

# What in the Galaxy is Scattering Cosmic Rays?

Iryna Butsky

NHFP Symposium 2024

Pasadena, CA

September 17., 2024



Caltech

**In collaboration with:** Phil Hopkins, Cameron Hummels, Philipp Kempf, Shreya Nakum, Sam Ponnada, Eliot Quataert, Jonathan Squire

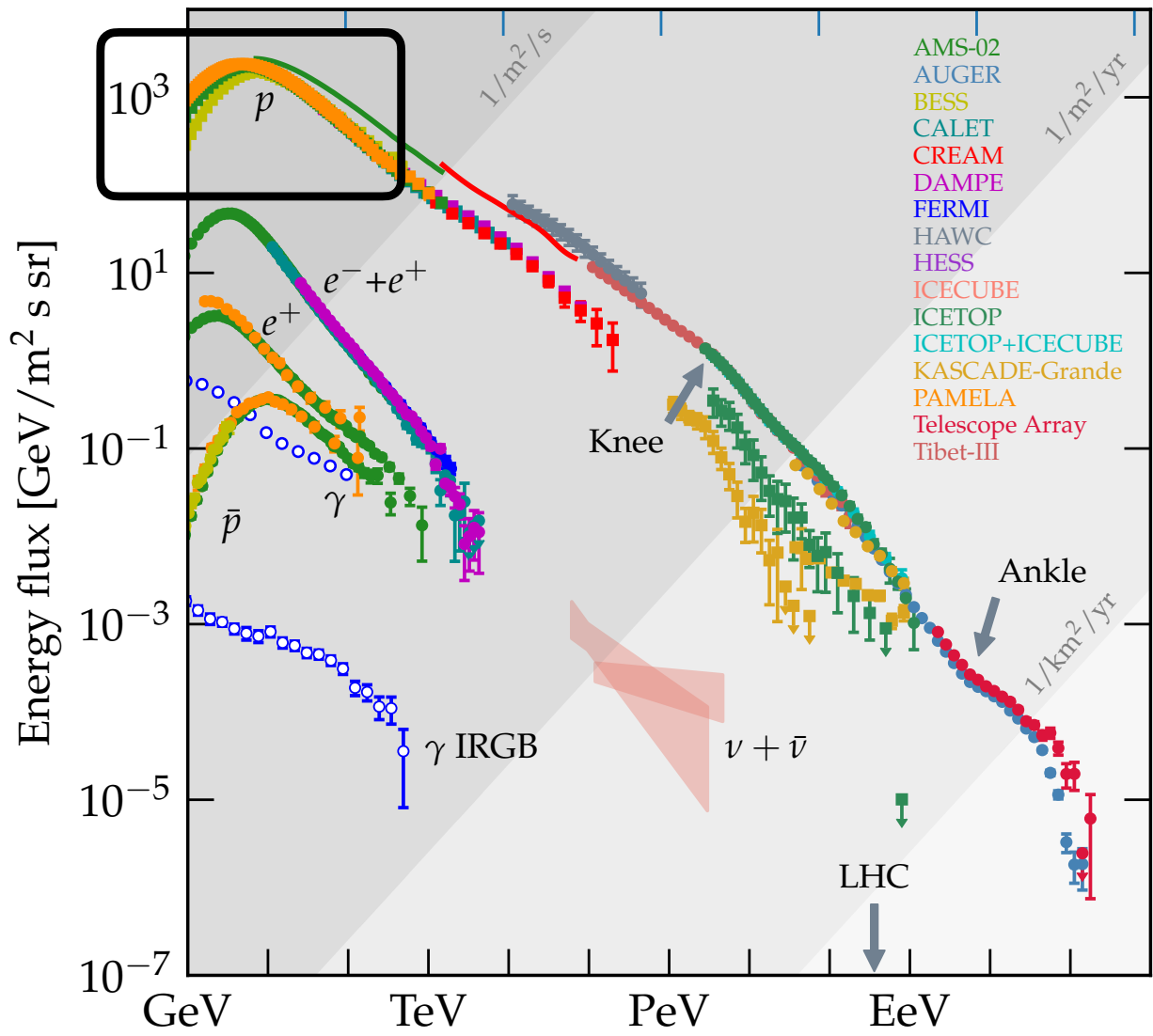
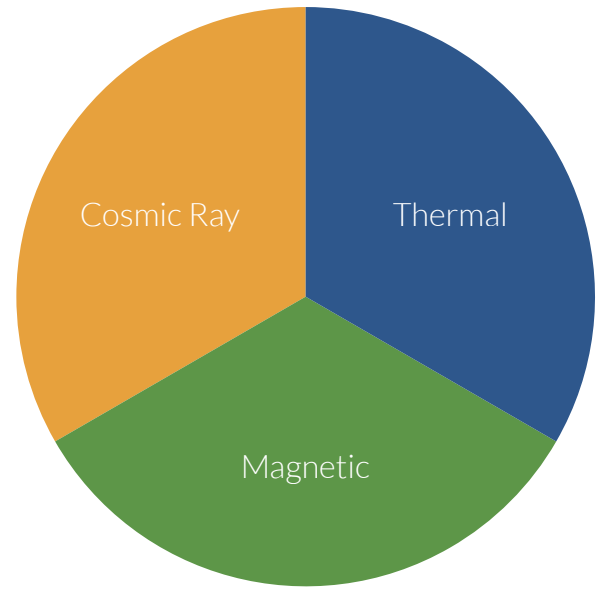
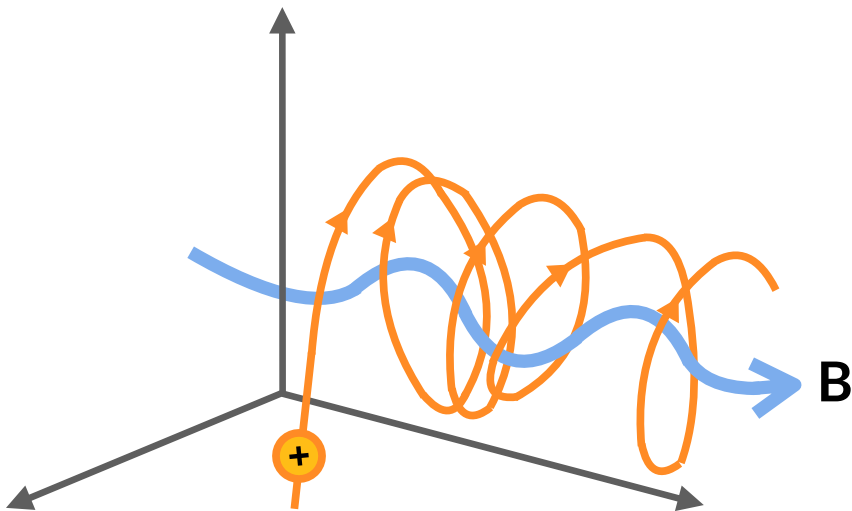


figure credit: Carmelo Evoli

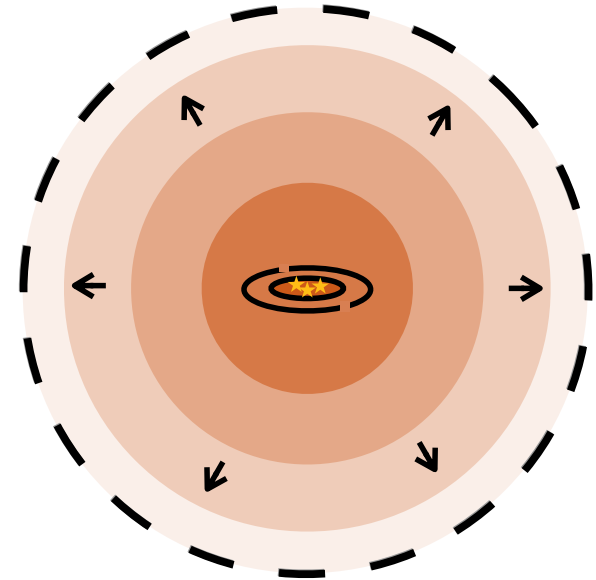
### ISM energy budget



# Cosmic rays interact with galactic magnetic fields



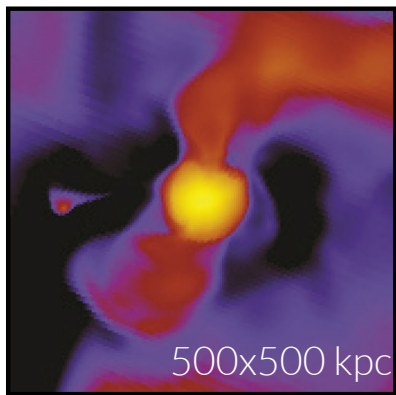
On small ( $\sim \text{au}$ ) scales, magnetic fluctuations “scatter” cosmic rays



This leads to a bulk “diffusion” of the cosmic-ray energy “fluid” on large ( $> \text{pc}$ ) scales

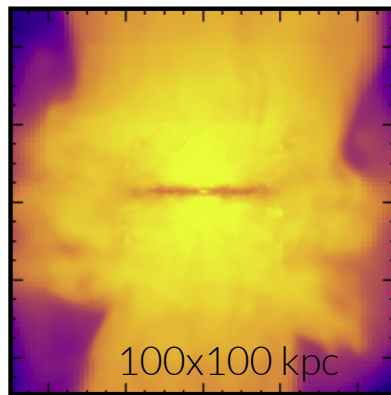
# Cosmic rays may be dominant CGM pressure (around low-redshift $L^*$ galaxies)

Enzo, PPM



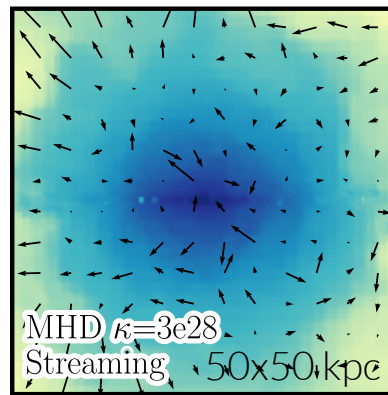
Salem et al. 2016

Enzo, MHDRK



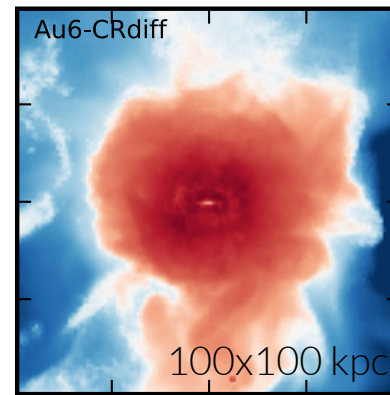
Butsky and Quinn 2018

Gizmo



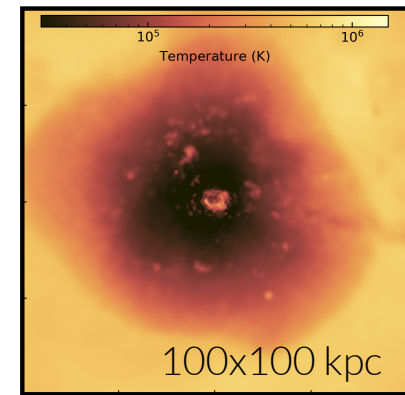
Chan et al. 2019

Arepo



Buck et al. 2020

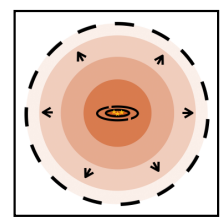
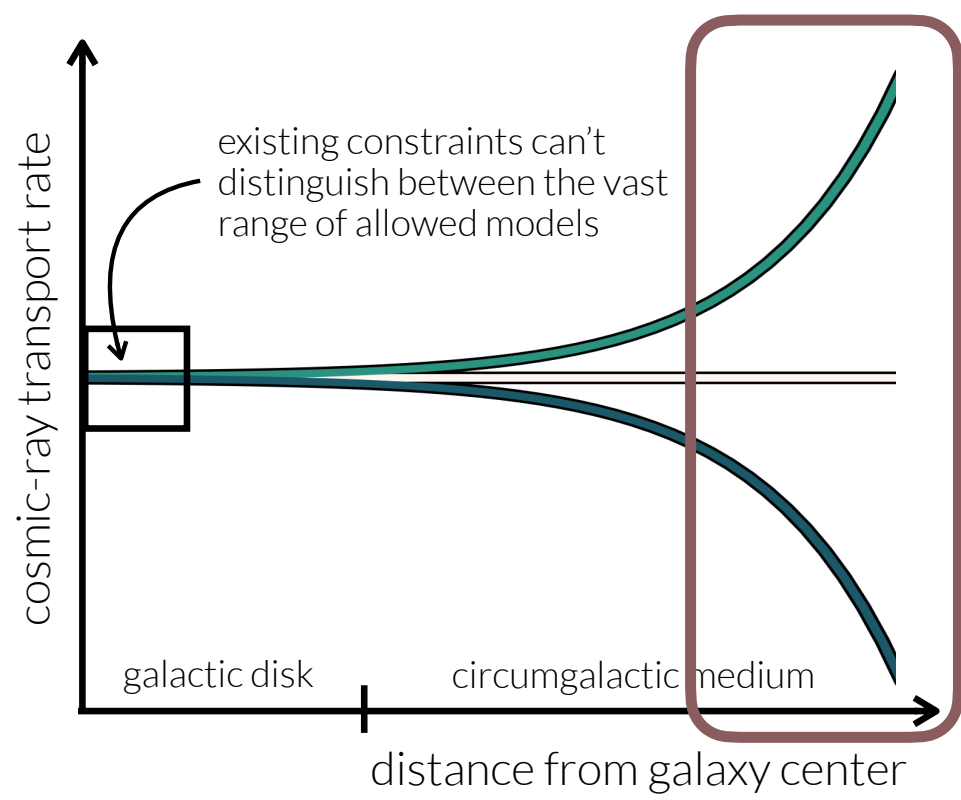
ChaNGa



Butsky et al. 2022

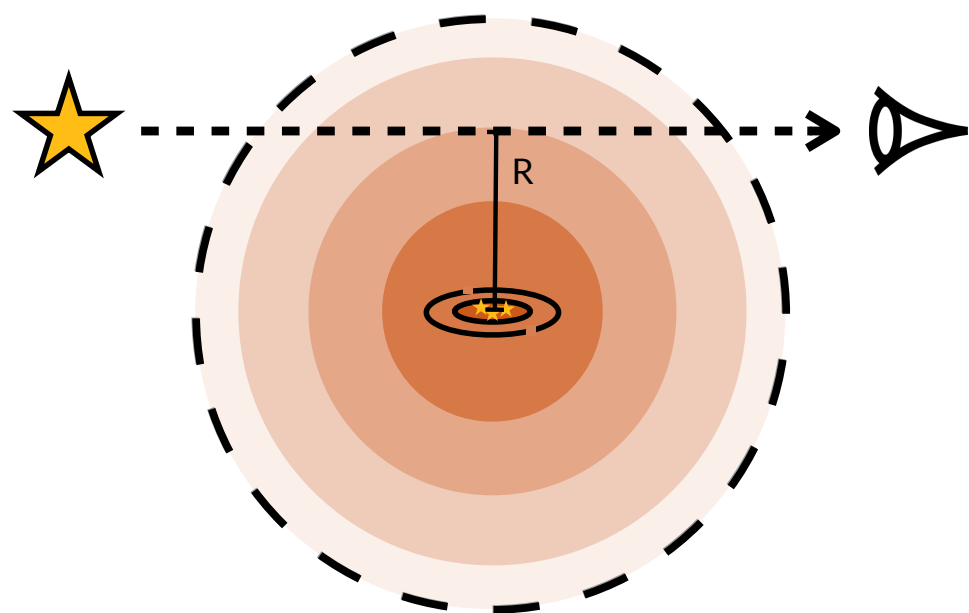
**Bad news:** predictions are extremely sensitive to assumed models of cosmic-ray transport 😞

# ~GeV Cosmic-ray transport is severely under-constrained



**Option 1:** constrain cosmic-ray transport in CGM

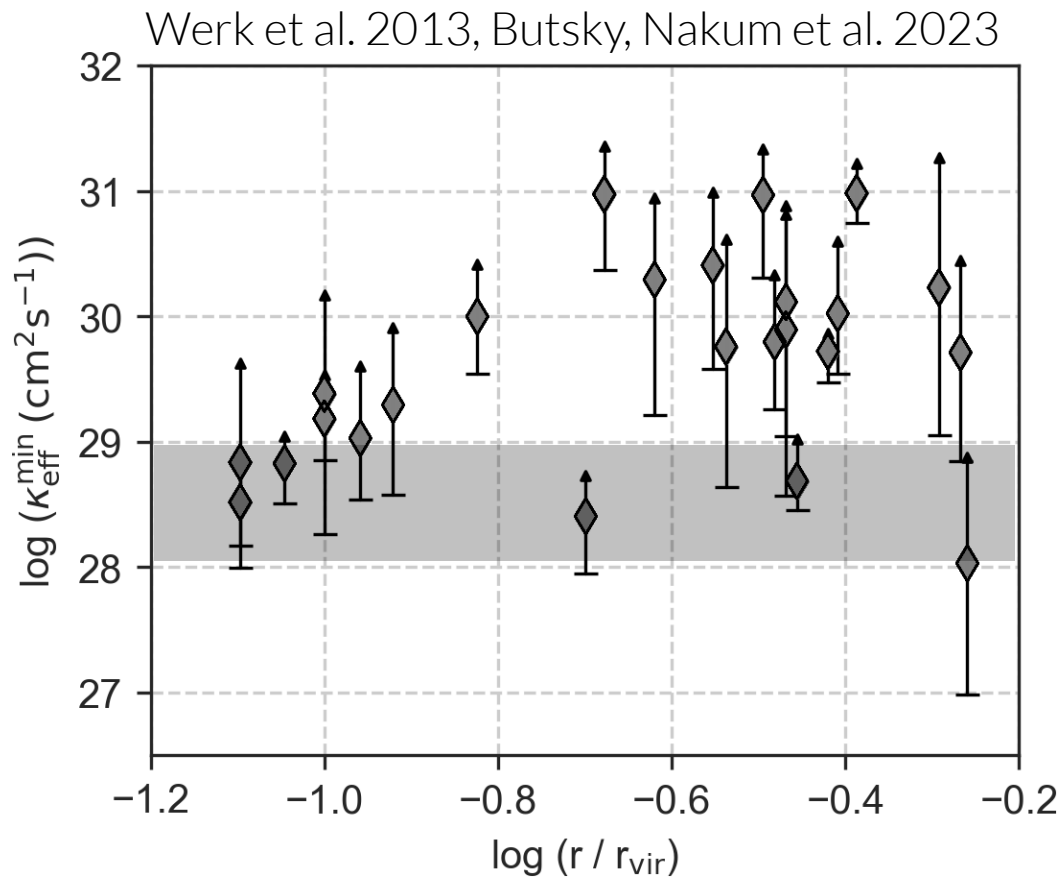
# Constraining CR transport in the CGM



$$\min K_{\text{eff}}(R) \sim \frac{\langle \dot{M}_* \rangle}{N_{\text{H}} V_{\text{c}}^2}$$

average star formation rate  
 total hydrogen column density  
 circular velocity

# First constraints on CR transport in CGM using COS-Halos! <sup>7</sup>



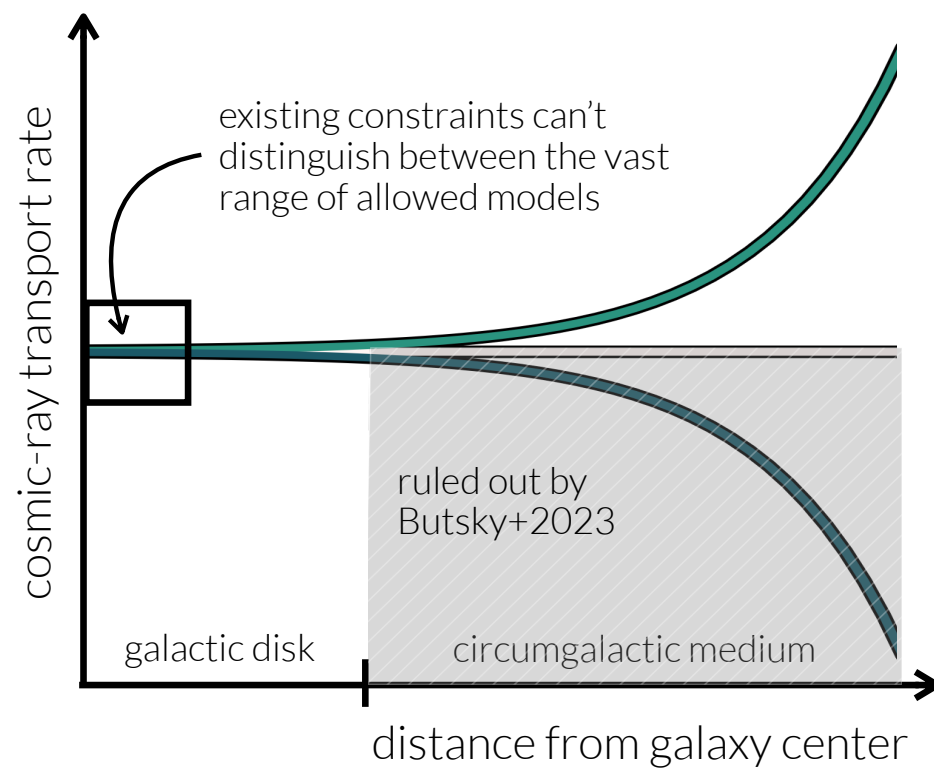
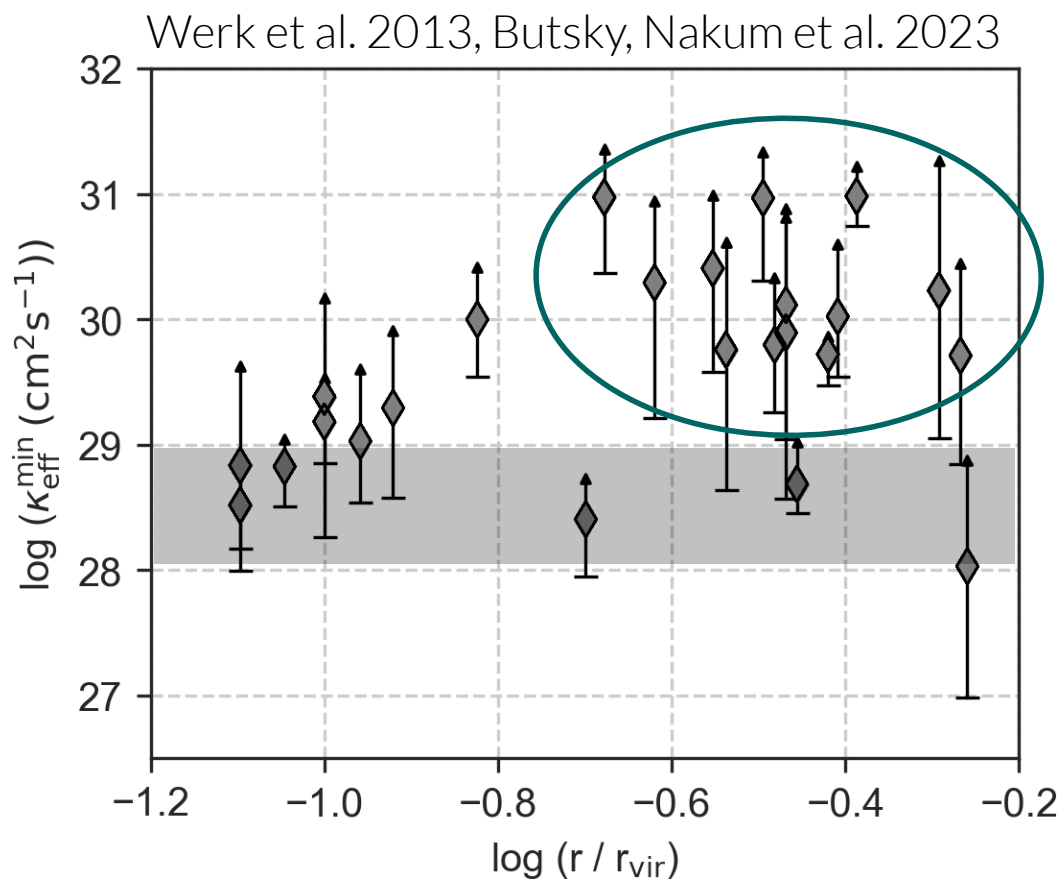
$$\kappa_{\text{eff}}^{\text{min}}(R) \sim \frac{\langle \dot{M}_* \rangle}{N_{\text{H}} V_{\text{c}}^2}$$

average star formation rate (pointing to  $\langle \dot{M}_* \rangle$ )  
 total hydrogen column density (pointing to  $N_{\text{H}}$ )  
 circular velocity (pointing to  $V_{\text{c}}$ )

Shreya Nakum  
UC Irvine '27

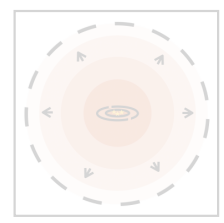
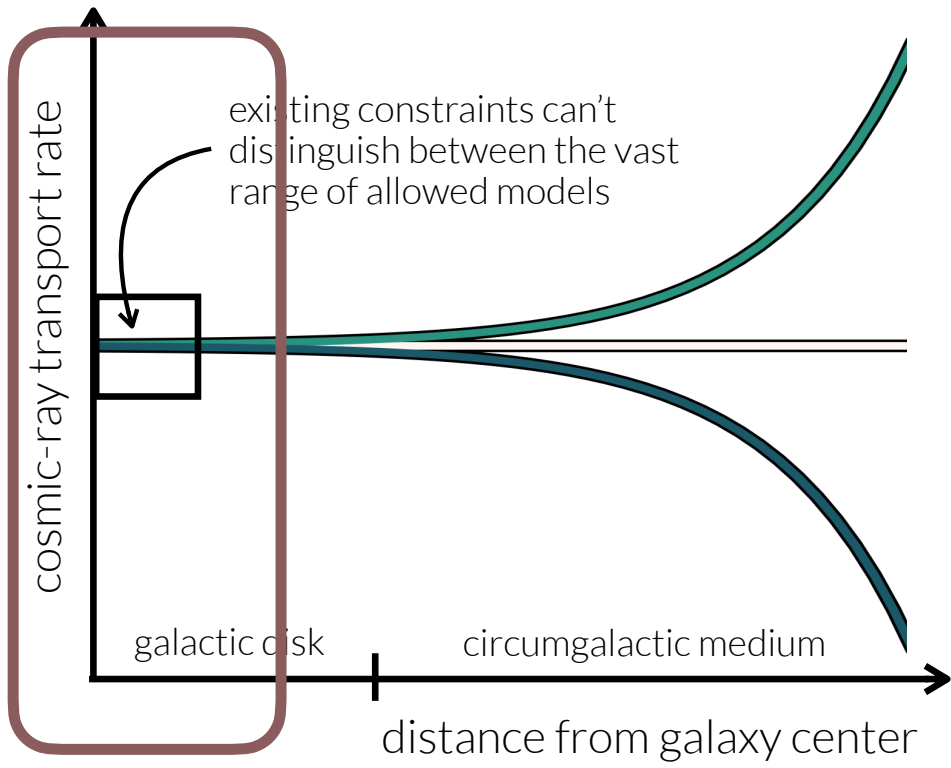


# First constraints on CR transport in CGM using COS-Halos! <sup>8</sup>

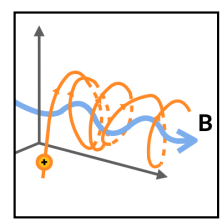




# ~GeV Cosmic-ray transport is severely under-constrained

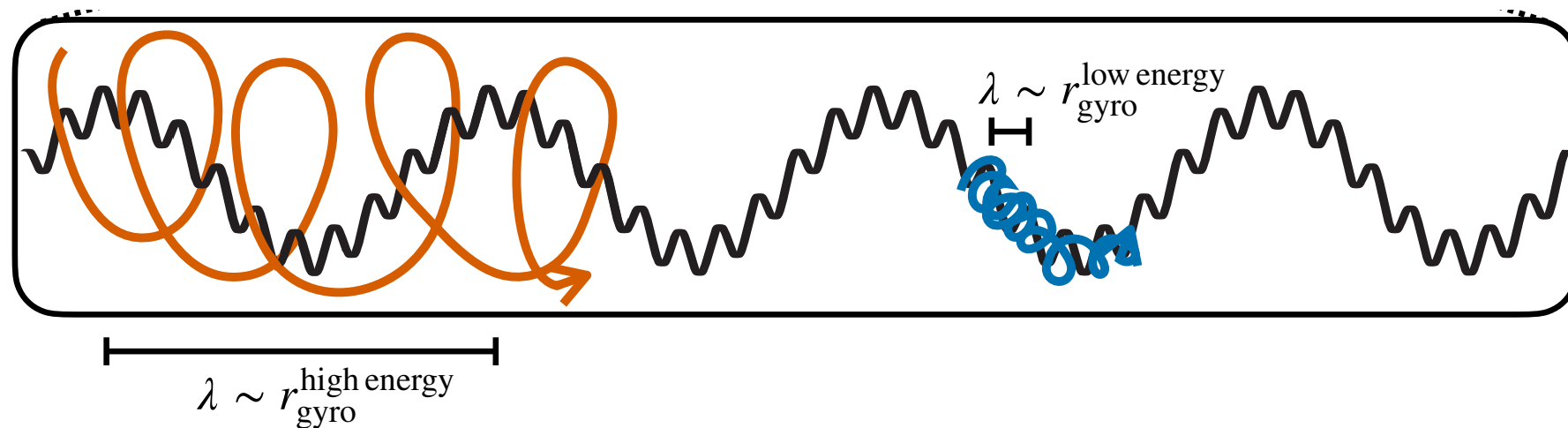


**Option 1:** constrain cosmic-ray transport in CGM



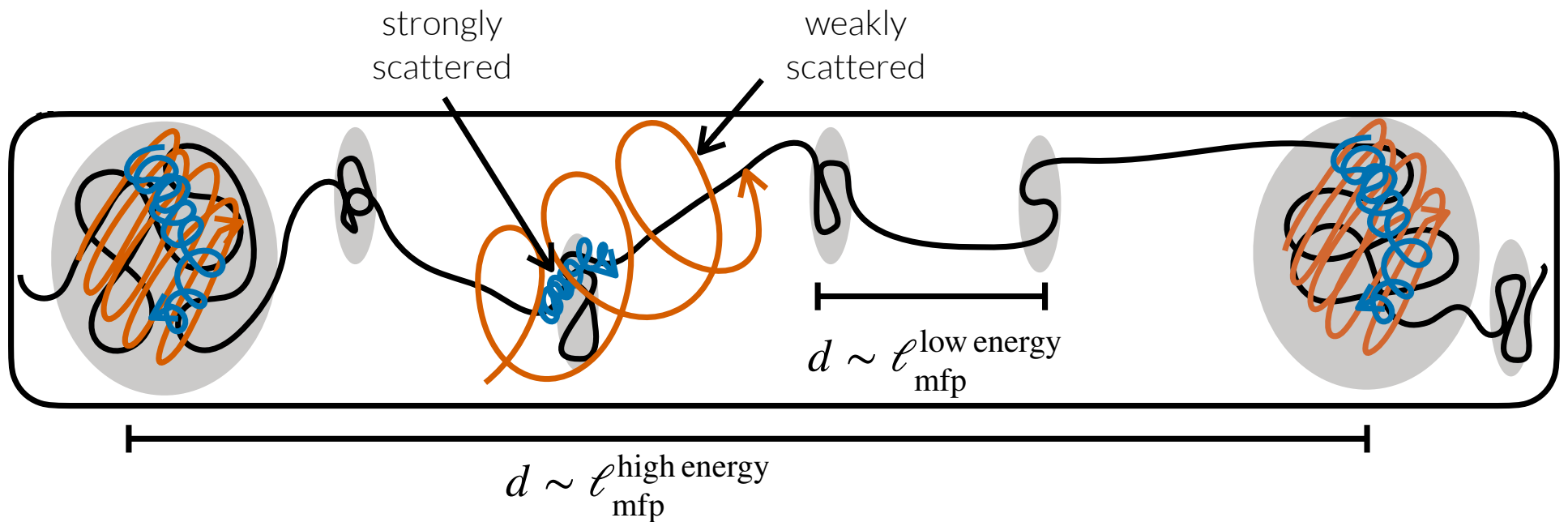
**Option 2:** constrain underlying scattering physics in ISM

Traditional, “continuous” CR scattering models are fundamentally flawed

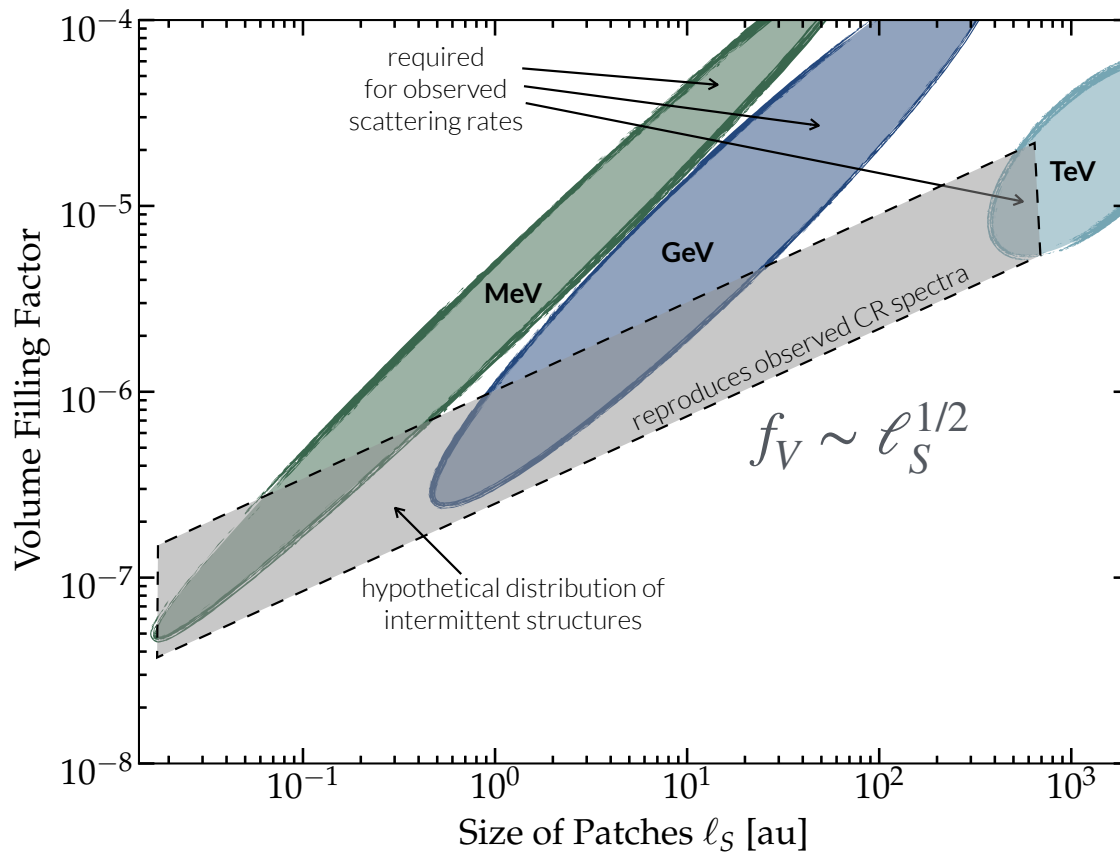


Hopkins, Squire, Butsky, et al. 2022; Kempster and Quataert 2022

# Intermittent / “patchy” model of CR scattering



# “Microscale” ISM may be scattering CRs



$$f_V \sim \ell_S / \ell_{\text{mfp}} < 1$$

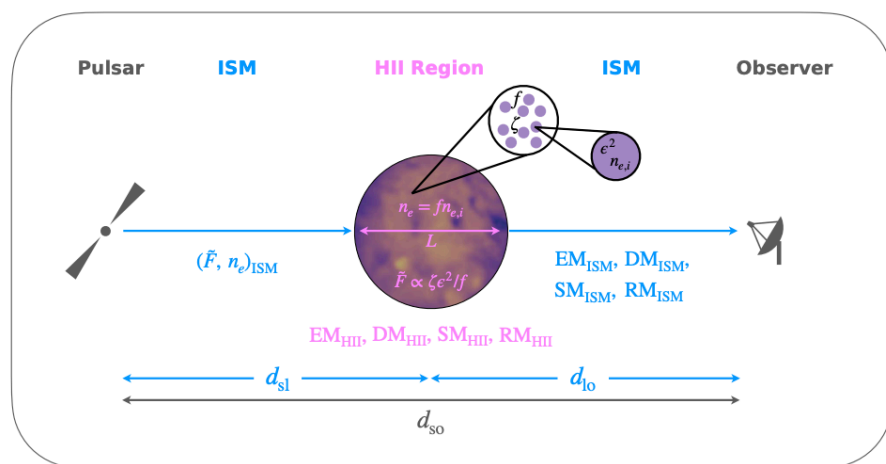
Need something that can strongly scatter cosmic-ray pitch angle with:

Mean-free-path:  $\sim 10$  pc

Size:  $>0.01$ - $0.1$  au

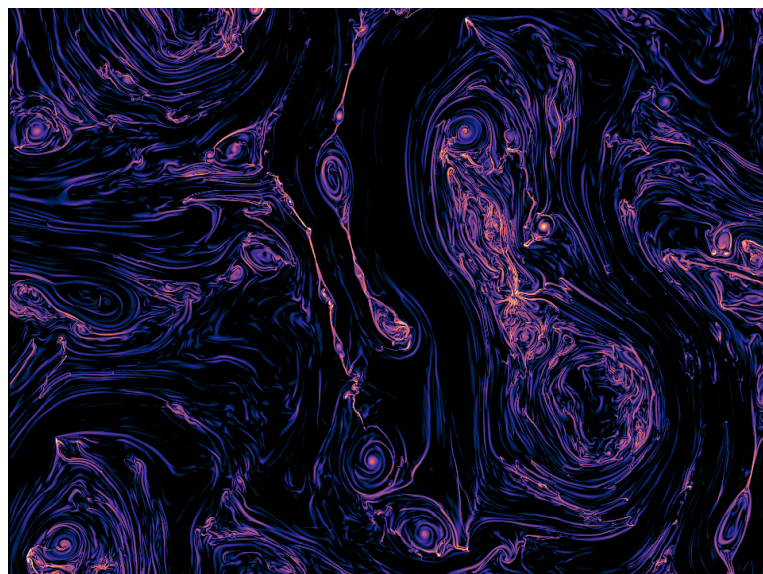
# Coincidence???

## Microstructure in diffuse ISM



see Stanimirovic and Zweibel  
2018, Ocker et al. 2024

## Magnetic plasmoids



see Fielding et al. 2023, Kempster et al. 2023,  
Lemoine et al. 2023

In summary, existing models of CR transport are broken, but I think we're close to figuring it out!

