Cosmic ray transport in the ISM

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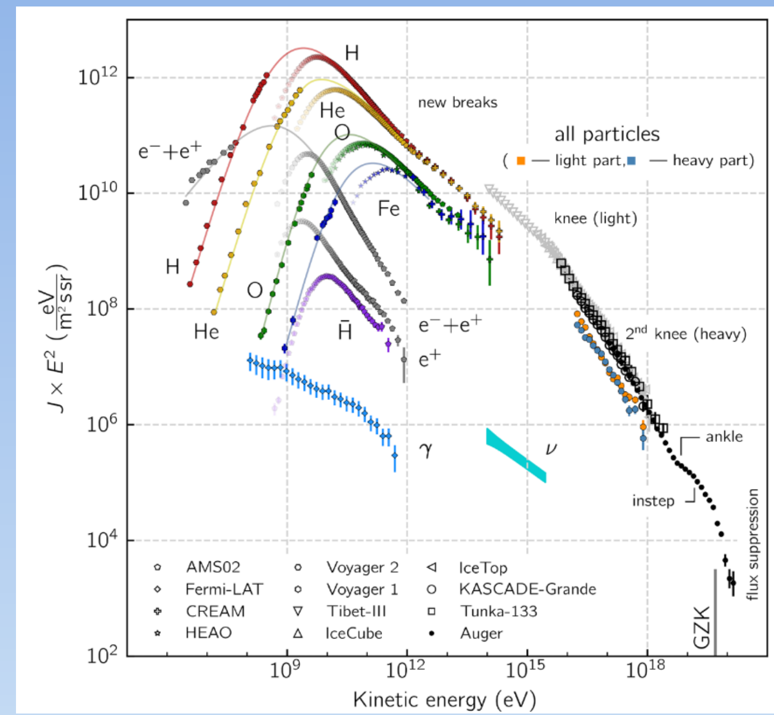
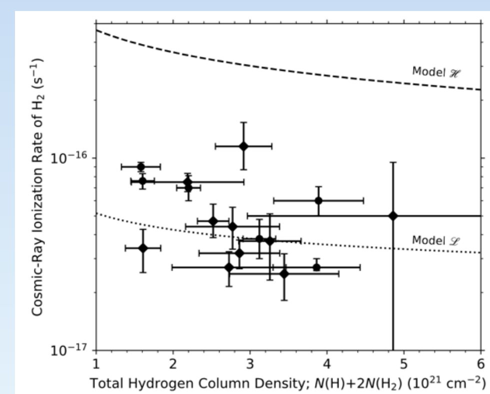
What are cosmic rays?

- Relativistic particles with a wide range of energies, species
- Believed to be accelerated in supernova shocks (~ 10% of E_{SN})
- Above 1 GeV, $d\Phi(E)/dE \propto E^{-2.7}$
  i.e. DF $f(p) \propto p^{-\gamma}$ with $\gamma = 4.7$
- Direct measurement below 1 GeV is modulated by Solar wind
  - Low-energy CR spectrum inferred from gamma-ray spectrum, chemical modeling ⇒ dominated by E~ GeV (Neronov et al 2017, Indriolo et al 2026)
  - Consistent with Voyager obs. (Padovani 2024)
- P_{CR} comparable to P_{th} , P_{turb}, P_{mag}
  ``equipartition''



Ruszkowski & Pfrommer (2023)



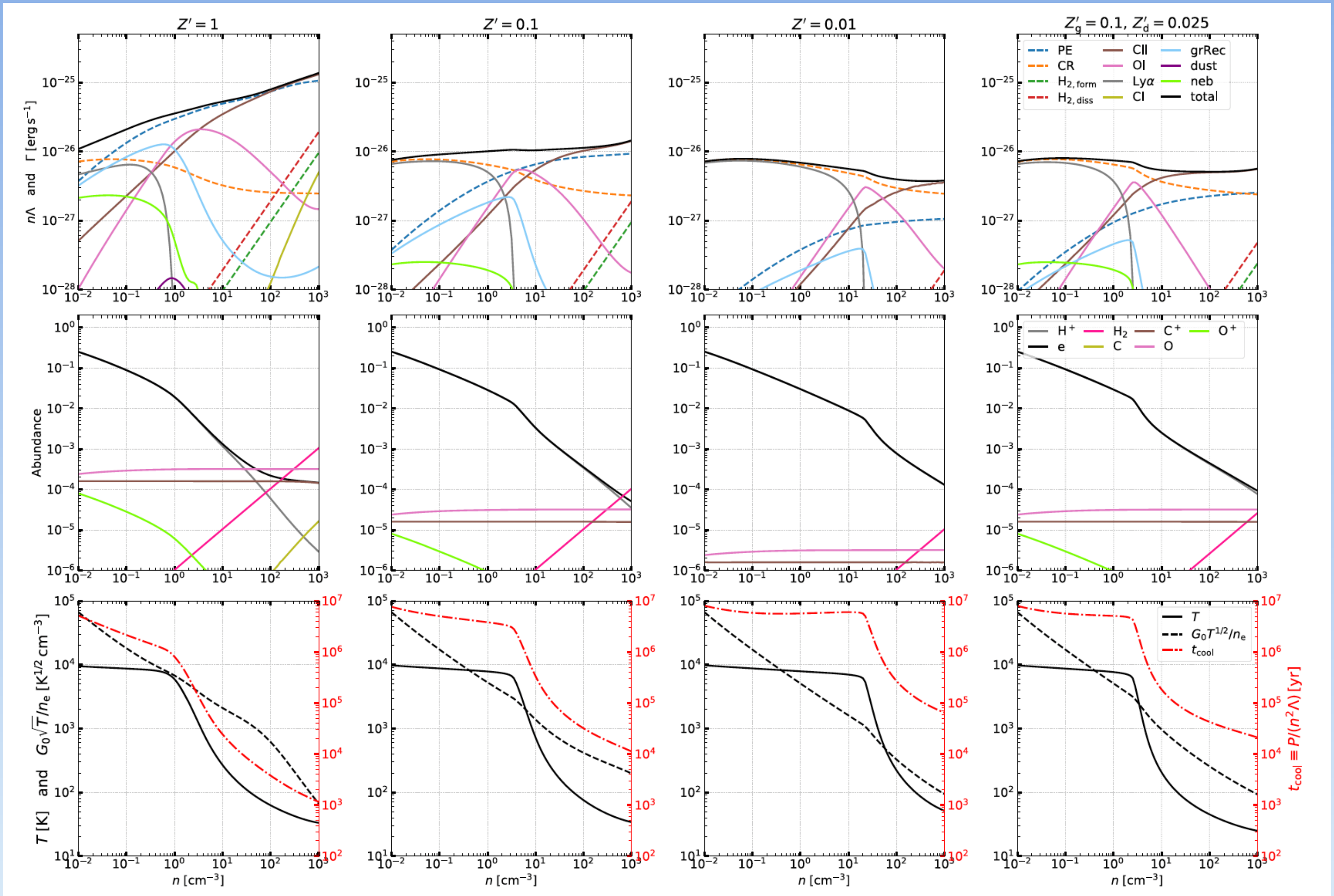
Indriolo et al (2026)

Why are CRs interesting?

- Theoretically rich subject, great physics
- Definitely important for ISM heating, ionization, chemistry in atomic & molecular gas shielded to EUV (majority of ISM)
- May be important for driving warm winds out of galaxies, supporting CGM
- A wide variety of CR-related observables want interpretation
- New technical challenge in computational ISM and CGM modeling, following implementation of radiation

CR heating

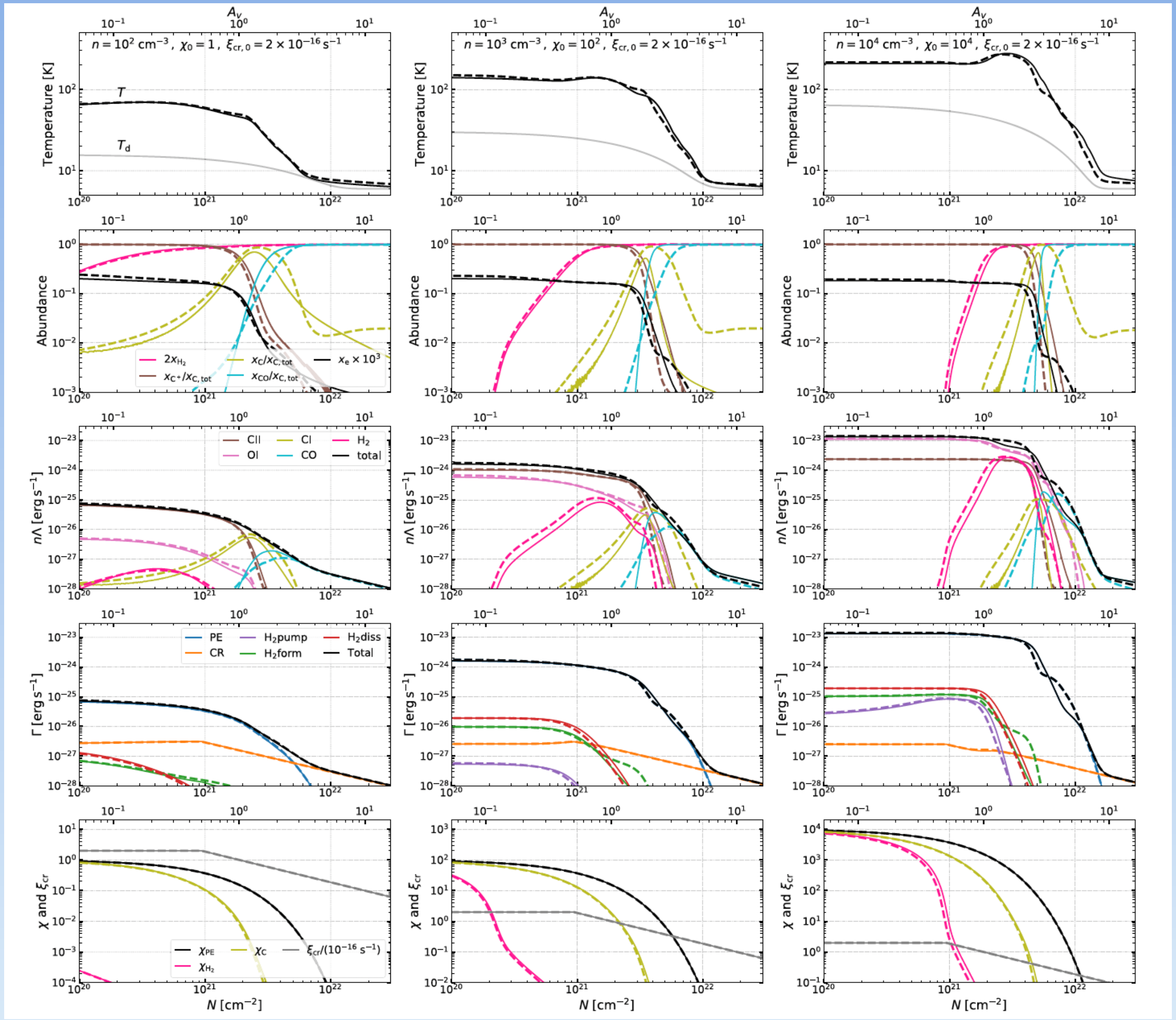
J.-G. Kim et al(2023)



Dominant heating in diffuse gas at low Z_d where PE heating from stellar FUV is reduced; dominant ionization in diffuse gas

CR heating

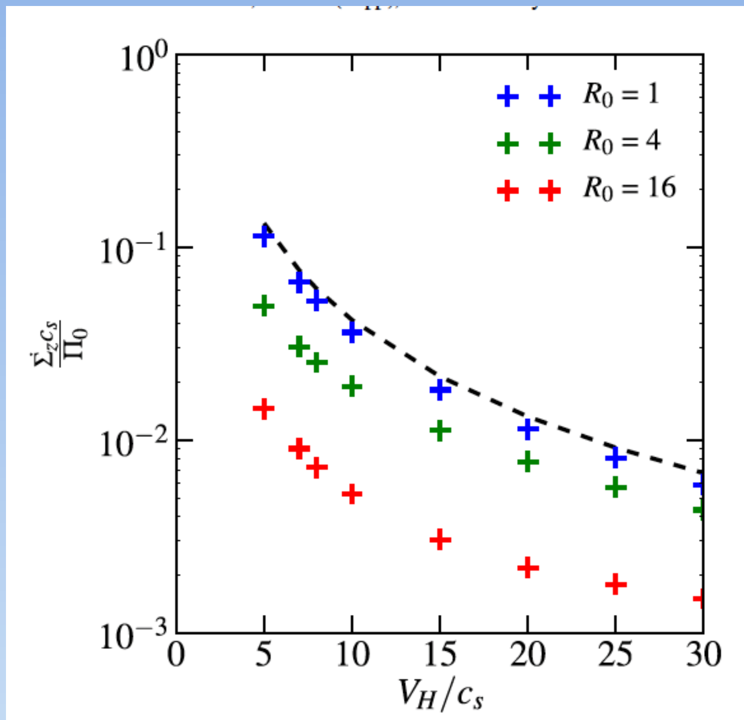
J.-G. Kim et al(2023)

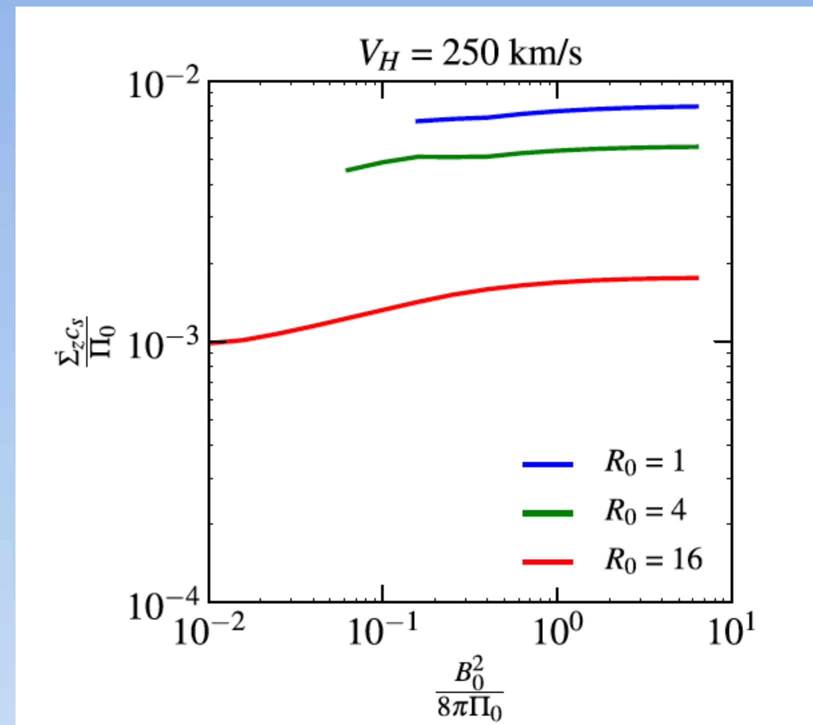


Dominant heating in dense, high-column gas where stellar FUV is attenuated; dominant ionization in dense gas

CR driven winds

Mao & Ostriker (2018)





$$\dot{\Sigma}_{\rm wind} \sim \frac{2}{3} P_{\rm cr} V_{\rm halo}^{-5/3} u_{\rm fountain}^{2/3}$$

$$\sim 3\times 10^{-3} M_\odot {\rm kpc}^{-2}\ {\rm yr}^{-1} \left(\frac{P_{\rm cr}}{1{\rm eV\ cm}^{-3}}\right)\left(\frac{V_{\rm halo}}{200\,{\rm kms}^{-1}}\right)^{-5/3}\left(\frac{u_{\rm fountain}}{50\,{\rm kms}^{-1}}\right)^{2/3}$$

- Order-unity mass-loading for MW-like galaxies; even higher for dwarfs!

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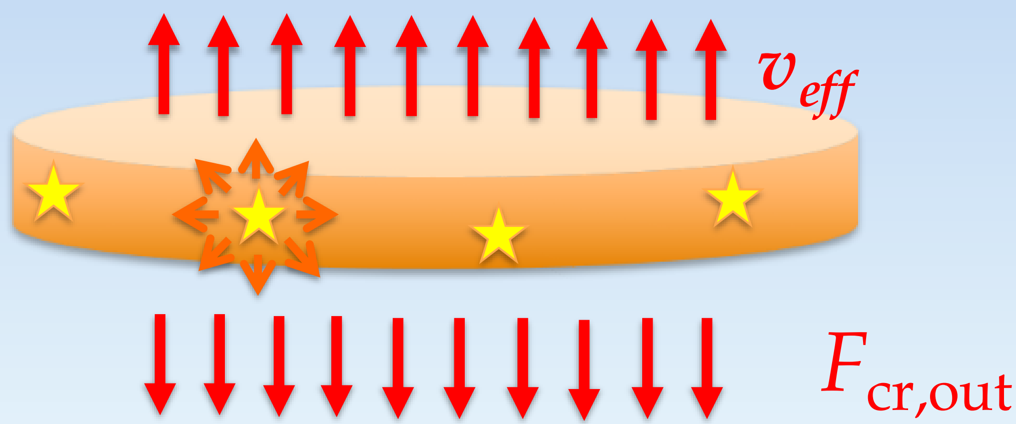
$$F_{\rm cr,inj} = 0.1 E_{SN} \Sigma_{\rm SFR}/m_* \quad \& \quad 2F_{\rm cr,out} = 2 \times v_{eff} (4/3)\mathcal{E}_{CR}$$

$$with\ E_{SN} = 10^{51}{\rm erg},\ m_* = 100 M_\odot;\ \Sigma_{\rm SFR} = 0.003 M_\odot\ {\rm kpc}^{-2}\ {\rm yr}^{-1},\ \mathcal{E}_{CR} = 1eV\ {\rm cm}^{-3}$$

$$F_{cr,inj} = 2\ F_{cr,out}$$



Advective transport

- Empirically, from equating CR injection energy/area/time from SNe with CR flux carried out of galaxy, dominated by GeV CRs, v_{eff}~25 km/s, comparable to dynamical velocities in ISM
- This value is also consistent with empirical estimates of v_{eff} and CR lifetime in disk τ at ~ 1GeV, based on CR abundances
  - total column of gas traversed (grammage), residence time of CRs can be inferred from empirical ratios of secondary/primary species and short-lived/long-lived isotopes

CR grammage

- From ratio of CR secondaries n_B produced in spallation reactions to CR primaries n_C, infer **grammage** $X \propto n_B / n_C$ of ISM traversed:

$$X(p) = \left\langle \int_{life} \rho v_p dt \right\rangle = \left\langle \rho v_p \frac{E}{\dot{E}} \right\rangle_{life} \rightarrow v_p \frac{\int dz \rho \mathcal{E}_{cr}(p)}{F_{cr,inj}(p)}$$

- With
$$\begin{aligned} F_{cr,inj}(p) &= 2F_{cr,out}(p) \\ &= (8/3) v_{eff}(p) \mathcal{E}_{cr}(p) \\ &= 8 v_{eff}(p) P_{cr}(p) \end{aligned}$$

  have $X(p) = (3/8)(v_p / v_{eff}(p)) \Sigma_{gas}$
- Resulting in $v_{eff}(p) = (3/8) c \Sigma_{gas} / X(p)$
- At 1 GeV, measured X~10 g/cm^2; using $\boldsymbol{\Sigma}_{gas}$~ 12 $M_\odot$/pc^2

  ⇒ v_{eff}(1 GeV/c) ~ 28 km/s

$$F_{CR,inj} = 0.1 E_{SN} \Sigma_{\rm SFR}/m_* \quad \& \quad 2F_{CR,out} = 2 \times v_{eff} (4/3)\mathcal{E}_{CR}$$

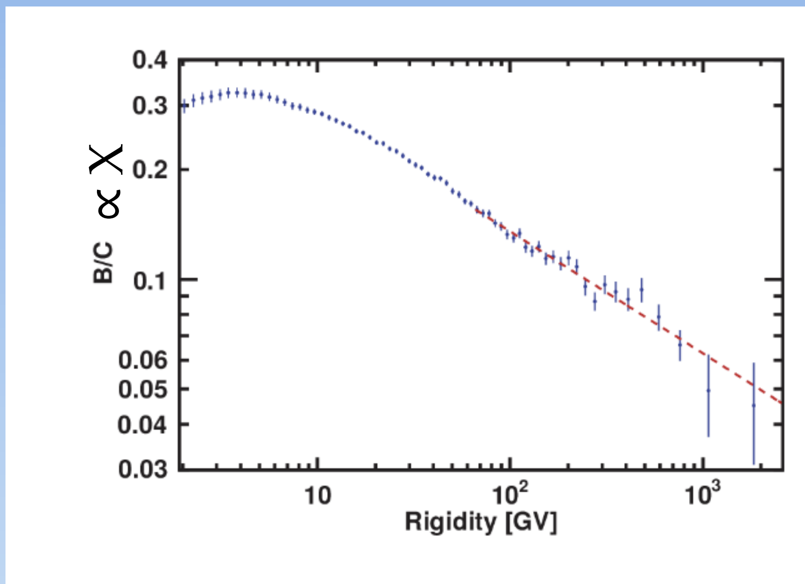
$$with\ E_{SN} = 10^{51}{\rm erg},\ m_* = 100 M_\odot;\ \Sigma_{\rm SFR} = 0.003 M_\odot\ {\rm kpc}^{-2}\ {\rm yr}^{-1},\ \mathcal{E}_{CR} = 1eV\ {\rm cm}^{-3}$$

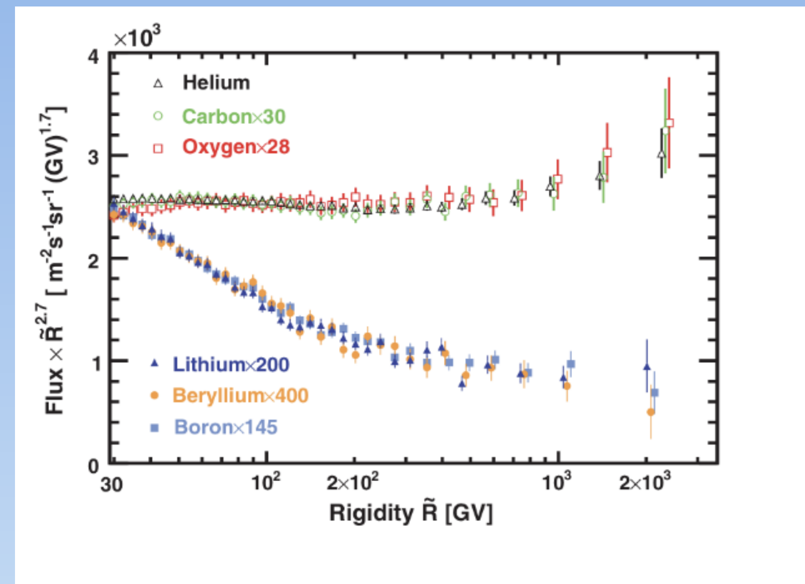
$$\tau = H_{\rm gas}/v_{\rm eff} \sim 250{\rm pc}/(25{\rm pc/Myr}) \sim 10{\rm Myr}$$

Advective-only transport?

- Empirically, from equating CR injection energy/area/time from SNe with CR flux carried out of galaxy, dominated by GeV CRs, v_{eff}~25 km/s, comparable to dynamical velocities in ISM
- This value is also consistent with empirical estimates of v_{eff} and CR lifetime in disk τ at ~ 1GeV
  - total column of gas traversed (grammage), residence time of CRs can be inferred from empirical ratios of secondary/primary species and short-lived/long-lived isotopes
- However, transport *cannot* be purely advective, based on empirical *energy dependence* of grammage and residence time:
  - Ratios are energy-dependent, implying $v_{eff} = F_{cr,inj}/4P_{cr}$ is energy-dependent

Energy-dependent transport from CR grammage





Ruszkowski and Pfrommer (2023),
From Aguilar et al (2016,2018)

- Energy dependence of grammage ⇒ energy-dependent CR transport $v_{\rm eff}(p) = (3/8)c\Sigma_{\rm gas}/X(p)$
- From empirical measurement of X(p), $v_{\rm eff} \propto 1/X(p) \propto p^{\delta}$ for δ~0.3-0.5

Diffusive-only transport?

- For pure diffusion,

$$F_{\rm cr}(p) = -\kappa(p)\nabla P_{\rm cr}(p) \to \kappa(p)P_{\rm cr}(p)/H_{\rm cr}(p)$$

$$\Rightarrow v_{\rm eff}(p) = \kappa(p)/[4H_{\rm cr}(p)]$$

- ***If*** H_{cr} is constant, independent of p,

  $\kappa(p) \propto v_{eff}(p) \propto 1/X(p) \propto p^{\delta}$ for $\delta \sim 0.3\text{-}0.5$

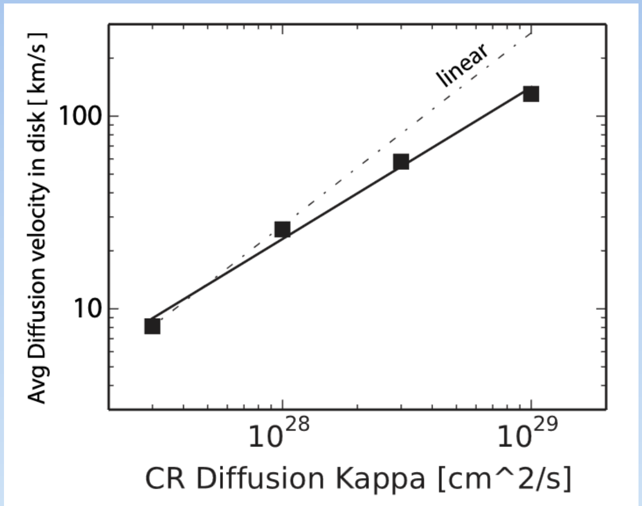
- In the **self-confinement paradigm**, wave amplitudes and scattering rate are set by balancing growth of streaming instability with damping
- Assuming nonlinear Landau damping in ionized gas, $\kappa(p) \propto [n_{cr}(p)]^{-1/2} \propto p^{0.85}$

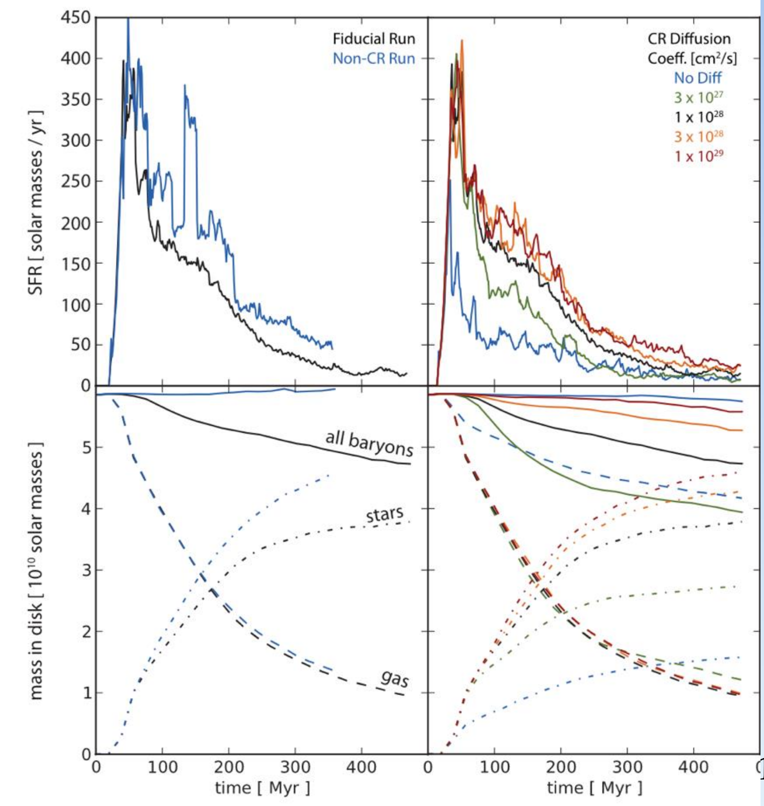
much too steep compared to empirical constraint

A conundrum since the 1970s!

Consequences of transport for ISM

- Understanding CR transport is interesting in itself, but also necessary to understand dynamical effects of CRs:
  - EG, for diffusion-only models, lower κ reduces the diffusion velocity $v_{\rm diff} \sim \kappa/H$ and increases the midplane CR pressure $P_{\rm cr} \sim F_{\rm cr,inj}\, H/\kappa$





- Strong CR-gas coupling (low, constant κ) suppresses star formation while increasing galactic outflows

Salem & Bryan (2013)

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Star-forming ISM with TIGRESS*/TIGRESS-NCR/TIGRESS++

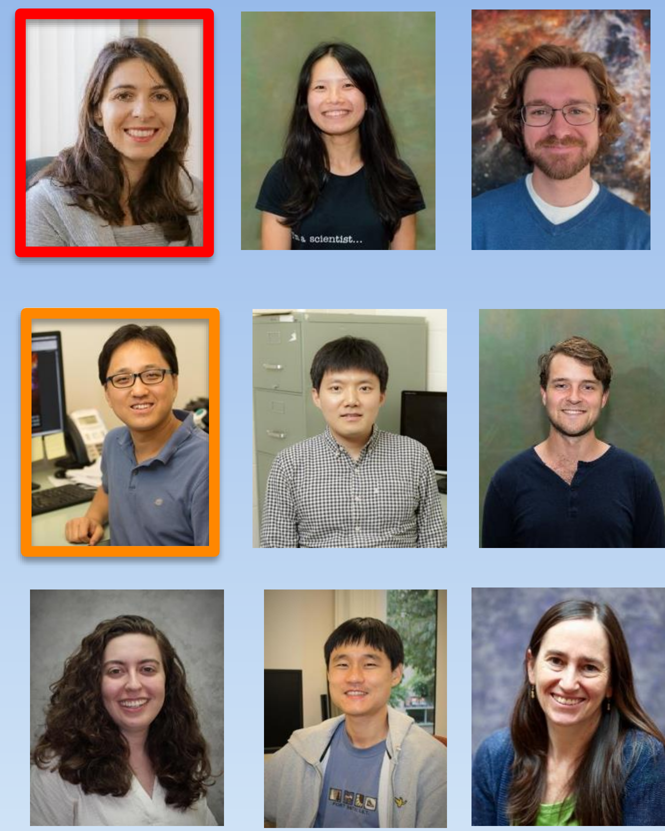
Key physics elements for studying the multiphase, star-forming ISM, from GMC scales to kpc-patch scales:

- magnetohydrodynamics
- gravity
- star formation/sink particles
- stellar feedback
  - supernovae
  - radiation *(adaptive ray tracing)*
  - stellar winds
  - cosmic rays
- photochemistry *(non-equilibrium)*
- multiphase gas cooling and heating

Implementated in Athena/Athena++

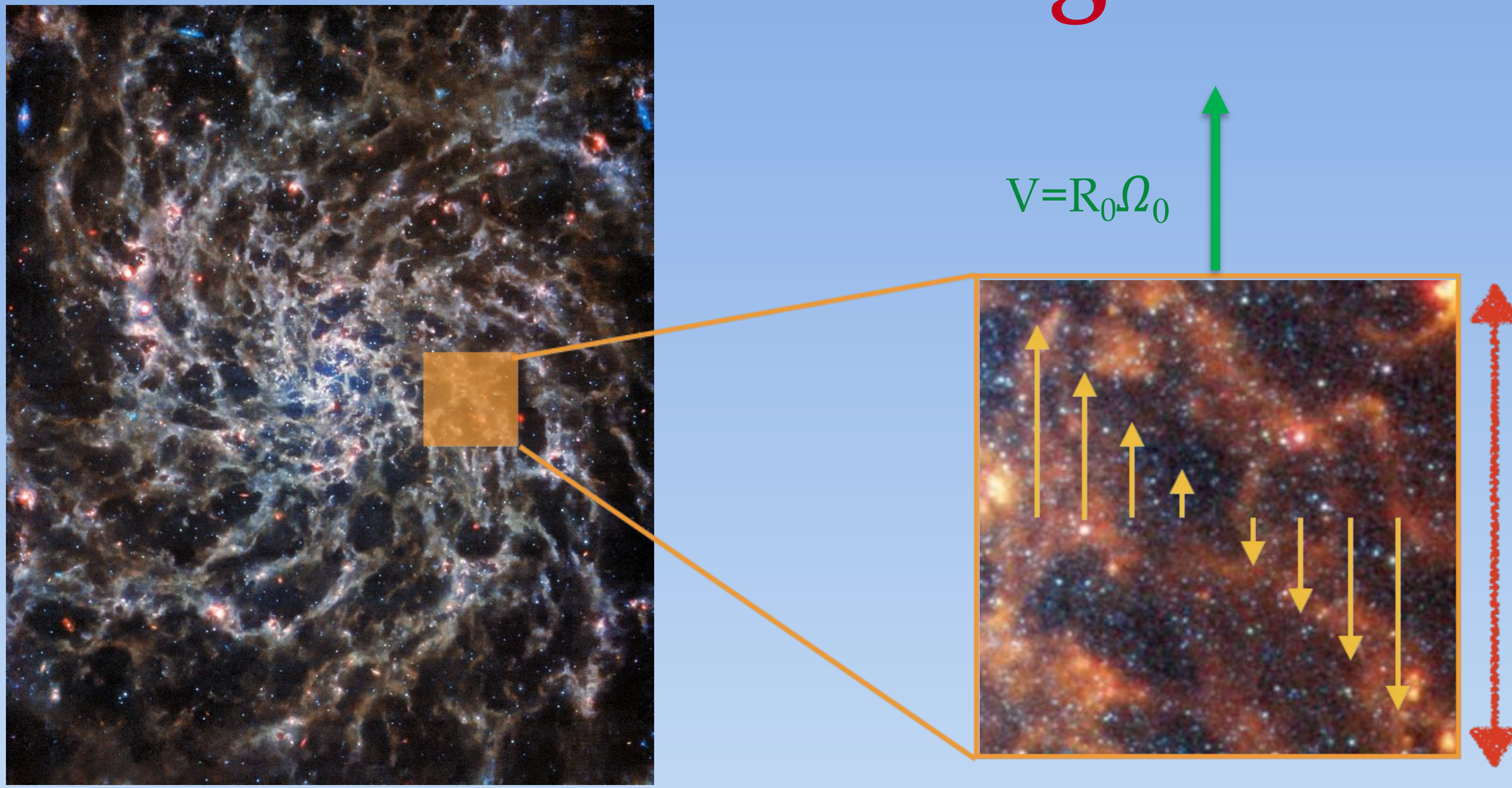
* *T*hree-phase *I*SM in *G*alaxies *R*esolving *E*volution with *S*tar formation and *S*tellar feedback

Team TIGRESS:



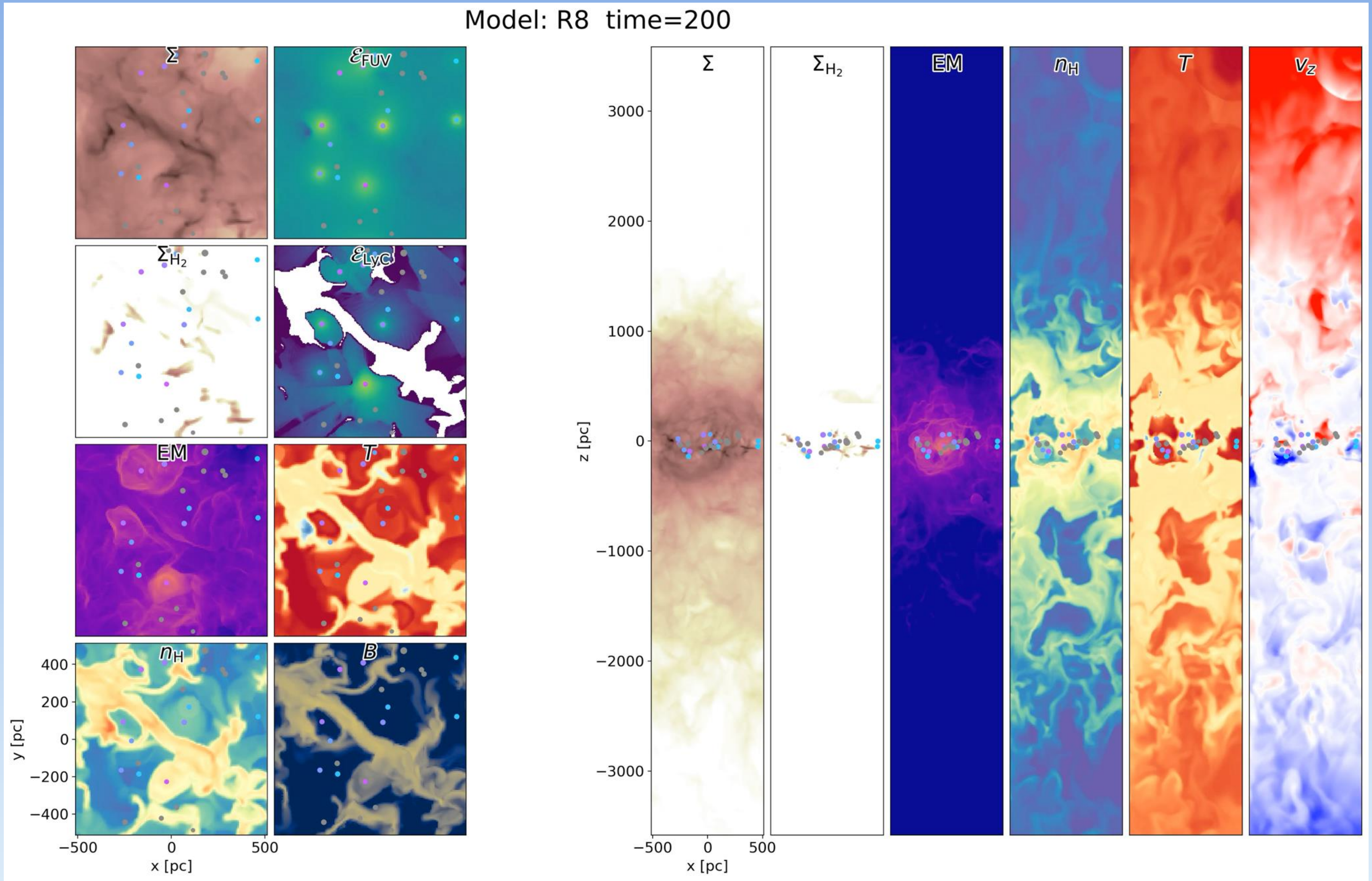
L. Armillotta, M. Gong, R. Hix, C.-G. Kim, J.-G. Kim, L. Lancaster, N. Linzer, S. Moon, E. Ostriker

Shearing box SF-ISM



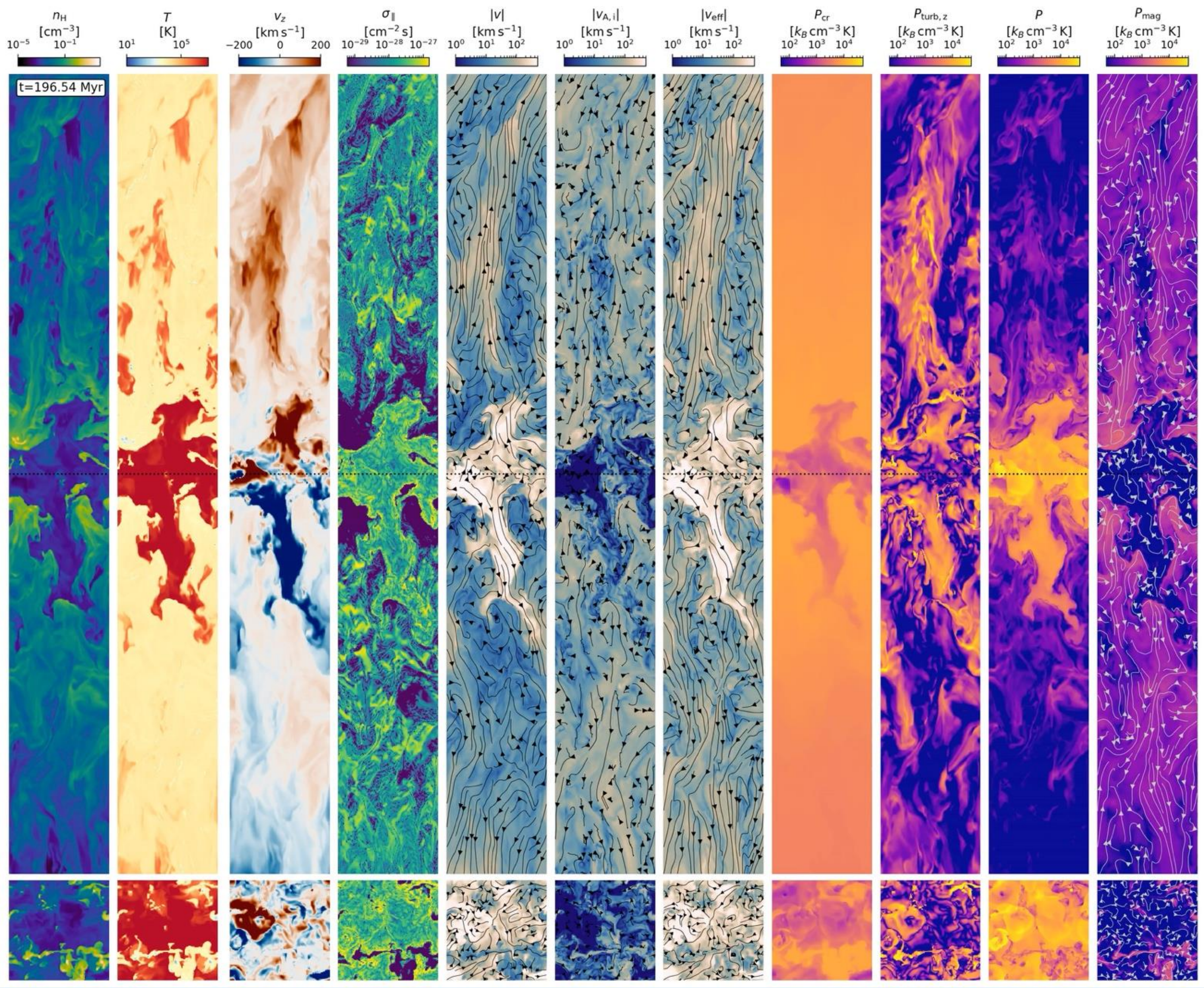
$\delta v_y = (1 - x/R_0)\ R_0\Omega$

Star-forming ISM with TIGRESS*/TIGRESS-NCR/TIGRESS++



* *T*hree-phase *I*SM in *G*alaxies *R*esolving *E*volution with *S*tar formation and *S*tellar feedback

CR-MHD simulations with TIGRESS++



C.-G. Kim, L. Armillotta, E. Ostriker et al (2026)

CR implementation for multiphase ISM simulations

Armillotta, Ostriker, & Jiang (2021)

- Two-moment CR evolution equations with reduced speed of light, integrated via HLLE Riemann solver in *Athena*++ (Jiang & Oh 2018)

$$\frac{\partial \mathcal{E}_{\rm cr}}{\partial t} + \nabla \cdot \mathbf{F}_{\rm cr} = -(\mathbf{v}+\mathbf{v}_{\rm st}) \cdot \sigma_{\rm tot} \cdot [\mathbf{F}_{\rm cr} - \mathbf{v}(\mathcal{E}_{\rm cr} + P_{\rm cr})] - \Lambda_{\rm coll} n_H \mathcal{E}_{\rm cr} + Q_{\rm SN}$$

$$\rightarrow (\mathbf{v}+\mathbf{v}_{\rm st}) \cdot \nabla P_{\rm cr} + Q_{\rm SN}$$

$$\frac{1}{\hat{c}^2}\frac{\partial \mathbf{F}_{\rm cr}}{\partial t} + \nabla \mathbf{P}_{\rm cr} = -\sigma_{\rm tot} \cdot [\mathbf{F}_{\rm cr} - \mathbf{v}(\mathcal{E}_{\rm cr} + P_{\rm cr})] - \Lambda_{\rm coll} n_H \mathrm{F}_{\rm cr}/v_p^2$$

$$\rightarrow -\sigma \cdot [\mathbf{F}_{\rm cr} - (\mathbf{v}+\mathbf{v}_{\rm st})(\mathcal{E}_{\rm cr} + P_{\rm cr})] - \Lambda_{\rm coll} n_H \mathrm{F}_{\rm cr}/v_p^2$$

- Scattering coefficient tensor $\boldsymbol{\sigma}_{\rm tot} = \boldsymbol{\kappa}^{-1}$ includes term to limit bulk velocity to $v_{\rm A,ion}$ at high scattering rate: $\sigma_{\rm tot,\parallel}^{-1} = \sigma_{\parallel}^{-1} + \frac{v_{A,ion}}{|\hat{B} \cdot \nabla P_{\rm cr}|} 4 P_{\rm cr}$
- Equivalent to $v \rightarrow v + v_{\rm st}$ in [...], and $\boldsymbol{\sigma}_{\rm tot} \rightarrow \boldsymbol{\sigma}$, where $v_{\rm st} = \pm v_{A,ion}$ and sign is chosen such that CRs stream down the gradient in $P_{\rm cr}$
- Scattering rate $\nu_\parallel = c^2 \sigma_\parallel$ is set by balancing streaming instability growth rate with physical damping rate from local ISM conditions: ***self-confinement paradigm*** *(Kulsrud & Pearce 1969; Wentzel 1969)*

CR scattering under self-confinement

- Streaming instability growth rate for wave @ $k=\Omega_0 m/p_1$

$$\Gamma_{\rm stream}(p_1) = \frac{\pi}{4}\frac{\Omega_0 m_p}{\rho}\left(\frac{v_{\rm D}}{v_{\rm A}} - 1\right)n_1,$$

$$n_1 \equiv 4\pi p_1 \int_{p_1}^{\infty} f(p)p\,dp \propto p_1^{3-\gamma}$$

- Quasi-steady local drift velocity in Alfven wave frame:

$$v_D - v_A = F_{\rm cr,\parallel}/(4P_{\rm cr}) - v_\parallel - v_A = |\hat{B}\cdot\nabla P_{\rm cr}|/(P_{\rm cr}\sigma_\parallel)$$

- Damping rates (ion-neutral and non-linear Landau):

$$\Gamma_{\rm damp,in} = \frac{1}{2}\frac{n_{\rm n} m_{\rm n}}{m_{\rm n}+m_i}\langle\sigma v\rangle_{\rm in},$$

$$\Gamma_{\rm damp,nll} = 0.3\frac{v_{t,i}}{c}\Omega\left(\frac{\delta B}{B}\right)^2 \to 0.4 v_{t,i} c\sigma_\parallel$$

- Resulting scattering rate coefficient $\sigma=(\pi/8)\Omega(\delta B/B)^2/c^2$:

$$\sigma_{\parallel,\rm in} = \frac{\pi}{8}\frac{|\hat{\mathbf{B}}\cdot\nabla P_c|}{v_{\rm A,i}P_c}\frac{\Omega_0}{\langle\sigma v\rangle_{\rm in}}\frac{m_p(m_n+m_i)}{n_n m_n m_i}\frac{n_1}{n_i}$$

$$\sigma_{\parallel,\rm nll} = \sqrt{\frac{\pi}{16}\frac{|\hat{\mathbf{B}}\cdot\nabla P_c|}{v_{\rm A,i}P_c}\frac{\Omega_0 c}{0.3 v_{\rm t,i} v_p^2}\frac{m_p}{m_i}\frac{n_1}{n_i}}$$

- Fits from simulations for GeV CRs (Hix et al 2025):

$$\sigma_{\parallel,\rm in} \sim 2.93\times 10^{-31}\frac{\rm s}{\rm cm^2}\frac{P_{\rm c,3}}{H_{\rm c,3}}(x_{i,-2}\, n_{\rm H,0}^3)^{-1/2}.$$

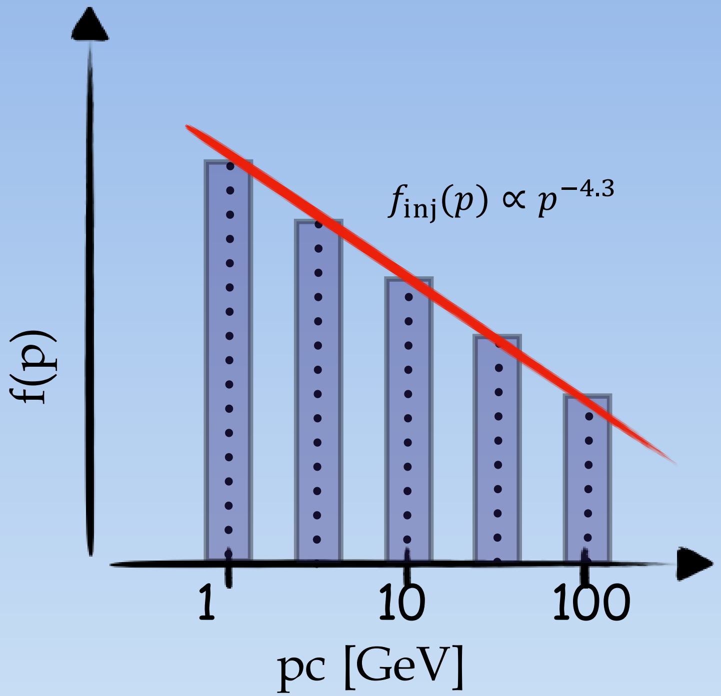
$$\sigma_{\parallel,\rm nll} \sim 1.96\times 10^{-28}\frac{\rm s}{\rm cm^2}\sqrt{\frac{P_{\rm c,3}}{H_{\rm c,3}}}(P_{\rm th,3}\, x_i)^{-1/4}$$

Dependence on CR momentum: $\propto p^{(3-\gamma)} \sim p^{-1.7}$ $\propto p^{(3-\gamma)/2} \sim p^{-0.85}$

CR spectral simulations

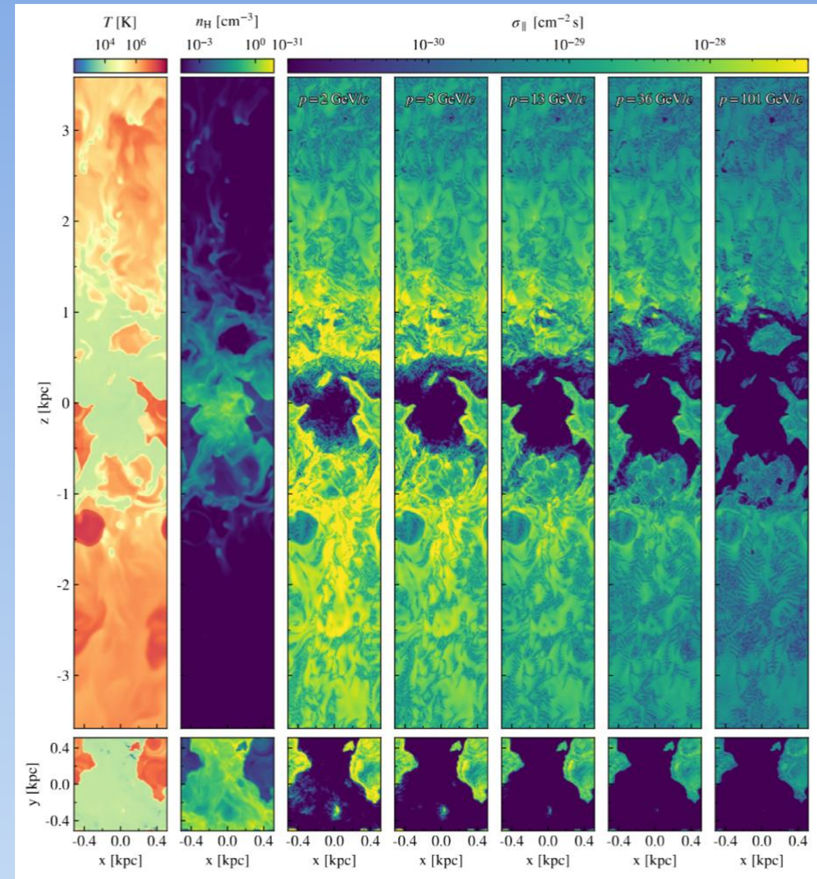
Linzer et al (2025); Armillotta, Ostriker, & Linzer (2025); Yu et al (2026)

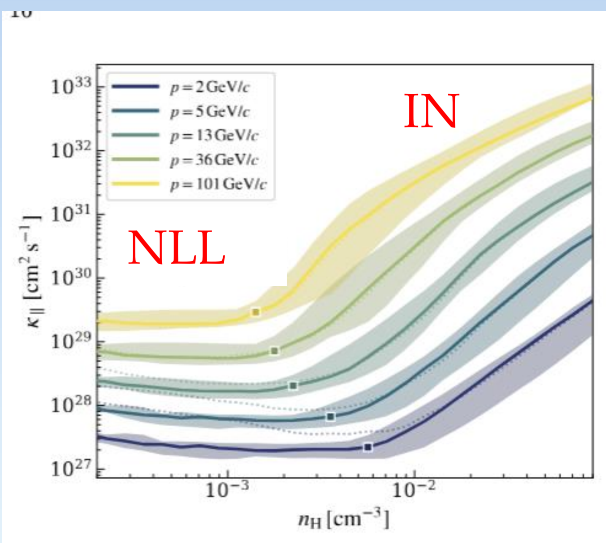
- Multi-group simulations of CR protons and electrons from ~1-100 GeV
- Injected spectrum $f(p) \propto p^{-\gamma_{\rm inj}}$ with $\gamma_{\rm inj}=4.3$
- Ionization at T$\lesssim 10^4$ K is due to MeV CRs (scaled from GeV). Ionization collisional at high T($\gtrsim 10^4$ K).
- "Post-processing" from TIGRESS snapshots: inject 10% of SN energy as CRs and follow their transport. Turn on MHD to relax but no long-term evolution.



CR scattering

- ISM is a two-zone system from point of view of CRs: diffusive midplane (high κ , low σ) sandwiched between stronger-scattering extraplanar layers
- $\kappa = 1/\sigma$ large where i-n collisions strongly damp waves
- $\kappa = 1/\sigma$ small when ion-neutral drops below non-linear Landau
- Transition at larger z for higher energy

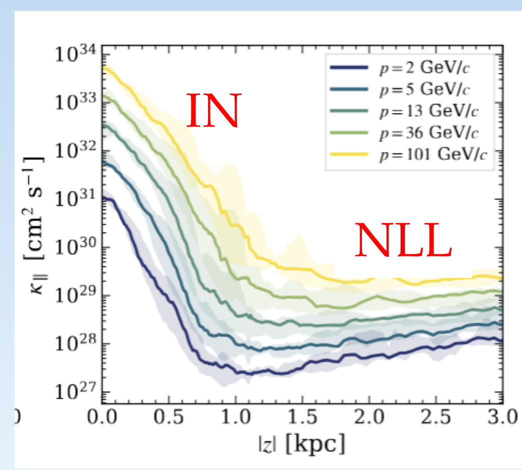




κ is a power law in $p=E/c$:

$\kappa_{NLL} \propto p^{(\gamma-3)/2}$

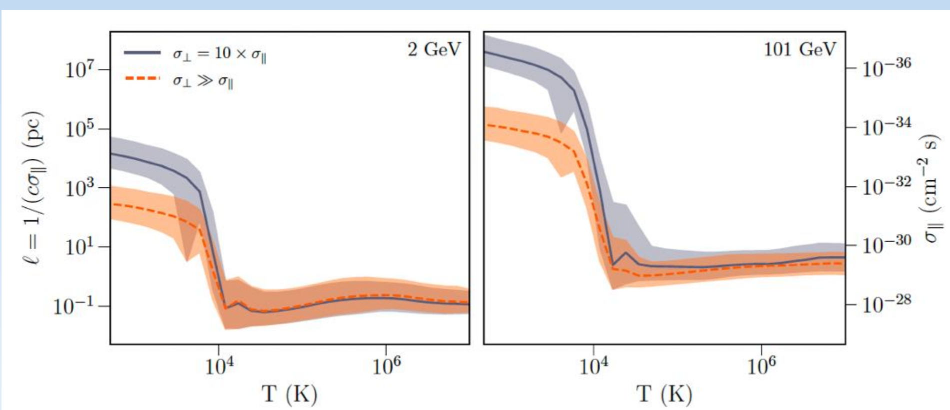
$\kappa_{IN} \propto p^{(\gamma-3)}$



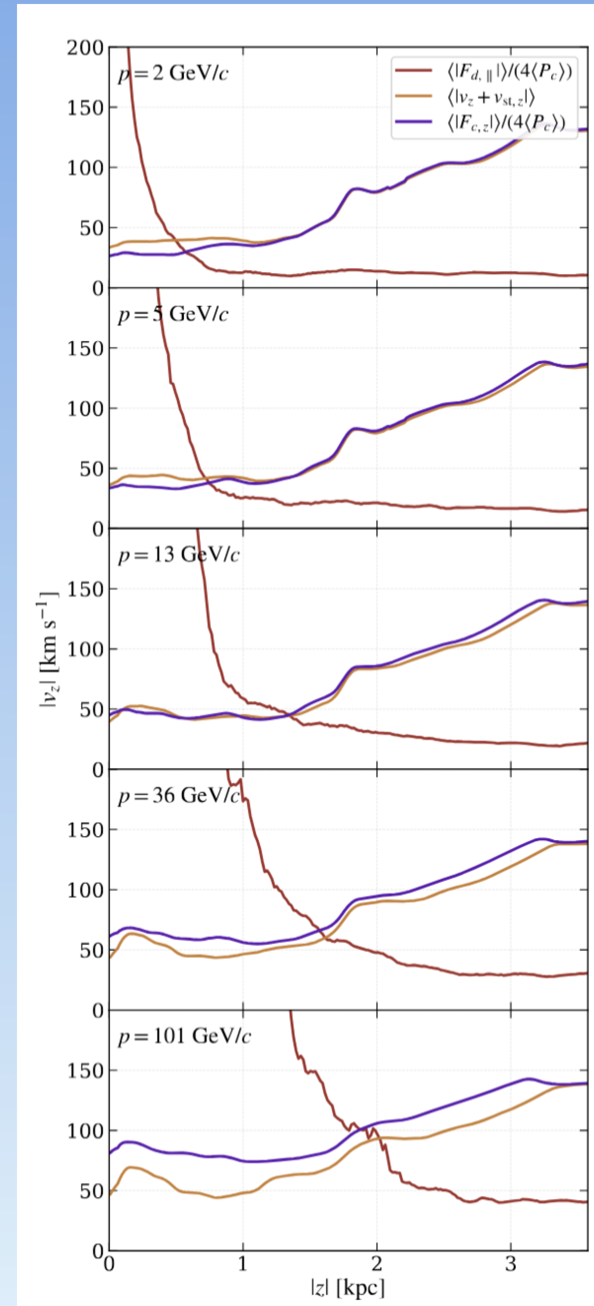
Yu, Armillotta, & Ostriker (2026)

CR scattering

- Mean free path $\ell = 1/(c\sigma_{\parallel})$ is very large in warm/cold dense gas where i-n damping is strong ⇒ *midplane transport dominated by diffusion*
- Mean free path $\ell = 1/(c\sigma_{\parallel})$ becomes short in low-density, higher-ionization gas ⇒ *extraplanar transport dominated by advection + streaming*
- Transition from $v_{diff} \gg v_{dyn}$ to $v_{diff} \ll v_{dyn}$ moves outward as CR energy increases



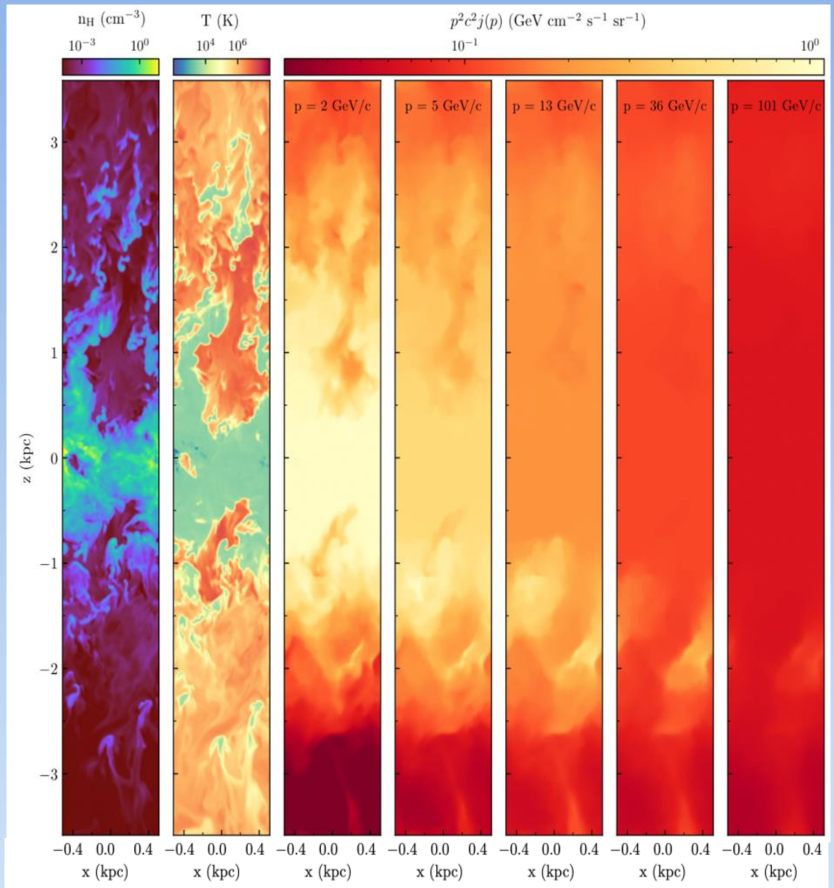
Linzer et al (2025)

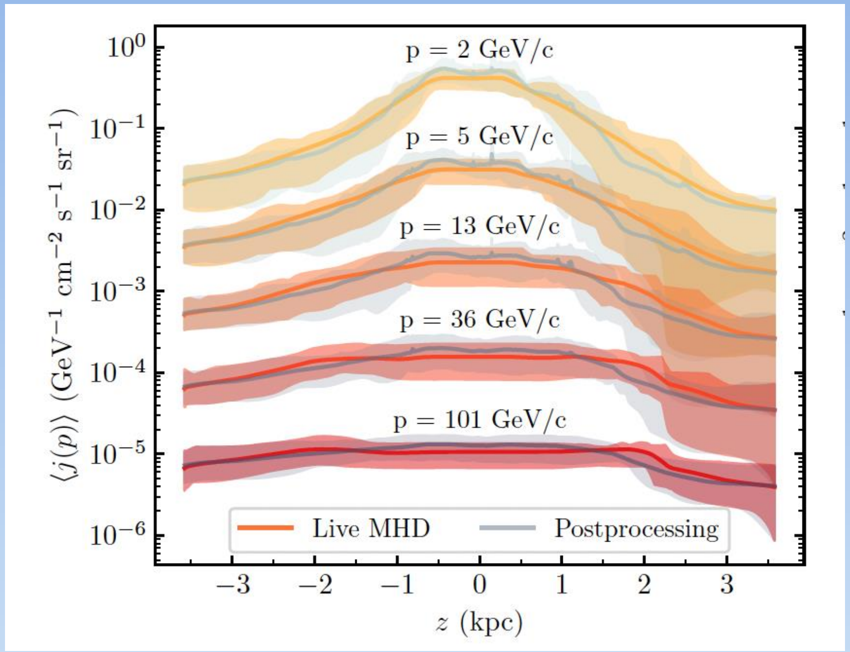


Yu, Armillotta, & Ostriker (2026)

Vertical structure and profiles

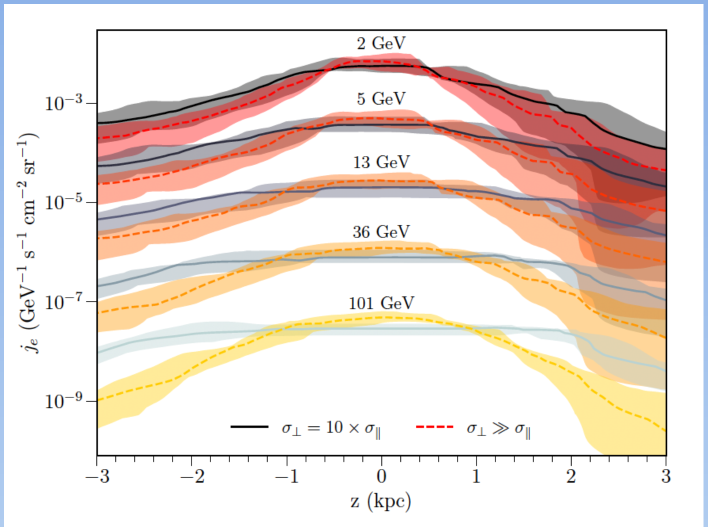
Amillotta et al (2025)



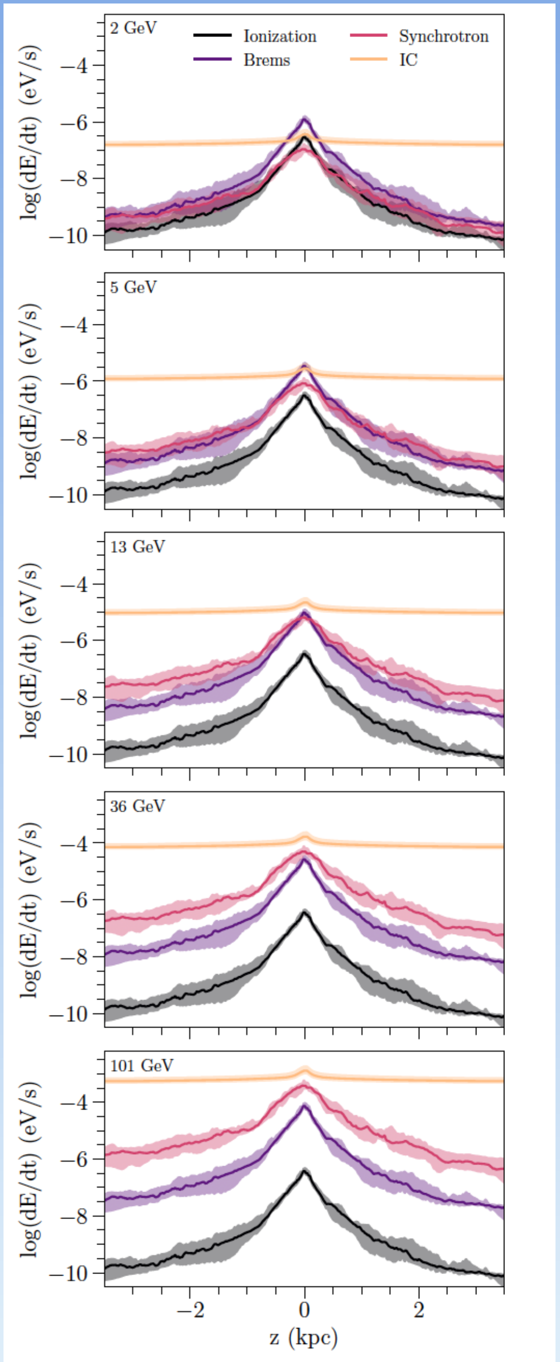


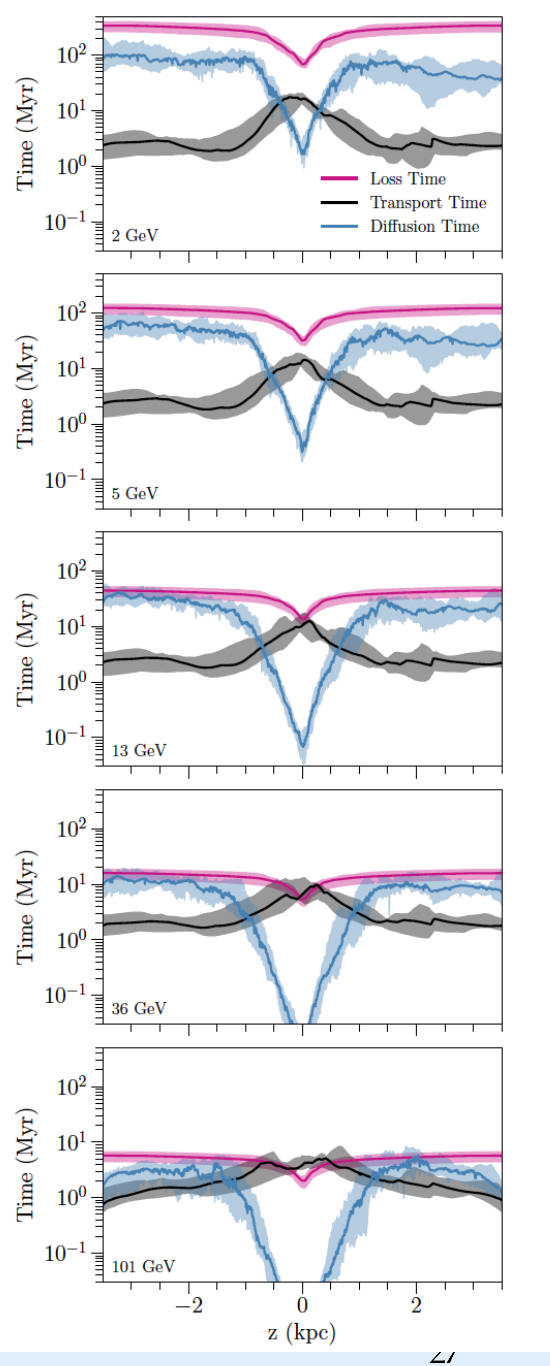
- CR pressure flat in midplane region, exponentially decreasing with *z* above *z* ~ 0.5 -2 kpc
- Transition from flat to exponentially decreasing occurs where dynamical and diffusive velocities are comparable

CR electrons



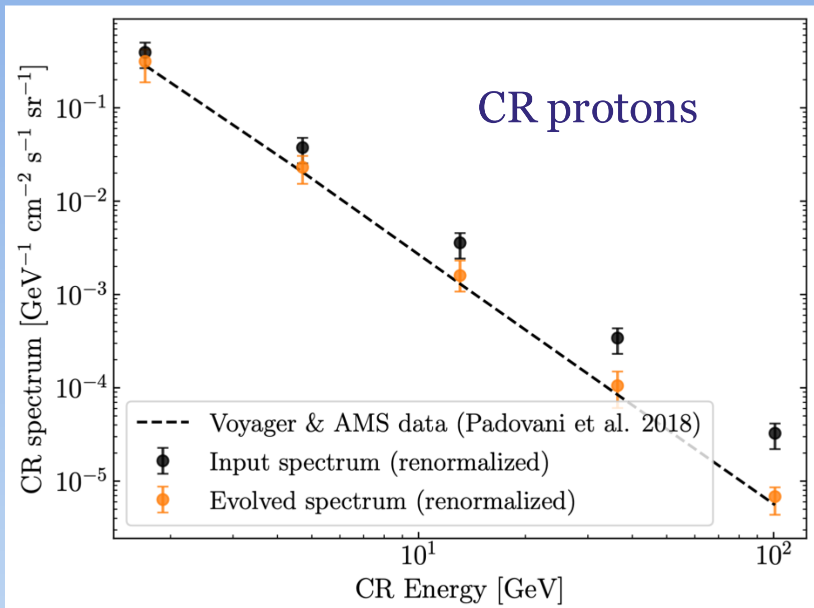
Linzer et al (2025)



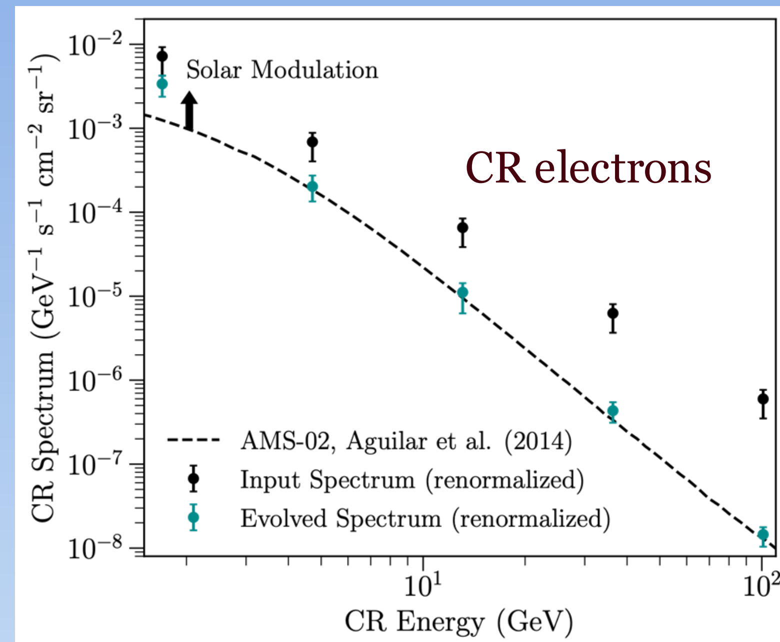


- Both energy-dependent losses and reduction in transport time at higher energy steepen the CR electron spectrum compared to the injected spectrum

CR proton and electron spectra



Armillotta, Ostriker, & Linzer 2025



Linzer et al., 2025

- CRs experience spectral steepening due to energy-dependent diffusion
- For electrons, there are additional losses: ionization, bremsstrahlung, synchrotron, inverse Compton
- Proton spectrum steepened to γ=4.6, ~0.3 dex relative to input spectrum γ_{inj}=4.3 , in agreement with observations (γ_{obs}=4.7)
- CR electron spectrum also agrees with observations, with γ=4.7 to 5.3 between 1 and 100 GeV (Linzer et al 2025)

Modeling relative importance of advection and diffusion

- Simplified 1D system (for each CR energy or momentum bin):

For $V = v_z + v_{st}$, where $v_{st} = -\text{sign}(dP_{cr}/dz)v_{A,ion,z}$, and $\kappa = 1/\sigma_{\|}$,

$$\frac{dF_{cr}}{dz} = V\frac{dP_{cr}}{dz} + Q$$
$$\frac{dP_{cr}}{dz} = -(1/\kappa)(F_{cr} - 4VP_{cr})$$

- Midplane region: κ large $\Rightarrow$ P_{cr}~const, $dF_{cr}/dz = Q$
- Extraplanar region: $Q=0$, κ~const, $F_{cr} = 4VP_{cr} - \kappa dP_{cr}/dz \Rightarrow$

$$\kappa\frac{d^2P_{cr}}{dz^2} - 3V\frac{dP_{cr}}{dz} - 4P_{cr}\frac{dV}{dz} = 0$$

- V increasing with z from outflowing warm fountain, hot wind

\+ \+ −

Limits

$$\kappa \frac{d^2 P_{cr}}{dz^2} - 3V \frac{dP_{cr}}{dz} - 4P_{cr} \frac{dV}{dz} = 0$$

- Diffusion-only: V=0, $d^2P_{cr}/dz^2=0 \Rightarrow$
  $dP_{cr}/dz = const.$; $P_{cr}=P_{midplane}(1- z/z_{max})$

- Streaming+advection only: $\kappa=0 \Rightarrow$
  $d\ln P_{cr}/dz =- (4/3)d\ln V/dz$;
  - with $v \gg v_A$, $d(\rho v)/dz=0 \Rightarrow V \propto \rho^{-1} \Rightarrow P_{cr} \propto \rho^{4/3}$
  - with $v \ll v_A$, $v_A \propto \rho^{-1/2} \Rightarrow V \propto \rho^{-1/2} \Rightarrow P_{cr} \propto \rho^{2/3}$

1D approximate solution

- P_{cr}=exp($-z/H_c$), $dV/dz=V/H_a \Rightarrow$ $$\frac{\kappa}{H_c^2}+3\frac{V}{H_c}-4\frac{V}{H_a}=0$$

$$H_c=\frac{3}{8}H_a\left[1+\left(1+\frac{16}{9}\frac{\kappa}{H_aV}\right)^{1/2}\right]$$

$$H_c \to \begin{cases} \frac{3}{4}H_a & \text{for } \kappa \ll H_aV \\ \frac{1}{2}\left(\frac{\kappa H_a}{V}\right)^{1/2} & \text{for } \kappa \gg H_aV \end{cases}$$

- Effective velocity: $F_{cr} \equiv 4\, v_{\rm eff} P_{cr}$; $v_{\rm eff}=V+\kappa/(4H_c)$

$$v_{\rm eff}=V\left[\frac{5}{8}+\frac{3}{8}\left(1+\frac{16}{9}\frac{\kappa}{H_aV}\right)^{1/2}\right]$$

$$v_{\rm eff} \to \begin{cases} V & \text{for } \kappa \ll H_aV \\ \frac{1}{2}\left(\frac{\kappa V}{H_a}\right)^{1/2} & \text{for } \kappa \gg H_aV \end{cases}$$

- Measure V, H_a, κ in each CR momentum bin:

  V~10-15 km/s; $H_a = V/(dV/dz)$~0.5-1 kpc; κ~$3\times10^{27}(cp/\mathrm{GeV})^{0.9}$

  since for streaming/NLL balance, $\kappa(p) \propto |\nabla P_{cr}(p)|^{-1/2} \propto p^{(\gamma-3)/2}$

1D approximate solution

- P_{cr}=exp(-z/H_c), dV/dz=V/H_a ⇒

$$\kappa \frac{d^2 P_{cr}}{dz^2} - 3V\frac{dP_{cr}}{dz} - 4P_{cr}\frac{dV}{dz} = 0 \;\rightarrow\; \frac{\kappa}{H_c^2} + 3\frac{V}{H_c} - 4\frac{V}{H_a} = 0$$

- *Solve quadratic for* H_c:

$$H_c = \frac{3}{8}H_a\left[1 + \left(1 + \frac{16}{9}\frac{\kappa}{H_a V}\right)^{1/2}\right] \qquad H_c \rightarrow \begin{cases} \frac{3}{4}H_a & \textit{for } \kappa \ll H_a V \\ \frac{1}{2}\left(\frac{\kappa H_a}{V}\right)^{1/2} & \textit{for } \kappa \gg H_a V \end{cases}$$

- Effective velocity: $F_{cr} \equiv 4\, v_{eff} P_{cr}$; $v_{eff} = V + \kappa/(4H_c)$

$$v_{eff} = V\left[\frac{5}{8} + \frac{3}{8}\left(1 + \frac{16}{9}\frac{\kappa}{H_a V}\right)^{1/2}\right] \qquad v_{eff} \rightarrow \begin{cases} V & \text{for } \kappa \ll H_a V \\ \frac{1}{2}\left(\frac{\kappa V}{H_a}\right)^{1/2} & \text{for } \kappa \gg H_a V \end{cases}$$

- In simulation, measure V, H_a, κ in each CR momentum bin:
  V~10-15 km/s; $H_a = V/(dV/dz)$~0.5-1 kpc; $\kappa \sim 3\times10^{27}(cp/\text{GeV})^{0.9}$

streaming/NLL balance: $\kappa(p) \propto |\nabla P_{cr}(p)|^{-1/2} \propto p^{(\gamma-3)/2}$

Two-zone D+D model

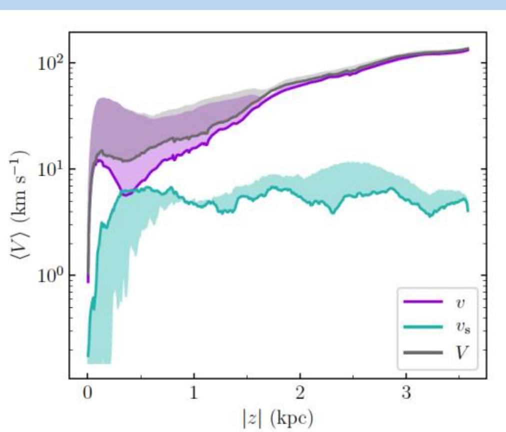
$$P_0 = \frac{F_{\mathrm{inj}}/2}{4V + \kappa_\parallel/H_c} \equiv \frac{F_{\mathrm{inj}}/2}{4v_{\mathrm{eff}}}$$

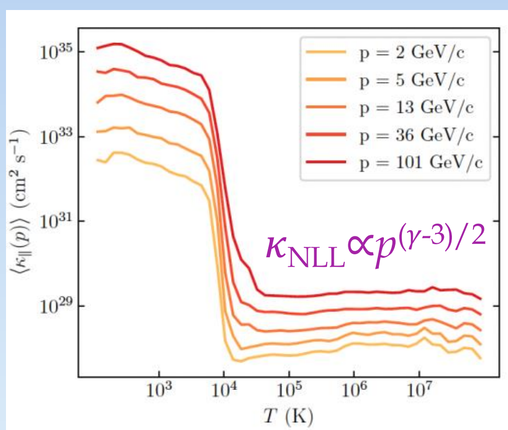
$$P_1 = P_0 \exp[-(z - z_{\mathrm{trans}})/H_c]$$

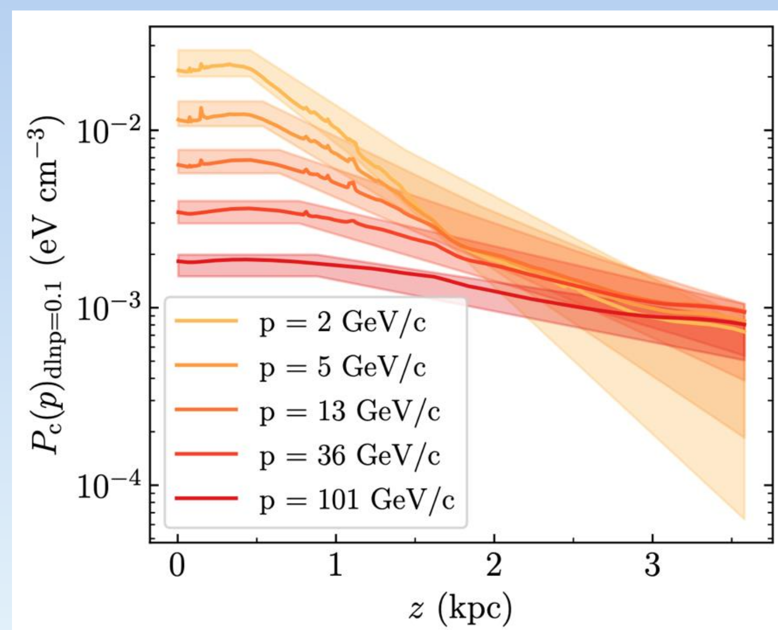
Three key parameters:

- $V = v + v_{st}$:dynamical speed
- $\kappa_\parallel \equiv 1/\sigma_\parallel$:diffusion coefficient
- H_a= acceleration scale height

$$H_c = \frac{3}{8}H_a\left(1 + \sqrt{1 + \frac{16}{9}\frac{\kappa_\parallel}{H_a V}}\right) \qquad v_{\mathrm{eff}} = V\left(\frac{5}{8} + \frac{3}{8}\sqrt{1 + \frac{16}{9}\frac{\kappa_\parallel}{H_a V}}\right)$$

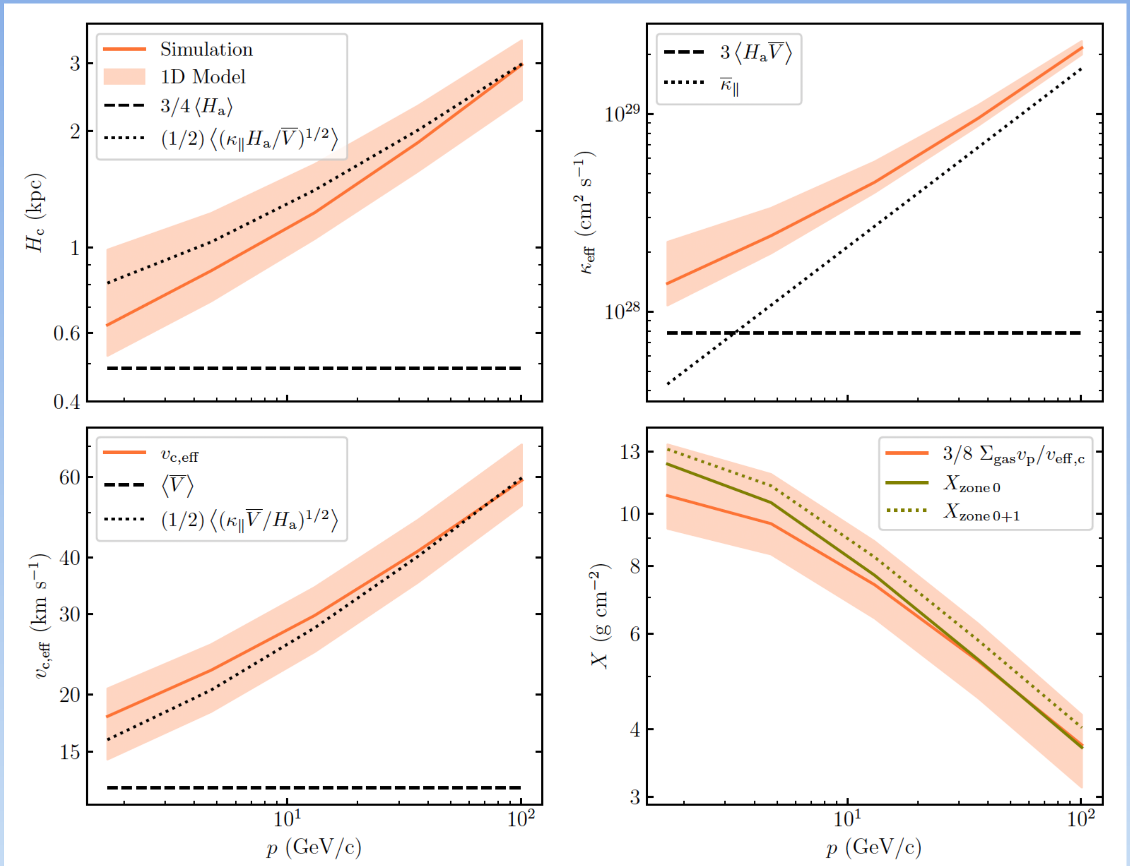






Armillotta, Ostriker, & Linzer (2025)

Numerical and analytic comparison



Armillotta, Ostriker, & Linzer (2025)

- Spectral steepening: $F_{\rm inj} = 8\, v_{\rm eff} P_{\rm mid} \Rightarrow p^{-\gamma_{\rm inj}} \propto p^{(\gamma-3)/4} p^{-\gamma} \Rightarrow$

  $\gamma = (4/3)\gamma_{\rm inj} - 1 = 4.7$ theoretically; 4.6 measured in simulation
- Grammage: $X(p) \propto 1/v_{\rm eff}(p) \propto p^{-(\gamma-3)/4} \sim p^{-(1-\gamma_{\rm inj}/3)} \sim p^{-0.4}$

Recall: Empirical $X \propto p^{-\boldsymbol{\delta}}$ with $\boldsymbol{\delta}$~0.3-0.5

- Averaging over the distribution,

$$\overline{v}_{\rm eff} = \frac{\int dp p^{2-\gamma_{\rm inj}}}{\int dp p^{2-\gamma_{\rm inj}}/v_{\rm eff}(p)} \rightarrow 23 \text{ km s}^{-1}$$

Further applications

- Recovering correct energy-dependent transport provides validation of the self-confinement paradigm, with spatially variable κ
- Within this paradigm, how do CR properties depend on SFR?
- What are the dynamical effects of the CRs on the gas?

CR transport in varying galactic environments

Armillotta et al (2022), Hix et al (2025)

- 4 Models to sample diverse environments
  - R2, R4, R8 - Galactic Disk Models
    - Span >3 orders of magnitude in Σ_{SFR}
  - R8 Arm - Solar Neighborhood with Spiral Arm
- Many snapshots per environment

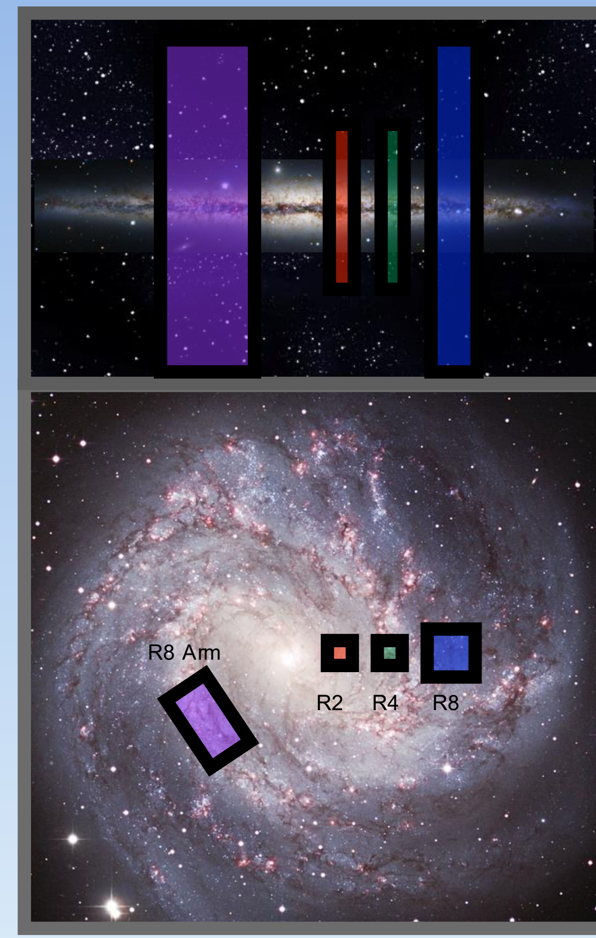
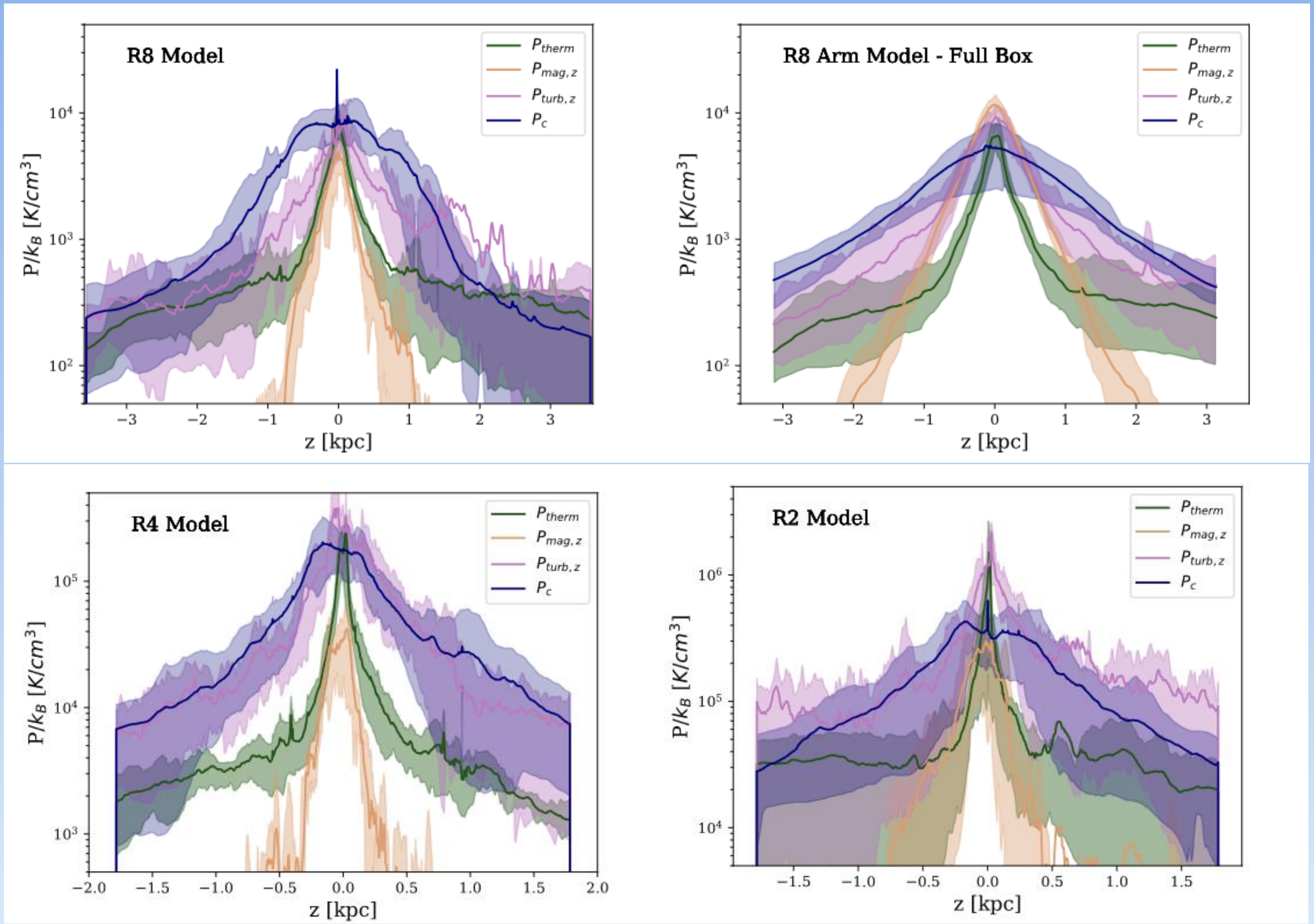


Table 1
Physical Parameters of the Model Environments Sampled in This Work

Model (1)	L_z (pc) (2)	Δx (pc) (3)	ρ_{DM} ($M_\odot$ pc^{-3}) (4)	Σ_{star} ($M_\odot$ pc^{-2}) (5)	$\Sigma_{gas,ini}$ ($M_\odot$ pc^{-2}) (6)	t_{orb} (Myr) (7)	$\langle\Sigma_{gas}\rangle$ ($M_\odot$ pc^{-2}) (8)	$\langle\Sigma_{SFR}\rangle$ ($M_\odot$ kpc^{-2} yr^{-1}) (9)	$\langle n_{mid}\rangle$ (cm $^{-1}$) (10)	$\langle P_{mid}/k_B\rangle$ (K cm^{-3}) (11)	$\langle H_{gas}\rangle$ (kpc) (12)
R2	±1792	4	8.0×10^{-2}	450	150	61	74	1.1	7.7	2.5×10^{6}	0.35
R4	±1792	4	2.4×10^{-2}	208	50	110	30	0.13	1.4	4.1×10^{5}	0.34
R8	±3584	8	6.4×10^{-2}	42	12	220	11	5.1×10^{-3}	0.9	1.9×10^{4}	0.33
R8 Arm	±3141	12.3	6.4×10^{-2}	42	13	205	10	4.2×10^{-3}	0.5	2.3×10^{4}	0.43

Pressure profiles



Hix et al (2025)

CR transport in varying environments

- For single-energy (GeV) CRs, we have measured $v_{\rm eff} = F_{\rm inj,cr}/(8P_{\rm cr})$ for different TIGRESS ISM and star formation environments (Hix et al 2025). Find:

$$v_{\rm eff} = 21 \pm 3 \ {\rm km\ s^{-1}} \left(\frac{\Sigma_{\rm SFR}}{0.01 \ {\rm M_\odot \ pc^{-2} \ Myr^{-1}}} \right)^{0.20 \pm 0.05} \quad (33)$$

and

$$v_{\rm eff} = 15 \pm 2 \ {\rm km\ s^{-1}} \left(\frac{P_{\rm DE}/k_B}{10^4 \ {\rm K\ cm^{-3}}} \right)^{0.26 \pm 0.05} . \quad (34)$$

- Measurement of $F_{\rm inj,cr}/(8P_{\rm cr})$ is consistent with measured value of $v_z + v_{A,z}$ in transition region
- Correction factor for spectrum between 1.4 (solar neighborhood) and 1.2 (galactic center conditions)

``Equipartition'' via mutual inheritance

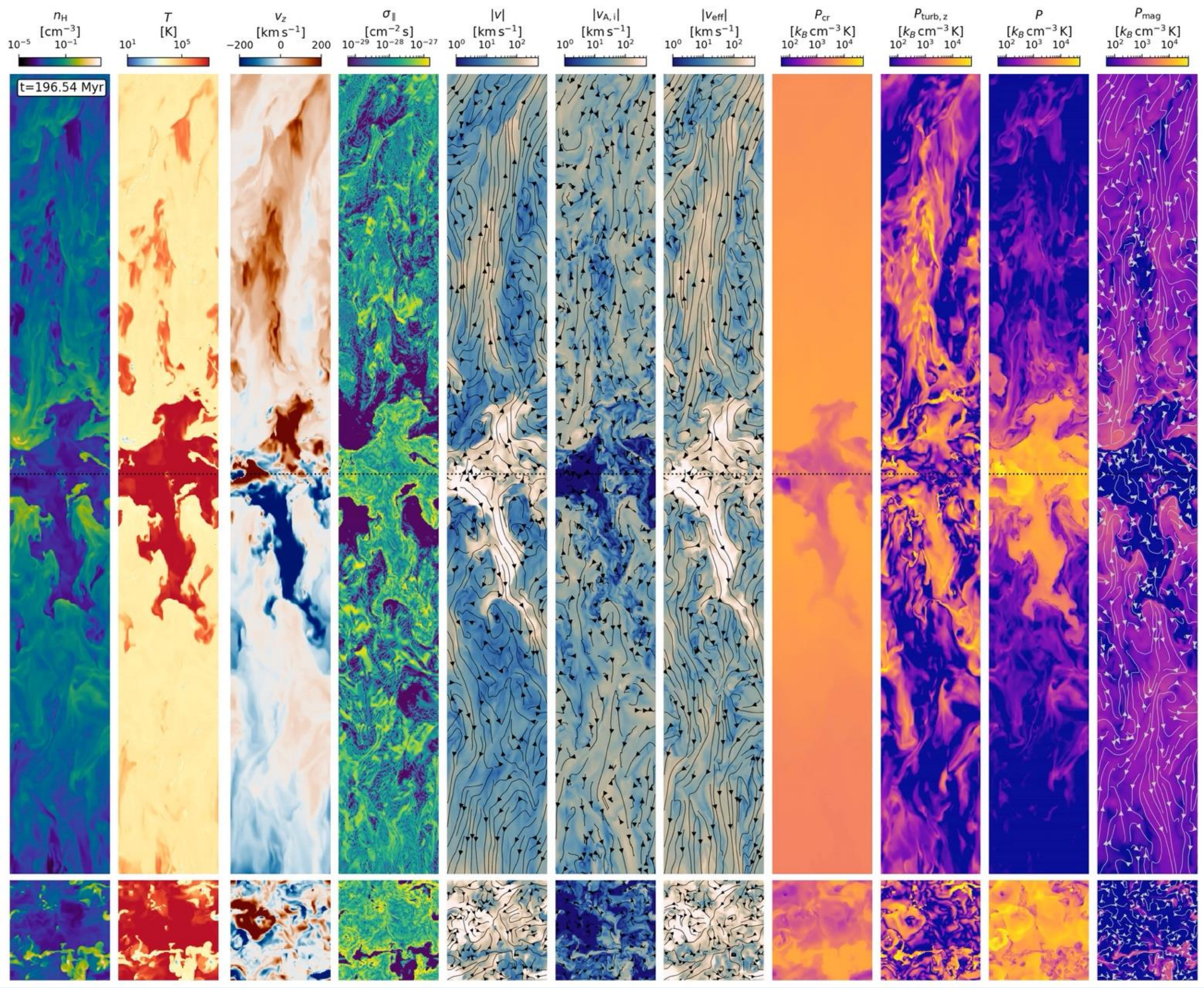
- $P_{\rm cr}$ and $P_{\rm mag}$ are measured to be comparable in varying environments
  - consistent with usual assumption to obtain B from synchrotron
- $P_{\rm turb}$ and $P_{\rm th}$ are also comparable
- **Not** a causal relation, but a result of mutual inheritance: $P_i = \Upsilon_i \, \Sigma_{\rm SFR}$
- The individual feedback yields Υ_i are set by different physical mechanisms:
  - $P_{\rm th}$ from balance of radiative cooling ($n\Lambda$) with stellar FUV heating ($\Gamma \propto \Sigma_{\rm SFR}$) Ostriker et al (2010), Kim et al (2011)
  - $P_{\rm turb}$ and $P_{\rm mag}$ from balance of driving (SN momentum) with dissipation Ostriker & Shetty (2011), Kim et al (2013, 2015)
  - $P_{\rm cr}$ from balance of energy injection (SNe) with dynamical transport at $V \sim v_z + v_{A,z}$

$$\Upsilon_c = (284 \pm 33)\ \mathrm{km\ s^{-1}} \times \left(\frac{\Sigma_{\rm SFR}}{0.01\ M_\odot\ \mathrm{pc^{-2}\ Myr^{-1}}}\right)^{-0.23\pm0.05}.$$

$$\Upsilon_c = (426 \pm 42)\ \mathrm{km\ s^{-1}} \times \left(\frac{P_{\rm DE}/k_B}{10^4\ \mathrm{K\ cm^{-3}}}\right)^{-0.29\pm0.04}$$

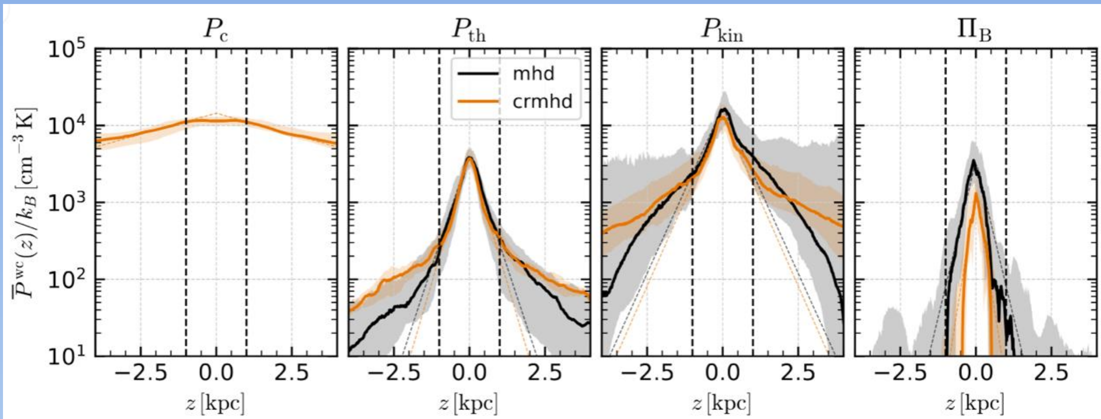
Hix et al (2025)

CR-MHD simulations with TIGRESS++



C.-G. Kim, L. Armillotta, E. Ostriker et al (2026)

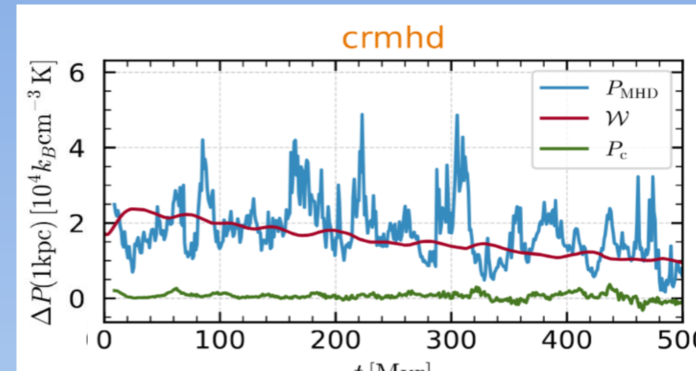
Pressure and SFR with TIGRESS++ CR-MHD

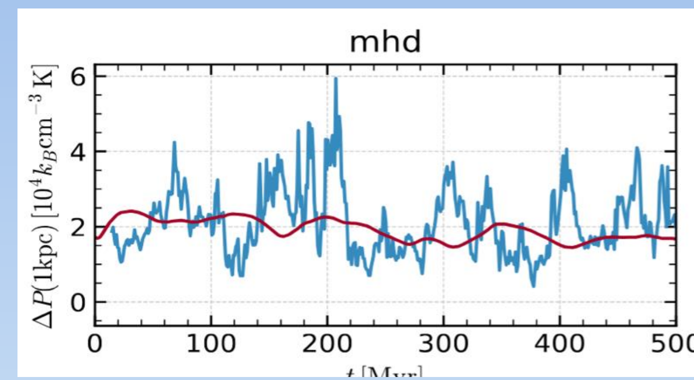


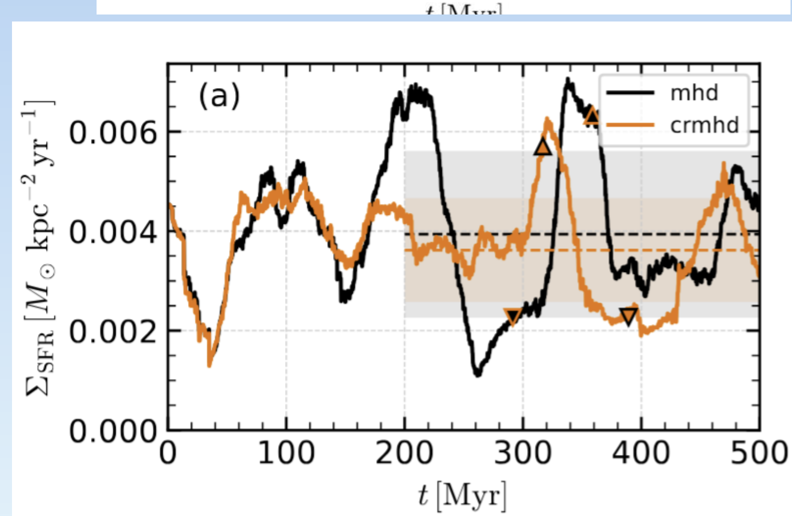
Kim, Armillotta, Ostriker, et al (2026)

- All component pressures comparable in midplane
- P_{cr} uniform in neutral gas ⇒ CR pressure forces are negligible
- CR scale height >> gas scale height ⇒ $\Delta P_{cr} \approx 0$ ⇒ CRs do not contribute to supporting disk ⇒ $\Delta P_{MHD} \approx P_{MHD} = \mathcal{W} \equiv \int \rho g_z\, dz$ ⇒ $\Sigma_{SFR} = \mathcal{W} / (\Upsilon_{th} + \Upsilon_{turb} + \Upsilon_{mag})$, unchanged from case *without* CRs

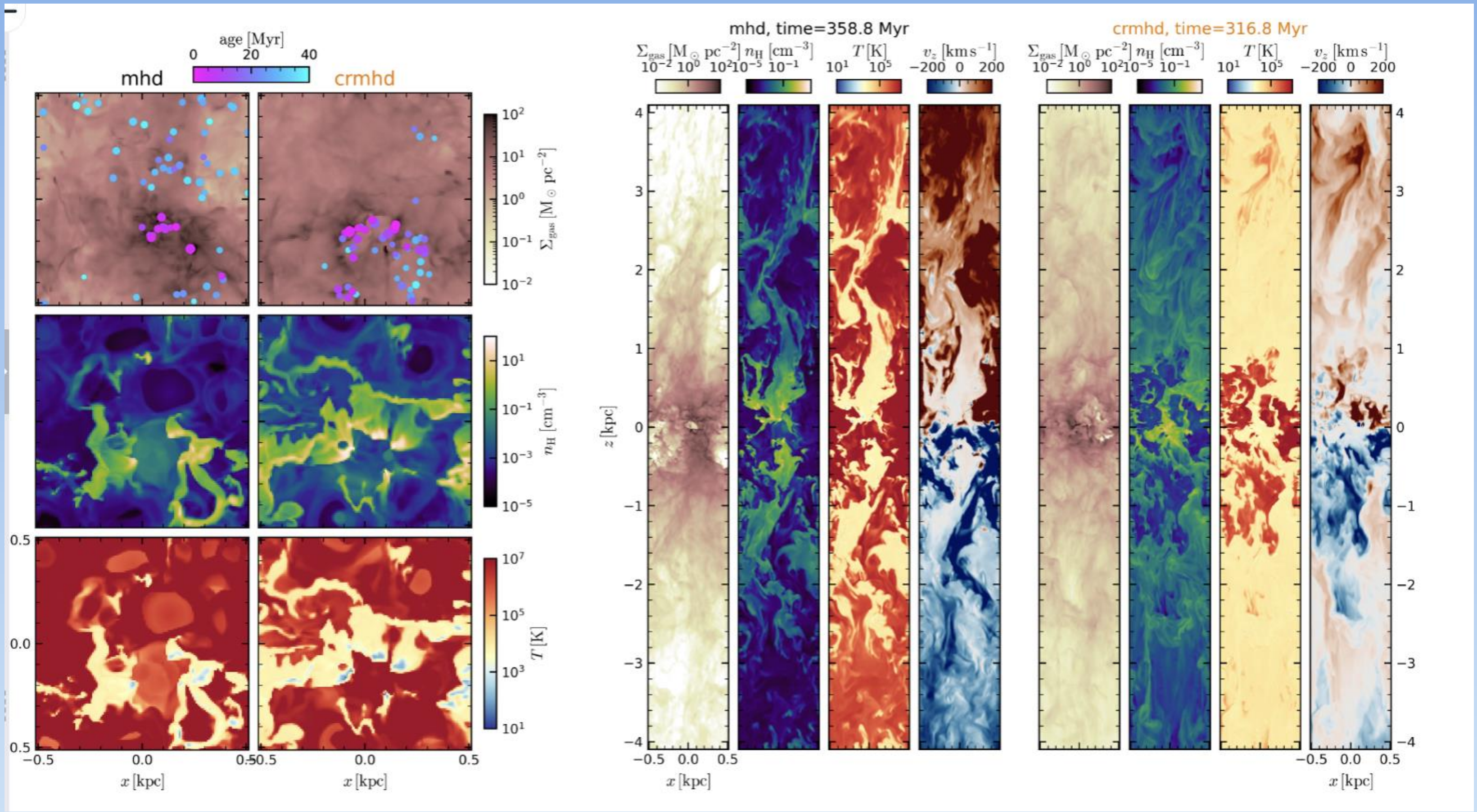
SFR not affected by CRs







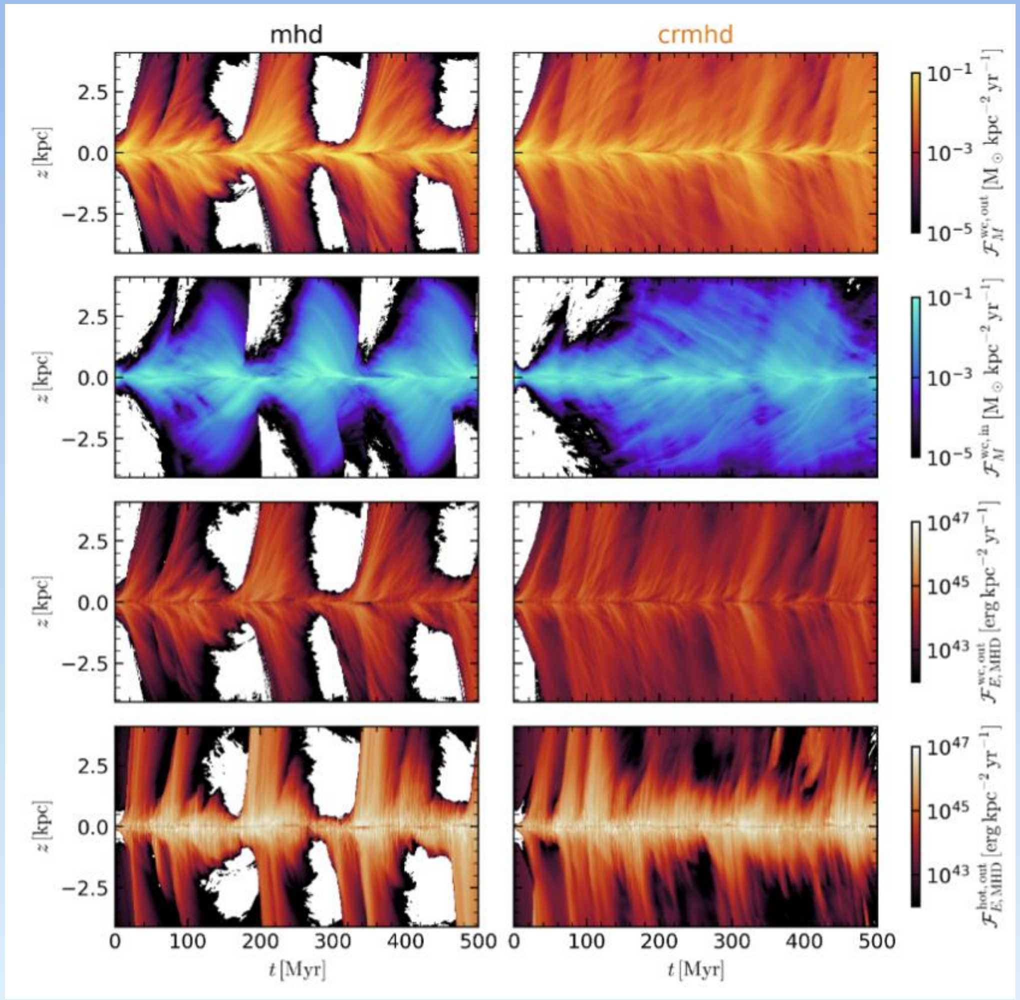
Outflows with TIGRESS++ CR-MHD

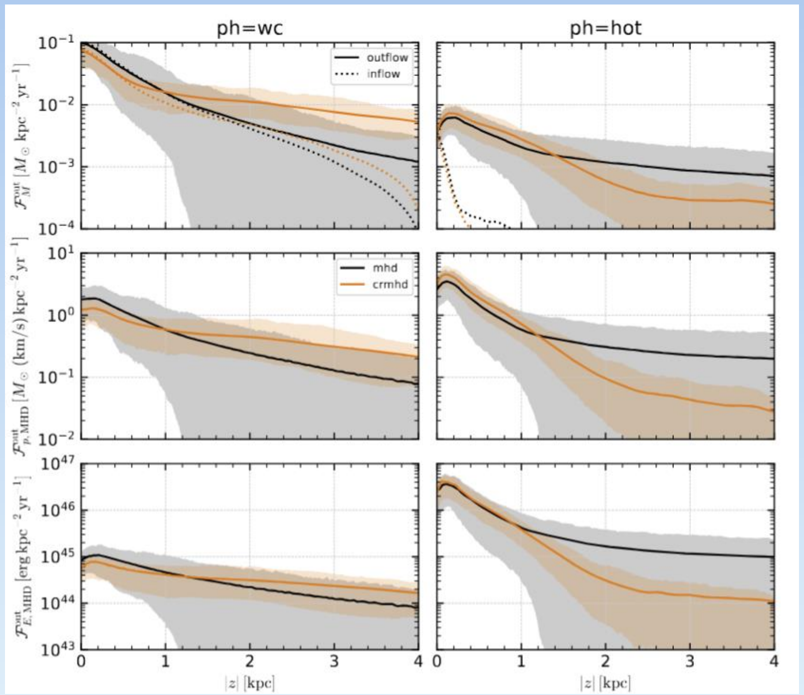


- With/without CRs, star-forming ISM disk at |z|≲ 500 pc very similar, in terms of pressures, filling factors of phases, mass fractions in warm vs. cold
- With CRs, galactic outflows are dominated by warm (T~10^4K) volume-filling gas, in contrast to hot+warm structure without CRs

Outflows with TIGRESS++ CR-MHD

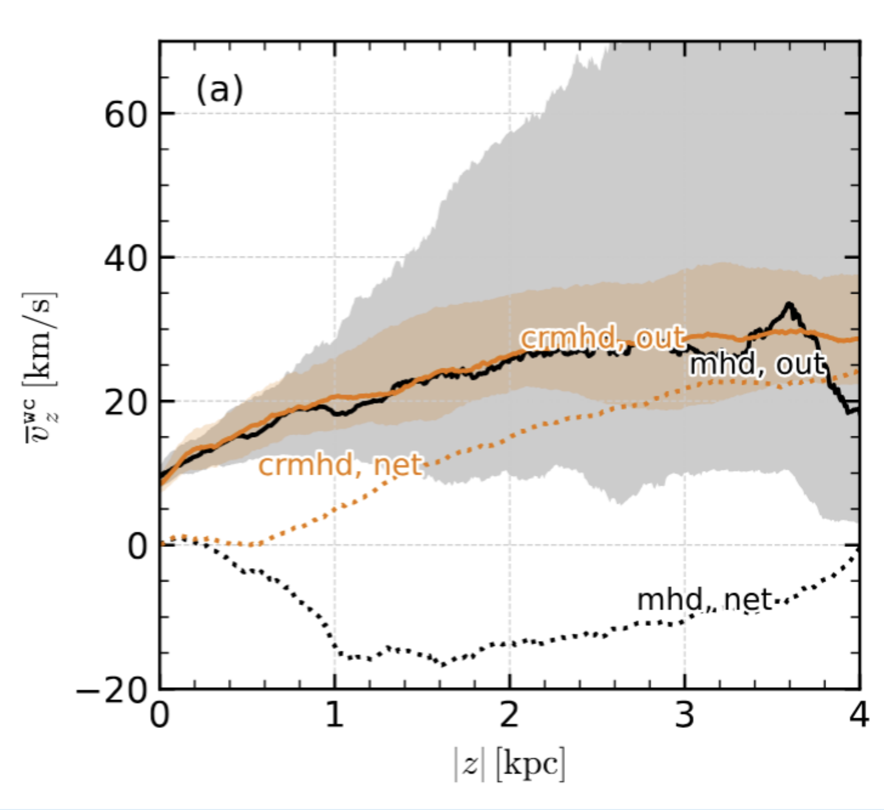
- With CRs, galactic outflows are less ``bursty''
  - Mass flux – mostly in warm gas – is increased
  - Energy flux – mostly in hot gas – is reduced
  - Momentum flux increased in warm and decreased in hot

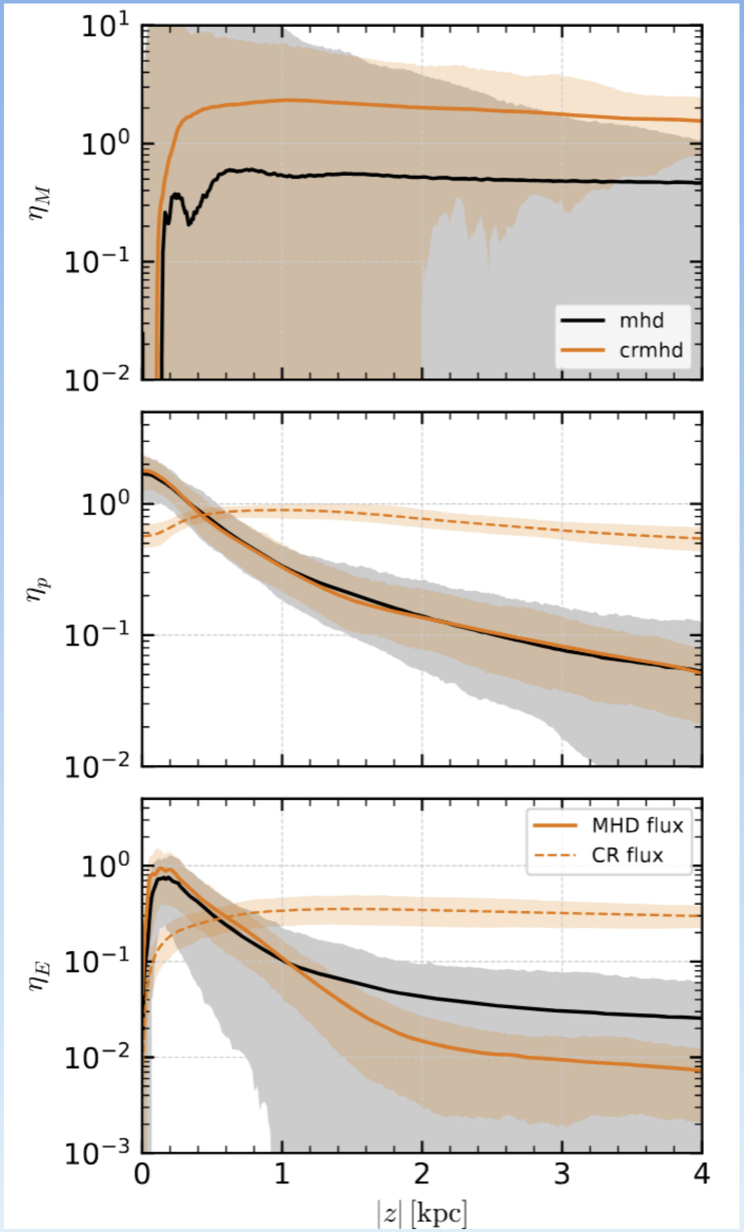




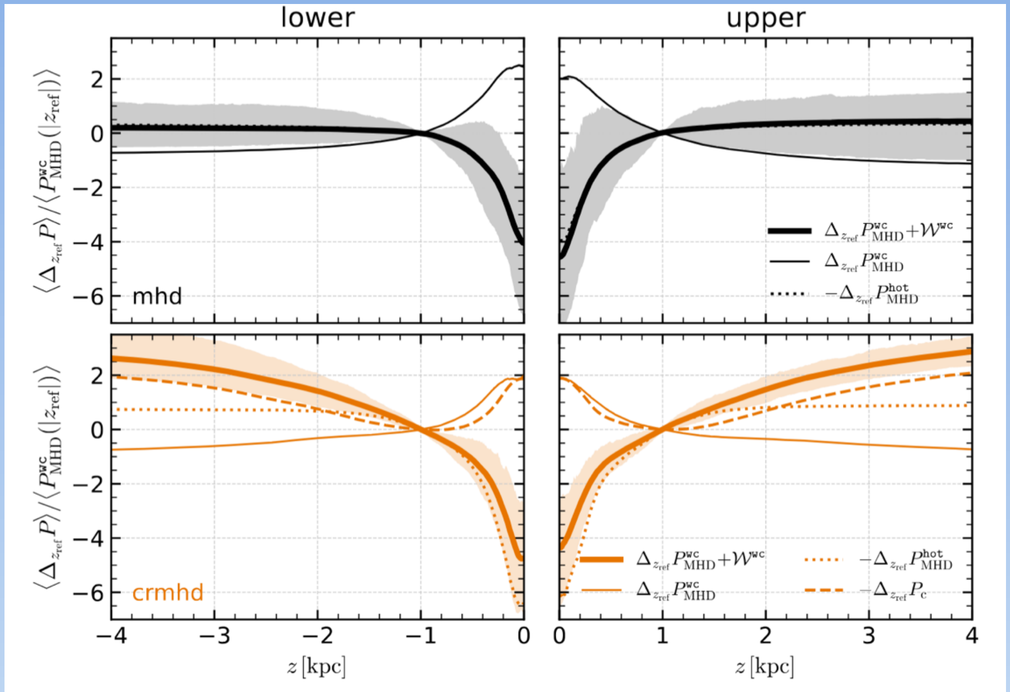
Outflows with TIGRESS++ CR-MHD

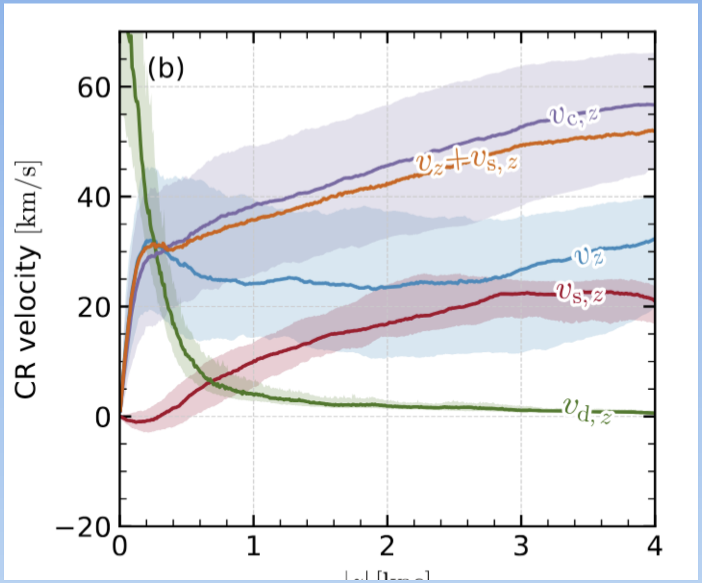
- Velocity profile of warm gas at $|z| \lesssim 3$ kpc is similar with/without CRs
- With CRs, mass loading increased 3x
- Energy and momentum loading are dominated by the CR fluid itself





Outflows with TIGRESS++ CR-MHD

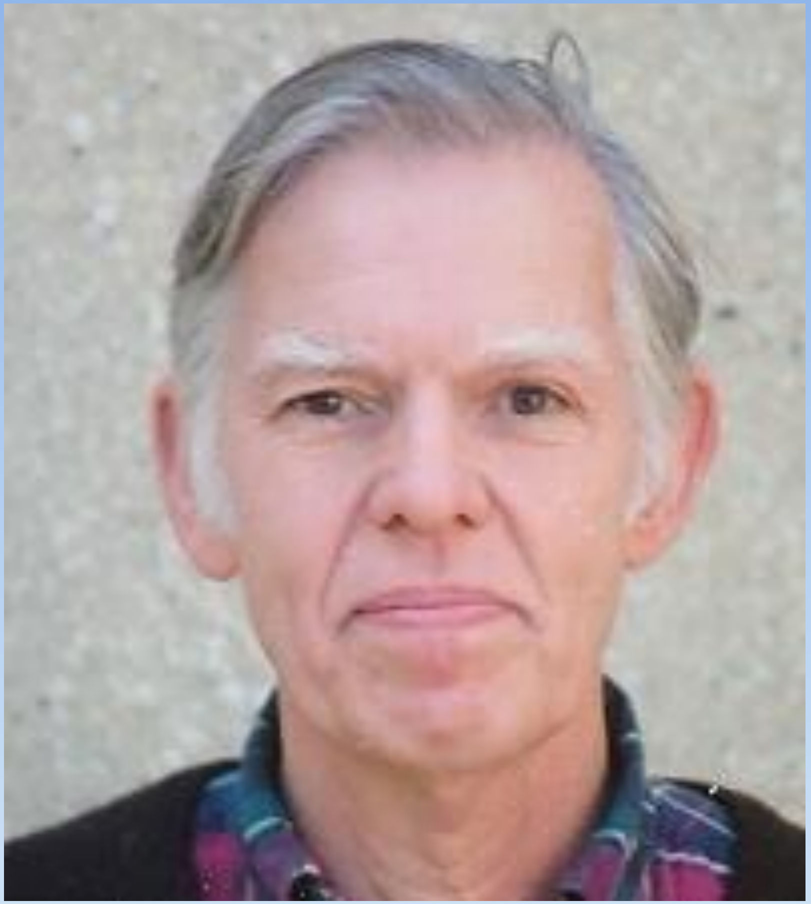




- At |z| ≲ 1 kpc, momentum flux transfer is primarily hot → warm gas, and similar with/without CRs
- GeV CRs transition from highly diffusive to dynamical at |z|~1 kpc
- Without CRs, little momentum flux transfer to warm at |z|≳ 1 kpc
- With CRs, significant momentum transfer from CRs to warm gas at |z|≳ 1 kpc, representing launch of CR-driven wind.

Cosmic ray self-confinement?

Donat G. Wentzel (1934 – 2013)



Russell M. Kulsrud (1928 – 2025)

56 years later: Yes…AND!

Summary

- In the self-confinement picture, the scattering rate coefficient of CRs with R_g=1/k, $\sigma \sim (\delta B(k)/B)^2\,\Omega/c^2$ is set by balancing the CR streaming instability growth rate with wave damping
- $\sigma=1/\kappa$ is small in neutral midplane gas (strong ion-neutral damping), large in extraplanar gas (weaker nonlinear Landau damping)
- High diffusion midplane ⇒$P\sim$const.
- CR transport in extraplanar region depends on both dynamical and diffusive terms, depending on $\kappa/H_a V = (\kappa/V)\, d\ln(V)/dz$
  - At $E \lesssim$ GeV where $\kappa/H_a V \lesssim 1$, resulting $v_{\rm eff} \rightarrow V = v_z + v_A$
  - At $E \gtrsim$ GeV where $\kappa/H_a V \gtrsim 1$, resulting $v_{\rm eff} \rightarrow (1/2)(\kappa dV/dz)^{1/2}$
- Confinement is due to extraplanar gas: $\kappa = 1/\sigma \propto p^{(\gamma-3)/2} \sim p^{0.85}$ increases for higher-energy CRs ⇒ $v_{\rm eff} \propto p^{0.4}$, explaining CR grammage $X \propto p^{-0.4}$
- For ~GeV CRs, dominating the energy density, $v_{\rm eff} \rightarrow V = v_z + v_A \sim 20\text{-}30\ km/s$
- Midplane pressure $P_{\rm c}(p) = \dfrac{F_{\rm c,in}(p)/2}{4v_{\rm eff}(p) + (3/2)\Lambda_{\rm c}(p)N_H} = \Upsilon_c \Sigma_{\rm SFR}$
- SFR unchanged with CRs, due to high midplane diffusion
- Mass loading rate in warm gas increases with CRs
- Dominant energy, momentum loading is in the CR fluid itself