Cosmic-ray transport and feedback in star-forming environments

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Building Galaxies from Scratch

Vienna, 19/02/2024

Microscopic - scale assumption

CRs with GeV kinetic energies are scattered by Alfvén waves excited by the CRs themselves via the streaming instability (e.g., Zweibel 2013, 2017; Evoli et al. 2018)

CR-fluid transport on galactic scales

CR-fluid propagation speed → $\mathbf{v}_{\rm CR} \approx \mathbf{v}_{\rm gas} + \mathbf{v}_{\rm stream} + \mathbf{v}_{\rm diff}$

- **Advection** along with the magnetic field by thermal gas
- **Streaming** along the magnetic field at the local ion Alfvén speed in the direction of decreasing pressure → $\mathbf{v}_{\rm stream} = -v_{\rm A,i}\dfrac{\hat{B}\cdot\nabla P_{\rm cr}}{|\hat{B}\cdot\nabla P_{\rm cr}|}$
- **Diffusion** in the wave frame due to pitch-angle scattering → $\mathbf{v}_{\rm diff} = -\dfrac{1}{\sigma}\dfrac{\hat{B}\cdot\nabla P_{\rm cr}}{P_{\rm cr}}\hat{B}$

Scattering coefficient (or diffusion coefficient $\kappa = 1/\sigma$)

LIMITATION: σ is generally assumed to be constant!

Towards a more realistic prescription for cosmic-ray transport

PHYSICALLY MOTIVATED PRESCRIPTION FOR THE CR SCATTERING COEFFICIENT

variable σ set by the balance of excitation and damping of streaming-driven Alfvén waves

↓ *included in*

ALGORITHM FOR CR-FLUID TRANSPORT IN ATHENA ++ (Jiang & Oh, 2018)

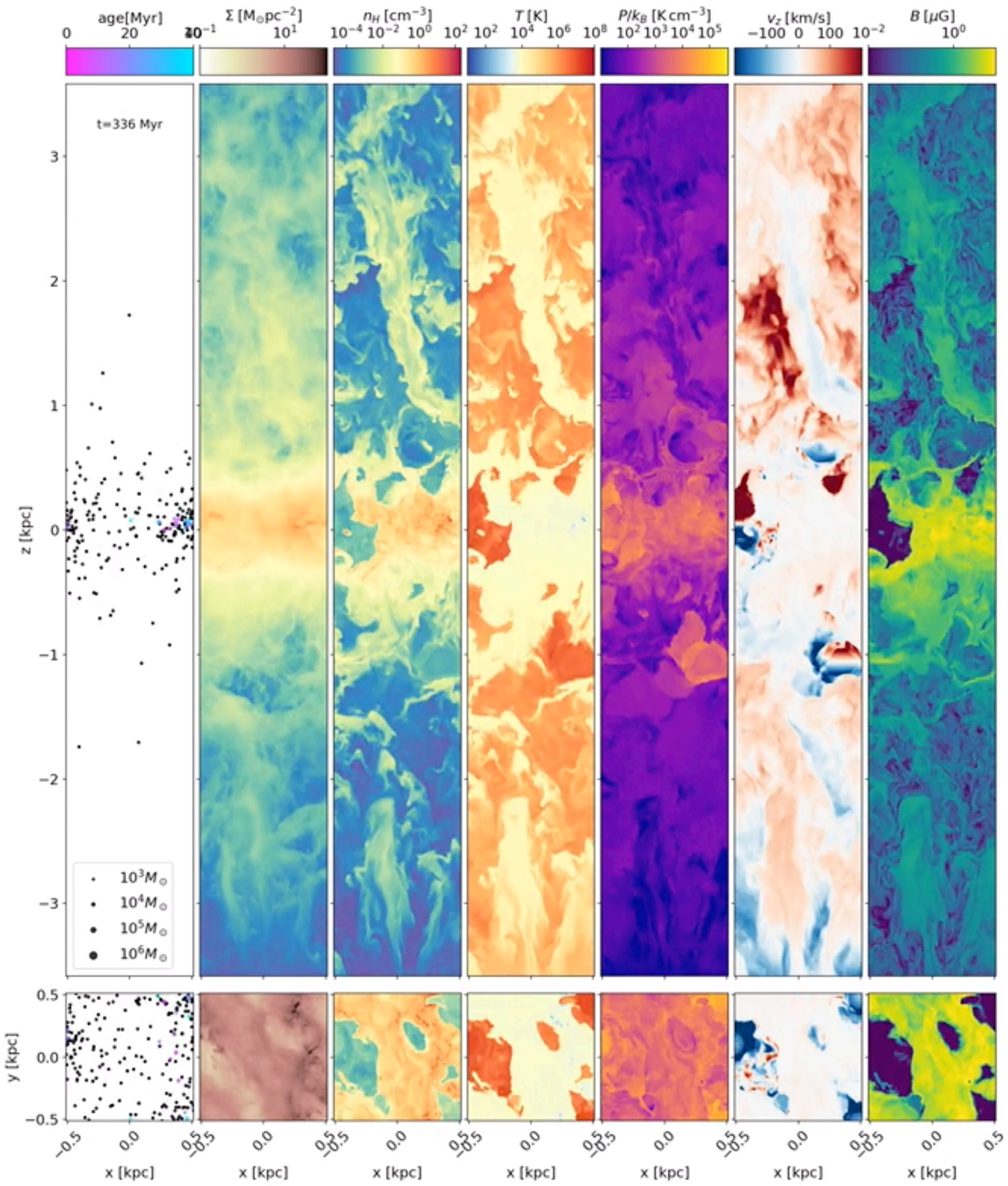
Two-momentum equations (CR energy and flux density)

valid for CR protons with GeV energies

↓ *used for*

POSTPROCESSING OF THE TIGRESS MHD SIMULATIONS (Kim & Ostriker 2017, Kim et al., 2020)

Local patches of galactic disk self-consistently modelled with resolved star formation and supernova feedback

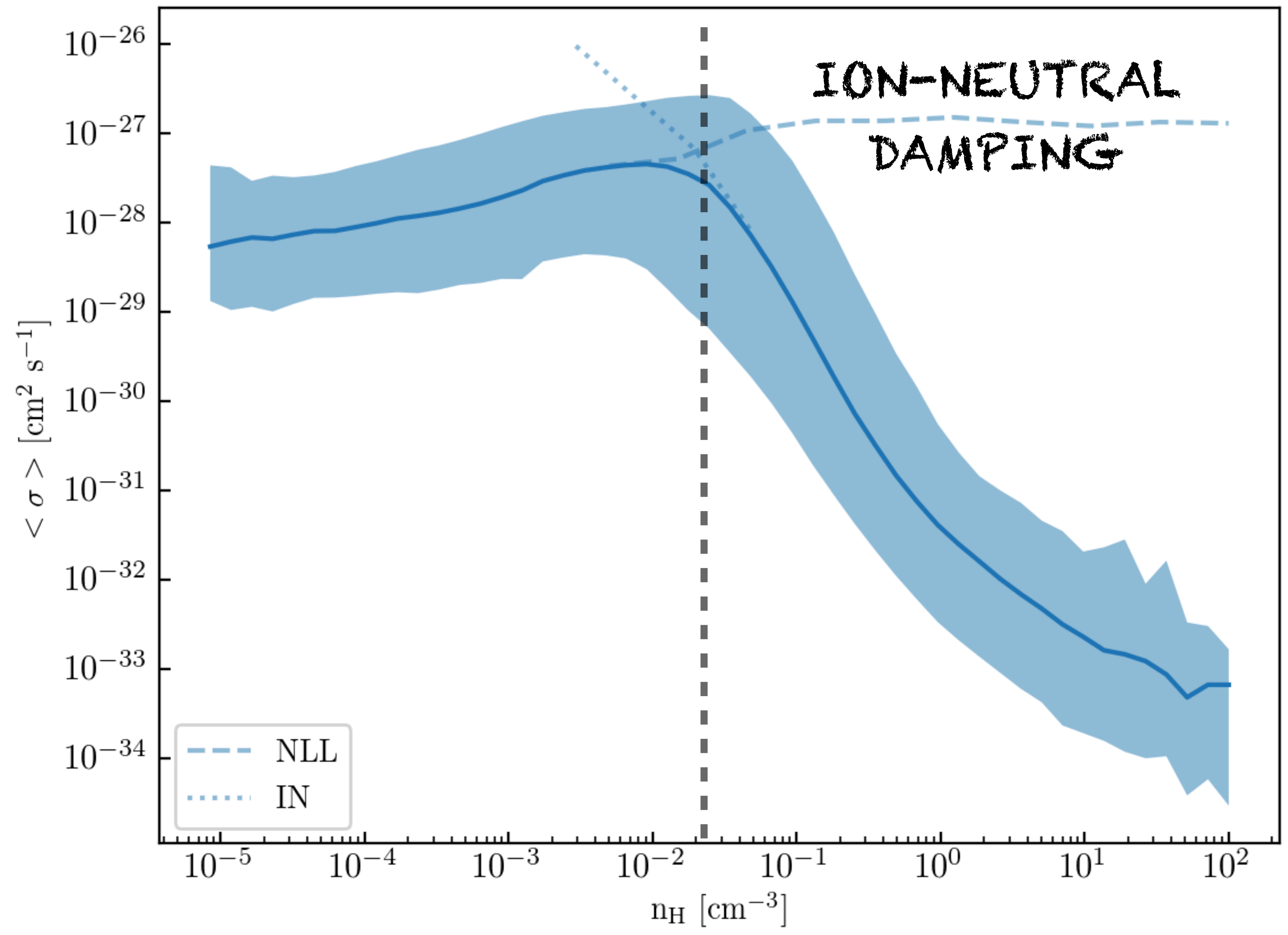


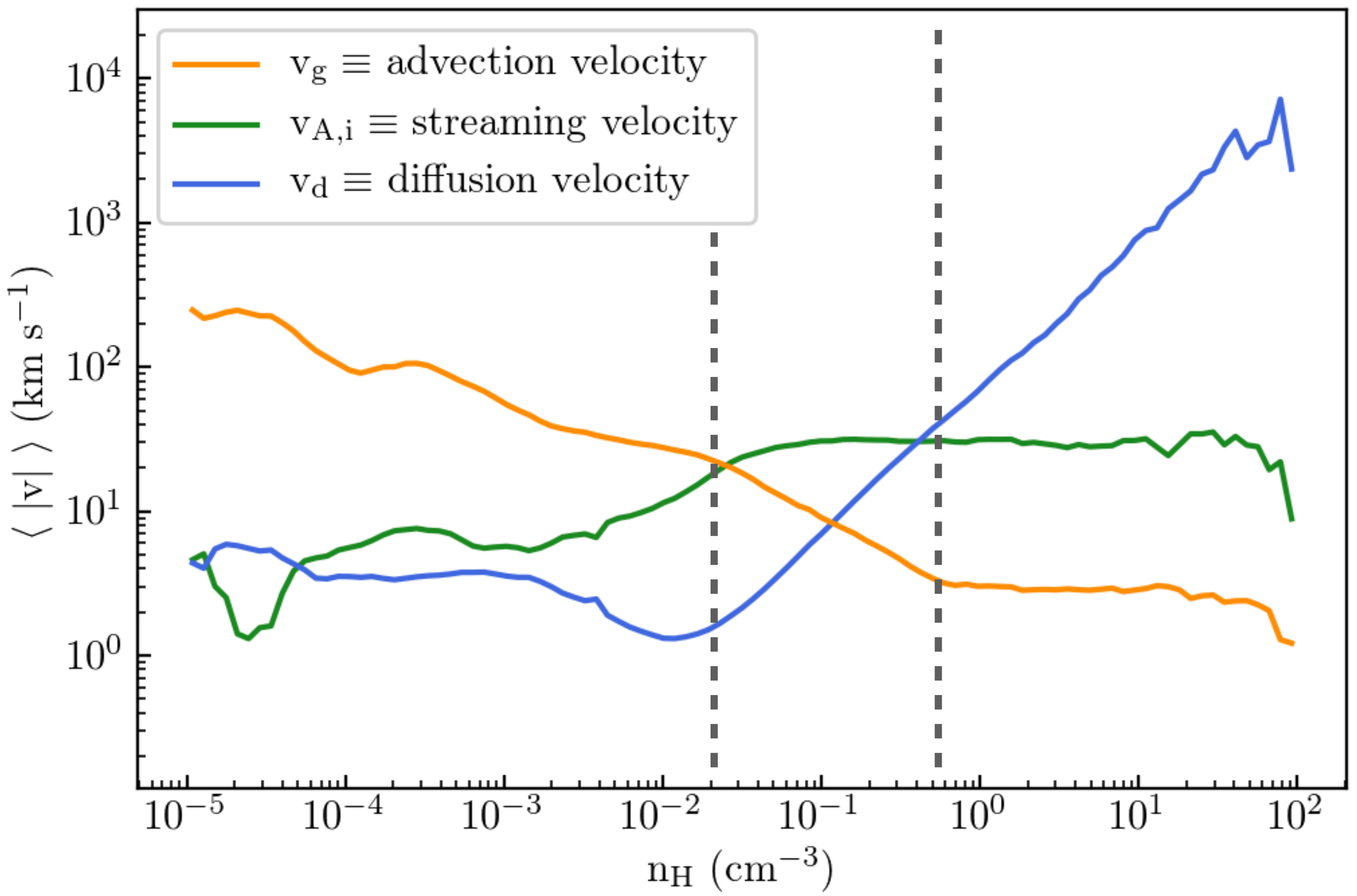
Armillotta et al., 2021, 2022, 2024

Propagation of cosmic rays in the multiphase ISM

Realistic representation of the multiphase ISM is crucial in studies of CR transport!

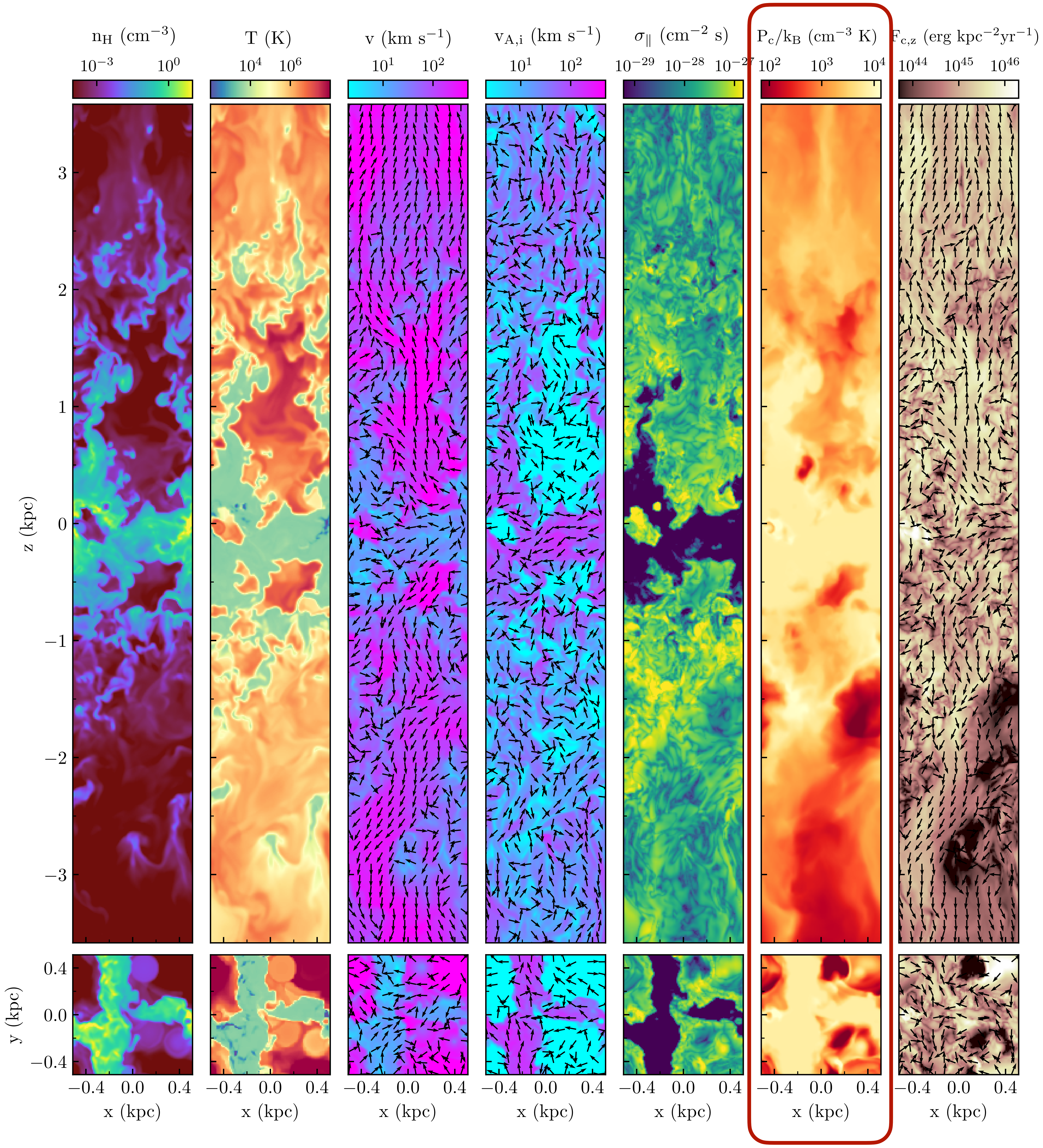
- CR scattering coefficient varies over more than four orders of magnitude
- Weak scattering in high-density regions where waves are efficiently damped by ion-neutral collisions

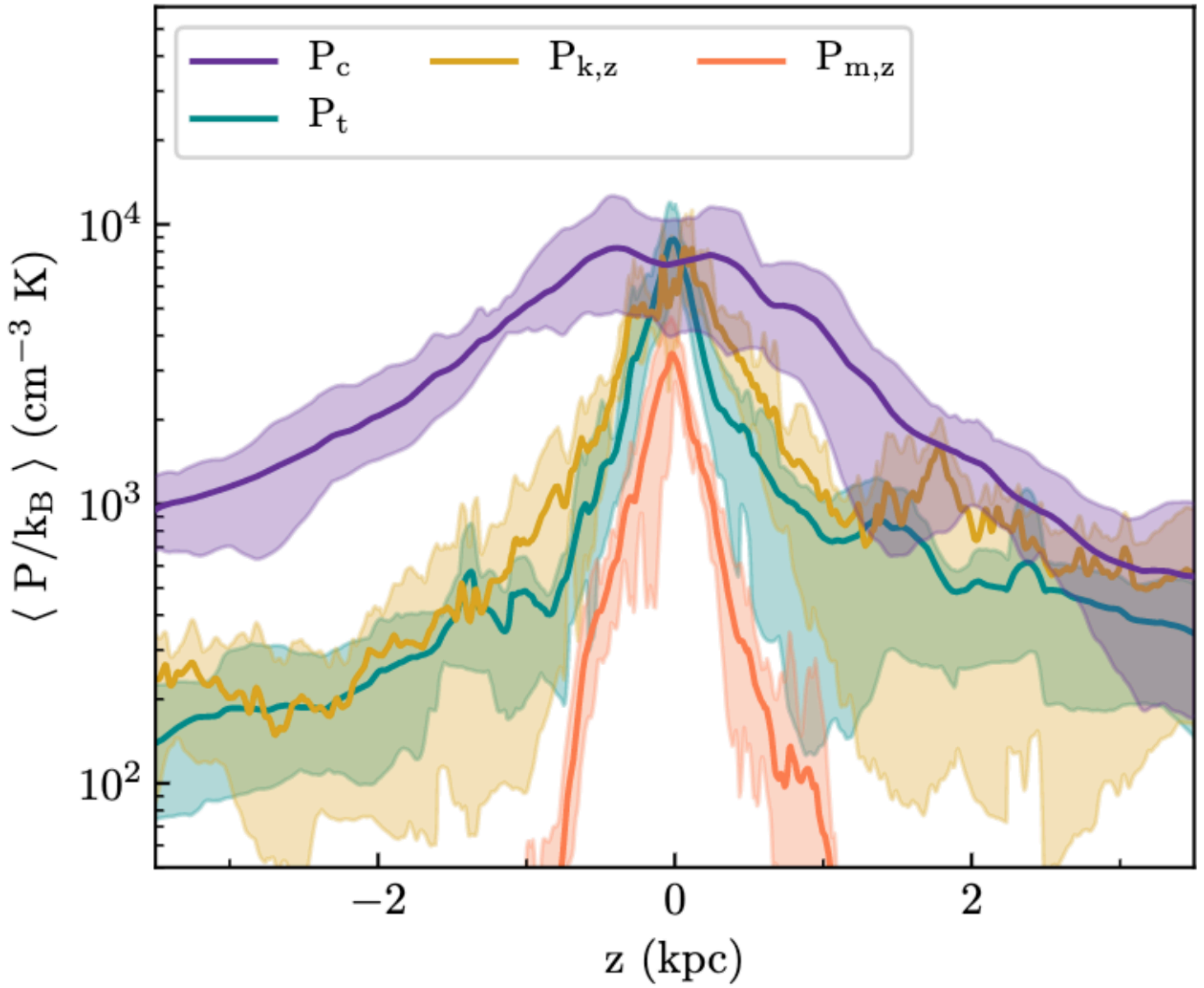




- Advection is the main mechanism responsible for propagation of CRs in the hot and rarefied gas
- Streaming and diffusion are important in higher-density cooler regions

Cosmic rays in the solar neighborhood environment





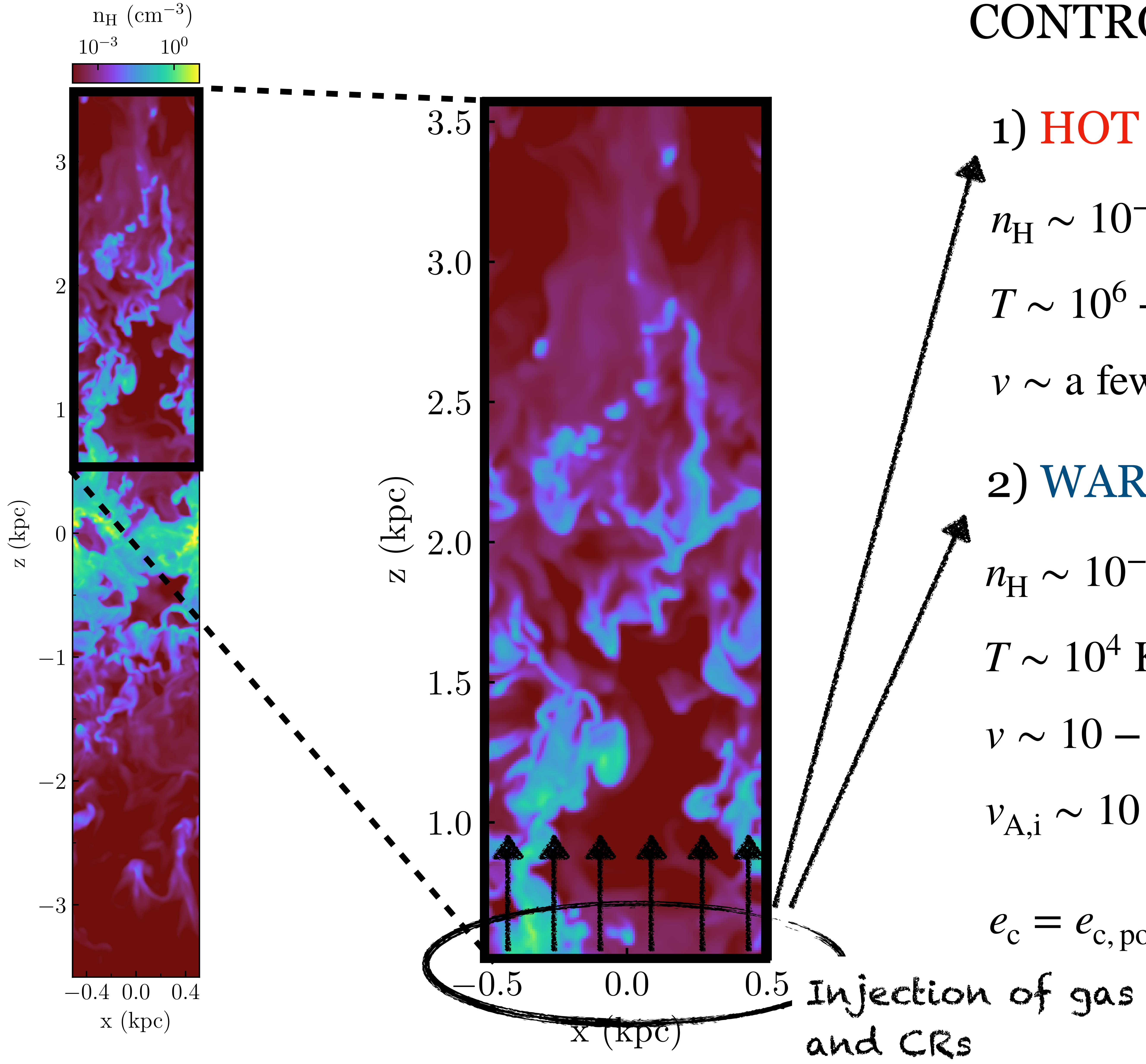
<u>Agreement with the observed energy equipartition near the midplane!</u>

Large CR pressure gradients in the extra-planar region

↓

Can CRs efficiently counteract gravity and drive flows of gas away from the disk?

MHD simulations of outflows including cosmic rays



CONTROLLED BOUNDARY CONDITIONS

1) HOT AND FAST WINDS

$n_{\rm H} \sim 10^{-4} - 10^{-3}\ {\rm cm^{-3}}$

$T \sim 10^6 - 10^7$ K

$v \sim$ a few $\times$ 100 km/s

Negligible CR effect in hot thermally-driven winds

2) WARM AND SLOW WINDS

$n_{\rm H} \sim 10^{-2} - 10^{-1}\ {\rm cm^{-3}}$

$T \sim 10^4$ K

$v \sim 10 - 20$ km/s

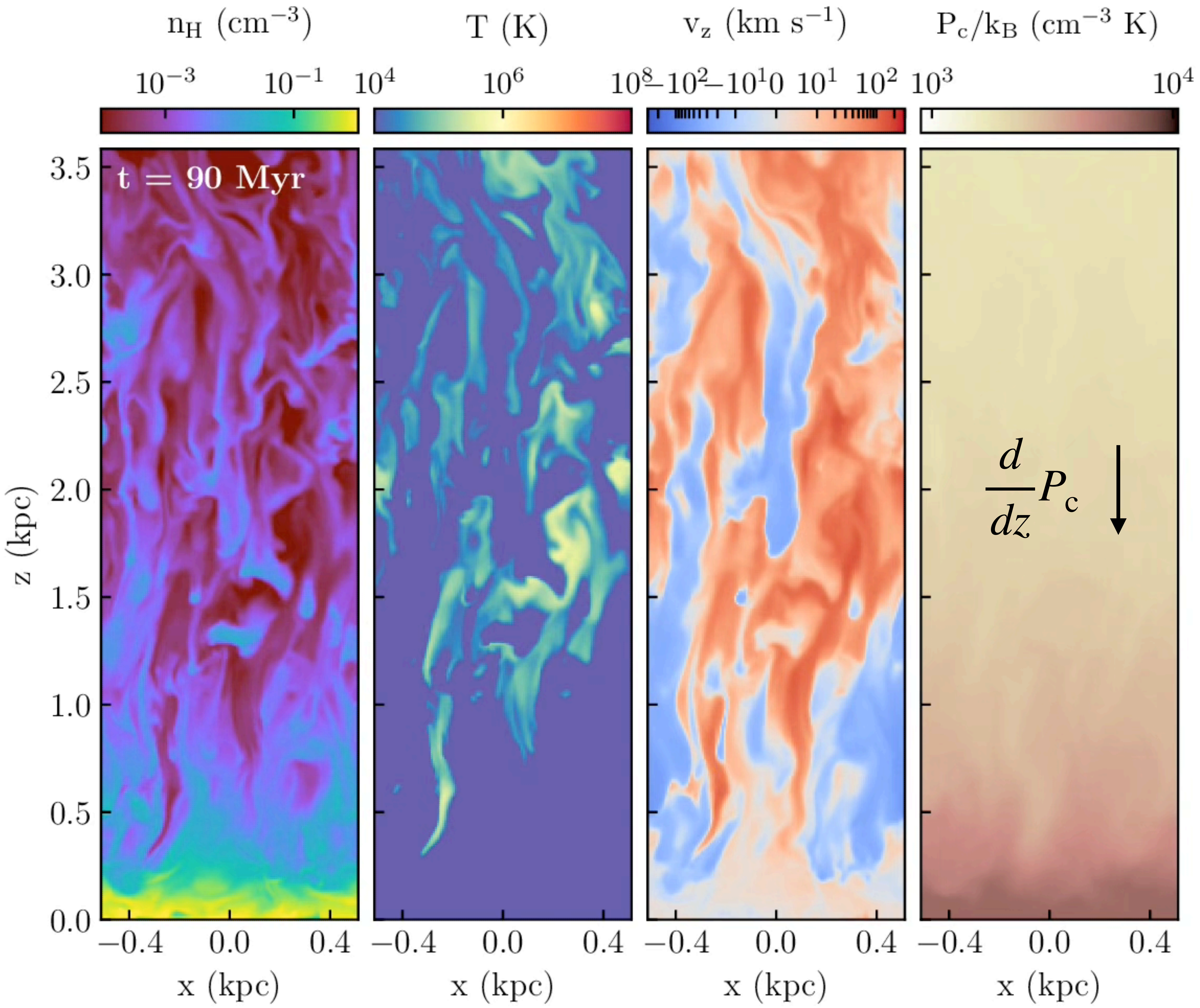
$v_{\rm A,i} \sim 10 - 20$ km/s

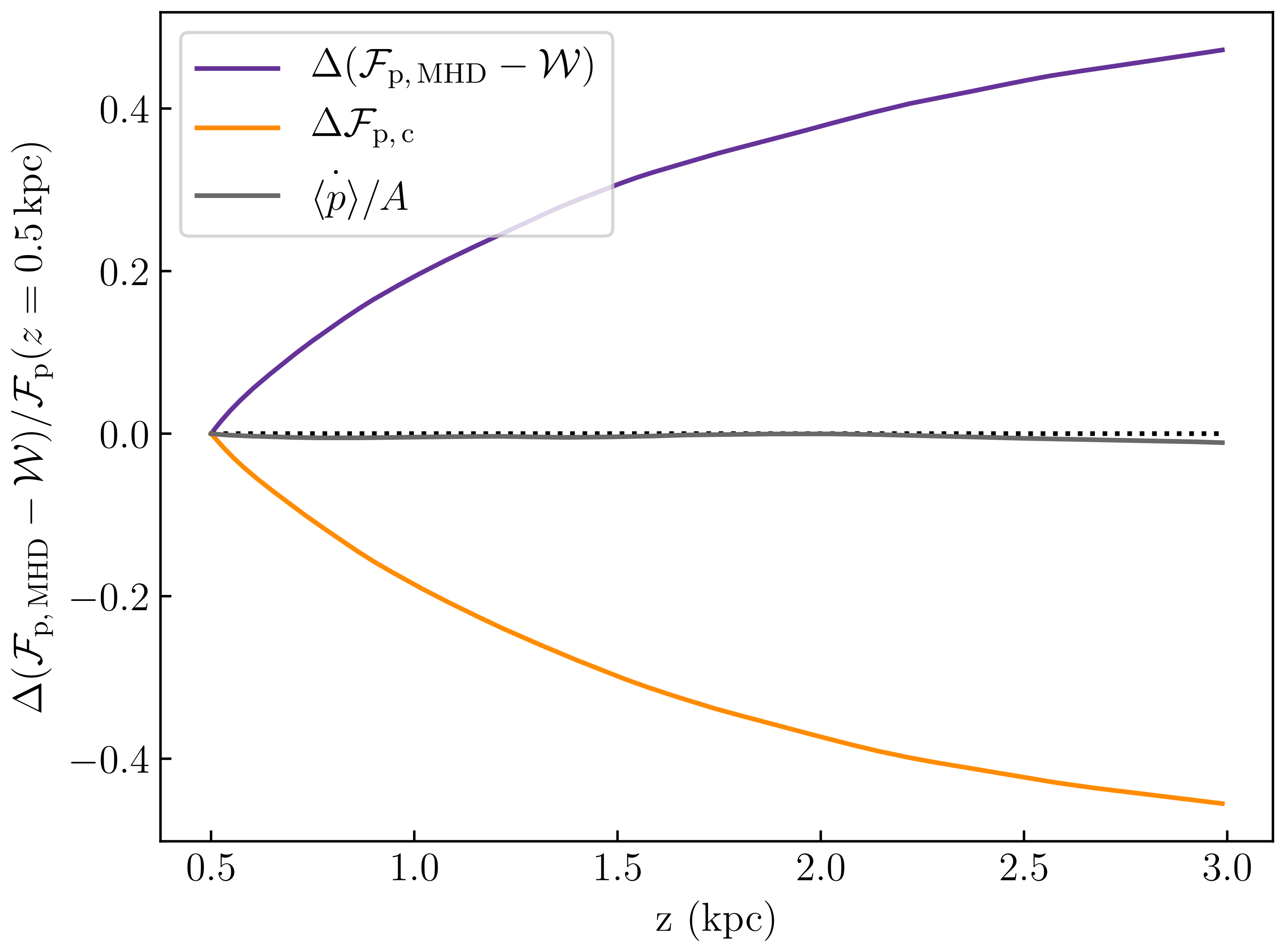
<u>CRs can efficiently drive flows of warm gas away from the disk!</u>

$$e_{\rm c} = e_{\rm c,\,post-process}\ ;\ F_{\rm c} = \frac{4}{3} e_{\rm c}(v + v_{\rm A,i})$$

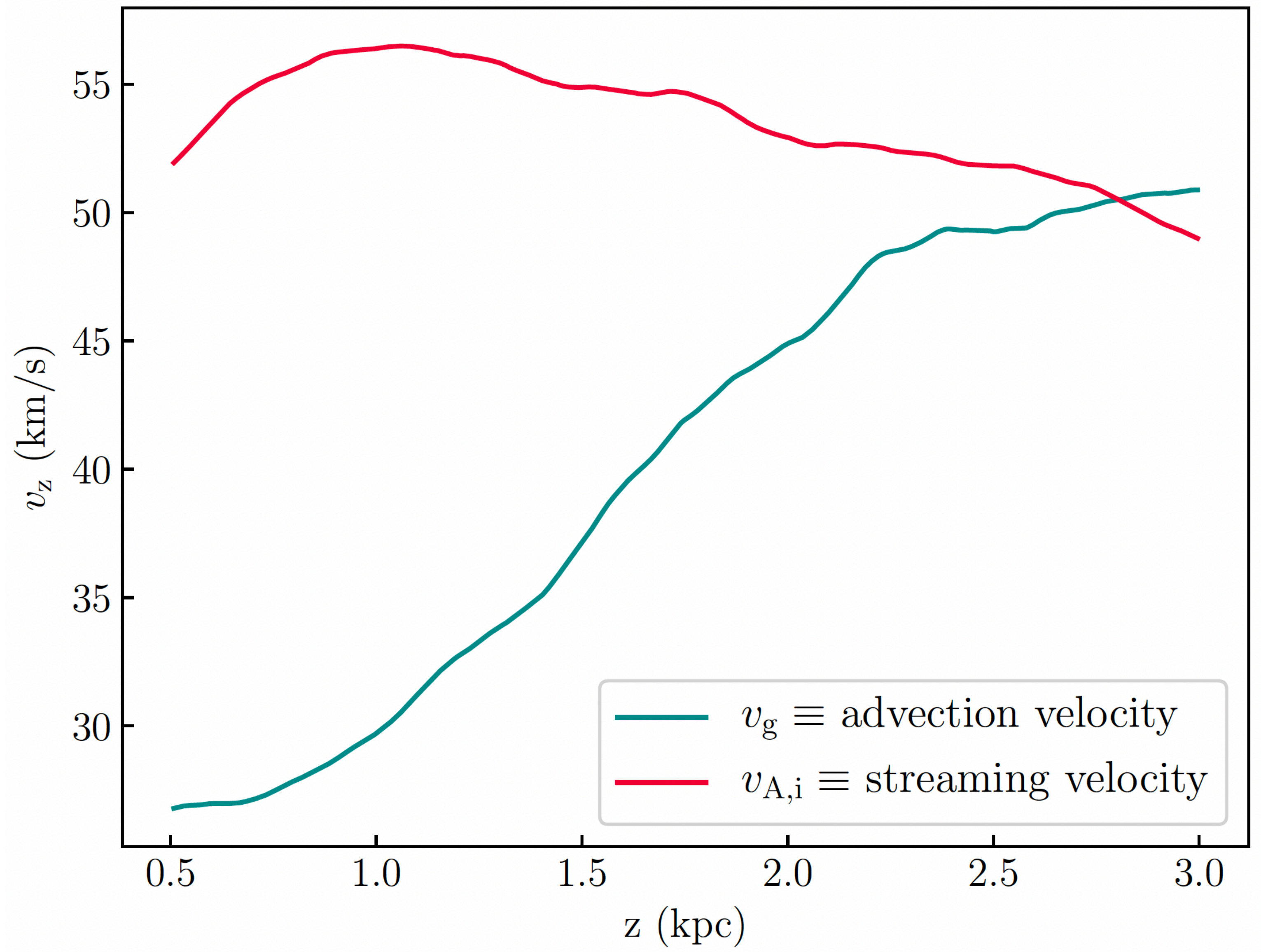
Armillotta et al. 2024

Cosmic ray-driven warm winds





CR-streaming limit $\longrightarrow C_{eff} \propto \rho^{-1/2}$



$$a_{z,c} = -\frac{1}{\rho}\frac{d}{dz}P_c \longrightarrow$$

P_c decreases towards higher z:

NET ACCELERATION AGAINST GRAVITY

Cosmic-ray transport and feedback in star-forming environments

- Resolving the multiphase structure of the ISM is crucial for properly modeling cosmic-ray transport: their propagation is different in different thermal phases of the gas

- There is no 'single' cosmic-ray diffusivity: scattering of cosmic rays significantly changes based on the properties of the background gas

- The predictions of our model for cosmic-ray transport agree with observations in the solar neighborhood: energy equipartition near the midplane

- Cosmic rays can efficiently drive warm flows of gas out of the plane: these outflows are overall smoother and slower than supernova-driven outflows