The Cosmic Baryons Illuminated by the Fast Radio Bursts

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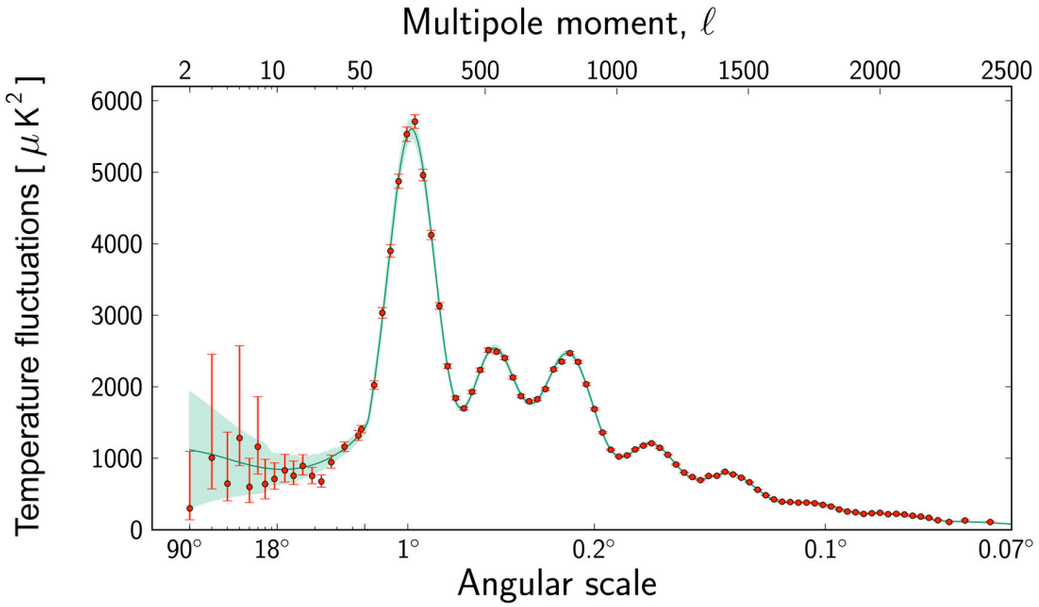
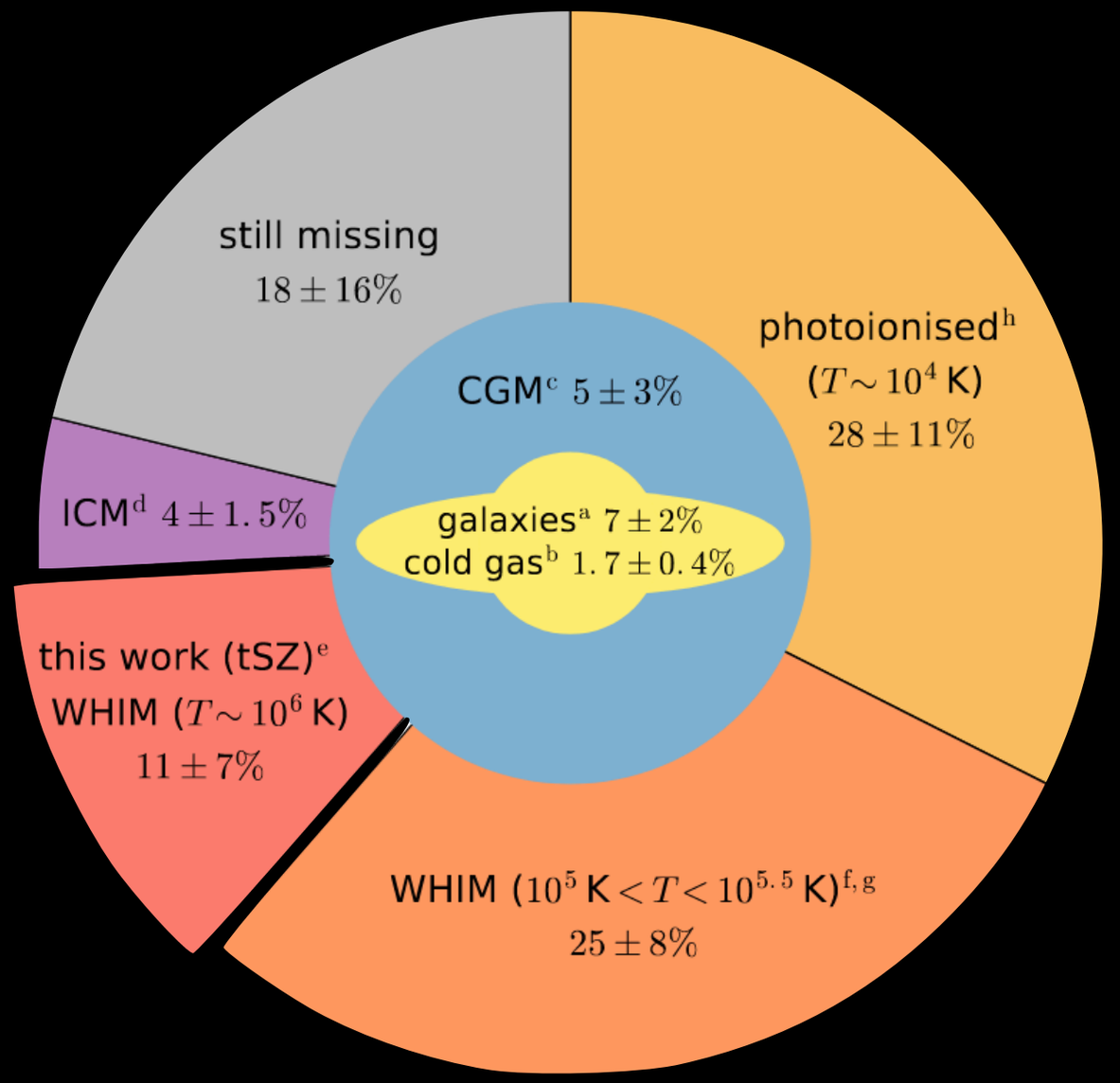
The Missing Baryons Problem



Planck Collaboration

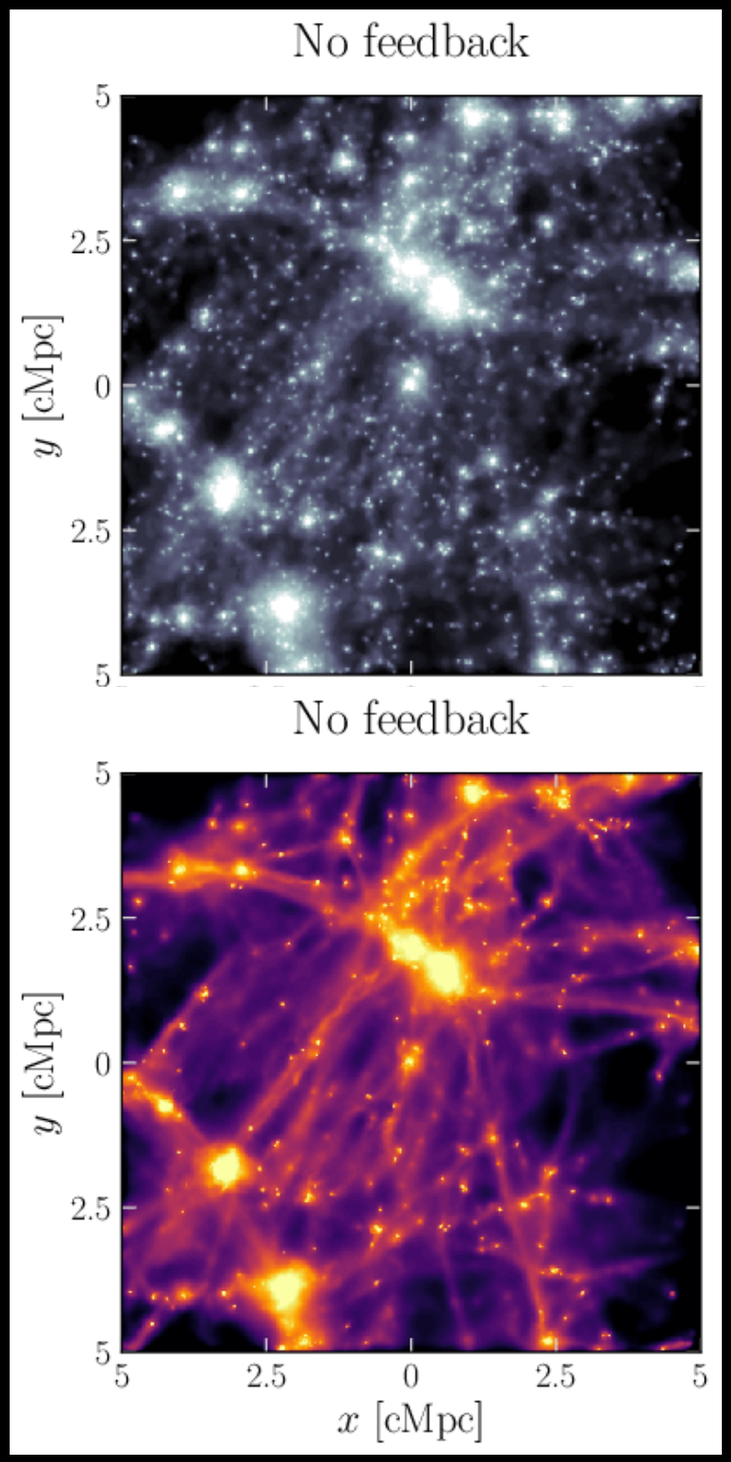
At z < 2 about 20-30% of baryons are observationally unaccounted for.



De Graff+2019

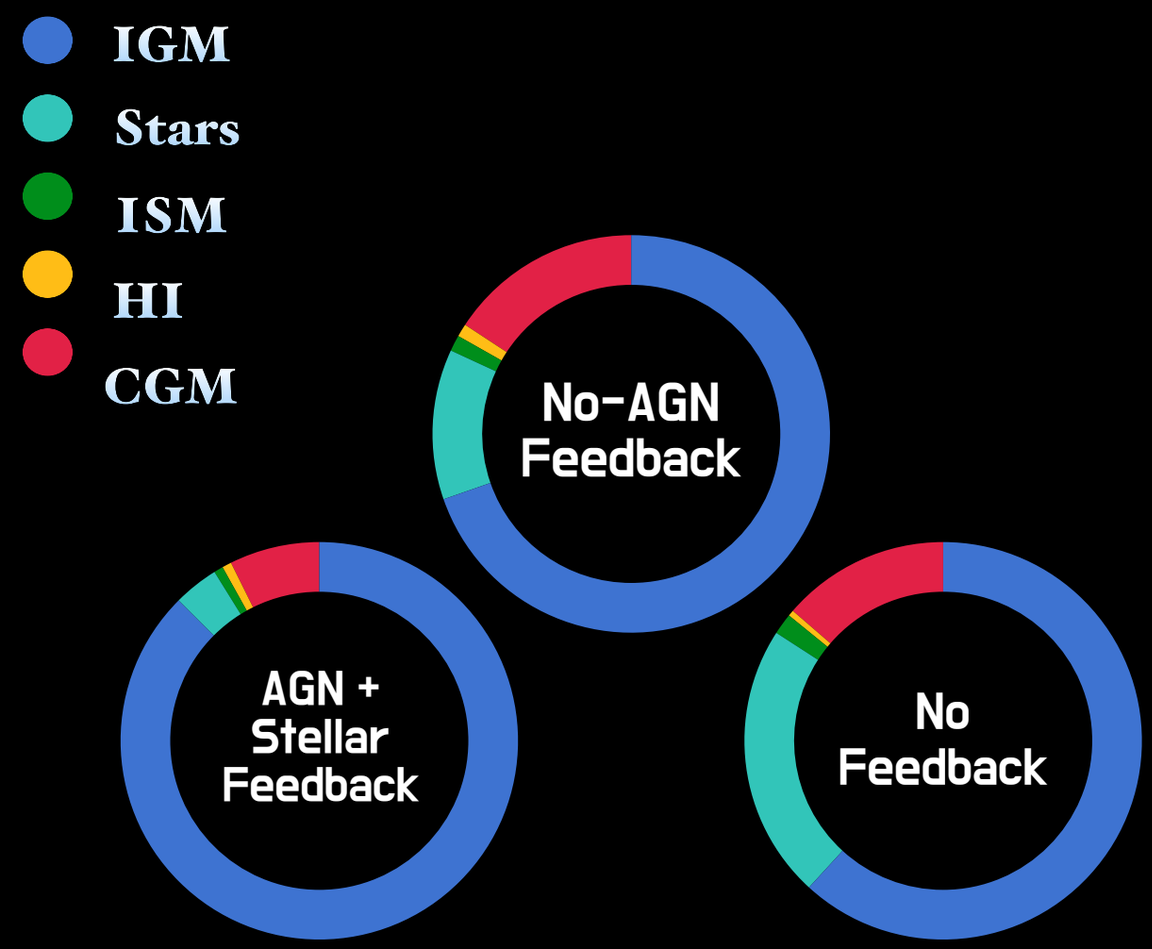
Feedback Mechanisms (example from SIMBA)

Dark Matter



Baryons

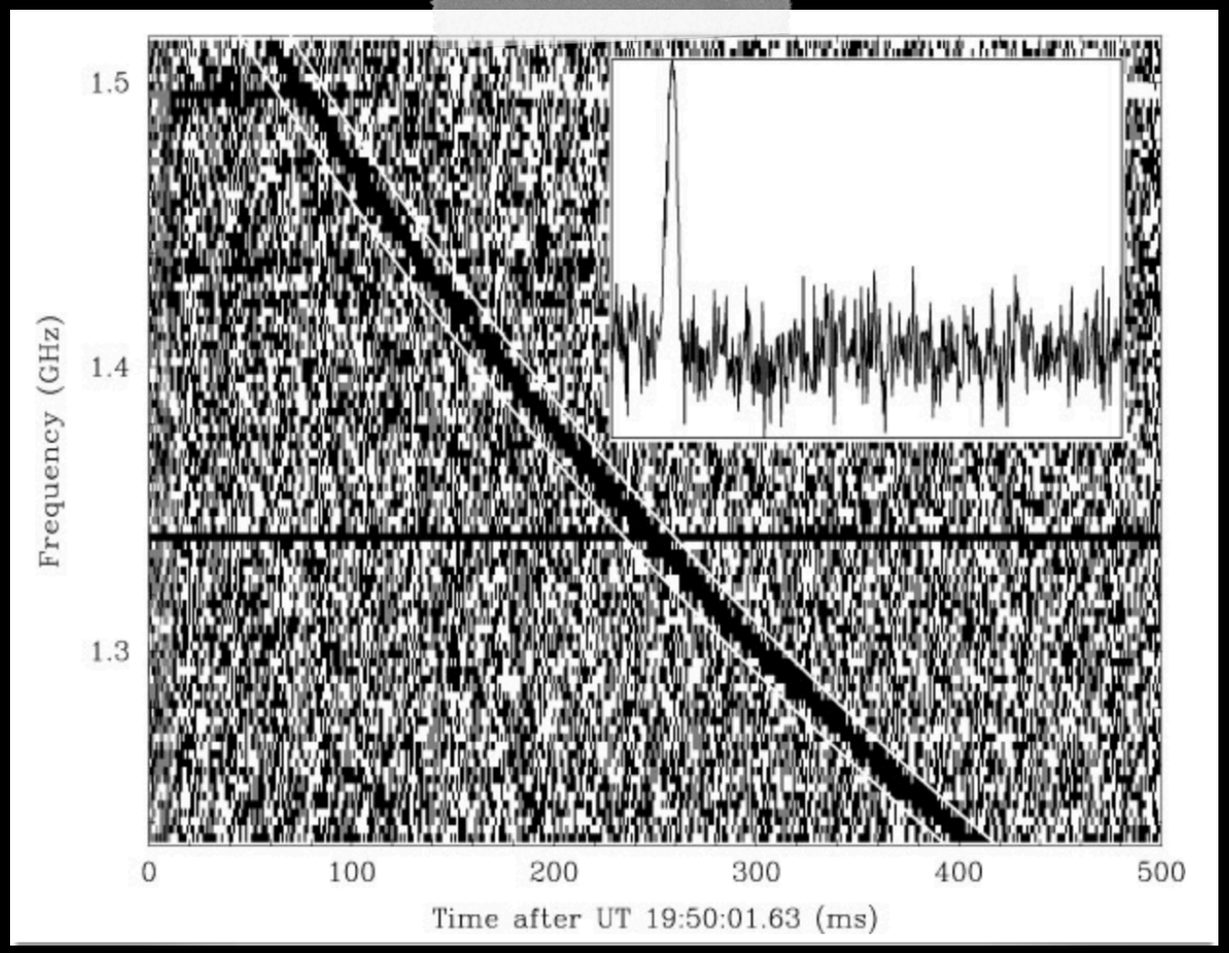
$M \sim 10^{12} M_\odot$ at $z = 1$ Sorini et al. (2024)



Partitioning of cosmic baryons at z=0.1 in SIMBA simulations with different feedback prescriptions

Khrykin et al. (2024a)

Fast Radio Bursts: a new probe of the IGM/CGM gas



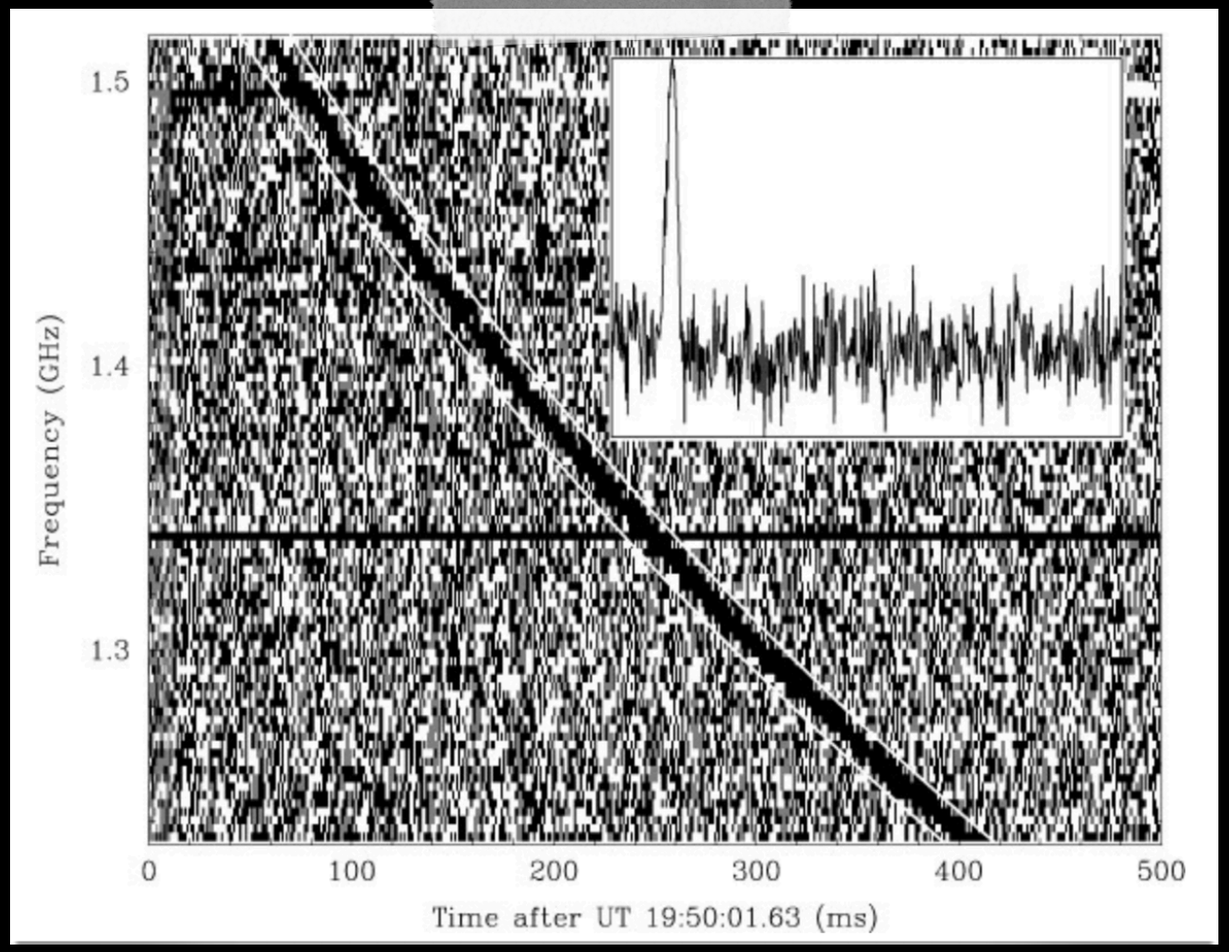
Lorimer et al. (2007)

FRB signal

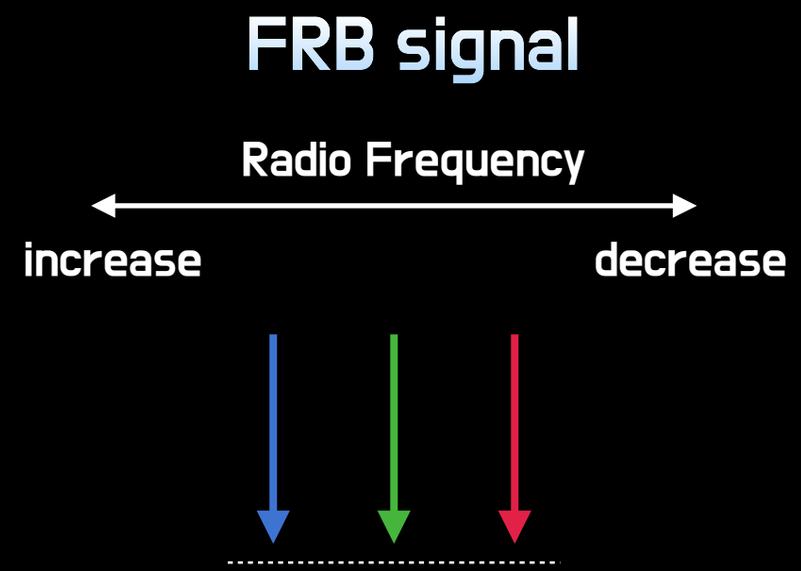
Radio Frequency

increase ⟷ decrease

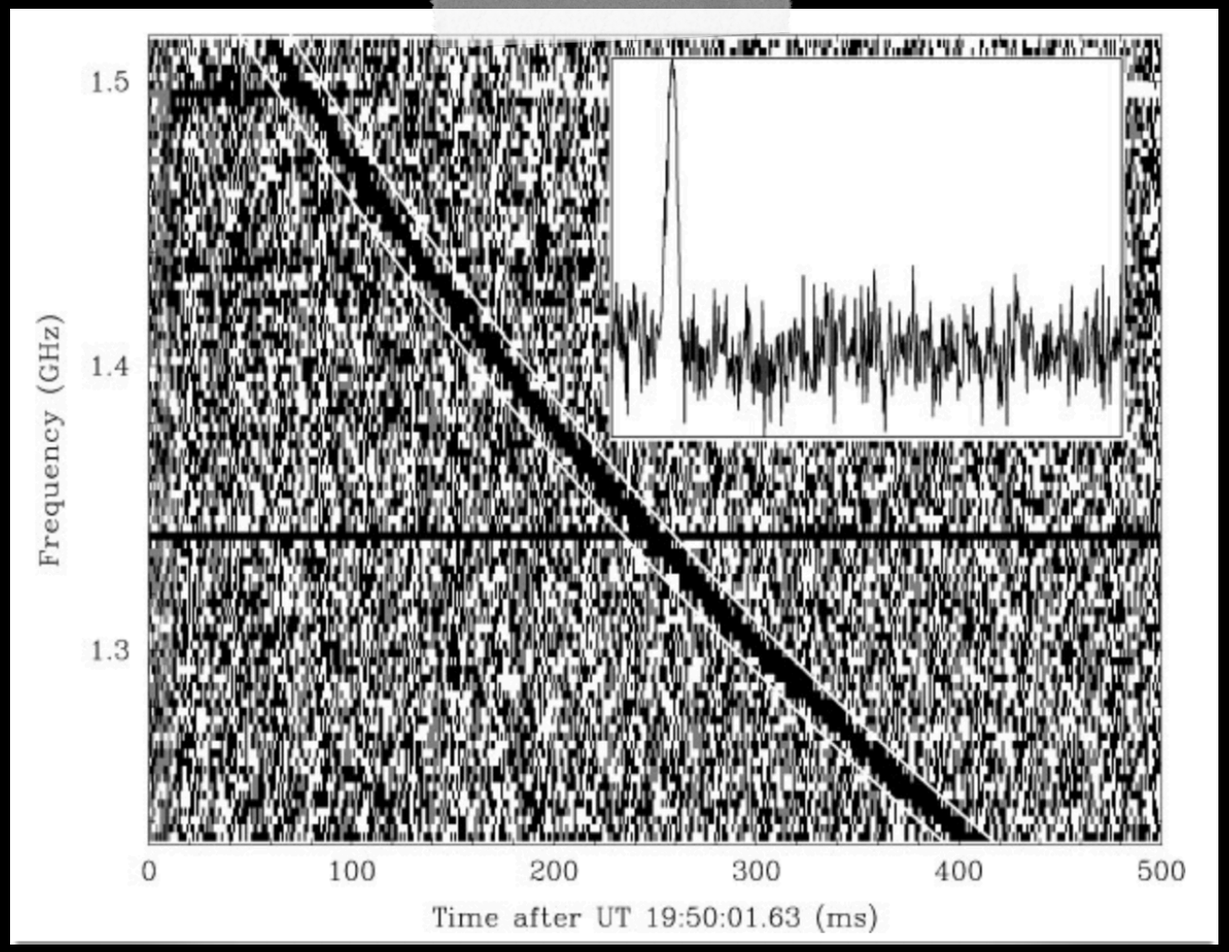
Fast Radio Bursts: a new probe of the IGM/CGM gas



Lorimer et al. (2007)



Fast Radio Bursts: a new probe of the IGM/CGM gas



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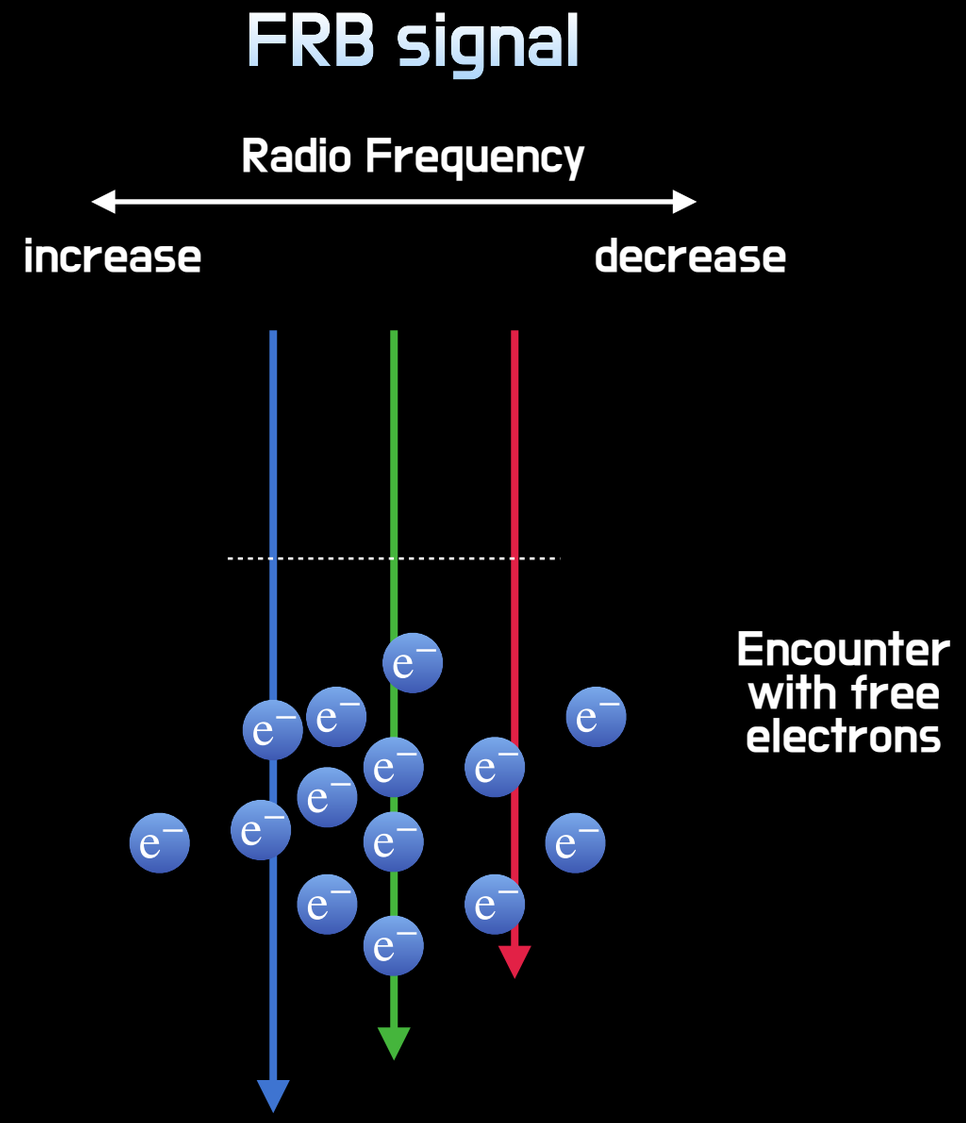
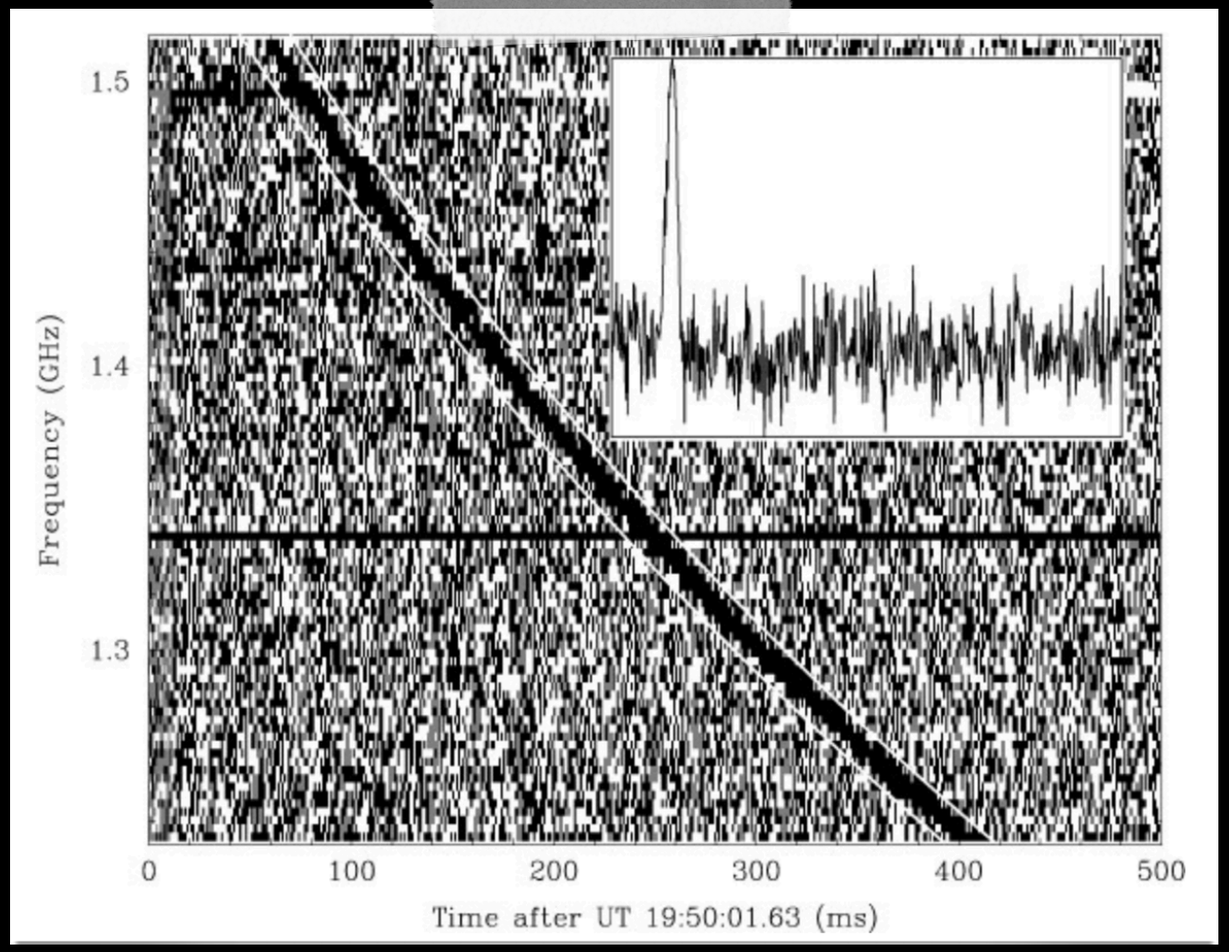


Fast Radio Bursts: a new probe of the IGM/CGM gas



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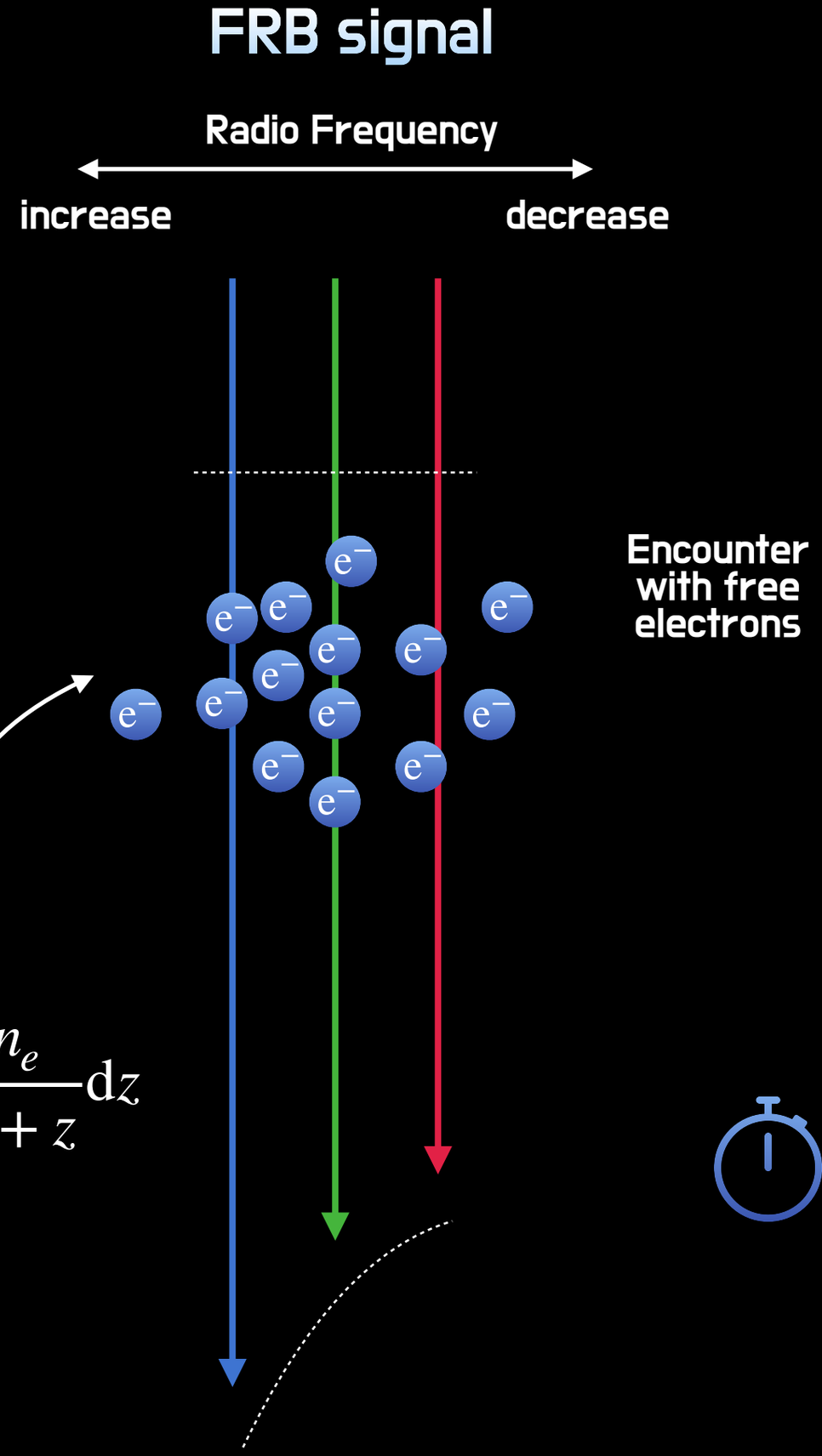


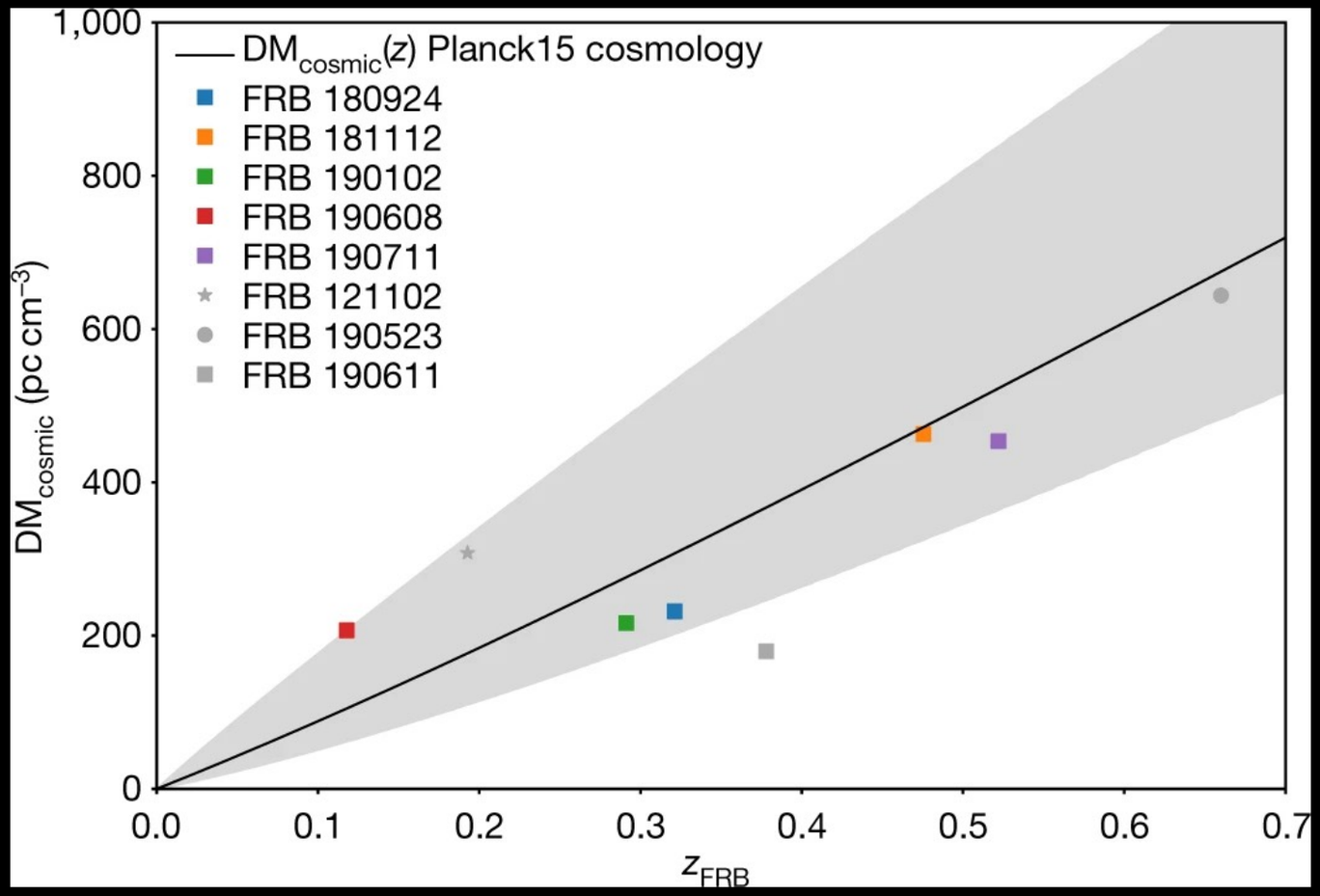
$$\mathrm{DM_{obs}} \propto \int_s \frac{n_e}{1+z}\mathrm{d}z$$

$$\tau\,(ms) = t_2 - t_1 = 4.15 \times \left[\frac{1}{\nu_2^2} - \frac{1}{\nu_1^2}\right] \times \mathrm{DM_{obs}}$$

The ~~Missing~~ (Homeless) Baryons

J.P. Macquart
1974–2020

The Macquart relation



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

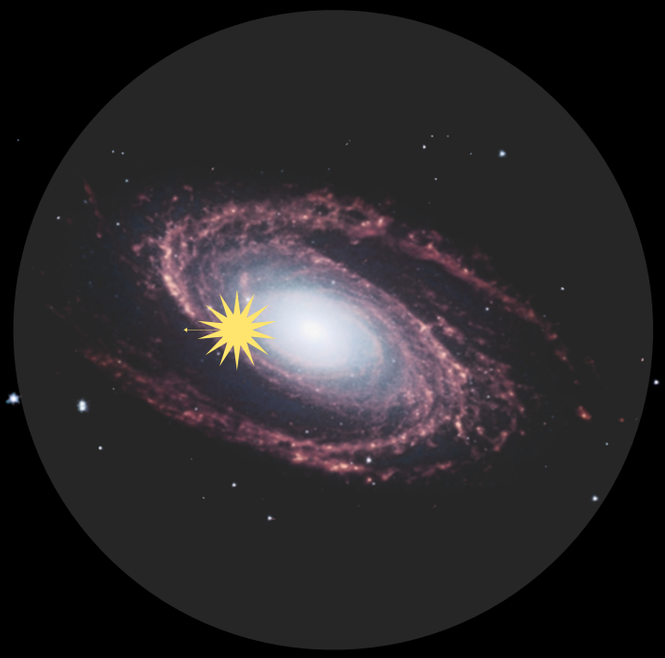
The Macquart relation solved the "missing" baryons problem, but due to the large scatter, their relative distribution between IGM and CGM remains unknown. Thus, making it hard to constrain the feedback mechanisms.

FRBs as tracers of the LSS

FRB host galaxy

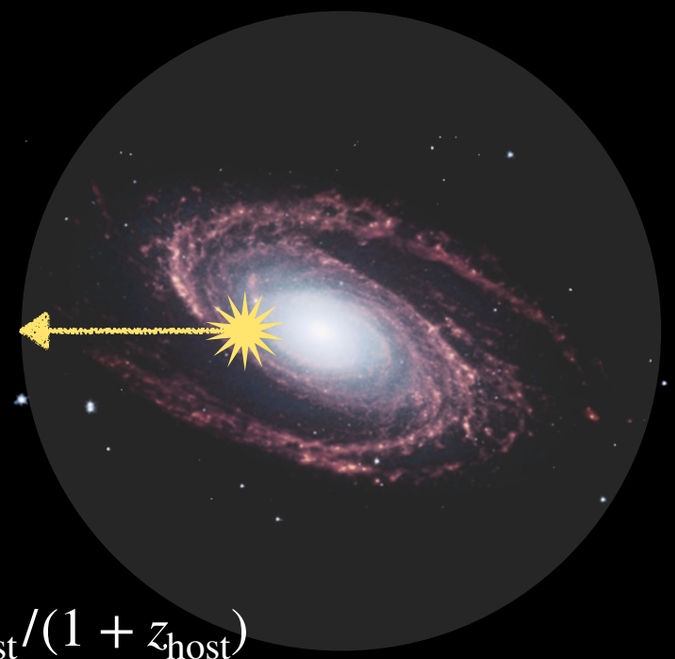
FRBs as tracers of the LSS

FRB host galaxy



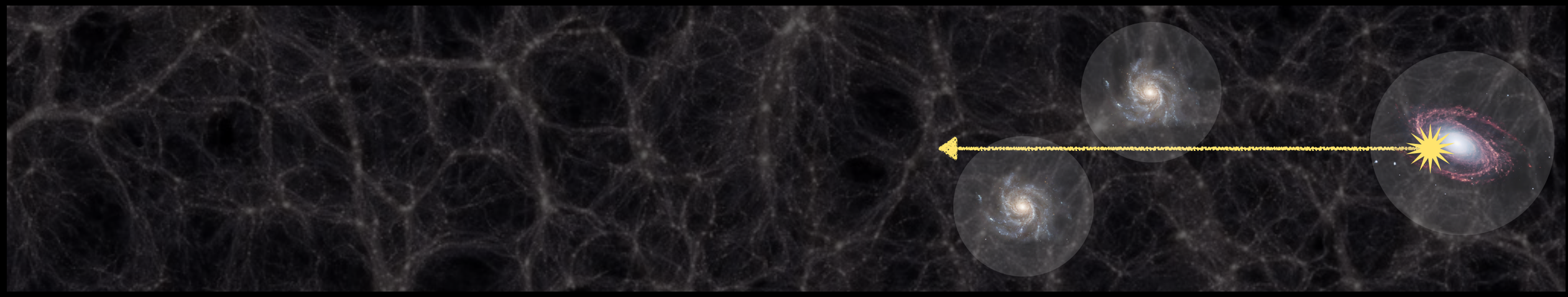
FRBs as tracers of the LSS

FRB host galaxy



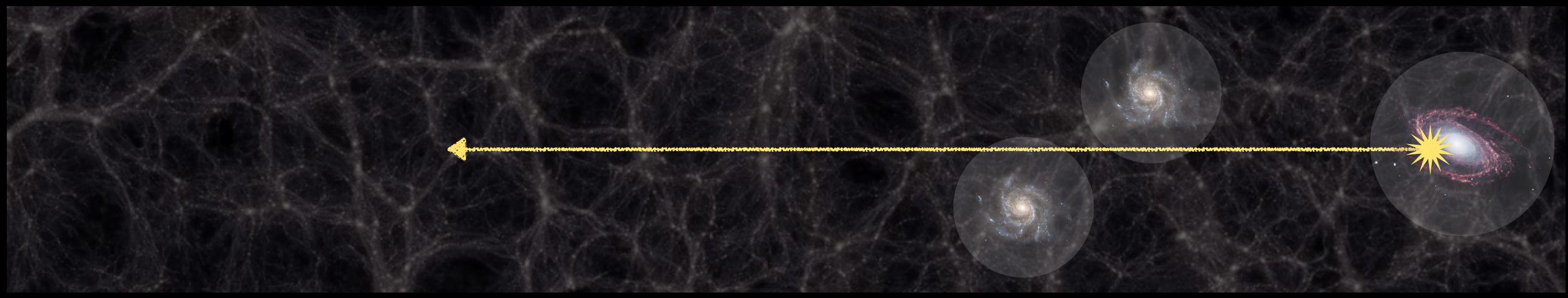
$$\mathrm{DM_{FRB}} = \cdot\ \mathrm{DM_{host}}/(1+z_{\mathrm{host}})$$

FRBs as tracers of the LSS



$$\mathrm{DM_{FRB}} = \cdot\, \mathrm{DM_{halos}}\left(f_{\mathrm{gas}}, r_{\mathrm{max}}\right) + \mathrm{DM_{host}}/(1 + z_{\mathrm{host}})$$

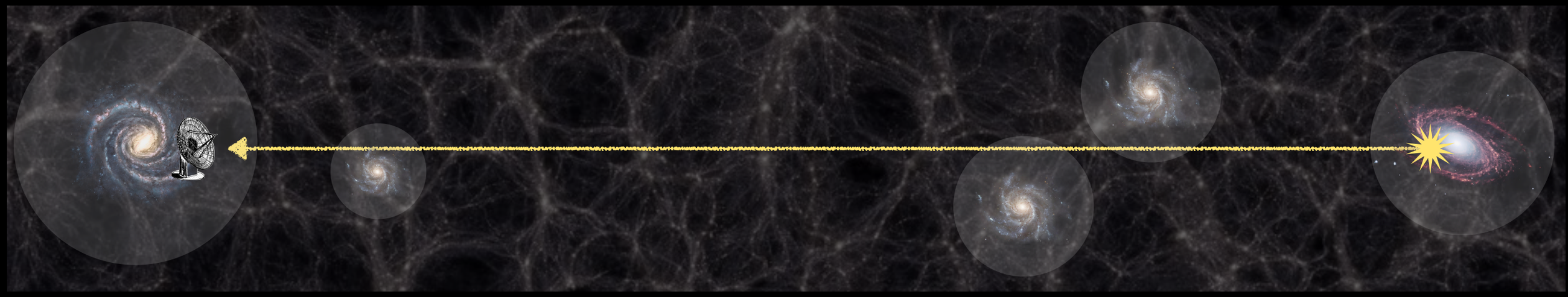
FRBs as tracers of the LSS



$$\mathrm{DM_{FRB}} = \mathrm{DM_{IGM}}\left(f_{\mathrm{igm}}\right) + \mathrm{DM_{halos}}\left(f_{\mathrm{gas}}, r_{\mathrm{max}}\right) + \mathrm{DM_{host}}/(1+z_{\mathrm{host}})$$

FRBs as tracers of the LSS

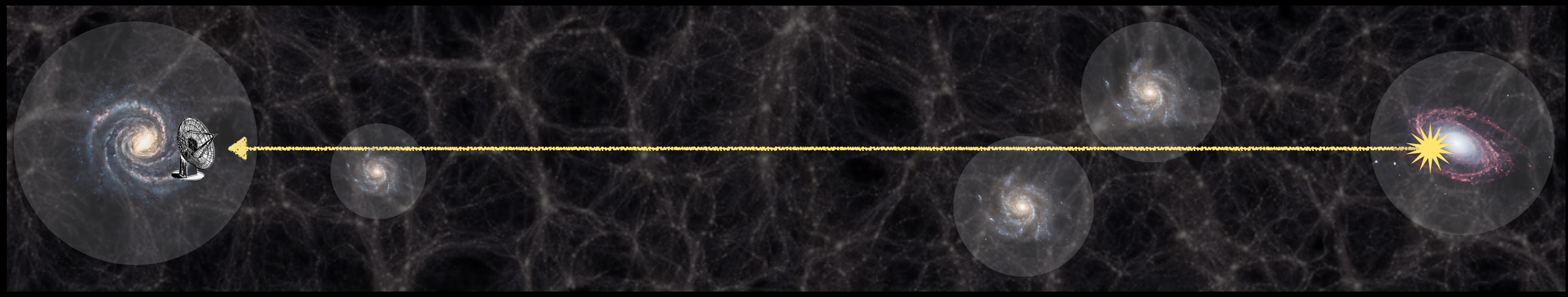
Milky Way' halo & ISM intergalactic medium foreground galactic halos FRB host galaxy



$$\mathrm{DM_{FRB}} = \mathrm{DM_{MW}} + \mathrm{DM_{IGM}}\left(f_{\mathrm{igm}}\right) + \mathrm{DM_{halos}}\left(f_{\mathrm{gas}}, r_{\mathrm{max}}\right) + \mathrm{DM_{host}}/(1+z_{\mathrm{host}})$$

FRBs as tracers of the LSS

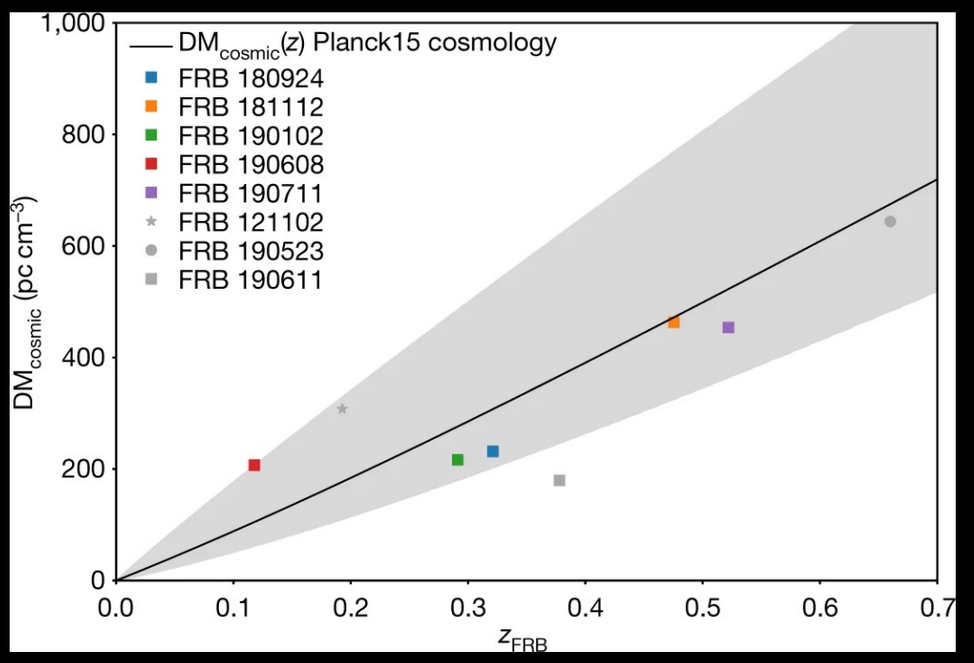
Milky Way' halo & ISM | intergalactic medium | foreground galactic halos | FRB host galaxy



$$\mathrm{DM_{FRB}} = \mathrm{DM_{MW}} + \mathrm{DM_{IGM}}\left(f_{\mathrm{igm}}\right) + \mathrm{DM_{halos}}\left(f_{\mathrm{gas}}, r_{\mathrm{max}}\right) + \mathrm{DM_{host}}/(1+z_{\mathrm{host}})$$

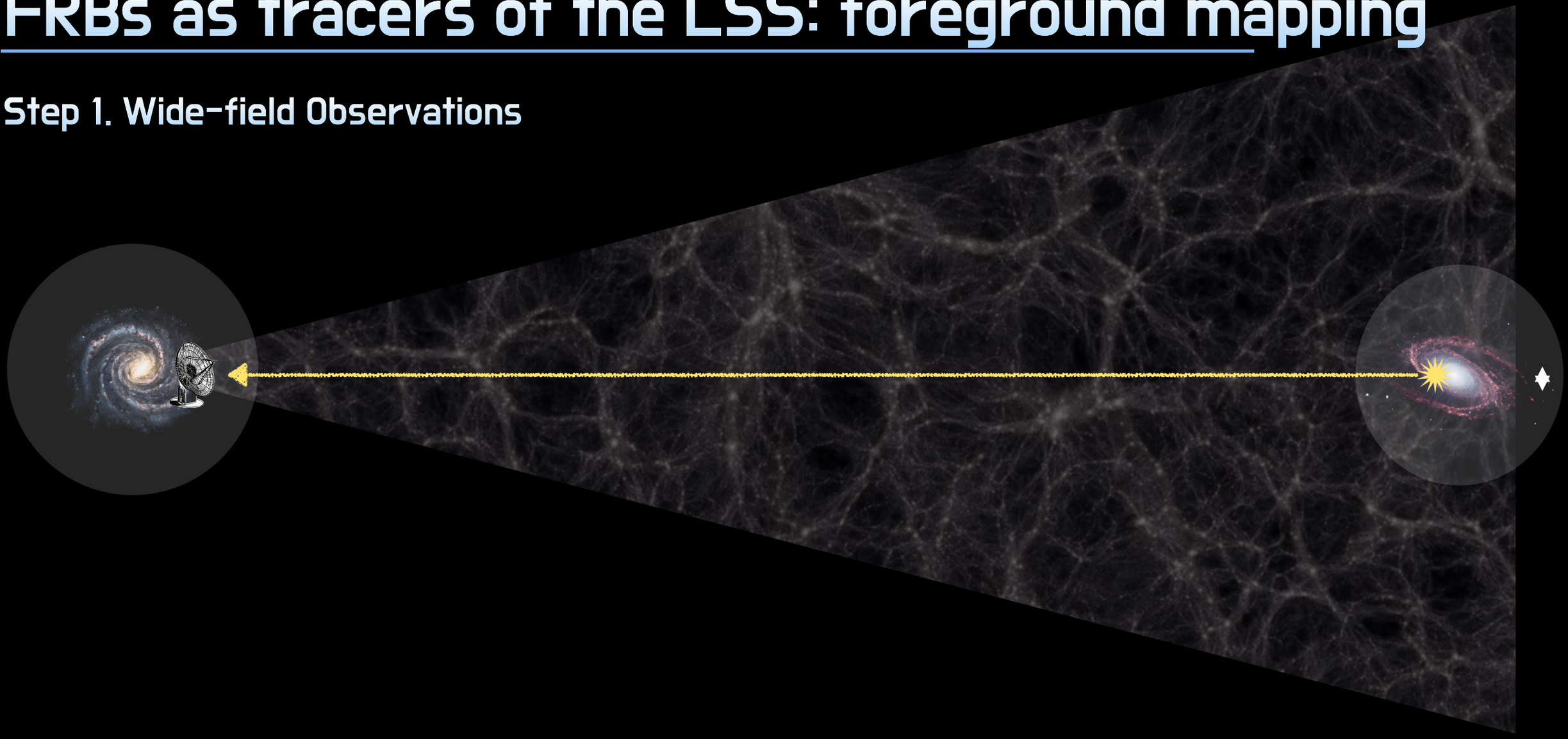
$\mathrm{DM_{cosmic}}$

Cannot be probed separately via the Macquart relation



FRBs as tracers of the LSS: foreground mapping

Step 1. Wide-field Observations



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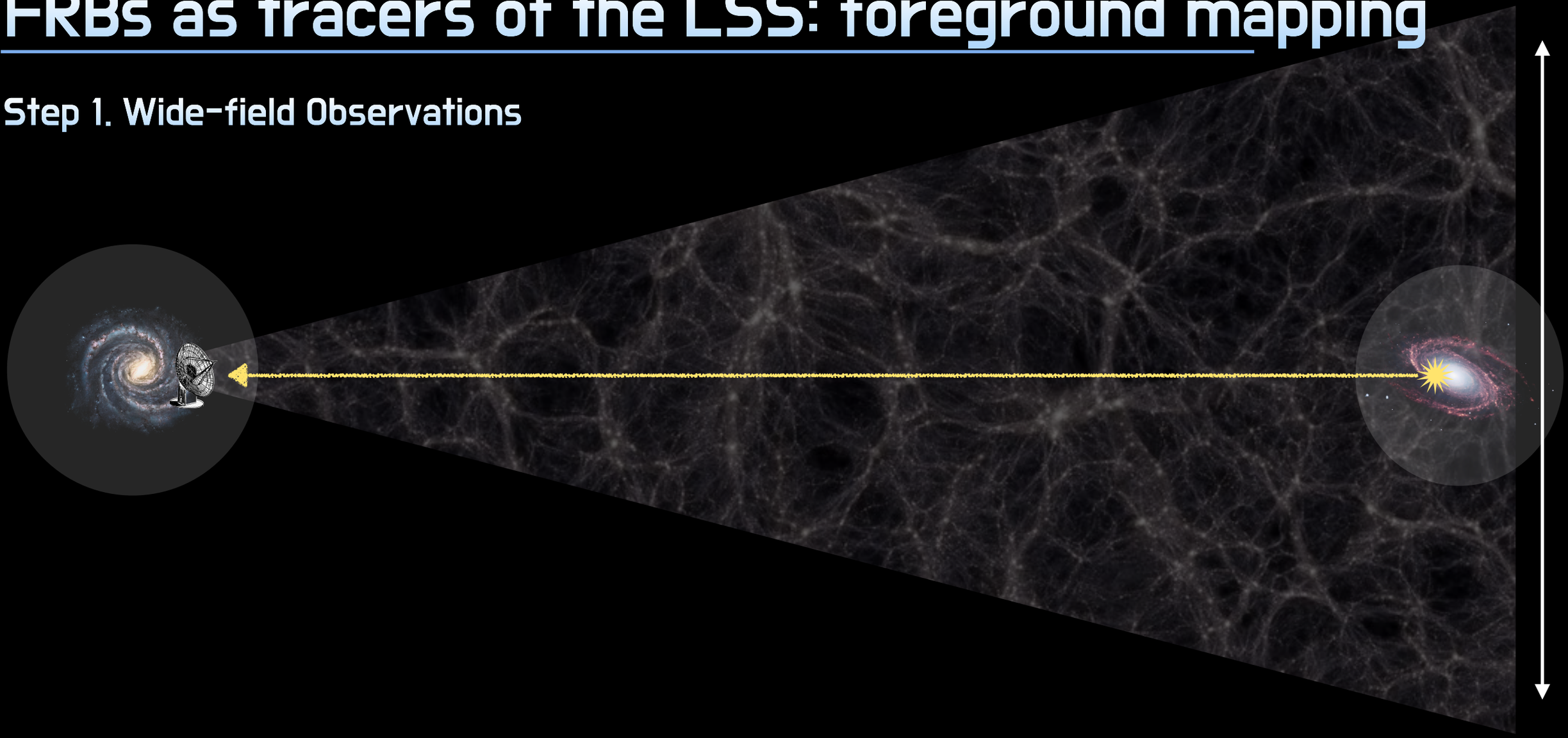

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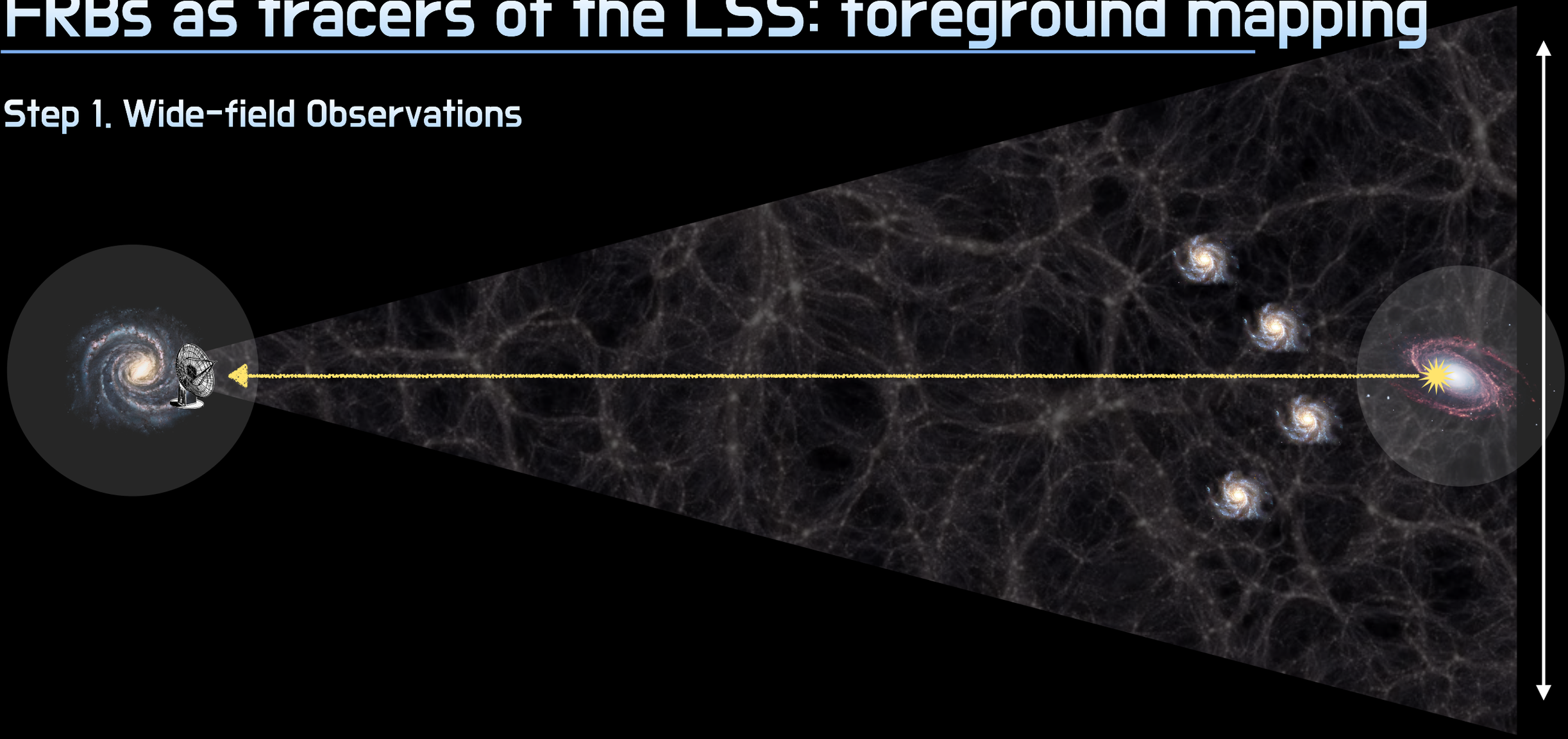

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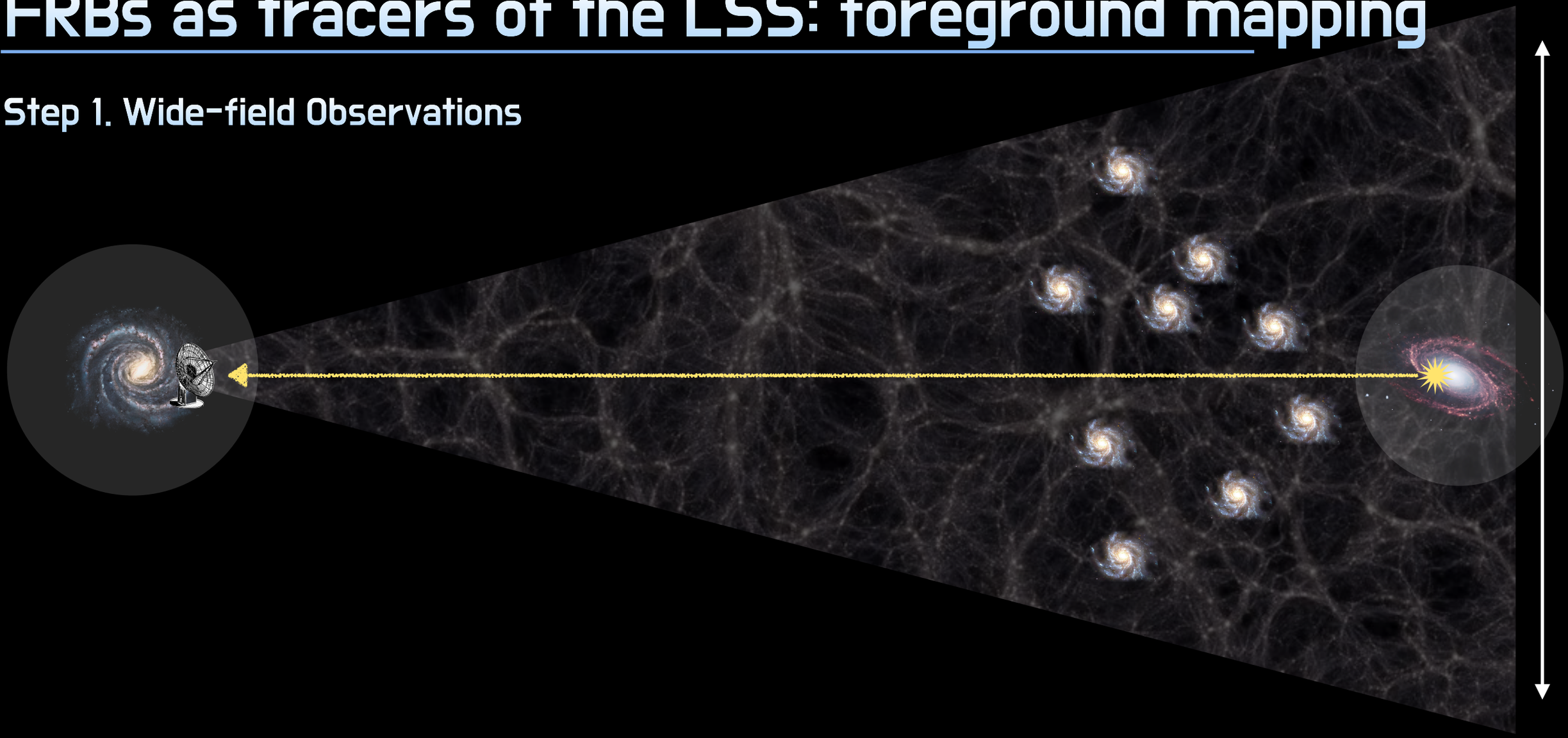

FRBs as tracers of the LSS: foreground mapping

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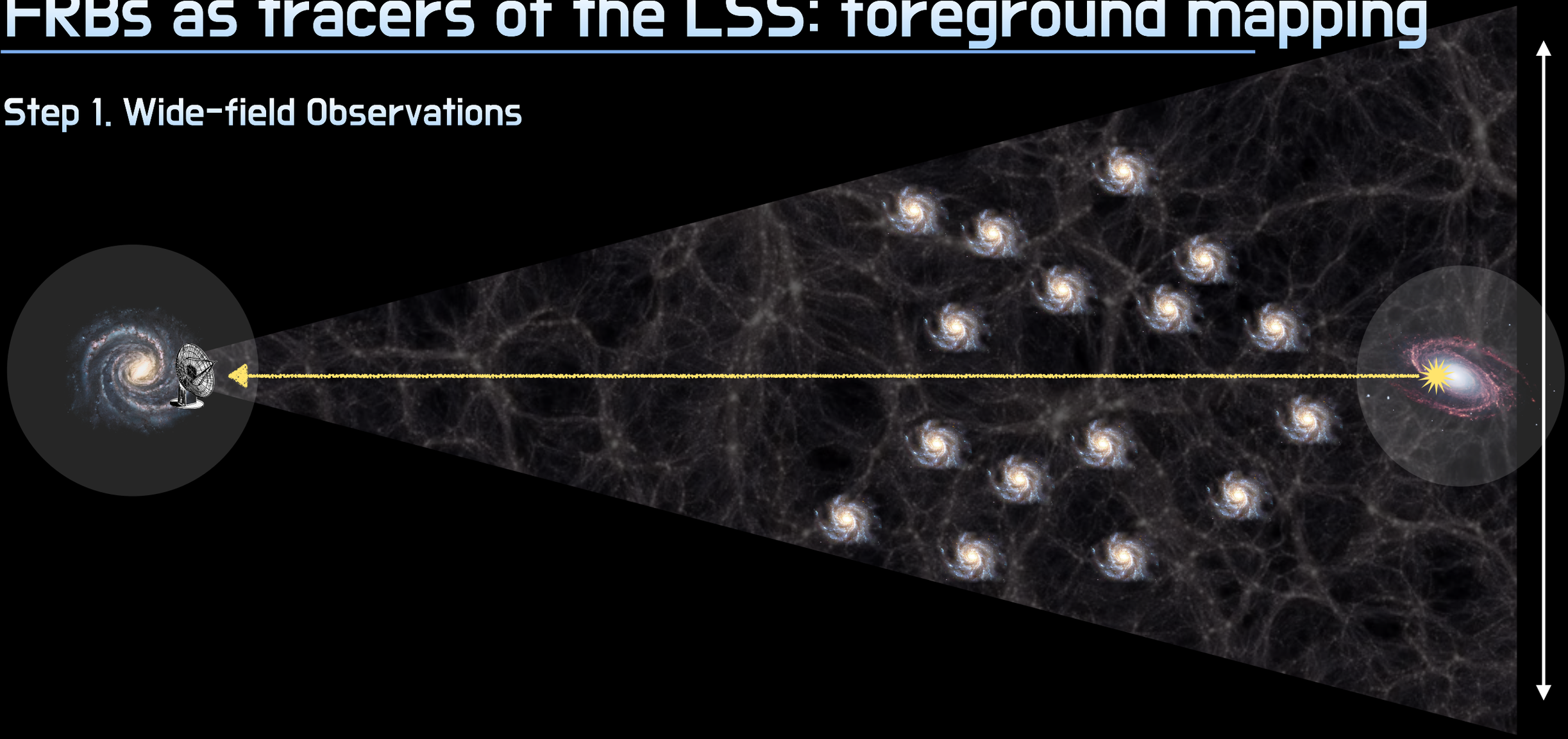

FRBs as tracers of the LSS: foreground mapping

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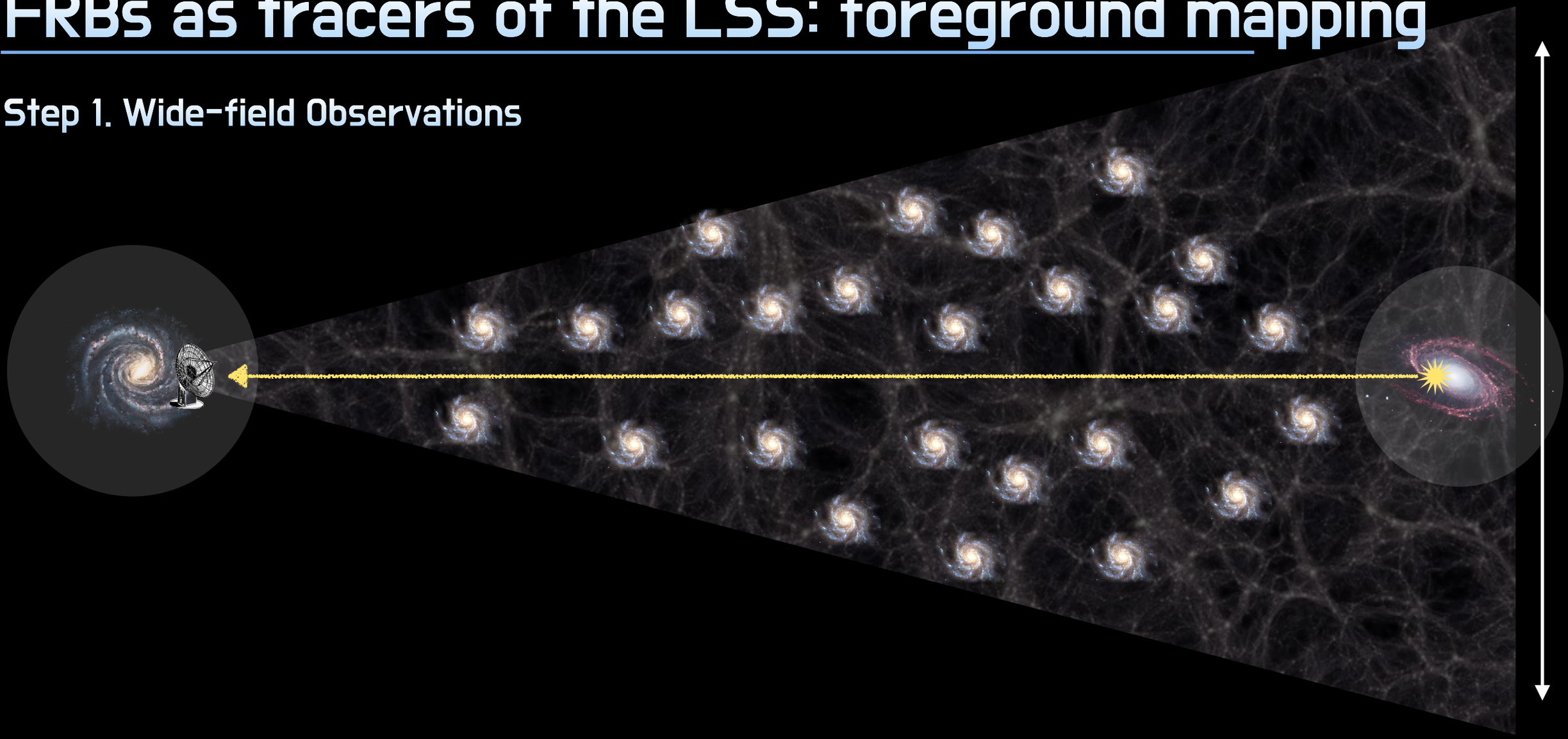
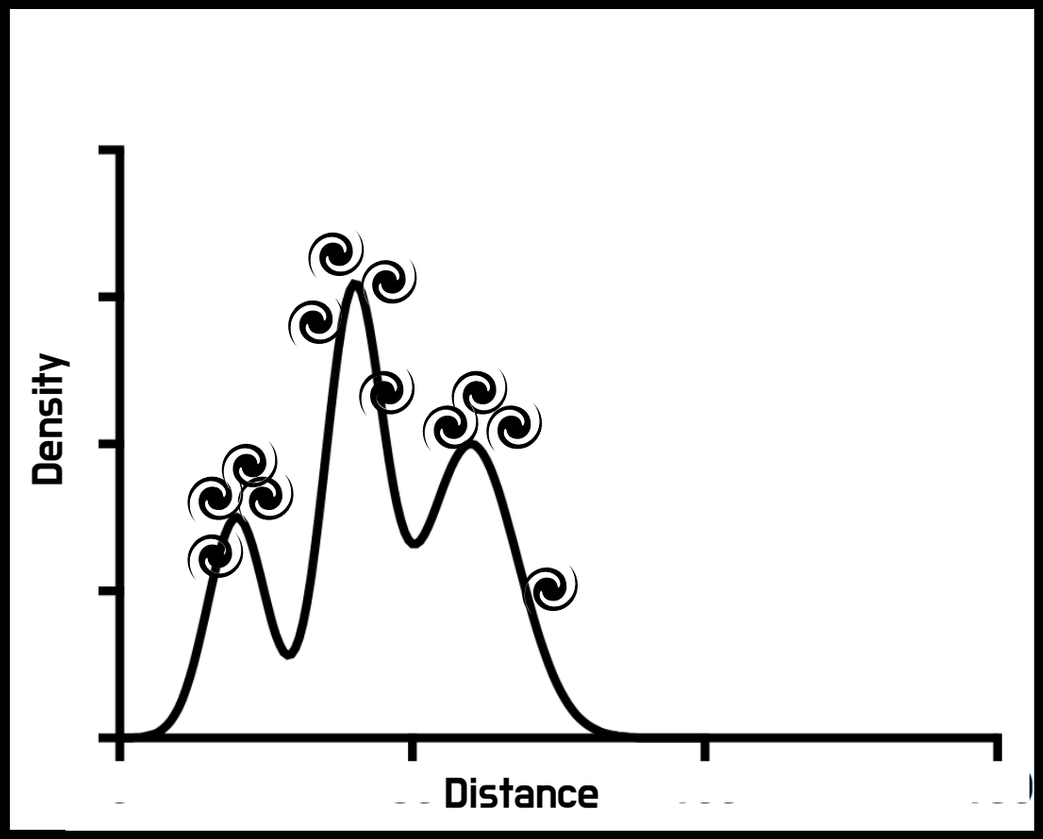


FRBs as tracers of the LSS: foreground mapping

Step 1. Wide-field Observations

a few degrees FoV

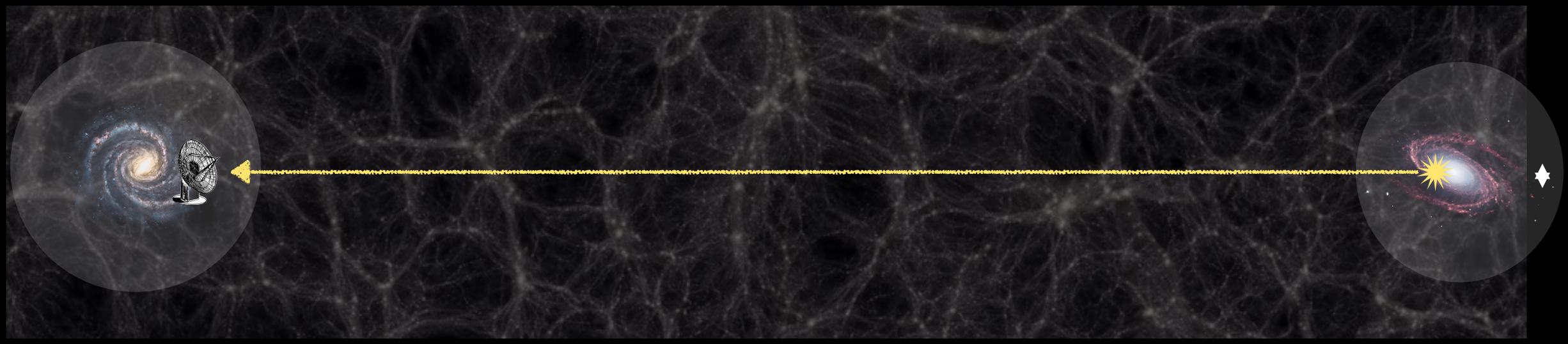


Galaxies trace the Large Scale distribution
of the cosmic matter

Estimate of the contribution
to the observed Dispersion Measure
from the Intergalactic Medium

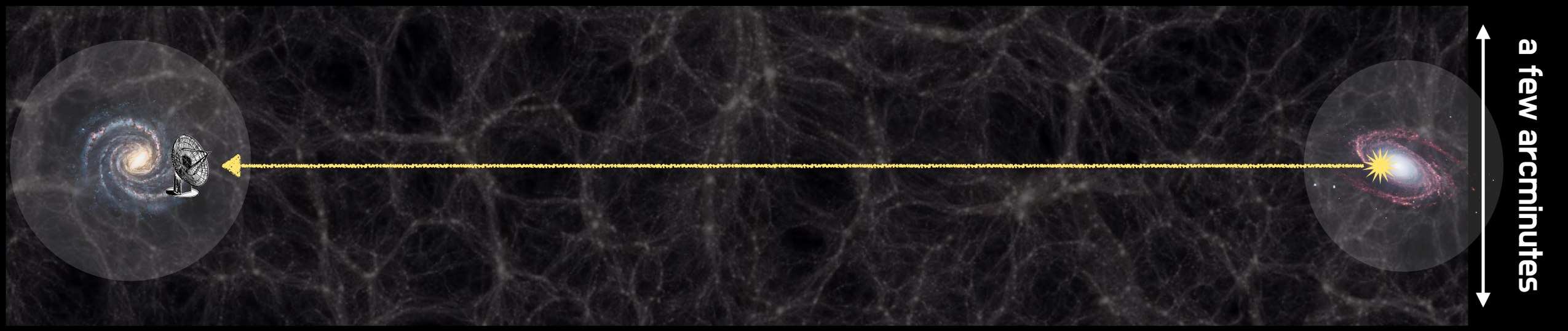
FRBs as tracers of the LSS: foreground mapping

Step 2. Narrow-field Observations



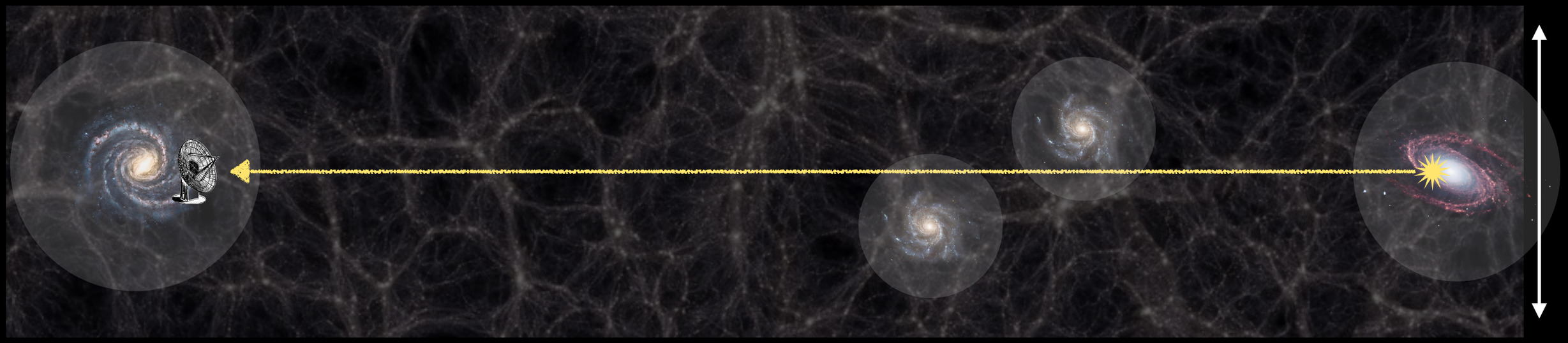
FRBs as tracers of the LSS: foreground mapping

Step 2. Narrow-field Observations



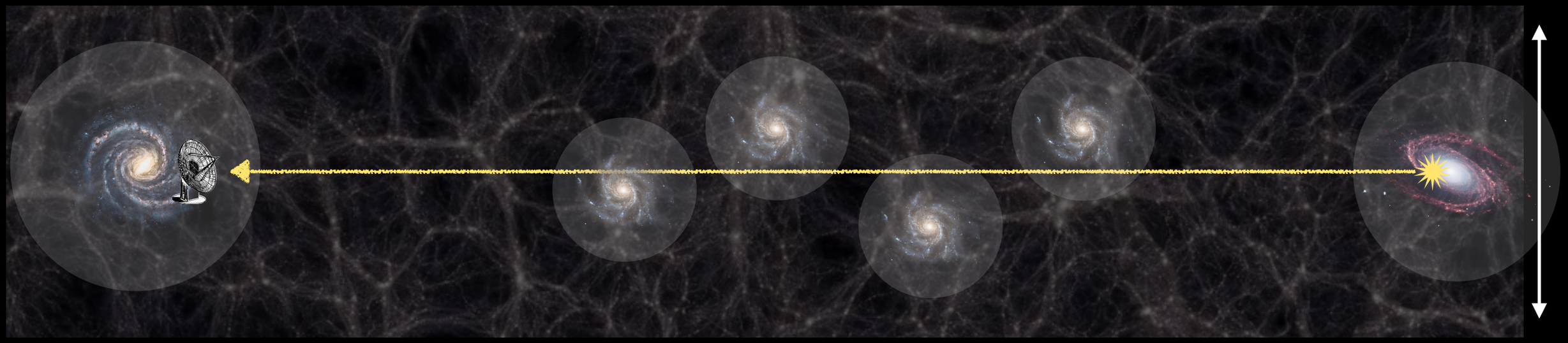
FRBs as tracers of the LSS: foreground mapping

Step 2. Narrow-field Observations



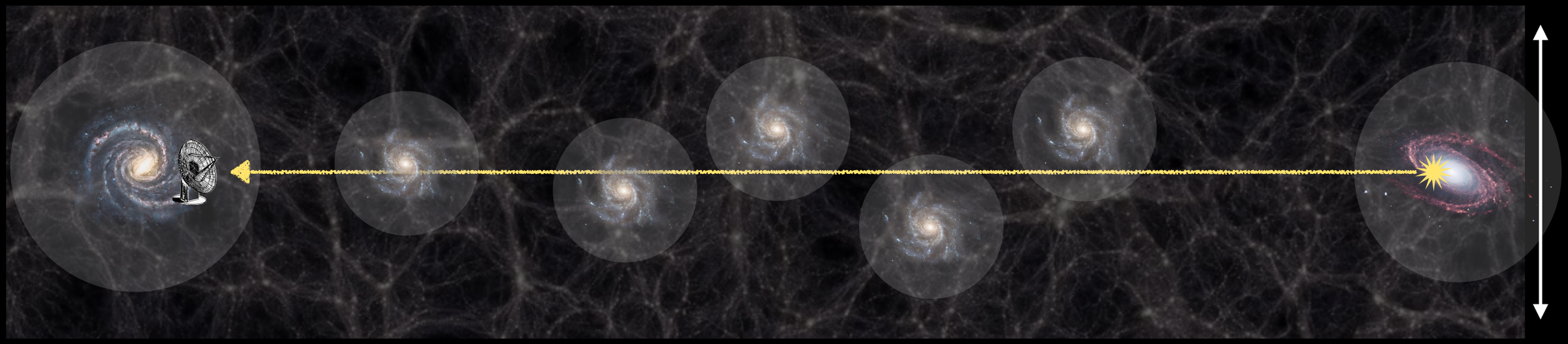
FRBs as tracers of the LSS: foreground mapping

Step 2. Narrow-field Observations



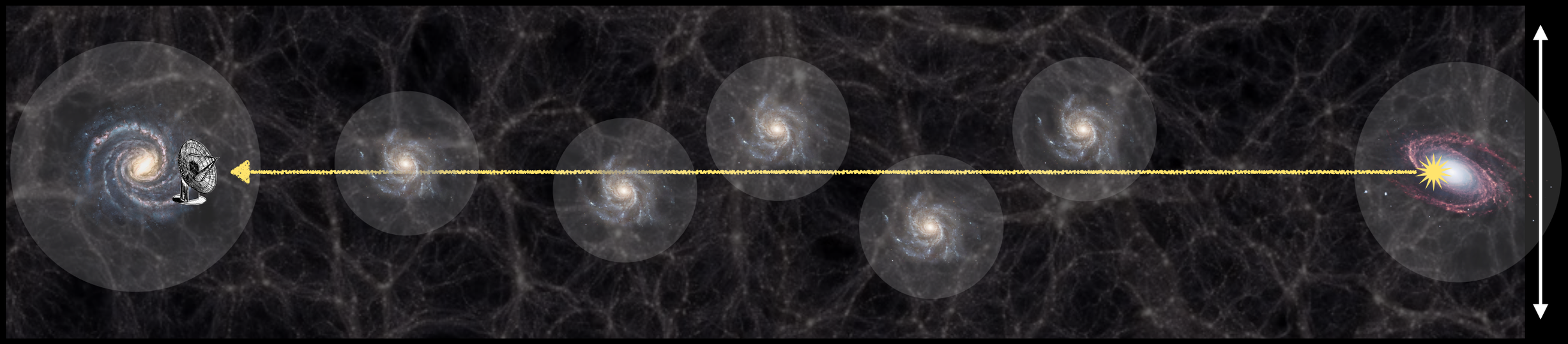
FRBs as tracers of the LSS: foreground mapping

Step 2. Narrow-field Observations



FRBs as tracers of the LSS: foreground mapping

Step 2. Narrow-field Observations

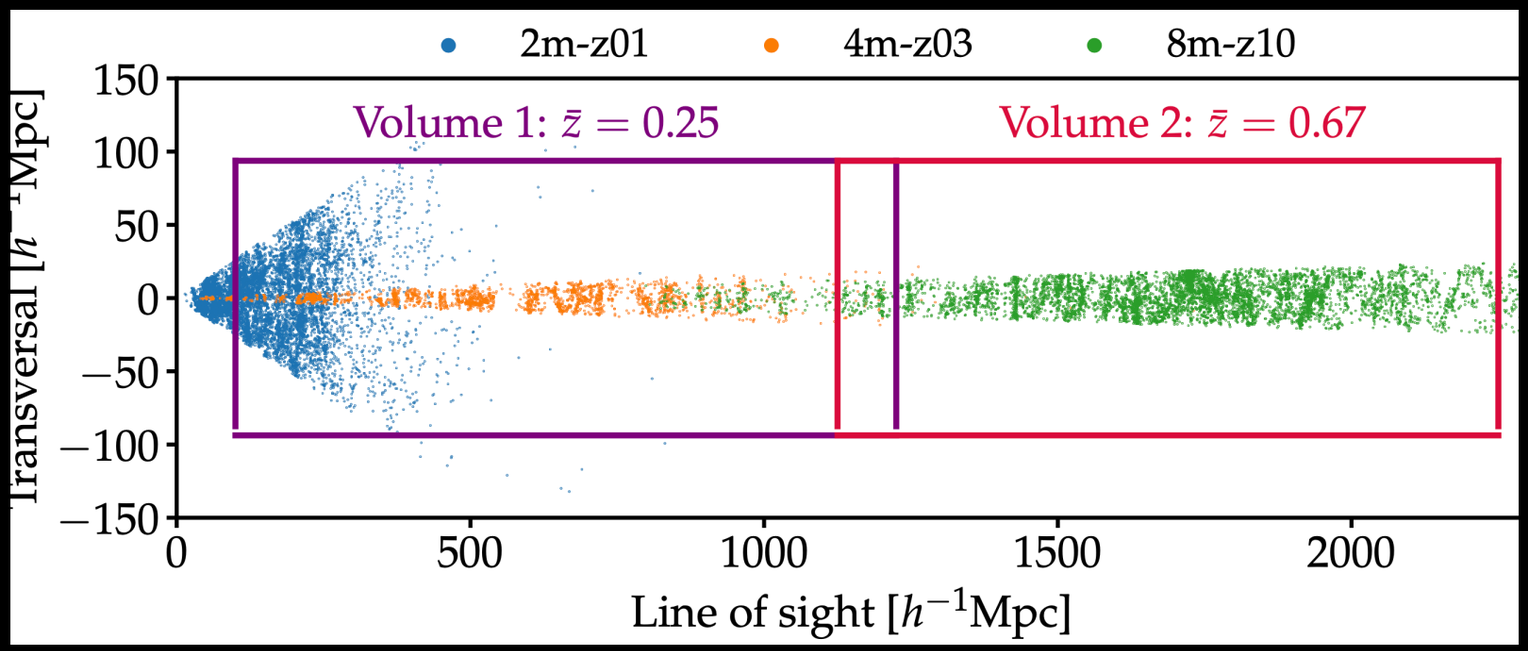


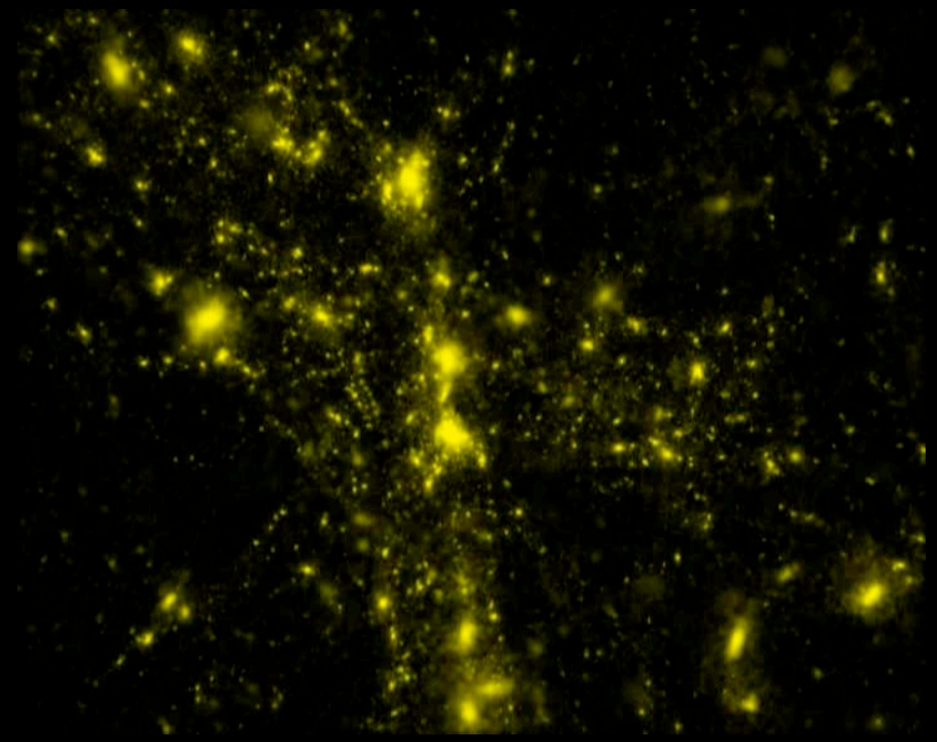
Each intersected halo contributes to the
cumulative $\mathrm{DM}_{\mathrm{halos}}$ contribution
to the observed Dispersion Measure

Predictions from the mocks

Build a sample of mock FRB sightline through the Millennium simulation box

Step 1. Wide-field Observations





Credit: Joerg Colberg/ Volker Springel

Mock Large-scale Catalogs Used for FRB Foreground Reconstruction

Catalog[a]	Redshift	Limiting r-mag	No. of Galaxies	Area (deg^2)	Area Density (deg^{-2})
2m-z01	$z \leqslant 0.1$	16.4	8400	700	12
4m-z03	$0.1 < z < 0.35$	19.8	2400	3.1	770
8m-z10	$0.35 < z < 1.0$	22.75	7500	1.25	6000

Lee, Ata, Khrykin et al. (2022)

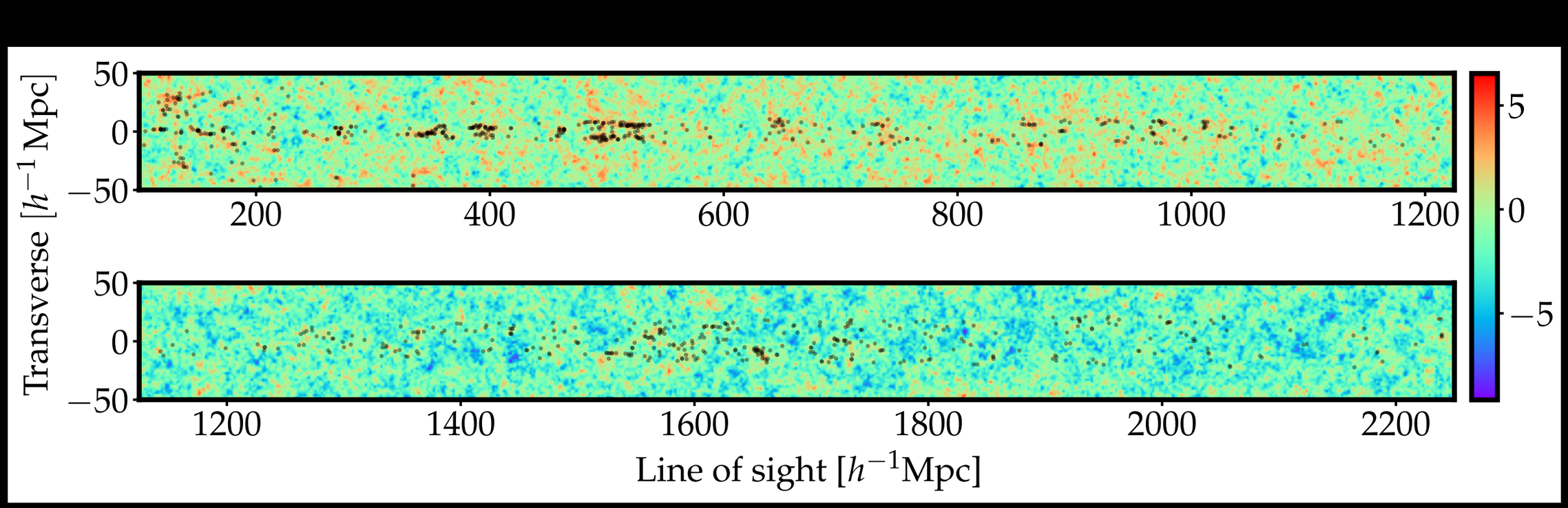
Predictions from the mocks: density reconstruction

ARGO density reconstruction algorithm (Ata et al. (2015,2017) input:

galaxy selection functions (radial & angular)
initial conditions (cosmology)

ARGO output:

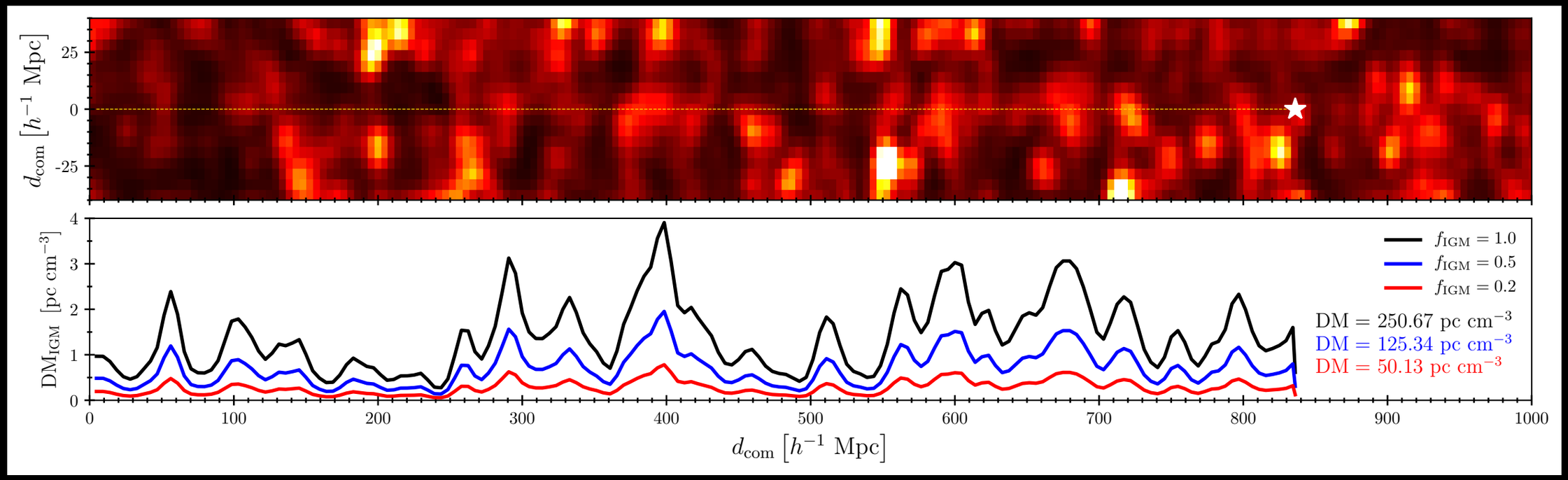
N realization of the matter density field in the specified volume
given the spacial distribution of the galaxies along the LoS



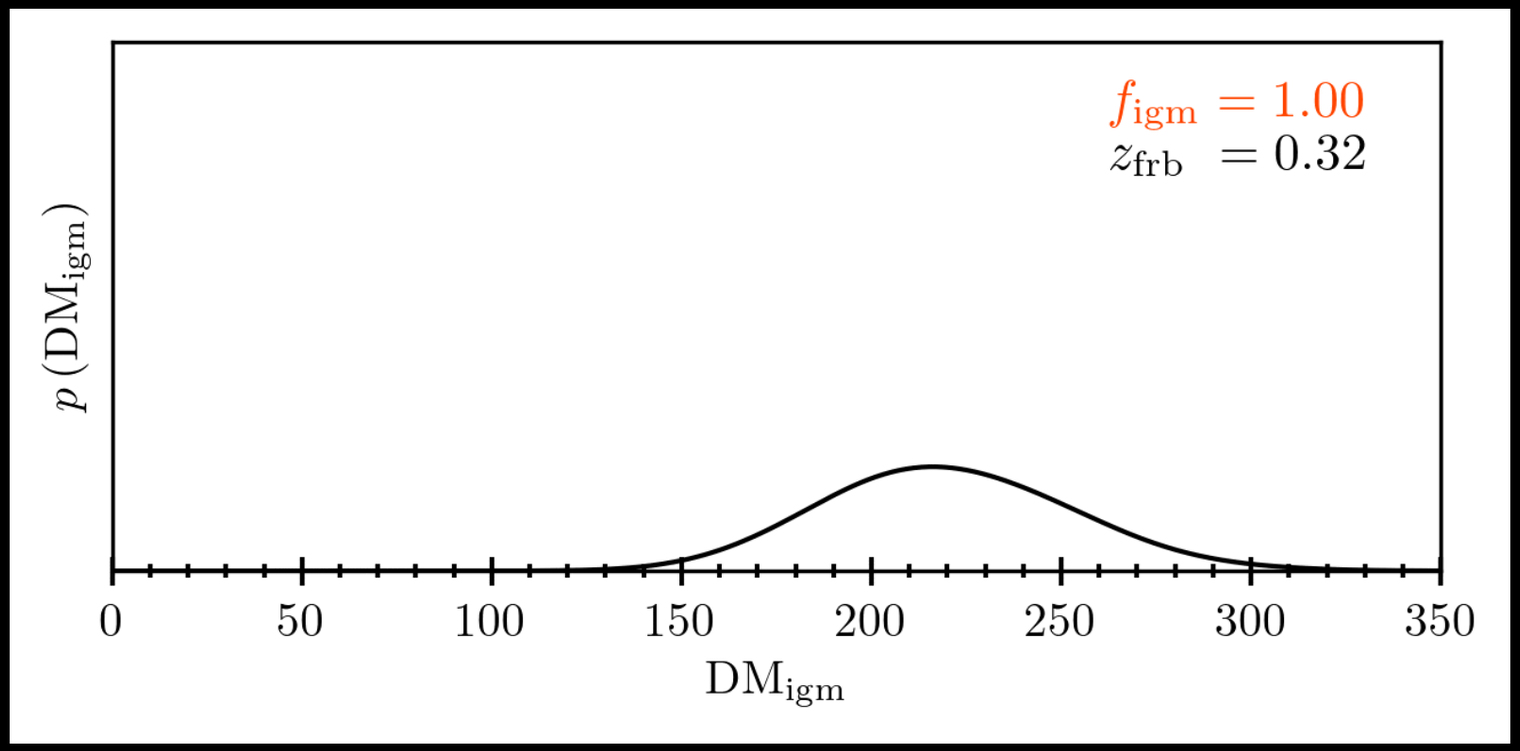
Realization of the real-space density field from ARGO reconstruction algorithm

Lee, Ata, Khrykin et al. (2022)

Predictions from the mocks: density reconstruction



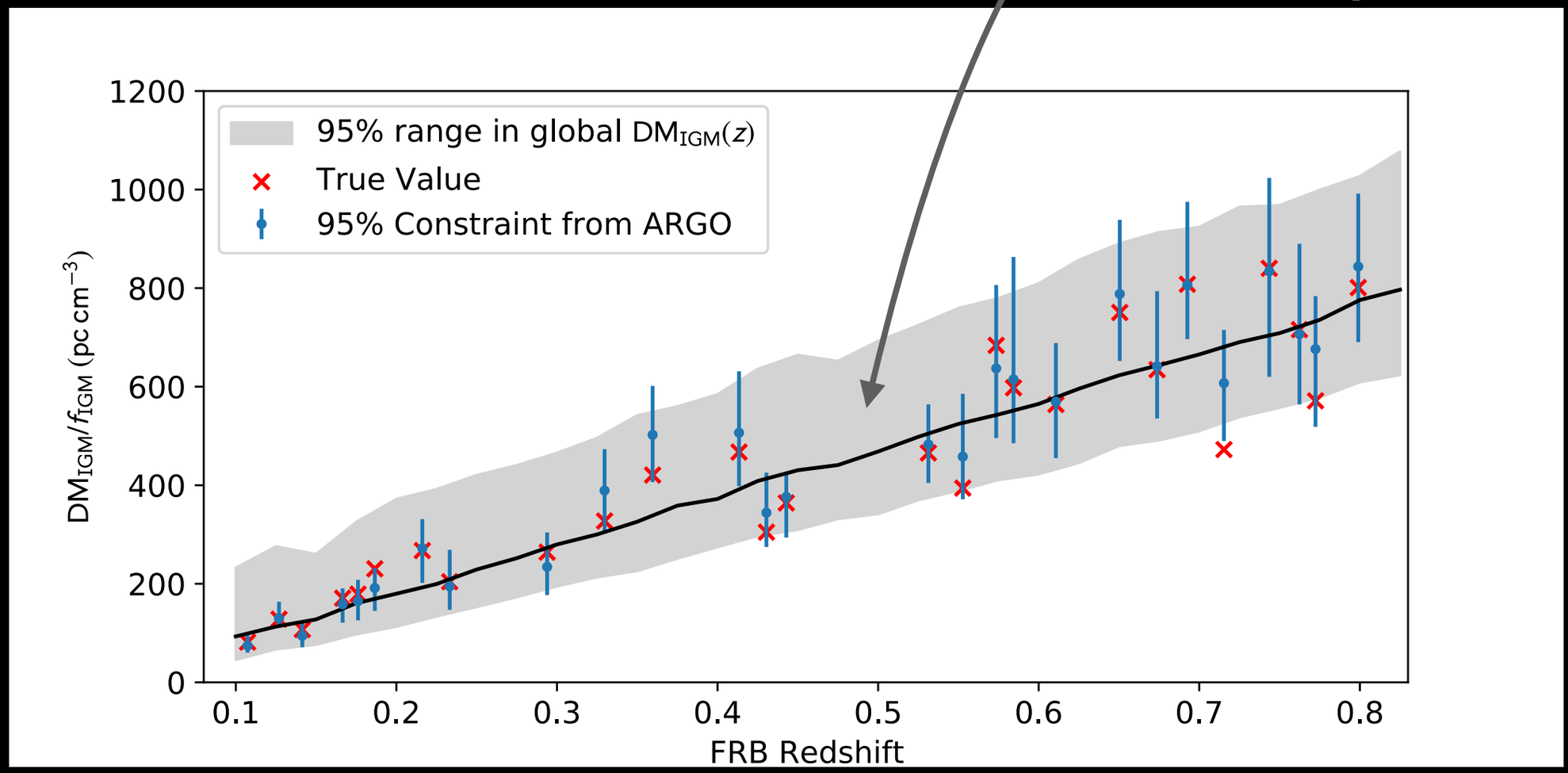
Example of the estimated $\rm DM_{igm}$ along the single sightline in on of the ARGO density reconstructions



Distribution of $\rm DM_{igm}$: the single sightline, 60 ARGO realizations

Predictions from the mocks: density reconstruction

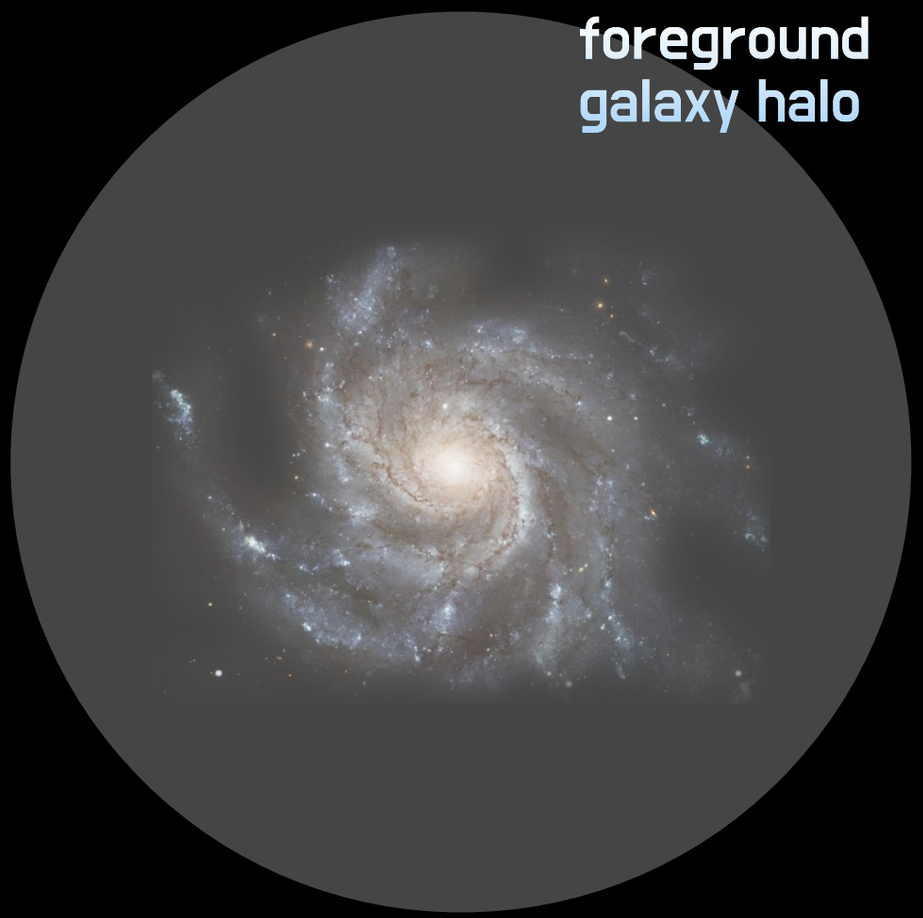
Efficacy of the ARGO reconstructions



Predictions from the mocks

Step 2. Narrow-field Observations

from FRB

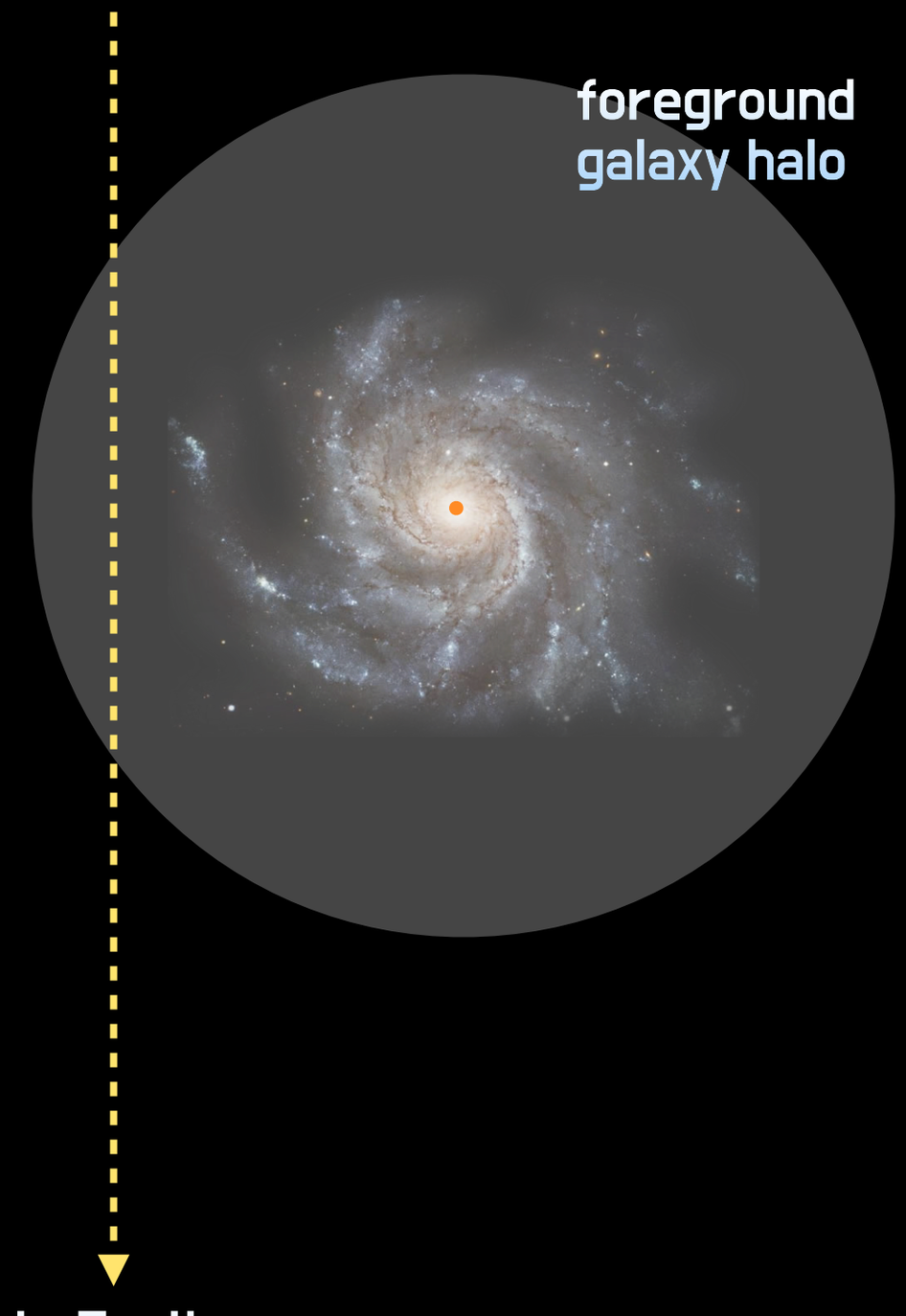


to Earth

Predictions from the mocks

Step 2. Narrow-field Observations

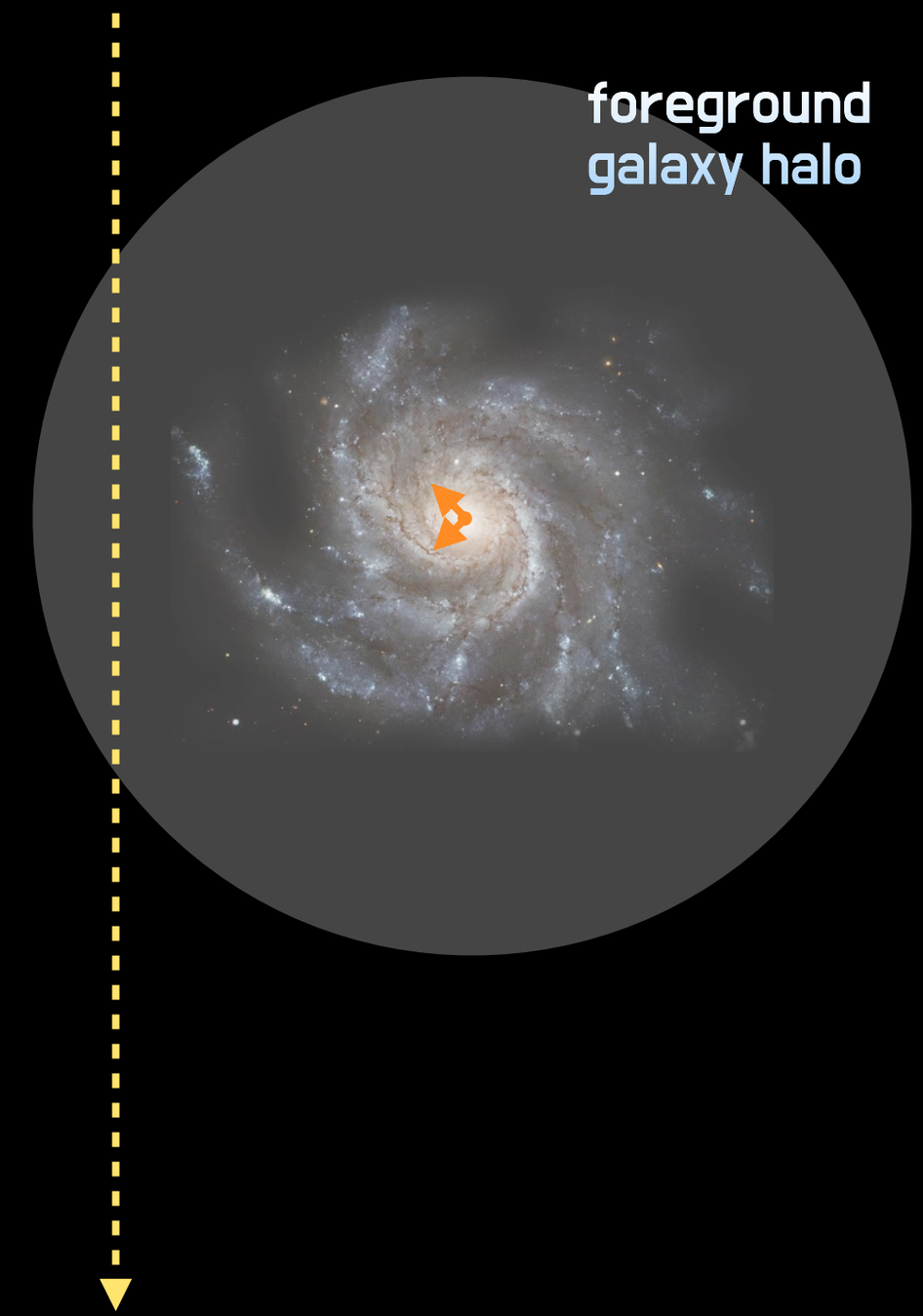
from FRB



Predictions from the mocks

Step 2. Narrow-field Observations

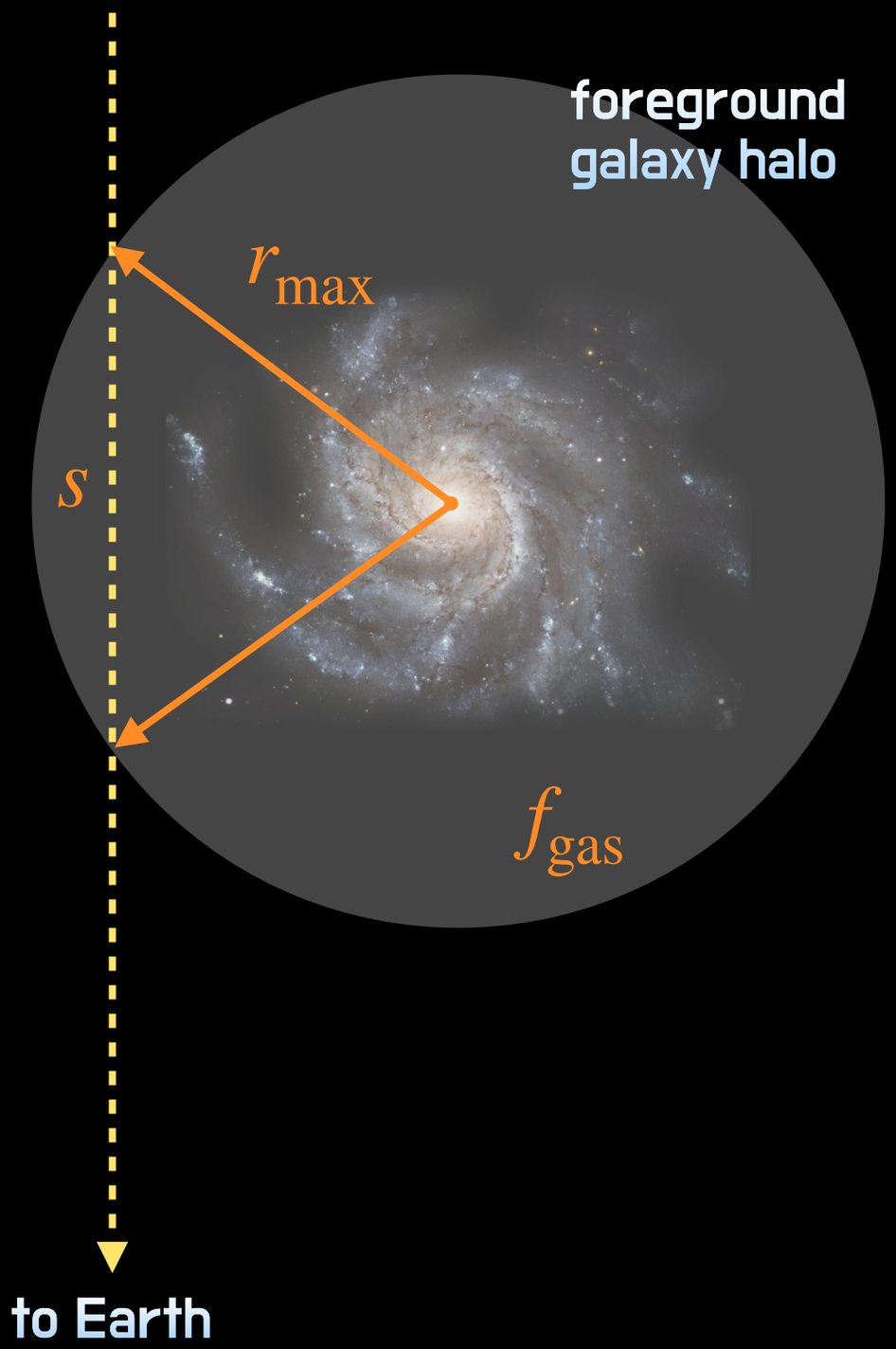
from FRB



Predictions from the mocks

Step 2. Narrow-field Observations

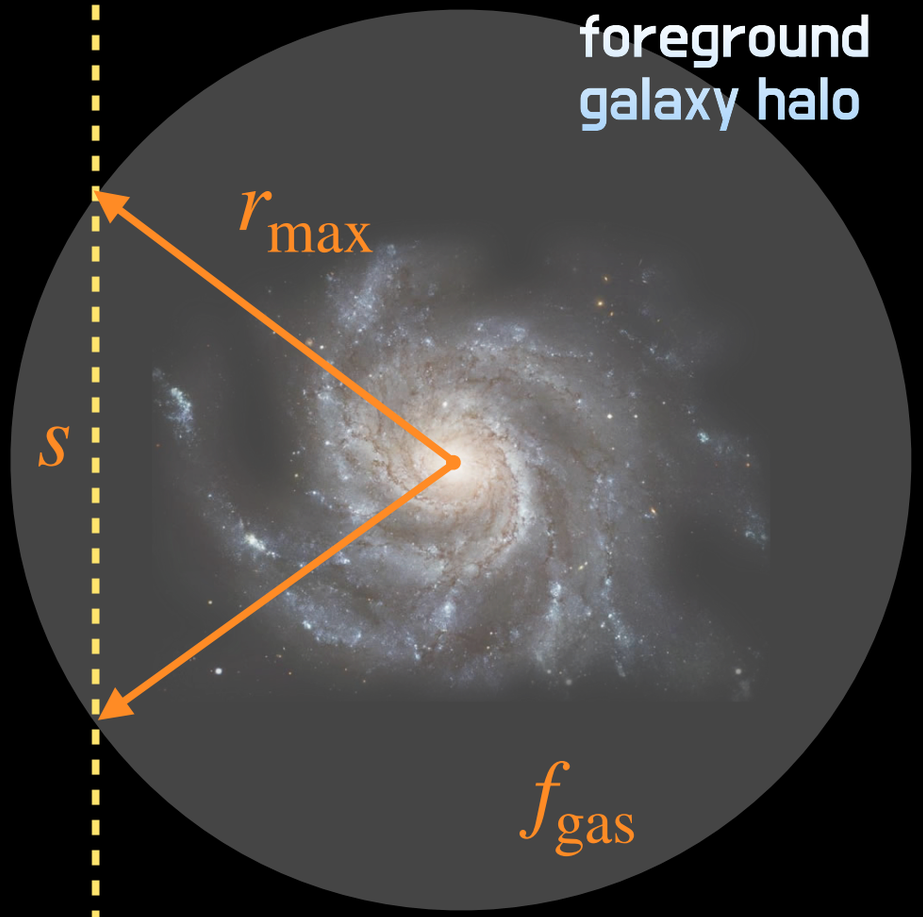
from FRB



Predictions from the mocks

Step 2. Narrow-field Observations

from FRB

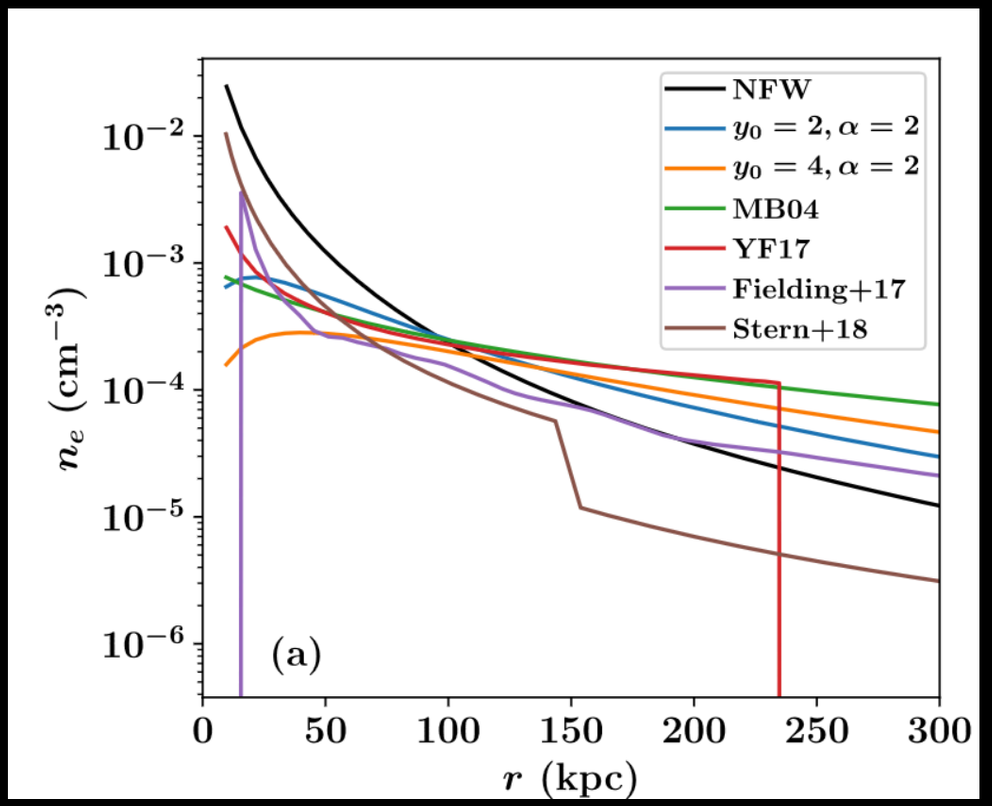


to Earth

Each galactic halo is described by the mNFW profile extending to $r_{\rm max}$

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

$$\mathrm{DM}_{\rm halo} \propto \int_s \frac{n_e\left(M_{\rm halo}, r_{\rm max}, f_{\rm gas}\right)}{1+z} ds$$

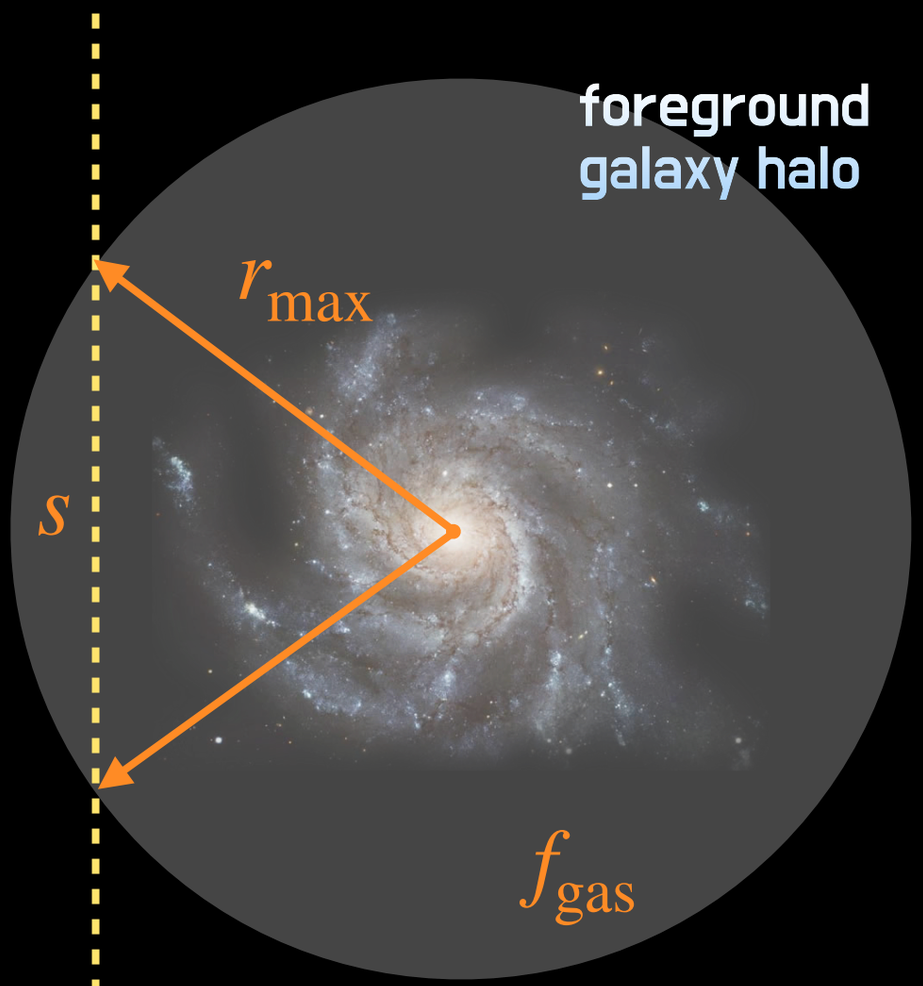


Mathews & Prochaska 2017

Predictions from the mocks

Step 2. Narrow-field Observations

from FRB



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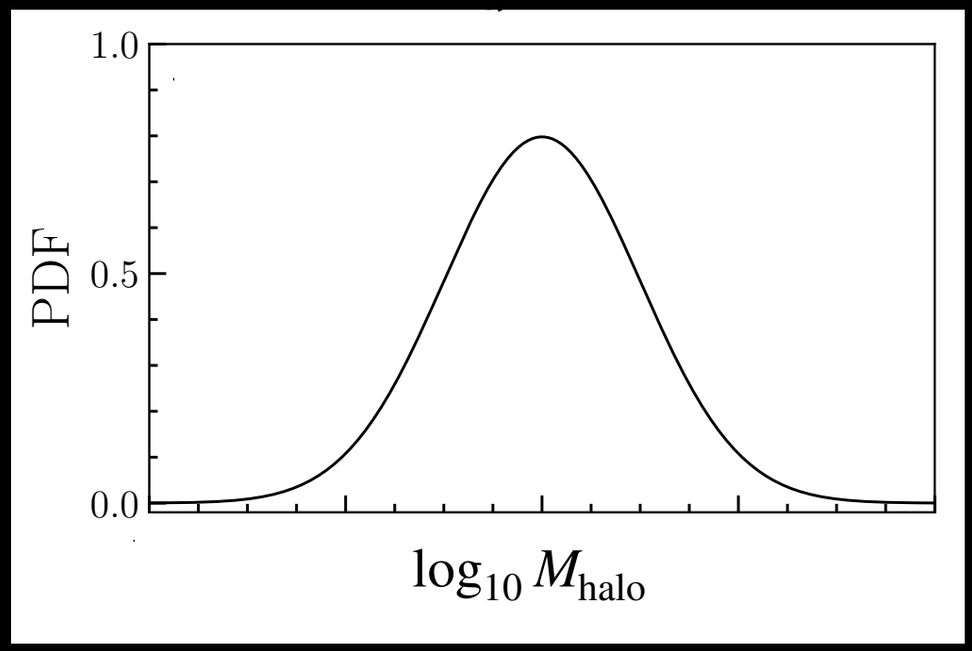
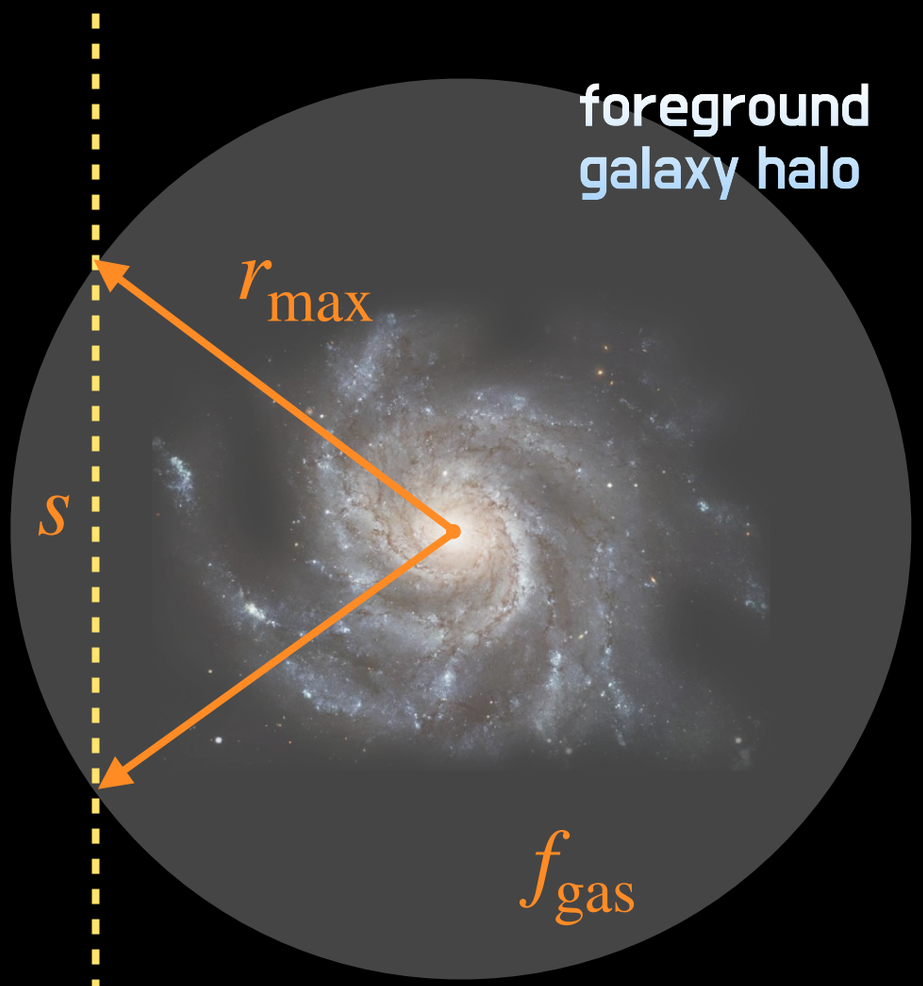


$$\mathrm{DM}_{\rm halo} \propto \int_s \frac{n_e\left(M_{\rm halo}, r_{\rm max}, f_{\rm gas}\right)}{1+z} ds$$

Predictions from the mocks

Step 2. Narrow-field Observations

from FRB



to Earth

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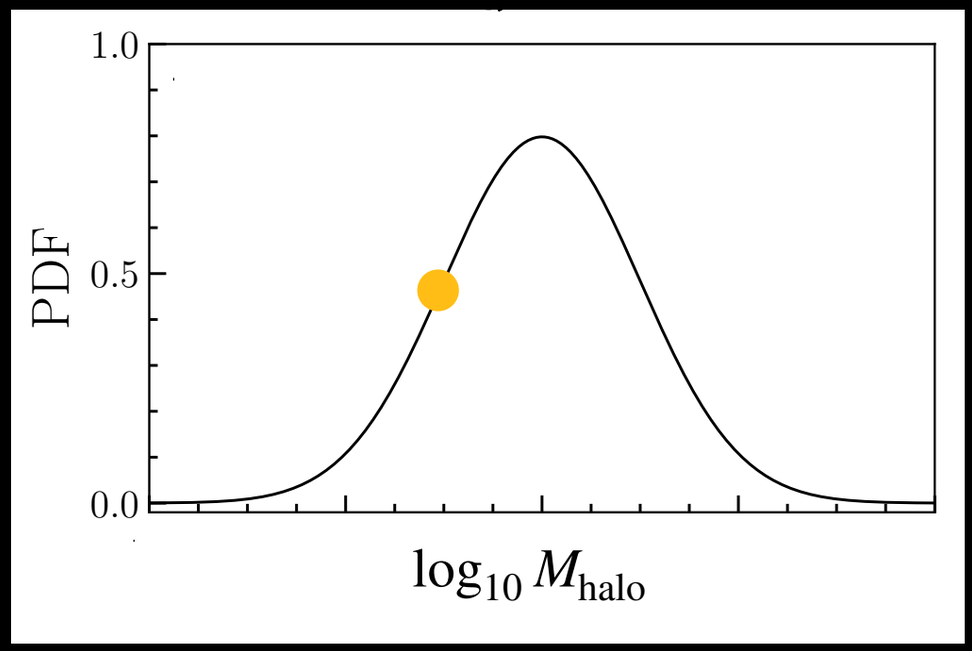

$$\mathrm{DM_{halo}} \propto \int_s \frac{n_e\left(M_{\rm halo}, r_{\rm max}, f_{\rm gas}\right)}{1+z} ds$$

Predictions from the mocks

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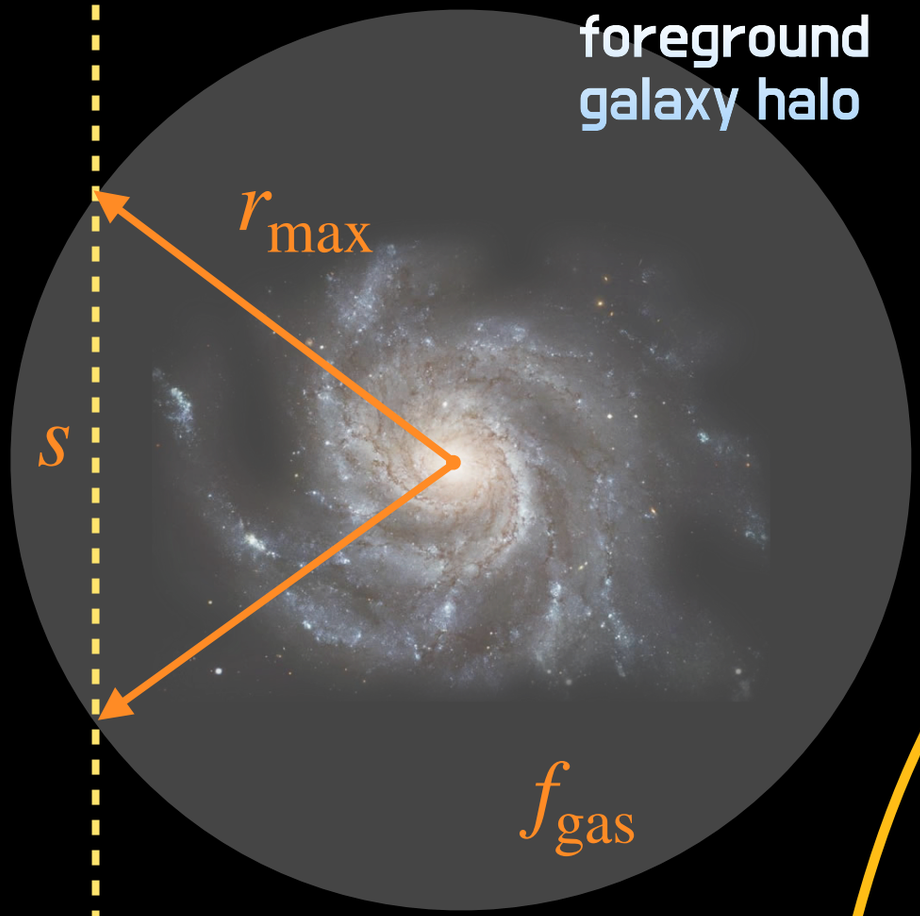

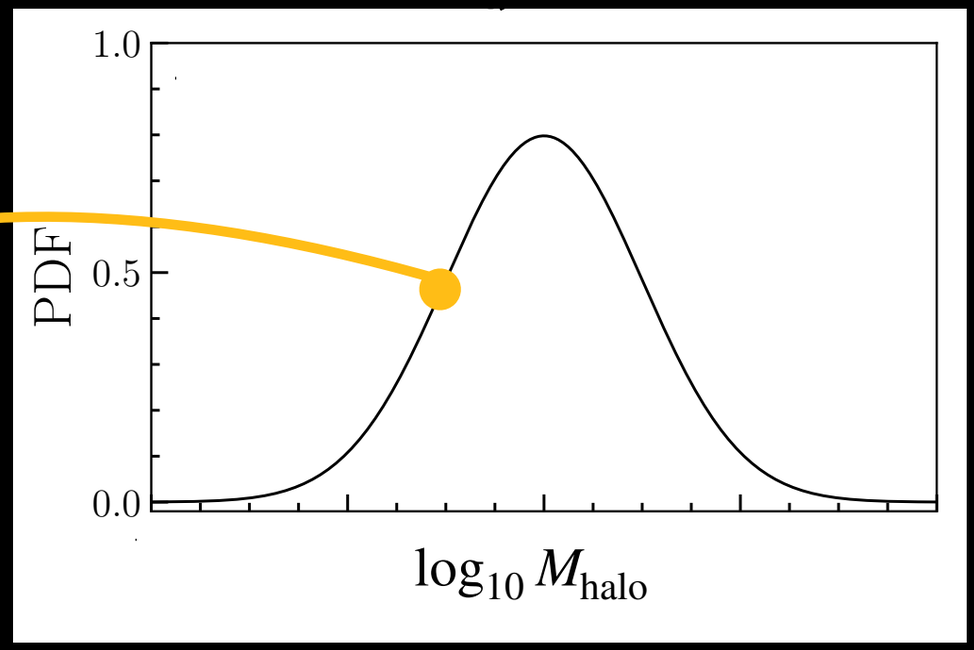

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to Earth

Predictions from the mocks

Step 2. Narrow-field Observations

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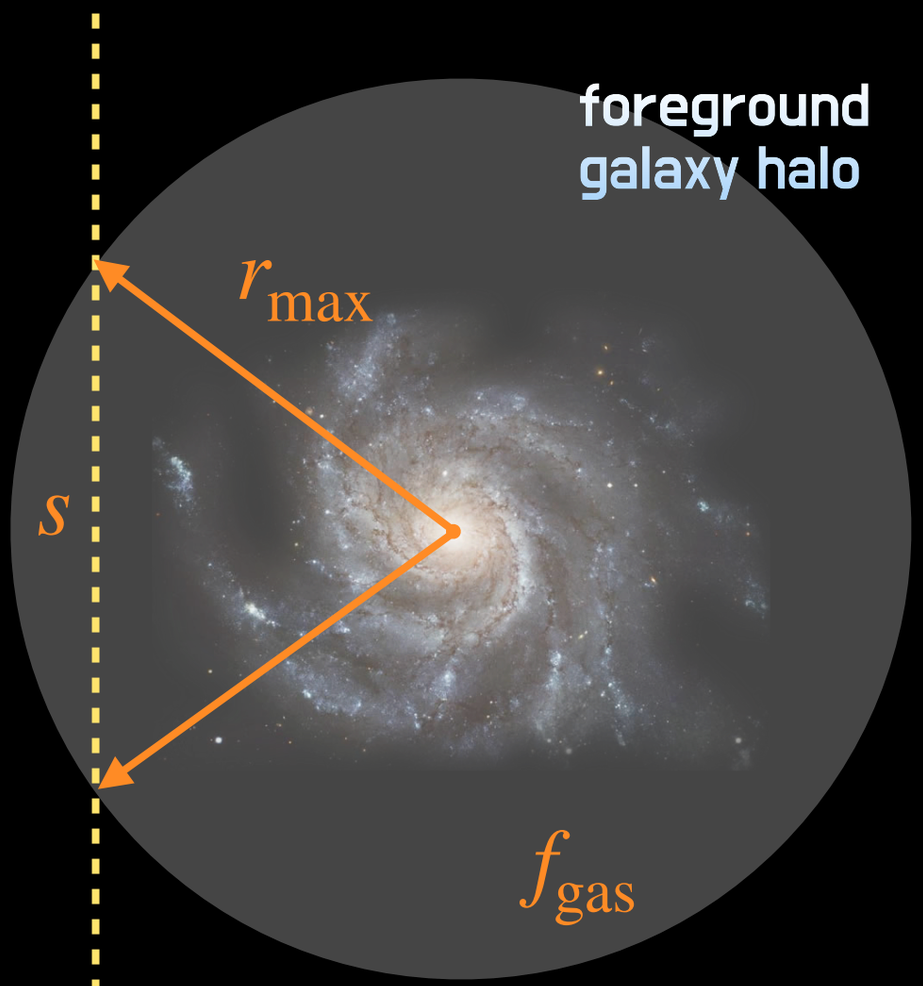

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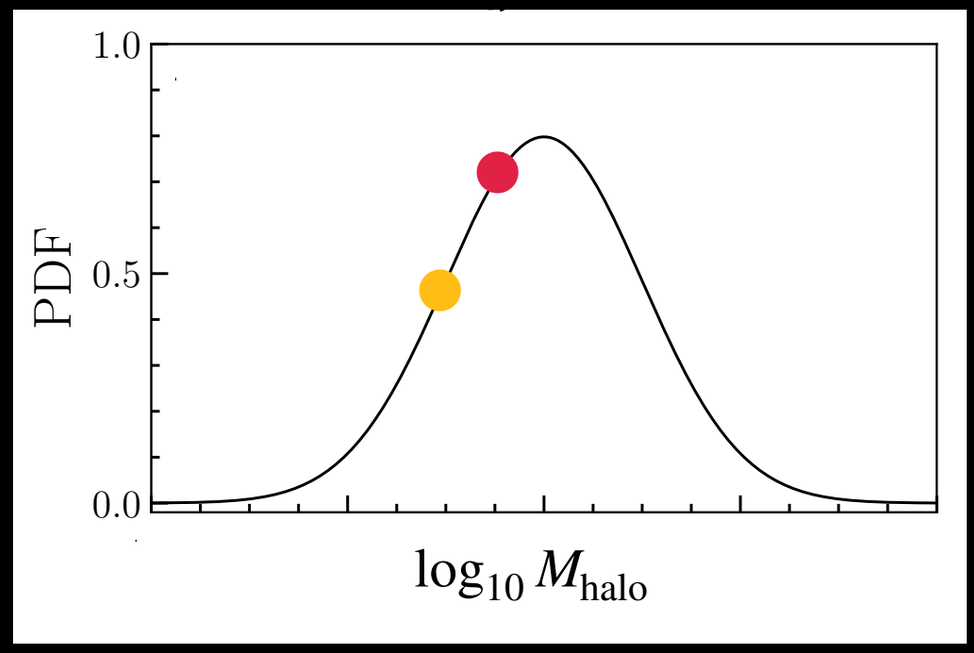

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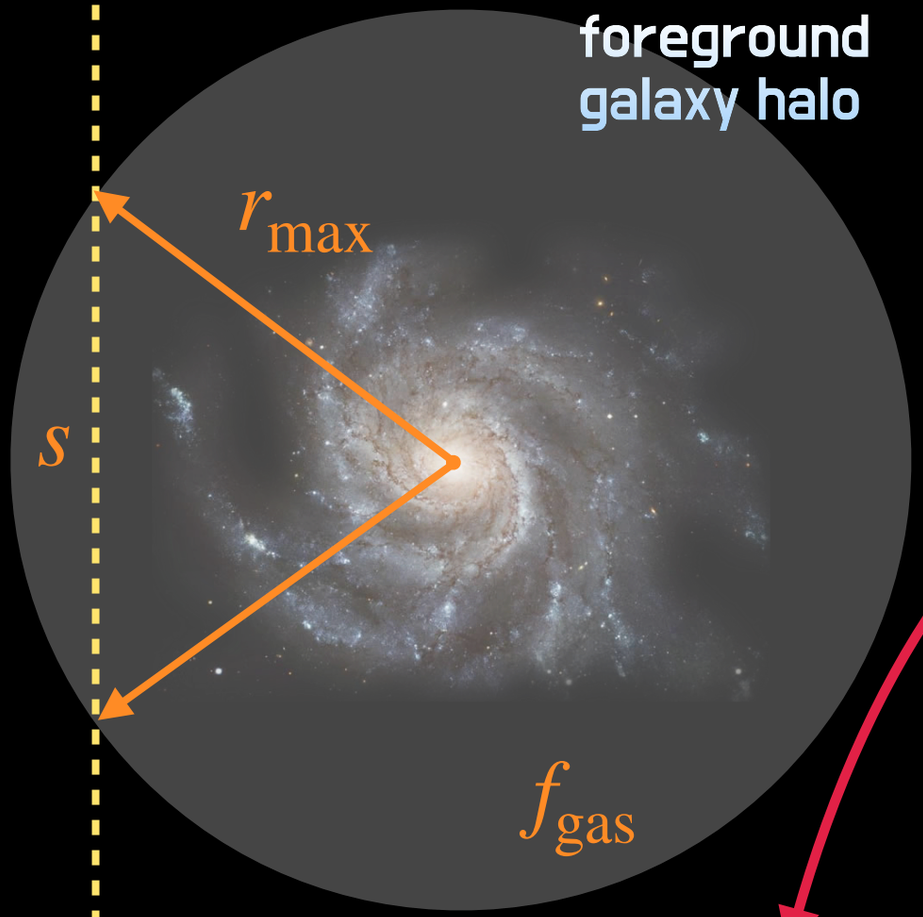

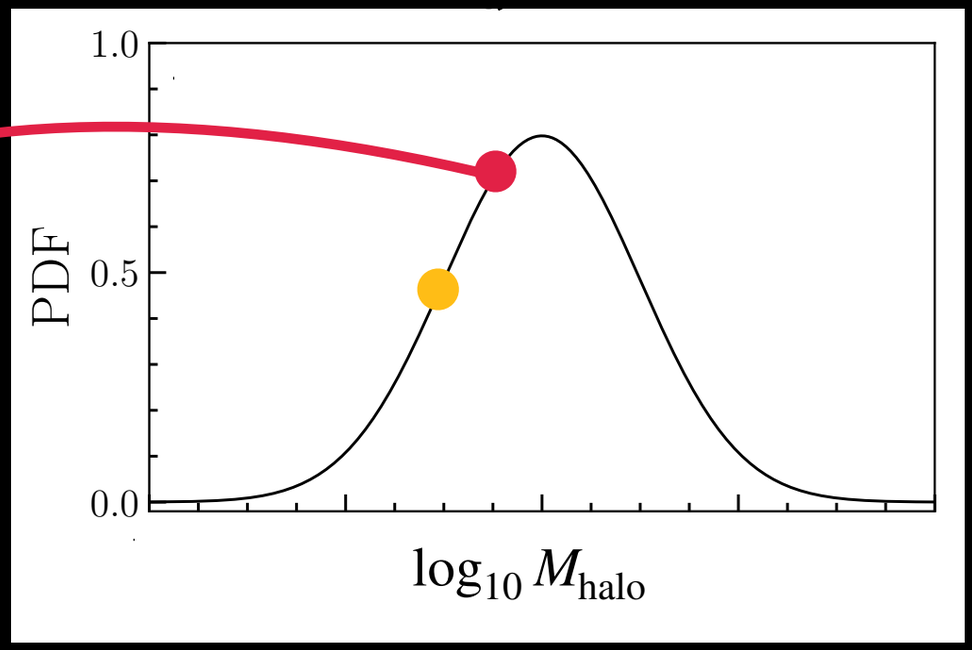

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to Earth

Predictions from the mocks

Step 2. Narrow-field Observations

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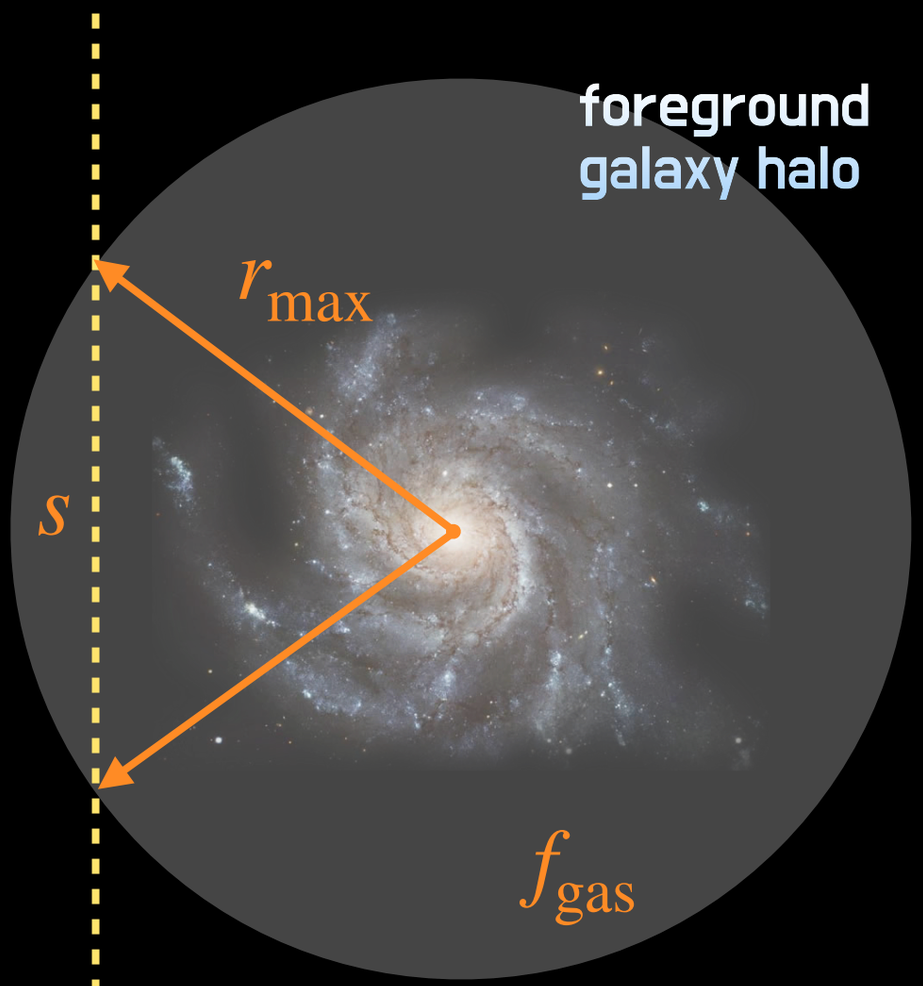

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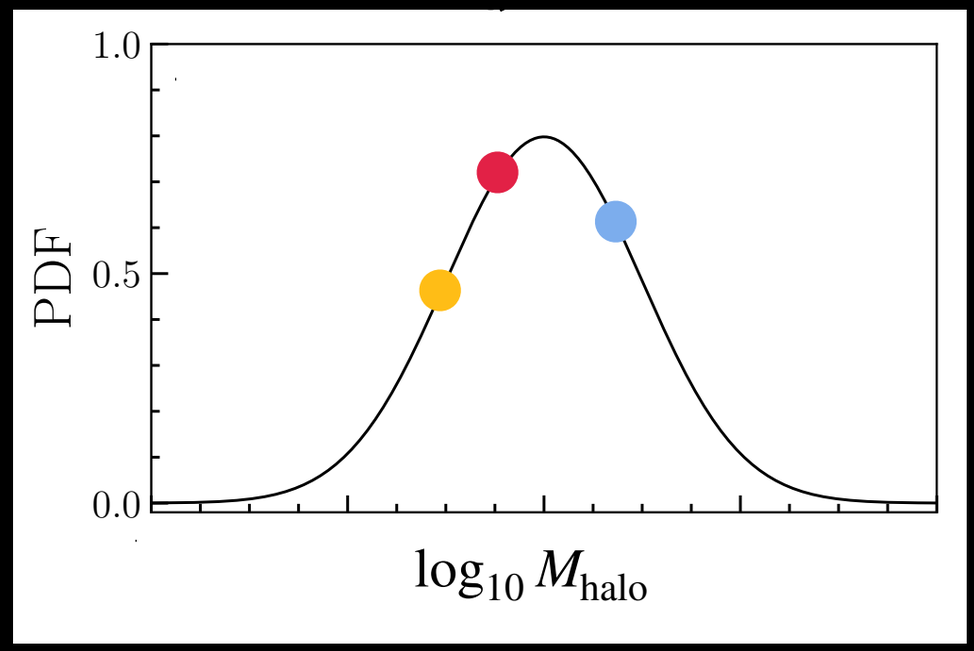

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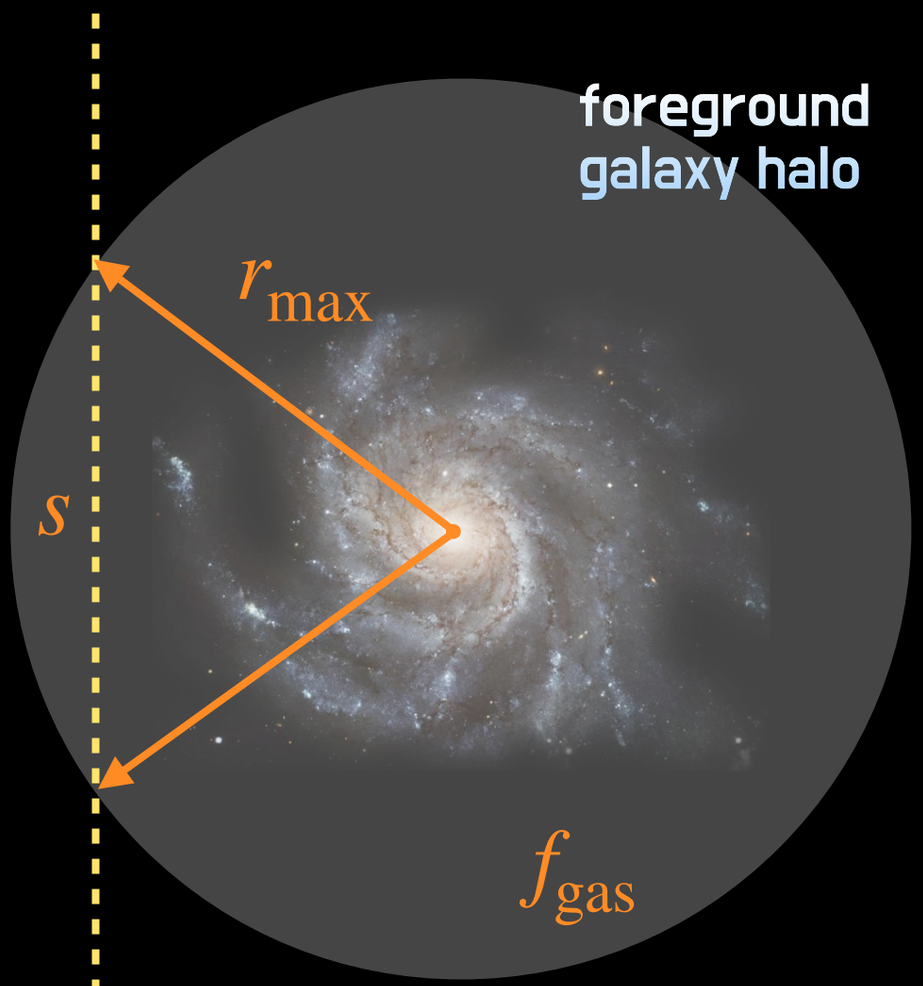
Resulting mean $\mathrm{DM}_{\rm halos}$ for a single sightline:

$$\mathrm{DM}_{{\rm halos},i} = f_{\rm gas} \frac{1}{N_{\rm real}} \sum_j^{N_{\rm real}} \sum_k^{N_{\rm halos}} \frac{\mathrm{DM}^j_{{\rm halo},k}}{1+z_{{\rm halo},k}}$$

Predictions from the mocks

Step 2. Narrow-field Observations

from FRB



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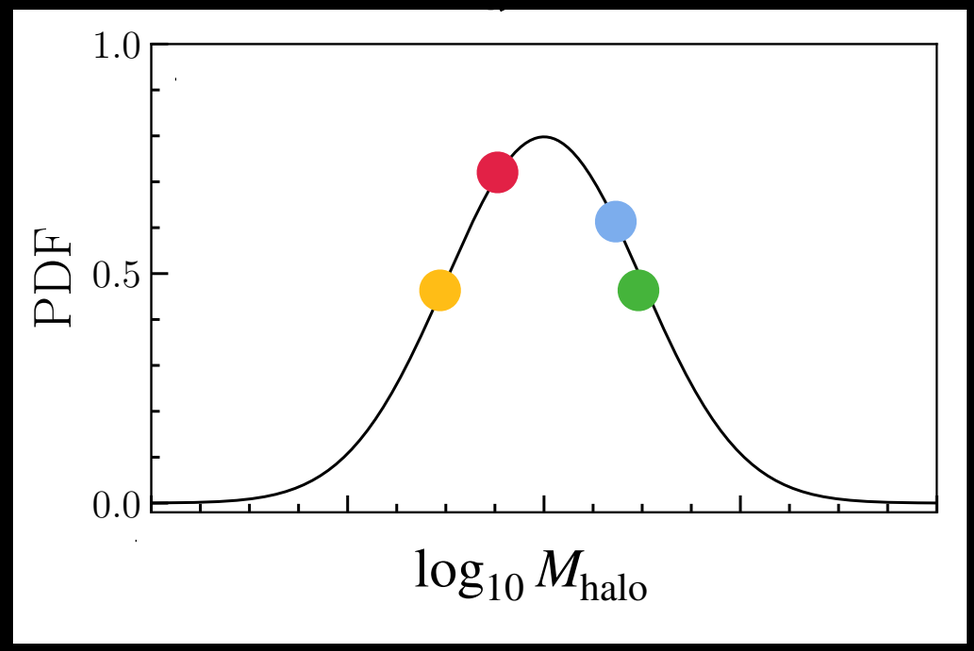

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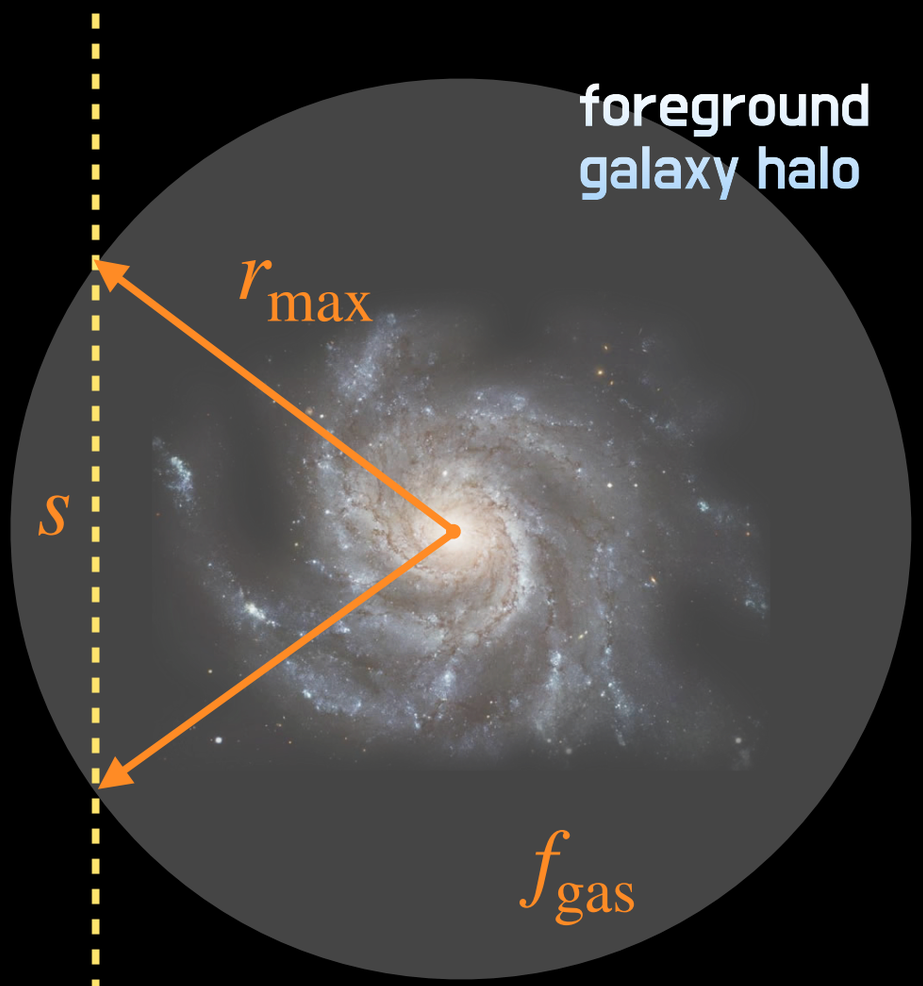
Predictions from the mocks

Step 2. Narrow-field Observations

from FRB



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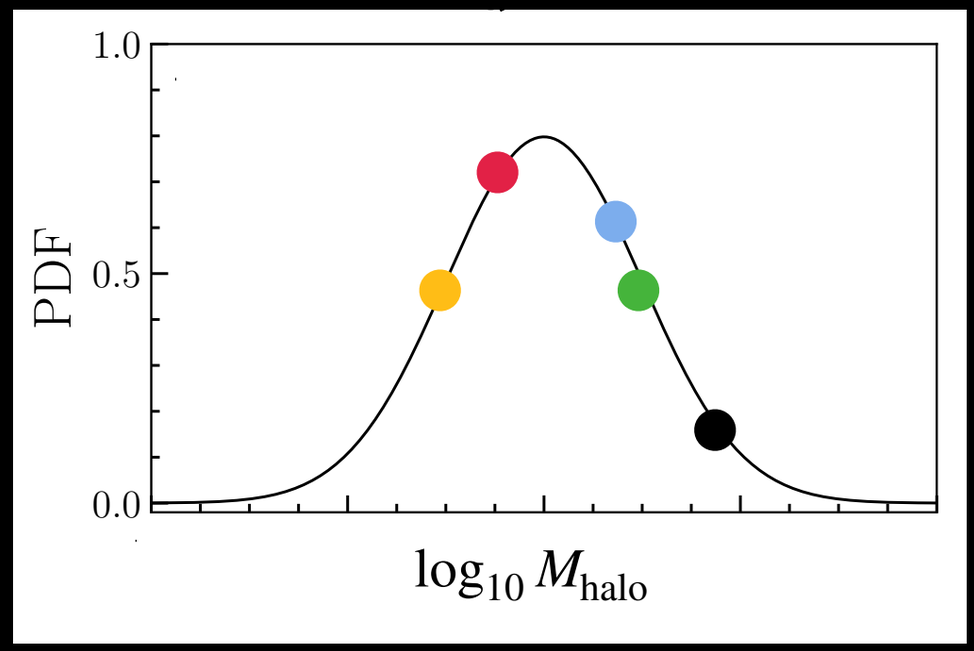

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Predictions from the mocks

Step 2. Narrow-field Observations

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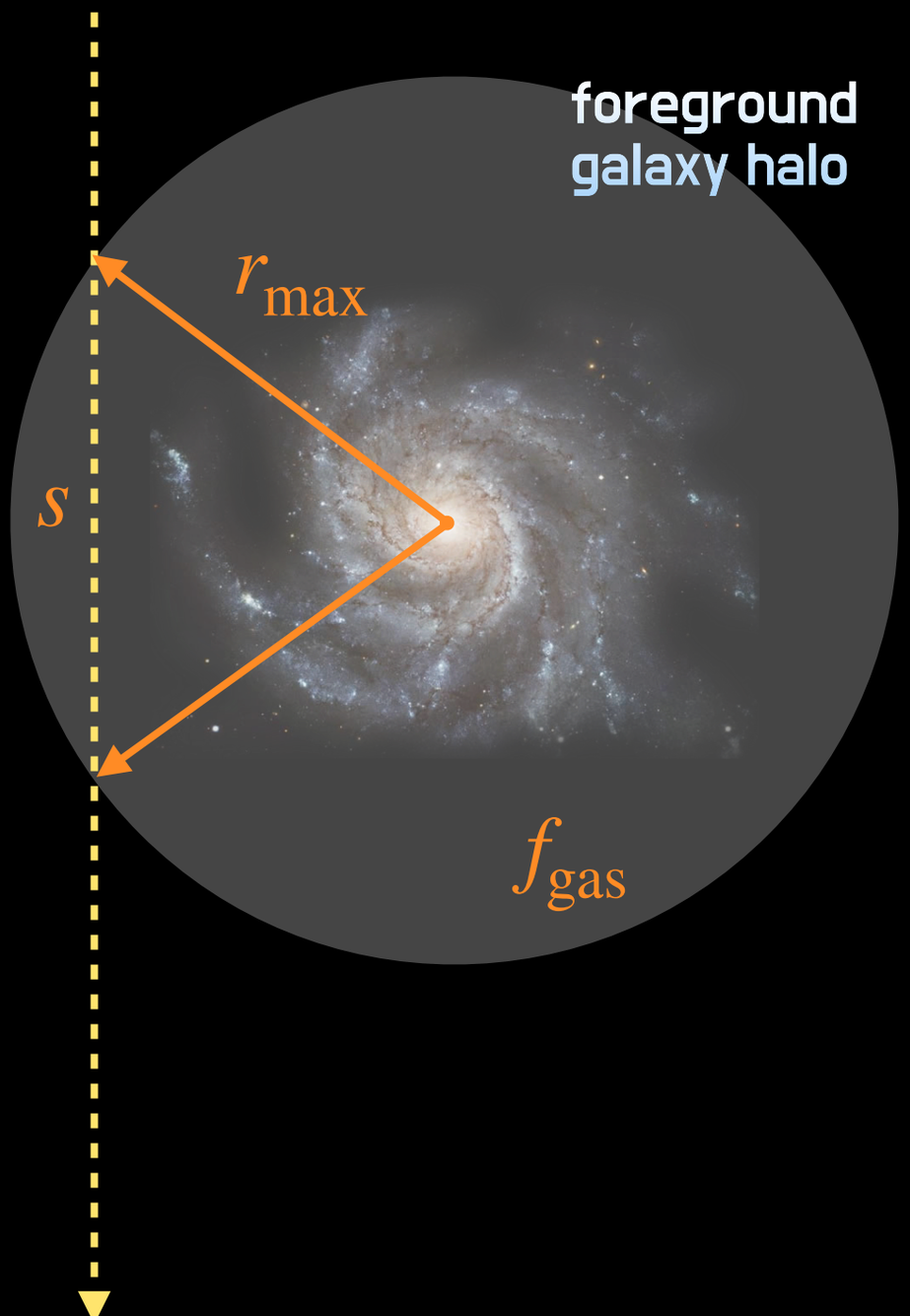

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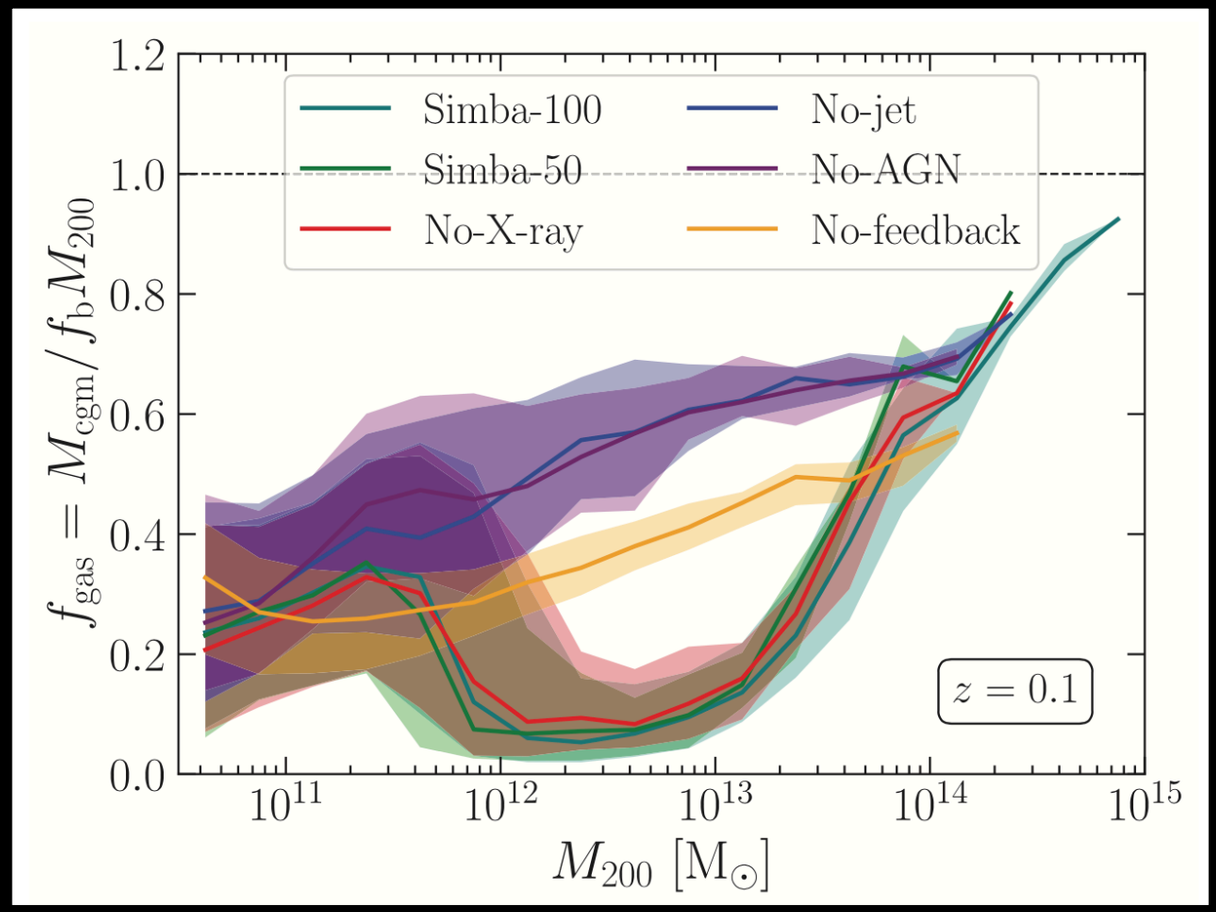


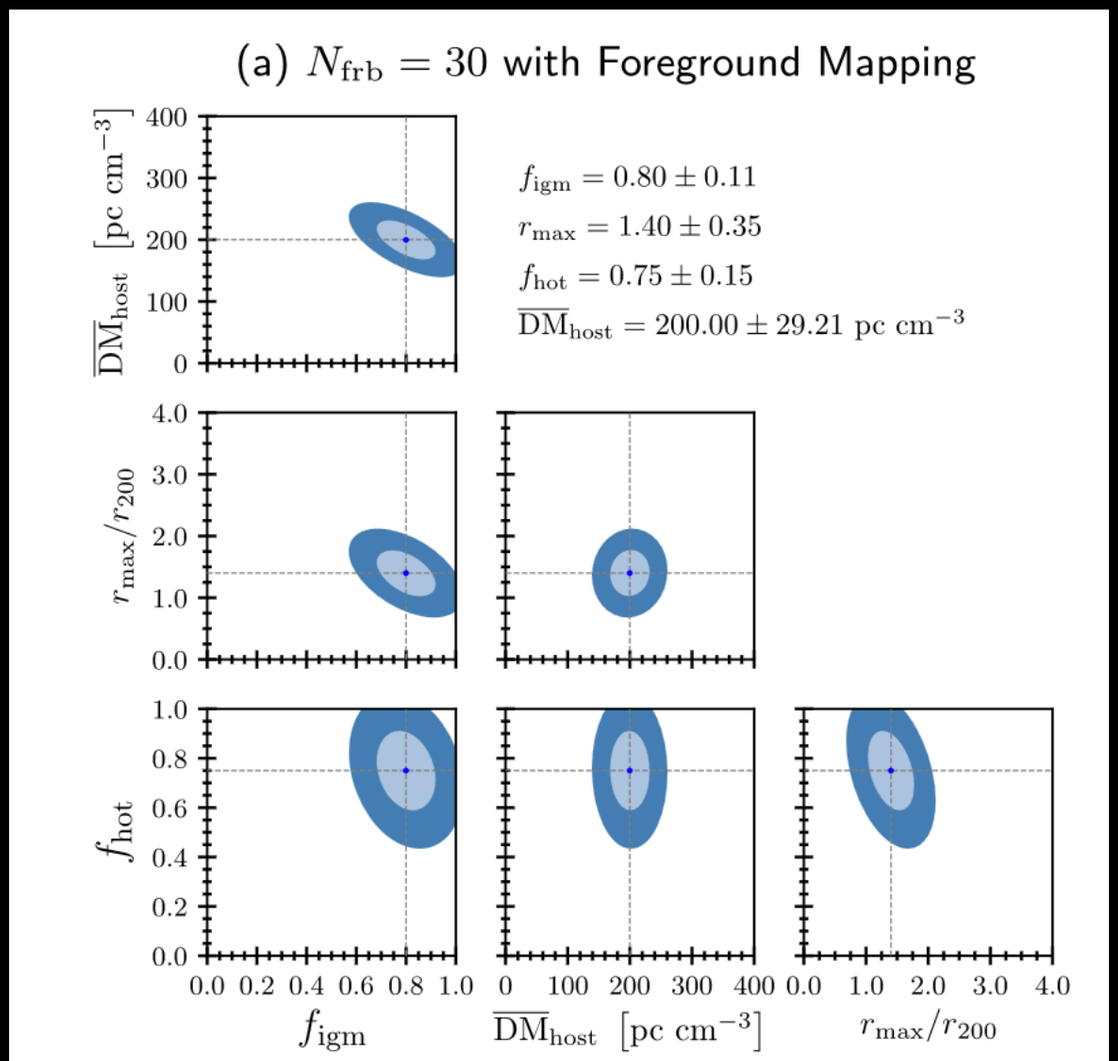
Khrykin, Sorini, Lee et al. (2024a)

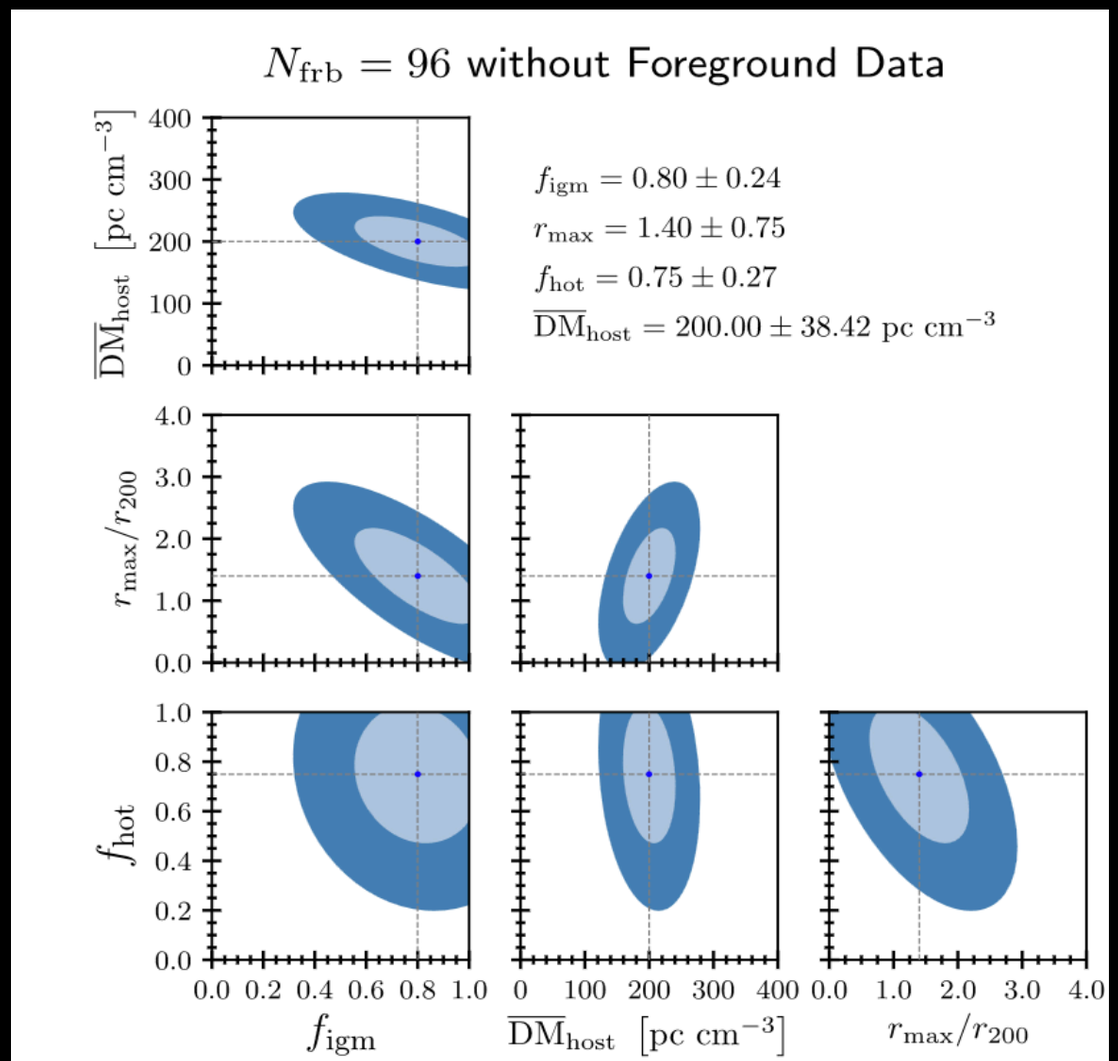
Predictions from the mocks: Fisher Matrix forecast

$$\mathrm{DM}^{\mathrm{e.g.}}_{\mathrm{model},i} = f_{\mathrm{igm}} \cdot \langle \mathrm{DM}^{\mathrm{ARGO}}_{\mathrm{igm},i} \rangle + f_{\mathrm{gas}} \cdot \langle \mathrm{DM}_{\mathrm{halos},i}\ (r_{\mathrm{max}}) \rangle + \langle \mathrm{DM}_{\mathrm{host}} \rangle / (1+z)$$

averaged over ARGO realizations

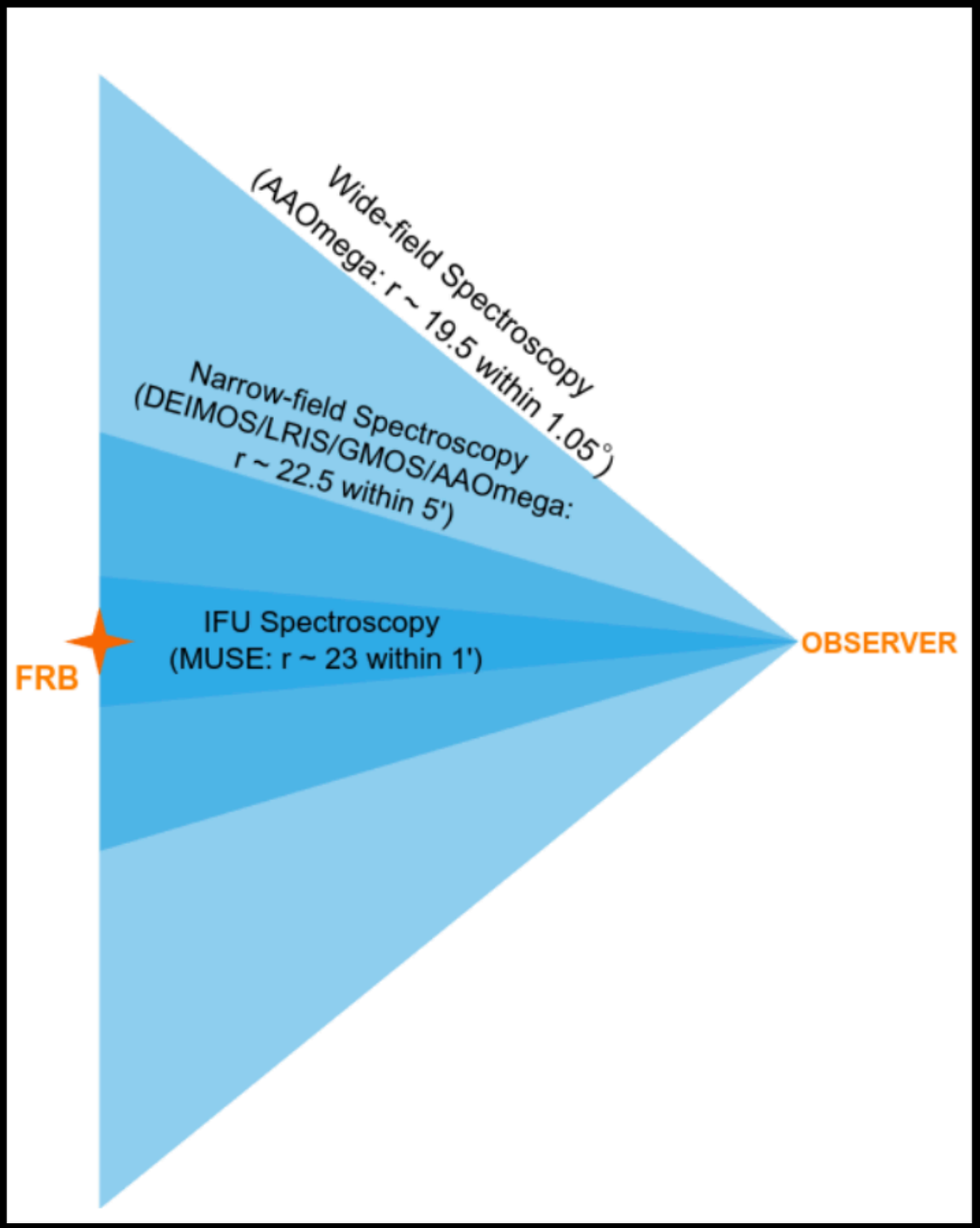
averaged over realizations of halo masses





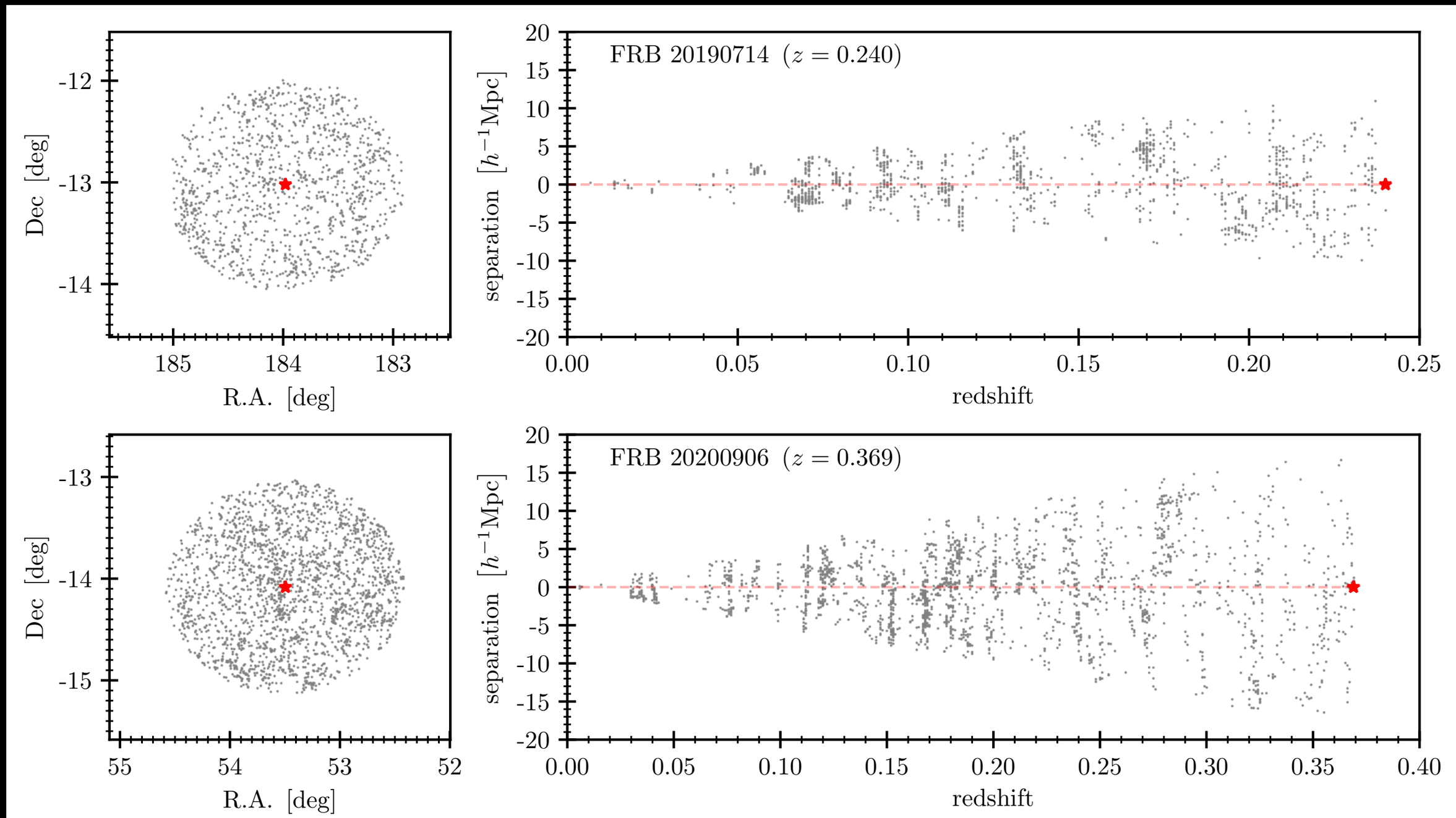
The FLIMFLAM survey

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



and any archival data from SDSS 6dF 2MASS

The FLIMFLAM survey: wide-field data



Huang, Simha, Khrykin et al. (2024a)

The FLIMFLAM survey: DR1

FLIMFLAM DR1: The First Constraints on the Cosmic Baryon Distribution from 8 FRB sightlines

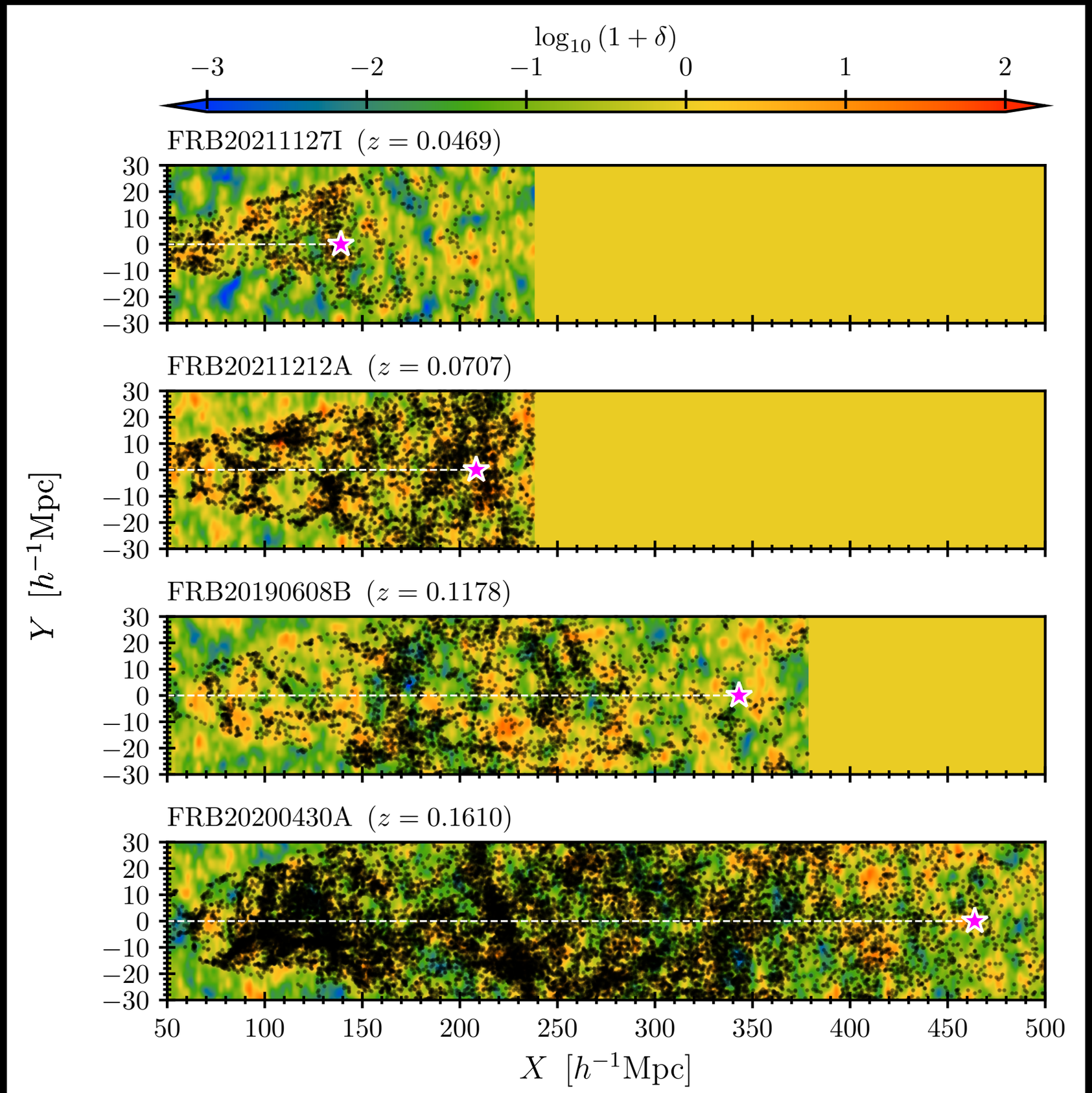
Ilya S. Khrykin [1,2] Metin Ata [3] Khee-Gan Lee [2,4] Sunil Simha [5] Yuxin Huang [2]
J. Xavier Prochaska [5,2,6] Nicolas Tejos [1] Keith W. Bannister [7] Jeff Cooke [8,9] Cherie K. Day [10]
Adam Deller [8] Alexa C. Gordon [11] Clancy W. James [12] Lachlan Marnoch [9,13,14,15]
Ryan. M. Shannon [8] Jielai Zhang [8,16] and Lucas Bernales–Cortes [1]

Sample of 8 FRBs:

FRB	R.A. (deg)	Decl. (deg)	Redshift	Wide-field data	Narrow-field data	DM_{FRB} (pc cm^{-3})	WF Survey source	Limiting r-mag	№ of galaxies
20211127A	199.8088	−18.8381	0.0469	6dF	AAT	234.83	6dF	15.60	1901
20211212A	157.3507	+01.3605	0.0713	SDSS	AAT	206.00	SDSS	17.77	15321
20190608A	334.0199	−07.8982	0.1178	SDSS, 6dF	SDSS, KCWI, MUSE	339.50	SDSS	17.77	6640
20200430A	229.7066	+12.3761	0.1608	SDSS, AAT	LRIS, DEIMOS, MUSE	380.10	6dF	15.60	1273
20191001A	323.3516	−54.7477	0.2340	AAT	AAT, MUSE	506.92	SDSS	17.77	30579
20190714A	183.9795	−13.0207	0.2365	AAT	LRIS, DEIMOS, MUSE	504.70	AAT	18.60	260
20180924B	326.1052	−40.9000	0.3212	AAT	AAT, MUSE	362.40	AAT	19.40	1712
20200906A	053.4956	−14.0833	0.3688	AAT	LRIS, DEIMOS, MUSE	577.80	AAT	19.40	1270
							AAT	19.80	2128
							AAT	19.80	2186

Khrykin et al. (2024a)
Huang, Simha, Khrykin et al. (2024a)

FLIMFLAM DR1: density reconstruction



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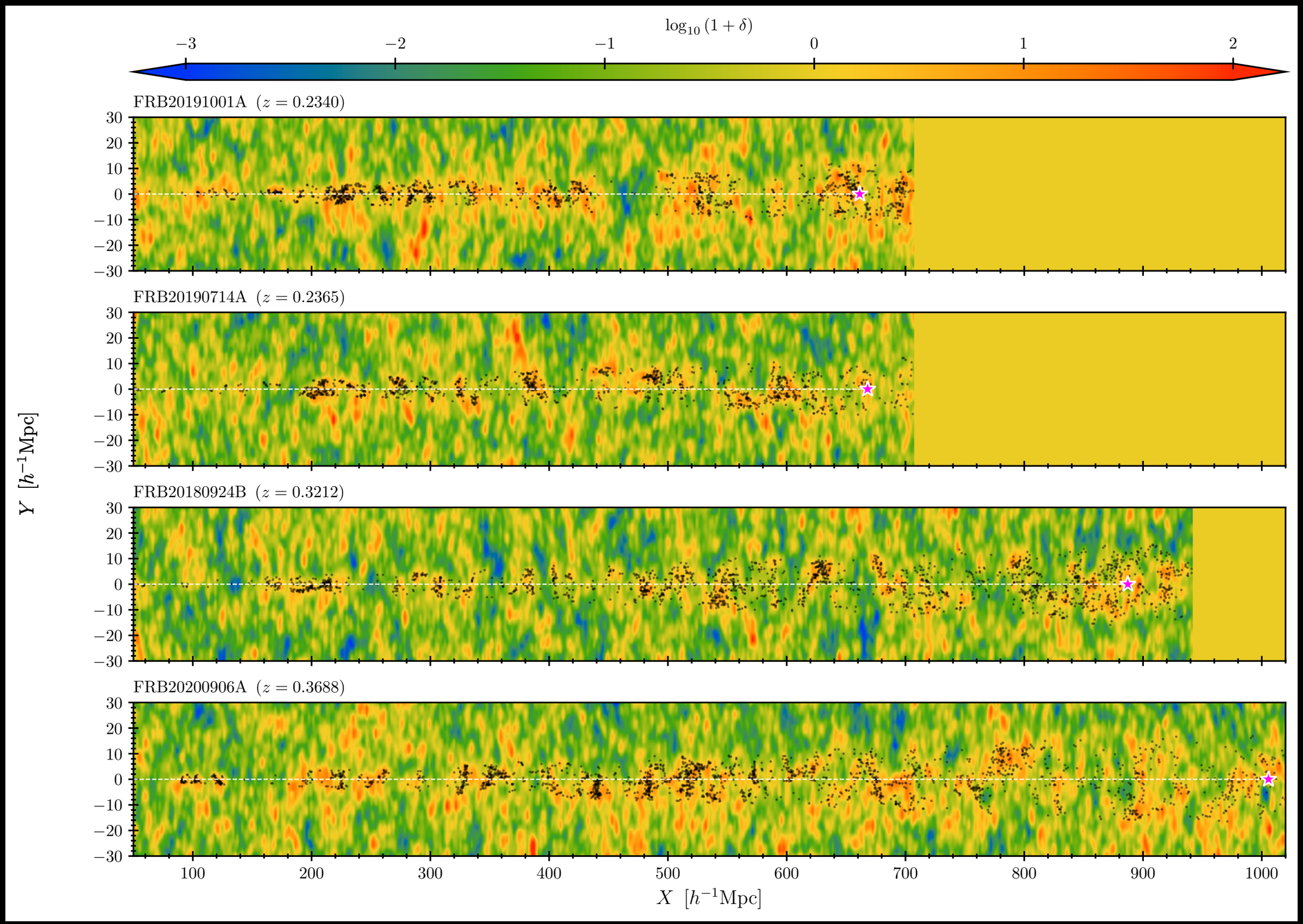
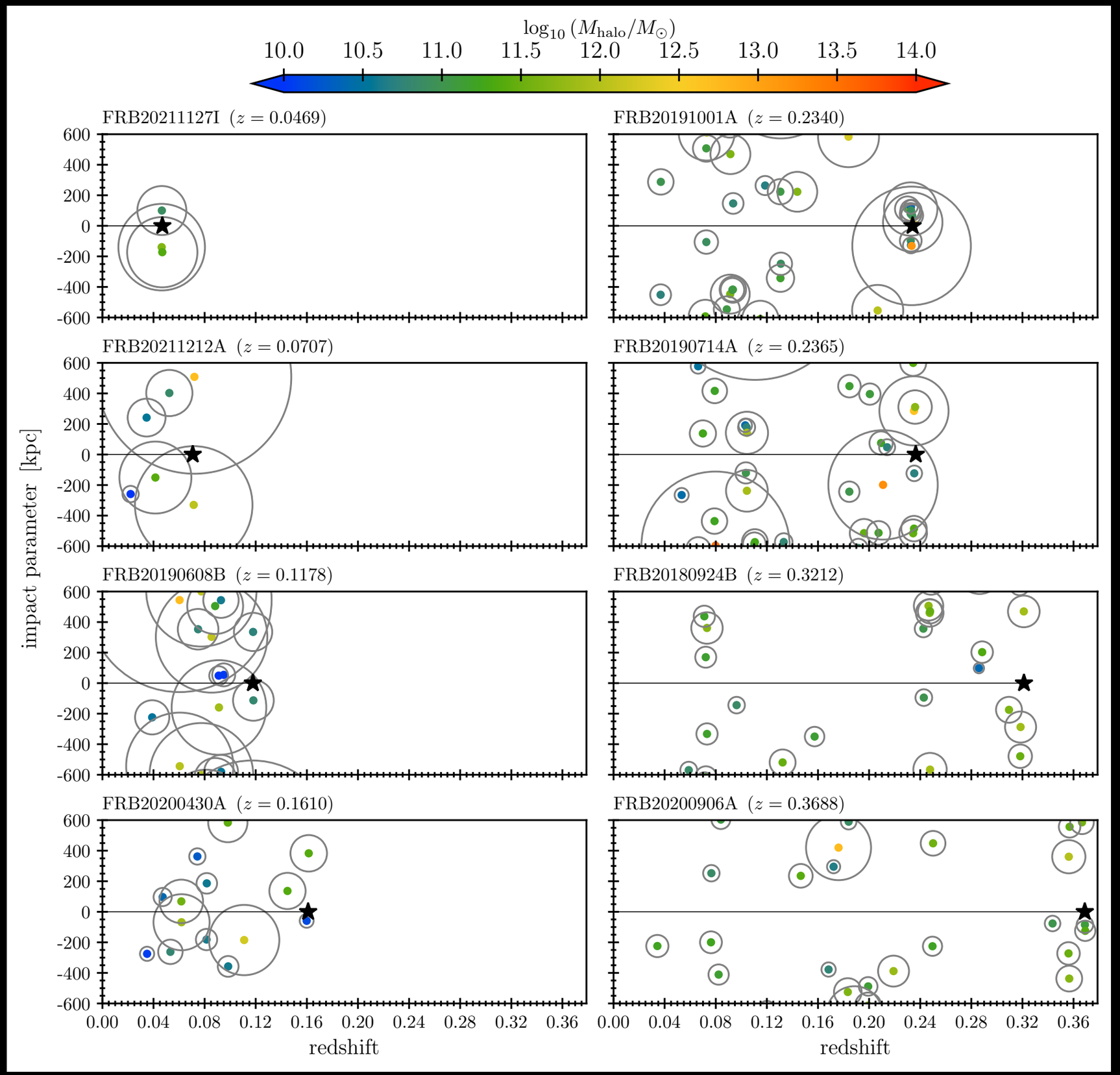
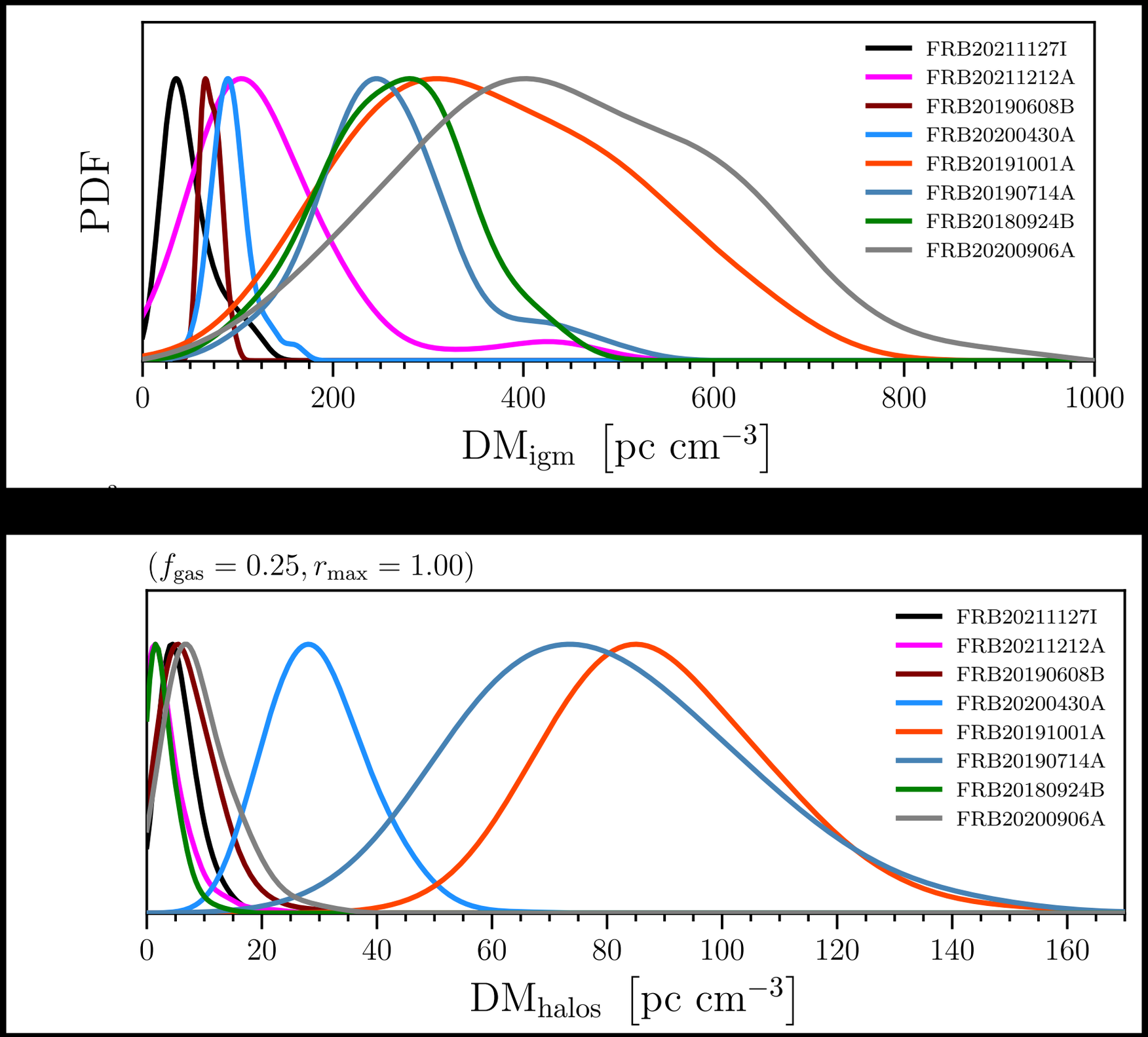


FLIMFLAM DR1: foreground halos

Distribution and sizes of the foreground halos given their mean masses



FLIMFLAM DR1: DM components



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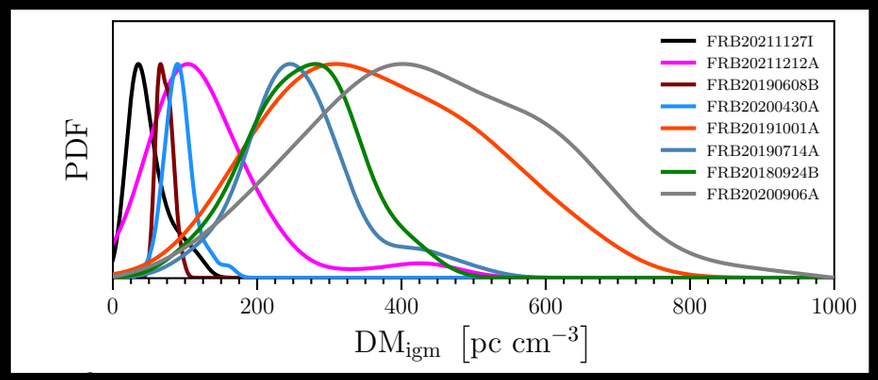
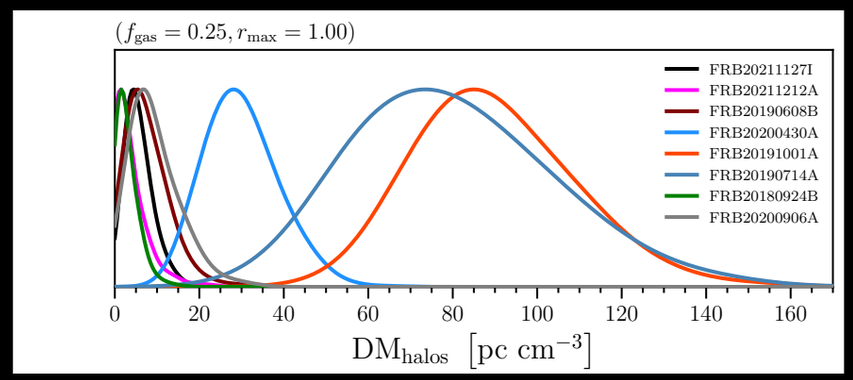




assuming $f_{\mathrm{igm}} = 1.0$ assuming $f_{\mathrm{gas}} = 1.0$

FRB	redshift	$\mathrm{DM}_{\mathrm{igm}}^{\mathrm{argo}}$	$\mathrm{DM_{halos}}$	$\mathrm{DM}_{\mathrm{host}}^{\mathrm{halo}}$	$\langle \log_{10} \left(M_{\mathrm{host}}^{\mathrm{halo}} / M_{\odot} \right) \rangle$	$\mathrm{DM_{MW}}$	$\mathrm{DM_{FRB}}$
20211127A	0.0469	61.6 ± 32.0	22.6 ± 13.2	24.1 ± 5.5	11.3	82.5	234.83
20211212A	0.0713	171.2 ± 106.4	13.4 ± 15.7	35.8 ± 8.1	11.7	67.1	206.00
20190608A	0.1178	89.9 ± 12.0	30.5 ± 20.4	46.1 ± 10.4	12.1	78.1	339.50
20200430A	0.1608	116.1 ± 5.6	120.0 ± 33.1	24.2 ± 5.7	11.2	67.0	380.10
20191001A	0.2340	466.3 ± 170.4	360.7 ± 72.4	58.1 ± 13.0	12.3	84.7	506.92
20190714A	0.2365	326.5 ± 94.7	321.4 ± 92.1	37.4 ± 8.7	11.8	78.0	504.70
20180924B	0.3212	329.2 ± 91.0	11.5 ± 10.6	44.0 ± 10.4	11.9	81.9	362.40
20200906A	0.3688	559.9 ± 202.8	37.4 ± 23.5	45.8 ± 10.8	11.9	75.9	577.80

FLIMFLAM DR1: parameter inference

$$\mathrm{DM}_{\mathrm{model},i} = \mathrm{DM}_{\mathrm{MW},i} + f_{\mathrm{igm}} \cdot \langle \mathrm{DM}^{\mathrm{ARGO}}_{\mathrm{igm},i} \rangle + f_{\mathrm{gas}} \cdot \langle \mathrm{DM}_{\mathrm{halos},i}\ (r_{\mathrm{max}} \equiv 1.0) \rangle + \mathrm{DM}_{\mathrm{host},i}$$

averaged over ARGO realizations

averaged over realizations of halo masses

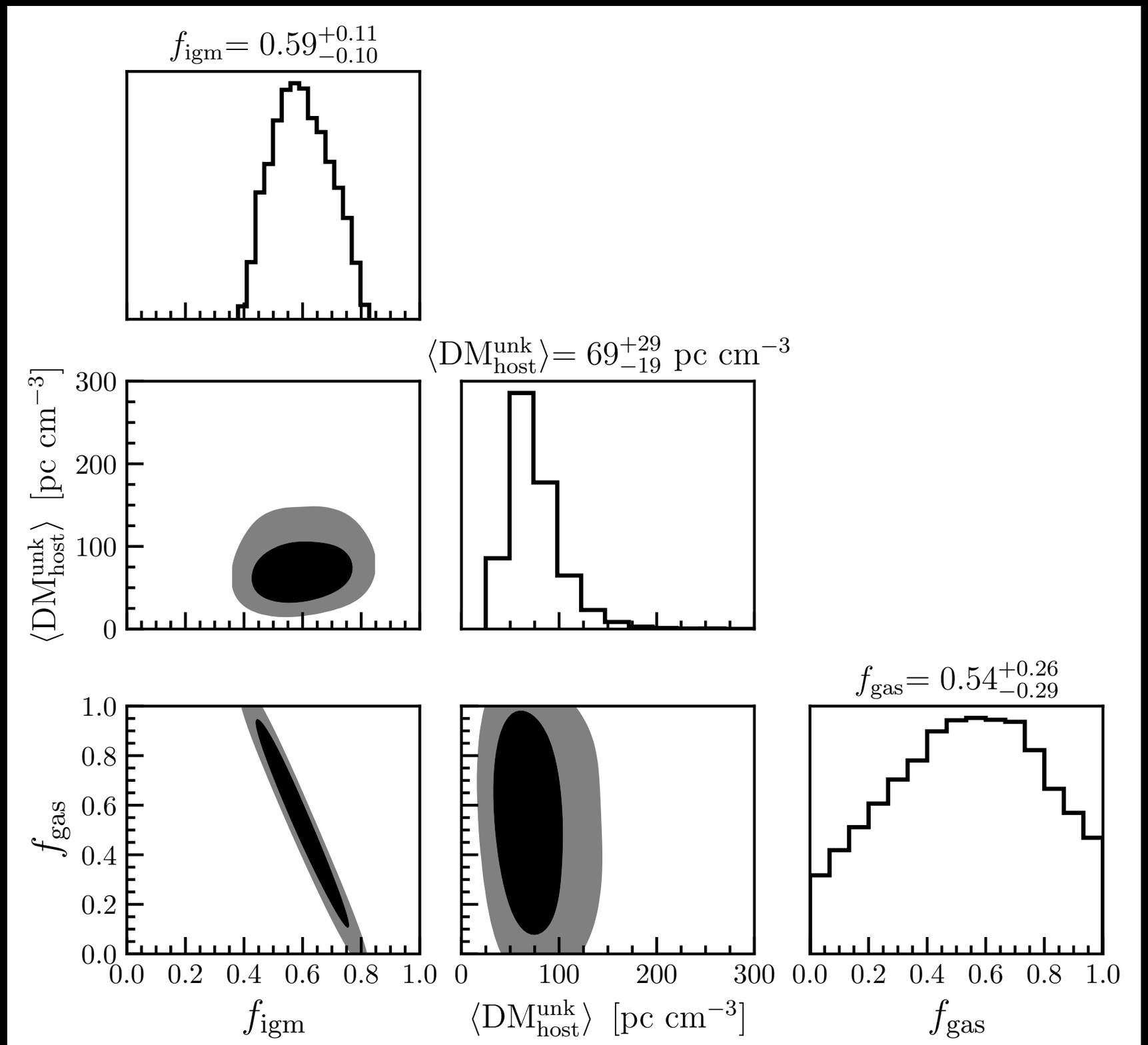
$$\mathrm{DM}_{\mathrm{host},i} = \mathrm{DM}^{\mathrm{halo}}_{\mathrm{host},i} + \langle \mathrm{DM}^{\mathrm{unk}}_{\mathrm{host}} \rangle$$

The joint likelihood for an ensemble of FRB:

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

$$\sigma_i^2 = \sigma^2_{\mathrm{argo},i} + \sigma^2_{\mathrm{halos},i} + \sigma^2_{\mathrm{MW}} + \sigma^2_{\mathrm{DM}^{\mathrm{unk}}_{\mathrm{host}}}$$

FLIMFLAM DR1: parameter inference (fiducial priors)



Fraction of baryons in the IGM

$$f_{\rm igm} = 0.59^{+0.11}_{-0.10}$$

Fraction of CGM baryons in individual halos

$$f_{\rm gas} = 0.54^{+0.26}_{-0.29}$$

Contribution from the FRB hosts' halos and the unknown part from ISM and/or FRB progenitor:

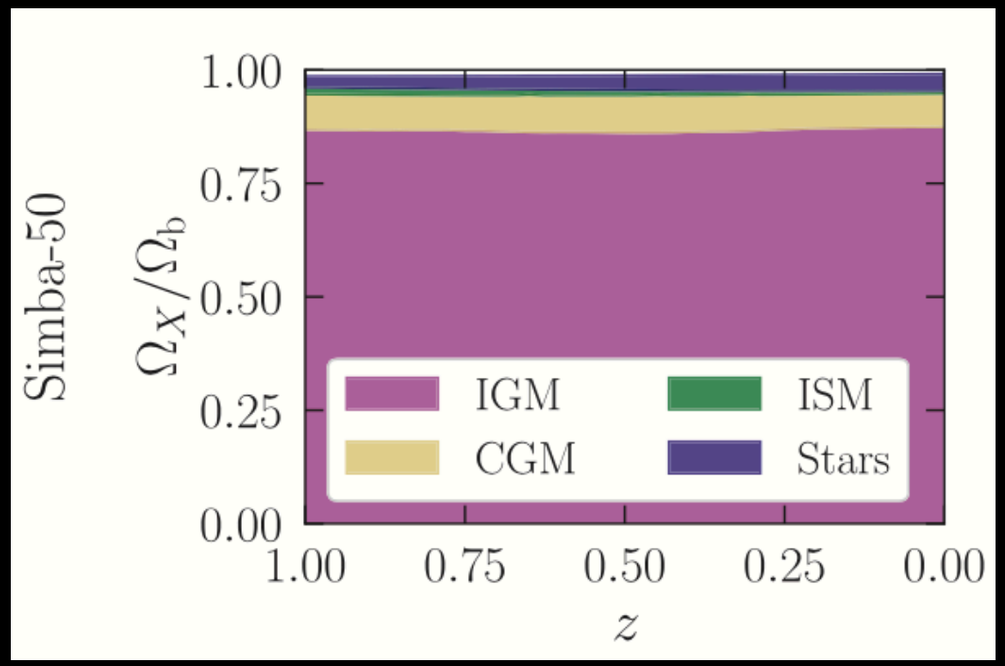
$$\langle {\rm DM}_{\rm host} \rangle = \langle {\rm DM}^{\rm halo}_{\rm host} + {\rm DM}^{\rm unk}_{\rm host} \rangle$$

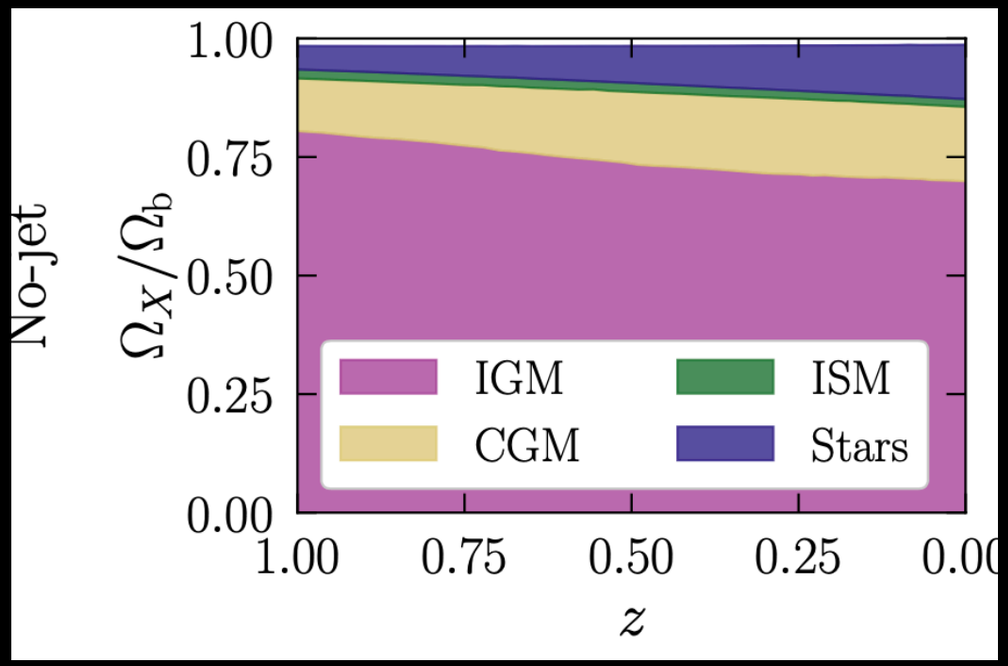
$$\langle {\rm DM}_{\rm host} \rangle = 90^{+29}_{-19}\ {\rm pc\ cm^{-3}}$$

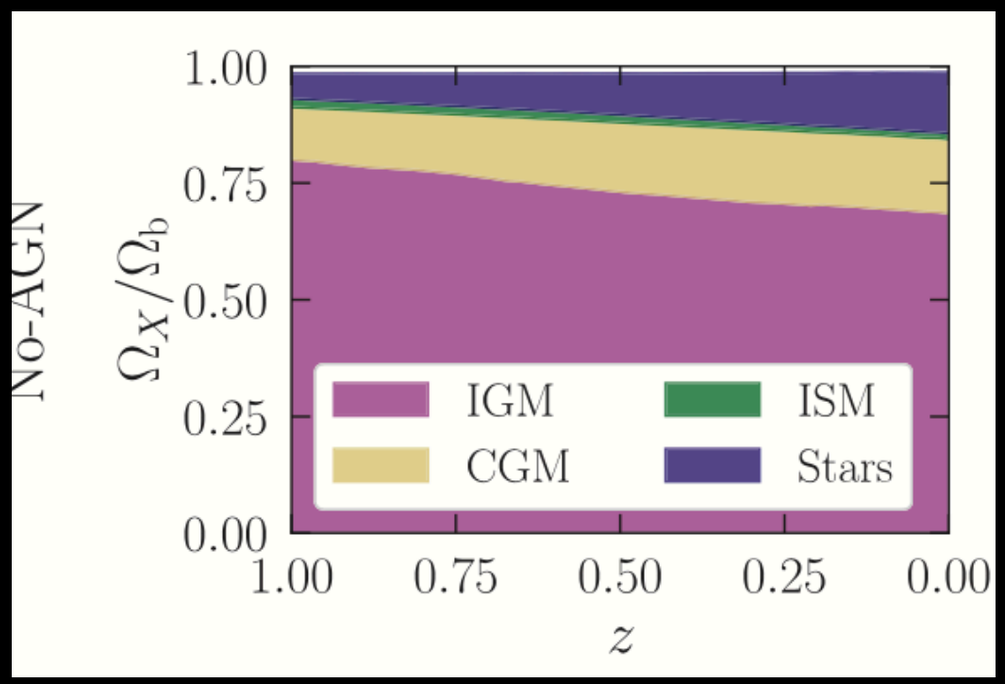
FLIMFLAM DR1 results in perspective

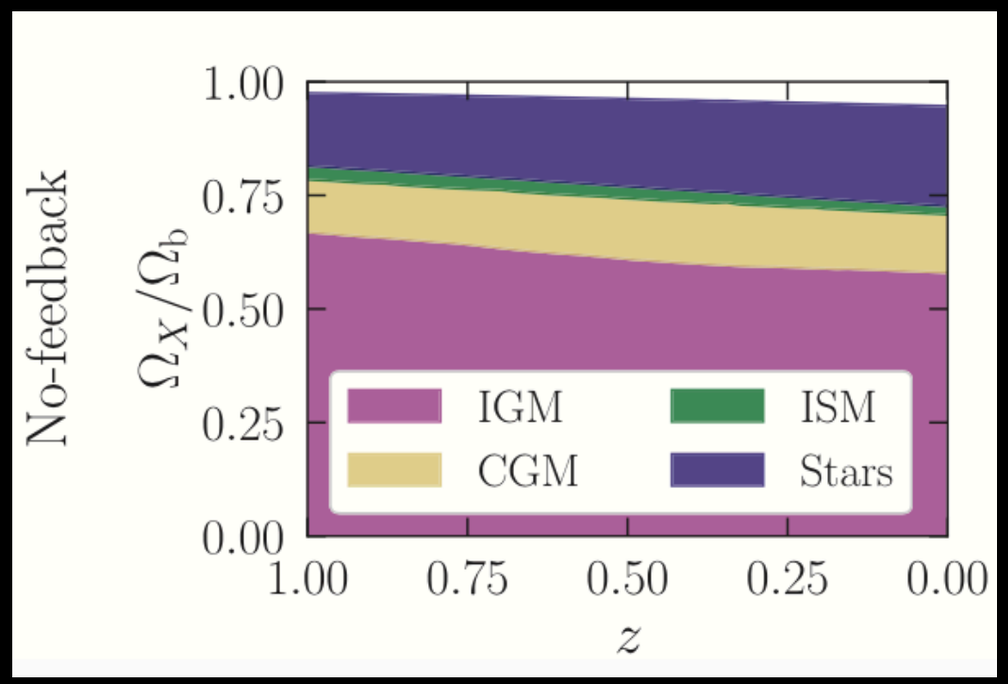
$f_{\rm igm} = 0.59^{+0.11}_{-0.10}$

Partition of cosmic baryons in SIMBA simulations with different feedback mechanisms (Khrykin+2024a)









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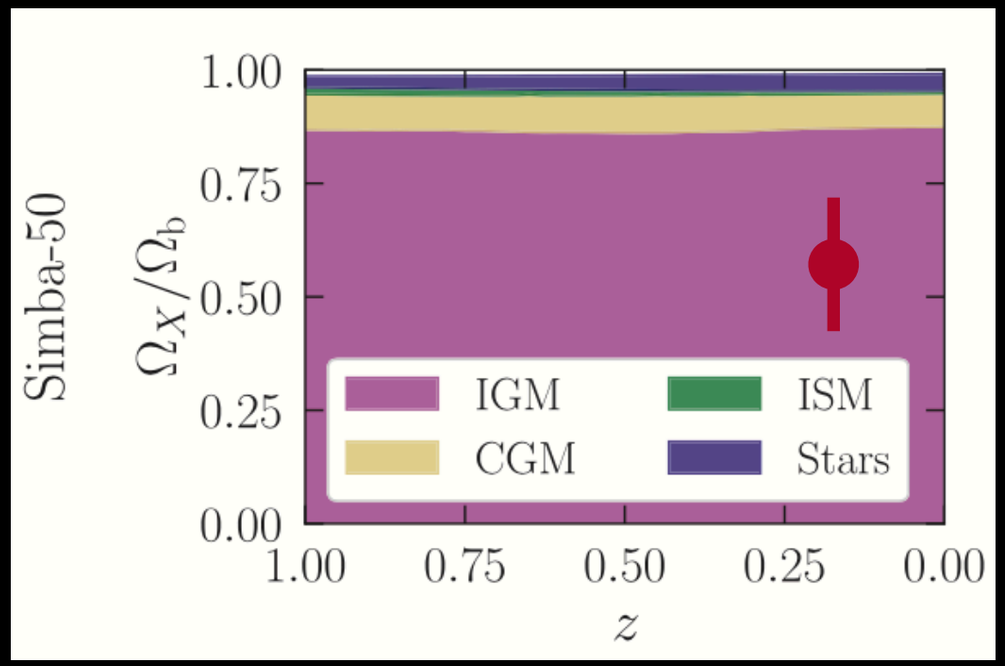

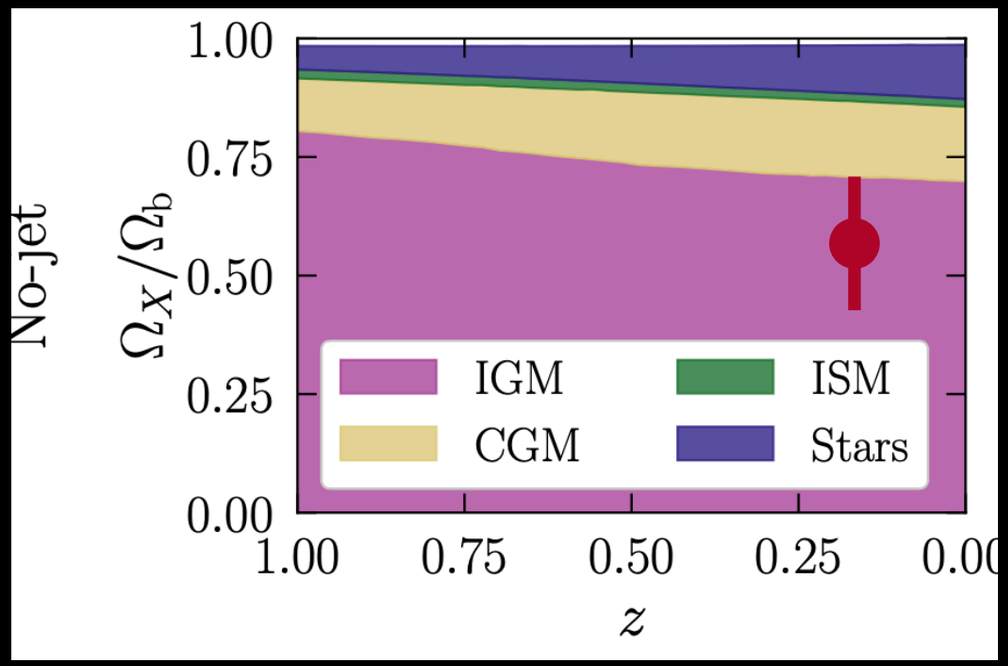

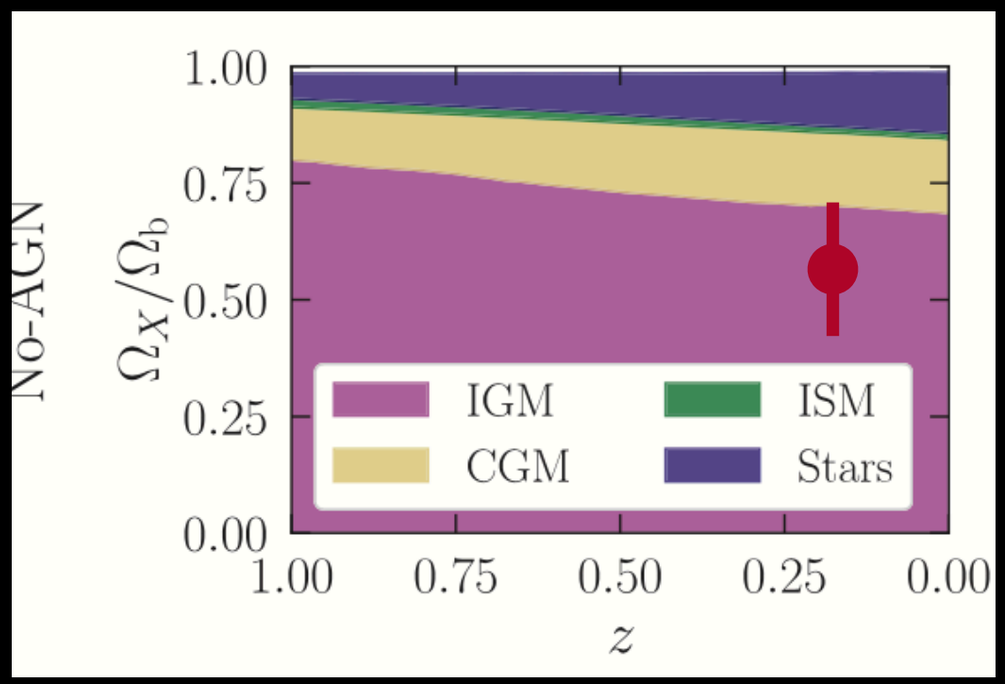

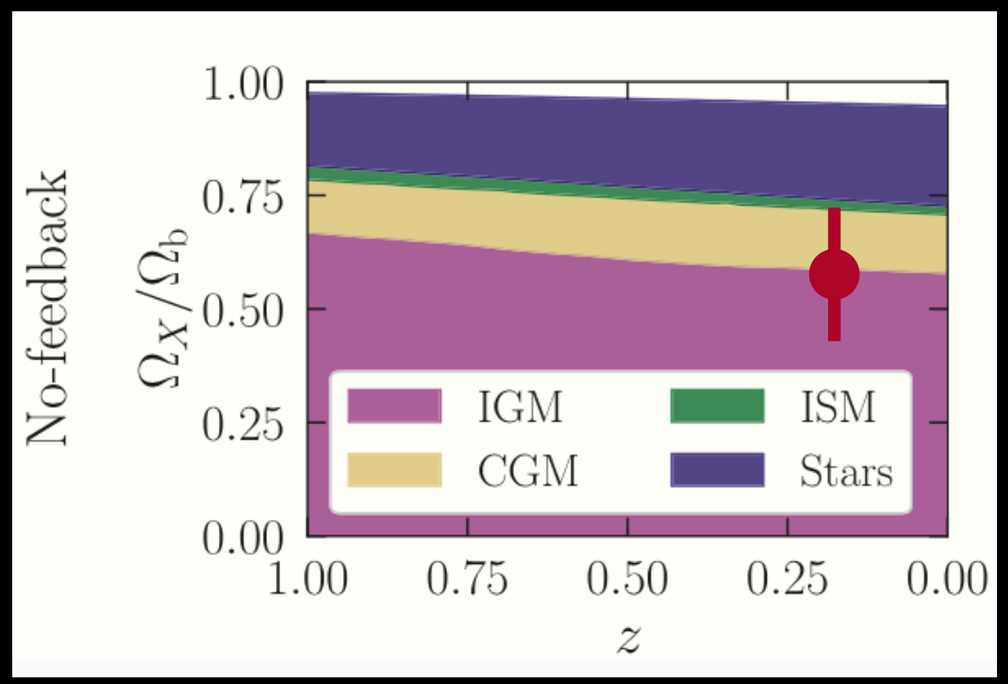

Looking forward: FLIMFLAM DR2

Key features of DR2:

* 3.5x the sample size: 27 FRB fields
* Wide-field data: AAT 2dF, AAT Koala, NED-LDS, Subaru PFS
* Narrow-field data: LRIS, DIEMOS, GMOS
* IFU data: AAT Koala, VLT MUSE

* More sophisticated model for the foreground/host galactic halos
* New, (much) faster and more accurate density reconstruction algorithm (GPU accelerated)
* Exploration of different IGM smoothing scales

Coming up in 2025 (hopefully)

Summary

FLIMFLAM is a spectroscopic survey at 3.9m AAT (complemented by Keck and VLT), that aims to map out the foreground structures in 30 FRB sightlines and measure the distribution of cosmic baryons.

FLIMFLAM Data Release 1 is out!

DR1 analysis constrains: $f_{\rm igm} = 0.59^{+0.11}_{-0.10}$ and $f_{\rm gas} = 0.54^{+0.26}_{-0.29}$. These results mildly consistent with no feedback hydrodynamical models, but the uncertainty is still too big. DR2 should be able to shed more light on this matter!

We also for the first time constrained the unknown contribution to the observed DM from the host ISM/FRB progenitor itself. Out analysis yielded $\langle {\rm DM}^{\rm unk}_{\rm host} \rangle = 69^{+28}_{-19}$ pc cm^{-3} and the total host contribution $\langle {\rm DM}_{\rm host} \rangle = 90^{+29}_{-19}$ pc cm^{-3}.

FLIMFLAM DR2 will refine and probe different CGM models, allowing to constrain also the baryonic fractions in the galactic halos.

Future facilities (4m-class like DESI, WEAVE, as well as 8m-class Subaru PSF and MOONS) will allow to push foreground mapping to higher redshifts, distinguishing between $f_{\rm gas}$ in galaxies, groups and clusters. Potentially also measuring the HeII reionization