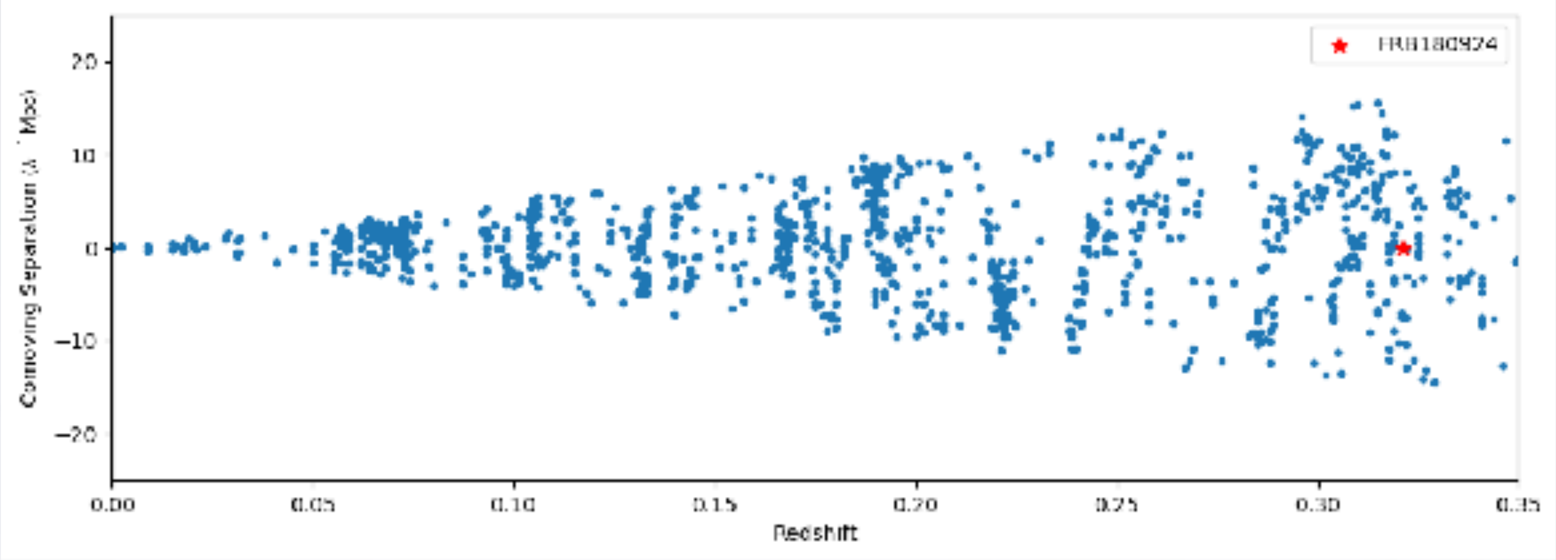
Measuring the Cosmic Baryon Budget with FRB Foreground Mapping



Subaru User's Meeting FY2024

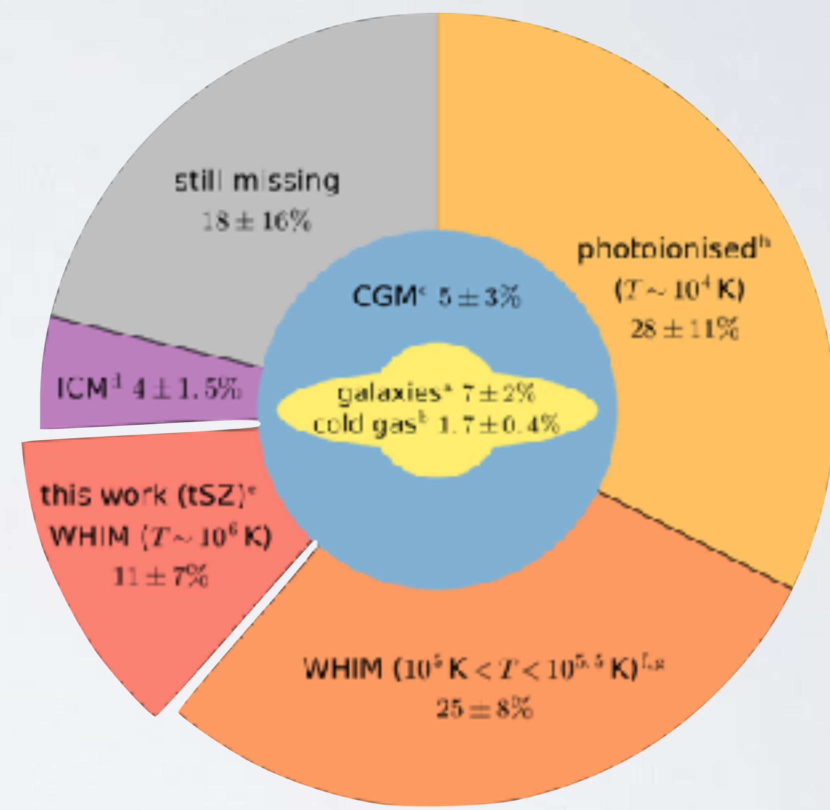
Jan 25, 2025

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

Kavli IPMU, University of Tokyo

The Missing Baryon Problem

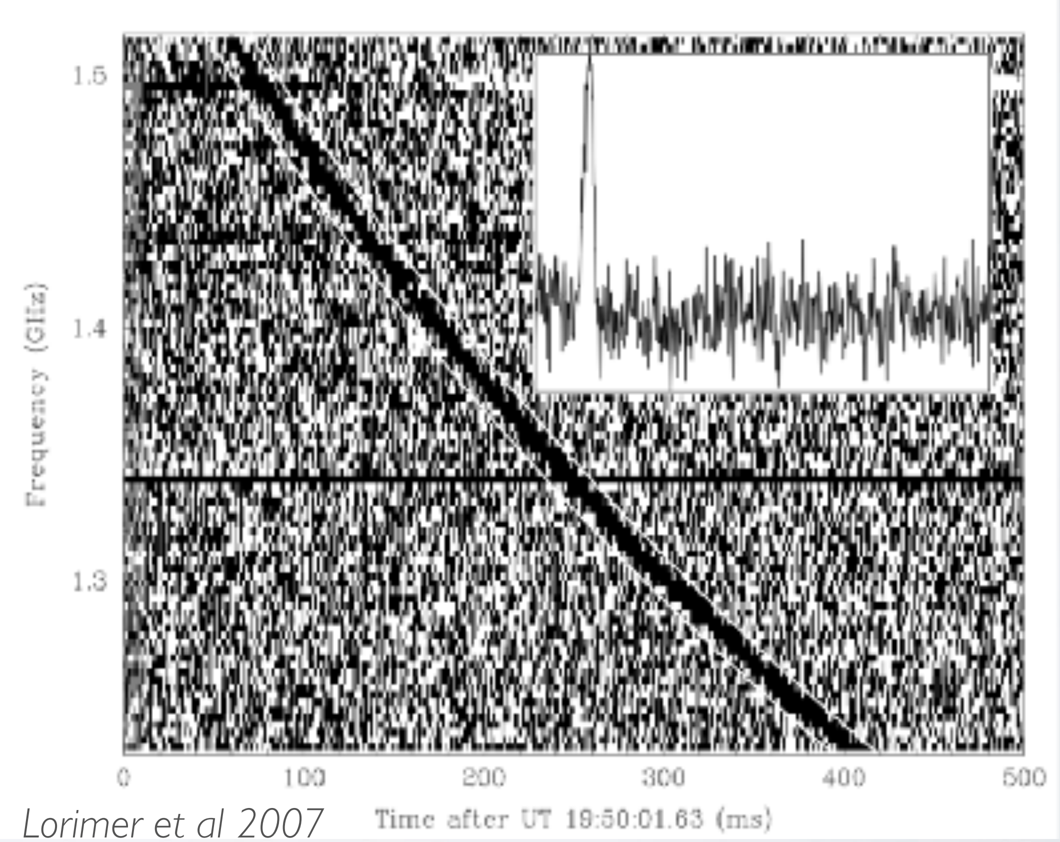
- *Does the baryonic content of the Universe square up with the precise predictions of Ω_{baryon} from Big-Bang Nucleosynthesis and the CMB?*
- Fukugita, Hogan & Peebles 1996 point out >80% of cosmic baryons have yet to be directly observed (<10% are in galaxies)
- By z<1, galaxy feedback and gravitational heating cause a complex multi-phase IGM, e.g. Cen & Ostriker 2006 (hard to detect in absorption or emission!)
- As of 2019, ~20-30% at z~0. were still missing despite best efforts



De Graaf+2019

Fast Radio Bursts

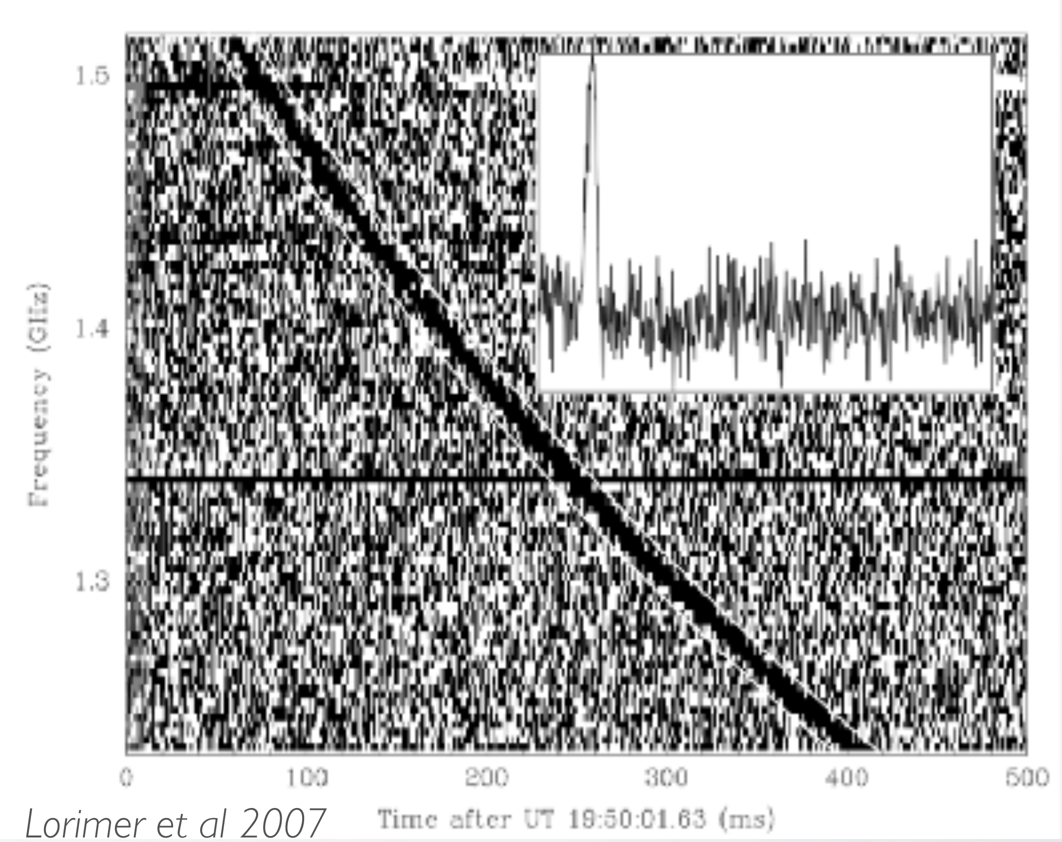
- Millisecond-duration radio bursts first identified by Lorimer et al 2007
- To-date ~5000 FRBs have been detected; ~80 have been *localized* to specific host galaxies. *Conclusively proven to be extragalactic sources.*
- Unknown progenitors: compact object merger? magnetar masers? ET solar sails? (>50 theories listed at http://frbtheorycat.org)



Lorimer et al 2007

FRB Dispersion Measures (DM)

- Integrated free electrons along the line-of-sight cause a frequency shift in a signal:
  $$\mathbf{DM} = \int n_e(s)\,\mathrm{d}s$$
- >99% of IGM/CGM atoms are ionized and arise from H + He with little metallicity or temperature dependence. Interpretation is very clean
- FRBs thus offer a clean probe of the IGM+CGM baryons, especially if the redshift or distance to the FRB is known
- See Głowacki & KGL 2024 for a review on FRB cosmology (arXiv:2410.24072)

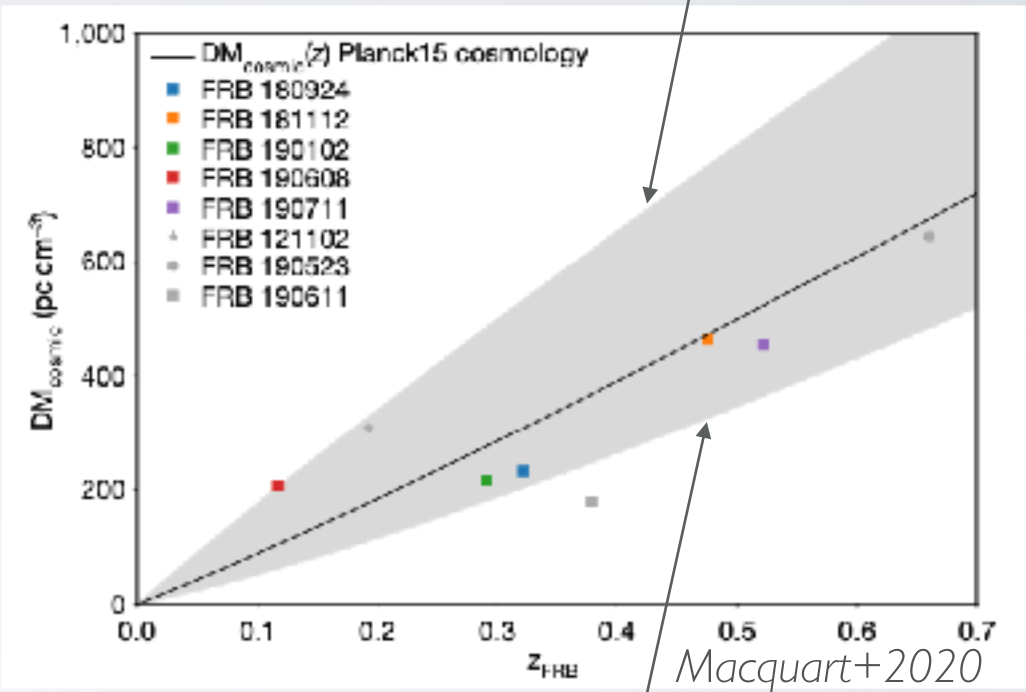


Lorimer et al 2007

The Macquart Relation

- 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!*

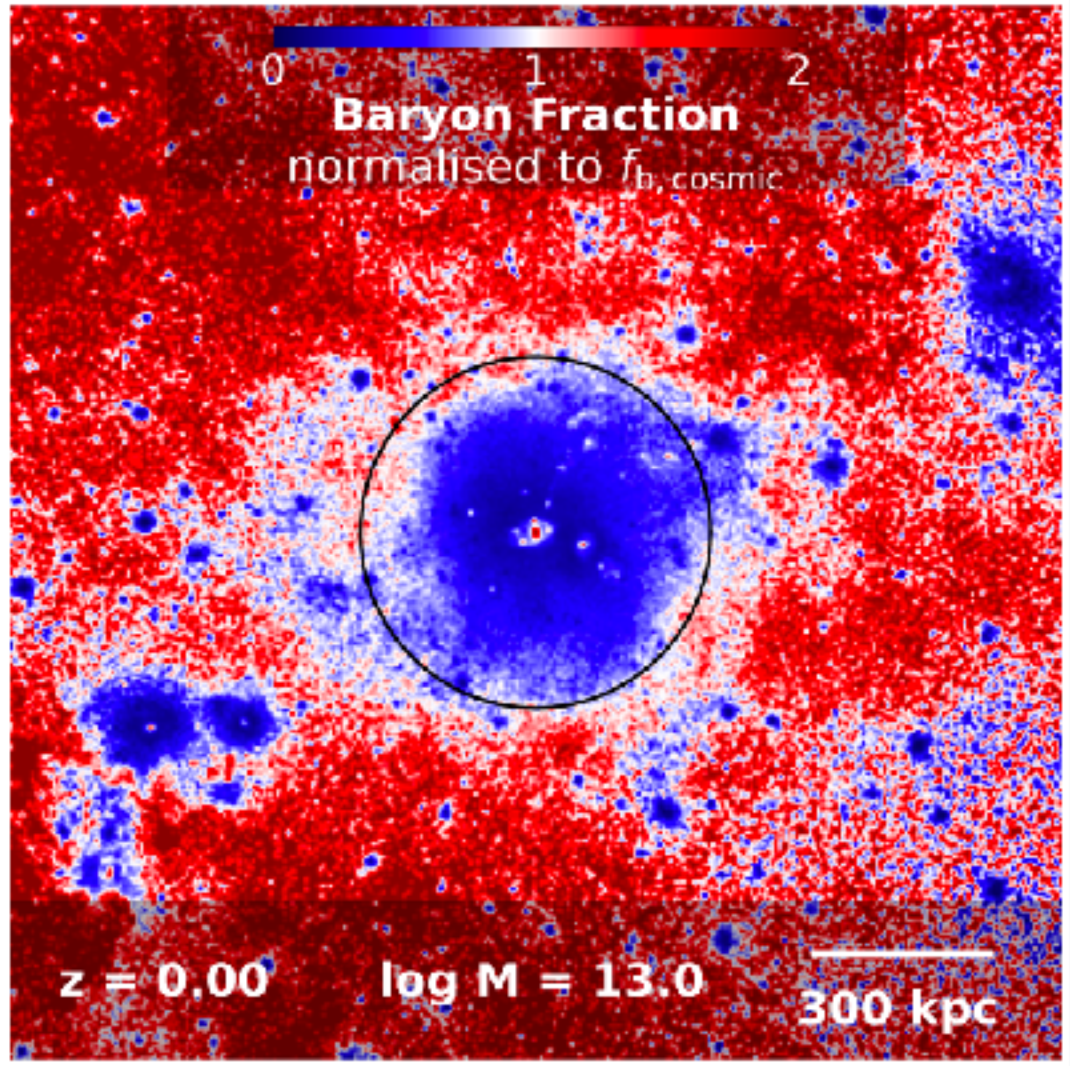
Sightlines passing through dense regions and/or through galactic CGM



Sightlines passing through underdense regions and no intervening CGM

The baryons are all there… but where exactly?

- 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, $f_{hot} << \rho_{bar}/\rho_m$
- Most other probes of cosmic baryons are *massive halo-centric* (X-rays, SZ effects etc). **FRBs offer an opportunity to constrain the halo and IGM contributions simultaneously.**



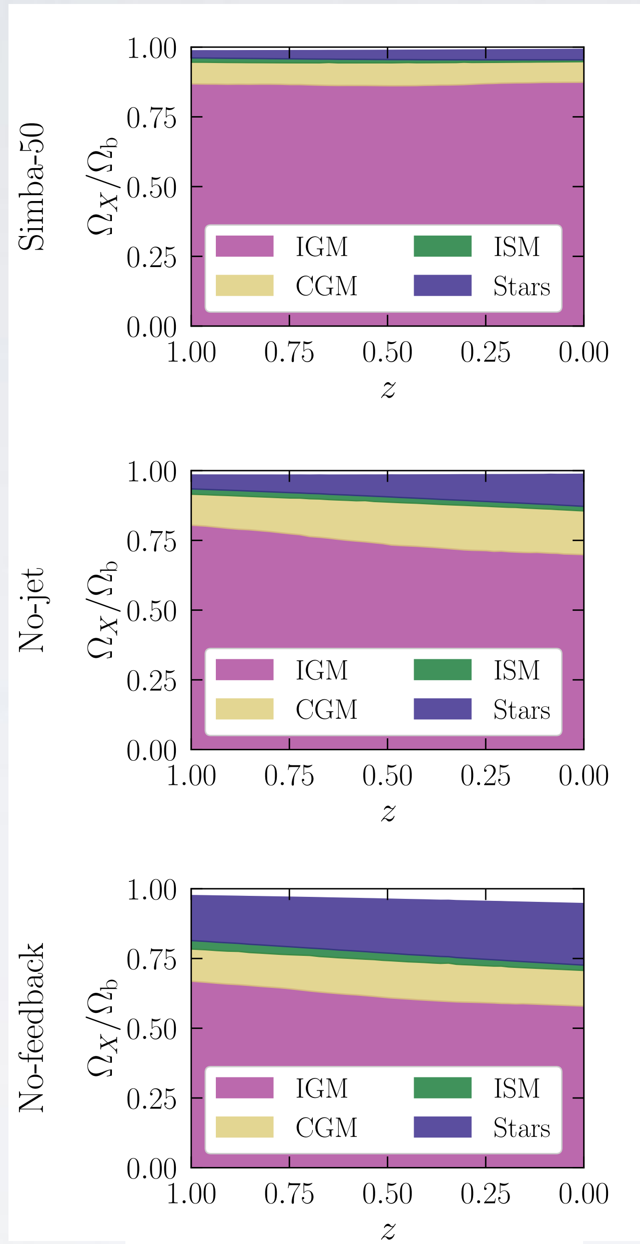
Baryon fraction around a small group; Ayromlou+2022 (arXiv:2211.07659)

Simba Hydrodynamical Simulation Results

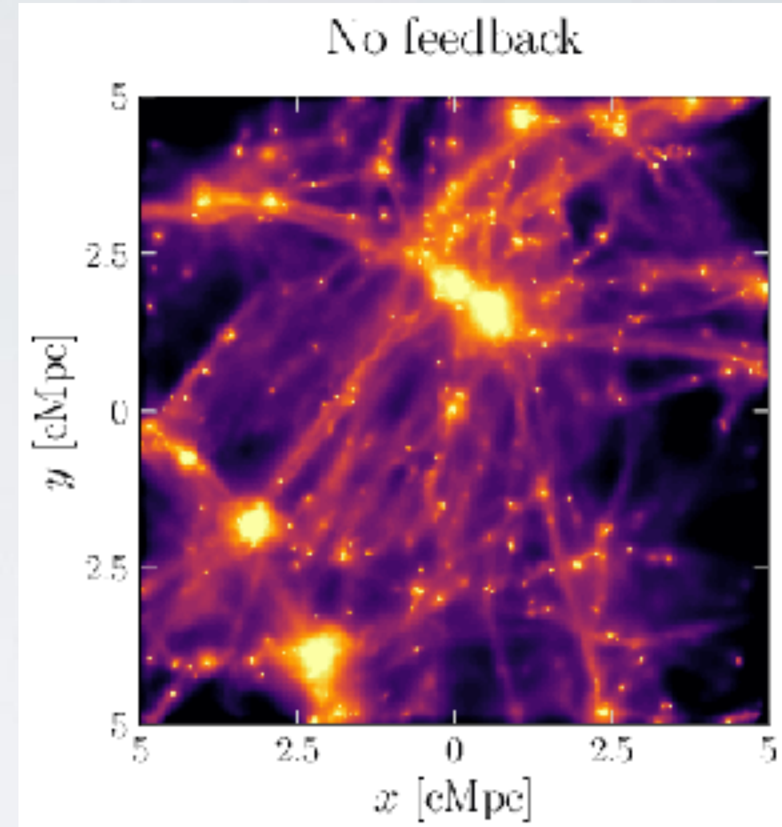
Full feedback: SNe & AGN jets+winds+X-ray
87% of baryons in IGM

No AGN jets/X-ray: SNe & AGN winds
70% of baryons in IGM

No feedback
60% of baryons in IGM



Khrykin, Sorin, **Lee** et al 2023



Ilya Khrykin
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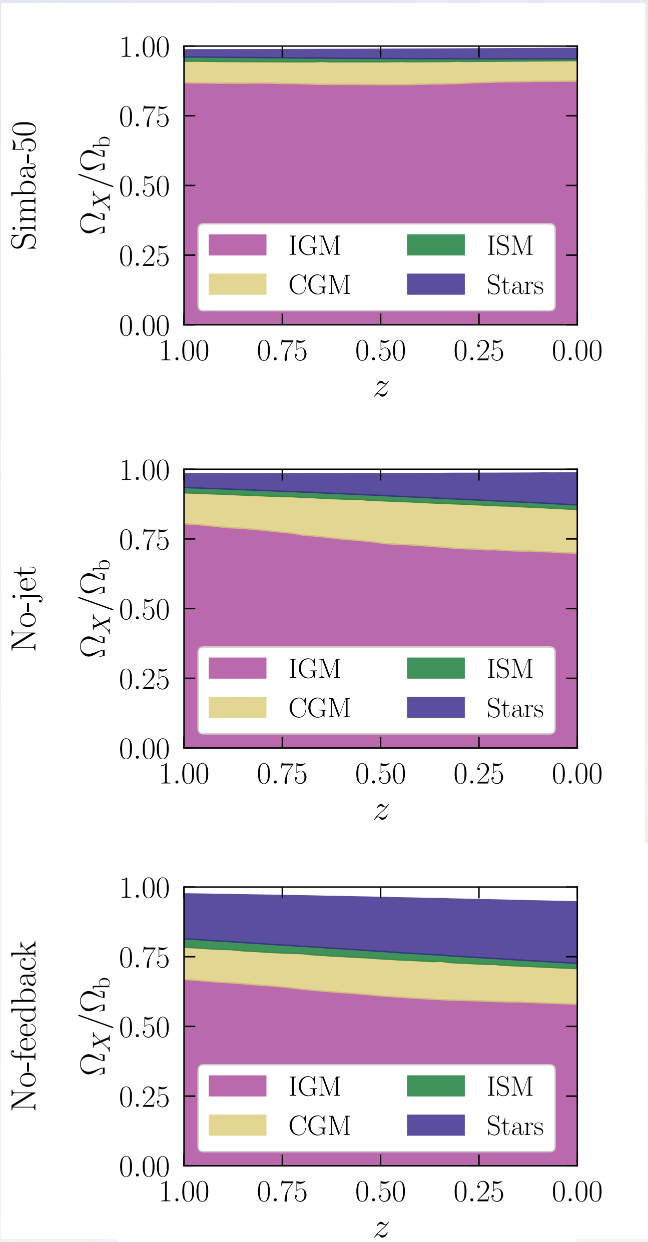
- Simba simulation L=50Mpc/h boxes with different feedback prescriptions give very different cosmic baryon distributions between the IGM and CGM of different halos (Khrykin, Sorini, KGL et al 2023, arxiv:2310.01496)

Simba Hydrodynamical Simulation Results

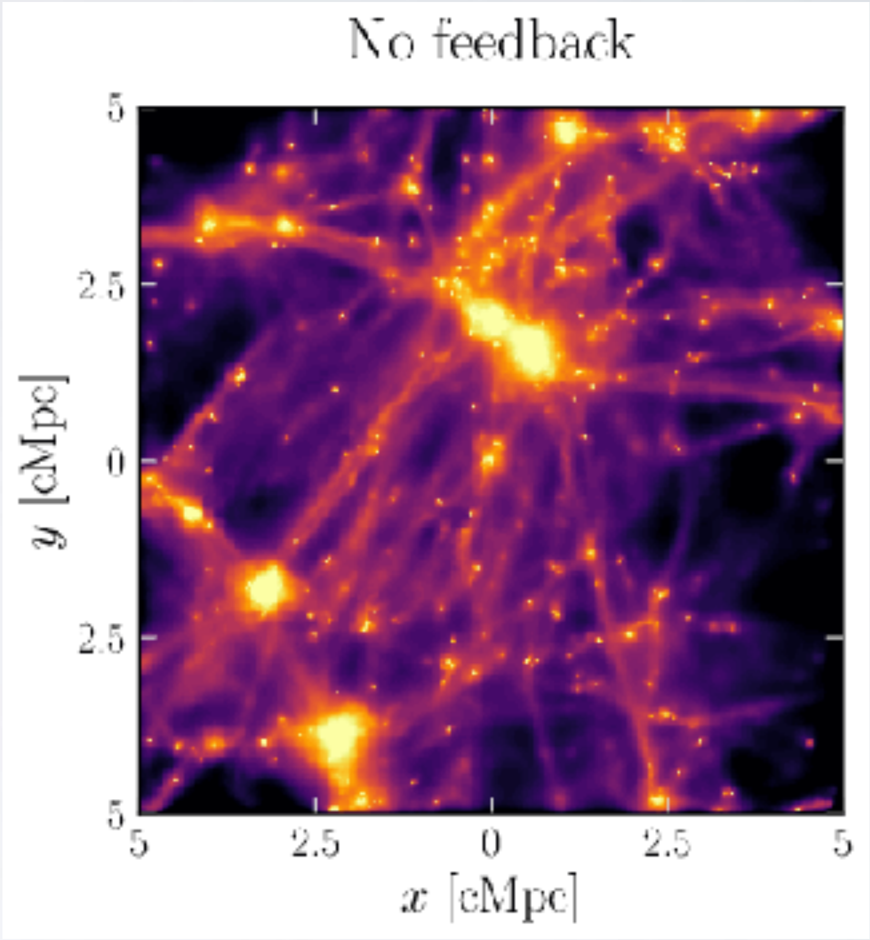
Full feedback: SNe & AGN jets+winds+X-ray
85% of baryons in IGM

No AGN jets/X-ray: SNe & AGN winds
70% of baryons in IGM

No feedback
60% of baryons in IGM

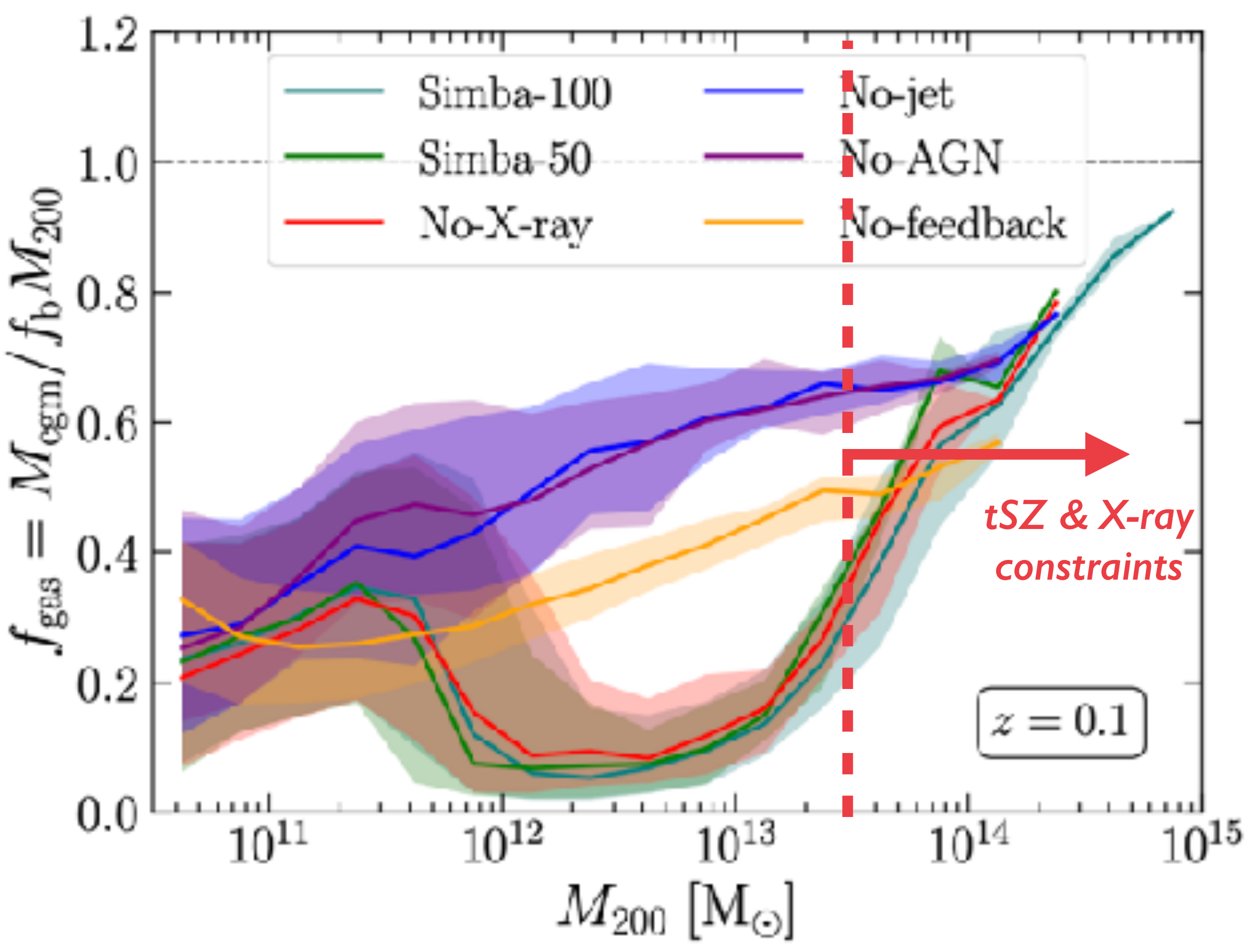


*Khrykin, Sorin, **Lee** et al 2023*



Bottom line: the simple dichotomy between the CGM and IGM baryon fractions (f_{cgm} vs f_{igm}) is useful for studying the cosmic baryons, and the effect of galaxy feedback

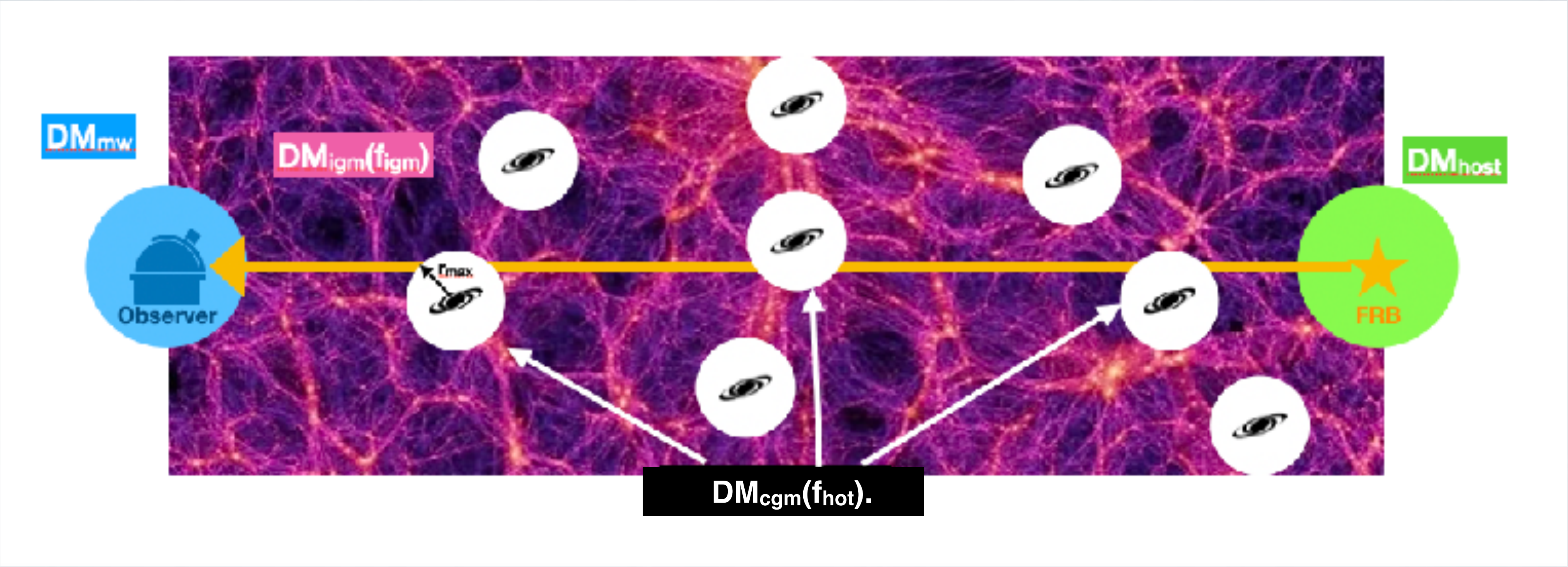
Halo Gas Fractions



Khrykin, Sorini, KGL et al 2023, arxiv:2310.01496

- Measuring the IGM fraction and CGM gas fraction over different halo masses will give powerful insights into feedback processes in the Universe
- Existing constraints from ICM X-ray and tSZ can only probe $M_h > 10^{13.5} M_\odot$ regime

Decomposing the FRB DM



- FRB signal measures the aggregate DM along LOS, assumed to be $DM = DM_{mw} + DM_{igm} + DM_{cgm} + DM_{host}$
  - DM_{igm} comes from diffuse large-scale structure (~Mpc-scale voids, sheets, filaments etc, with matter densities of $0 \lesssim \rho_{matter}/\langle\rho_{matter}\rangle \lesssim 10$). ***Sensitive to f_{igm}***
  - DM_{cgm} arises directly from intersecting the CGM of intervening galaxies (~r_{200} or < few arcmin). ***Sensitive to f_{gas} or f_{cgm}***
  - DM_{host} has a distribution, has contributions from host galaxy halo (+ possibly from engine)
- 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*. First attempt by Simha et al 2020 on FRB190608

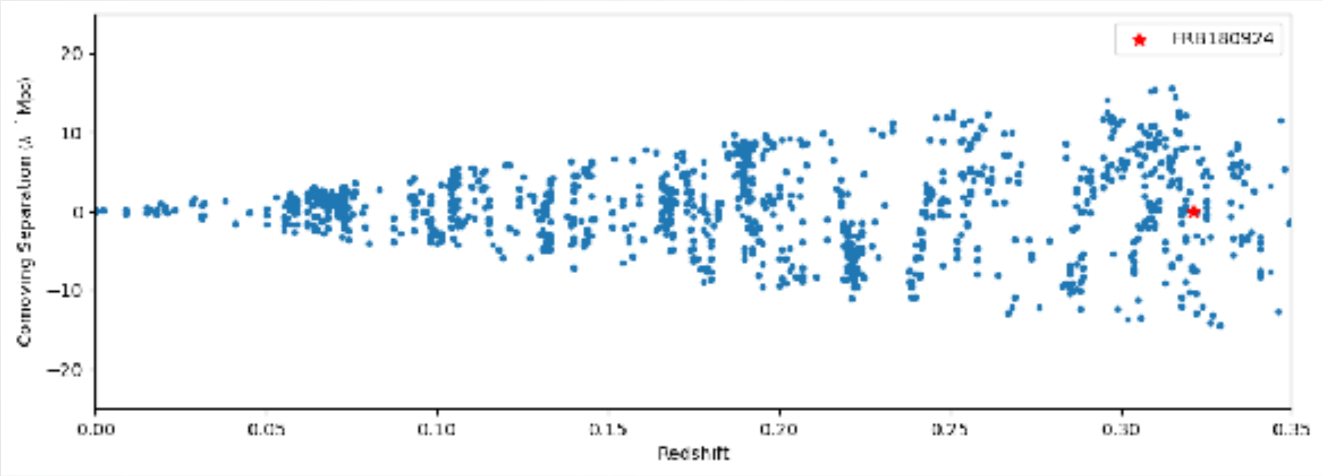
Yuxin Huang
UTokyo PhD Student

FLIMFLAM on the AAT

Sunil Simha
Northwestern U/UChicago

- FRB Line-of-sight Ionization Measurement From Lightcone AAOmega Mapping (FLIMFLAM) Survey targeting localized FRB fields
- Dedicated observations to map <u>large-scale cosmic web</u> in Southern Hemisphere FRBs not already covered by large spectroscopic surveys
- **Anchored by 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
- 8 localized FRBs now covered with 20k redshifts ➞ Public Data Release 1 (Huang et al 2025, ApJS in press)

2dF/AAOmega on AAT,
Siding Spring, Australia



Keck-I Telescope,
Maunakea, Australia

Gemini South,
Cerro Bachen, Chile

FLIMFLAM DR1 Analysis…

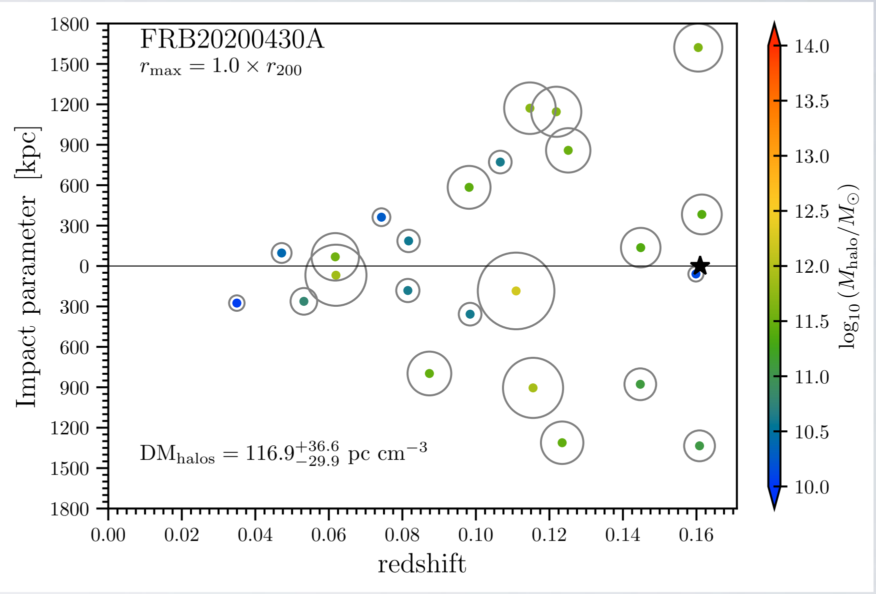
FRB	R.A. (deg)	Decl. (deg)	Redshift	Wide data	Narrow data	$DM_{MW,ISM}$ ($pc\ cm^{-3}$)	DM_{obs} ($pc\ cm^{-3}$)	Ref.
20211127A	199.8088	−18.8381	0.0469	6dF	AAT	42.50	234.83	Deller et al. (in prep)
20211212A	157.3507	+01.3605	0.0713	SDSS	AAT	27.10	206.00	Deller et al. (in prep)
20190608A	334.0199	−07.8982	0.1178	SDSS, 6dF	SDSS, KCWI	37.20	339.50	Macquart et al. (2020)
20200430A	229.7066	+12.3761	0.1608	SDSS, AAT	LRIS, DEIMOS	27.00	380.10	Heintz et al. (2020)
20191001A	323.3516	−54.7477	0.2340	AAT	AAT	44.20	506.92	Bhandari et al. (2020)
20190714A	183.9795	−13.0207	0.2365	AAT	LRIS, DEIMOS	38.50	504.70	Heintz et al. (2020)
20180924B	326.1052	−40.9000	0.3212	AAT	AAT, MUSE	40.50	362.40	Bannister et al. (2019)
20200906A	053.4956	−14.0833	0.3688	AAT	LRIS, DEIMOS	35.90	577.80	Bhandari et al. (2020)

*Khrykin, Ata, **Lee** et al 2024 (arXiv:2402.00505)*

- Analysis on our first data release (DR1) of 8 FRBs+foreground data (Huang et al 2024; arXiv:2408.12864)
- FRBs mostly from CRAFT/ASKAP and F^4 localization efforts
- Goal: constrain as free parameters the IGM + CGM baryon fractions, and DM_{host}
- Khrykin, Ata, **Lee** et al 2024 (arXiv:2402.00505)

3-Parameter DM Model

Comparison with DM measured from FRB, with model constructed using foreground FLIMFLAM data.

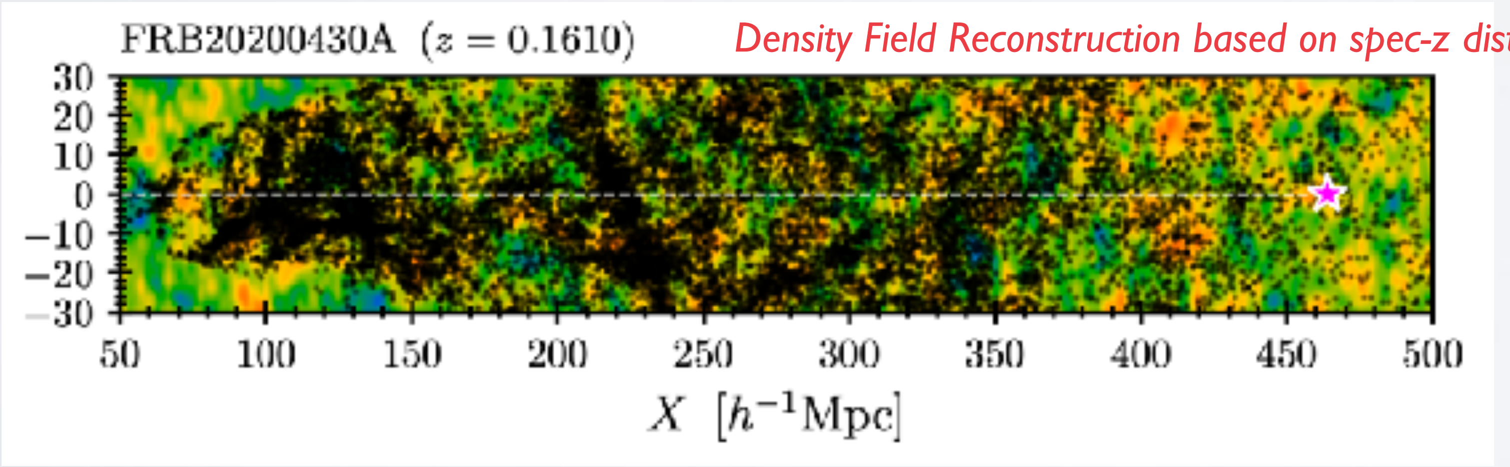


Fraction of baryons residing in CGM, relative to $(\Omega_b/\Omega_m)M_{\rm halo}$

$$\mathrm{DM}_{\mathrm{model},i} = \boxed{f_{\rm igm}} \cdot \mathrm{DM}^{\rm ARGO}_{\mathrm{igm},i} + \boxed{f_{\rm gas}} \cdot \mathrm{DM}_{\mathrm{halos},i}\ (r_{\rm max} \equiv r_{200}) + \boxed{\mathrm{DM}_{\mathrm{host},i}} + \mathrm{DM}_{\mathrm{MW},i}$$

Fraction of all cosmic baryons residing in IGM

Set $\langle DM_{host} \rangle$ as a free parameter



Density Field Reconstruction based on spec-z distribution

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N.B. can compute $f_{\rm cgm}$ from $f_{\rm gas}$ by integrating over halo mass function, such that $f_{\rm igm}+f_{\rm cgm}+f_{\rm stars}+f_{\rm blackholes}=1$

FLIMFLAM DR1 Results

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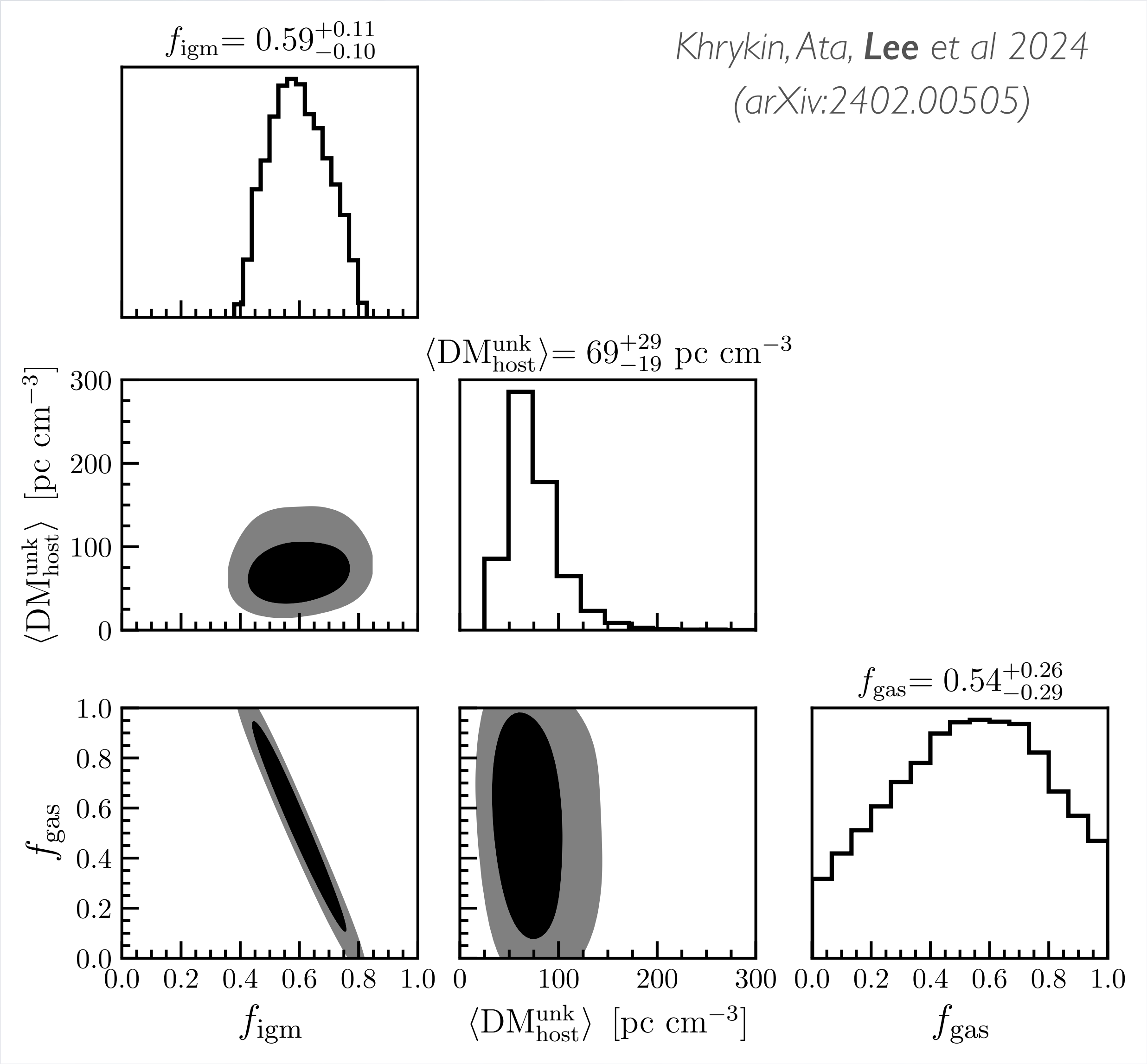
PUC Valparaiso

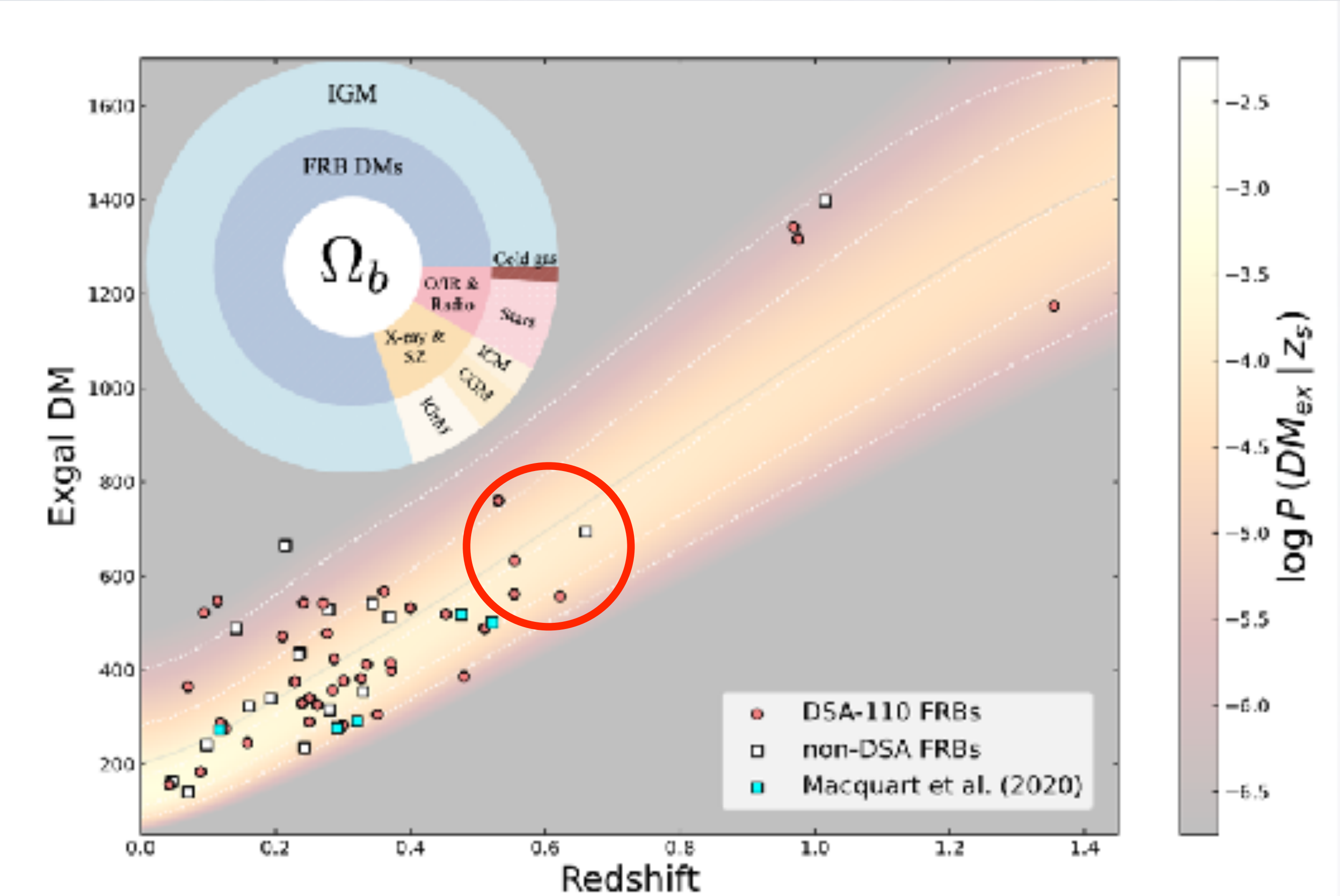


$$\langle {\rm DM}_{\rm host}\rangle = \langle {\rm DM}^{\rm halo}_{\rm host} + {\rm DM}^{\rm unk}_{\rm host}\rangle$$

$$\langle {\rm DM}_{\rm host}\rangle = 91^{+29}_{-19}\ {\rm pc\ cm}^{-3}$$

- <u>**First direct measurement**</u> of partition between IGM and CGM baryons with 8 FRBs
  - 10% constraints on $f_{\rm igm}$, still too loose to constrain feedback models ($0.6<f_{\rm igm}<0.85$)
  - Halo mass range $10^{11}M_\odot<M_{\rm halo}<10^{13.5}M_\odot$ probed by our data
  - The current $f_{\rm gas}$ constraint implies that this halo mass range contributes $f_{\rm cgm} = 0.20^{+0.10}_{-0.11}$ of cosmic baryon budget
- <u>First</u> attempt to decompose host DM into halo components and 'unknown' contribution from host engine and ISM
- DR2 sample has ~20 FRBs, analysis underway!

FRB Foreground Mapping with PFS



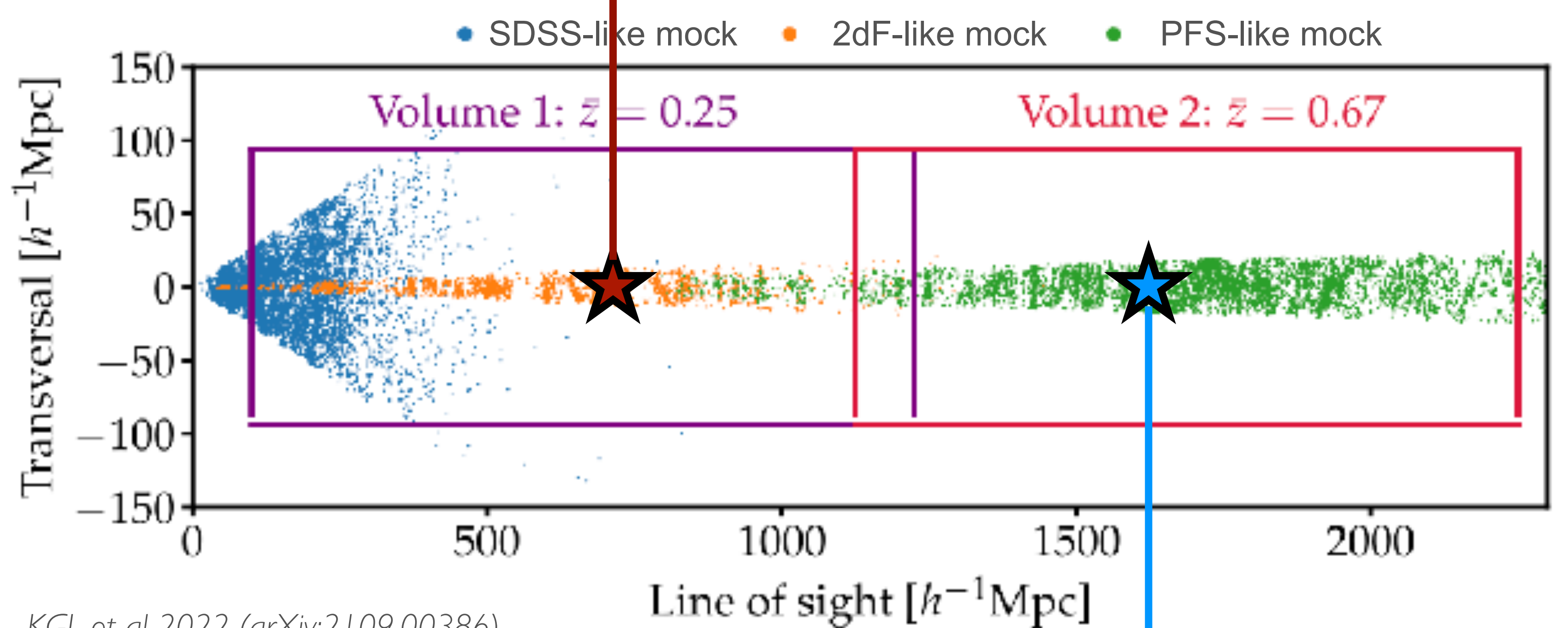
Connor et al 2024 (arXiv:2409.16952)

- Subaru PFS is the most powerful multi-object spectrograph in the world!
- In S25A+S25B, target relatively high redshift (z~0.5-0.6) FRBs (c.f. ⟨z⟩=0.16 in FLIMFLAM sample)
- Most z>1 FRBs is in the Southern Hemisphere, one Northern object published after S25A proposal submitted

FRB Foreground Mapping with PFS

FRB20191001A, z=0.234 (D=955cMpc)

~2200 foreground galaxies @ r<19.4
→ 8hrs with AAT/2dF-AAOmega



KGL et al 2022 (arXiv:2109.00386)

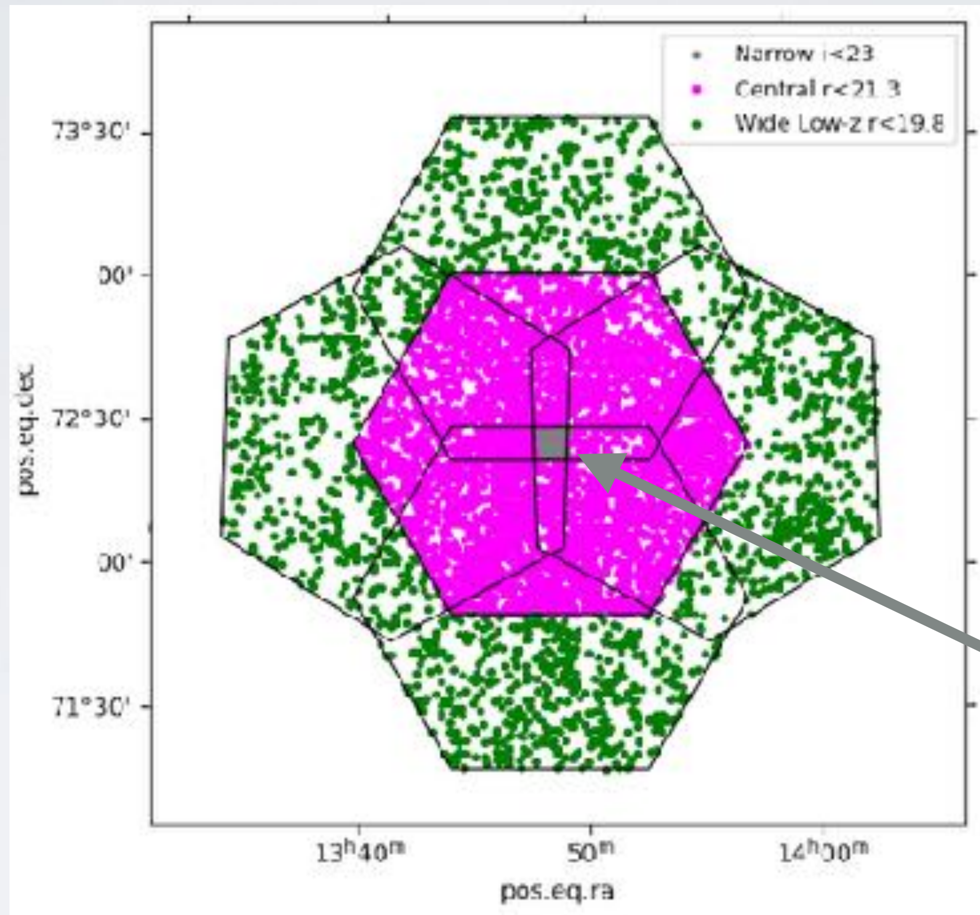
~6000 foreground galaxies @ r<21.3
→ 3.5hrs with Subaru PFS!

FRB20230907A, z=0.636 (D=2343cMpc)

- Targeting higher-redshift FRB allows much longer IGM path length and $(1+z)^{-1}$ dilution of DM_{host} contribution
- Factor of >6-7x improvement in effective survey speed w.r.t. f_{igm} and f_{cgm}

PFS Observing Strategy

~24cMpc @ z=0.5



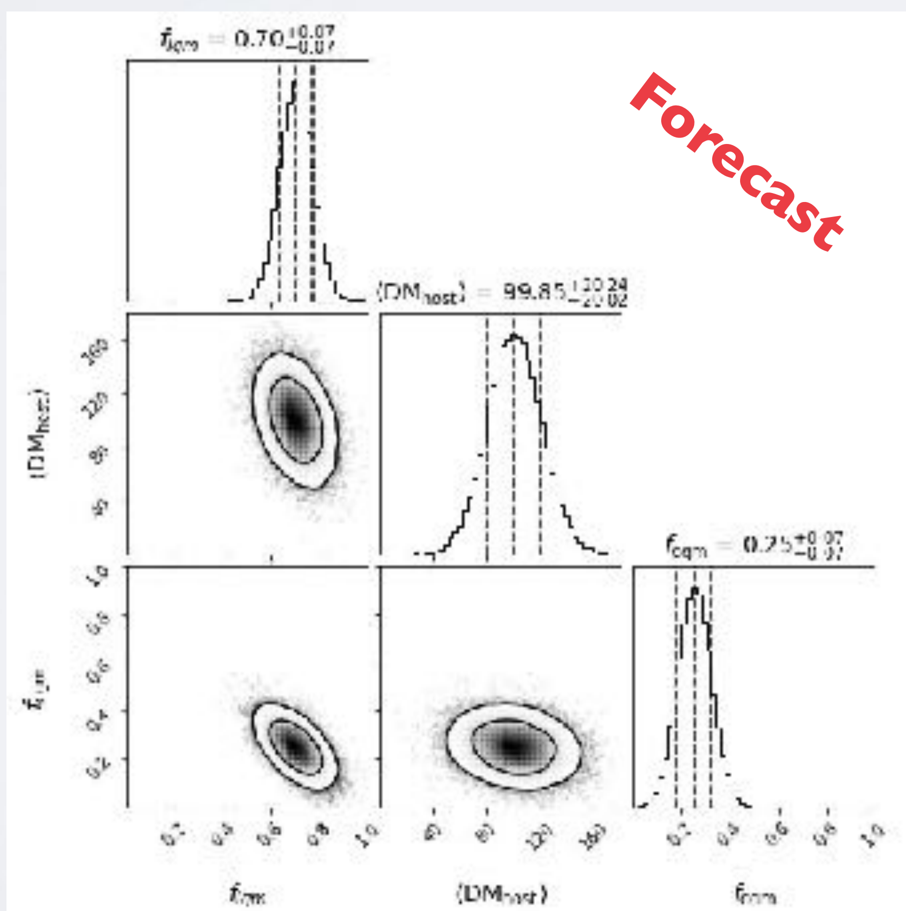
~20cMpc @ z=0.15

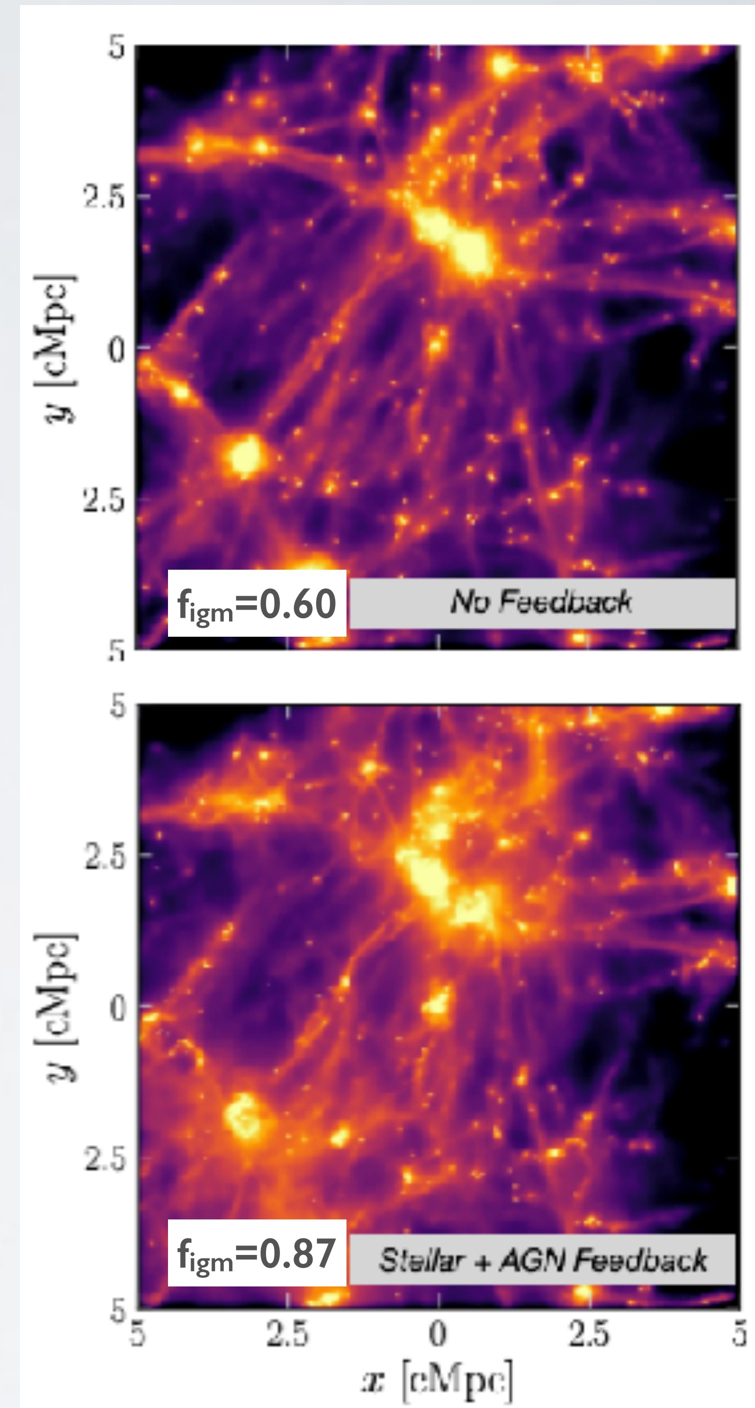
~100 galaxies at a few arcmins

- 1 PFS night allocated through Open Use in S25A,; aim to observe <u>4 FRB fields at 0.3<z<0.7</u>
- 3-tier observing strategy for strawman z=0.6 field
  - ~5000 '**Central**' targets covers r<21.3 galaxies in a single PFS footprint, covering 0.3<z<0.6
  - ~2000 '**Wide**' galaxies at r<19.8 over extended mosaic pointings to cover wider transverse footprint at low-z (~20 cMpc)
  - ~100 '**Deep**' galaxies possibly intersected by FRB sightline, down to r<23

PFS+FLIMFLAM Early Science Goals

- Combining 22 FLIMFLAM fields + 10 PFS fields, we expect to get $\sigma(f_{igm}) = 0.07$
- With reference to simulations of Khrykin et al 2024a, we should be able to place 3.8σ on the most extreme galaxy feedback scenarios
- At least 1-2 nights required in S25B in addition to 1 night in S25A to reach this limit

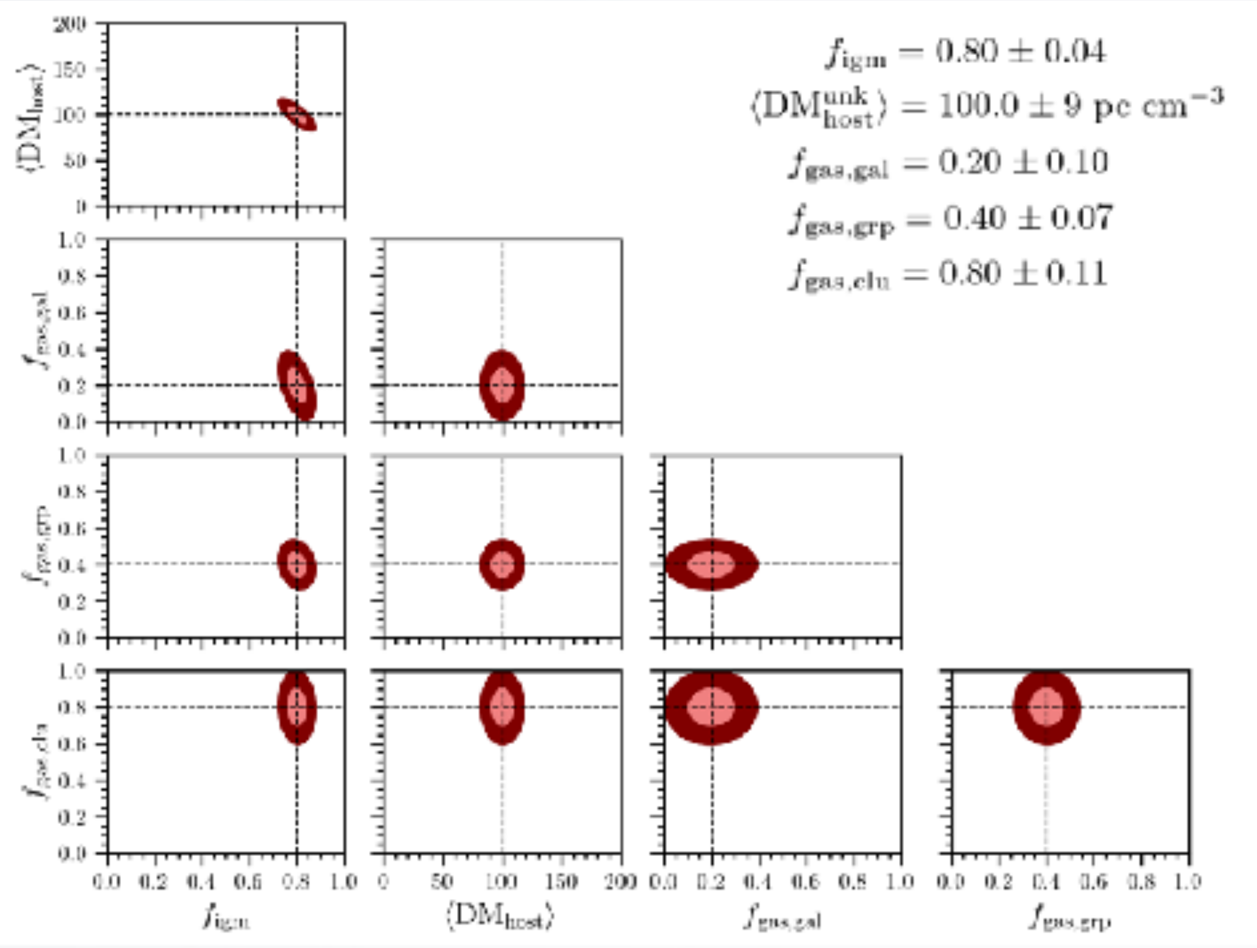


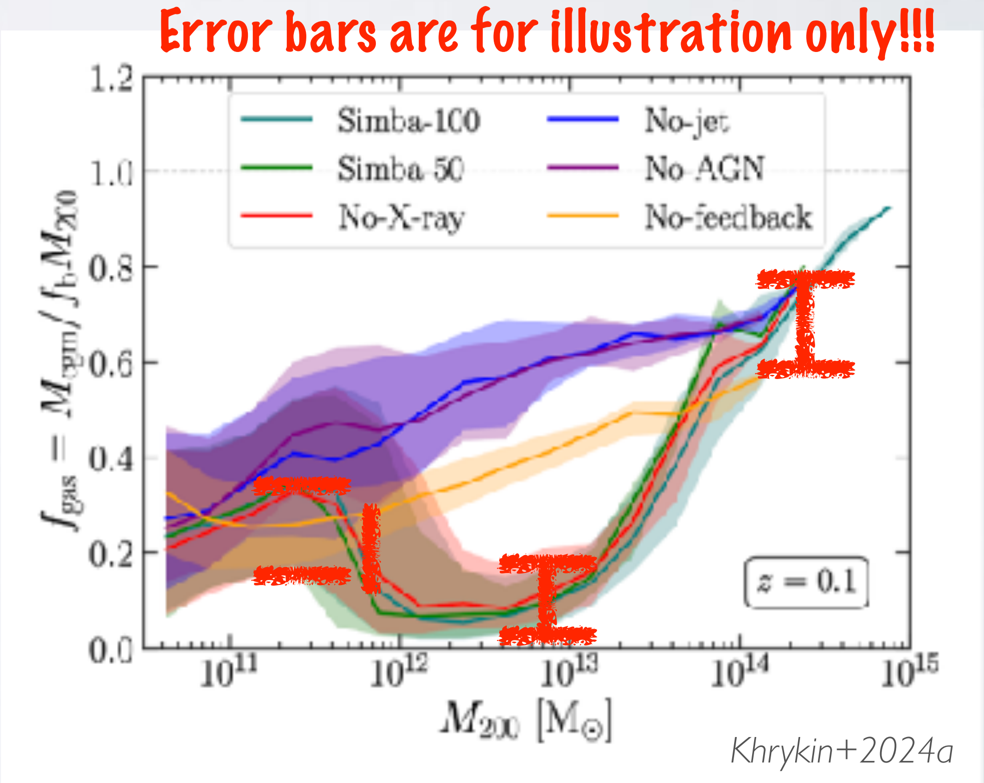


Credit: D. Sorini (Durham)

Longer-Term Forecast

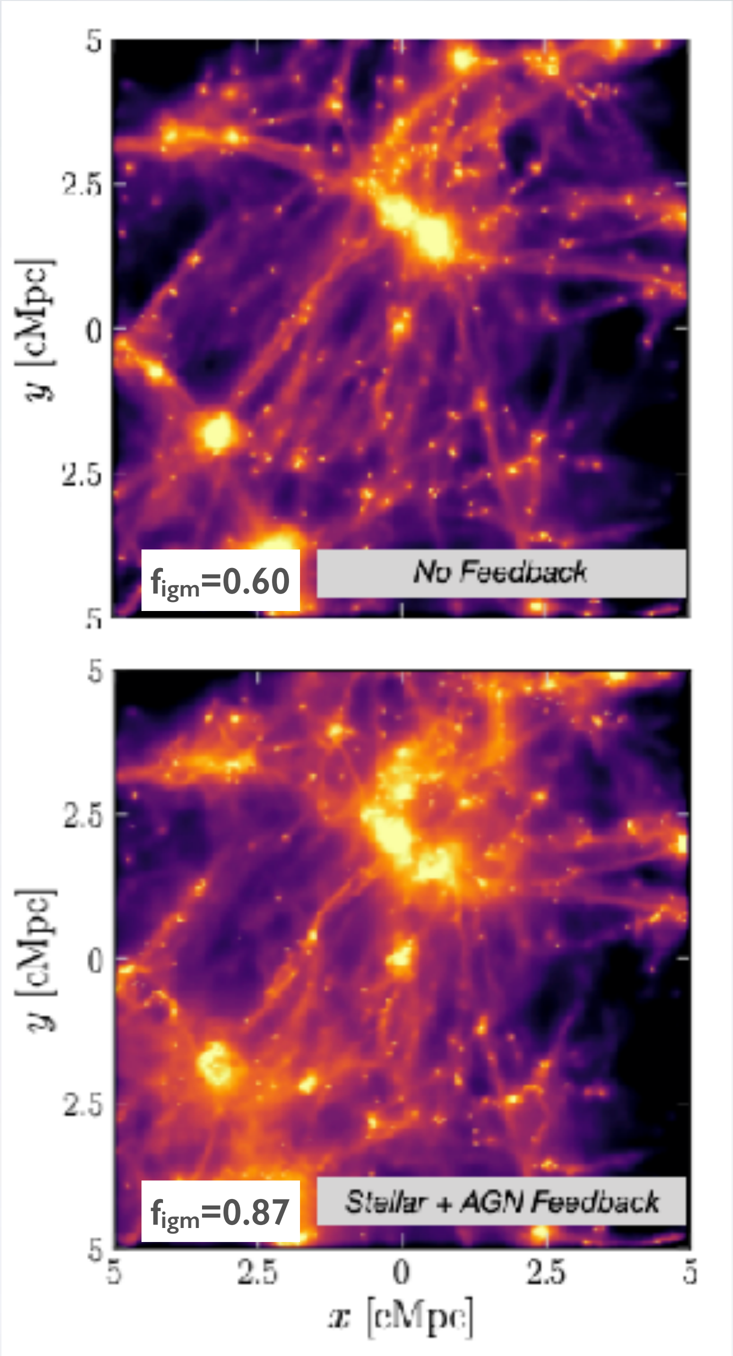
- ~100 localized high-z FRBs targeted by PFS would require ~30 Subaru nights in total
- Such a sample will allow f_{igm} measurements down to a few percent, and f_{gas} measurements *over multiple halo mass bins* to enable precise tests of galaxy feedback models
- Can also potentially start constraining the redshift evolution of these quantities



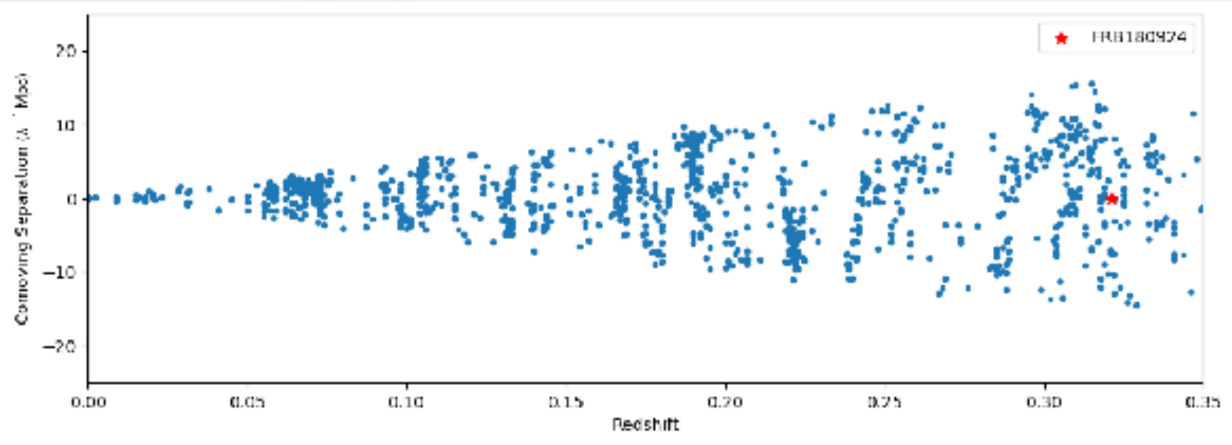


Summary

- By combining the DM measured in localized FRBs with the data of the foreground cosmic web and galaxies, we have the opportunity to map in detail the cosmic baryon distribution (basic idea described in Lee+2022, arXiv:2109.00386)
- FLIMFLAM survey has data on 22 FRB foreground fields:
  - Large spectroscopic campaign, anchored by 4m AAT/2dF-AAOmega multi-object fiber spectrograph
  - Analysis of 8 FRB fields (DR1) has made first explicit measurement of IGM/CGM cosmic baryon partition (Khrykin et al 2024b)
  - DR1 data has been released (Huang et al 2024)
- Subaru PFS enables a dramatic acceleration of this technique
  - ~3 - 3.5hr on PFS (inc overheads) allows full foreground data on each z~0.6 FRB
  - S25A+S25B early observations aims to target 10 FRB fields in 2-3 nights (Open-Use) → 3.8 sigma constraints on extreme feedback scenarios
  - A modest Intensive Progam (~25 nights over 3 yrs) will cover ~100 FRB fields that will comprehensively measure f_{igm} and f_{gas} over a range of galaxy halo masses.



Credit: D. Sorini (Durham)



Extragalactic Model DM

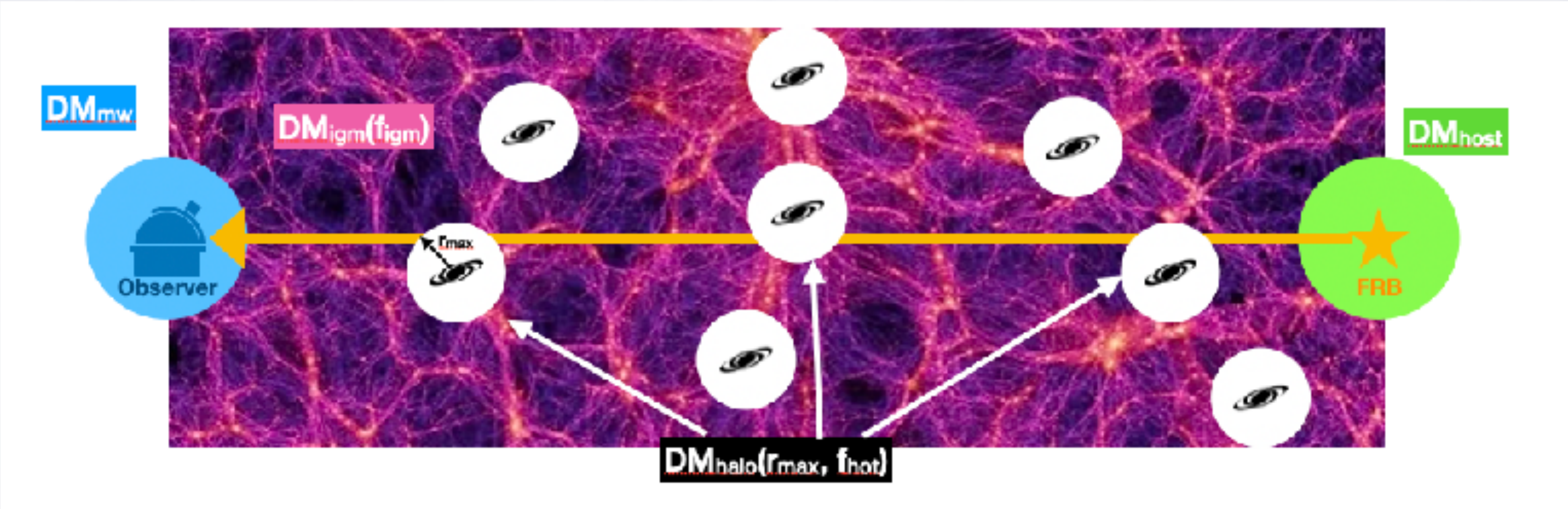
For a given FRB sightline, we can calculate a model $DM_{igm}(f_{igm})$ + $DM_{halo}(f_{gas})$ + DM_{host}

- **f_{igm}**: fraction of cosmic baryons residing in the diffuse IGM
- **f_{gas}**: fraction of halo baryons in the hot CGM phase in intervening galaxies (note: $f_{igm} + f_{gas} \neq 1$)

$$M_{cgm} = f_{gas} \frac{\Omega_b}{\Omega_{dm} + \Omega_b} \int_0^{r_{200}} 4\pi\, M_{halo}(r)\, r\, dr$$

- **DM_{host}**: Assume a unknown population for all FRBs, with a given mean and scatter
- 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



Reconstructing the Large-scale Cosmic Web

- The scatter in DM_{igm} dominates in z<0.5, so we would like to be able to nail down the underlying large-scale matter field in front of targeted FRBs.
- **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
- The IGM gas contribution can then be obtained by scaling the density field with $f_{igm}(\Omega_b/\Omega_m)$

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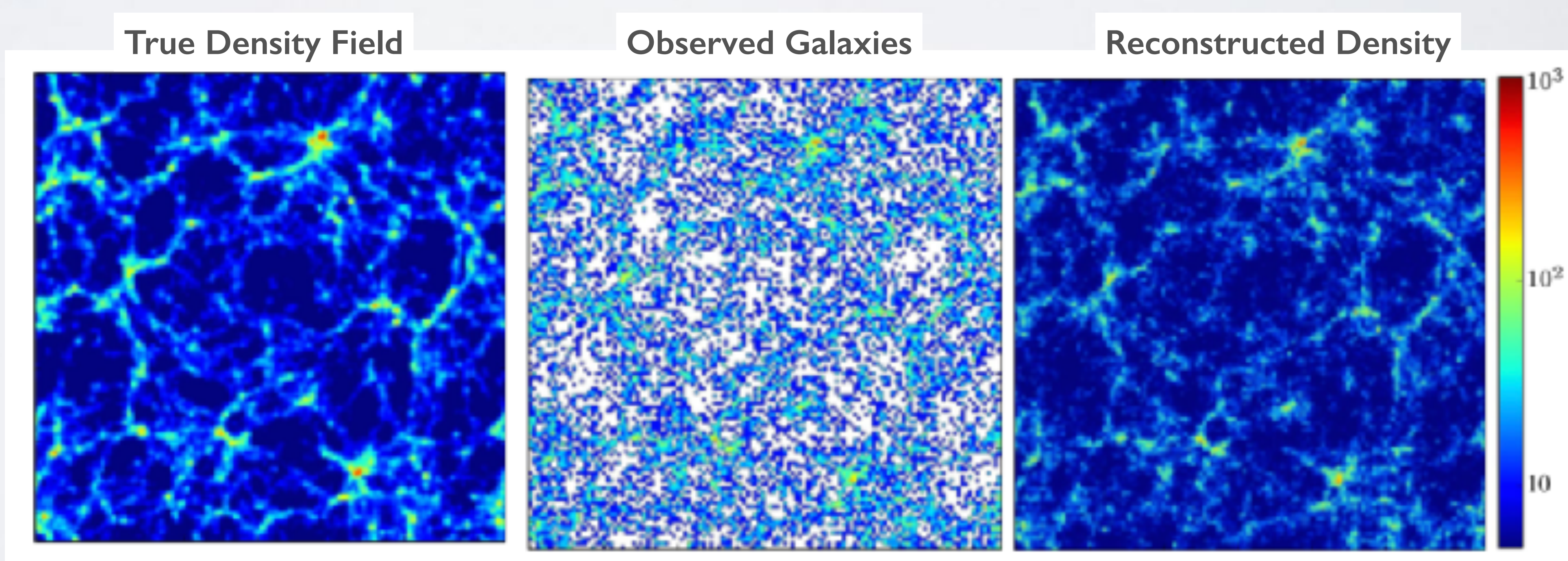
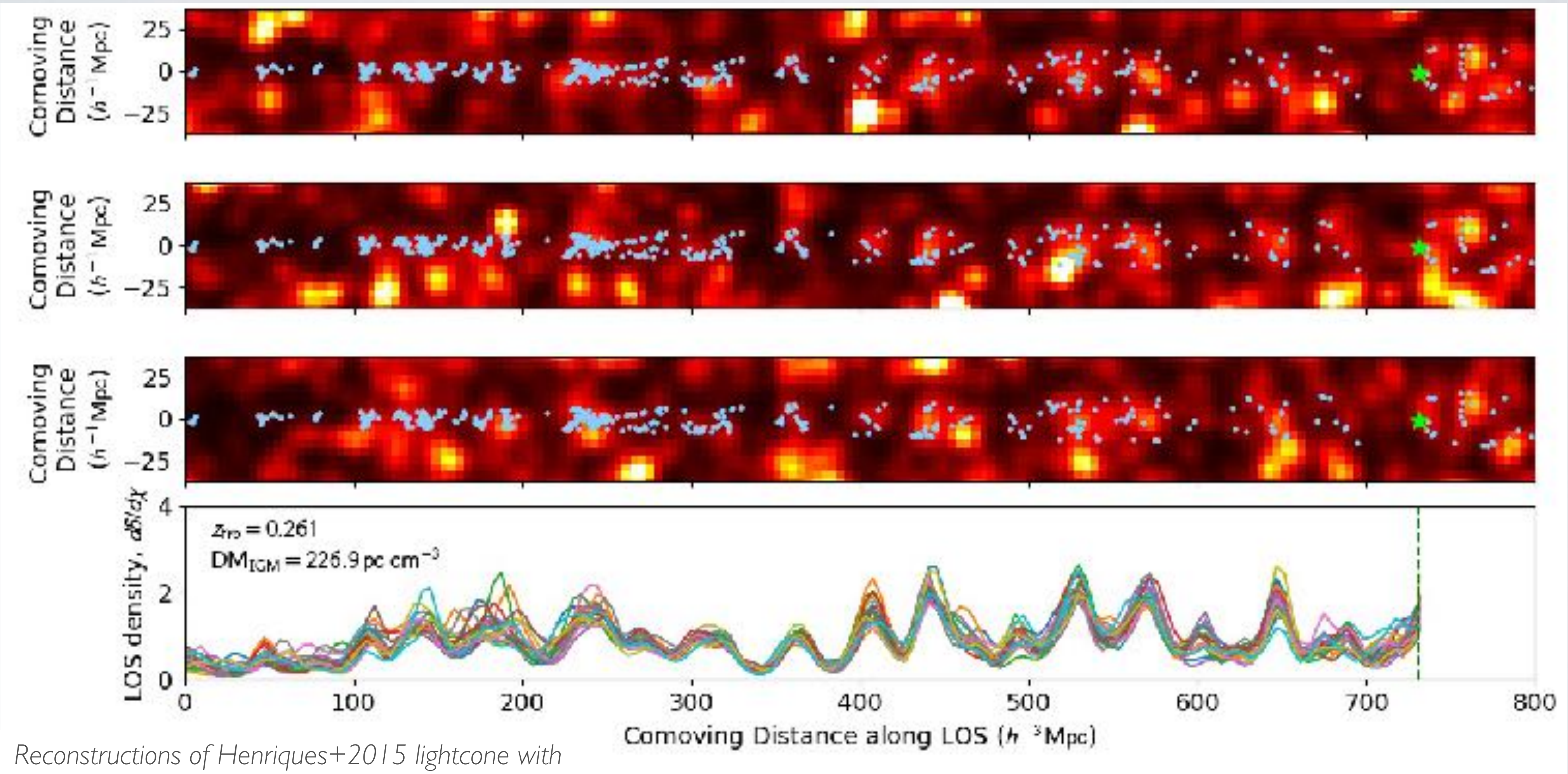


Ata et al 2015

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