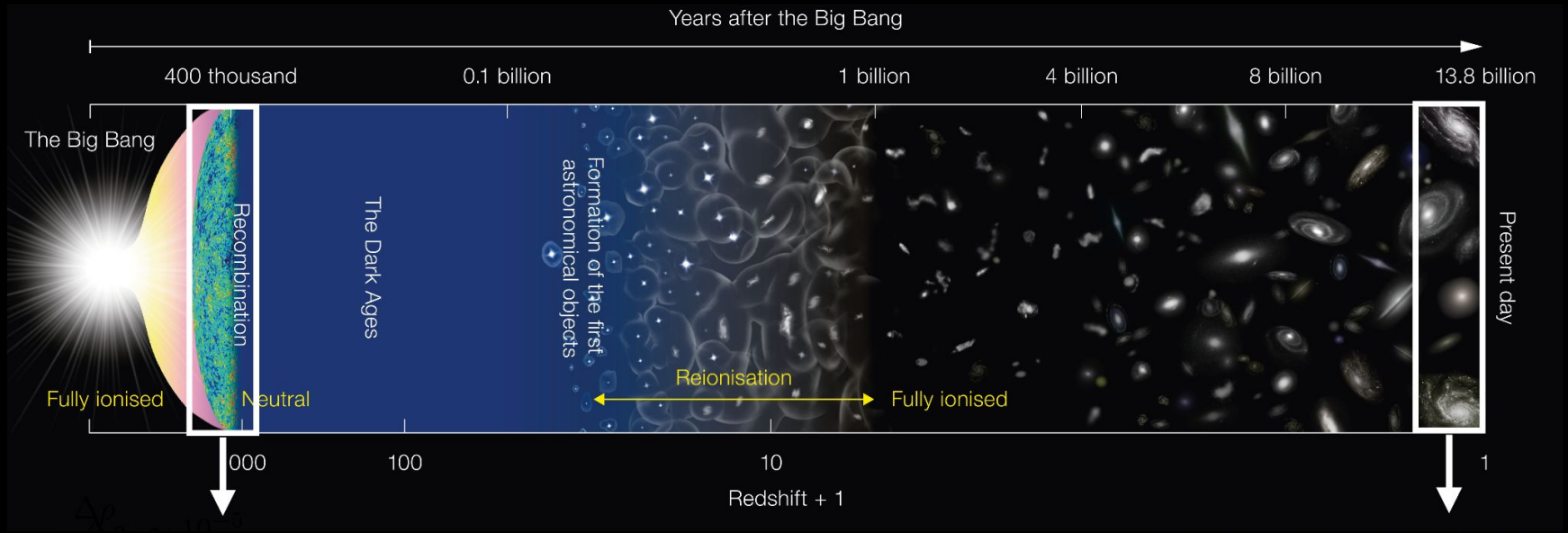
Modelling the epoch of reionisation on a computer

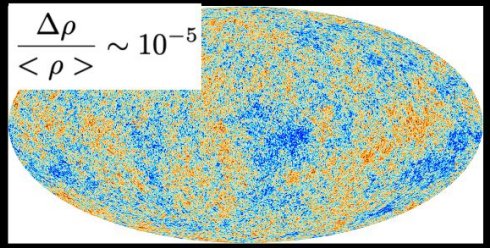
Oliver Zier (CfA, ITC Fellow)

(together with Aaron Smith, Rahul Kannan, Mark Vogelsberger, Xuejian Shen, Volker Springel, Ruediger Pakmor, …)



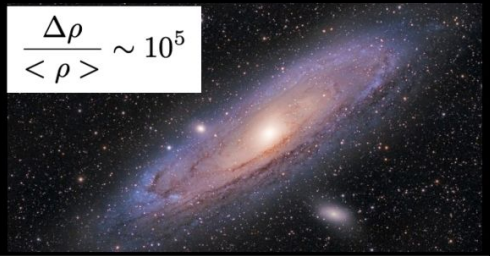
The evolution of the universe





~14 Billion years of evolution

Gravity, Hydrodynamics
Star and black hole formation, feedback



Epoch of reionization (z = 15 - 5)

IGM:

- What are the sources of reionization?
- When did reionization happen?
- What is the duration of this process?
- Can we constrain cosmology and physics of structure formation using reionization?

Galaxy formation:

- Too massive/bright galaxies?
- SMBH seeding and growth?
- Morphology of galaxies
- Early quenching?

Reionization is inherently multi-scale

Stars and AGNs generate photons (pc)

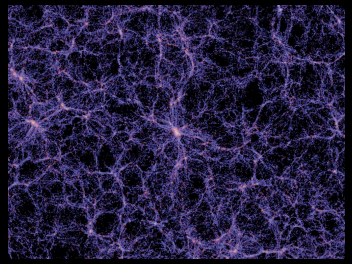




Transmission through ISM (100s pc)



back reaction



Ionizing IGM (100s Mpc)

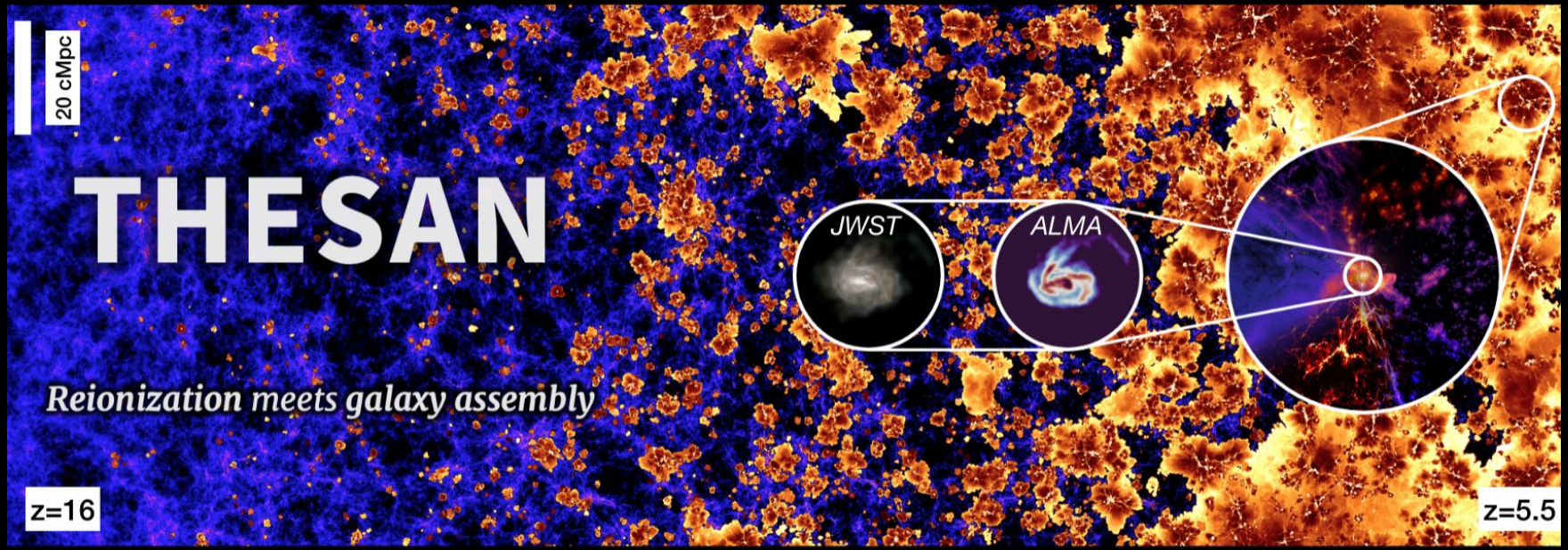


Transmission through CGM (100s kpc)

Cosmological boxes:

large scale + simplified galaxy formation

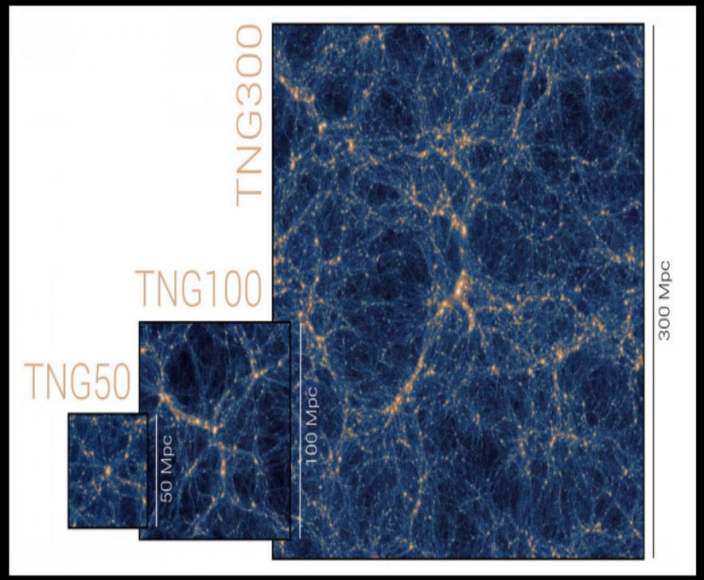
The THESAN project



Large volume — high resolution — coupled reionization and galaxy formation simulations

Kannan+22a,b, Smith+22, Garaldi+22

The THESAN project

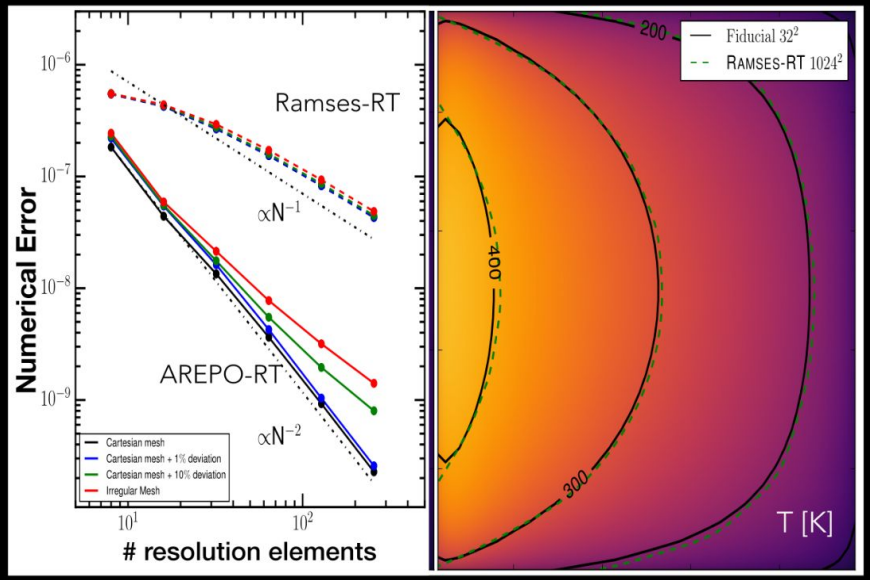


IllustrisTNG

(Springel+18)

- Well tested galaxy formation model, works extremely well down to z=0

+



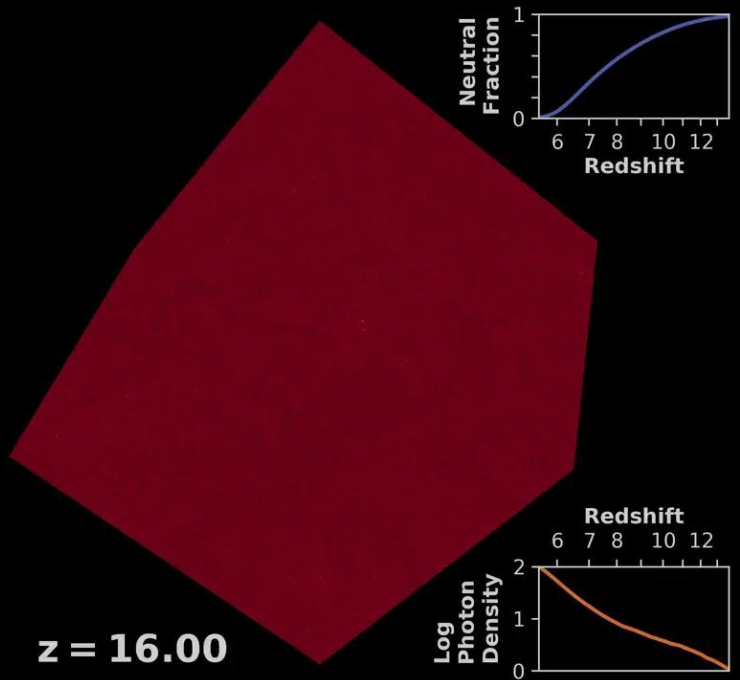
AREPO-RT

(Kannan+19)

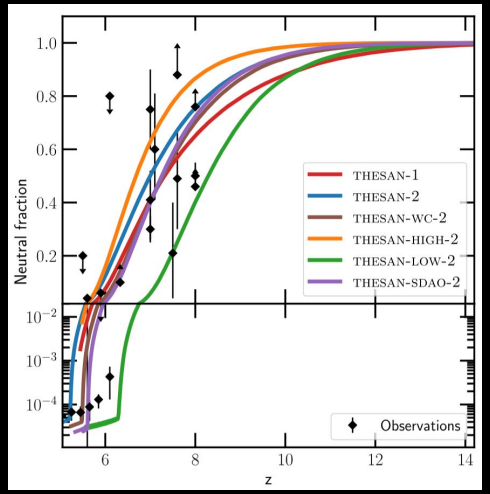
- Efficient and highly scalable radiation hydrodynamics module that solves the RT equations on the native Voronoi Mesh

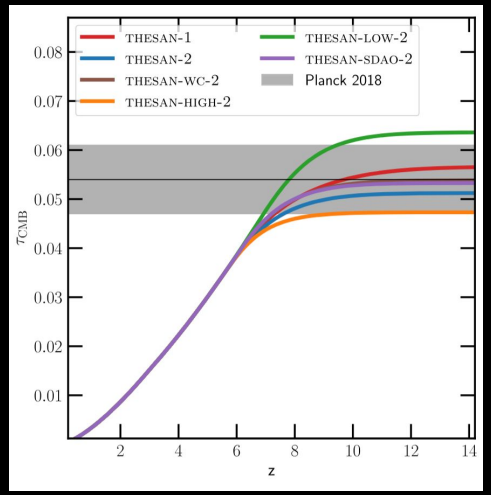
The THESAN project

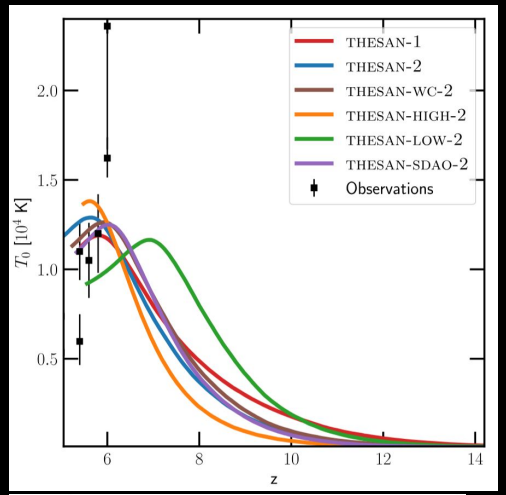
- volume: $(95.5\ \mathrm{cMpc})^3$
- end: z = 5.5
- particle number: 2 x 2100^3
- end: z = 5.5

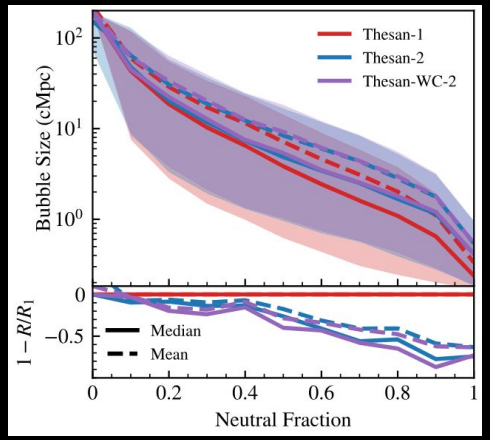


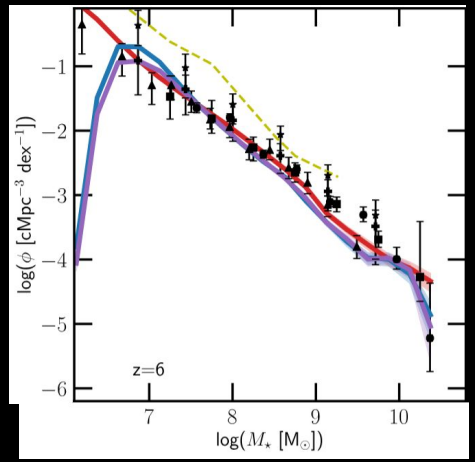
The THESAN project

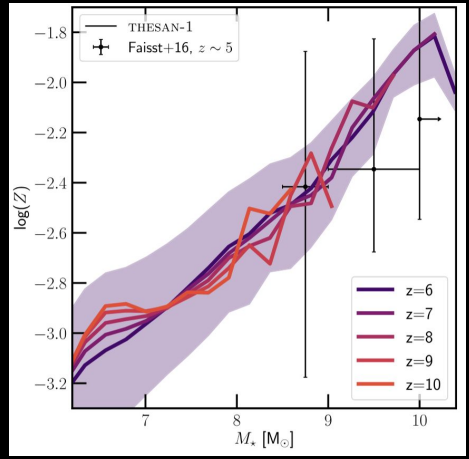








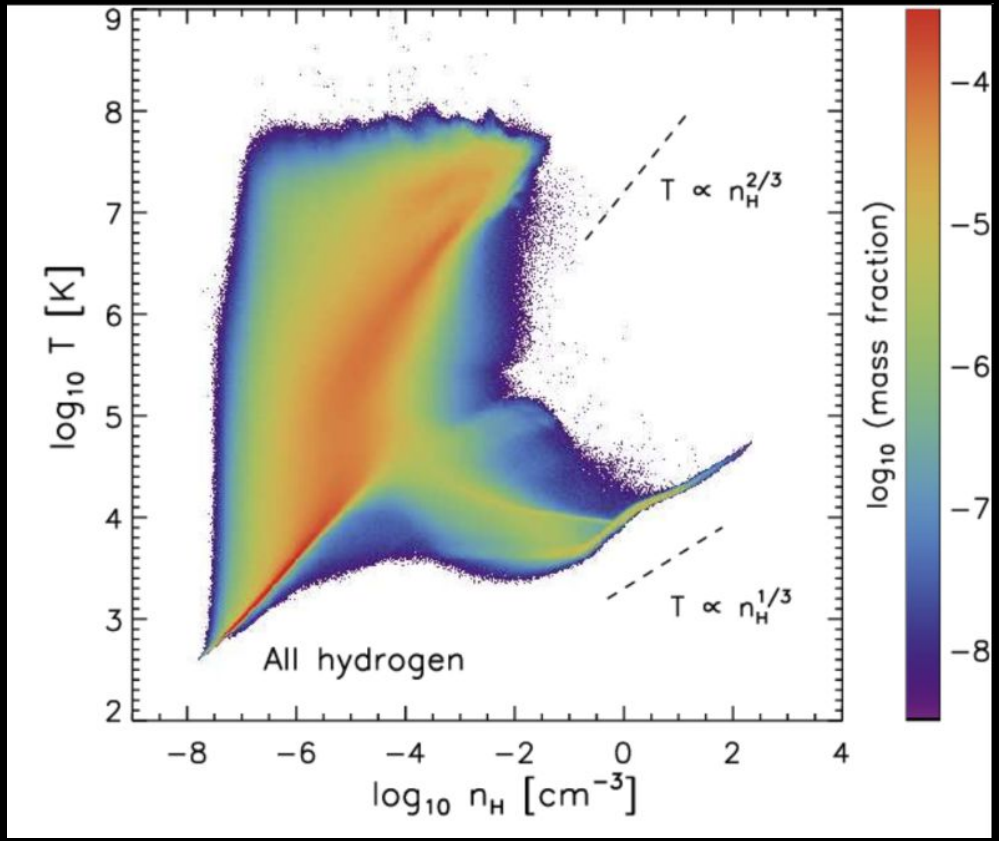




Problem equation of state

works well and robust
BUT:

- does not resolve ISM
- requires subgrid escape fraction
- star formation is smoothed
- BH growth is simplified



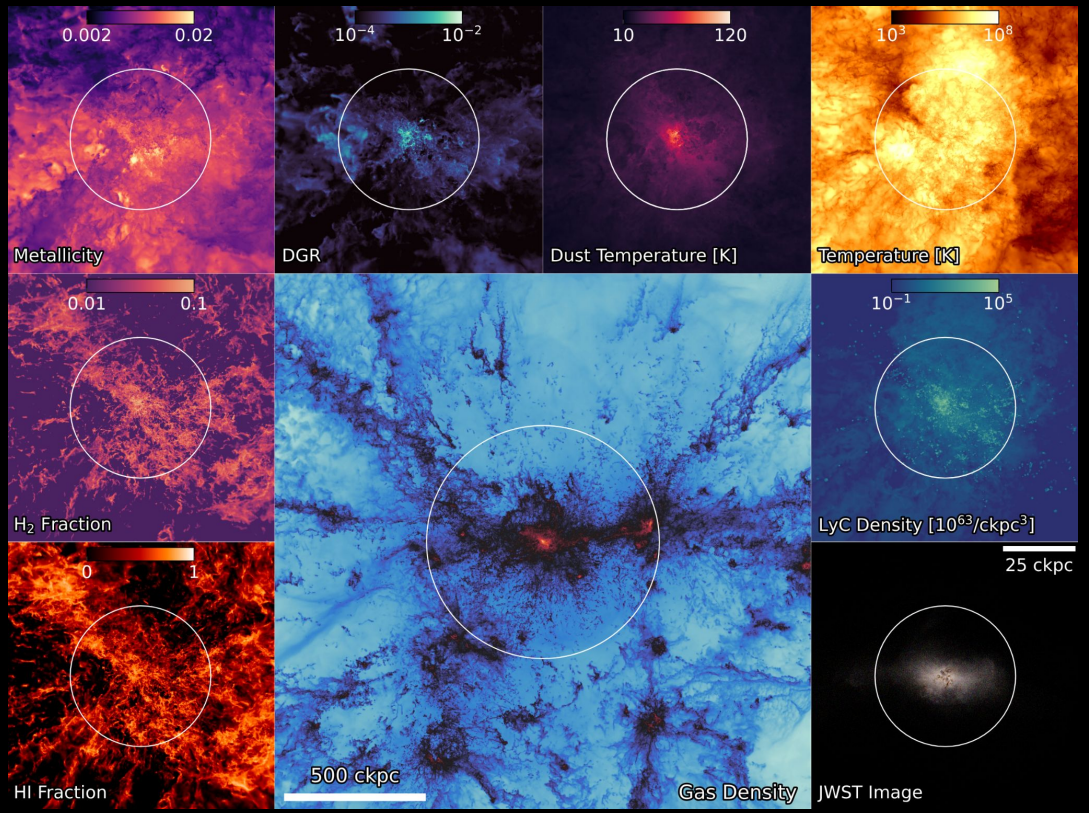
Zoom in simulations:

detailed galaxy formation, low statistics

The THESAN-ZOOM Project

- 14 galaxies selected from THESAN volume
- higher resolution and multiphase ISM (explicit star-formation & stellar feedback model)
- dust, molecular hydrogen, 7 radiation bins (including LW)
- until z = 3
- $M_{halo} = 10^8$ - 10^{13} M_{sun}
- resolution:

Name	$N^{\rm eff}_{\rm particles}$	$m_{\rm DM}$ [$M_\odot$]	$m_{\rm gas}$ [$M_\odot$]	$\epsilon_{\rm DM,stars}$ [cpc]	$\epsilon^{\rm min}_{\rm gas}$ [cpc]
L16	2×33600^3	7.62×10^2	1.42×10^2	138.30	17.30
L8	2×16800^3	6.09×10^3	1.14×10^3	276.79	34.60
L4	2×8400^3	4.86×10^4	9.09×10^3	553.59	69.20



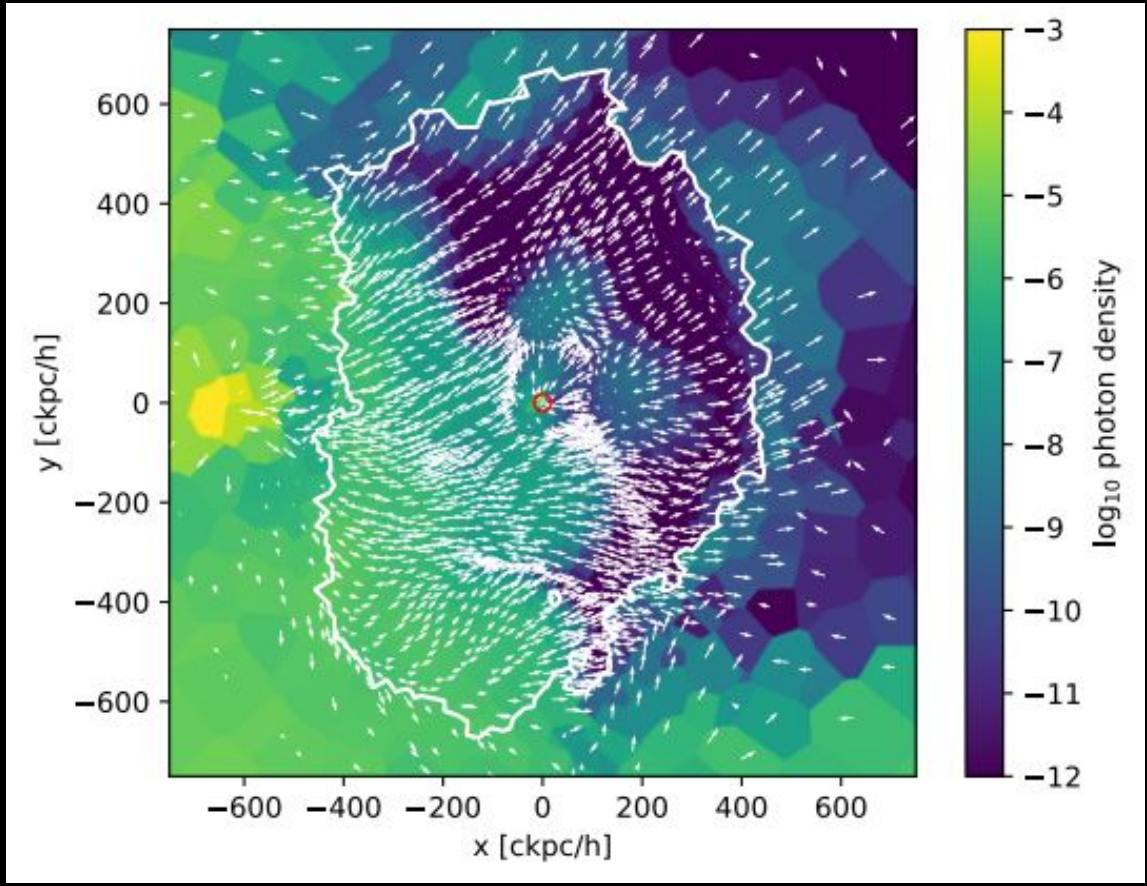
Rahul Kannan, Ewald Puchwein, Aaron Smith, Josh Borrow, Enrico Garaldi, Laura Keating, Mark Vogelsberger, **Oliver Zier**, Will McClymont, Xuejian Shen — Kannan+2025.

Large scale radiation field information

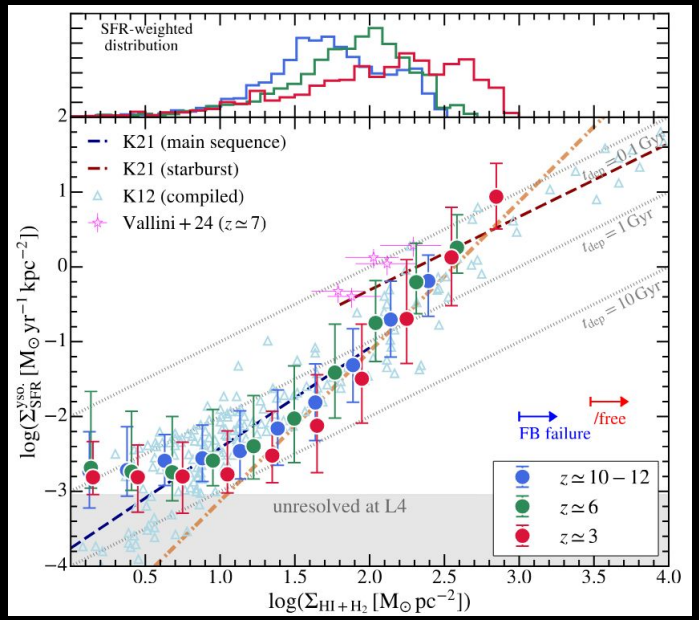
use large scale UV field as boundary condition

=> self-consistent reionization

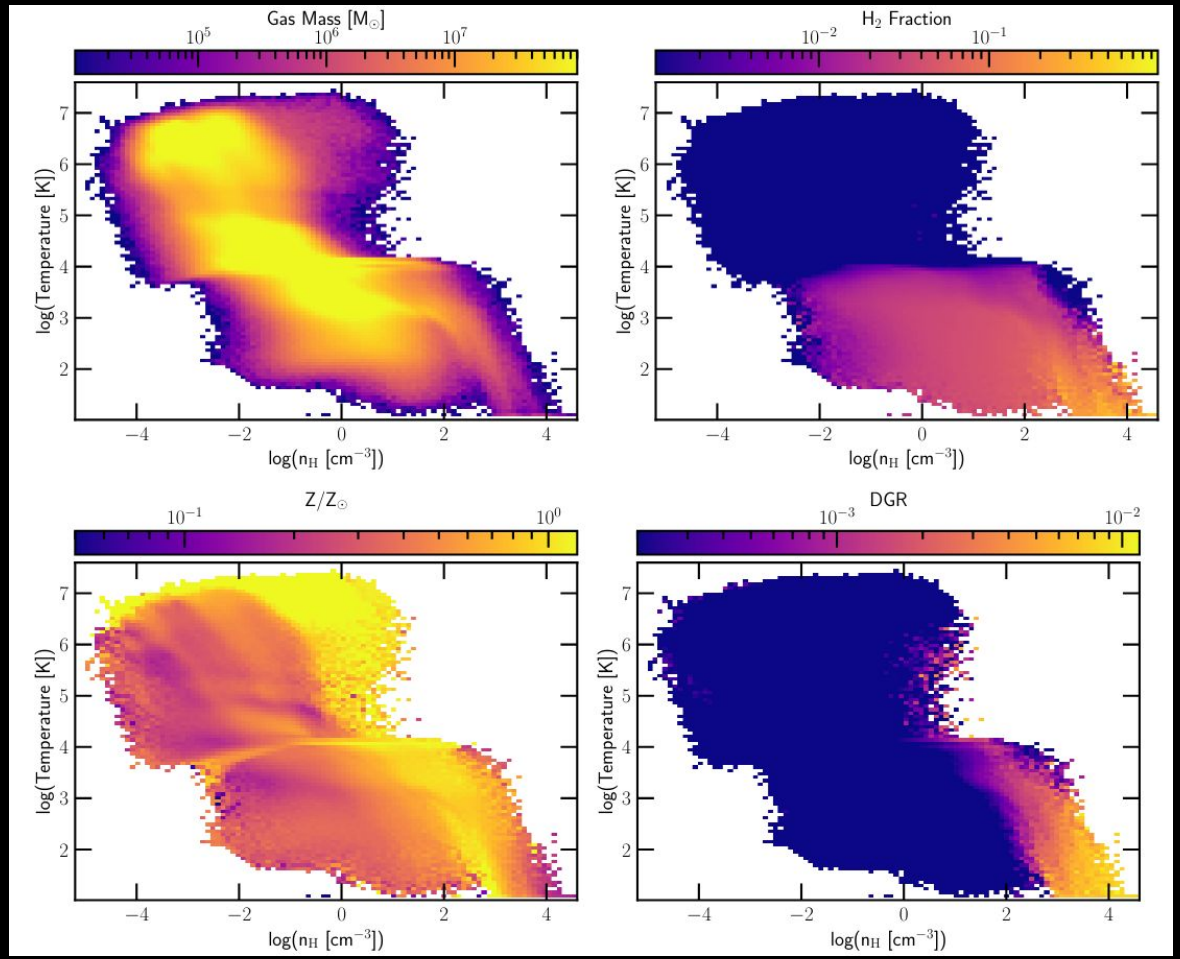
=> no uniform UVB



Multi phase ISM + self regulation

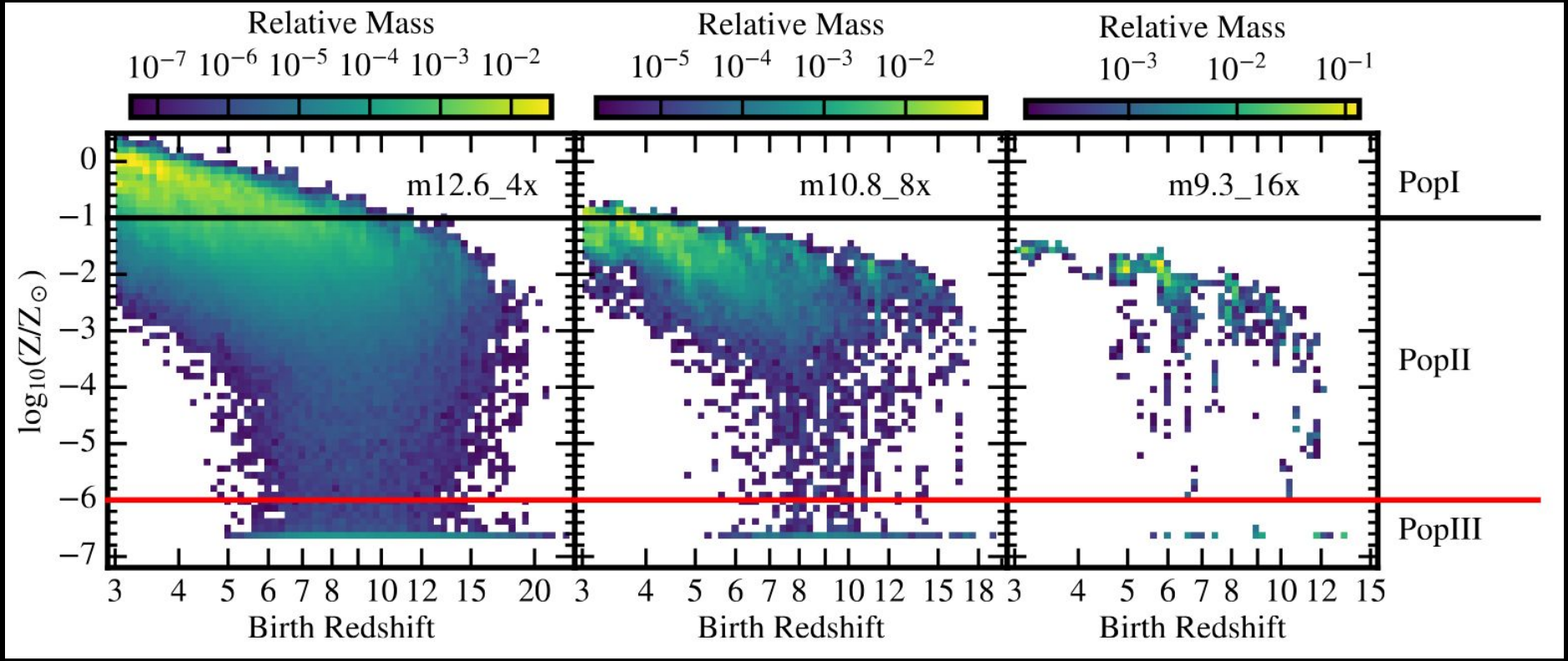


Shen+ 2025



Kannan+ 2025

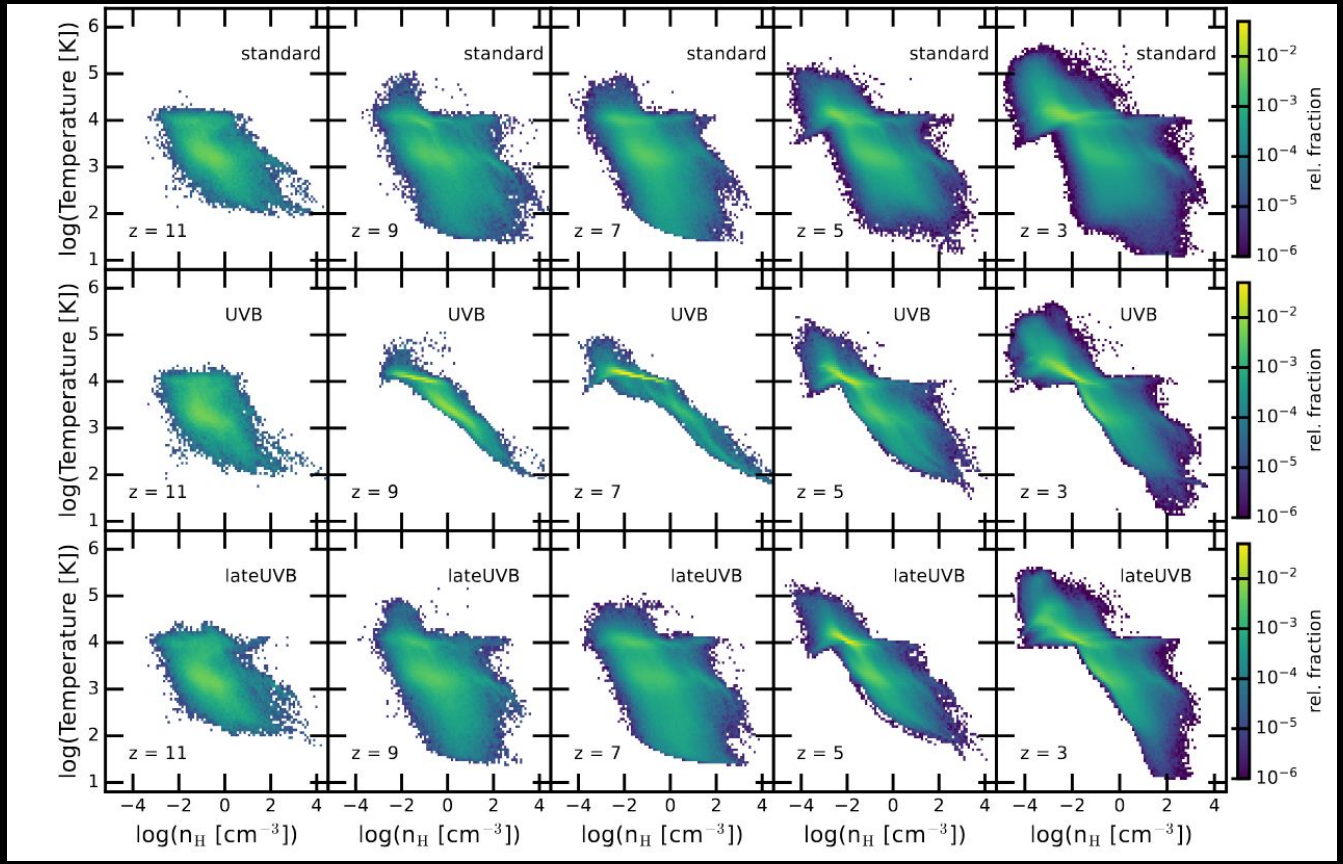
Stellar metallicity distribution in haloes at z = 3



All halos contain stars at metallicity floor formed during EoR

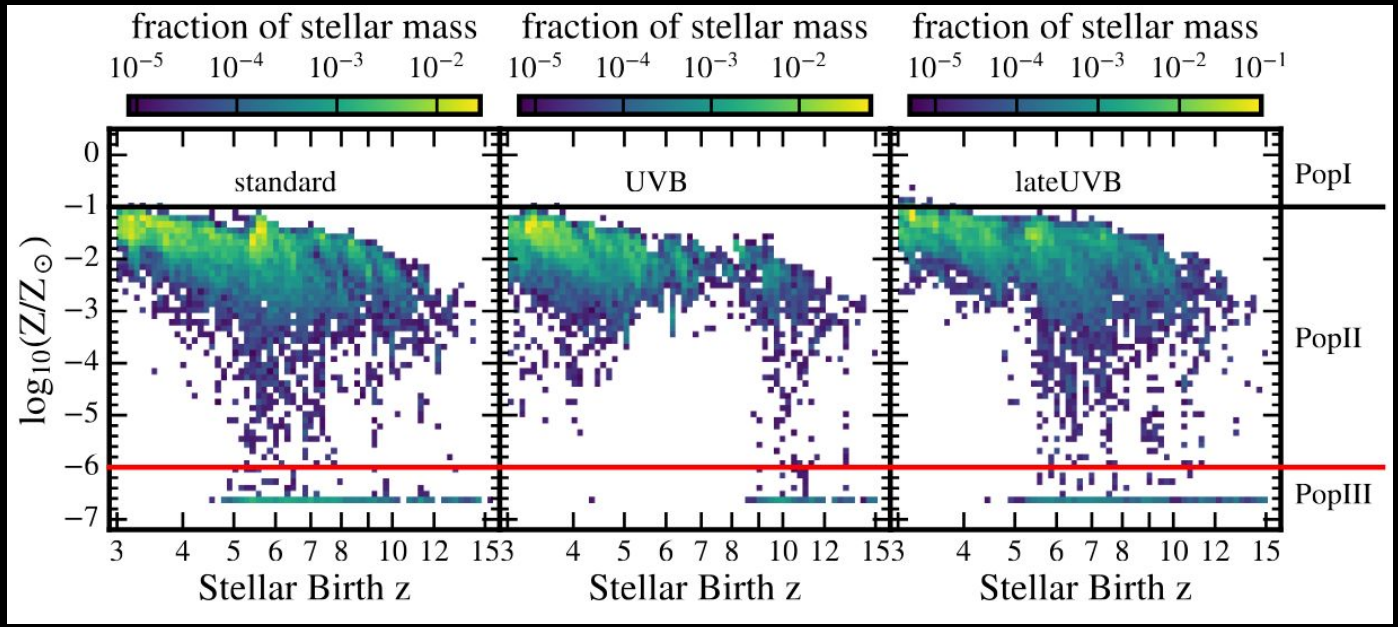
Zier+ 2025a

Impact of external radiation



Zier+ 2025

Impact of external radiation



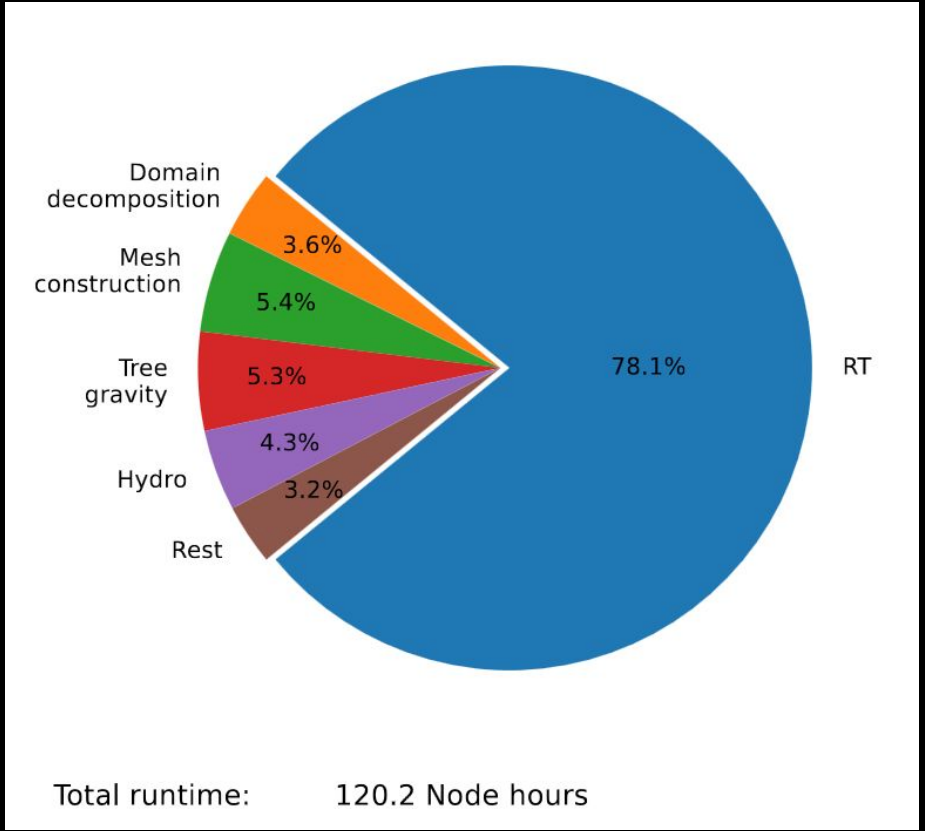
Computational challenges

Small reionization box

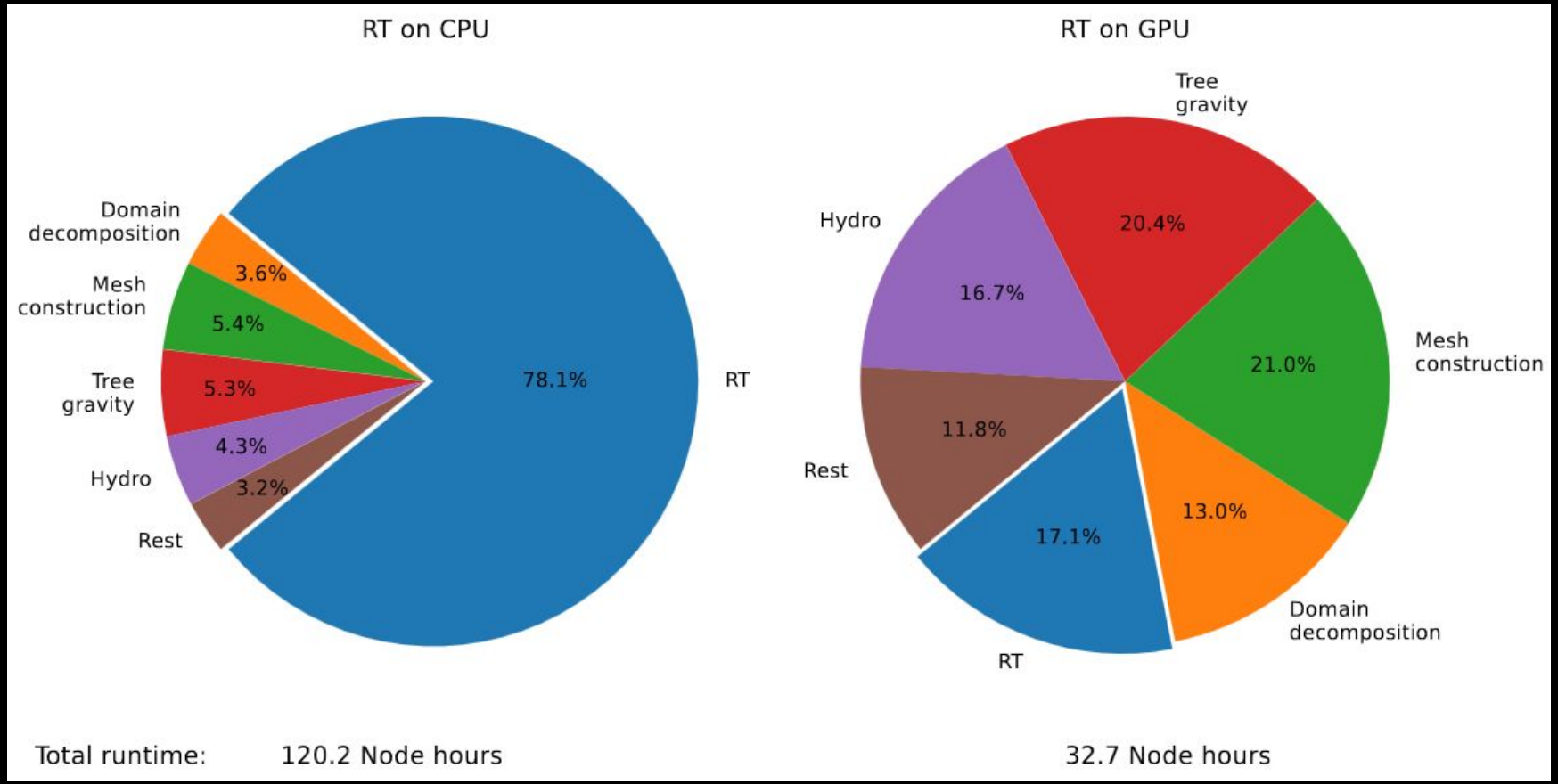
- 1 computing Node (72 cores)
- THESAN model
- 256^3 cells

time step criterion: $$\Delta t_{\mathrm{RT}} \leq \eta \frac{\Delta x}{\tilde{c} + |\boldsymbol{v}_c|},$$

=> subcycling
=> RT dominates costs



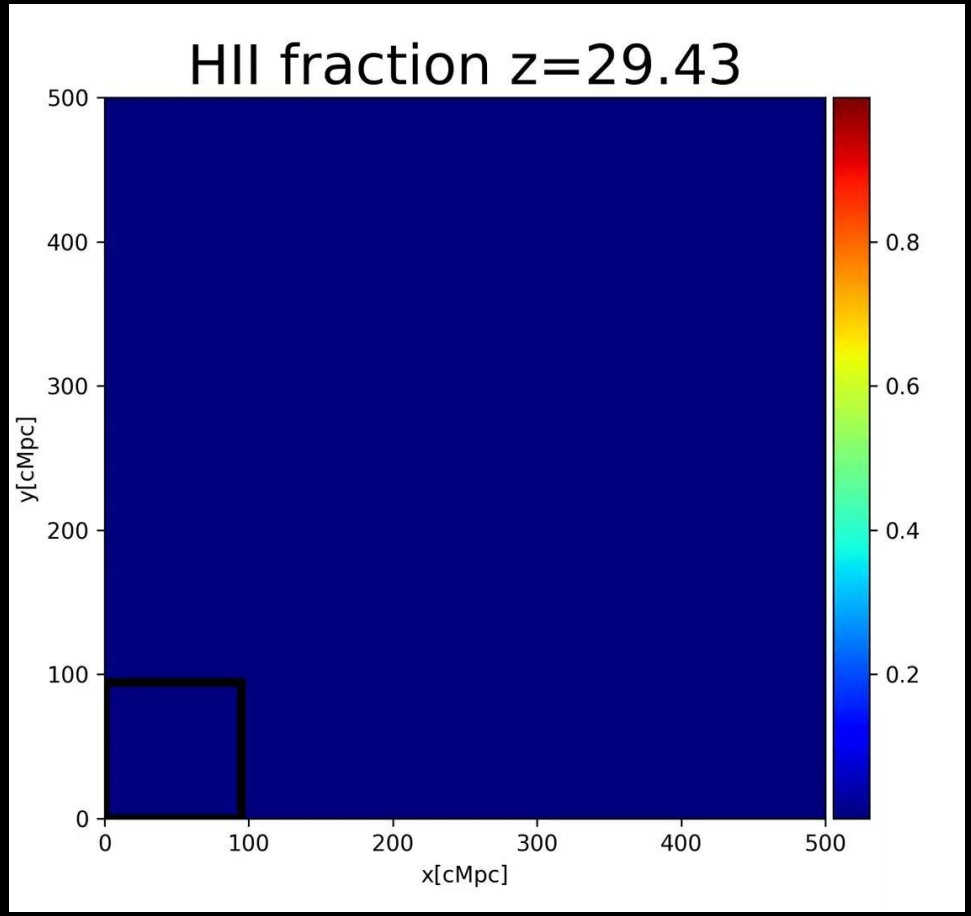
Acceleration using GPUs (Zier+ 2024)



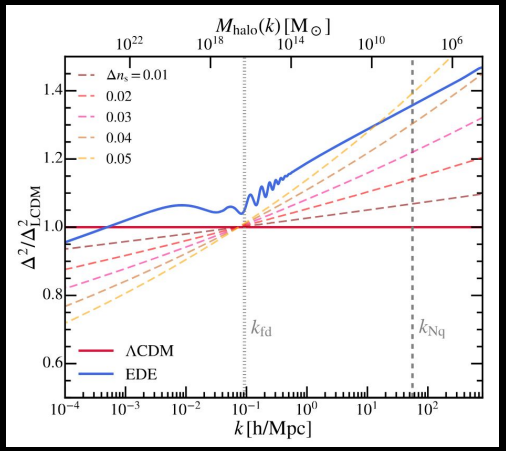
Larger Reionization box: THESAN-XL

currently running on Frontier:

- connect galaxy formation with cosmology + reionization
- expected early 2026



Constraining cosmology with reionization: EDE



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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 [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

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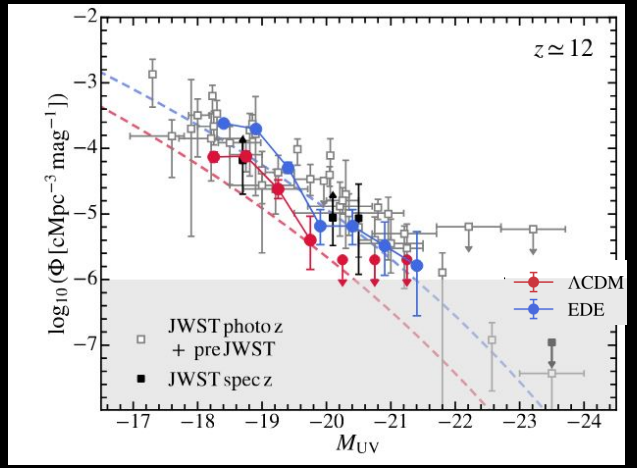


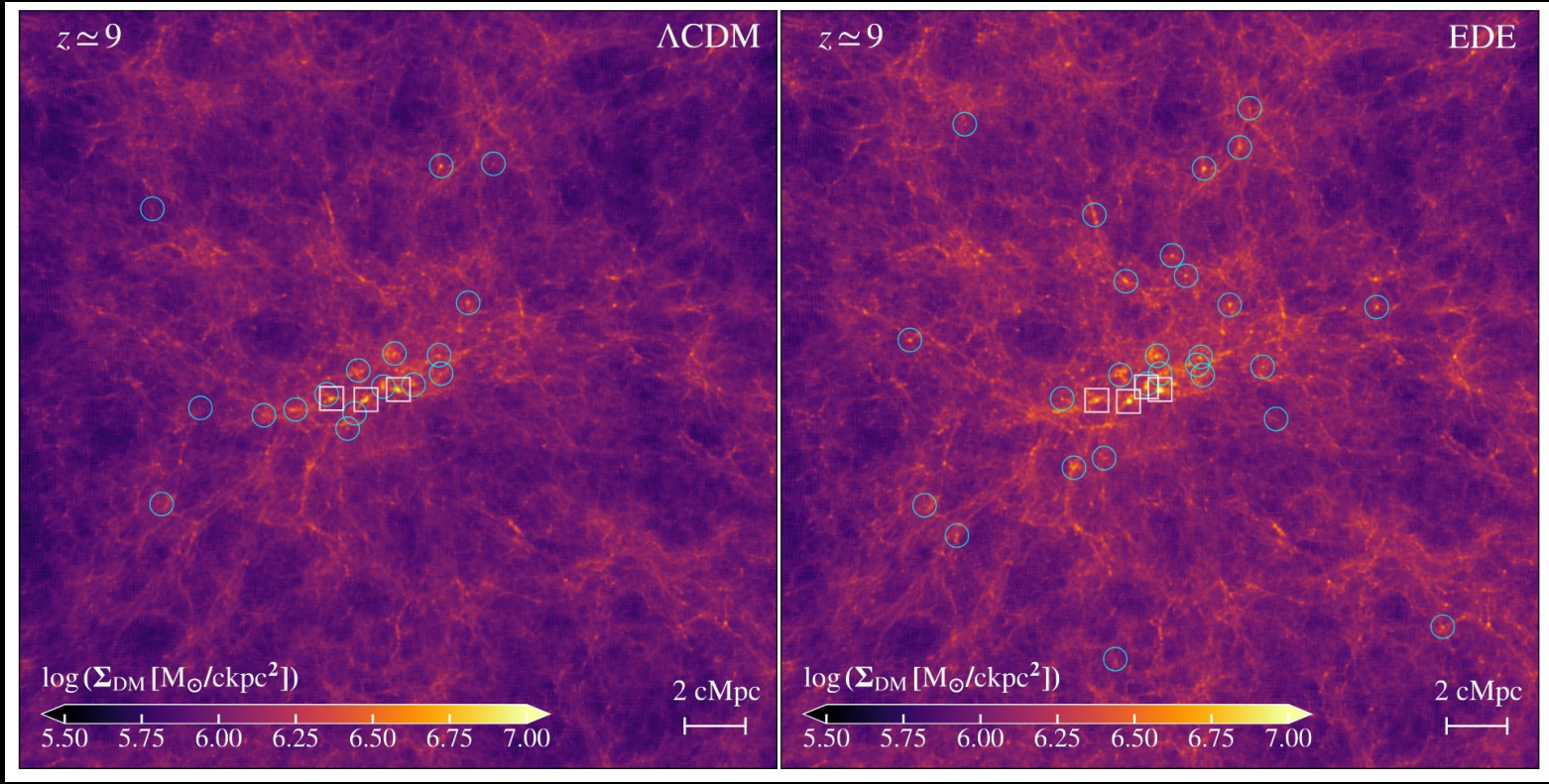
Changes initial power spectra

Changes Hubble constant

Vanilla TNG modell

Shen, Zier+ 2025

Constraining cosmology with reionization: EDE



Different clustering, impact on patchiness of reionization?

Summary

Reionization Multi scale problem

Cosmological boxes (e.g. THESAN):

- “large” scale, topology of reionization
- simplified galaxy formation model

Zoom in simulations (e.g. THESAN-Zoom):

- detailed ISM physics
- low statistics, no back reaction on larger scales

Improve algorithms / GPU acceleration:

- larger boxes (THESAN-XL)
- more boxes (different cosmologies)