Implications of the Scattering Budget

for Fast Radio Burst Sources & Applications

Stella Koch Ocker
PhD Candidate
Cornell University

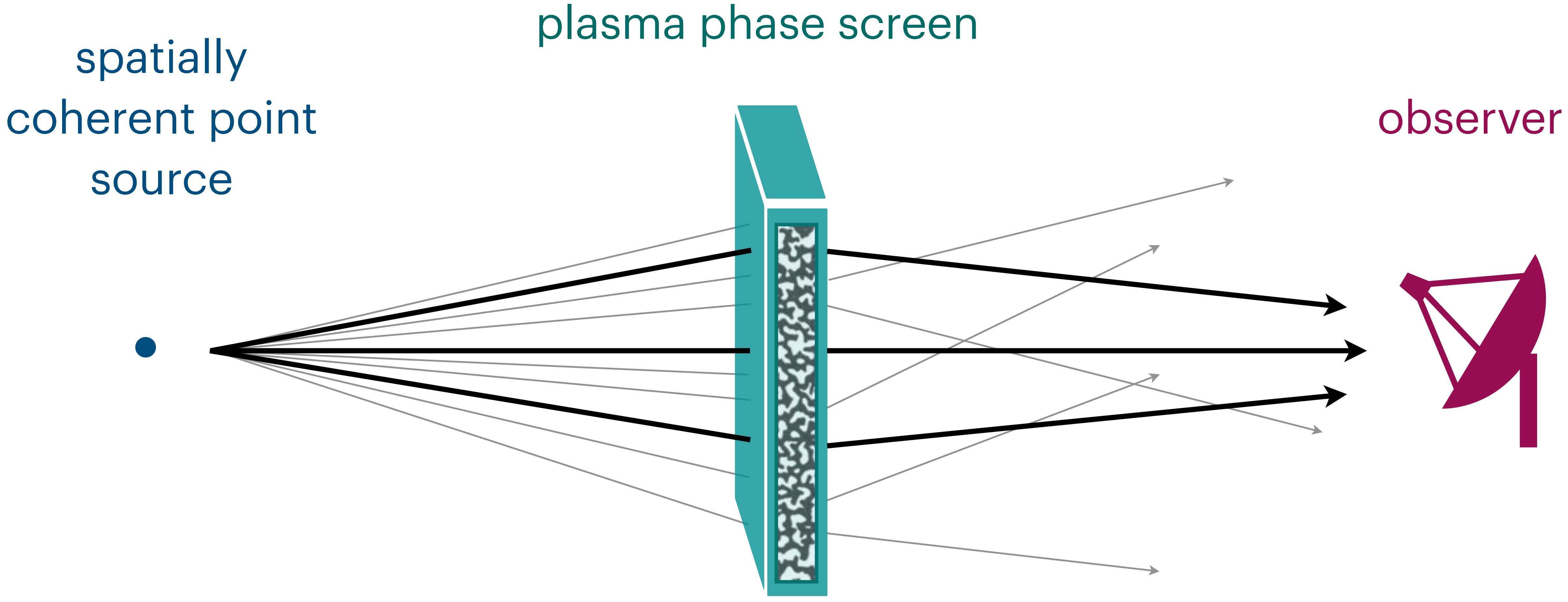
Advisors: Jim Cordes & Shami Chatterjee

stellakochocker.com

Relevant papers: Ocker+2021 (ApJ 911:2); Ocker+2022a (ApJ 931:87); Cordes+2022b (ApJ 931:88); Ocker+2022b (ApJ 934:71); Ocker+2022c (under review)

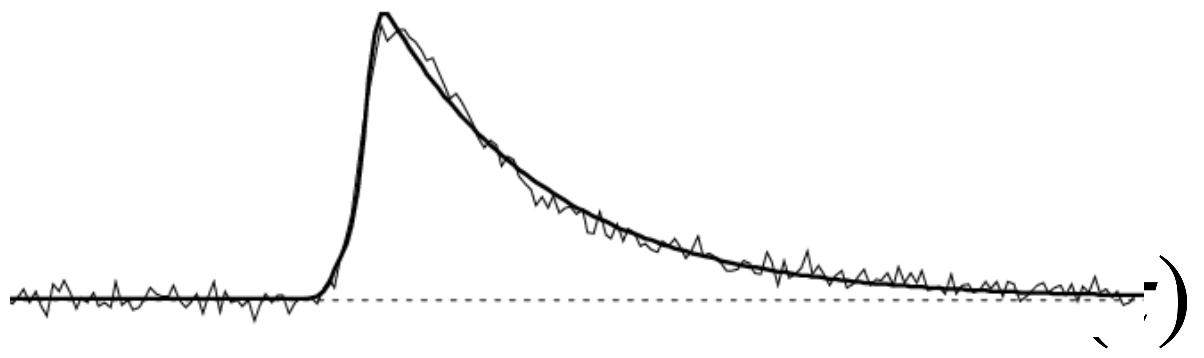
FRB Scattering
Basic Phenomena

FRBs undergo multi-path propagation due to turbulent, small-scale ($\lesssim$ au) electron density fluctuations (highly frequency-dependent)



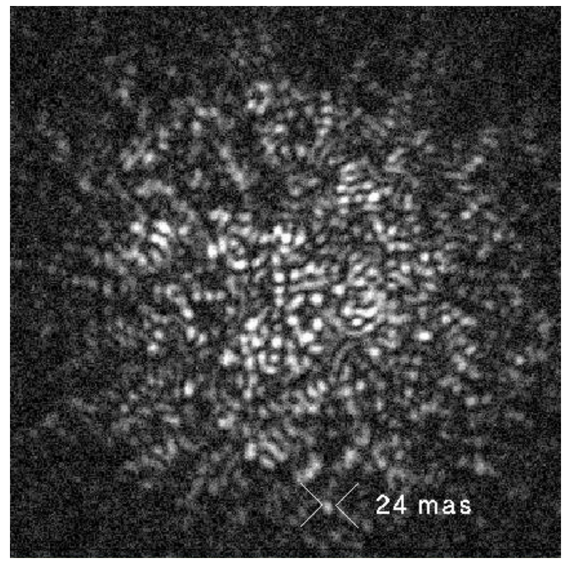
observables

scattering time (τ)



scintillation bandwidth ($\Delta\nu_d$)

angular broadening (θ_d)

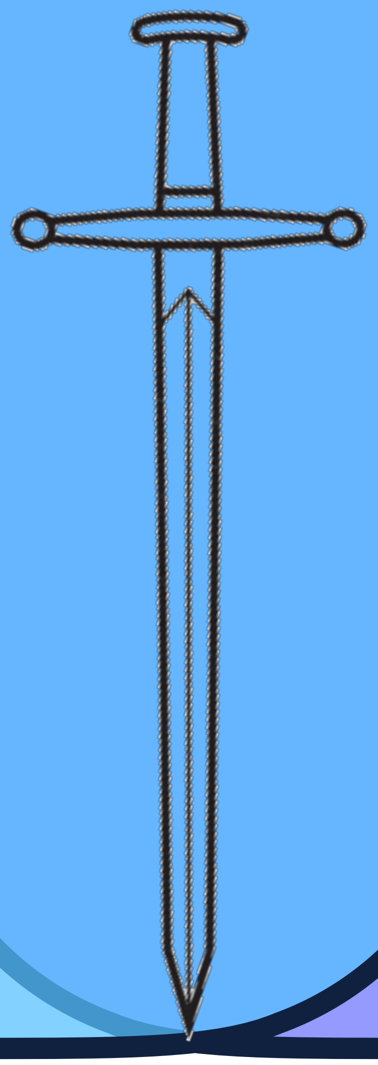


Selection Effect

- larger scattering time —> lower S/N
- selection bias depends on observing frequency, density regime, LOS configuration

CHIME/Catalog 1: large population of bursts may be unobserved due to scattering

scattering



Astrophysical Probe

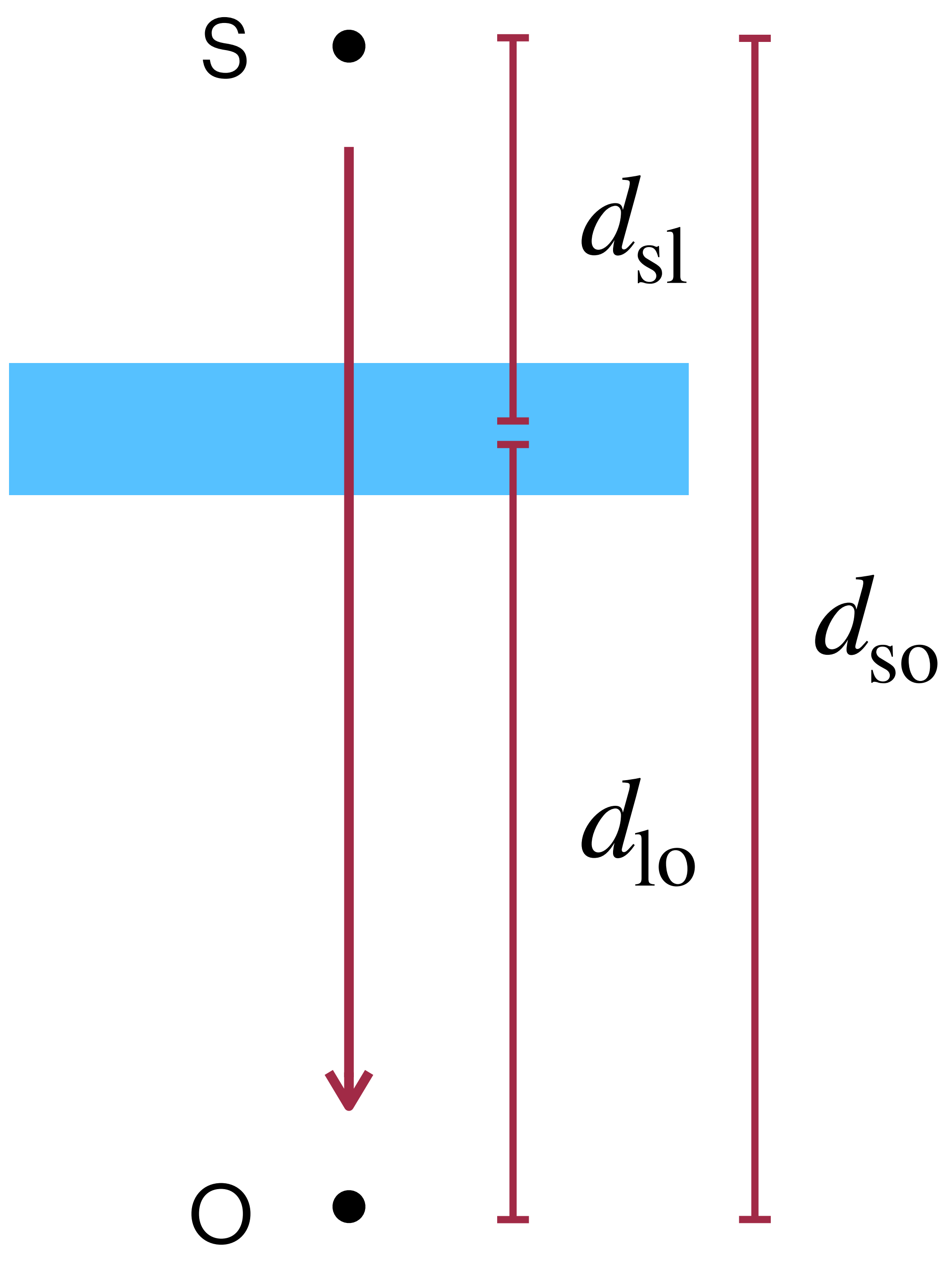
- density fluctuations in ionized gas (turbulence, small-scale structure)
- attributable to specific media along LOS
  - characterizing host ISMs & source environments
  - limits on multi-phase CGM

FRB Scattering
Single Screen

$$2\pi\tau\Delta\nu_{\rm d} \approx 1$$

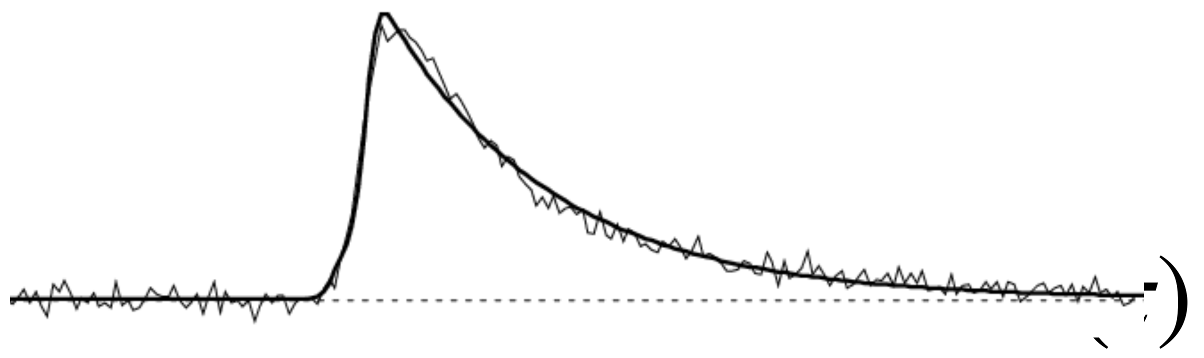
$$\tau \approx \left(\frac{d_{\rm sl}d_{\rm lo}}{d_{\rm so}}\right)\frac{\theta_{\rm s}^2}{8(\ln 2)c}$$

$$\theta_{\rm d}^{(\rm obs)} = \theta_{\rm s}\left(d_{\rm sl}/d_{\rm so}\right)$$



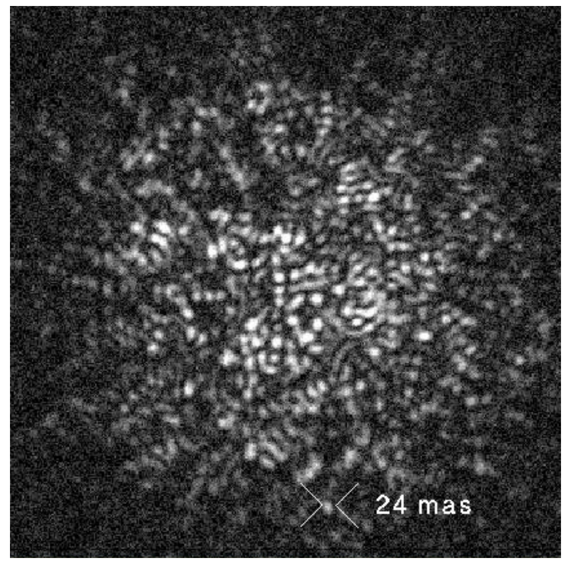
observables

scattering time (τ)



scintillation bandwidth ($\Delta\nu_{\rm d}$)

angular broadening ($\theta_{\rm d}$)



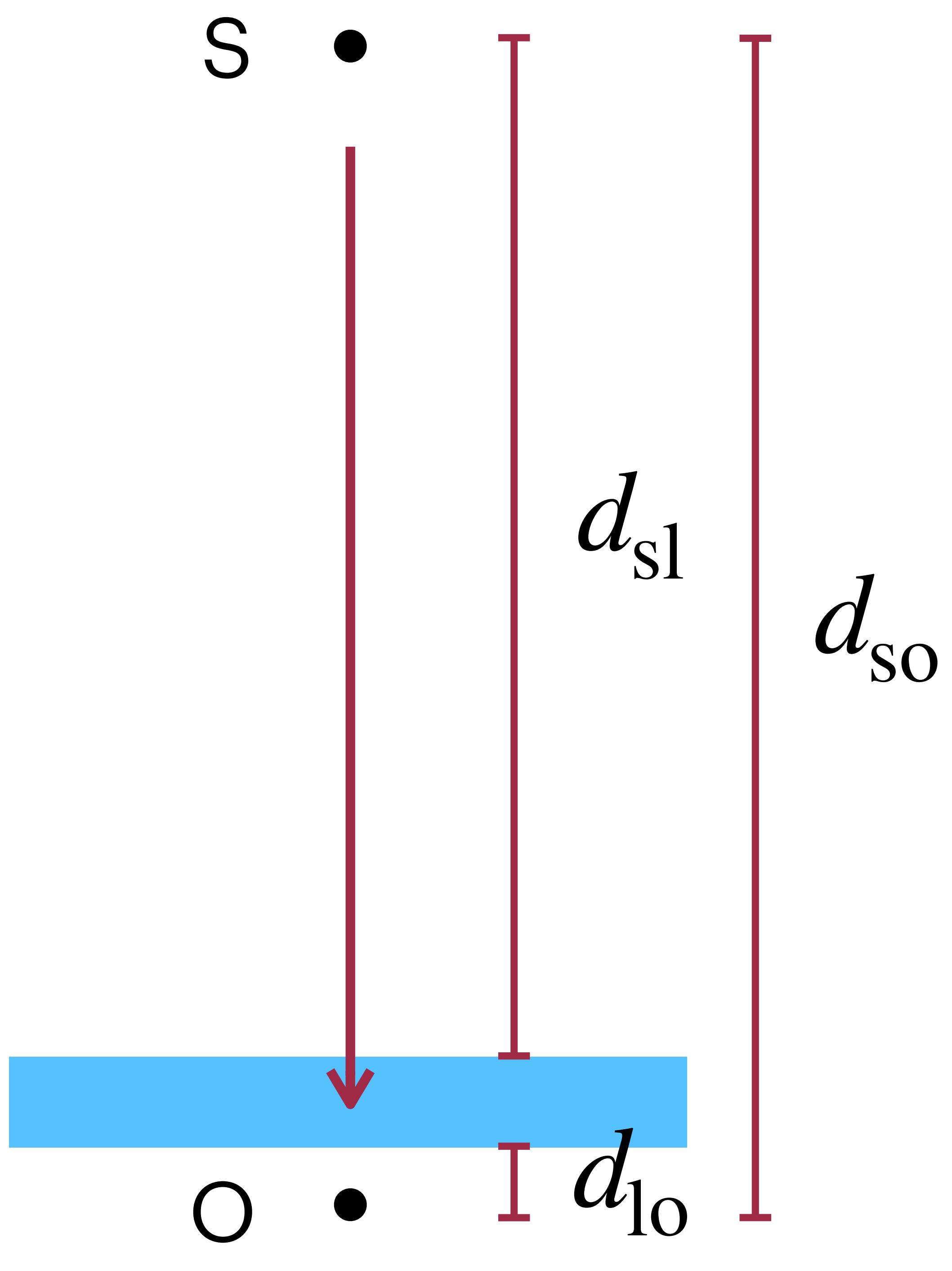
FRB Scattering

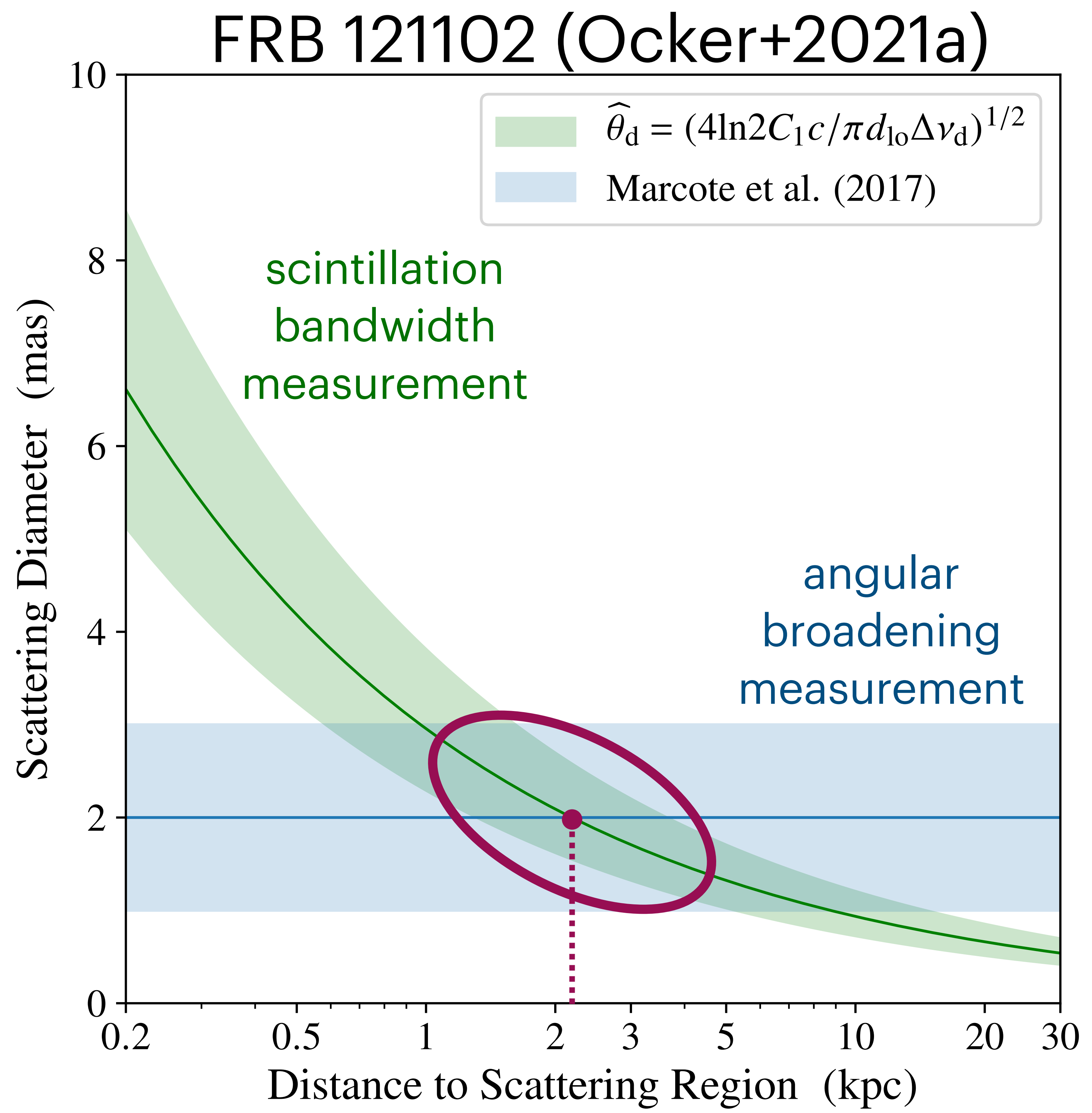
Single Screen: FRB 121102

$$2\pi\tau\Delta\nu_{\rm d} \approx 1$$

$$\tau \approx \left(\frac{d_{\rm sl} d_{\rm lo}}{d_{\rm so}}\right)\frac{\theta_{\rm s}^2}{8(\ln 2)c}$$

$$\theta_{\rm d}^{\rm (obs)} = \theta_{\rm s}(d_{\rm sl}/d_{\rm so})$$





scintillation & angular broadening in Milky Way ISM (outer spiral arm)

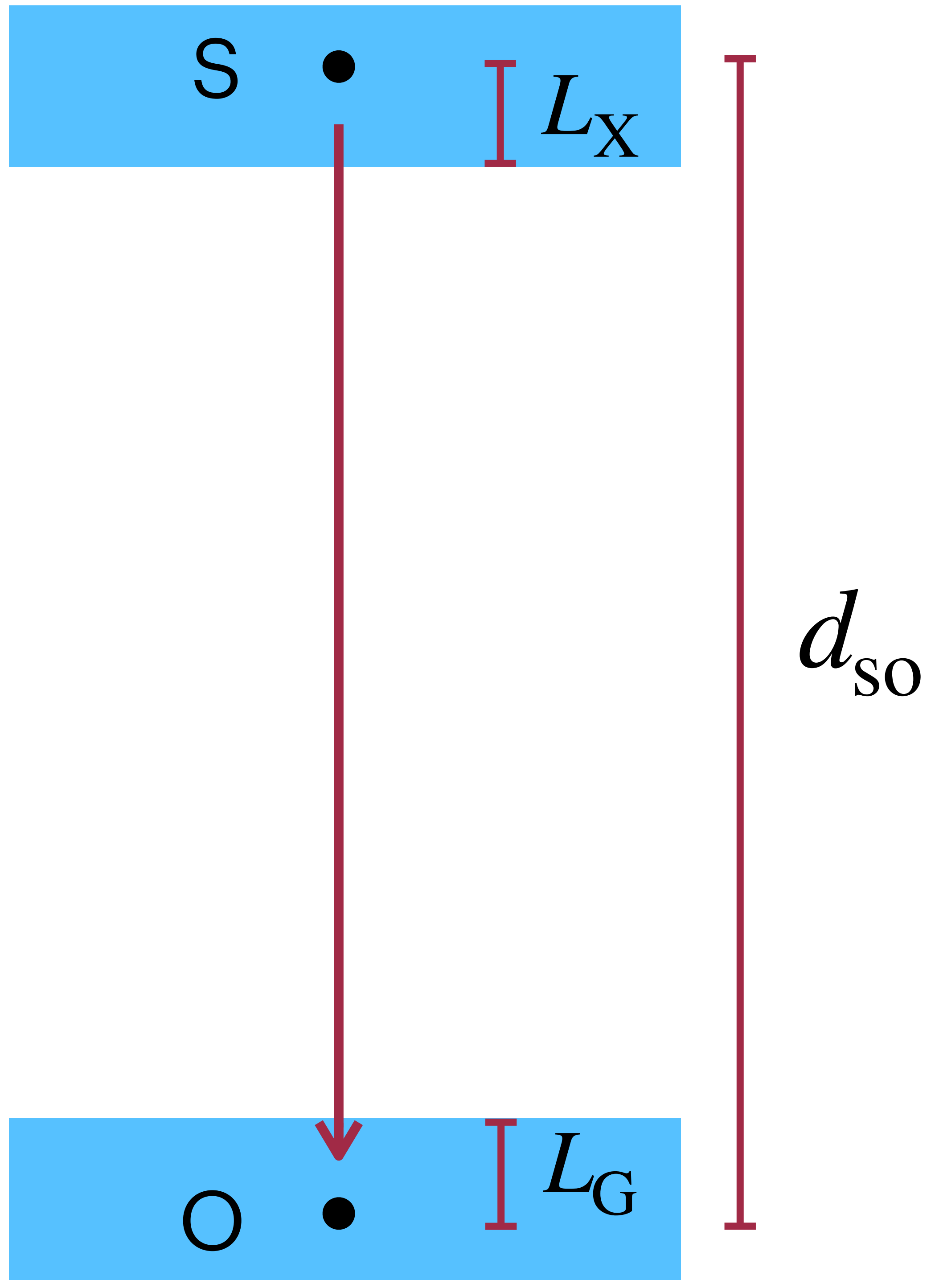
FRB Scattering
Two Screens

$$2\pi\tau\Delta\nu_{\rm d} \not\approx 1$$

extragalactic scattering attenuates Galactic scintillations

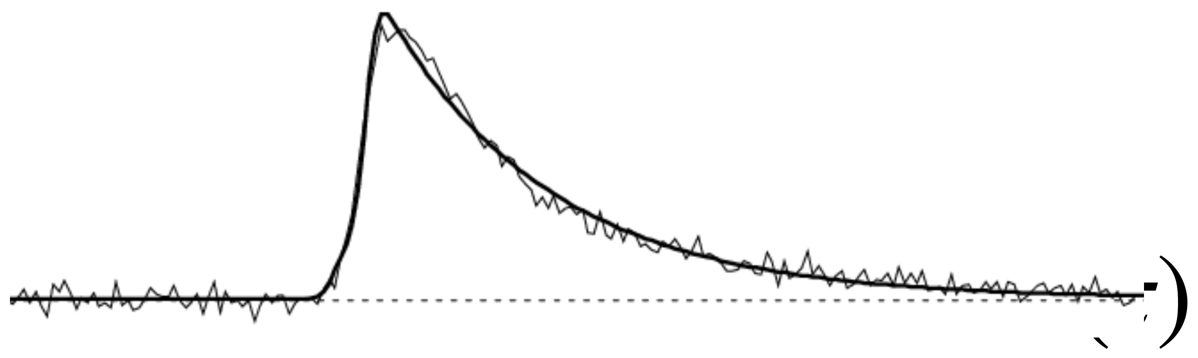
➡ limit on screen distances required to detect pulse broadening & scintillation from 2 screens:

$$\tau_X\tau_G \lesssim \frac{1}{(2\pi\nu)^2}\frac{d_{\rm so}^2}{L_X L_G}$$



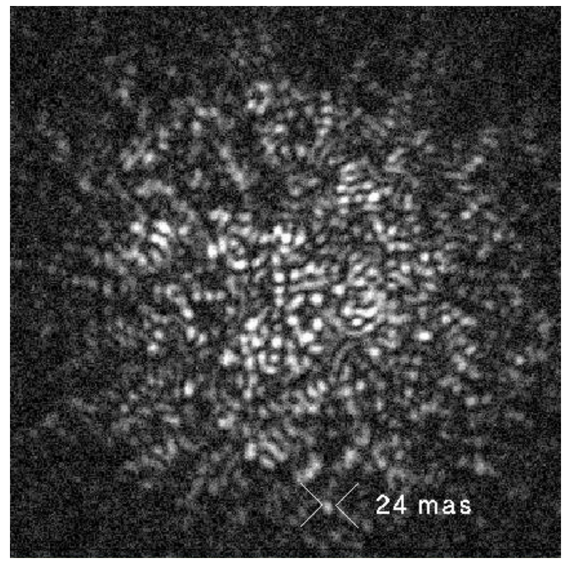
observables

scattering time (τ)



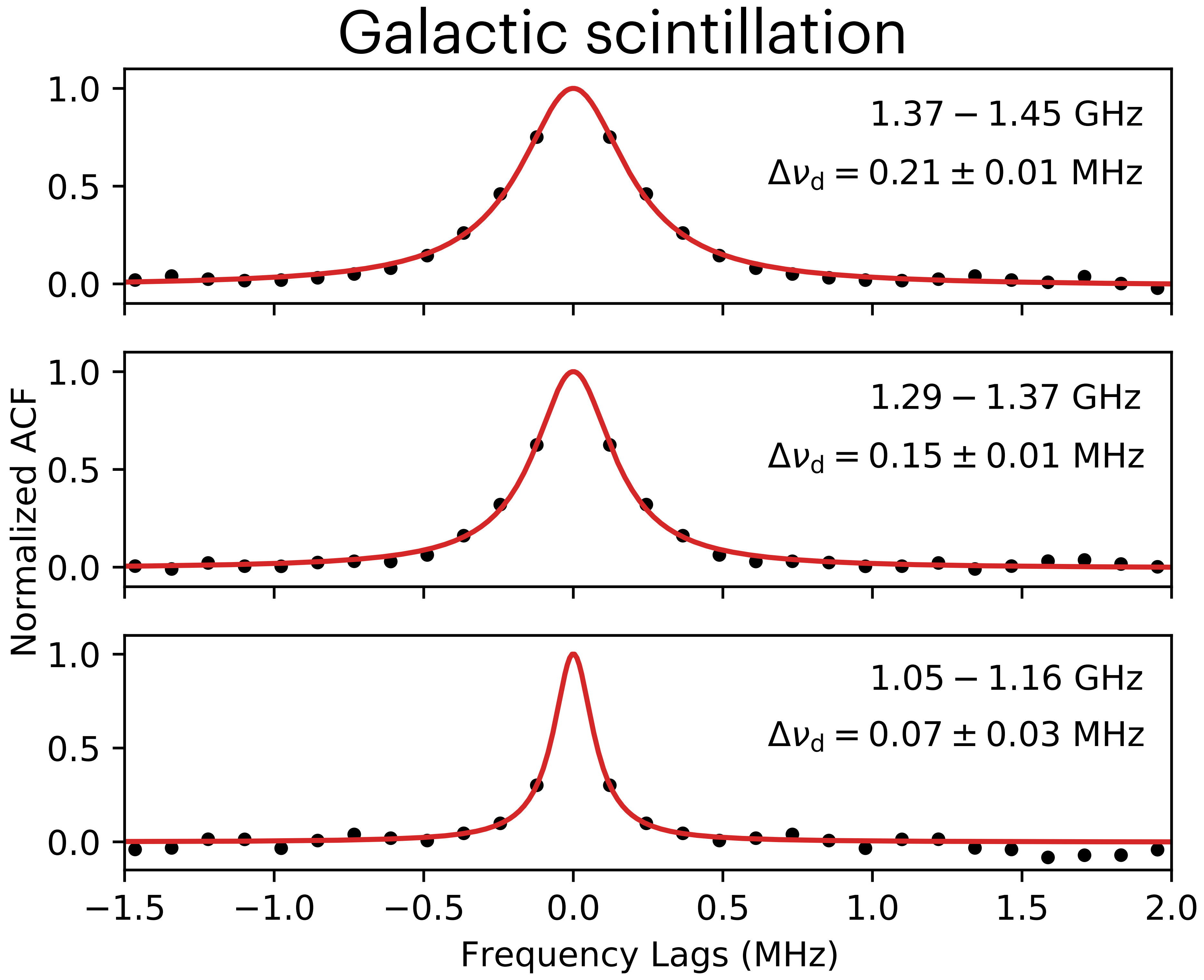
scintillation bandwidth ($\Delta\nu_{\rm d}$)

angular broadening ($\theta_{\rm d}$)



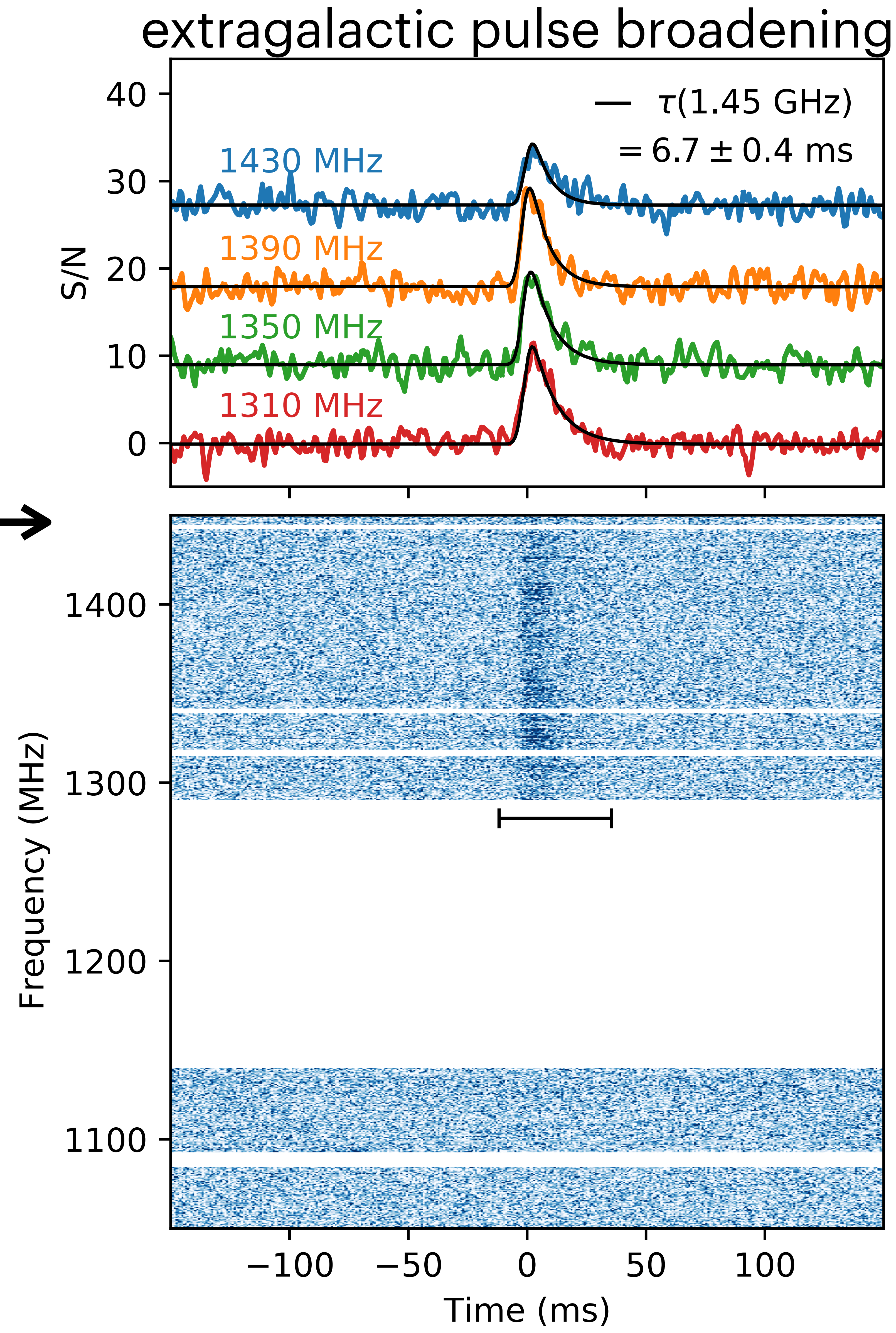
FRB Scattering

Two Screens: FRB 20190520B



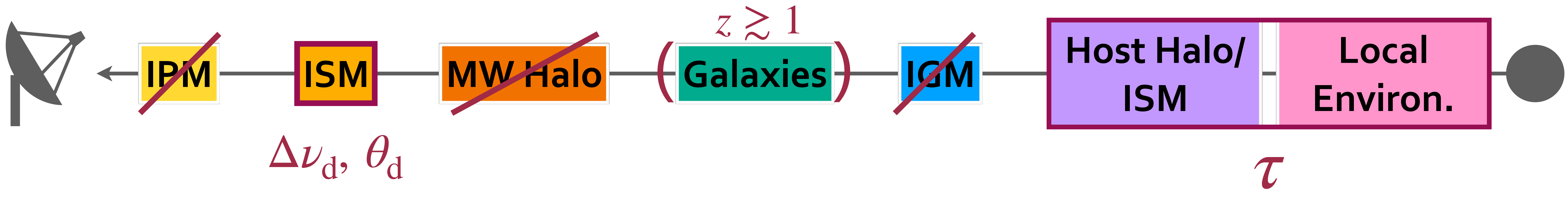
$$\longleftarrow 2\pi\tau\Delta\nu_{\mathrm{d}} \not\approx 1 \longrightarrow$$

xgal screen
< 100 pc
from
source



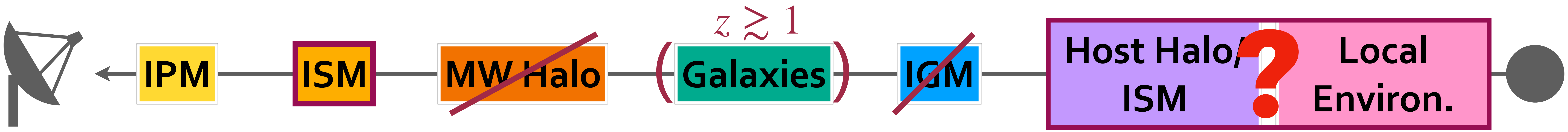
Scattering Budget Overview

Scattering Budget Overview



Ocker+(2021a, 2022ab)
Cordes+(2022b)

Host Galaxy Scattering



FRB 20190520B — scattering definitively from local source environment:

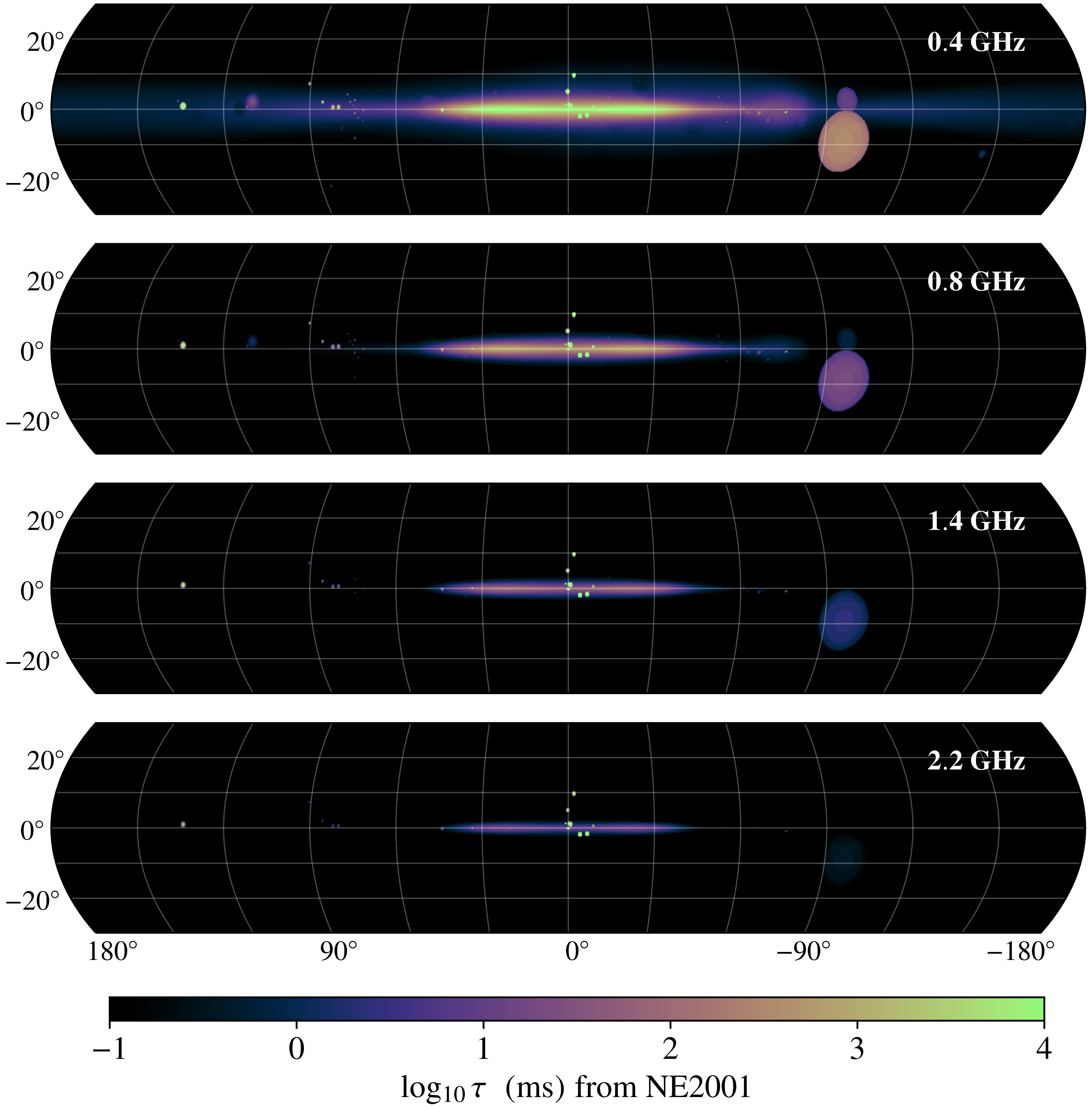
1) mean scattering time & scintillation bandwidth —> screen dist. < 100 pc
2) scattering time varies burst-to-burst (—> screen dist. ~pc)

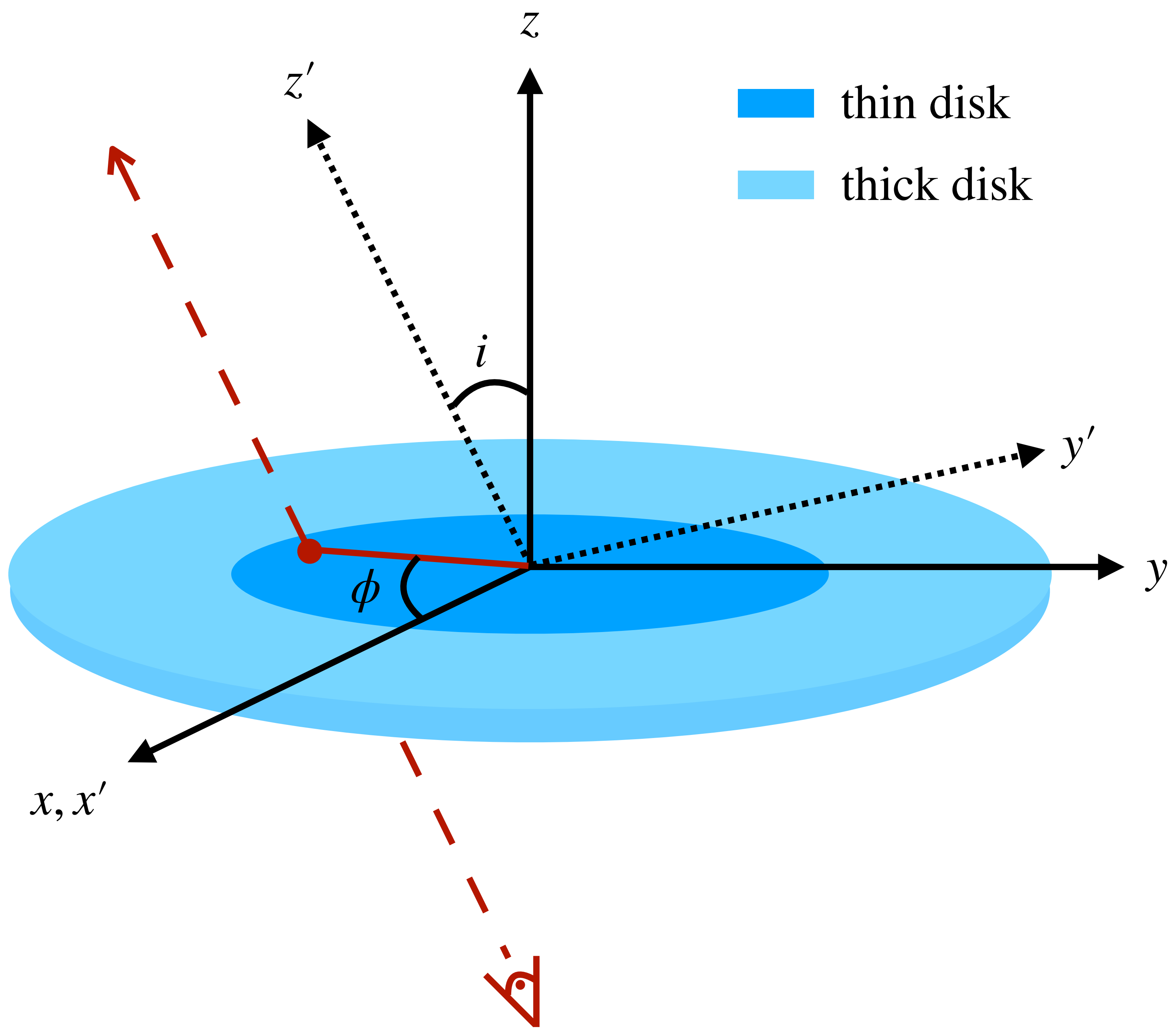
ISM vs. local scattering more ambiguous for most FRBs

Ocker+(2022ab)

Host Scattering: Implications

Galactic scattering (NE2001)





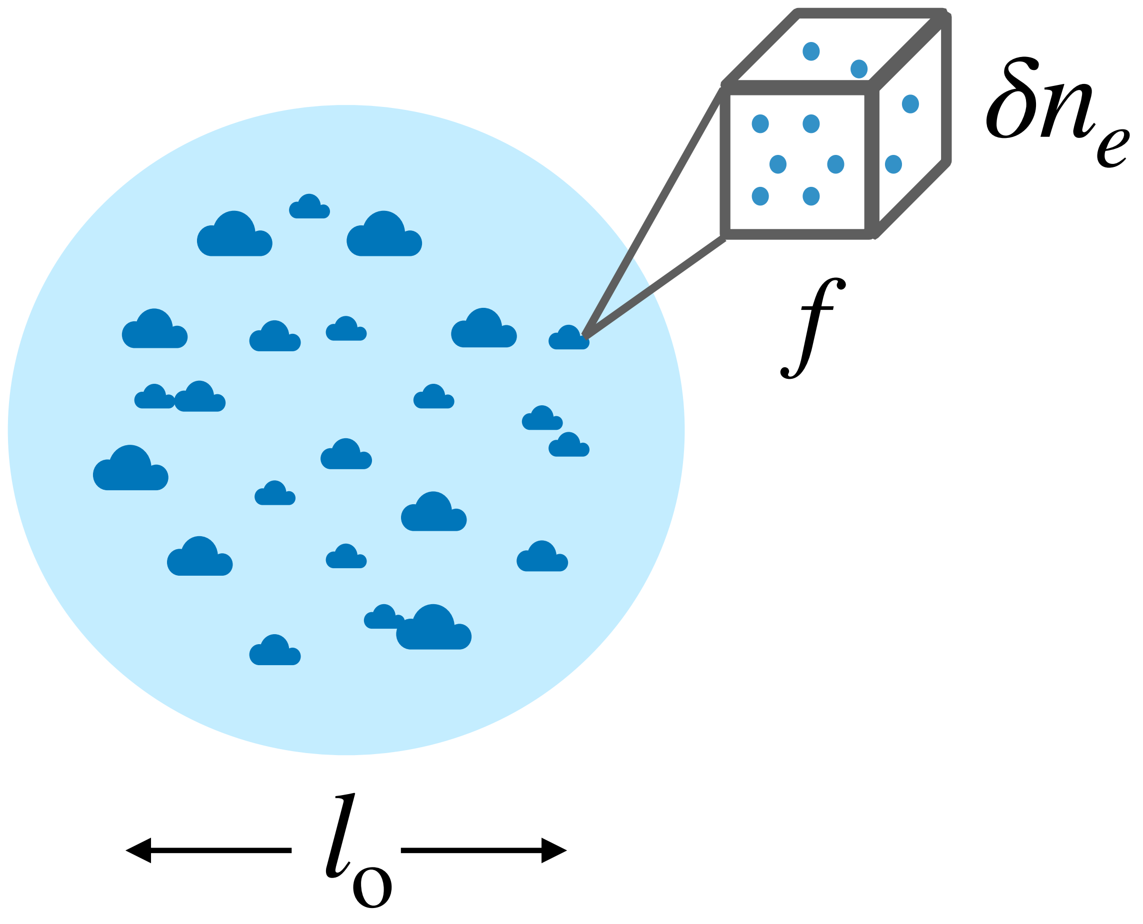
scattering depends on LOS through galaxy
—> impacts interpretation of source locations & host galaxies in terms of progenitor populations

selection effects aside, how do we translate the scattering budget into interesting astrophysical constraints?

Ionized Cloudlet Model: Fluctuation Parameter

amount of pulse broadening per unit DM given by the “fluctuation parameter”

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



$$\tilde{F} = \frac{\zeta \epsilon^2}{f \left(l_{\rm o}^2 l_{\rm i}\right)^{1/3}}$$

fluctuation parameter = composite characterization of turbulent density fluctuations

Ionized Cloudlet Model

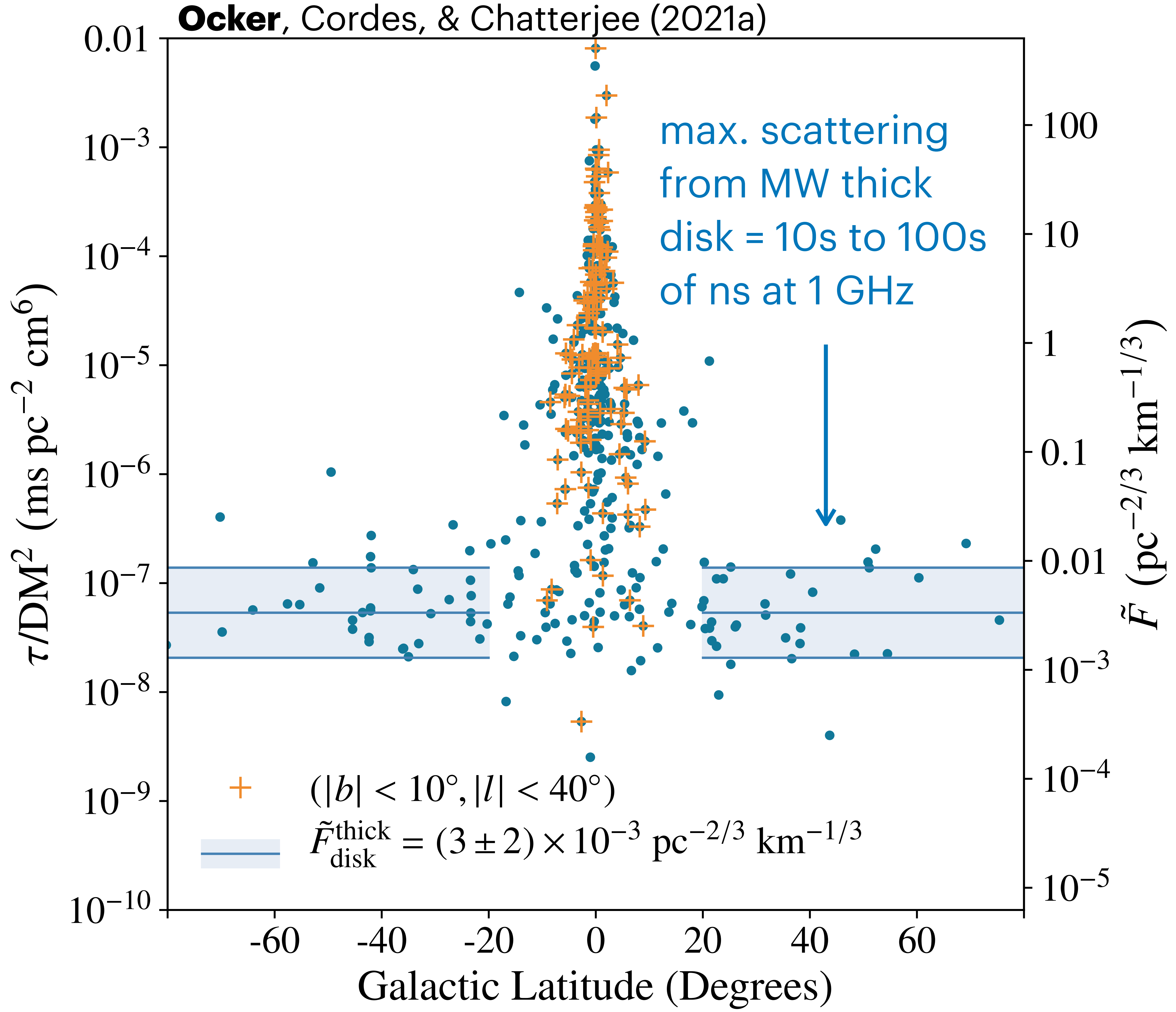
fluctuation variance: $\epsilon^2 = \langle (\delta n_e)^2 \rangle / n_e^2$

cloud-cloud variations: $\zeta = \langle n_e^2 \rangle / \langle n_e \rangle^2$

filling factor: f

outer/inner scales of turbulence: $l_{\rm o,i}$

Interpreting Fluctuation Parameters



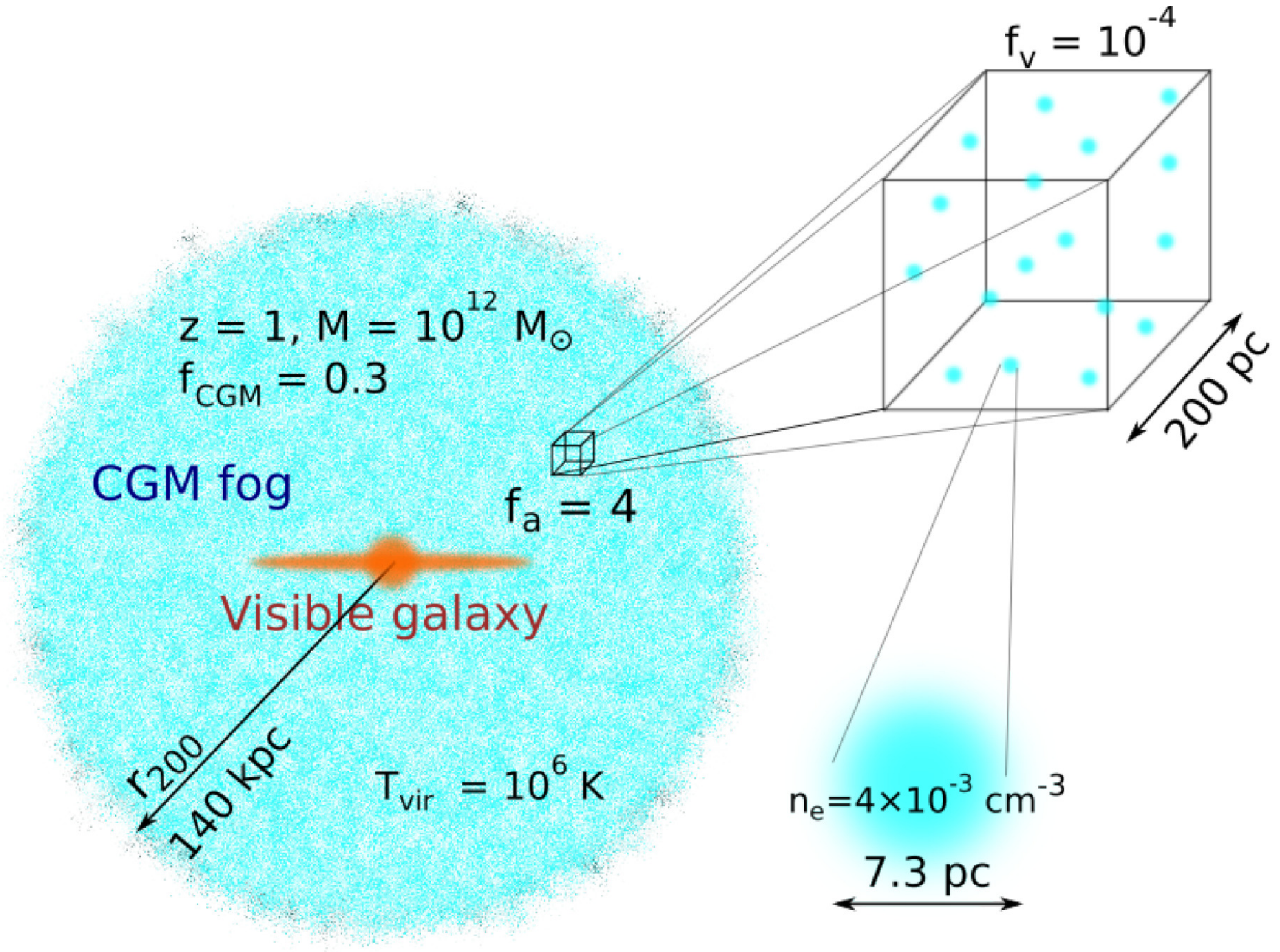
observed distribution of fluctuation parameter in MW

= reference point for extragalactic environments

limits on MW CGM from FRBs 121102, 180916, 20200120E

limit on M33 CGM from FRB 191108

Implications for Multi-Phase CGM



Vedantham & Phinney (2019)

- abundance of evidence for T < 10^6 K gas out to virial radii of L* galaxies
- observational evidence for cloudlets on ~0.1 - 10 kpc scales (possibly smaller) in CGM
- likely testable w/ FRBs

QSO absorption lines (sparse sampling for individual galaxies)

c.f. Tumlinson+2017 (ARA&A)

Implications for Multi-Phase CGM

requirements for multi-path scattering:

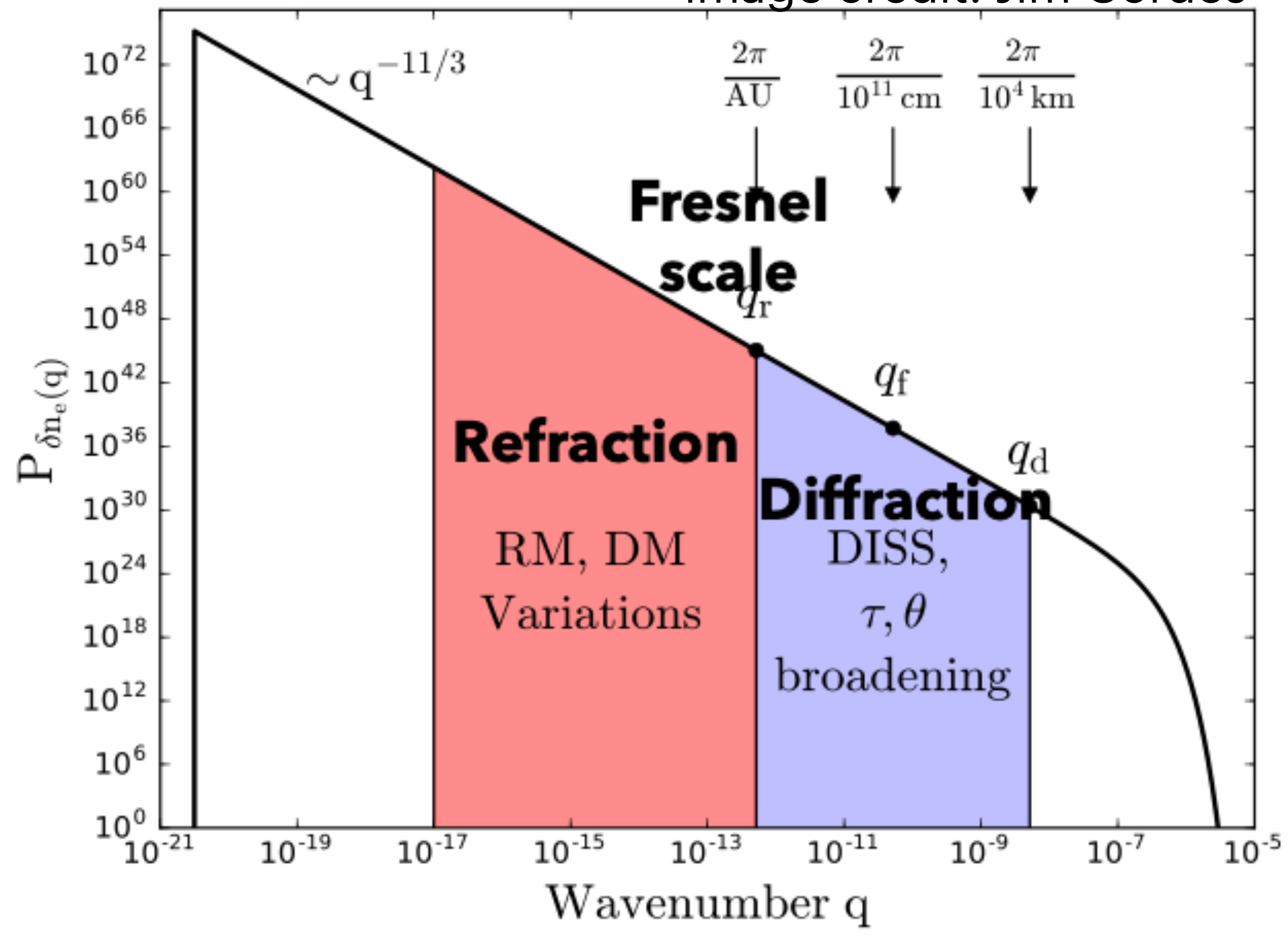
- inner scale << Fresnel scale

$$r_{\mathrm{F}} \sim \left(\frac{\lambda d}{2\pi}\right)^{1/2} \sim \begin{cases} \sim 0.01 & \mathrm{au} \quad \mathrm{(ISM)} \\ \sim 6 & \mathrm{au} \quad \mathrm{(intervening\ CGM)} \end{cases}$$

- bending angles > angular size of cloudlets

➡ large enough $\tilde{F}$

image credit: Jim Cordes

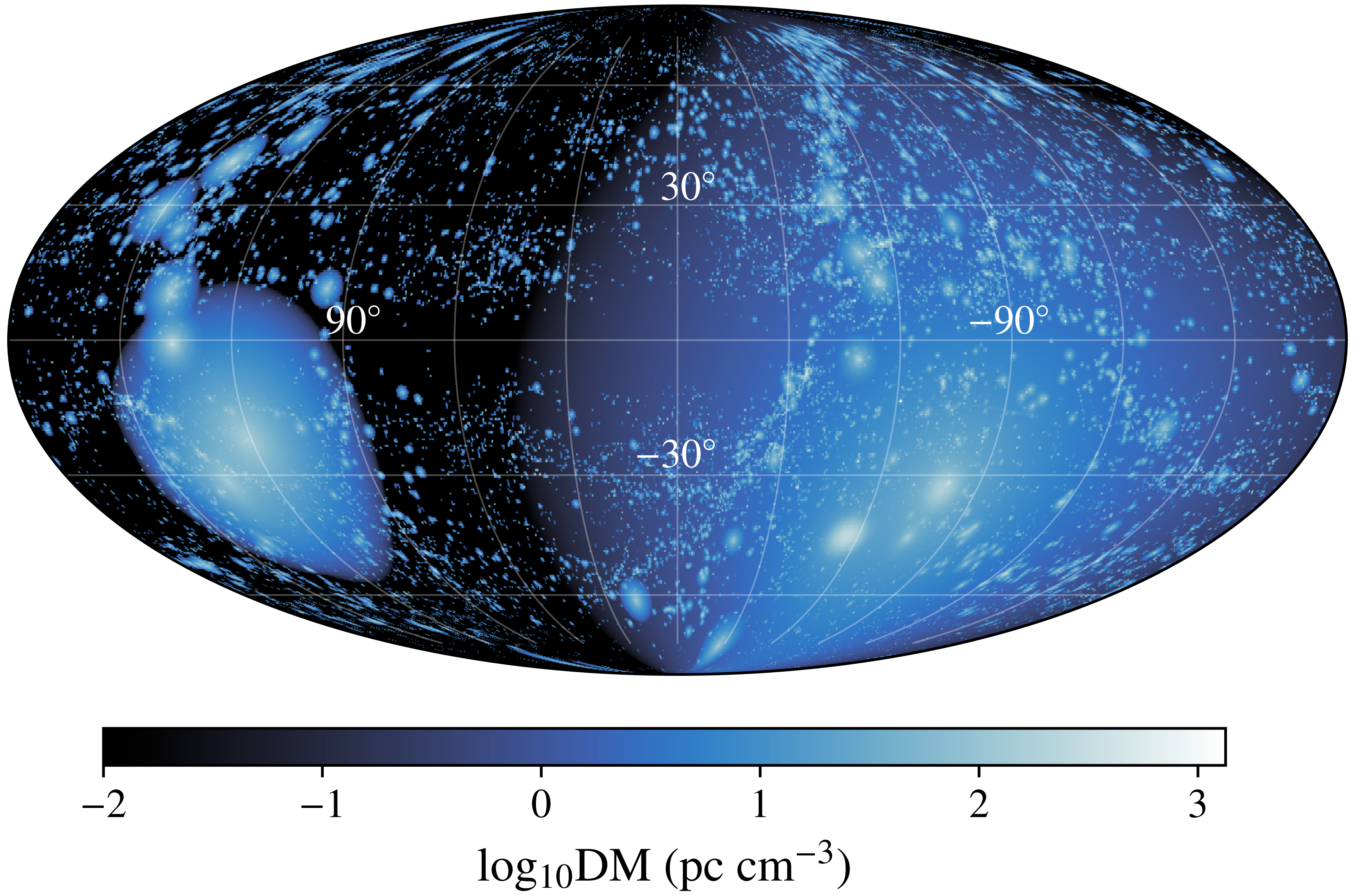


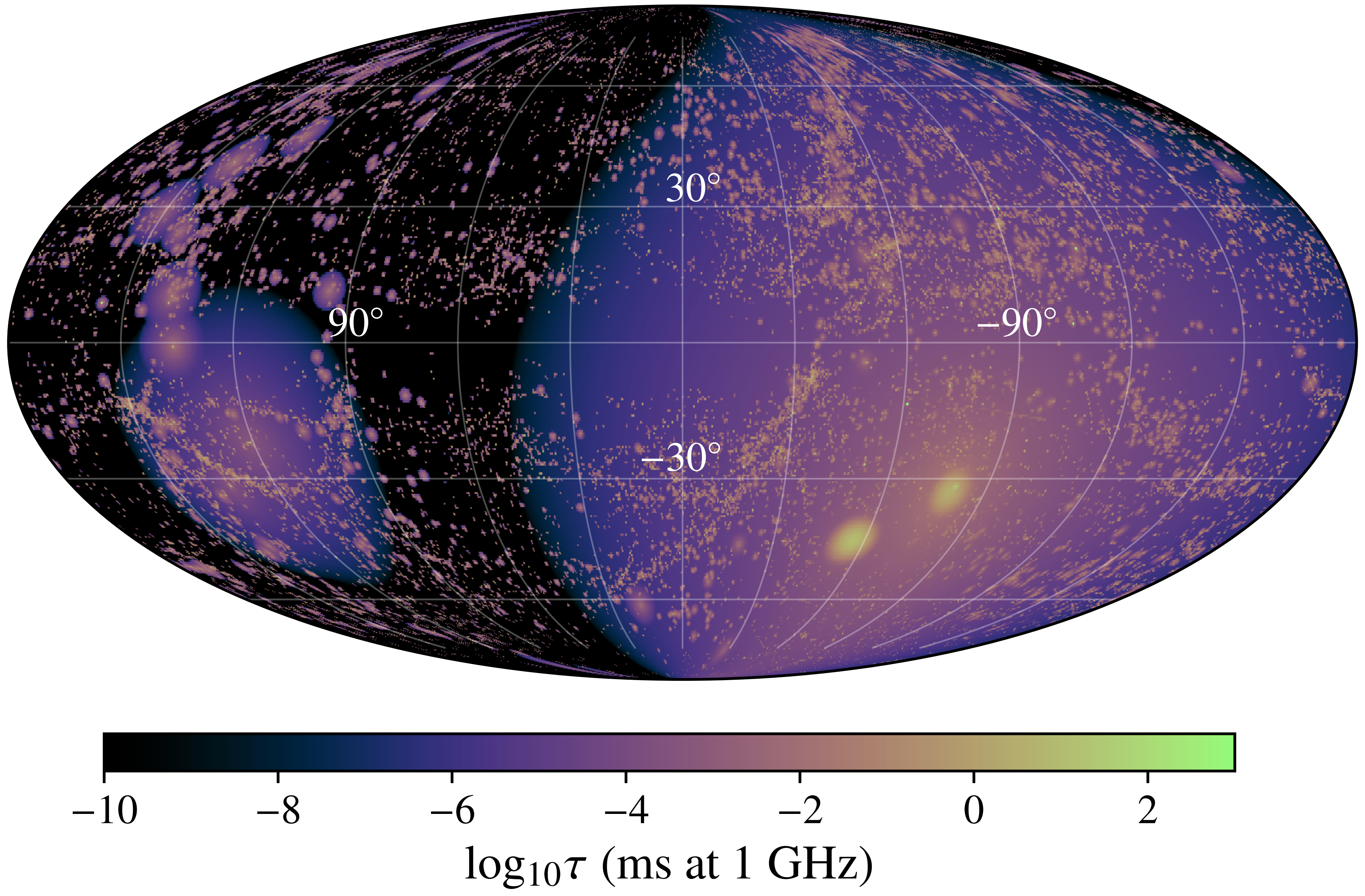
thermal proton gyroradius: $l_i \propto \sqrt{T}/B$

Low-z Science: Local Group Galaxies

galaxies in GWGC* w/ halo diameter > 1/2 deg; includes ISM (galaxy-type dependent) & CGM (generic)

DM





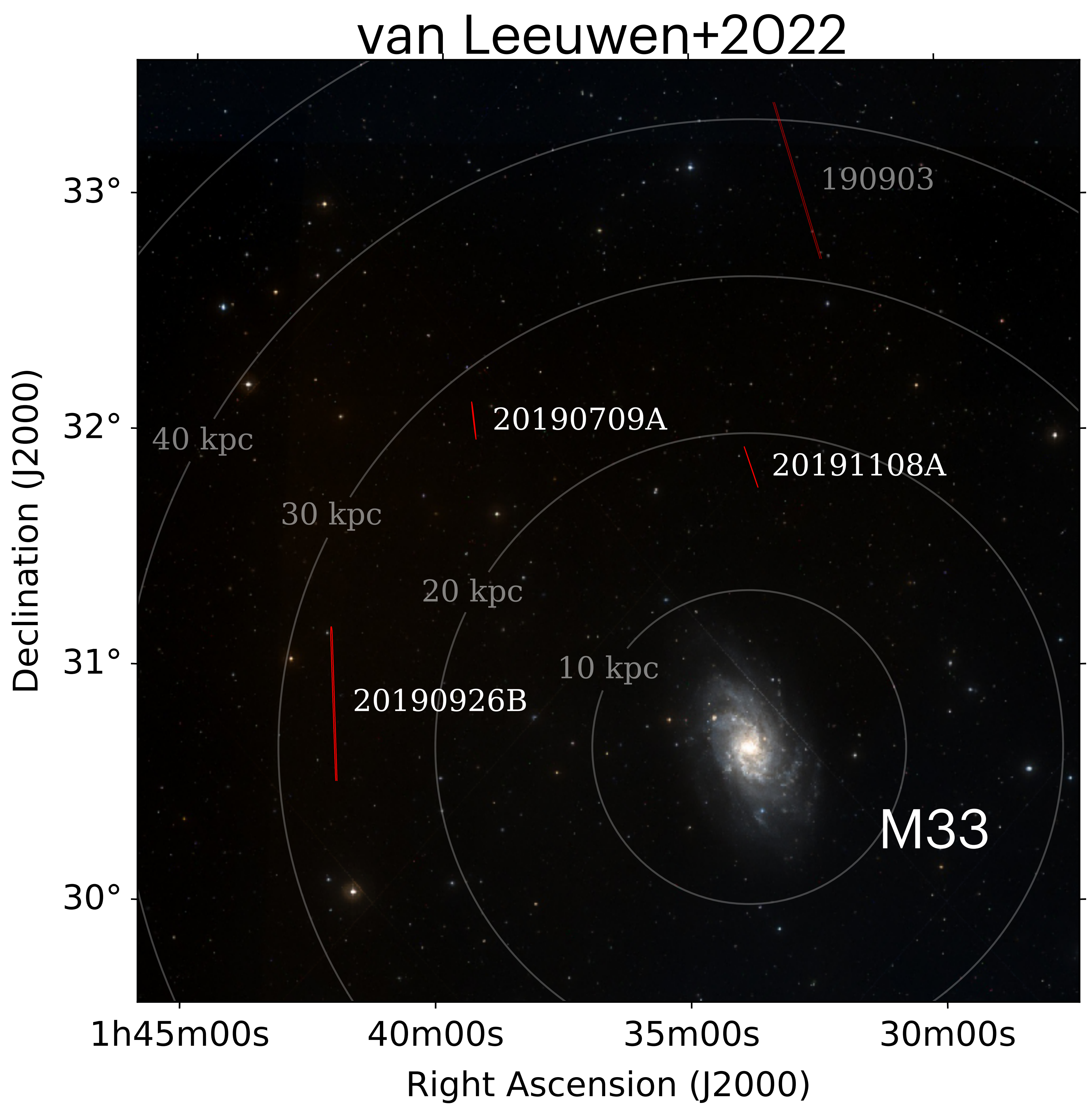
τ

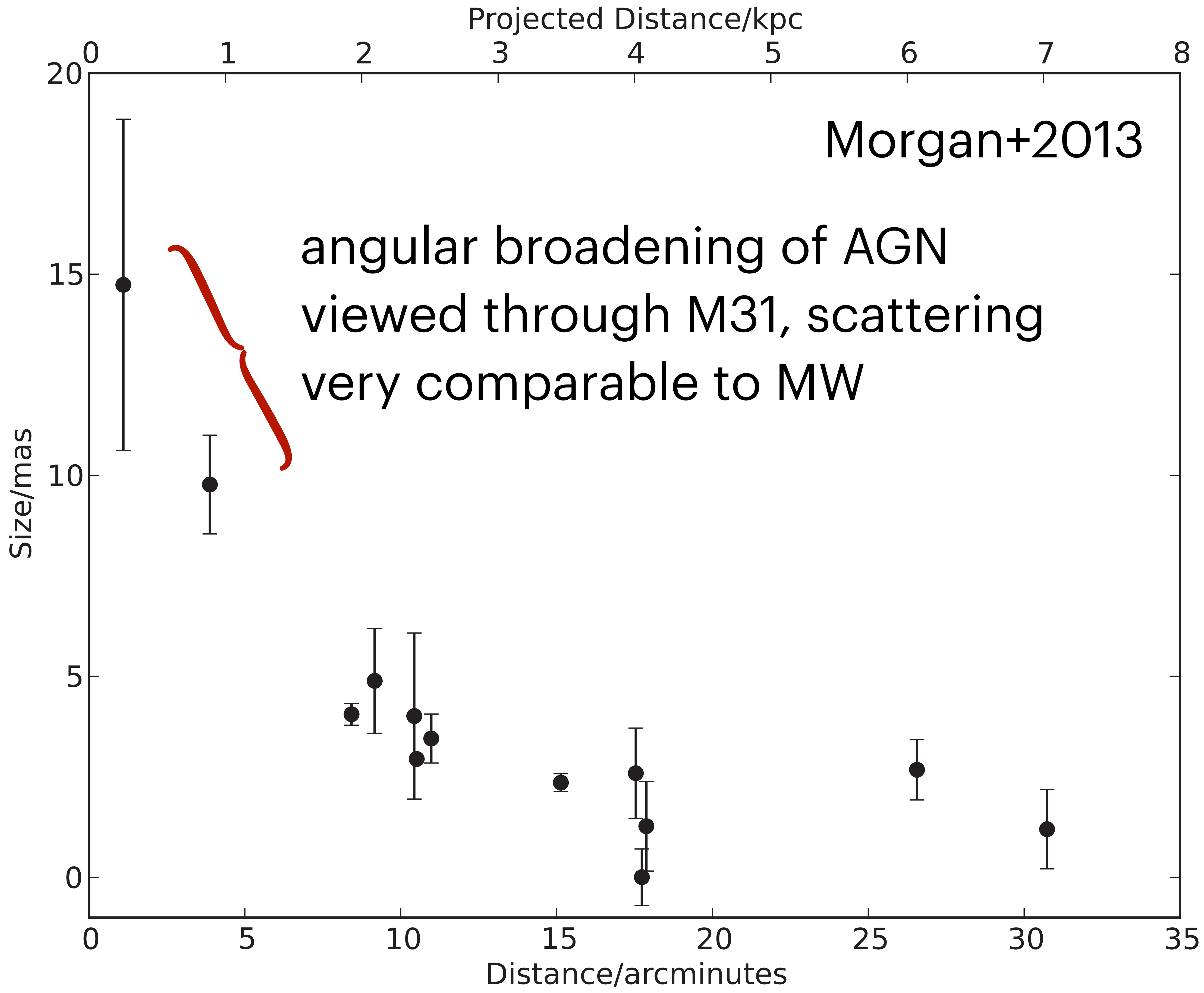
(applicable to FRB source redshifts >0.1)

*Gravitational Wave Galaxy Catalog

Ocker+2022b

Low-z Science: Local Group Galaxies

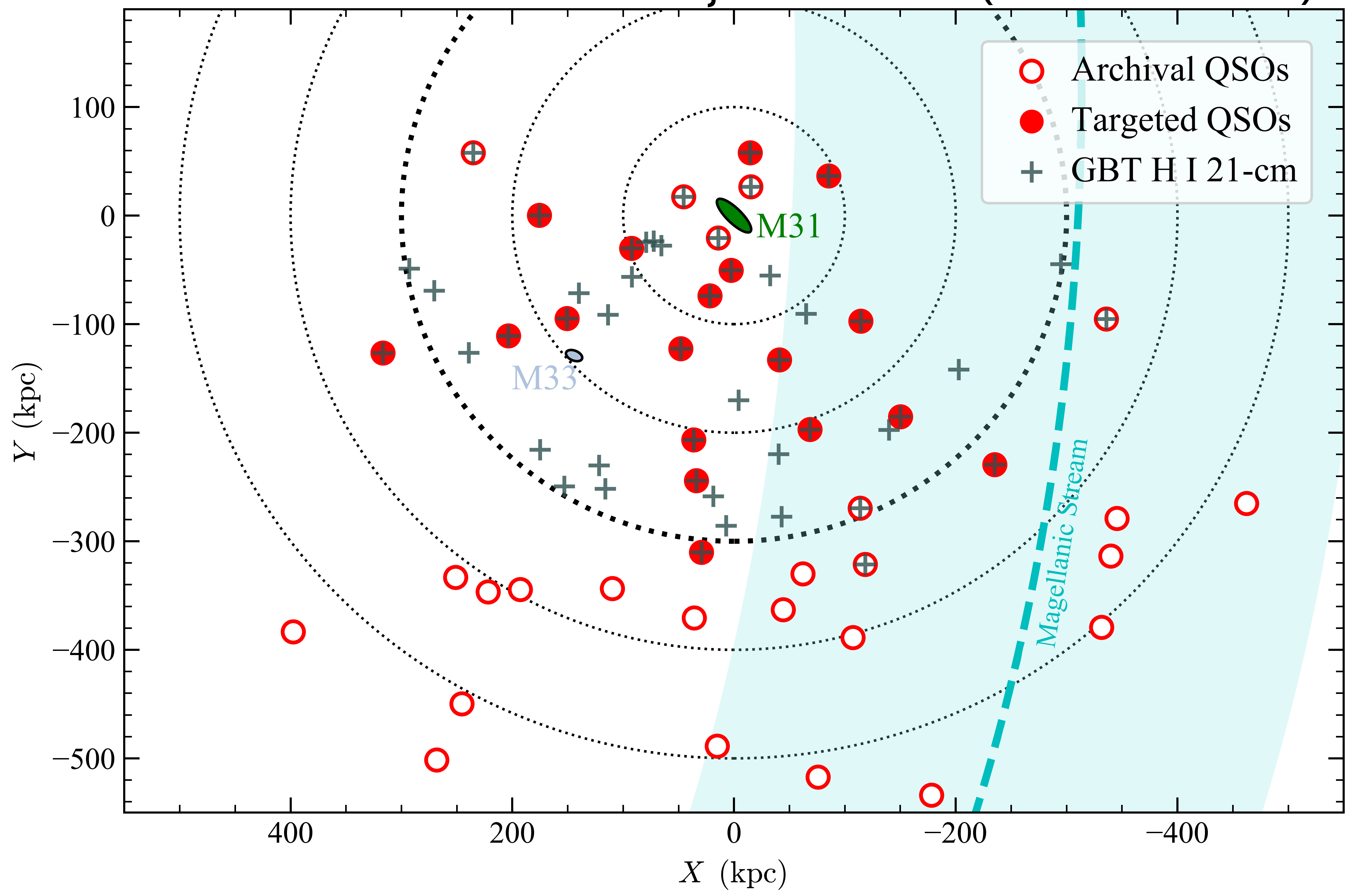




Low-z Science: Local Group Galaxies

- wealth of QSO absorption line data on M31/M33 halos
- very hot gas (T >~10^6 K) still not well-constrained for Local Group medium / nearby halos

Project AMIGA (Lehner+2020)



Back to where it all began: SMC/LMC