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

Iryna Butsky

Blue Waters Graduate Fellow 2016-2017

University of Washington

Advisor: Thomas R. Quinn

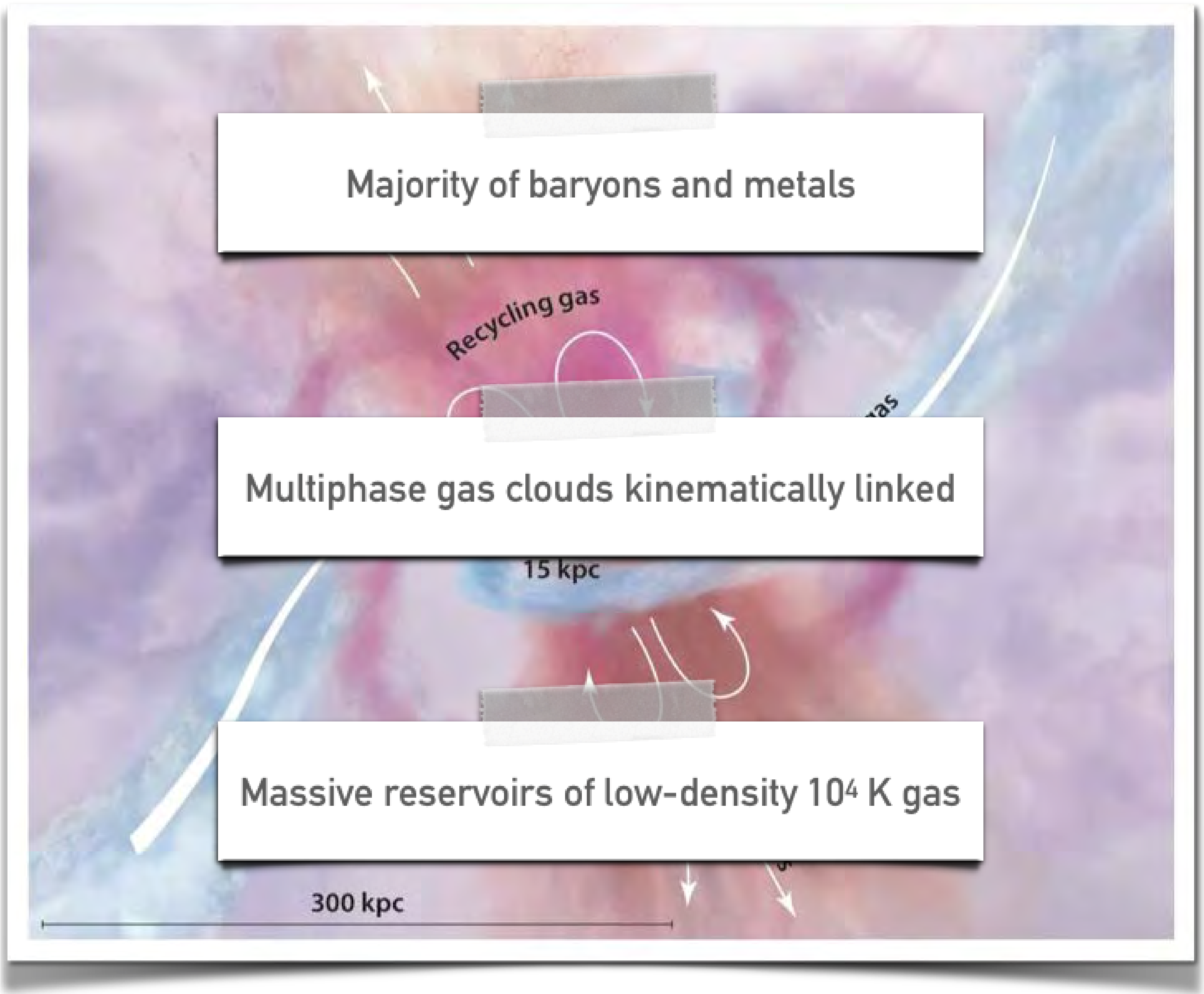
BLUE WATERS
SUSTAINED PETASCALE COMPUTING

MOTIVATION (KEY CHALLENGES)

METHODS (WHY BLUE WATERS)

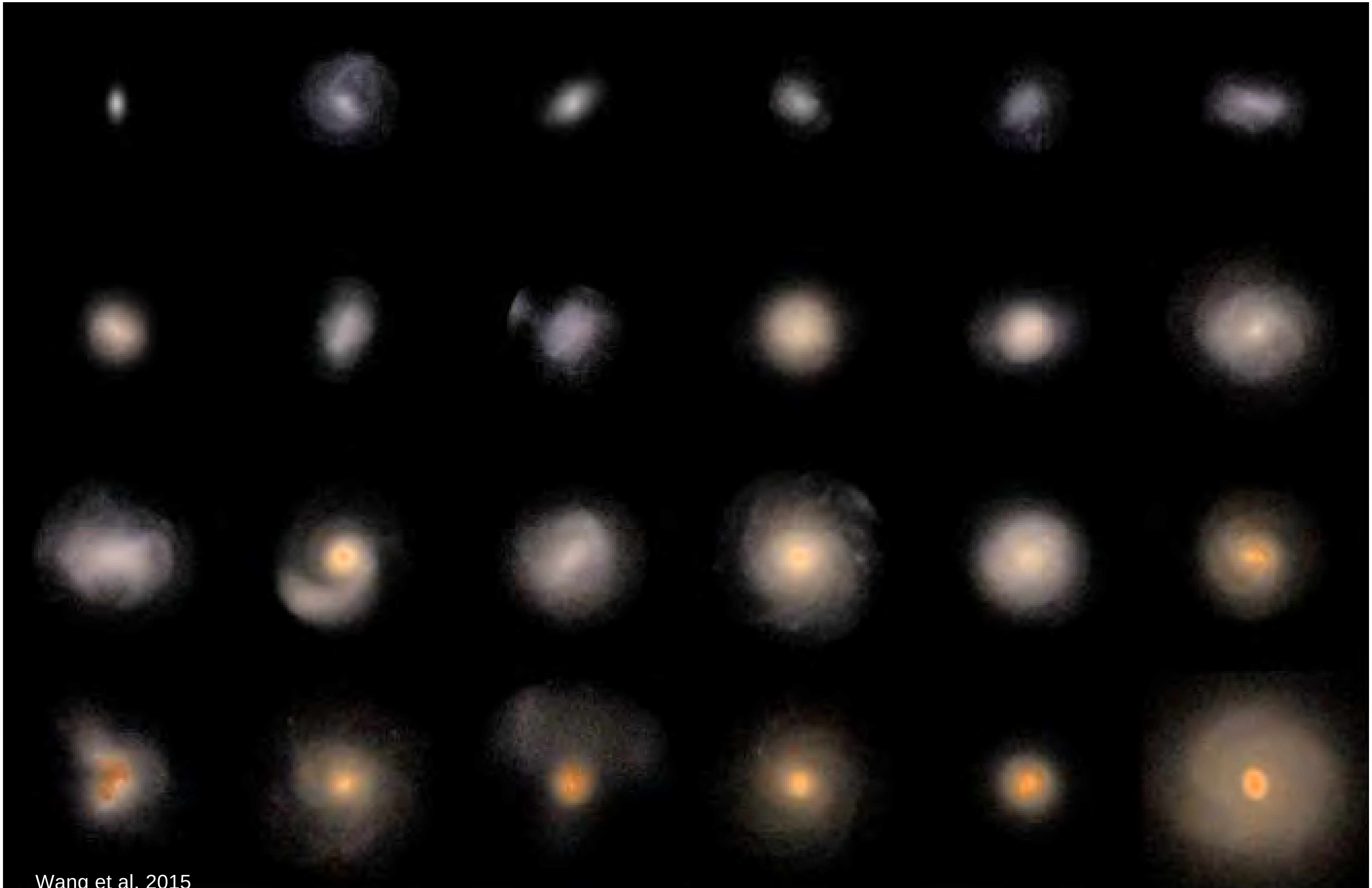
RESULTS (ACCOMPLISHMENTS)

THE CIRCUMGALACTIC MEDIUM (CGM)



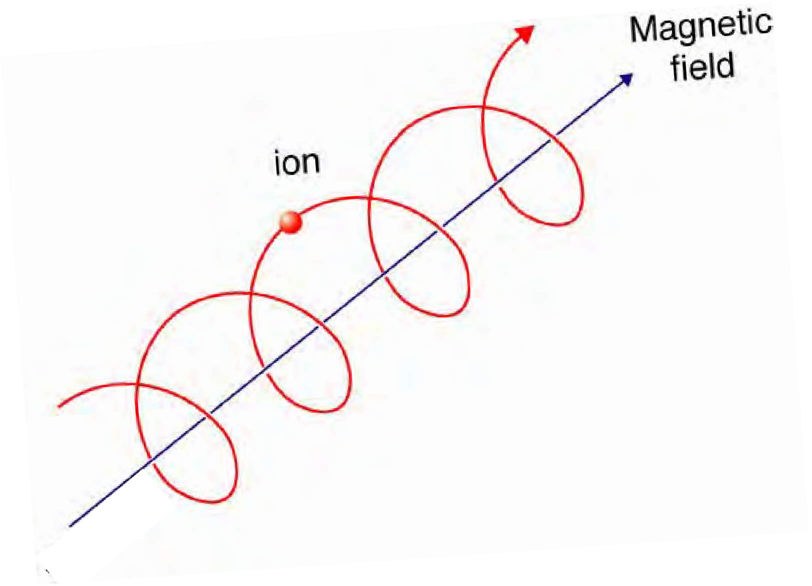
Tumlinson, Peeples, Werk 2017

SIMULATIONS REPRODUCE GALACTIC DISK STRUCTURE, BUT NOT CGM

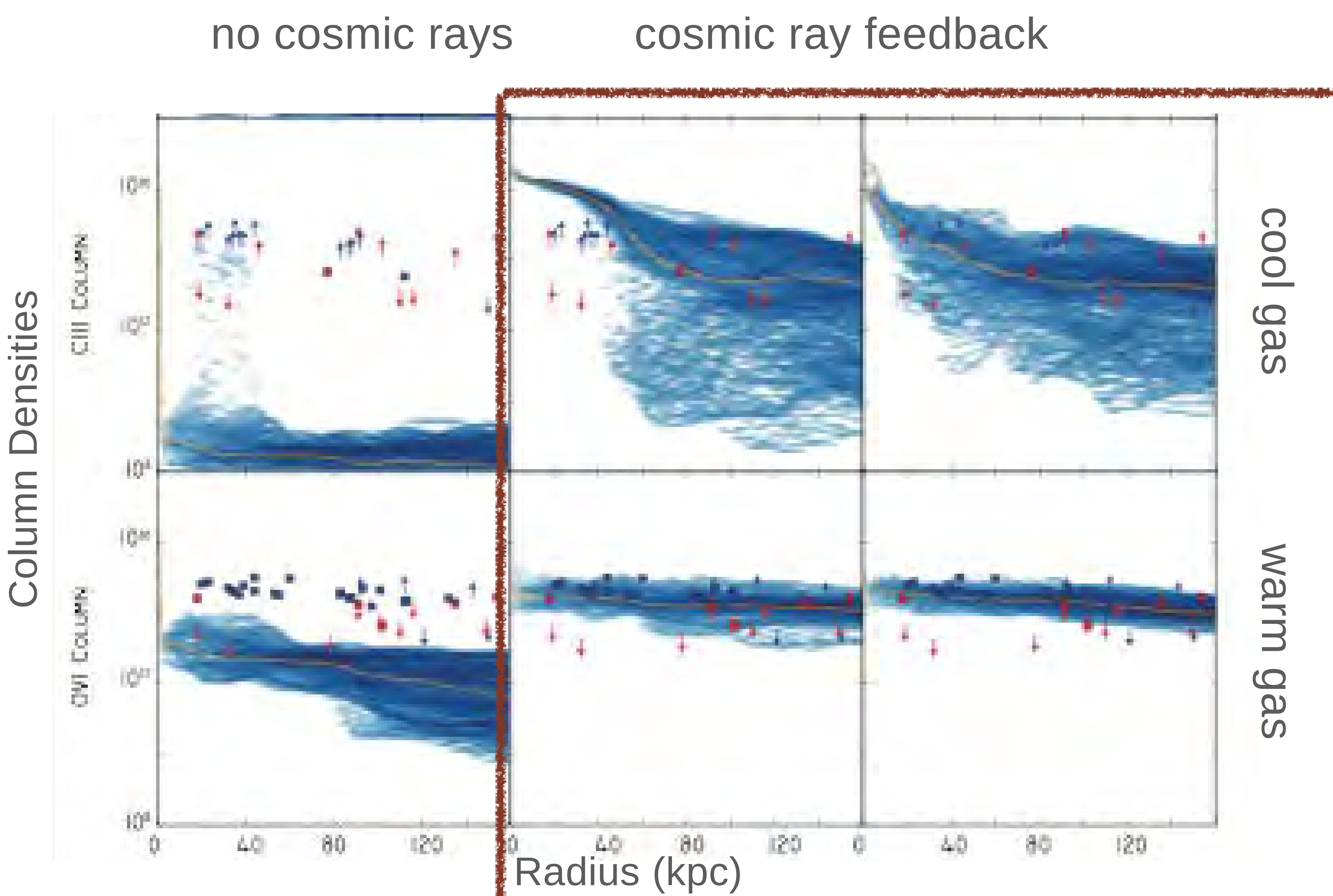


NON-THERMAL SUPERNOVA FEEDBACK: COSMIC RAYS

- Charged particles (protons) accelerated to relativistic velocities in extreme shocks (supernovae)
- Propagate along magnetic field lines
- Provide pressure support to thermal gas
  - Drive outflows
  - Support low-density 10^4 K gas



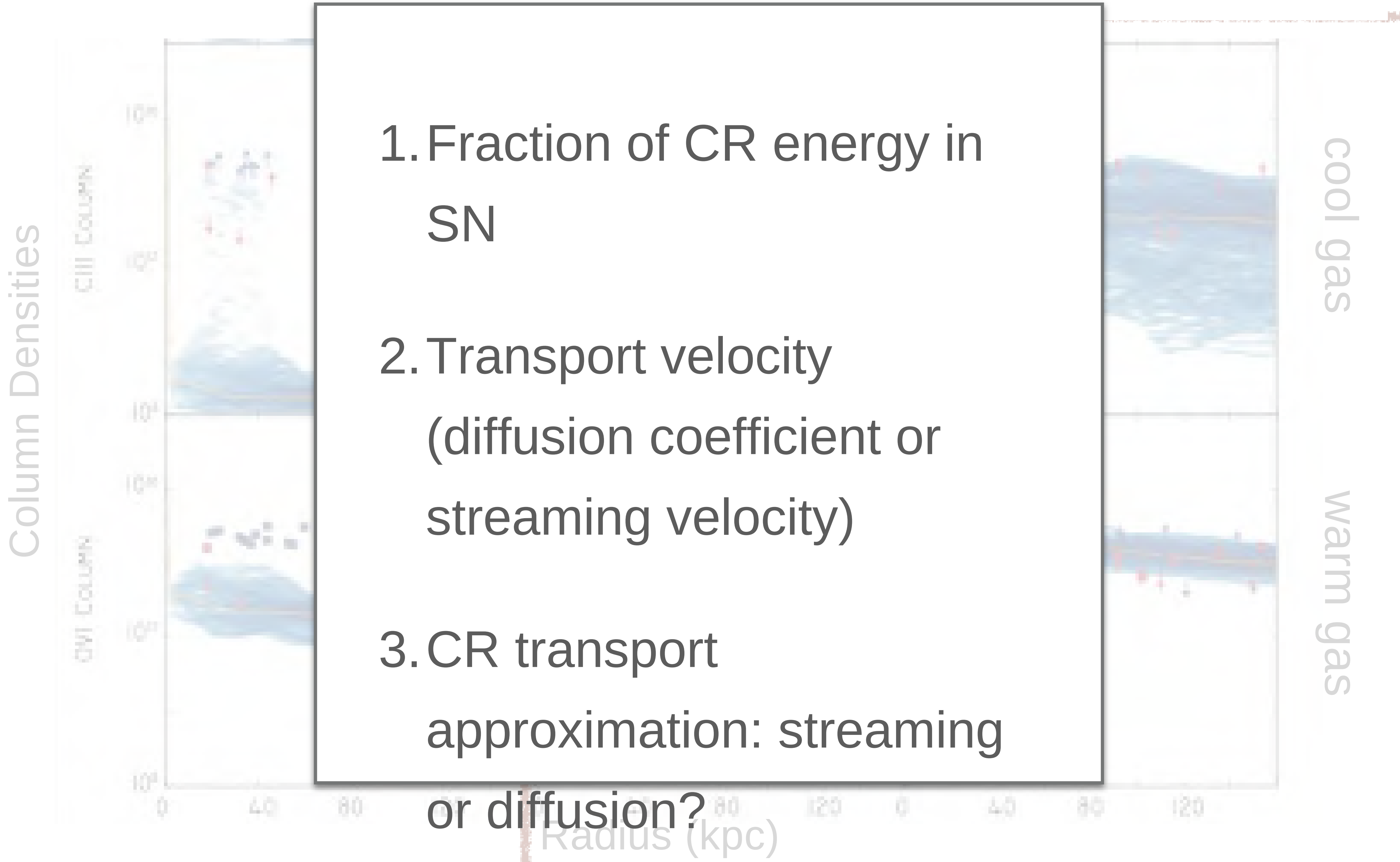
SIMULATIONS WITH COSMIC RAY FEEDBACK BETTER MATCH OBSERVATIONS



Salem, Bryan, and Corlies 2016

SIMULATIONS WITH COSMIC RAY FEEDBACK BETTER

sources of uncertainty in modeling



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

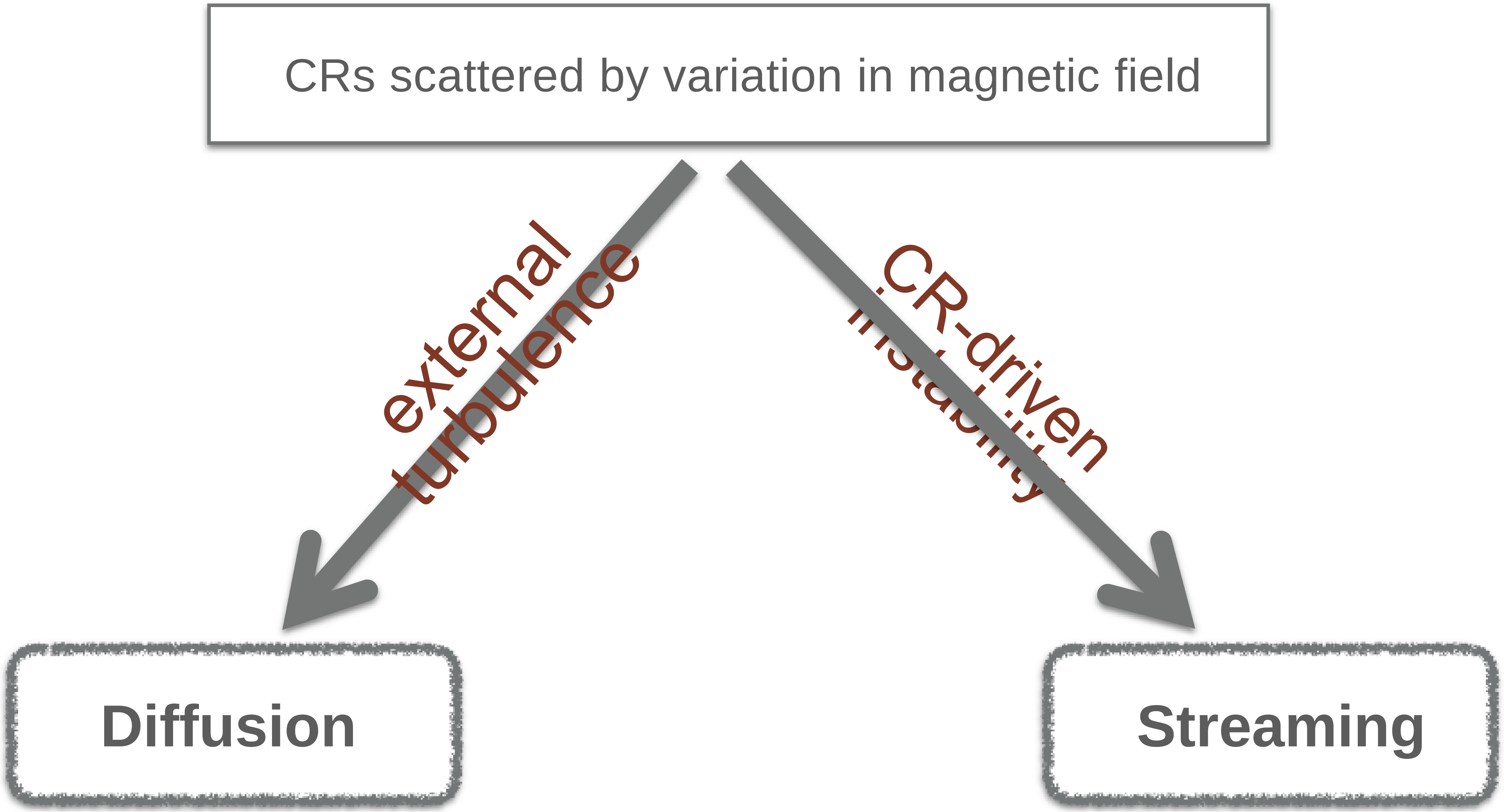
Salem, Bryan, and Corlies 2016

MOTIVATION (KEY CHALLENGES)

METHODS (WHY BLUE WATERS)

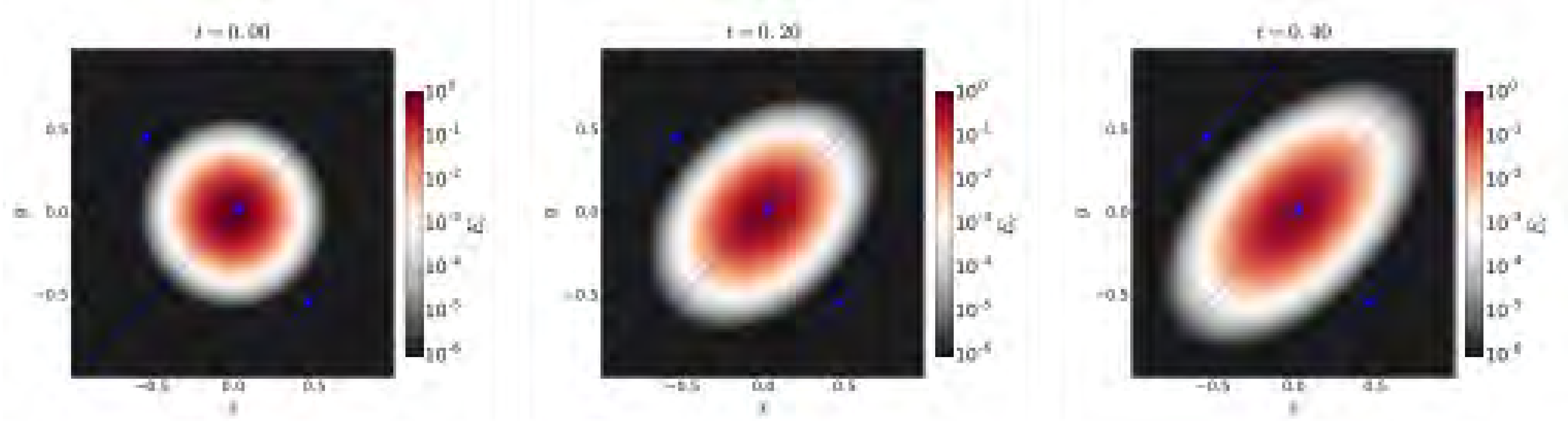
RESULTS (ACCOMPLISHMENTS)

MODELING THE COSMIC RAY “FLUID”

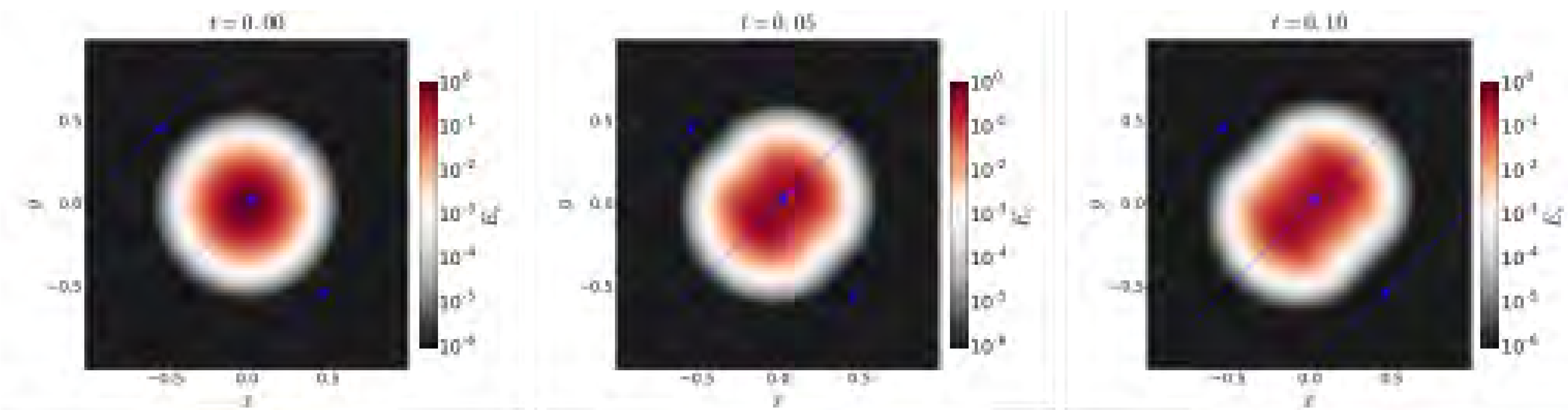


Jiang and Oh 2018

DIFFUSION

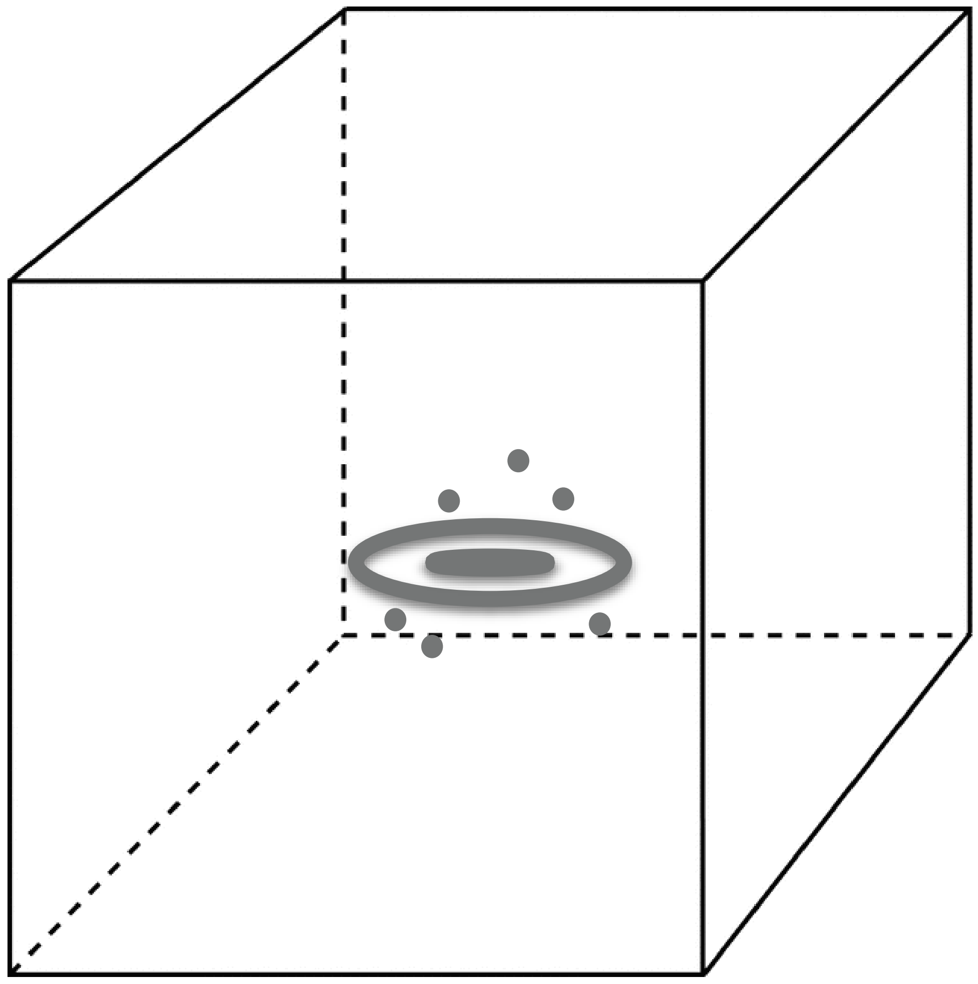


STREAMING



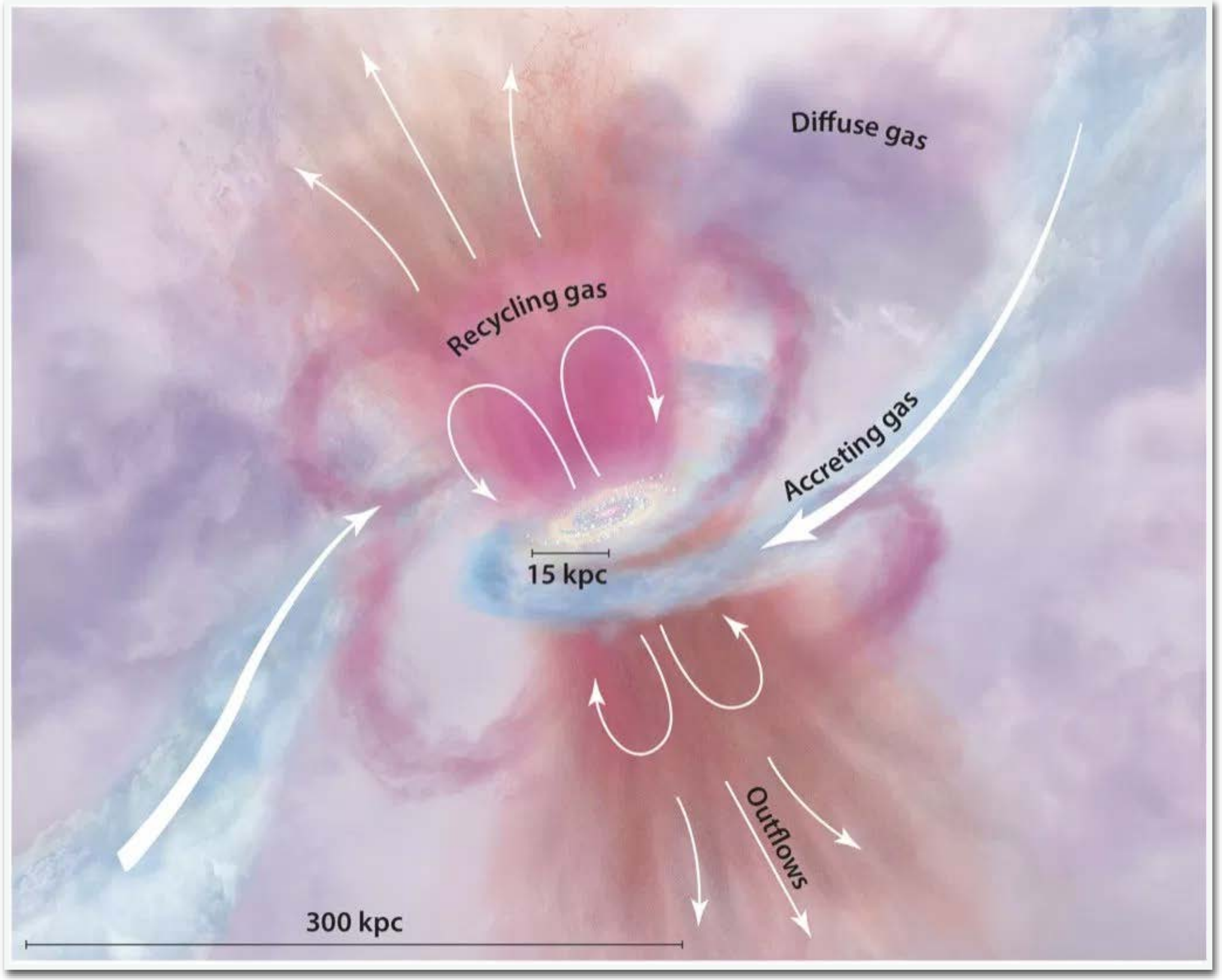
METHODS

- Suite of isolated disk galaxies (Milky Way type)
  - Supernova source of cosmic rays
  - Differ in cosmic ray transport
- ENZO astrophysical simulation code (Bryan et al. 2014)
- Analysis tools:
  - yt (Turk et al. 2011)
  - Trident (Hummels et al. 2016)



WHY BLUE WATERS

- Huge variation in simulation scale
- Each cell follows complex interaction rules



WHY BLUE WATERS

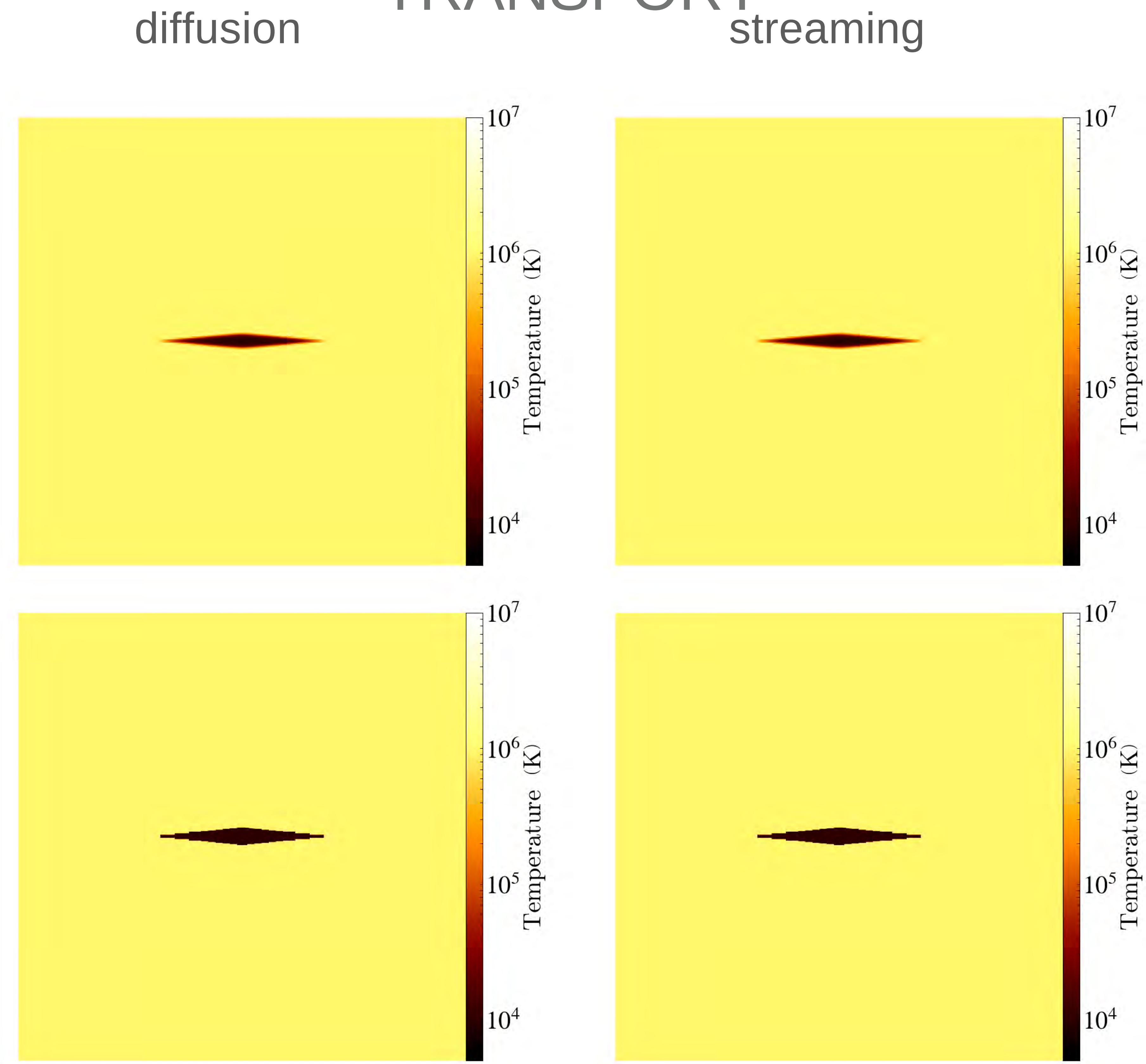
- Huge variation in simulation scale
- Each cell follows complex interaction rules
- Efficient parallelization
- Sufficient data storage
- Awesome support team!

KEY CHALLENGES (MOTIVATION)

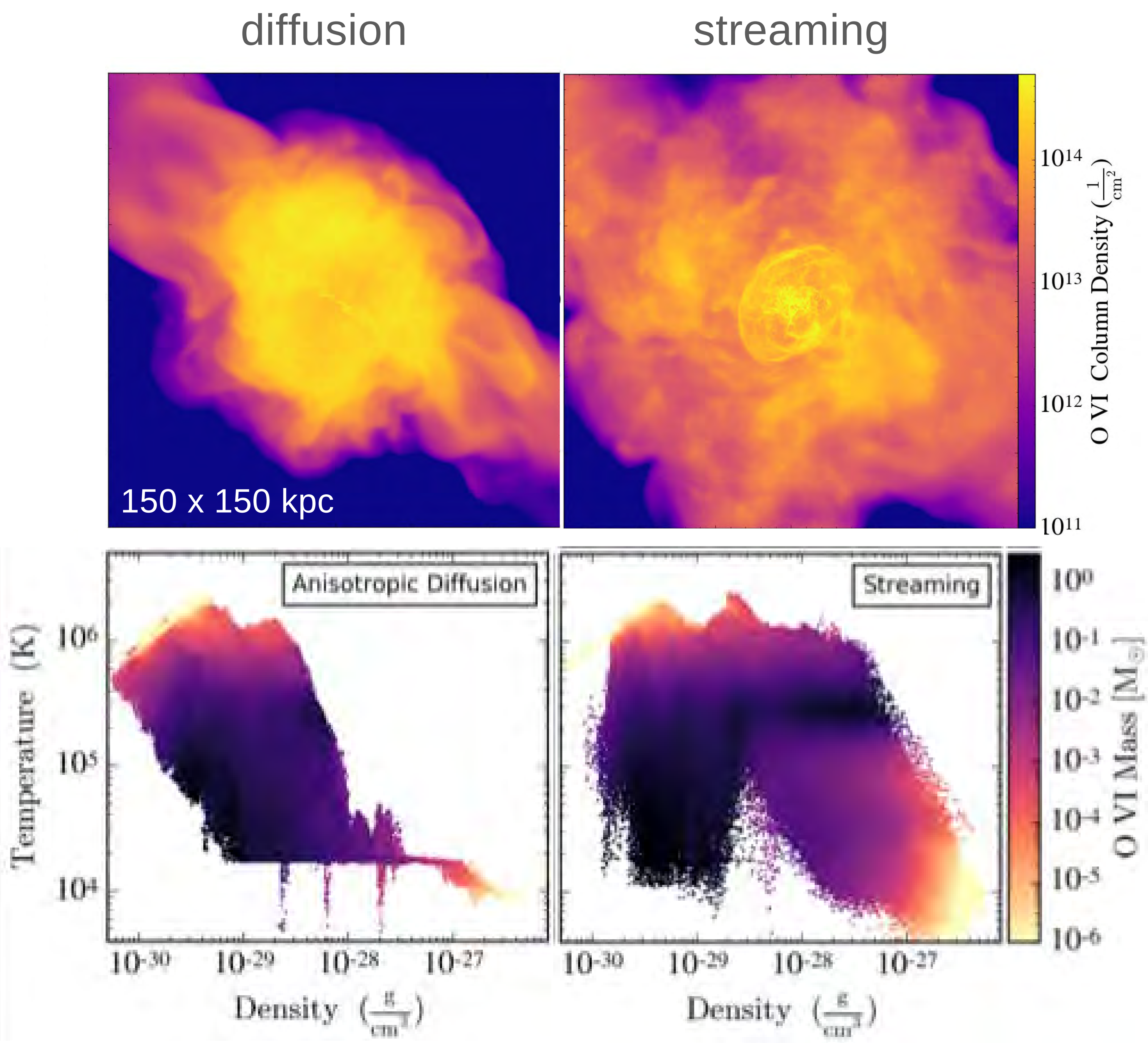
WHY BLUE WATERS (METHODS)

ACHIEVEMENTS (RESULTS)

CGM TEMPERATURE SENSITIVE TO CR TRANSPORT

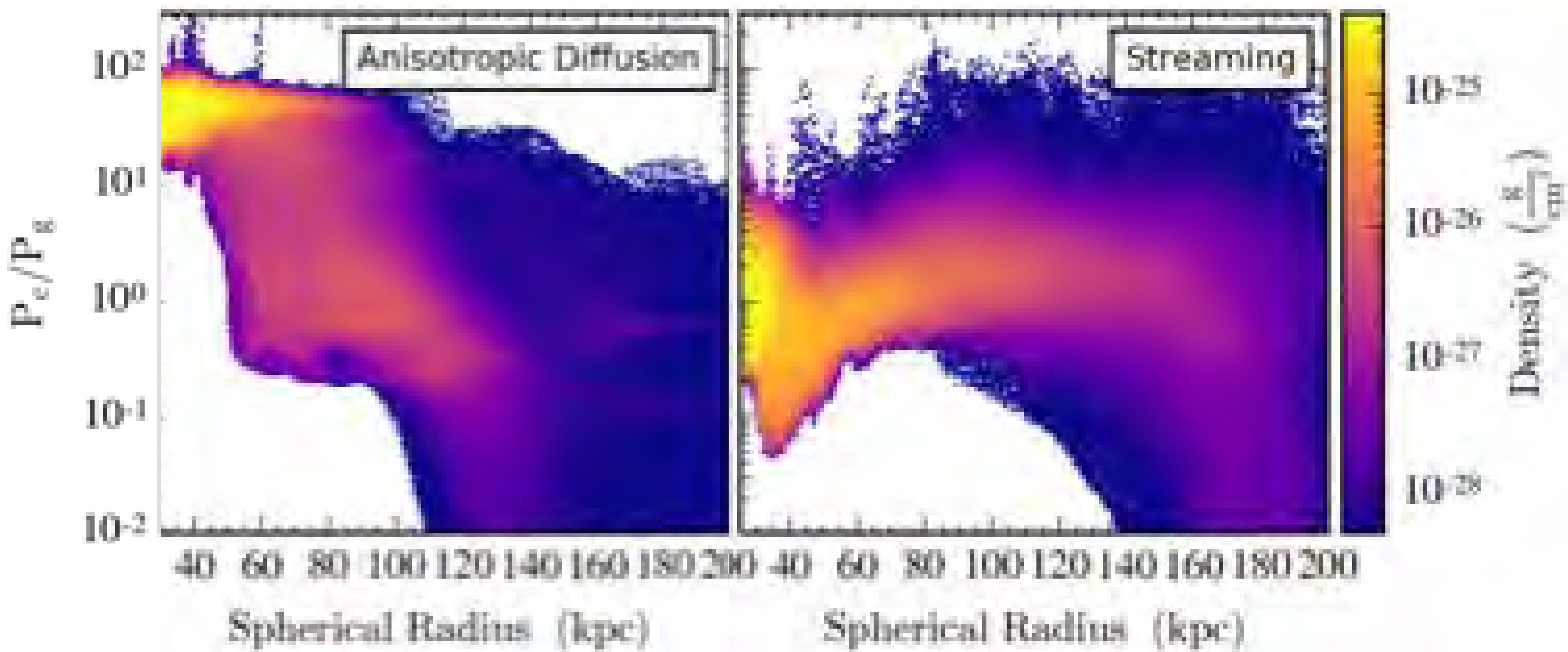


APPLICATION: UNDERSTANDING THE ORIGINS OF O VI



Butsky and Quinn 2018, submitted to ApJ

DISTRIBUTION OF CR PRESSURE IN THE CGM DEPENDS ON INVOKED TRANSPORT

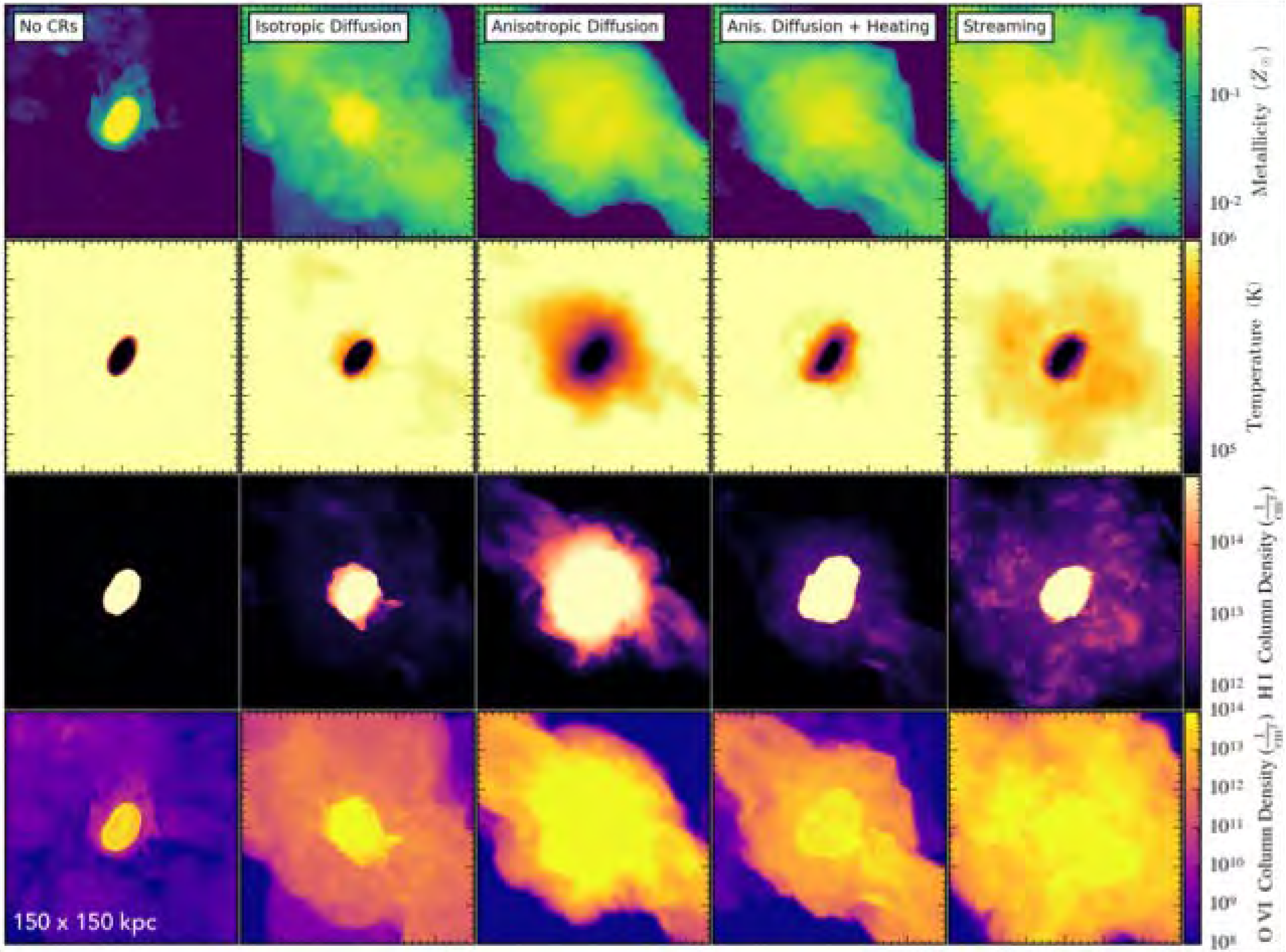


Butsky and Quinn 2018, submitted to ApJ

SUMMARY/FUTURE WORK

- Cosmic rays are observed to be in equipartition with the turbulent and magnetic pressures in the galaxy
- Cosmic ray feedback in simulations drives stronger outflows and can reproduce observed ionization structure of the GGM
- Existing simulations with cosmic ray feedback lack predictive power because simulated cosmic ray transport is poorly constrained
- Streaming is a better approximation than diffusion, but in reality, both effects are present. Need to model both self-consistently (e.g. Jiang & Oh 2018, Thomas and Pfrommer 2018)
- Need detailed parameter studies!

THANK YOU!



Butsky and Quinn 2018, submitted to ApJ

FLUID EQUATIONS

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

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

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

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

$$\frac{\partial \varepsilon_c}{\partial t} + \nabla \cdot \mathbf{F}_c = -P_c \nabla \cdot \mathbf{v} - H_c + \Gamma_c + \Lambda_c \,. \qquad (5)$$

$$\mathbf{F}_c = \mathbf{v}\varepsilon_c + \mathbf{v}_s(\varepsilon_c + P_c) - \kappa_c \mathbf{b}(\mathbf{b} \cdot \nabla \varepsilon_c) \qquad (6)$$