Title: Resolving Multiphase Gas Production in the kpc-Scale Intergalactic Medium

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Collection/Series: Cosmic Ecosystems

Subject: Cosmology

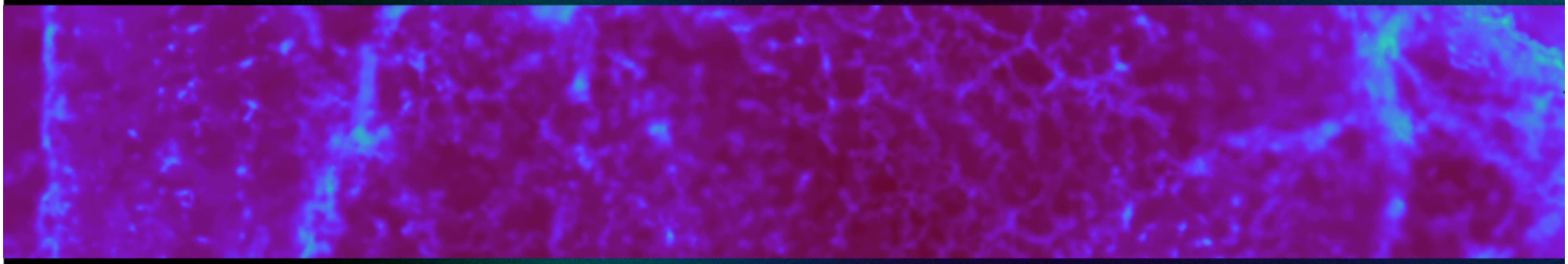
Date: July 29, 2025 - 1:45 PM

URL: https://pirsa.org/25070027

Abstract:

The ultra-diffuse nature of the Intergalactic Medium (IGM) makes it inherently difficult to resolve at high spatial resolution in simulations. Typical cosmological simulations are resolution limited by large box sizes (L > 50 Mpc) used to capture accurate statistical properties of large-scale structure, while higher-resolution zoom-in simulations rarely focus on the IGM. Thus, few simulations to date resolve IGM gas at sub-kpc scales, leaving potentially important scales for gas physics unresolved. We present semi-idealized simulations of cosmic sheet collapse at higher resolutions than previously explored to study the substructure and characteristics of IGM gas. We introduce a small 1D density perturbation to the initial conditions, allowing us to use small box volumes (L = 4-8 cMpc) to resolve IGM gas at kpc scales. We confirm previous work suggesting the IGM is inherently multiphase due to cooling-based instabilities causing fragmentation. We explore how IGM multiphase fragmentation manifests with both changing resolution and sheet-virial mass/temperature. With increasing resolution, we observe enhanced neutral hydrogen column densities through the cosmic sheet. Similar to subgrid-feedback physics, the unknown effects of resolution-limited cooling instabilities represent a fundamental limitation in our understanding of diffuse baryons in the universe. We aim to quantify this phenomenon and its broader implications for Lyman limit system statistics and the Lyman-alpha forest.

Resolving Multiphase Gas Production in the kpc-Scale Intergalactic Medium



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07/29/2025
Cosmic Ecosystems Conference
Perimeter Institute

What is the small-scale structure of intergalactic gas?

- The IGM is ultra diffuse and spans Mpc regions
  - Difficult to probe at kpc scales in simulations.
- Previous work suggests the z>=4 IGM gas may exist as a multiphase medium at kpc scales.
  - (eg. McCourt et al. 2017, Mandelker et al. 2019/2020, Yao et al. 2025)
- We present numerical experiments exploring the inhomogeneities present in the small-scale IGM. (eg. Resolution, Collapse Geometry, Power Spectrum Perturbations)
- Motivation
  - The IGM is a ‘simpler’ environment than the CGM in which to study these mechanisms.
  - Potential for unresolved Lyman Alpha and Lyman Limit Systems

IGM Fragmentation	Variation in Morphology w/ T_virial	Fragmentation Mechanism	Enhanced Lyman Alpha Absorption

Semi-Idealized Simulations of Individual Cosmic Sheets

We achieve high SPH resolutions via small box volumes.

Volume
$(4\ \text{cMpc/h})^3$ & $(8\ \text{cMpc/h})^3$

➡

Virial Temperature
$2\text{x}10^5$ K & 10^6 K

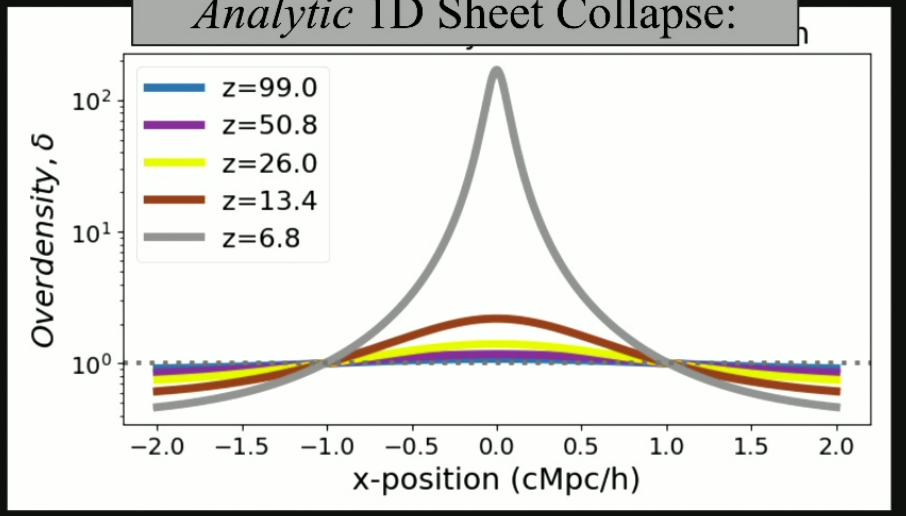
Induce Zeldovich Approximation 1D perturbations
- Forces sheet collapse despite small box volumes
- Tophat & Gaussian geometries.

Resolution
N = $[128, 256, 512, 1024]^3$ particles
$dM_{baryon} = 5\text{x}10^6 - 1\text{x}10^3\ M_\odot$

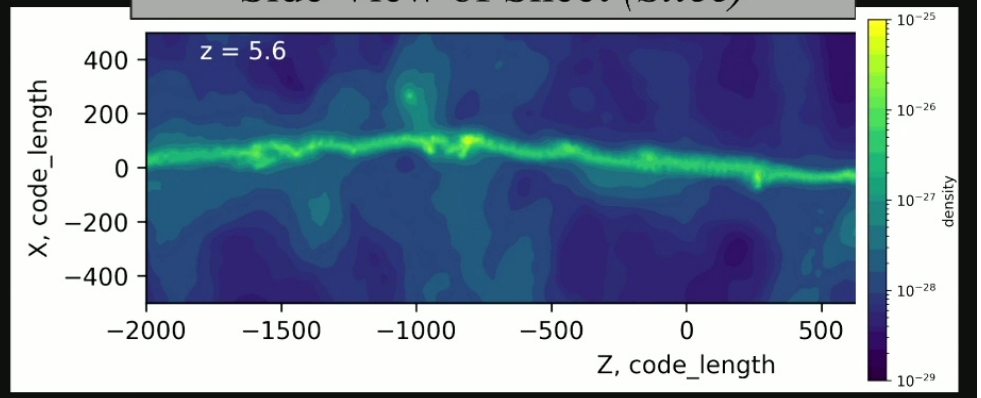
Fiducial Case
$P_m(k) = P_{m,\Lambda CDM}(k)$

- *Reduced Power Case*
- *Cutoff Small-k Fluctuations*
- *Cut-Off Large-k Fluctuations*

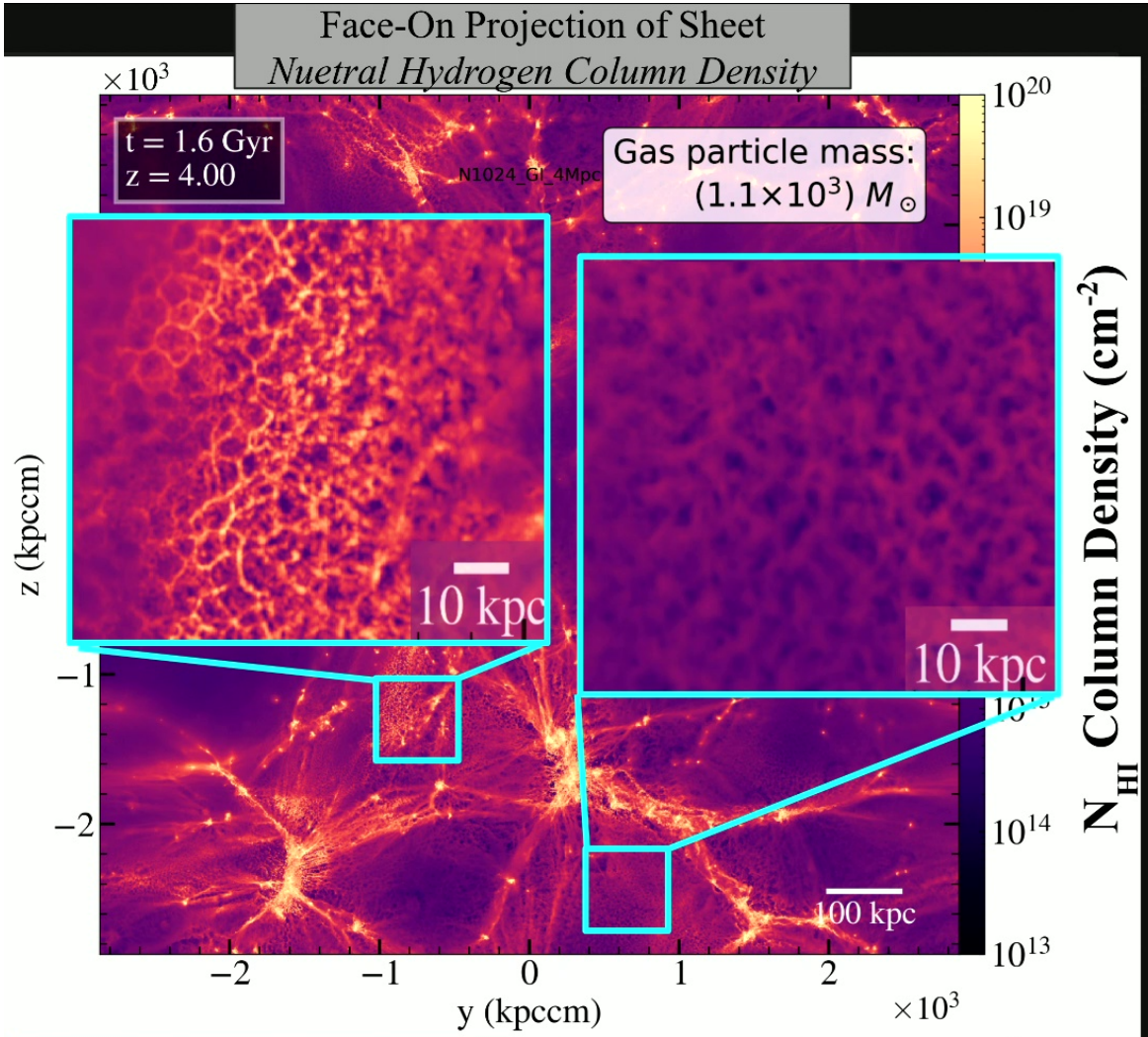
Analytic 1D Sheet Collapse:



Side View of Sheet *(Slice)*



IGM Fragmentation	Variation in Morphology w/ T_virial	Fragmentation Mechanism	Enhanced Lyman Alpha Absorption



Enhanced Resolution

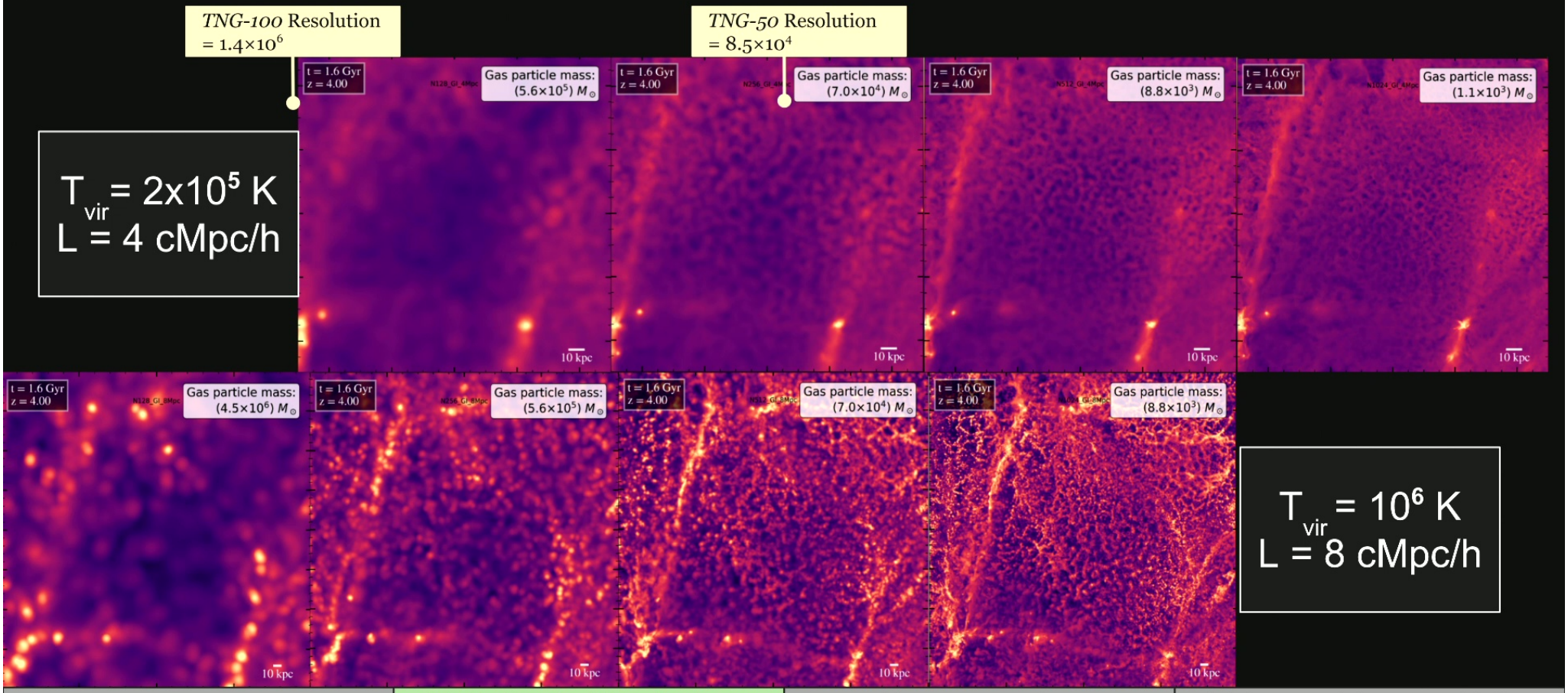
Increased Fragmentation

Strong variations in column densities emerge at <10 kpc scales.

The IGM is highly inhomogeneous and of varying morphology.

IGM Fragmentation	Variation in Morphology w/ T_virial	Fragmentation Mechanism	Enhanced Lyman Alpha Absorption

Fragmentation Variations with Virial Temperature



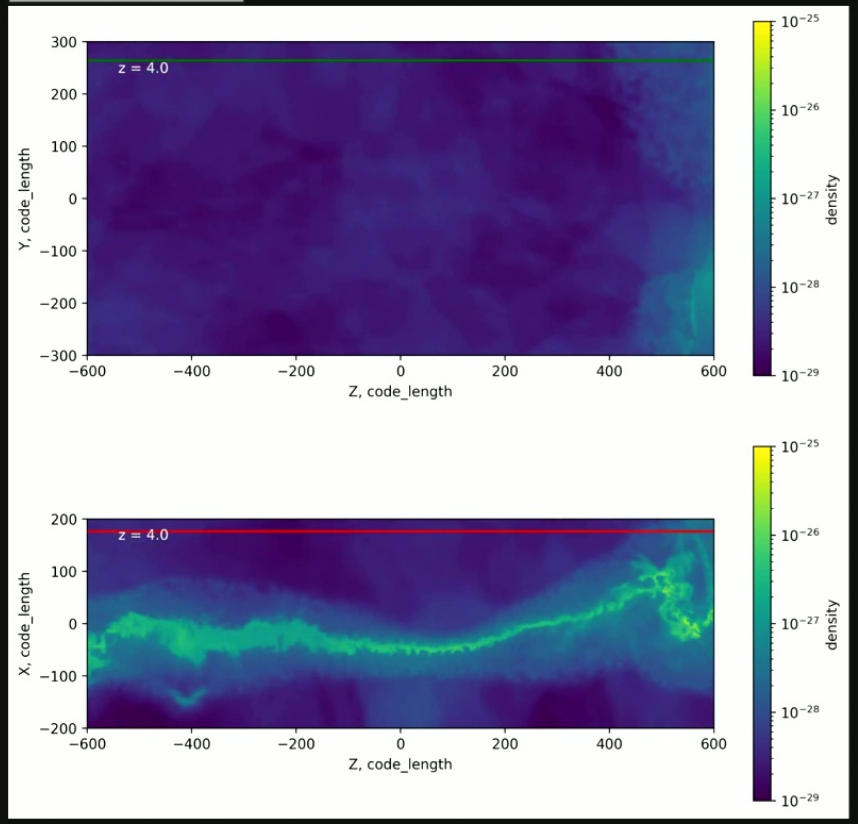
IGM Fragmentation | Variation in Morphology w/ T_virial | Fragmentation Mechanism | Enhanced Lyman Alpha Absorption

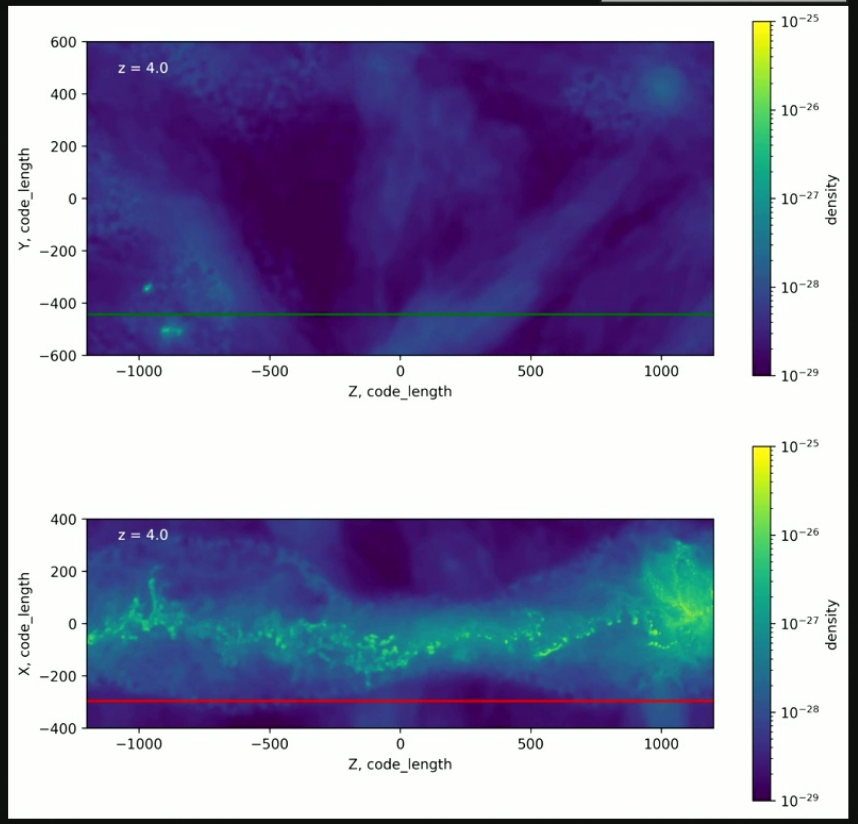
What is the 3D gas structure in these fragmented regions?

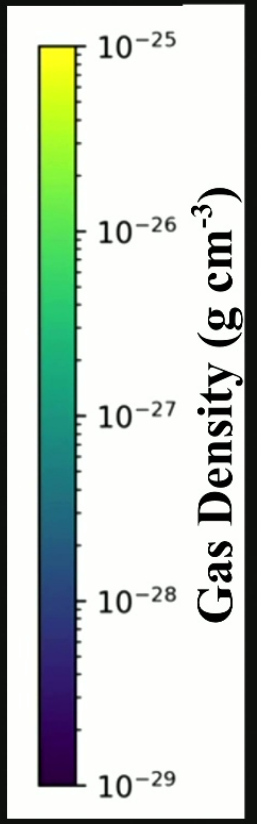
Low T_{vir} Box

⬇ Slice Within the Sheet Plane ⬇

High T_{vir} Box







⬆ Slice Perpendicular to Sheet Plane ⬆

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What is the 3D gas structure in these fragmented regions?

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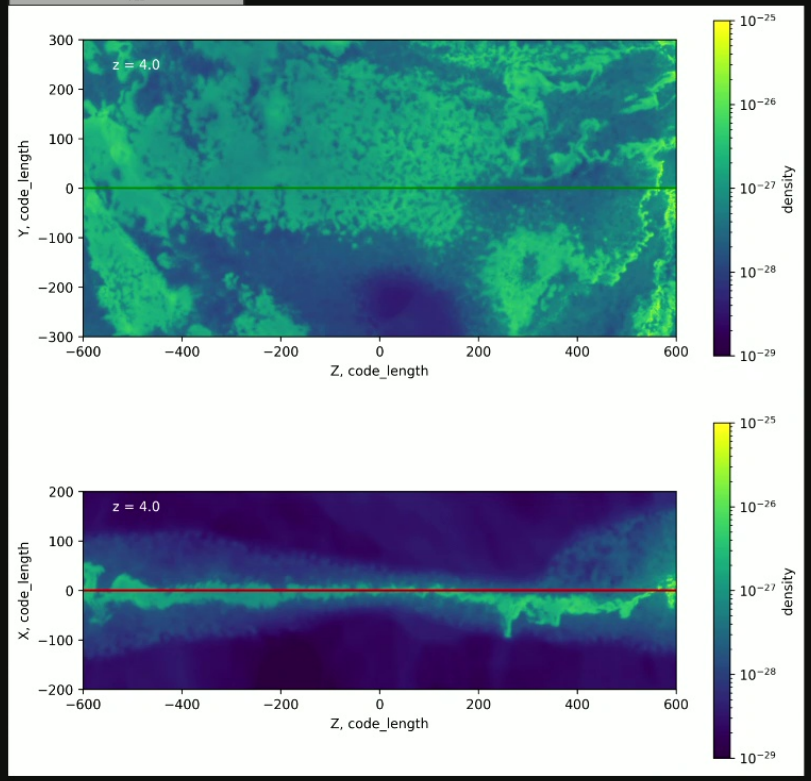
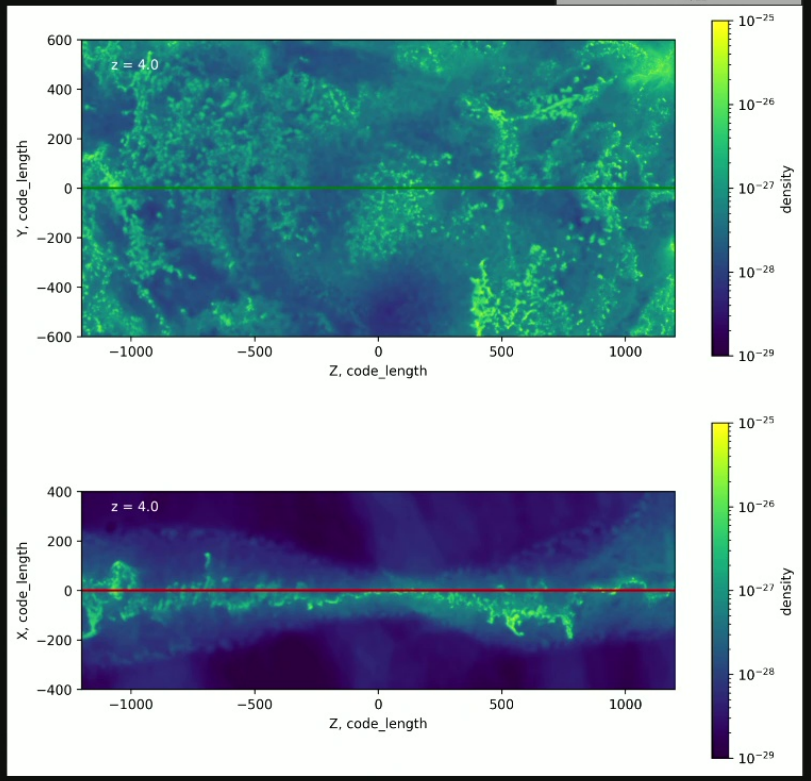
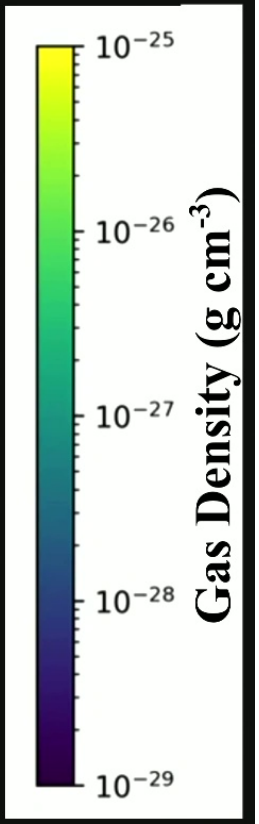


Hight T_{vir} Box



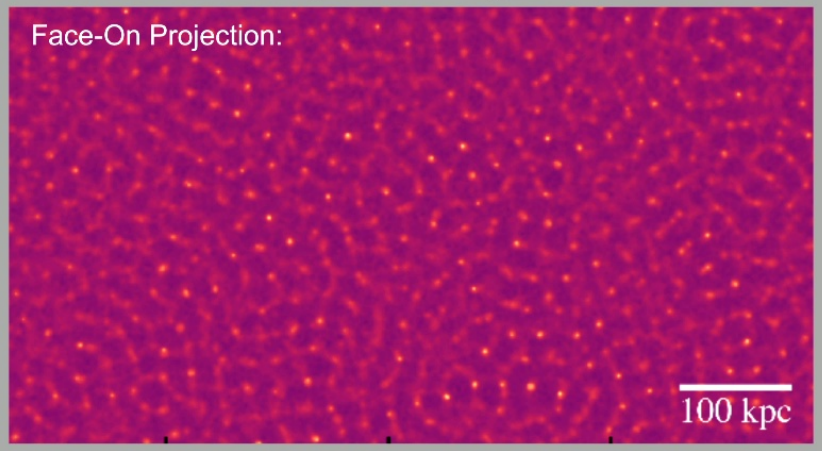


Hydrodynamic Instabilities/Turbulence | Cooling Instabilities

IGM Fragmentation	Variation in Morphology w/ T_virial	Fragmentation Mechanism	Enhanced Lyman Alpha Absorption

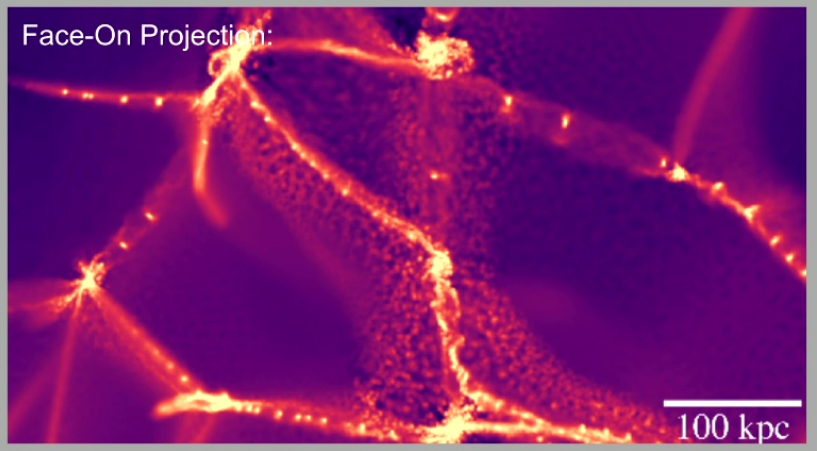
Results of Power Spectrum Experiments: *Scale Cutoff Tests*

No Large-Scale Perturbations
Only L<100 ckpc/h



Even including all small scale perturbations (<100 ckpc/h), we do not observe notable fragmentation.

No Small-Scale Perturbations
Only L > 1 cMpc/h:



IGM gas only fragments in the presence of gravitationally collapsing systems.
(eg. filaments/nodes)

IGM Fragmentation	Variation in Morphology w/ T_virial	Fragmentation Mechanism	Enhanced Lyman Alpha Absorption

What is the principal mechanism for IGM Fragmentation?

Cooling Instabilities

- **Majority of IGM phase space meats Field and Balbus instability criterion.**
- **Short Cooling Times**
  - **$t_{cool}(2x10^5\,K) \approx 1Gyr < H(z=4)^{-1}$**
  - **$t_{cool}(10^6\,K) \approx 1.5Gyr \approx H(z=4)^{-1}$**
- **Consistent w/ Cloudlet Formation in pressure disequilibrium**
  - ***(8 cMpc/h box)***

Mechanisms discussed in McCourt et al. 2017, Waters & Proga 2019/2023

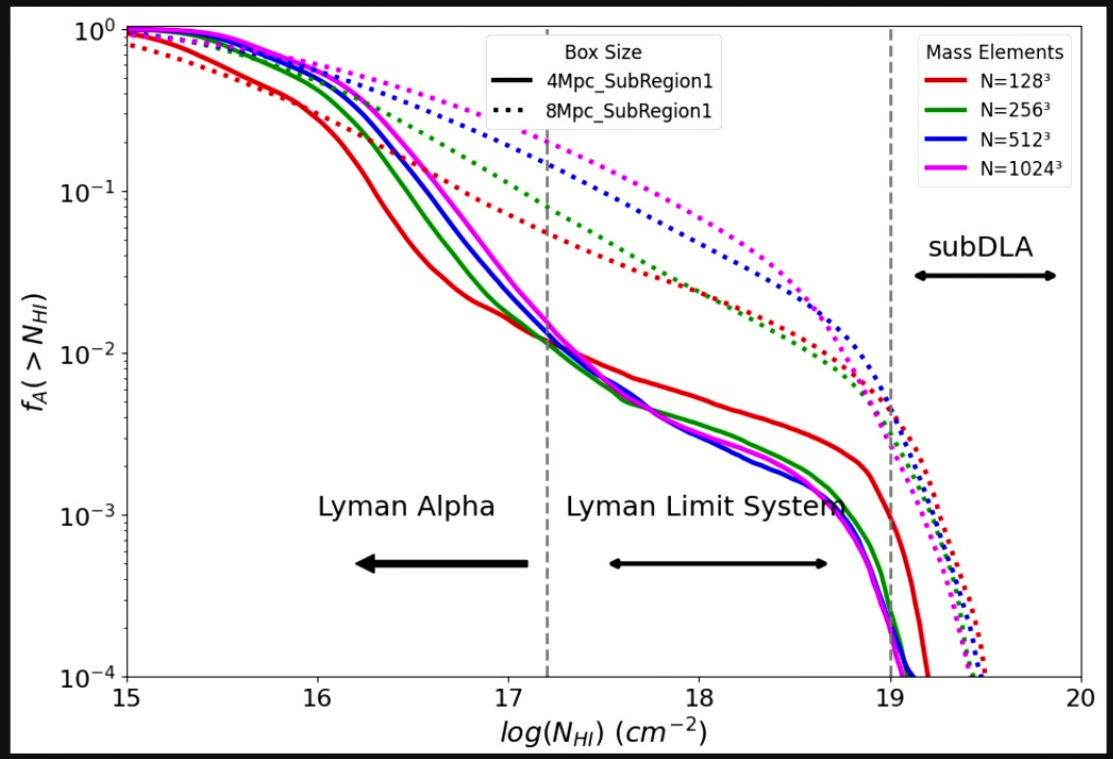
Hydrodynamic Instabilities/Turbulence

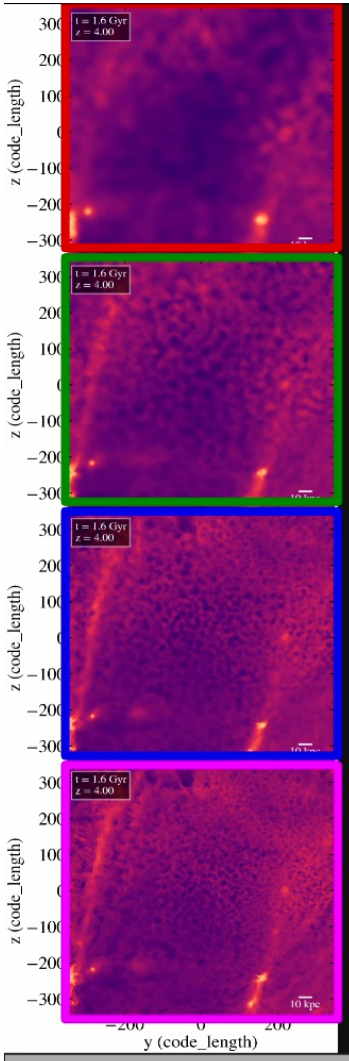
- **Richtmyer-Meshkov Instability**
  - ***Cosmic sheets are an ideal setup for RMI's.***
  - ***Consistent with necessity for larger scale perturbations.***
  - ***Spike/bulb gas morphology***
    - ***(4 cMpc/h box)***

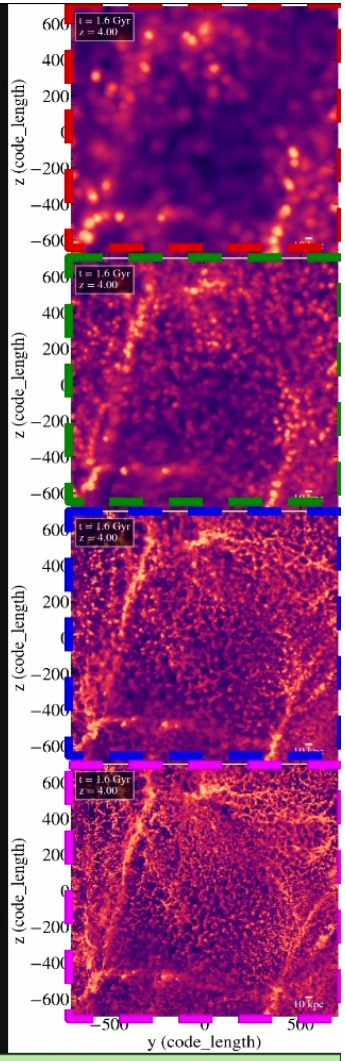
Mechanisms discussed in Gronke & Oh 2020, Yao et al. 2025

IGM Fragmentation	Variation in Morphology w/ T_virial	Fragmentation Mechanism	Enhanced Lyman Alpha Absorption

HI Column Density Enhancement







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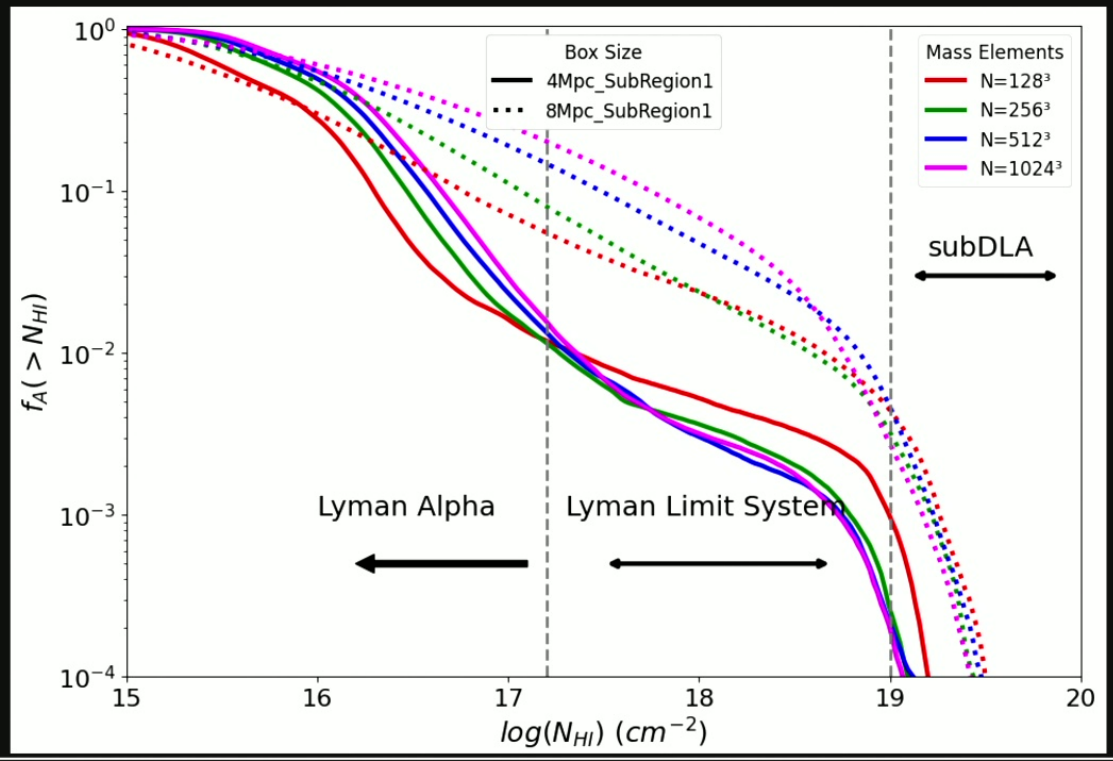
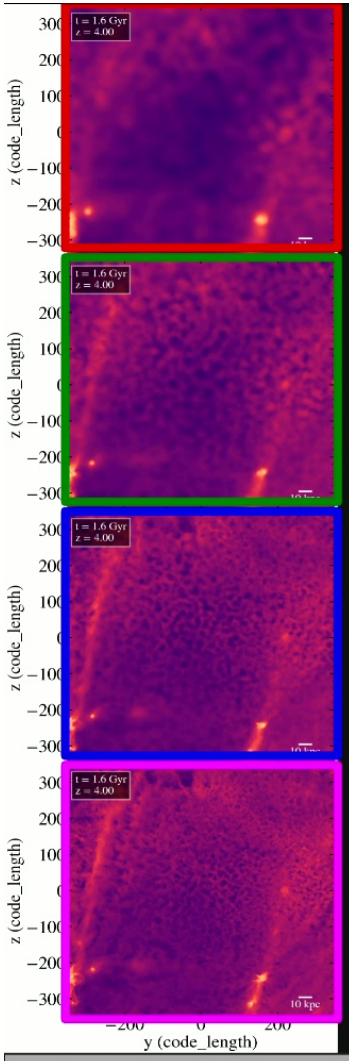
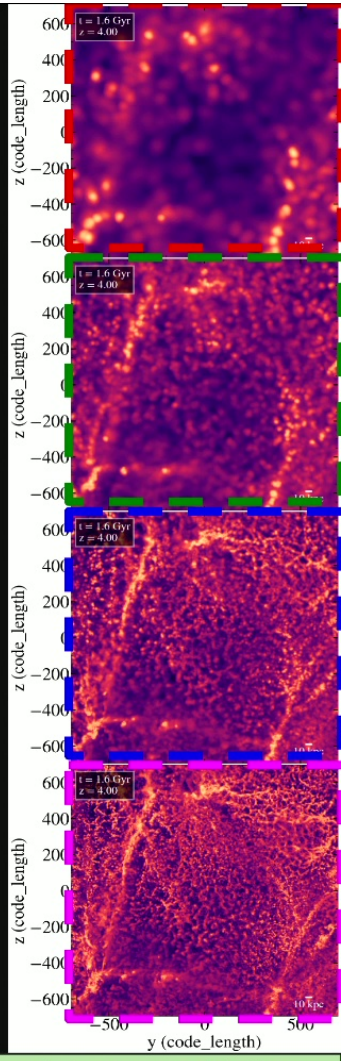






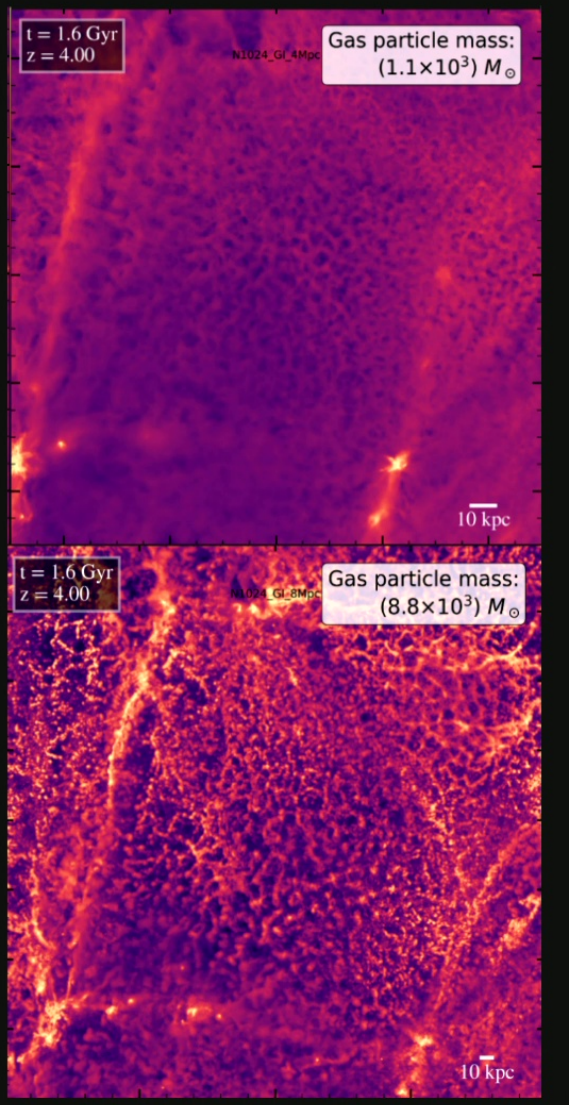
Both boxes are not converged, even between N512→N1024 simulations.

- 20% enhancement in Lyman Alpha Absorbers in low T_{vir} box
- 30% enhancement in Lyman Limit Systems in high T_{vir} box

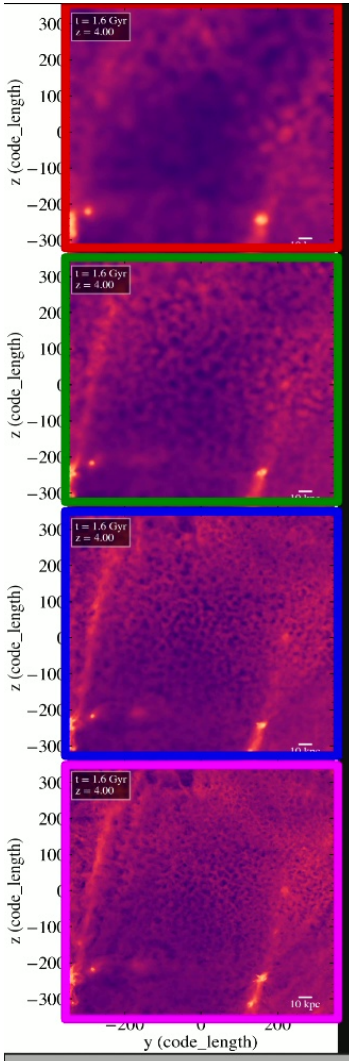
IGM Fragmentation	Variation in Morphology w/ T_virial	Fragmentation Mechanism	Enhanced Lyman Alpha Absorption

Conclusions

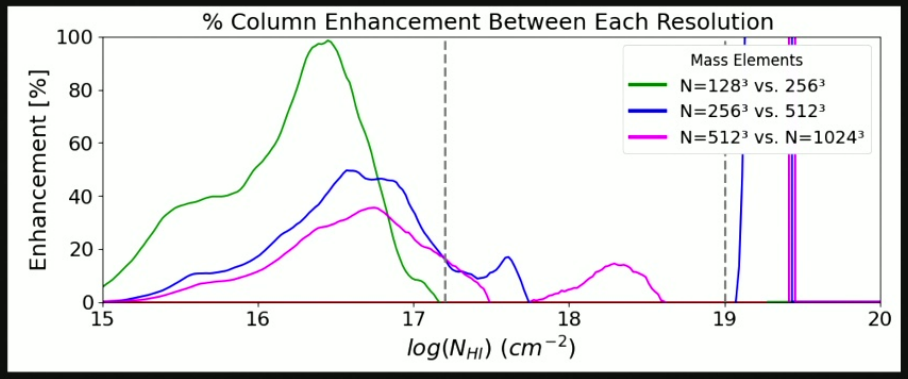
- We confirm that the kpc scale IGM fragments into multiphase gas, of multiple morphologies.
- Flagship Cosmological & Lyα-Forest simulations do not resolve these scales.
- In even our high-resolution simulations, N_{HI} only converged at the 20-30% level.
- Both Cooling and Hydrodynamic based instabilities likely play a role in fragmentation.
- Large-scale perturbations are necessary for fragmentation.
- Future work is needed confirm the exact nature of fragmentation as well as understand how this multiphase gas effects Lyα Observables and lower orders of cosmic structure (Filaments/CGM).

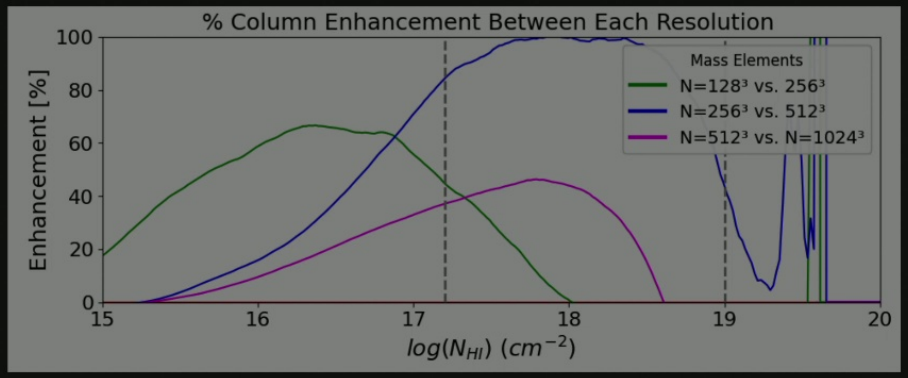


Neutral Hydrogen Column Density Enhancement

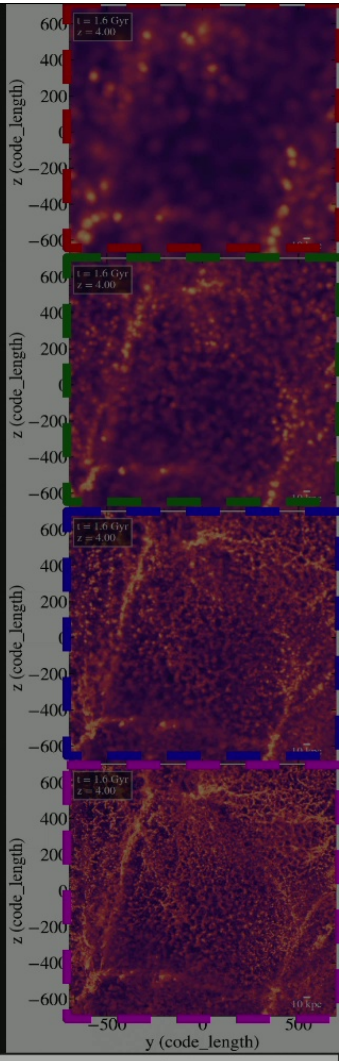


L = 4 cMpc/h





L = 8 cMpc/h



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