On the role of galactic wind termination shocks in (re-)accelerating Galactic cosmic rays

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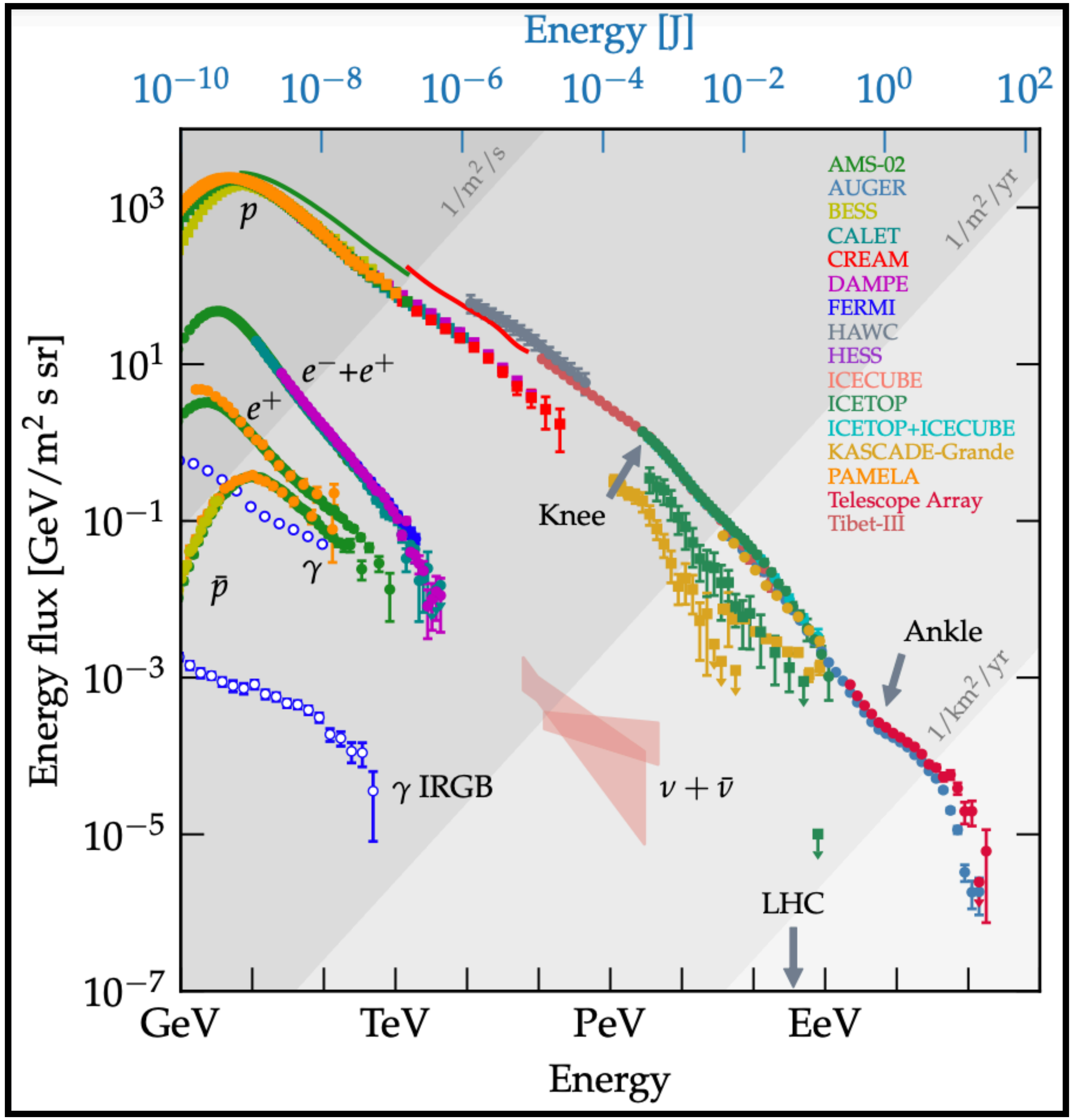
Cosmic rays between knee and ankle



Cosmic ray spectrum up to the knee are thought to be produced locally - e.g SNRs.

Origin of CRs between knee and ankle is unknown.

In this talk, we focus on the termination shock of Galactic wind (GWTS) as a CR source between the knee and ankle.

Galactic CRs re-accelerated at GWTS: contribute between knee and ankle?

Possible future works: associated gamma ray and neutrino fluxes.

CR and wave driven galactic winds

$$\nabla \cdot (\rho \mathbf{v}) = 0$$

$$\nabla \cdot \left(\rho \mathbf{v}\, \mathbf{v} + \left[P_g + P_c + \frac{\langle (\delta \mathbf{B})^2 \rangle}{8\pi} \right] . \mathbf{I} \right) = -\rho \nabla \Phi$$

$$\nabla \cdot \left(\rho \mathbf{u} \left[\frac{1}{2} v^2 + \frac{\gamma_g}{\gamma_g - 1} \frac{P_g}{\rho} + \Phi \right] + \frac{\gamma_c}{\gamma_c - 1} [P_c \times (\mathbf{v} + \mathbf{v}_A)] + \frac{\langle (\delta \mathbf{B})^2 \rangle}{4\pi} \left[\frac{3}{2} \mathbf{v} + \mathbf{v}_A \right] \right) = 0$$

$$\nabla . \left(\frac{\gamma_c}{\gamma_c - 1} (\mathbf{v} + \mathbf{v}_A) P_c \right) = (\mathbf{v} + \mathbf{v}_A) \nabla P_c$$

$$\nabla . \left(\frac{\langle (\delta \mathbf{B})^2 \rangle}{4\pi} \left[\frac{3}{2} \mathbf{v} + \mathbf{v}_A \right] \right) = \mathbf{v} \nabla \left(\frac{\langle (\delta \mathbf{B})^2 \rangle}{8\pi} \right) - \mathbf{v}_A \nabla P_c$$

$$\nabla . \mathbf{B} = 0$$

Galactic winds in starburst galaxies are thought to be purely driven by thermal gas pressure.

For Milky Way, Galactic winds are probably caused by a combination of CR and thermal gas pressure, possibly also aided by the pressure of self-excited Alfven waves.

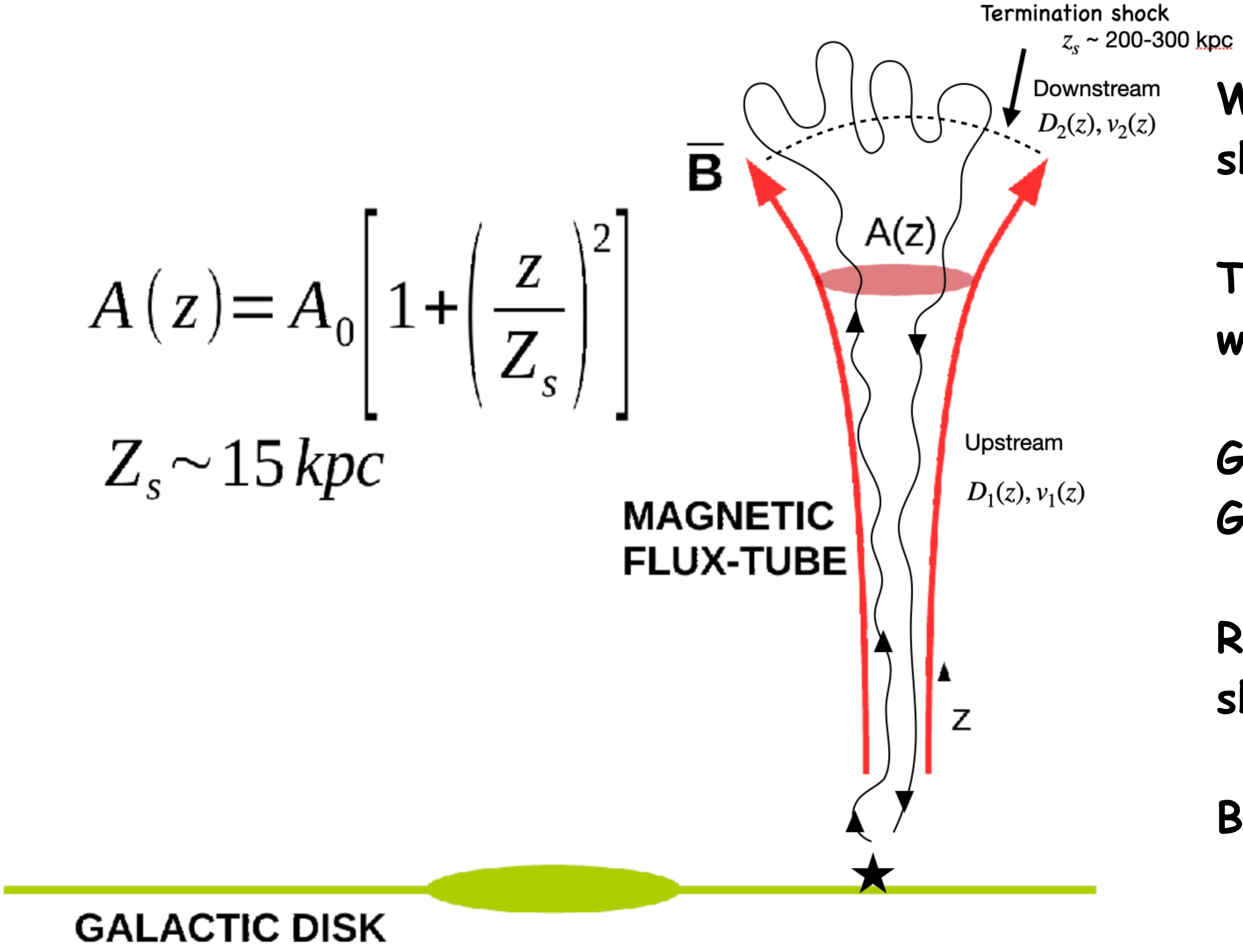
We solve hydrodynamic equations for the overall balance of mass, momentum and energy balance for gas, CRs and fluctuating wave fields.

Well known treatment adapted from seminal paper of Breitschwerdt (1991).

Schematics of the re-acceleration process

$$A(z) = A_0\left[1 + \left(\frac{z}{Z_s}\right)^2\right]$$

$$Z_s \sim 15\,kpc$$



Winds can form termination shocks at ~200-300 kpc.

Transport of CRs — diffusion as well as advection in the wind.

Galactic CRs transported up to GWTS.

Re-acceleration by Diffusion shock acceleration.

Backstreaming and escaping flux.

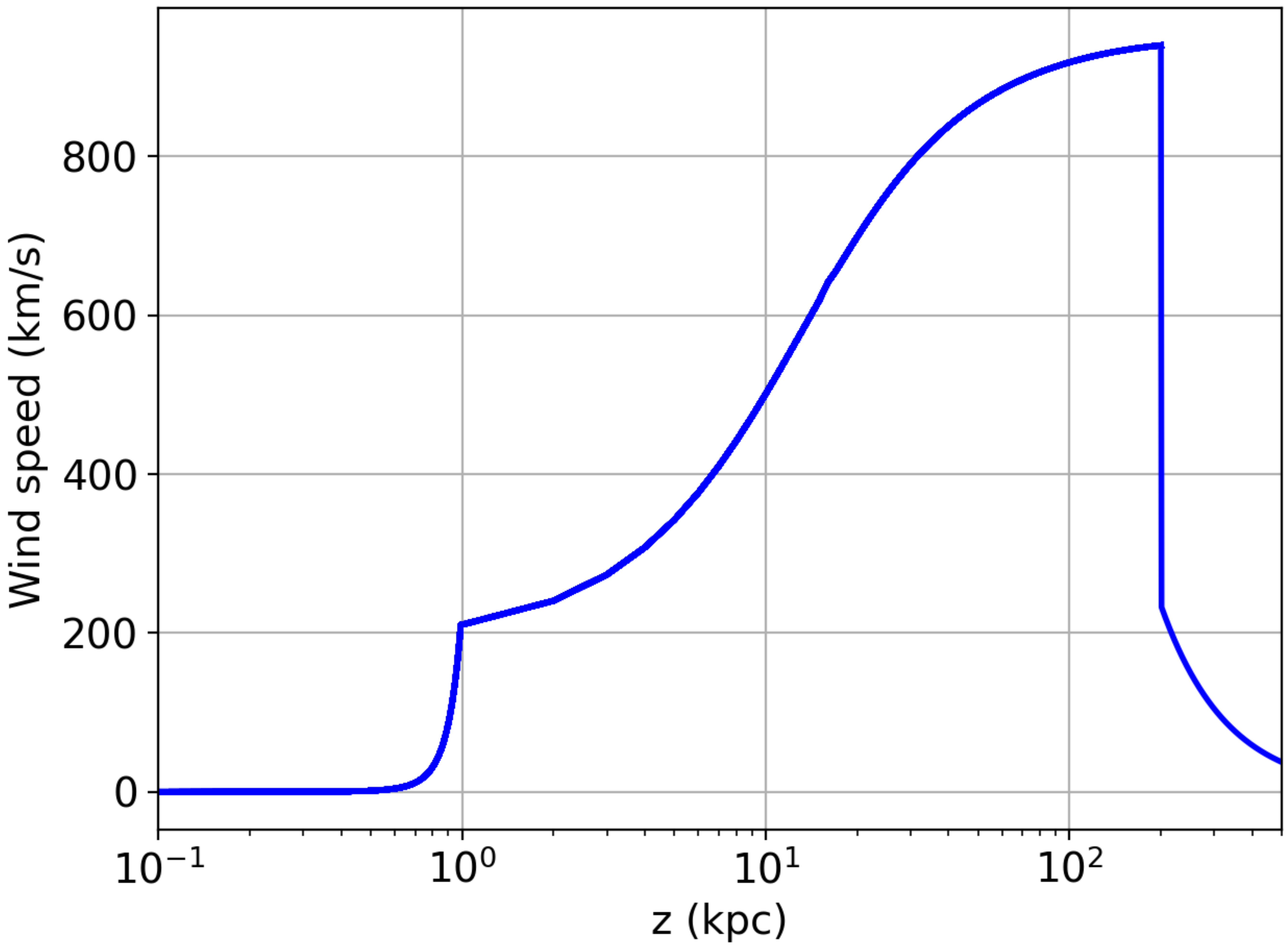
Wind velocity profile

Hydrodynamic equations solved to obtain velocity profiles of the wind.

Inner boundary condition is set by the observed energy flux of galactic cosmic rays.

Outer boundary condition set by the pressure of the Intergalactic Medium (IGM) which is thought to be ~ $10^{-15} - 10^{-14}$ erg/cm^3.

Rankine-Hugoniot shock jump conditions employed at the termination shock located at ~200 kpc.



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Cosmic ray transport in the wind

- CRs undergo diffusion as well as advection in the wind.
- We solve the convection-diffusion equation to solve for the transport of particles in the wind bubble.

$$\frac{1}{A(z)}\frac{\partial}{\partial z}\left(A(z)D(z,p)\frac{\partial f}{\partial z}\right) - v(z)\frac{\partial f}{\partial z} + \frac{1}{A(z)}\frac{d}{dz}(A(z)v(z))\frac{1}{3}\frac{\partial f}{\partial \ln p} = -Q(z,p)$$

$$Q(z,p) = Q_0(p)\frac{\exp\left(-\frac{z^2}{2\sigma_z^2}\right)}{\sqrt{2\pi\sigma_z^2}}. \quad Q_0(p) = \frac{\mathcal{F}_{\rm SN}\mathcal{R}_{\rm SN}}{\pi R_d^2}, \quad \mathcal{F}_{SN}(p) = \frac{\xi_{CR}E_{SN}}{I(\alpha)}\left(\frac{p}{m}\right)^{-\alpha}\exp\left\{\left(-\frac{p}{p_{c,SNR}}\right)\right\},$$

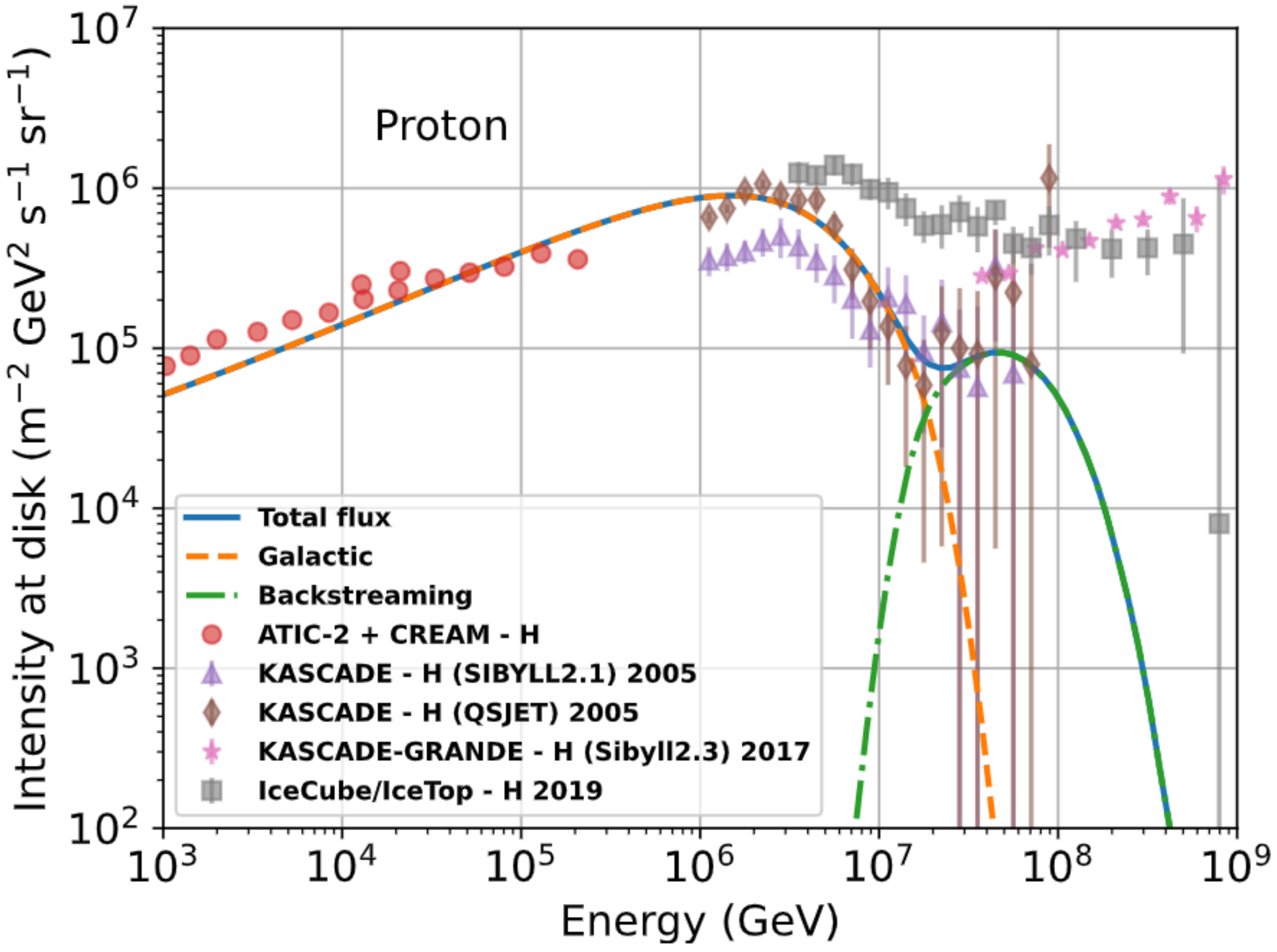
$$\text{Defaultvalues:} E_{SN} = 10^{51}\text{ergs}, \xi_{CR} = 0.1, \alpha = 4.4, p_{c,SNR} = 4\times 10^6\text{GeV}$$

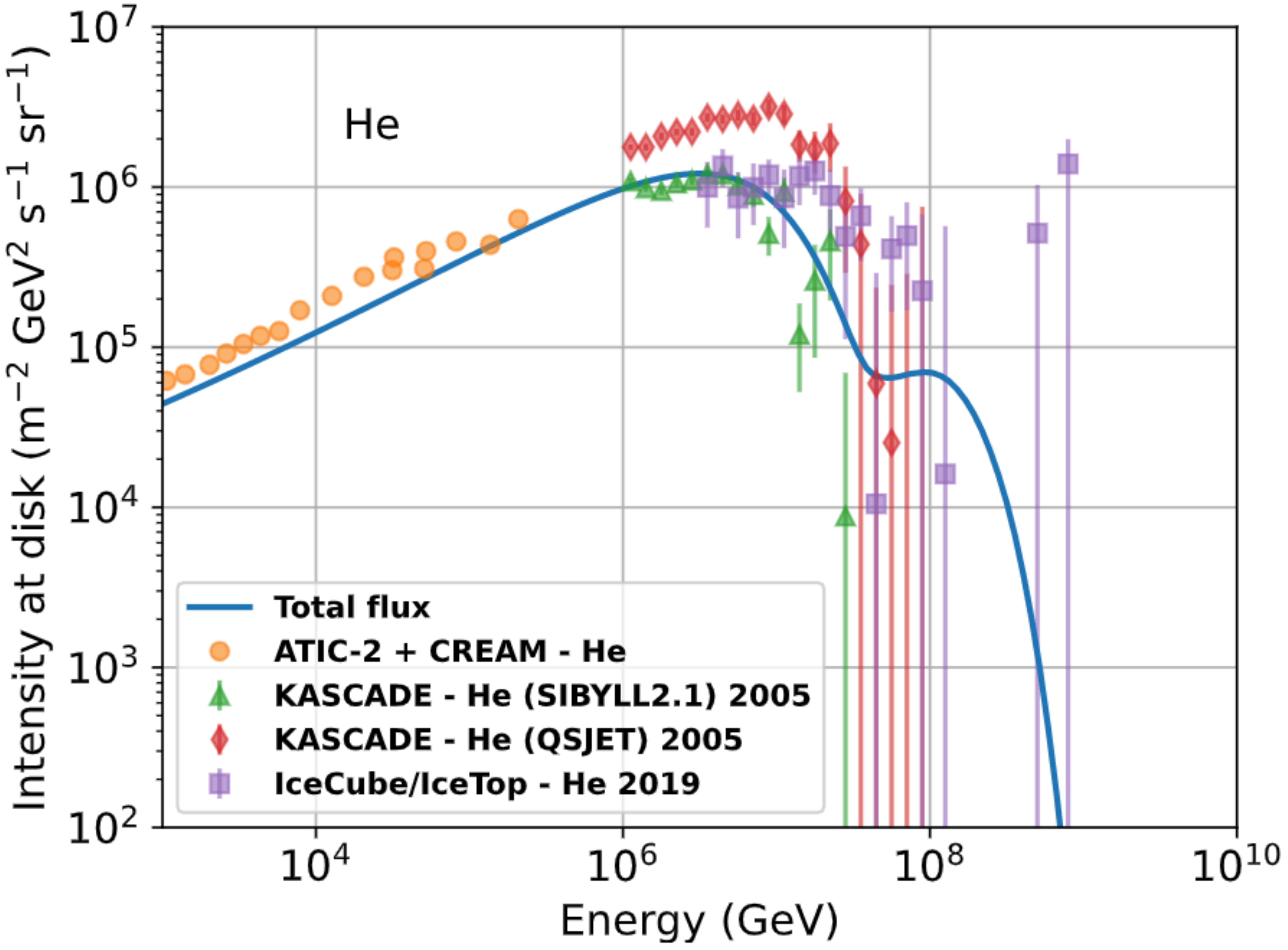
- Velocity profile separate taken hydrodynamic calculation discussed.
- Diffusion coefficient (quasi-linear theory) : $D(z) = \frac{1}{3}r_L(p)c\left(\frac{r_L(p)}{L_c}\right)^{1-\delta}$
- L_c is a coherence length which is kept as a free parameter.
- Equation is solved using an iteration technique introduced in Morlino et al. (2021).

Re-acceleration of CRs the termination shock

- Strong shock: re-acceleration via diffusive shock acceleration (DSA).
- Backstreaming particles propagating back to the Galaxy?
- Escape from the Galaxy into the Intergalactic medium.
- Max rigidities ~ 50 PV.
- Order of magnitude estimate for max energy: $D_1(p_{max}) \sim v z_{shock}$.

Results - Backstreaming flux





Bumps in the spectrum - transition from galactic component to the GWTS backstreaming component
Protons can be re-accelerated up to 50 PeV and can contribute upto 10-20% of the observed flux

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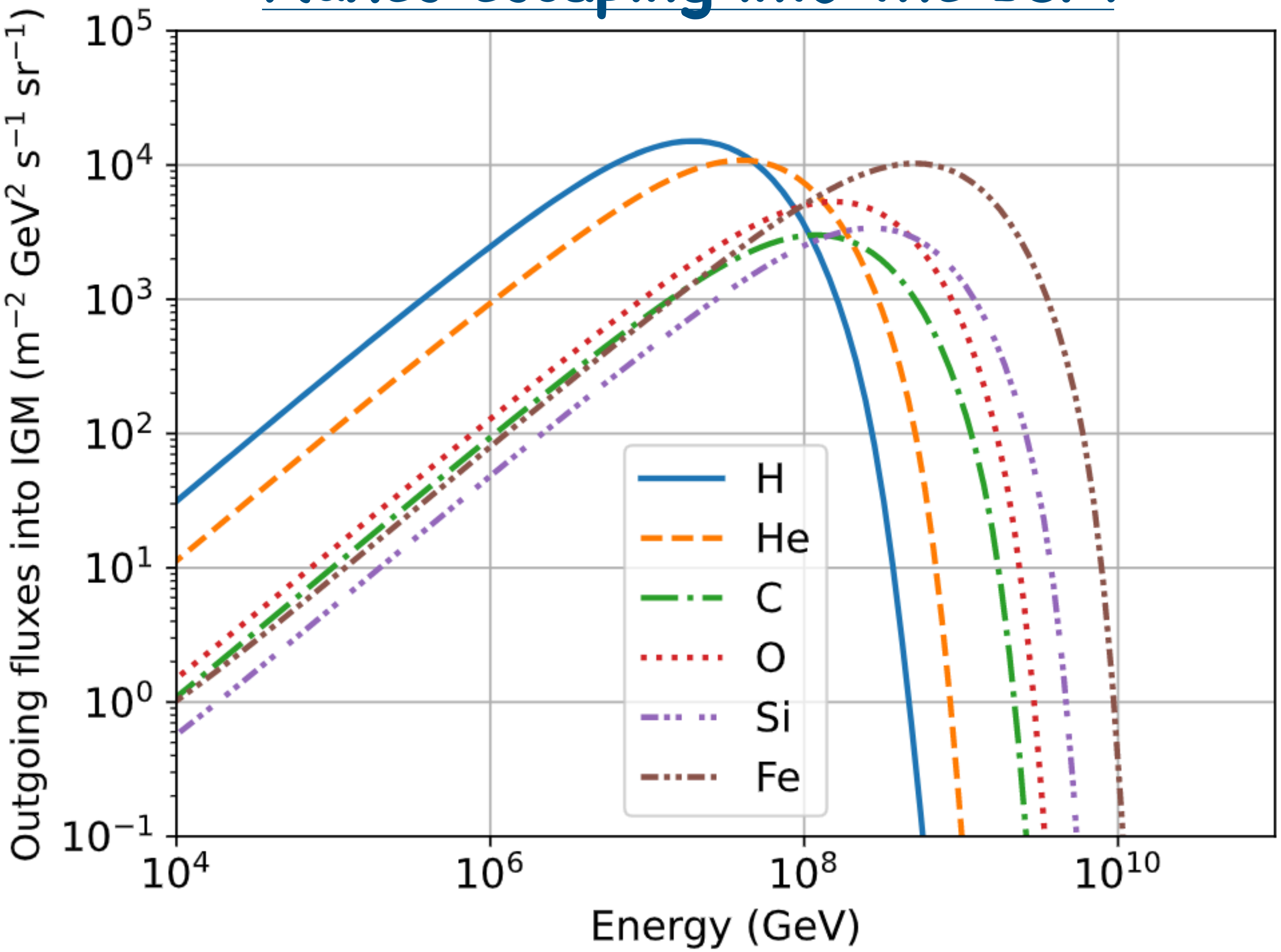
Fluxes escaping into the IGM



GTWS can seed the IGM with energetic particles ranging from 50-1000 PeV, depending on mass

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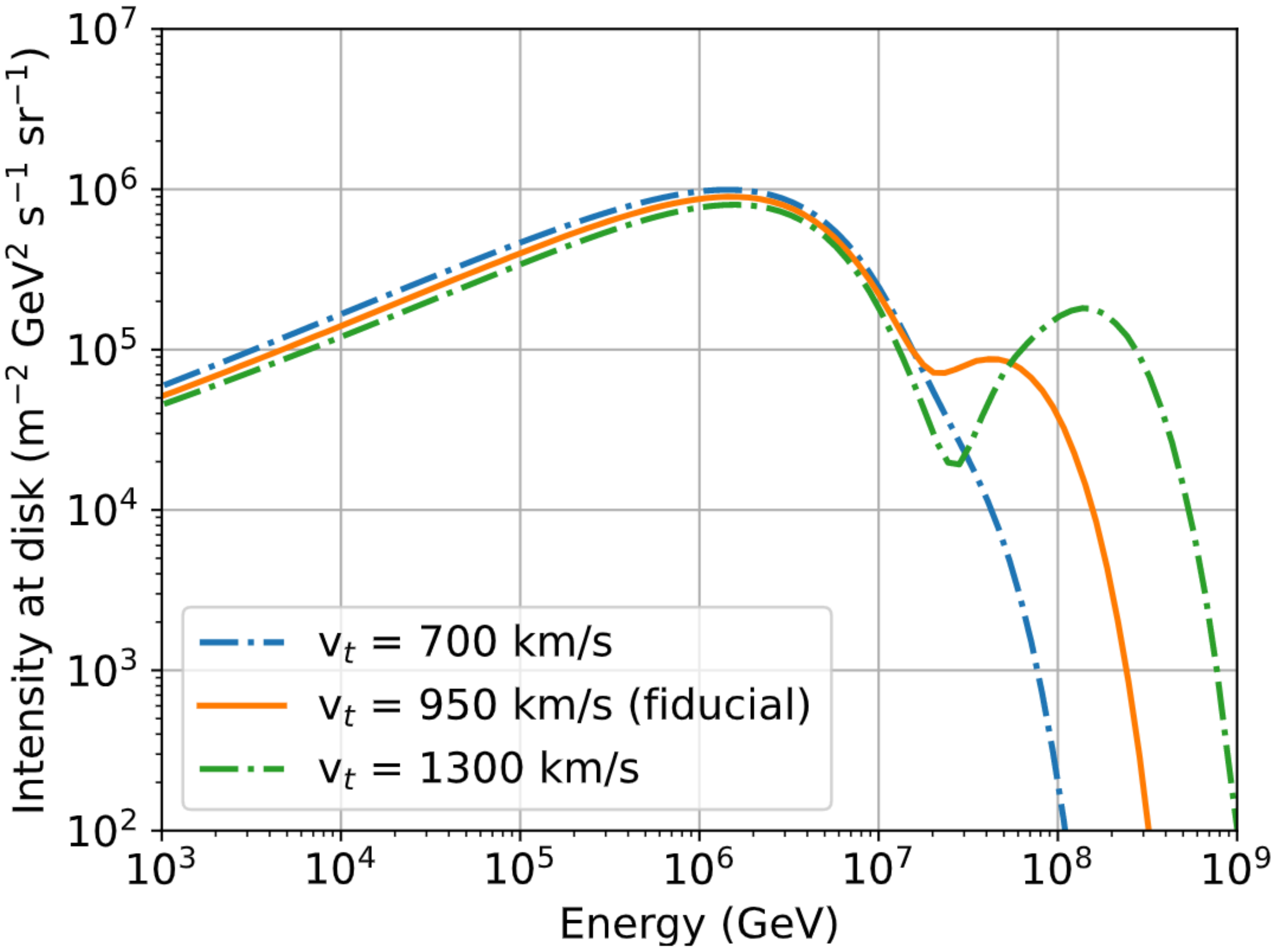
Parameter space variation – wind speed

The terminal wind speed crucially impacts the maximum energy achieved in re-acceleration.

Increasing the wind speed allows higher achievable energy even reaching up to 200-300 PeV for protons.



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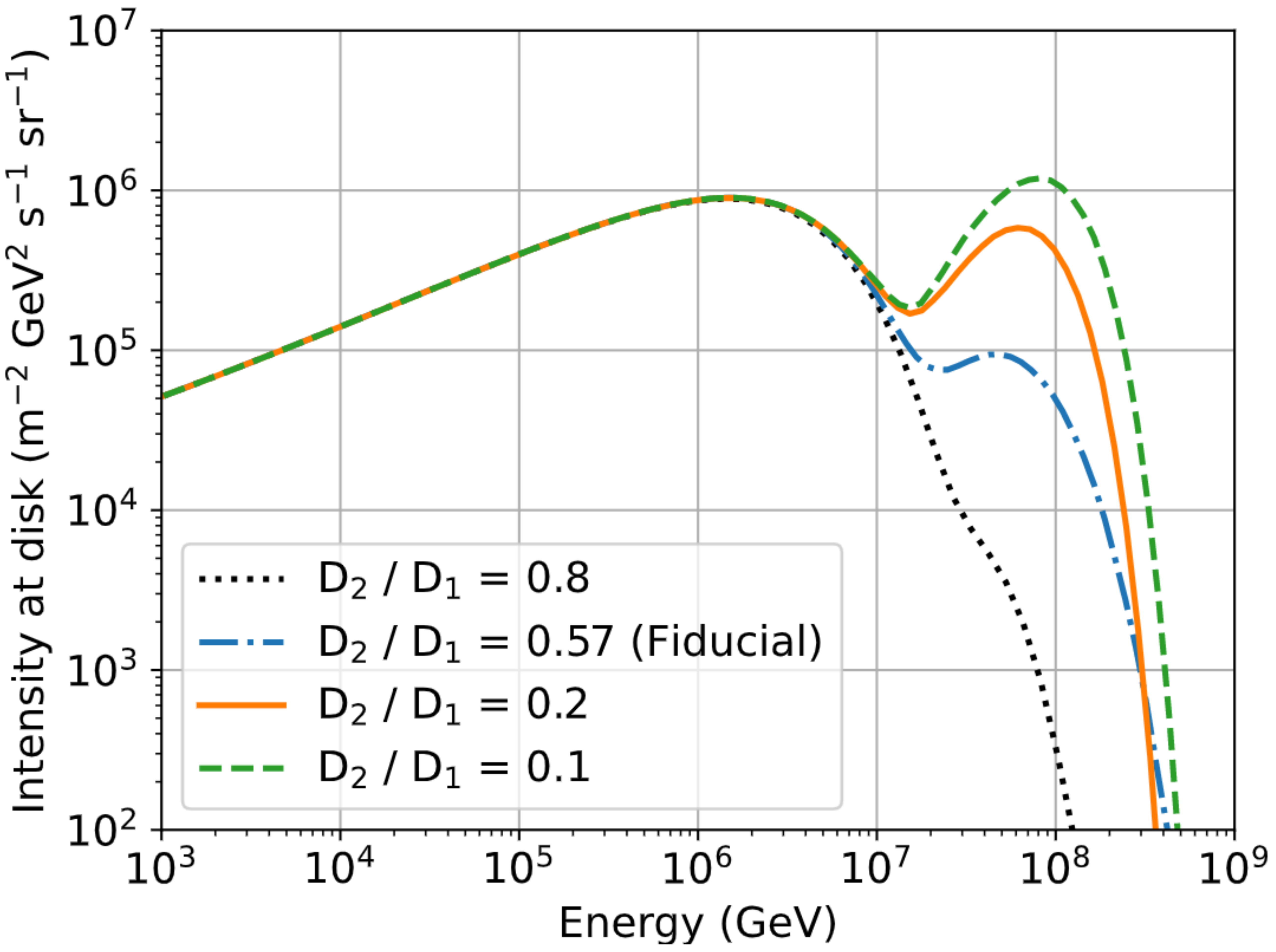
Parameter space variation - diffusion coefficient

D_1 - upstream diffusion, D_2 - downstream diffusion.

The ratio of downstream to upstream diffusion coefficient crucially impacts the flux of back streaming particles.

Decreasing D_2 decreases the flux of particles escaping into the IGM and consequently increases the flux of back streaming particles.



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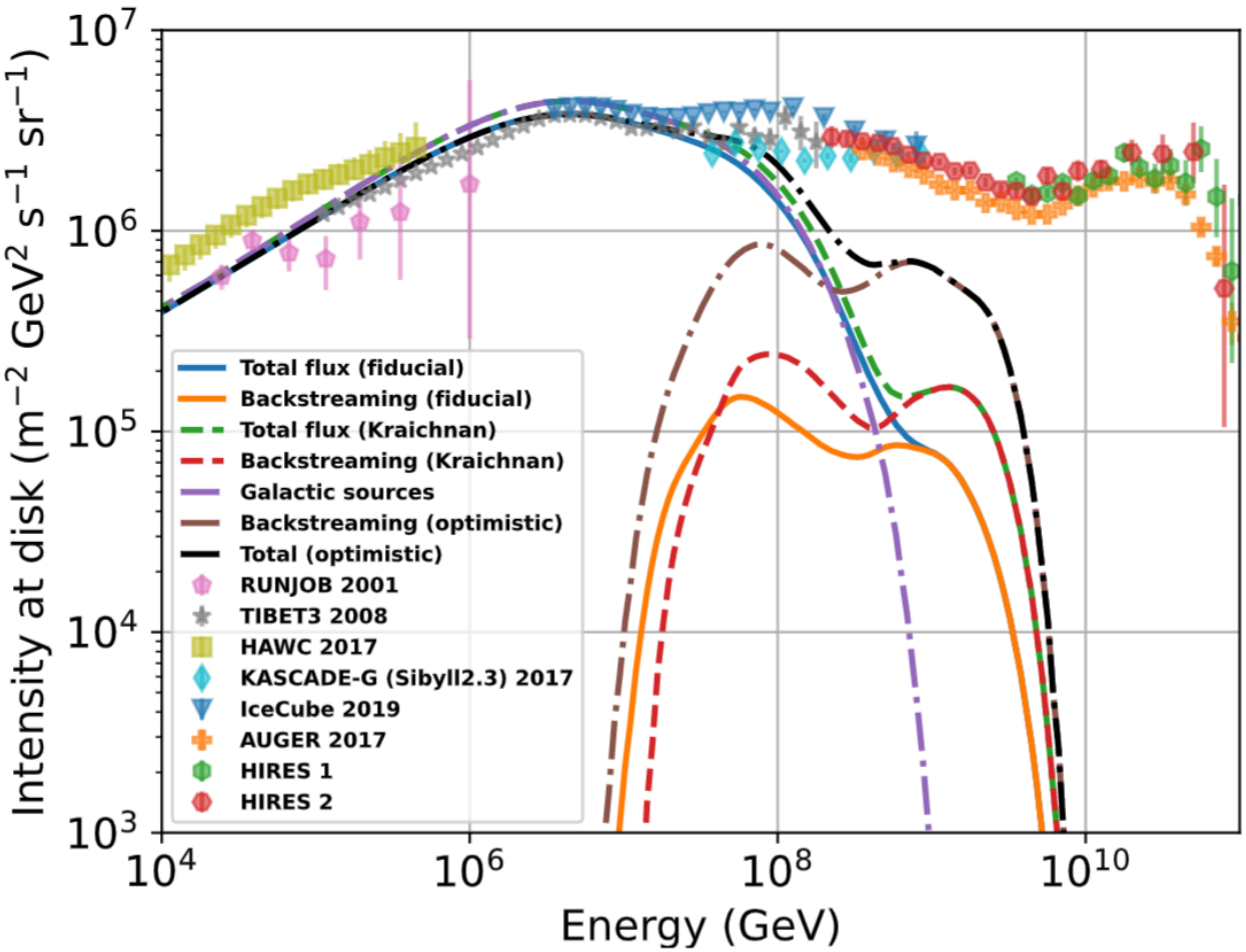
All particle spectrum

All particle spectrum computed in our models. Galactic and backstreaming component shown separately.

Spectrum computed with optimistic models (black dash-dot) can contribute between 20-50% of the total flux in the 100 PeV-2 EeV range.



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Thanks!