The Cosmic Dispersion Measure of Fast Radio Bursts using the EAGLE Simulations

Adam Batten

Alan Duffy, Nastasha Wijers, Vivek Gupta, Chris Flynn, Joop Schaye, Emma Ryan-Weber

Swinburne University of Technology, Melbourne Australia

abatten@swin.edu.au @adamjbatten

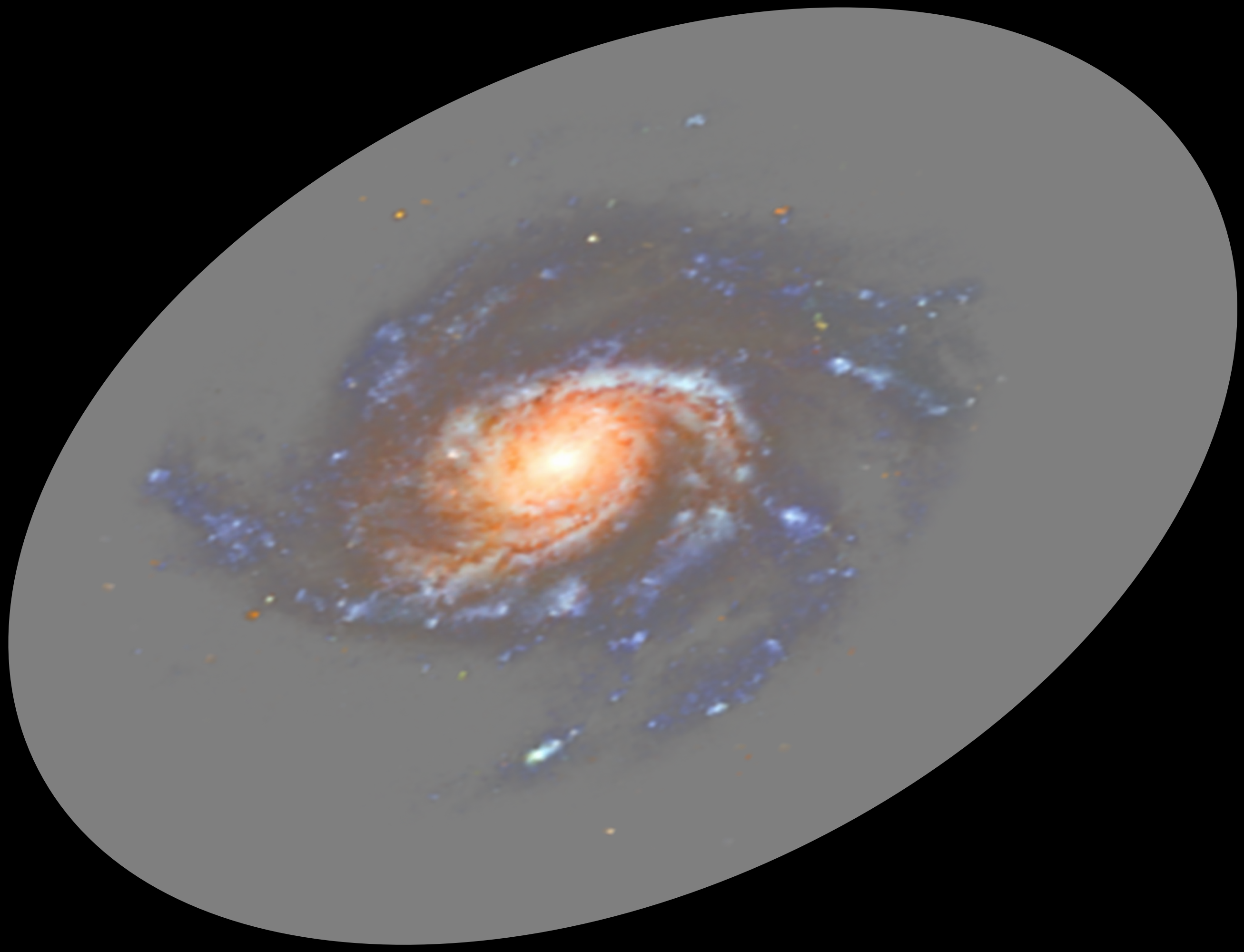
ECR Astronomers in Australia Seminar Series

2021-05-27

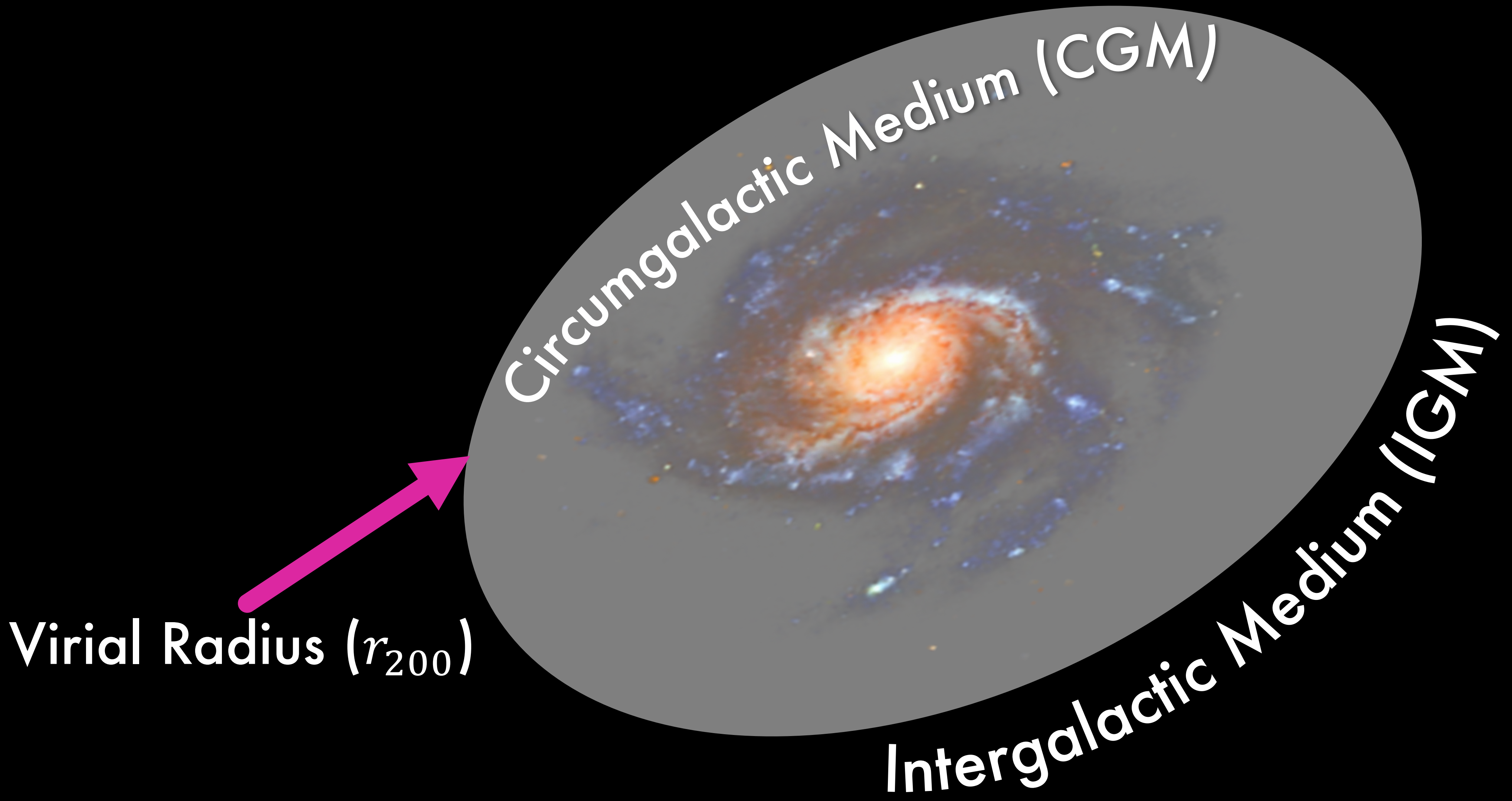
ASTRO 3D

SWIN BUR NE Centre for Astrophysics and Supercomputing

What is the Intergalactic Medium?



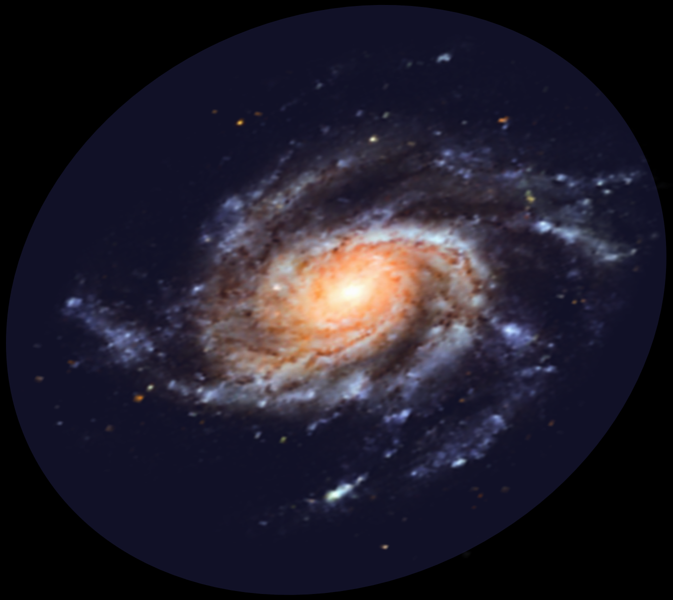
What is the Intergalactic Medium?



Tumlinson et al. (2017)

Why Do We Care About the Intergalactic Medium?

Why Do We Care About the Intergalactic Medium?



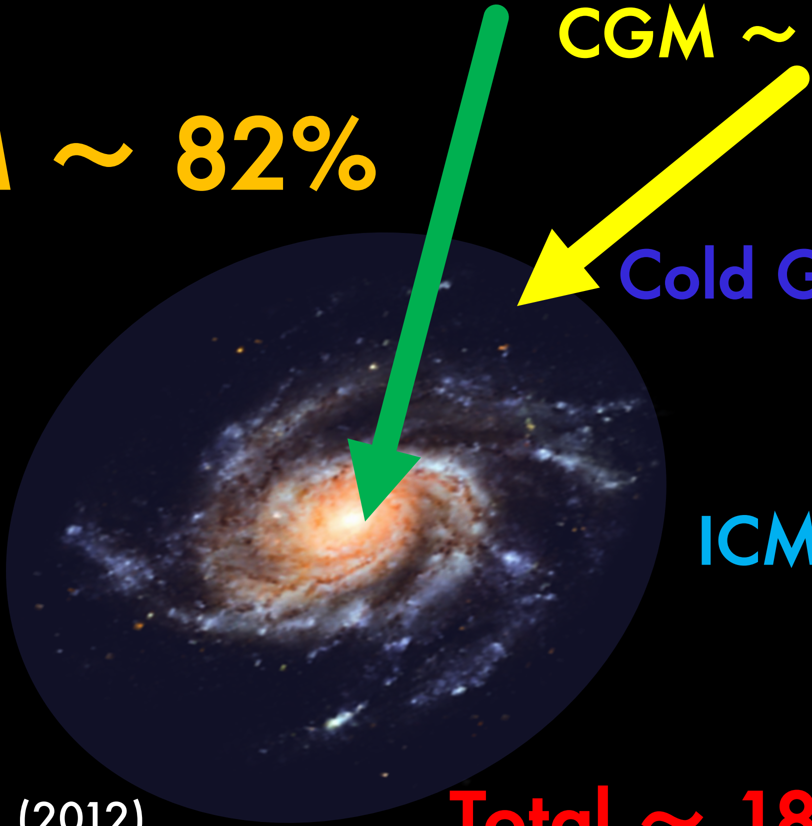
1. The IGM contains most of the baryonic matter

Why Do We Care About the Intergalactic Medium?

Galaxies ~ 7%

CGM ~ 5%

IGM ~ 82%



Cold Gas ~ 2%

ICM ~ 4%

Total ~ 18%

Shull et al. (2012)

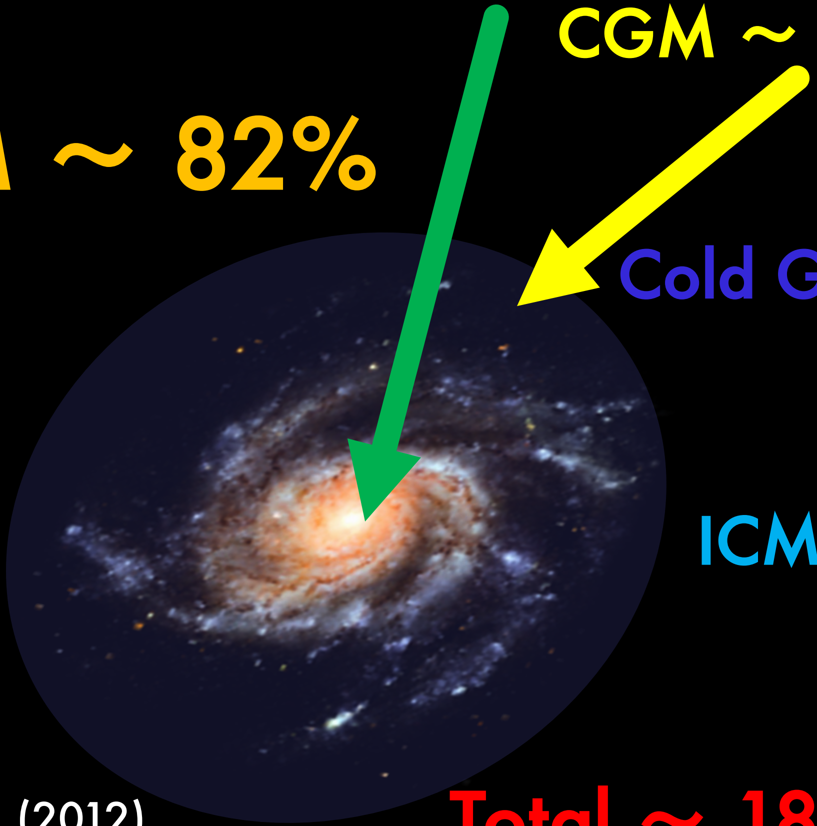
1. The IGM contains most of the baryonic matter

Why Do We Care About the Intergalactic Medium?

Galaxies ~ 7%

CGM ~ 5%

IGM ~ 82%

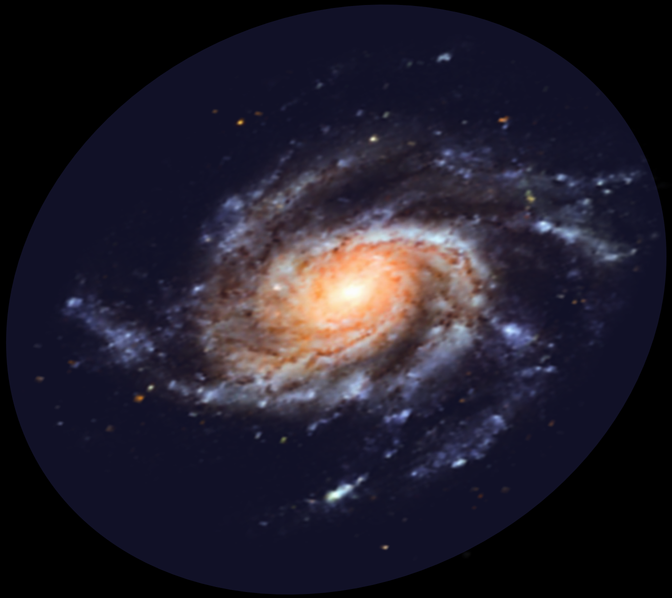


Cold Gas ~ 2%

ICM ~ 4%

Shull et al. (2012)

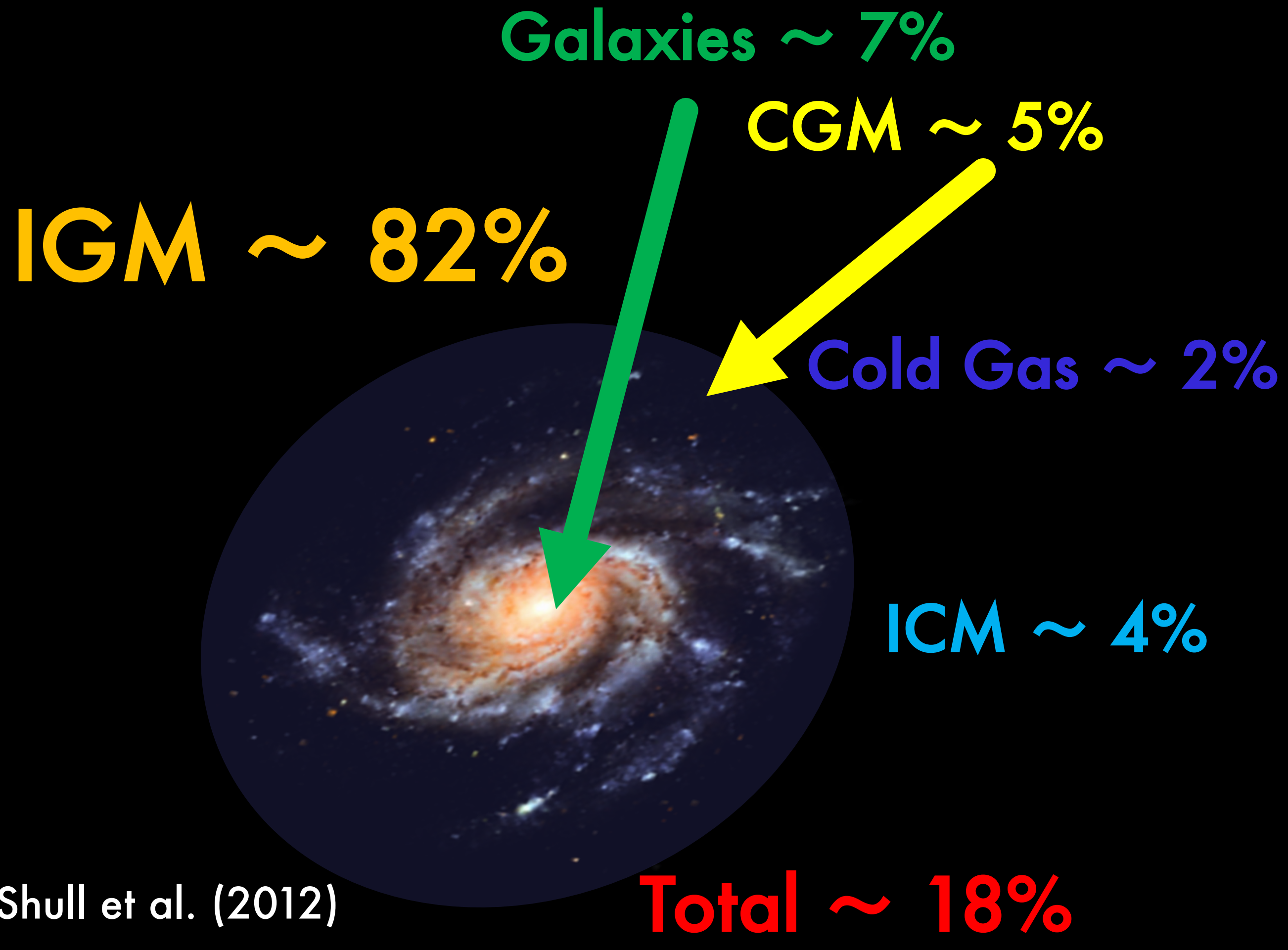
Total ~ 18%



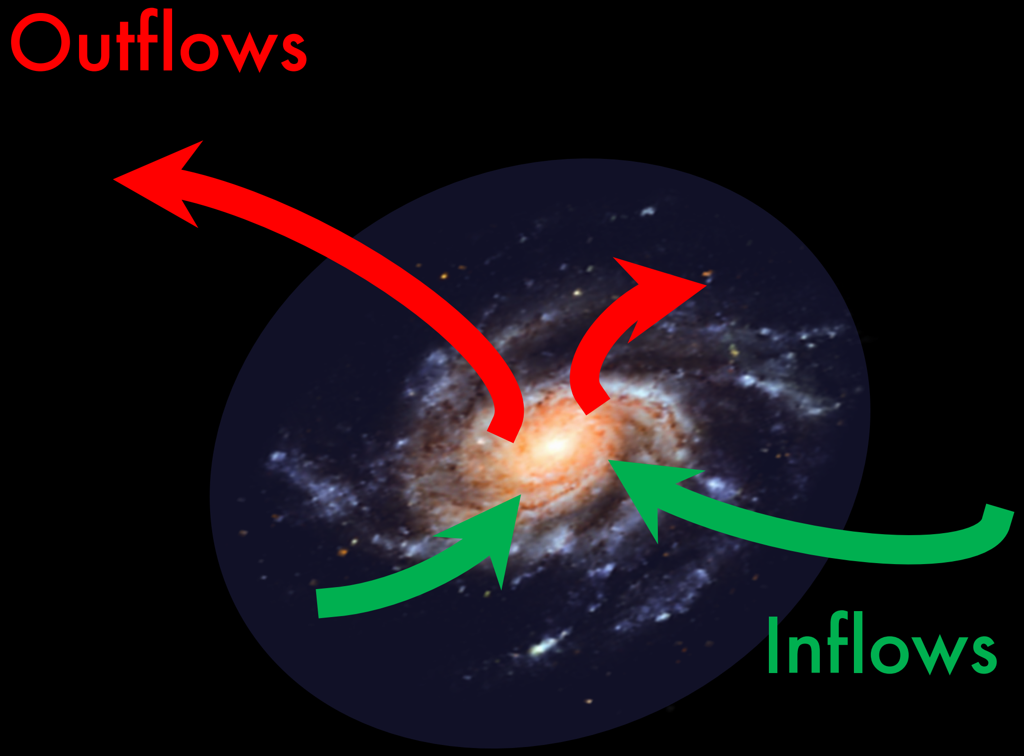
1. The IGM contains most of the baryonic matter

2. Galaxies and the IGM evolve together

Why Do We Care About the Intergalactic Medium?



Shull et al. (2012)



1. The IGM contains most of the baryonic matter

2. Galaxies and the IGM evolve together

Problems Observing the Intergalactic Medium

- Density ~ 1 particle per cubic meter
- Temperature $\sim 1 \times 10^6$ K

Problems Observing the Intergalactic Medium

- Density $\sim$ 1 particle per cubic meter
- Temperature $\sim 1 \times 10^6$ K

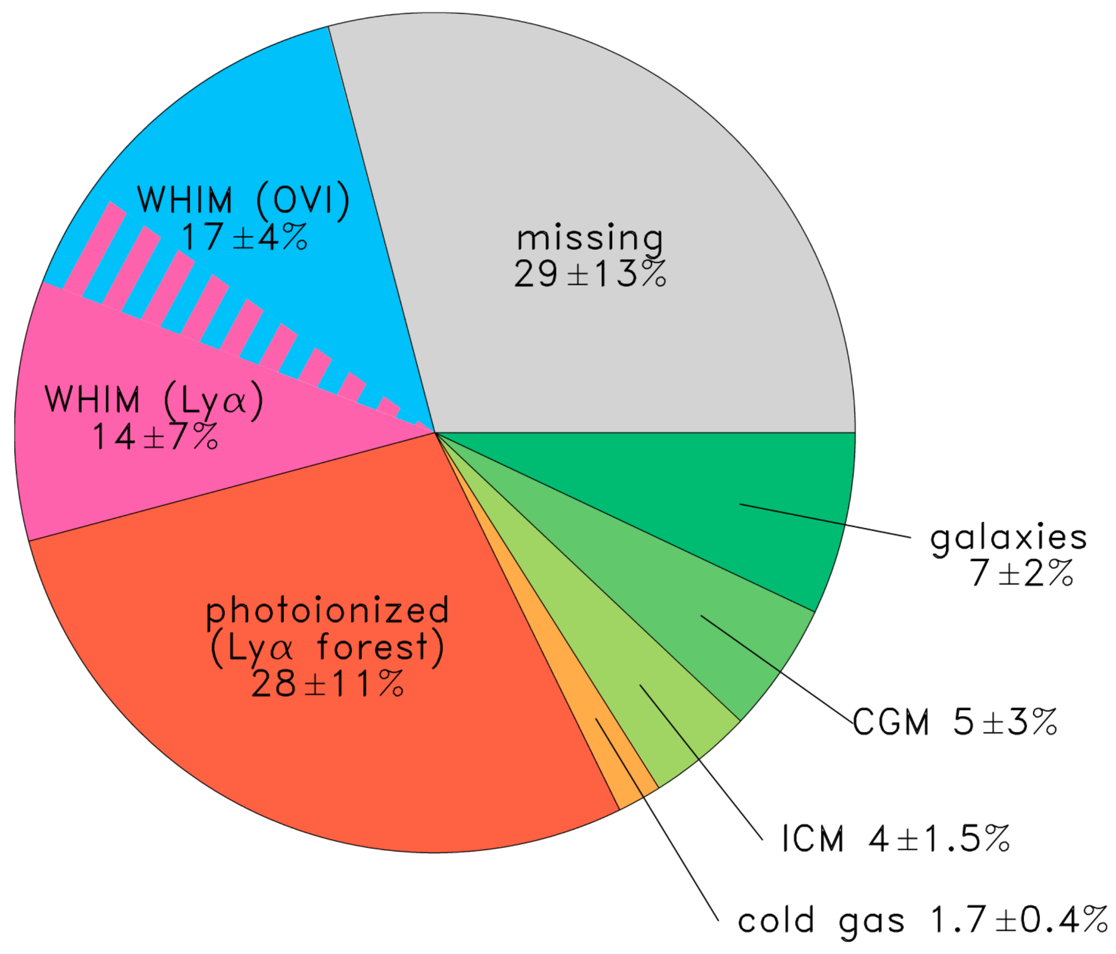
➽ Lack of favourable UV/Optical transition lines. Hard to observe!!!

Problems Observing the Intergalactic Medium

- Density ~ 1 particle per cubic meter
- Temperature ~ 1×10^6 K

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

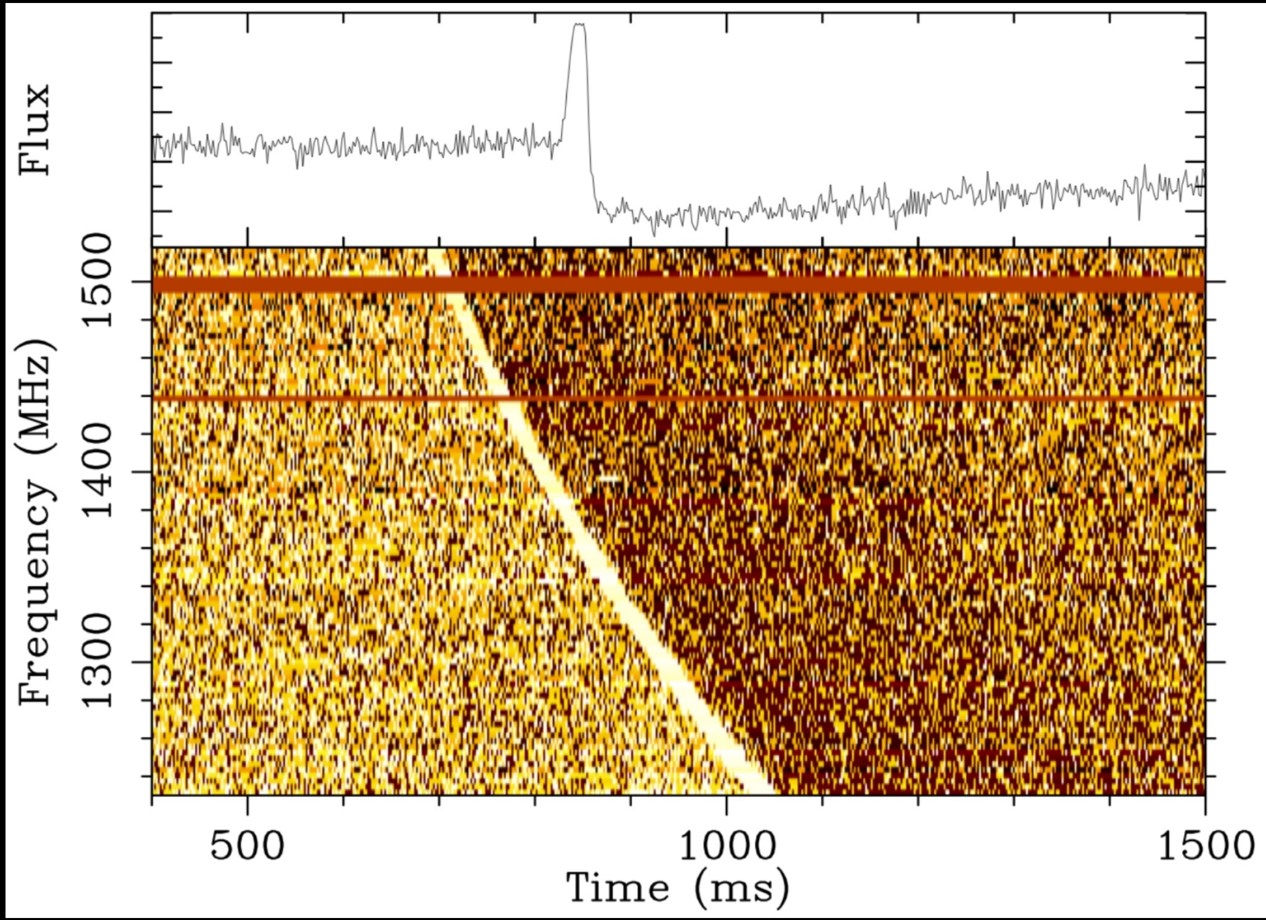
The Missing Baryon Problem: ~ 30% of baryons at low redshift appear to be missing!



Shull et al. (2012)

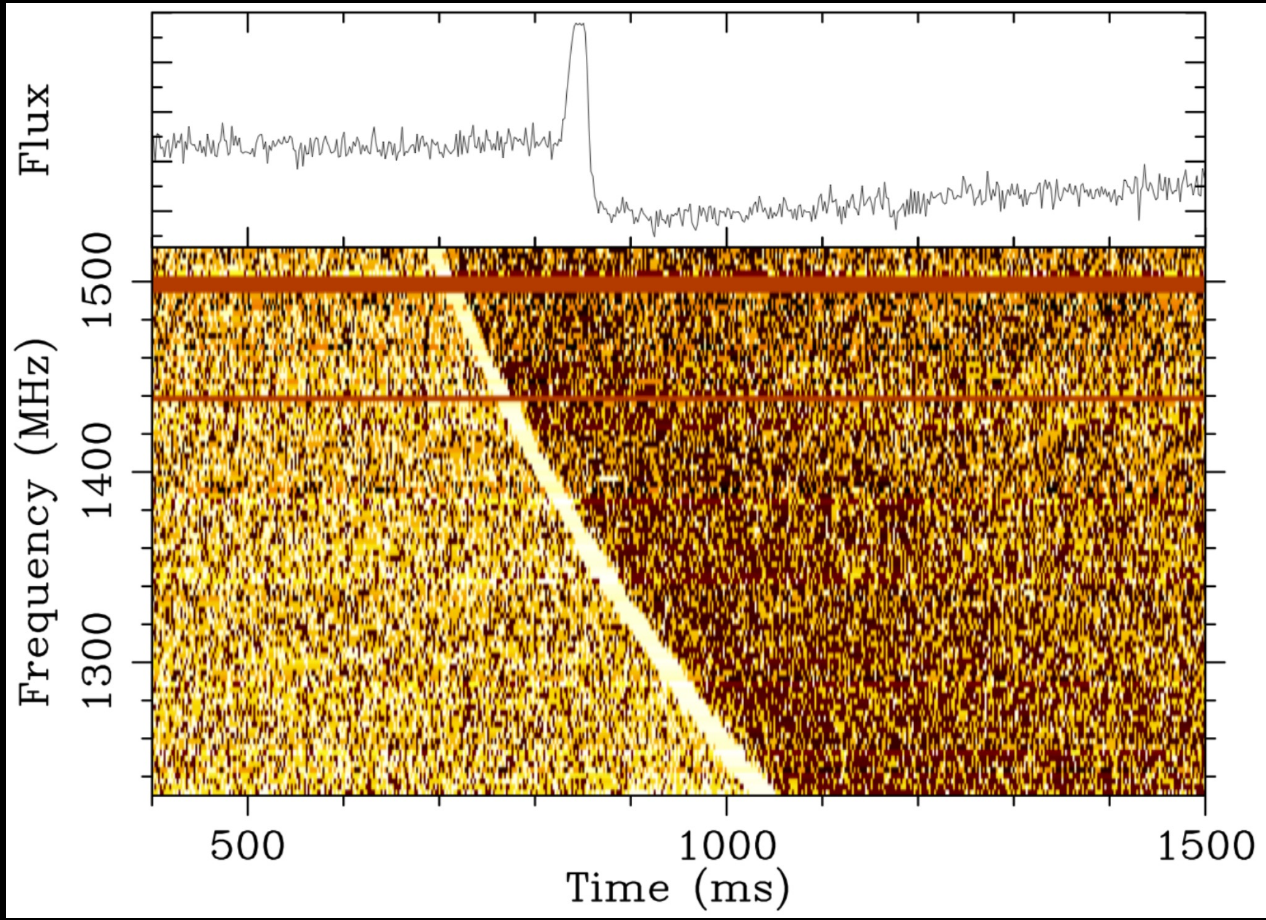
How do Fast Radio Bursts (FRBs) help?

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



How do Fast Radio Bursts (FRBs) help?

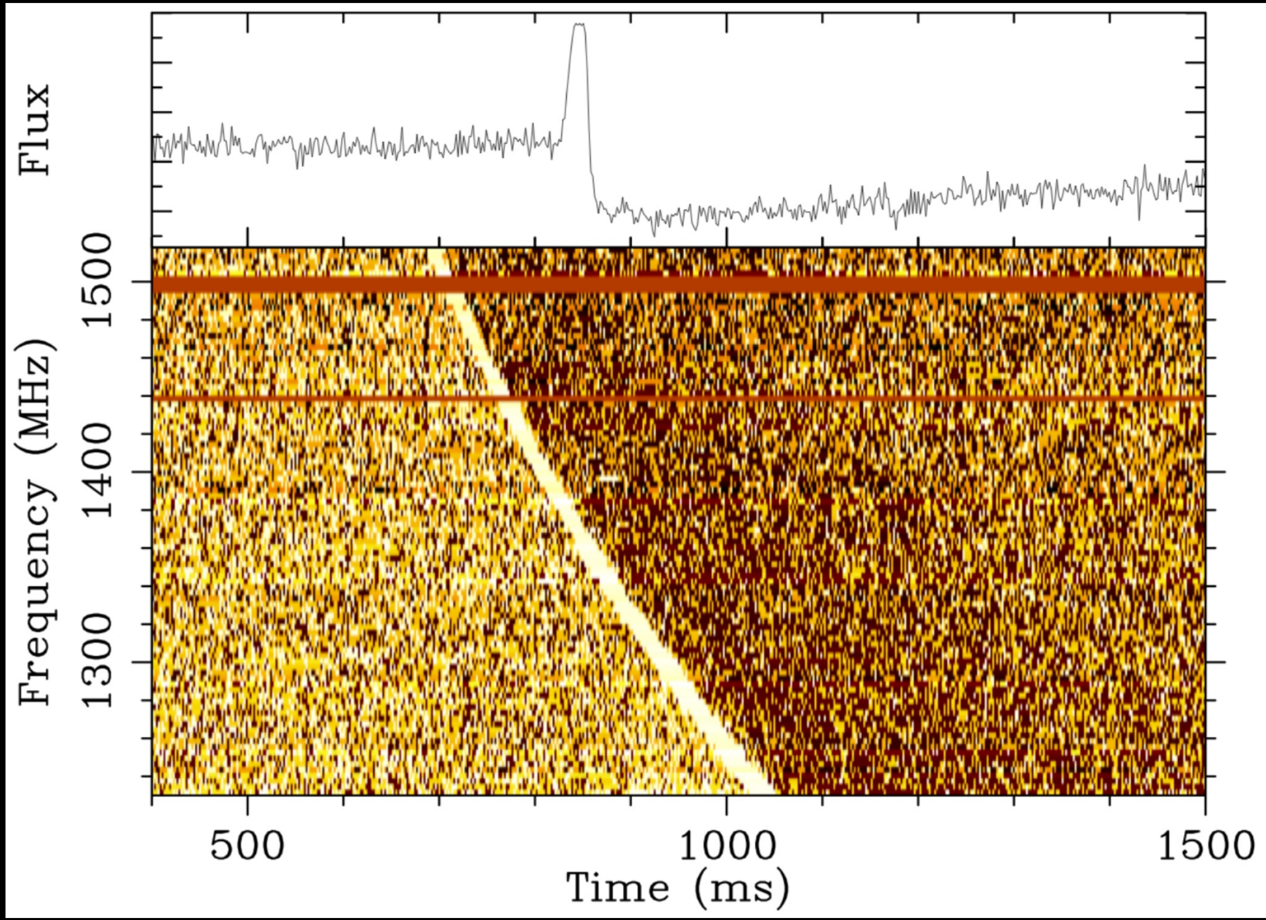
Lorimer et al. (2007)
Petroff et al. (2019)



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

How do Fast Radio Bursts (FRBs) help?

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

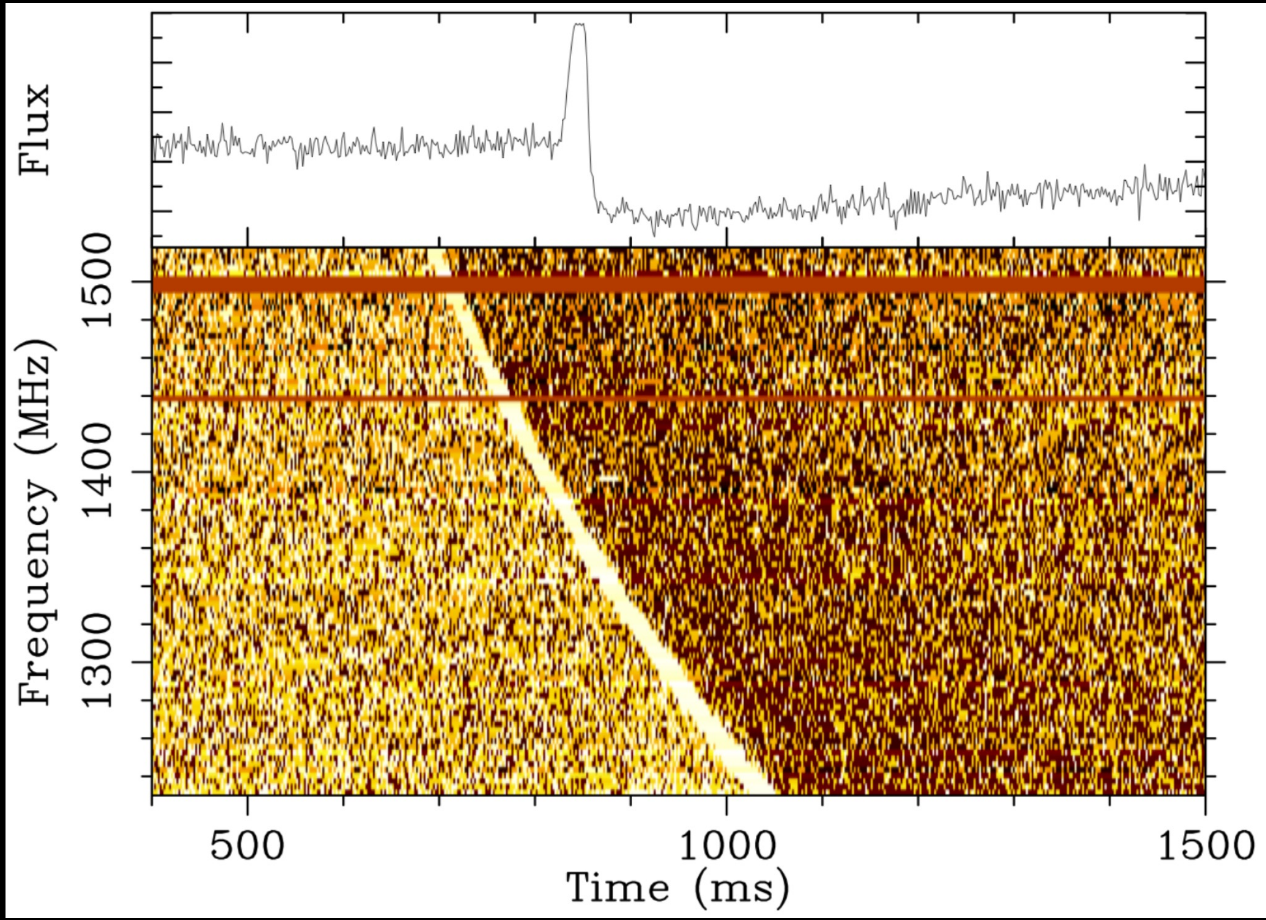


Electron number density

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

How do Fast Radio Bursts (FRBs) help?

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



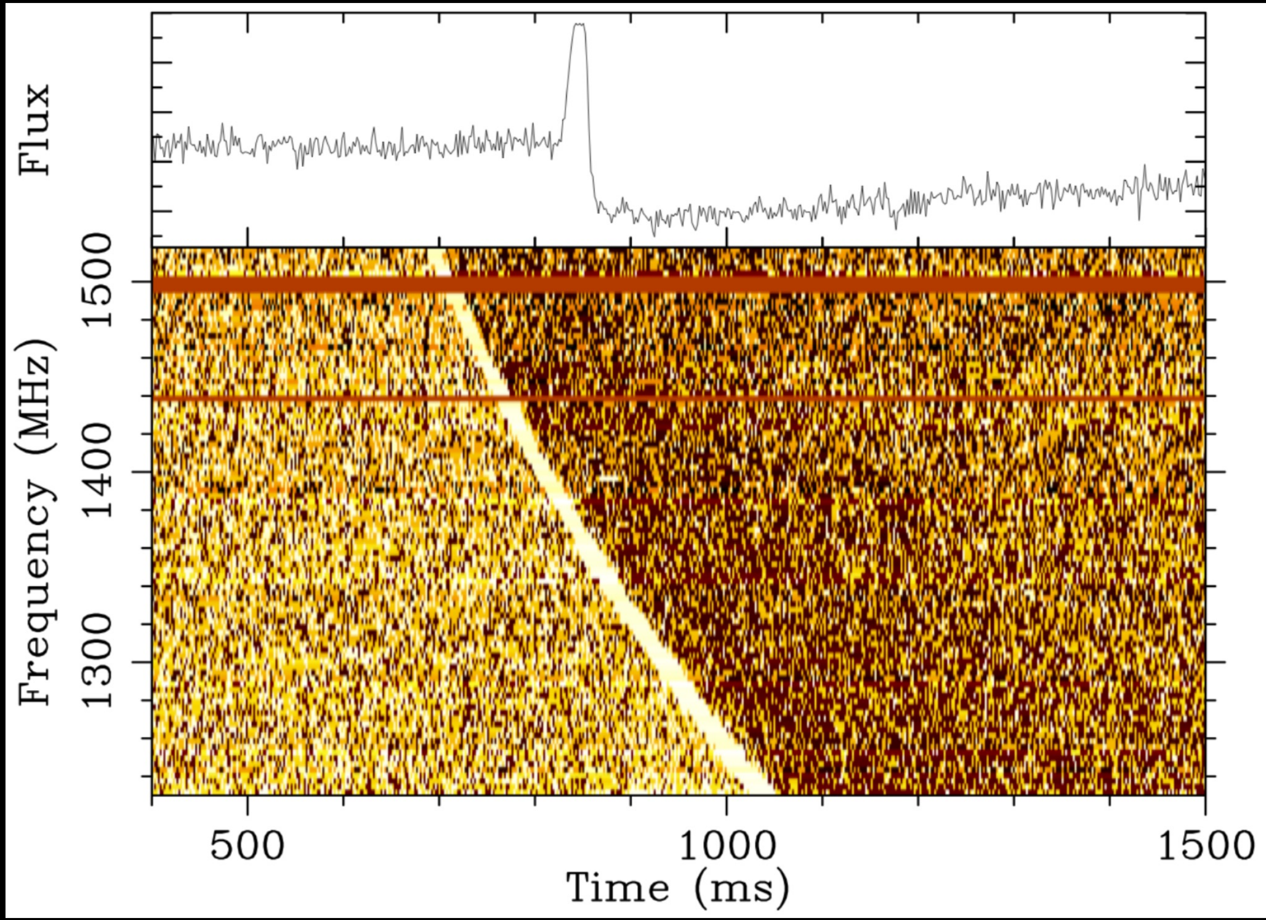
$$t = k\nu^{-2} \int_0^d n_e \, dl$$

Frequency

Electron number density

How do Fast Radio Bursts (FRBs) help?

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



Constant

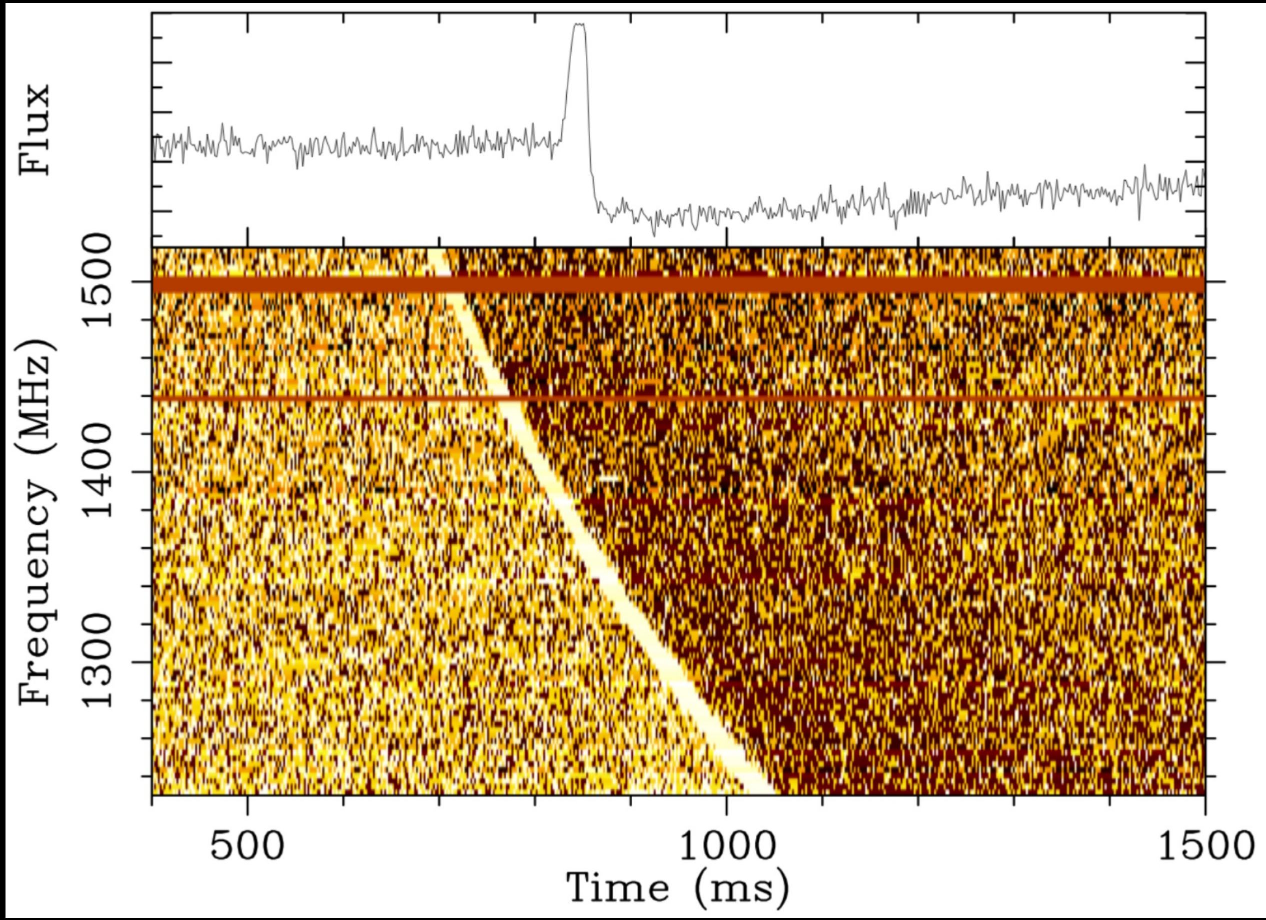
Electron number density

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

Frequency

How do Fast Radio Bursts (FRBs) help?

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



Constant

Frequency

Electron number density

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

$$\boxed{\mathrm{DM} = \int_0^d n_e \, dl}$$

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

Milky Way

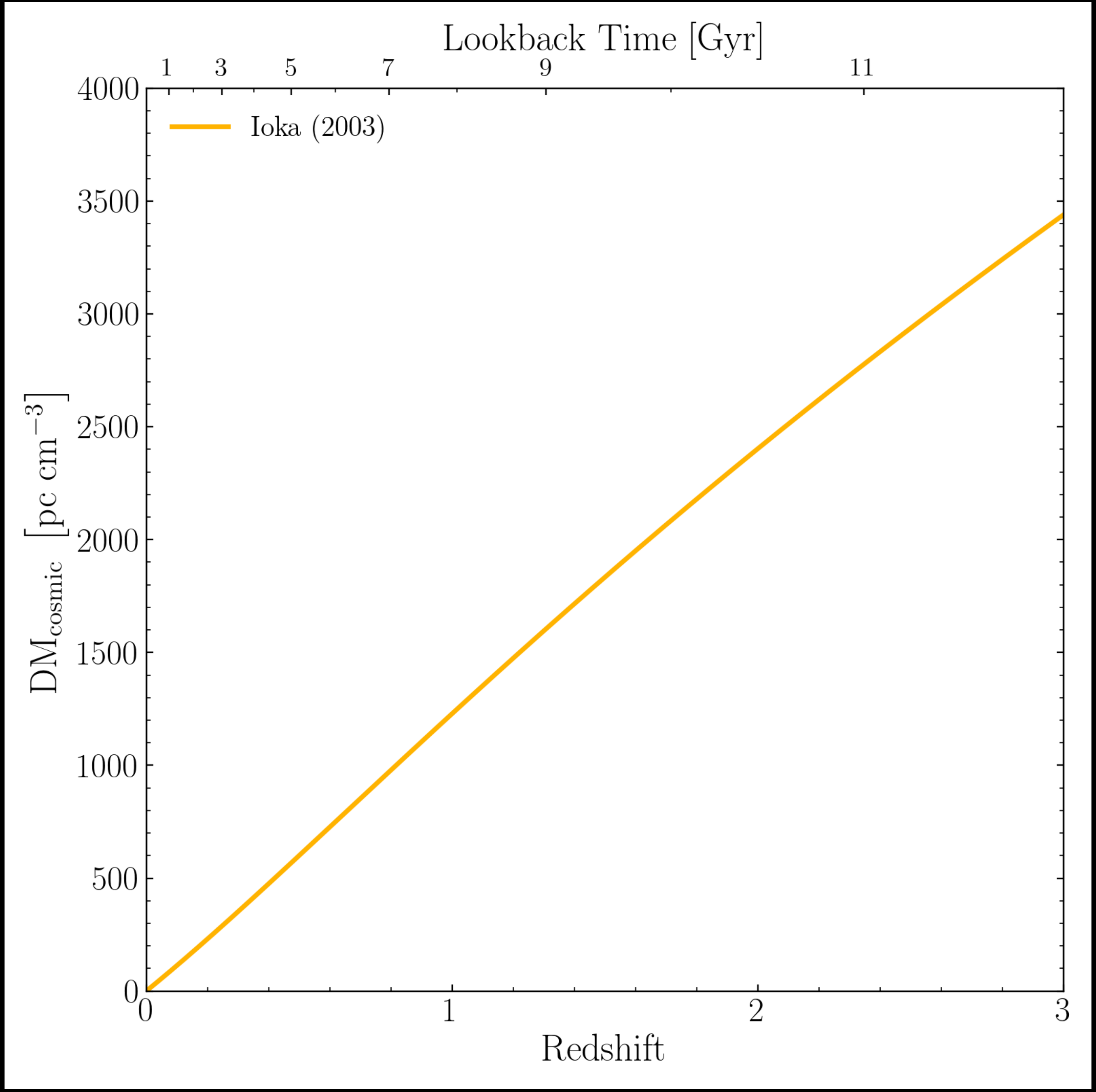
Host Galaxy/Local Environment

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

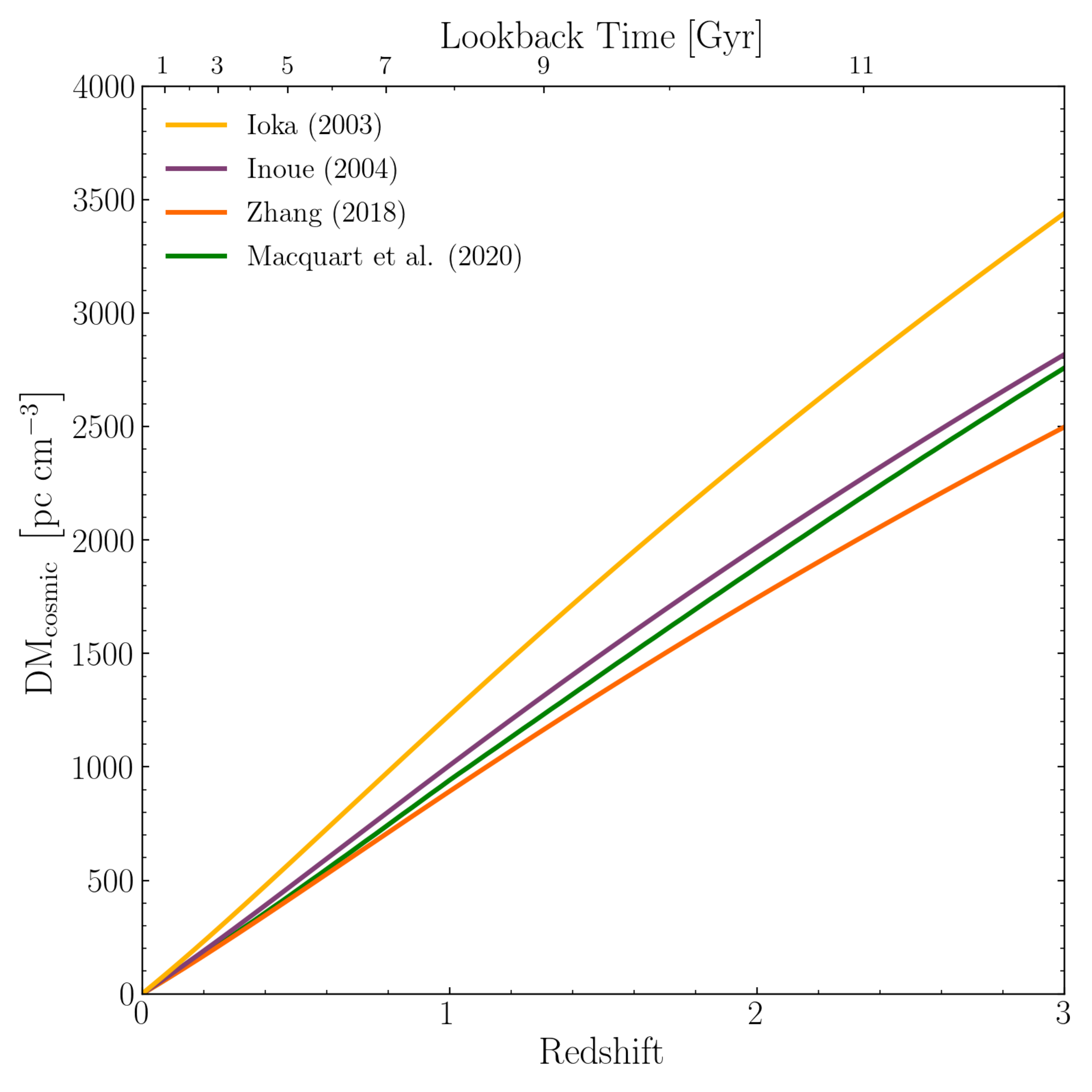
$$\mathrm{DM}_{\mathrm{cosmic}}(z) = \mathrm{DM}_{\mathrm{IGM}}(z) + \mathrm{DM}_{\mathrm{CGM,Interlopers}}$$

Intergalactic Medium

The CGM of Galaxies along the line-of-sight



Ioka (2003) [Analytic]

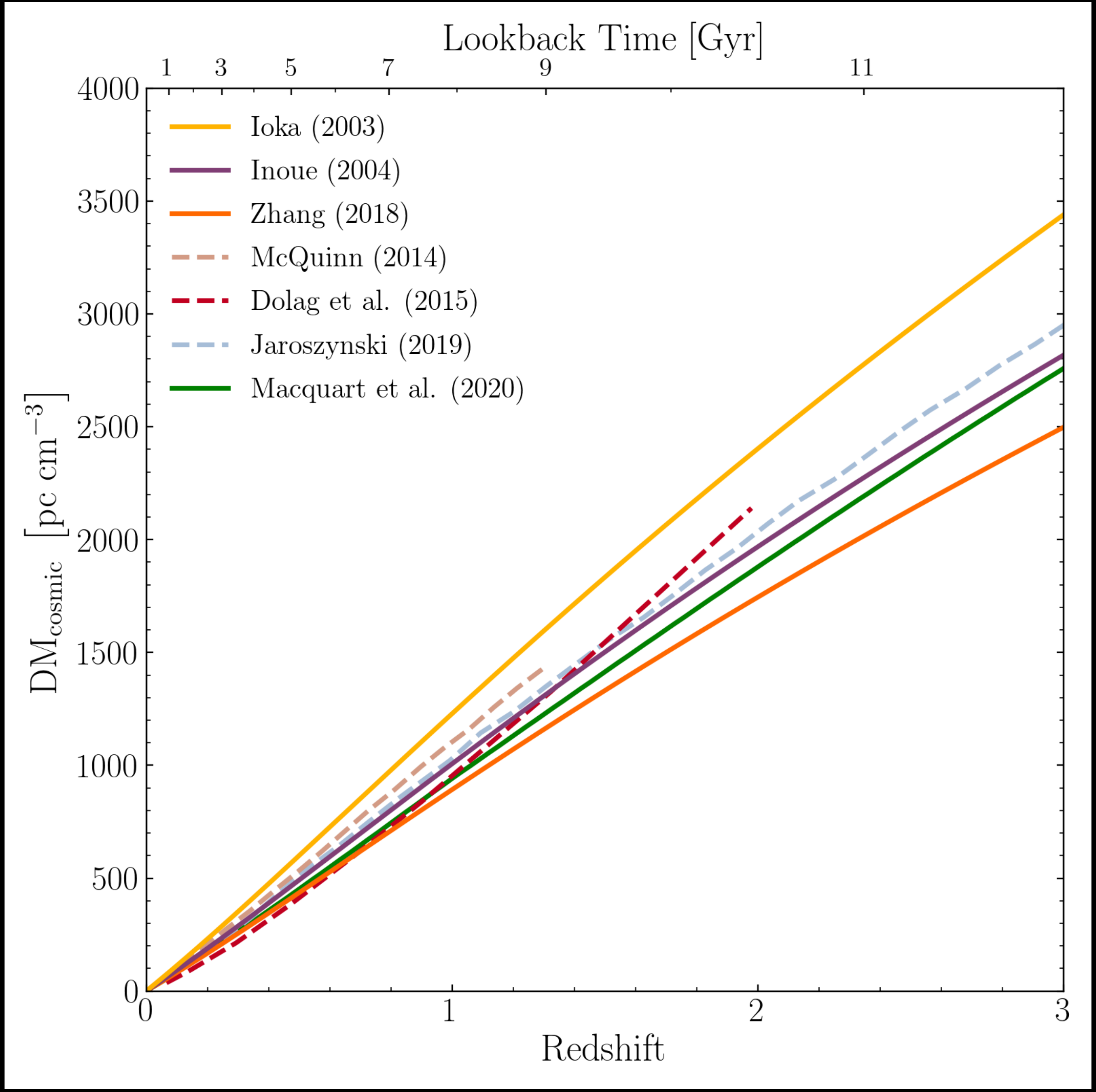


Ioka (2003) [Analytic]

Inoue (2004) [Analytic]

Zhang (2018) [Analytic]

Macquart+(2020) [Analytic]



Ioka (2003) [Analytic]

Inoue (2004) [Analytic]

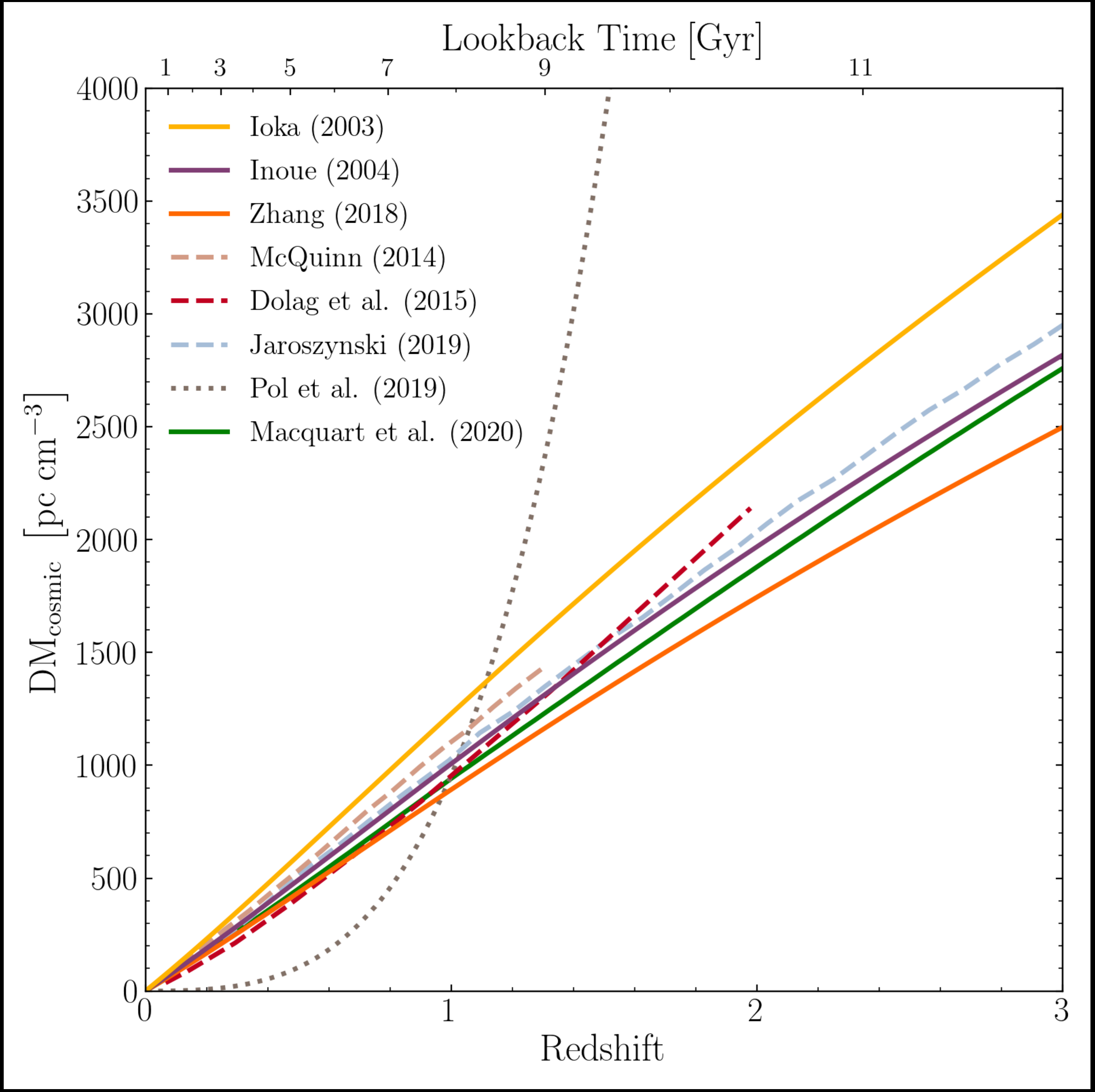
Zhang (2018) [Analytic]

McQuinn (2014) [Analytic+Hydro]

Dolag+(2015) [Hydro; Magneticum]

Jaroszynski (2019) [Hydro; Illustris]

Macquart+(2020) [Analytic]



Ioka (2003) [Analytic]

Inoue (2004) [Analytic]

Zhang (2018) [Analytic]

McQuinn (2014) [Analytic+Hydro]

Dolag+(2015) [Hydro; Magneticum]

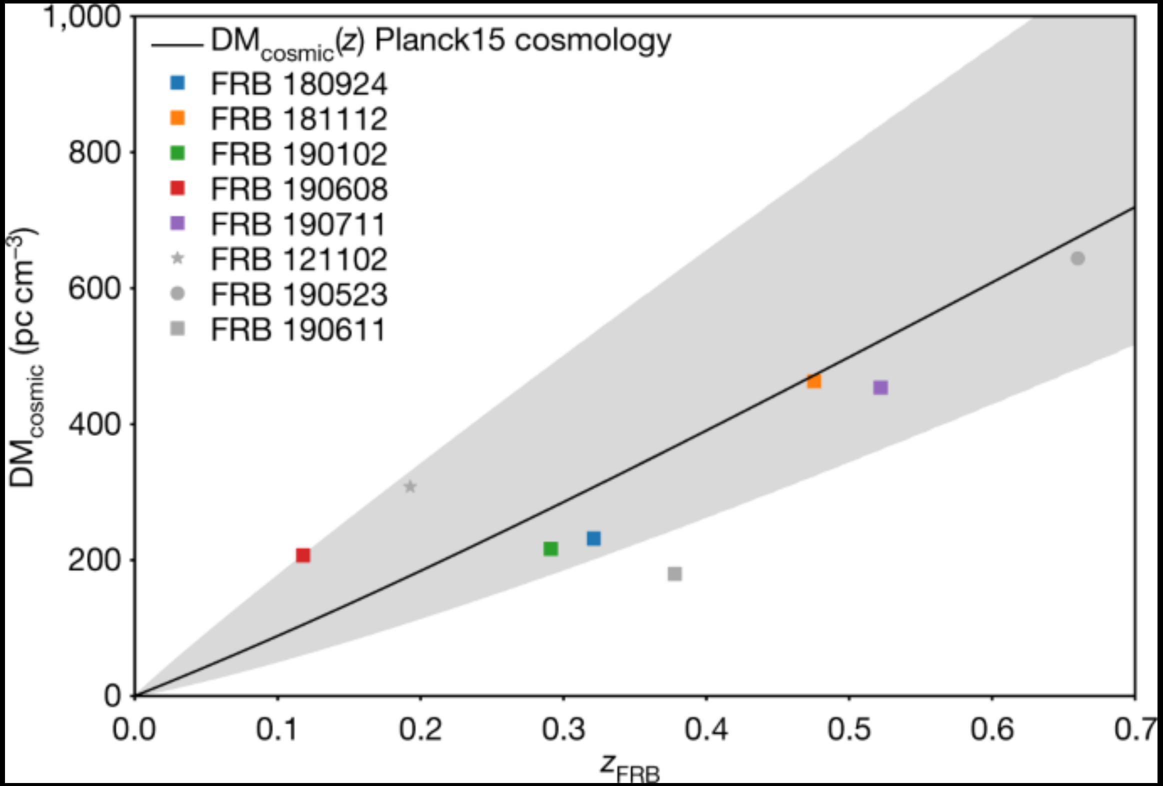
Jaroszynski (2019) [Hydro; Illustris]

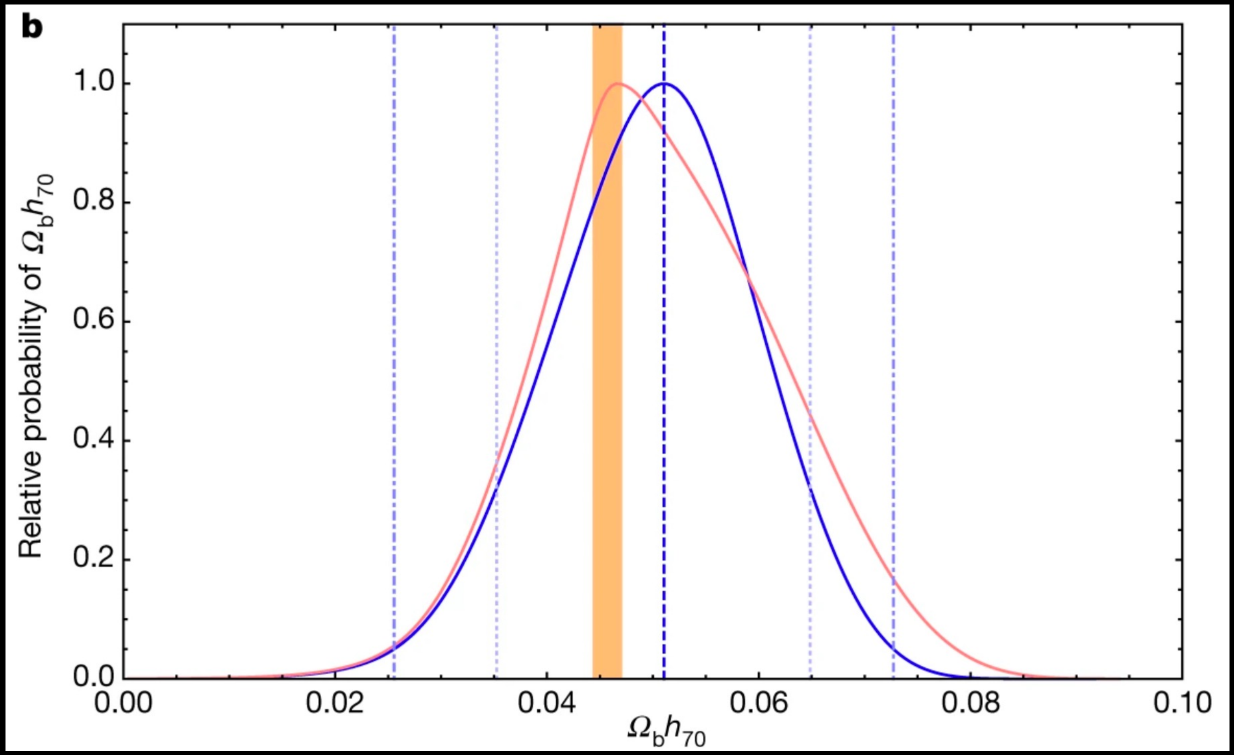
Pol+(2019) ["Semi-Analytic"; MICE]

Macquart+(2020) [Analytic]

Macquart et al. (2020)

FRBs and the Missing Baryon Problem





Batten et al. 2021a (arxiv:2011.14547)

The Cosmic Dispersion Measure in the EAGLE Simulations

Adam J. Batten,[1,2]★ Alan R. Duffy,[1,2] Nastasha A. Wijers,[3] Vivek Gupta,[1] Chris Flynn,[1]
Joop Schaye,[3] Emma Ryan-Weber[1,2]

[1] *Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Melbourne, Victoria 3122, Australia*
[2] *ARC Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D)*
[3] *Sterrewacht, Leiden University, Niels Bohrweg 2, 2333 CA Leiden, The Netherlands*

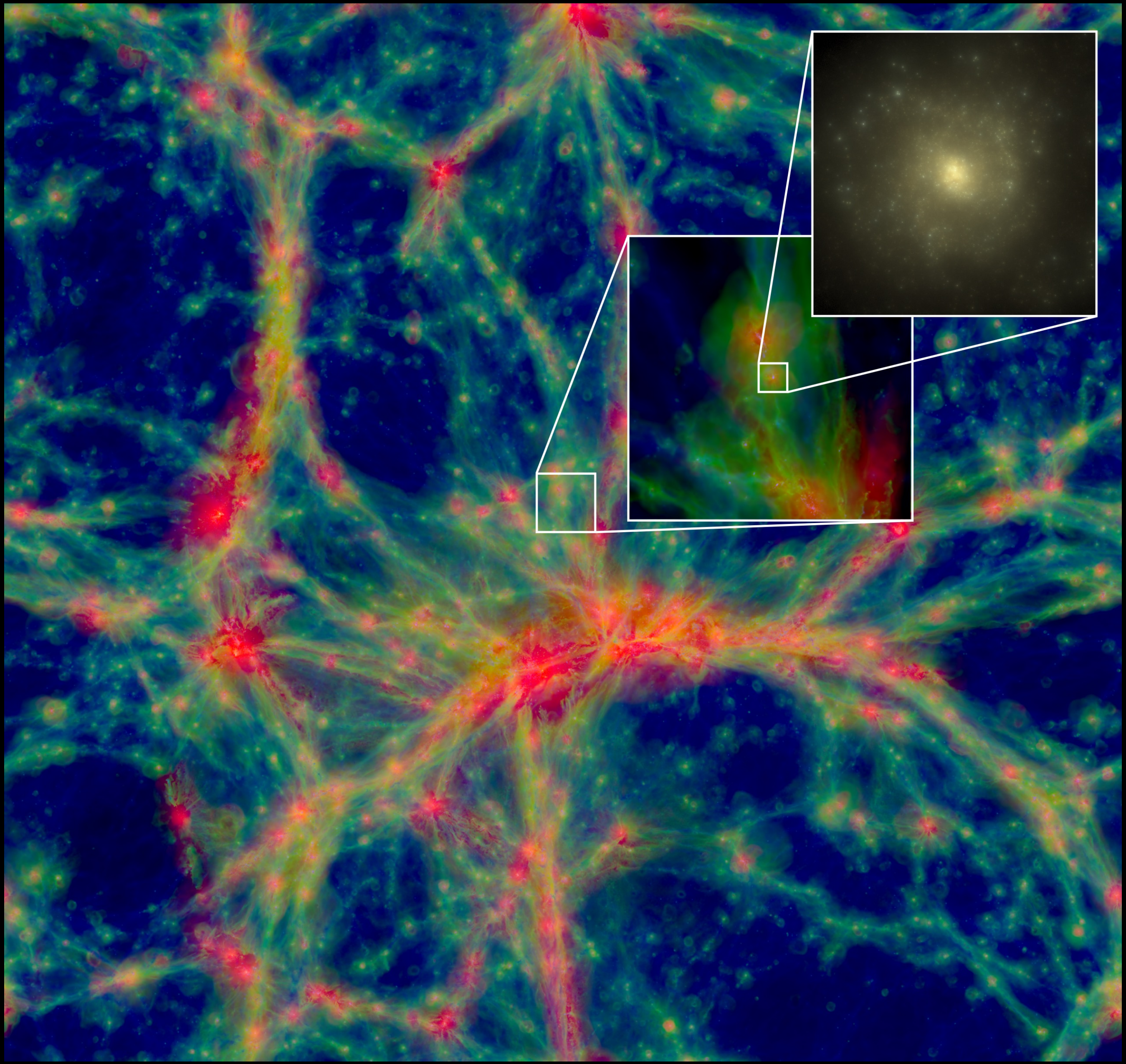
Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

The dispersion measure (DM) of fast radio bursts (FRBs) provides a unique way to probe ionised baryons in the intergalactic medium (IGM). Cosmological models with different parameters lead to different DM-redshift (DM – z) relations. Additionally, the over/under-dense regions in the IGM and the circumgalactic medium of intervening galaxies lead to scatter around the mean DM – z relations. We have used the Evolution and Assembly of GaLaxies and their Environments (EAGLE) simulations to measure the mean DM – z relation and the scatter around it using over one billion lines-of-sight between redshifts $0 < z < 3$. We investigated two techniques to estimate line-of-sight DM: ‘pixel scrambling’ and ‘box transformations’. We find that using box transformations (a technique from the literature) causes strong correlations due to repeated replication of structure. Comparing a linear and non-linear model, we find that the non-linear model with cosmological parameters, provides a better fit to the DM – z relation. The differences between these models are the most significant at low redshifts ($z < 0.5$). The scatter around the DM – z relation is highly asymmetric, especially at low redshift ($z < 0.5$), and becomes more Gaussian as redshift approaches $z \sim 3$, the limit of this study. The increase in Gaussianity with redshift is indicative of the large scale structures that is better probed with longer lines-of-sight. The minimum simulation size suitable for investigations into the scatter around the DM – z relation is 100 comoving Mpc. The DM – z relation measured in EAGLE is available with an easy-to-use python interface in the open-source FRB redshift estimation package FRUITBAT.

Key words: intergalactic medium – hydrodynamics – methods: numerical – radio continuum: general

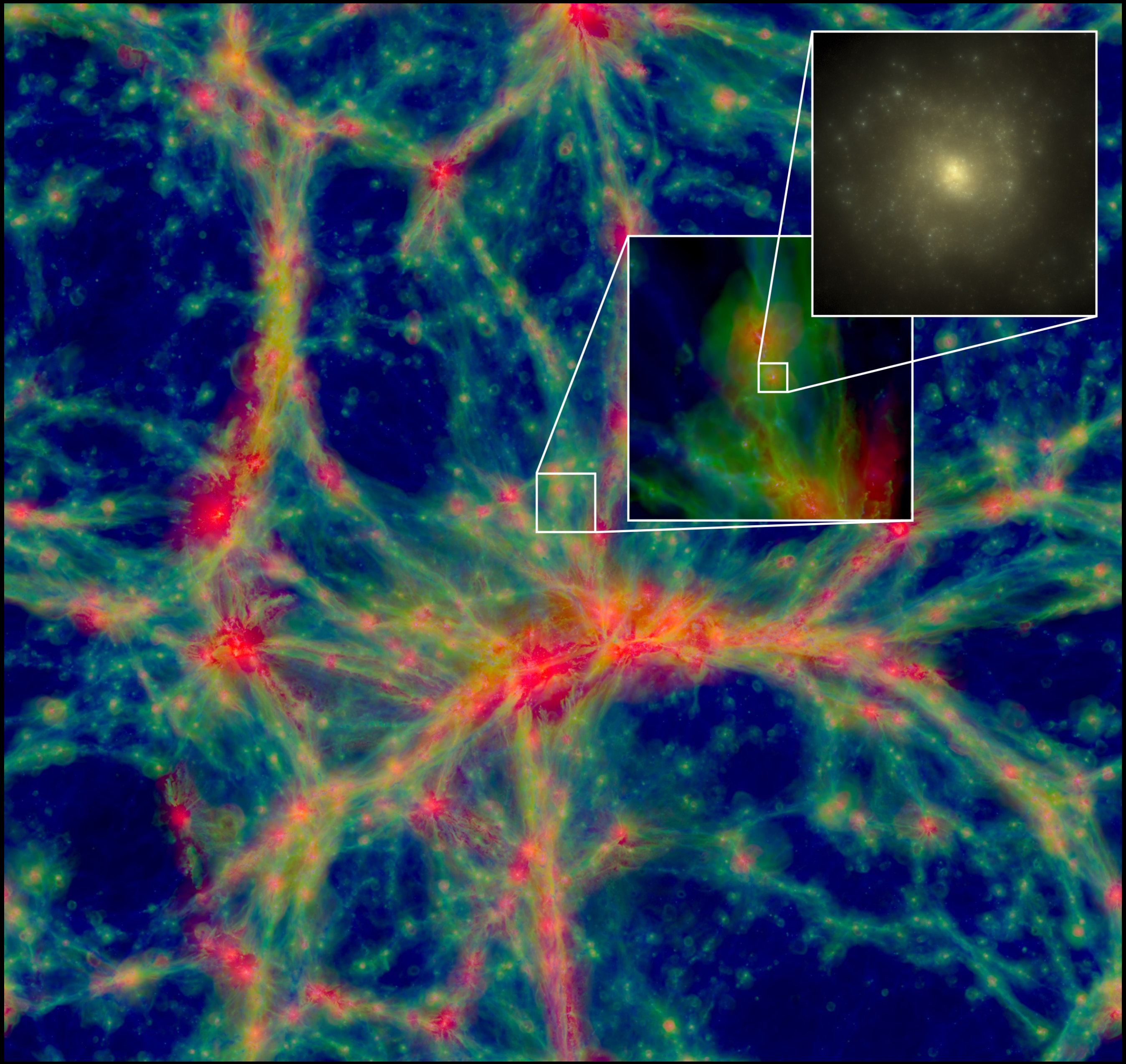
Batten et al. 2021a (arxiv:2011.14547)



EAGLE Simulations

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

Batten et al. 2021a (arxiv:2011.14547)

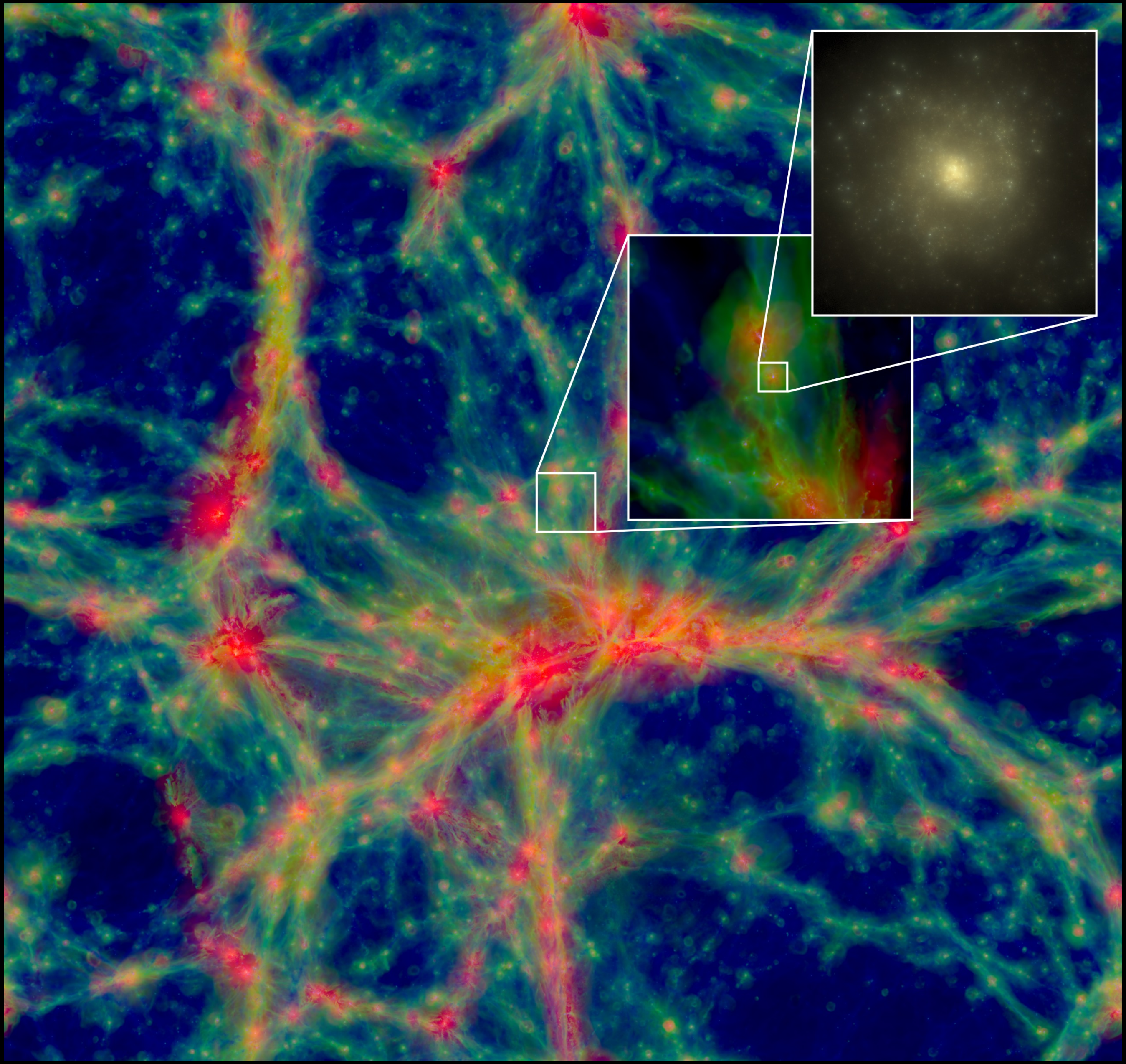


EAGLE Simulations

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

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

Batten et al. 2021a (arxiv:2011.14547)



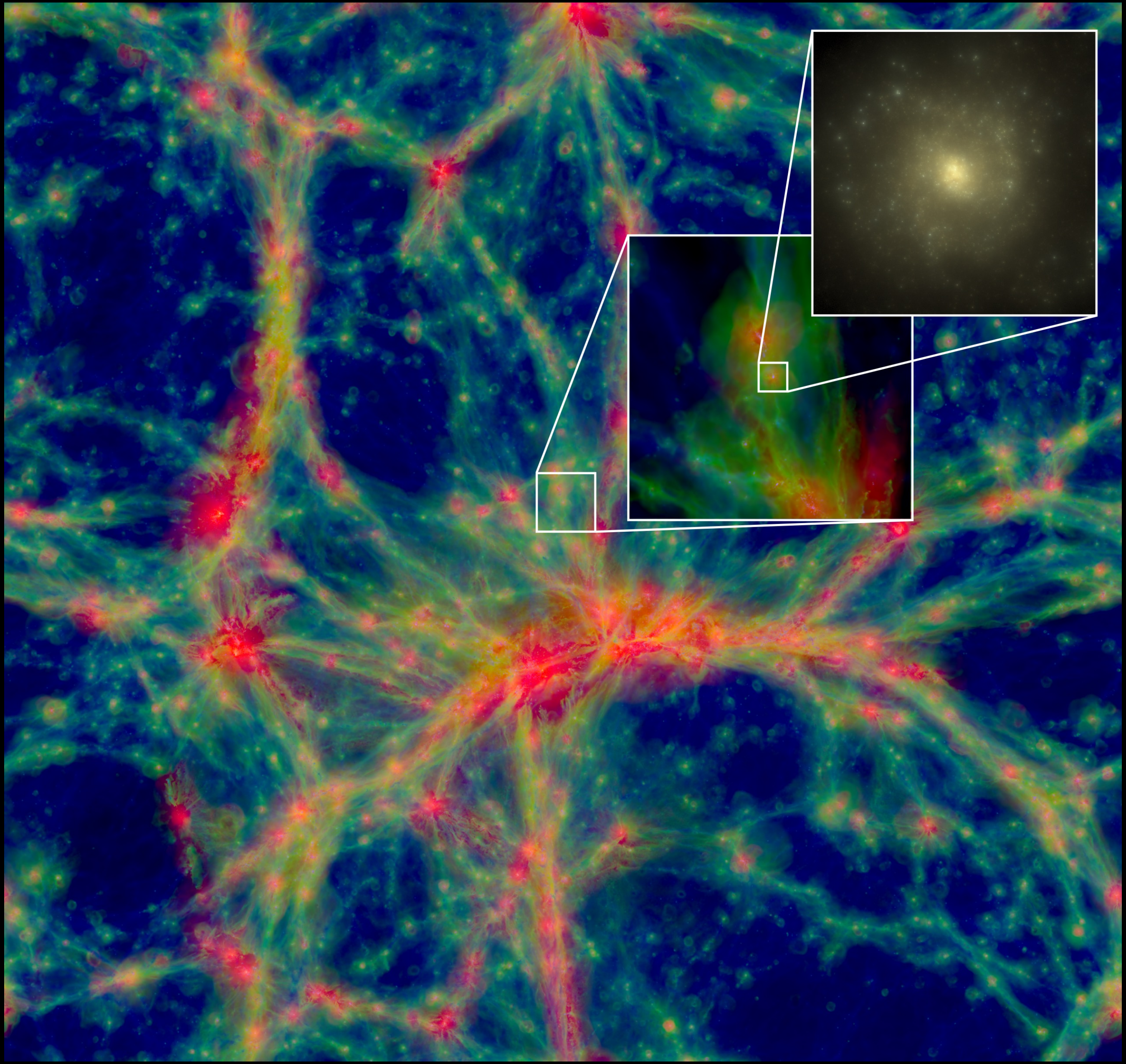
EAGLE Simulations

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

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

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

Batten et al. 2021a (arxiv:2011.14547)



EAGLE Simulations

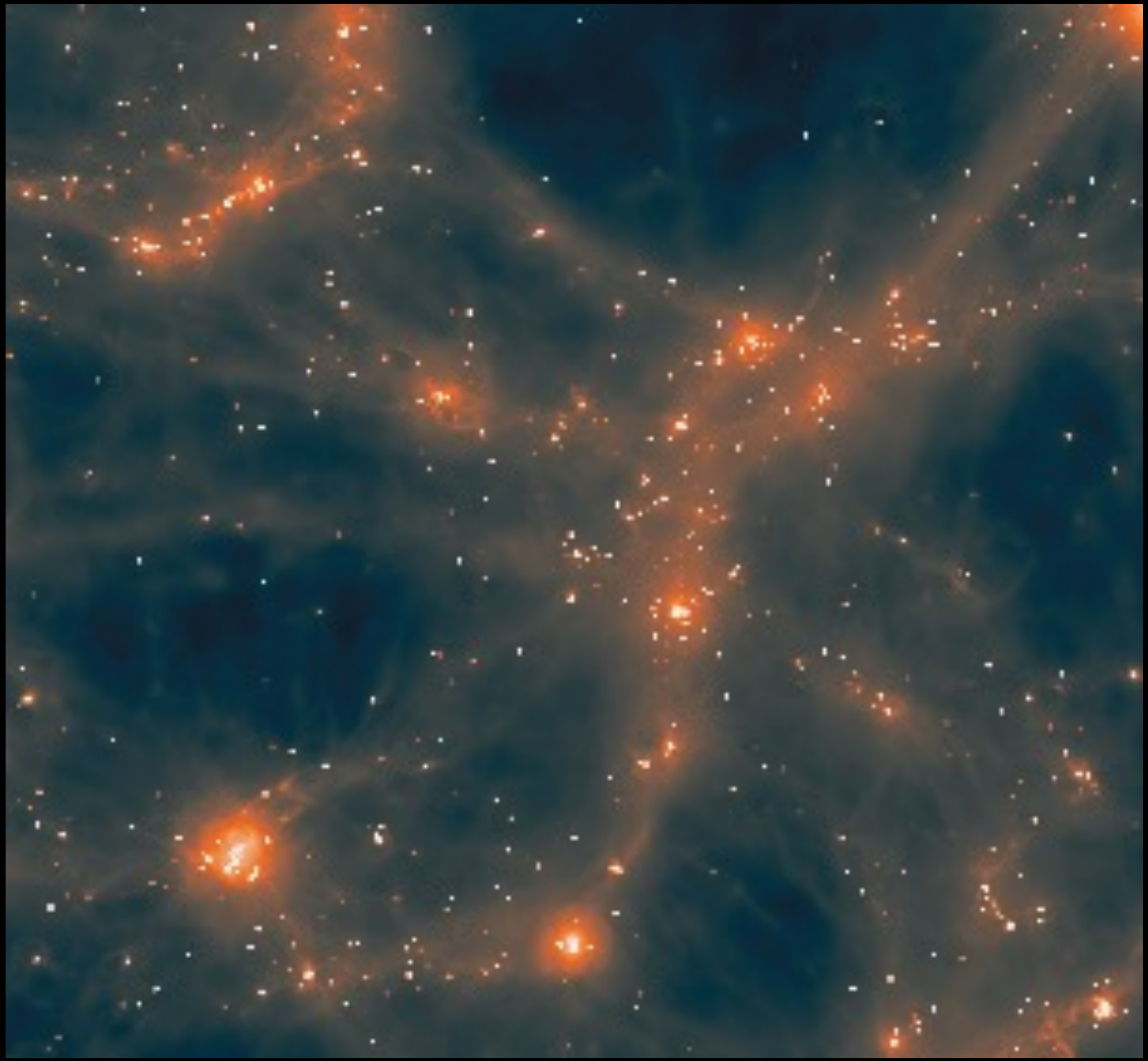
Schaye et al. (2015), Crain et al (2015)

- 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

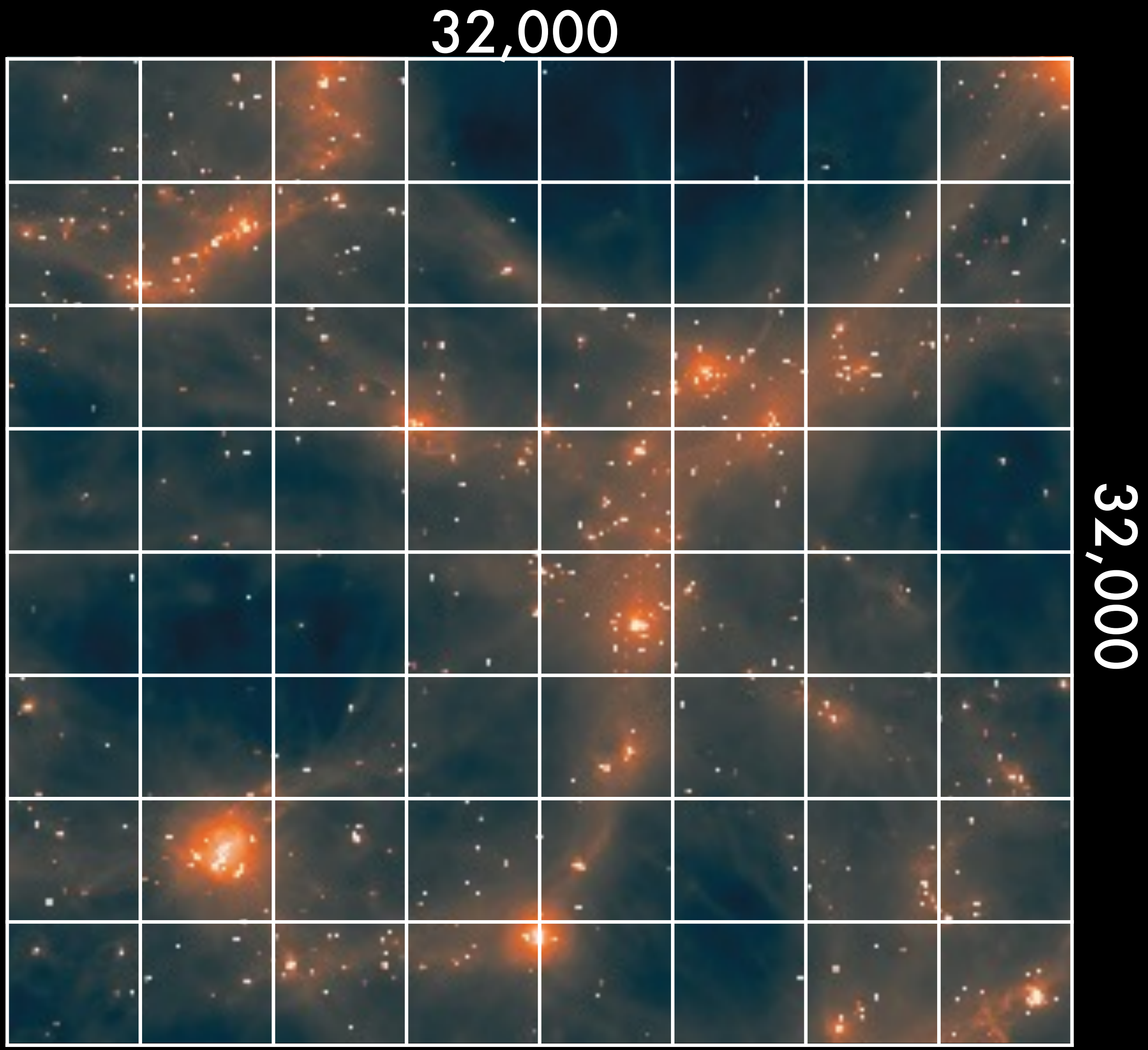
- Resolution: $\sim$ 0.7 ckpc
- Particle Masses: $\sim 10^6\ M_\odot$

Batten et al. 2021a (arxiv:2011.14547)



EAGLE Simulations

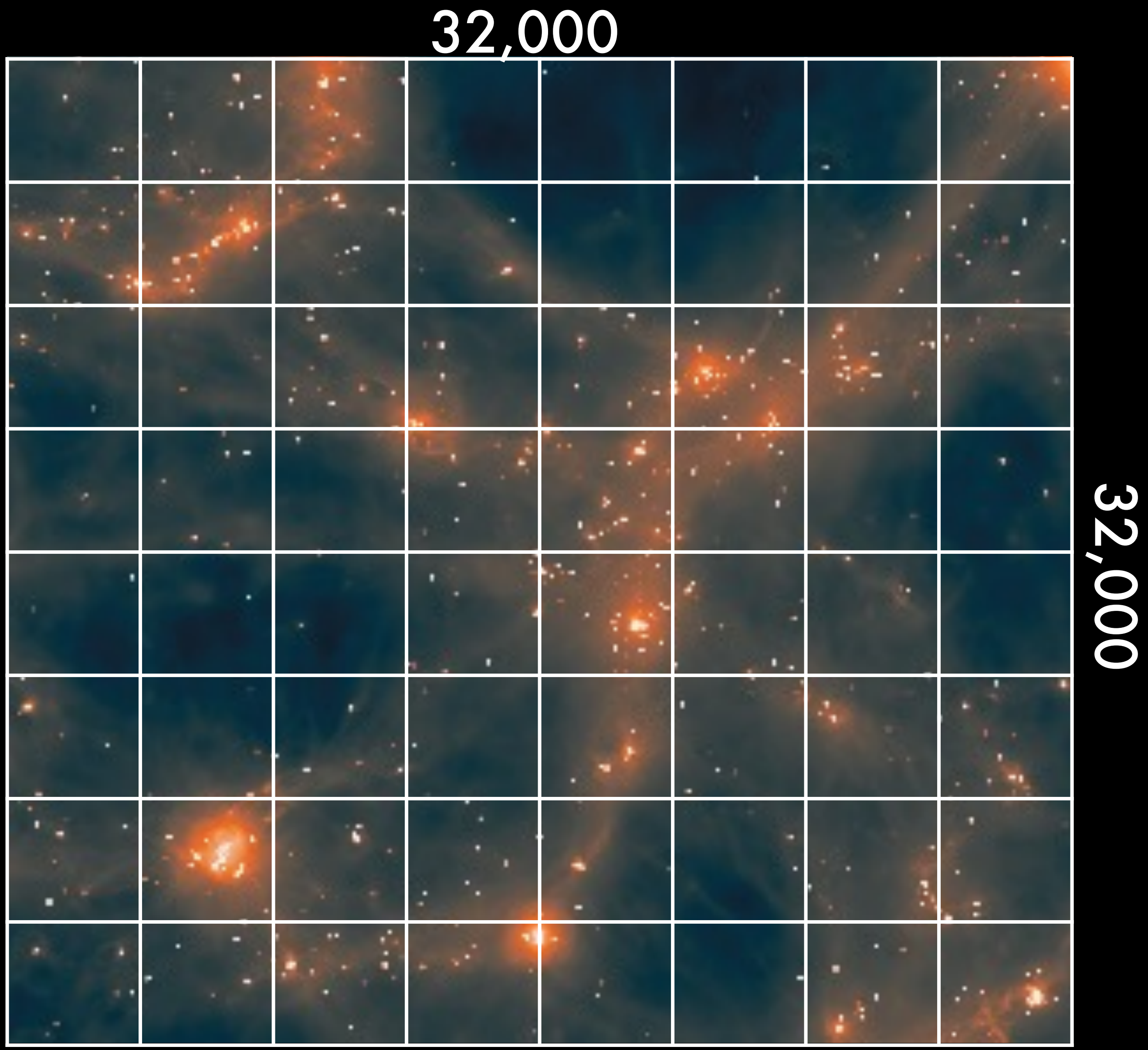
Batten et al. 2021a (arxiv:2011.14547)



EAGLE Simulations

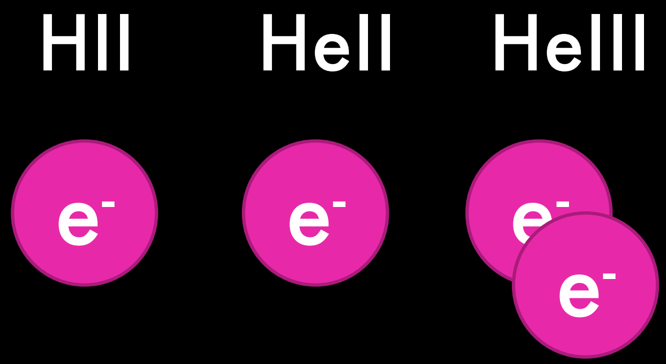
- Divide cube into columns

Batten et al. 2021a (arxiv:2011.14547)

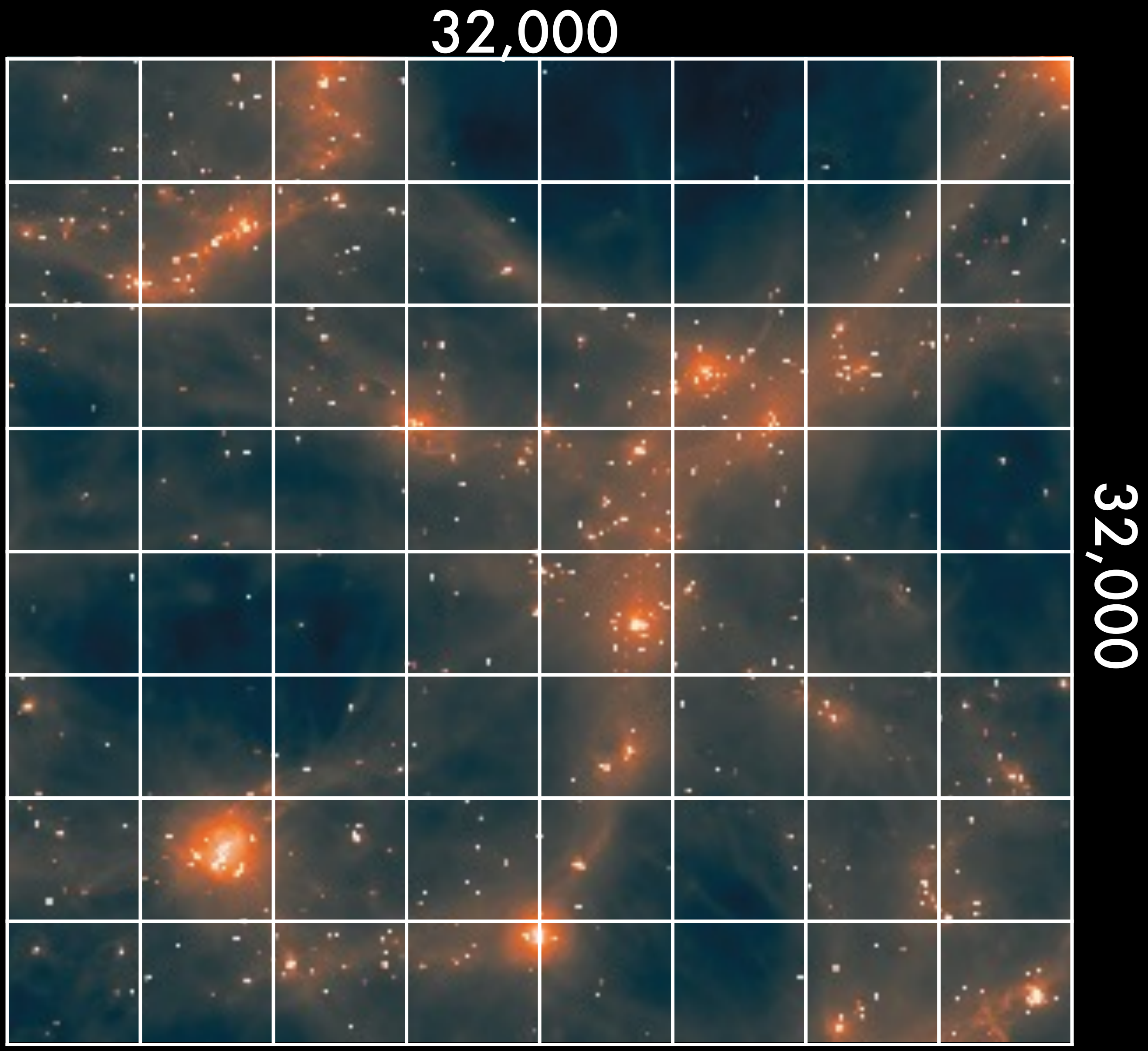


EAGLE Simulations

- ➢ Divide cube into columns
- ➢ Calculate column densities
  - Rahmati et al. (2013) (SS)
  - Wijers et al. (2019)

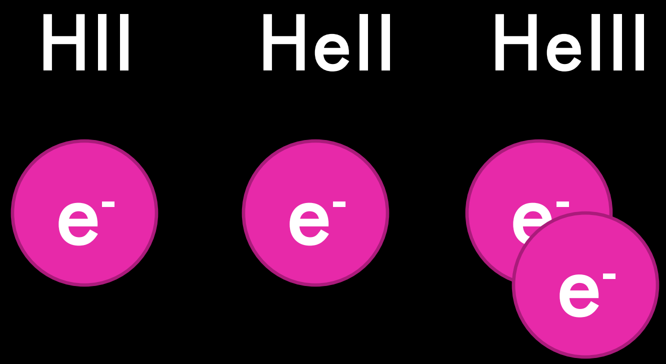


Batten et al. 2021a (arxiv:2011.14547)



EAGLE Simulations

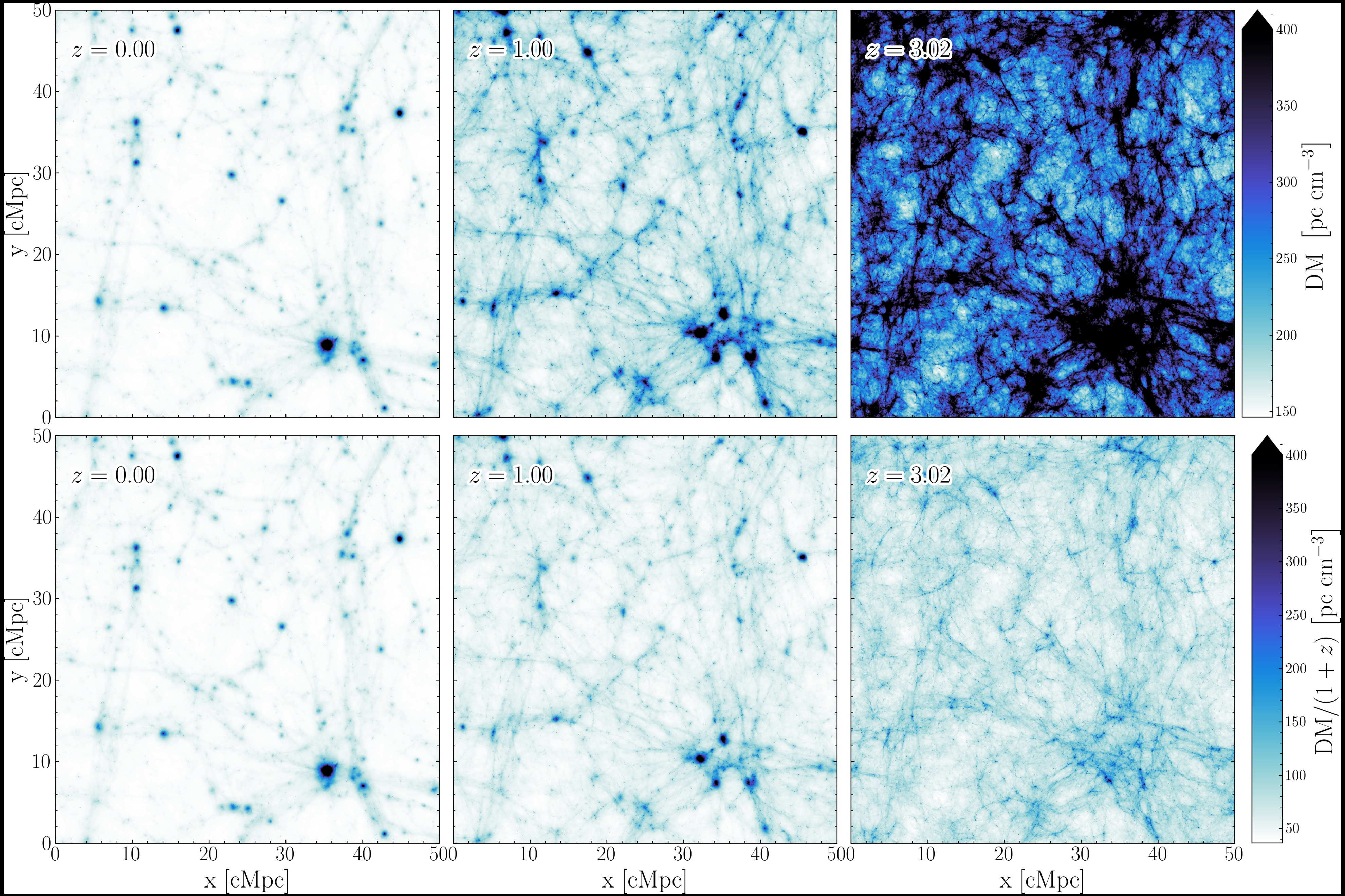
- Divide cube into columns
- Calculate column densities
  - Rahmati et al. (2013) (SS)
  - Wijers et al. (2019)
- Convert column densities to units of pc cm^{-3}



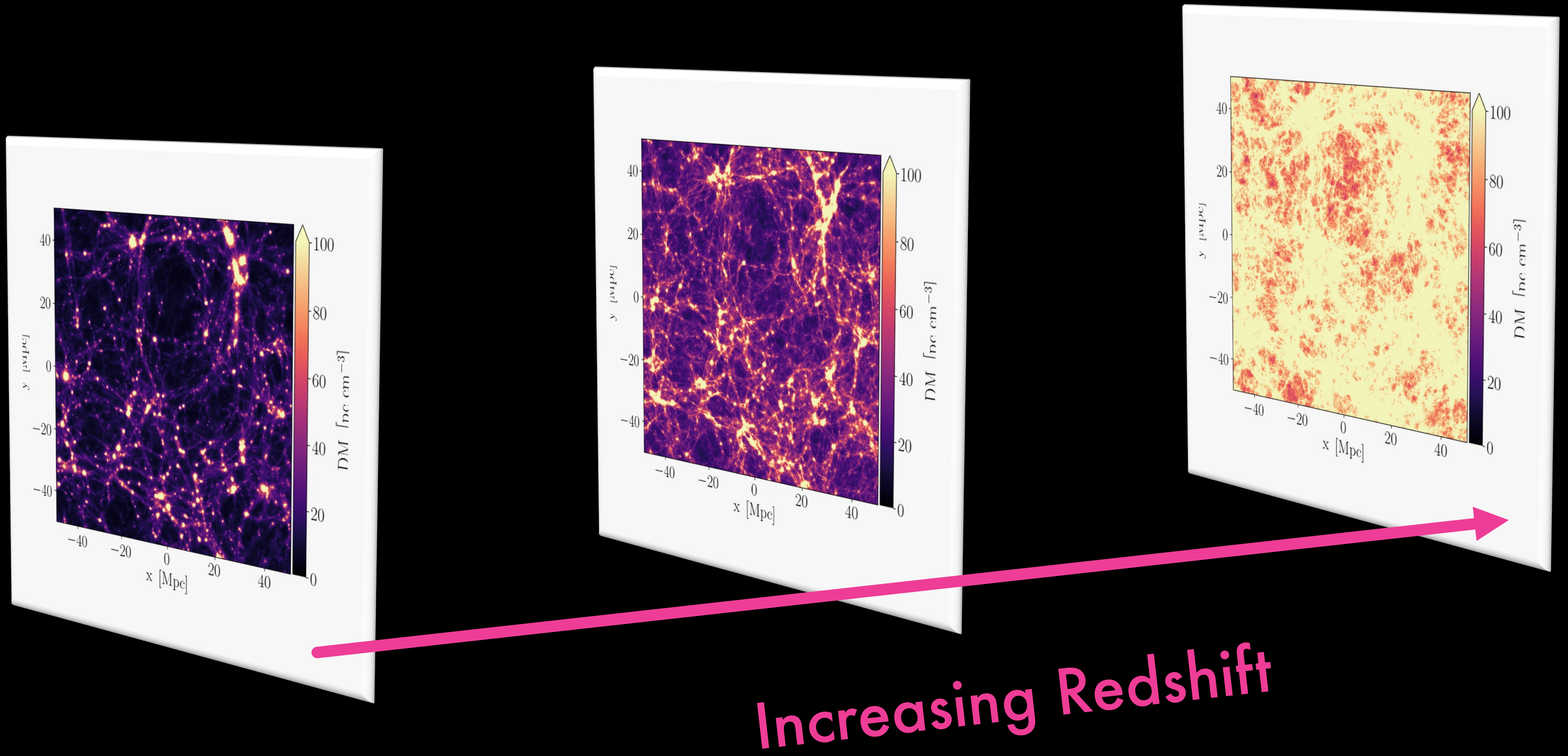
Batten et al. 2021a (arxiv:2011.14547)

Local Observer

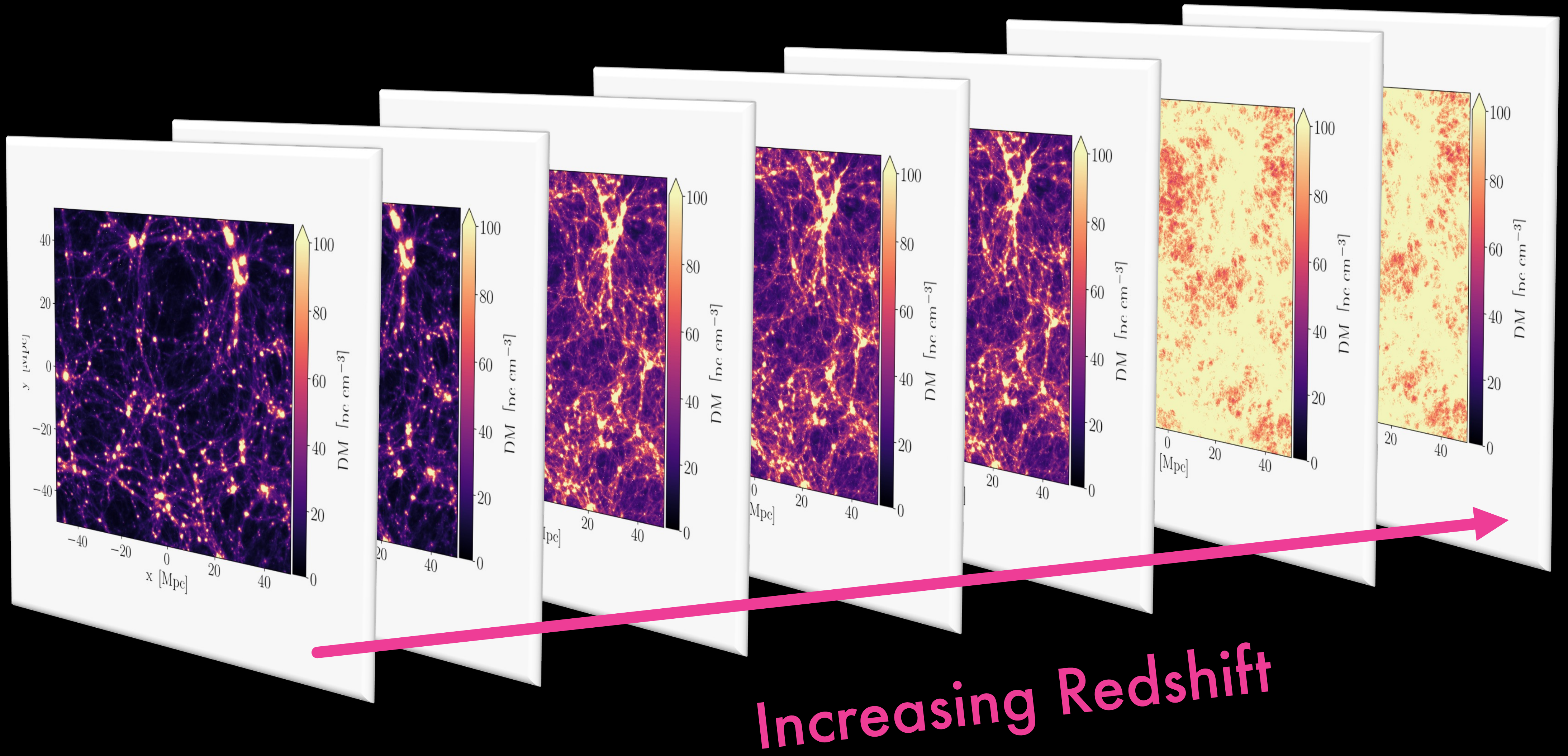
$z = 0$ Observer



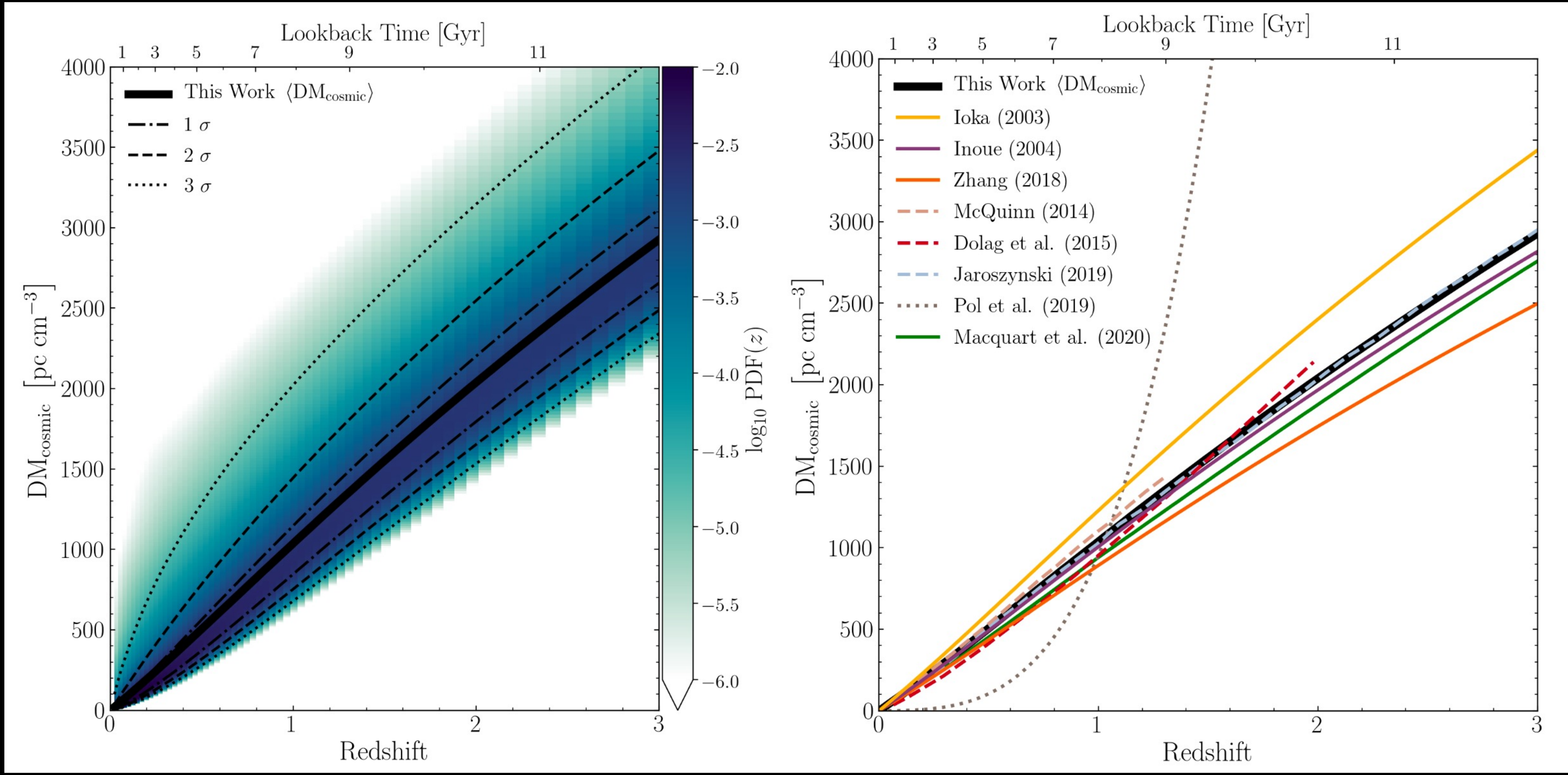
Batten et al. 2021a (arxiv:2011.14547)



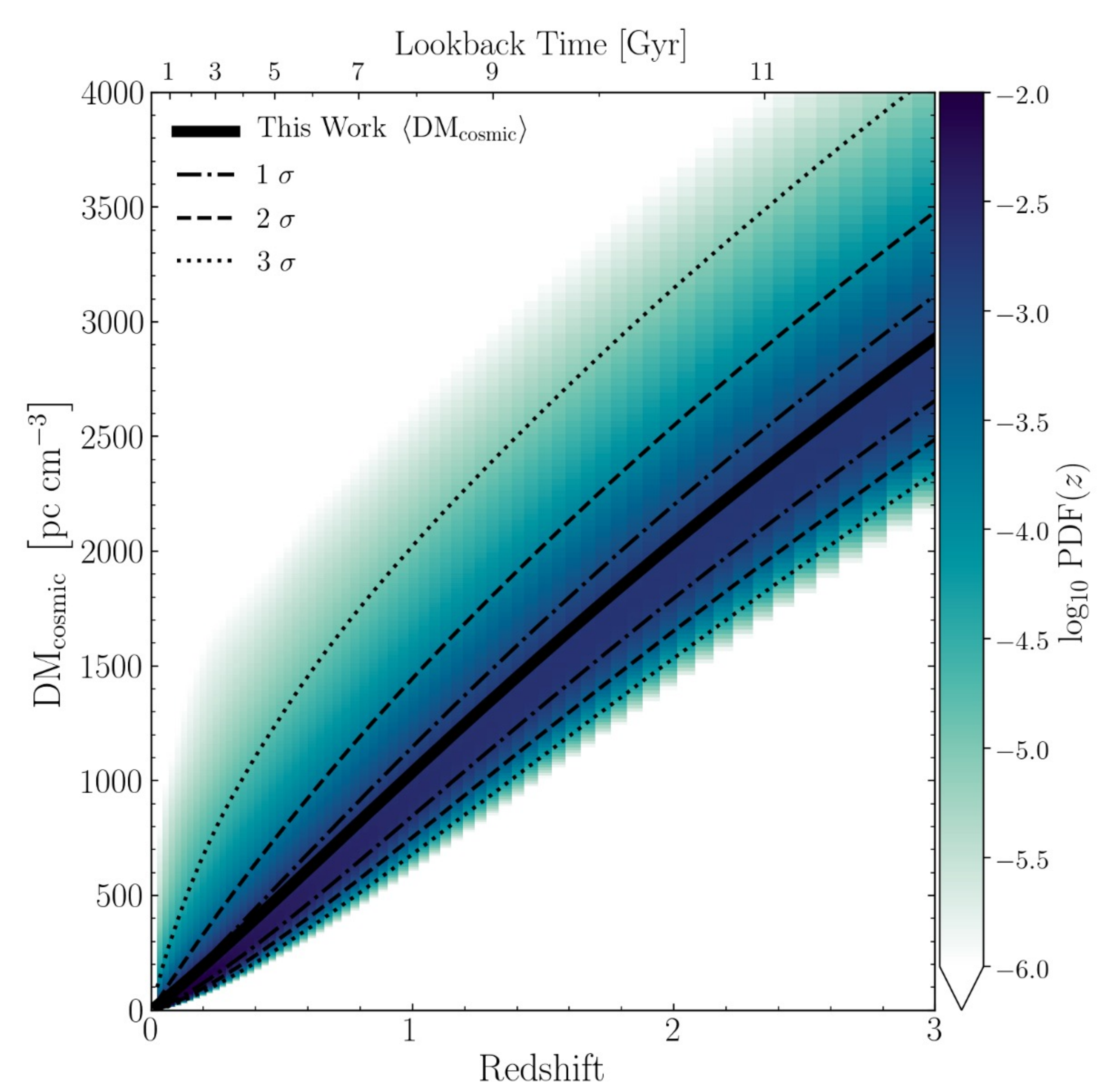
Batten et al. 2021a (arxiv:2011.14547)

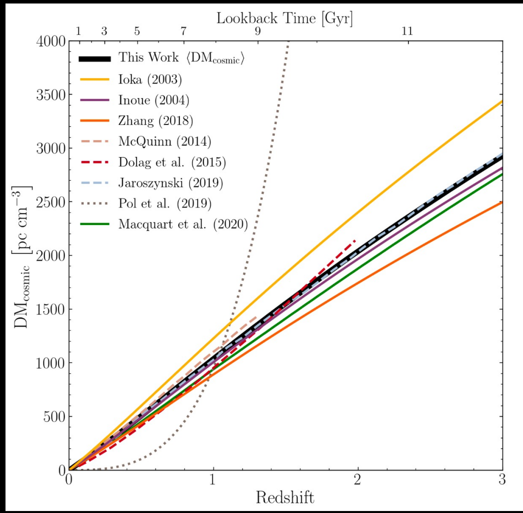


Batten et al. 2021a (arxiv:2011.14547)

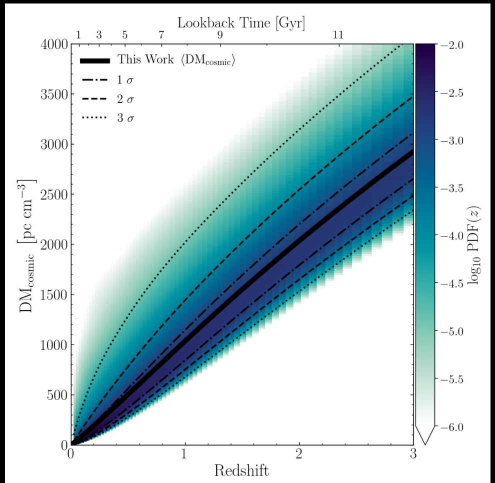


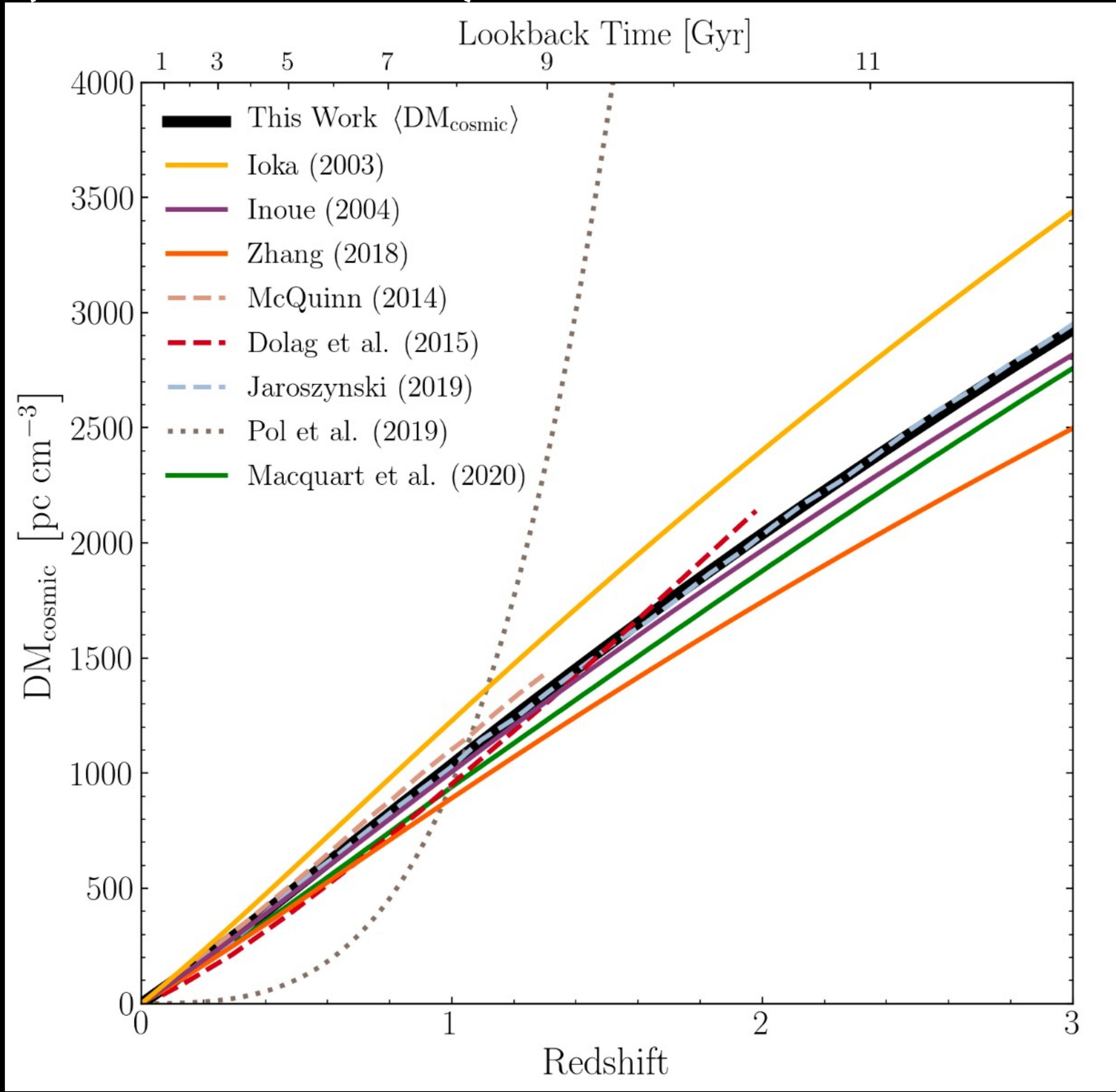
Batten et al. 2021a (arxiv:2011.14547)



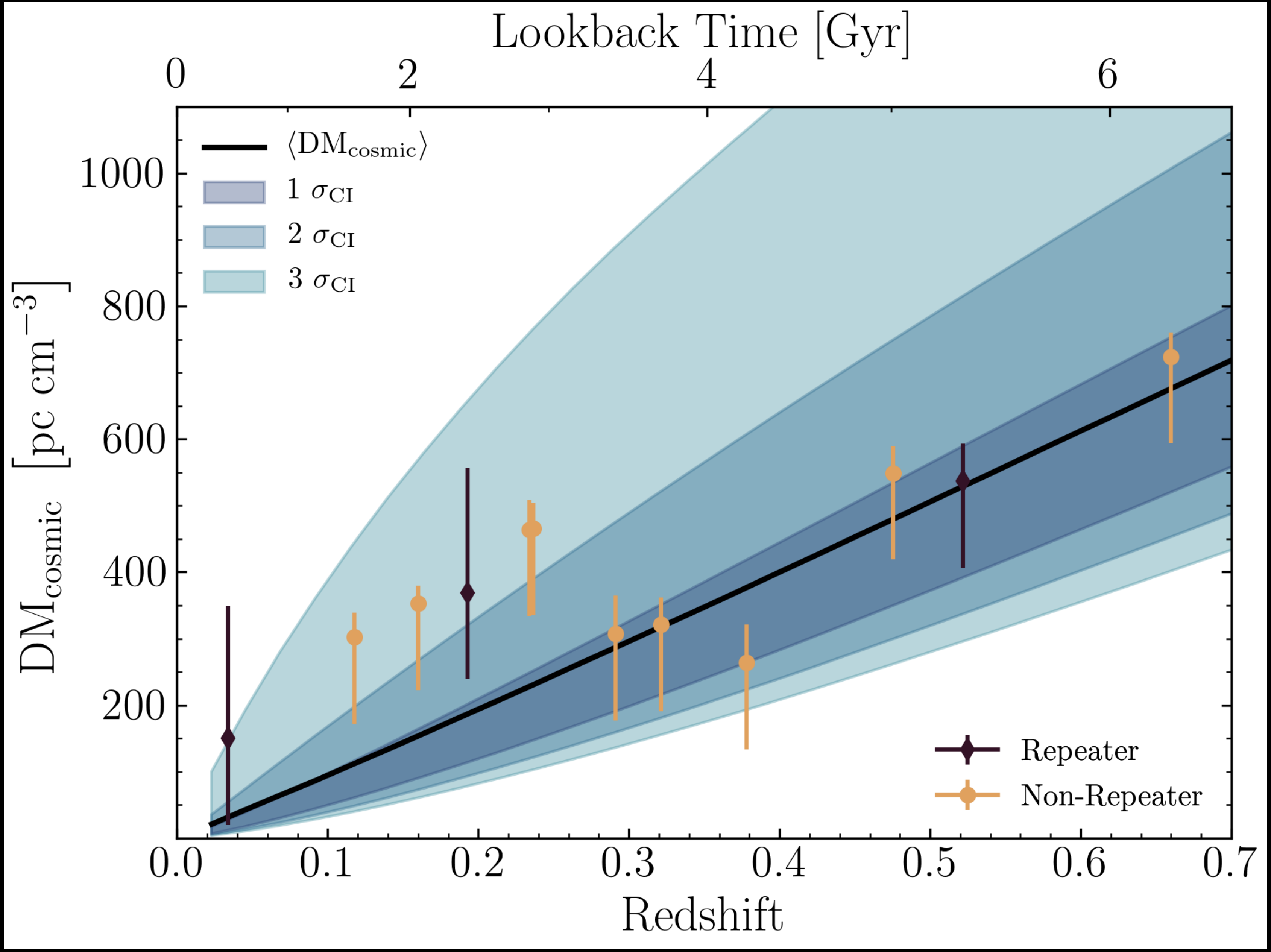


Batten et al. 2021a (arxiv:2011.14547)



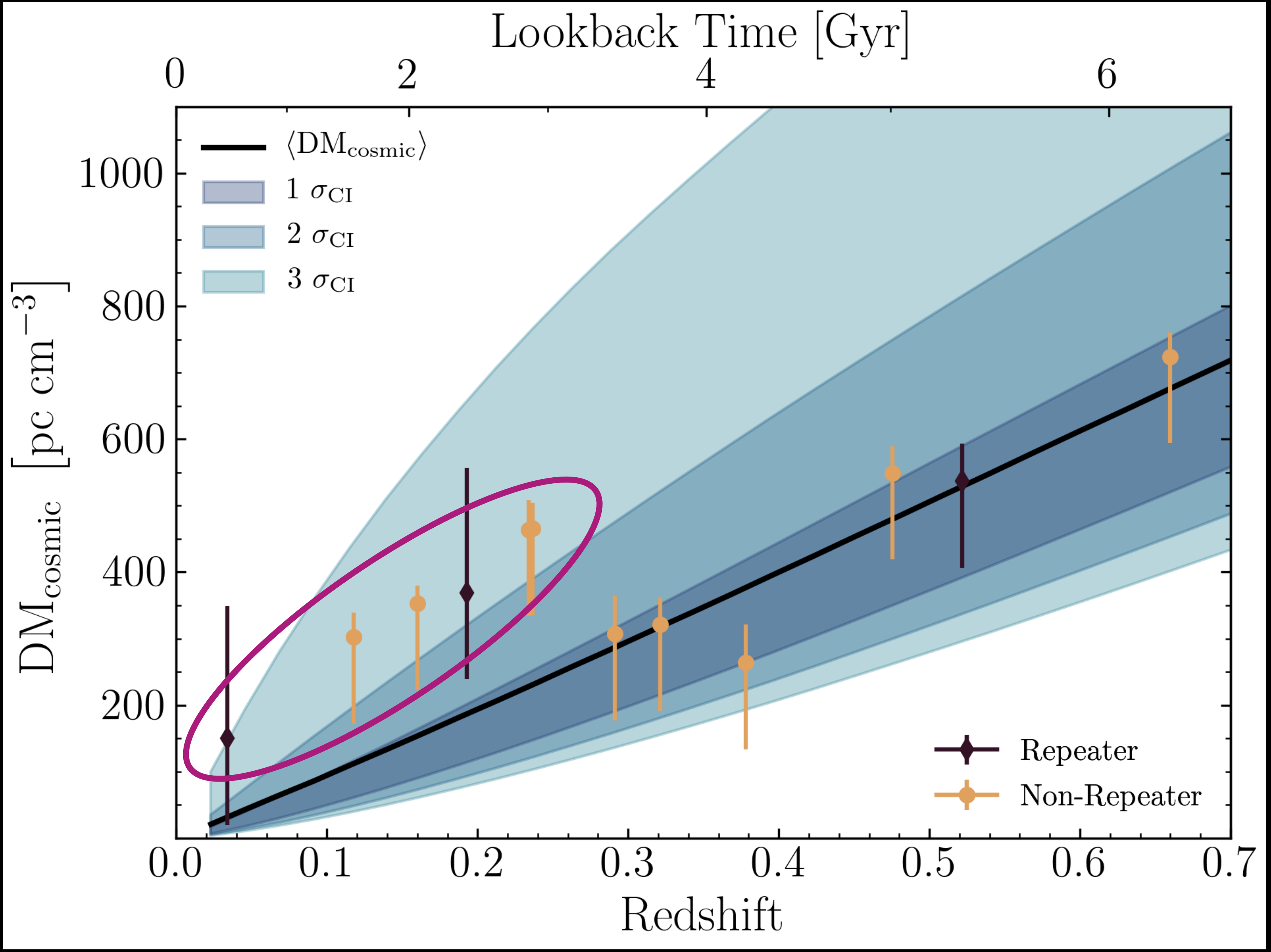


Batten et al. 2021a (arxiv:2011.14547)

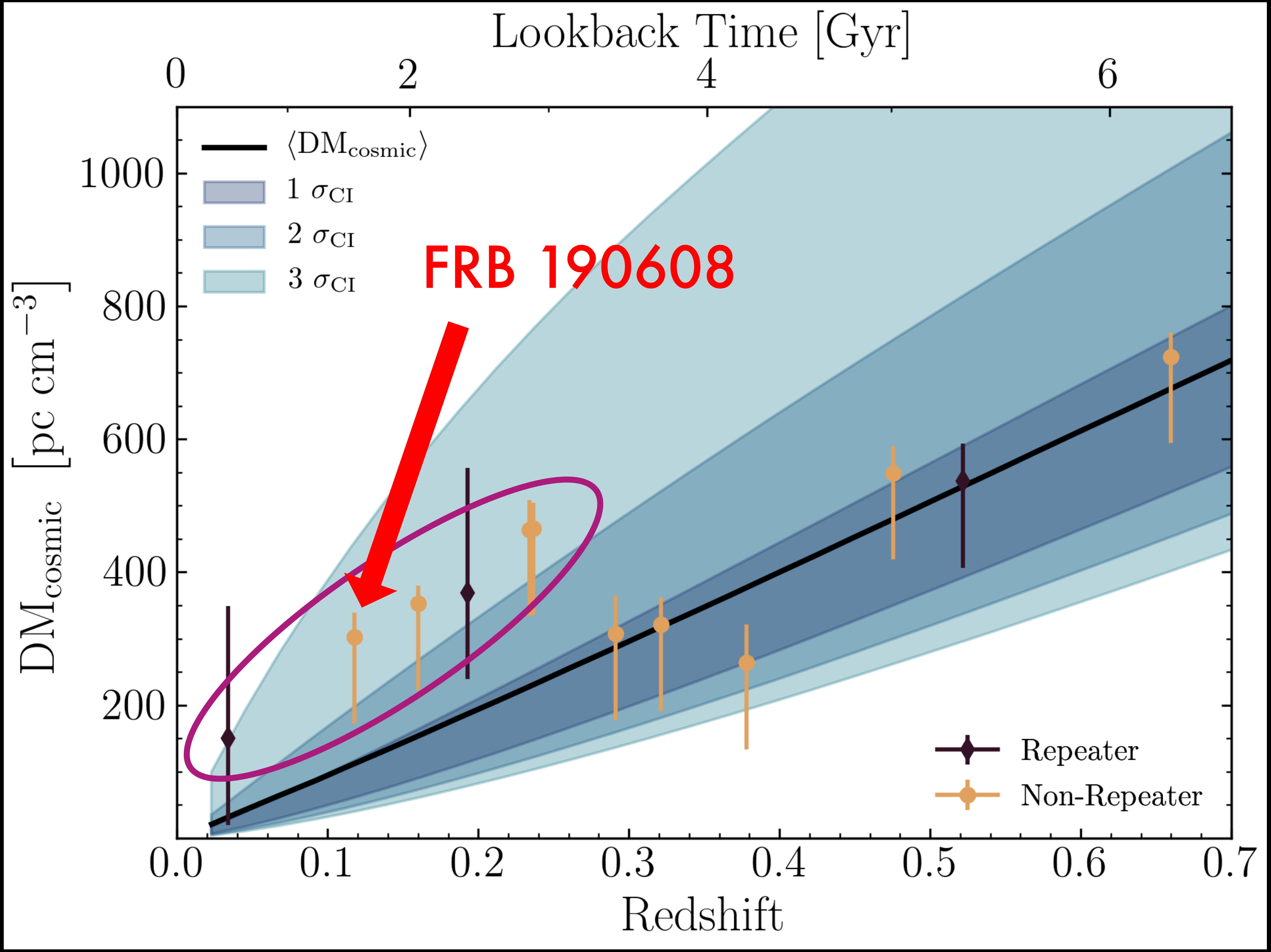


Batten et al. 2021a (arxiv:2011.14547)

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

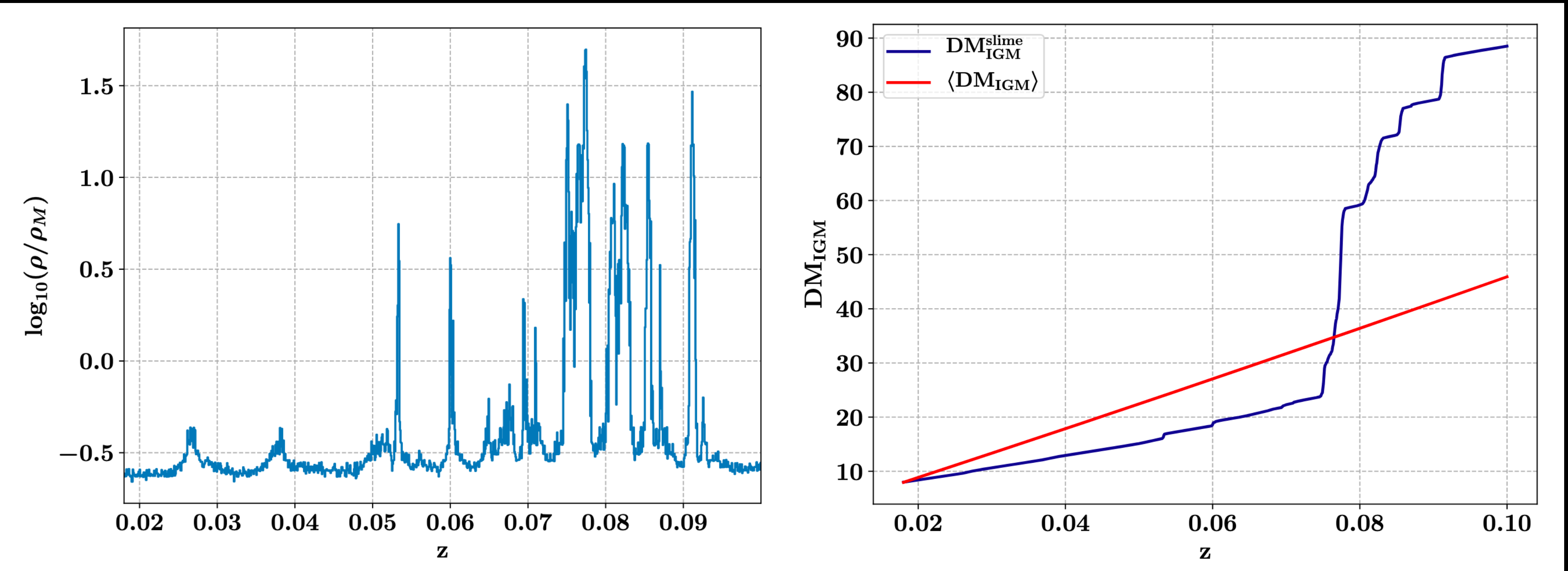


Batten et al. 2021a (arxiv:2011.14547)



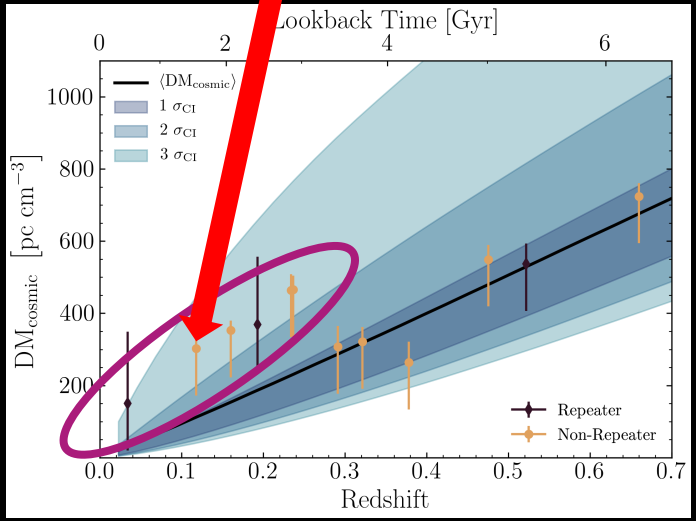
Batten et al. 2021a (arxiv:2011.14547)

IGM Density Reconstruction Towards FRB 190608



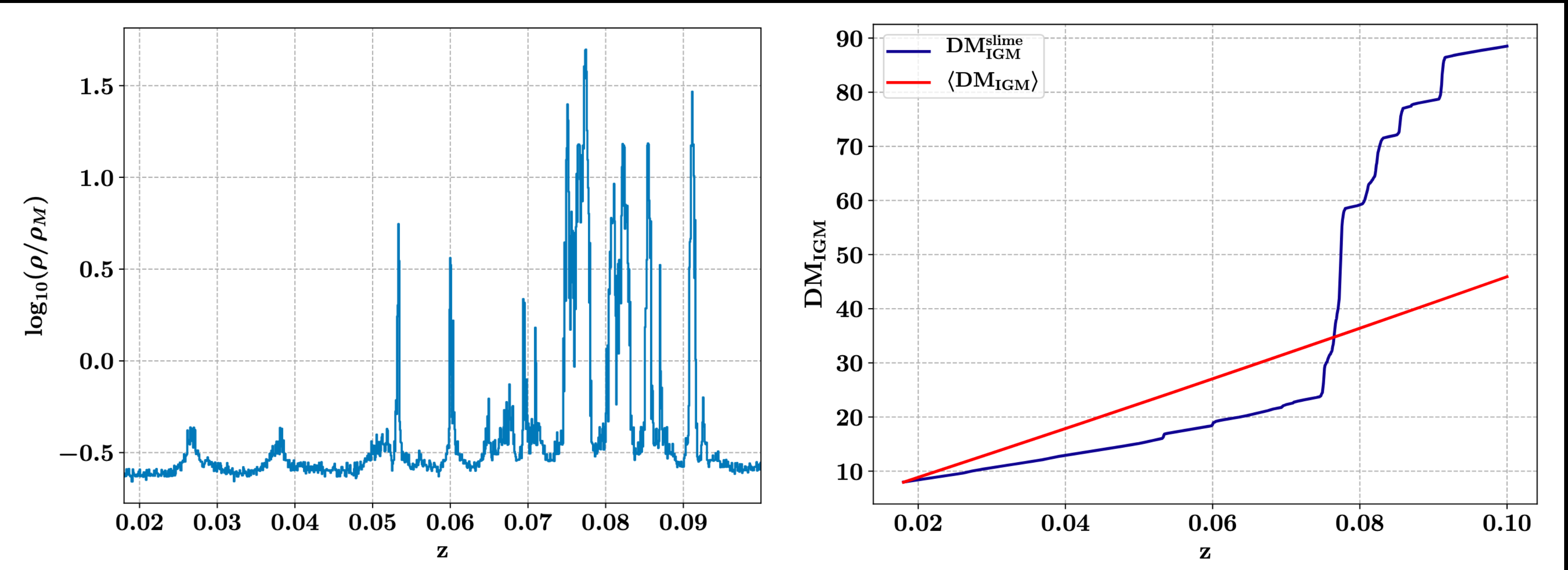
Simha et. al 2020

FRB 190608



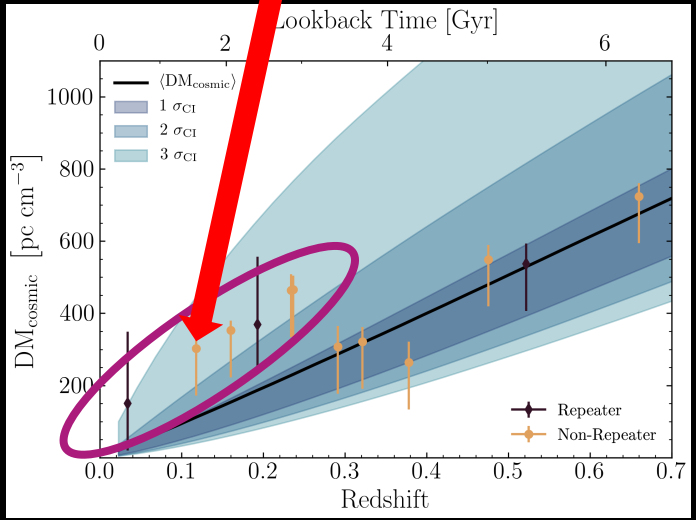
Batten et al. 2021a (arxiv:2011.14547)

IGM Density Reconstruction Towards FRB 190608



Simha et. al 2020

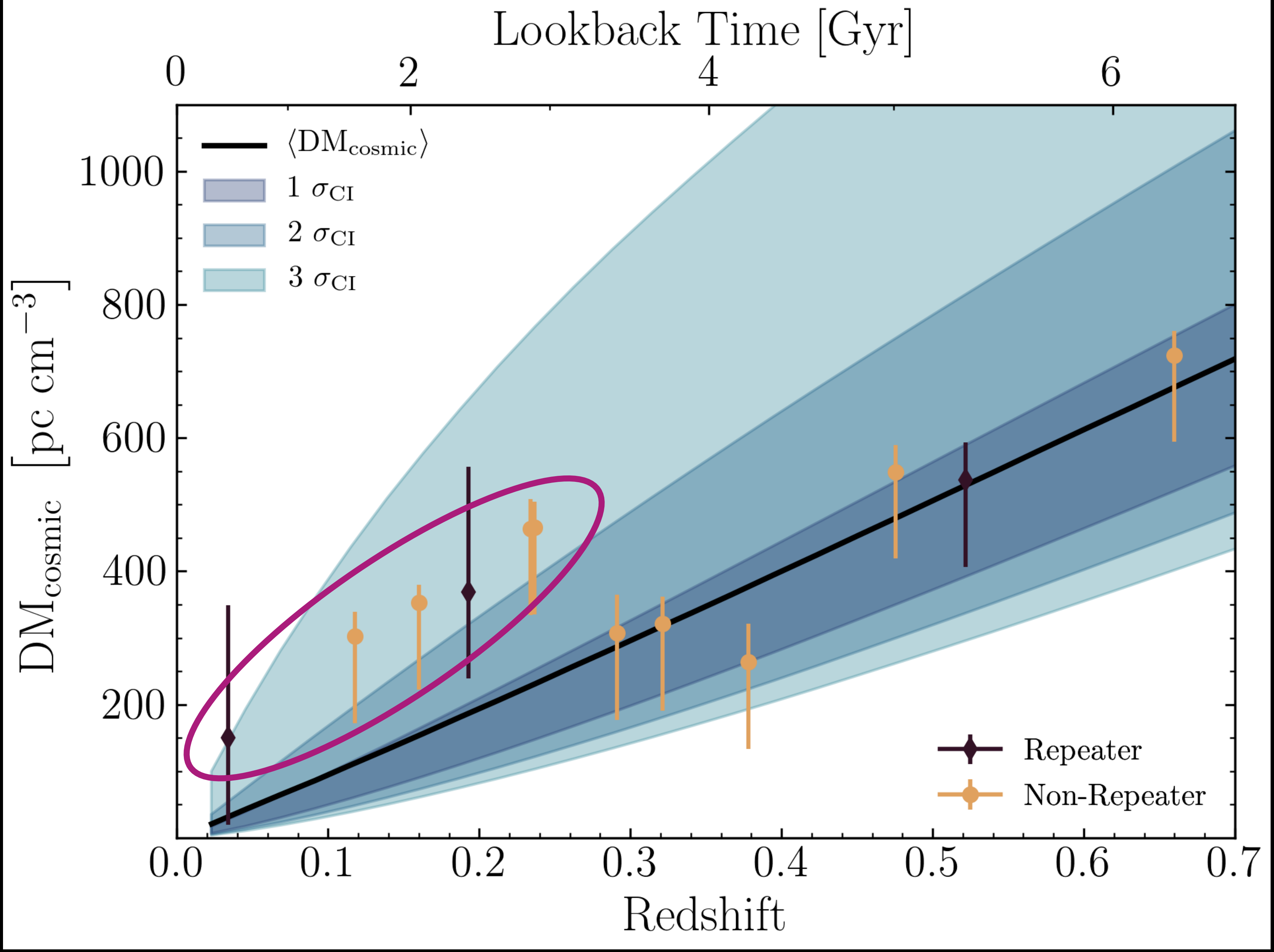
FRB 190608



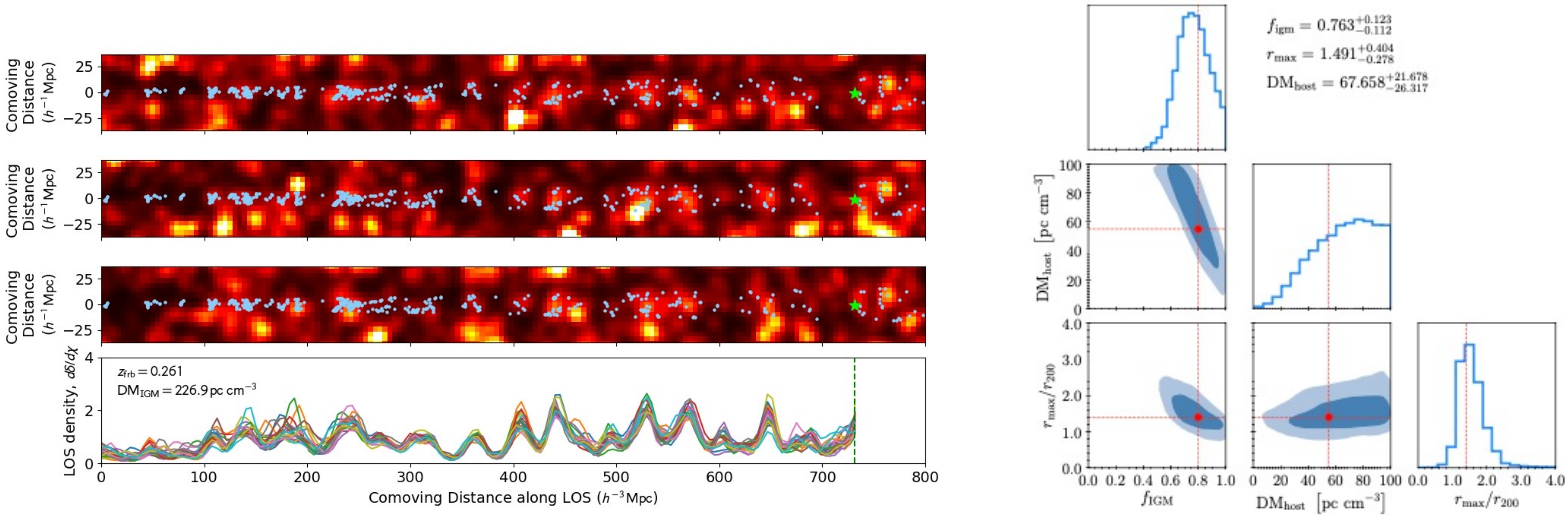
FRB 190608 intersects overdense IGM filaments along the line of sight!

Batten et al. 2021a (arxiv:2011.14547)

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



Mapping Foreground Large Scale Structure in FRB Fields

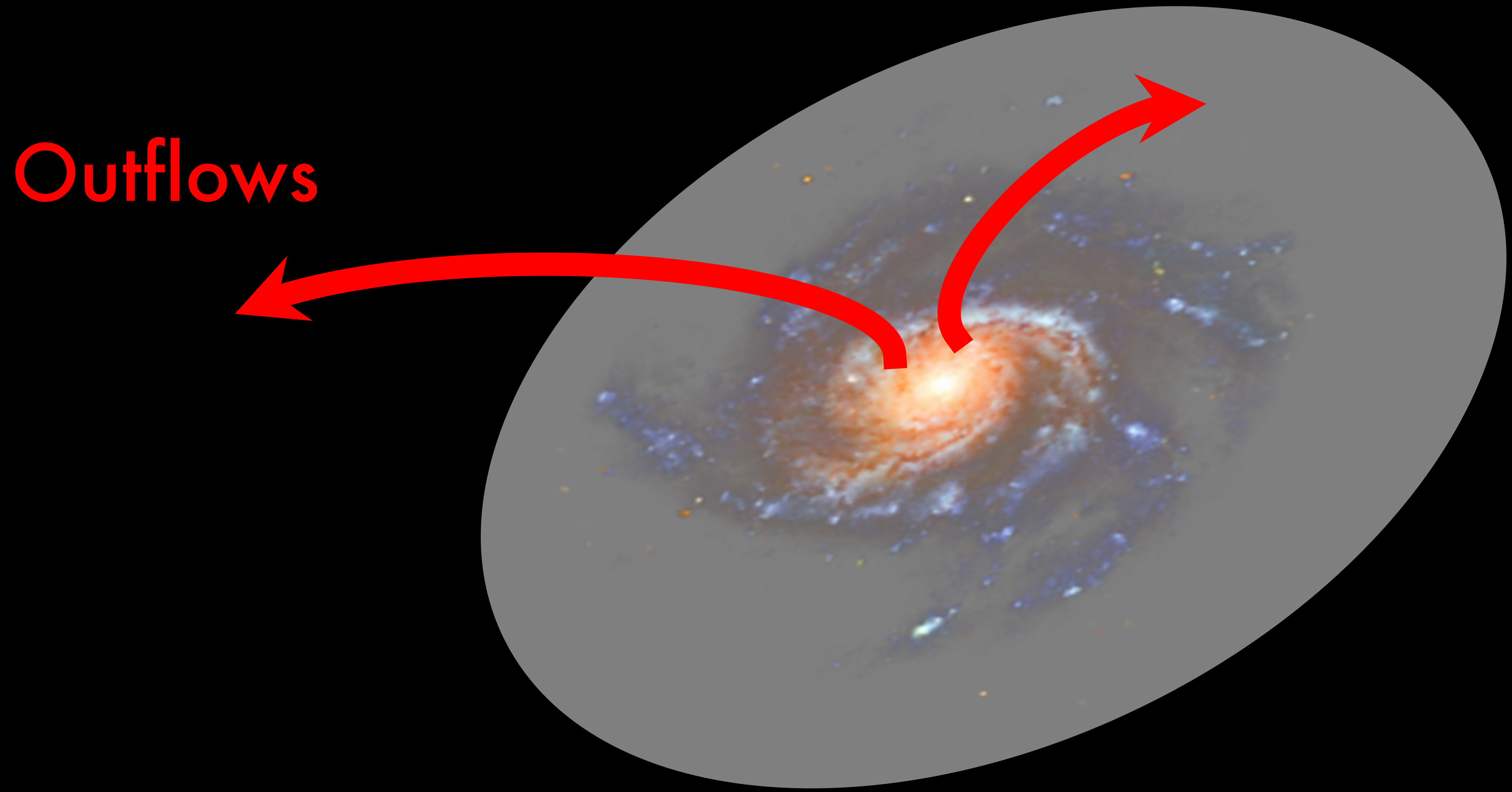


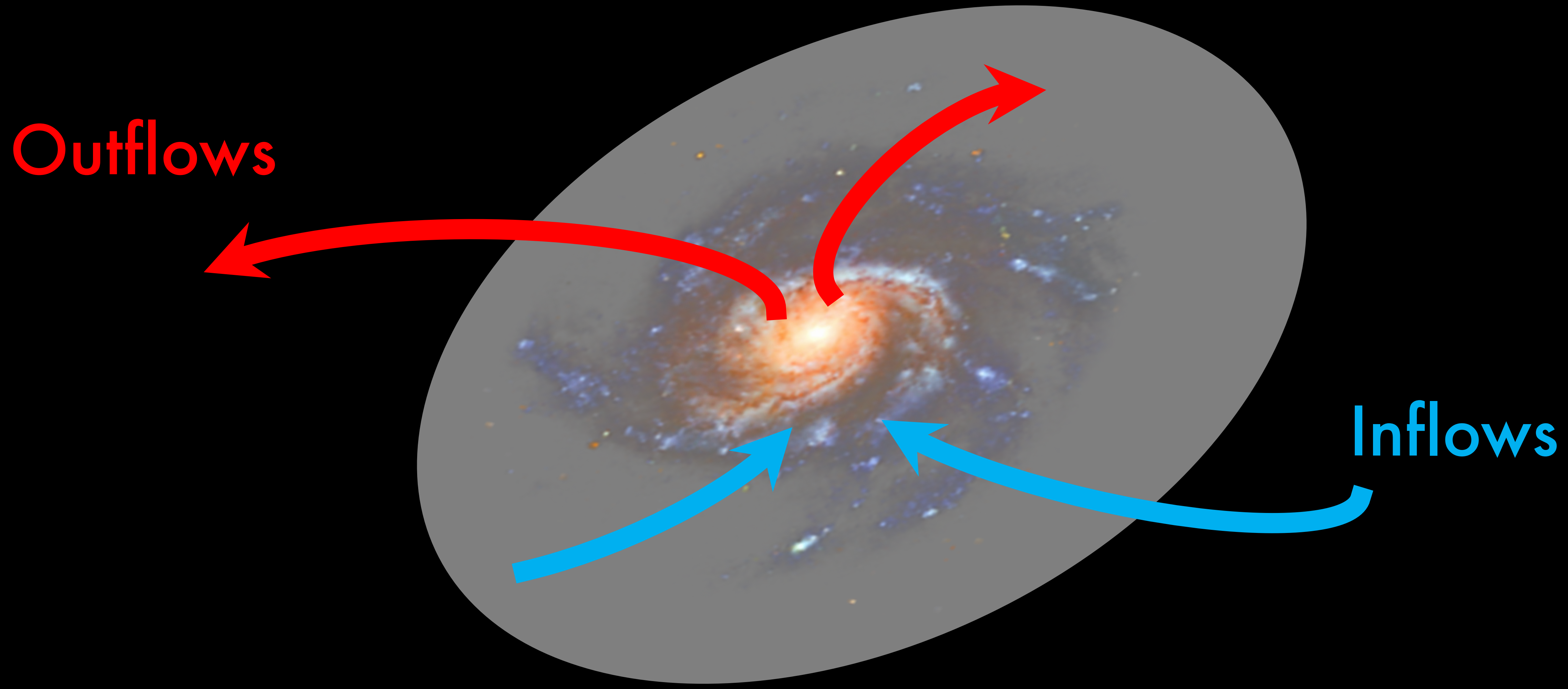
Credit: KG Lee

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

Batten et al. *in prep.*

FRBs as Probes of Galaxy Feedback


Outflows

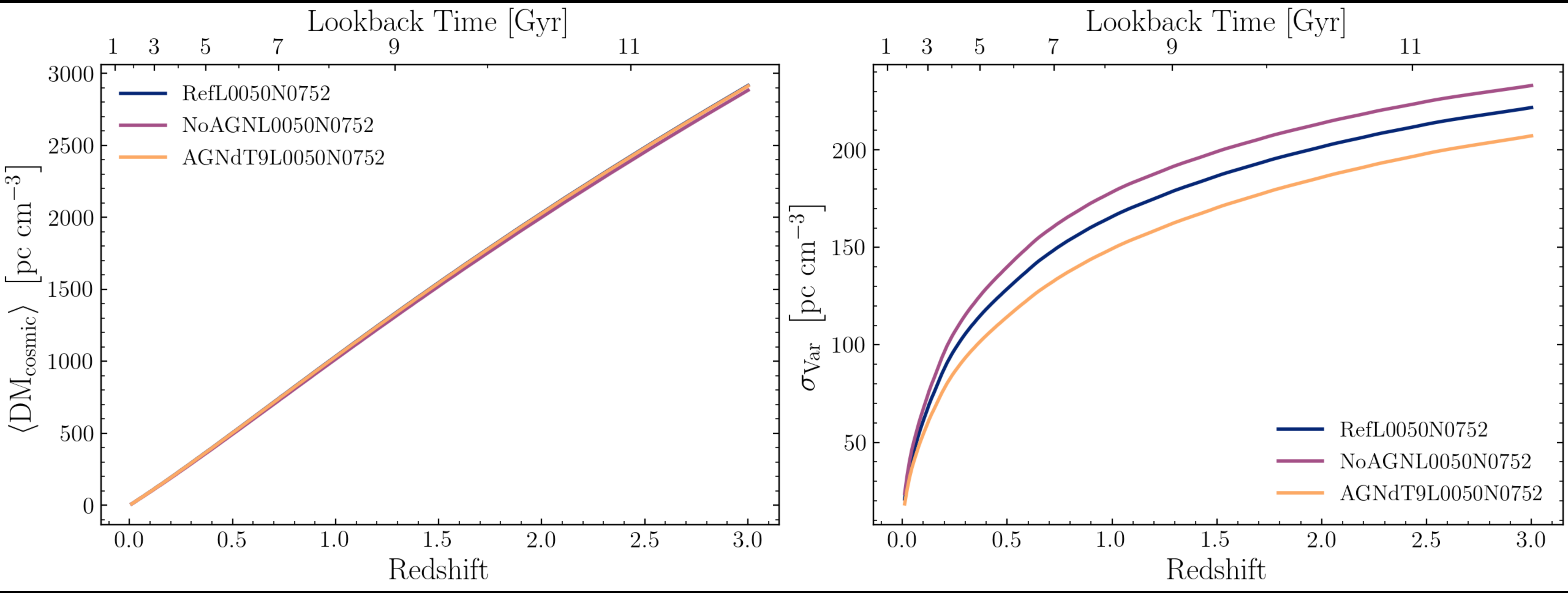

Outflows
Inflows

Batten et al. *in prep.*

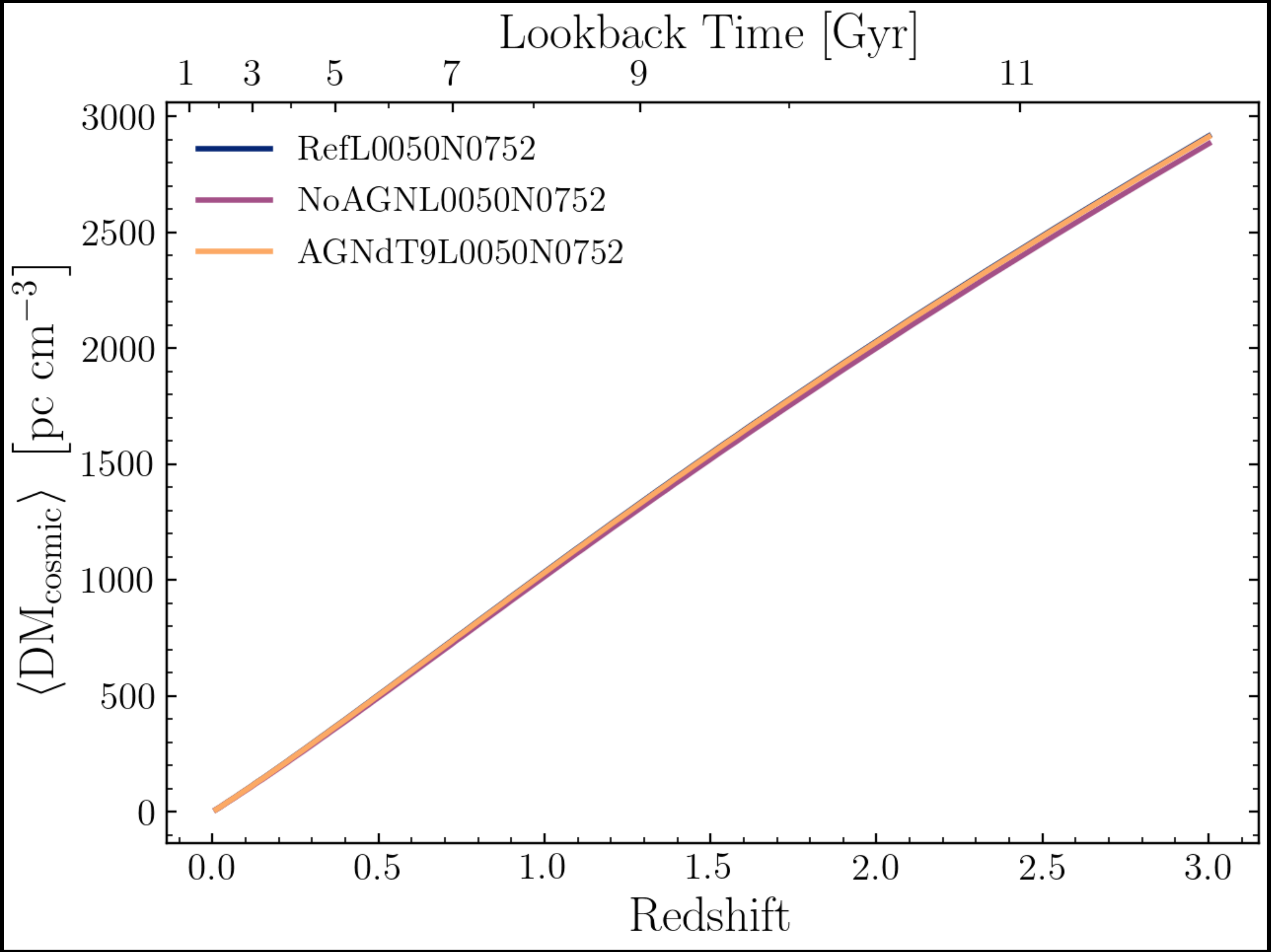
EAGLE Simulations

◈ RefL0050N0752	Reference Simulation
◈ NoAGN	No Active Galactic Nuclei
◈ AGNdT9	More Efficient AGN Feedback

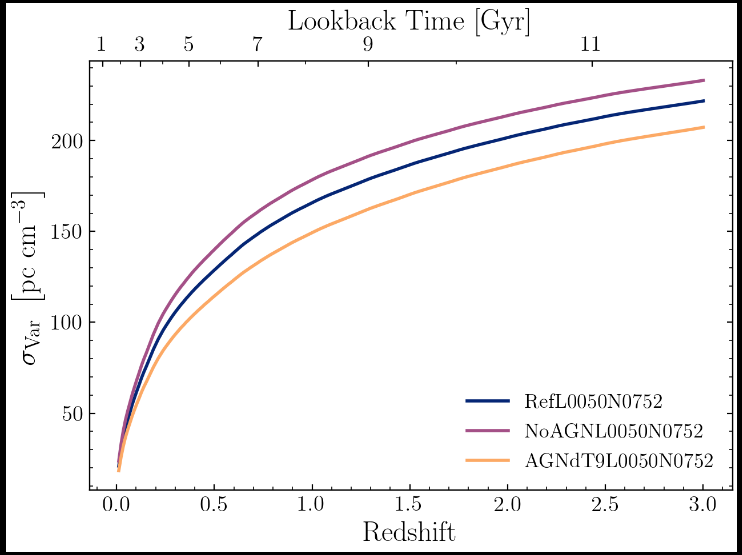
Batten et al. *in prep.*



Batten et al. *in prep.*

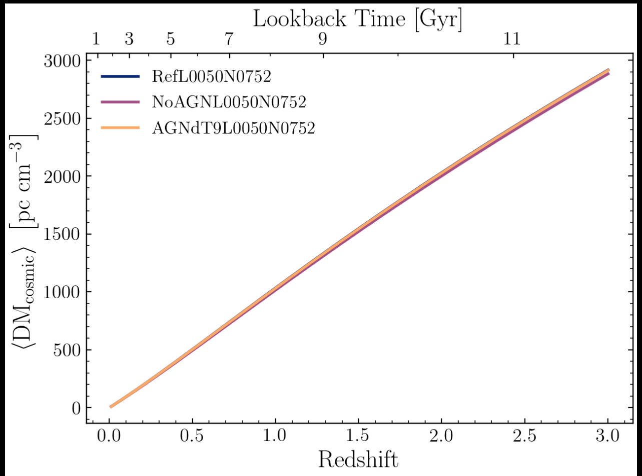


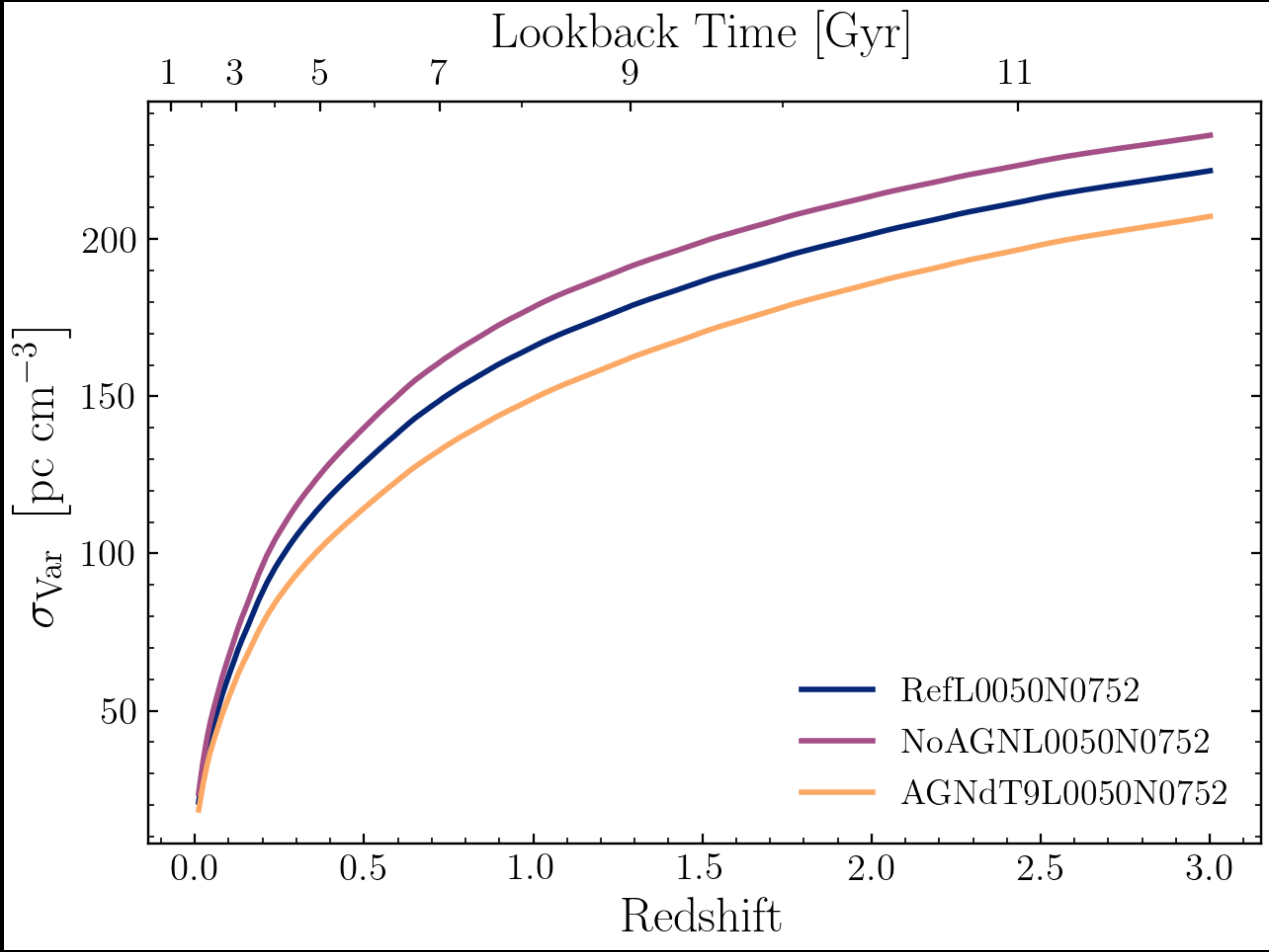
Mean DM-z Relation extremely robust to changes in galaxy feedback!



Batten et al. *in prep.*

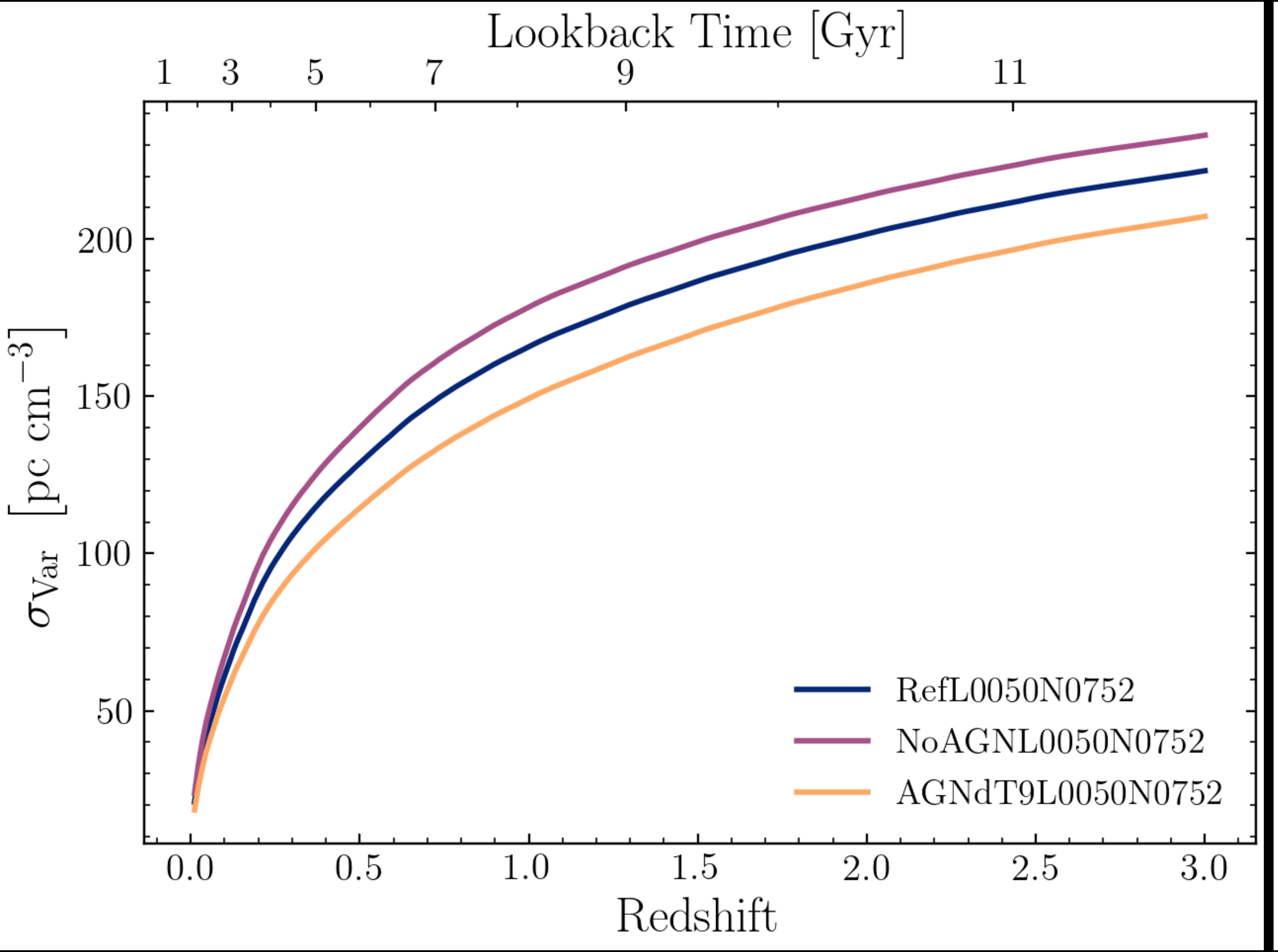
Main difference between models is in the standard deviation around the mean!

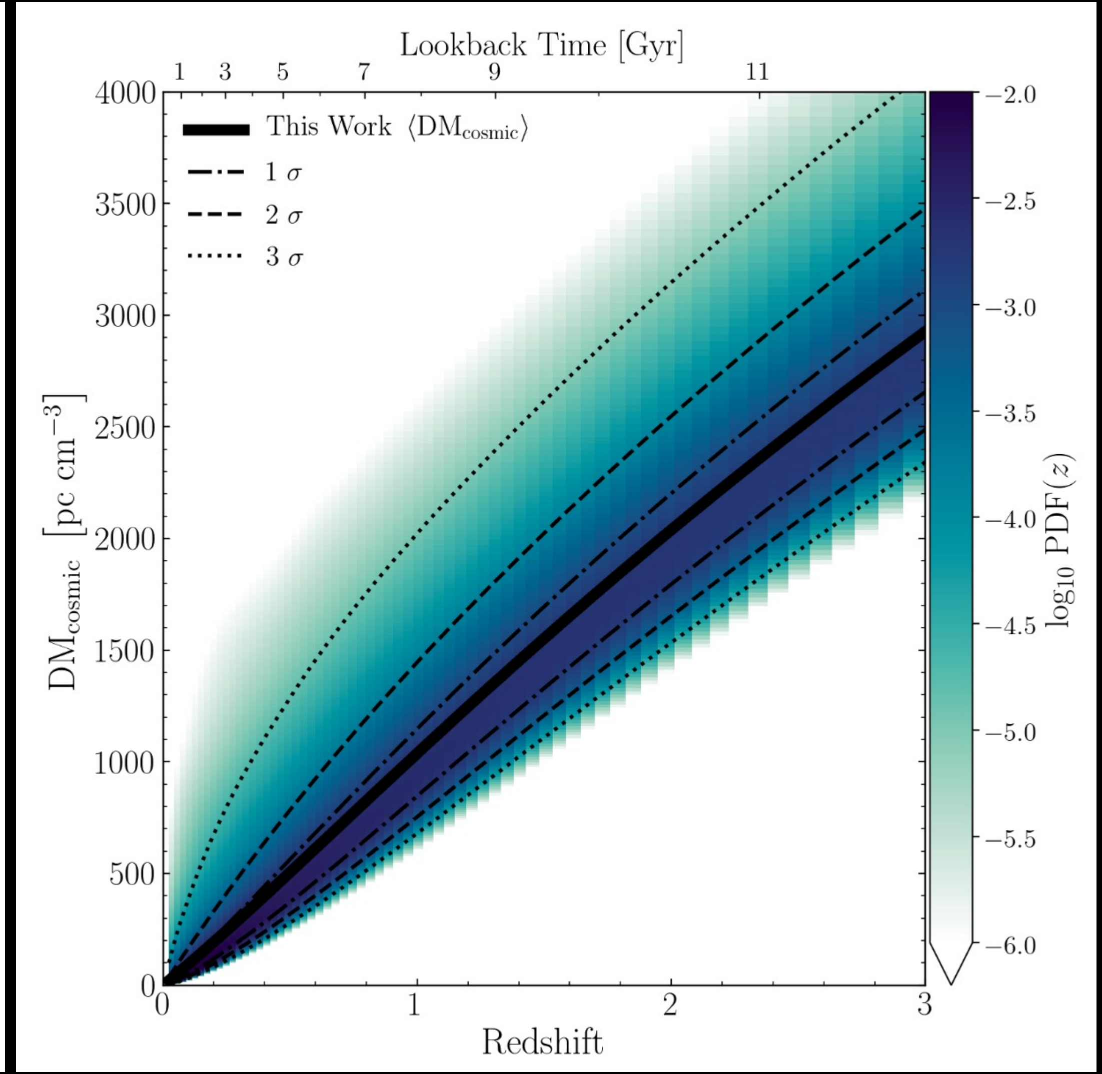




Batten et al. *in prep.*

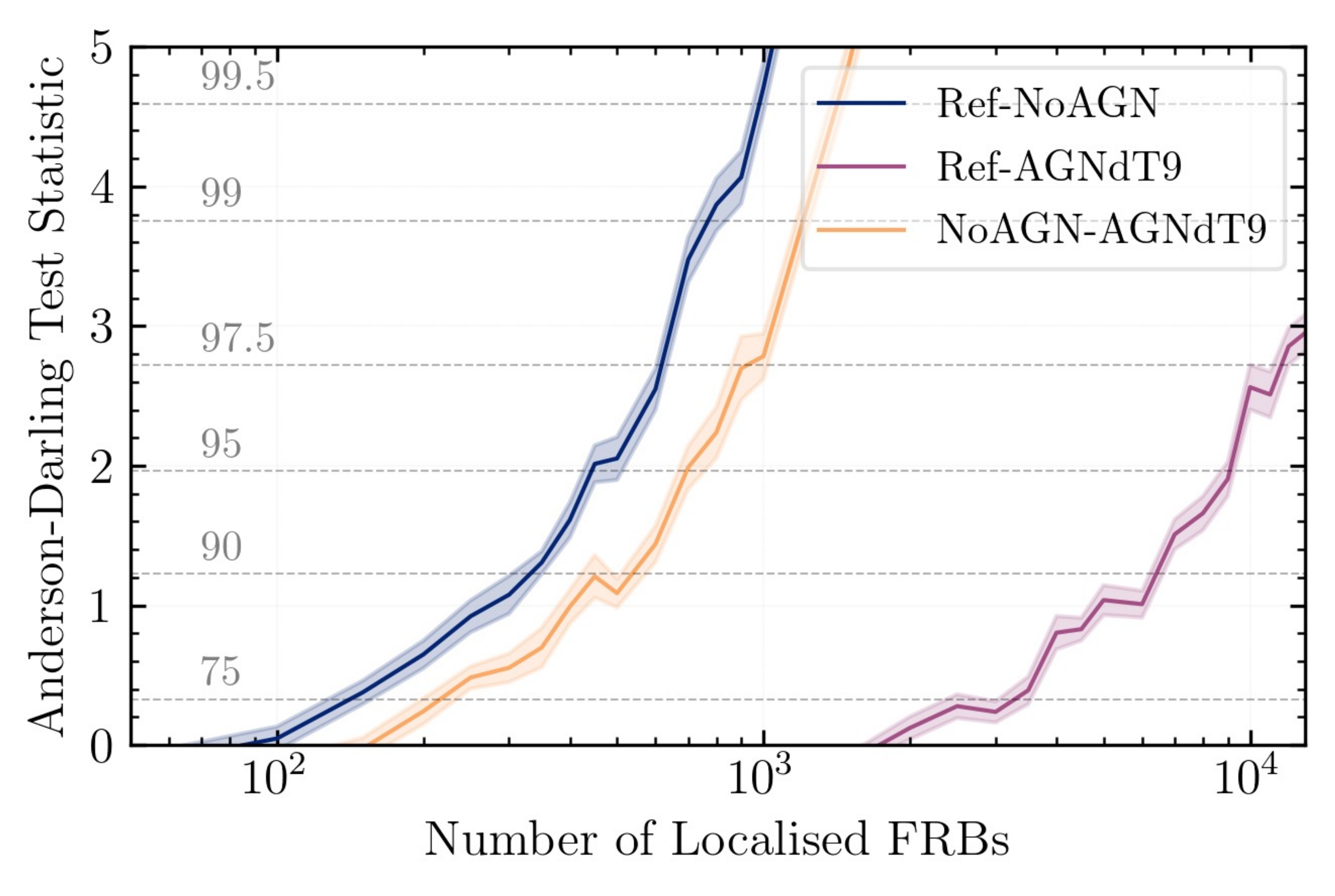
How many localized FRBs do we need?





Batten et al. *in prep.*

How many localized FRBs do we need?

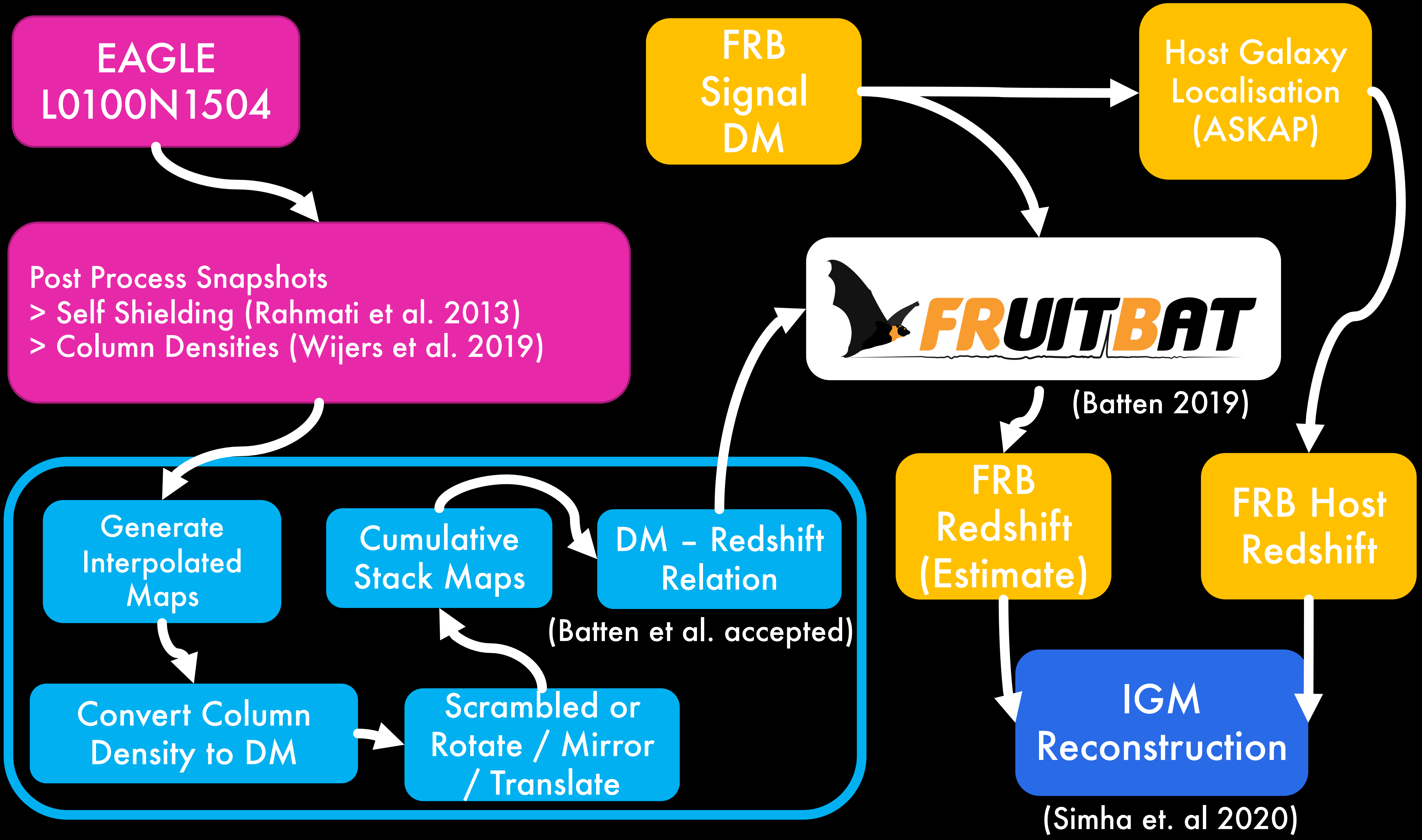


(Between redshift z = 0.5 – 1)

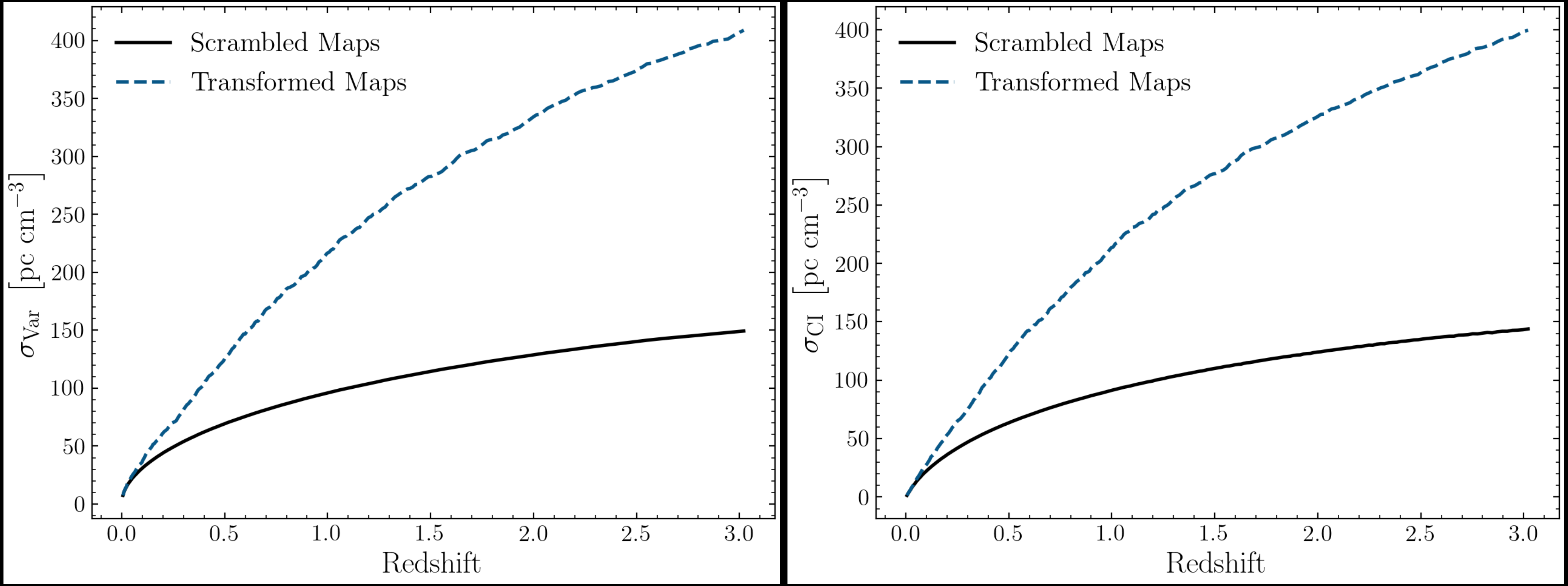
Summary:

- Fast Radio Bursts provide a unique new way to probe the electron/baryon distribution in the IGM.
- Batten+2021a: *The Cosmic Dispersion Measure in EAGLE* (arxiv:2011.14547)
  - ➥ 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 $2 - 3\sigma$ confidence intervals.
  - ➥ Indicates intersection with IGM filaments, or possibly high host/source contributions.
- Batten+ *in prep.: Galaxy Feedback and the Dispersion Measure of FRBs*
  - ➥ The mean DM-z relation is very robust against different galaxy feedback.
  - ➥ It appears that the scatter around the DM-z relation might be able to probe galaxy feedback.
  - ➥ Would need approximately 9000 localized FRBs between $z = 0.5 - 1$ to constrain galaxy feedback.
  - ➥ Need more large box simulations required with different galaxy feedback prescriptions.

Adam Batten abatten@swin.edu.au @adamjbatten


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. accepted)
FRB Signal DM
Host Galaxy Localisation (ASKAP)
FRUITBAT
(Batten 2019)
FRB Redshift (Estimate)
FRB Host Redshift
IGM Reconstruction
(Simha et. al 2020)

RefL0025N0752



RefL0100N1504