THE ROLE OF COSMIC RAY TRANSPORT IN SHAPING THE SIMULATED CIRCUMGALACTIC MEDIUM

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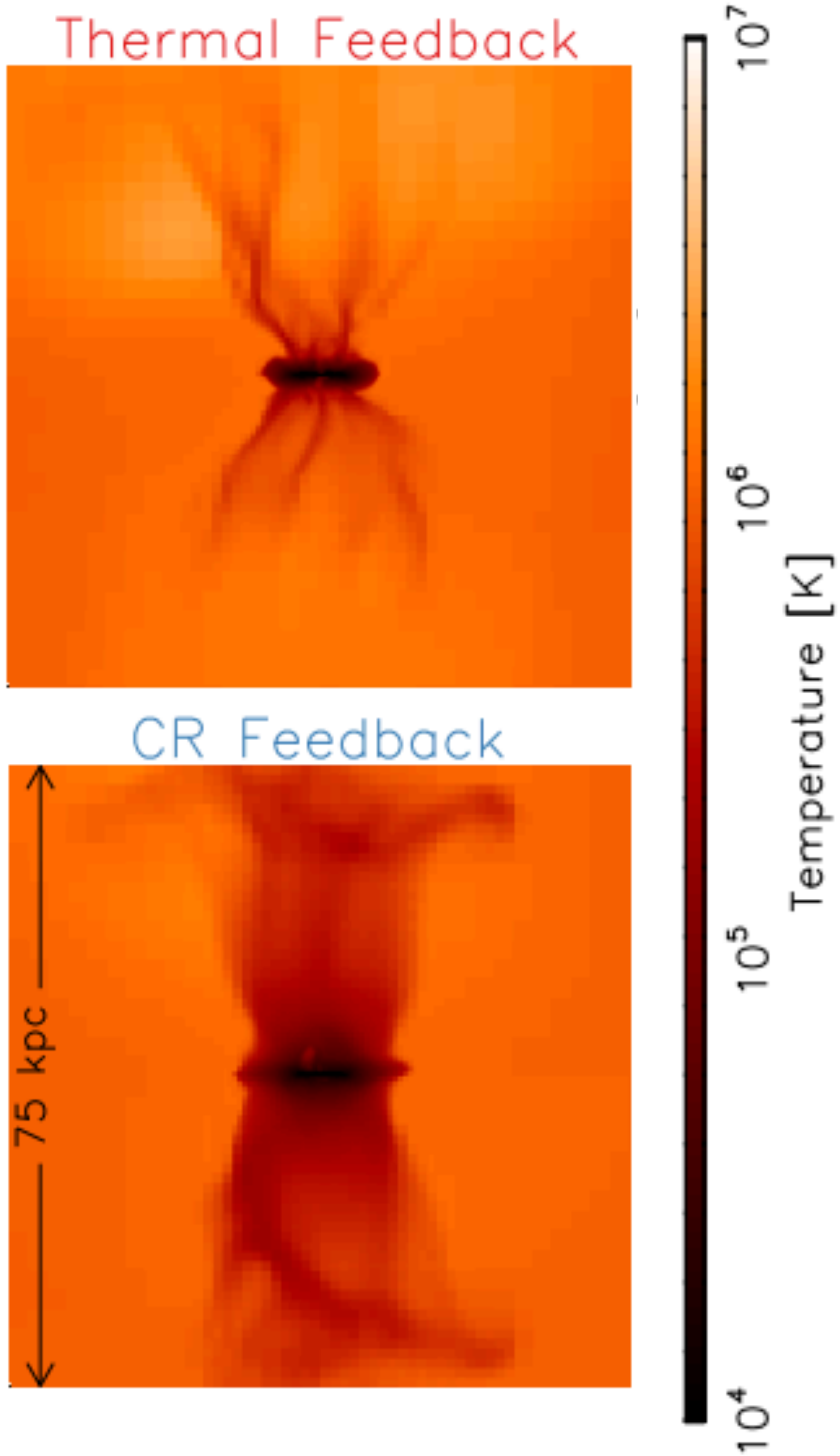
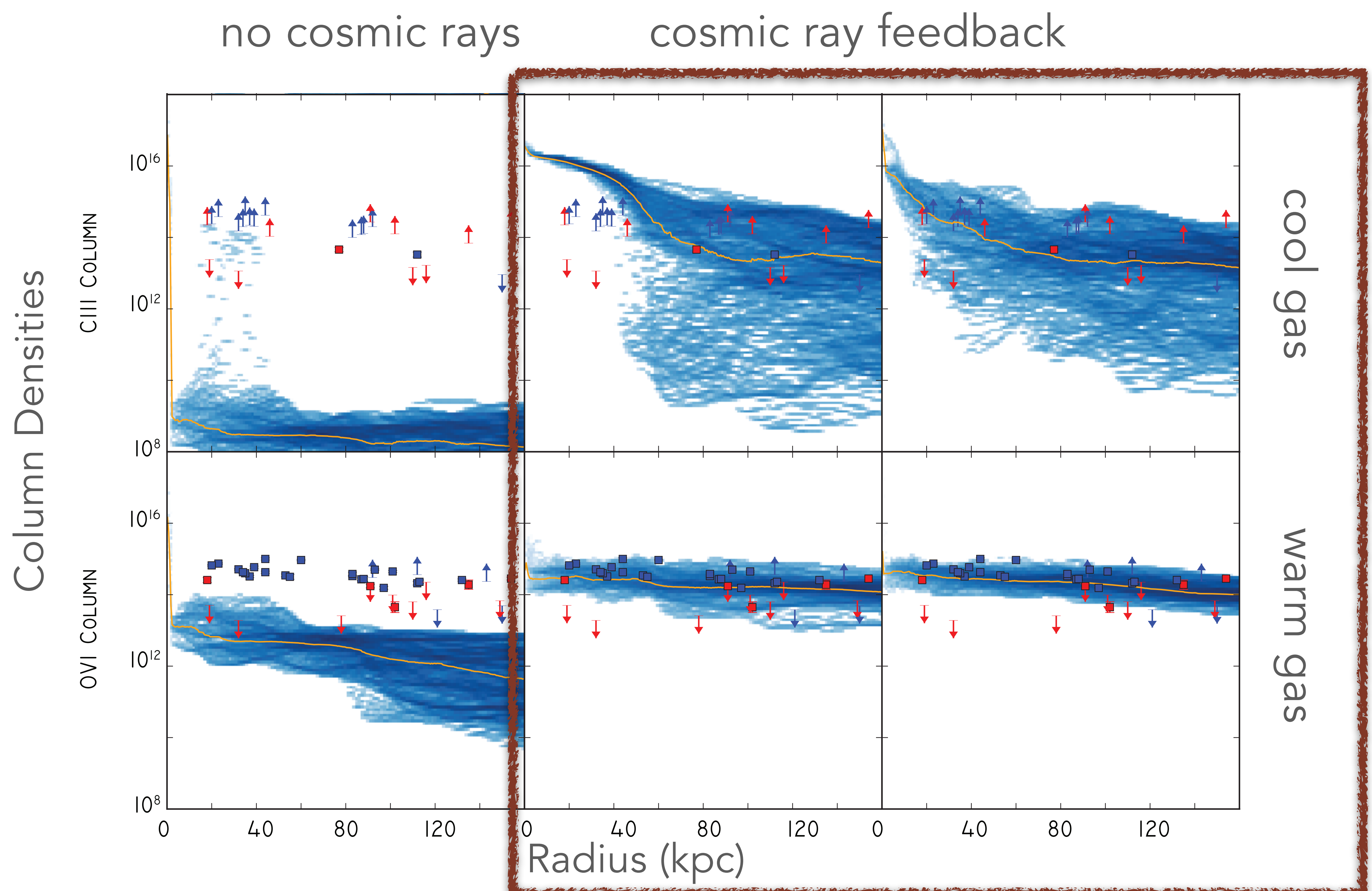
WHY INCLUDE COSMIC RAY FEEDBACK?

- Simulations with **purely thermal** supernova feedback tuned to reproduce disk structure, not CGM
- **Cosmic rays:** charged particles (protons) accelerated to relativistic velocities in extreme shocks (supernovae)
- Cosmic ray energy in equipartition with turbulent and magnetic energies in galactic disk (Boulares and Cox 1990)
- Simulations with non-thermal cosmic ray (CR) feedback
  - Drive strong outflows
  - Provides non-thermal pressure support to gas



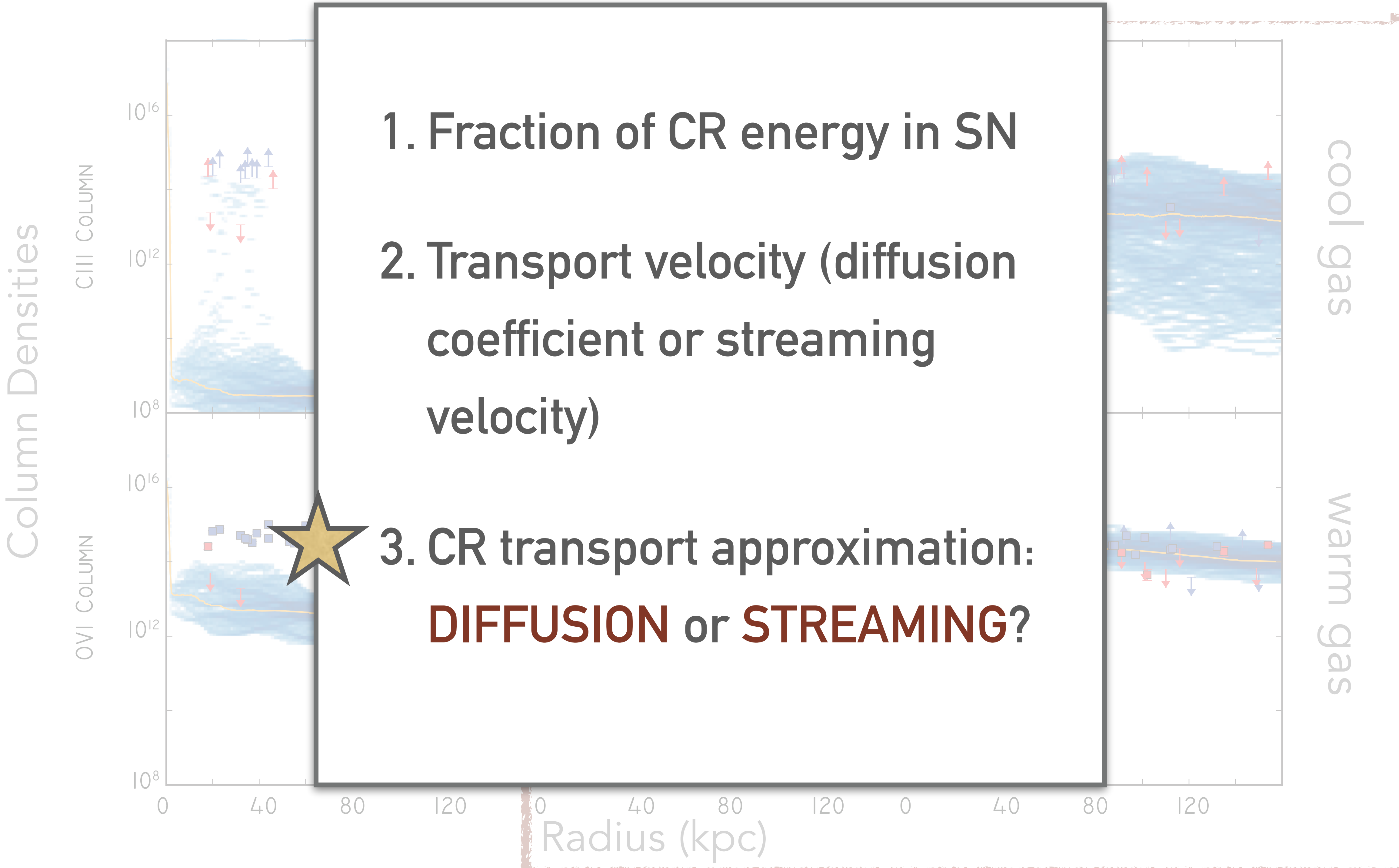
Booth et al. 2013

SIMULATIONS WITH COSMIC RAY FEEDBACK BETTER MATCH OBSERVED COLUMN DENSITIES



Salem, Bryan, and Corlies 2016

Sources of uncertainty in modeling:



1. Fraction of CR energy in SN
2. Transport velocity (diffusion coefficient or streaming velocity)
3. CR transport approximation: **DIFFUSION** or **STREAMING**?

Salem, Bryan, and Corlies 2016

MODELING THE COSMIC RAY “FLUID”

CRs scattered by variation in magnetic field

external turbulence

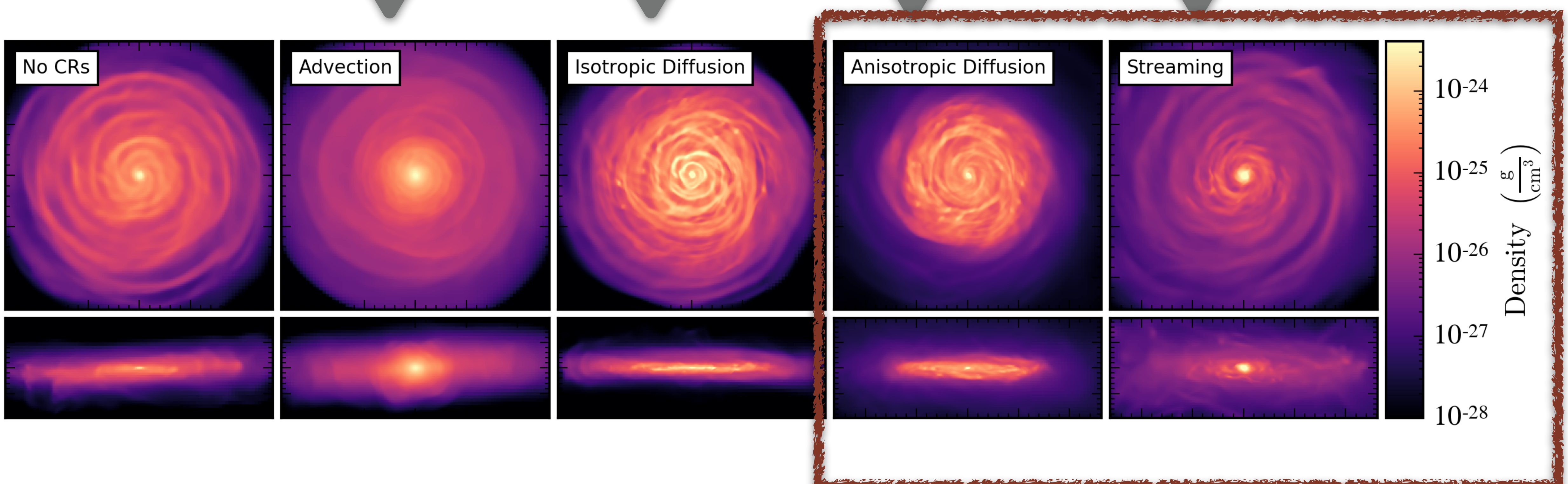
CR-driven instability

Diffusion

Streaming

HOW DOES CR-TRANSPORT AFFECT THE PROPERTIES OF THE CGM?

Same CR supernova feedback,
different CR transport



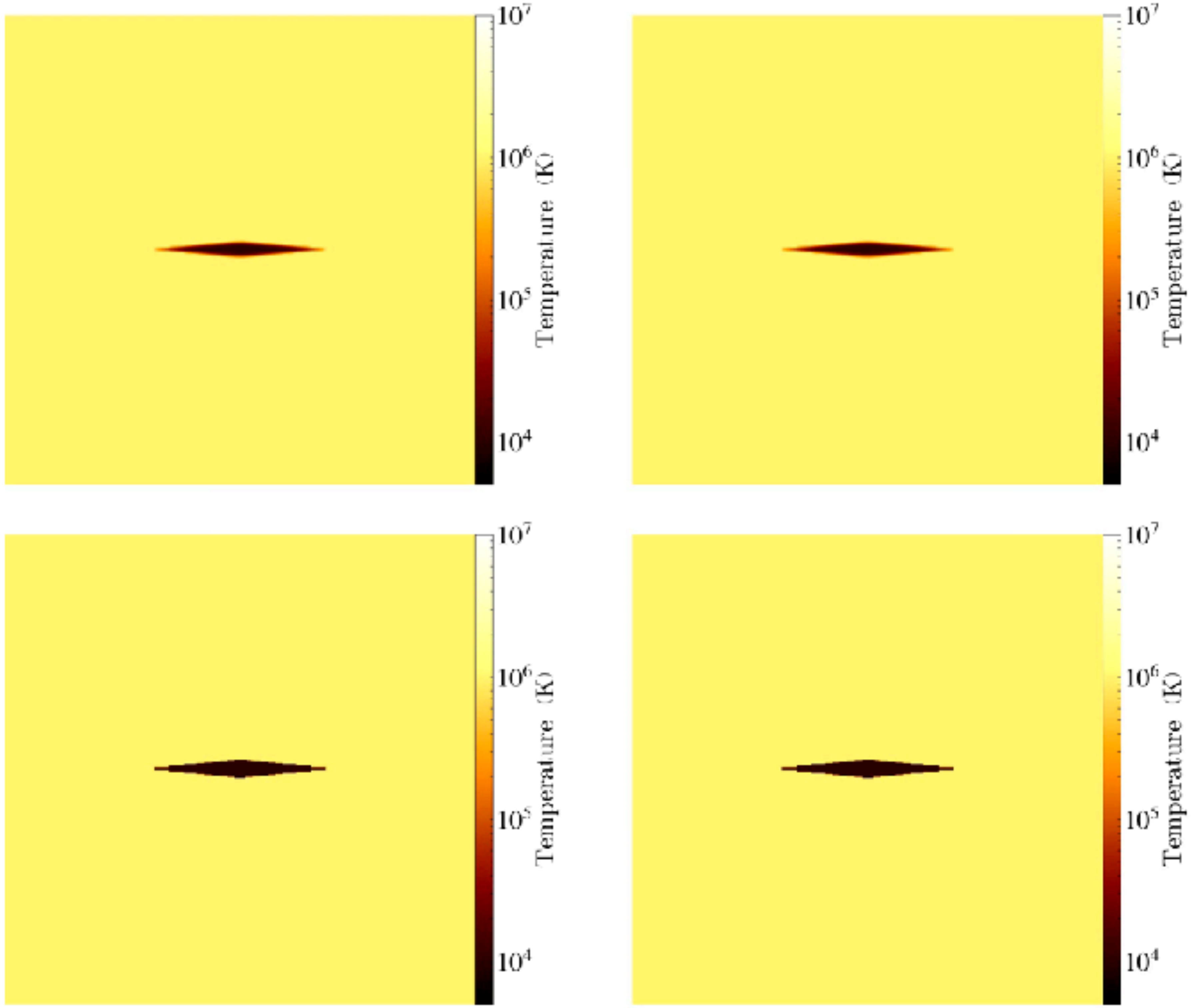
ENZO simulation code (Bryan et al. 2014)

modified AGORA initial conditions (Kim et al. 2014)

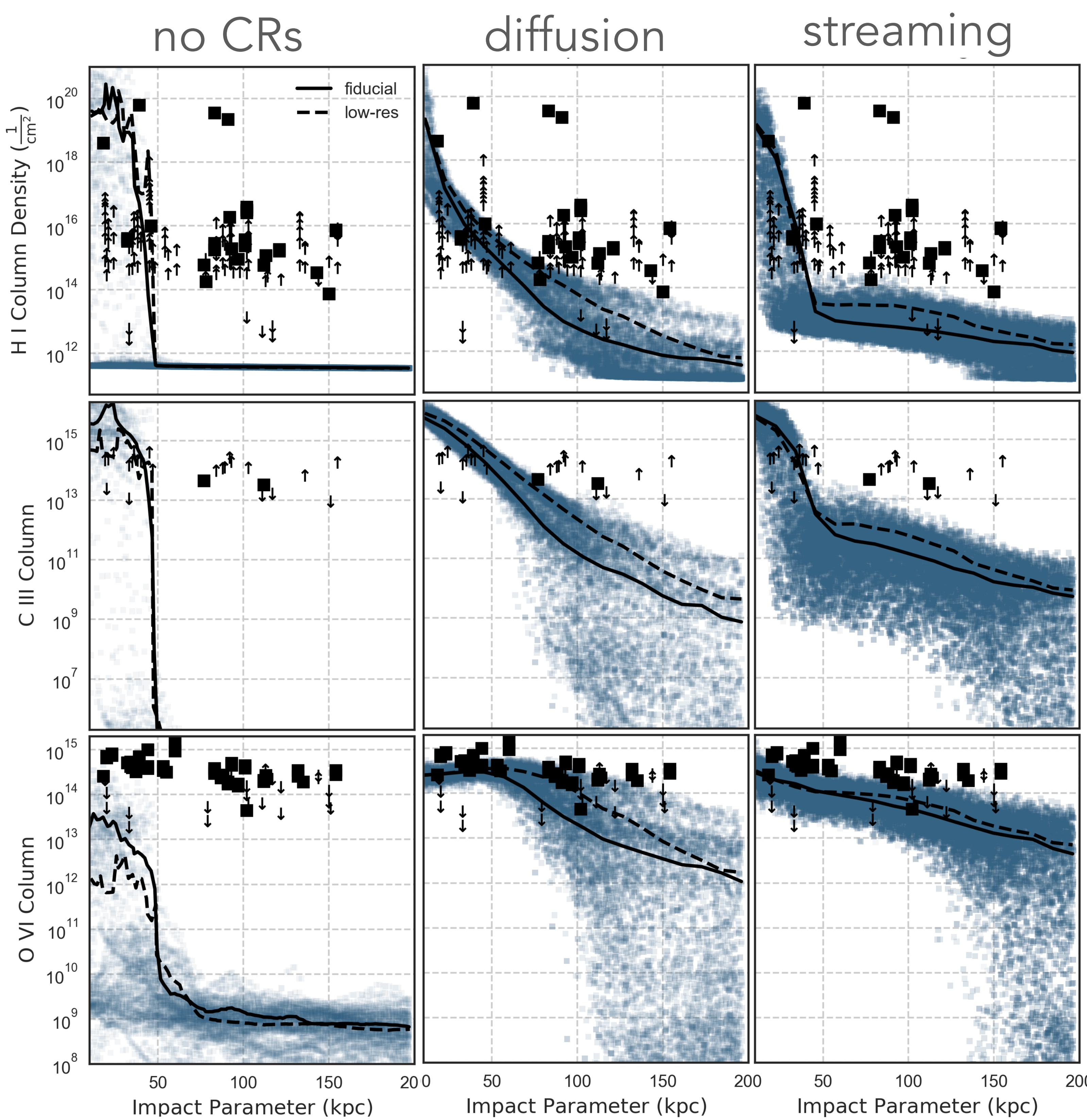
CGM TEMPERATURE SENSITIVE TO CR TRANSPORT

diffusion

streaming



IMPACT ON COLUMN DENSITIES



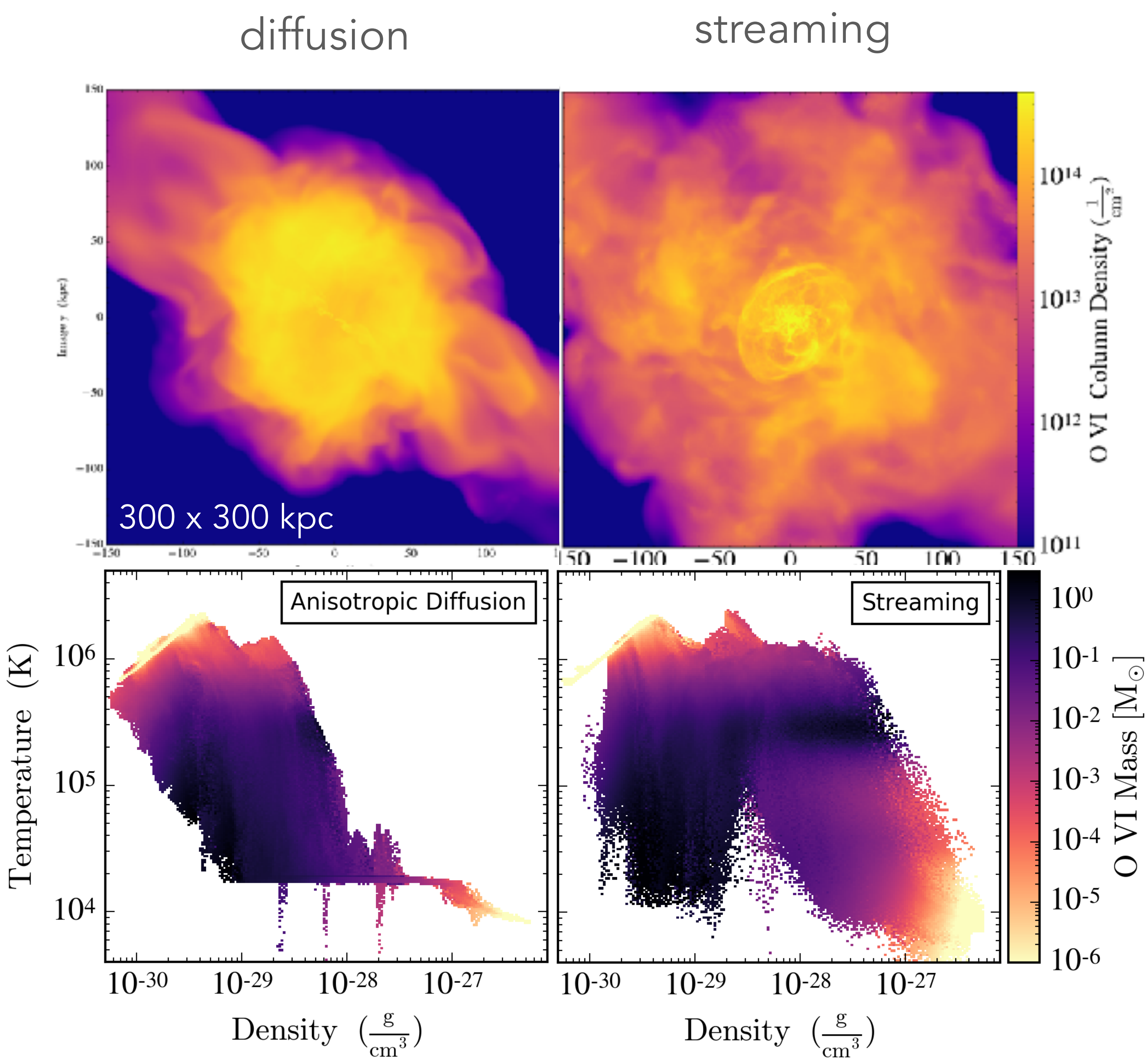
Trident

Hummels et al. 2017

Both models with cosmic ray feedback drive strong outflows and have strong ion column densities

Butsky and Quinn 2018

APPLICATION: UNDERSTANDING THE ORIGINS OF O VI



Streaming model predicts both **photoionized** and **collisionally** ionized O VI

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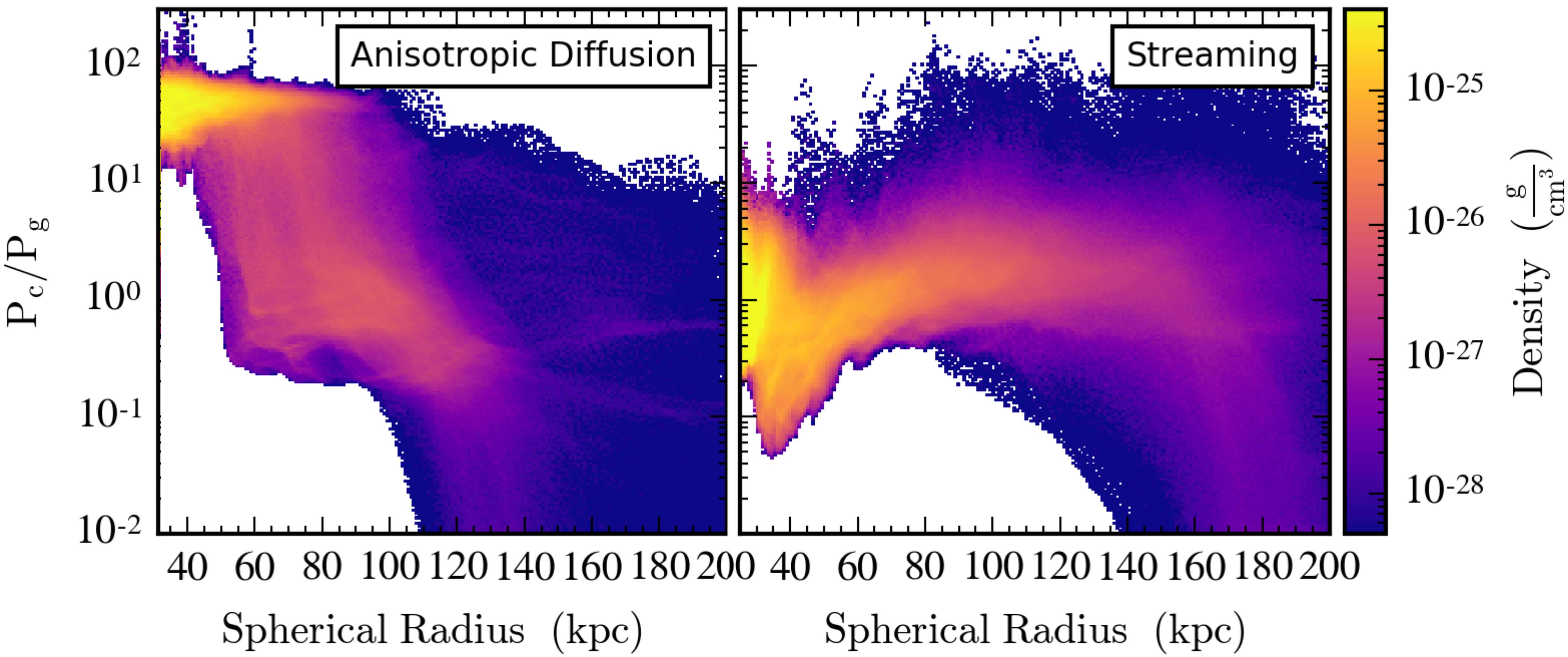
DISTRIBUTION OF CR PRESSURE IN THE CGM DEPENDS ON INVOKED TRANSPORT

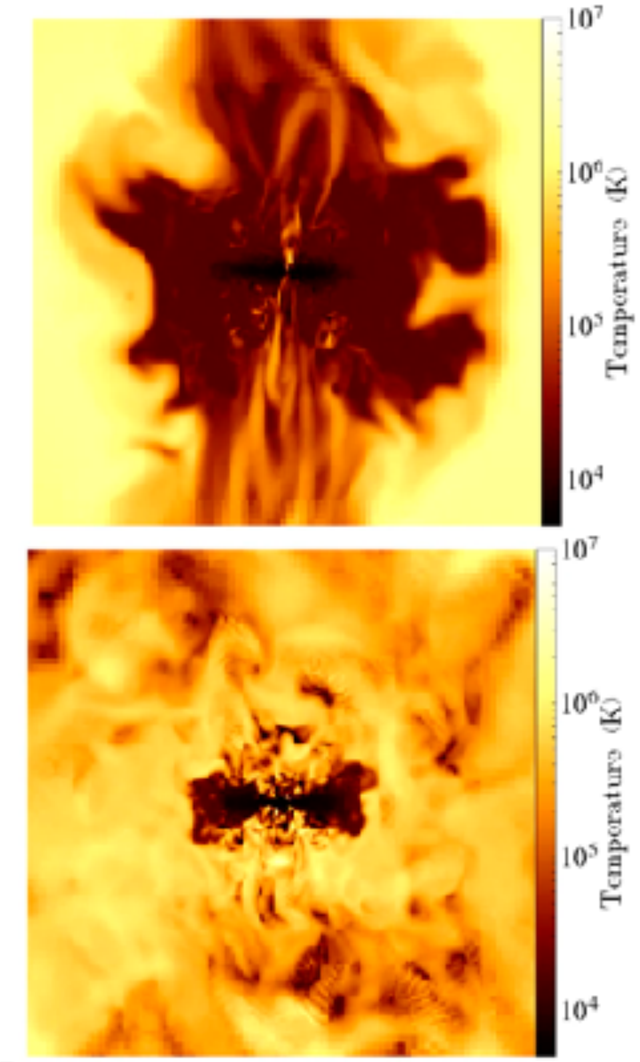


This fundamental difference in the distribution of cosmic ray pressure **cannot** be reconciled by tweaking runtime parameters. Need self-consistent model to handle both diffusion and streaming (see Jiang and Oh 2018, Thomas and Pfrommer 2018)

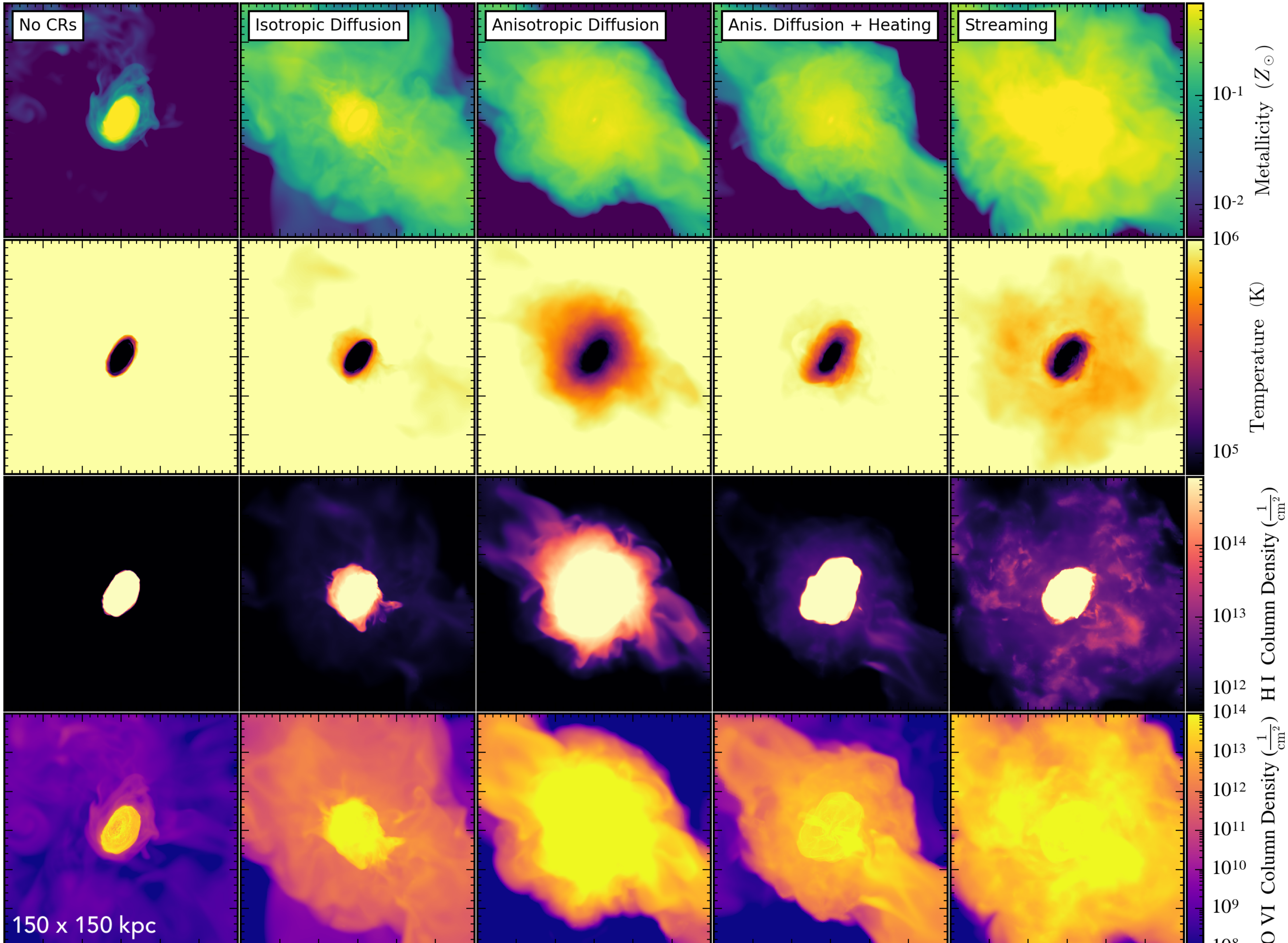
Butsky and Quinn 2018

SUMMARY

- Simulations need to include cosmic rays for robust stellar feedback models.
- Many existing simulations with cosmic ray feedback lack predictive power because simulated cosmic ray transport is poorly constrained
- The choice of cosmic ray transport matters! Need to handle cosmic ray streaming and diffusion self-consistently (see Jiang and Oh 2018; Thomas and Pfrommer 2018)
- Next steps: developing a robust prescription for simulating CR feedback, constrained by CGM observations



THANK YOU!


No CRs
Isotropic Diffusion
Anisotropic Diffusion
Anis. Diffusion + Heating
Streaming
150 x 150 kpc
Metallicity $(Z_\odot)$
10^{-1}
10^{-2}
Temperature (K)
10^6
10^5
H I Column Density $(\frac{1}{\mathrm{cm}^2})$
10^{14}
10^{13}
10^{12}
O VI Column Density $(\frac{1}{\mathrm{cm}^2})$
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^9
10^8

FLUID EQUATIONS

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \tag{1}$$

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v}^T + P_g + P_c) = -\rho \nabla \Phi \tag{2}$$

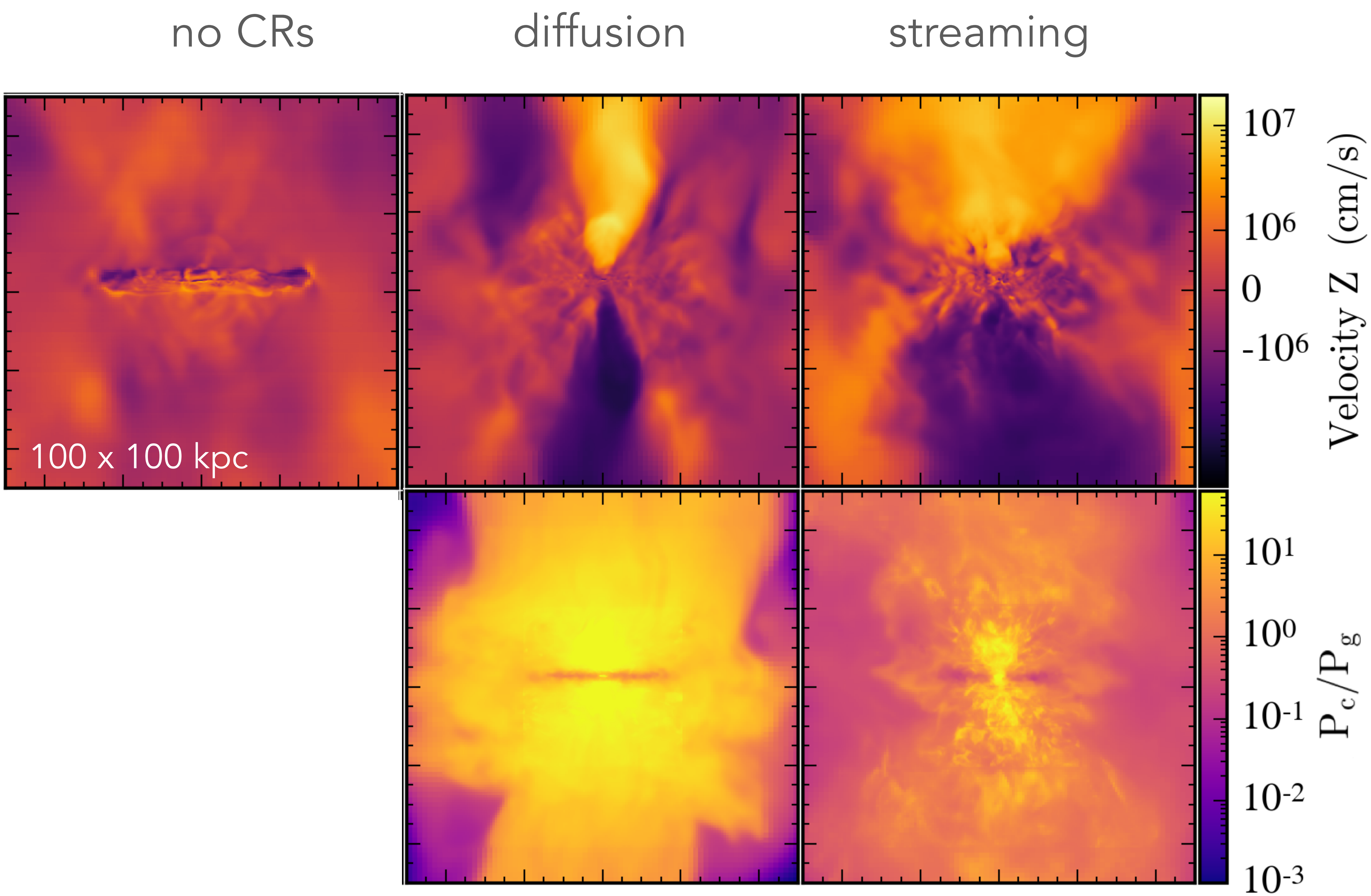
$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{B}\mathbf{v}^{\mathrm{T}} - \mathbf{v}\mathbf{B}^{\mathrm{T}}) = \mathbf{0} \tag{3}$$

$$\frac{\partial \varepsilon_g}{\partial t} + \nabla \cdot (\mathbf{v}\varepsilon_g) = -P_g \nabla \cdot \mathbf{v} + H_c + \Gamma_g + \Lambda_g \tag{4}$$

$$\frac{\partial \varepsilon_c}{\partial t} + \nabla \cdot \mathbf{F}_{\mathrm{c}} = -P_{\mathrm{c}} \nabla \cdot \mathbf{v} - H_{\mathrm{c}} + \Gamma_{\mathrm{c}} + \Lambda_{\mathrm{c}}. \tag{5}$$

$$\mathbf{F}_{\mathrm{c}} = \mathbf{v}\varepsilon_{\mathrm{c}} + \mathbf{v}_{\mathrm{s}}(\varepsilon_{\mathrm{c}} + P_{\mathrm{c}}) - \kappa_{\varepsilon}\mathbf{b}(\mathbf{b} \cdot \nabla \varepsilon_{\mathrm{c}}) \tag{6}$$

CR-DRIVEN GALACTIC WINDS SENSITIVE TO CR TRANSPORT



Butsky and Quinn 2018, *submitted to ApJ*