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Lee, Ata, Khrykin+2021 (arXiv: 2109.00386)

Constraining the Cosmic Baryon Distribution with FRB foreground Maps

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YITP Workshop: Fast Radio Bursts and Cosmic Transients 2022

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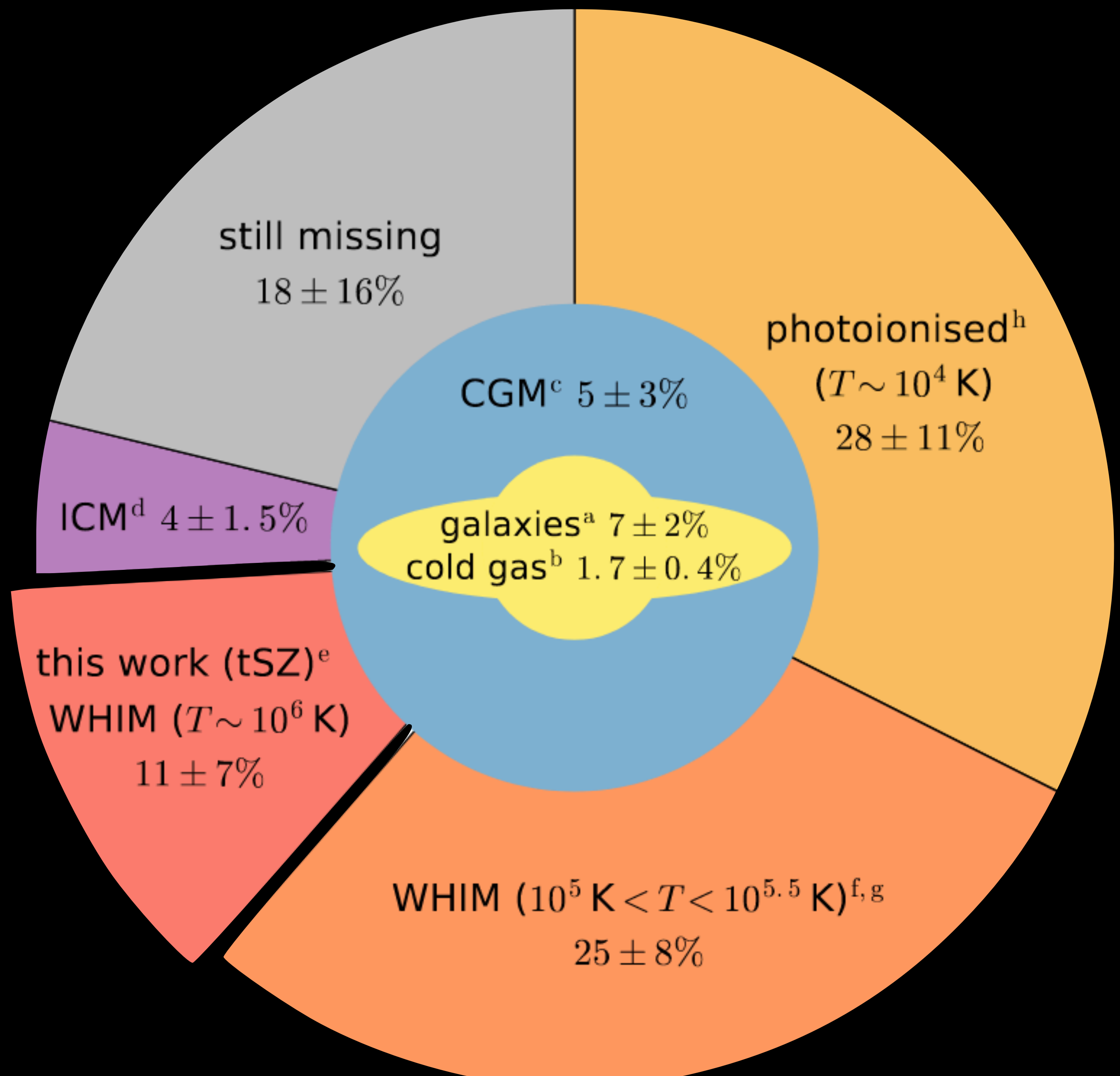
Motivation: the "missing" baryons

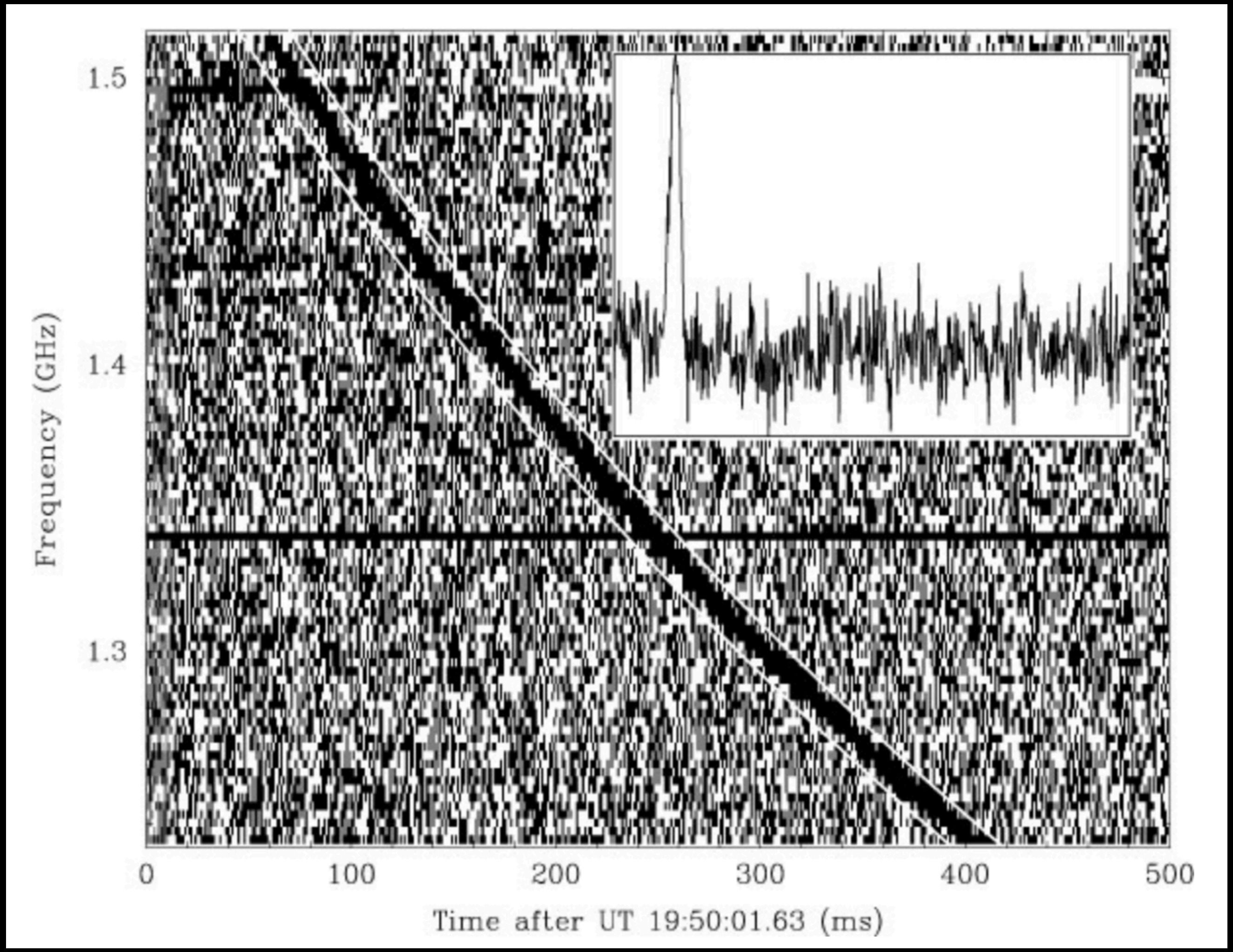


At z<2, about 20-30% of baryons are unaccounted for.

Finding where these "missing" baryons are located is crucial for understanding IGM/galaxy evolution and feedback mechanisms

De Graff+2019

Fast Radio Bursts as tracers of the Cosmic Web



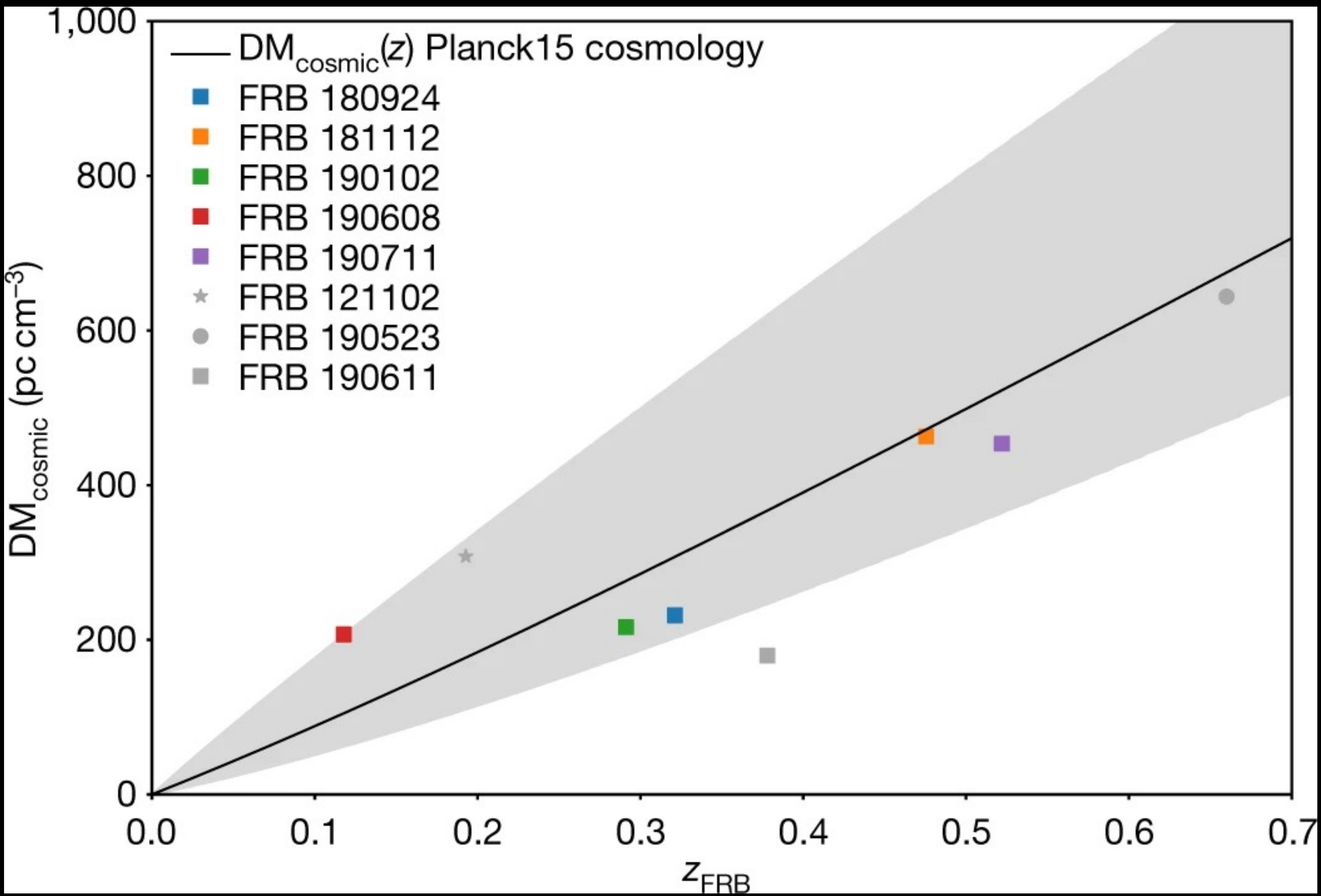
Lorimer+2007

- bright millisecond radio transients of unknown nature of extragalactic origin (Lorimer+2007, Thornton+2013)
- wavelength-dependent time delay of the components frequencies is described by the characteristic "dispersion measure" (DM)
- DM is a measure of the integrated electron column densities along the line-of-sight - for ionized medium this means DM also probe baryons

Fast Radio Bursts as tracers of the Cosmic Web

$$\langle \mathrm{DM_{cosmic}} \rangle = \int_0^{z_{\mathrm{frb}}} \frac{c f_{\mathrm{d}} \rho_b(z) m_p (1 - Y_{\mathrm{He}}/2)}{H_0 (1+z)^2 \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}} dz$$

The Mcquart Relation



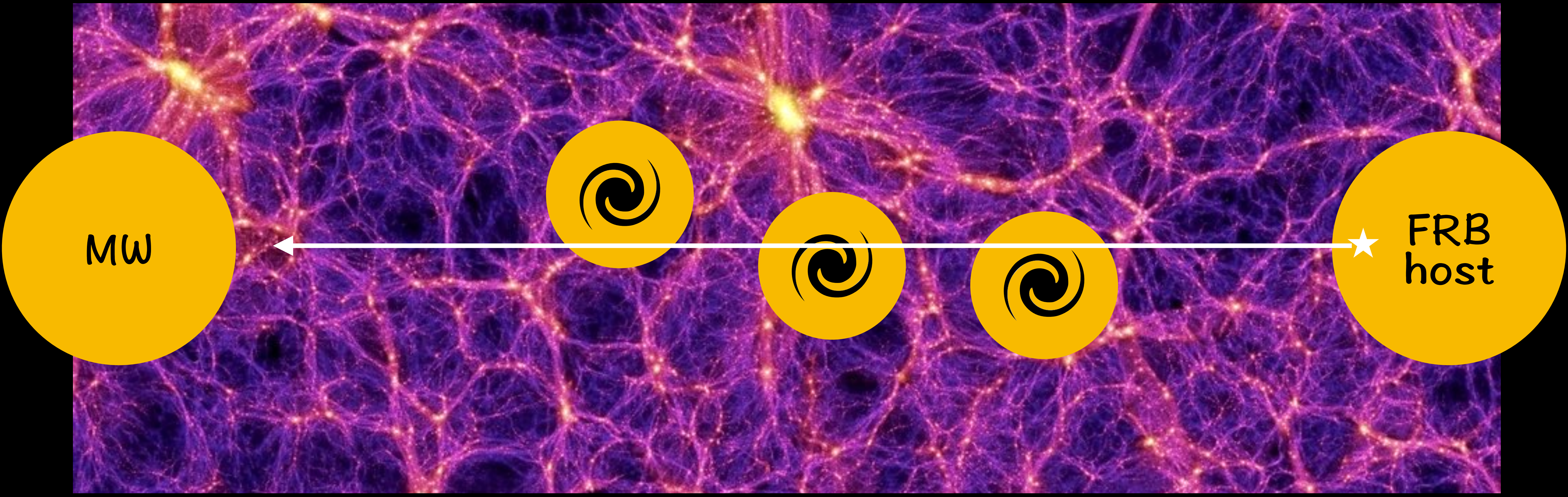
The “missing” baryons are found, but little is known about their distribution:

- in the diffuse gas tracing Cosmic Web or
- inside the hot galactic halos?
- but then what is the extent of these halos?

Mcquart+2020

Fast Radio Bursts as tracers of the Cosmic Web

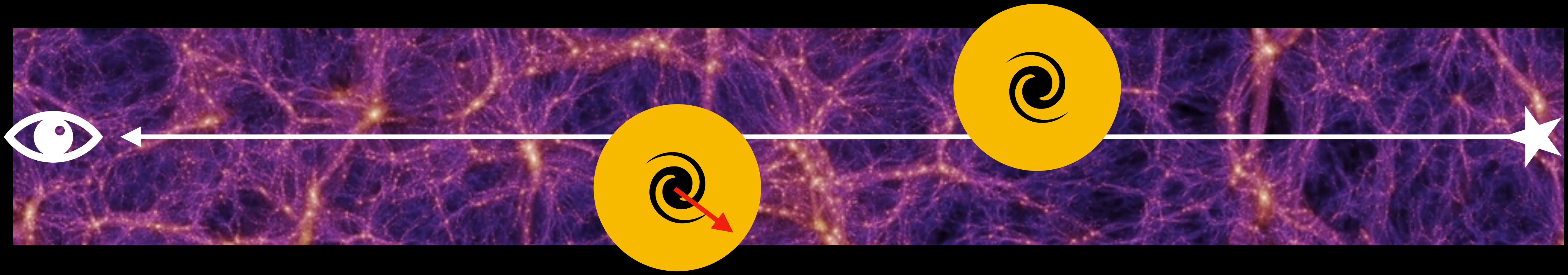
$$\mathrm{DM_{obs}} = \int n_e(s)\mathrm{d}s$$



$$\mathrm{DM_{obs}} = \mathrm{DM_{MW}} + \mathrm{DM_{igm}} + \mathrm{DM_{halo}} + \mathrm{DM_{host}}$$

FRB foreground mapping technique

Step 1. Creation of the mock dataset



1. Calculate the $\mathrm{DM}_{\mathrm{igm}}$ from the Millennium density fields along the path of the FRB assuming $f_{\mathrm{igm}} = 0.8$: $\mathrm{DM}_{\mathrm{igm}} = \int n_{\mathrm{e,igm}}(s)\mathrm{d}s \propto f_{\mathrm{igm}} \int n_{\mathrm{lss}}(s)\mathrm{d}s$

2. Calculate $\mathrm{DM}_{\mathrm{halo}}$ contribution. Each f/g galactic halo is described by the mNFW profile extending to r_{max}. The total mass of baryons in the halo is $M^b_{\mathrm{halo}} \equiv f_{\mathrm{hot}} \cdot \frac{\Omega_b}{\Omega_m} M_{\mathrm{halo}}$

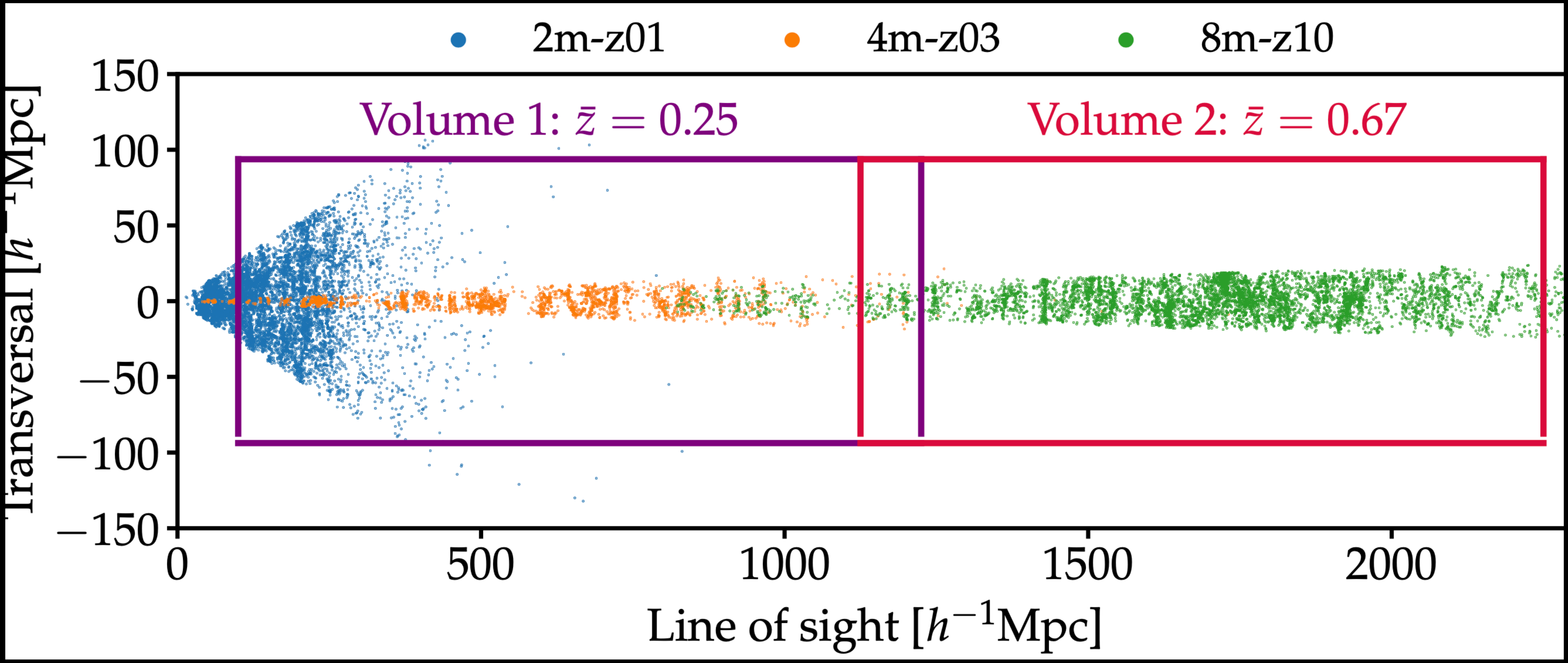
We assume $r_{\mathrm{max}}/r_{200} = 1.4$, $f_{\mathrm{hot}} = 0.75$

Model parameters: f_{igm}, r_{max}, f_{hot}

FRB foreground mapping technique

Step 2. Using Henriques+2015 lightcones, we generate f/g galaxy catalogs to be used for reconstructing the underlying density field along the FRBs line-of-sight

Galaxy positions in the mock spectroscopic surveys

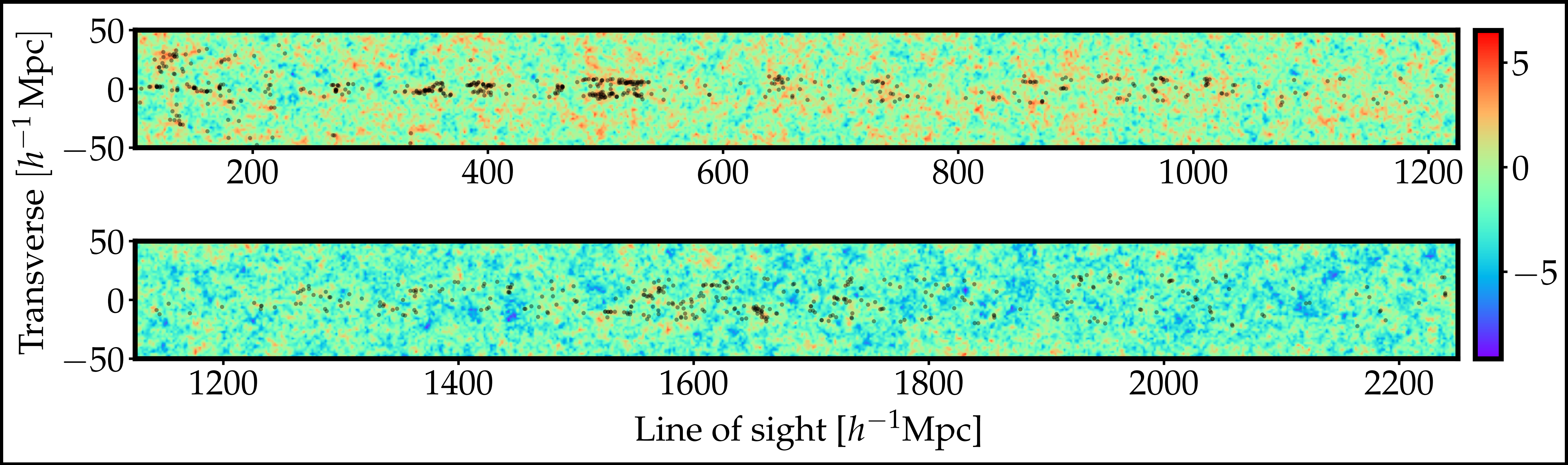


ARGO reconstructions of the matter density field

ARGO - Bayesian density reconstruction code (Ata+2015,2017)

Metin Ata
(Kavli IPMU)

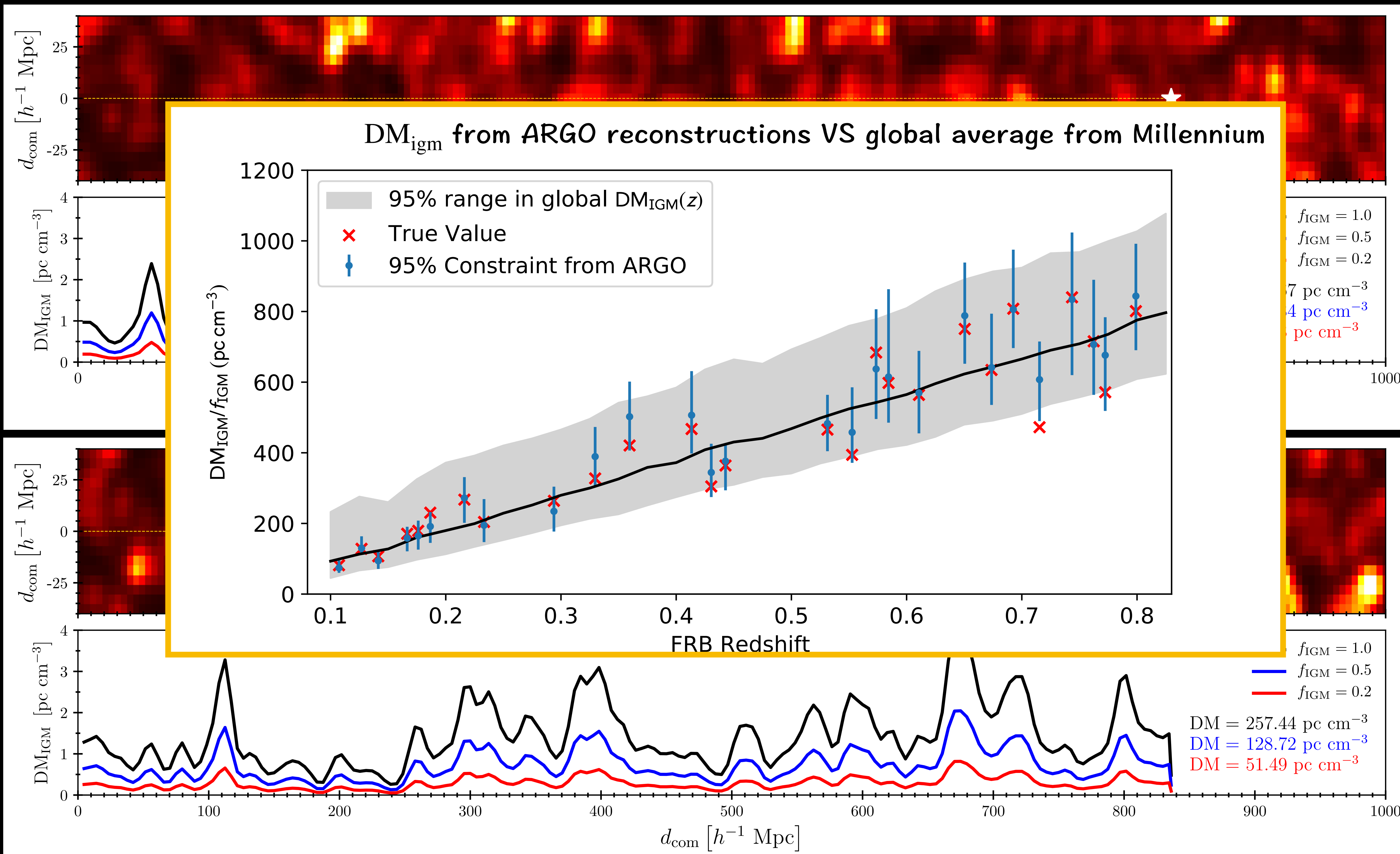
Example ARGO reconstructed underlying density field from Millennium simulations



ARGO yields N=50 realizations of the density field, allowing robust estimate of the uncertainties

ARGO reconstructions of the matter density field

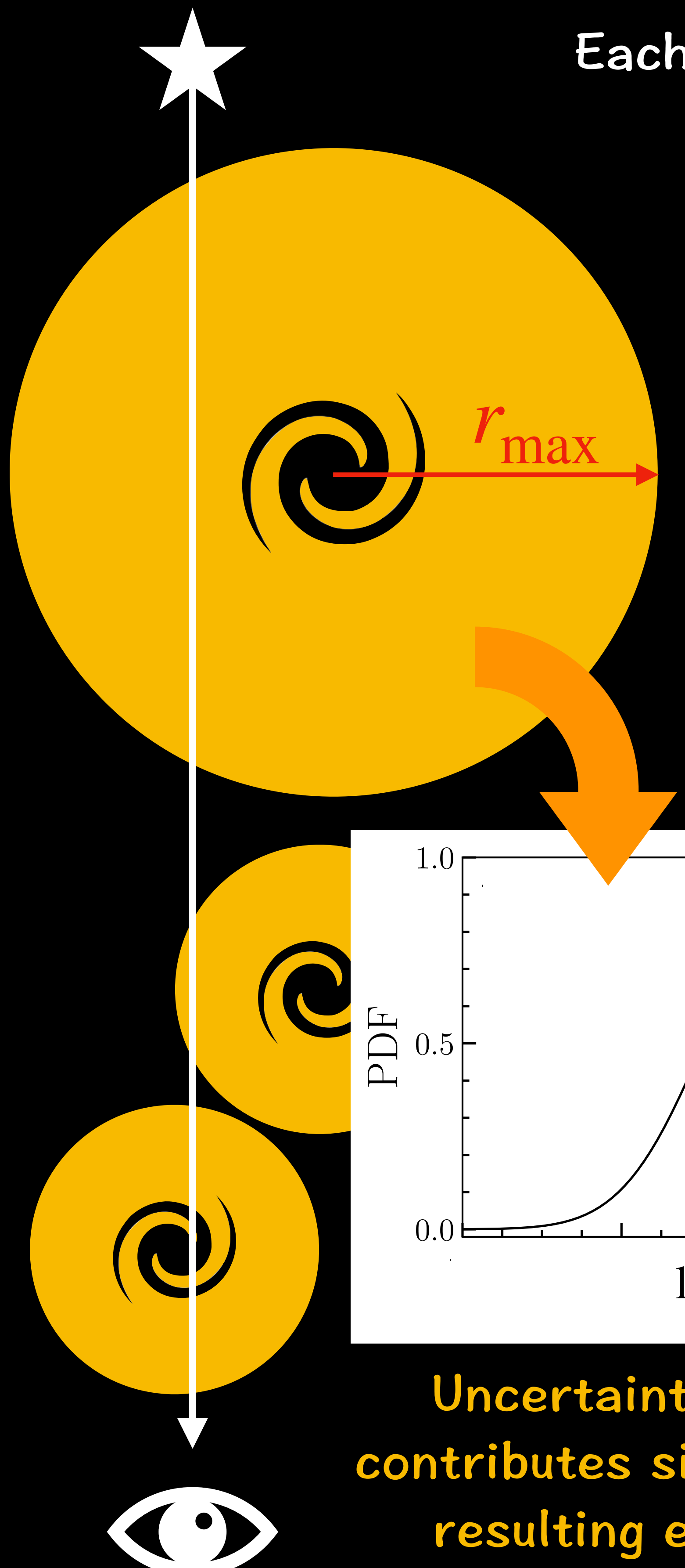
Example $\mathrm{DM_{igm}}$ contributions from ARGO realizations of the density field

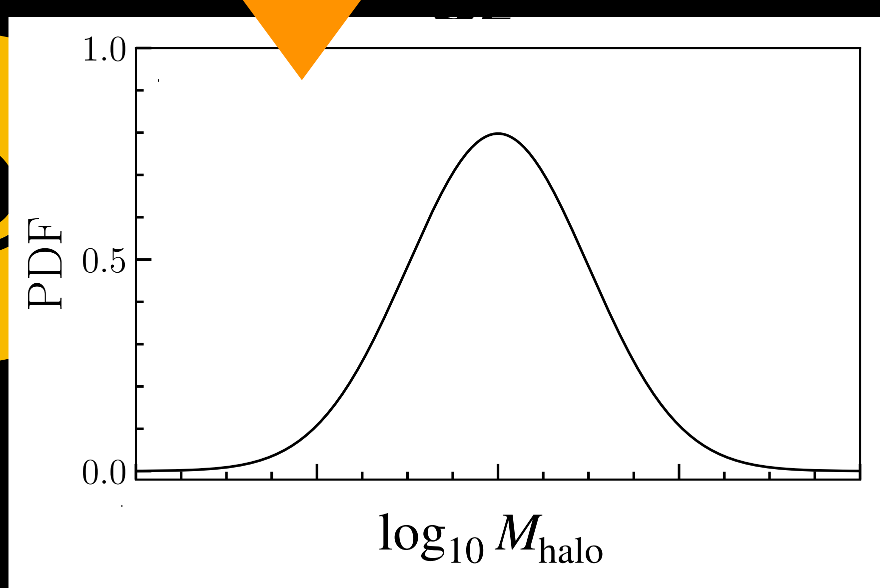


The f/g Galactic Halos Component ($\mathrm{DM_{halo}}$)

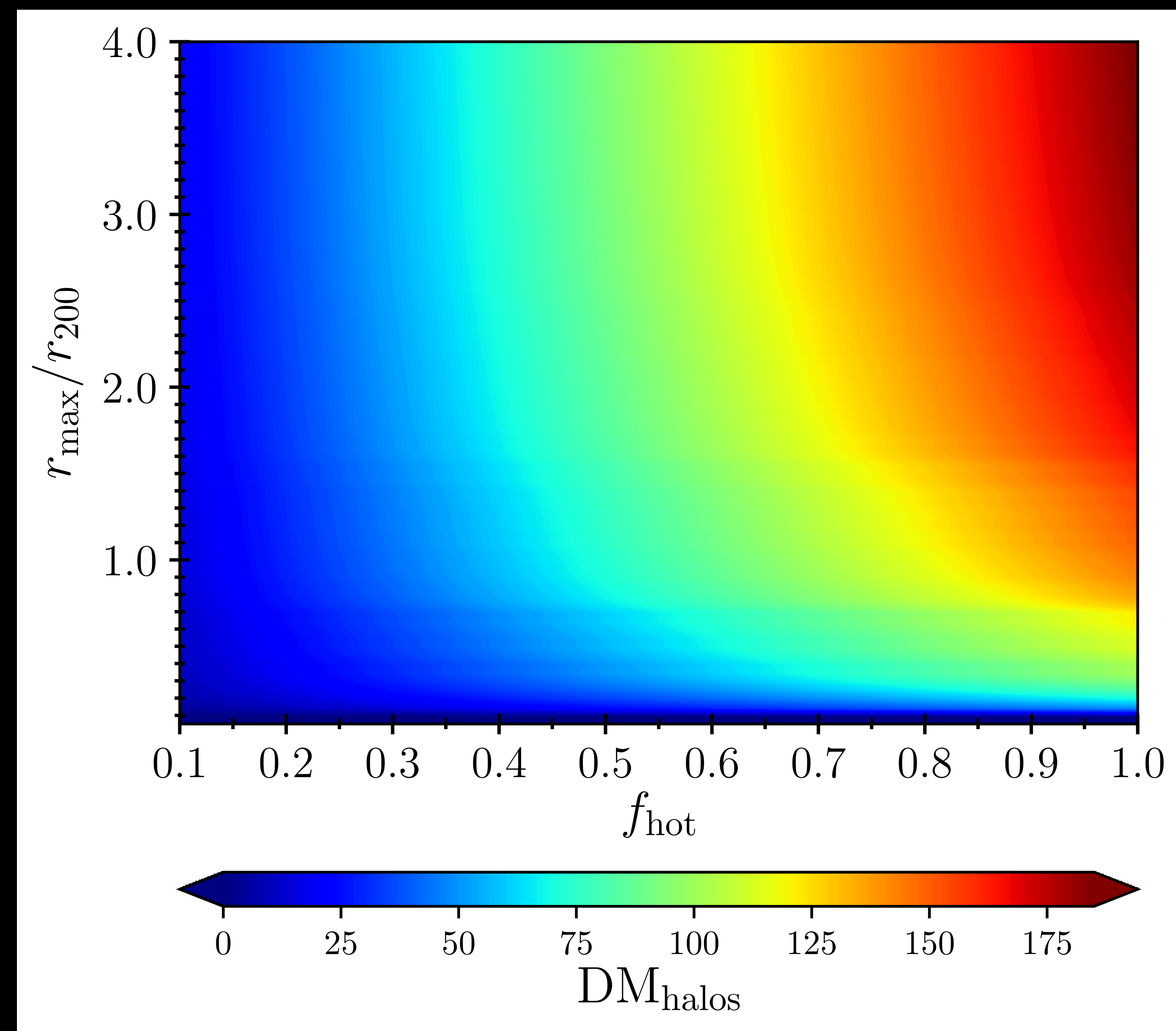
Each f/g galactic halo is described by the mNFW profile extending to r_{max}

The total mass of baryons in the halo is $M^b_{\mathrm{halo}} \equiv f_{\mathrm{hot}} \cdot \frac{\Omega_b}{\Omega_m} M_{\mathrm{halo}}$

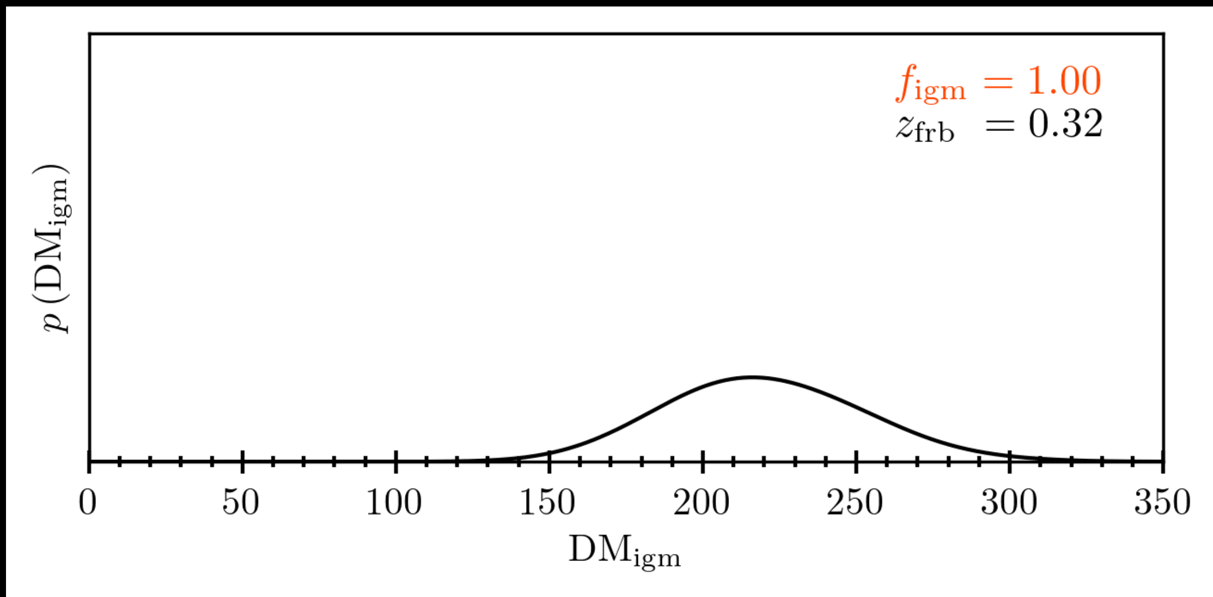




Uncertainty in halo mass contributes significantly to the resulting error on $\mathrm{DM_{halo}}$

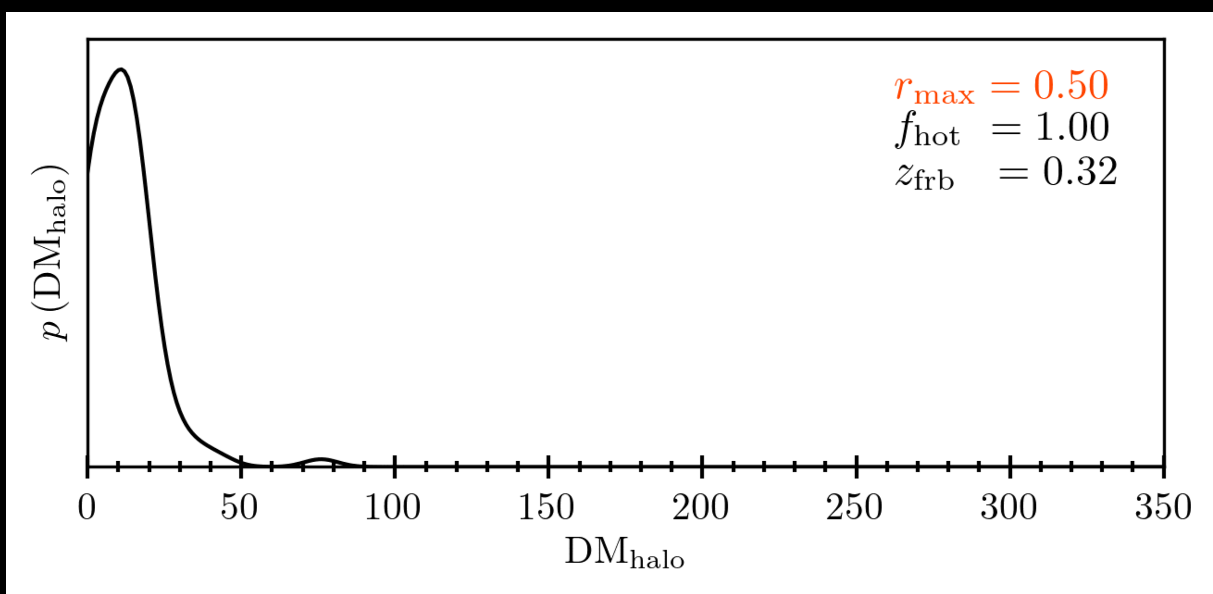


DM contributions as functions of model parameters



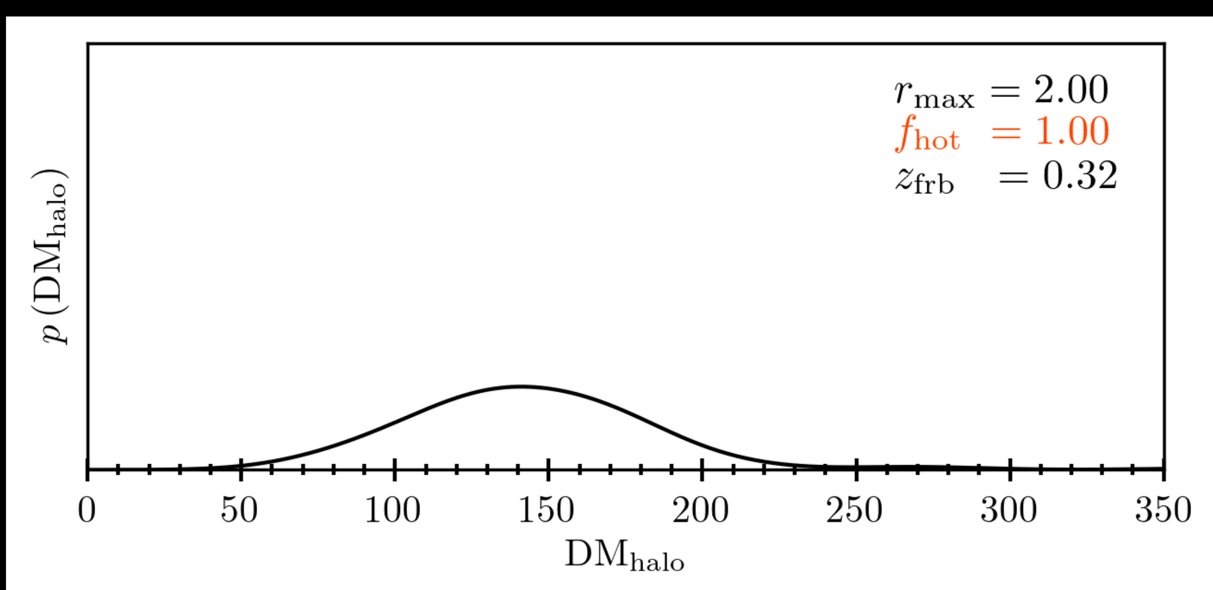
Changing the fraction of baryons inside the diffuse IGM

$$\mathrm{DM_{igm}} = \mathit{func}(f_{\mathrm{igm}})$$



Changing the extent of the f/g galactic halos

$$\mathrm{DM_{halo}} = \mathit{func}(r_{\mathrm{max}})$$



Changing the fraction of baryons inside the hot CGM of f/g galactic halos

$$\mathrm{DM_{halo}} = \mathit{func}(f_{\mathrm{hot}})$$

MCMC inference on the mocks

Mock data is constructed from Millennium mock FRB catalogs:

$$\mathrm{DM}_{\mathrm{data}} = \mathrm{DM}_{\mathrm{igm}}^{\mathrm{true}}(f_{\mathrm{igm}} \equiv 0.8) + \mathrm{DM}_{\mathrm{halo}}^{\mathrm{true}}(r_{\max} \equiv 1.4, f_{\mathrm{hot}} \equiv 0.75)\rangle + \langle \mathrm{DM}_{\mathrm{host}}(z)\rangle$$

Model is given by ARGO density reconstructions and NFW model of f/g halos

$$\mathrm{DM}_{\mathrm{model}} = \langle \mathrm{DM}_{\mathrm{igm}}(f_{\mathrm{igm}})\rangle + \langle \mathrm{DM}_{\mathrm{halo}}(r_{\max}, f_{\mathrm{hot}})\rangle + \langle \mathrm{DM}_{\mathrm{host}}(z)\rangle$$

$$\langle \mathrm{DM}_{\mathrm{host}}(z)\rangle = 100\ \mathrm{pc\ cm}^{-3} \cdot \left(1 + z_{\mathrm{frb}}\right)^{-1}$$

The joint likelihood for an ensemble of FRB:

$$\log \mathscr{L}_{\mathrm{joint}} \propto \sum_{i}^{N_{\mathrm{frb}}=30} \frac{\left(\mathrm{DM}_{\mathrm{data},i} - \mathrm{DM}_{\mathrm{model},i}\right)^2}{\sigma_i^2}$$

$$\sigma_i^2 = \sigma_{\mathrm{argo},i}^2 + \sigma_{\mathrm{halo},i}^2 + \sigma_{\mathrm{MW}}^2$$

$f_{\mathrm{igm}} \in [0.00, 1.00]$ $r_{\max}/r_{200} \in [0.05, 2.00]$ $f_{\mathrm{hot}} \in [0.05, 1.00]$

MCMC inference on the mocks (preliminary results)

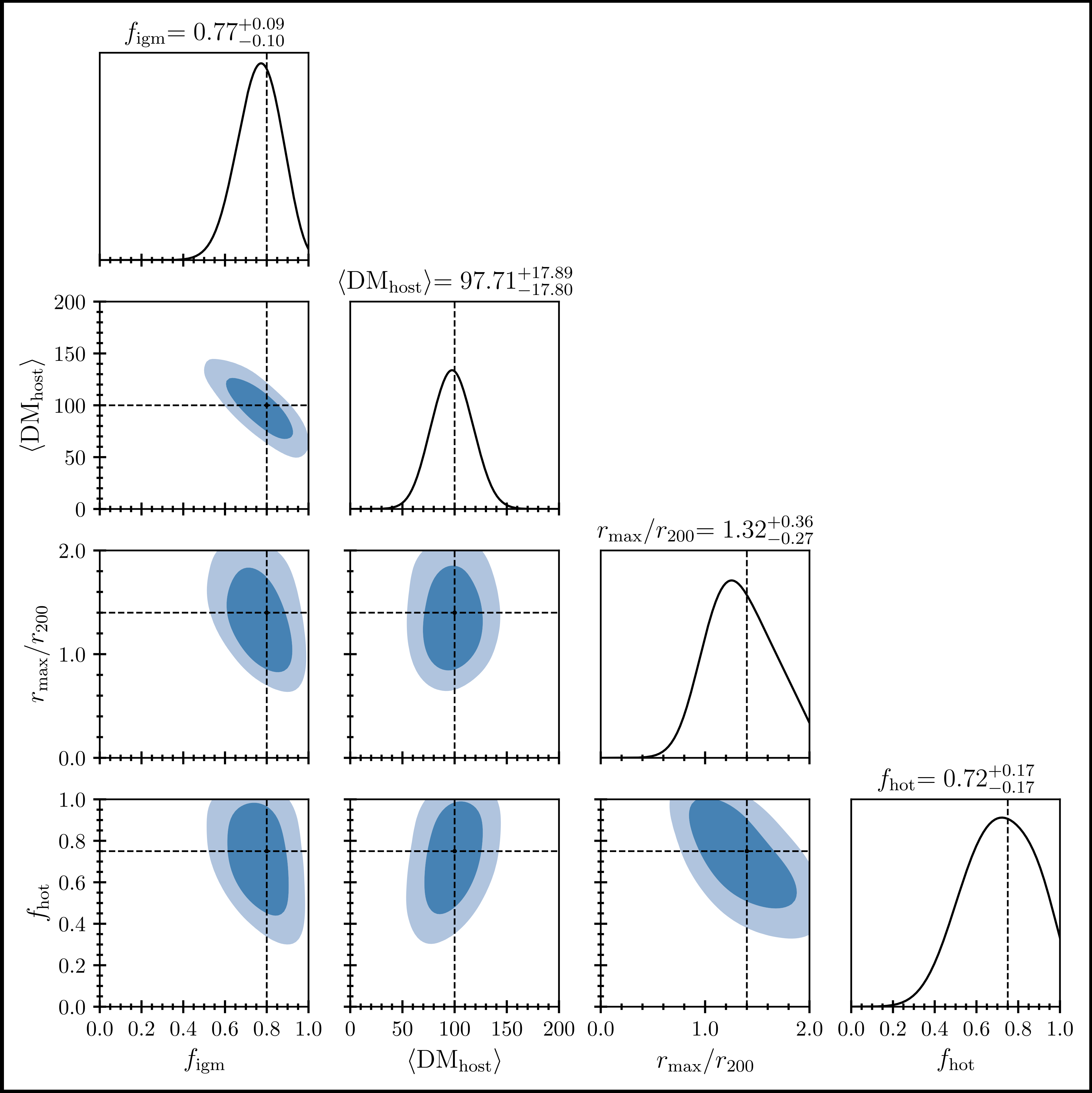
$N_{\rm frb} = 30$

$0.01 \lesssim z_{\rm frb} \lesssim 0.50$

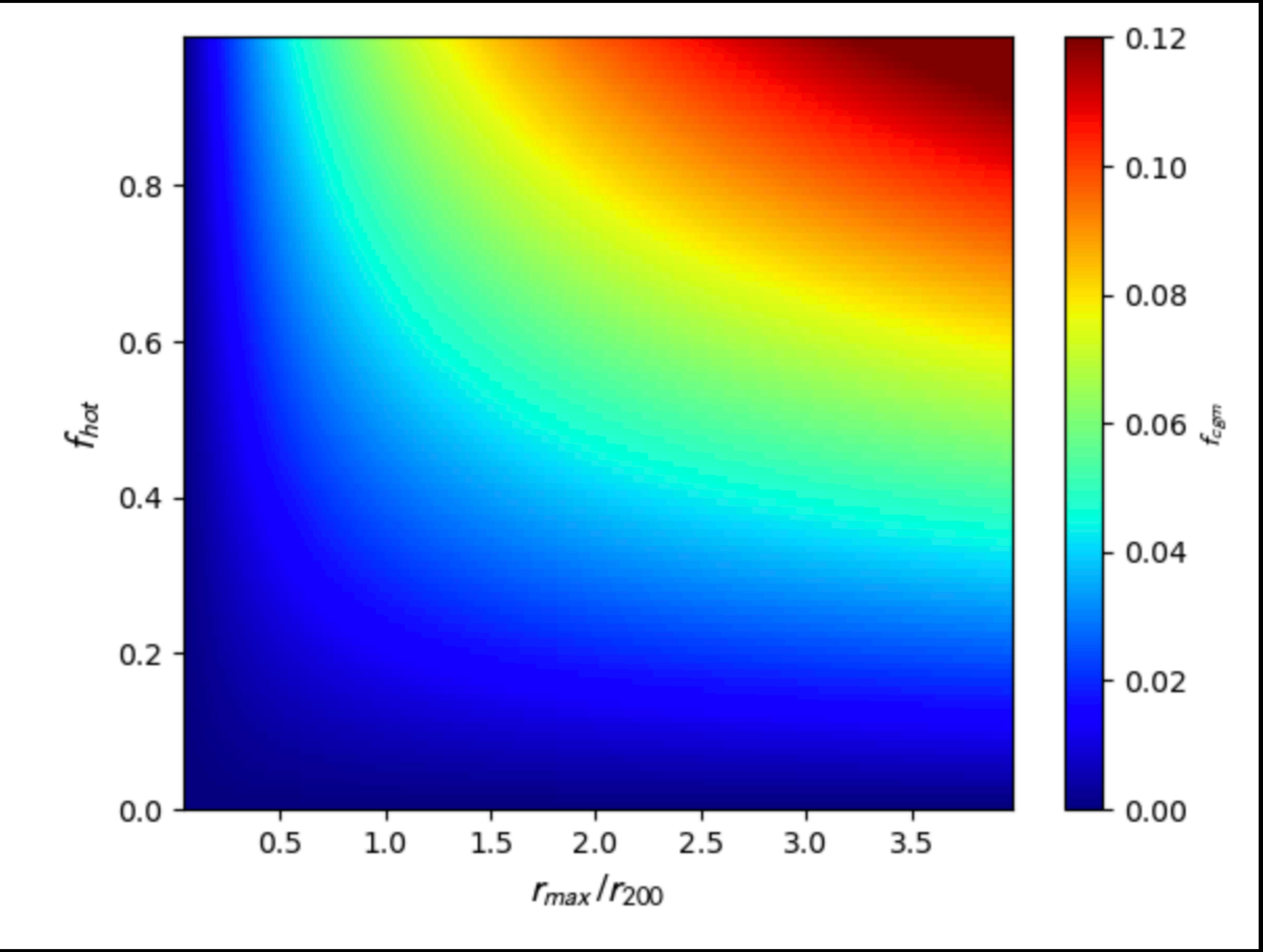
~10% precision on $f_{\rm igm}$

~25% precision on $r_{\rm max}$

~15% precision on $f_{\rm hot}$



Connecting the extent of the f/g halos and $f_{\rm hot}$ to the $f_{\rm cgm}$



MCMC inference on the mocks (preliminary results)

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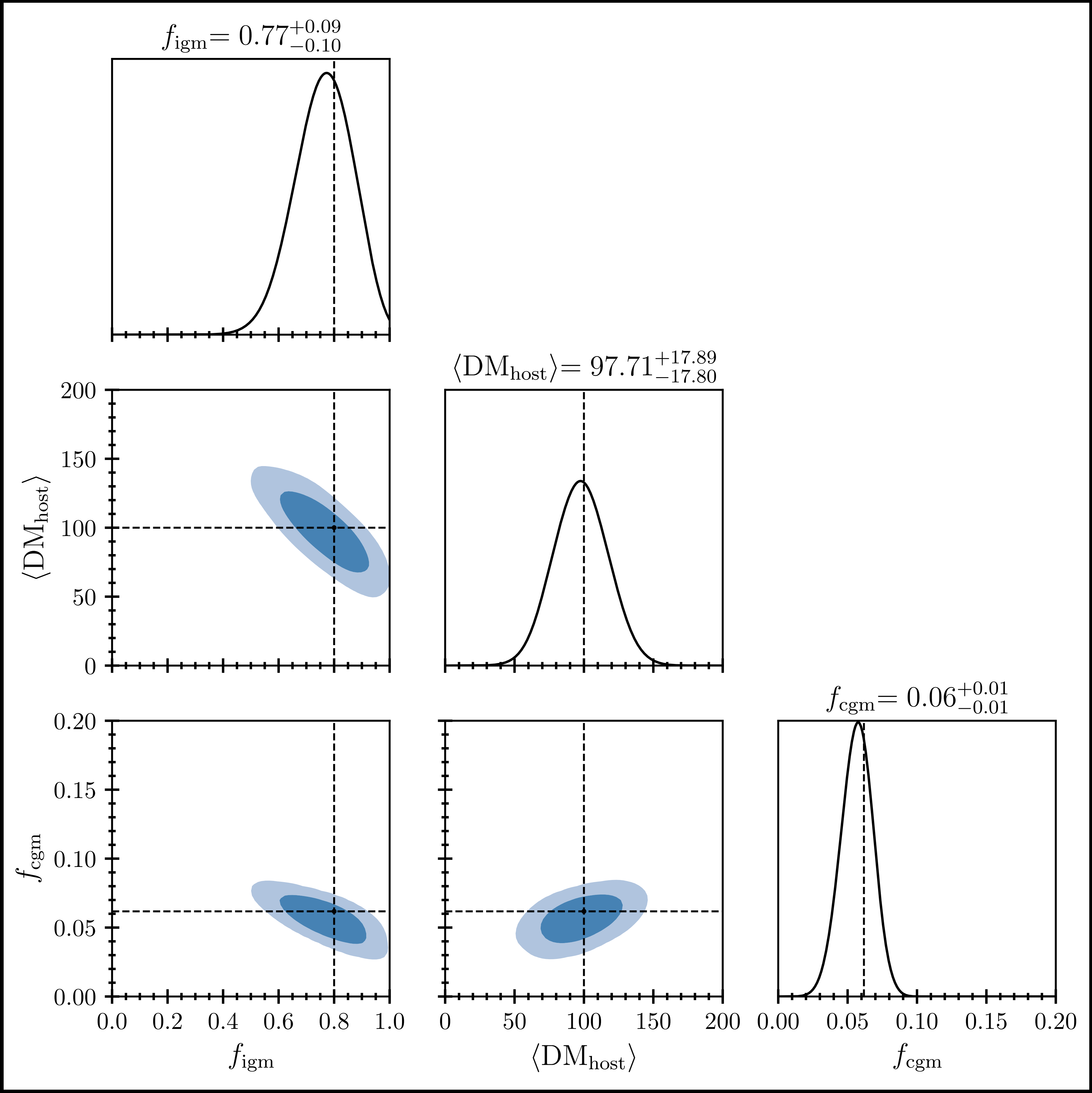
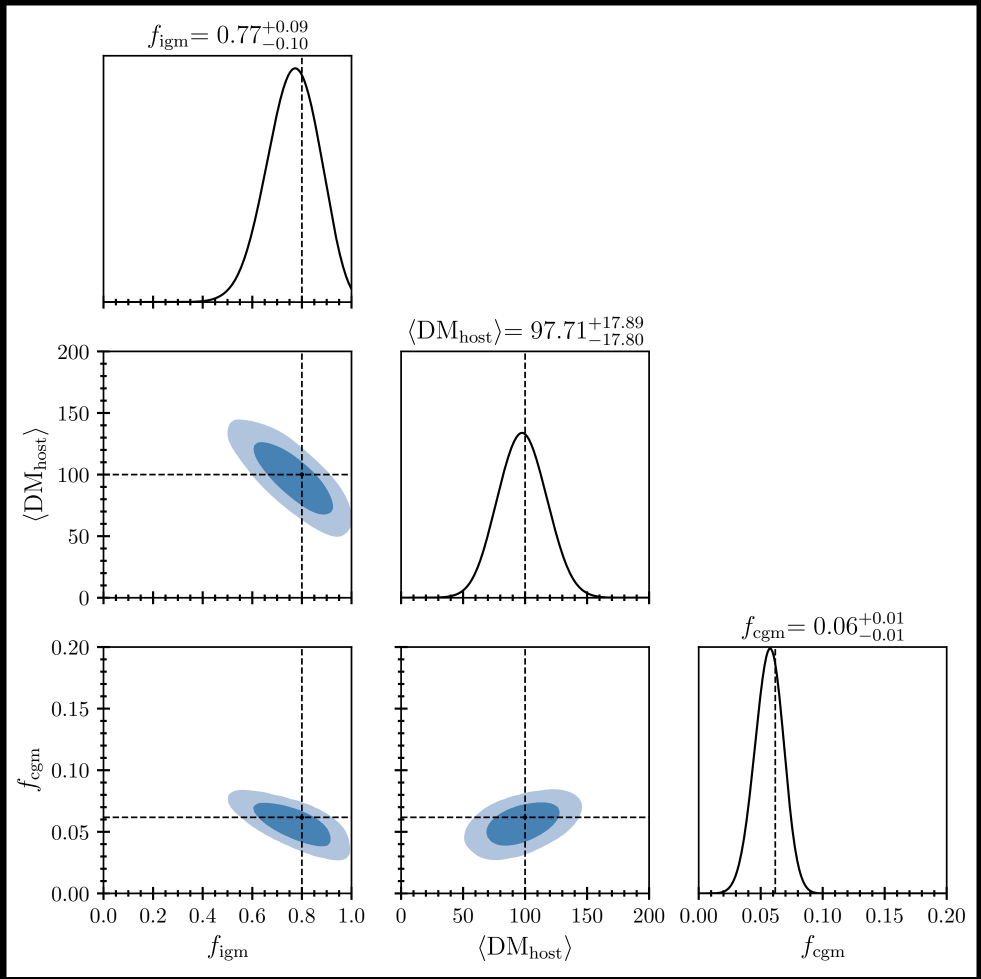
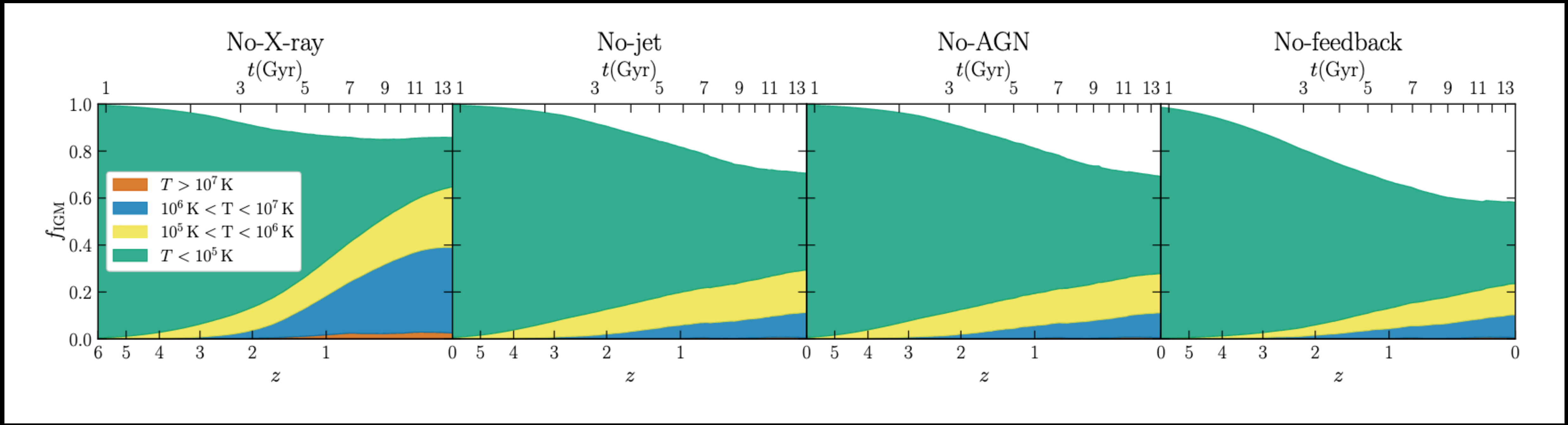


Cosmic baryons as tracers of the galaxy feedback mechanisms



Effect of different feedback prescriptions on the mass fraction of cosmic baryons located in the IGM/CGM (estimated in SIMBA hydrodynamical simulations)

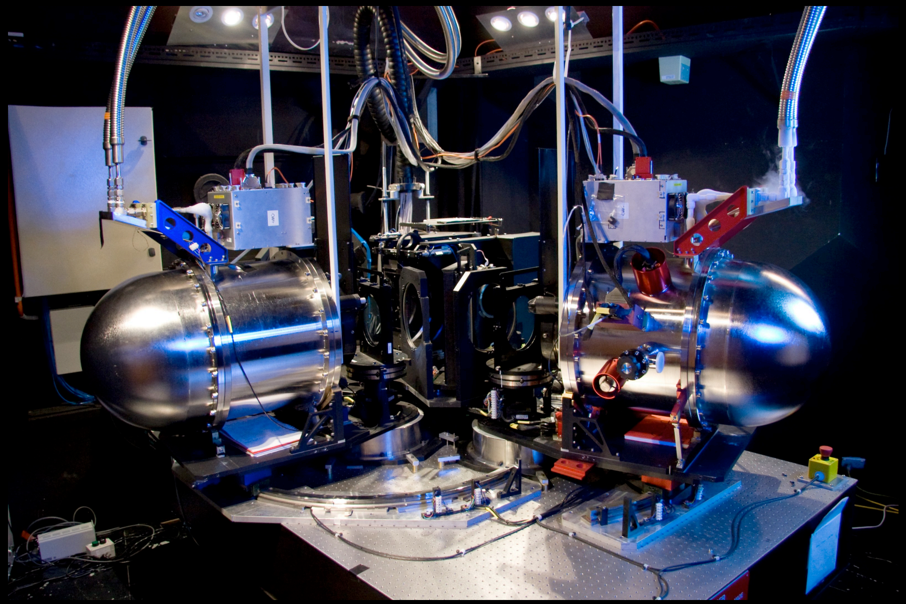


Sorini+2021

FRB foreground mapping on AAT (FLIMFLAM)

FLIMFLAM = FRB Line-of-sight Ionization Measurement From Lightcone AAOmega Mapping

Yuxin Huang (Kavli IPMU)



2dF-AAOmega fiber spectrograph at 3.9m Anglo-Australian Telescope

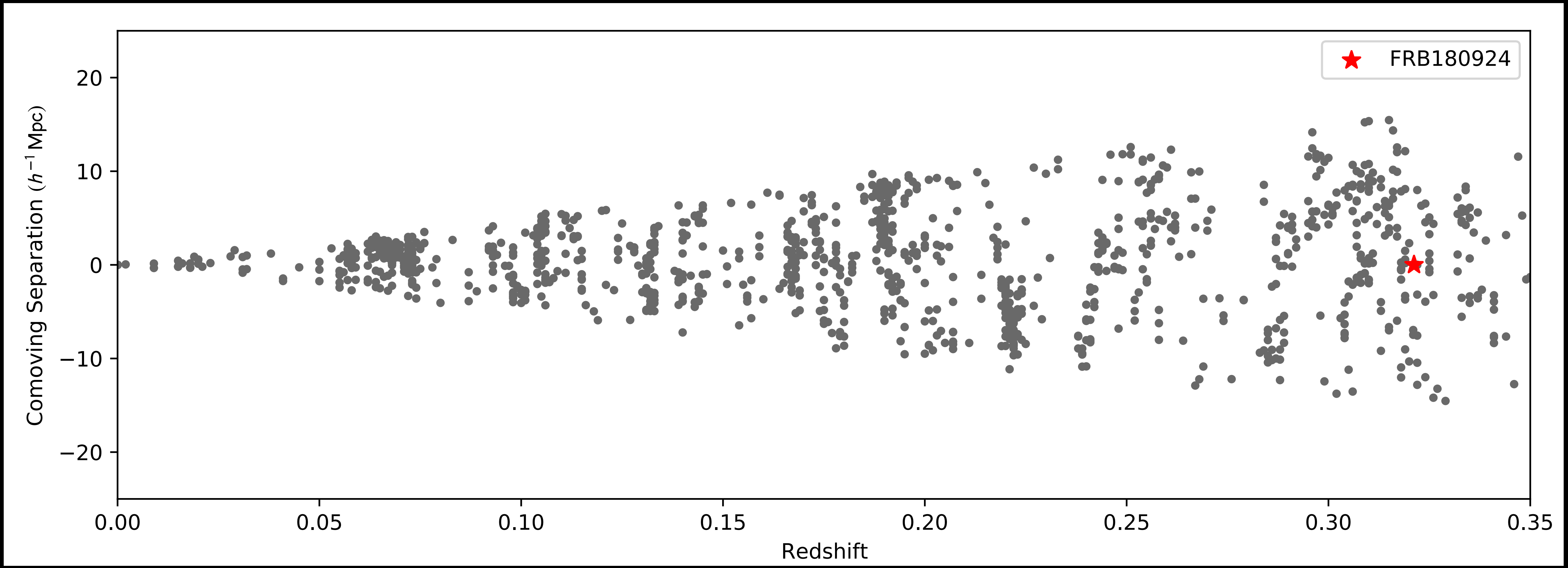
FLIMFLAM goal: spectroscopic observations of galaxies in the f/g of N=30 localized FRBs at $0.1 < z < 0.5$ with limiting magnitudes $19.2 < r_{AB} < 20.6$

~40 observational nights for the sample of 30 FRBs

FRB foreground mapping on AAT (FLIMFLAM)

Yuxin Huang
(Kavli IPMU)

First preliminary results of the FLIMFLAM observational campaign



Conclusions

Lee+2021 (arXiv: 2109.00386)

- Using hydrodynamical simulations and semi-analytical prescriptions we created mock FRB dispersion measures and f/g galaxy catalogs

- We applied ARGO - state-of-the-art Bayesian algorithm to reconstruct the underlying density fields, allowing to measure the line-of-sight dispersion measures of the mock FRBs to a factor of ~2-3x better accuracy than allowed by cosmic variance.

- Applying MCMC algorithm to the mock samples of N=30 FRBs at $0.1 < z < 0.5$ we can achieve ~10% precision on estimating the fraction of baryons in the diffuse Cosmic Web, as well as ~10-20% accuracy on f/g halos parameters.

- We began observational campaign FLIMFLAM at 3.9m AAT, aimed to obtain spectroscopic maps of the foregrounds of N=30 FRBs and measure baryon distribution

- Future facilities (4m-class DESI and WEAVE, as well as 8m-class Subaru PSF and MOONS) will allow to push foreground mapping to higher redshifts, potentially even measuring the stages of HeII reionization (z~3)