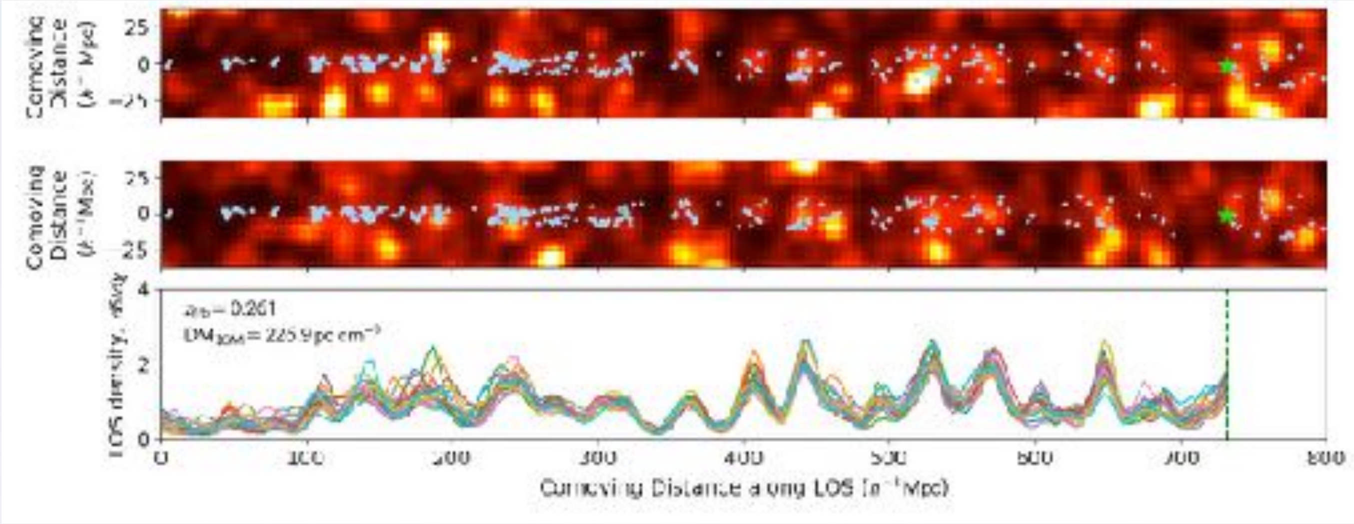
Constraining the Cosmic Baryon Distribution with FRB Foreground Spectroscopy



“From Galaxies to Cosmology with Deep Spectroscopic Surveys”, A Tribute to Olivier Le Fèvre, Marseille

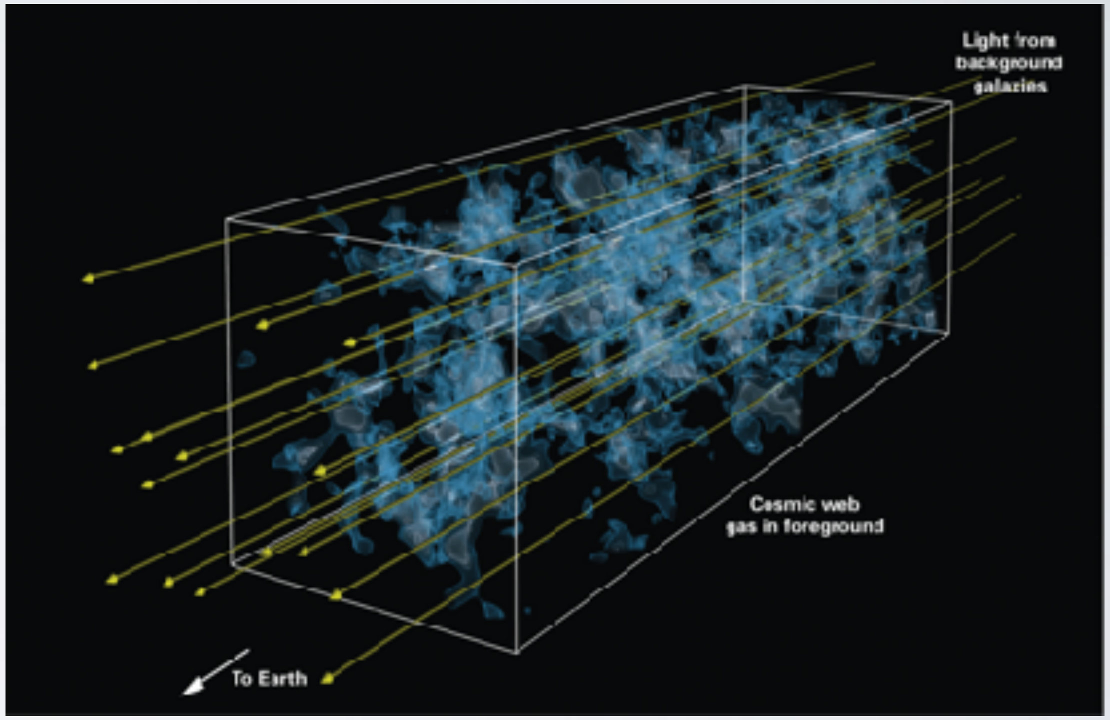
July 6, 2022

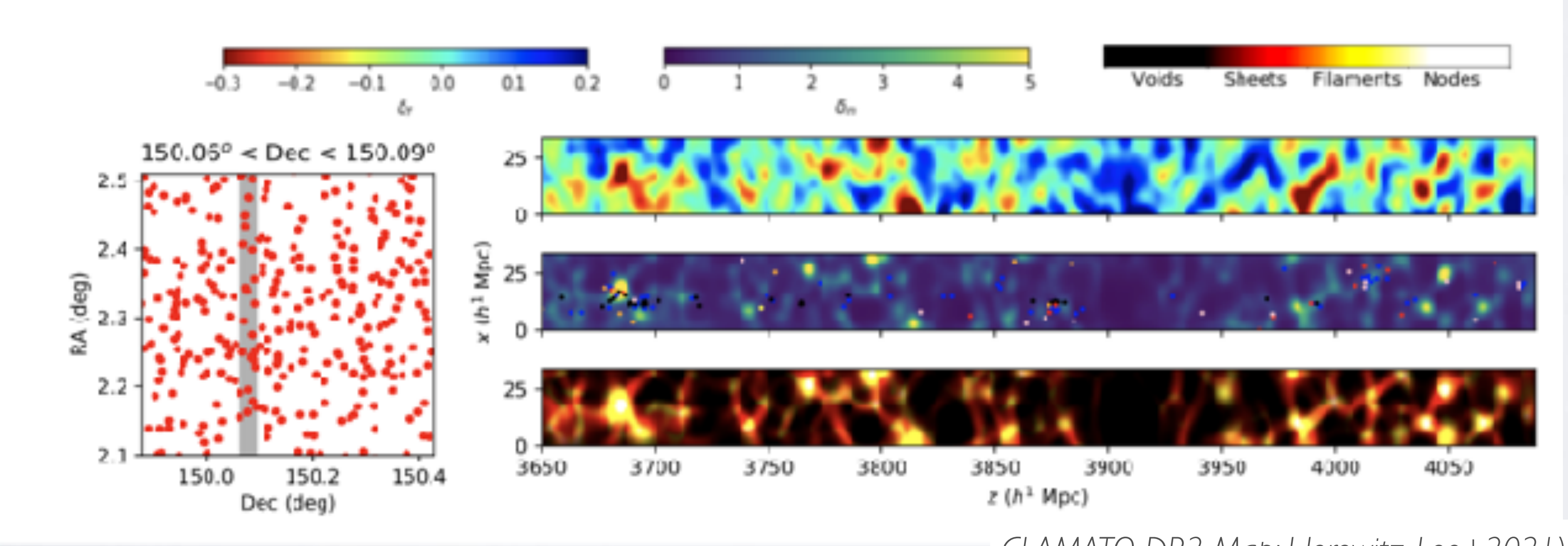
Khee-Gan (“K.-G”) Lee

Kavli IPMU, University of Tokyo

Apologies… I will *not* be talking about:

- IGM tomography: mapping the Lyman-alpha forest at z~2 with dense grids of background LBG spectra (Pichon+2002, Caucci+2008, **Lee**+2014a)
- CLAMATO Survey on Keck: 0.2 sq deg at 2.0<z<2.5 in the COSMOS field: Data Release 2 (Horowitz, **Lee**+2021, arXiv:2109.09660)
- Wide-field IGM tomography with Subaru PFS over ~12.5 sq deg (Starting 2024; see John Silverman talk)





CLAMATO DR2 Map; Horowitz, Lee+2021)

Credits

- **Lee**, Ata, Khrykin et al 2022, ApJ, 928, 1, 9
- Ongoing observations: Yuxin Huang (UTokyo master's student), Jeff Cooke (Swinburne), Xavier Prochaska (UCSC), Sunil Simha (UCSC) , Nicolas Tejos (Catolica @Valparaiso)
- CRAFT/ASKAP collaboration for FRB detection
- F^4 collaboration for host galaxy follow-up

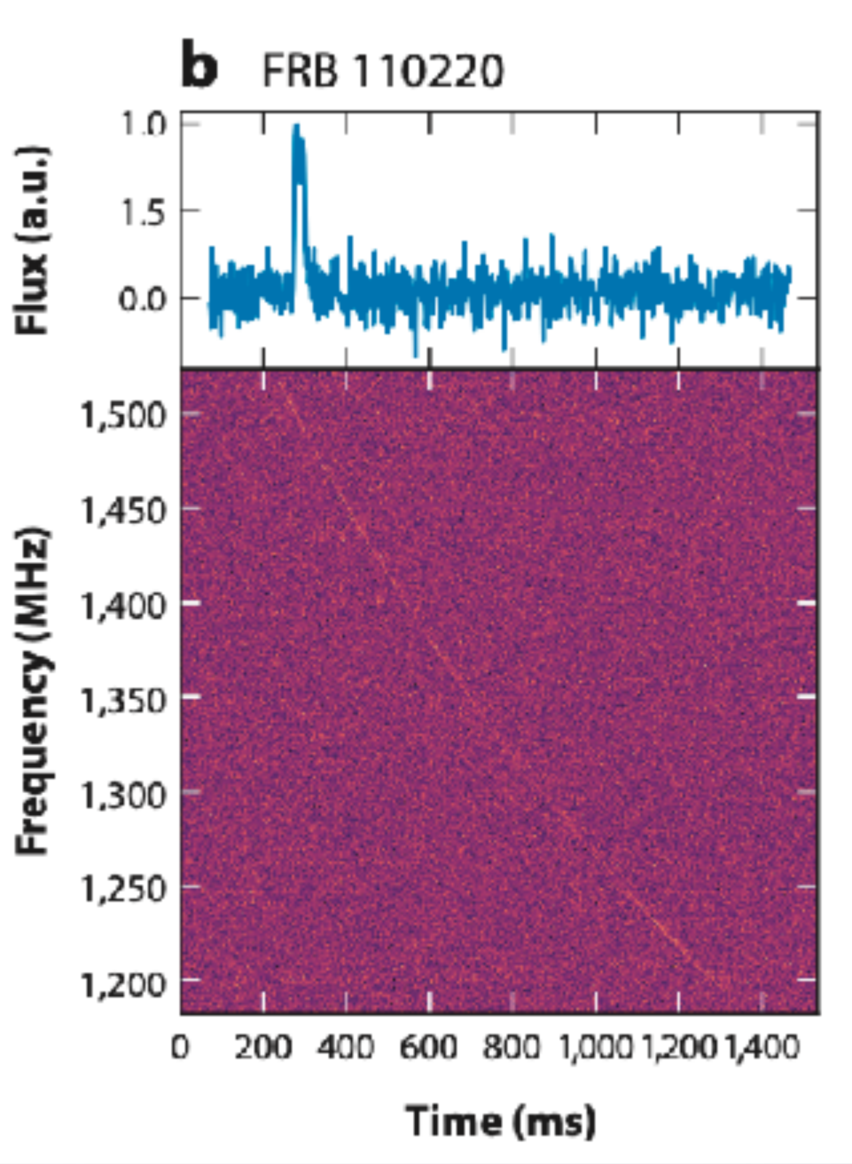
Metin Ata
Kavli IPMU Postdoc

Ilya Khrykin
Kavli IPMU Postdoc

Yuxin Huang
UTokyo Master's Student

Fast Radio Bursts: A Quick Overview

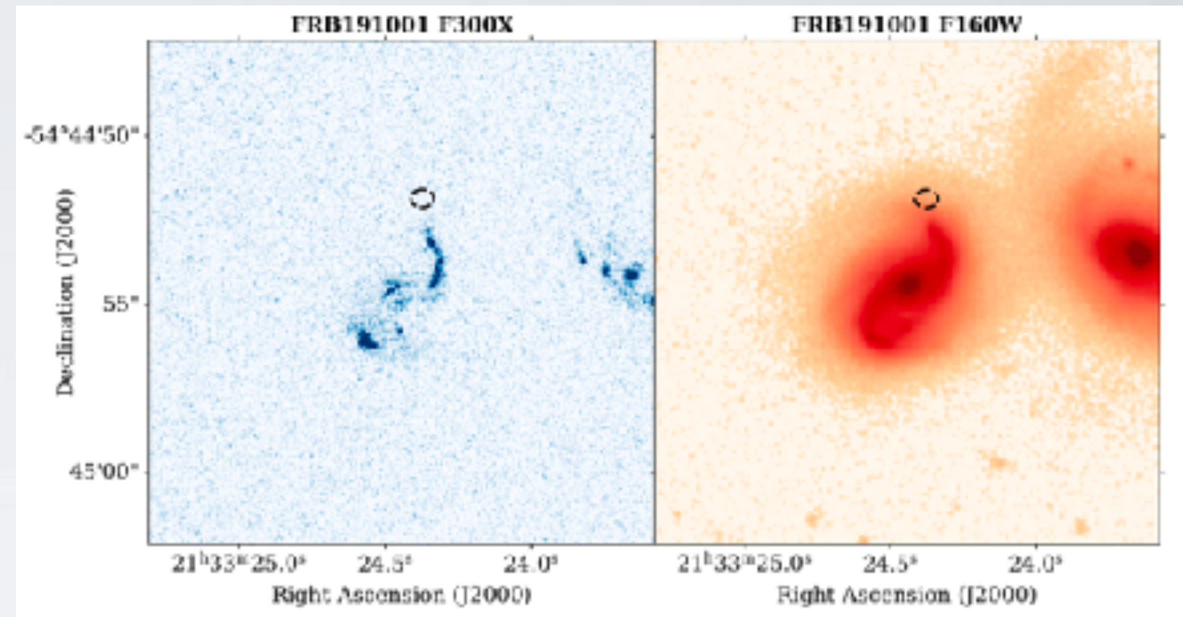
- Millisecond-duration radio bursts first identified by Lorimer et al 2007
- To-date >1000 FRBs have been detected; ~30 have been *localized* to specific host galaxies by interferometric experiments. *Conclusively proven to be extragalactic sources.*
- Unknown progenitors: compact object merger? magnetar masers? ET solar sails? (>50 theories listed at http://frbtheorycat.org)



See review by Cordes & Chatterjee, ARAA 2019

CRAFT/ASKAP and F^4 Collaborations

12m antennas of the Australian SKA Pathfinder



HST Imaging of FRB host galaxies (Mannings+2020)

- Commensal Realtime ASKAP Fast Transients (CRAFT) collaboration carrying interferometric observations of FRBs → ~0.1 arcsec positional accuracy
- Fast and Fortunate FRB Followup (F^4) team is pursuing optical follow-up to measure host galaxy redshifts and properties. See e.g. Heintz+2020 and Mannings+2020

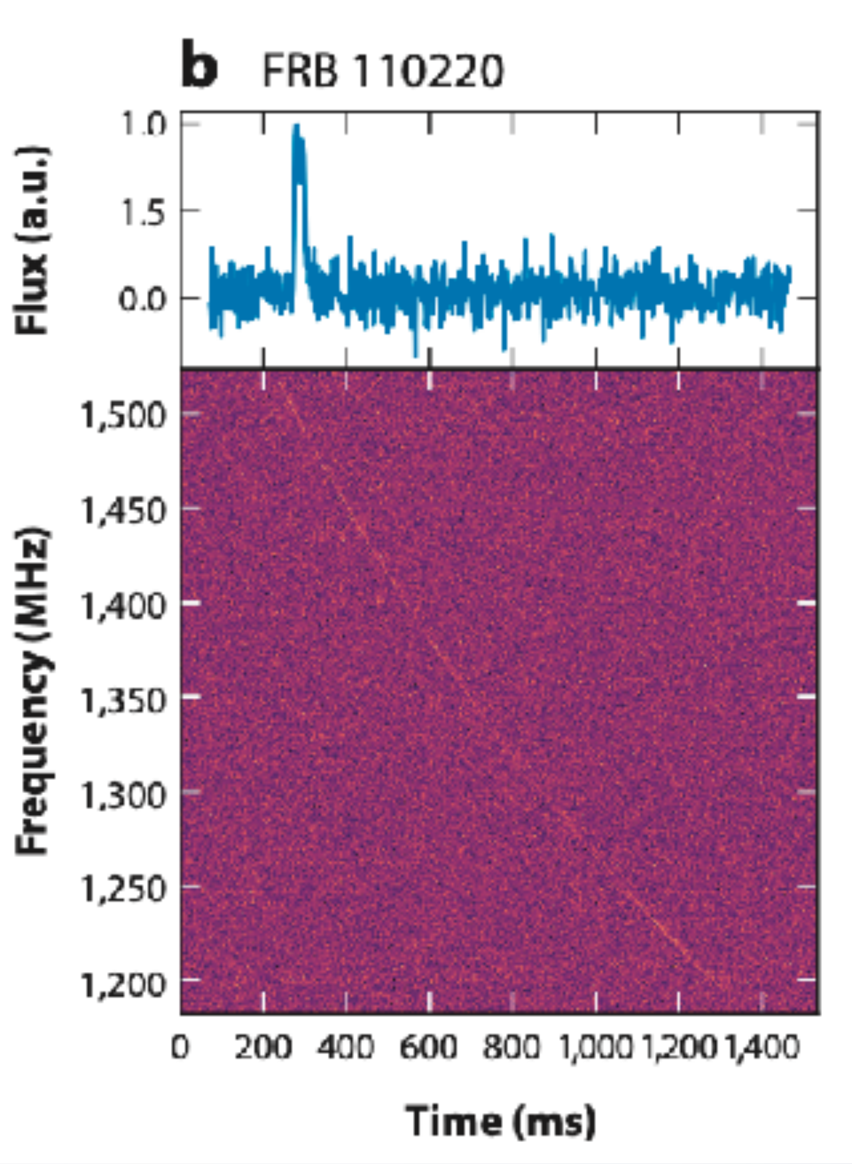
FRB Dispersion Measures (DM)

- Integrated free electrons along the line-of-sight cause a frequency shift in a signal:

$$\mathbf{DM} = \int n_e \mathrm{d}s$$

- For extragalactic sightlines, the DM is dominated by the ionized IGM and CGM

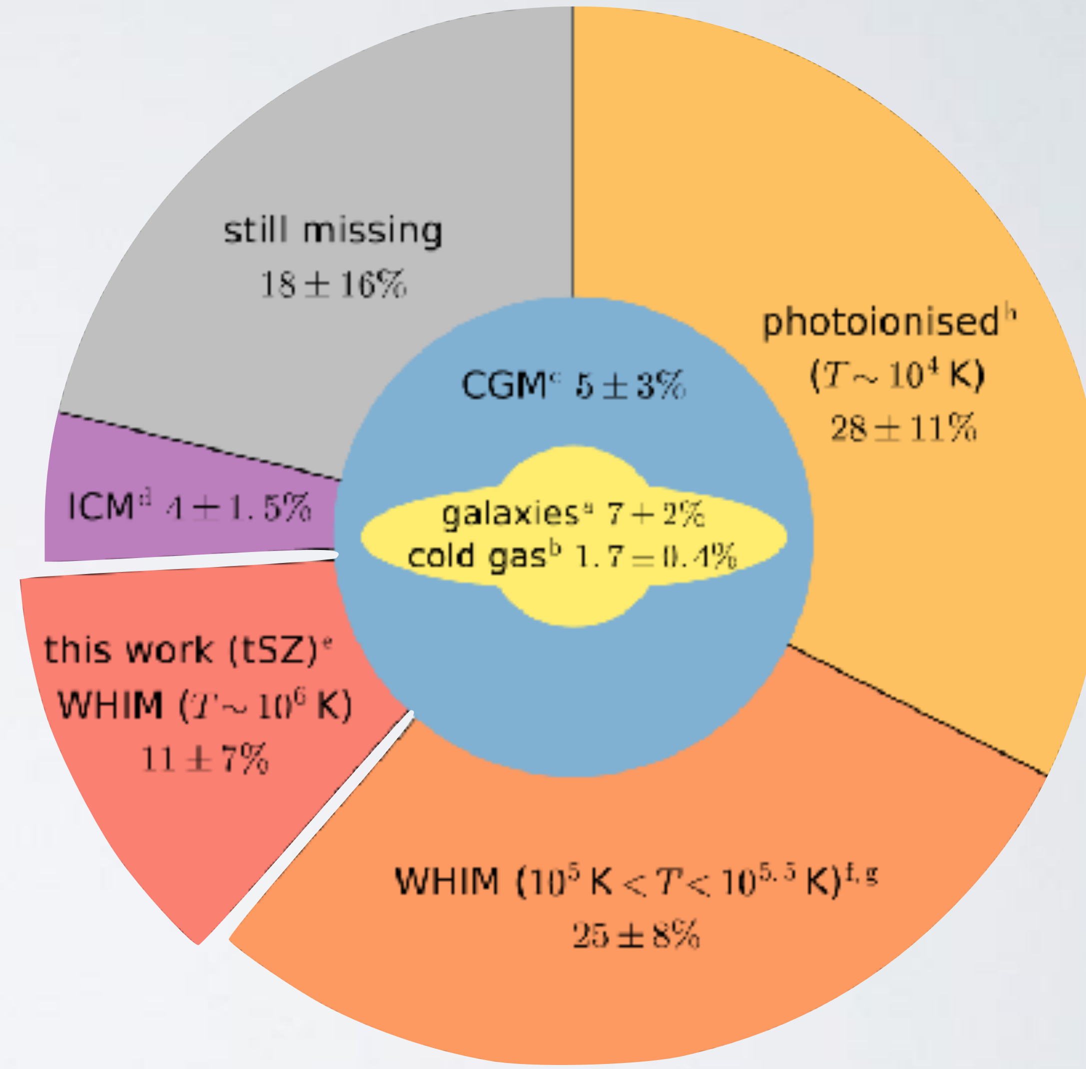
- FRBs thus offer a clean probe of the IGM+CGM, especially if the redshift or distance is known



See review by Cordes & Chatterjee, ARAA 2019

The Missing Baryon Problem

- *Does the baryonic content of the Universe square up with the precise predictions of Ω_{baryon} from Big-Bang Nucleosynthesis and the CMB?*
- At z>2 the astrophysics of intergalactic medium (IGM) is relatively simple (mostly Lyman-alpha forest) — baryons all accounted for
- By z<1, galaxy feedback and gravitational heating cause a complex multi-phase IGM
- As of 2019, ~20-30% at z~0. were still missing despite best efforts

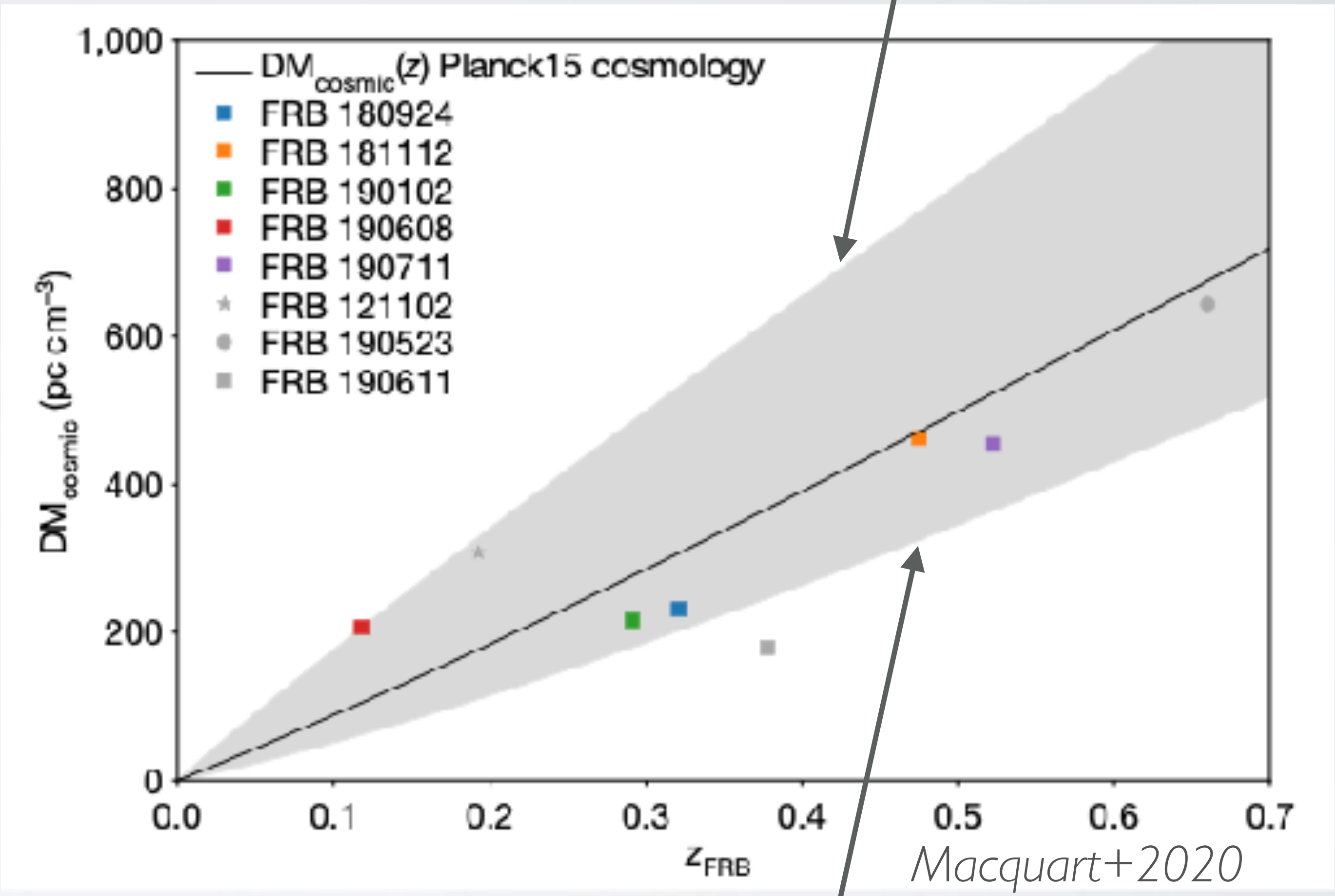


De Graaf+2019

Constraining Cosmic Baryons with FRBs

- Dispersion measure (DM) is a constraint on the integrated free electrons (i.e. ionized gas) along the LOS ($DM = \int n_e/(1+z)\, ds$)
- Macquart+2020 demonstrated that DM-redshift relationship of <u>localized</u> FRBs are consistent with Ω_{baryon} from ΛCDM cosmology → *No more 'missing baryon problem', but relative distribution of baryons still unknown!*
- Individual sightlines at fixed redshift exhibit large cosmic variance from both large-scale structure and individual galaxy haloes.

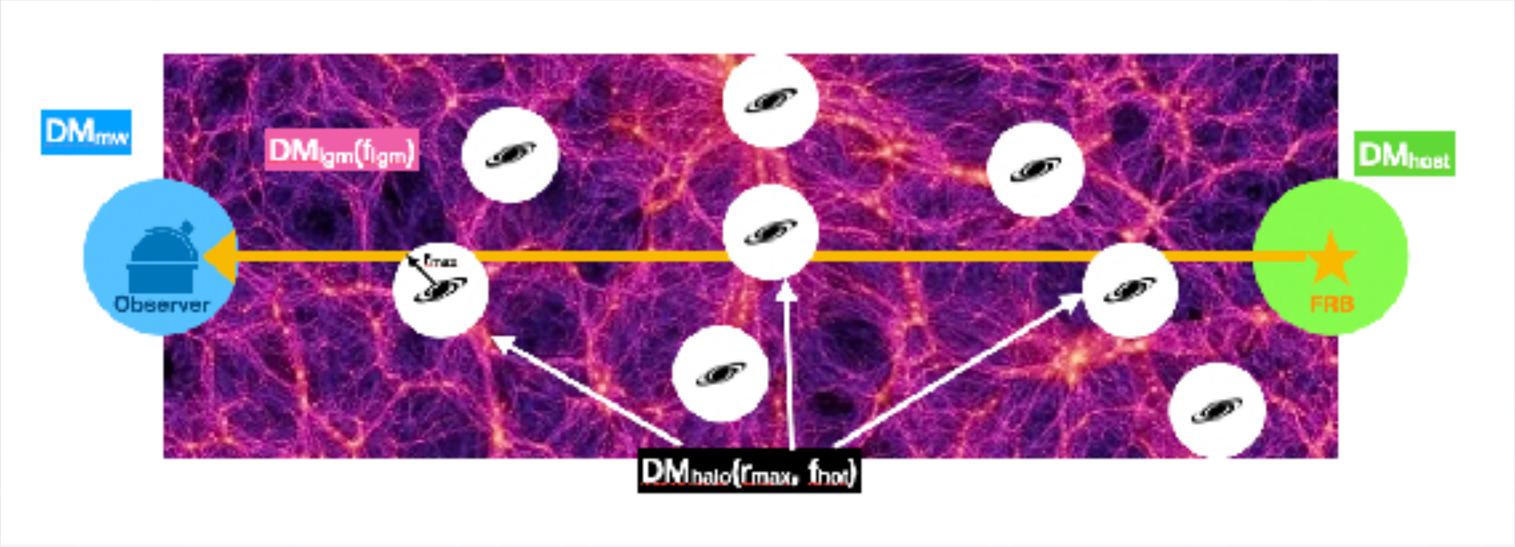
Sightlines passing through dense regions and/or through galactic CGM



Macquart+2020

Sightlines passing through underdense regions and no intervening CGM

Observational Census of Intervening Halos and Foreground Large-Scale Structure



- FRB signal measures the aggregate DM, assumed to be $DM = DM_{mw} + DM_{igm} + DM_{halo} + DM_{host}$
  - DM_{igm} comes from diffuse large-scale structure (voids, sheets, filaments etc, with matter densities of $0 \lesssim \rho_{matter}/\langle\rho_{matter}\rangle \lesssim 10$)
  - DM_{halo} arises directly from intersecting the CGM of intervening galaxies ($\sim r_{200}$ or < few arcmin)
- If we assume that the diffuse IGM gas linearly traces the large-scale structure, can map the cosmic web in foreground with a galaxy redshift survey to derive DM_{igm}, i.e.

$$\mathrm{DM_{igm}} = f_{igm} \frac{\Omega_b}{(\Omega_b + \Omega_{dm})} \int \frac{n_{\mathrm{matter}}(s)}{(1+z)} ds$$

- DM_{halo} can be calculated for individual galaxies based on e.g. their stellar mass, given a CGM model
- Spectroscopic data on the galaxies in FRB foregrounds allows us to calculate the DM contributions for a given model, and compare with the observed extragalactic DM *for each FRB*

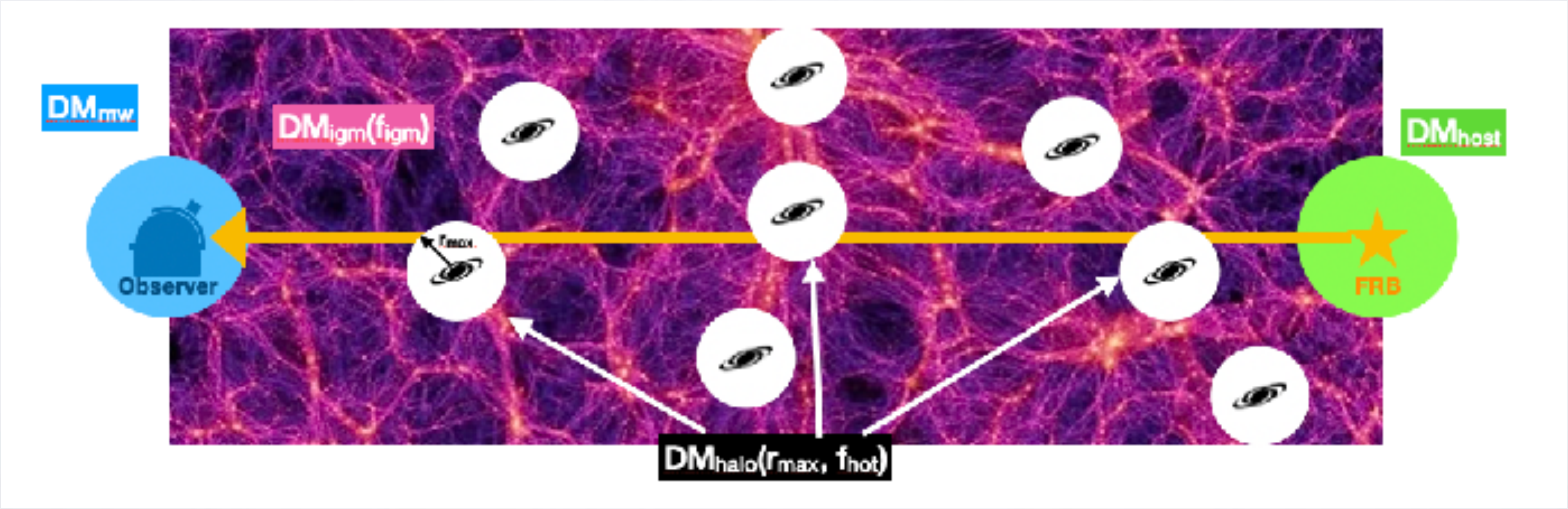
Extragalactic Model DM

For a given mock FRB sightline in the simulation, calculate $DM_{igm}(f_{igm})$ + $DM_{halo}(f_{hot}, r_{max})$ + DM_{host}

- **f_{igm}**: fraction of cosmic baryons residing in the diffuse IGM
- **r_{max}**: maximum extent of CGM hot gas of intervening galaxies (in units of the halo virial radius)
- **f_{hot}**: fraction of halo baryons in the hot CGM phase in intervening galaxies (note: $f_{igm} + f_{hot} \neq 1$)
- **DM_{host}**: Assume a (unknown) fixed value for all FRBs
- Assume DM_{MW} has been subtracted, introducing a 15 pc cm^{-3} error in (DM_{igm} + DM_{halo} + DM_{host})

Halo CGM model is based on Prochaska & Zheng 2019, i.e. hot CGM assumed to trace modified NFW profile as a function of halo mass

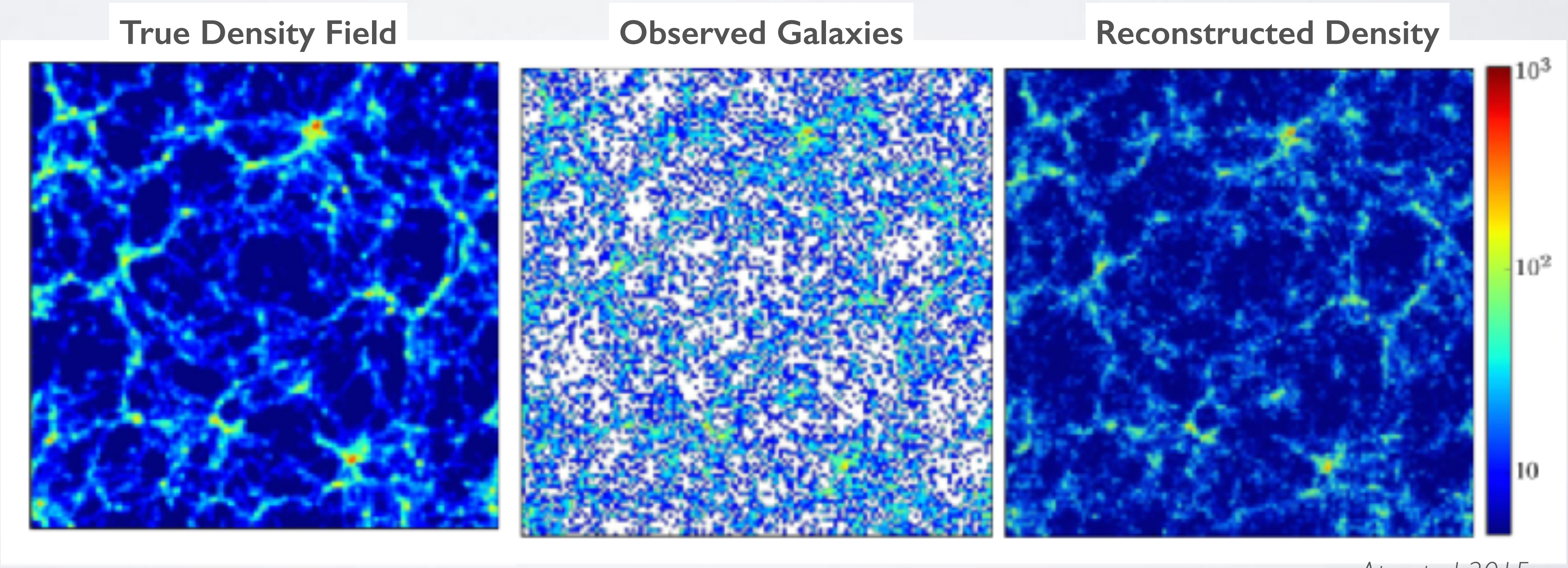
$$M_{cgm} = f_{hot} \frac{\Omega_b}{\Omega_{dm} + \Omega_b} \int_0^{r_{max}} M_{halo}(r) dr$$



Large-scale Cosmic Web: Matter Density Reconstructions

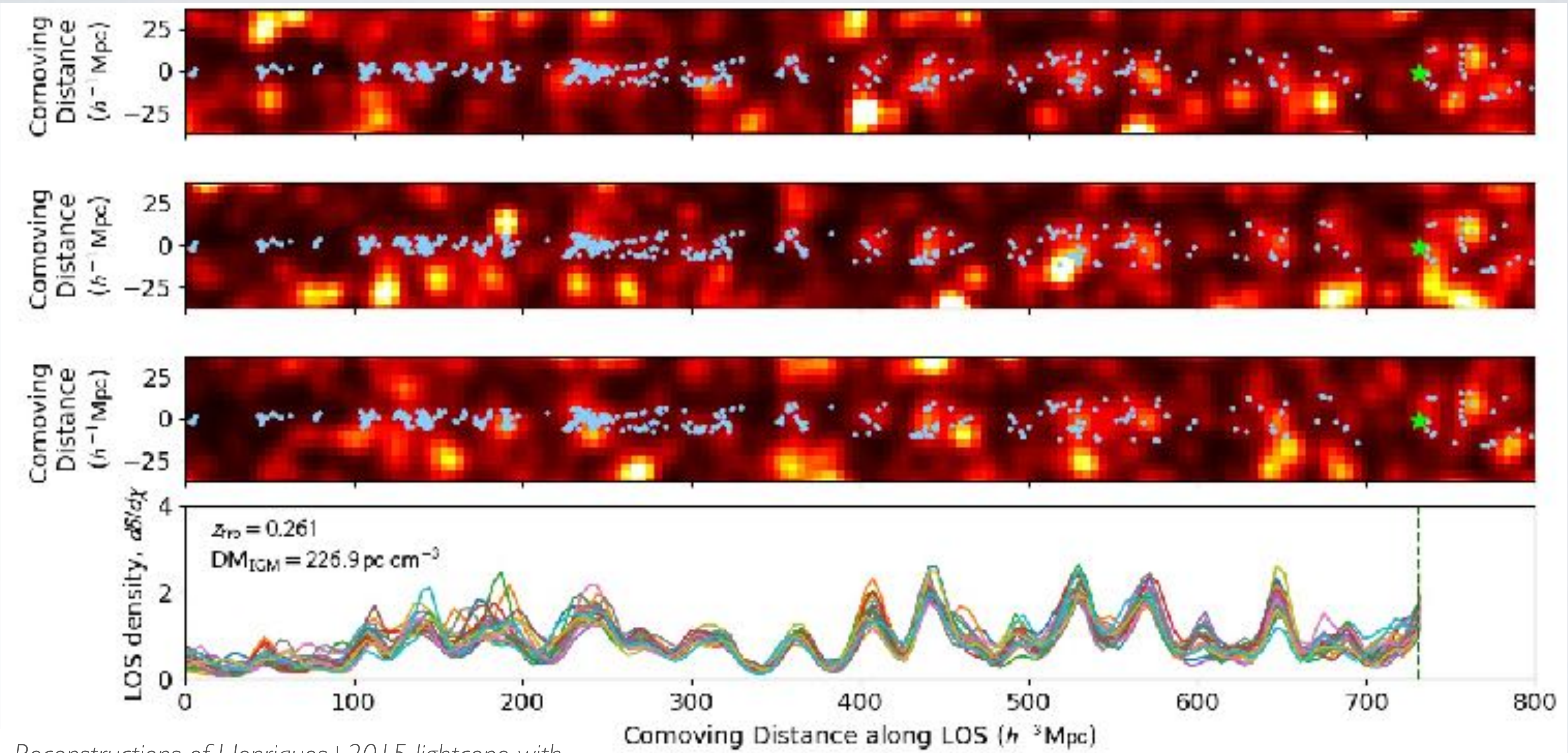
- Matter Density Reconstruction ≡ Estimation of underlying 3D matter density field given a spectroscopic galaxy survey catalog
- Apply ARGO Bayesian density reconstruction code to galaxy survey data (Ata et al 2015)
  - Hamiltonian MC method sampling lognormal matter density field
- Significant recent improvements to incorporate multiple 'tracers' each with their own selection functions

Metin Ata
Kavli IPMU Postdoc



Ata et al 2015

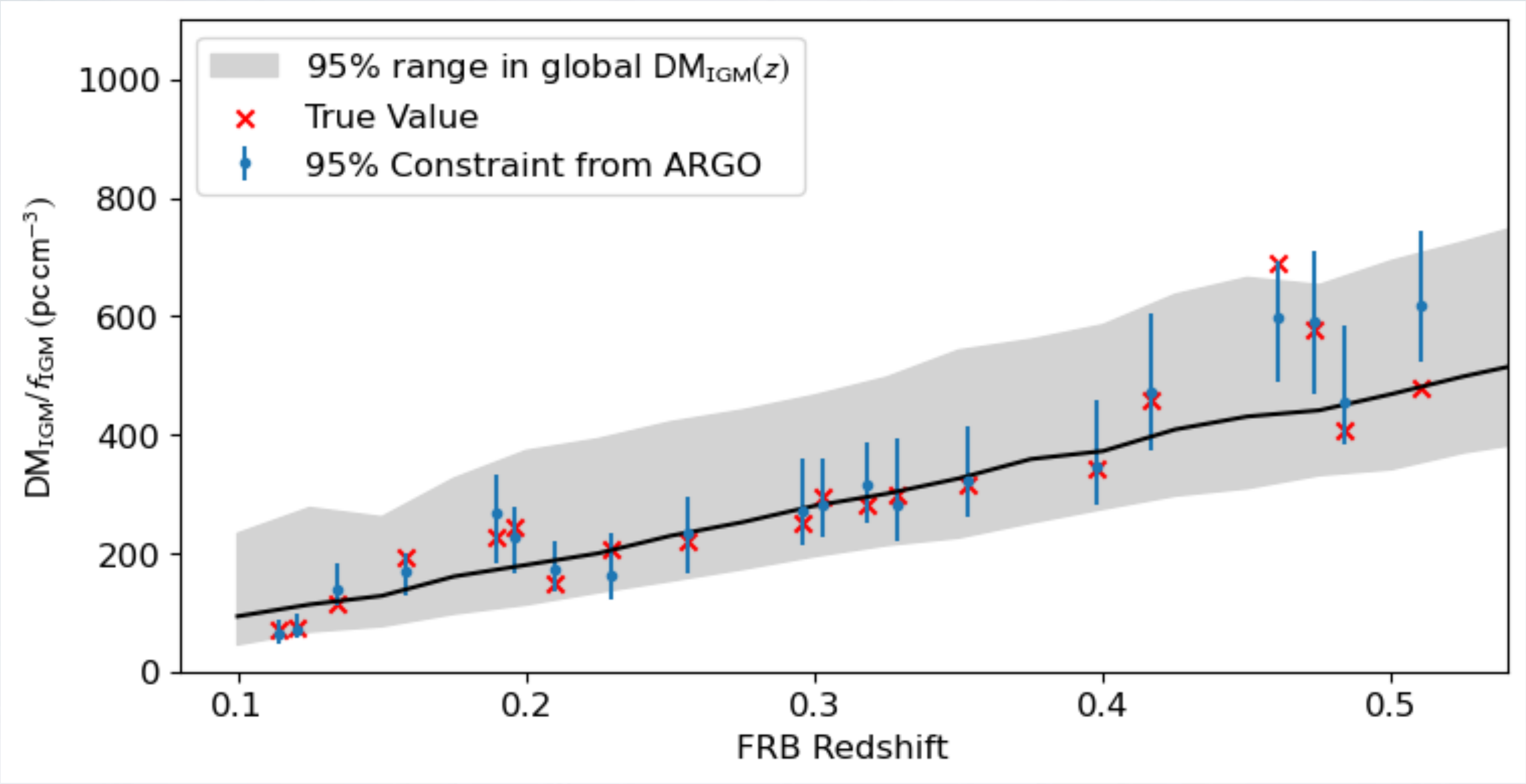
ARGO Density Reconstruction



Reconstructions of Henriques+2015 lightcone with Metin's ARGO algorithm

- ARGO is Hamiltonian MC method, provides thousands of posterior realizations. Top 3 panels: 3 different density realizations from mock galaxy redshift sample (dots)
- Bottom: LOS density to simulated FRB, to be used to calculate model DM_{igm} given f_{igm}
- Scatter of different HMC realizations provide error estimate of reconstruction

ARGO DM vs Cosmic Variance



- Note: Cosmic variance here is only from DM_{igm} component
- Beat cosmic variance by ~2-3x on average (might improve further with algorithmic improvements)

Analogy to Linear Equations

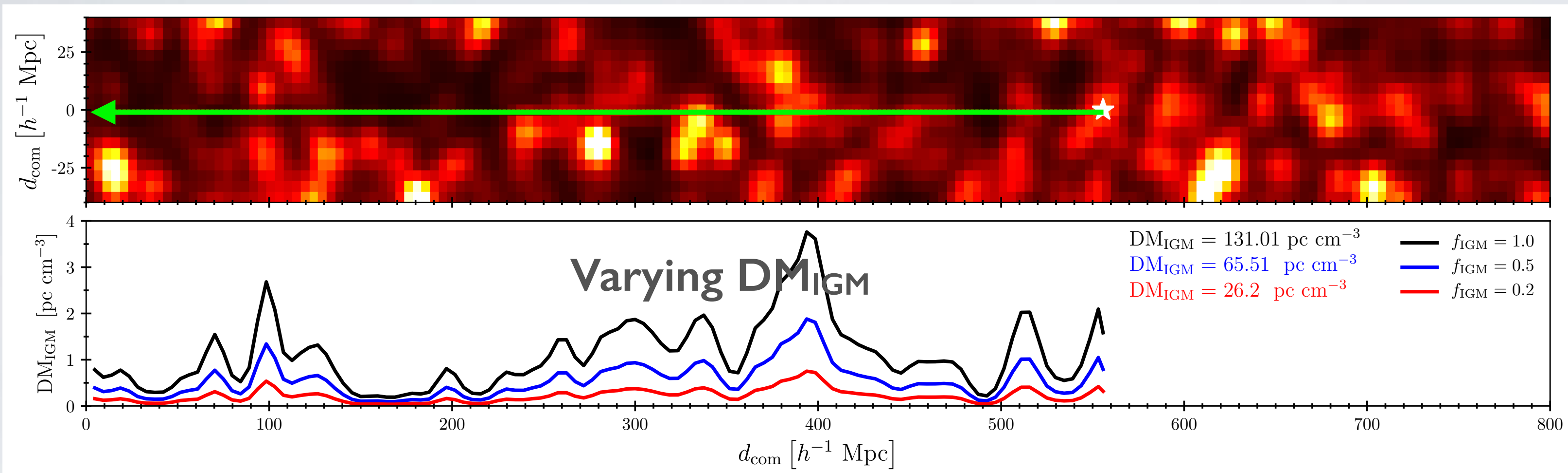
- Given an ensemble of FRBs and their foreground data, the problem becomes analogous to a linear equation: $\mathrm{DM}_i = \mathrm{DM}_{igm,i} + \mathrm{DM}_{halo,i} + \mathrm{DM}_{host,i}$

- Foreground galaxies and density field reconstruction allows us to compute the different DM components as a function of free parameters

$$\begin{bmatrix} \mathrm{DM}_1 \\ \mathrm{DM}_2 \\ \mathrm{DM}_3 \\ \vdots \end{bmatrix} = \begin{bmatrix} \mathrm{DM}_{igm,1}(f_{igm}) & \mathrm{DM}_{cgm,1}(r_{max}, f_{hot}) & \mathrm{DM}_{\mathrm{host}} \\ \mathrm{DM}_{igm,2}(f_{igm}) & \mathrm{DM}_{cgm,2}(r_{max}, f_{hot}) & \mathrm{DM}_{\mathrm{host}} \\ \mathrm{DM}_{igm,3}(f_{igm}) & \mathrm{DM}_{cgm,3}(r_{max}, f_{hot}) & \mathrm{DM}_{\mathrm{host}} \\ \vdots & \vdots & \vdots \end{bmatrix}$$

Measured from FRB itself *Computed from foreground data*

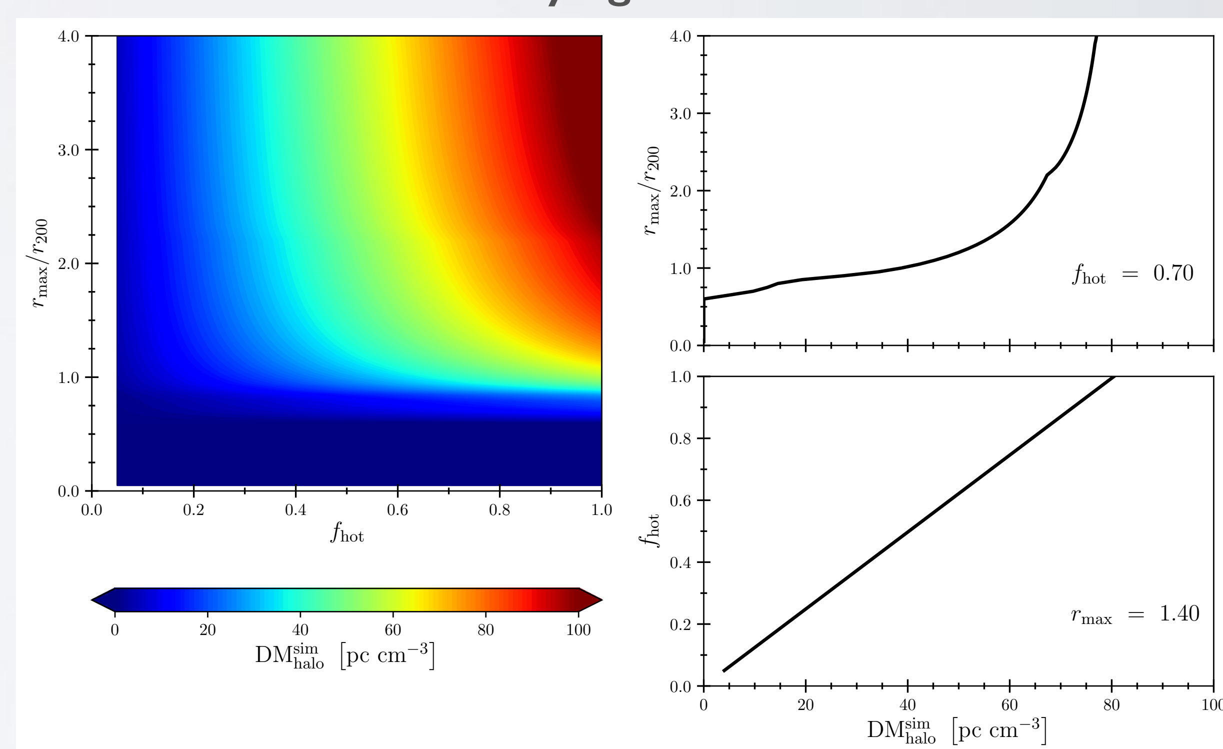
Parameter Analysis



Ilya Khrykin
Kavli IPMU Postdoc

$$\mathscr{L} \propto \frac{\left(\mathrm{DM_{obs}} - \mathrm{DM_{model}}(f_{igm}, r_{max}, f_{hot}, DM_{host})\right)^2}{\sigma^2}$$

Varying DM$_{halo}$



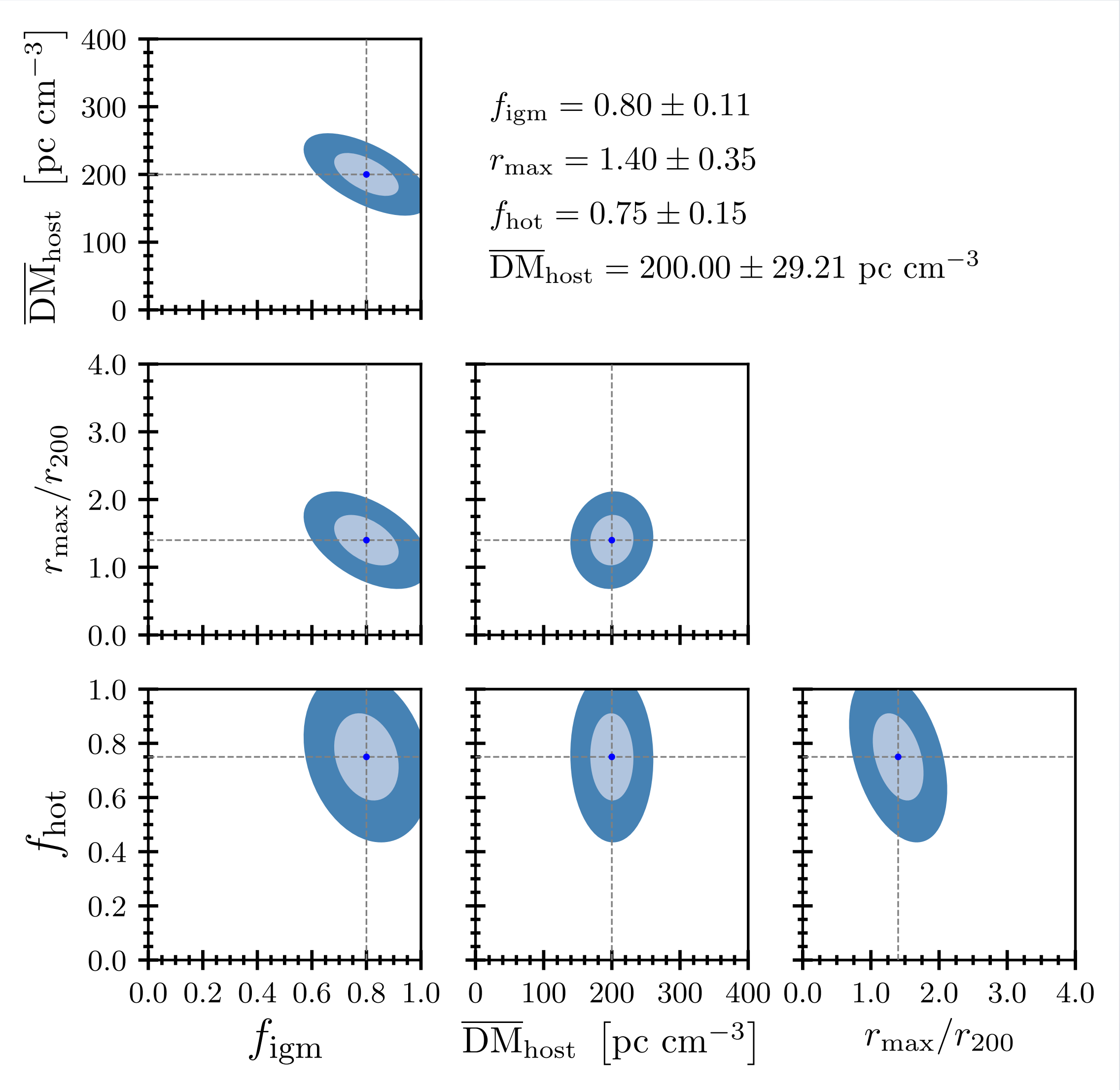
- We want to sample the parameter space to place simultaneous constraints on [f_{igm}, r_{max}, f_{hot}, DM$_{host}$], assuming cosmology is fixed
- In layperson terms, want find the combination of parameters that best fits the observed DM given the foreground galaxy distribution for each FRB

Fisher Forecast

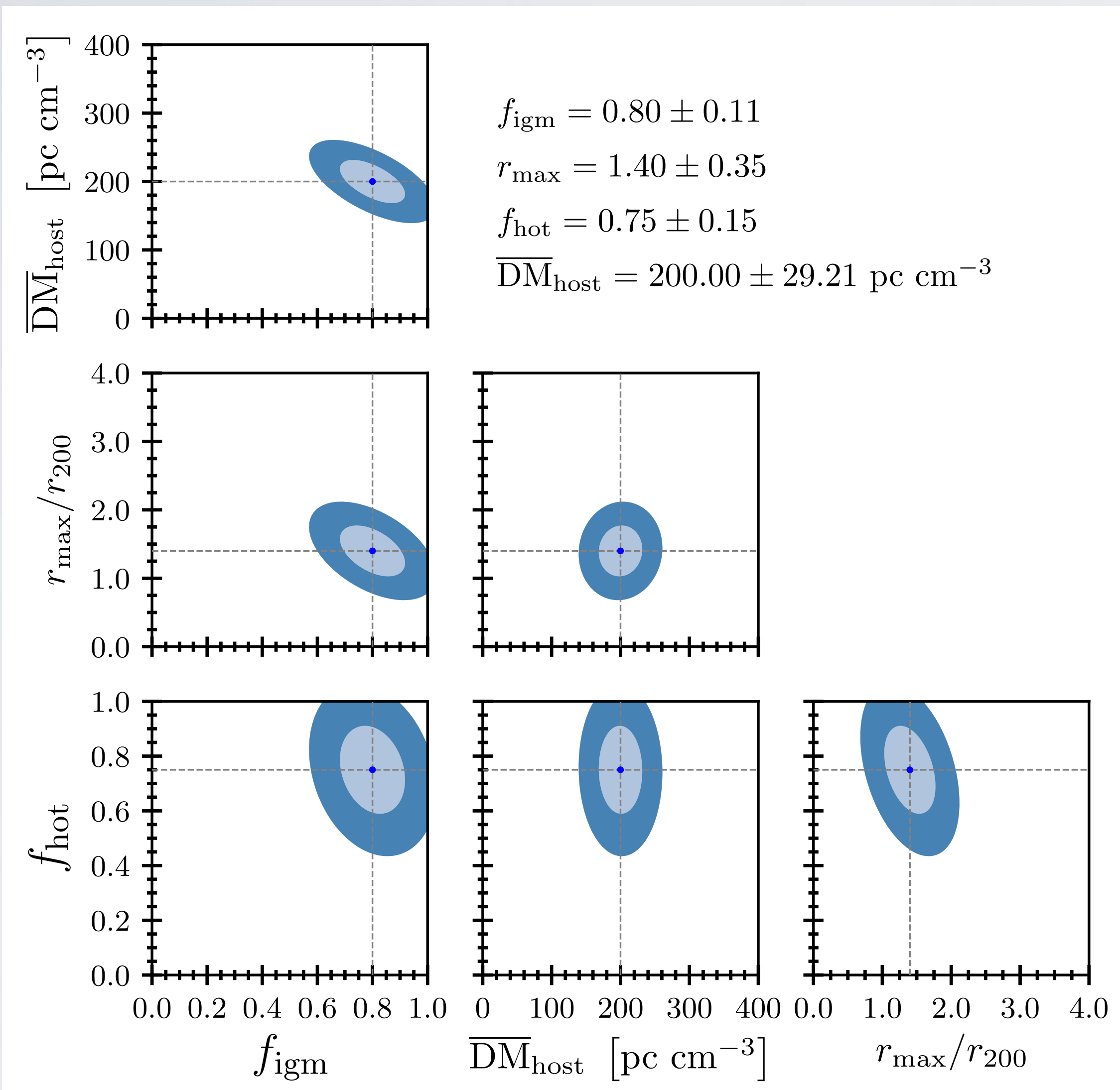
- Sampling the scatter caused by the ARGO uncertainties and intervening halo masses allows us to quickly calculate the Fisher matrix

$$\mathcal{F}_{i,j} = \sum_b \frac{1}{\sigma_b^2} \frac{\partial f_b}{\partial p_i} \frac{\partial f_b}{\partial p_j}$$

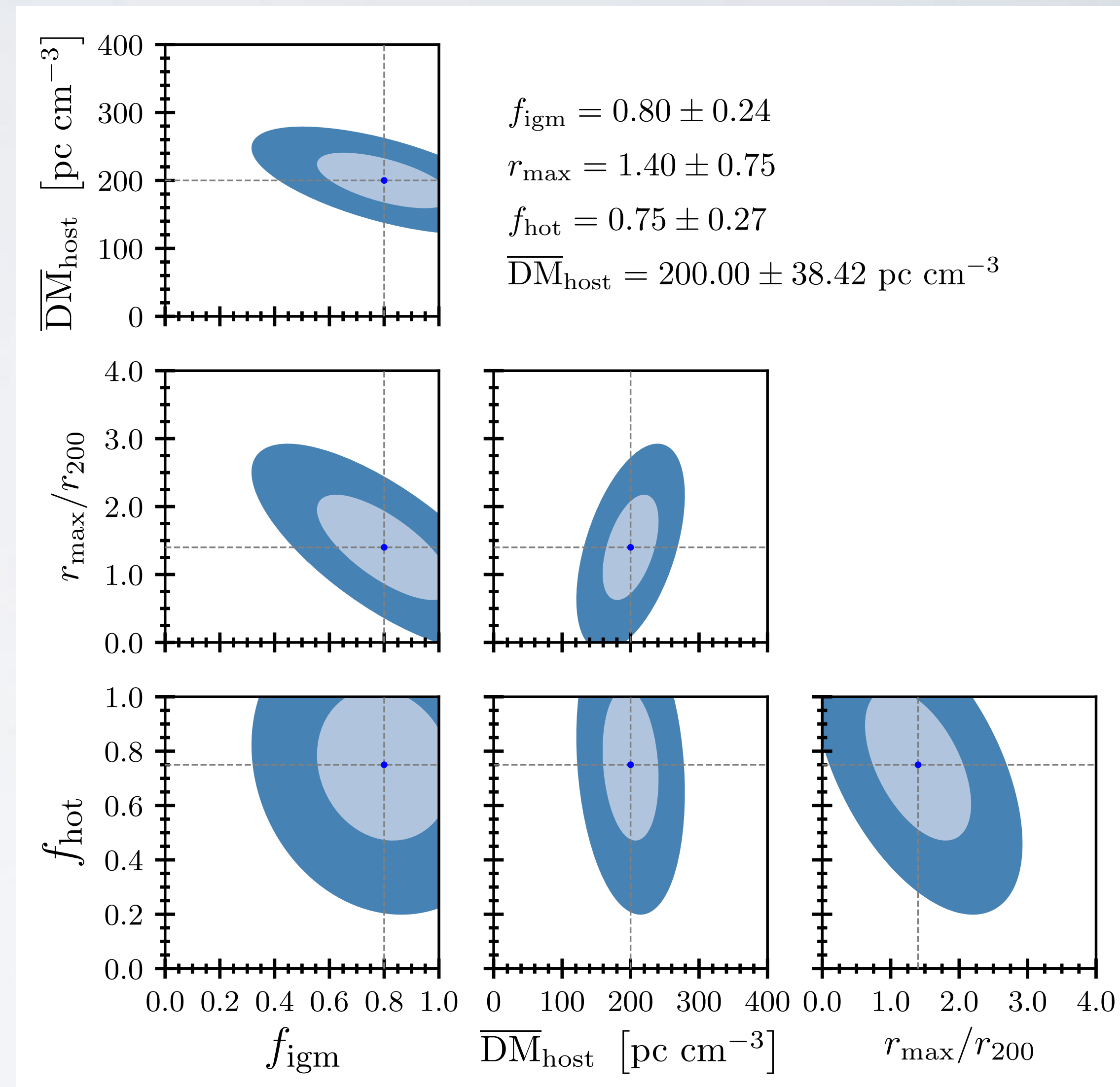
- Assume errors in LOS density from ARGO, and 0.3 dex halo masses uncertainty of intervening galaxies (<10 arcmin)
- Right: estimated model uncertainties from 30 FRBs at 0.1<z<0.5
- Approx ~10% constraints expected for f_{igm} and ~20% constraints on CGM halo parameters
- Some degeneracy between DM_{host} and f_{igm}, but little degeneracy between IGM and halo parameters



$N_{frb}=30, 0.1<z<0.5$



$N_{frb}=100, 0.1<z<0.5$, No Foreground Data



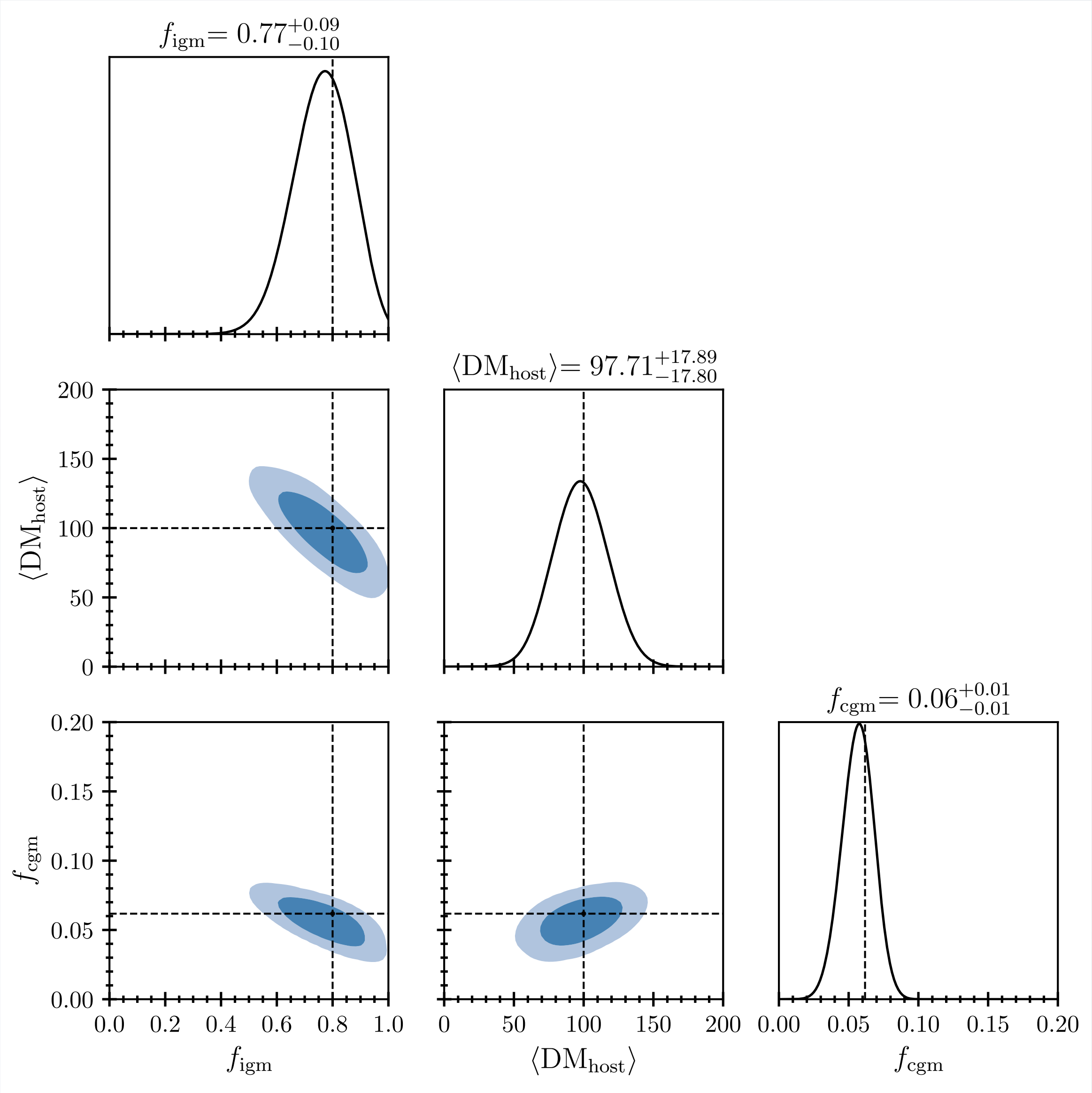
In the absence of foreground data, ~25x more localized FRBs would be needed to make equivalent constraints on the baryon partition between IGM and CGM (see also Batten+2022)

CGM/IGM Baryon Partition

- Alternative parametrization: convert r_{max} and f_{hot} into the global fraction of CGM baryons, such that $f_{cgm}+f_{igm}+f_{stars}=1$

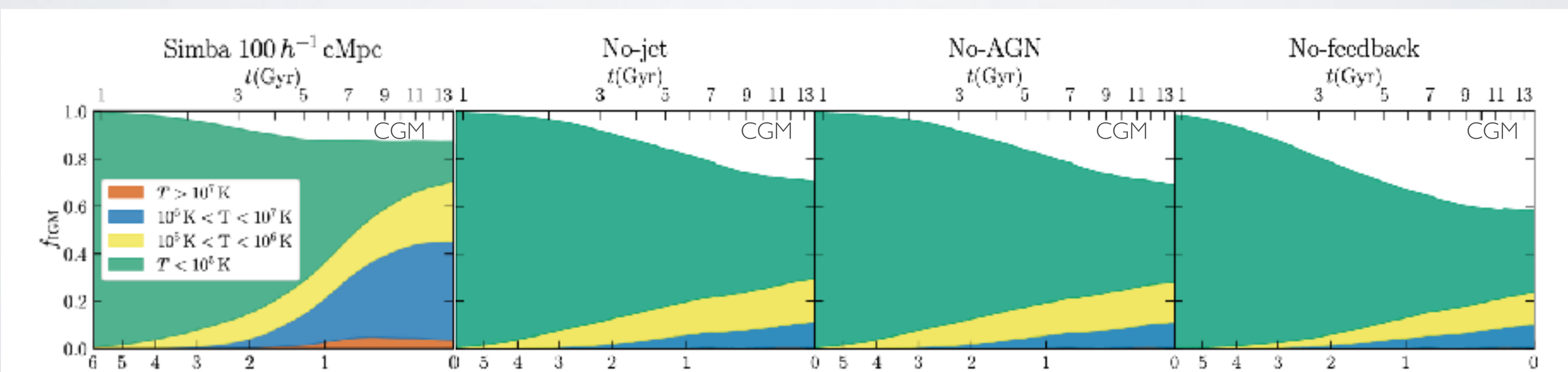
- Expect to be able to measure f_{cgm} to within a couple of percent!

N_{frb}=30, 0.1<z<0.5



The Imprint of Galaxy Feedback on Cosmic Baryon Distribution

- Galaxy feedback regulates the relative amount of gas in CGM ($r < r_{200}$) vs IGM
    - See e.g. Simba sims with different feedback models in Sorini+2021
    - Note: the FRB DM does not care about temperature of IGM
- Even ~30 FRB + foreground maps can be an interesting probe of galaxy feedback! (c.f. ~1000 FRBs needed to demonstrate effect of feedback *without* foreground data)



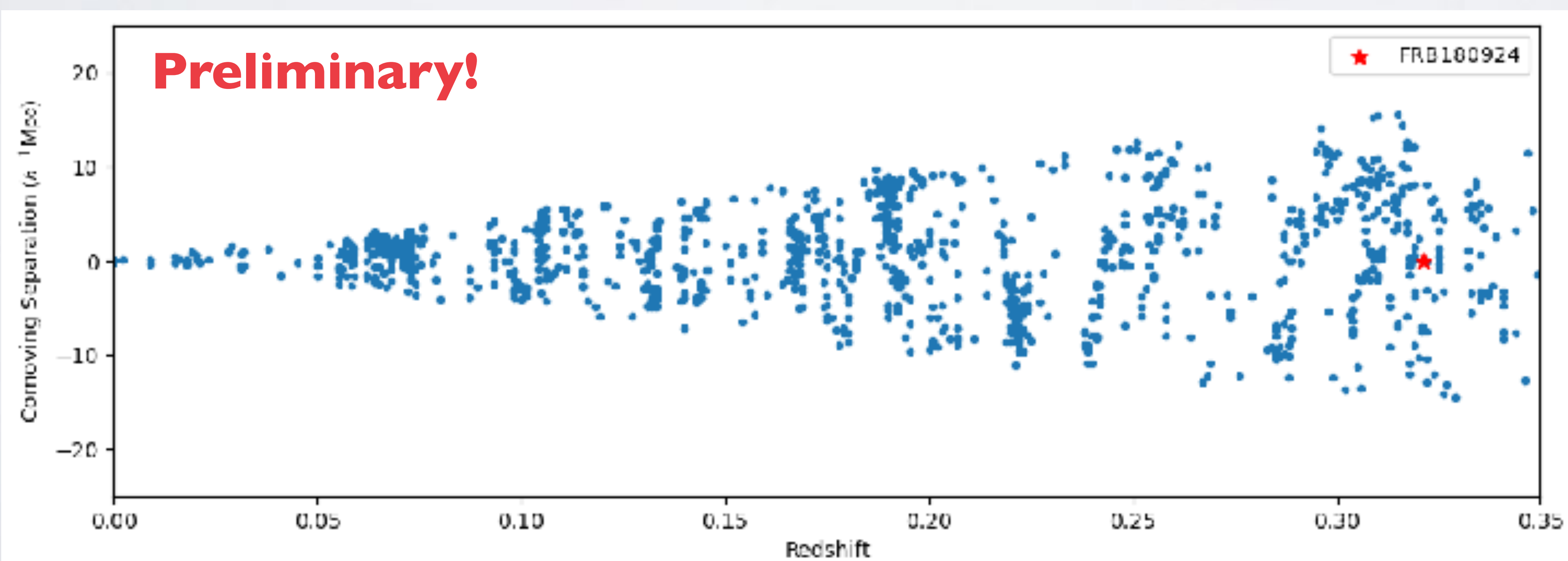
Sorini+2021

FLIMFLAM

- FRB Line-of-sight Ionization Measurement From Lightcone AAOmega Mapping (FLIMFLAM) Survey (2020-2023)
- Co-PIs: KGL and Jeff Cooke (Swinburne)
- Using 4m AAT with AAOmega/2dF spectrograph: ~350 science fibers simultaneously over a 3.1 sq deg FOV
- Observational goal: ~25-30 FRB fields at $0.05<z<0.5$
- Approx 10 localized FRBs now covered → DR1

FLIMFLAM Survey Design

- Typical FRB field will be targeted for multiple visits of a single 3.1 deg^2 field centered on the FRB
- Simple magnitude-limited selection to enable clean determination of selection functions
- Magnitude limit, number of galaxies and exposure times depend on FRB redshift. But for a fiducial z=0.3 FRB:
  - Selection of r<19.8 (same as GAMA, Driver+2011)
  - ~1500-2000 galaxies per 2dF field → 1 night of AAT observations per FRB field
- Coordinated with 8-10m class observations of ~arcmin intervening galaxies, led by Simha, Tejos, Prochaska etc



Yuxin Huang
UTokyo Master's Student

Summary

- Localized FRBs with known redshifts provide a unique opportunity to target their foreground matter distribution with large-scale spectroscopic galaxy data → build bespoke models to compare with observed DM
- FLIMFLAM and associated programs aim to map foreground intervening galaxies and large-scale structure
  - Boosts the constraining power of localized FRBs toward cosmic baryons by >25x
  - In ~2 years, aim to constrain the partition of baryons between IGM and CGM to ~10% at z~0.2
  - Can also constrain global amount of CGM gas and radial extent. Currently using simple models tracing modified NFW as function of M_{200}, but more sophisticated modeling e.g. as function of SFR is possible
  - Use partition of CGM and IGM baryons is a unique probe of galaxy feedback
- Future interferometric FRB programs (e.g. CHIME Outrigger) in the North will be able to take advantage of DESI Bright Galaxies at z<0.3
  - Pushing toward the epoch of HeII reionization with 8m multiplexed facilities?

Future Work

- **Incorporate individual FRB DM_{host} estimates (if available) into the likelihood estimation**
- **Further improvements in ARGO reconstructions**
    - Better treatment of galaxy bias
    - More accurate modeling of selection functions
- **Improved estimation of halo mass**
    - Currently assume 0.3 dex uncertainty in estimating halo mass from stellar mass via SHMR
    - A factor of 2 error in the halo mass of intervening massive galaxies ($>10^{12}\ M_{\odot}$) can lead to large errors in DM_{halo}!
    - Can ML inference be applied to improve on the halo mass estimation?
- **Inversion of our method to identify FRB host galaxies**
    - If have multiple possible host galaxies with different redshifts, modeling the foreground DM_{igm} and DM_{halo} can help nail down the correct host!
- **More sophisticated modeling of DM_{igm} and DM_{halo}** using hydrodynamical simulations (e.g. Jaroszynski 2019, Batten+2020, Zhang+2021)
- **Leveraging foreground data for RM studies of cosmic magnetism**
- **Adopting cosmology parameters as free parameters (H_0, Ω_b etc)**

Comparison of Millennium with Illustris DM

- Comparison with Jaroszynski 2019: DM and variance from Illustris
- Solid curves: results from Jaroszynski. Note: separation between DM_{igm} and DM_{halo} is ambiguous!
- Points: varying Millenium density field smoothing length r_{sm} and halo cutoff r_{max} (in principle f_{hot} should also be free parameter)
- Conclusion: r_{sm} ~ 0.5 Mpc/h is a good smoothing scale to mimic diffuse IGM with matter density field
- Note: σ_{igm} !=10 pc/cm^3