Simulating the interstellar medium with cosmic rays

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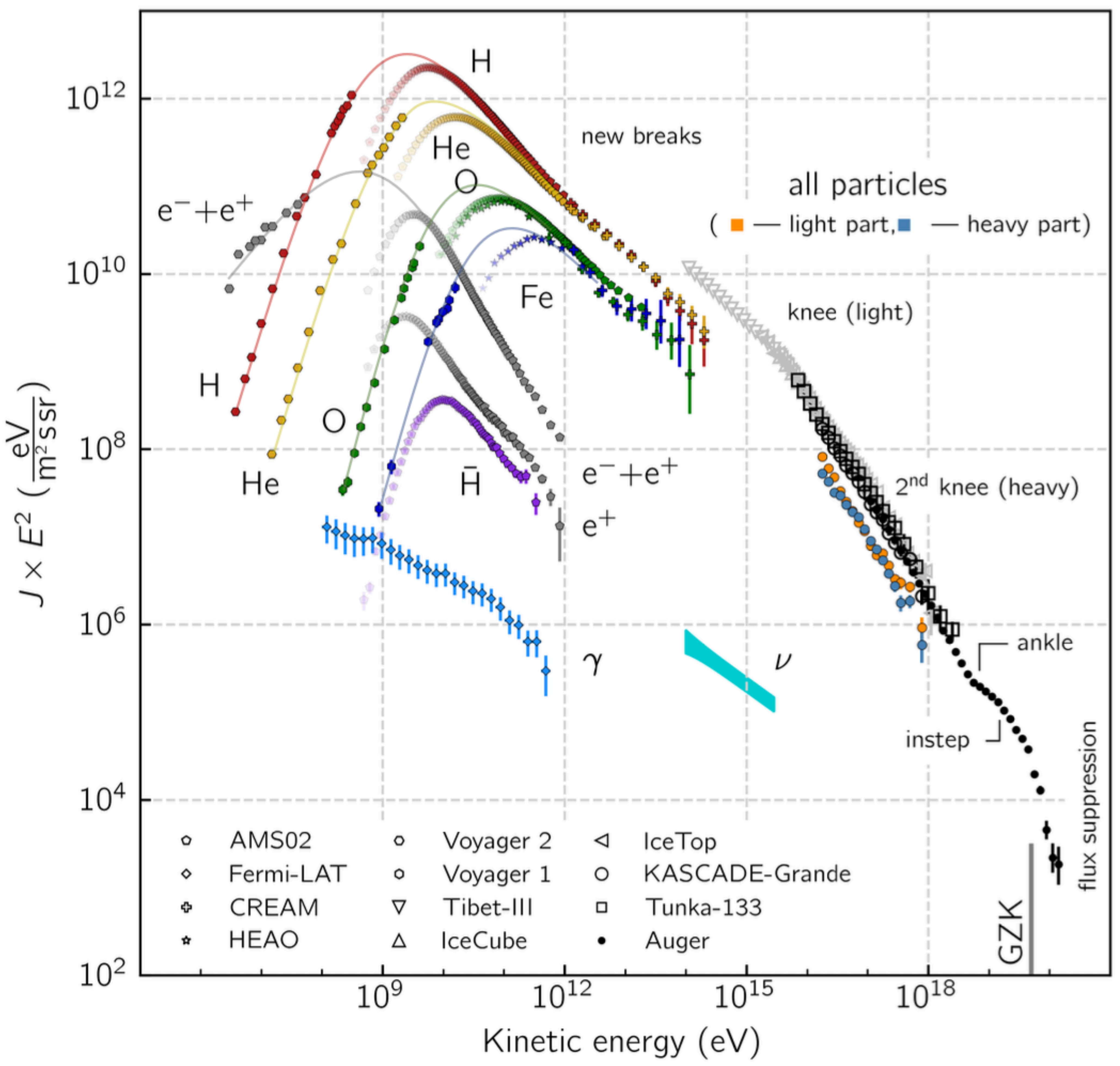
The role of feedback in galaxy formation: from small-scale winds to large-scale outflows

Potsdam, 15/07/2024

Galactic cosmic rays

- High-energy non-thermal particles mostly accelerated at supernova shocks
- Mostly composed of protons
- Average kinetic energy ~ 1-10 GeV
- Small number density ~ 10^{-9} cm^3
- Energy density ~ 1 eV/cm^3 in equipartition with thermal, kinetic and magnetic energy densities in the ISM → CRs may play a **significant role in regulating the ISM dynamics**

From Ruszkowski & Pfrommer 2023

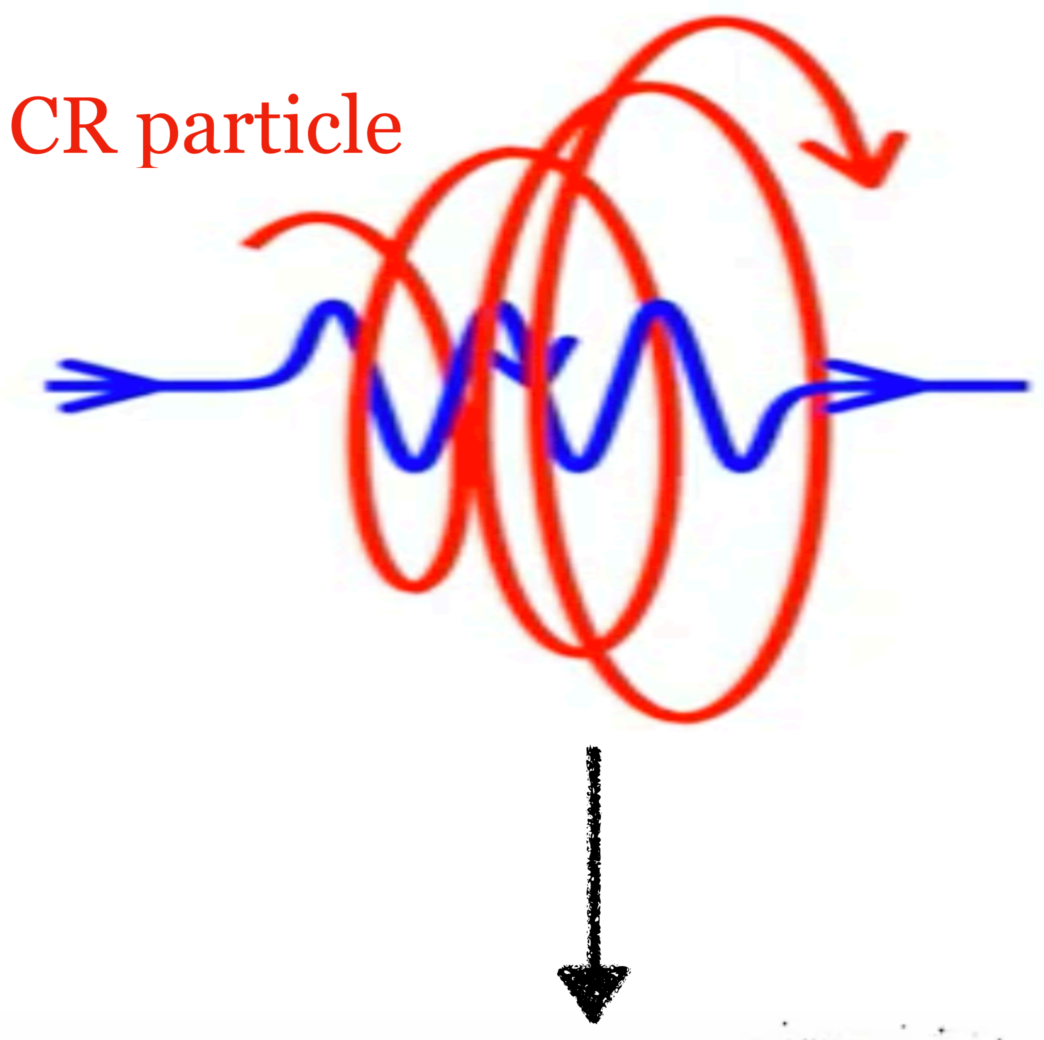


- CRs scatter off gyro-radius scale magnetic fluctuations
- Frequent scattering makes the CR mean free path very small → **CRs** are treated as a **relativistic fluid in MHD studies** of ISM/galaxies
- **Self-confinement scenario for CR scattering**: GeV CRs protons mostly scatter off self-excited Alfvèn waves
- **CR-fluid transport**:

  - **Advection** by background gas at v

  - **Streaming** with the confining waves at v_A

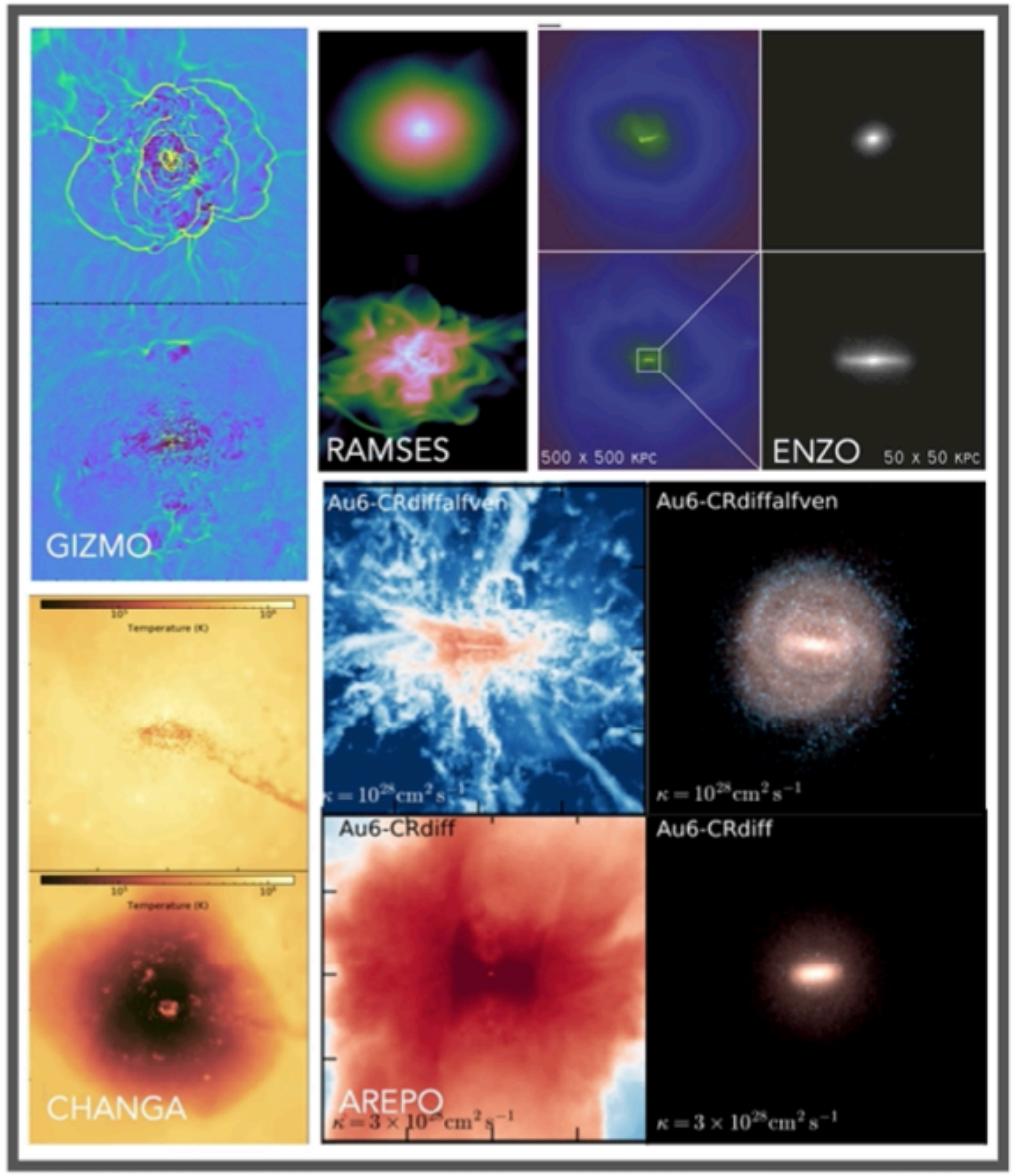
  - **Diffusion** relative to waves at rate κ in case of effective wave damping
- Magnetic field mediates **transfer of momentum between CRs and** thermal **gas** at a rate $\propto \nabla P_c$, while wave damping causes transfer of CR energy to the gas at a rate $\propto v_A \cdot \nabla P_c$



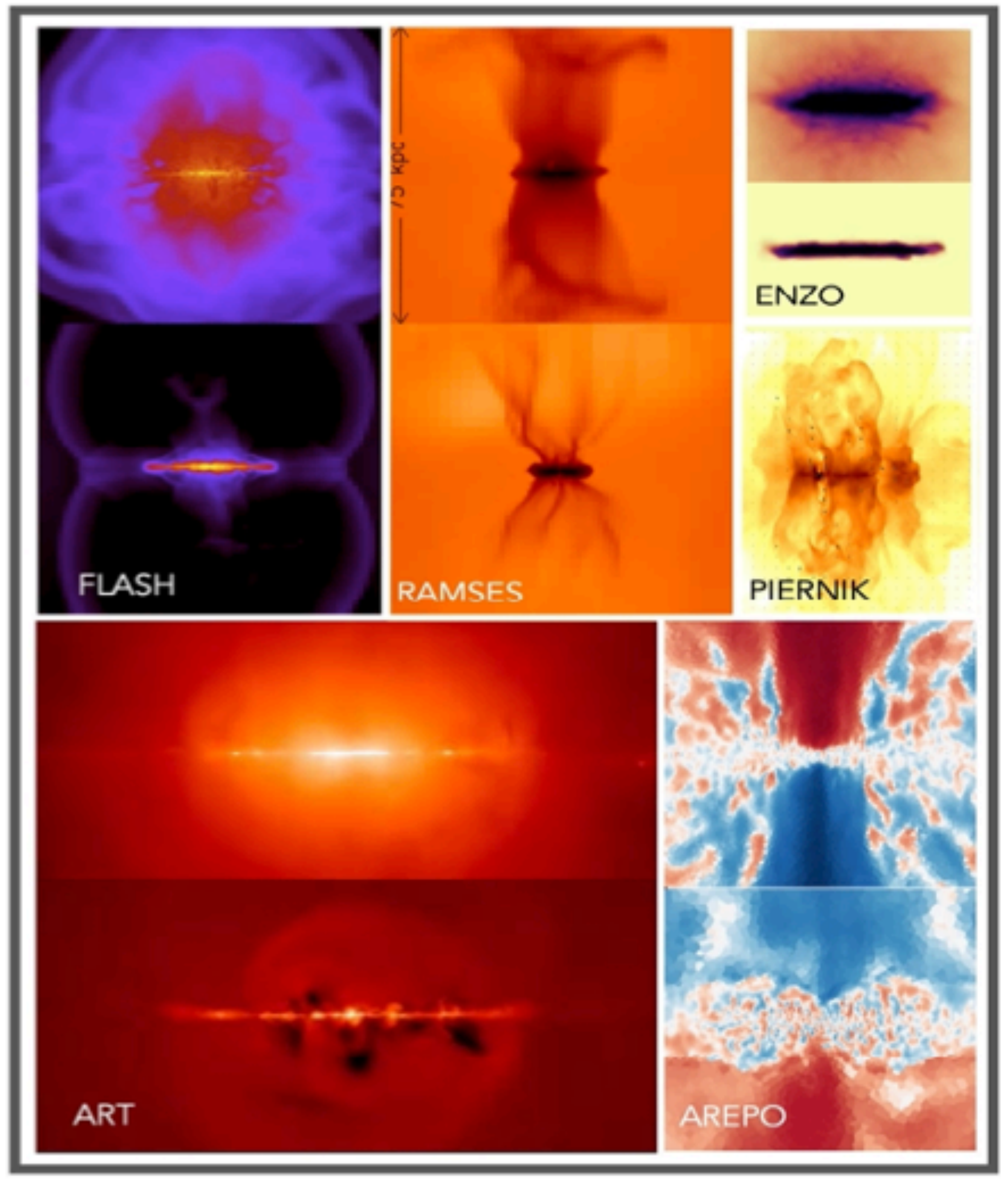
Kulsrud & Pearce 1969, Skilling 1971, Zweibel 2013

Cosmic-ray feedback in galaxies: state of the art

COSMO



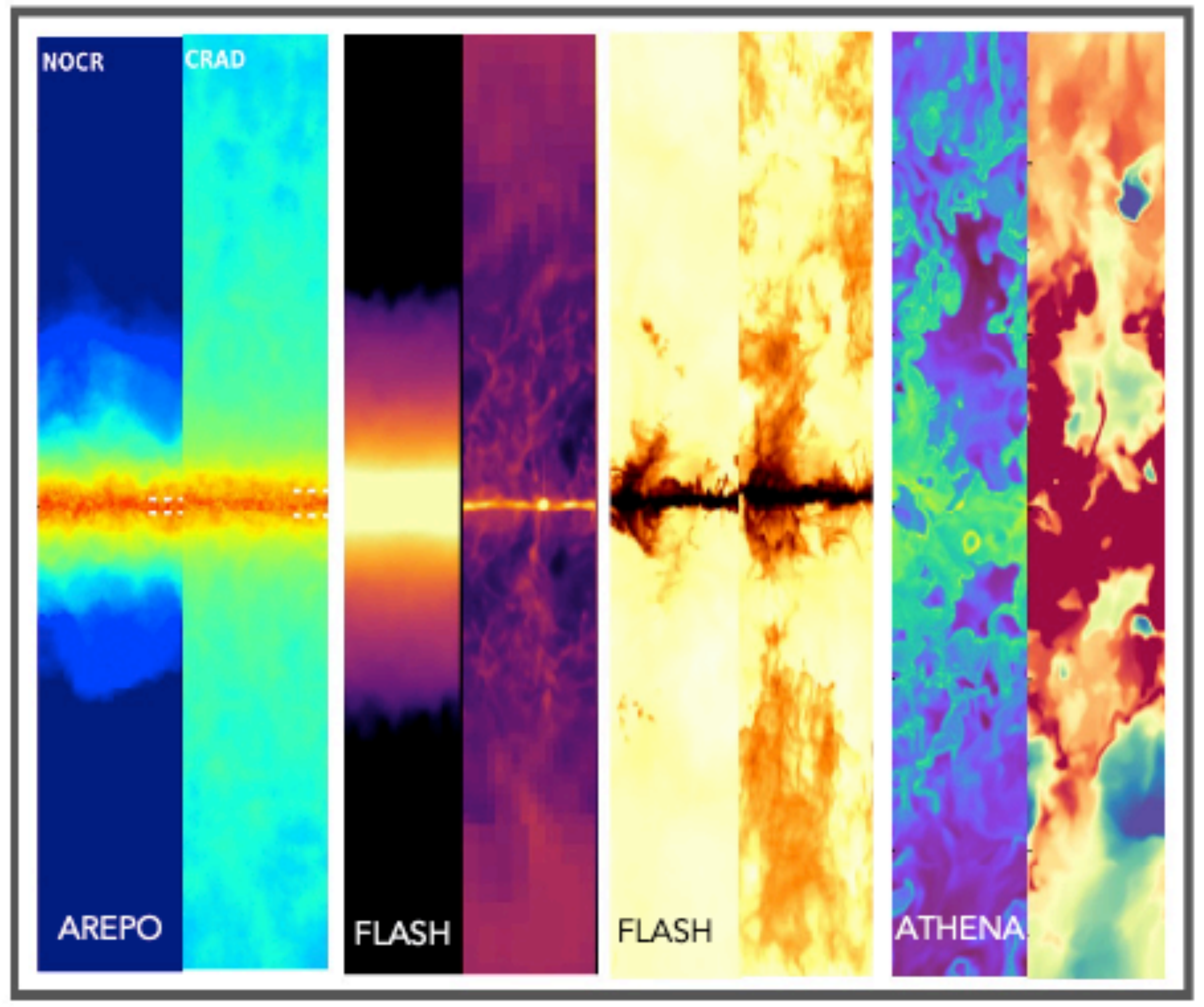
GLOBAL



See Mateusz Ruszkowski's talk

From Pfrommer & Ruszkowski 2023

ZOOM

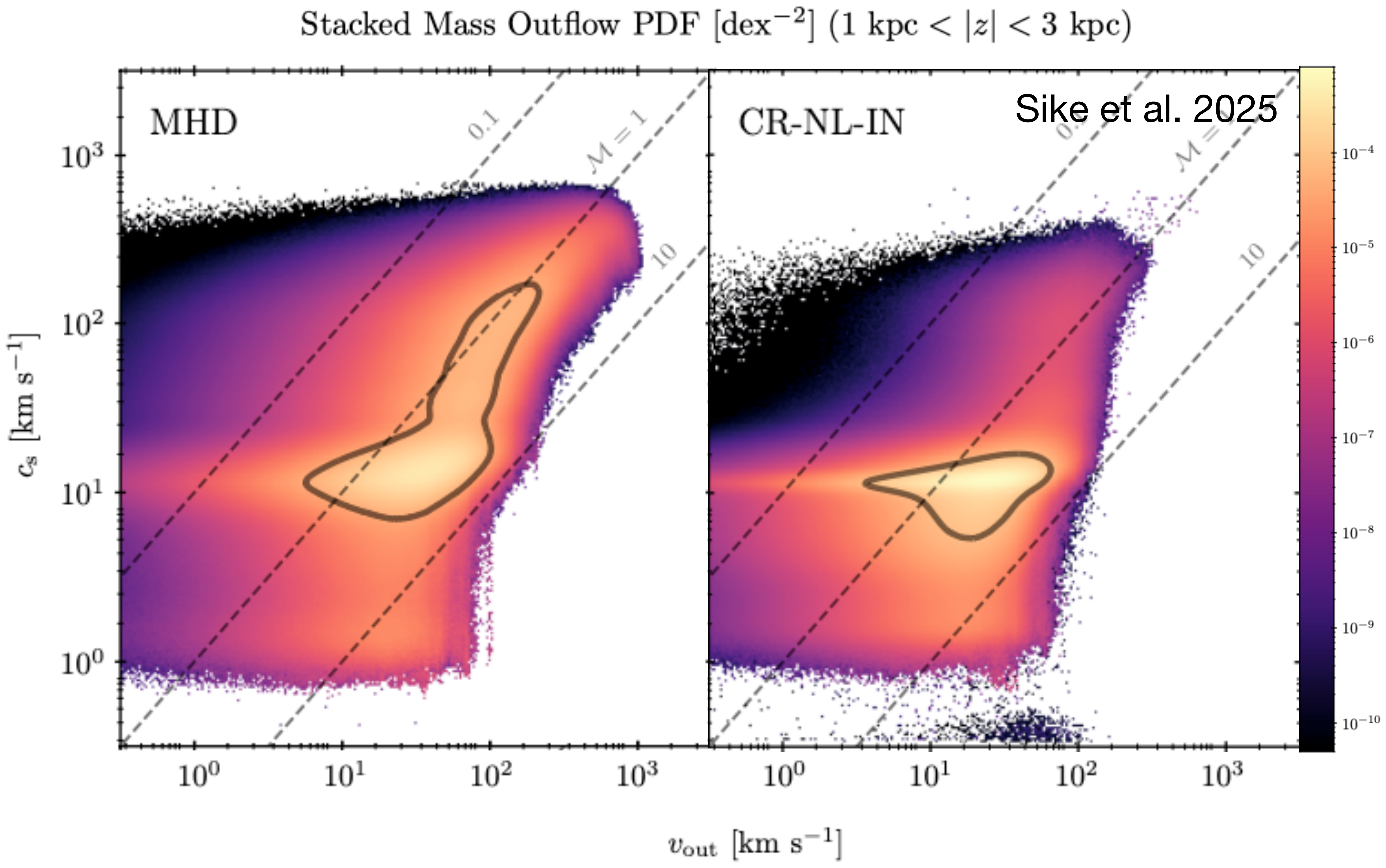


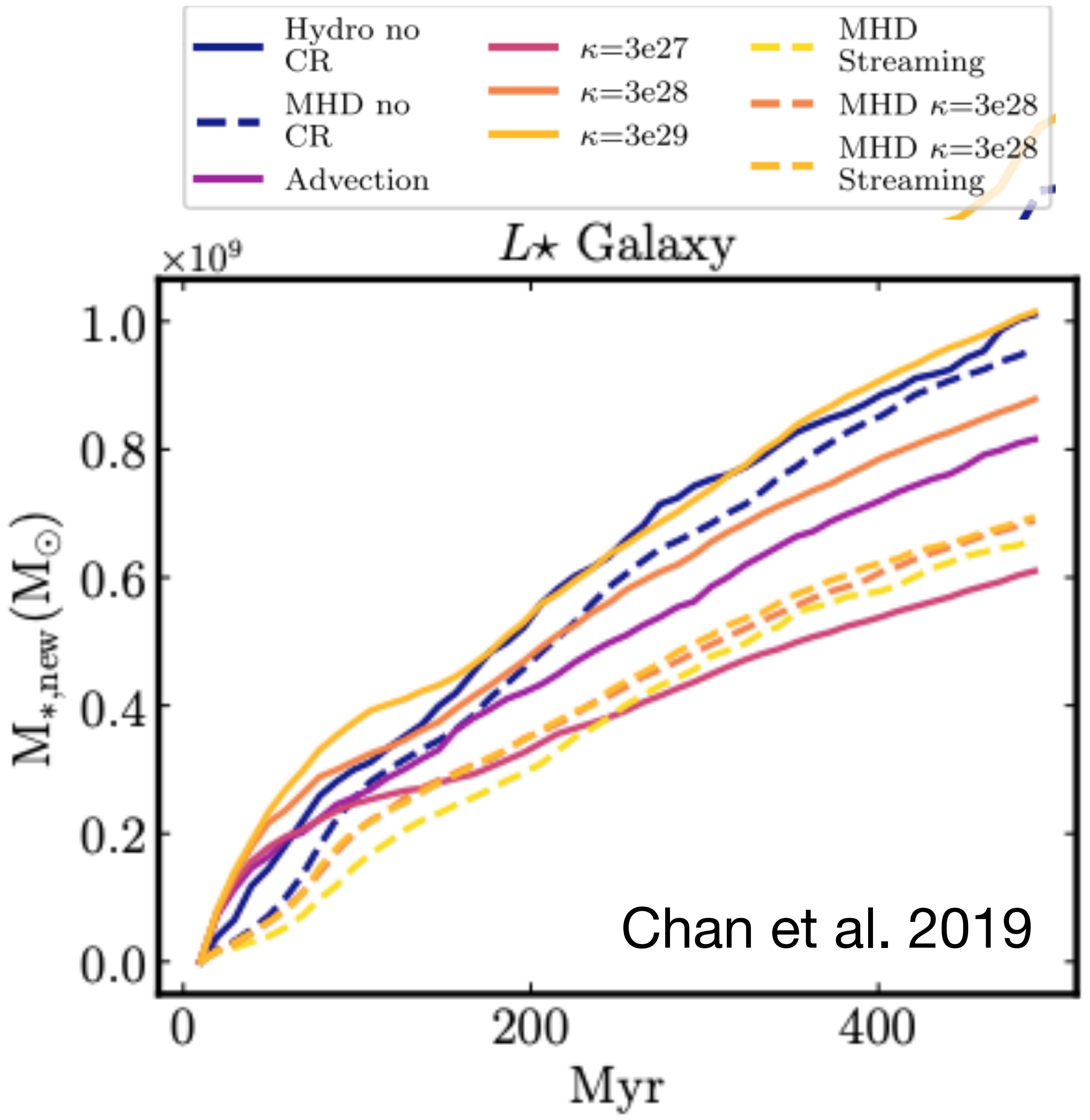
Central topic in recent studies of galaxy evolution, explored through MHD simulations of cosmological zoom-ins, isolated galaxies, and local patches of the ISM

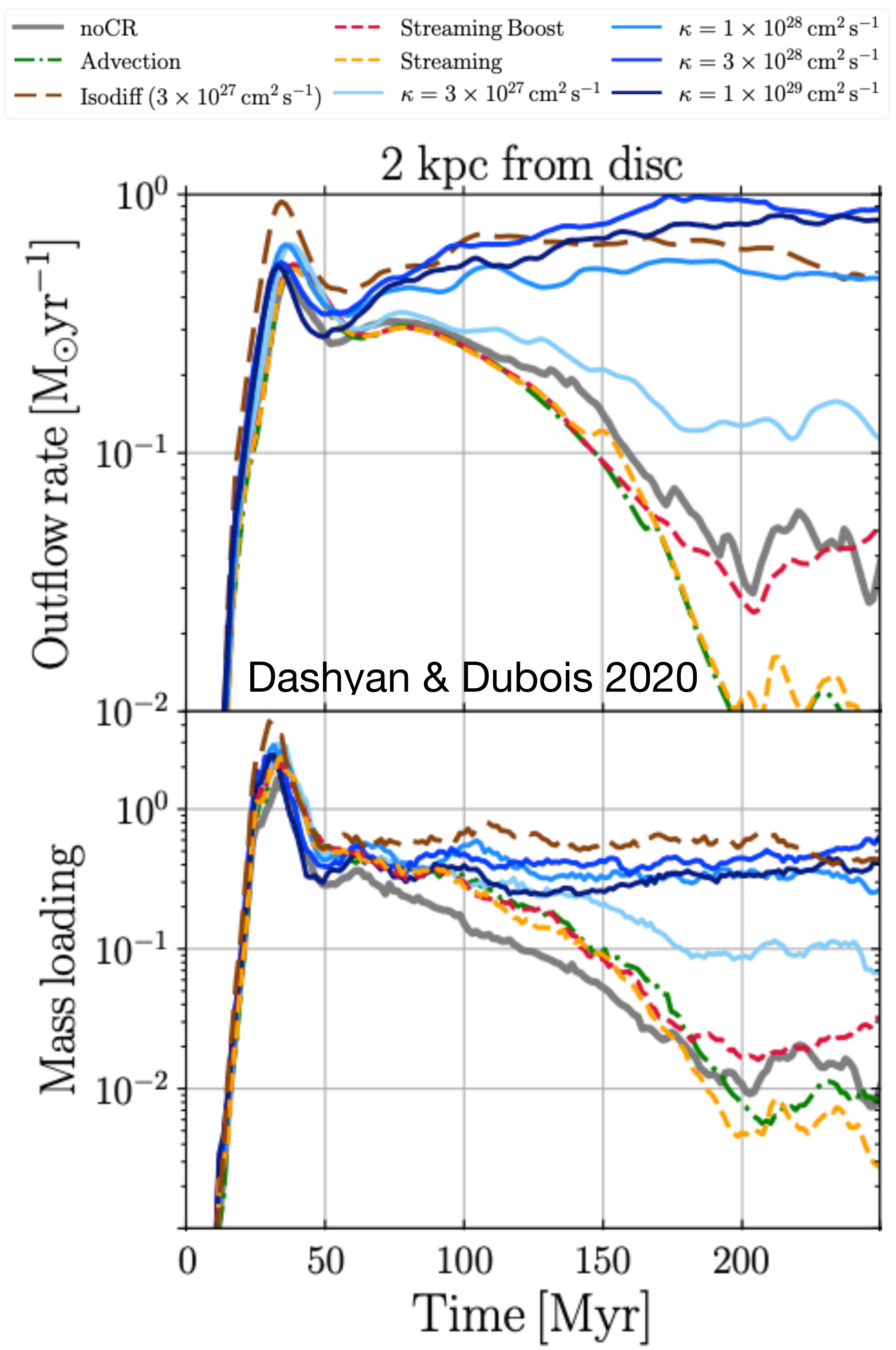
Uhlig et al. 2012; Booth et al. 2013; Hanasz et al. 2013; Salem & Bryan 2014; Pakmor et al. 2016; Salem et al. 2016; Simpson et al. 2016; Ruszkowski et al. 2017; Farber et al. 2018; Girichidis et al. 2018, 2022; Armillotta et al. 2021, 2022, 2024; Hopkins et al. 2021, 2022; Rathjen et al. 2021, 2023; Chan et al. 2022; Peschken et al. 2023; Thomas et al. 2023, 2025; Tsung et al. 2023; Sike et al. 2025, Habegger & Zweibel 2025; and more (see reviews by Pfrommer & Ruszkowski 2023)

Cosmic-ray feedback in galaxies: state of the art

- CRs can regulate star formation, depending on galactic environment and conditions
- CRs launch cooler, denser, slower winds than thermal feedback
- **BUT… the degree of CR impact depends strongly on how their transport is modelled**





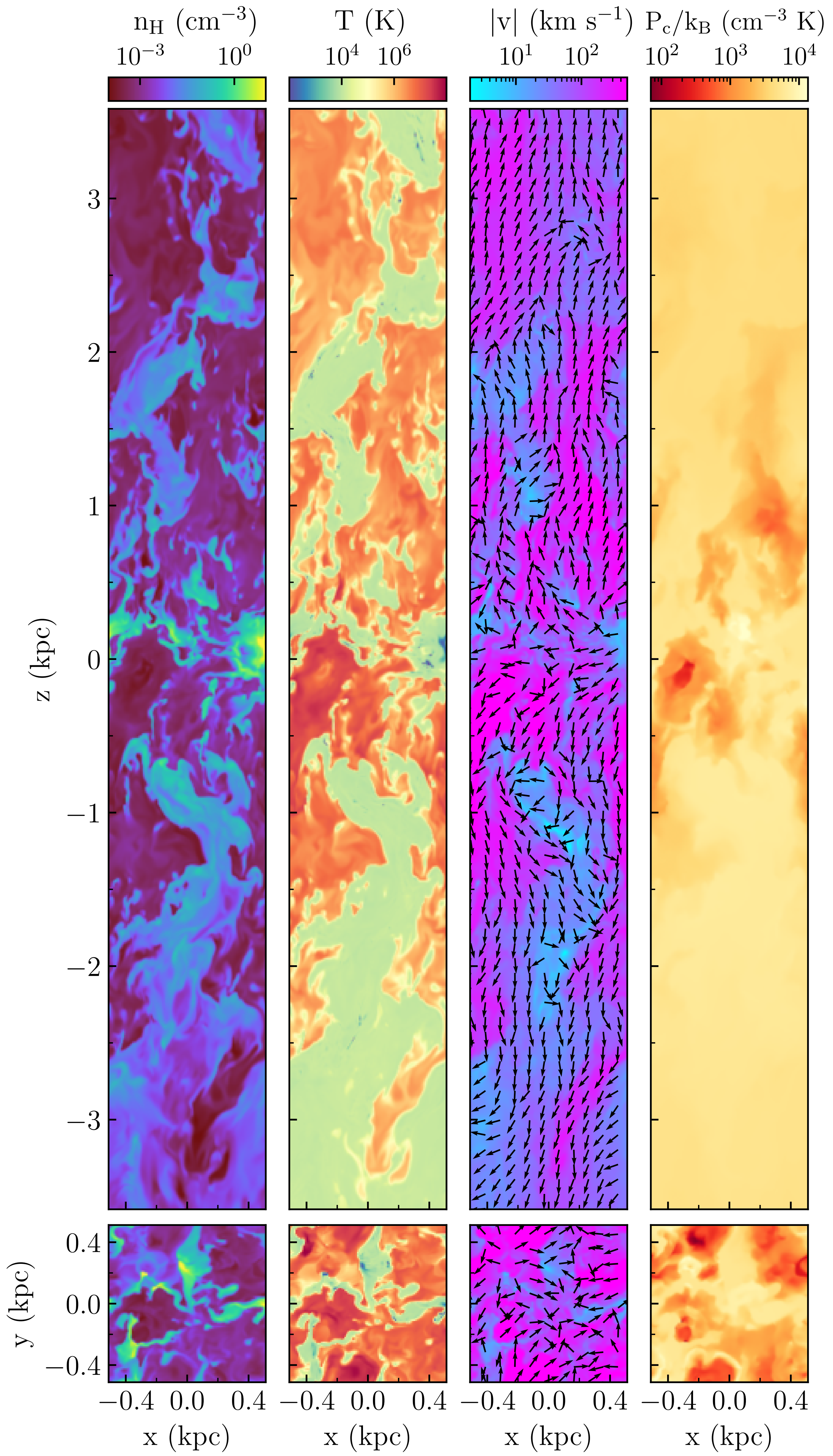


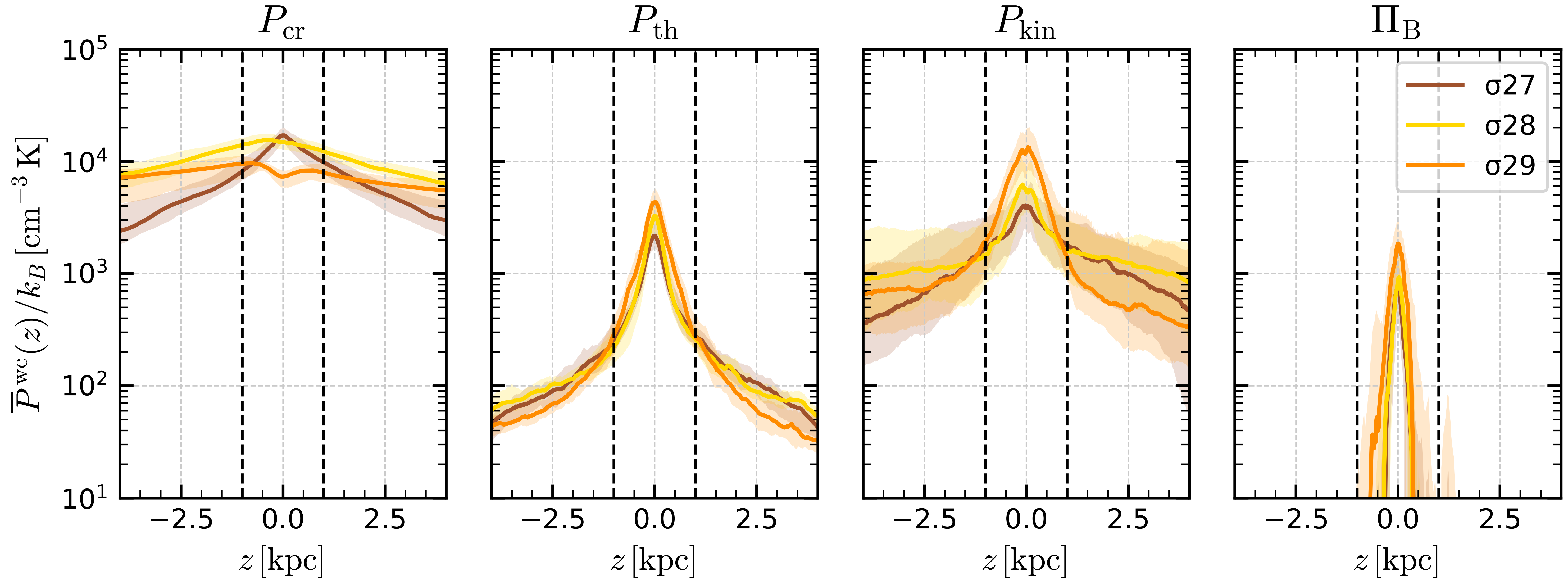
Why transport models matter?

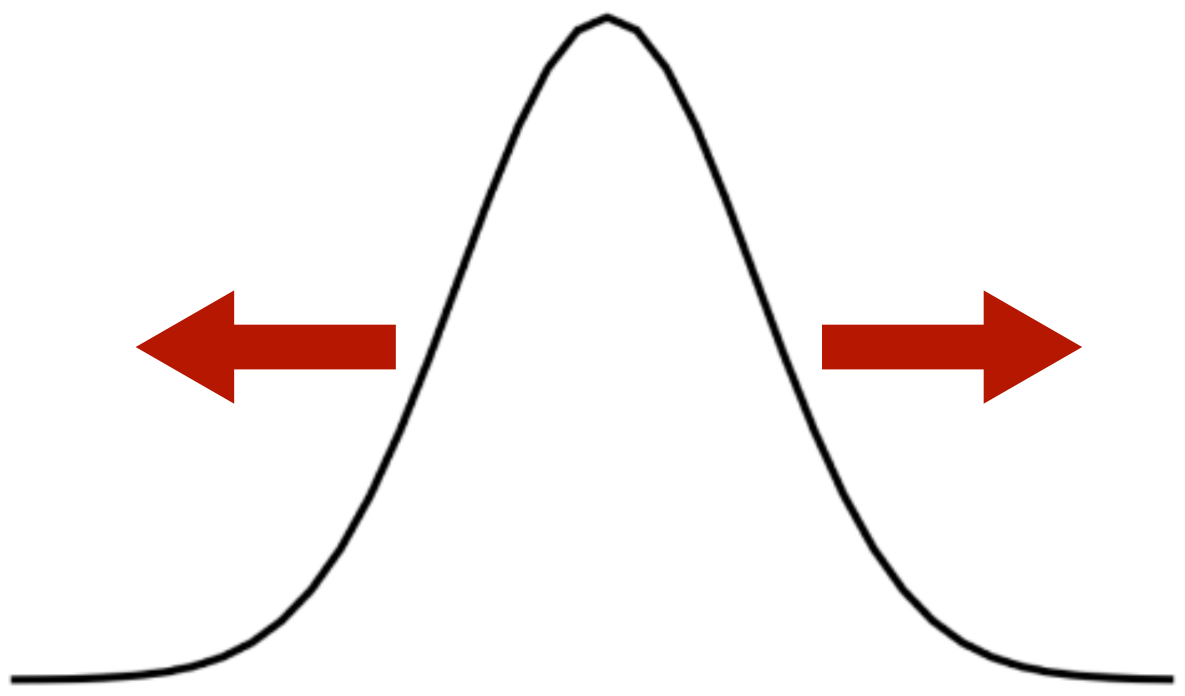
CR-MHD TIGRESS SIMULATIONS OF A KPC-SCALE PATCH OF DISK

Kim, Armillotta, et al., in prep.

Constant scattering coefficient $\sigma = \kappa^{-1}$ ($\sigma = 10^{-27}, 10^{-28}, 10^{-29}\ \mathrm{s\,cm^{-2}}$), $v_A = B/\sqrt{4\pi\rho}$







If $\nabla P_{\mathrm{MHD}} + \nabla P_c > \rho \nabla \Phi$

- CRs affect the ISM dynamics by exerting pressure gradient forces
- Different scattering coefficients → different CR distributions → different CR forces

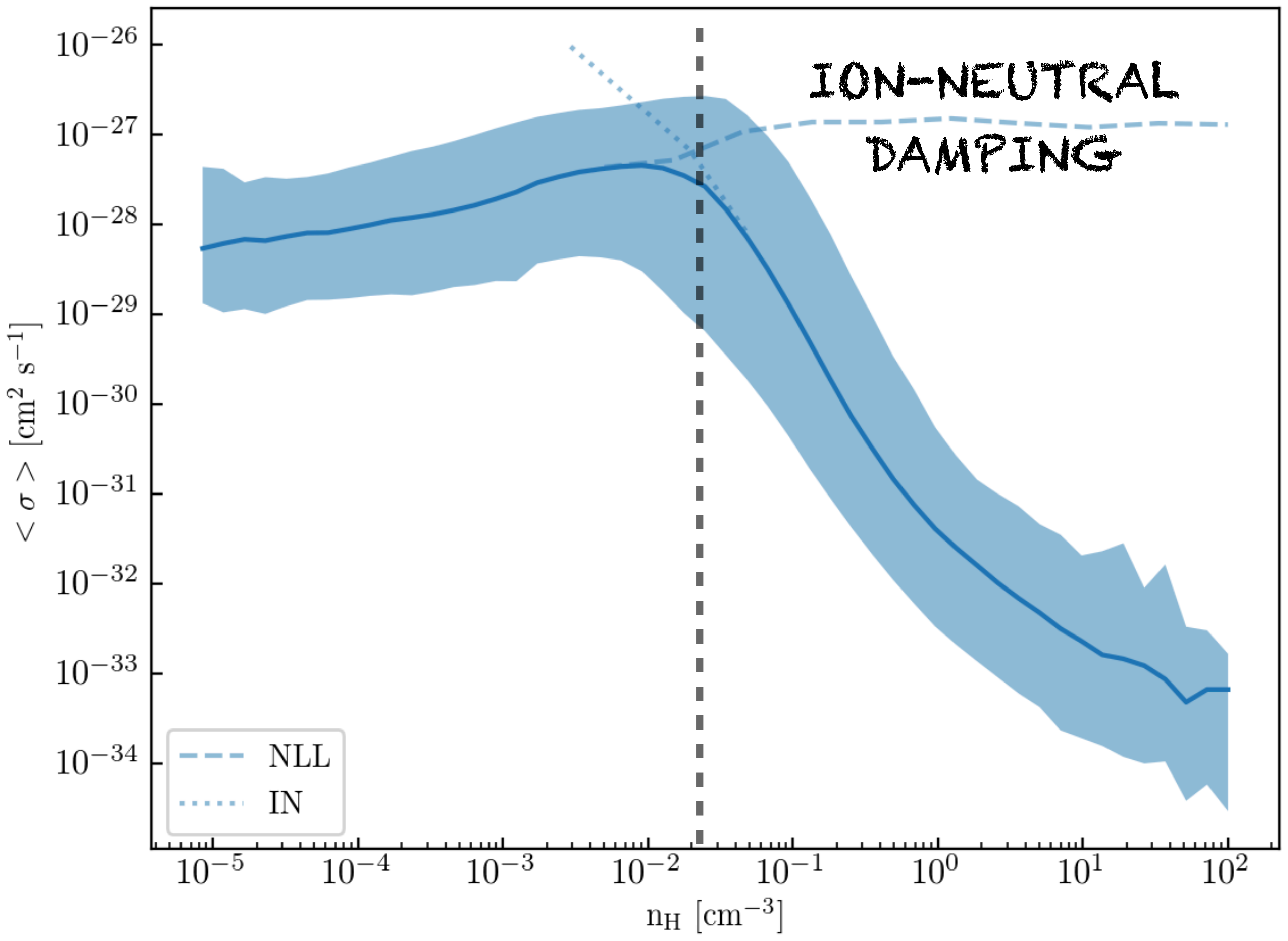
Towards a more physical transport prescription

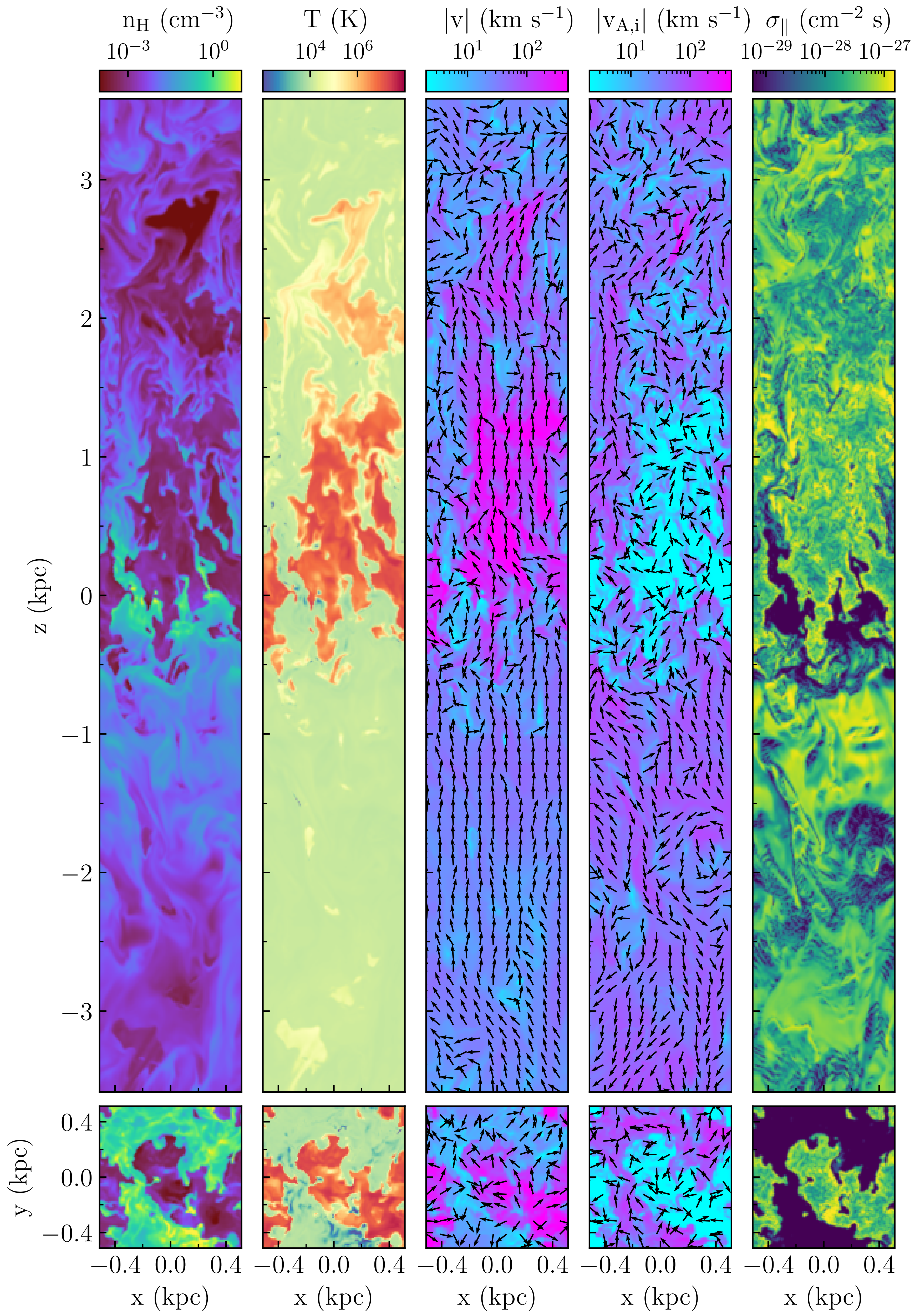
- Scattering coefficient computed by balancing wave growth and nonlinear Landau + ion-neutral damping

$$\Gamma_{\rm growth} = \Gamma_{\rm damp} \rightarrow \sigma_{\parallel}$$

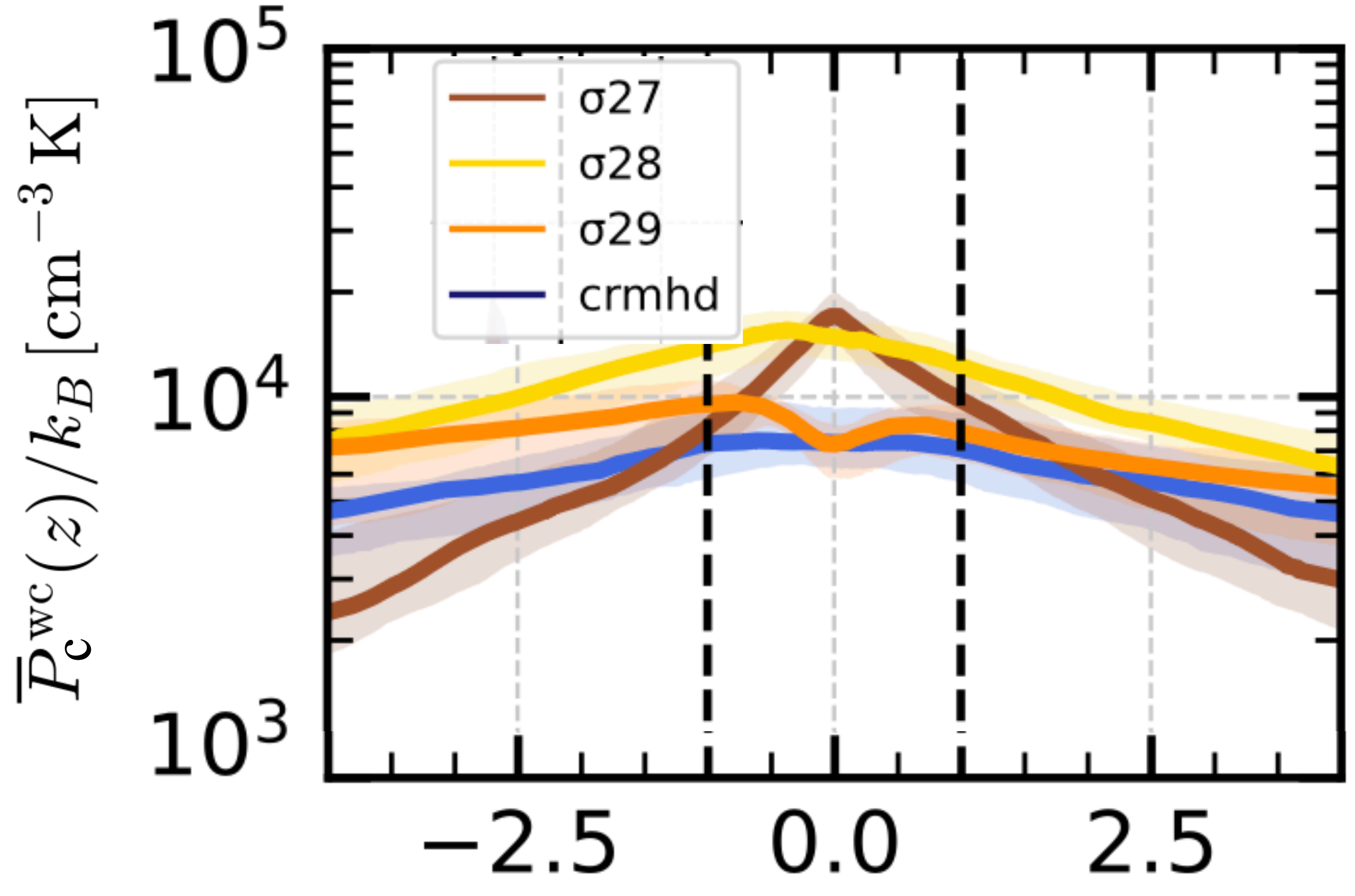
- $v_{\rm s} = v_{\rm A,i} = B/\sqrt{4\pi\rho_{\rm i}}$

Armillotta, et al. 2021;
Hopkins et al. 2021, 2022;
Thomas et al. 2023, 2025;
Sike et al. 2025





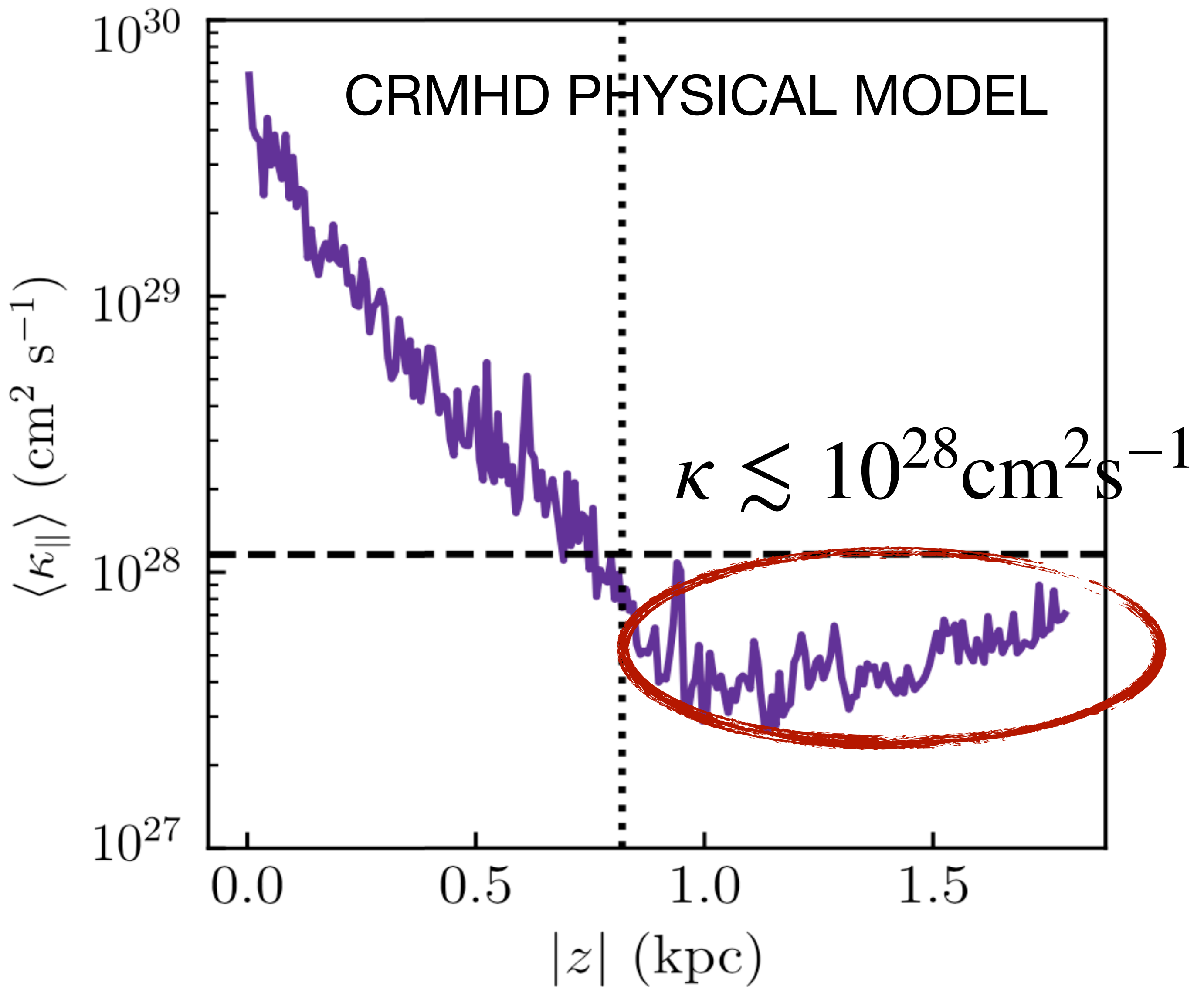
Why accurate CR transport and ISM modelling matters?

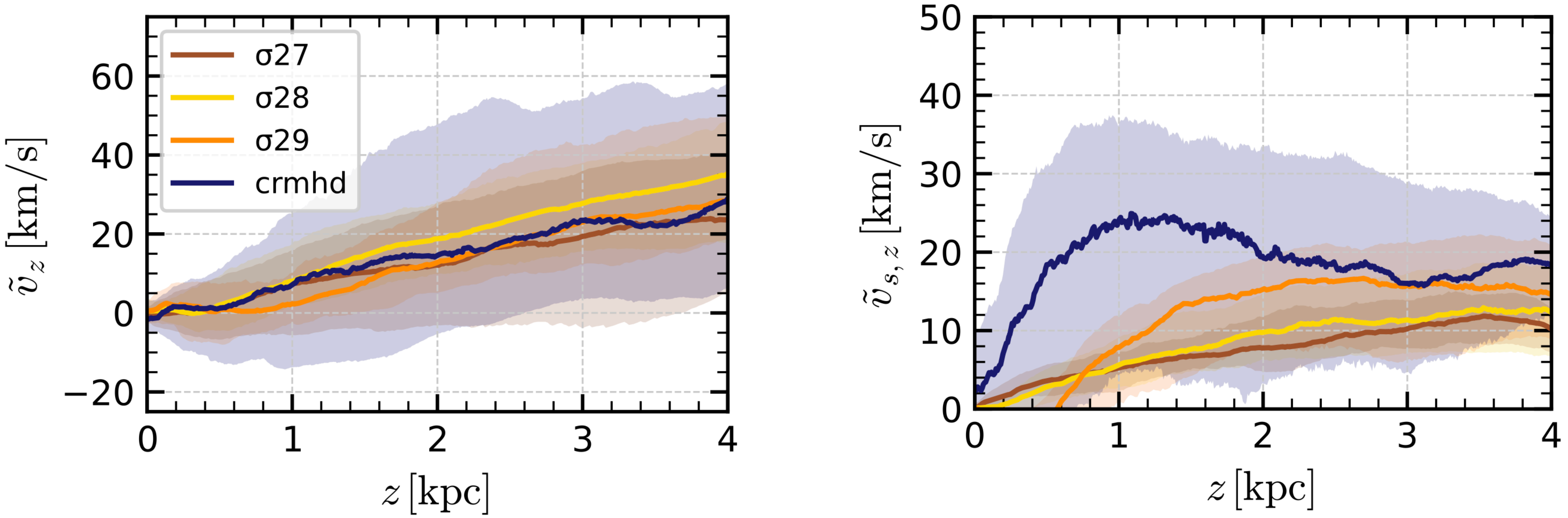


<u>SIMPLE ANALYTIC MODEL</u> Armillotta et al. 2025, Hix, Armillotta et al. sub.

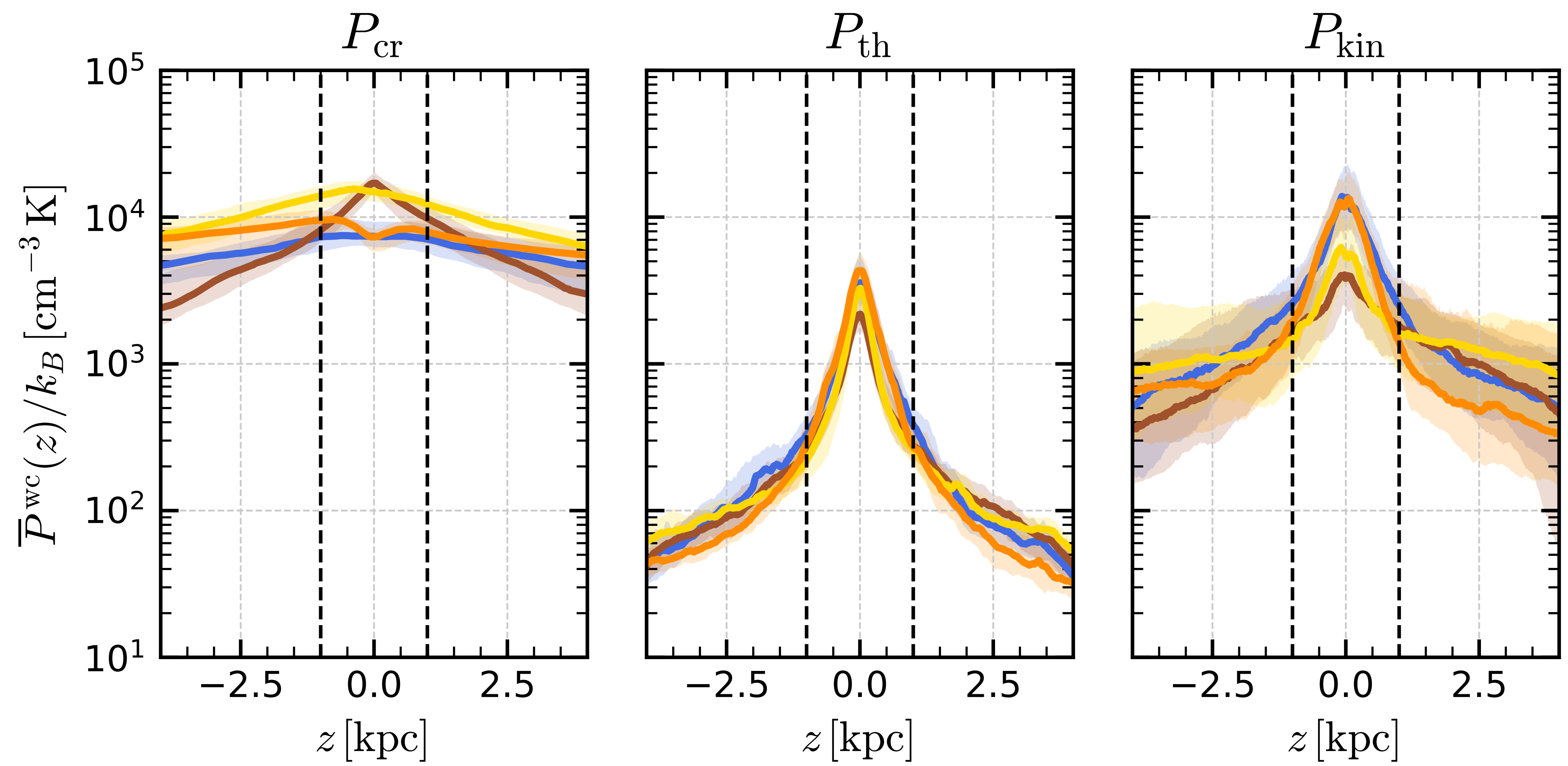
- **CRs** are **confined within the** neutral **midplane by the surrounding ionized gas → accurate ISM modelling is crucial**!
- $$P_{c,\mathrm{mid}} = \frac{F_{\mathrm{in}}}{4v_{\mathrm{eff}} + 3/2\Lambda_{\mathrm{coll}} N_{\mathrm{H}}} \simeq \frac{\epsilon_c E_{\mathrm{SN}} \Sigma_{\mathrm{SFR}}/m_*}{4v_{\mathrm{eff}} + 3/2\Lambda_{\mathrm{coll}} N_{\mathrm{H}}}$$
- $v_{\mathrm{eff}} = v + v_s + \kappa/H_c$ with $H_c[v + v_s, d(v+v_s)/dz, \kappa]$ the scale height

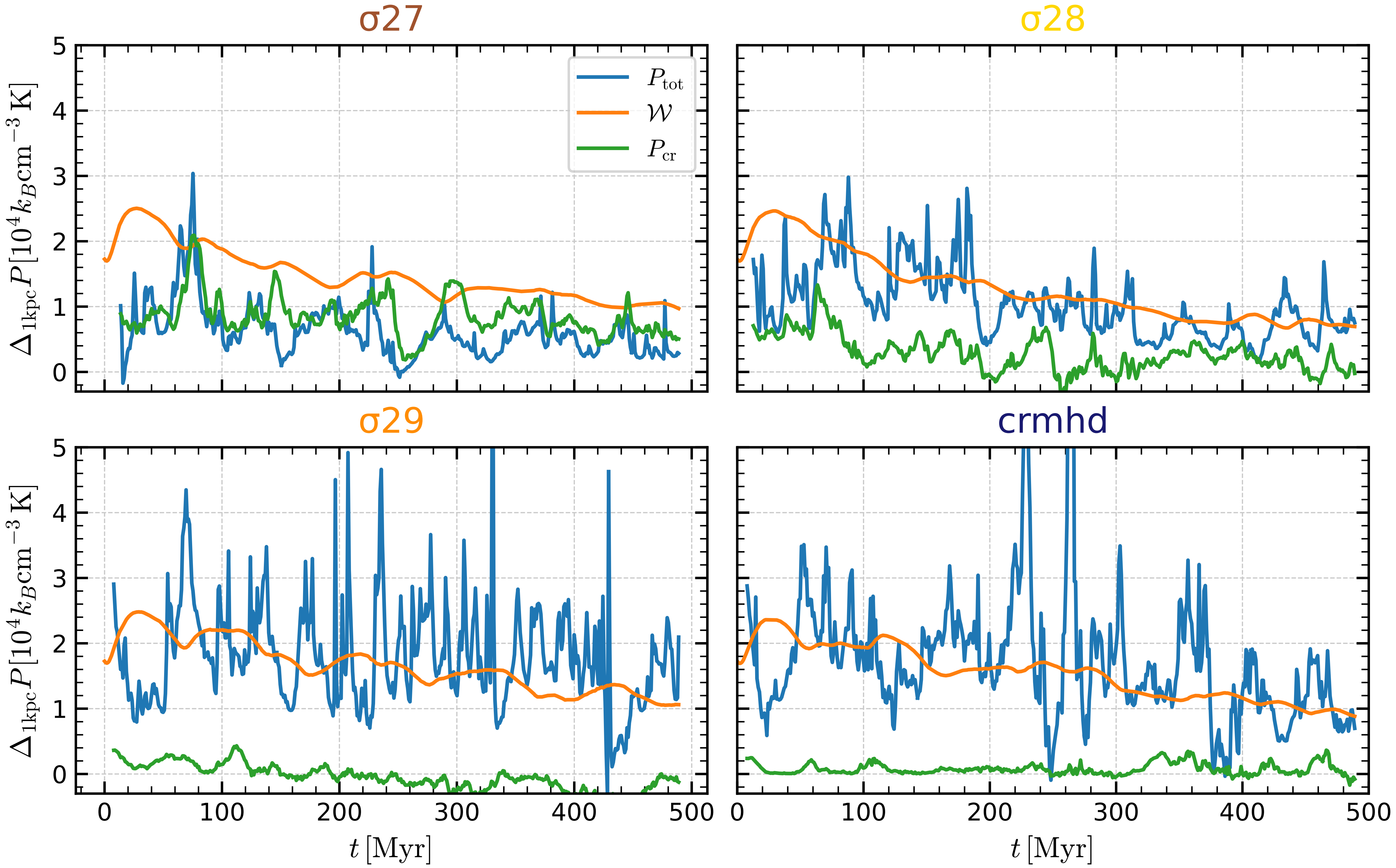
What sets v_{eff}?

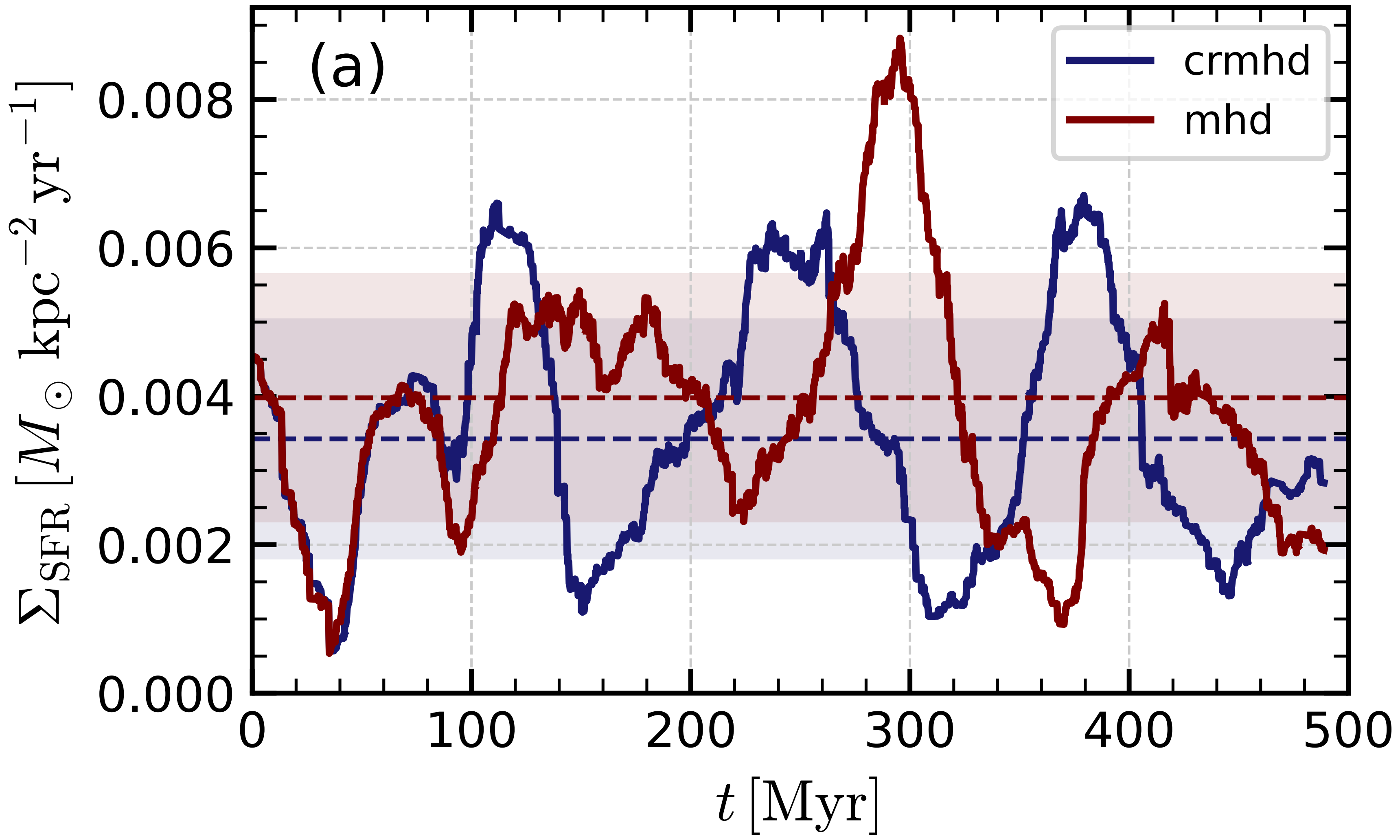




Impact on disk support and star formation rate







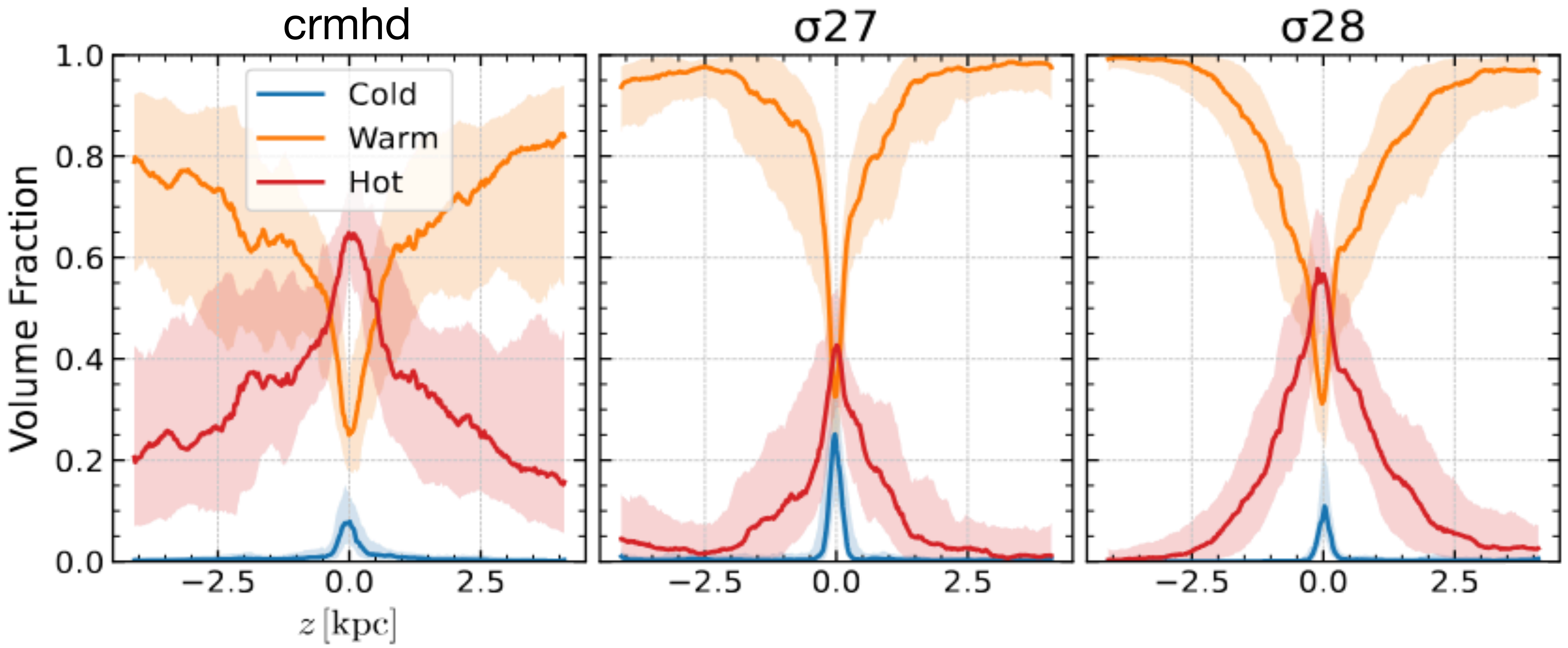
- Higher diffusion → weaker disk support and less SF suppression
- **CR-MHD self-consistent model:**

  - Only marginal star formation reduction

  - CRs spread in the disk via advection + field-aligned transport → lateral CR forces are negligible, not just vertical forces

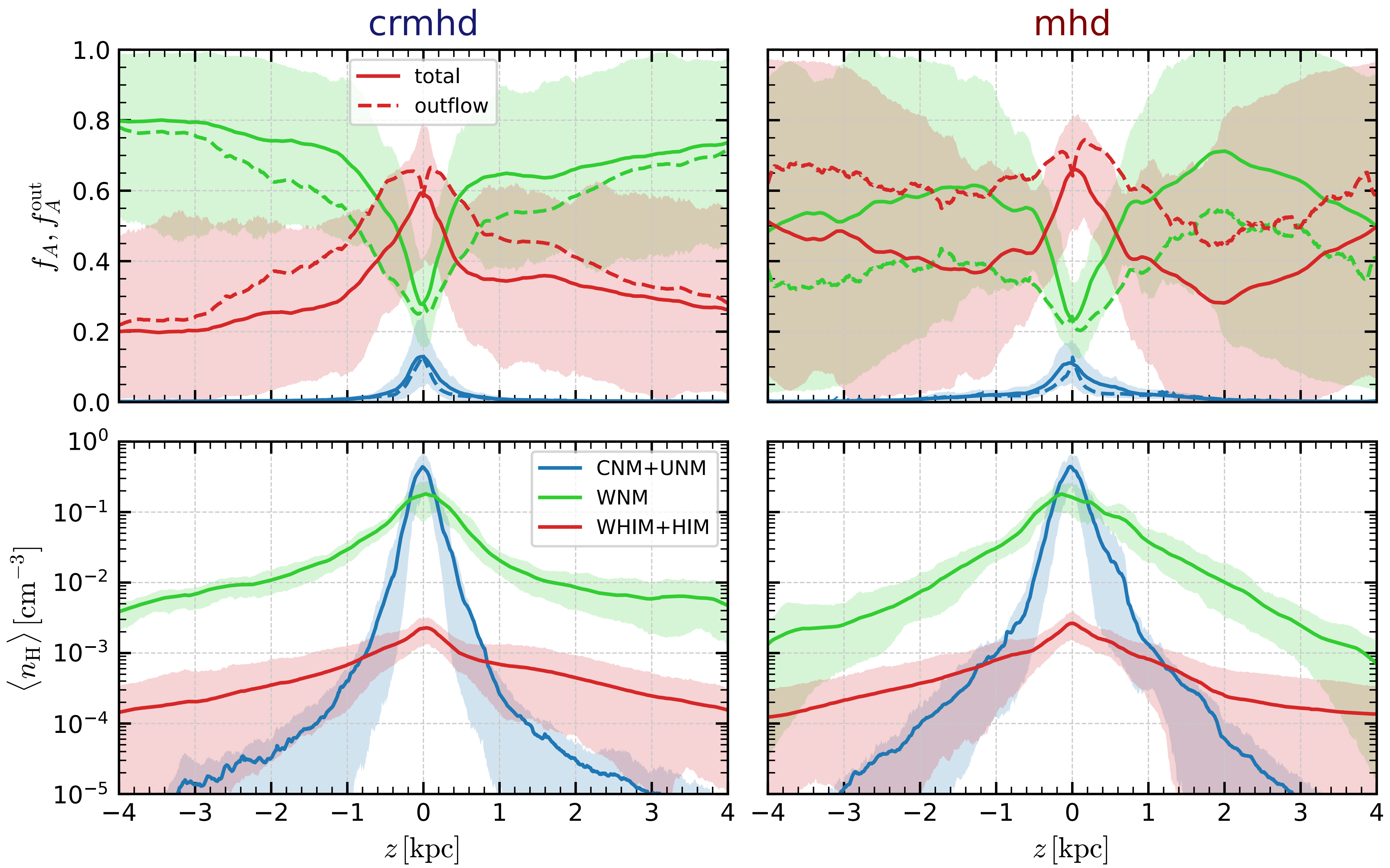
Kim, Armillotta, et al., in prep.

Impact on ISM structure



- **With CRs: Warm gas dominates the outflow**
  → Self-consistent model: 75% WNM / 25% HIM at 2 kpc

- **Without CRs: Hot gas dominates**
  → Pure MHD model: 35% WNM / 65% HIM



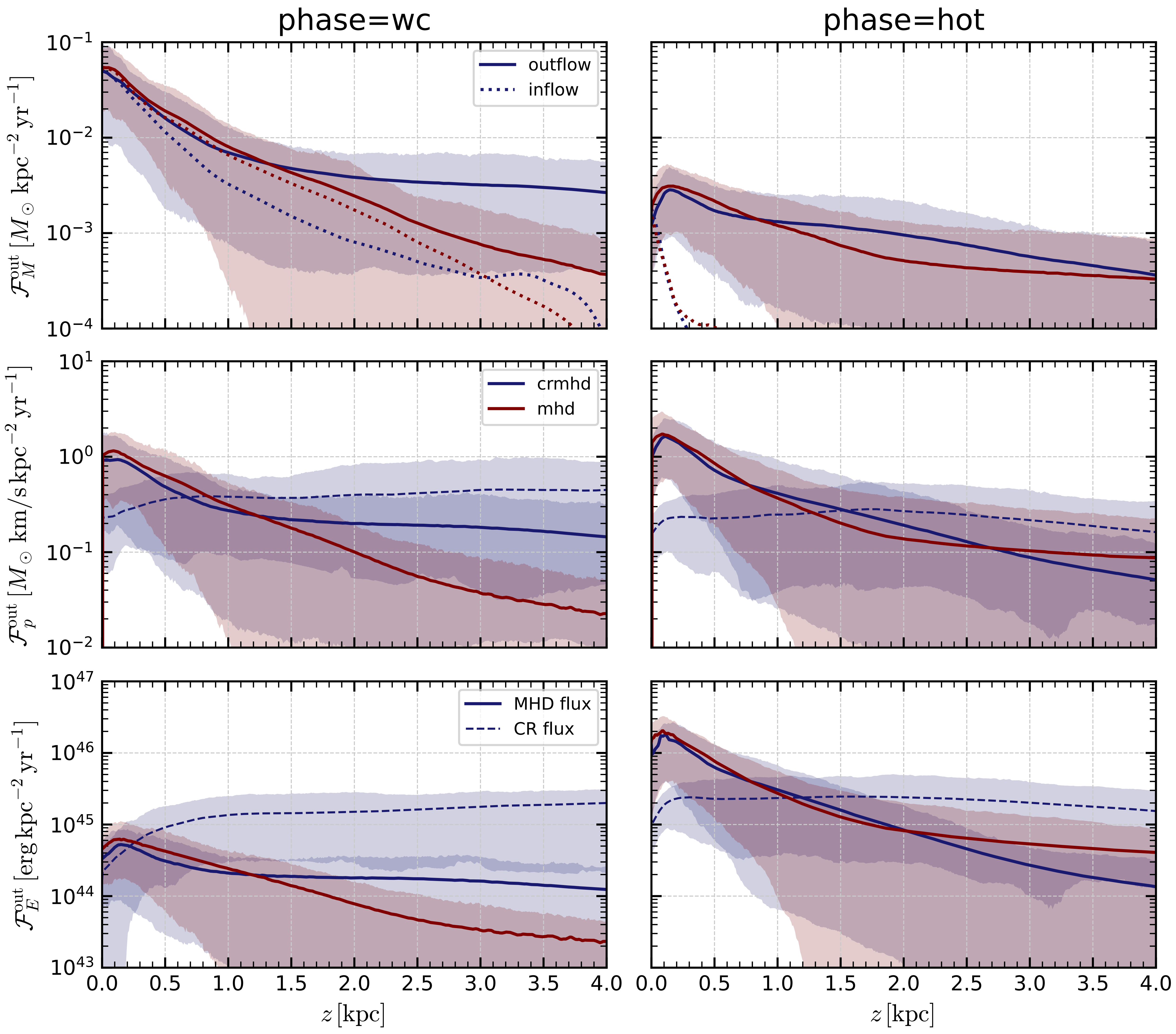
- Warm gas dominates the extraplanar region (both mass and volume) in all models

- Constant-σ models: more cold-warm gas in both the midplane and extraplanar region

- Constant-σ models: Reduced SF → weaker thermal feedback → less hot gas

Kim, Armillotta, et al., in prep.

Impact on outflow loading factors



- **MHD model: alternating outflows and inflows**
- **CR-MHD self-consistent model: Steady warm-cold outflows**; warm flux remains constant; hot flux gradually decreases with height.
- CRs efficiently accelerate warm gas because the effective sound speed increases as density decreases ($C_{\rm c}^2 \propto P_{\rm c}/\rho \propto v_{\rm A}^{4/3}/\rho \propto \rho^{1/3}$)

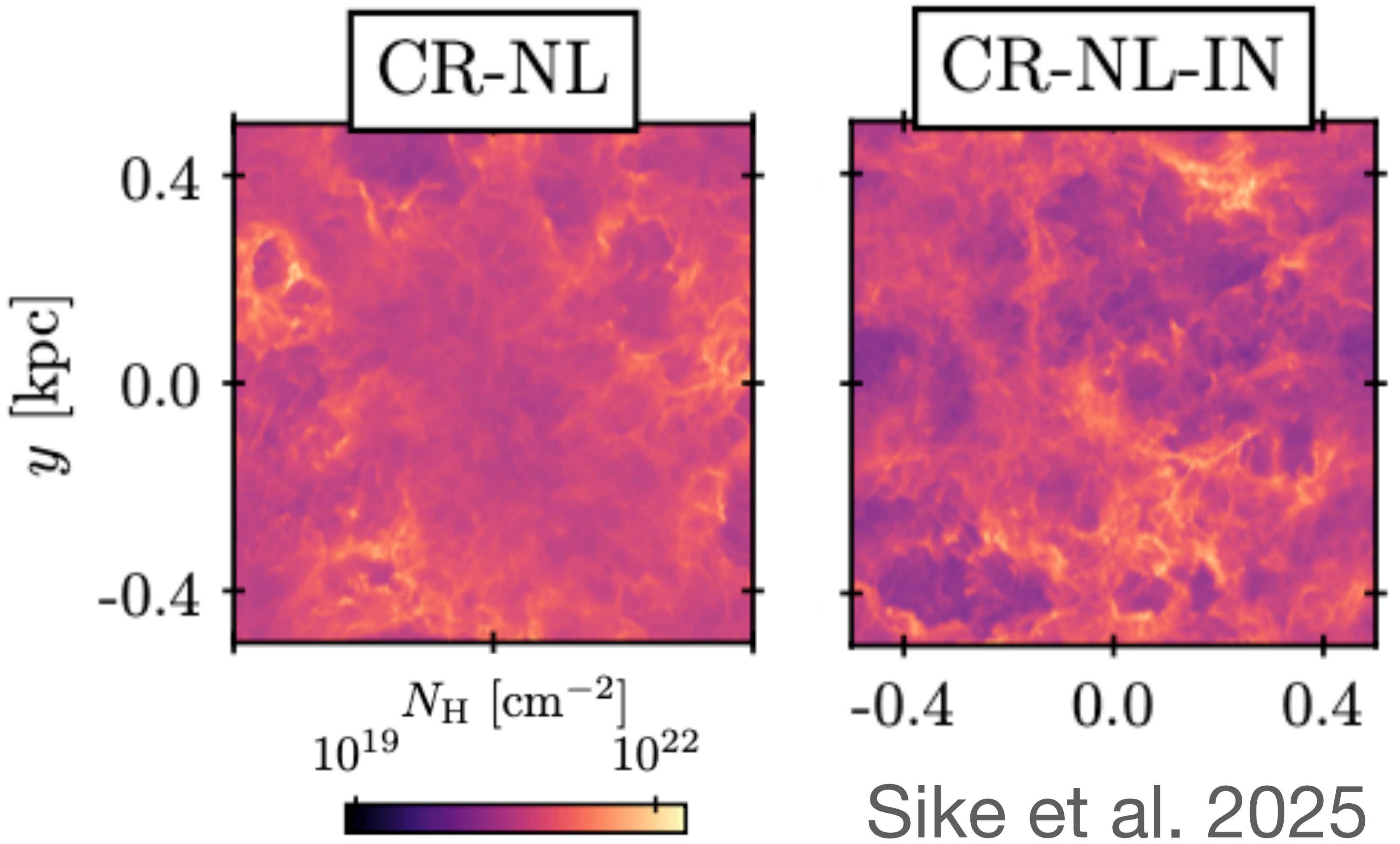
See also talks by Mateusz Ruszkowski and Timon Thomas

Kim, Armillotta, et al., in prep.

Open questions

1) IMPROVING MICROPHYSICS SUBGRID RECIPES

- What about other wave damping mechanisms (turbulent, linear Landau, dust)? And extrinsic turbulence? → Controlled experiments with different mechanisms

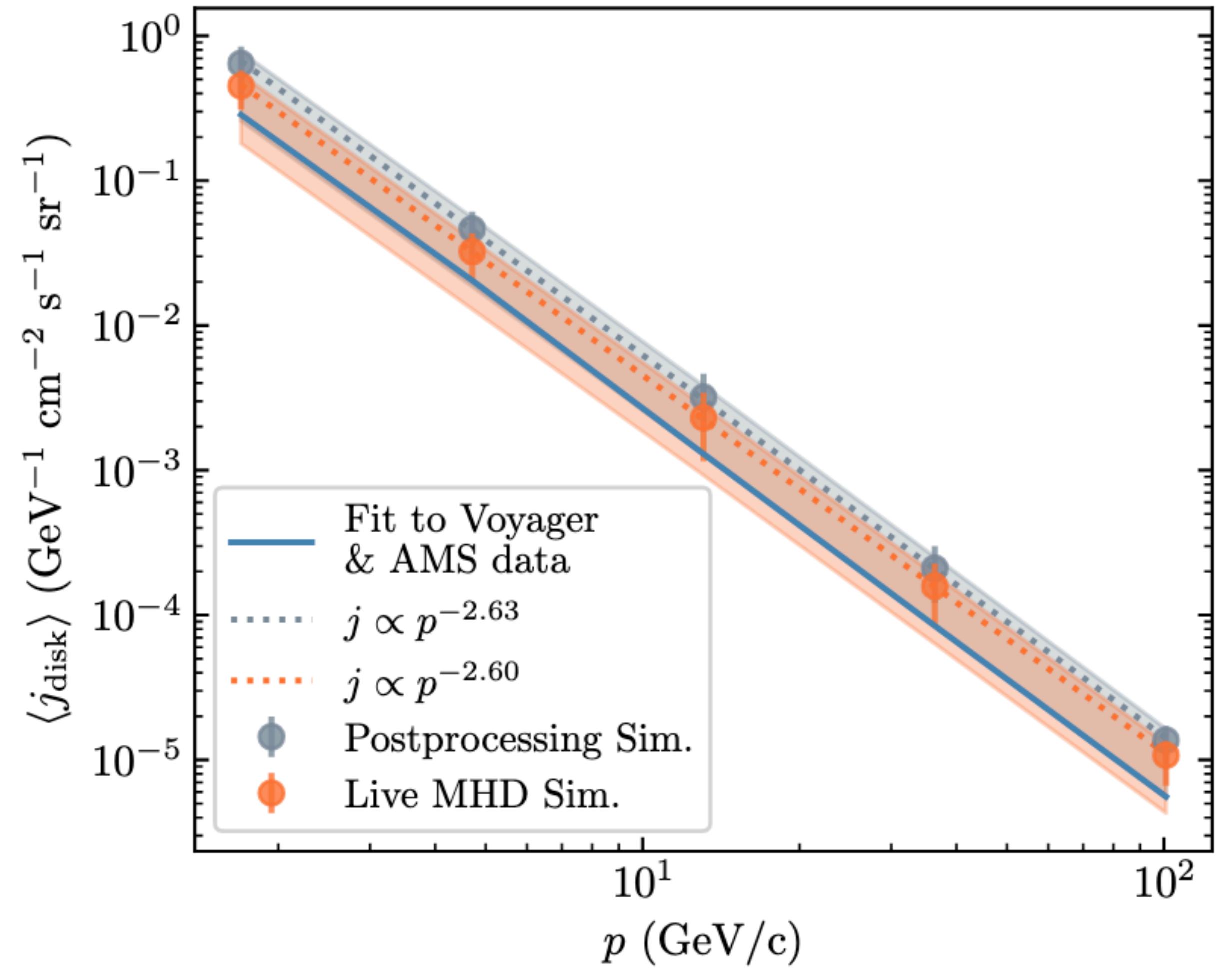


Sike et al. 2025

2) COMPARISONS WITH DATA TO VALIDATE MODELS

- Simulations with spectrally-resolved CRs → does the standard self-confinement theory reproduce the observed spectra?

  - FIRE zoom-in simulations: NO
    (Hopkins et al. 2022; see also Kempski & Quataert 2023)
  - TIGRESS local-box simulations: YES
    (Armilotta et al. 2025, Linzer et al. 2025)



- Need for synthetic maps of non-thermal emission

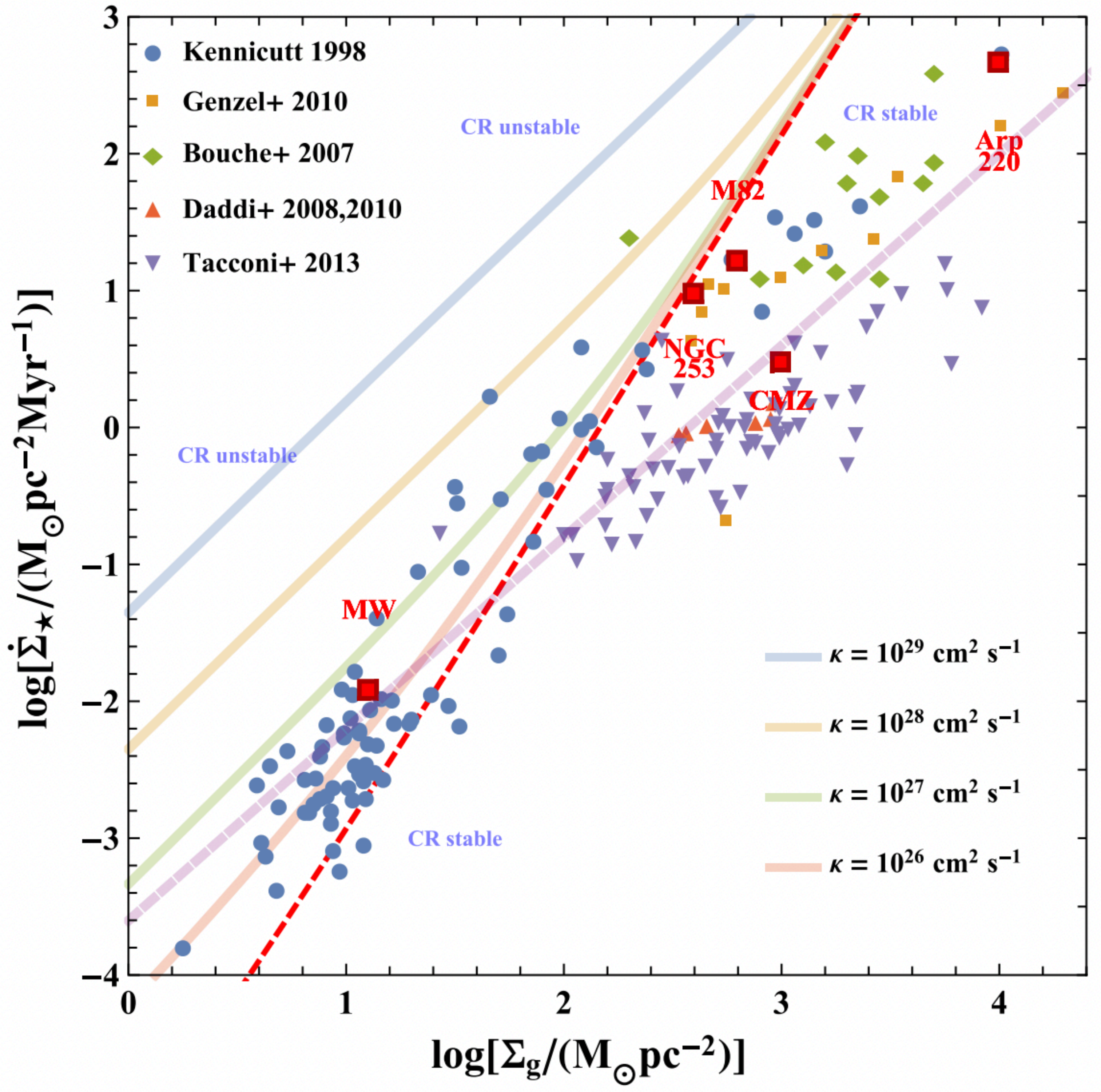
See talks by Karen Yiang, Maria Werhahn, and Philipp Girichidis

Open questions

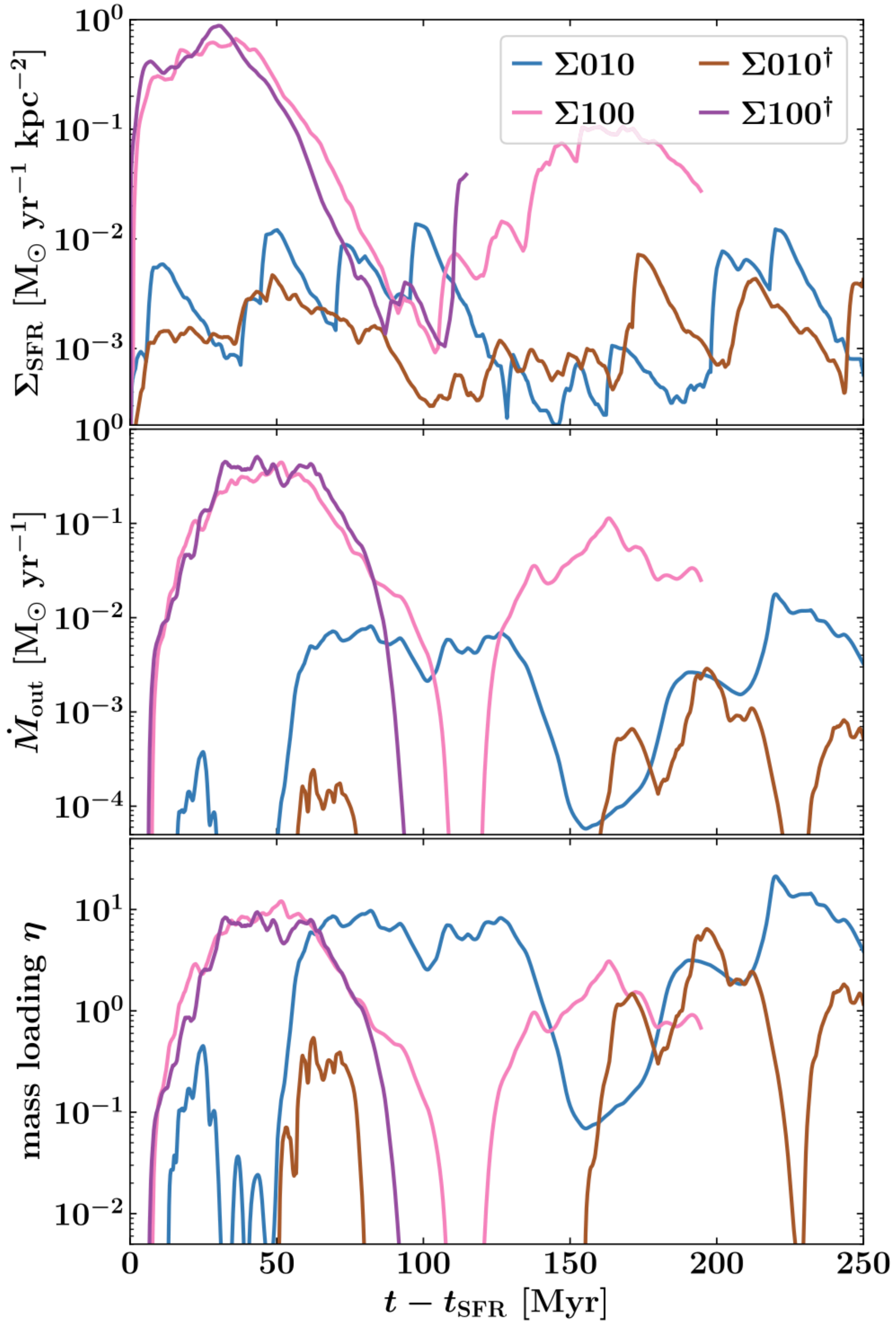
3) <u>EXPLORING CR TRANSPORT AND IMPACT ACROSS A RANGE OF GALACTIC ENVIRONMENTS</u>

- **Higher density, more star-forming environments** are characterised by **faster outflows** → lower CR pressure ($P_{c,mid} \propto v_{eff}^{-1}$) and lower CR vertical forces?
- CRs experience **stronger collisional losses** in denser environments? → lower $P_{c,mid} \propto \Lambda^{-1}$?
- What about the scattering rate?
- Importance of global models

Crocker et al. 2021



SILCC simulations (Rathjen et al. 2023)



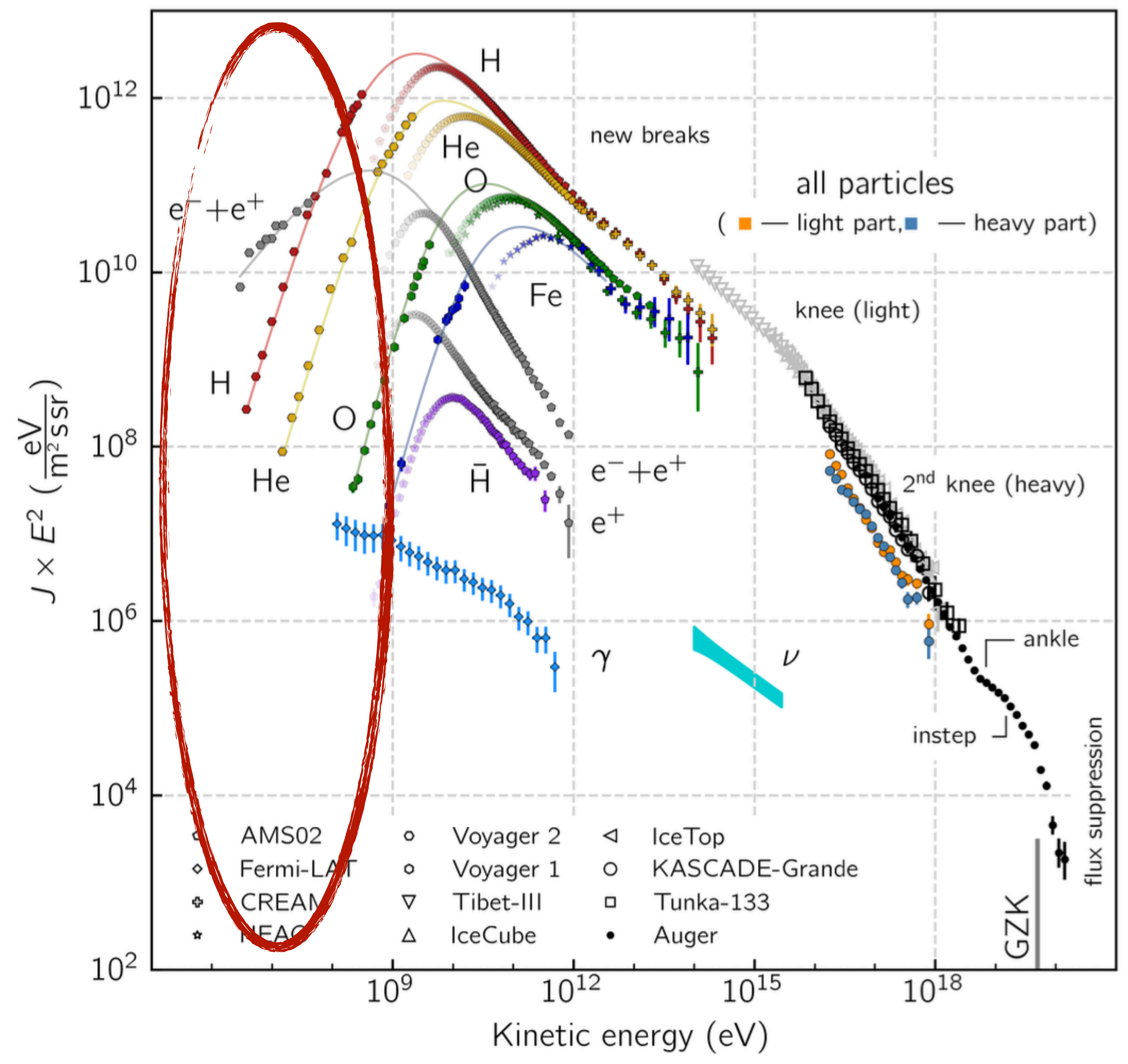
3) LOW-ENERGY MEV CRS

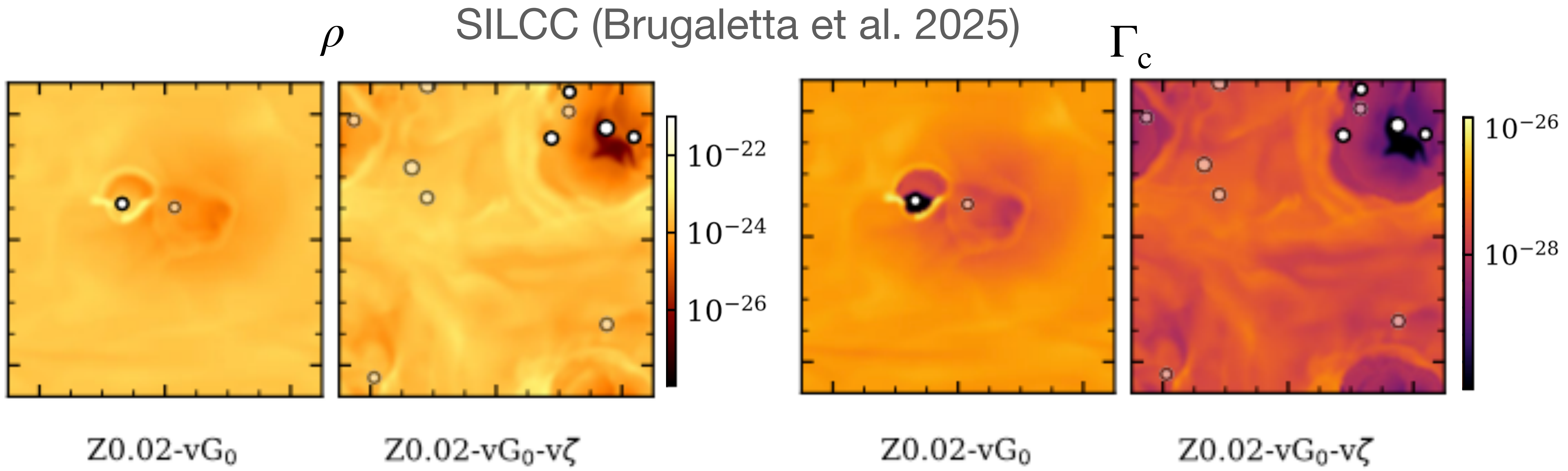
- **Crucial source of ionisation and heating of the ISM**
  → How do CRs shape the thermal state of the ISM and local star formation?

- In low-metallicity environments, photoelectric heating falls below CR heating → recent local box simulations show importance of P_c-dependent and N_H-dependent heating rates for proper star formation modelling

- Importance of simulations with spectrally-resolved CRs

See Philipp Girichidis's talk





Final summary

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

- Realistic models of CR transport predicts that in Milky Way-like environments:

  - CRs marginally contribute to disk support against gravity and star formation regulation

  - CRs generate warm-cold steady outflows

- **Open questions & future directions**:

  - Improving microphysics subgrid recipes

  - Comparisons with observational data to validate models

  - Systematic investigation of CR transport and impact across varying galactic environments

  - Modelling low-energy CRs in MHD simulations of the ISM