**Title:** Probing cosmic plasmas at sub-au scales with fast radio bursts

**Speakers:** Stella Koch Ocker

**Collection/Series:** Cosmic Ecosystems

**Subject:** Cosmology

**Date:** August 01, 2025 - 11:25 AM

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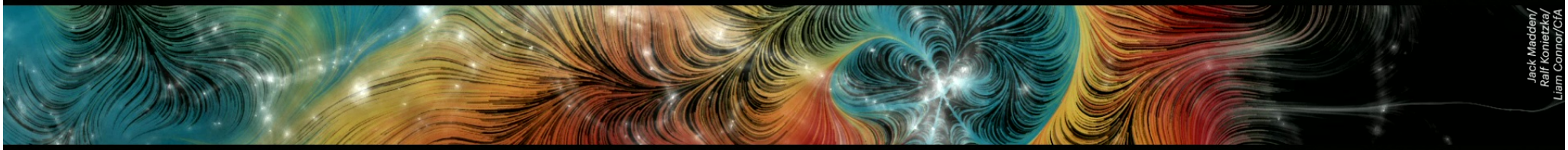
**Abstract:**

Fast radio bursts (FRBs) are dispersed and scattered by plasma density fluctuations along the line-of-sight, making them sensitive probes of diffuse ionized gas across interstellar, circumgalactic, and intergalactic media. In this talk I will discuss how FRB propagation effects are unveiling cosmic plasmas at extremely small (sub-au) spatial scales in both interstellar and circumgalactic media, and how they may be used in tandem with quasars to constrain the turbulent dynamics of ionized gas in these environments.

# Probing Cosmic Plasmas at Sub-AU Scales with Fast Radio Bursts



Jack Madden/
Ralf Konietzka/
Liam Connor/CfA

**Stella Koch Ocker**
*Brinson Prize Postdoctoral Fellow*
*Caltech & Carnegie Observatories*

**Collaborators:** Mandy Chen, Peng Oh, Prateek Sharma, ++

Caltech

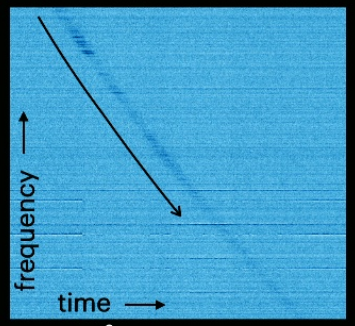
CARNEGIE SCIENCE | Observatories

COSMIC ECOSYSTEMS | Perimeter Institute

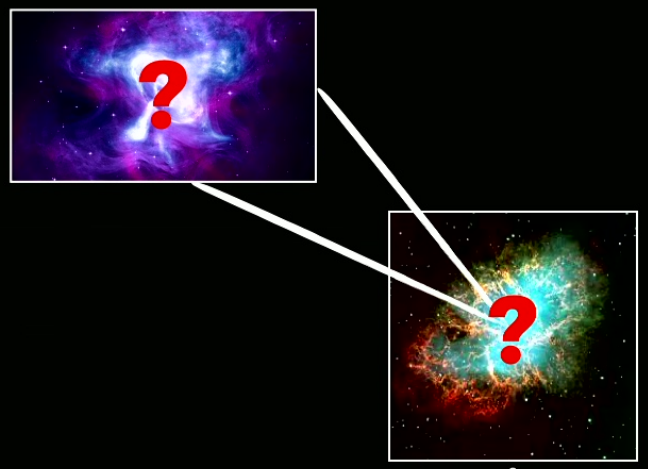
# Fast Radio Bursts (FRBs)

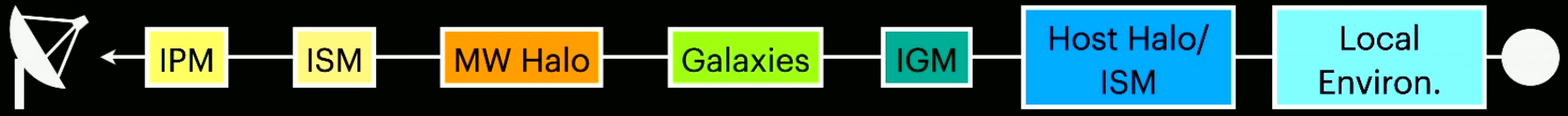
dispersion measure:

$$\mathrm{DM} = \int_0^D n_e dl$$




- extremely bright (<kJy)
- ~ ms durations
- ubiquitous (~ 1000s/day/sky)
- mostly extragalactic ($z \lesssim 2$)
- physical sources unclear
- ~4000+ known





# FRBs probe intervening plasmas

**dispersion measure**

$$\mathrm{DM} = \int_0^D n_e dl$$

**rotation measure**

$$\mathrm{RM} = \int_0^D n_e B_{||} dl$$

**scattering measure**

$$\mathrm{SM} \propto \int_0^D \langle \delta n_e^2 \rangle dl$$

(x other factors)

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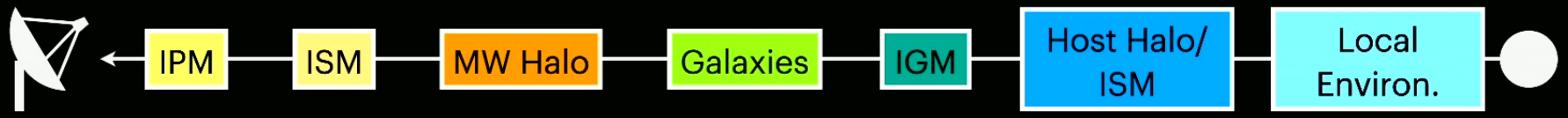
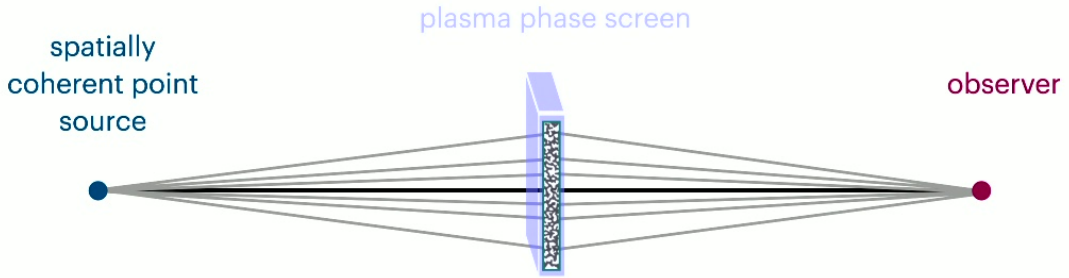
*Applications: cosmic baryon budget; electron cross-power spectrum; CGM density/B-field profiles; gravitational lensing by dark matter; HeII reionization; ISM feedback; ISM/CGM/IGM turbulence, ...*



# FRBs probe intervening plasmas

**Scattering: Multipath propagation due to small-scale plasma density fluctuations.**




$$\theta \propto l^{-1}$$

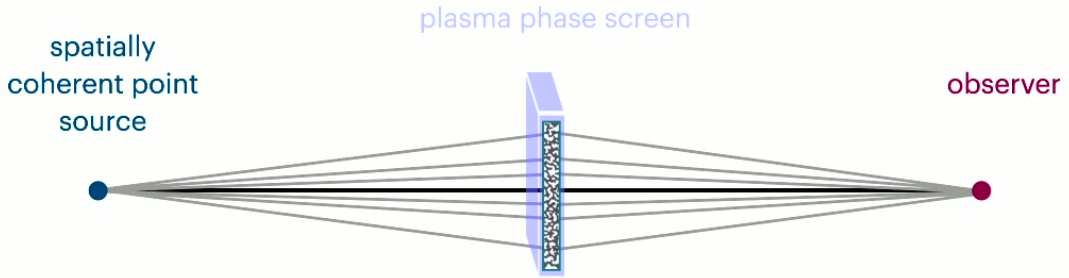
smallest spatial scales <=>
largest scattering angles



*Images: Ocker+(2022; 2023); Chatterjee+(2017)*

# FRBs probe intervening plasmas

**Scattering: Multipath propagation due to small-scale plasma density fluctuations.**

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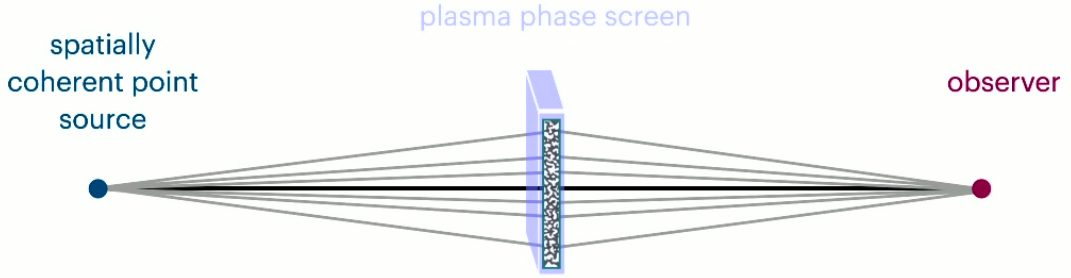
*Images: Ocker+(2022; 2023); Chatterjee+(2017)*

# FRBs probe intervening plasmas

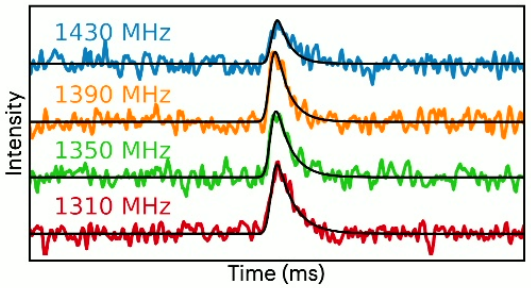
**Scattering: Multipath propagation due to small-scale plasma density fluctuations.**



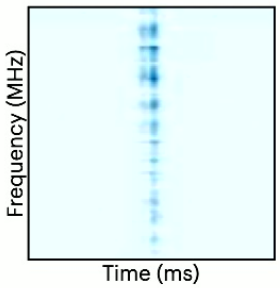

$$\theta \propto l^{-1}$$

smallest spatial scales <=> largest scattering angles

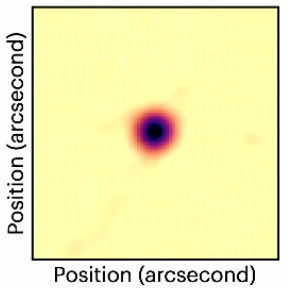
**pulse broadening**




**scintillation**




**angular broadening**






*Images: Ocker+(2022a; 2023); Chatterjee+(2017)*

# FRBs probe tiny spatial scales

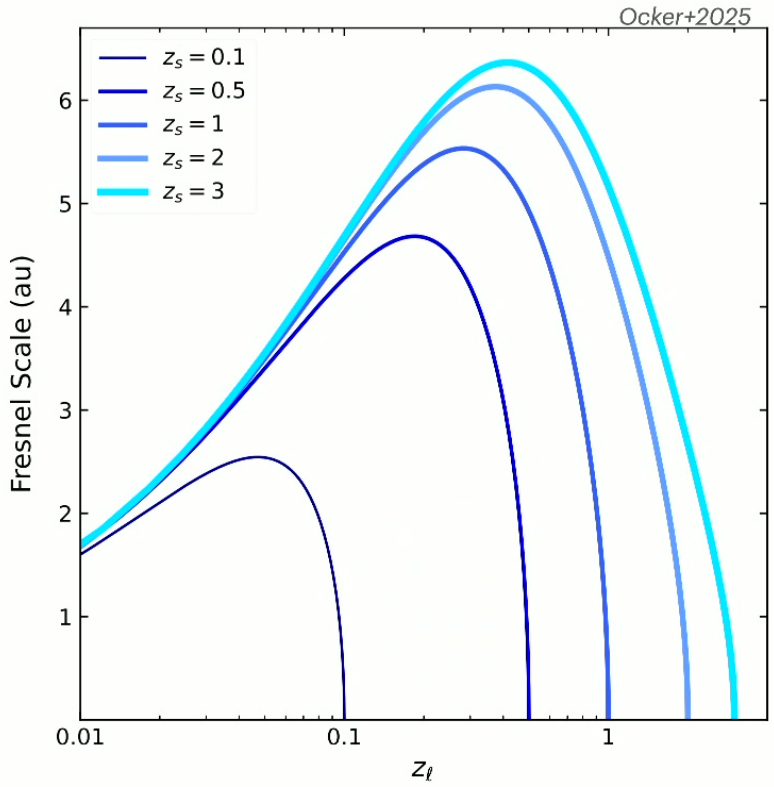
**Two scattering regimes:**

**Refraction & diffraction, separated by the Fresnel scale.**

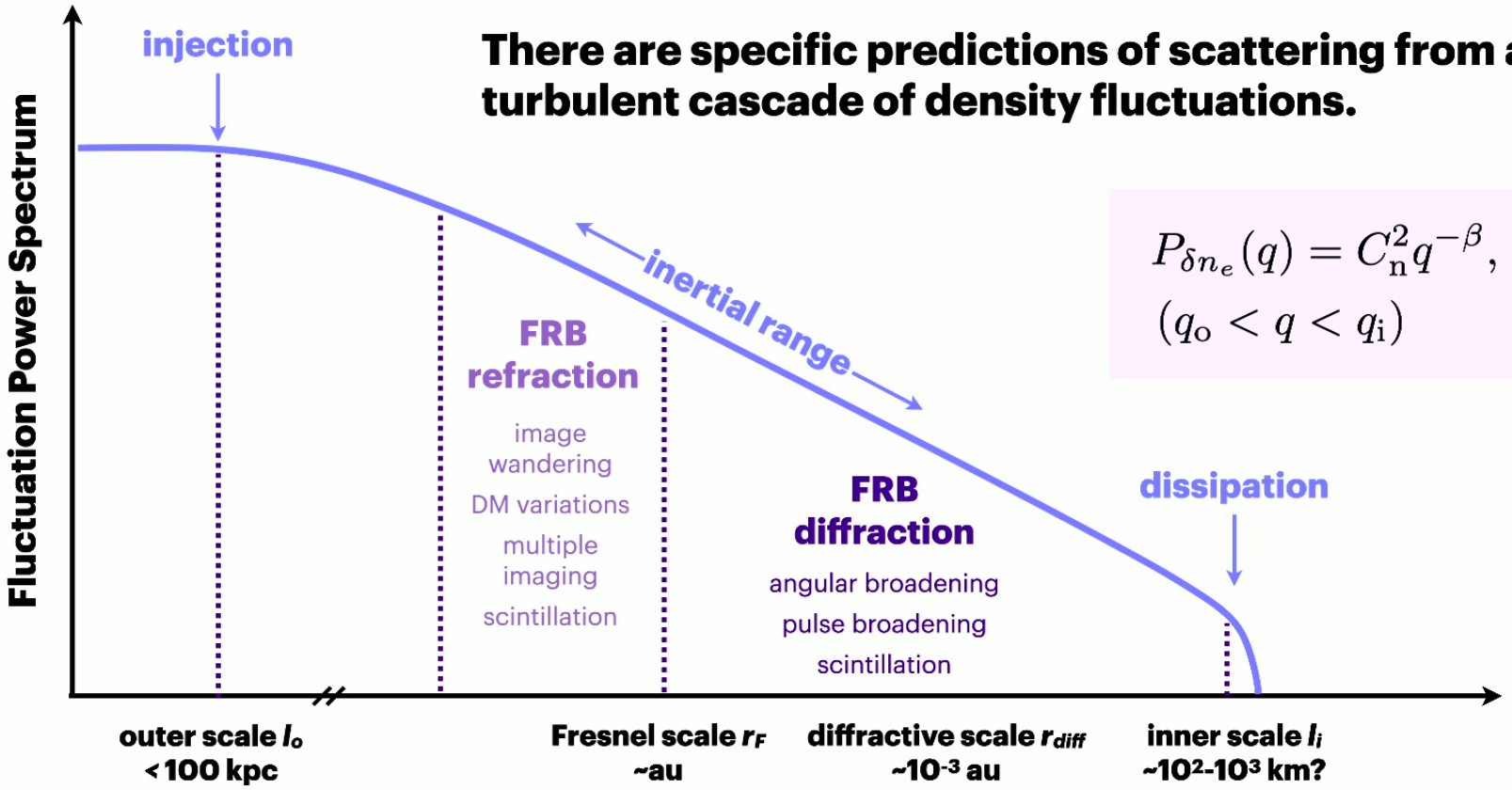
In the ISM, the Fresnel scale is ~0.01 au.

In foreground halos, the Fresnel scale is a few au.

This talk focuses on diffraction (i.e., sub-au).



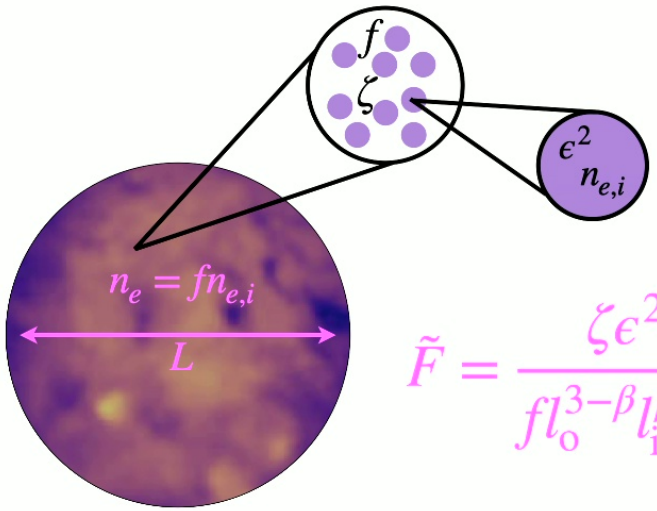
# Notional Turbulence Cascade



# Relating Scattering Delay to Density Fluctuations

**mean pulse delay encodes turbulence via the "fluctuation parameter":**

$$\tau_\ell \propto \nu^{-4} \times G_{\rm scatt} \times \tilde{F} \times {\rm DM}_\ell^2 \times (1+z_\ell)^{-3}$$



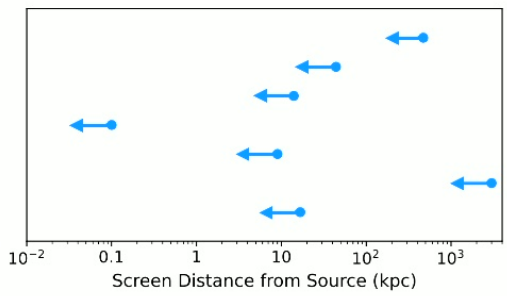

$$\tilde{F} = \frac{\zeta \epsilon^2}{f l_{\rm o}^{3-\beta} l_{\rm i}^{\beta-4}}$$

$$\tilde{F} \propto \frac{\overline{C_{\rm n}^2}}{\bar{n}_e^2 \, l_{\rm i}^{1/3}}$$

- $\overline{C_{\rm n}^2}$ → amplitude of density fluctuation spectrum
- $l_{\rm i}^{1/3}$ → Kolmogorov $\beta = 11/3$
- $\bar{n}_e^2$ → mean electron density
- $l_{\rm i}$ → inner scale

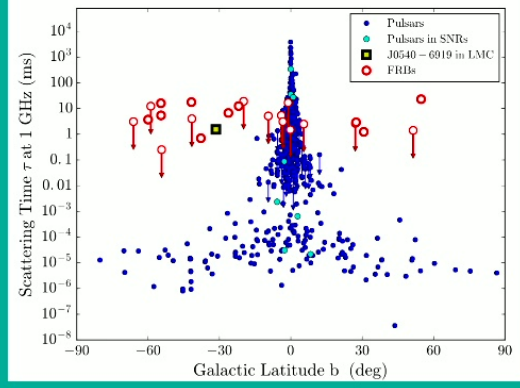
*separable for different line-of-sight components*

Masui+2015, Ocker+2022a, Sammons+2023



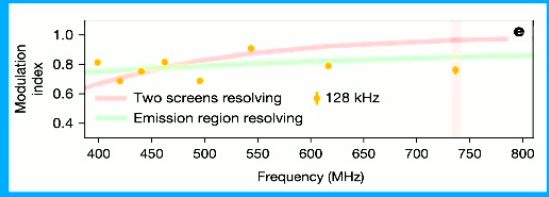

localizing plasma structures

Cordes+2016, Ocker+2021



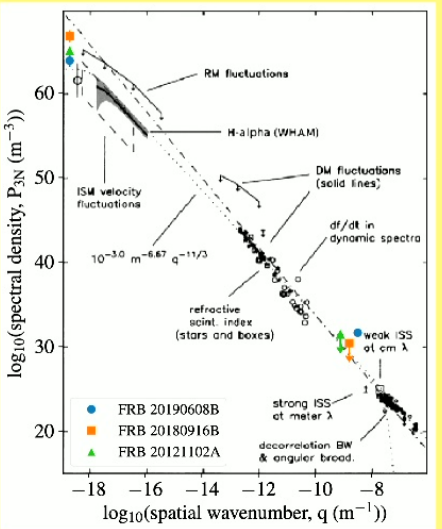

Galactic structure

Nimmo+2025



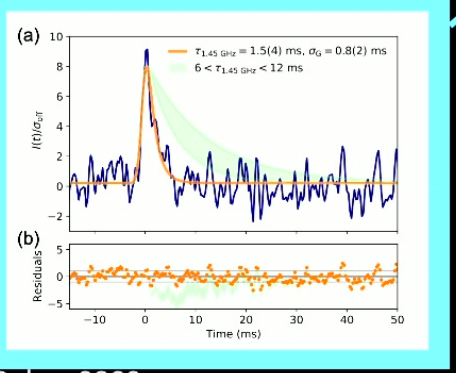

emission region size

ISM density power spectrum



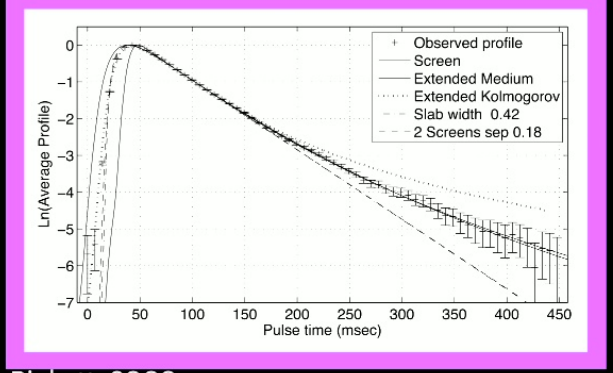

Armstrong+95; Simard & Ravi (2021)

circumsource media



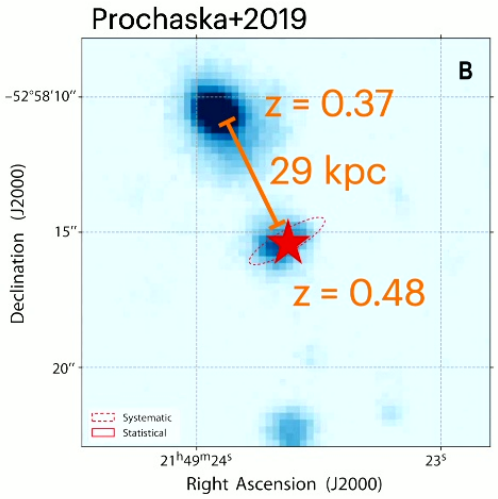

Ocker+2023

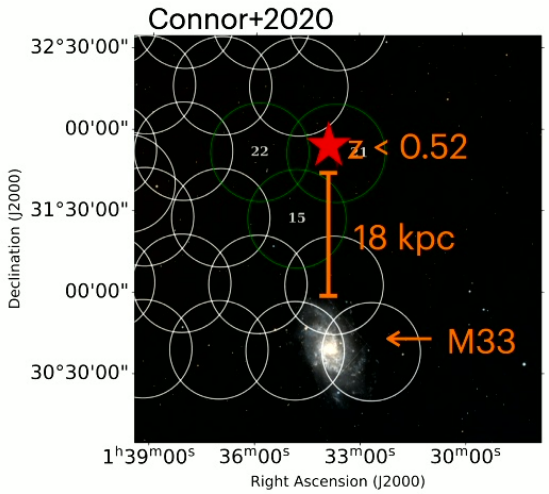
turbulent dissipation

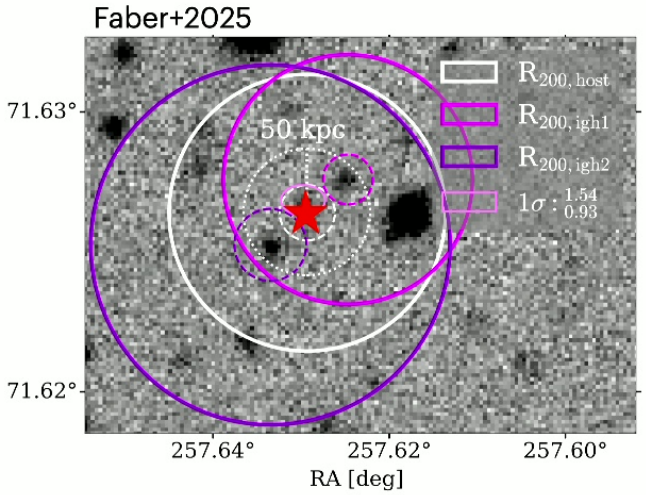



Rickett+2009

# FRBs probe the CGM



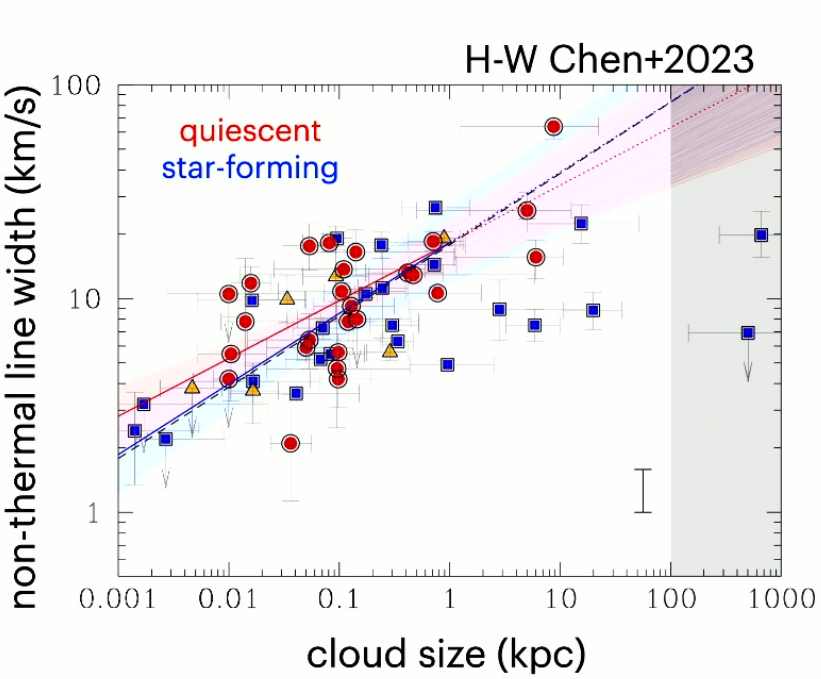



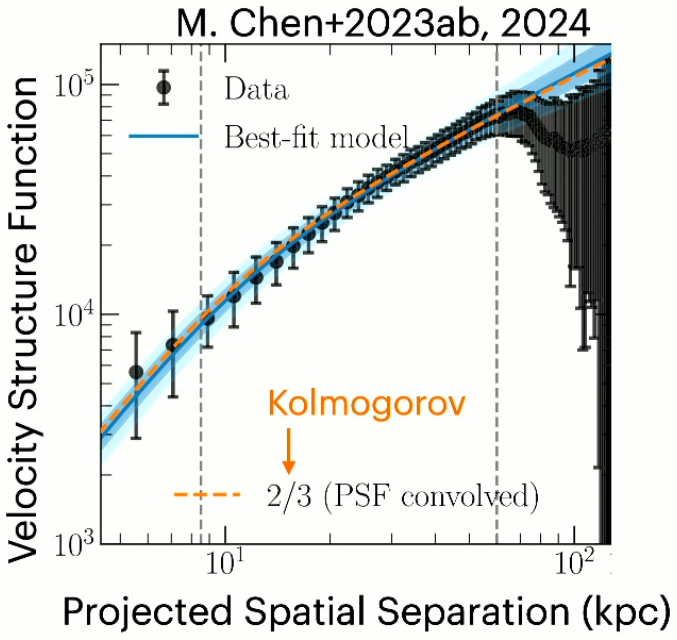

**Most FRBs at $z \gtrsim 0.3$ pass within 2x virial radius of a MW-mass galaxy.**
**The CGM contribution to FRB scattering is unknown.**
**CGM turbulence is observed, which suggests scattering may also occur in the CGM.**

*Macquart & Koay (2013); McQuinn (2014); Vedantham & Phinney (2019); Ocker+(2022b)*

# Observations of CGM Turbulence

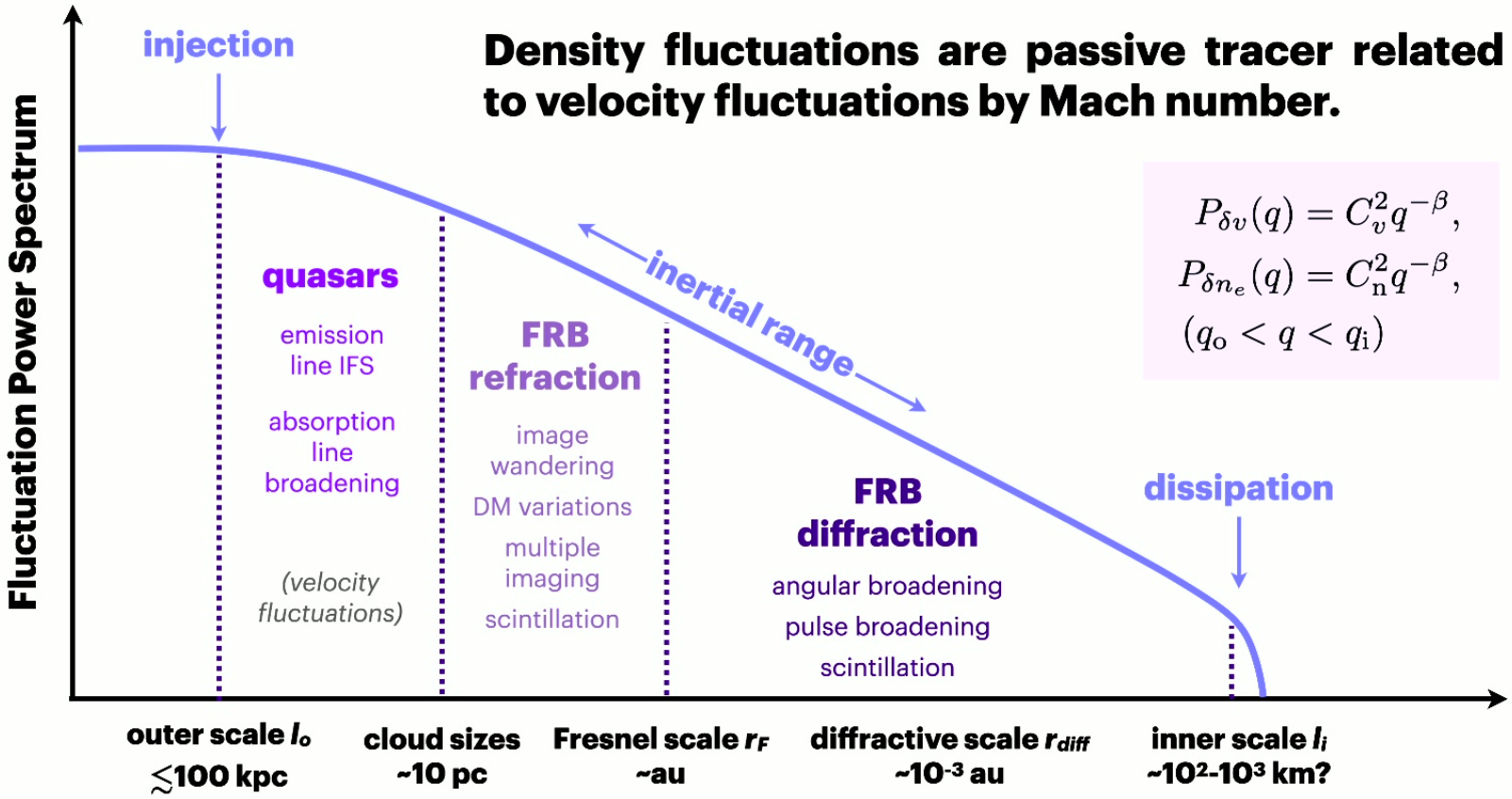



**cool | hot**

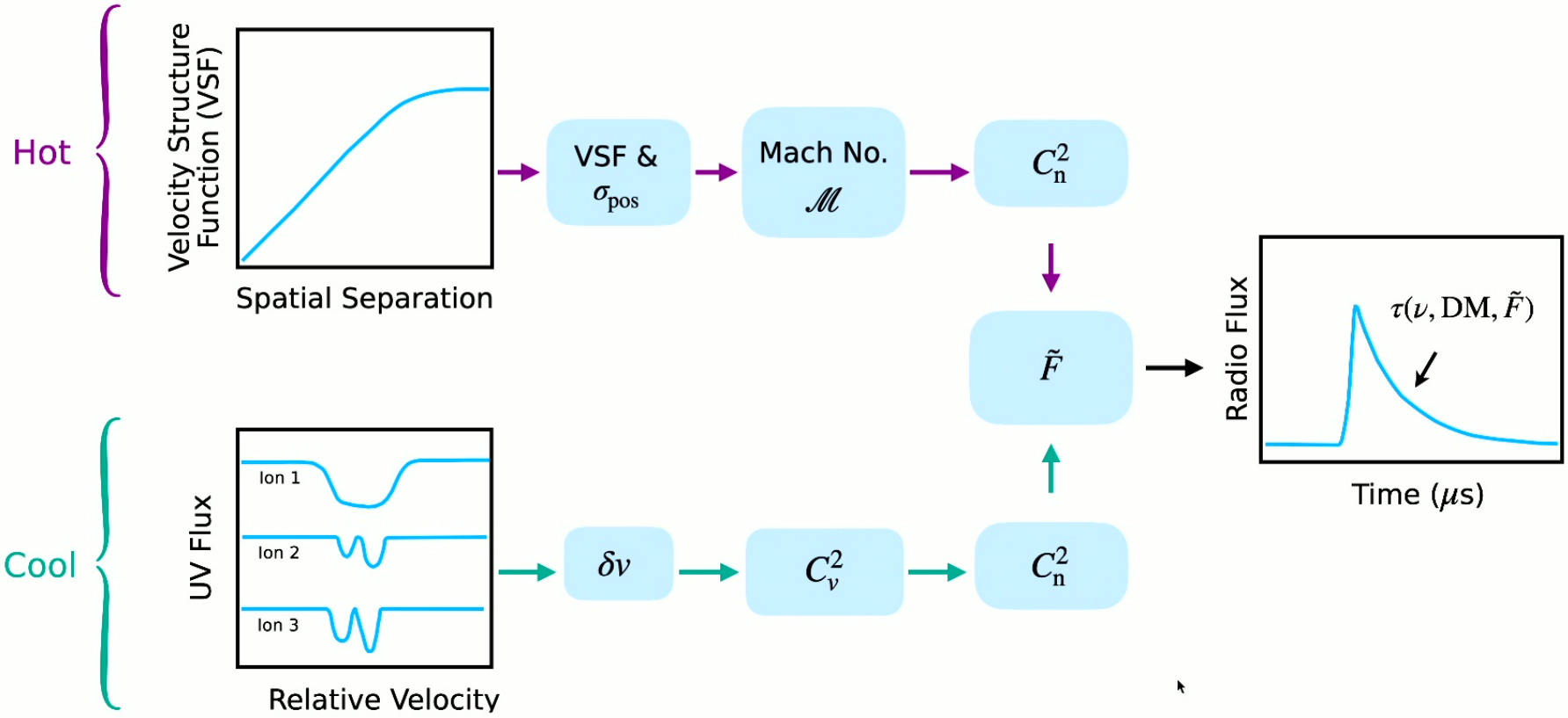



**absorption & emission line studies suggest turbulence mostly subsonic, ~Kolmogorov in both hot & cool CGM**

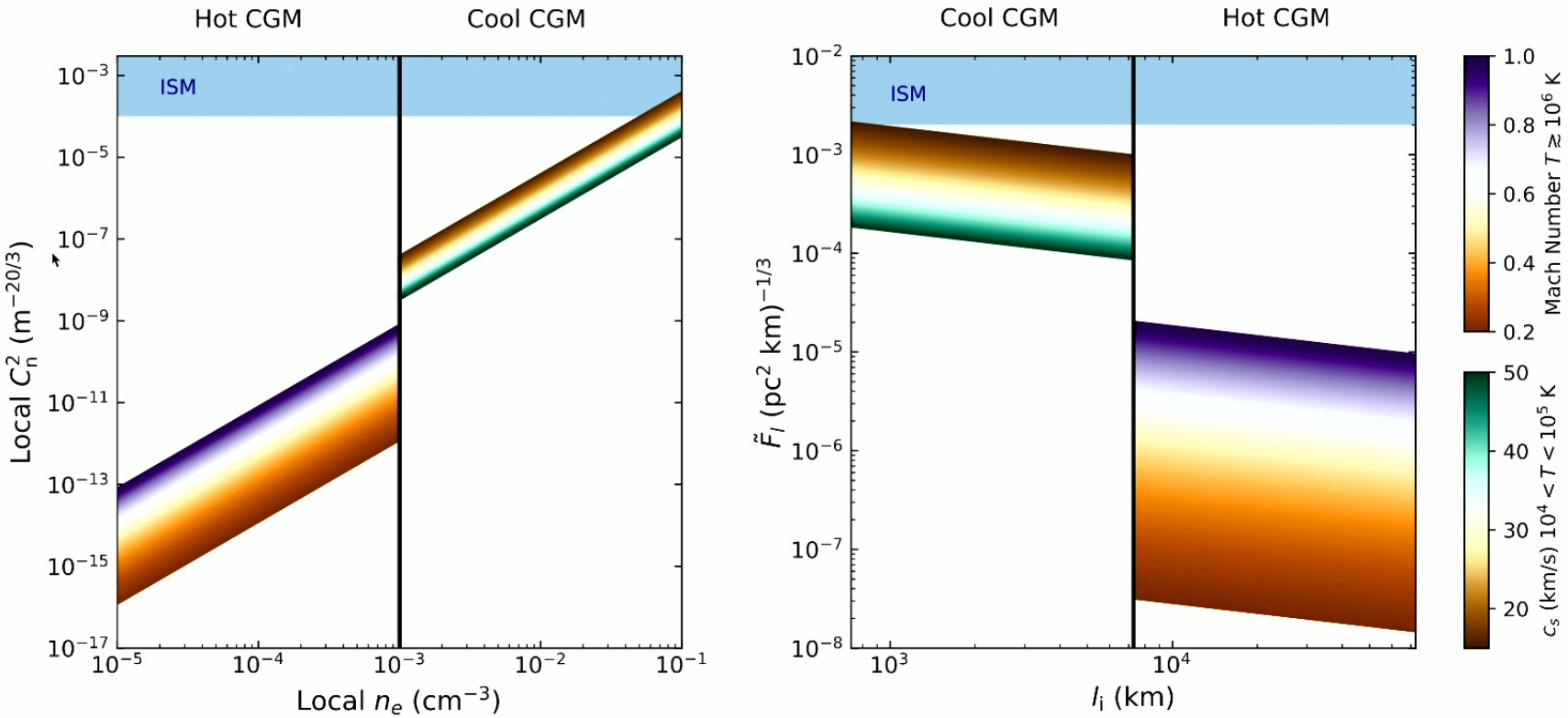
# Notional Turbulence Cascade



# Connecting Quasar & FRB Observables

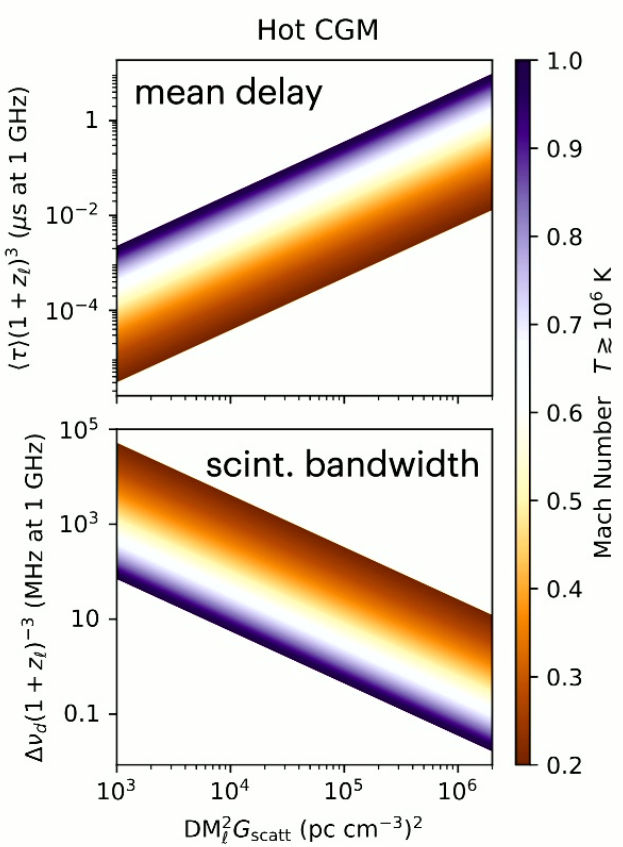


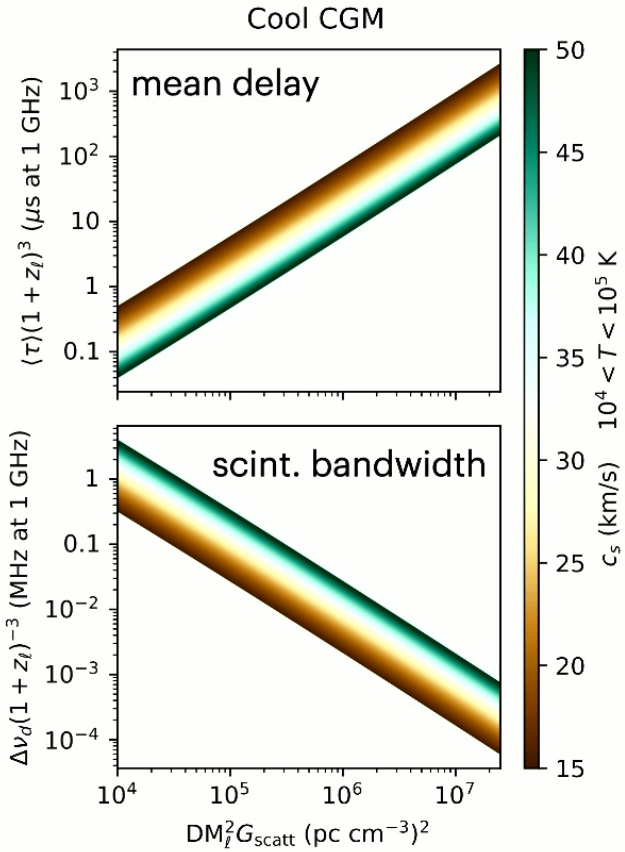
# Results: Strength of Density Fluctuations in CGM



# **Results:** Predicted FRB Scattering in CGM

**hot CGM scattering negligible, even w/ large geometric leverage**

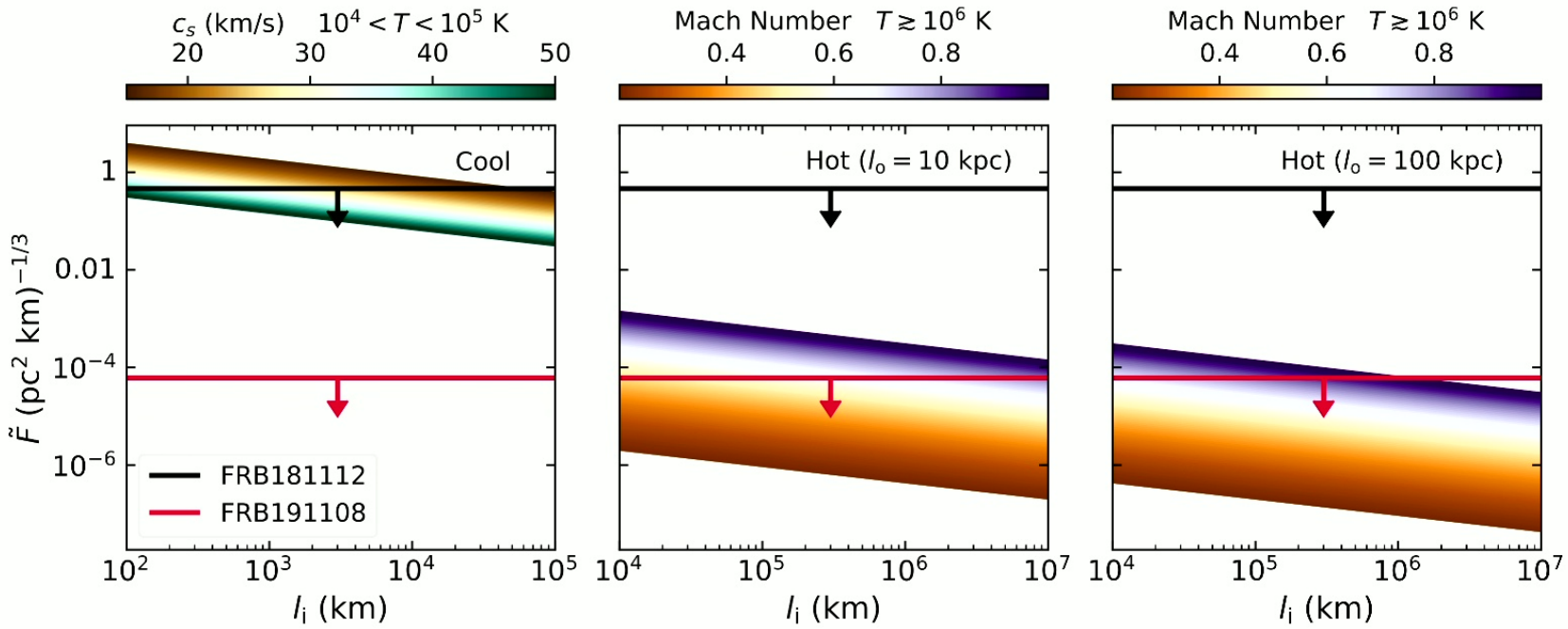



**cool CGM scattering detectable when DM and/or geometric leverage large**

*but not always distinguishable from MW ISM*

# Results: The Dissipation Scale

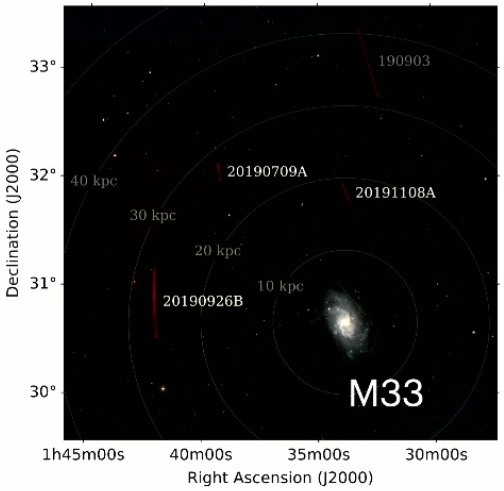



**combining quasar-inferred $\tilde{F}$ & FRB-inferred $\tilde{F}$**
**=> lower bound (or perhaps in future, measurement) of inner scale**

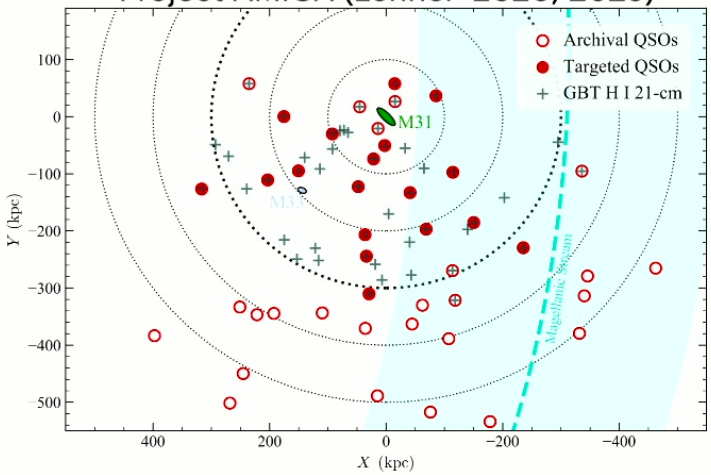
# Prospects: Combining Quasar & FRB Sightlines

**Most powerful application = FRBs & quasars probing the same halos.**
**This is within reach.**

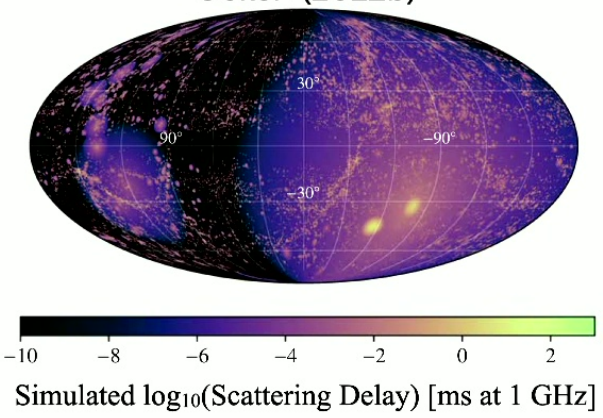
van Leeuwen+2022




Project AMIGA (Lehner+2020; 2025)

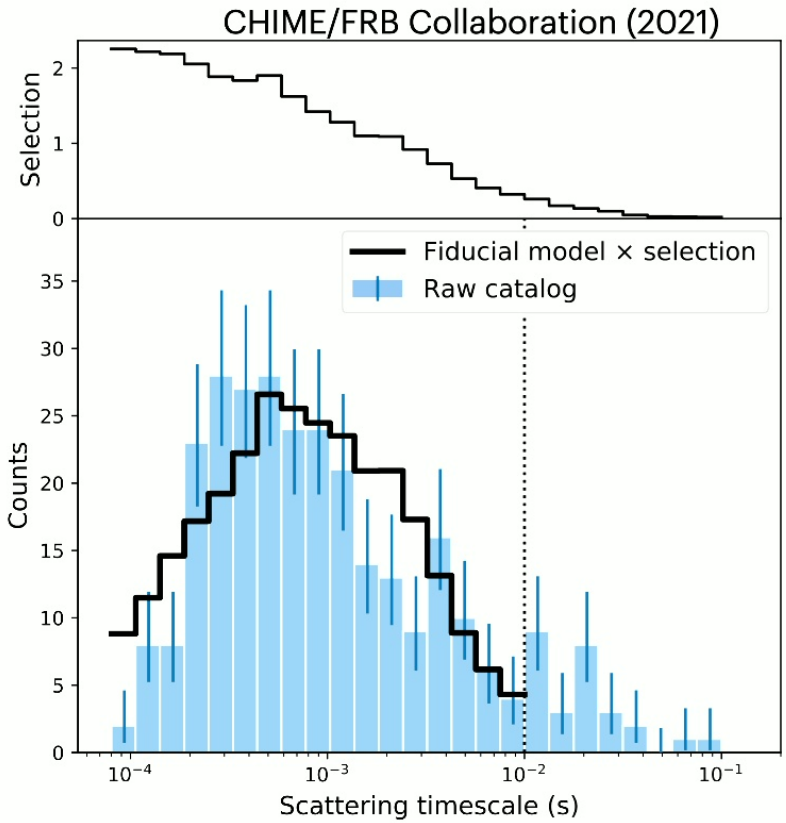



Ocker+(2022b)




*Connor & Ravi (2022); Wu & McQuinn (2023); Anna-Thomas+(2025)*

# Where are the missing FRBs?




**There is a significant population of FRBs that are *undetected* due to large scattering.**

Where do these unseen FRBs reside in the universe? How do they acquire so much scattering?

*High-redshift FRBs may not be observed, at least in part, due to scattering in foreground halos.*

**=> Scattering = important consideration in forecasting high-z FRB applications.**

# Summary.

FRB scattering is uniquely sensitive to plasmas @ sub-au scales.

Quasar observations yield empirically motivated predictions of turbulent density fluctuations @ scales probed by FRBs.

Combining quasar and FRB sightlines through a galaxy halo may constrain the amplitude, spectral index, and dissipation scale of CGM turbulence.

arXiv:2503.02329

*Ocker, Chen, Oh, & Sharma (2025)*

Stella Koch Ocker (Caltech/Carnegie)