The Intergalactic Dispersion Measure in the EAGLE Simulations

Adam Batten

Prof. Alan Duffy & A/Prof. Emma Ryan-Weber

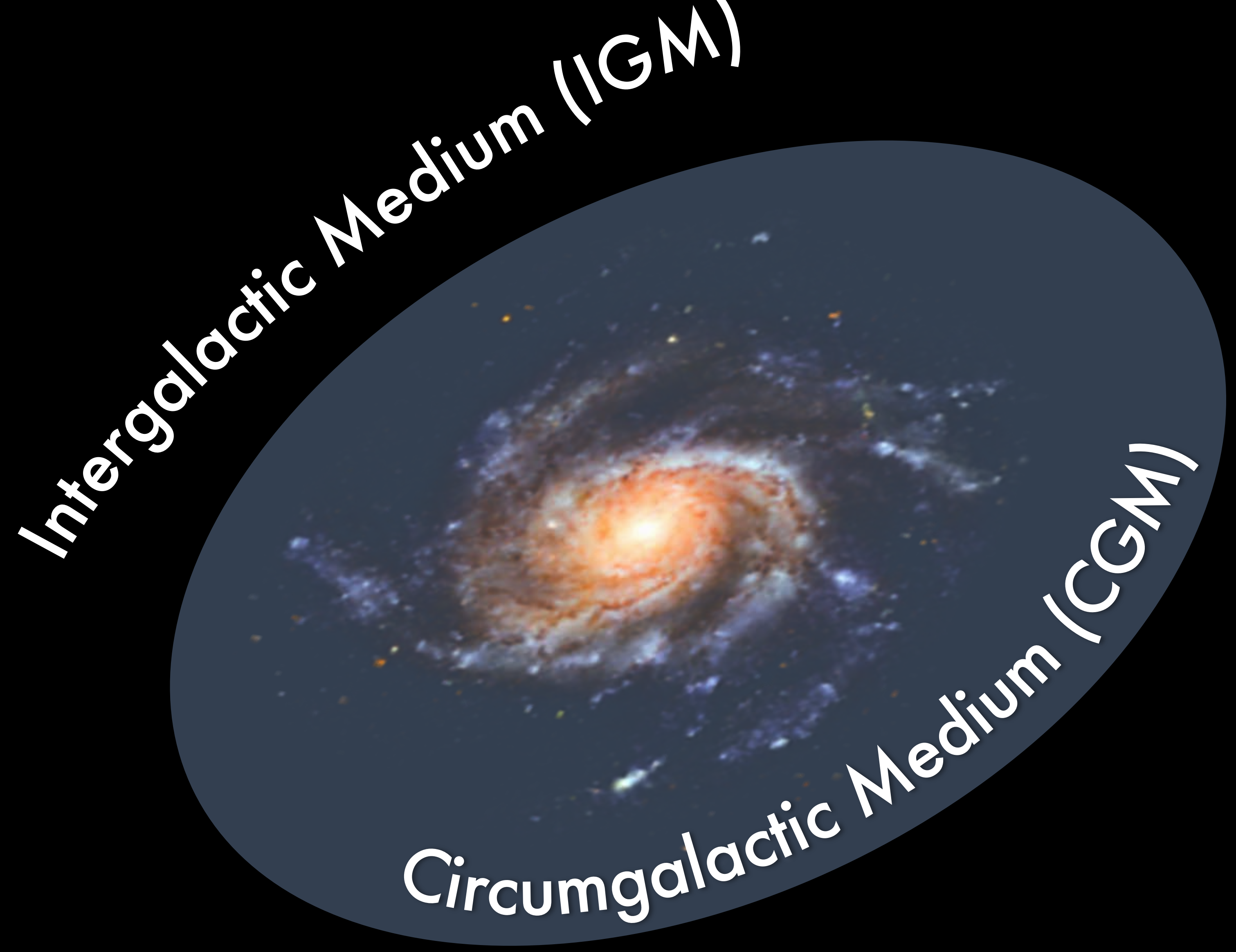
Nastasha Wijers (Leiden), Joop Schaye (Leiden), Vivek Gupta (Swinburne), Chris Flynn (Swinburne), Chris Blake (Swinburne)

Swinburne Centre for Astrophysics and Supercomputing

@adamjbatten

Australia-ESO joint conference 19/02/2020

ASTRO 3D


Intergalactic Medium (IGM)
Circumgalactic Medium (CGM)

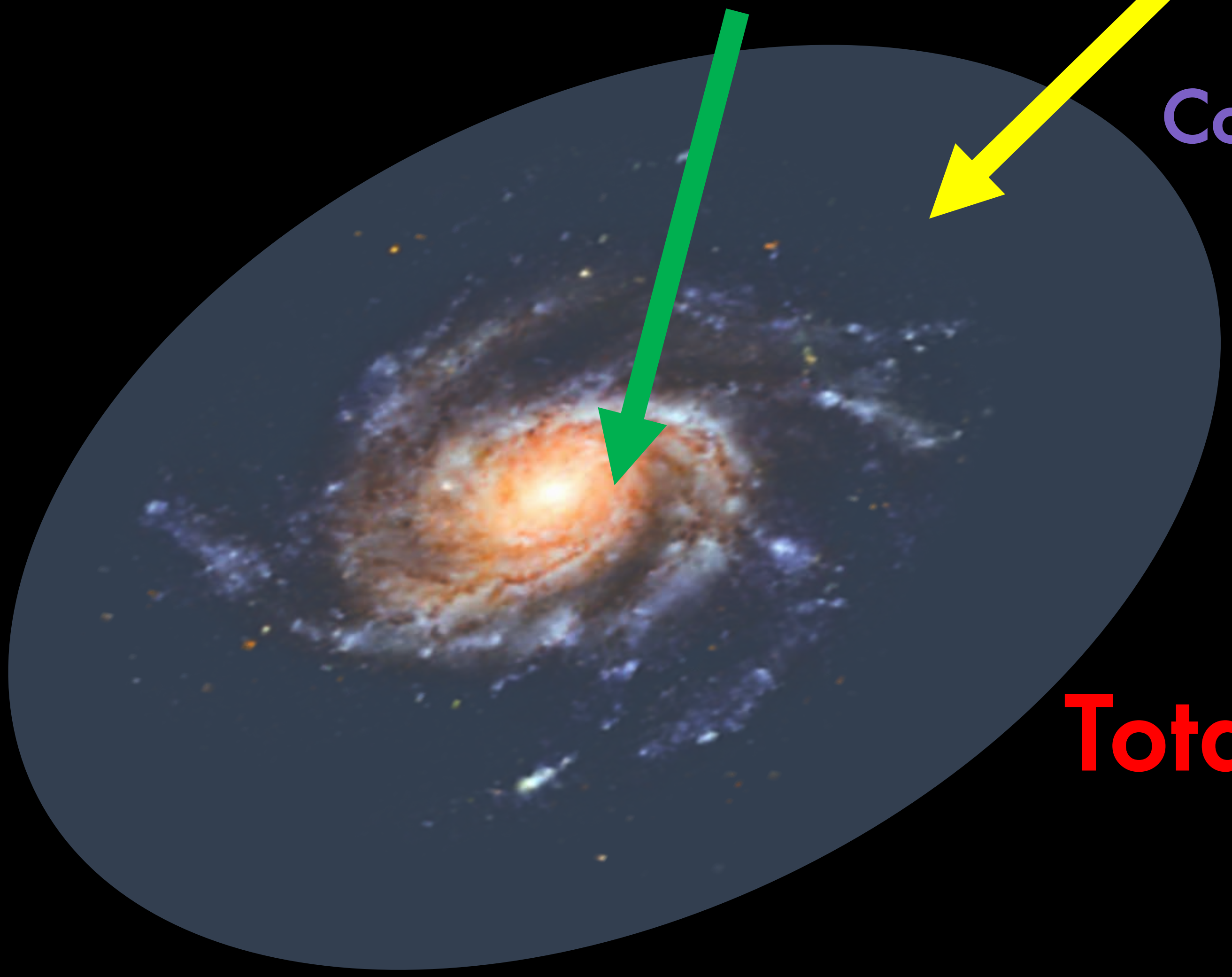
Shull et al. (2012)

Galaxies ~ 7%

CGM ~ 5%

Cold Gas ~ 2%

ICM ~ 4%



Total ~ 18%

Shull et al. (2012)

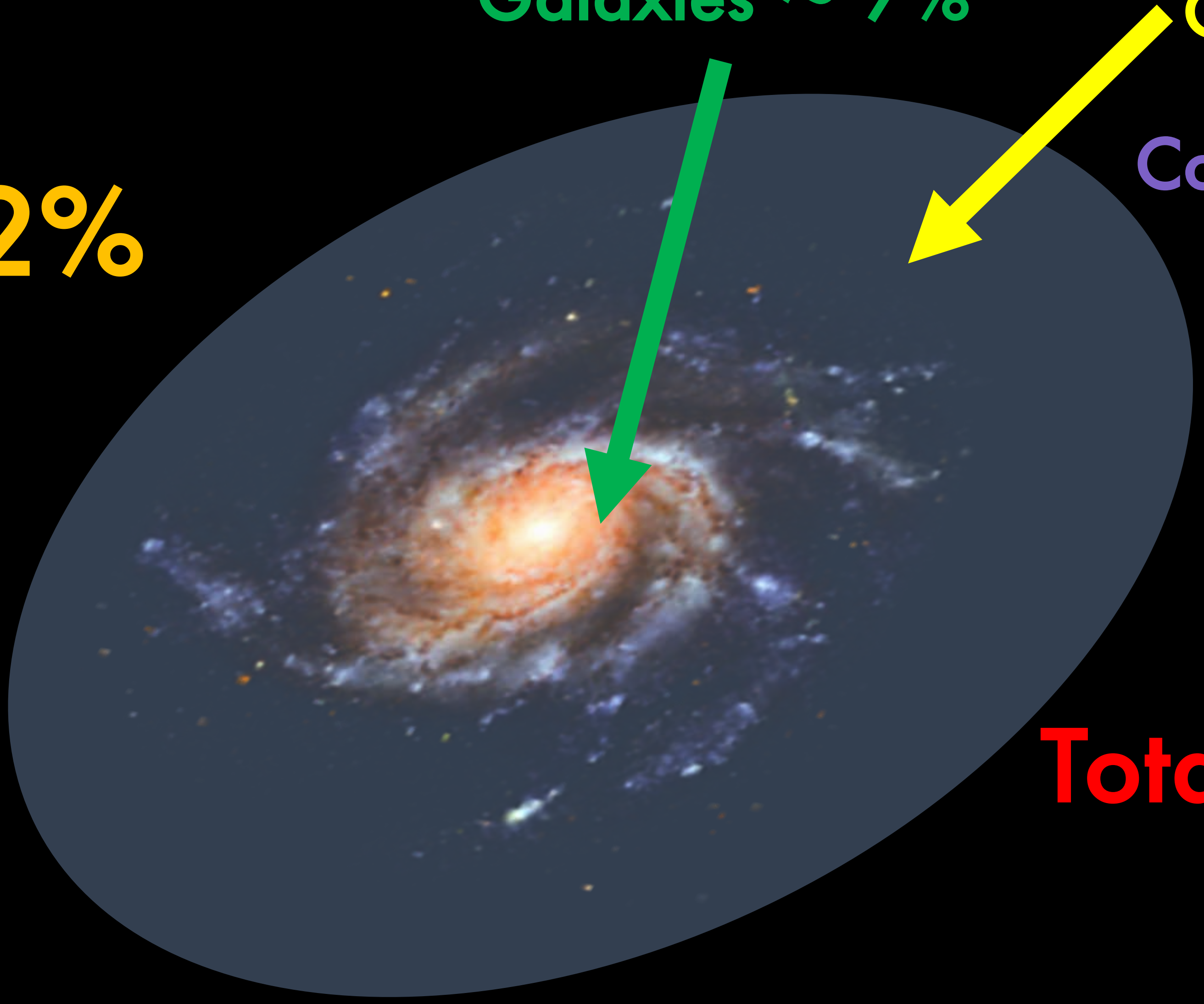
Galaxies ~ 7%

CGM ~ 5%

Cold Gas ~ 2%

ICM ~ 4%

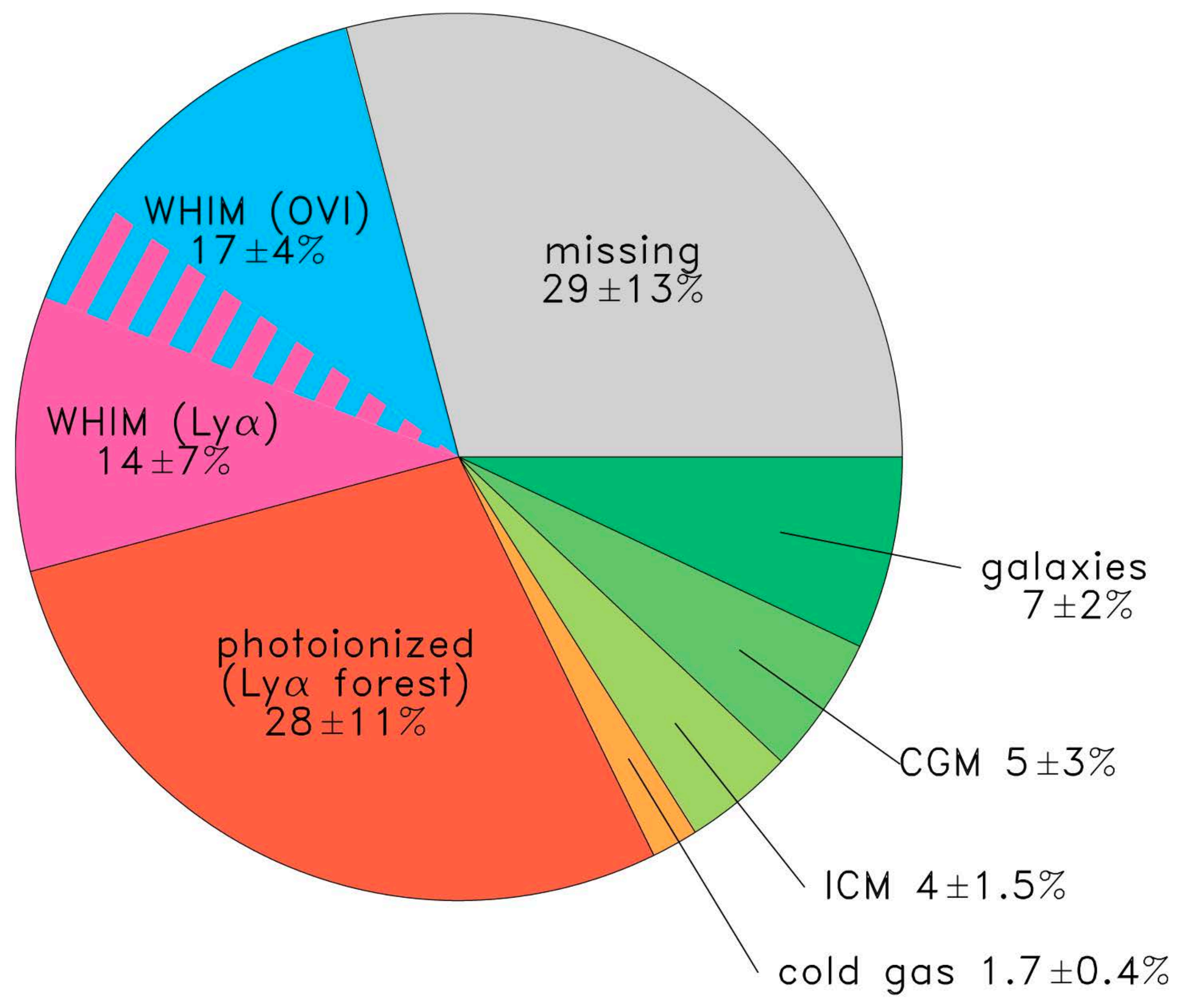
IGM ~ 82%



Total ~ 18%

The IGM contains most of the baryonic matter

The "Missing Baryon" Problem

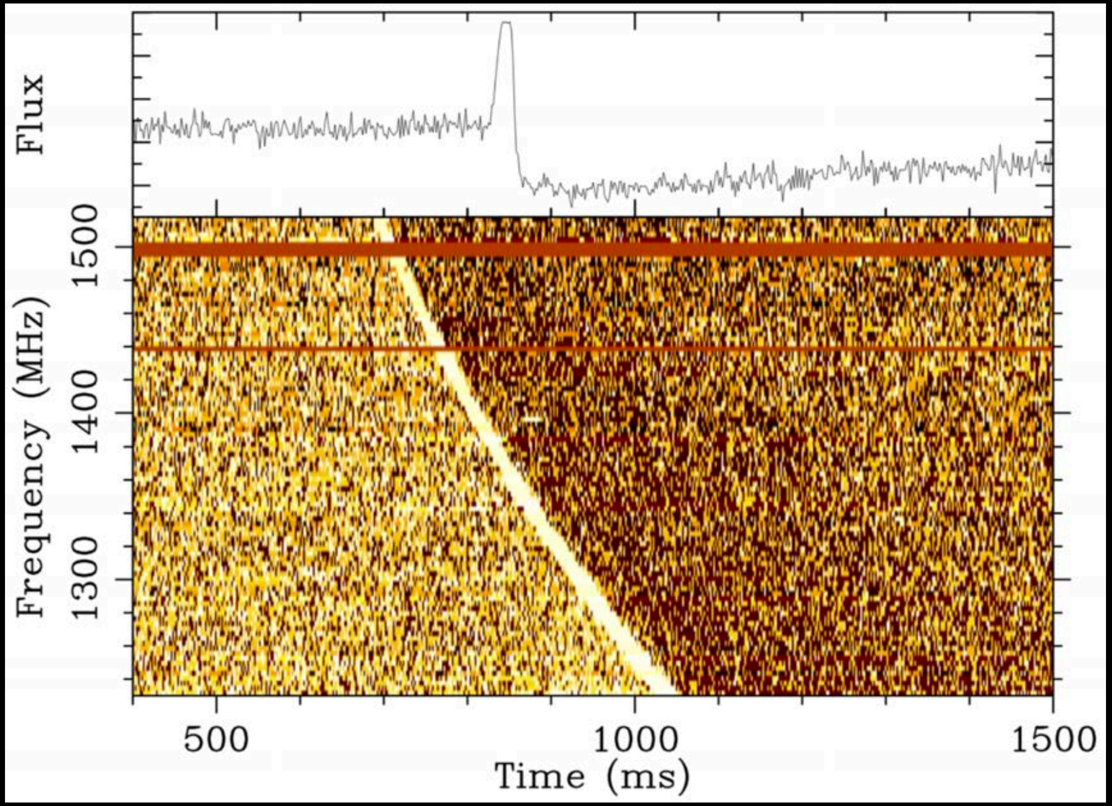


~ 30% of baryons at low redshift appear to be missing!

Shull et al. (2012)

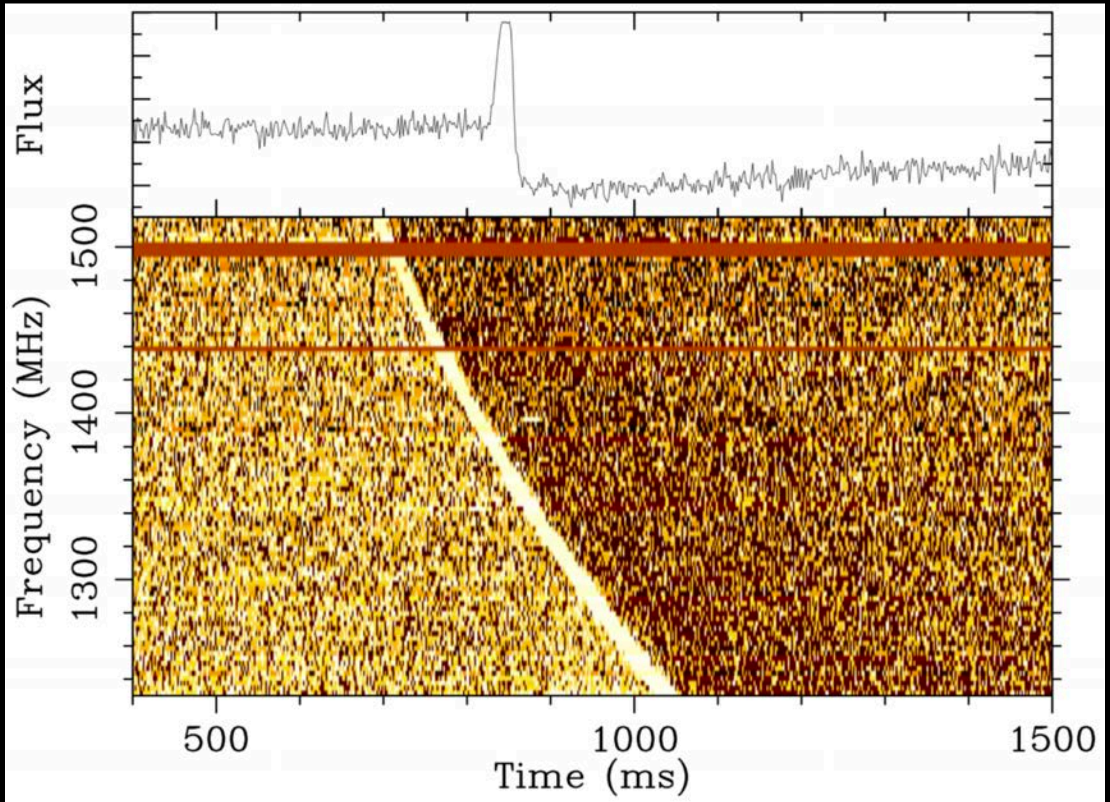
Lorimer et al. (2007)
Petroff et al. (2019)
Deng & Zhang (2014)

Fast Radio Bursts (FRBs)



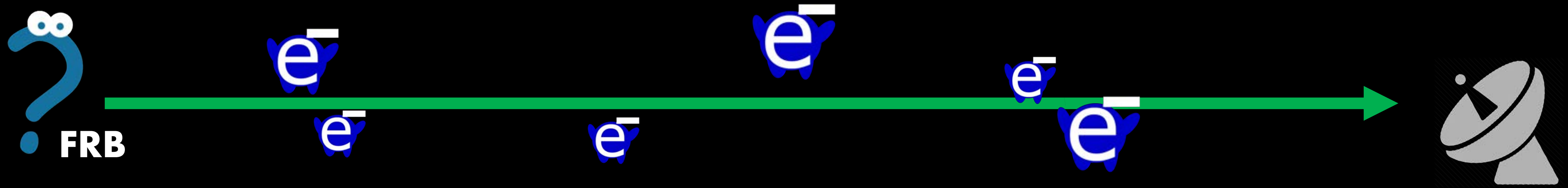
Lorimer et al. (2007)
Petroff et al. (2019)
Deng & Zhang (2014)

Fast Radio Bursts (FRBs)



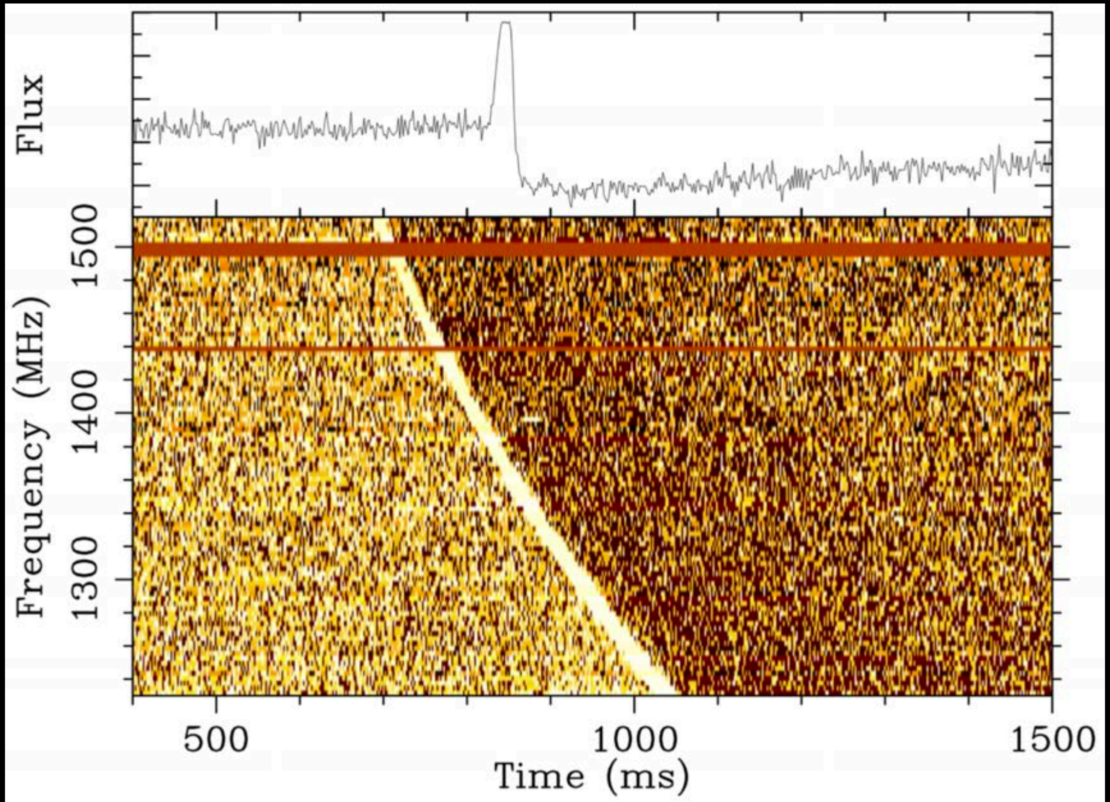
$$\mathrm{DM_{tot}} = \mathrm{DM_{MW}} + \mathrm{DM_{IGM}} + \mathrm{DM_{host}}$$

$$\Omega_b f_{\mathrm{IGM}} = \frac{8\pi G m_p \mathrm{DM_{IGM}}}{3cH_0} \Bigg/ \int_0^z \frac{\left[\frac{3}{4}y_1\chi_{e,\mathrm{H}}(z) + \frac{1}{8}y_2\chi_{e,\mathrm{He}}(z)\right](1+z)dz}{[\Omega_m(1+z)^3 + \Omega_\Lambda]^{1/2}}$$



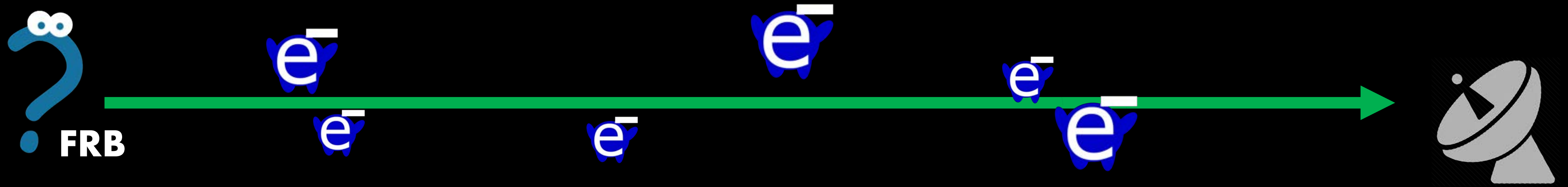
Lorimer et al. (2007)
Petroff et al. (2019)
Deng & Zhang (2014)

Fast Radio Bursts (FRBs)

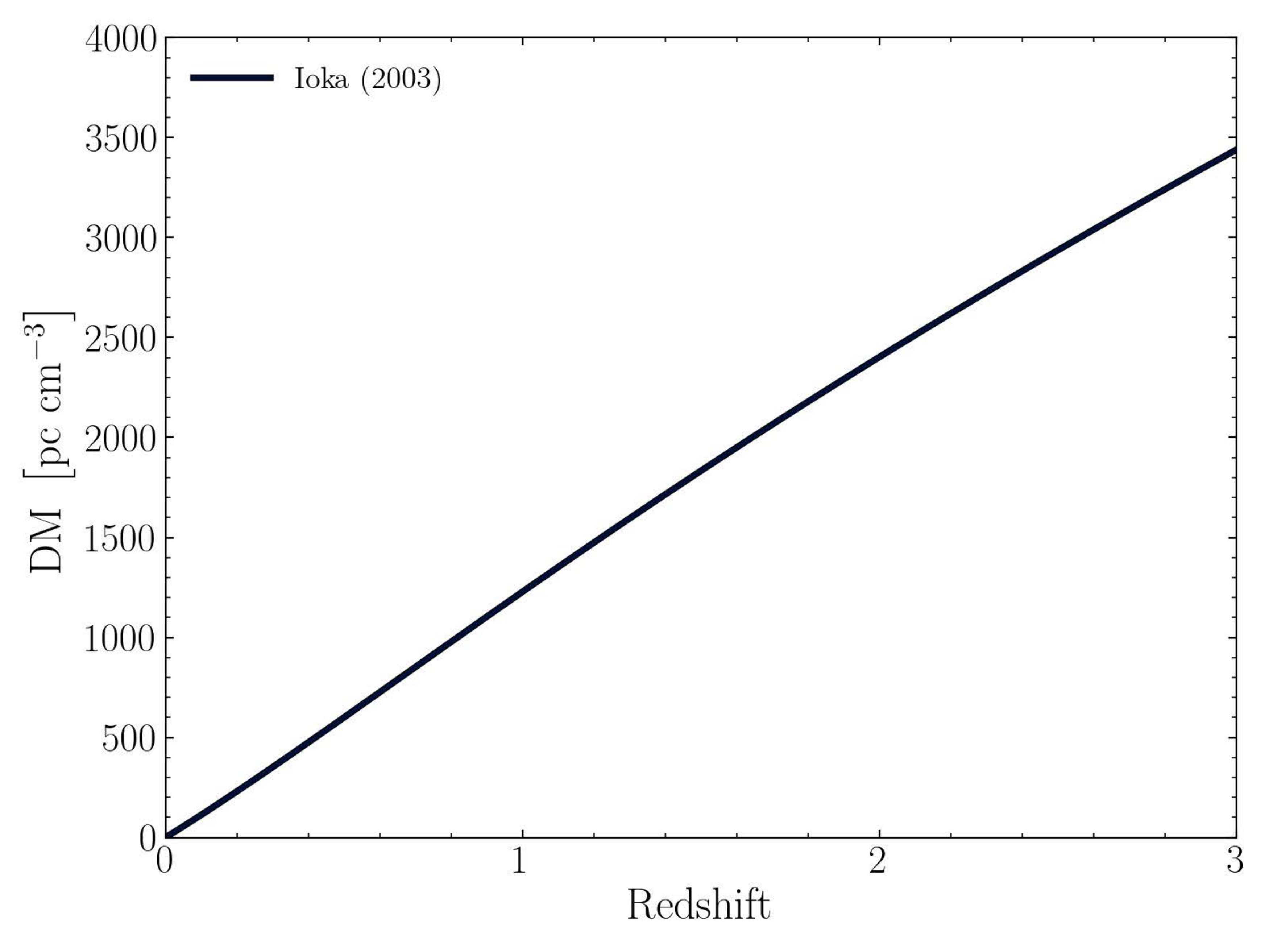


$$\mathrm{DM_{tot}} = \mathrm{DM_{MW}} + \mathrm{DM_{IGM}} + \mathrm{DM_{host}}$$

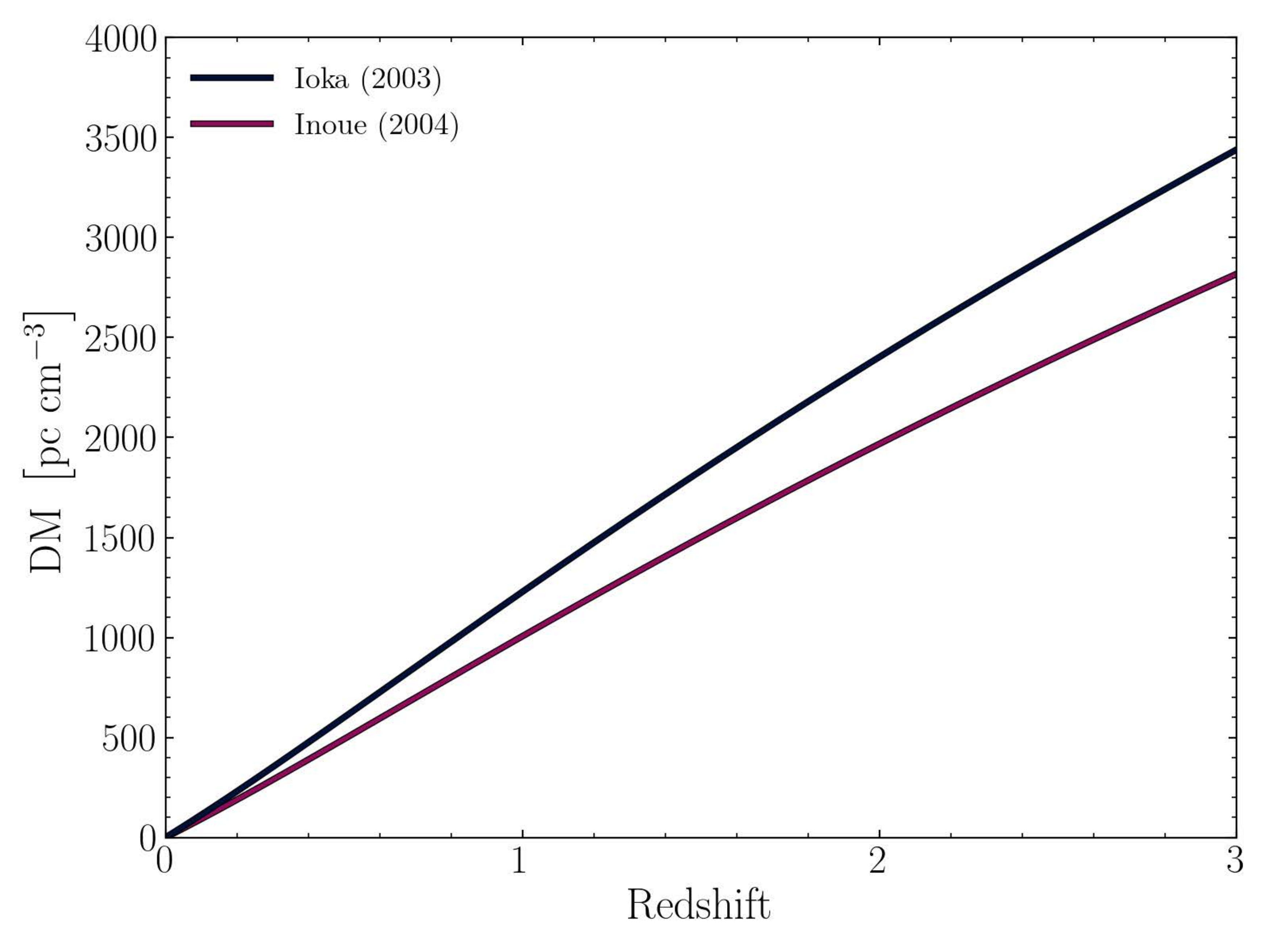
$$\Omega_b f_{\rm IGM} = \frac{8\pi G m_p \mathrm{DM_{IGM}}}{3 c H_0} \Bigg/ \int_0^z \frac{\left[\frac{3}{4} y_1 \chi_{e,\rm H}(z) + \frac{1}{8} y_2 \chi_{e,\rm He}(z)\right](1+z)dz}{\left[\Omega_m (1+z)^3 + \Omega_\Lambda\right]^{1/2}}$$



DM-z Relations



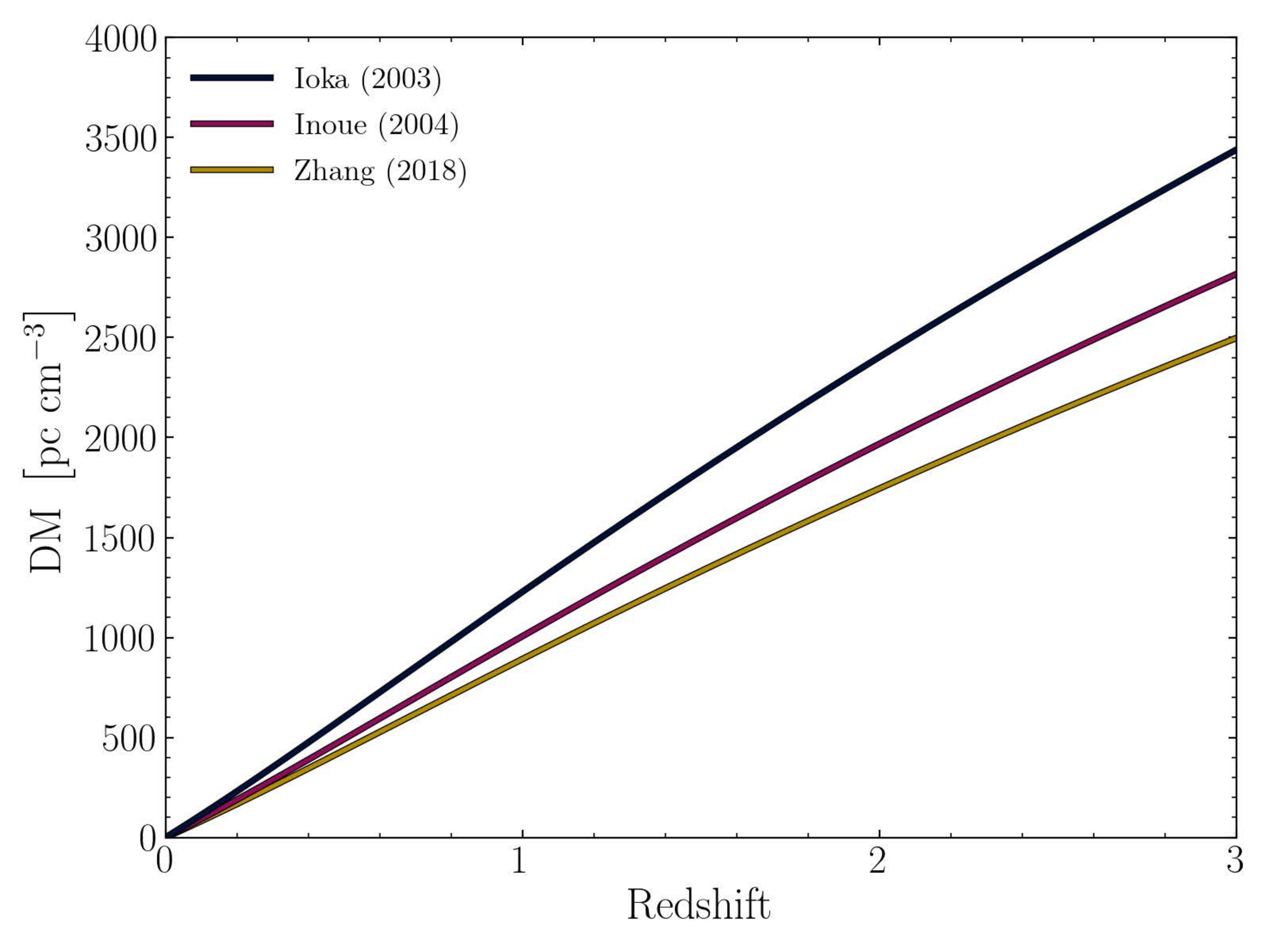
Ioka (2003) [Analytic]



DM-z Relations

Ioka (2003) [Analytic]

Inoue (2004) [Analytic]

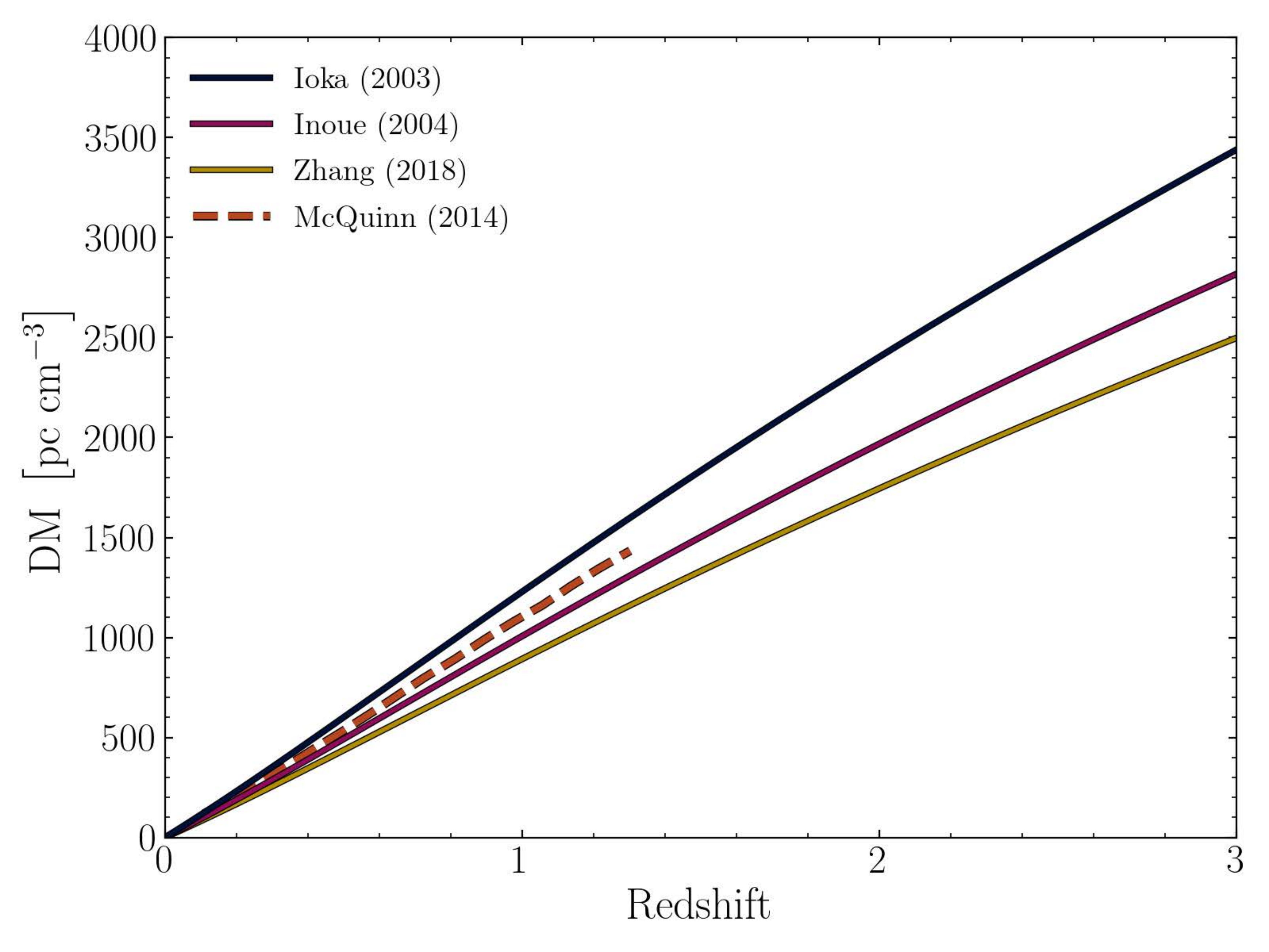


DM-z Relations

Ioka (2003) [Analytic]

Inoue (2004) [Analytic]

Zhang (2018) [Analytic]



DM-z Relations

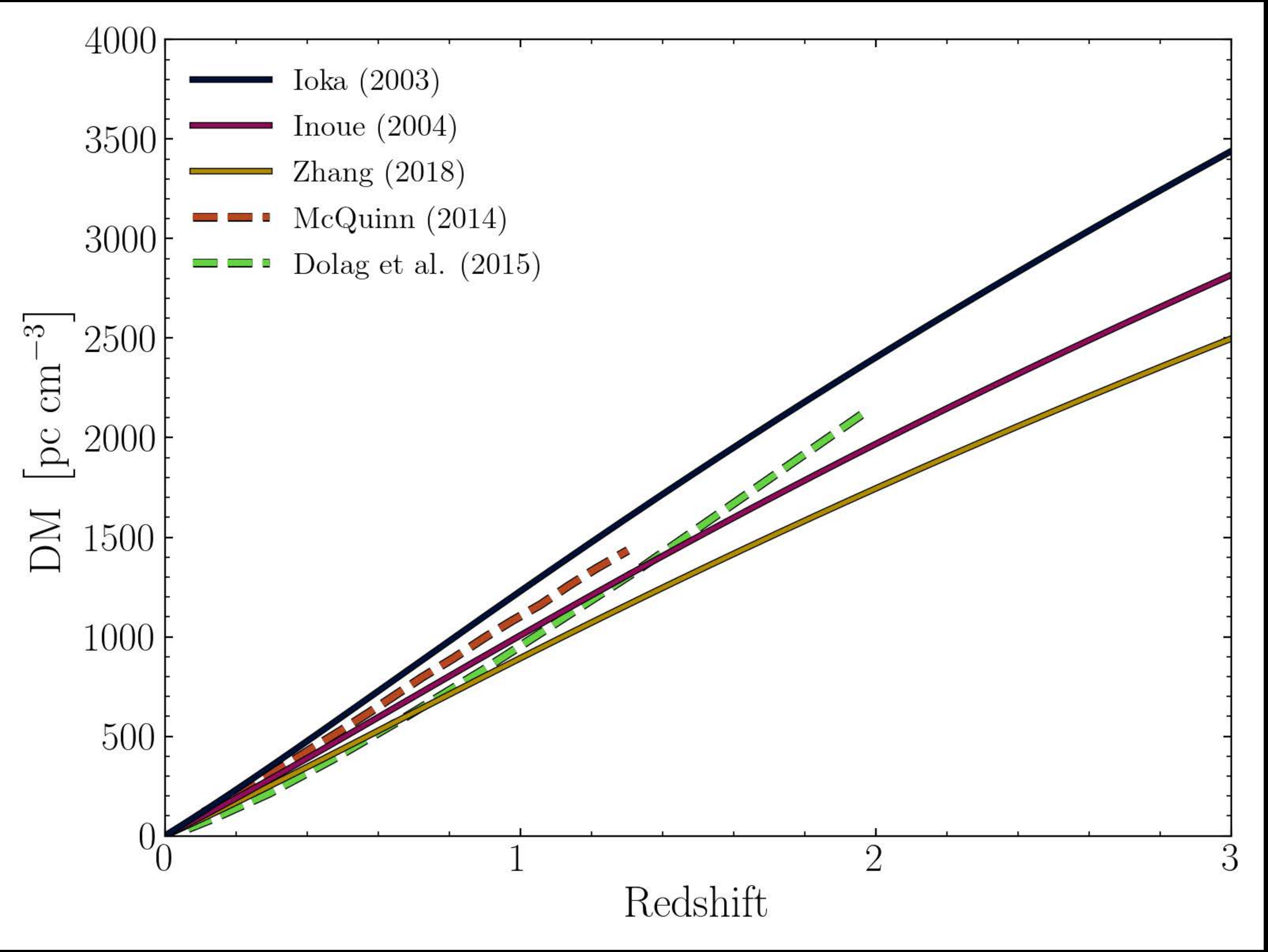
Ioka (2003) [Analytic]

Inoue (2004) [Analytic]

Zhang (2018) [Analytic]

McQuinn (2014) [Hydro]

DM-z Relations



Ioka (2003) [Analytic]

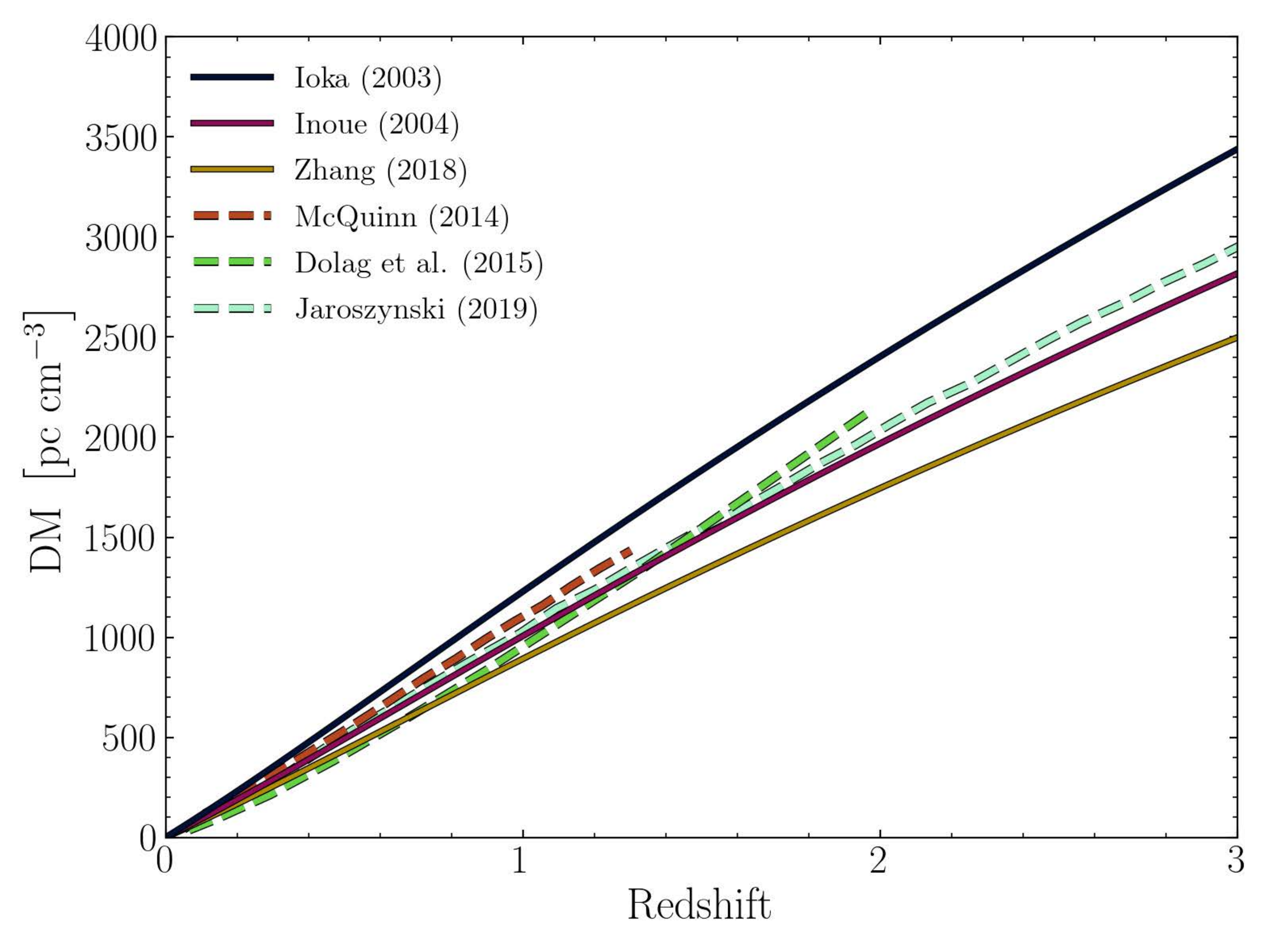
Inoue (2004) [Analytic]

Zhang (2018) [Analytic]

McQuinn (2014) [Hydro]

Dolag et al. (2015) [Hydro]

DM-z Relations



Ioka (2003) [Analytic]

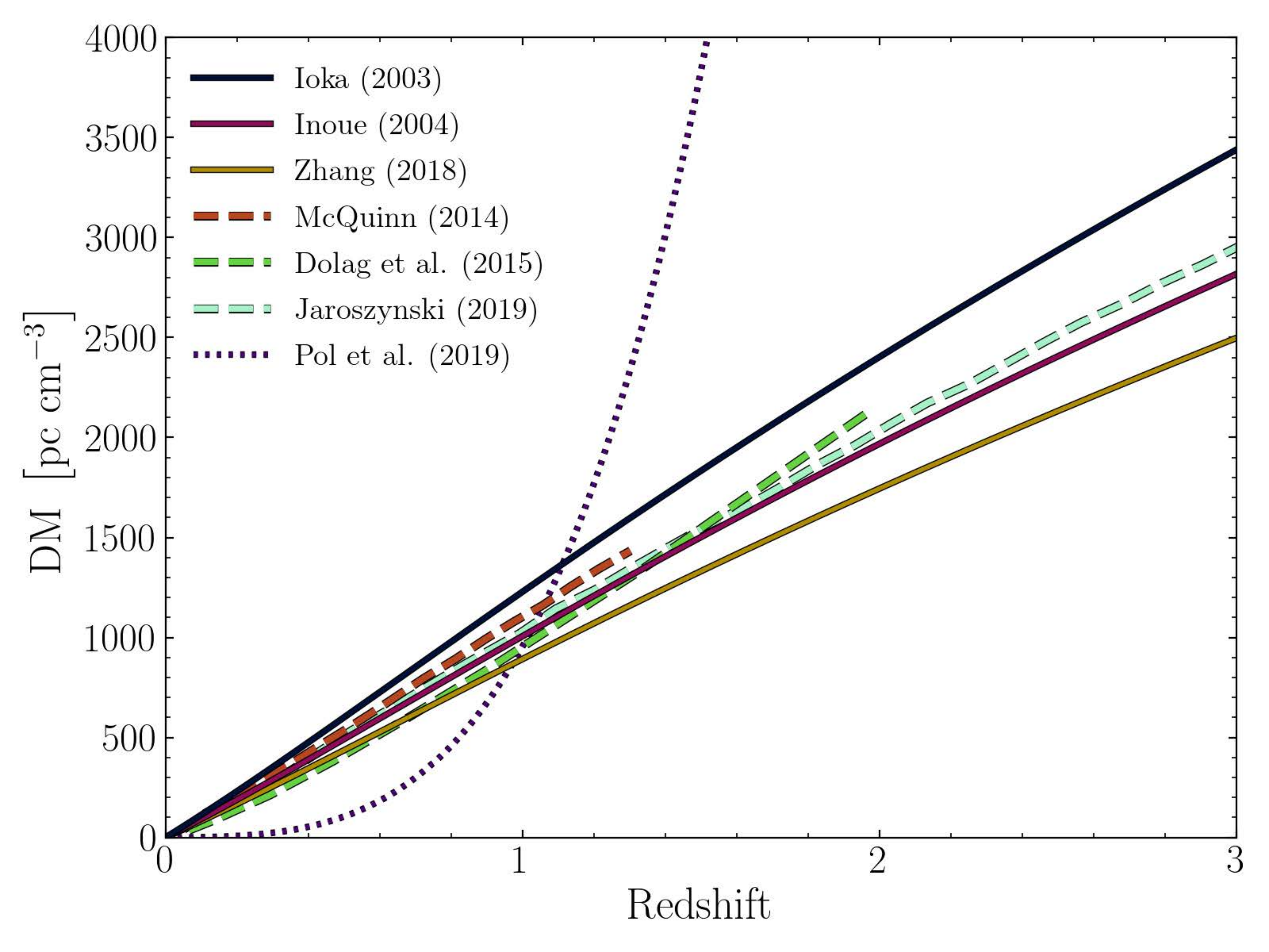
Inoue (2004) [Analytic]

Zhang (2018) [Analytic]

McQuinn (2014) [Hydro]

Dolag et al. (2015) [Hydro]

Jaroszynski (2019) [Hydro]



DM-z Relations

Ioka (2003) [Analytic]

Inoue (2004) [Analytic]

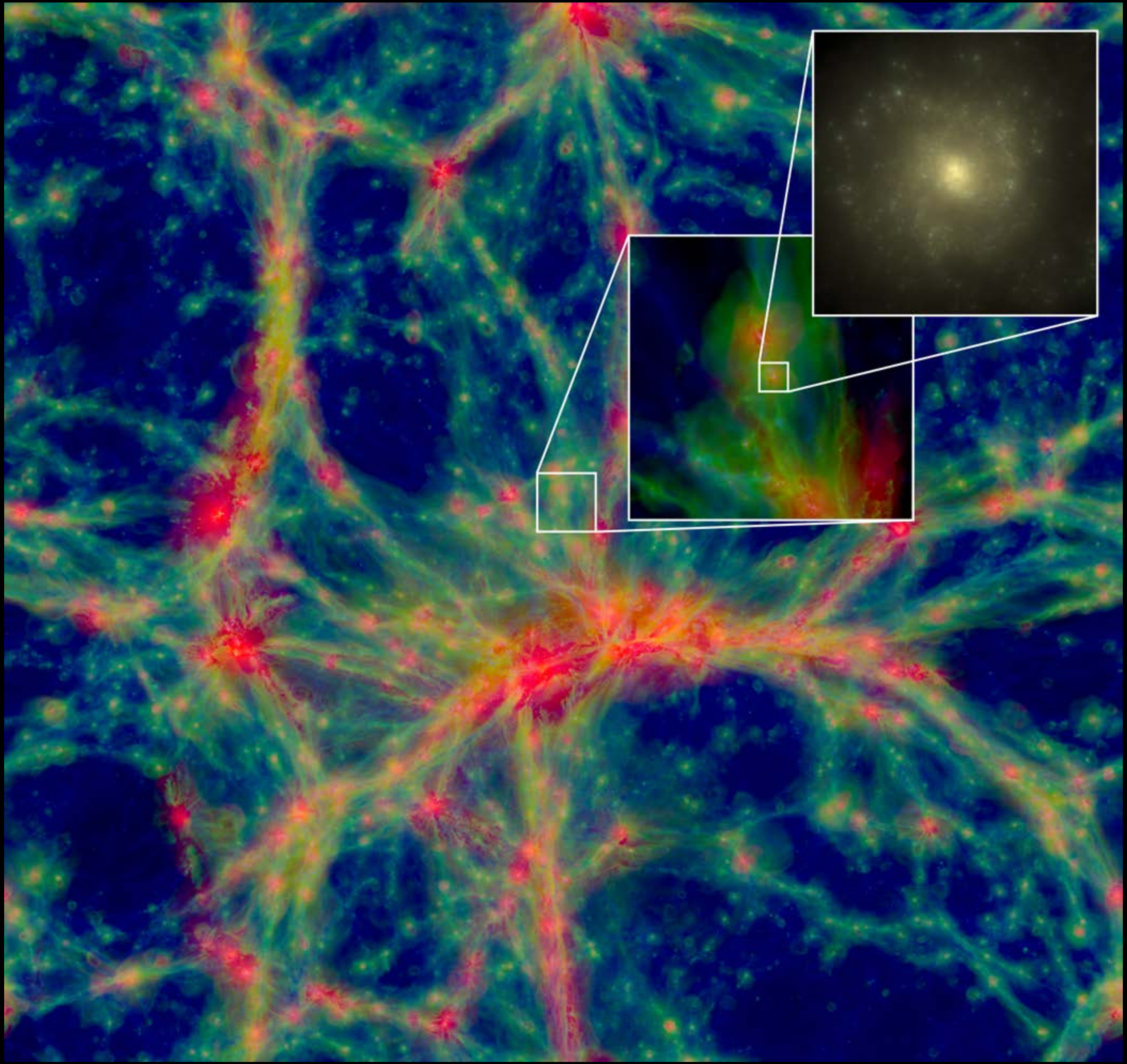
Zhang (2018) [Analytic]

McQuinn (2014) [Hydro]

Dolag et al. (2015) [Hydro]

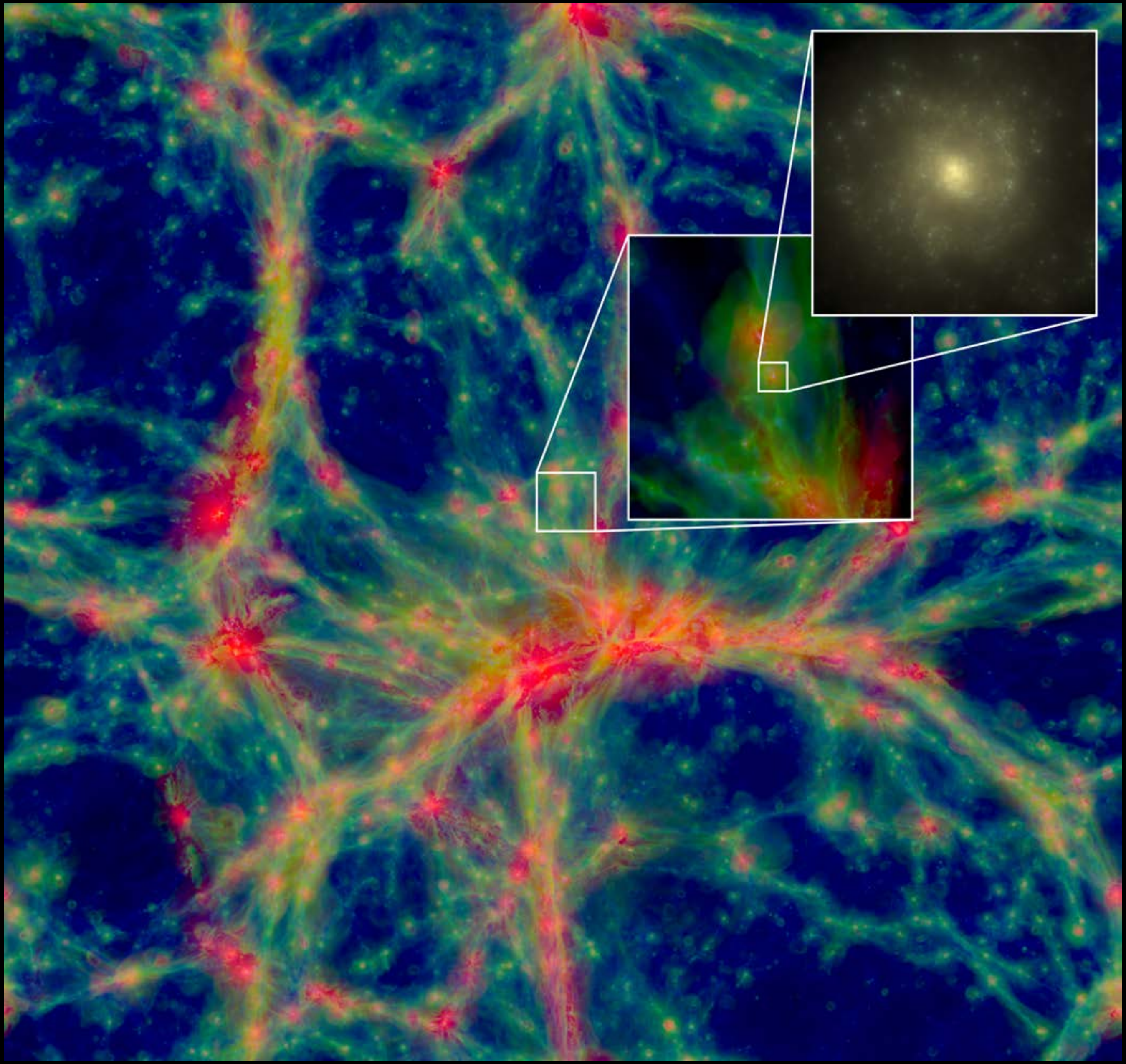
Jaroszynski (2019) [Hydro]

Pol et al. (2019) [Semi-Analytic]



EAGLE Simulations

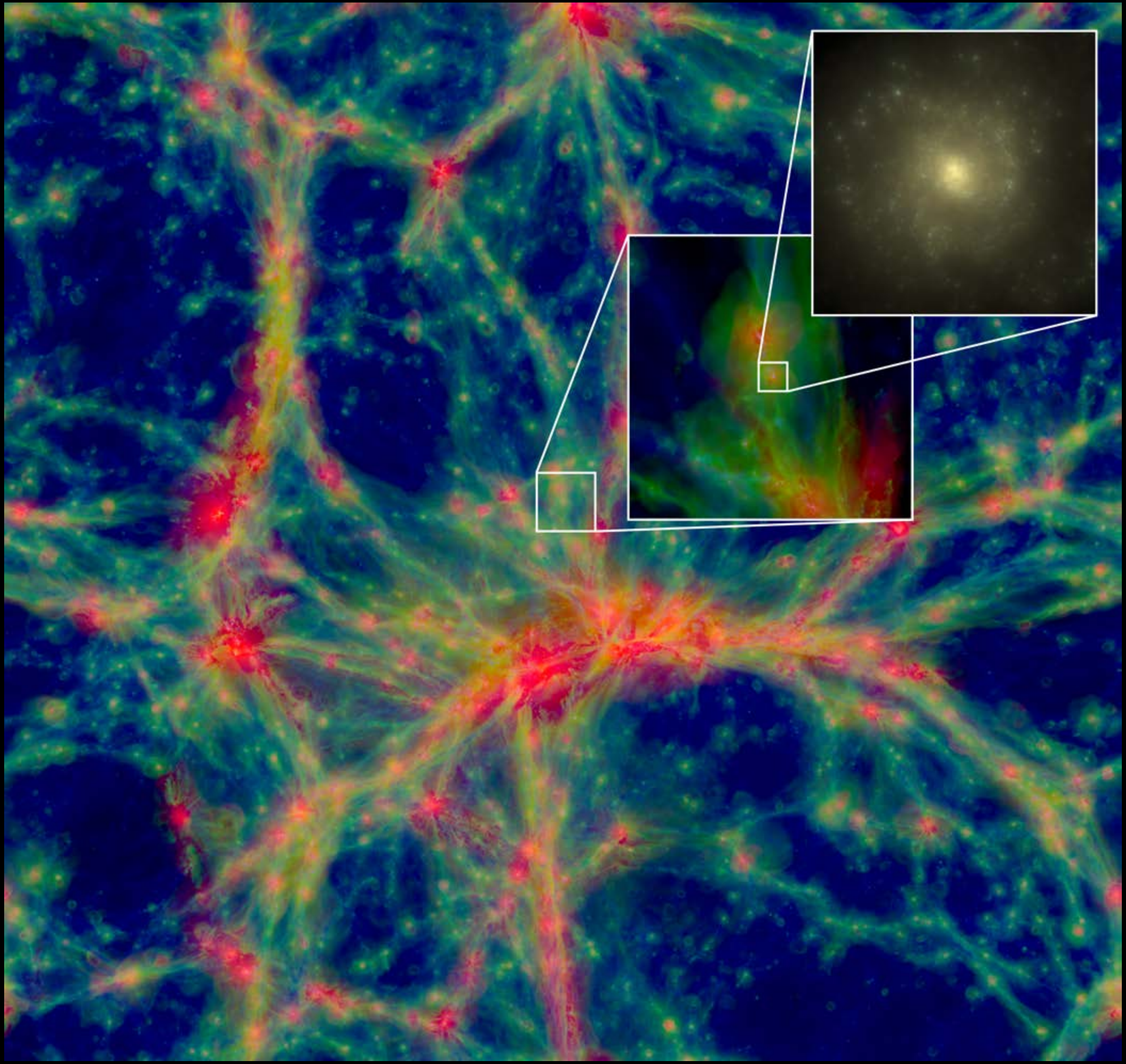
Schaye et al. (2015), Crain et al (2015)



EAGLE Simulations

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

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

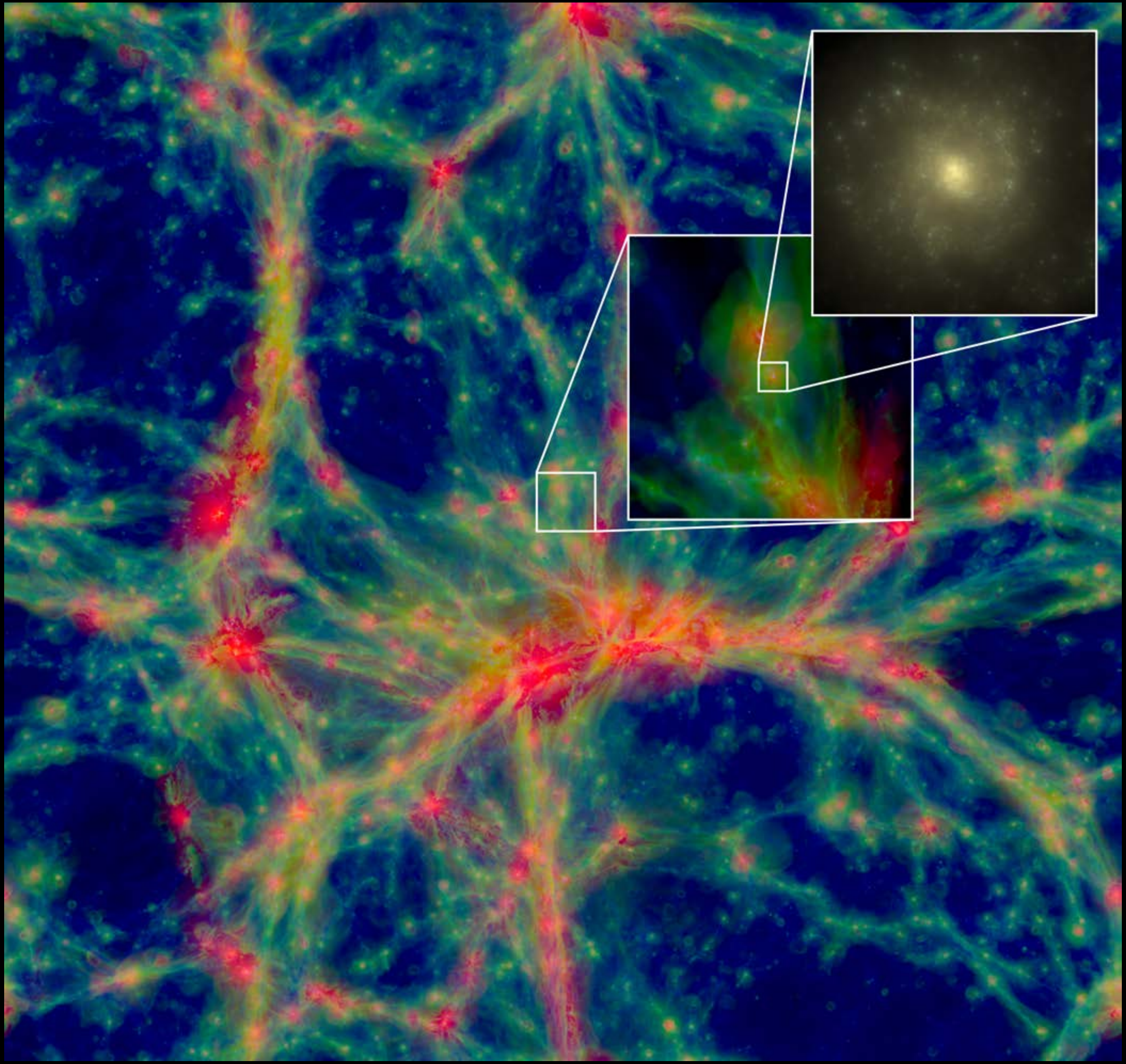


EAGLE Simulations

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: Supernovae, AGN



EAGLE Simulations

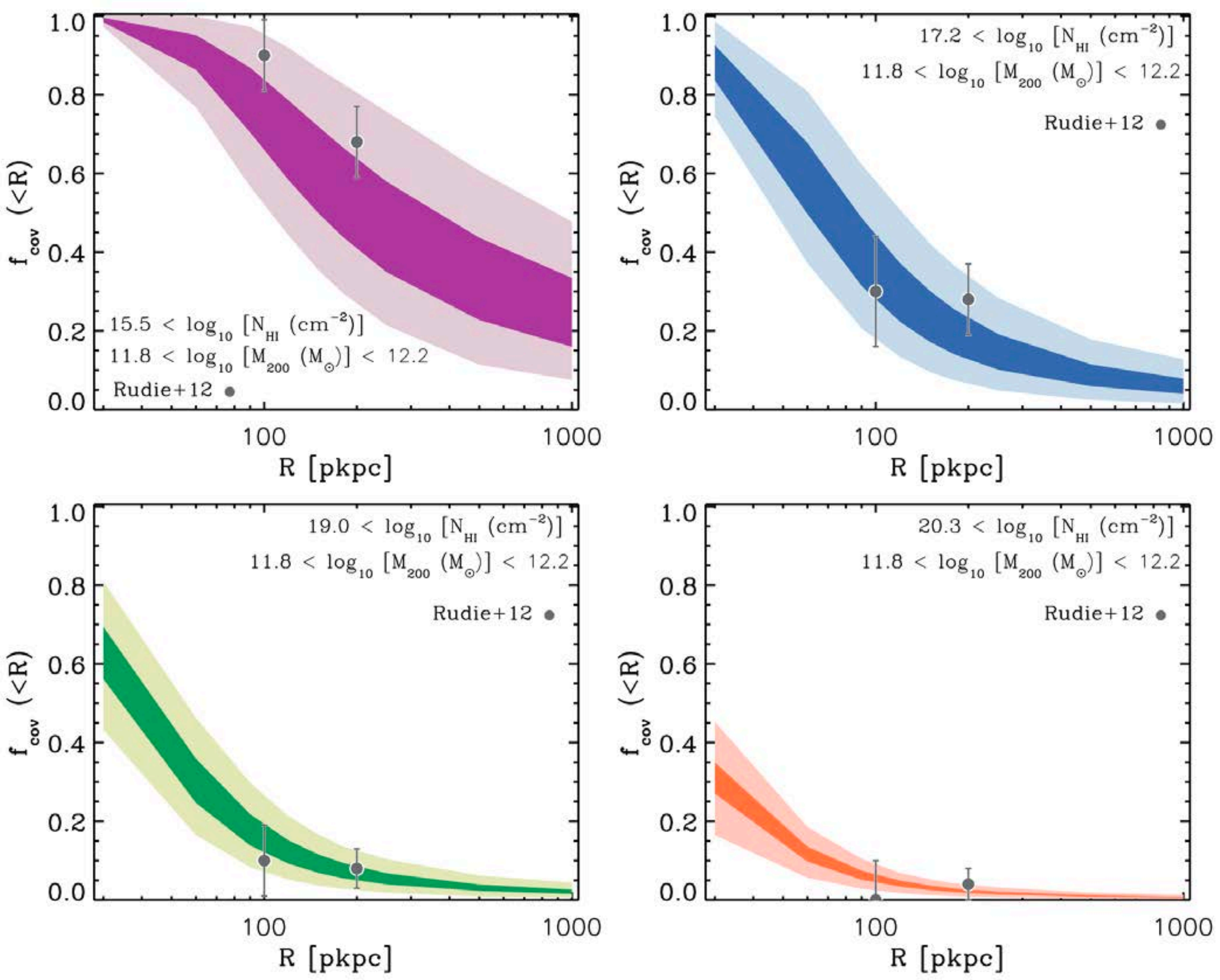
Schaye et al. (2015), Crain et al (2015)

- 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: Supernovae, AGN

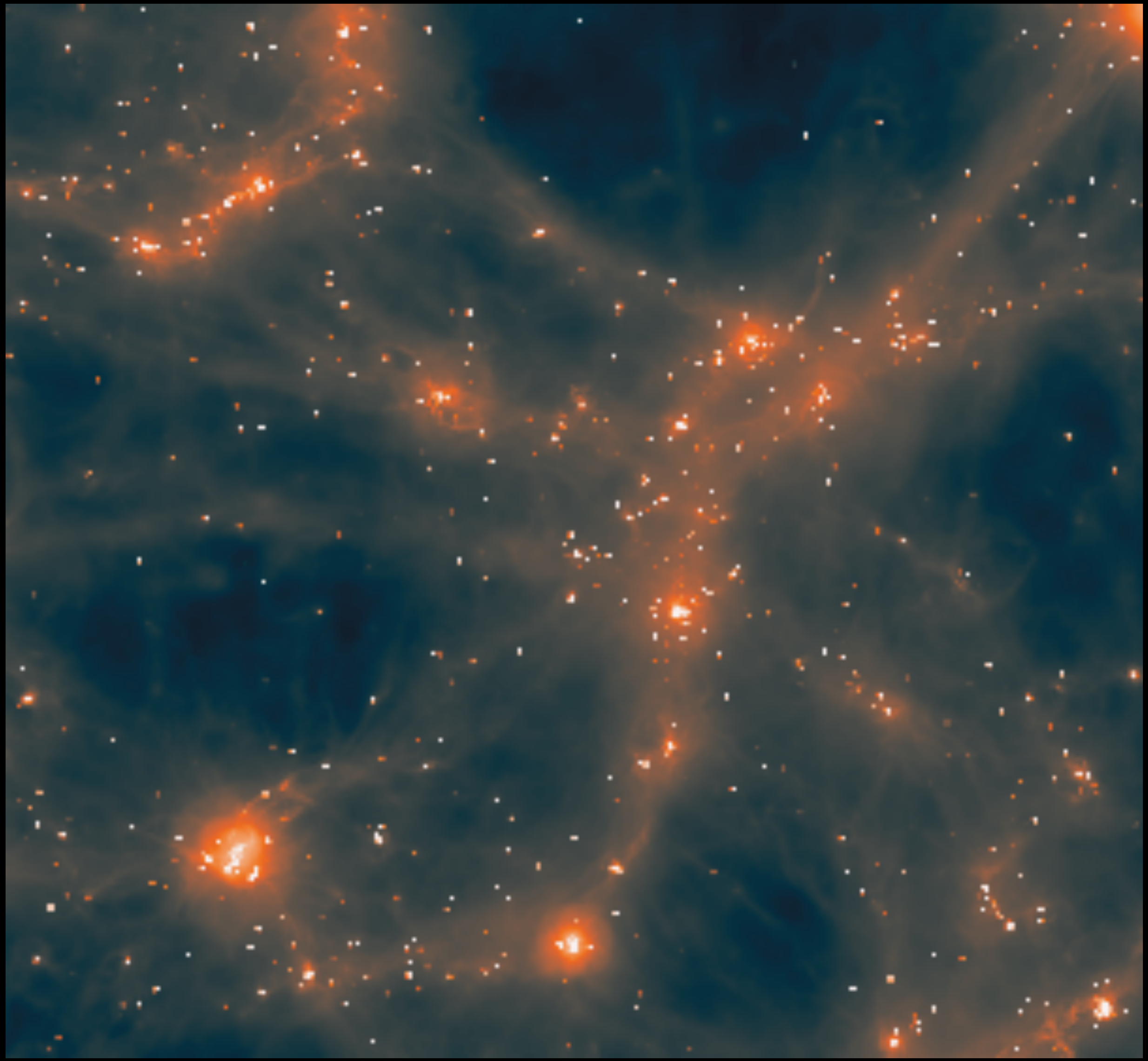
- Resolution: ~ 0.7 ckpc
- Particle Masses: ~ $10^6\ M_\odot$

EAGLE Simulations



- ✓ Gets the HI column density distribution correct!

Rahmati et al. (2015)

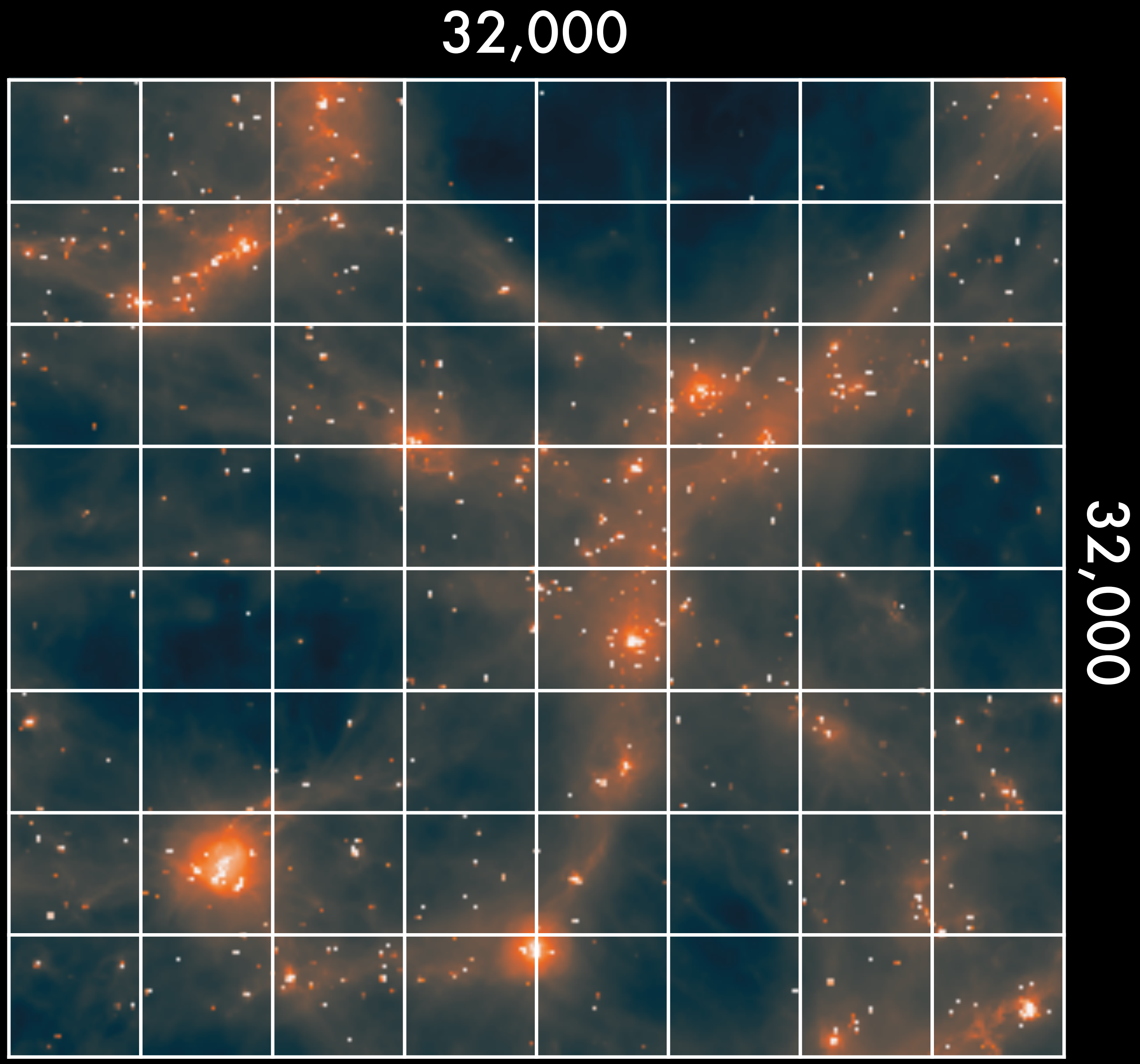


Batten et al. *in prep*

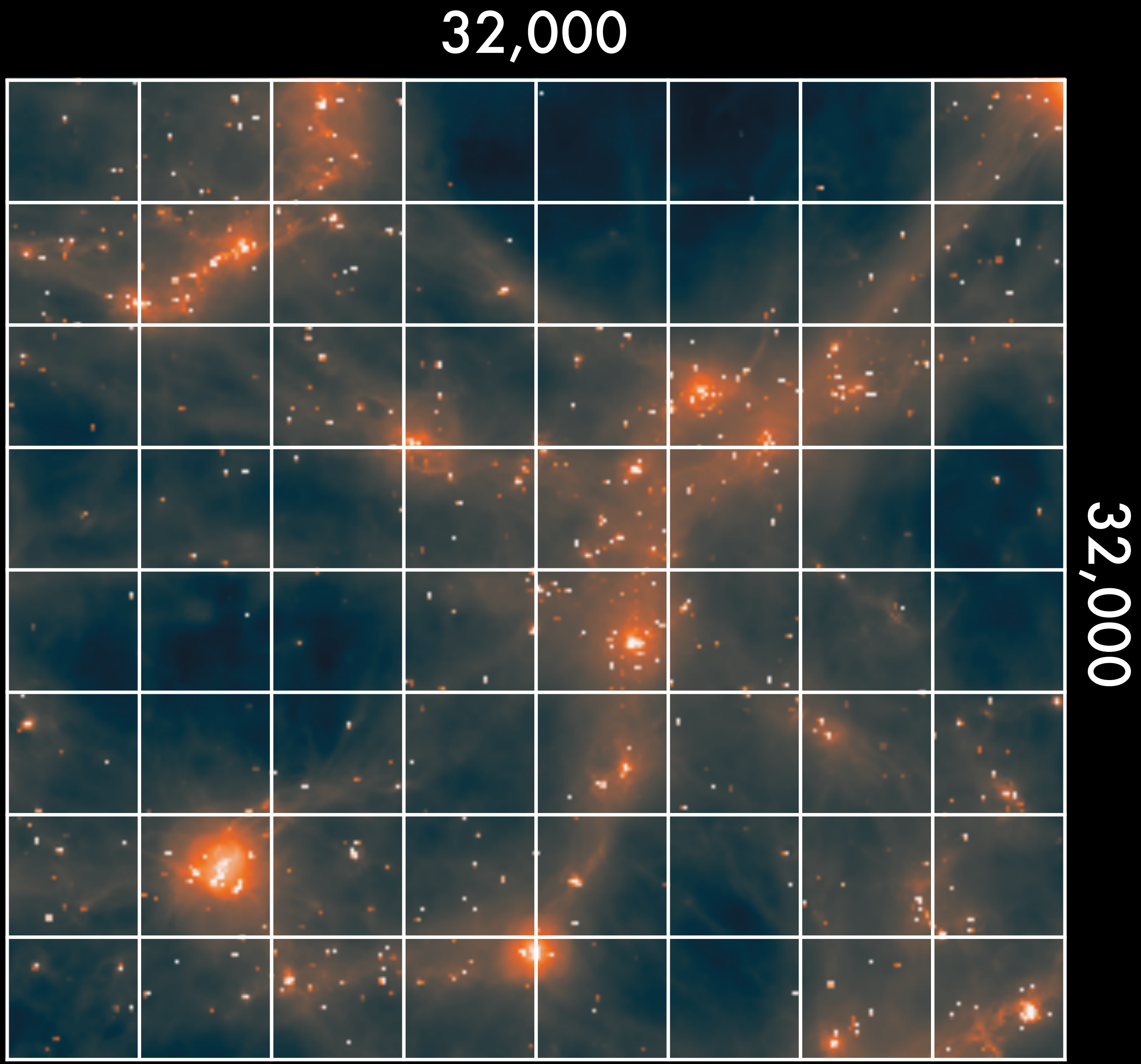
EAGLE Simulations

EAGLE Simulations

- Divide cube into columns



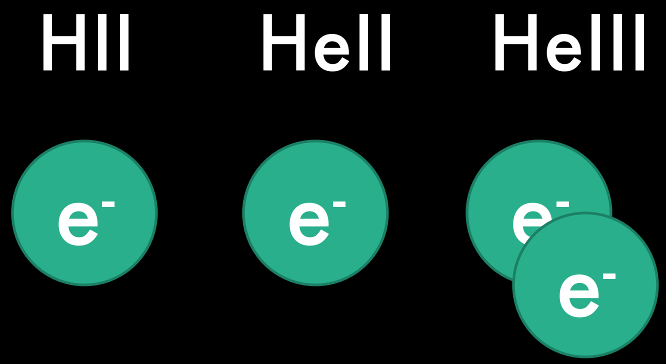
Batten et al. *in prep*



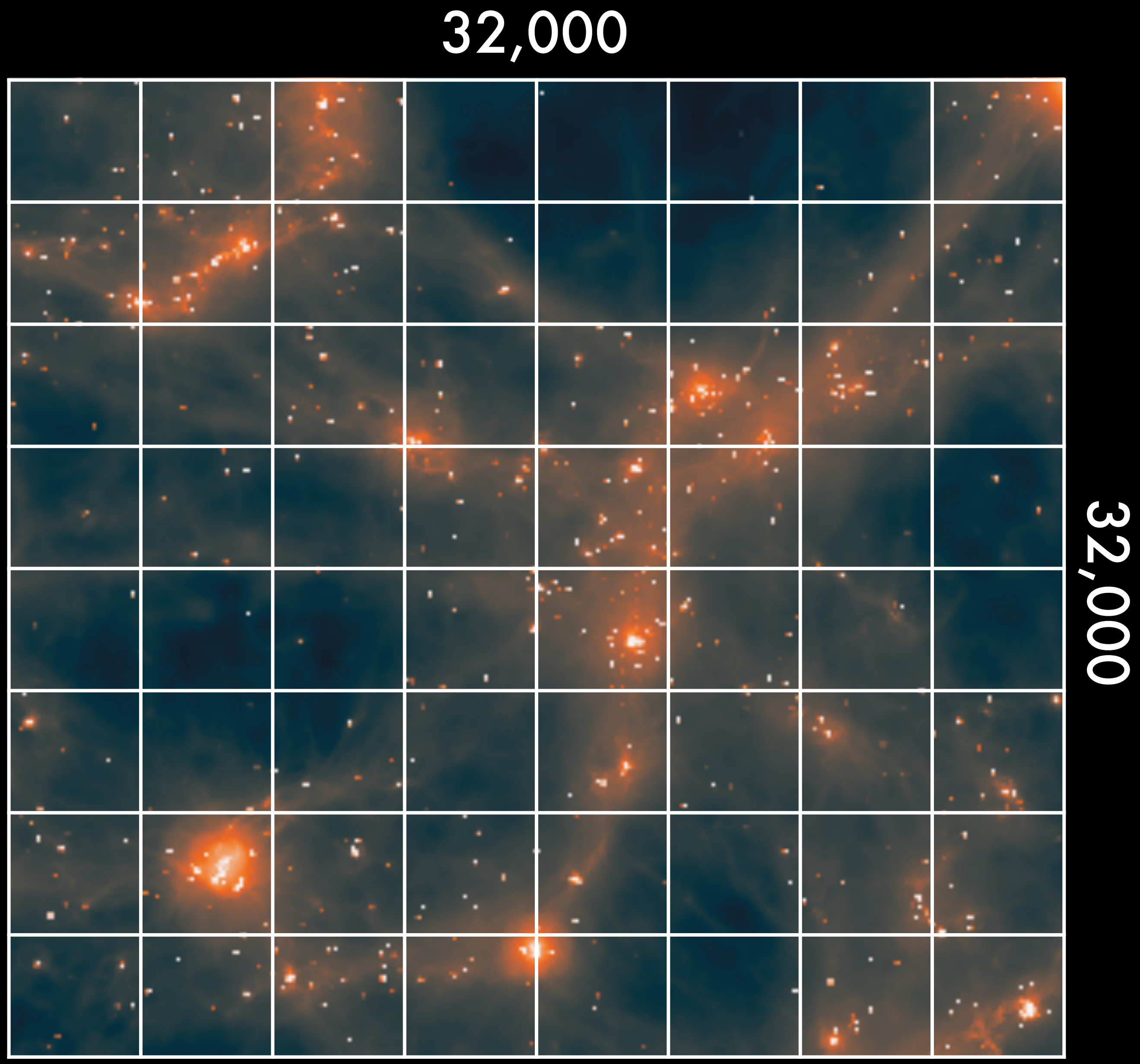
Batten et al. *in prep*

EAGLE Simulations

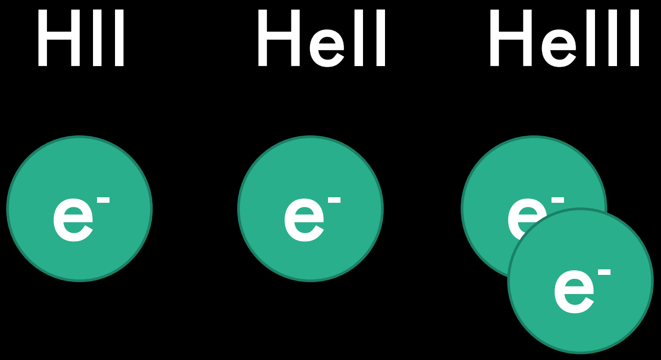
- ➢ Divide cube into columns
- ➢ Calculate column densities
  - ○ Rahmati et al. (2013) (SS)
  - ○ Wijers et al. (2019)
  - ○ EOS: $T = 10^4$ K



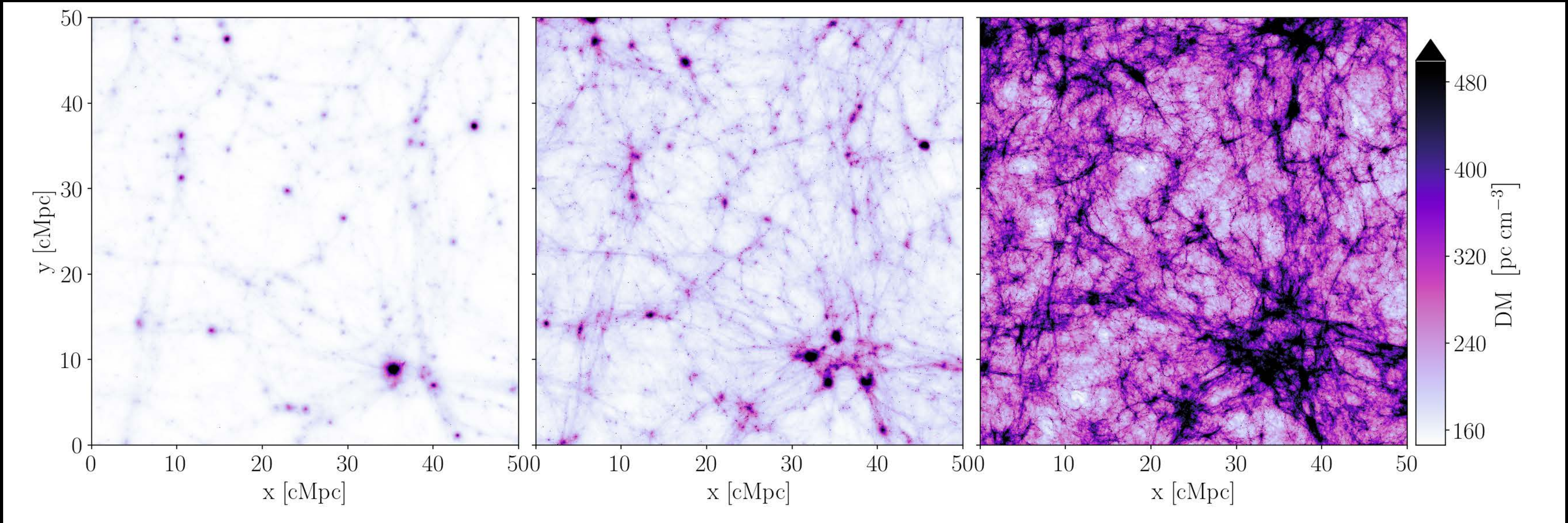
EAGLE Simulations



- Divide cube into columns
- Calculate column densities
  - Rahmati et al. (2013) (SS)
  - Wijers et al. (2019)
  - EOS: $T = 10^4$ K
- Convert column densities to units of pc cm^{-3}

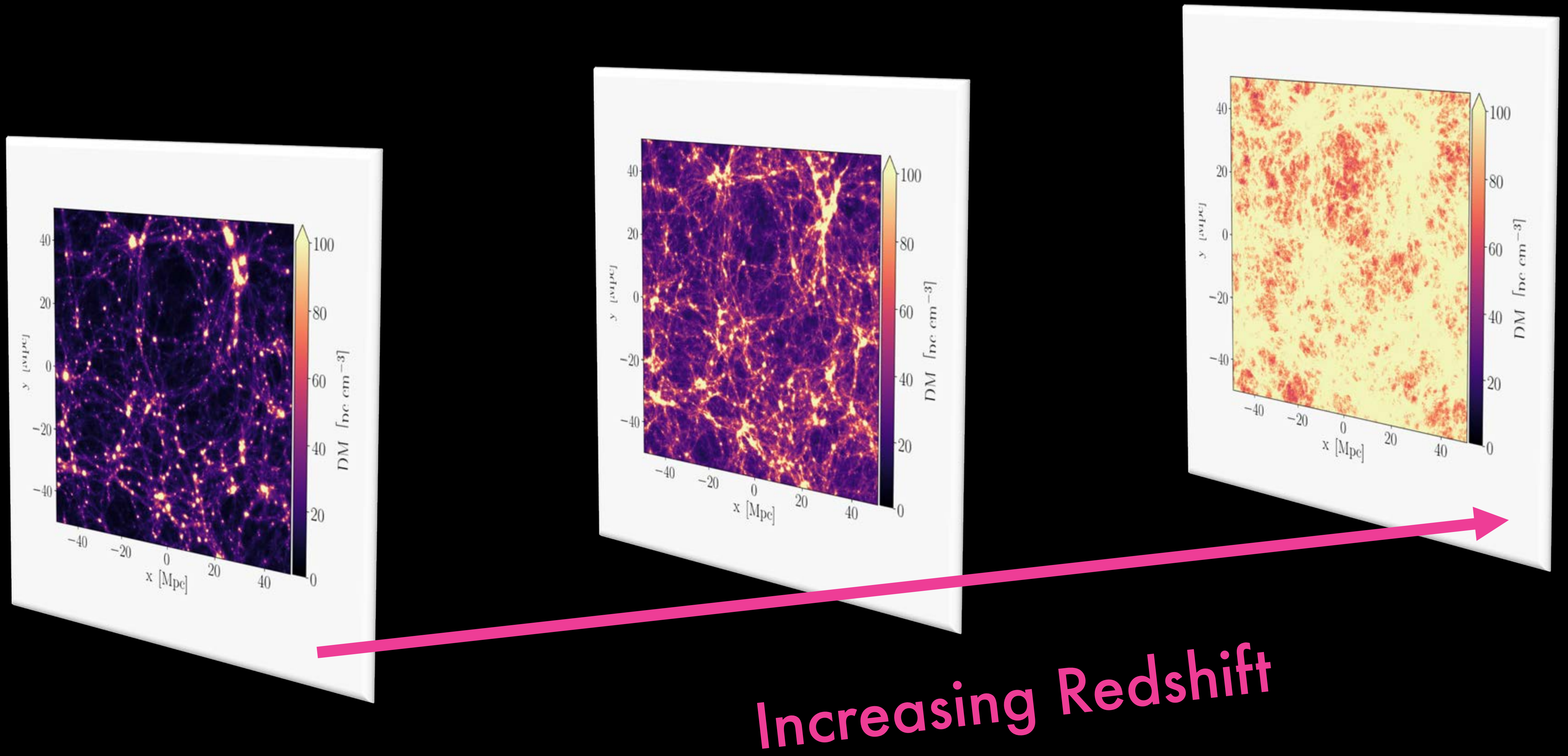


Batten et al. *in prep*

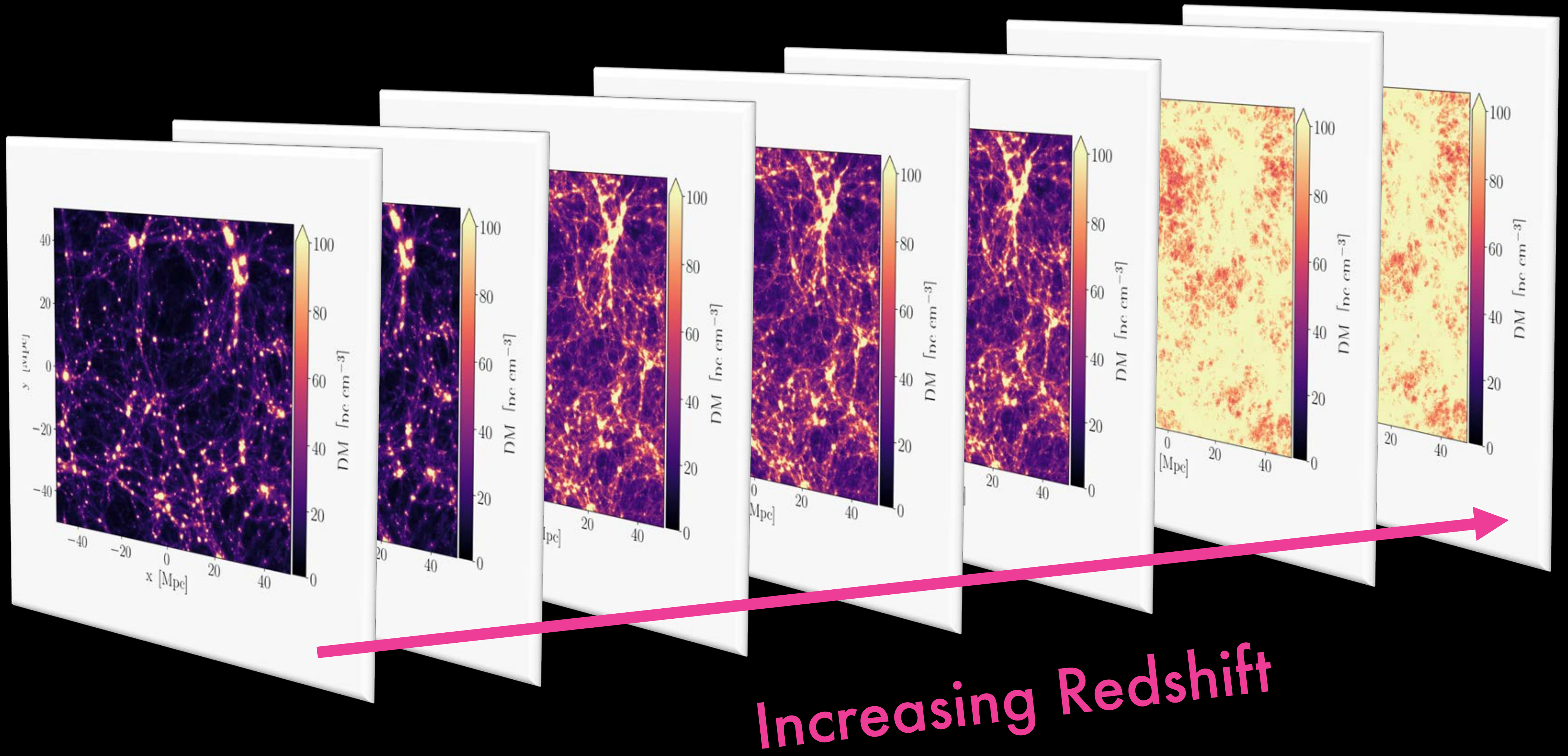


z = 0 z = 1 z = 3

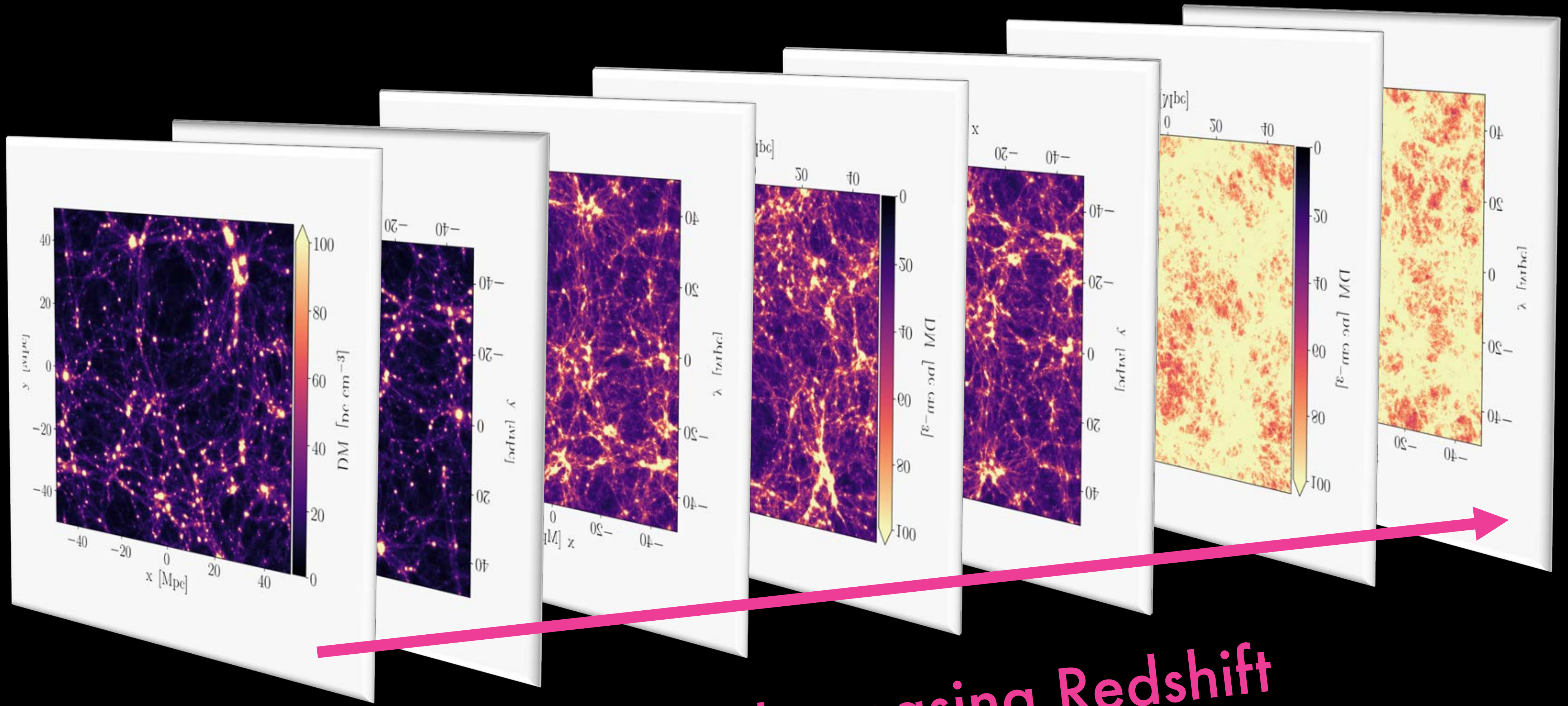
Batten et al. *in prep*



Batten et al. *in prep*

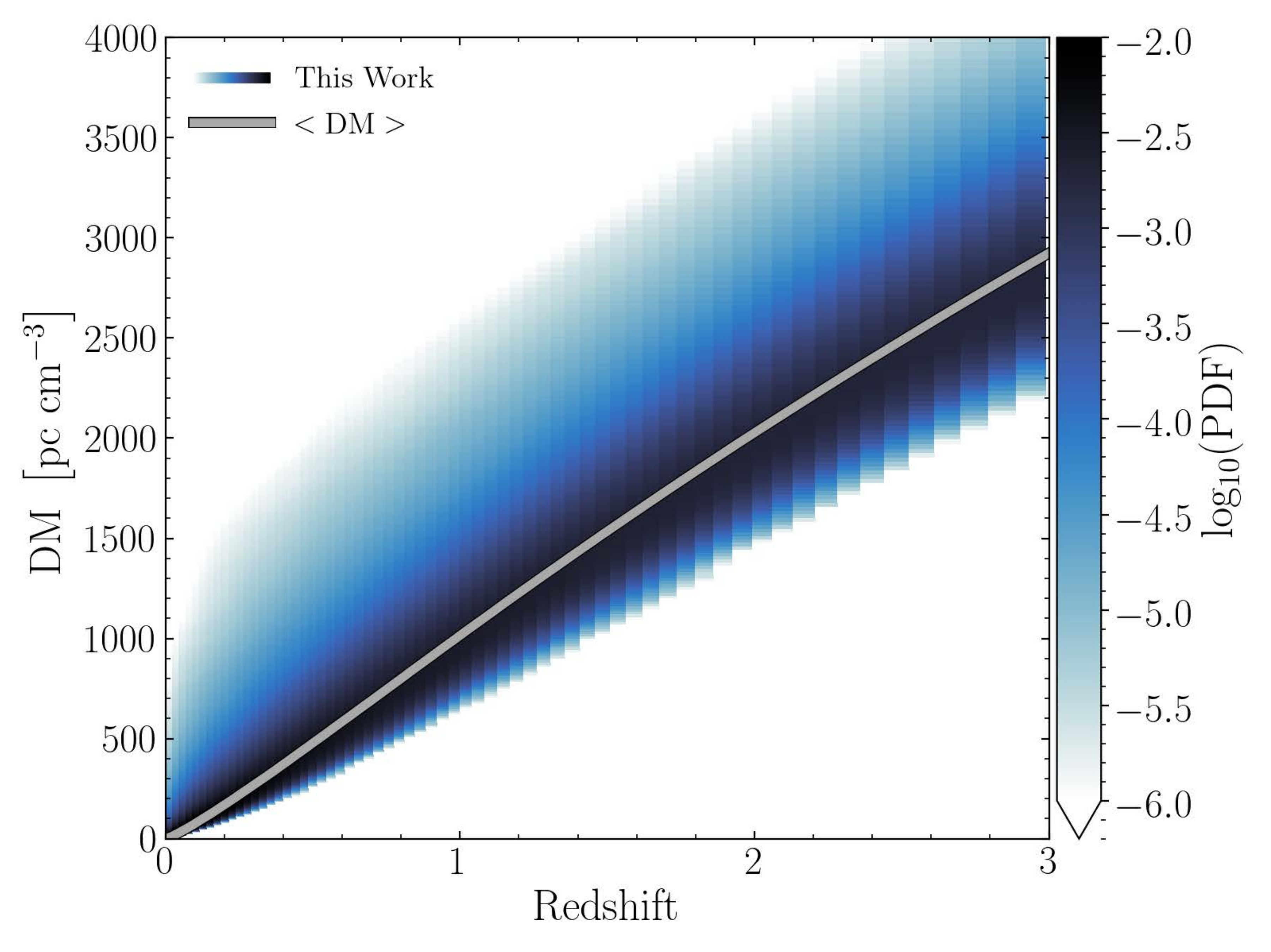


Batten et al. *in prep*

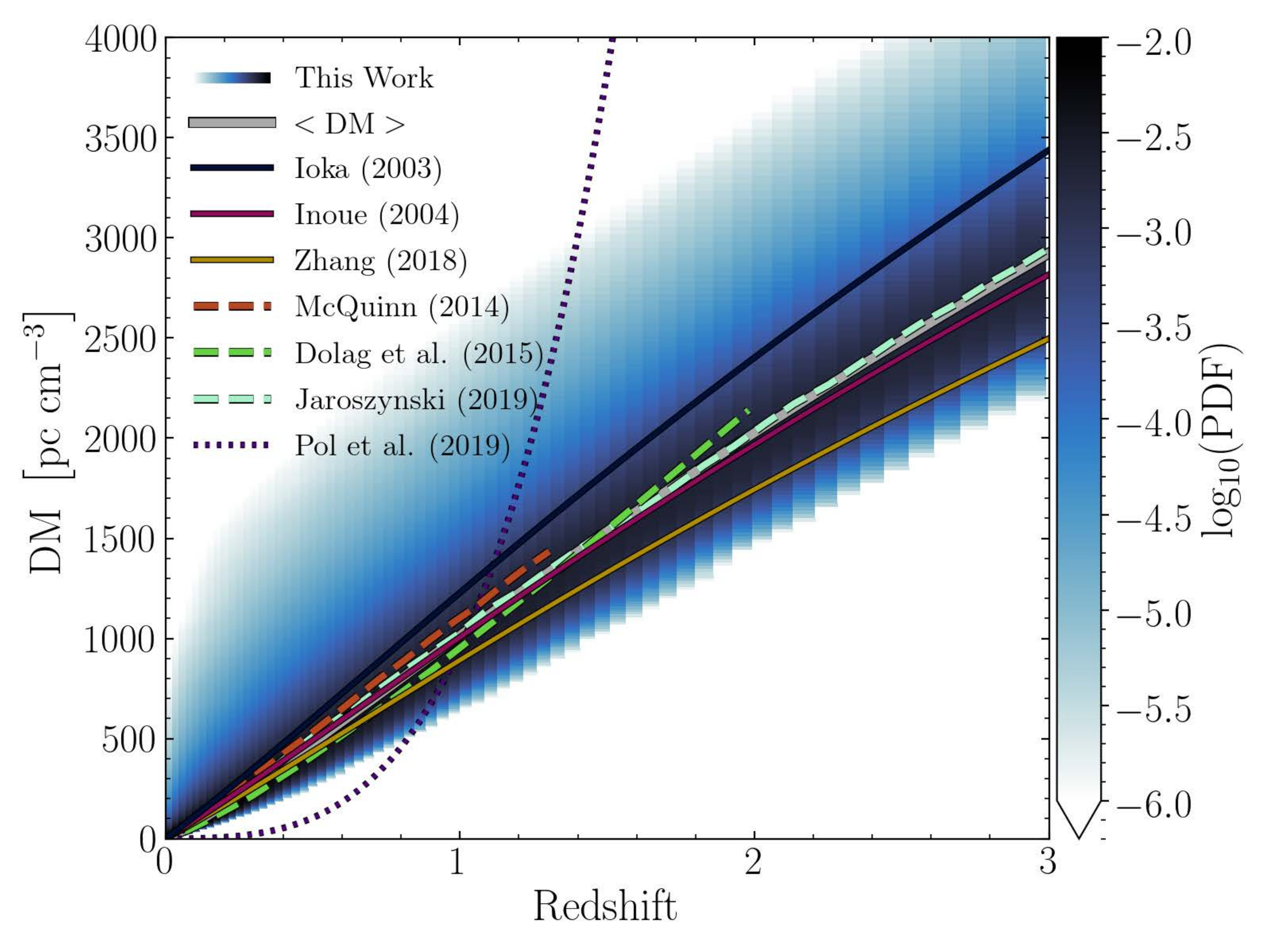


Increasing Redshift

Batten et al. *in prep*

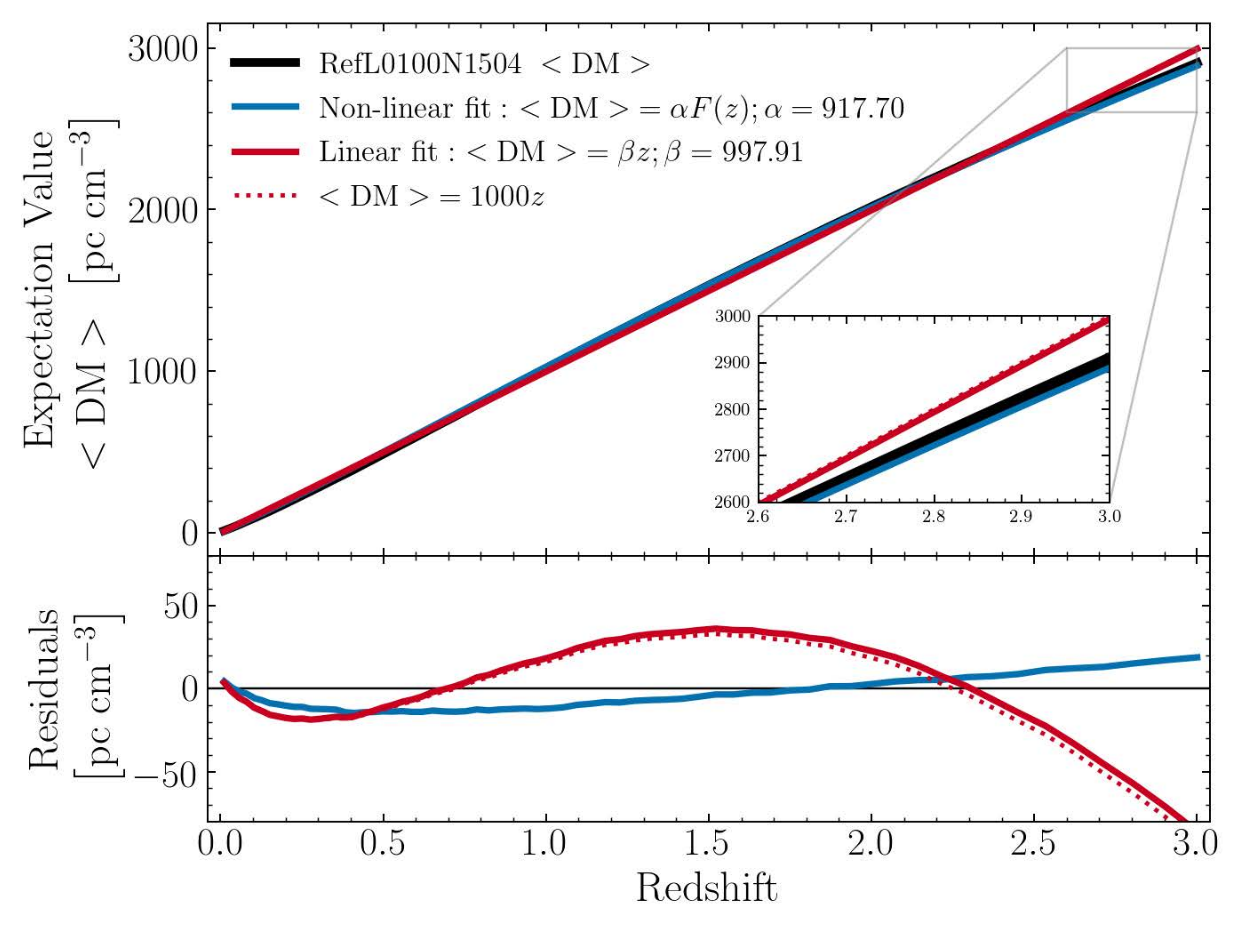


Batten et al. *in prep*



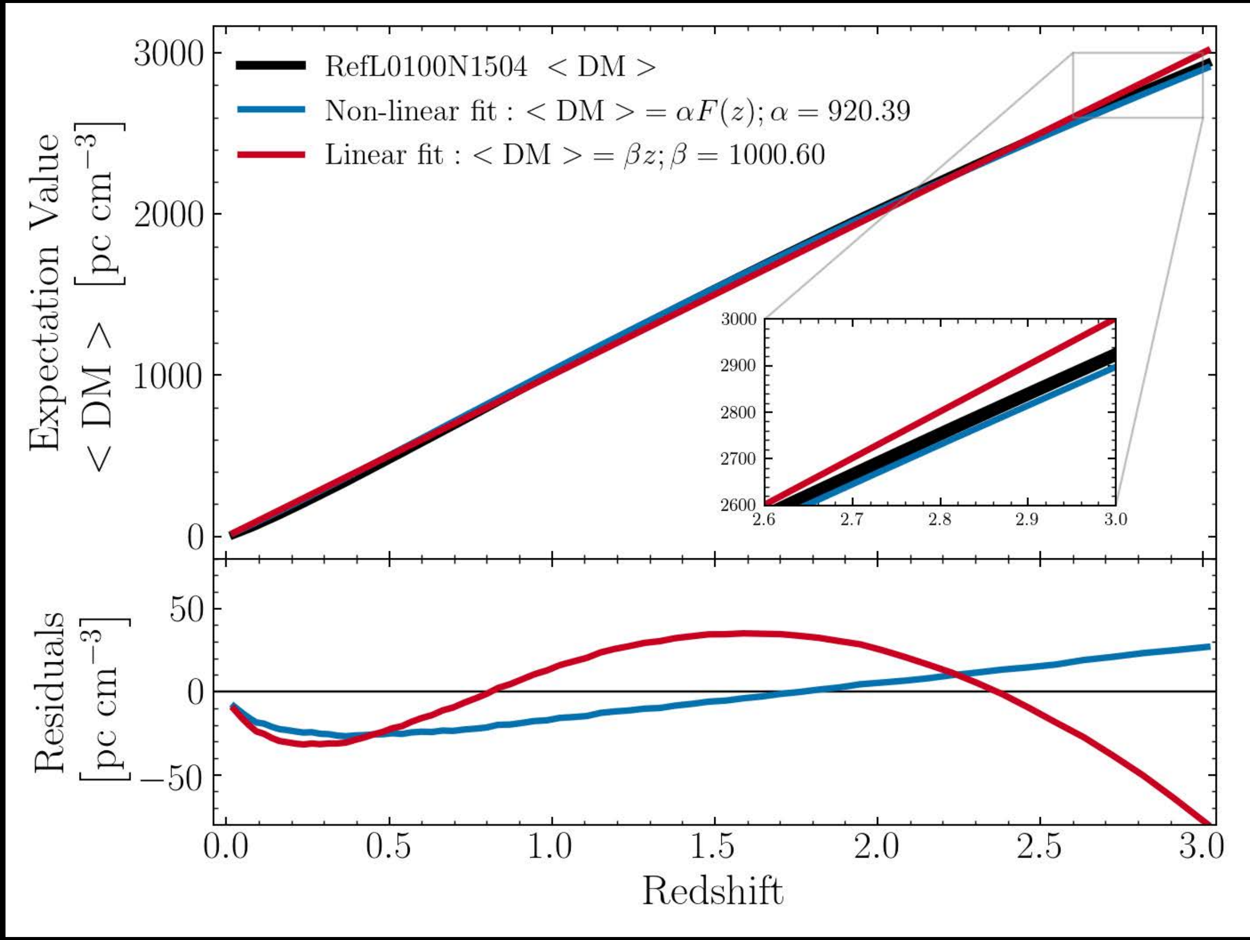
Batten et al. *in prep*

Log-Normal Mean



$$< \mathrm{DM} > \approx 998\ \mathrm{pc\,cm^{-3}}\ z$$

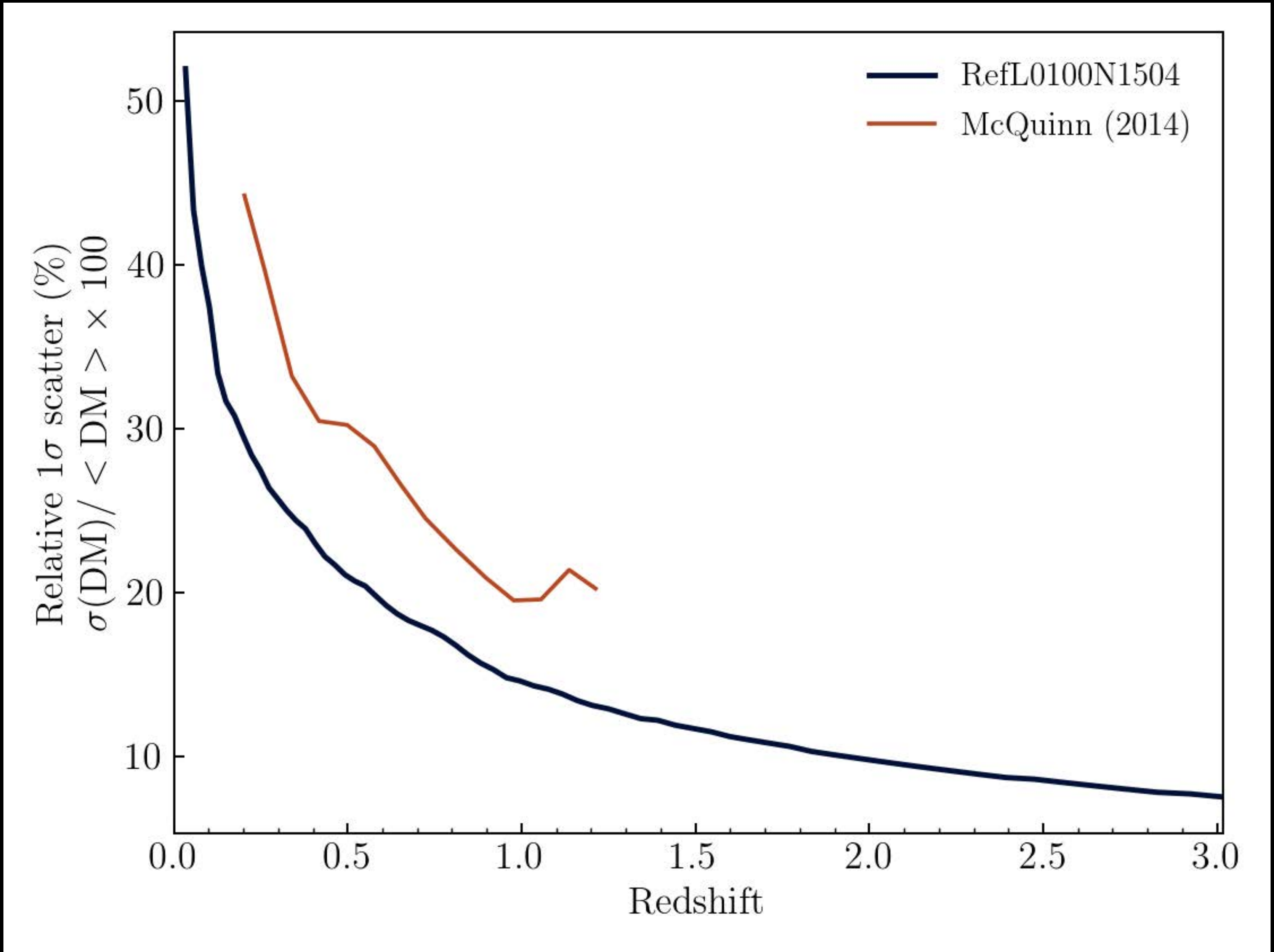
Weighted Mean



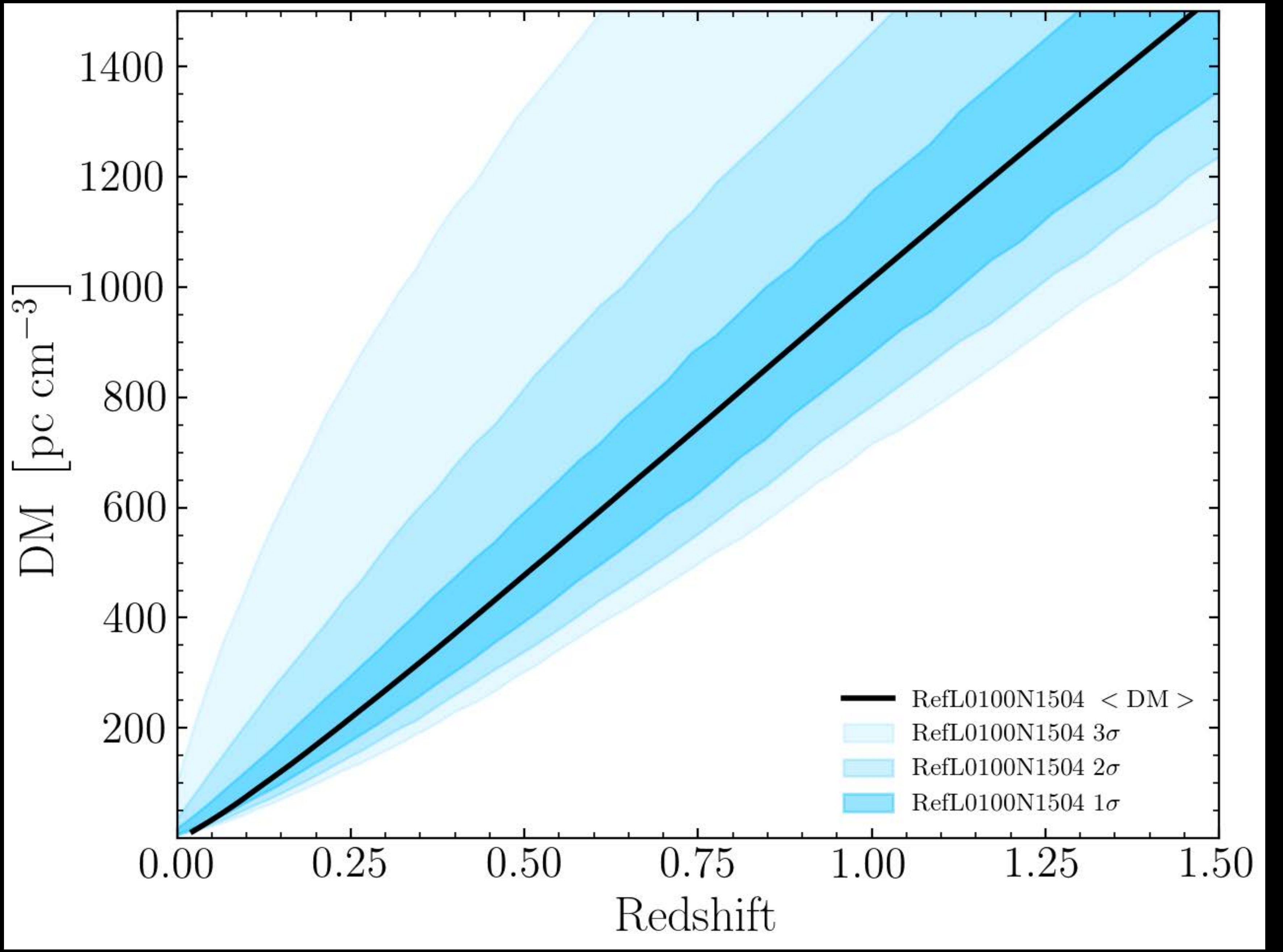
$$< \mathrm{DM} > \approx 1000\ \mathrm{pc\,cm^{-3}}\ z$$

Batten et al. *in prep*

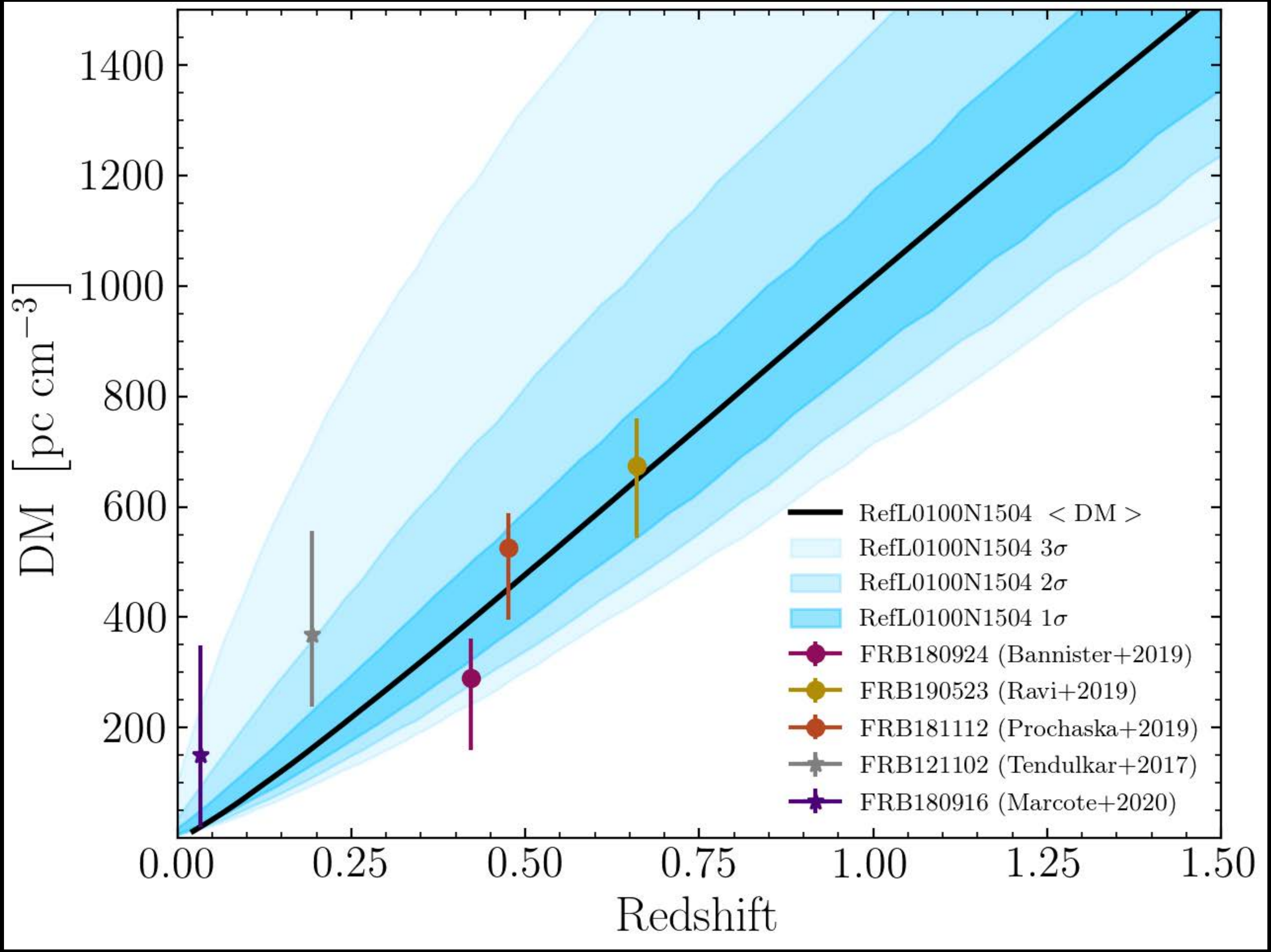
Much lower scatter than McQuinn (2014).



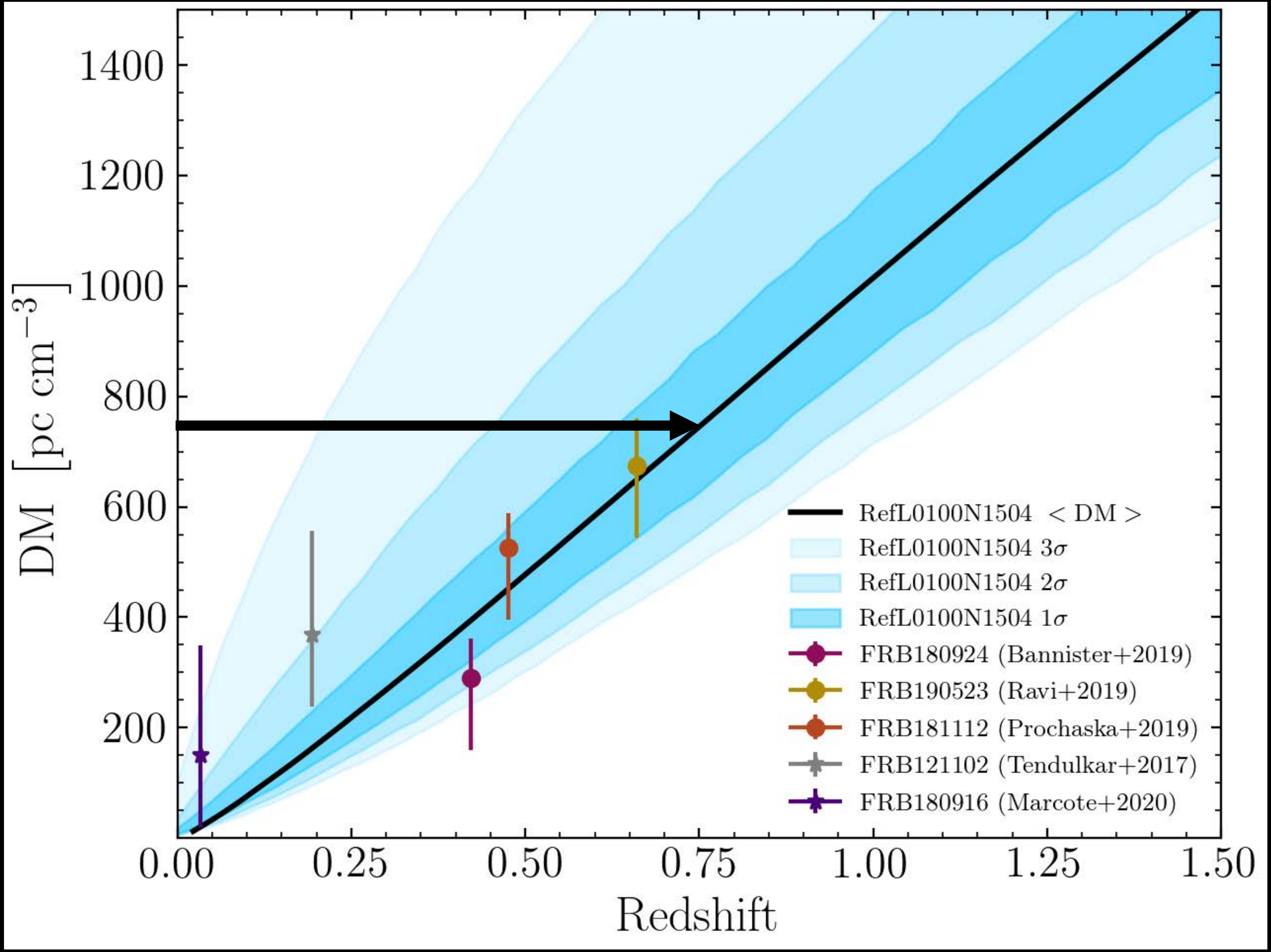
Batten et al. *in prep*



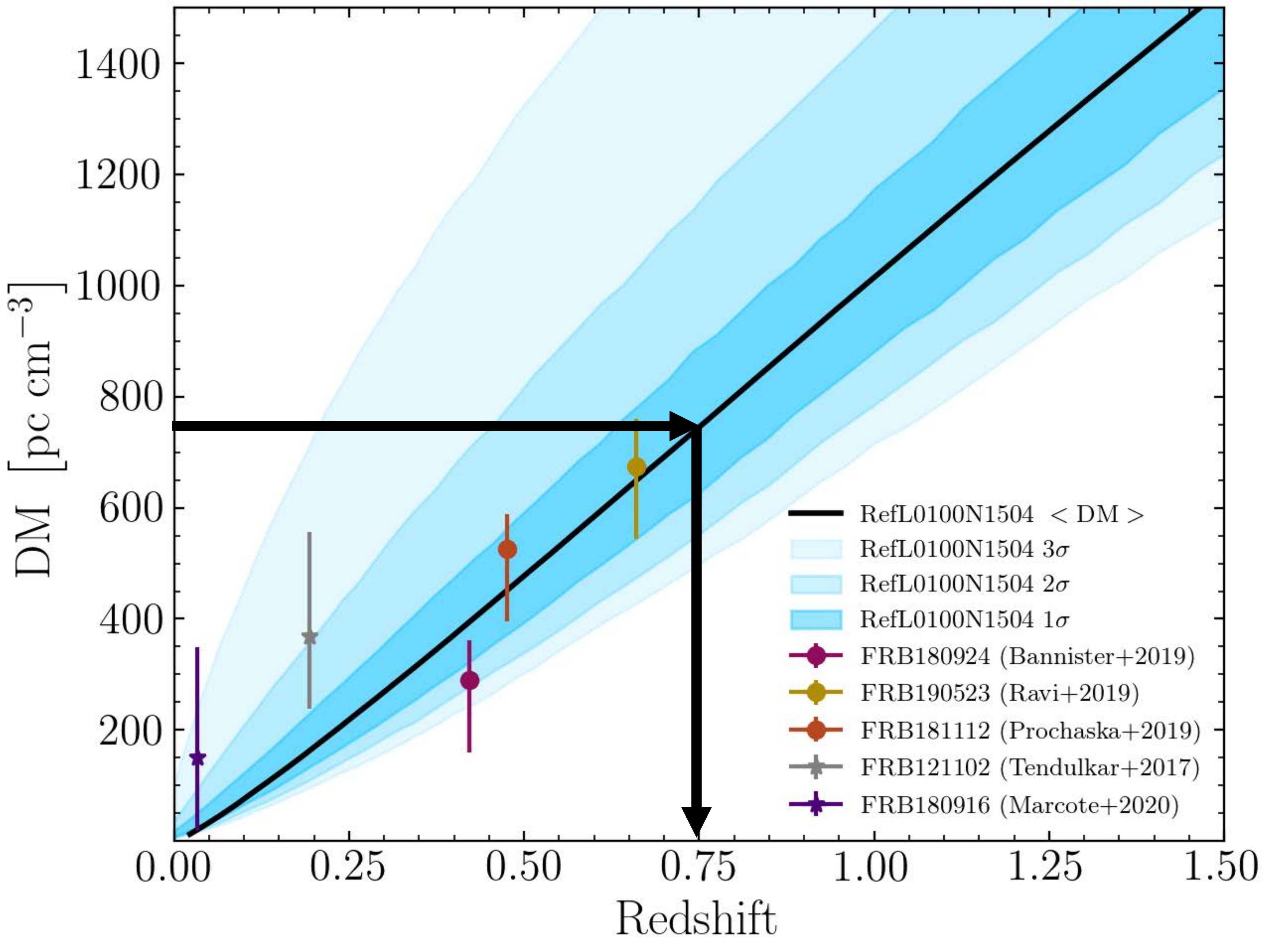
Batten et al. *in prep*



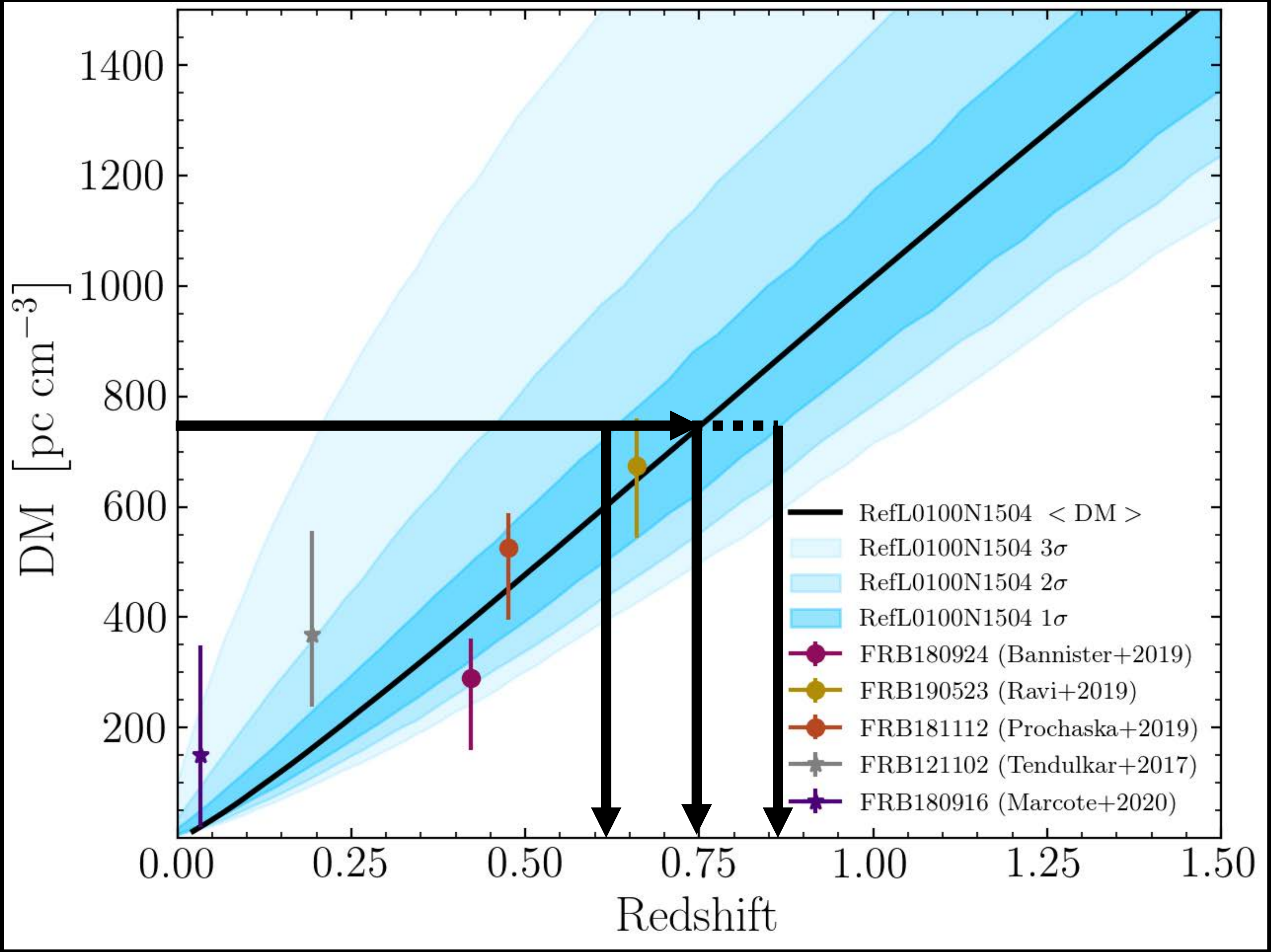
Batten et al. *in prep*



Batten et al. *in prep*



Batten et al. *in prep*

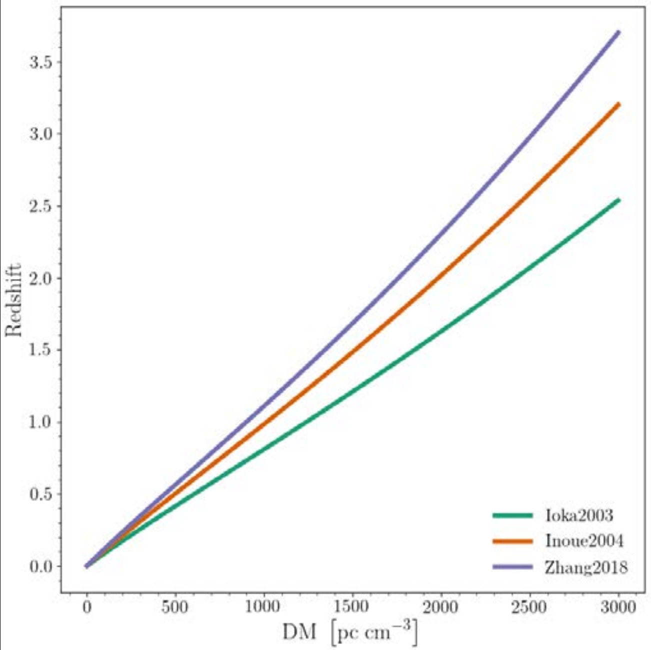


Batten et al. *in prep*

Batten (2019)

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

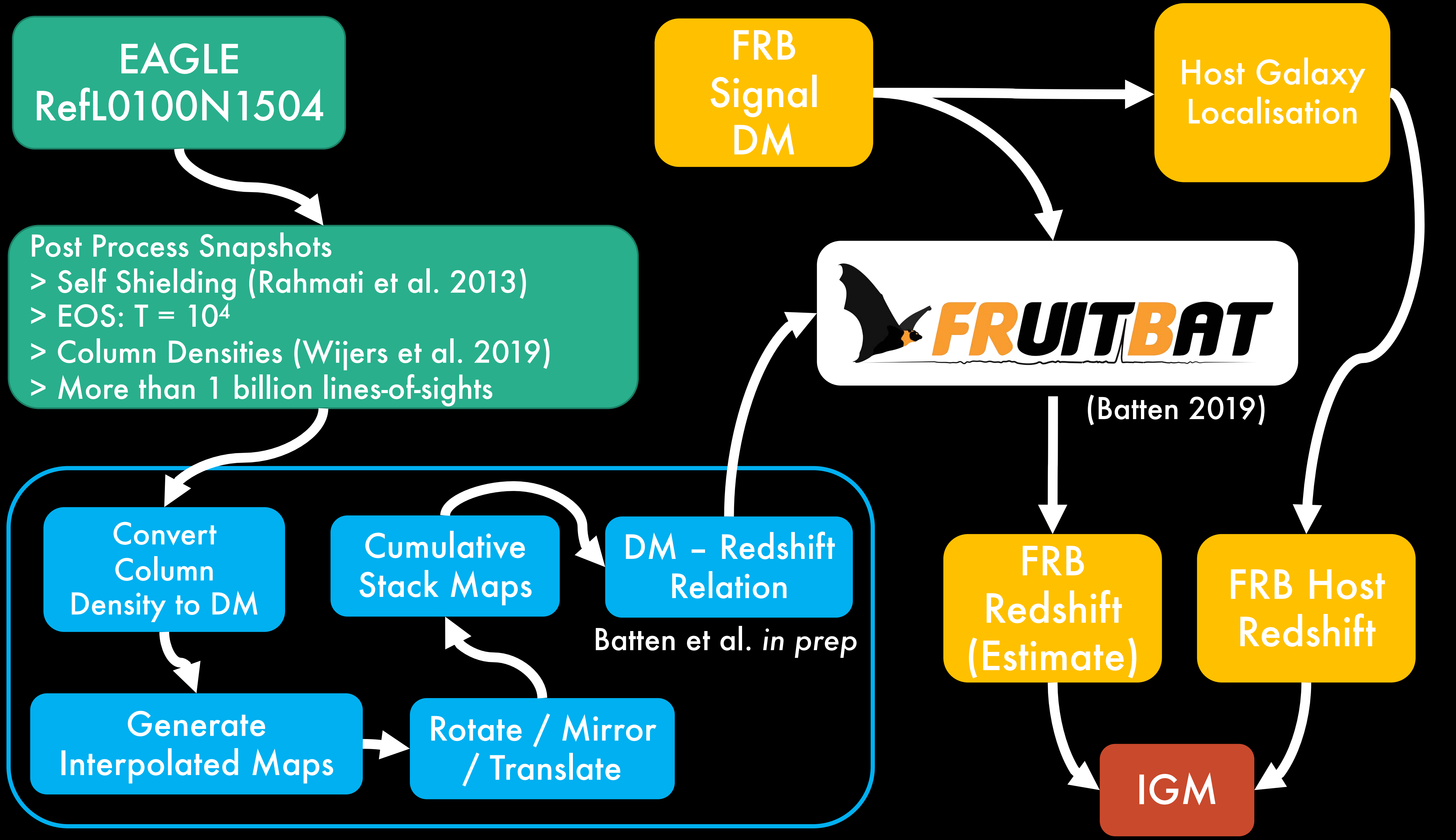
FRB Signal DM → FRUITBAT → FRB Redshift



DM-z lookup tables:

- Ioka (2003)
- Inoue (2004)
- Zhang (2018)
- Batten et al. *in prep*

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


EAGLE
RefL0100N1504
Post Process Snapshots
> Self Shielding (Rahmati et al. 2013)
> EOS: T = 10⁴
> Column Densities (Wijers et al. 2019)
> More than 1 billion lines-of-sights
Convert Column Density to DM
Cumulative Stack Maps
DM – Redshift Relation
Batten et al. *in prep*
Generate Interpolated Maps
Rotate / Mirror / Translate
FRB Signal DM
Host Galaxy Localisation
FRUITBAT
(Batten 2019)
FRB Redshift (Estimate)
FRB Host Redshift
IGM

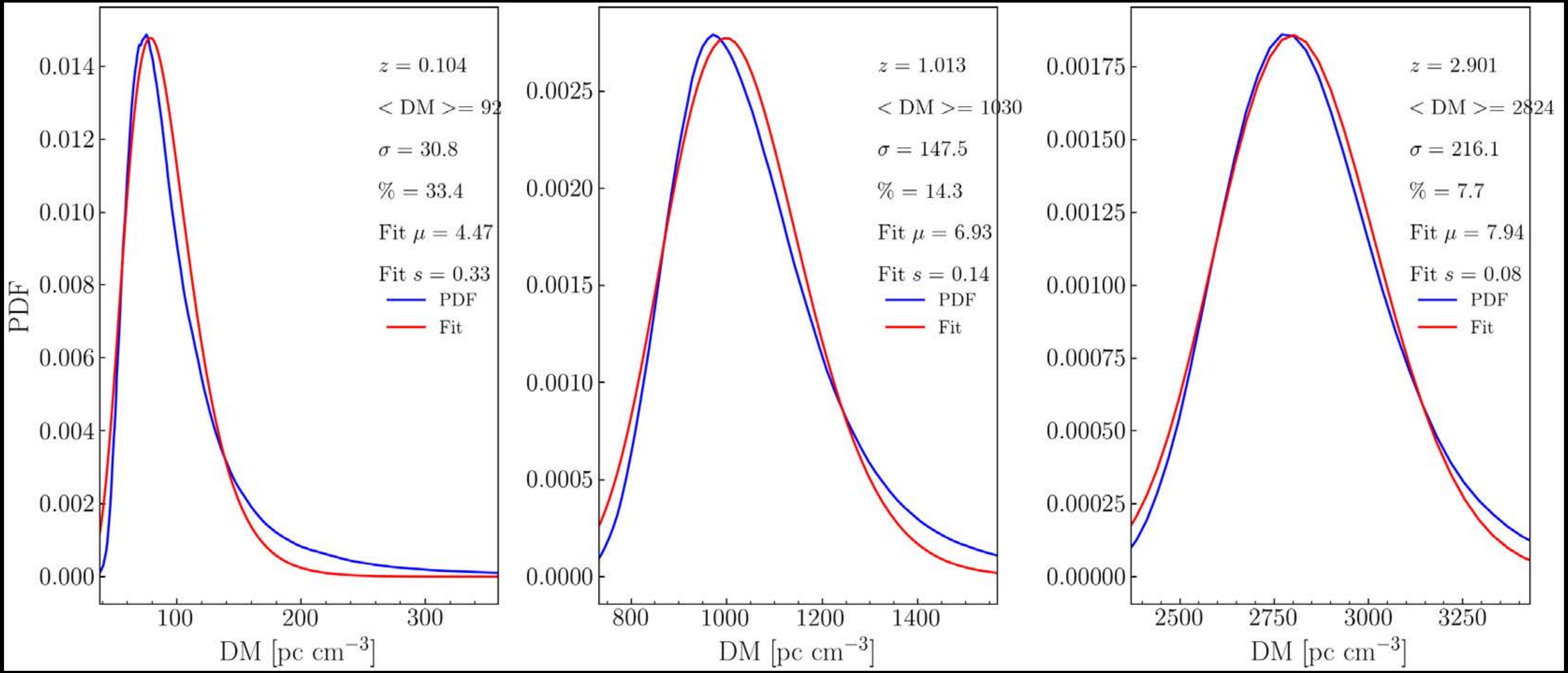
Summary:

- We measured the DM for more than 1 billion lines-of-sights through the EAGLE simulations

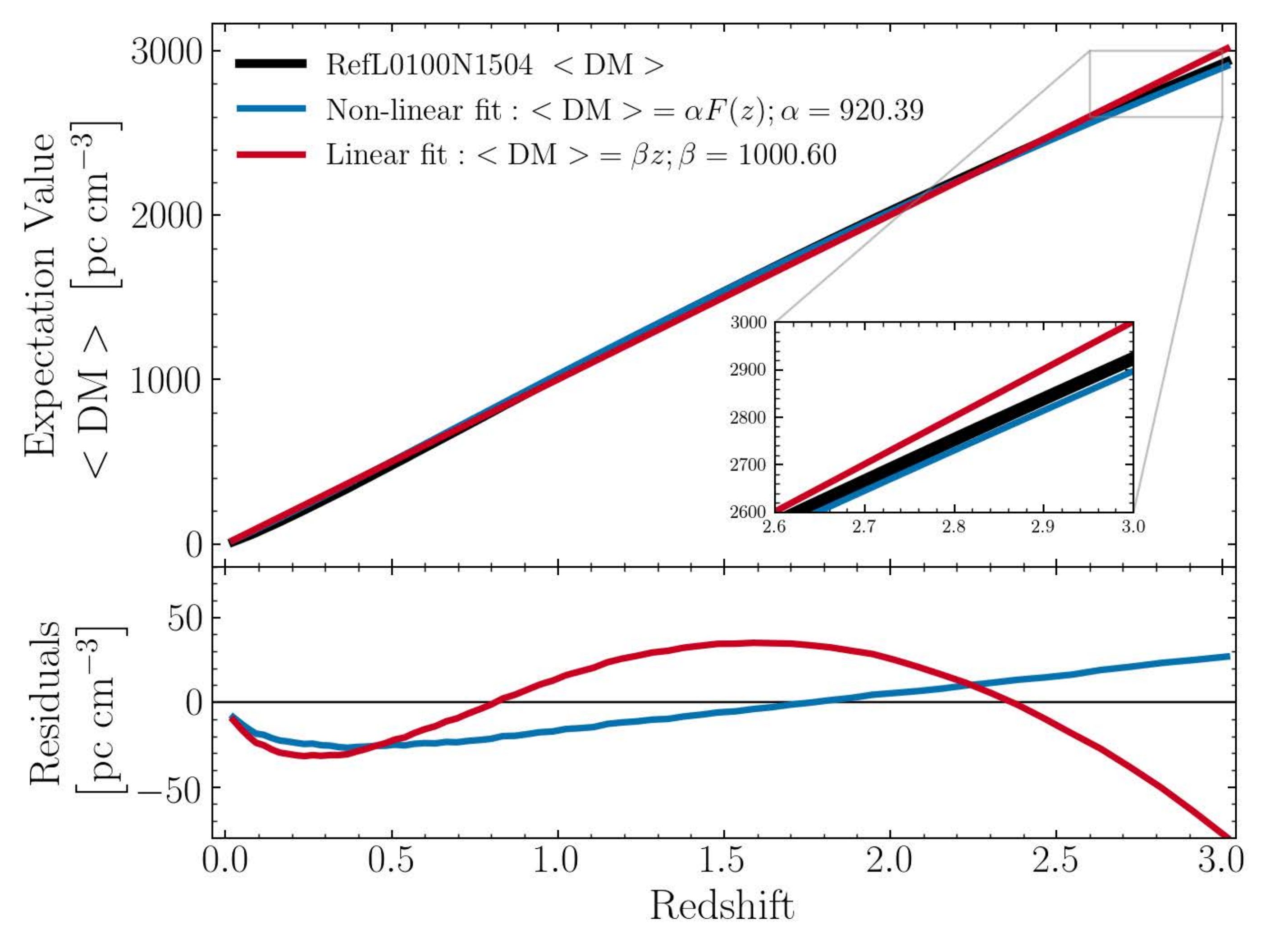
- We find a DM-z relation with a slope of approx. 1000 pc cm^{-3}

- We find a scatter around the mean much lower than McQuinn (2014).

- Our model will be added to FRB redshift estimation code FRUITBAT



PDF
DM [pc cm^{-3}]
$z = 0.104$
$< \mathrm{DM} >= 92$
$\sigma = 30.8$
$\% = 33.4$
Fit $\mu = 4.47$
Fit $s = 0.33$
PDF
Fit
$z = 1.013$
$< \mathrm{DM} >= 1030$
$\sigma = 147.5$
$\% = 14.3$
Fit $\mu = 6.93$
Fit $s = 0.14$
PDF
Fit
$z = 2.901$
$< \mathrm{DM} >= 2824$
$\sigma = 216.1$
$\% = 7.7$
Fit $\mu = 7.94$
Fit $s = 0.08$
PDF
Fit



$$< \mathrm{DM} > = \alpha F(z)$$

$$F(z) = \int_0^{z'} \frac{1+z}{\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}} dz$$

$$\alpha = \frac{3\mathrm{cH_0}\chi}{8\pi \mathrm{G} m_p} \Omega_b \mathrm{f_{IGM}}$$