Searching for the sources of excess extragalactic dispersion of FRBs

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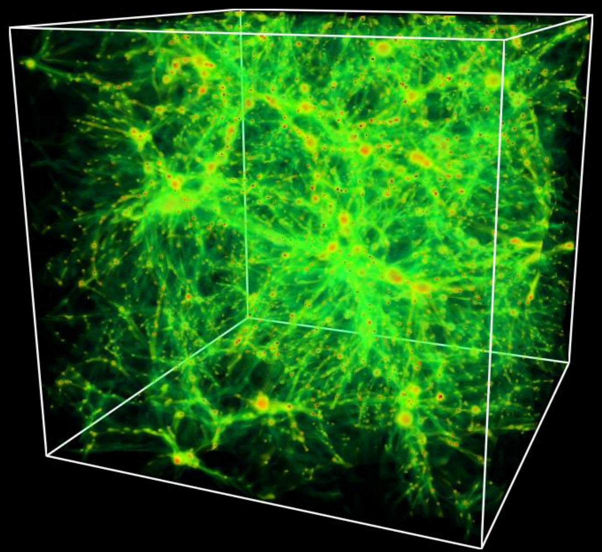
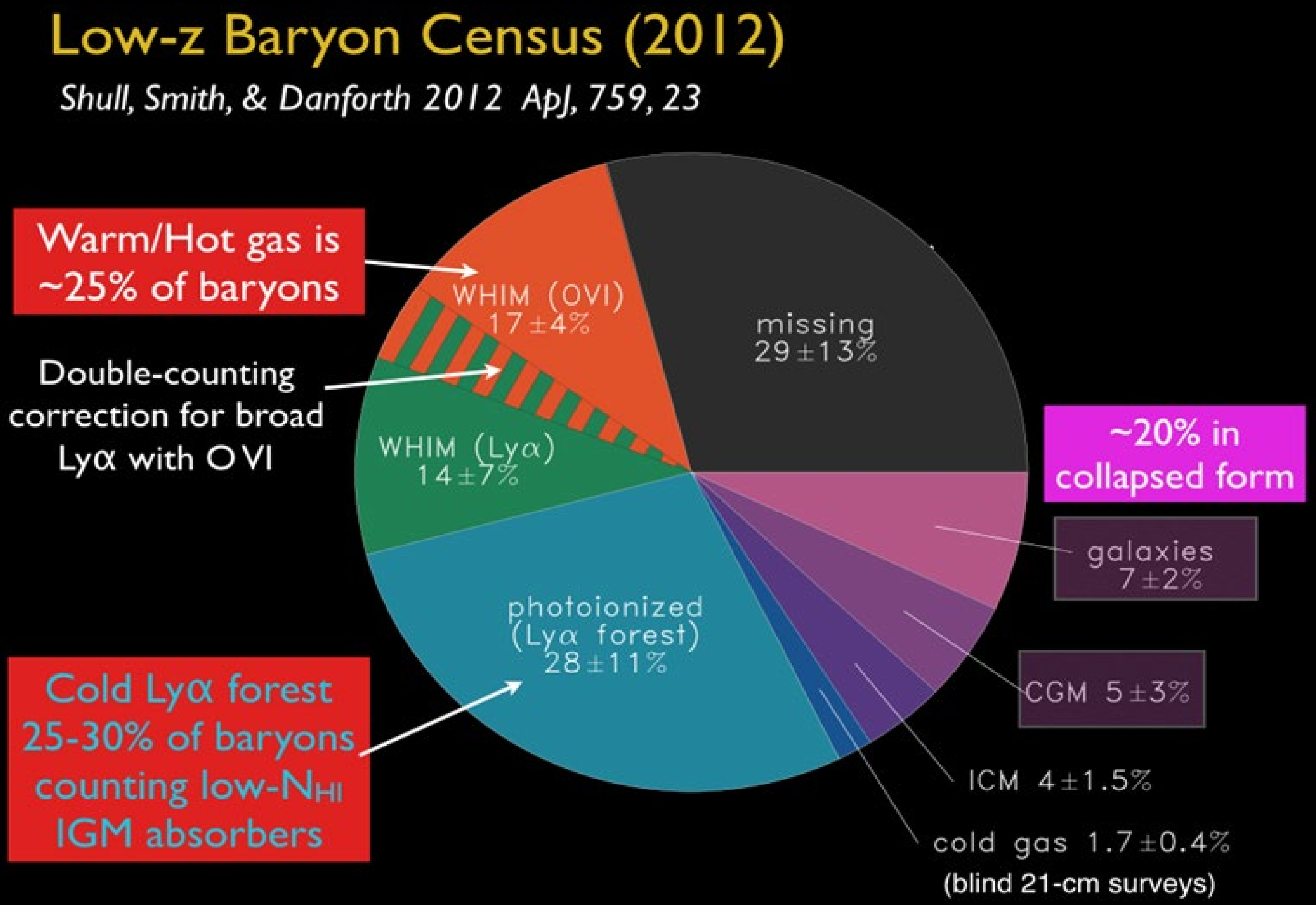
In collaboration with: Khee-Gan Lee, J. Xavier Prochaska, Ilya S. Khrykin, Yuxin Huang, Nicolas Tejos, Lachlan Marnoch, Metin Ata, Lucas Bernales, Shivani Bhandari, Jeff Cooke, Adam T. Deller, Stuart D. Ryder, and Jielai Zhang

The Missing Baryon Problem



Davé et al 2001, ApJ



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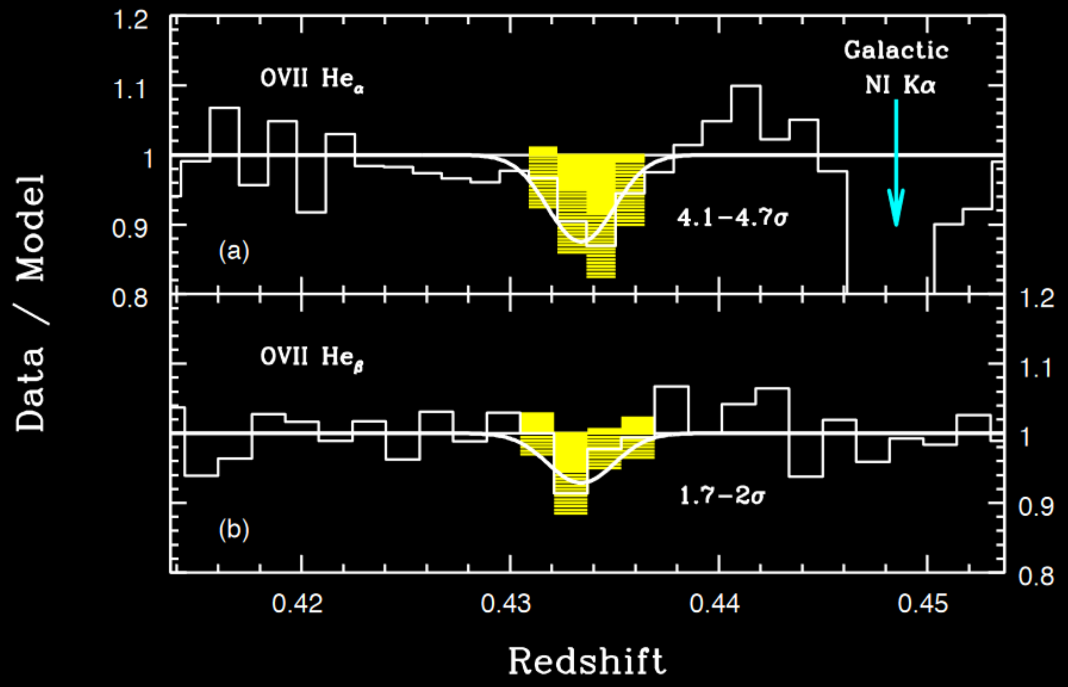
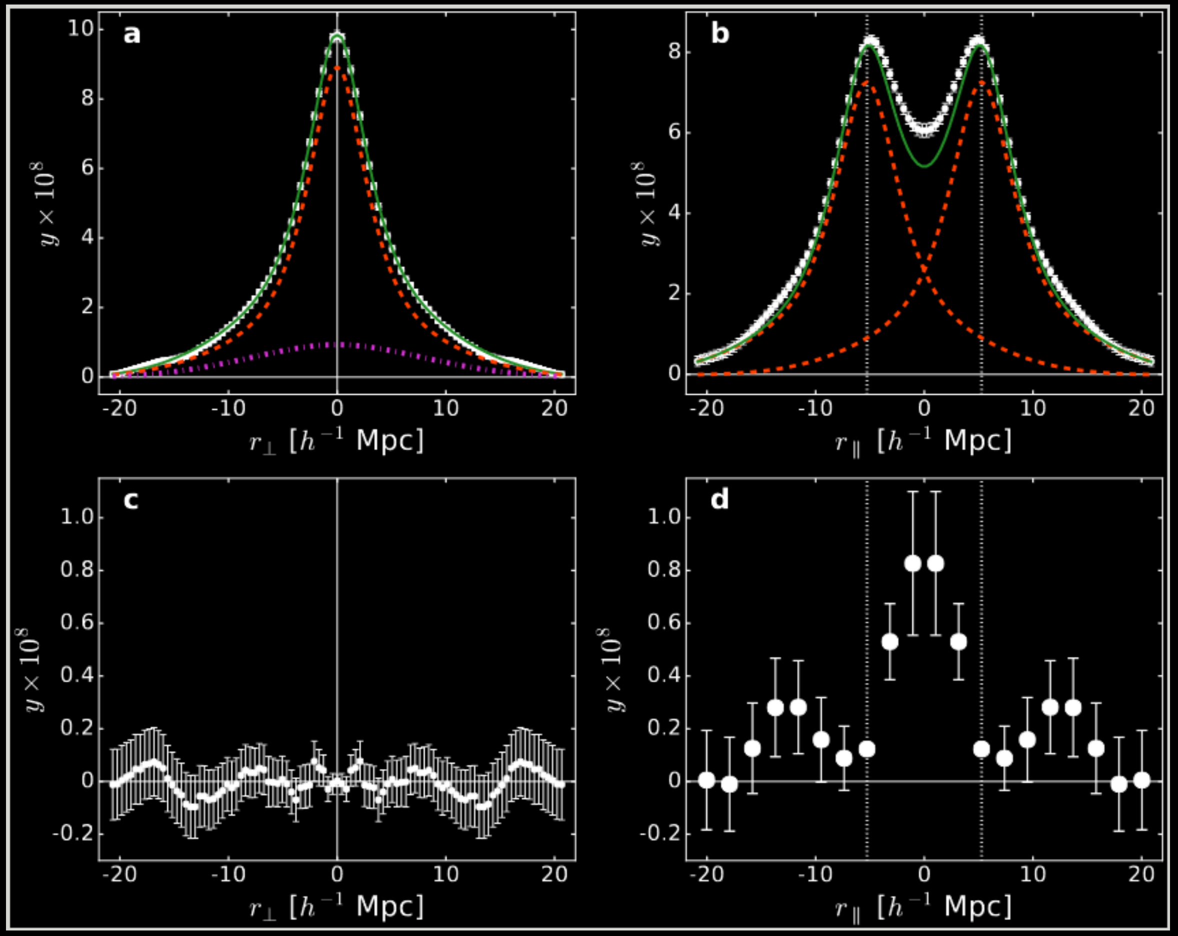


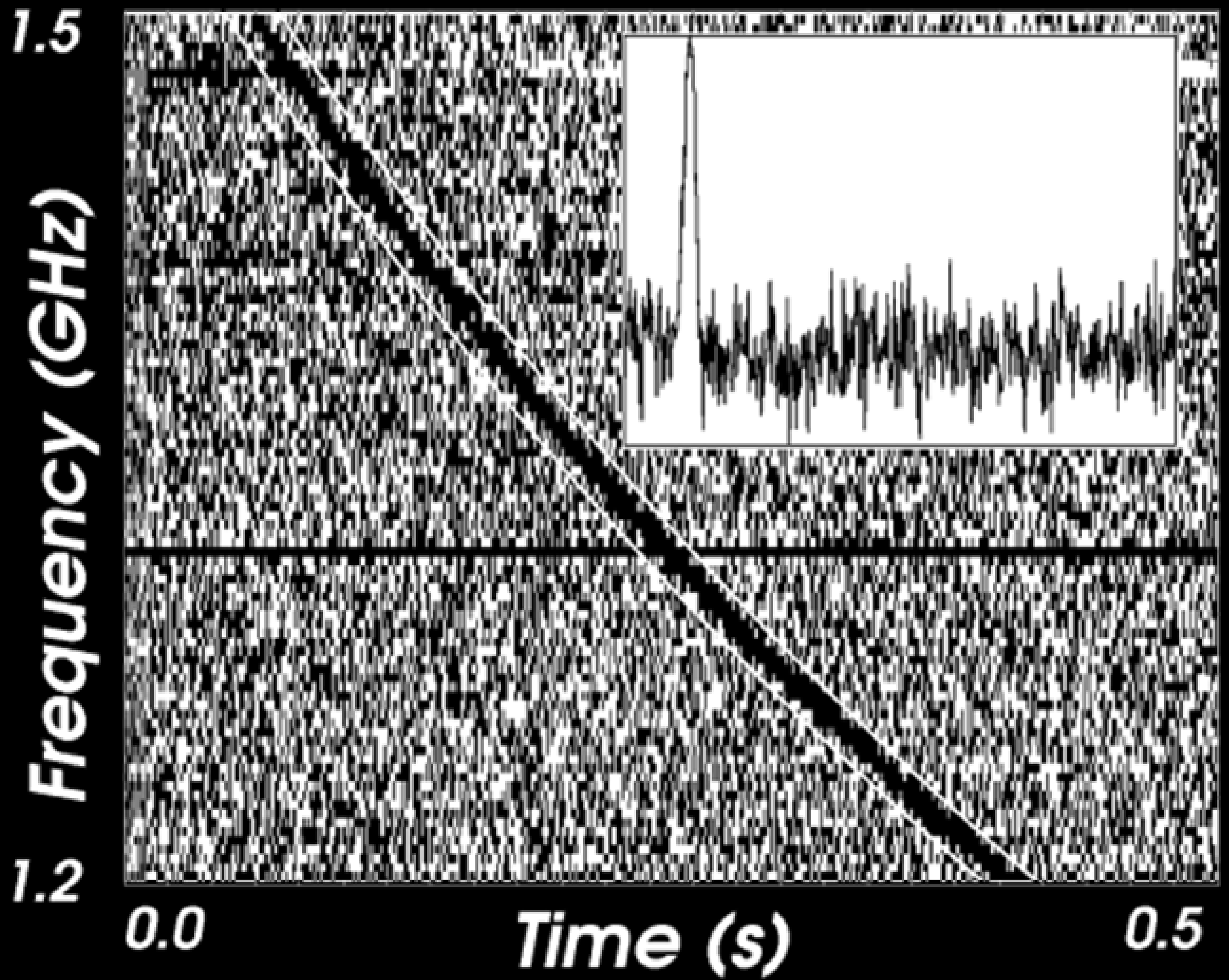
Nicastro et al 2018



De Graaf et al 2019

The Lorimer Burst

- An isolated burst that Lorimer et al found was likely extragalactic (~$4\ Gly$).
- If extragalactic, this must have been quite energetic ($\sim 10^{40}\,\mathrm{erg}$).



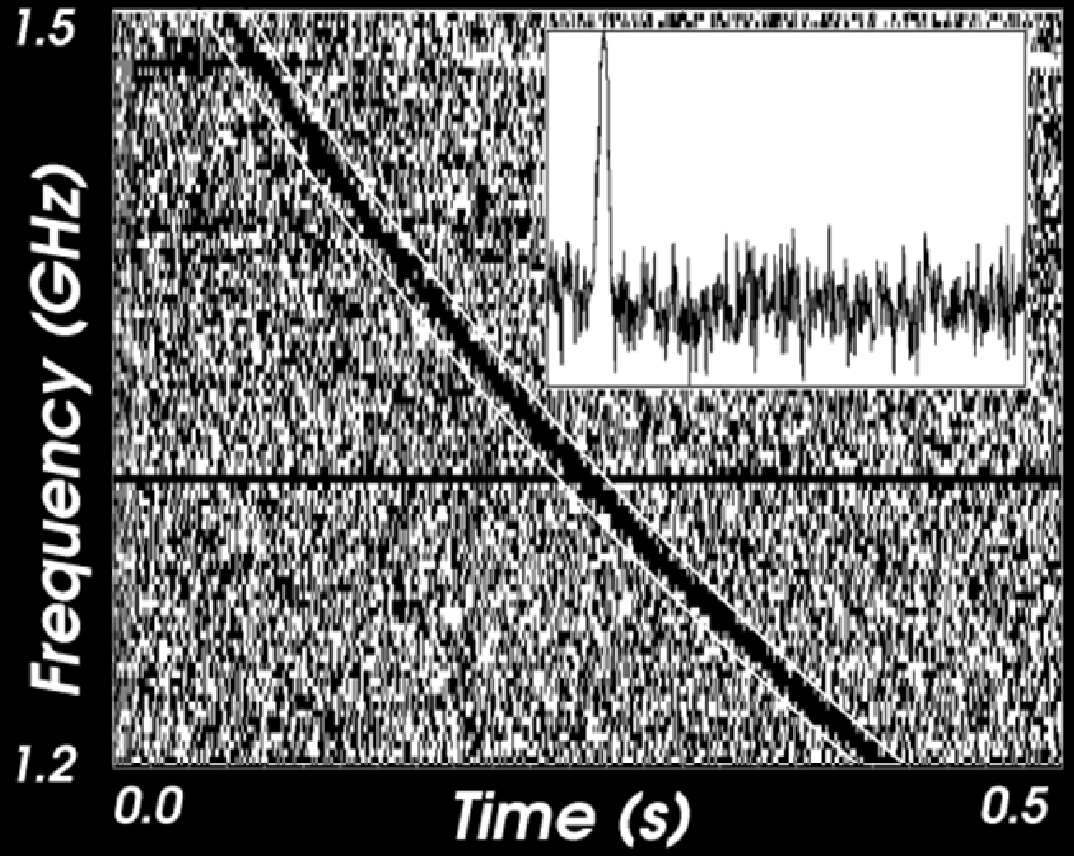
Lorimer et al 2007, Science

Burst Properties: Dispersion Measure

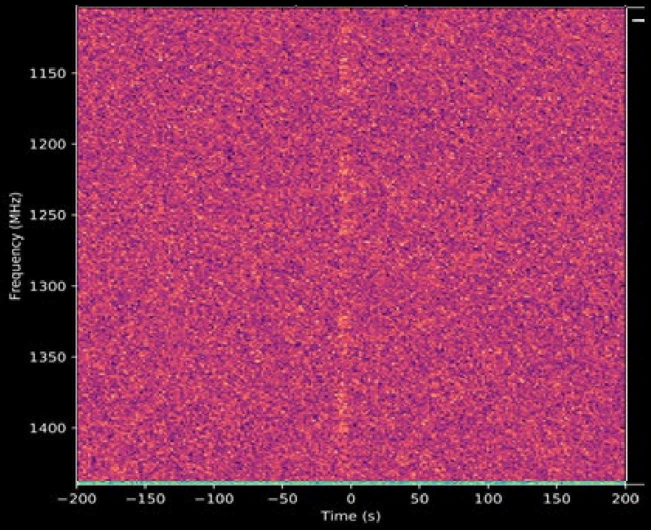
- Radio waves travelling through plasma are dispersed.

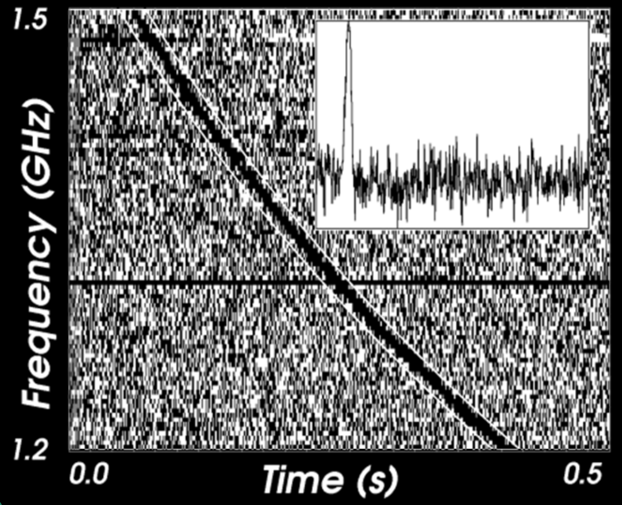
$$t = (4.15\ ms)\left(\frac{DM(z)}{pc\ cm^{-3}}\right)\left(\frac{\text{GHz}}{\nu}\right)^2$$

$$DM(z) = \int_0^d \frac{n_e}{1+z}\,dl$$



Probing ionized matter with FRBs



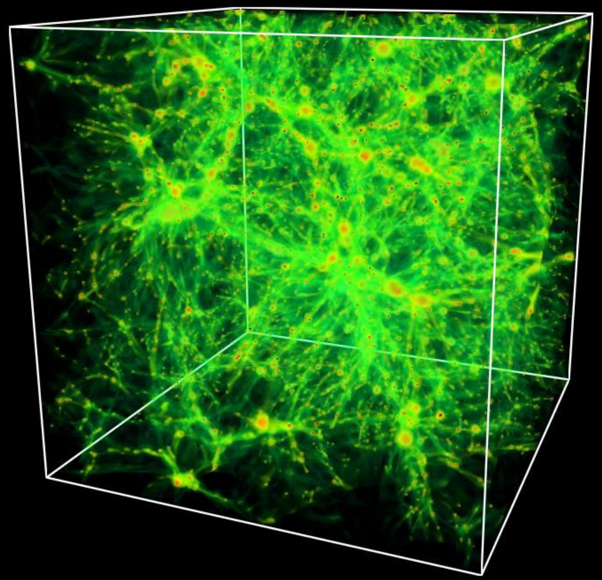


FRB

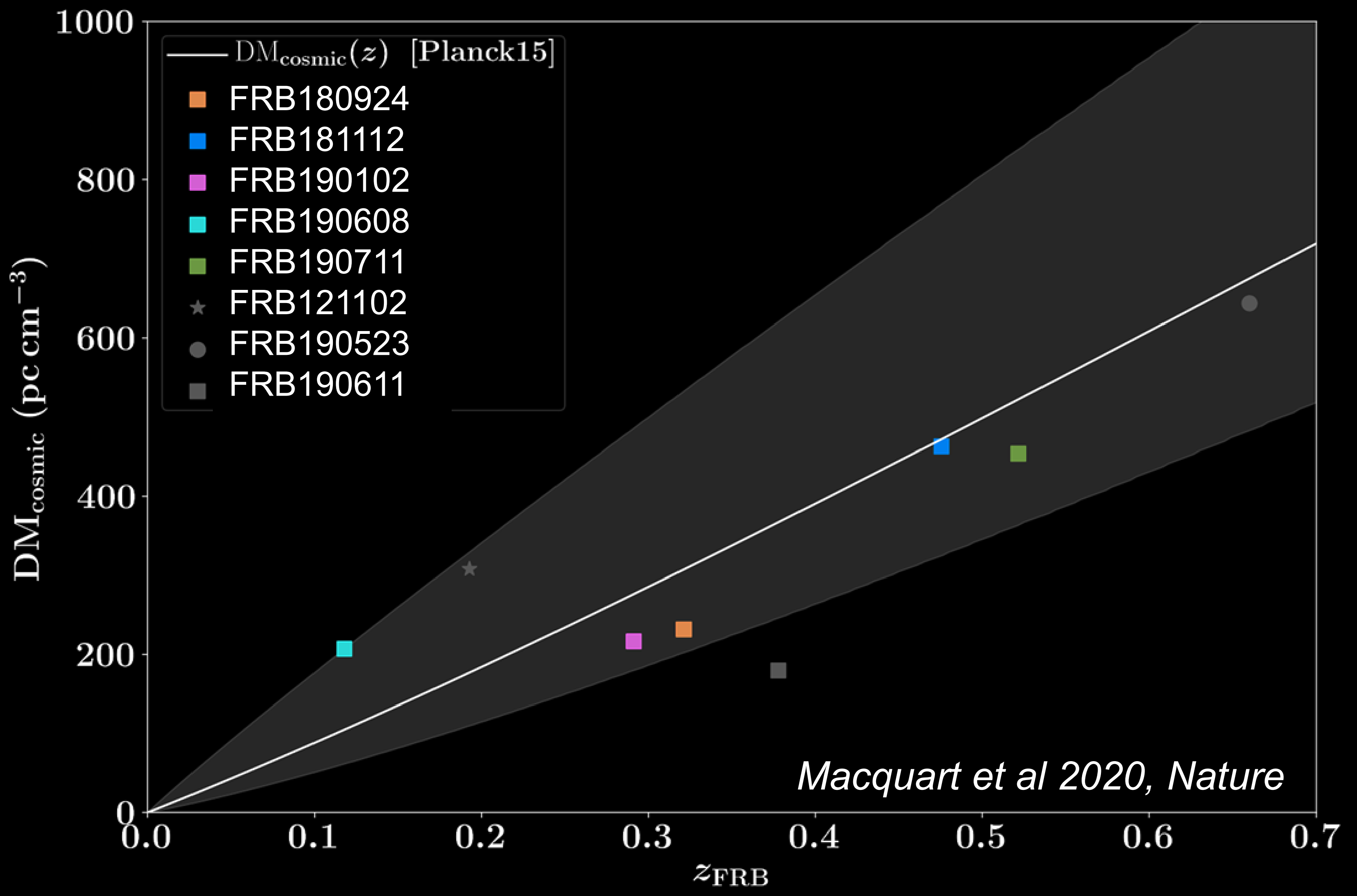
Host galaxy ISM → Host halo → Cosmic Web → Milky Way halo → Milky Way ISM

$$DM = \int_0^d \frac{n_e}{1+z} dl = DM_{Host} + DM_{Cosmic} + DM_{MW}$$

Probing matter with FRBs



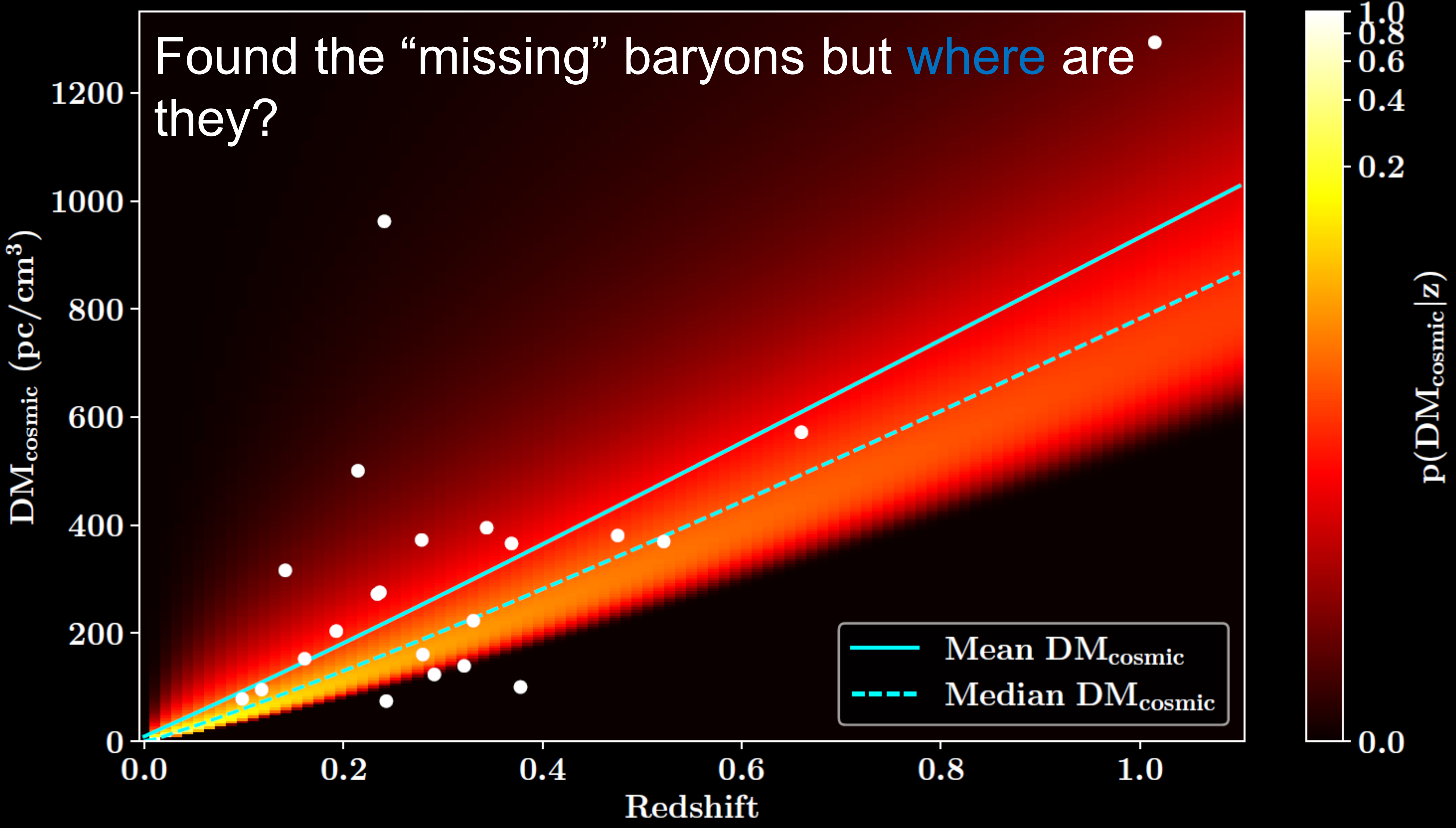
Davé et al 2001, ApJ



Macquart et al 2020, Nature

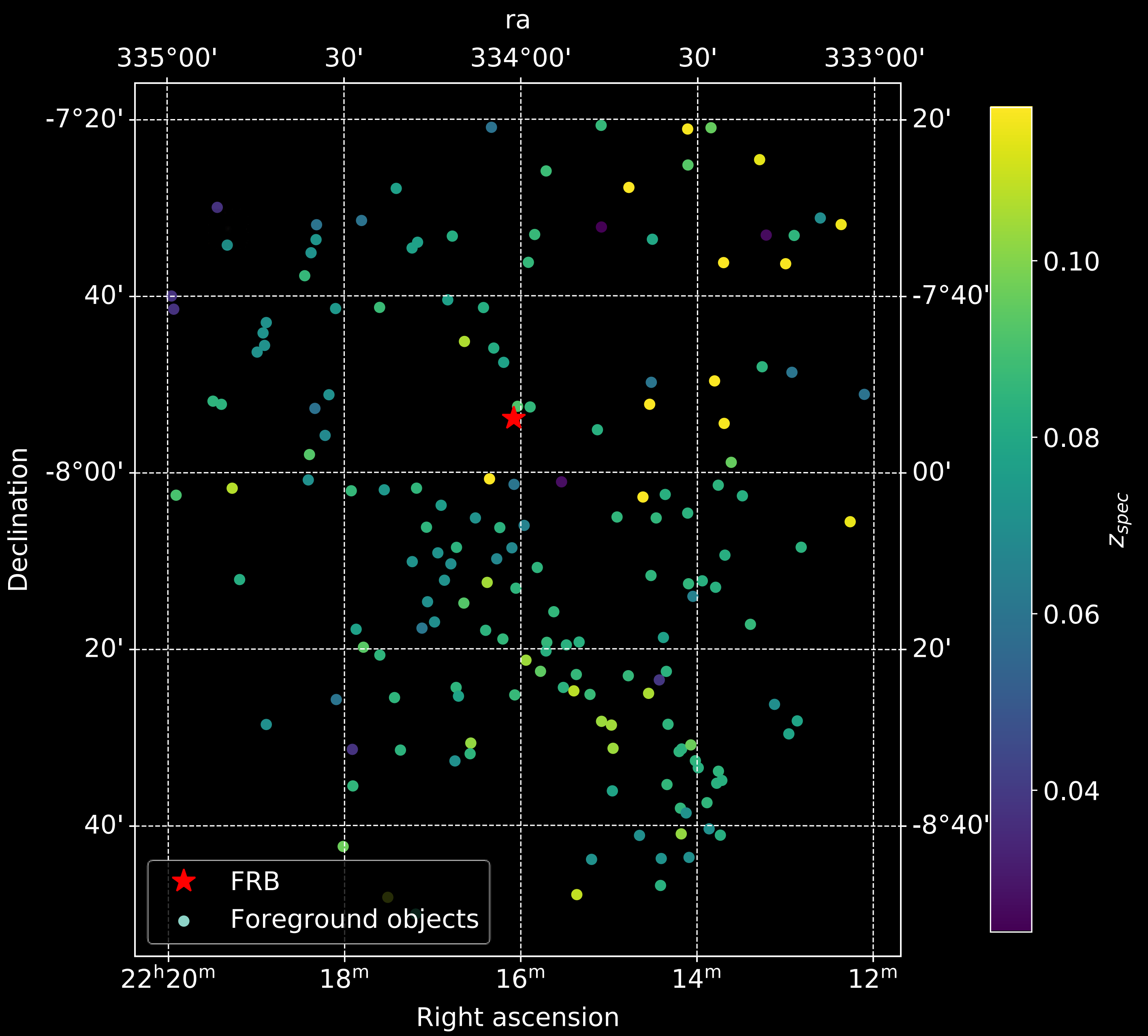
The Macquart Relation

$$DM_{cosmic} = DM_{FRB} - DM_{MW} - DM_{Host}$$



FRB20190608A

- Redshift = 0.11778
- DM = 340 $\mathrm{pc\ cm^{-3}}$



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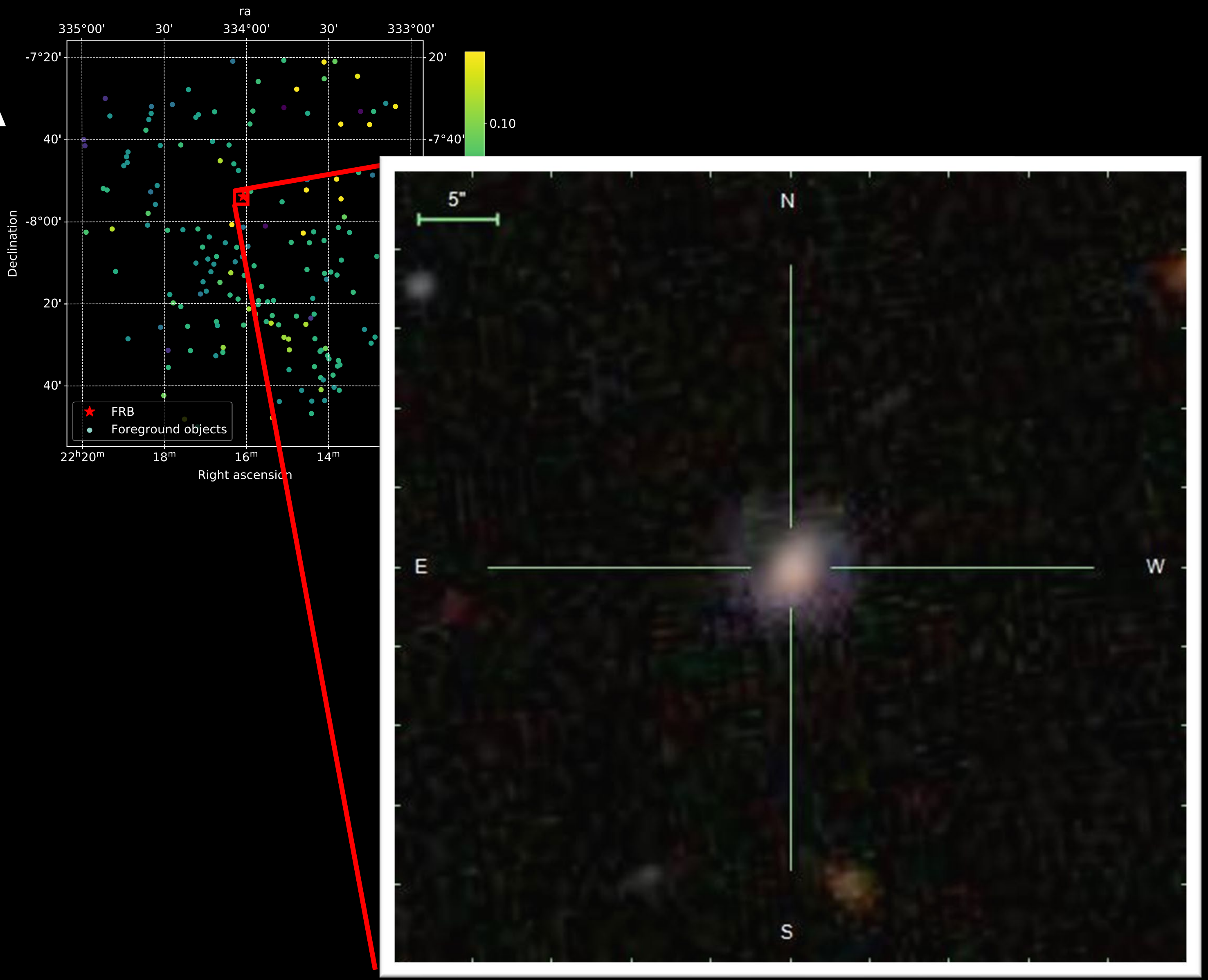

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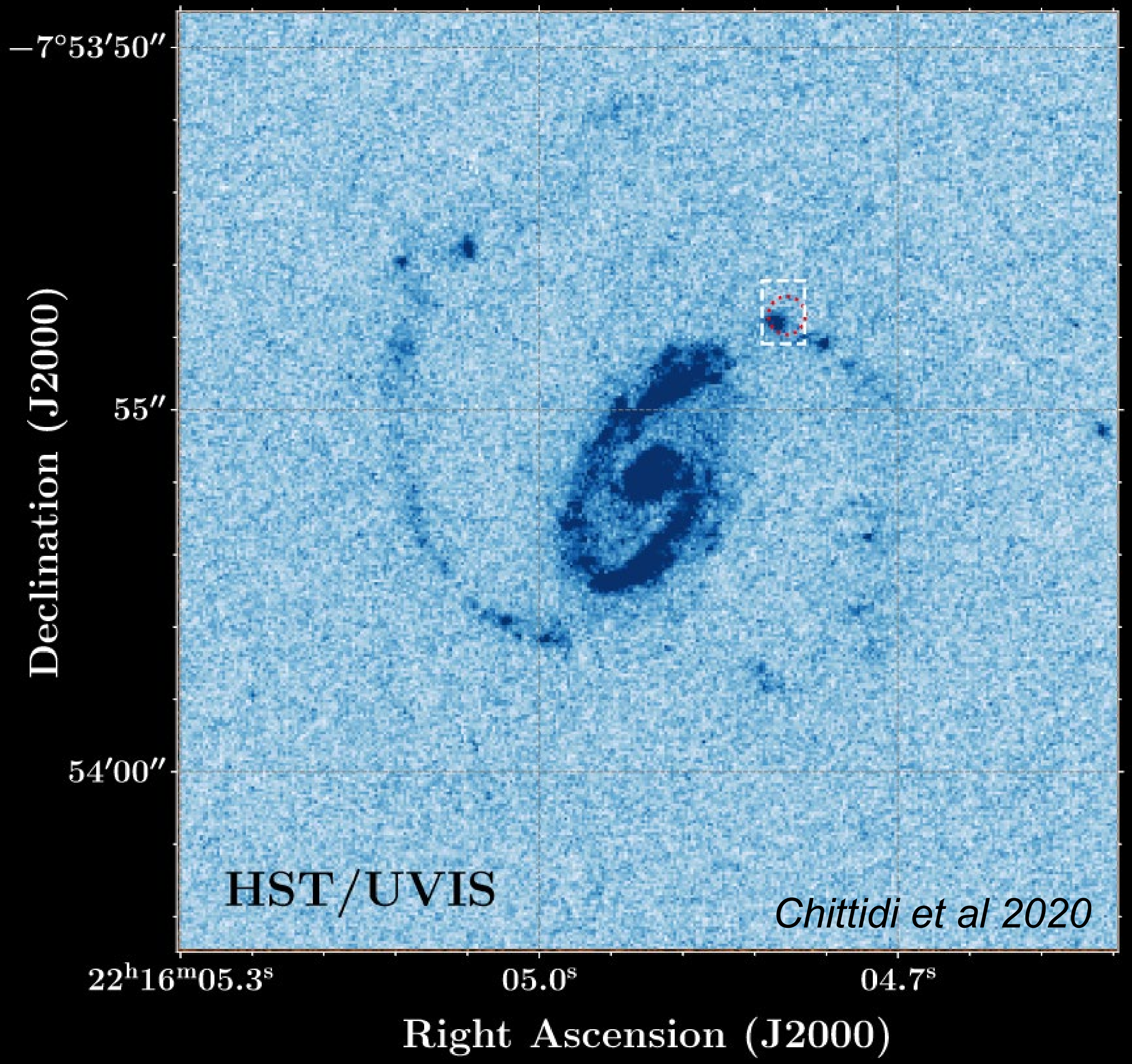
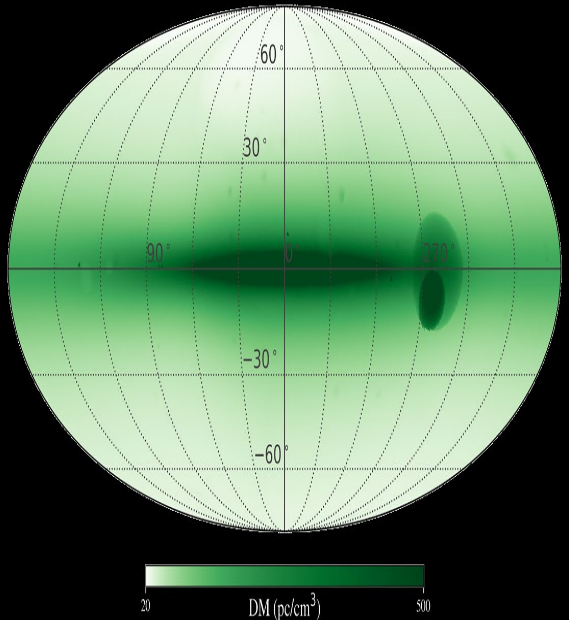


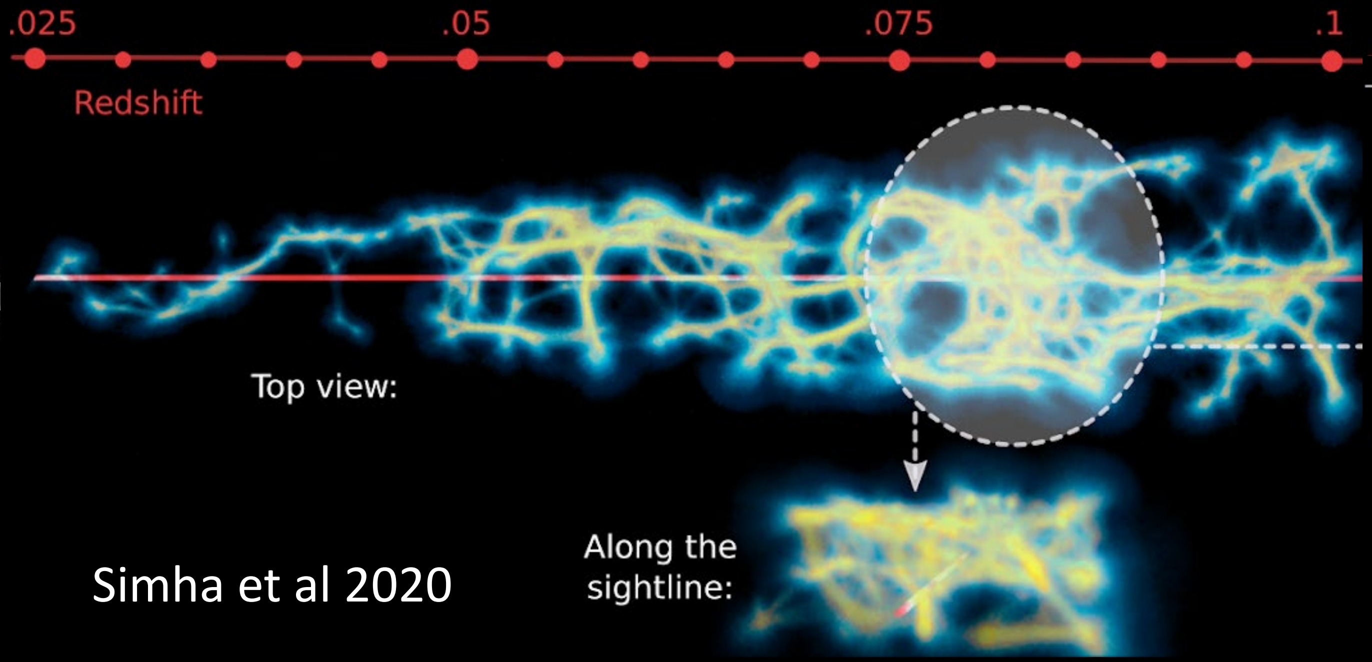
FRB 190608: An end-to-end study

DM_{MW}



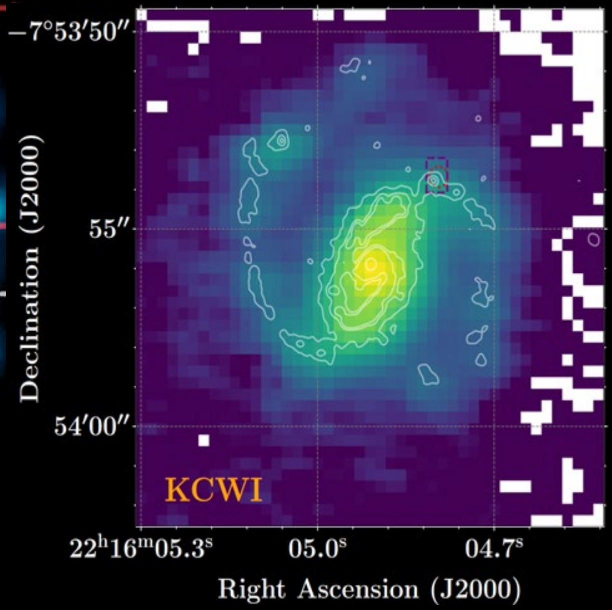
NE 2001

DM_{cosmic} (SDSS, KCWI)



Simha et al 2020

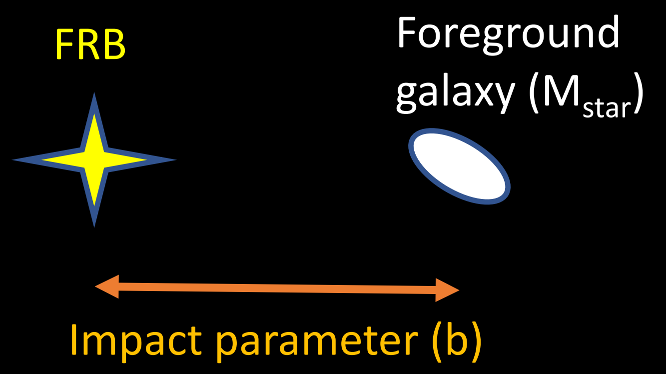
DM_{host} (KCWI)



Chittidi et al 2020

DM estimation: Intervening Halos

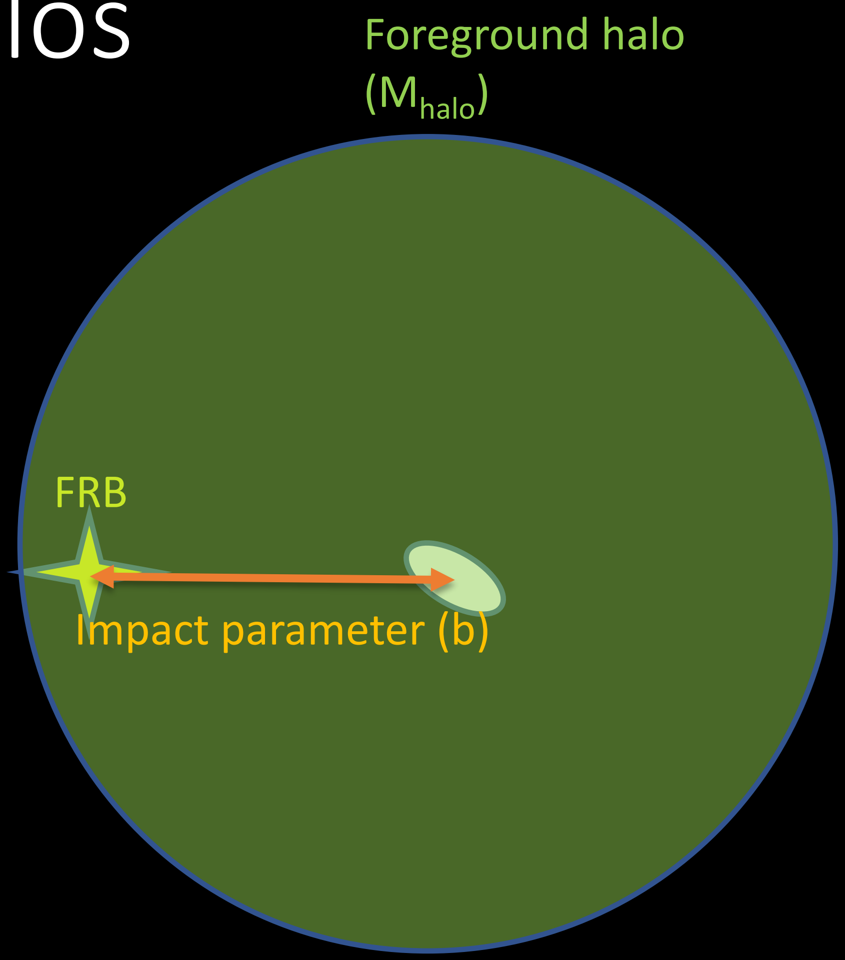
1. Estimate stellar mass from SED fitting (CIGALE).



DM estimation: Intervening Halos

1. Estimate stellar mass from SED fitting (CIGALE).

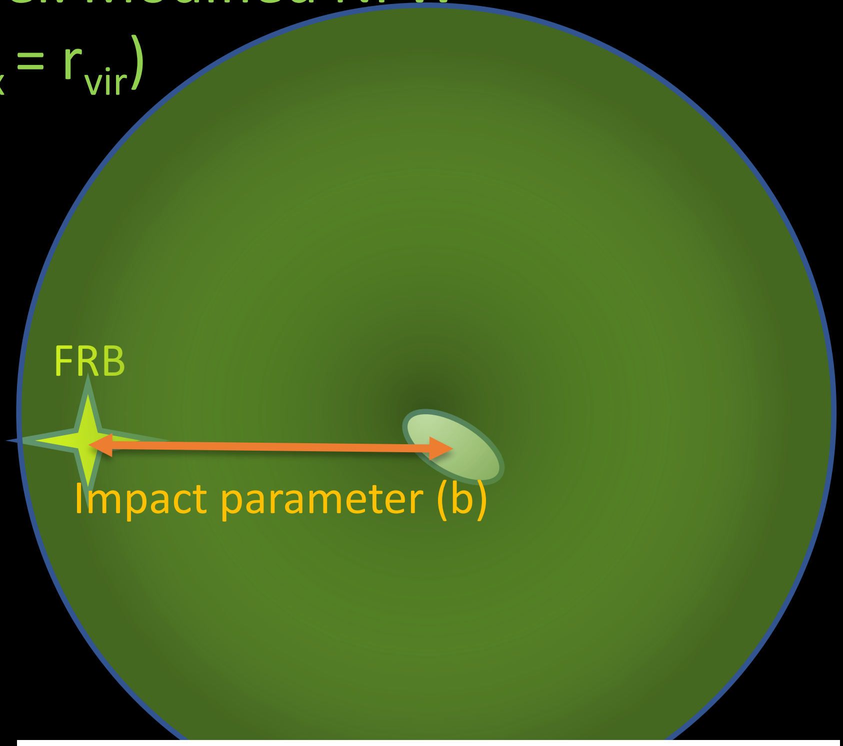
2. Estimate halo mass from the stellar mass using the stellar-to-halo-mass ratio (Moster et al 2013).



DM estimation: Intervening Halos

1. Estimate stellar mass from SED fitting (CIGALE).
2. Estimate halo mass from the stellar mass using the stellar-to-halo-mass ratio (Moster et al 2013).
3. Estimate DM_{halo} from a halo model of baryons (Prochaska and Zheng 2019).
4. Repeat for all foreground galaxies near the sightline.

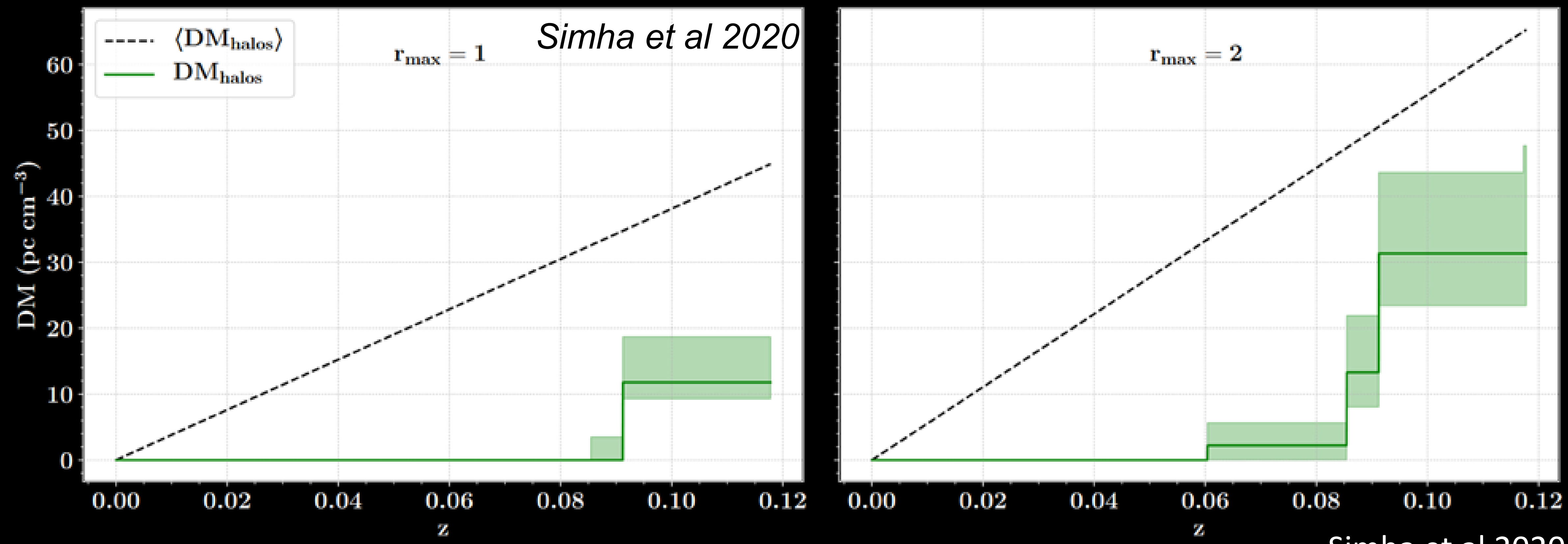
Halo gas model: Modified NFW
(f_{ion}= 0.75, r_{max} = r_{vir})



$$\rho_{\rm b} = \frac{\rho_{\rm b}^0}{y^{1-\alpha}(y_0 + y)^{2+\alpha}},$$

Foreground halos of FRB20190608A

Less than average contribution from intervening halos ($7 - 28\ \mathrm{pc\ cm^{-3}}$).

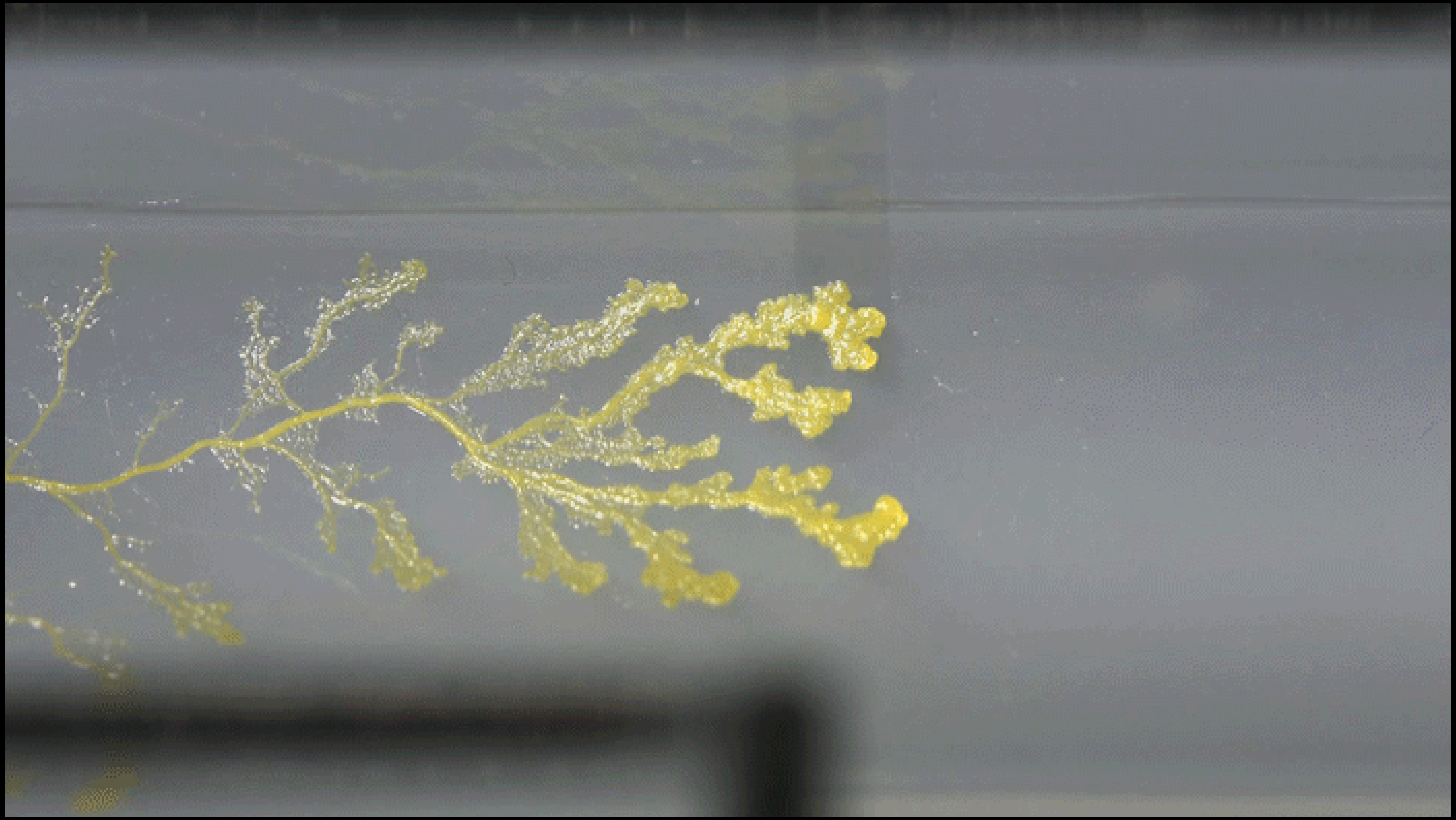


Simha et al 2020

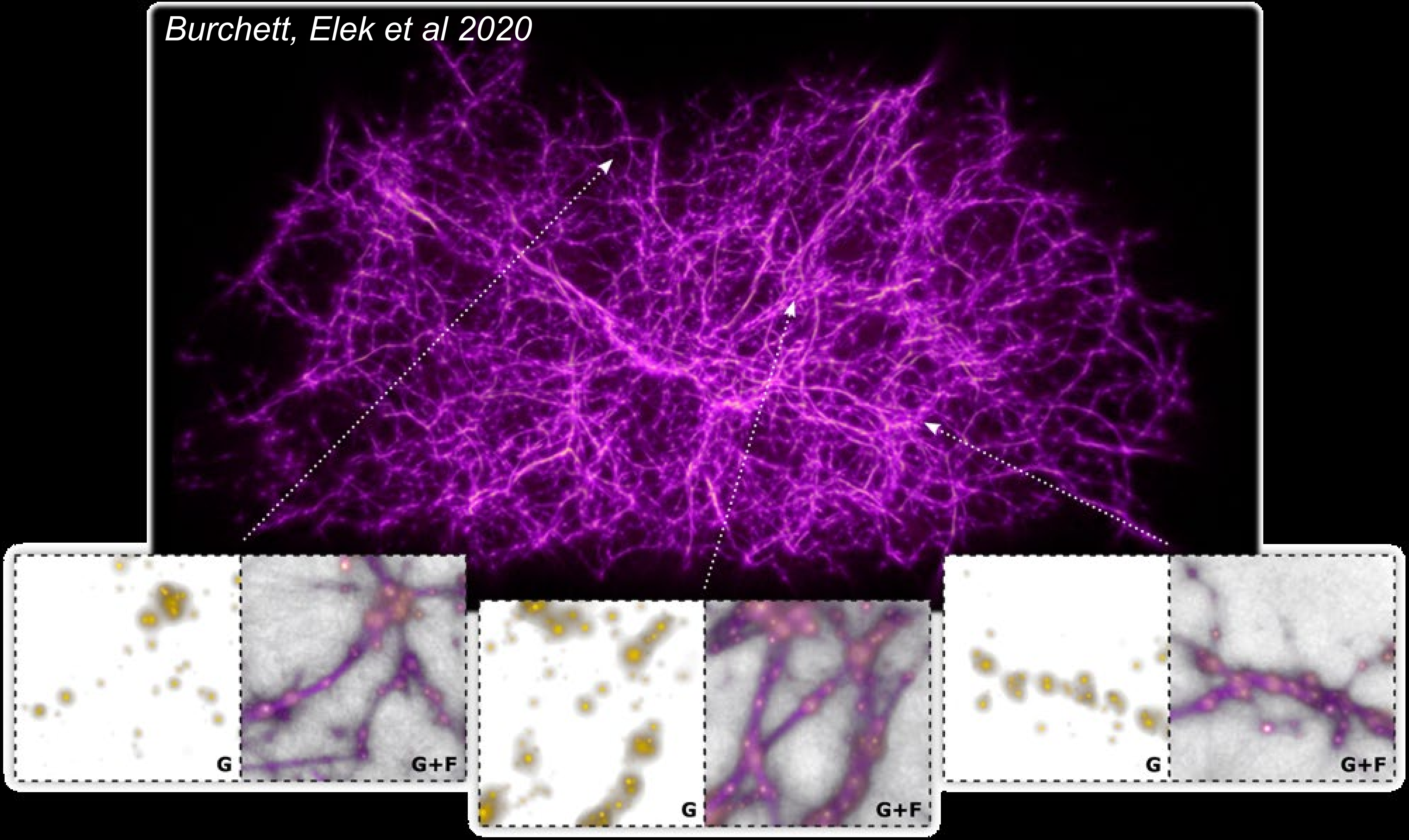
DM estimation: Diffuse IGM

A solution from an unlikely source:

Slime-mold-inspired estimator of IGM gas density.

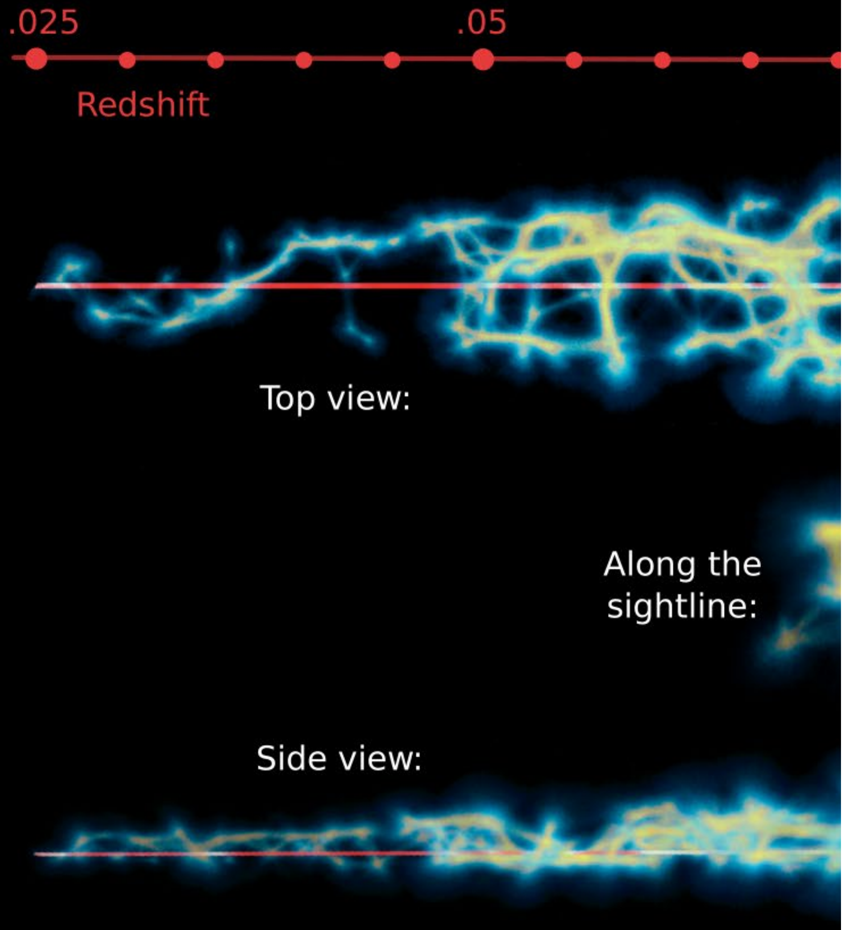


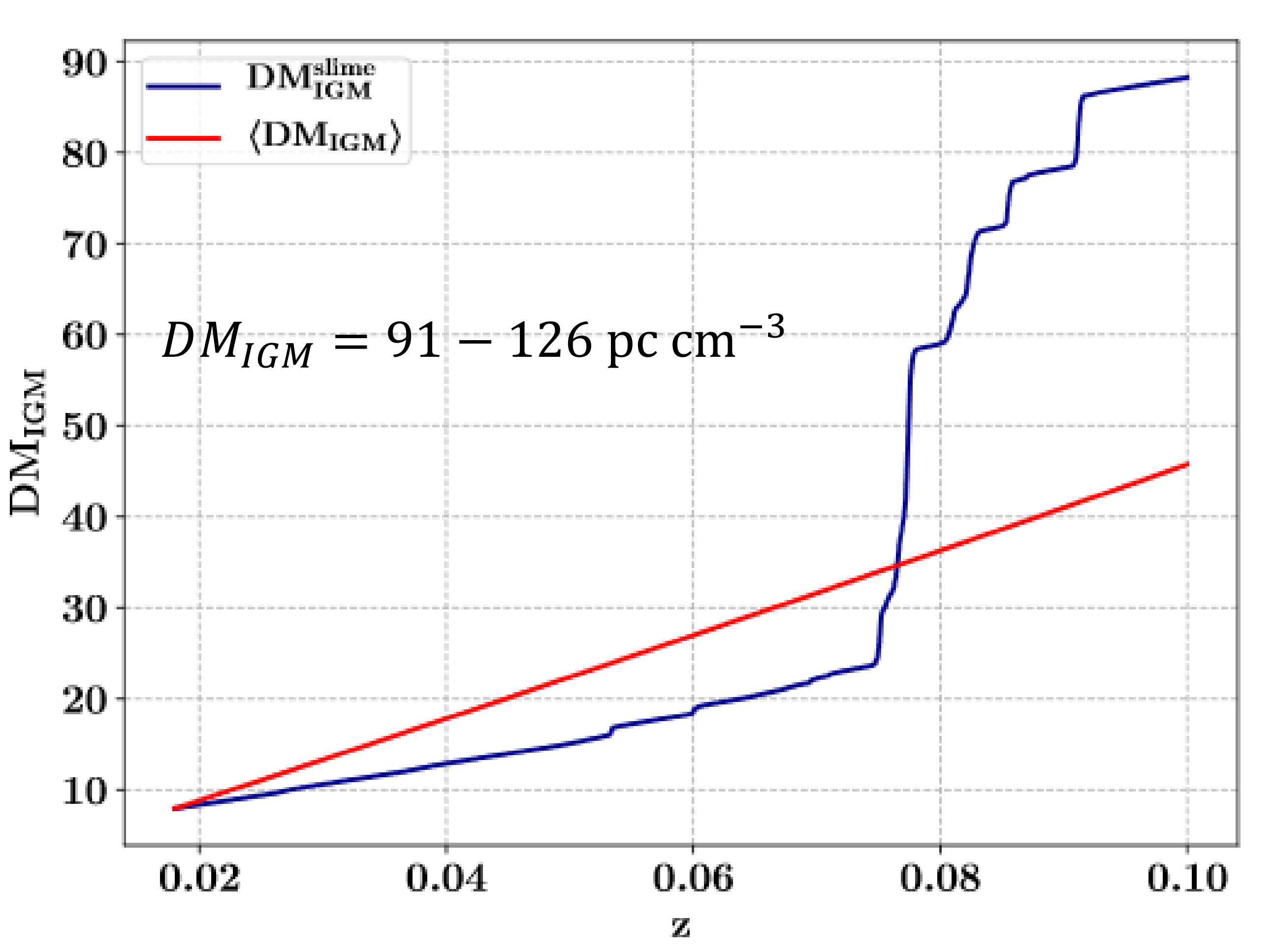
Monte Carlo Physarum Machine



DM estimation: Diffuse IGM

Simha et al 2020

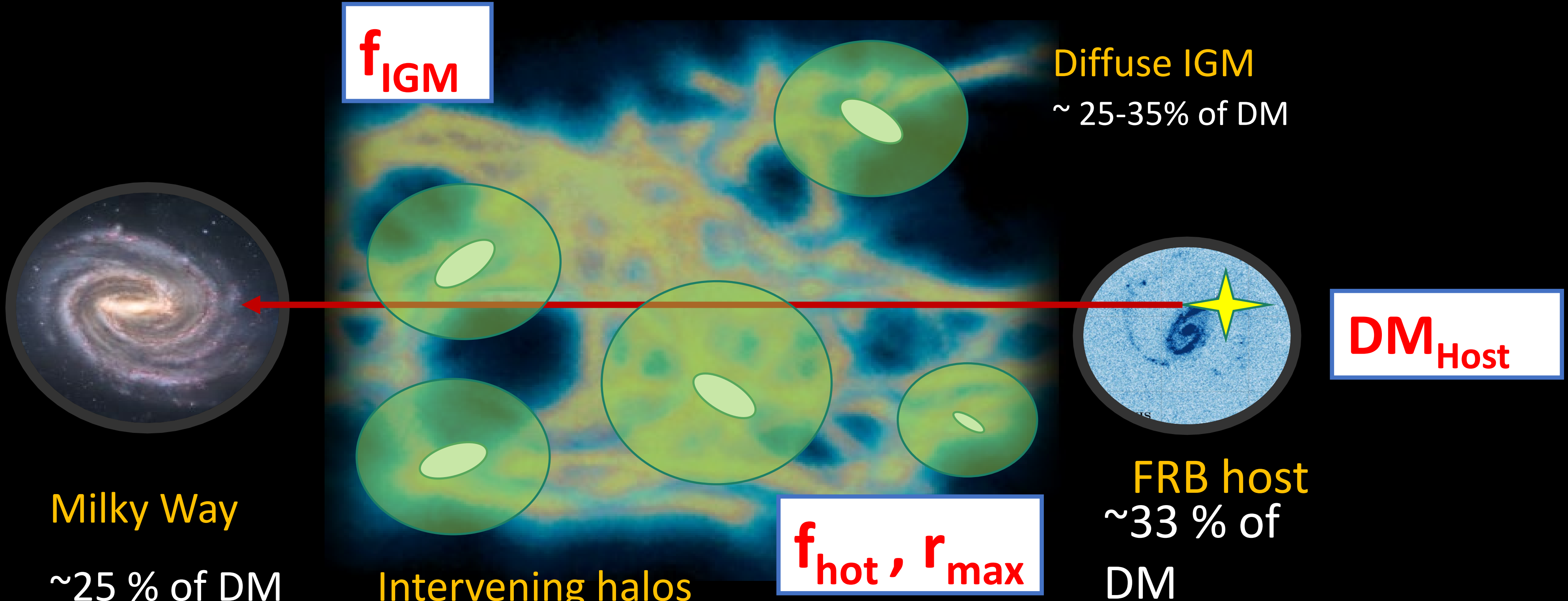




$$DM_{IGM} = 91 - 126 \text{ pc cm}^{-3}$$

FRB 190608: An end-to-end study

Unconstrained model parameters.

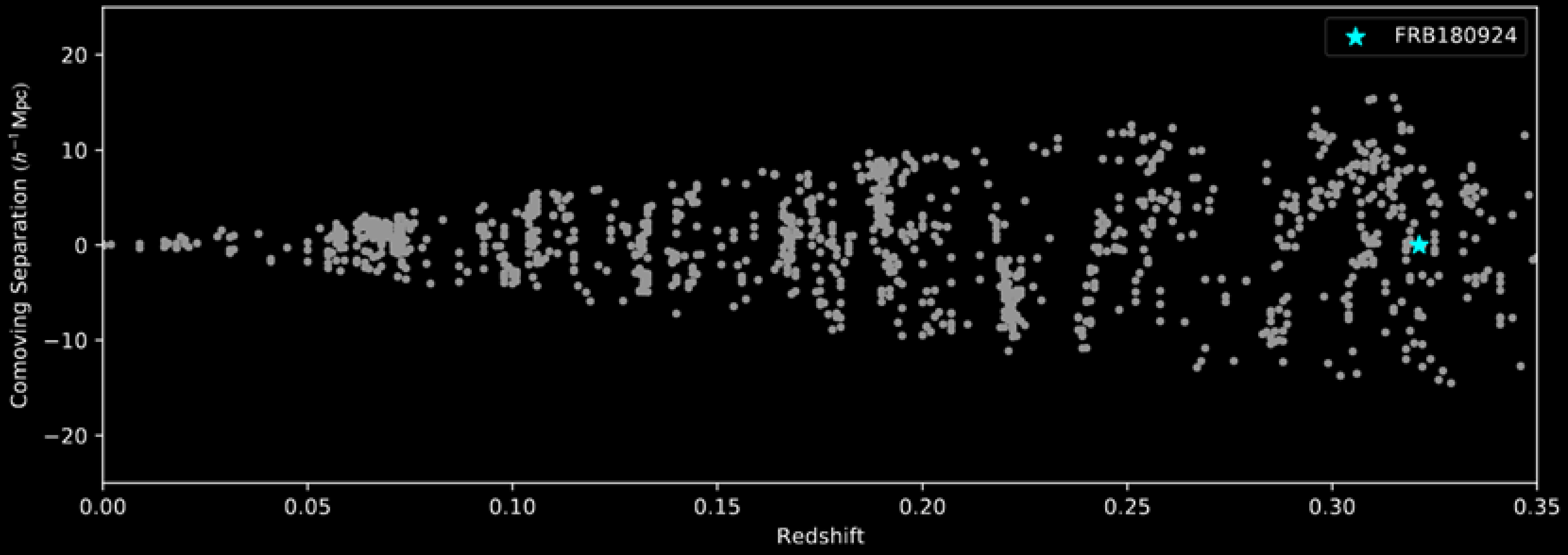


Simha et al 2020

Foreground mapping can determine where the missing baryons are!

The FLIMFLAM Survey

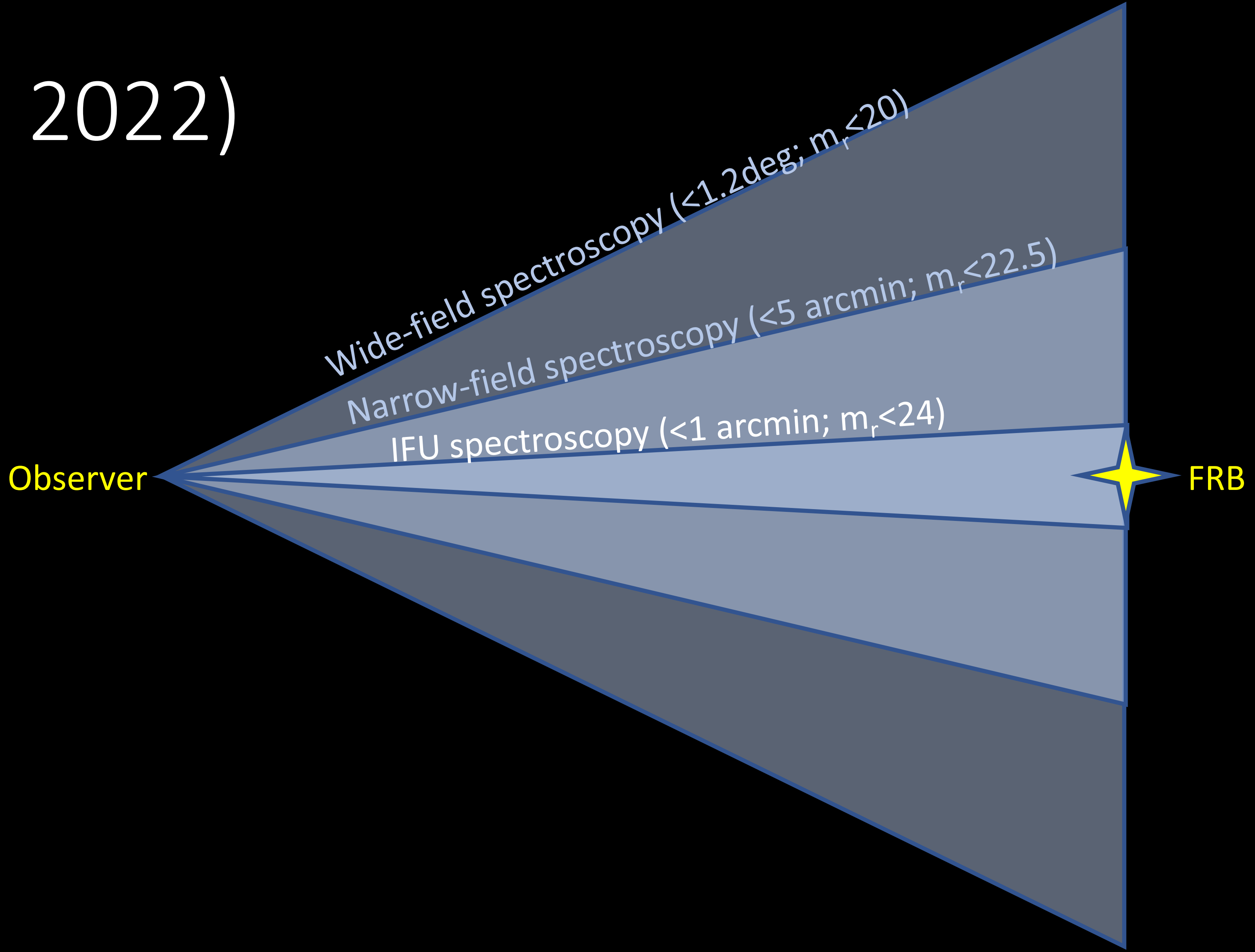
- FRB
- Line-of-Sight
- Ionization
- Measurement
- From
- Light-cone
- AAOmega
- Mapping



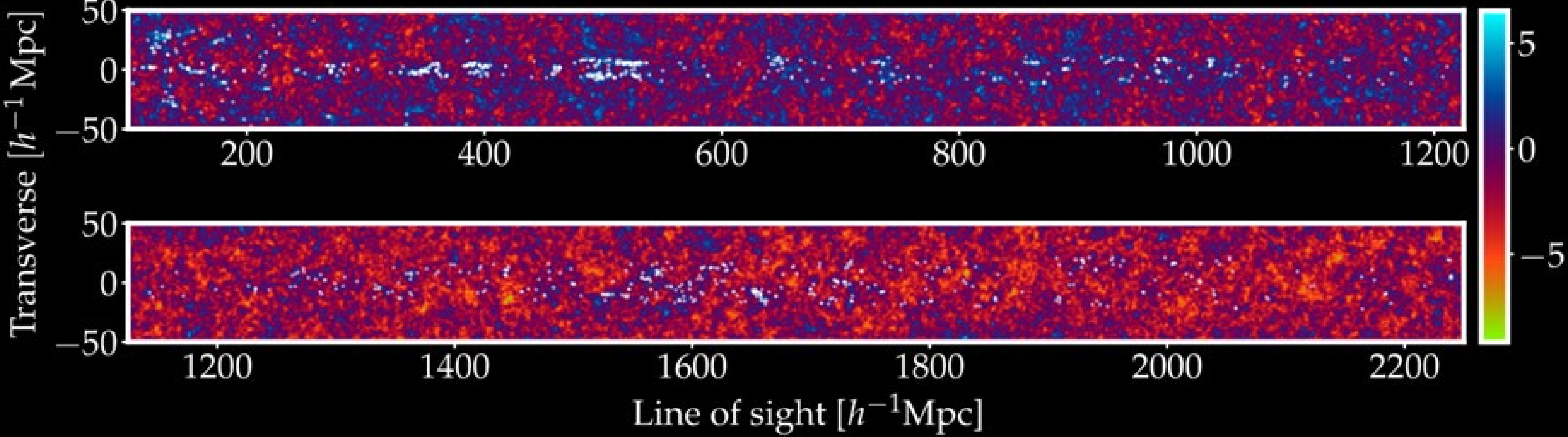
Lee et al. 2022

The FLIMFLAM survey (Lee et al. 2022)

- Ongoing spectroscopic survey of ~30 FRB sightlines for foreground galaxy redshifts.
- Aim to constrain the fraction of baryons in diffuse IGM to ~10% precision.



Density field reconstruction with ARGO



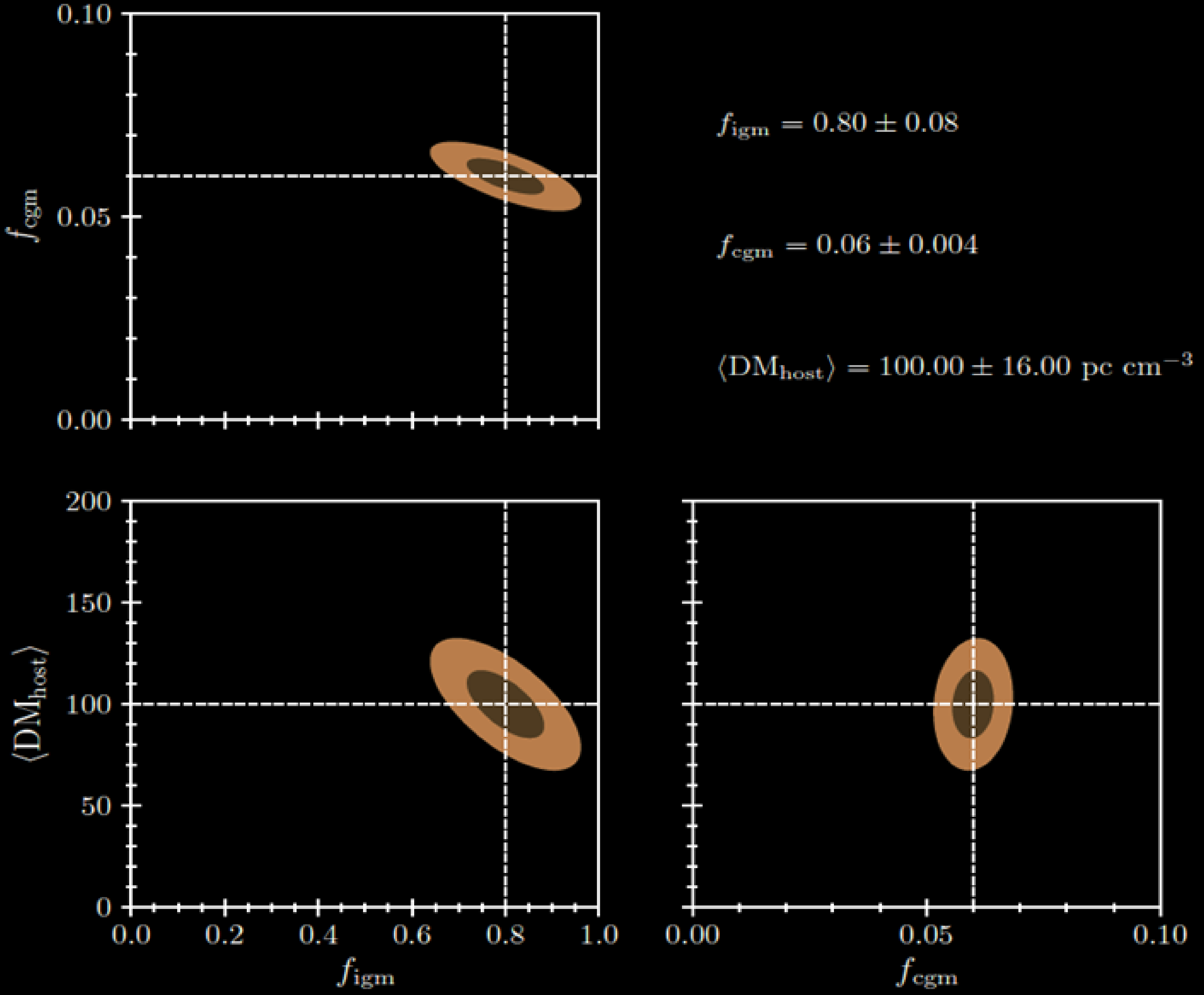
Bayesian inference of the matter density given the galaxy halo masses and locations.

Ata et al 2015, 2017; Lee et al 2021

Fisher matrix predictions for model parameters

Based on mock sightlines from the semi-anlytical lightcone catlogs of Henriques et al (2015) associated with the Millenium cosmological simulations.

Lee et al 2022

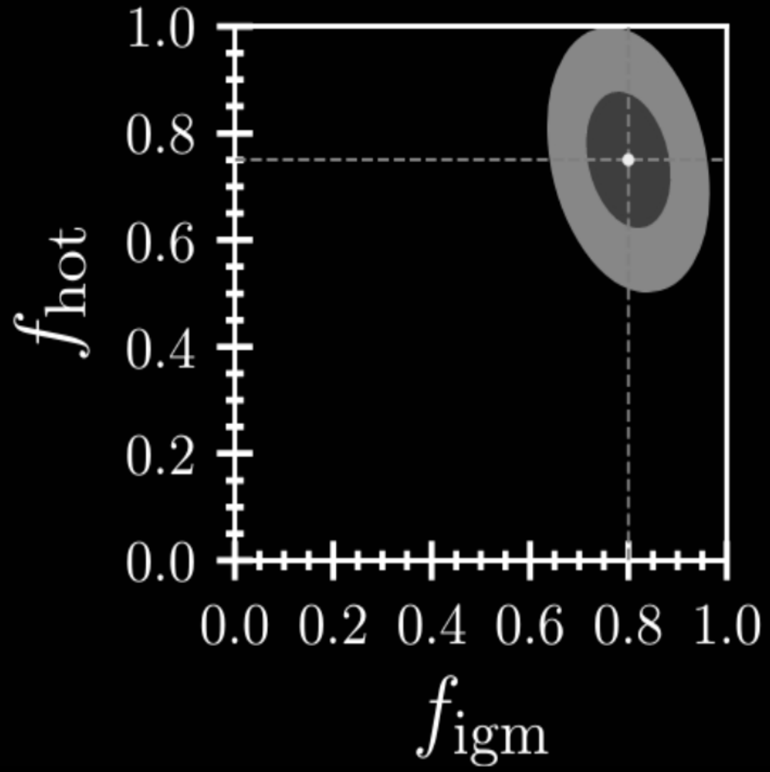


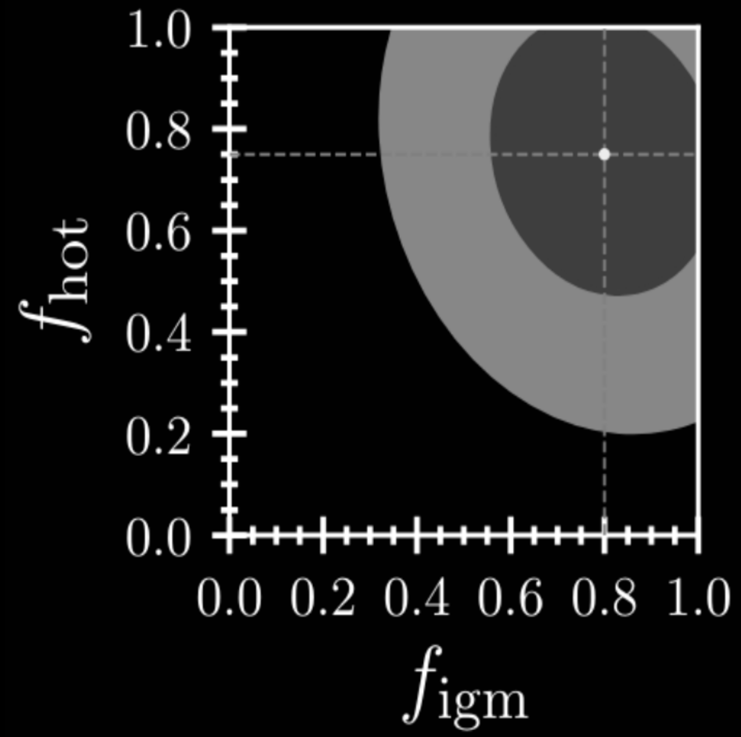
Fisher matrix predictions for model parameters

Foreground mapping is essential for tighter constraints on model parameters with fewer sightlines.

Large-scale density field reconstructions with AAOmega redshifts.

Narrow-field spectroscopy is key in determining foreground halo contributions to FRB DMs.



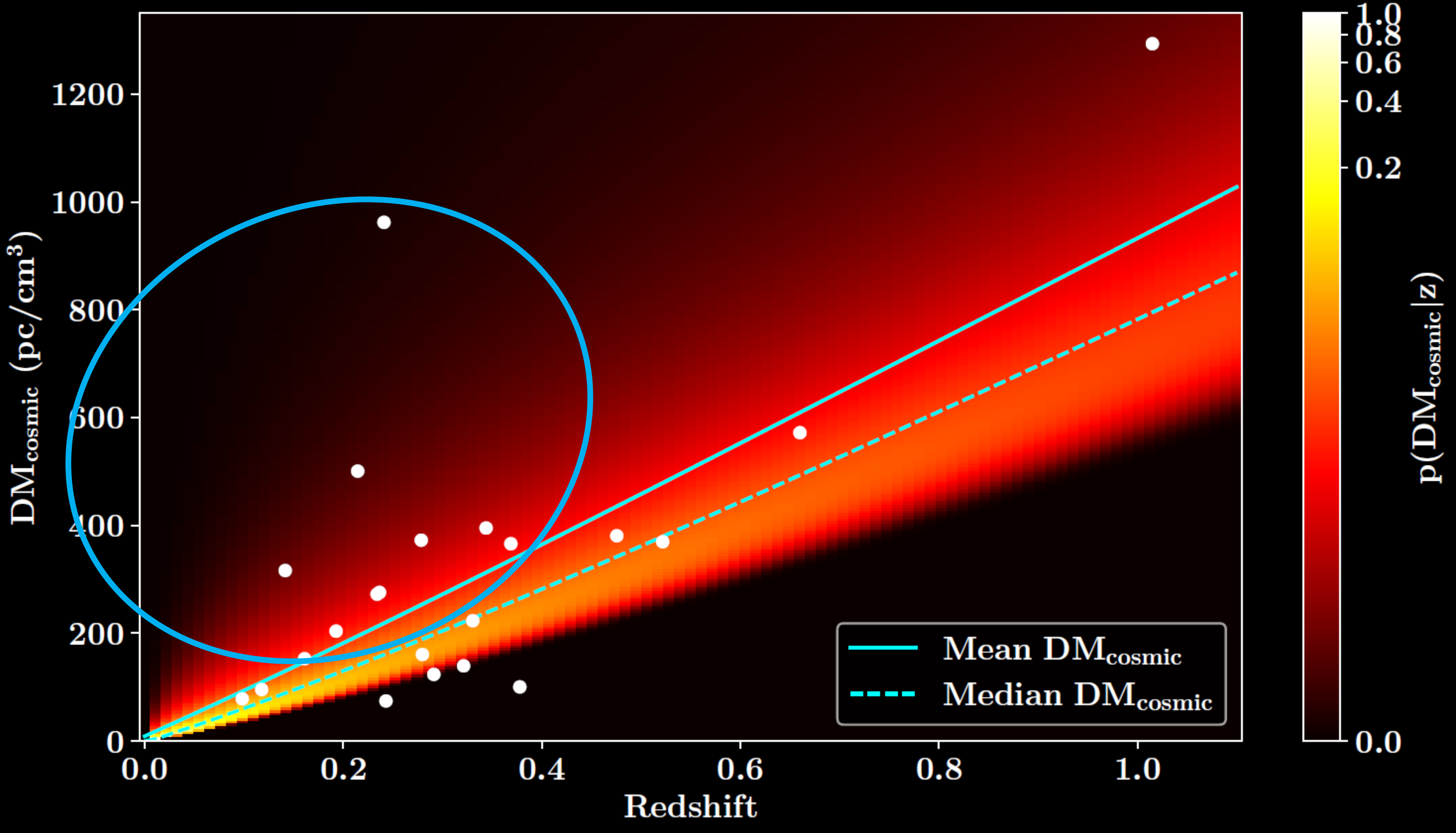


Lee et al 2022

Early results: Excess extragalactic DM

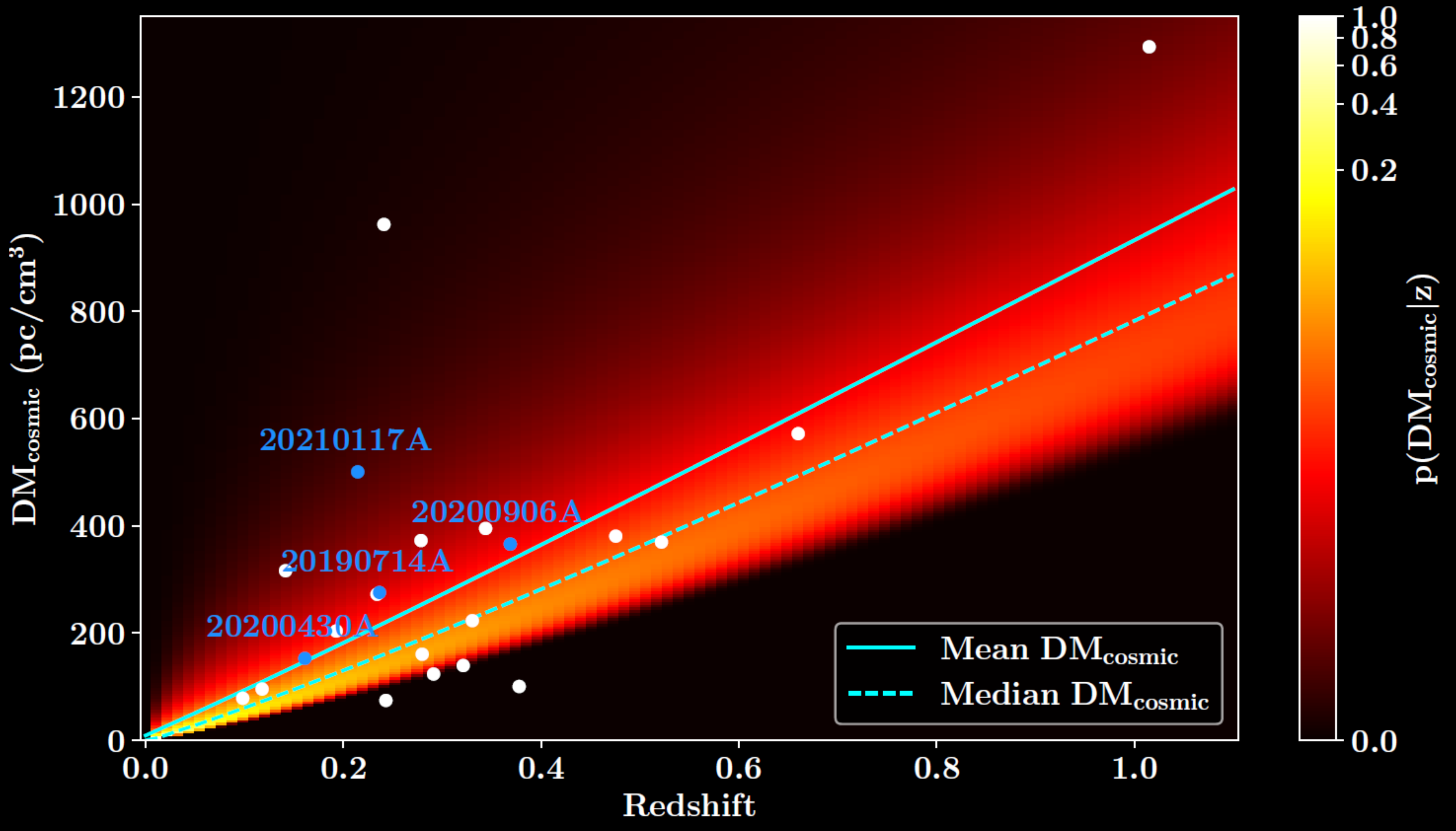
The Macquart Relation

$DM_{cosmic} = DM_{FRB} - DM_{MW} - DM_{Host}$



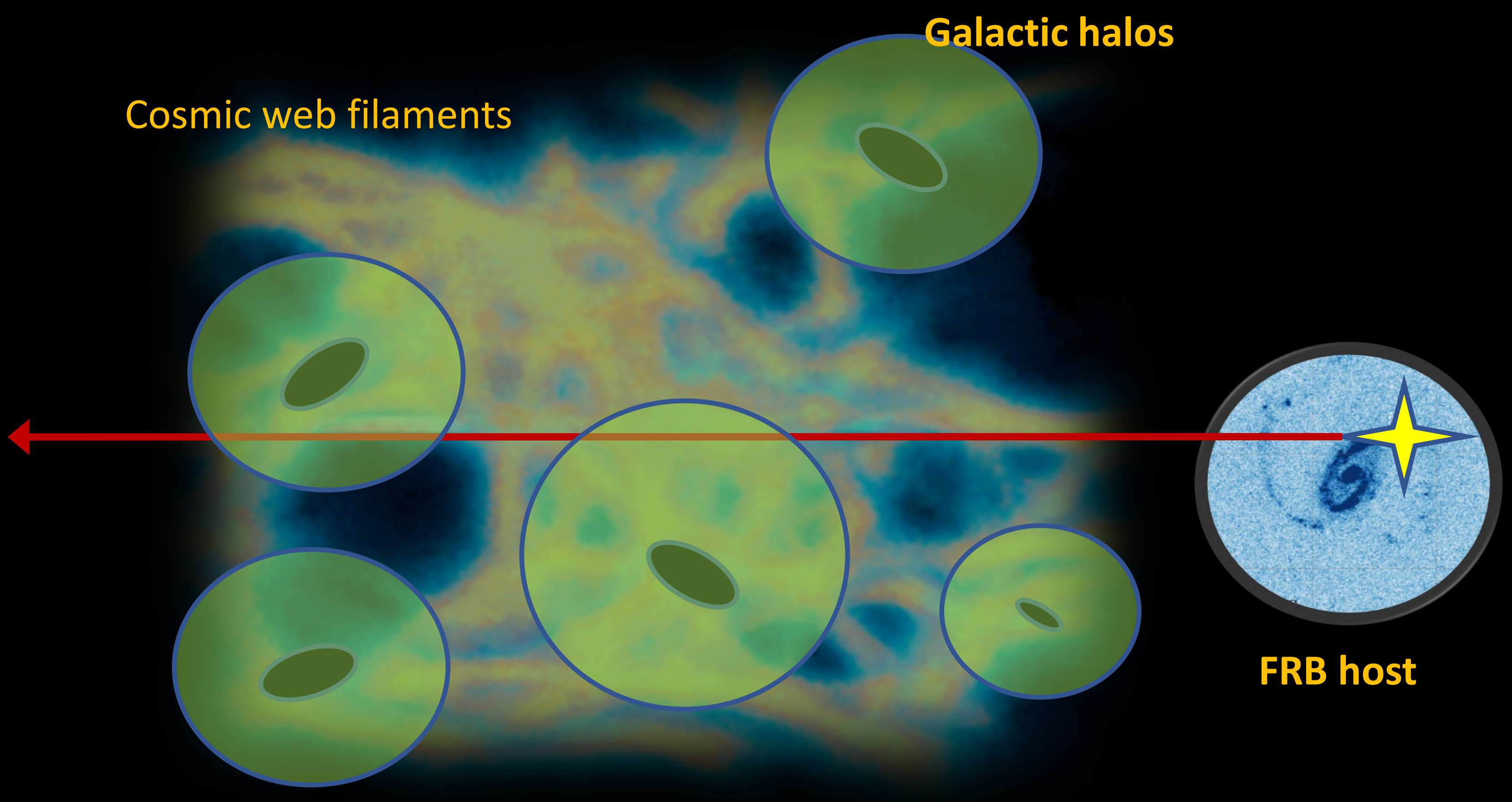
Four excess DM sightlines observed

- Wide-field AAOmega fiber observations (m_r<20).
- DEIMOS/LRIS slitmask observations. (m_r<22.5).
- MUSE observation for FRB190714.



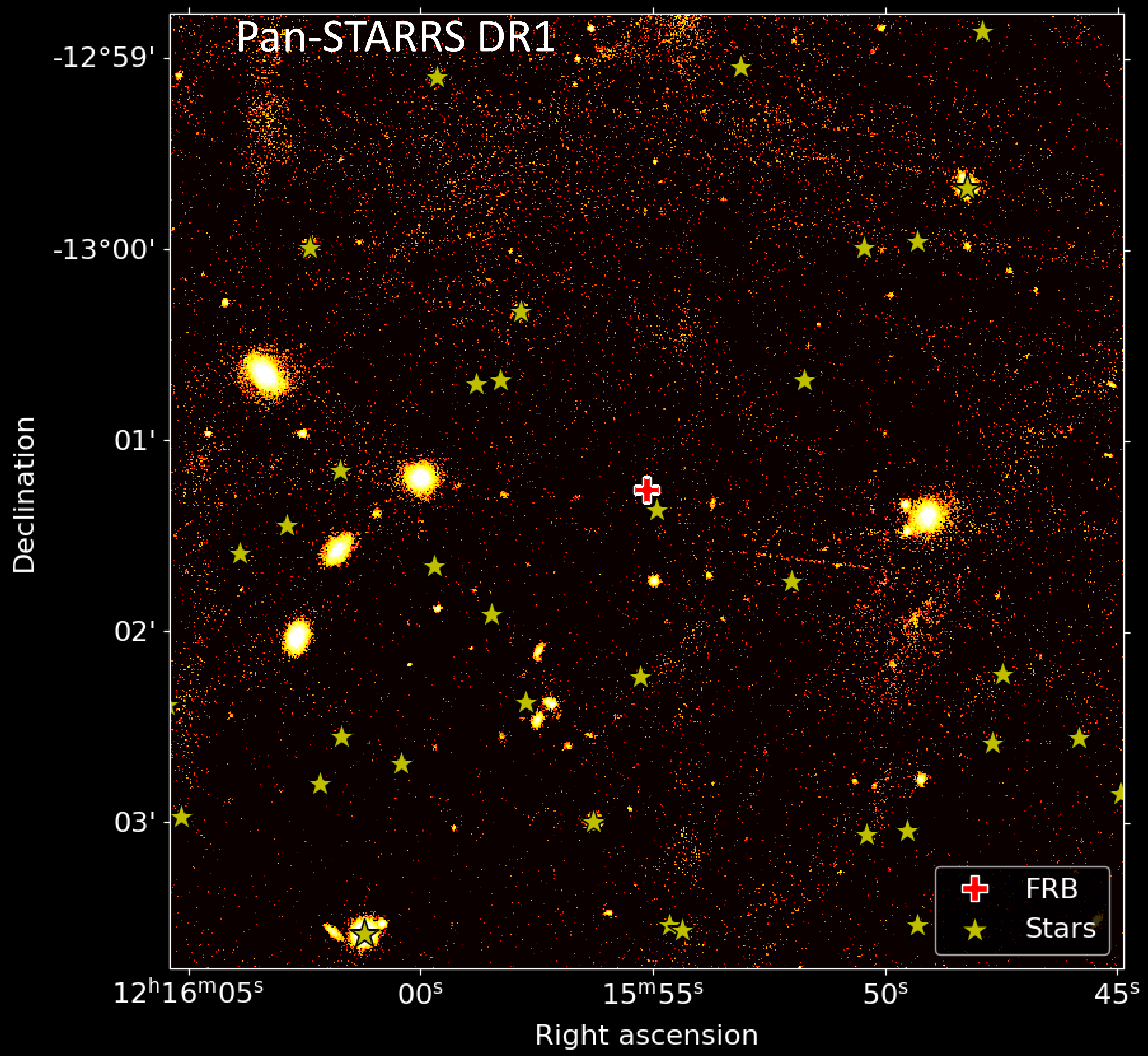
Plausible sources of the excess?

- Large number of intervening foreground halos.
- Galaxy groups?
- Larger host/progenitor environment contribution.
- Excessive IGM contribution? Likely not.



FRB20190714A

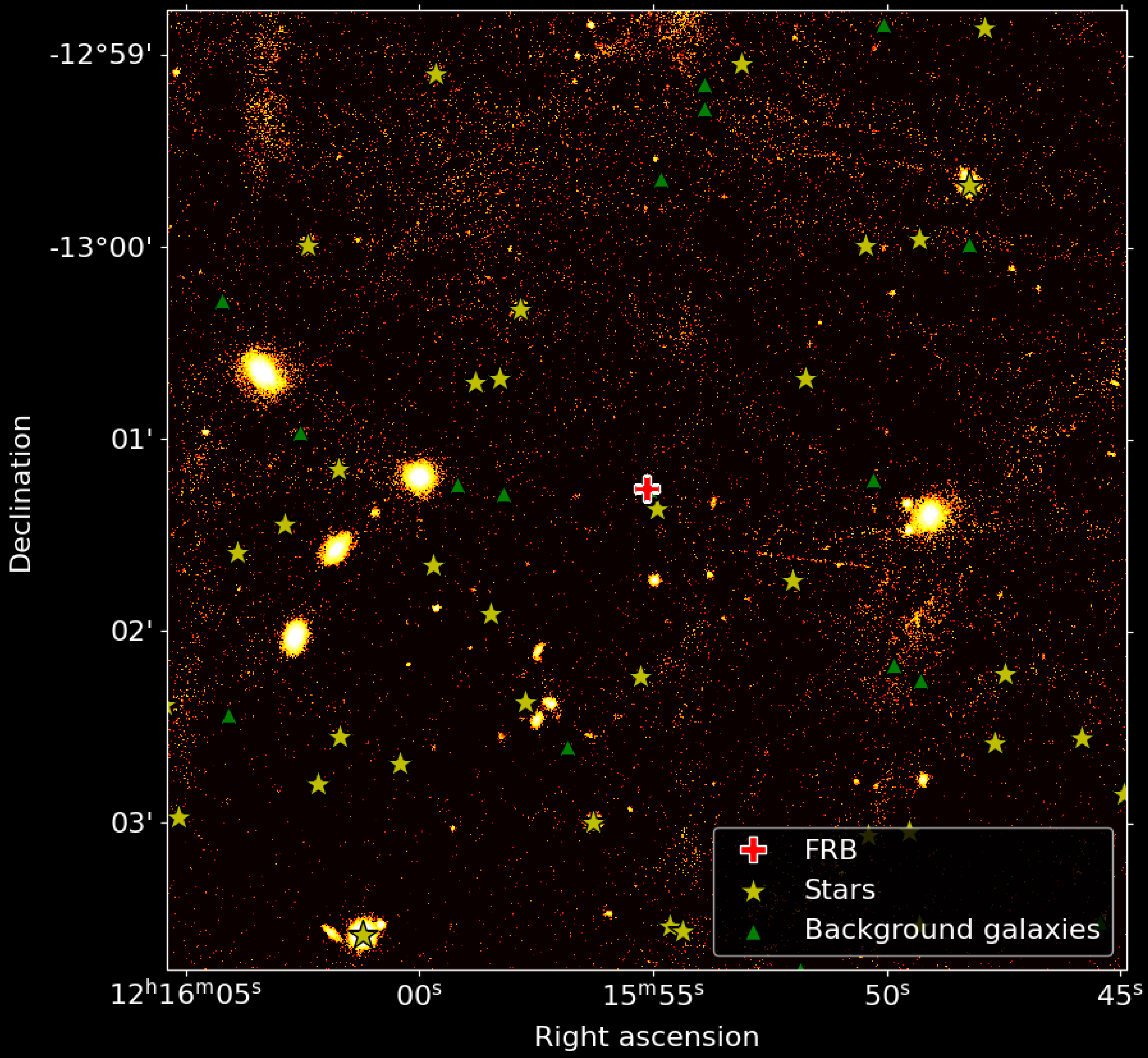
1. Start with imaging data and exclude stars.



FRB20190714A

1. Start with imaging data and exclude stars.

2. Identify background galaxies.

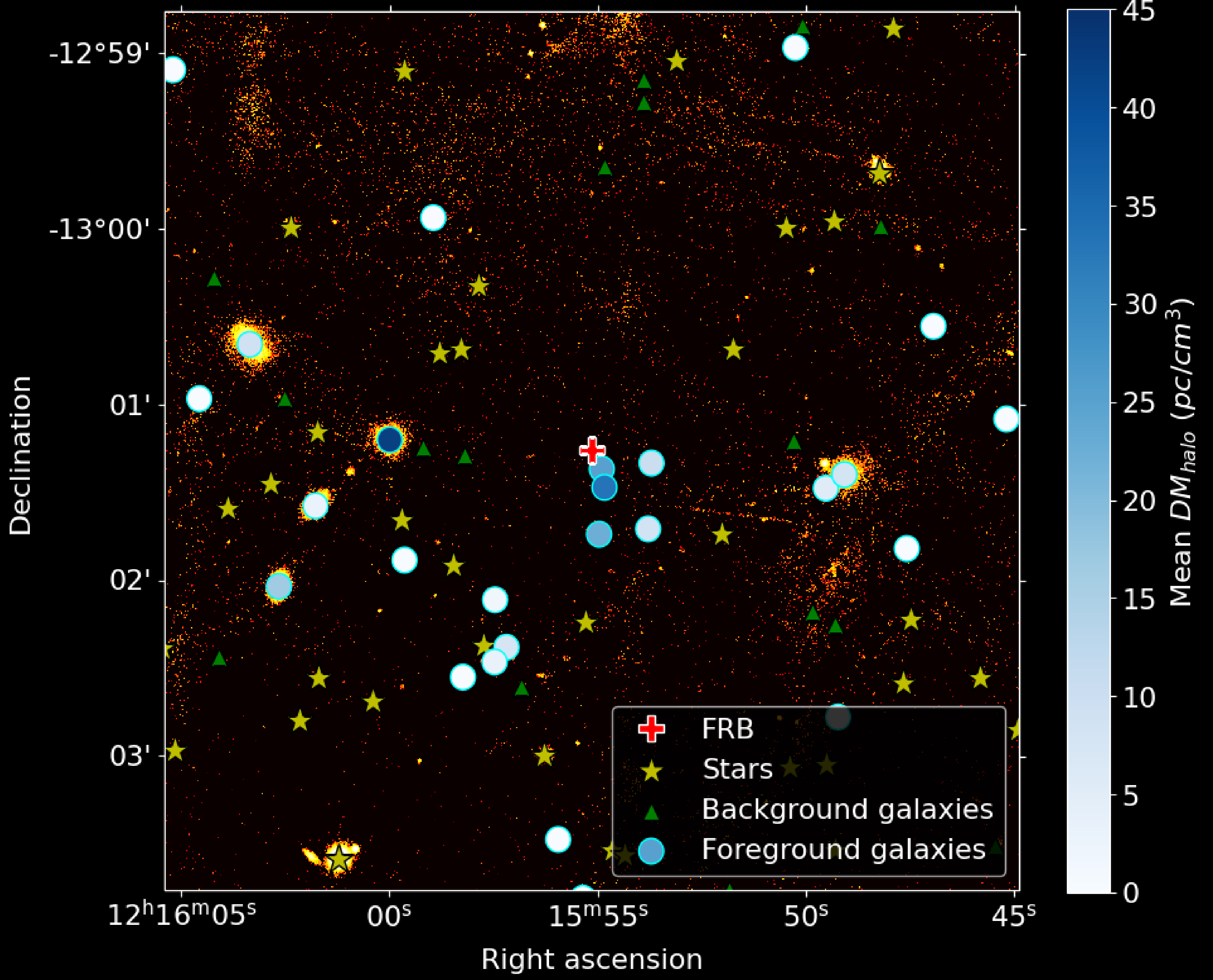


FRB20190714A

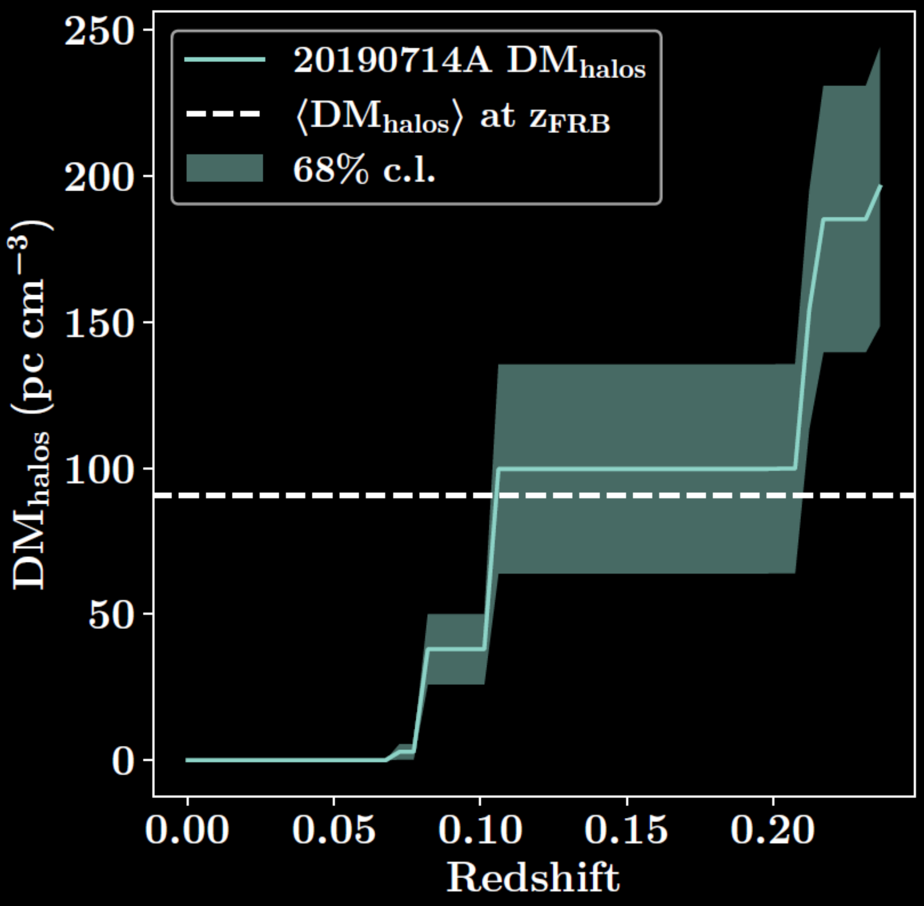
1. Start with imaging data and exclude stars.

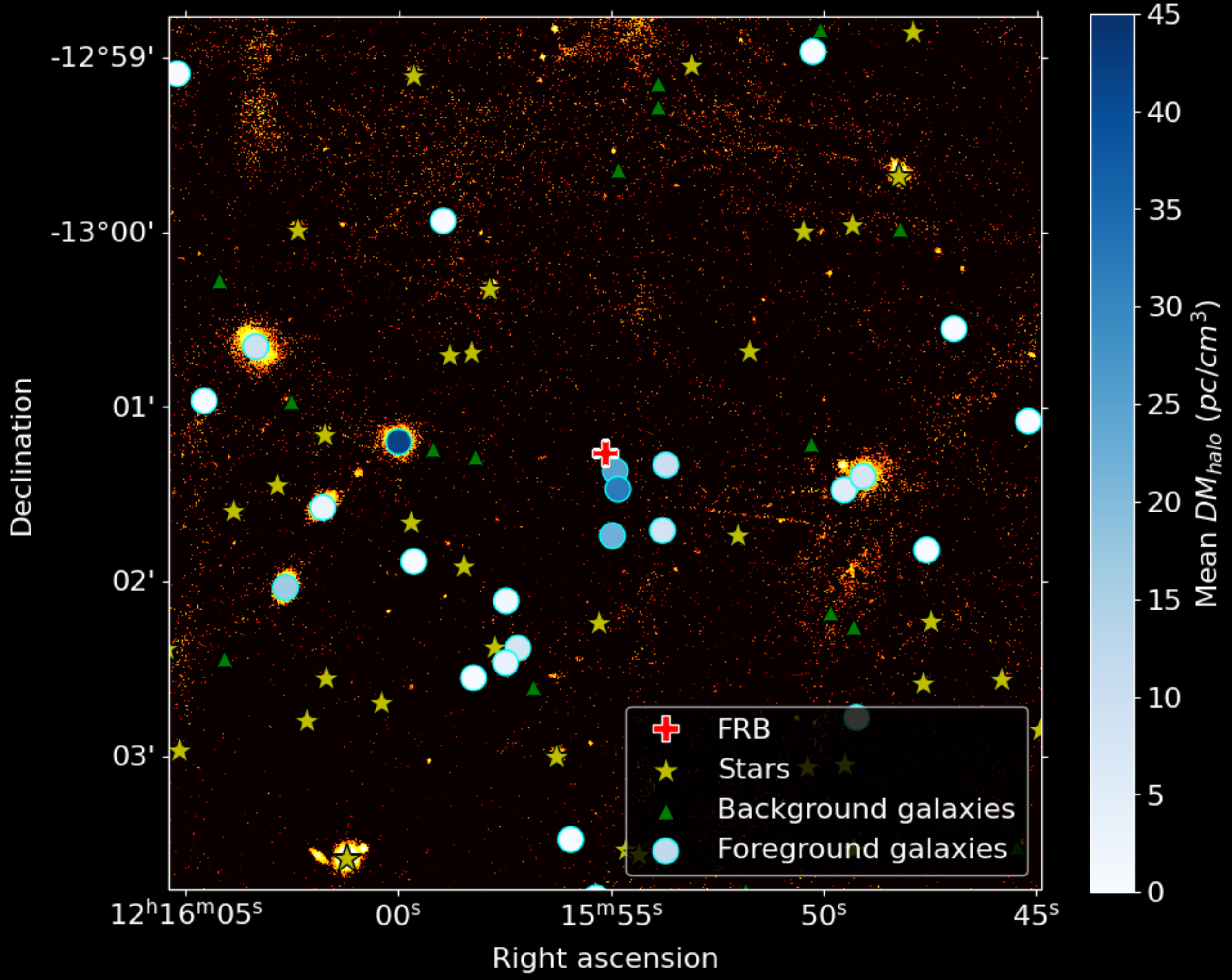
2. Identify background galaxies.

3. Identify foreground galaxies and their DM_{halo}.



FRB20190714A

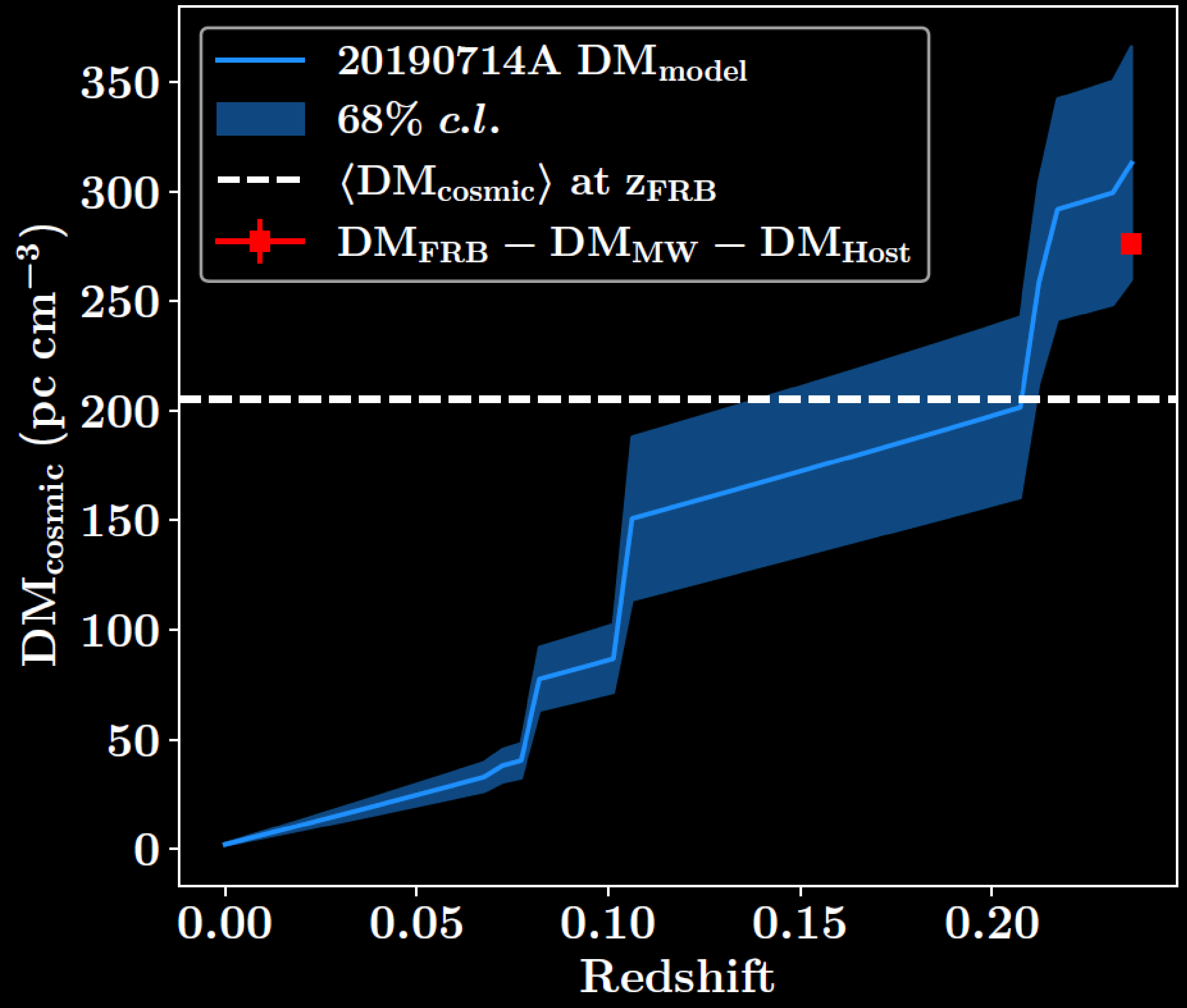




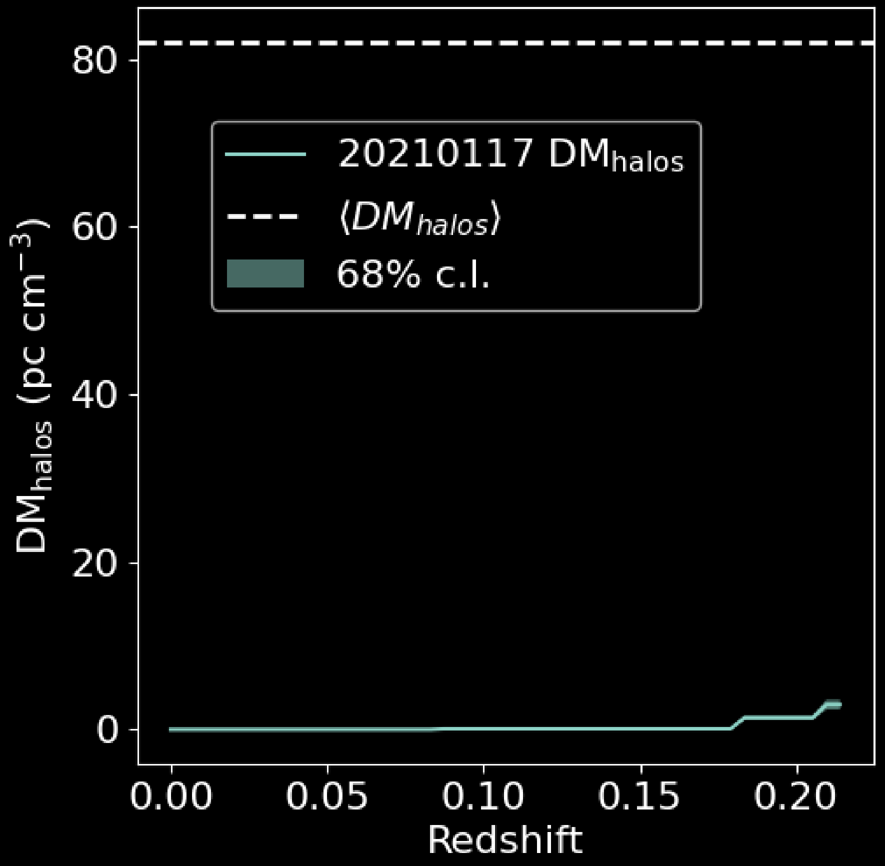
Significant portion of the excess from DM_{halo} contribution.

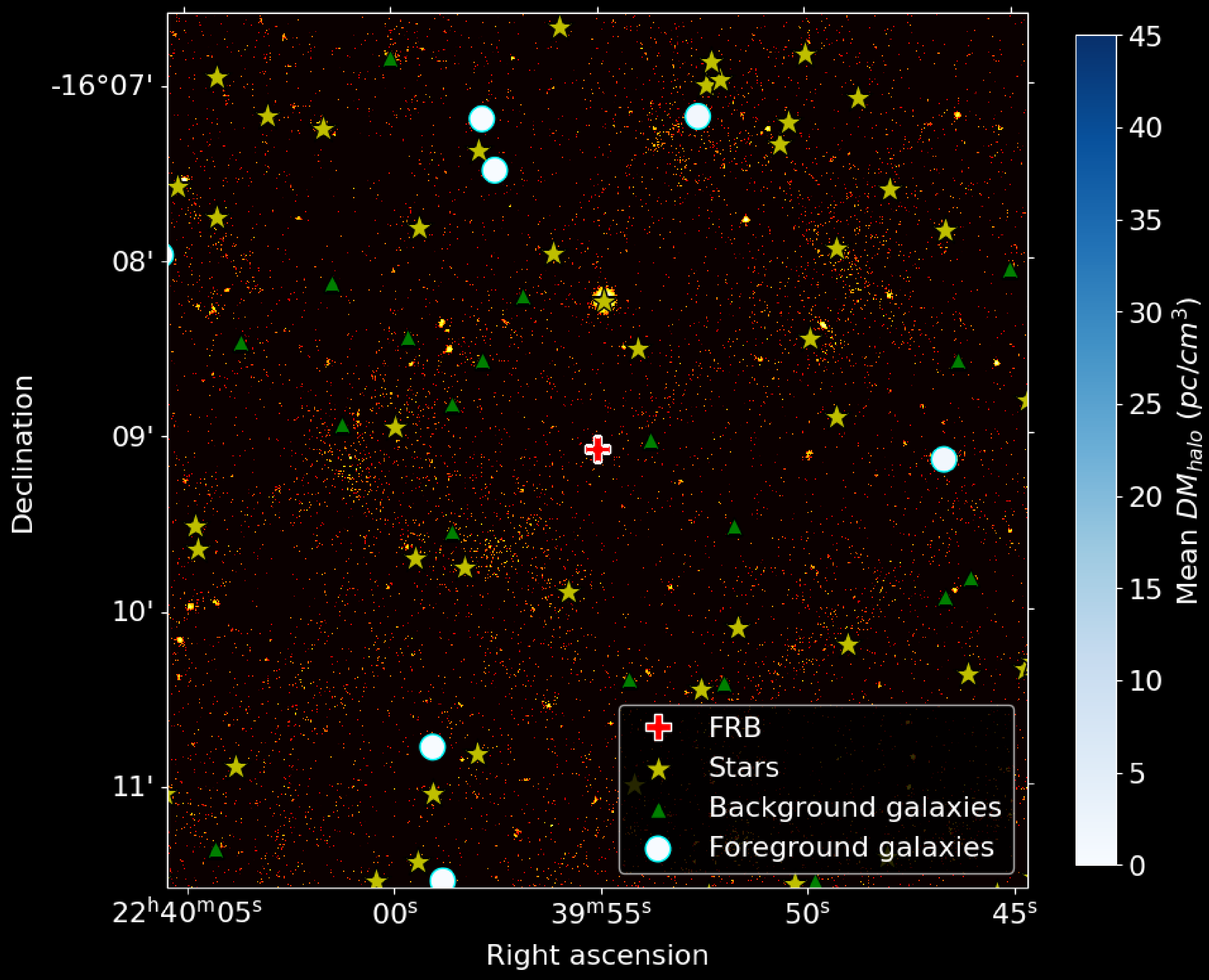
FRB20190714A

- Even with an average IGM sightline, the excess DM can be fully accounted for.
- Therefore, it is likely that DM_{host} is not much more than 80 pc/cm³.



FRB20210117A

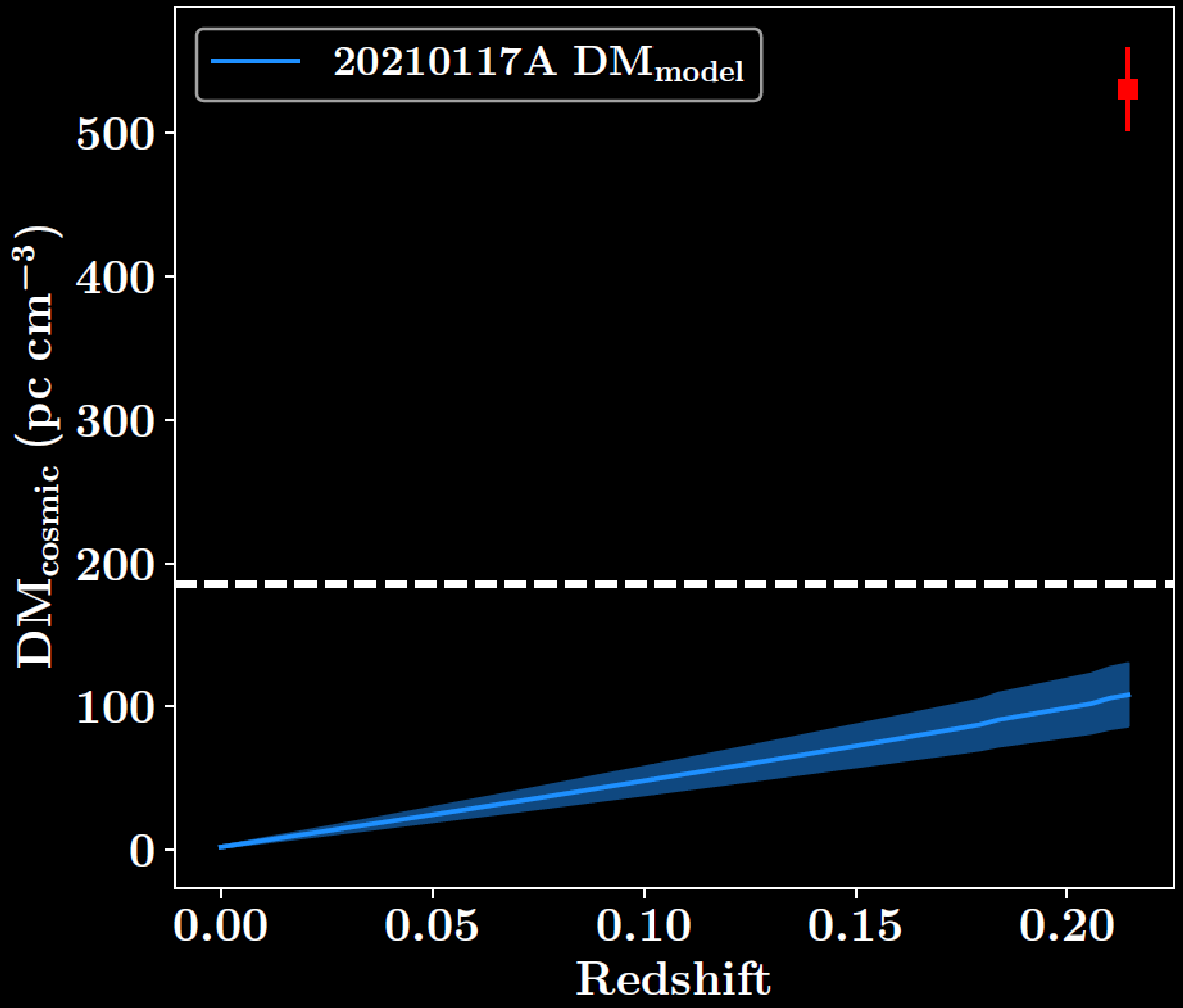




Virtually negligible DM_{halo} contribution!

FRB20210117A

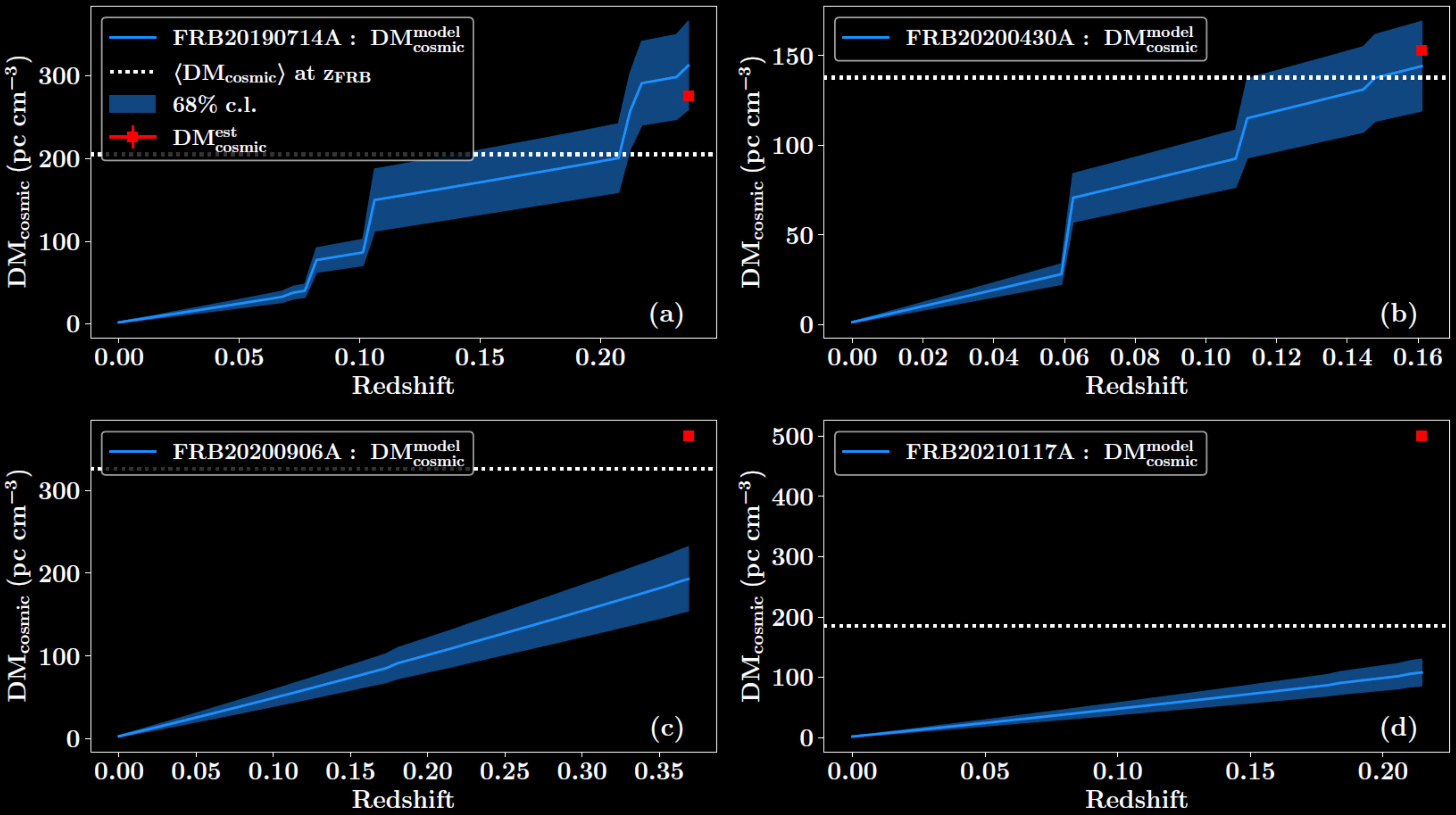
- Even increasing halo gas extent to $2r_{vir}$ and assuming the IGM contribution is 20% above average is insufficient to explain the excess.
- Majority of the excess must therefore come from the host!



Galaxy group contributions:

Group finder algorithm applied to our spectroscopic sample: Anisotropic Friends-of-Friends (Tempel et al 2014). Only the FRB20190714A field has a sufficiently close group that can contribute ~50 pc cm^{-3} but only if halo model is extended to $2r_{vir}$.

Excess DM analysis results



Summary

- Foreground spectroscopic mapping of FRB sightlines can yield constraints on matter distribution in the universe.
- The FLIMFLAM survey aims to measure, among other parameters, the baryon fraction in the diffuse IGM to ~10% precision with ~30 FRB sightlines.
- Early analysis of data from 4 FRB sightlines has revealed the source of their excess extragalactic DM:
  - FRB20190714A and FRB20200430A likely have most of the excess coming from foreground galaxies.
  - FRB200906A and FRB20210117A likely has a majority of its excess from the host/progenitor environment.
  - Equally likely foreground and host contributions in excess DM sightlines.
- Work in progress:
  - Collecting more data: narrow-field spectra and IFU observations.
  - Identifying galaxy groups and their DM contribution.
  - IGM reconstruction from AAOmega redshifts.

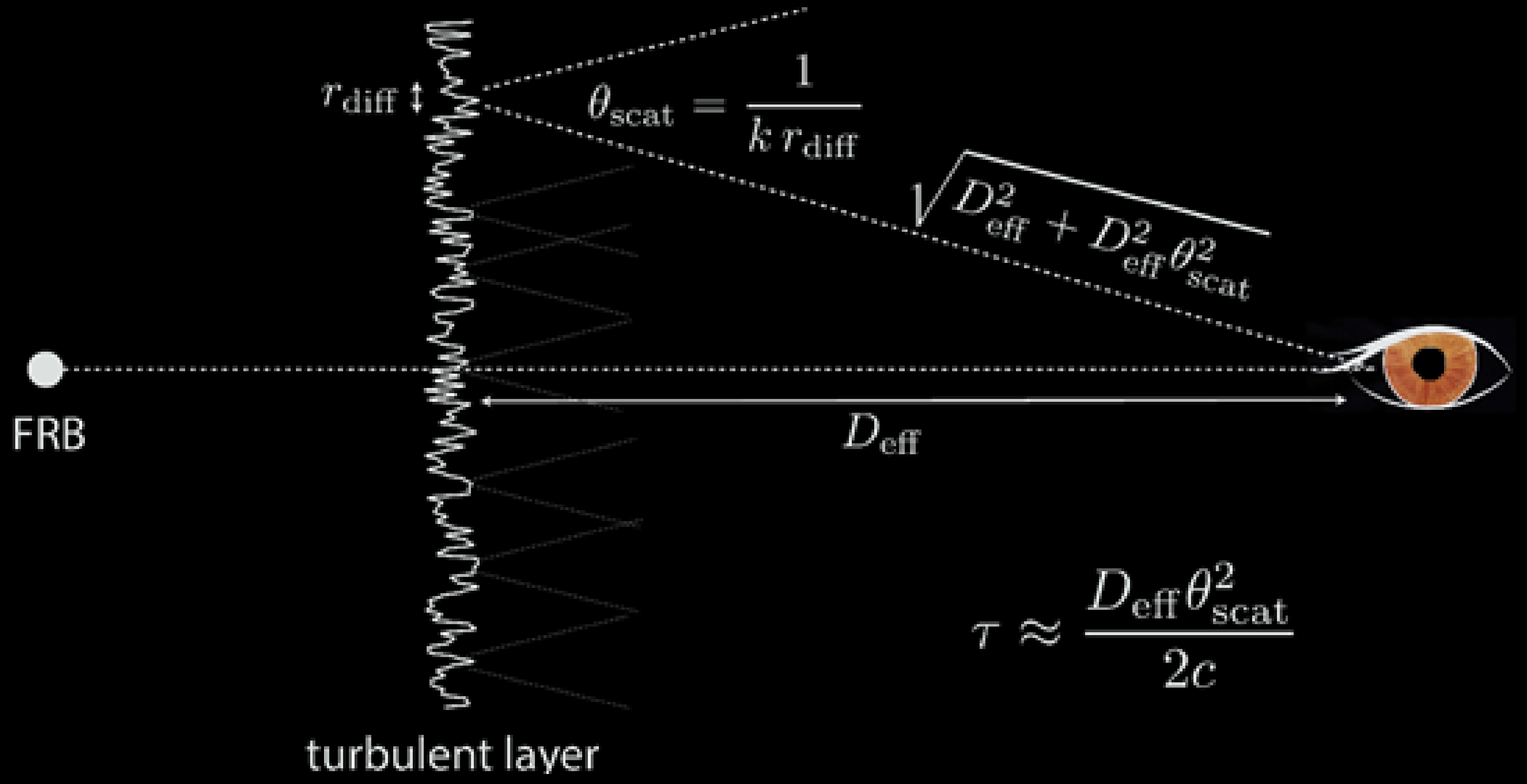
Additional slides

Burst Properties: Pulse width

Scattering from turbulent plasma broadens a pulse.

$$\tau \approx \frac{D_{eff}\theta_{scat}^2}{2c}$$

Like gravitational lensing, the effect is maximized when the screen is halfway between the observer and the source.

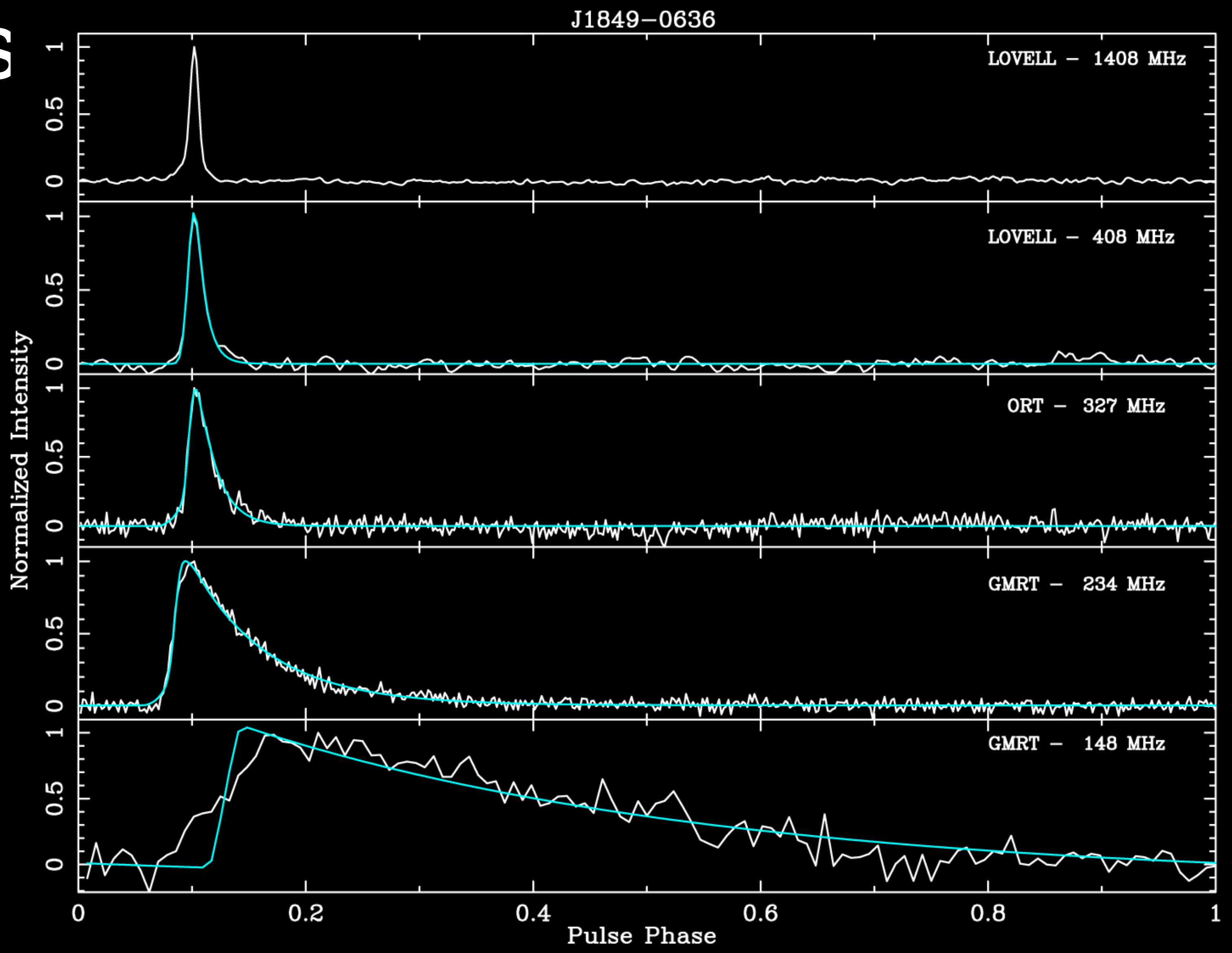


Burst Properties
Pulse width

Pulse broadening is frequency dependent.

$$\tau \propto \theta_{scat}^2 \propto \nu^{-4\ to\ -4.4}$$

for Kolmogorov turbulence.



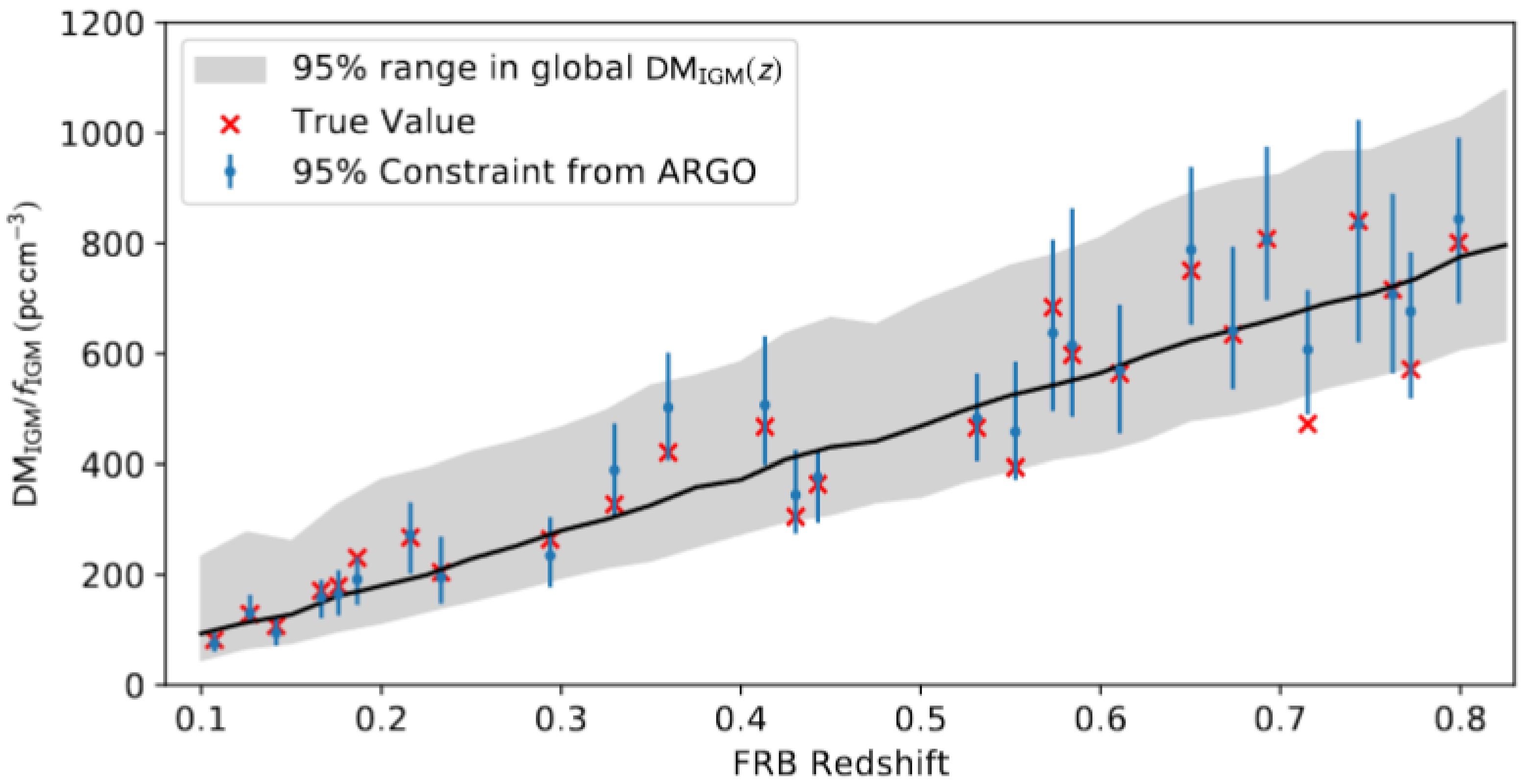


Figure 9. Solid line and gray regions show the mean and central 95% range of the the global DM_{igm} distribution within the Millennium simulation as a function of redshift, assuming $f_{igm} = 1$. Red crosses show the DM_{igm} toward randomly-selected sightlines within the H15 lightcone catalogs, the blue error bars show the DM_{igm} constraint from the `ARGO` matter density reconstructions of the same catalogs.