**Title:** Probing the Effect of Feedback on the IGM with FRBs

**Speakers:** Khee-Gan Lee

**Collection/Series:** Cosmic Ecosystems

**Subject:** Cosmology

**Date:** August 01, 2025 - 11:00 AM

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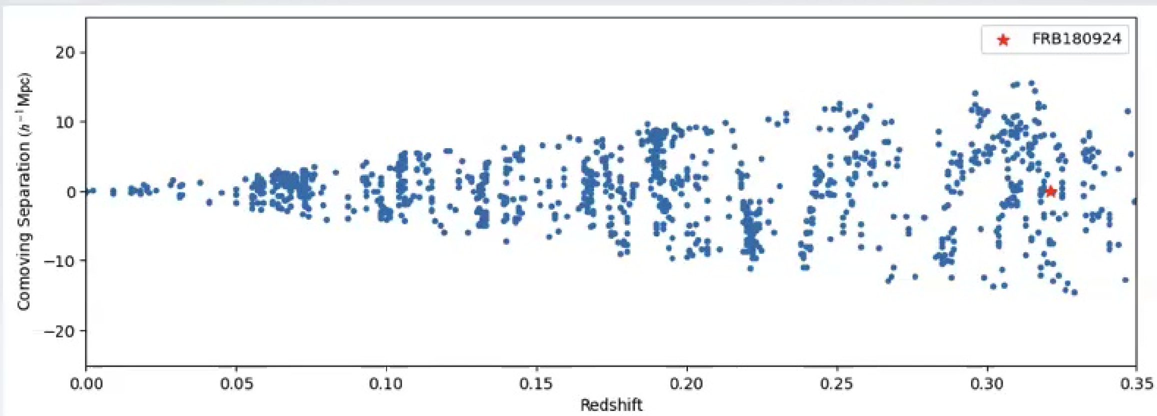
**Abstract:**

The intergalactic medium gas is usually believed to simply trace the cosmic web structures traced by dark matter, but AGN feedback (especially jets) will probably modify this simple picture especially the IGM and CGM baryon budgets. I will talk primarily about the combining spectroscopic galaxy surveys with FRBs to probe the IGM and CGM balance, which is being implemented in the FLIMFLAM survey. I will highlight the role of Subaru PFS, the world's most powerful multiobject spectrograph, in efficiently mapping the cosmic web out to high redshift, and new applications of the field level inference technique towards this problem.

# Probing the Effect of Feedback on the IGM with FRBs




*"Cosmic Ecosystems", Perimeter Institute*

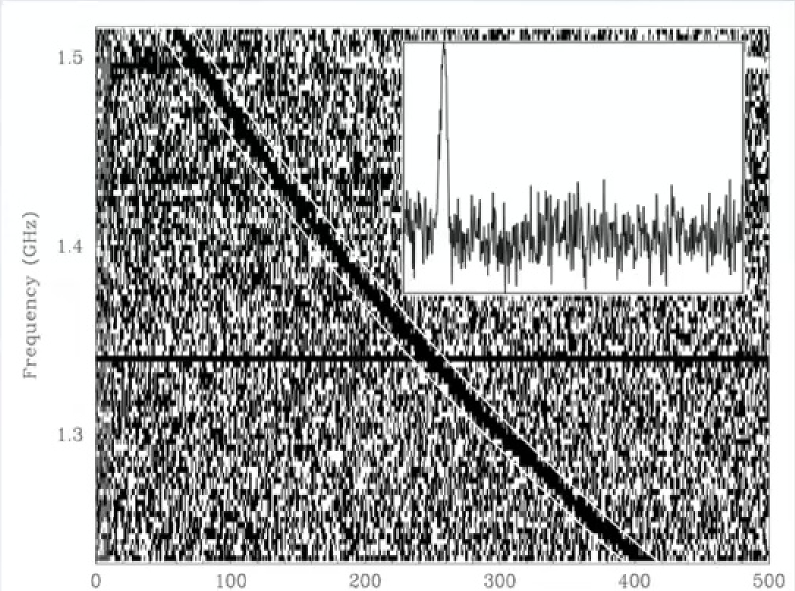
**Aug 1, 2025**


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

*Kavli IPMU, University of Tokyo*

# Fast Radio Bursts

- Millisecond-duration radio bursts first identified by Lorimer et al 2007
- To-date ~5000 FRBs have been detected; ~100 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)



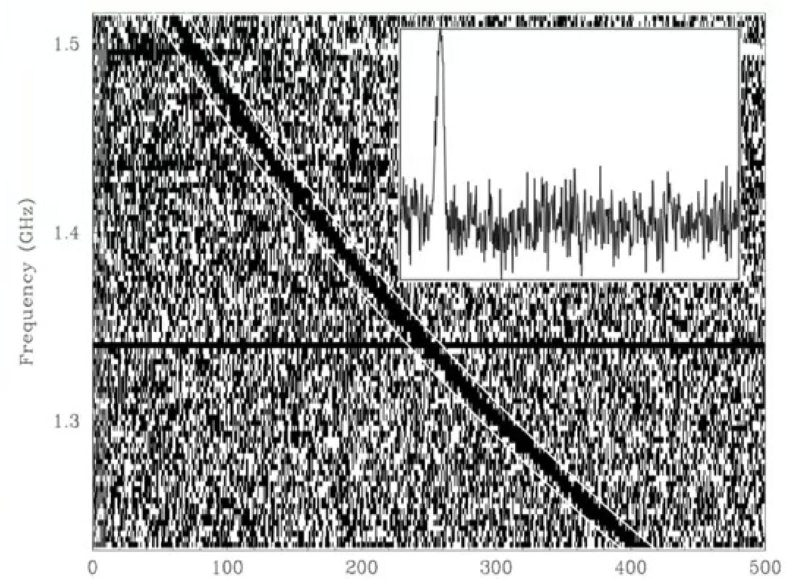

*Lorimer et al 2007*

# 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

# FRB DM is Volume-Weighted!

- Galaxies (and groups, clusters) are mass-weighted (i.e. biased) relative to the matter density field ($\boldsymbol{\delta} \gtrsim 100$)

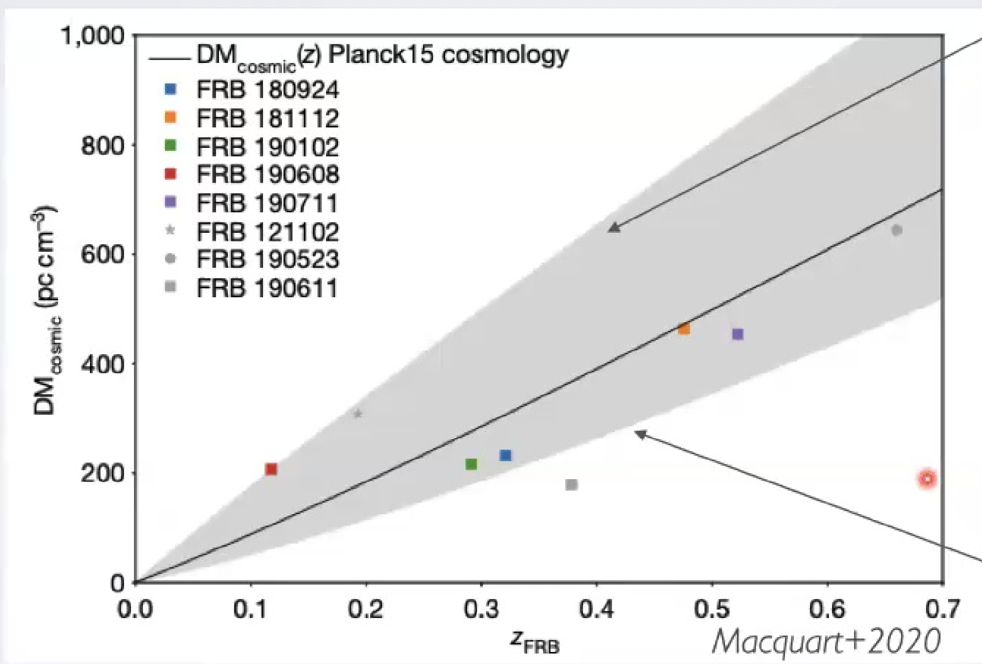
- The DM probed by FRBs is a path integral, i.e. it is *volume-weighted* $\mathbf{DM} = \int n_e(s)\, \mathrm{d}s$

- Can detect gas even in mean cosmic density and voids ($\boldsymbol{\delta} \sim 1$)

# The Macquart Relation

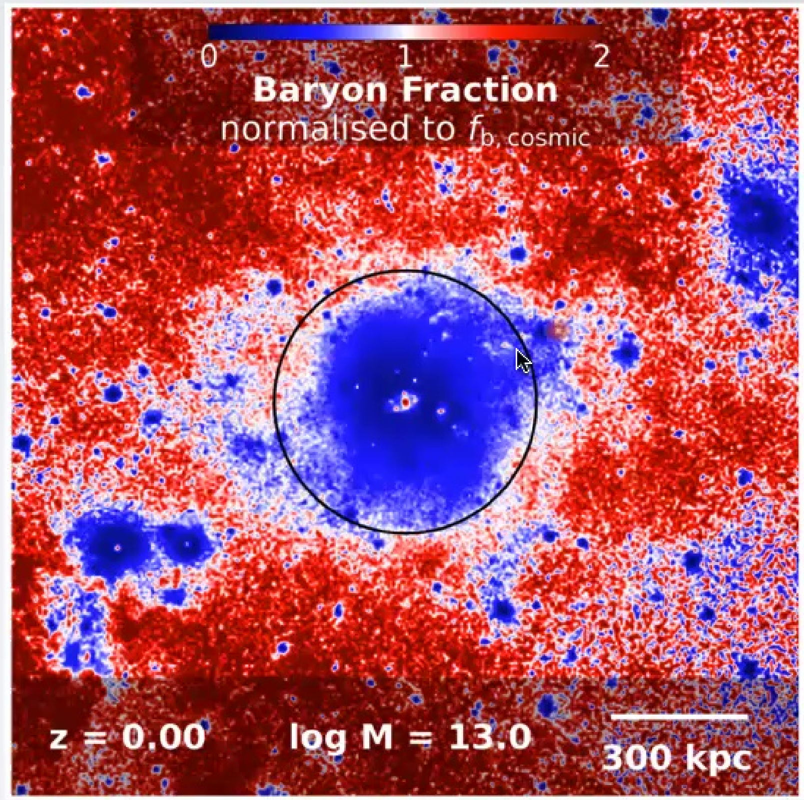
Macquart+2020 demonstrated that DM-redshift relationship of <u>localized</u> FRBs are consistent with $\Omega_{baryon}$ from CMB and BBN

→ *No more 'missing baryon problem', but relative distribution of baryons still unknown!*



# 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)

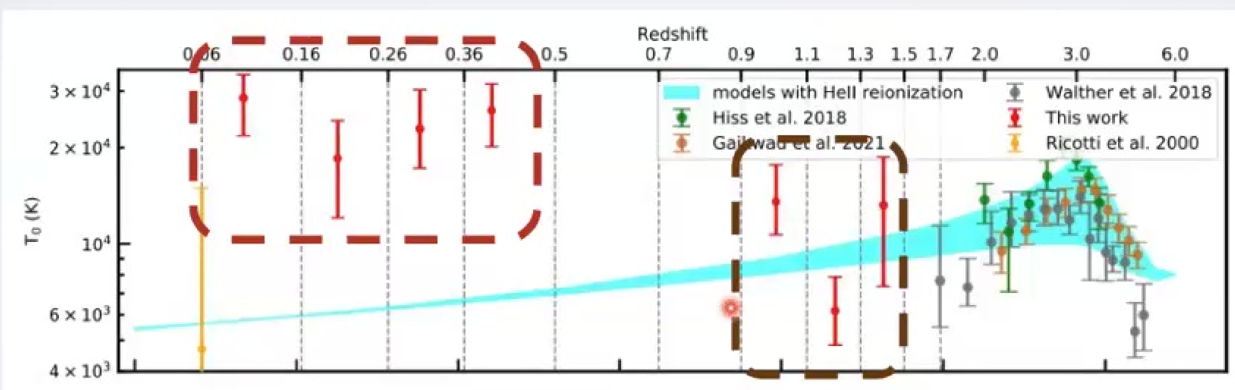
# The IGM is possibly more interesting than you think

- Known population of giant radio galaxies (>0.7Mpc) has increased by ~20-30x over the past 5 years thanks to LOFAR, MeerKAT, and other radio surveys (e.g. ~8k in Mostert+2024)

- Constraints on the z<1 IGM temperature from COS Ly-alpha forest suggests that the IGM temperature is significantly hotter than expected from most models (Hu+2024, 2025, Khaire+2024)

- See also kSZ constraints: more gas residing outside halos than expected from e.g. IllustrisTNG (Hadzhiyska+2025)


~5Mpc giant radio galaxy detected by LOFAR (Oei+2022)



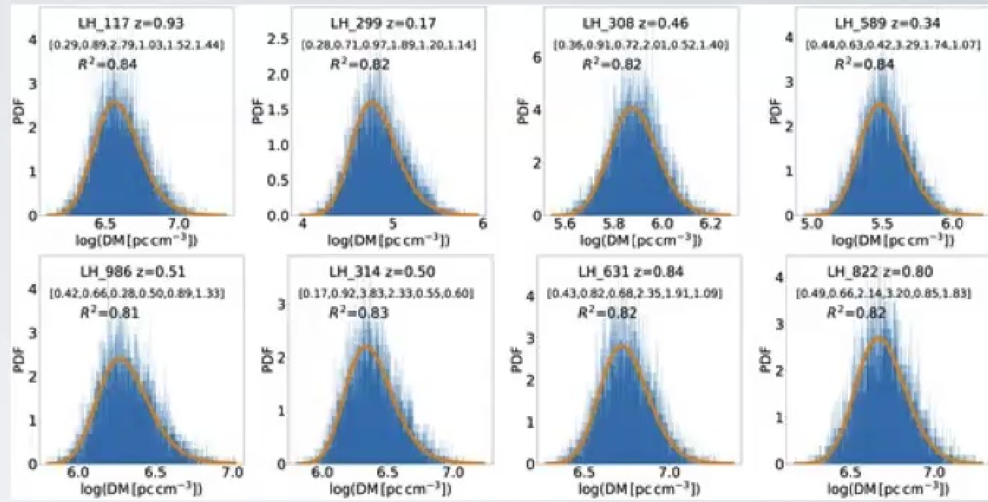

*Credit: Teng Hu (LAM), from Hu+2024 and in prep*

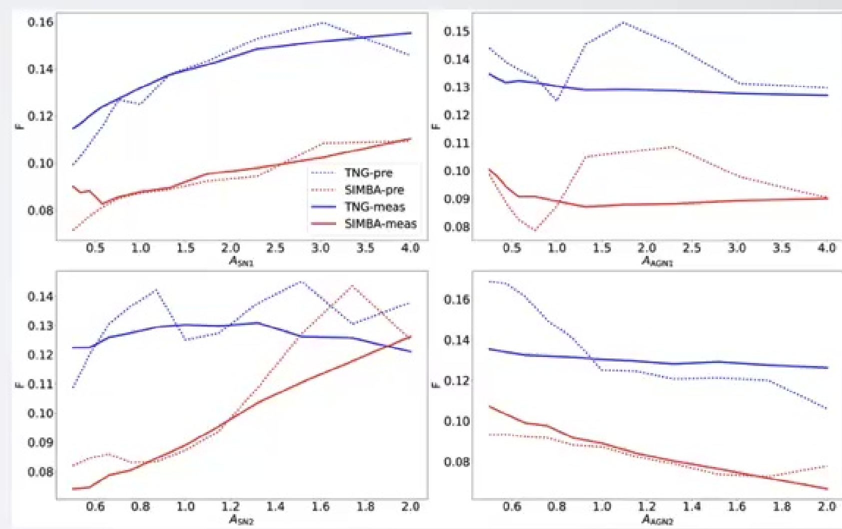
# Using p(DM) as a probe of feedback

- Goal: Create a neural network model of the p(DM) at fixed redshift, as a function of $\Omega_m$, $\sigma_8$, and SN+AGN feedback parameters $[A_{SN1}, A_{SN2}, A_{AGN1}, A_{AGN2}]$
  - Trained using sightlines drawn from the ~1000 CAMELS simulations (L=25Mpc/h)
- Fitted simulation $p(\Delta \equiv \mathrm{DM}/\langle \mathrm{DM} \rangle)$ with fitting function:

$$p_{\mathrm{cosmic}}(\Delta) = A\Delta^{-\beta} \exp\left[-\frac{(\Delta^{-\alpha} - C_0)^2}{2\alpha^2\sigma_{\mathrm{DM}}^2}\right]$$

- NN is quite successful at predicting the correct p(DM) shape given $[A_{SN1}, A_{SN2}, A_{AGN1}, A_{AGN2}]$
- But we find overall widths of the simulated p(DM) **too narrow** compared to observations (e.g. Baptista+2024)
  - → CAMELS boxes likely too small to capture full variance of cosmic structures
- Qi & KGL 2025 (arXiv:2501.16709)



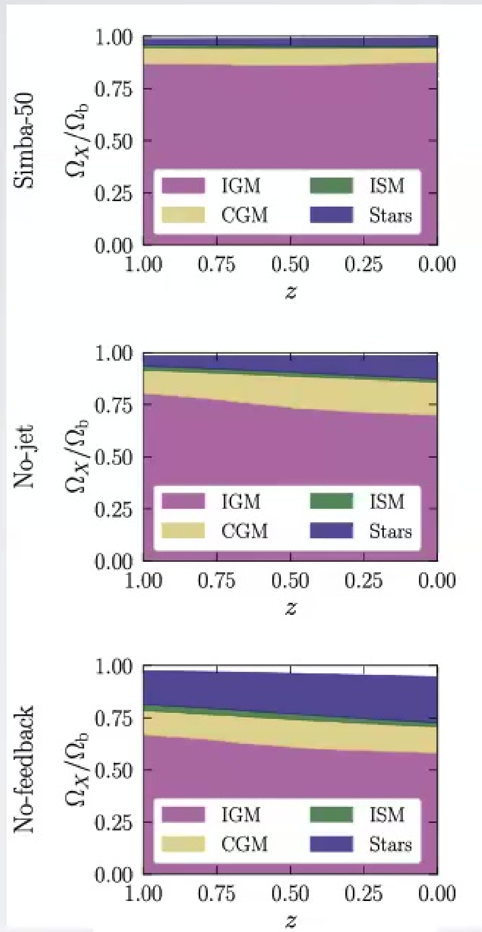

Solid curves (1P models); dotted (NN model)

# Simba Hydrodynamical Simulation Results

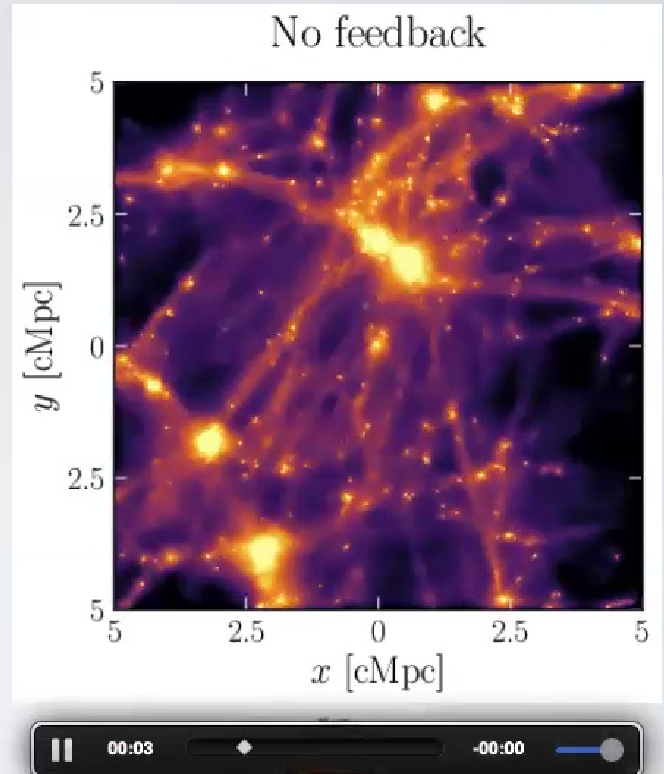
**Full feedback: SNe & AGN jets+winds+X-ray**
85% of baryons in IGM

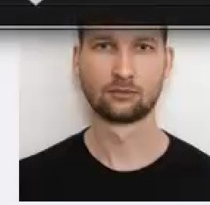
**No AGN jets/X-ray: SNe & AGN winds**
70% of baryons in IGM

**No feedback**
60% of baryons in IGM




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



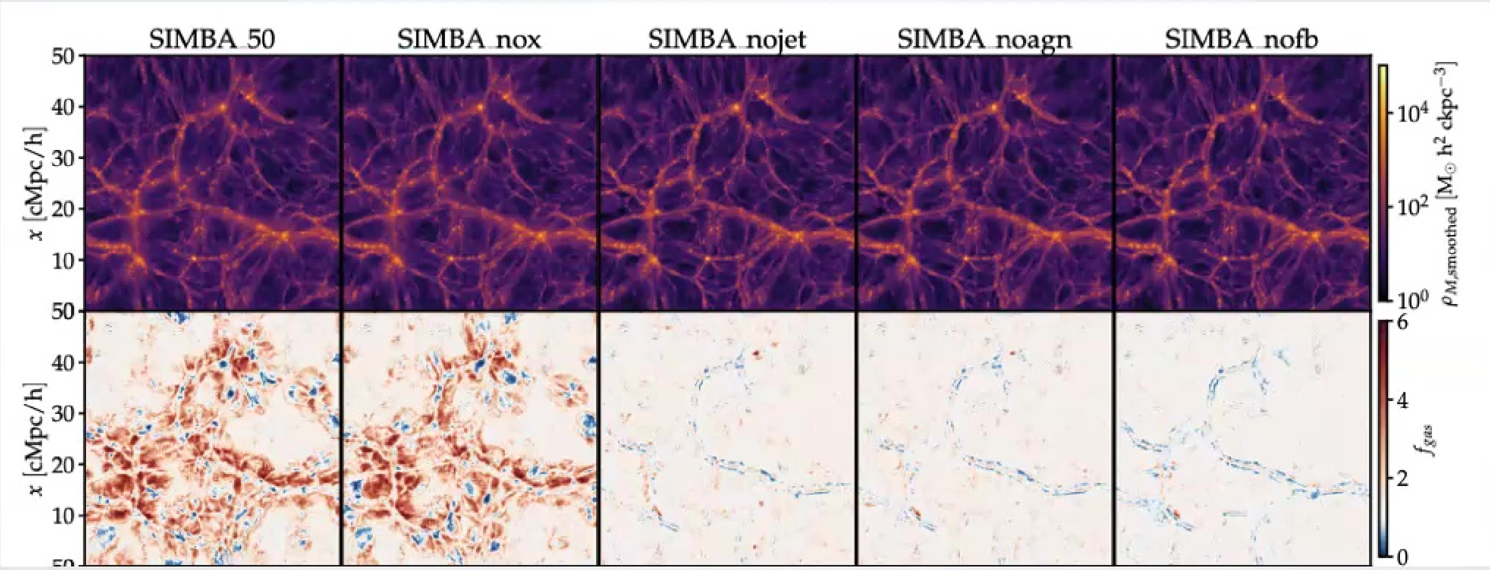



*Ilya Khrykin*
*PUC Valparaiso*

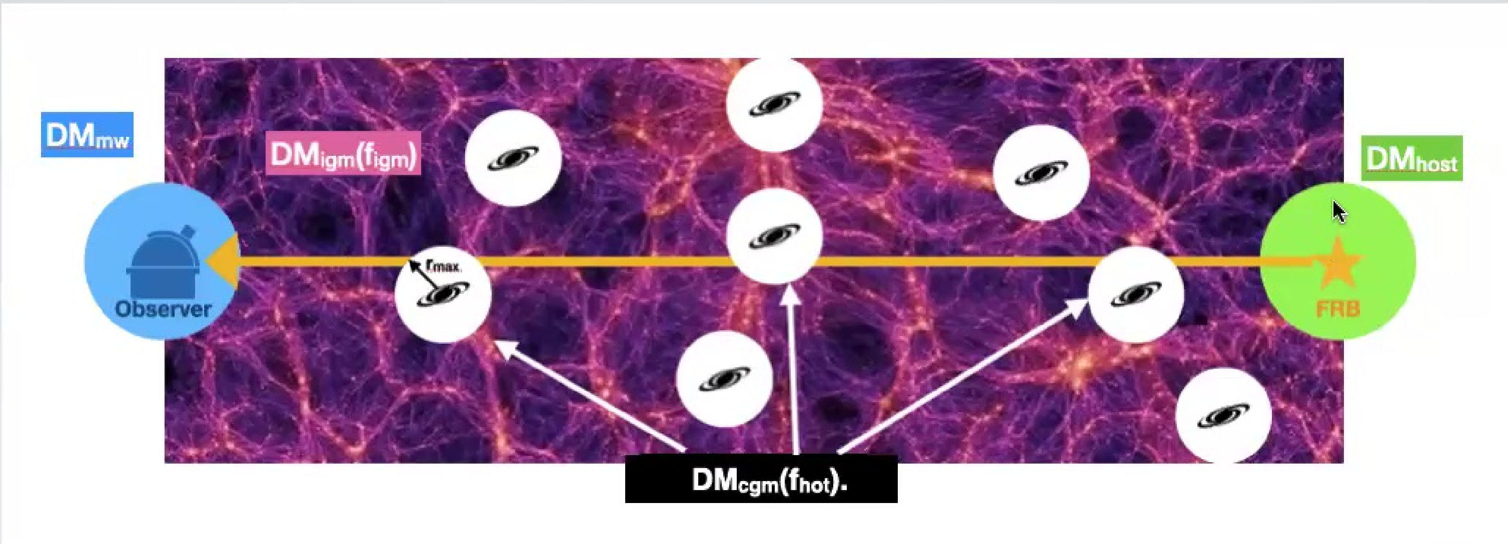
***The simple dichotomy between the CGM and IGM baryon fractions ($f_{cgm}$ vs $f_{igm}$) is useful for studying the cosmic baryons, and study the effect of galaxy feedback in modes that might be degenerate in the galaxy population/properties***

# Is there baryon redistribution *across* the cosmic web?

- Follow-up paper: Dong, Dedieu et al 2025 (arXiv:2507.16115)
- Categorize the SIMBA simulations into different cosmic web components (nodes, sheets, filaments, voids) to see if baryons are redistributed across them
    - 'Pile-up' of gas content at node and filament boundaries caused by the SIMBA AGN jets
    - On ~Mpc scales these translate to percent level differences (hard to detect with near-future observations

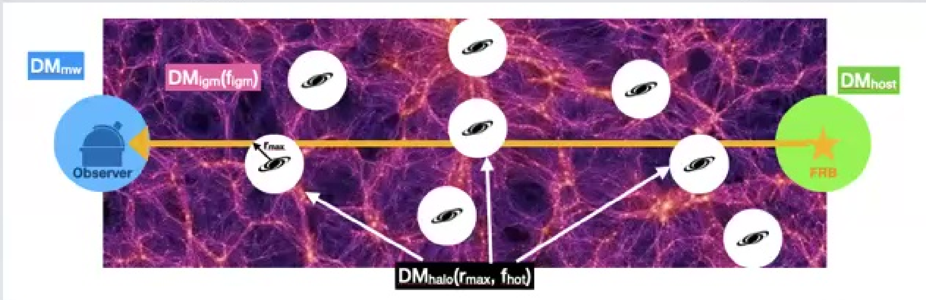


# Decomposing the FRB DM




- 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)
- ***FRB observations can in principle decompose the IGM and CGM contributions!***
- Lee+2022 forecasted that FRBs with wide-field foreground spectroscopy is equivalent to 100x increase in FRB numbers
  - Few thousand FRB DMs needed to detect AGN feedback (Batten+2022)
  - ~30 FRBs needed if spectroscopic data is available

# Analogy to Linear Equations




- Given an ensemble of FRBs and their foreground data, after subtracting the MW component the problem becomes analogous to a linear equation by writing down models for each sightline contribution: $DM_i = DM_{igm,i} + DM_{halo,i} + DM_{host,i}$
- Observed foreground galaxies (with estimated halo mass) and density field reconstruction allows us to compute the different DM components as a function of model parameters $[f_{igm}, f_{gas}, DM_{host}]$
- Given perfect knowledge of the foreground cosmic web and intervening galaxies, and assuming:
  - Baryons perfectly trace large-scale + halo density field ($\mathbf{DM}_{\rm igm} \propto f_{igm}\Delta_{\rm matter}$ and $\mathbf{DM}_{\rm halo} \propto f_{gas}\Delta_{\rm halo}$
  - All FRBs have the same $DM_{host}$
  - ➔ only 3 FRBs are needed to measure $[f_{igm}, f_{gas}, DM_{host}]$

$$\begin{bmatrix} DM_1 \\ DM_2 \\ DM_3 \\ \vdots \end{bmatrix} = \begin{bmatrix} DM_{igm,1}(f_{igm}) & DM_{halo,1}(f_{gas}) & DM_{host} \\ DM_{igm,2}(f_{igm}) & DM_{halo,2}(f_{gas}) & DM_{host} \\ DM_{igm,3}(f_{igm}) & DM_{halo,3}(f_{gas}) & DM_{host} \\ \vdots & \vdots & \vdots \end{bmatrix}$$

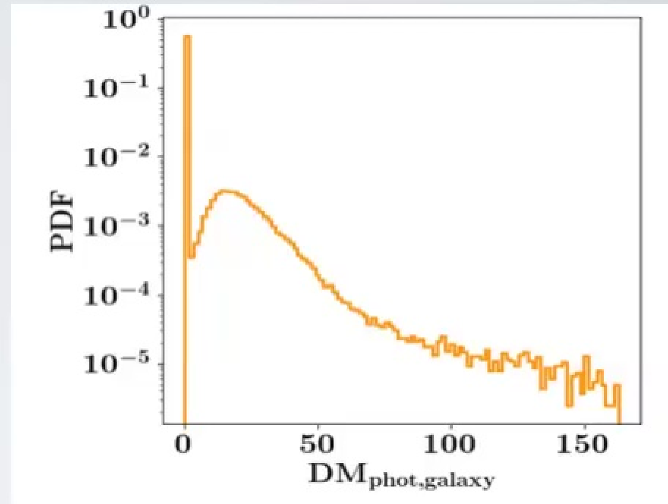
*Measured from FRB itself*

*Computed from foreground data*

*Alas, the parameters are not necessarily linear and there's observational noise…in practice we*

# Why Is Spectroscopy Important?

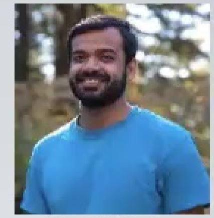
- Mapping the Cosmic Web is functionally impossible with just photometric data (discovery of the cosmic web itself in the 1980s was fundamentally thanks to spectroscopic surveys)
- Photometric redshifts from typical wide-field surveys have uncertainties of 20-30% at best
  - Propagates not only to where a foreground galaxy might be along the LOS, but also to its estimated mass (see Simha, Prochaska, KGL et al 2021) and hence DM contribution




*Simha, Prochaska, KGL et al 2021*

*Yuxin Huang*
*UTokyo PhD Student*

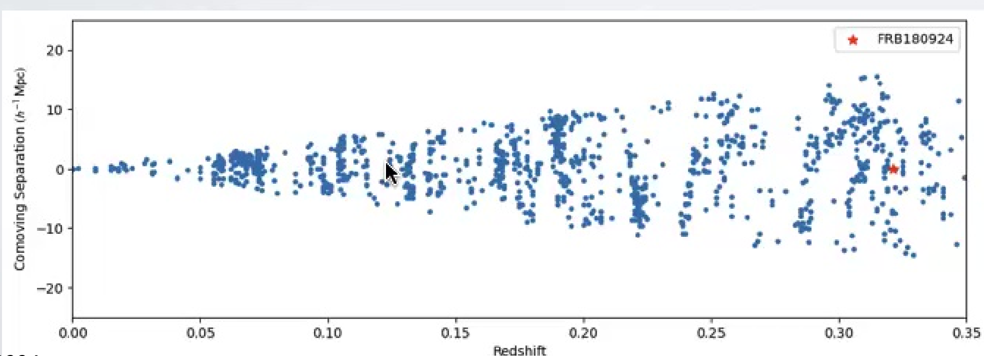
# FLIMFLAM on the AAT



*Sunil Simha*
*Northwestern U/UChicago*

- FRB Line-of-sight Ionization Measurement From Lightcone AAOmega Mapping (FLIMFLAM) Survey targeting localized FRB fields
- Campaign to spectroscopically map large-scale cosmic web in foregrounds of FRBs
- Anchored by 4m AAT with AAOmega/2dF spectrograph: ~350 science fibers simultaneously over a 3.1 sq deg FOV
    - Supplemented by public spectroscopic data from SDSS and 6dF where available (and soon DESI)
- Simultaneous deep campaign with Keck/DEIMOS, Gemini/GMOS, VLT-MUSE (led by S. Simha and N. Tejos)
- FLIMFLAM DR1: 12k redshifts in 10 localized FRB fields → Huang, KGL et al 2025, ApJS

*2dF/AAOmega on AAT, Siding Spring, Australia*



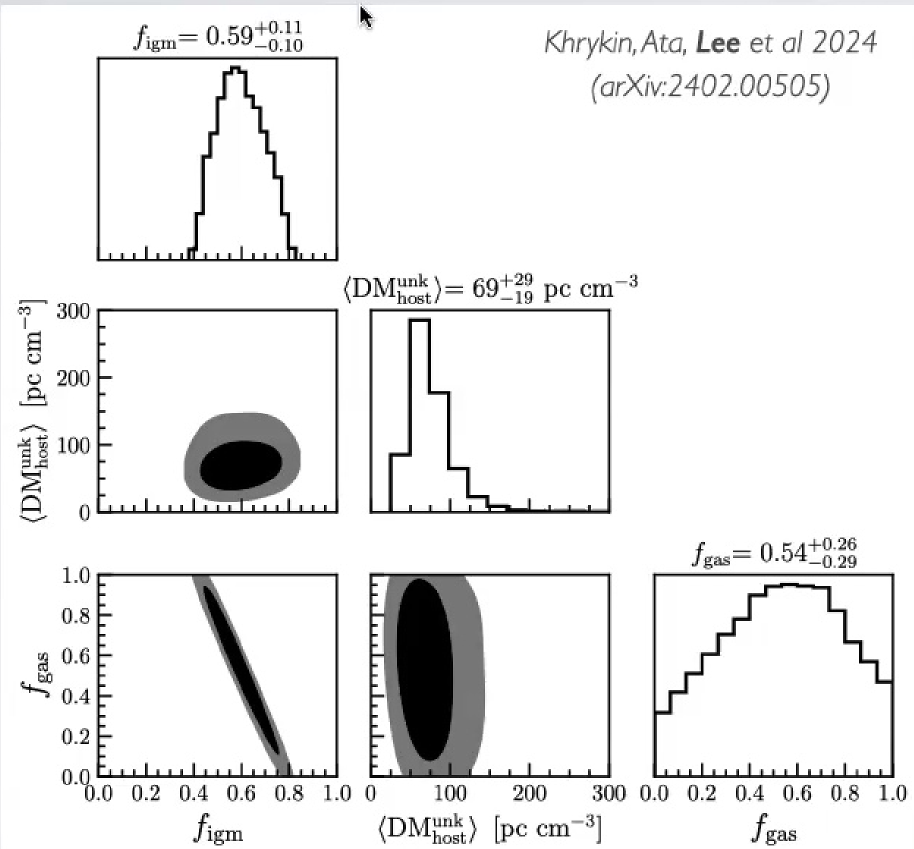


*Keck-I Telescope, Maunakea, Australia*

*Gemini South, Cerro Pachon, Chile*

# FLIMFLAM DR1 Results

*Ilya Khrykin*
*PUC Valparaiso*



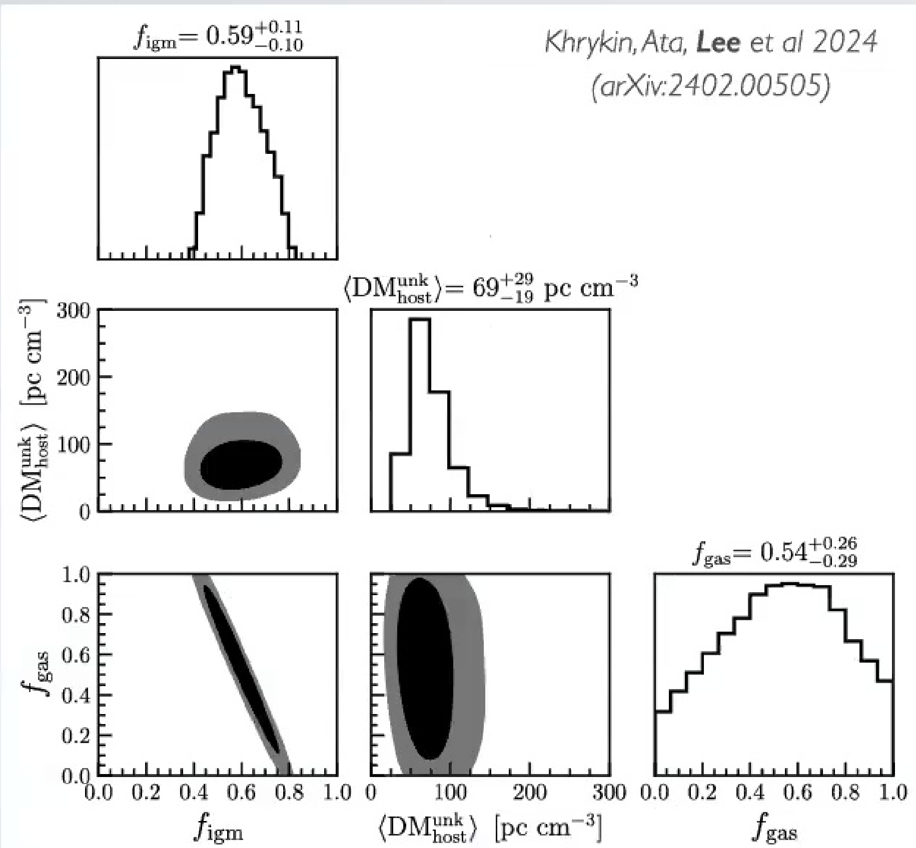

$$\langle DM_{host} \rangle = \langle DM^{halo}_{host} + DM^{unk}_{host} \rangle$$

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

- **<u>First direct measurement</u>** of partition between IGM and CGM baryons with 8 FRBs
  - 10% constraints on $f_{igm}$, still too loose to constrain feedback models ($0.6 < f_{igm} < 0.85$)
  - Halo mass range $10^{11} M_\odot < M_{halo} < 10^{13.5} M_\odot$ probed by our data
  - The current $f_{gas}$ constraint implies that this halo mass range contributes $f_{cgm} = 0.20^{+0.10}_{-0.11}$ 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!

# FLIMFLAM DR1 Results

*Ilya Khrykin*
*PUC Valparaiso*

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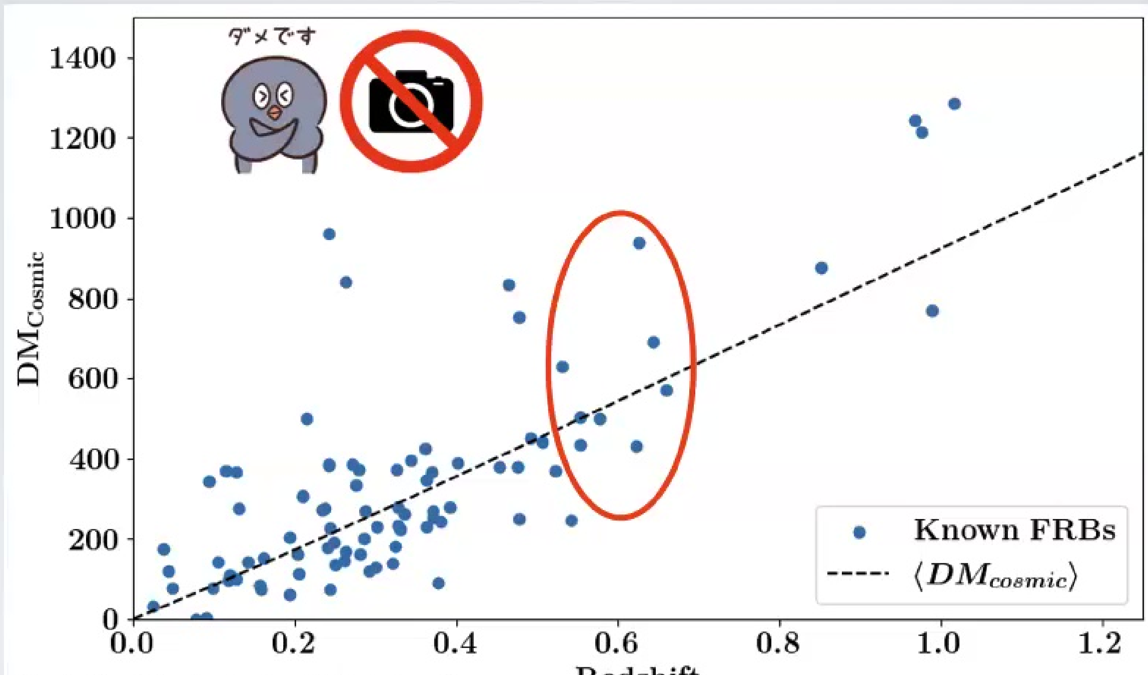
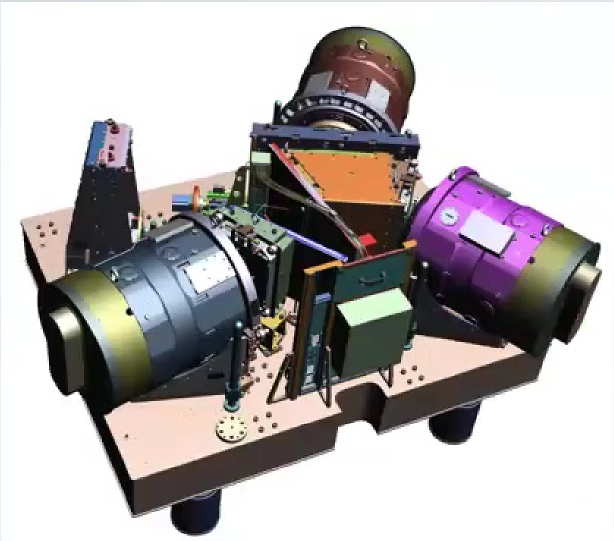
# FRB Foreground Mapping with PFS



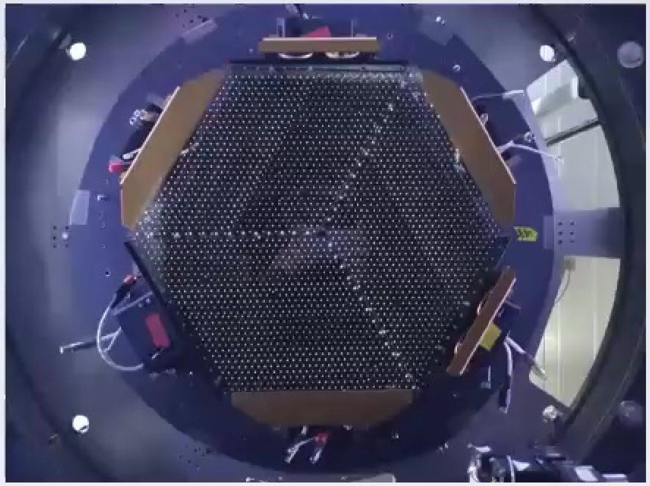

*Credit: Sunil Simha & the F4 Collaboration*

- 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. Considered too ambitious for early PFS observations.

# Subaru-Prime Focus Spectrograph (PFS)



*3-channel spectrographs*



*Prime-focus fiber positioner module*

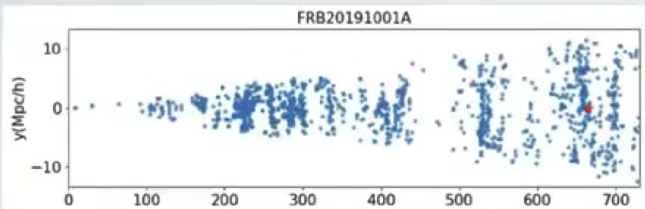
*Subaru Telescope*

- PFS: Multi-object fiber spectrograph on 8.2m Subaru Telescope on Maunakea, Hawai'i
- Simultaneously observe **~2000 targets over 1.3deg$^2$ FOV**
- Broadband wavelength coverage: 380nm-1.3 micron at R~3000
- Science operations started spring 2025!

# FRB Foreground Mapping with PFS

FRB20191001A,
z=0.234
(D=955cMpc)

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



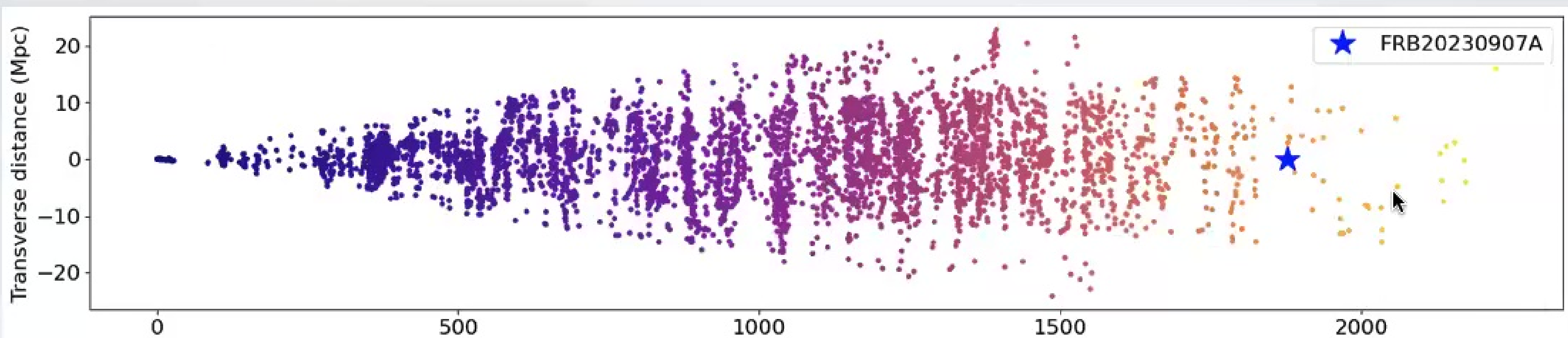




*Figure credit: S. Simha*

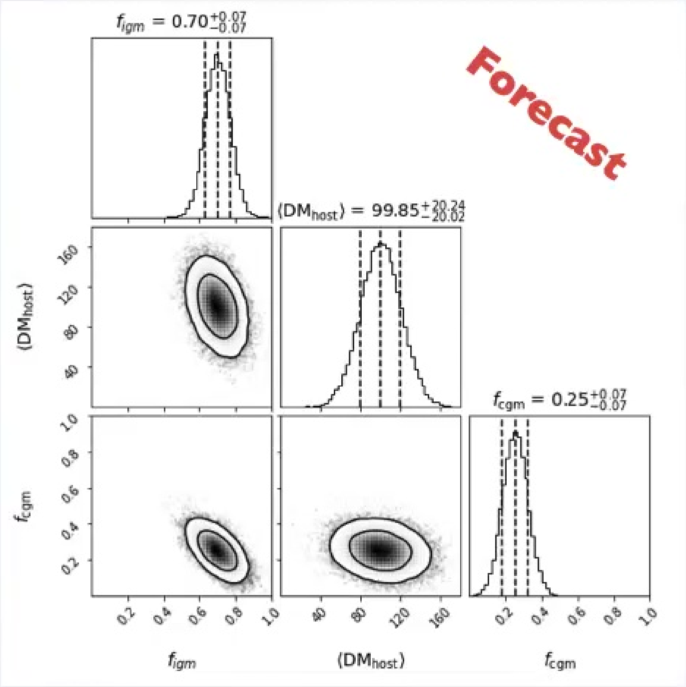
~6000 foreground galaxies @ r<21.3
→ 3.5hrs with Subaru PFS!

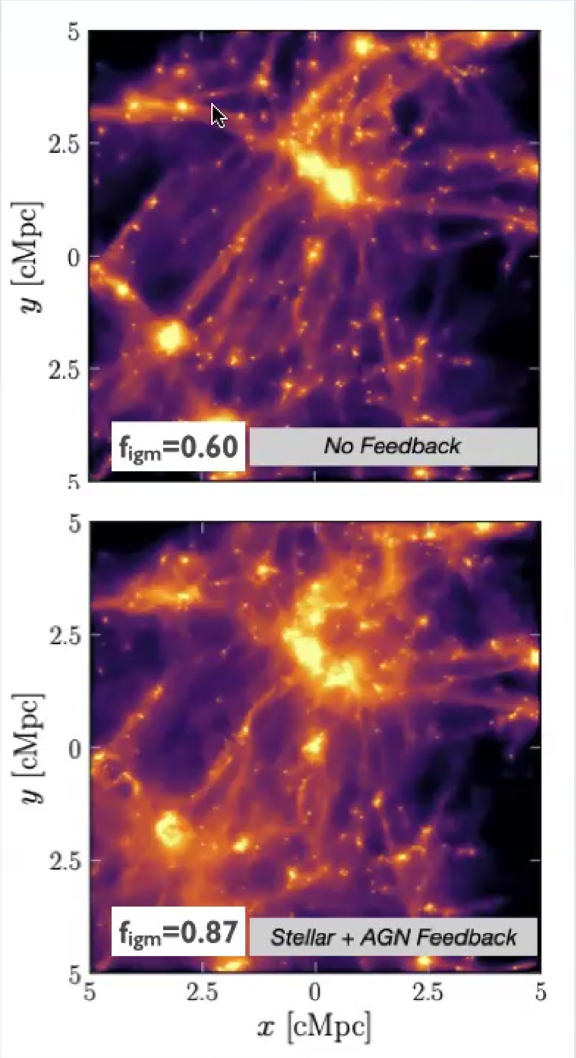
FRB20230907A,
z=0.636
(D=2343cMpc)

- 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 $f_{cgm}$

# FLIMFLAM DR2 Science Goals

- Approx 35 FRB fields now in hand for DR2 (~18 AAT + 13 SDSS/DESI/ + 4 PFS)
  - Forecasted precision is $\sigma(f_{igm}) = 0.07$
- With reference to simulations of Khrykin et al 2024a, we should be able to place 3.8$\sigma$ limits on the most extreme galaxy feedback scenarios

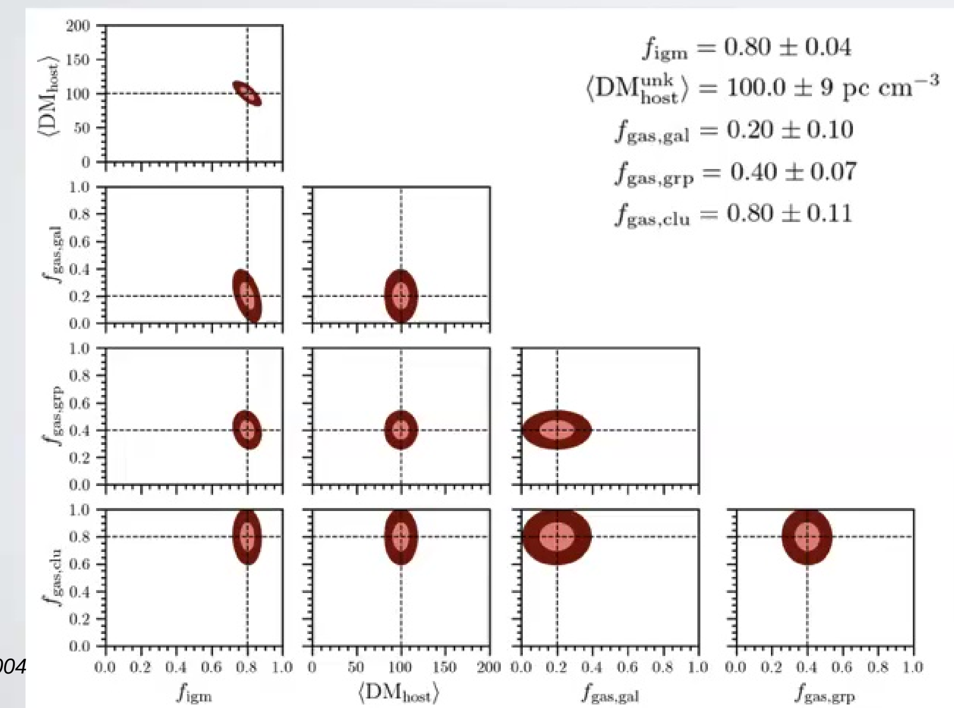


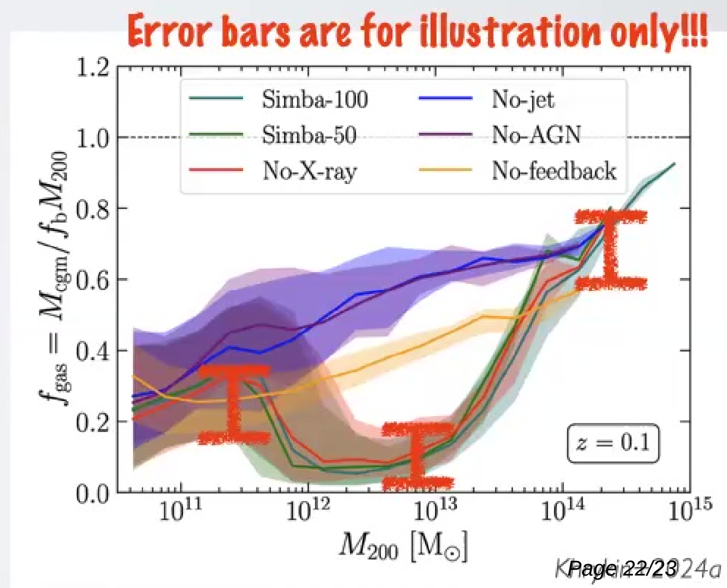




Credit: D. Sorini (Durham)

# Longer-Term Forecast

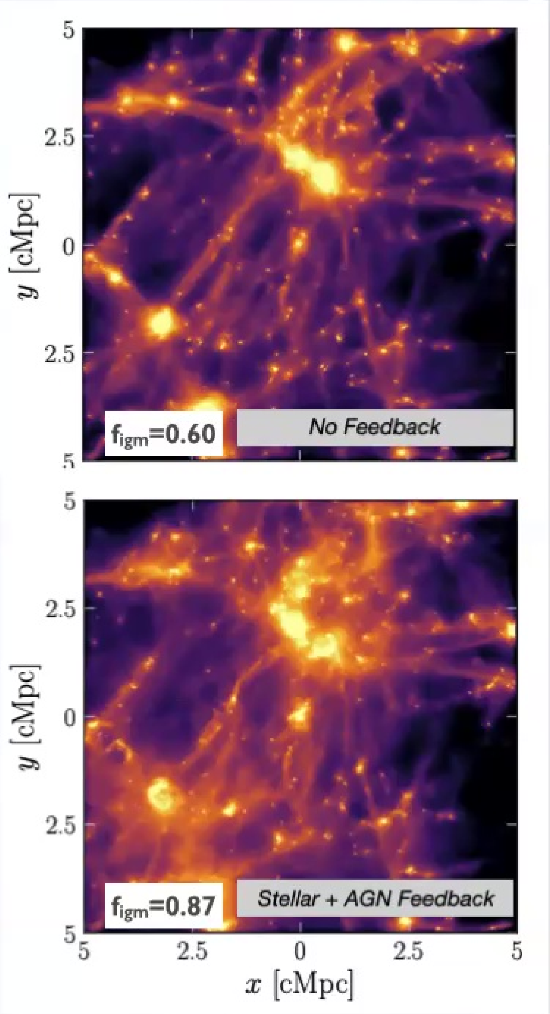
- ~100 localized high-z FRBs targeted by PFS would require ~30 Subaru nights in total
- Such a sample will allow $f_{igm}$ measurements down to a few percent, and $f_{gas}$ measurements *over multiple halo mass bins* to enable precise tests of galaxy feedback models
- Can also potentially start constraining 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)
    - Basic IGM and CGM baryon fractions is a probe of feedback models
- FLIMFLAM survey has data on 35 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)
- 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
    - In near future aim to target 10 FRB fields in 2-3 nights (Open-Use) → 4 sigma constraints on extreme feedback scenarios
- Expect $f_{gas}$ as a function of galaxy mass down to sub-L* with samples of ~100 within next few years




*Credit: D. Sorini (Durham)*