

The LUMINA Simulation

Simulating hydrogen and helium reionization self-consistently

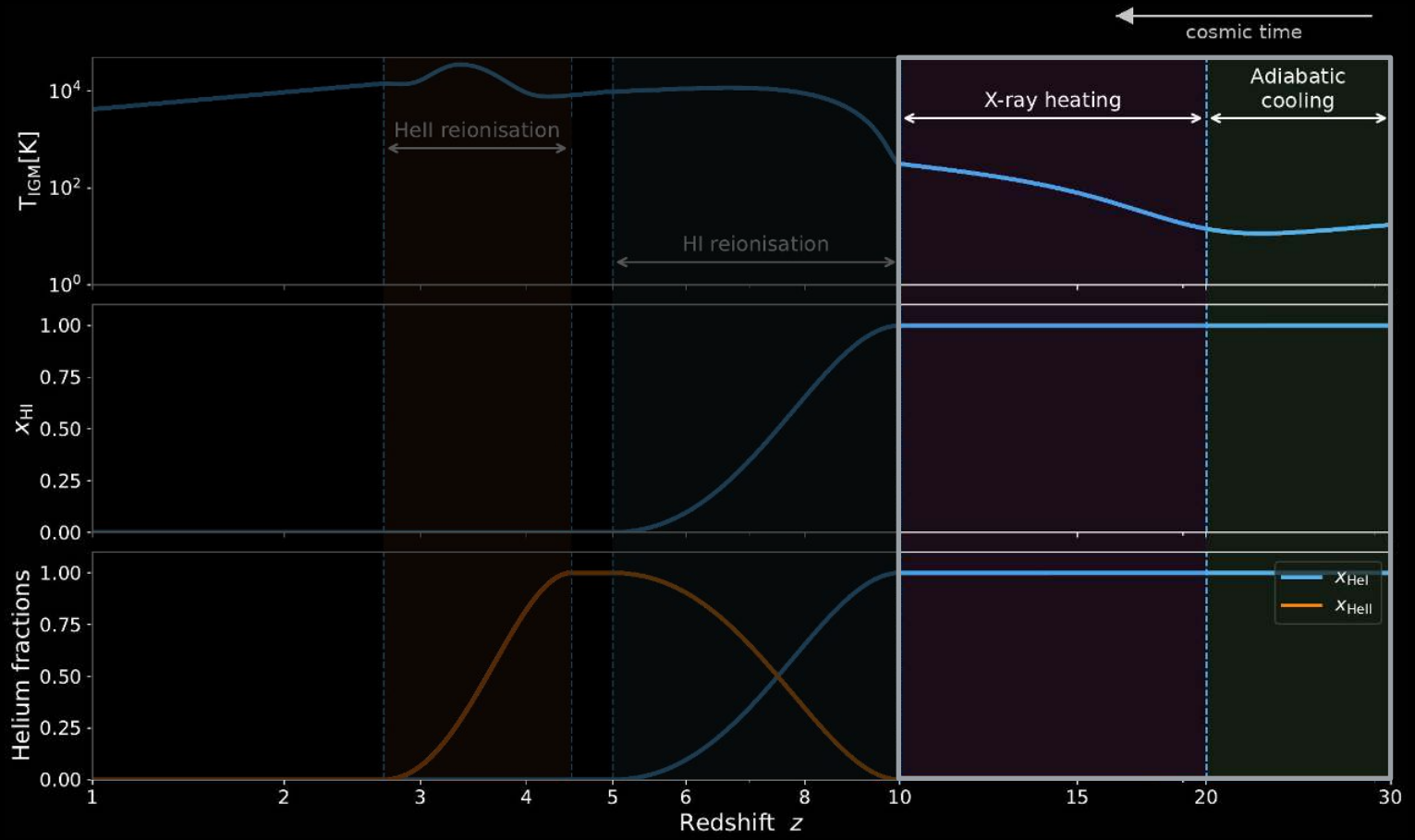
Oliver Zier

with **Aaron Smith**, **Xuejian Shen**, **Rongrong Liu** and the LUMINA team

CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

lumina-simulation.com

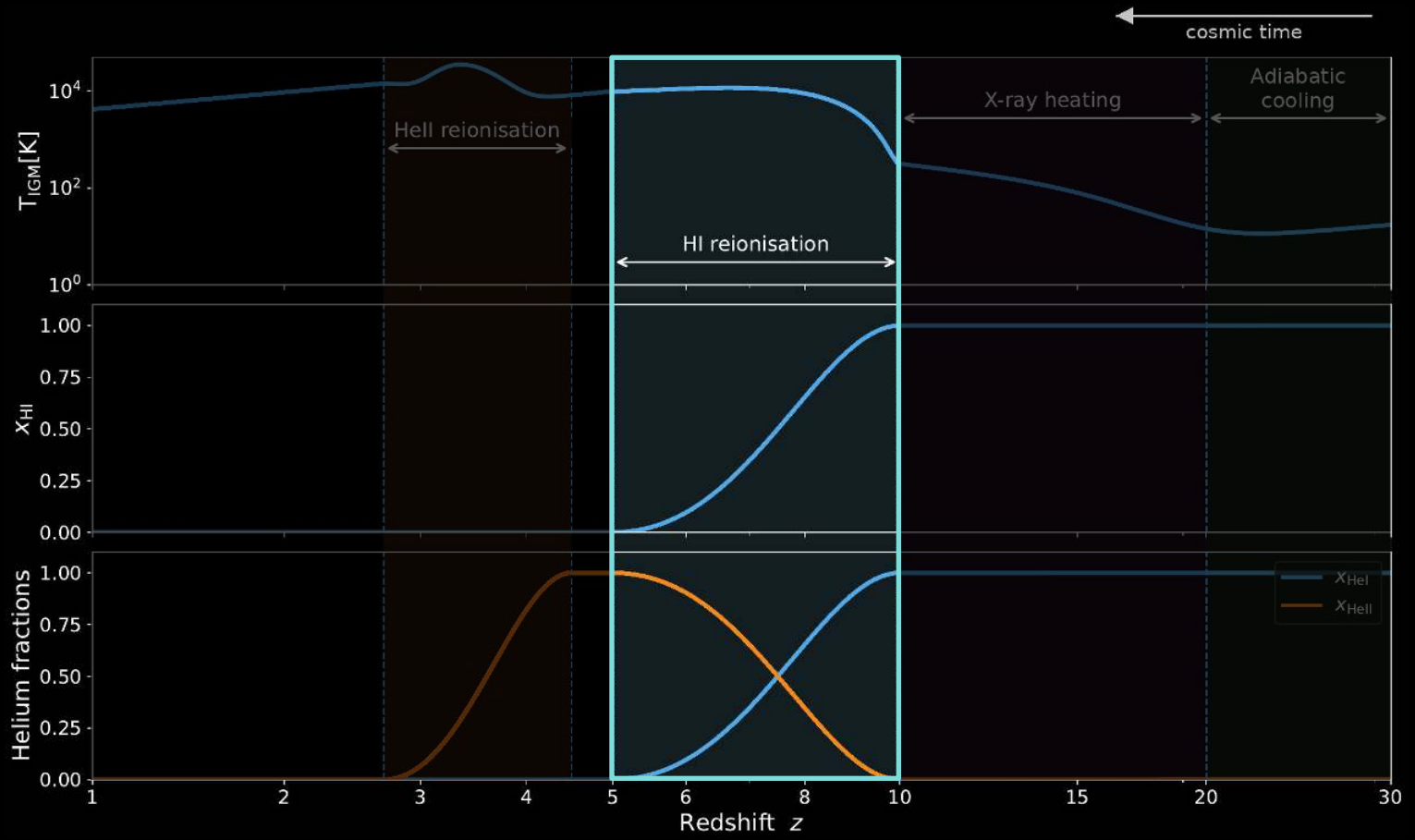
The (simplified) evolution of the IGM



Early on

neutral gas cools; X-rays from the first galaxies warm it slightly

The (simplified) evolution of the IGM



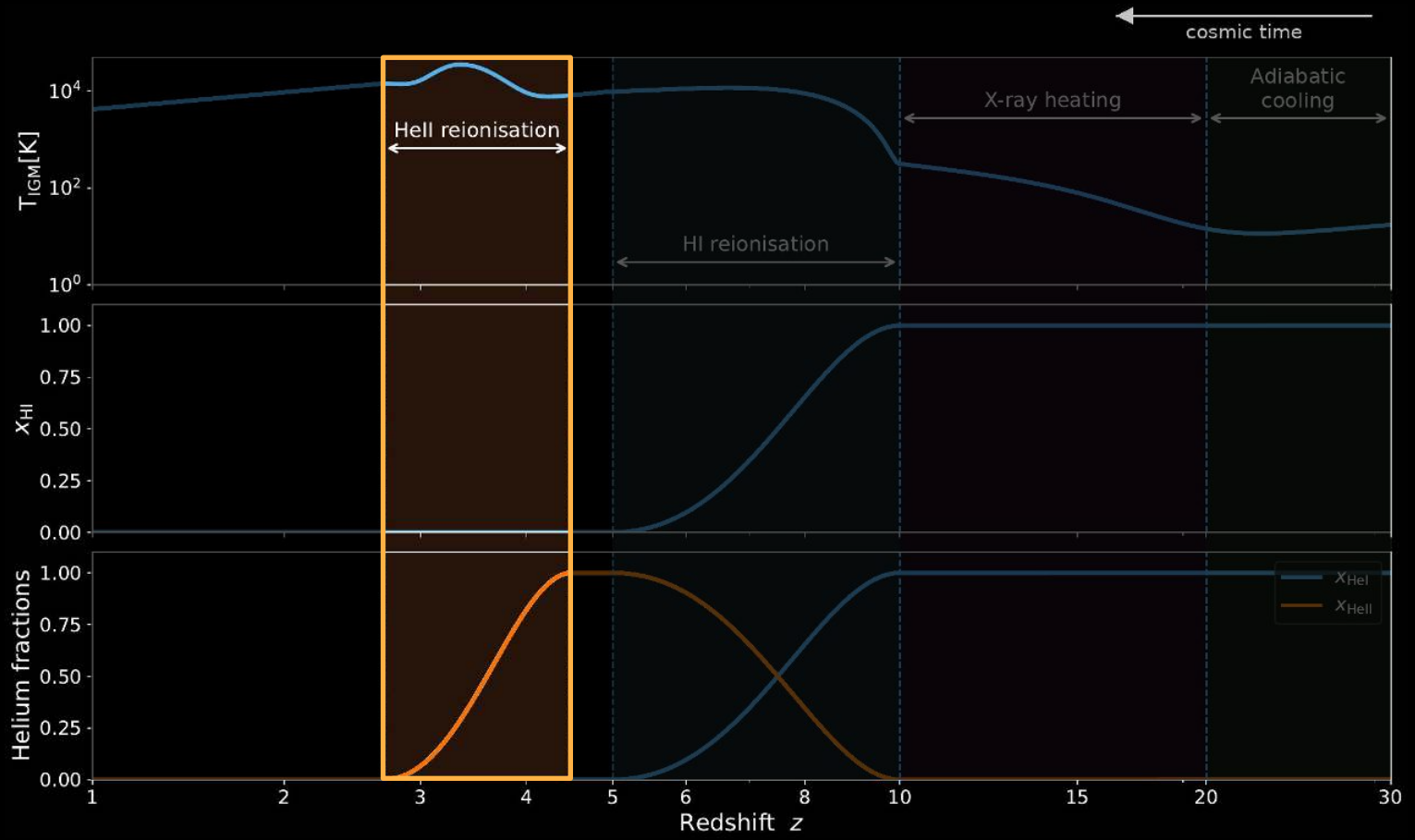
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Stars

ionize H I and He I at z ≈ 10 → 5

The (simplified) evolution of the IGM



Early on

neutral gas cools; X-rays from the first galaxies warm it slightly

Stars

ionize H I and He I at z ≈ 10 → 5

Accreting black holes

ionize He II about 1 Gyr later, z ≈ 5 → 3

- Goal: follow this whole sequence self-consistently, galaxies included

Requirements for simulations of the EoR

Resolve the sources

10^8–10^9 $M_\odot$

halos hosting faint galaxies

Resolve the largest bubbles

H I > 100 cMpc
He II > 300 cMpc

Radiation on the fly

$\Delta t \propto 1/c$

very small time steps

Lagrangian method

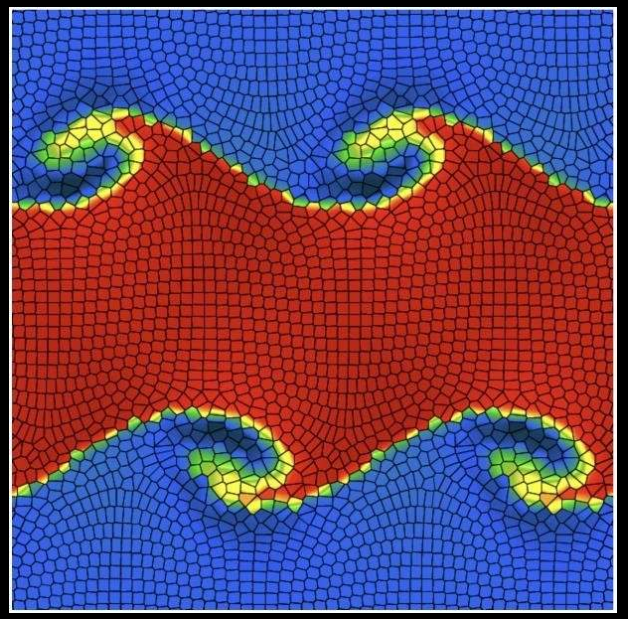
density-adaptive resolution

GPU acceleration

fast radiation transport

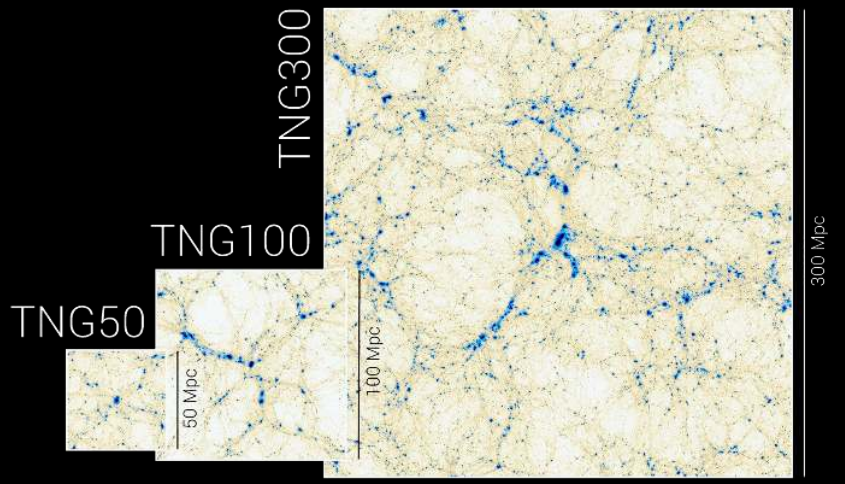
- Resolution, volume and radiation compete: we need all three at once

The LUMINA model



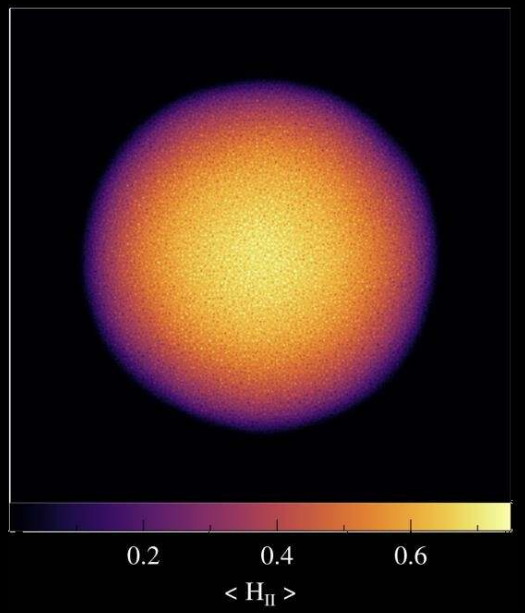
AREPO moving mesh

Springel 2010; Pakmor et al. 2016



IllustrisTNG galaxy model, unchanged

Weinberger et al. 2017; Pillepich et al. 2018

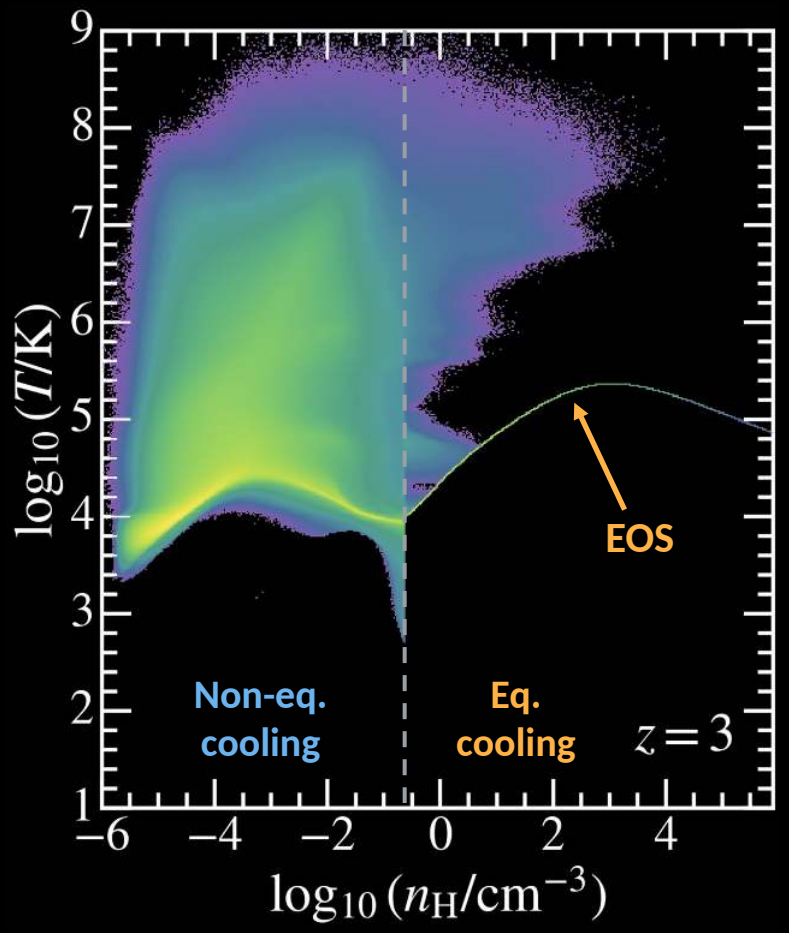


AREPO-RT (M1) on GPUs

Kannan et al. 2019; Zier et al. 2024

+ non-equilibrium H/He chemistry, 4 source classes (stars, AGN, hot ISM, X-ray binaries), 6 frequency bins

Transparent equation of state



Problem

the Springel & Hernquist (2003) model does not define the ISM structure

On the EOS

equilibrium cooling; the cells are transparent to radiation

Off the EOS

non-equilibrium H/He chemistry coupled to the radiation field

Stellar escape fraction f_{esc} = 18%

calibrated to account for absorption in the unresolved ISM

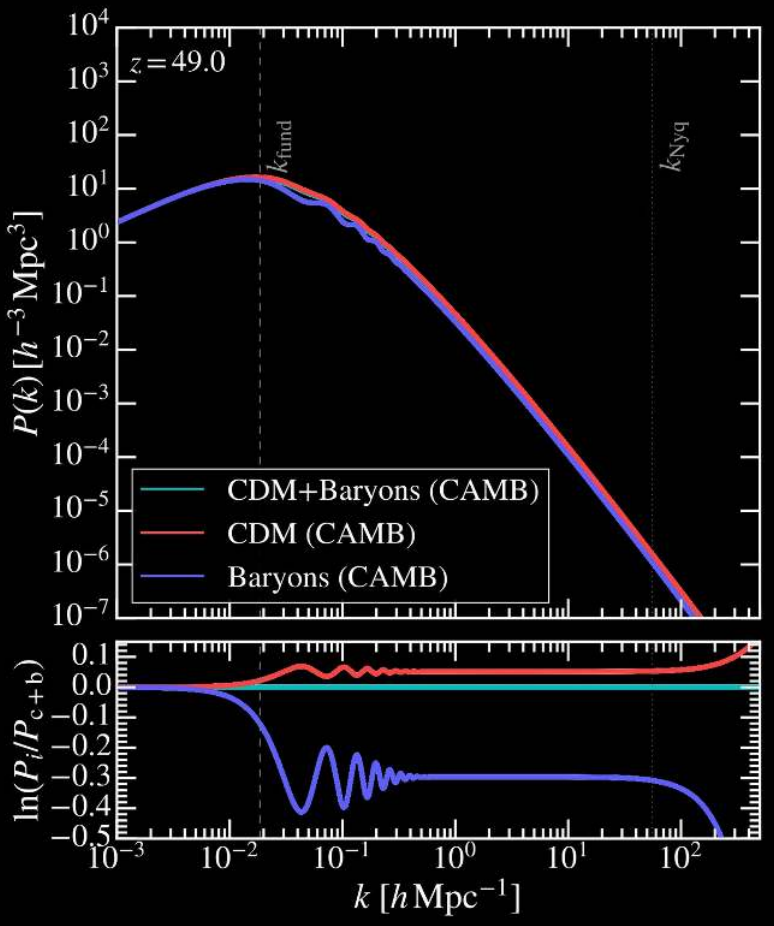


Teodora Bulichi

MIT

Bulichi, Zier et al. 2025

Better initial conditions



Two transfer functions

2nd-order LPT for dark matter and baryons separately

Streaming velocity

2nd-order LPT for the relative baryon–dark-matter velocity

Expansion history

neutrinos and the radiation background included in the Hubble rate

Baryons lag behind the dark matter on small scales at z = 49

- Essential for the first galaxies at the highest redshifts

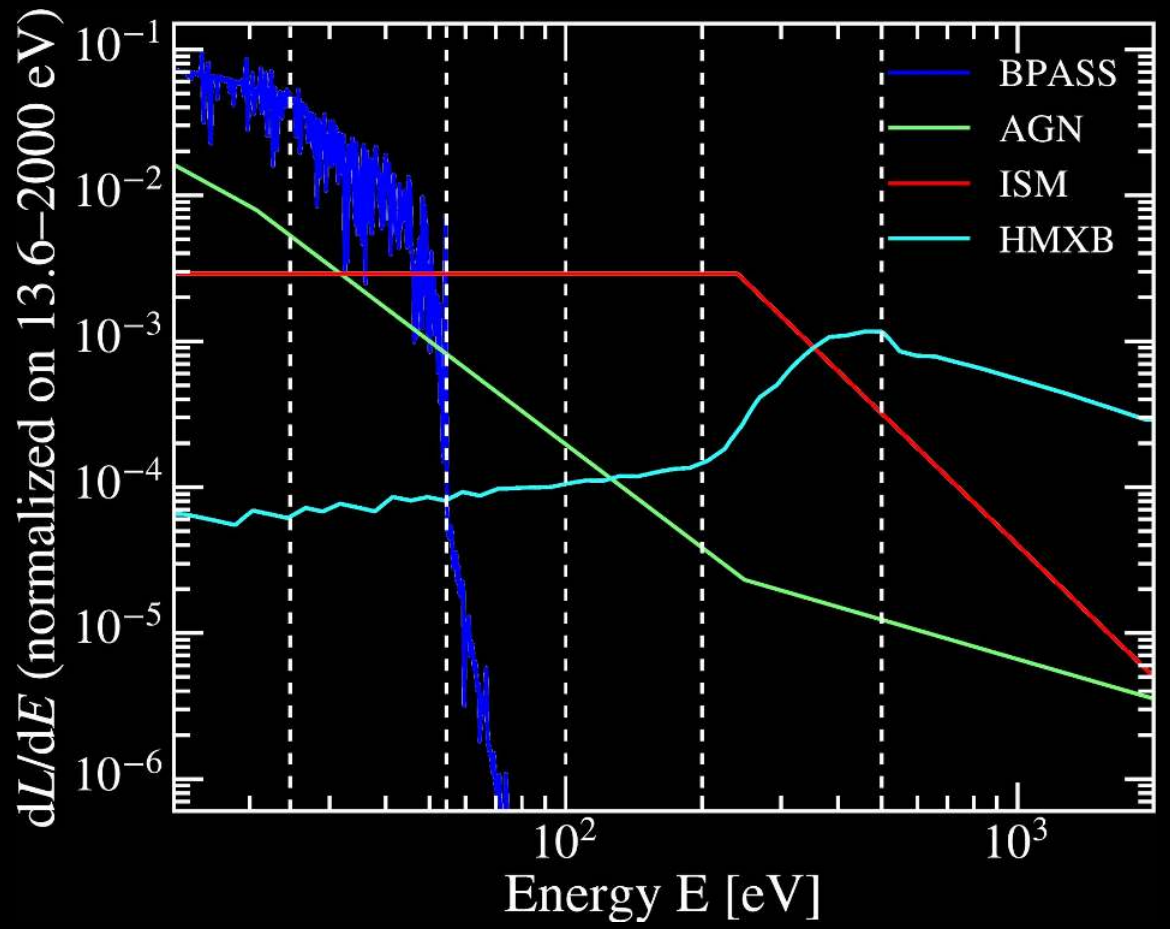
Radiation sources

Stars

BPASS v2.2.1
f_{esc} = 18%

Shock-heated ISM

T = 240 eV



Black holes

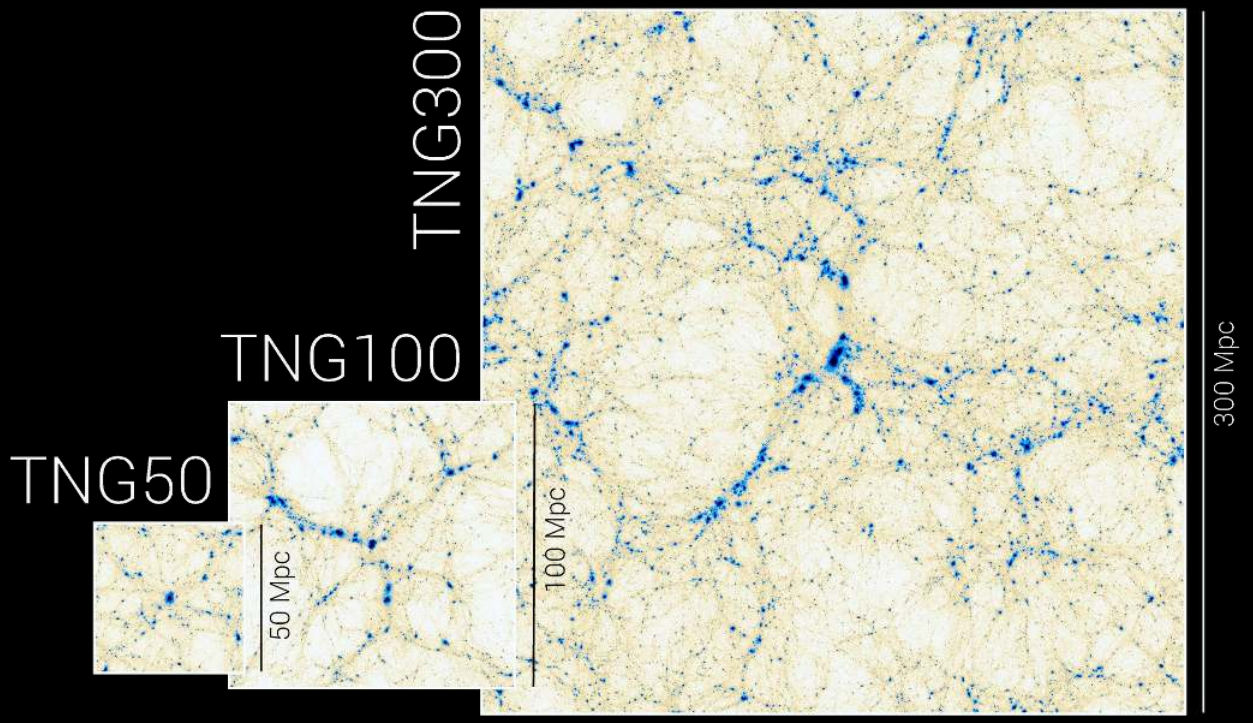
Shen et al. (2020)
ε_{rad} = 20%

HMXBs

Fragos et al. (2013)

- Six frequency bins from 13.6 eV to 2 keV; AGN supply the hard He II photons

The LUMINA simulation

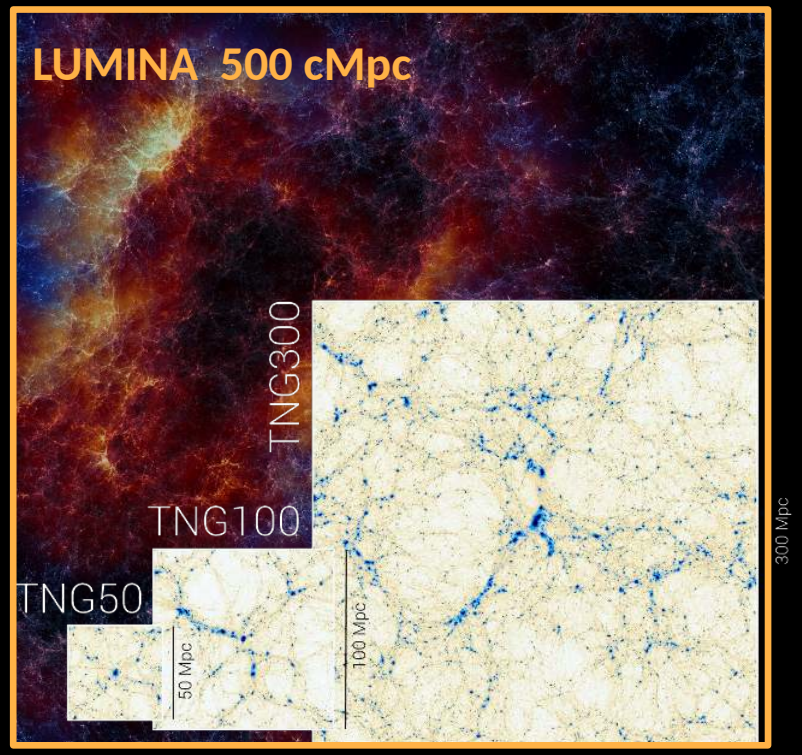


TNG100
110.7 cMpc

TNG300
302.6 cMpc

Run	Box [cMpc]	Elements	m_b [M⊙]	m_DM [M⊙]	ε_DM [ckpc]
TNG100	110.7	2×1820^3	1.4×10^6	7.5×10^6	1.48
TNG300	302.6	2×2500^3	1.1×10^7	5.9×10^7	2.95

The LUMINA simulation



TNG100
110.7 cMpc

TNG300
302.6 cMpc

LUMINA
500 cMpc

90× the volume of TNG100

Run	Box [cMpc]	Elements	m_b [M⊙]	m_DM [M⊙]	ε_DM [ckpc]
TNG100	110.7	2×1820^3	1.4×10^6	7.5×10^6	1.48
LUMINA	**500**	$\mathbf{2 \times 6000^3}$	$\mathbf{3.6 \times 10^6}$	$\mathbf{1.9 \times 10^7}$	**1.77**
TNG300	302.6	2×2500^3	1.1×10^7	5.9×10^7	2.95



Run on Frontier

105,504
CPU cores

7,536
AMD MI250X GPUs

109 M
CPU hours

600 TB
peak memory

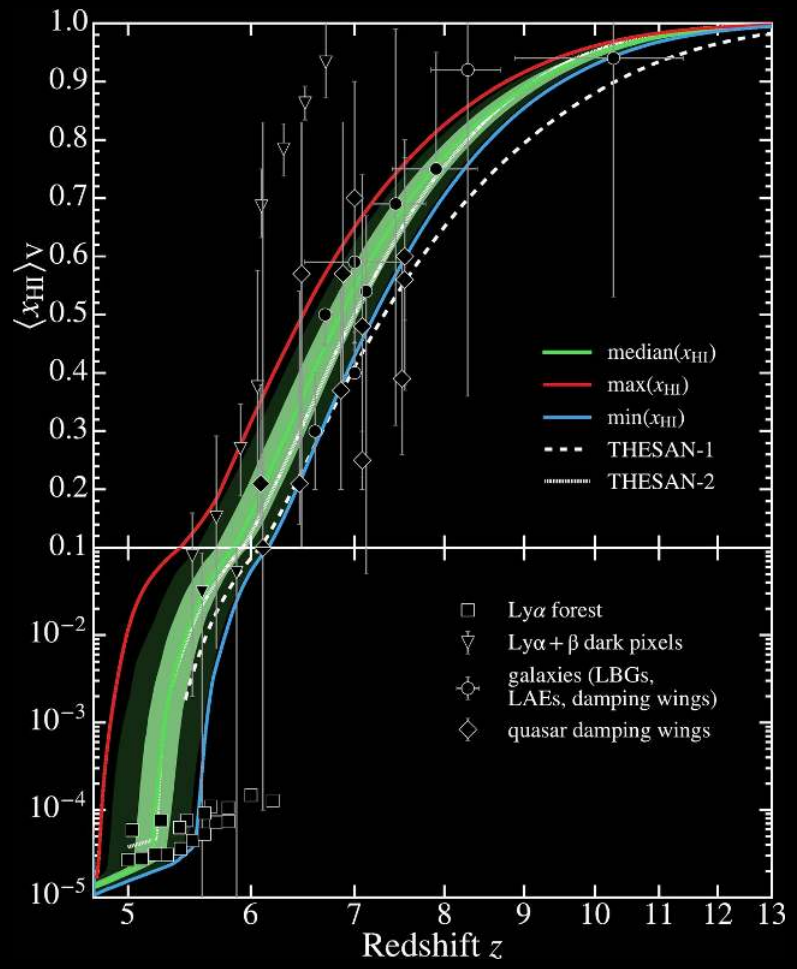
250 TB
per checkpoint, written at 800 GB/s

140 PB
restart files written in total

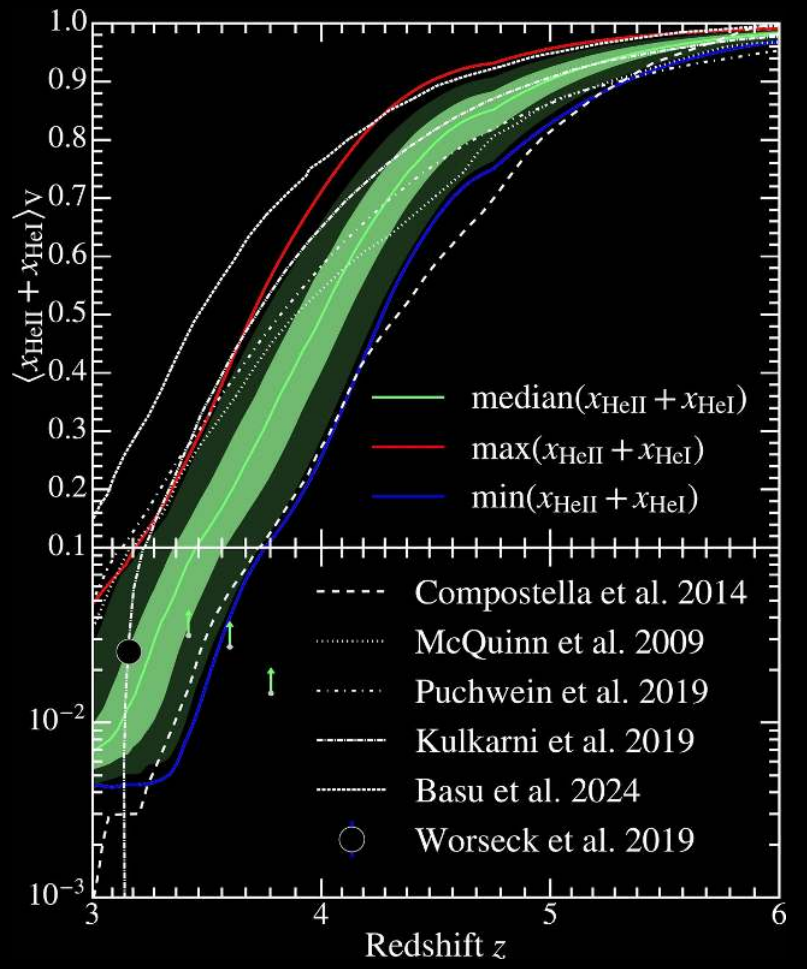
Frontier, OLCF/ORNL (CC BY 2.0)

Oliver Zier, The LUMINA simulation

Reionization histories



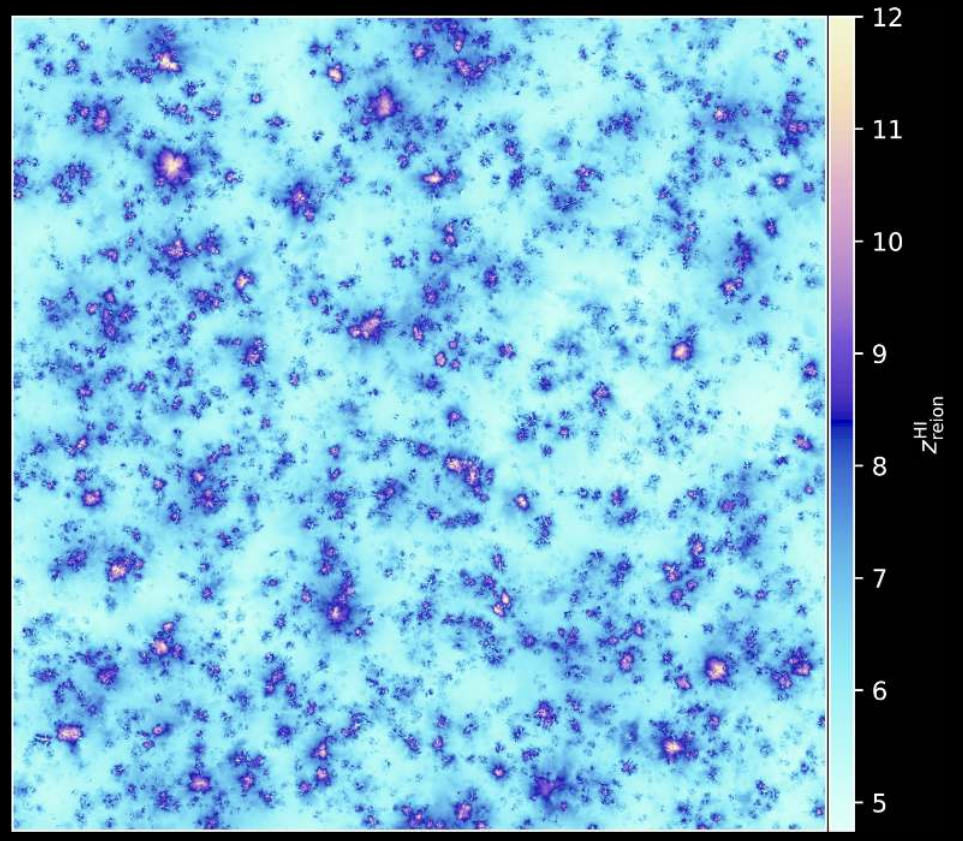
H I: calibrated with f_{esc}



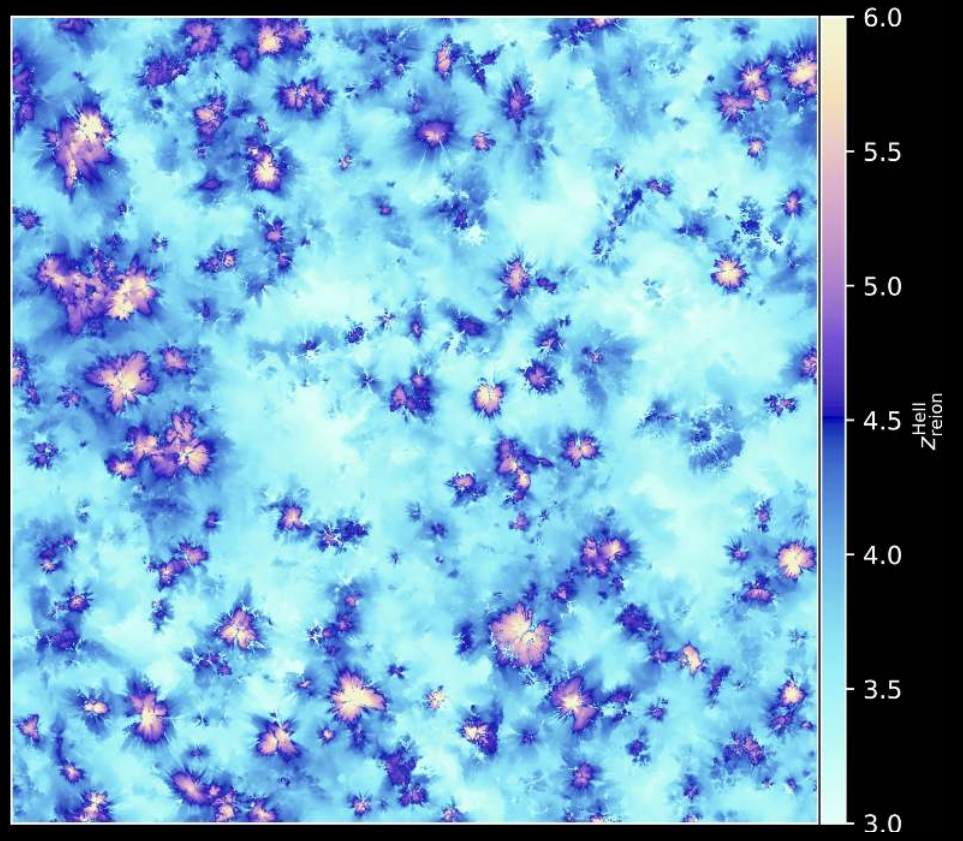
He II: no calibration!

Patchy reionization: hydrogen vs. helium

H I stars, done by z ≈ 5

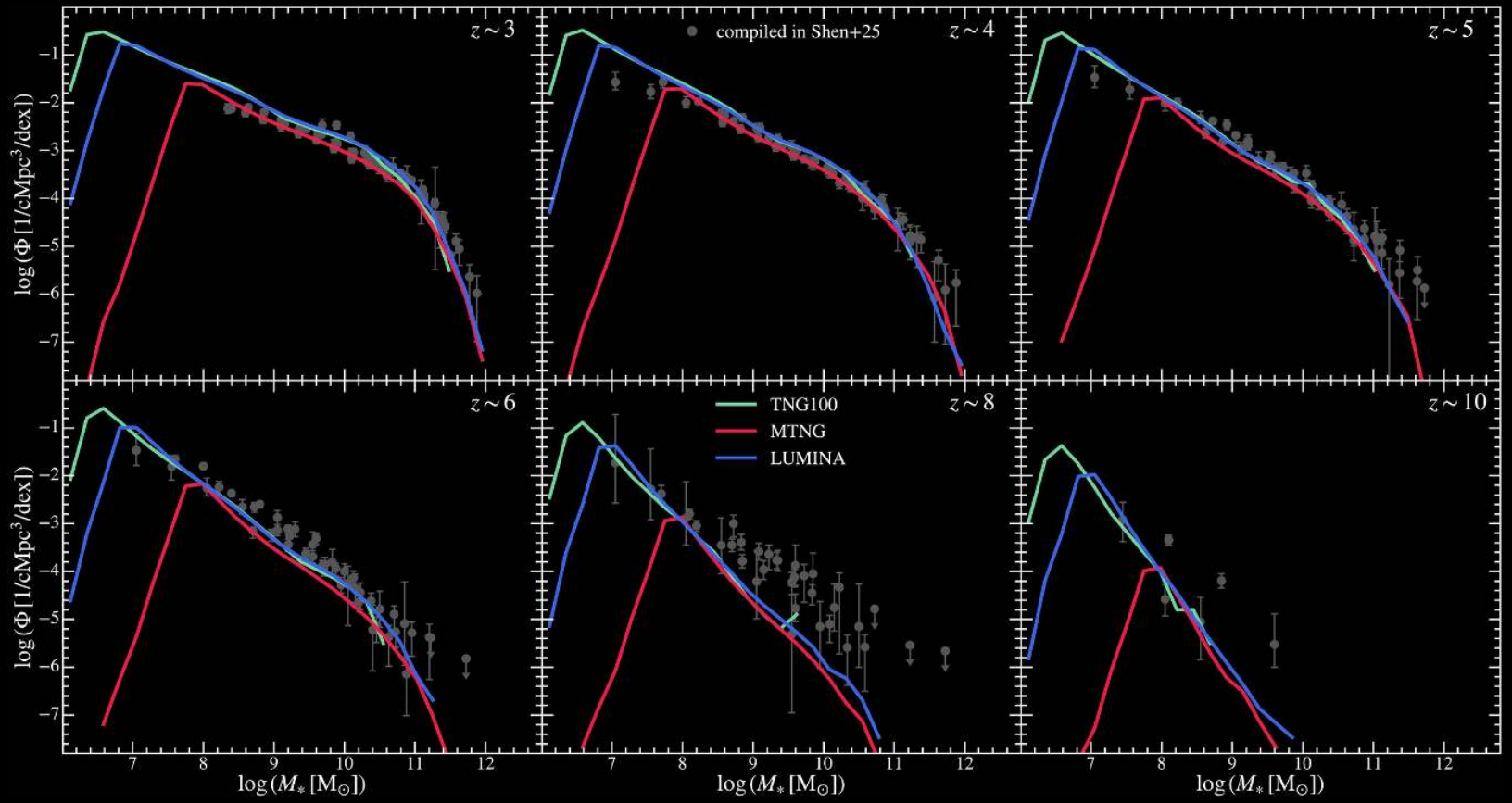


He II AGN, nearly complete by z = 3



- He III bubbles around rare bright AGN are far larger than the H II bubbles

Stellar mass function



Same model as TNG

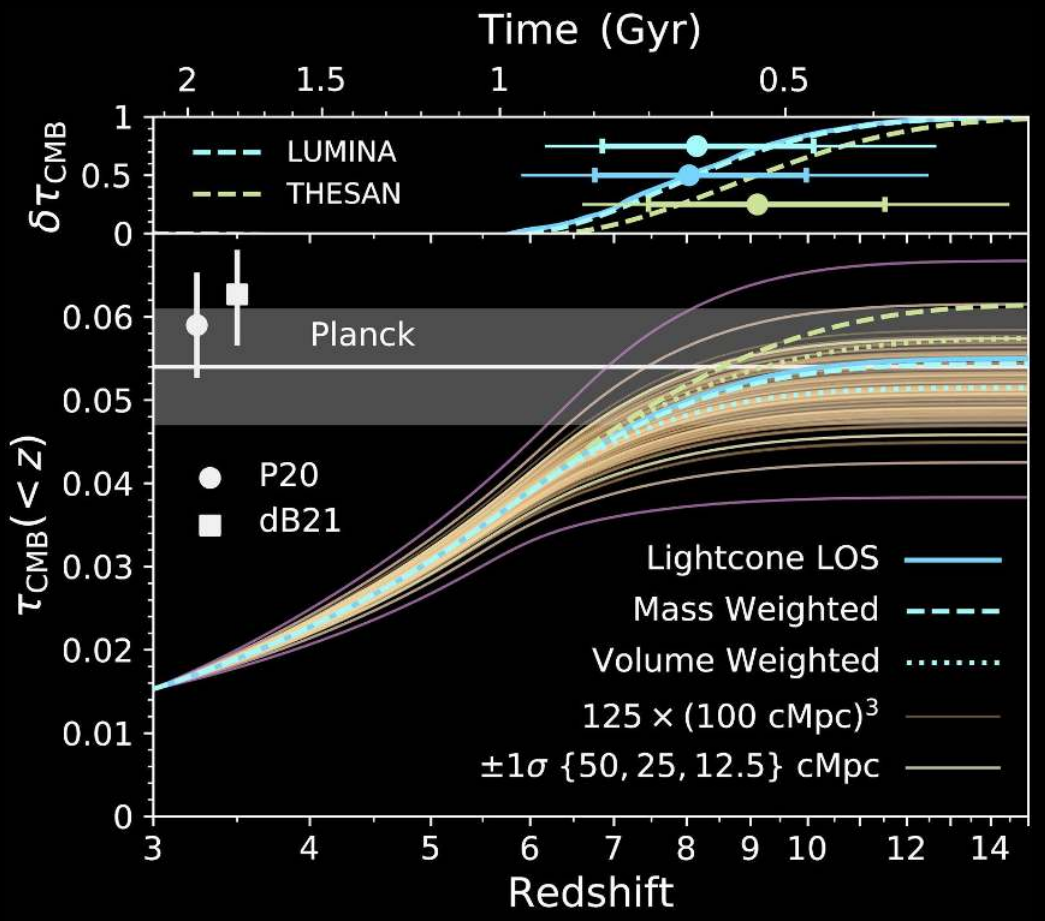
agrees with TNG100 and MTNG where the boxes overlap, z = 3–10

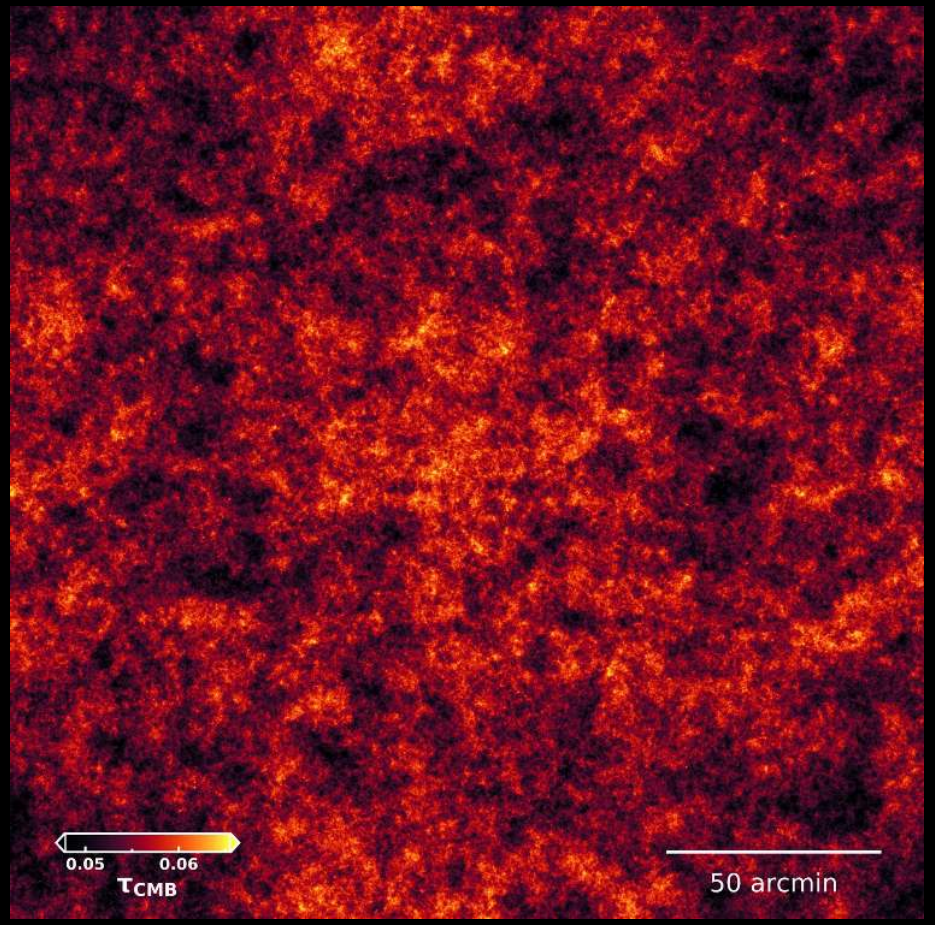
Adds the massive end

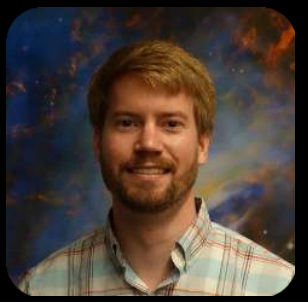
rare objects and large-scale environments

- Perfect agreement with the TNG galaxies, plus the rare massive ones

CMB optical depth







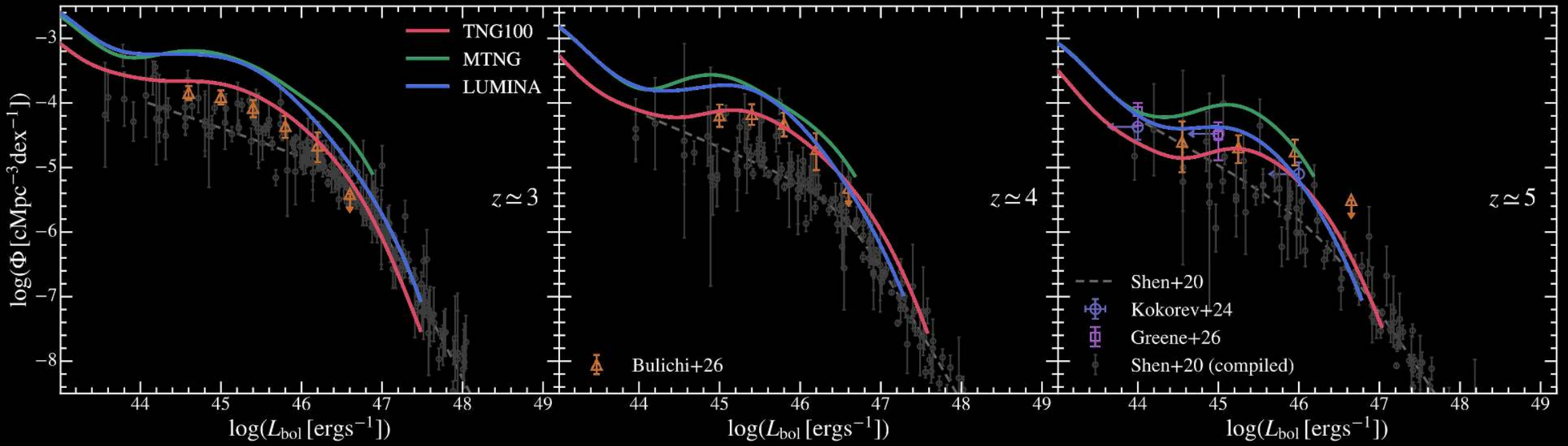
Aaron Smith

UT Dallas

Smith et al. 2026

- Consistent with Planck; patchy across the sky, ~7% above the global value

AGN luminosity function





Xuejian (Jacob) Shen

CfA, Shen et al. 2026

1,979,361

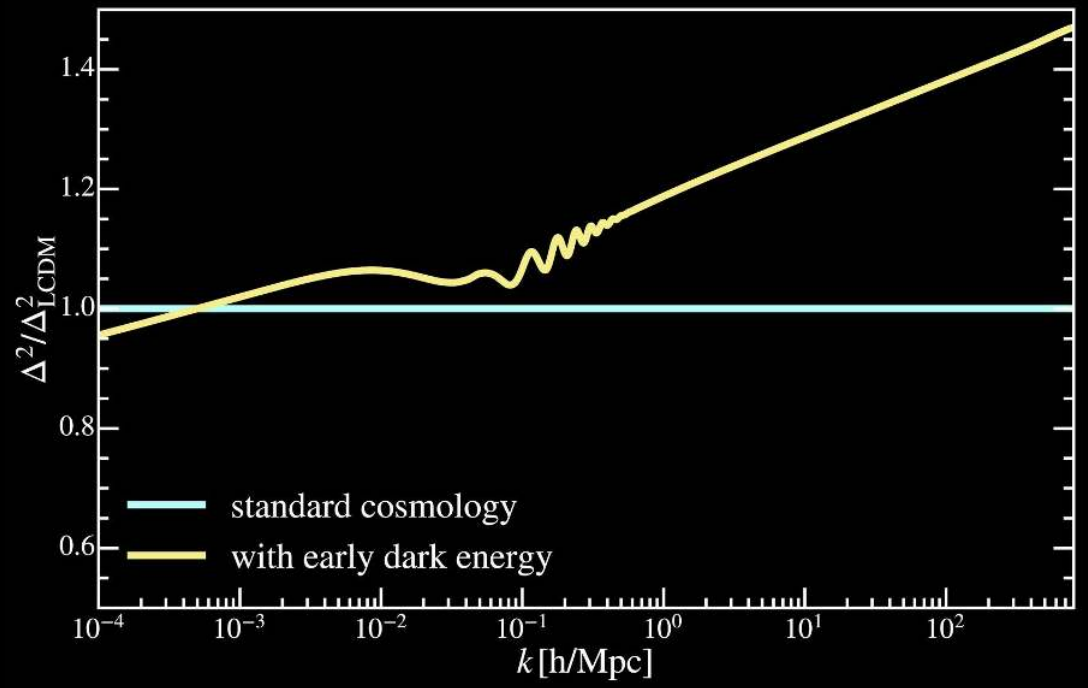
SMBHs in the box at z = 3

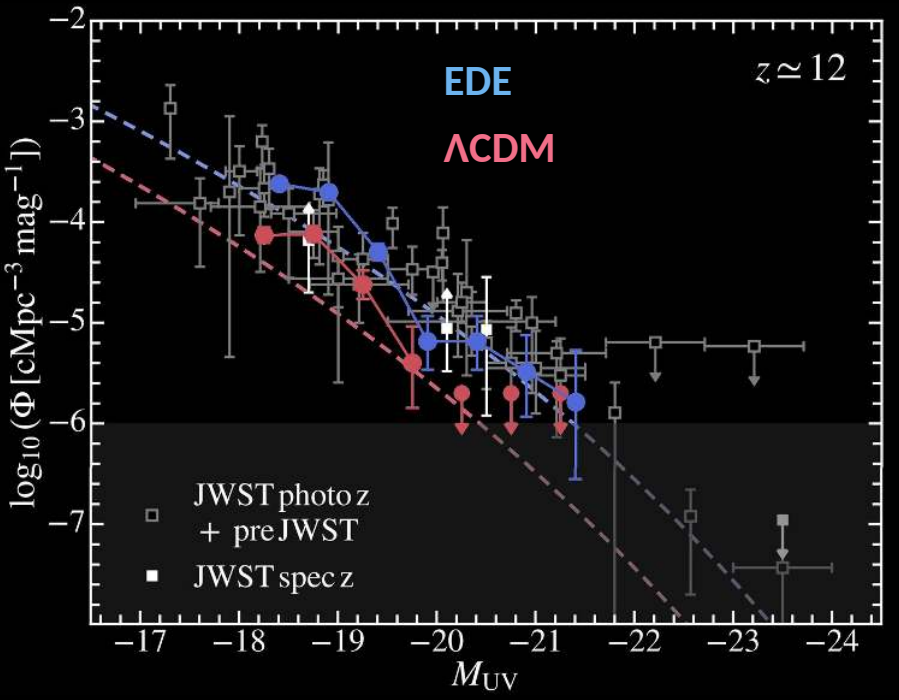
No retuning

luminosities from the TNG black-hole model

- Realistic sources for He II reionization

Early dark energy: LUMINA-EDE





More small-scale power

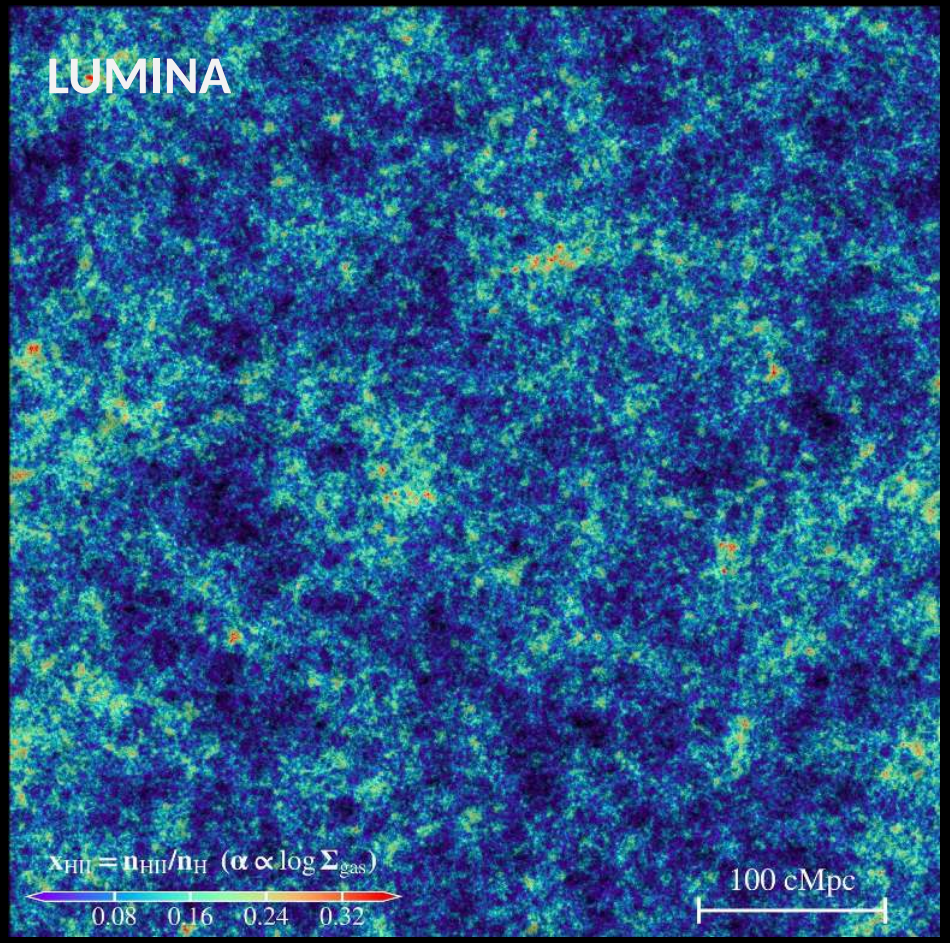
proposed to solve the Hubble tension; it also boosts structure on small scales

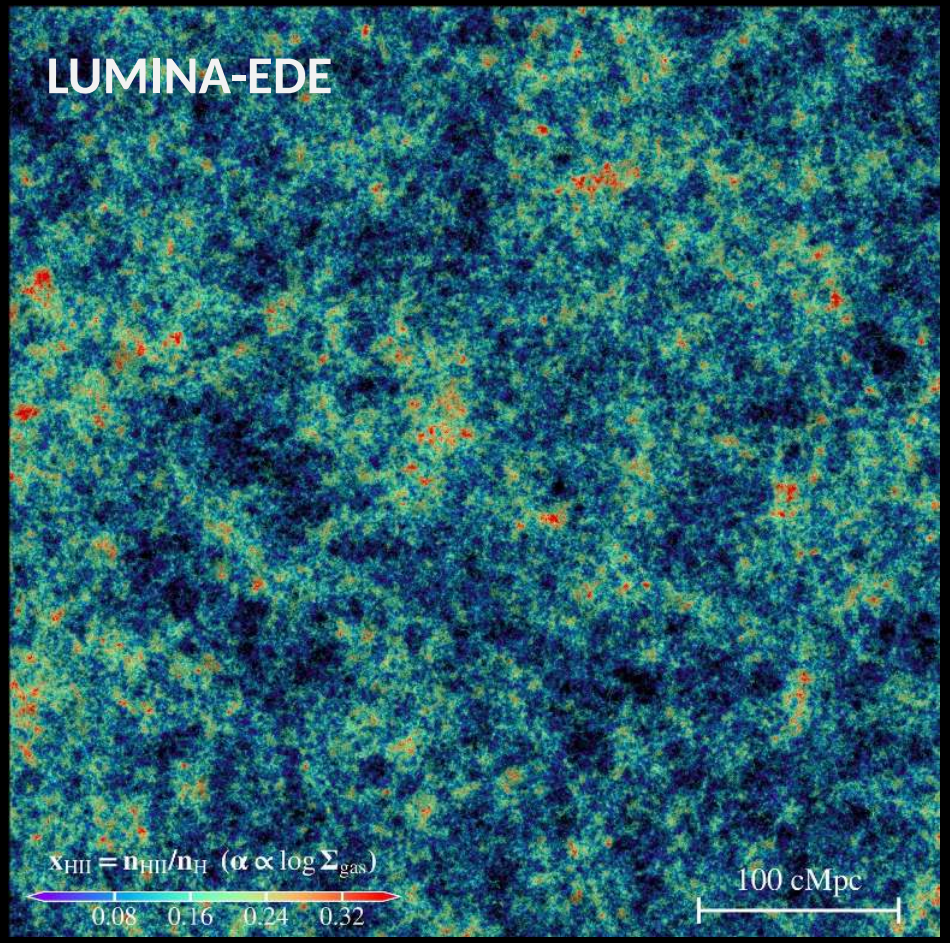
Earlier galaxy formation

more UV-bright galaxies at z ≈ 12 (Shen, Zier et al. 2026)

- LUMINA-EDE: the same simulation with an EDE cosmology

Reionization in LUMINA-EDE





Ionized hydrogen fraction x_{HII}, brightness $\propto \log \Sigma_{gas}$. Shen, in prep.

Summary

1 LUMINA model

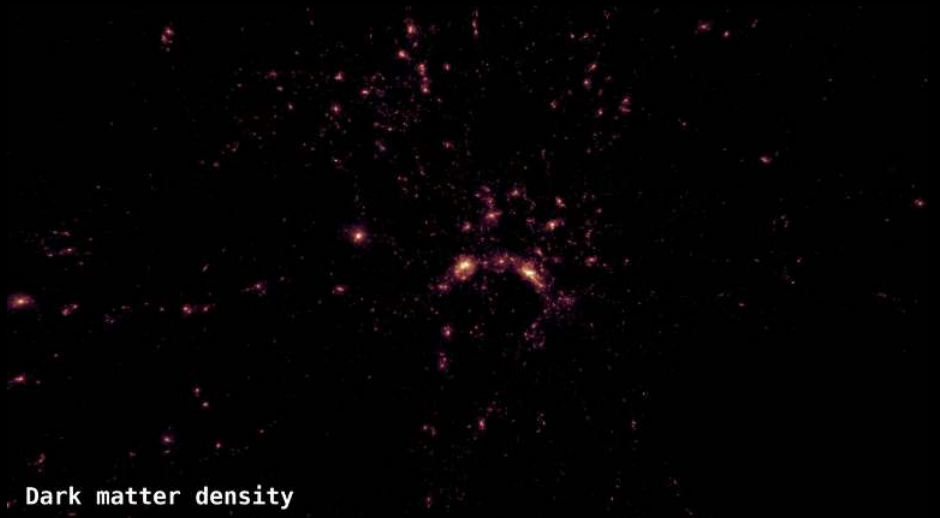
IllustrisTNG + GPU-accelerated on-the-fly radiation, transparent EOS, improved initial conditions

2 Reionization

self-consistent H I (stars) and He II (AGN) reionization in a 500 cMpc box, down to z = 3

3 Large volume for statistics

TNG-like resolution in 500 cMpc: millions of galaxies and black holes, 125 sub-volumes for cosmic variance



Flythrough of LUMINA around a massive halo at z = 3

lumina-simulation.com
data & papers