

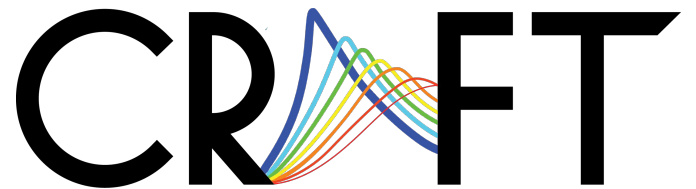
# Probing the Cosmic Web with Fast Radio Bursts (FRBs)

J. Xavier (ザビエル) Prochaska

(UC Santa Cruz, Kavli IPMU, Simons Pivot Fellow, NAOJ)

on behalf of the Fast and Fortunate for FRB Follow-up (F<sup>4</sup>) team

SIMONS FOUNDATION



*realfast*

# Congrats to Rich Matsuda!



International search  
confirms local-born  
executive to lead the  
Observatory



# Fast and Fortunate for FRB Follow-up (F<sup>4</sup>)



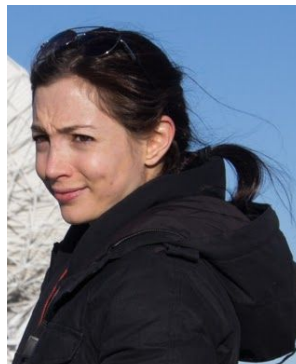
Alexandra Mannings  
(UC Santa Cruz)



Sunil Simha  
(UC Santa Cruz)



Lordrick Kahinga  
(UC Santa Cruz)



Tarraneh Eftekhari  
(Northwestern U.)



Alexa Gordon  
(Northwestern U.)



[www.uclick.org/f-4](http://www.uclick.org/f-4)



Regina Jorgenson  
(Director, MMO)



Nicolas Tejos (PUCV)



Wen-Fai Fong  
(Northwestern U.)

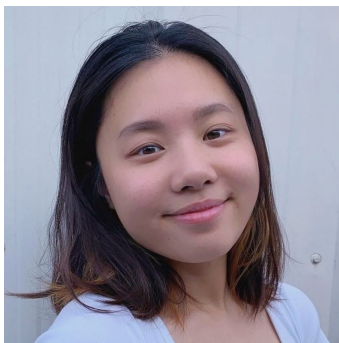


Charlie Kilpatrick  
(Northwestern U.)

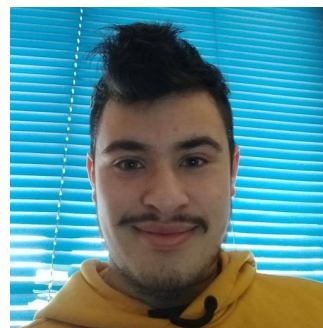
# Fast and Fortunate for FRB Follow-up (F<sup>4</sup>)



Jay Baptista  
(Stanford)



YuXin Dong  
(Northwestern U)



Lucas Bernales  
(PUCV)



August Muller  
(MMO)



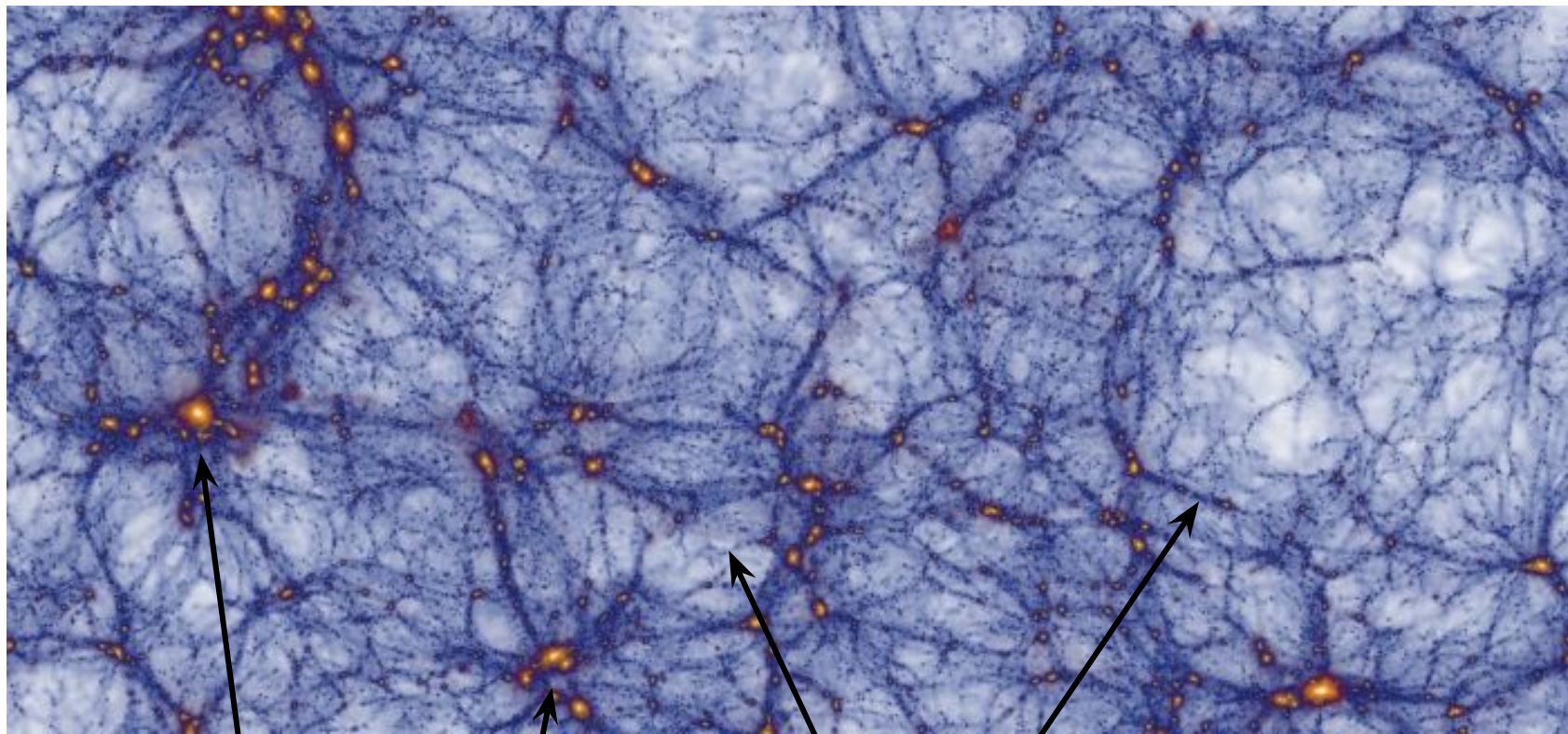
Michele Woodland  
(MMO)



[frb-f4.org](http://frb-f4.org)



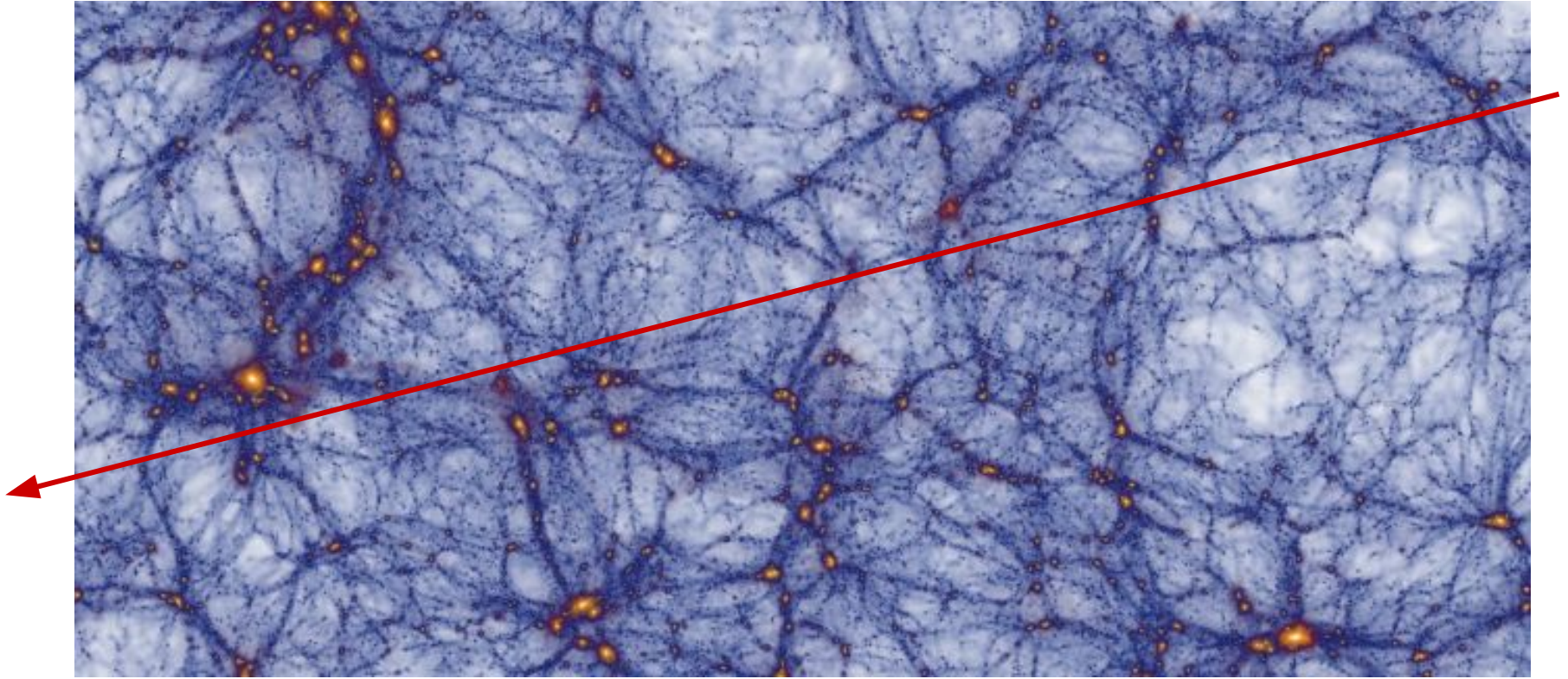
# The Cosmic Web



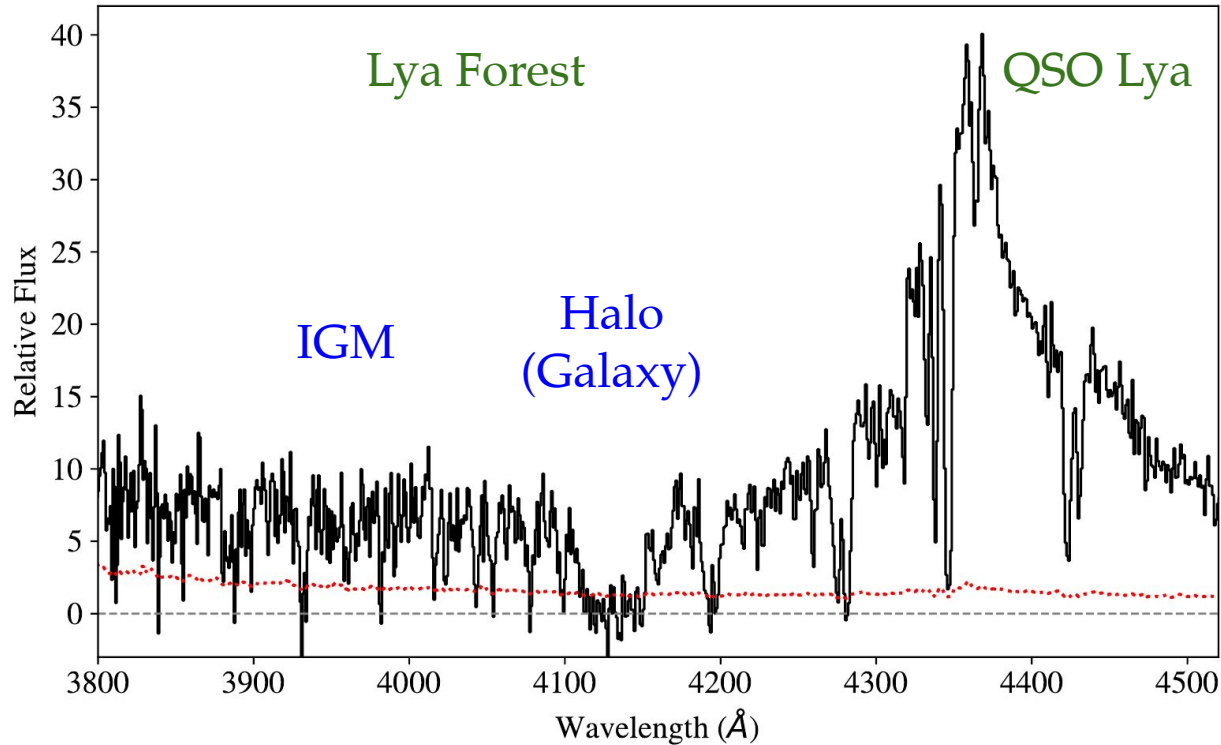
Galactic Halos

IGM

# Evidence: Quasar Absorption Lines



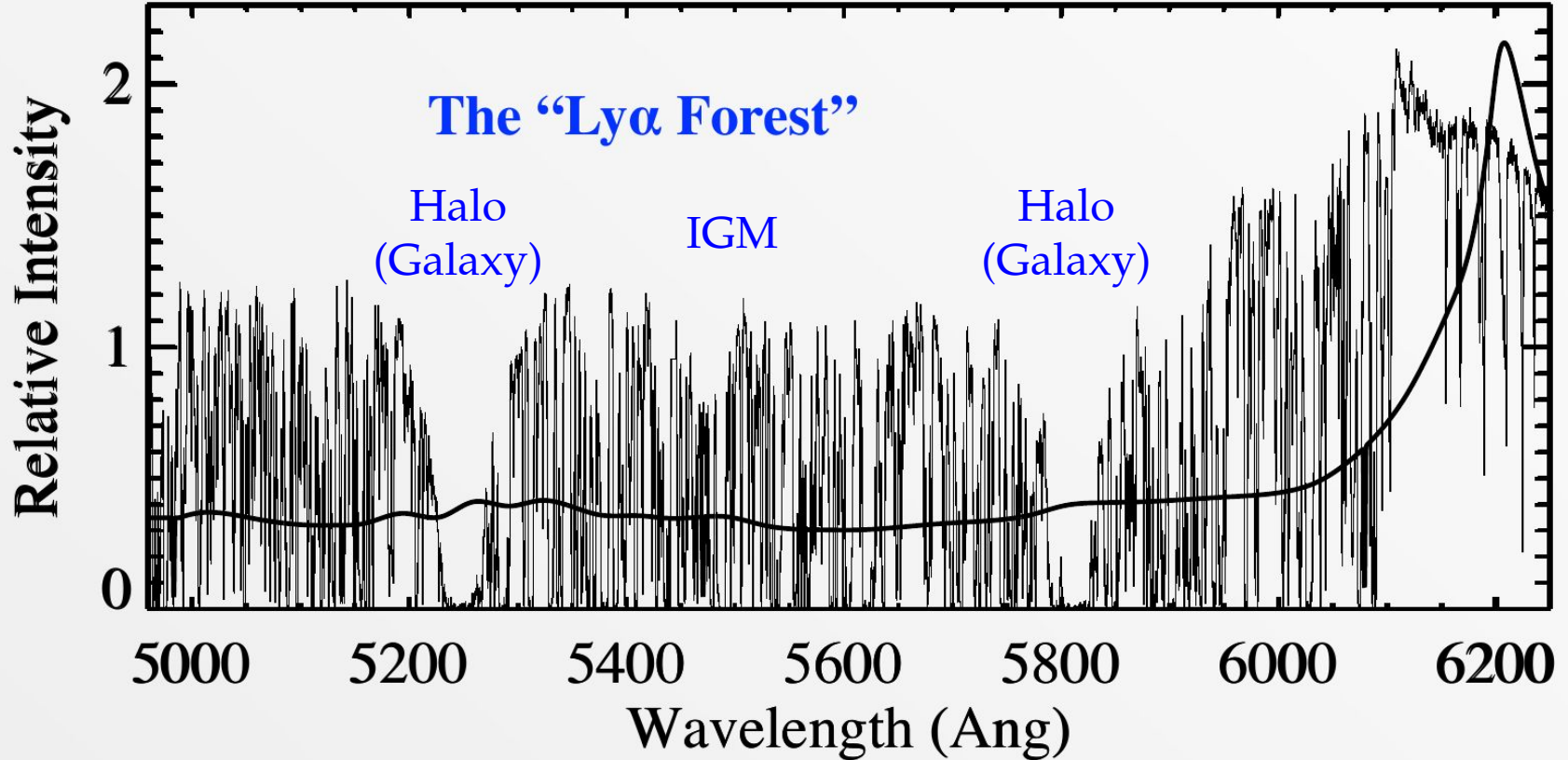
# High-z Quasar Absorption



- Infer >90% of the baryons reside in the highly ionized IGM
- Remainder are in the actively growing galaxies and their halo gas

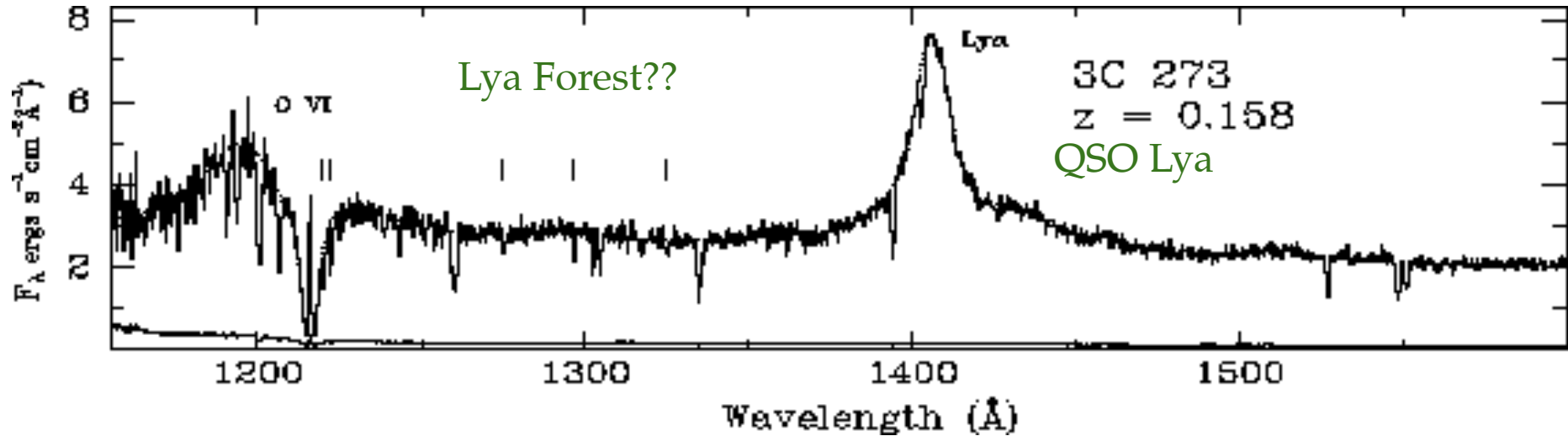


# High-z Quasar Absorption



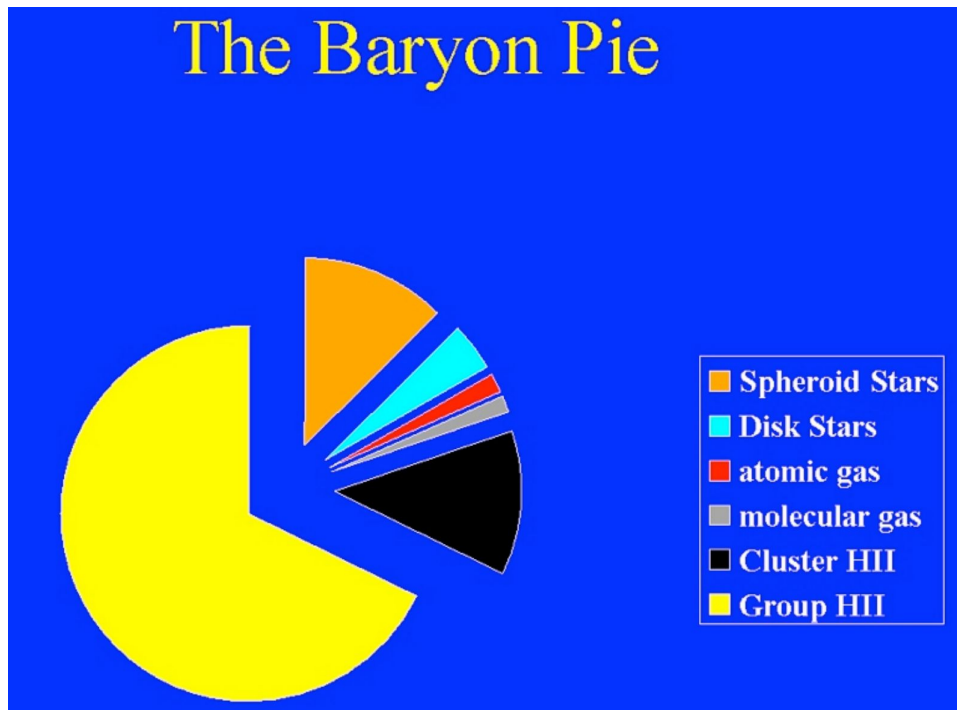


# Low-z Quasar Absorption



- Where did the cosmic web go??
- Has it all just “drained” into halos and their galaxies?

# The Cosmic “Missing Baryons Problem”



THE ASTROPHYSICAL JOURNAL, 503:518–530, 1998 August 20  
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## THE COSMIC BARYON BUDGET

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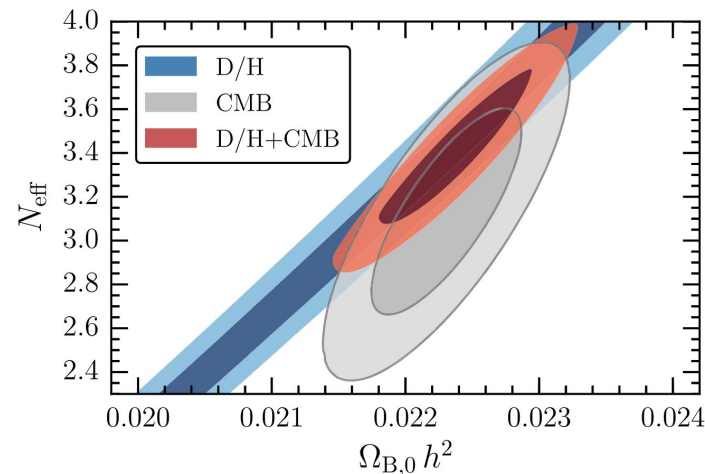
AND

P. J. E. PEEBLES

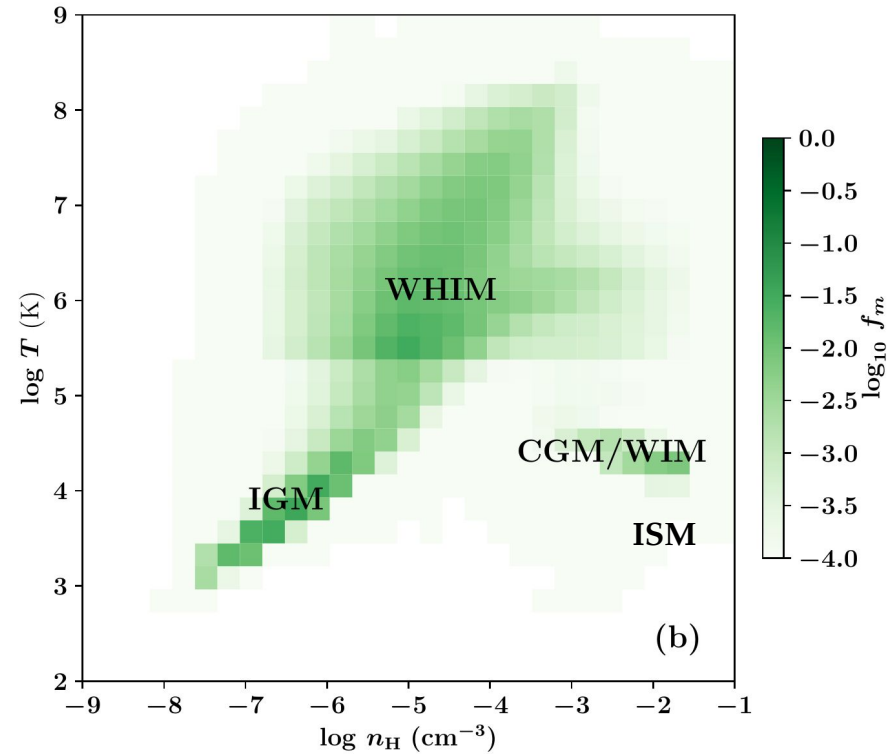
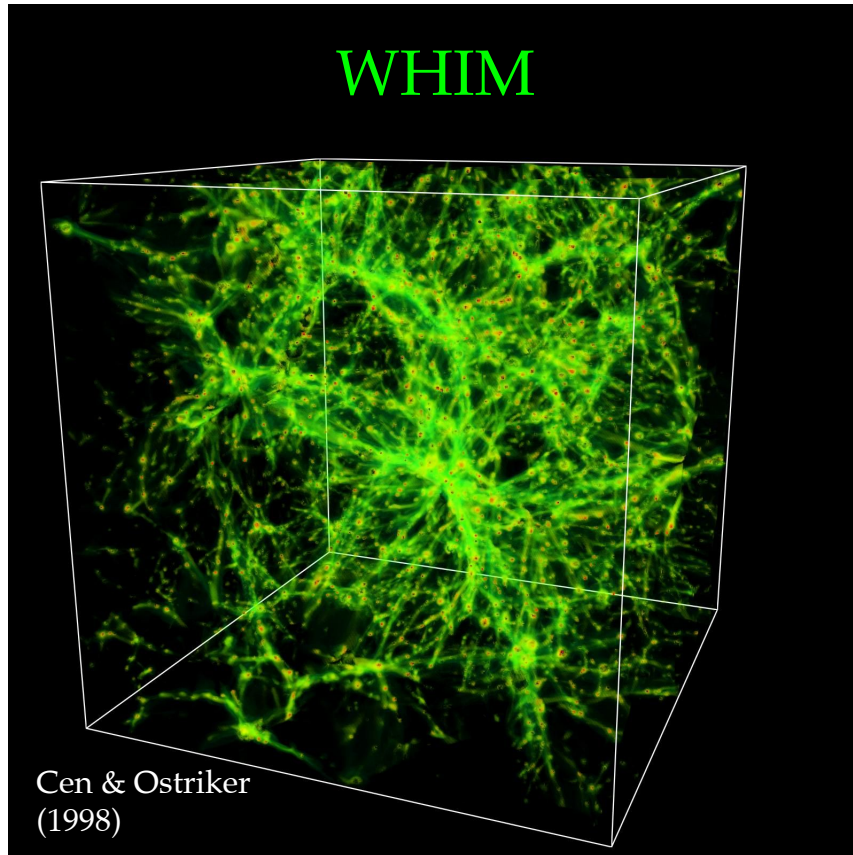
Joseph Henry Laboratories, Princeton University, Princeton, NJ 08544; pjep@pupgg.princeton.edu

Received 1997 December 2; accepted 1998 March 26

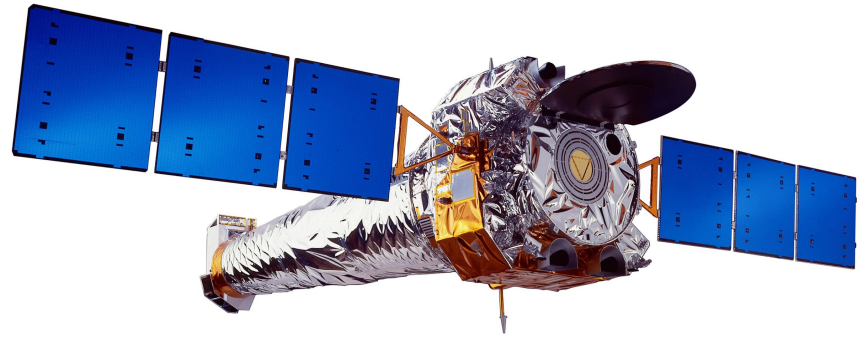
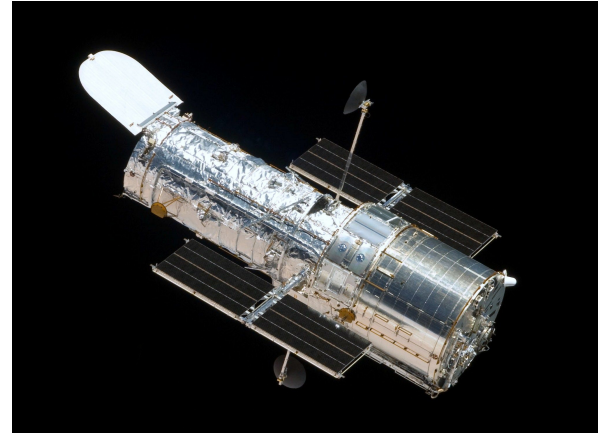
Cooke, Pettini, & Steidel



# Warm-Hot Intergalactic Medium (WHIM)



# Missing Baryons: Stymied for ~20 years..



(~\$50M USD in operations alone)



# An Serendipitous Solution... FRBs



# The Lorimer (Fast Radio) Burst

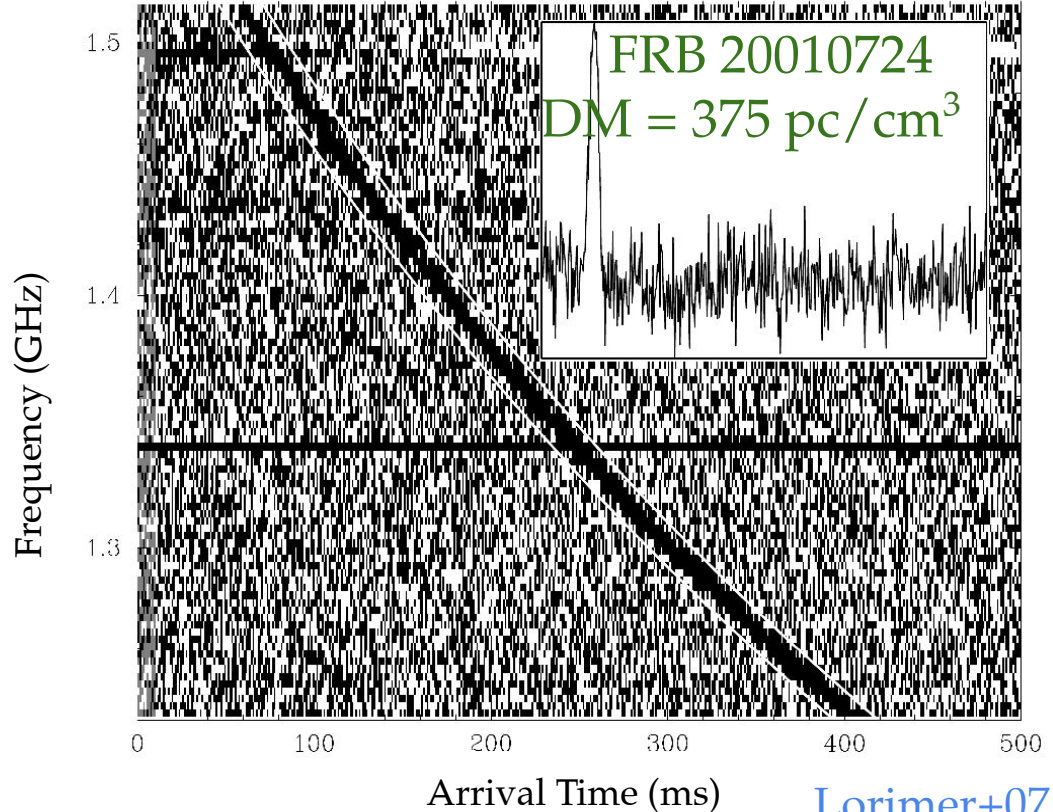
## Arrival Time

$$\tau = 4.15 \text{ ms} \left( \frac{\text{DM}}{\text{pc cm}^{-3}} \right) \left( \frac{\text{GHz}}{\nu} \right)^2$$

## Dispersion Measure

$$\text{DM} = \int \frac{n_e}{1+z} ds$$

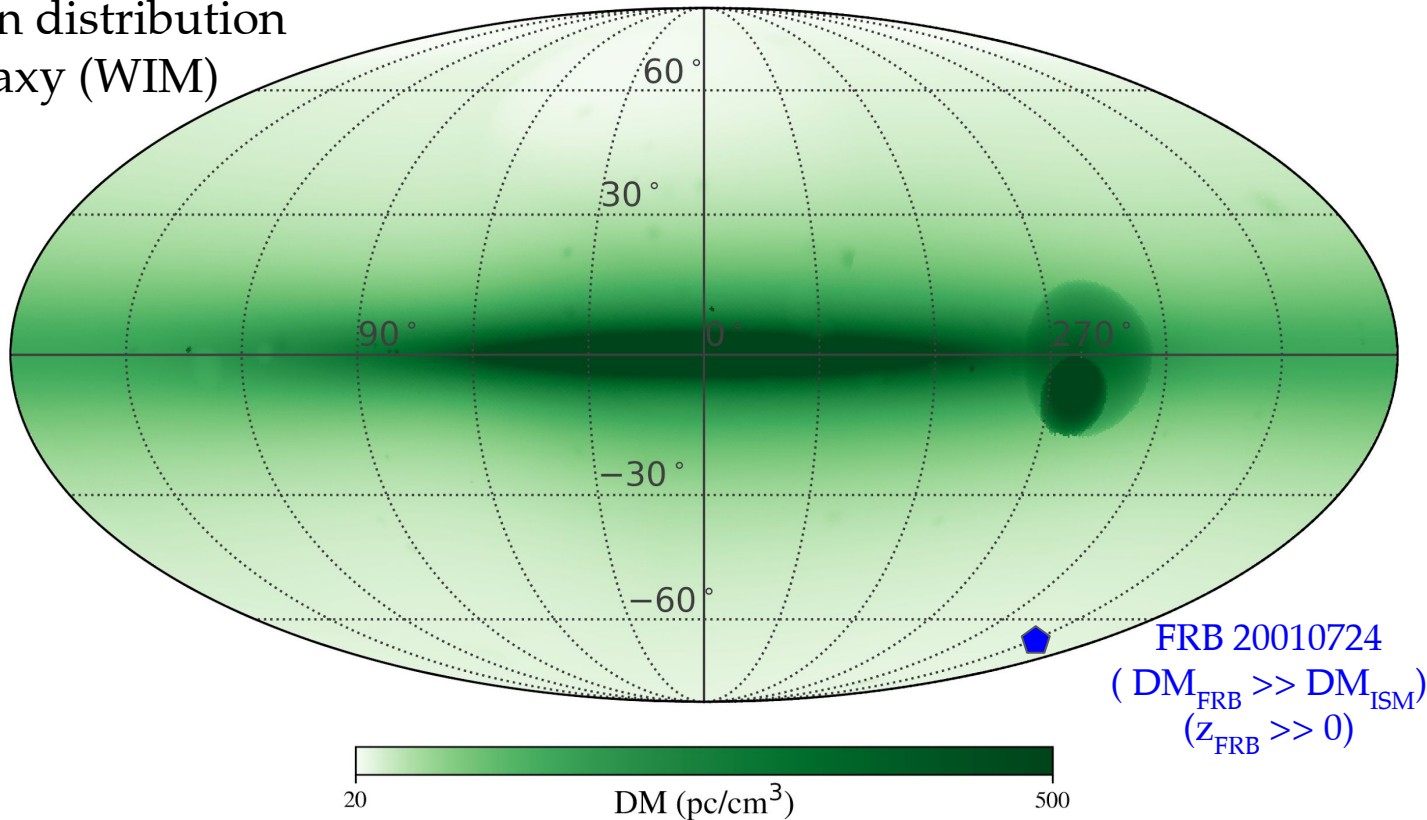
DM: The Ultimate way to  
count electrons



# DM of our Galactic ISM (via Pulsars)

Data-driven model of  
the electron distribution  
of our Galaxy (WIM)

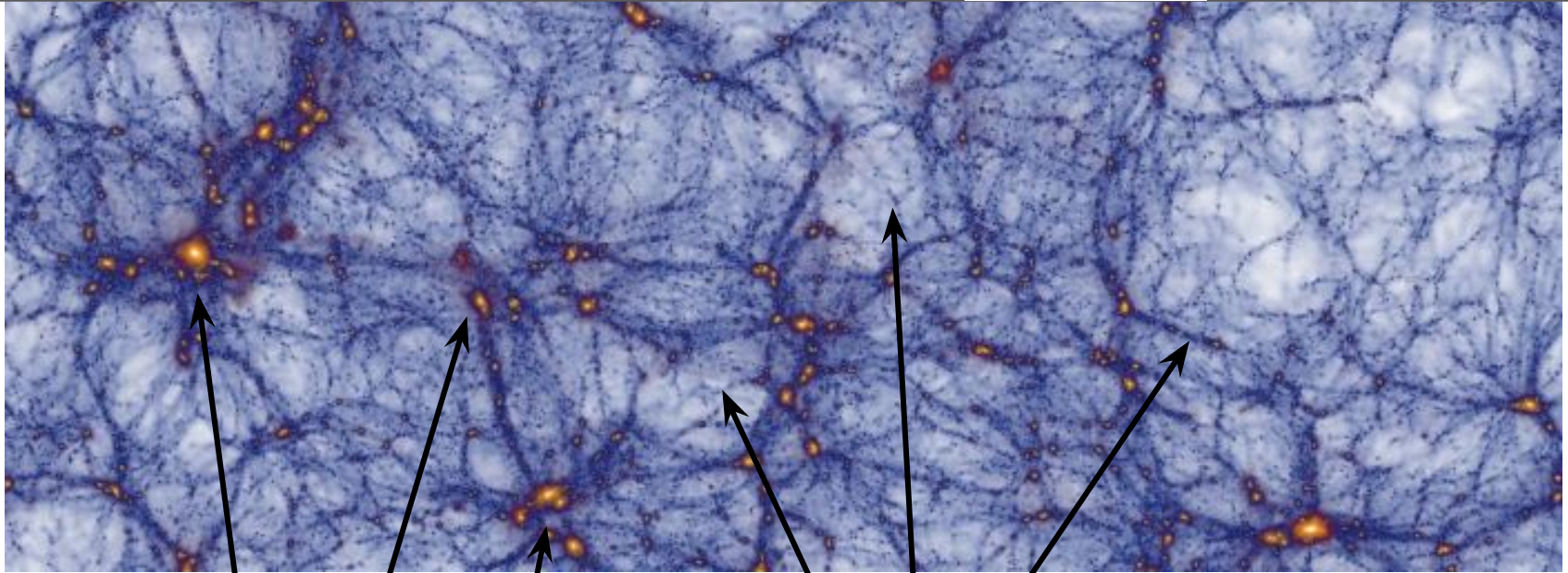
NE2001  
(Cordes &  
Lazio)





# The Cosmic Dispersion Measure: $DM_{\text{cosmic}}$

$$\langle DM_{\text{cosmic}} \rangle = \int \frac{c\bar{n}_e(z)dz}{H_0(1+z)^2 \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}}$$
$$\bar{n}_e = f_d \rho_b(z) m_p (1 - Y_{\text{He}}/2)$$
$$\rho_b \equiv \Omega_b \rho_c$$

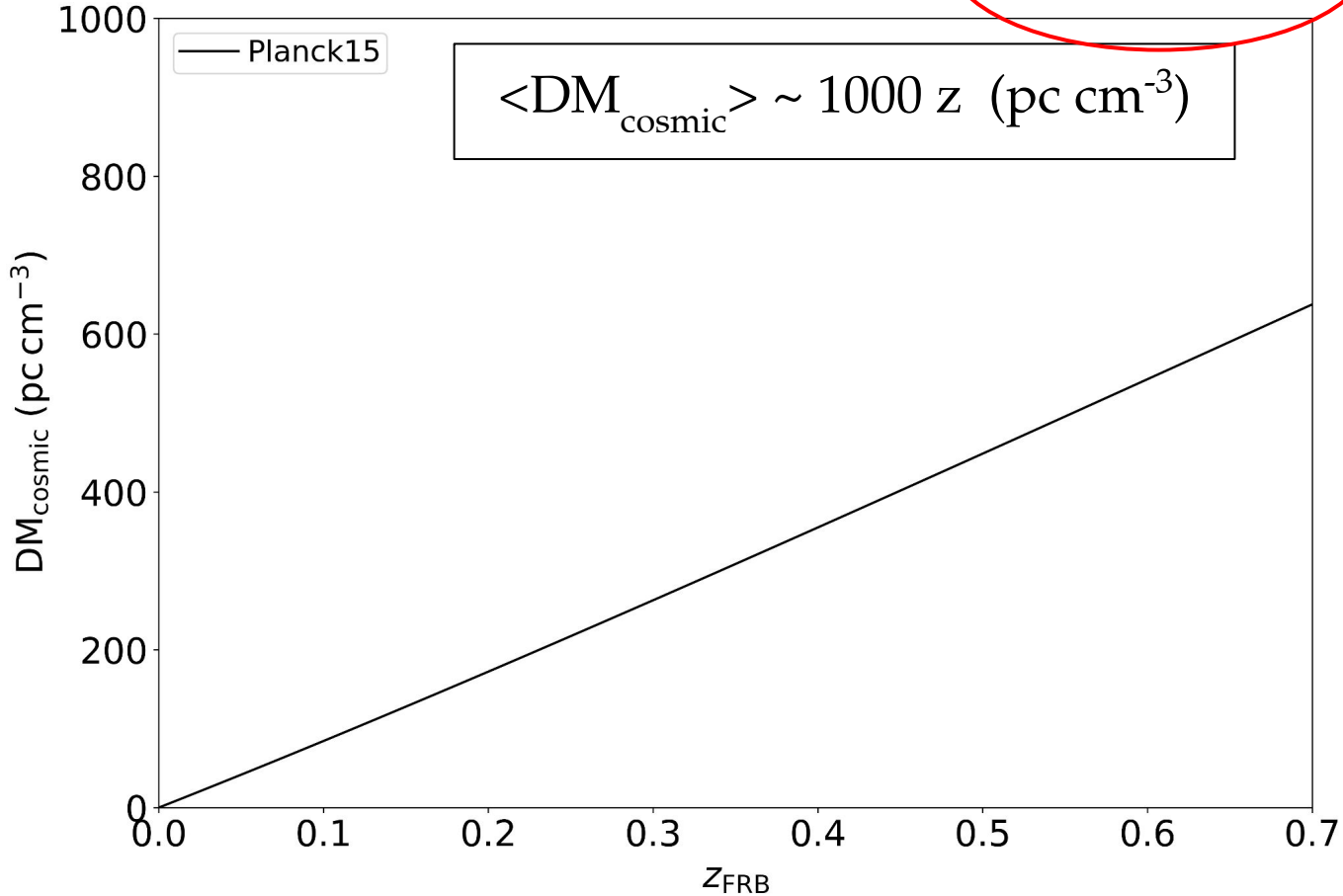


Galactic Halos

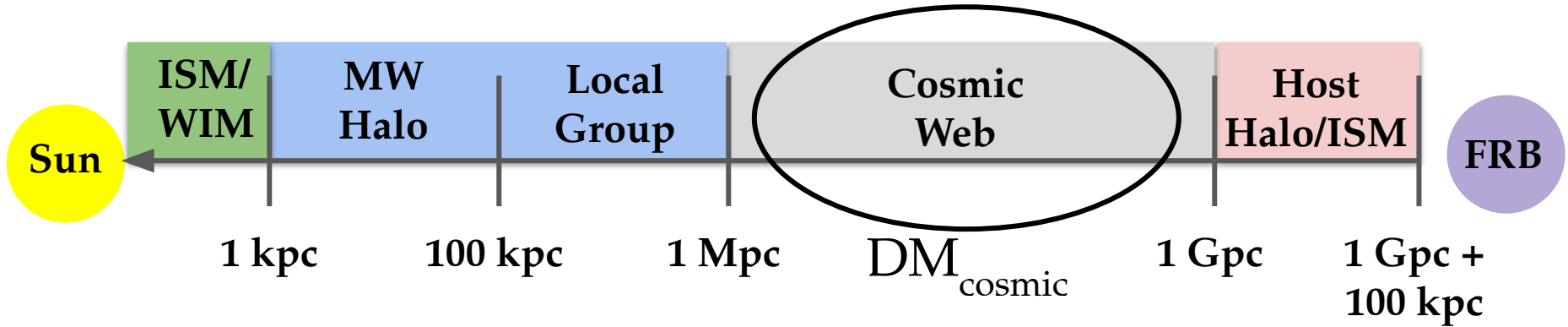
IGM



# FRBs and the Cosmic Web: $DM_{\text{cosmic}}$ vs $z$



# FRB Dispersion Measure (DM)

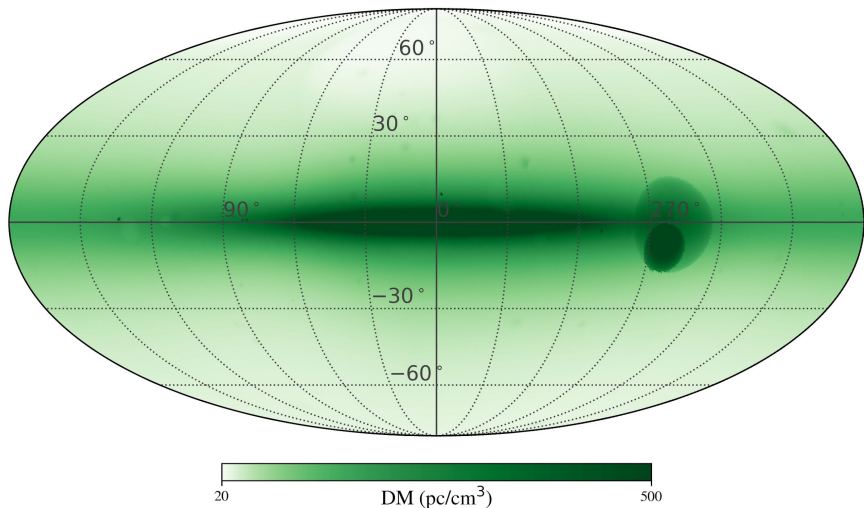


$$DM = \int \frac{n_e}{1+z} ds$$

FRBs: A Blessing and a Curse!

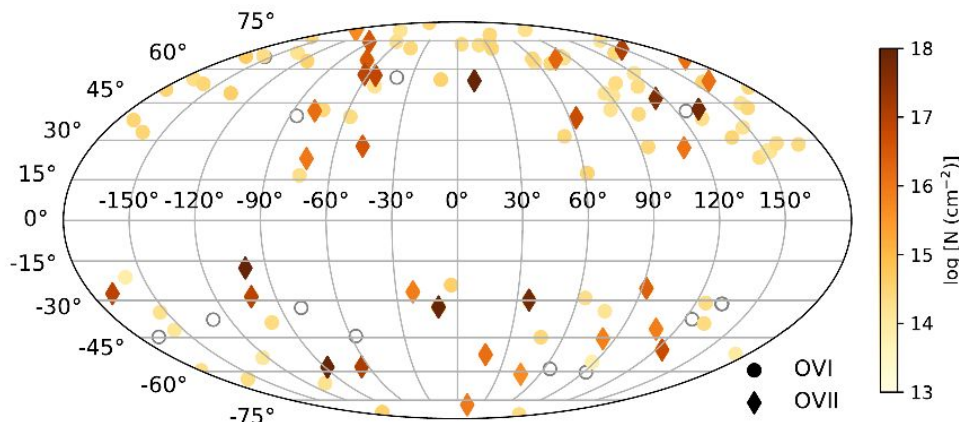
# DM of our Galaxy (and its Halo)

$DM_{MW,ISM}$



NE2001 (Cordes & Lazio)

$DM_{MW,Halo}$



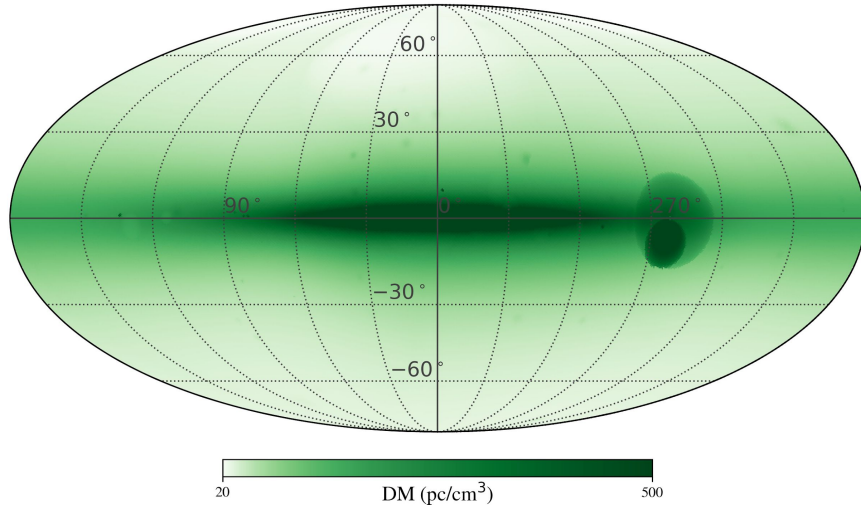
OVI, OVII, OVIII indicate a hot, galactic corona with  $DM_{MW,halo} \sim 50 \text{ pc cm}^{-3}$

But it's density is poorly constrained.. 19

# DM of the FRB Host Galaxy: $DM_{\text{host}}$ (the great “nuisance”)

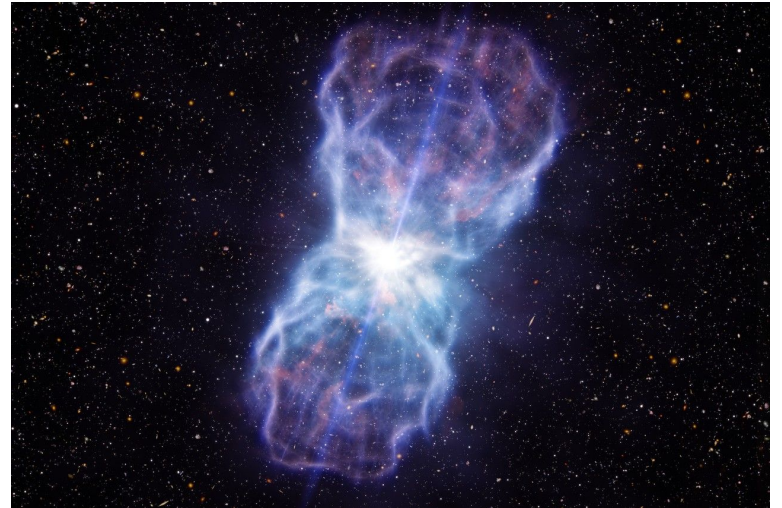
## Expectation

Something similar to our  
Galaxy ( $DM_{\text{host}} \sim 50 \text{ pc cm}^{-3}$ )



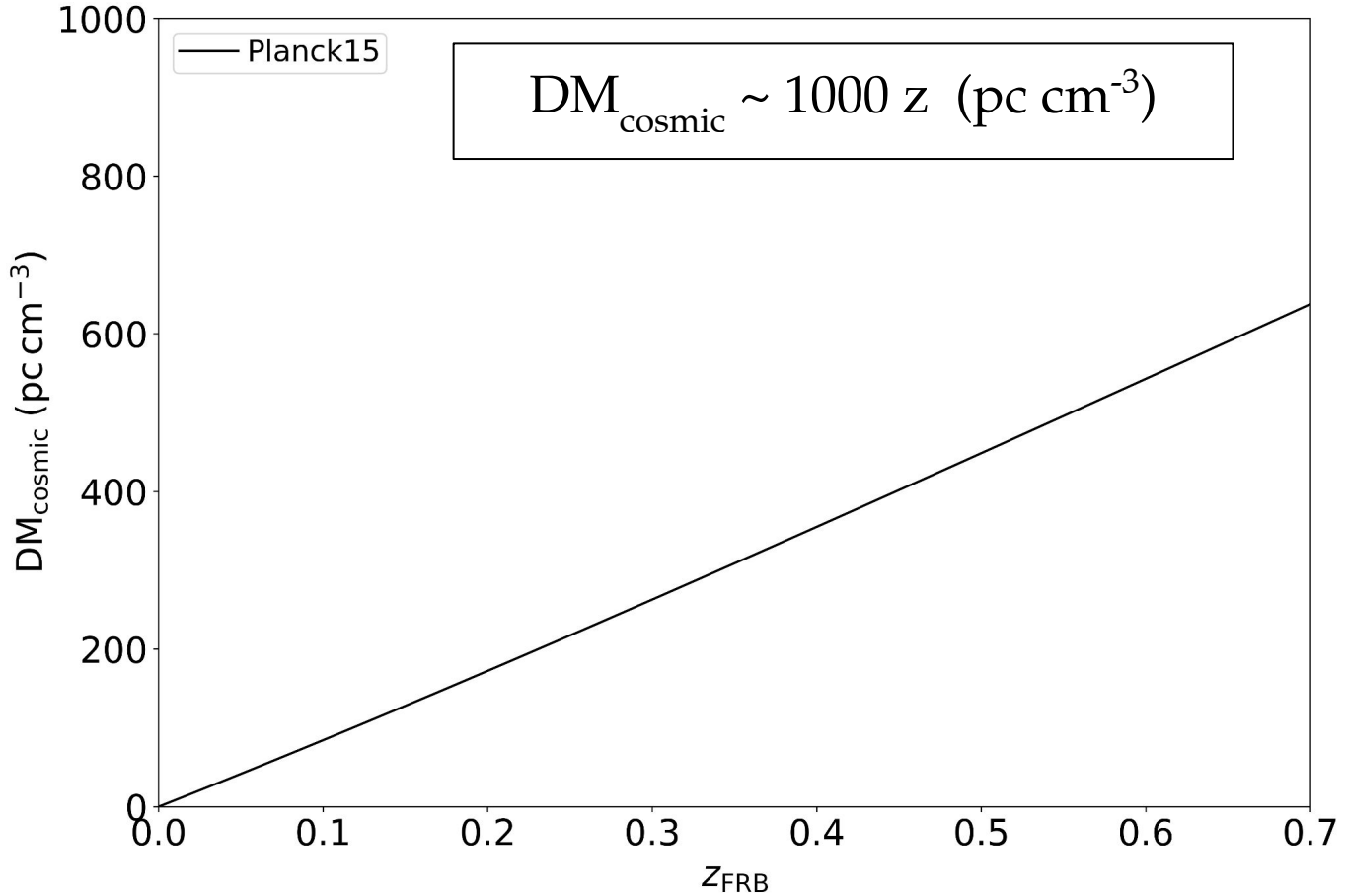
## But...

FRBs may arise from magnetars  
in star-forming regions

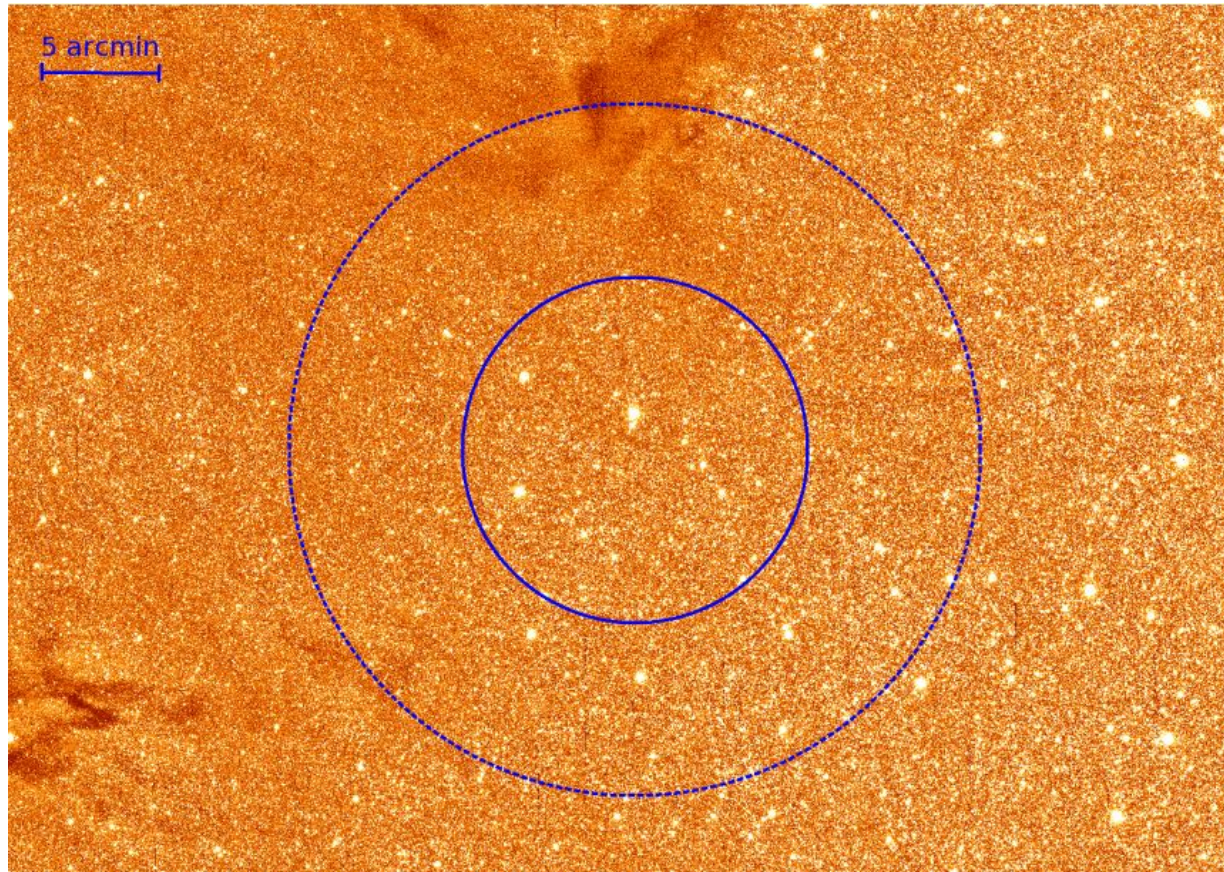




# FRBs and the Cosmic Web: $DM_{\text{cosmic}}$ vs $z$

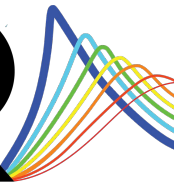


# Parques Localization



# ASKAP - Australian SKA Pathfinder

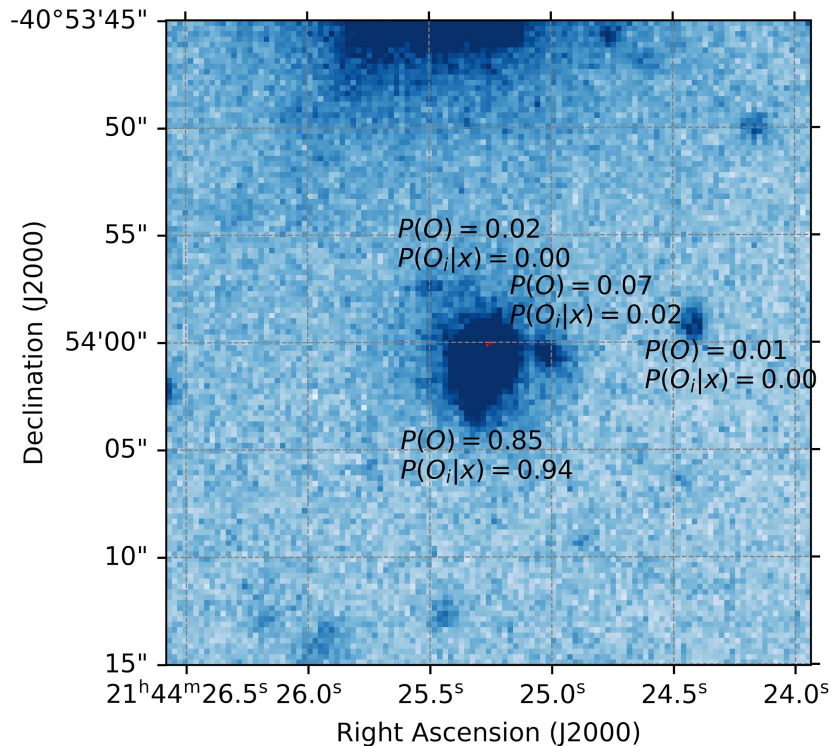


**CR****FT**



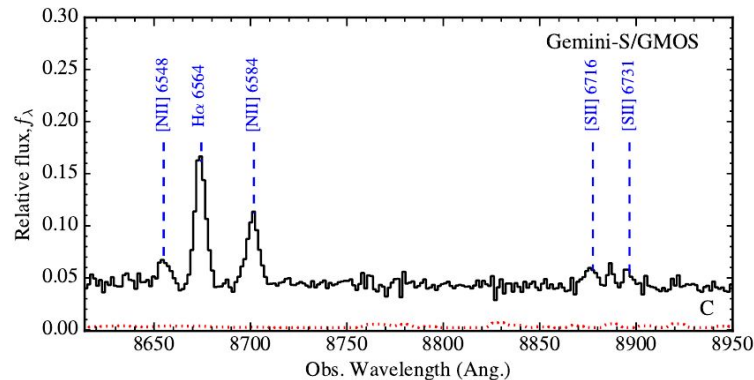
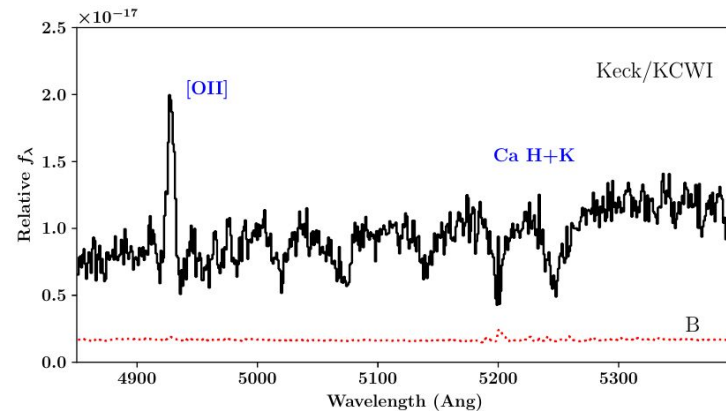
# Host Association + FRB Redshift

Probabilistic Association of Transients to Hosts (PATH)

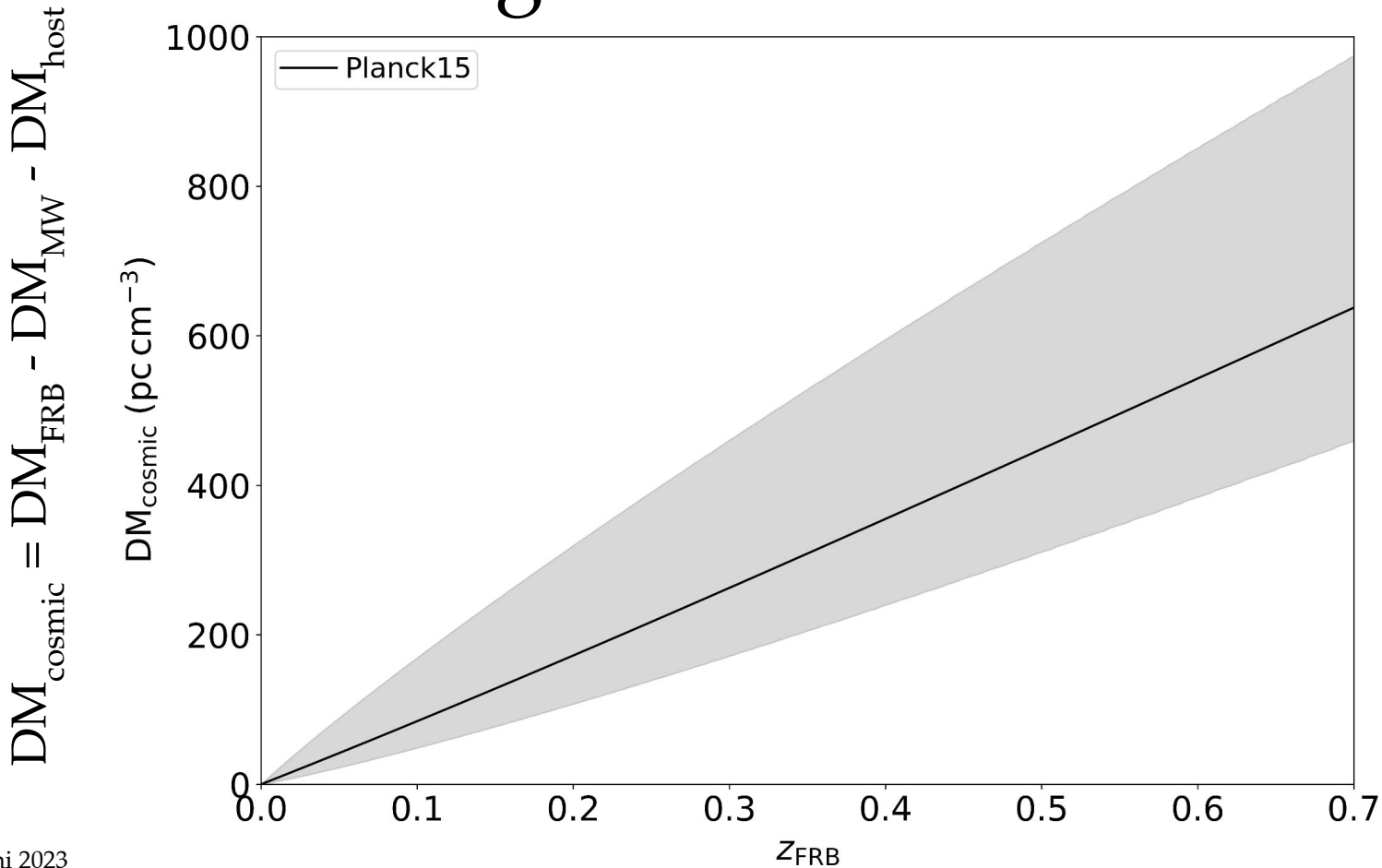


Bannister+2019

Aggarwal+ 2021



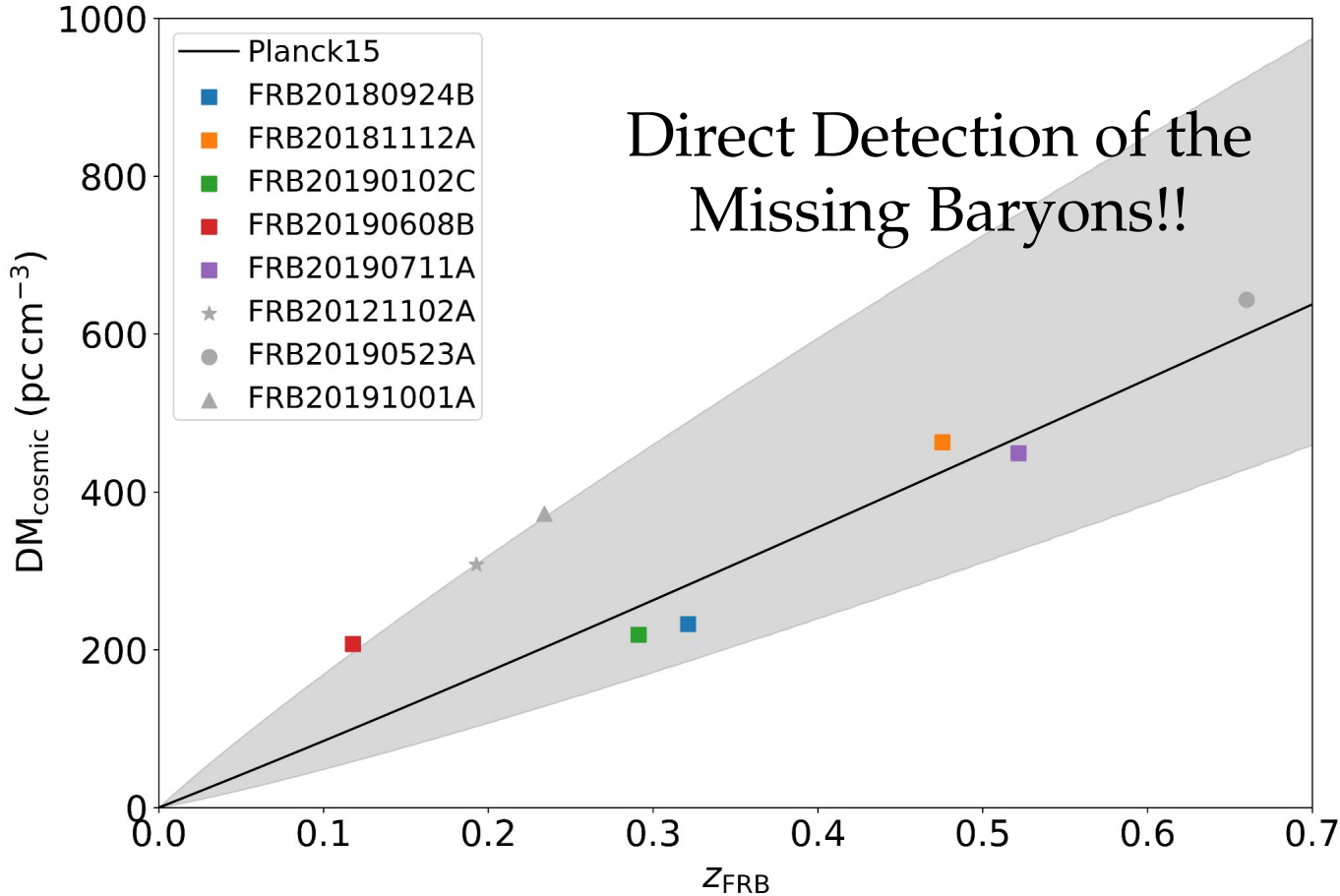
# FRBs Probing the Cosmic Web: DM vs z





# The Macquart Relation

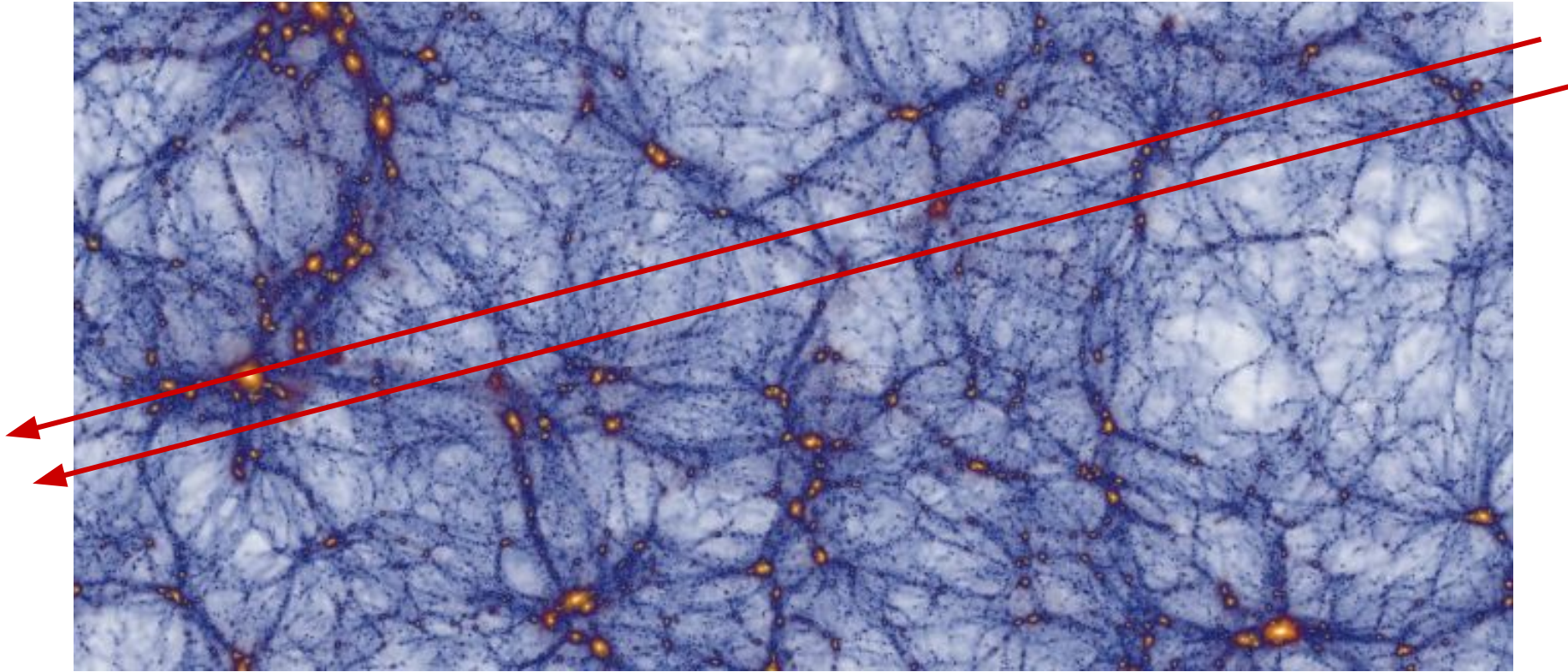
$$DM_{\text{cosmic}} = DM_{\text{FRB}} - DM_{\text{MW}} - DM_{\text{host}}$$



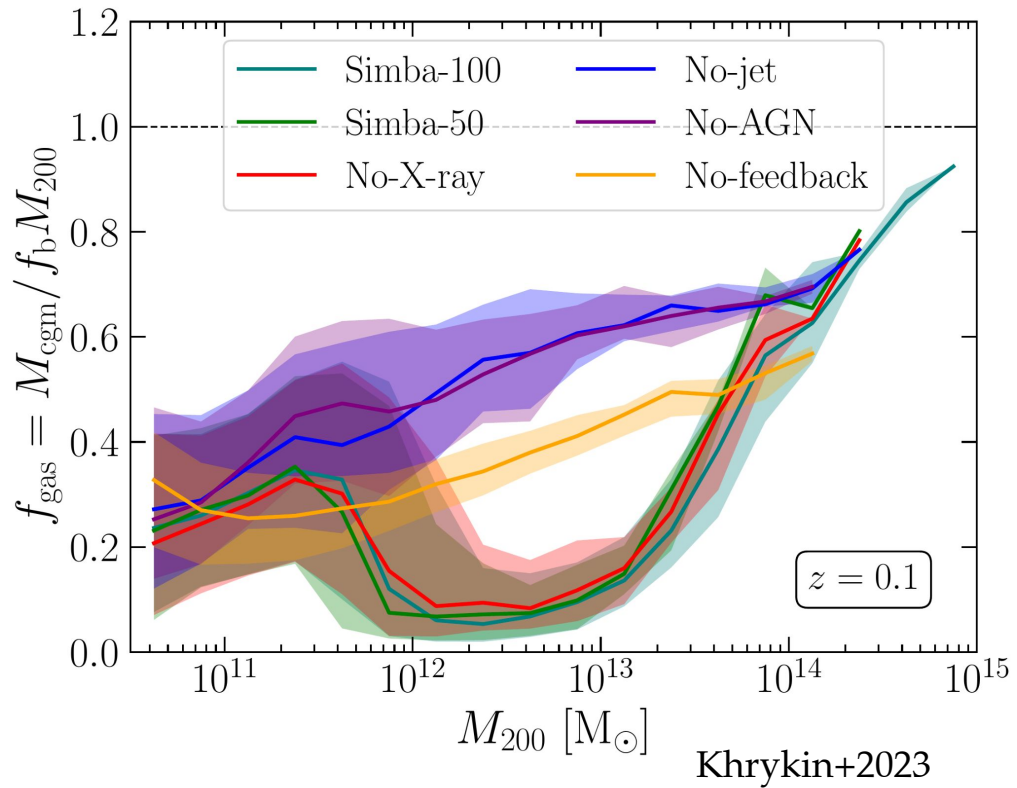
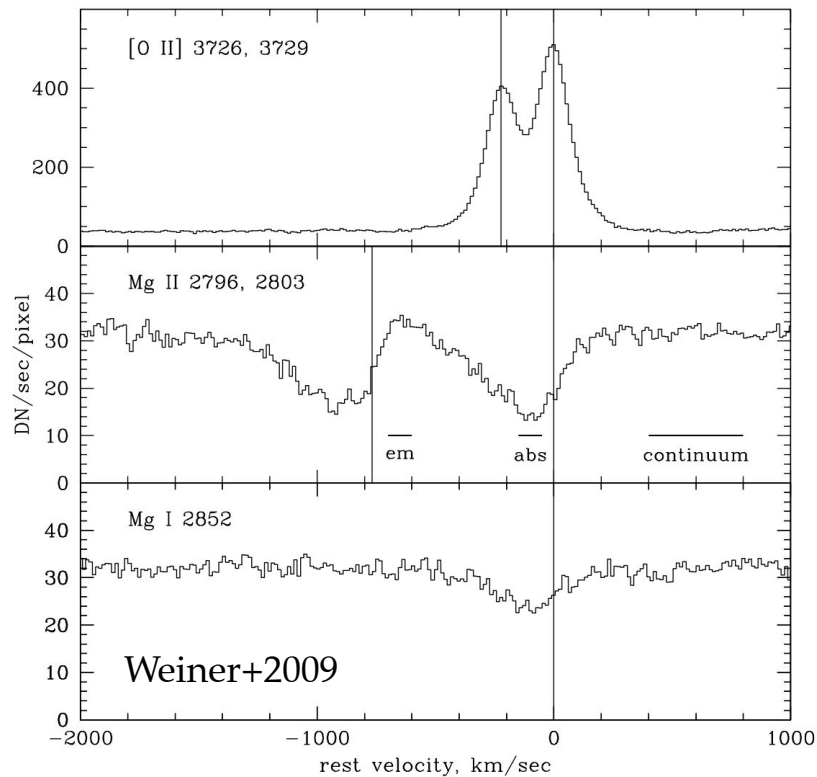
Macquart+,  
*Nature*,  
2020



# Locating the Baryons: Variations in $DM_{\text{cosmic}}$



# Confronting Galaxy Feedback Scenarios



# FRBs Probing the Cosmic Web: F

$$\langle \text{DM}_{\text{cosmic}} \rangle = \int \frac{c \bar{n}_e(z) dz}{H_0 (1+z)^2 \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}} \quad \bar{n}_e = f_d \rho_b(z) m_p (1 - Y_{\text{He}}/2)$$

$$\rho_b \equiv \Omega_b \rho_c$$

$$\Delta \equiv \text{DM}_{\text{cosmic}} / \langle \text{DM}_{\text{cosmic}} \rangle$$

$$\rho_{\text{cosmic}}(\Delta) = A \Delta^{-\beta} \exp \left[ -\frac{(\Delta^{-\alpha} - C_0)^2}{2\alpha^2 \sigma_{\text{DM}}^2} \right]$$

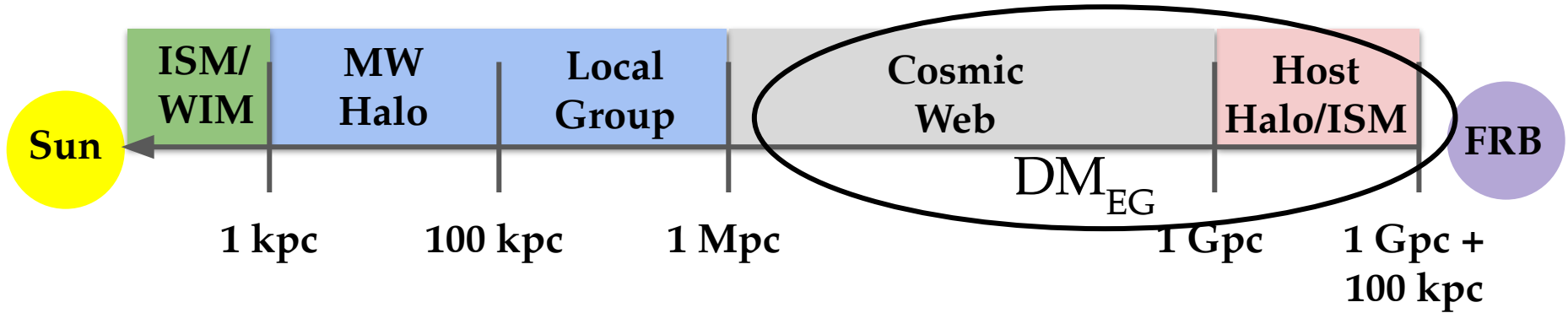
$$\sigma_{\text{DM}} = F z^{-0.5}$$

Galactic Halos

IGM



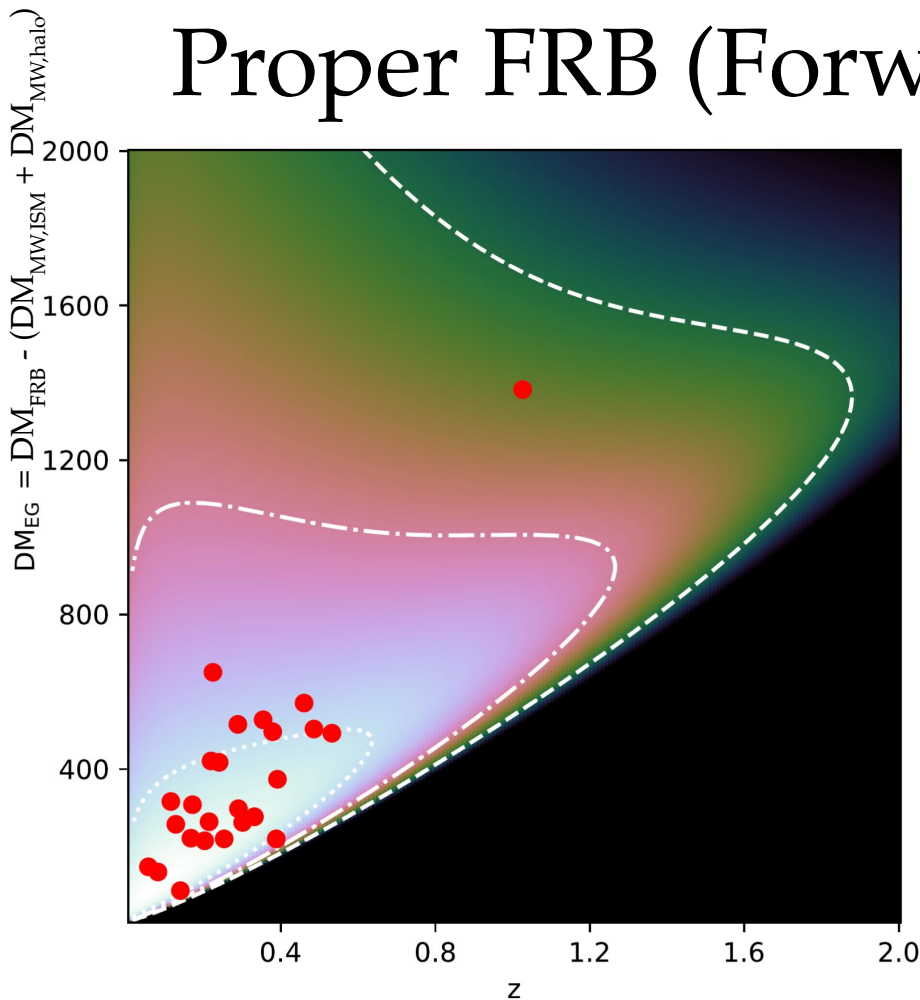
# FRB Dispersion Measure (DM)



$$DM = \int \frac{n_e}{1+z} ds$$

FRBs: A Blessing and a Curse!

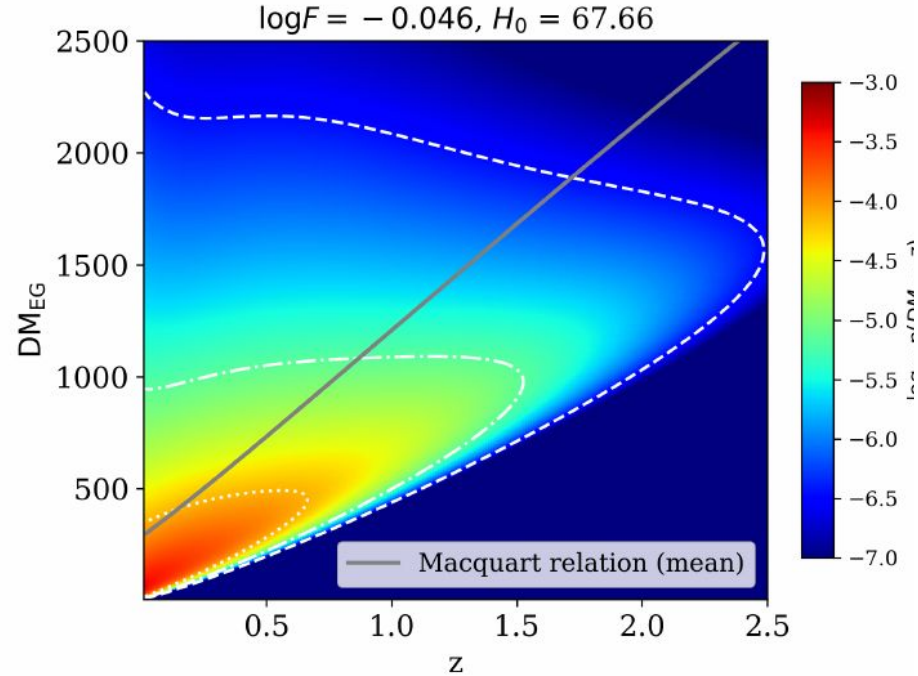
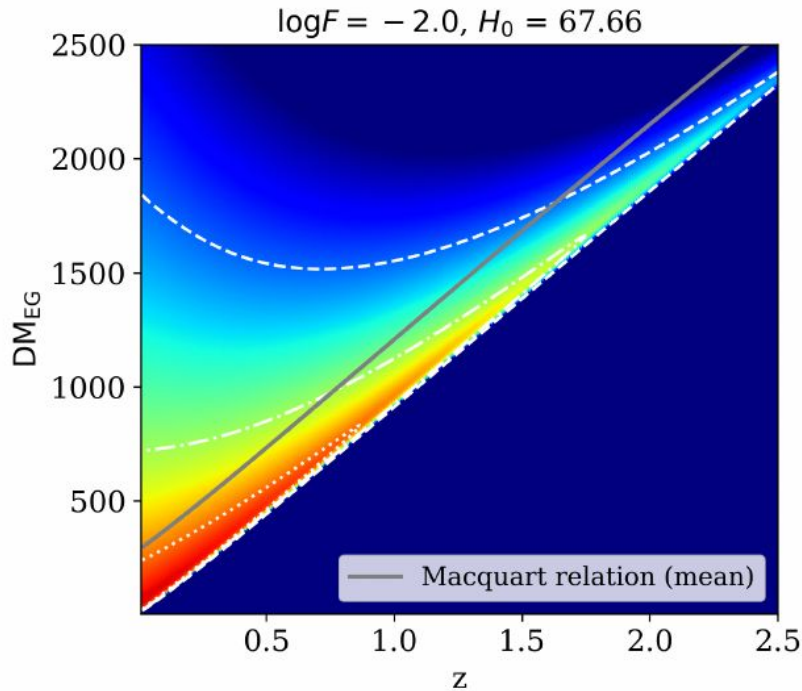
# Proper FRB (Forward) Modeling



- Host DM (log-normal PDF)
- FRB Energetics: (SED, SFR scaling,  $L(E)$ )
- FRB width, scattering
- Telescope (beam, sensitivity)
- Hubble's Parameter:  $H_0$
- Scatter in  $DM_{cosmic}$  ( $F$ )

James+2022a  
James+2022b  
James+ 2022c  
Baptista+2023

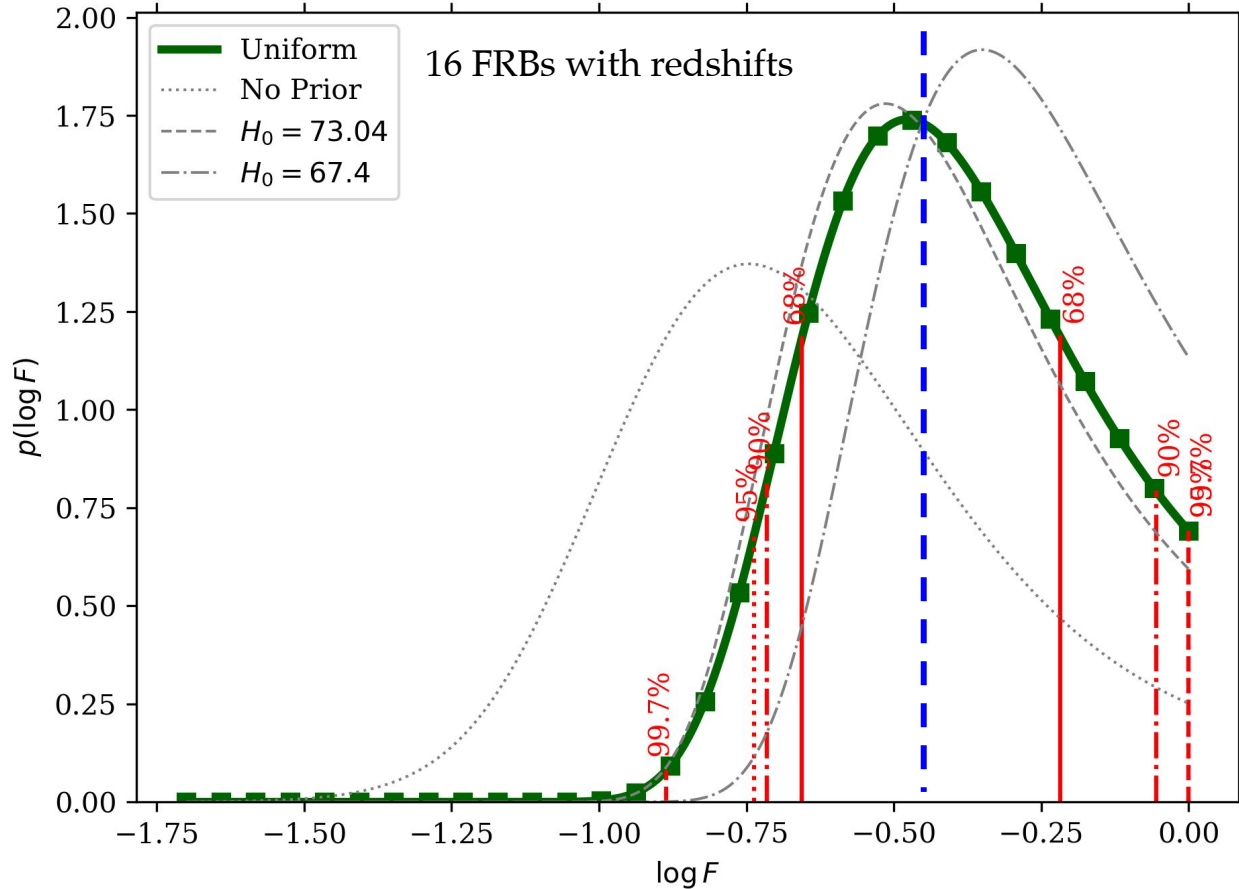
# FRBs Constraining $F$ (and Feedback)



Baptista et al. 2023

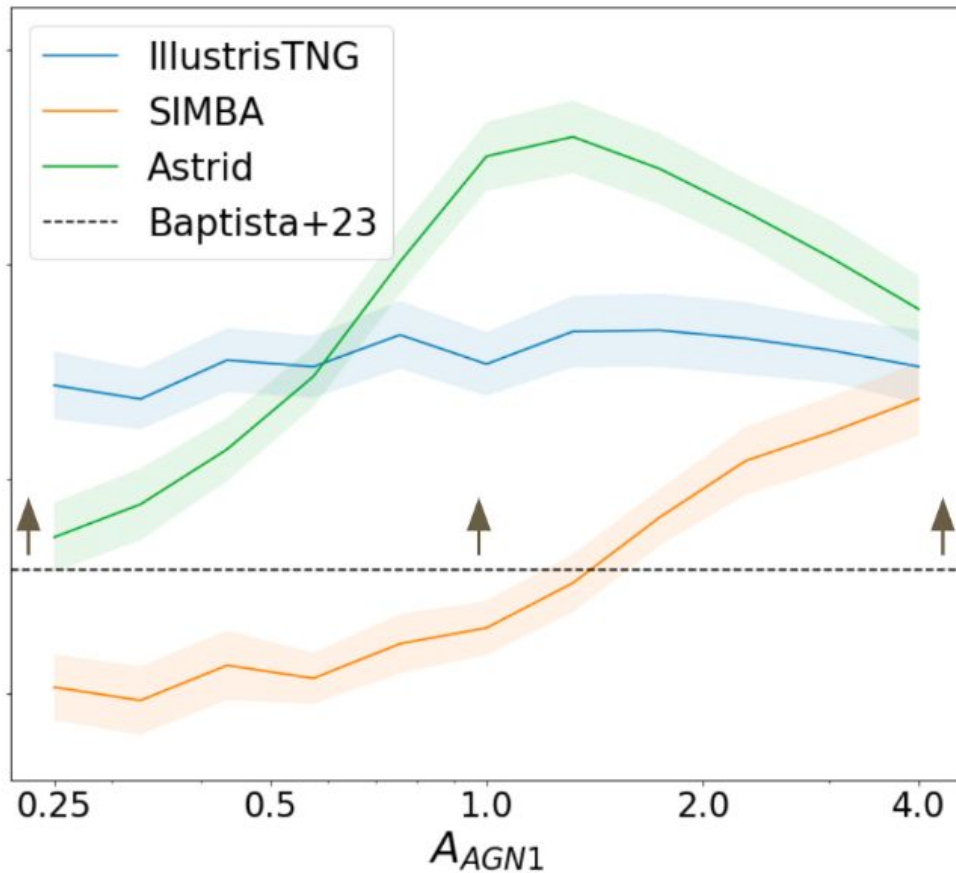
# FRBs Constraining $F$

Baptista et al. 2023



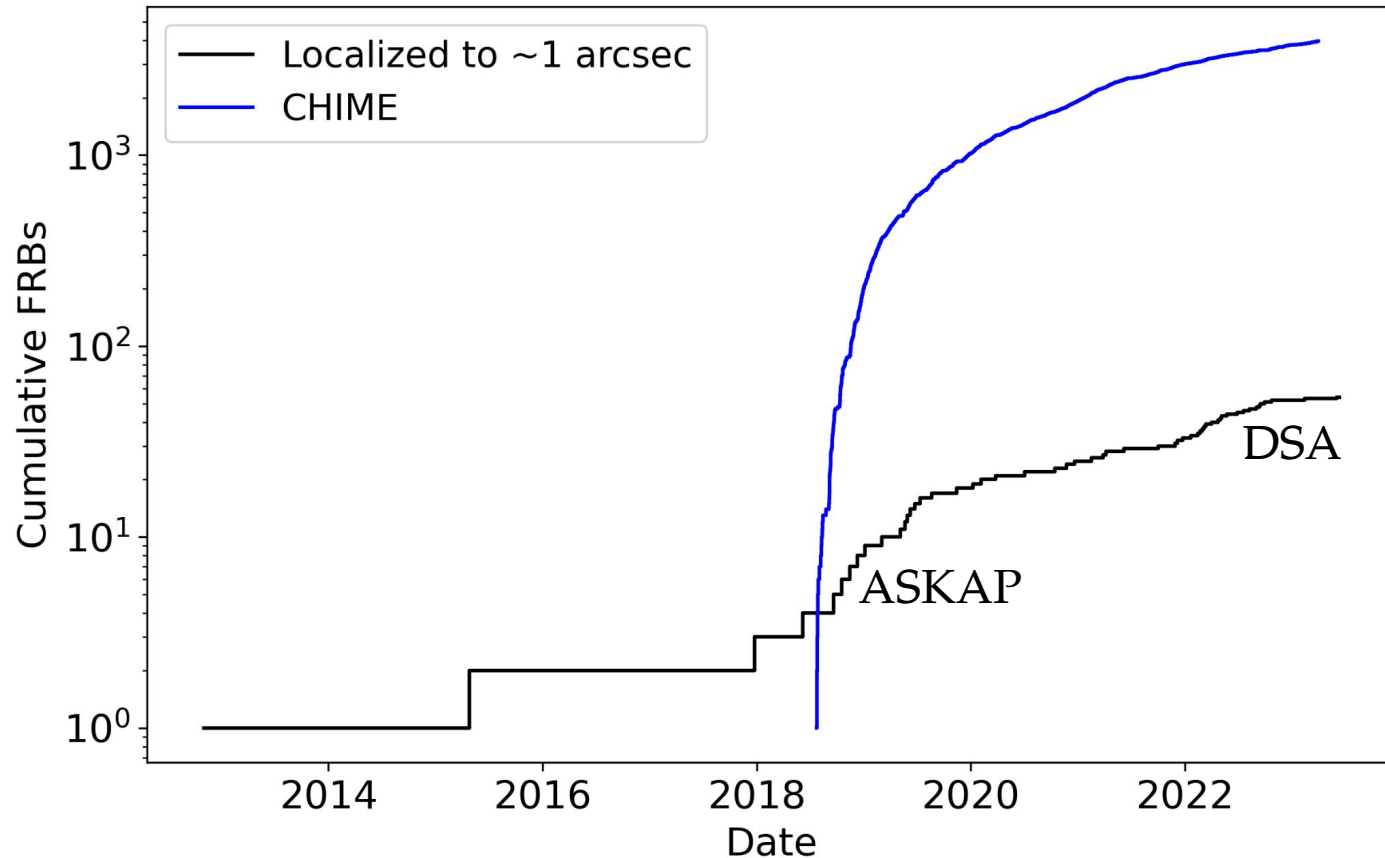


# FRBs Constraining $F$

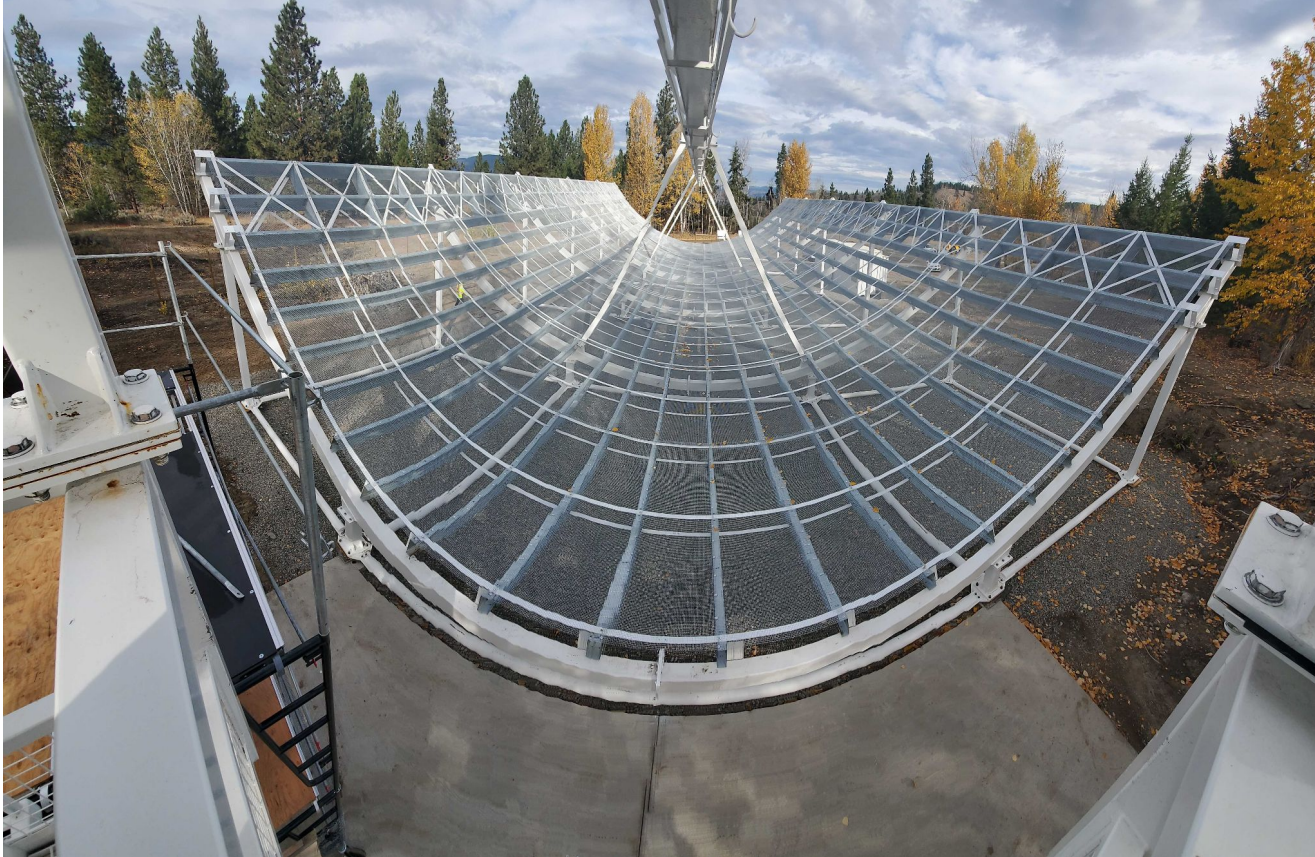


Medlock et al. in prep

# FRBs: So what's Next??



# CHIME Outriggers: $\sim 500$ FRBs/yr at $<1''$





# Towards 1000 FRB Redshifts

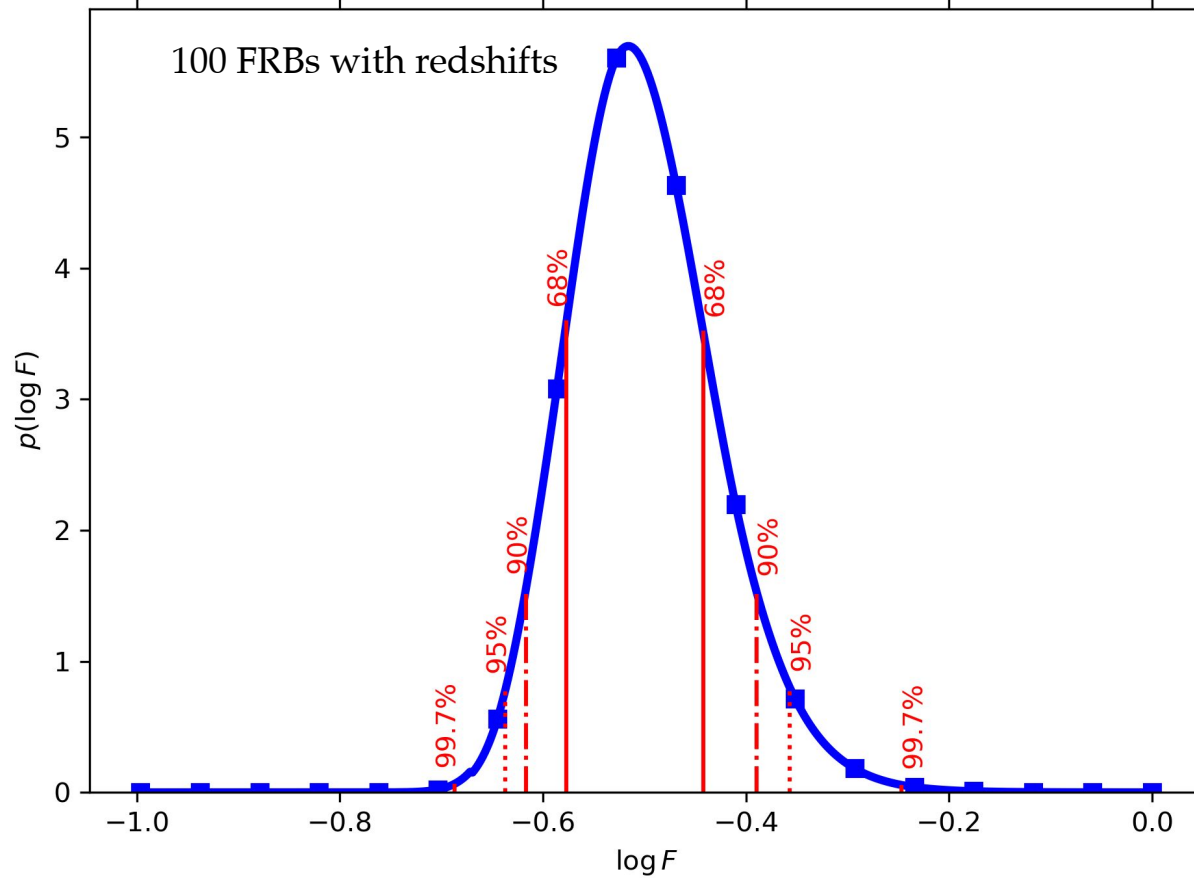
## Gemini/GMOS Large Program

- PI T. Eftekhari
- 2024A - 2026A
- 200 hours
- Longslit + Masks of Gemini/Outrigger Candidate Host Galaxies

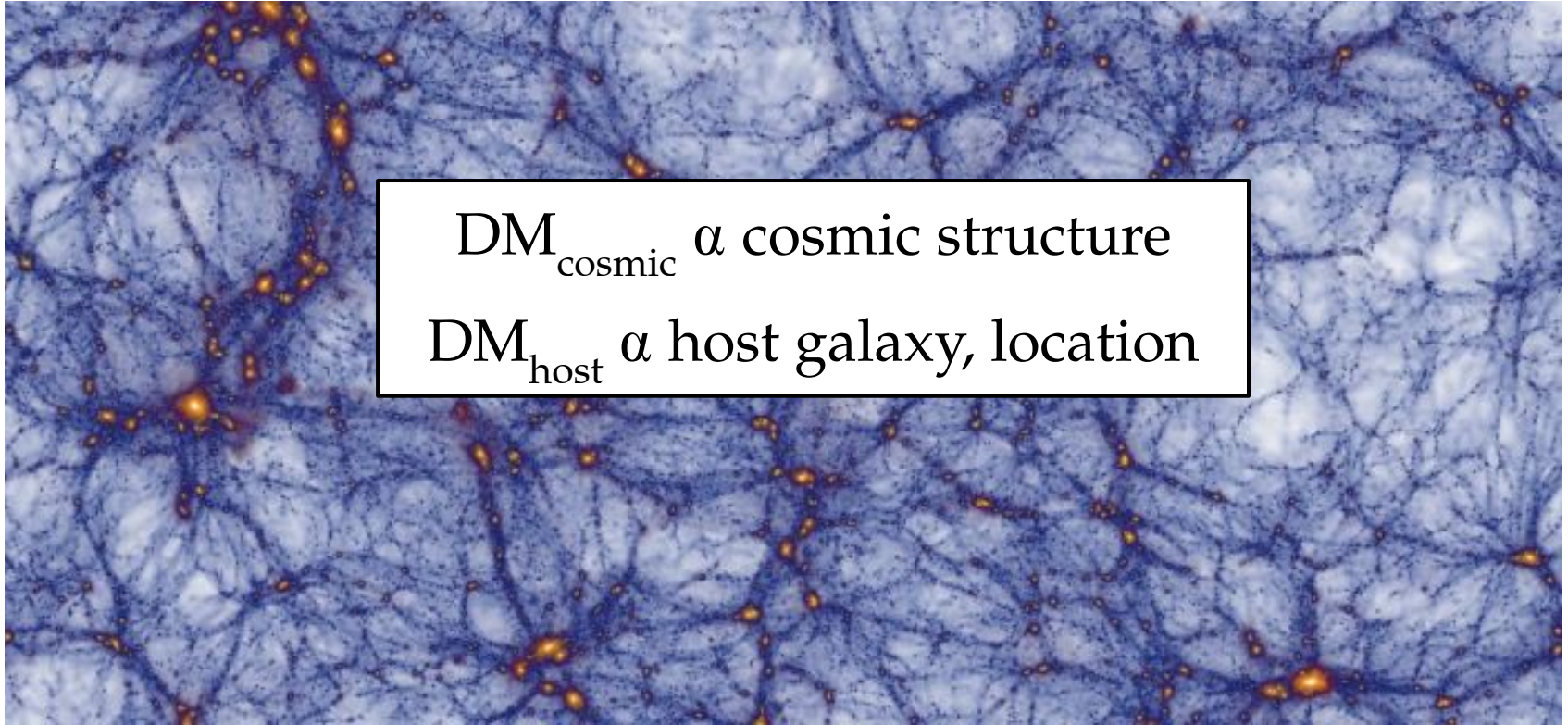




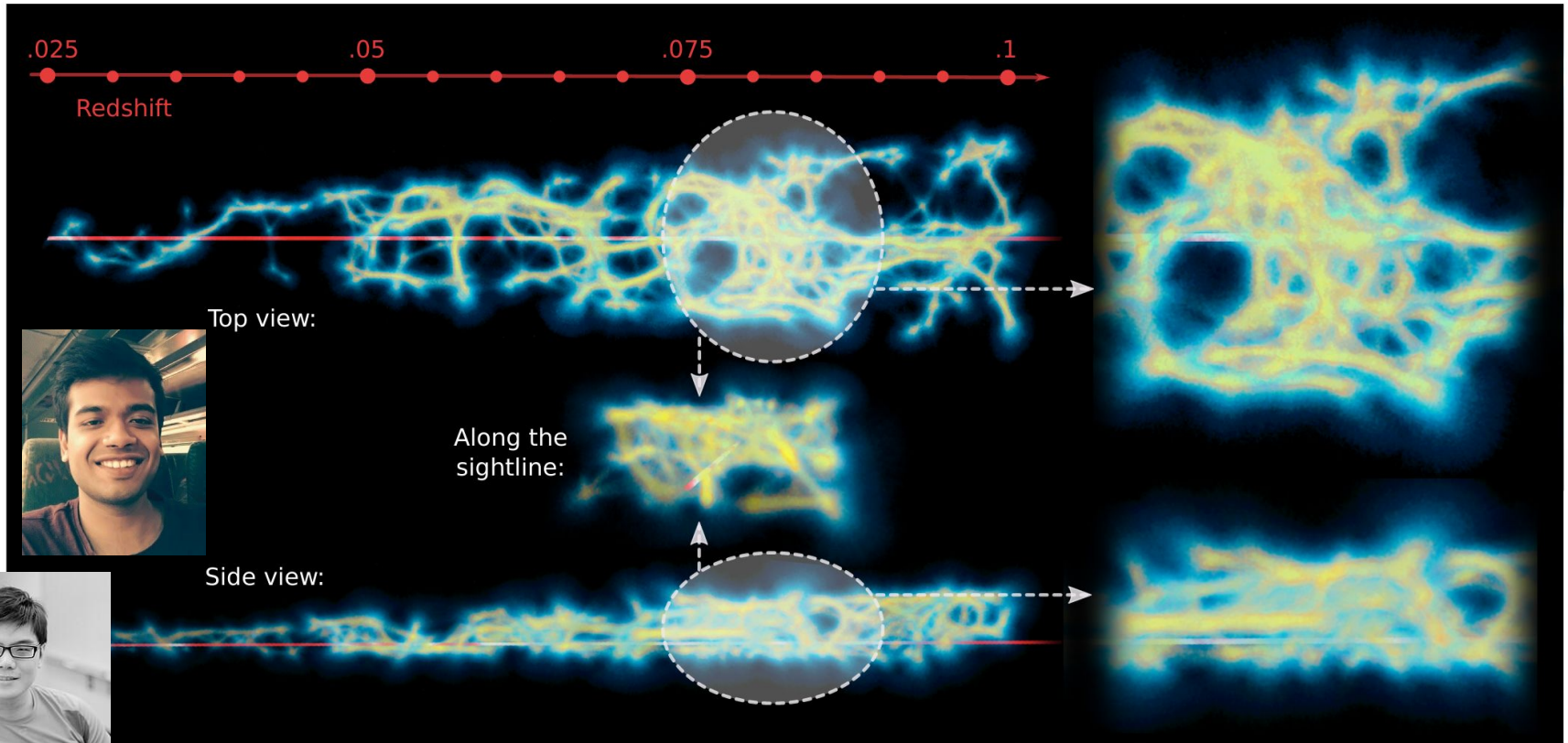
# $F$ Forecast (FRBs and $z$ 's alone)



# Locating the Baryons w/ Cross-Correlation



# Locating the Baryons w/ Cross-Correlation

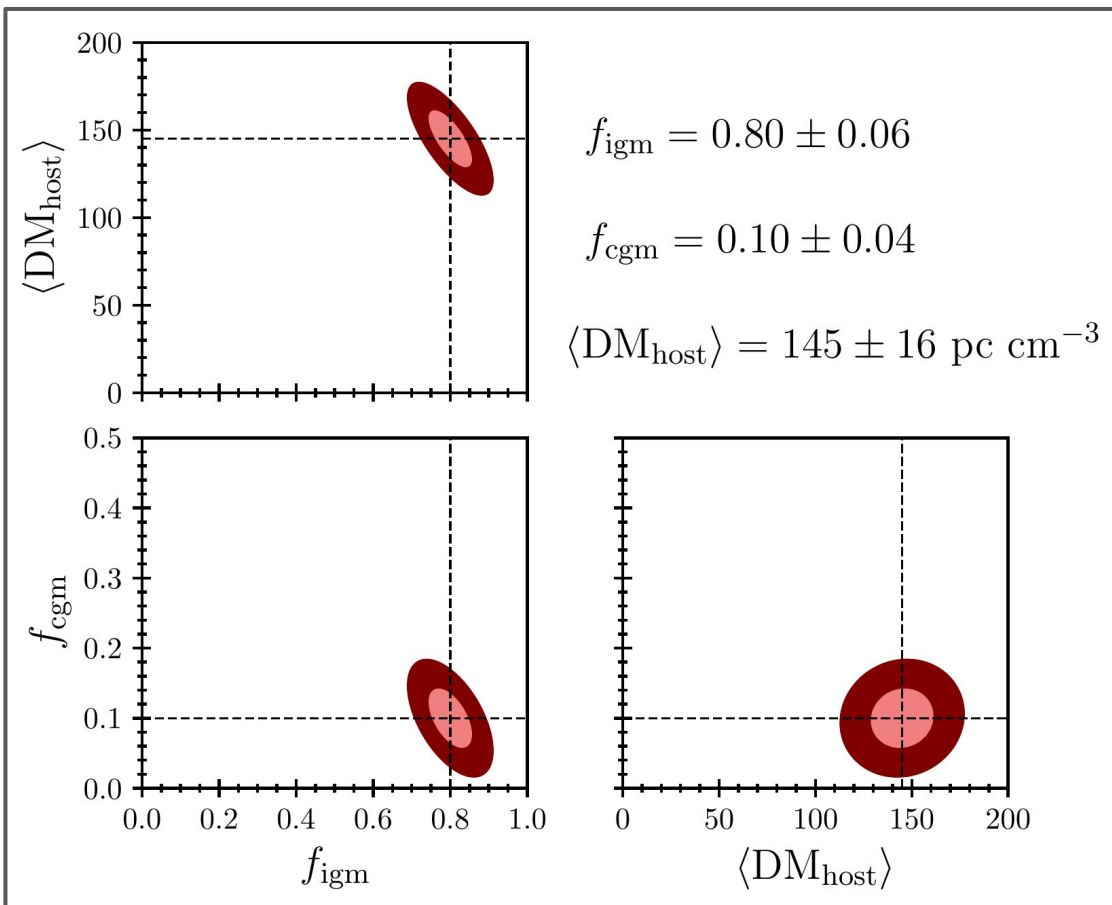


# FLIMFLAM

$f_{\text{igm}}$   
Fraction of  
baryons in IGM

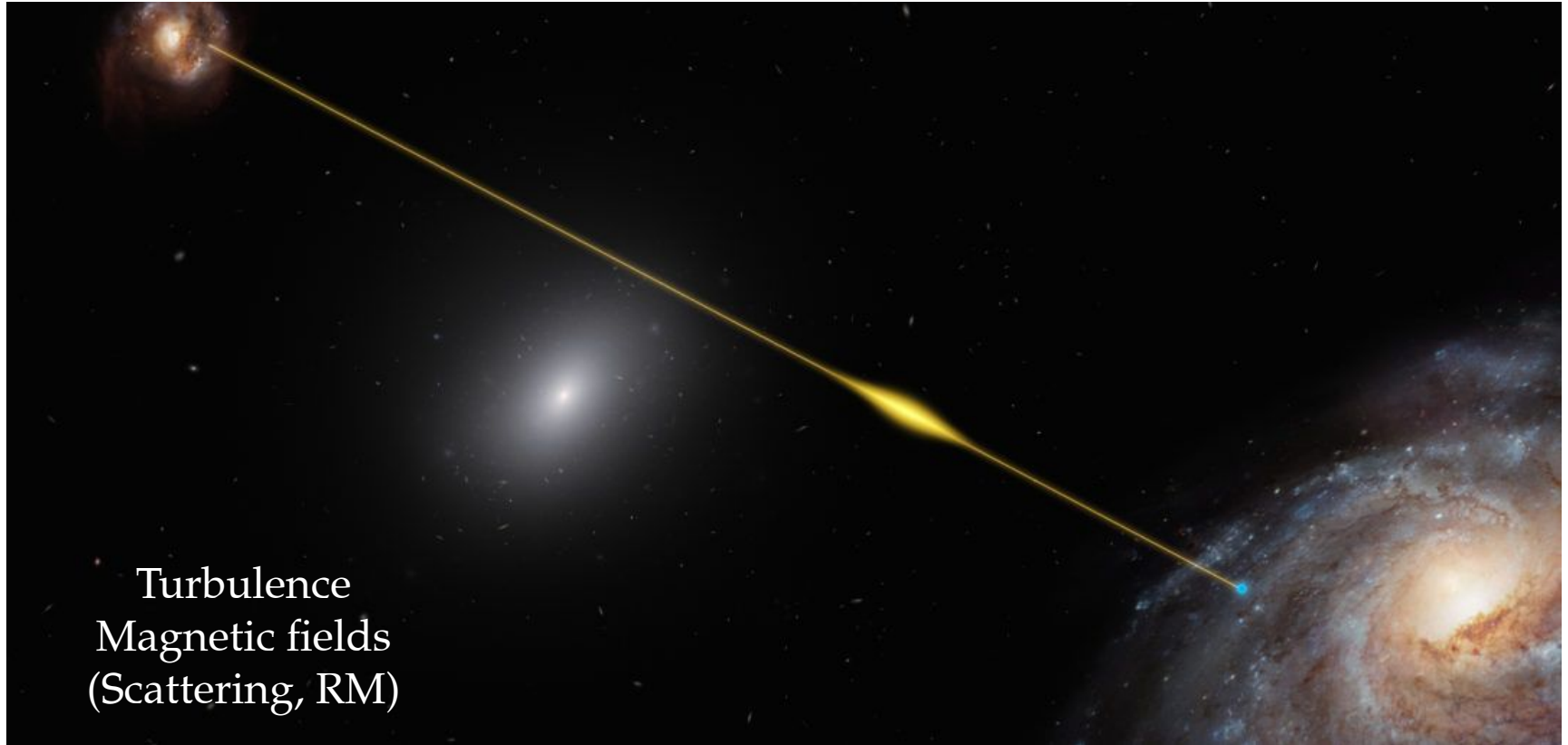
$f_{\text{cgm}}$   
Fraction of hot  
baryons  
retained by halo

$r_{\text{max}}$   
Characteristic  
extent of the  
CGM



Lee+2022

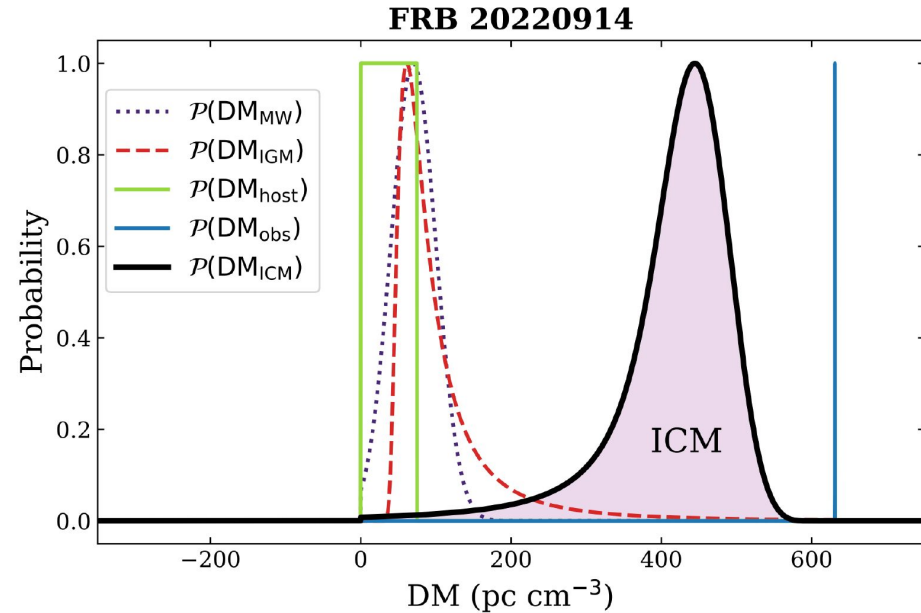
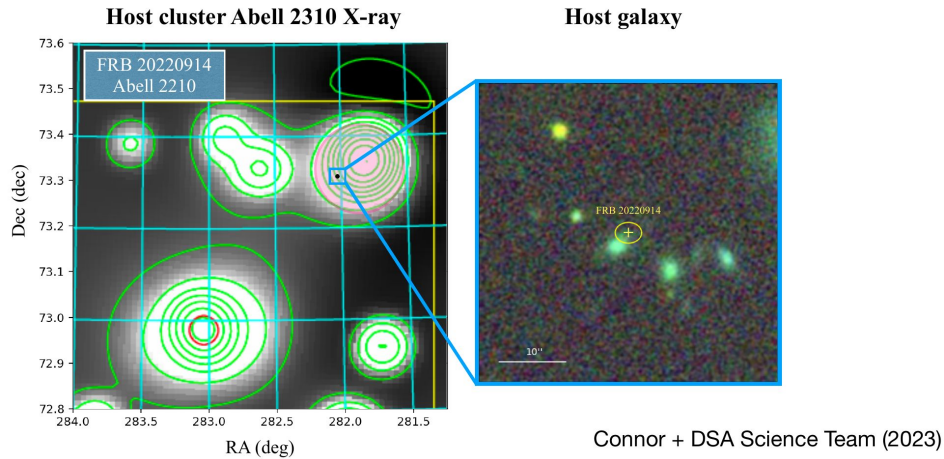
# FRBs Probing Individual Galactic Halos



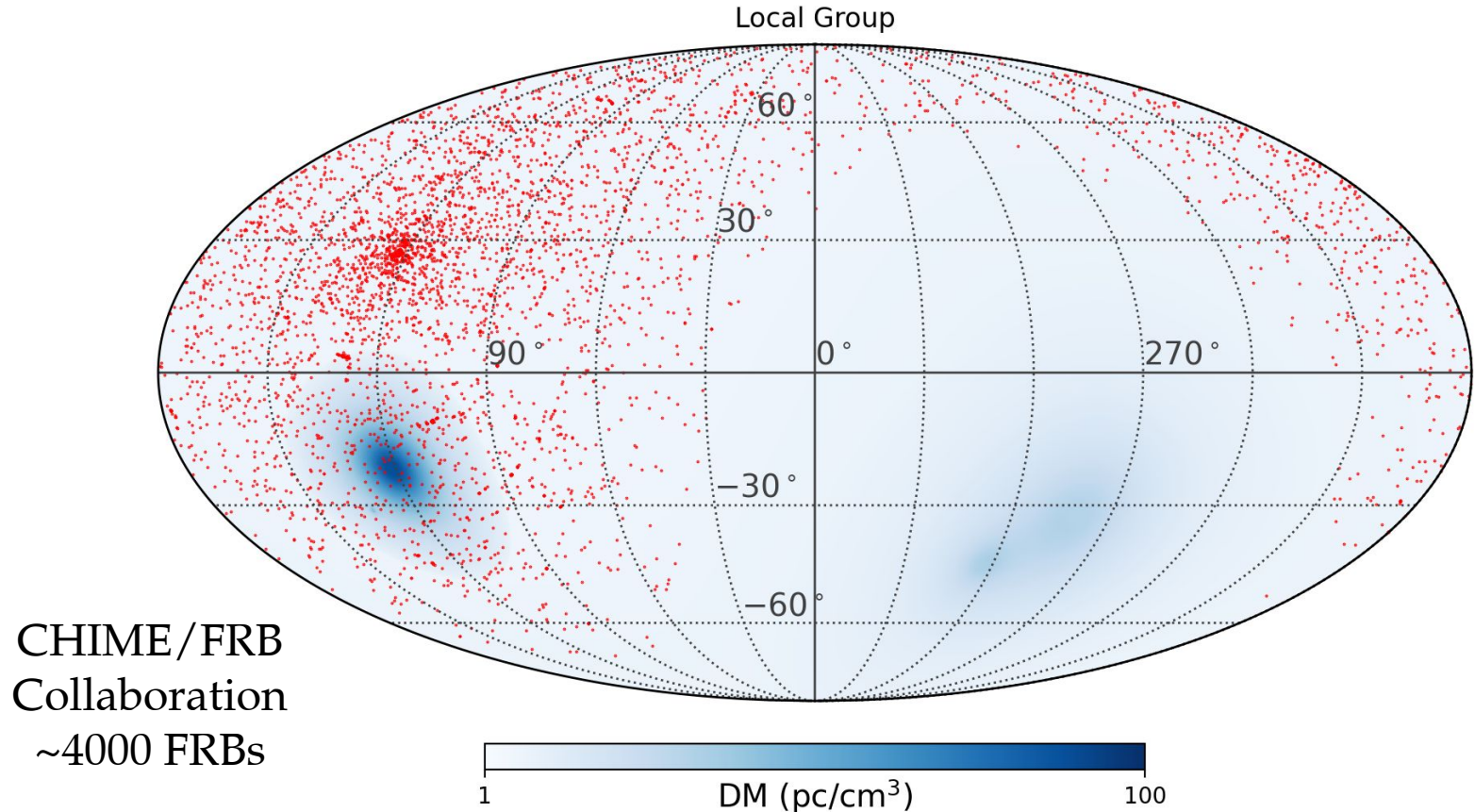


# FRBs Probing the Intracluster Medium (ICM)

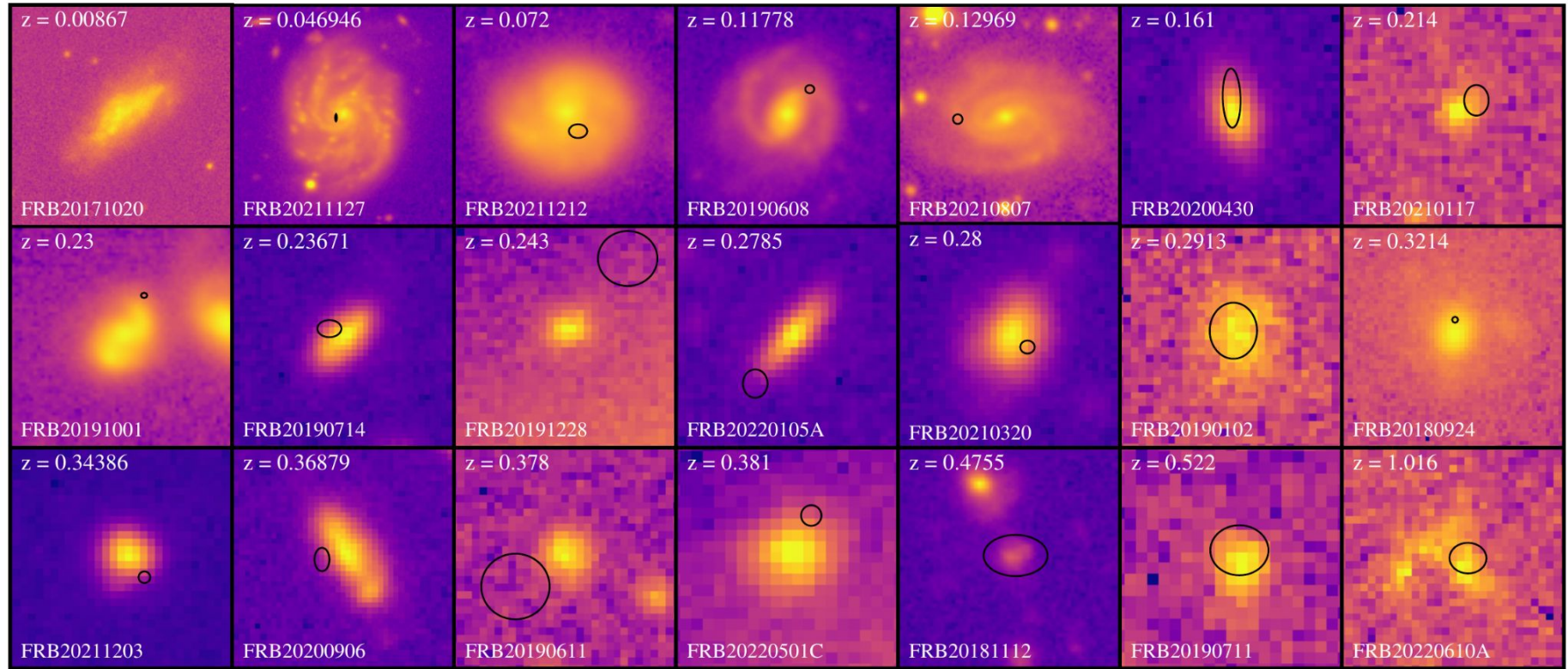
Connor et al. 2023



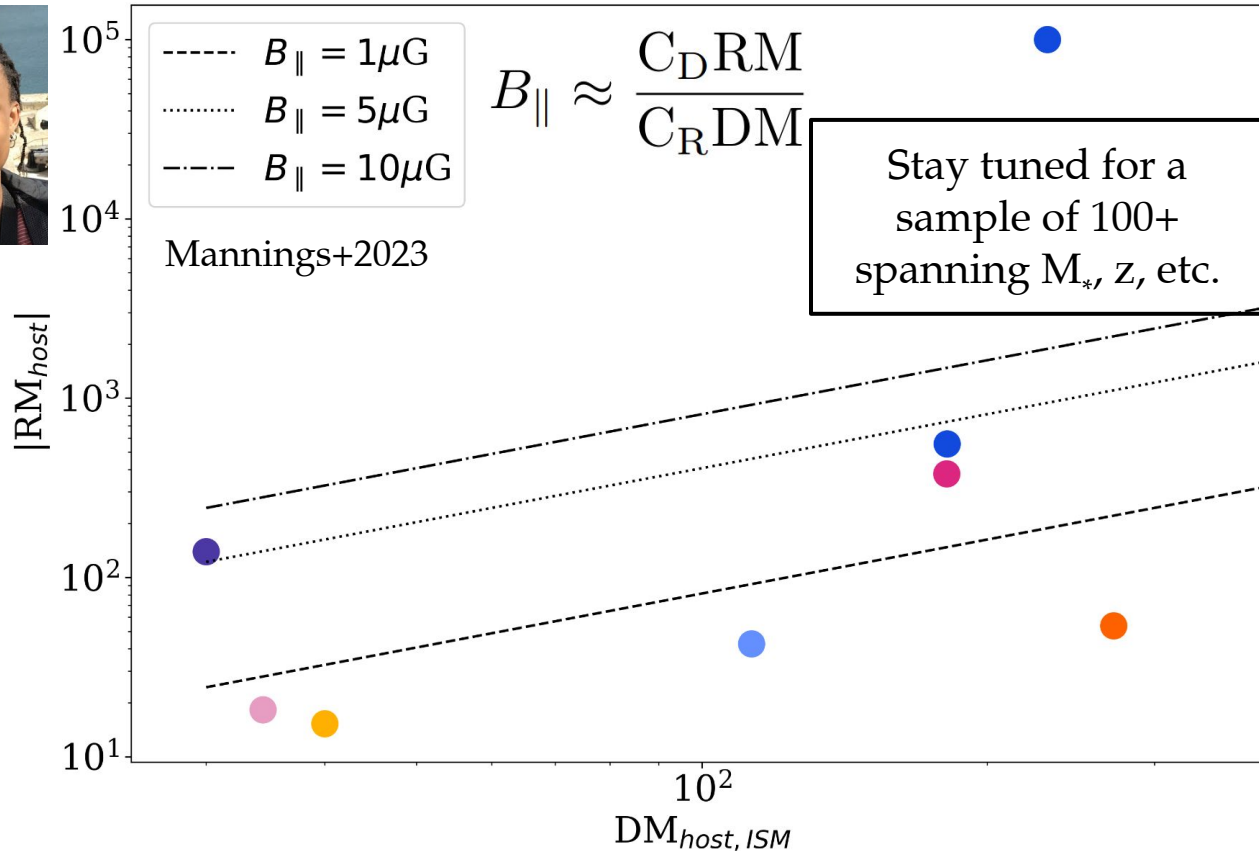
# M31's Halo (More Cross-Correlating)



# Future: Hosts by the dozens



# (Approximate\*) ISM Magnetic Field Strength



\*Disclaimer:  
Beware of varying  
RM in FRBs....

Characteristic field  
strengths are low, e.g.  
below typical values  
of the Milky Way.

But are consistent  
given expected field  
reversals

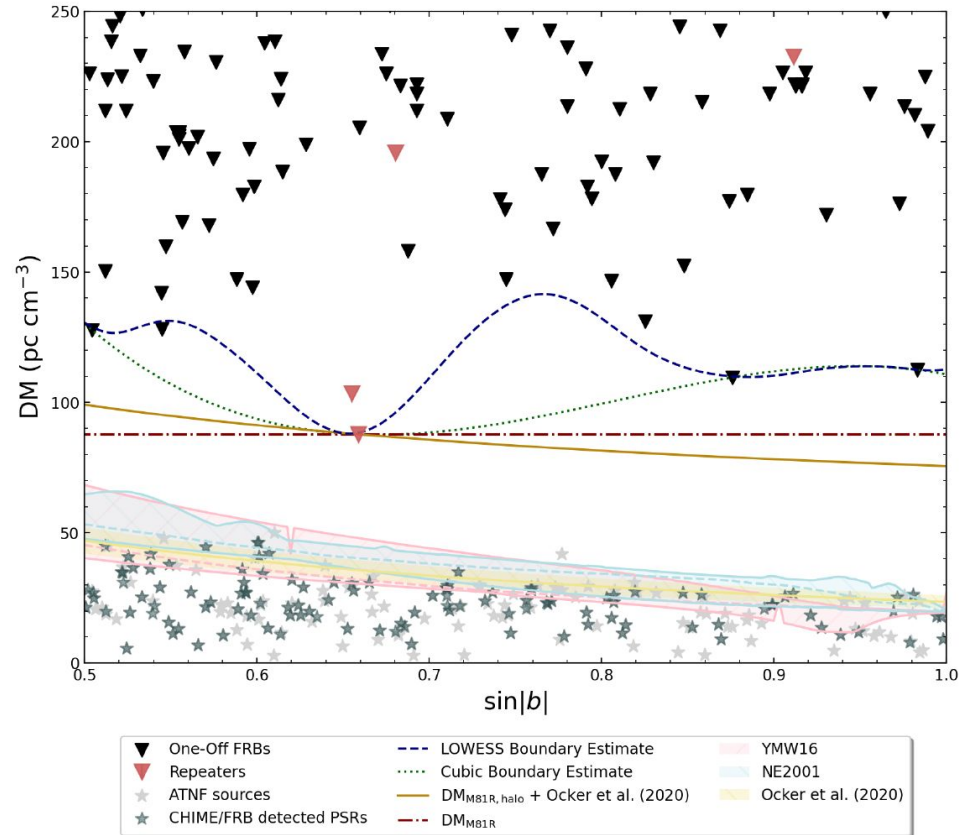


# FRBs Probing our Galactic Halo

COOK ET AL.



$DM_{MW,halo} < 55 \text{ pc cm}^{-3}$   
(Cook+2023) FRBs



# Future: FRB Probes of our Universe

## Probable

- ISM turbulence in host galaxies
- CGM gas profiles (galactic feedback)
- $H_0$  to 10%
- Resolve M31 halo
- Galactic halo
- Observe the WHIM

## Optimistic

- Lensing measurements
- $H_0$  to 5%
- HeII reionization
- IGM magnetic fields

## Overly Optimistic?

- HI Reionization
- Dark Energy
- $H_0$  to 1%

