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

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ANITA Workshop

2021-02-12

ASTRO 3D

SWIN BUR NE Centre for Astrophysics and Supercomputing

What is the Intergalactic Medium?

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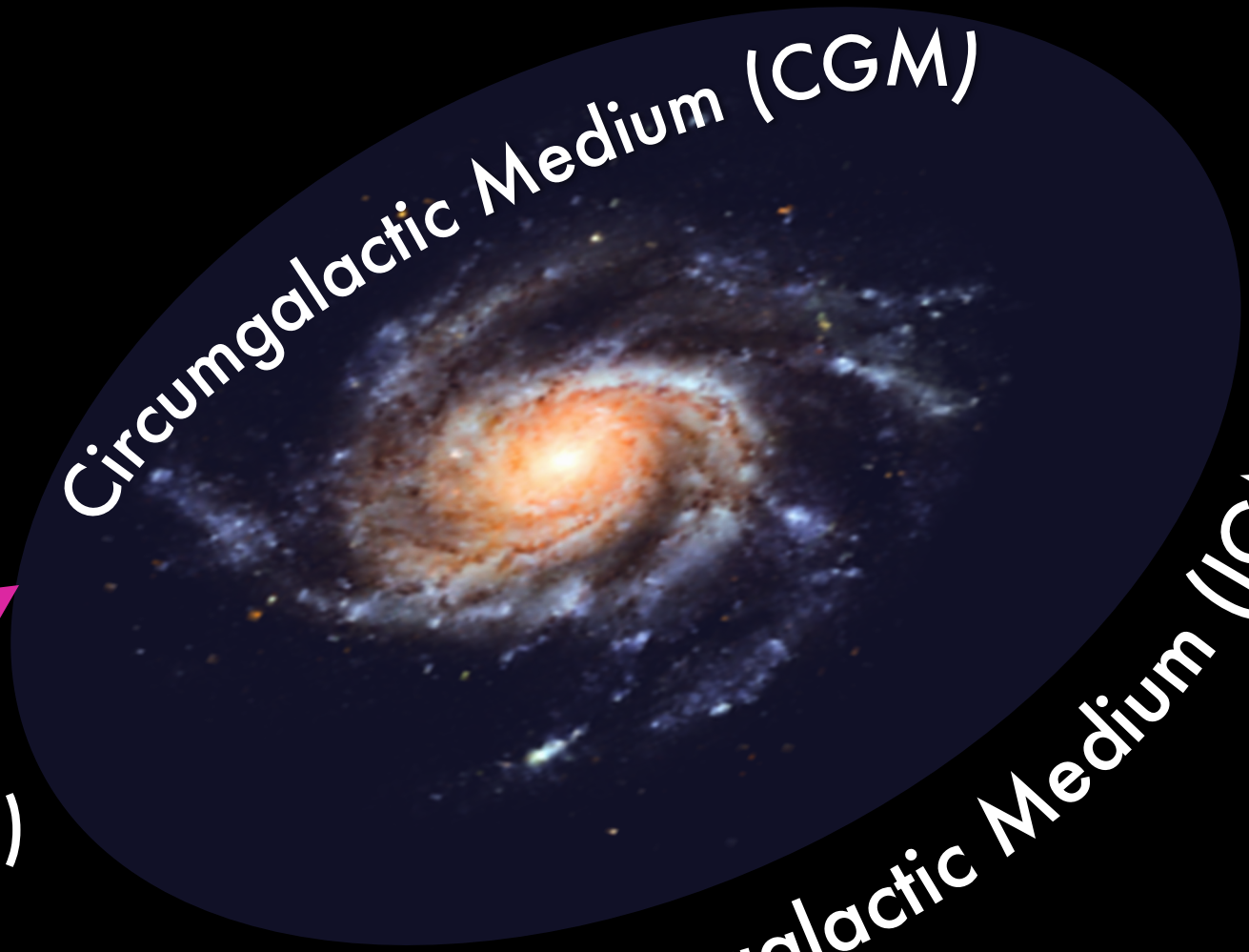

Virial Radius (r_{200})

Tumlinson et al. (2017)

Why Do We Care About the Intergalactic Medium?

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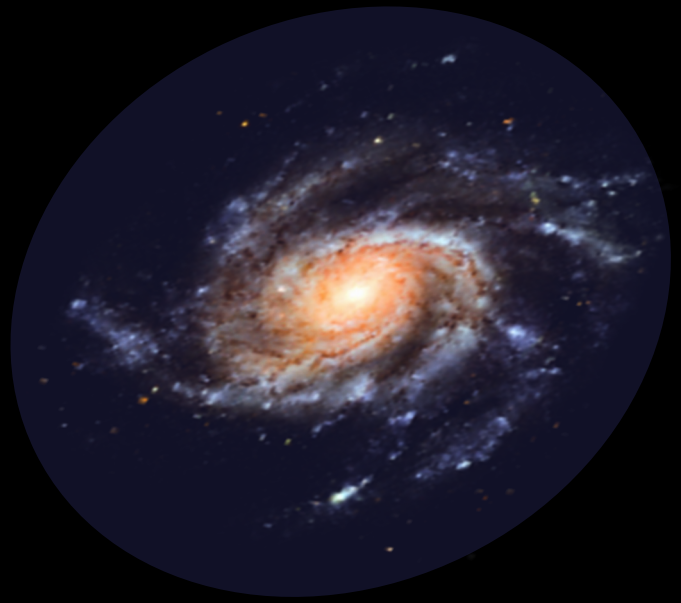

1. The IGM contains most of the baryonic matter

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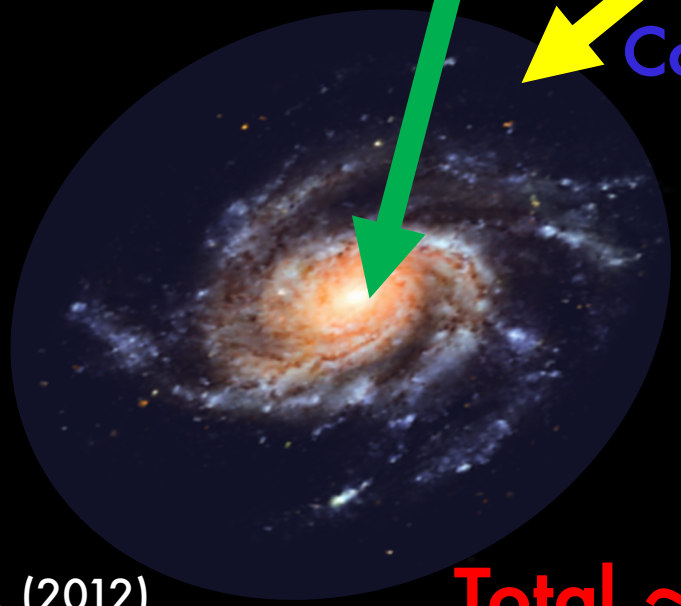

Galaxies ~ 7%

CGM ~ 5%

IGM ~ 82%

Cold Gas ~ 2%

ICM ~ 4%

Shull et al. (2012)

Total ~ 18%

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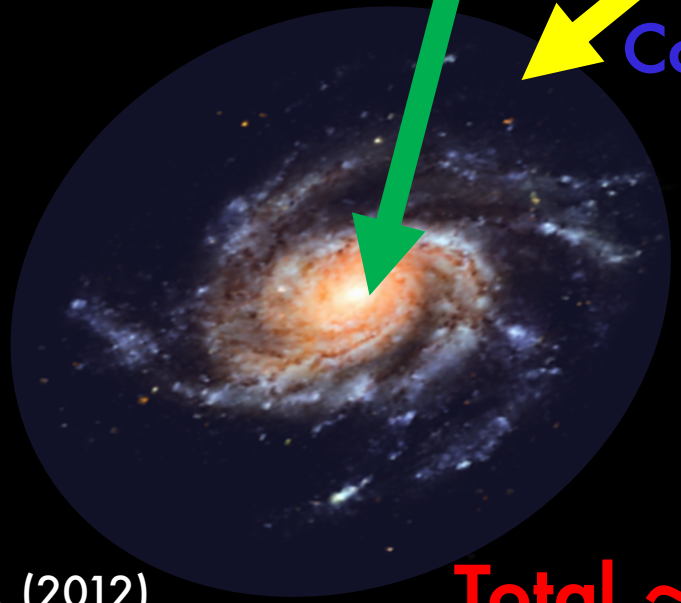

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2. Galaxies and the IGM evolve together

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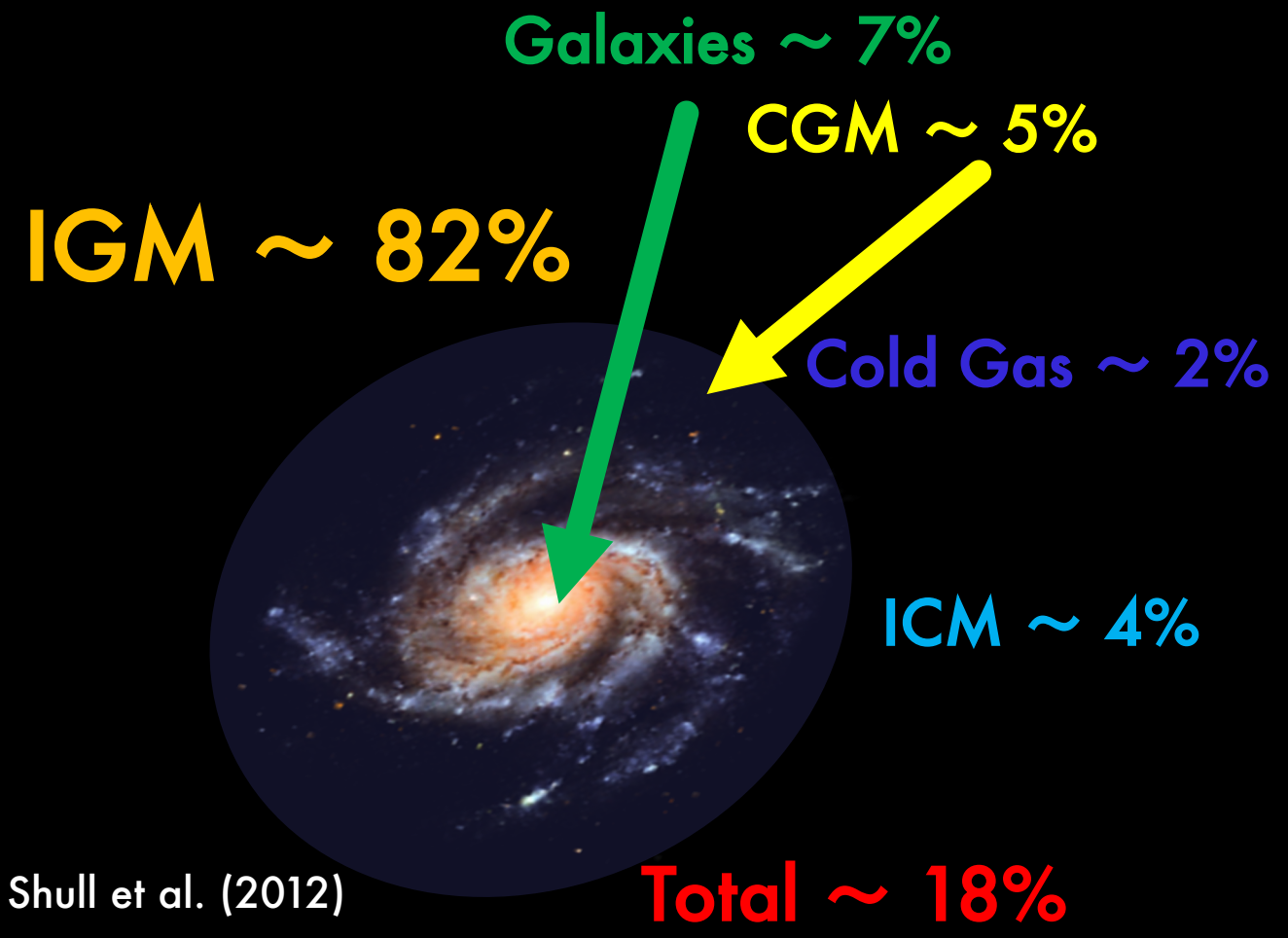

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Problems Observing the Intergalactic Medium

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

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Problems Observing the Intergalactic Medium

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- Temperature ~ 1×10^6 K

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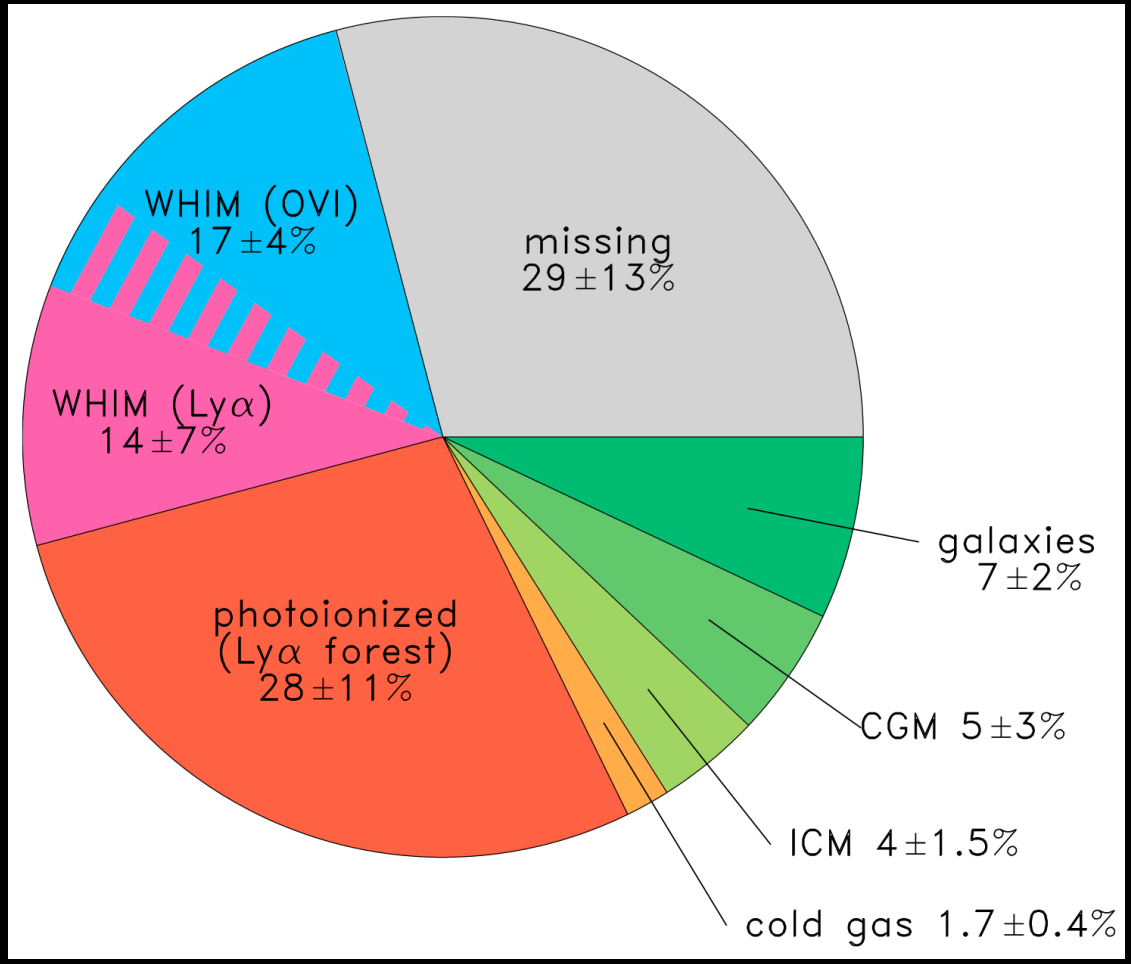
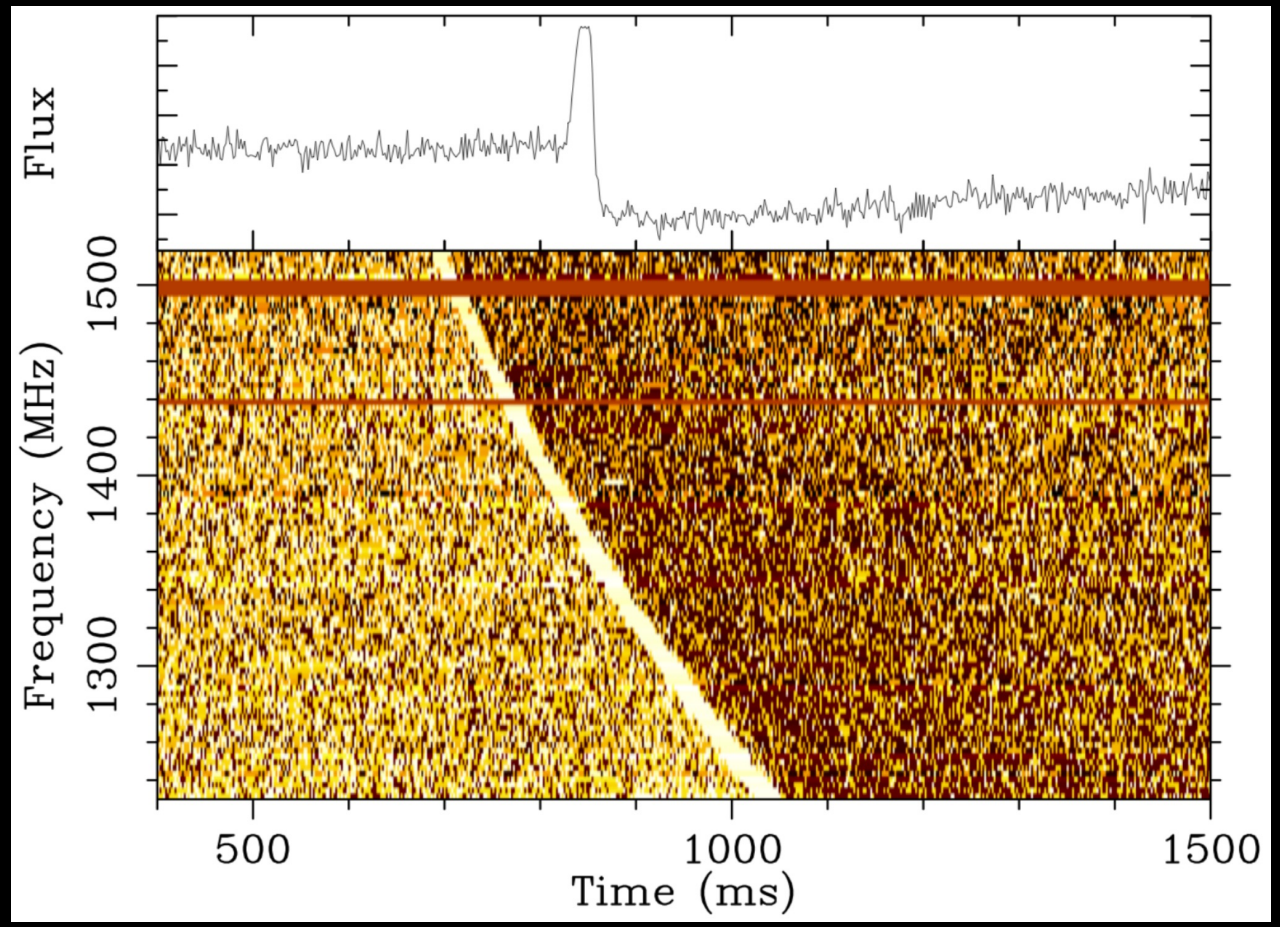
The Missing Baryon Problem:
~ 30% of baryons at low redshift appear to be missing!



Shull et al. (2012)

How do Fast Radio Bursts (FRBs) help?

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



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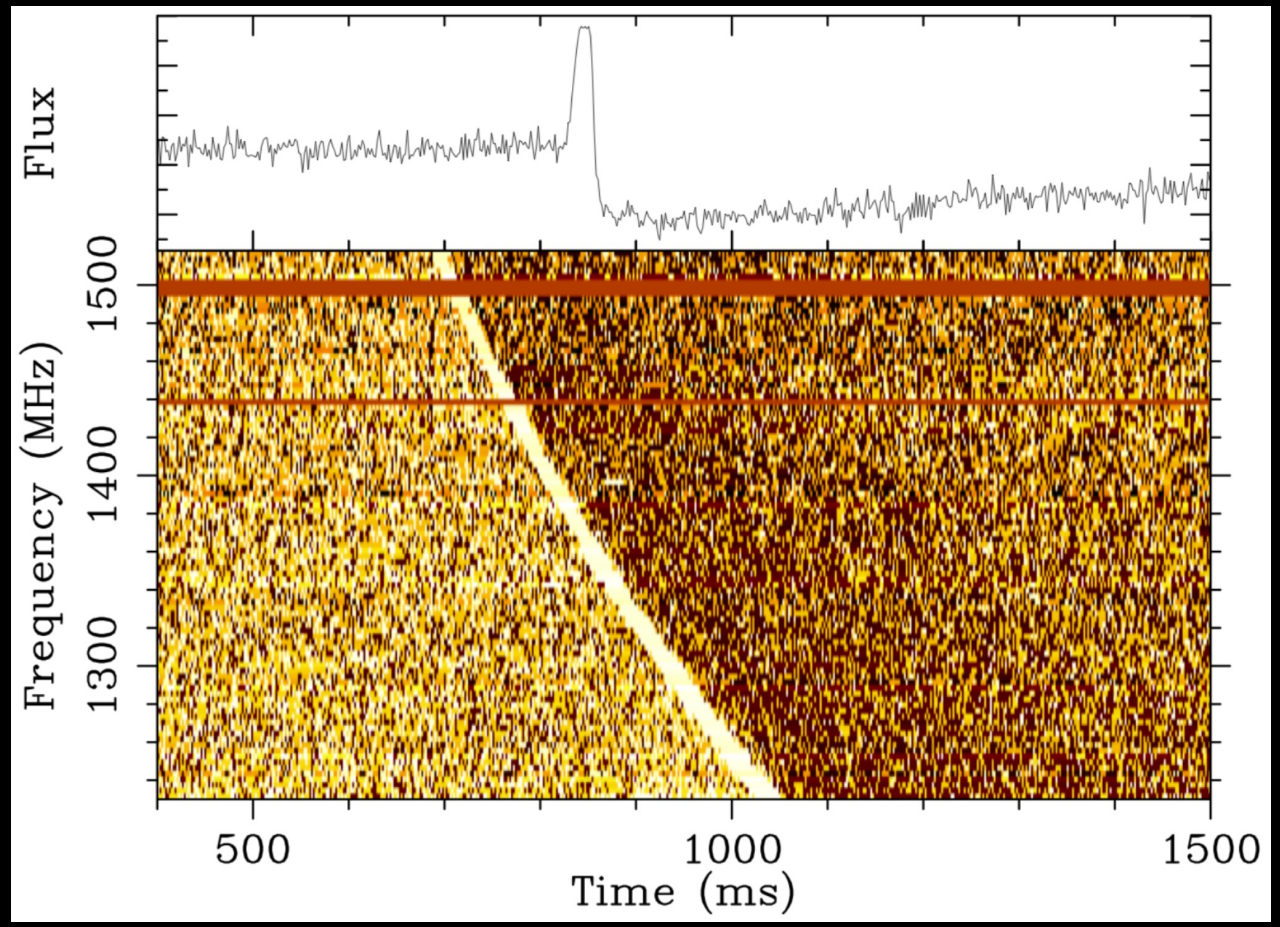

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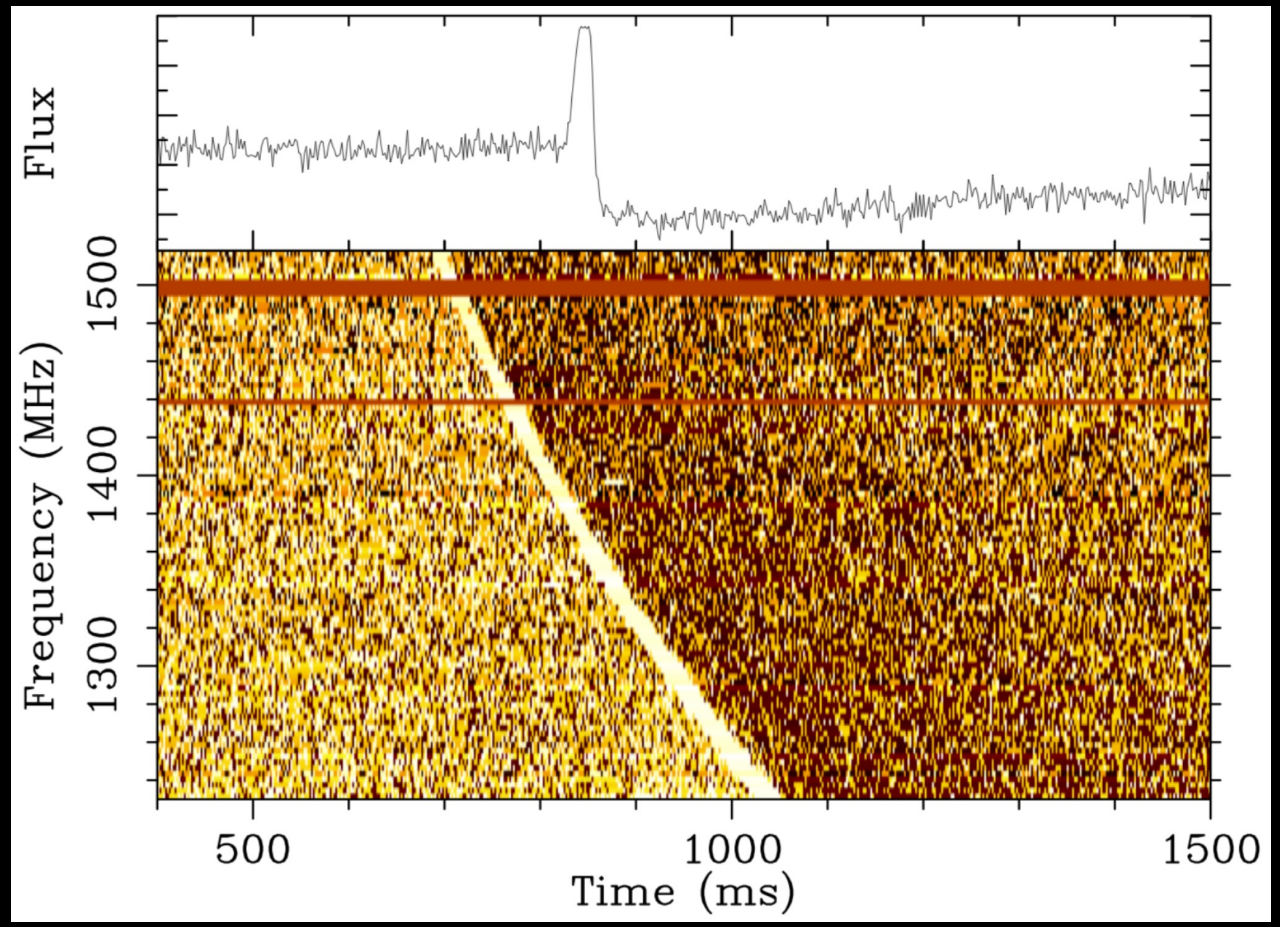

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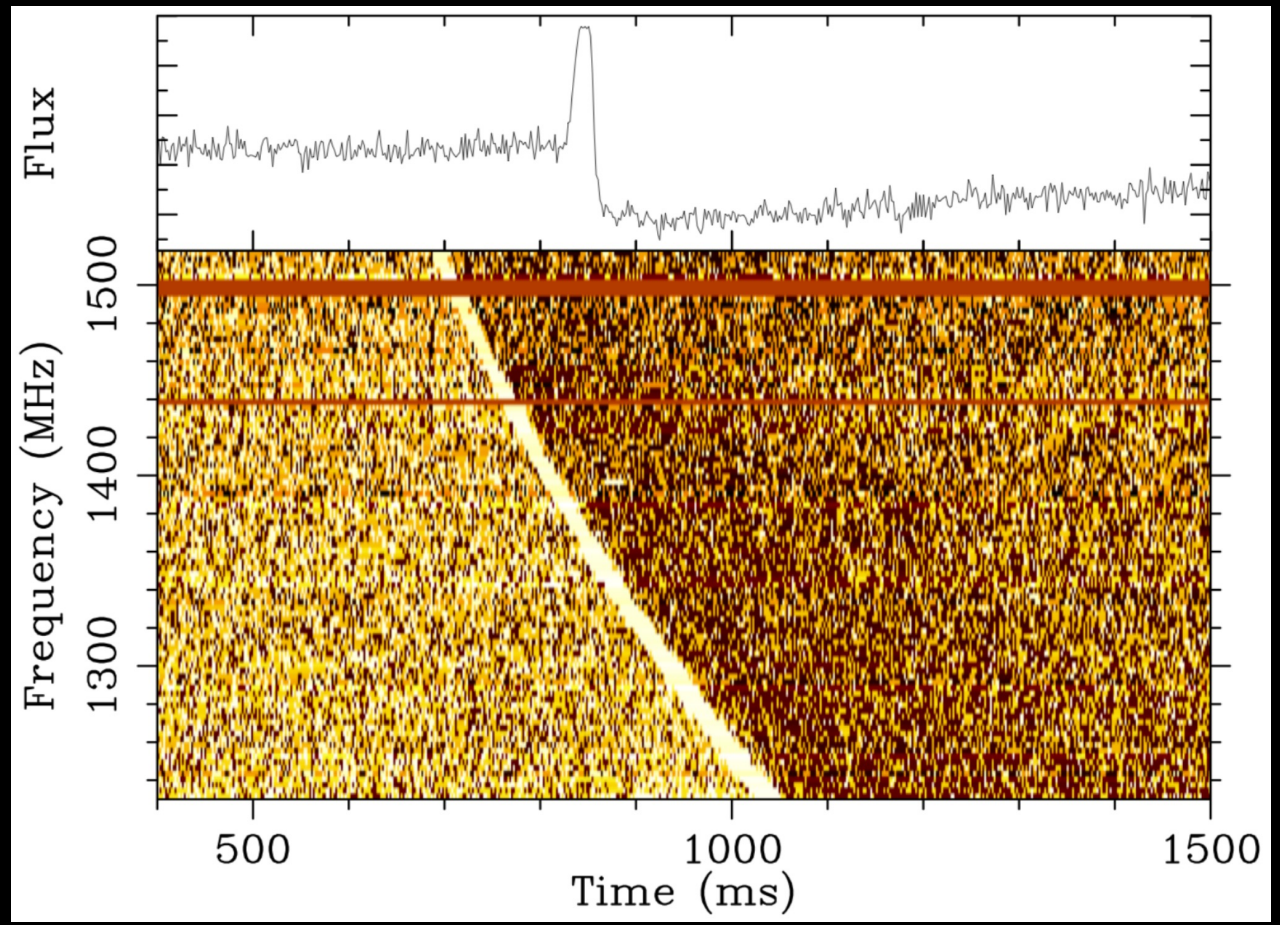

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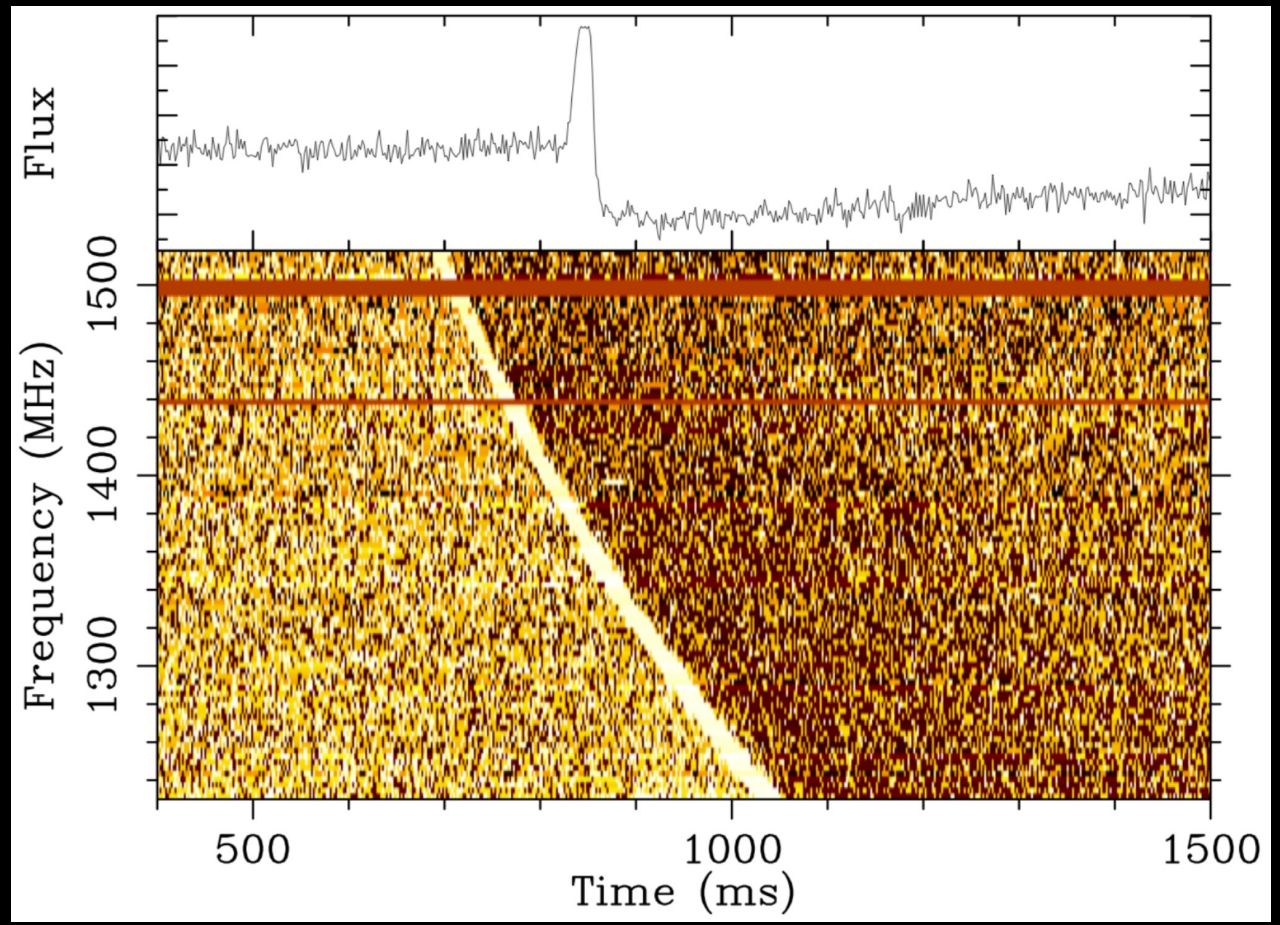

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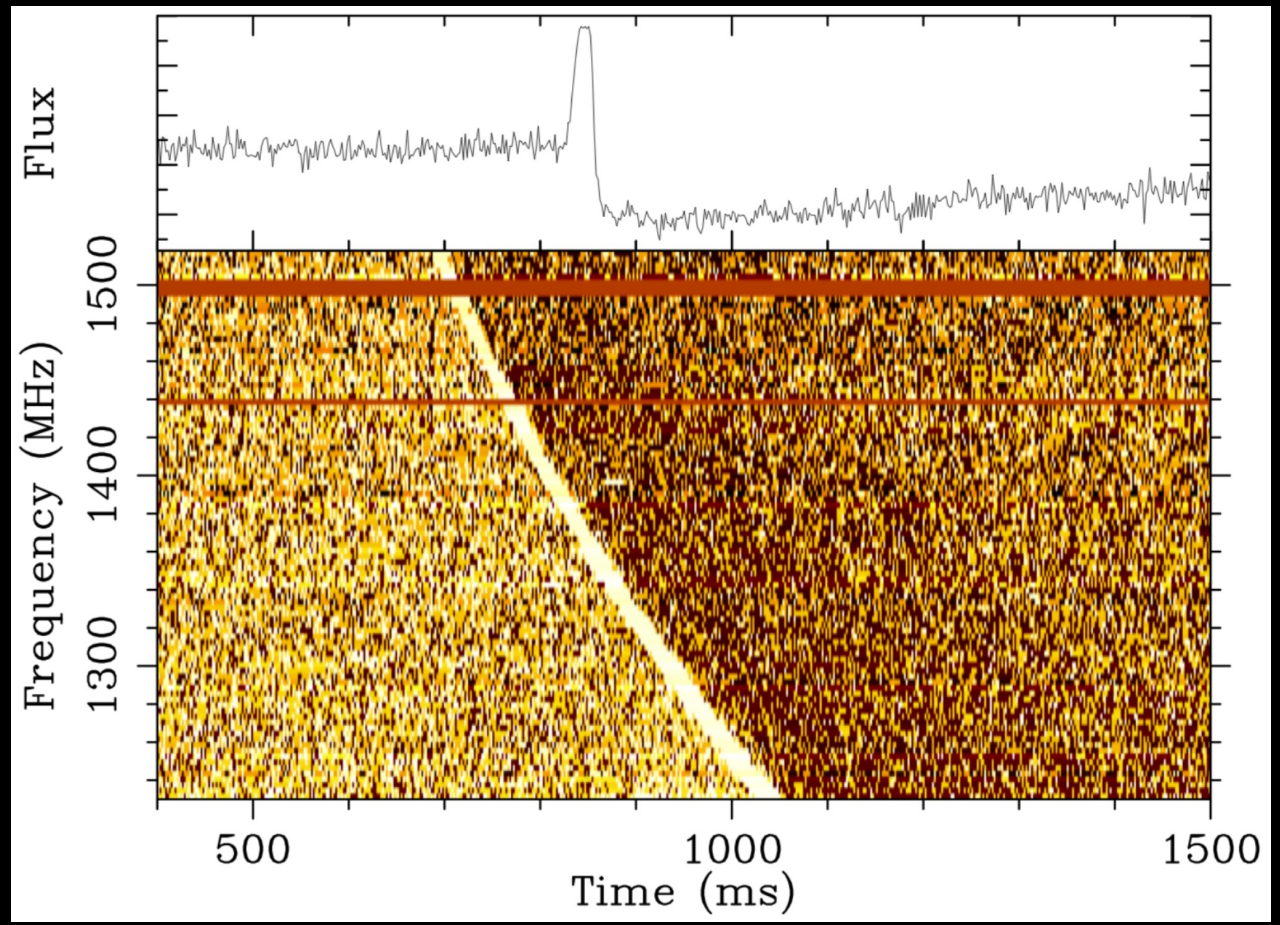

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Electron number density

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

Frequency

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

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

Milky Way

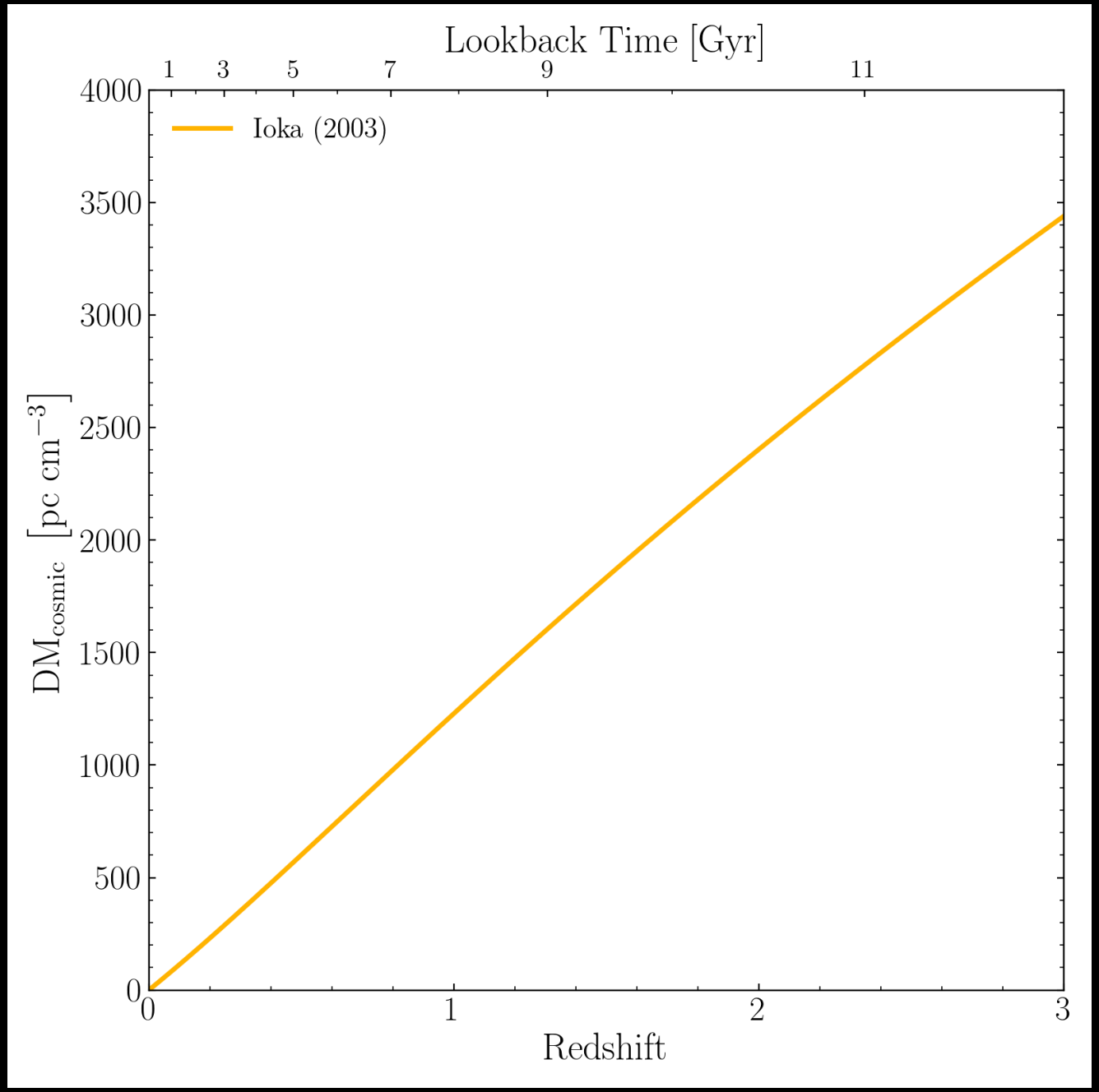
Host Galaxy/Local Environment

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

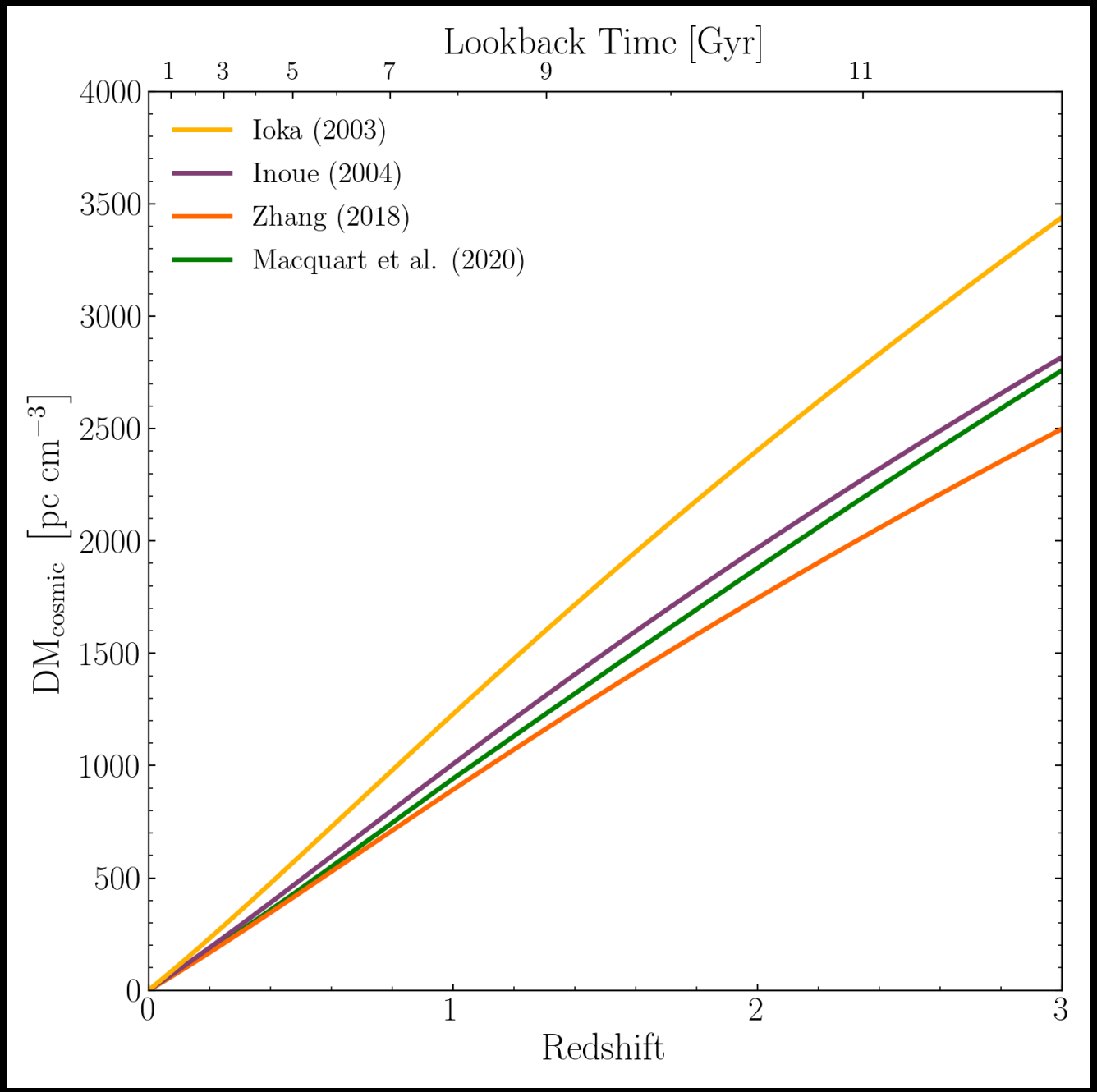
$$\mathrm{DM}_{\mathrm{cosmic}}(z) = \mathrm{DM}_{\mathrm{IGM}}(z) + \mathrm{DM}_{\mathrm{CGM,Interlopers}}$$

Intergalactic Medium

The CGM of Galaxies along the line-of-sight



Ioka (2003) [Analytic]



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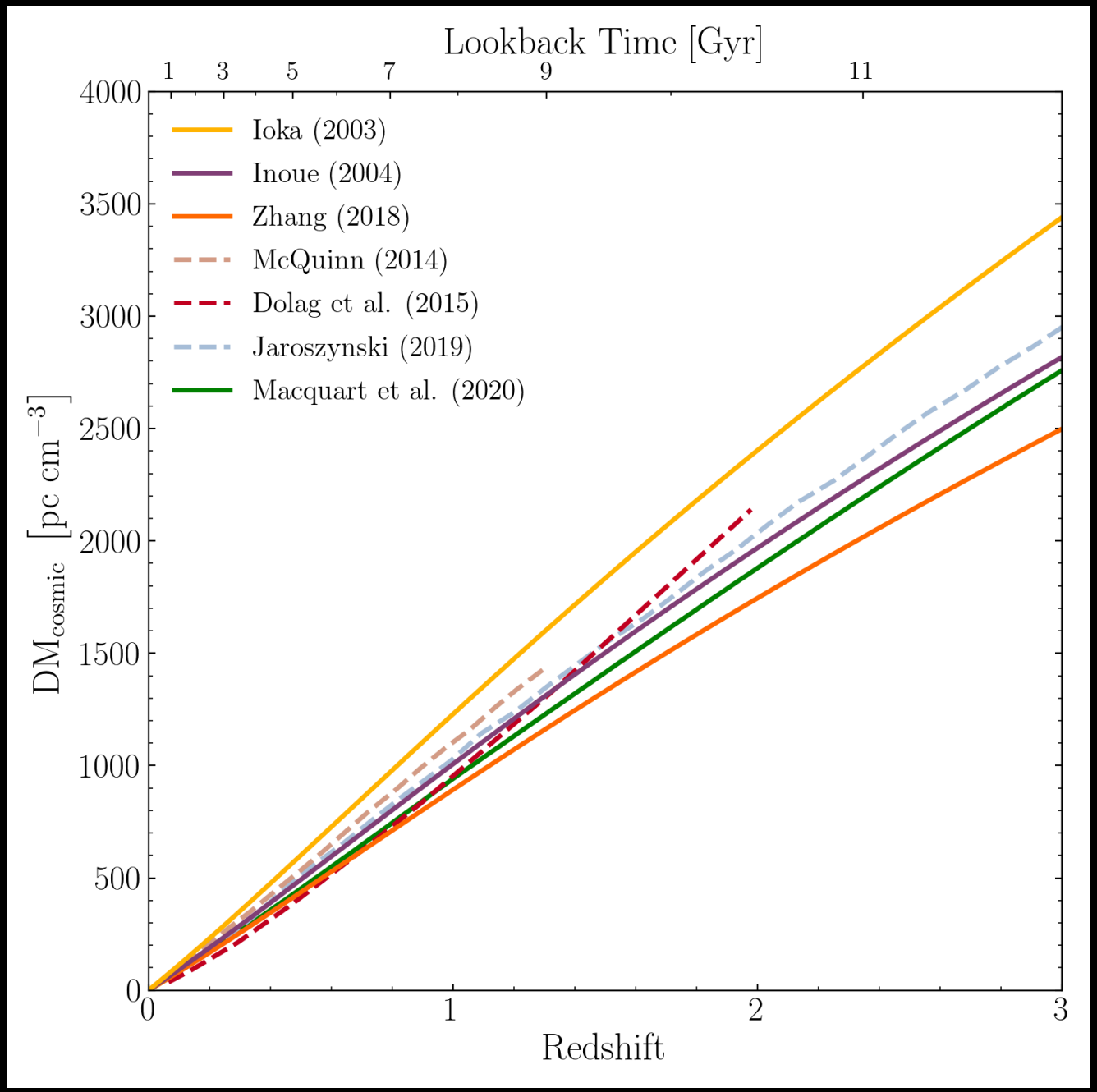

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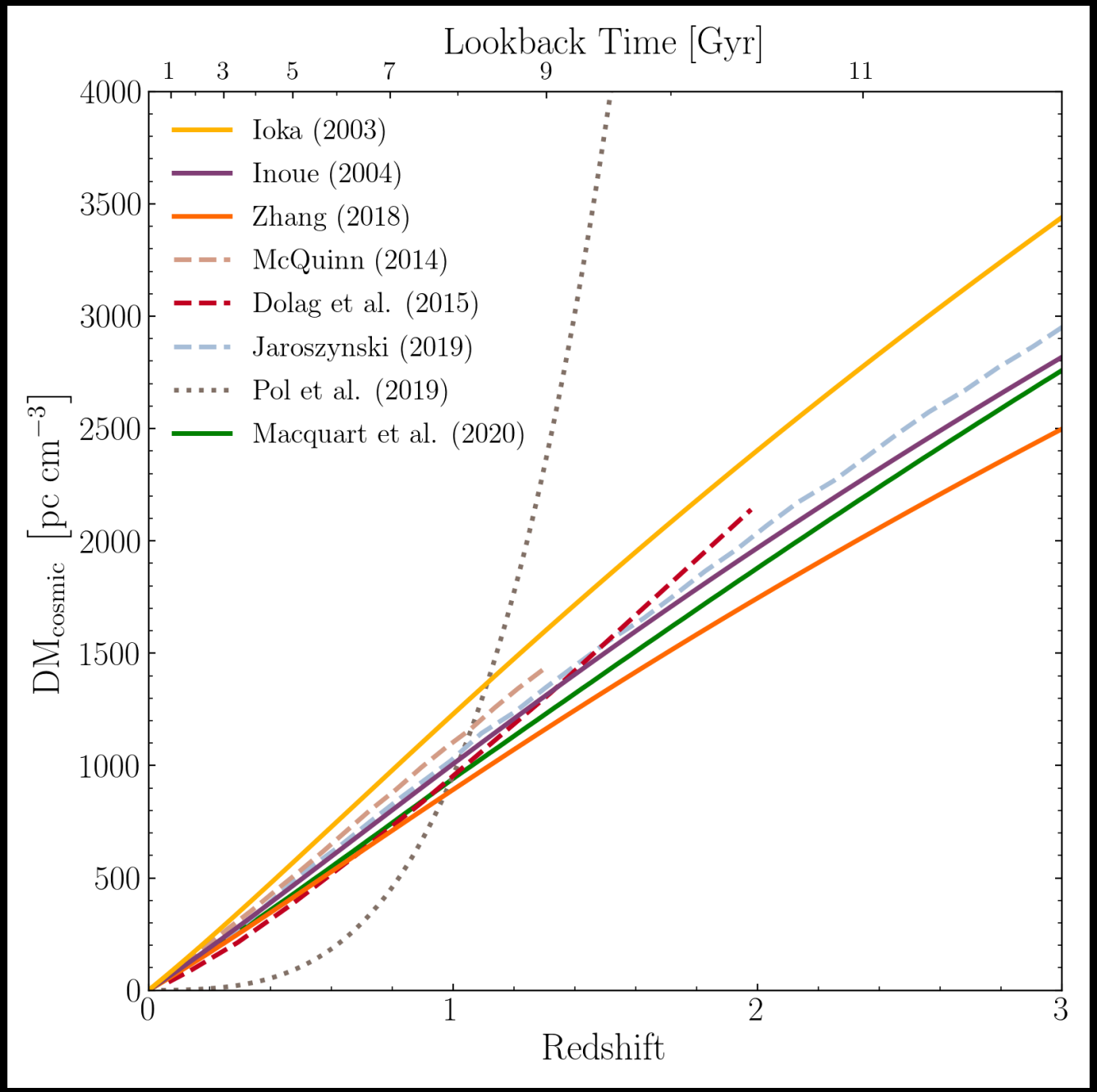

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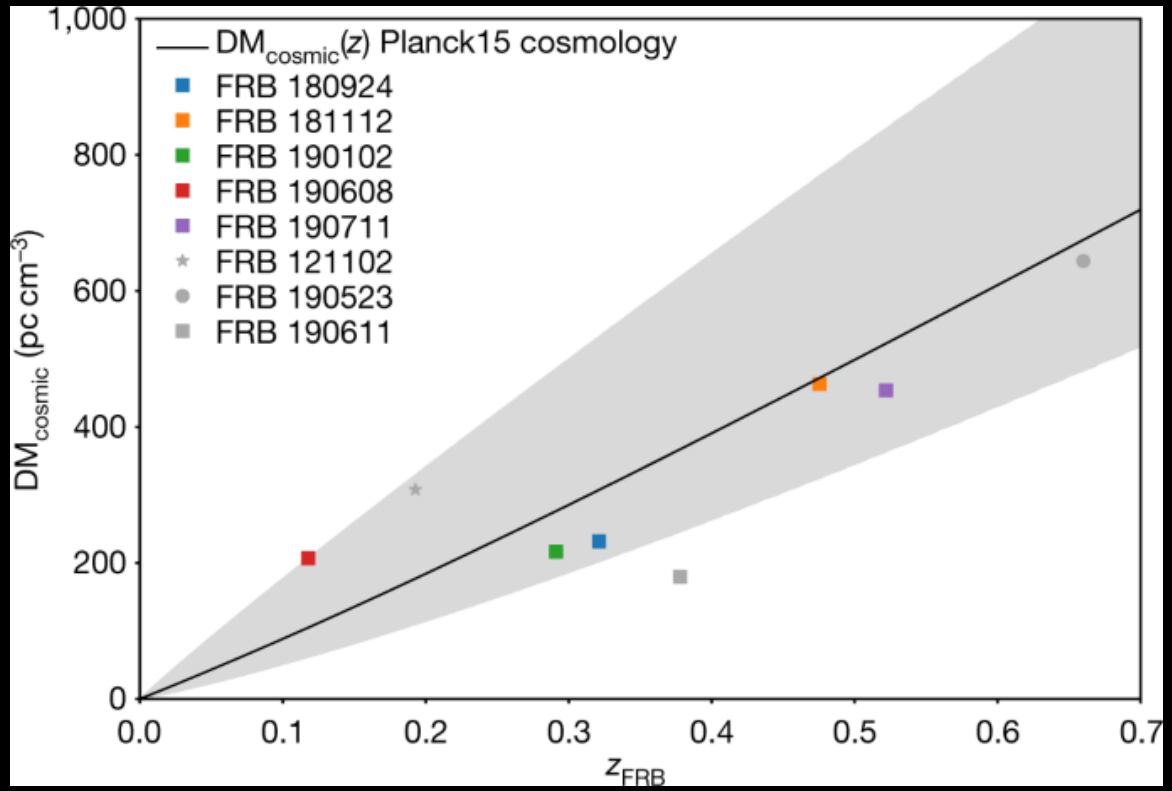
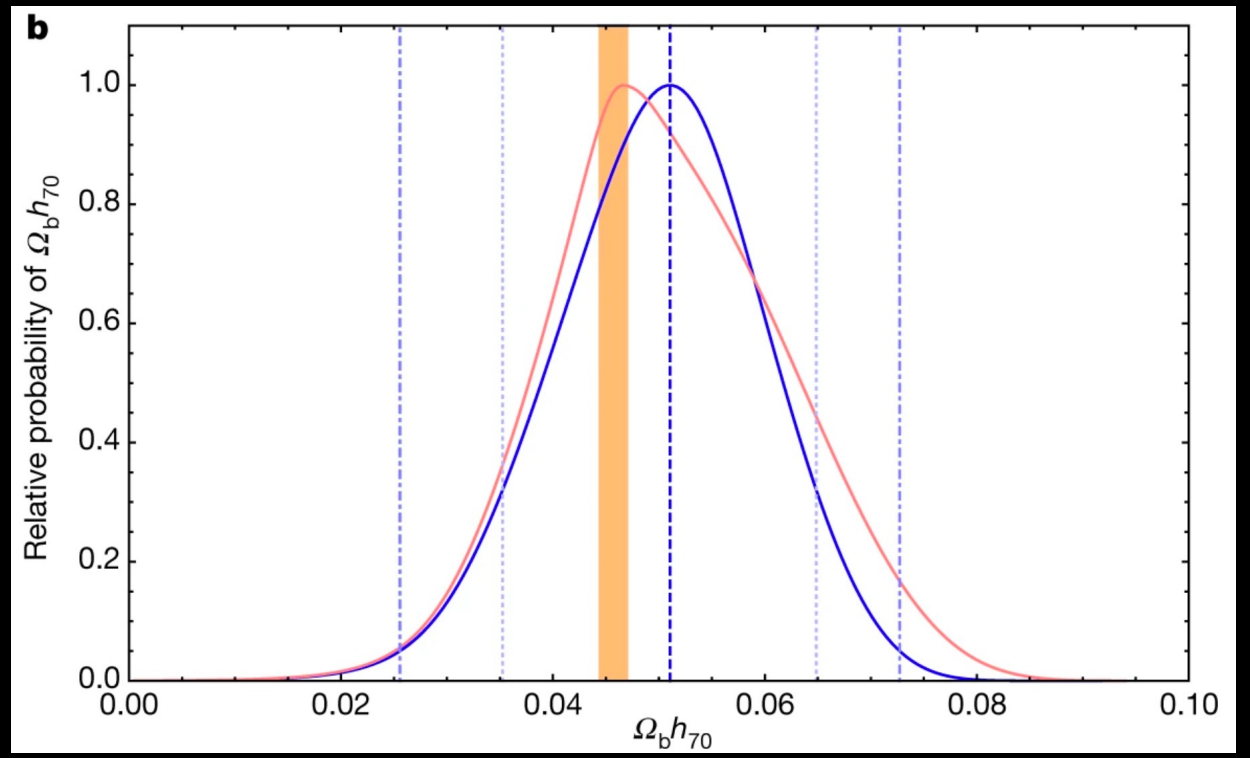
Pol+(2019) ["Semi-Analytic"; MICE]

Macquart+(2020) [Analytic]

Macquart et al. (2020)

FRBs and the Missing Baryon Problem





Batten et al. *accepted* (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

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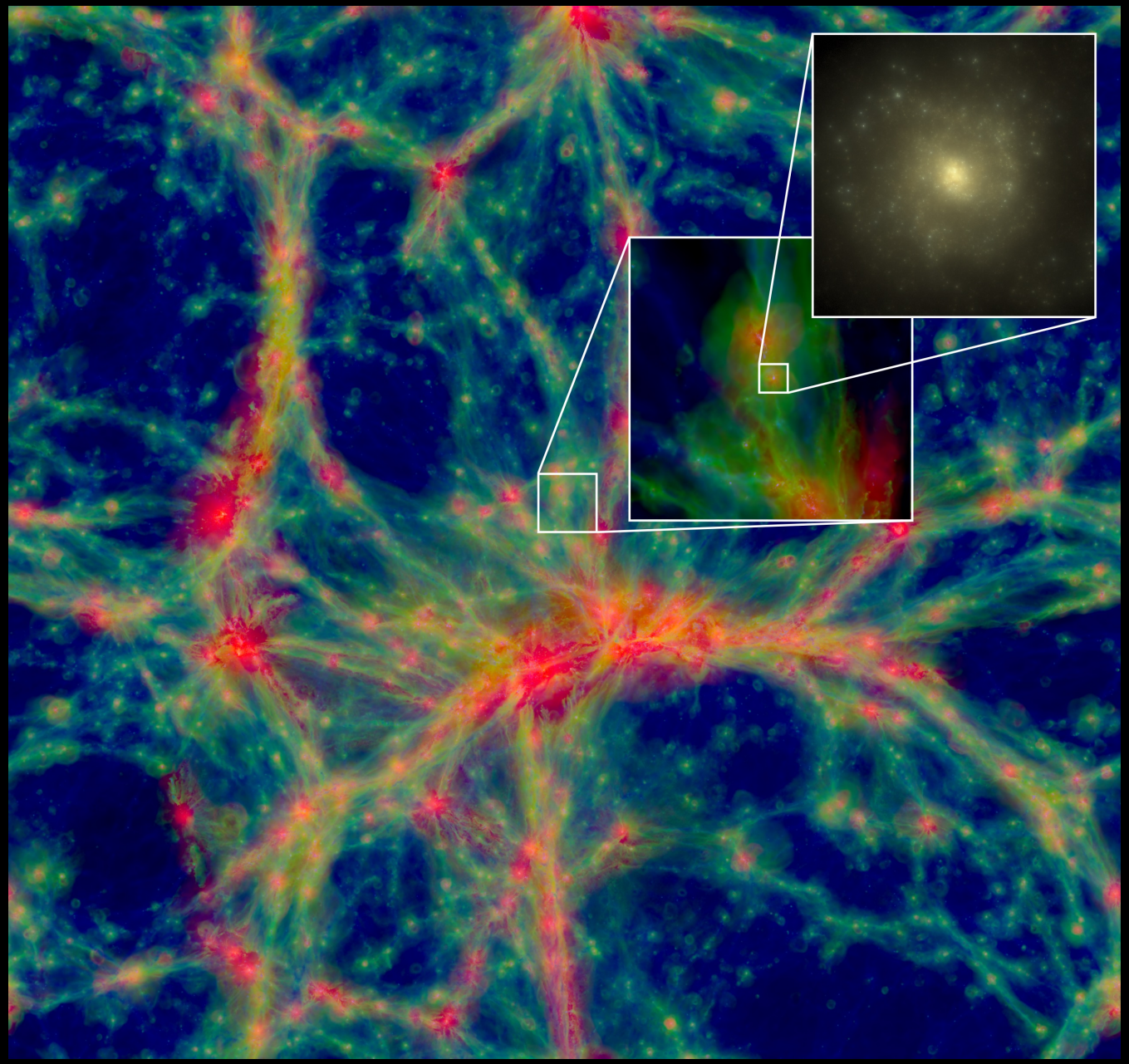

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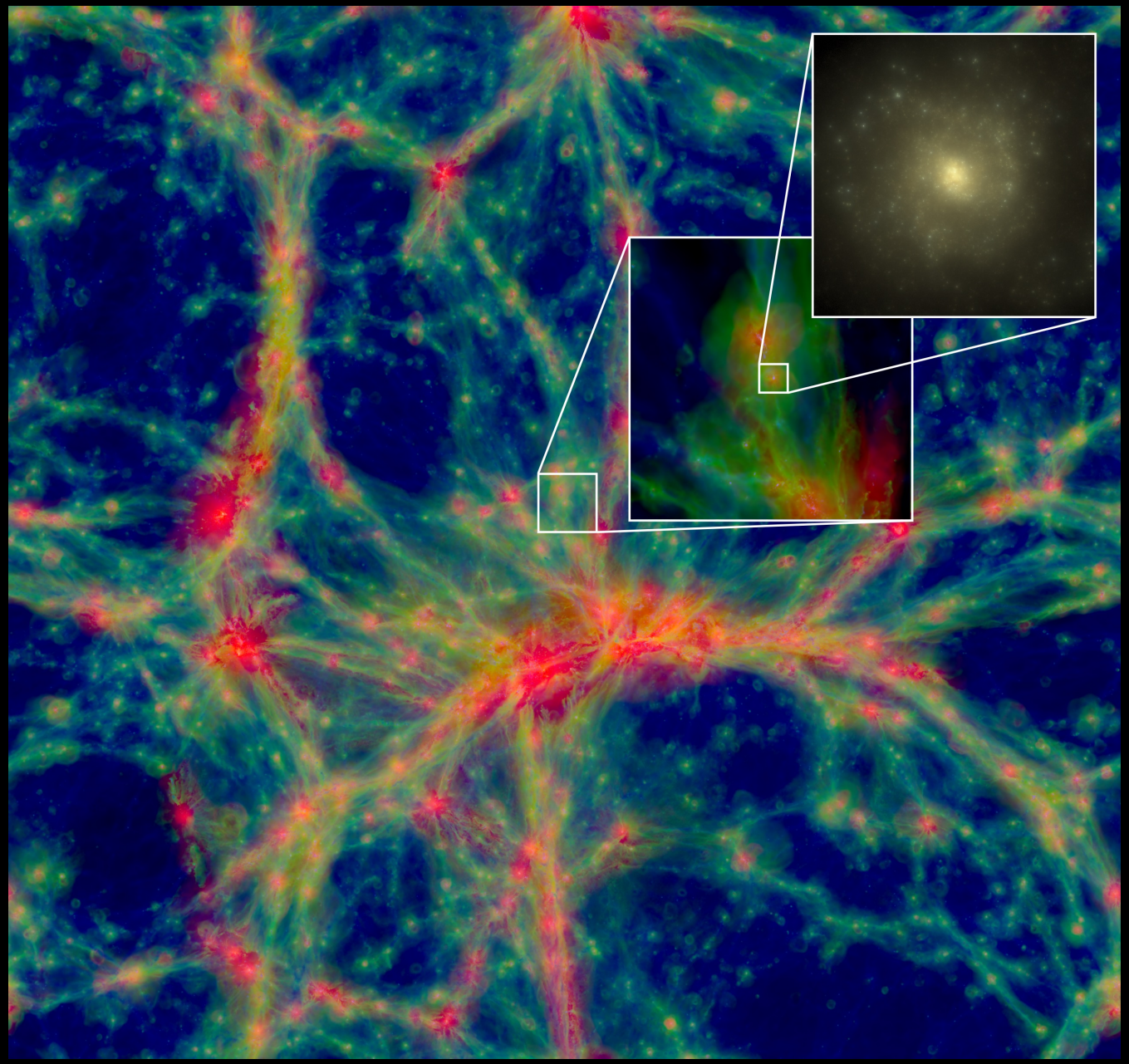

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- Hydrodynamics + Nbody
- Large cosmological volume (100 cMpc)
- Redshift range ($z \sim 127$ to $z = 0$)

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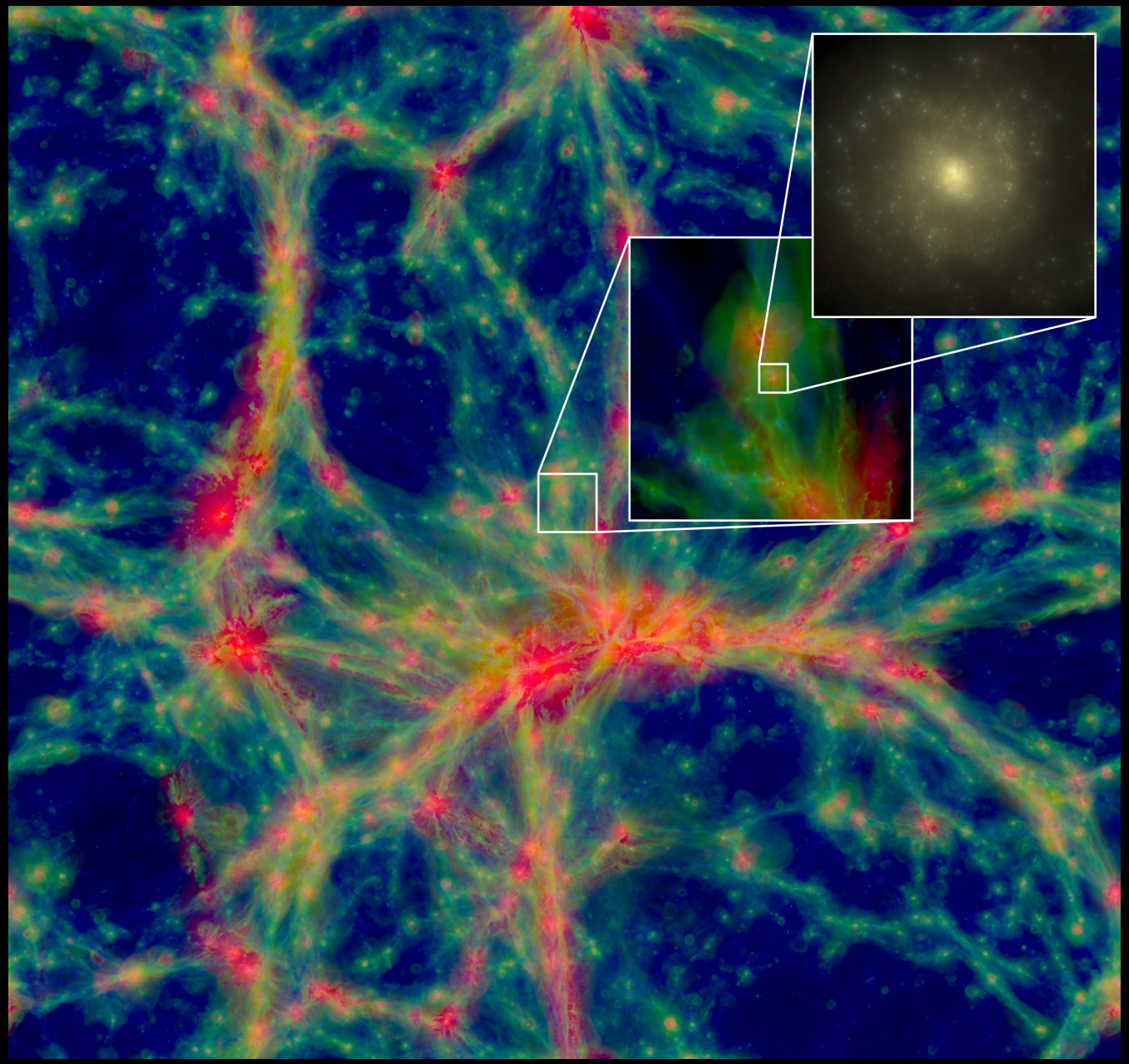

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- HM12 UV Ionising Background
- Galactic Winds: Star formation & AGN

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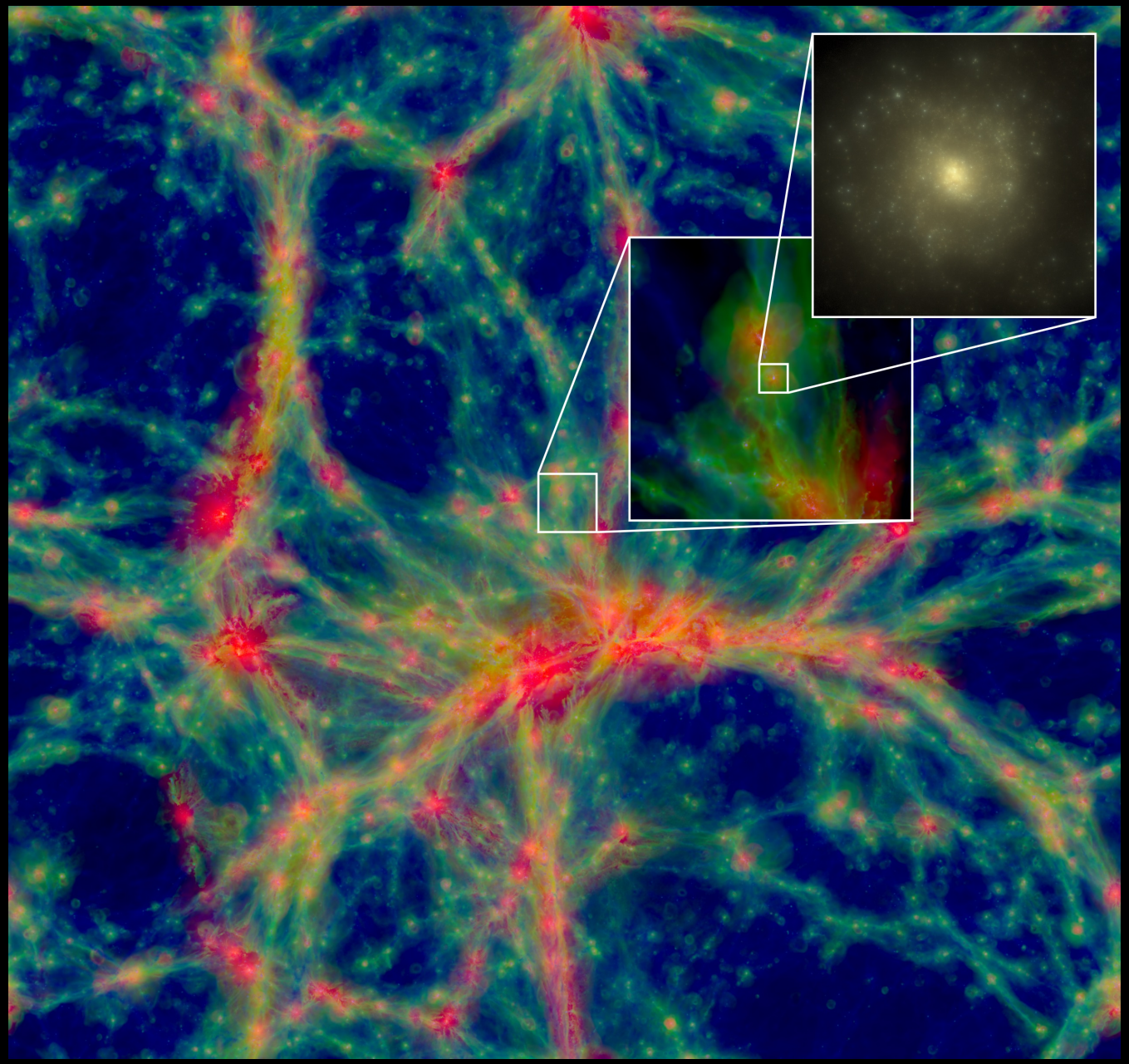

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- Resolution: ~ 0.7 ckpc
- Particle Masses: ~ $10^6\ M_\odot$

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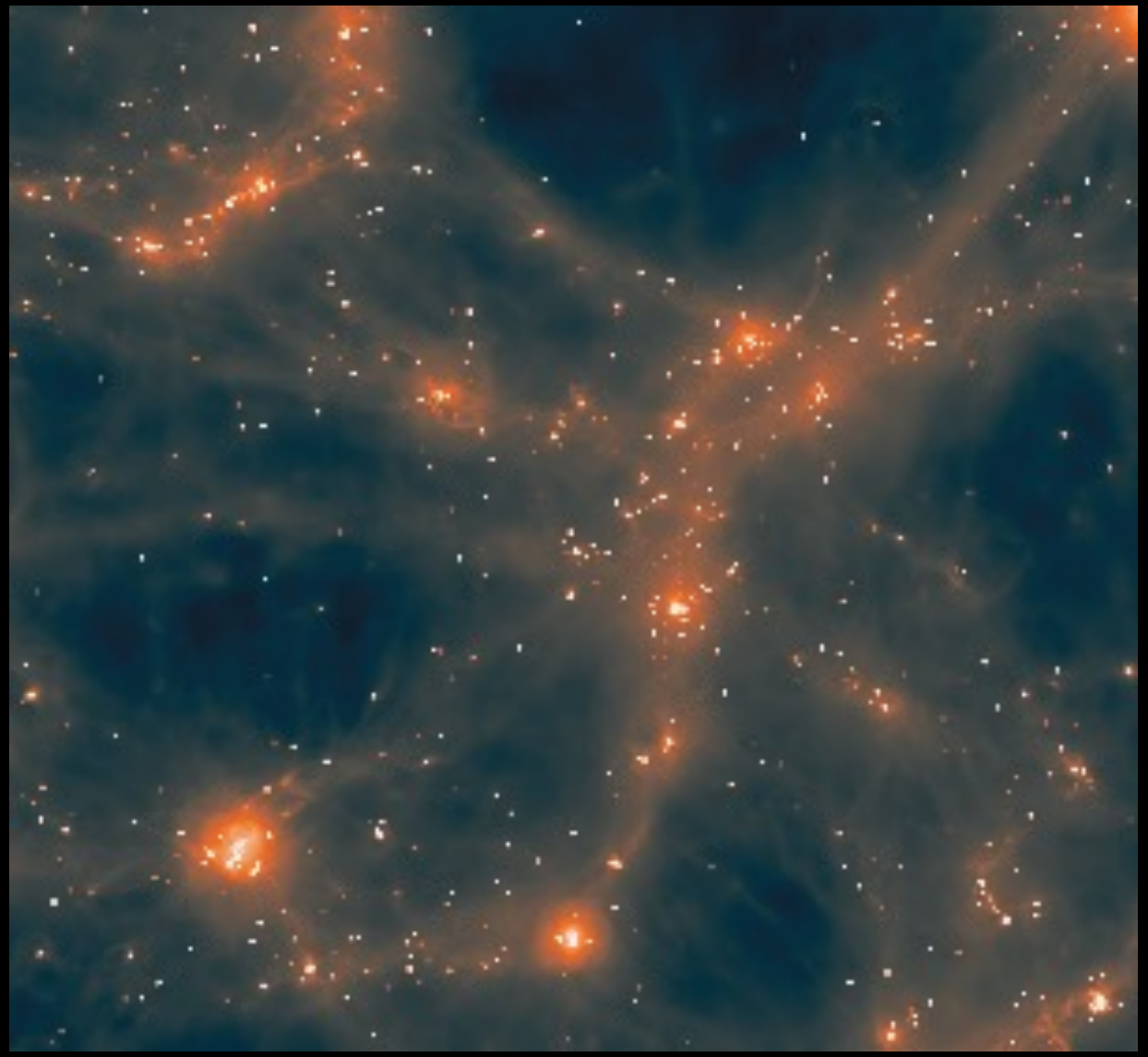

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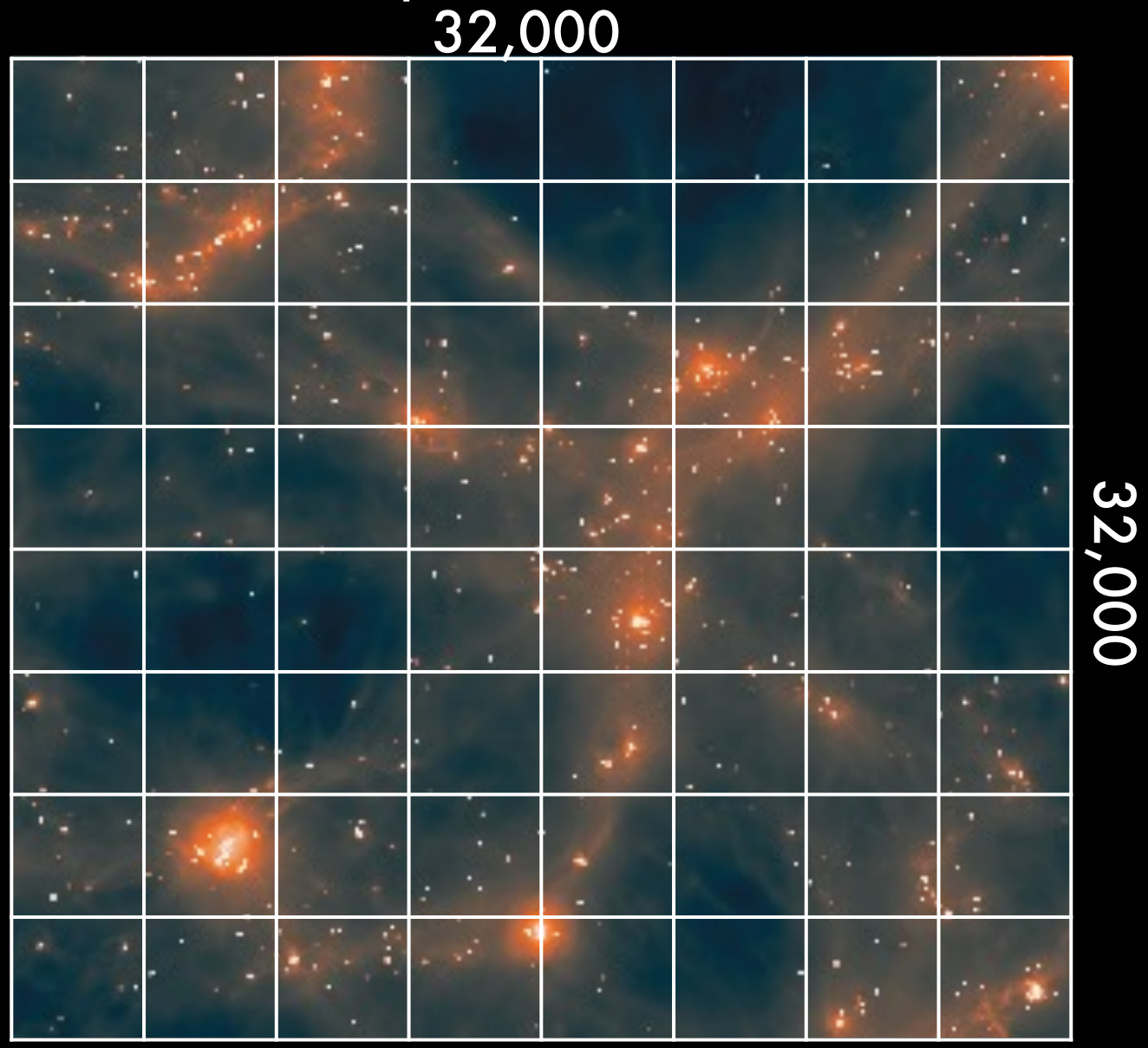

EAGLE Simulations

- Divide cube into columns

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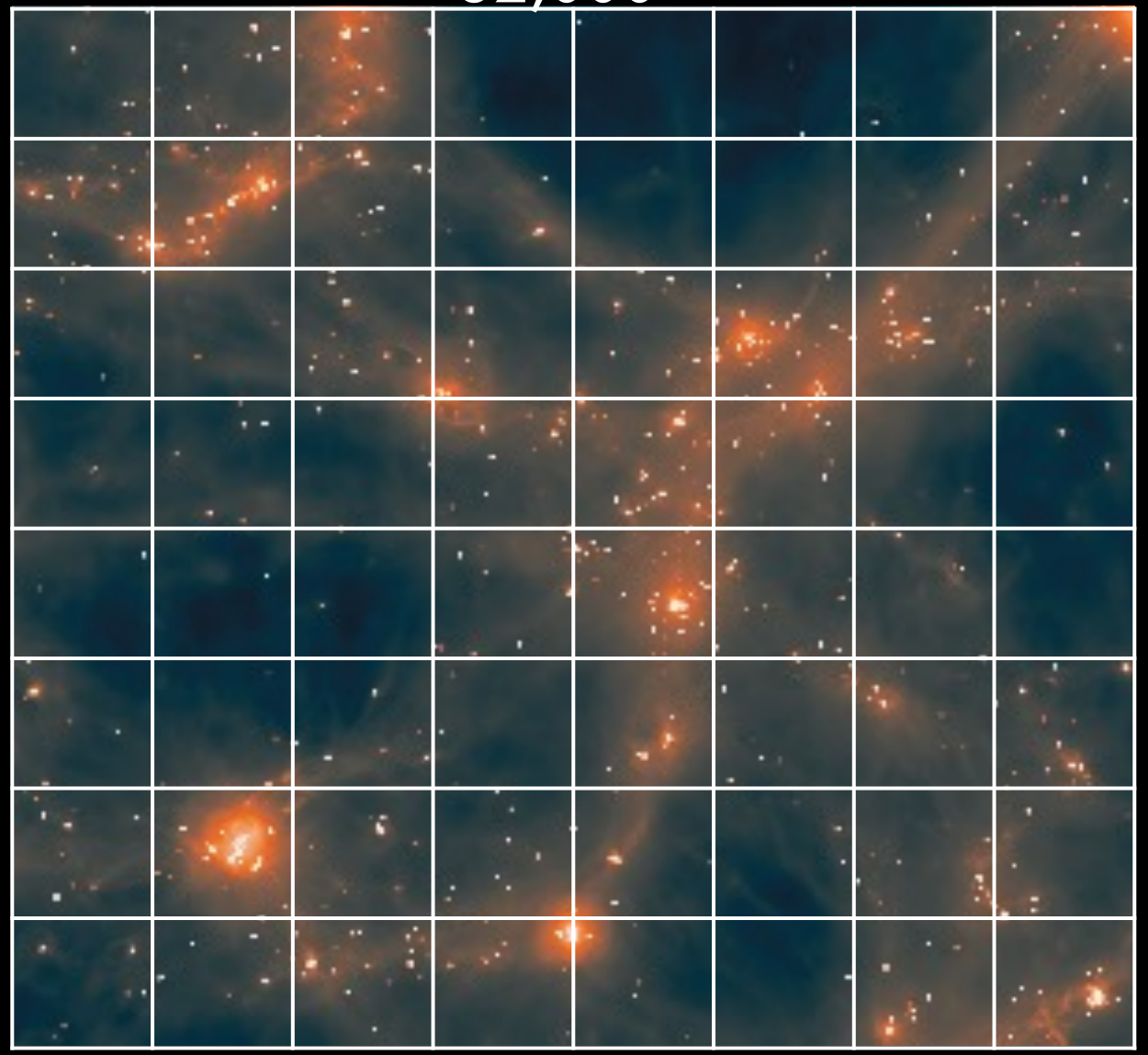

EAGLE Simulations

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

HII HeII HeIII

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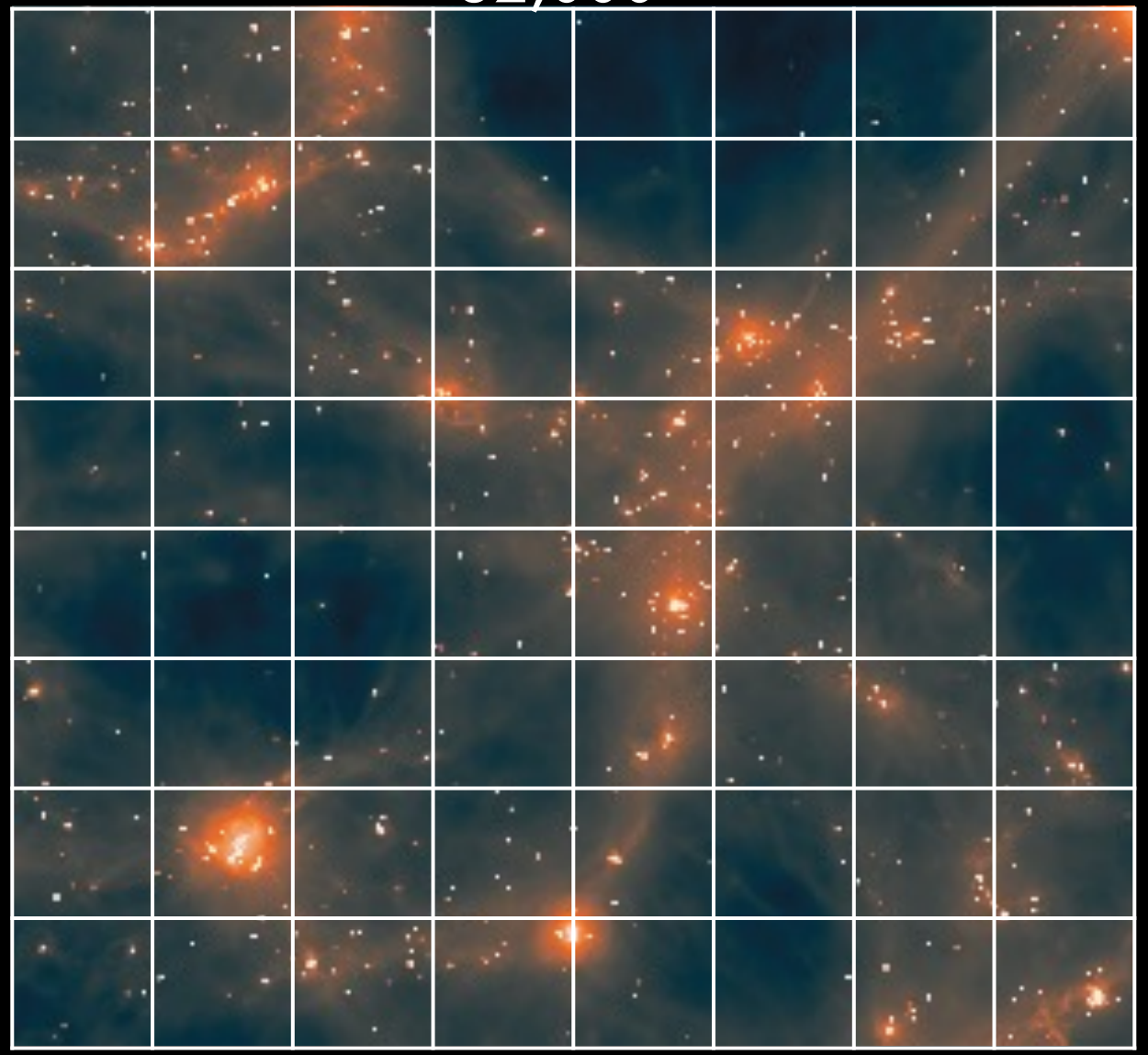

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  - Wijers et al. (2019)
- Convert column densities to units of pc cm^{-3}

HII HeII HeIII

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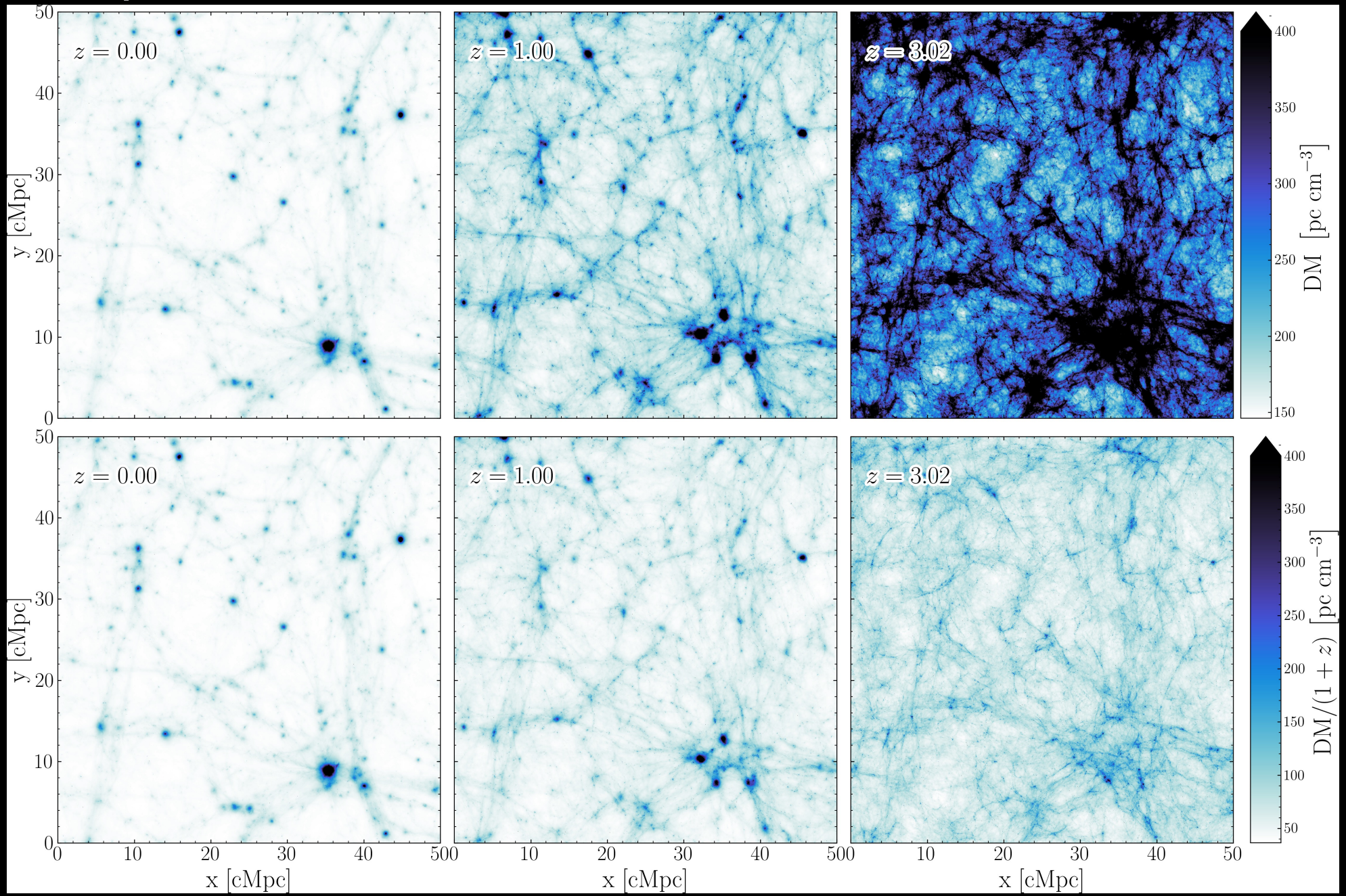
Local Observer

$z = 0$ Observer



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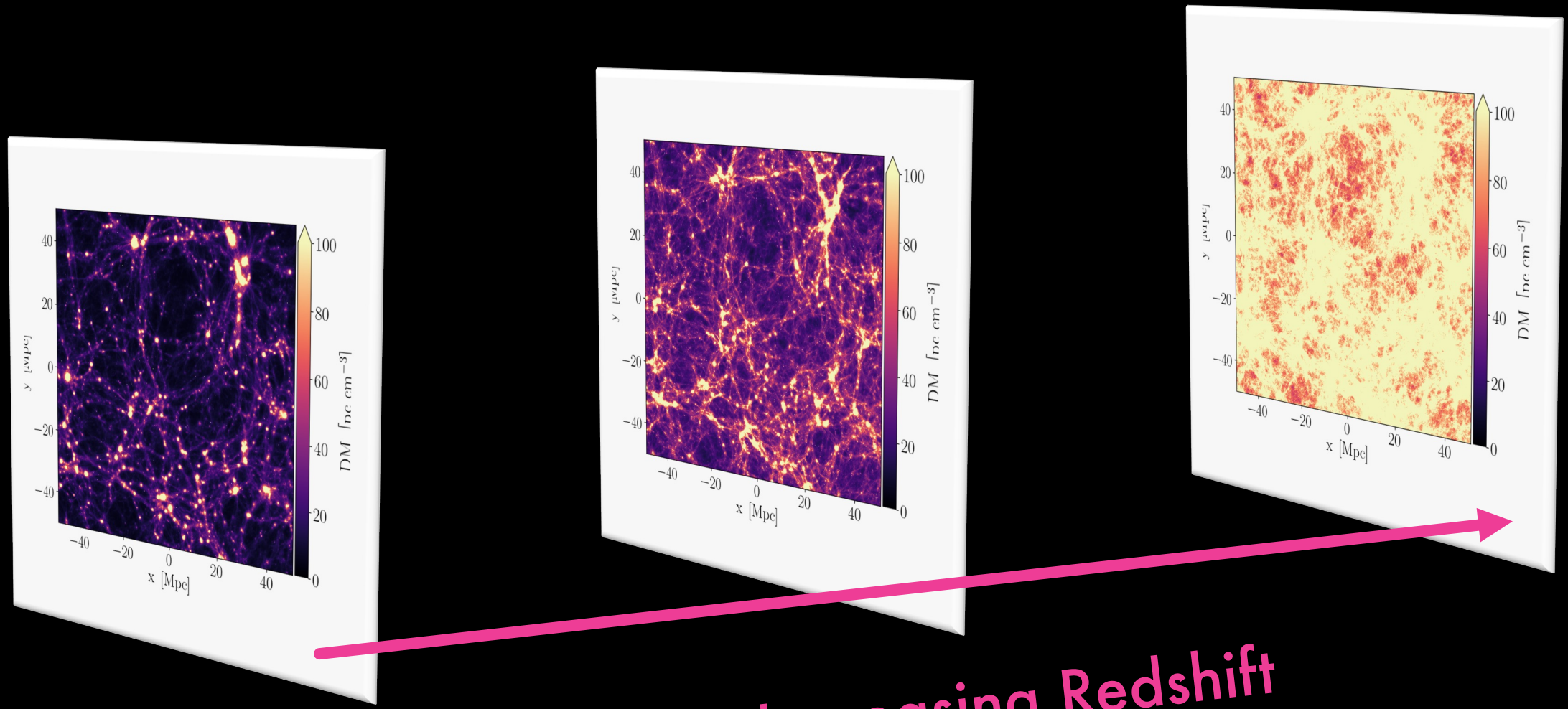

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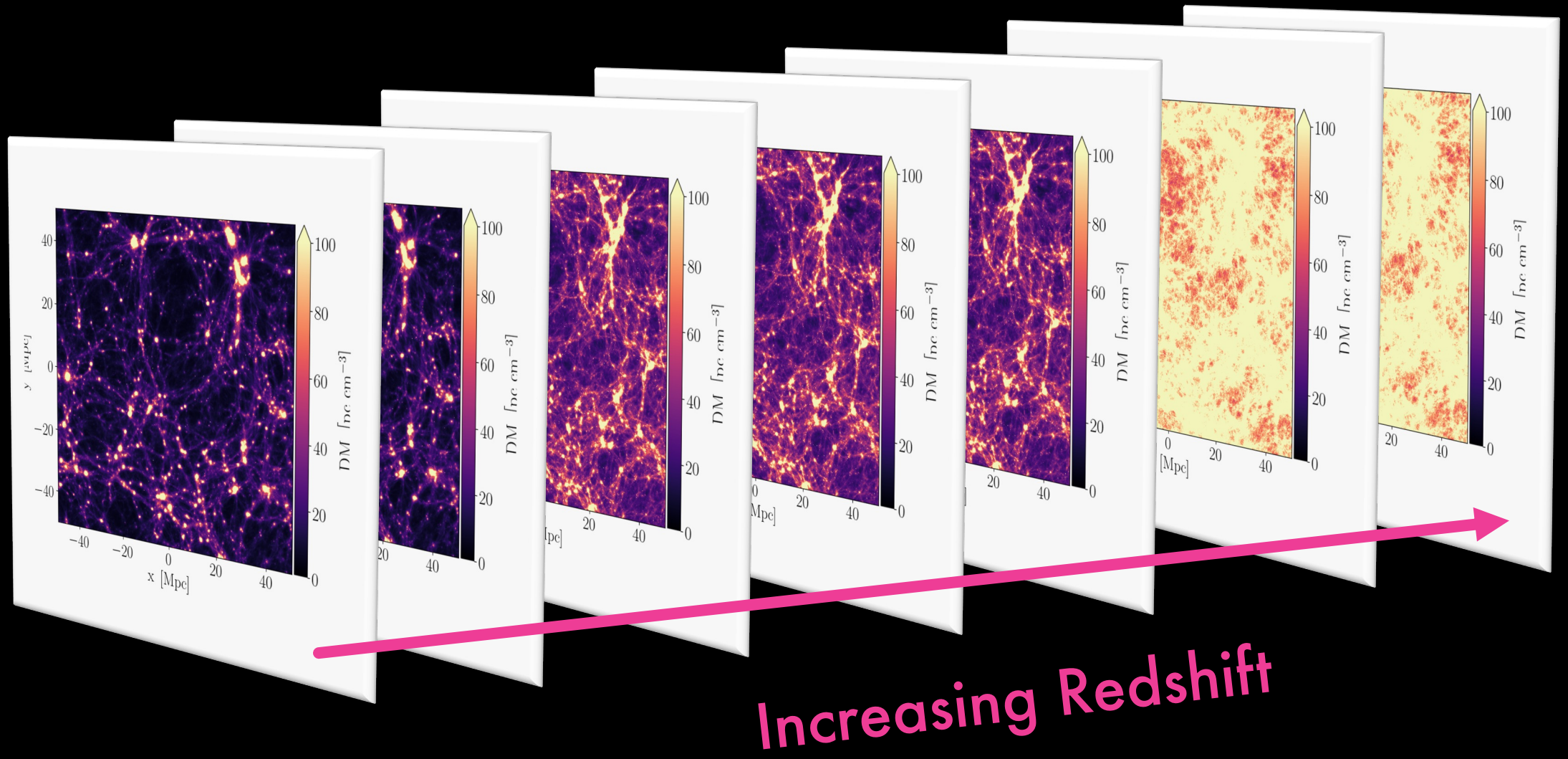

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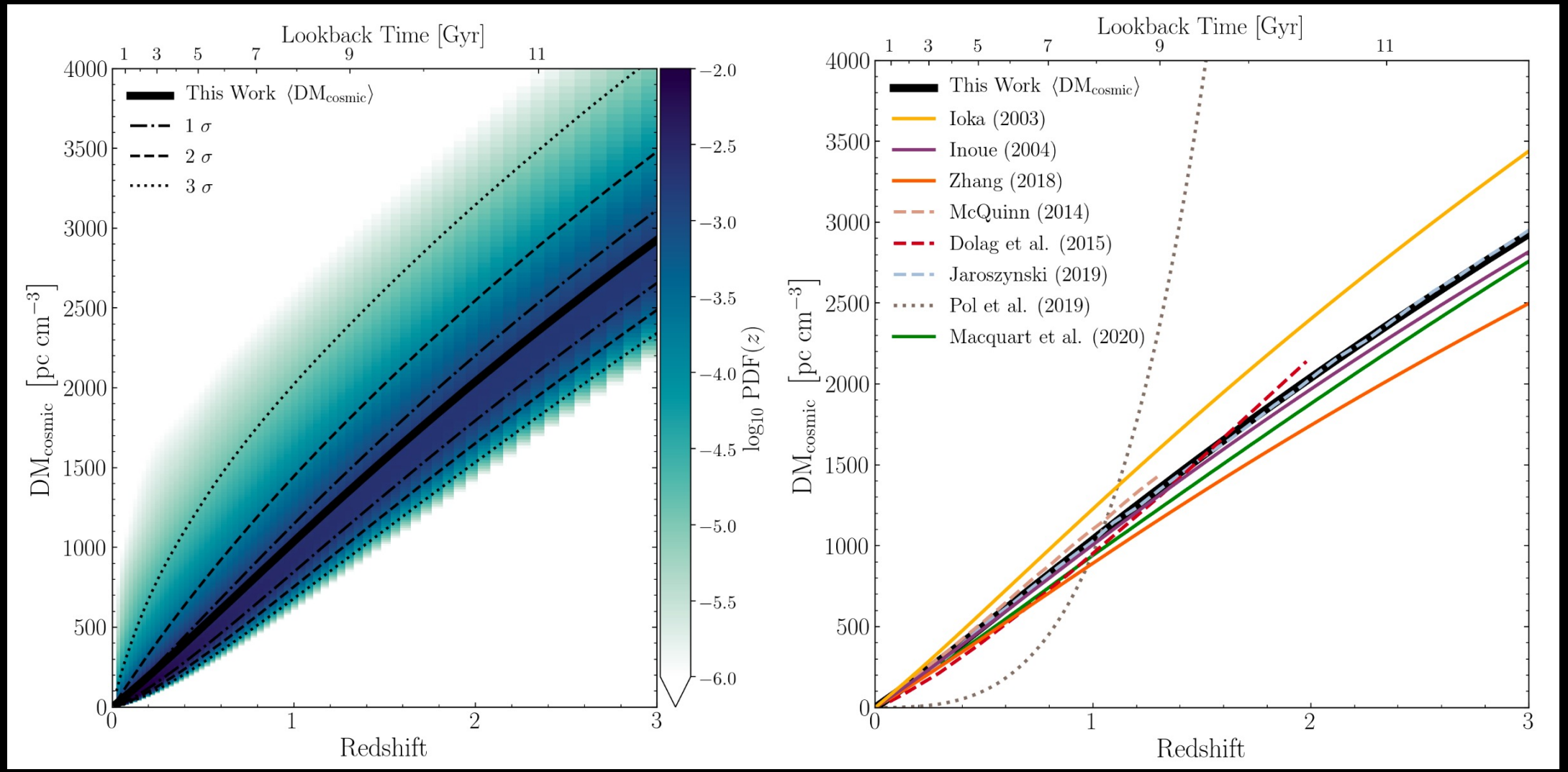

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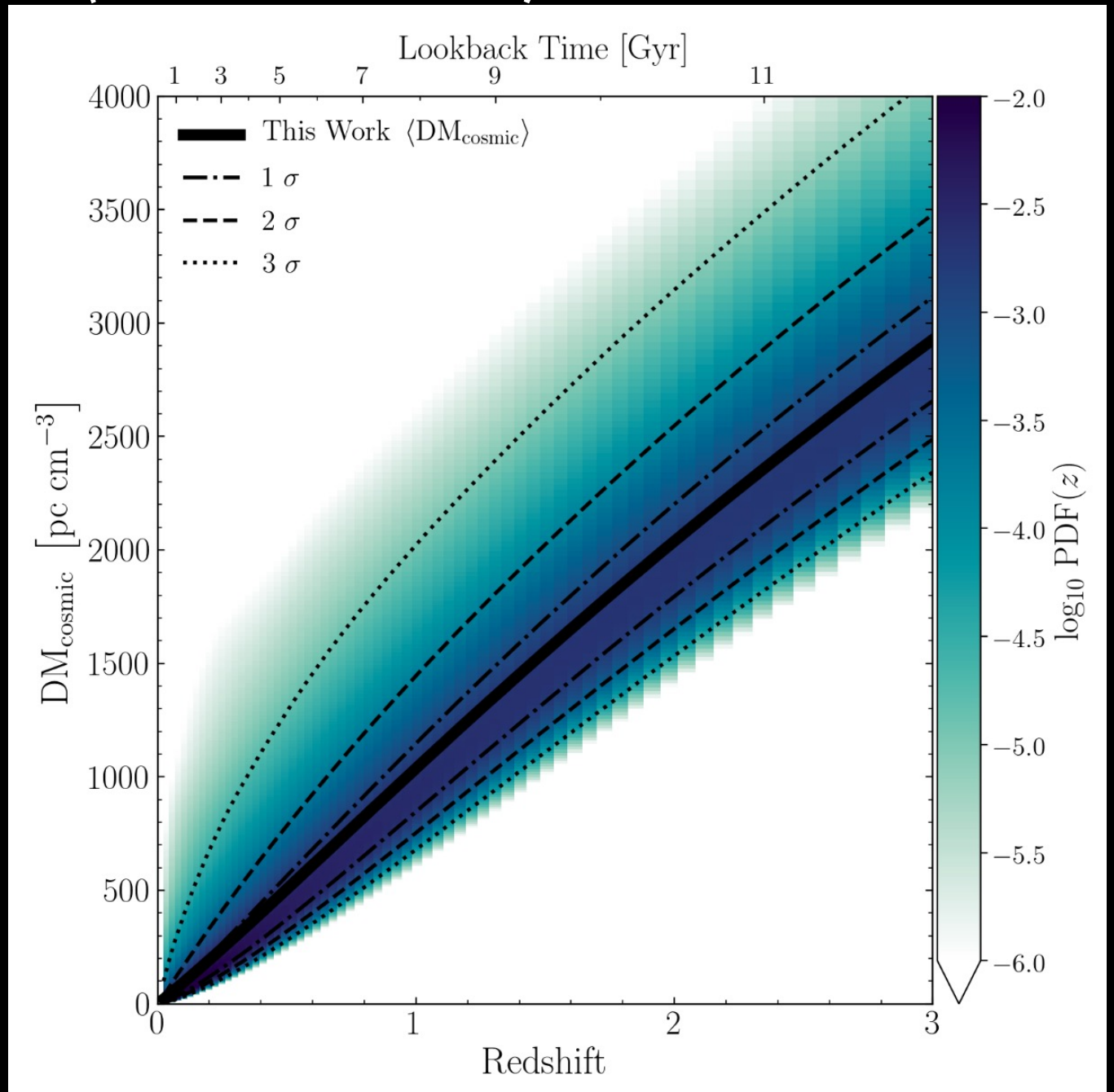

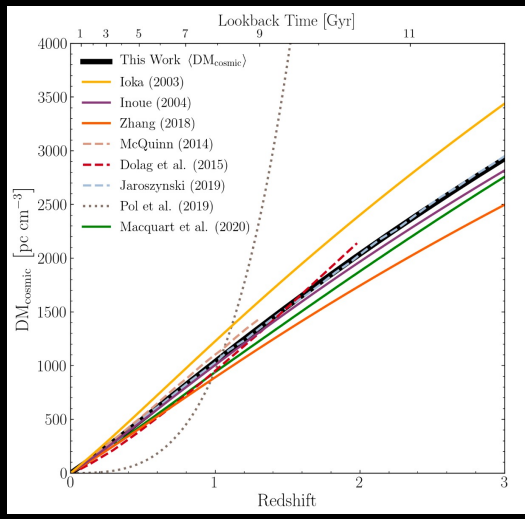

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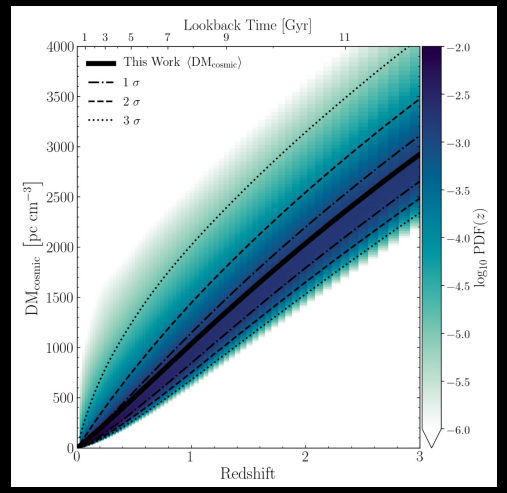

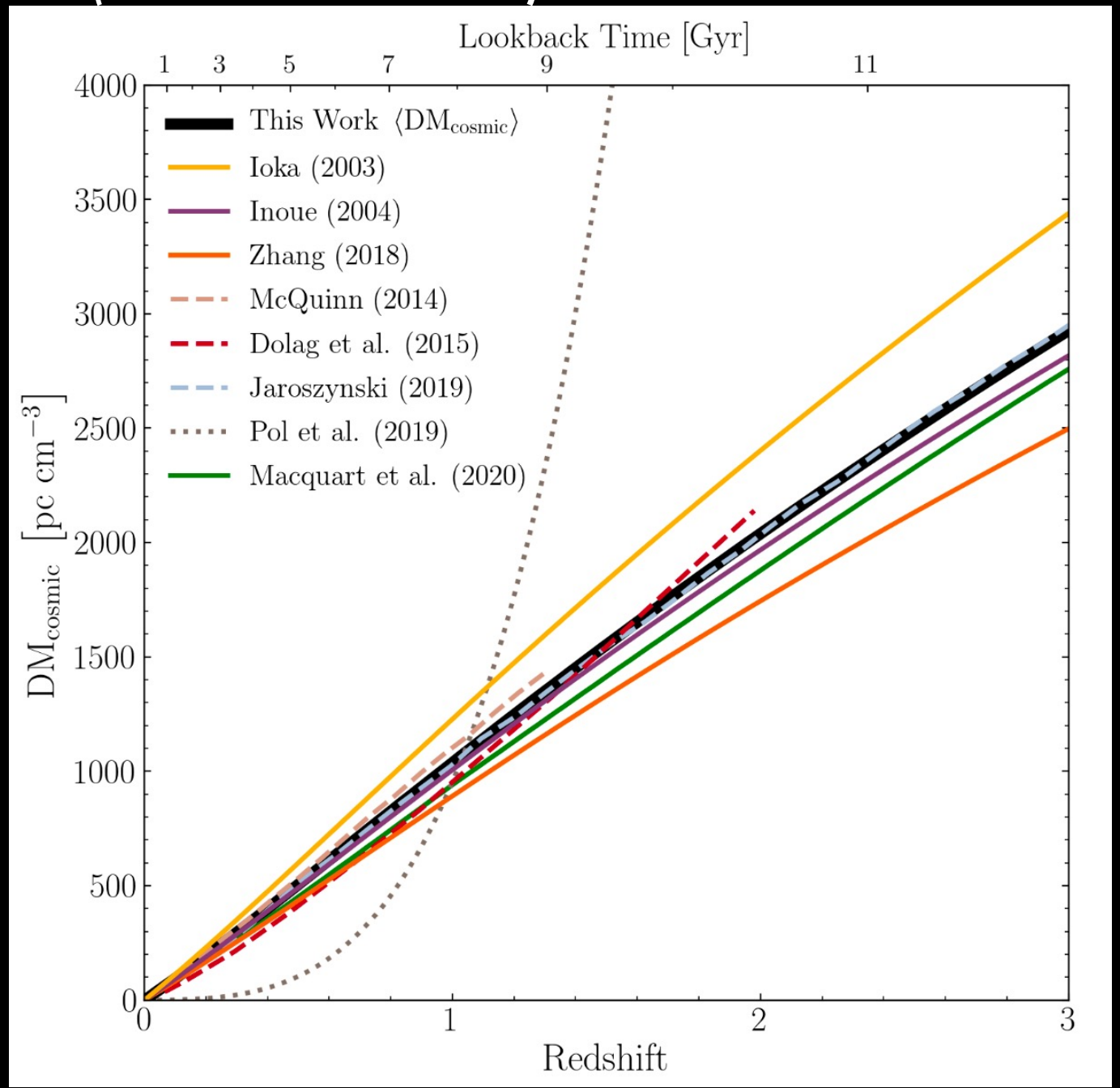

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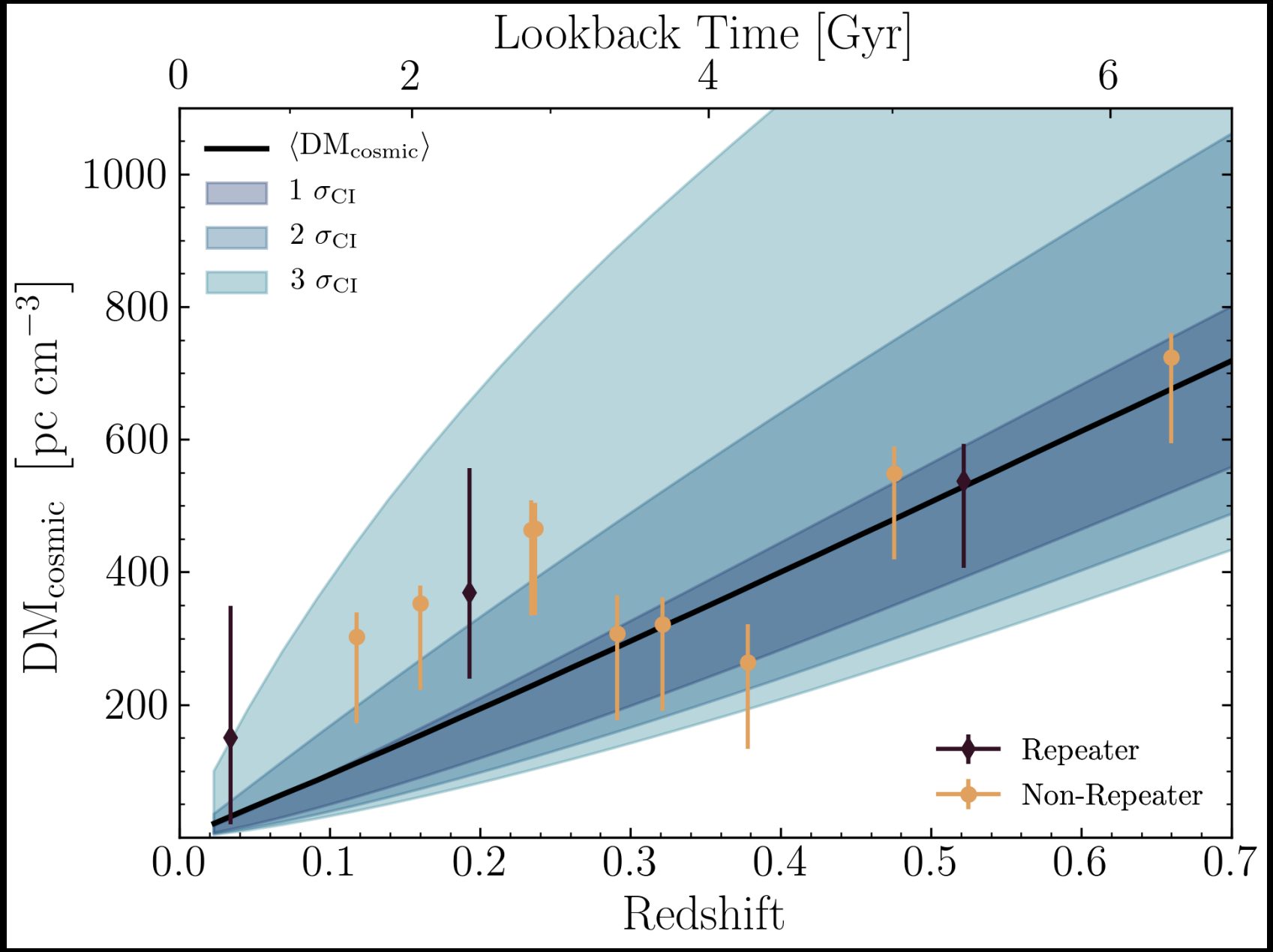

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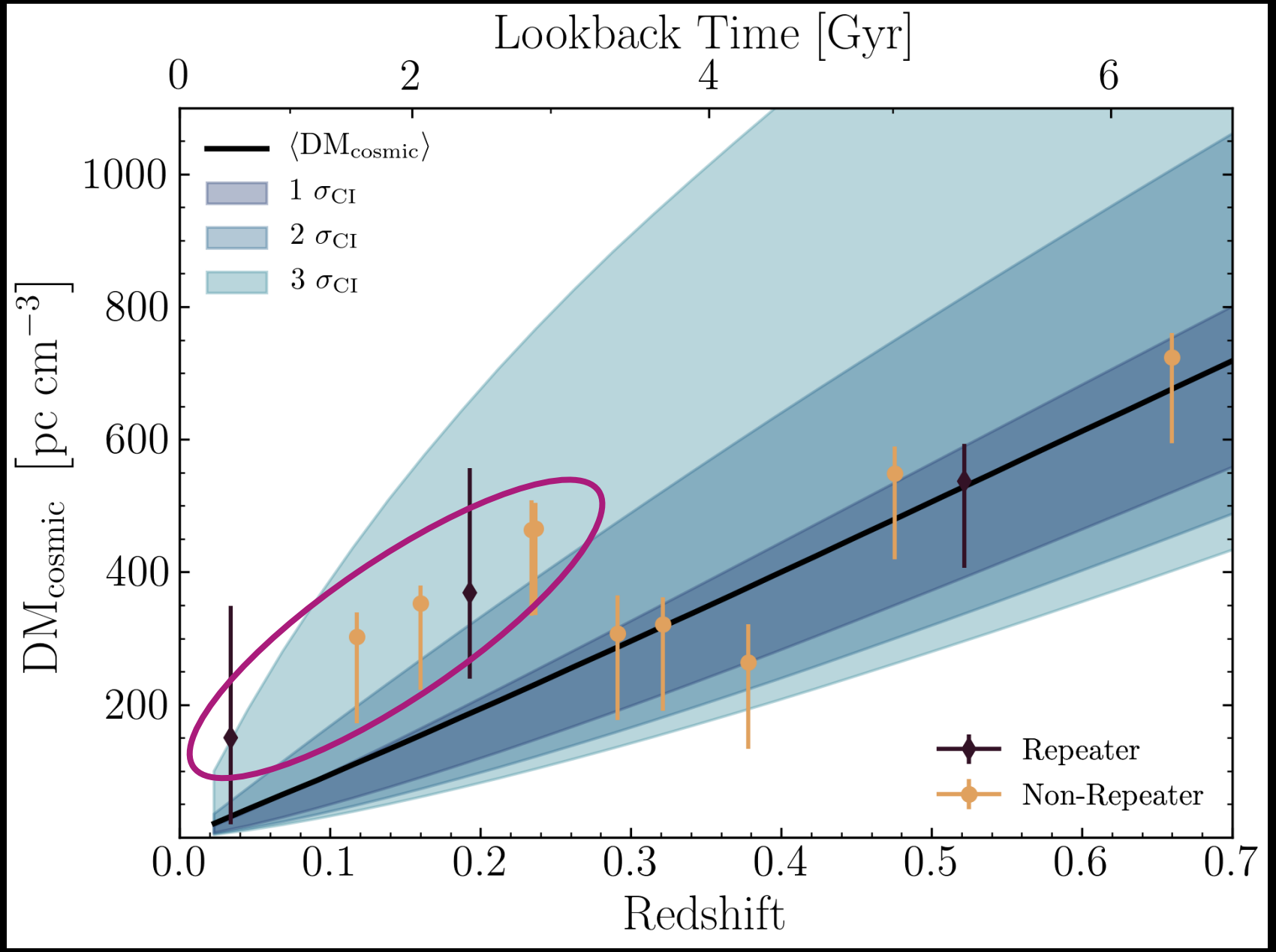
The $\mathbf{DM_{cosmic}}$ of most FRBs at low redshift appear to be $2-3\sigma$ sigma above the mean.



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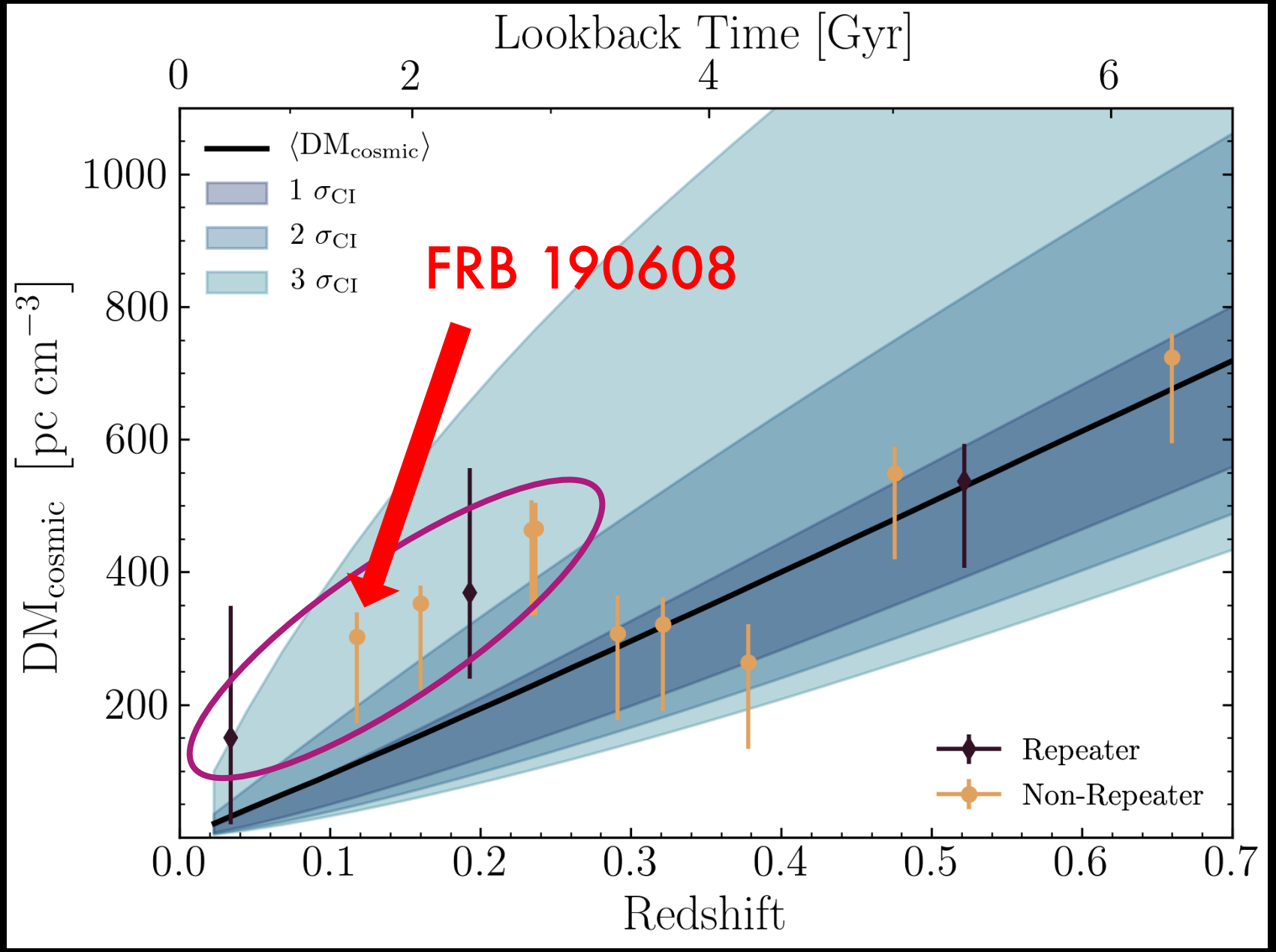
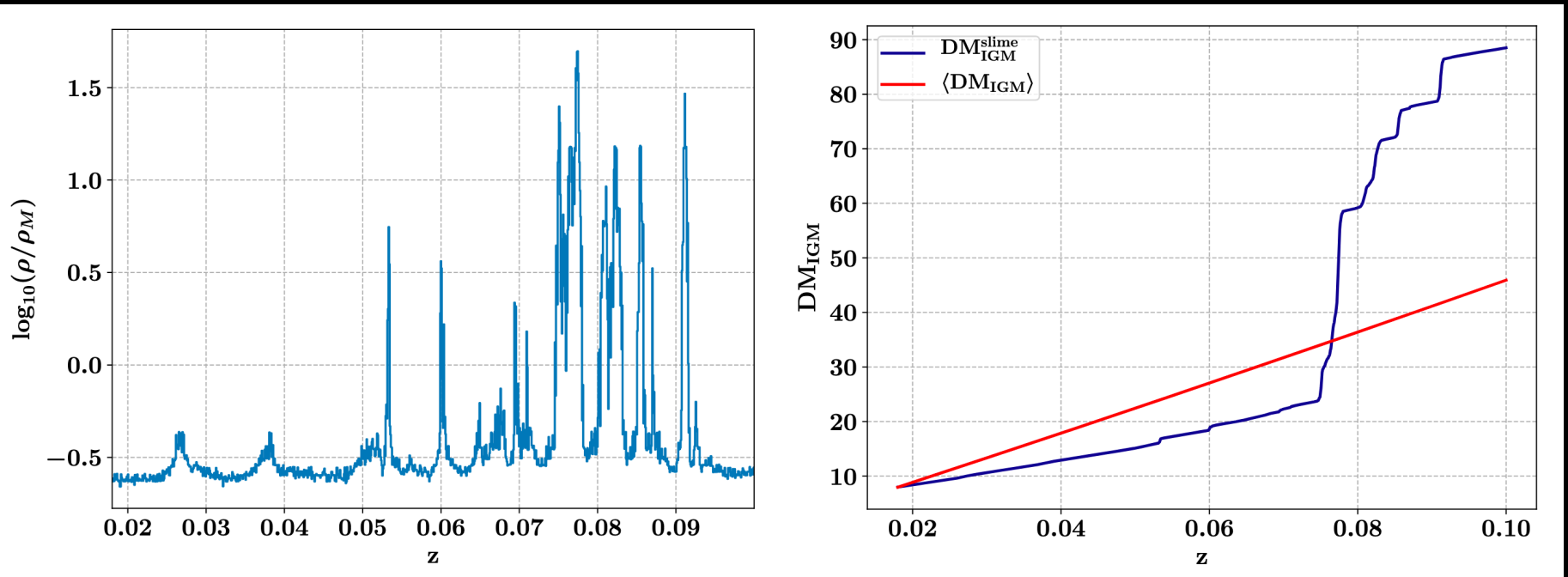


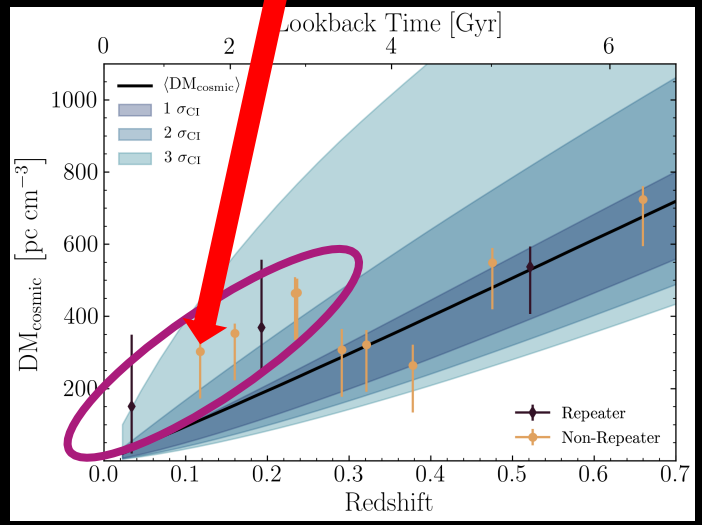
Paper 2: Batten et al. *submitted*

IGM Density Reconstruction Towards FRB 190608



Simha et. al 2020

FRB 190608



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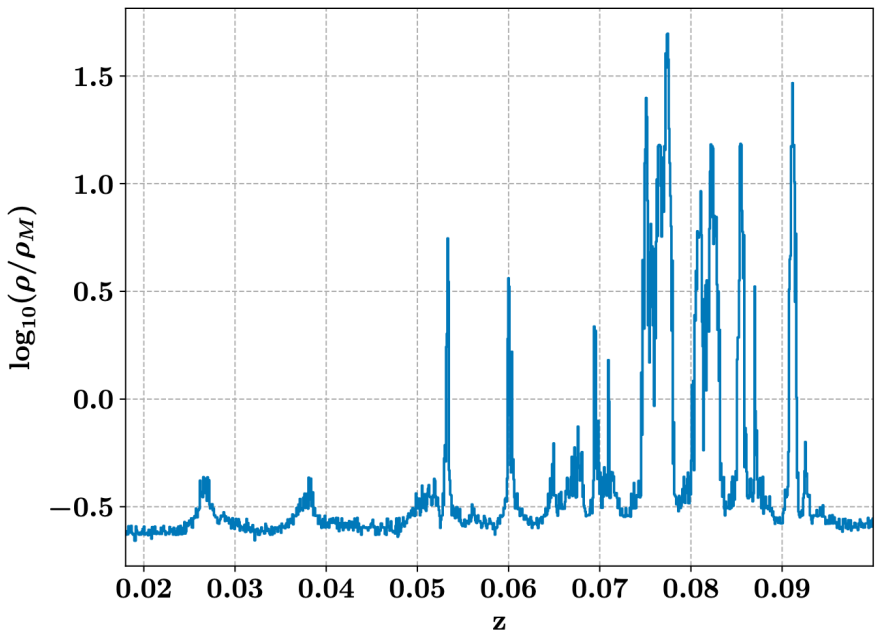
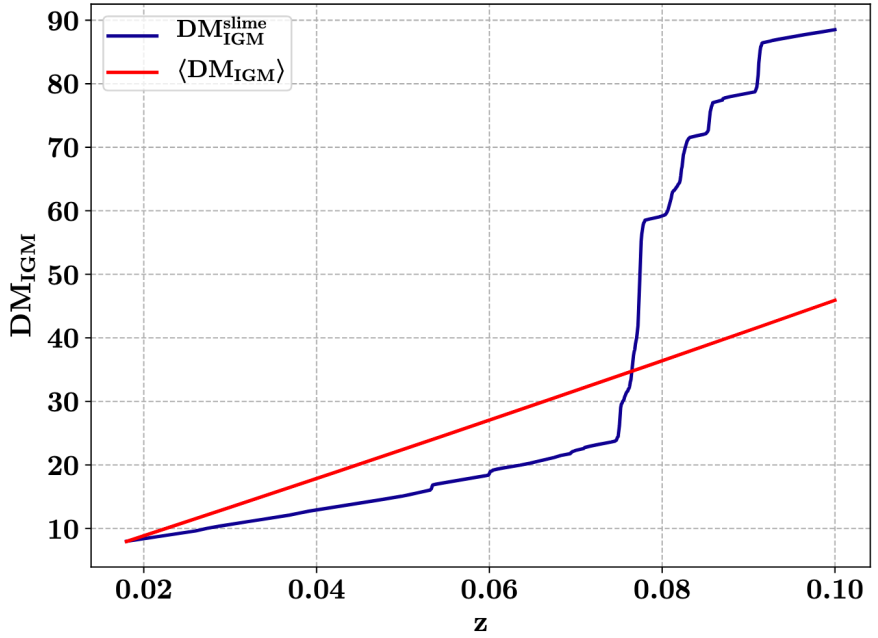
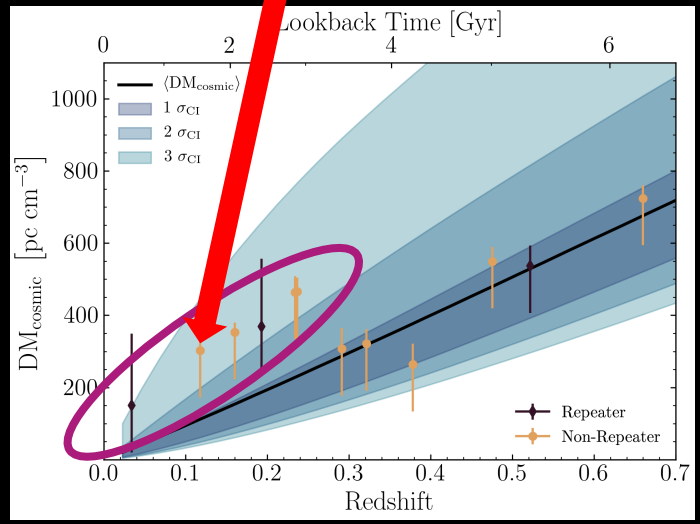




Simha et. al 2020

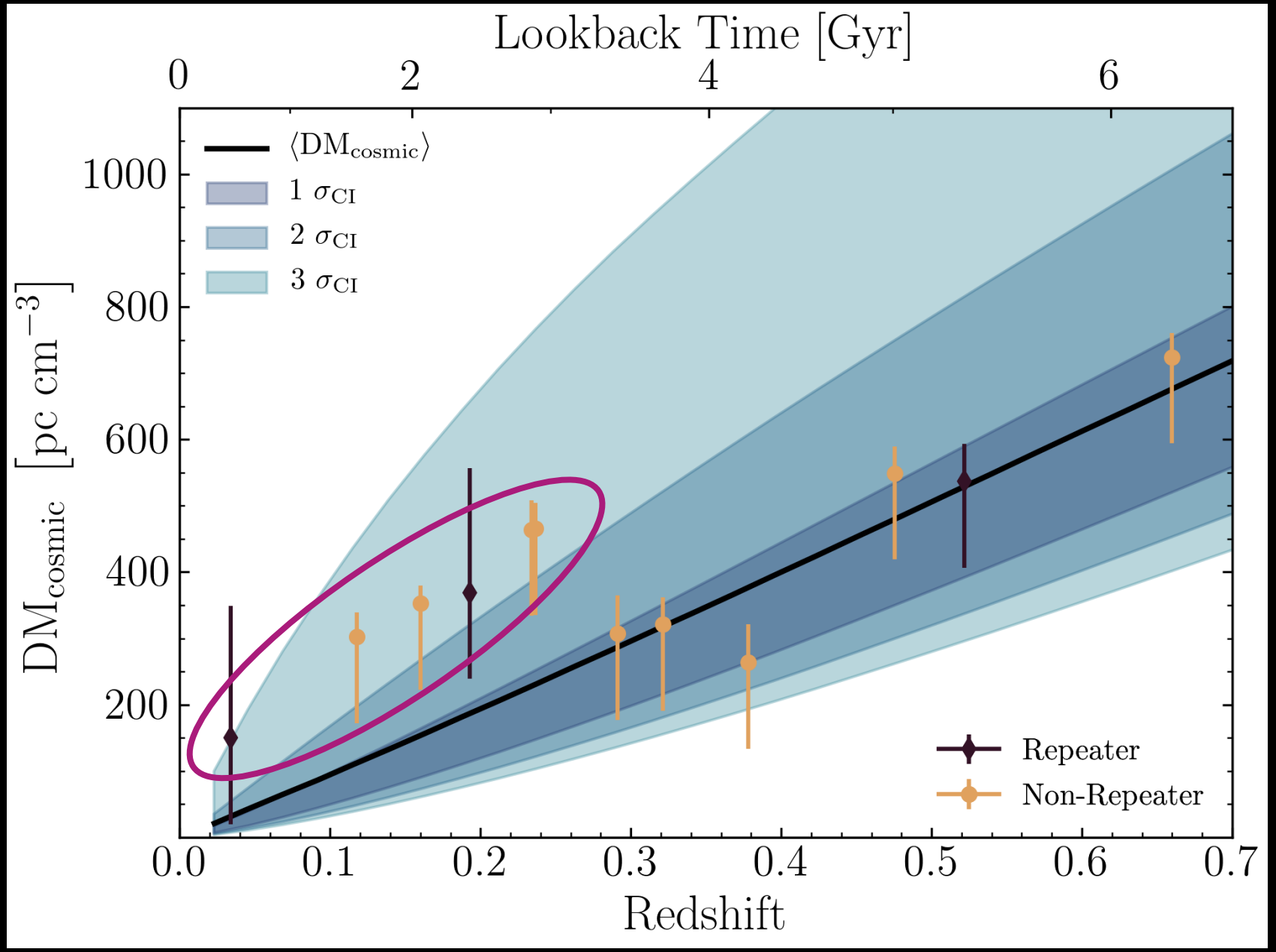
FRB 190608



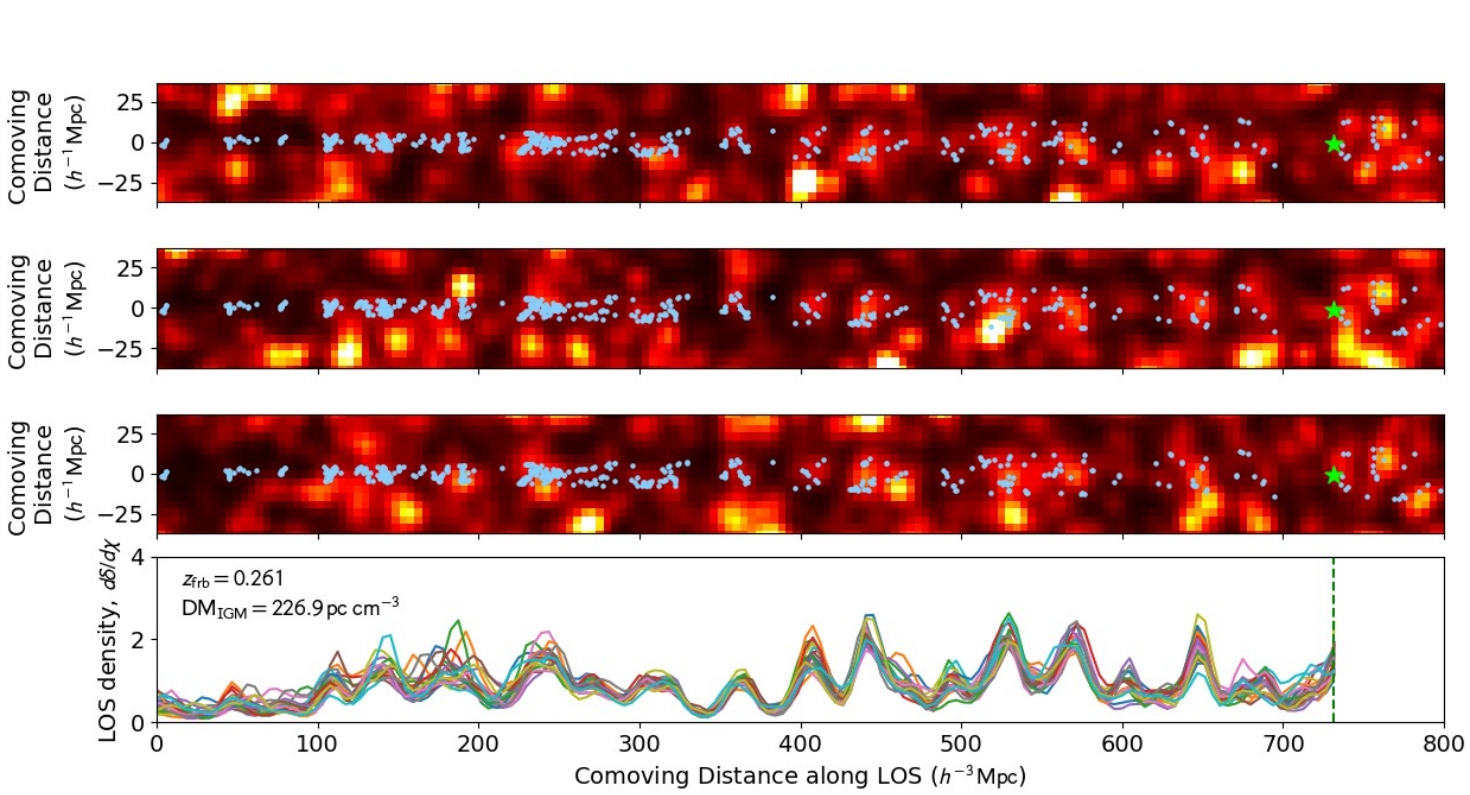
FRB 190608 intersects overdense IGM filaments along the line of sight!

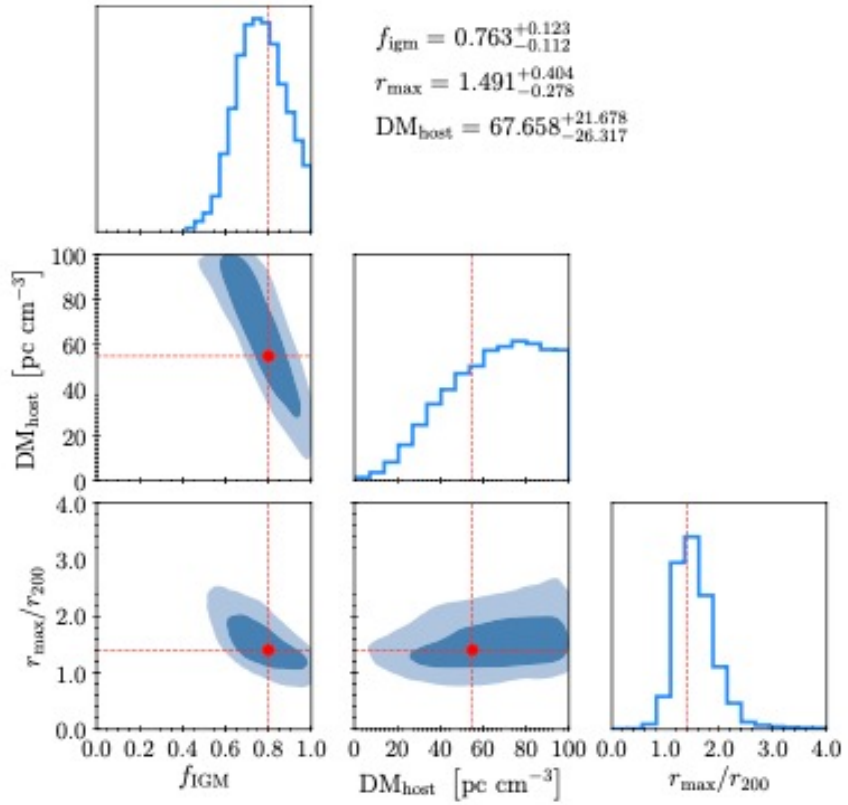
Batten et al. *accepted* (arxiv:2011.14547)

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



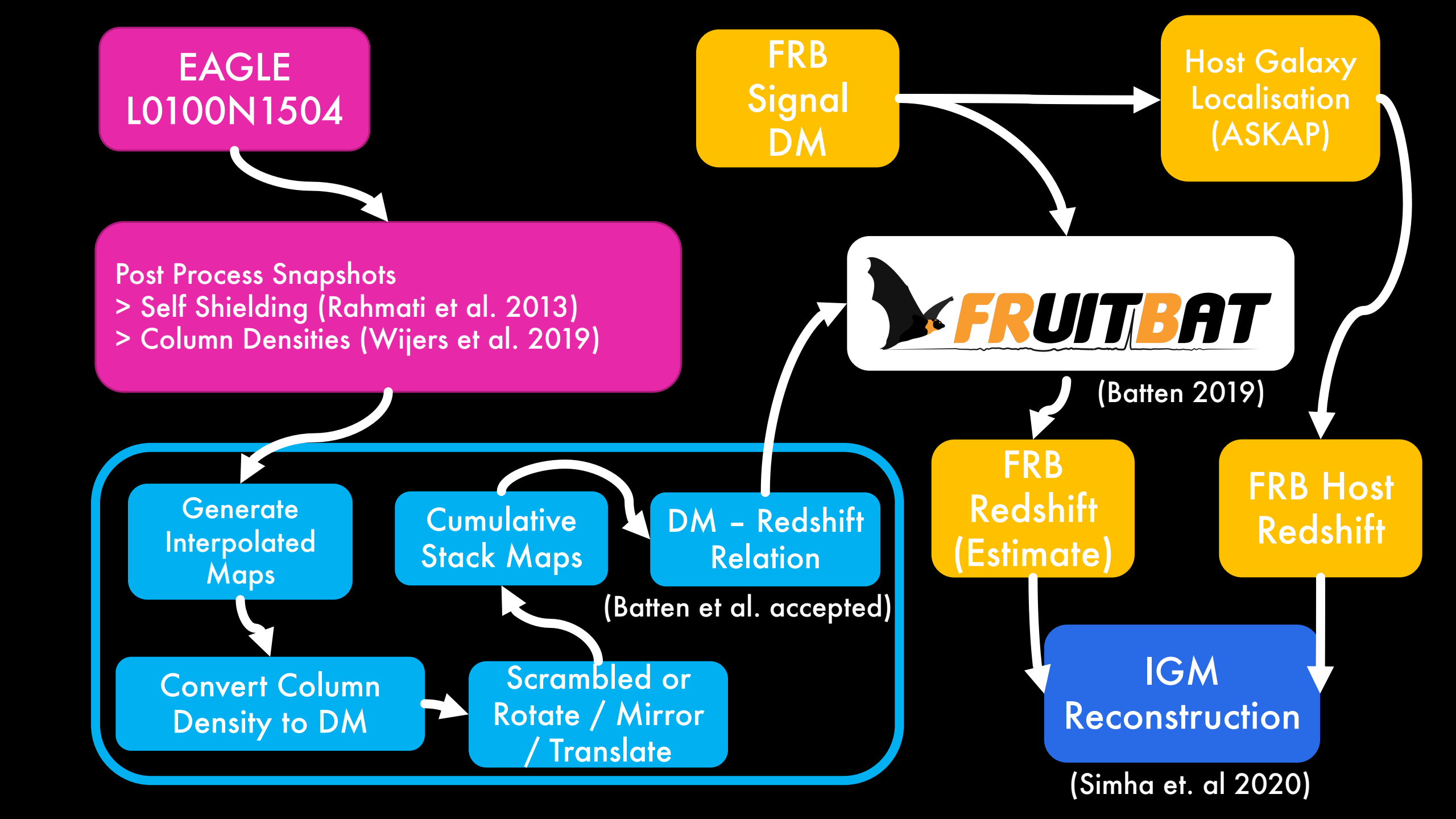
Mapping Foreground Large Scale Structure in FRB Fields





Credit: KG Lee

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


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)

Summary:

- The IGM is critical to understanding galaxy evolution and the Universe, but is difficult to observe at low redshift.
- Fast Radio Bursts provide a unique new way to probe the electron/baryon distribution in the IGM.
- *Paper Accepted: 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 2-3σ confidence intervals.
  - ➥ Indicates intersection with IGM filaments, or possibly high host/source contributions.

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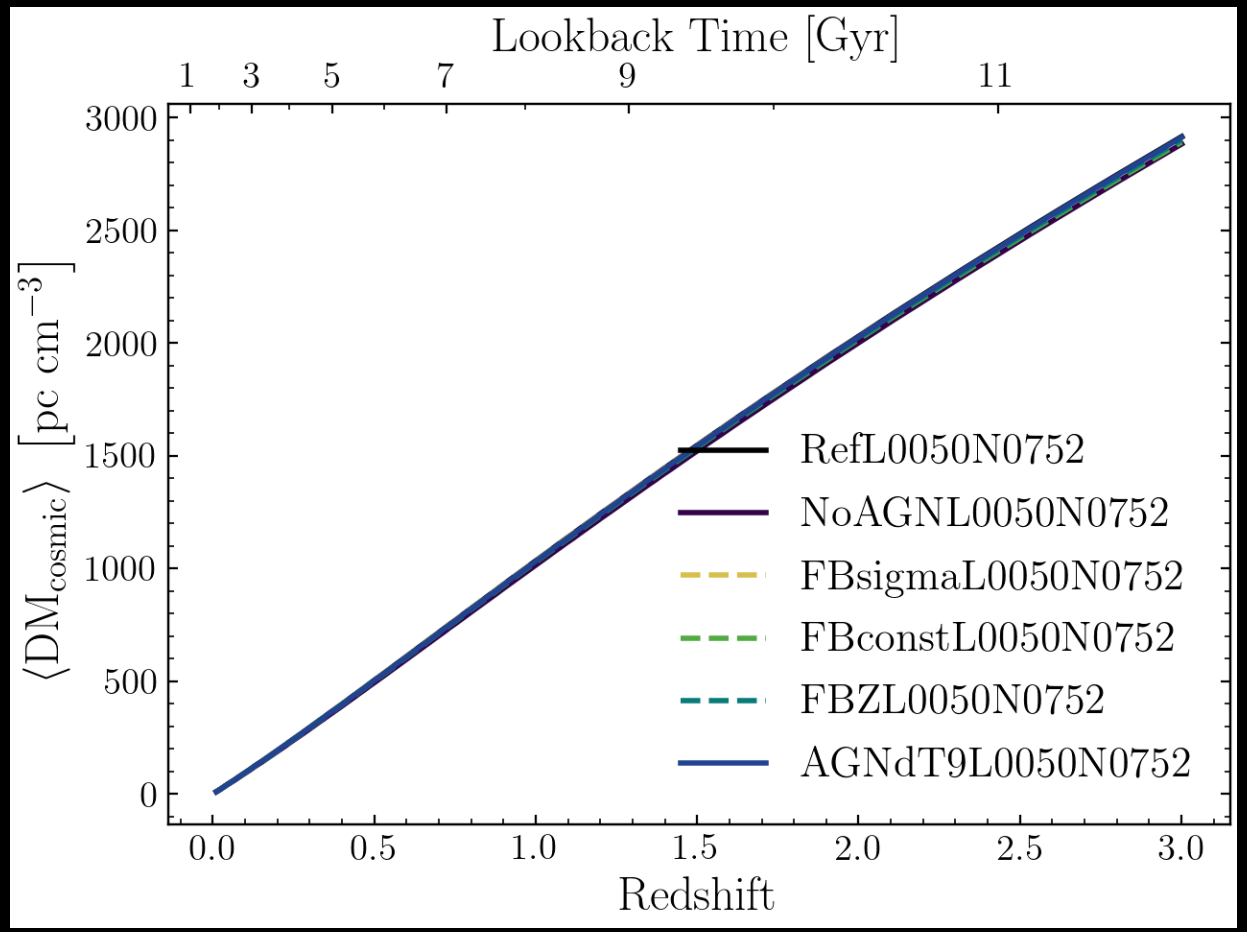
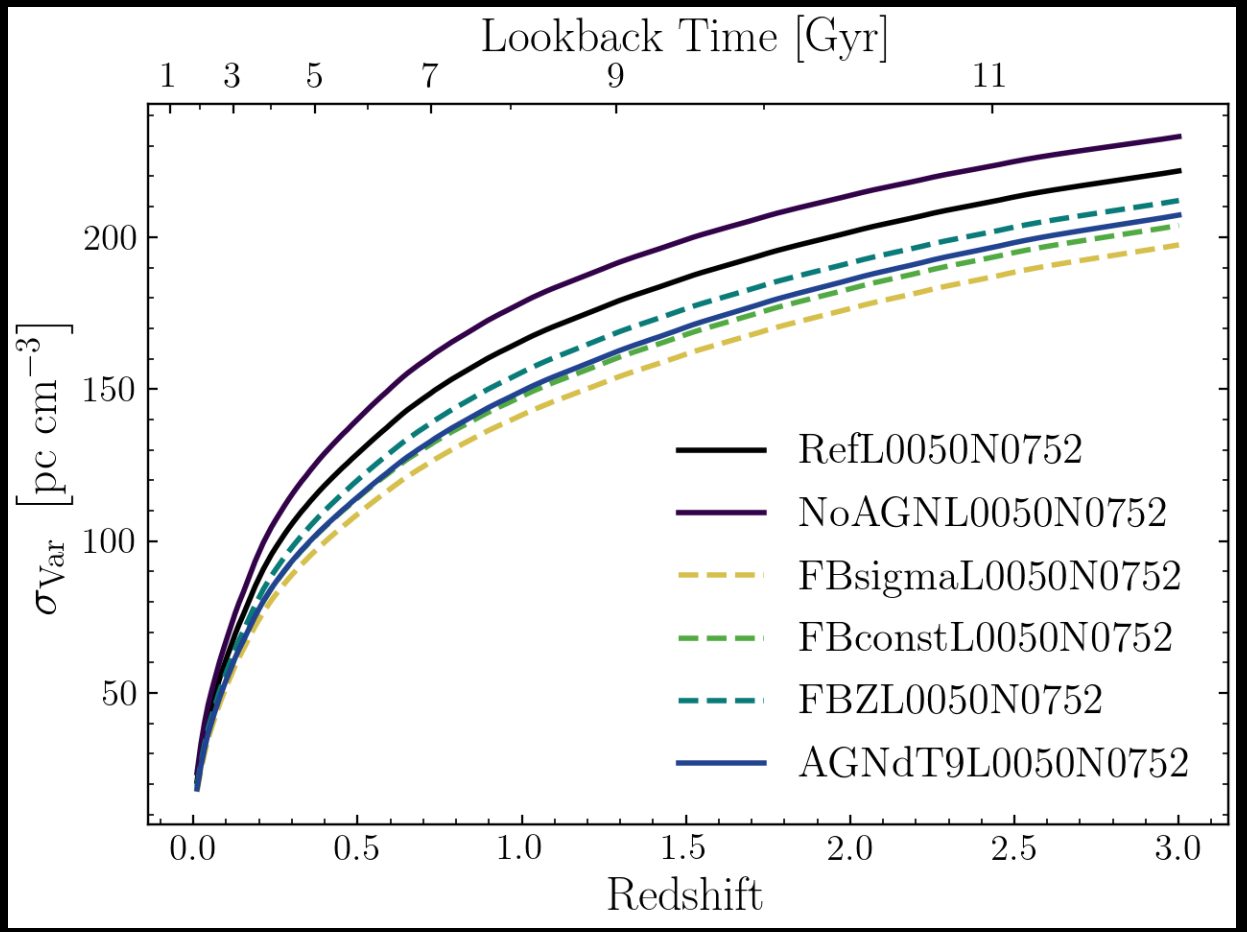
Paper 3: Batten et al. *in prep*.

FRBs as Probes of Galaxy Feedback

Paper 3: Batten et al. *in prep.*





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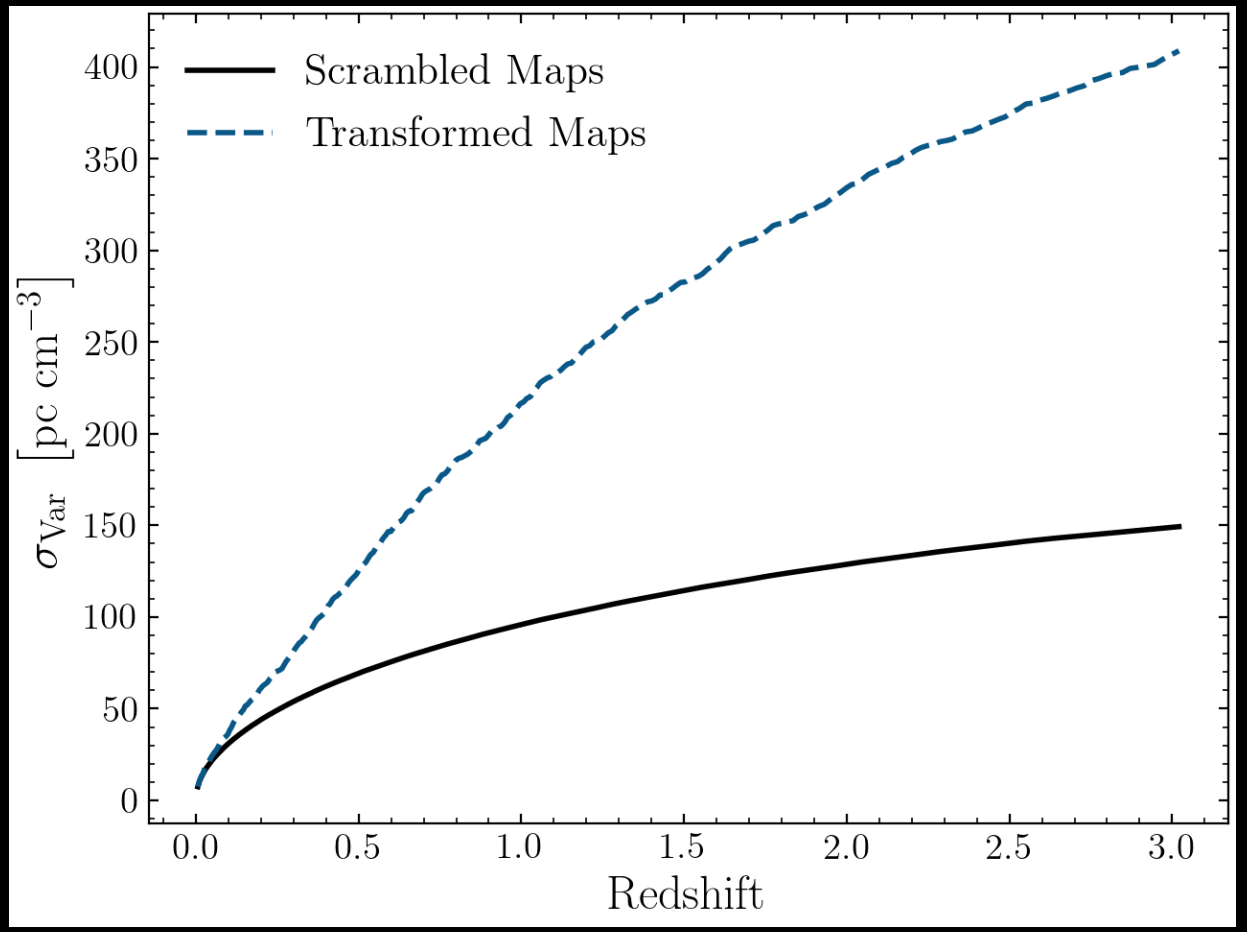

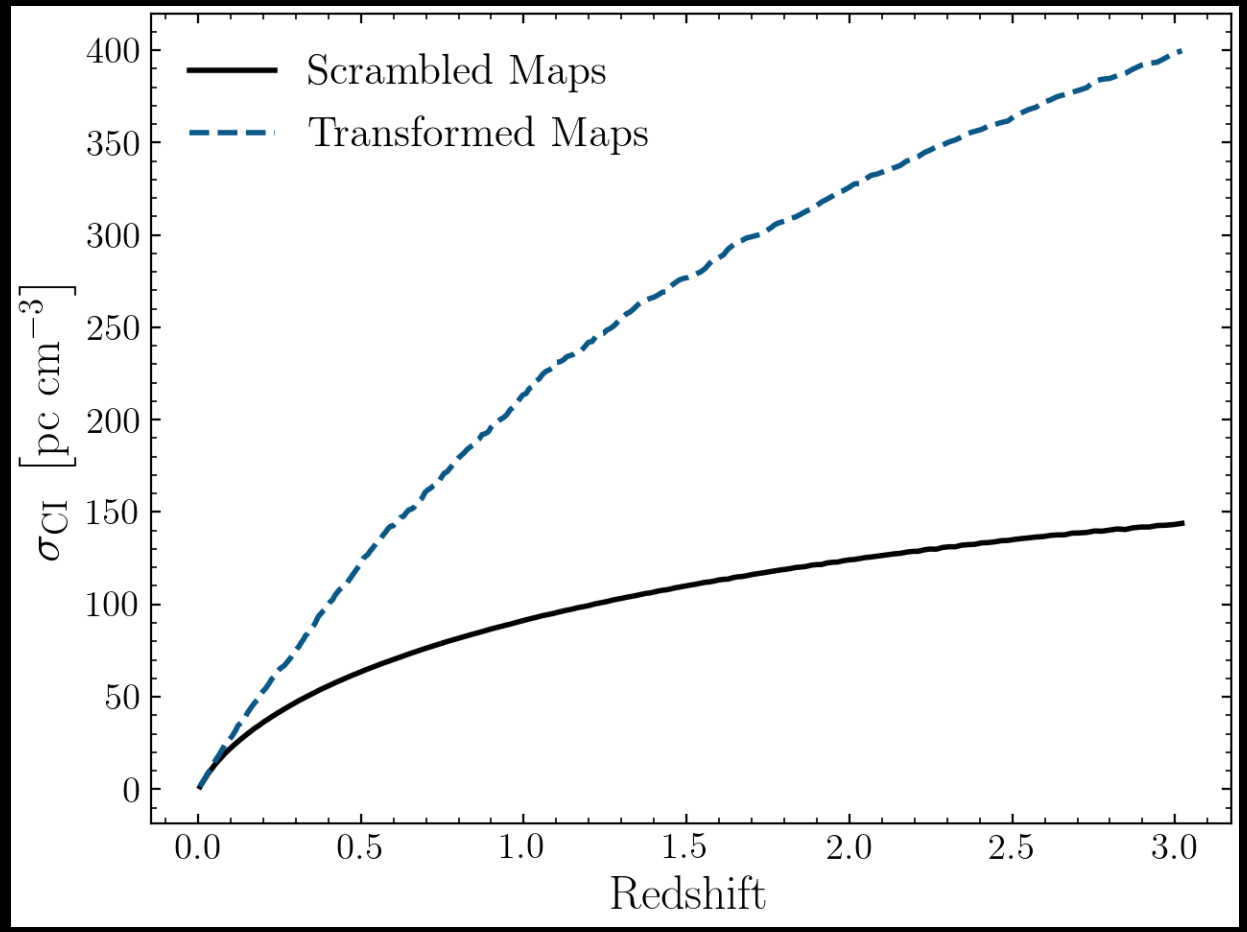

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