The Lumina Simulation: A large-volume radiation-hydrodynamics simulation of the epoch of reionization

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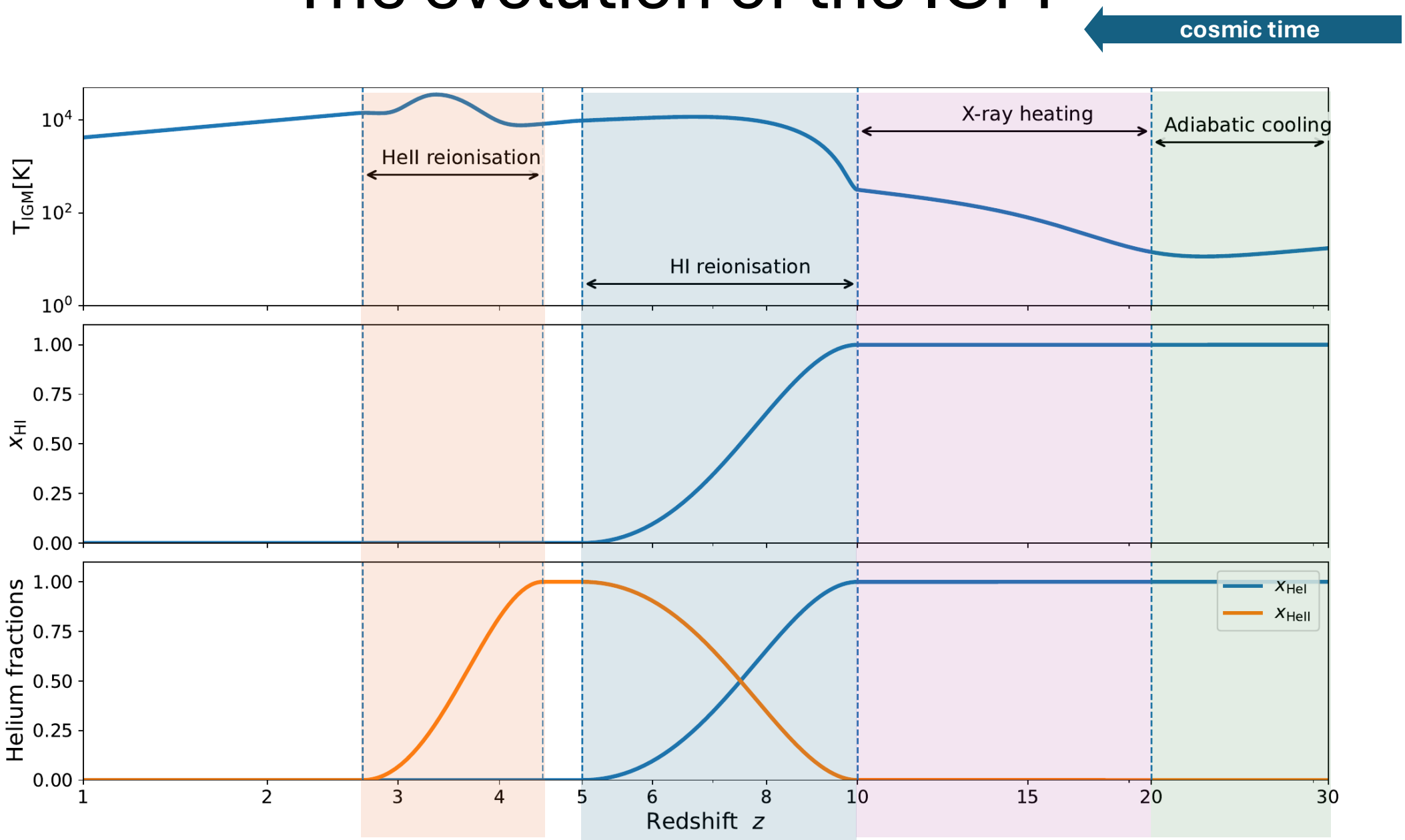
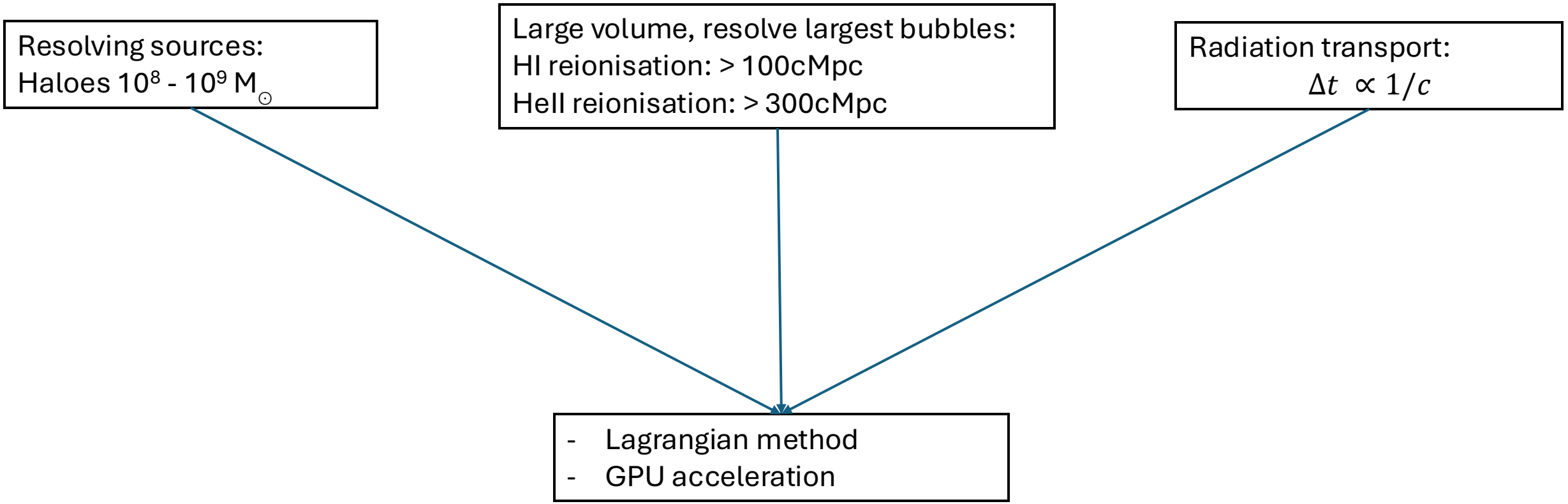
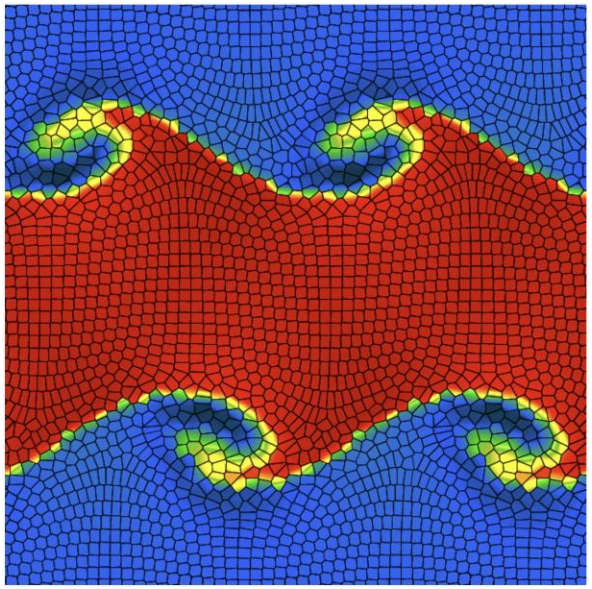
The evolution of the IGM



Requirements for simulations of the EOR



The Lumina model



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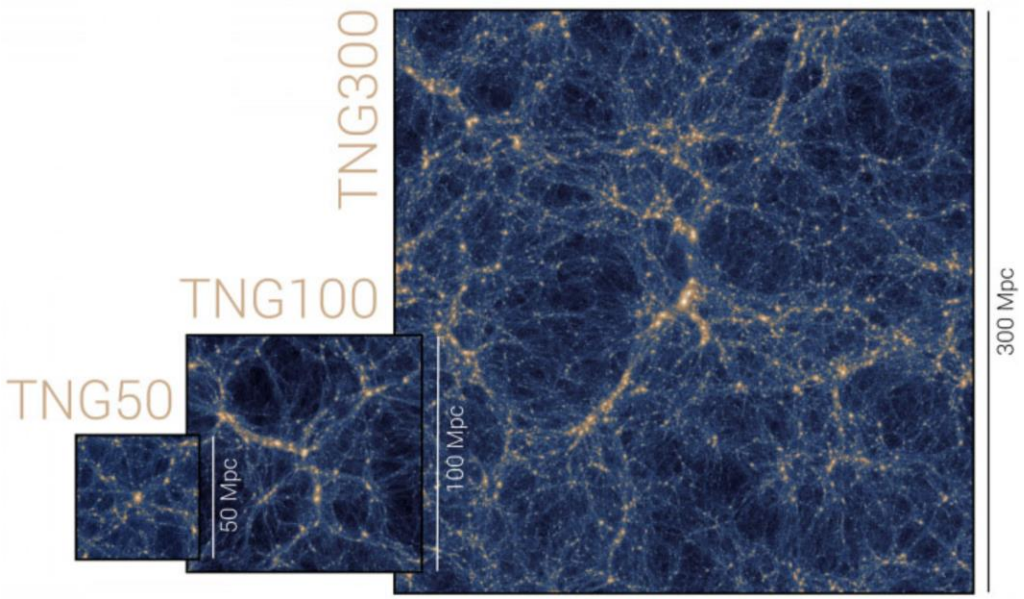

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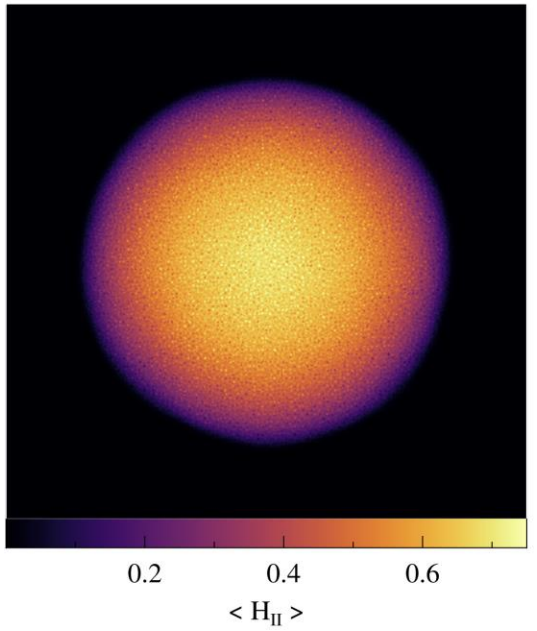
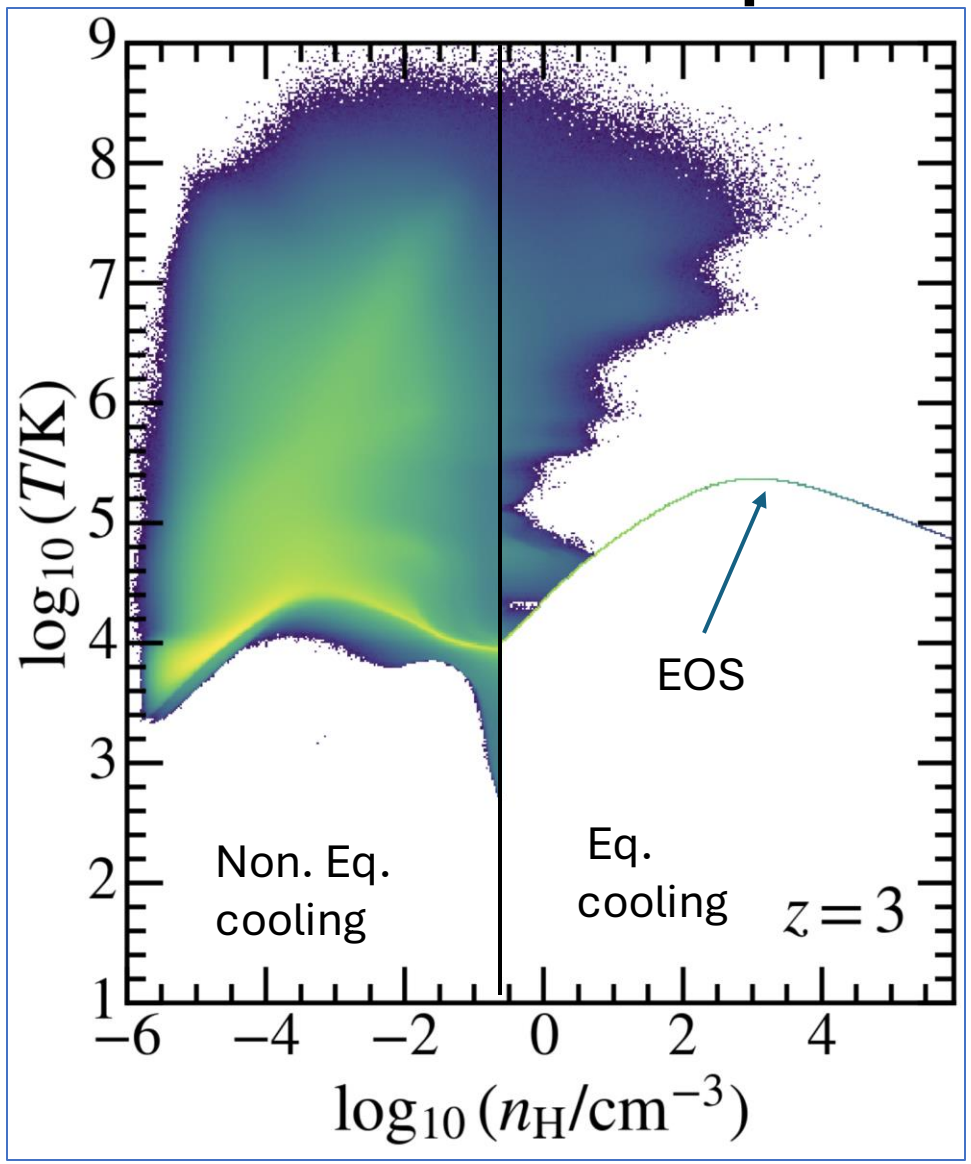


AREPO code
(Springel 2009, Pakmor 2023)

Illustris TNG model
(Pillepich et al. 2018,
Weinberger et al. 2016)

GPU accelerated RT, M1
(Kannan et al. 2018,
Zier et al. 2024)

Transparent equation of state



Problem: Springel & Hernquist does not define ISM structure:

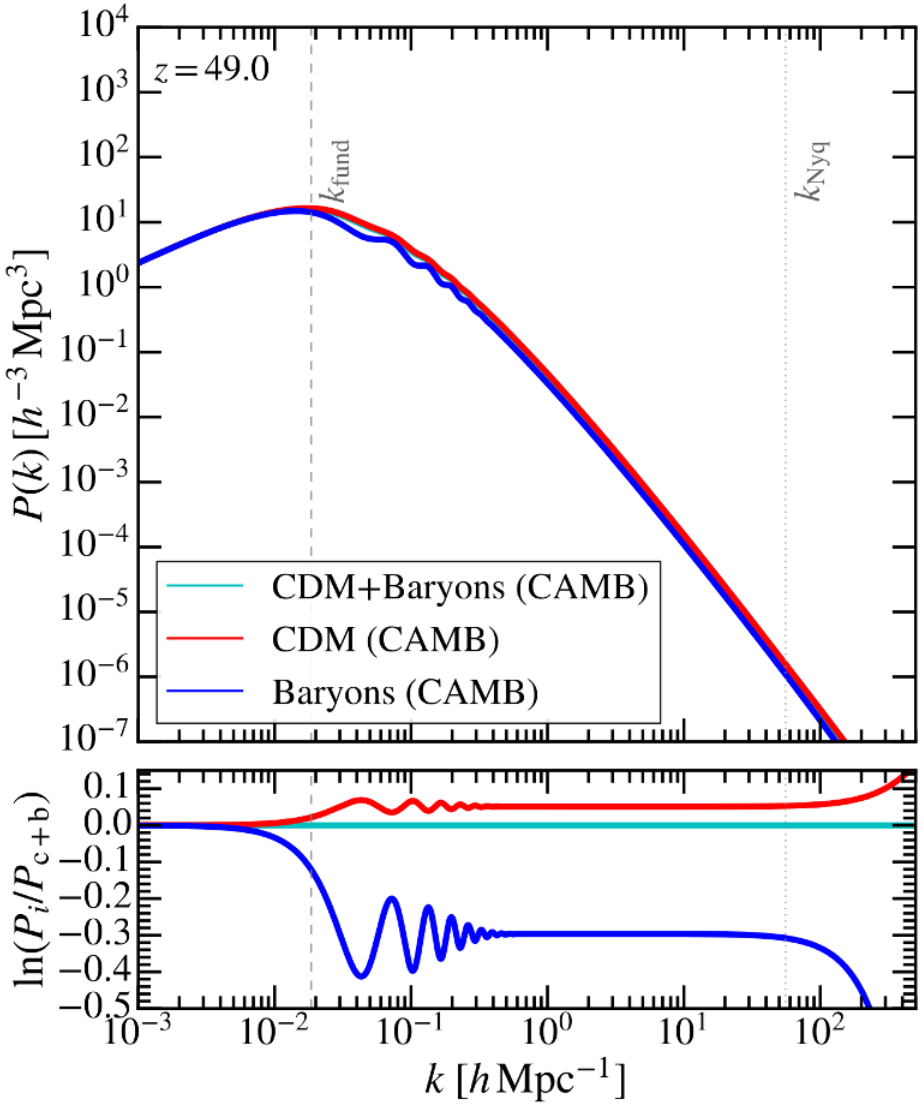
- Equilibrium cooling on EOS
- Transparent EOS
- Non-equilibrium chemistry outside of EOS
- Introduce escape fraction for stars (18%)



See Bulichi, Zier et al. 2025

Teodora Bulichi (MIT)

Self-consistent initial conditions



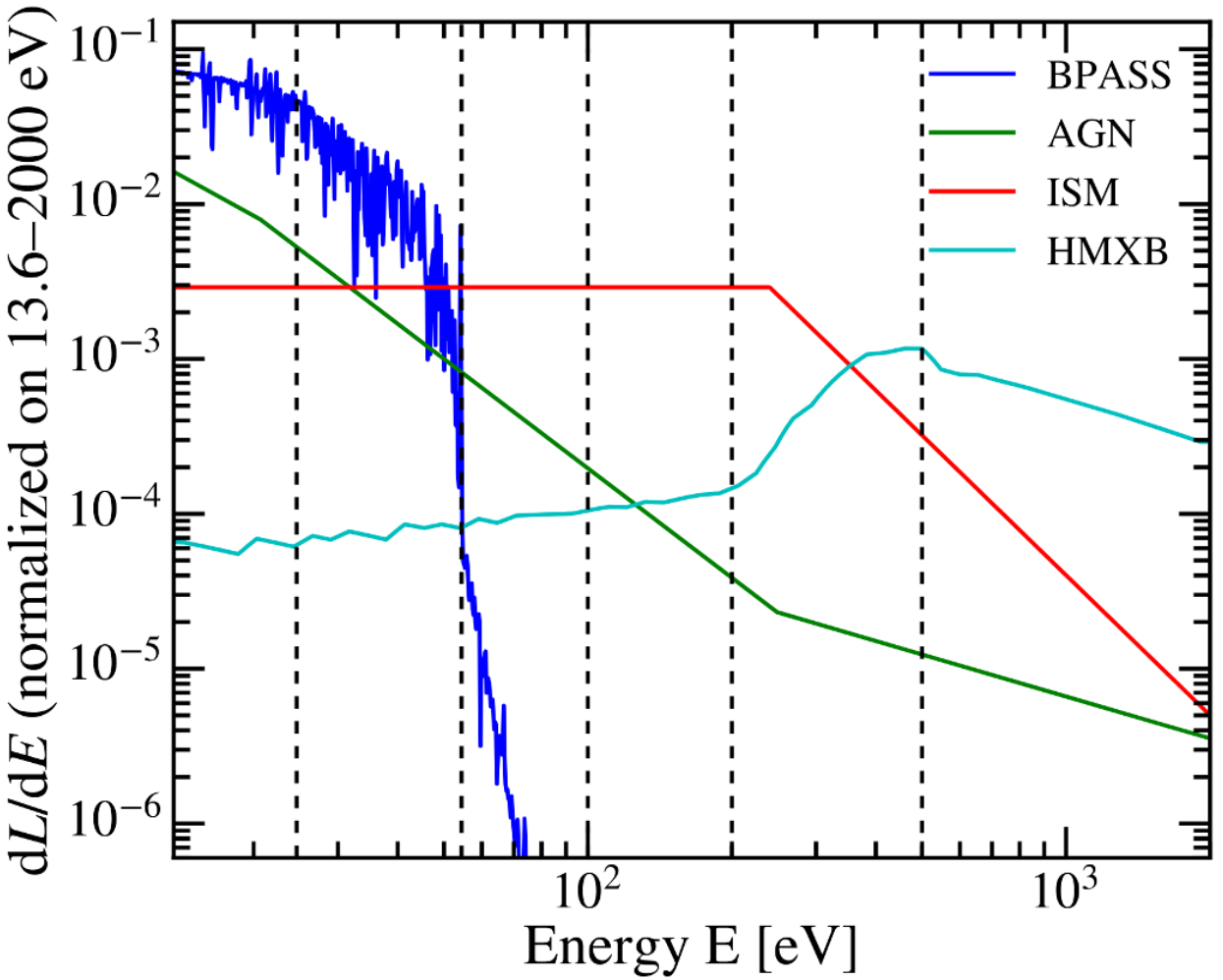
2nd order LPT for both transfer functions
2nd order LPT for relative streaming velocity
Including neutrino/radiation background in Hubble rate

Essential for early galaxy formation

Radiation sources

Stars
BPASS v2.2.1
f_{esc} = 18%

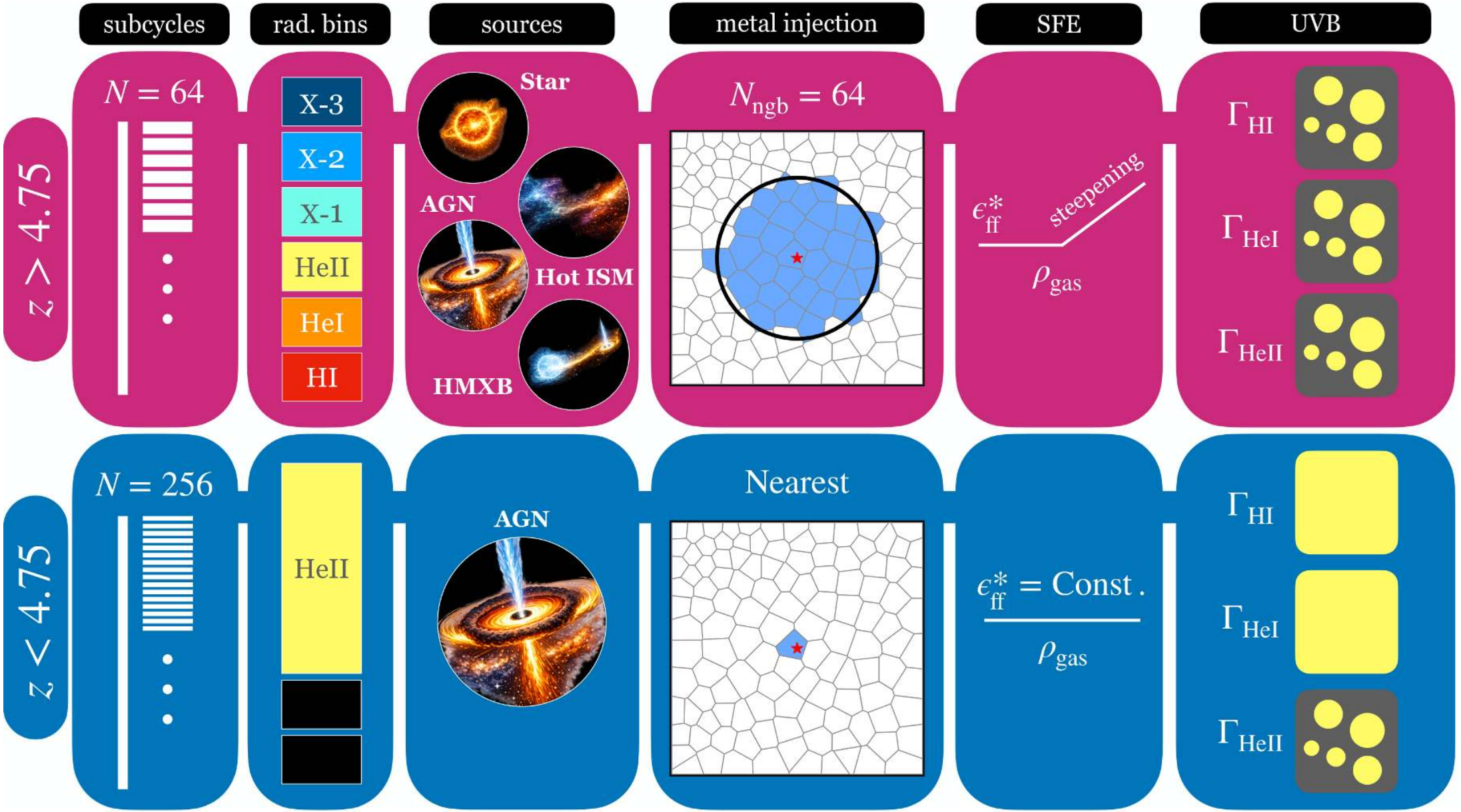
Shock heated ISM
T = 240eV



Black holes
Shen et al. (2020)
ε_{rad} = 20%

HMXB
Fragos et al. (2013)

HI -> HeII reionization



The Lumina simulation

Run	Boxsize		$N_{\rm gas}$	$N_{\rm dm}$	$m_{\rm b}$	$m_{\rm dm}$	ϵ	$\epsilon_{\rm gas,min}$	$z_{\rm final}$
	(h^{-1} cMpc)	(cMpc)			($M_\odot$)	($M_\odot$)	[ckpc]	[ckpc]	
LUMINA	338.3	500	6000^3	6000^3	3.6×10^6	1.9×10^7	1.77	0.44	3
DM-3000	338.3	500	0	3000^3	–	1.8×10^8	1.77	–	0
DM-1500	338.3	500	0	1500^3	–	1.4×10^9	1.77	–	0
Reference simulations									
THESAN-1	64.7	95.5	2100^3	2100^3	5.8×10^5	3.1×10^6	2.2	2.2	5.5
THESAN-2	64.7	95.5	1050^3	1050^3	4.7×10^6	2.5×10^7	4.4	4.4	5.5
TNG100	75	110	1820^3	1820^3	1.4×10^6	7.5×10^6	0.74	0.19	0
MTNG	500	740	4320^3	4320^3	3.1×10^7	1.7×10^8	3.7	0.37	0

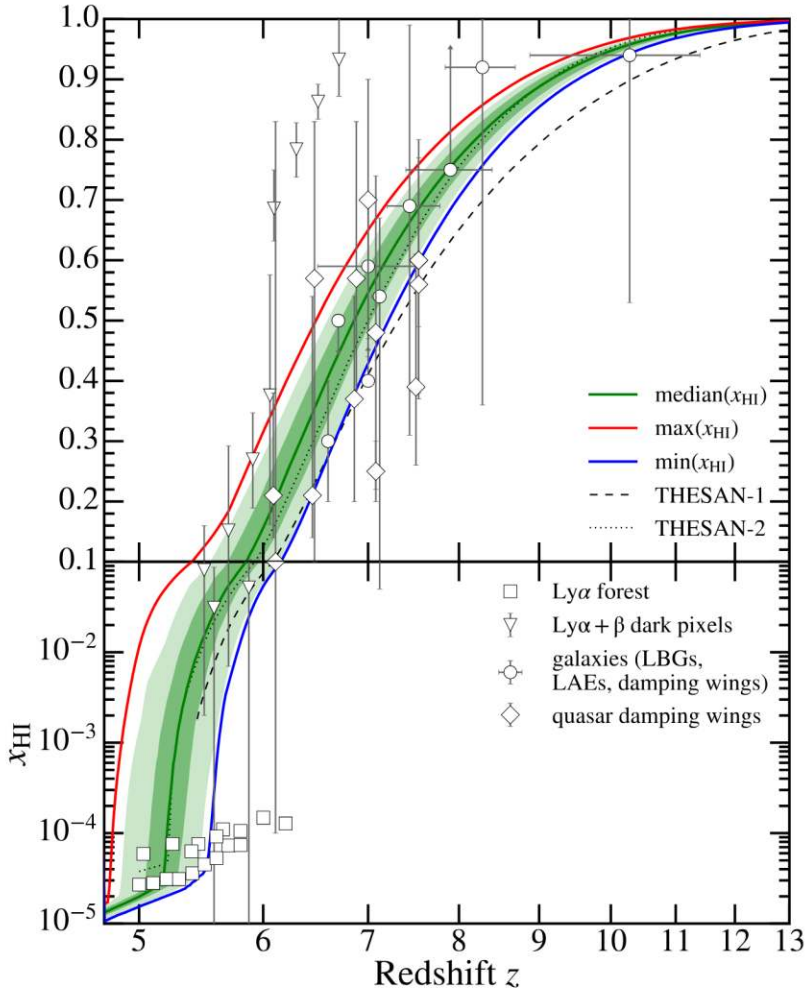
Technical details

- 105,504 CPU cores
- 15,072 GPU accelerators
- 1035h Wall clock time
- 109 x 10^6 CPU hours
- 140PB restart files

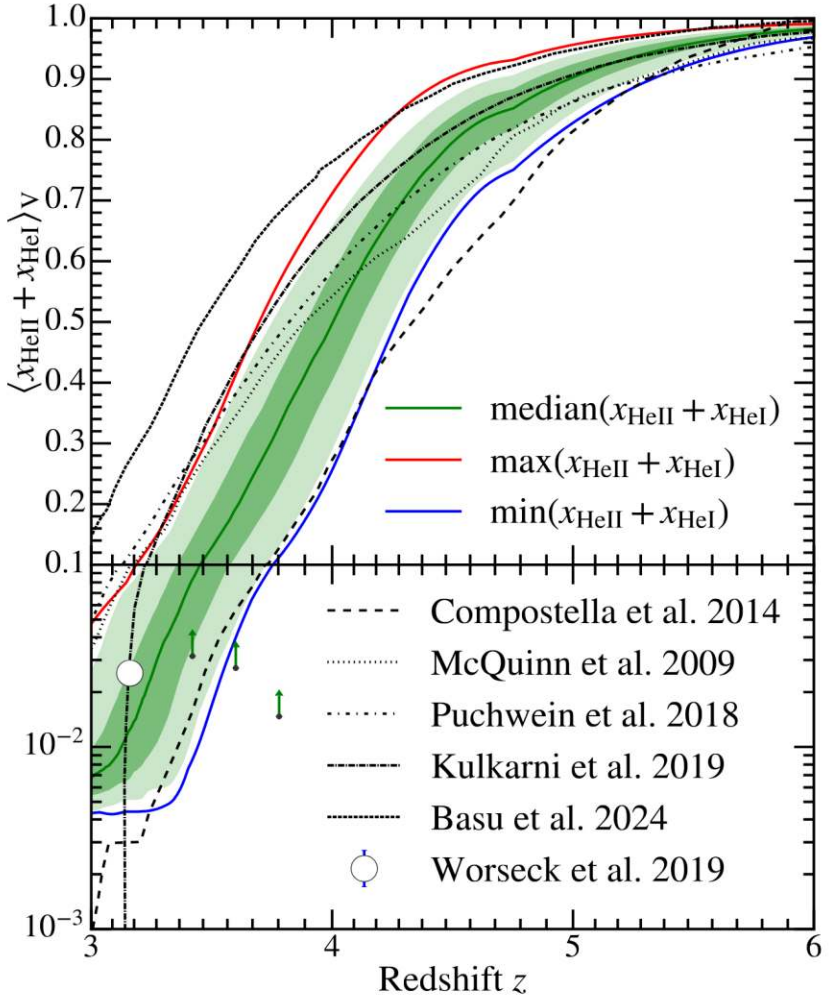


Frontier @ OLCF

Reionisation history



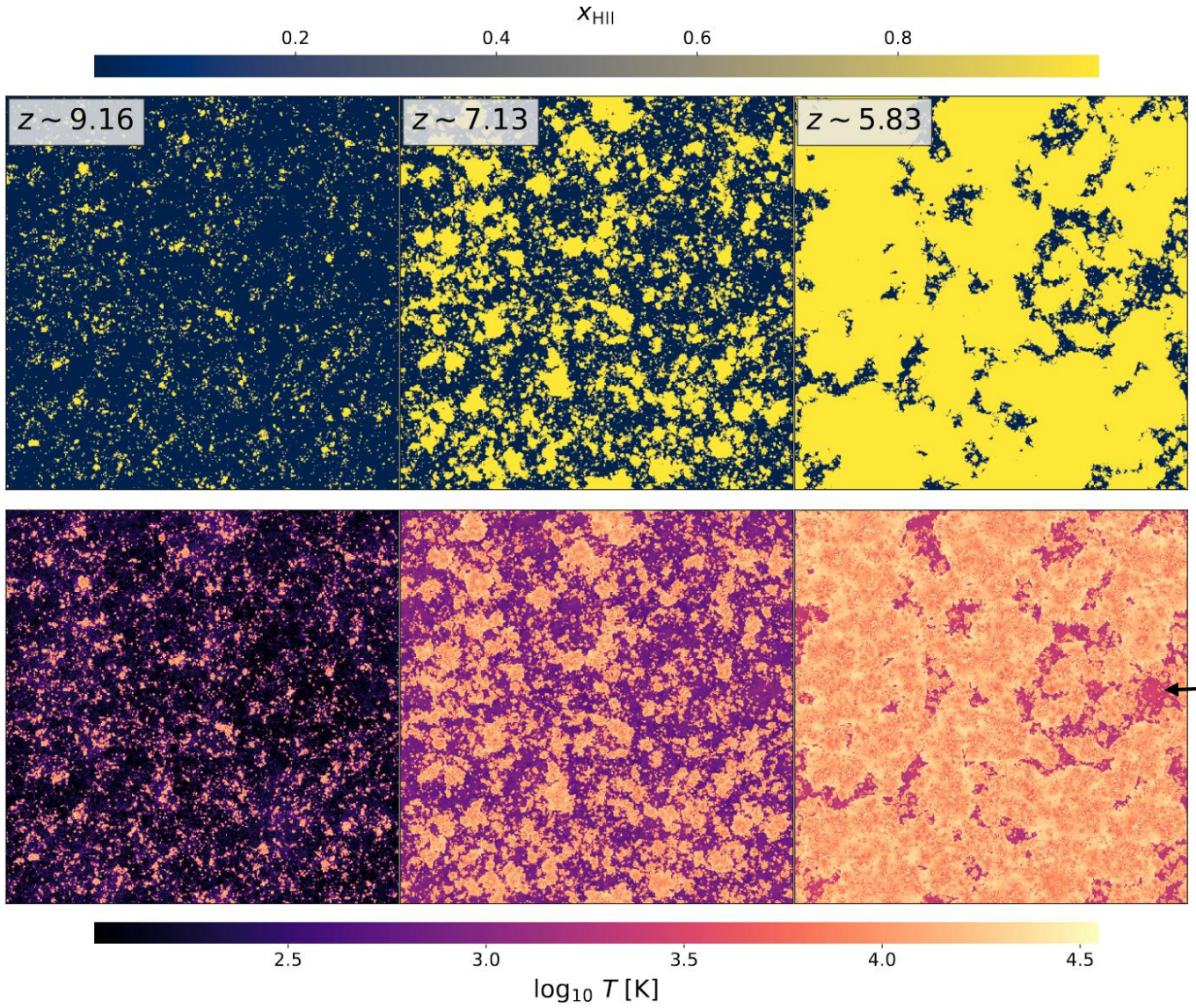
Split into 125 subboxes with L = 100cMpc



Calibrated with f_{esc}

No calibration!

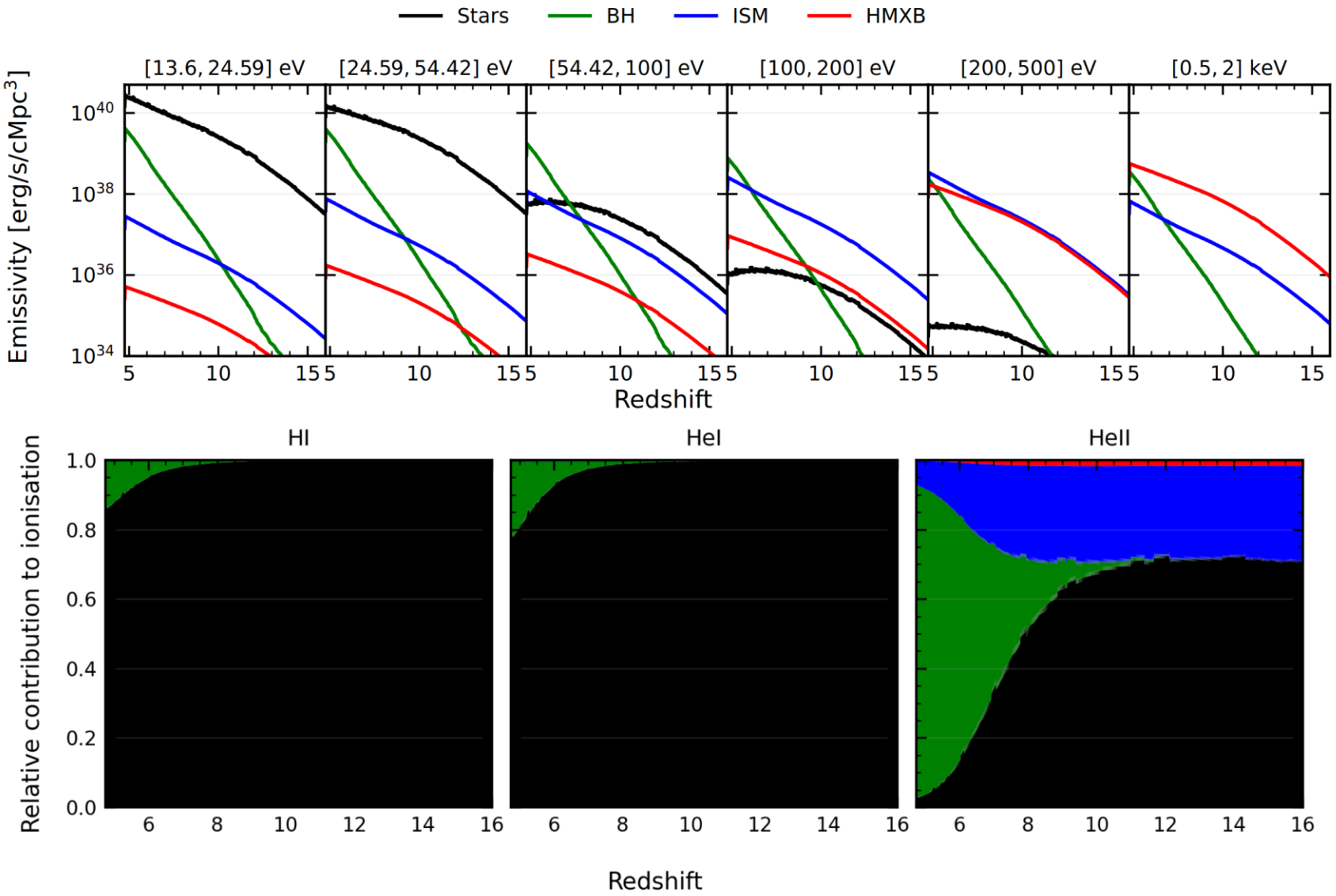
Hydrogen reionisation



Driven by small, overlapping bubbles

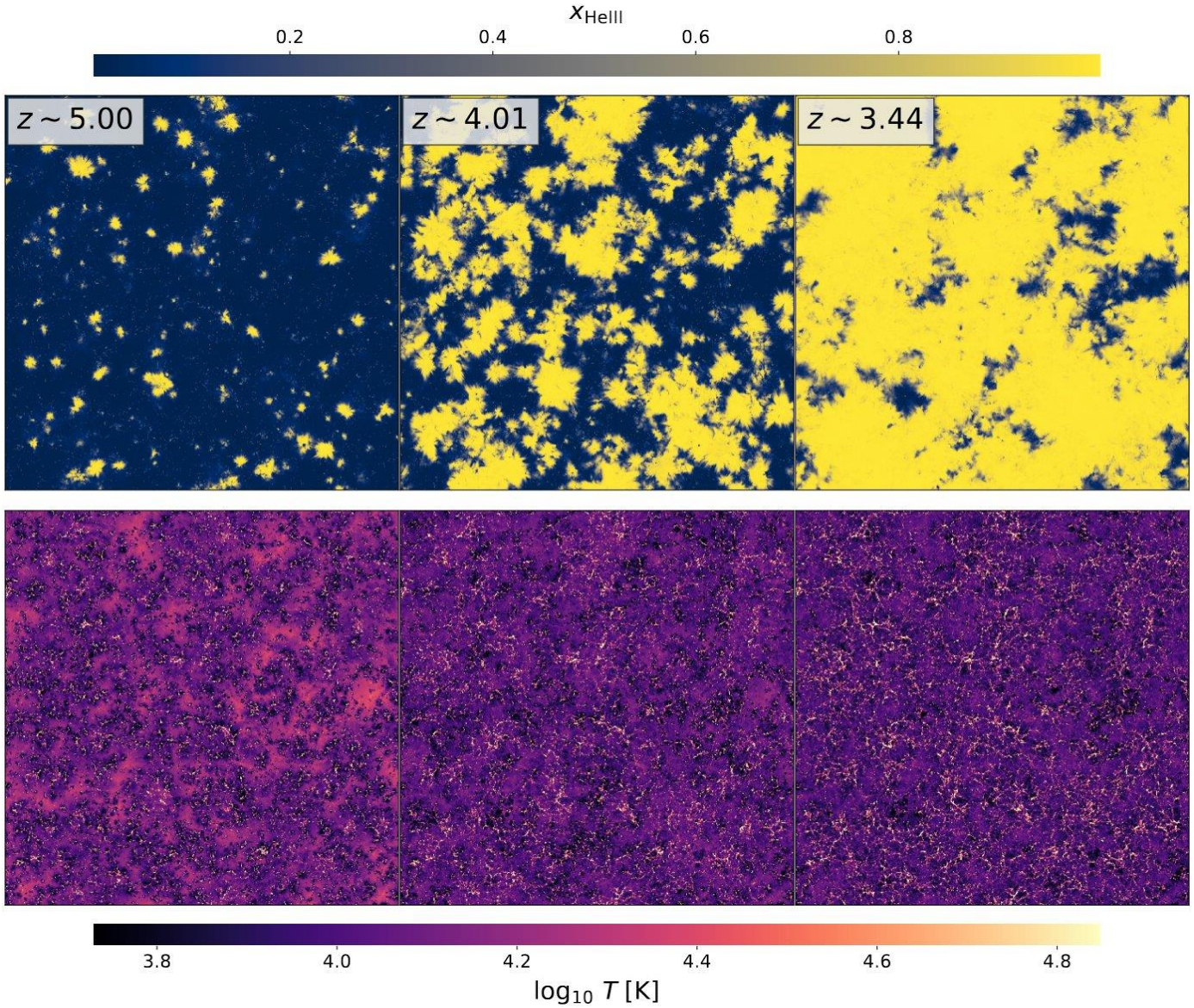
Preheating of IGM by X-rays

Driver of HI reionisation



Stars drive HI + HeI reionisation
AGN drive HeII reionisation (z < 7)
ISM + HMXB dominate Xrays

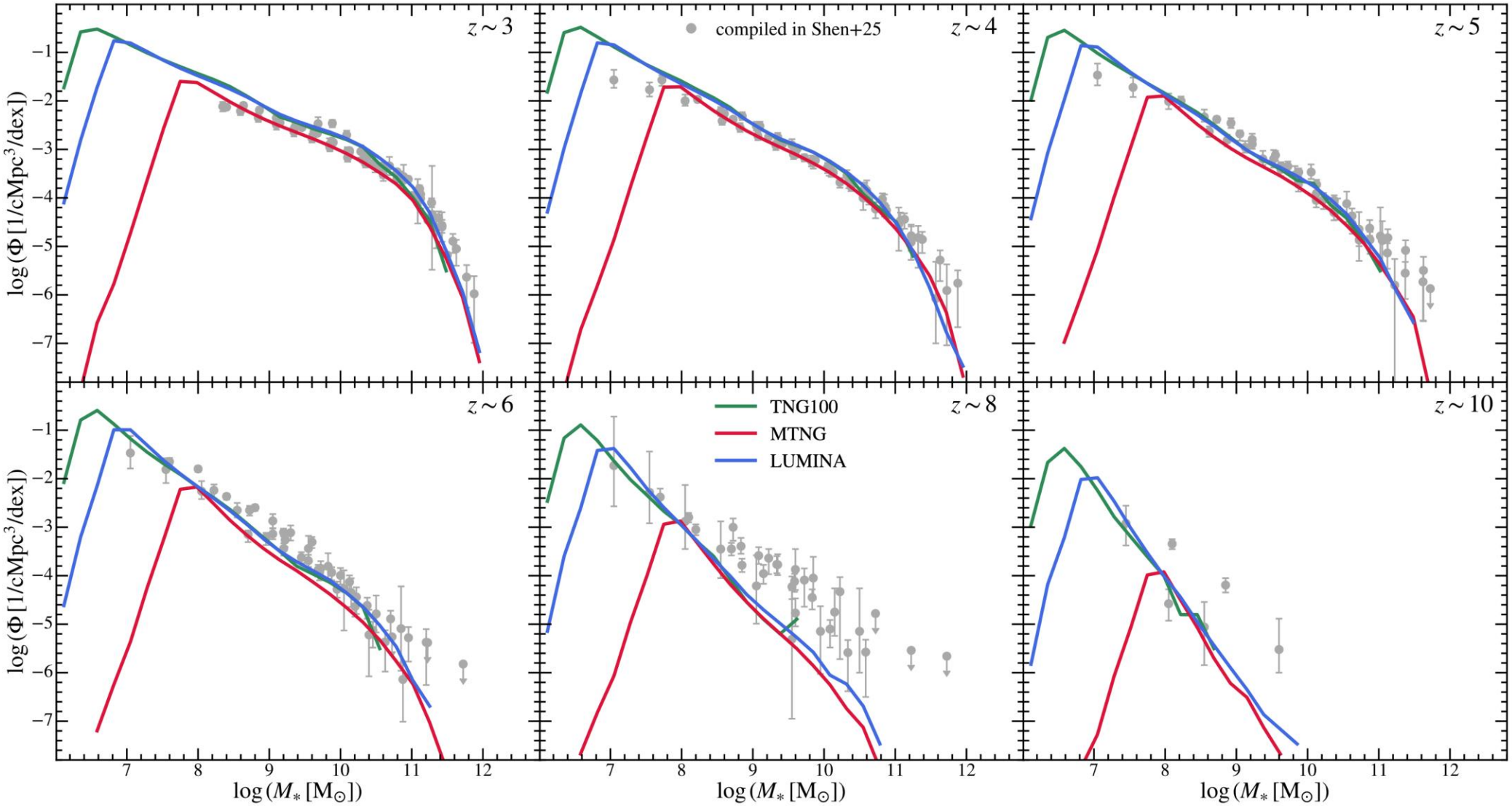
HeII reionisation



Driven by large bubbles

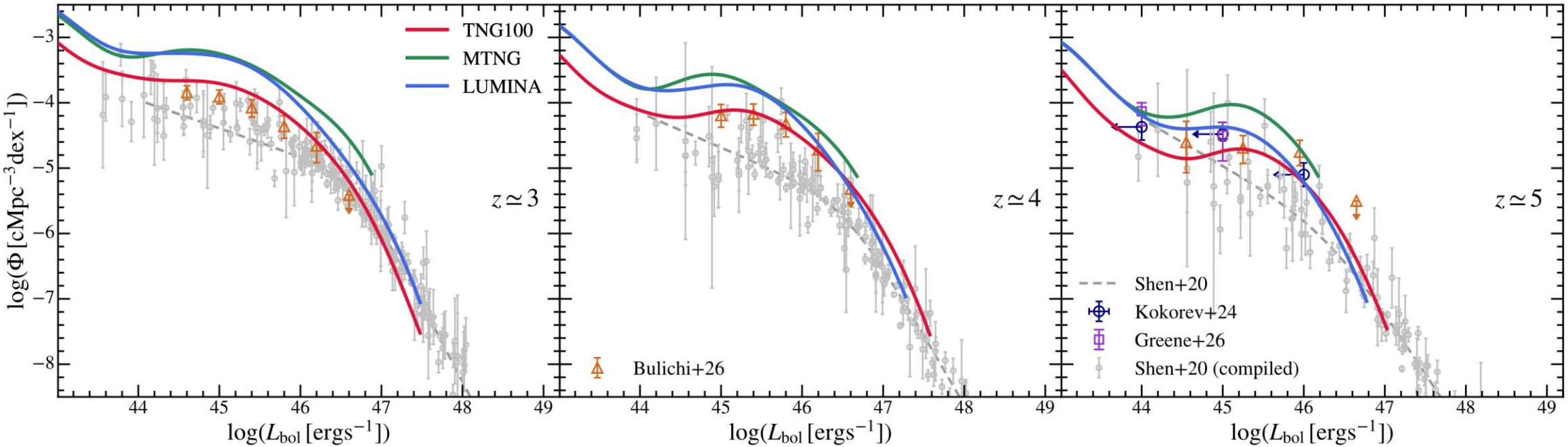
Competition: adiabatic cooling + HeII photoheating

Stellar mass function



Perfect agreement with TNG galaxies

AGN luminosity function



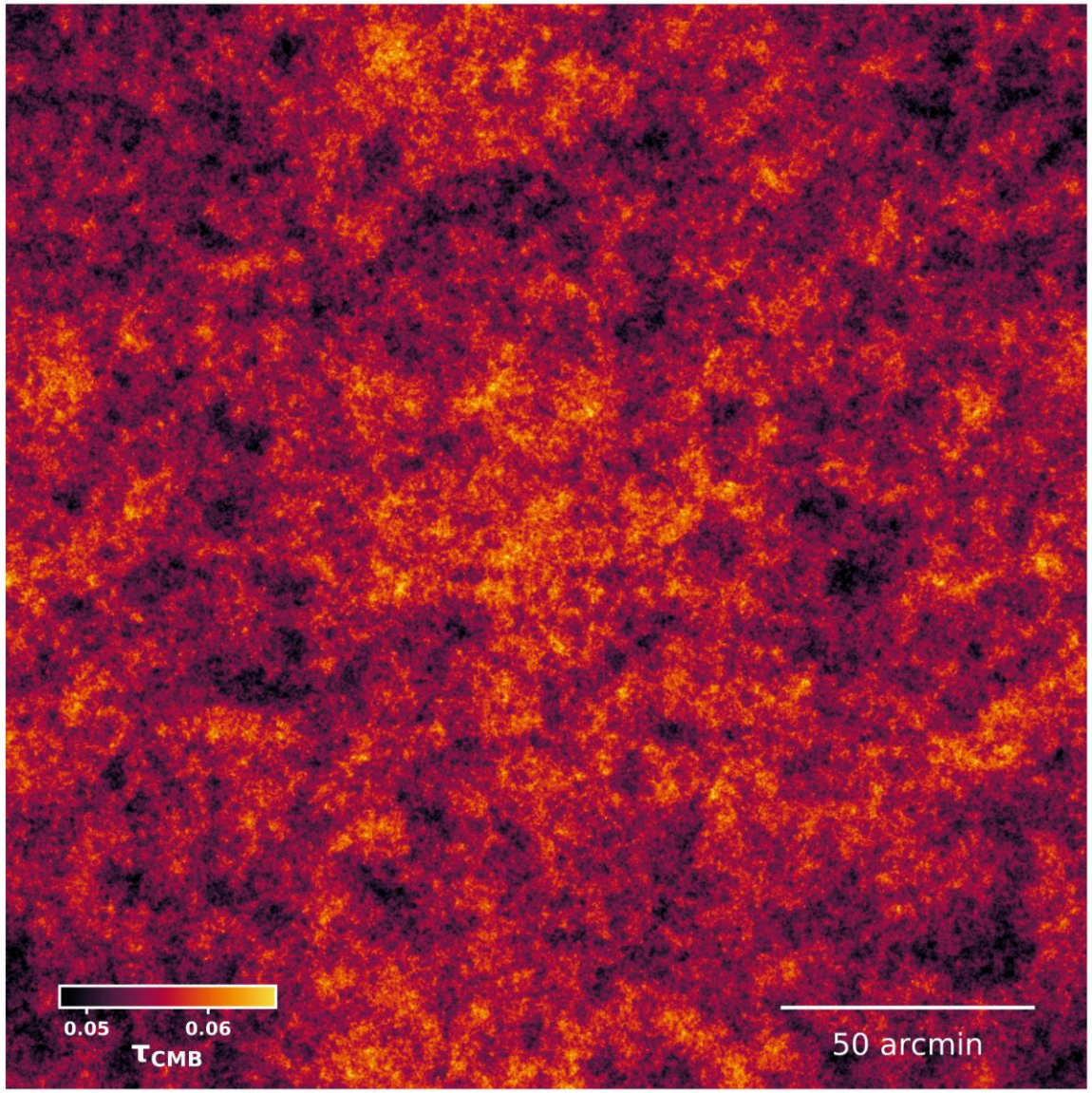


Jacob Shen (CfA)

Realistic sources for HeII reionisation

1,979,361 SMBH at z = 3

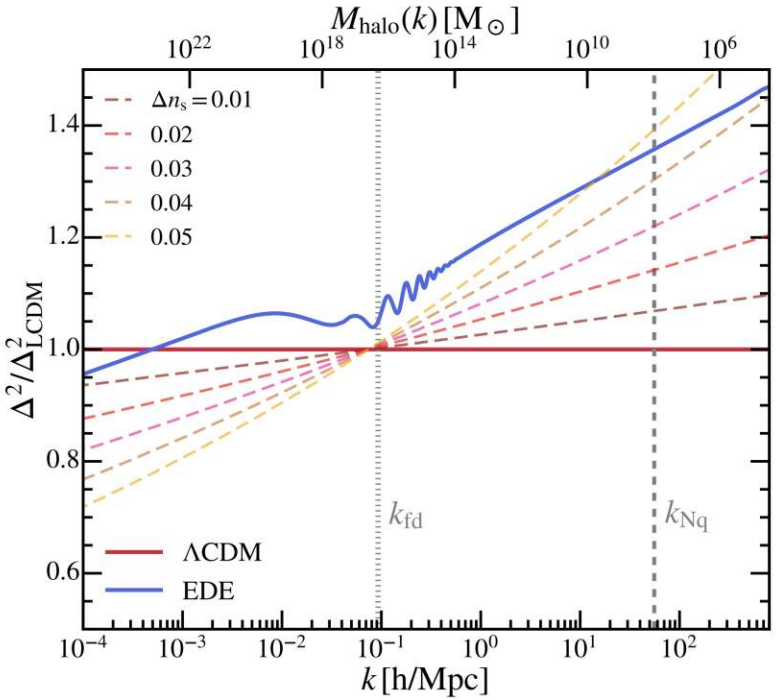
Variance of optical depth



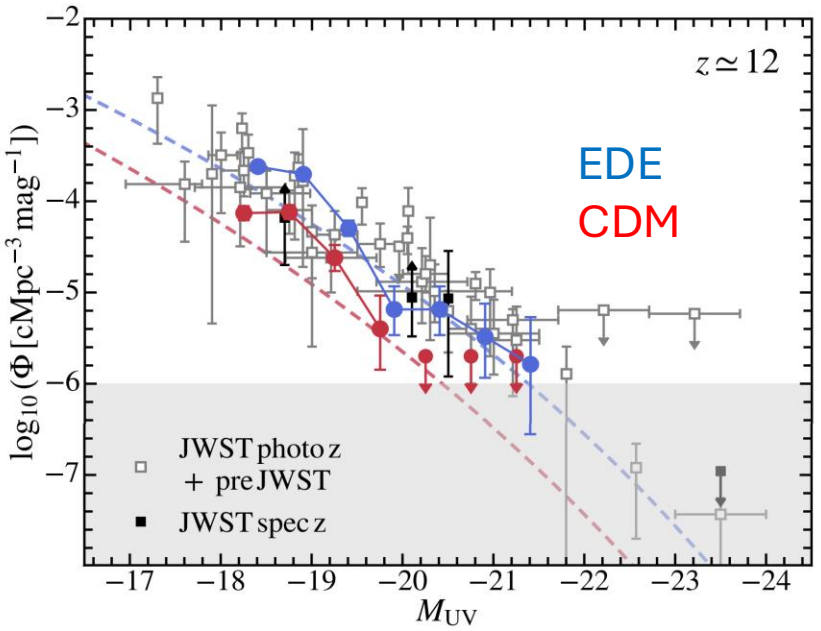


Aaron Smith
(UT Dallas)

Early dark energy



Model	ΛCDM	EDE
$f_{\rm EDE}(z_{\rm c})$	-	$0.179^{+0.047}_{-0.04}$
$\log_{10}(z_{\rm c})$	-	$3.528^{+0.028}_{-0.024}$
$\theta_{\rm i}$	-	$2.806^{+0.098}_{-0.093}$
$m\ (10^{-28}{\rm eV})$	-	4.38 ± 0.49
f (Mpl)	-	0.213 ± 0.035
$H_0\ [{\rm km\,s^{-1}\,Mpc^{-1}}]$	$67.81^{+0.64}_{-0.6}$	$74.83^{+1.9}_{-2.1}$
$100\omega_{\rm b}$	$2.249^{+0.014}_{-0.013}$	$2.278^{+0.018}_{-0.02}$
$\omega_{\rm cdm}$	$0.1191^{+0.0014}_{-0.0015}$	$0.1372^{+0.0053}_{-0.0059}$
$10^9 A_{\rm s}$	$2.092^{+0.035}_{-0.033}$	$2.146^{+0.041}_{-0.04}$
$n_{\rm s}$	$0.9747^{+0.0046}_{-0.0047}$	$1.003^{+0.0091}_{-0.0096}$
S_8	0.821 ± 0.017	$0.829^{+0.017}_{-0.019}$
$\Omega_{\rm m}$	$0.309^{+0.009}_{-0.008}$	0.287 ± 0.009

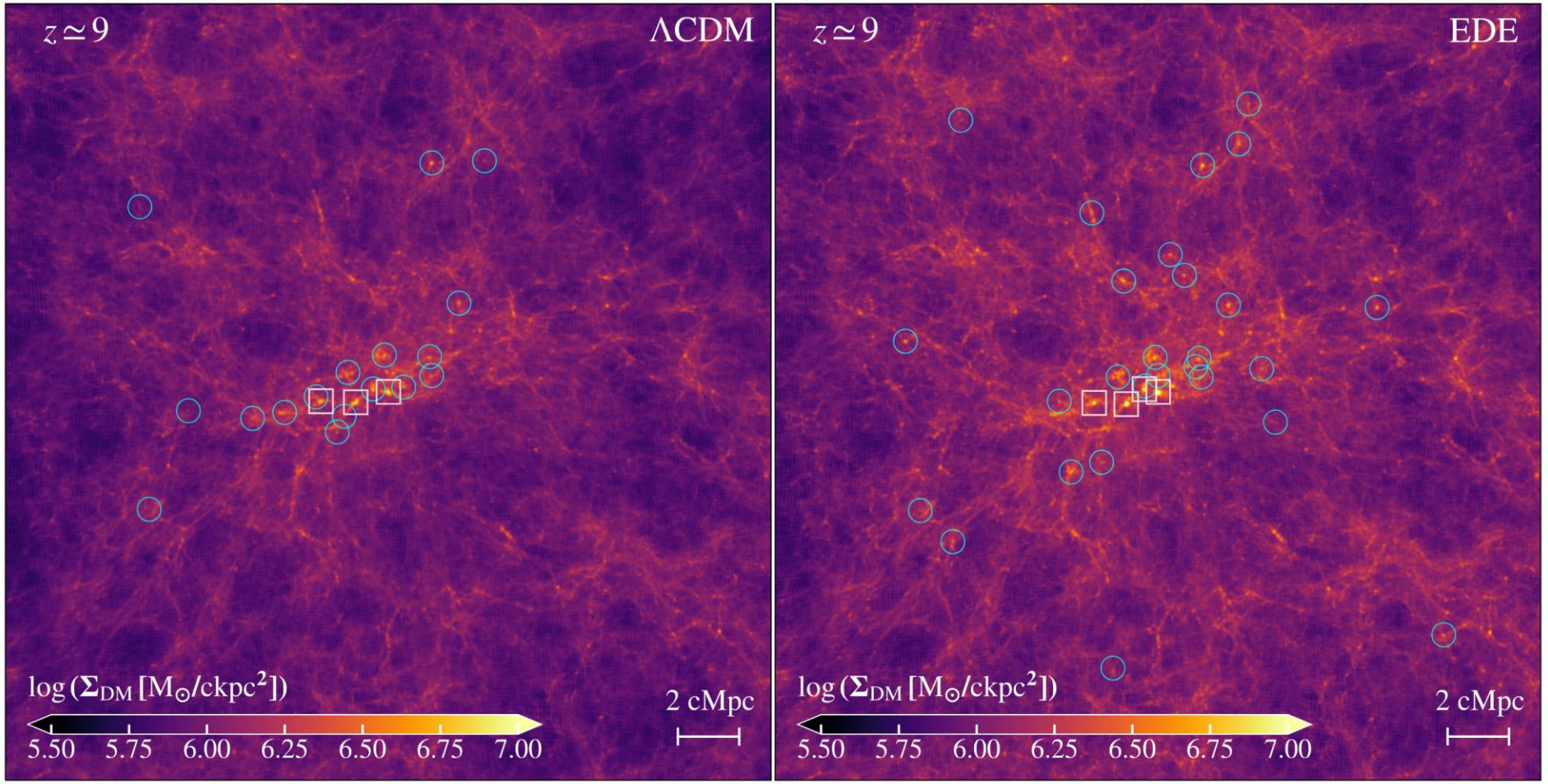


Originally motivated to solve Hubble tension

Increase small scale power spectra => earlier high z galaxy formation

See Shen, Zier et al. (2026)

Outlook: LUMINA-EDE



Solves Hubble tension
Early galaxy formation?

LUMINA with EDE, Goals:

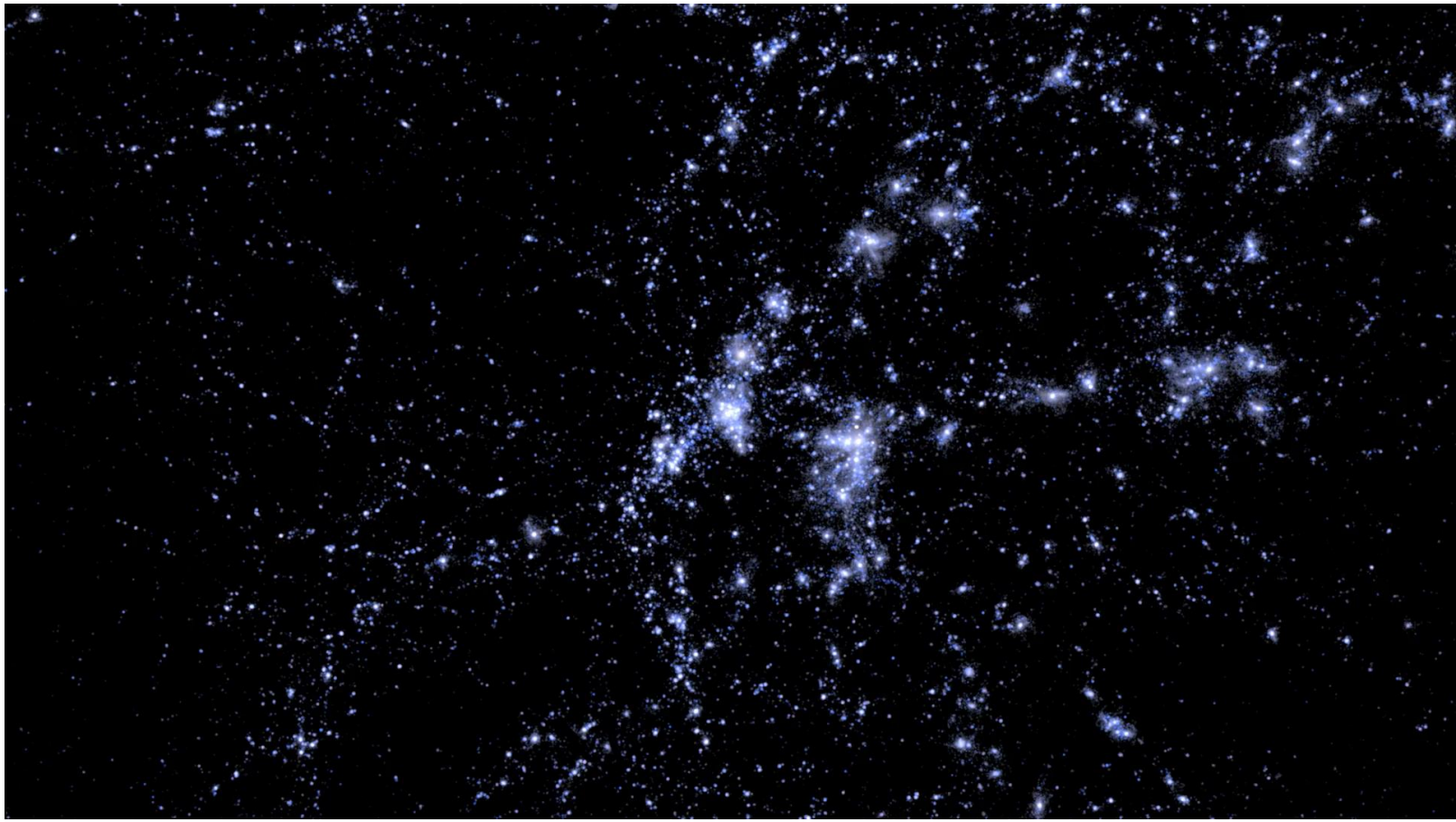
- Galaxy clustering
- Quasar clustering
- Topology of reionisation

See also Shen, Zier et al. (2026)

Start April 2026

Summary

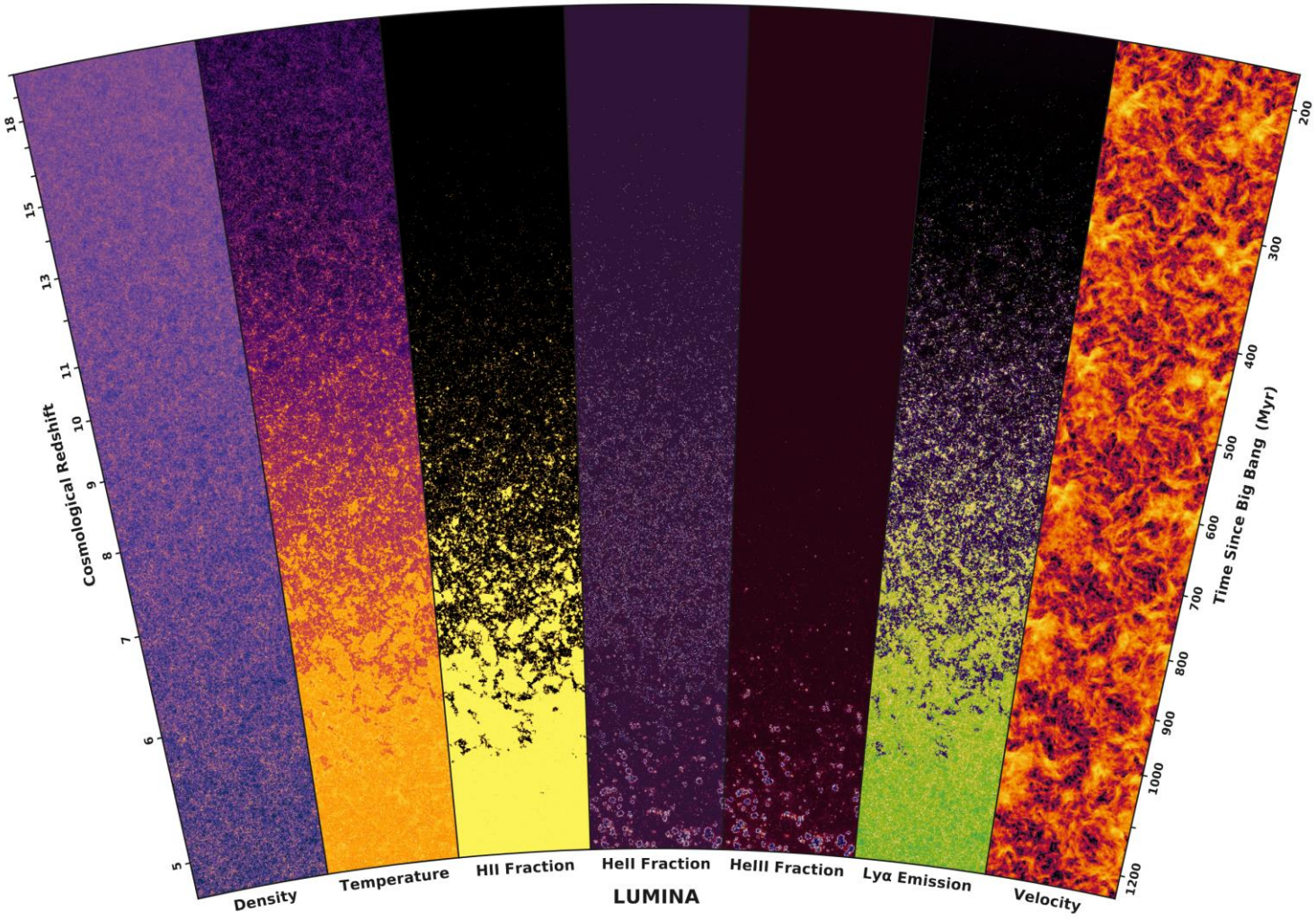
- Lumina model: TNG + GPU accelerated RT
- Self consistent HI + HeII reionisation
- Improved initial conditions
- To z = 3
- Equivalent early dark energy run available



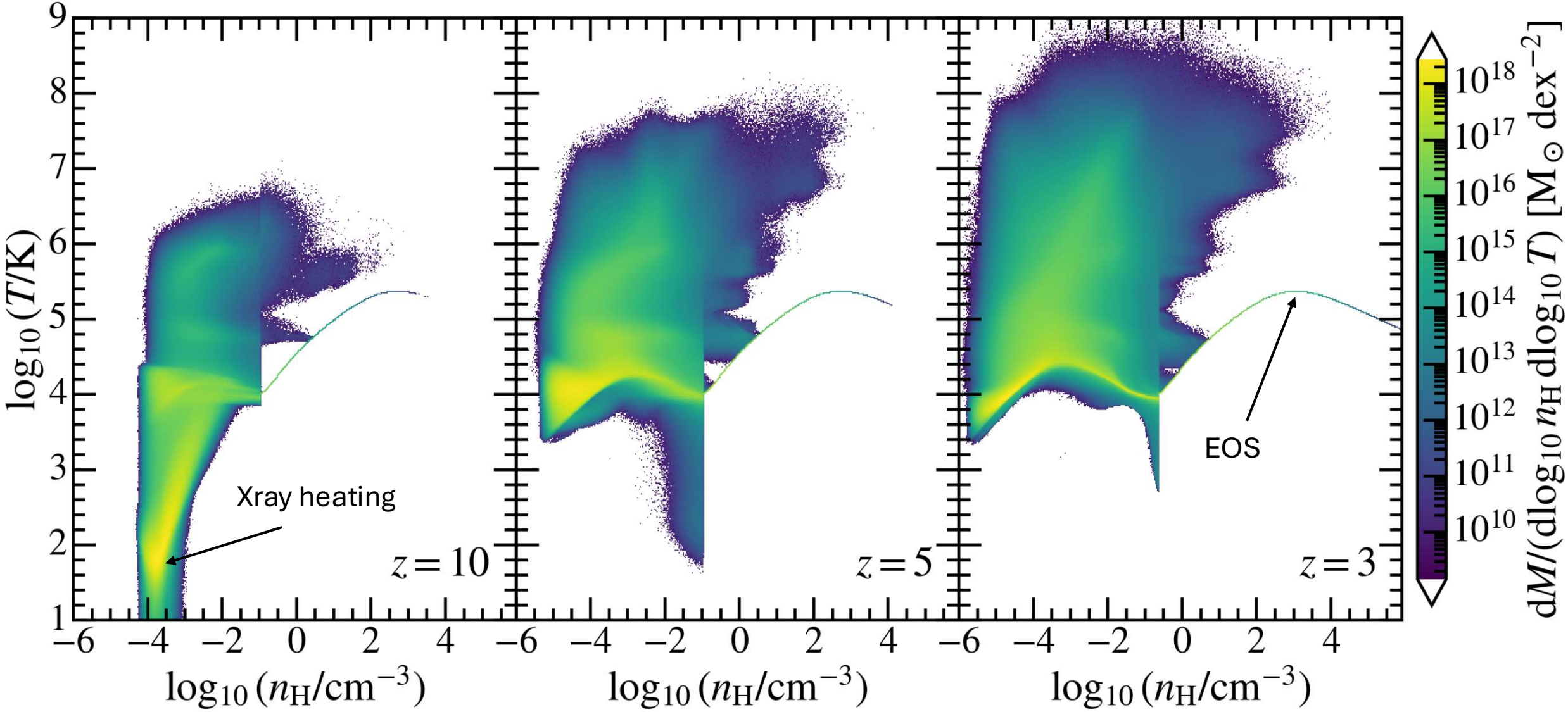
Backup

Data products (1PB)

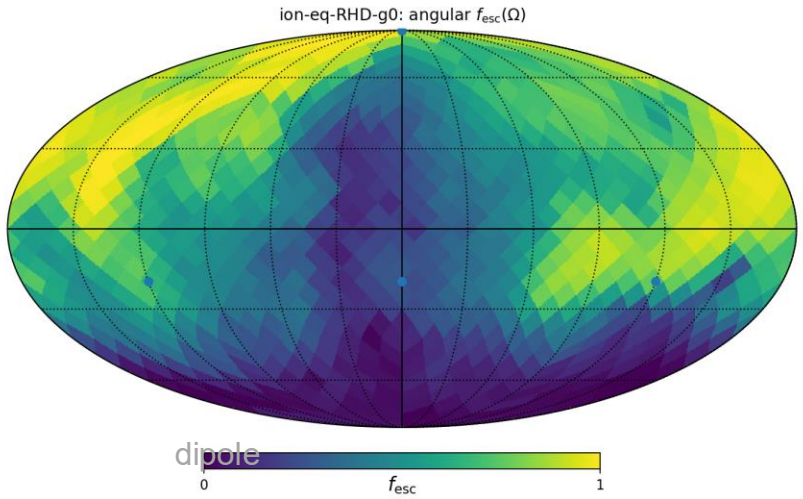
- Full snapshots (33)
- Group catalogues (158)
- 3d uniform grid (IGM, every 2 million years
- Continuous light cone
- High-Frequency BH output (2x10^6 SMBH at z =3)
- BH merger tree



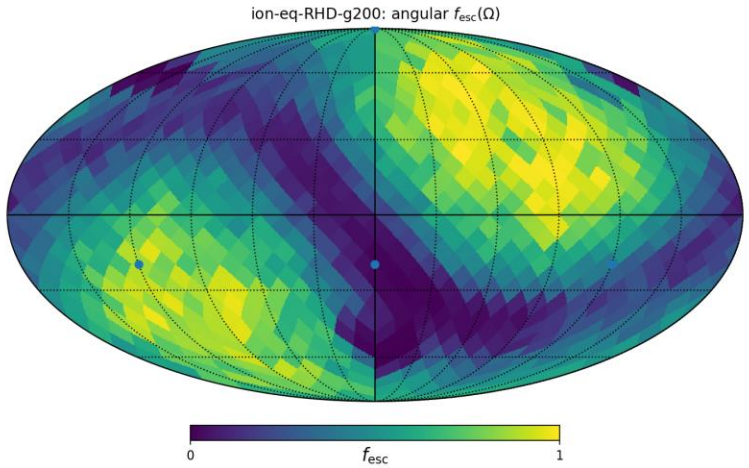
Gas structure



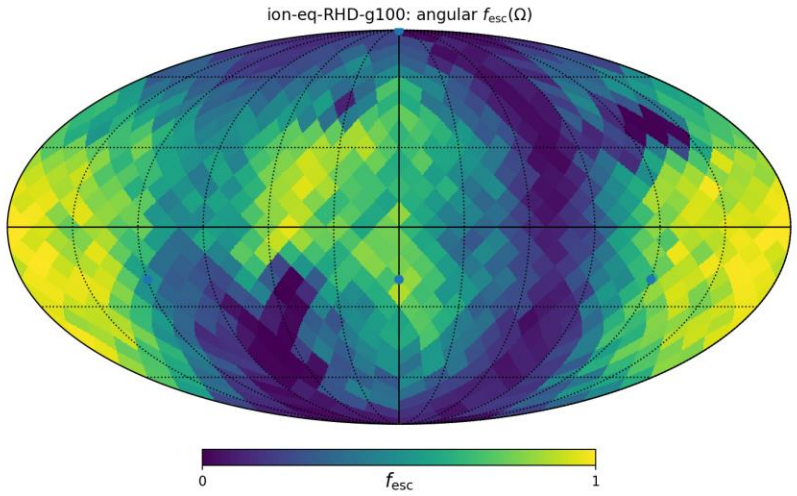
Anisotropy of LyC Escape in Lumina



dipole



quadrupole



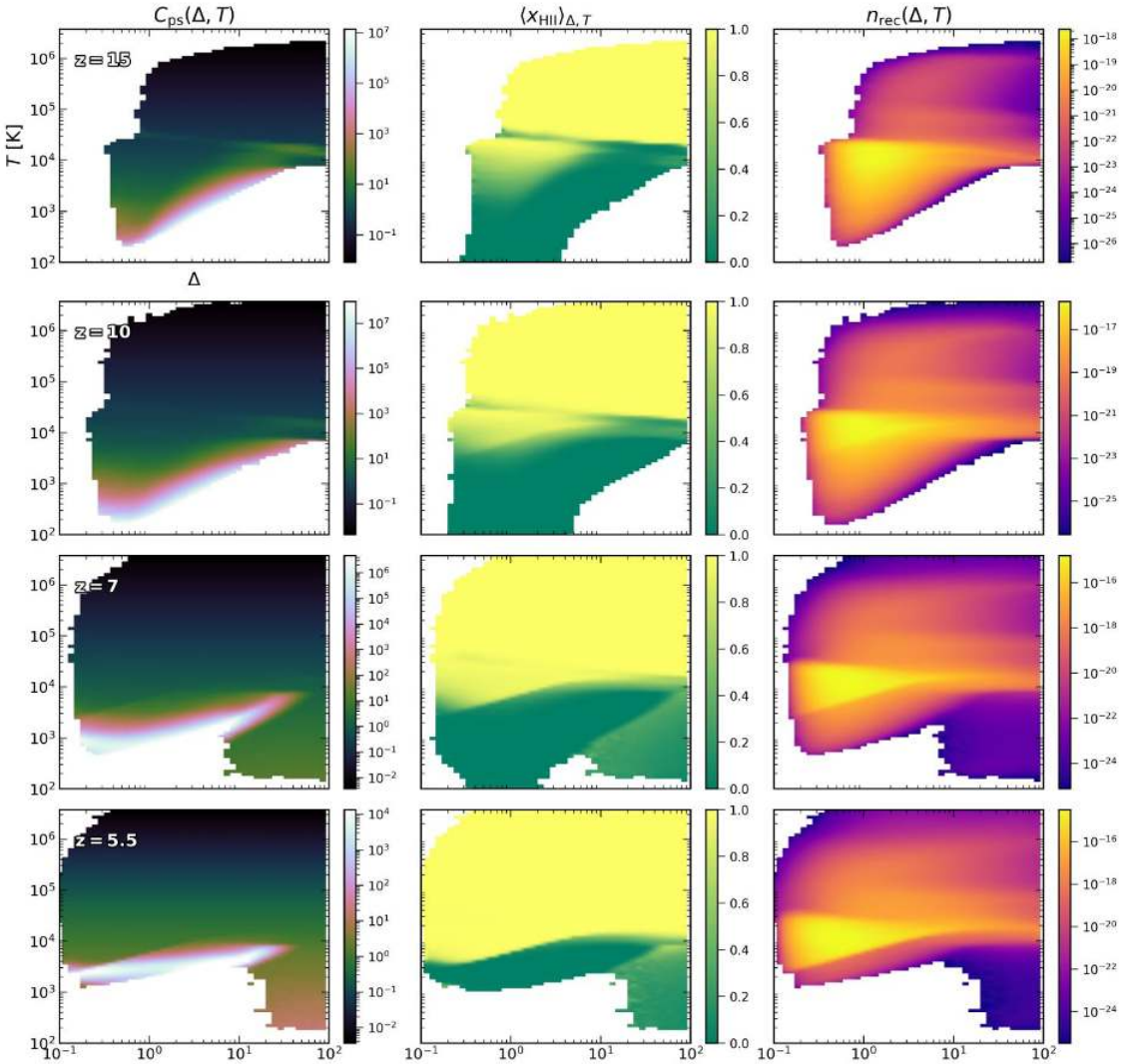
patchy

Postprocessed with COLT

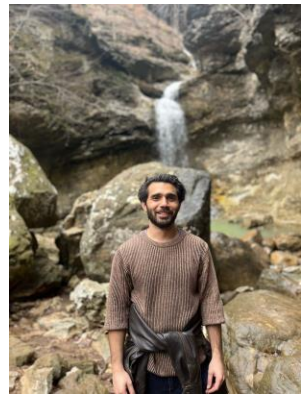


Yuan Bian
(UT Dallas)

Intergalactic clumping

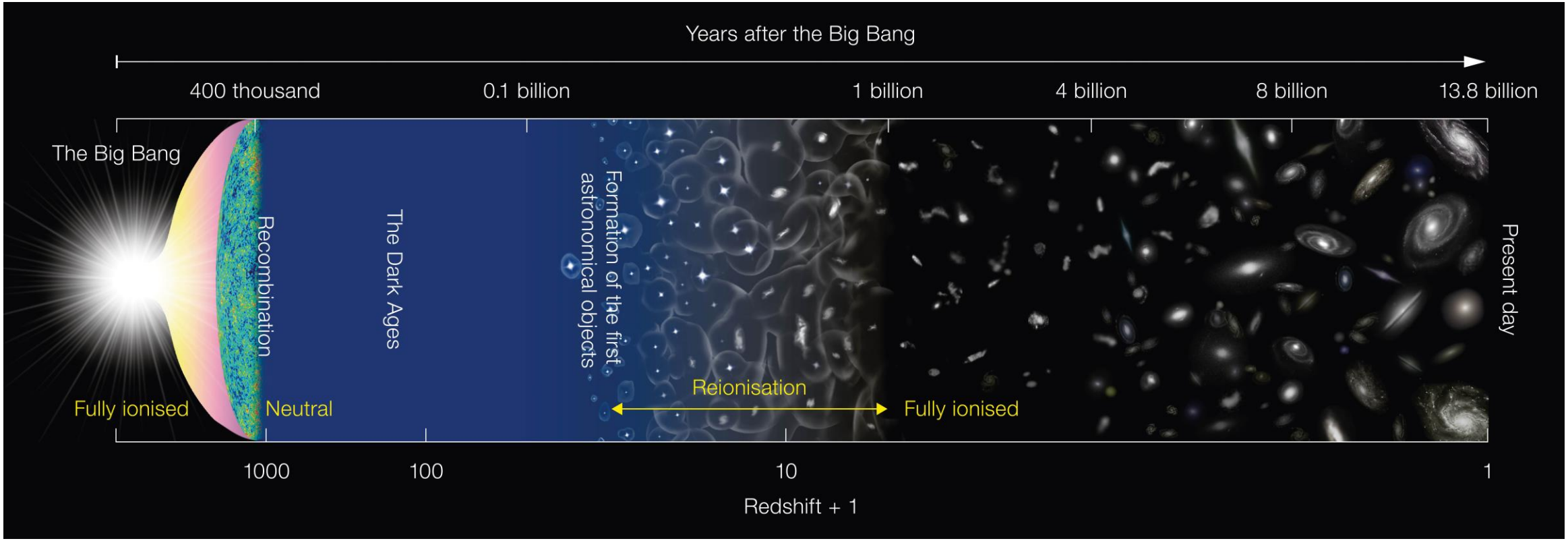


Clumping factor
Ionisation fraction
Recombination rate

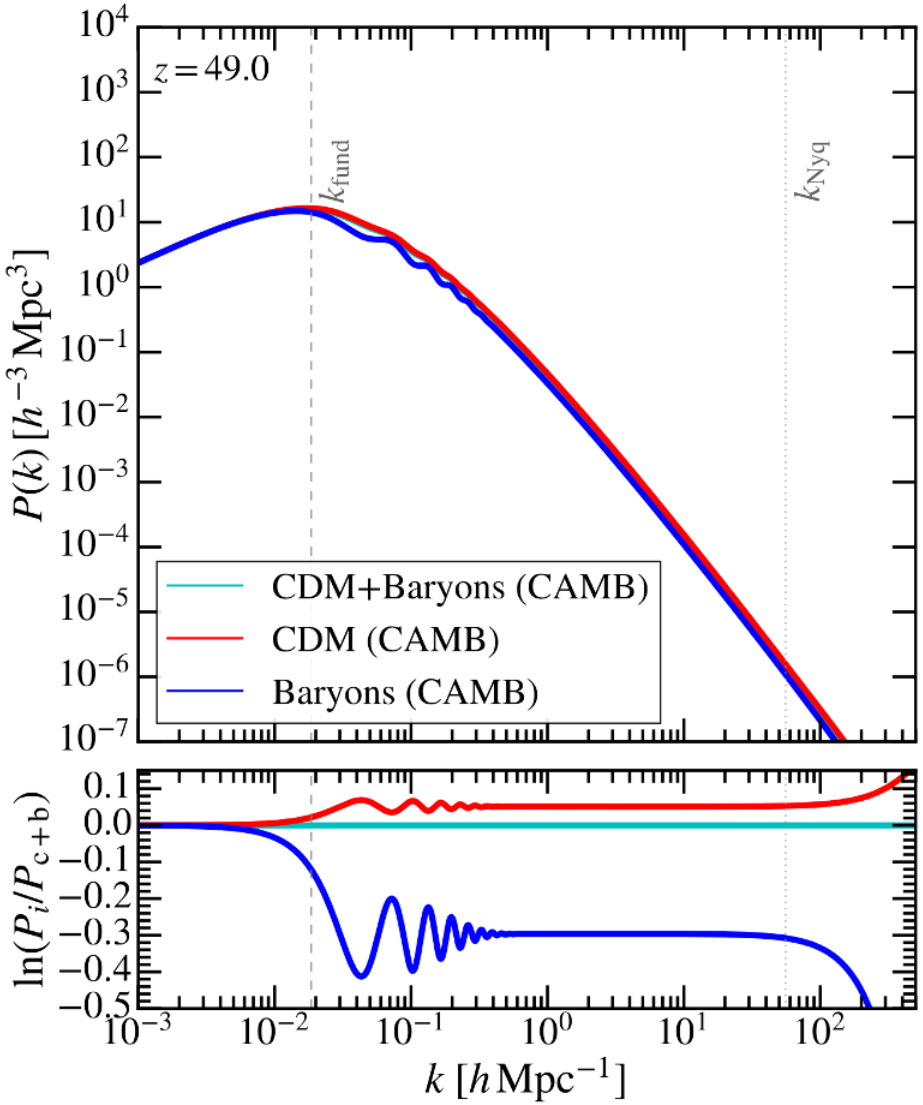


Ali Sadain
(UT Dallas)

The evolution of the Universe



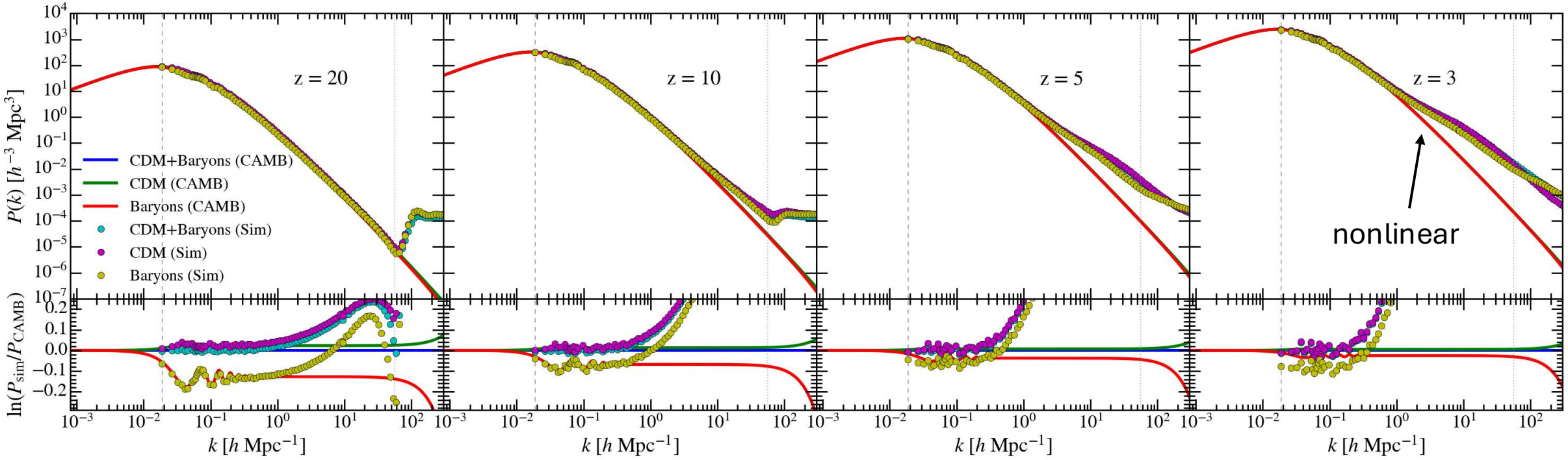
Self-consistent initial conditions



2nd order LPT for both transfer functions
2nd order LPT for relative streaming velocity
Including neutrino/radiation background in Hubble rate

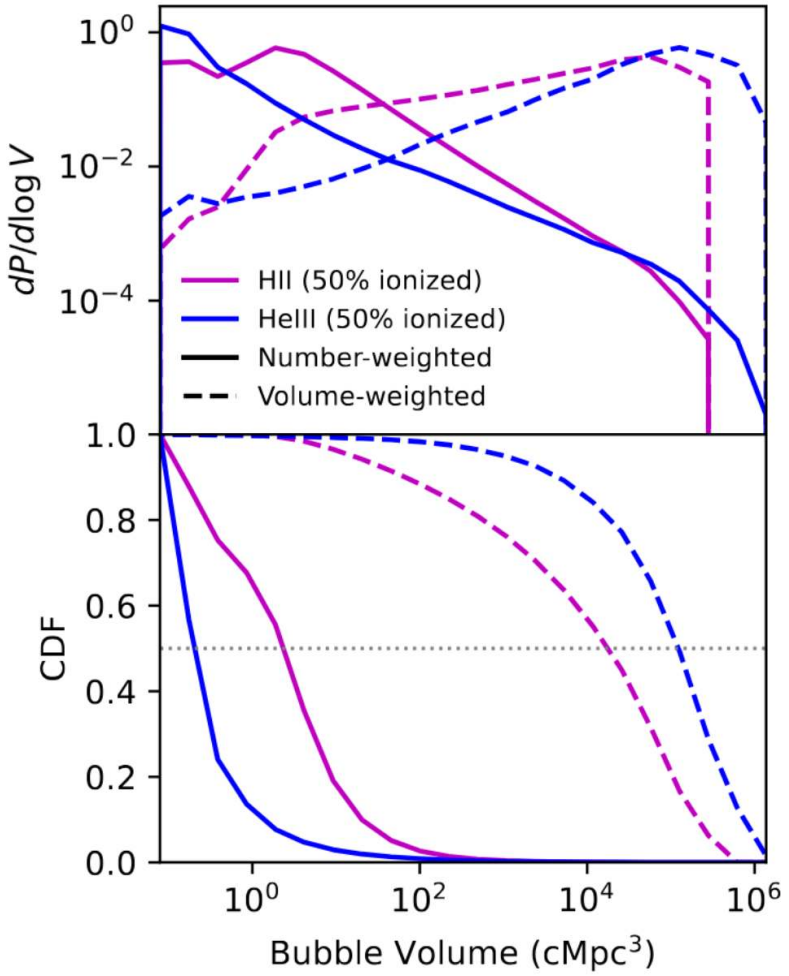
Essential for early galaxy formation

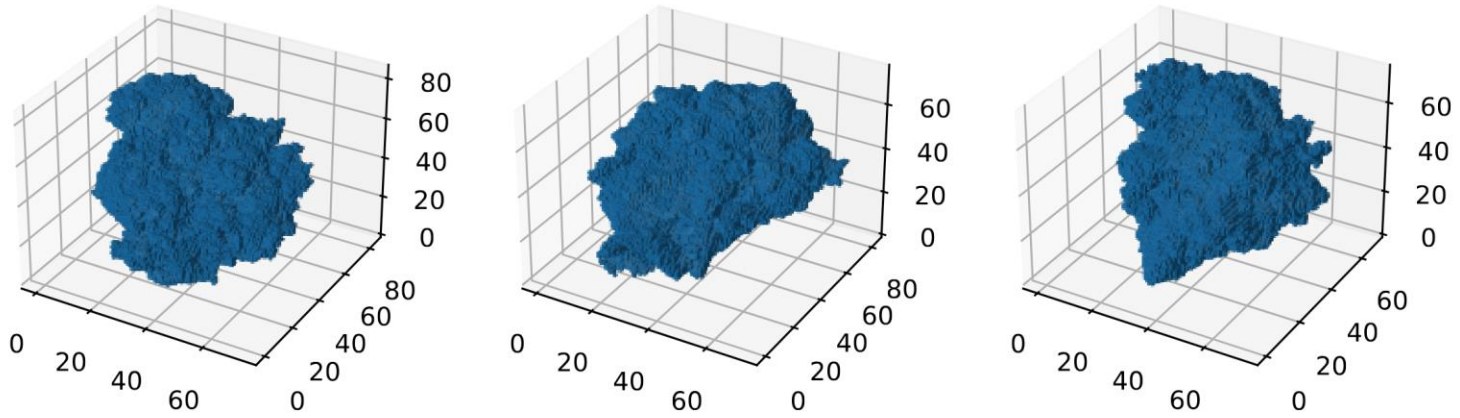
Large scale structure



Almost perfect agreement
with linear theory

Bubble size distributions





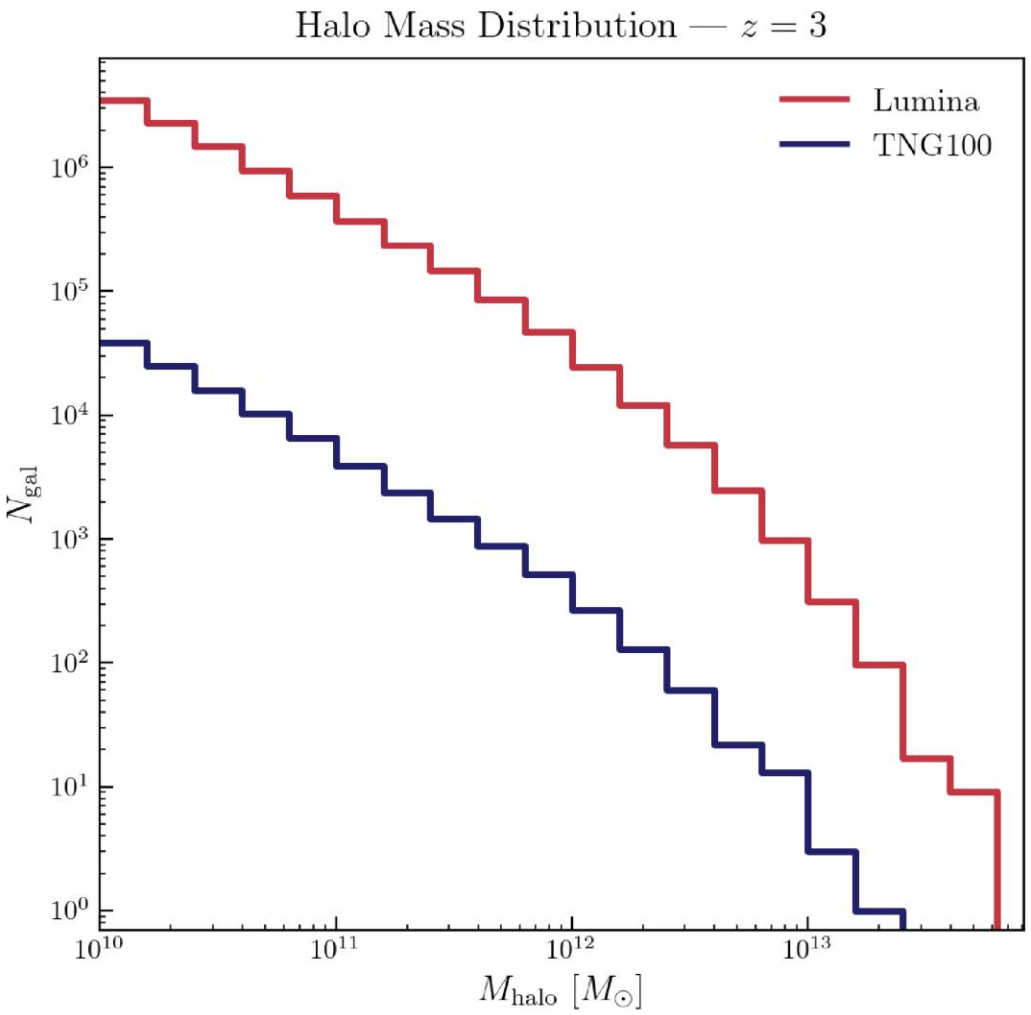
HII bubble morphology at z = 9

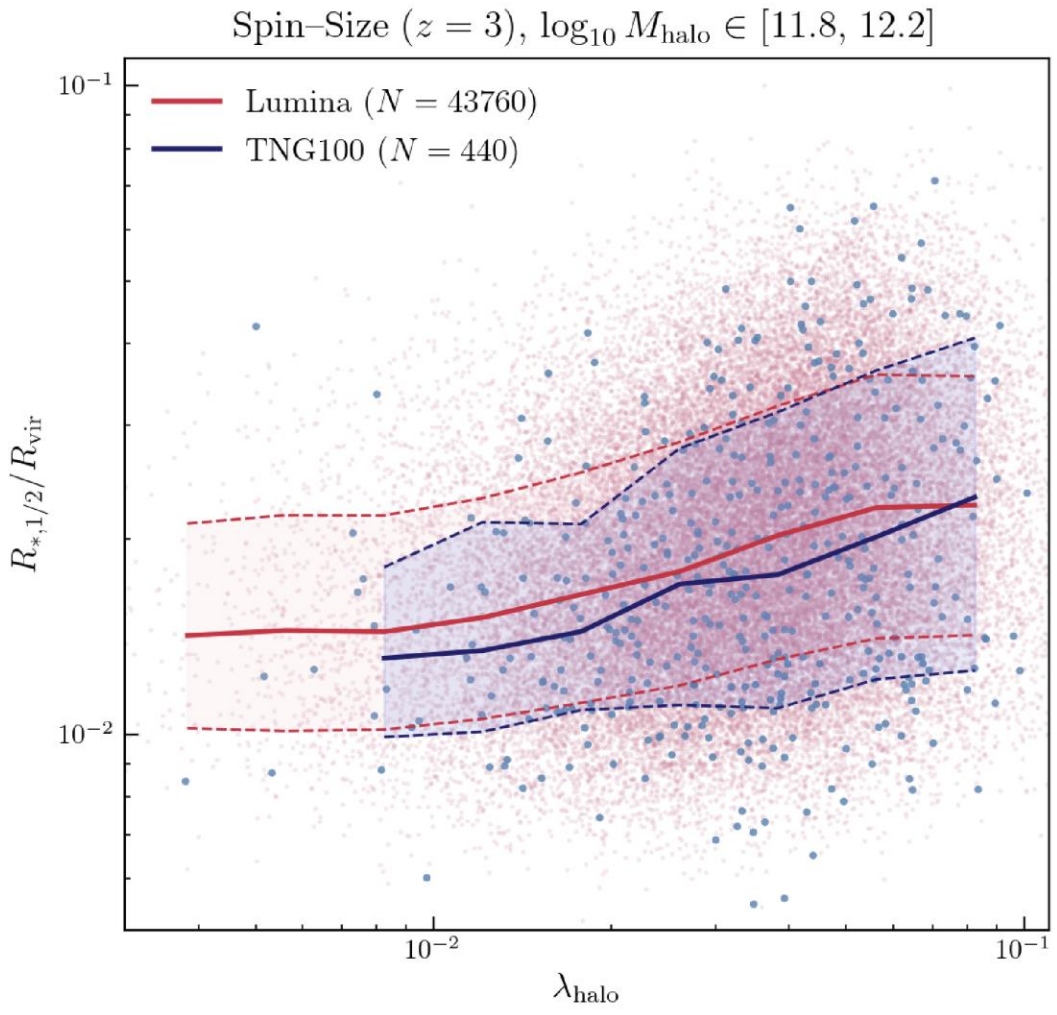
HeIII bubbles larger than
HI at 50% reionisation



Meredith Neyer
(MIT)

Galaxy morphology

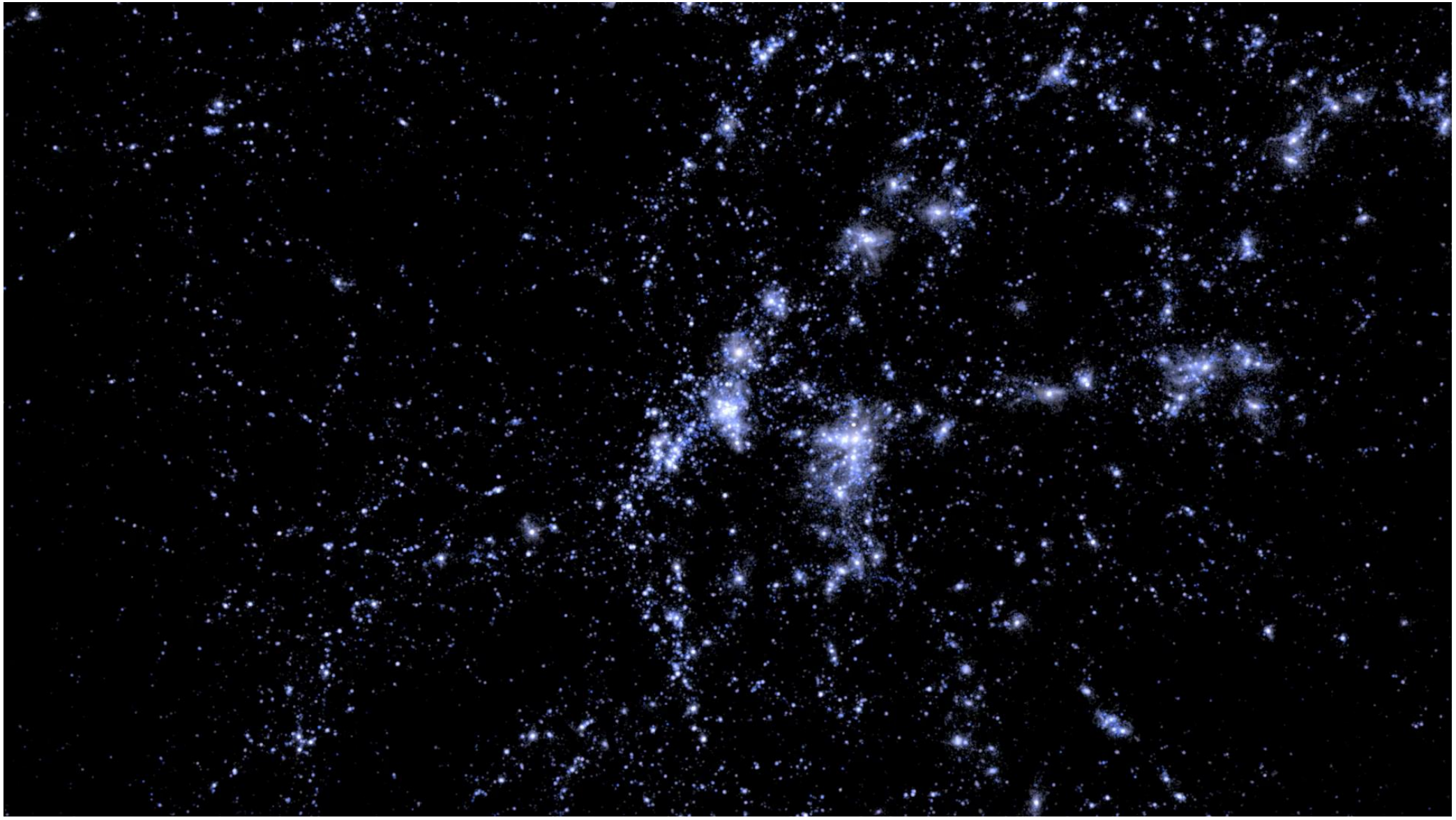






Rongrong Liu
(CfA)

Galaxy morphology





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