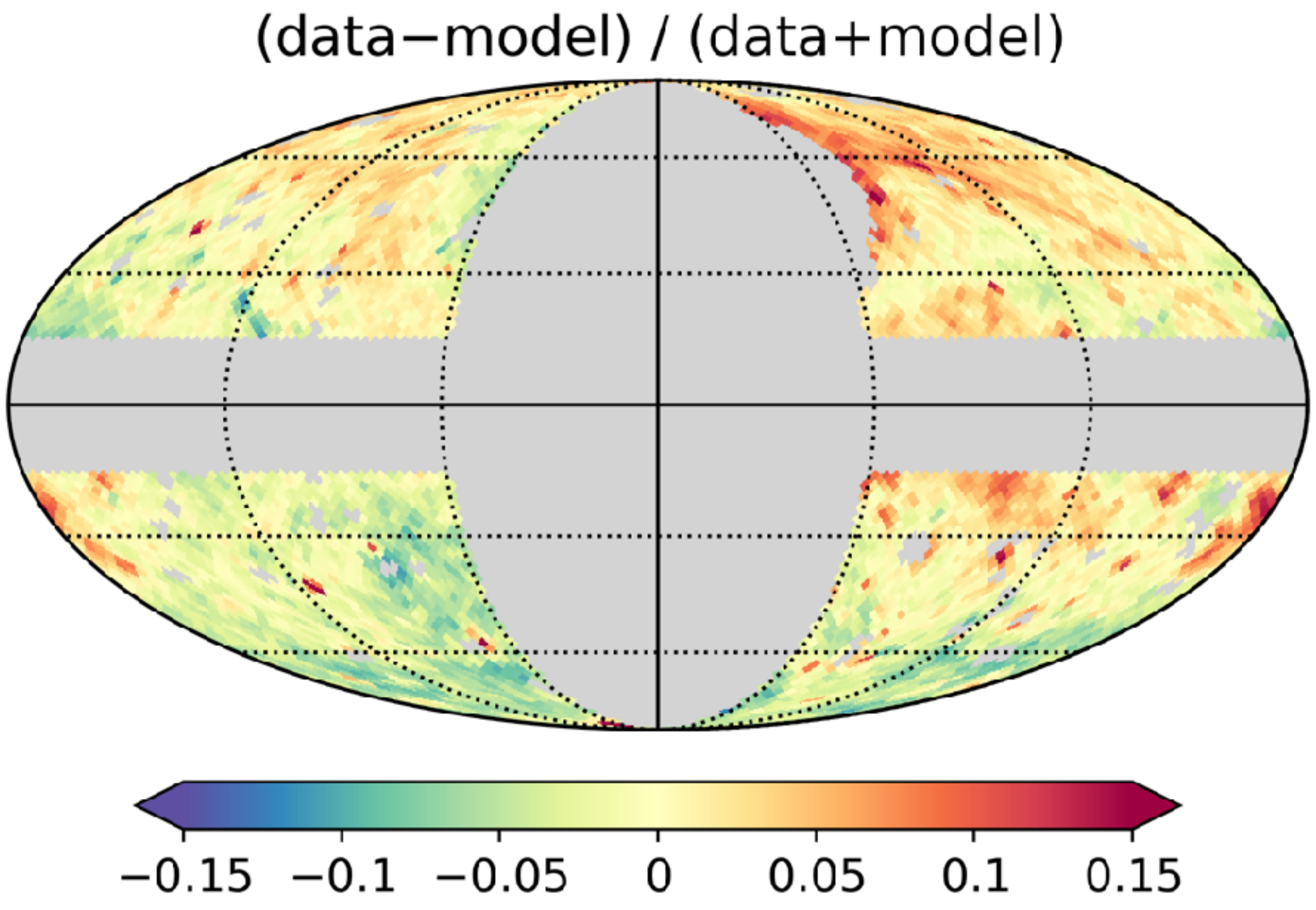
Template Fit



[Widmark, MK, Linden, 2022]

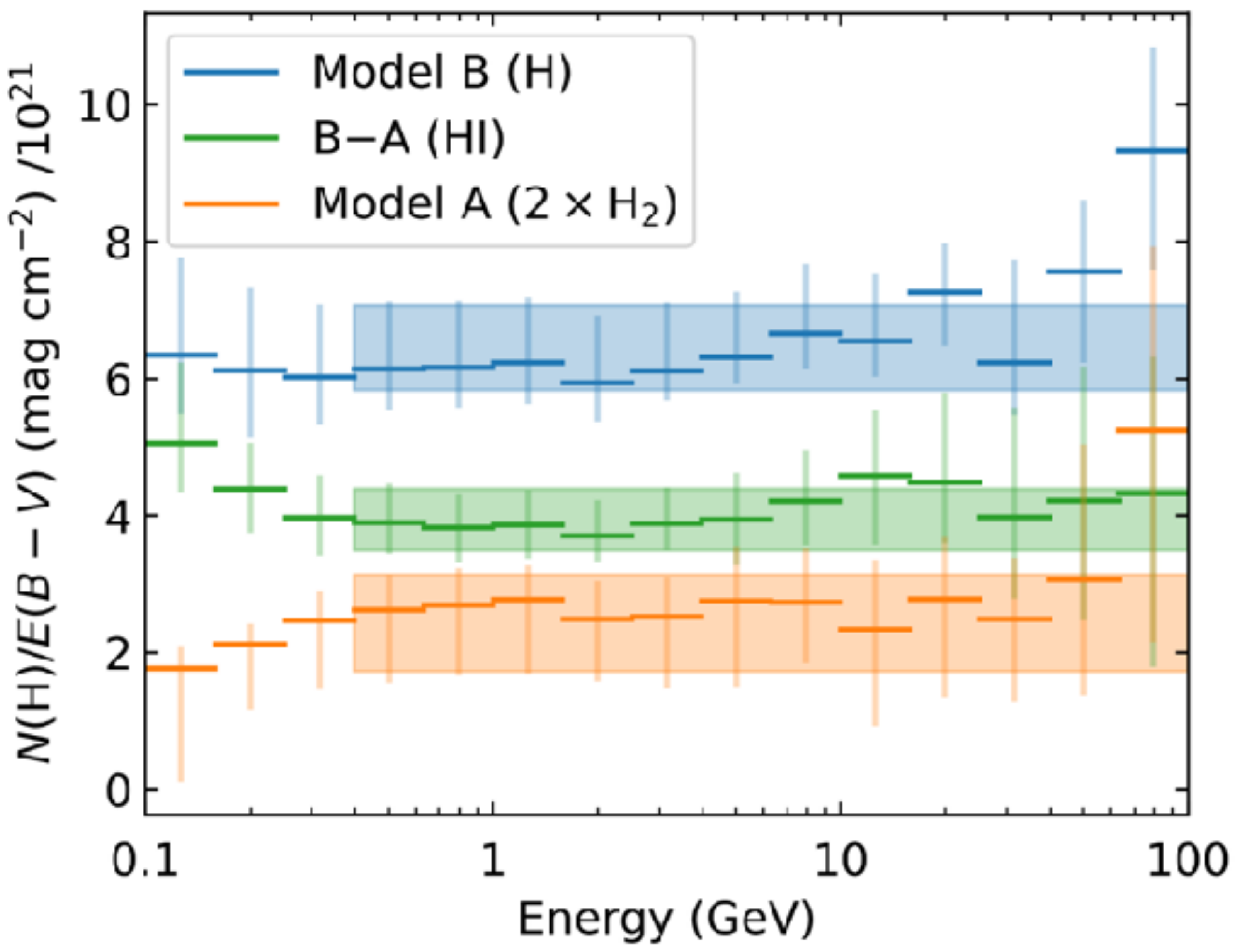
Template Fit



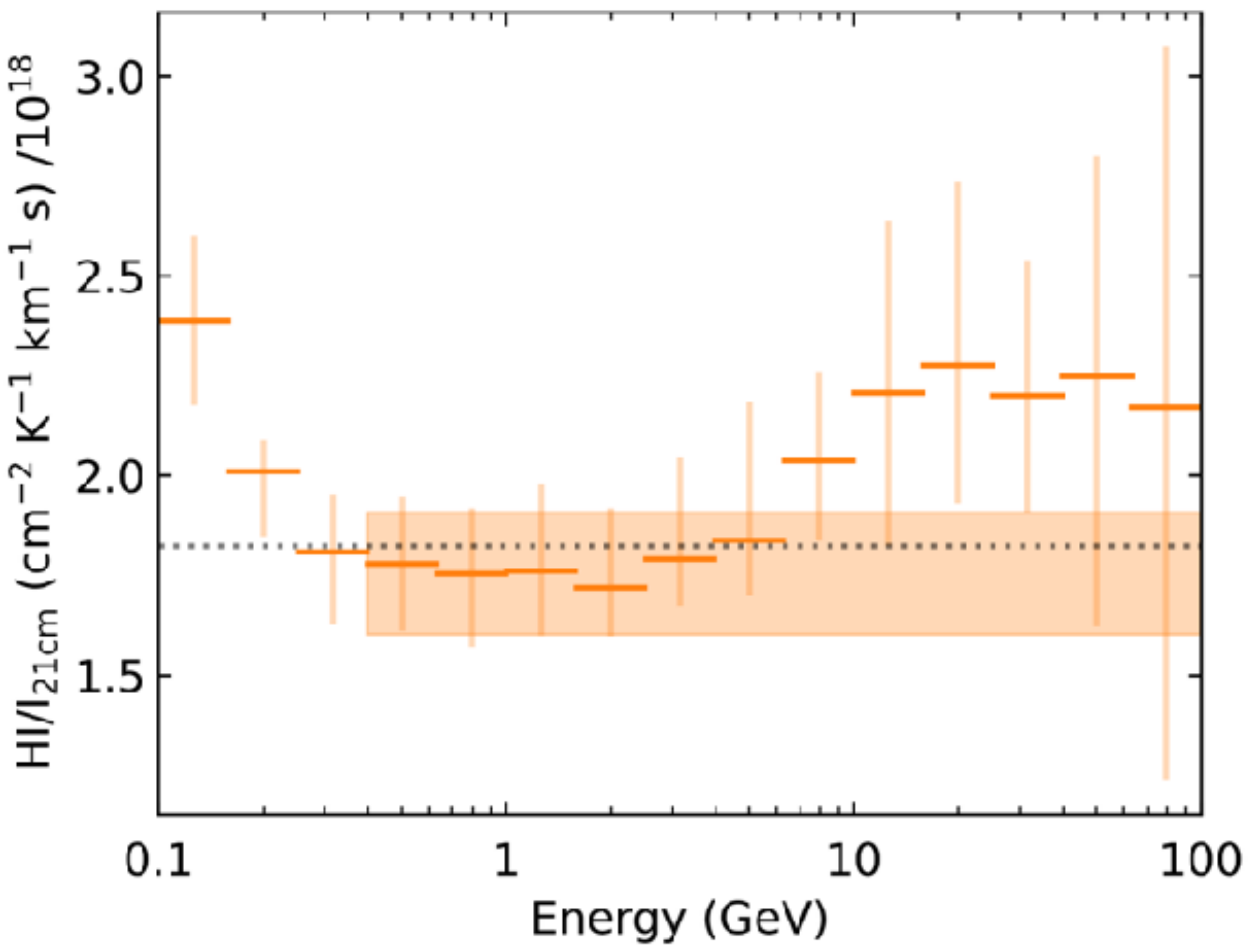


Results for the Gas Components

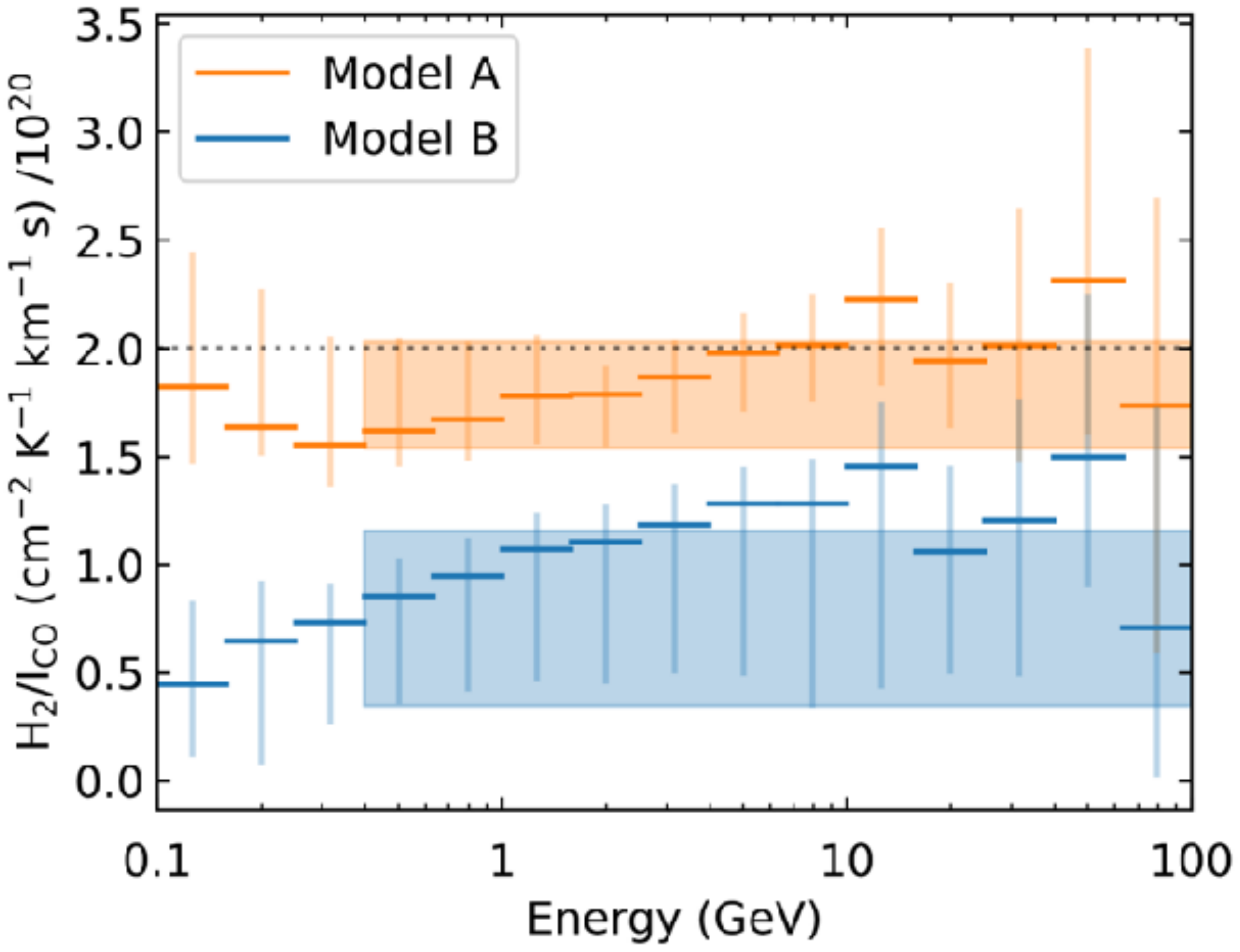
Dust reddening → H density



21 cm Intensity → HI density



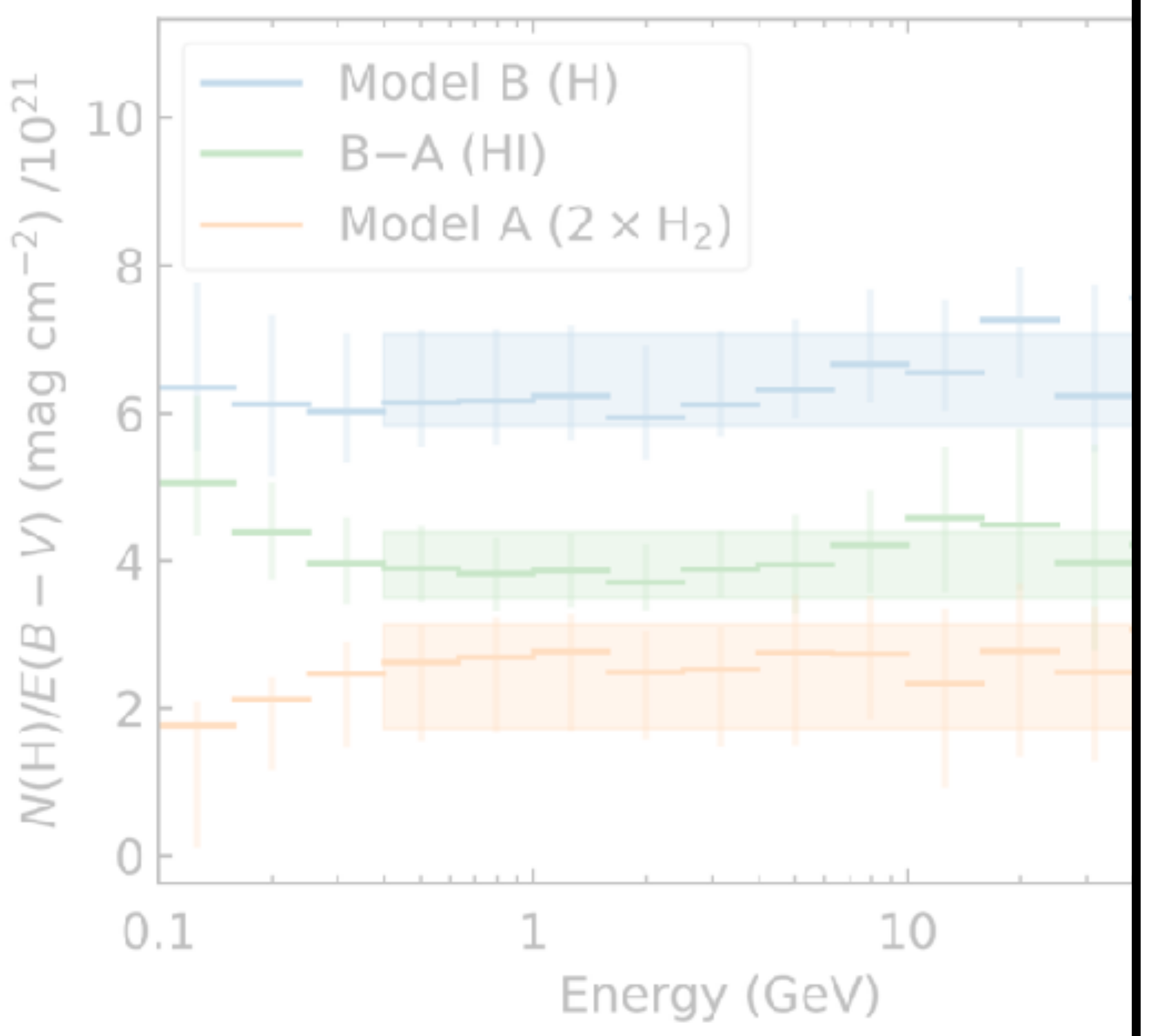
CO → H_2 density

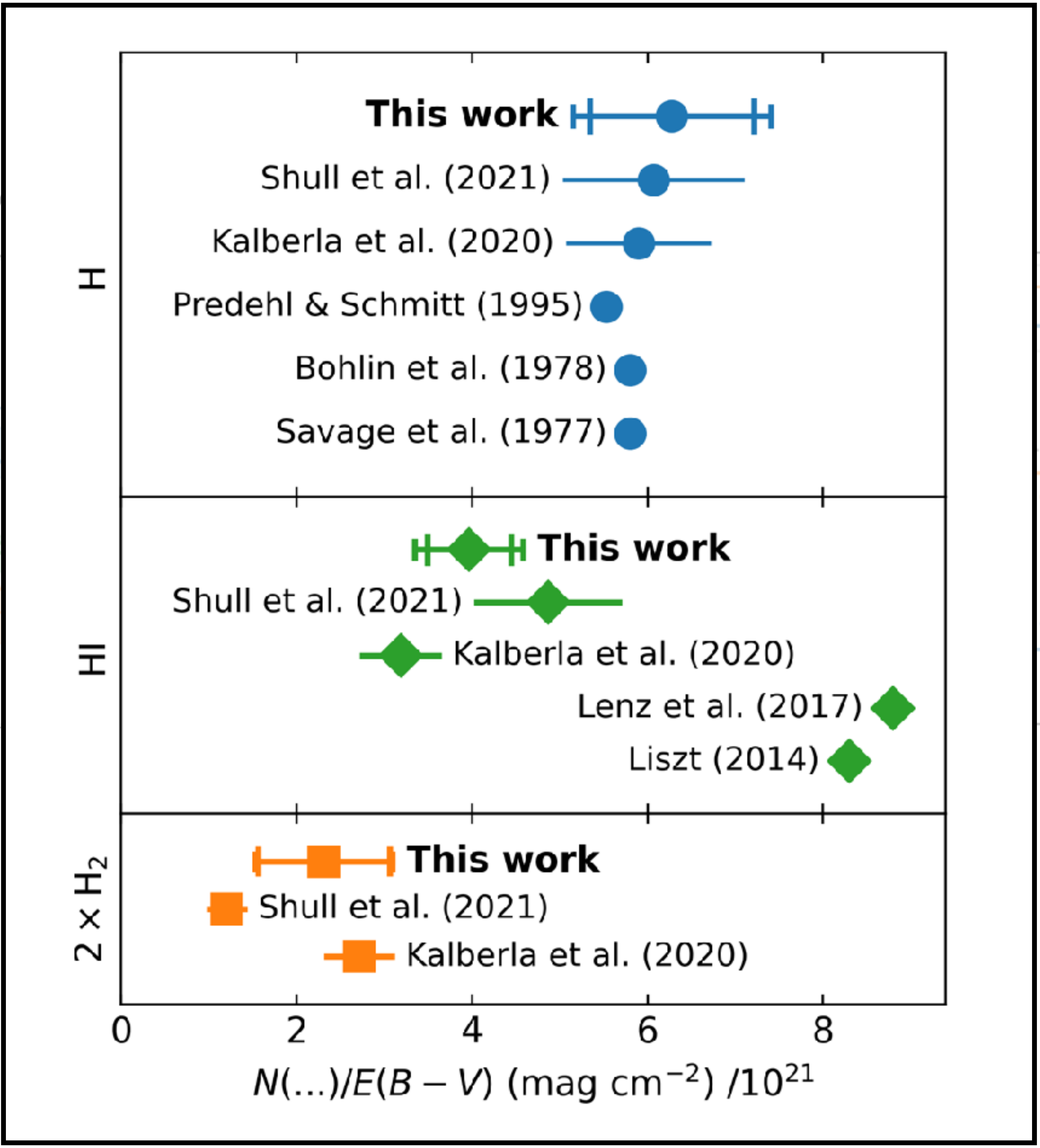


[Widmark, MK, Linden, 2022]

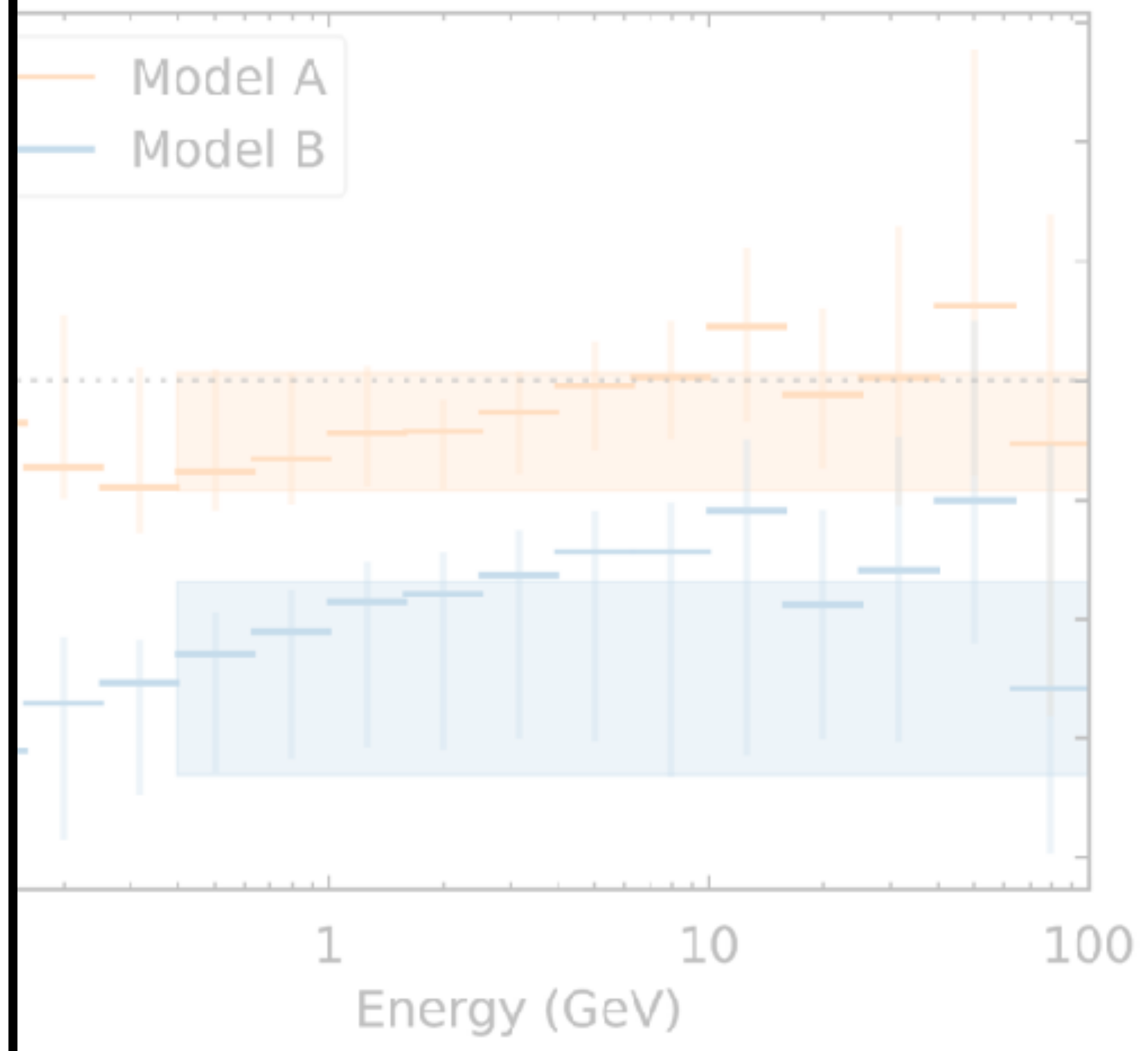
Results for the Gas Components

Dust reddening → H density



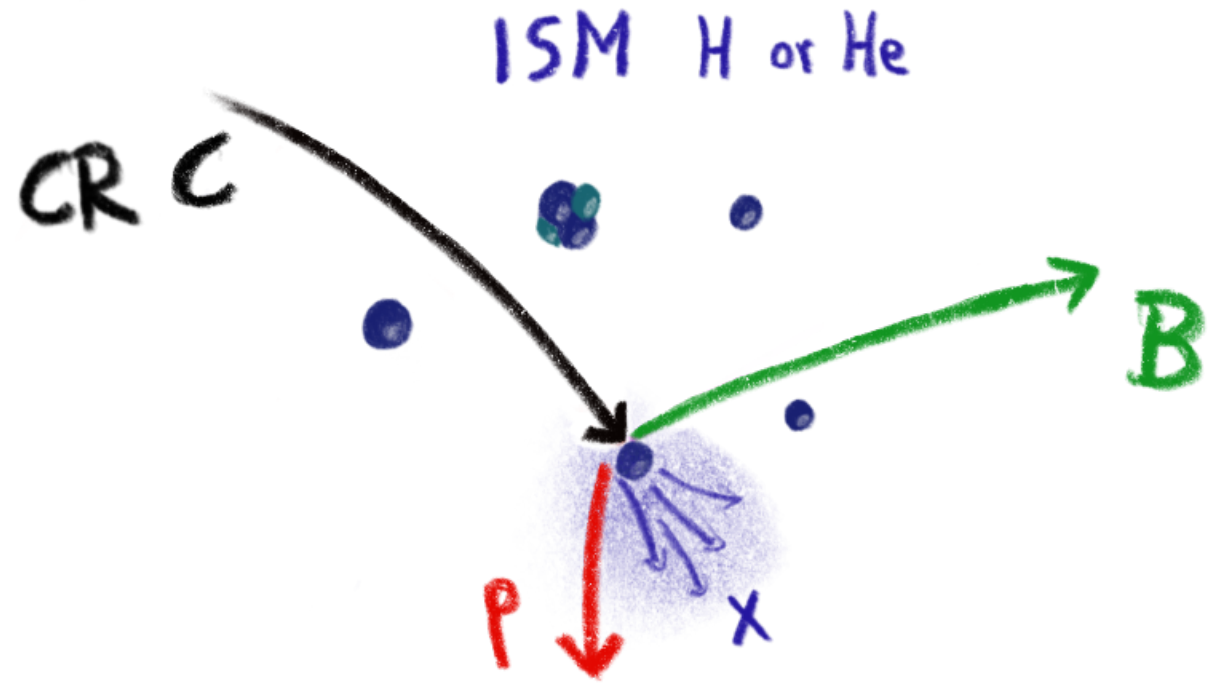


CO → H_2 density

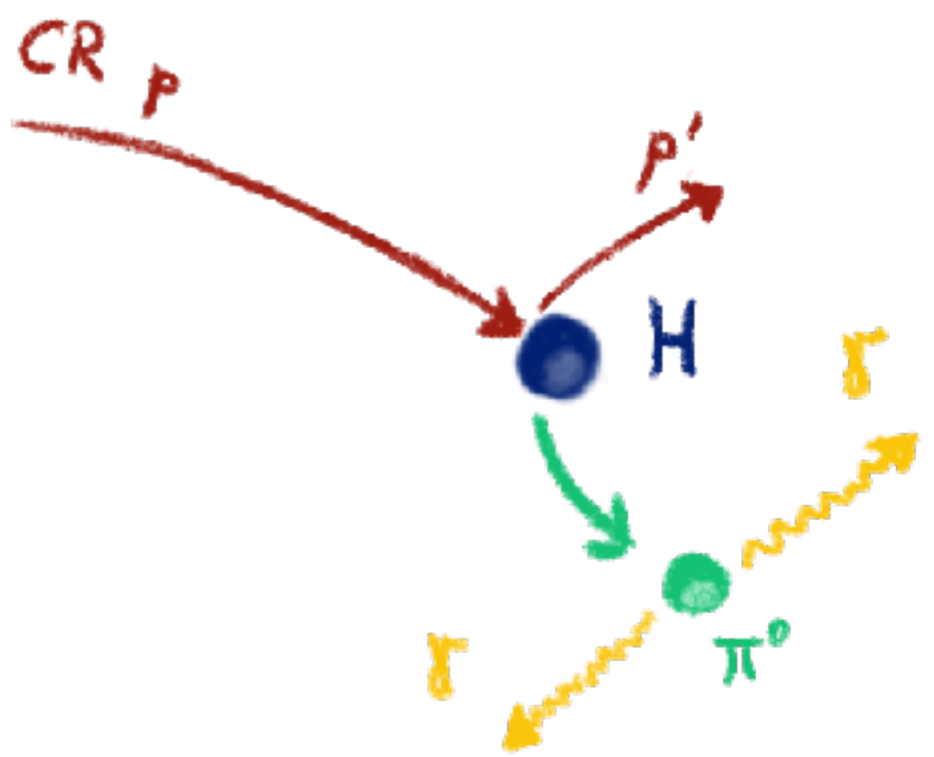


Summary

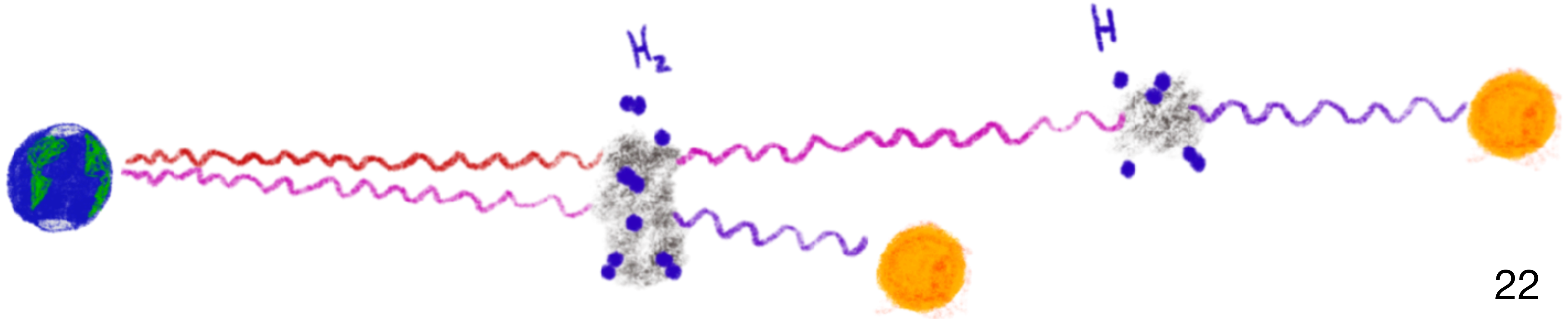
Cosmic rays are provided with unprecedented precision by AMS-02



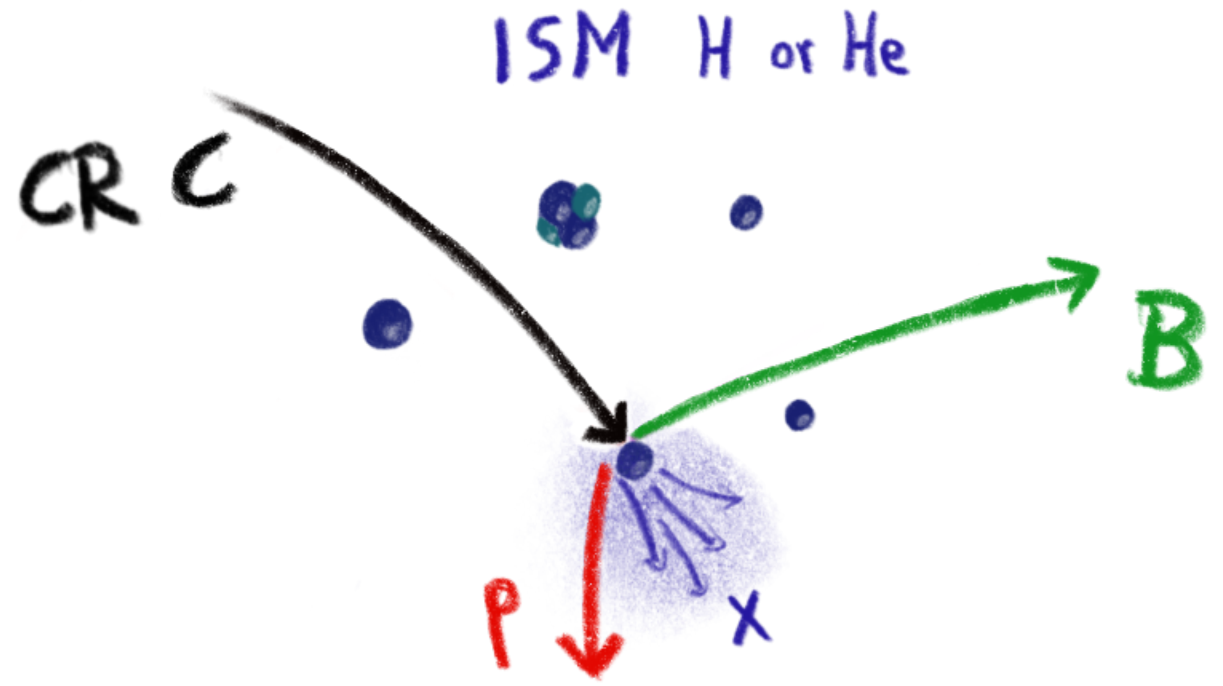
Diffusion models explain spectra of cosmic-ray nuclei and electrons/positrons

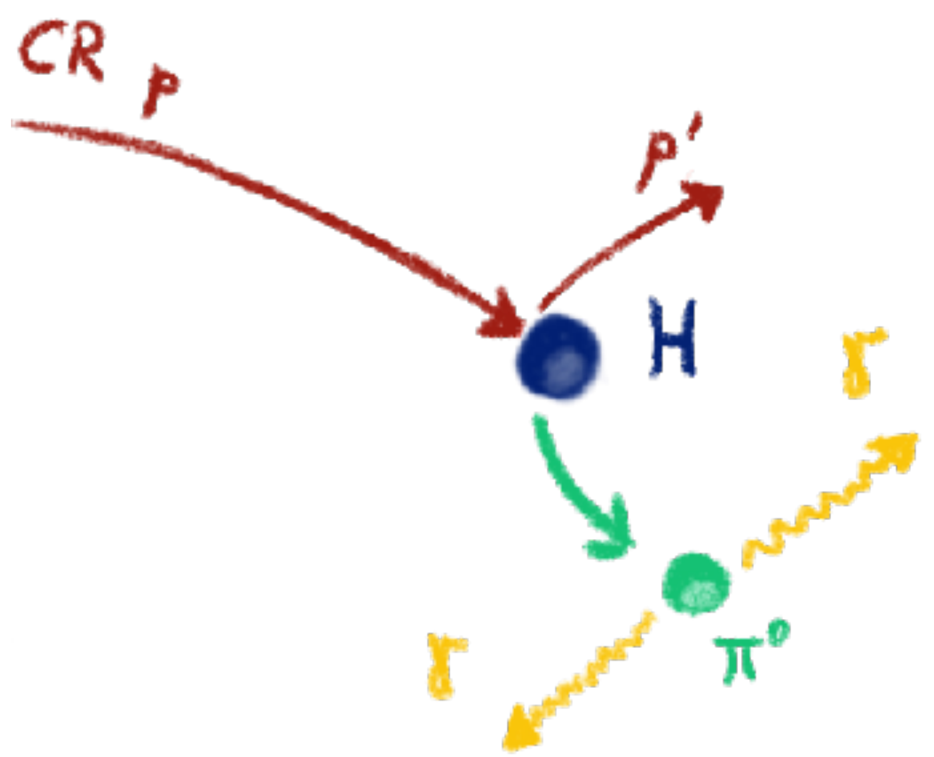


We can study our local environment using the combination of cosmic rays and gamma-rays

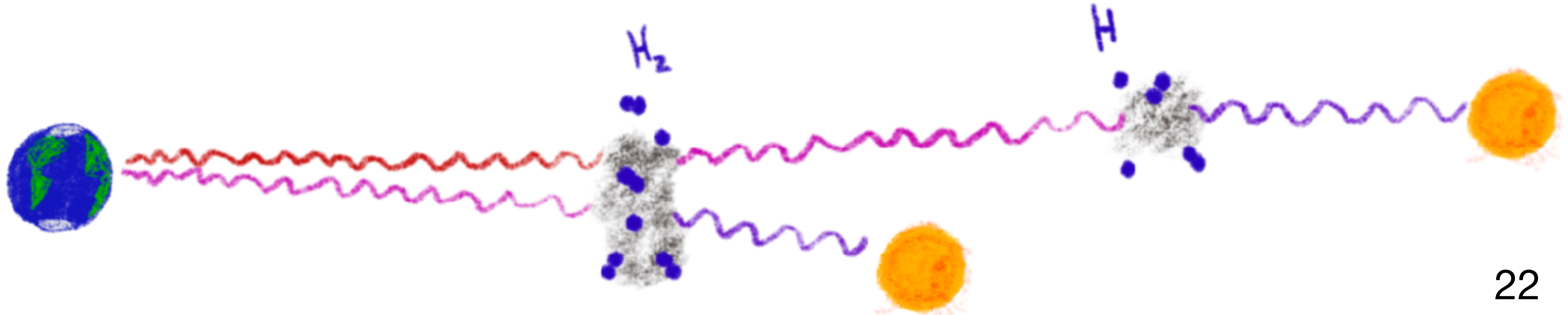


Summary

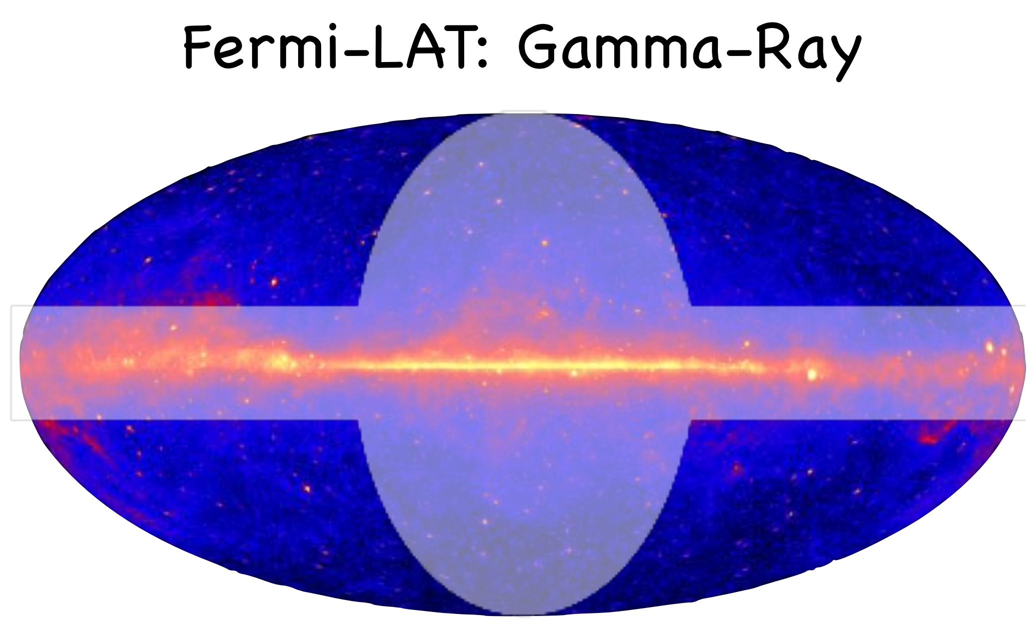


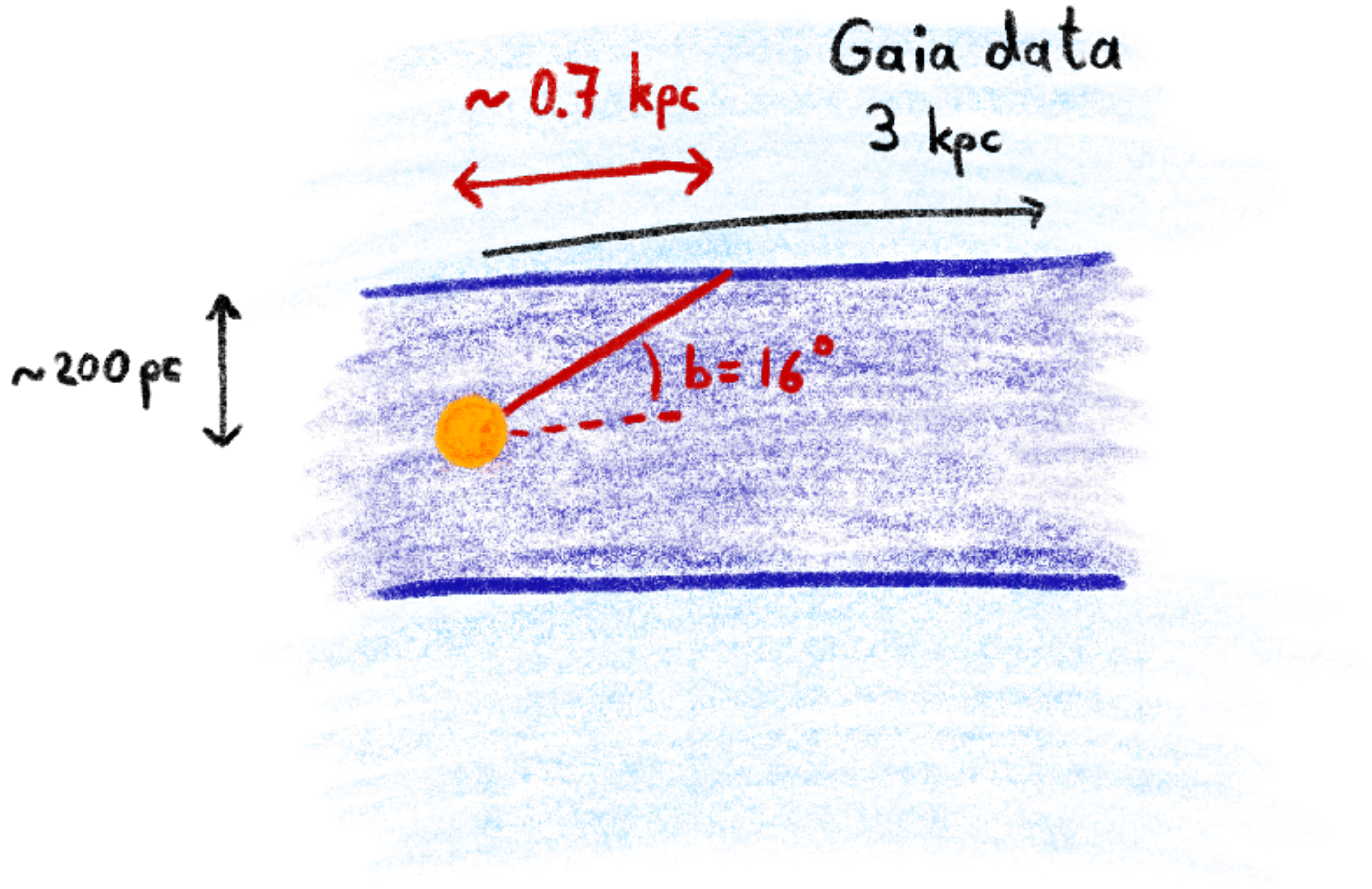


Thank you for your attention!



Why High Latitudes?





- Focus on the local Galaxy reduces systematics from CRs
- Avoid Galactic point sources
- Exclude *Fermi* Bubbles