

Title: From the biggest things to the Biggest Bang

Date: Jul 13, 2011 10:15 AM

URL: <http://www.pirsa.org/11070031>

Abstract: Galaxy clusters are the biggest gravitationally bound structures in the Universe. Simple features of these objects can help us reconstruct the initial conditions at the Big-Bang and test the fundamental laws of physics.



From the Biggest Things to the Biggest Bang

Louis Leblond

... and to the biggest questions

Observe 1.

- we will observe our biggest things in three different way.



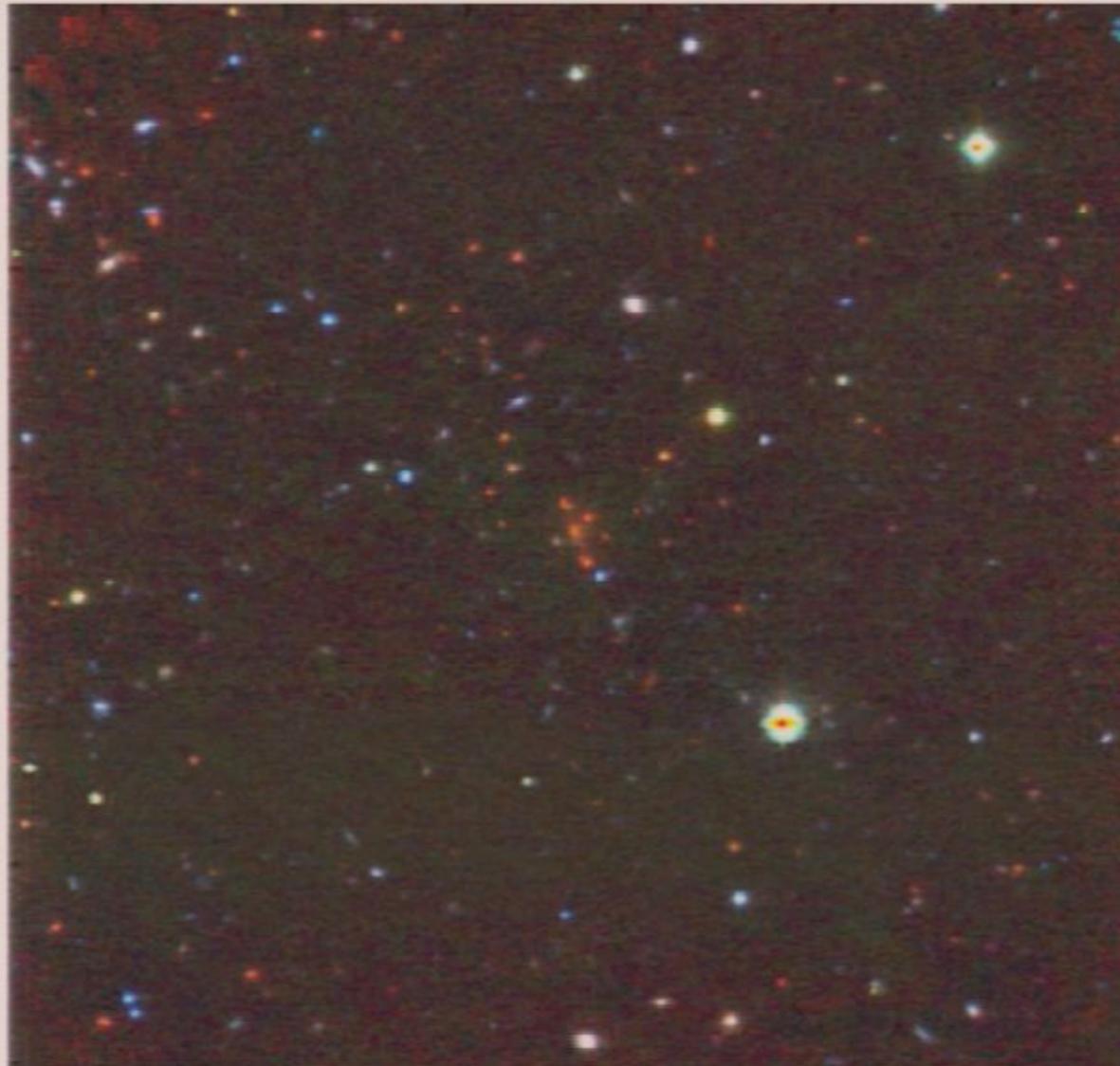




XMMUJ2235.3+2557

Visible

~ 5 Mpc
~ 10^{20} km





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Galaxy Clusters

- 10-1000 galaxies appear to be held together by some kind of gravitational attraction.
- Galaxies have a typical mass of $10^{11} M_{\odot}$

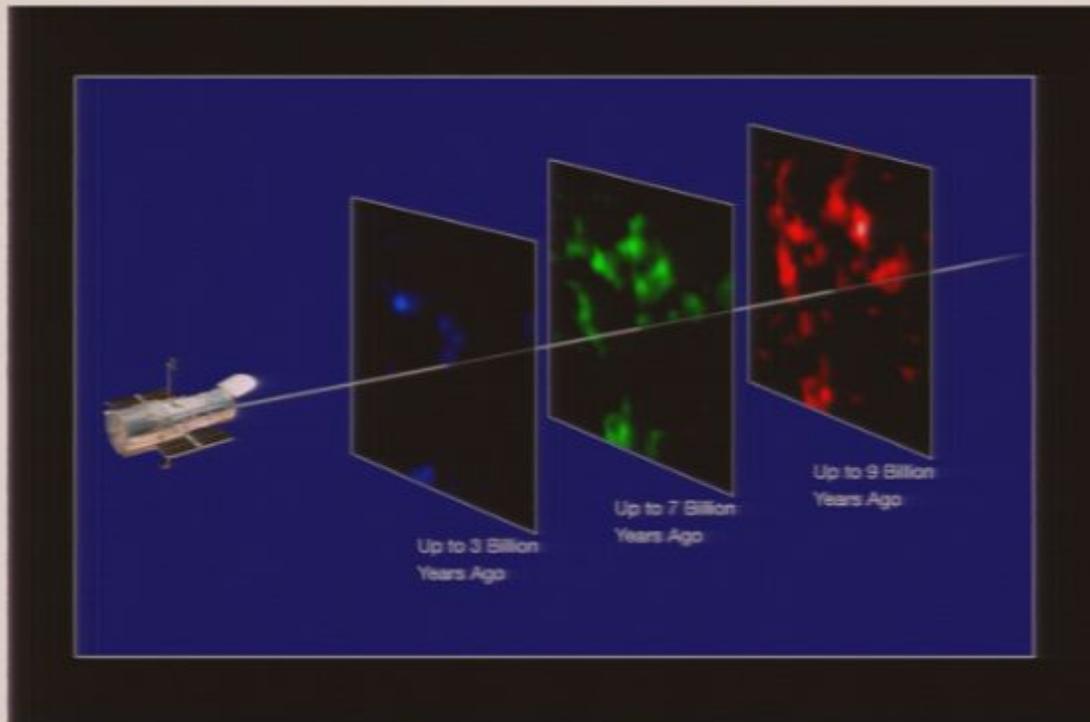
$\sim 30 \text{ Kpc} \sim 10^{17} \text{ km}$



Redshift

- XMMUJ2235.3+2557 $z=1.4$

$$z = \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}}$$



Redshift is both due to expansion of Universe and peculiar motion

$z > 0.1$
expansion is main effect

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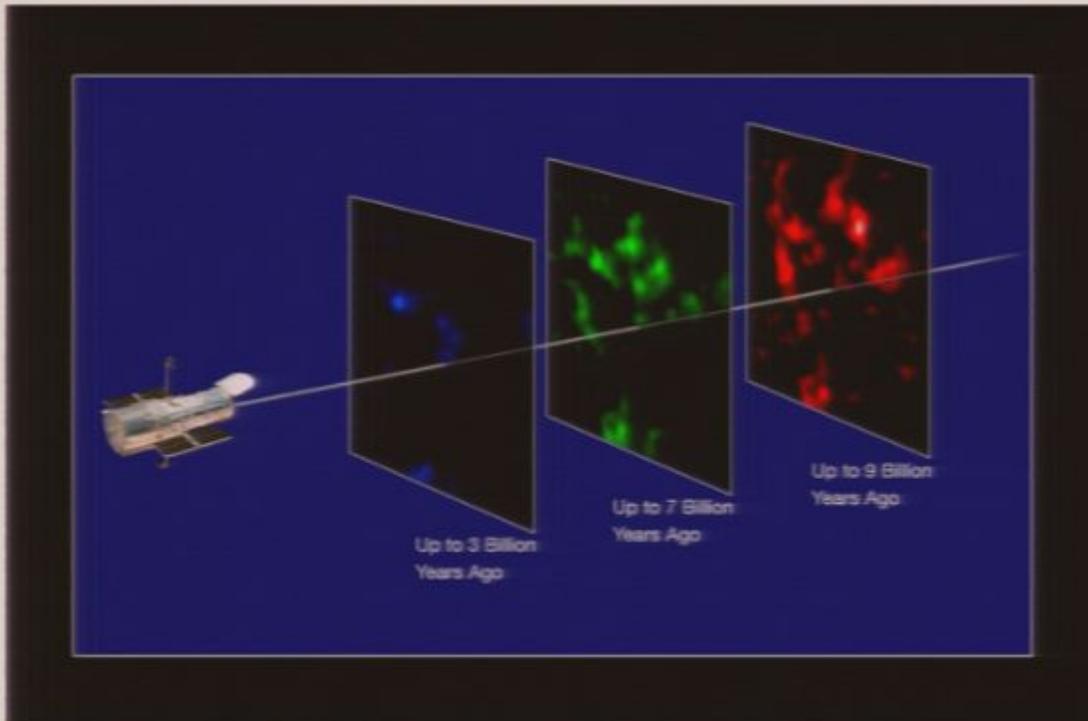
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The biggest things are close by

- quasar and GRB (small galaxies) have been observed up to redshift of $z = 7$

- 770 millions year after Big-Bang, 12.9 billions for the light to reach us.

- Fun facts, at redshift of $z > 1.407$, recession velocity is greater than the speed of light!

Measured

Assume a cosmological model
 Λ CDM

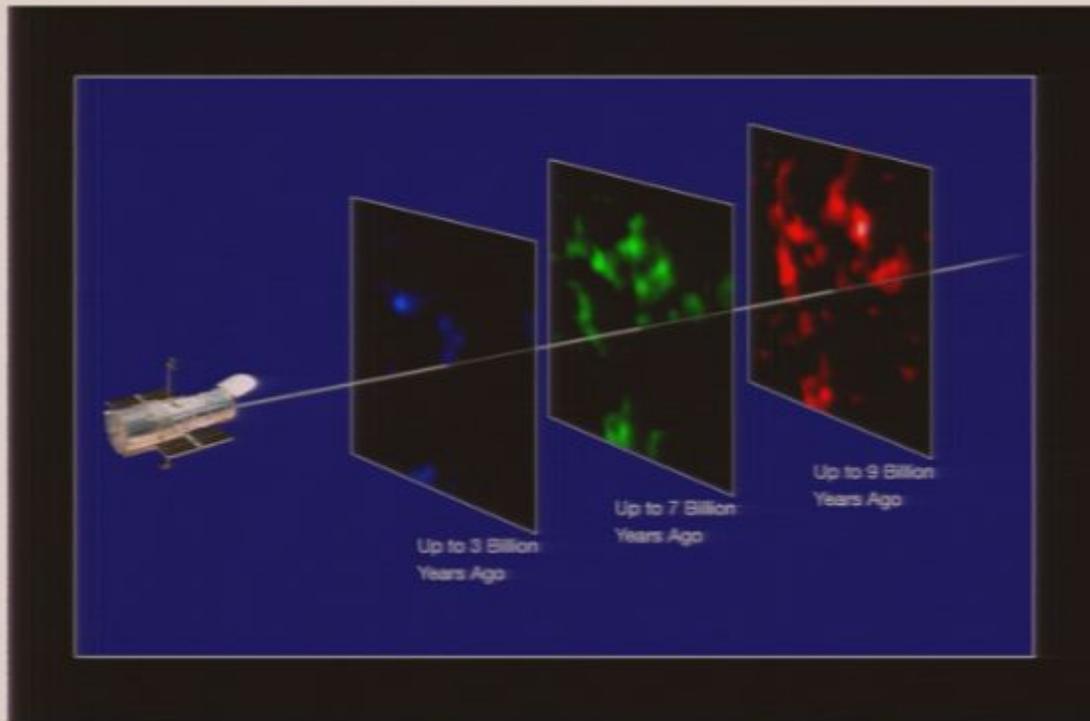


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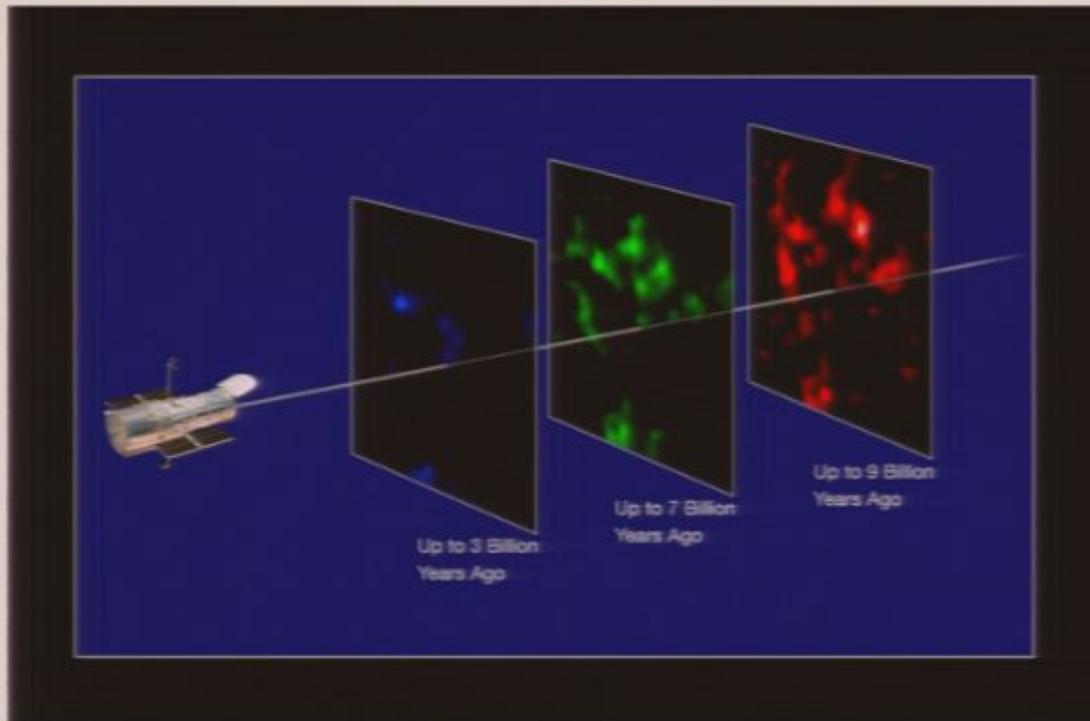
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Peculiar velocities of Galaxy

- by measuring relative redshift we can figure their peculiar velocities. Spread of velocities for a typical clusters is around 800-1000 km/s

$$v_e = \sqrt{\frac{2GM}{r}}$$

- speed is too high. The galaxies cannot be bound.

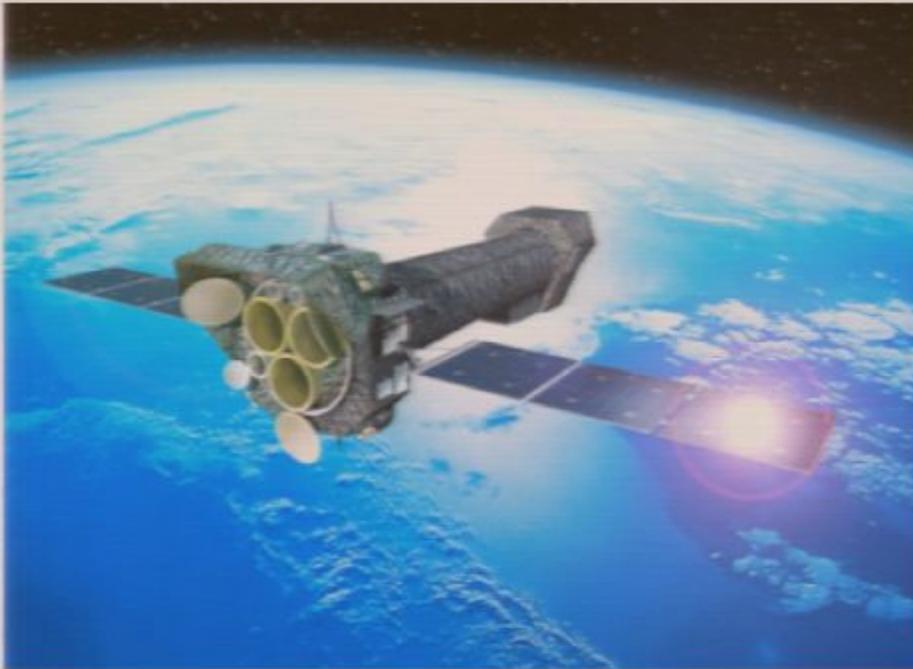
1000 galaxies @ $10^{11} M_{\odot}$	r	G
$\sim 10^{45} \text{ kg}$	$\sim 10^{20} \text{ km}$	$\sim 10^{-20} \frac{\text{km}^3}{\text{kg s}^2}$

First Puzzle

- Galaxies should not be bound, they move too fast. Either
 - we are missing mass
 - or our formula is wrong (or maybe G is wrong?)

$$v_e = \sqrt{\frac{2GM}{r}}$$

Observe 2. X-Rays



← ESA, XMM-Newton



NASA, Chandra →

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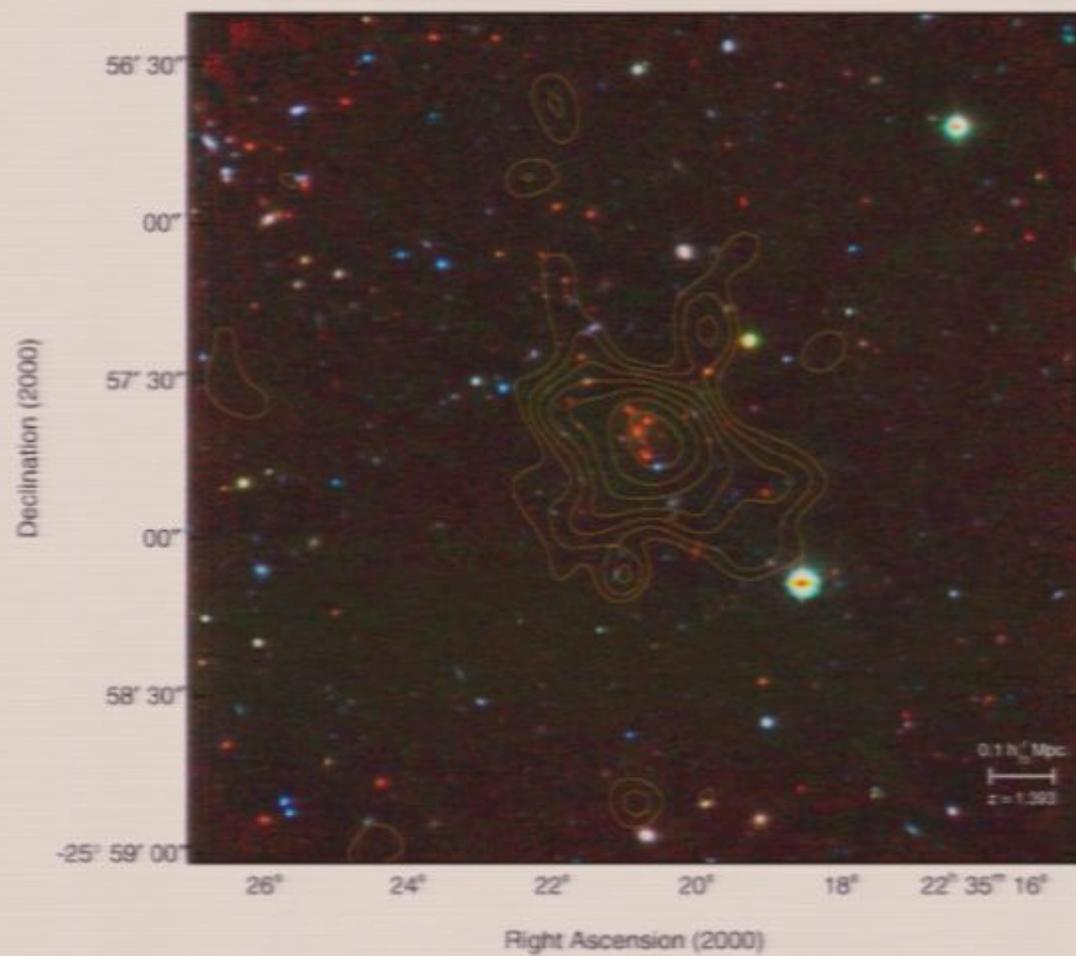
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XMMUJ2235.3+2557

X-rays contour



XMMUJ2235.3+2557

X-rays



XMMUJ2235.3+2557

- Was discovered as an extended x-rays source in archival XMM-Newton.
- X-rays is from an intergalactic gas known as intercluster gas.
- The gas is very hot ... 10^7 - 10^8 K

Mass of Gas = 2 x Mass of galaxies

Still mass missing

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Still mass missing

Dark Matter

Gas is in approximate hydrostatic equilibrium with cluster gravitational field, we can estimate the total mass

$$\text{Total Mass} \approx 6 \times (\text{mass of gas} + \text{galaxy})$$

mass	
5%	galaxies
10%	gas
85%	dark matter



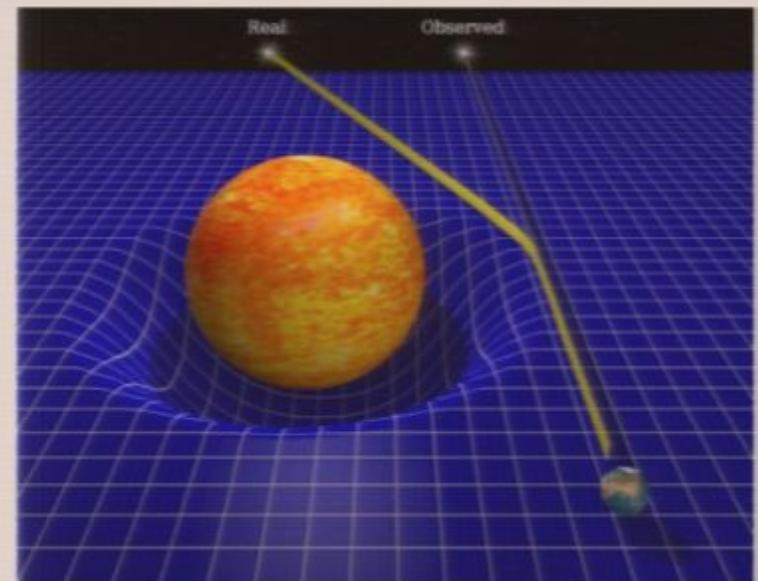
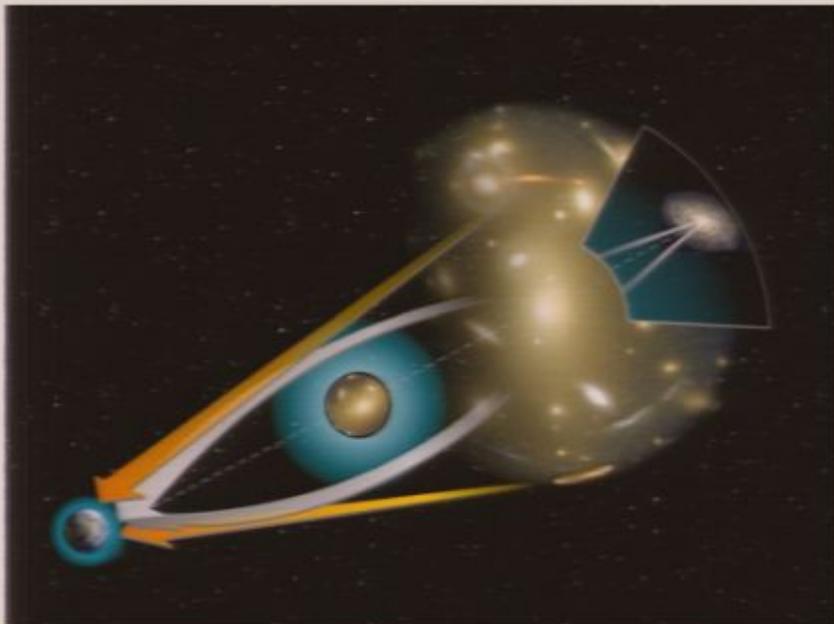
dark matter as seen using visible lights

dark matter also seems to be needed to exist inside galaxies

great, we can't see it...
can we test it?

Observe 3. Gravitational lensing

Strong Gravitational lensing





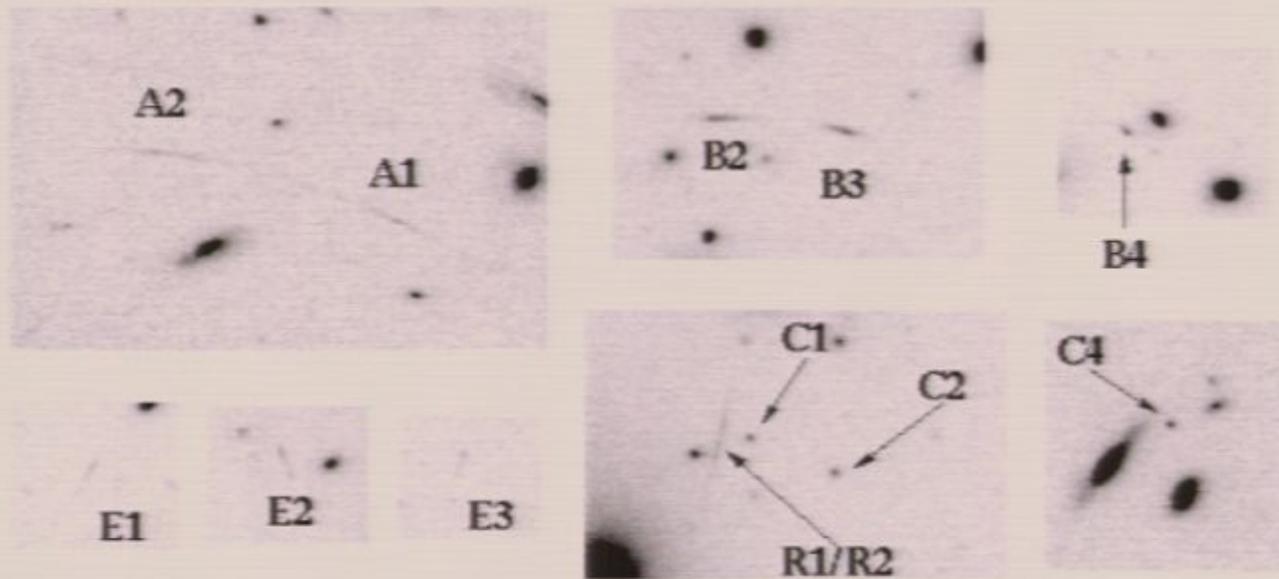


Fig. 1. Detailed view of the multiple image candidates detected in the WFPC2/F675W image. B2-B3-B4 is a triple image configuration, as well as C1-C2-C4. R1/R2 is a radial arc. E1-E2-E3 is also a triple configuration with a clear inversion of parity between E2 and E1/E3 (see text for more details).

From strong gravitational lensing we can figure out the total
mass in Abell 370

But we can do better



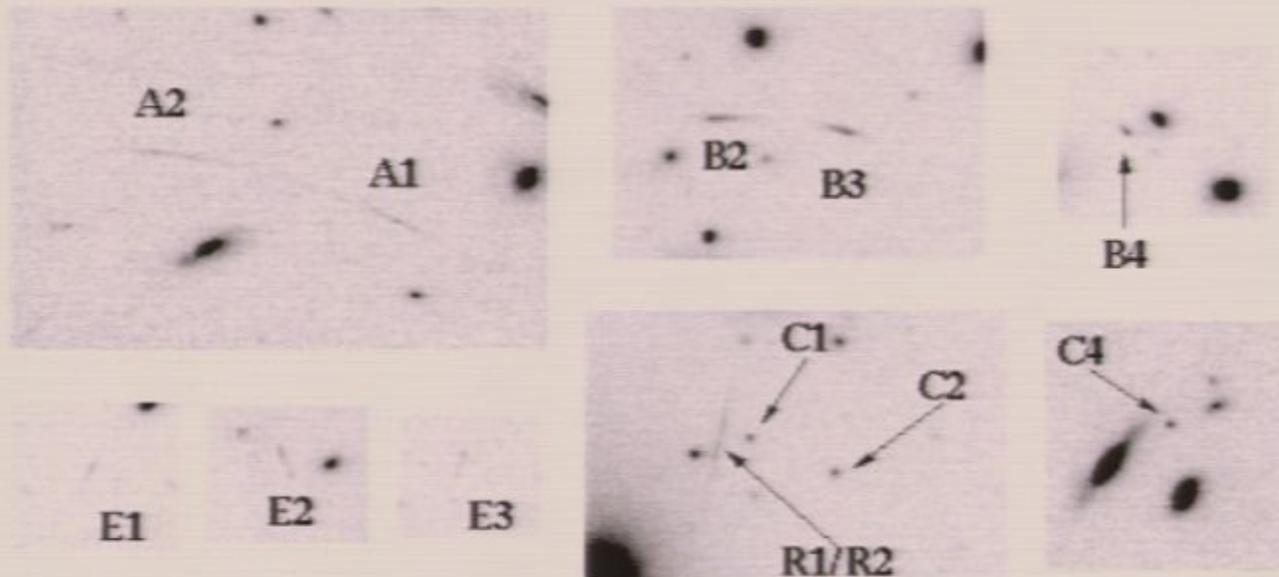


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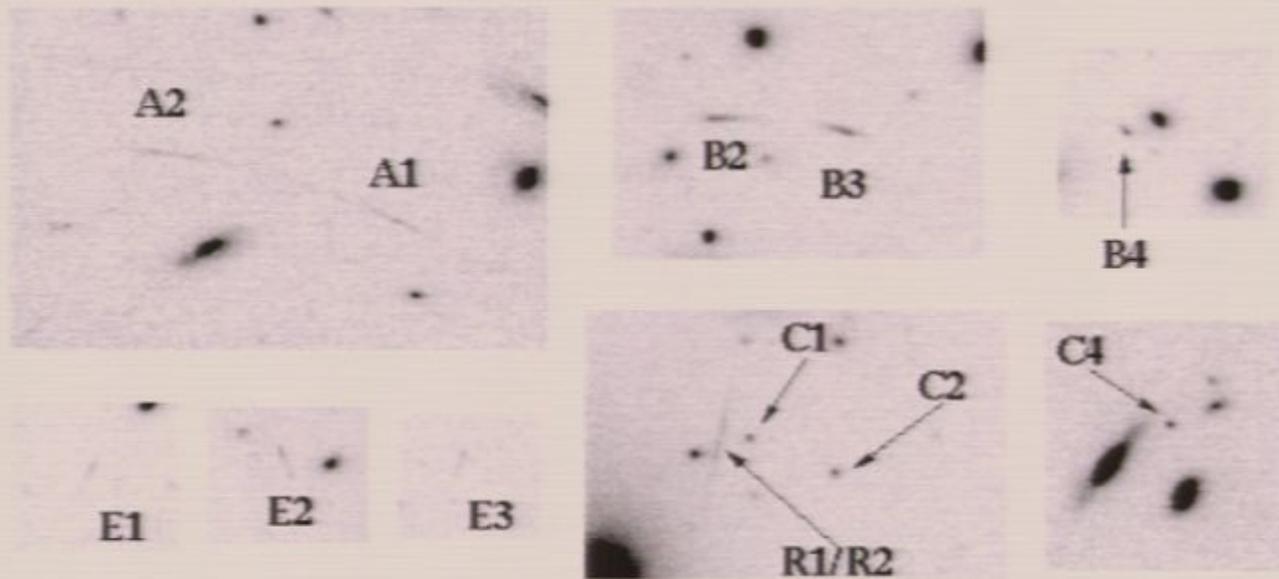
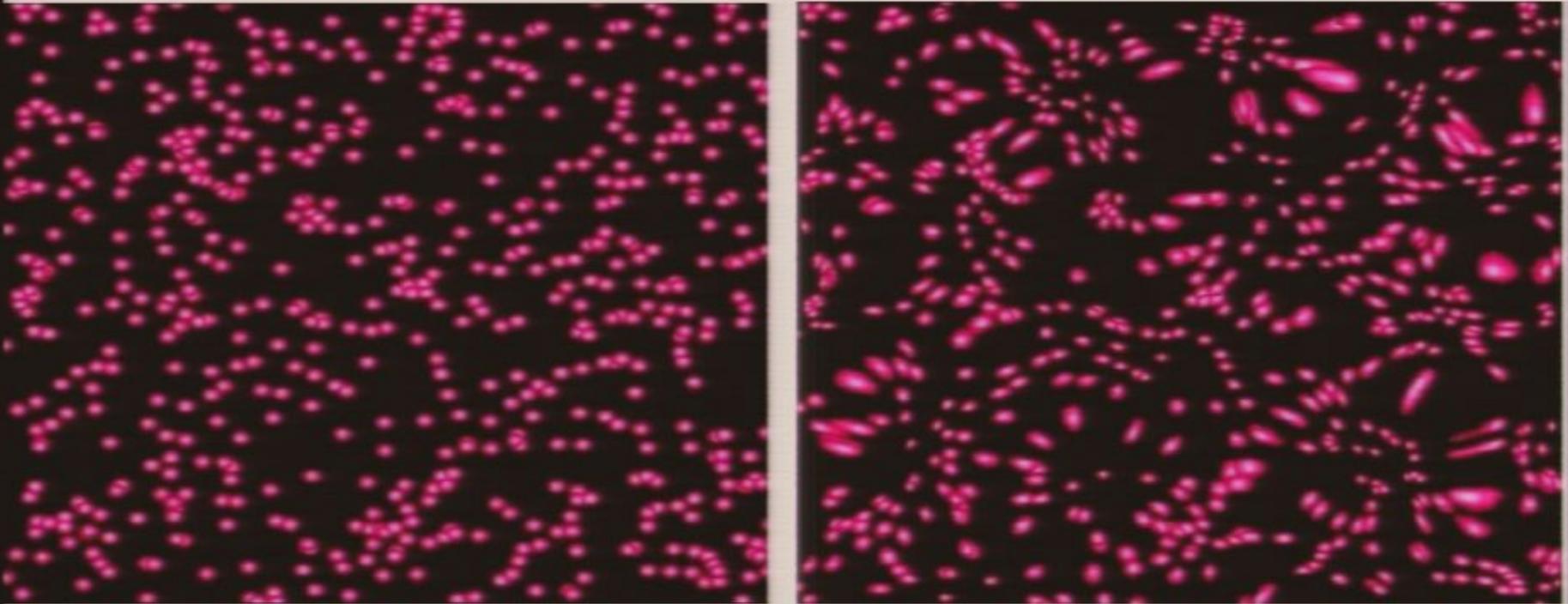


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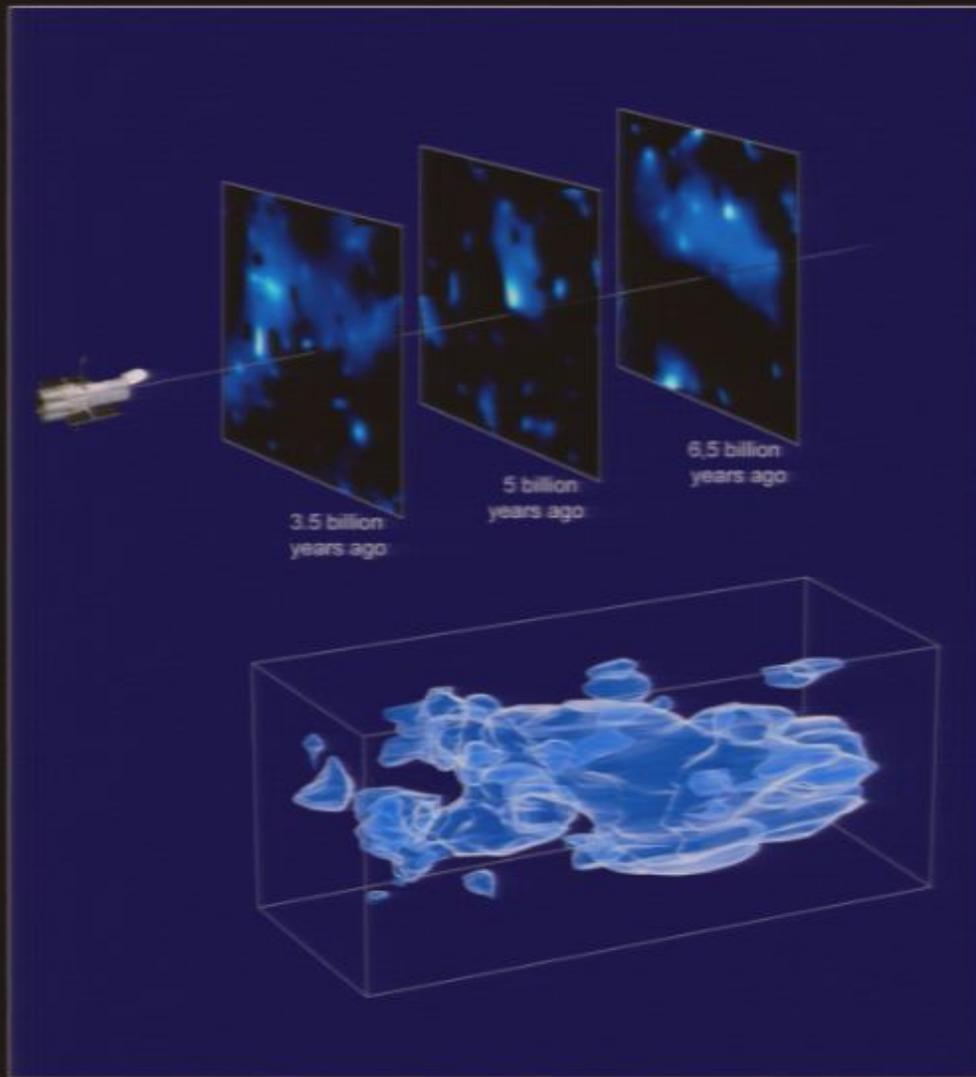
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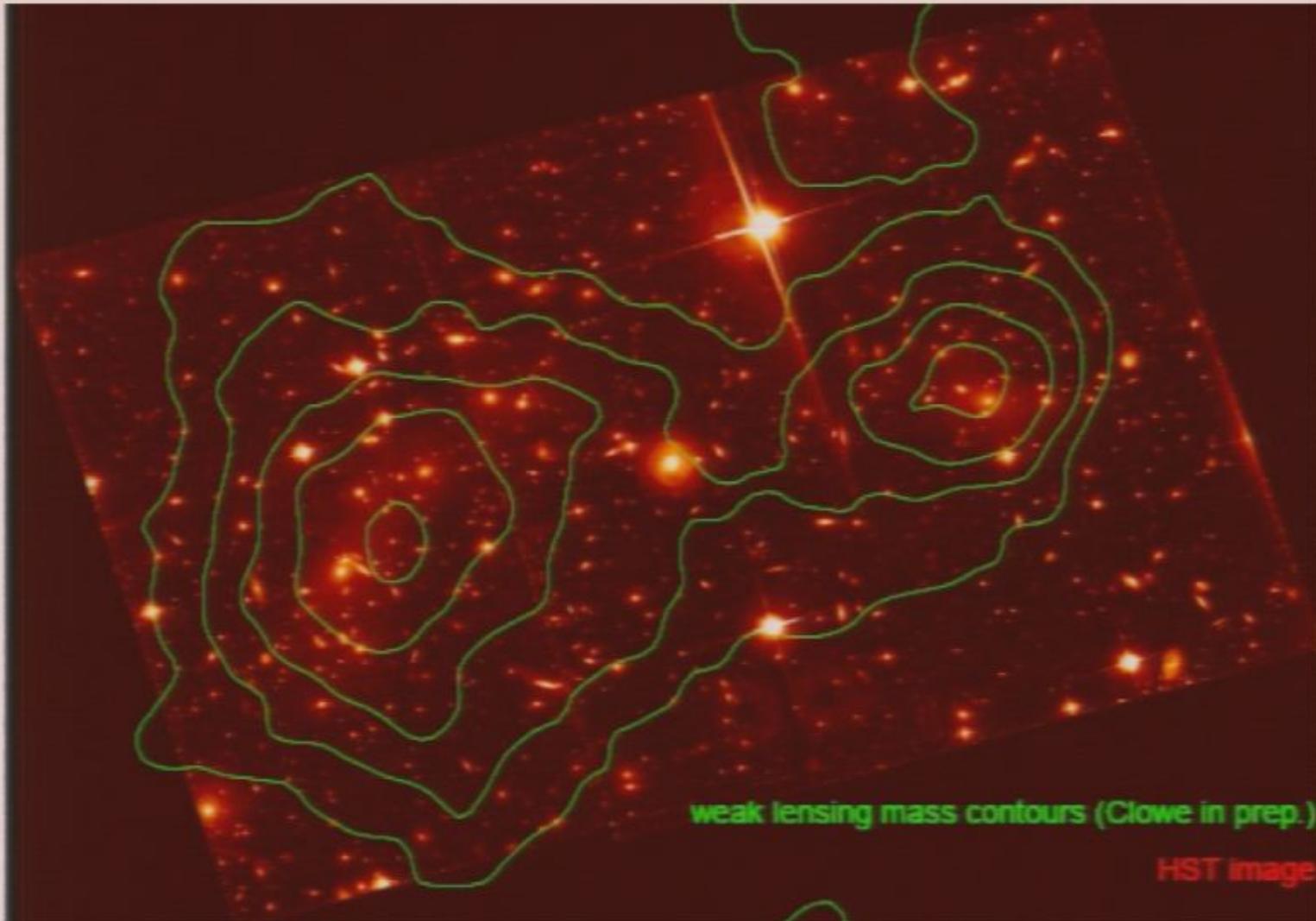
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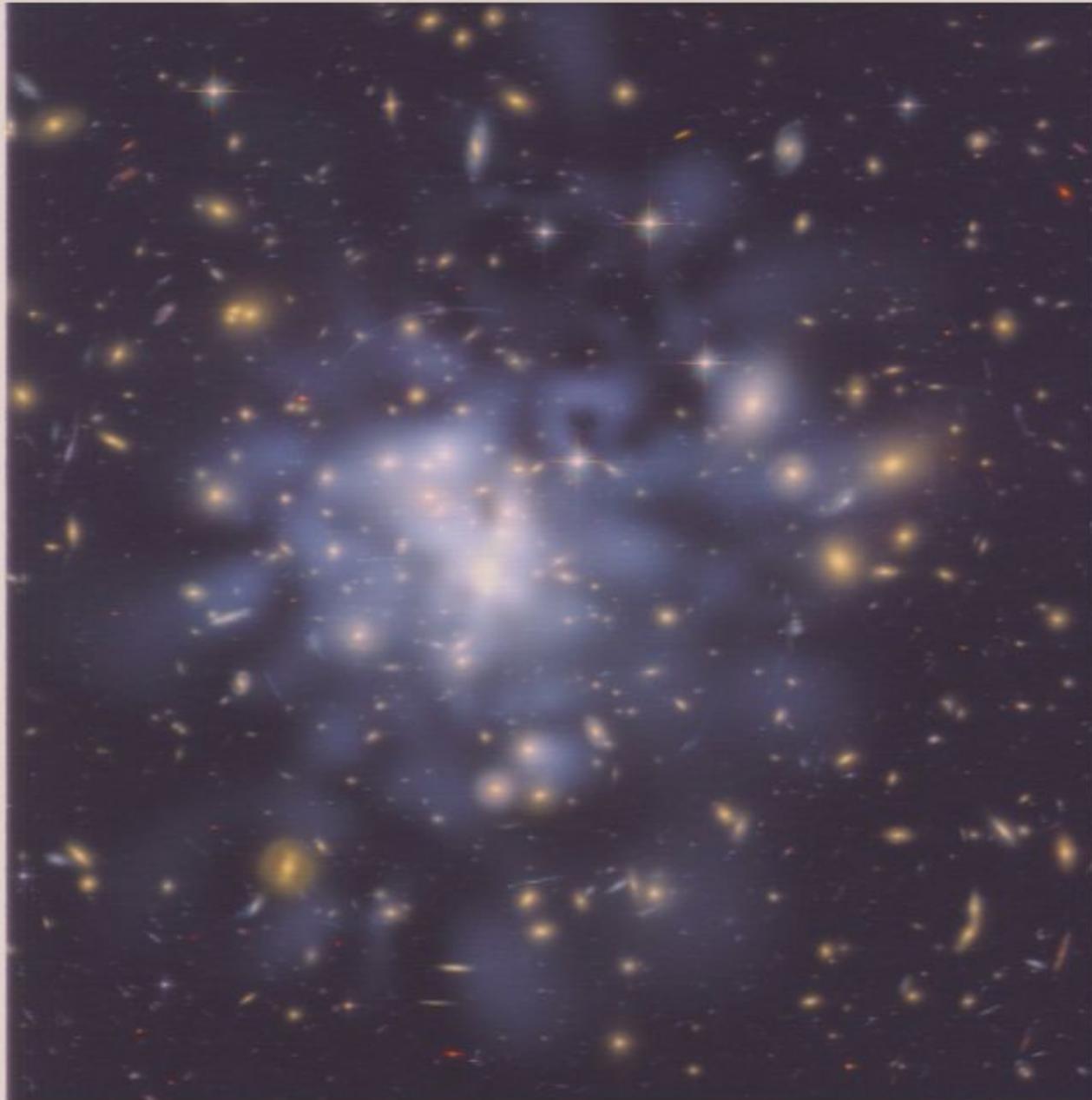
Weak Gravitational Lensing



Gravitational lensing acts as a coordinate transformation that distorts the images of background objects (usually galaxies) near a foreground mass. The transformation can be split into two terms, the convergence and shear.







Coe et al



Optical X-ray Gas



Optical Dark Matter

Optical Dark Matter X-ray Gas



Cosmology: neglecting us

- Forget about baryons (only about 15 %).
There is only dark matter.

Λ CDM

Cold Dark matter

Particle with no interaction
with a mass

How do we get structure in the Universe?

Original seeds

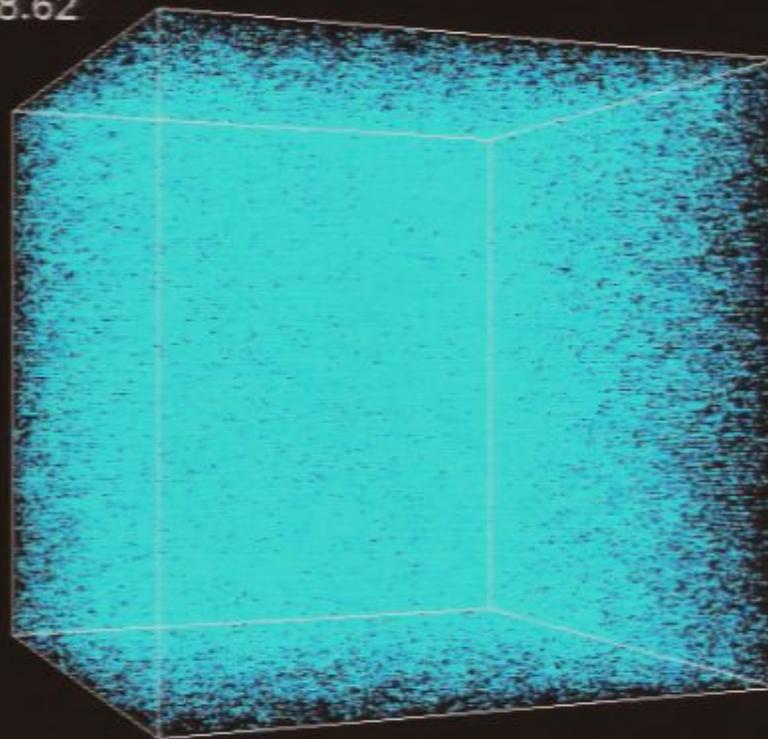
- Start with some small perturbation on top of a smooth background.

The Model

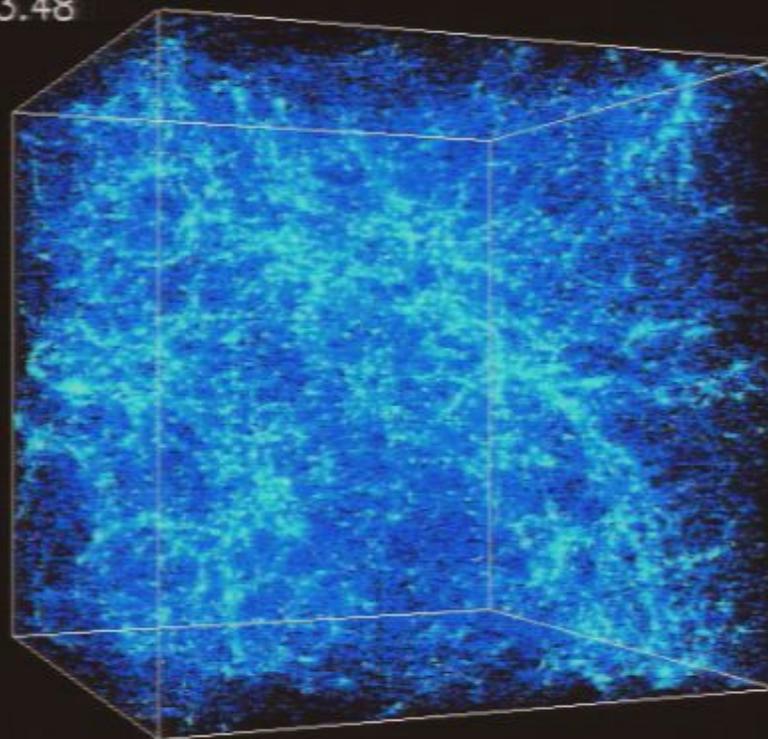
1. Dark matter particles with mass m
2. Gravity, General Relativity
3. a spectrum of perturbations

N-body Simulation on a supercomputer

Z=28.62

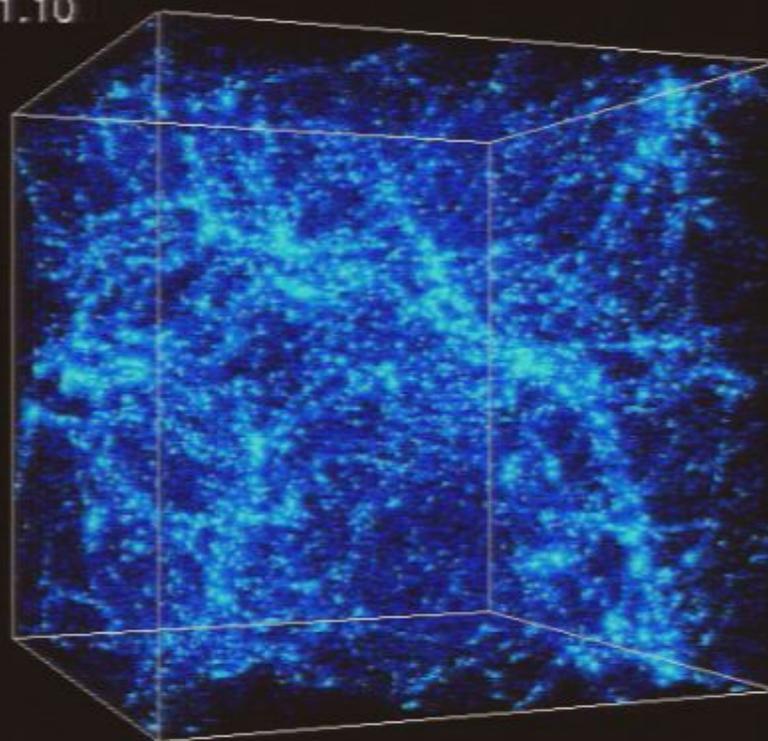


Z= 3.48

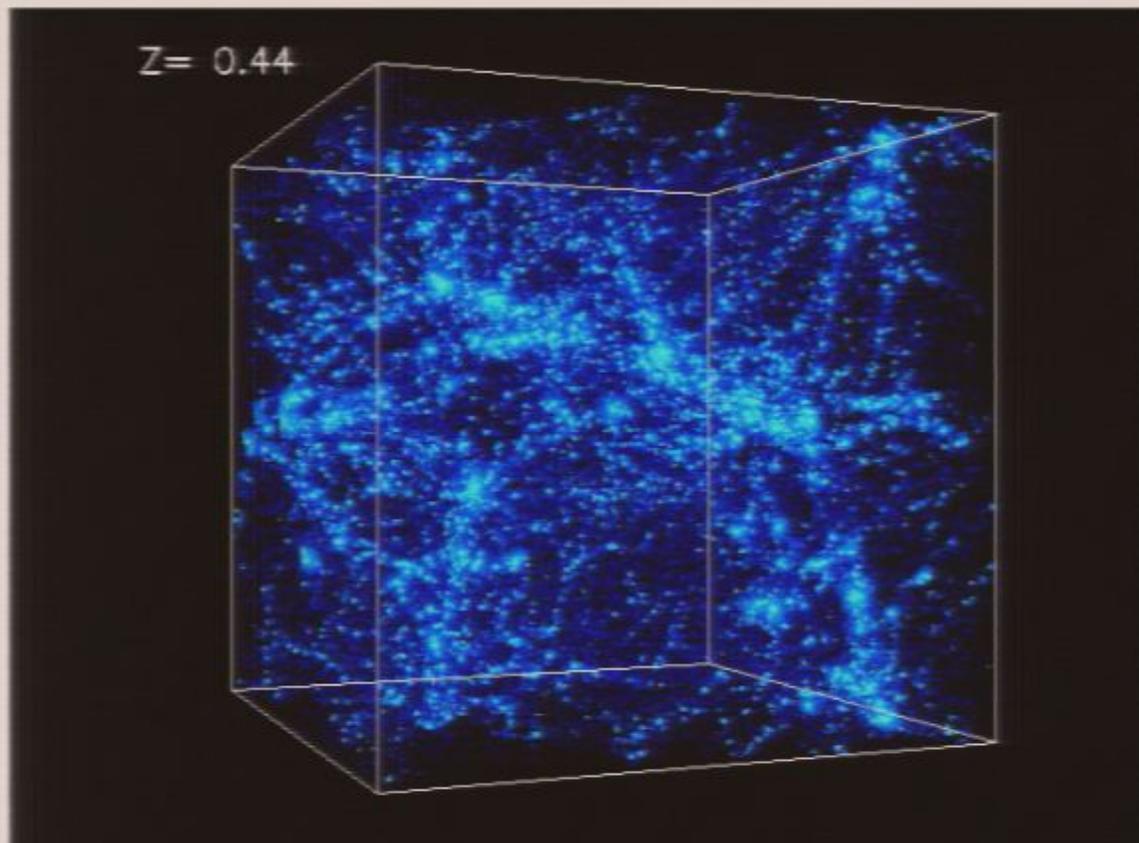


U. Chicago

Z= 1.10

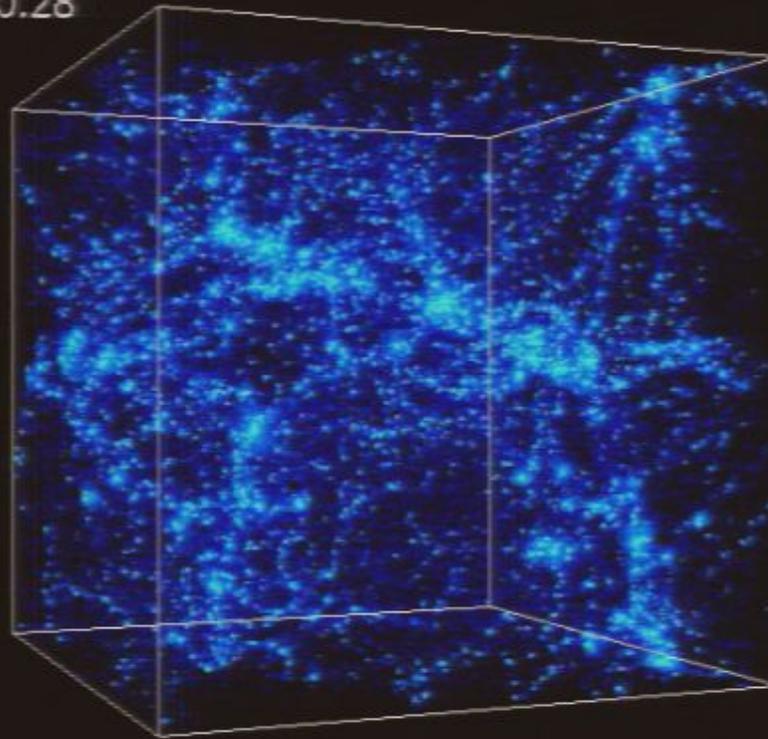


U. Chicago



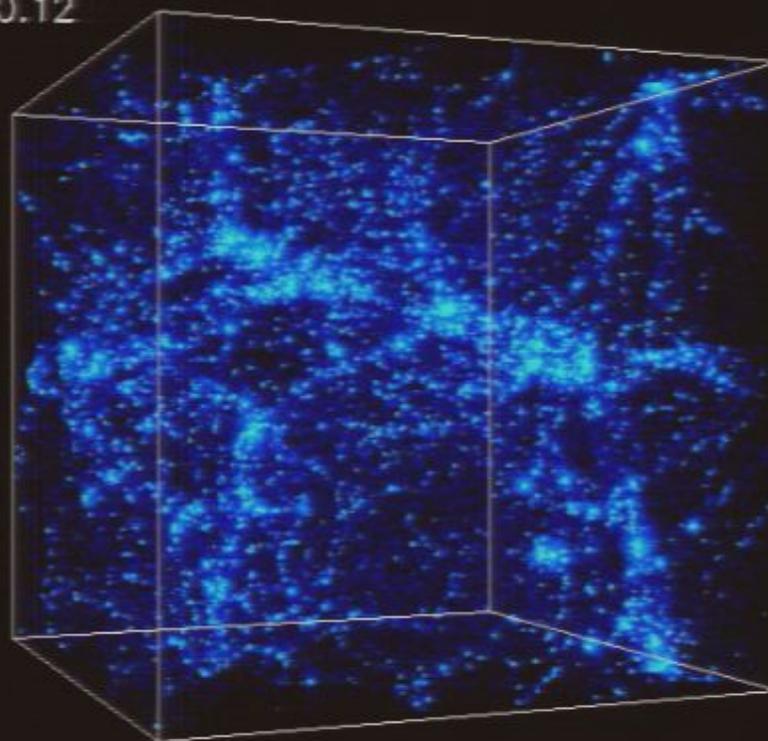
U. Chicago

$Z = 0.28$



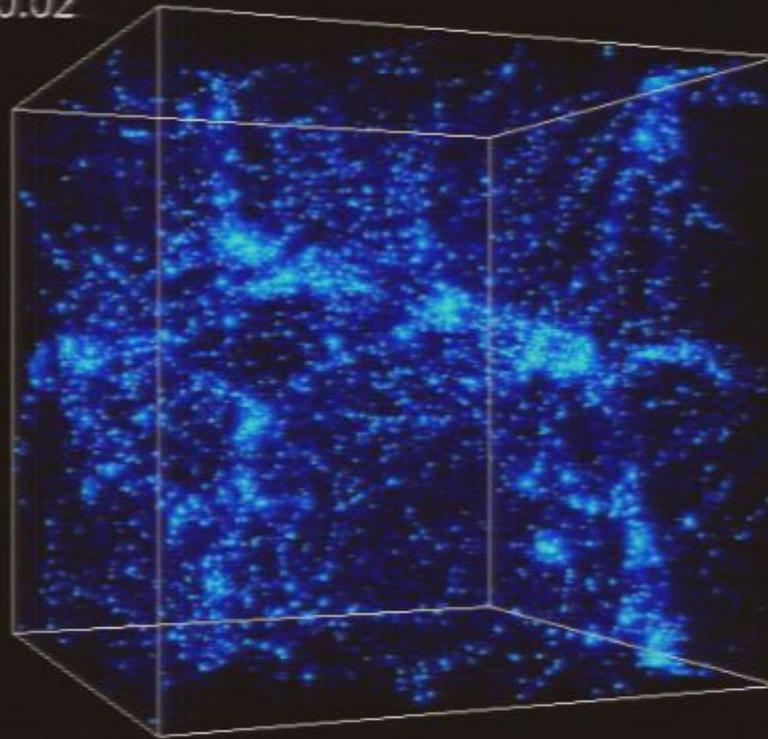
U. Chicago

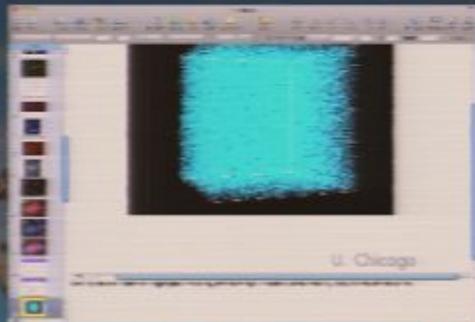
Z= 0.12



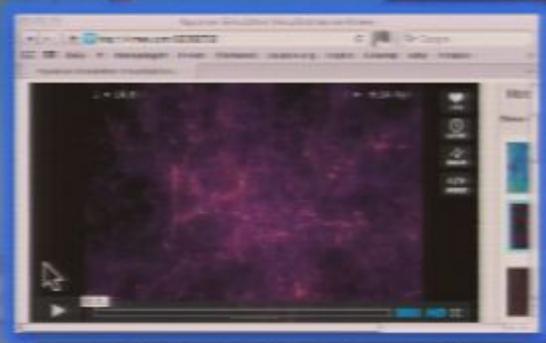
U. Chicago

$Z = 0.02$

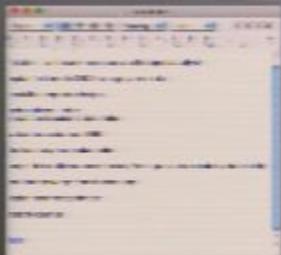




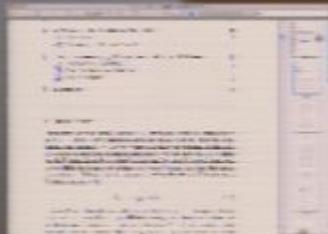
Biggest



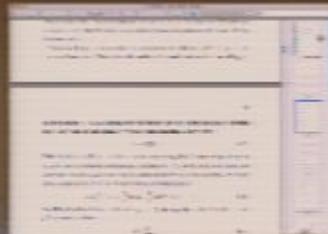
Aquarius Simulation Visualization on Vimeo



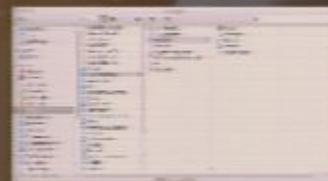
comments



arXiv 2006 ...ge 2 of 17)



1107.1840...ge 3 of 15)



Biggest



Aquarius Simulation Visualization on Vimeo

<http://vimeo.com/22082732>

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Aquarius Simulation Visualization...

$z = 24.8$ $T = 8.14 \text{ Gyr}$

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Gravity causes matter to aggregate into long, intersecting filaments surrounded by vast, nearly empty voids

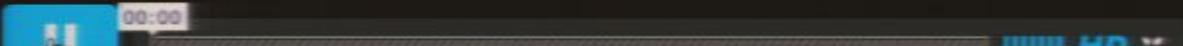
$z = 24.8$

$T = 0.14 \text{ Gyr}$

Press Esc to exit full screen mode.

500 kpc





$z = 40.3$

$T = 0.07 \text{ Gyr}$

500 kpc

$z = 37.8$

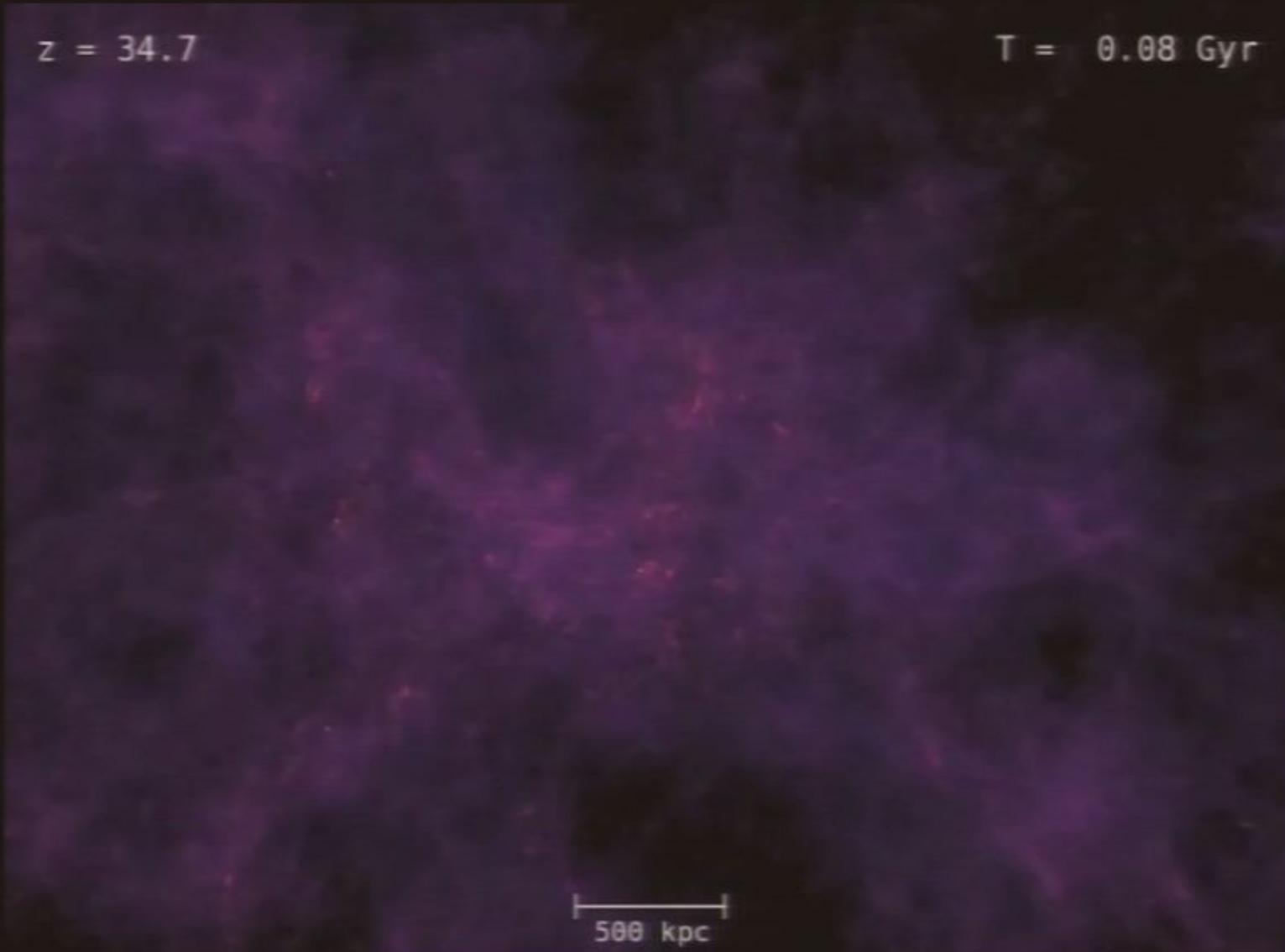
$T = 0.07 \text{ Gyr}$



500 kpc

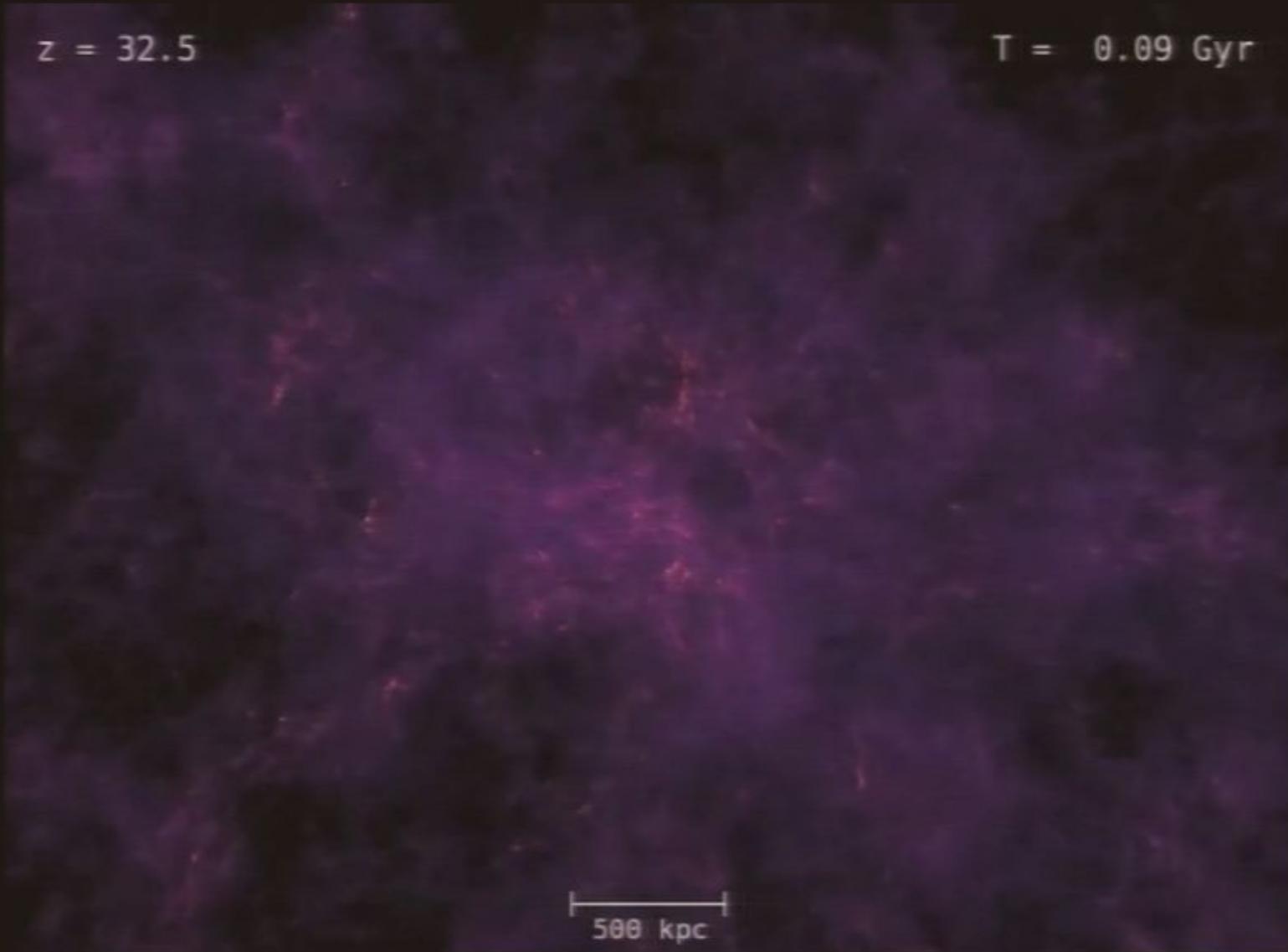
$z = 34.7$

$T = 0.08 \text{ Gyr}$



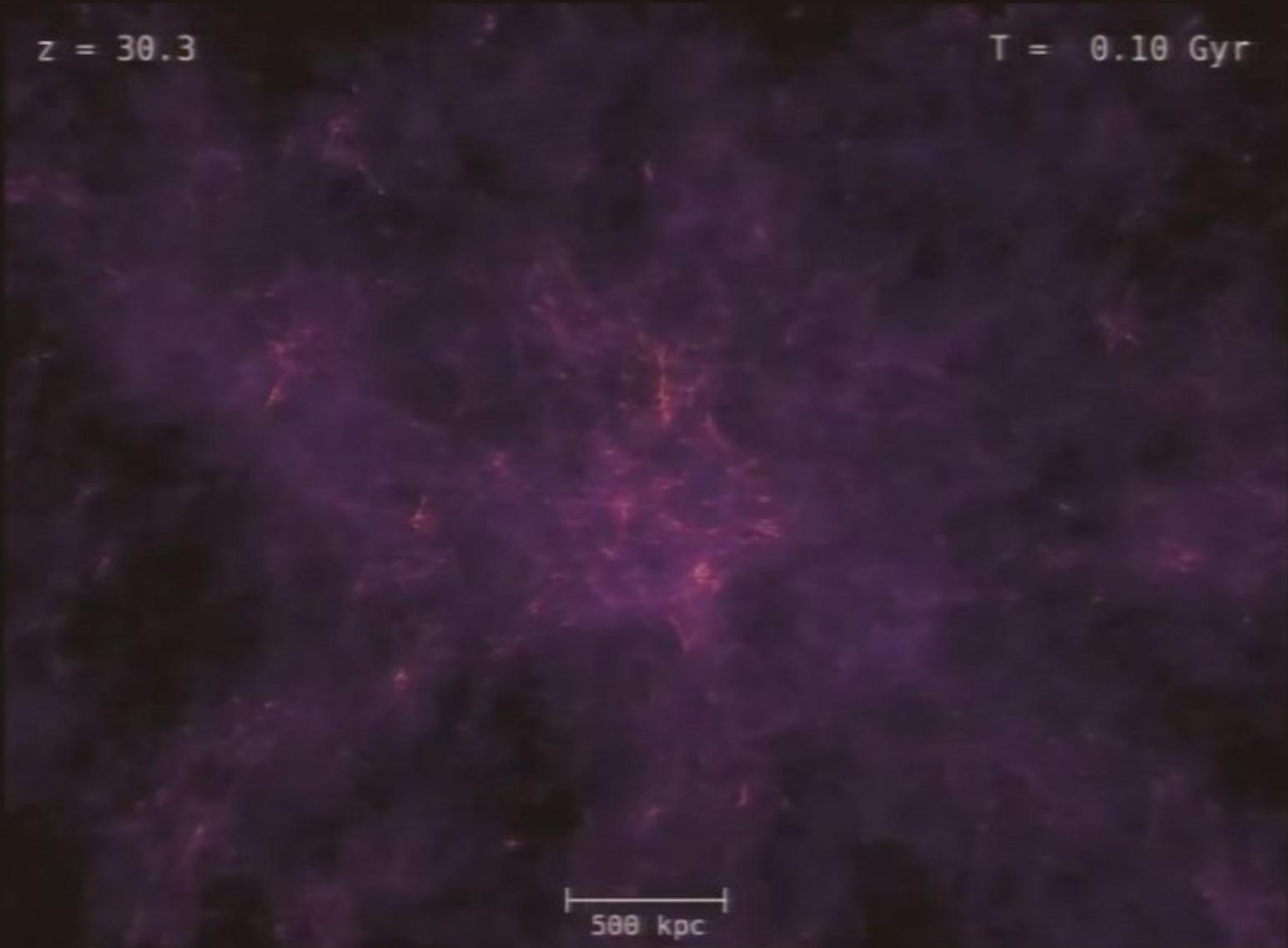
$z = 32.5$

$T = 0.09 \text{ Gyr}$



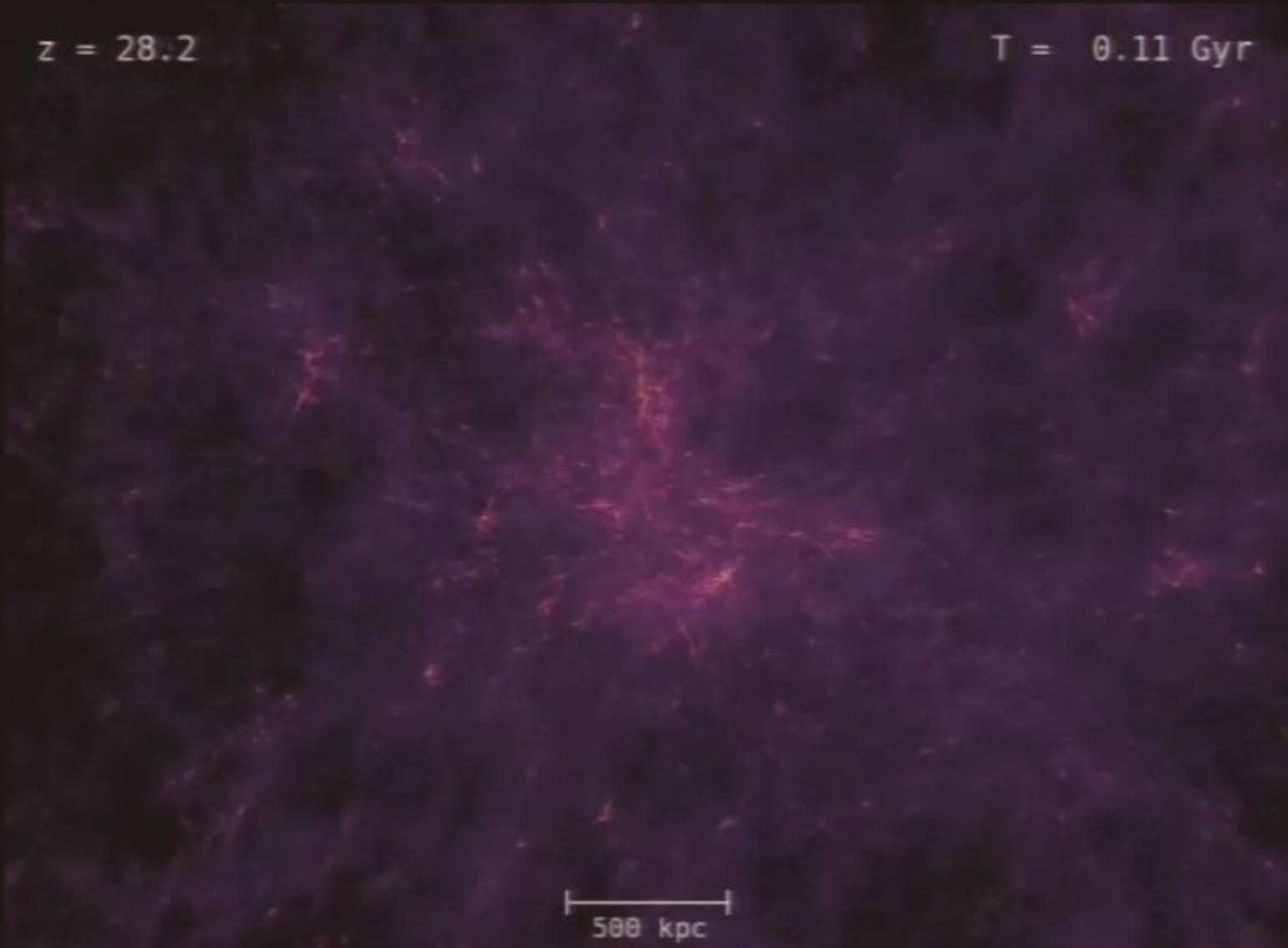
$z = 30.3$

$T = 0.10 \text{ Gyr}$



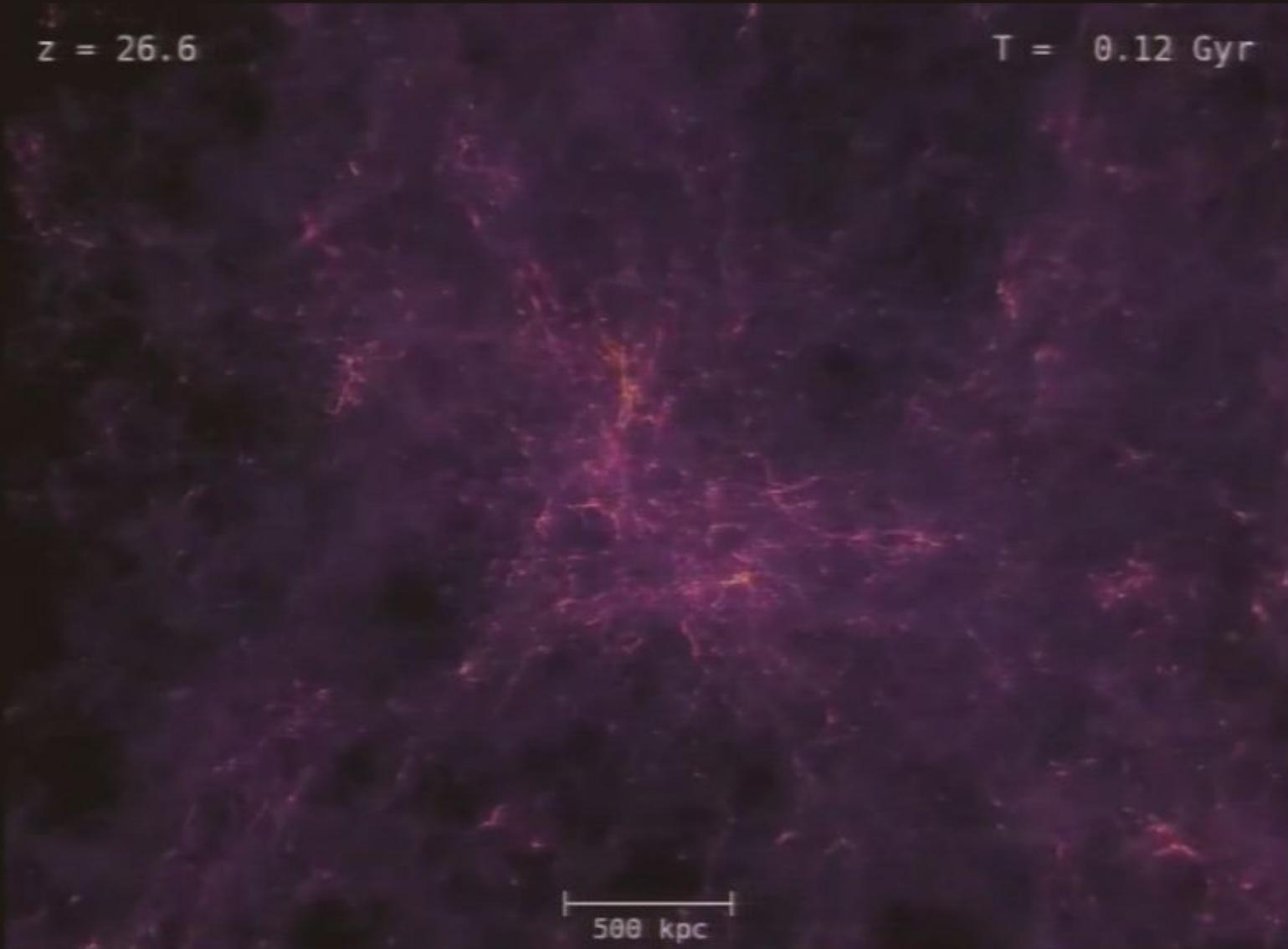
$z = 28.2$

$T = 0.11 \text{ Gyr}$



$z = 26.6$

$T = 0.12 \text{ Gyr}$



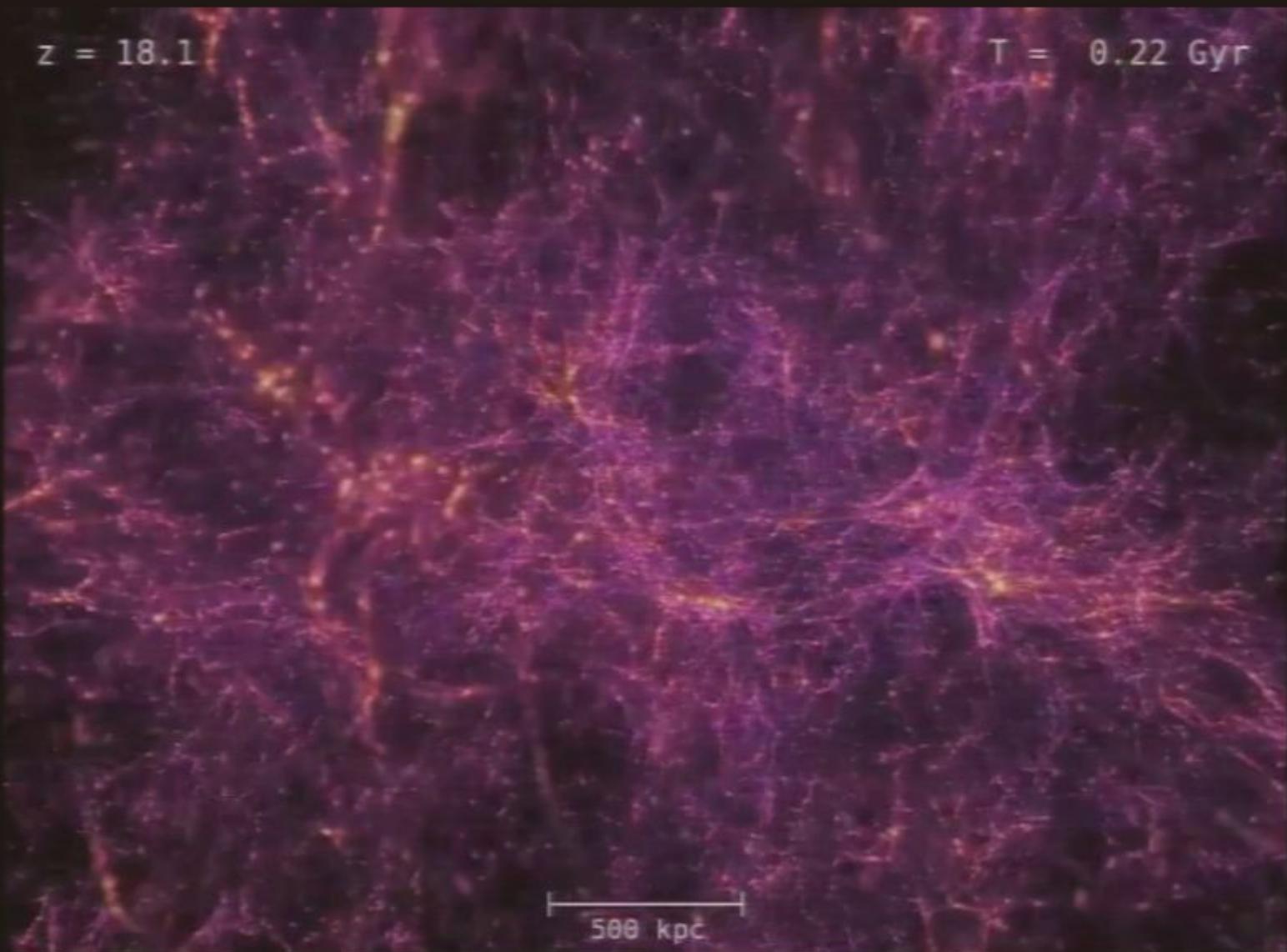
$z = 24.2$

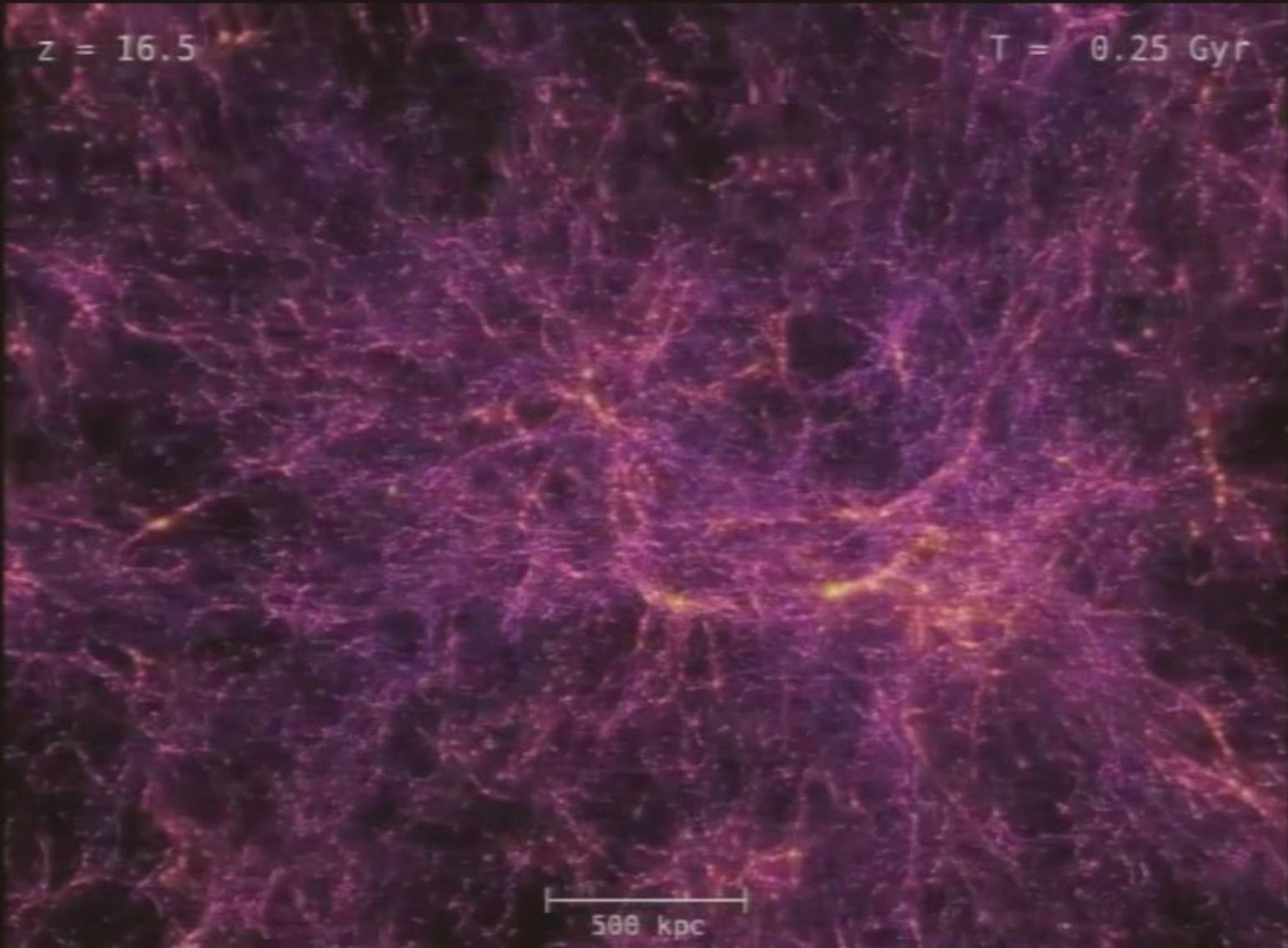
$T = 0.14 \text{ Gyr}$

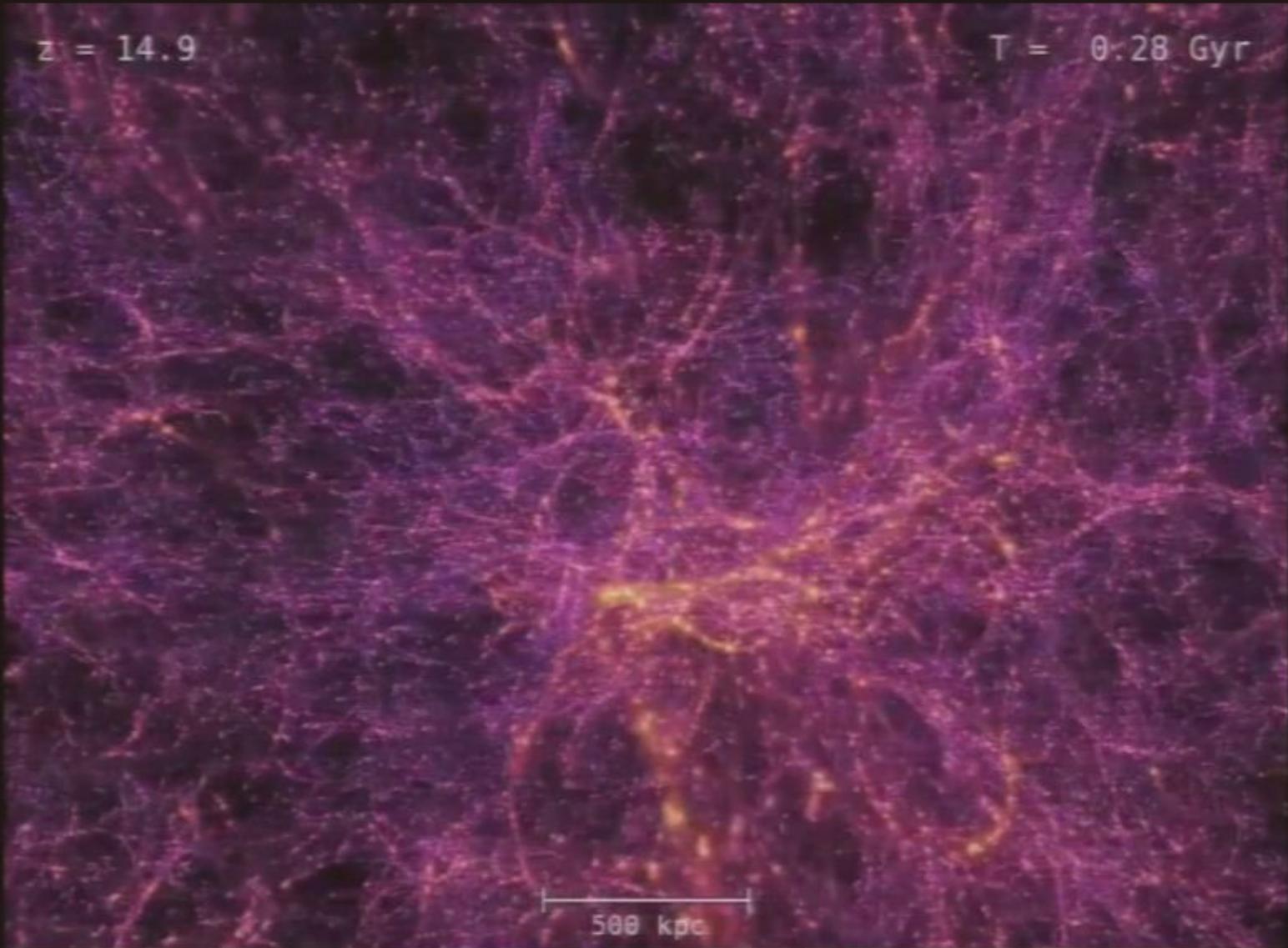


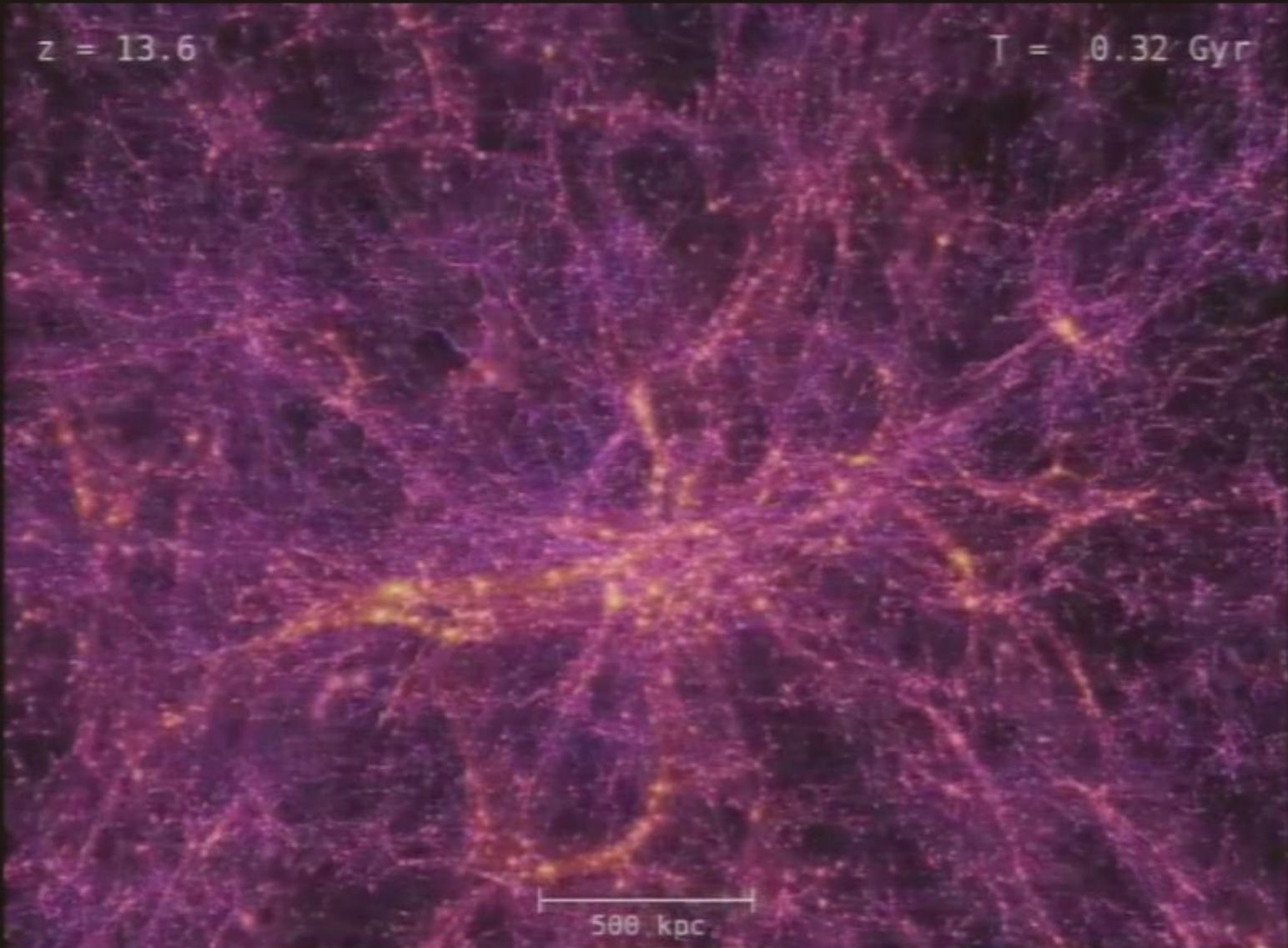


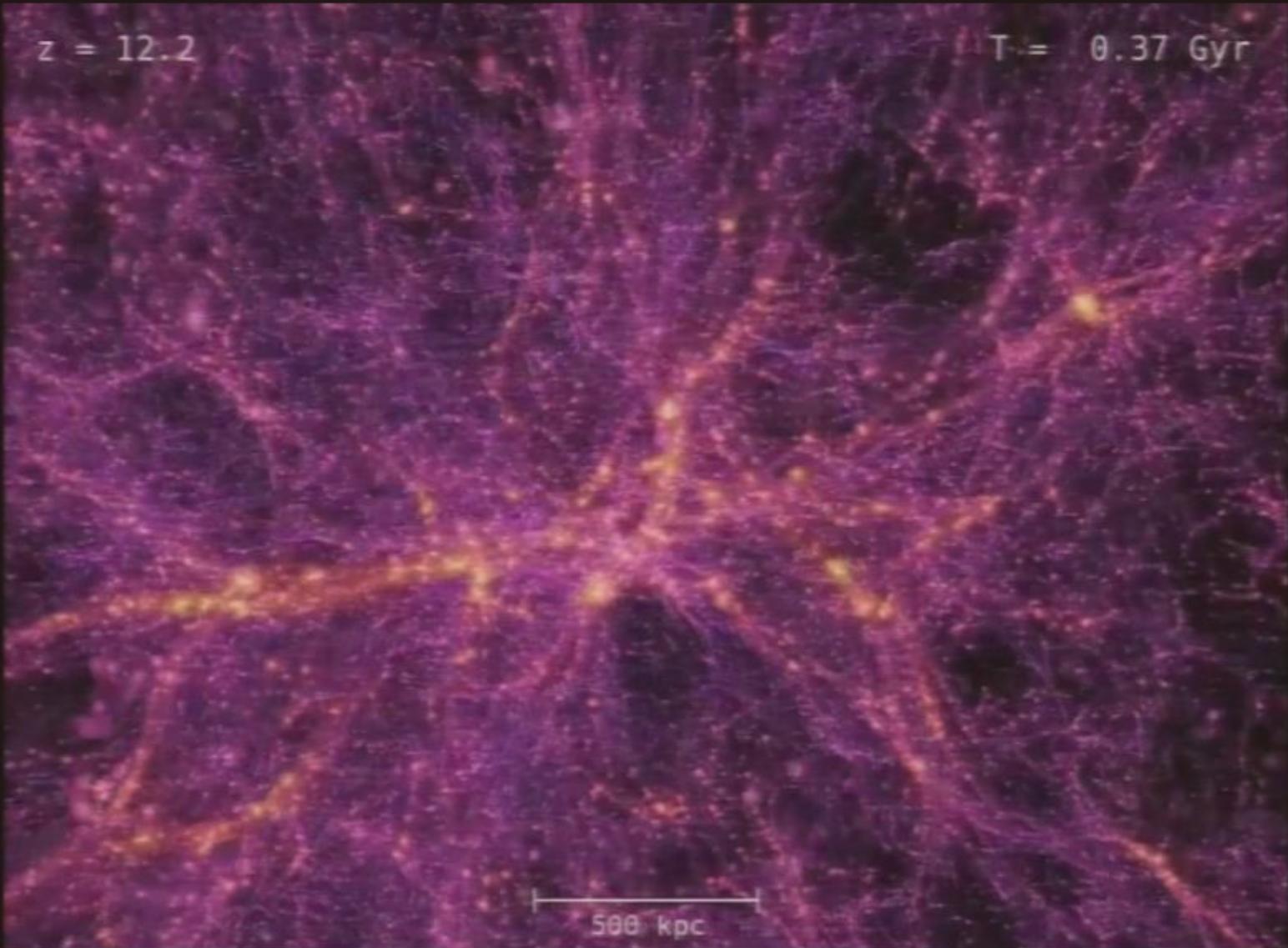




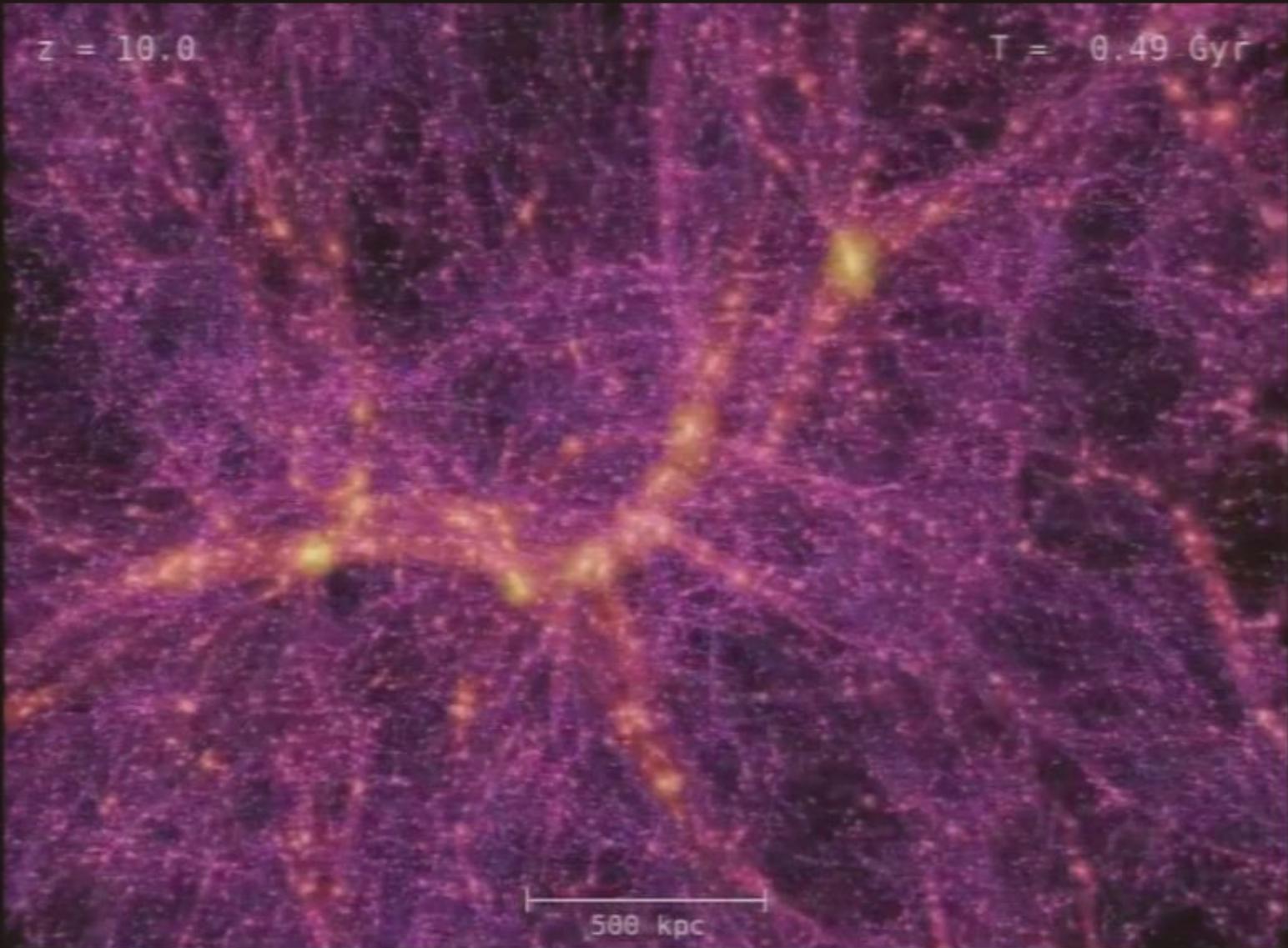


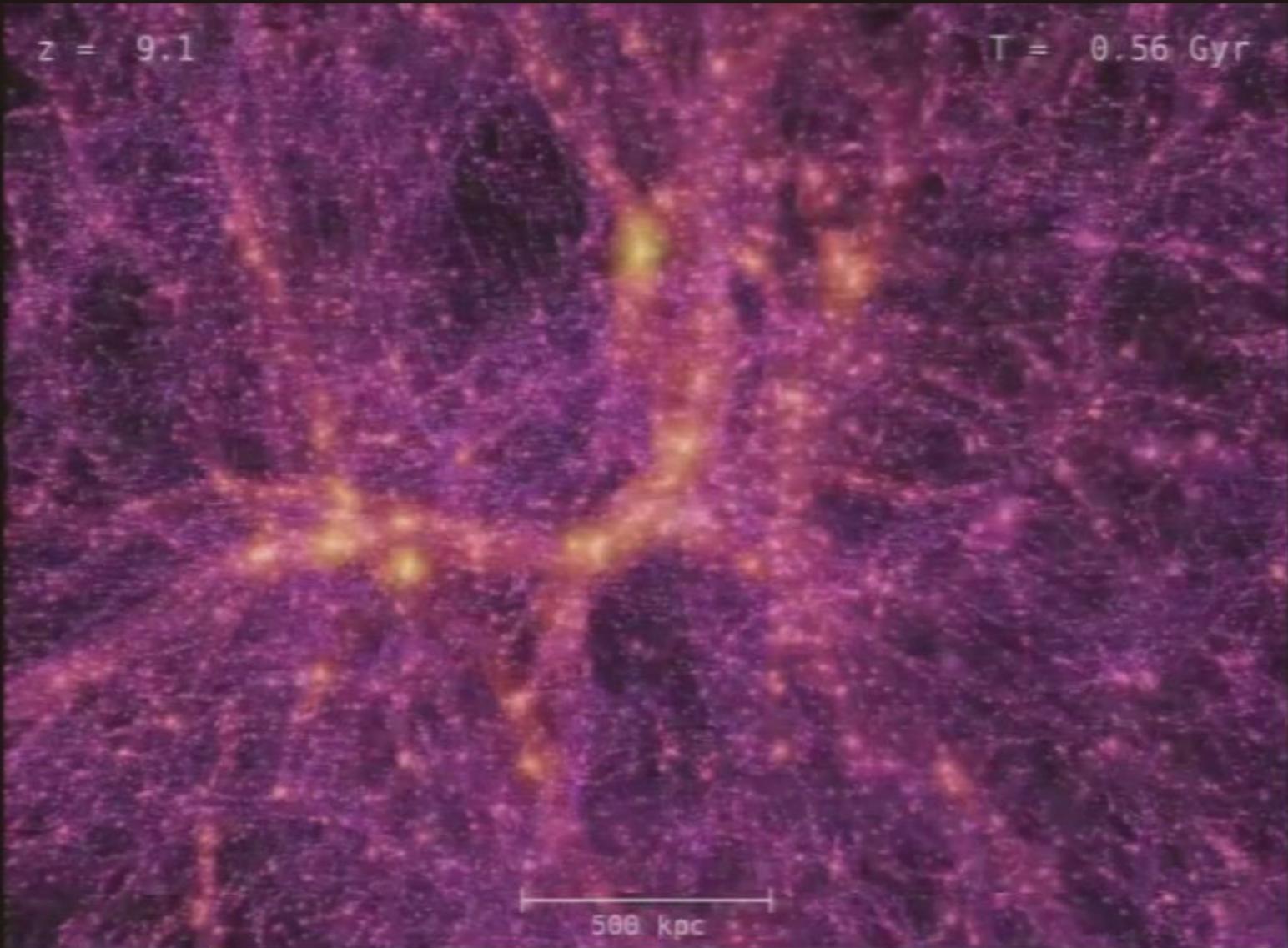


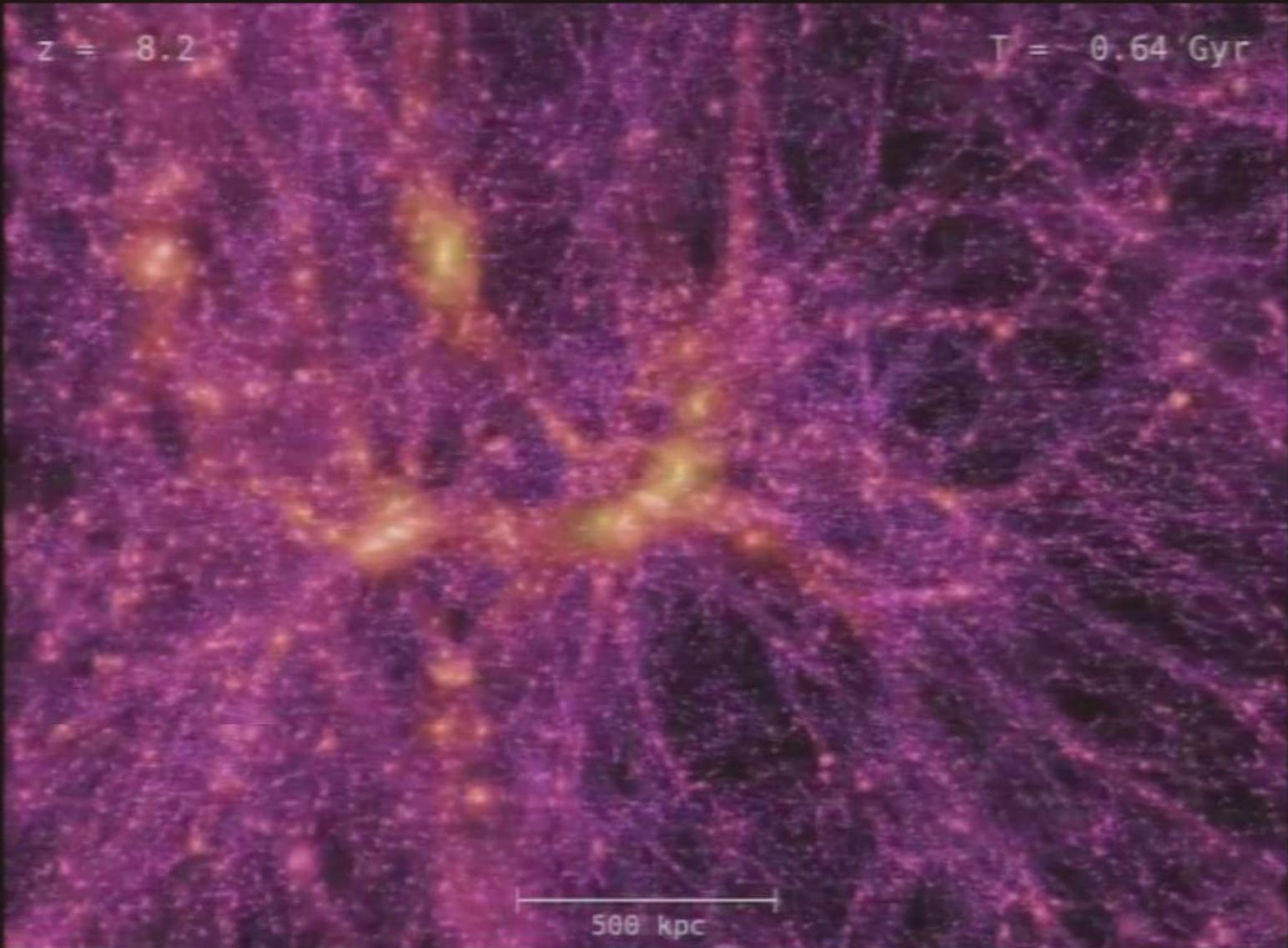






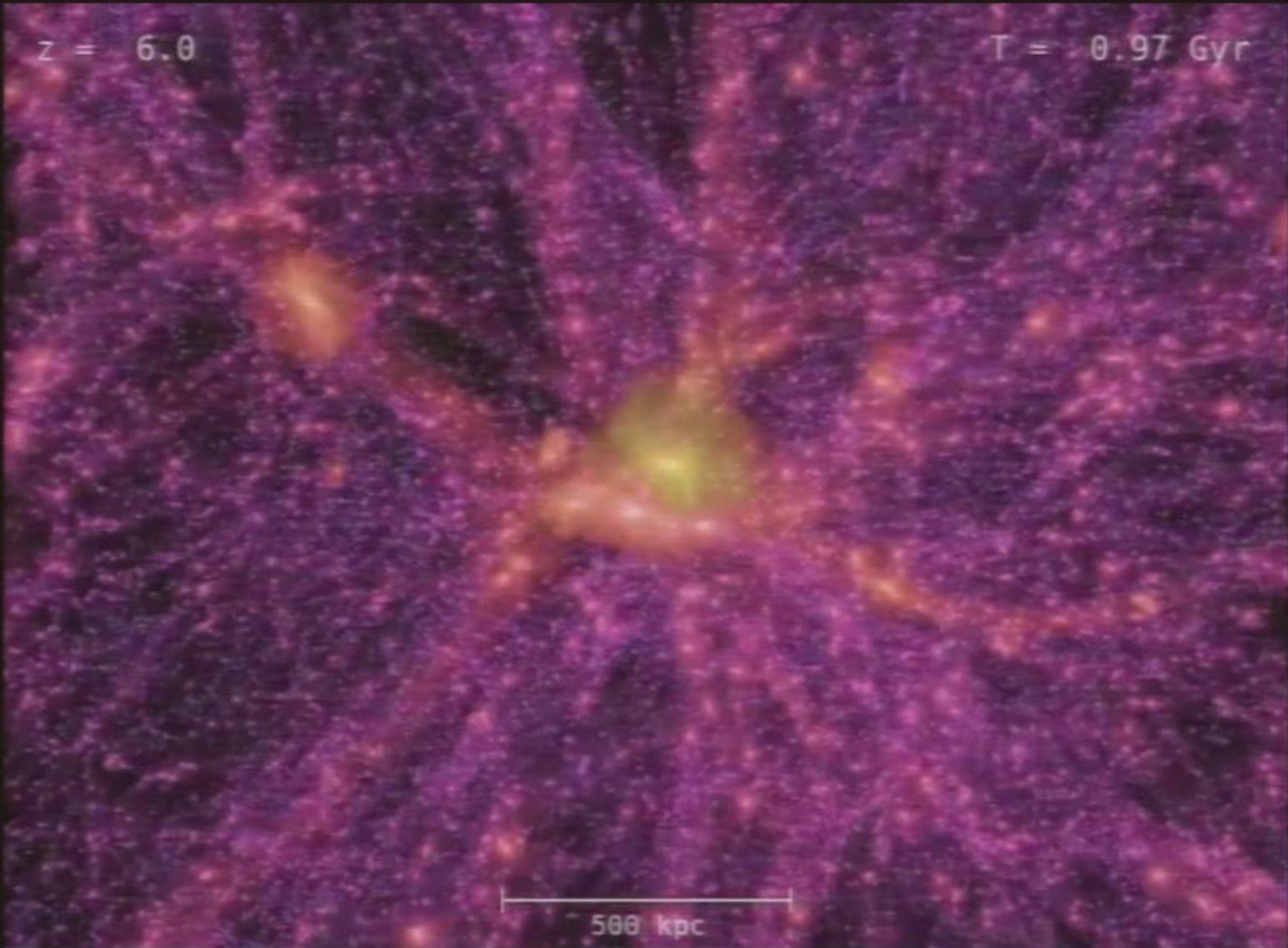


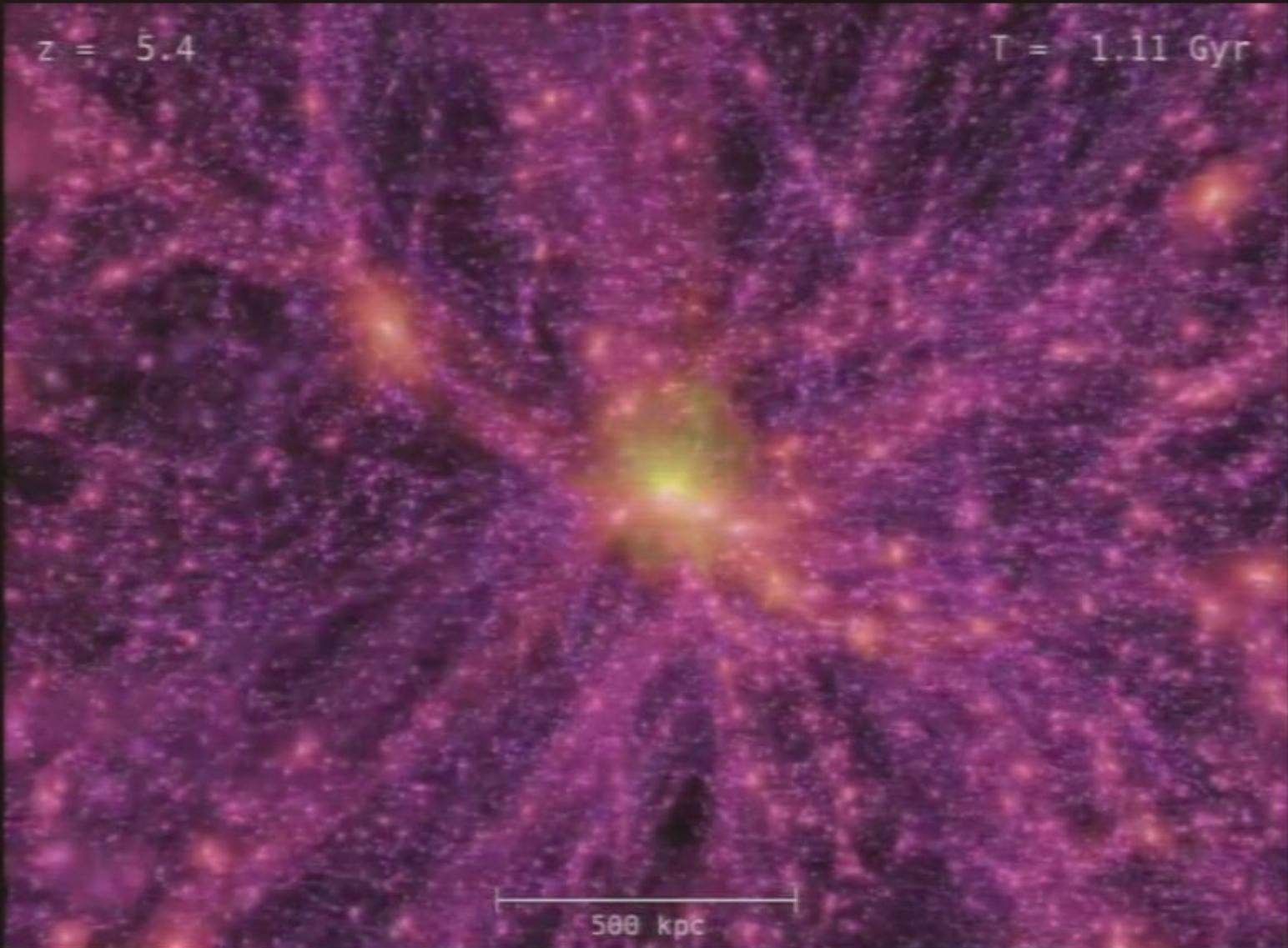




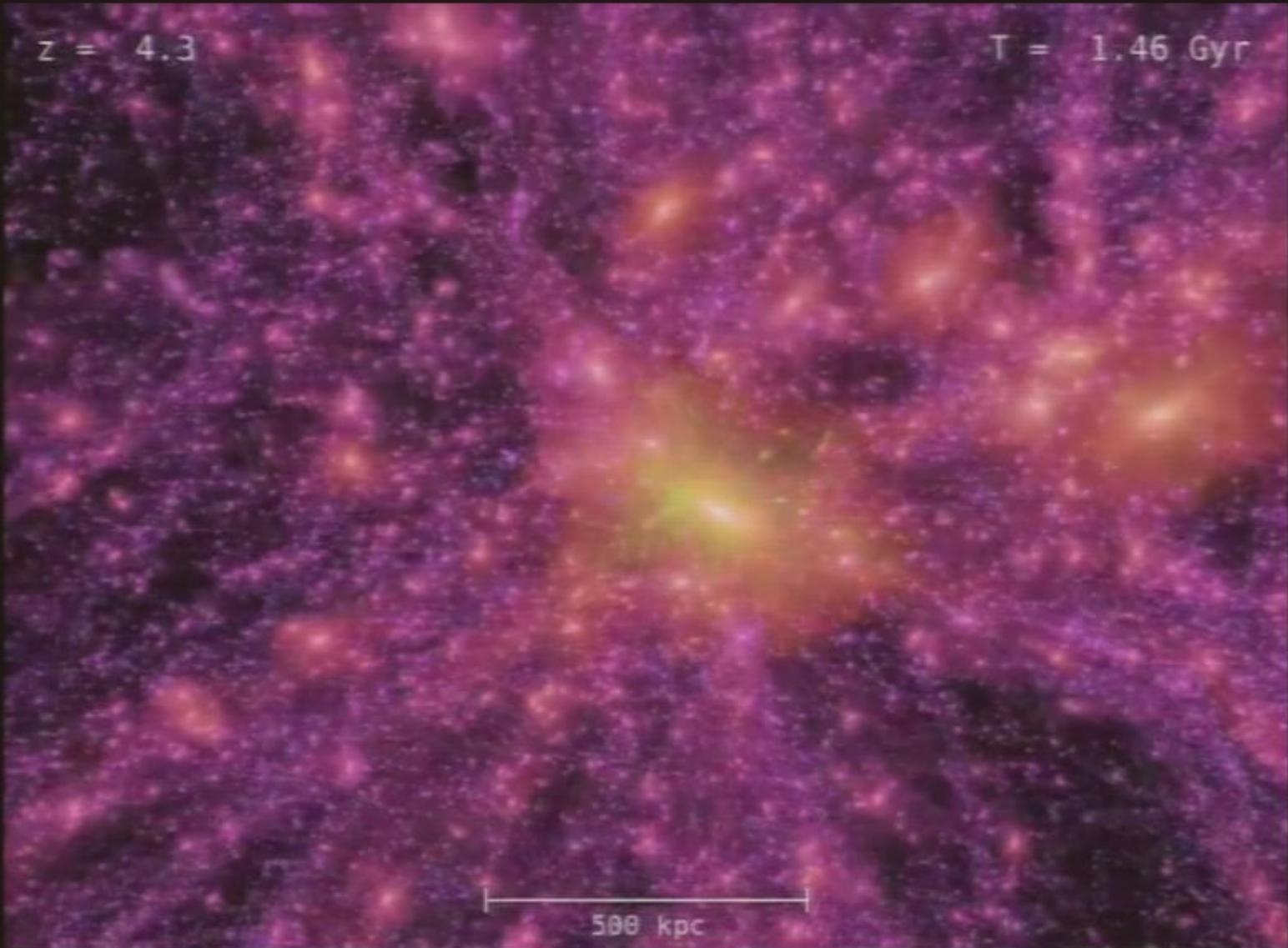




























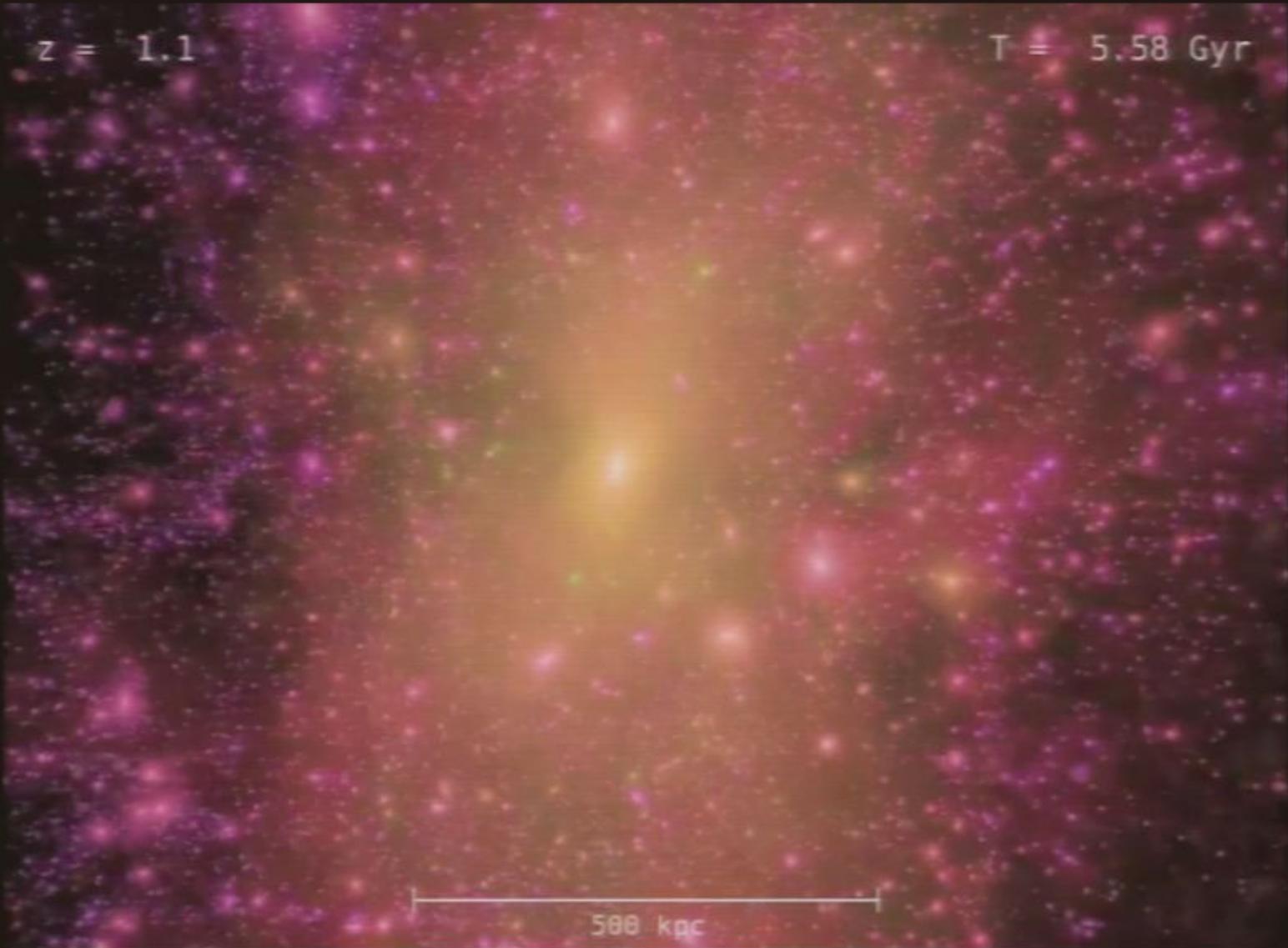




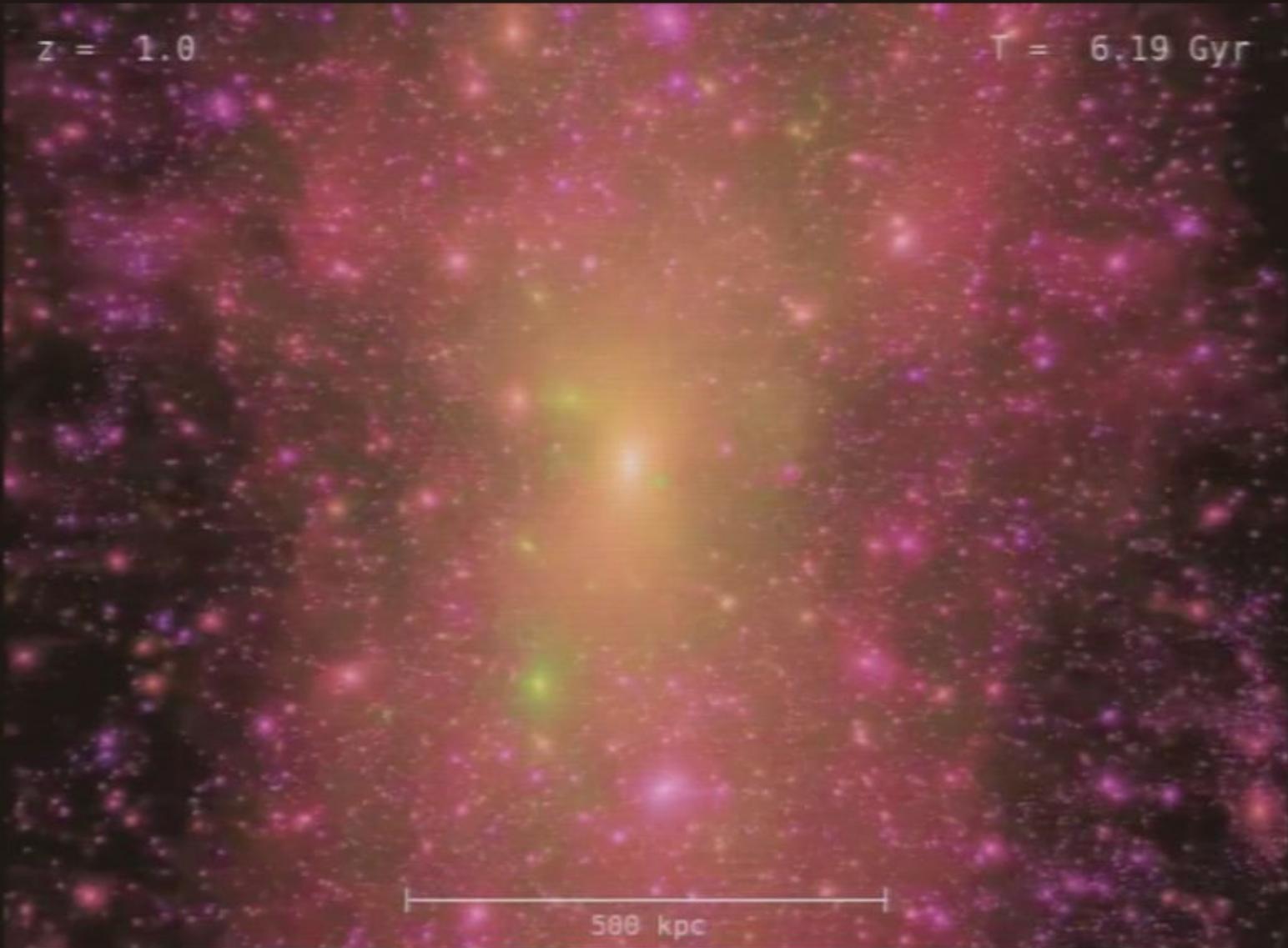






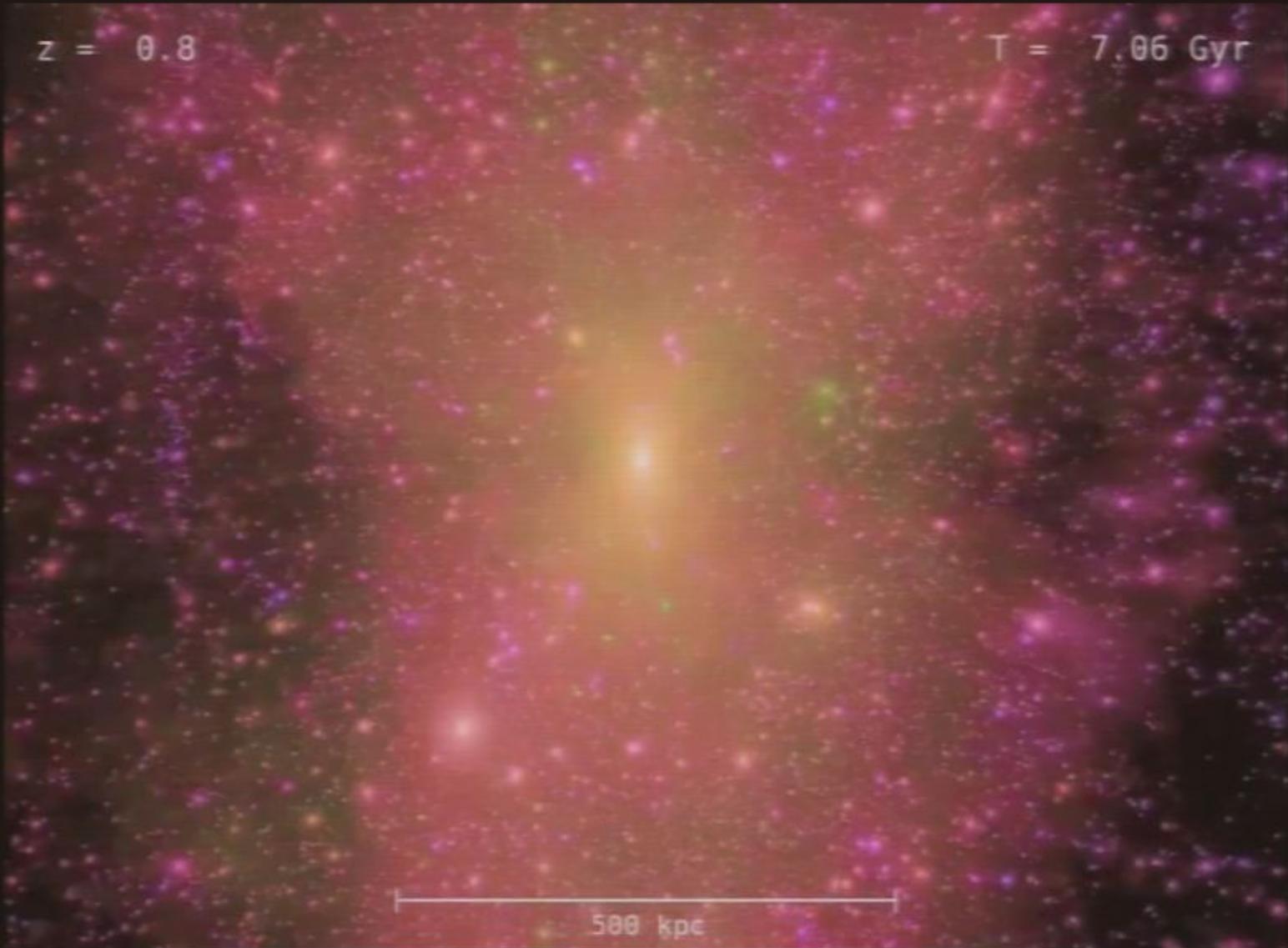
















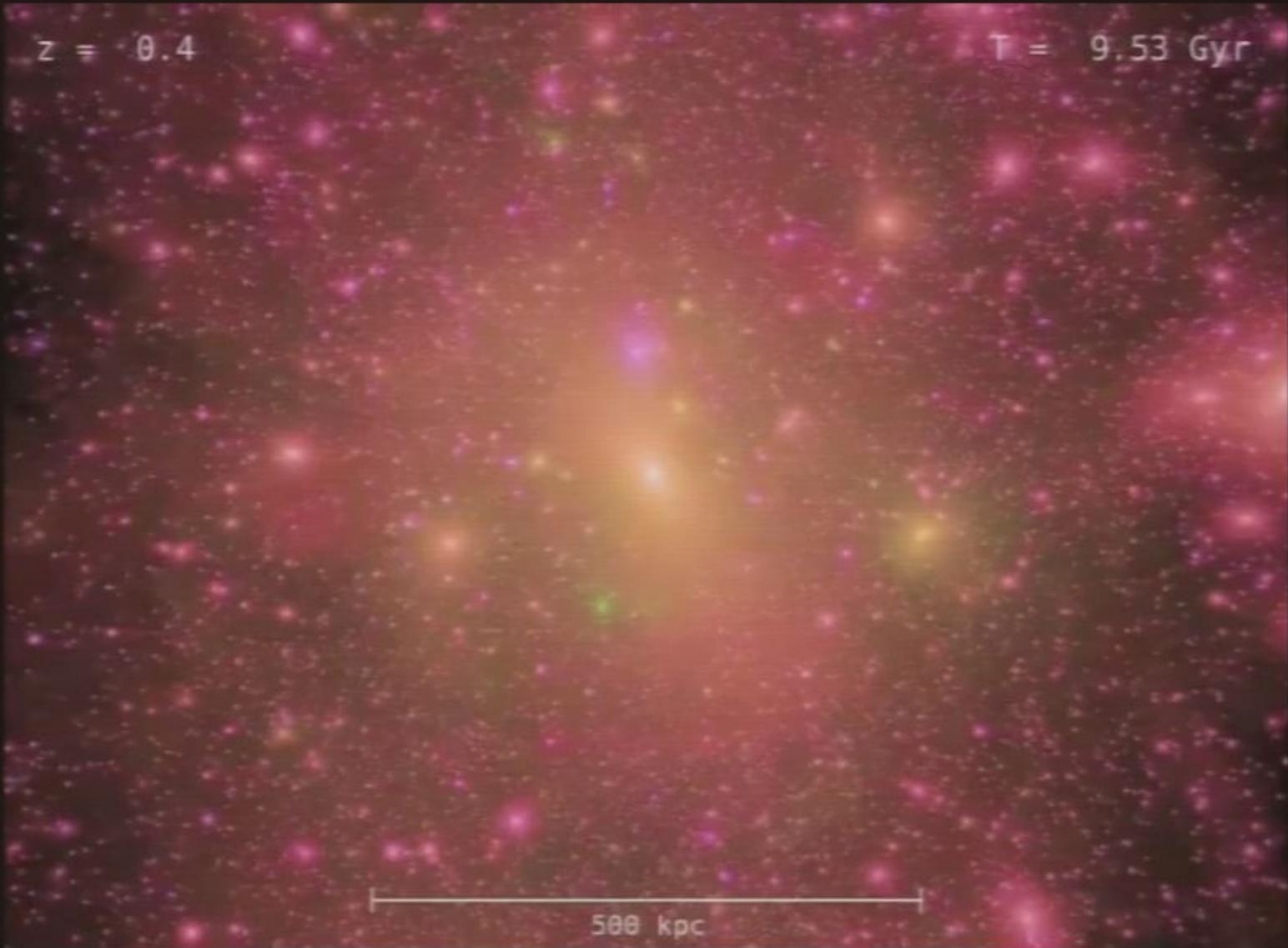








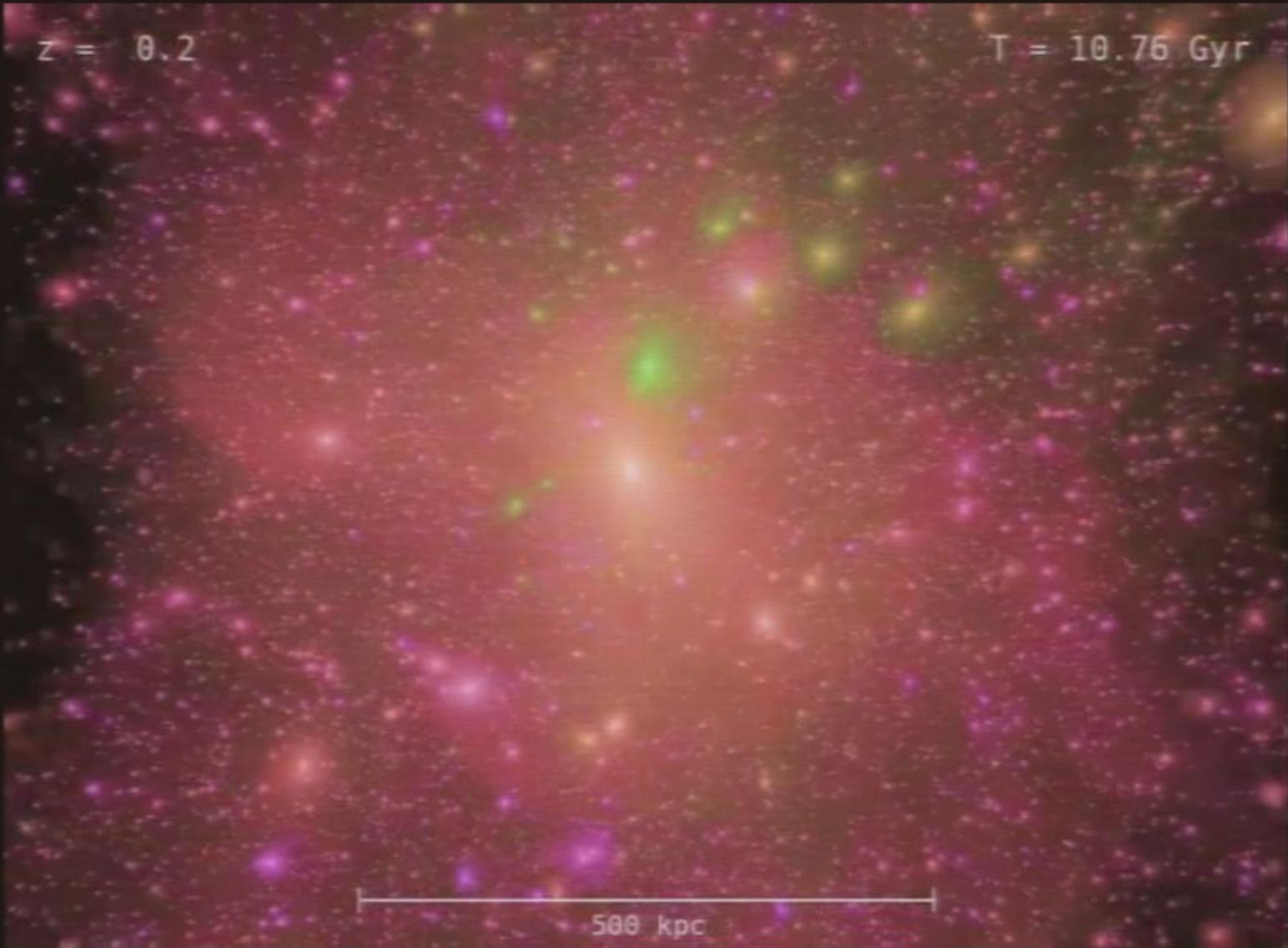


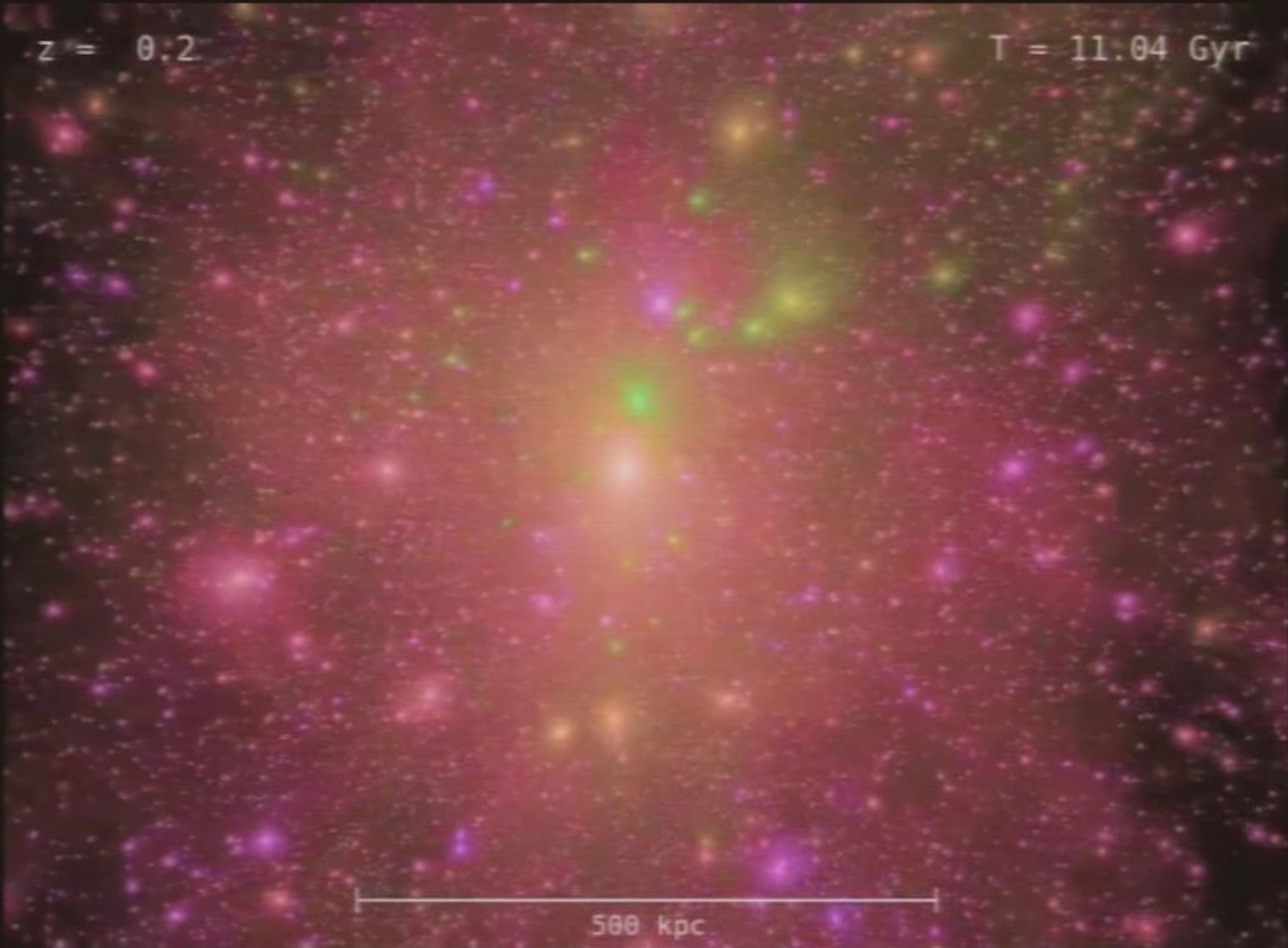


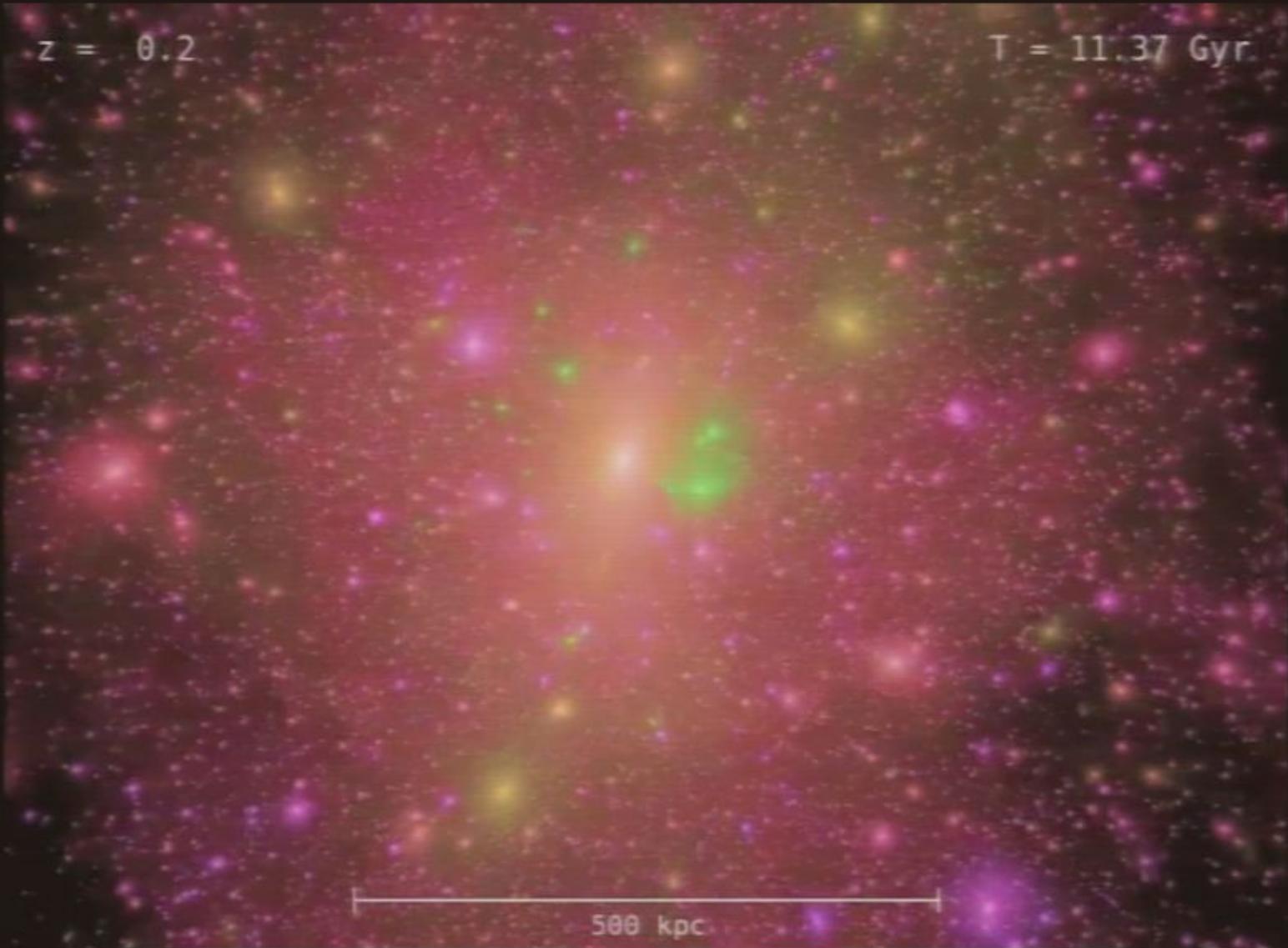


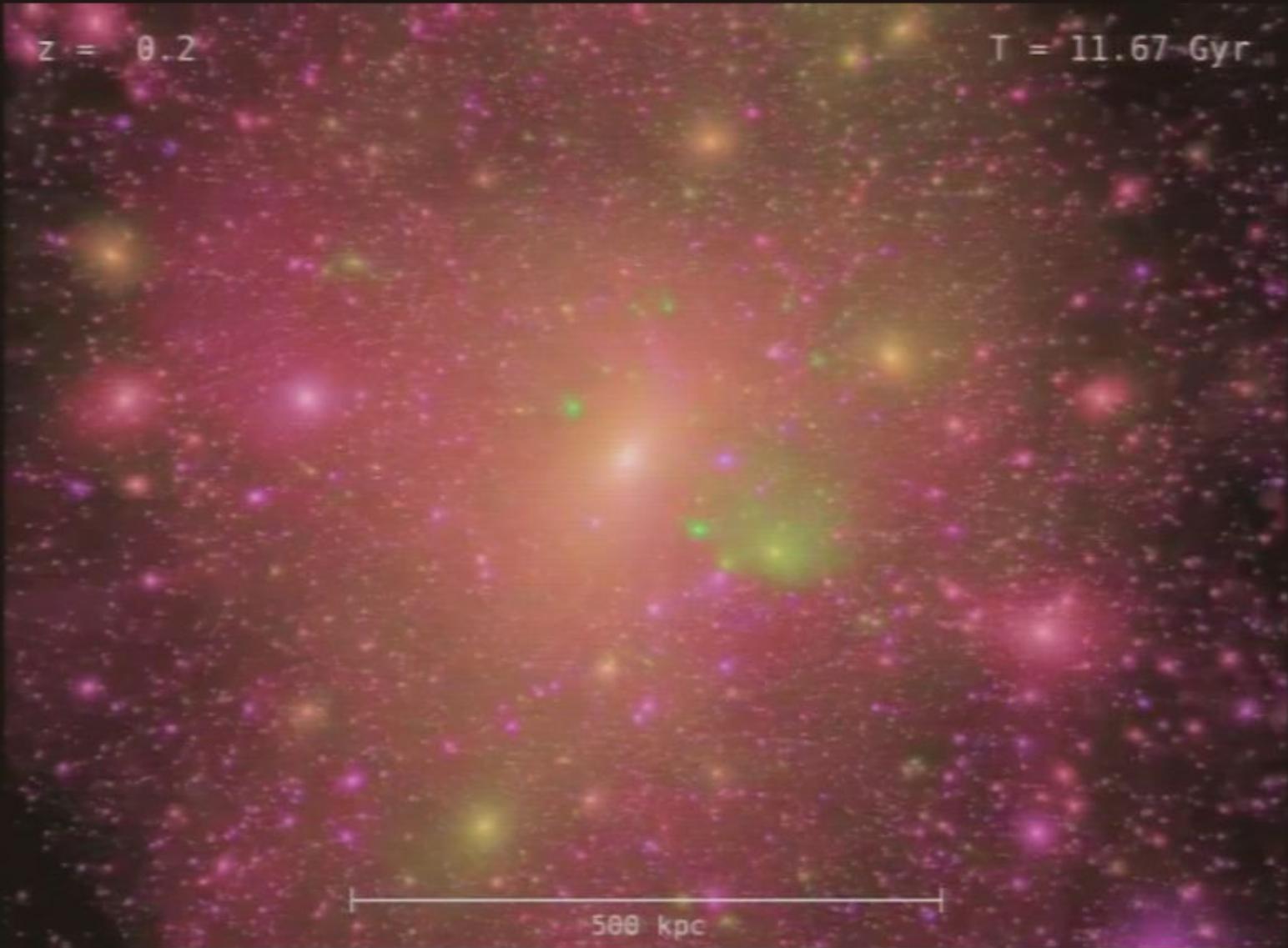


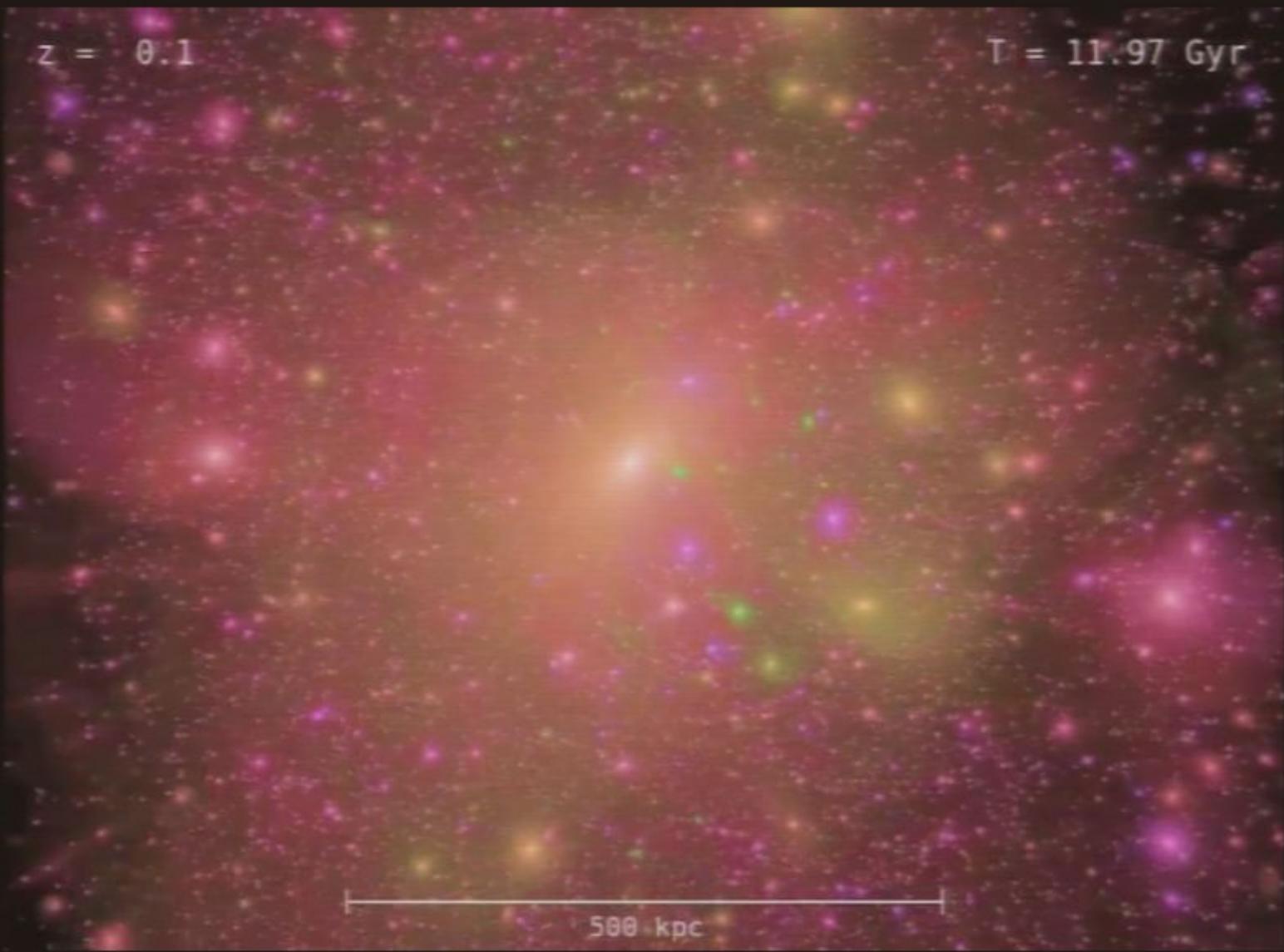
















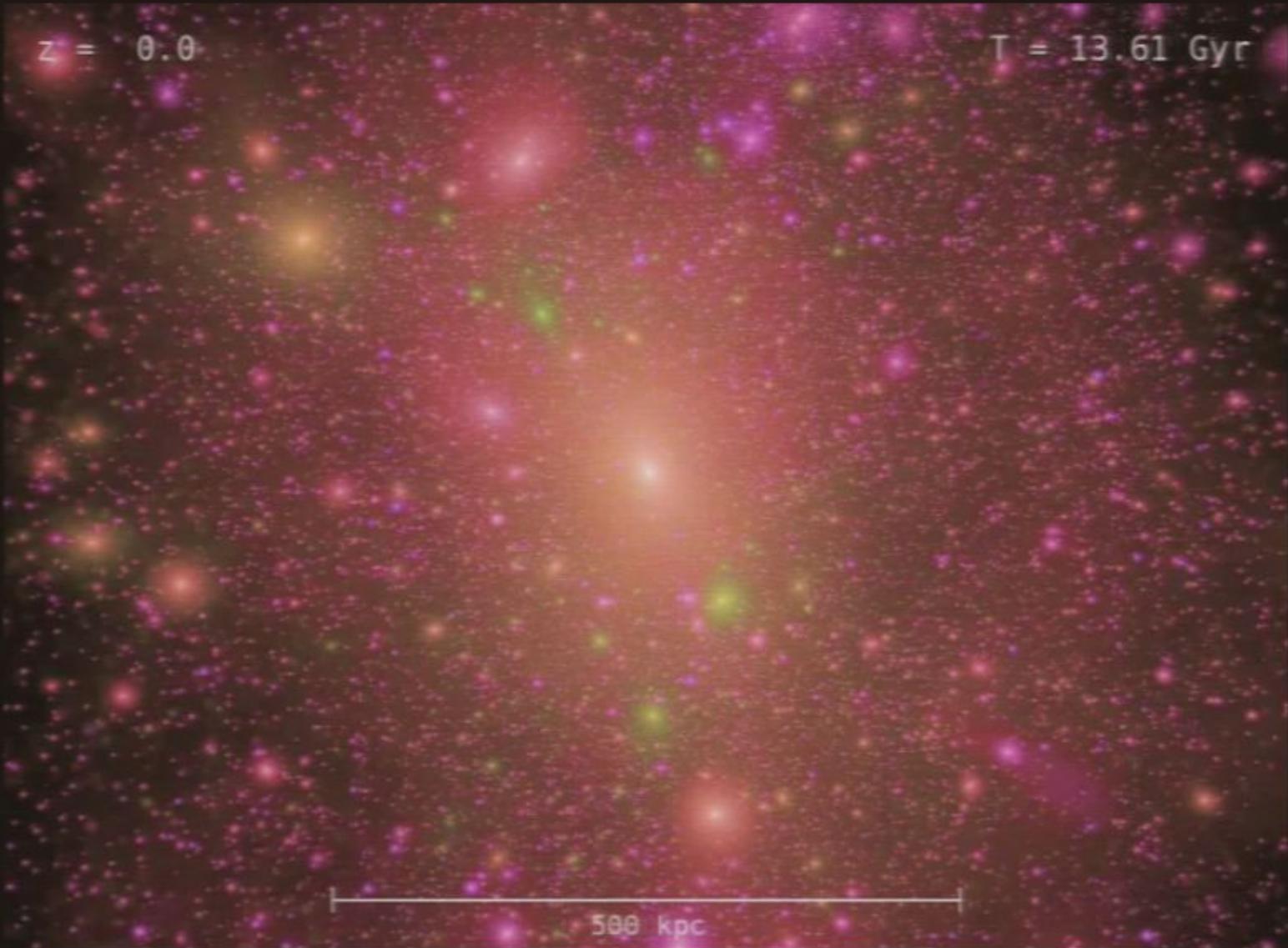


$z = 0.0$

$T = 13.20 \text{ Gyr}$









Volker Springel
Max-Planck-Institute
for Astrophysics





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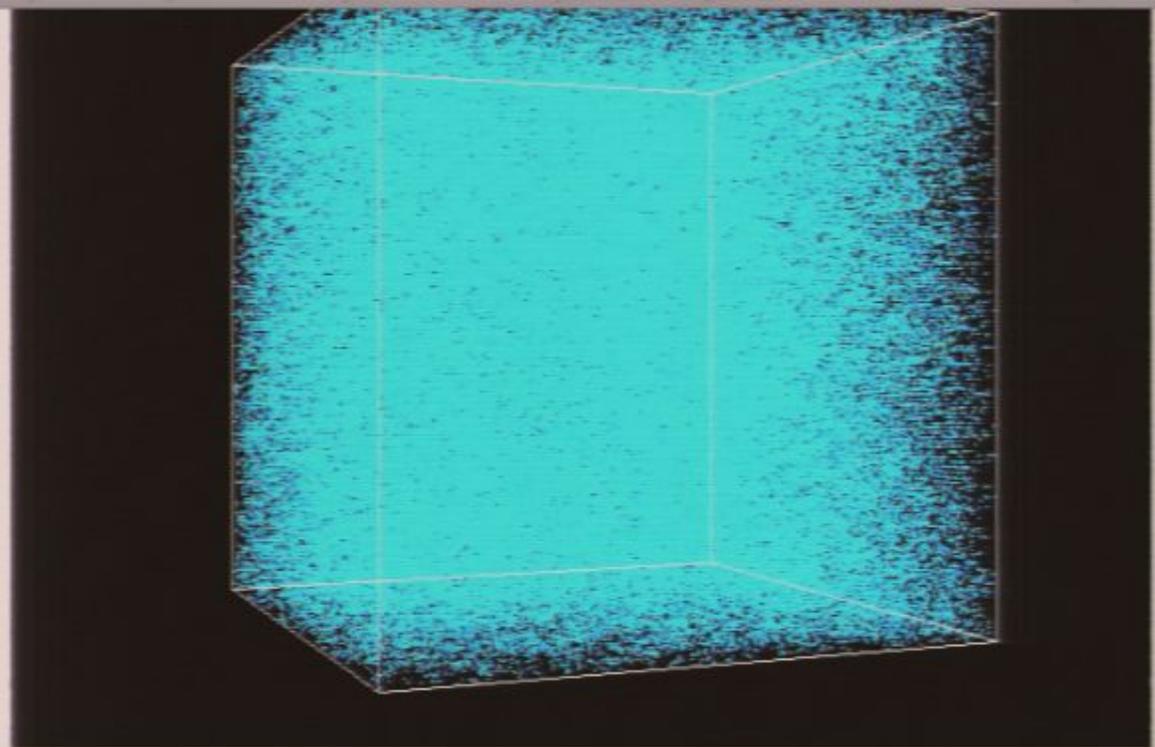
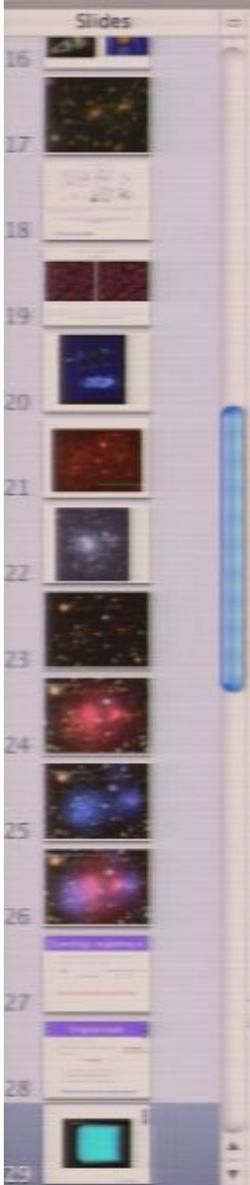
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Max-Planck-Institute
for Astrophysics

A video player window titled "Aquarius Simulation Visualization on Vimeo" is overlaid on the slide. The address bar shows the URL "http://vimeo.com/22082732". The video content shows a dense field of stars in various colors (red, orange, yellow, green, blue, purple) against a dark background. The video player includes a progress bar at the bottom and a "More" section on the right with a "Show" button. The Max-Planck-Institute for Astrophysics logo and name are visible in the bottom right corner of the video frame.

U. Chicago

100% Gravity causes matter to aggregate into long, intersecting filaments surrounded by vast, nearly empty voids

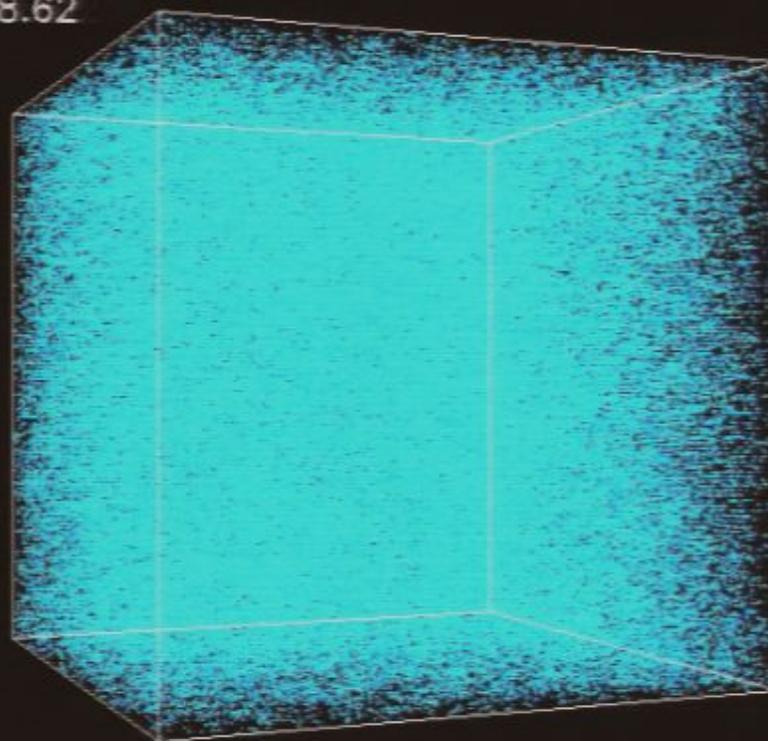


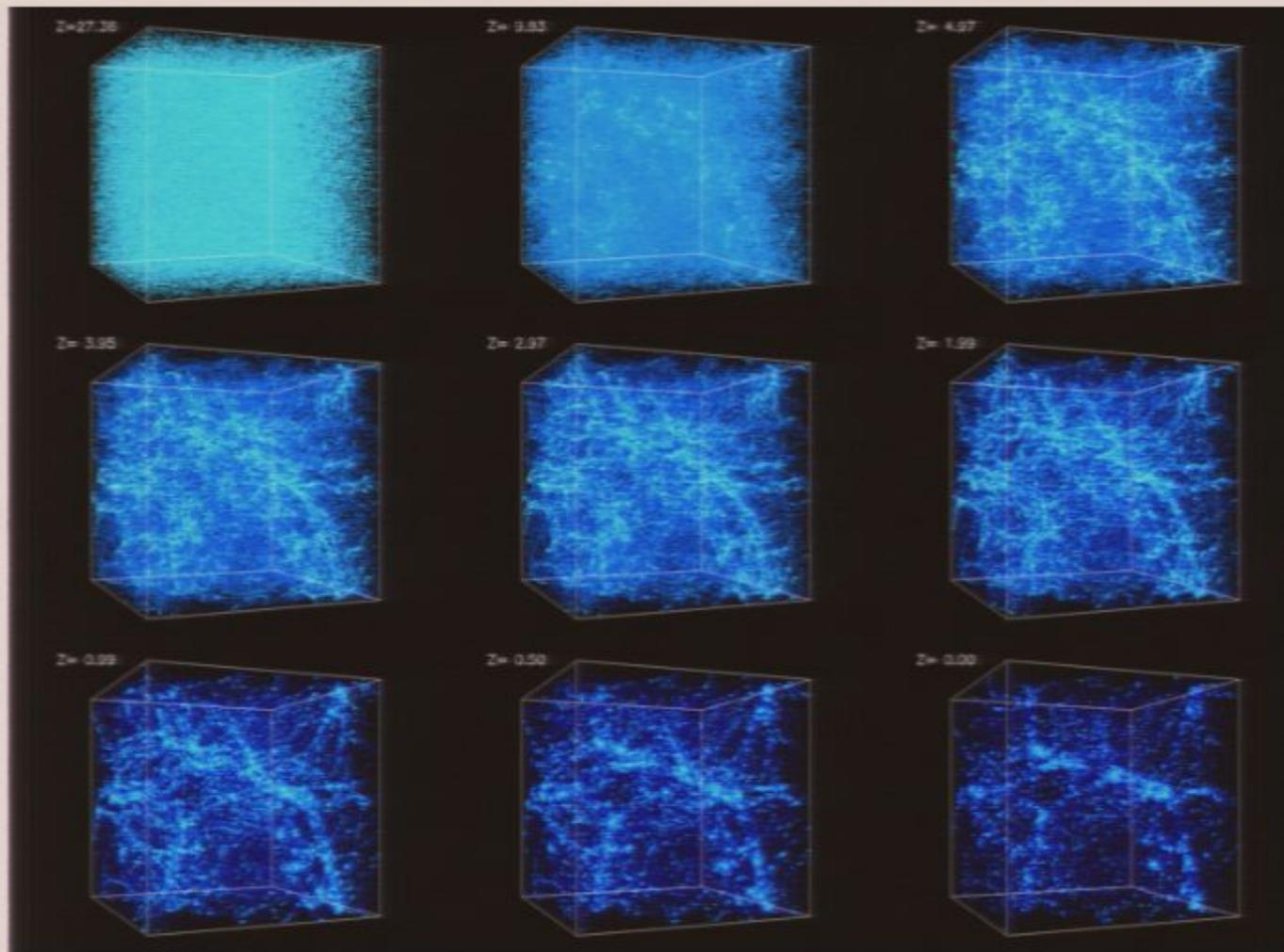
U. Chicago

100% [Progress bar]

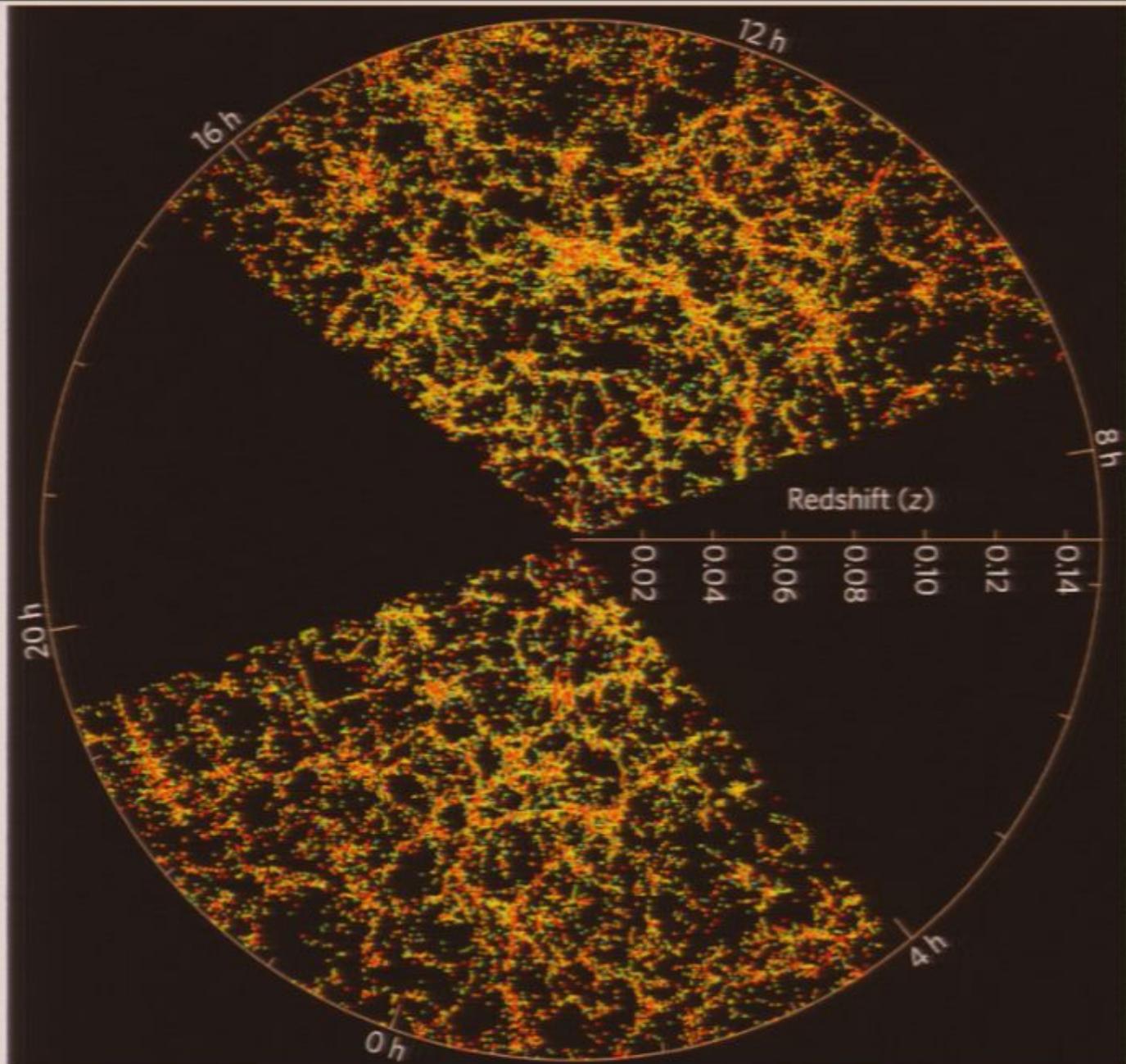
Gravity causes matter to aggregate into long, intersecting filaments surrounded by vast, nearly empty voids

Z=28.62





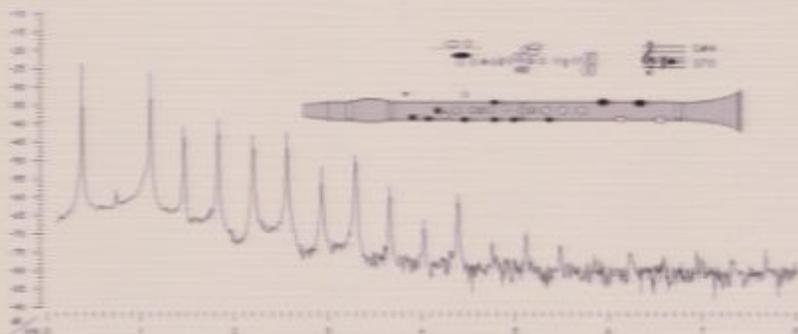
SDSS



Harmonics

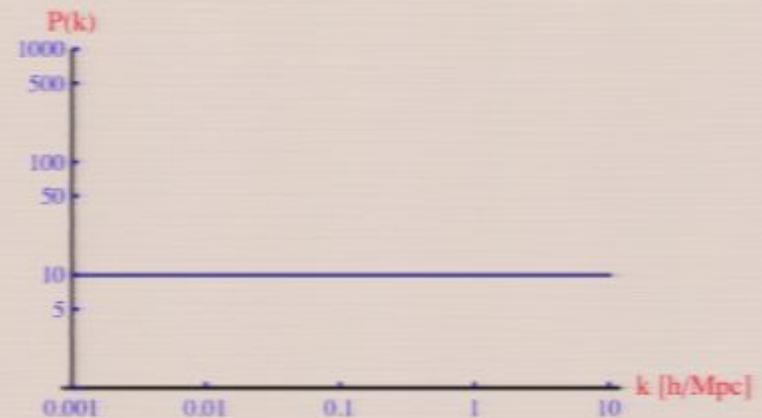
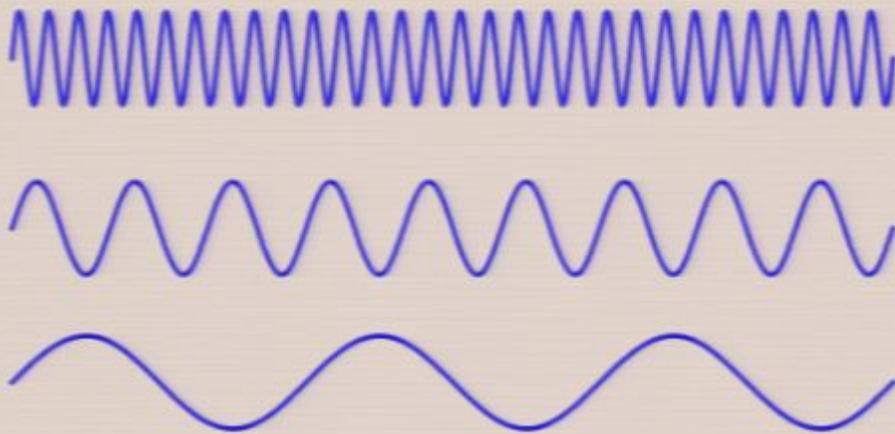
- Decompose into Harmonics

Sound of clarinet



Scale Invariance

Perturbations in gravitational potential. All wavelength, amplitude for each wave is drawn from a gaussian with variance 10^{-5}



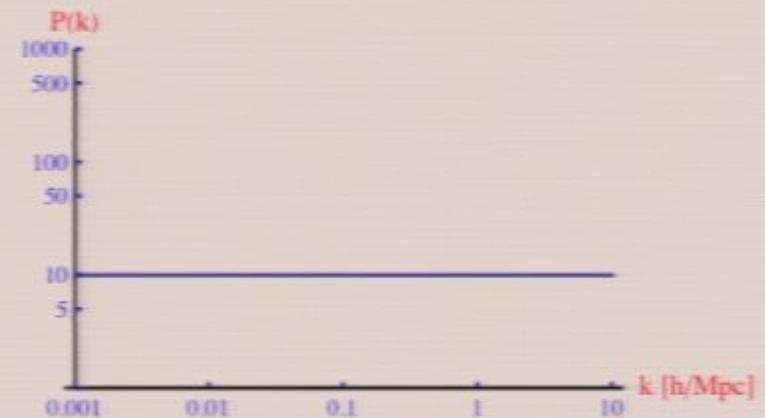
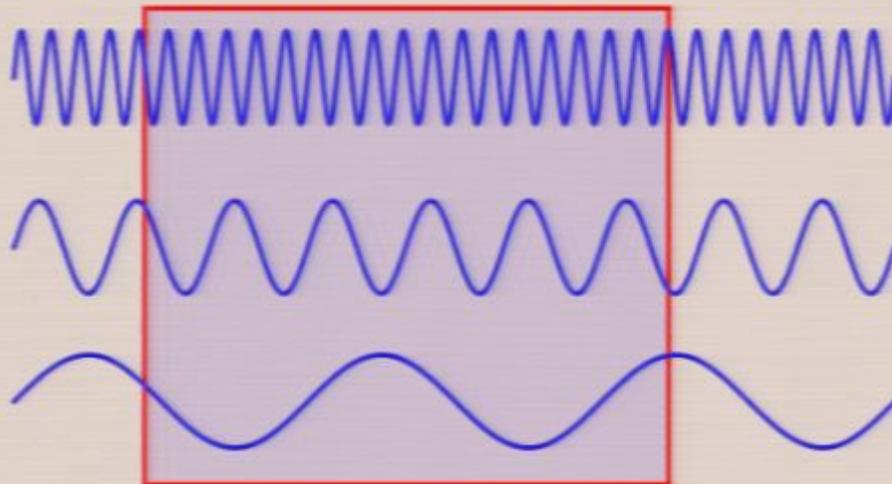
When the wave enter the horizon, dark matter falls in

Perturbations grow

$$\Phi \propto \frac{\delta\rho}{\rho}$$

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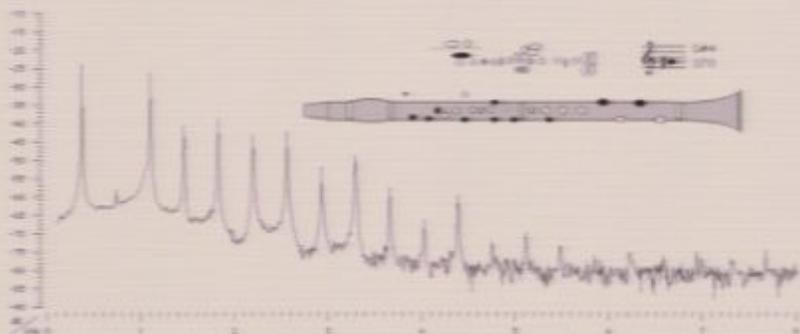
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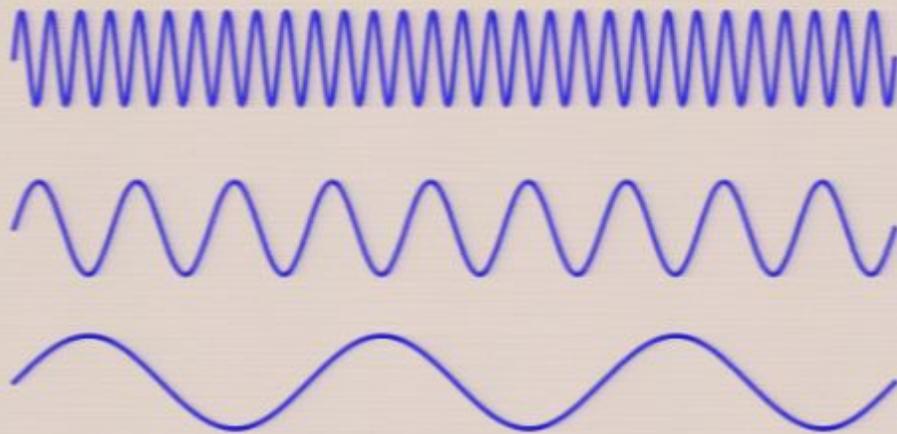
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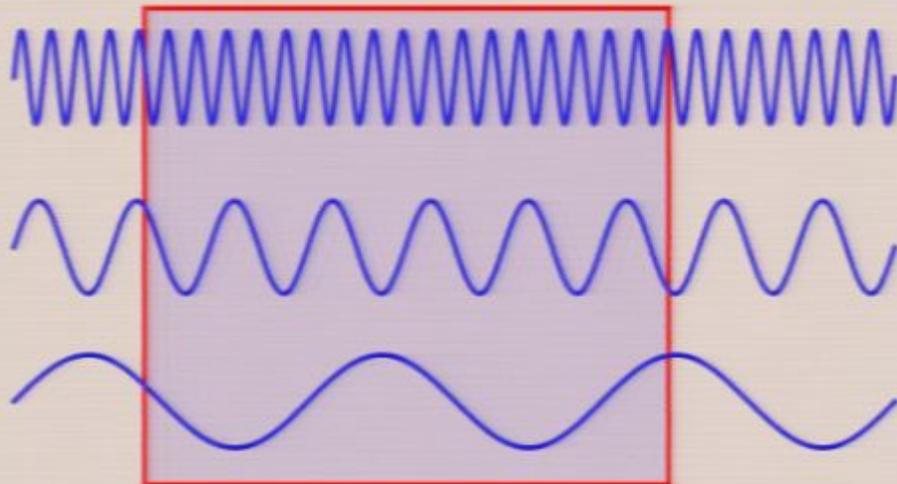
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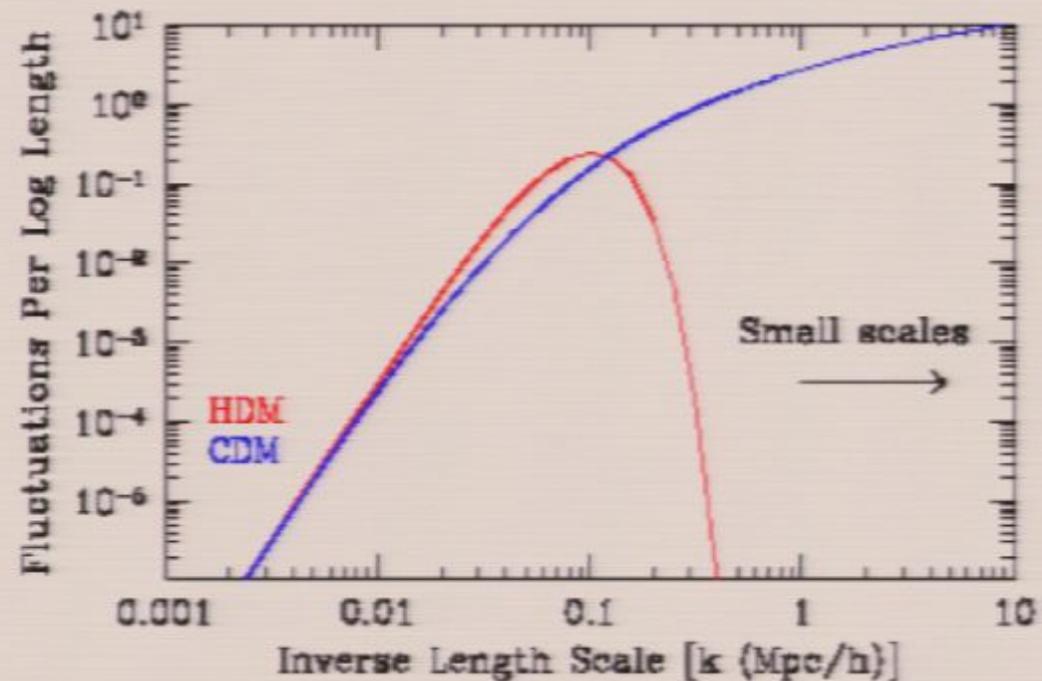
Linear theory just matter

Small scale have grown for longer because they entered first

Hot dark matter washes out small scale structure

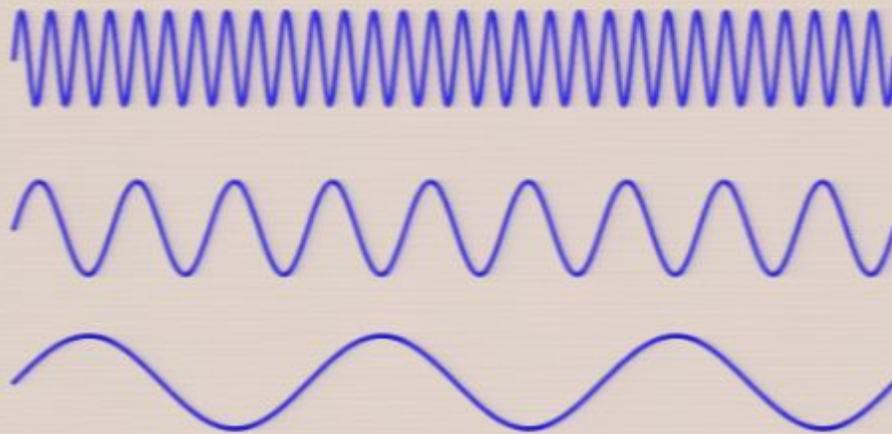


Ruled out



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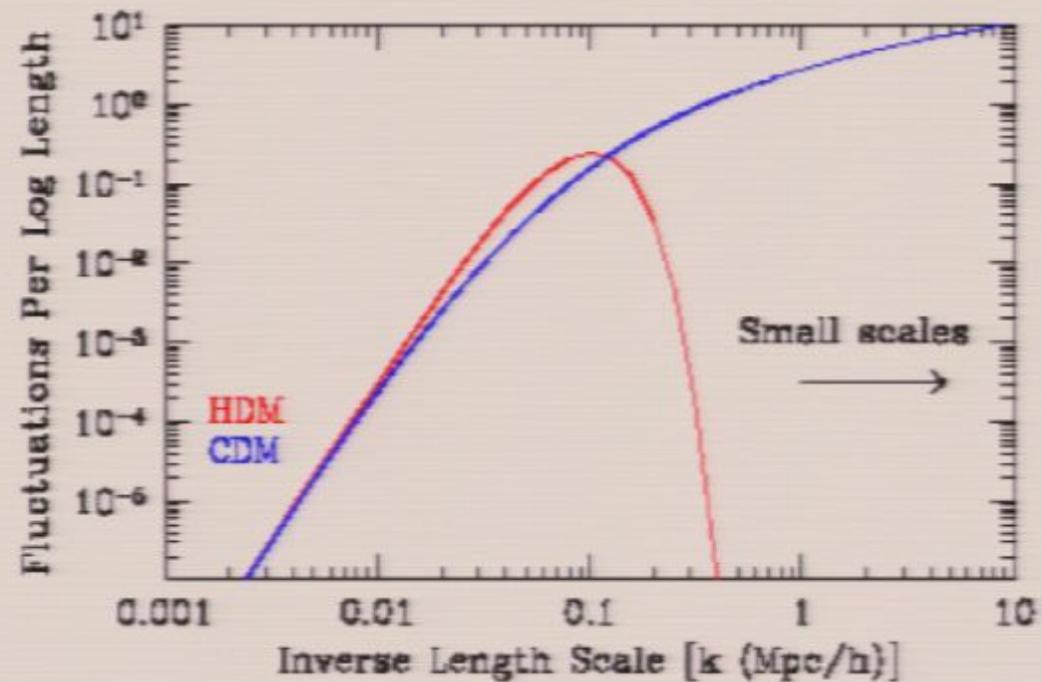
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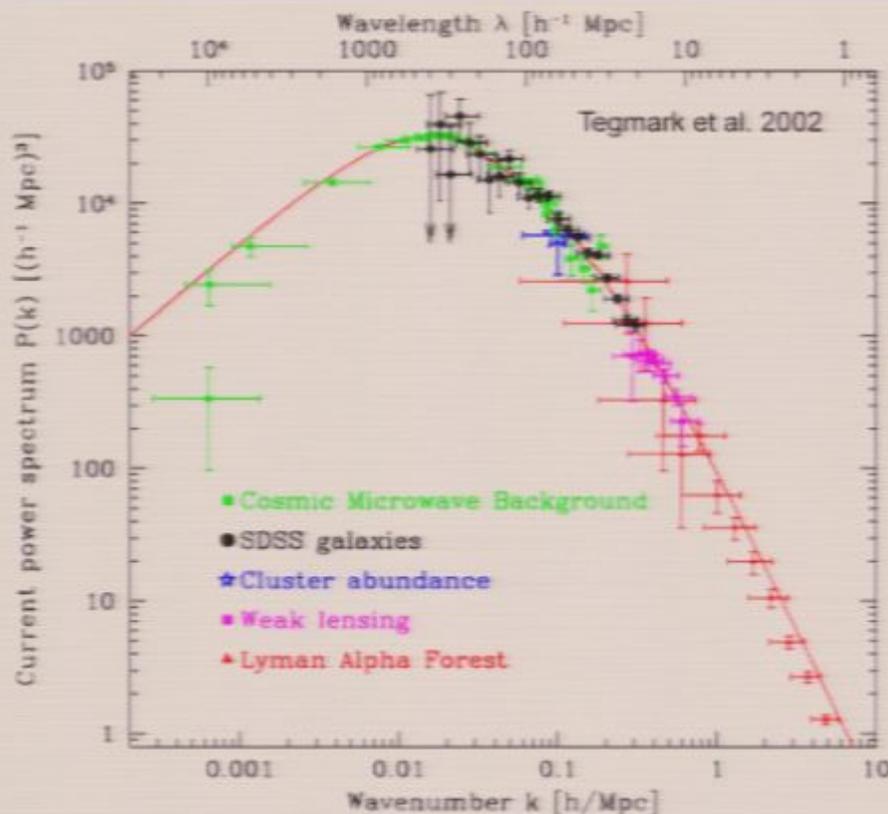
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Ruled out



Radiation era. Transfer function

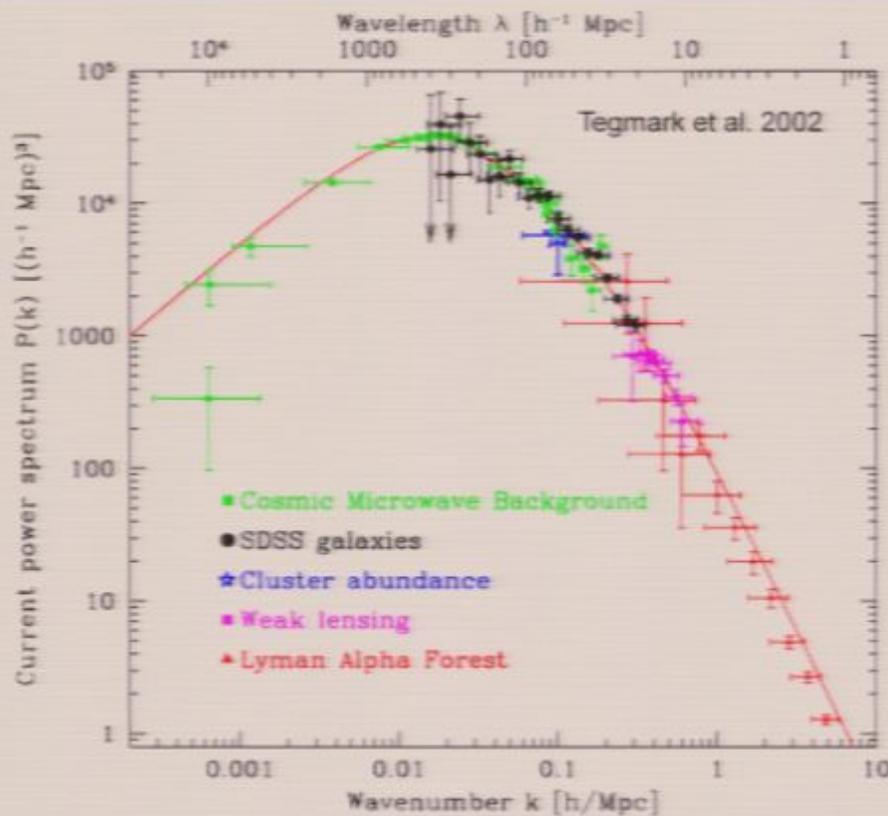


Power is decreased on small scale.

Those modes entered back when radiation dominated pressure decreases

one more step,
we don't see the overall field,
we see collapsed objects

Radiation era. Transfer function



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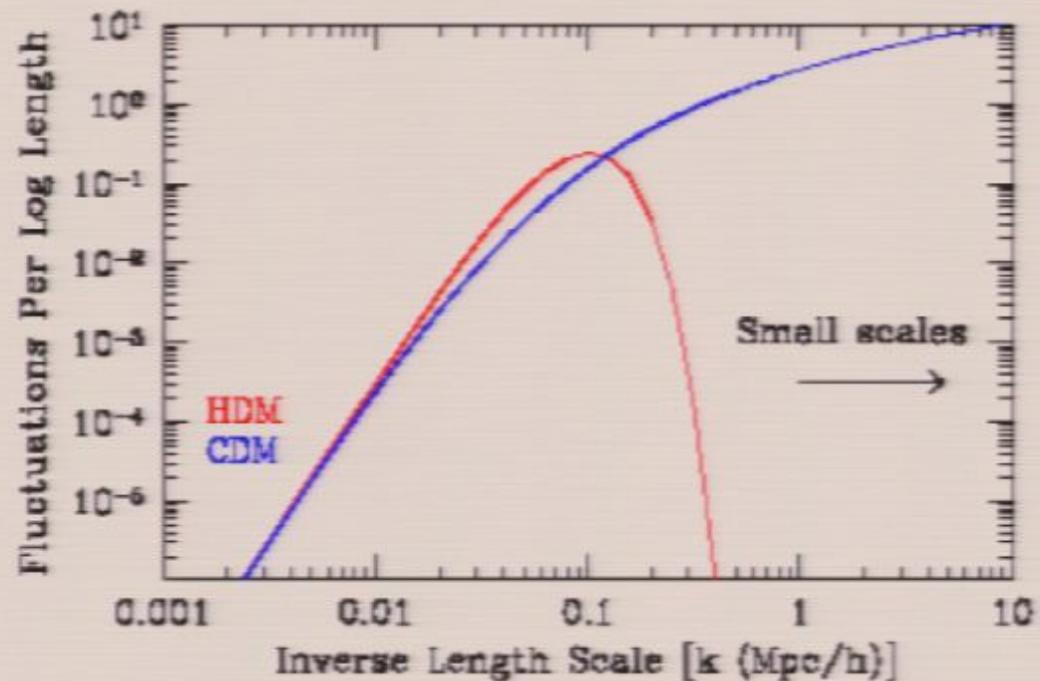
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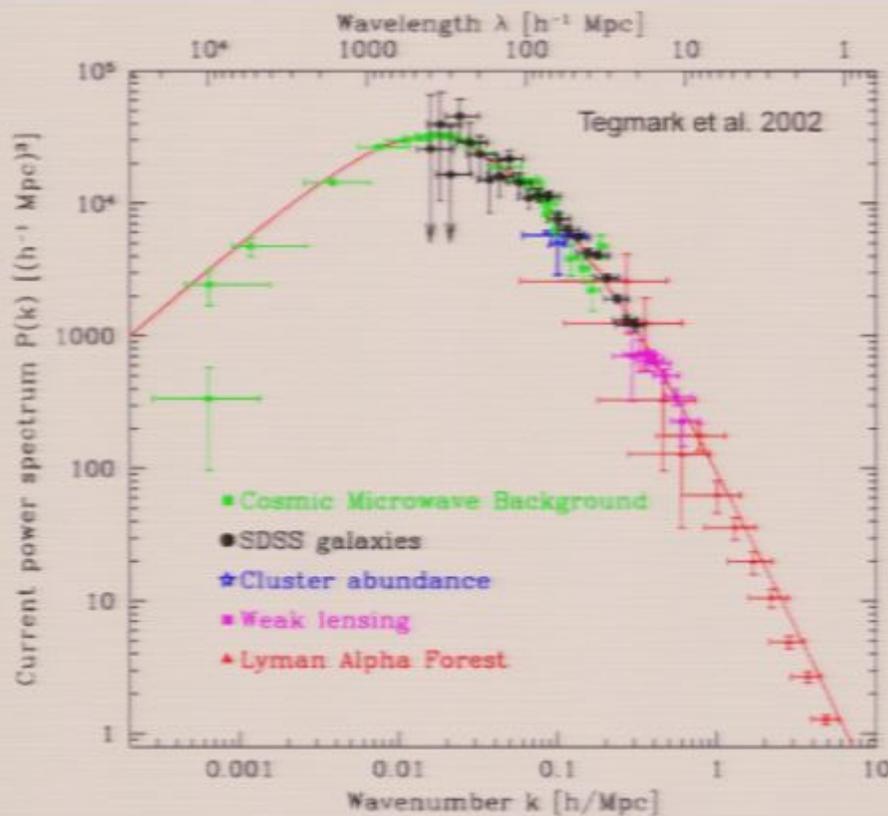
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Ruled out



Radiation era. Transfer function

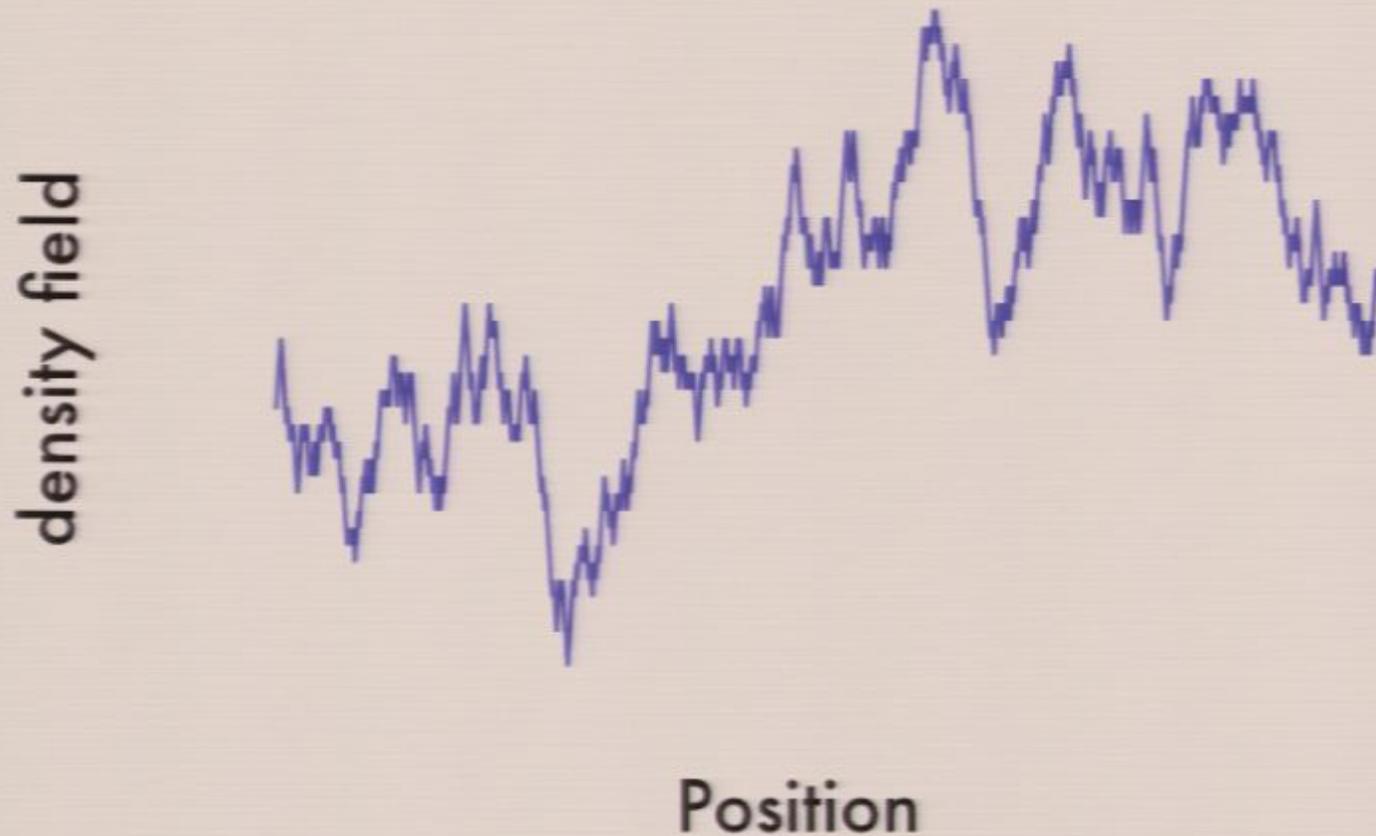


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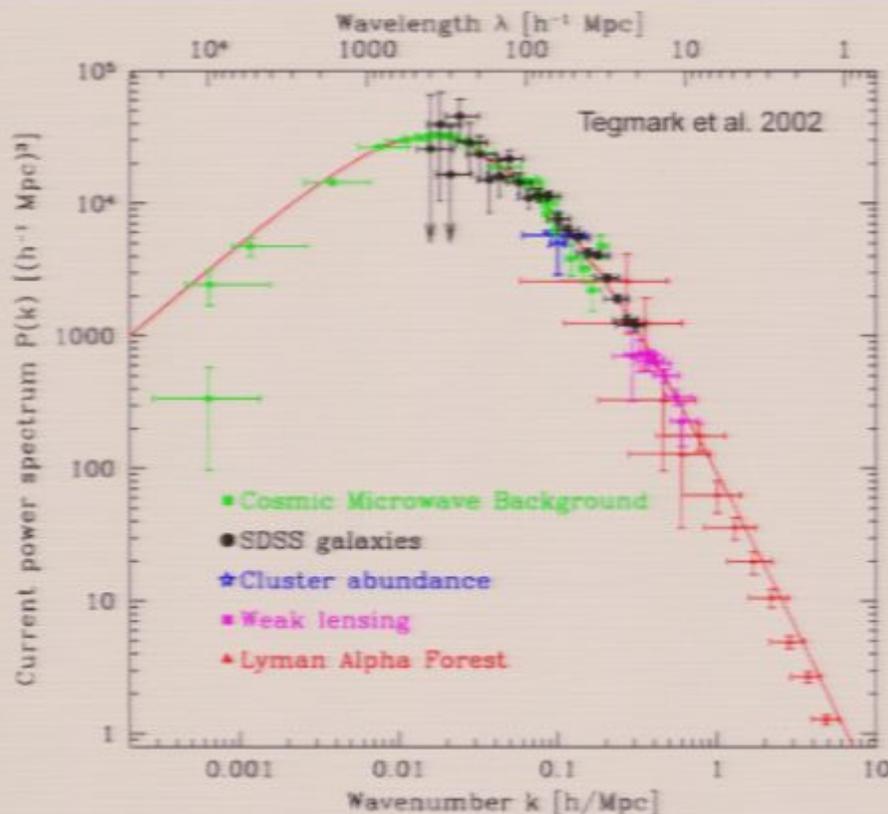
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Collapse Objects



Radiation era. Transfer function

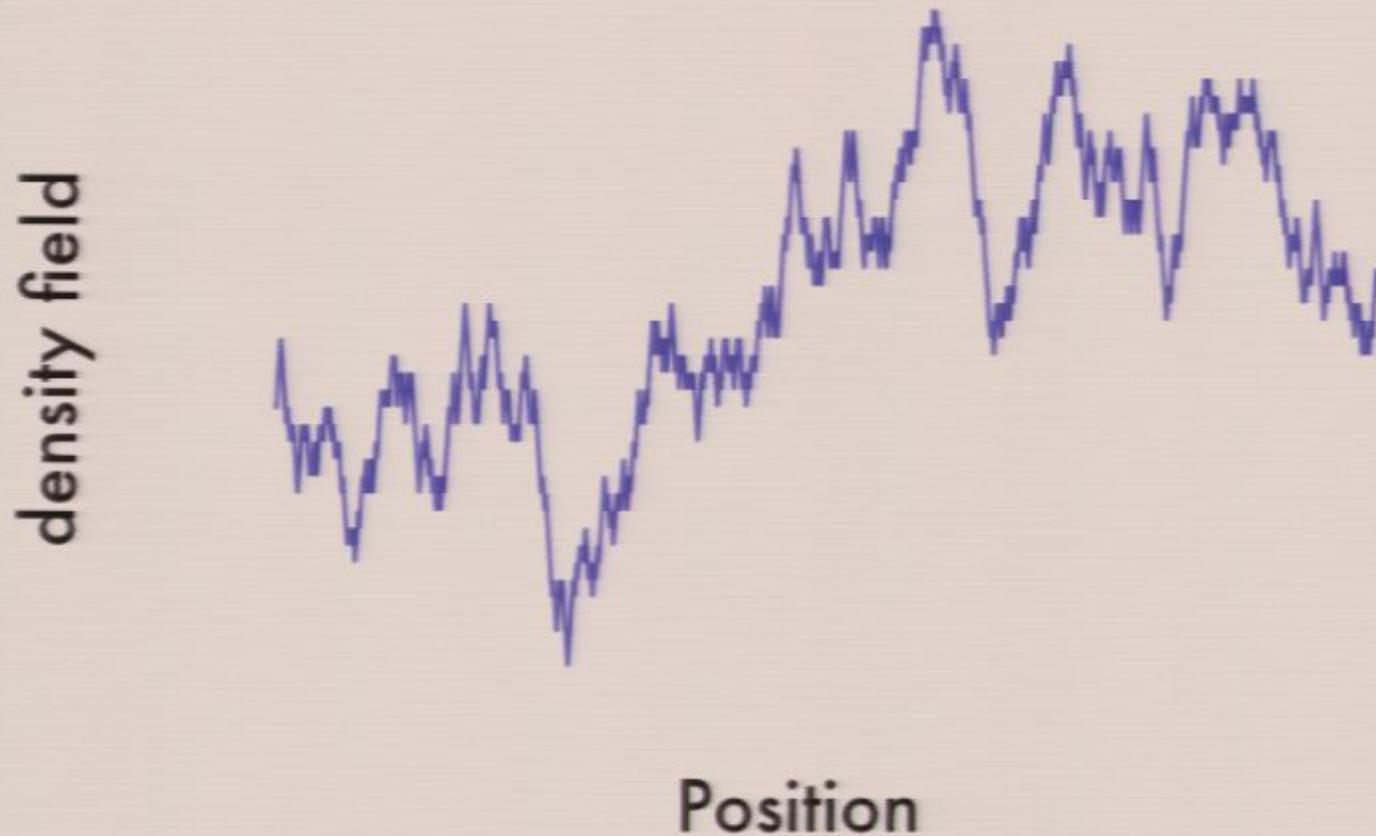


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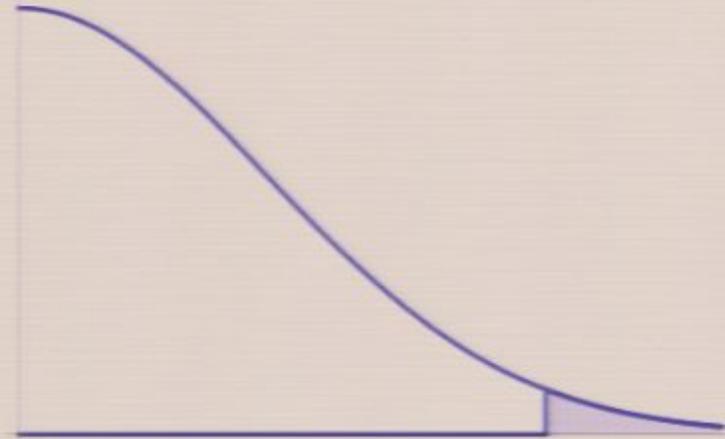


Collapse Objects



Collapse objects are coming only from the tail of the probability distribution function

$$\frac{\delta\rho}{\rho}$$

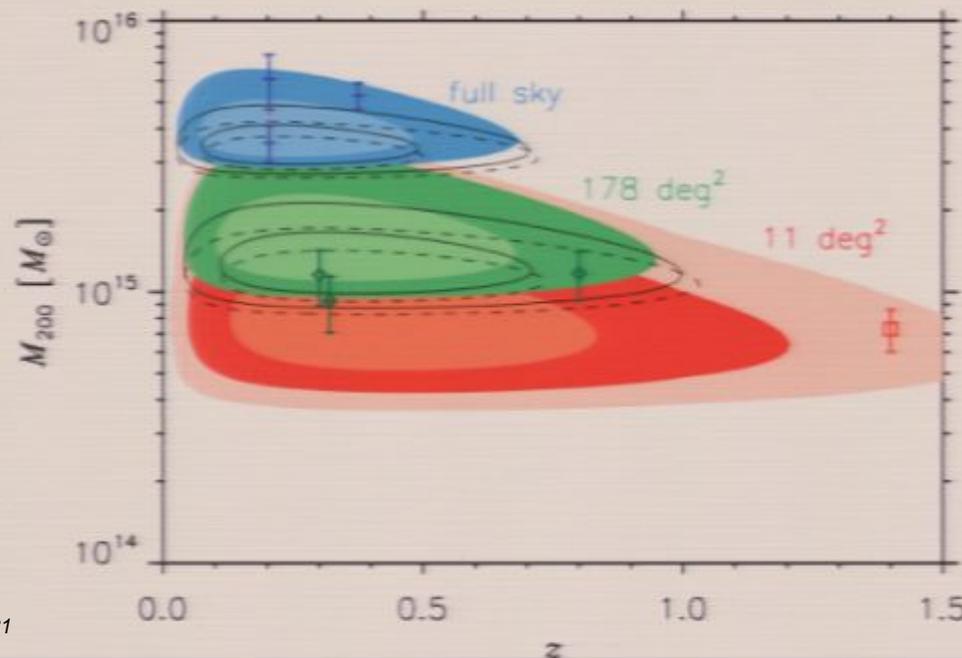
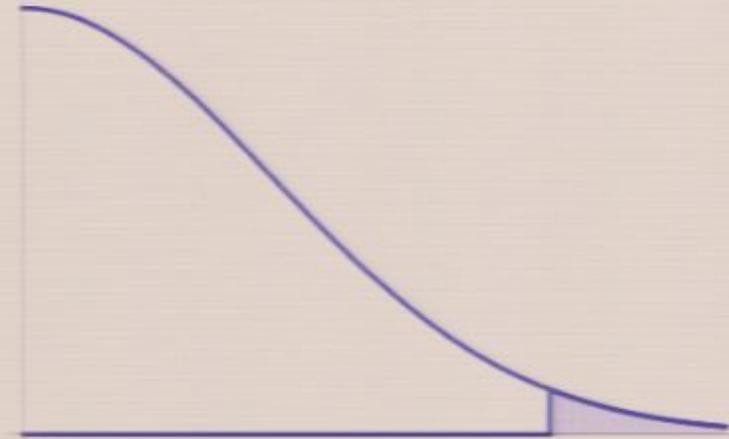


What is the probability of seeing the big objects given our best models for cosmology?

Λ CDM

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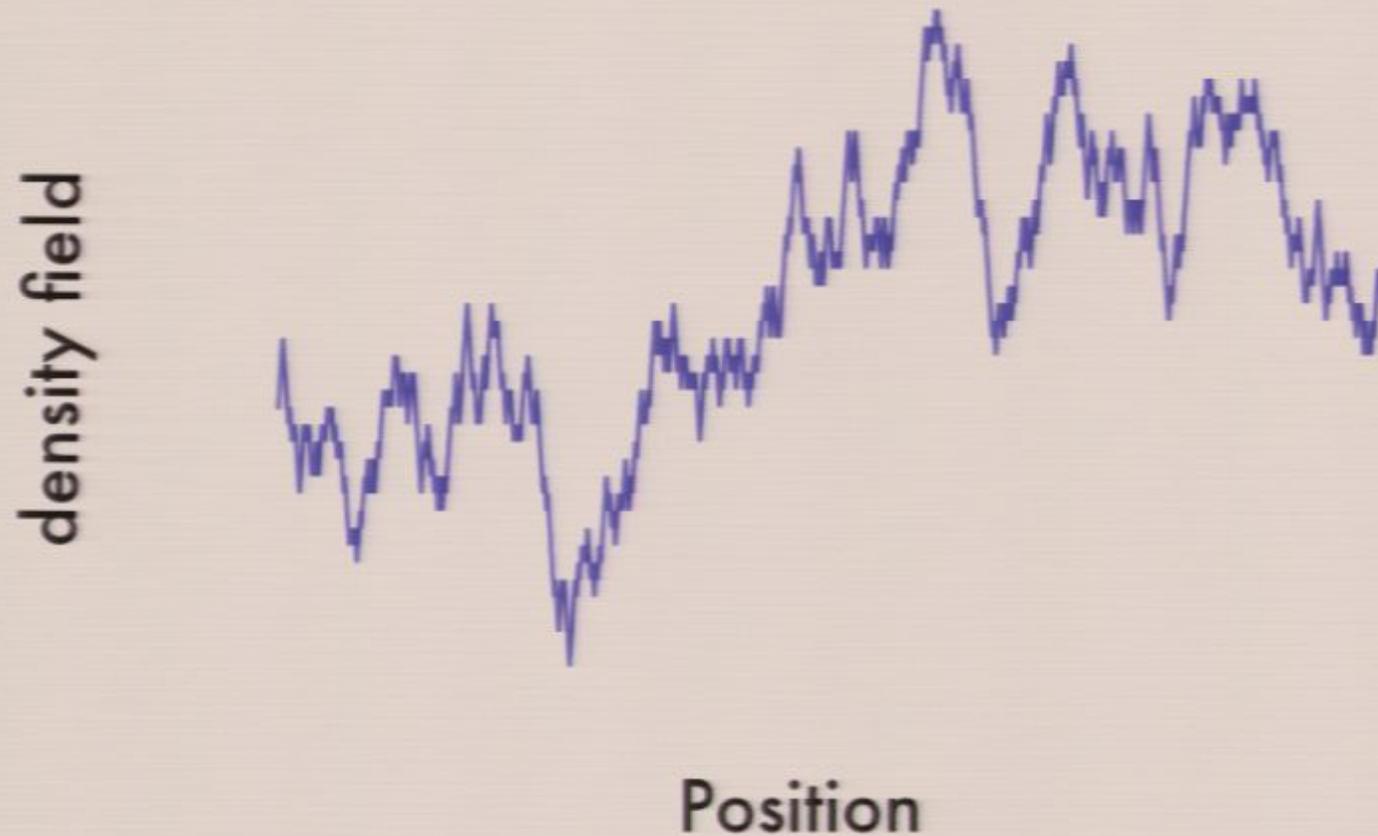


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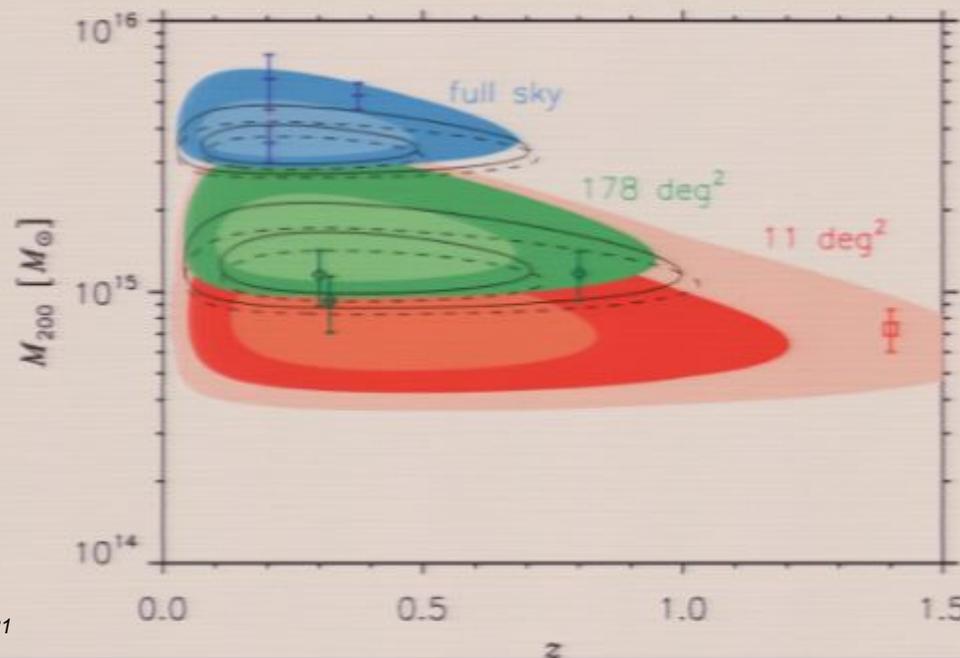
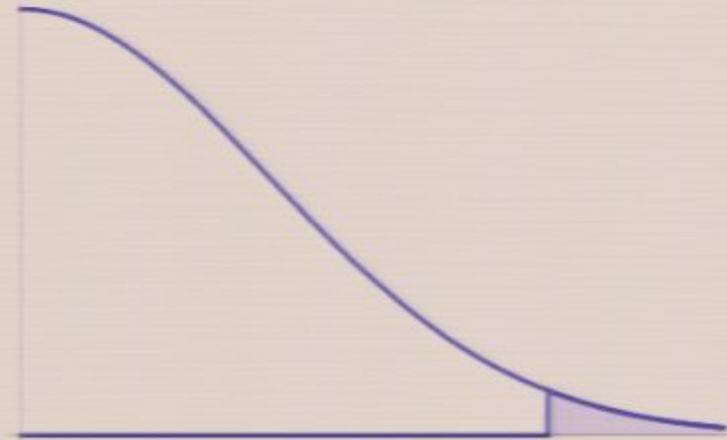
Holz, Perlmutter

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XMMUJ2235.3+2557

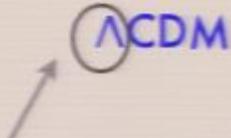
Holz, Perlmutter

So what do we have?

- We can explain the large scale structure of the Universe using a gas of cold dark matter (radiation early on needed as well).
- under initial perturbations, scale invariant, gaussian and frozen.

This model fails on very small scales...
where baryons should be important

More importantly
it fails recently. Perturbations have stop
growing starting at redshift of $z = 0.5$

Dark energy The diagram shows the text "Dark energy" with an arrow pointing to a circle containing the Greek letter Lambda followed by "CDM".

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Dark energy

A hand-drawn arrow in black ink points from the text "Dark energy" below to the symbol "ΛCDM" above. The symbol consists of the Greek letter Lambda (Λ) followed by the letters "CDM".

Why? Why? Why?

- Why gaussian initial conditions?
- Why scale invariant?
- Why fixed on superhorizon scales?

Inflation

- era of dark energy early (very high energy)
- Spacetime is in accelerated expansion very very fast
- small quantum fluctuation are amplified and their wavelength stretched
- when inflation ends, the perturbations have been laid down.

Start with a smooth patch

dark energy Λ



$$l \sim \frac{1}{\Lambda^{1/4}}$$

$$l \sim [10^{-25} \text{ cm}, 10^{-29} \text{ cm}]$$

many models smaller than that

bound from data

Inflate!



Our horizon, anything outside that circle is unobservable unless it comes back in

Quantum fluctuations
(perturbations of the metric)
are amplified and grow



Cooling



horizon expands
perturbations come back in
the horizon

Quantum fluctuations
(perturbations of the metric)
are amplified and grow

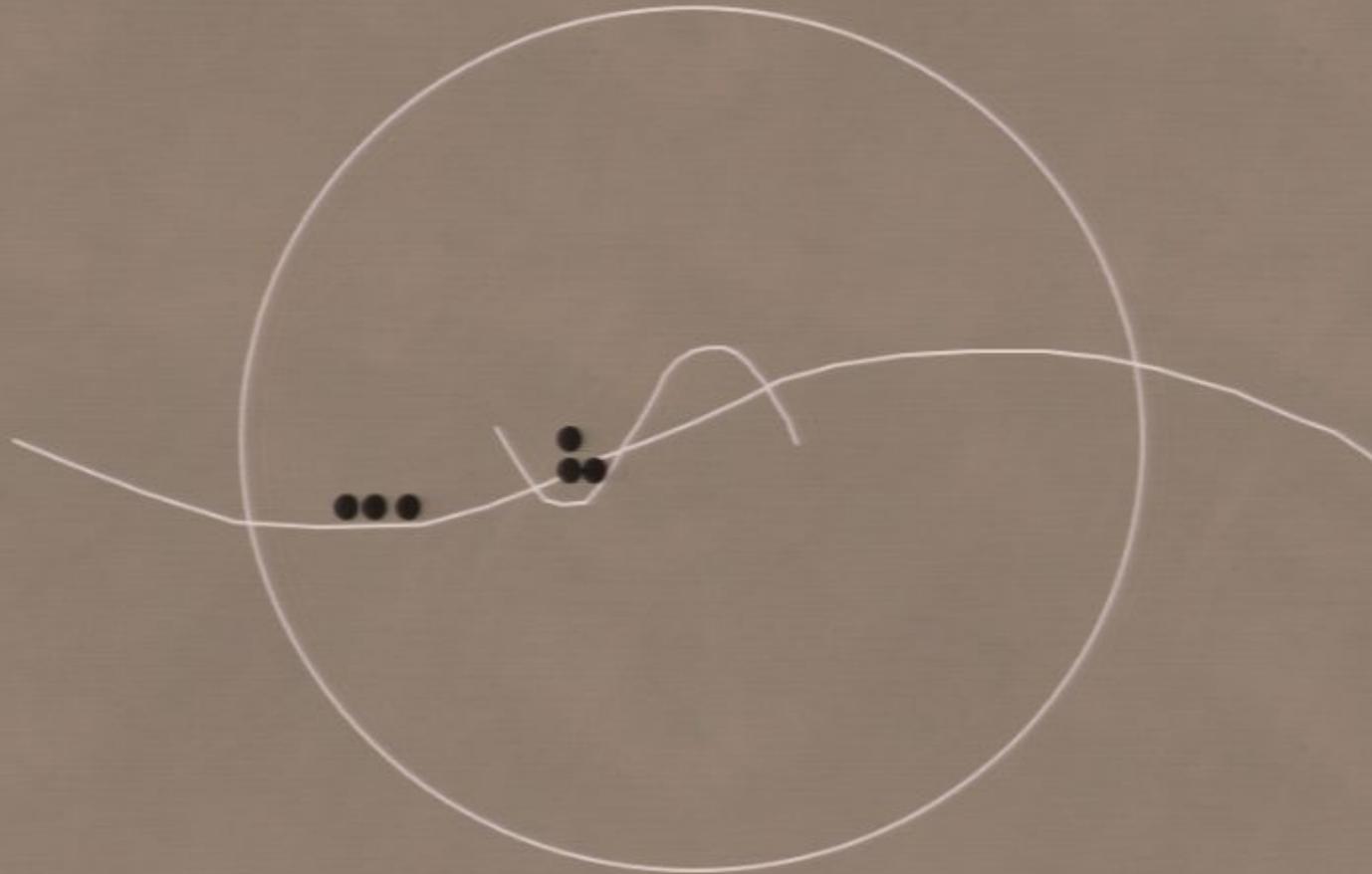


Cooling



horizon expands
perturbations come back in
the horizon

Dark matter



fall into potential well

Structure forms



$t = -3.60$ Gyr

$z = 0.32$

Conclusion

- the biggest things are big



Conclusion

- but don't worry, we have a theory

Conclusion

- but don't worry, we have a theory

Λ CDM

And its great because it works well
and because it may be wrong