# Reacceleration of Galactic Cosmic Rays Beyond the Knee at the Termination Shock of a Cosmic-Ray-Driven Galactic Wind

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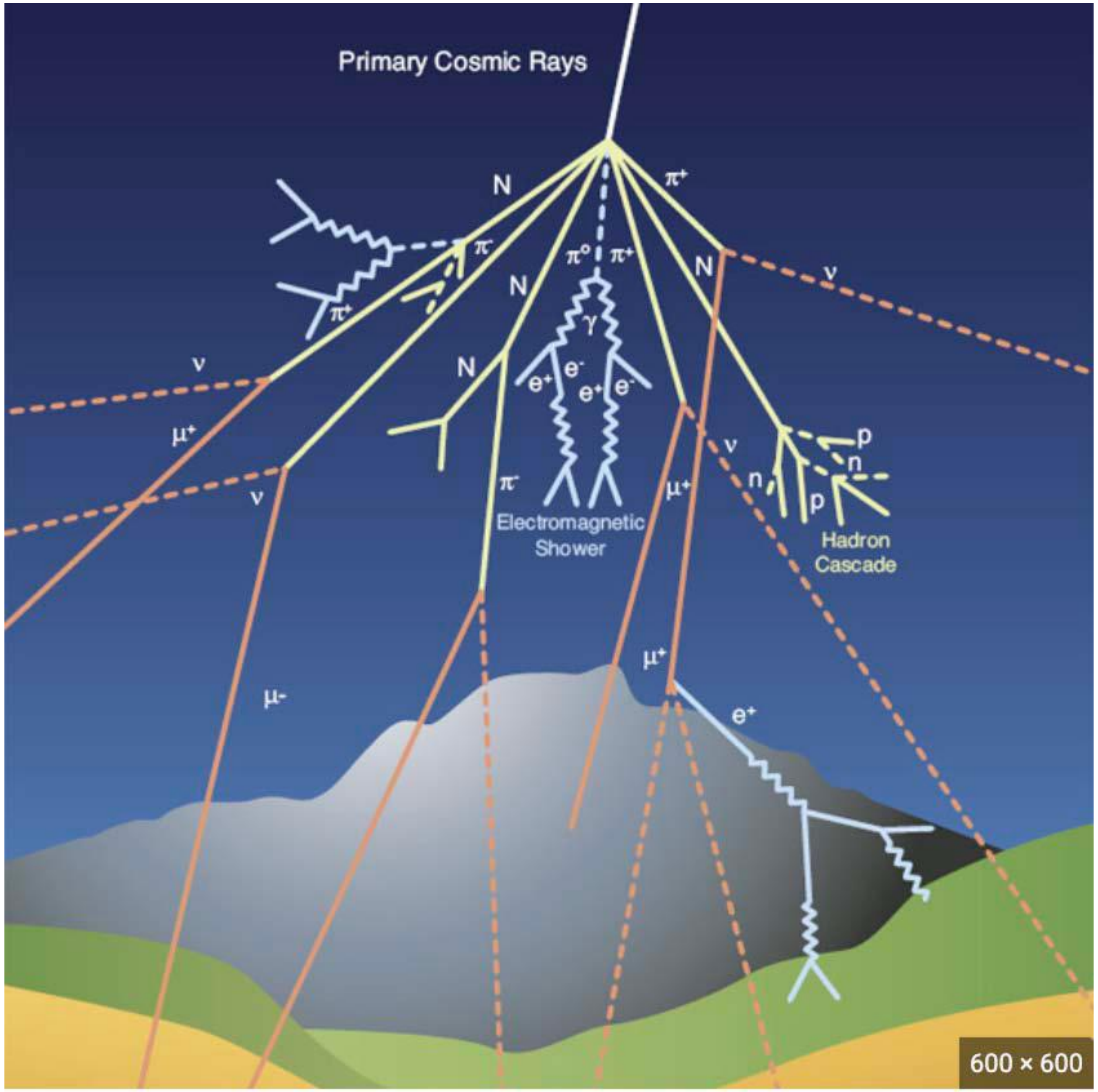
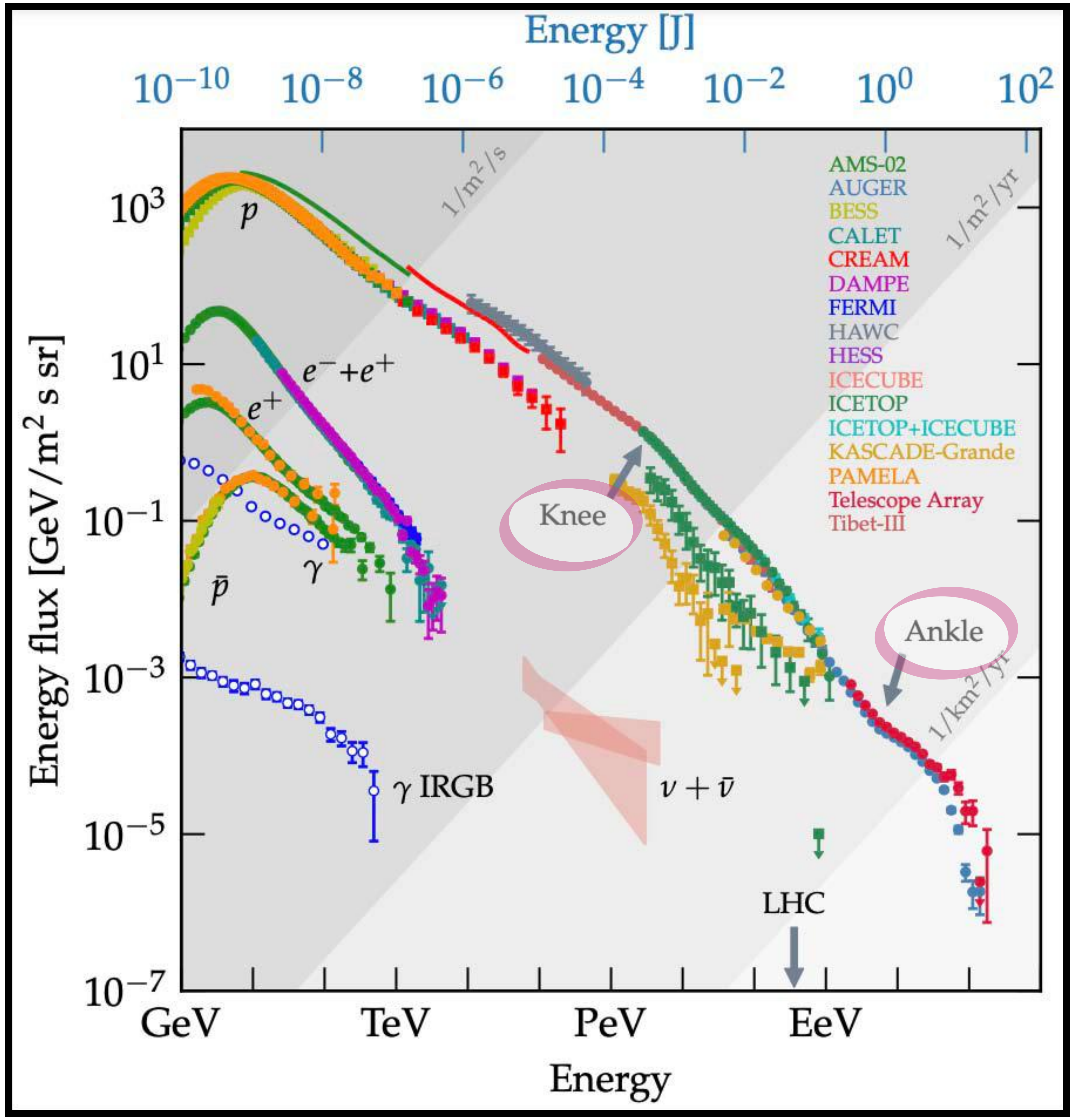
N3AS seminar - Feb, 2023

# Cosmic rays




1. Discovered in 1912 by Victor Hess.
2. Relativistic particles of cosmic origin.
3. Rate of 1 particle $cm^{-2}\,s^{-1}$.
4. Very isotropic.
5. ~90% protons, ~8% Helium and rest are heavy nuclei.

# Origin of cosmic rays - longstanding puzzle

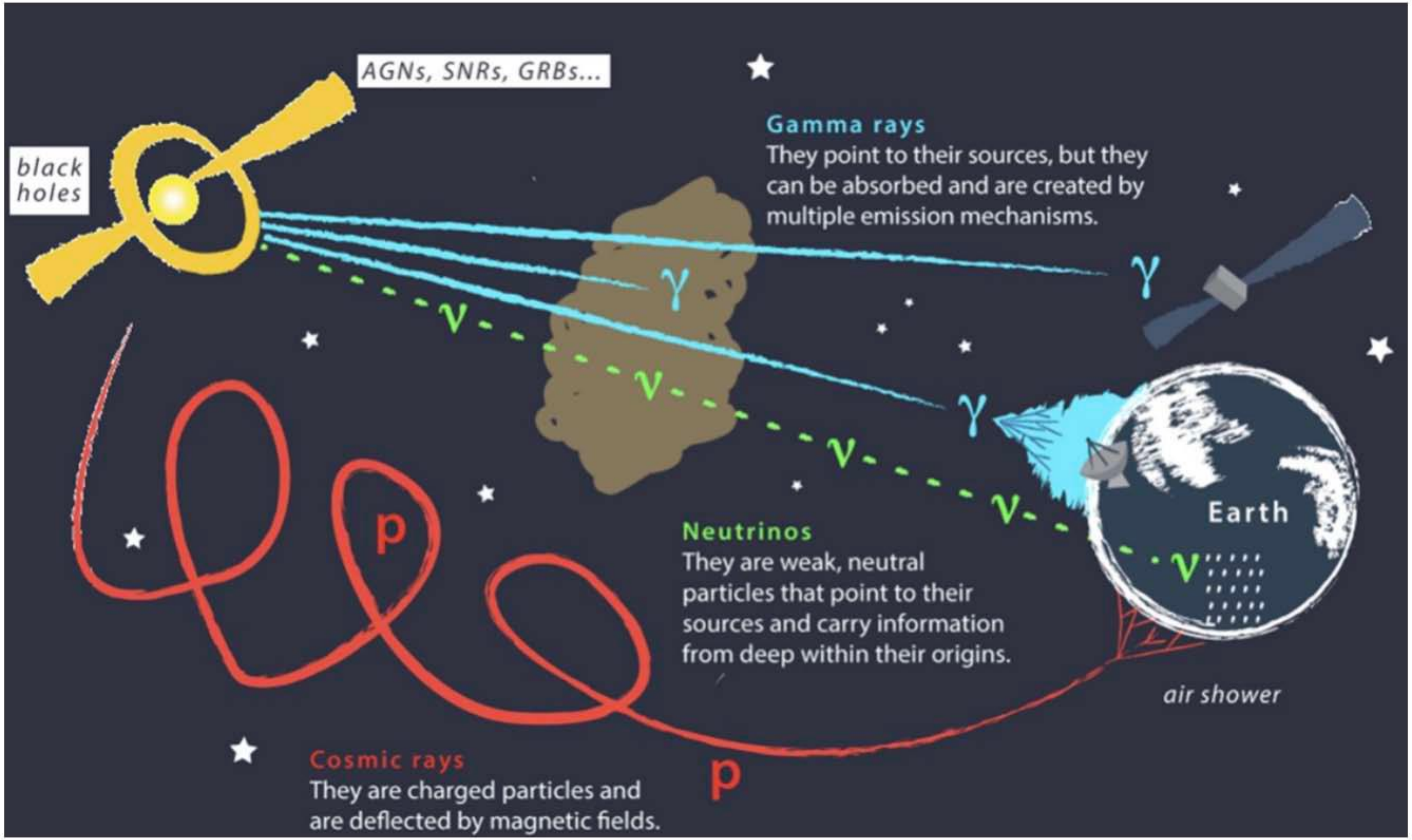



https://zenodo.org/record/2360277

Proposed sources of cosmic rays

1. Up to the knee (~ 3 PeV)
    1. Supernova Remnants
    2. Star clusters
    3. Activity at the Galactic Center
    4. Unidentified ‘PeVatrons’
2. Beyond the ankle (~ 3 EeV) - Extragalactic
    1. Active Galactic Nuclei
    2. Starbursts
    3. Cluster accretion shocks
    4. Gamma ray bursts
3. Between the knee and the ankle (shin) - unknown
    1. Galactic wind termination shocks
    2. Reacceleration in the FERMI bubbles
    3. Superbubbles
    4. Super PeVatrons?

# Multimessenger astronomy




Juan Antonio Aguilar & Jamie Yang, IceCube/WIPAC

# Original motivation

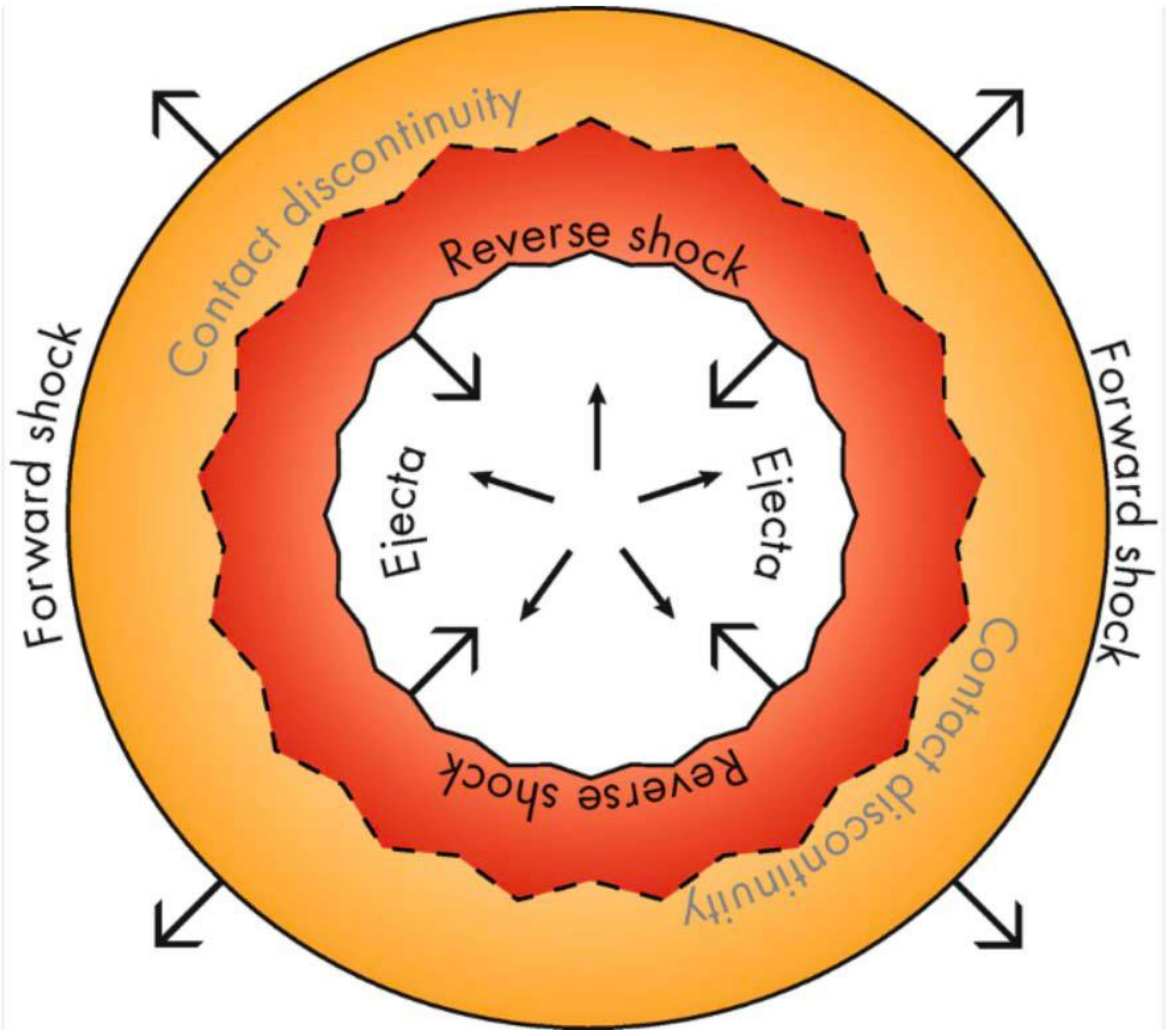
Can we develop a unified, refutable model of cosmic ray acceleration that can explain the entire spectrum from GeV up to 100 EeV?

How viable is such a model?

# Overarching goals of this research programme

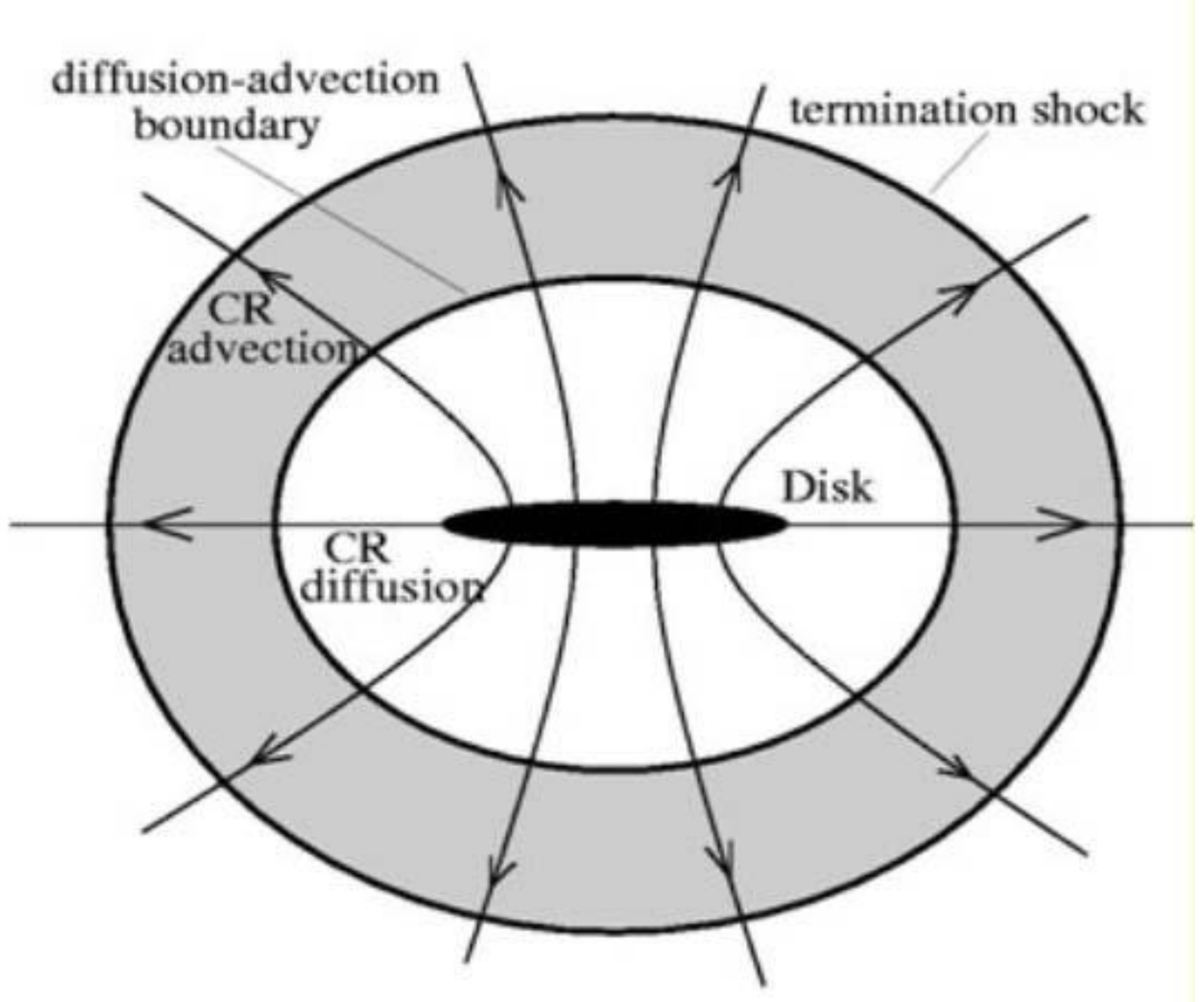
Postulate that the cosmic rays from GeV to 100 EeV all form as a result of diffusive shock acceleration on shocks of different scales.

O (1–10 pc)



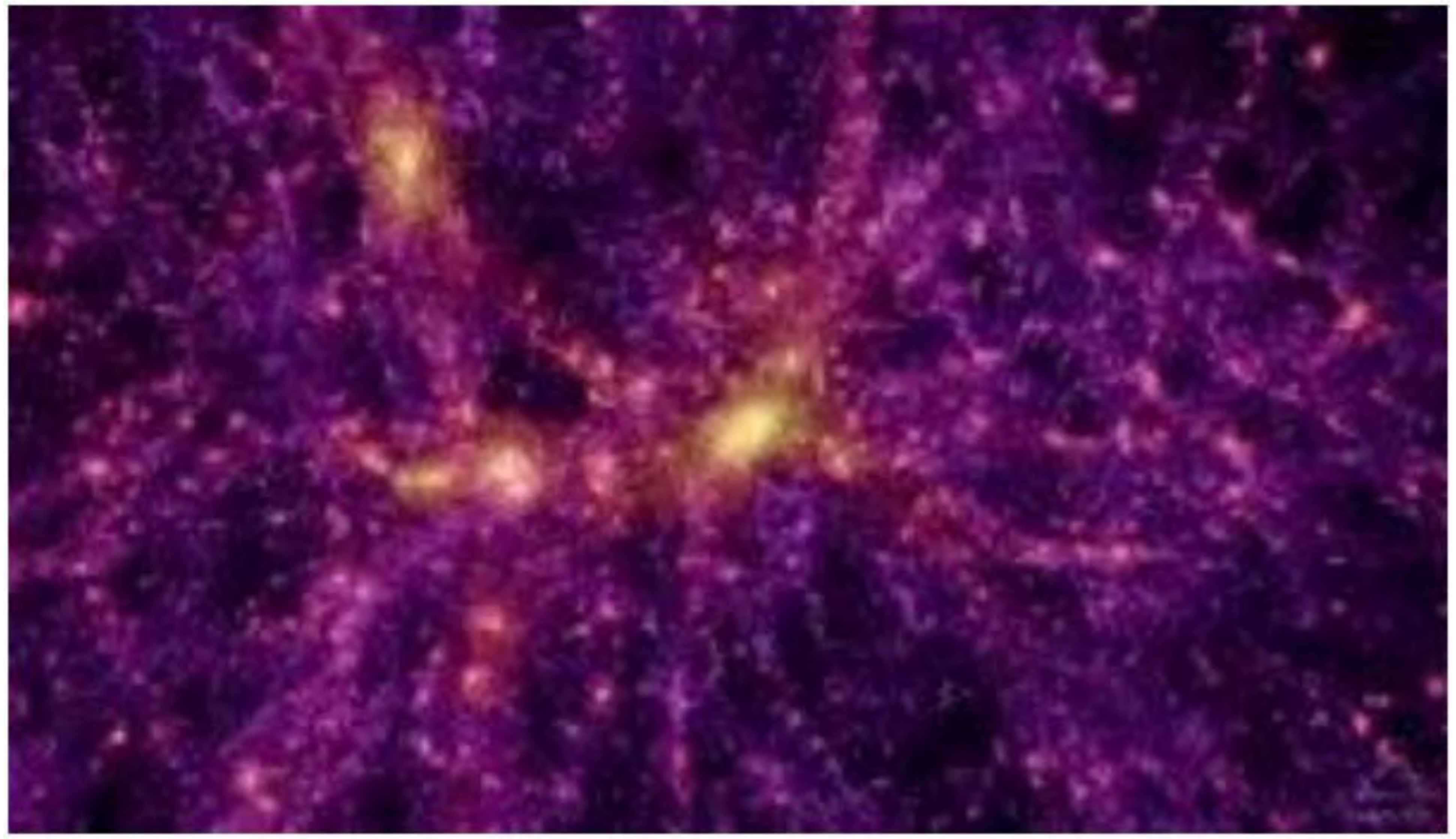

Jacco Vink (2020)

O (100 kpc)




V.N Zirakashvilli (2006)

O (1 Mpc)



Ćiprijanović (2020)

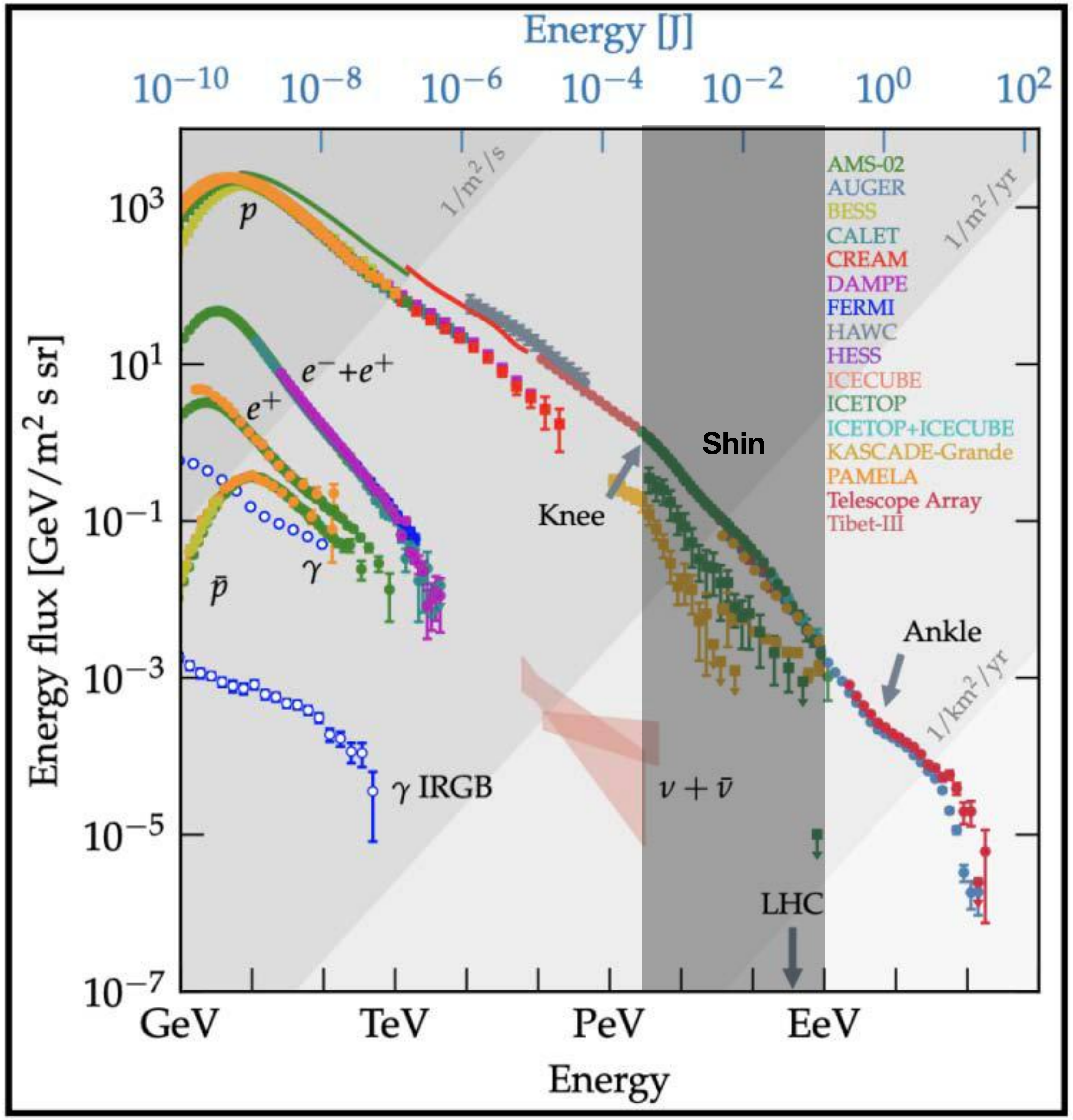
CRs up to knee ~ 3 PeV

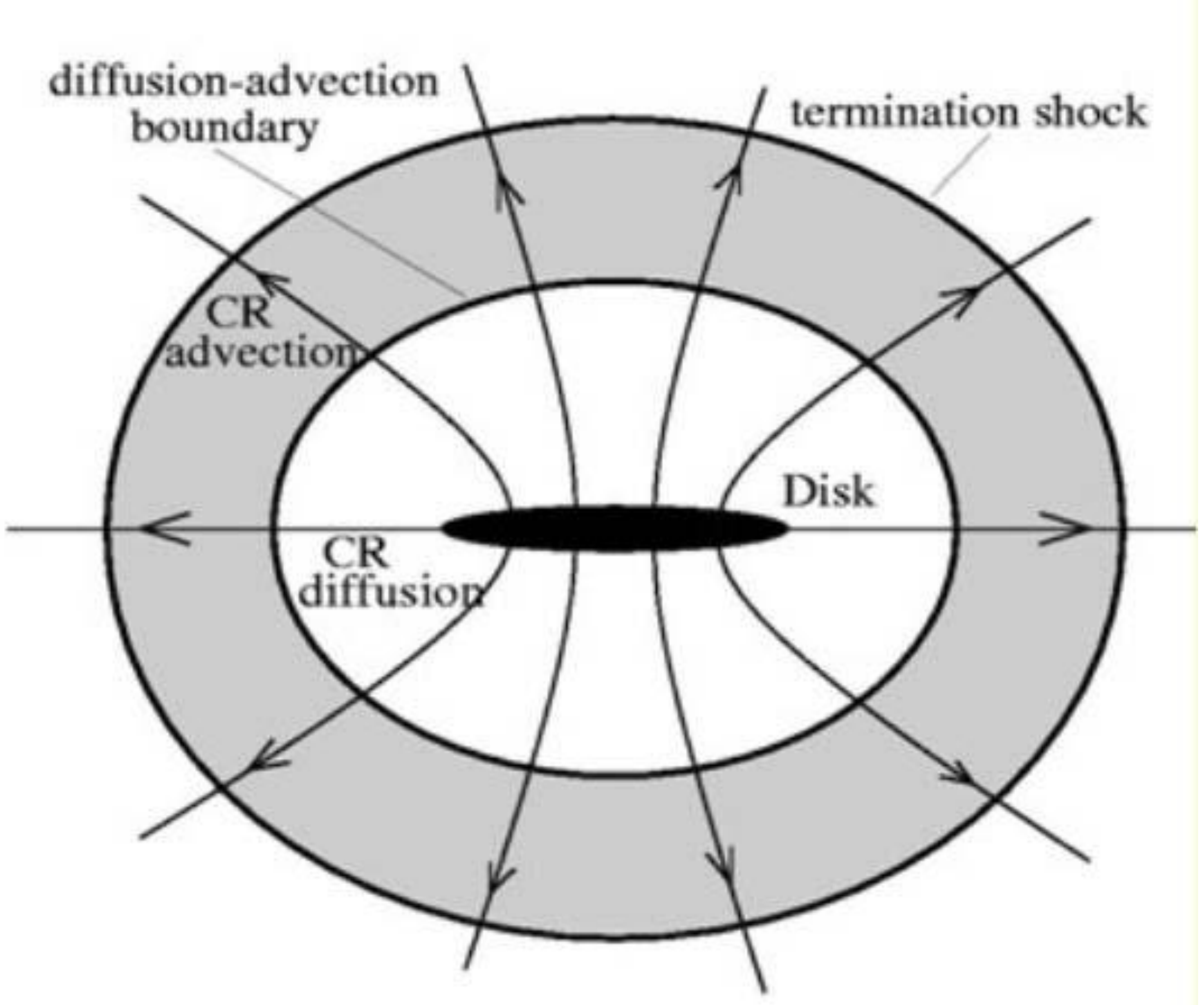
CRs in the shin?

CRs beyond the ankle?

1. Heliosphere to supernova remnants to rich cluster accretion shocks.
2. Each level feeds cosmic rays into the next level.
3. Prescriptive, refutable idea.

# In this talk, we focus on the shin — Galactic wind termination shocks




V.N Zirakashvilli (2006)

https://zenodo.org/record/2360277

Wind termination shocks can recycle Galactic cosmic rays to higher energies.

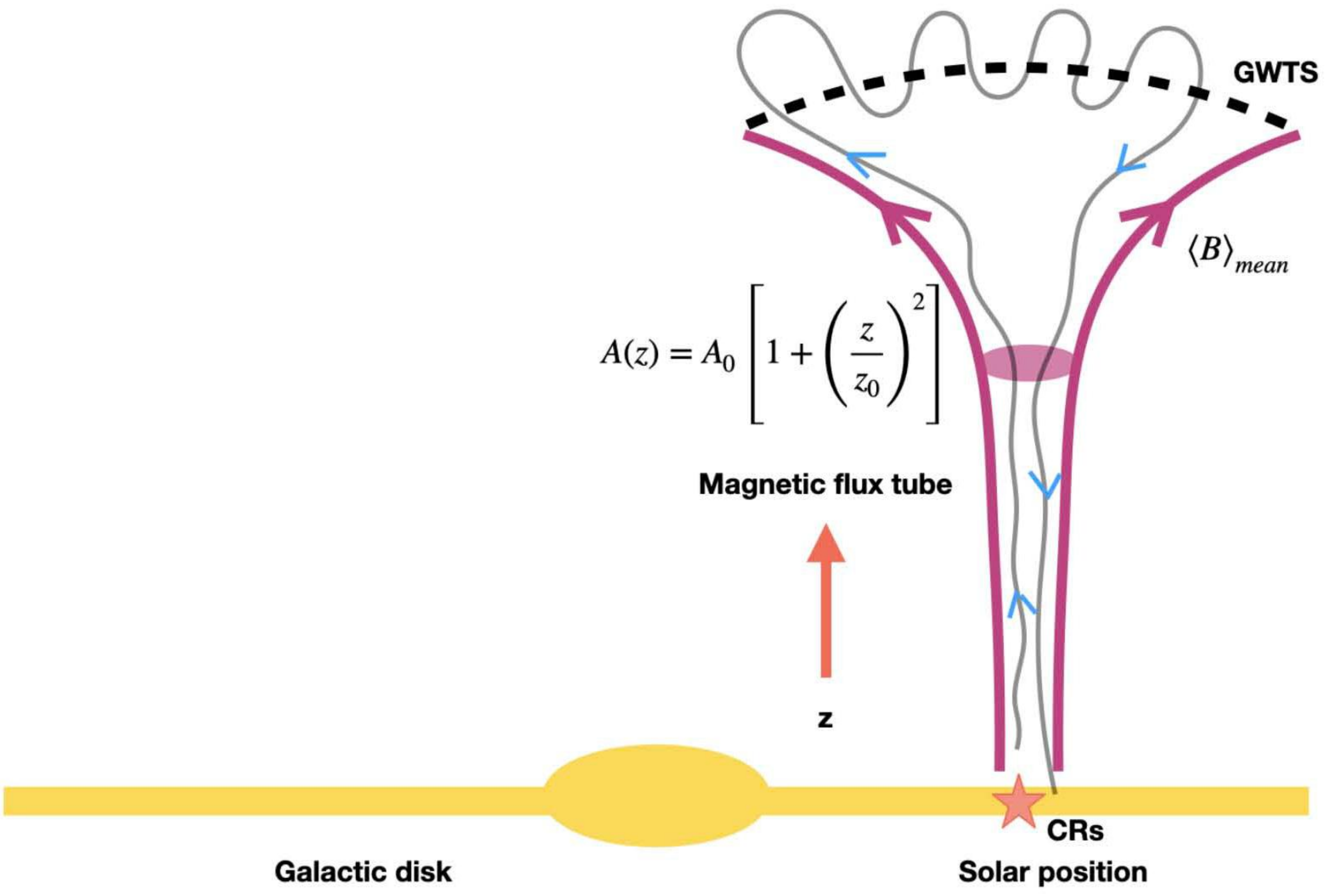
Variants of this idea has been around since 1980s.
(Jokipii 1987, Zirakashvilli 2006, Merten 2018)

A natural way to fill the shin region?

How good are these termination shocks?

We critically analyze the situation.

# Schematics of reacceleration at the galactic wind termination shock




Cosmic rays (CRs) will drive a strong wind of ~1000 km/s.

The wind forms termination shock at ~200 kpc.

Galactic CRs produced by SNRs transported up to GWTS.

Transport of CRs in the wind — diffusion and advection.

Reacceleration by diffusive shock acceleration.

Backstreaming and escaping flux.

Natural mechanism with recycled cosmic rays.

(Mukhopadhyay et al, 2023)

# Cosmic ray and Alfven wave driven galactic winds

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

Mass conservation

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

Total energy conservation

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

Momentum conservation

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

Energy balance of CRs

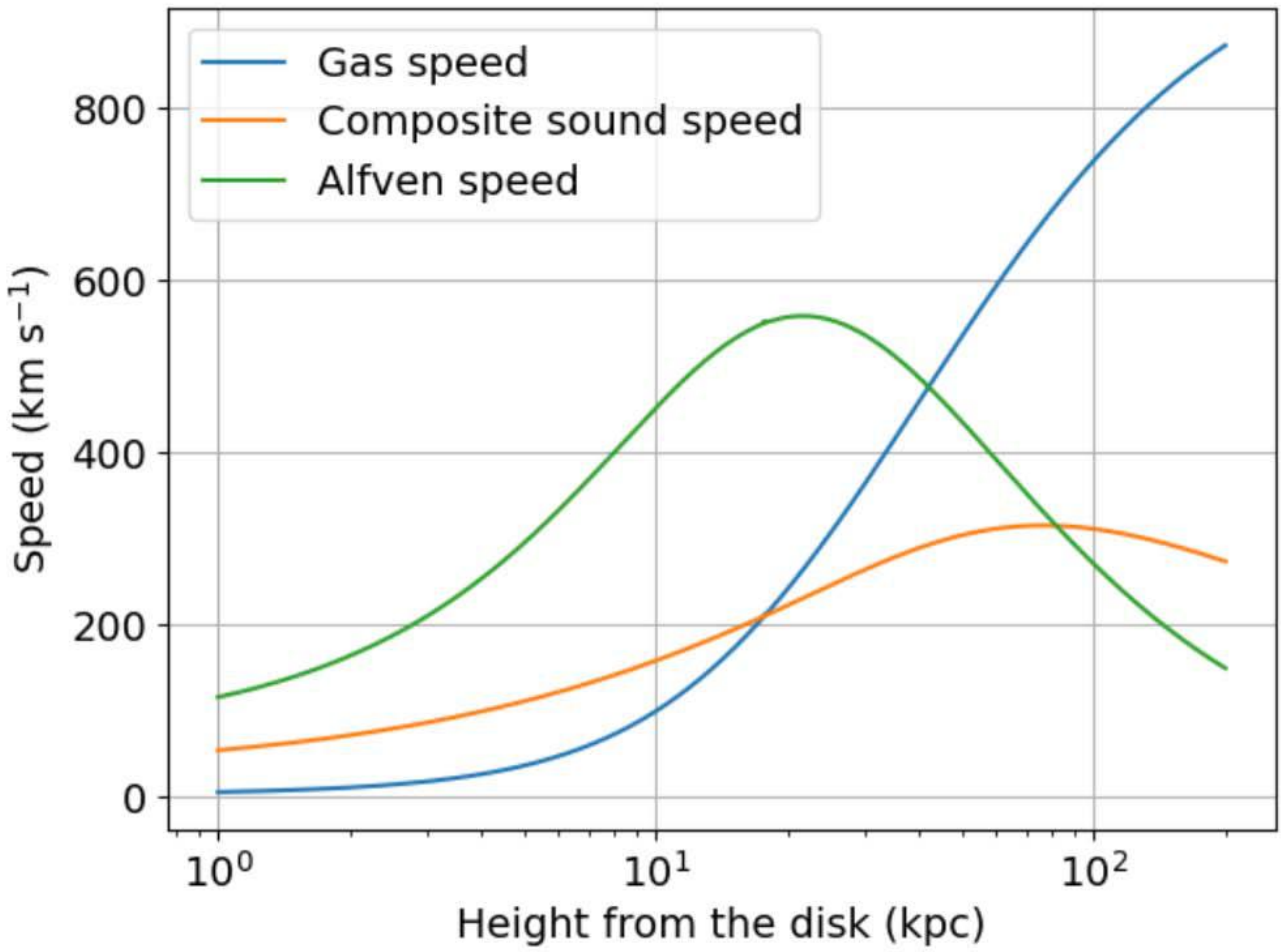
$$\nabla . \left( \frac{\langle (\delta \mathbf{B})^2 \rangle}{4\pi} \left[ \frac{3}{2} \mathbf{v} + \mathbf{v}_A \right] \right) = \mathbf{v} \nabla \left( \frac{\langle (\delta \mathbf{B})^2 \rangle}{8\pi} \right) - \mathbf{v}_A \nabla P_c$$

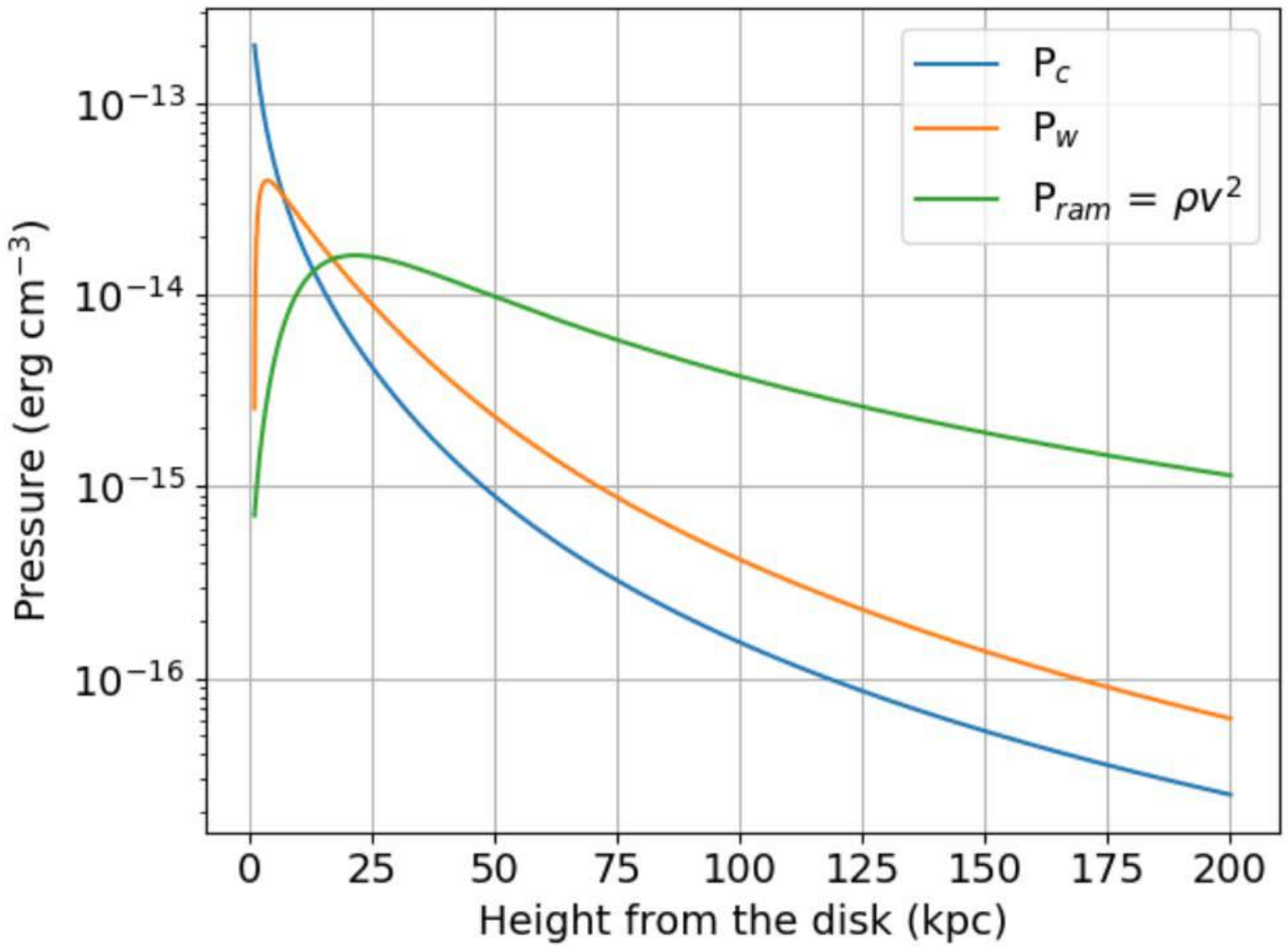
Energy balance of waves

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

Vanishing magnetic field divergence

# Fast winds can be launched — important for efficient CR acceleration




Mass outflow rates of O(1 $\mathrm{M_\odot yr^{-1}}$) found, comparable to the star formation rate of the Galaxy.

Forms a strong wind termination shock at ~ 200 kpc.

(Mukhopadhyay et al, 2023)

# We transport the cosmic rays in this wind

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

Diffusion

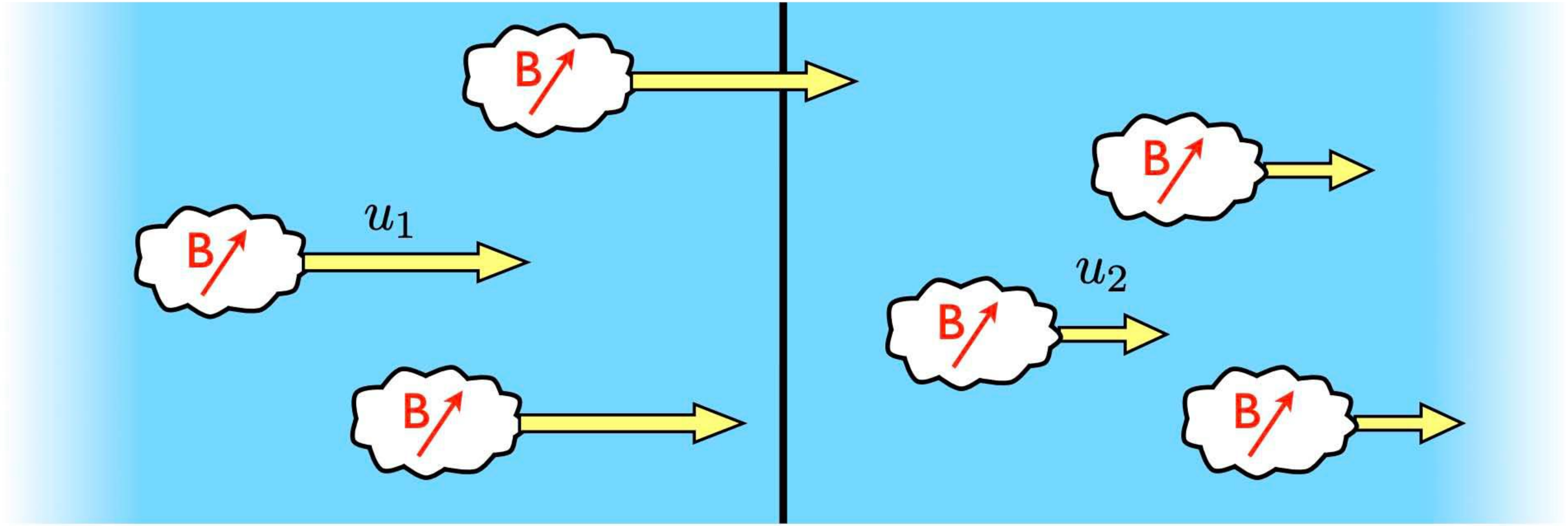
Advection

# Diffusive shock acceleration mechanism for cosmic rays

Diffusion is the key

# Diffusive shock acceleration

Shock + Magnetic fields

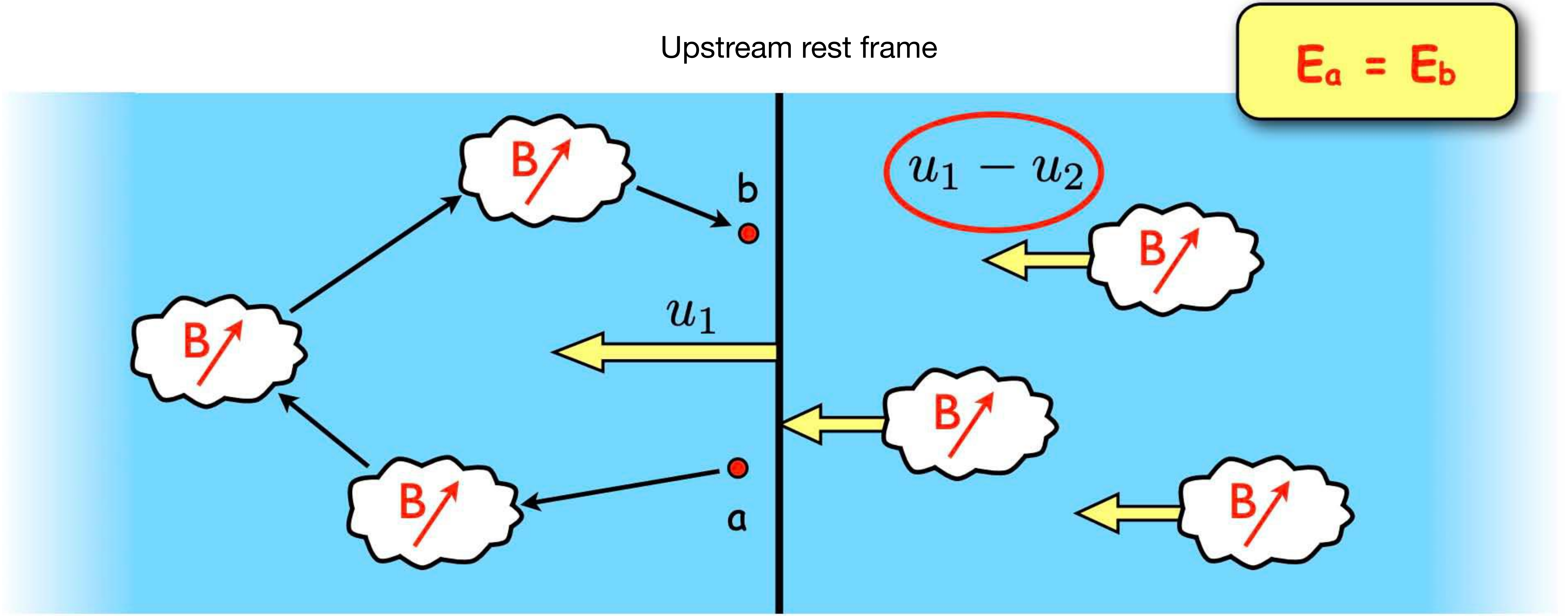



Upstream Shock Downstream

Stefano Gabici (2012)

# Diffusive shock acceleration

Upstream rest frame

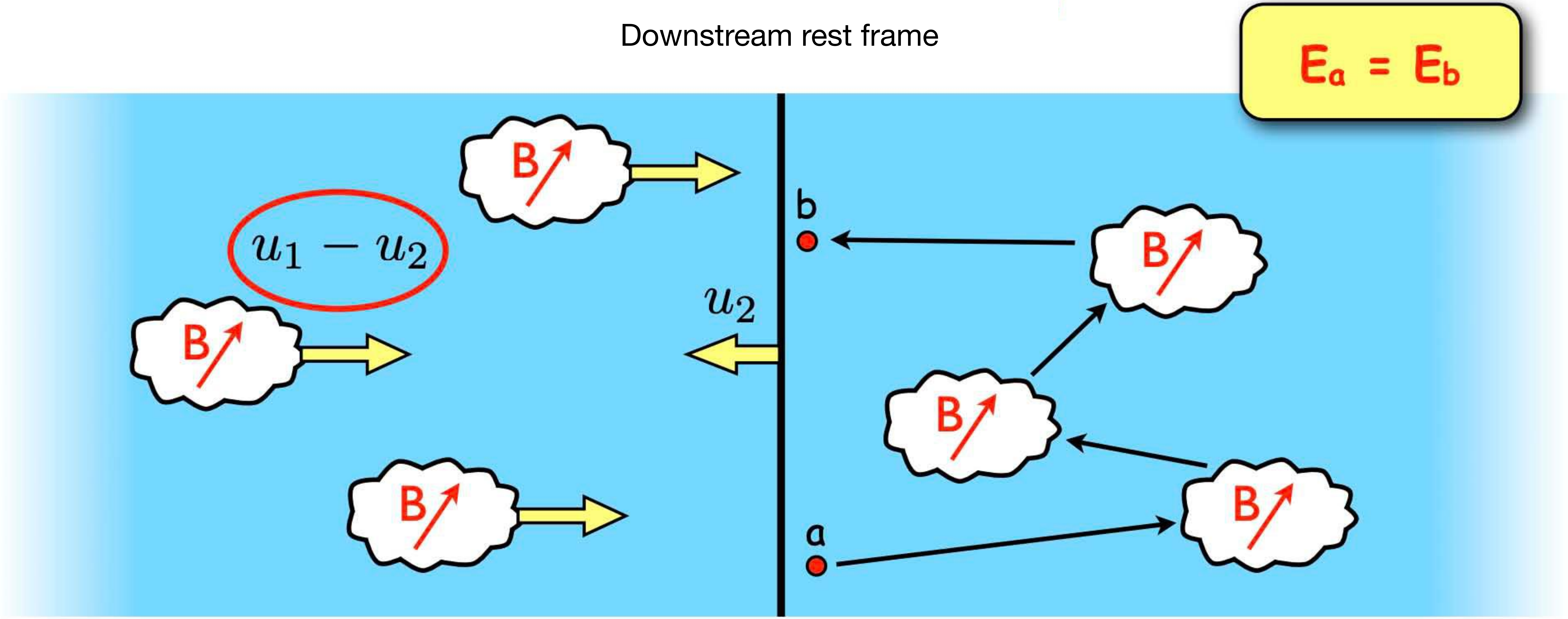



Upstream Shock Downstream

Stefano Gabici (2012)

# Diffusive shock acceleration

Downstream rest frame

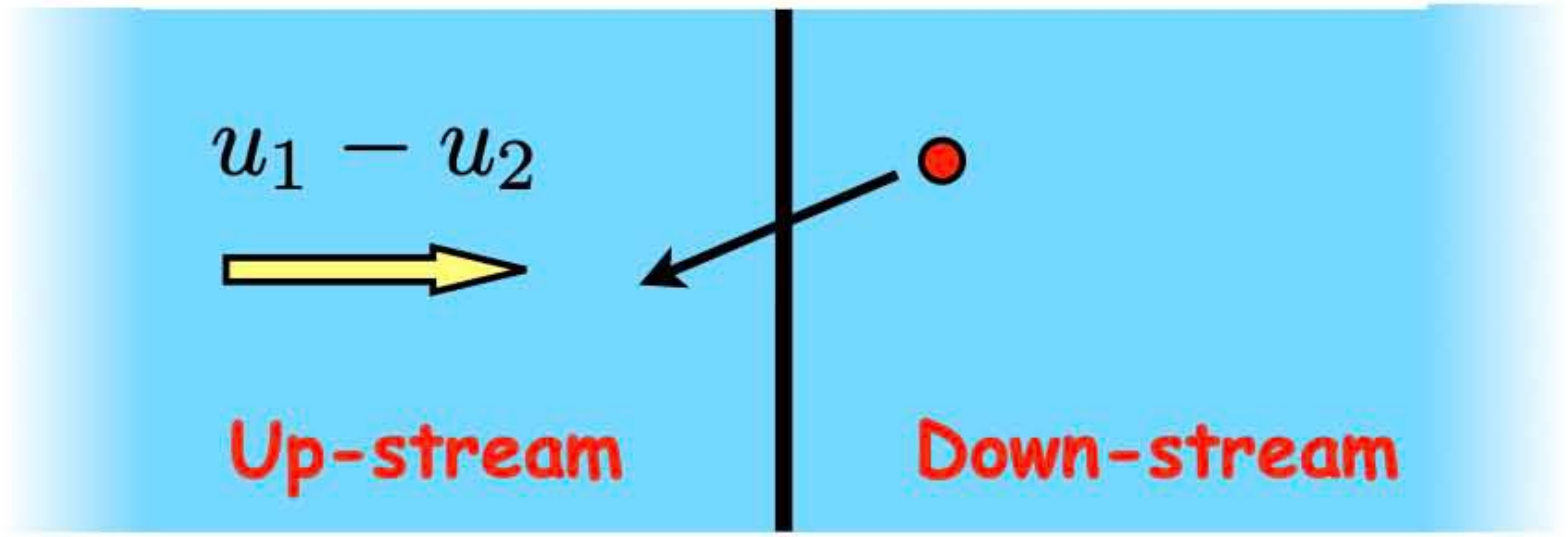


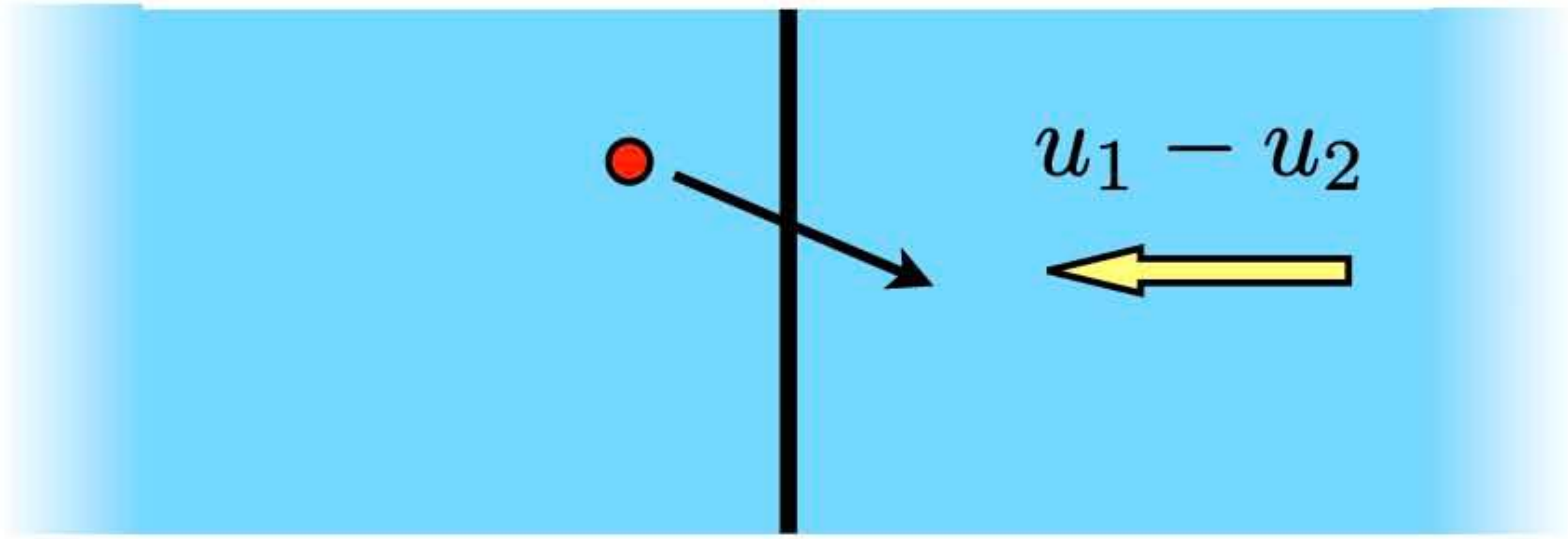

Upstream Shock Downstream

Stefano Gabici (2012)

# Diffusive shock acceleration

Stefano Gabici (2012)




Every time the particle crosses the shock (up -> down or down -> up), it undergoes a head-on collision with a plasma moving at $u_1 - u_2$. Gain in energy at each crossing.

Energy gain per cycle

$$< \frac{\Delta E}{E} > = \frac{4}{3} \left(\frac{v}{c}\right) = \frac{4}{3} \left(\frac{u_1 - u_2}{c}\right)$$

Stefano Gabici (2012)

First order Fermi mechanism

# Diffusive shock acceleration

Energy increases by a small factor after each cycle

$$E_{i+1} = \left(1 + \frac{4}{3}\frac{v}{c}\right) E_i$$

↓

$$E_{i+1} = \beta \; E_i$$

For strong shocks, successive energy gain gives rise to a power law spectrum

$$n(E) \propto E^{-2}$$

Factors limiting the maximum energy achieved

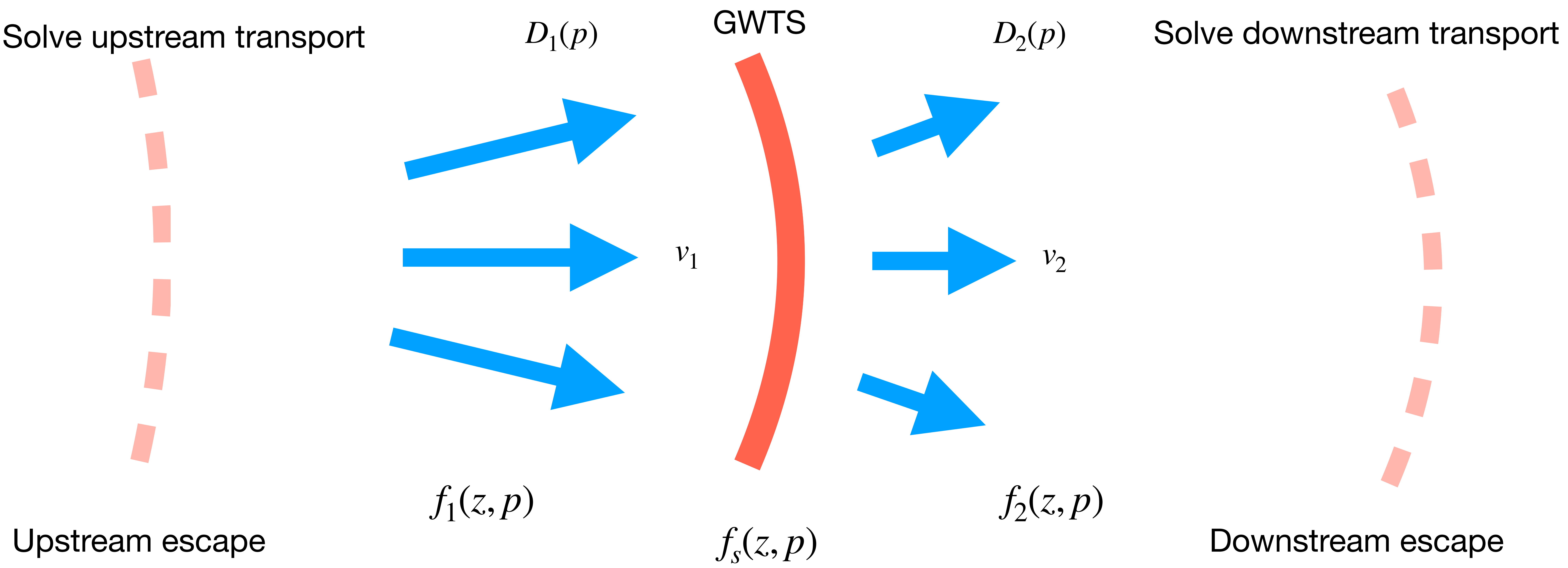
Acceleration time

$$t_{acc} = \left(\frac{1}{E}\frac{dE}{dt}\right)^{-1} < t_{age}$$

Confinement

$$L_{\rm diff} = \frac{D(E)}{v_{\rm sh}} < L$$

# DSA at the Galactic wind termination shock




Join the solutions at the shock

Upstream, downstream, and DSA at the shock treated consistently for the first time



(Mukhopadhyay et al, 2023)

# Maximum cosmic ray energy attained at the GWTS

$E_{\rm max}$ governed by the diffusion coefficient, wind speed and size of the shock:

$$R_{\rm sh} \sim \frac{D(E_{\rm max})}{v}$$

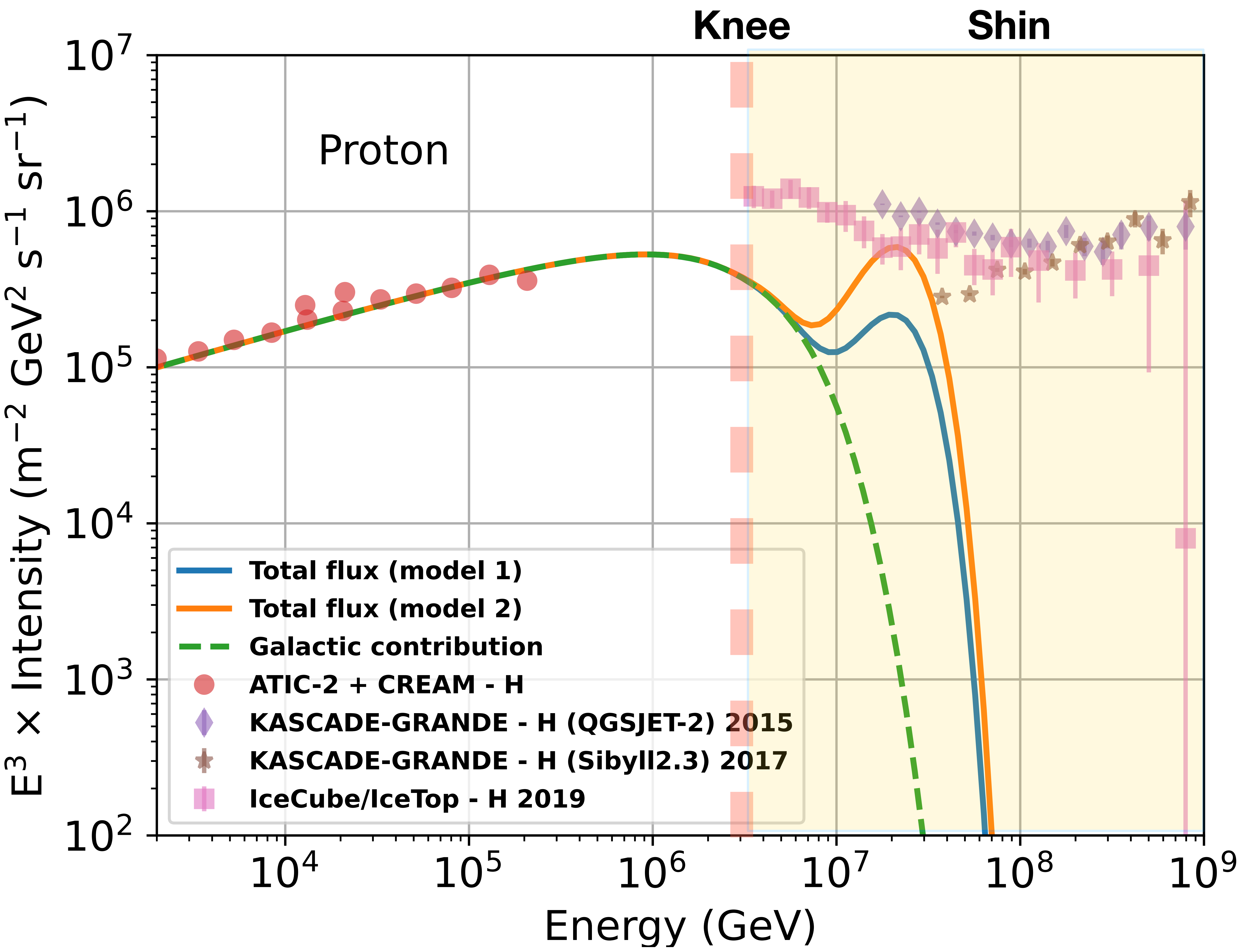
Kolmogorov type magnetic turbulence:

$$D(E) = D_0 E^{1/3}$$

$E_{\rm max}$ increases with faster winds, and larger shocks and smaller upstream diffusion coefficient:

$$E_{\rm max} \sim \left(\frac{vR_{\rm sh}}{D_0}\right)^3$$

# GWTS can accelerate cosmic rays beyond the knee




Robust reacceleration of CRs up to ~30 PeV.

An order of magnitude gain from the proton knee.

Overall normalisation is model dependent.

The model predicts a ‘bump’ marking transition from Galactic CRs to GWTS CRs.

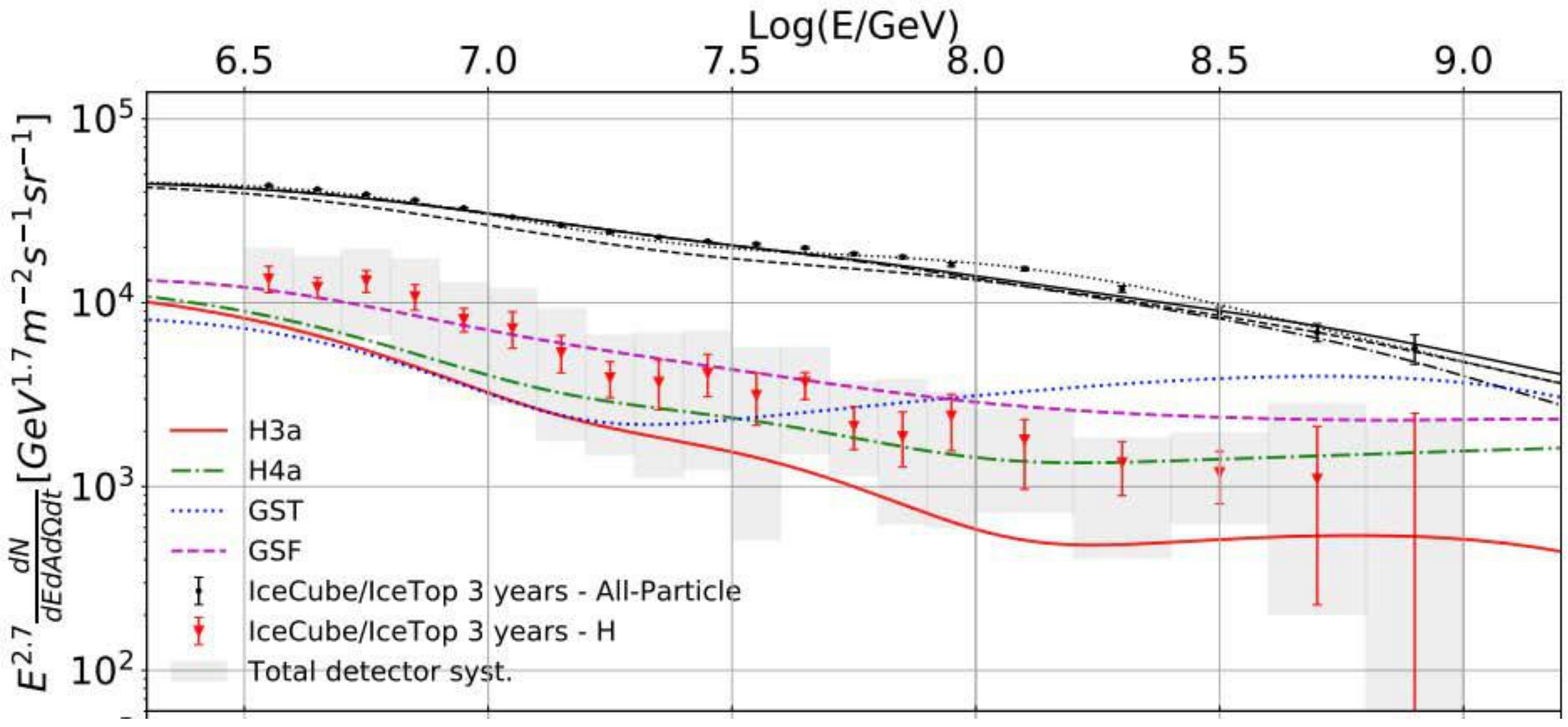
IceCube/IceTop and KASCADE-GRANDE experiments provide data beyond the knee.

Significant component of the measured spectrum at O(10 PeV).

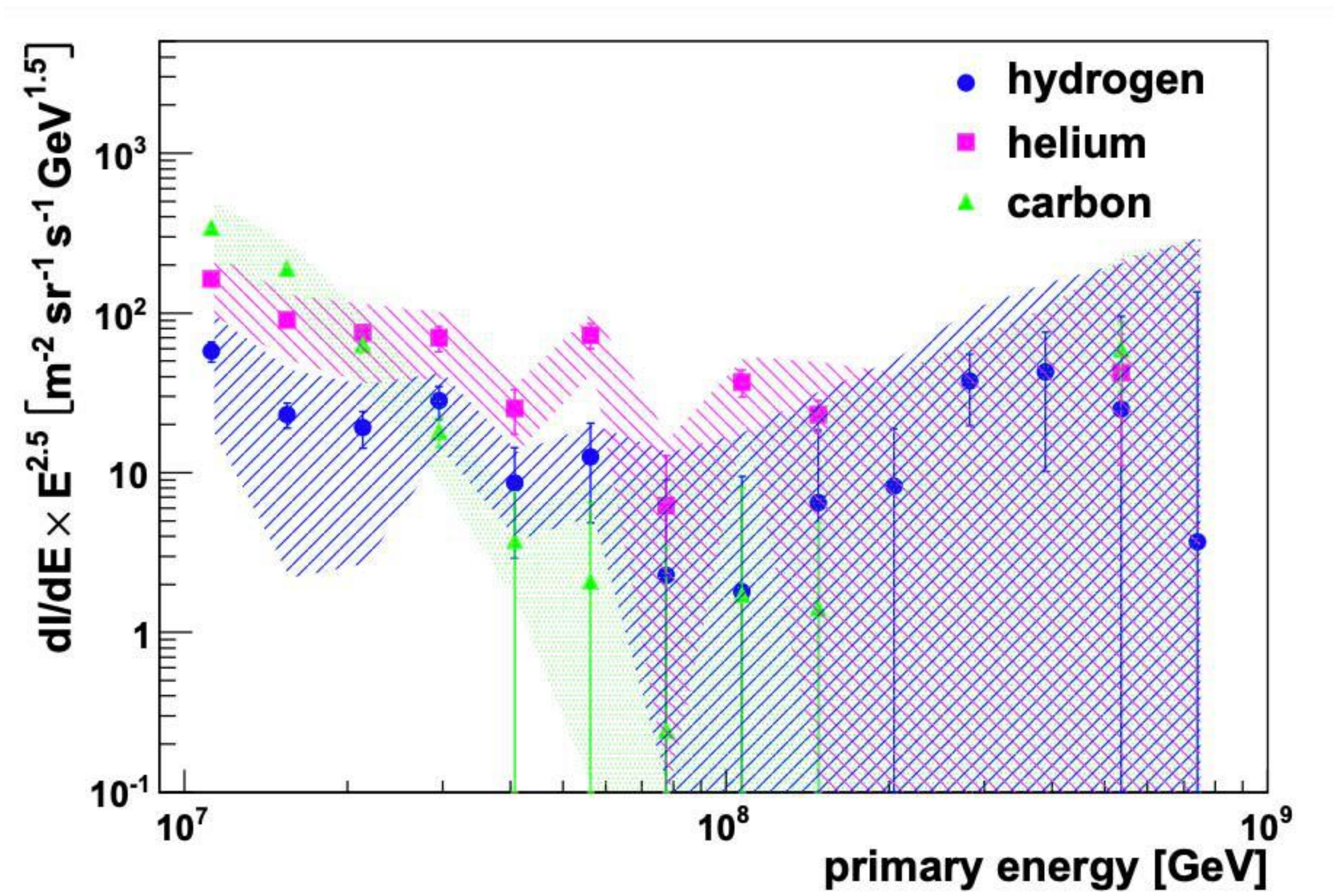
This `bump’ feature can be constrained in future experiments.

(Mukhopadhyay et al, 2023)

# Cosmic ray proton data

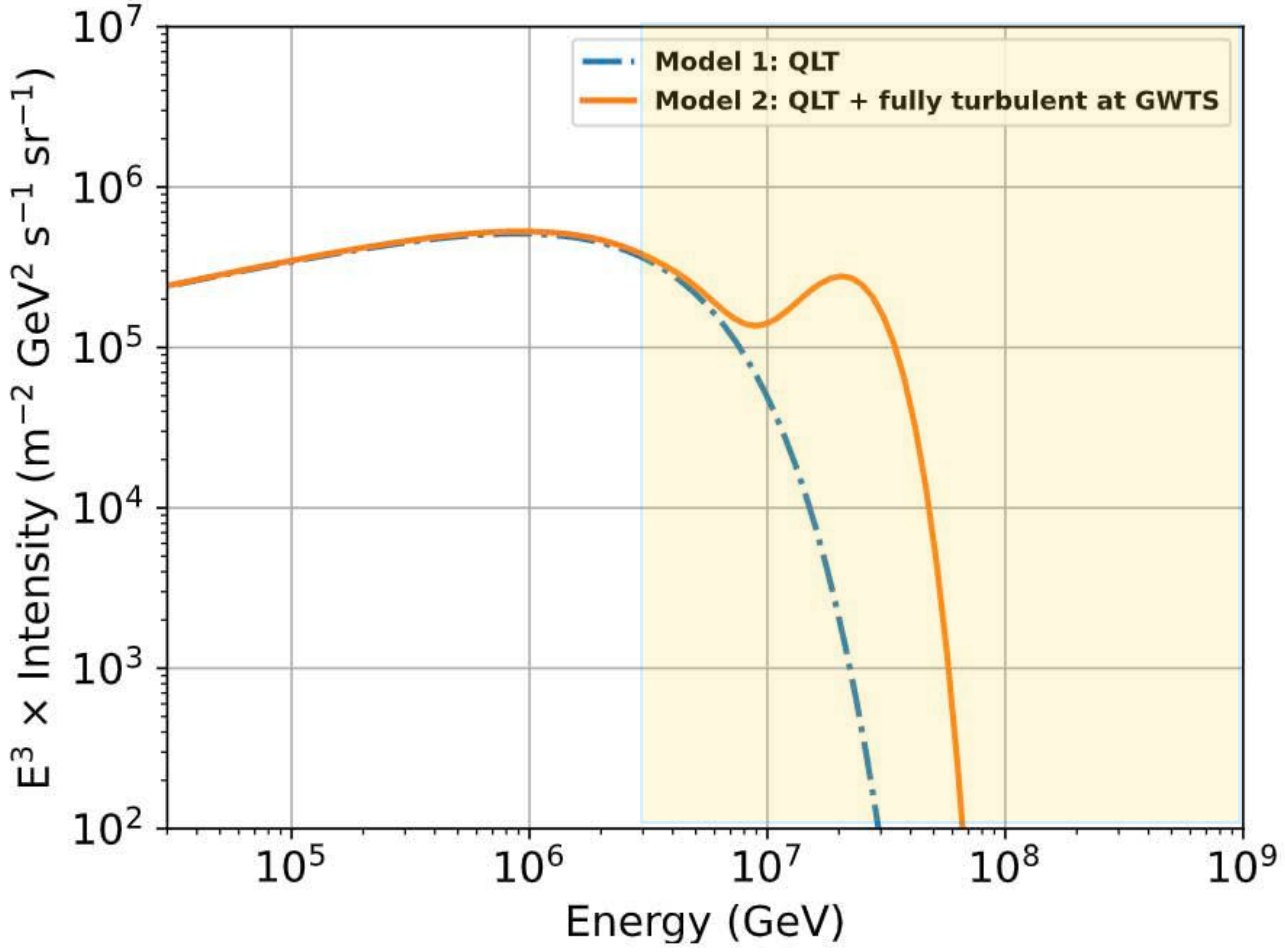


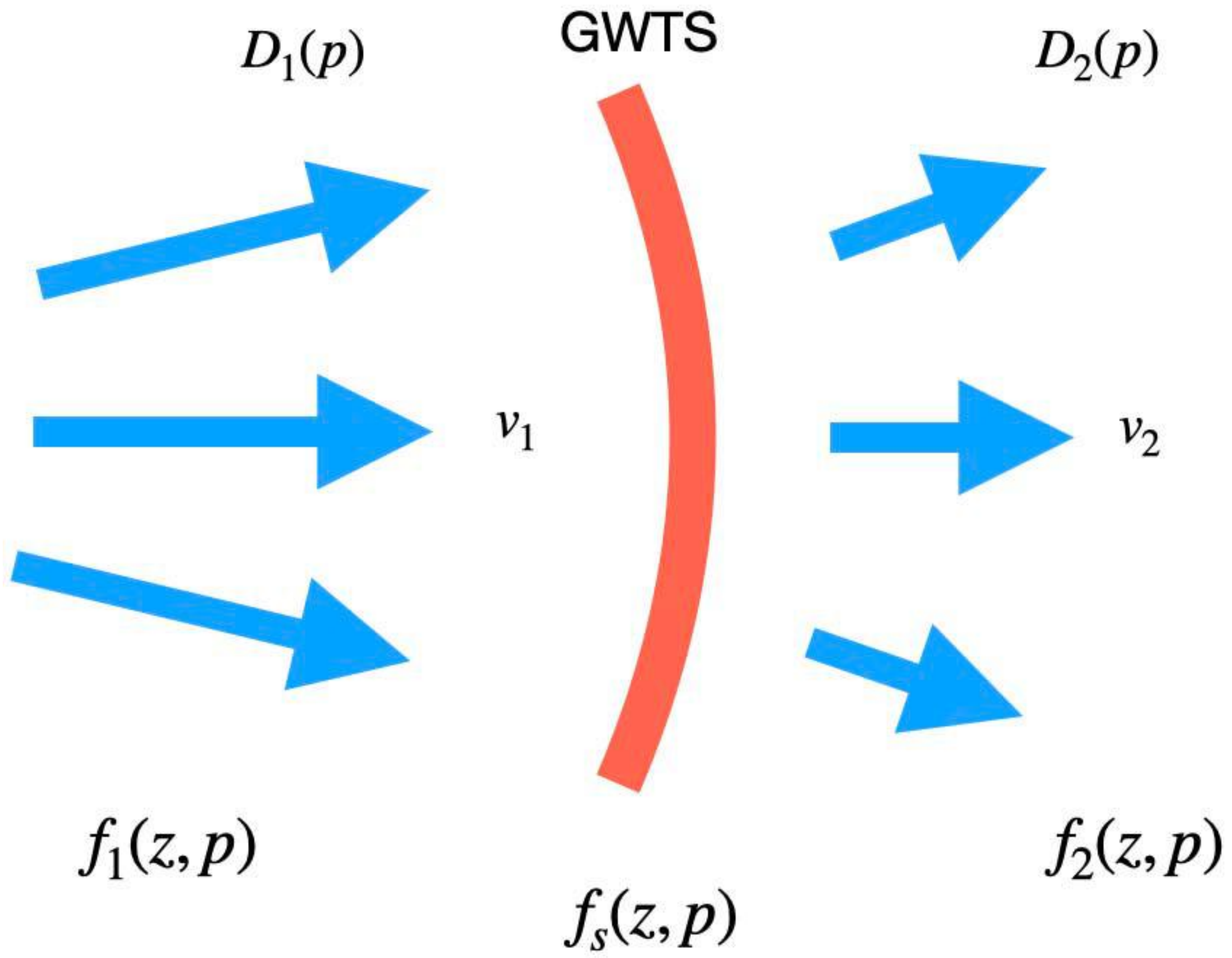

IceCube/IceTop coincident analysis (2019)




KASCADE/GRANDE (2011)

# Conditions under which efficient reacceleration can occur

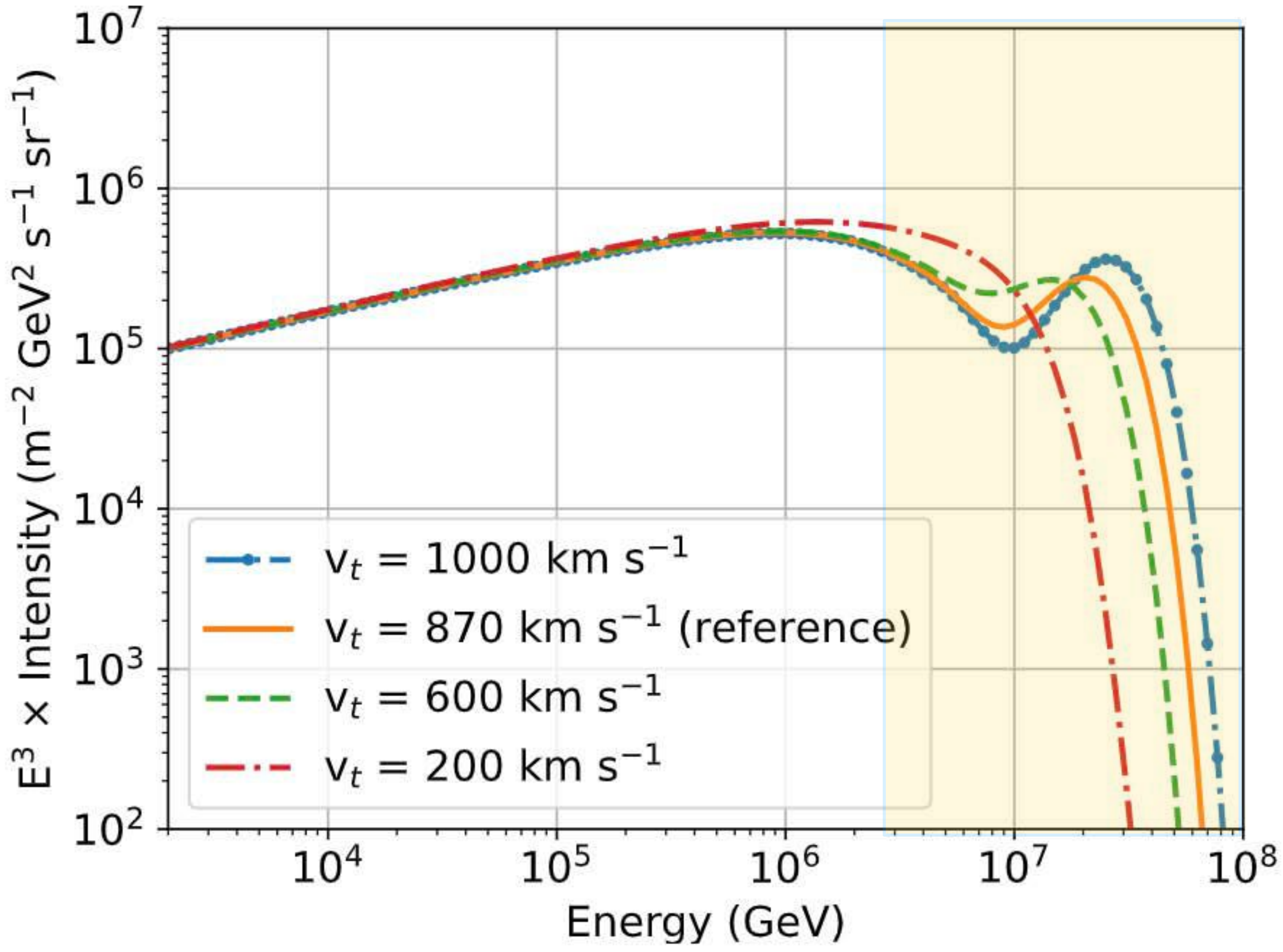


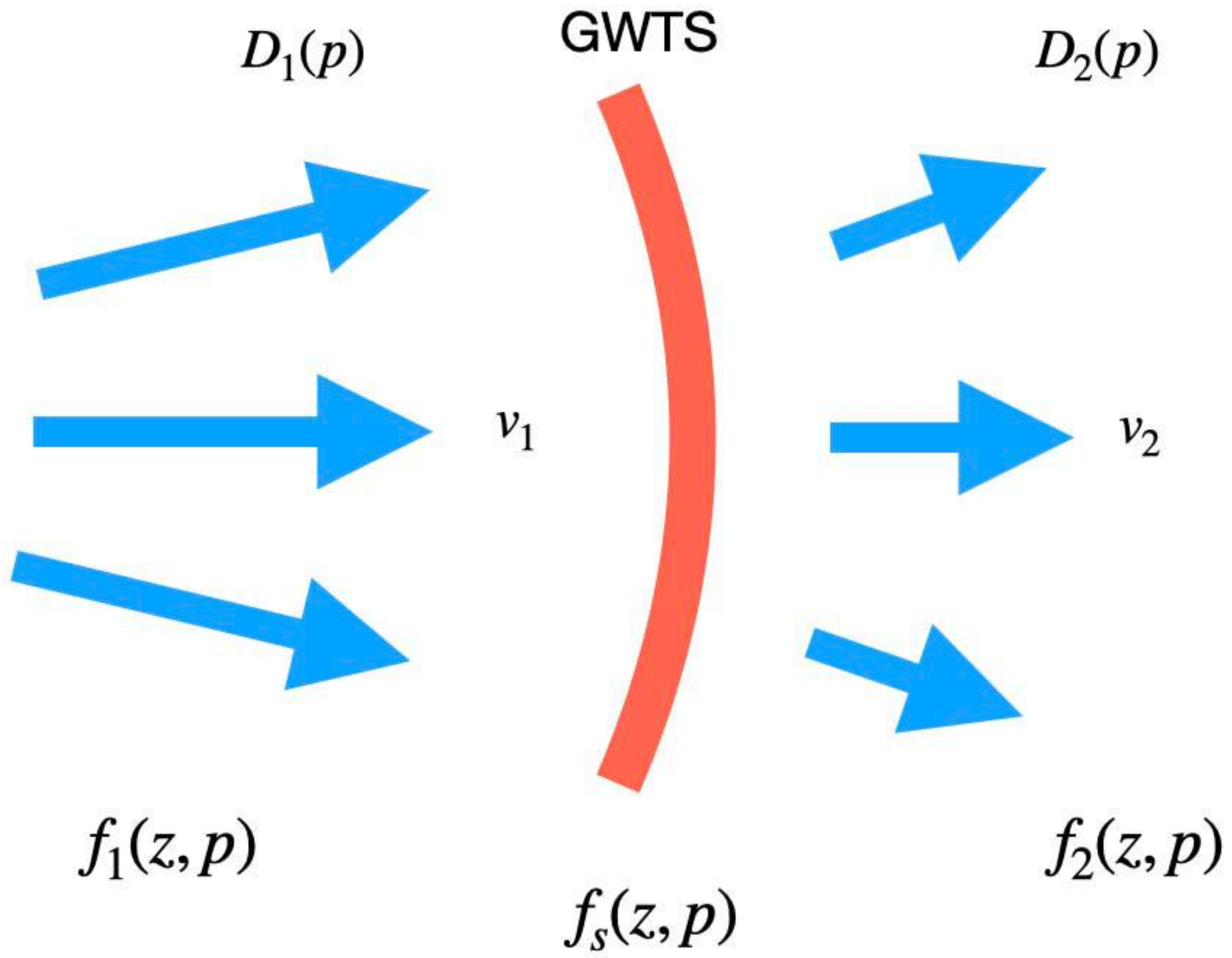




Increasing upstream diffusion coefficient can dramatically lower $E_{\max}$.
Low diffusion near the GWTS is motivated by the expectation of enhanced turbulence due to plasma instabilities.

(Mukhopadhyay et al, 2023)

# Conditions under which efficient reacceleration can occur




Decreasing the wind speed will decrease $E_{\max}$.

In the future, observational constraints on the parameters of the Galactic wind can strongly constrain our model.

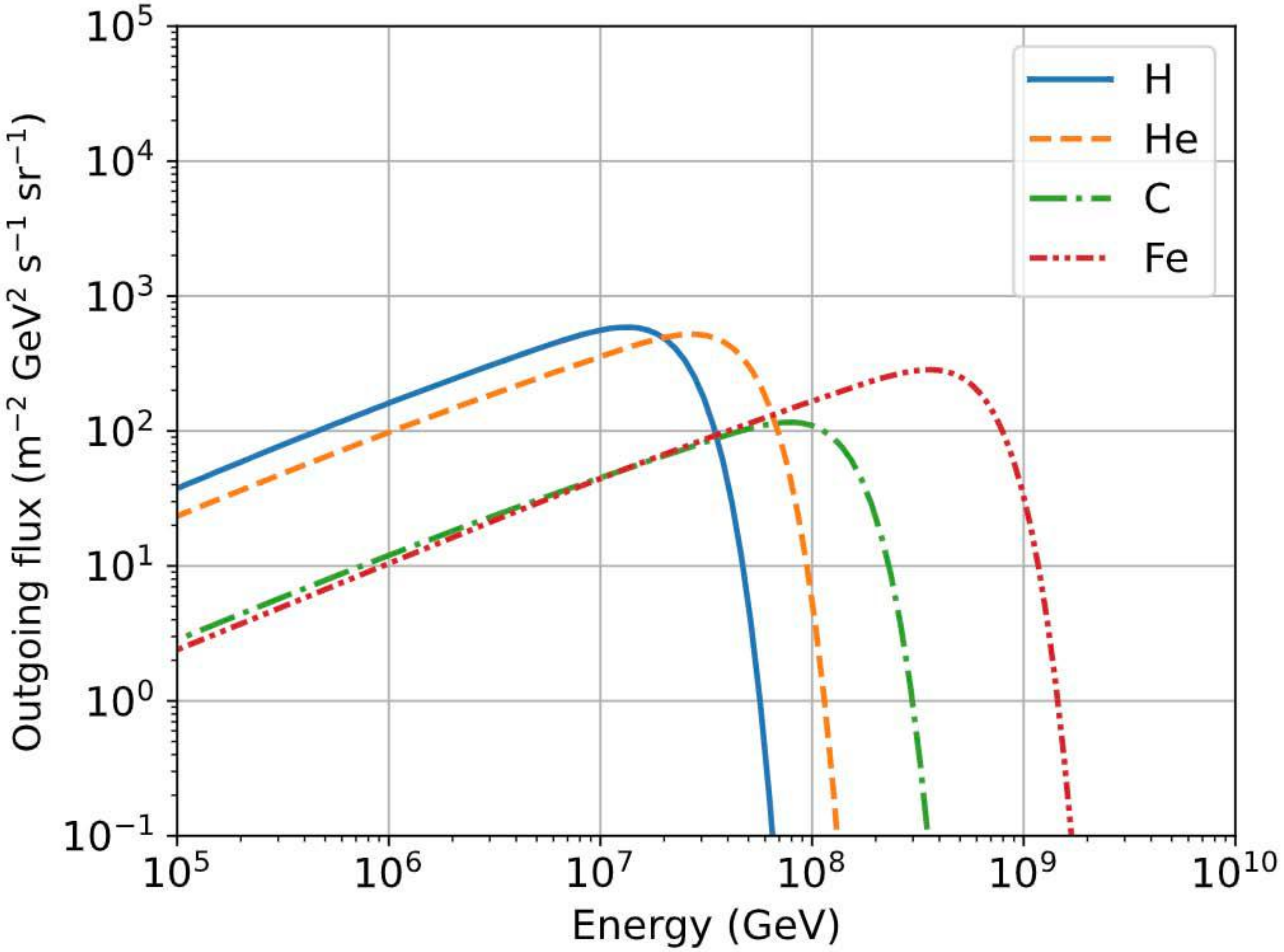
(Mukhopadhyay et al, 2023)

# Downstream escape of GWTS cosmic rays

A fraction of the reaccelerated cosmic rays escape into the circumgalactic medium.

Seeds the CGM with high energy cosmic rays.

Further reacceleration up to O(10-100 EV) at accretion shocks around galaxy clusters and filaments (**Simeon et al, in prep**).




Active galaxies, such as starbursts will be dominant.

(Mukhopadhyay et al, 2023)

# Summary of our reacceleration model

1. We have critically analyzed the role of a popular cosmic ray acceleration site, Galactic wind termination shocks in the context of reacceleration of Galactic cosmic rays produced by supernova remnants, PeVatrons etc.
2. These shocks can reaccelerate Galactic cosmic rays to up to an order of magnitude beyond the knee at ~ 3 PV.
3. Robust reacceleration between ~30—70 PV occurs over a broad range of physically plausible conditions.
4. Backstreaming particles can account anywhere between ~10–100% of the observed spectrum in the shin region.
5. This model cannot account for the entire spectrum of the shin region.
6. These termination shocks may be probed for edge-on galaxies with radio telescopes in the future.
7. We are learning more about magnetic field in the halo, motivated by various cosmological questions. That could test some of these ideas in the future.

# Can the GWTS do better?

Yes! CRs can achieve more than ~ 100 PeV at the GWTS (**Blandford et al., in prep**)
Magnetocentrifugally driven wind + Bootstrap mechanism for DSA
Subject to strong observational constraints

# Future works

Multimessenger signals, cosmic ray anisotropy predicted by the GWTS models.
Plasma instabilities close to the GWTS can impact reacceleration. MHD simulations are the way to go.

Galactic wind termination shocks can be one of the main but likely not the only source for the shin cosmic rays.

They are one of the most well-motivated and testable sites for cosmic ray acceleration.

Future data will constrain a range of acceleration models.

Fully consistent MHD simulations of the wind and the acceleration will provide even more detailed insights into the problem.

Thanks!