Cosmic Rays in the Context of Multimessenger Astronomy

GeV Cosmic Ray Transport: Confronting Simulations with Observations

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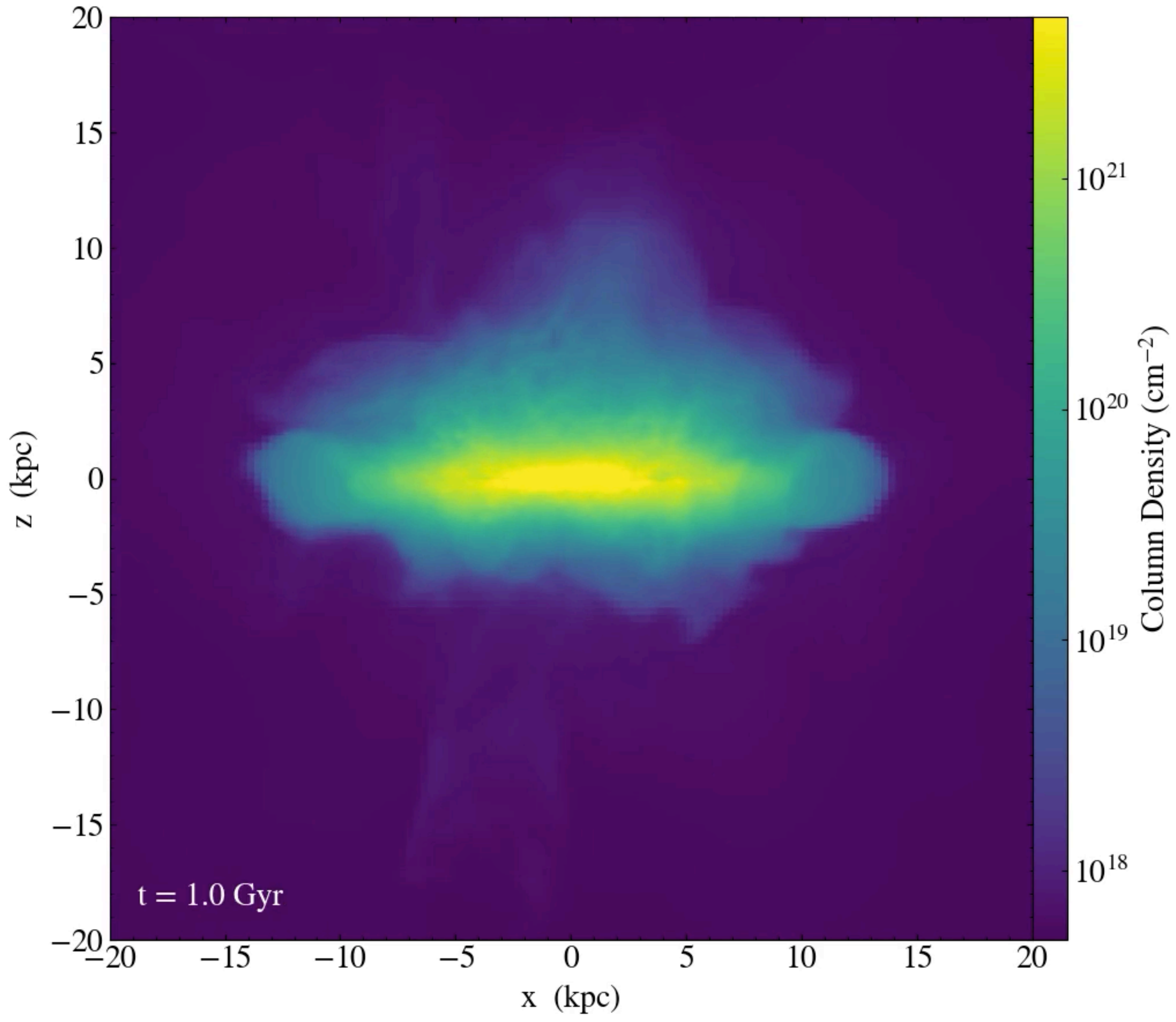
REFERENCES: BUSTARD AND ZWEIBEL 2021
BUSTARD & OH 2022, IN PREP

Background

- Two recent advances:
  - **Multimessenger astronomy** helps us constrain cosmic ray propagation and cosmic ray sources
  - **“Live” galaxy evolution simulations** with cosmic rays, spanning a range of galaxy types*

See e.g. Uhlig+ 2012, Hanasz+ 2013, Salem and Bryan 2014, Ruszkowski+ 2017, Farber+ 2018, Chan+ 2019, Buck+ 2020, Hopkins+ 2020, 2021, Yohan and Dubois 2020, Bustard+ 2020

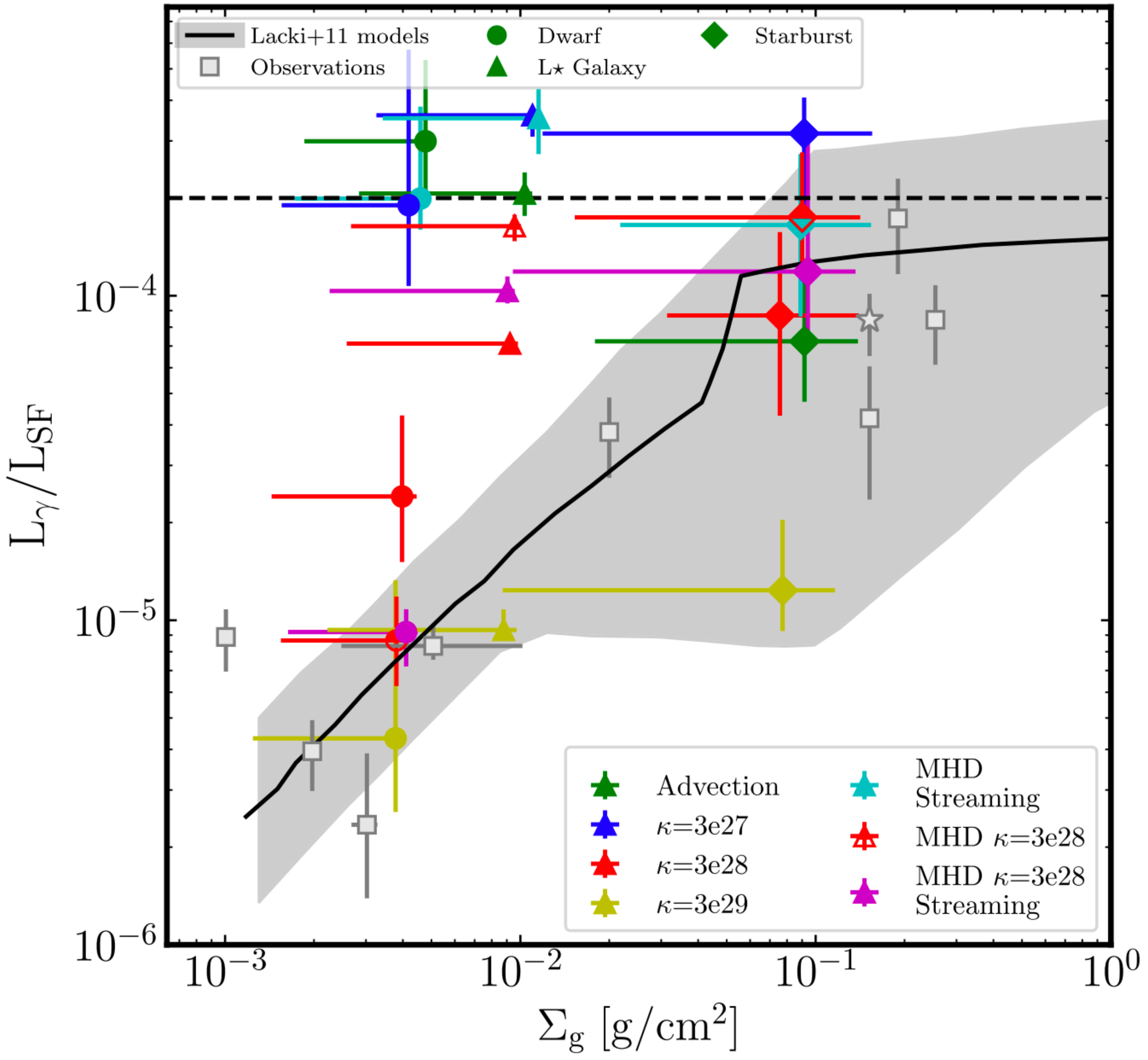
Bustard+ 2020



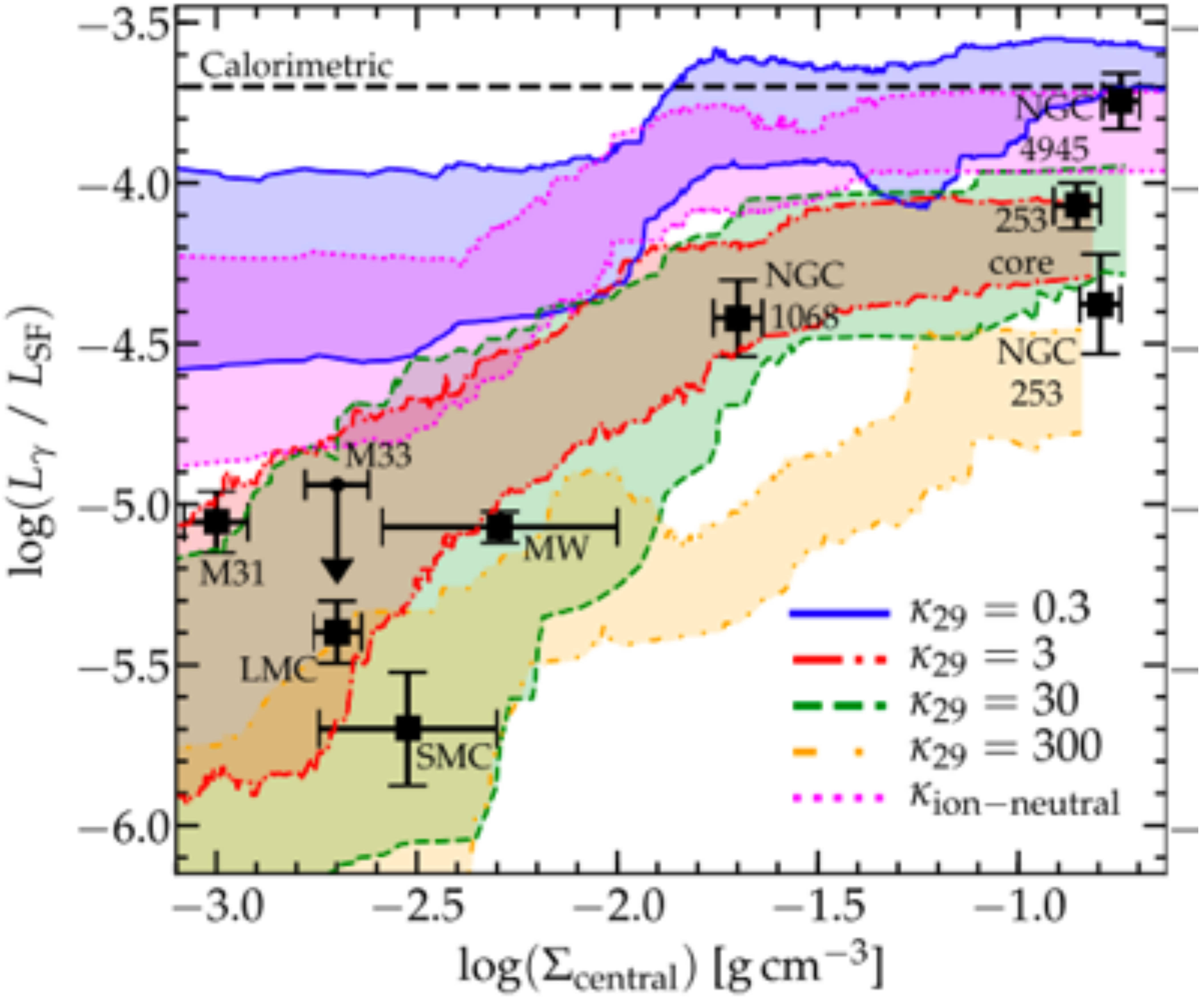
Cosmic rays help drive galactic winds, regulating star formation

Problem #1:

Simulated dwarf galaxies have far too much γ-ray emission compared to Fermi-LAT data



Chan+ 2019 (FIRE Collaboration)

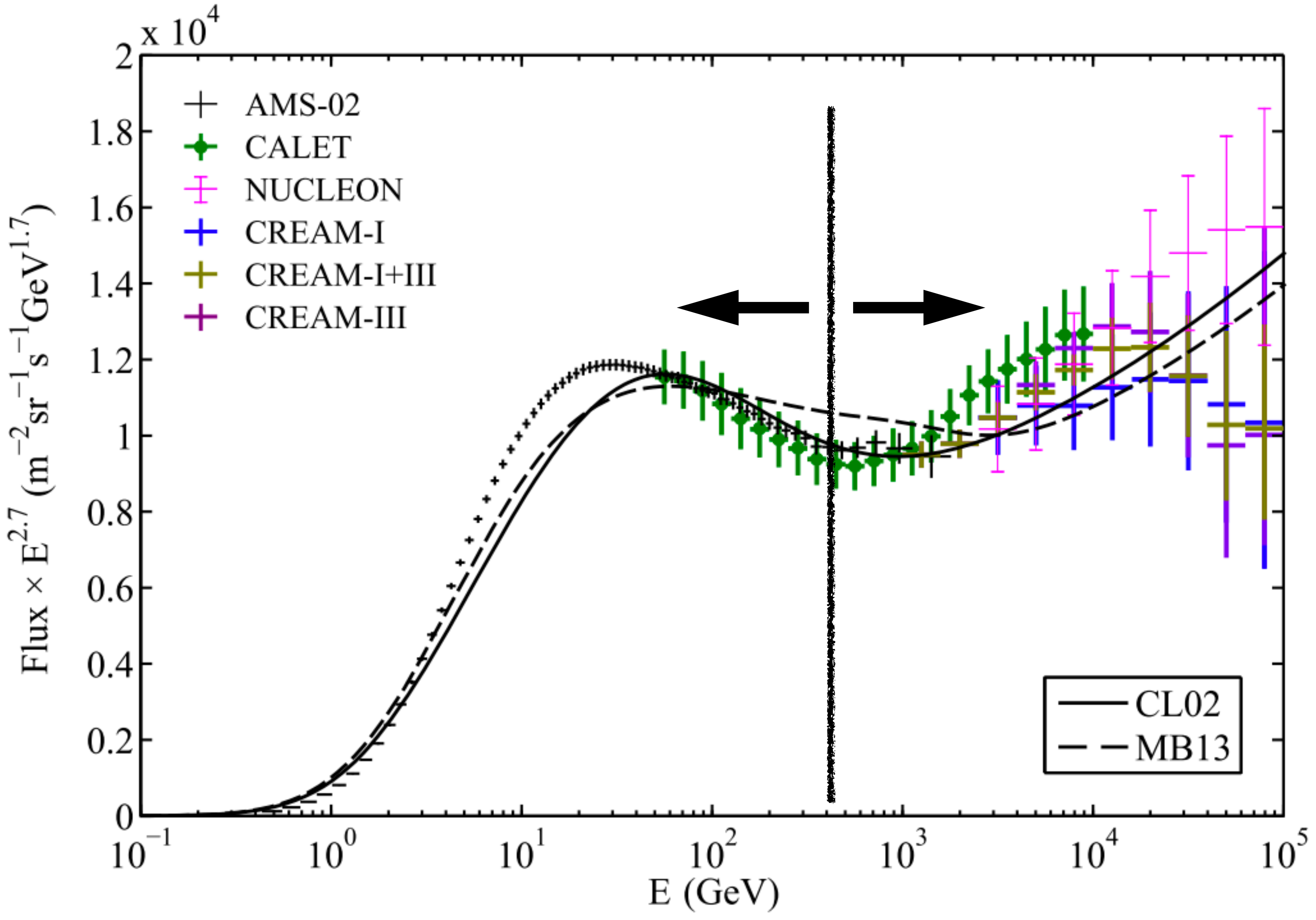


Hopkins+ 2021 (FIRE collaboration)

Cosmic Ray Propagation and Confinement

Self-confinement (E < 300 GeV)

- Cosmic rays scatter off waves driven by a resonant **streaming** instability
- Propagation is at ~ Alfven speed $v_A^{ion} = \frac{B}{\sqrt{4\pi\rho_{ion}}}$
- Cosmic rays *do* transfer energy to the gas at a rate $v_A^{ion} \cdot \nabla P_{CR}$



Dogiel+ 2020

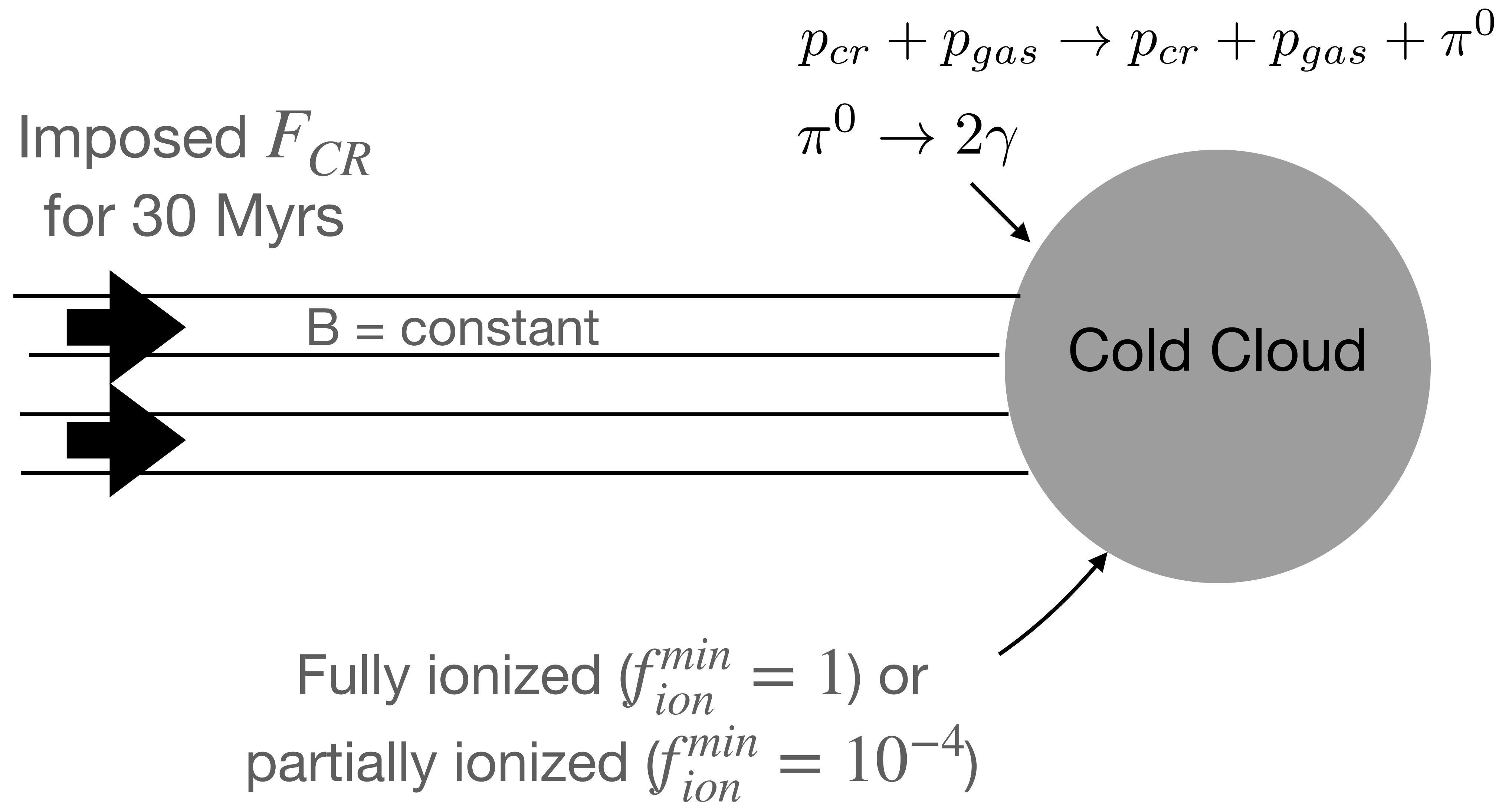
Extrinsic Turbulence (E > 300 GeV)

- Cosmic rays scatter off waves in a turbulent cascade
- Propagation is diffusive along magnetic field lines
- Cosmic rays *don't* transfer energy to gas

Cosmic Ray Hydrodynamics in the Multiphase ISM

MHD Simulations w/Athena++

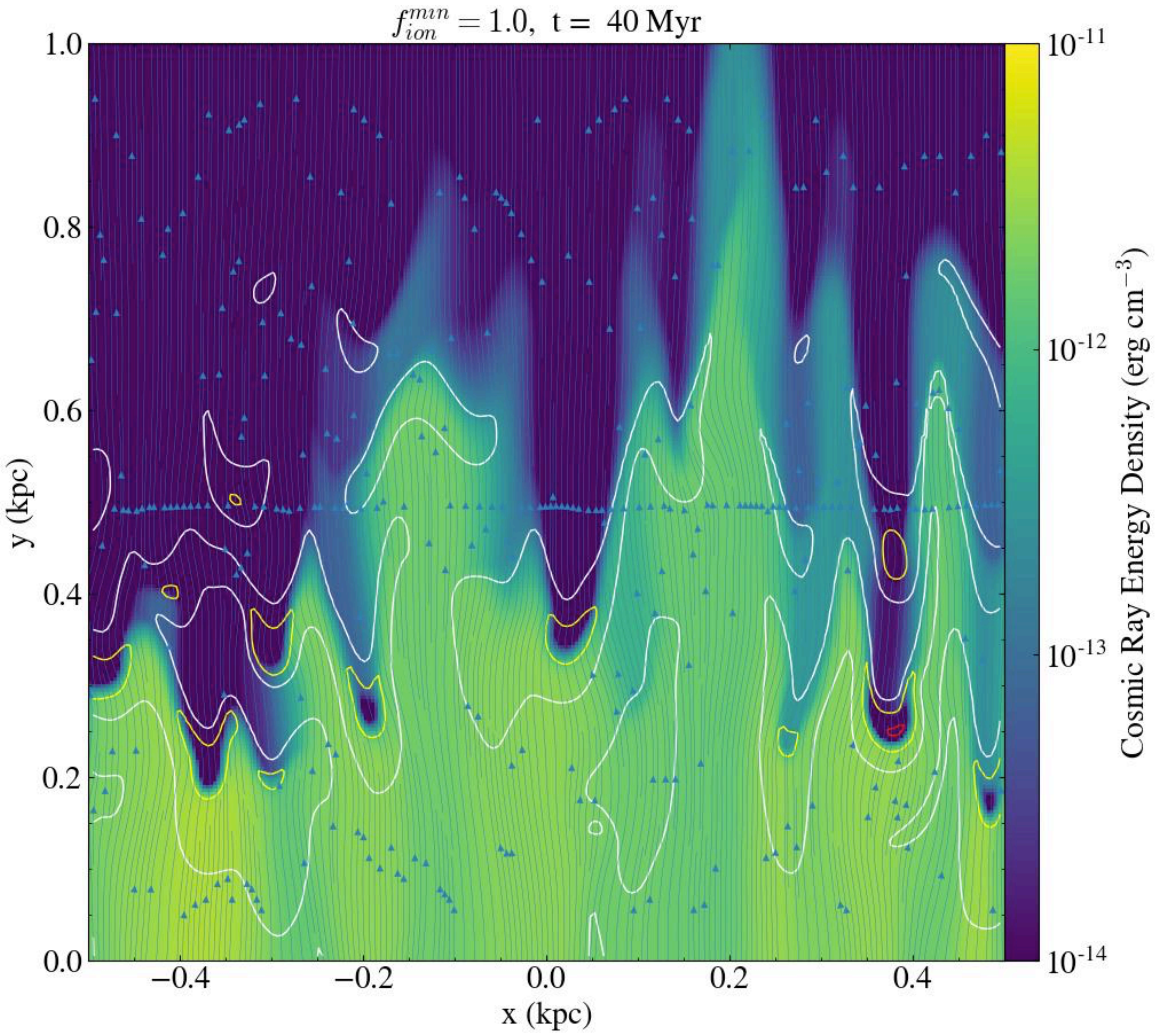
- Single energy bin approximation for the CRs
- Evolve cosmic ray energy E_{cr} and flux F_{cr} using two-moment technique borrowed from radiative transfer *(Jiang and Oh 2018)*
- "Collisionless" energy loss at rate $v_A^{ion} \cdot \nabla P_{CR}$ + hadronic and Coulomb collisions



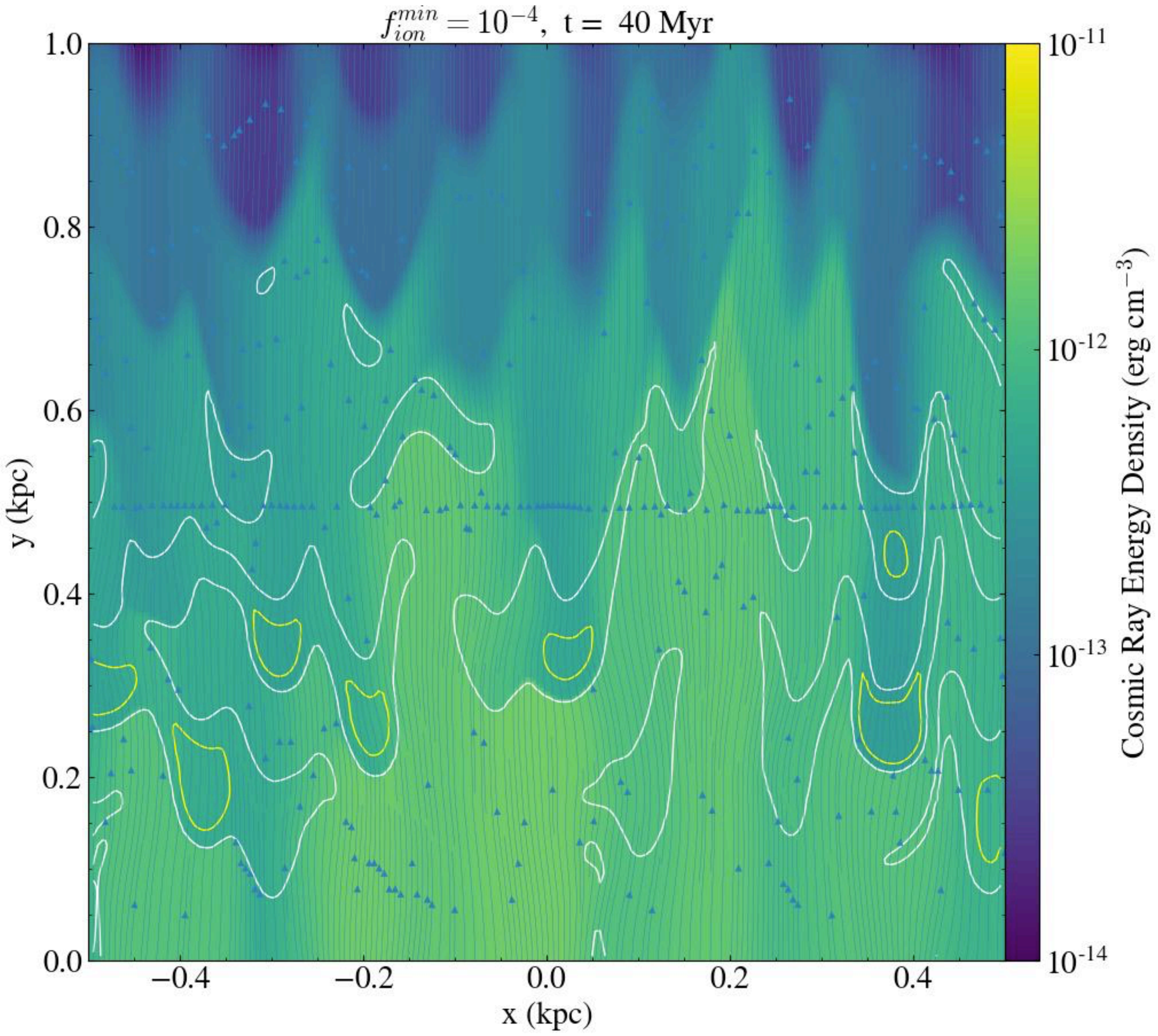
Case #1: Assume the gas is fully ionized. Streaming at $v_A = \frac{B}{\sqrt{4\pi\rho}}$, no diffusion

Case #2: Include *ionization-dependent* transport. Streaming at $v_A^{ion} = \frac{B}{\sqrt{4\pi\rho f_{ion}}}$, diffusion due to ion-neutral damping *(see e.g. Skilling 1971, Everett and Zweibel 2011, Farber+ 2018)*

Assuming Fully Ionized Gas



Ionization-Dependent Transport



Bustard and Zweibel 2021

Case 1: Assuming fully ionized

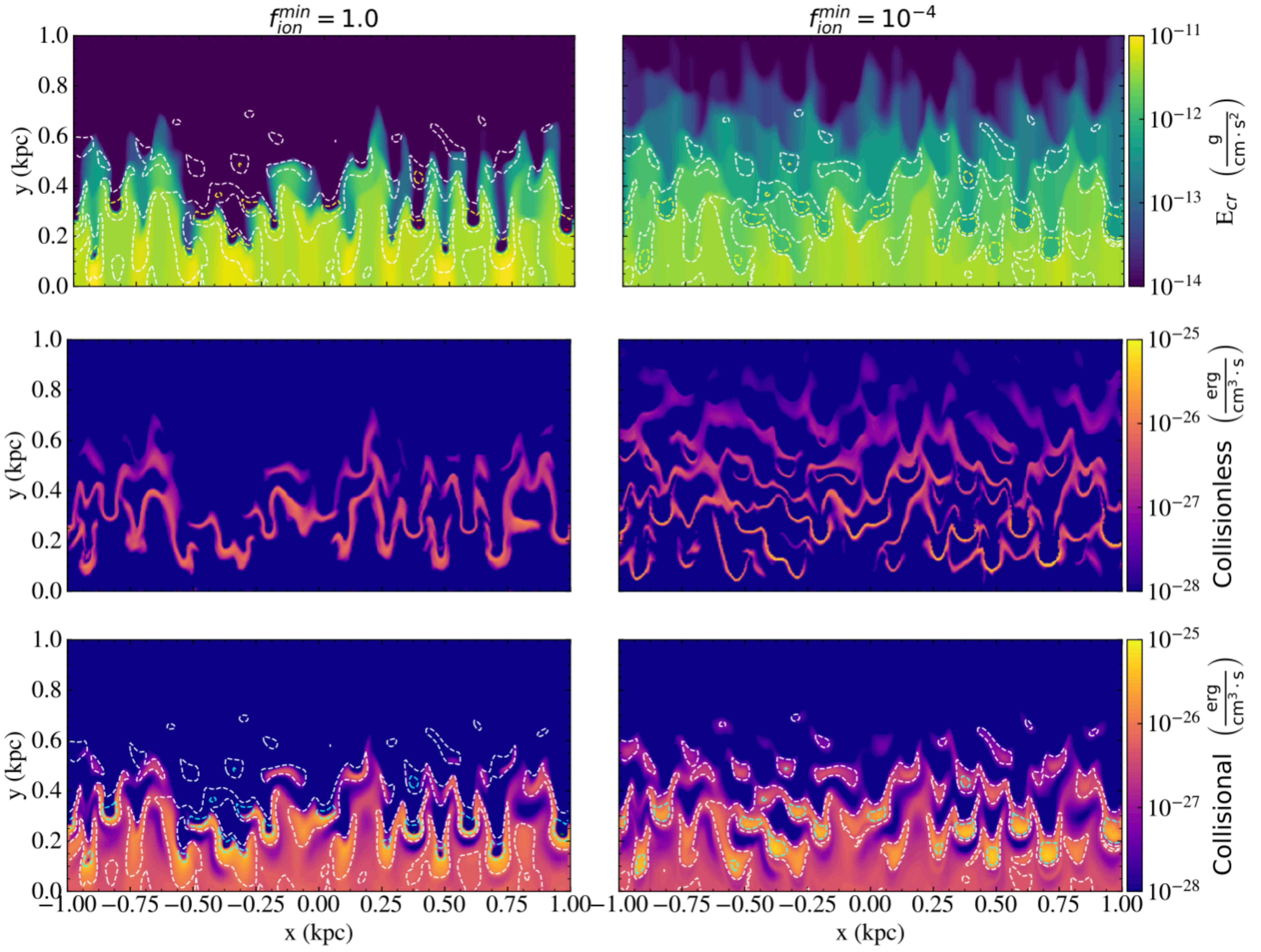
Collisionless energy loss (streaming loss) is **distributed throughout the cloud**

Collisions are biased towards **cloud interfaces**

Case 2: Ionization-dependent

Collisionless energy transfer is **focused at cloud interfaces**

Collisions are biased towards **cloud interiors**



$\propto v_A \cdot \nabla P_{cr}$

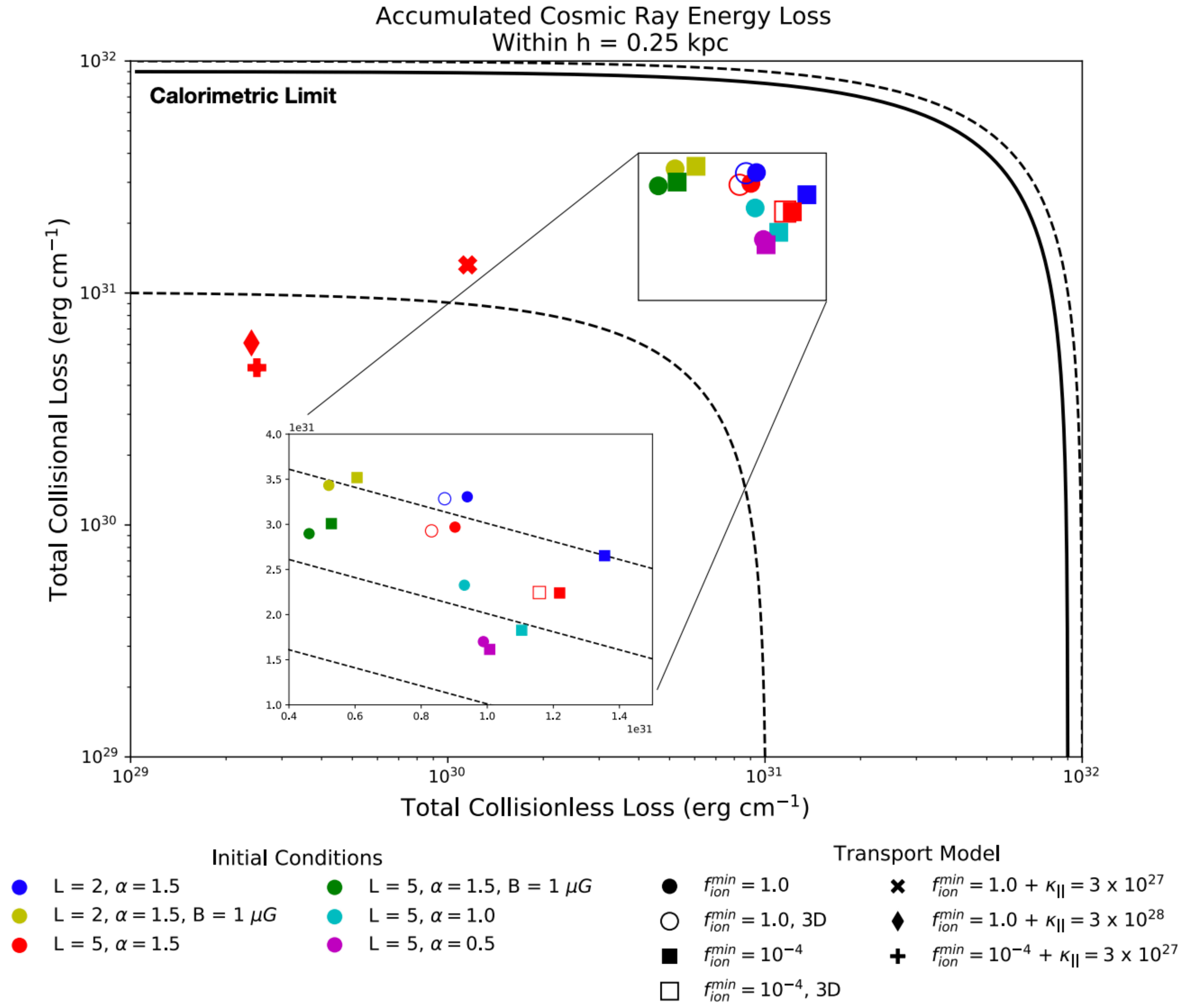
$\propto nE_{cr}$

Bustard and Zweibel 2021

Total energy loss and γ-ray luminosity are largely **unchanged** when ionization-dependent transport is accounted for

Possible solutions:

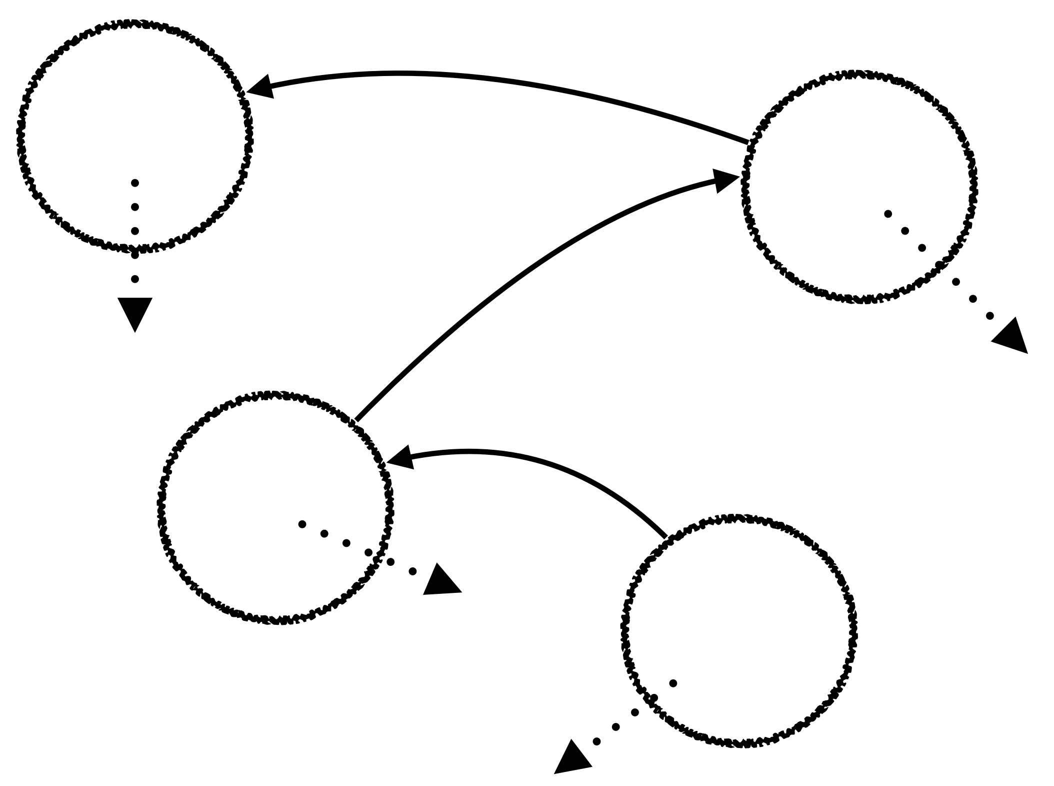
- Increased transport speeds in diffuse, ionized gas *(Chan+ 2019, Hopkins+ 2021)*
    - A new damping mechanism?
- Improved statistics: more observed γ-ray luminosities for dwarf galaxies
- An entirely new paradigm for what scatters cosmic rays?



Bustard and Zweibel 2021

Cosmic Rays in a Turbulent Medium

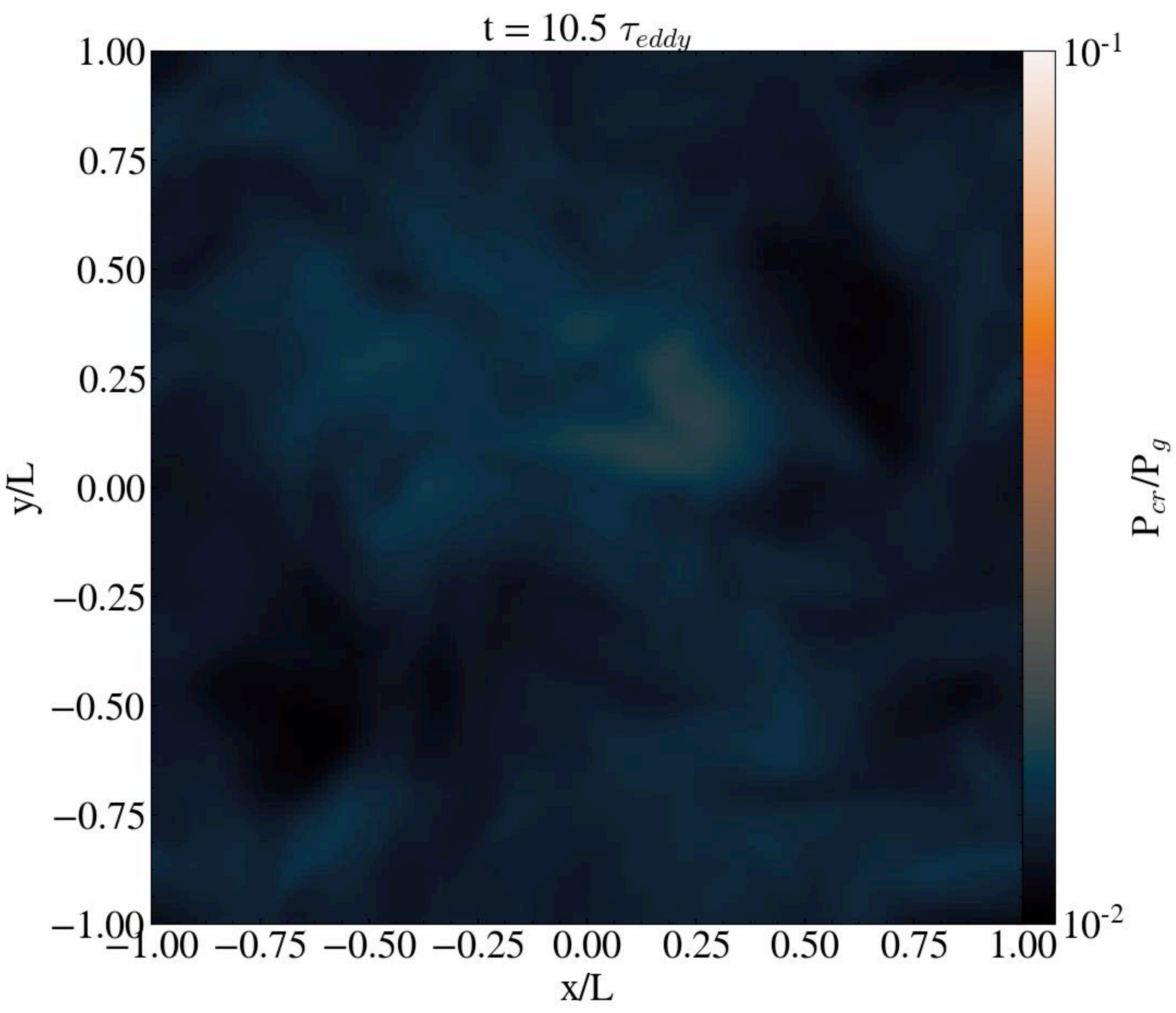
Turbulent Reacceleration
(2nd order Fermi)



$$\frac{\Delta E}{E} \sim \mathcal{O}\left(\frac{v^2}{c^2}\right)$$

= magnetic perturbations

- Size ~ r_g (resonant scale)
- Size ~ L_{outer} (non-resonant)

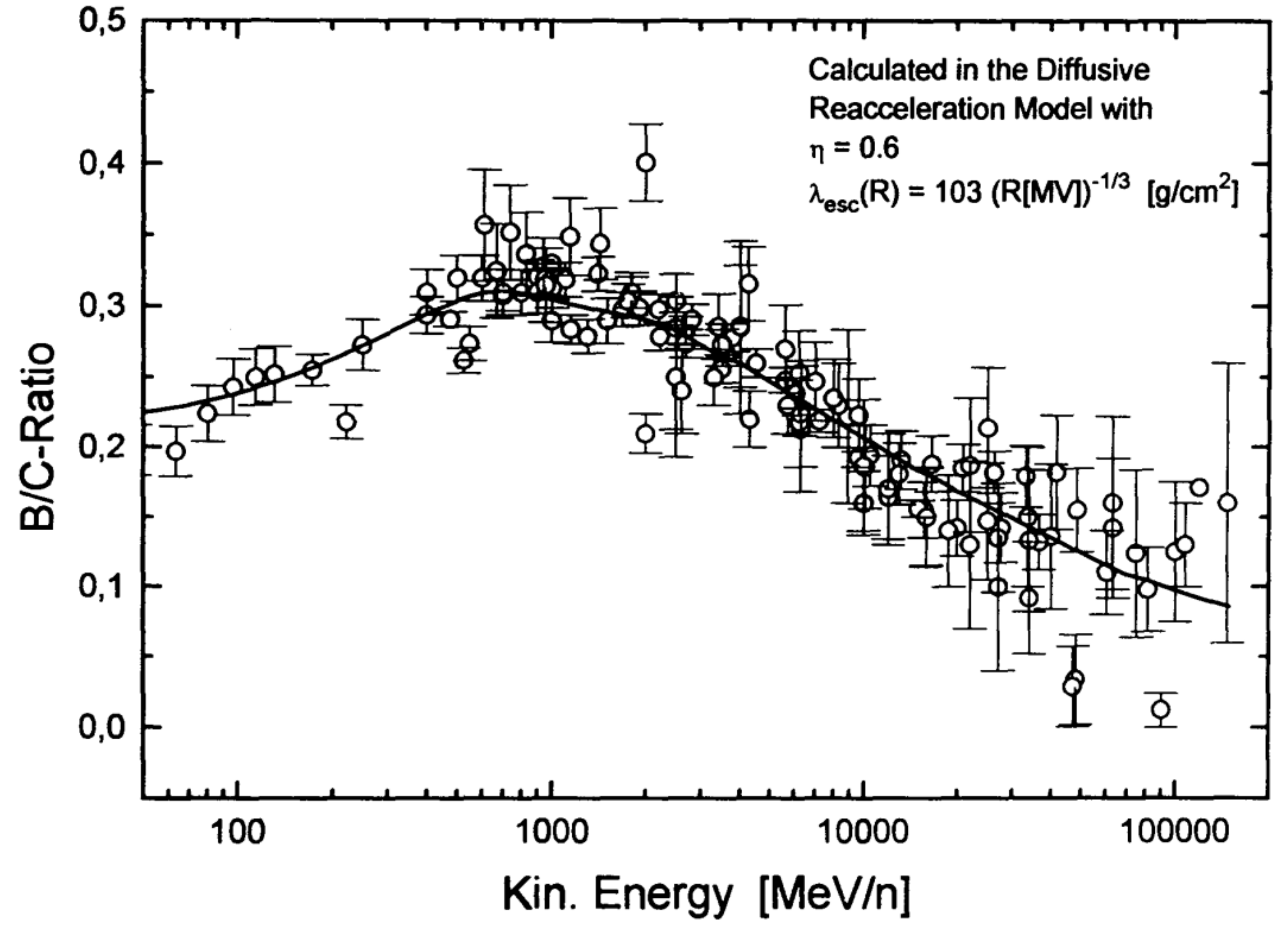


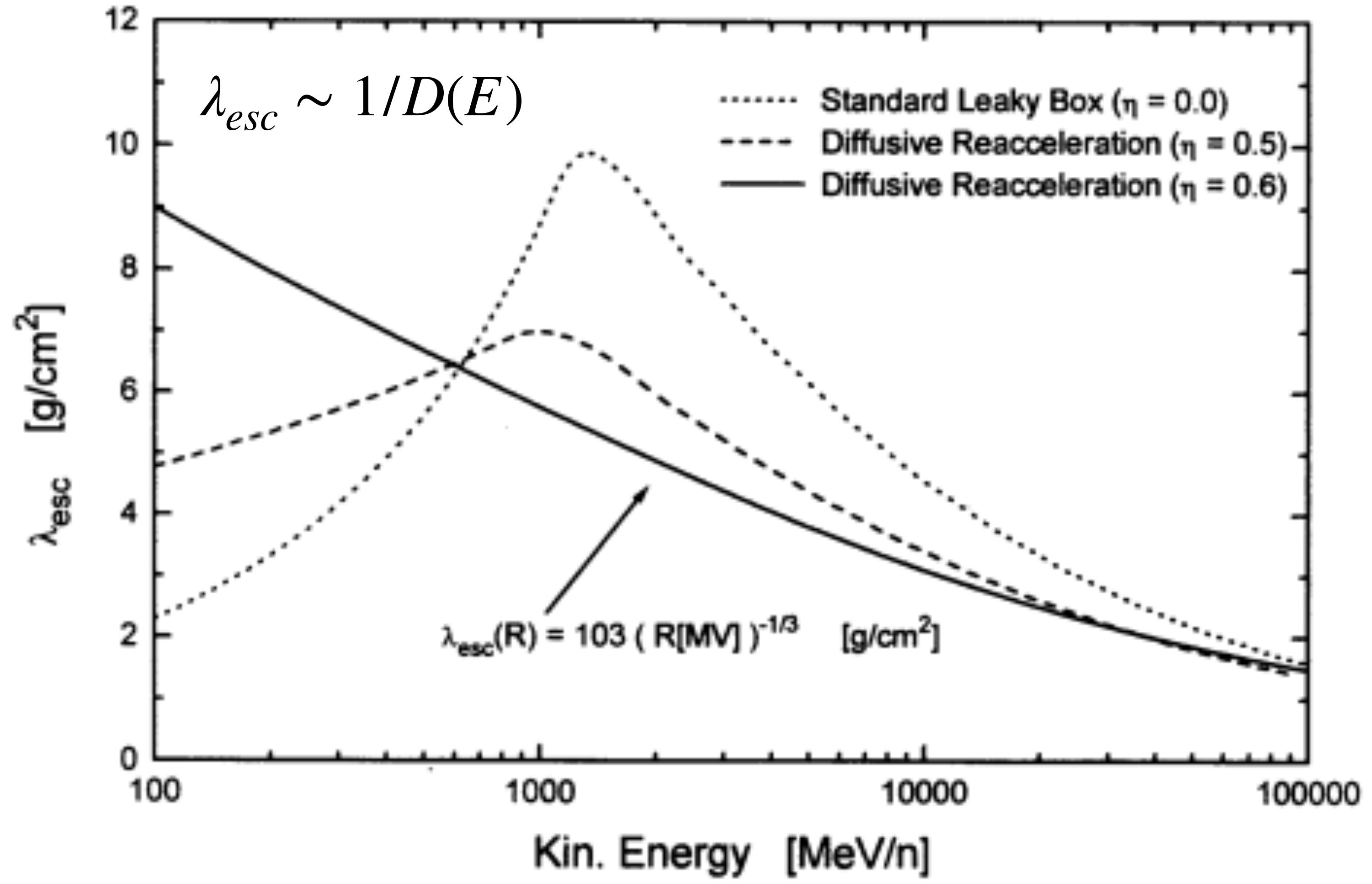
Bustard and Oh 2022, in prep

- Reacceleration is a favored explanation for radio haloes in merging galaxy clusters *(Brunetti and Jones 2014)*
- Reacceleration simultaneously explains the bump in B/C ratio at ~1 GeV **while maintaining a single power-law diffusion coefficient** *(e.g. Heinbach and Simon 1995)*

Problem #2:

- Propagation models fit to both γ-ray and synchrotron data disfavor reacceleration *(Trotta+ 2011, Di Bernardo+ 2013, Orlando and Strong 2013, Gabici+ 2019)*
- Too much power (possibly 50%) is in reaccelerated cosmic rays *(Thornbury and Drury 2014, Drury and Strong 2017)*





Heinbach and Simon 1995

Reacceleration of Self-Confined CRs

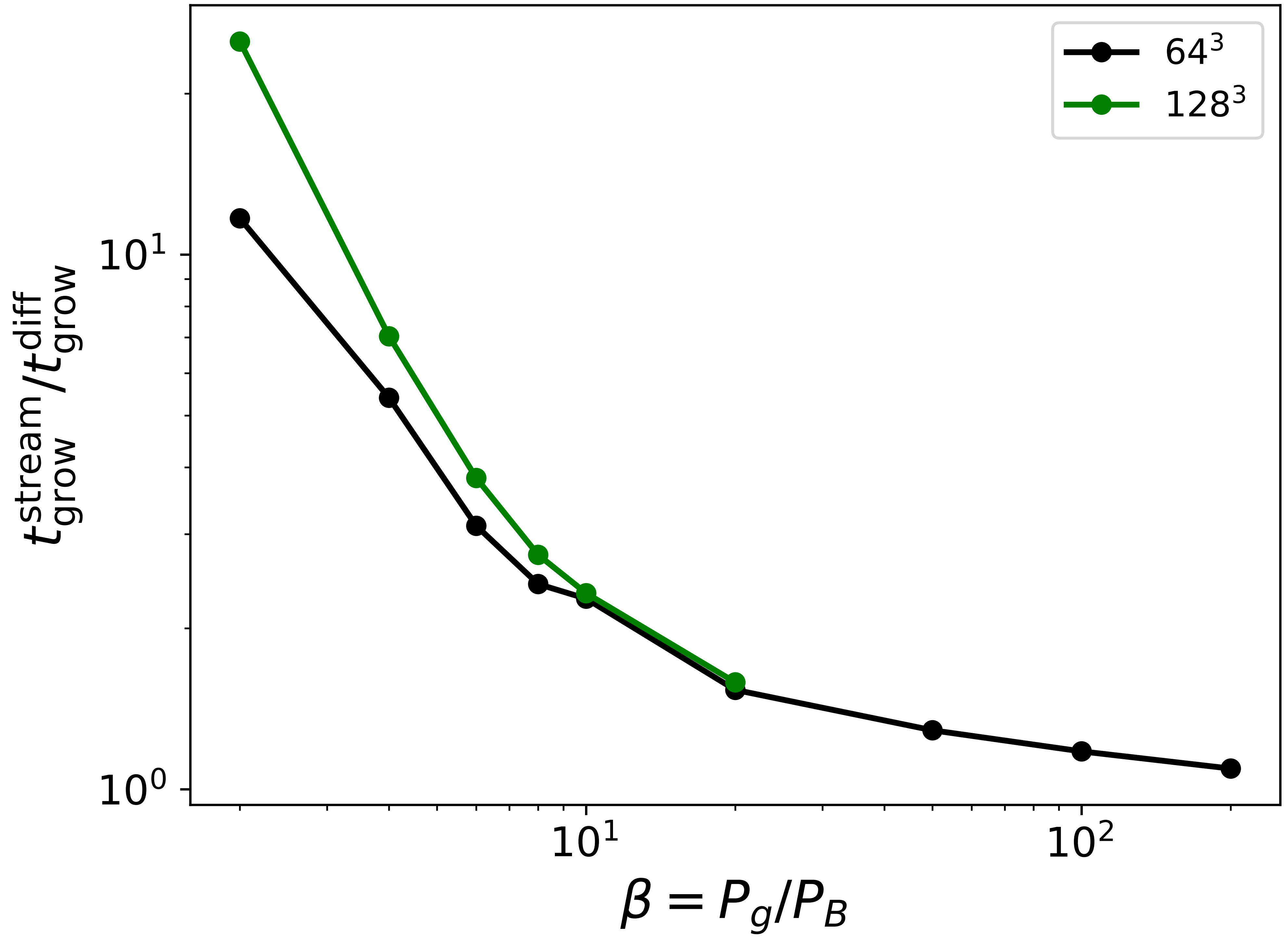
- Question: Is reacceleration efficient at GeV energies?

Resonant Reacceleration

$$D_{xx}D_{pp} = p^2 V_A^2 \left\langle \frac{1-\mu^2}{\nu_+ + \nu_-} \right\rangle \left\langle \frac{(1-\mu^2)\nu_+\nu_-}{\nu_+ + \nu_-} \right\rangle \qquad \nu_- = 0$$

Non-Resonant Reacceleration (Bustard and Oh 2022, in prep)

- Athena++ simulations of compressive, subsonic, isothermal turbulence
- Transport: Anisotropic diffusion *(Ptuskin 1988, Chandran 2004, Lynn+ 2014)* + streaming at Alfven speed
- With streaming energy loss included (relevant for E < 300 GeV), growth times are **significantly longer** in low-β environments like the ISM



Bustard and Oh 2022, in prep

Conclusions

- Two examples of idealized, high-resolution, cosmic ray hydrodynamics simulations vs observations
  - Propagation of self-confined (~ GeV) cosmic rays in the multiphase ISM (Bustard and Zweibel 2021)
    - **Ionization-dependent transport doesn't solve the overproduction of γ-rays in simulated dwarf galaxies**
  - Reacceleration of self-confined (~ GeV) cosmic rays in a turbulent ISM (Bustard and Oh 2022, in prep)
    - **Streaming energy loss significantly reduces the efficiency of non-resonant reacceleration in ISM-like environments**
    - Synchrotron observations and analytic estimates hint at this