# Diffuse gamma-ray Emission

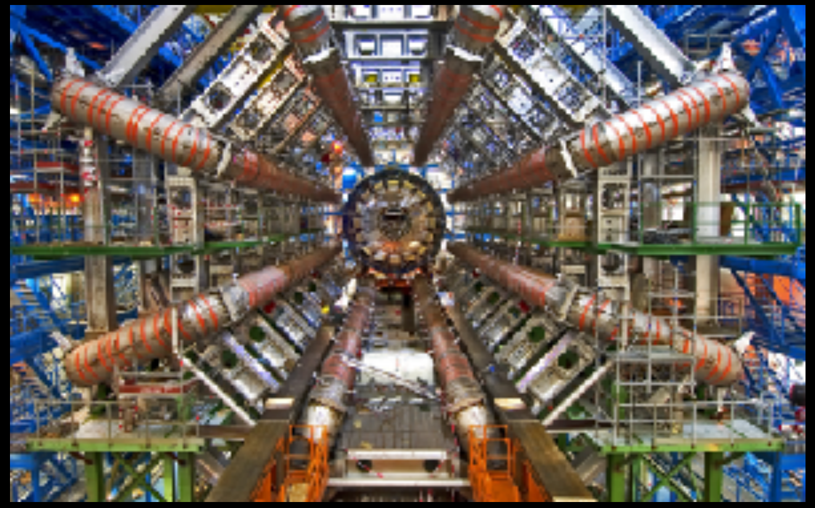
## Cosmic-Ray Acceleration, Propagation, and Emission

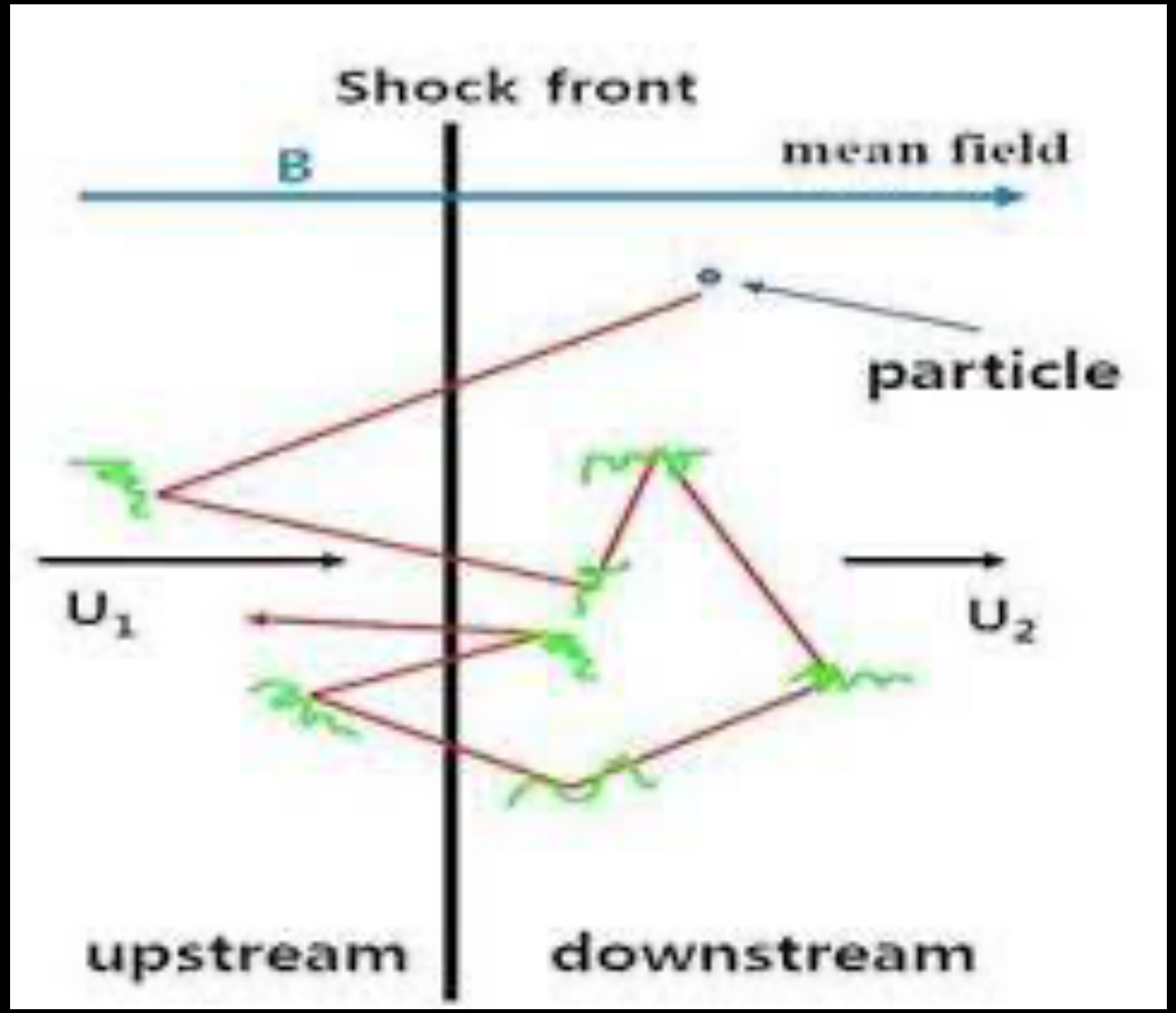
**Tim Linden — Fermi Summer School, 2023**

# Overview


$\pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm}$
SNR
p,e$^-$
Sun
p
$\tilde{\chi}$
e$^-$
e$^+$
$\tilde{\chi}$

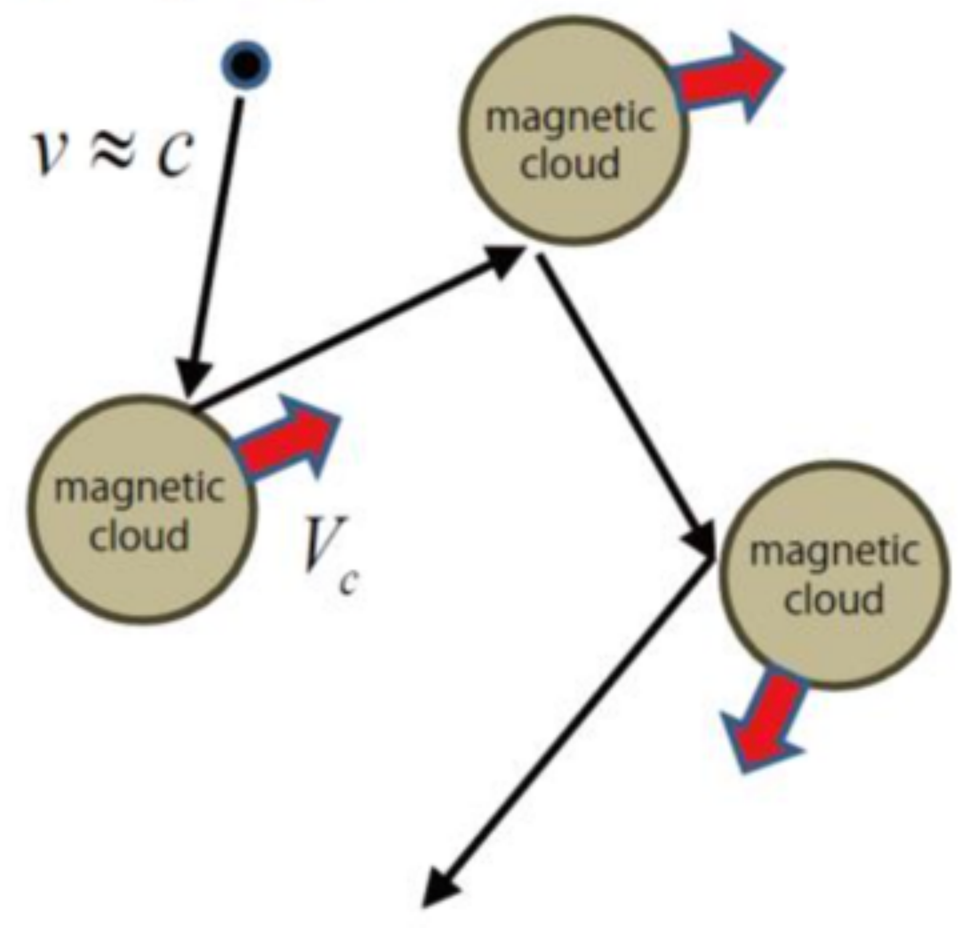
# Cosmic-Ray Acceleration





- First Order Fermi Acceleration
  - Charged particles moving in an outgoing shock front
  - Reflected by stationary turbulence in ISM -> energy gain
  - Re-enter shock front and reflect -> more energy gain!

$$\frac{dN(\epsilon)}{d\epsilon} \propto \epsilon^{-p}$$



- Second order Fermi acceleration
  - Similar to 1st Order Fermi acceleration, but particle is in the ISM and bounces off of randomly moving shocks.
  - More bounces with incoming clouds -> net energy gain
  - Second order in energy gain per collision (due to bounces off of retreating clouds)

# Cosmic-Ray Acceleration - Not Stars

- The maximum energy of first-order Fermi acceleration depends on the magnetic field strength and the shock velocity:

$$E_{\mathrm{max}} \simeq \alpha \left(\frac{n_{\mathrm{ISM}}}{\mathrm{cm}^{-3}}\right)^{\frac{1}{2}} \left(\frac{v_{\mathrm{sh}}}{10^3\ \mathrm{km\ s}^{-1}}\right)^2 \left(\frac{R_{\mathrm{sh}}}{\mathrm{pc}}\right)\ \mathrm{GeV}$$

- With $\alpha \sim 10^3$

- For the Sun (coronal mass ejection)
  - $n_{ISM} = 10^8\ \mathrm{cm}^{-3}$
  - $v_{sh} = 200\ \mathrm{km\ s}^{-1}$
  - $R_{sh} = 100\ \mathrm{R}_\odot$

Which gives us an energy around 1 GeV:

$$E_{max} = 10^3 \times 10^4 \times 0.2^2 \times 2.5 \times 10^{-6} \approx 1\ \mathrm{GeV}$$

Diesling 2023 (2305.07697)

# Supernova Remnants

- The maximum energy of first-order Fermi acceleration depends on the magnetic field strength and the shock velocity:

$$E_{\rm max} \simeq \alpha \left(\frac{n_{\rm ISM}}{\rm cm^{-3}}\right)^{\frac{1}{2}} \left(\frac{v_{\rm sh}}{10^3\ {\rm km\ s^{-1}}}\right)^{2} \left(\frac{R_{\rm sh}}{\rm pc}\right)\ {\rm GeV}$$

- With $\alpha \sim 10^3$

- For a supernova remnant:
  - $n_{ISM} = 10^0\ \mathrm{cm}^{-3}$
  - $v_{sh} = 10^4\ \mathrm{km\ s}^{-1}$
  - $R_{sh} = 10\ \mathrm{pc}$

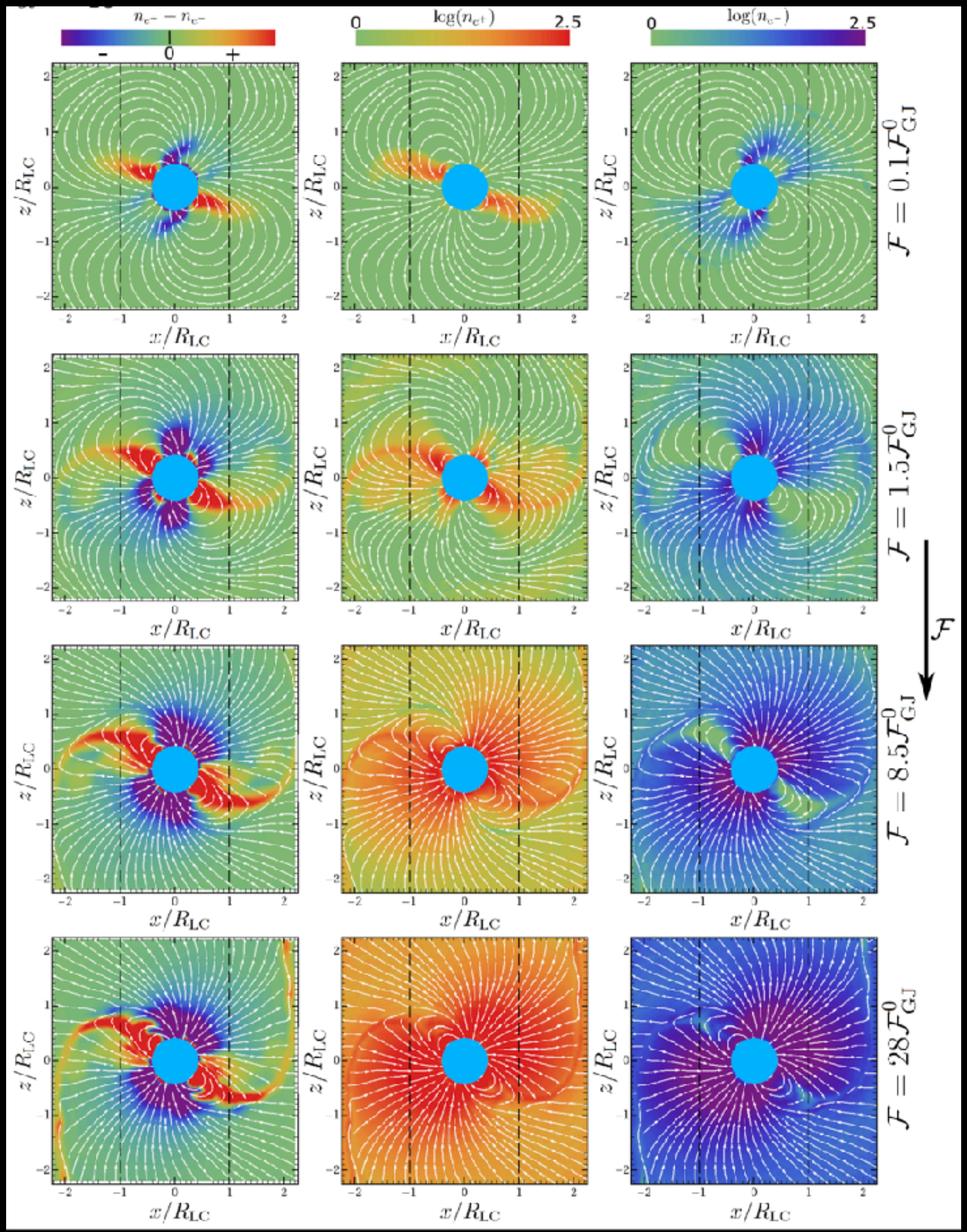
Which gives us an energy around 1 GeV:

$$E_{max} = 10^3 \times 1 \times 10^2 \times 10 = 1\ \mathrm{PeV}$$

Diesling 2023 (2305.07697)

# Pulsars/Pulsar Wind Nebulae

- Critical $e^+e^-$ creation point is the pulsar magnetosphere.
  - 1.) Electrons “boiled” off the pulsar surface, and accelerated to TeV-PeV energies.
  - 2.) Synchrotron emission produces $e^+e^-$ pairs which then cascade to produce a high $e^+e^-$ multiplicity.



# Pulsars/Pulsar Wind Nebulae

Blandford & Ostriker (1978)
Hoshino et al. (1992)
Coroniti (1990)
Sironi & Spitkovsky (2011)

- PWN termination shock:
  - Voltage Drop > 30 PV
  - $e^+e^-$ energy > 1 PeV (known from synchrotron)
- Resets $e^+e^-$ spectrum.
- Many Possible Models:
  - 1st Order Fermi-Acceleration
  - Magnetic Reconnection
  - Shock-Driven Reconnection

# Cosmic-Ray Transport

Latex by Isabelle John

$$\overbrace{\frac{\partial \psi\left(\vec{r}, p, t\right)}{\partial t}}^{\text{flux}} = \overbrace{Q\left(\vec{r}, p, t\right)}^{\text{source}} + \vec{\nabla} \times ( \overbrace{D_{xx} \vec{\nabla} \psi}^{\text{diffusion}} - \overbrace{\vec{V} \psi}^{\text{convection}} ) + \overbrace{\frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p^2} \psi}^{\text{re-acceleration}}$$

$$- \underbrace{\frac{\partial}{\partial p} \left( \dot{p} \psi - \frac{p}{3} \left( \vec{\nabla} \times \vec{V} \right) \psi \right)}_{\text{energy loss}} - \frac{\psi}{\underbrace{\tau_f}_{\text{fragmentation}}} - \frac{\psi}{\underbrace{\tau_r}_{\text{radioactive decay}}}$$

- **Source term - inhomogeneous term of PDE**
- **Diffusion:**
  - **Kolmogorov:** $D \propto E^{-1/3}$
  - **Kraichnan:** $D \propto E^{-1/2}$
- **Reacceleration: Diffusion in momentum space**

# Cosmic-Ray Transport

Latex by Isabelle John

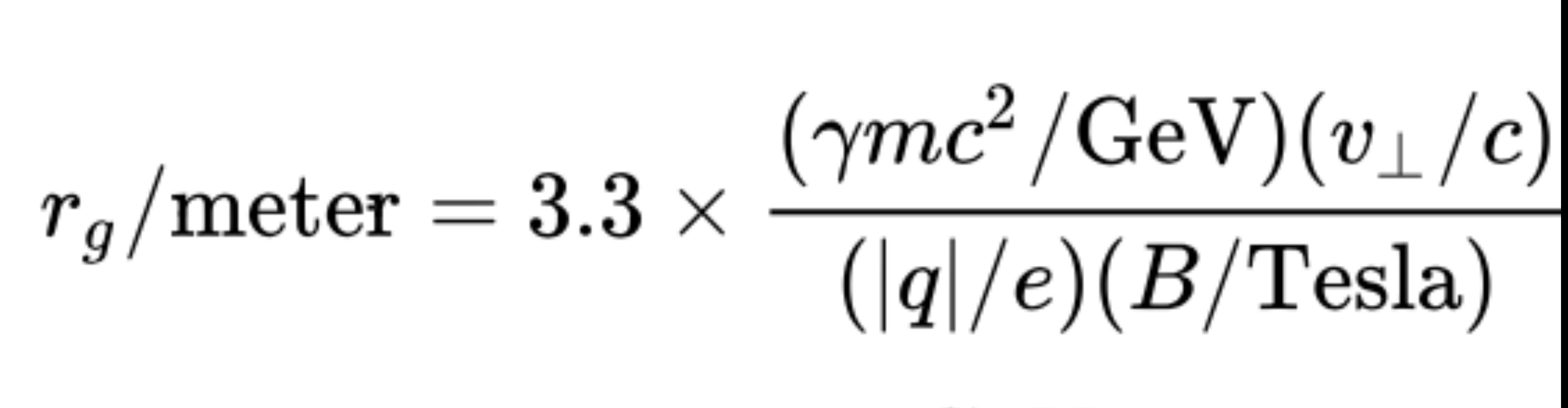
$$\overbrace{\frac{\partial\psi\left(\vec{r},p,t\right)}{\partial t}}^{\text{flux}} = \overbrace{Q\left(\vec{r},p,t\right)}^{\text{source}} + \vec{\nabla}\times( \overbrace{D_{xx}\vec{\nabla}\psi}^{\text{diffusion}} - \overbrace{\vec{V}\psi}^{\text{convection}} ) + \overbrace{\frac{\partial}{\partial p}p^2D_{pp}\frac{\partial}{\partial p^2}\psi}^{\text{re-acceleration}}$$

$$-\underbrace{\frac{\partial}{\partial p}\left(\dot{p}\psi-\frac{p}{3}\left(\vec{\nabla}\times\vec{V}\right)\psi\right)}_{\text{energy loss}} - \frac{\psi}{\underbrace{\tau_f}_{\text{fragmentation}}} - \frac{\psi}{\underbrace{\tau_r}_{\text{radioactive decay}}}$$

- **Convection: Winds driven by injection of cosmic-rays and relativistic gas from the Milky Way**
- **Energy Losses: (Next Section)**
- **Fragmentation: Nuclei can be split by interactions**
- **Radioactive Decay: For radioactive nuclei**

# Note About Scales

- Gyroradius of particles in a magnetic field is small:

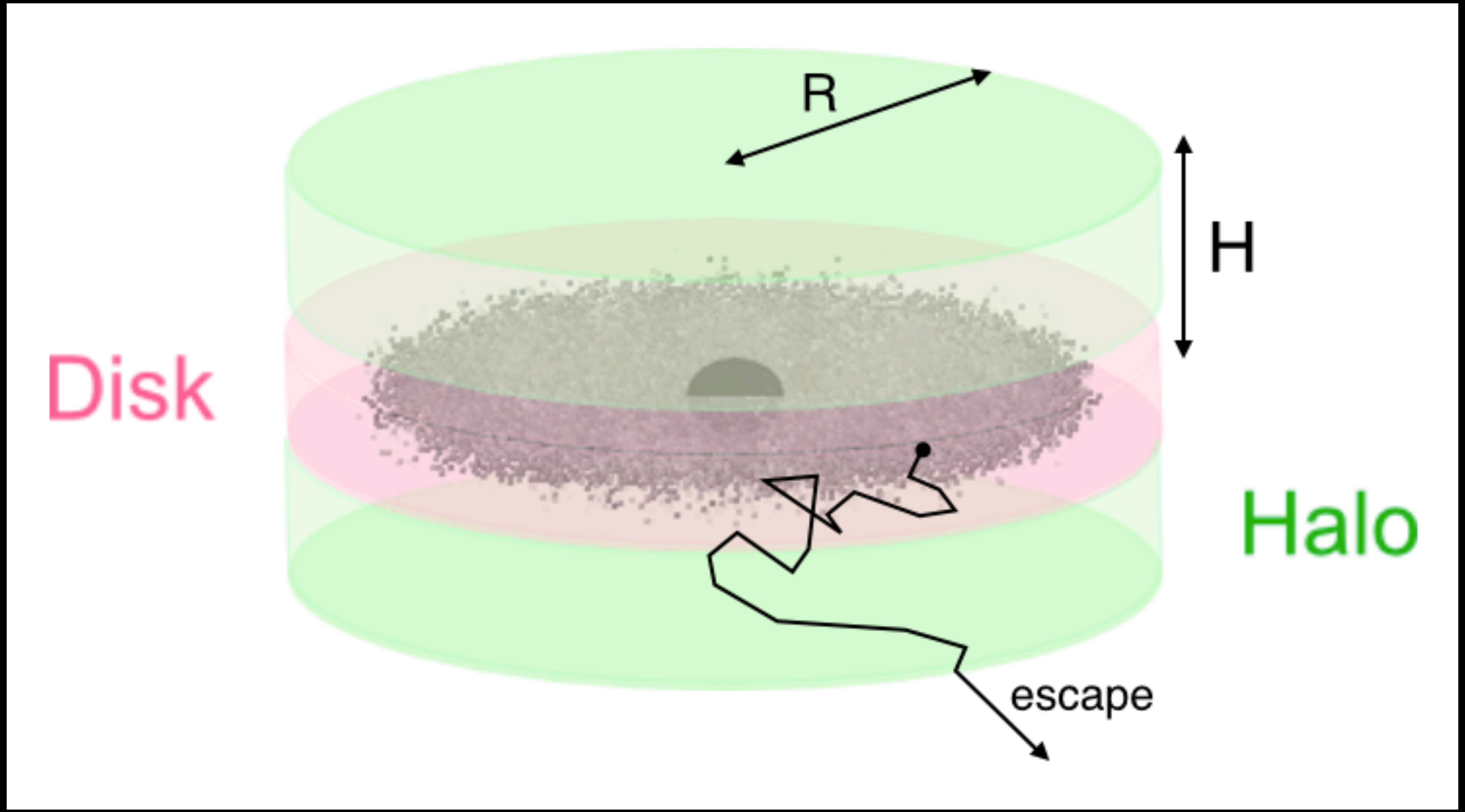


$$r_g/\text{meter} = 3.3 \times \frac{(\gamma m c^2/\text{GeV})(v_\perp/c)}{(|q|/e)(B/\text{Tesla})}$$

- "Stepsize" of particles diffusing through the Milky Way is large:
  - $D \approx 3 \times 10^{28}\ \frac{\text{cm}^2}{\text{s}} \rightarrow l = \frac{D}{c} = \frac{D}{3 \times 10^{10}\ \text{cm s}^{-1}} = 10^{18}\ \text{cm} = 0.3\ \text{pc}$

- On small scales - particles are locked into the preferential direction of the local field.

# Leaky Box Model

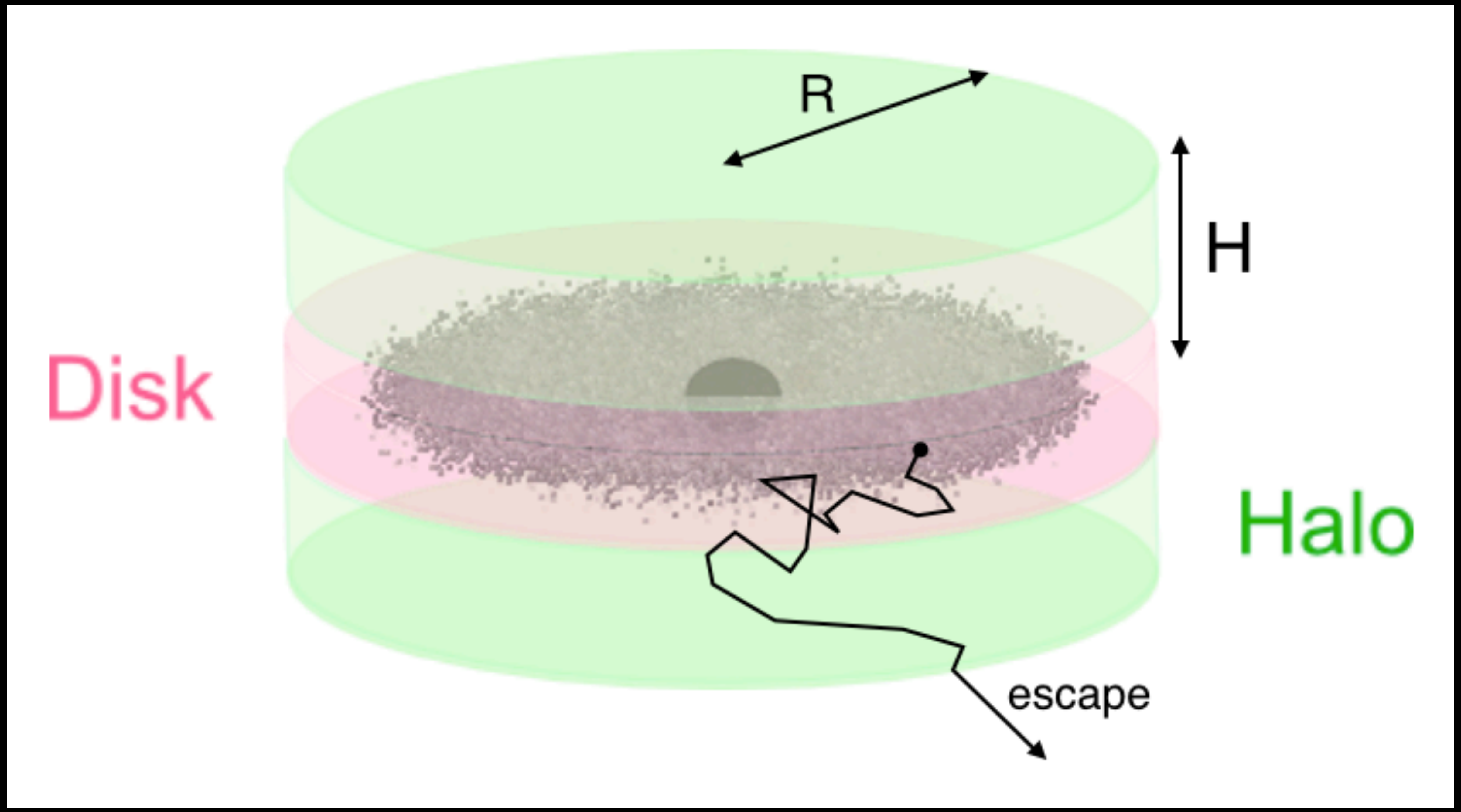


- Cosmic-Rays produced in the thin disk, and diffuse until they leave the thick disk (halo)

- Thin Disk is ~100 pc
- Thick disk is ~5 kpc
- Radius of Milky Way is ~20 kpc

# Leaky Box Model

- Cosmic-Rays produced in the thin disk, and diffuse until they leave the thick disk (halo)



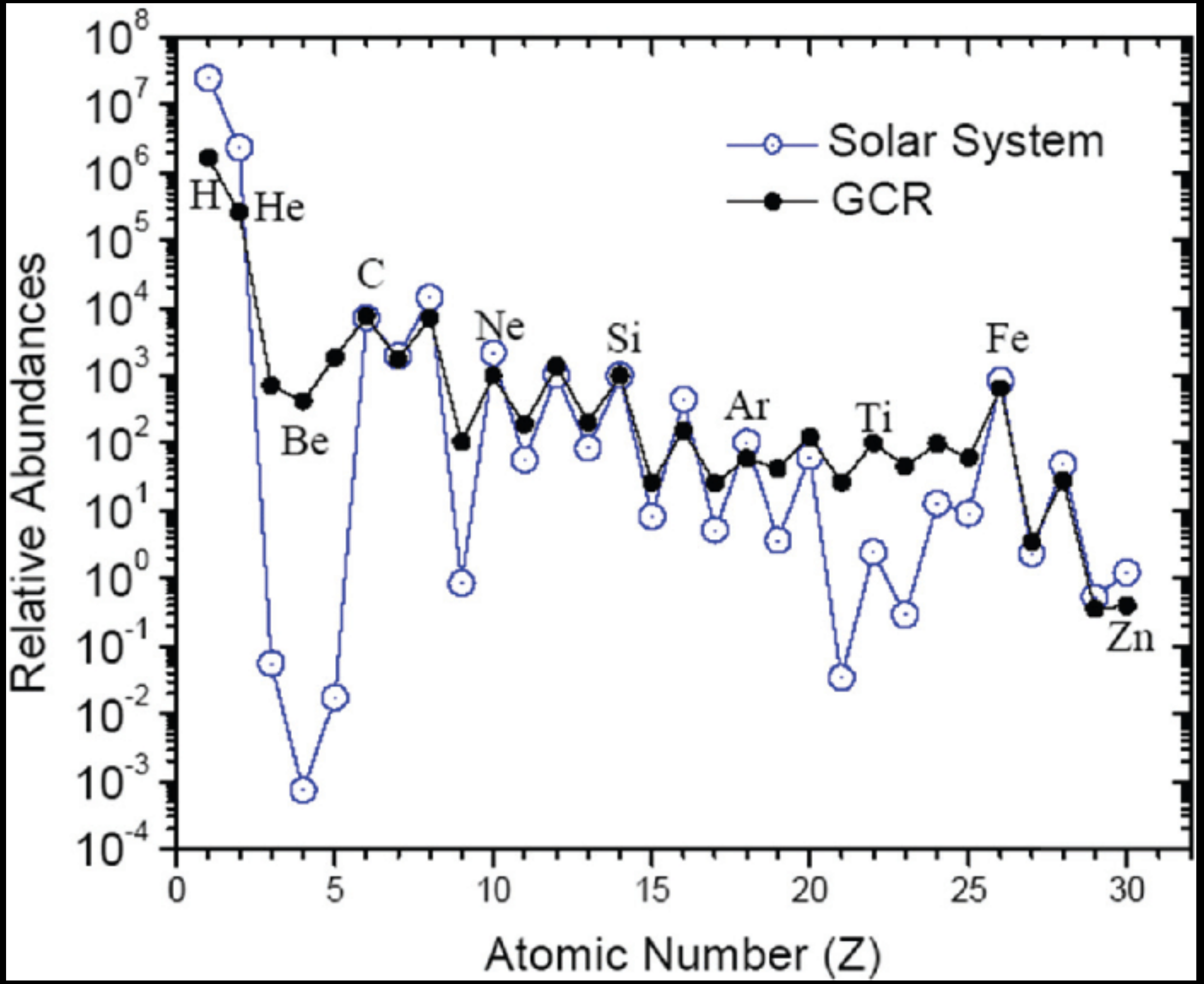
- Residence time: $\sim 10\ \mathrm{Myr}\left(\frac{E}{1\mathrm{GeV}}\right)^{-1/3}$
- Interaction probability: $\sim 10\ \mathrm{Myr}\ \sigma_{pp}\left(\frac{V_{disk}}{V_{halo}}\right)\left(\frac{E}{1\mathrm{GeV}}\right)^{-1/3}$

# Calorimetry

- Fraction of cosmic-rays that have an interaction before leaving the medium.
- Calorimetric fraction of 1 means that cosmic-rays undergo one e-fold of interactions.
- Milky Way - Average cosmic ray proton has calorimetric fraction of 0.1
- Star-forming Galaxy (e.g., NGC 253) calorimetric fraction >1.

# Primary Cosmic Rays

- Primary cosmic rays are those that are produced in the final stages of stellar evolution, and thus efficiently accelerated in supernova explosions/ SNR



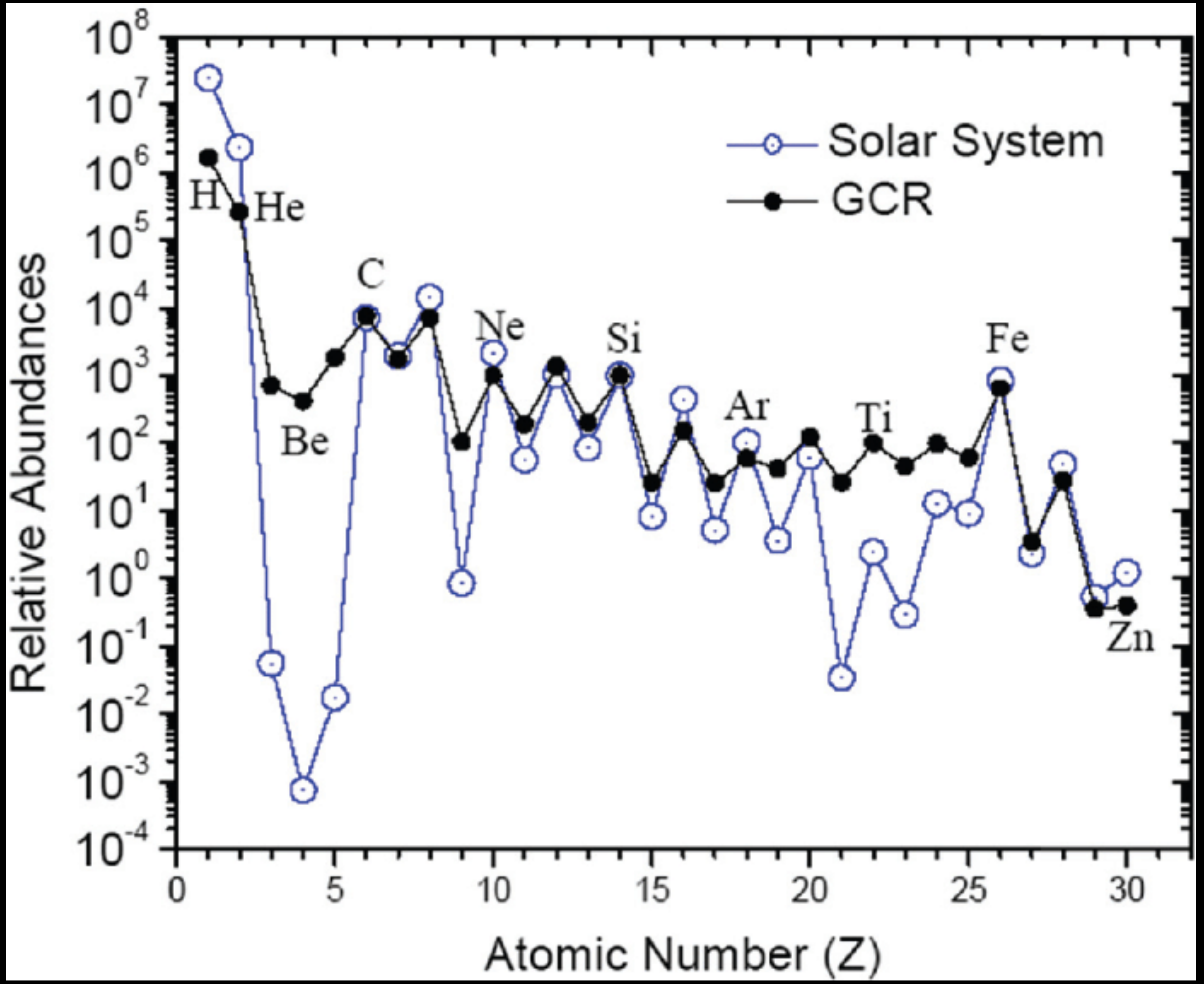
- H/He/C/O/Ne/Si/Fe

- Models of stellar nuclear synthesis provide these elements (e.g., CNO cycle)

- Local Spectrum: $E^{-p-\delta} = E^{-2.X-0.Y} = E^{-2.7}$

# Secondary Cosmic Rays

- Secondary cosmic rays are not directly produced in supernovae, but are instead produced via the spallation of heavier cosmic-rays.

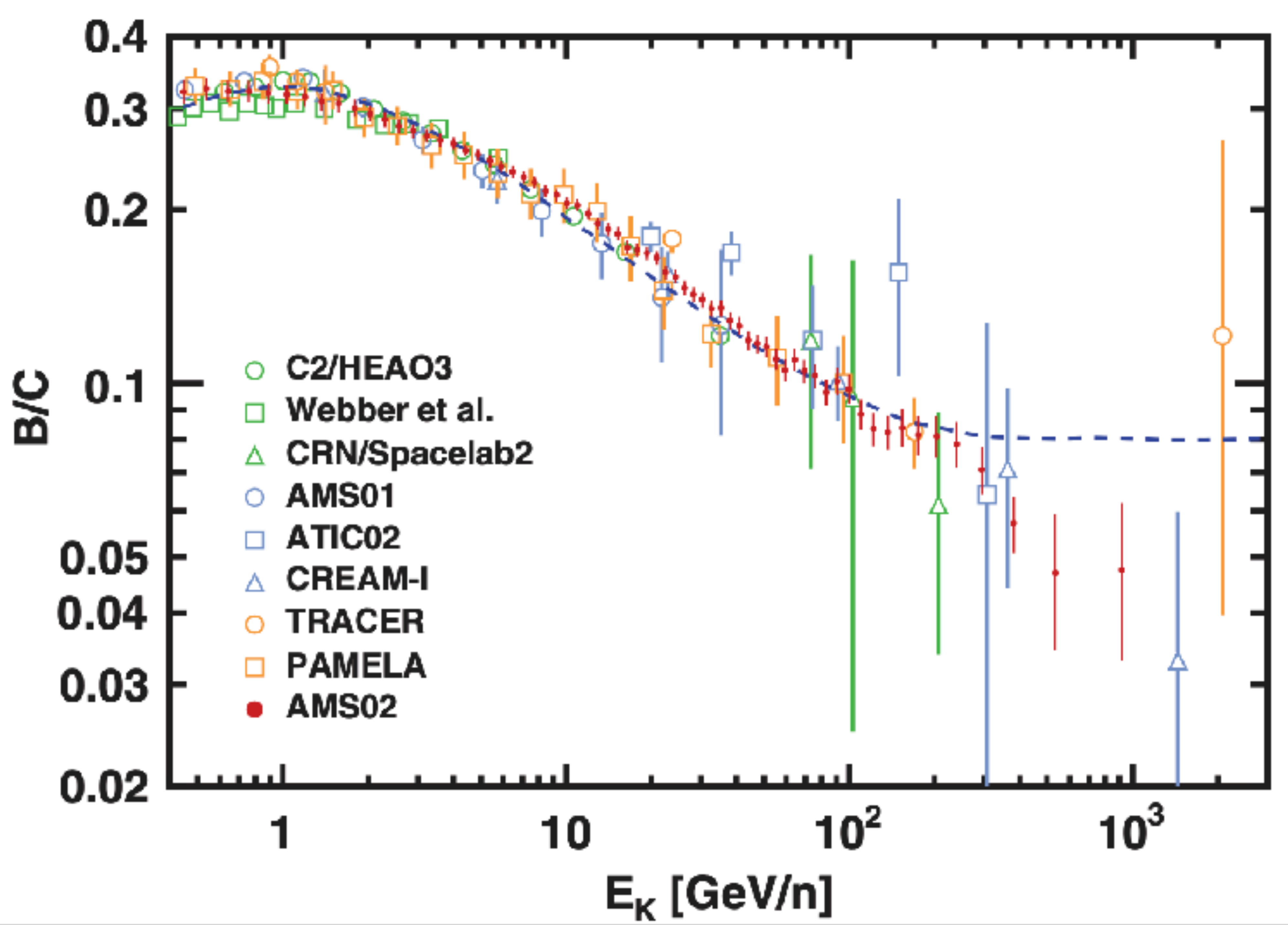


- e.g., C + H -> B + ?

- Local Spectrum: $E^{-p-2\delta} = E^{-2.X-2\ 0.Y} = E^{-3.1}$

# Primary-to-Secondary Ratios

- Measurements of the cosmic-ray secondary to primary ratios isolate the value of $\delta$.
- Amplitude of the ratios tests a combination of the residence time and the gas density (or a preference for particles staying in the thin disk).
- Verifies the main features of diffusion model.

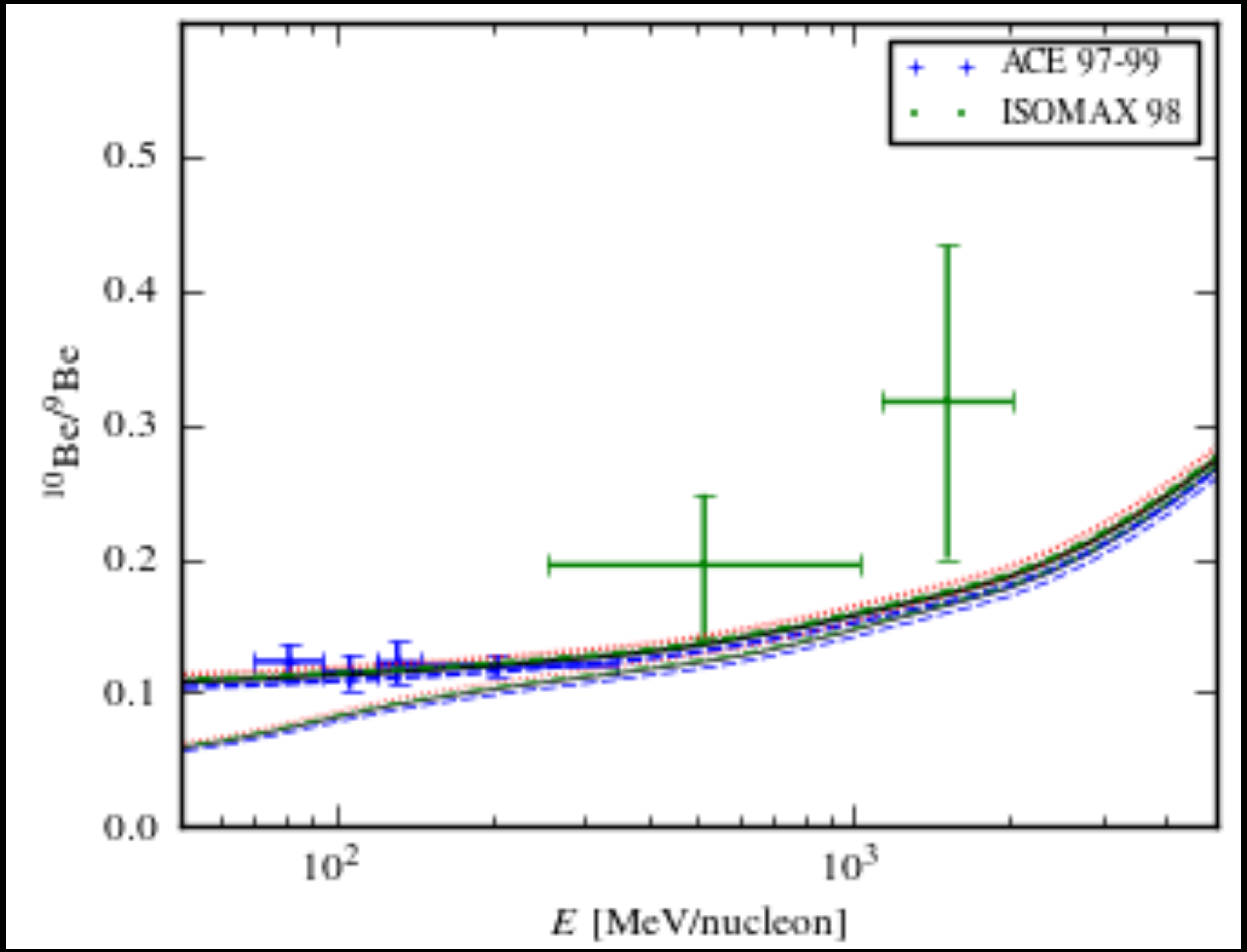


# Primary-to-Secondary Ratios

- Can use radioactively decaying nuclei to isolate the dependence on the residence time.

- Does not depend on gas density (independent information).

- Isotopic ratios very hard to measure with things like AMS-02



# Cosmic-Ray Electron Propagation

- Different cooling mechanisms than protons (inverse Compton scattering, synchrotron (does not produce gammas), bremsstrahlung
- Which produces the following energy loss rate:

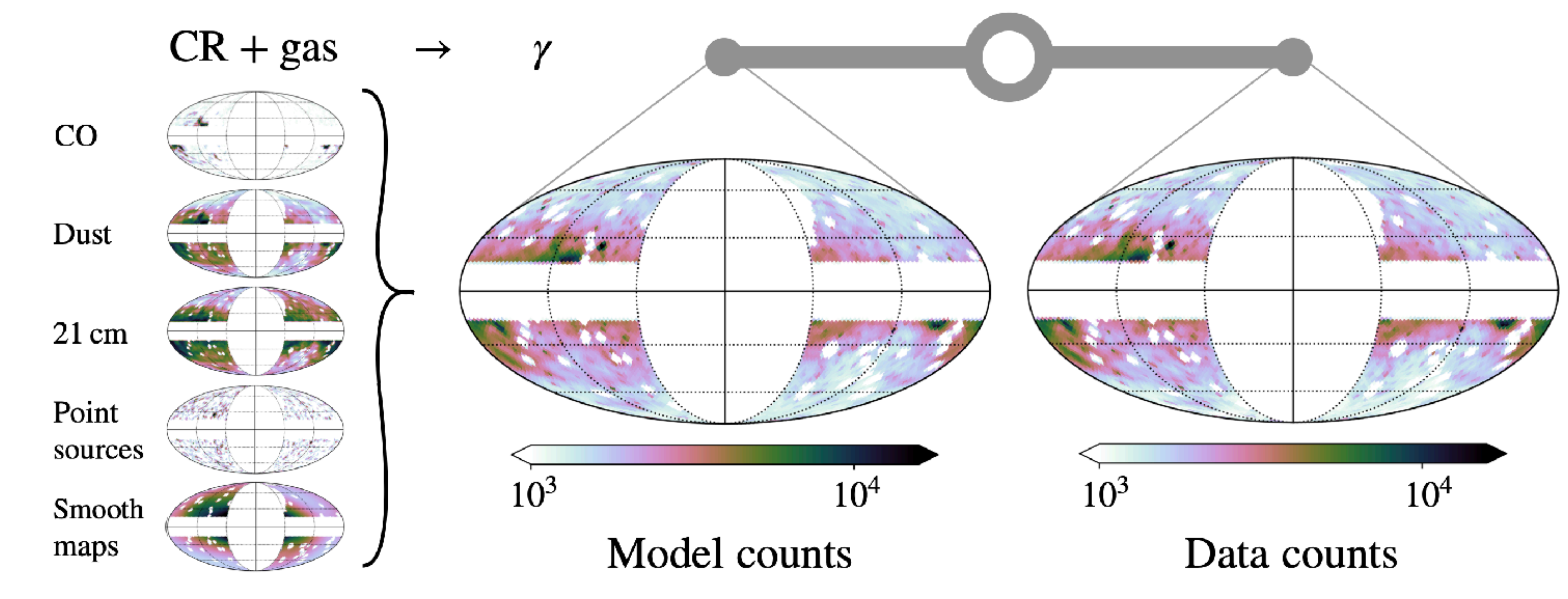
$$\frac{dE}{dt} = -\frac{4}{3}\sigma_T c \left(\frac{E}{m_e}\right)^2 \left[\rho_B + \sum_i \rho_i(\nu_i) S(E,\nu_i)\right]$$

$$t_{loss} \approx 320\ \mathrm{kyr} \left(\frac{E}{1\ \mathrm{TeV}}\right)^{-1} \left(\frac{\rho_{\mathrm{tot}}\, S_{\mathrm{eff}}(E)}{1\ \mathrm{eV\ cm}^{-3}}\right)$$

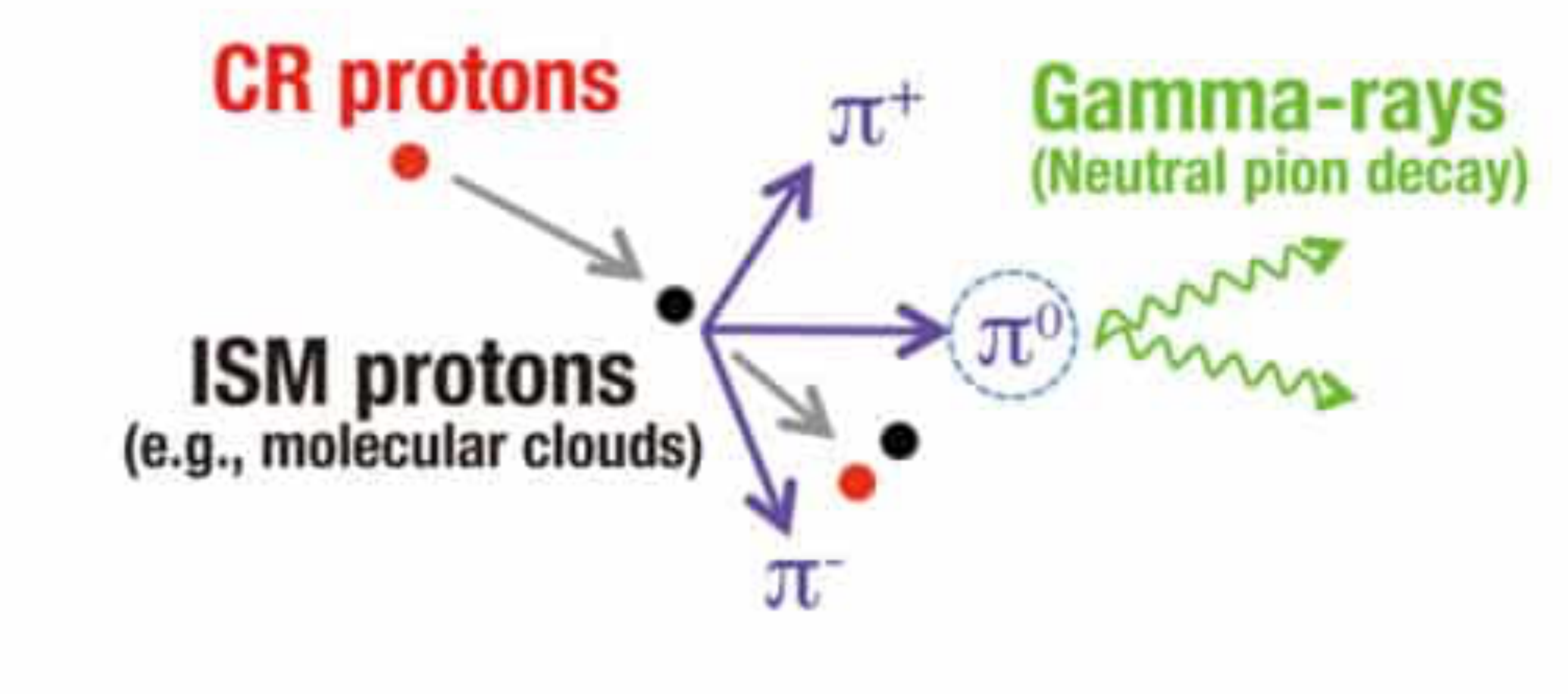
- Calorimetric at high energies! (But not at low energies).

# Diffuse Emission

- Calculated by multiplying the steady state cosmic-ray density (fit by Galprop to local observations) by the observed gas density.



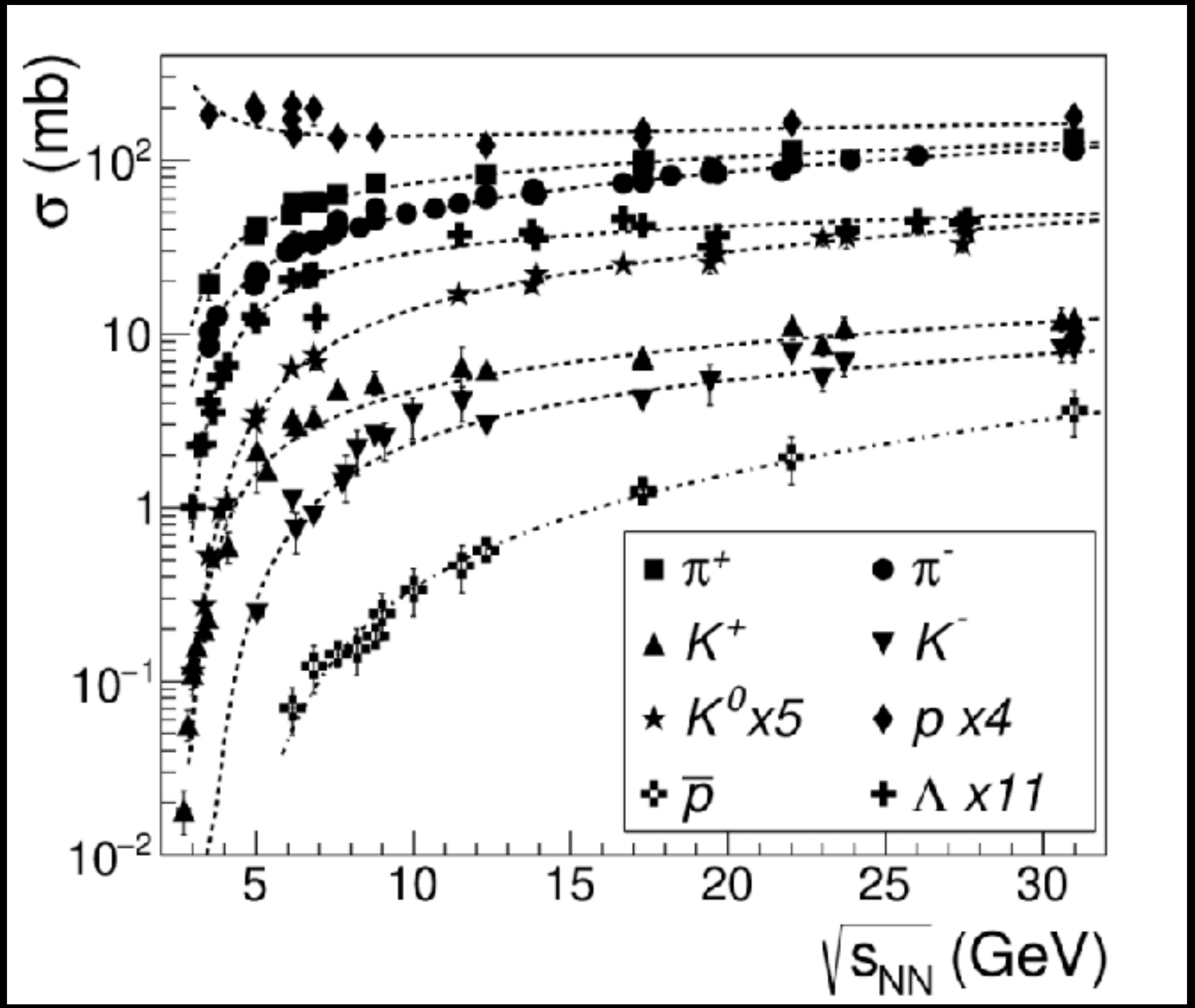
# Pion-Decay (Hadronic)



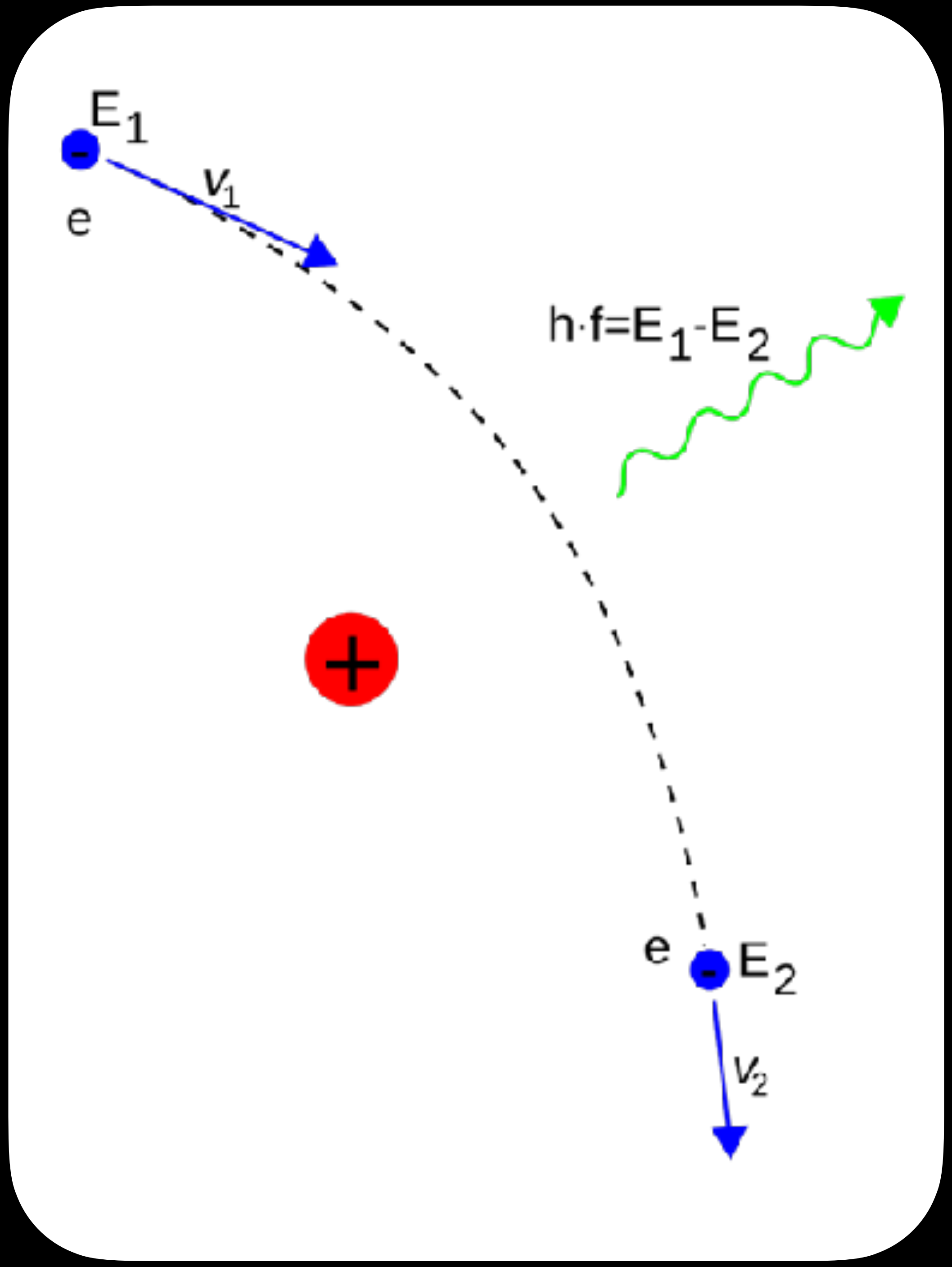
- Cosmic ray protons strike ambient gas in the Milky Way
- Produce both charged and neutral pions
  - Ratio between neutrino and gamma-ray flux

- Gamma-Ray energy is ~1/20 of proton energy
- Cross-section is roughly energy independent

- Gamma-Ray spectrum mirrors proton spectrum

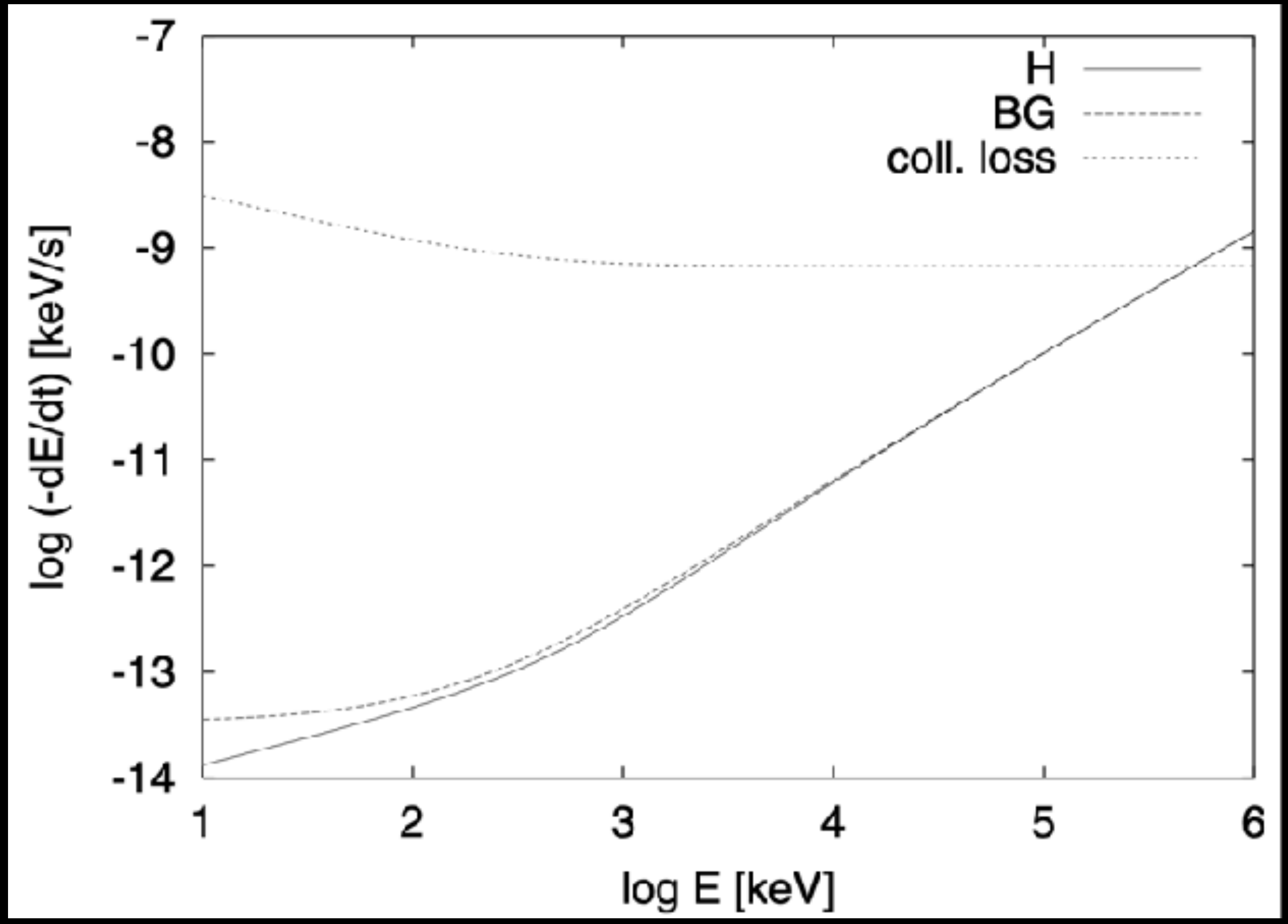


# Bremsstrahlung



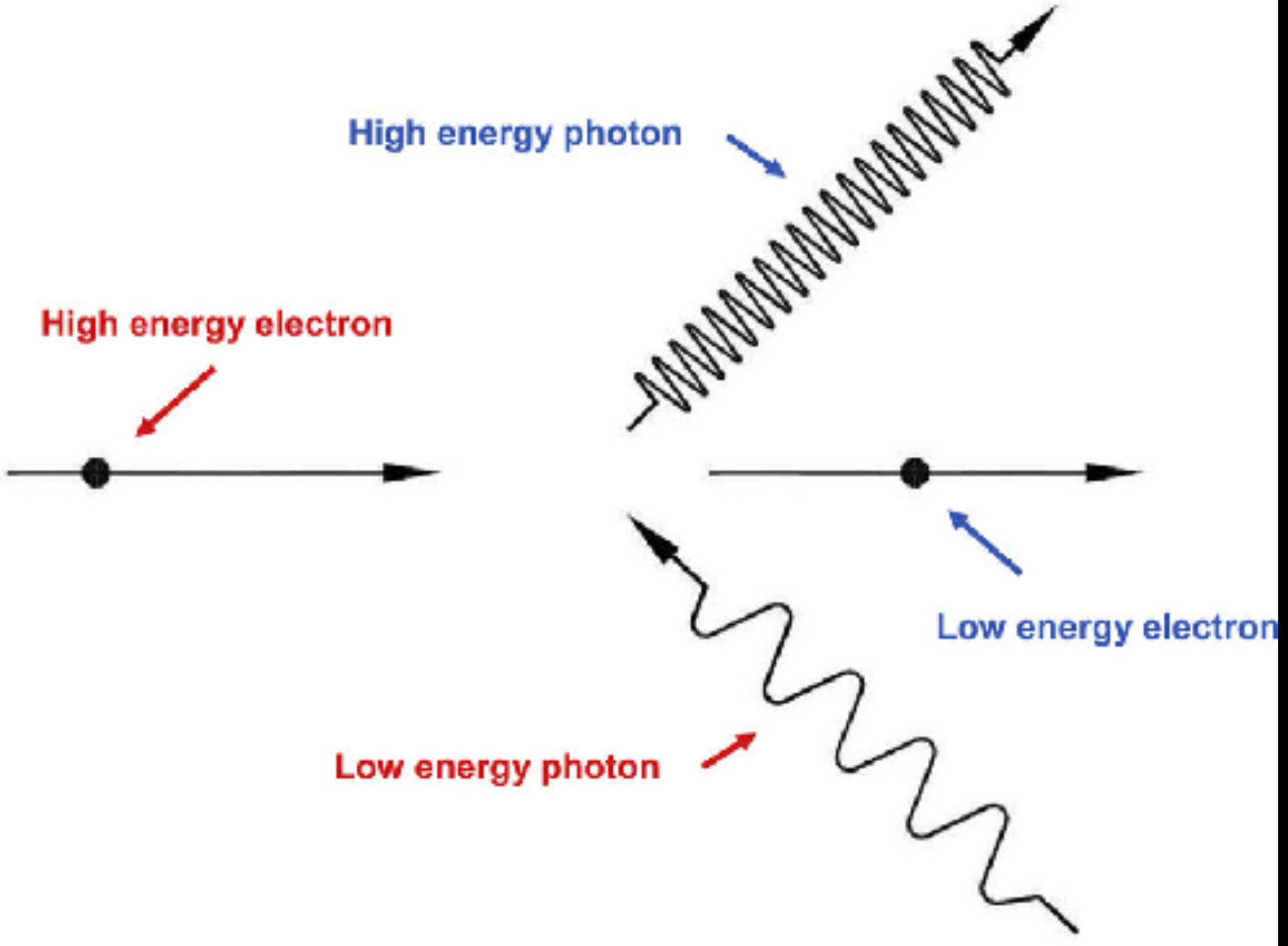
- Cosmic-ray electrons are deflected when moving near plasma
- Lose energy via these interactions, which release MeV and GeV scale photons

$$P = \frac{q^2\gamma^4}{6\pi\varepsilon_0 c}\left(\dot{\beta}^2 + \frac{\left(\boldsymbol{\beta}\cdot\dot{\boldsymbol{\beta}}\right)^2}{1-\beta^2}\right)$$



- Energy loss rate is linear, meaning the timescale for particle energy loss is energy independent.

# inverse-Compton Scattering



- inverse-Compton scattering based on the following cross-section

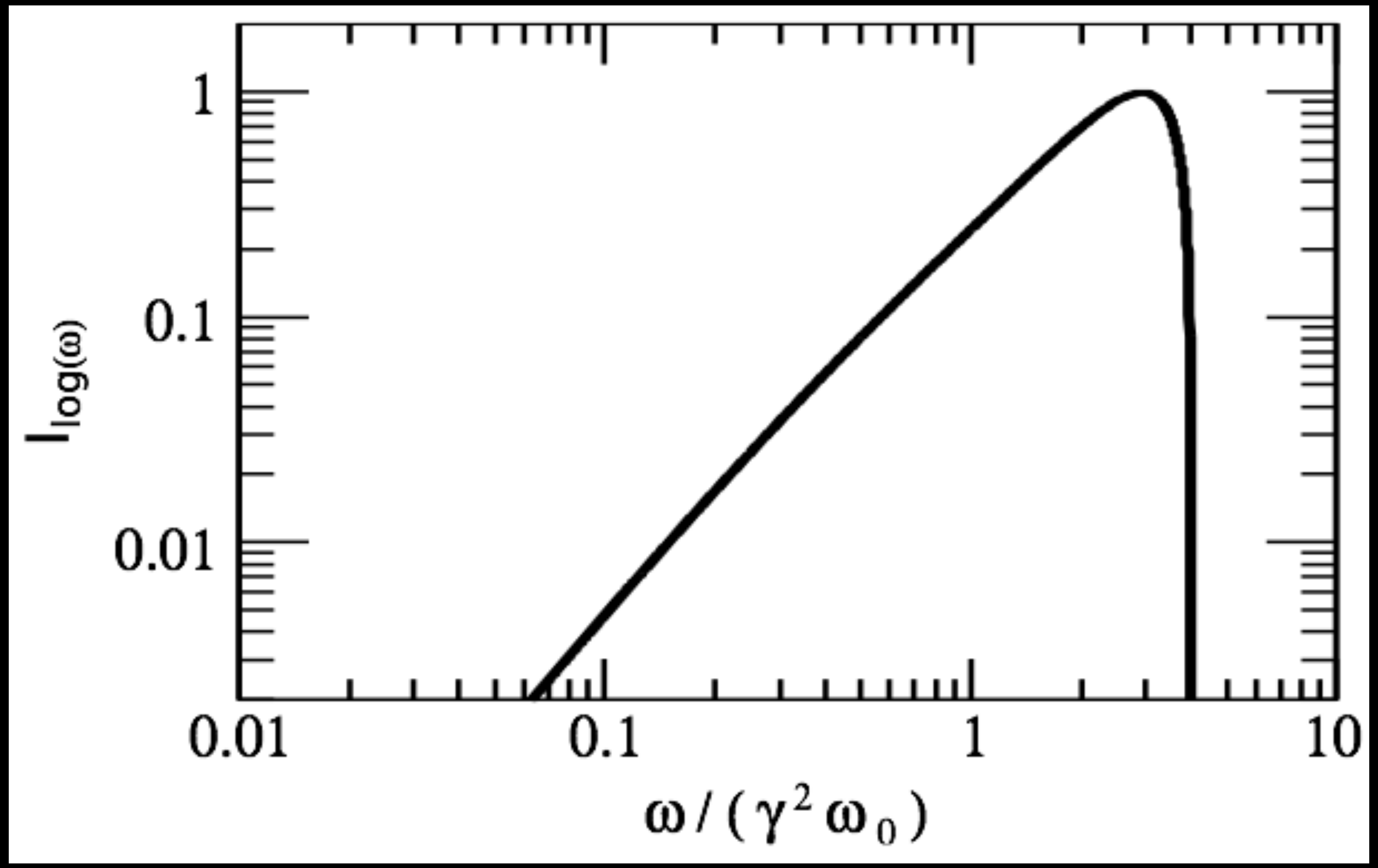
$$\frac{d^2\sigma(E_\gamma,\theta)}{d\Omega dE_\gamma} = \frac{r_0^2}{2\nu_i E^2} \times \left[1+\frac{z^2}{2(1-z)} - \frac{2z}{b_\theta(1-z)} + \frac{2z^2}{b_\theta^2(1-z)^2}\right]$$

- Which produces the following energy loss rate:

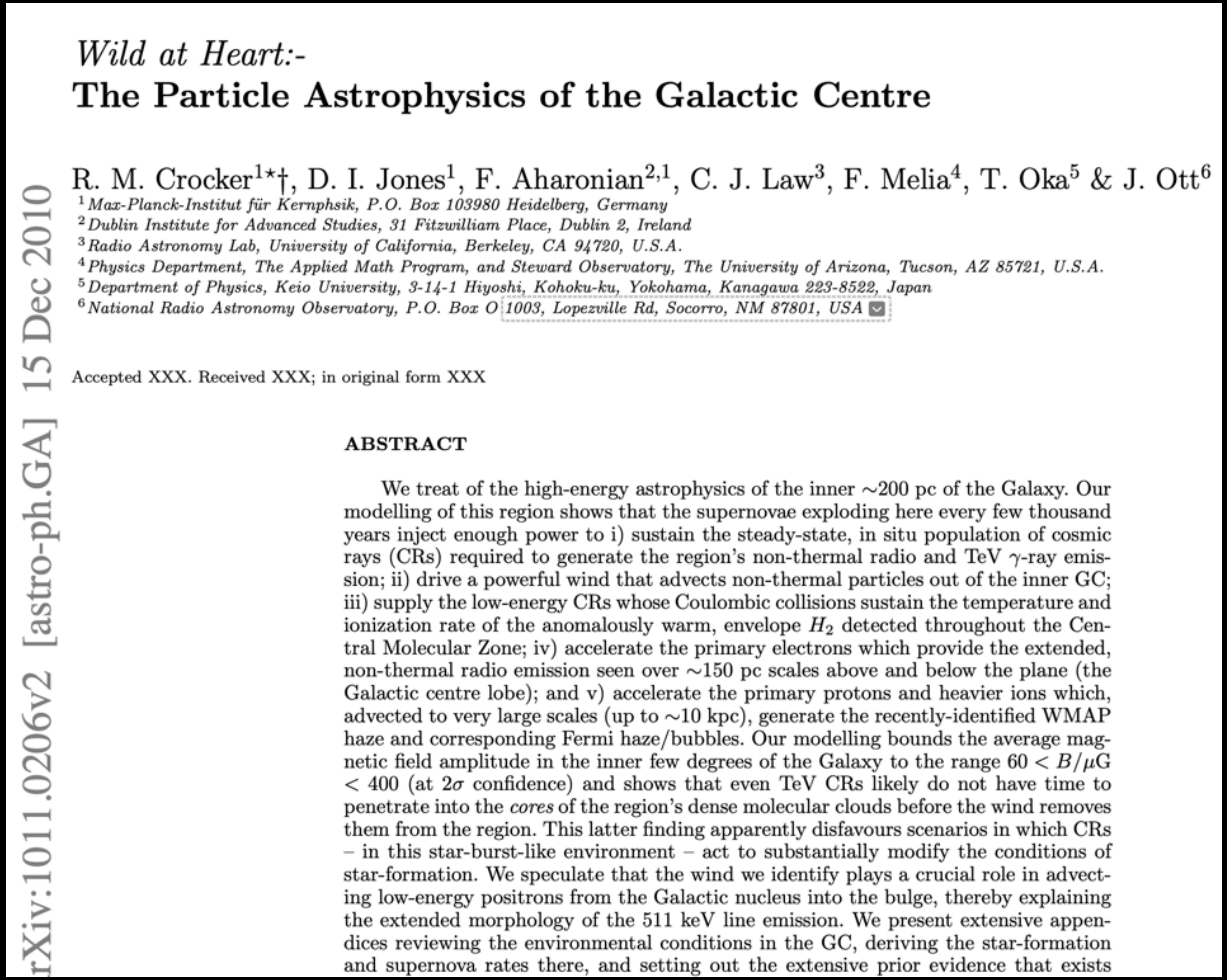
$$E_{\gamma,c} = \frac{4}{3}\gamma^2\nu_i$$

$$\frac{dE}{dt} = -\frac{4}{3}\sigma_T c\left(\frac{E}{m_e}\right)^2\left[\rho_B+\sum_i \rho_i(\nu_i)S(E,\nu_i)\right]$$

$$t_{loss}\approx 320\text{ kyr}\left(\frac{E}{1\text{ TeV}}\right)^{-1}\left(\frac{\rho_{\rm tot}\,S_{\rm eff}(E)}{1\text{ eV cm}^{-3}}\right)$$



# Energy Loss Timescales (Overview)



*Wild at Heart:-*

**The Particle Astrophysics of the Galactic Centre**

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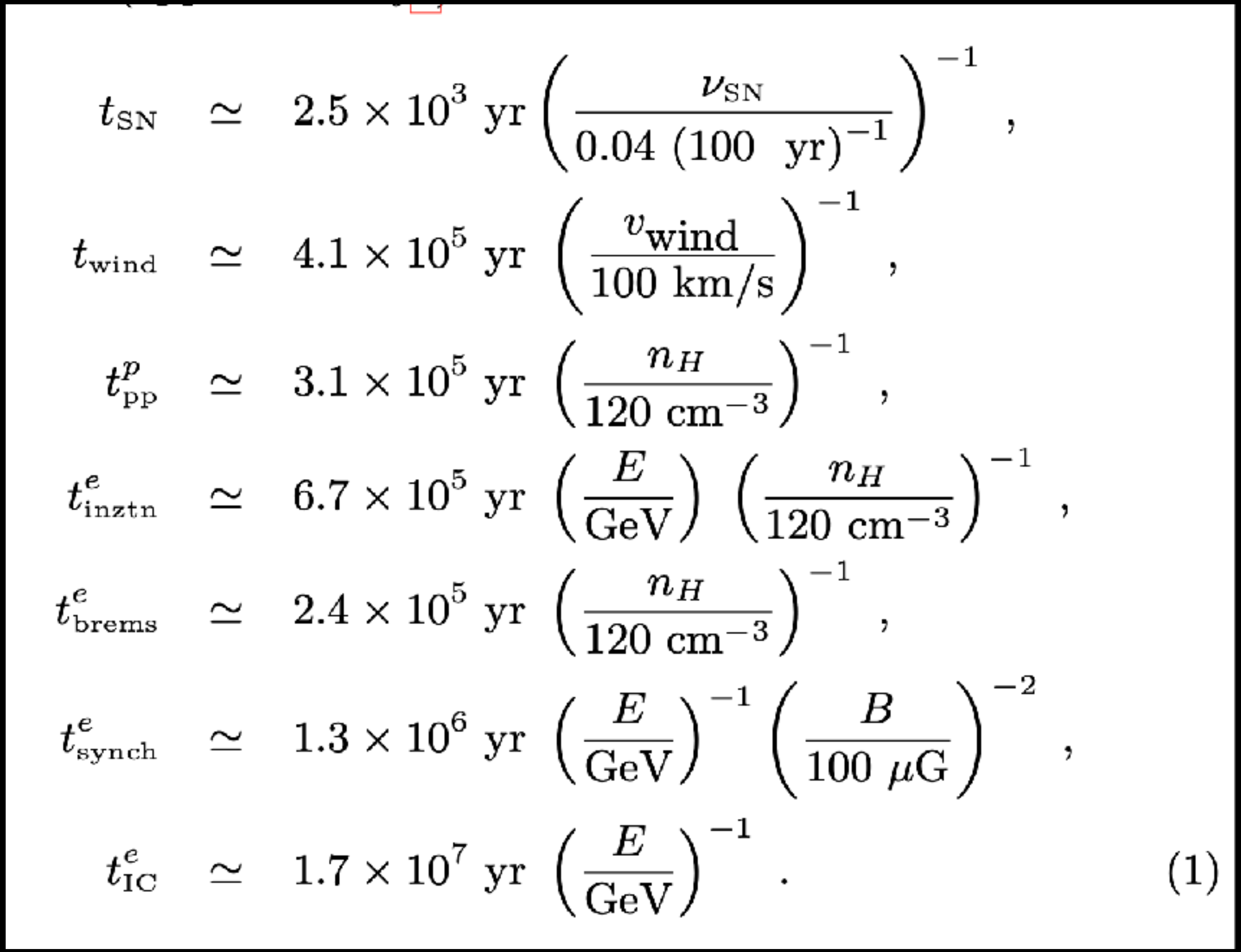
## ABSTRACT

We treat of the high-energy astrophysics of the inner ∼200 pc of the Galaxy. Our modelling of this region shows that the supernovae exploding here every few thousand years inject enough power to i) sustain the steady-state, in situ population of cosmic rays (CRs) required to generate the region's non-thermal radio and TeV $\gamma$-ray emission; ii) drive a powerful wind that advects non-thermal particles out of the inner GC; iii) supply the low-energy CRs whose Coulombic collisions sustain the temperature and ionization rate of the anomalously warm, envelope $H_2$ detected throughout the Central Molecular Zone; iv) accelerate the primary electrons which provide the extended, non-thermal radio emission seen over ∼150 pc scales above and below the plane (the Galactic centre lobe); and v) accelerate the primary protons and heavier ions which, advected to very large scales (up to ∼10 kpc), generate the recently-identified WMAP haze and corresponding Fermi haze/bubbles. Our modelling bounds the average magnetic field amplitude in the inner few degrees of the Galaxy to the range $60 < B/\mu\mathrm{G} < 400$ (at $2\sigma$ confidence) and shows that even TeV CRs likely do not have time to penetrate into the *cores* of the region's dense molecular clouds before the wind removes them from the region. This latter finding apparently disfavours scenarios in which CRs – in this star-burst-like environment – act to substantially modify the conditions of star-formation. We speculate that the wind we identify plays a crucial role in advecting low-energy positrons from the Galactic nucleus into the bulge, thereby explaining the extended morphology of the 511 keV line emission. We present extensive appendices reviewing the environmental conditions in the GC, deriving the star-formation and supernova rates there, and setting out the extensive prior evidence that exists

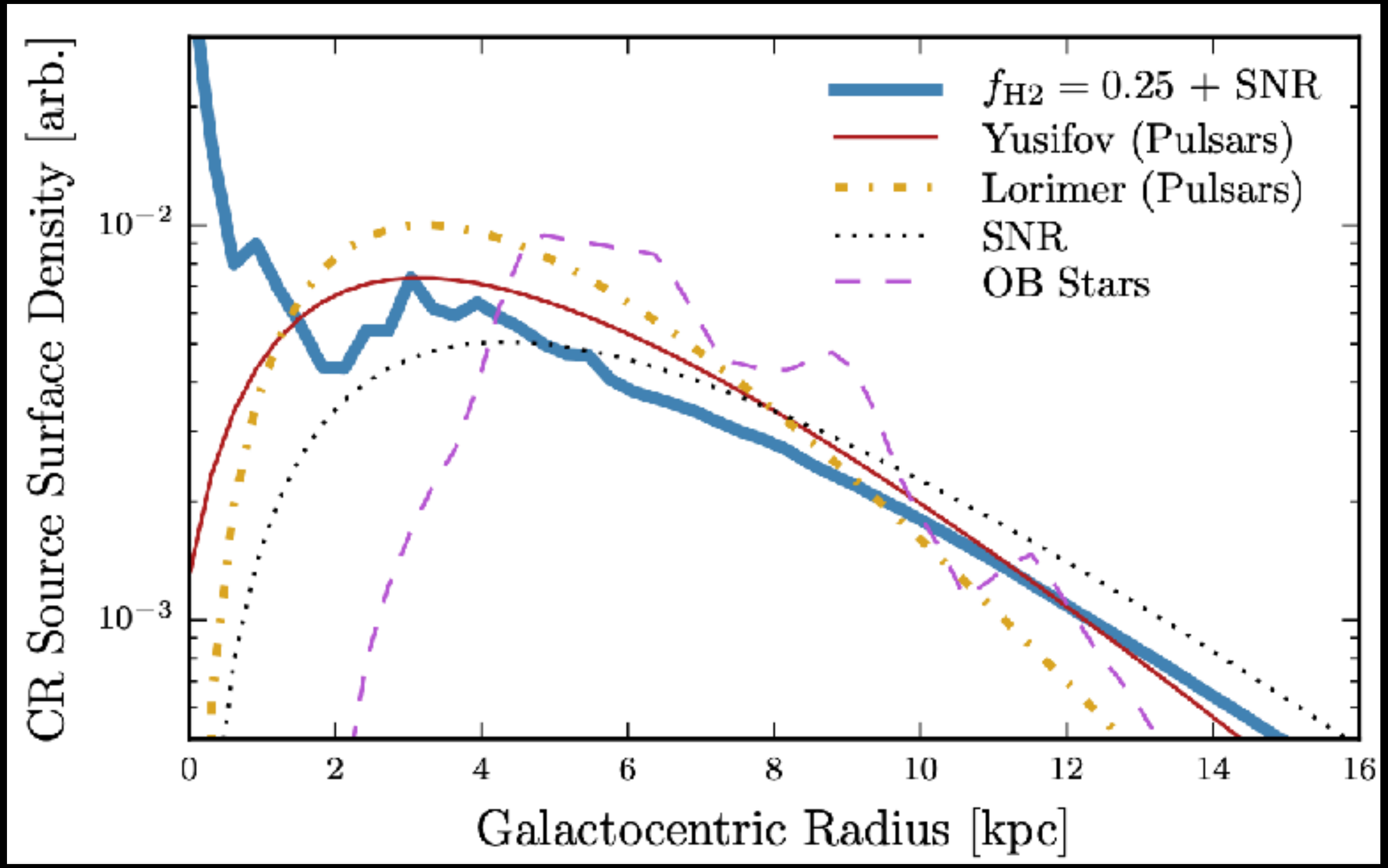


$$
\begin{aligned}
t_{\rm SN} &\simeq 2.5 \times 10^3 \ {\rm yr} \left(\frac{\nu_{\rm SN}}{0.04 \ (100 \ \ {\rm yr})^{-1}}\right)^{-1}, \\
t_{\rm wind} &\simeq 4.1 \times 10^5 \ {\rm yr} \left(\frac{v_{\rm wind}}{100 \ {\rm km/s}}\right)^{-1}, \\
t^p_{\rm pp} &\simeq 3.1 \times 10^5 \ {\rm yr} \left(\frac{n_H}{120 \ {\rm cm}^{-3}}\right)^{-1}, \\
t^e_{\rm inztn} &\simeq 6.7 \times 10^5 \ {\rm yr} \left(\frac{E}{\rm GeV}\right) \left(\frac{n_H}{120 \ {\rm cm}^{-3}}\right)^{-1}, \\
t^e_{\rm brems} &\simeq 2.4 \times 10^5 \ {\rm yr} \left(\frac{n_H}{120 \ {\rm cm}^{-3}}\right)^{-1}, \\
t^e_{\rm synch} &\simeq 1.3 \times 10^6 \ {\rm yr} \left(\frac{E}{\rm GeV}\right)^{-1} \left(\frac{B}{100 \ \mu{\rm G}}\right)^{-2}, \\
t^e_{\rm IC} &\simeq 1.7 \times 10^7 \ {\rm yr} \left(\frac{E}{\rm GeV}\right)^{-1}. \qquad (1)
\end{aligned}
$$

# Topic: Galprop/Dragon

- Codes that solve cosmic-ray propagation numerically.
- Grid galaxy in r, z, and p
- Take a cosmic ray injection profile from models
- Calculate diffusion, secondary production and gamma-ray generation

- Step 1:
  - Start with a model for the energy spectrum and morphology of cosmic-ray injection



# Topic: Galprop/Dragon

- Codes that solve cosmic-ray propagation numerically.
- Grid galaxy in r, z, and p
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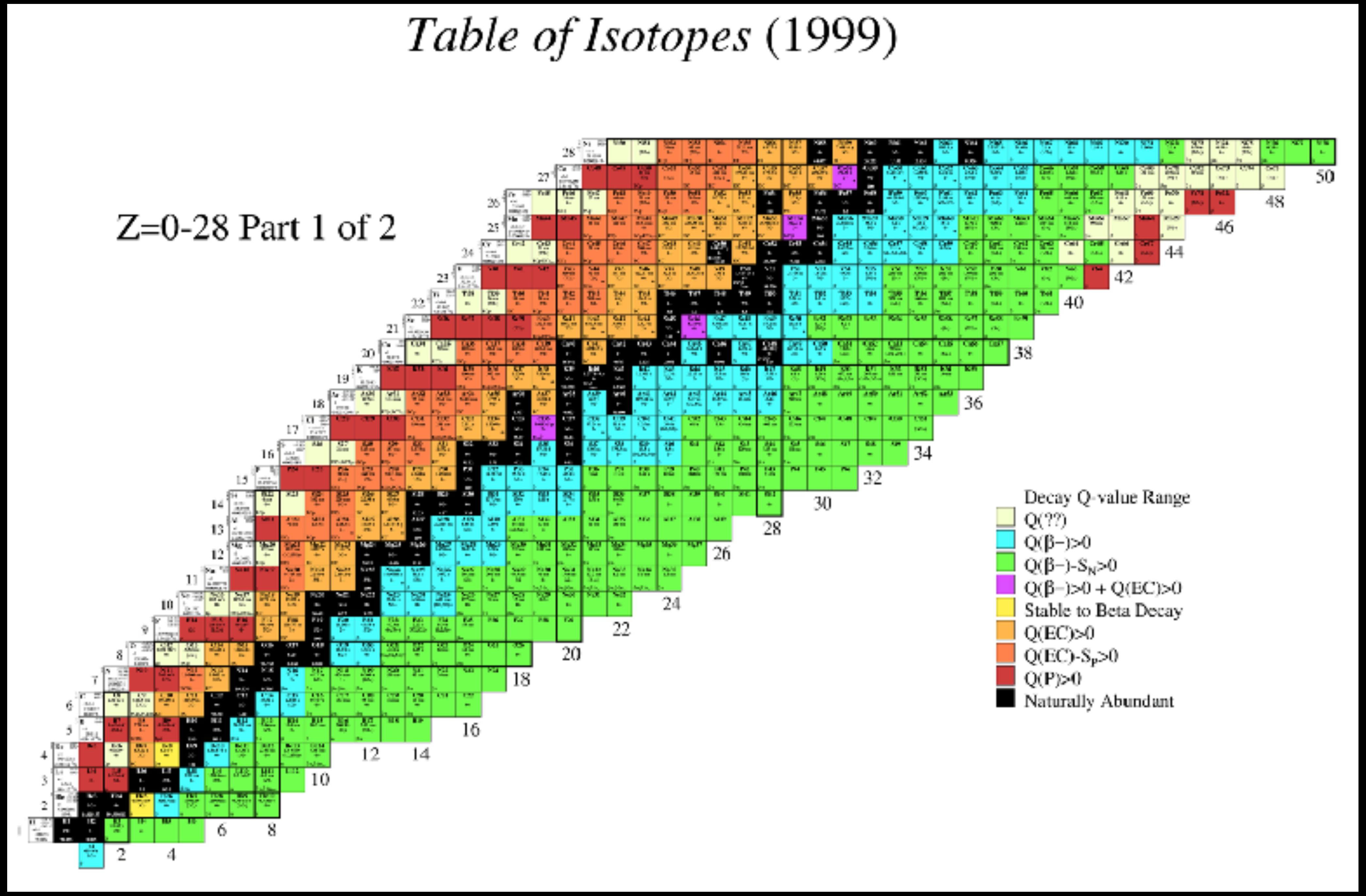
- <u>Step 2:</u>
  - Solve the PDE numerically on a grid



# Topic: Galprop/Dragon

- Codes that solve cosmic-ray propagation numerically.
- Grid galaxy in r, z, and p
- Take a cosmic ray injection profile from models
- Calculate diffusion, secondary production and gamma-ray generation

- Step 3:
  - Combine with gas density to produce a diffuse emission model.

# Topic: Galprop/Dragon

Enter the desired GALPROP v. 54 parameters and click 'Submit' at **the bottom of the form** ⇓

### Common Parameters

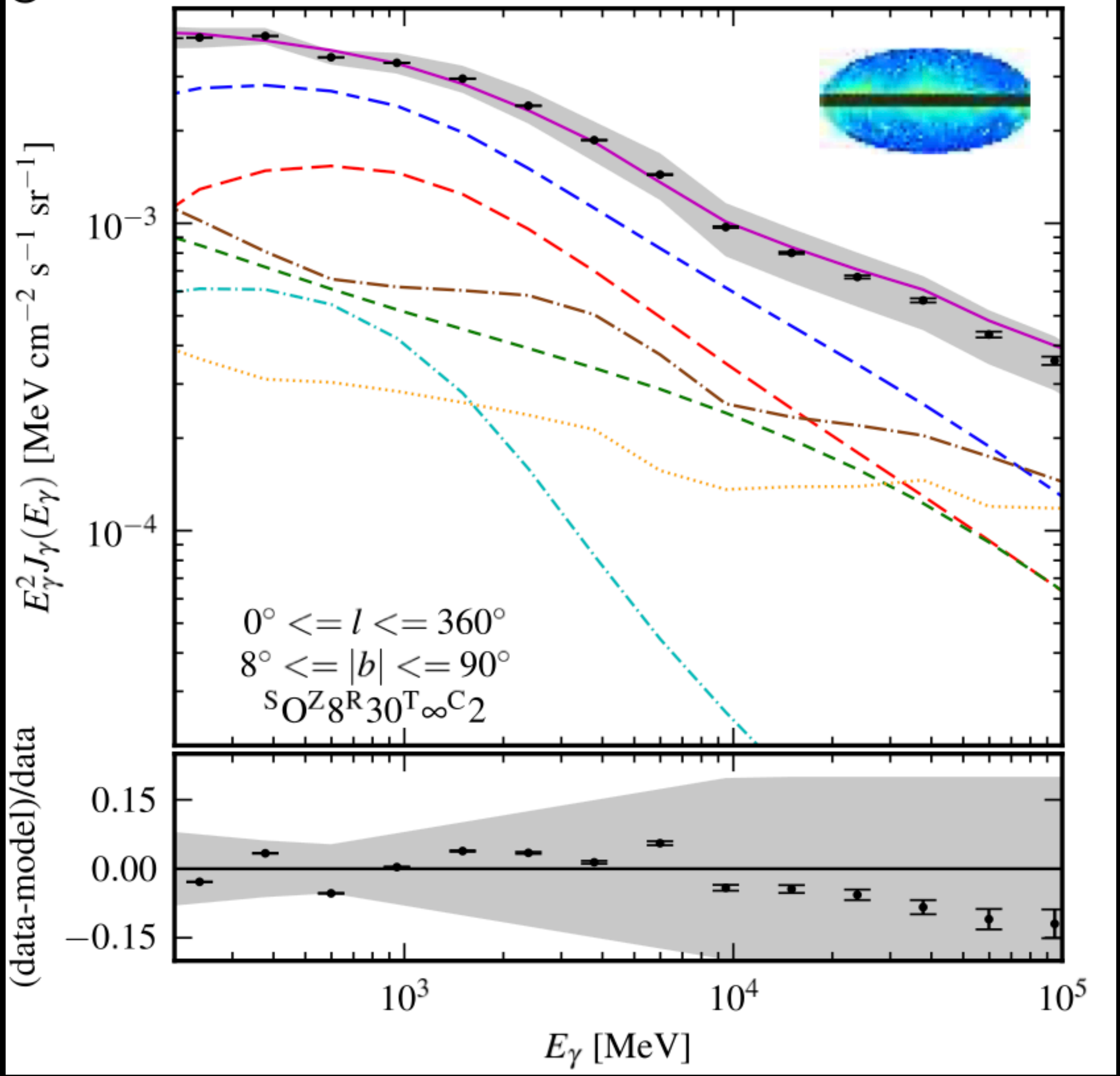
| Name | Value | Description |
|---|---|---|
| Title | Untitled WebRun cal | Descriptive title used to identify the run. |
| n_spatial_dimensions | 2 | Specifies whether 2 or 3 spatial dimensions. |

### Energetic and Spatial Grids

| Name | Value | Description |
|---|---|---|
| r_min | 0.0 | Minimum galactocentric radius (R) for 2D case, in kpc. Ignored for 3D. |
| r_max | 25.0 | Maximum galactocentric radius (R) for 2D case, in kpc. Ignored for 3D. |
| dr | 0.2 | Cell size in galactocentric radius (R) for 2D case, in kpc. |
| z_min | -04.0 | Minimum height for 2D and 3D case, in kpc. |
| z_max | +04.0 | Maximum height for 2D and 3D case, in kpc. |
| dz | 0.1 | Cell size in z for 2D and 3D case, in kpc |

### CR Propagation

| Name | Value | Description |
|---|---|---|
| D0_xx | 6.10e28 | The value of the spatial diffusion coefficient D for a particle of rigidity rho is determined via the formula:<br>D=beta D0_xx (rho / D_rigid_br)^D_g,<br>where beta=v/c, rho=cp/(Ze), D_rigid_br is a reference rigidity (see parameter D_rigid_br), and the power law index D_g=D_g_1 for rho<D_rigid_br, and D_g=D_g_2 for rho>D_rigid_br. The units of D0_xx are cm$^2$ s$^{-1}$, and c, e, Z, v and p have their usual meanings. |
| D_rigid_br | 4.0e3 | Rigidity for D0_xx formula, in MV, and also break point in case D_g_1 != D_g_2. |
| D_g_1 | 0.33 | Diffusion coefficient index below reference rigidity. See formula for D0_xx. Kolmogorov turbulence corresponds to a value 1/3. |
| D_g_2 | 0.33 | Diffusion coefficient index above reference rigidity. See formula for D0_xx. Kolmogorov turbulence corresponds to a value 1/3. |
| diff_reacc | 1 | Indicates whether diffusive reacceleration is to be included in propagation (0=no, >=1 yes). **Recommended 0, 1 or 2 for first time users.** 1 and 11=Kolmogorov turbulence, 2 and 12=Kraichnan turbulence. 1 and 2=no damping, 11 and 12=with wave-damping (additional parameters describe the regime of damping). |
| v_Alfven | 30.0 | Alfven speed for computation of reacceleration momentum diffusion coefficient. This parameter is in fact Alfven speed/sqrt(w), where w is the ratio of MHD wave energy density to magnetic field energy density, see Strong & Moskalenko (1998). |
| convection | 0 | Set to 1 to indicate if convection is to be included in propagation. |
| cross_section_option | 012 | Options for determining isotopic production cross sections. Experimental data (table or fit) are used whenever available. Otherwise, for cross_section_options=012, the code of Webber et al. 93 is used (re-normalized if data exist), and for cross_section_option=022, the code of TS'00 is used (re-normalized if data exist). |
| primary_electrons | 1 | Indicates whether to propagate primary electrons (0: no, 1: yes). Set to 1 if inverse Compton and/or synchrotron skymaps are to be computed. |
| secondary_electrons | 0 | Indicate whether to propagate secondary electrons (0: no, 1: yes). |



- Red: Pion decay
- ICS: green dashed
- Brem: Cyan dot-dashed
- Total: Blue dashed

- Orange: All Sources
- Brown: Isotropic background (assumed extragalactic)

- Note Residuals are ~10%

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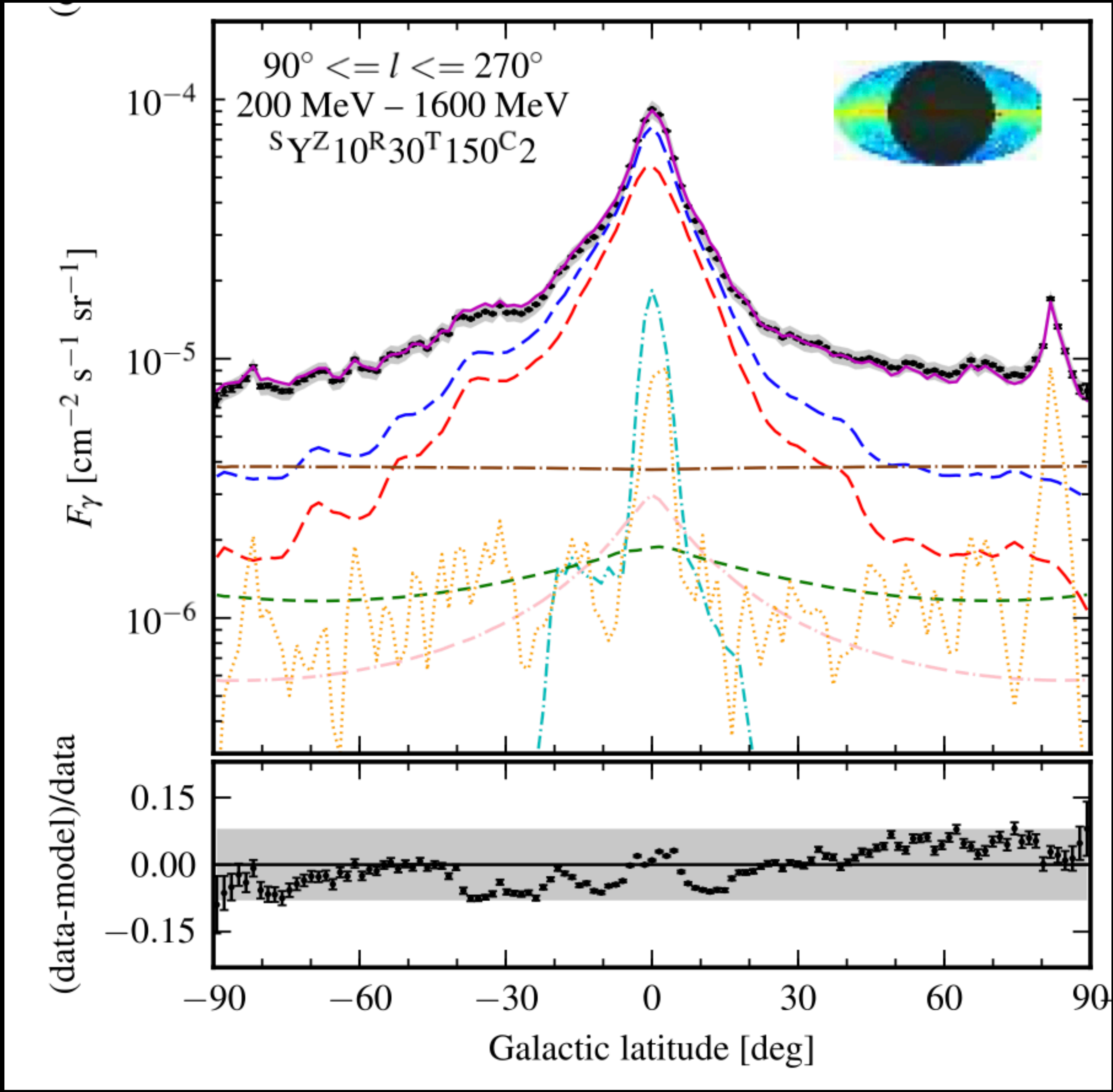
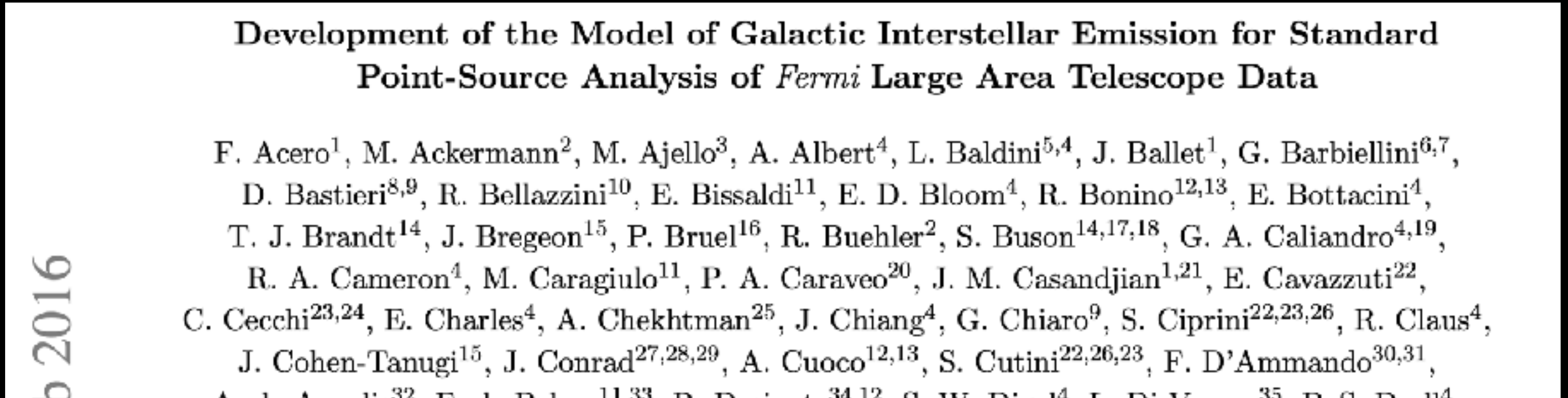
- Brown: Isotropic background (assumed extragalactic)

- Note Residuals are ~10%



# Results: Fermi Diffuse Emission Model

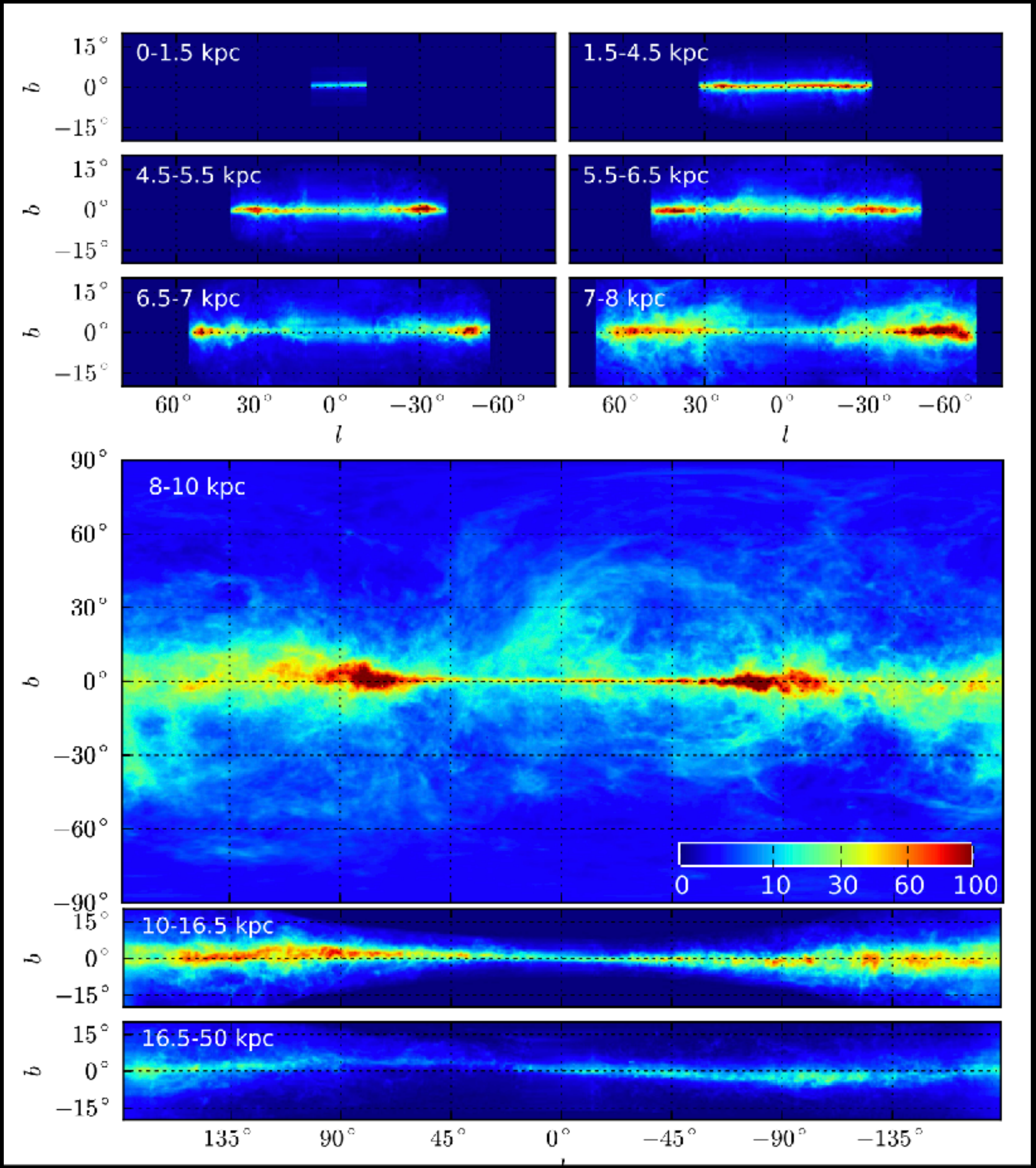
- Ring based model developed for point source analyses
- Break down gas densities into galactocentric rings
- Additional post-processing fits to large scale residuals (since p7v6)
- Additional included templates for the Fermi bubbles, Loop I.



**Development of the Model of Galactic Interstellar Emission for Standard Point-Source Analysis of *Fermi* Large Area Telescope Data**

F. Acero[1], M. Ackermann[2], M. Ajello[3], A. Albert[4], L. Baldini[5,4], J. Ballet[1], G. Barbiellini[6,7], D. Bastieri[8,9], R. Bellazzini[10], E. Bissaldi[11], E. D. Bloom[4], R. Bonino[12,13], E. Bottacini[4], T. J. Brandt[14], J. Bregeon[15], P. Bruel[16], R. Buehler[2], S. Buson[14,17,18], G. A. Caliandro[4,19], R. A. Cameron[4], M. Caragiulo[11], P. A. Caraveo[20], J. M. Casandjian[1,21], E. Cavazzuti[22], C. Cecchi[23,24], E. Charles[4], A. Chekhtman[25], J. Chiang[4], G. Chiaro[9], S. Ciprini[22,23,26], R. Claus[4], J. Cohen-Tanugi[15], J. Conrad[27,28,29], A. Cuoco[12,13], S. Cutini[22,26,23], F. D'Ammando[30,31],

2016



# Implications

- Need a diffuse model to do any Fermi science on point sources.

- Diffuse Emission Interesting on its Own!
  - Cosmic-ray driven feedback
  - Regulation of star formation
  - Information about pulsar, supernova sources
  - Understanding of interstellar turbulence, magnetic fields throughout the universe.
  - Particle physics properties - studies of the highest energy particles, and new constraints on particle cross-sections.

# Fermi Bubbles

- Gigantic lobes of gamma-ray emission from cosmic-rays launched out of the Milky Way Core.

- 10 kpc in height above the galactic plane
- Unknown origins?
  - Prior AGN activity in the Milky Way?!
  - Winds launched from supernova explosions in Milky Way Galactic Center
- Has been subsequently detected in WMAP and ROSAT data.