The Intergalactic Medium through the lens of Fast Radio Bursts and Hydrodynamic Simulations

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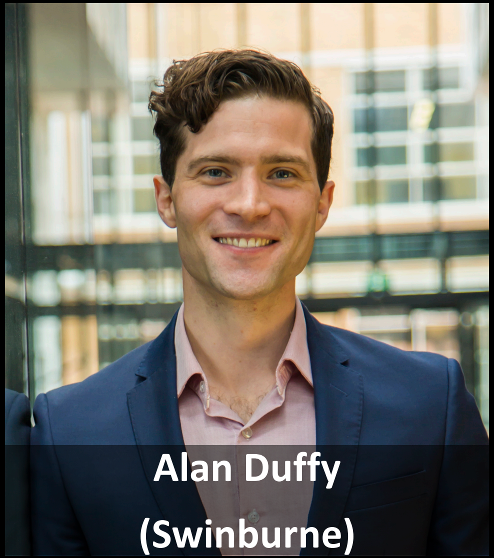
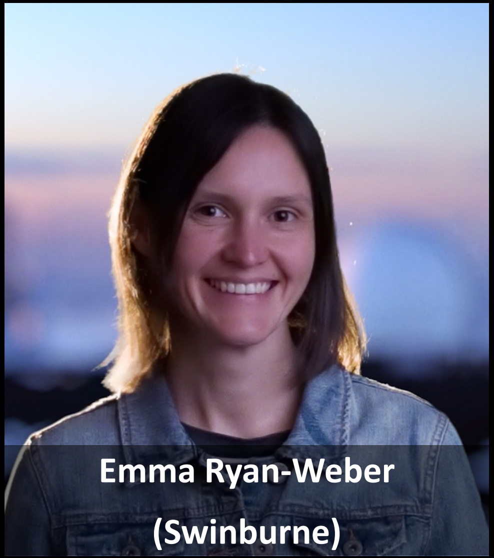
AAAstroseminar (2021-07-30)


Alan Duffy
(Swinburne)


Emma Ryan-Weber
(Swinburne)


Nastasha Wijers
(Leiden)


Vivek Gupta
(Swinburne)


Chris Flynn
(Swinburne)

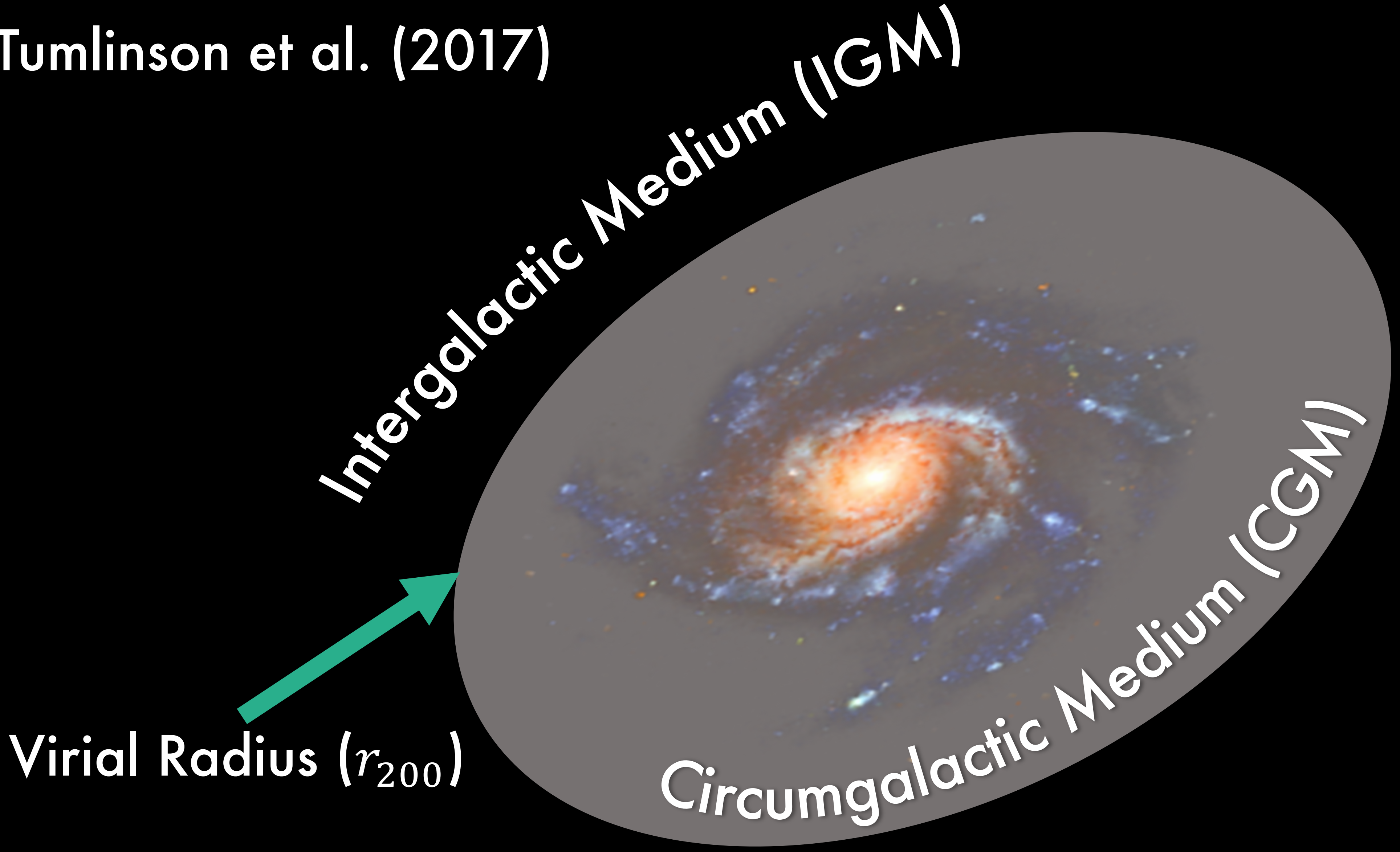

Joop Schaye
(Leiden)


Adam Batten
(Swinburne University of Technology)

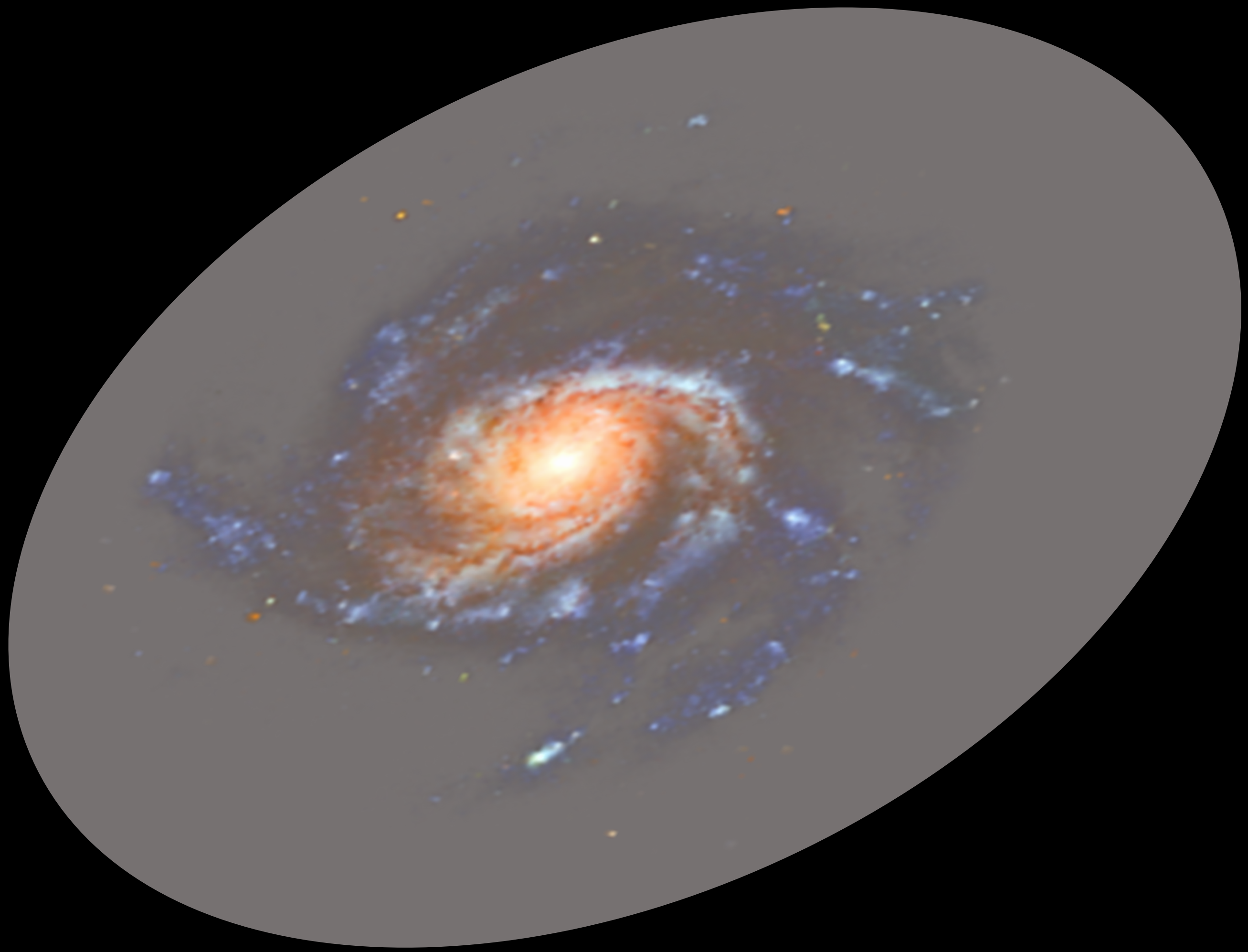
Outline

- Why do we care about the intergalactic medium?
- The trouble with observing the intergalactic medium.
- What are fast radio bursts and how do they help?
- The Dispersion Measure - Redshift Relation
- The EAGLE simulations
- The Dispersion measure – redshift Relation in EAGLE (Batten+2021)
- Fast radio bursts as a probe for galaxy feedback (Batten+ in prep)
- New Project: Metallicity of the IGM between $3 < z < 7$ (Metal Bubbles)

Tumlinson et al. (2017)



Shull et al. (2012)



1. The IGM contains most of the baryonic matter

Shull et al. (2012)

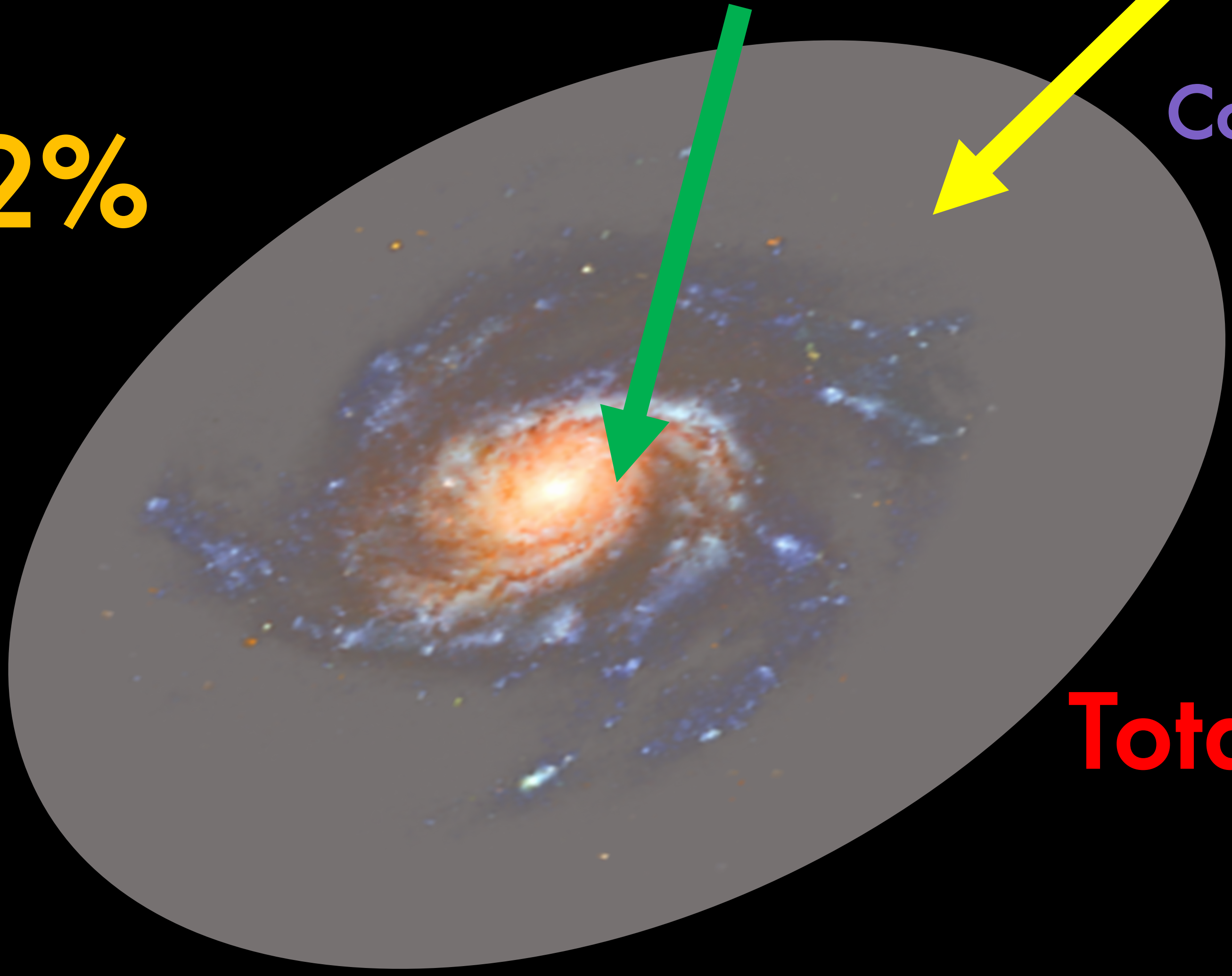
IGM ~ 82%

Galaxies ~ 7%

CGM ~ 5%

Cold Gas ~ 2%

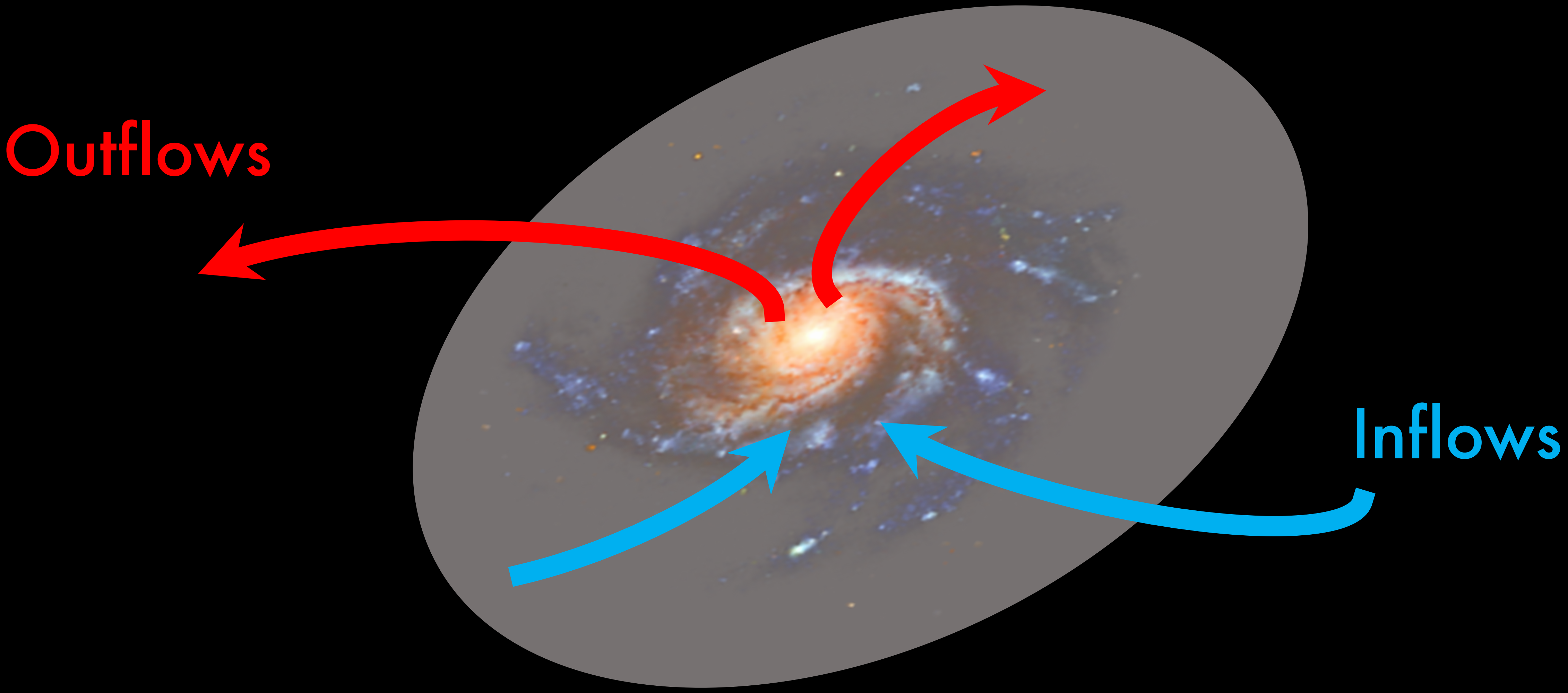
ICM ~ 4%



Total ~ 18%

1. The IGM contains most of the baryonic matter

2. Galaxies and the IGM evolve together



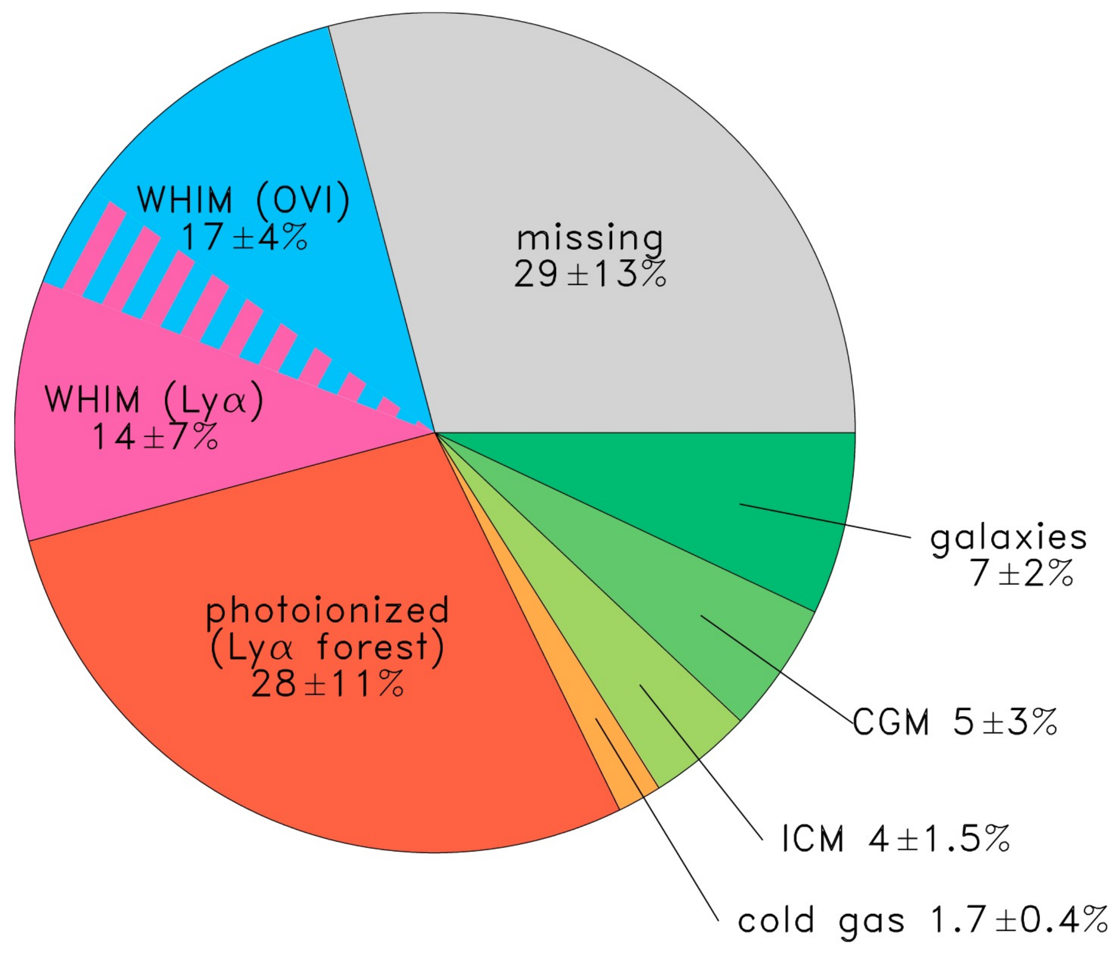
2. Galaxies and the IGM evolve together

Problems Observing the Intergalactic Medium

- Density ~ 1 particle per cubic meter
  - $n_H \sim 10^{-6} - 10^{-7}\ \mathrm{cm}^{-3}$
- Temperature ~ 10^6 K

➽ Lack of favourable UV/Optical transition lines. Hard to observe!!!

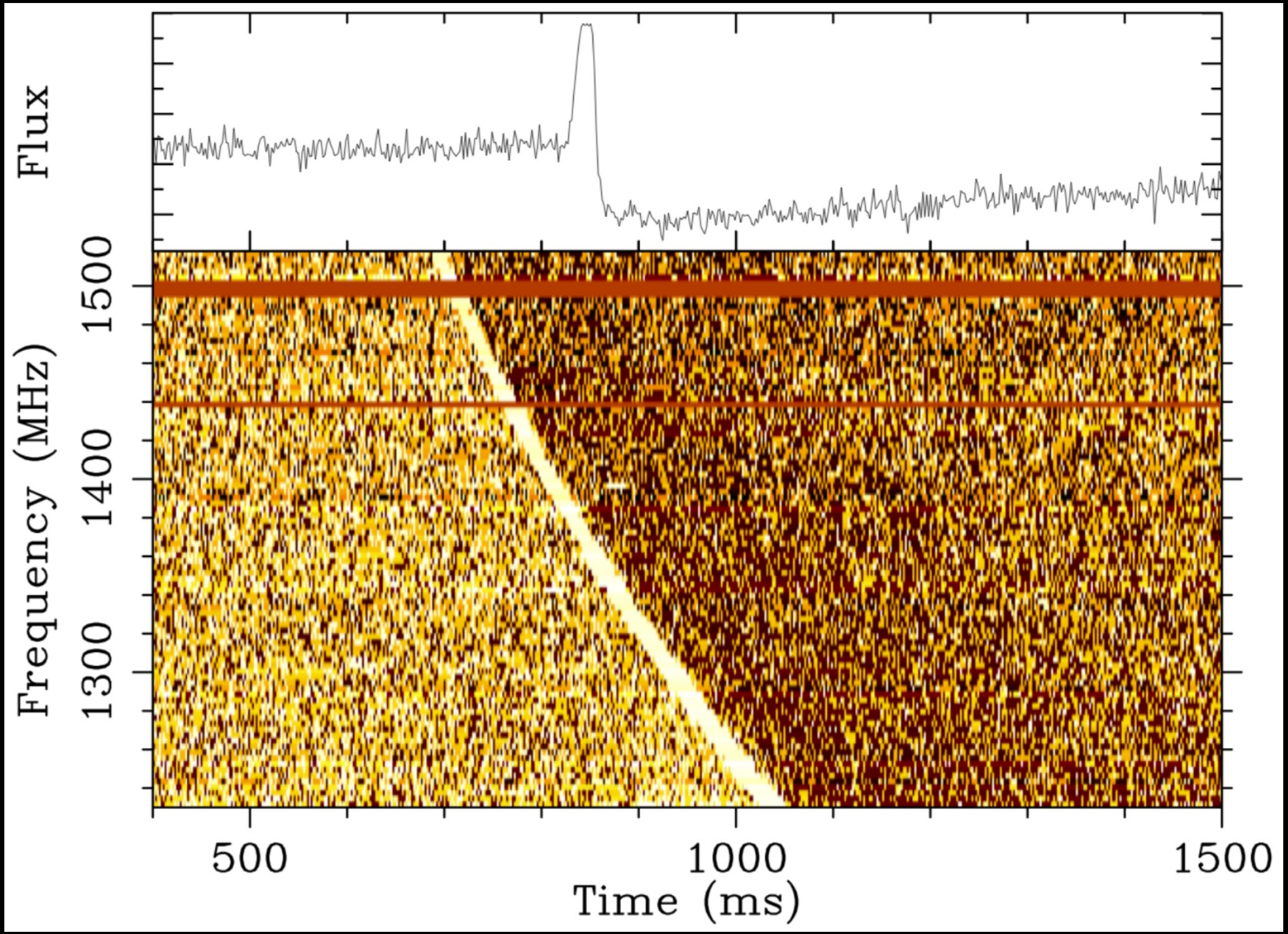
The Missing Baryon Problem:
~ 30% of baryons at low redshift appear to be missing!



Shull et al. (2012)

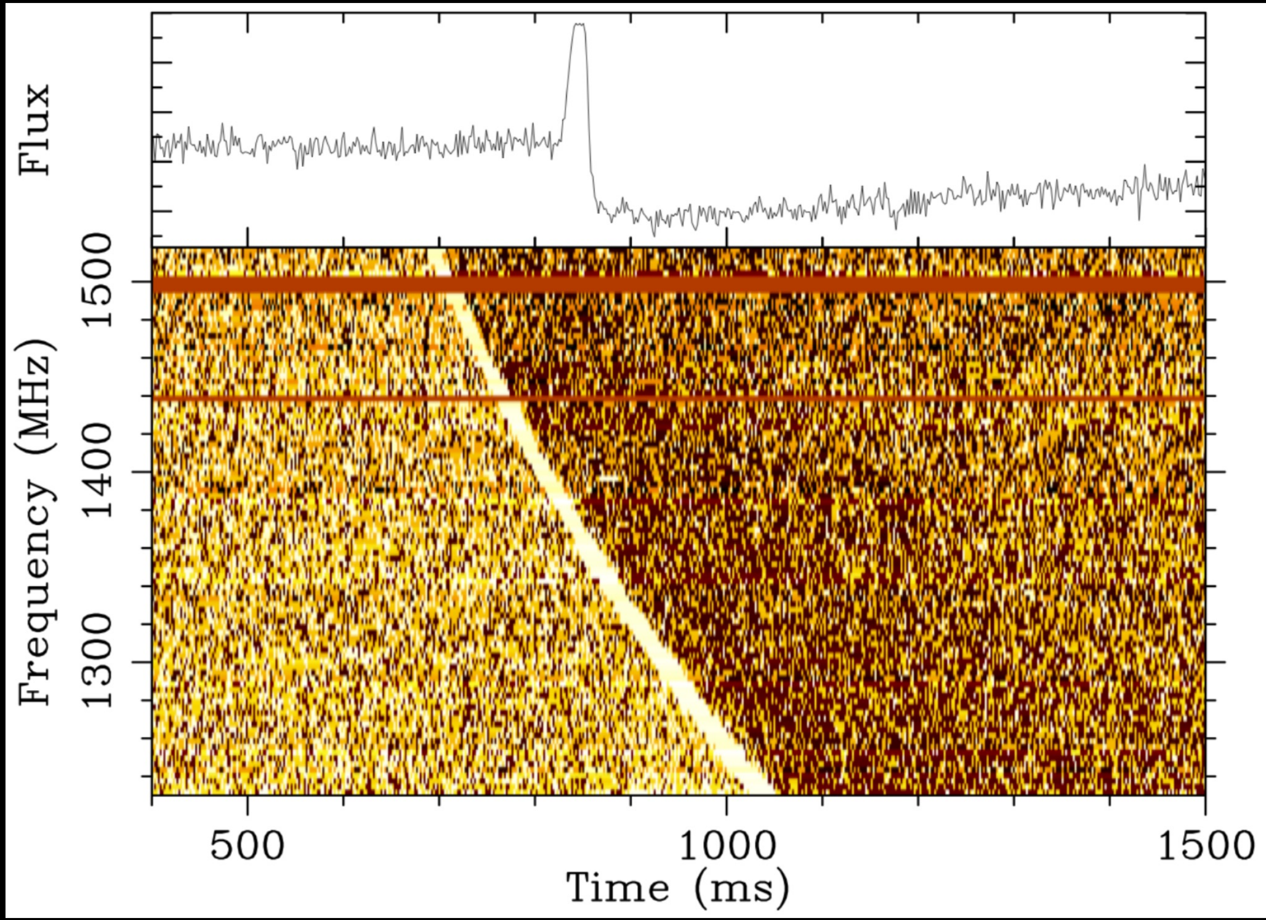
Lorimer et al. (2007)
Petroff et al. (2019)

Fast Radio Bursts (FRBs)



Lorimer et al. (2007)
Petroff et al. (2019)

Fast Radio Bursts (FRBs)



Constant

Electron number density

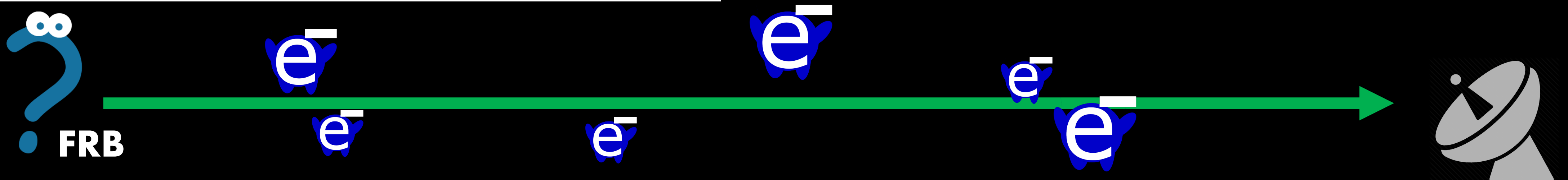
$$t = k\nu^{-2}\int_0^d n_e\, dl$$

Frequency

$$\boxed{\mathrm{DM} = \int_0^d \frac{n_e}{1+z}\, dl}$$

DM = Dispersion Measure

Not Dark Matter



$$\mathrm{DM} = \mathrm{DM}_{\mathrm{MW}} + \mathrm{DM}_{\mathrm{cosmic}}(\mathrm{z}) + \frac{\mathrm{DM}_{\mathrm{Host}}}{1+\mathrm{z}}$$

Milky Way

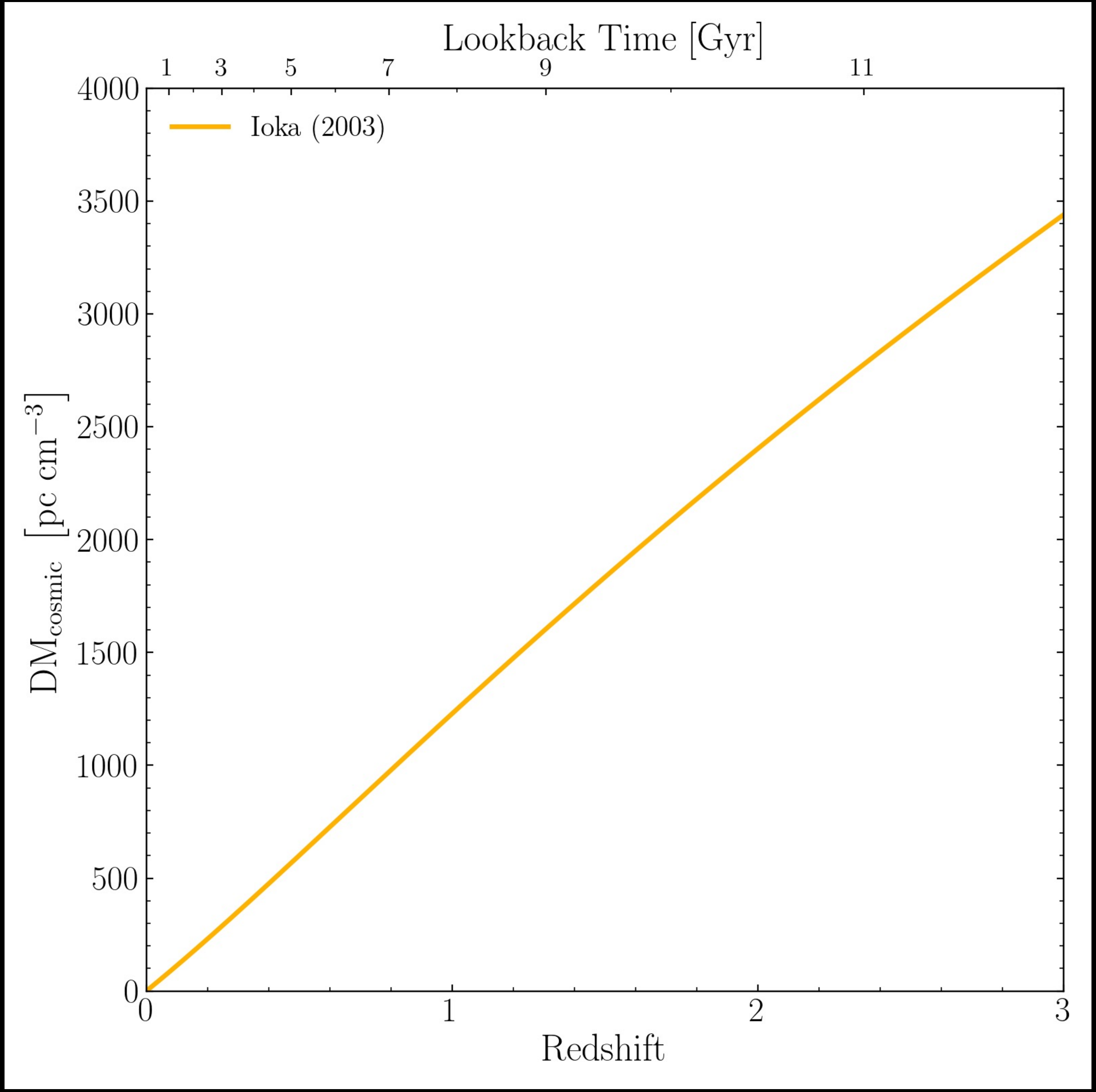
Host Galaxy/Local Environment

$$\mathrm{DM} = \mathrm{DM}_{\mathrm{MW}} + \mathrm{DM}_{\mathrm{cosmic}}(z) + \frac{\mathrm{DM}_{\mathrm{Host}}}{1+z}$$

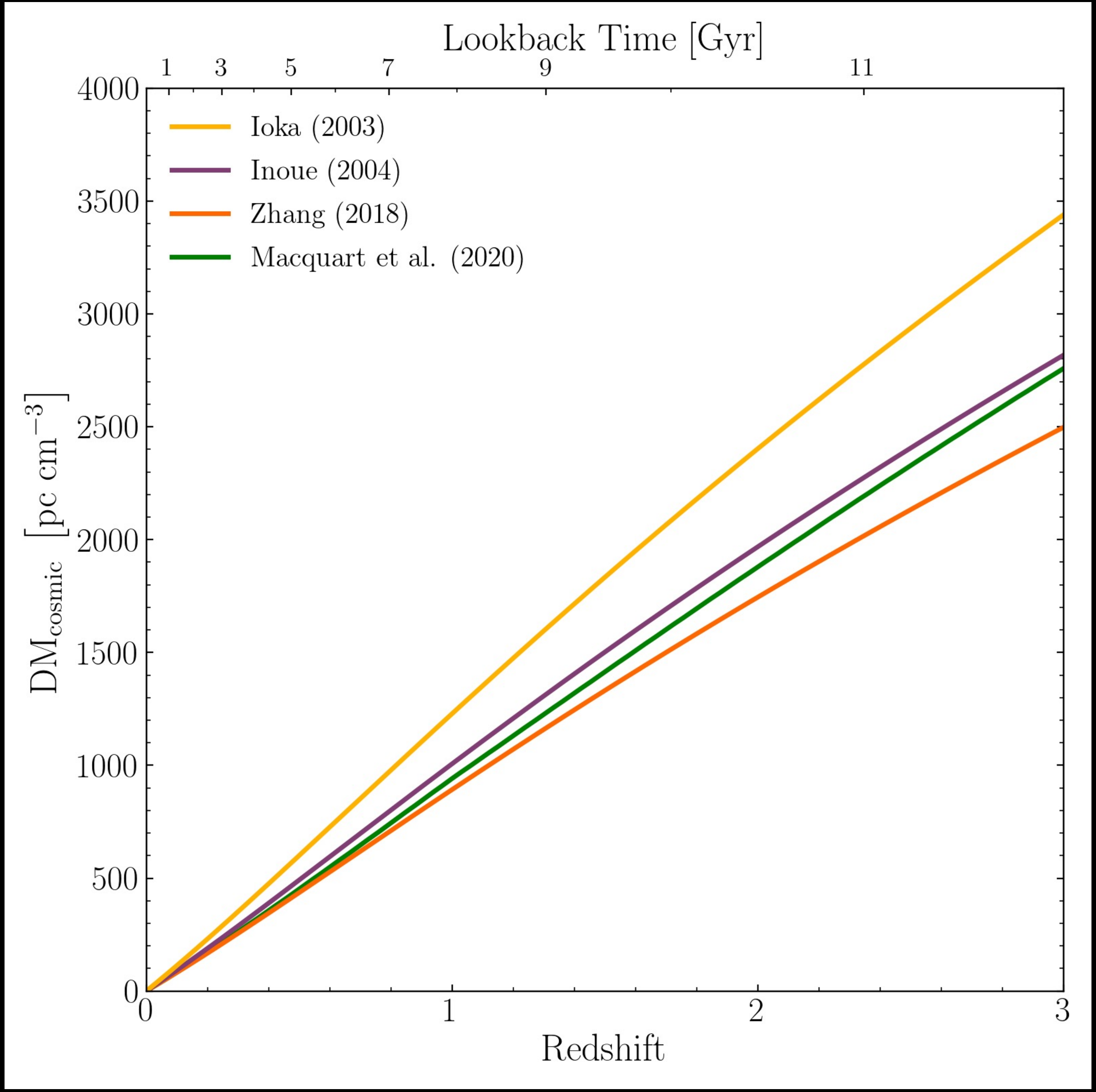
$$\mathrm{DM}_{\mathrm{cosmic}}(z) = \mathrm{DM}_{\mathrm{IGM}}(z) + \mathrm{DM}_{\mathrm{CGM,Interlopers}}$$

Intergalactic Medium

The CGM of Galaxies along the line-of-sight



Ioka (2003) [Analytic]

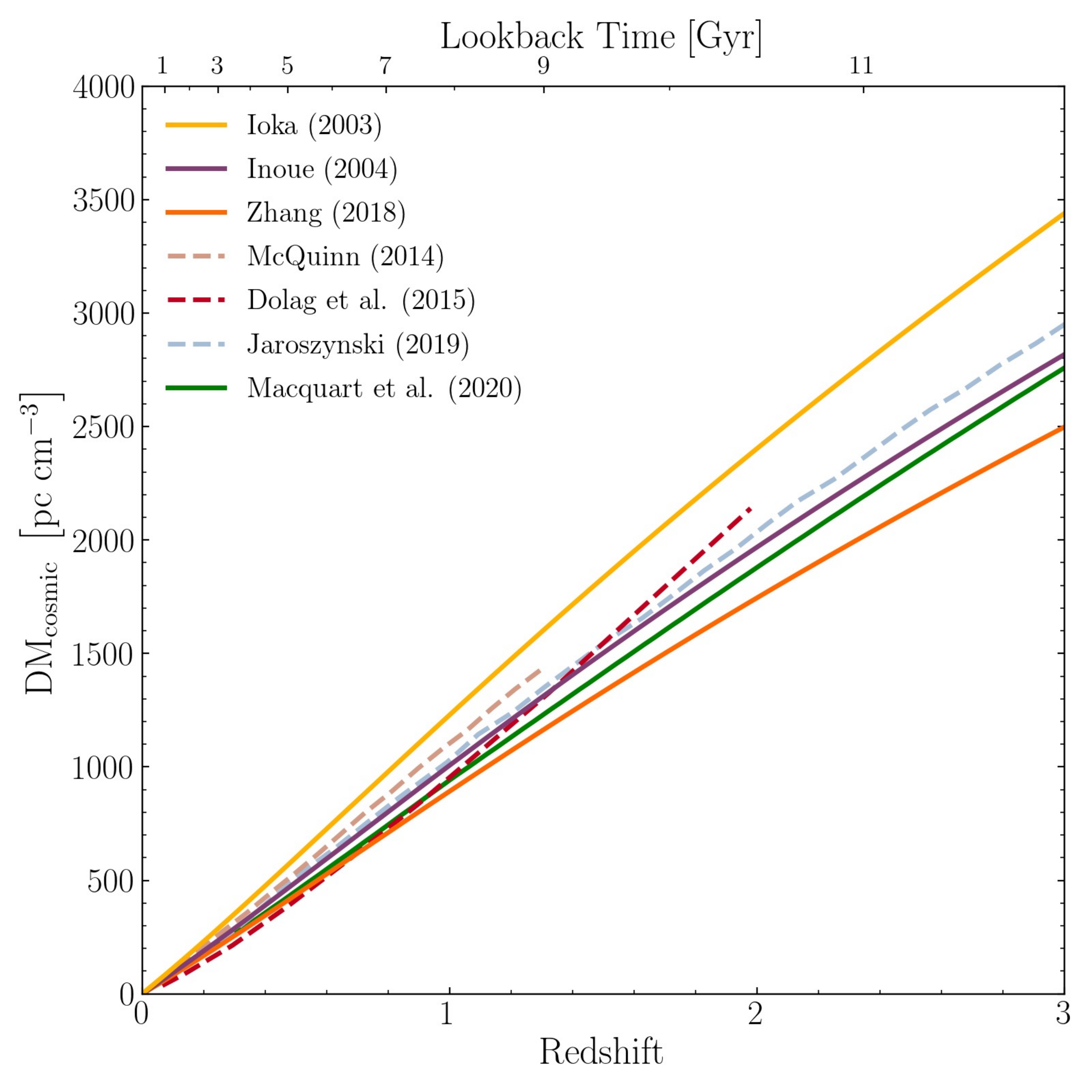


Ioka (2003) [Analytic]

Inoue (2004) [Analytic]

Zhang (2018) [Analytic]

Macquart+(2020) [Analytic]



Ioka (2003) [Analytic]

Inoue (2004) [Analytic]

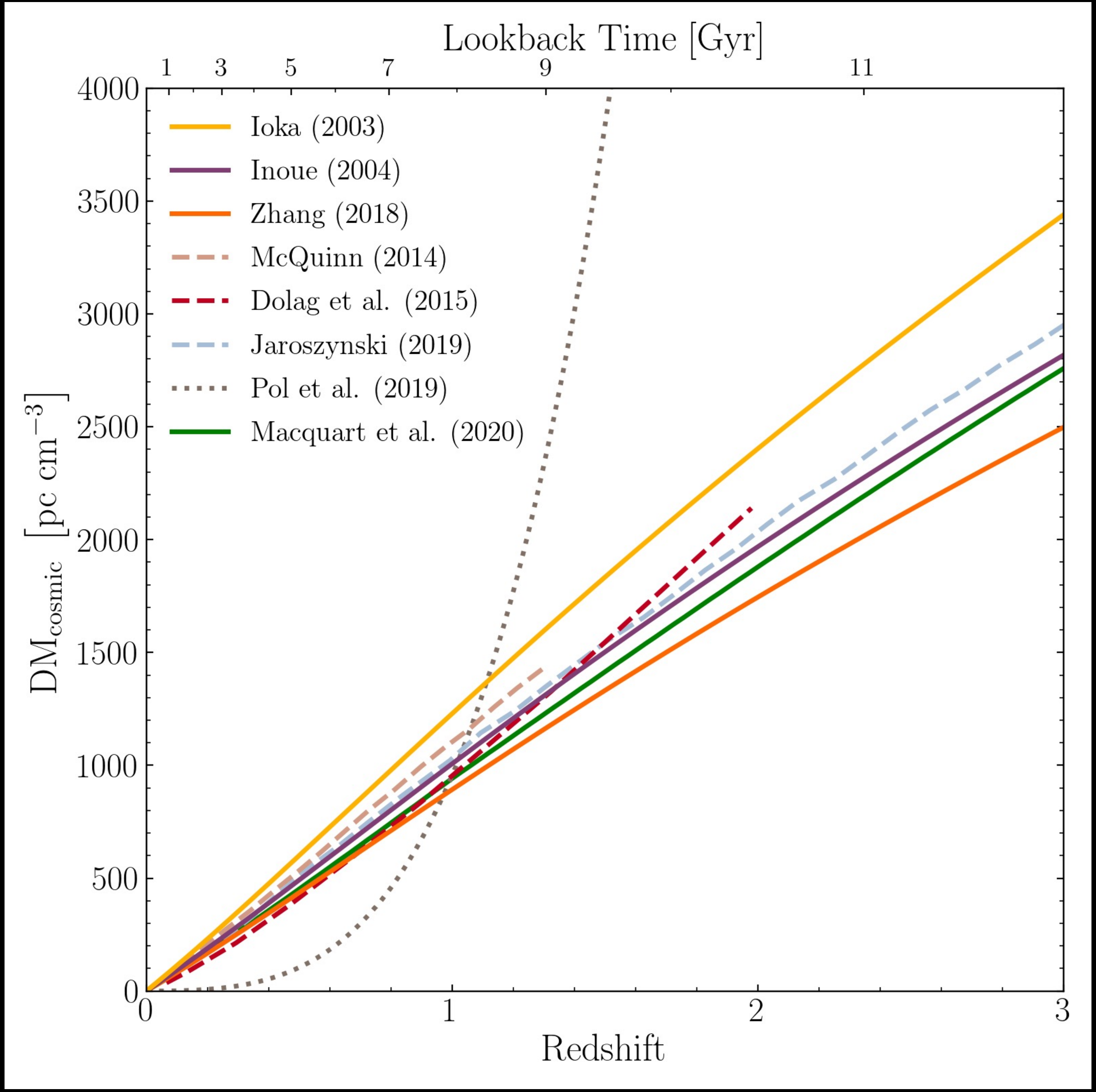
Zhang (2018) [Analytic]

McQuinn (2014) [Analytic+Hydro]

Dolag+(2015) [Hydro; Magneticum]

Jaroszynski (2019) [Hydro; Illustris]

Macquart+(2020) [Analytic]



Ioka (2003) [Analytic]

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Zhang (2018) [Analytic]

McQuinn (2014) [Analytic+Hydro]

Dolag+(2015) [Hydro; Magneticum]

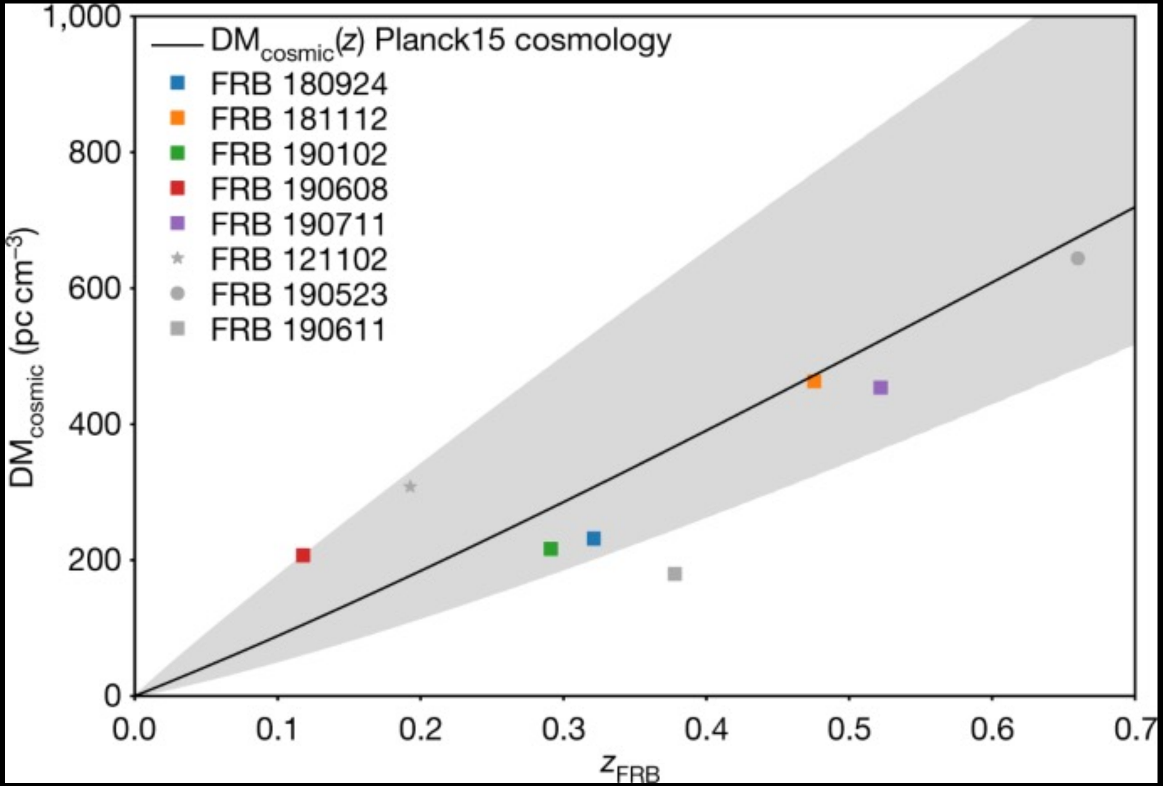
Jaroszynski (2019) [Hydro; Illustris]

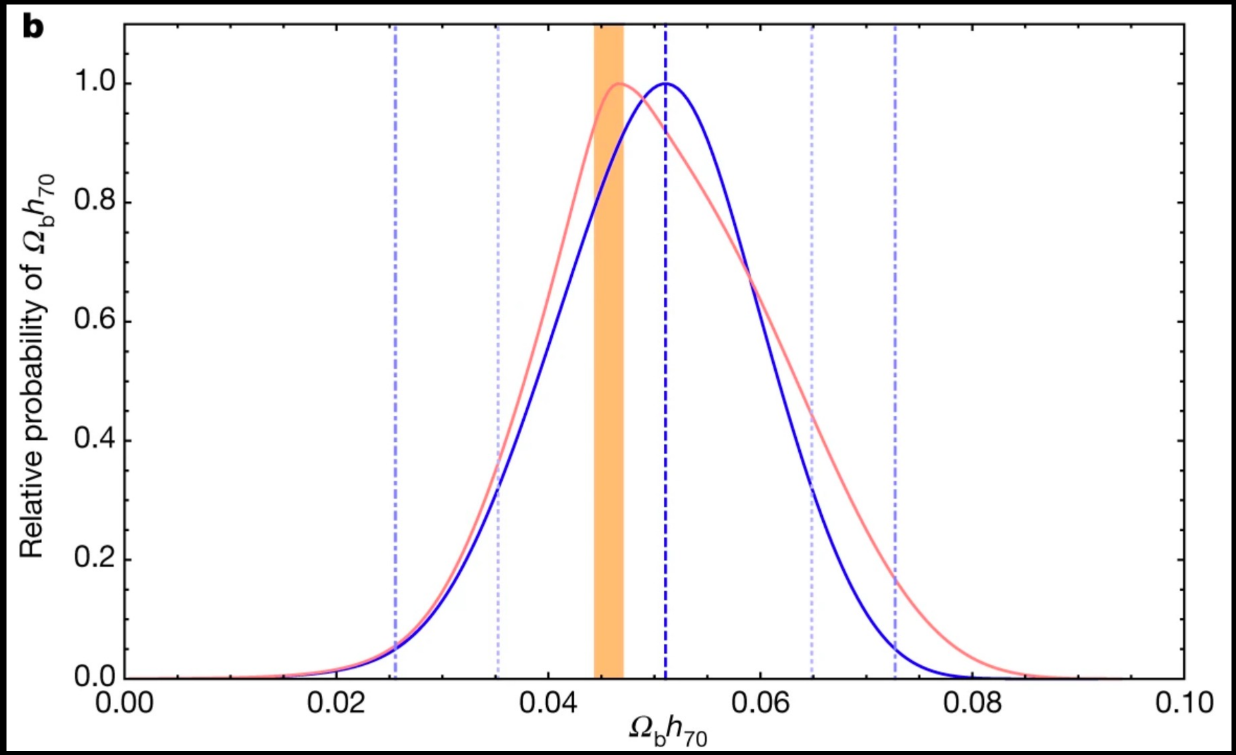
Pol+(2019) ["Semi-Analytic"; MICE]

Macquart+(2020) [Analytic]

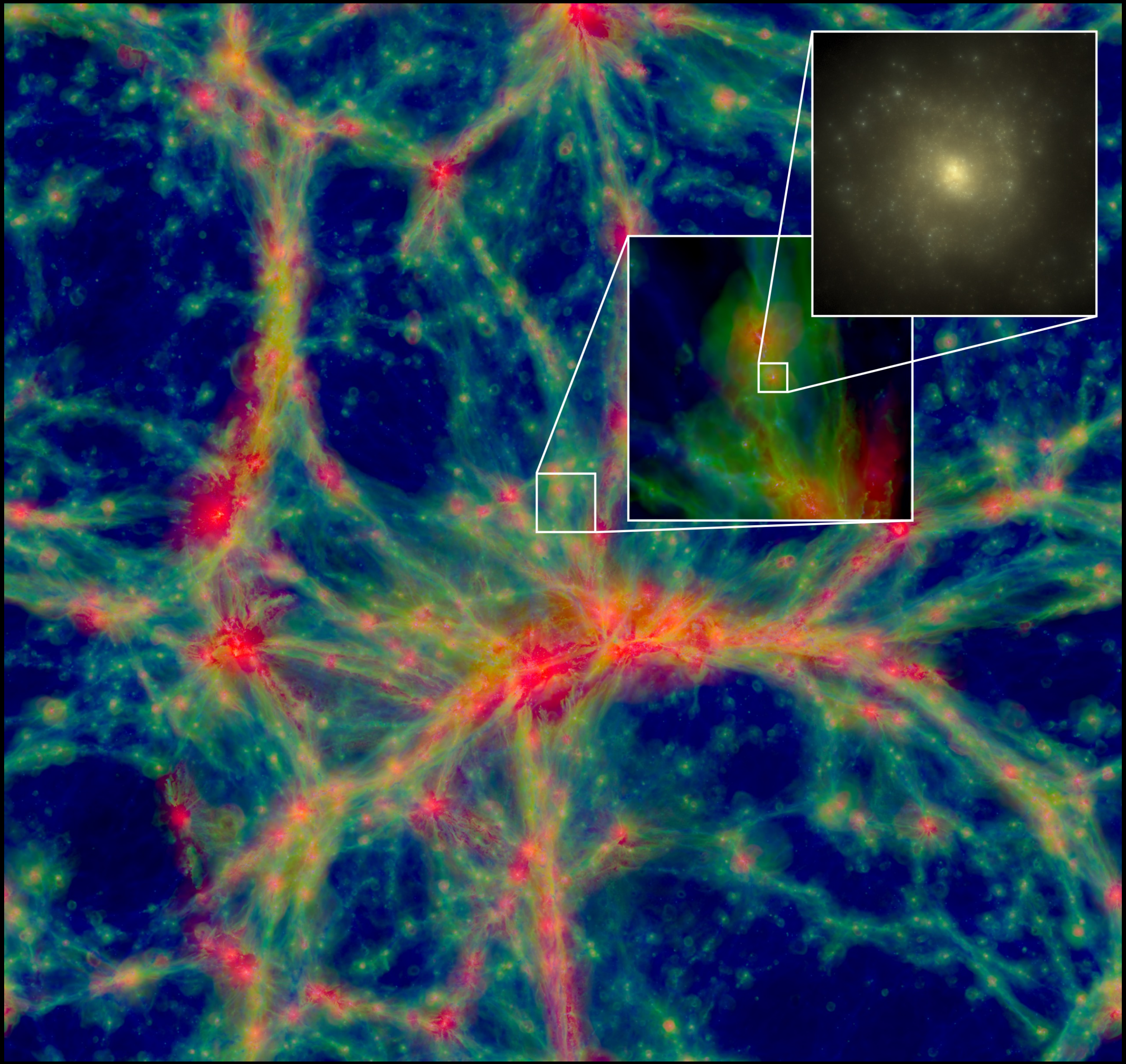
Macquart et al. (2020)

FRBs and the Missing Baryon Problem





Batten+(2021)a



EAGLE Simulations

Schaye et al. (2015), Crain et al (2015)

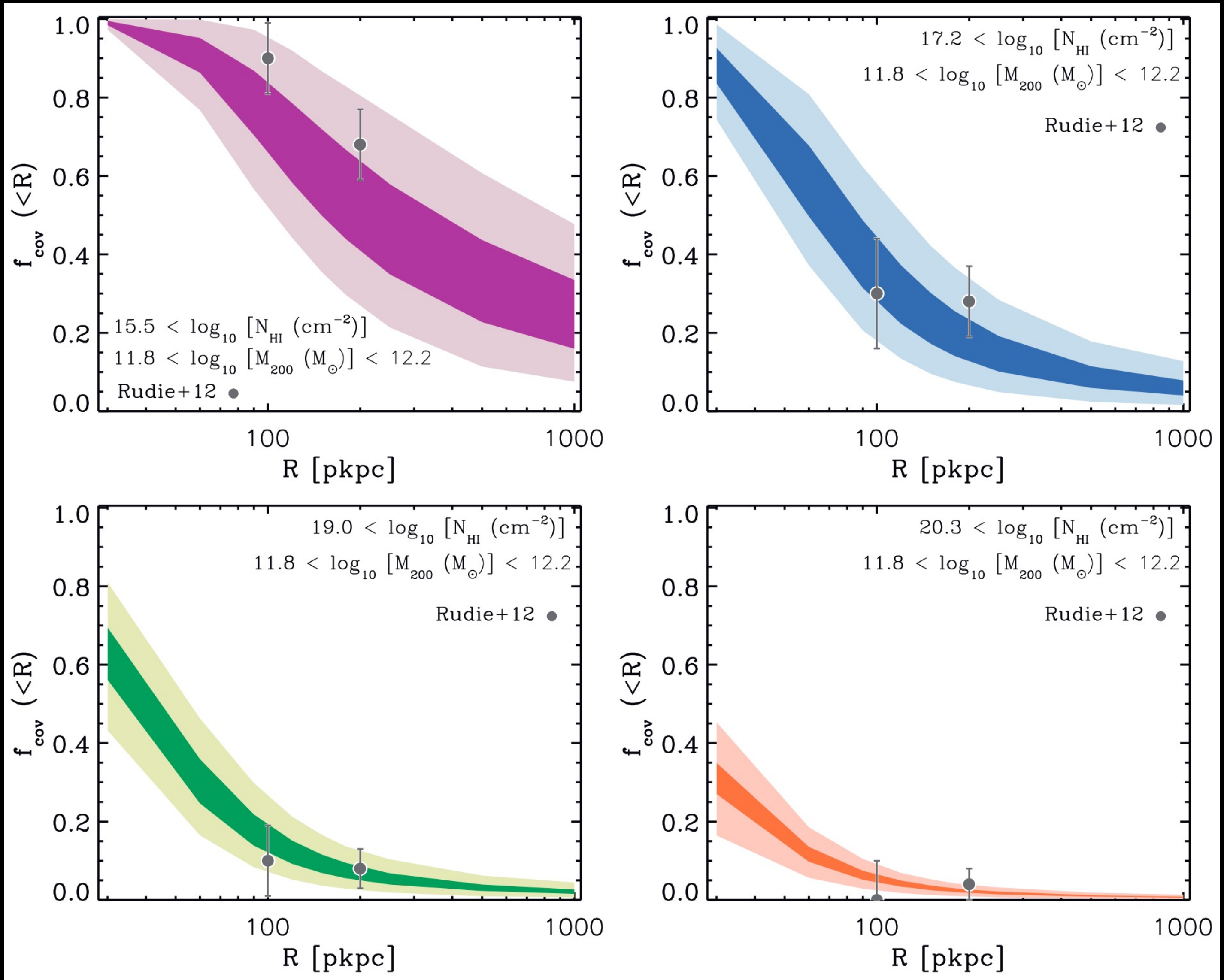
- Hydrodynamics + Nbody
- Large cosmological volume (100 cMpc)
- Redshift range ($z \sim 127$ to $z = 0$)

- Abundances for 11 different elements.
- HM12 UV Ionising Background
- Galactic Winds: Star formation & AGN

- Resolution: $\sim$ 0.7 ckpc
- Particle Masses: $\sim 10^6\ M_\odot$

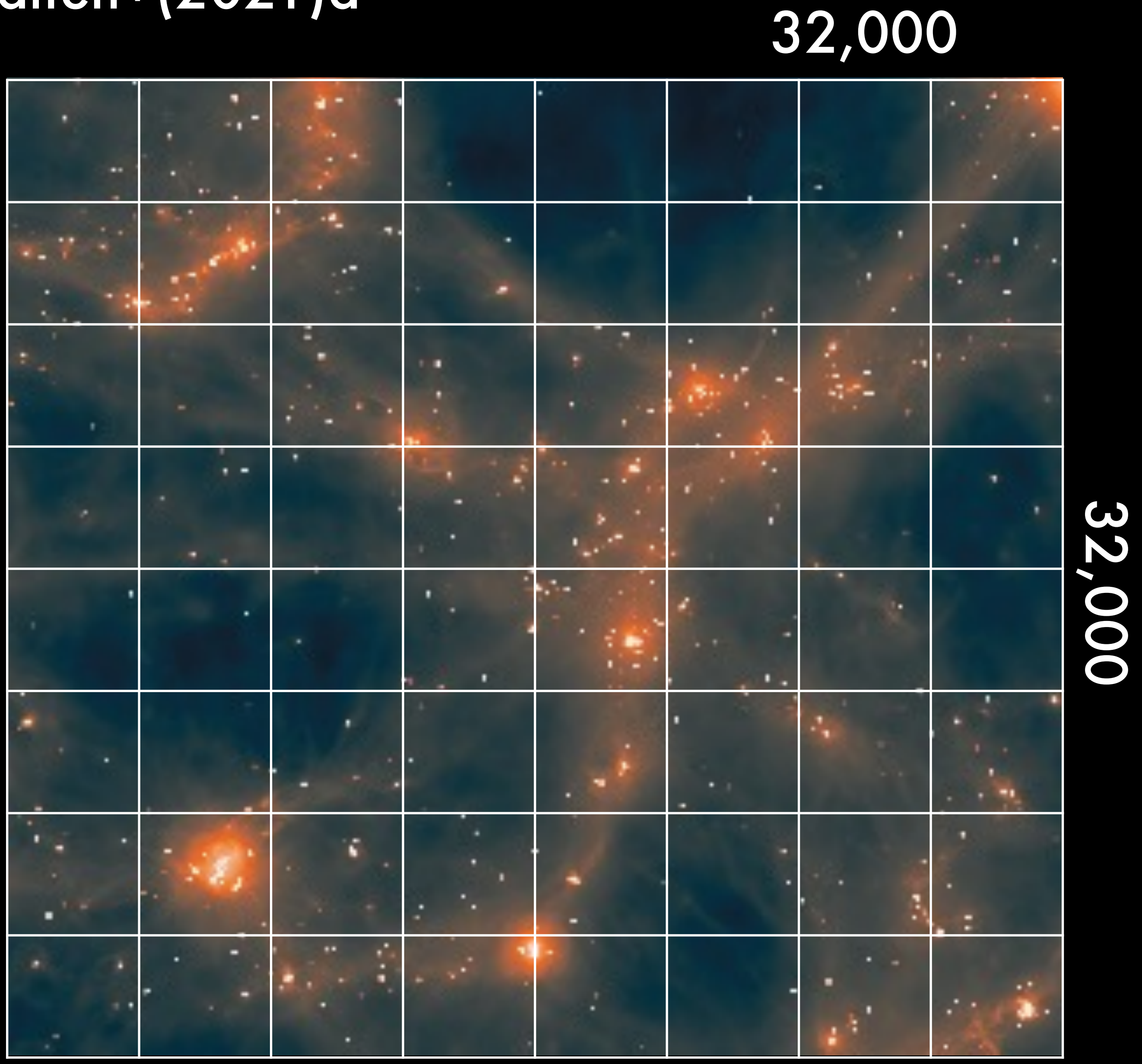
Rahmati et al. (2015)

EAGLE Simulations



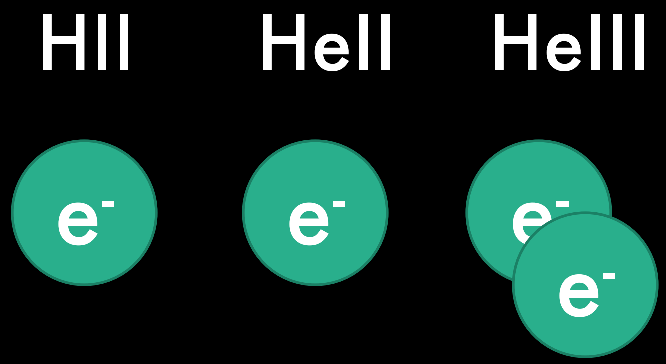
✓ Gets the HI column density distribution correct!

Batten+(2021)a

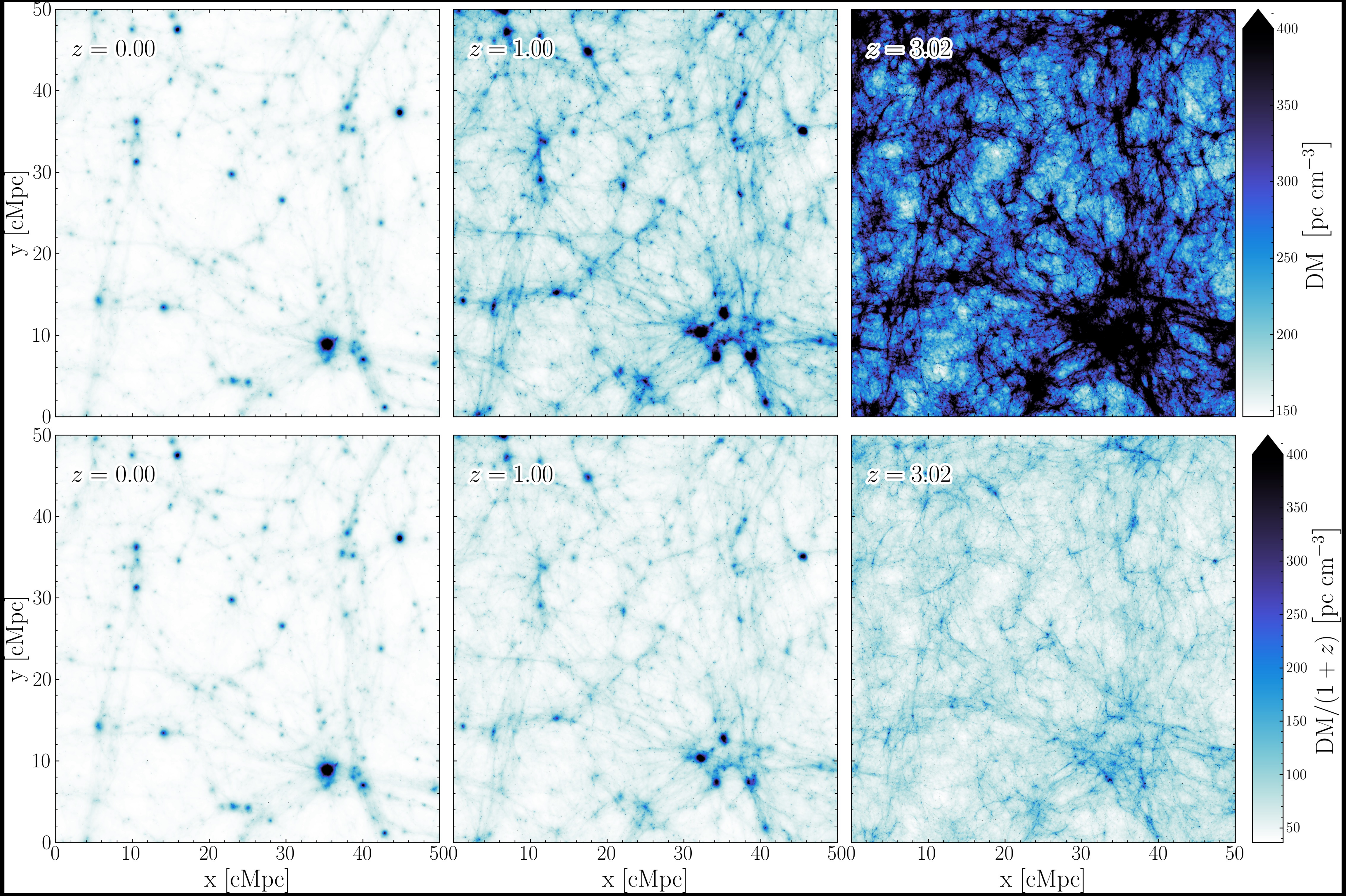


EAGLE Simulations

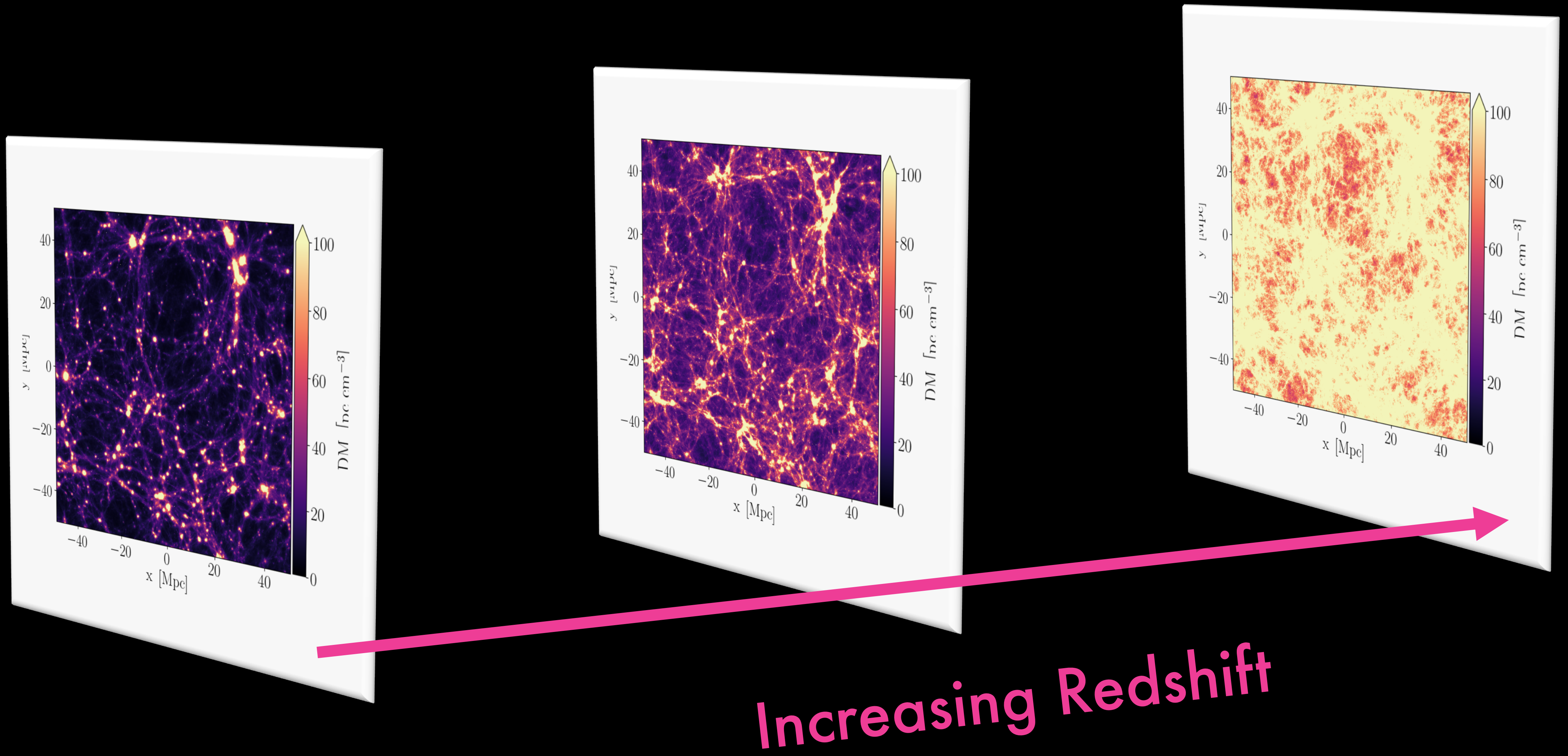
- Divide cube into columns
- Calculate column densities
  - Rahmati et al. (2013) (SS)
  - Wijers et al. (2019)
- Convert column densities to units of pc cm^{-3}



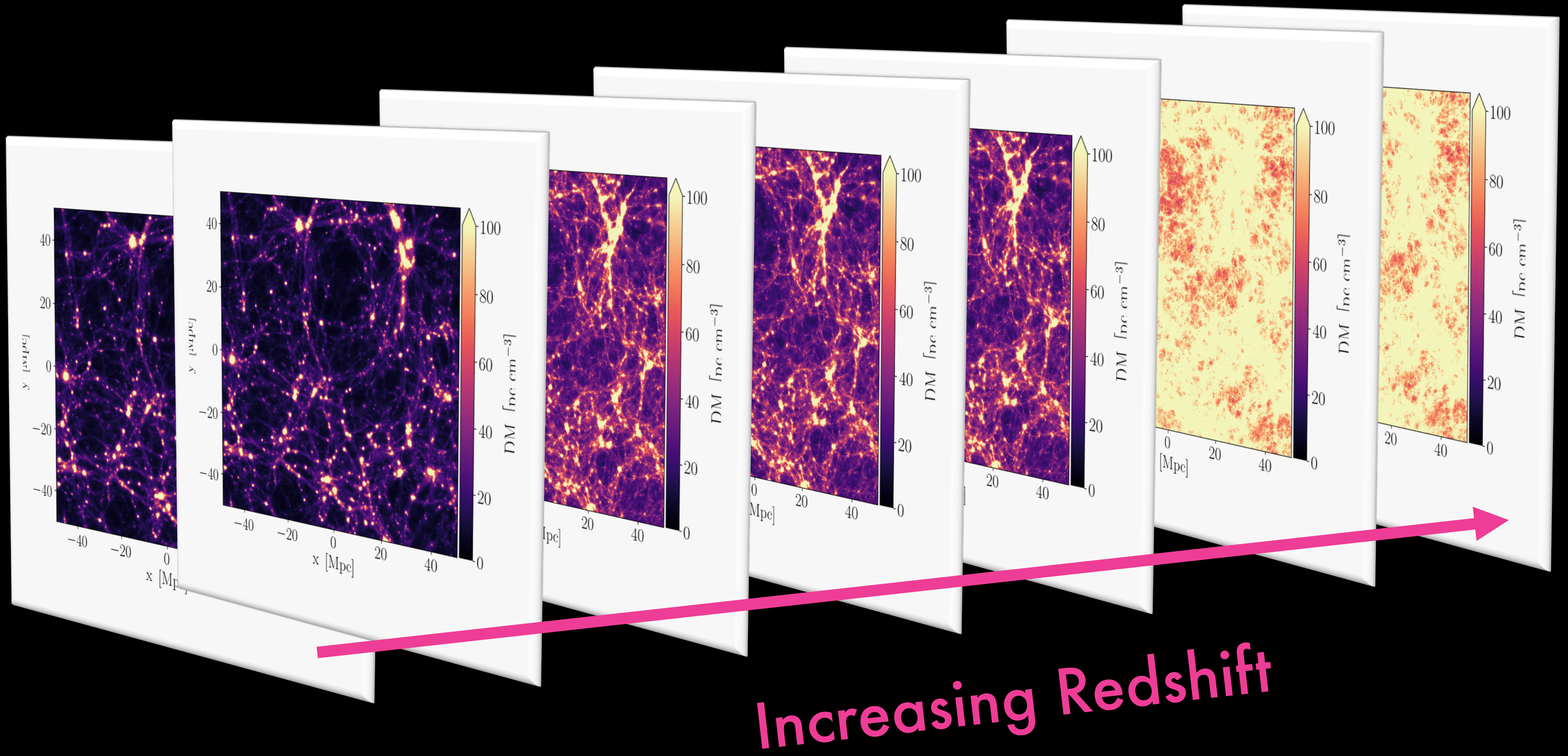
Batten+(2021)a



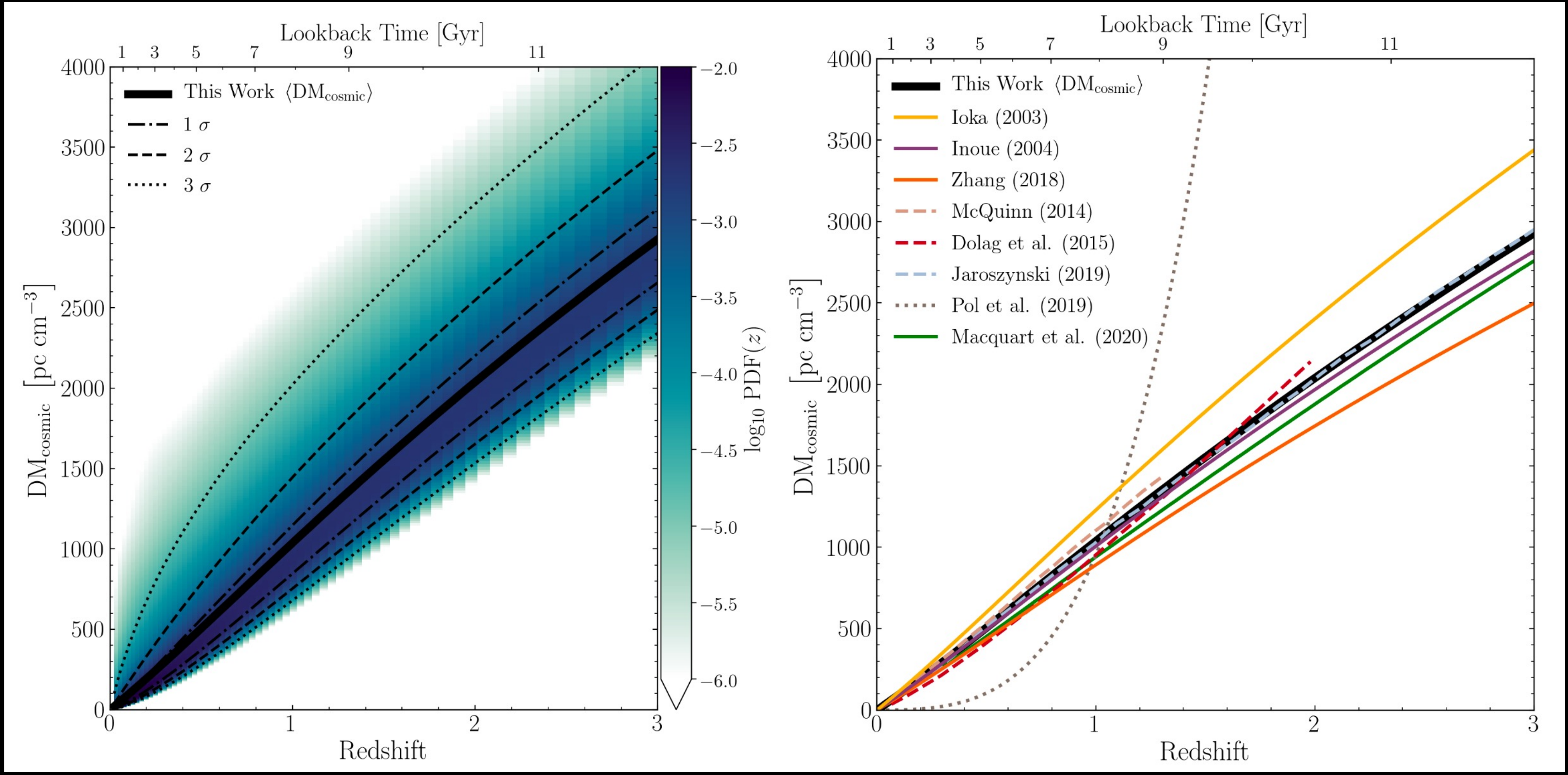
Batten+(2021)a



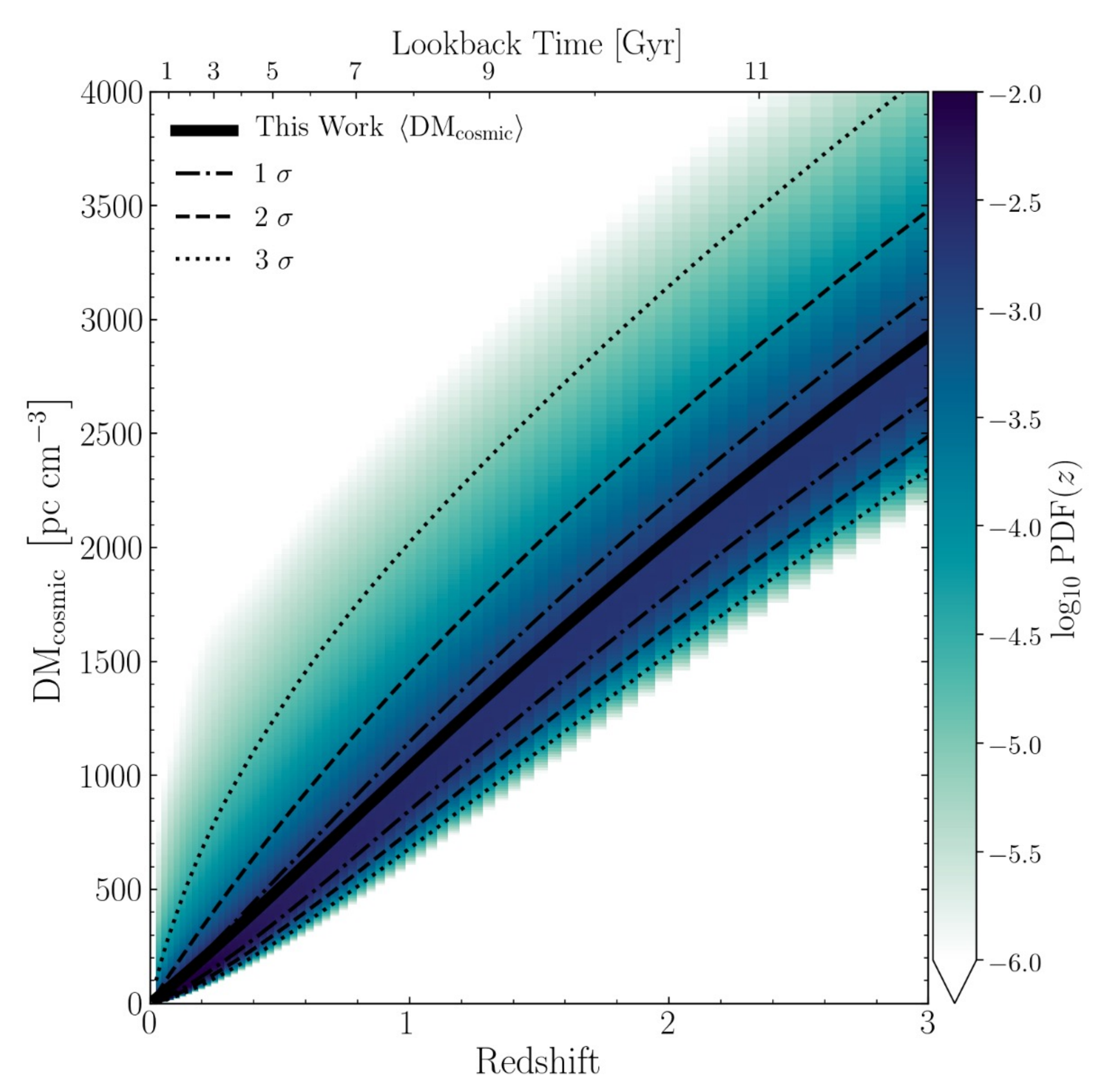
Batten+(2021)a

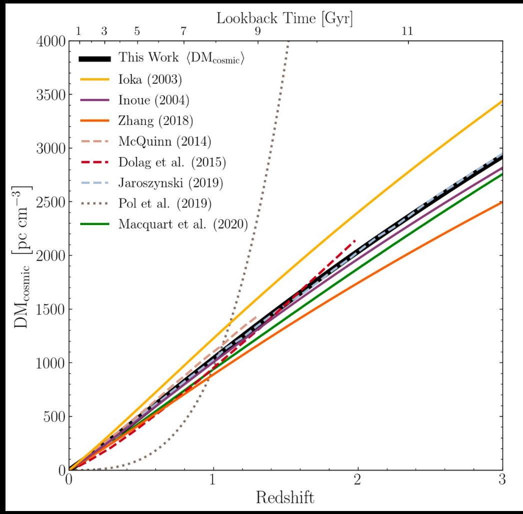


Batten+(2021)a

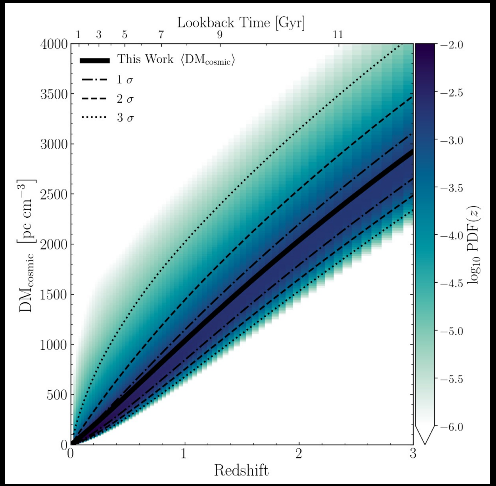


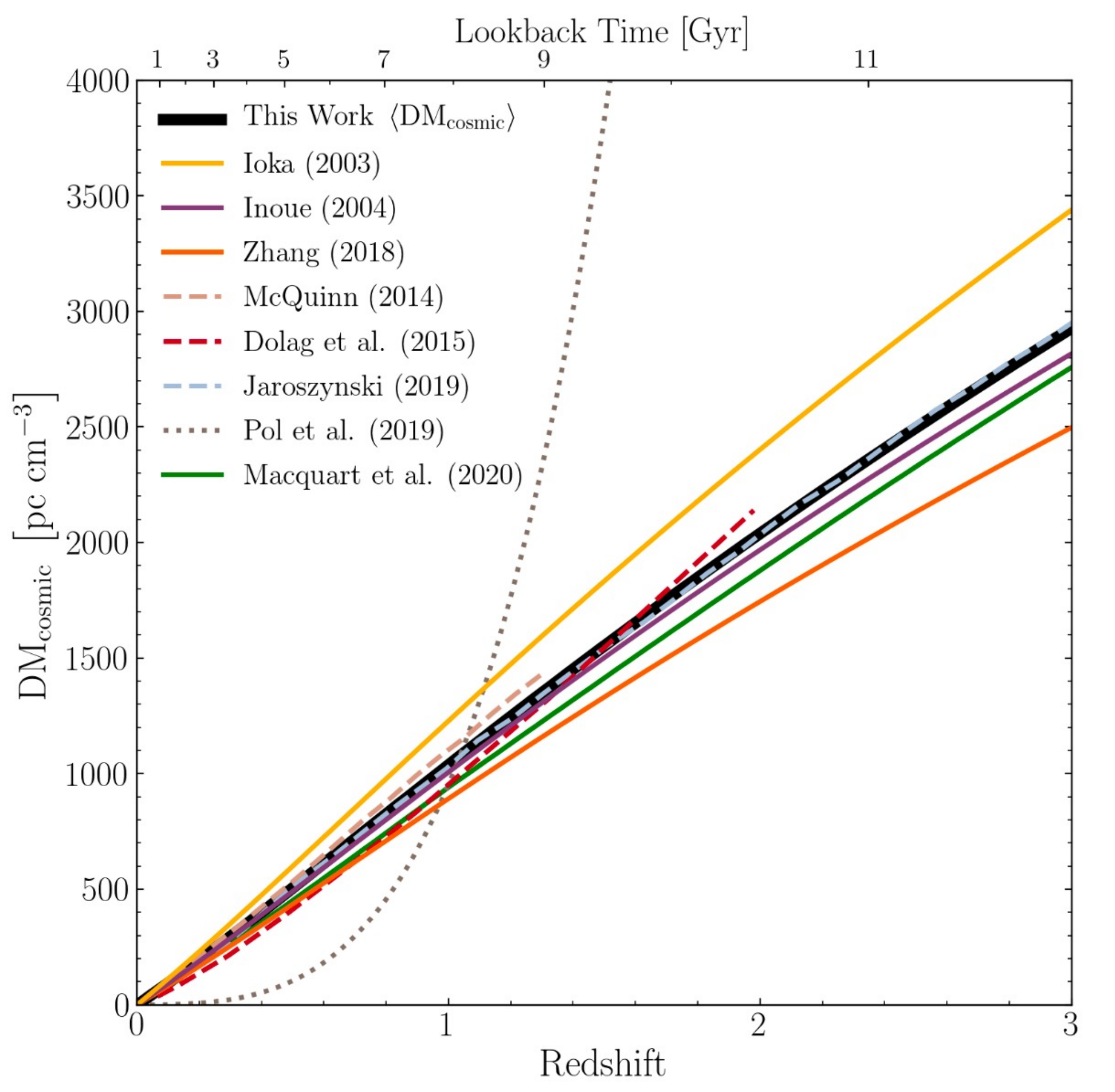
Batten+(2021)a





Batten+(2021)a





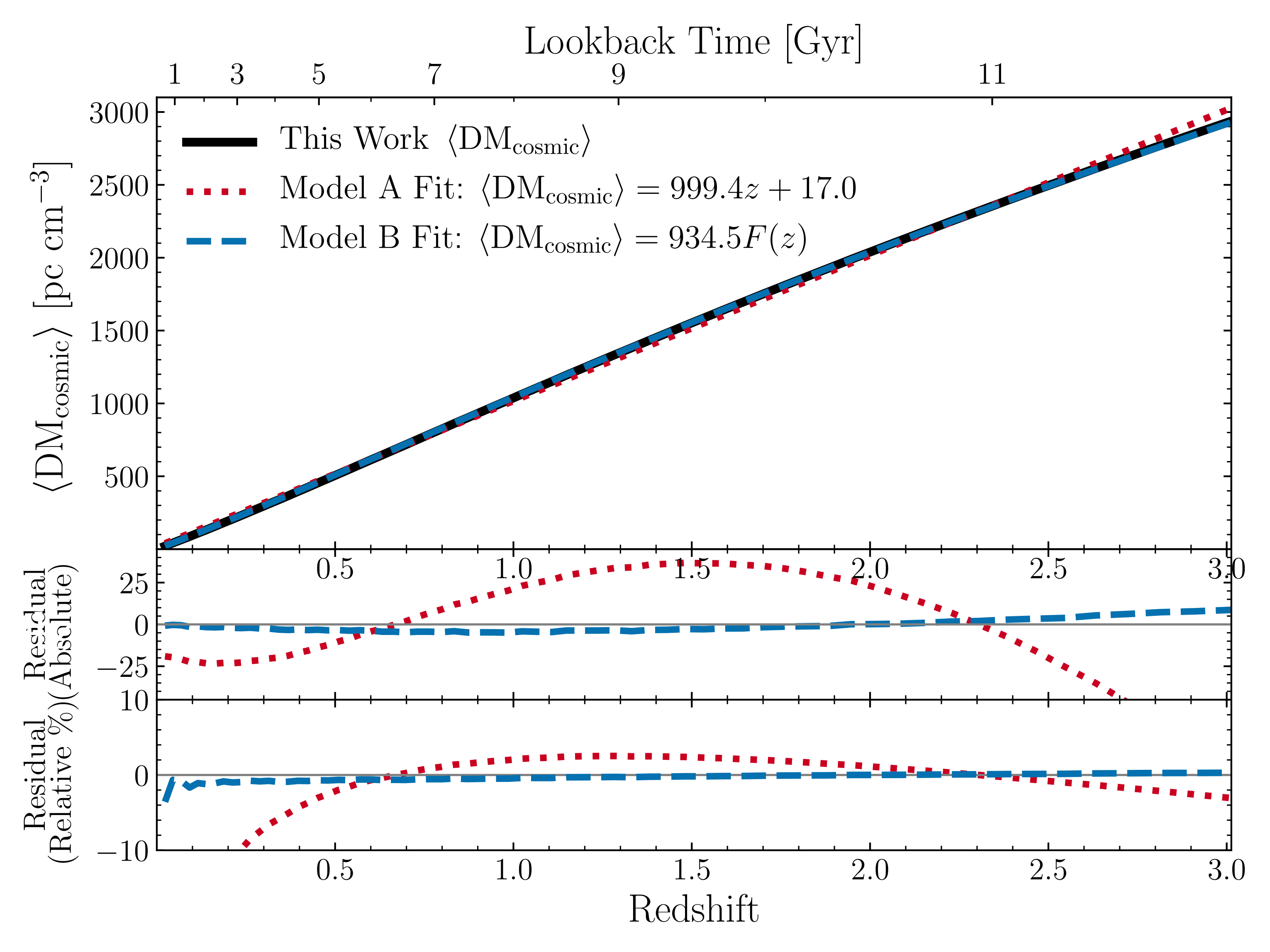
Batten+(2021)a

Model A:

$$\langle \mathrm{DM_{cosmic}} \rangle \propto z$$

Model B:

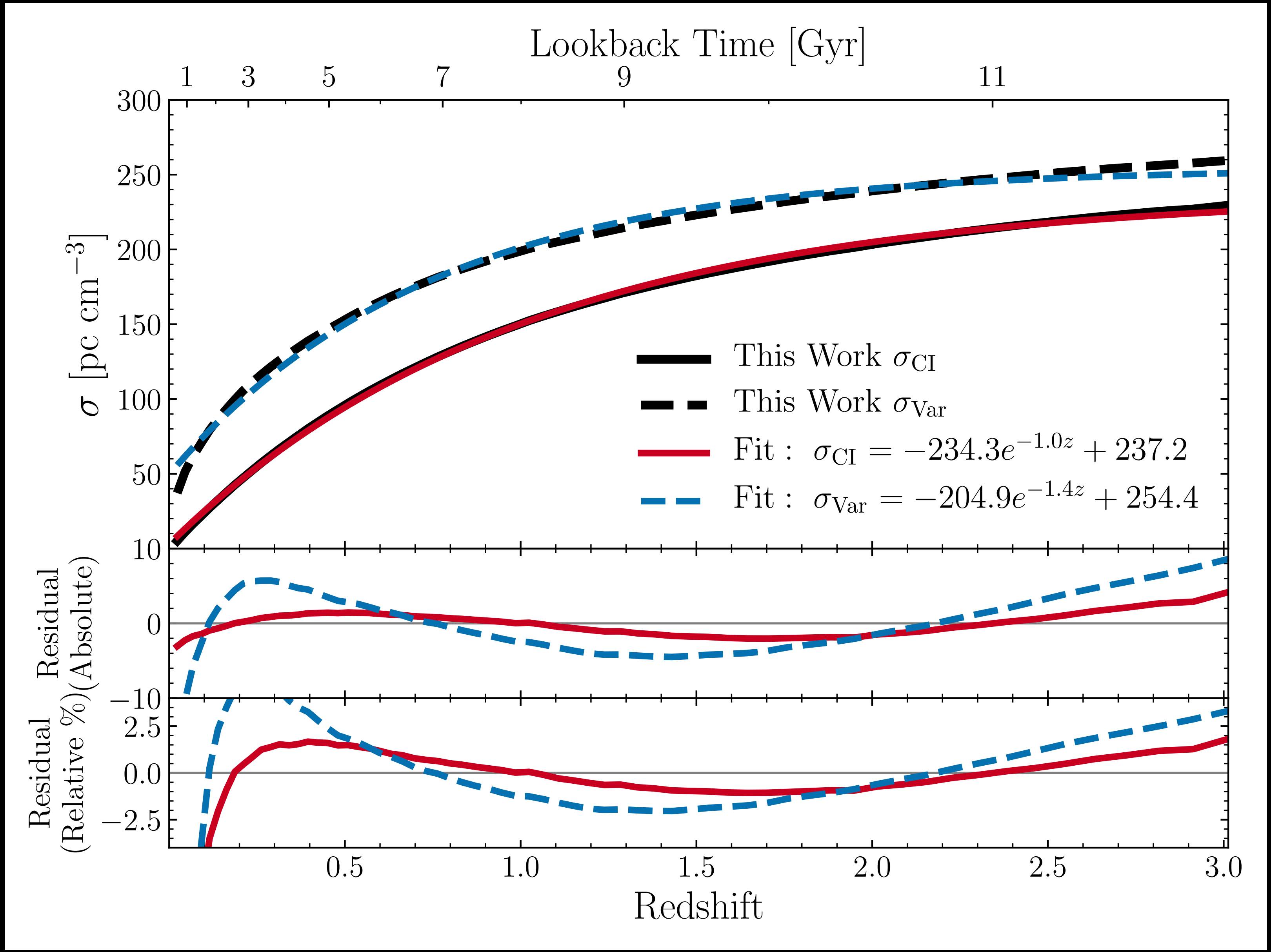
$$\langle \mathrm{DM_{cosmic}} \rangle \propto \int_0^z \frac{1+z}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}$$



Batten+(2021)a

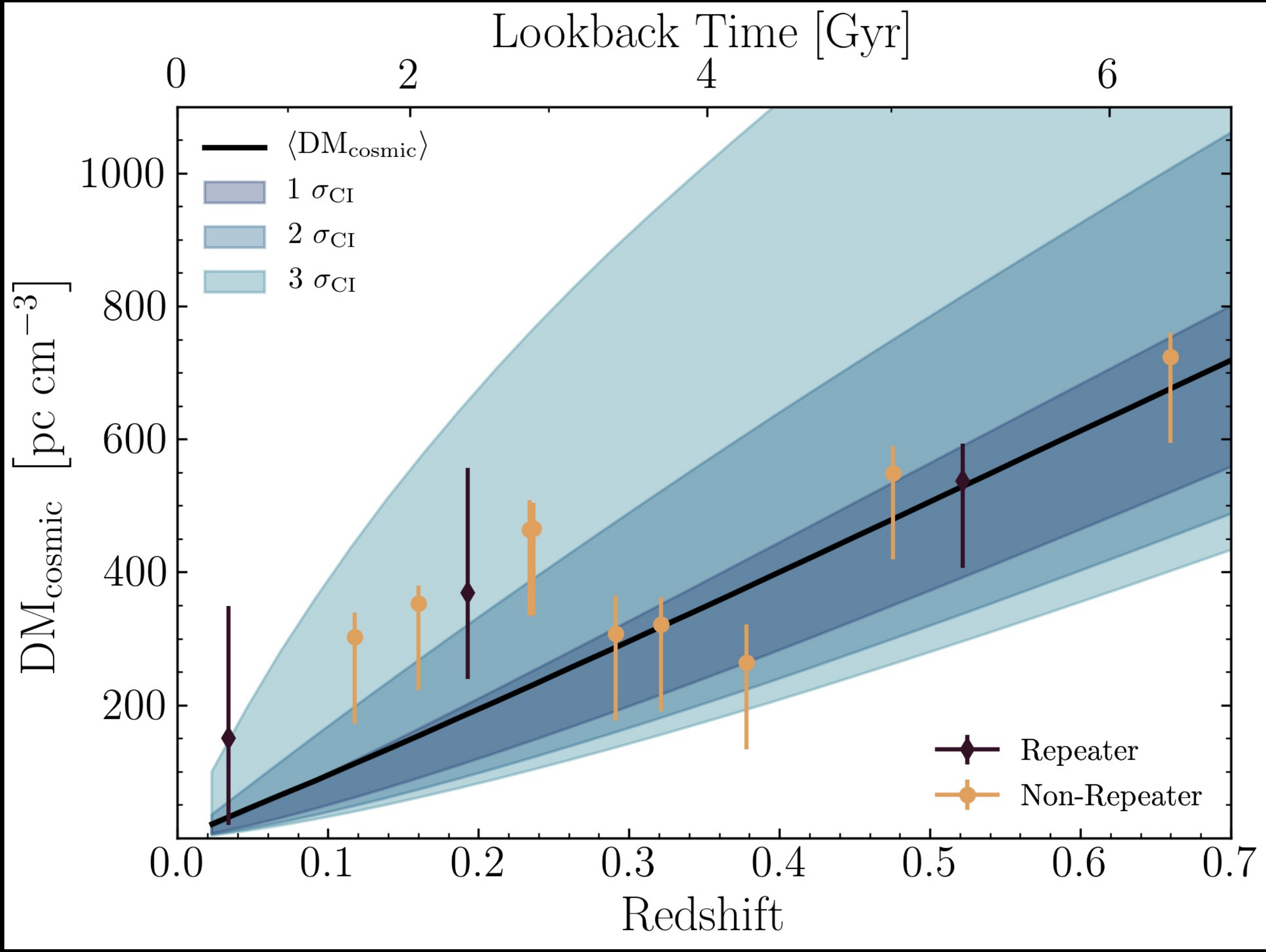
σ_{Var} ~ Variance

σ_{CI} ~ 68% confidence interval



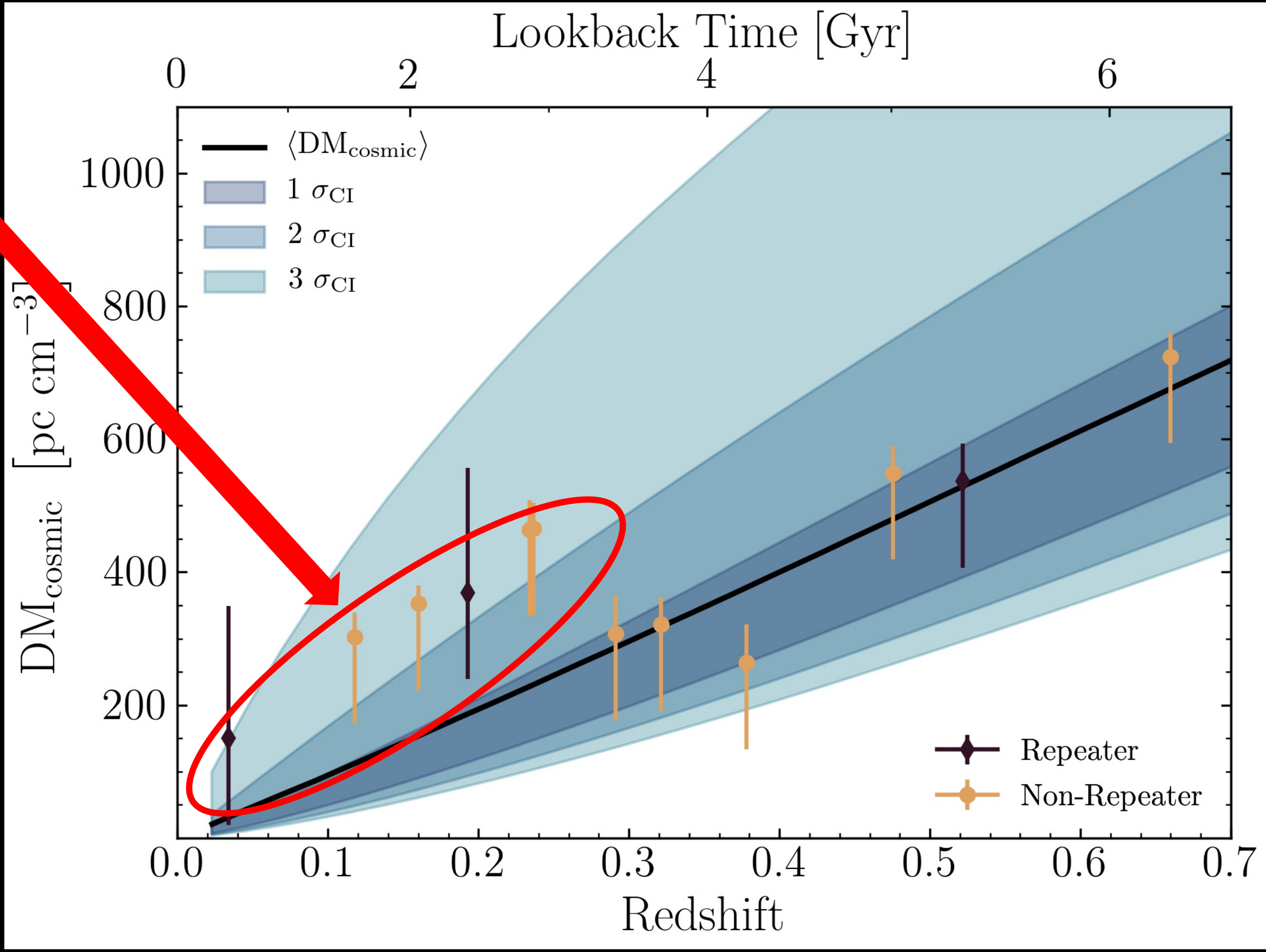
Batten+(2021)a

The $\mathbf{DM_{cosmic}}$ of most FRBs at low redshift appear to be $2-3\sigma$ sigma above the mean.



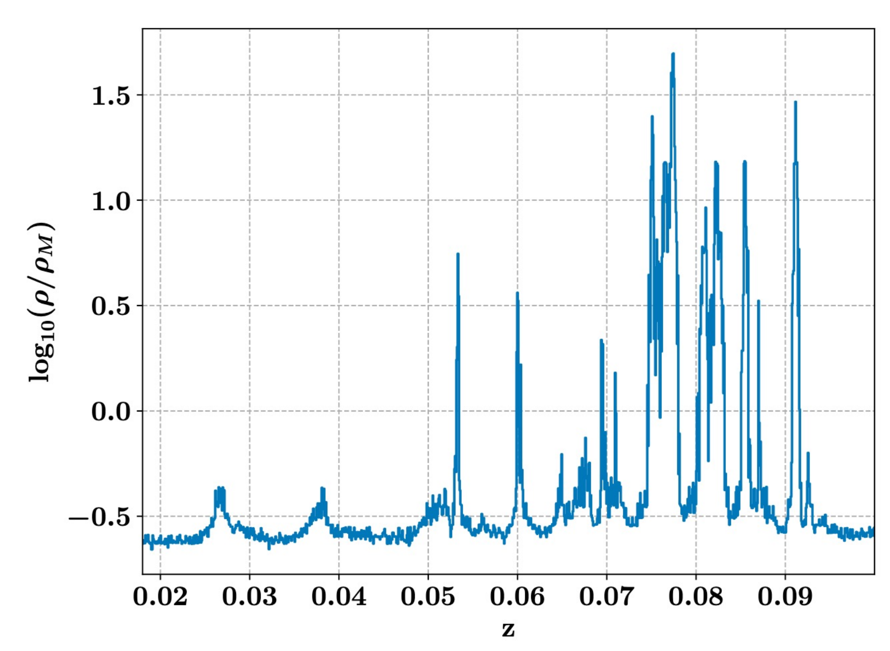
Batten+(2021)a

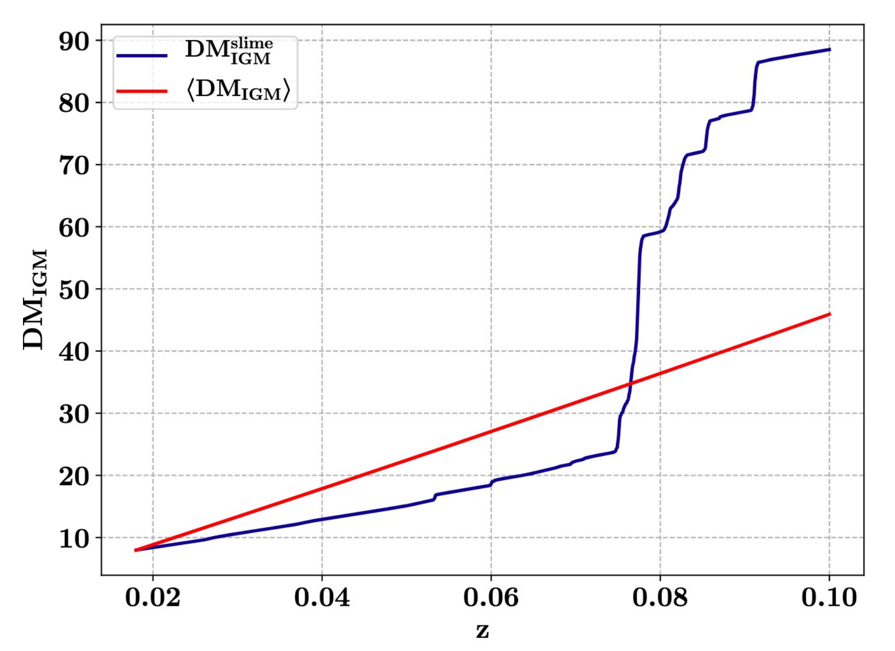
FRB 190608



Batten+(2021)a

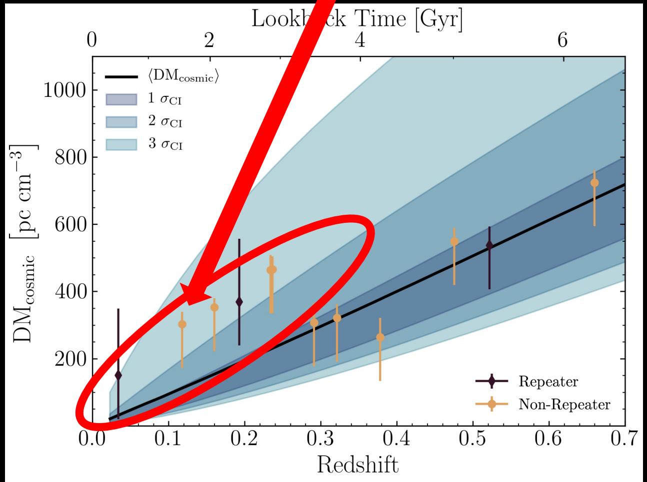
IGM reconstruction from SDSS galaxies in the same field





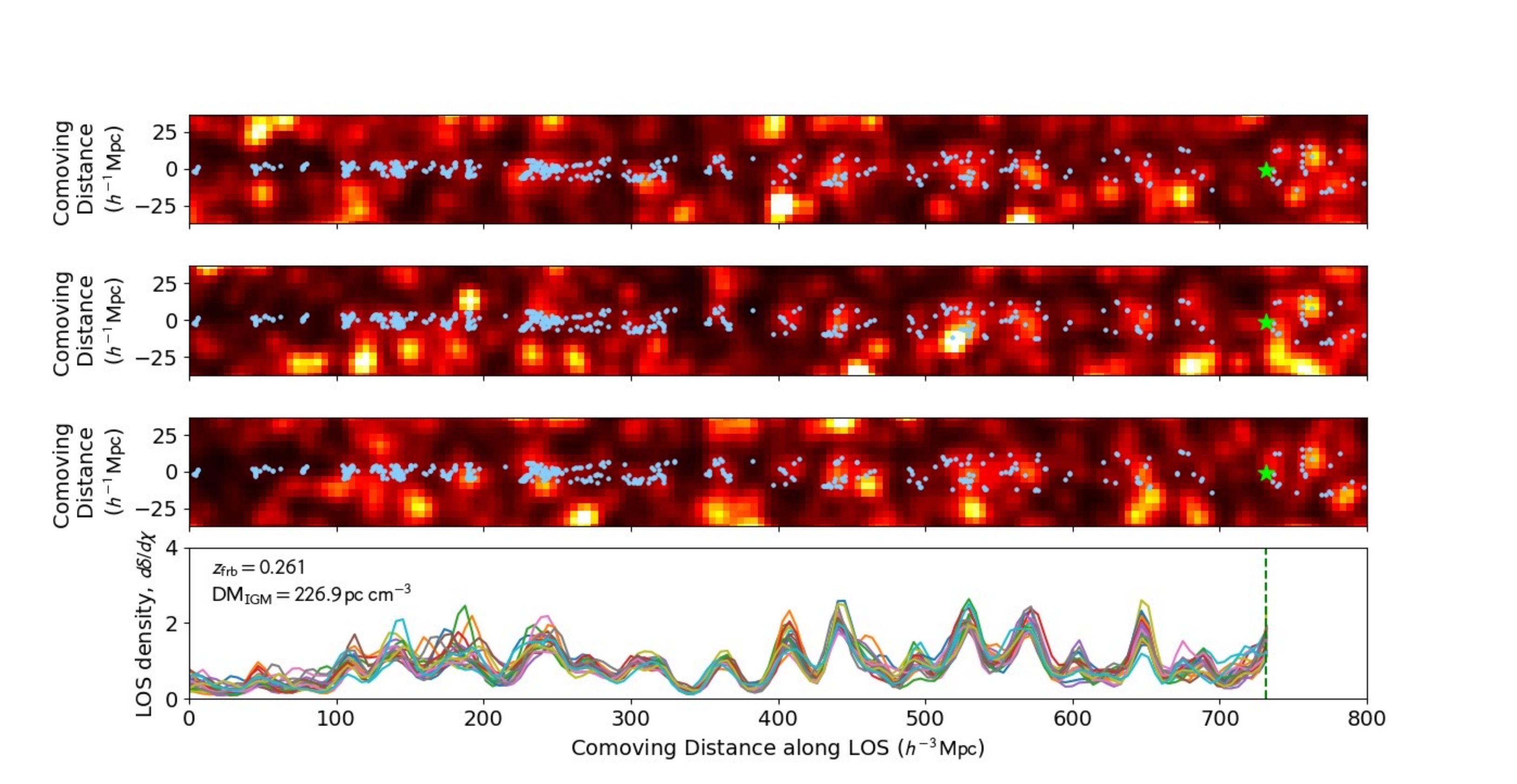
Simha et. al (2020)

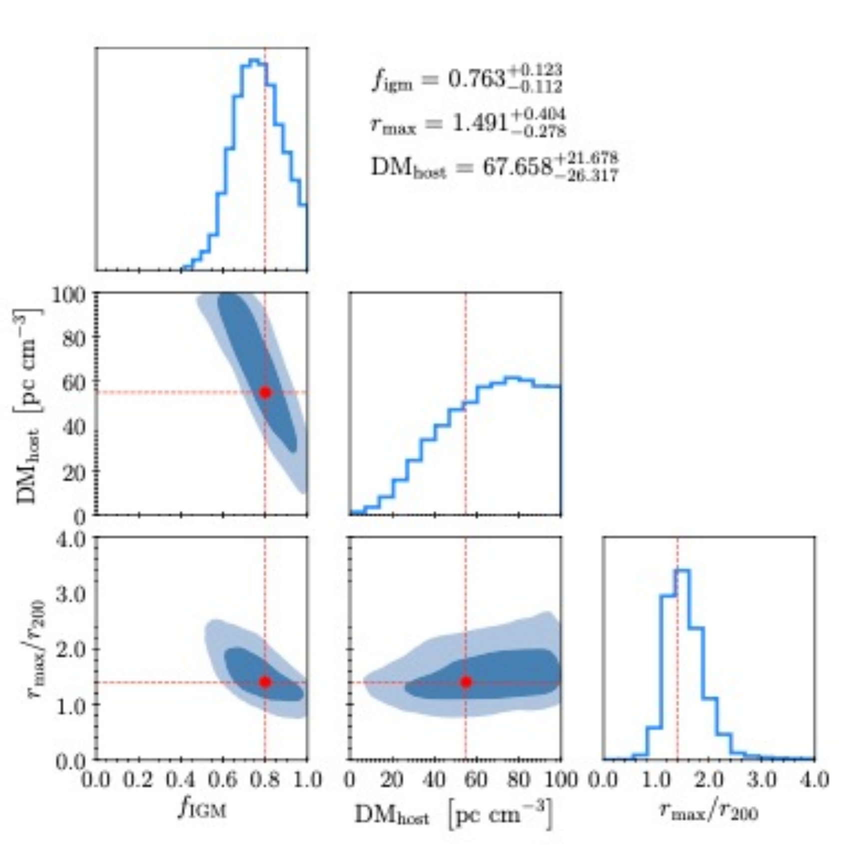
FRB 190608



FRB 190608 intersects over-dense IGM filaments along the line of sight!

Mapping Foreground Large Scale Structure in FRB Fields

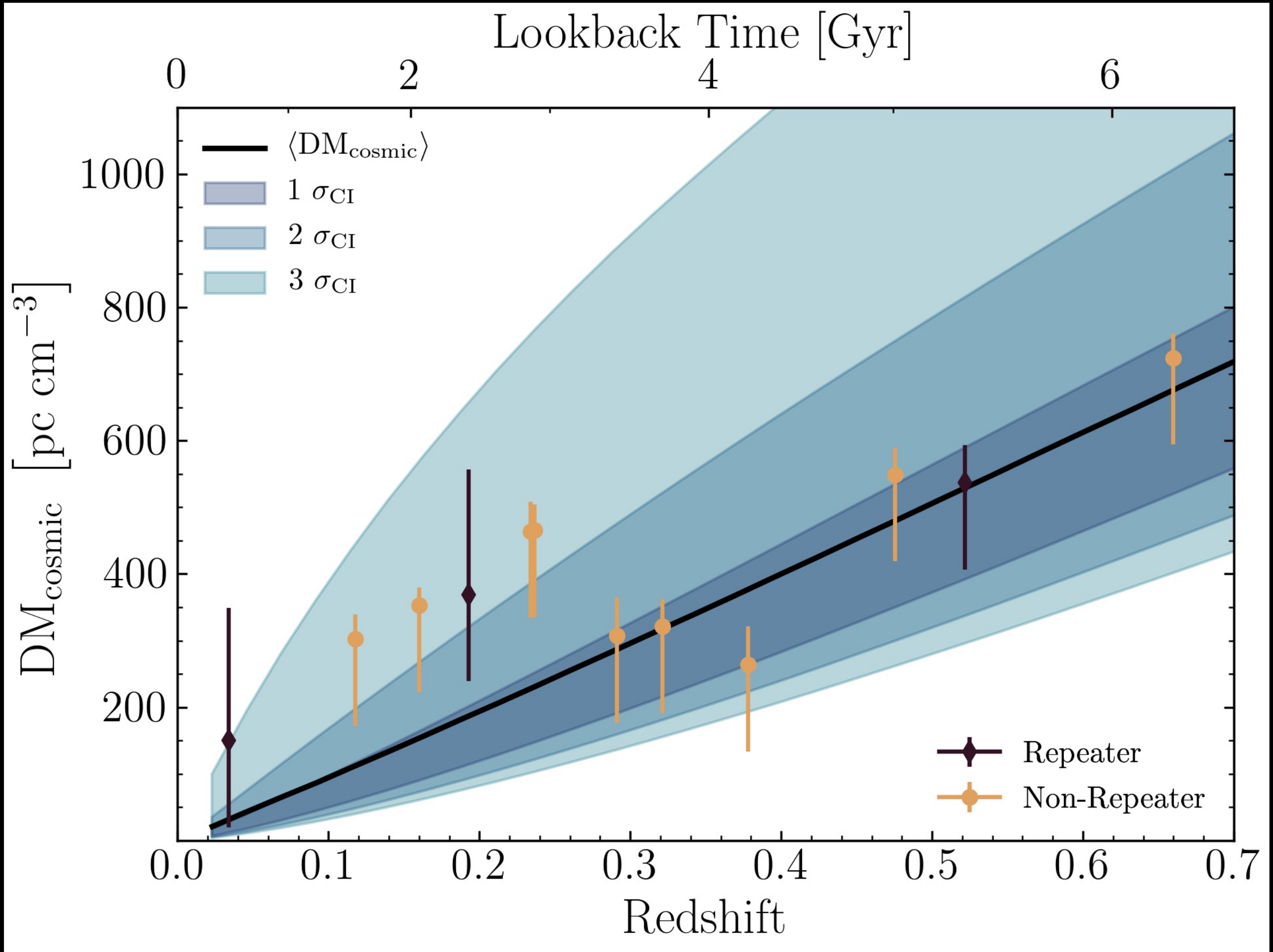




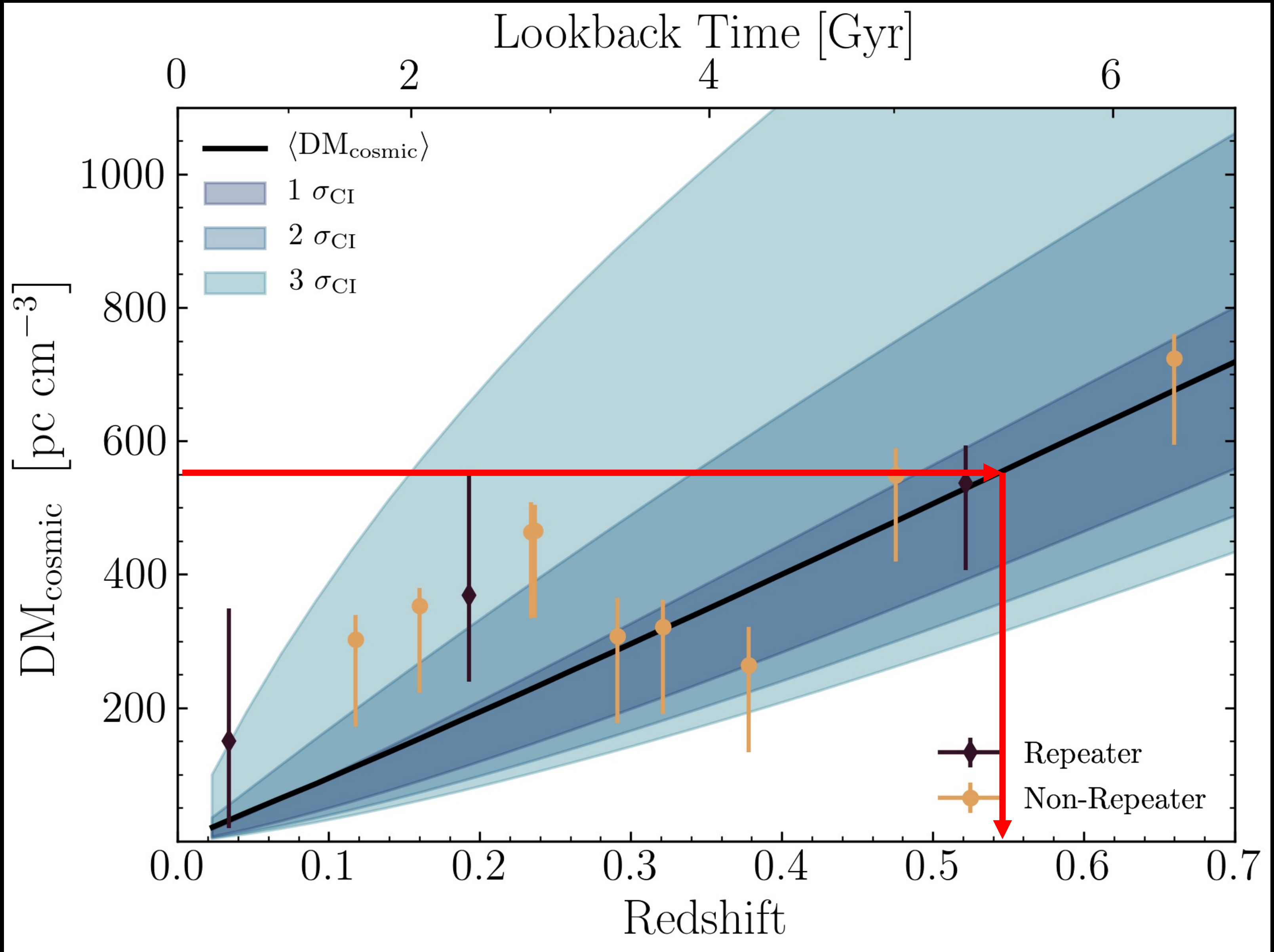
Using 2df on the AAT to follow up these FRBs and perform IGM reconstructions.

Credit: KG Lee

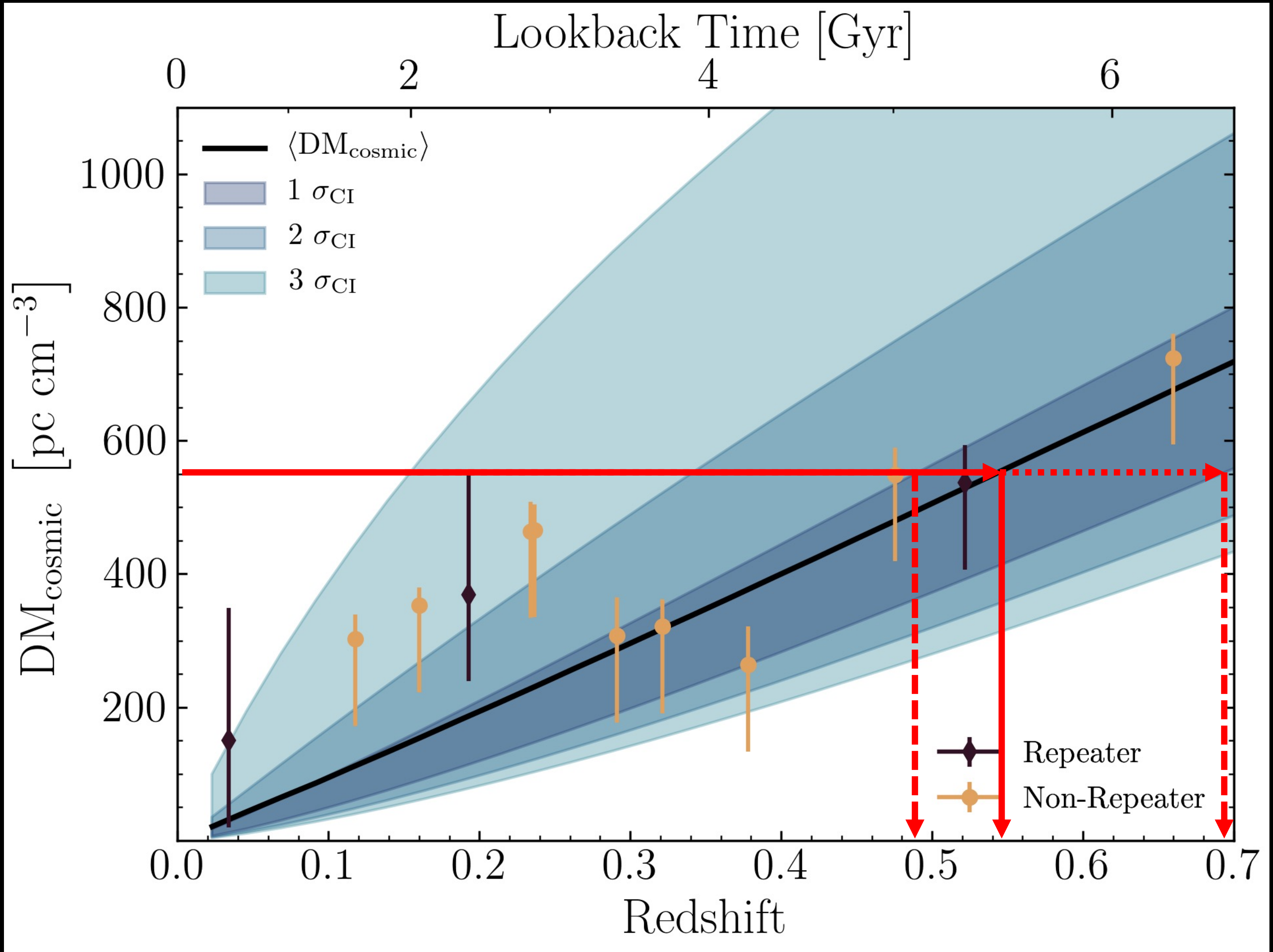
Batten+(2021)a



Batten+(2021)a



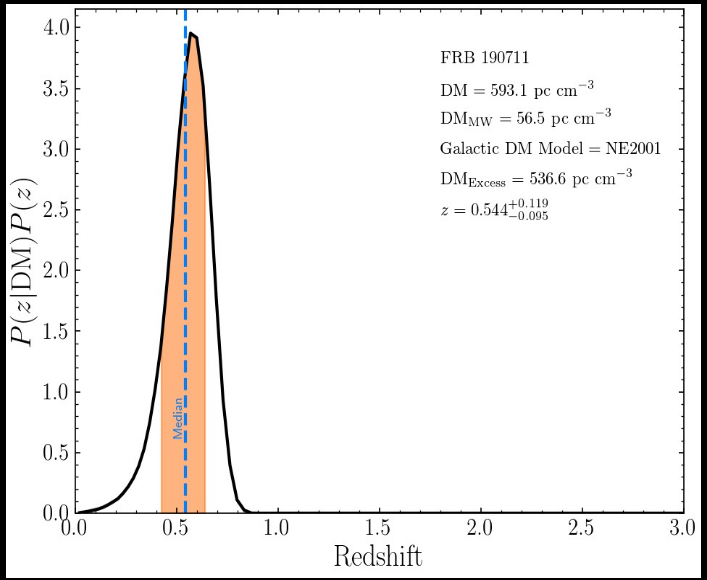
Batten+2021a



Batten (2019)

JOSS Paper: 10.21105/joss.01399
Source Code: https://github.com/abatten/fruitbat

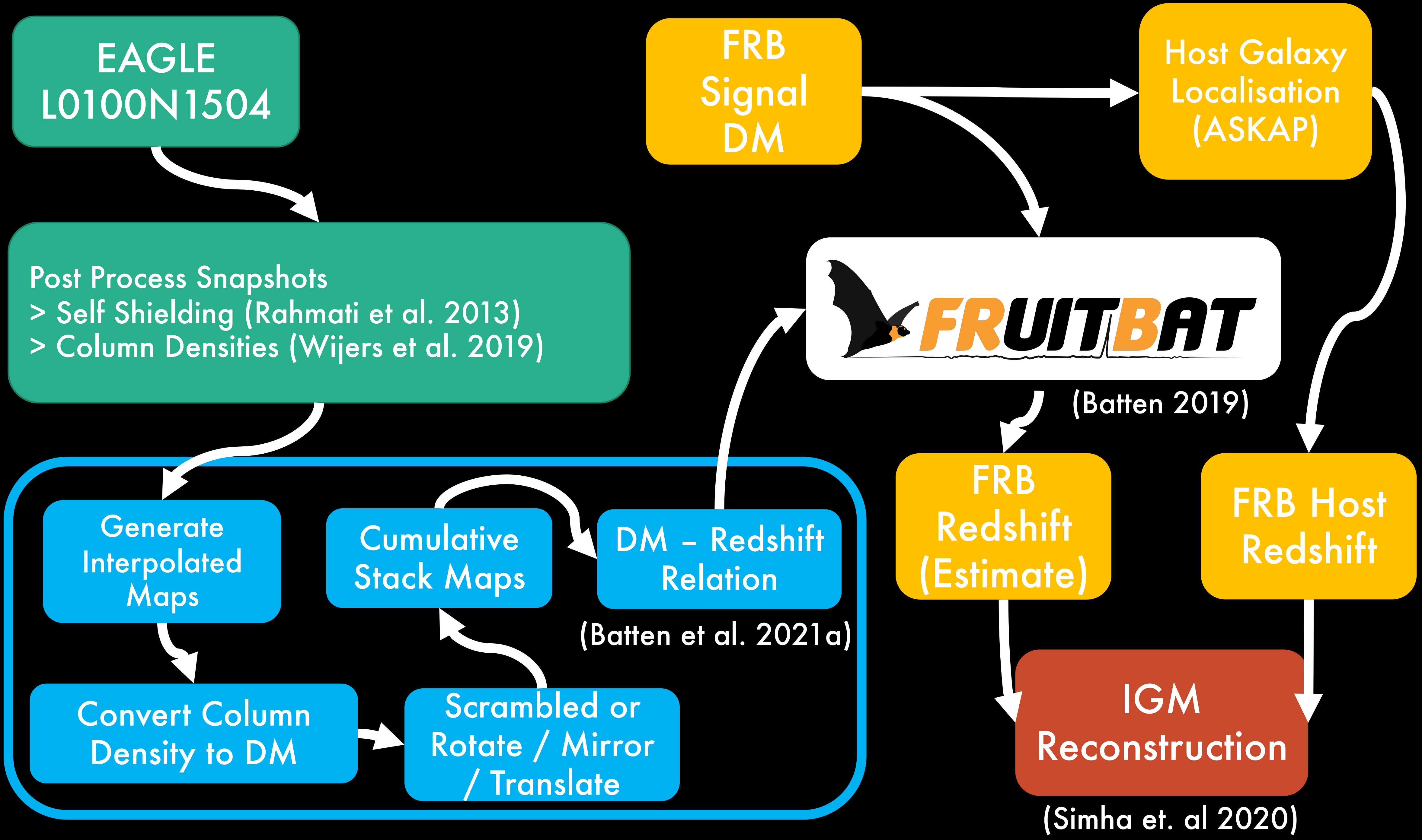
FRB Signal DM → → FRB Redshift



DM-z lookup tables:

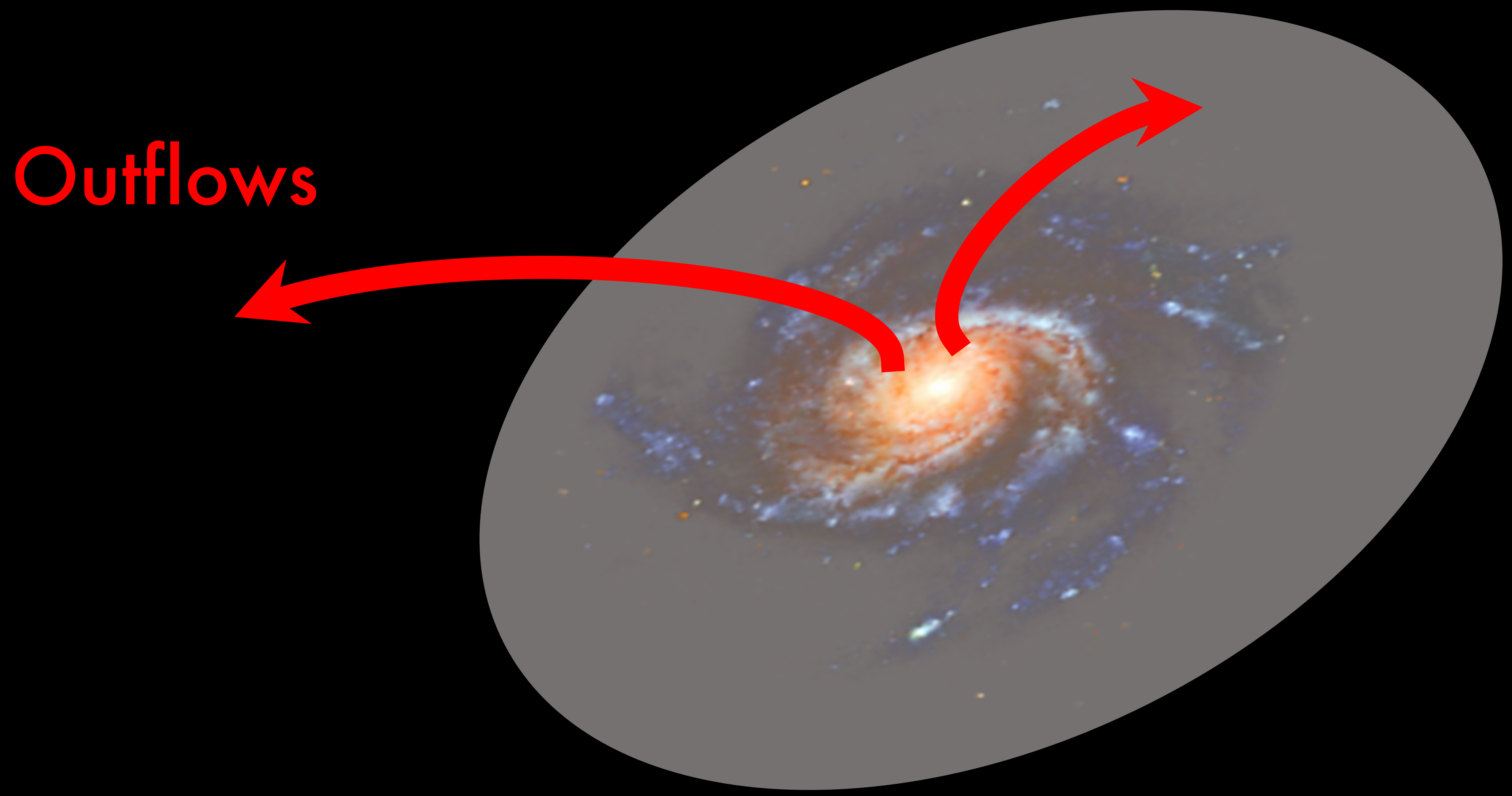
- Ioka (2003)
- Inoue (2004)
- Zhang (2018)
- *Batten et al. (2021)a*

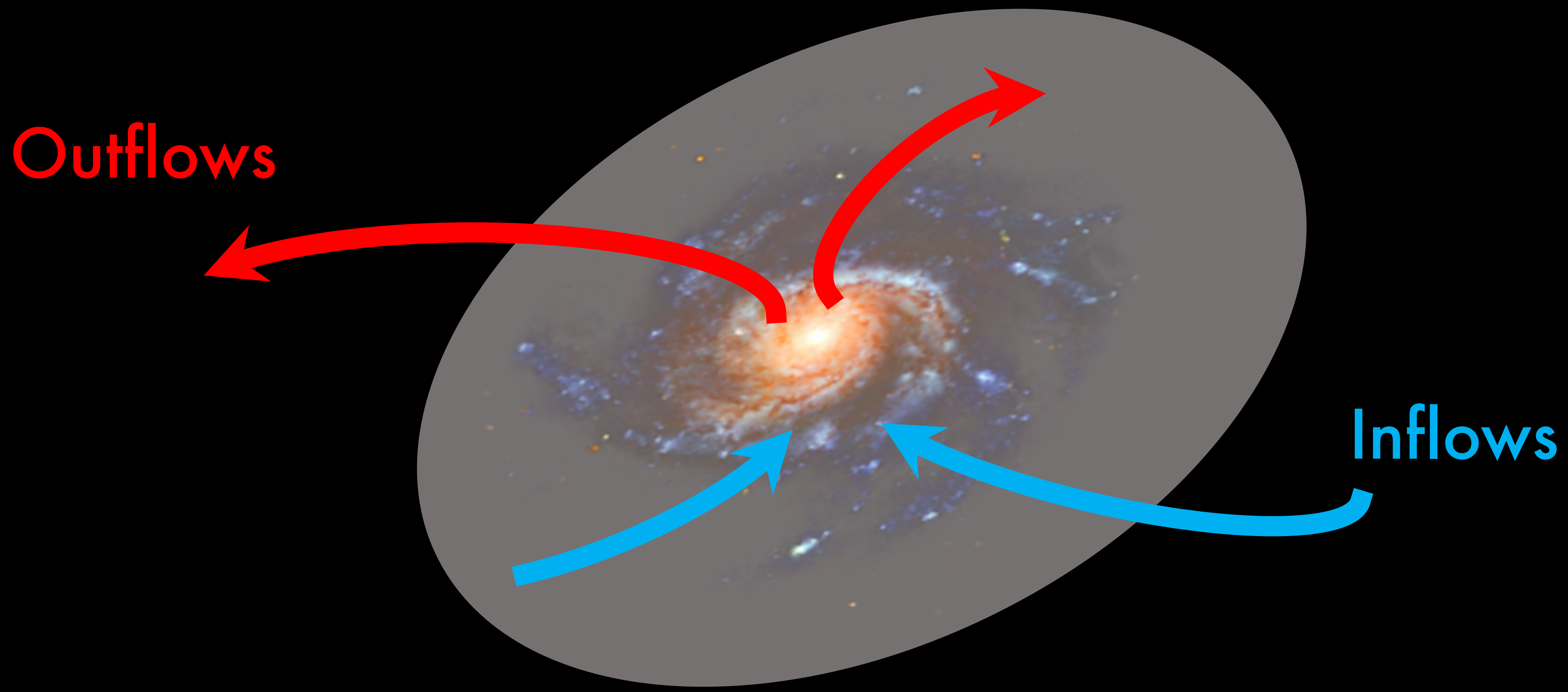
- Milky Way Galaxy Subtraction
- Average Luminosities
- Burst Energy
- WMAP & Planck Cosmologies


EAGLE L0100N1504
Post Process Snapshots
> Self Shielding (Rahmati et al. 2013)
> Column Densities (Wijers et al. 2019)
Generate Interpolated Maps
Convert Column Density to DM
Scrambled or Rotate / Mirror / Translate
Cumulative Stack Maps
DM – Redshift Relation
(Batten et al. 2021a)
FRB Signal DM
Host Galaxy Localisation (ASKAP)
FRUITBAT
(Batten 2019)
FRB Redshift (Estimate)
FRB Host Redshift
IGM Reconstruction
(Simha et. al 2020)

Batten et al. *in prep.*

Fast Radio Bursts as Probes of Galaxy Feedback


Outflows


Outflows
Inflows

Batten et al. *in prep.*

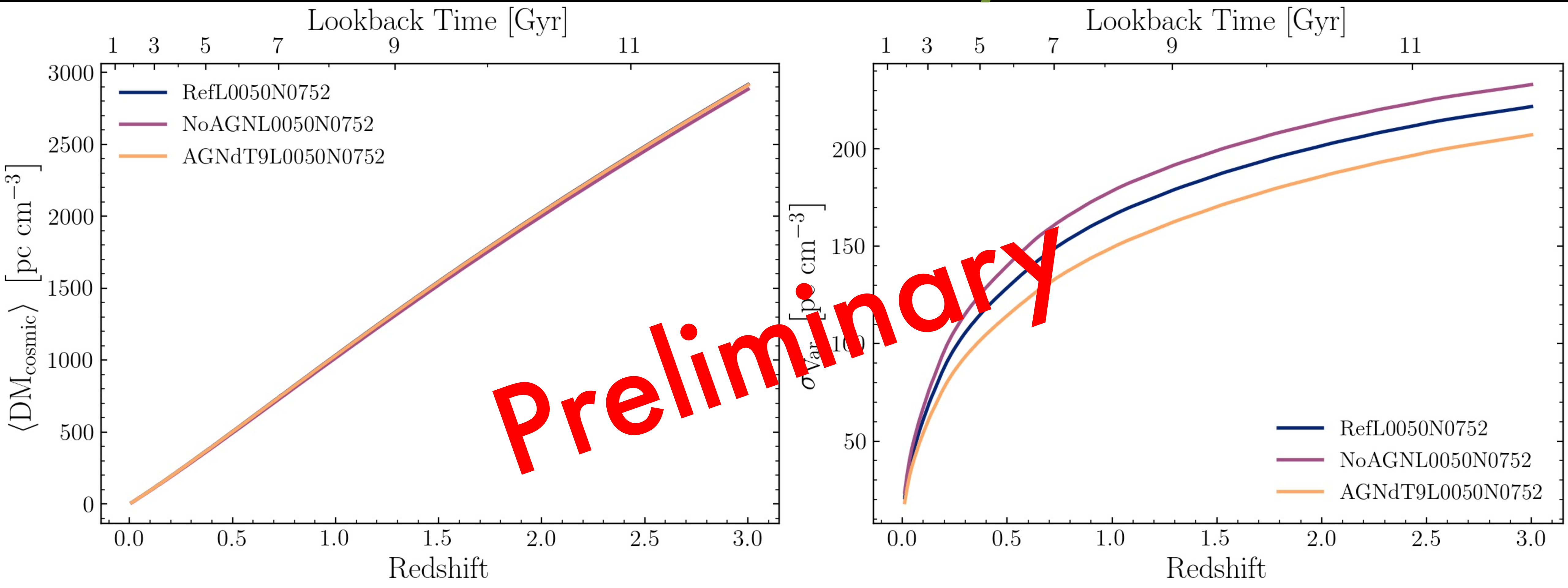
EAGLE Simulations varying AGN feedback

- RefL0050N0752 Reference Simulation

- NoAGN No Active Galactic Nuclei
- AGNdT9 More Efficient AGN Feedback

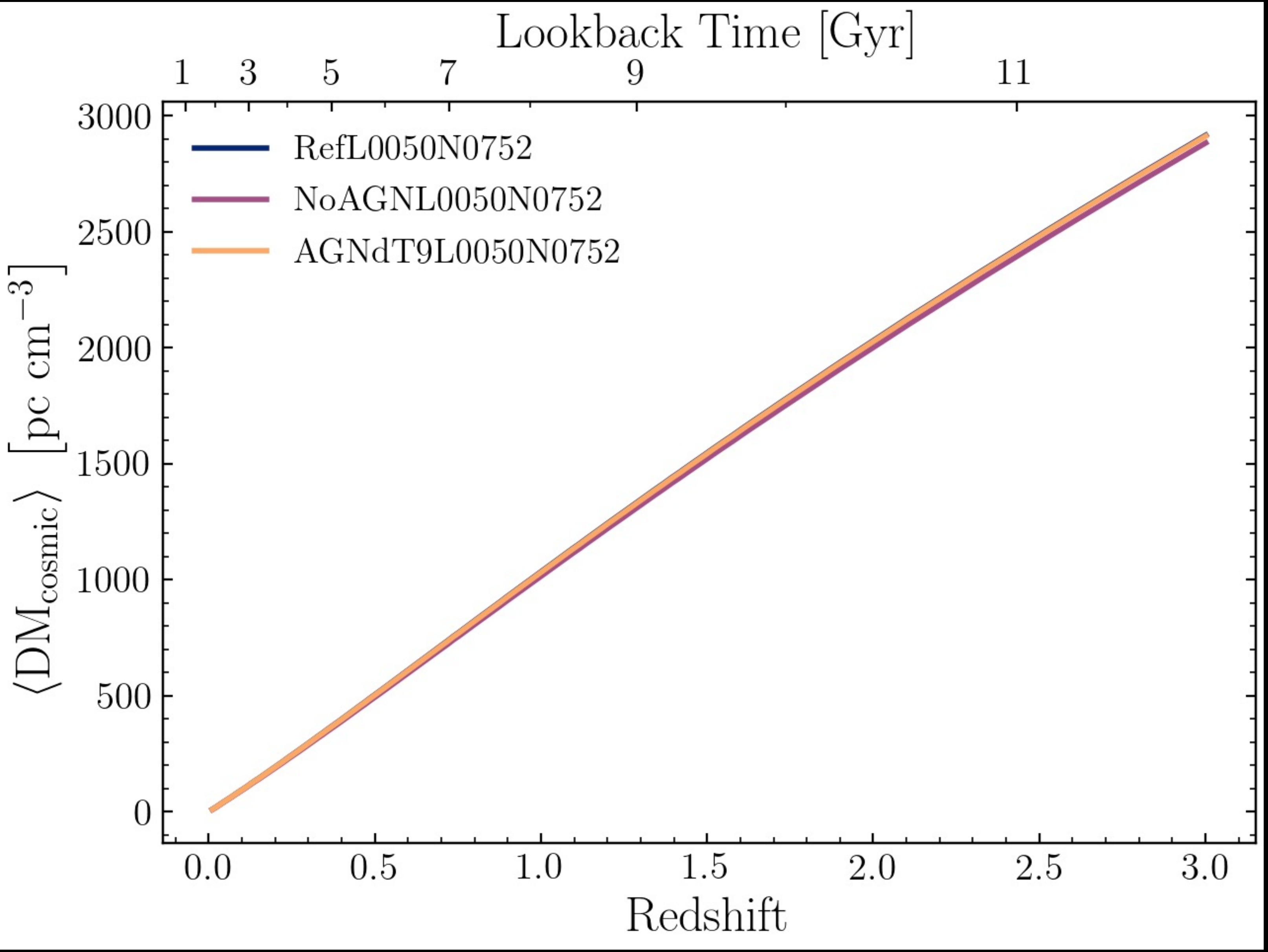
Batten et al. *in prep.*

FRBs as Probes of Galaxy Feedback

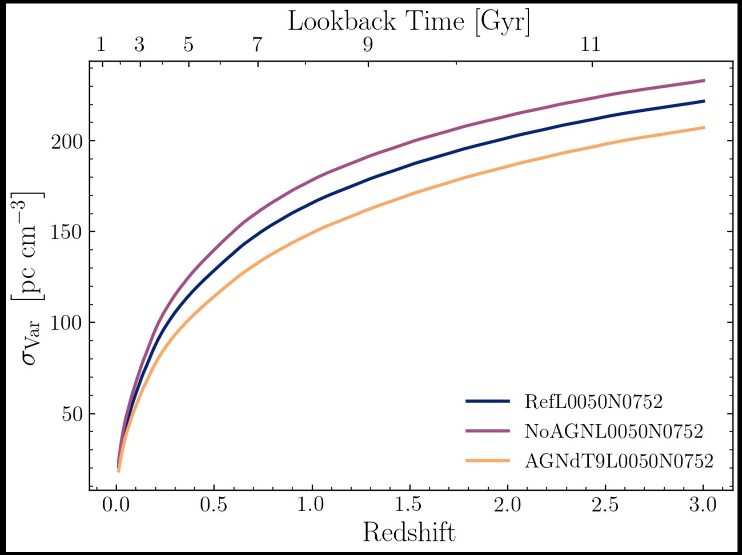


Coming Soon to an Arxiv near you!

Batten et al. *in prep.*

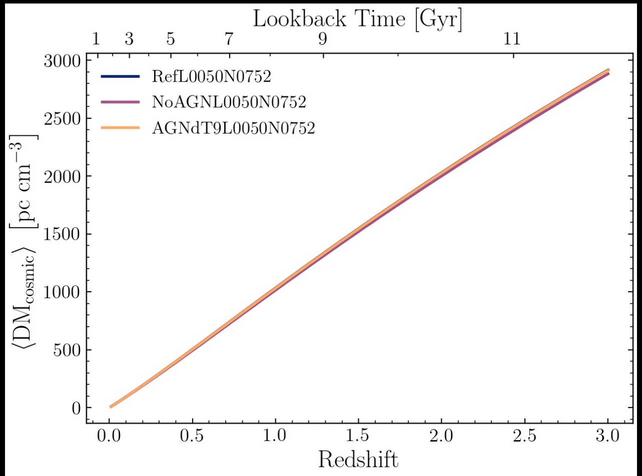


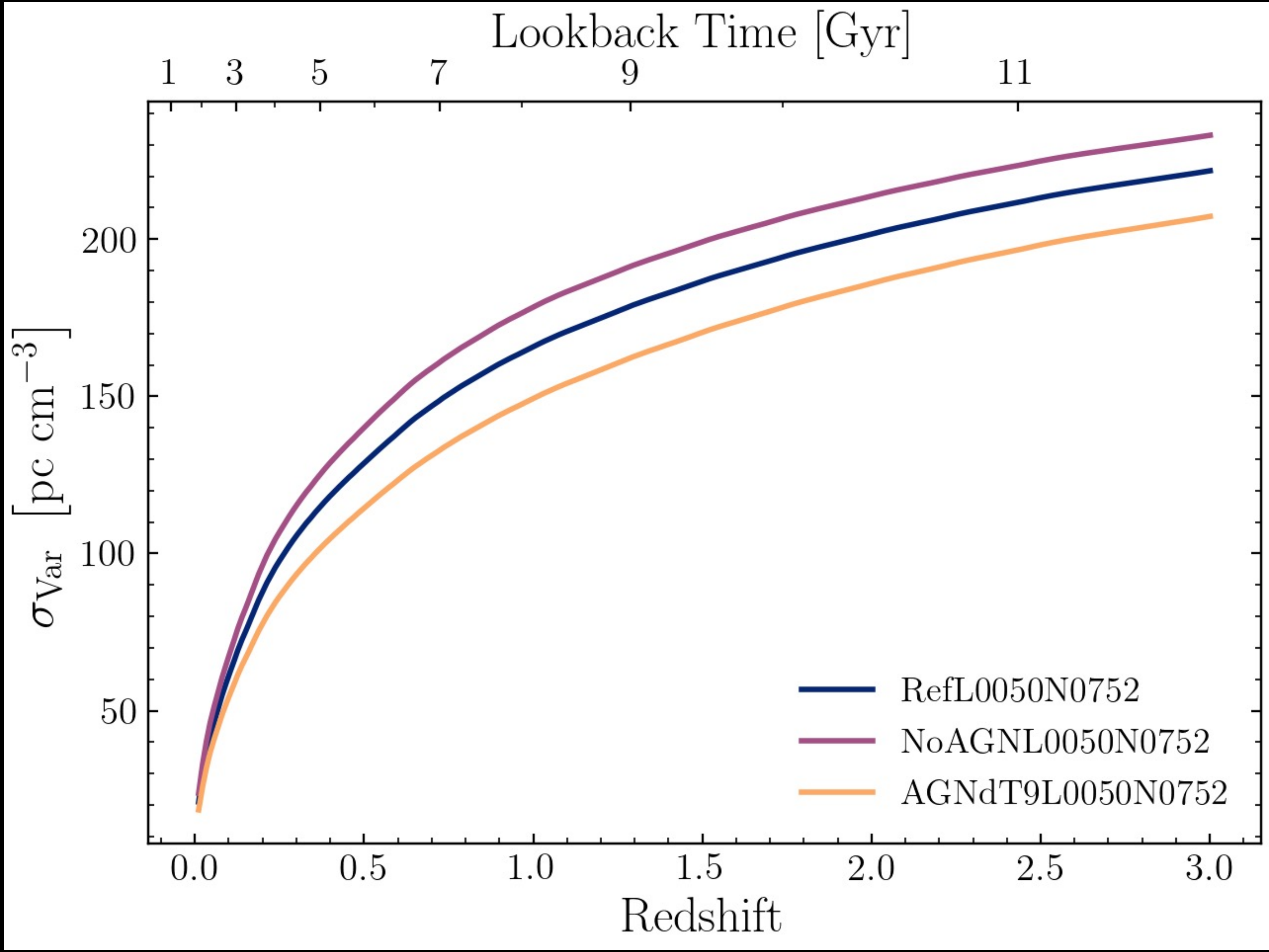
Mean DM-z Relation extremely robust to changes in galaxy feedback!

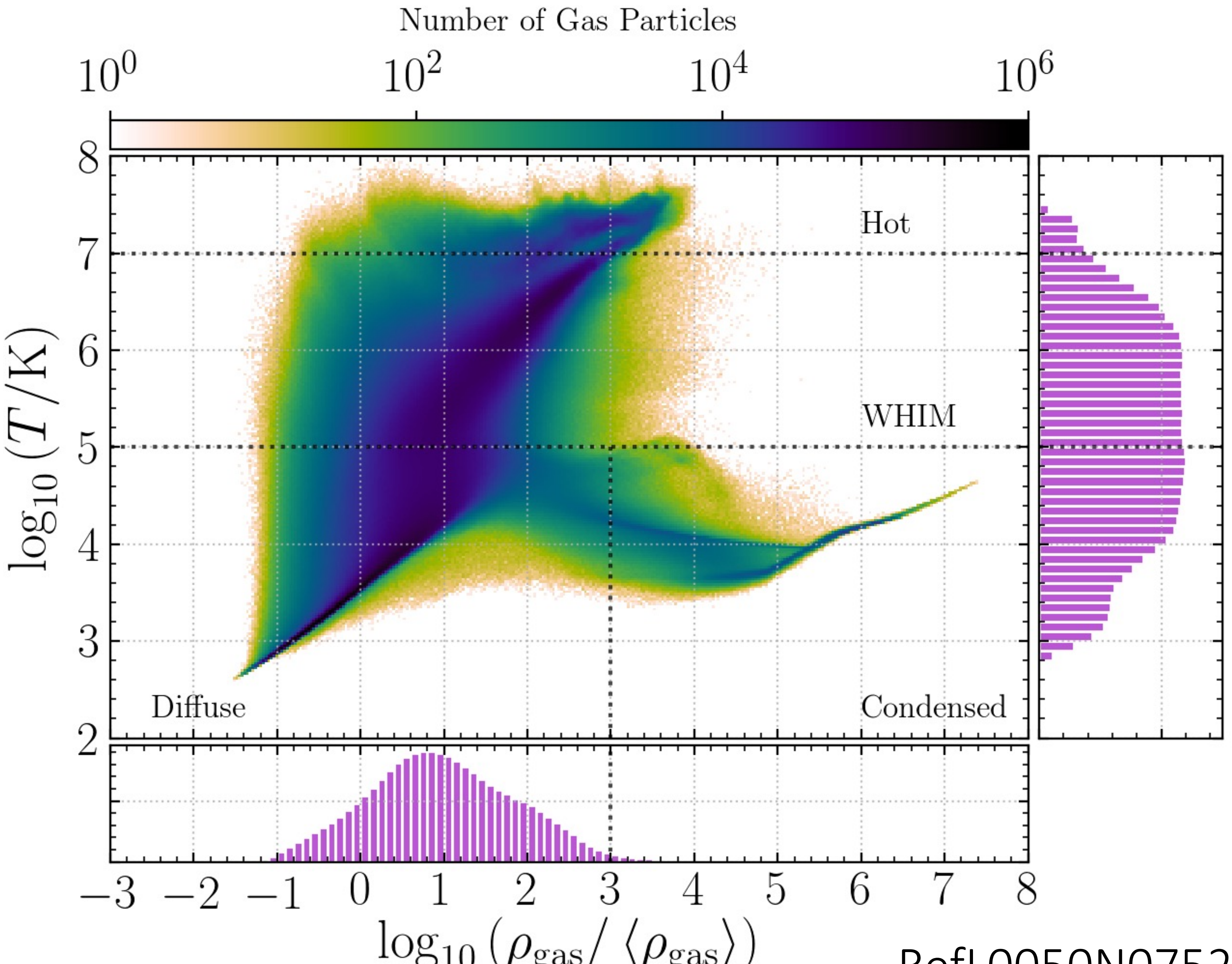


Batten et al. *in prep.*

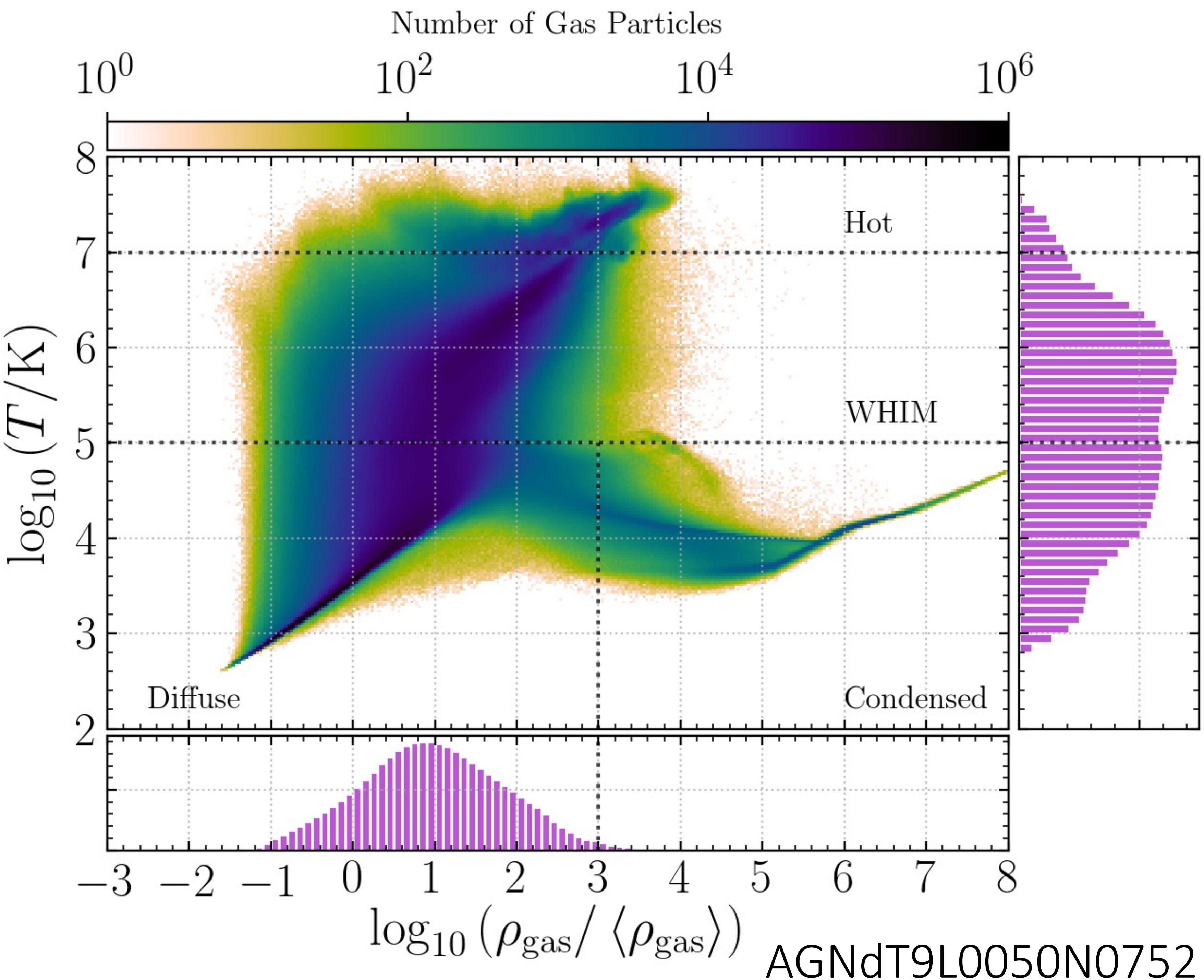
Main difference between models is in the standard deviation around the mean!

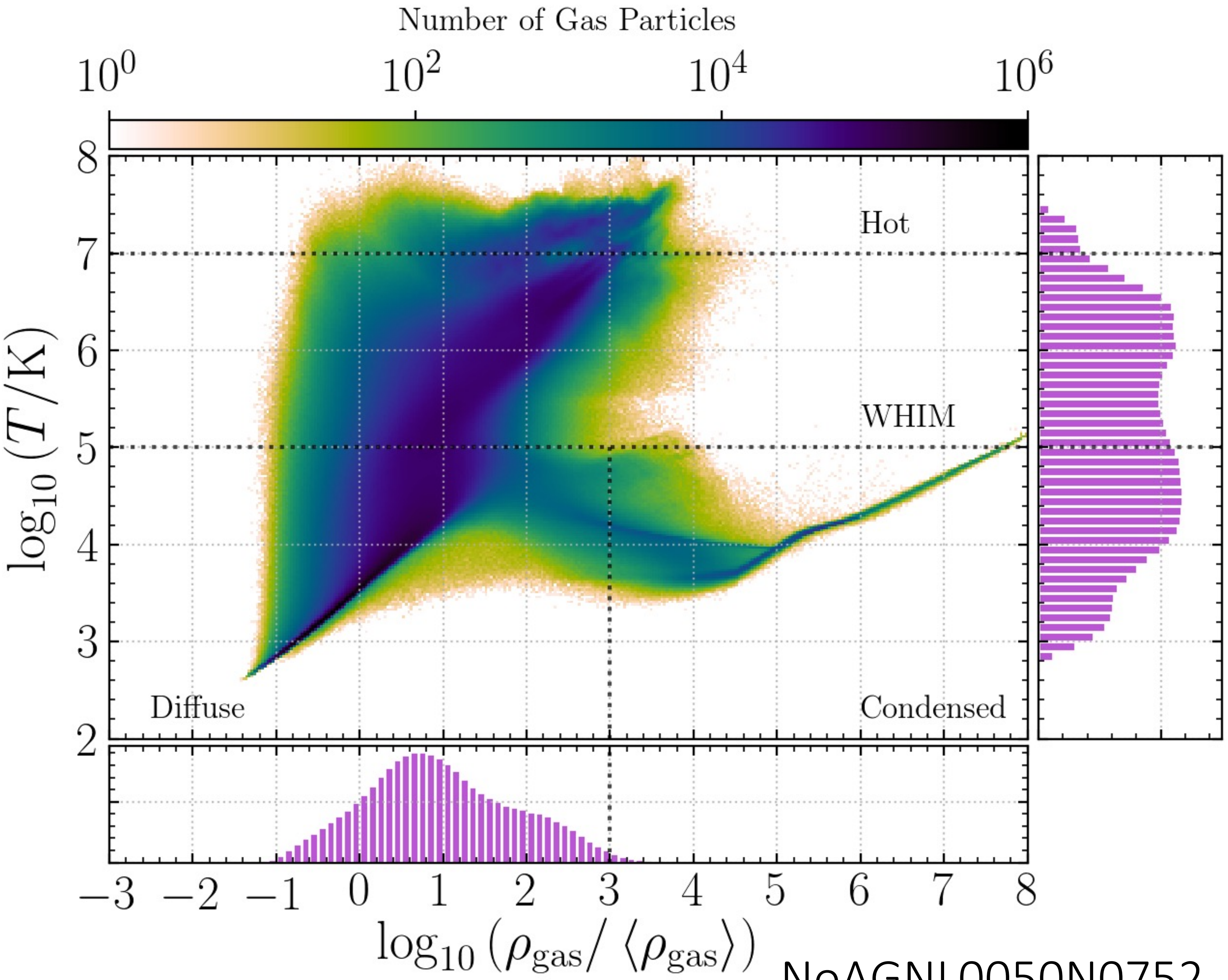






RefL0050N0752

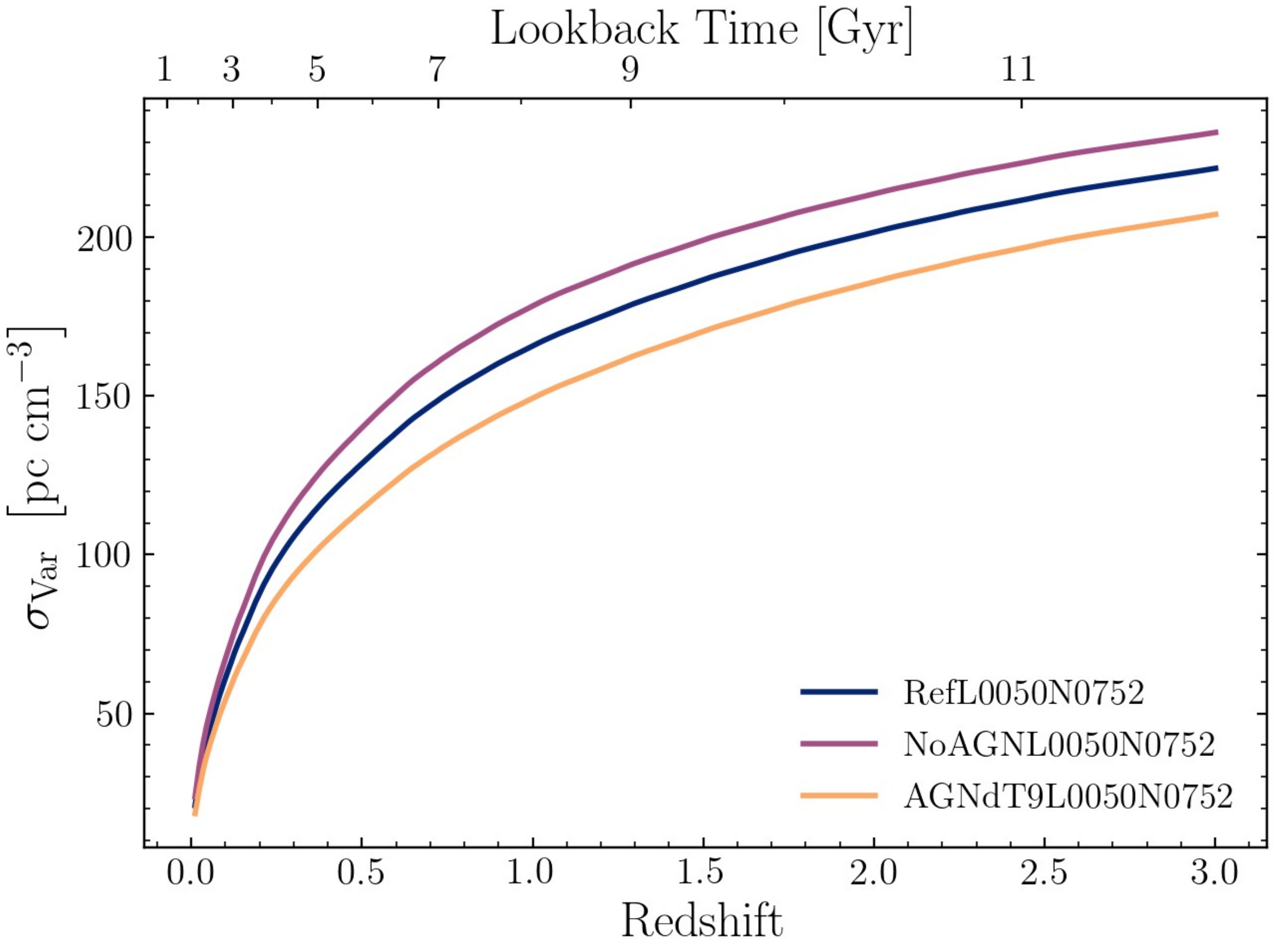

Number of Gas Particles
10^0
10^2
10^4
10^6
Hot
WHIM
Diffuse
Condensed
$\log_{10}(T/\mathrm{K})$
$\log_{10}(\rho_{\mathrm{gas}}/\langle\rho_{\mathrm{gas}}\rangle)$
AGNdT9L0050N0752

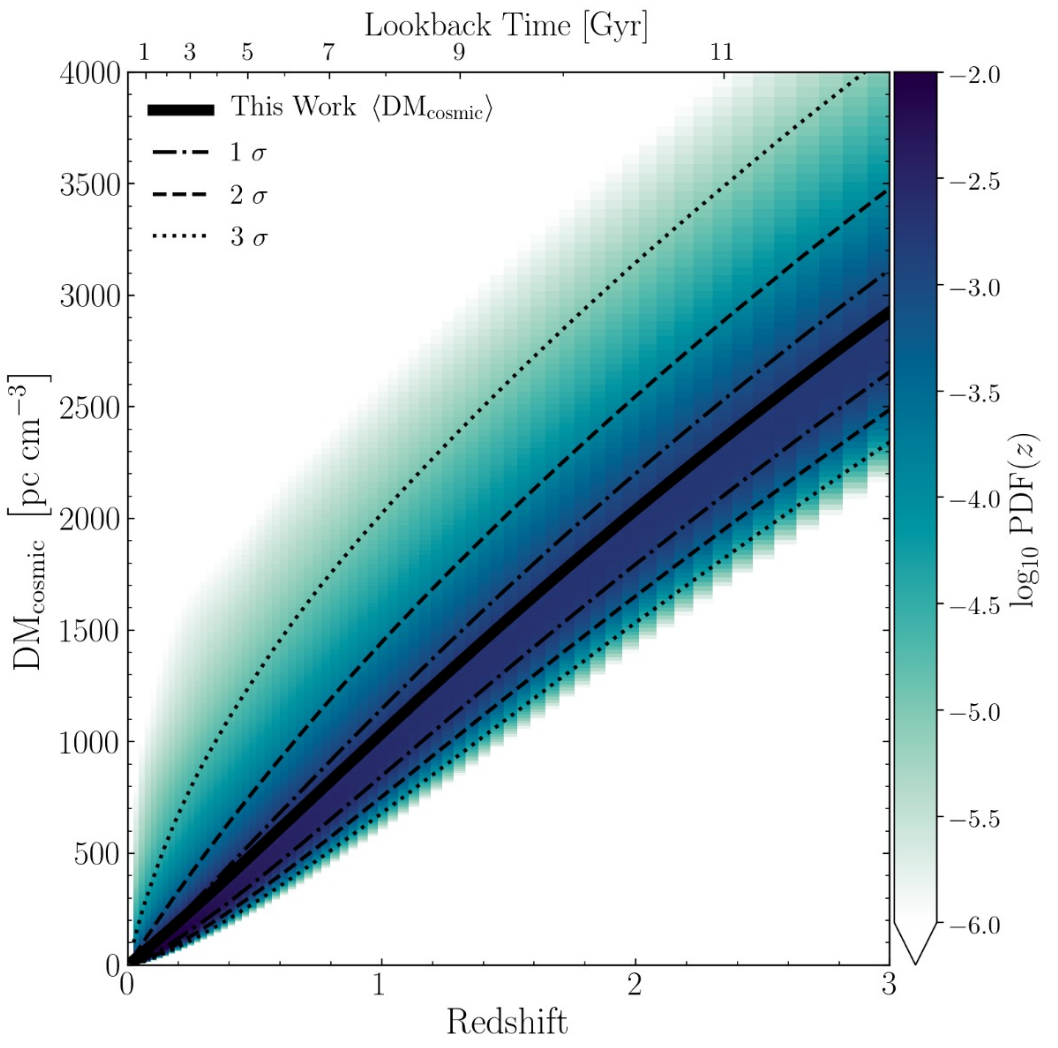


NoAGNL0050N0752

Batten et al. *in prep.*

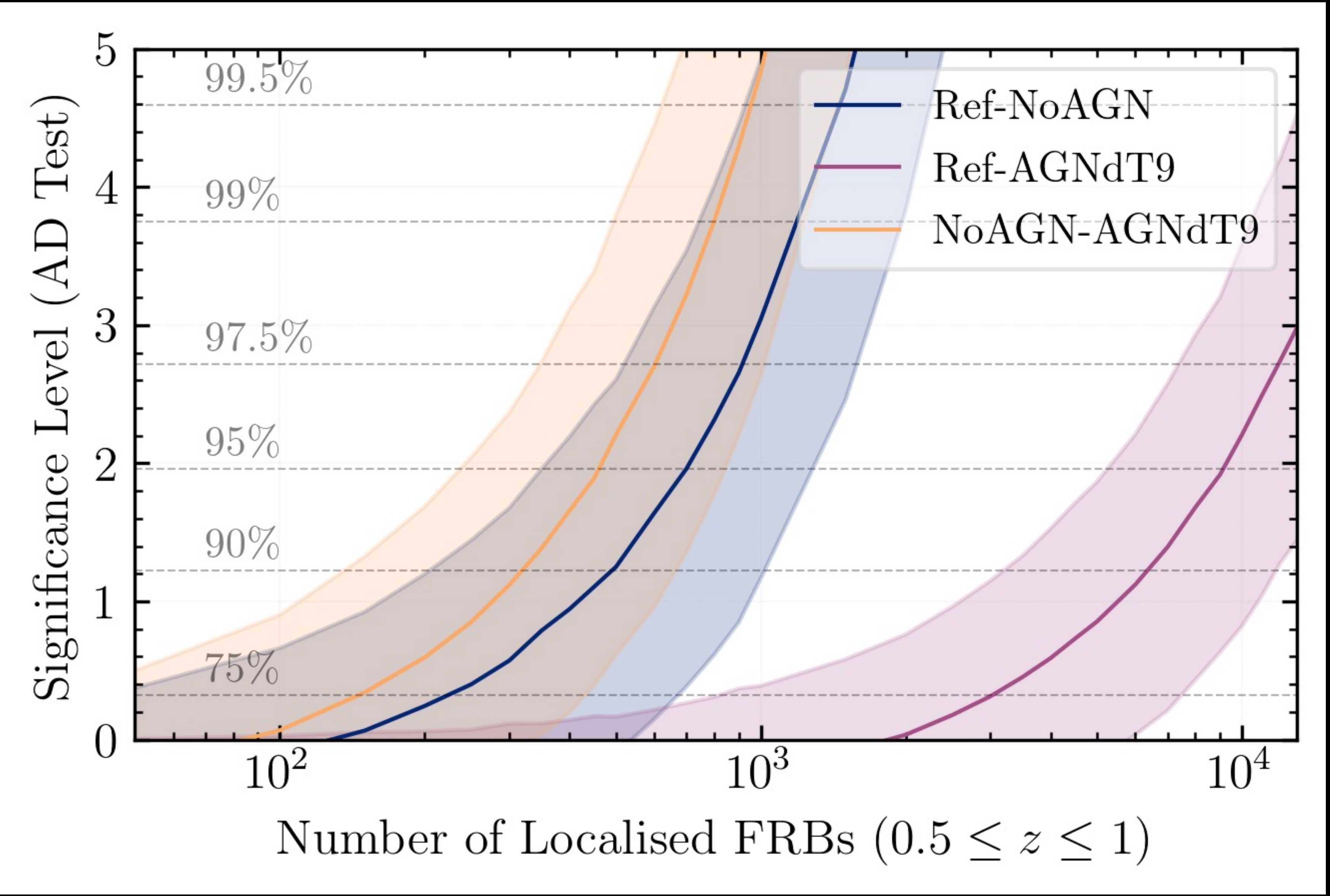
How many localised FRBs do we need?





Batten et al. *in prep.*

How many localised FRBs do we need?



Summary:

- Fast Radio Bursts provide a new way to probe the electron/baryon distribution in the IGM.
- Batten+2021: *The Cosmic Dispersion Measure in EAGLE (MNRAS, Volume 505, Issue 4)*
    - ➥ I used the EAGLE simulations to calculate DM-z relation and the scatter around it.
    - ➥ Large scatter around relation, with extremely skewed PDFs at low redshifts.
    - ➥ Most low redshift FRBs lie in the 2 – 3σ confidence intervals.
    - ➥ Indicates intersection with IGM filaments, or possibly high host/source contributions.
- Batten+ *in prep.: The Dispersion Measure of FRBs as probes of AGN feedback*
    - ➥ The mean DM-z relation is very robust against different AGN feedback.
    - ➥ It appears that the scatter around the DM-z relation might be able to probe galaxy feedback.
    - ➥ Approx. 9000 localised FRBs are needed between z = 0.5 – 1 to constrain AGN feedback.
    - ➥ Need more large box simulations required with different galaxy feedback prescriptions.

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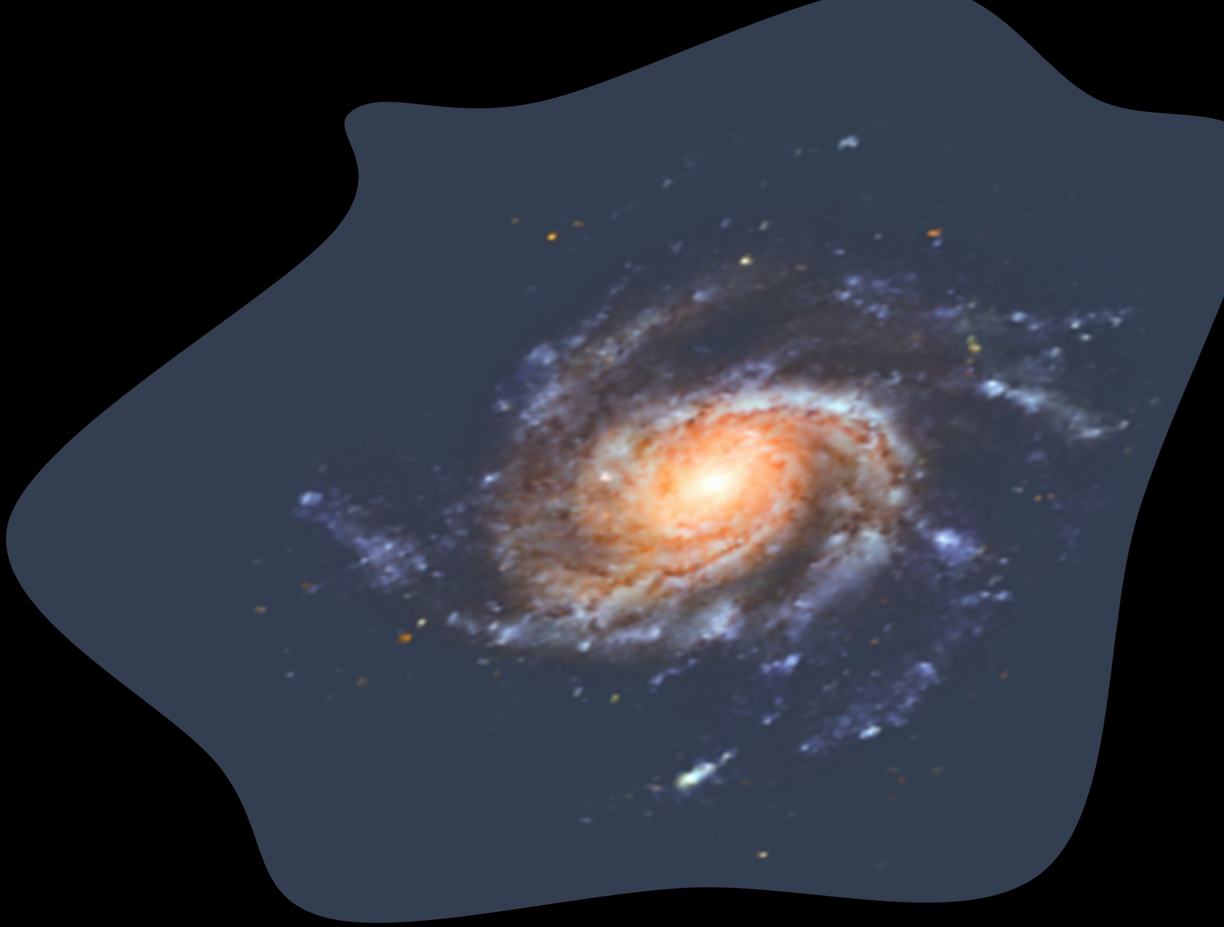
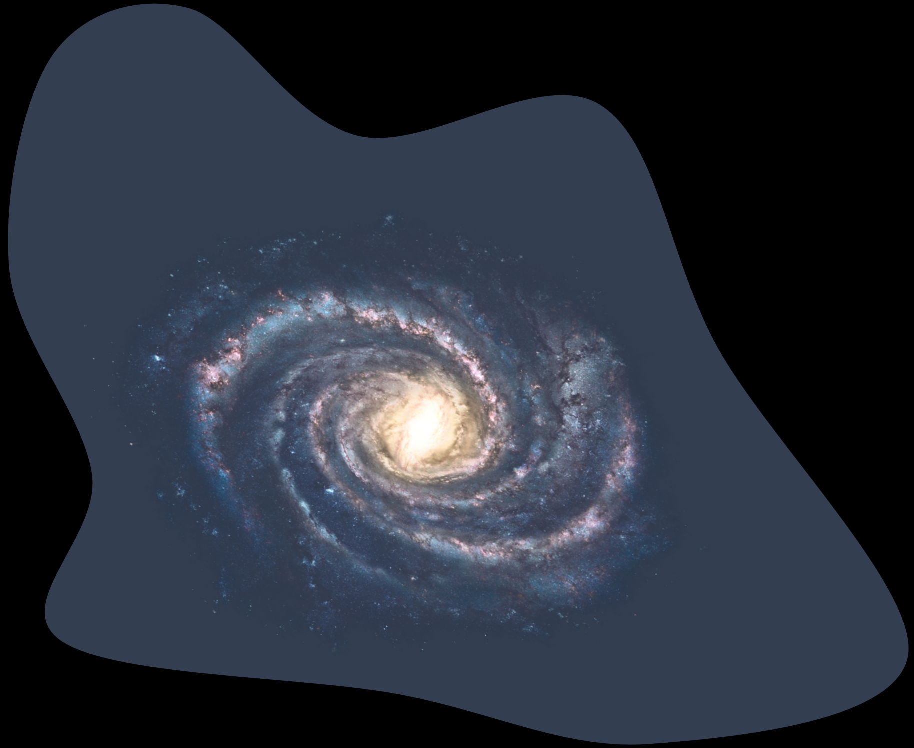
Metal `Bubbles' Project



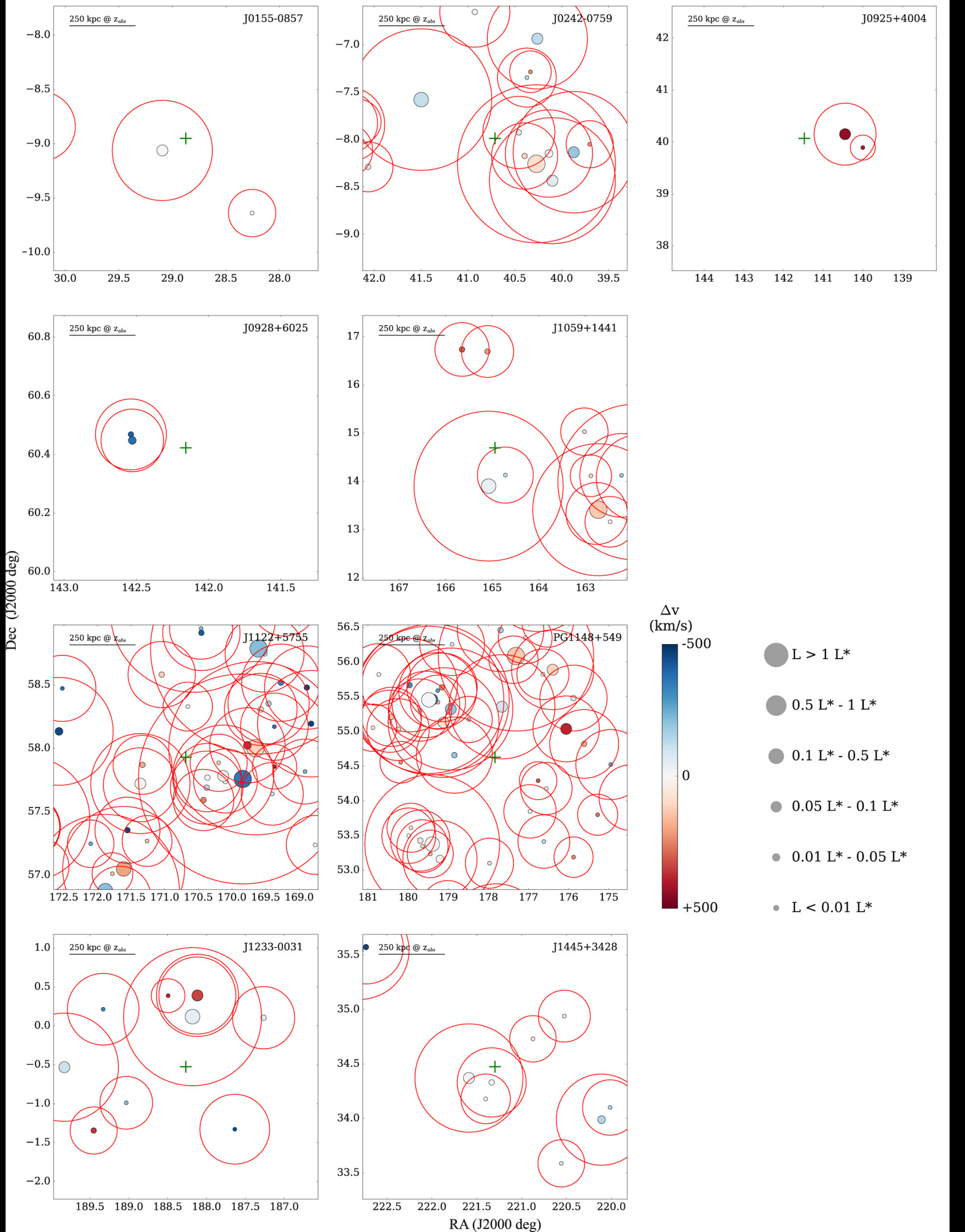


Metal `Bubbles’ Project

Metal `Bubbles' Project

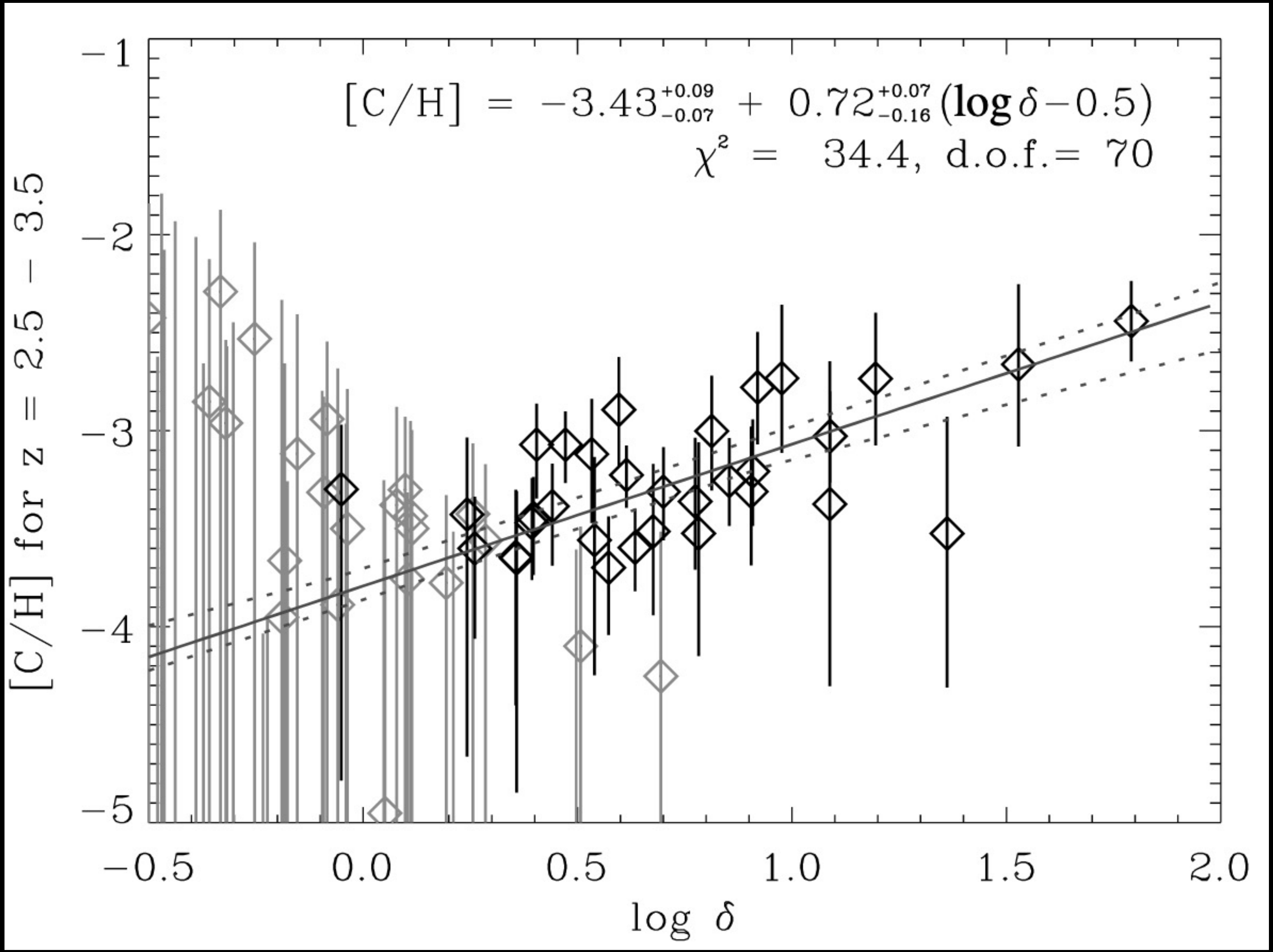
At z < 1, the CGM has overlapping metal bubbles!

When does the IGM start to overlap?



Burchett+(2016)

Metal `Bubbles' Project



At redshift $z \sim 3$, the IGM is enriched to about 10^{-3} solar.

Schaye+(2003)

Main Science Questions:

Which halos contribute the most to enriching the IGM with metals?

What is the size of the enriched region around halos?

At which redshift do the ‘metal bubbles’ around galaxies overlap?