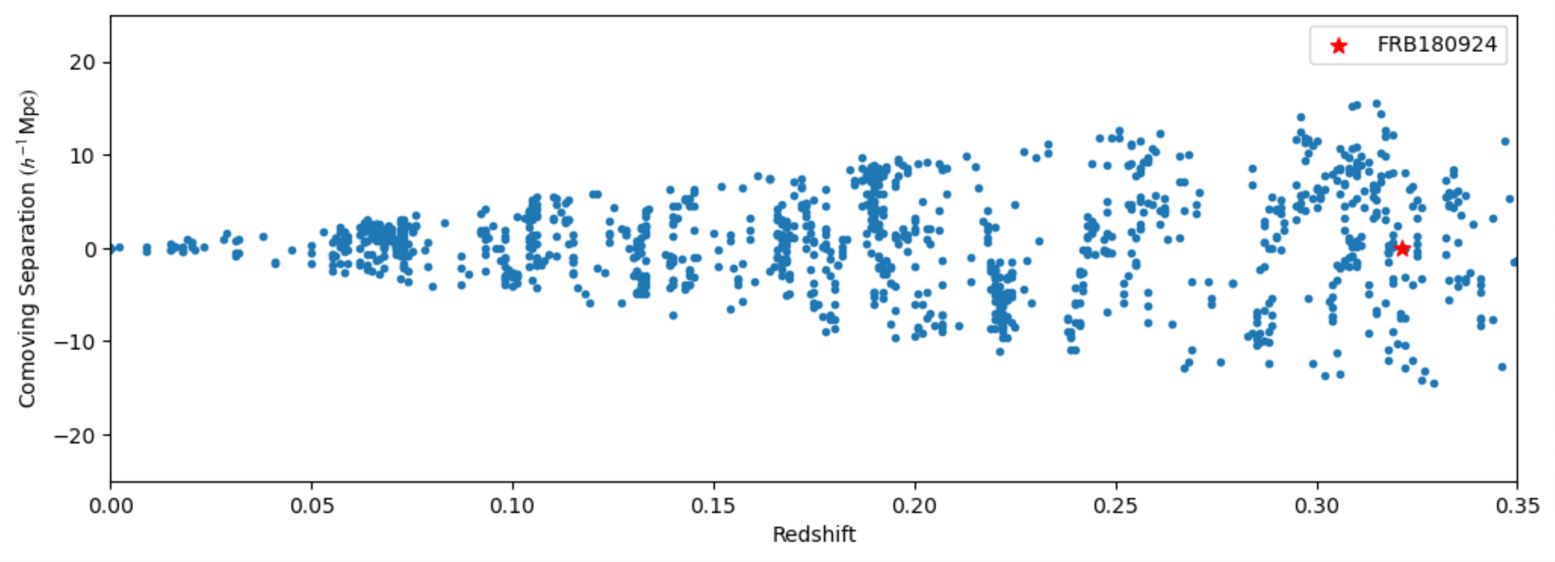
Constraining the Cosmic Partition of IGM and CGM Baryons with FRB Foreground Mapping



The Co-evolution of the Cosmic Web and Galaxies across Cosmic Time, KITP

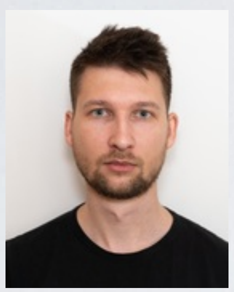
December 798, 2020

Khee-Gan ("K.-G") Lee

Kavli IPMU, University of Tokyo

Credits

Metin Ata
Kavli IPMU Postdoc → Stockholm U



Ilya Khrykin
Kavli IPMU Postdoc

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

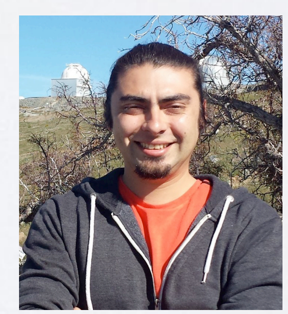
CRAFT

FAST & FORTUNATE
FRB FOLLOW-UP

Yuxin Huang
UTokyo PhD Student

Sunil Simha
UCSC PhD Student

Xavier Prochaska
UCSC

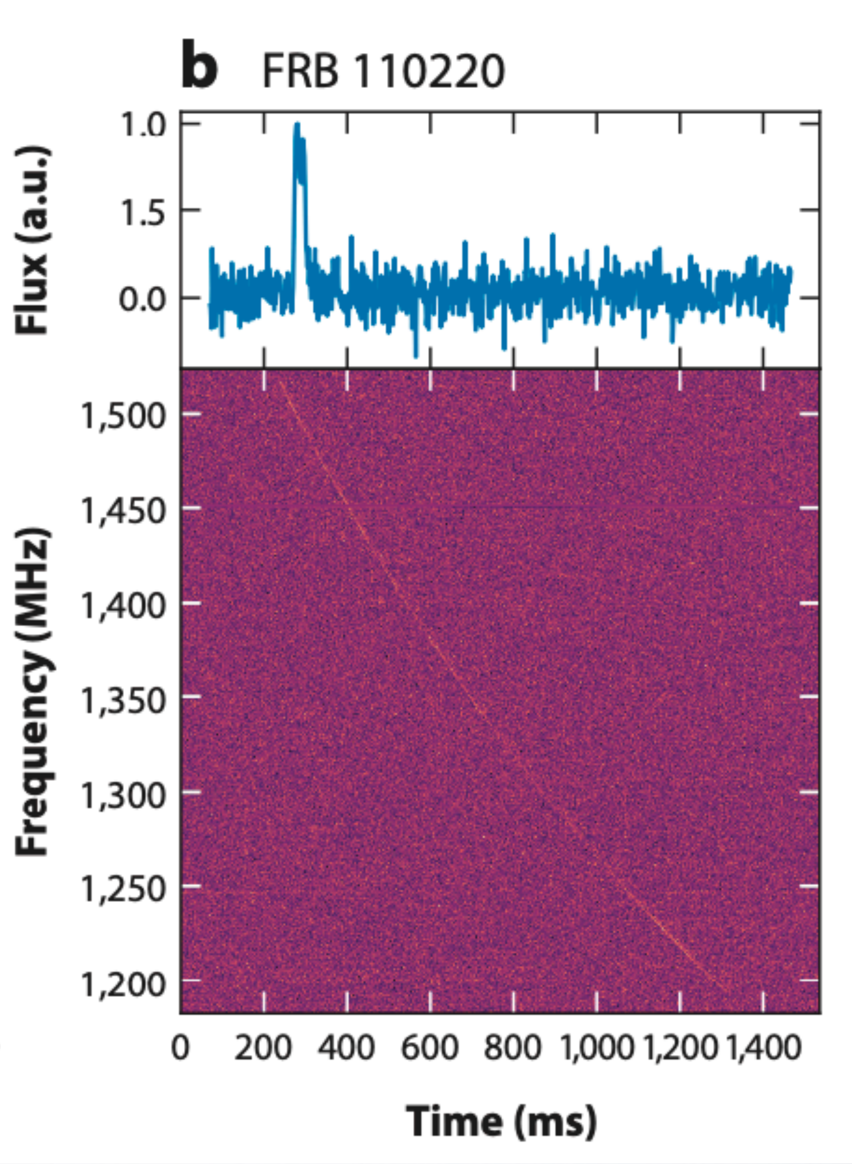


Nicolas Tejos
PUC Valparaiso

Jeff Cooke
Swinburne

Fast Radio Bursts

- 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

FRB Dispersion Measures (DM)

- Integrated free electrons along the line-of-sight cause a frequency shift in a signal: $\mathbf{DM} = \int n_e \mathbf{d}s$

- For extragalactic sightlines, the DM is dominated by the ionized IGM and CGM in the z<1 Universe.

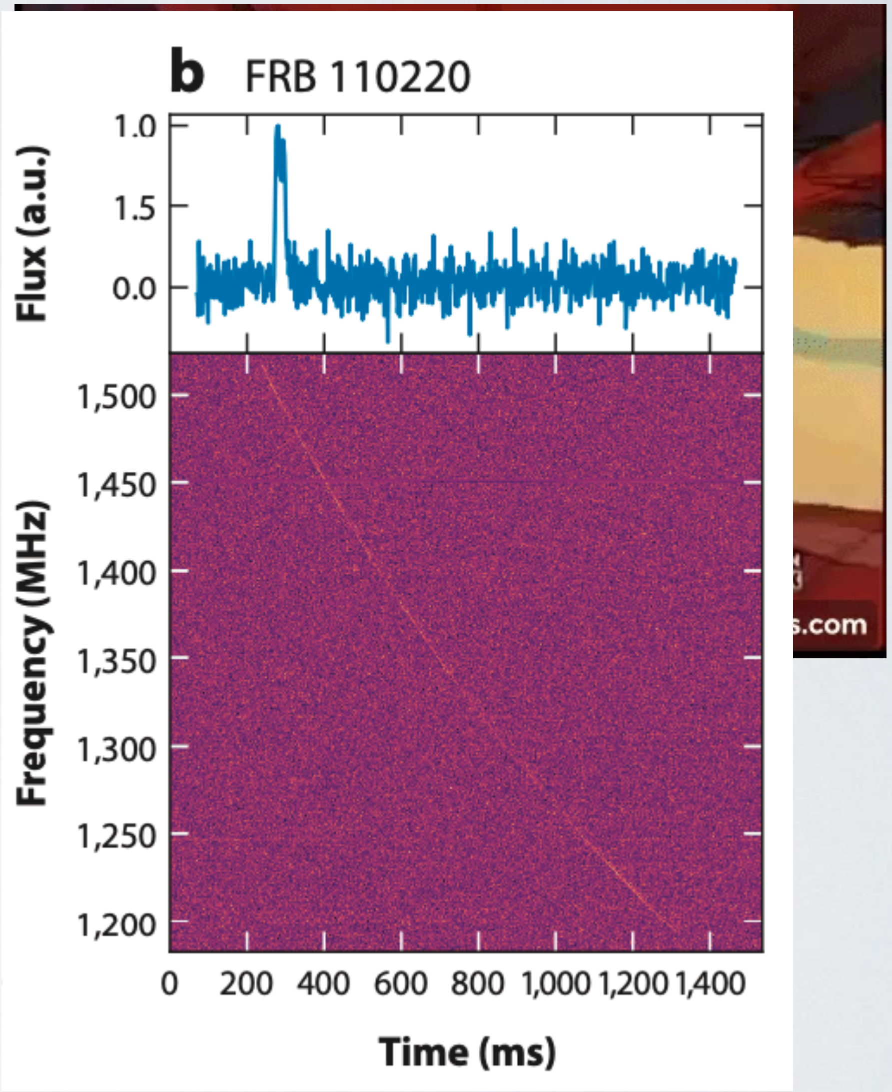
  - There is a neutral fraction entrained in IGM/CGM but is negligible (Ω_{HI}<0.5%). So $n_e \rightarrow n_{bar}$

  - Metallicity/Ionization dependence negligible post-reionization (<<1%)

Probing cosmic free electrons → cosmic baryons

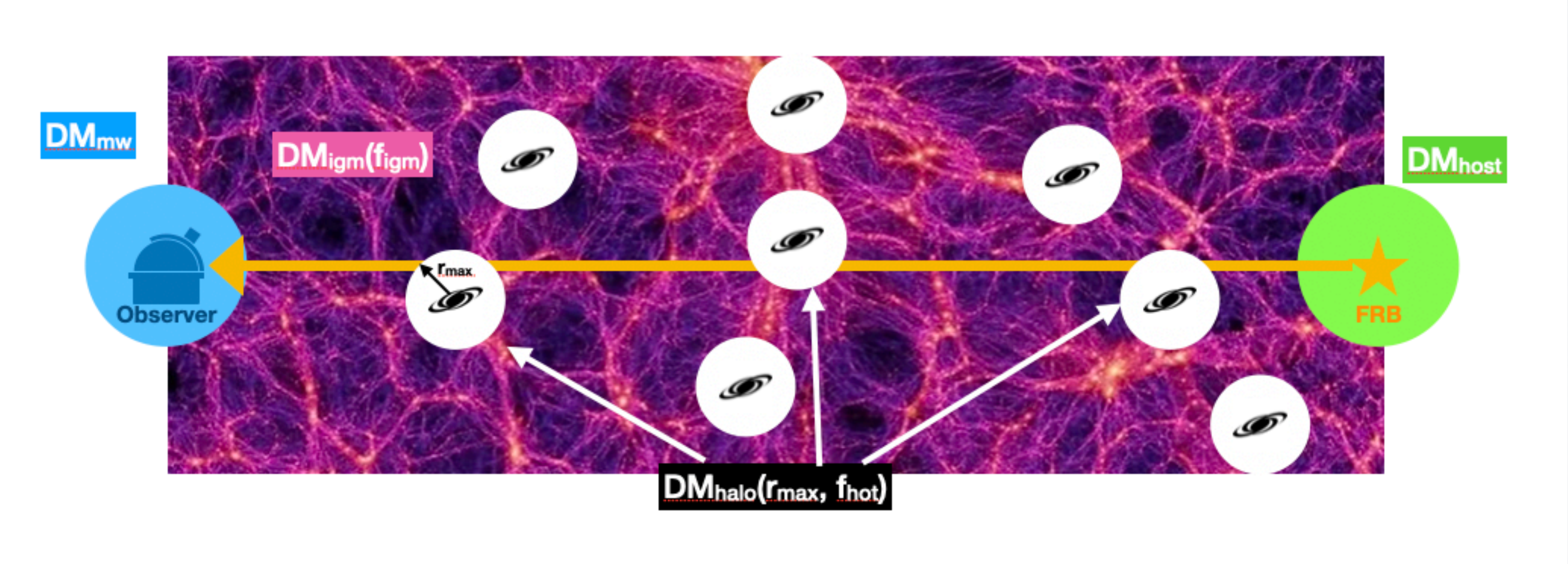
- FRBs thus offer a clean probe of the baryons in IGM+CGM, especially if the redshift or distance is known

See review by Cordes & Chatterjee, ARAA 2019



Sonification Credit: Vivek Gupta (Swinburne U)

Contributions to the Extragalactic DM



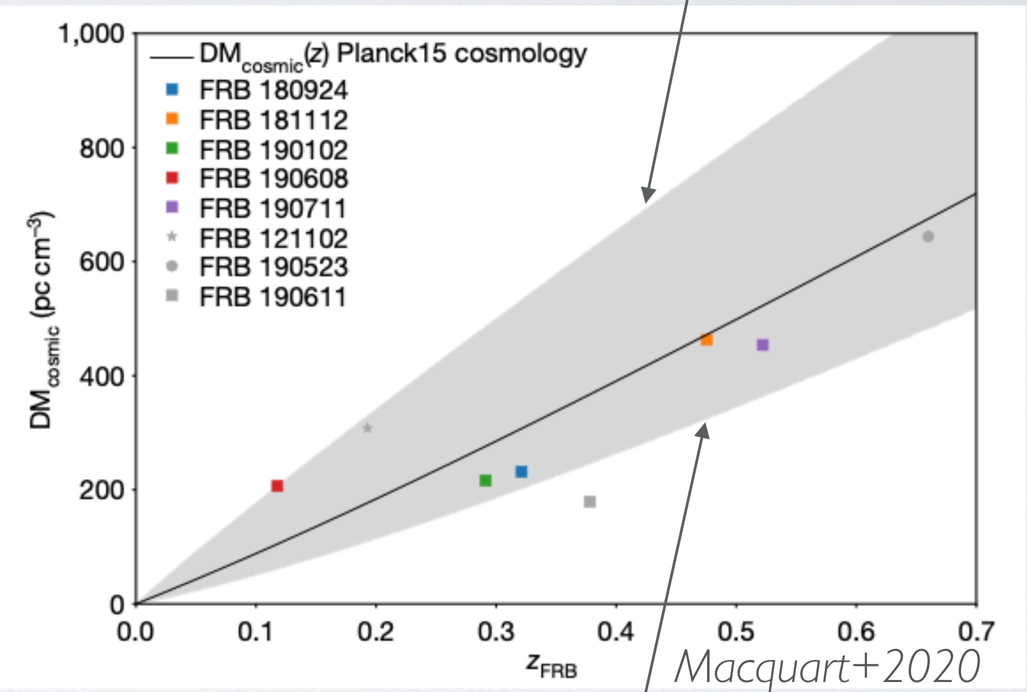
- FRB signal measures the aggregate DM, assumed to be DM = DM_{mw} + DM_{igm} + DM_{halos} + DM_{host}
  - DM_{igm} comes from diffuse large-scale structure (~Mpc-scale voids, sheets, filaments etc, with matter densities of $0 \lesssim \rho_{matter}/\langle\rho_{matter}\rangle \lesssim 10$)
  - DM_{halos} arises directly from intersecting the CGM of intervening galaxies (~r_{200} or < few arcmin)
- $$\mathrm{DM_{igm}} = f_{igm} \frac{\Omega_b}{(\Omega_b + \Omega_{dm})} \int \frac{n_{\mathrm{matter}}(s)}{(1+z)} ds$$

The Macquart Relation

- Macquart+2020 demonstrated that DM-redshift relationship of localized 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



Sightlines passing through underdense regions and no intervening CGM

Assumptions

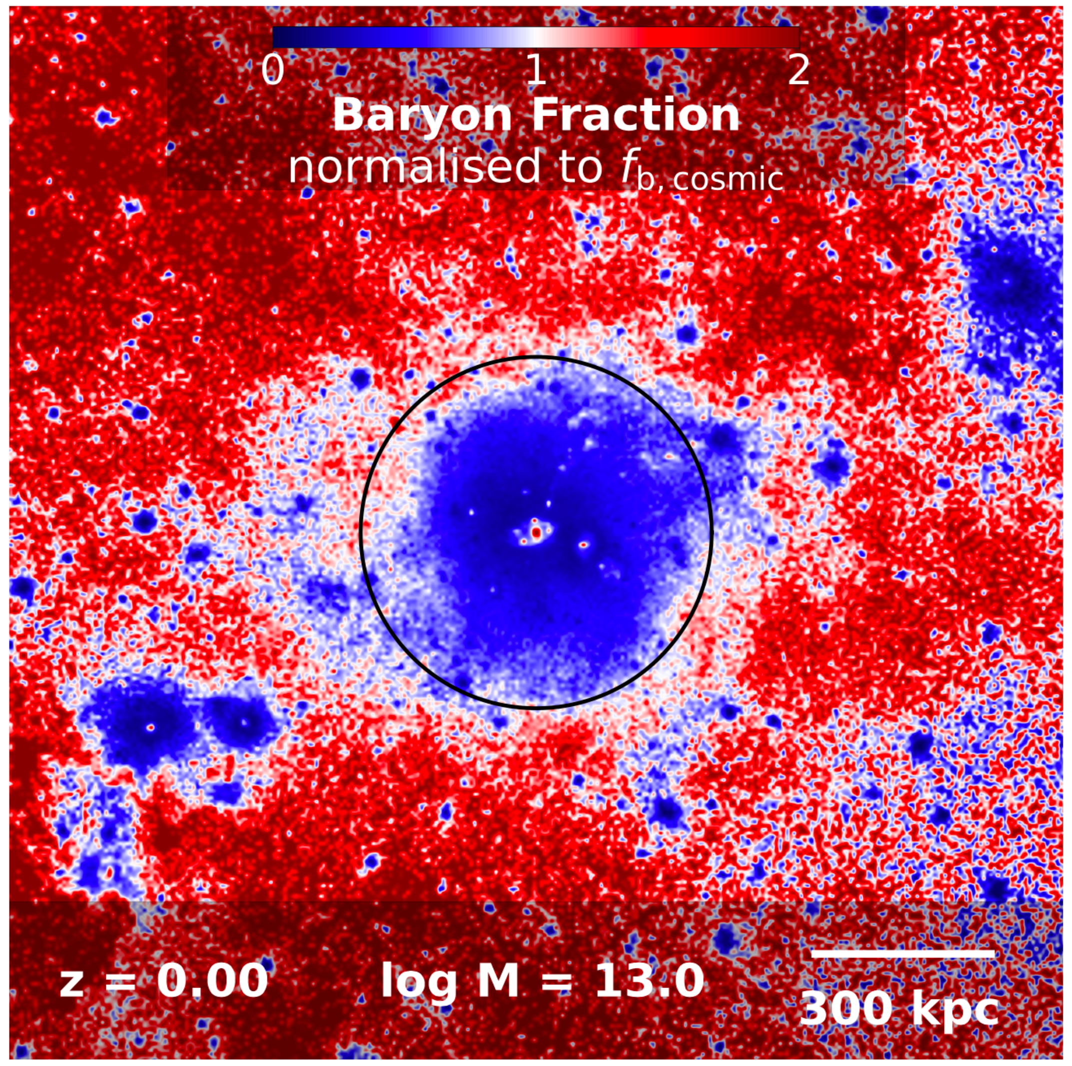
- There is an diffuse IGM contribution of ionized gas that traces the underlying large-scale (>Mpc) density field which follows ΛCDM cosmology

- There exists a CGM contribution residing in galaxy halos that traces a NFW-like profile out to ~100kpc scales

- Observations of foreground galaxies on both large- and small-scales in front of localized FRBs should therefore allow us to constrain their relative distributions

Scientific Question

- Approx ~50% of dark matter is within galaxy halos at z~0.
- If assume baryons trace the overall density field, then expect ~50% of baryons to lie inside halos also. This is likely not true!
- Galaxy/AGN feedback processes are expected to remove gas from galaxy halos, so in hydro sims, $f_{hot} << \rho_{bar}/\rho_m$
- **The reduction in baryon fraction and its sphere of influence has never been directly constrained** observationally for ~L* galaxies

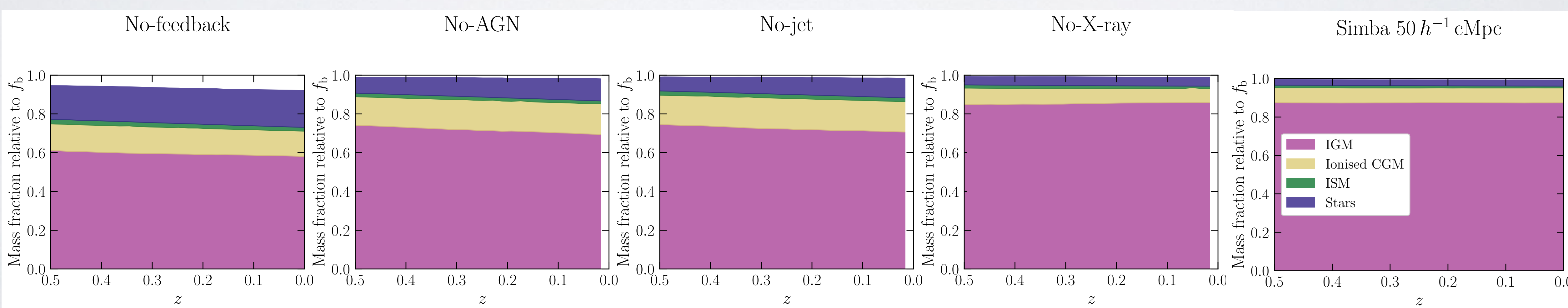


Baryon fraction around a small group; Ayromlou+2022 (arXiv:2211.07659)

The Imprint of Galaxy Feedback on the Cosmic Baryon Budget

- 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 ~20 FRBs + foreground maps can be an interesting probe of galaxy feedback! (c.f. >1000 localized FRBs needed to detect effect of feedback *without* foreground data, Batten+2022)

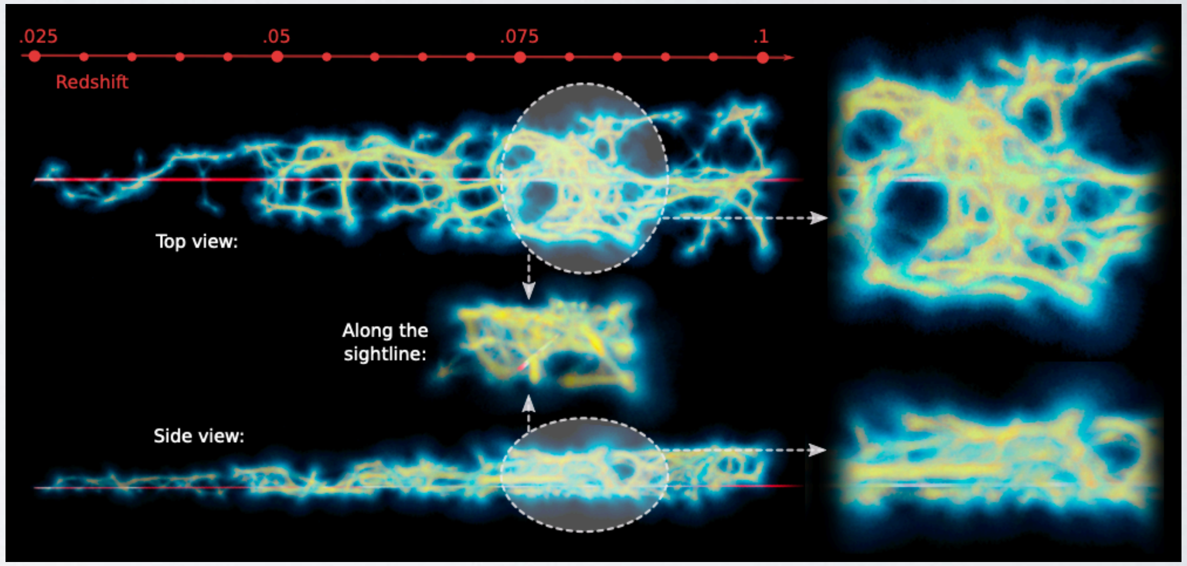
Daniele Sorini
Edinburgh→Durham

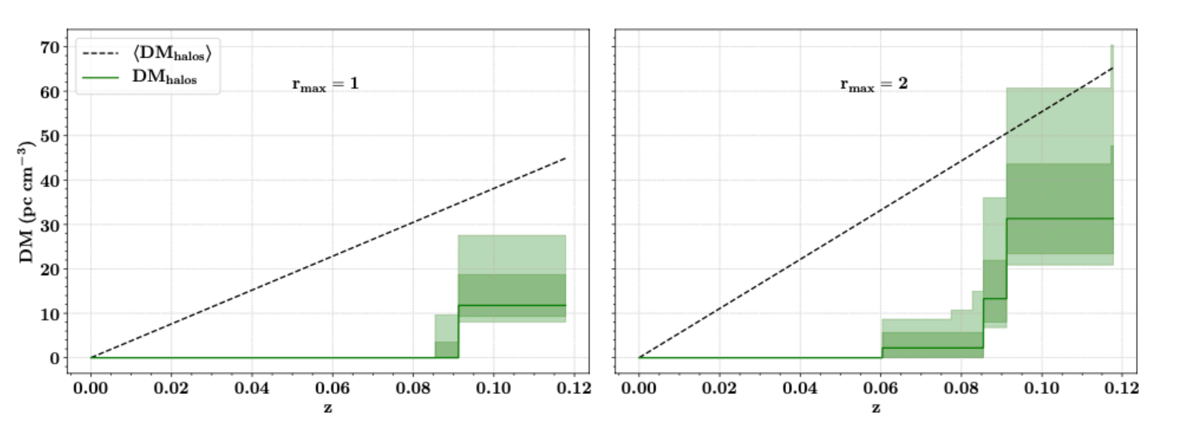


Sorini & Lee, in prep

FRB190608 (Simha+2020)

- First application of foreground galaxy spectroscopy to a localized FRB
- z=0.117 FRB
- Used SDSS spectroscopic sample to estimate both DM_{igm} and DM_{halo} contributions (<u>with assumptions on halo CGM model and f_{igm}</u>)
- Next step would like to obtain equivalent foreground data on a large sample of localized FRBs out to z<0.5, then use Bayesian framework to constrain f_{igm} and CGM model as free parameters



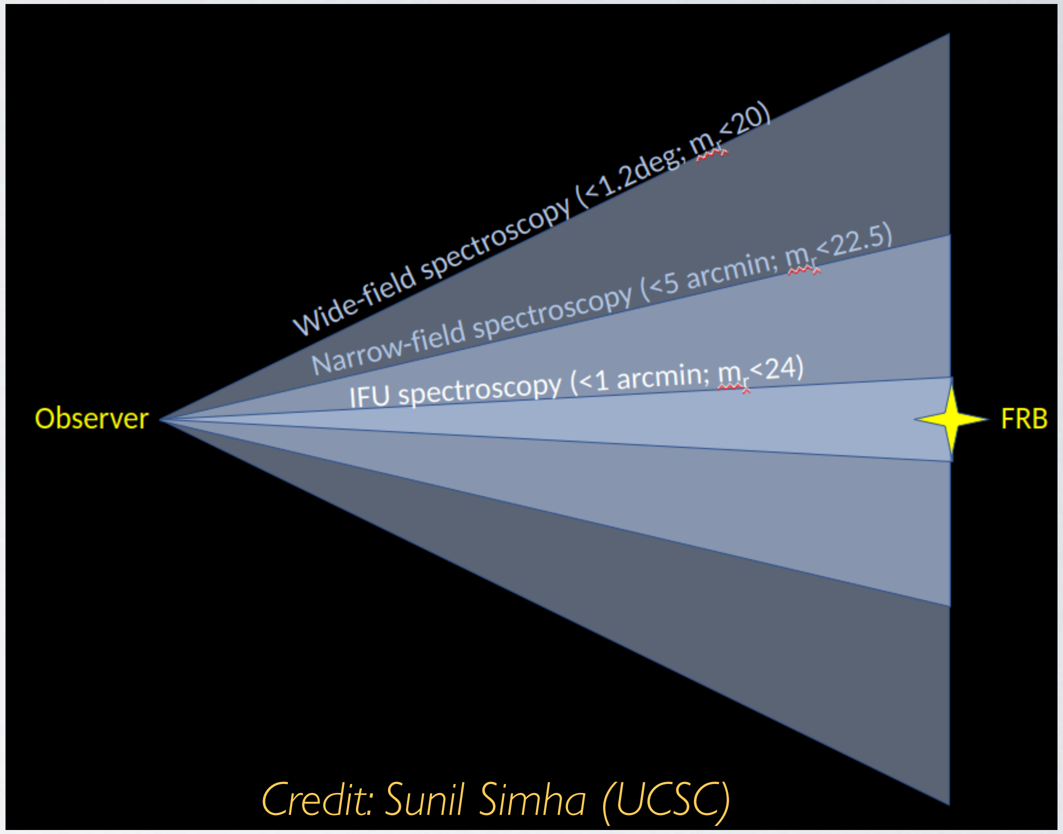


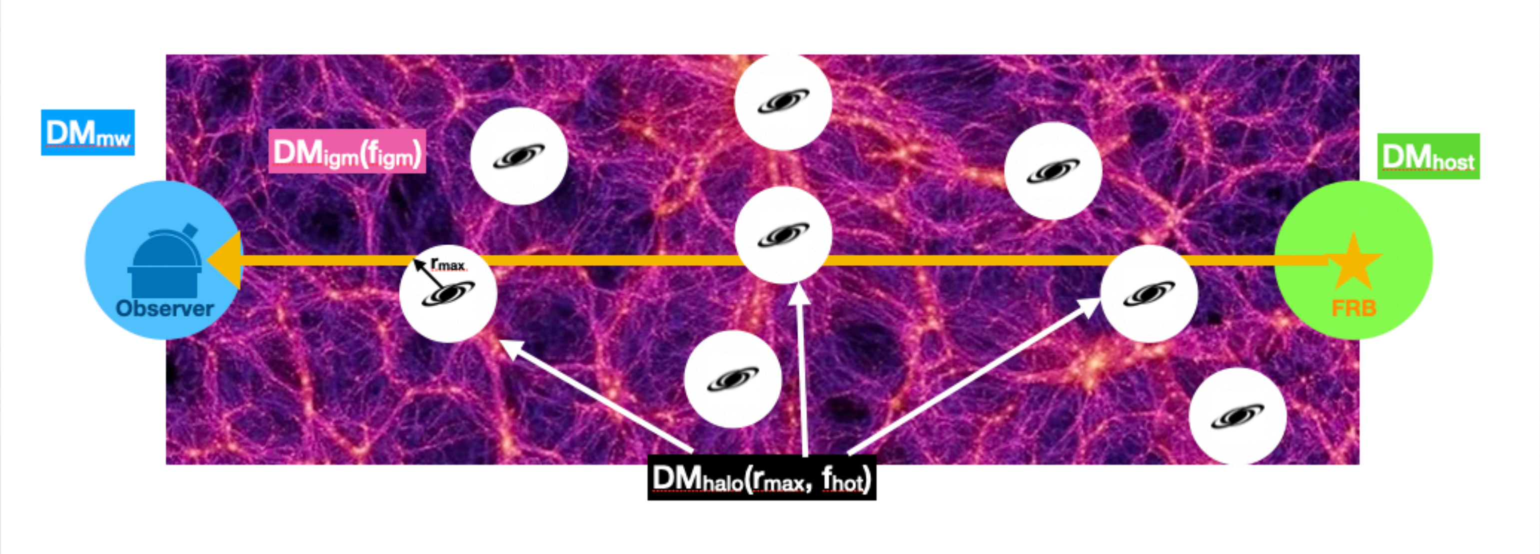
Simha et al 2020

Observational Design for FRB fields

'Wedding cake' strategy driven by dichotomy between:

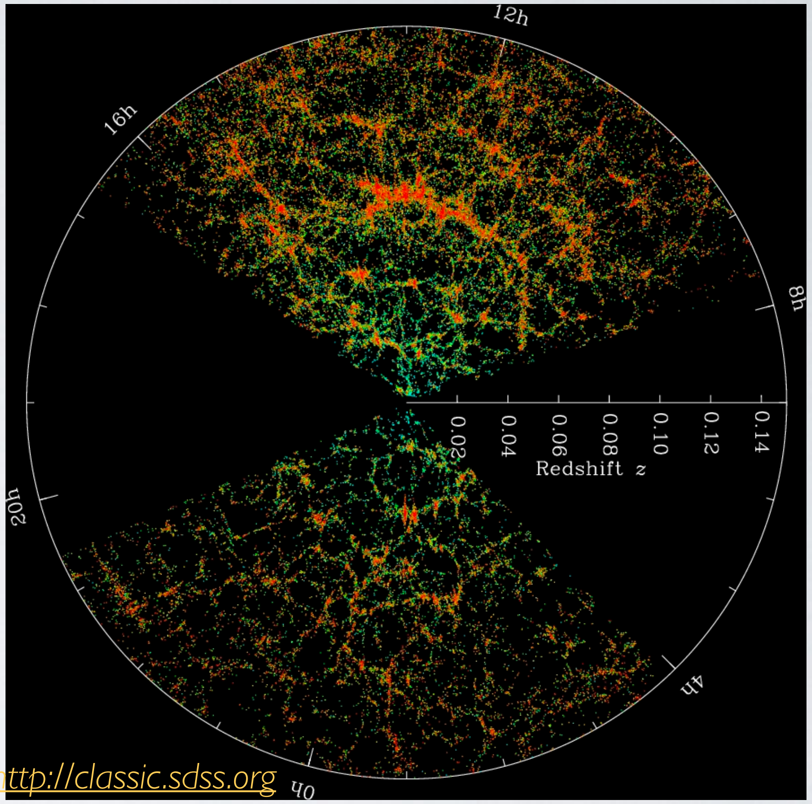
- halo contribution (~10-100kpc physical or arcmin angular scales)
  - 8-10m class IFU observations to target ~24th mag sources within ~1 arcmin (e.g. Keck-KCWI or VLT-MUSE)
  - 8-10m class multiobject spectroscopy of few dozen ~22 mag galaxies within a few arcmin (e.g. Keck-DEIMOS, Gemini-GMOS)
- large-scale (~Mpc/degree) cosmic web contributions
  - Wide-field spectroscopy with 2-4m telescopes





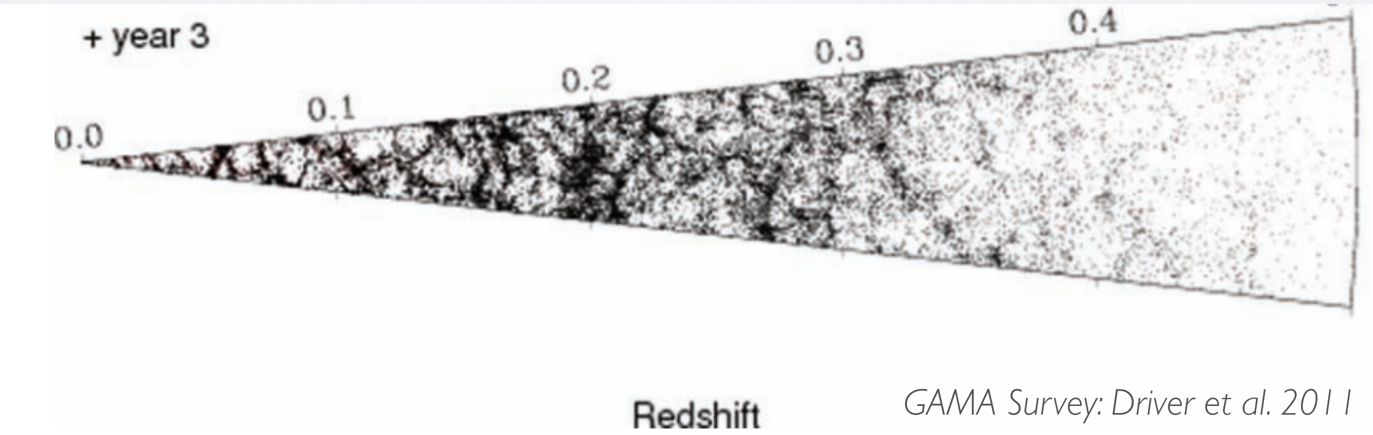
What is needed to map the cosmic web?

Requires shallow-but-wide spectroscopy of thousands of galaxies over at least multiple square degress



http://classic.sdss.org

- SDSS Main Galaxy Survey (DR7: Abazajian+2009): $r < 17.77$ over the Northern Hemisphere covering z≲0.15
- GAMA Survey (Driver+2011, 2022) at a depth of r<19.8 and redshifts covering z<0.4. *But only 250 sq deg…*
- To-date, most localized FRBs are from ASKAP → Southern Hemisphere with little pre-existing spectroscopic coverage…



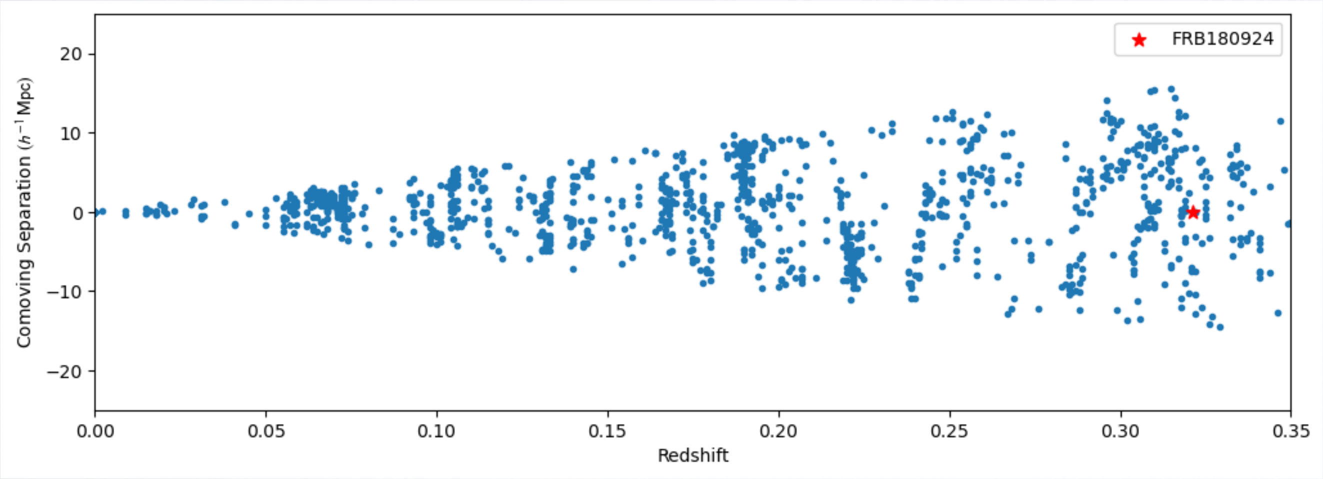
GAMA Survey: Driver et al. 2011

FLIMFLAM on the AAT

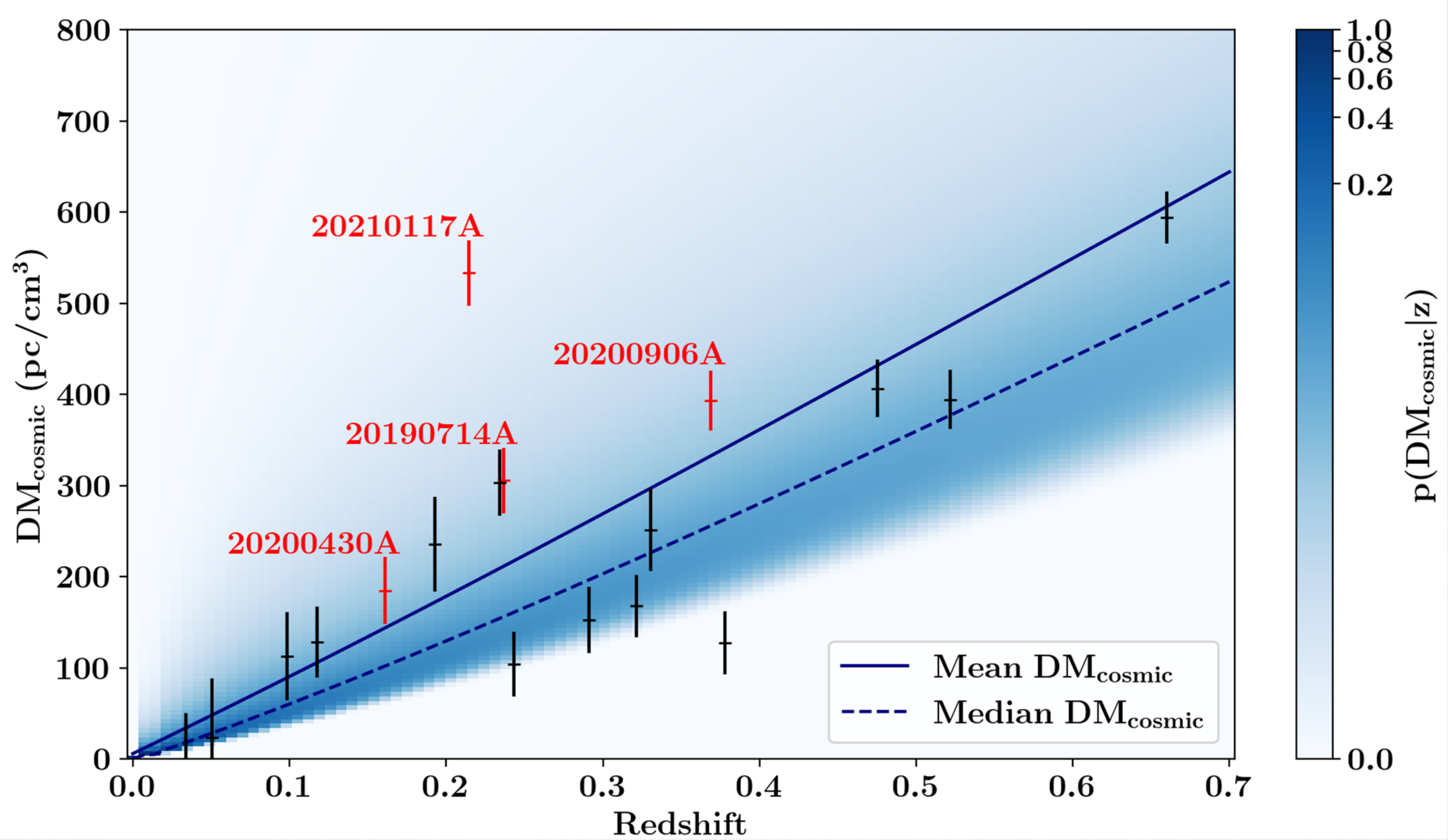
- FRB Line-of-sight Ionization Measurement From Lightcone AAOmega Mapping (FLIMFLAM) Survey
- Dedicated observations to map large-scale cosmic web in FRBs not already covered by large spectroscopic surveys
- Co-PIs: KGL and Jeff Cooke (Swinburne)
- Using 4m AAT with AAOmega/2dF spectrograph: ~*350 science fibers simultaneously* over a 3.1 sq deg FOV
- Simultaneous deep campaign with Keck/DEIMOS, Gemini/GMOS, VLT-MUSE (led by S. Simha and N. Tejos)
- Observational goal: ~20 FRB fields at 0.05<z<0.5
- Approx 10 localized FRBs now covered with 20k redshifts → DR1

Yuxin Huang
UTokyo PhD Student

Sunil Simha
UCSC PhD Student



Preliminary Study using FLIMFLAM: Excess DM sightlines

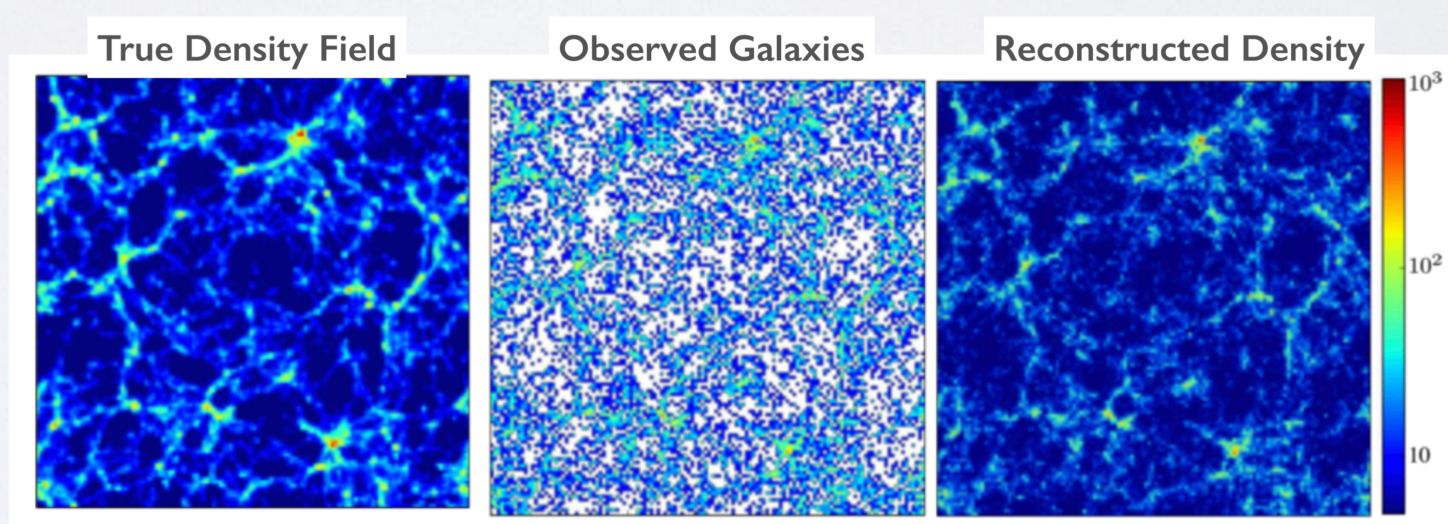


- Some sightlines seem to have statistically unlikely high-DMs
- Does this tell us something about our assumptions about the IGM+CGM contribution, or there is more host contribution than expected? → See poster by **Sunil Simha**

Large-scale Cosmic Web: Matter Density Reconstructions

- Matter Density Reconstruction ≡ Estimation of underlying 3D matter density field given a spectroscopic galaxy survey catalog and assuming basic ΛCDM cosmology
- Apply ARGO Bayesian density reconstruction code to large-scale galaxy redshifts (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
UStockholm Postdoc



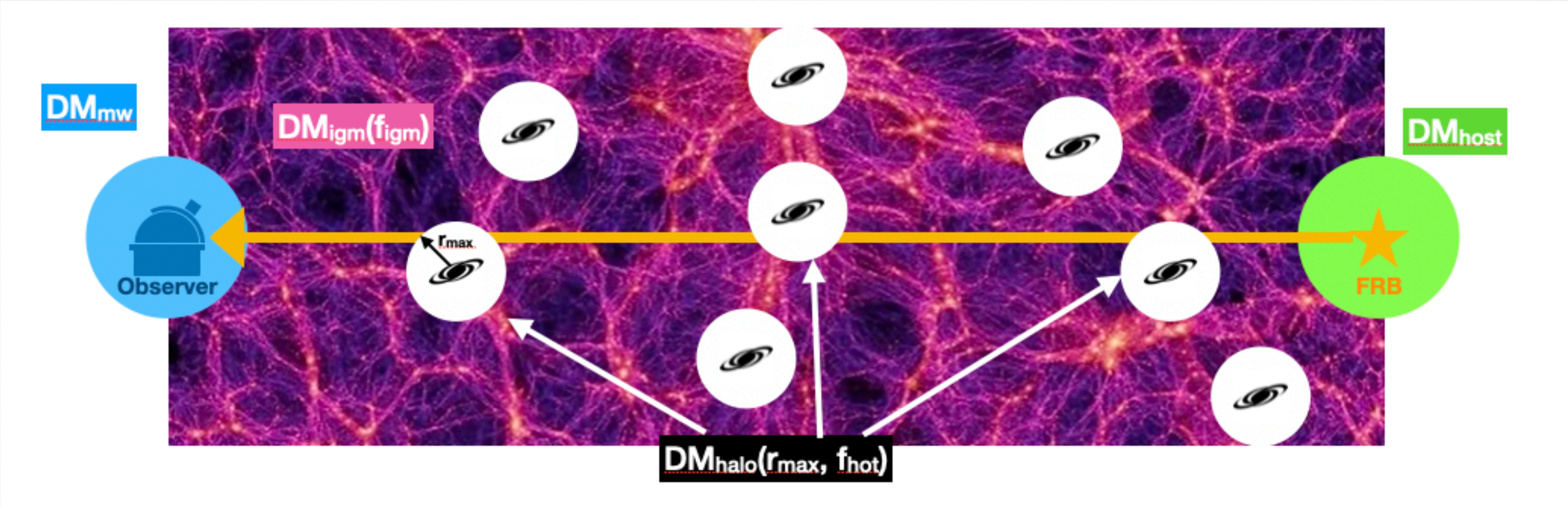
Ata et al 2015

Extragalactic Model DM

For a given mock FRB sightline in the simulation, calculate $DM_{igm}(f_{igm})$ + $DM_{halo}(f_{hot} \mid M_{halo}, d_{\perp})$ + DM_{host}

- **f_{igm}**: fraction of cosmic baryons residing in the diffuse IGM, assumed to linearly trace matter field estimated from galaxy redshifts
- **f_{hot}**: fraction of halo baryons in the hot CGM phase in galaxies, within r_{200}
- **DM_{host}**: Assume a different value for each FRB, drawn from Gaussian distribution with some $\langle DM_{host} \rangle$

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



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

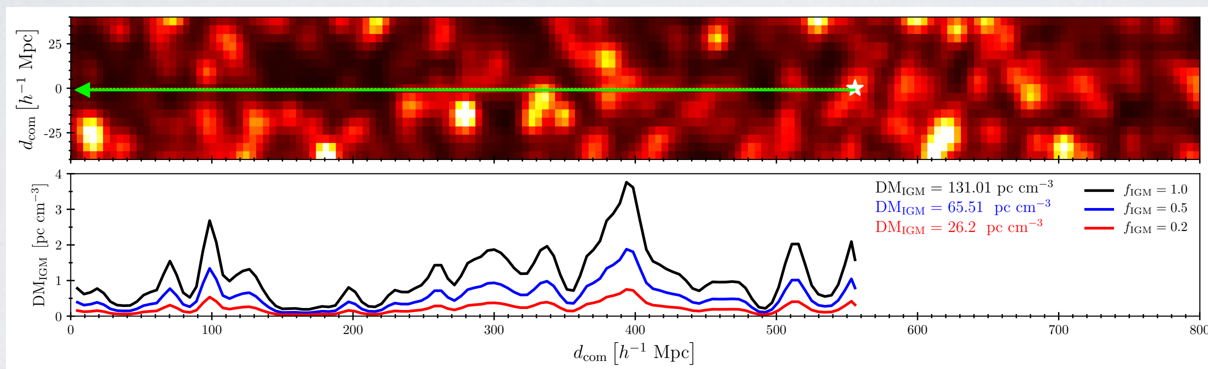
$$\begin{bmatrix} \mathrm{DM}_1 \\ \mathrm{DM}_2 \\ \mathrm{DM}_3 \\ \vdots \end{bmatrix} = \begin{bmatrix} \mathrm{DM}_{igm,1}(f_{igm}) & \mathrm{DM}_{cgm,1}(r_{max}, f_{hot}) & \mathrm{DM}_{\mathrm{host}} \\ \mathrm{DM}_{igm,2}(f_{igm}) & \mathrm{DM}_{cgm,2}(r_{max}, f_{hot}) & \mathrm{DM}_{\mathrm{host}}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

Measured from FRB itself

Computed from foreground data

Parameter Analysis

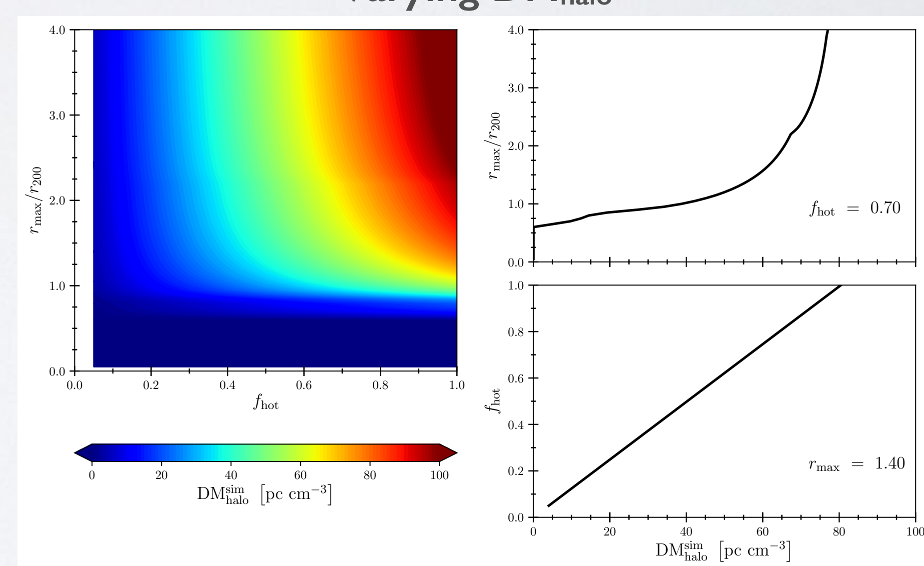
Varying DM_{IGM}



Ilya Khrykin
Kavli IPMU Postdoc

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

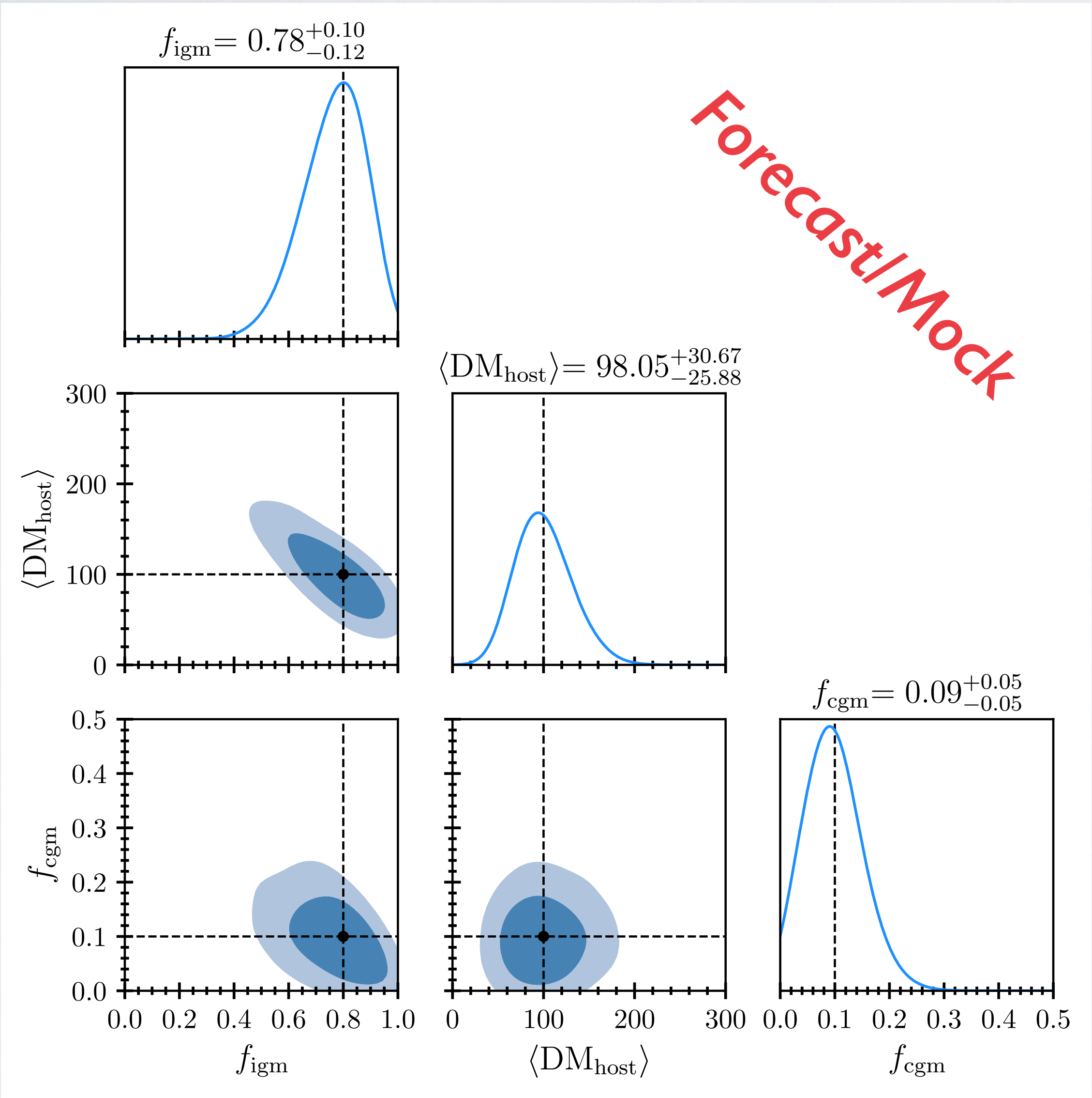
Varying DM_{halo}



- We want to sample the parameter space to place simultaneous constraints on [f_{igm}, 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

Forecasts for CGM/IGM Baryon Partition

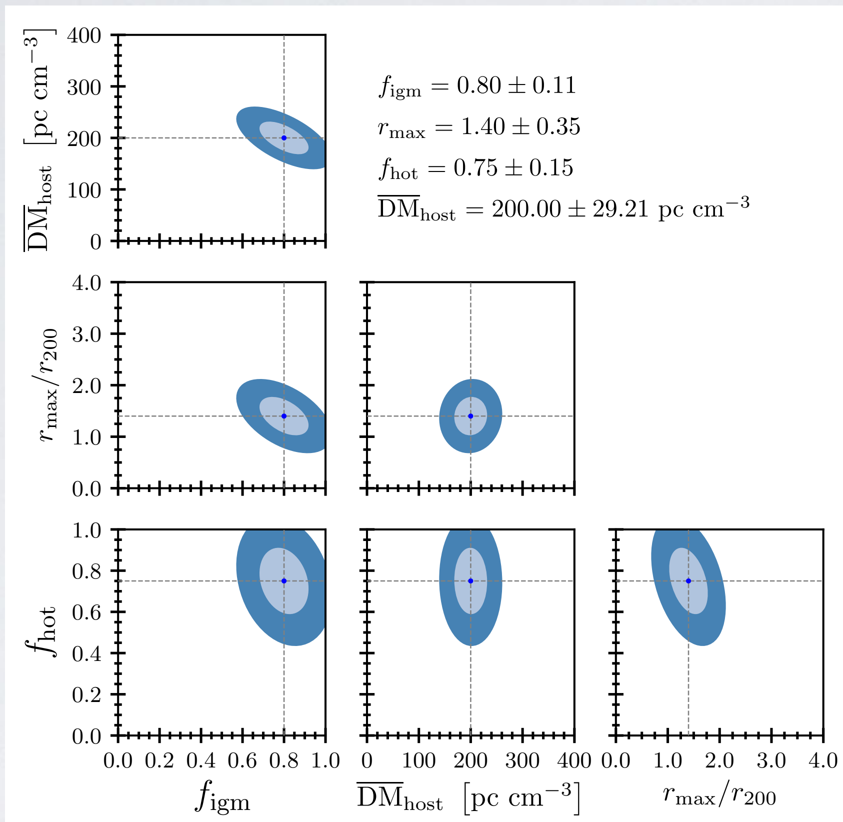
N_{frb}=24 at 0.1<z<0.4



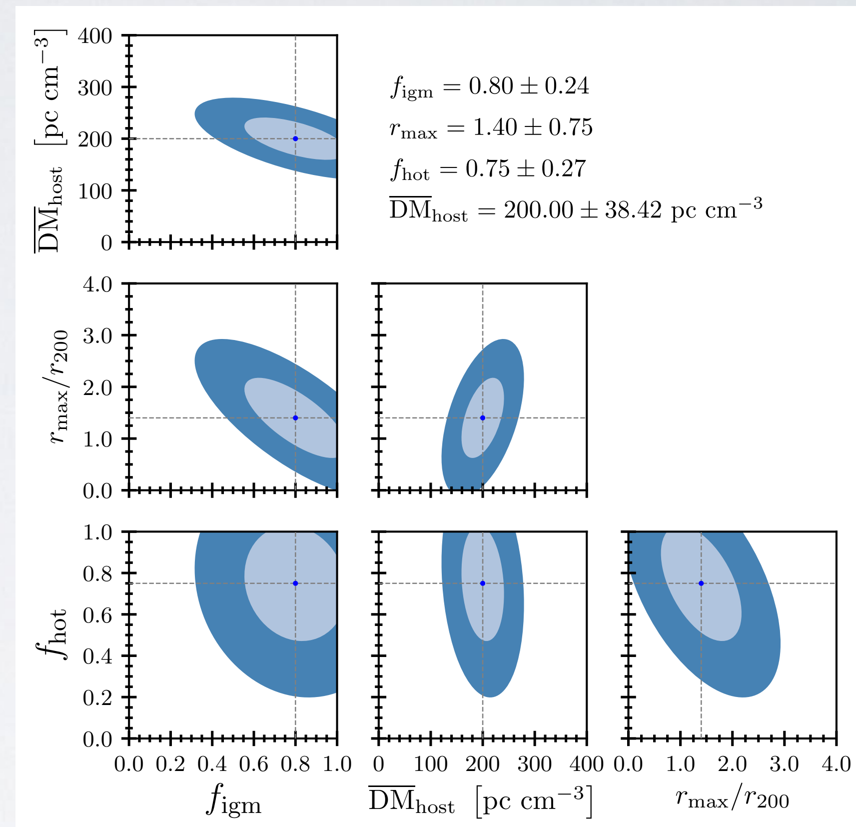
- Initial science goal: *measure the relative global fractions of CGM and IGM baryons* (such that $f_{cgm}+f_{igm}+f_{stars} + f_{ism}=1$)
- DM_{host} modeled as a Gaussian distribution with unknown <DM_{host}>
- Expect to be able to measure f_{cgm} to within a few of percent with FLIMFLAM!
- Future goals: measure characteristic scale of CGM around galaxies (e.g. Williams+2022, arXiv:2207.05233)

Foreground Data *dramatically* Improves the Constraining Power of FRBs!

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, ~2000 localized FRBs would be needed to make equivalent constraints on the baryon partition between IGM and CGM (see also Batten+2022)
- *Without* localized FRBs, Shirasaki+2021 estimates 20k FRBs cross-correlated with group+cluster catalogs can make 10% constraints on halo gas (see also Xiaohan Wu talk 15mins ago!)

Summary

- Localized FRBs with known redshifts provide a unique opportunity to target their foreground matter distribution with large-scale spectroscopic galaxy data → fit models to compare with observed DM
- Boosts the constraining power of localized FRBs toward cosmic baryons by >25x (>1000x relative to *unlocalized* FRBs)
- FLIMFLAM and associated programs aim to map foreground intervening galaxies and large-scale structure
    - Data for 10 FRBs and 20k foreground galaxies now in hand
    - Will aim to constrain the partition of baryons between IGM and CGM to ~10% with ~20 FRBs at z~0.2
        - Will be first analysis to freely constrain $\langle DM_{host} \rangle$, simultaneous with IGM and CGM contributions → Please stay tuned!
        - Cosmic partition of CGM and IGM baryons as a unique probe of galaxy feedback
- With samples of ~100 (e.g. DESI + CHIME Outriggers), more detailed analysis will be available, and more sophisticated modeling e.g. as function of M_* is possible