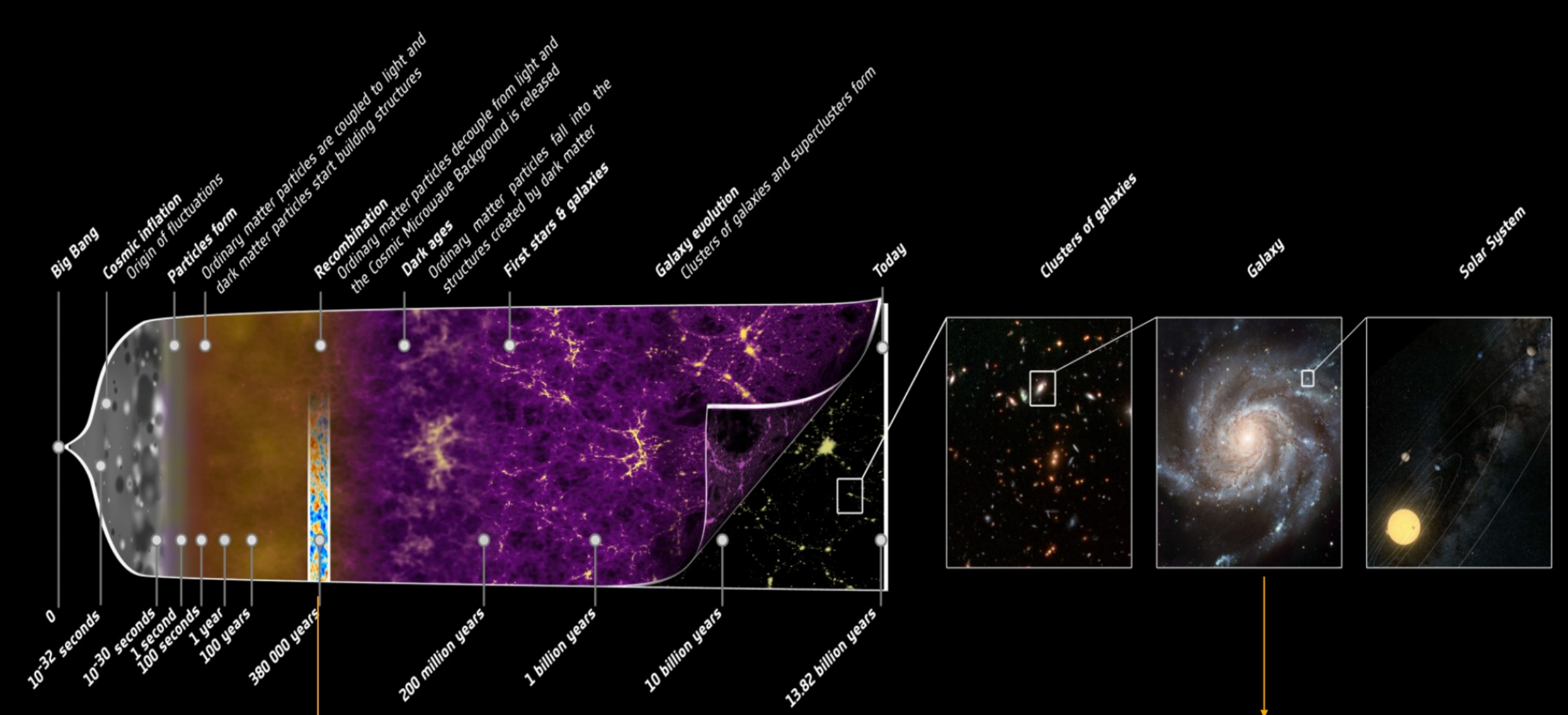
Simulating Early Structure and Galaxy Formation
- The THESAN Project -
(a brief overview)

Mark Vogelsberger

Massachusetts Institute of Technology



$$\frac{\Delta\rho}{<\rho>} \sim 10^{-5}$$

Gravity, (radiation-magneto) Hydrodynamics

Star & BH formation, Feedback

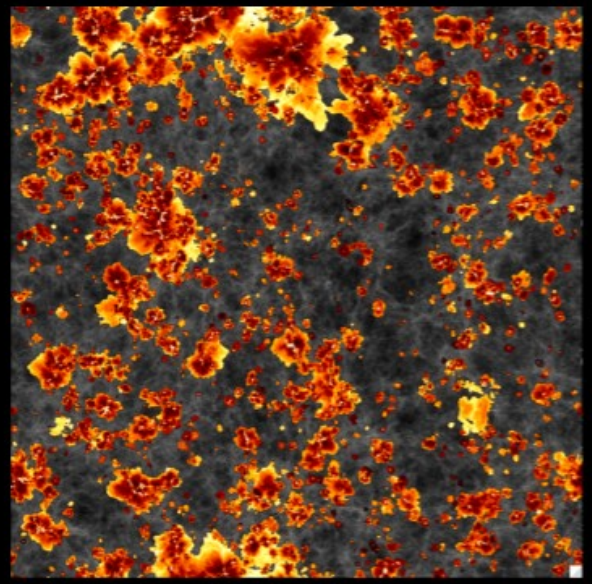
$$\frac{\Delta\rho}{<\rho>} \sim 10^{5}$$

Modeling Reionization

Stars (GMCs) and BH generate photons (~ pc)

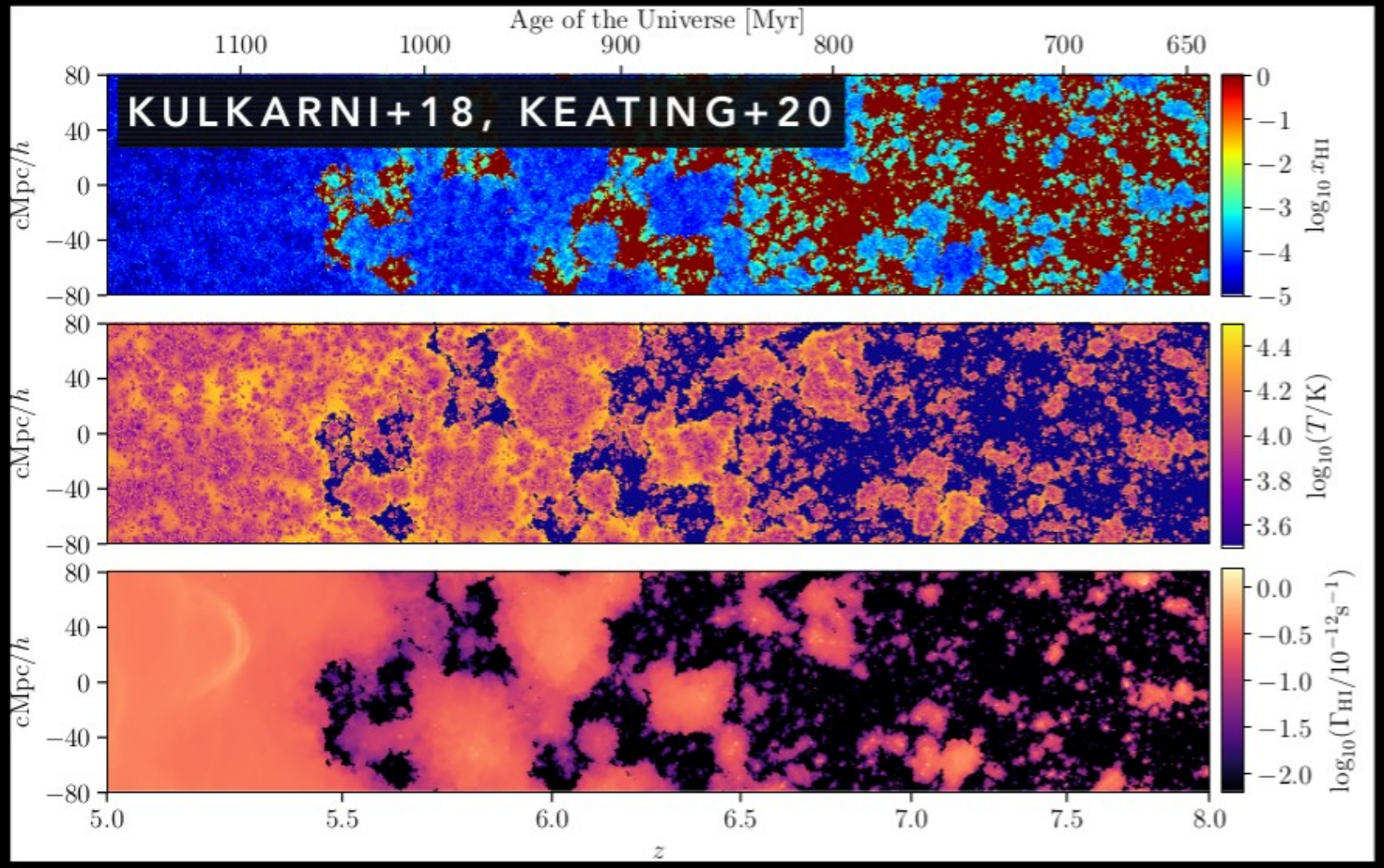
Transmission through ISM (~ kpc)

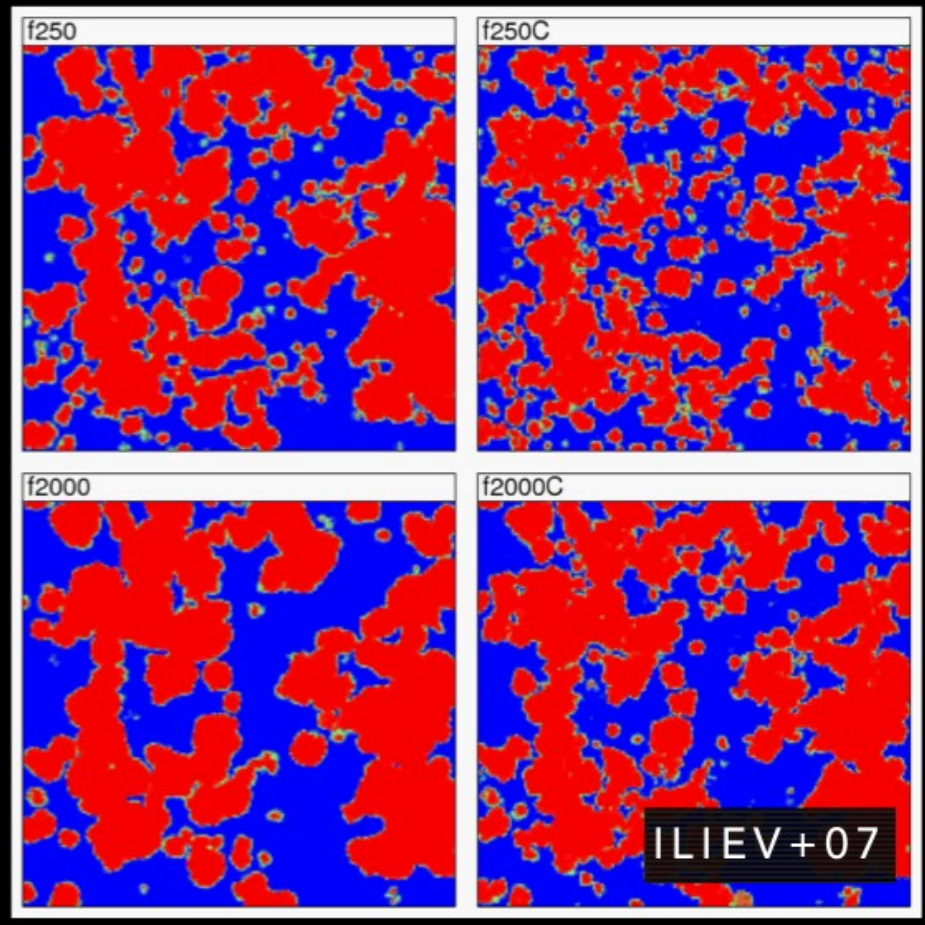
Transmission through CGM (~ 100s kpc)



Affect on IGM (~100s Mpc)

Post-Processing





→ post-process RT on grid

→ approximate source functions, escape fractions, gas self shielding, source SEDs

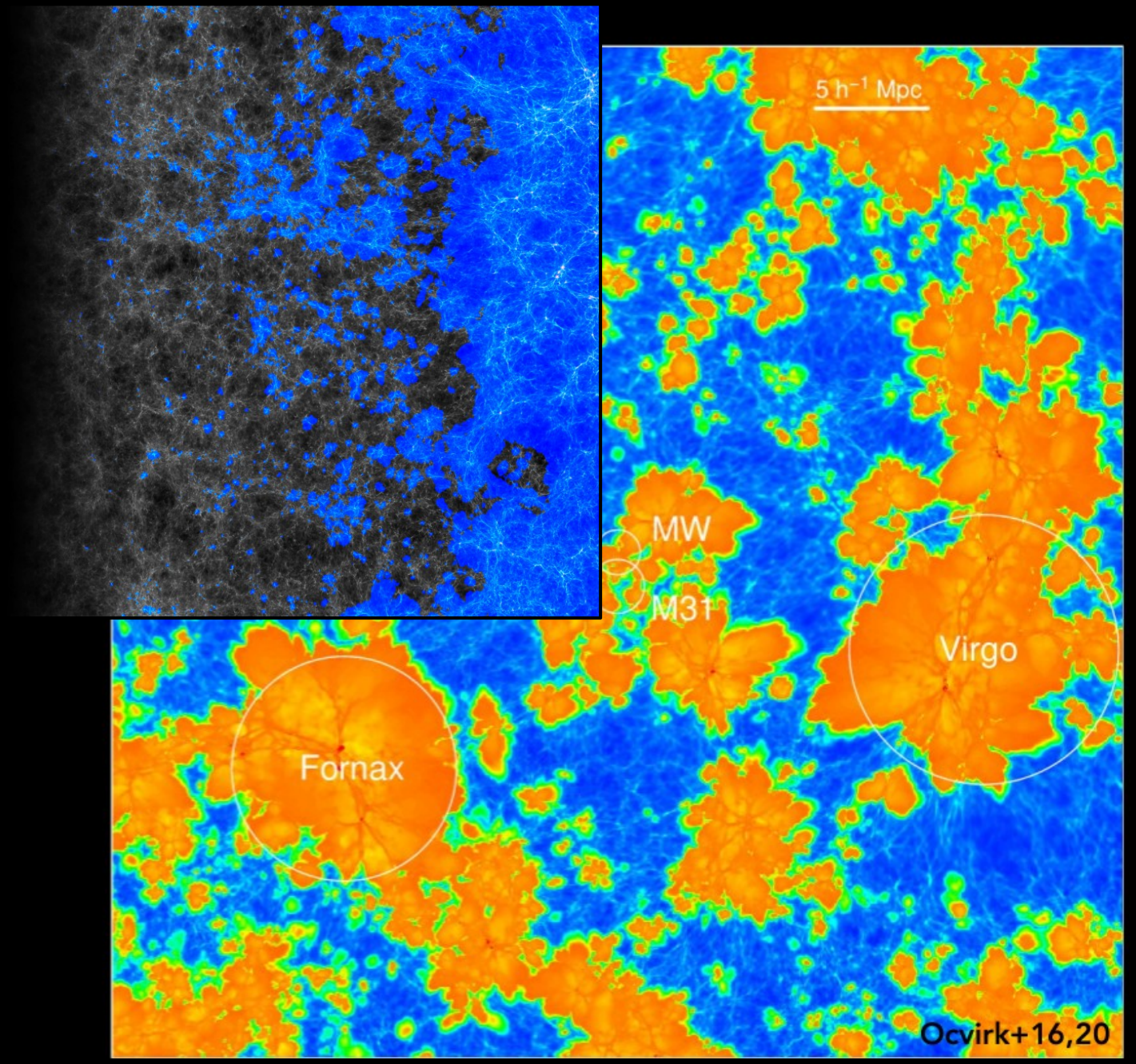
→ efficient parameter exploration

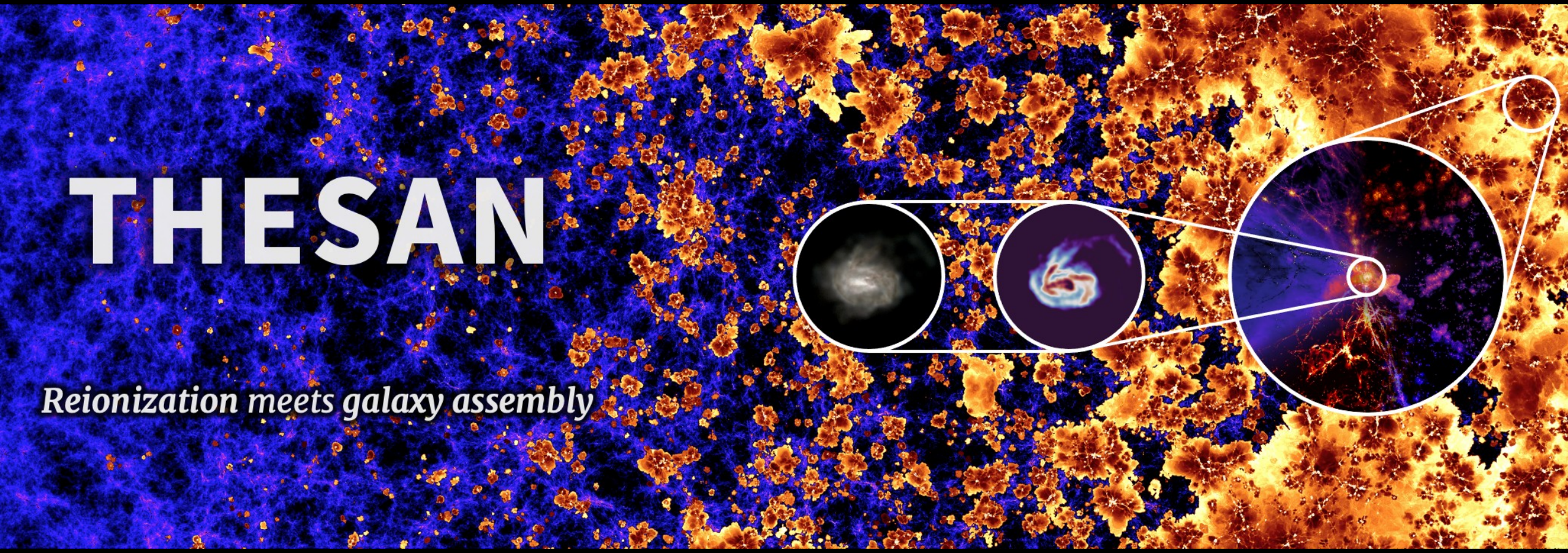
Full RHD-Simulations

→ computationally expensive

→ requires efficient RT solver

→ requires accurate modeling of sources



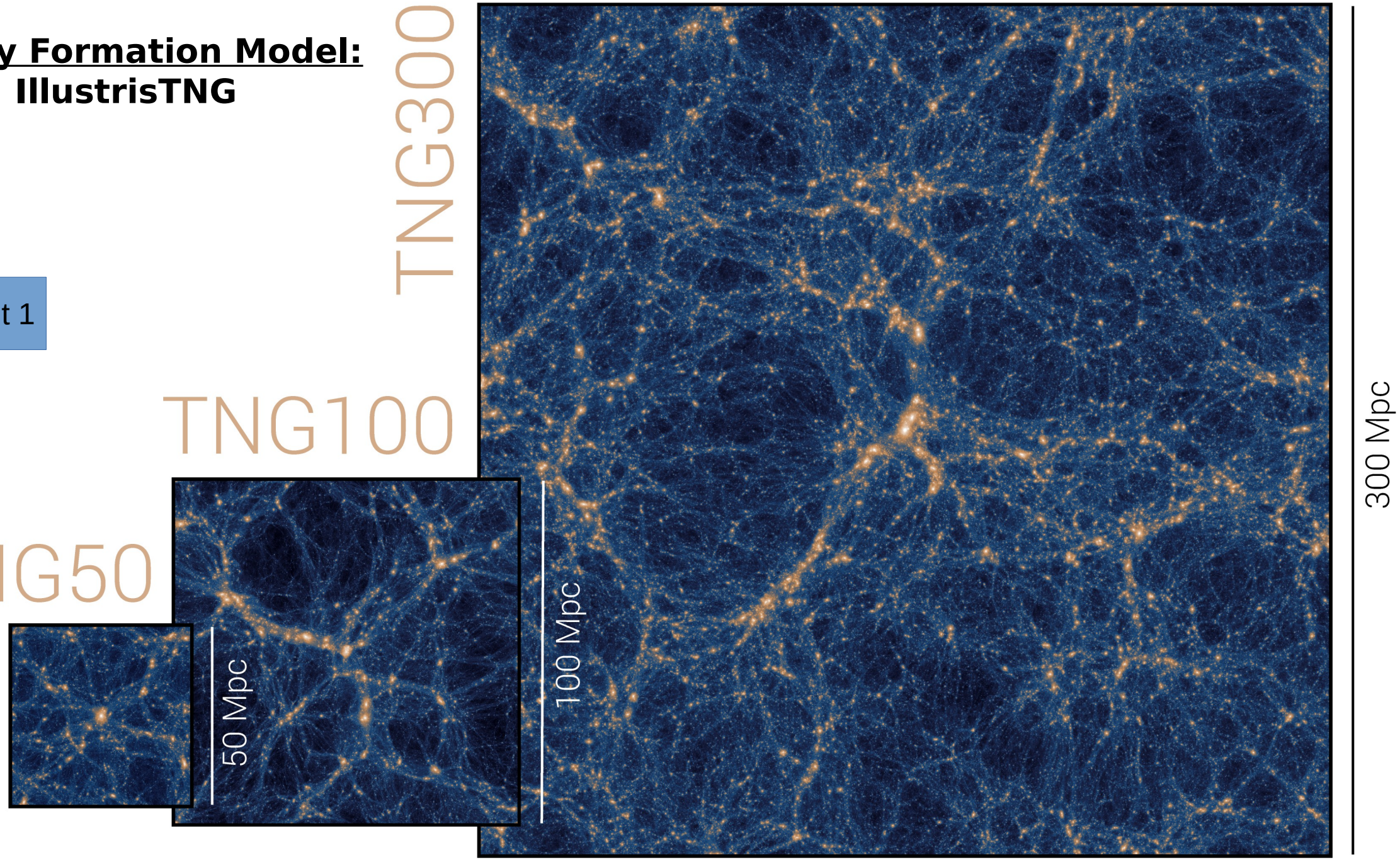


Rahul Kannan **Aaron Smith** **Enrico Garaldi**
Mark Vogelsberger Rüdiger Pakmor Volker Springel Lars Hernquist

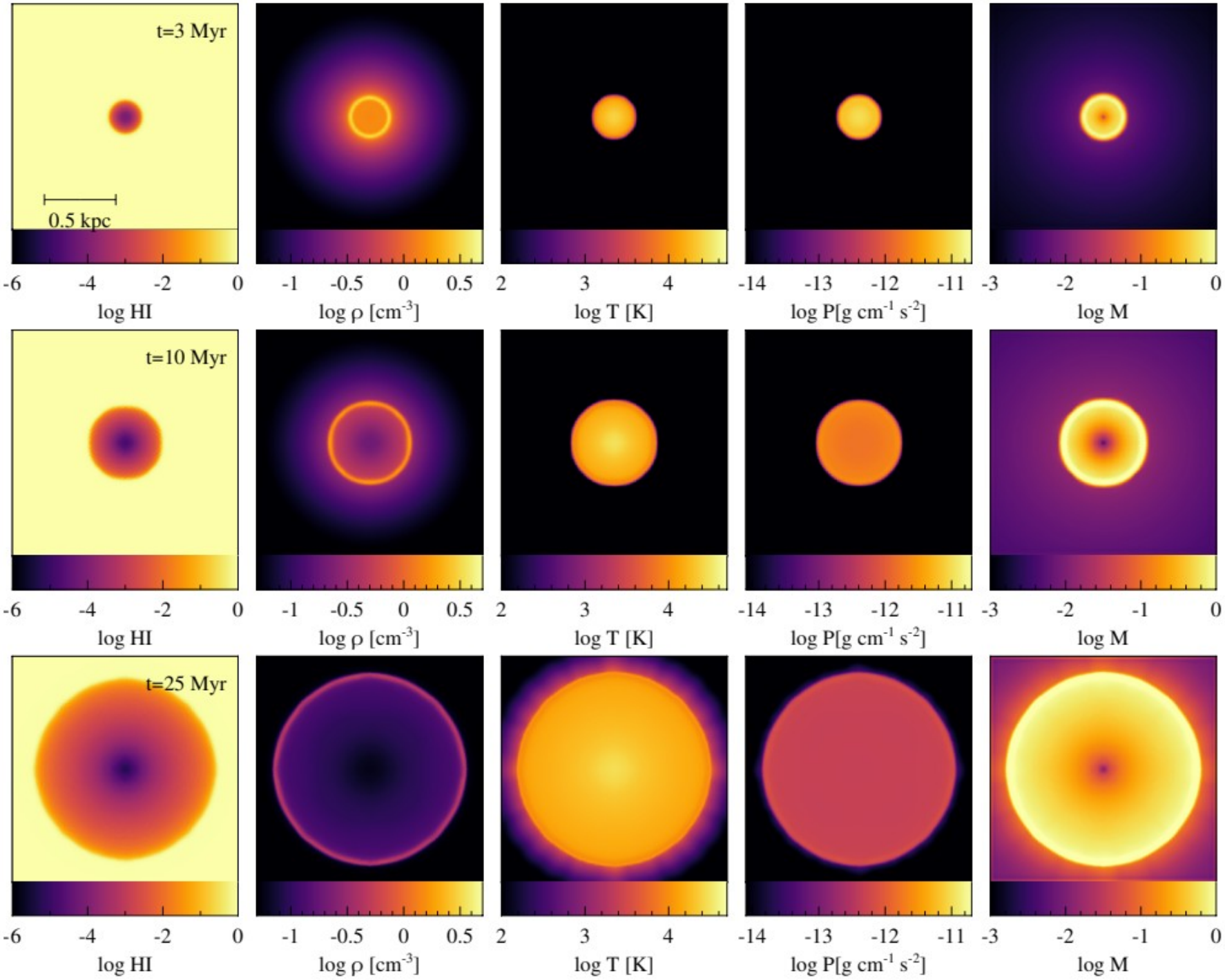
www.thesan-project.com

Galaxy Formation Model:
IllustrisTNG

Ingredient 1



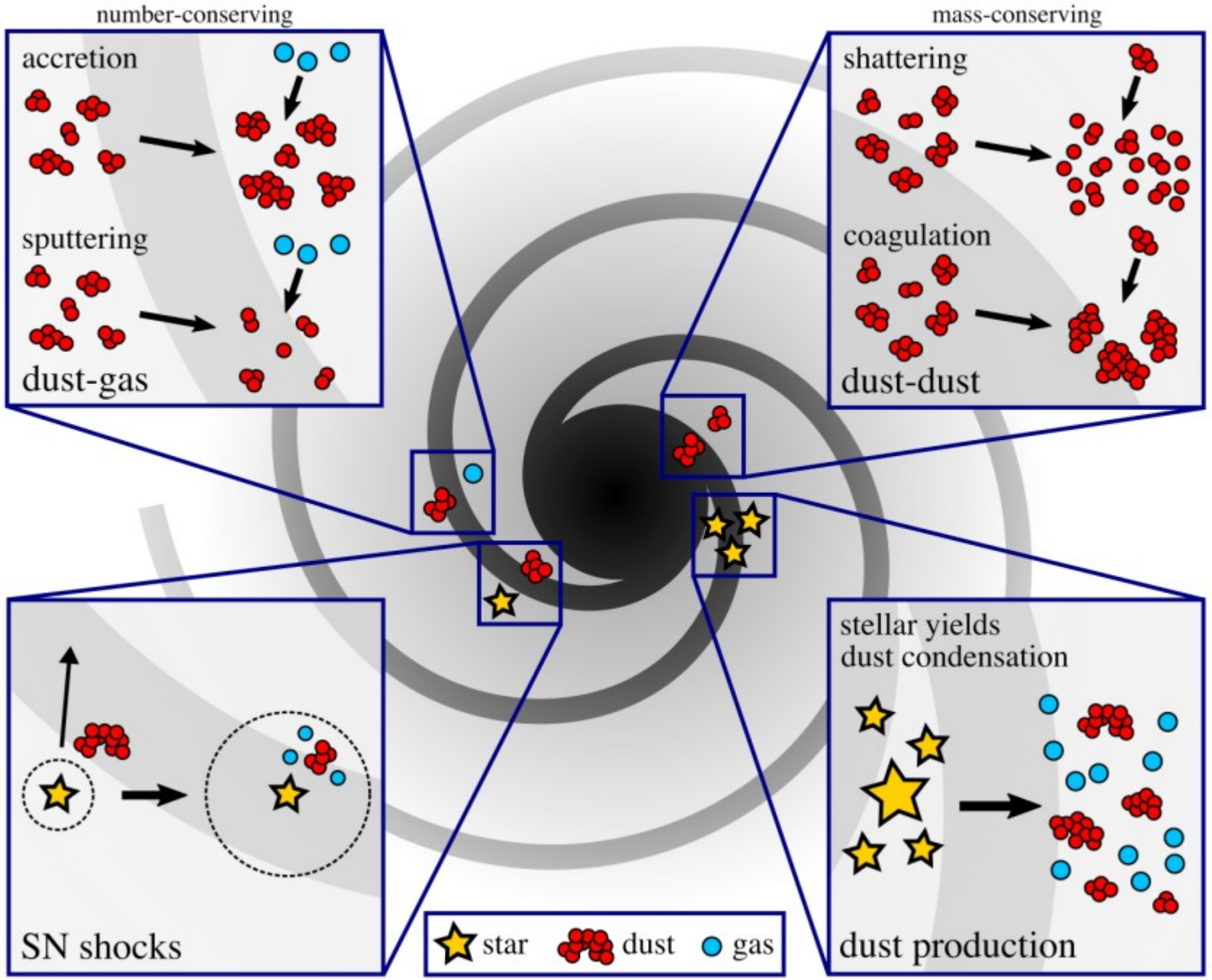
Radiative Transfer: Arepo-RT



- → **moment-based approach**
- → **second-order**
- → **3 frequency bins: [13.6, 24.6, 54.4, ∞) eV**
- → **reduced speed of light 0.2 c**

Ingredient 2

Kannan+ 2019



Dust Model:
Scalar Dust / Live Dust

$$\frac{\mathrm{d}M_{\mathrm{dust}}}{\mathrm{d}t} = \left(1 - \frac{M_{\mathrm{dust}}}{M_{\mathrm{metal}}}\right) \frac{M_{\mathrm{dust}}}{\tau_{\mathrm{g}}}$$

$$\frac{\mathrm{d}M_{\mathrm{dust}}}{\mathrm{d}t} = -\frac{M_{\mathrm{dust}}}{\tau_{\mathrm{sh}}} - \frac{M_{\mathrm{dust}}}{\tau_{\mathrm{sp}}/3}$$

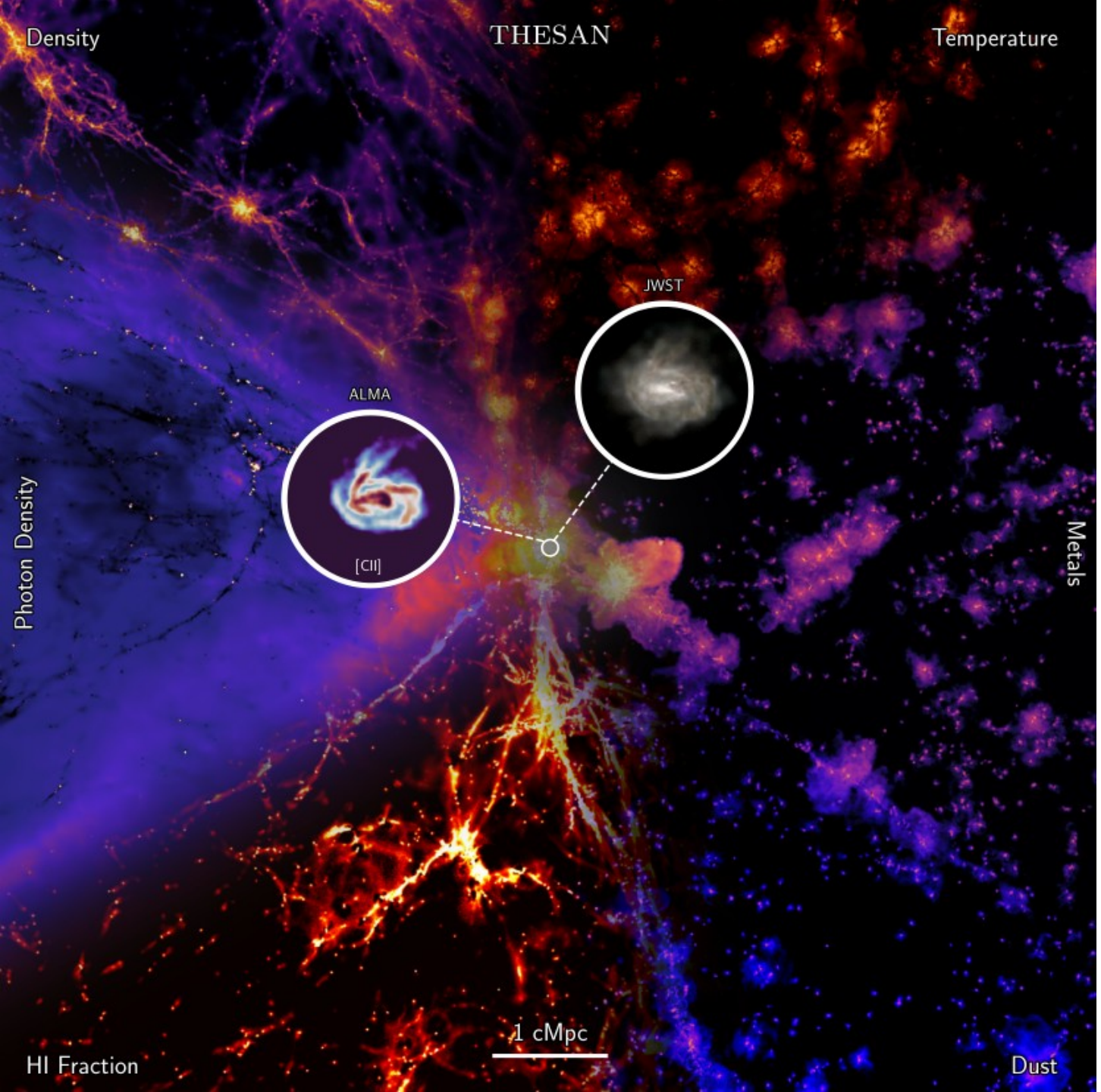
→ growth depends on local gas density and temperature

→ shock-driven destruction depends on local SN rate

→ sputtering depends on local gas temperature

Ingredient 3

McKinnon+ 2018



Thesan Simulation Parameters

- → **volume: (95.5 cMpc)^3**
- → **particle number: 2 x 2100^3**
- → **dark matter particle mass: 3.1 x 10^6 $M_\odot$**
- → **gas cell mass: 5.8 x 10^5 $M_\odot$**
- → **softening length: 2.2 ckpc**
- → **smallest cell size: 10 pc**

Kannan+ 2022

Thesan Simulation Suite

Name	$L_{\rm box}$ [cMpc]	$N_{\rm particles}$	$m_{\rm DM}$ [$M_\odot$]	$m_{\rm gas}$ [$M_\odot$]	ϵ [ckpc]	$r_{\rm cell}^{\rm min}$ [pc]	$z_{\rm end}$	$f_{\rm esc}$	Description
THESAN-1	95.5	2×2100^3	3.12×10^6	5.82×10^5	2.2	~ 10	5.5	0.37	fiducial
THESAN-2	95.5	2×1050^3	2.49×10^7	4.66×10^6	4.1	~ 35	5.5	0.37	fiducial
THESAN-WC-2	95.5	2×1050^3	2.49×10^7	4.66×10^6	4.1	~ 35	5.5	0.43	weak convergence of $x_{\rm HI}(z)$
THESAN-HIGH-2	95.5	2×1050^3	2.49×10^7	4.66×10^6	4.1	~ 35	5.5	0.8	$M_{\rm halo}(> 10^{10})$
THESAN-LOW-2	95.5	2×1050^3	2.49×10^7	4.66×10^6	4.1	~ 35	5.5	0.95	$M_{\rm halo}(< 10^{10})$
THESAN-SDAO-2	95.5	2×1050^3	2.49×10^7	4.66×10^6	4.1	~ 35	5.5	0.55	Strong dark acoustic oscillations
THESAN-TNG-2	95.5	2×1050^3	2.49×10^7	4.66×10^6	4.1	~ 35	5.5	-	original TNG model
THESAN-TNG-SDAO-2	95.5	2×1050^3	2.49×10^7	4.66×10^6	4.1	~ 35	5.5	-	original TNG model + sDAO
THESAN-NORT-2	95.5	2×1050^3	2.49×10^7	4.66×10^6	4.1	~ 35	5.5	-	no radiation
THESAN-DARK-1	95.5	2100^3	3.70×10^6	-	2.2	-	0.0	-	DM only
THESAN-DARK-2	95.5	1050^3	2.96×10^7	-	4.1	-	0.0	-	DM only

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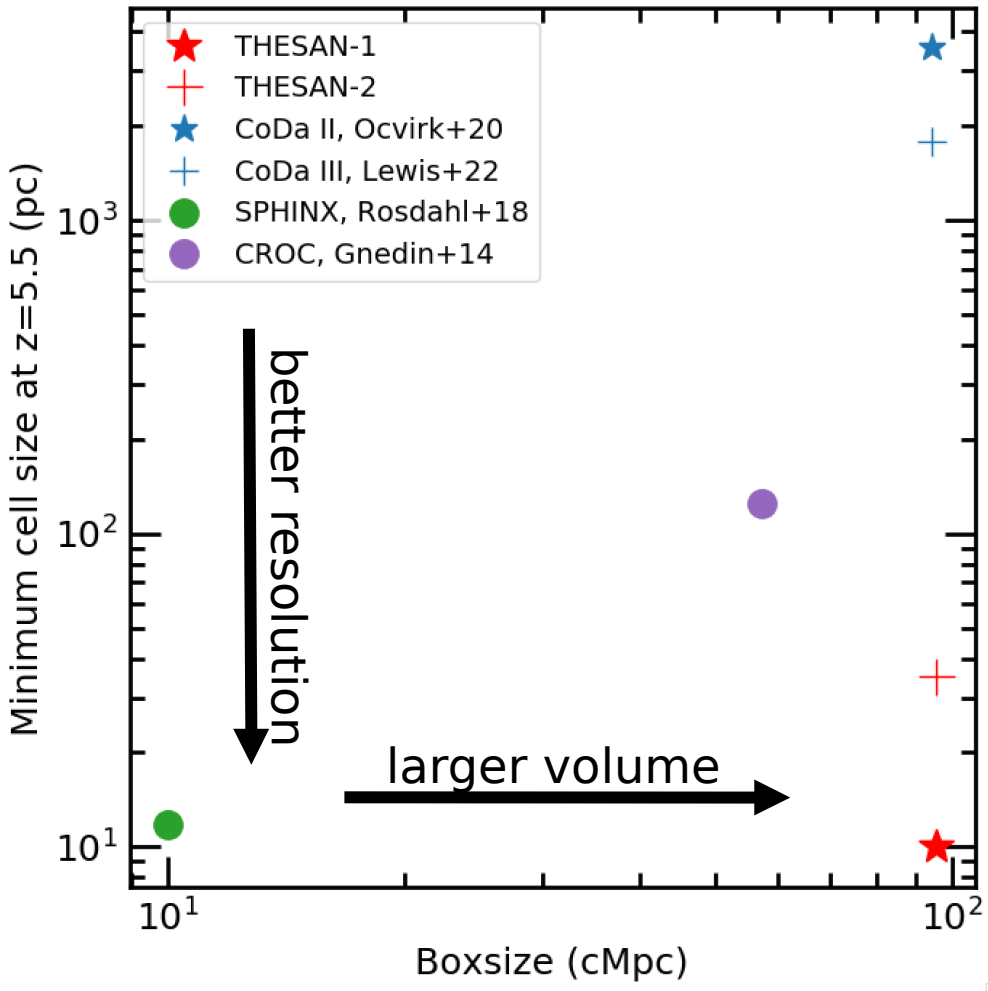
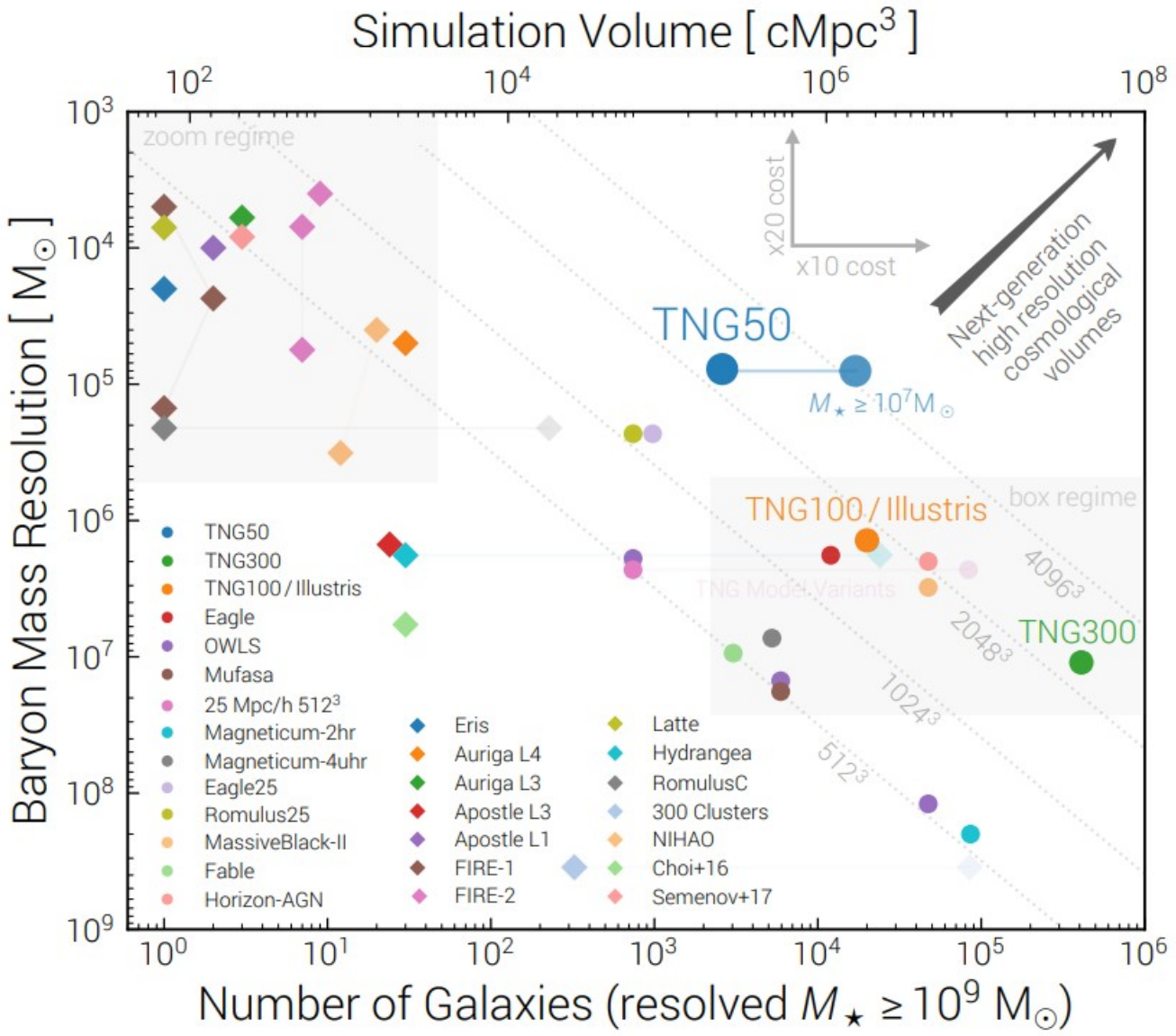
Resolution and Volume Comparison

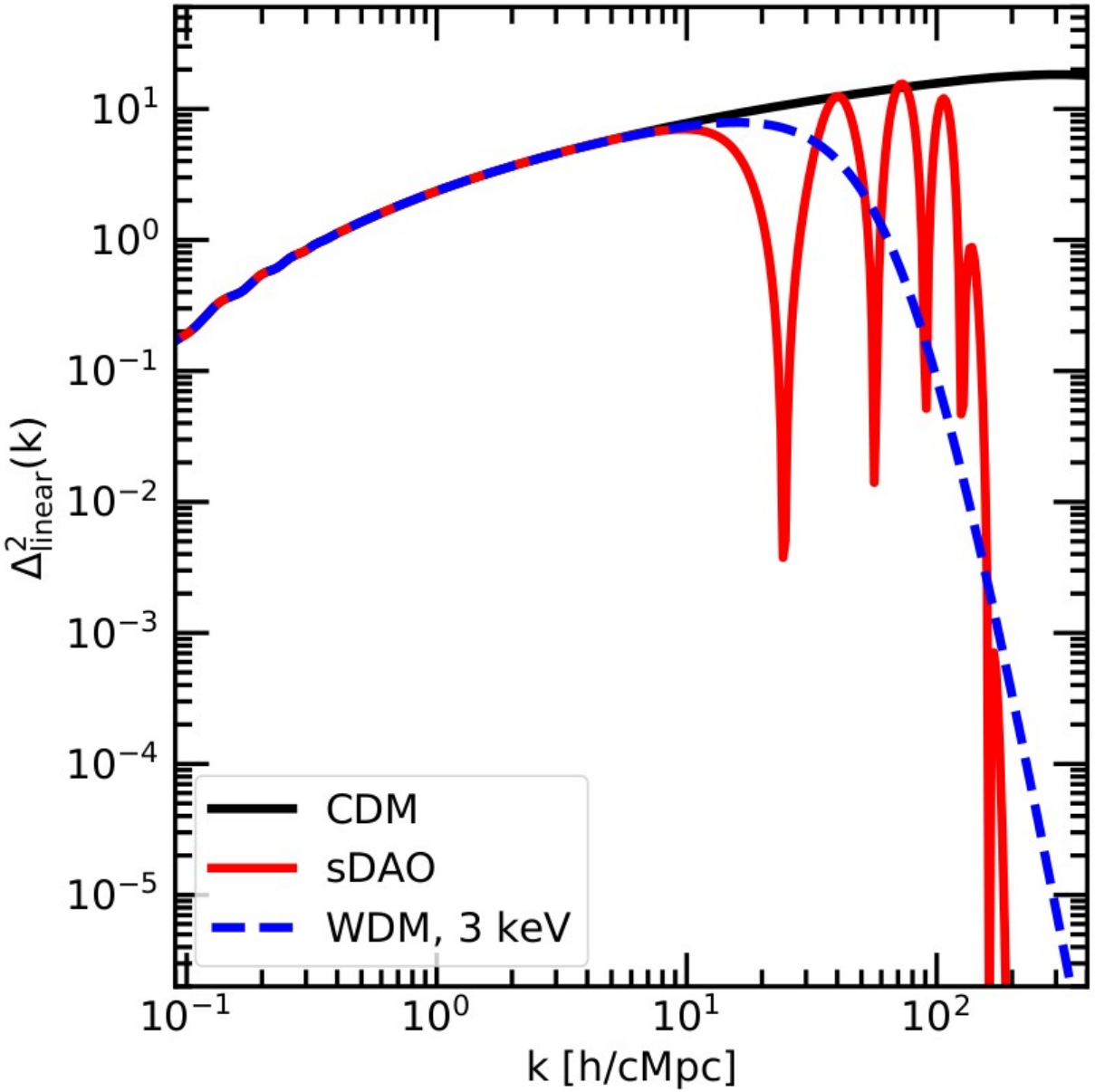




Credit: Rahul Kannan

Nelson+ 2019

Alternative Dark Matter Models



→ alternative DM models at level 2 resolution

→ sDAO model: collisional damping due to interactions between DM particles and relativistic particles in the early Universe causing Dark Acoustic Oscillations

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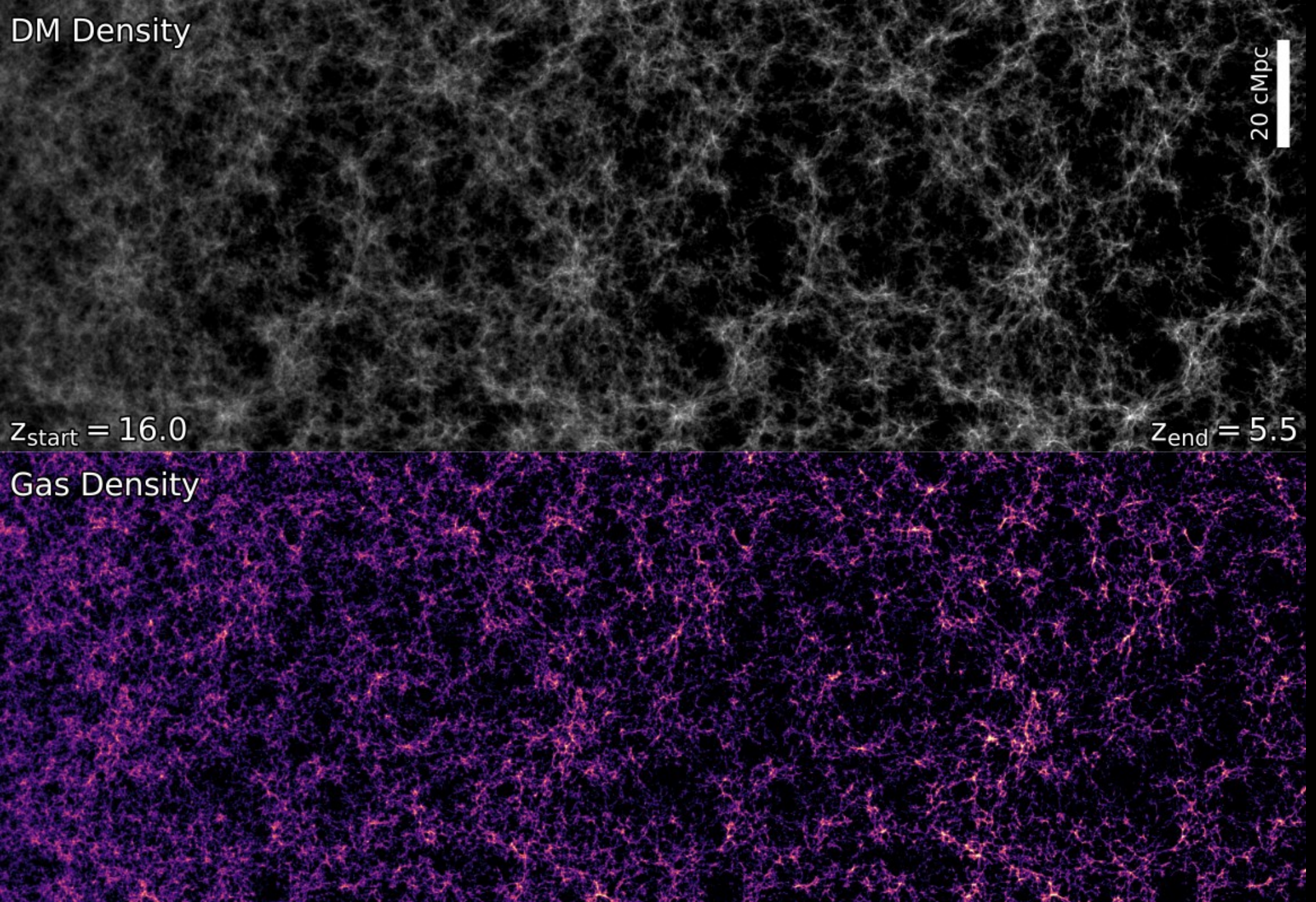
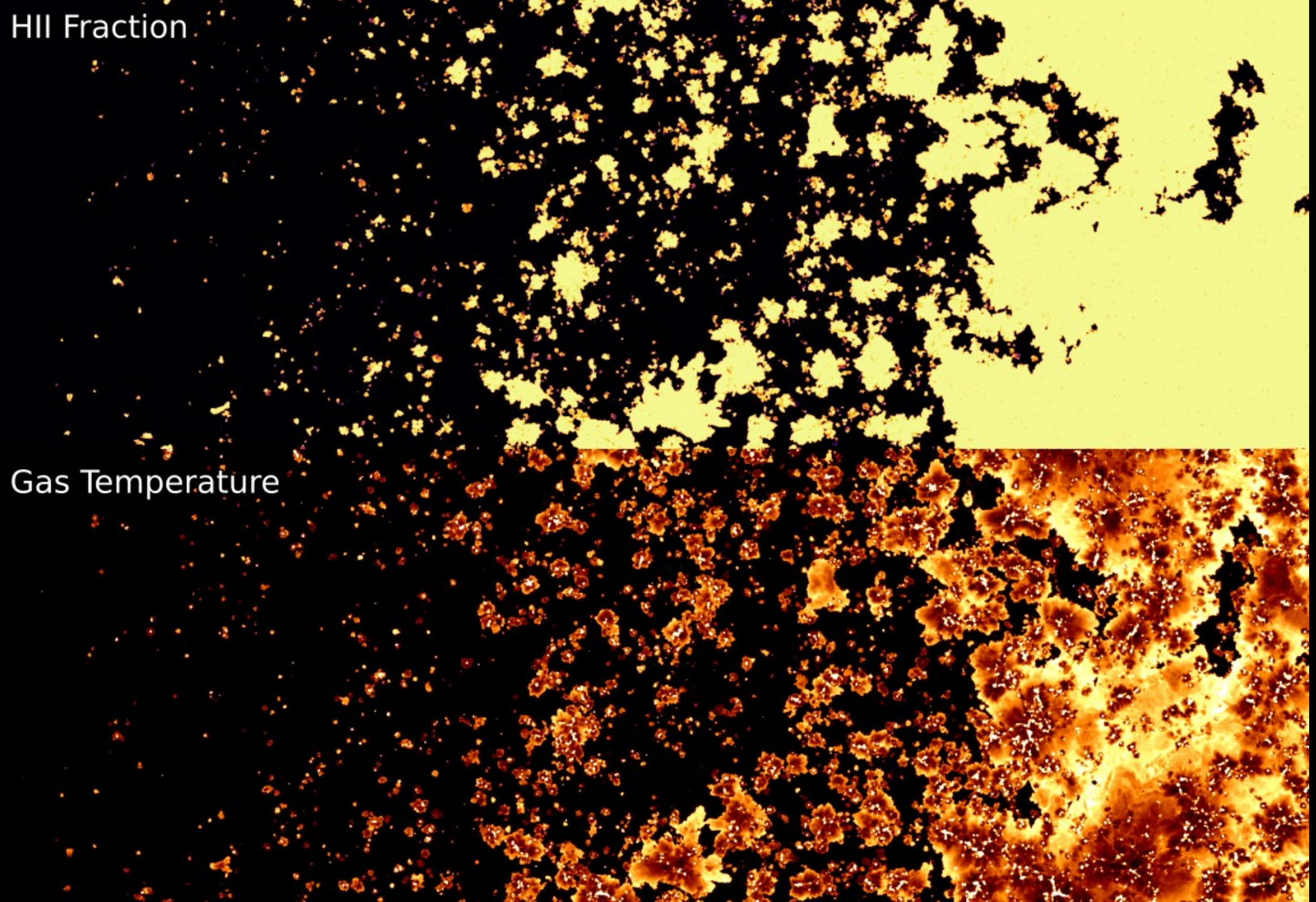


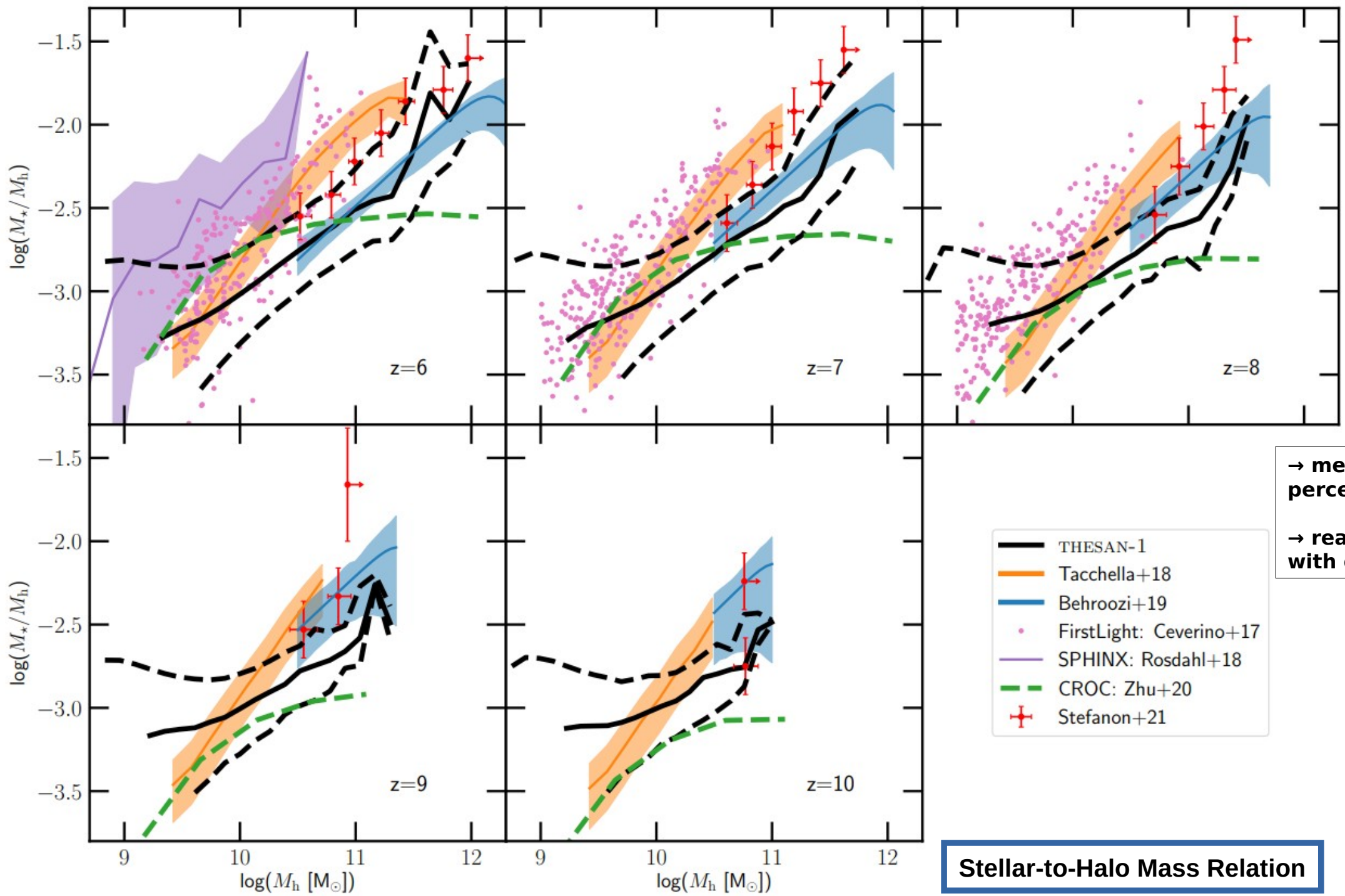
THESAN-1 light cones

Kannan+ 2022



THESAN-1 light cones

Kannan+ 2022

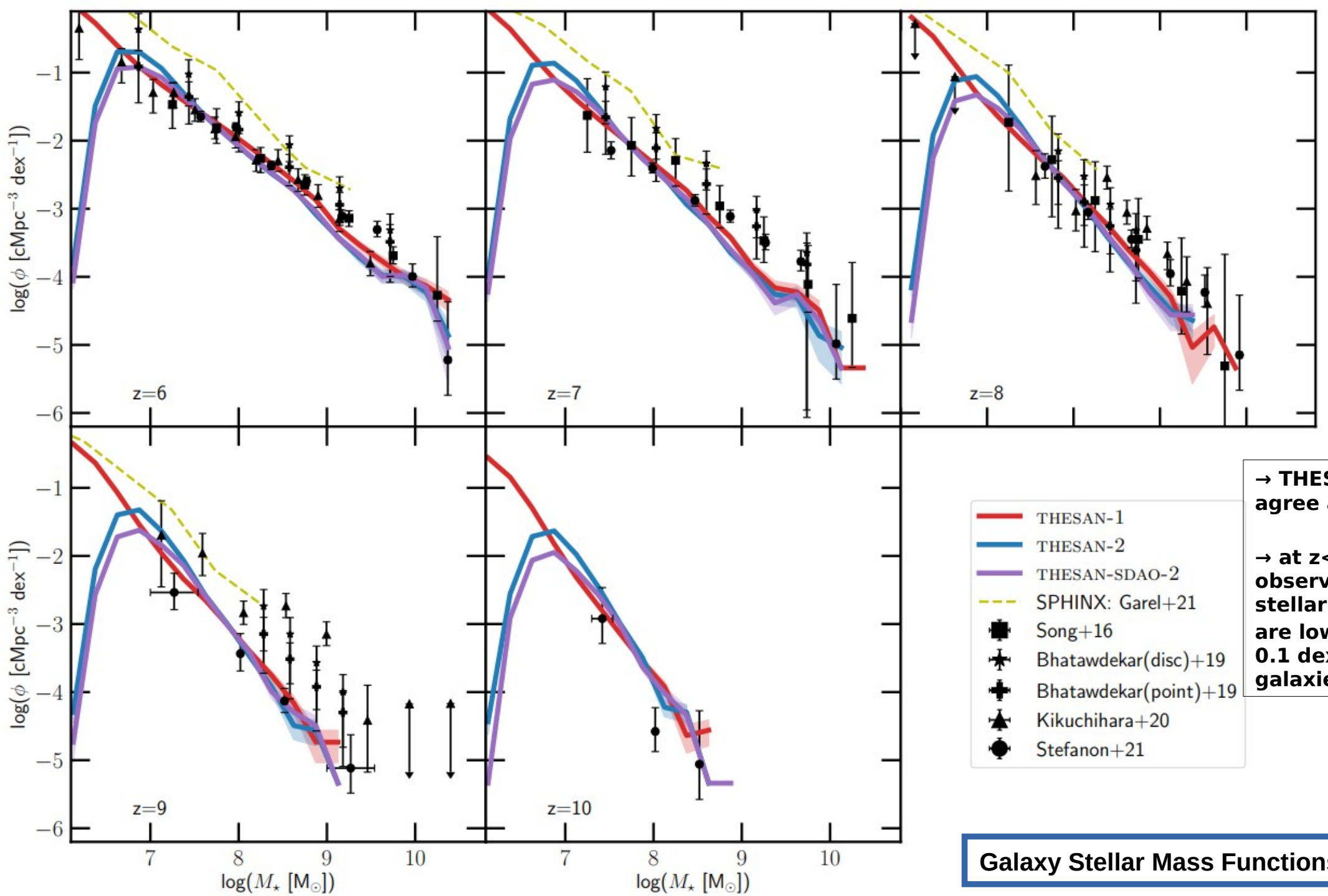


→ median and 10/90 percentiles

→ reasonable agreement with data

Stellar-to-Halo Mass Relation

Kannan+ 2022



→ THESAN-2 and THESAN-1 agree above 10^7 $M_\odot$

→ at z<8 THESAN-1 matches observational results below stellar masses of 10^9 $M_\odot$ but are lower less than about 0.1 dex for higher mass galaxies

Galaxy Stellar Mass Functions

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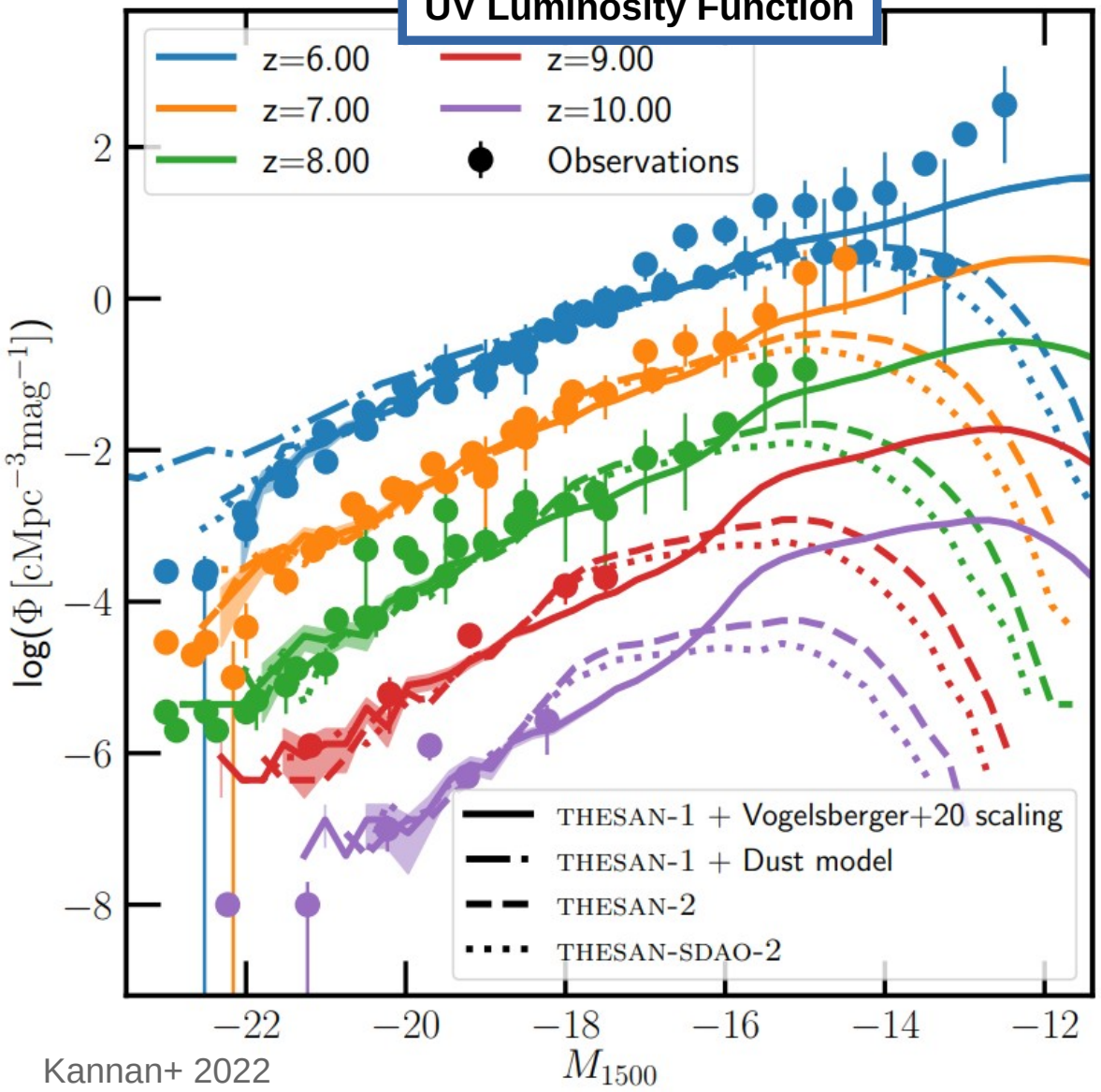
UV Luminosity Function



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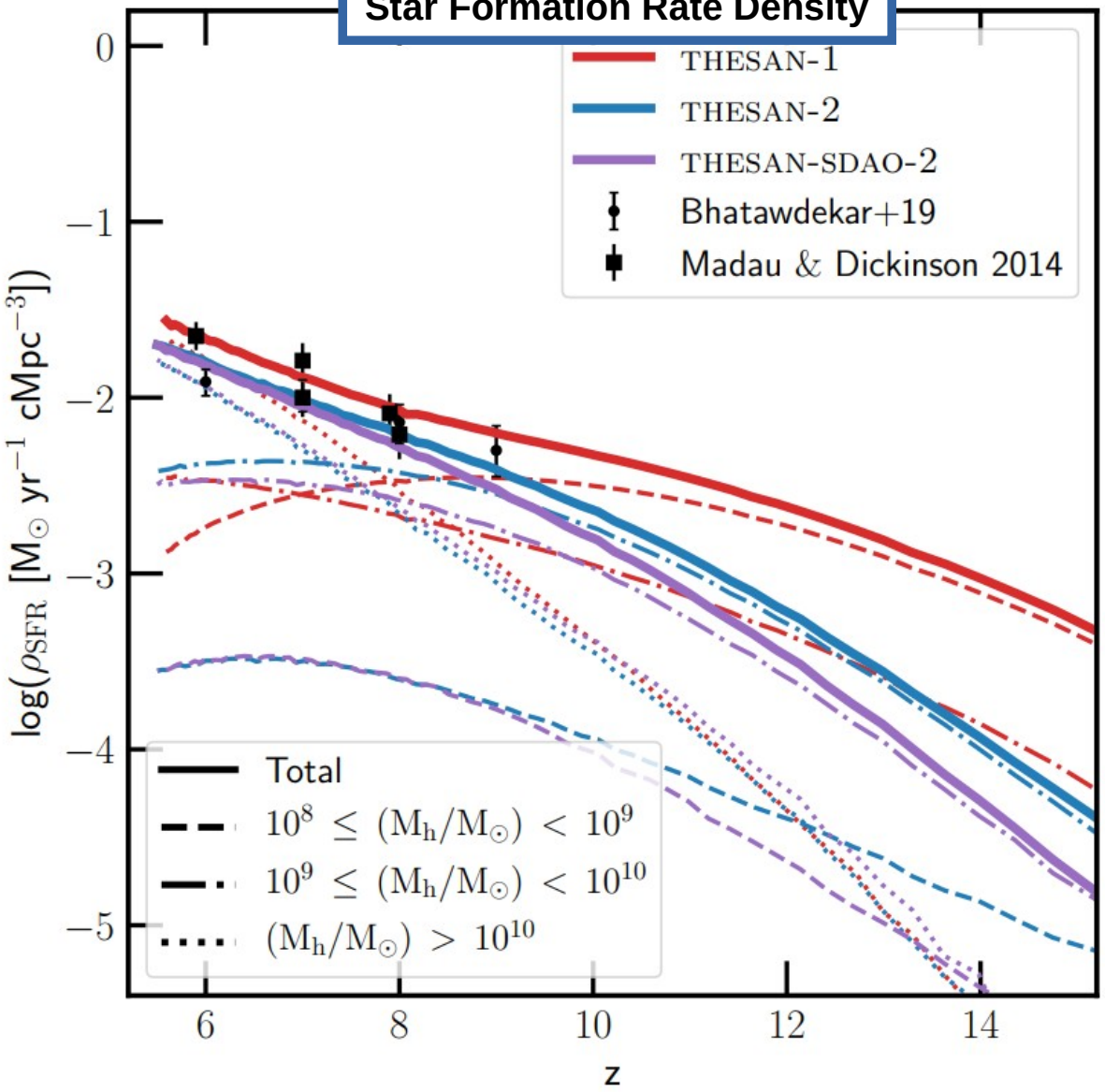
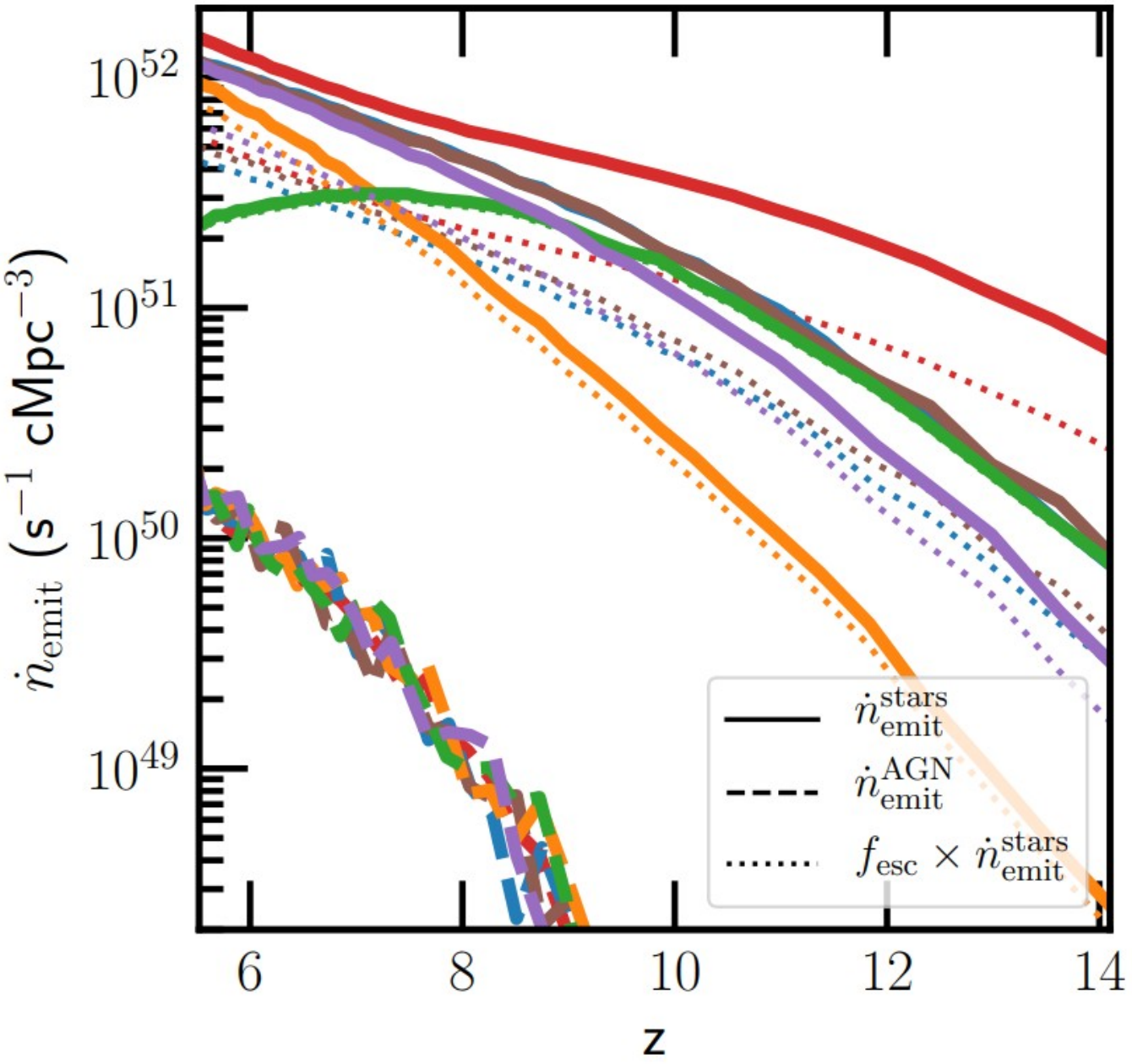
→ **UV luminosity function (1500 Å)**
→ **sDAO model shows stronger suppression than THESAN-2**

Star Formation Rate Density



→ **sDAO has lower star formation rates in low mass systems**
→ **dip in star formation in low mass halos as reionization progresses (probably photoheating feedback)**



Total Ionizing Emissivity

THESAN-1
THESAN-2
THESAN-WC-2
THESAN-HIGH-2
THESAN-LOW-2
THESAN-SDAO-2

small contribution of AGN to total ionizing photon budget

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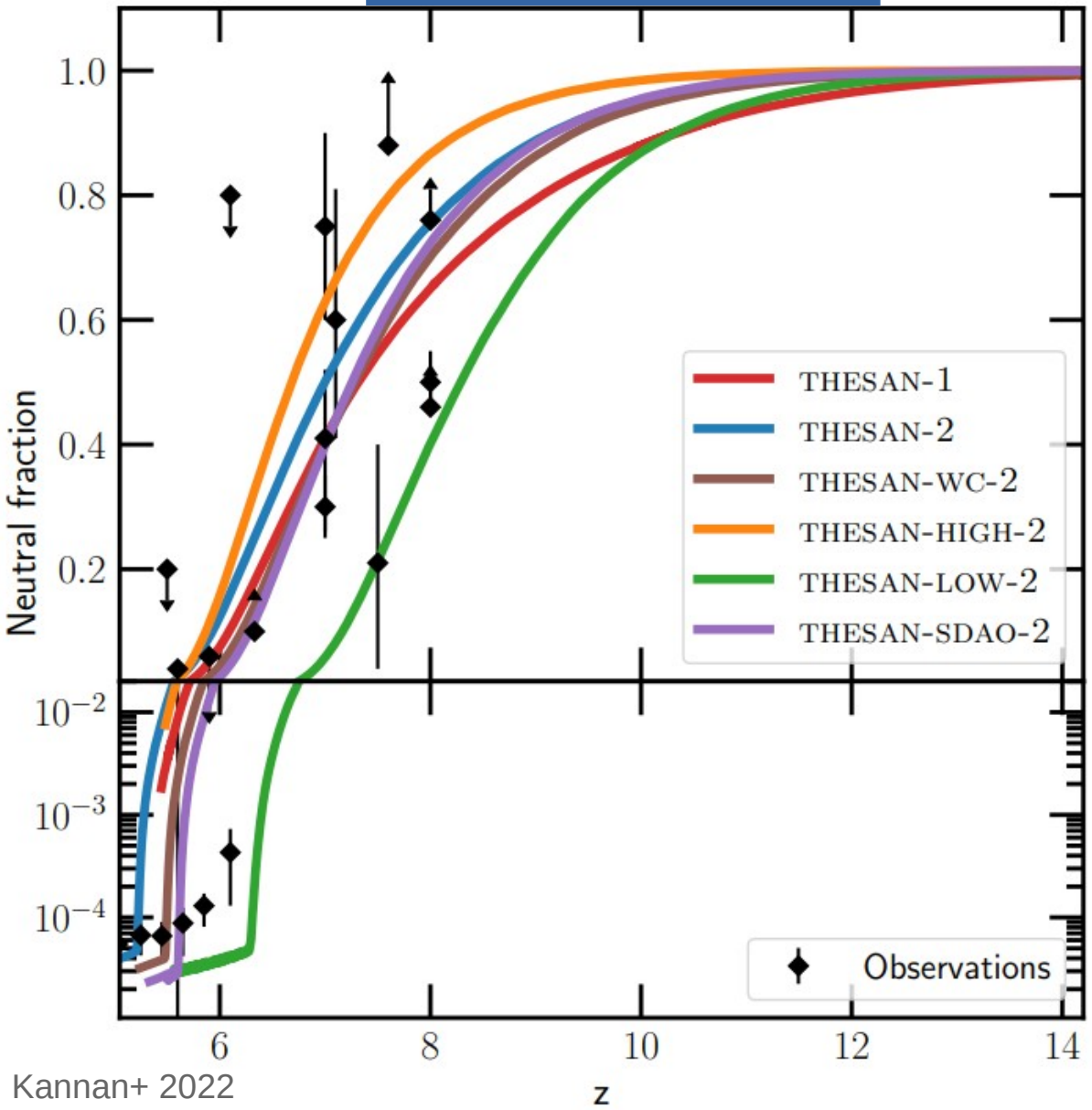
Neutral Hydrogen Fraction



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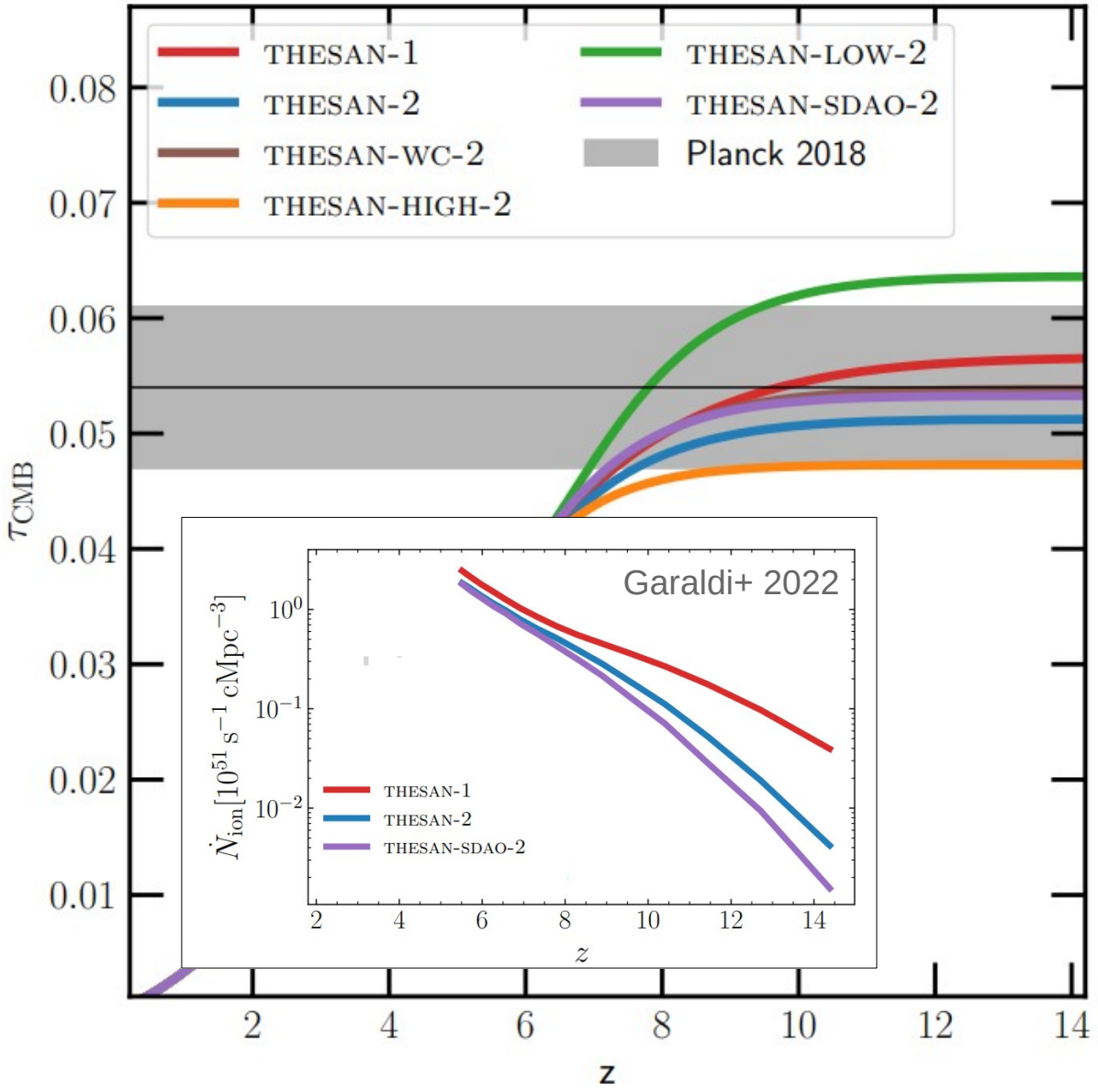
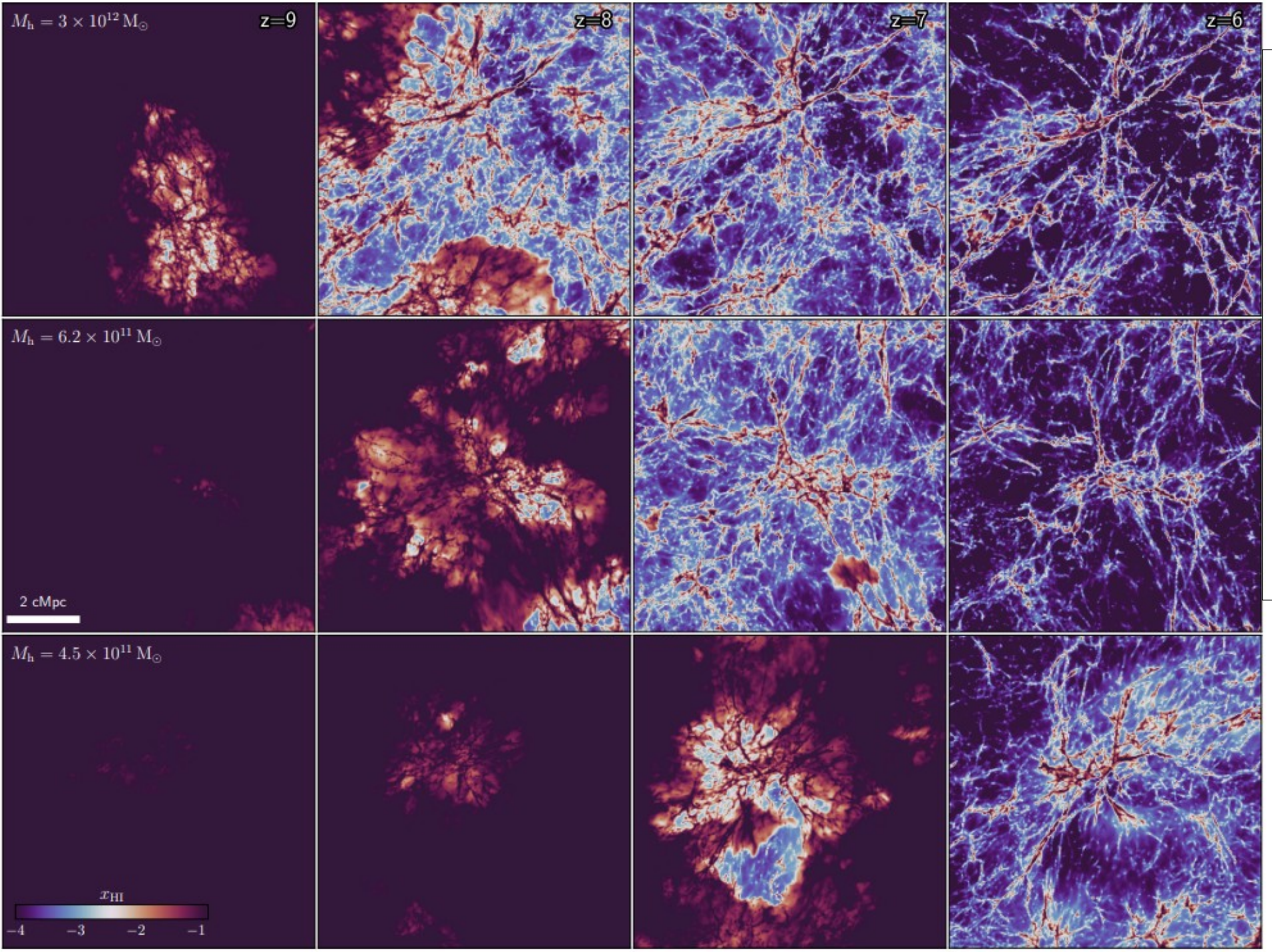
→ **THESAN-1 has extended reionization history / late reionization**
→ **THESAN-LOW-2 shows early reionization**

Optical Depth



THESAN-LOW-2 slightly too large optical depth b/c reionization fully completed already by z around 6.3



neutral hydrogen fractions around relatively massive halos:

→ early stages: I-fronts stall close to sources due to quick absorption / short re-combination time scales

→ as I-fronts reach low density gas, they speed up, causing rapid expansion of ionized bubbles

→ by z=6 all gas in the selected volume is ionized, except for high density filaments and nodes

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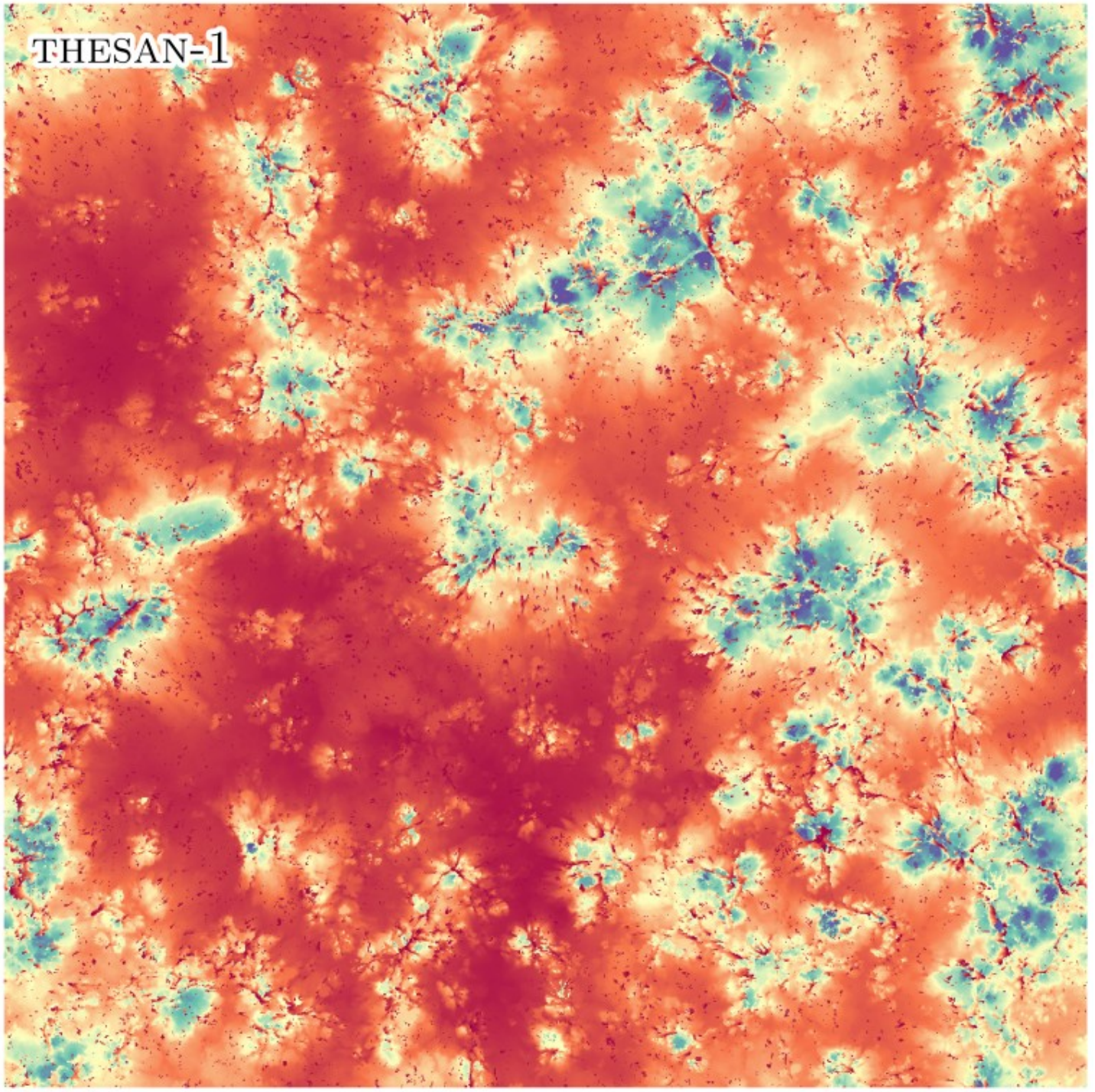
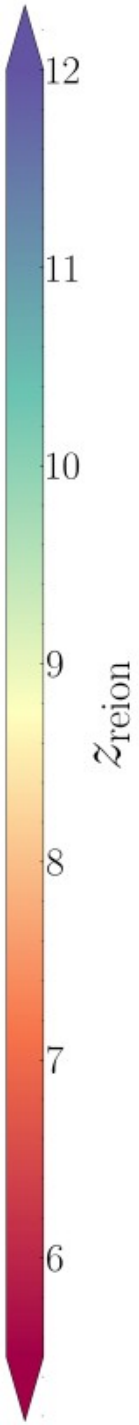




Reionizatîon Redshift

→ reionization redshift = minimum redshift with hydrogen ionization fraction >= 0.99

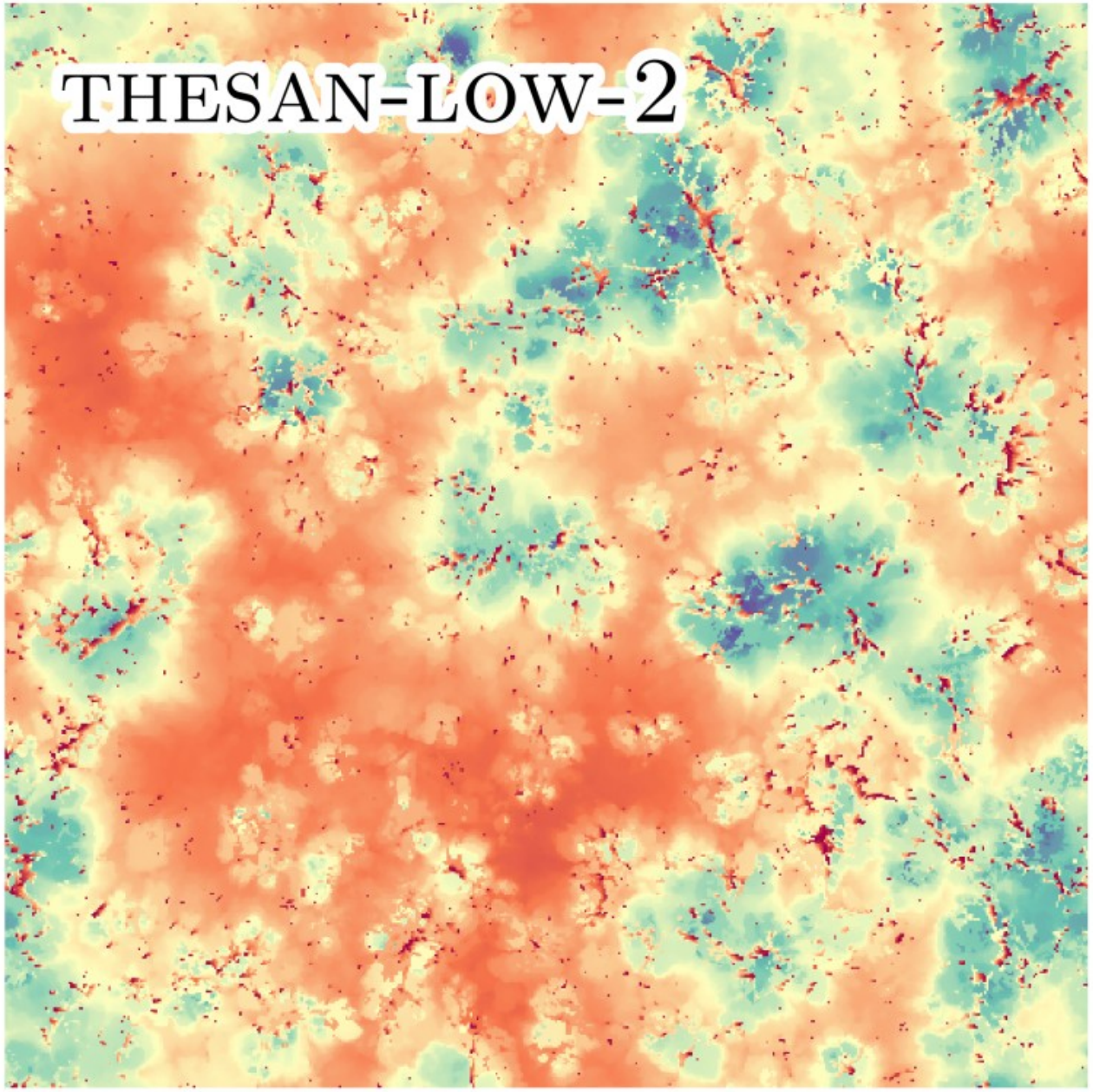
→ inside-out reionization

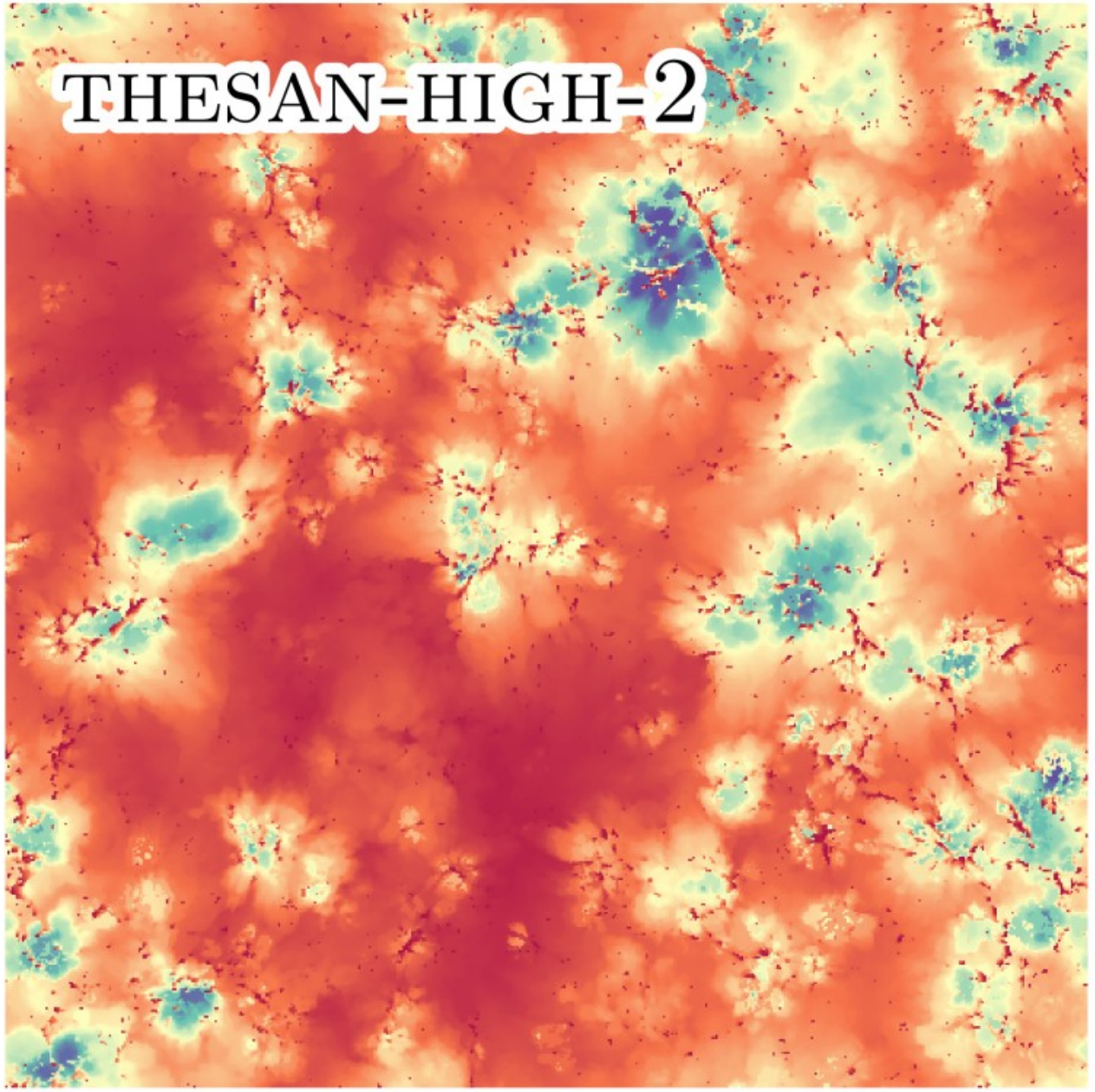
→ largest structures reionize first (z>=10) (blue)

→ much later low density IGM regions (yellow to red)

→ densest structures (galaxies and filaments) stay neutral until the end of the simulation

Garaldi+ 2022



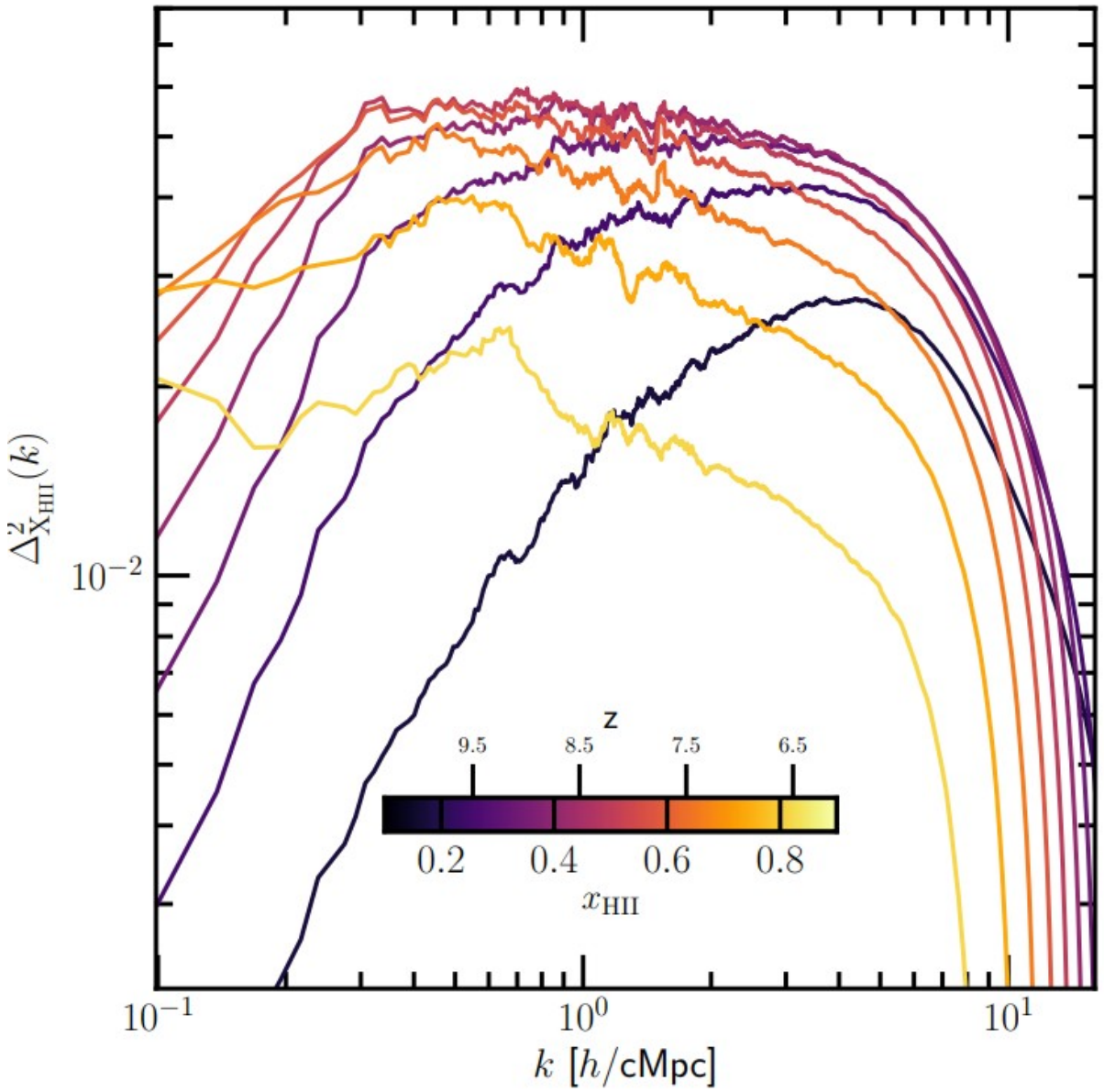


THESAN-LOW-2: earlier reionization

THESAN-HIGH-2: later reionization

Garaldi+ 2022

Power Spectra of Ionized Hydrogen



→ HII regions formed during the initial phases of the reionization process are quite small b/c early sources of radiation not very luminous

→ as reionization progresses ionized regions begin to become larger as galaxies become bigger and star formation rates increase

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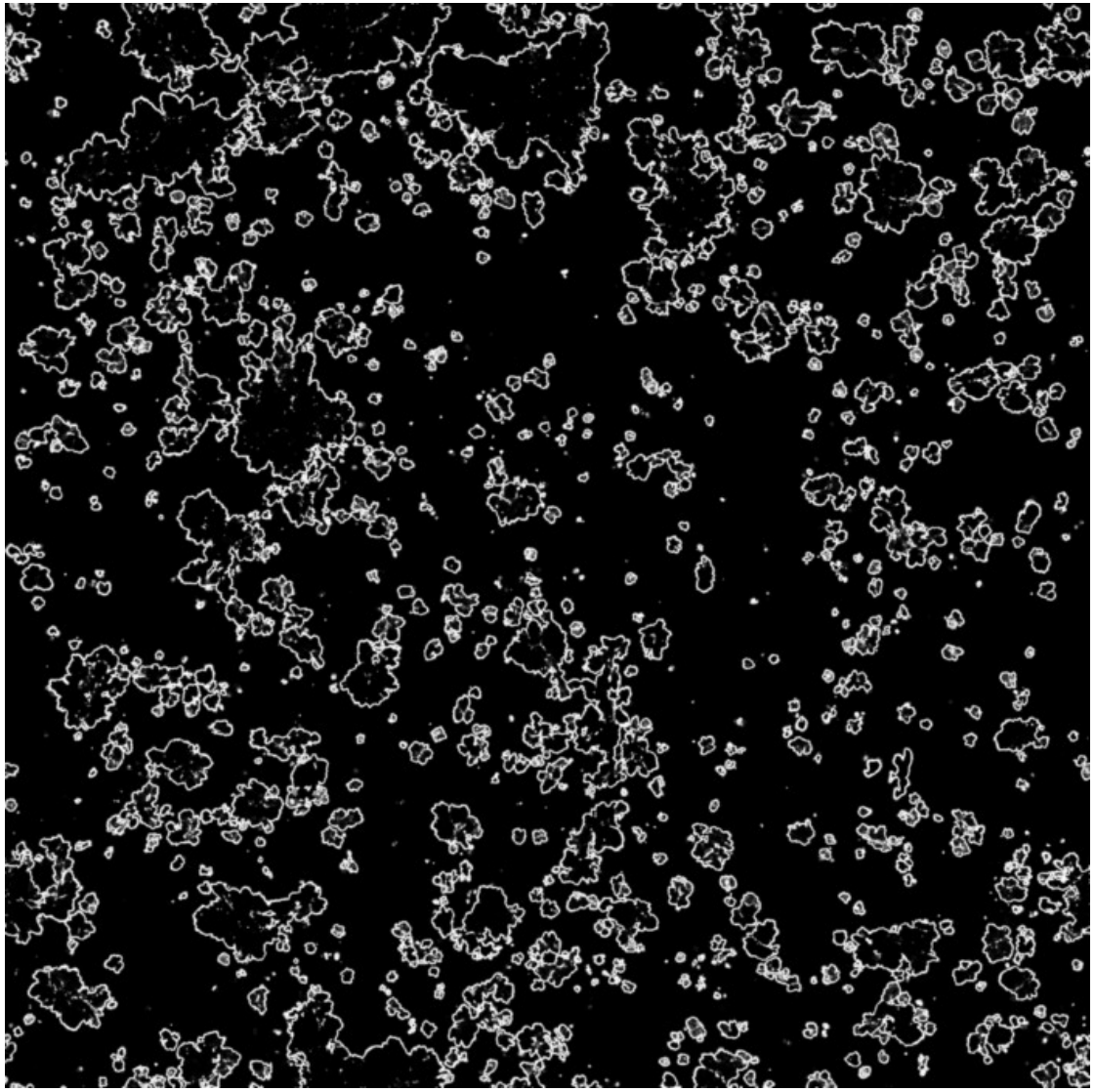
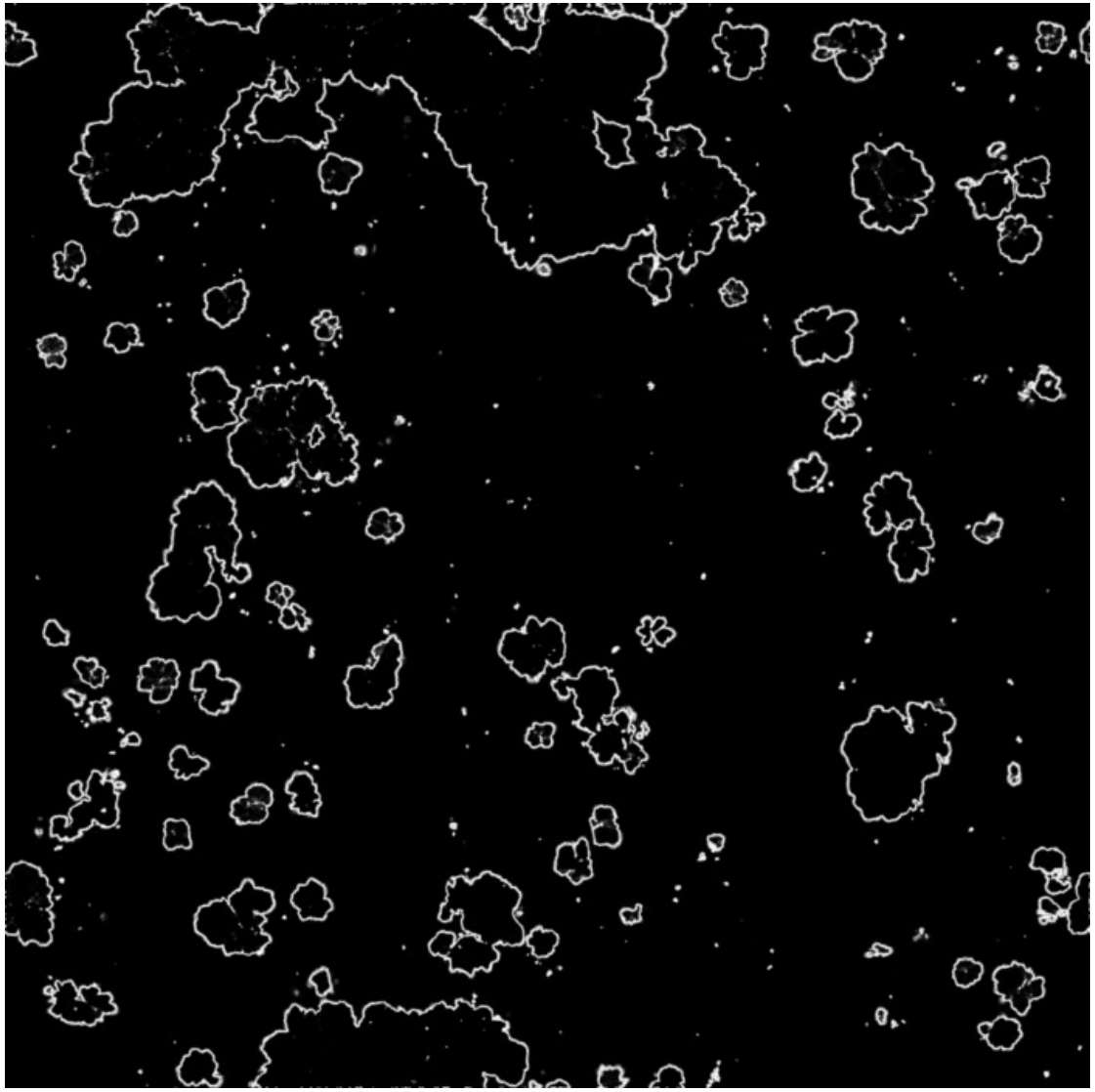
Bubble Size Distribution at Ionization Fraction 0.3



THESAN-1



THESAN-HIGH-2

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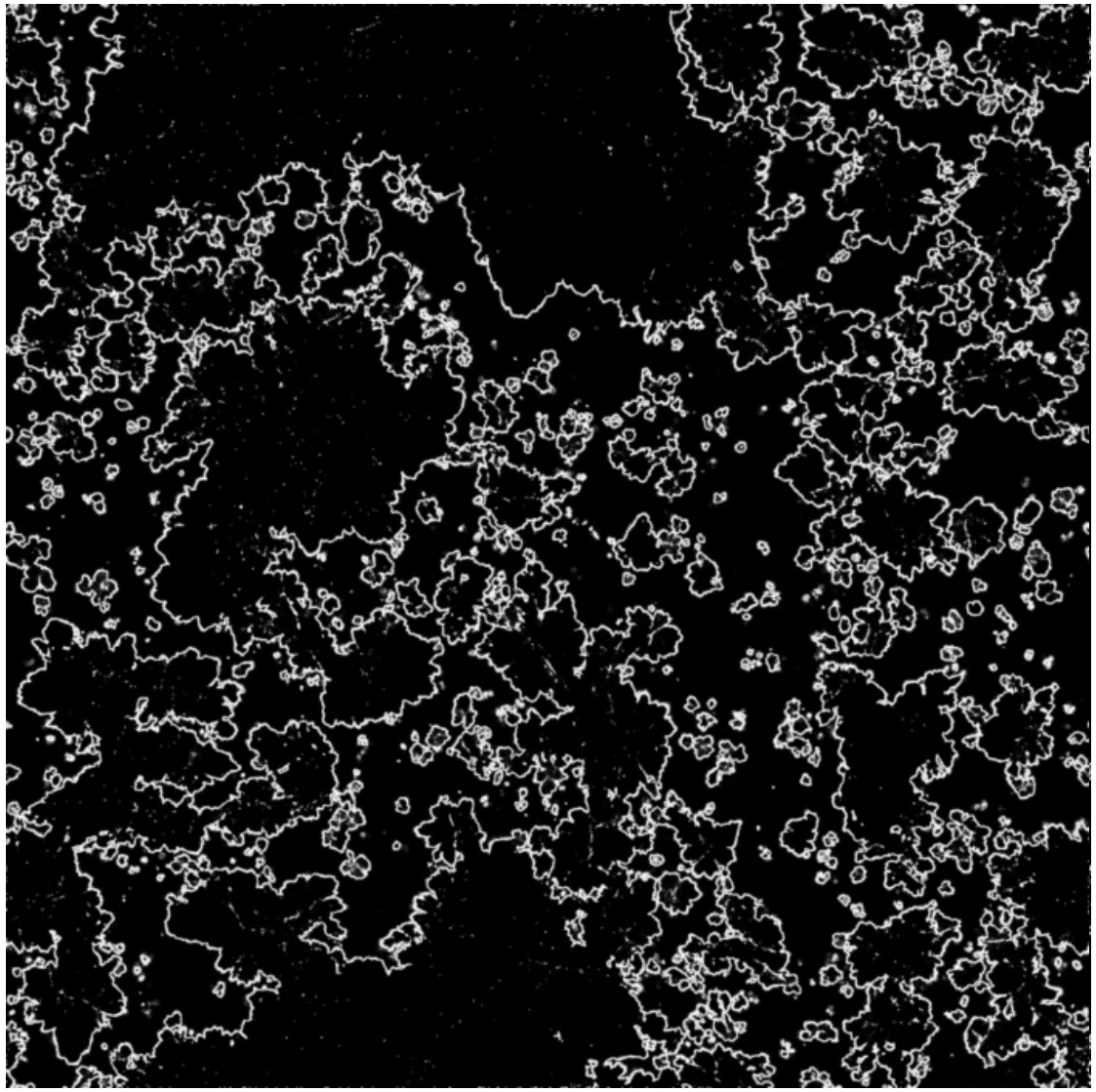
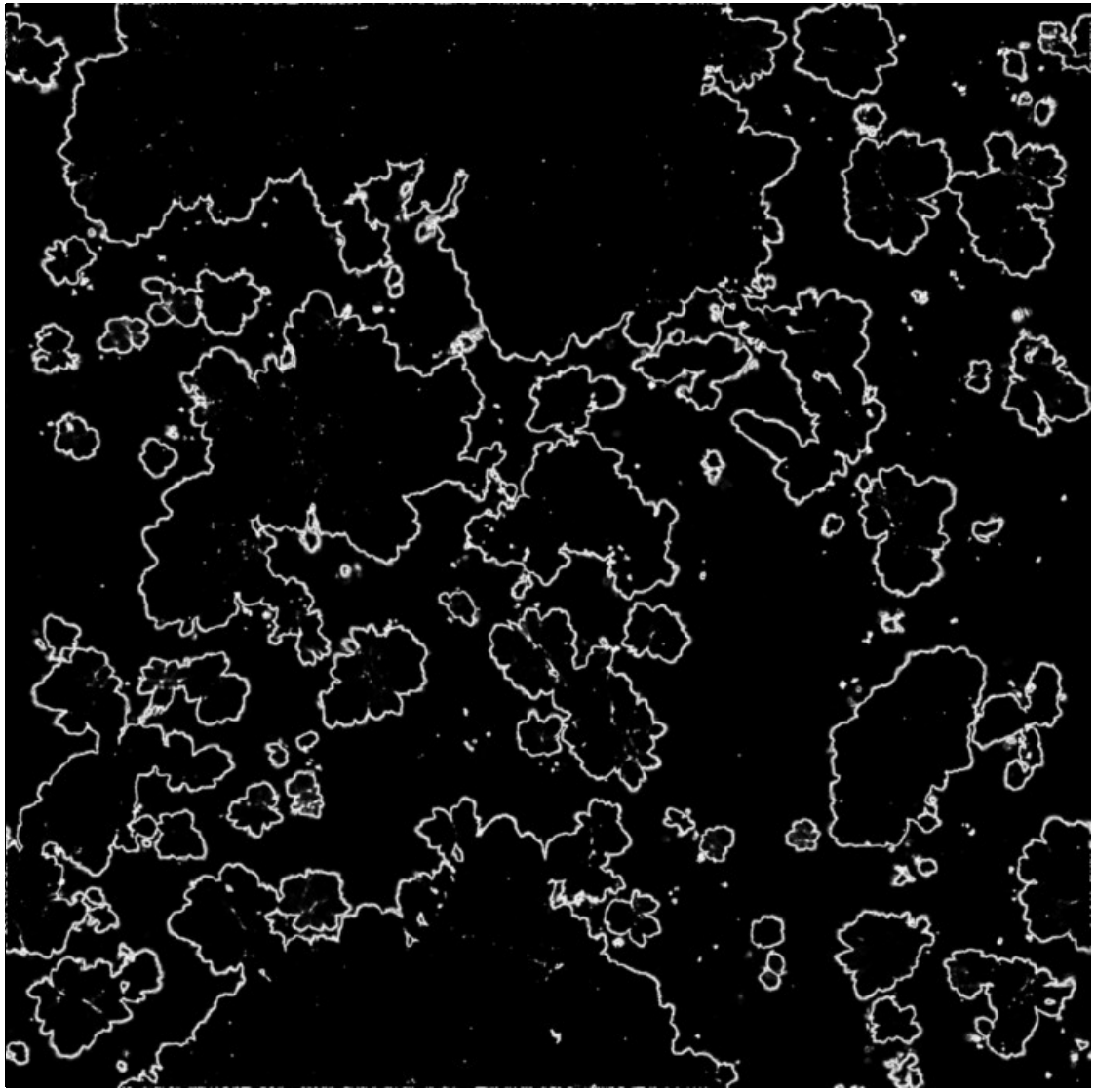
Bubble Size Distribution at Ionization Fraction 0.7



THESAN-1



THESAN-HIGH-2

size / distribution ionized bubbles depend on astrophysics and cosmology:
star formation rate, escape fractions, gas distribution, dark matter models etc.

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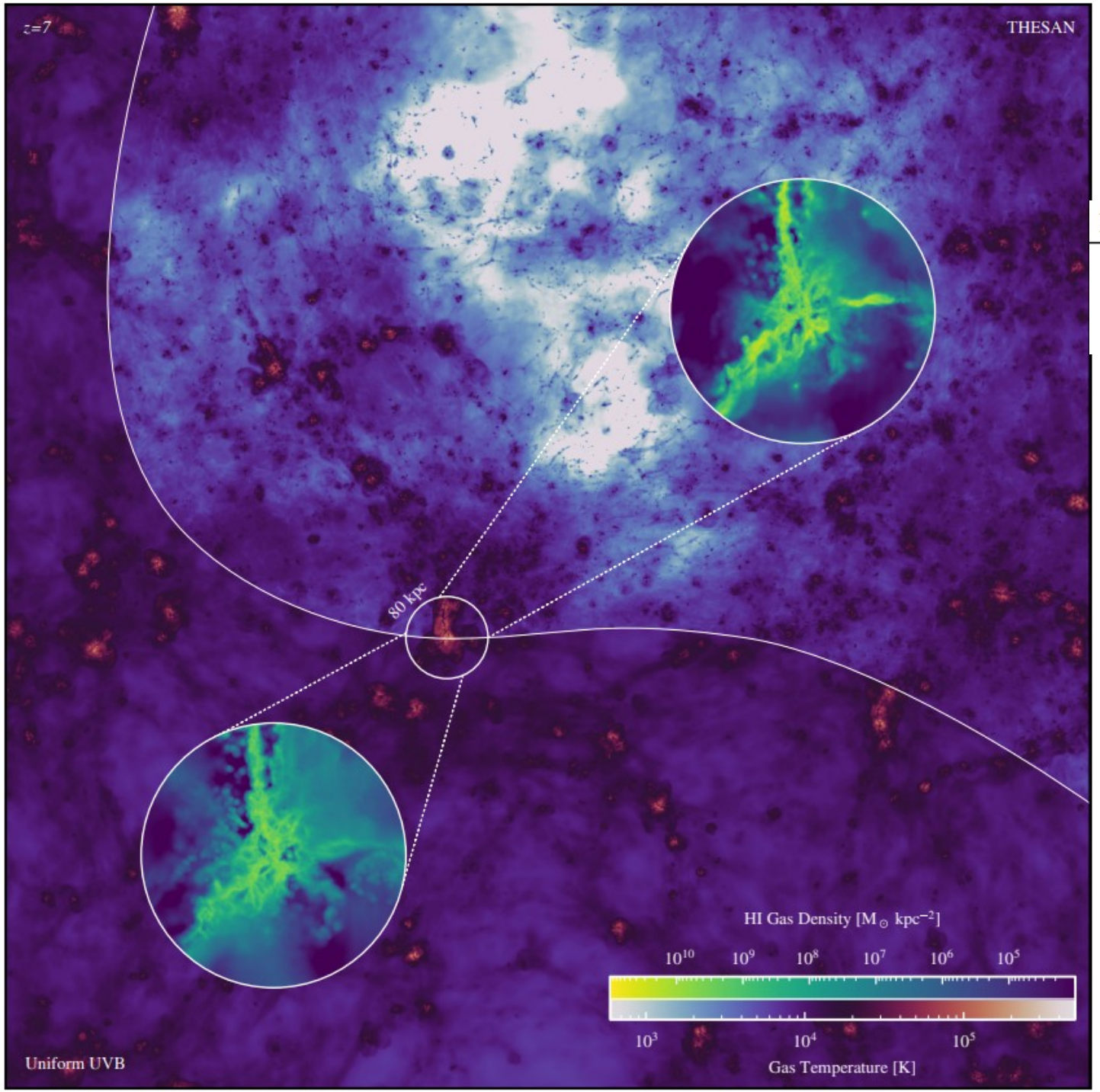
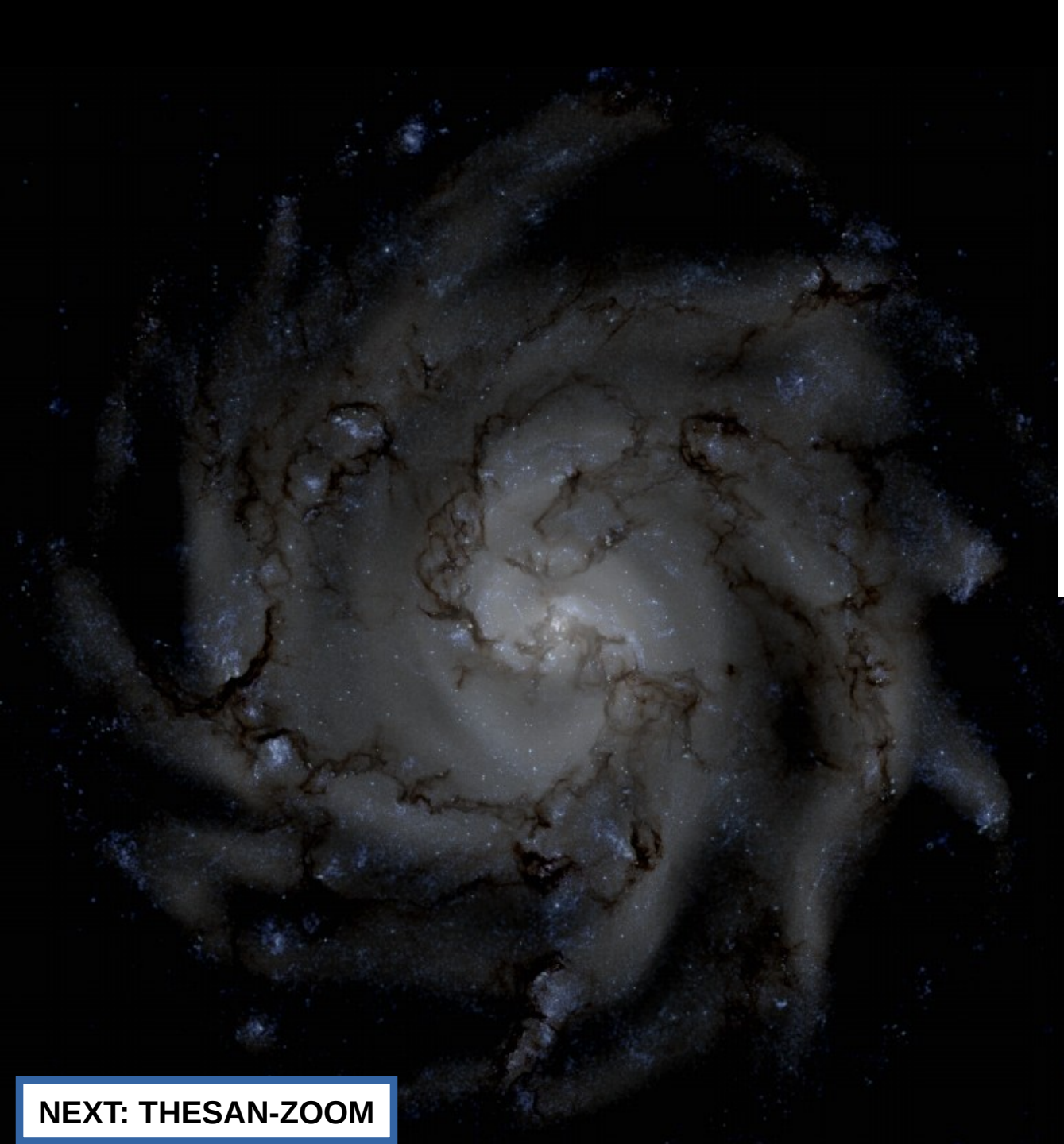
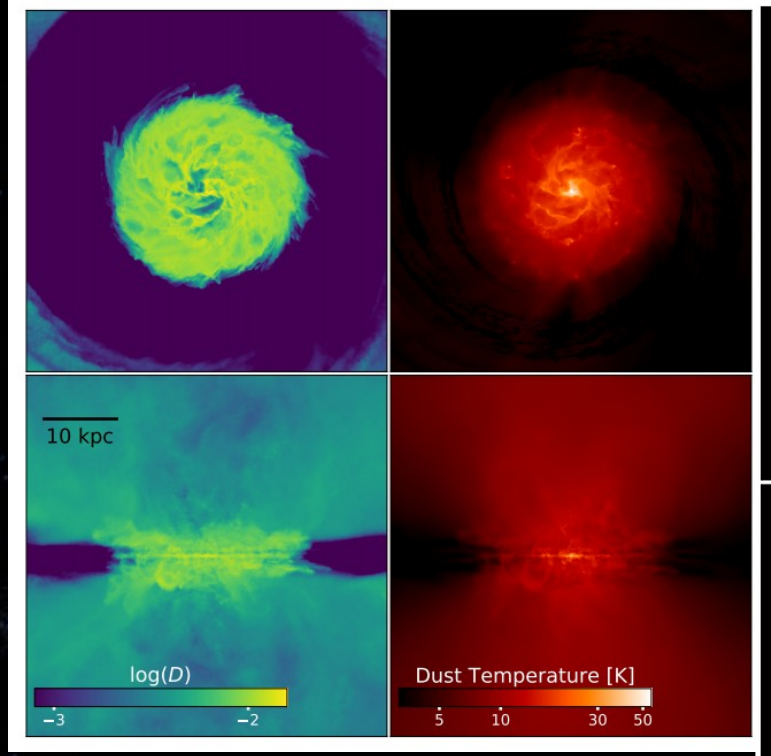


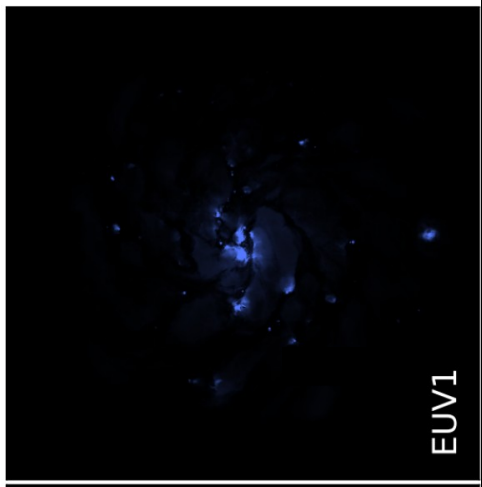
NEXT: THESAN-HR

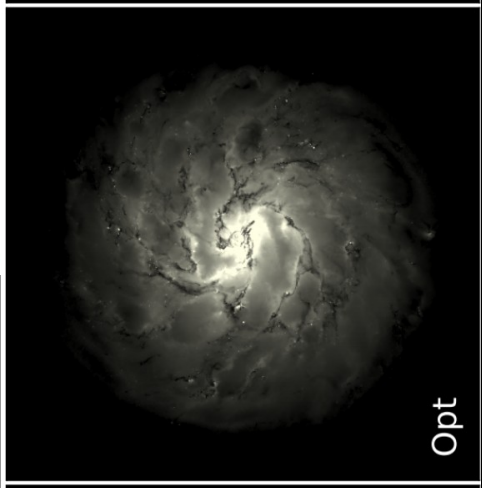
Box Length [cMpc]	m_g [$M_\odot$]	m_{DM} [$M_\odot$]	ε_g [ckpc]	ε_{DM} [ckpc]
95.5	5.82×10^5	3.12×10^6	2.2	2.2
5.9	1.13×10^4	6.03×10^4	0.425	0.425
11.8	9.04×10^4	4.82×10^5	0.85	0.85

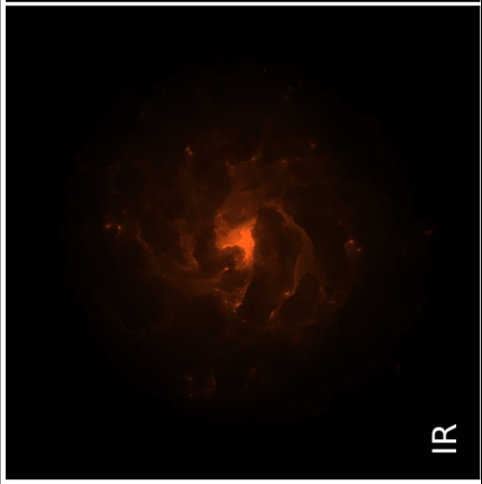
Borrow+ 2023











Kannan+ 2021

NEXT: THESAN-ZOOM

- **Introducing the THESAN project: radiation-magnetohydrodynamic simulations of the epoch of reionization**
  Kannan, Rahul (et al.)
  MNRAS, 2022, 511, 4005 [ads] [arXiv]
- **The THESAN project: properties of the intergalactic medium and its connection to reionization-era galaxies**
  Garaldi, Enrico (et al.)
  MNRAS, 2022, 512, 4909 [ads] [arXiv]
- **The THESAN project: Lyman-alpha emission and transmission during the Epoch of Reionization**
  Smith, Aaron (et al.)
  MNRAS, 2022, 512, 3243 [ads] [arXiv]

More Results....

PAPERS USING THESAN DATA

- **The THESAN project: predictions for multi-tracer line intensity mapping in the Epoch of Reionization**
  Kannan, Rahul (et al.)
  MNRAS, 2022, 514, 3857 [ads] [arXiv]
- **The THESAN project: ionizing escape fractions of reionization-era galaxies**
  Yeh, Jessica Y.-C. (et al.)
  MNRAS, Submitted [arXiv]
- **An Effective Bias Expansion for 21 cm Cosmology in Redshift Space**
  Qin, Wenzer (et al.)
  Phys. Rev. D, Submitted [arXiv]
- **Bridging the Gap between Cosmic Dawn and Reionization favors Faint Galaxies-dominated Models**
  Bera, Ankita (et al.)
  ApJ, Submitted [arXiv]
- **The MillenniumTNG Project: The galaxy population at $z \geq 8$**
  Kannan, Rahul (et al.)
  MNRAS, Submitted [arXiv]
- **The THESAN project: Lyman-alpha emitter luminosity function calibration**
  Xu, Clara (et al.)
  MNRAS, Submitted [arXiv]
- **EIGER I: a large sample of [OIII]-emitting galaxies at $5.3<z<6.9$ and direct evidence for local reionization by galaxies**
  Kashino, Daichi (et al.)
  ApJ, Submitted [arXiv]