Title: Cosmic Ray Coupling and Subgrid Modeling in the CGM

Speakers: Irina Butsky

Collection/Series: Cosmic Ecosystems

Subject: Cosmology

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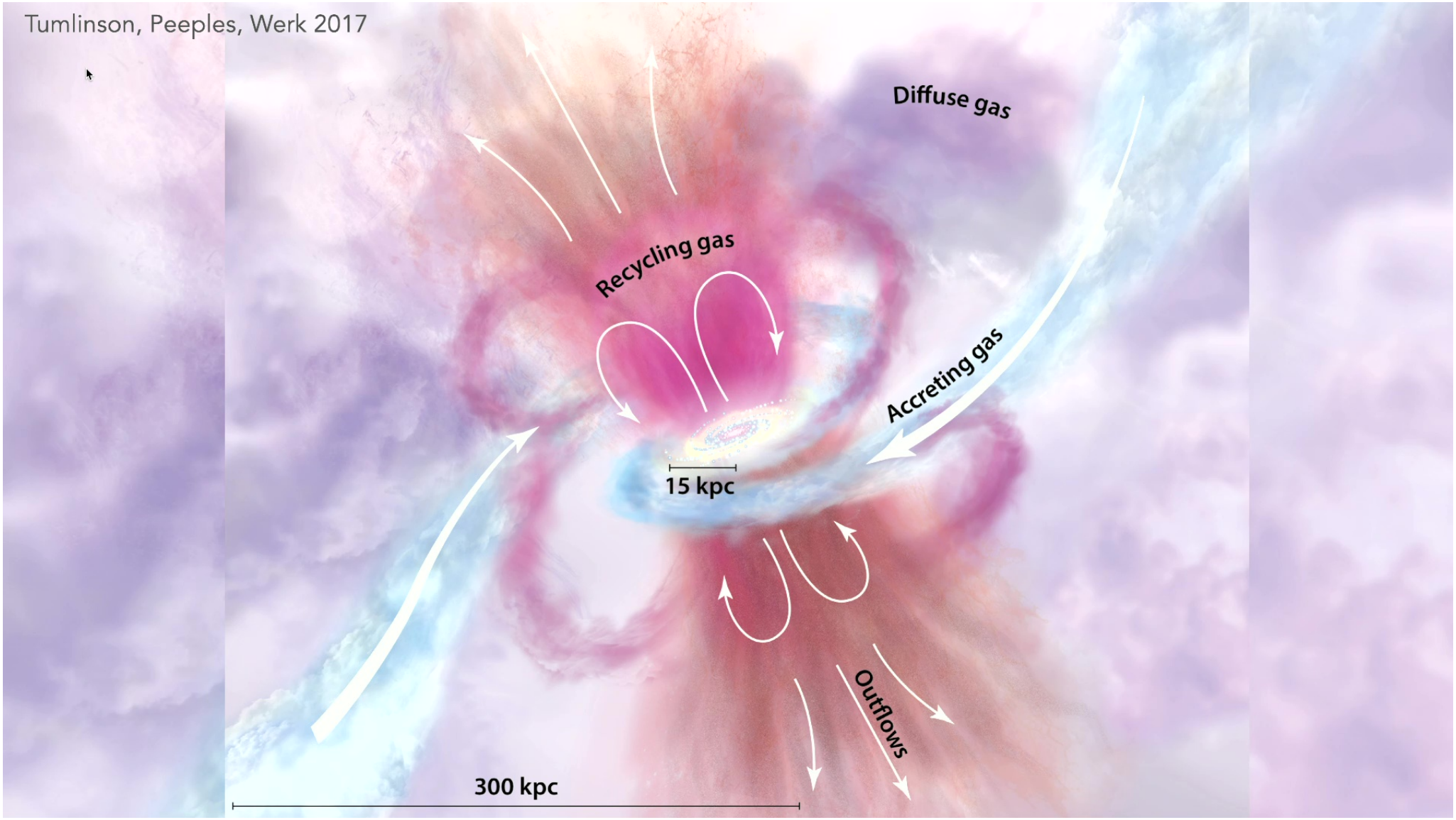
Abstract:

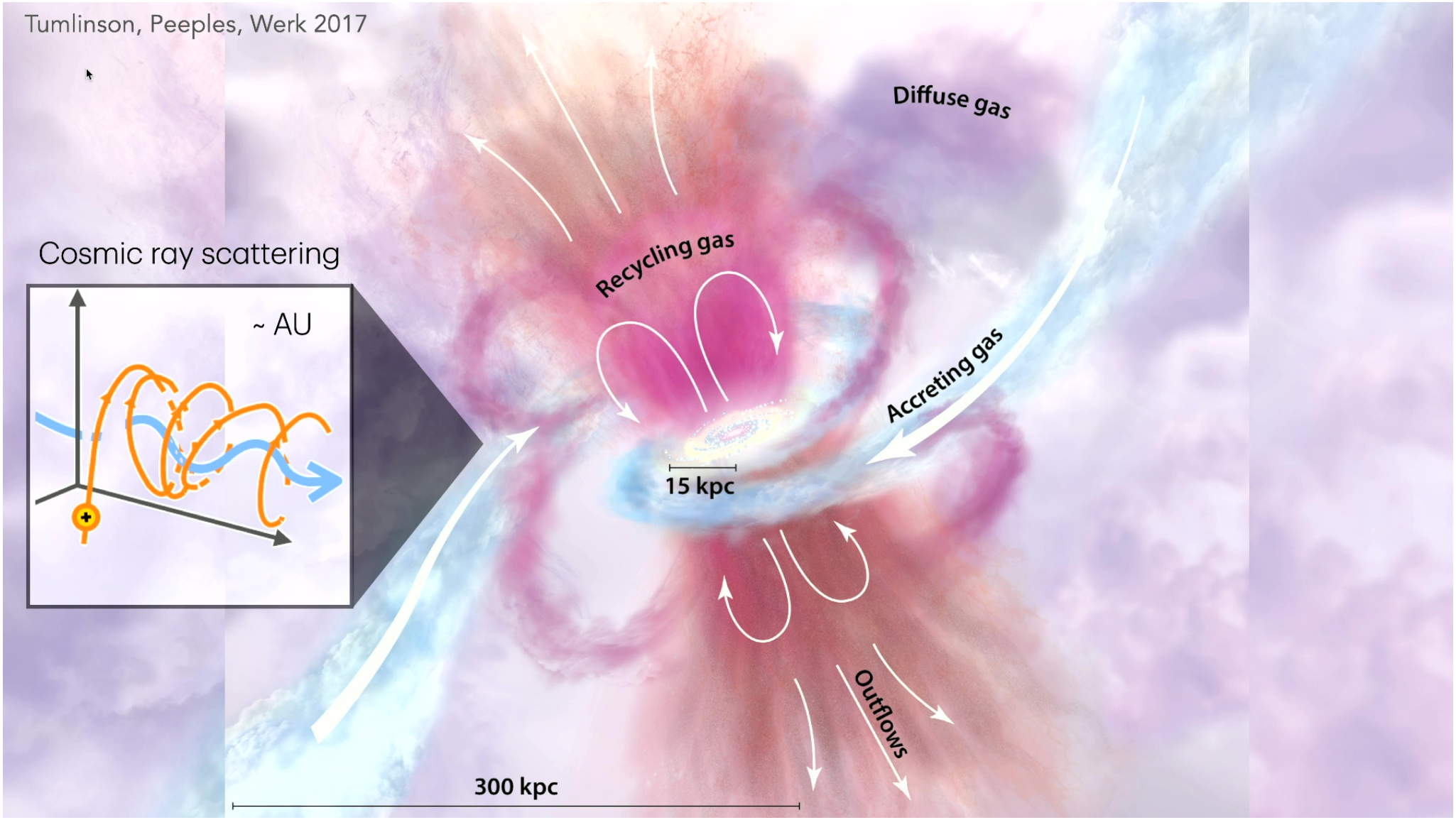
Despite its vast extent—spanning hundreds of kiloparsecs beyond the galactic disk—the circumgalactic medium (CGM) is shaped by microphysical processes operating on much smaller scales. One key example is the coupling between cosmic rays and gas. Under the right conditions, cosmic rays can dominate the pressure support in the CGM of low-redshift L* galaxies. However, this coupling depends sensitively on AU-scale magnetic field fluctuations—well below the resolution limit of modern galaxy-scale simulations. In this talk, I will highlight recent theoretical developments in cosmic-ray transport and their implications for CGM pressure profiles. I'll also introduce CGSM, a new subgrid model designed to represent unresolved cold gas structures in hydrodynamic simulations, and discuss its potential to bridge the gap between microphysics and galaxy evolution.

Cosmic-ray Coupling and Subgrid Modeling in the CGM

Iryna Butsky

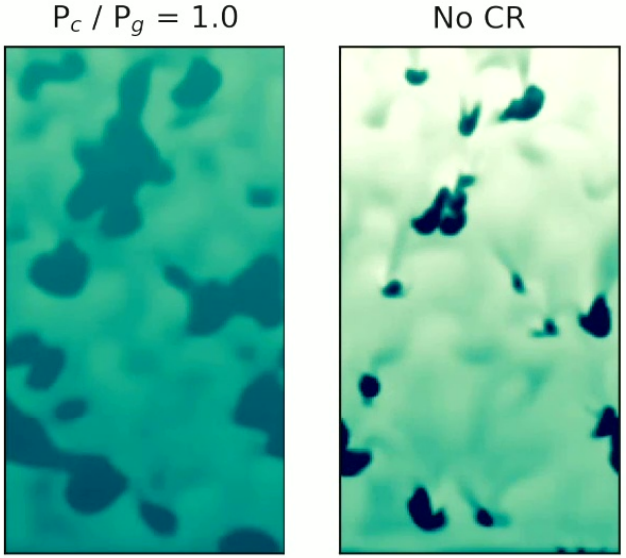
Cosmic Ecosystems
Perimeter Institute
July 31, 2025


Tumlinson, Peeples, Werk 2017
Diffuse gas
Recycling gas
Accreting gas
15 kpc
Outflows
300 kpc


Tumlinson, Peeples, Werk 2017
Diffuse gas
Recycling gas
Accreting gas
Cosmic ray scattering
~ AU
15 kpc
Outflows
300 kpc

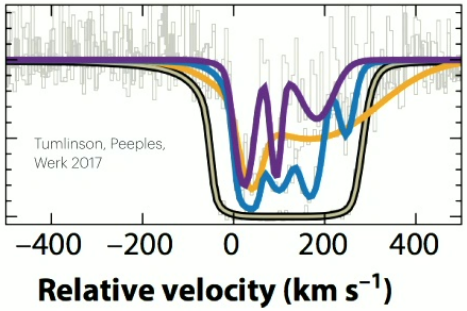
Cosmic ray pressure can explain many CGM observations

Prevalence and inferred low densities of cool gas



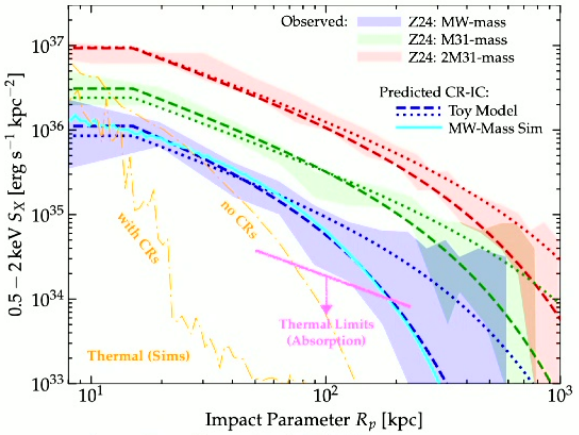
(e.g. Butsky et al. 2018, 2020)

Kinematic alignment

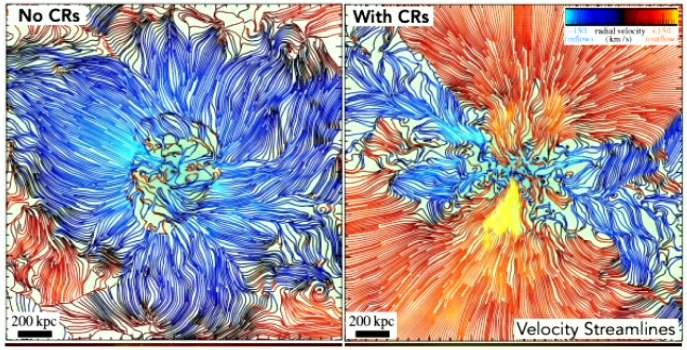


(e.g. Butsky et al. 2022)

Soft X-ray emission



(e.g. Hopkins et al. 2025)

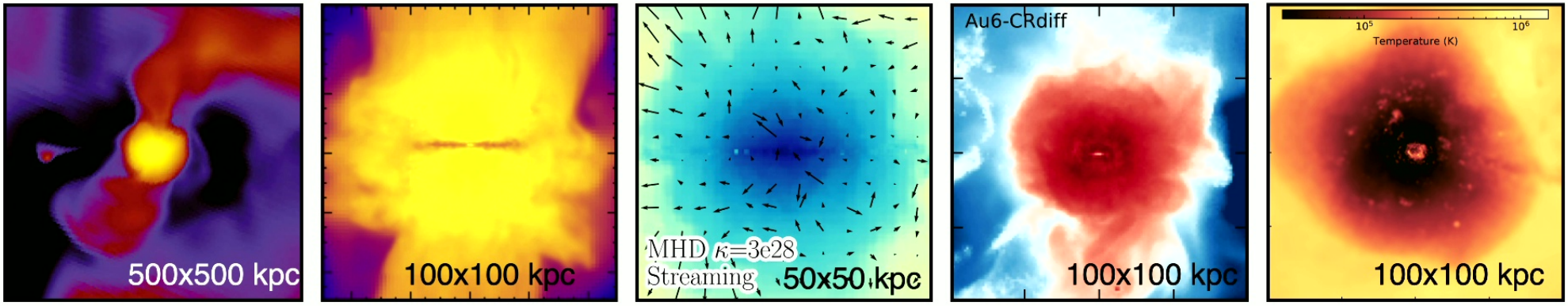


Accelerating outflows

Quataert and Hopkins 2025; Ji et al. 2020, 2021

Cool core clusters?...

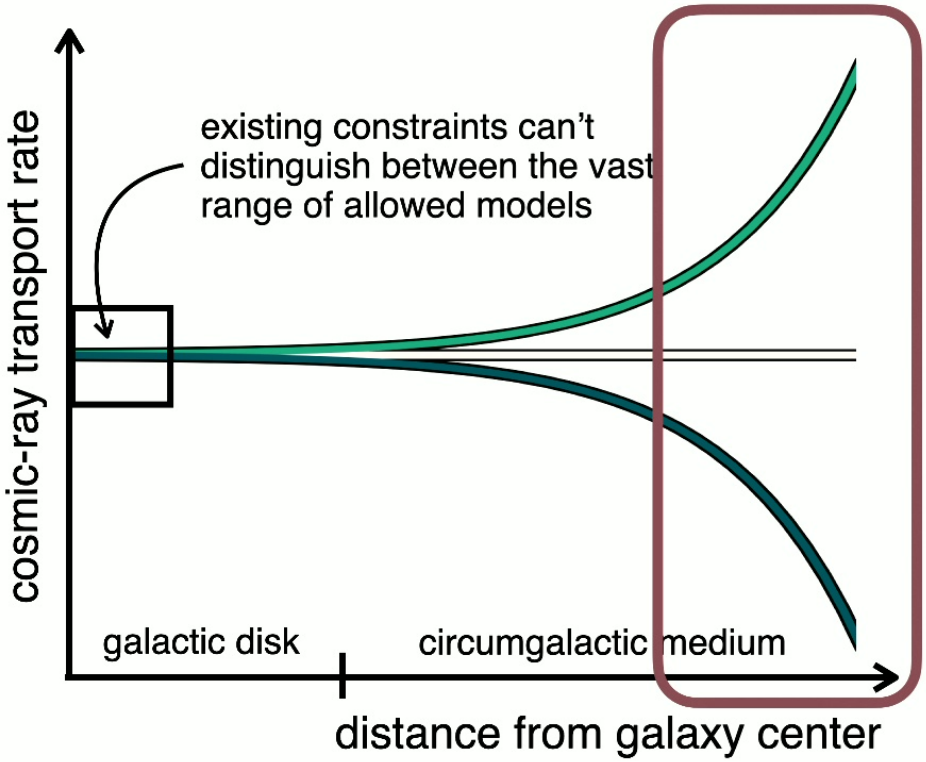
Cosmic rays may be dominant CGM pressure
(around low-redshift L* galaxies)

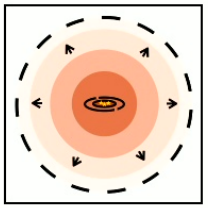


Salem et al. 2016 | Butsky and Quinn 2018 | Chan et al. 2019 | Buck et al. 2020 | Butsky et al. 2022

caveat: predictions are sensitive to assumed models of cosmic-ray transport

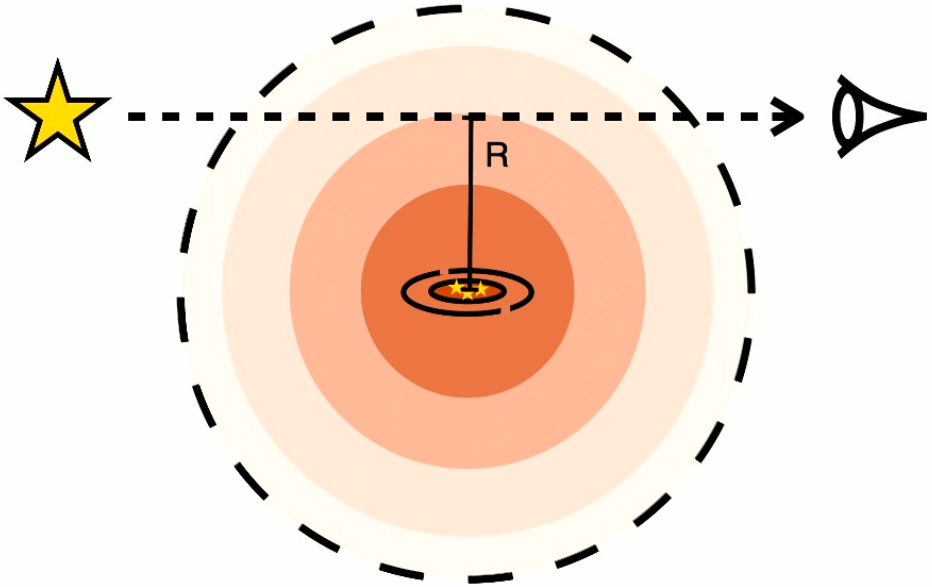
~GeV Cosmic-ray transport is severely under-constrained





Option 1: constrain cosmic-ray transport in CGM

Constraining CR transport in the CGM



average star formation rate

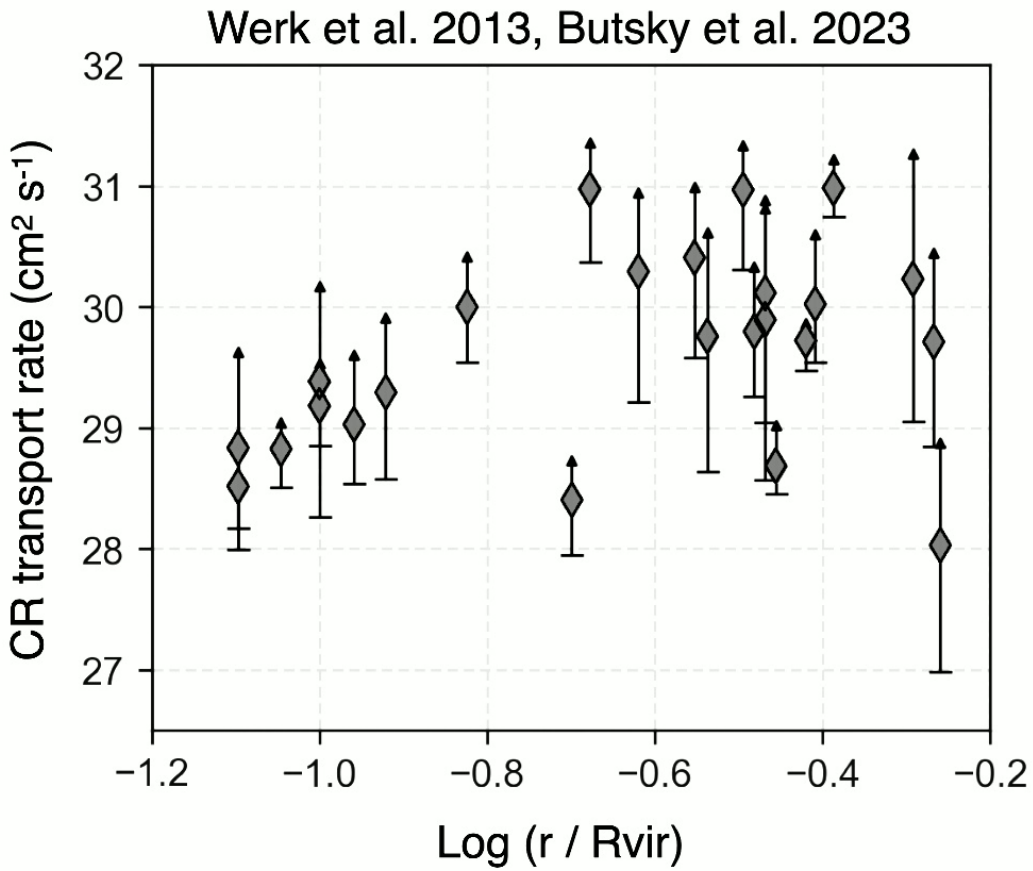
$$\kappa_{\mathrm{eff}}^{\mathrm{min}}(R) \sim \frac{\langle \dot{M}_* \rangle}{N_H V_c^2}$$

total hydrogen column density

circular velocity

Butsky et al. 2023

First constraints on CR transport in CGM using COS-Halos!



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Shreya Nakum
UC Irvine '27

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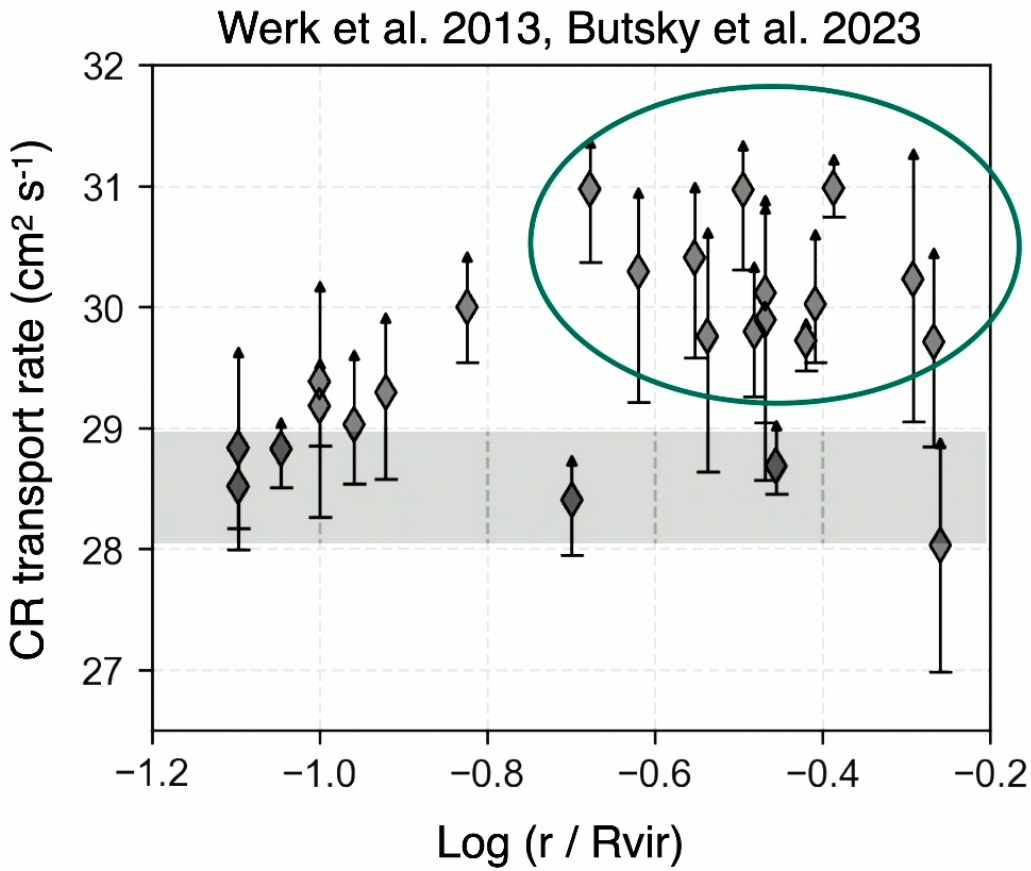

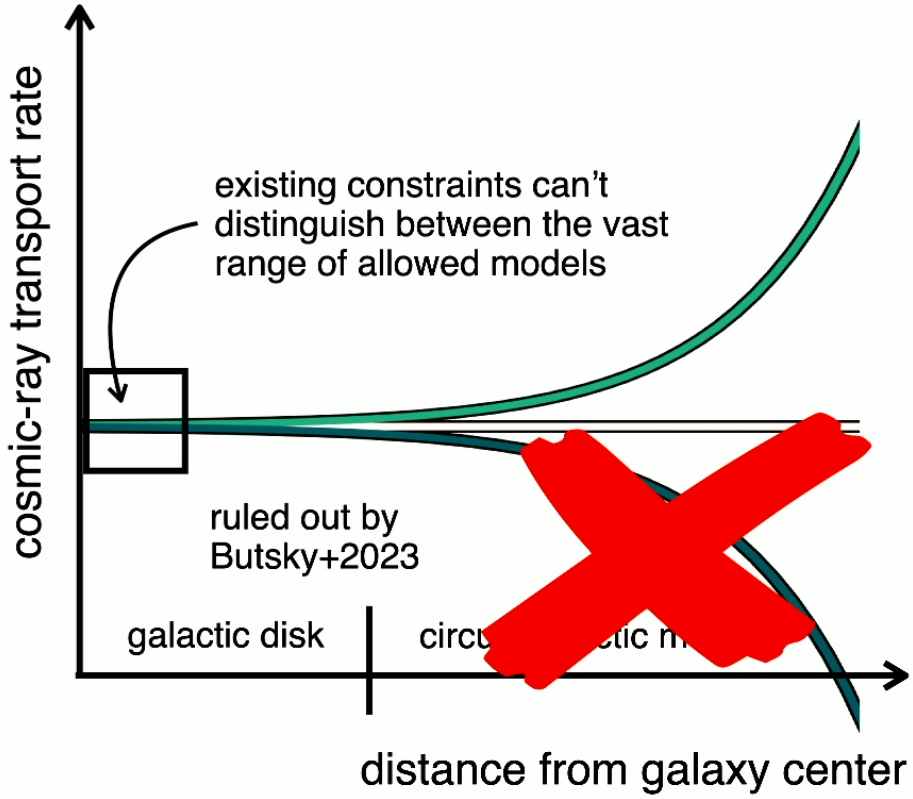

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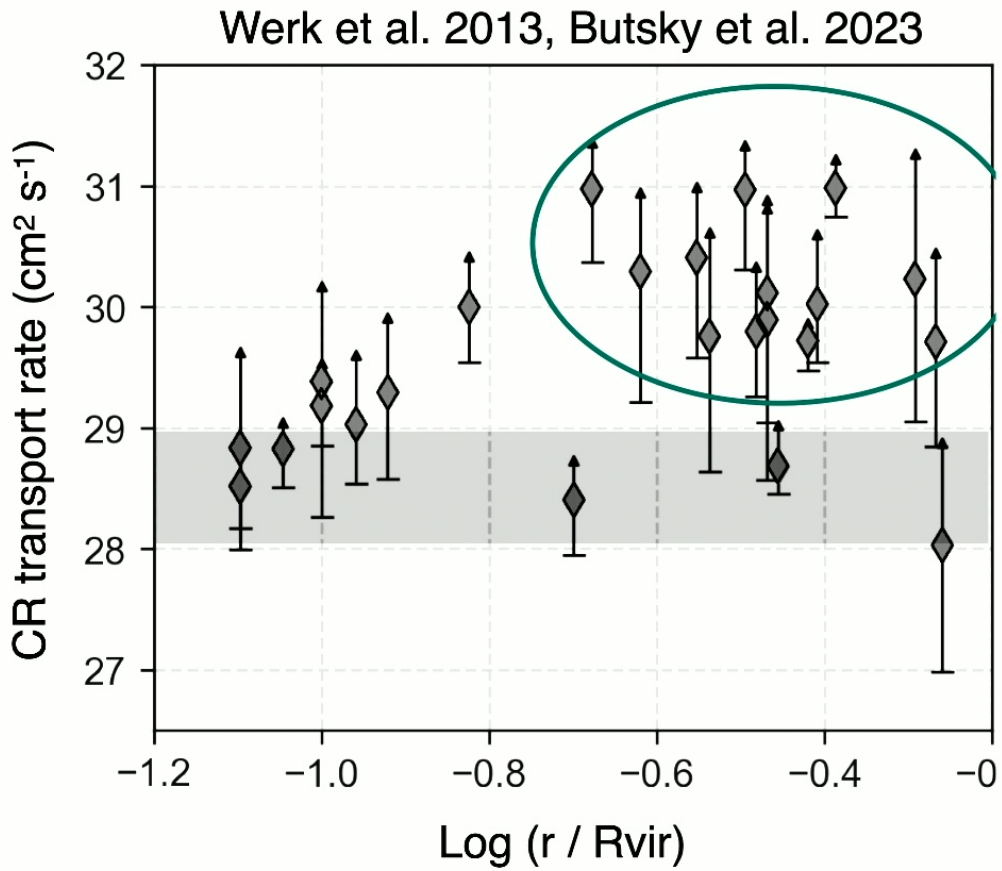
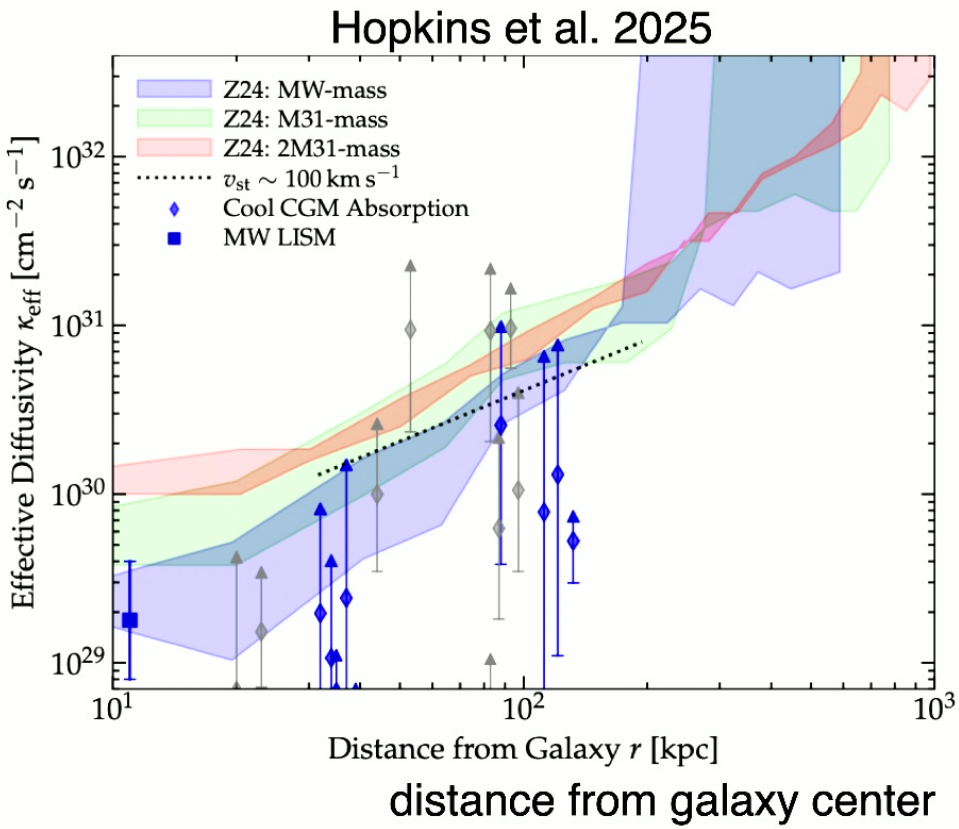
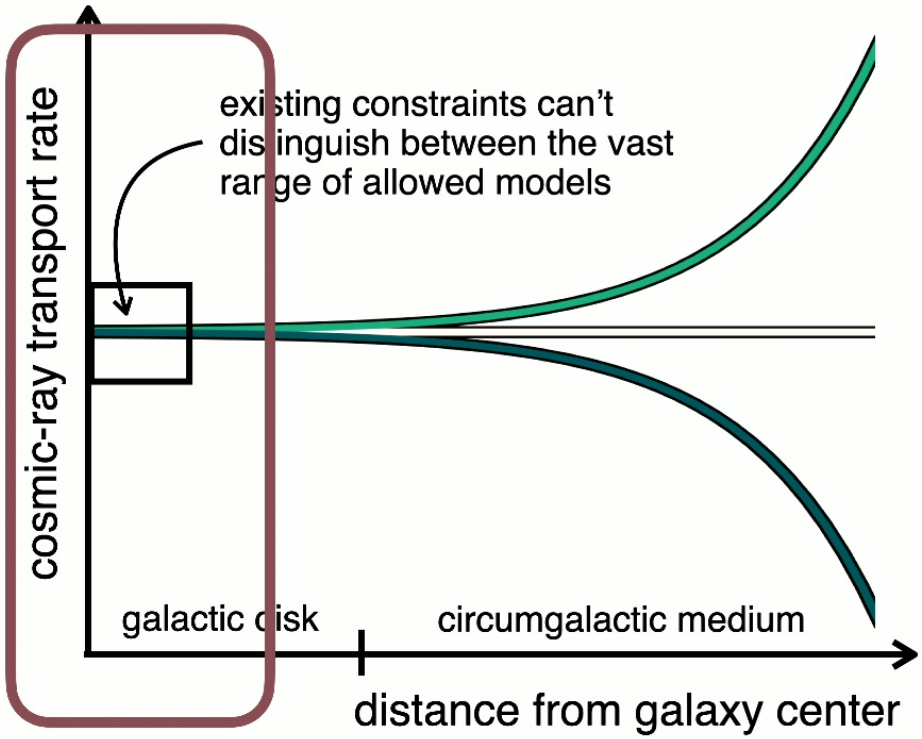




distance from galaxy center

~GeV Cosmic-ray transport is severely under-constrained



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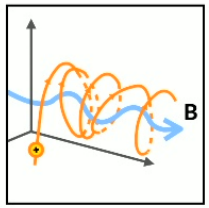
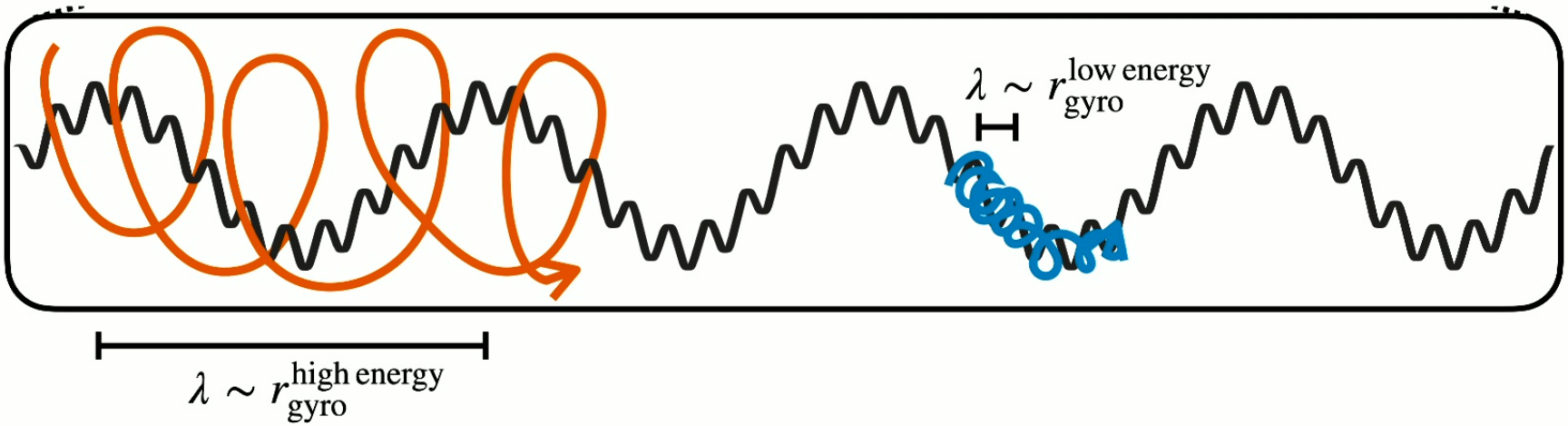


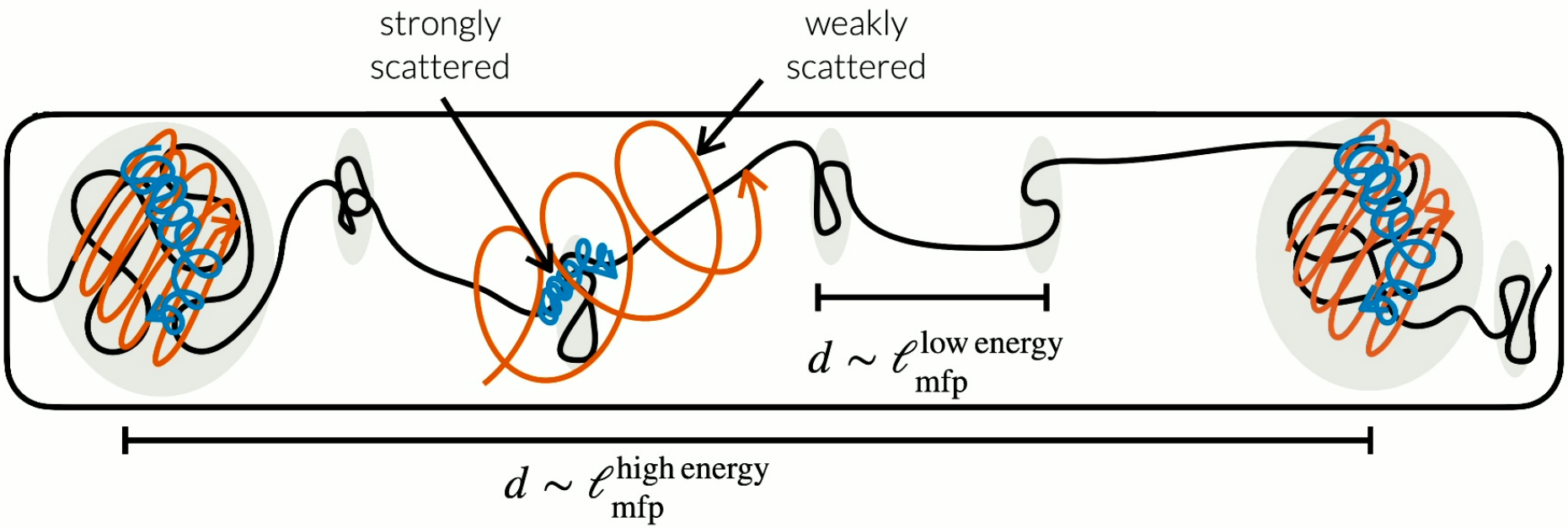
Option 2: constrain underlying scattering physics in ISM

Traditional, "continuous" CR scattering models are fundamentally flawed



Hopkins, Squire, Butsky, et al. 2022; Kempski and Quataert 2022

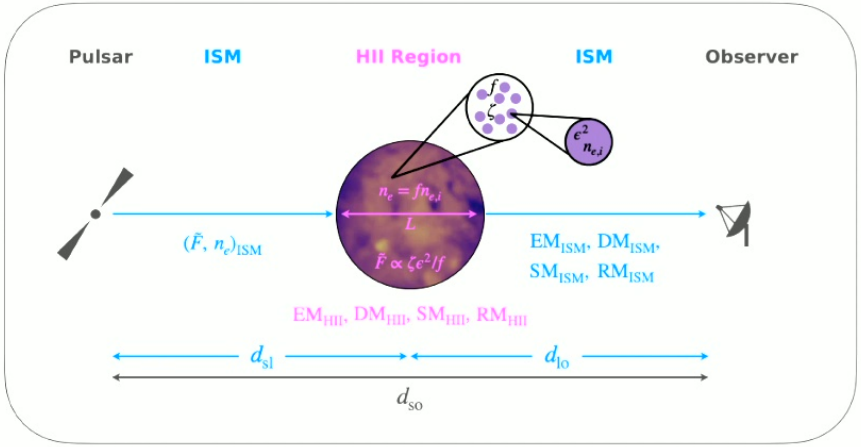
Intermittent / "patchy" model of CR scattering



Butsky et al. 2024a

Coincidence??? 👀

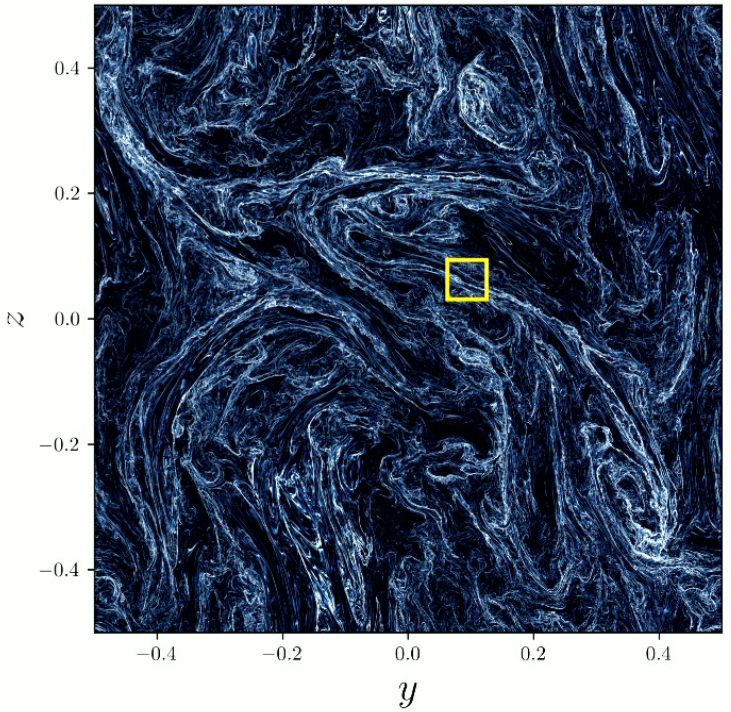
Microstructure in diffuse ISM



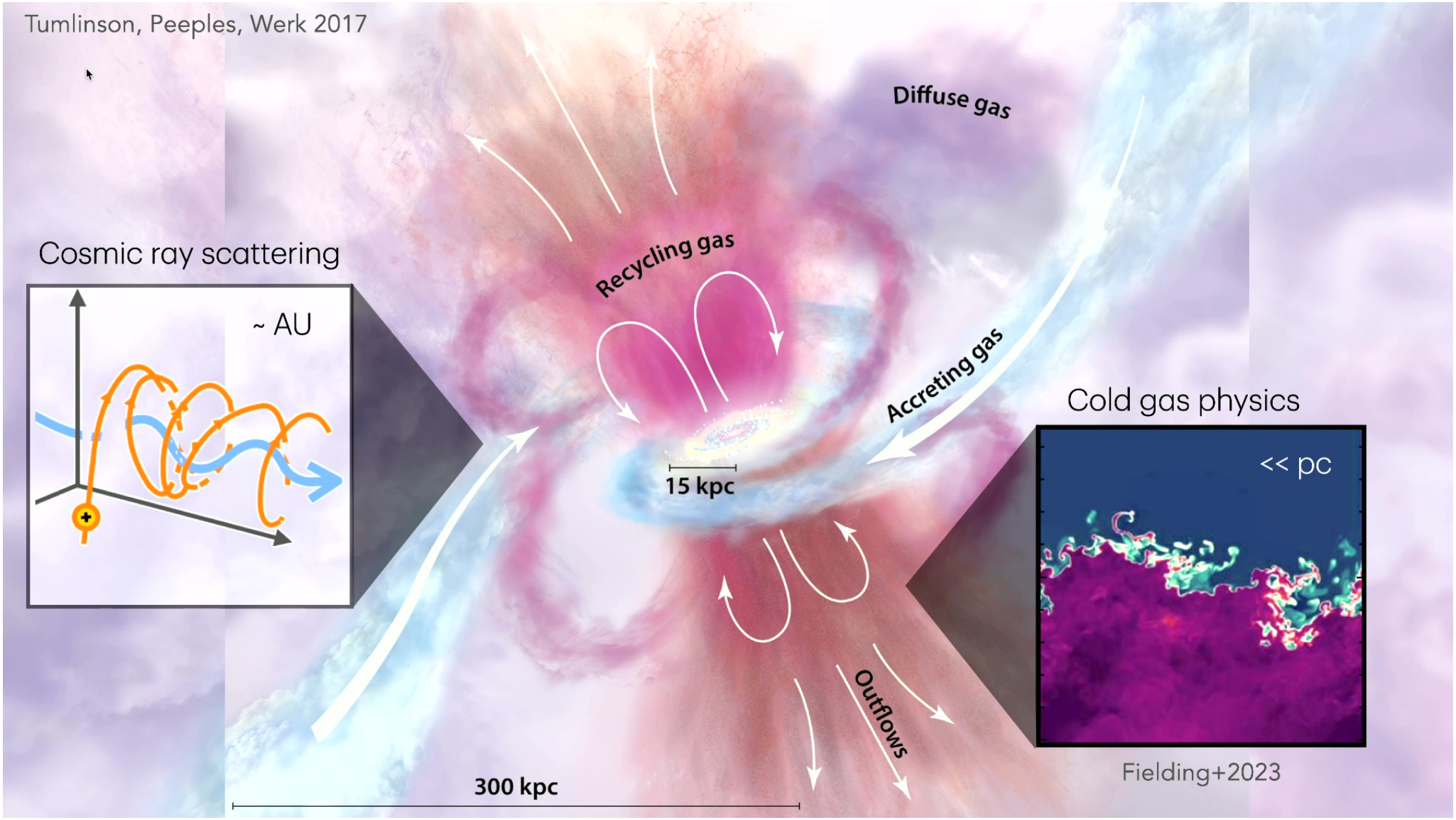
Stanimirovic and Zweibel 2018, Ocker et al. 2024

see Stella Ocker's talk tomorrow!

Intermittent magnetic structures: folds, plasmids, mirrors



Kempski et al. 2023, 2024, 2025, Fielding et al. 2023, Lemoine et al. 2023


Tumlinson, Peeples, Werk 2017
Diffuse gas
Recycling gas
Cosmic ray scattering
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Accreting gas
Cold gas physics
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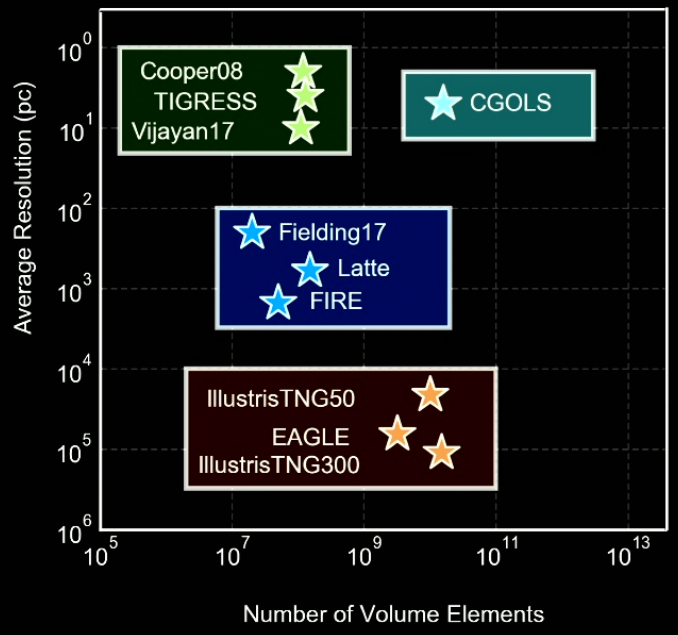
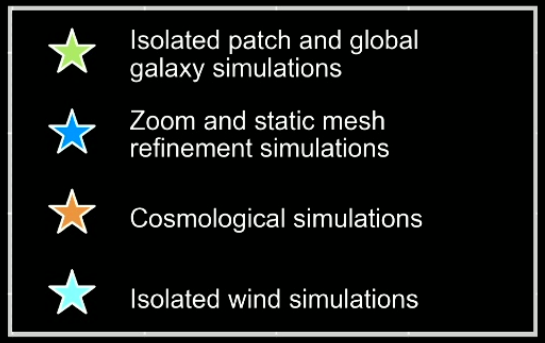
Outflows
300 kpc
Fielding+2023

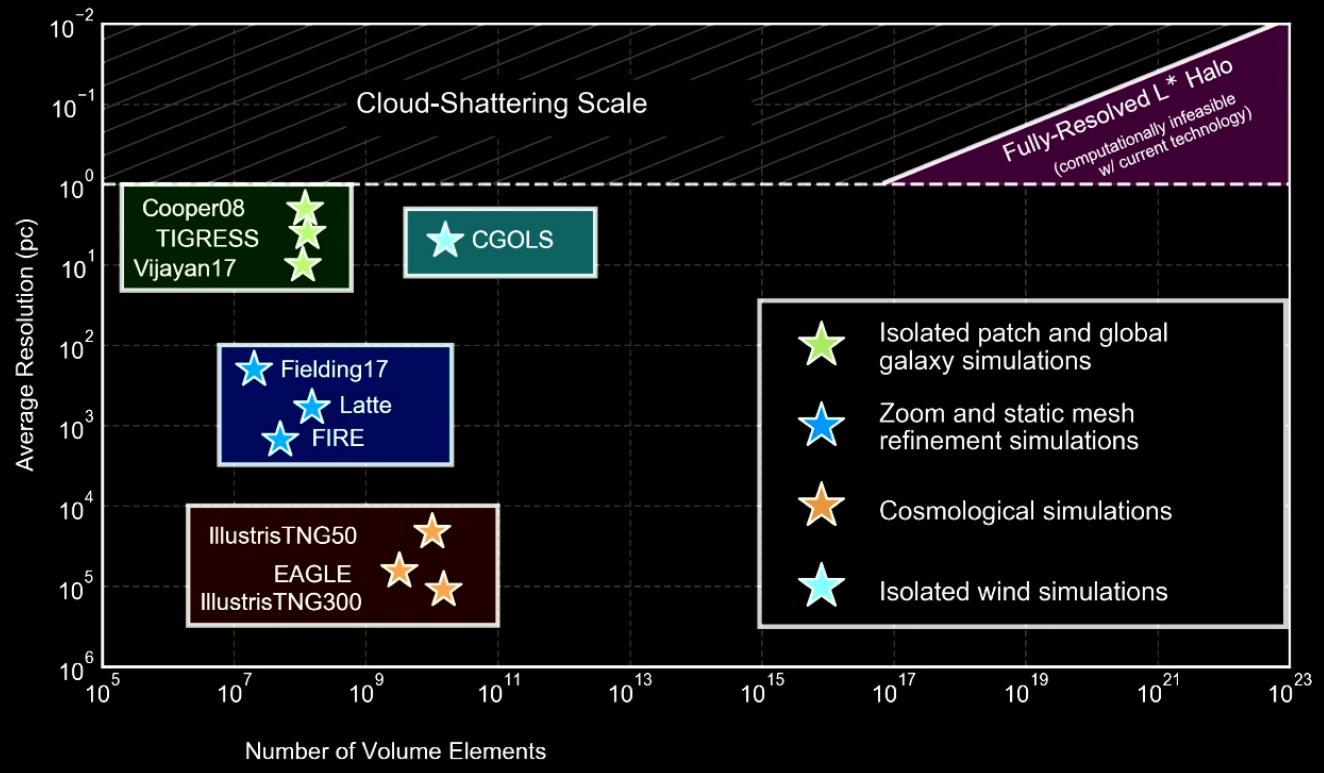
Resolving <pc-scale physics in galaxy-scale simulations





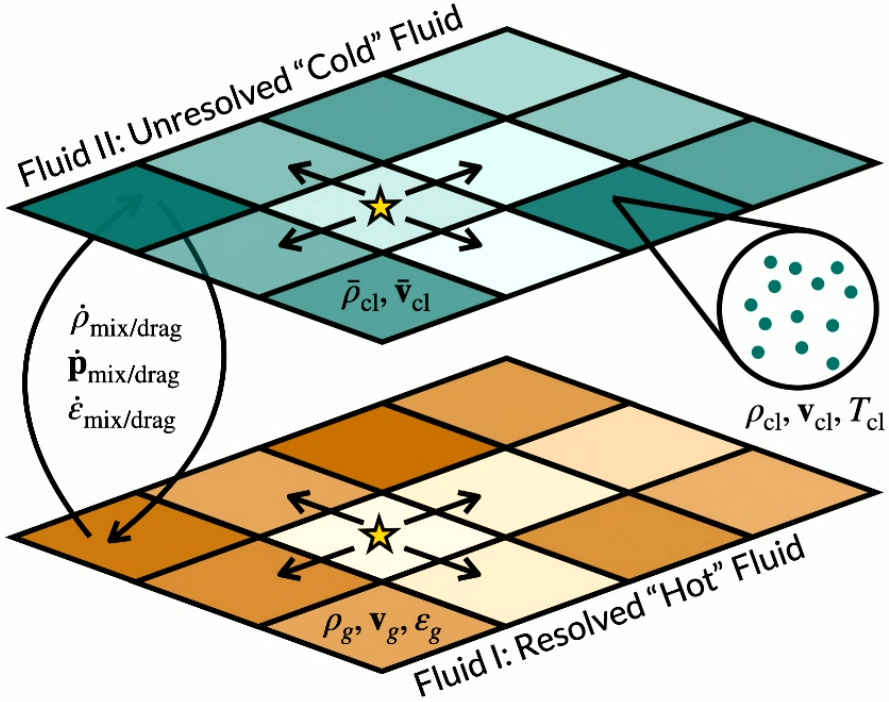
* figure adapted from Schneider+ 2018

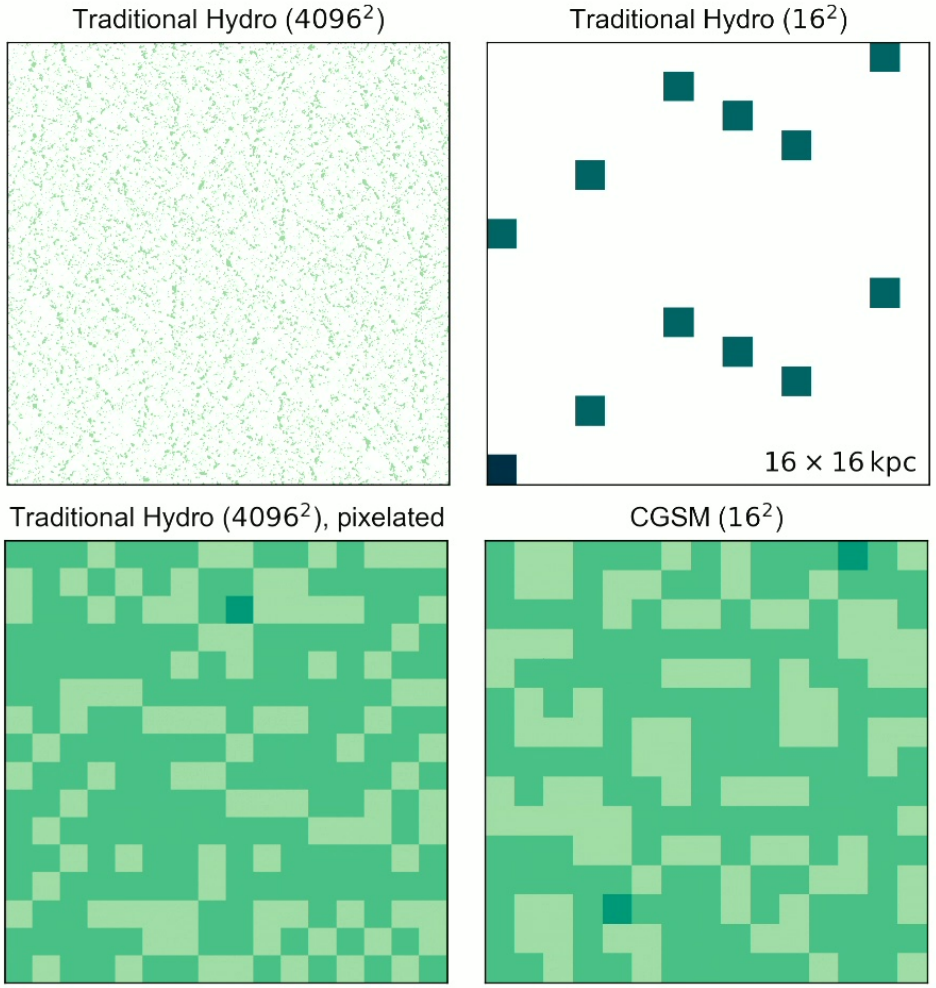
Resolving <pc-scale physics in galaxy-scale simulations



* figure adapted from Schneider+ 2018

Cold Gas Subgrid Model (CGSM)

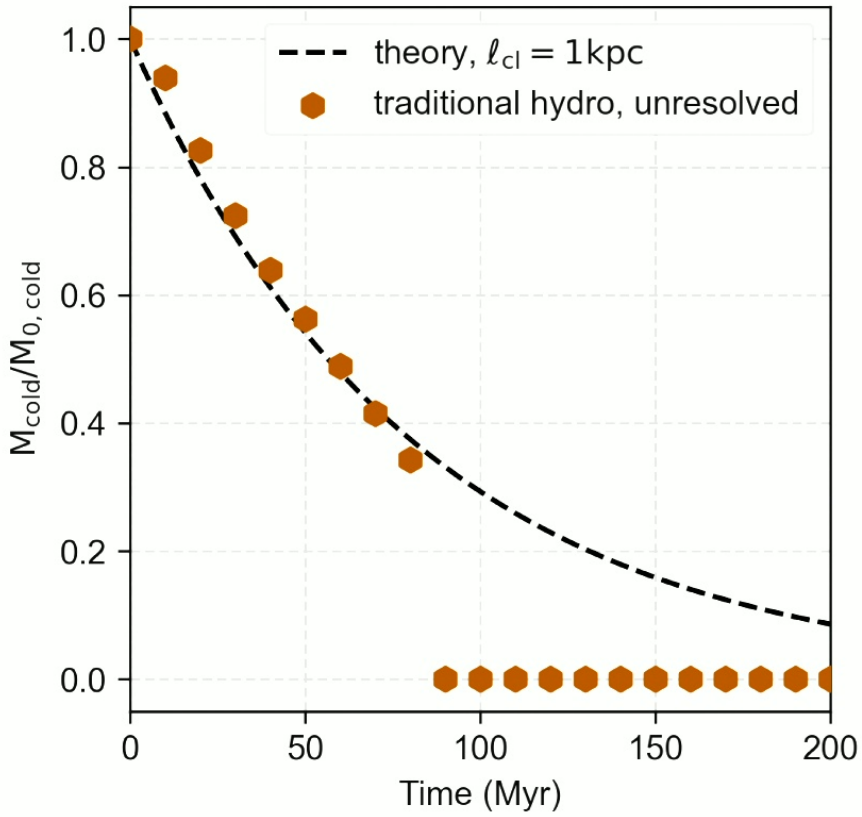


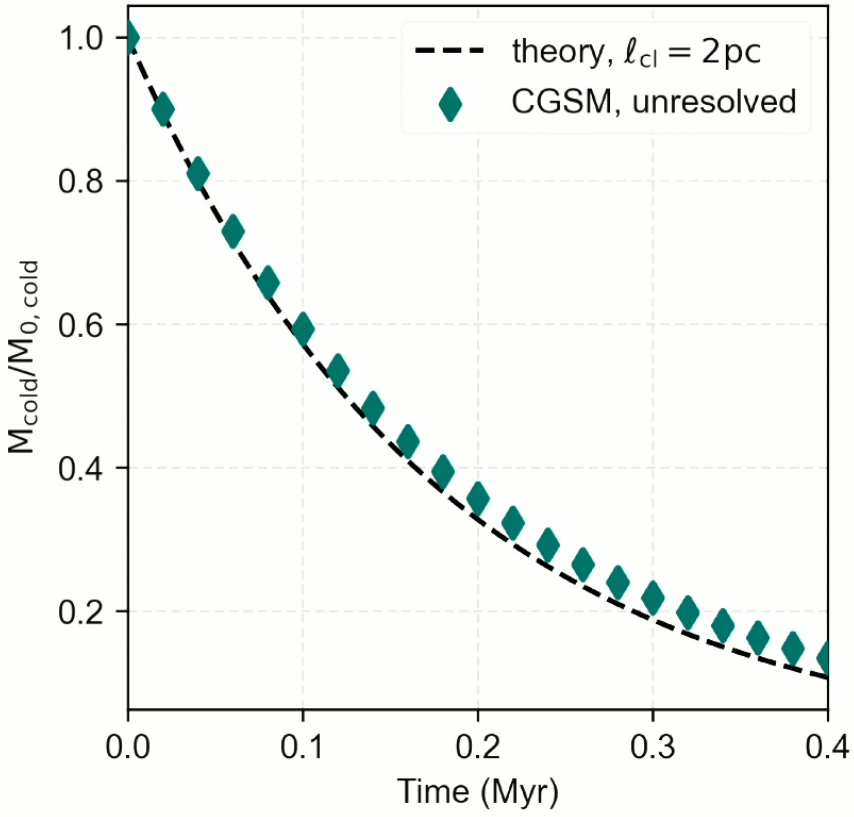


Butsky, Hummels et al. 2024b, Fielding et al. 2023

Unresolved traditional hydro gets the wrong timescales

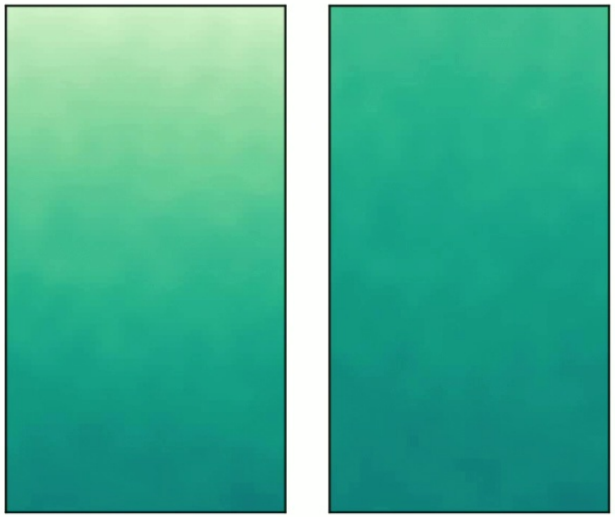
Butsky et al. 2024b



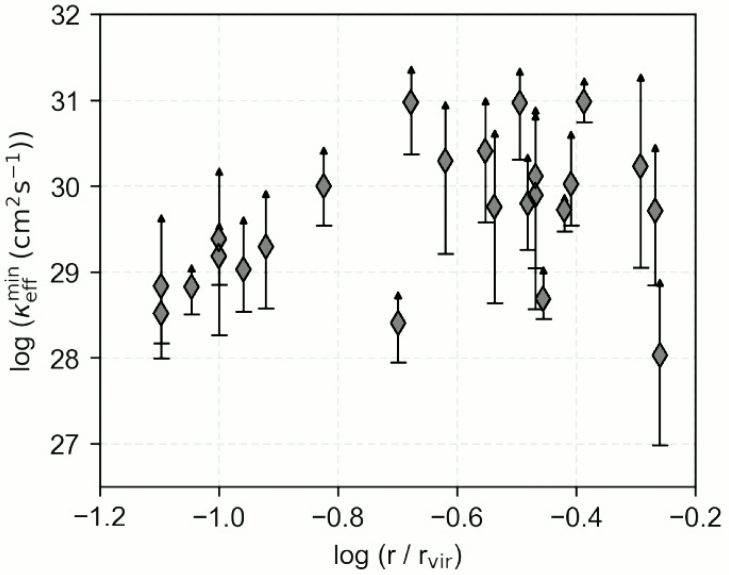


Take-aways

We should all be thinking about cosmic rays



We can learn SO much about CRs with more estimates of N_H



We need to rethink how we simulate the CGM subgrid scales