Title: The Aquarius Project: Cold Dark Matter under a Numerical Microscope

Date: Feb 27, 2009 11:00 AM

URL: http://pirsa.org/09020044

Abstract: I will report results from simulations of galaxy-scale dark halos of unprecedented numerical resolution. Convergence tests demonstrate detailed convergence for (sub)structures for over six decades in mass, enabling detailed forecasts of the expected dark matter signal both in Earth-bound direct-detection experiments as well as in indirect detection experiments which attempt to image dark matter annihilation radiation in gamma rays.

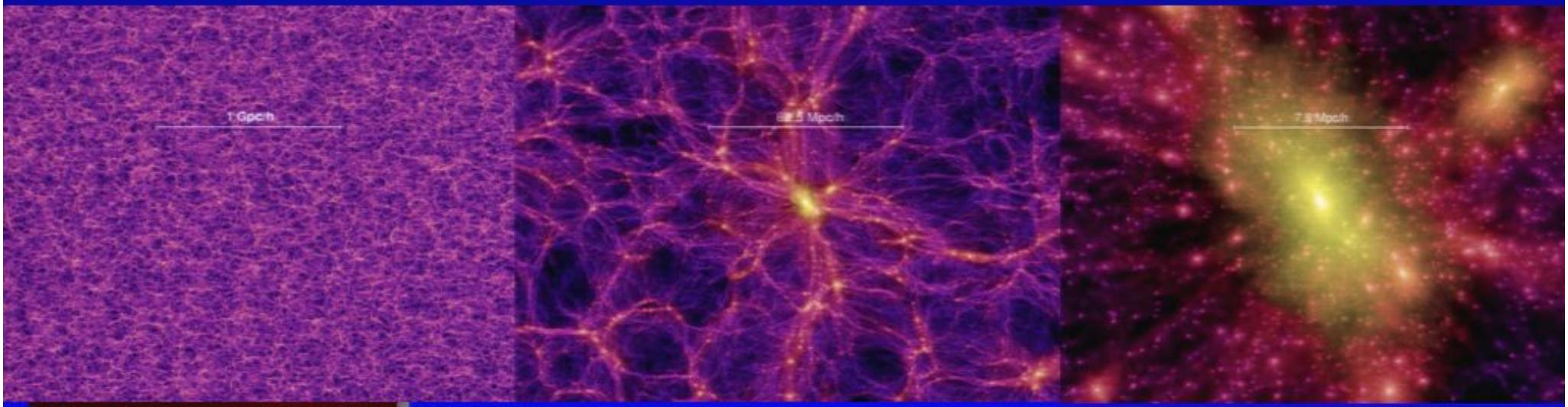
The Aquarius Programme: Cold Dark Matter under a Numerical Microscope

Julio Navarro
University of Victoria

The Virgo Consortium

N-body simulations track the clustering evolution of the dark matter from the Big Bang to the present

Millennium Simulation



Springel et al '05

VIRGO

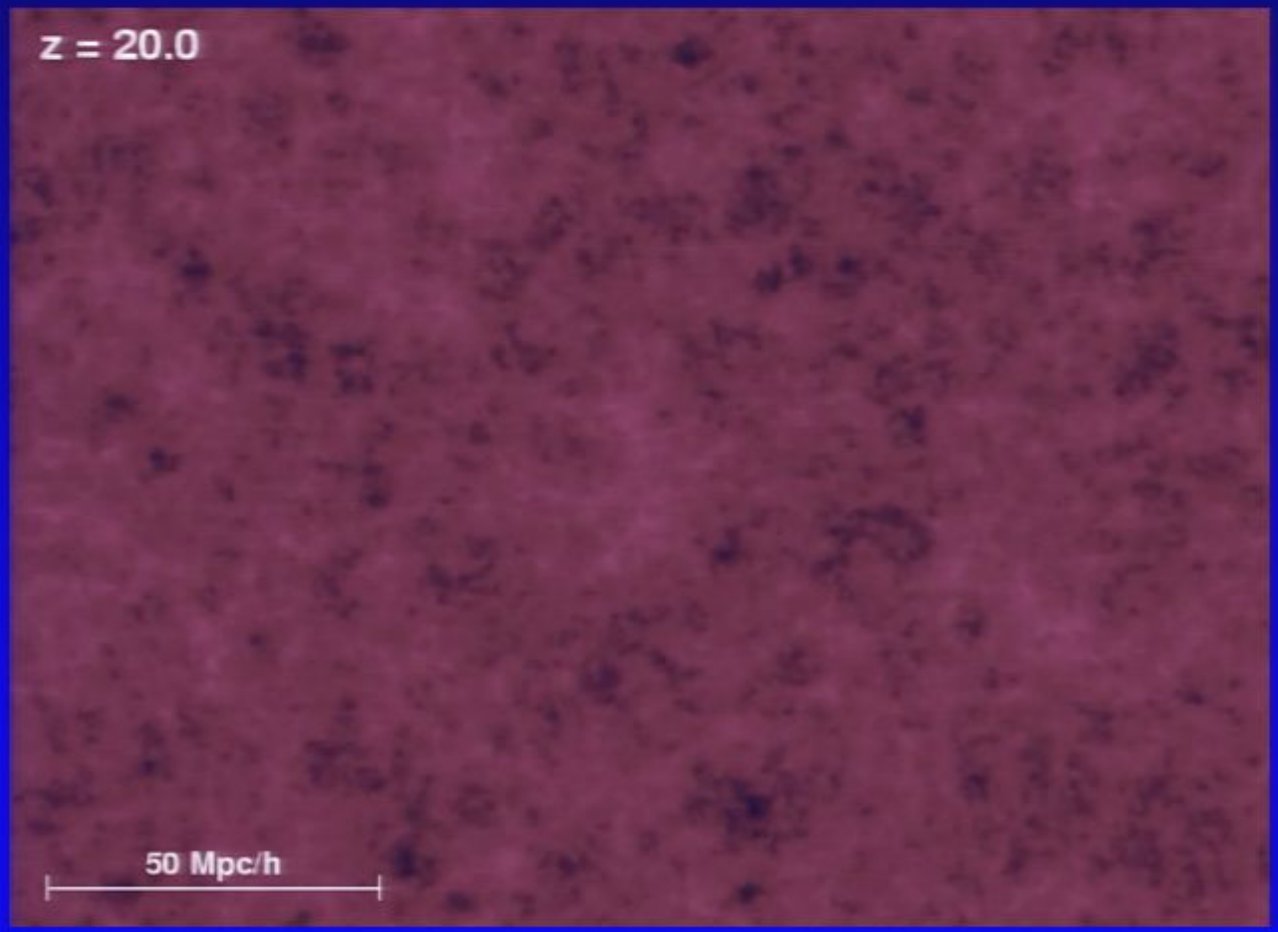
UK, Germany, Canada, Japan, US collaboration

Simulation data, movies, pictures available at:

www.mpa-garching.mpg.de/Virgo

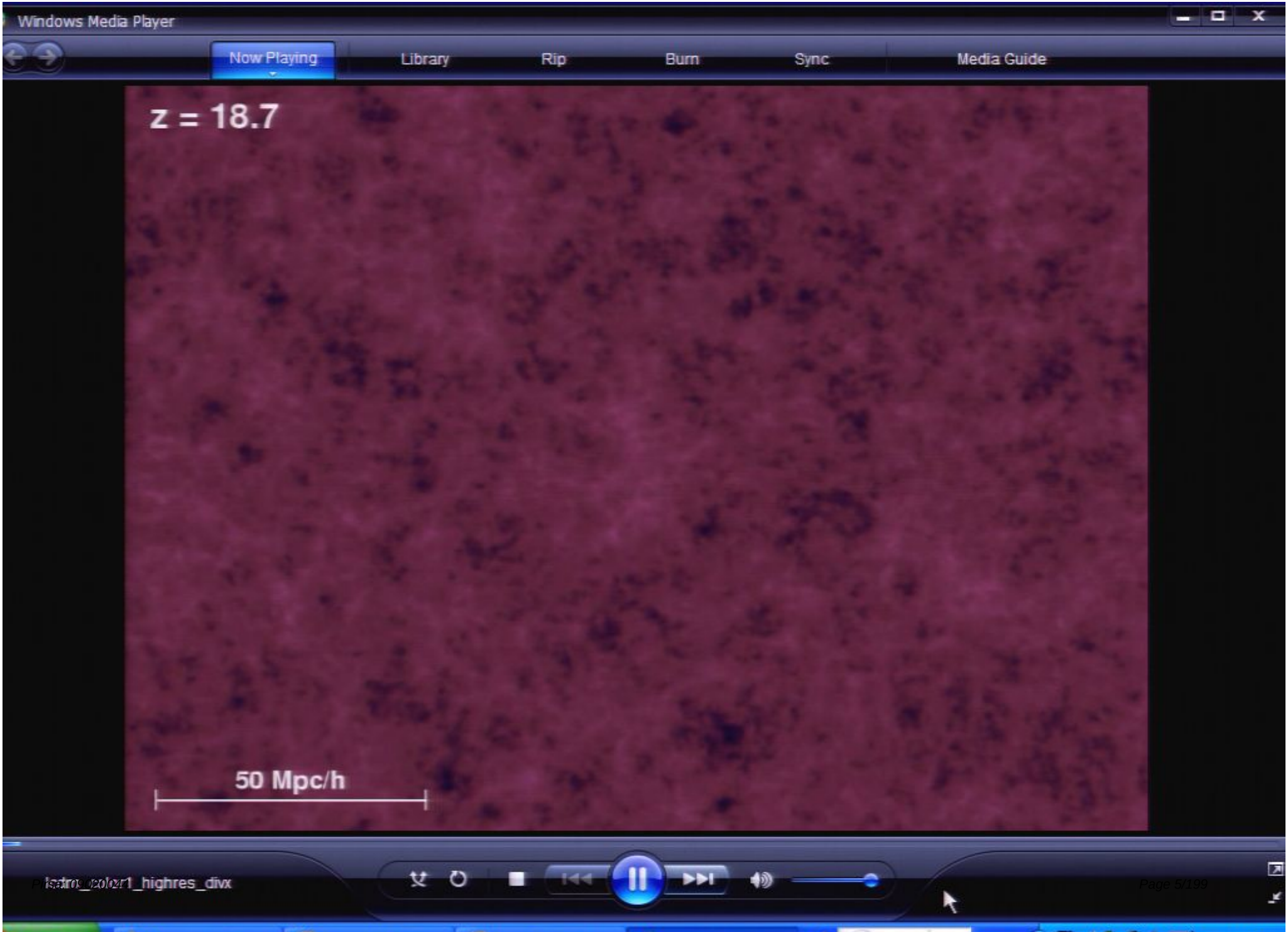
www.durham.ac.uk/virgo

The Origin of Structure



Evidence suggests that dark matter is non-baryonic, most likely some kind of Weakly Interacting Massive Particle (WIMP)

Play Movie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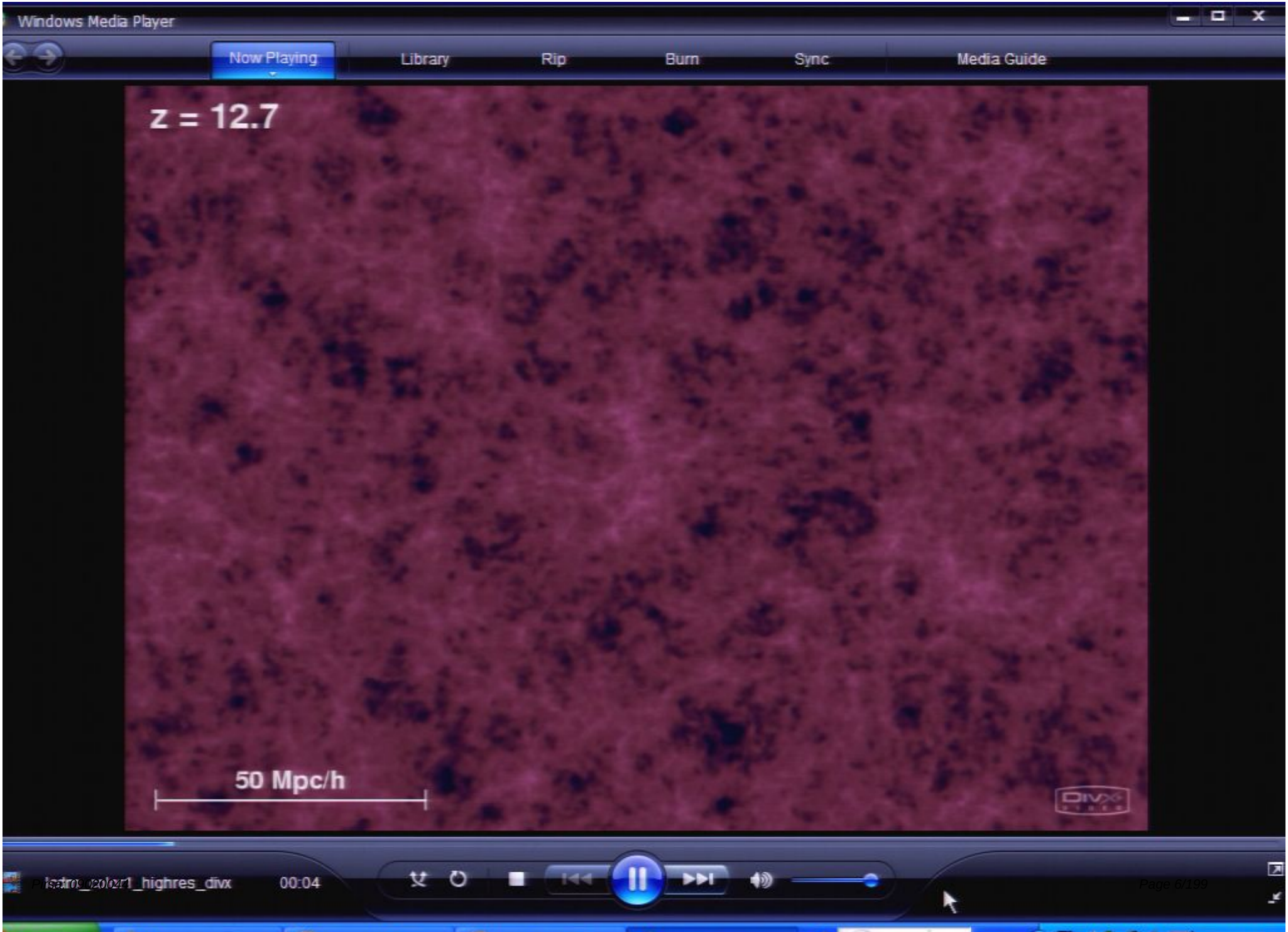
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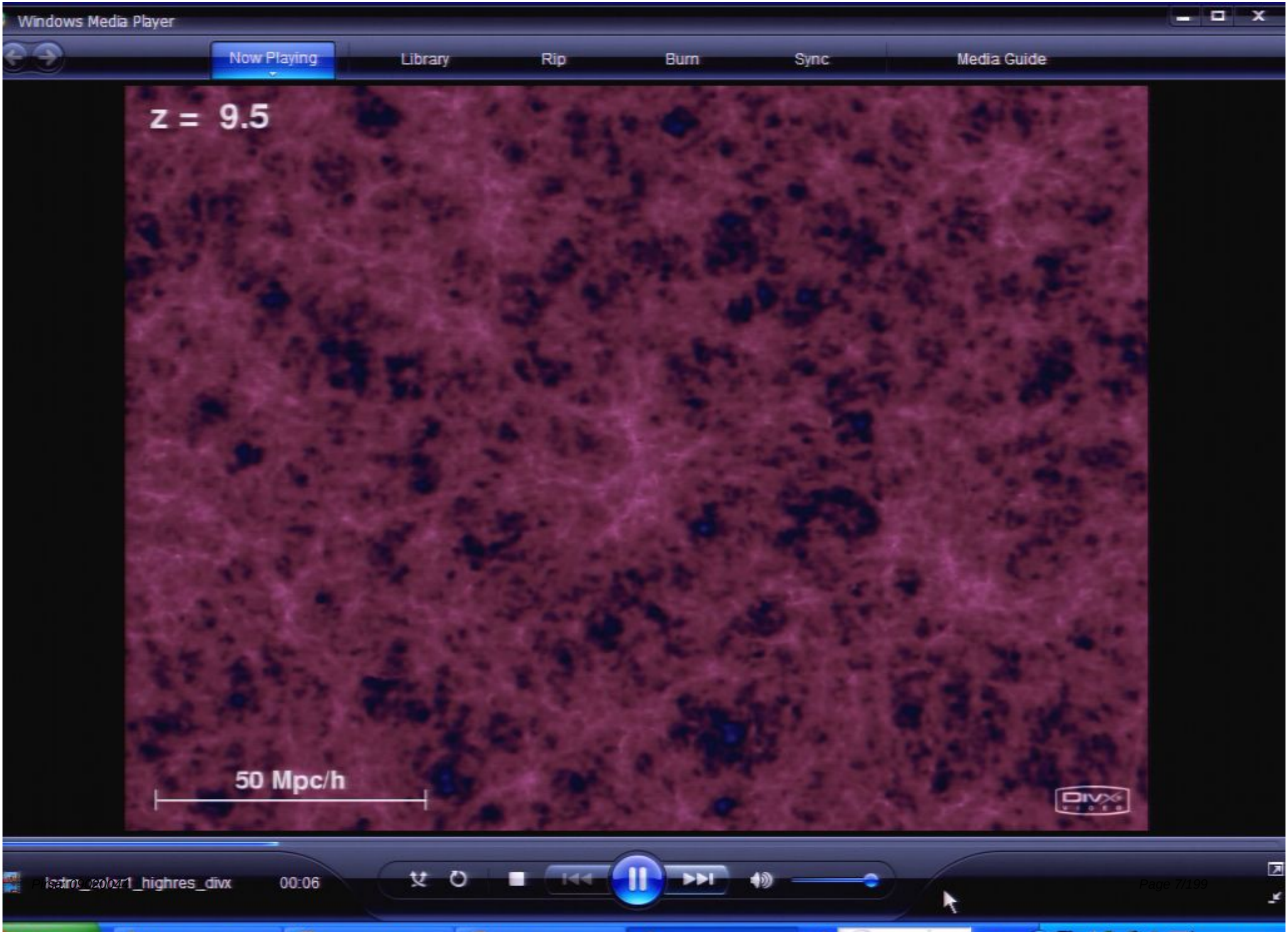
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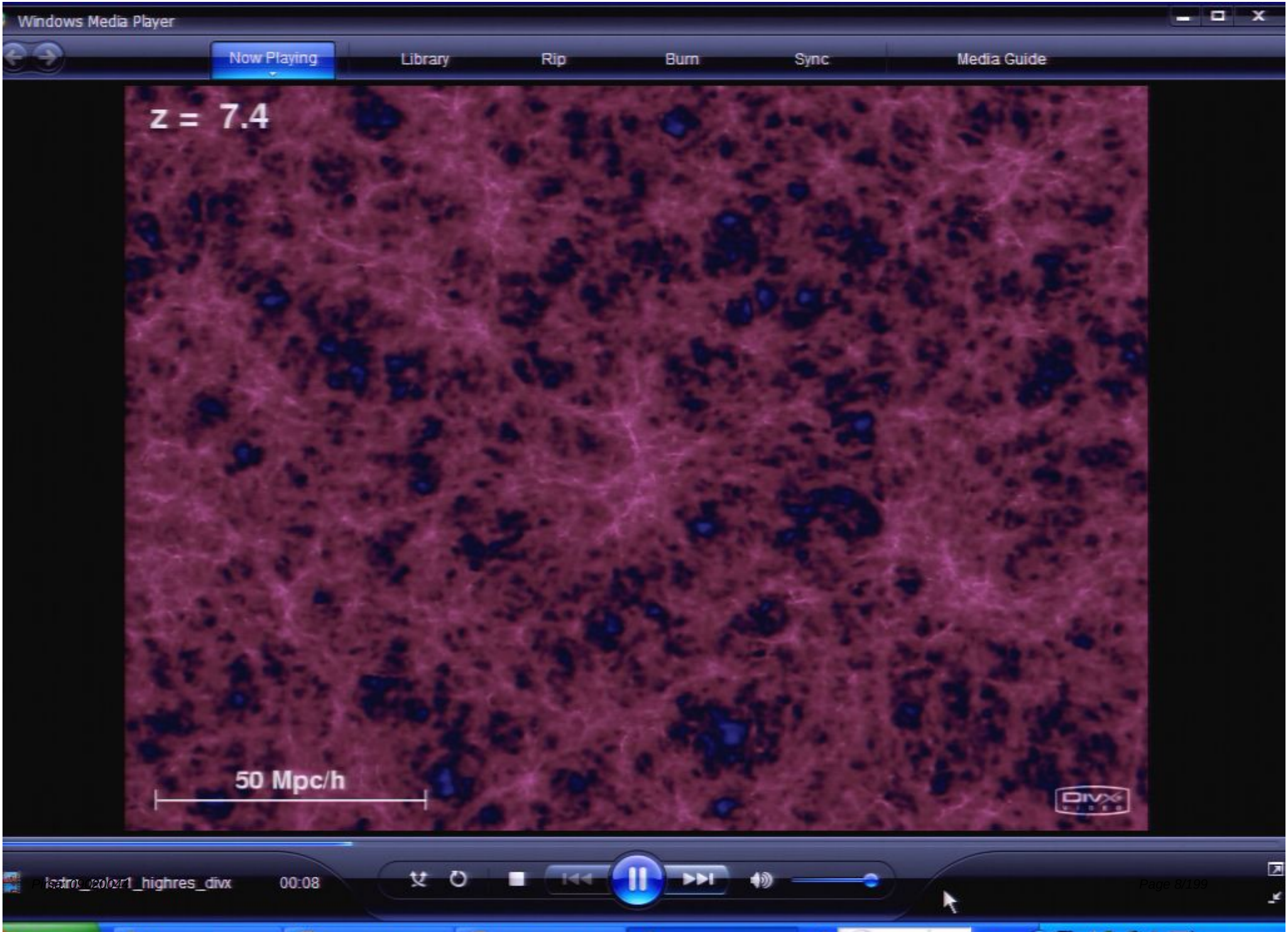
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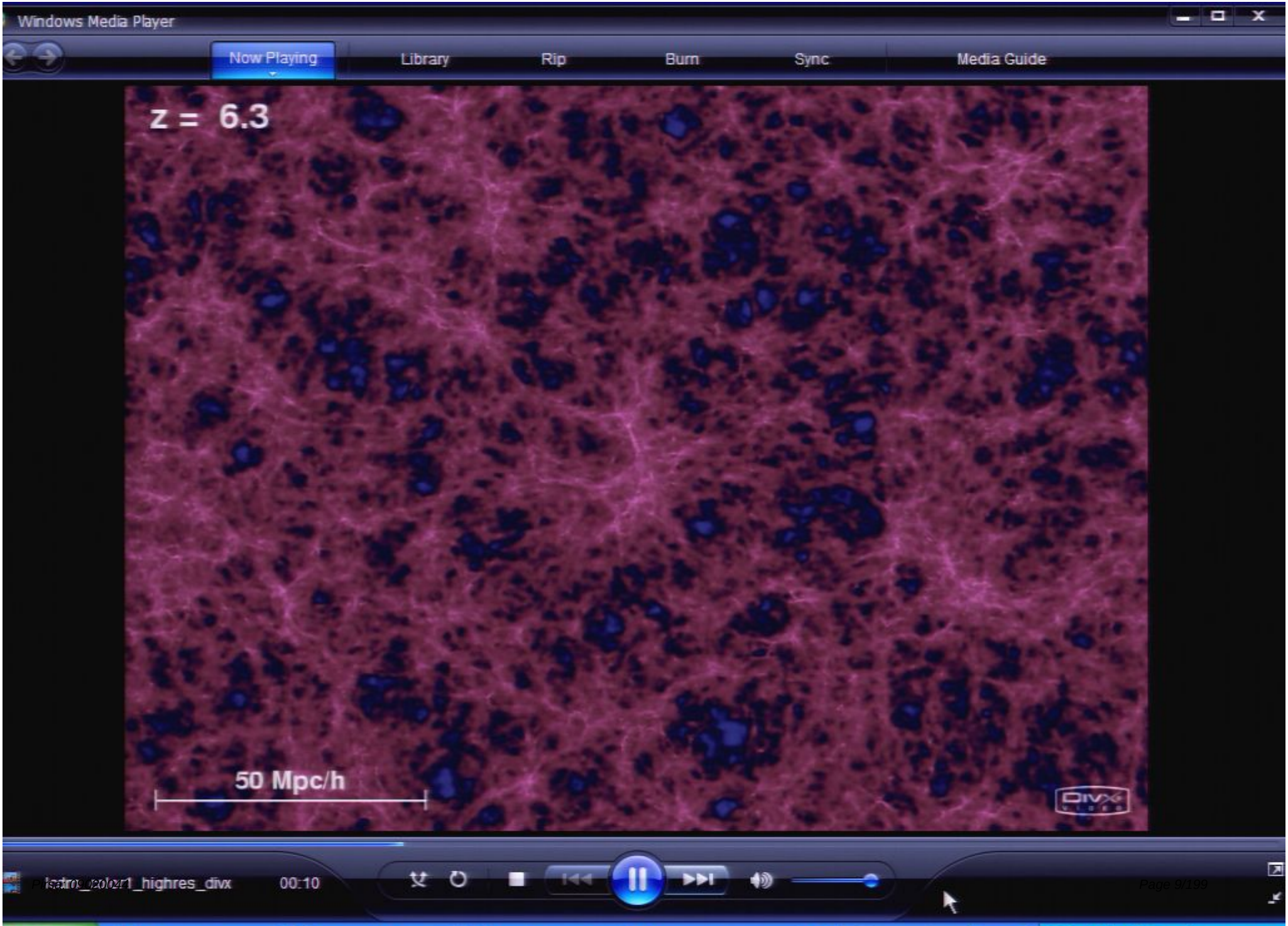
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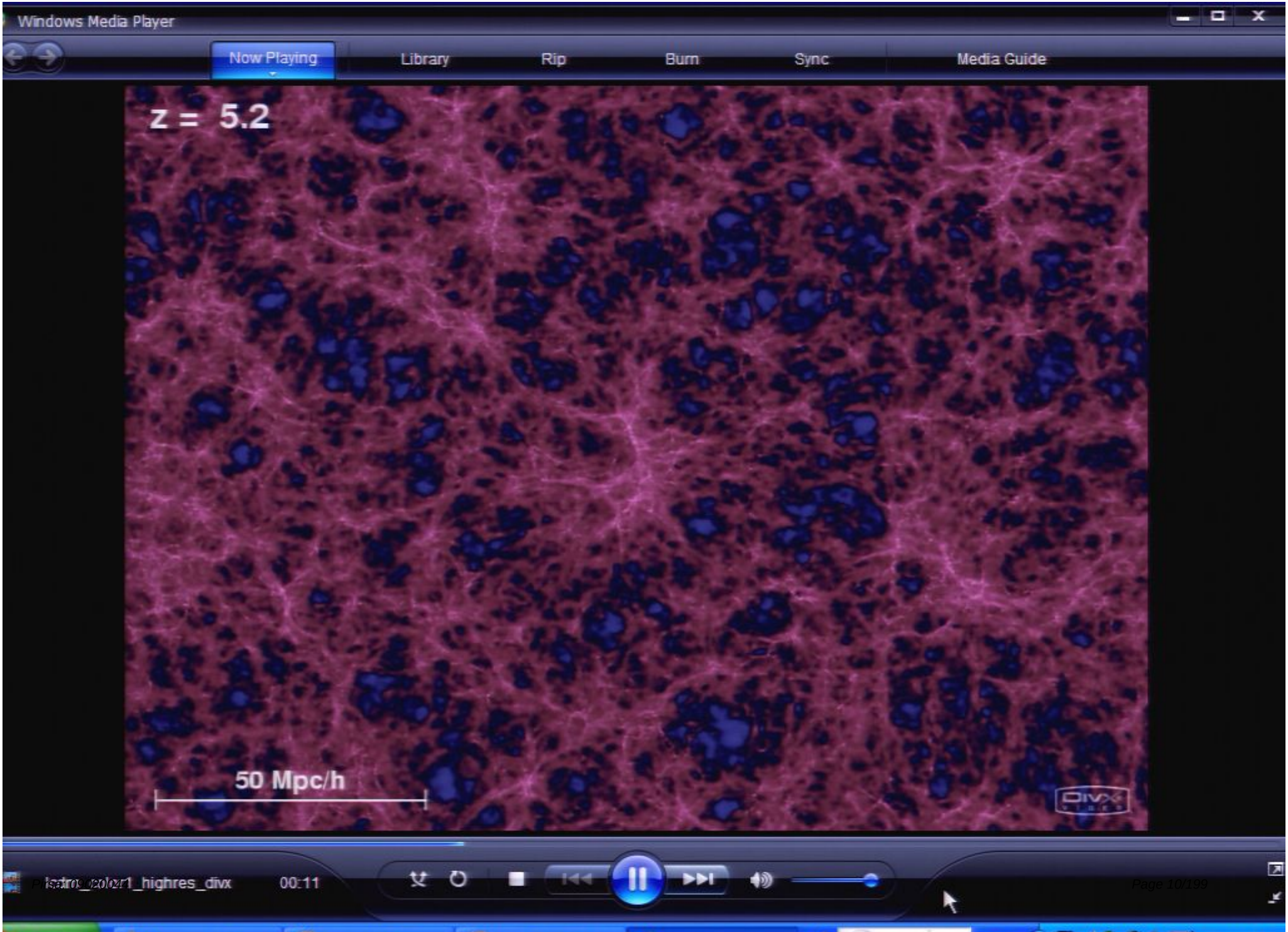
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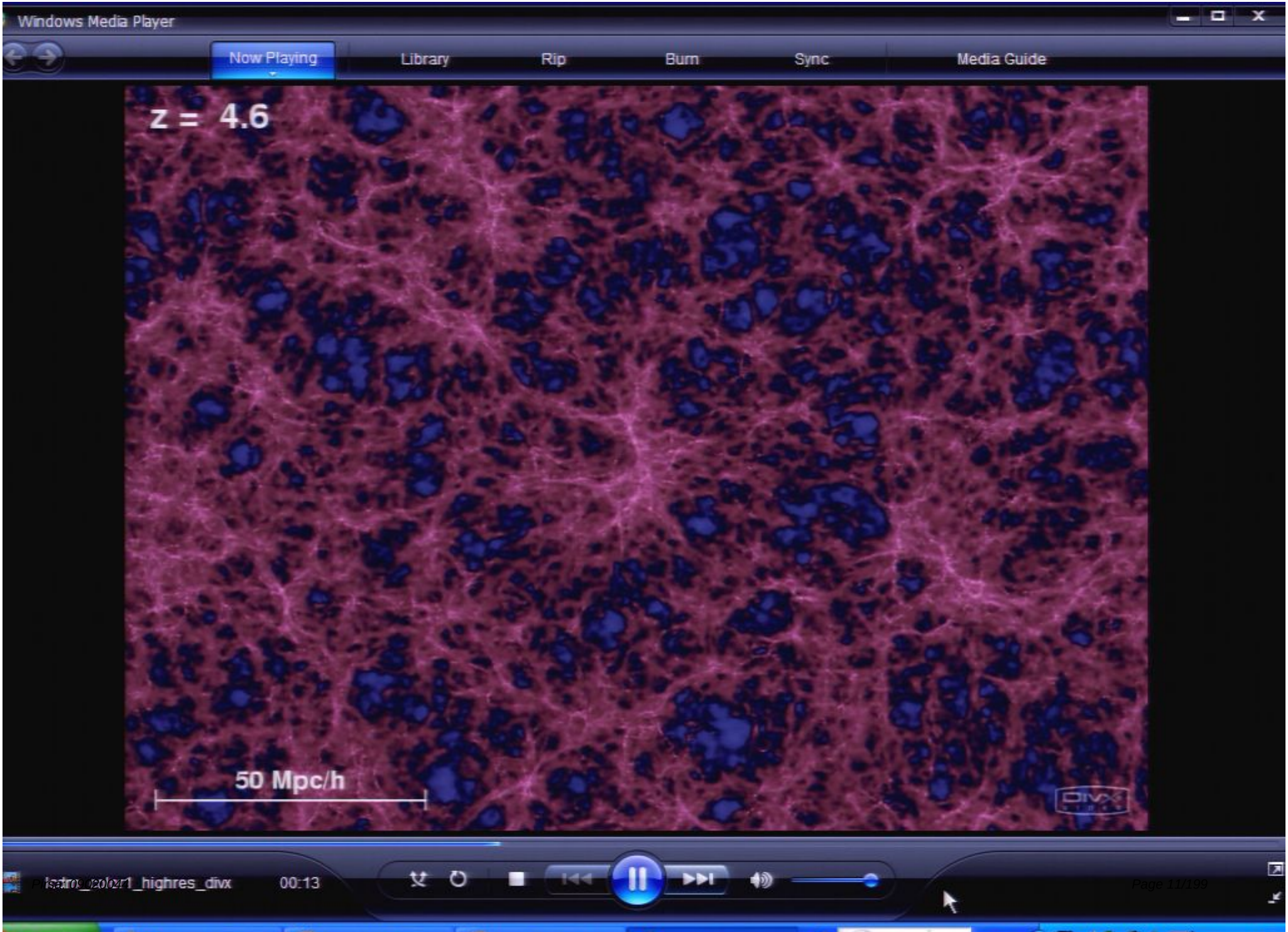
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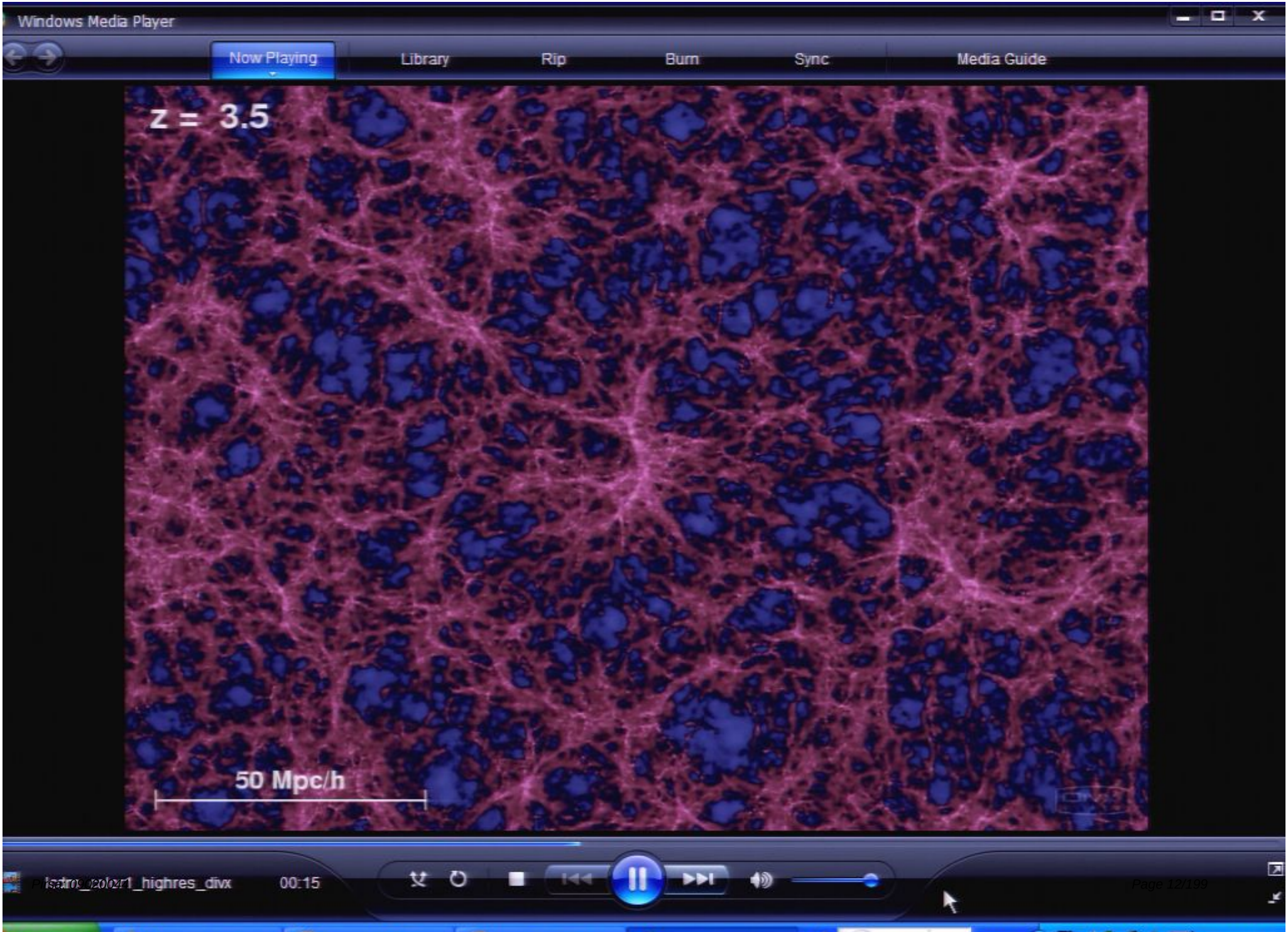
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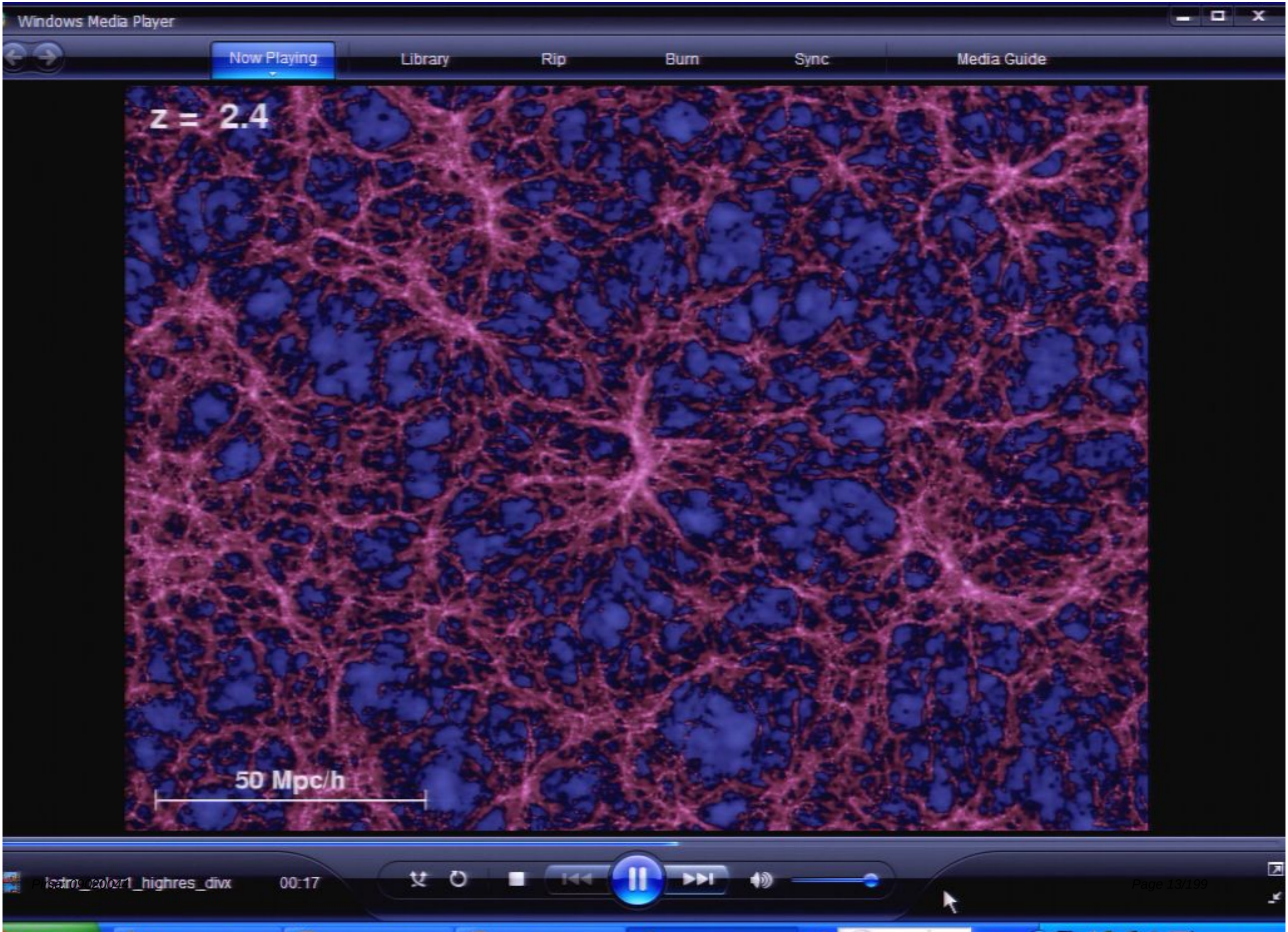
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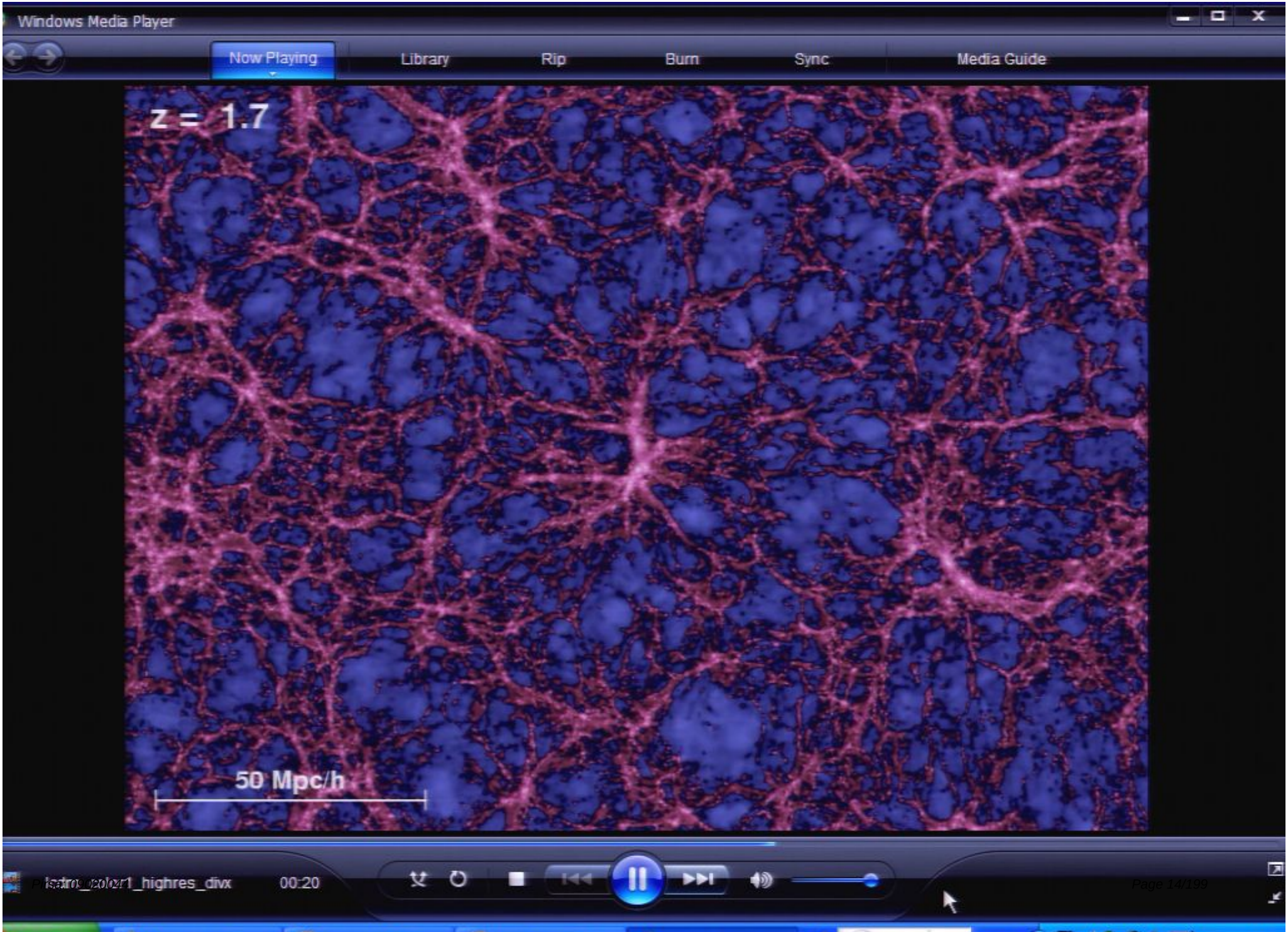
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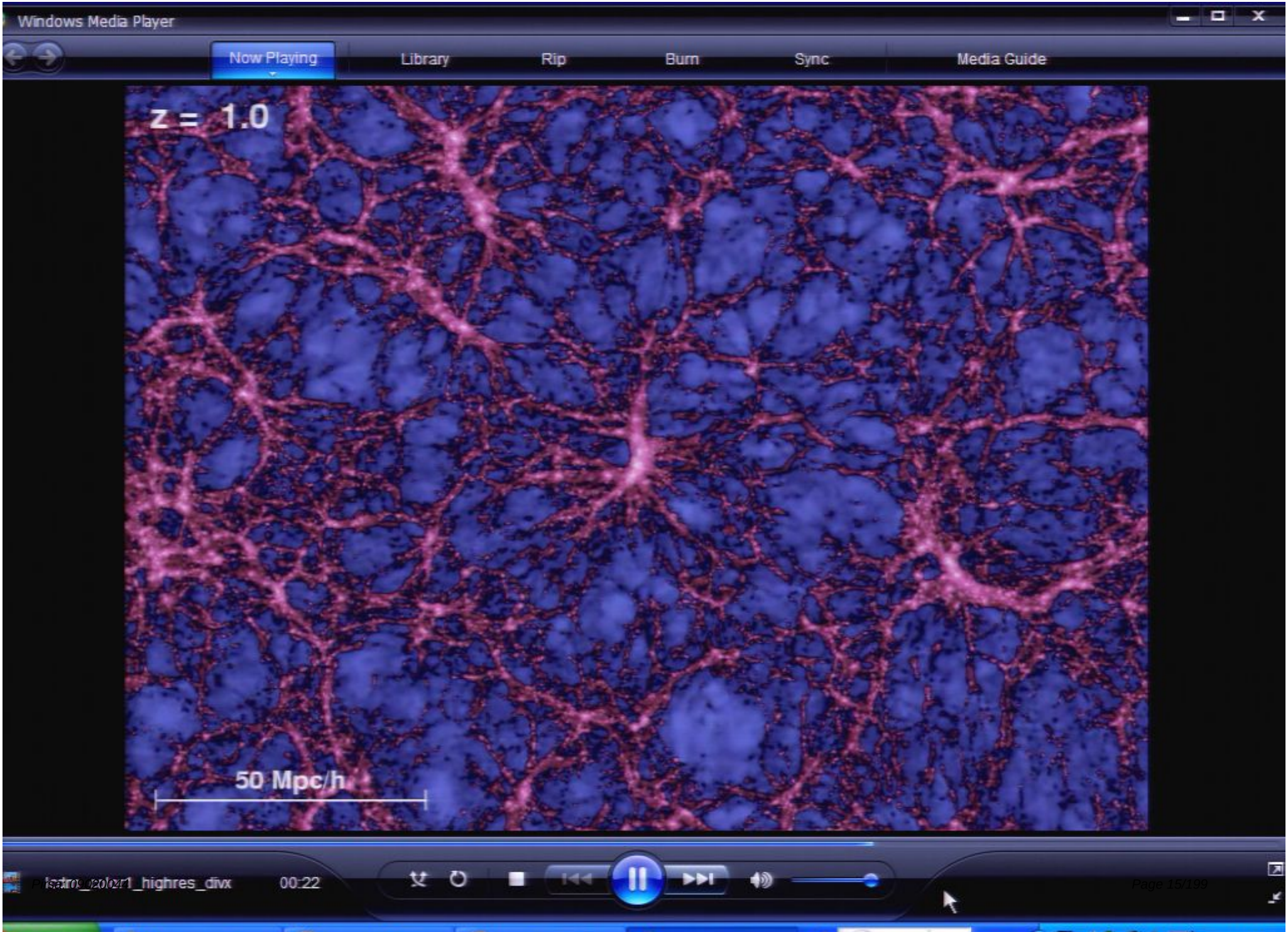
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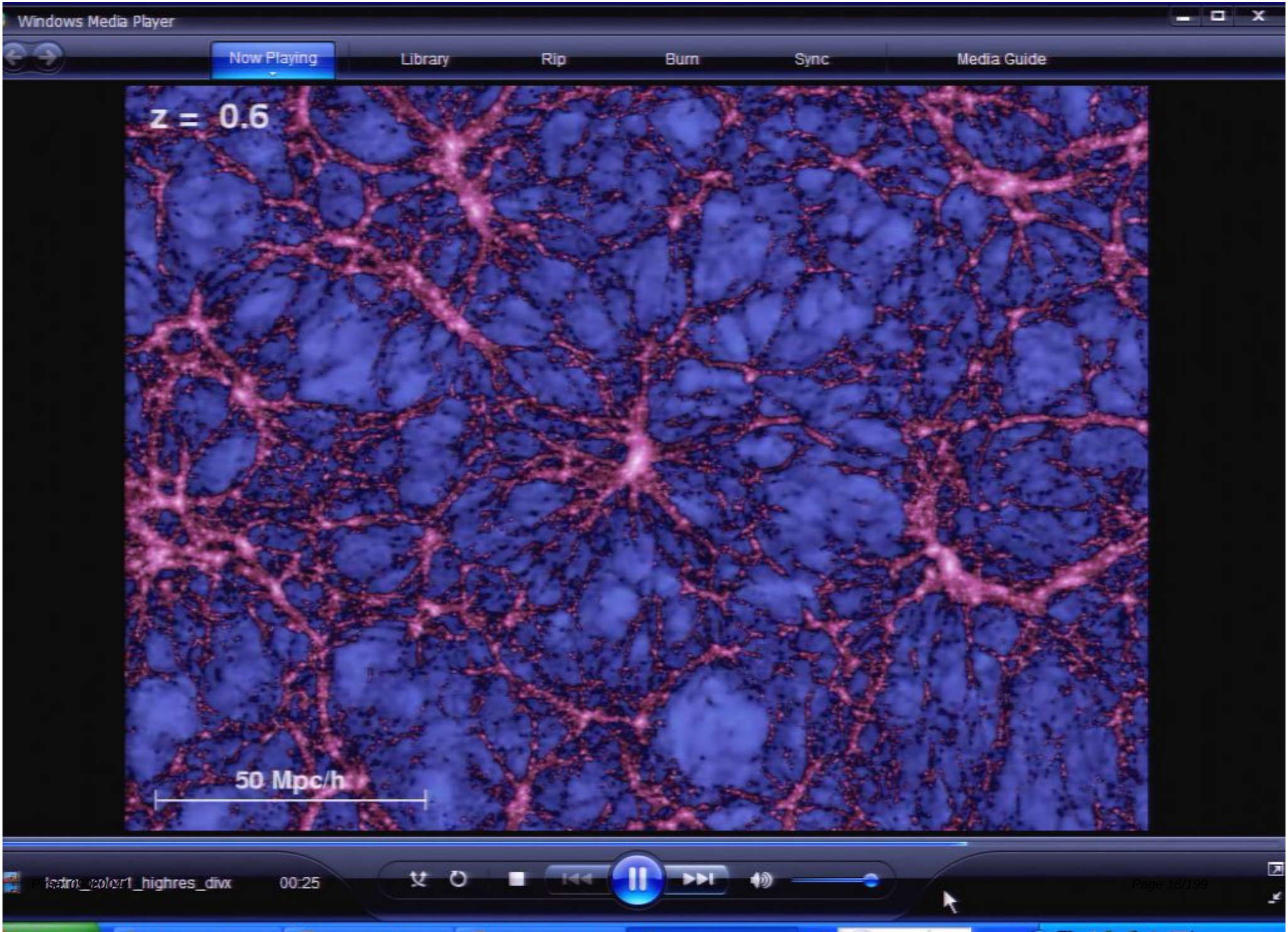
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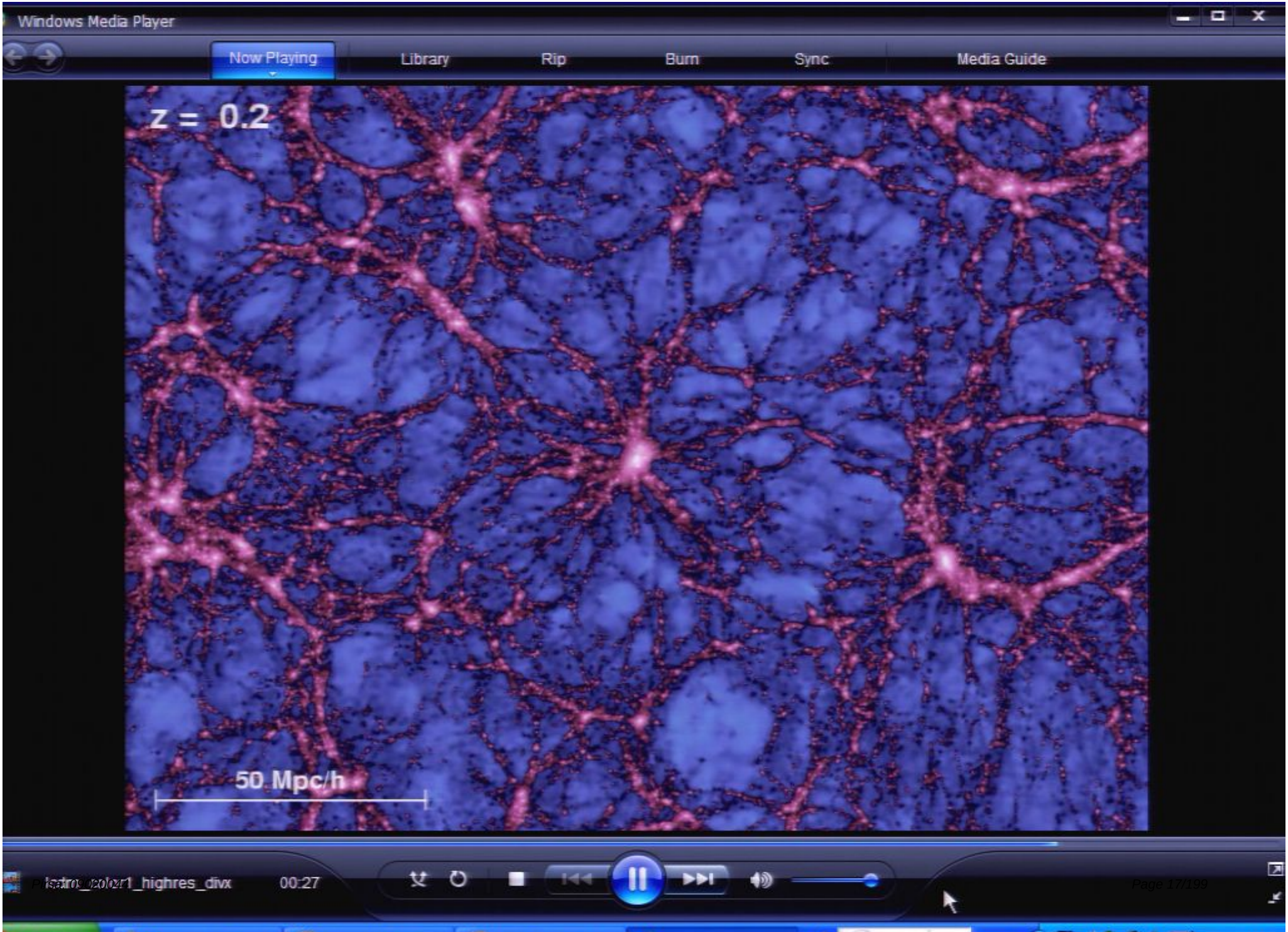
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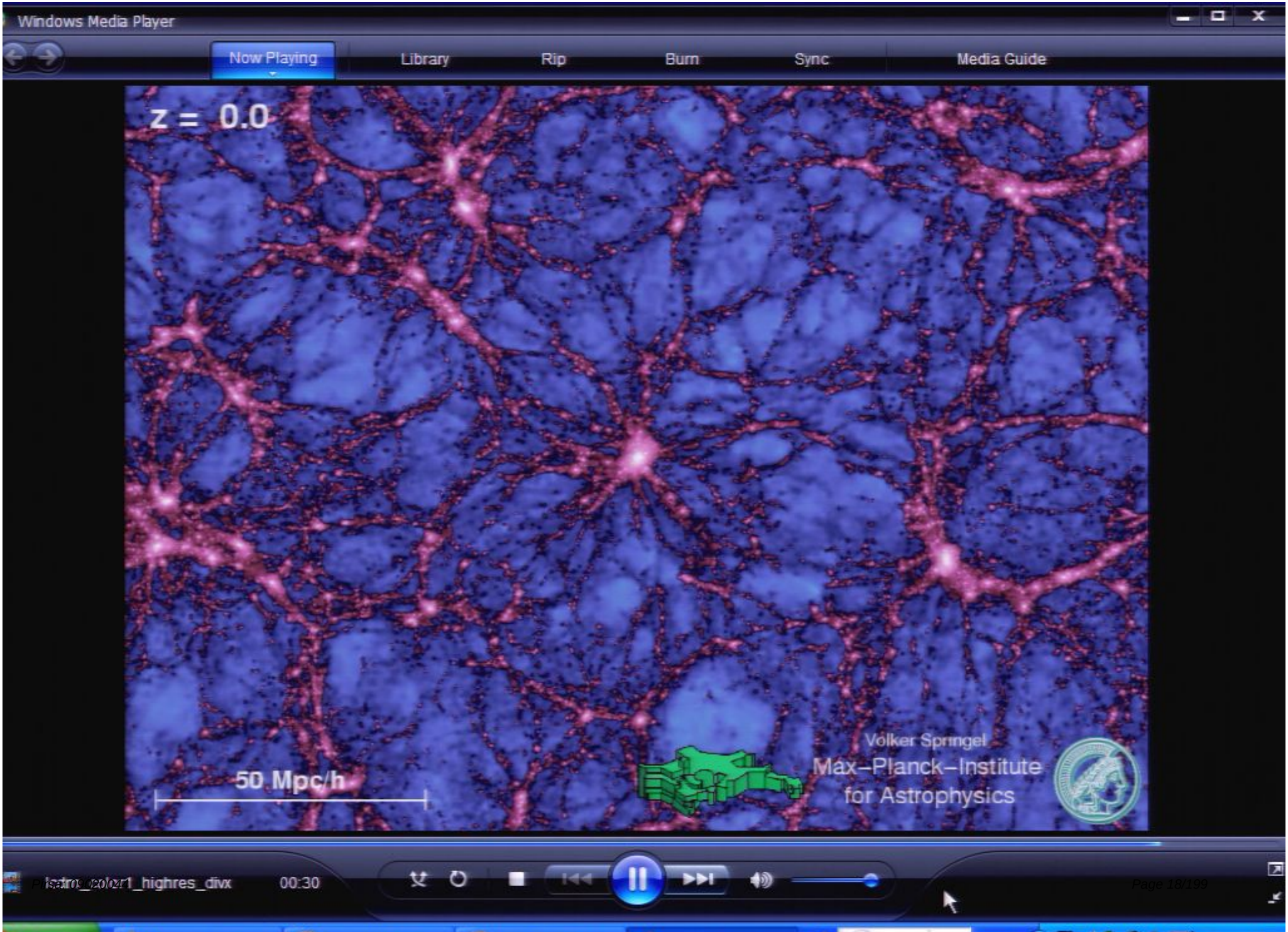
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Volker Springel
Max-Planck-Institute
for Astrophysics
00:30


Windows Media Player
Now Playing
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Rip
Burn
Sync
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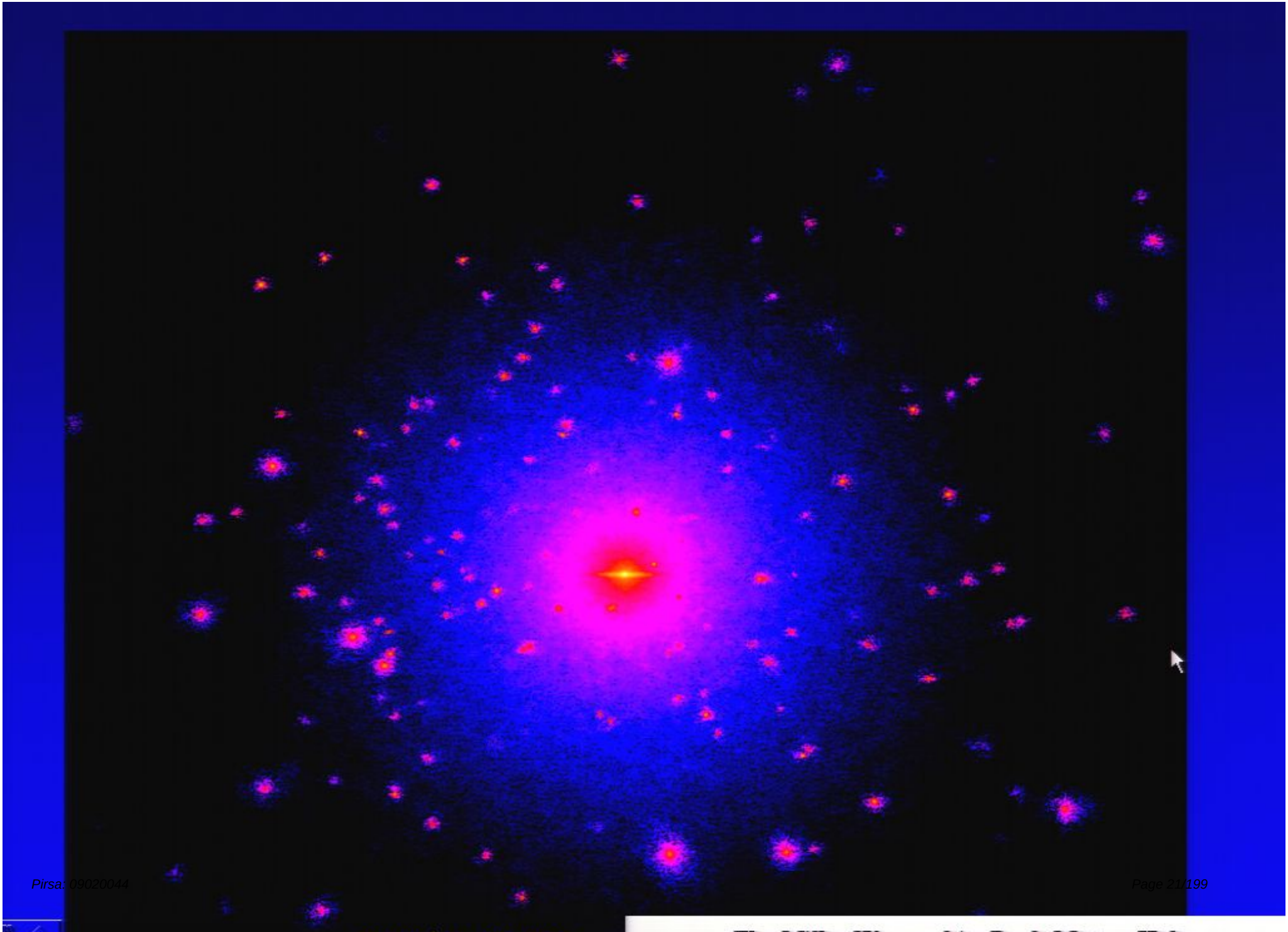
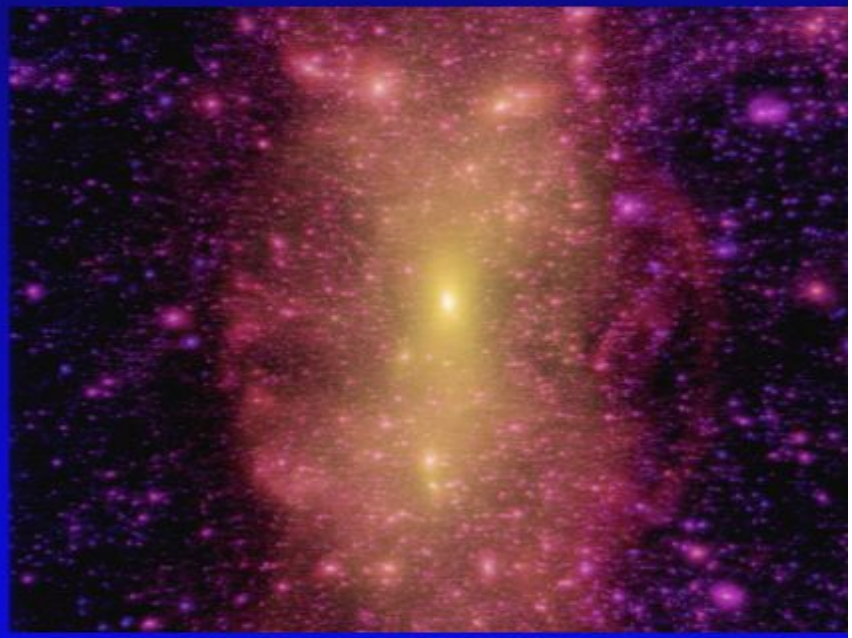
Play Movie



CDM halos: Main results

- CDM mass profiles are nearly **universal**
  - shape is independent of mass
- CDM density profiles are **cuspy**
  - no evidence for a constant-density central "core"
- CDM halos are **clumpy**
  - Abundant but non-dominant substructure
- CDM halos are **triaxial**
  - Preference for prolate configuration, asphericity increasing toward the center.



CDM halos: Outstanding issues

- **The Structure of the Central Cusp**
  - Power-law divergent slope ($\rho \propto r^{-1}$ or $\rho \propto r^{-1.2}$ or $\rho \propto r^{-1.5}$?)
    - Annihilation signal
  - Disk galaxy rotation curves (cusp vs core vs triaxiality)
- **The Structure of Substructure**
  - Mass profile and abundance of Local Group satellites
  - Annihilation signal from substructures and "boost factors"
  - Abundance, spatial distribution and kinematics
    - lensing flux ratio anomaly, satellite distribution + orbits
- **The Phase-Space Distribution of Dark Matter**
  - Implications for direct dark matter detection experiments
- **The Origin of a Universal Density Profile**
  - Theoretical interest
  - Important to understand baryon-induced transformations of dark halo structure

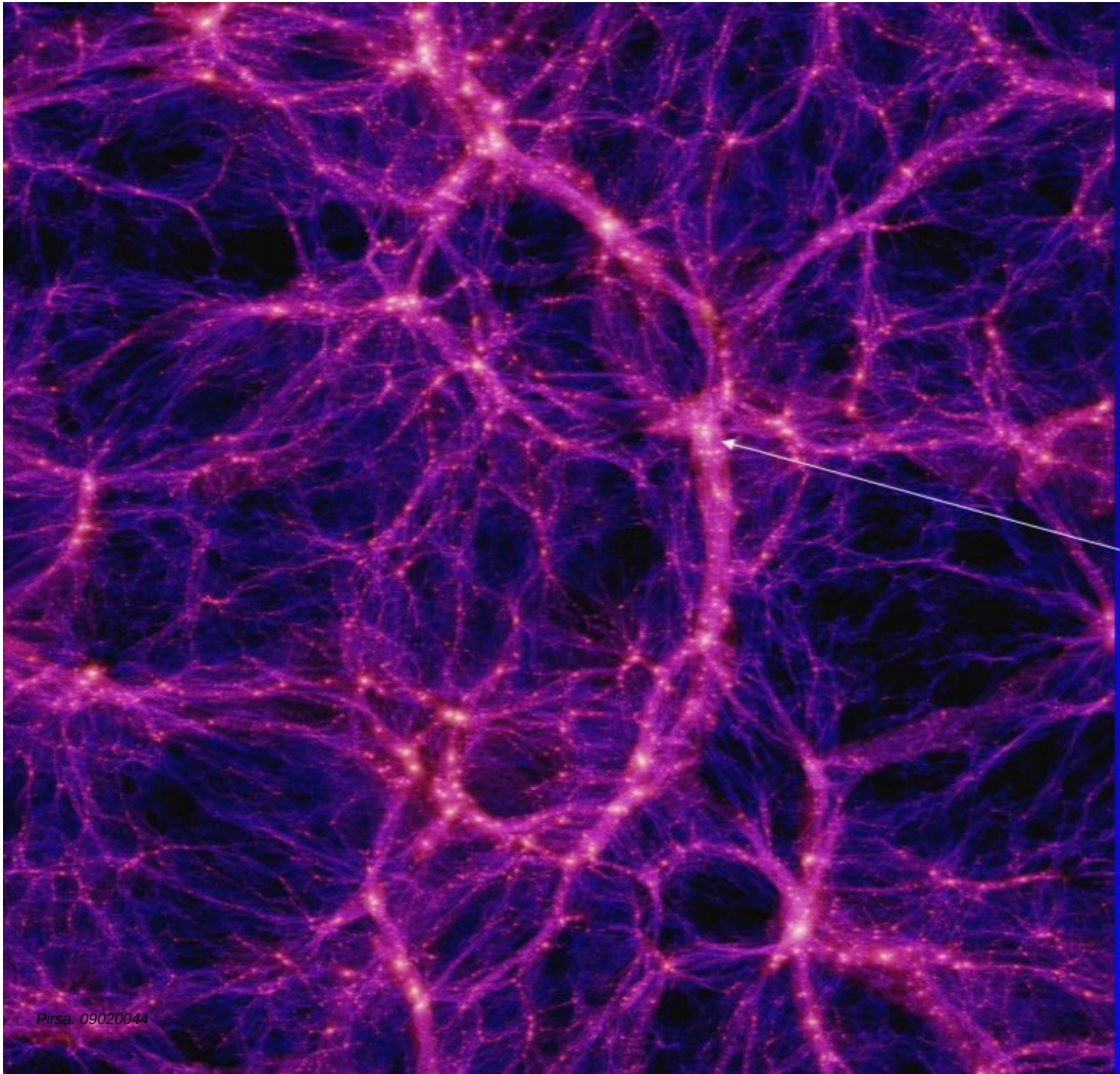
The Aquarius programme

6 different galaxy size halos simulated at varying resolution, allowing for a proper assessment of numerical convergence and cosmic variance

Numerical resolution	Particle number in halo (N_{50})	# of substructures	mass resolution
Aq-A-5	808,479	299	3.14×10^6 M_0
Aq-A-4	6,424,399	1,960	3.92×10^5 M_0
Aq-A-3	51,391,468	13,854	4.91×10^4 M_0
Aq-A-2	184,243,536	45,024	1.37×10^4 M_0
Aq-A-1	1,473,568,512	297,791	1.71×10^3 M_0 (15 pc/h softening)

Springel et al '08

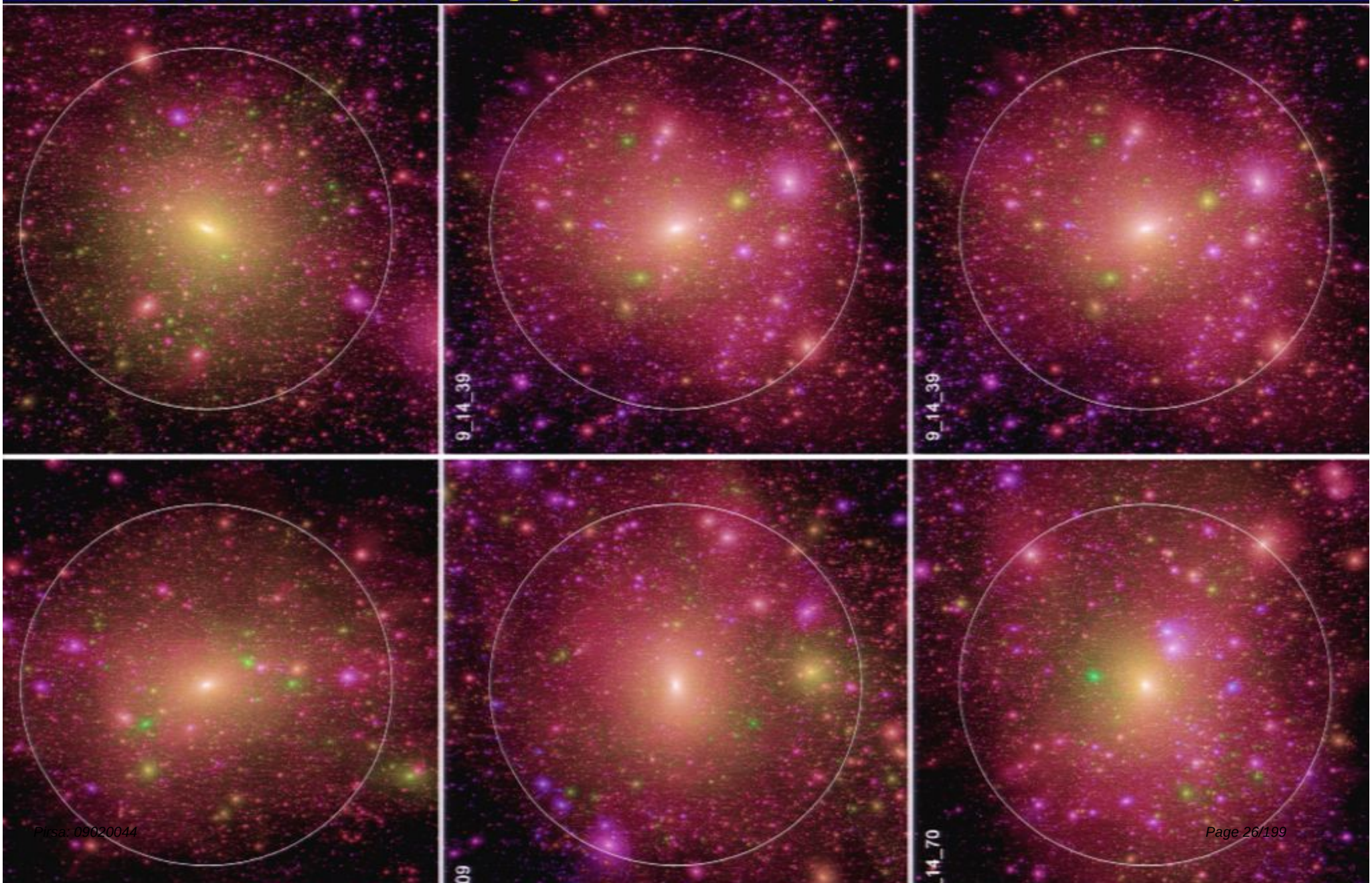
"Via Lactea I simulation"	84,700,000	~10,000	2.18×10^4 M_0
"Via Lactea II simulation"	470,000,000	~100,000	3.92×10^3 M_0



Aquarius halos in the Millennium-2 Run

One of the Aquarius halos in the 100Mpc/h box parent simulation.

Pictures of all Aquarius halos (level-2 resolution)



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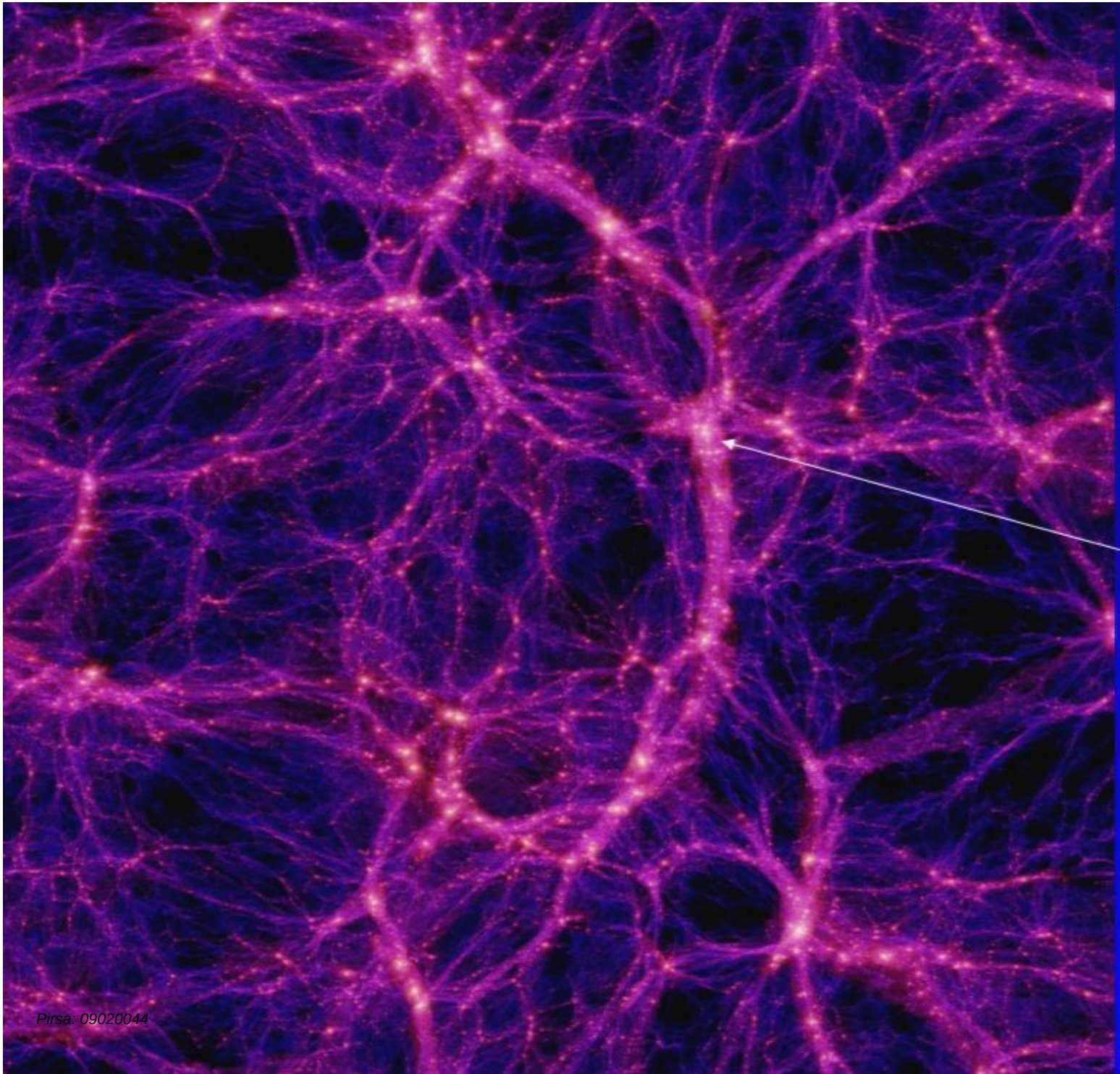

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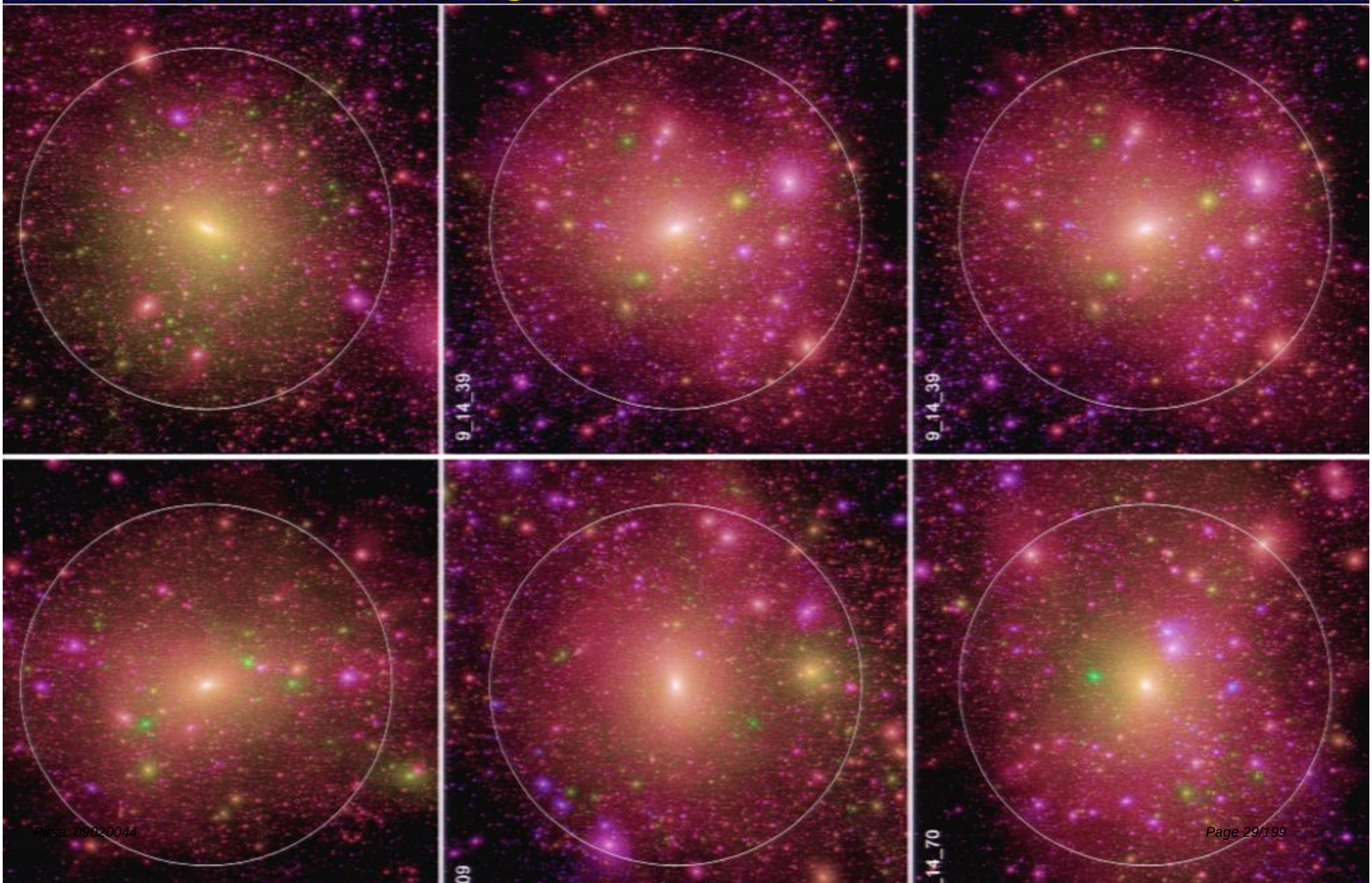

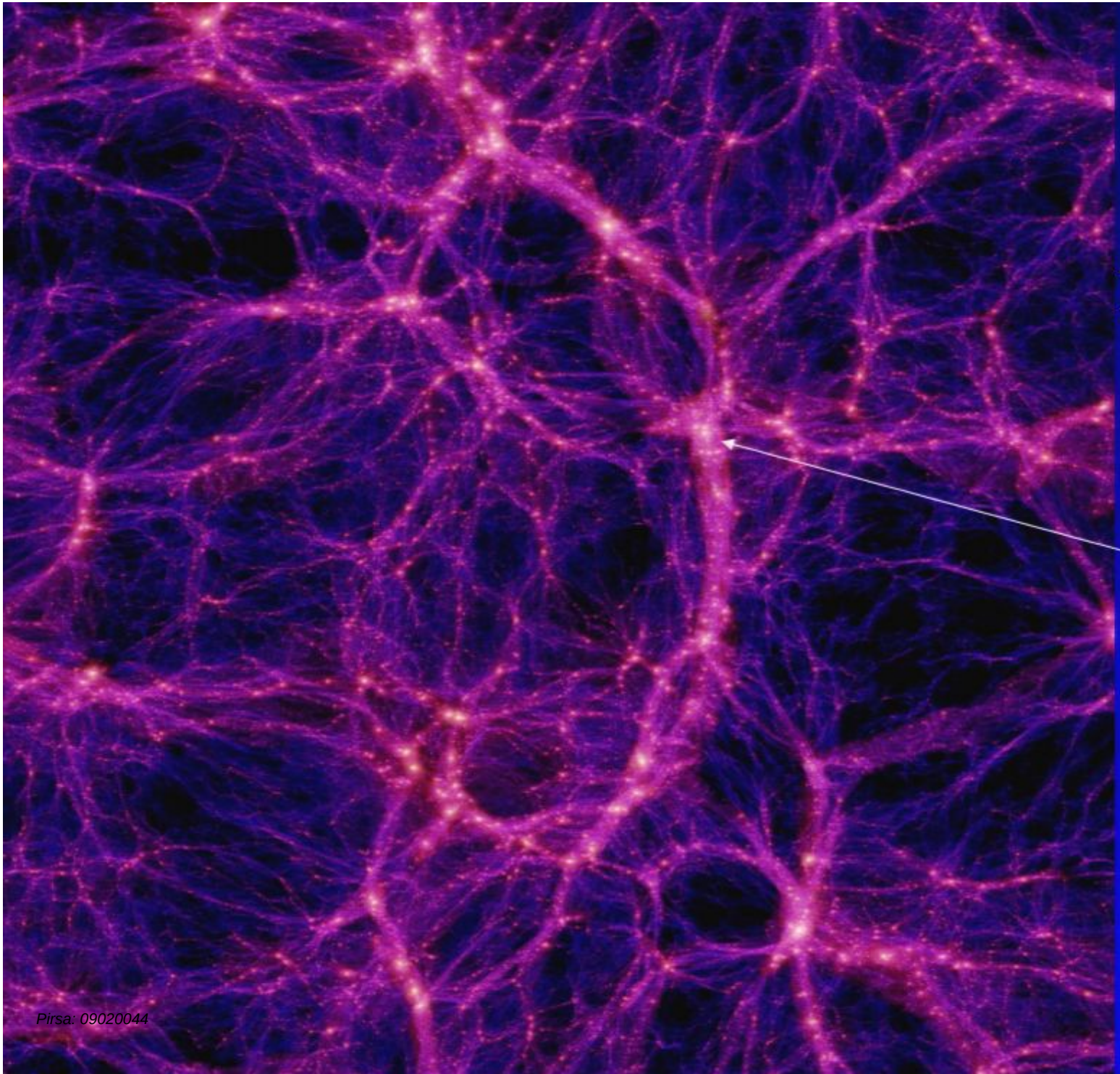

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rotation curves (cusp vs core vs triaxiality)

e of Substructure

and abundance of Local Group satellites

signal from substructures and "boost factors"

spatial distribution and kinematics

ratio anomaly, satellite distribution + orbits

pace Distribution of Dark Matter

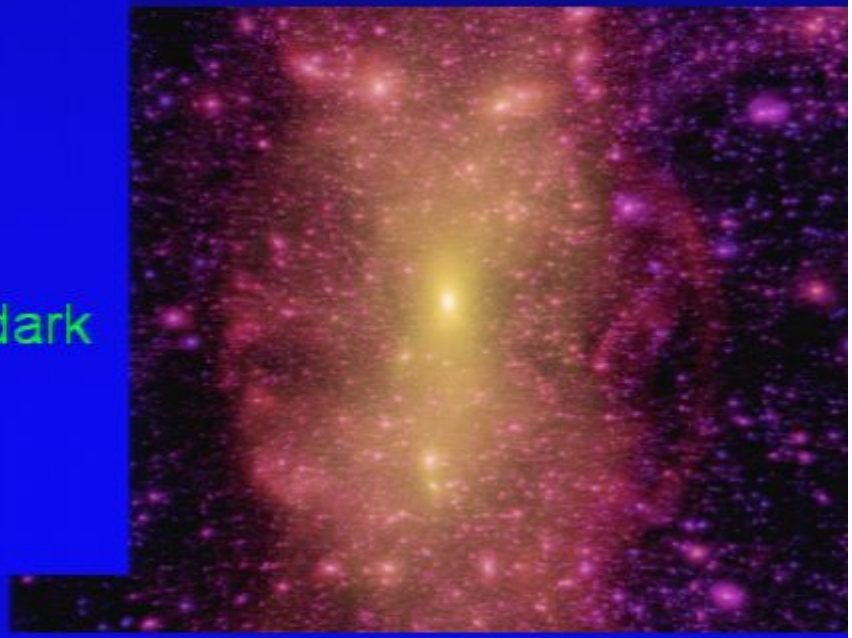
r direct dark matter detection experiments

a Universal Density Profile

terest

nderstand baryon-induced transformations of dark

esults



substructure

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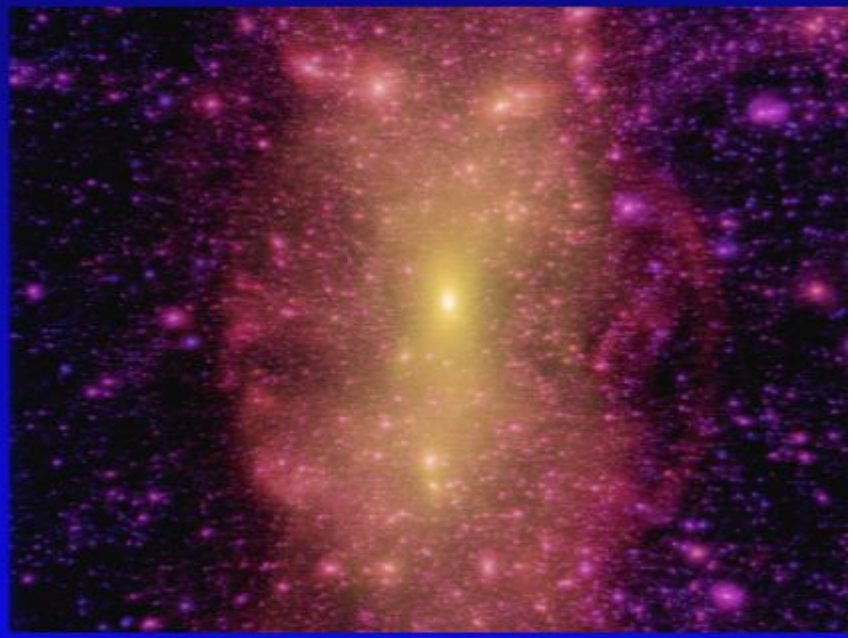

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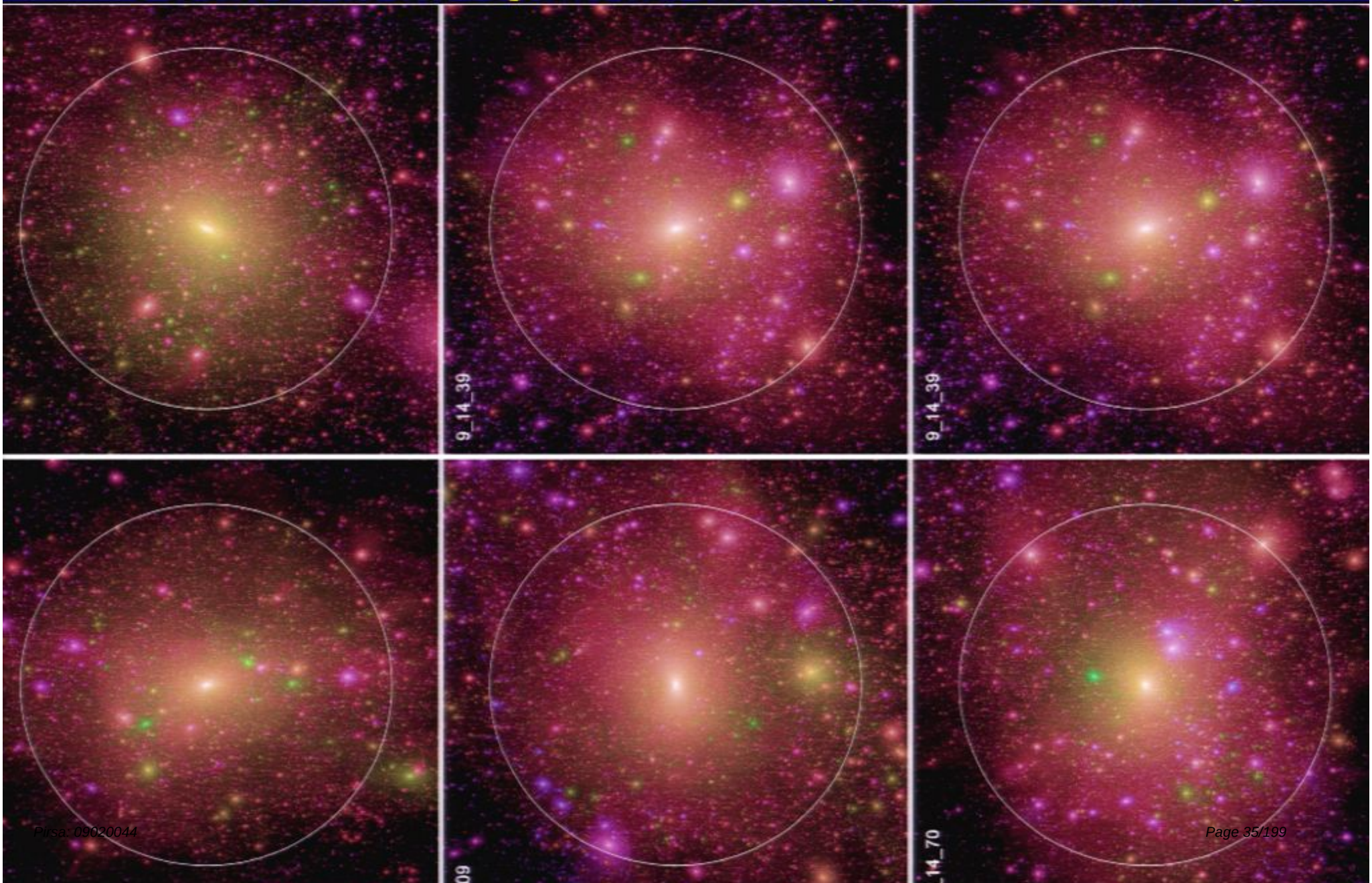

Aquarius: the Billennium simulation

The Aquarius "Billennium" halo simulation. A dark matter halo with 1 billion particles within the virial radius.

Play Movie

Aquarius: the Billennium simulation

The Aquarius "Billennium" halo simulation. A dark matter halo with 1 billion particles within the virial radius.

C:\Documents and Settings\Julio Navarro\My Documents\jfn\Movies/VolkerSpringel/C02 1200_evolution.avi

Play Movie


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
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Windows Media Player
Now Playing
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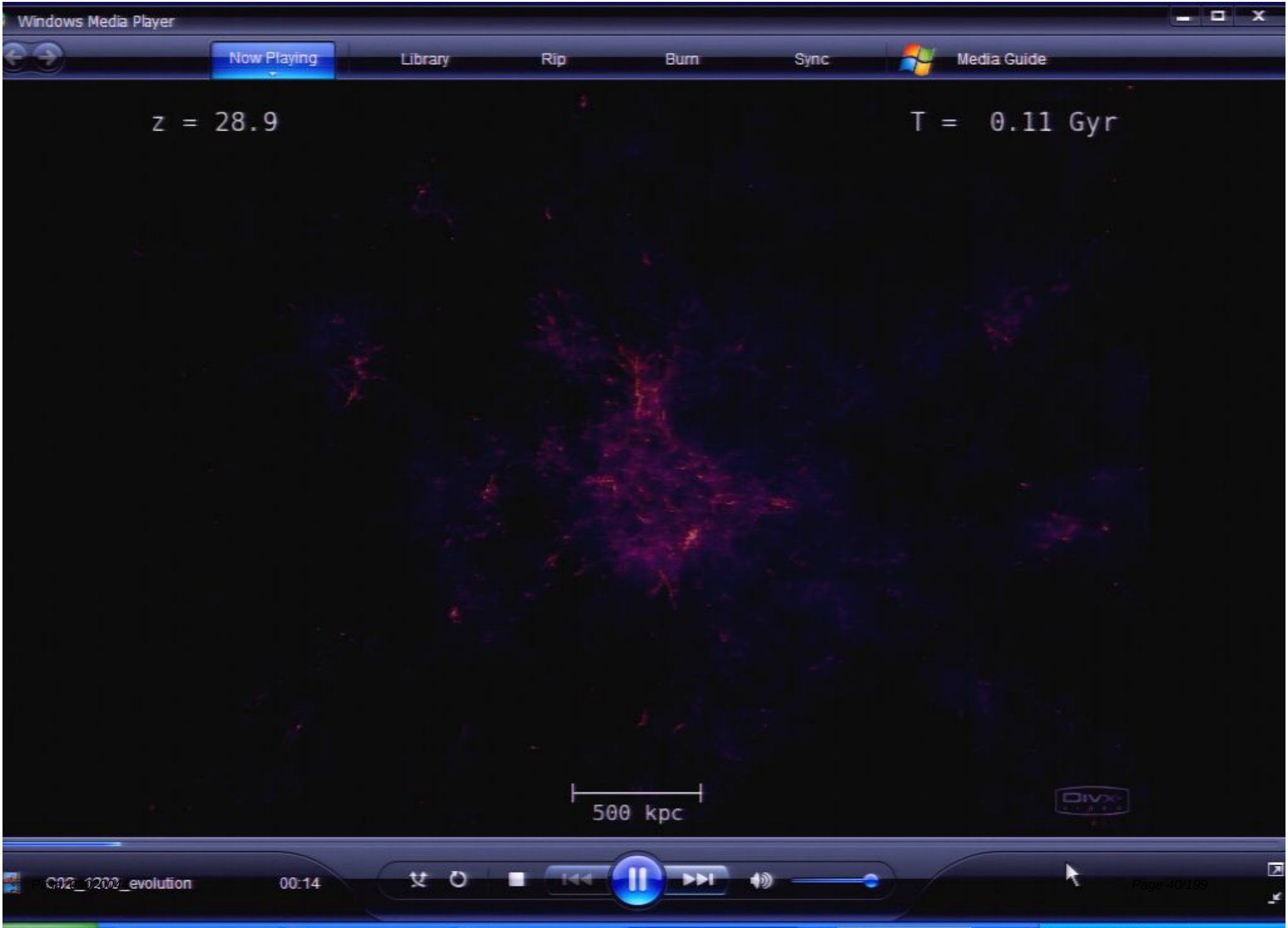
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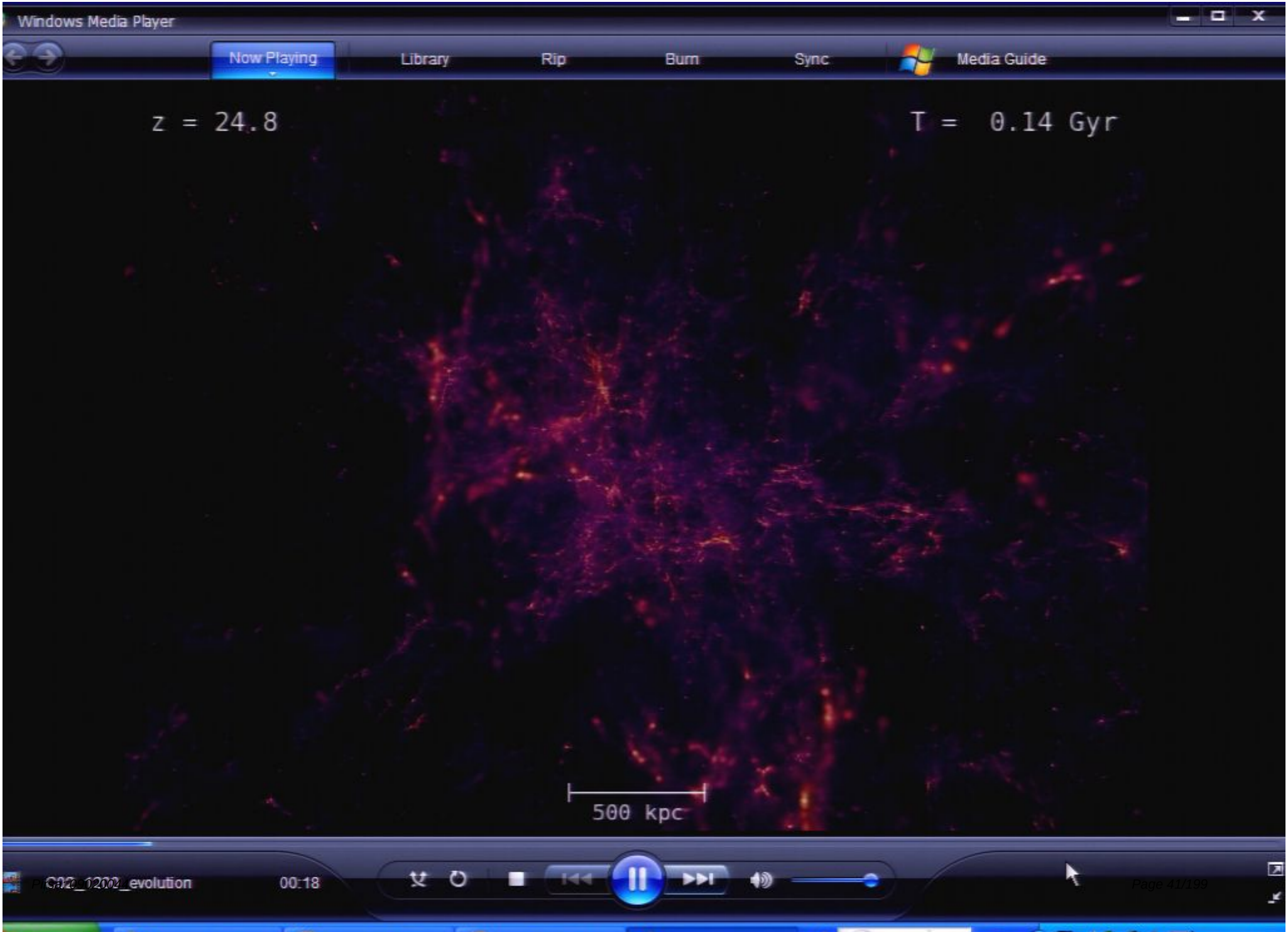
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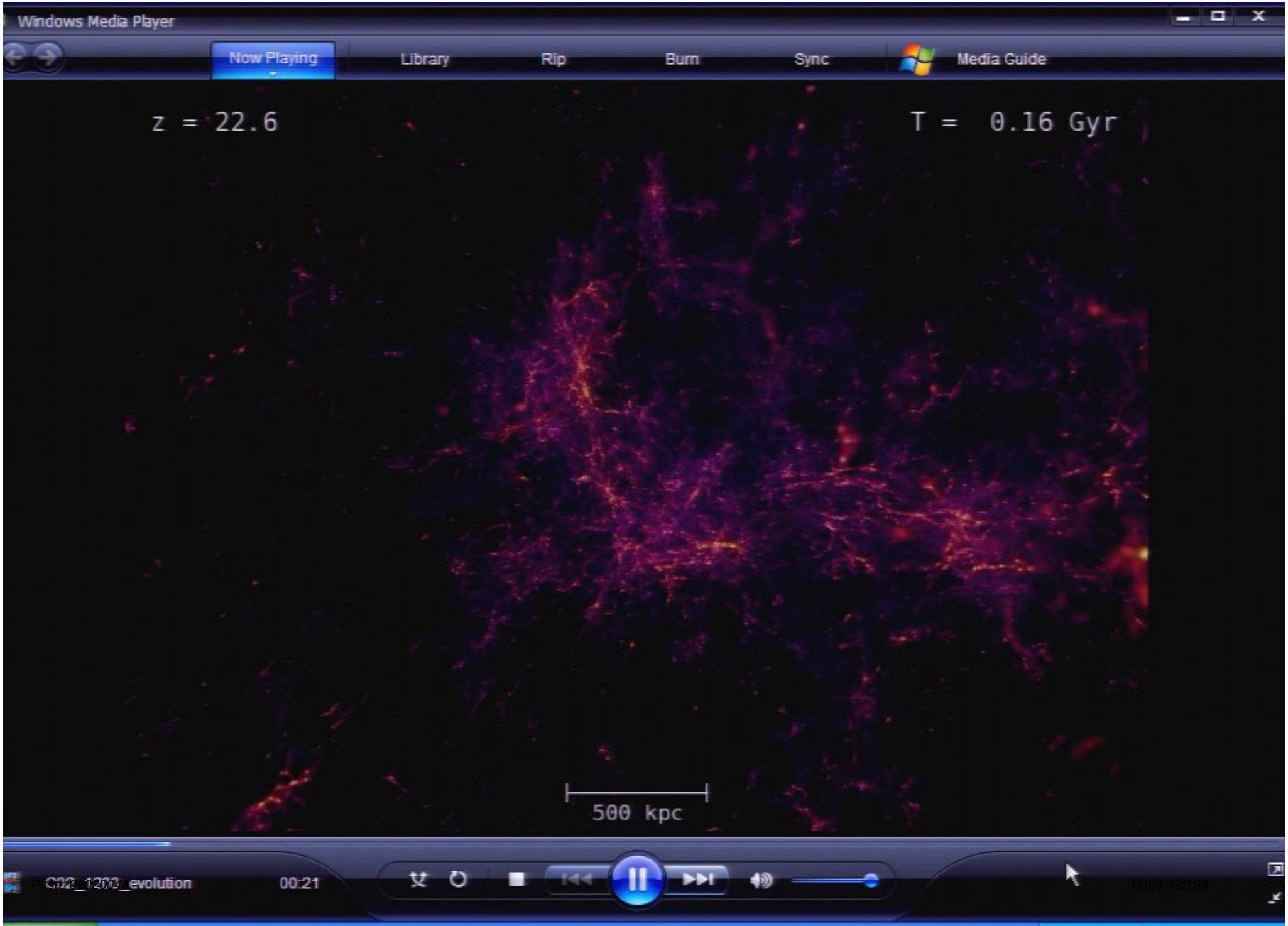
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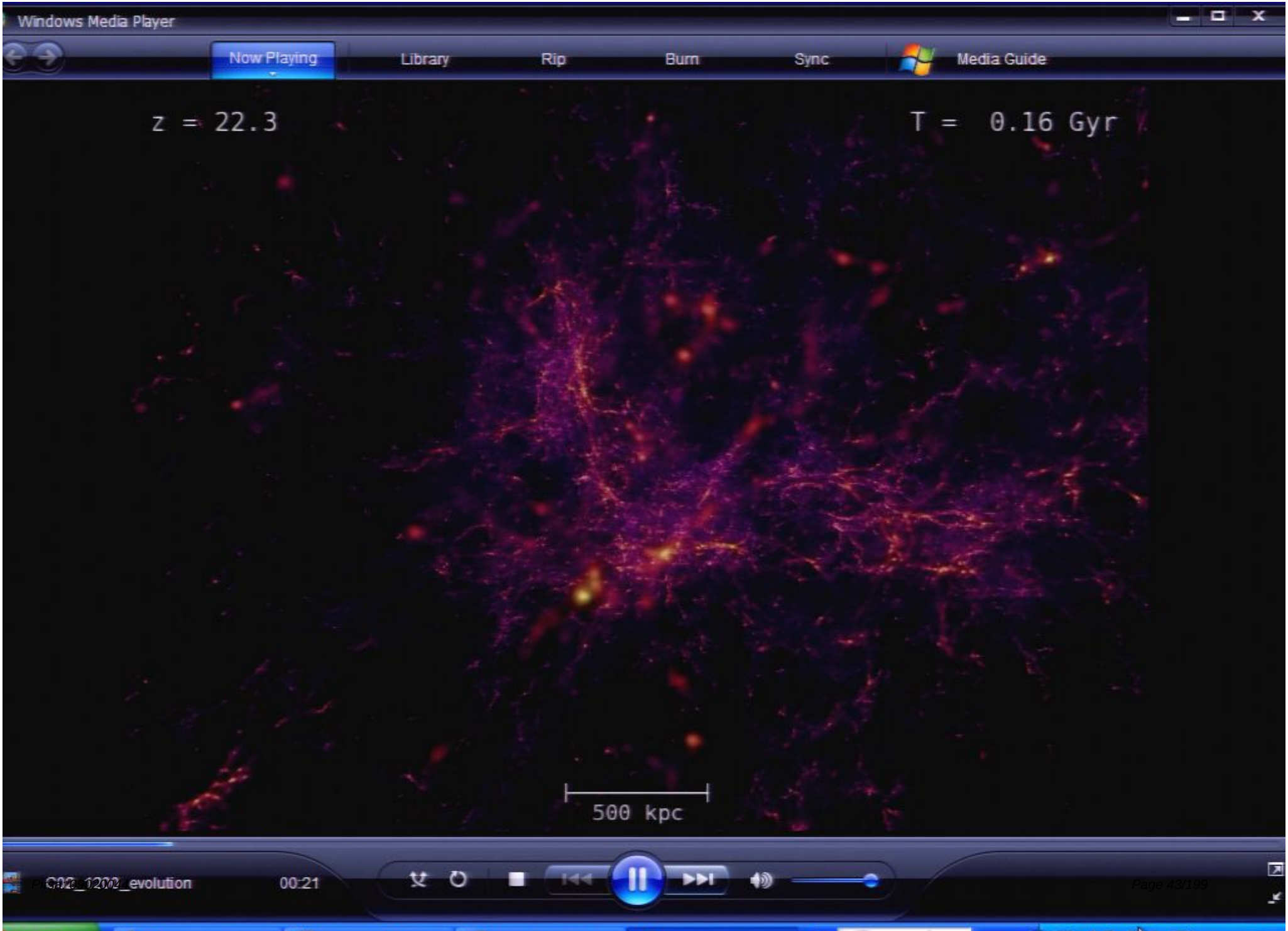
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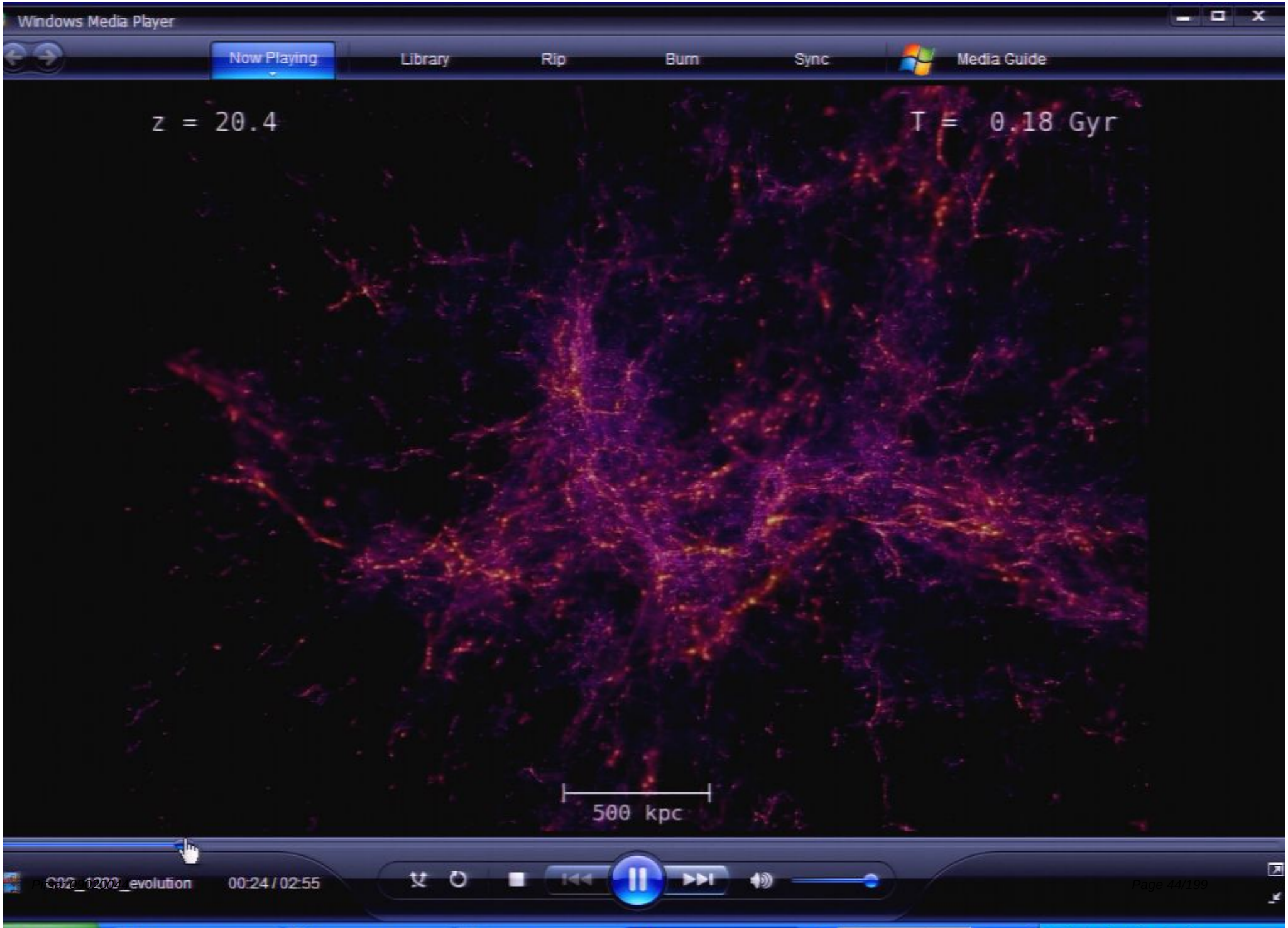
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Rip
Burn
Sync
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Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
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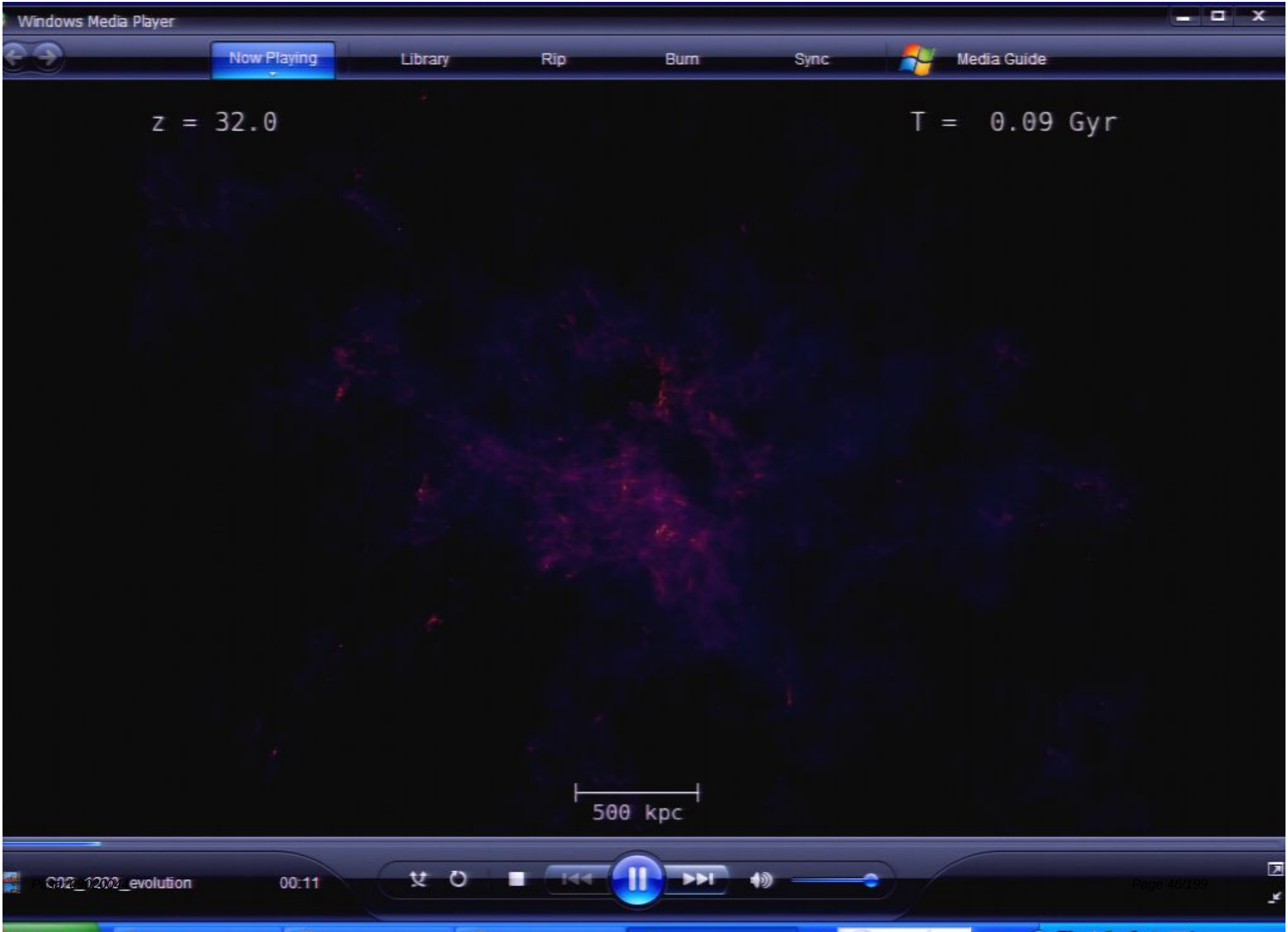
500 kpc
00:00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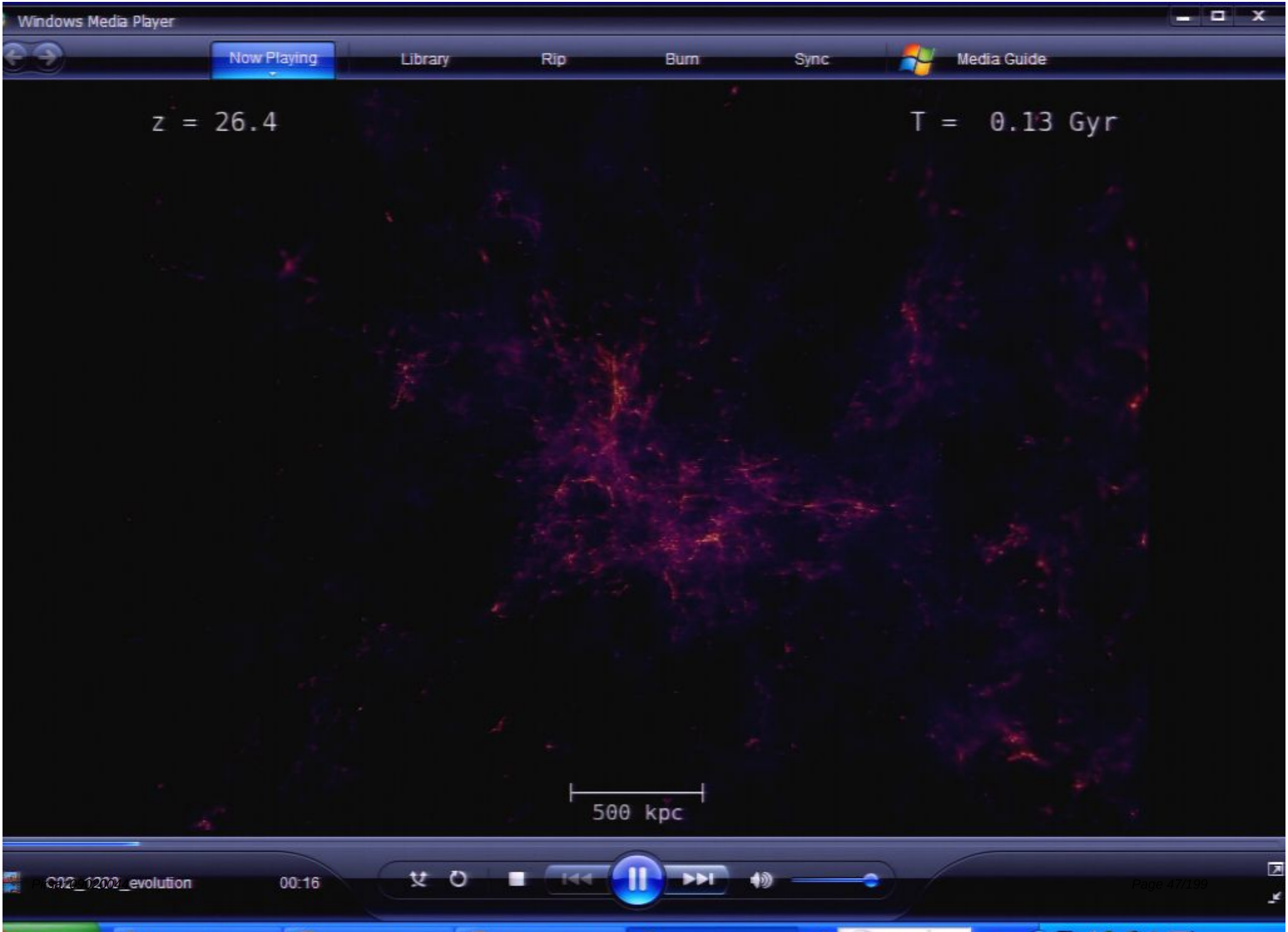
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Rip
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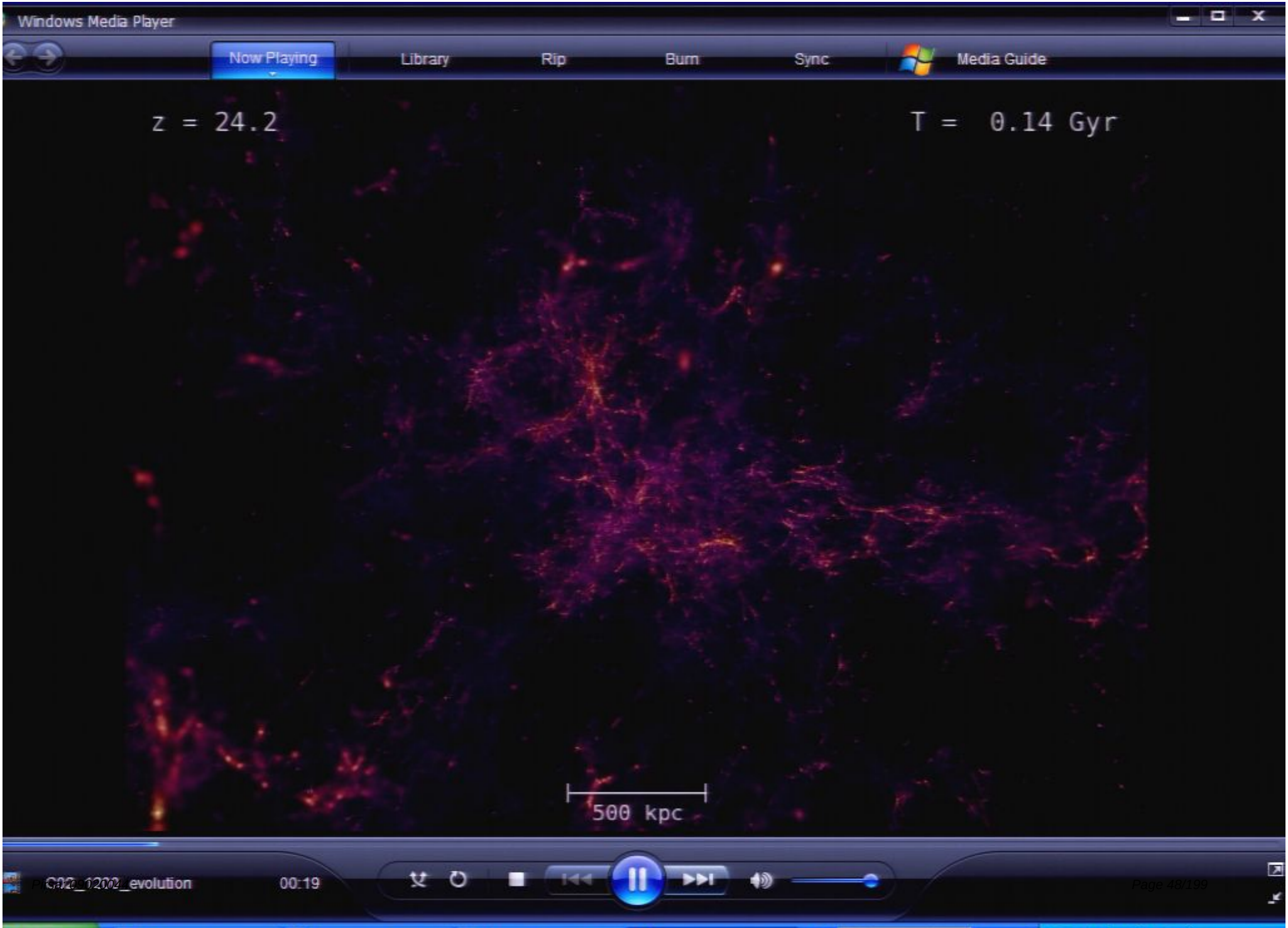
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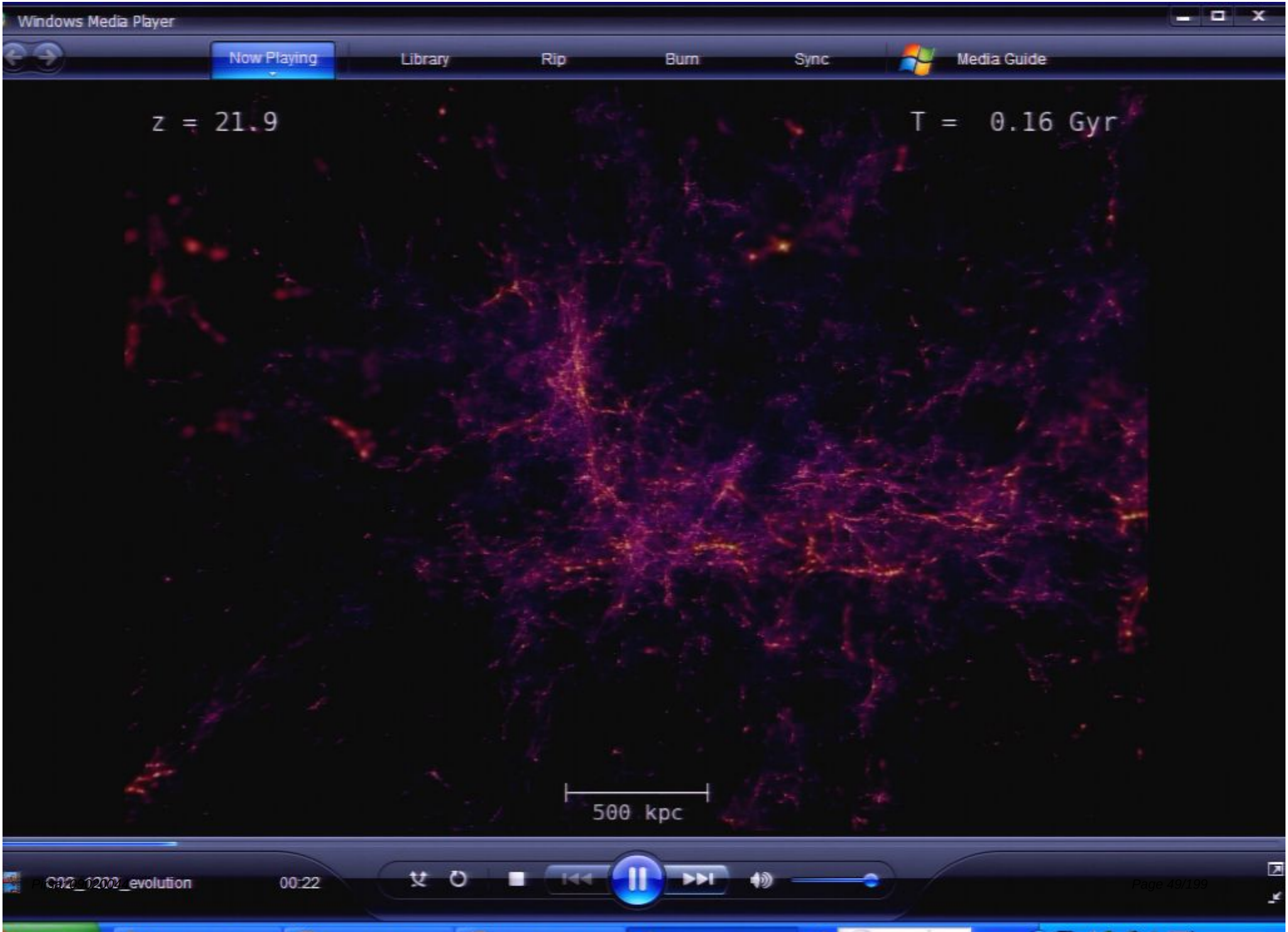
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Now Playing
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Rip
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Sync
Media Guide
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T = 0.16 Gyr
500 kpc
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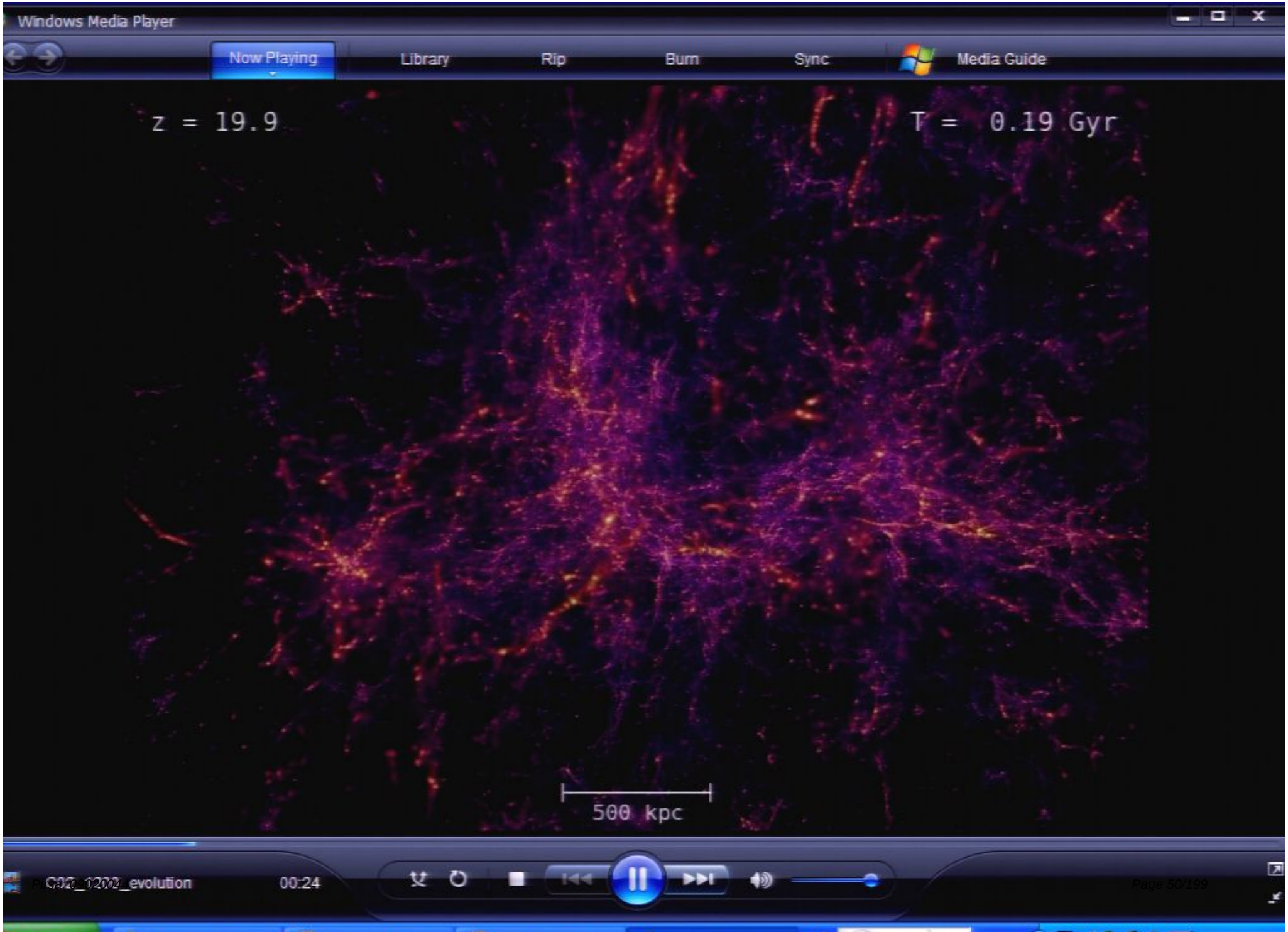
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Library
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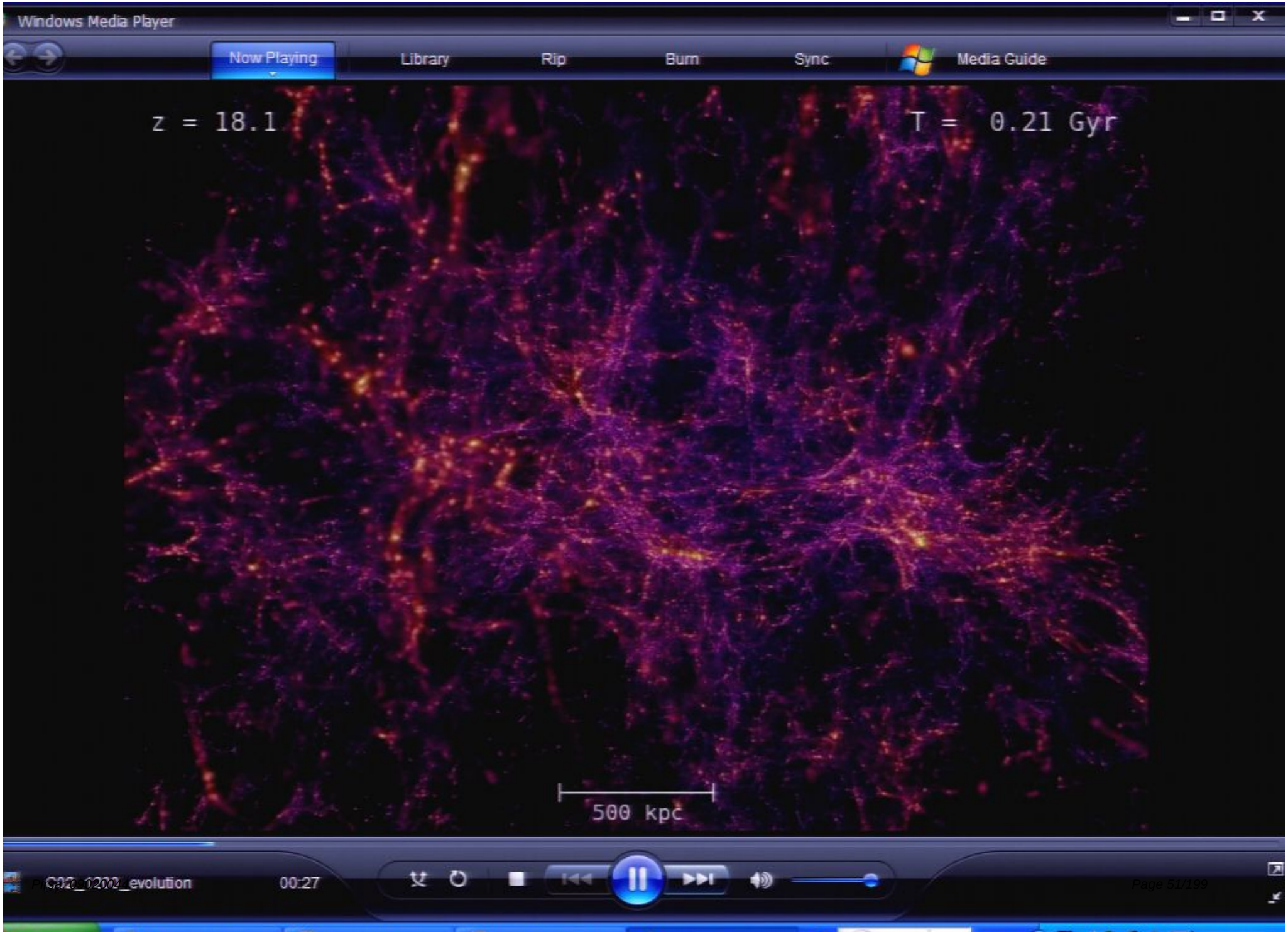
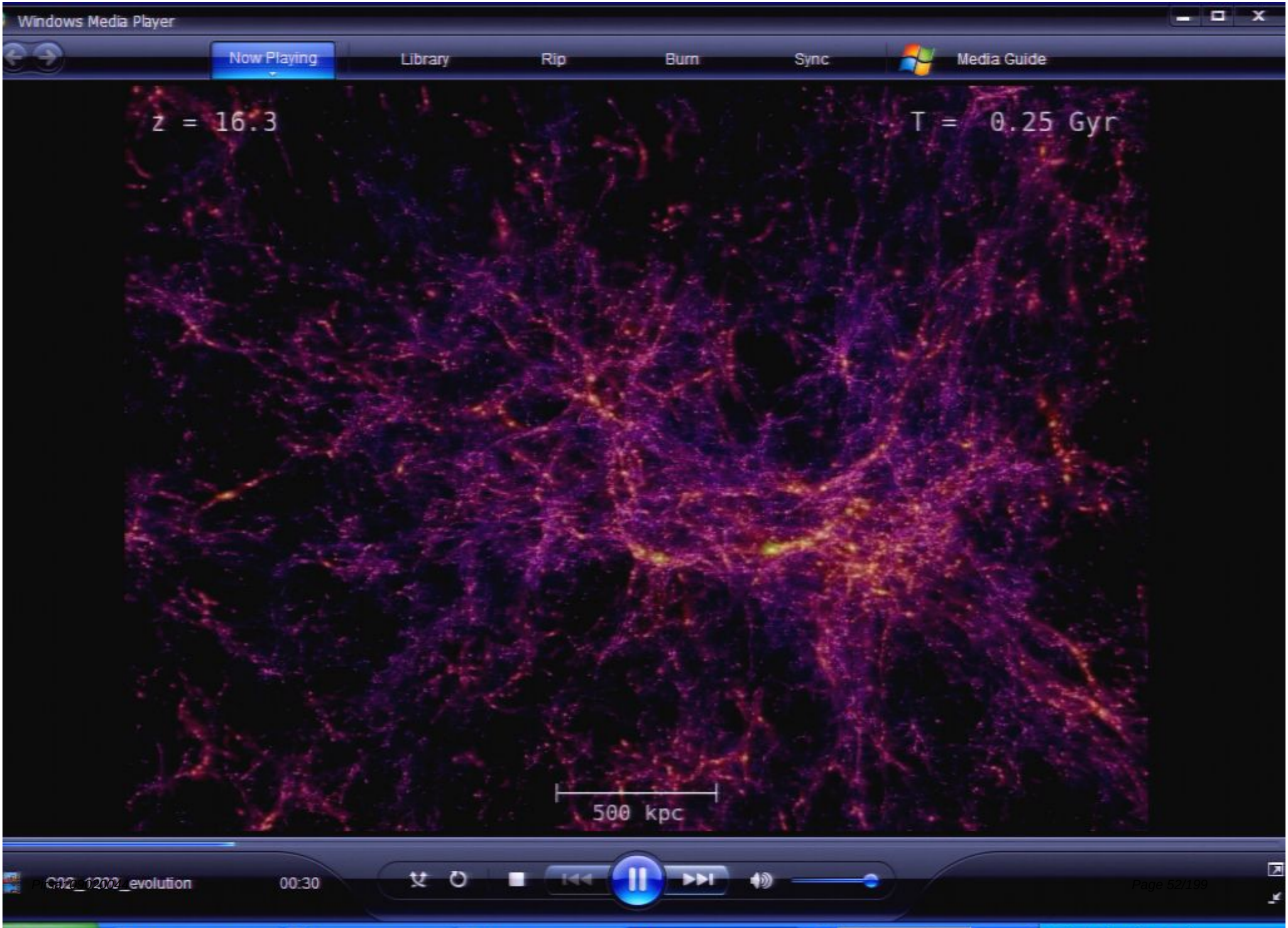
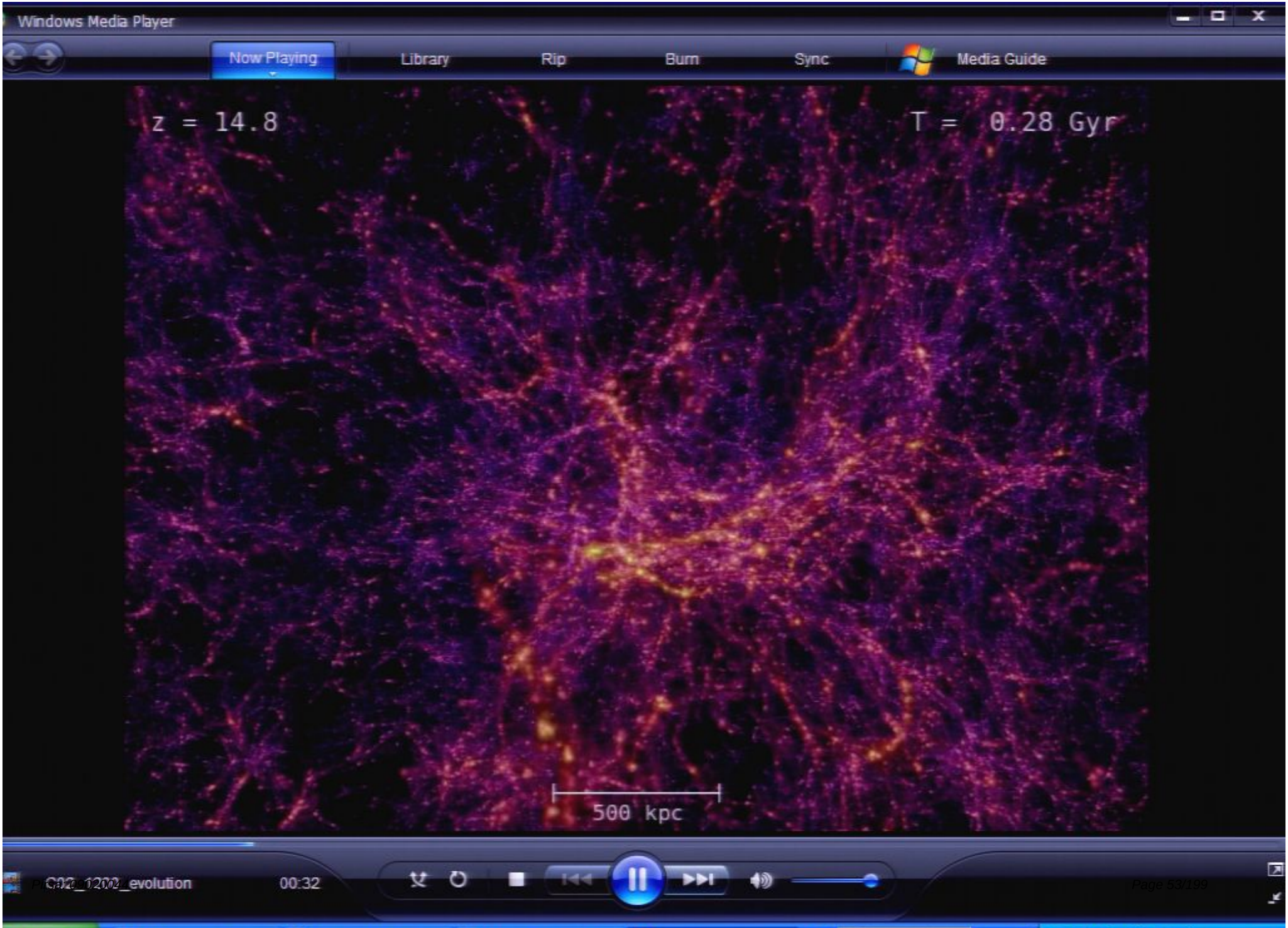
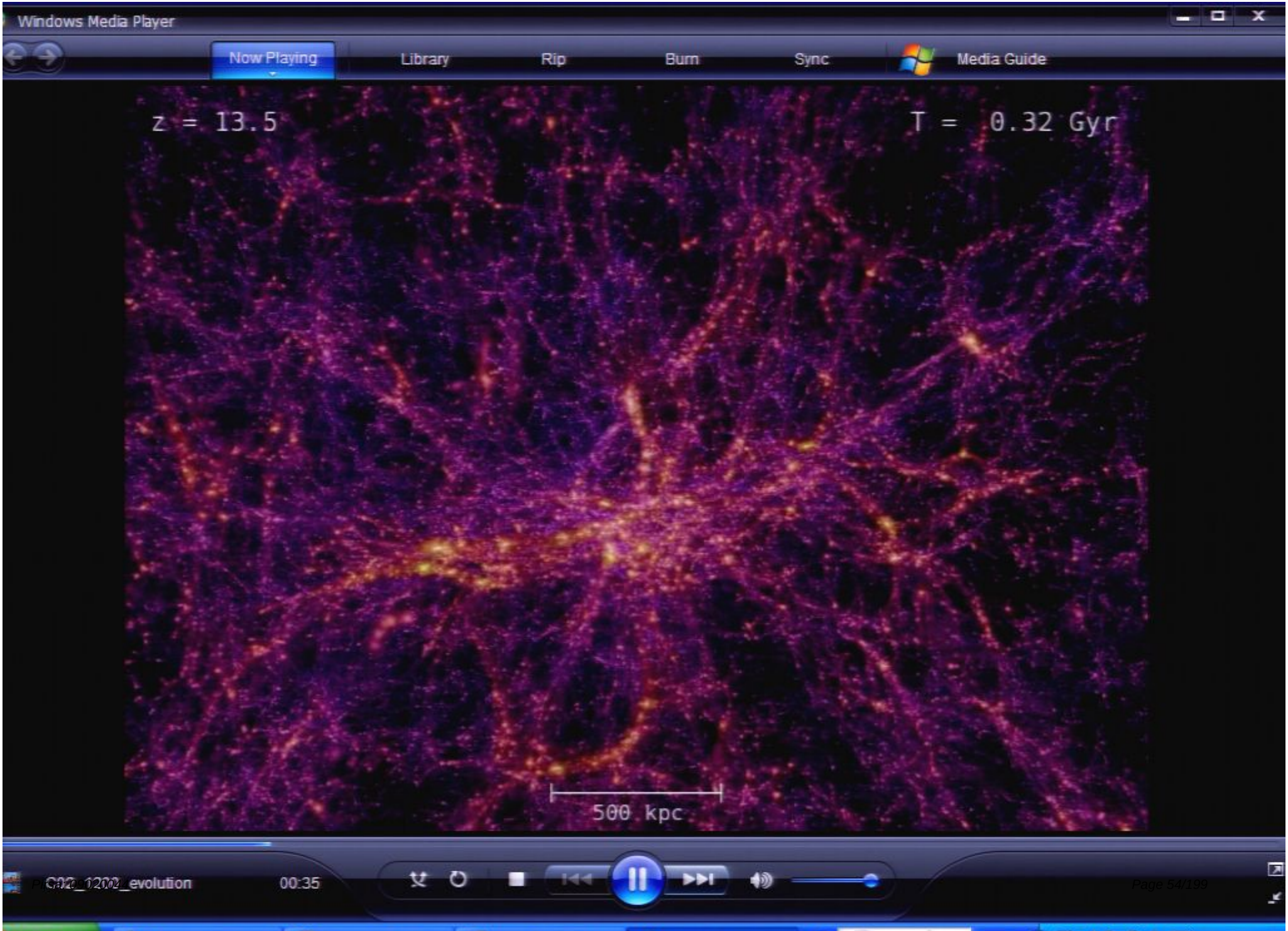
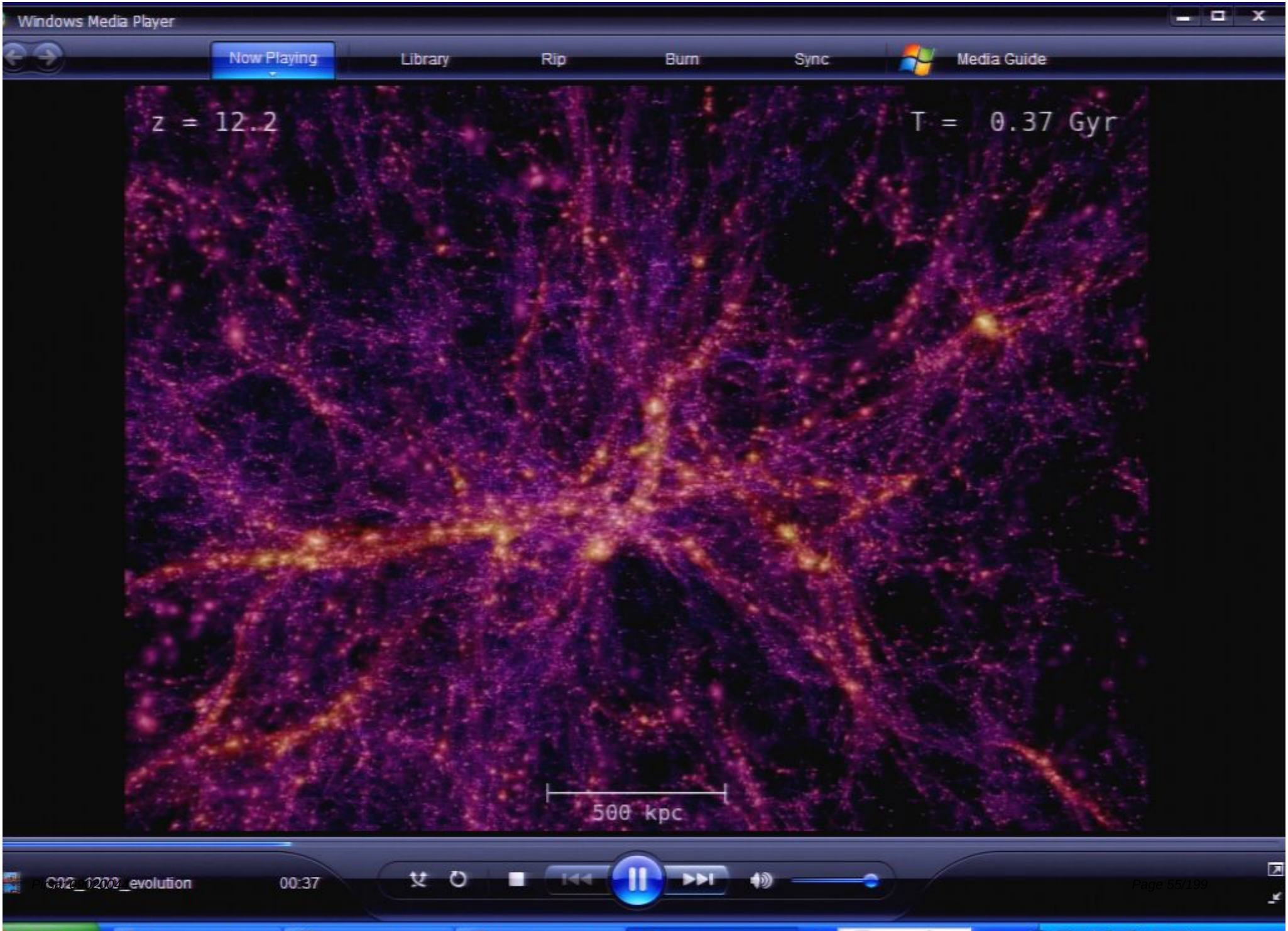
Sync
Media Guide
z = 19.9
T = 0.19 Gyr
500 kpc
00:24

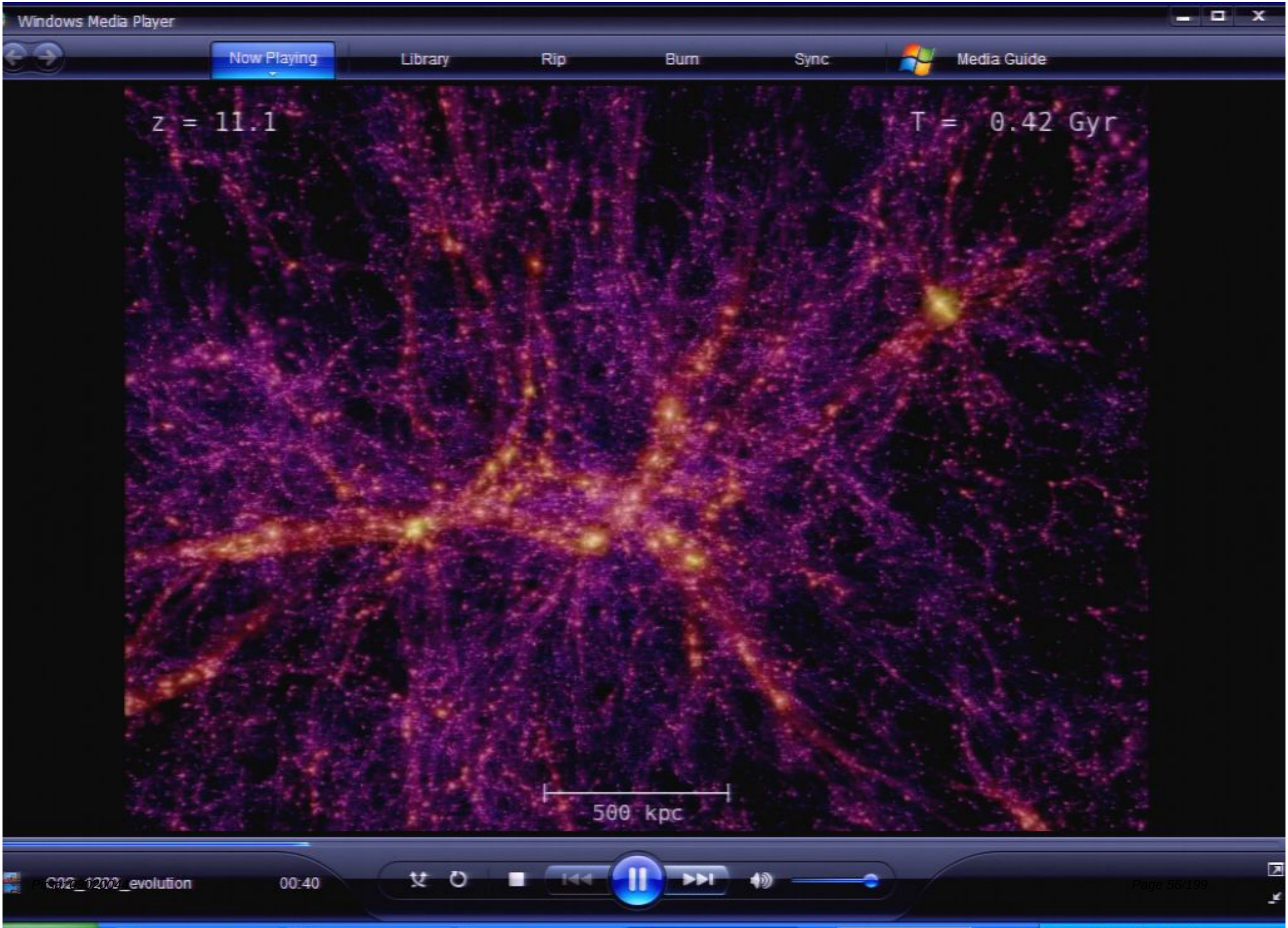

Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 18.1
T = 0.21 Gyr
500 kpc
00:27

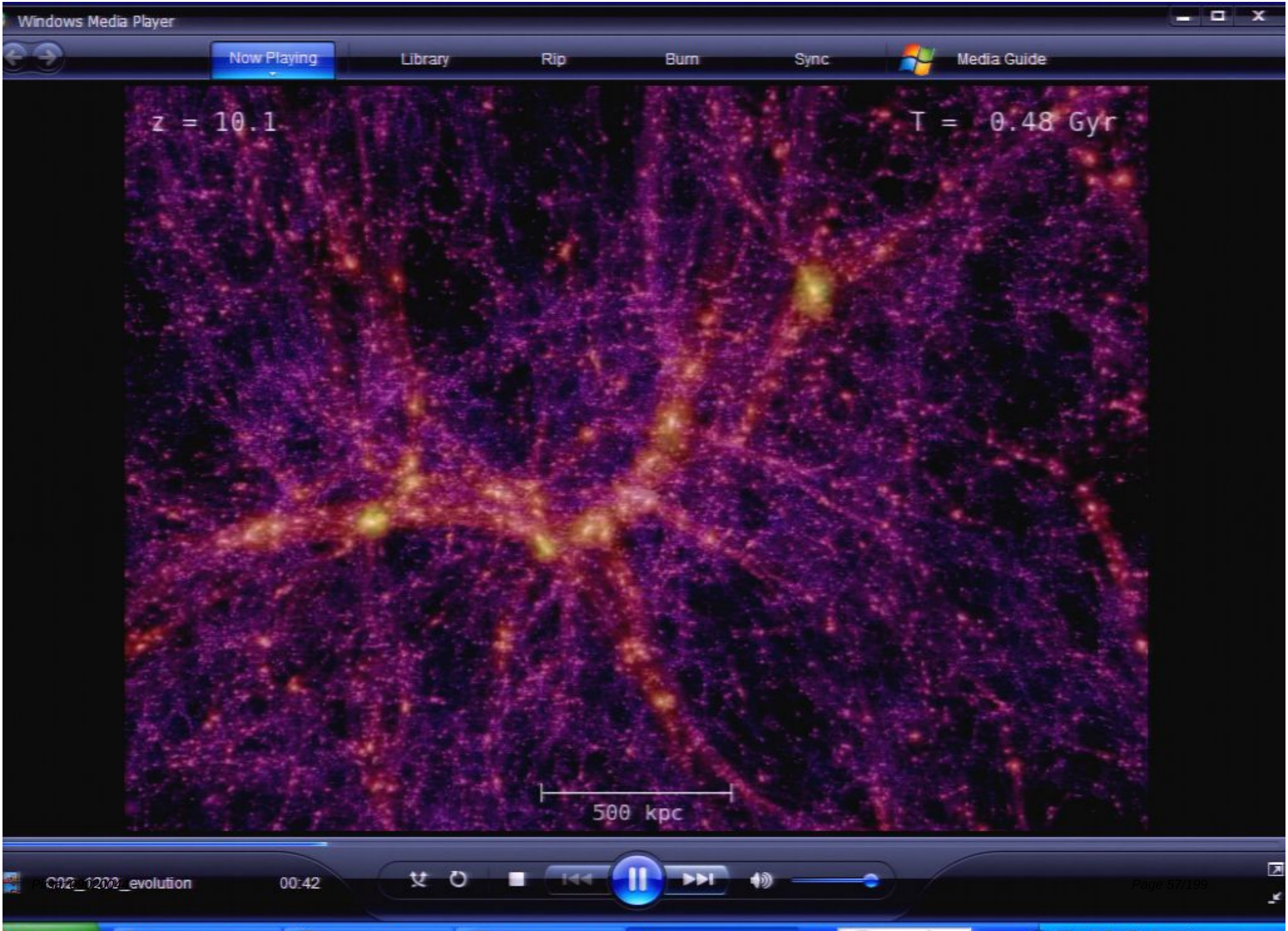

Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 16.3
T = 0.25 Gyr
500 kpc
00:30

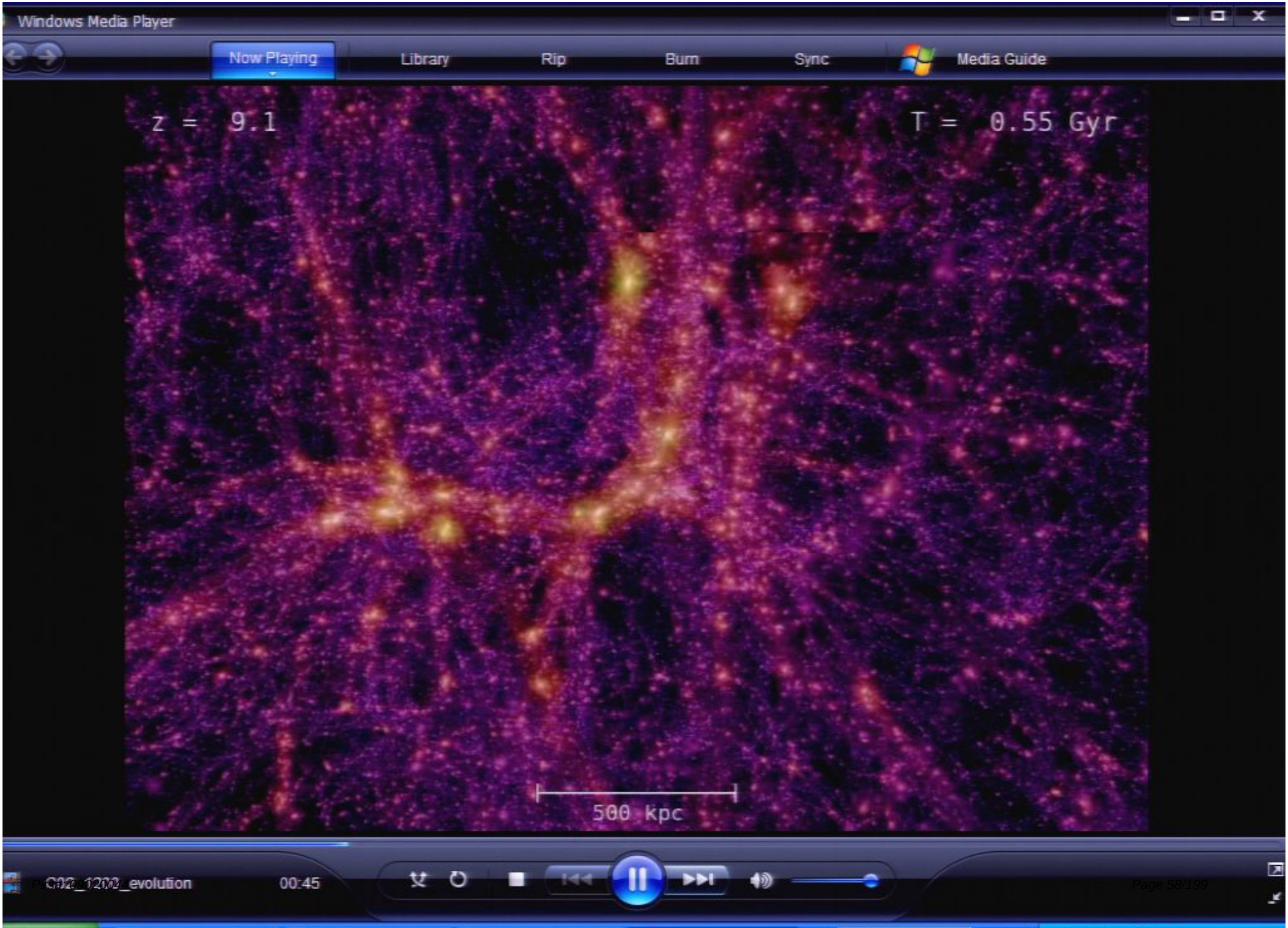

Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 14.8
T = 0.28 Gyr
500 kpc
00:32

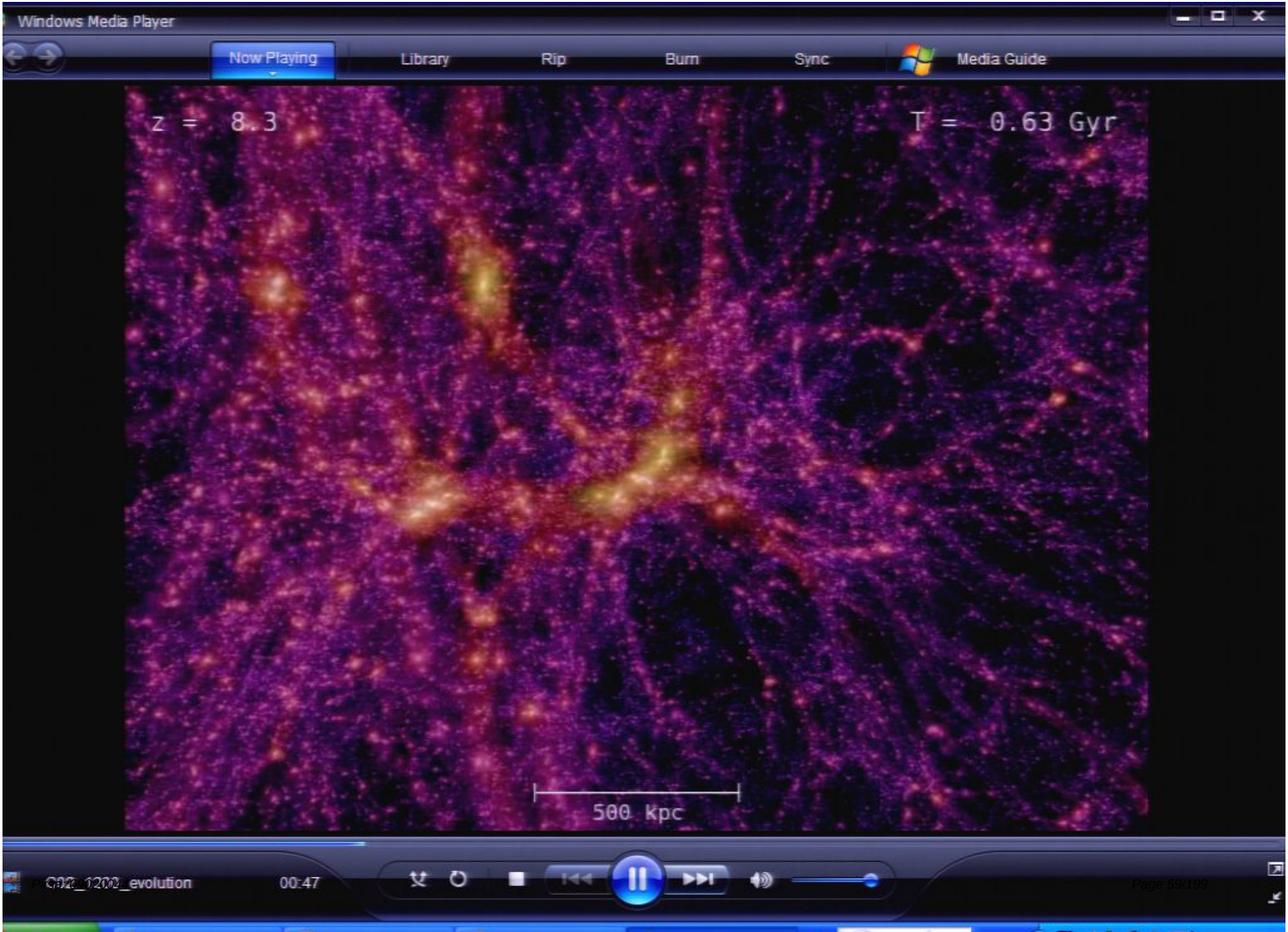

Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 13.5
T = 0.32 Gyr
500 kpc
00:35


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 12.2
T = 0.37 Gyr
500 kpc
00:37

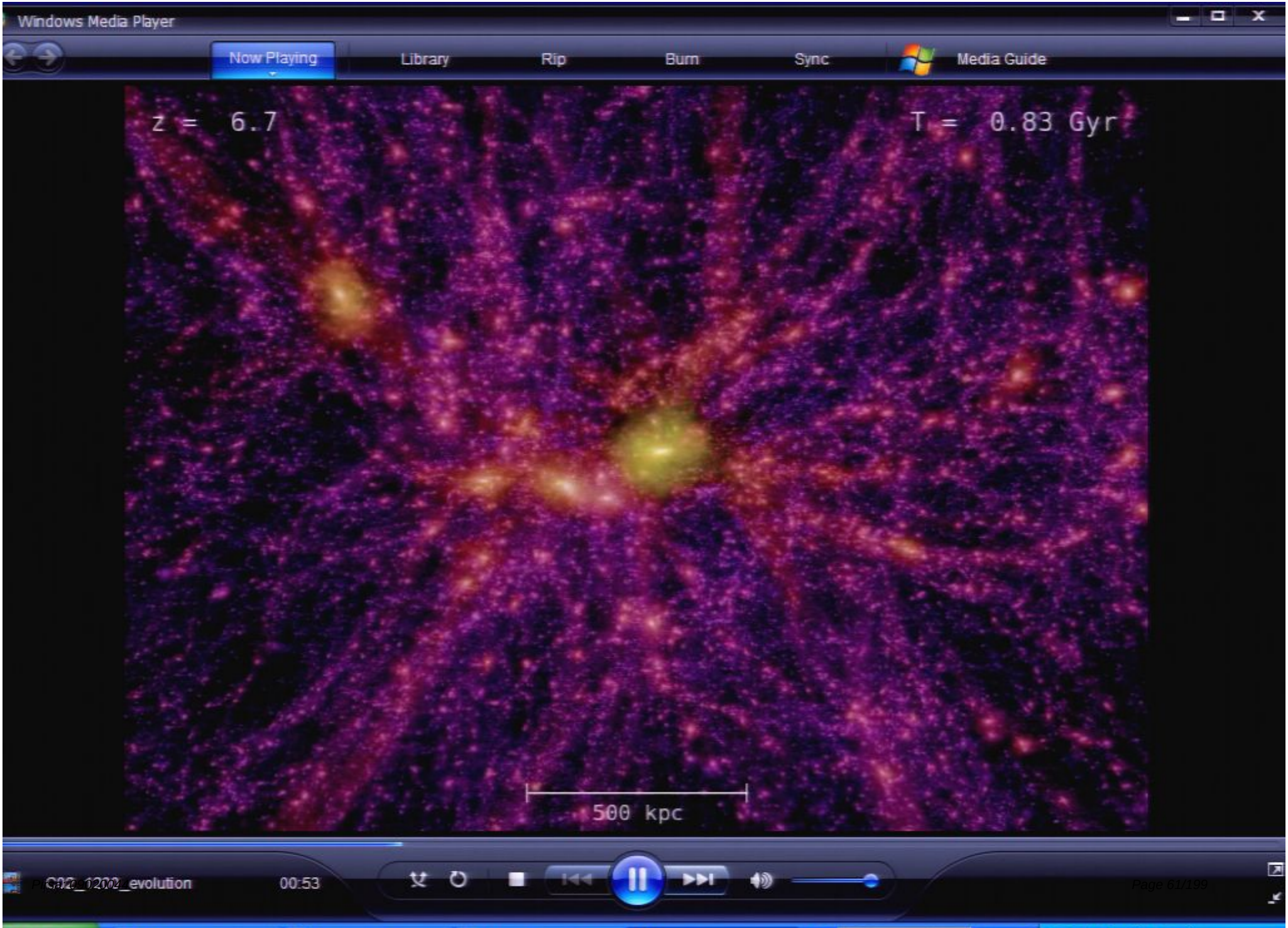

Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 11.1
T = 0.42 Gyr
500 kpc
00:40


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 10.1
T = 0.48 Gyr
500 kpc
00:42


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 9.1
T = 0.55 Gyr
500 kpc
00:45


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 8.3
T = 0.63 Gyr
500 kpc
00:47


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 7.5
T = 0.73 Gyr
500 kpc
00:50


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 6.7
T = 0.83 Gyr
500 kpc
00:53


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 6.1
T = 0.95 Gyr
500 kpc
00:55


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 5.4
T = 1.10 Gyr
500 kpc
00:58


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 4.9
T = 1.25 Gyr
500 kpc
01:00


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 4.4
T = 1.43 Gyr
500 kpc
01:03


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 3.9
T = 1.64 Gyr
500 kpc
01:06


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 3.5
T = 1.89 Gyr
500 kpc
01:09


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 3.1
T = 2.15 Gyr
500 kpc
01:11


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 2.7
T = 2.45 Gyr
500 kpc
01:14


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 2.4
T = 2.78 Gyr
500 kpc
01:16


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 2.2
T = 3.08 Gyr
500 kpc
01:19


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 2.0
T = 3.36 Gyr
500 kpc
01:21


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 1.8
T = 3.69 Gyr
500 kpc
01:24


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 1.7
T = 3.99 Gyr
500 kpc
01:27


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 1.6
T = 4.26 Gyr
500 kpc
01:29


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 1.4
T = 4.59 Gyr
500 kpc
01:32


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 1.3
T = 4.89 Gyr
500 kpc
01:34


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 1.2
T = 5.20 Gyr
500 kpc
01:37


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 1.1
T = 5.50 Gyr
500 kpc
01:40


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 1.0
T = 5.80 Gyr
500 kpc
01:42


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 1.0
T = 6.10 Gyr
500 kpc
01:45


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 0.9
T = 6.43 Gyr
500 kpc
01:48


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 0.8
T = 6.70 Gyr
500 kpc
01:50


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 0.8
T = 7.01 Gyr
500 kpc
01:53


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 0.7
T = 7.33 Gyr
500 kpc
01:56


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 0.7
T = 7.64 Gyr
500 kpc
01:58


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 0.6
T = 7.94 Gyr
500 kpc
02:01


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 0.6
T = 8.24 Gyr
500 kpc
02:03


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 0.5
T = 8.55 Gyr
500 kpc
02:06


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 0.5
T = 8.85 Gyr
500 kpc
02:09


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 0.4
T = 9.15 Gyr
500 kpc
02:11


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 0.4
T = 9.45 Gyr
500 kpc
02:14


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 0.4
T = 9.75 Gyr
500 kpc
02:16


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 0.3
T = 10.06 Gyr
500 kpc
02:19


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 0.3
T = 10.38 Gyr
500 kpc
02:22


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 0.3
T = 10.66 Gyr
500 kpc
02:24


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 0.2
T = 10.96 Gyr
500 kpc
02:27


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 0.2
T = 11.29 Gyr
500 kpc
02:30


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 0.2
T = 11.57 Gyr
500 kpc
02:32


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 0.1
T = 11.87 Gyr
500 kpc
02:35


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 0.1
T = 12.17 Gyr
500 kpc
02:37


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 0.1
T = 12.48 Gyr
500 kpc
02:40


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 0.1
T = 12.78 Gyr
500 kpc
02:43


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 0.0
T = 13.10 Gyr
500 kpc
02:45


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 0.0
T = 13.38 Gyr
500 kpc
02:48


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 0.0
T = 13.61 Gyr
500 kpc
02:50


Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
Volker Springel
Max-Planck-Institute
for Astrophysics
02:53

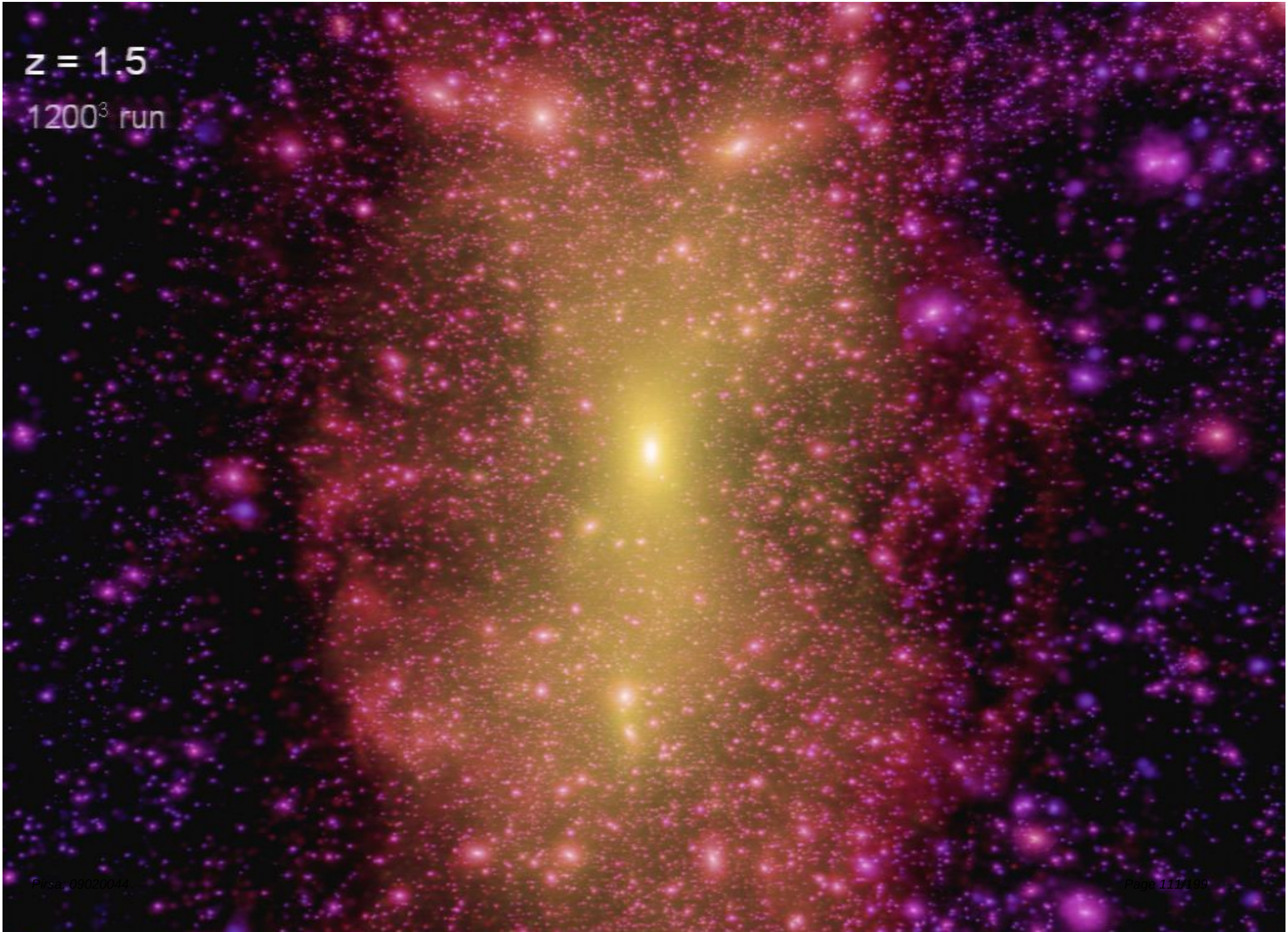

Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Media Guide
z = 48.4
T = 0.05 Gyr
500 kpc

Aquarius: the Billennium simulation

The Aquarius "Billennium" halo simulation. A dark matter halo with 1 billion particles within the virial radius.

Play Movie


z = 1.5
400^3 run


z = 1.5
1200^3 run


z = 1.5
2400^3 run

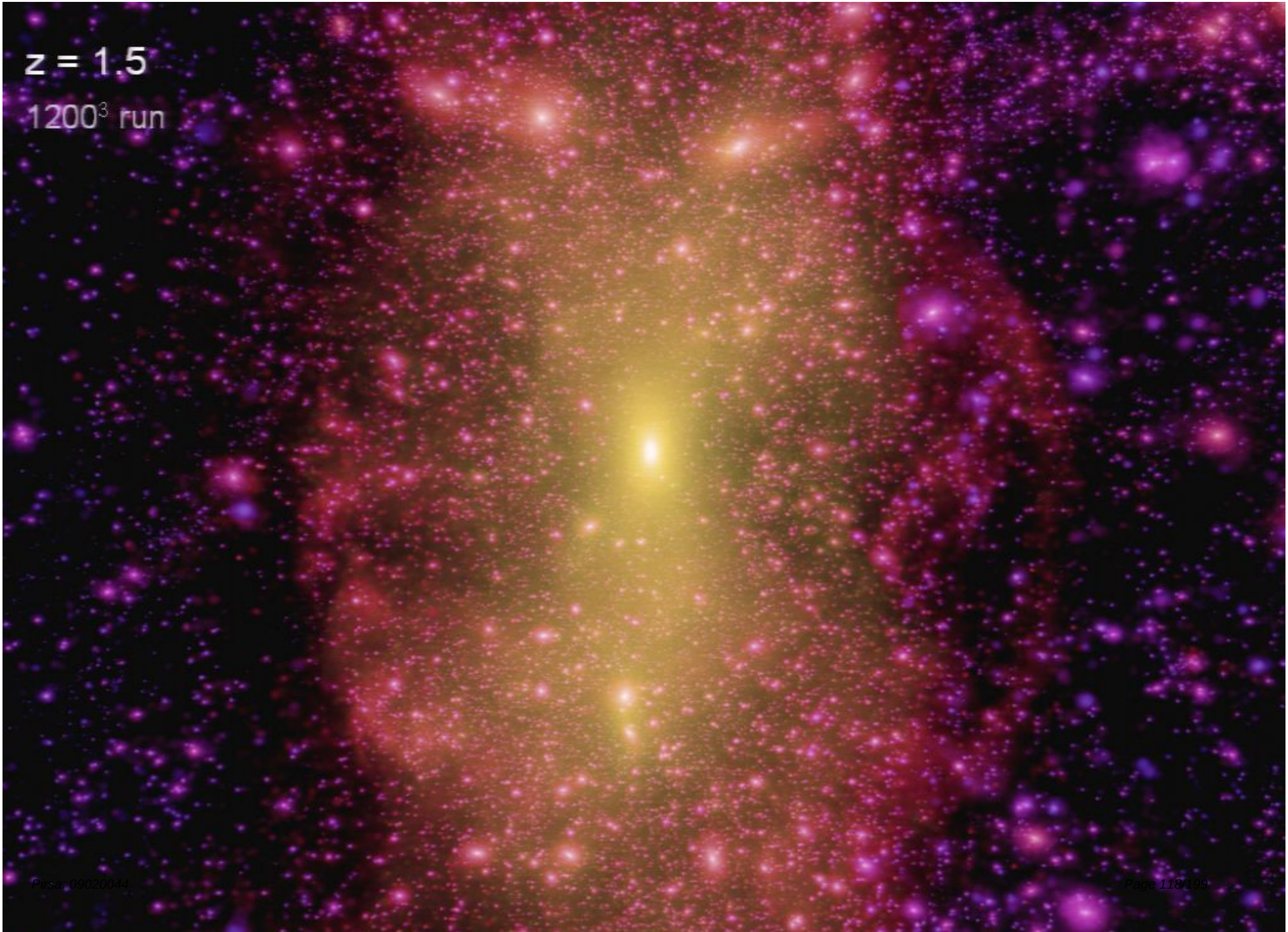

z = 1.5
400^3 run


z = 1.5
1200^3 run


z = 1.5
2400^3 run


z = 0.1
2400³ run


z = 1.5
2400^3 run


z = 1.5
1200^3 run


z = 1.5
2400^3 run

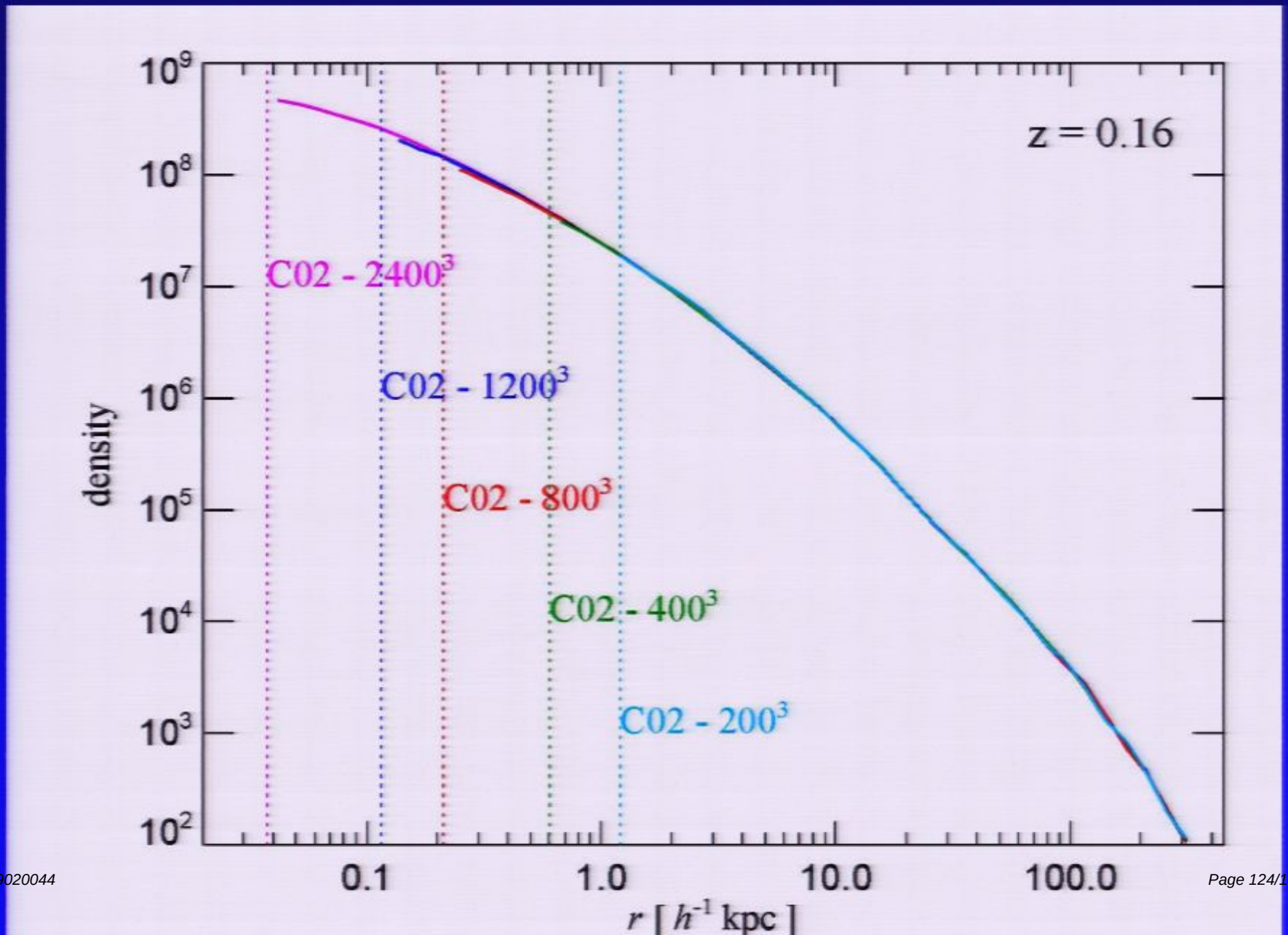

z = 0.1
2400³ run


z = 0.1
2400³ run

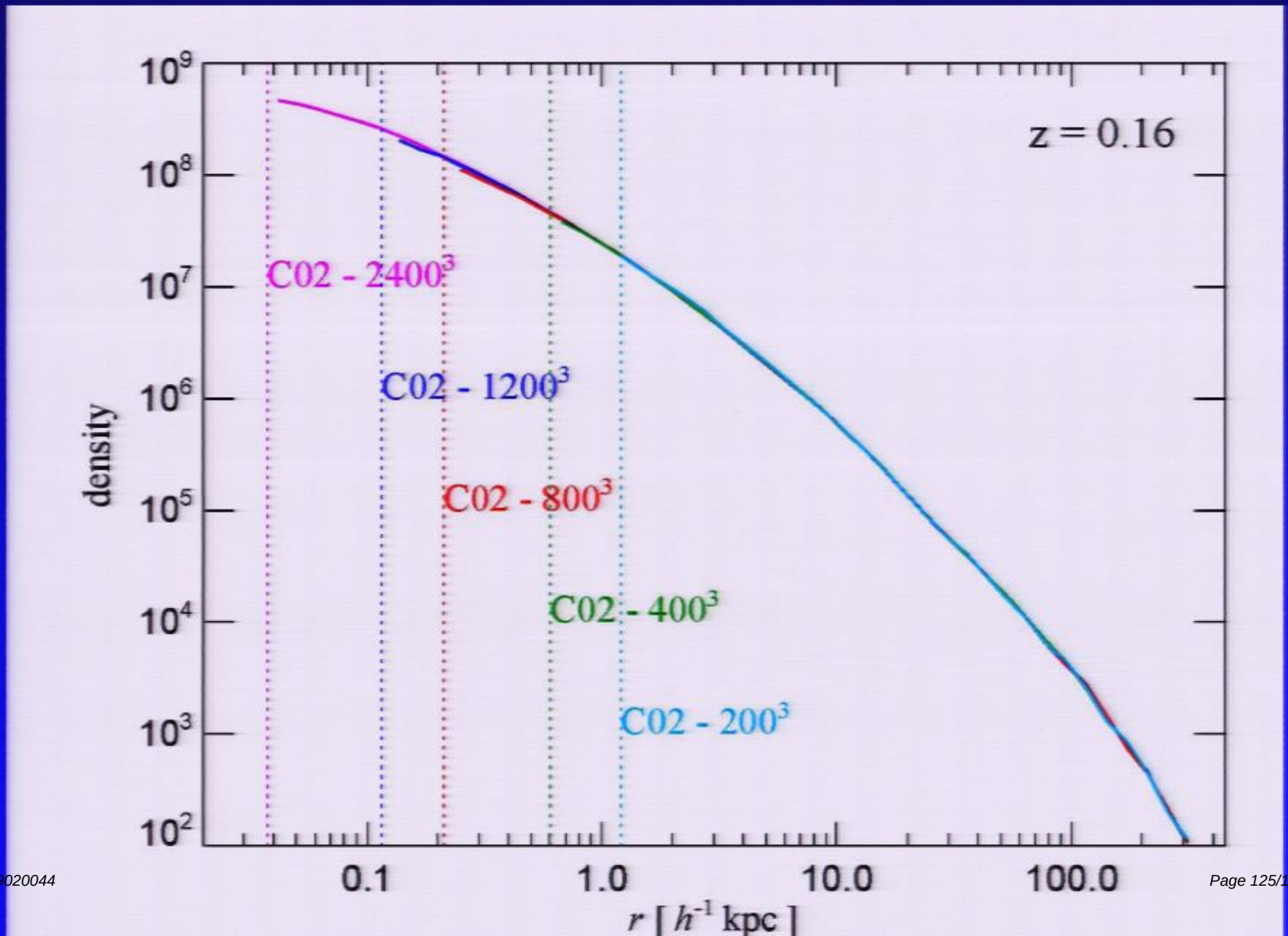

z = 1.5
2400^3 run


z = 0.1
2400³ run

The Density Profile: numerical convergence



The Density Profile: numerical convergence




z = 1.5
2400^3 run


z = 1.5
400^3 run


z = 1.5
2400^3 run


z = 0.1
2400³ run


z = 0.1
2400³ run


z = 0.1
2400³ run


z = 1.5
2400^3 run


z = 1.5
400^3 run


z = 1.5
1200^3 run


z = 1.5
2400^3 run


z = 1.5
1200^3 run


z = 1.5
400^3 run


z = 1.5
2400^3 run


z = 1.5
1200^3 run


z = 1.5
400^3 run


z = 1.5
1200^3 run

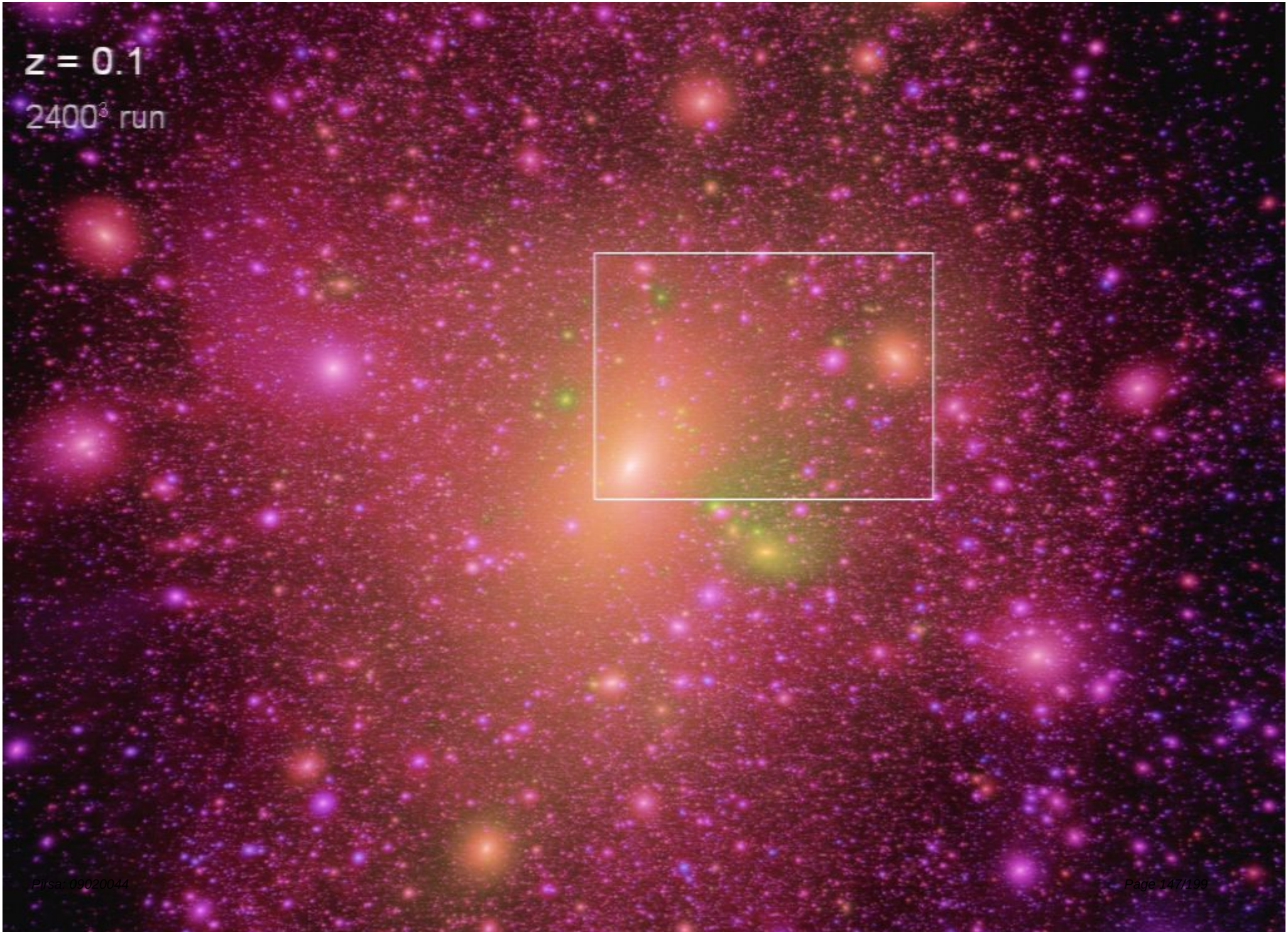

z = 1.5
2400^3 run


z = 0.1
2400³ run


z = 1.5
400^3 run

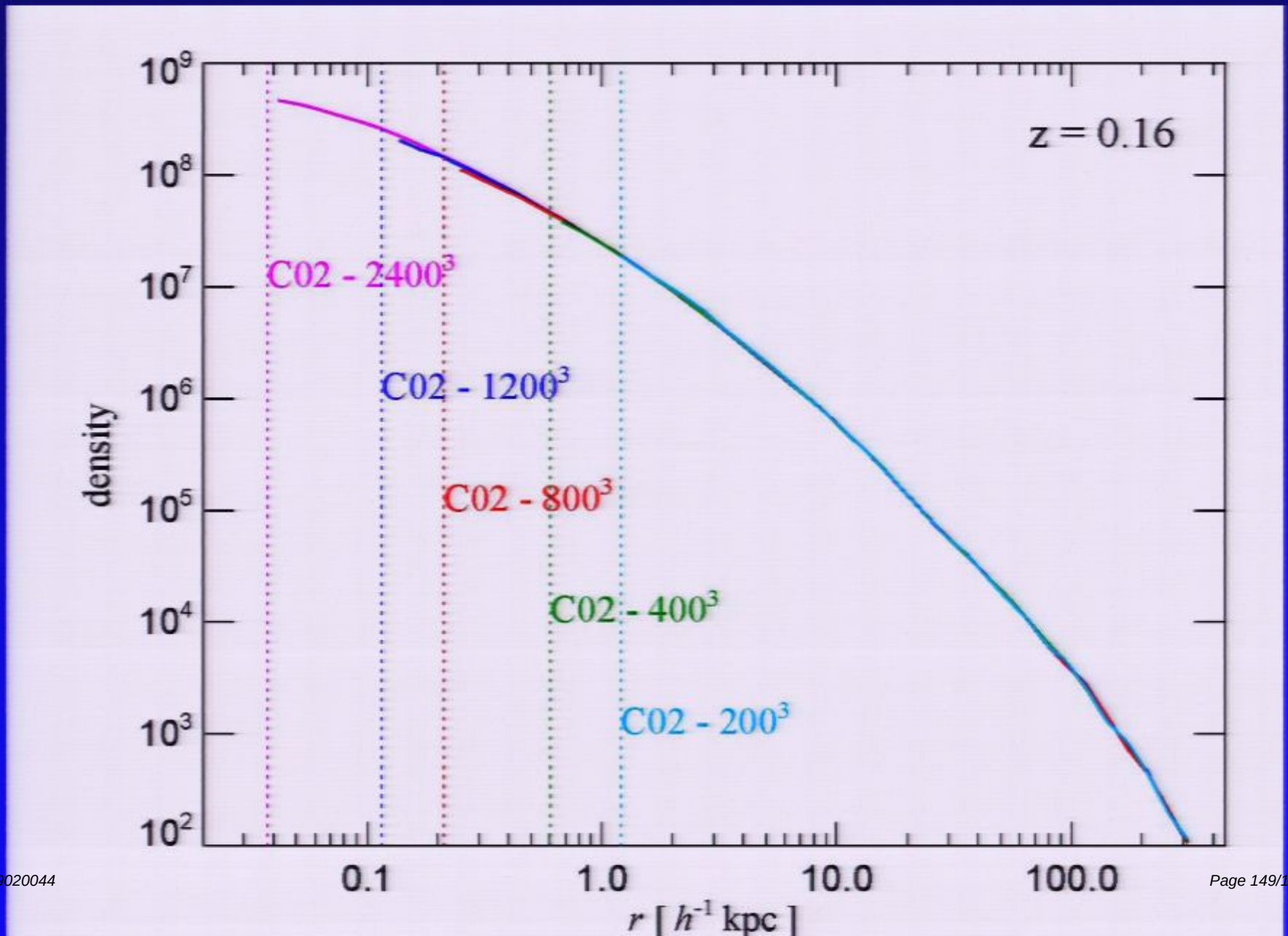

z = 1.5
2400^3 run


z = 0.1
2400³ run


z = 0.1
2400³ run

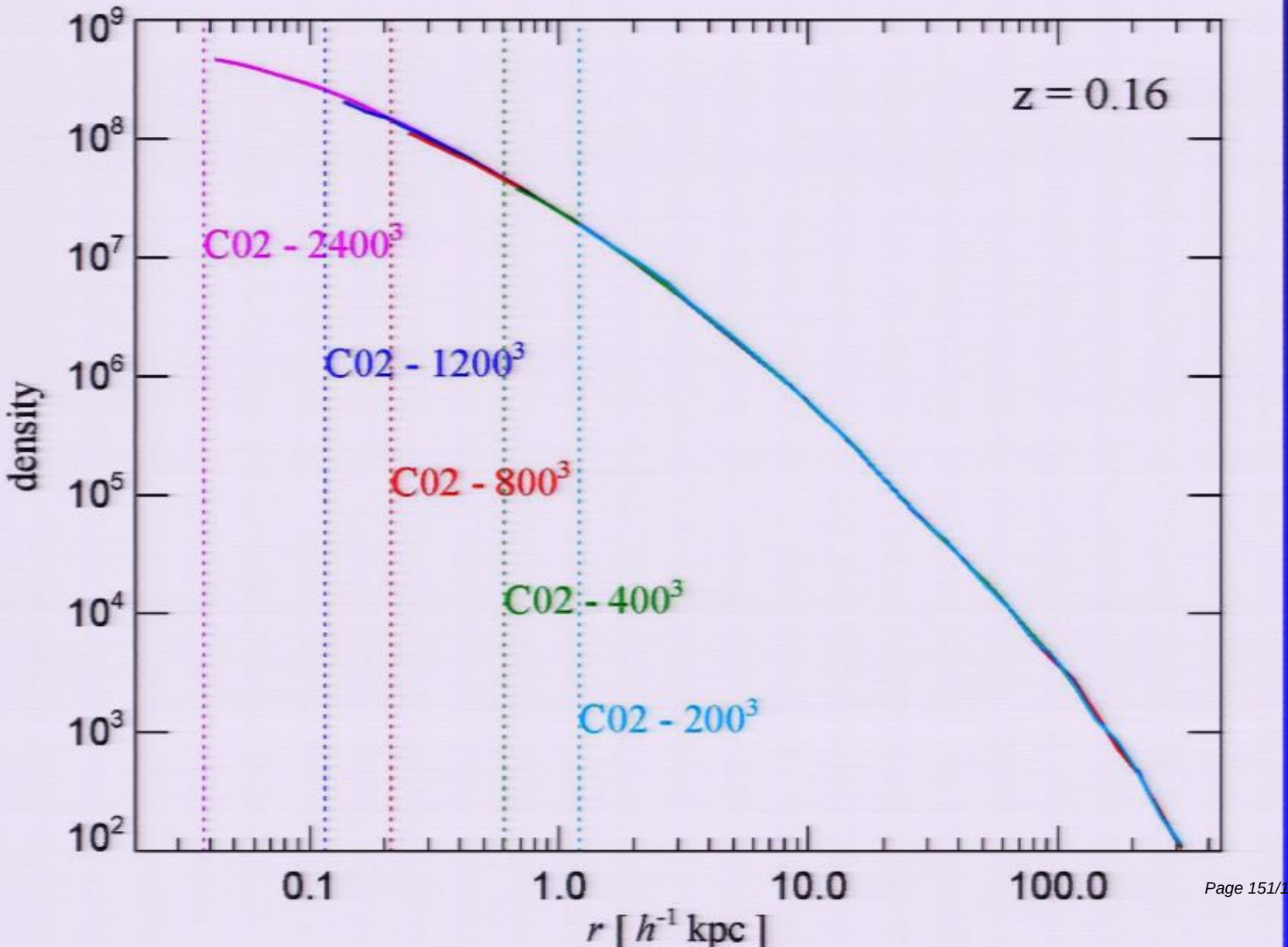

z = 0.1
2400³ run

The Density Profile: numerical convergence

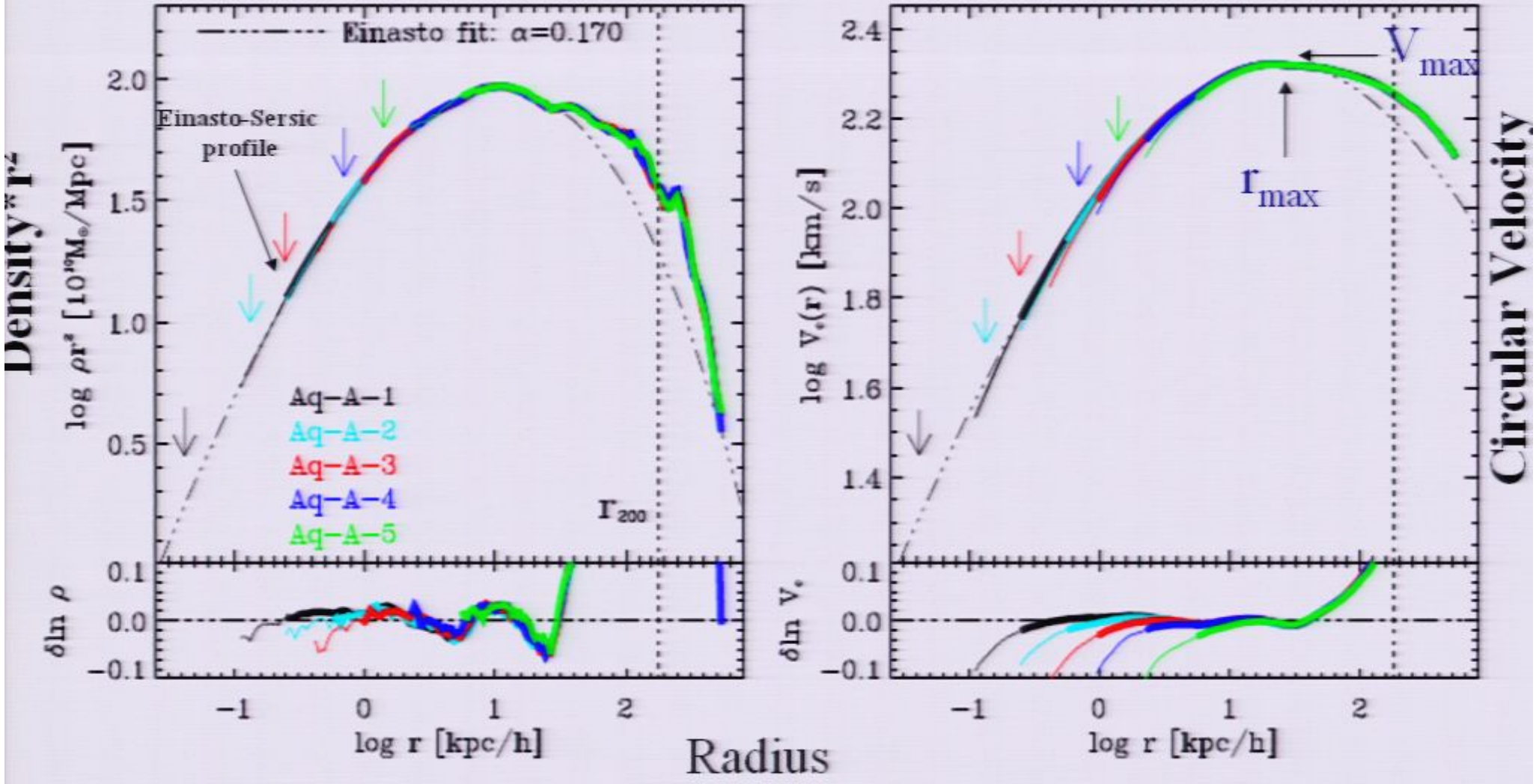



z = 0.1
2400³ run

The Density Profile: numerical convergence

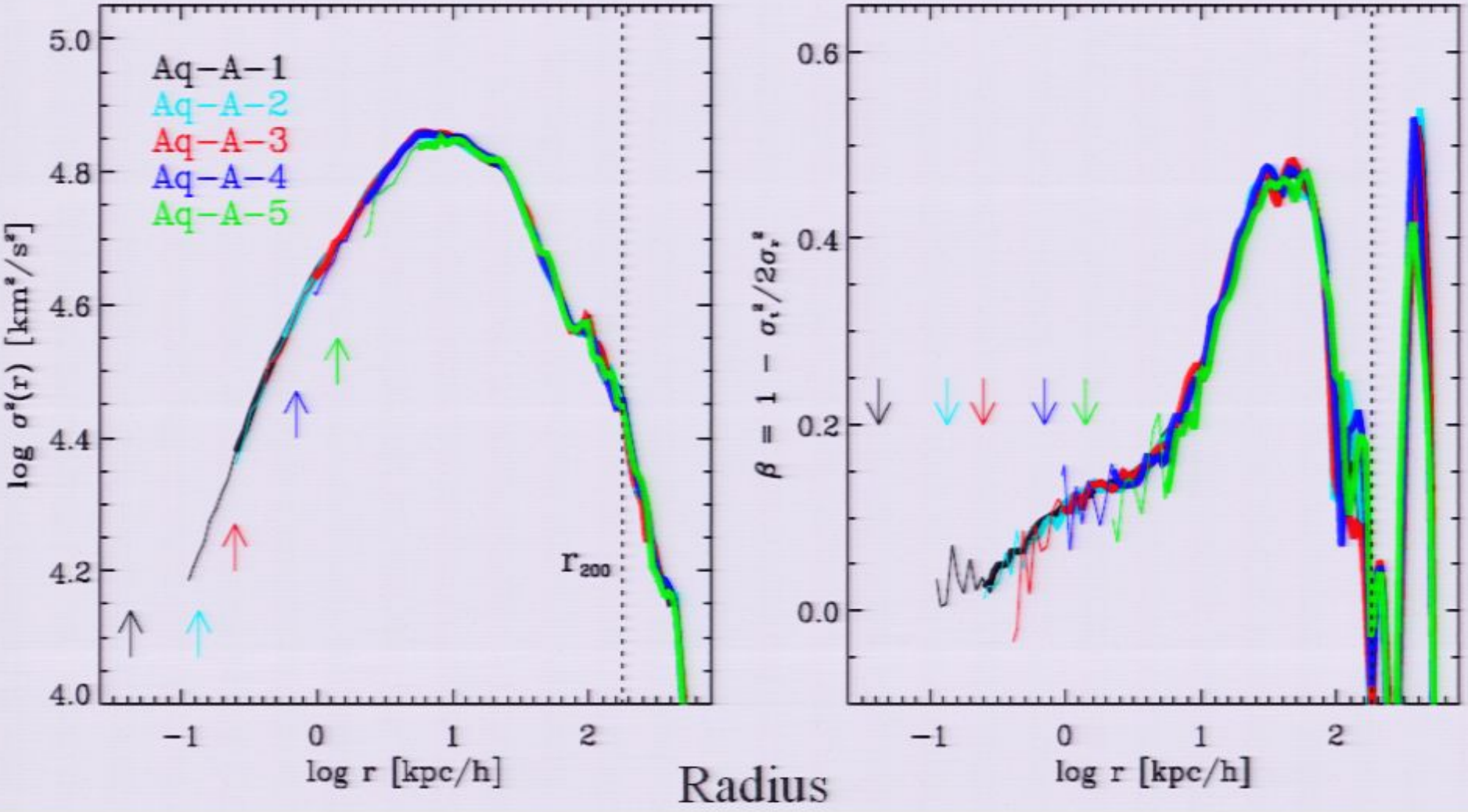


The Mass Profile: numerical convergence



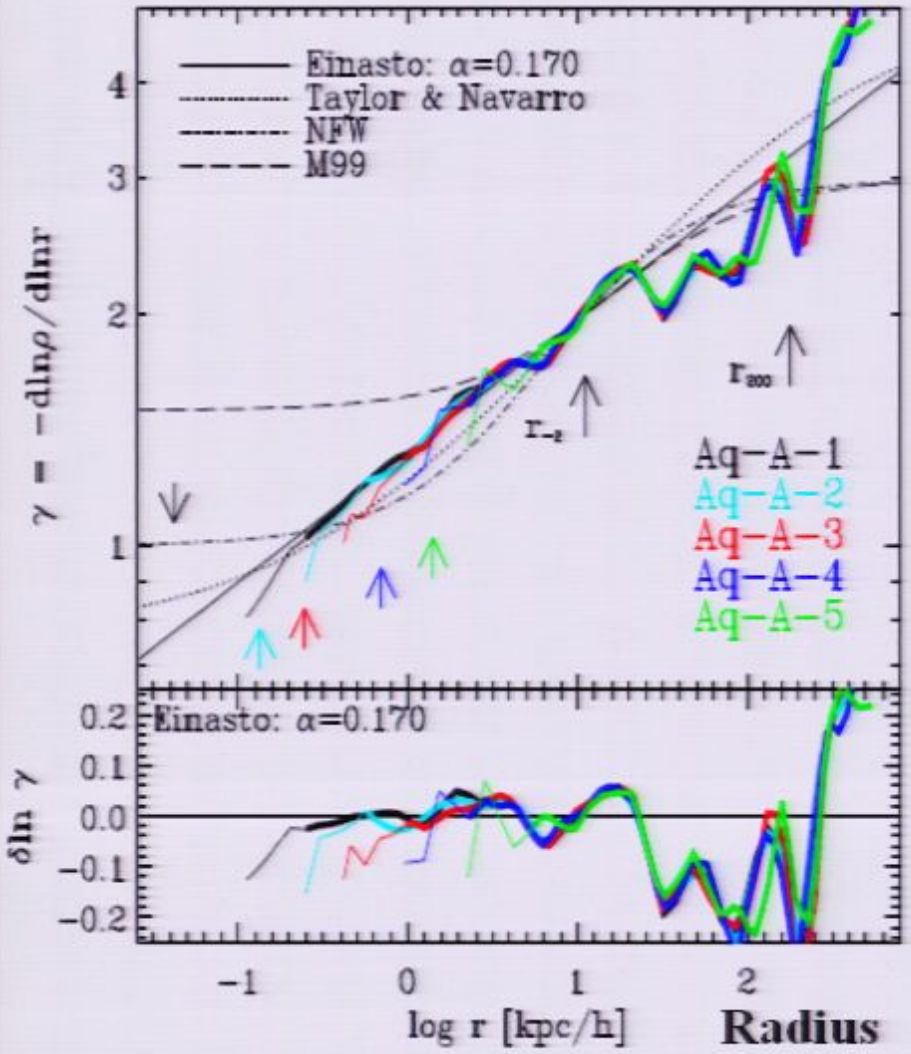
•Excellent numerical convergence down to radius where the collisional relaxation time approaches the age of the universe

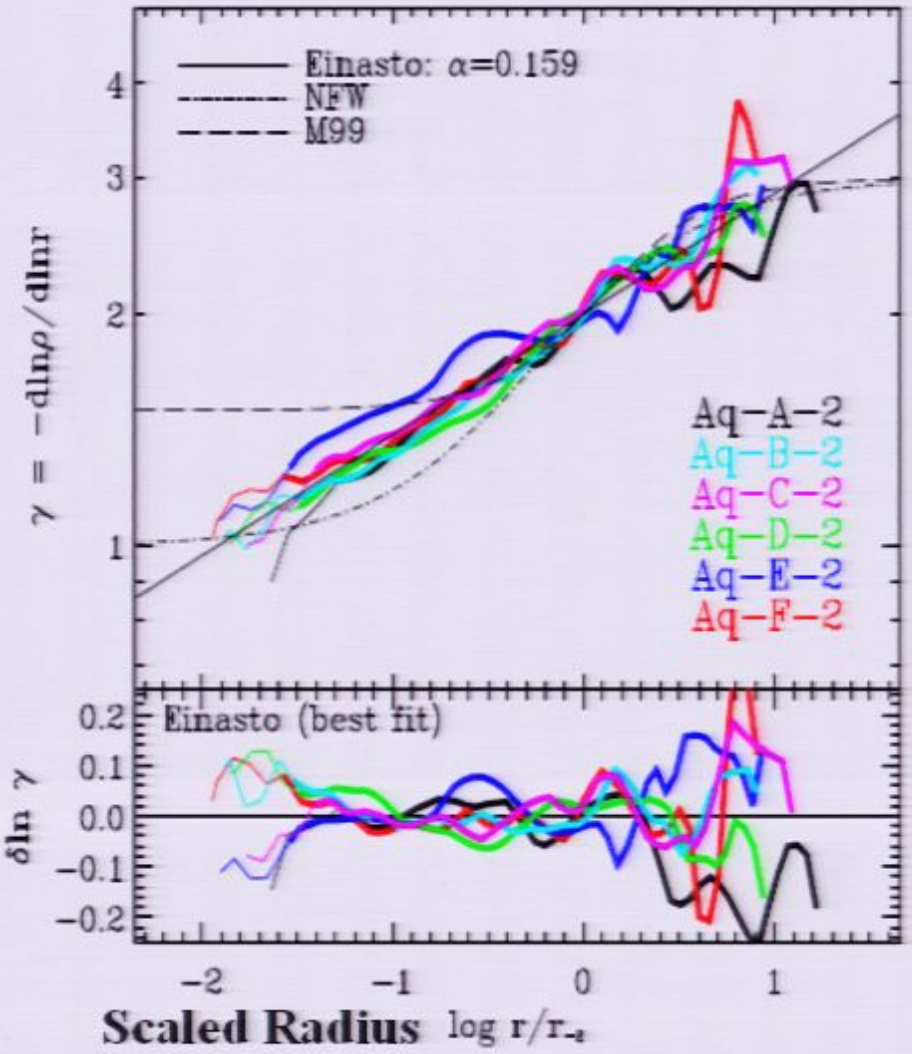
Velocity structure: convergence



- Excellent numerical convergence down to radius where the collisional relaxation time approaches the age of the universe

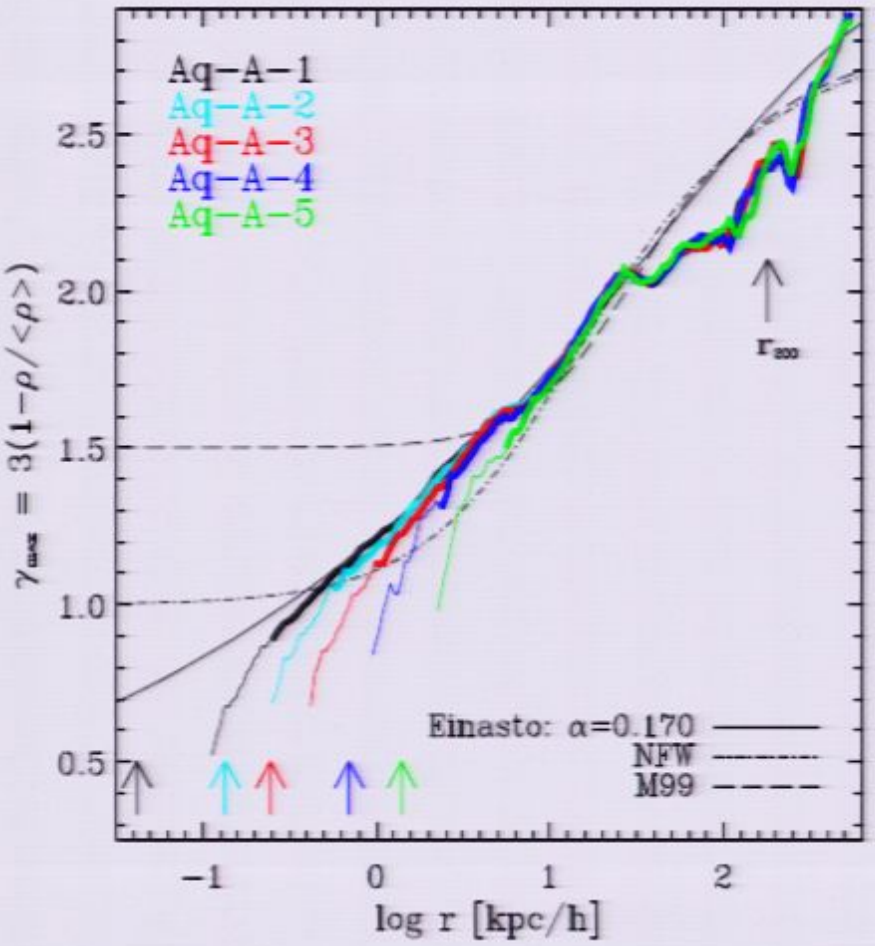
The Structure of the Cusp

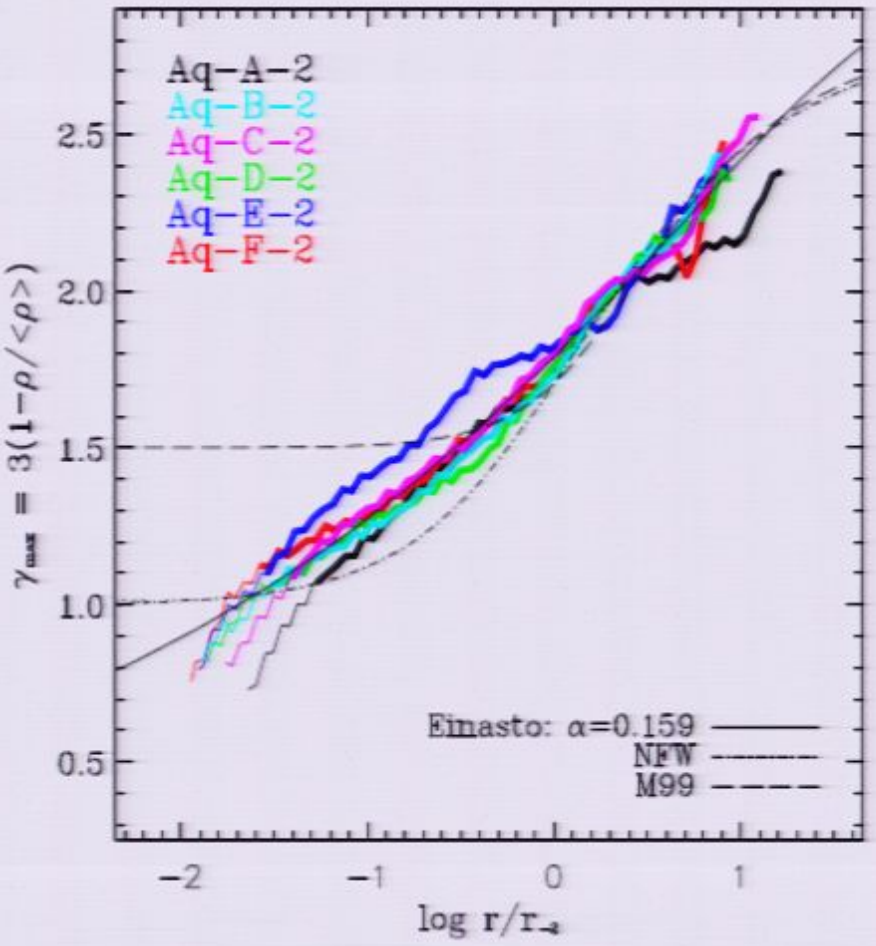




- Logarithmic slope scales like a power-law of radius: the Sersic/Einasto profile
- Innermost profile much shallower than $r^{-1.5}$ and probably shallower than r^{-1}

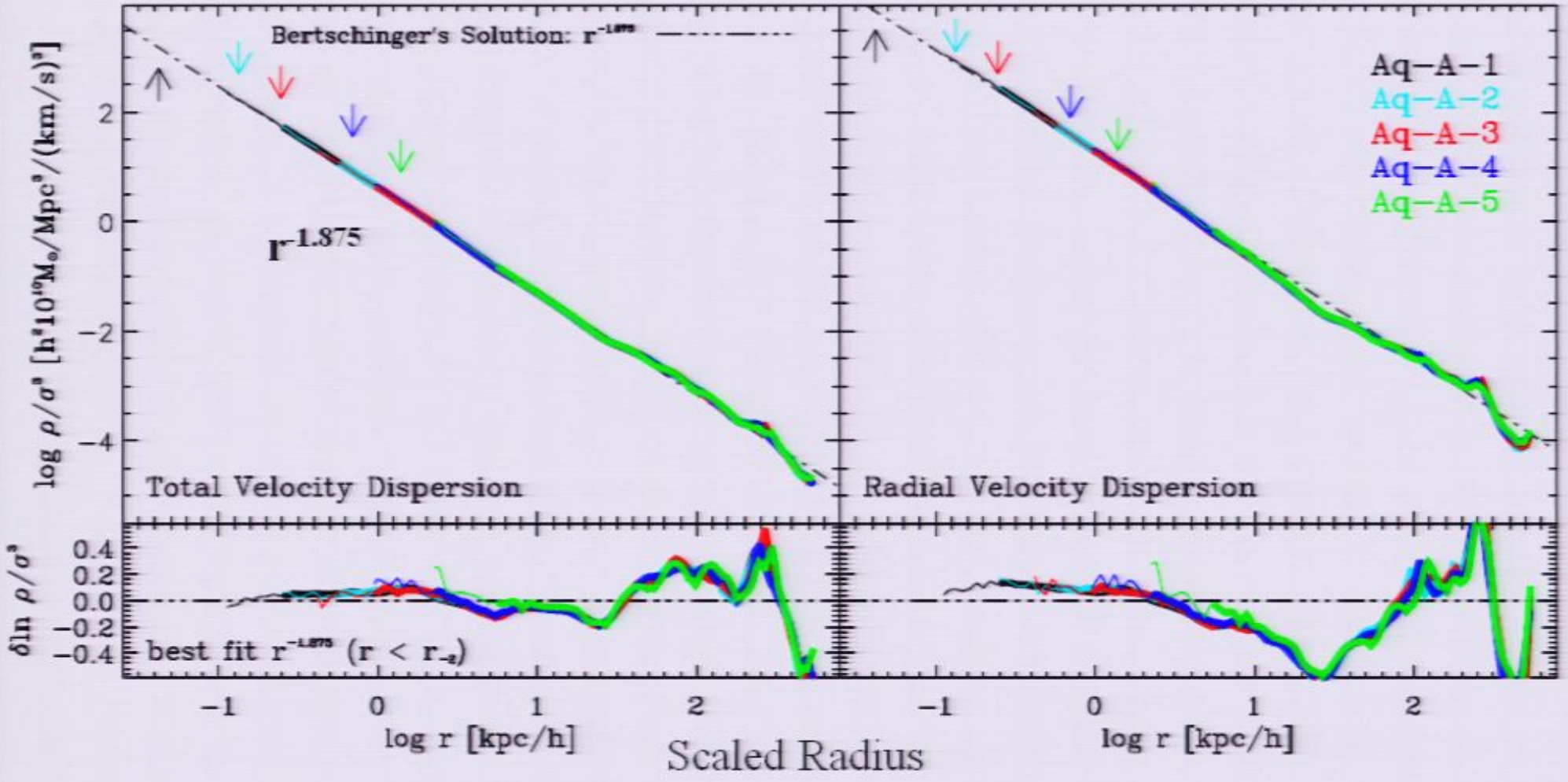
The Cusp: Maximum Asymptotic Slope





- Maximum asymptotic slope of the cusp: shallower than r^{-1}

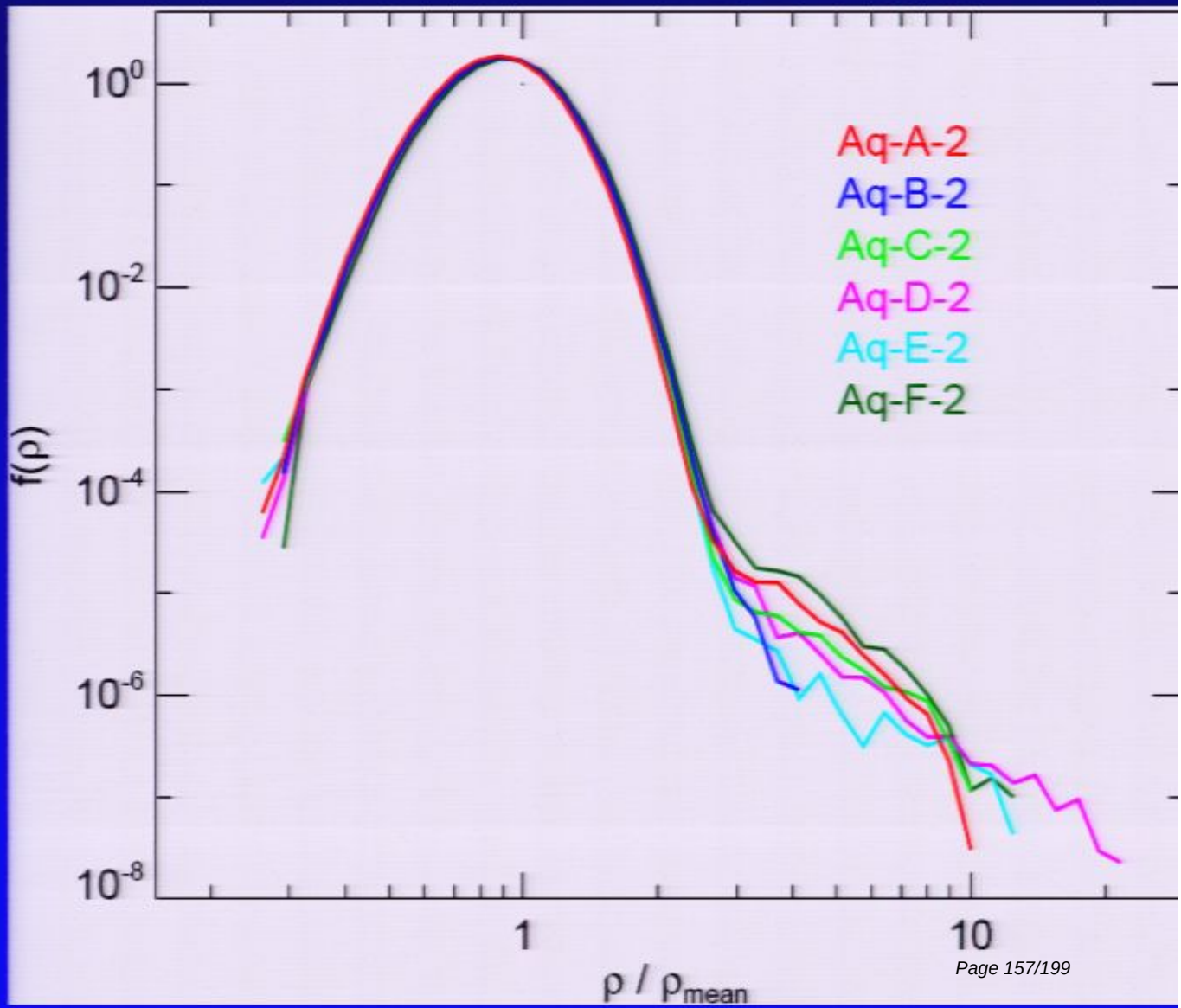
The "Phase-Space Density" Profile



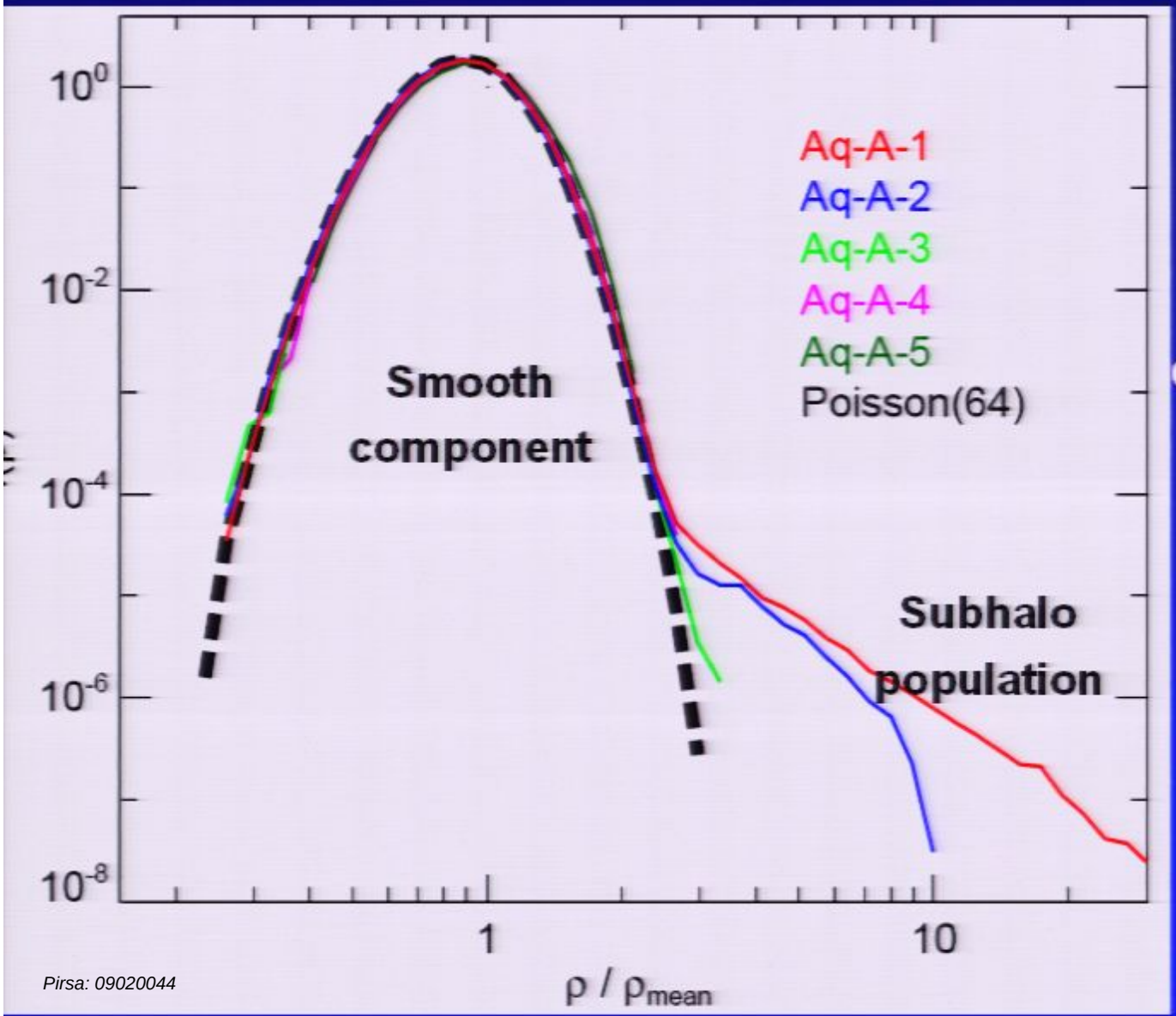
- Remarkably, the "phase-space density", ρ/σ^3, scales like a power law of radius
- This is the same dependence as in Bertschinger's secondary infall similarity solution

Density PDF: object-to-object scatter

Changes of 'hitting' a subhalo are very small: ~10^{-4}

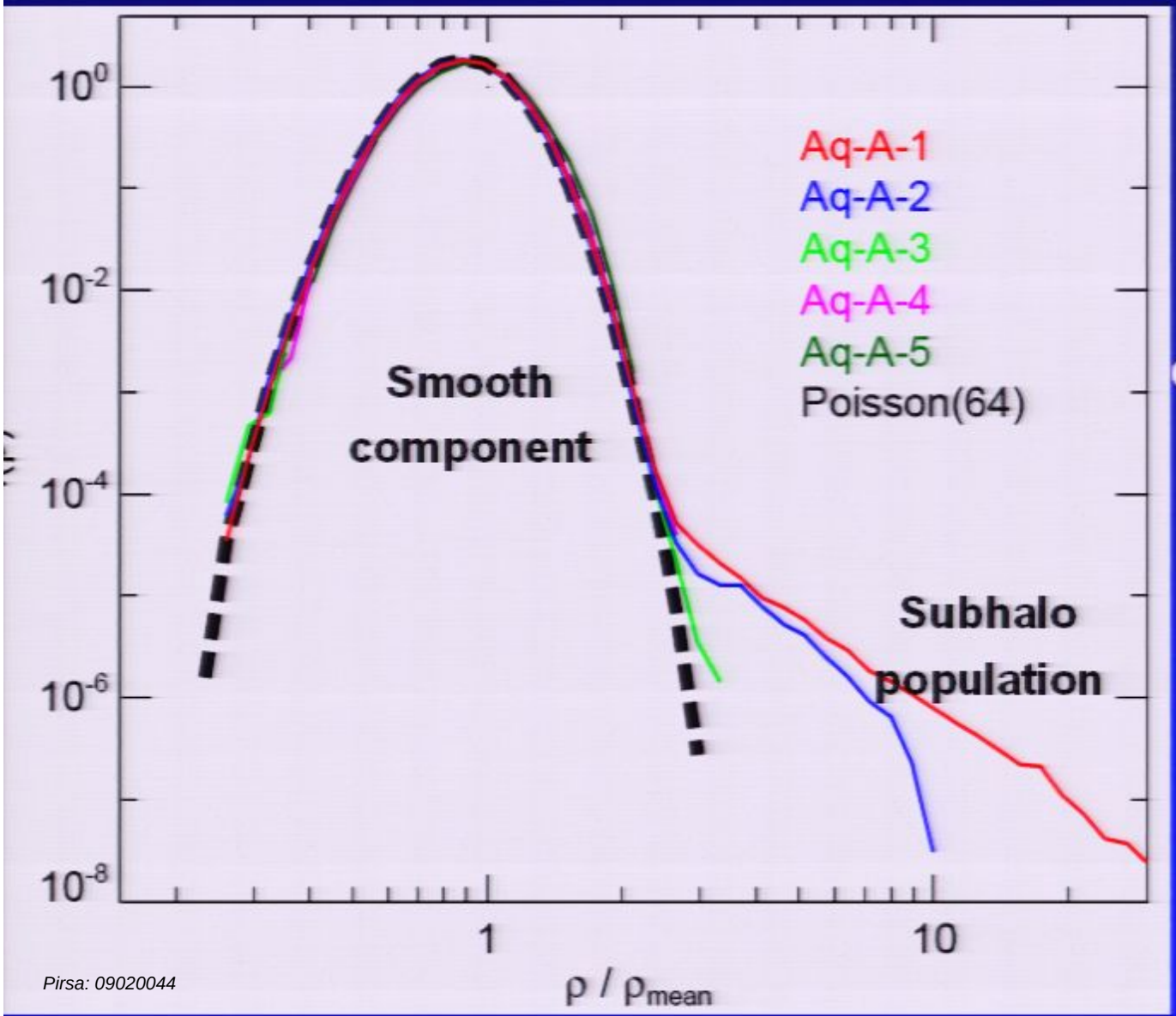


Density PDF



Density probability distribution function around solar circle

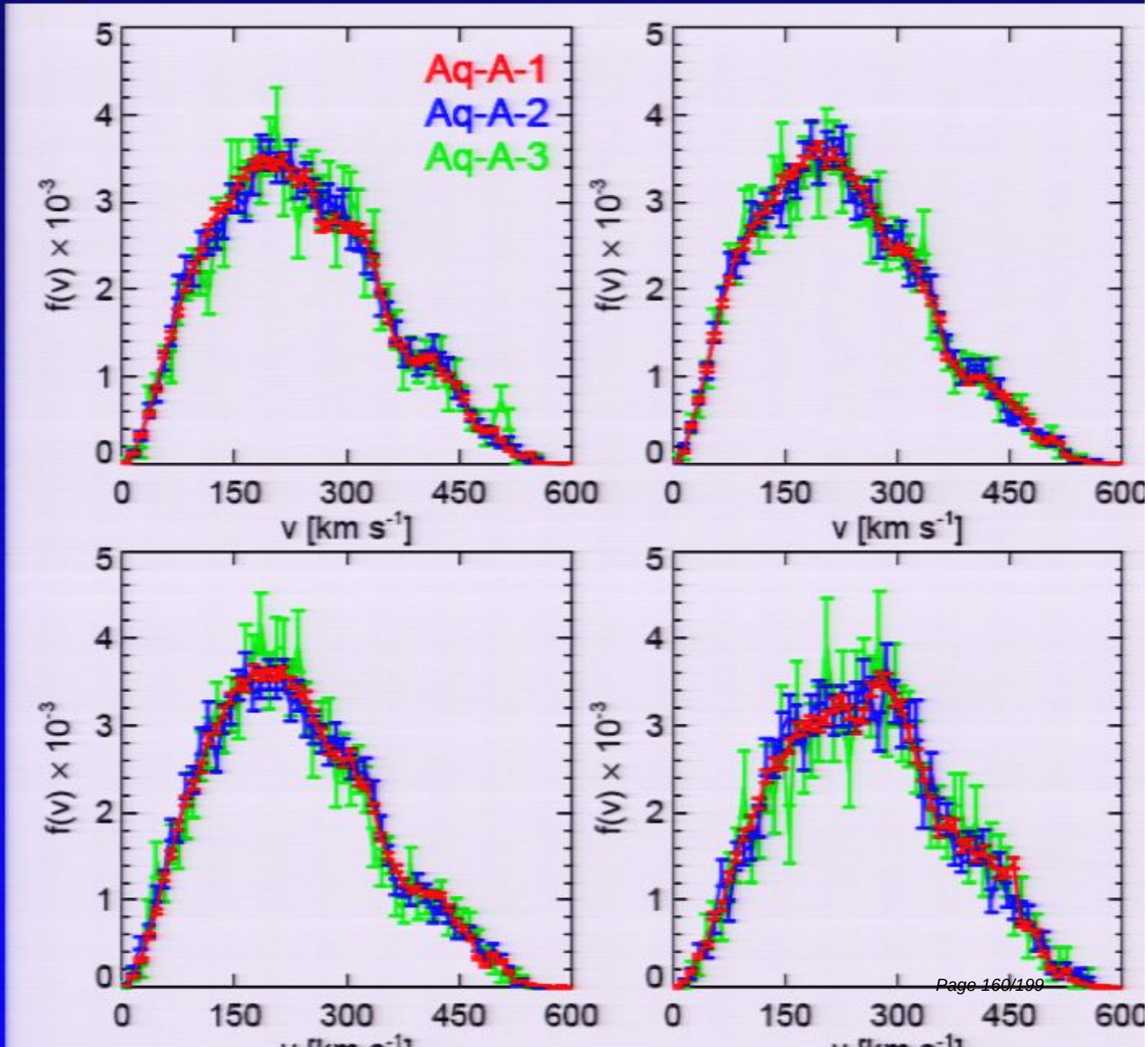
Density PDF



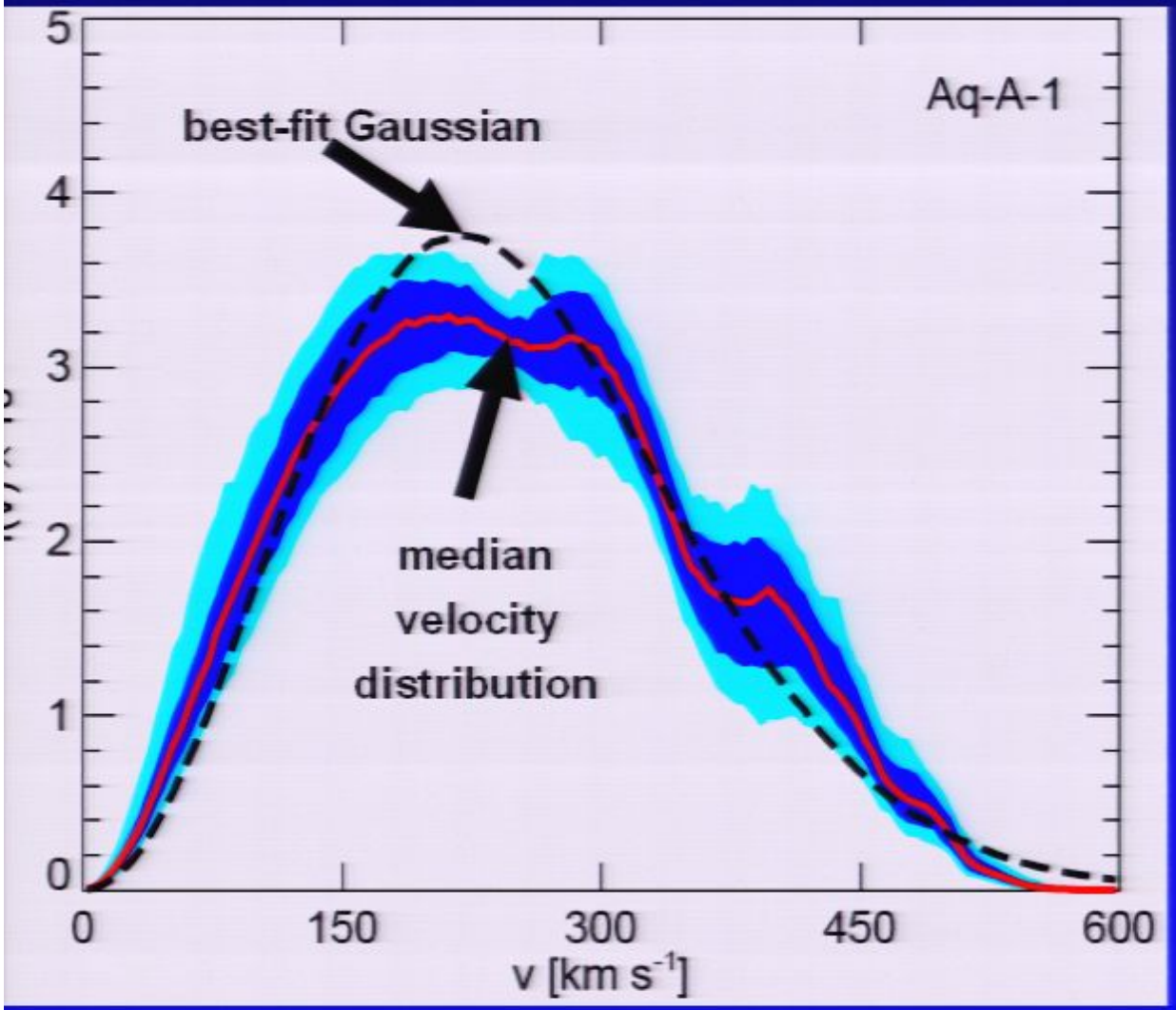
Density probability distribution function around solar circle

Convergence of the modulus

Velocity distribution at different positions and different resolutions



Modulus at different locations



AGAIN:

No sign for distinct/ massive streams

BUT:

Bumps in velocity modulus at the same velocity

Not Maxwellian

Not exactly multivariate Gaussian

A blueprint for detecting halo the CDM annihilation signal in the Galactic halo

Springel et al, 2008 Nature

CDM particles may annihilate and lead to production of γ-rays which could be observable by GLAST/FERMI

Emission of annihilation radiation depends on:

$$\int \rho^2(\boldsymbol{x}) \, \langle \sigma v \rangle \, dV$$

halo density at $\boldsymbol{x}$ — cross-section

$\Rightarrow$ Theoretical expectation requires knowing $\rho(\boldsymbol{x})$

$\Rightarrow$ Need accurate high resolution N-body simulations of halo formation from CDM initial conditions

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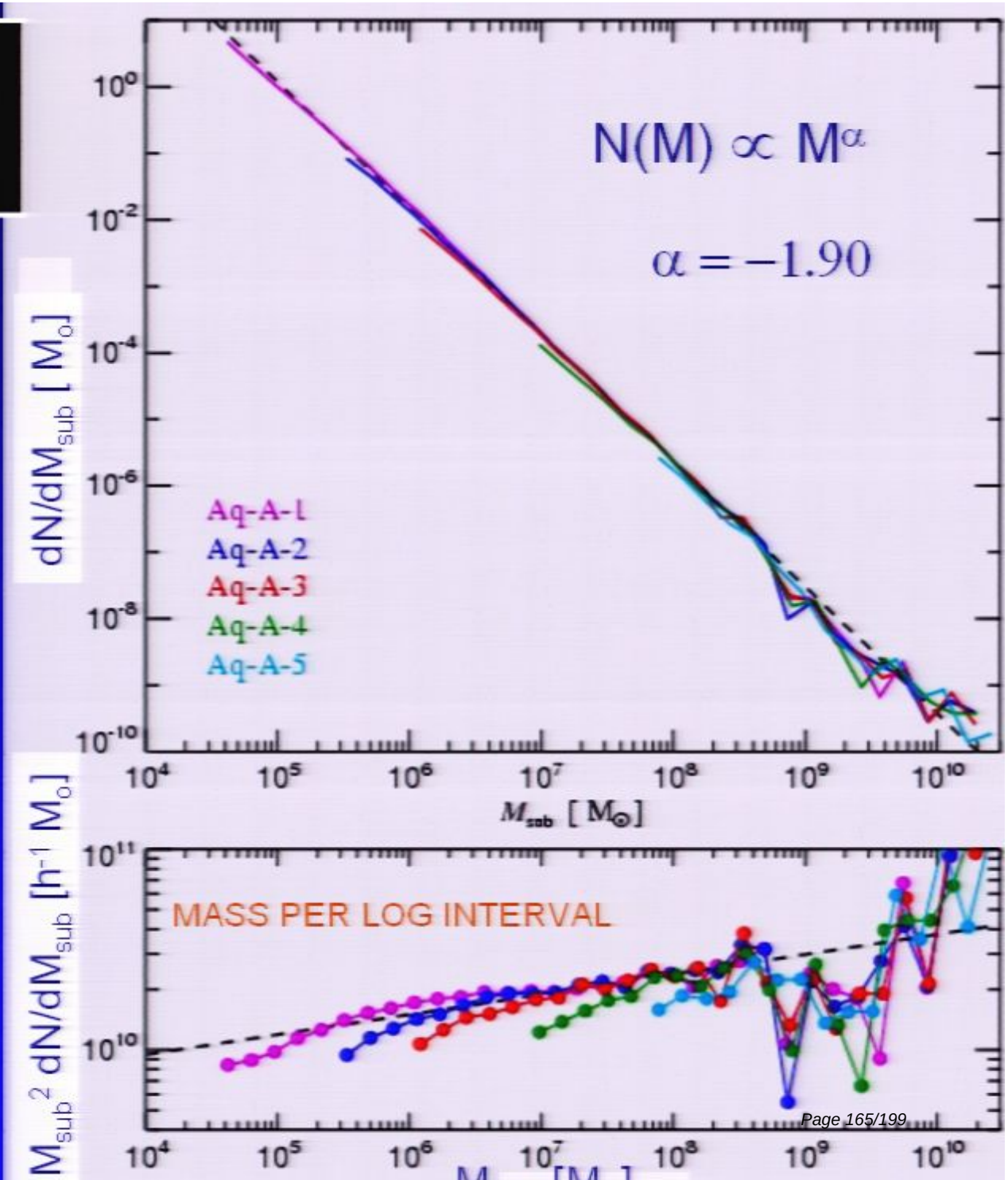
Myths about Cold Dark Matter halo substructure and annihilation signal

- Halo DM is mostly in small (e.g. Earth mass) clumps
- Small (Earth-mass) clumps should dominate DM annihilation signal observable from Earth
- Dwarf spheroidals/luminous satellites are the best targets for detecting DM annihilation signal
- Halo DM is in a self-similar (fractal) distribution of nested substructure halos (subhalos)
- Annihilation signal/detectability is significantly boosted by sub-substructure

The mass function of substructures

The subhalo mass function is shallower than M^2

- Most of the substructure mass is in the few most massive halos
- The total mass in substructures (5 to10% of the total) converges well even for moderate resolution



The substructure circular velocity function

e of substructure halos

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Via l

tial distribution of subhalos
for the few most massive
is independent of mass

- Cosmic
- Substruc
algorithm

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los are more effectively
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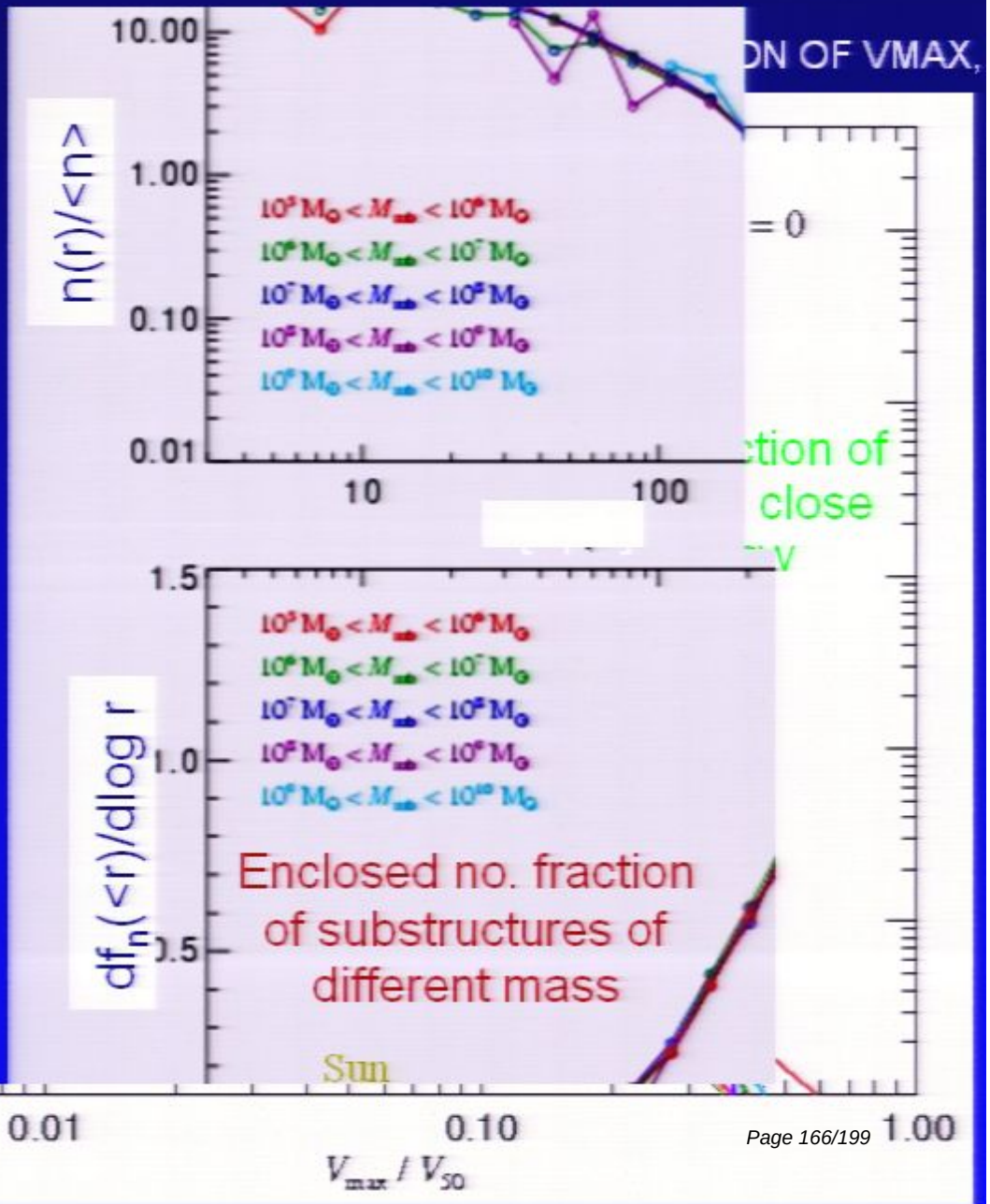
halos are far from the Sun



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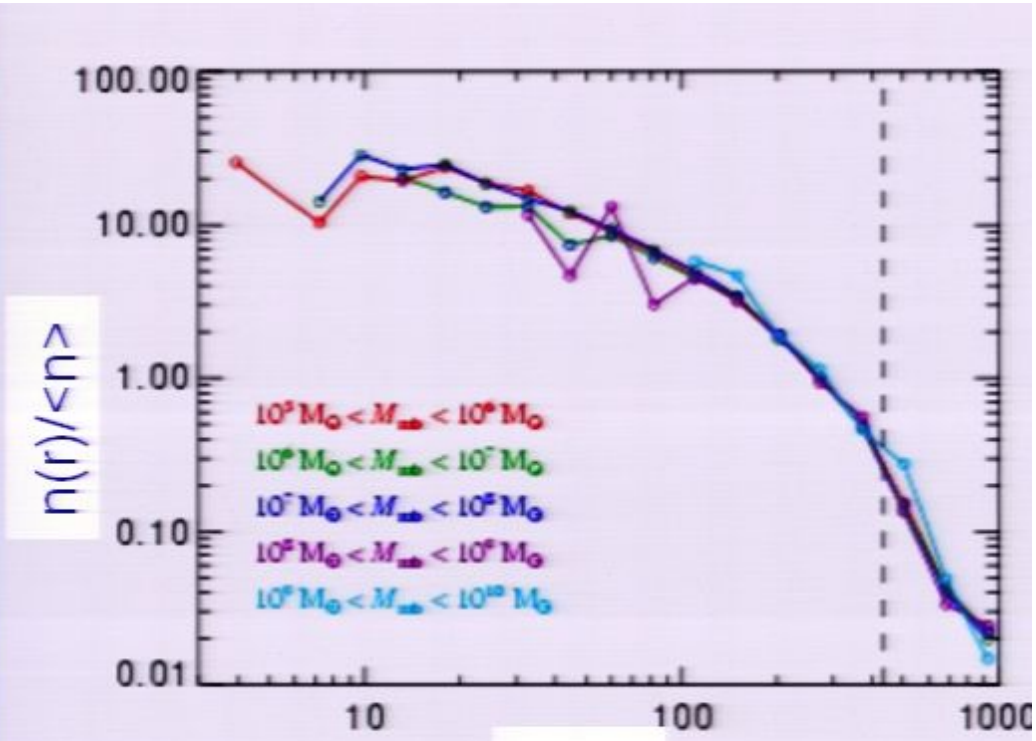
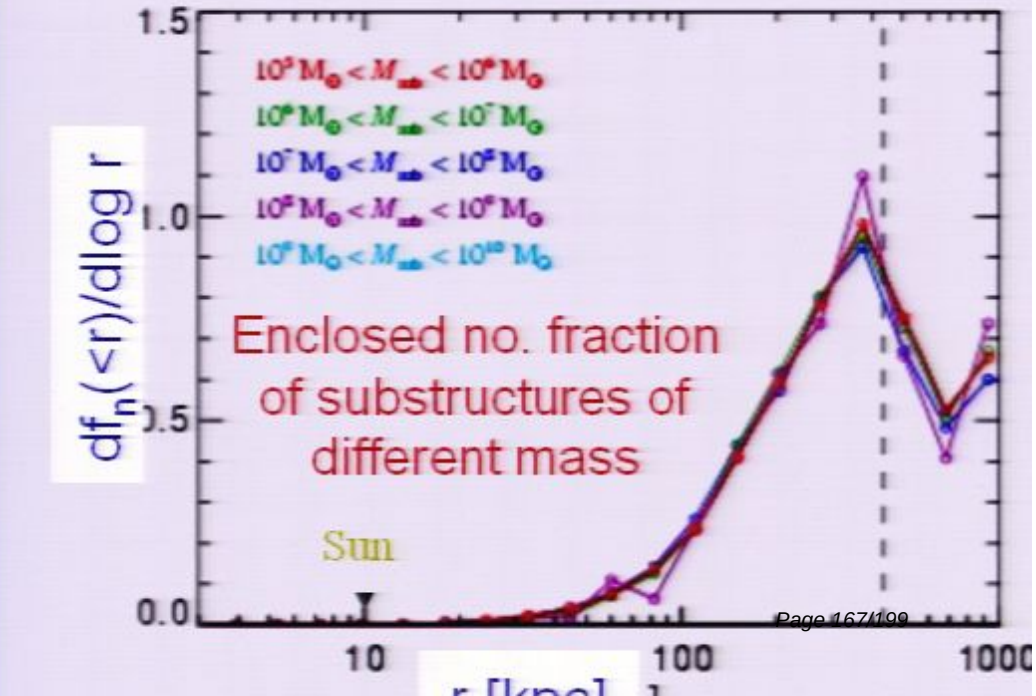
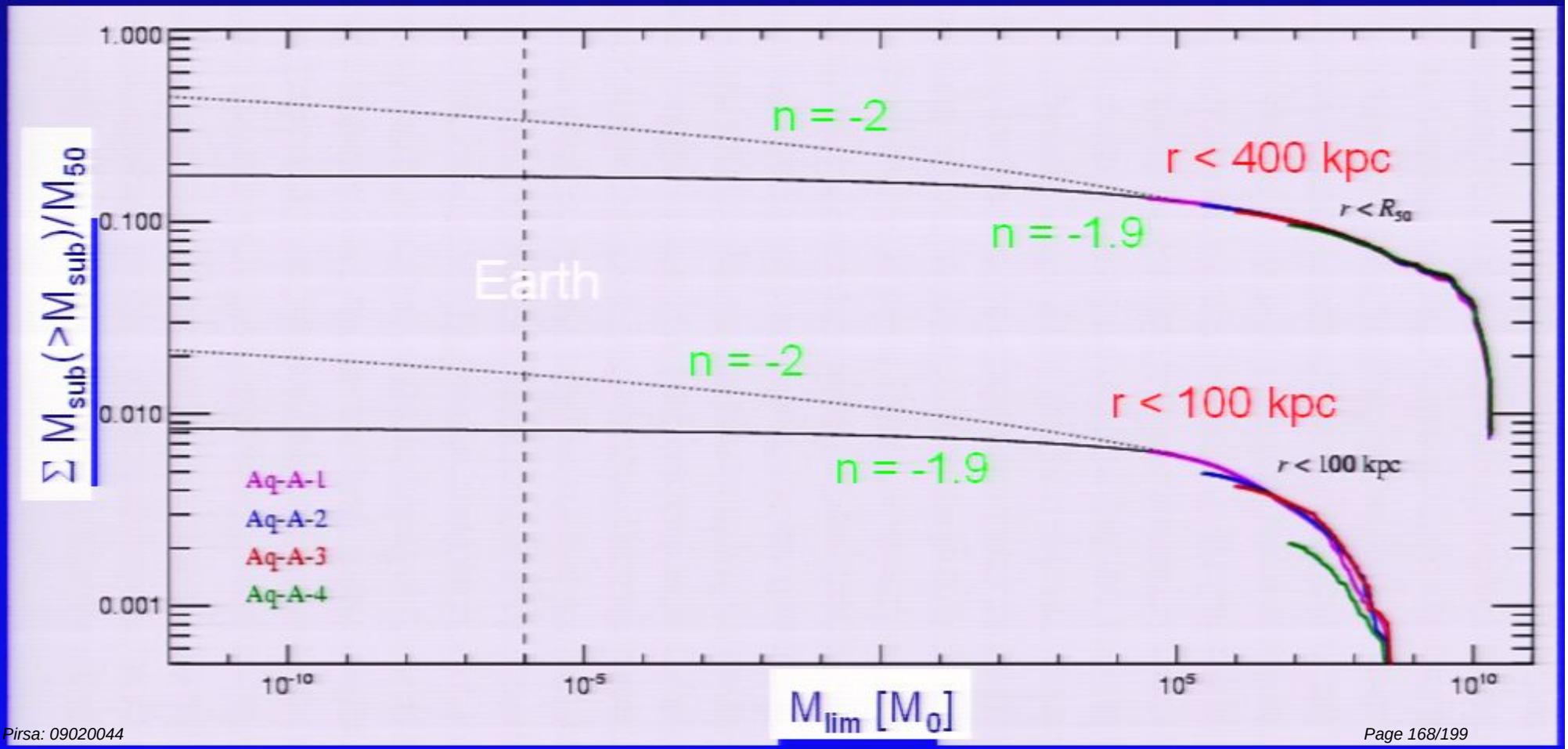




How lumpy is the MW halo?

Mass fraction in subhalos as a function of the free-streaming cutoff mass in the CDM power spectrum



Substructure mass fraction within R_sun < 0.1%

3 times as
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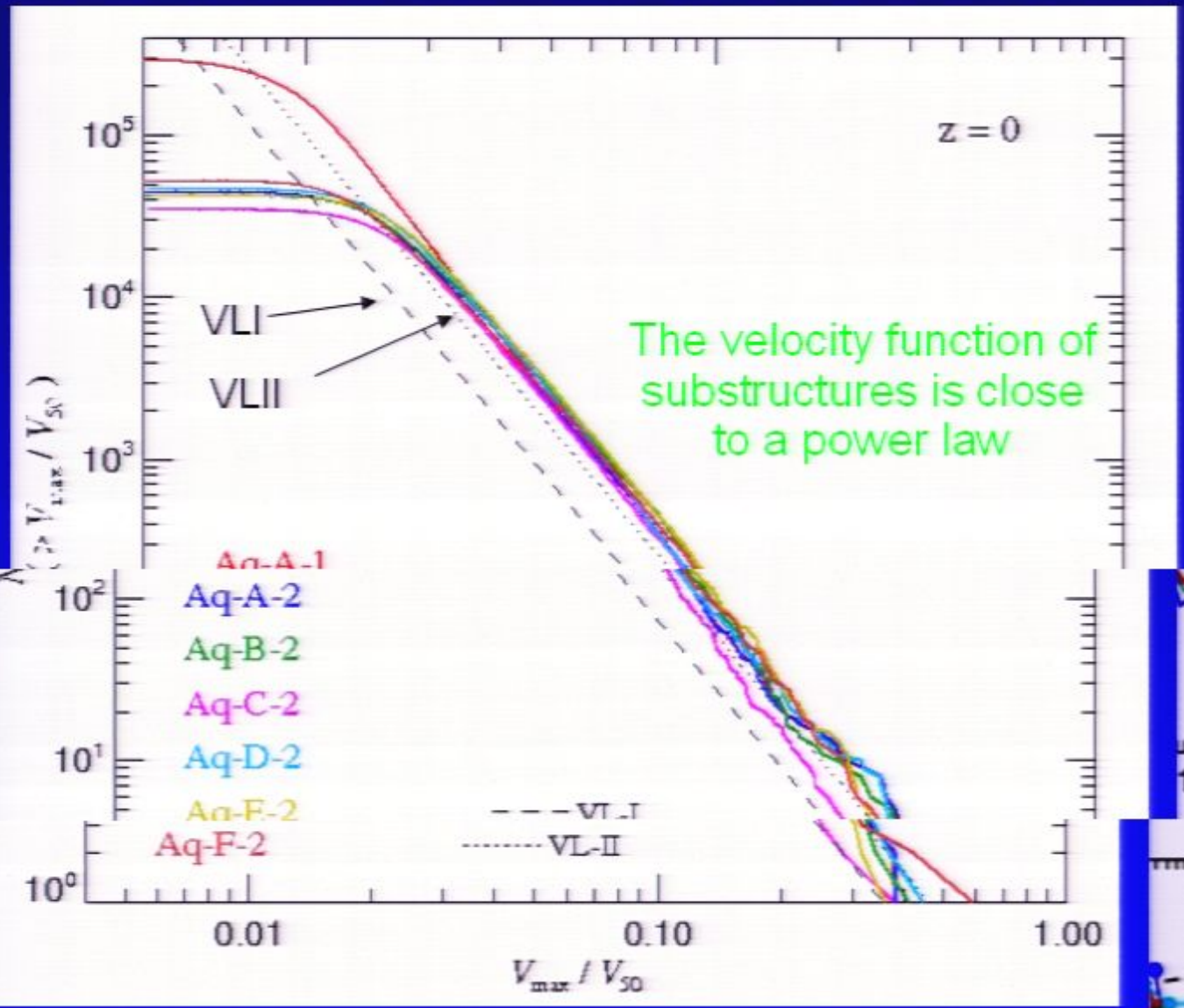
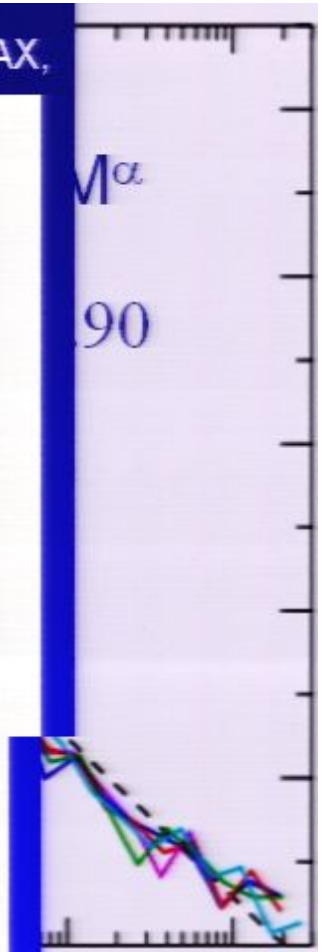
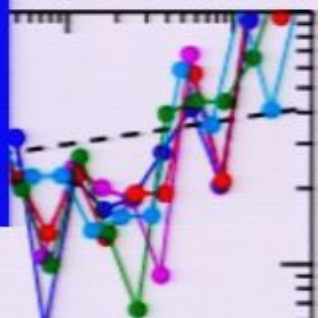
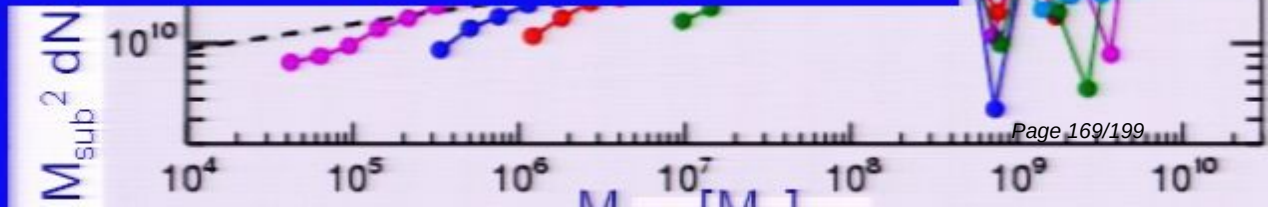
CUMULATIVE NUMBER OF SUBSTRUCTURES AS A FUNCTION OF VMAX,









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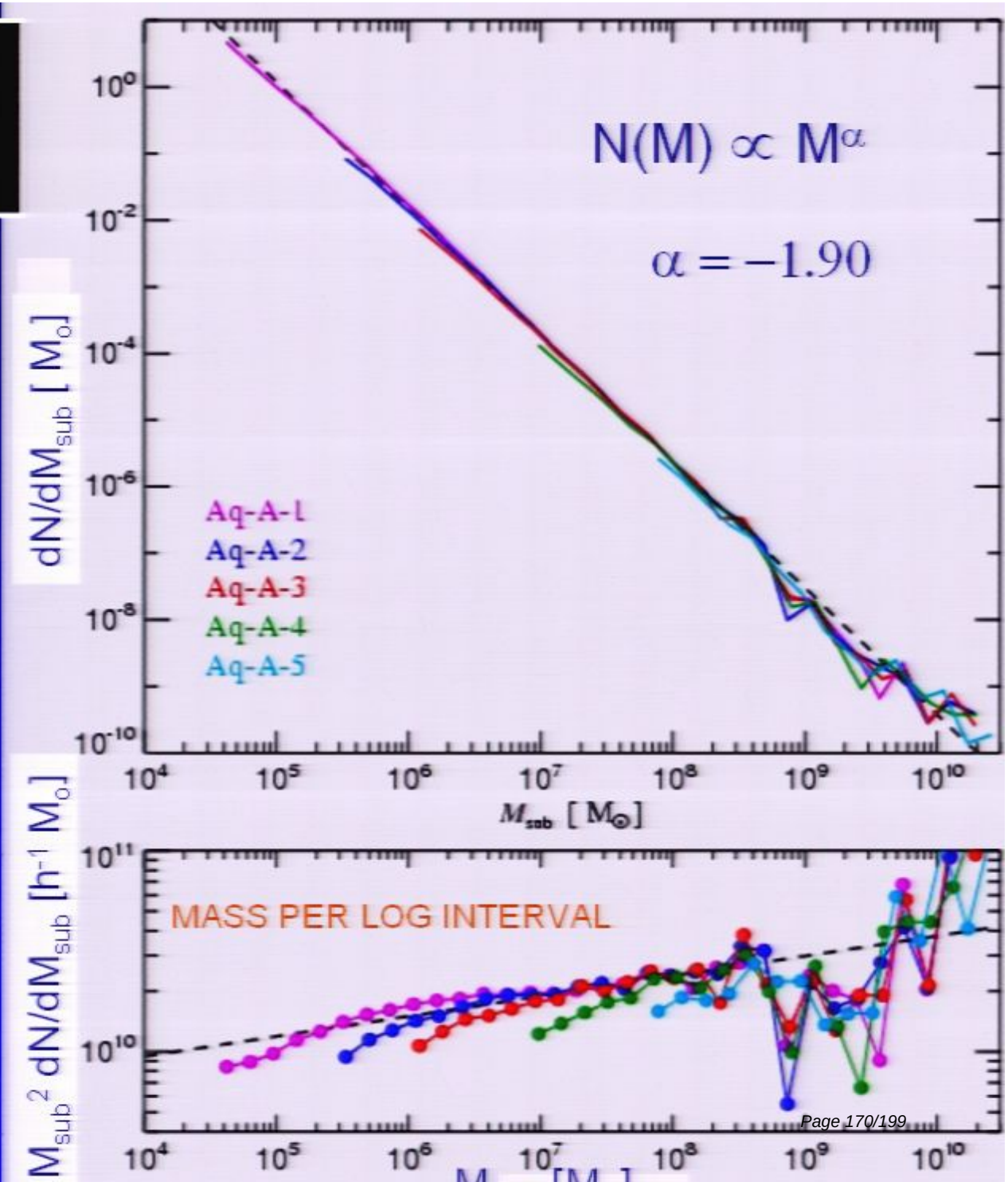

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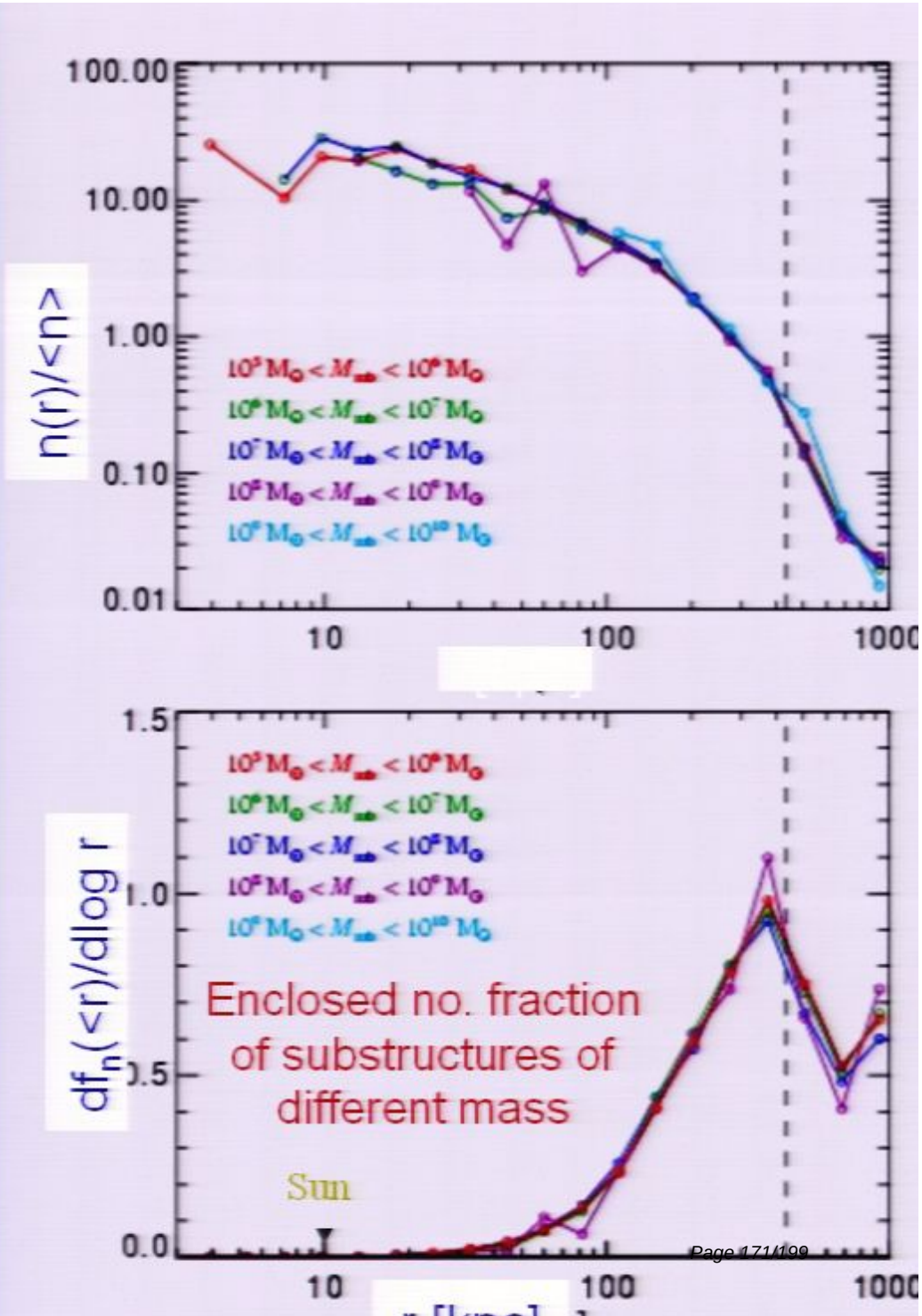

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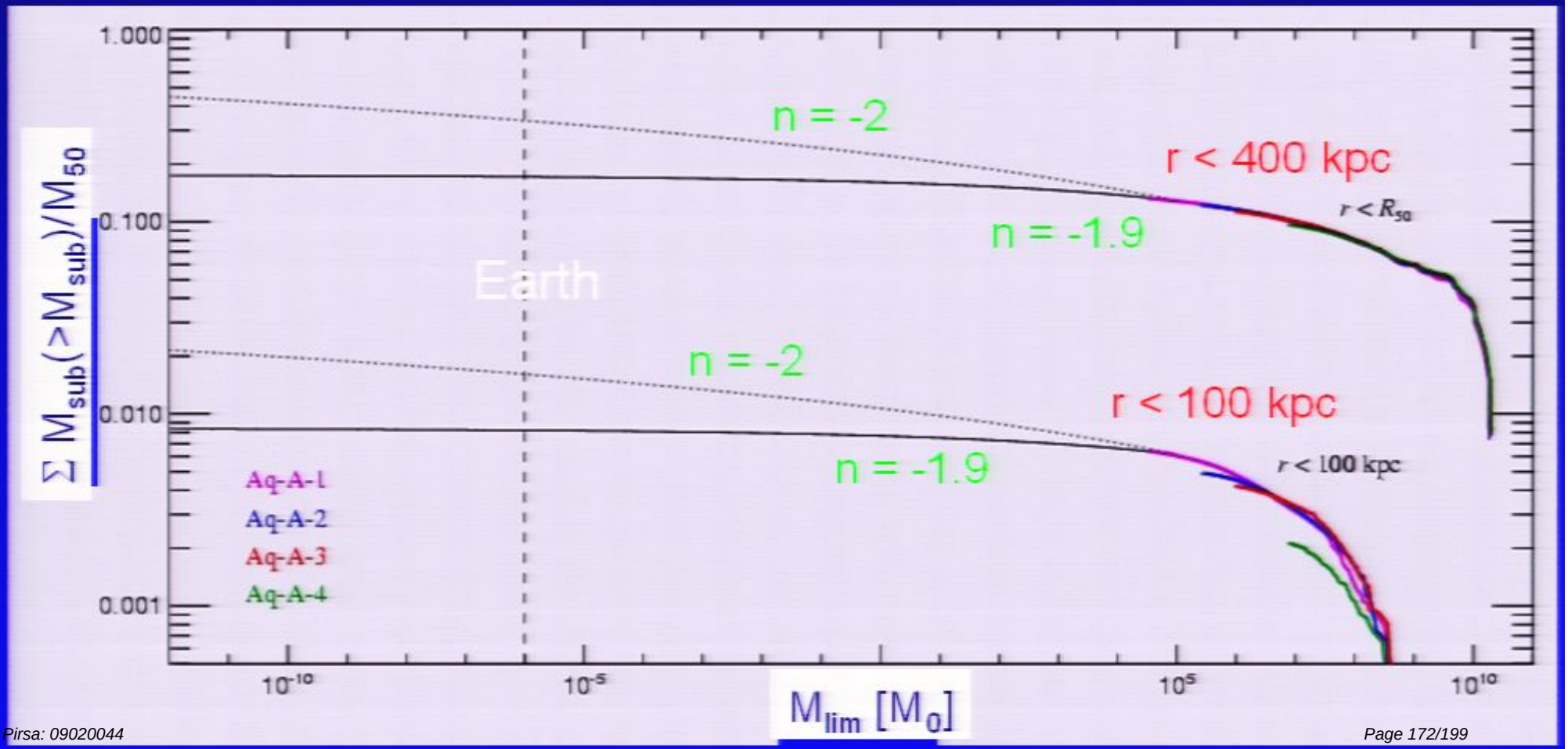


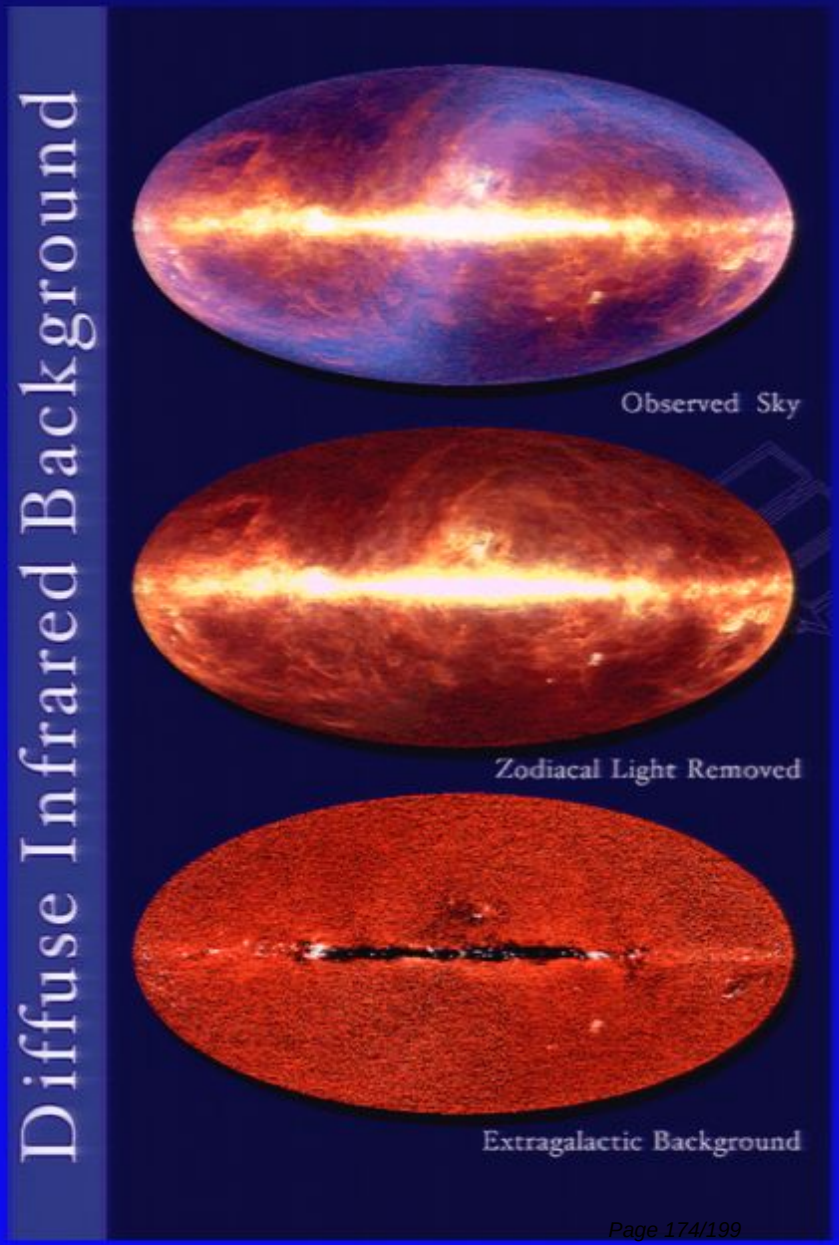
Substructure mass fraction within R$_{\odot}$ < 0.1%

Annihilation radiation from the Milky Way halo and subhalos

- If small-scale clumping and angular variations in the background may be neglected, then for systems with similar density profiles:
  1. Luminosity $\propto V_{max}^4/r_{max}$
  2. Flux $\propto V_{max}^4/(r_{max}*d^2)$
  3. Signal-to-noise $\propto V_{max}^4/(r_{max}^2*d)$

The Milky Way (our home)

- The known substructure with largest signal-to-noise is the LMC, and it is easy to show that
  - $(S/N)_{MW}/(S/N)_{LMC} \sim 134$!
- Substructures are easier to detect than the main halo only if the "boost factor" from small-scale clumping overwhelms this simple scaling.



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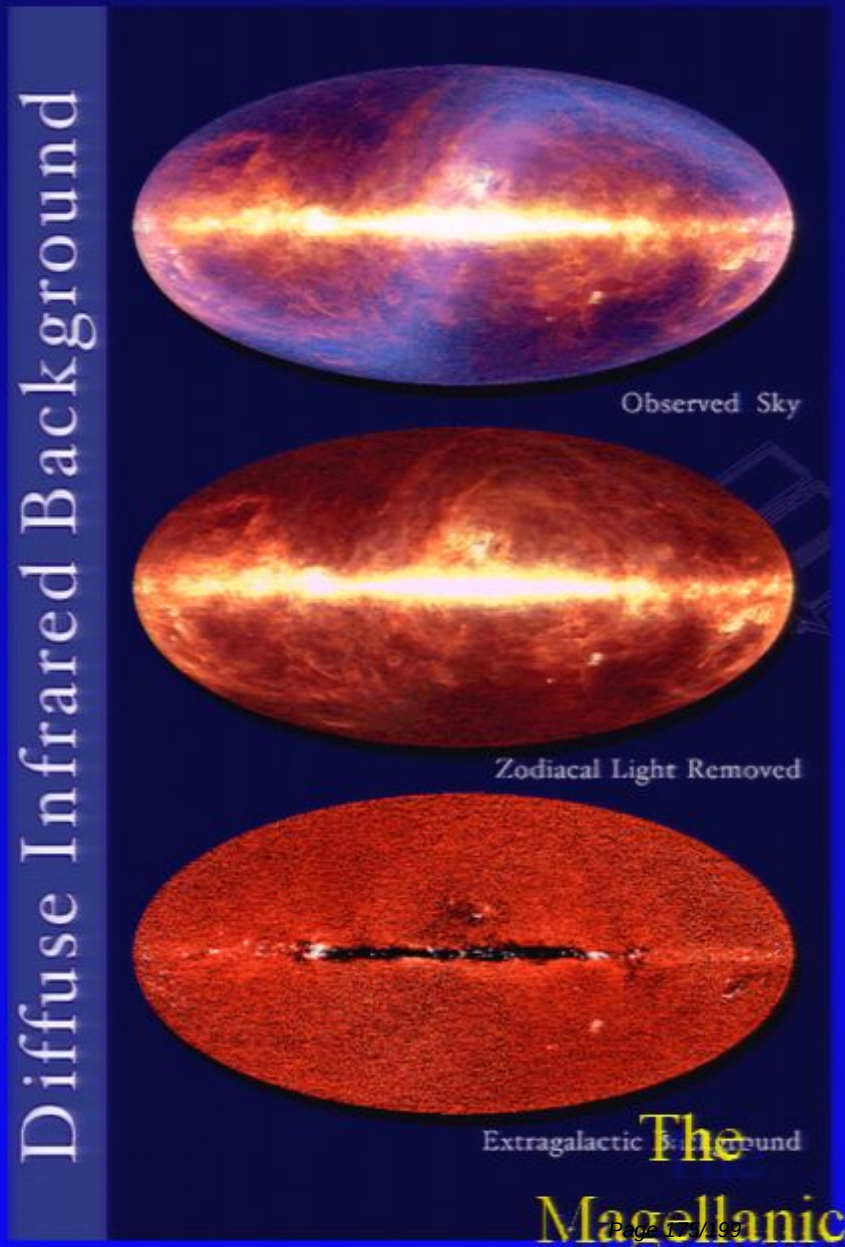
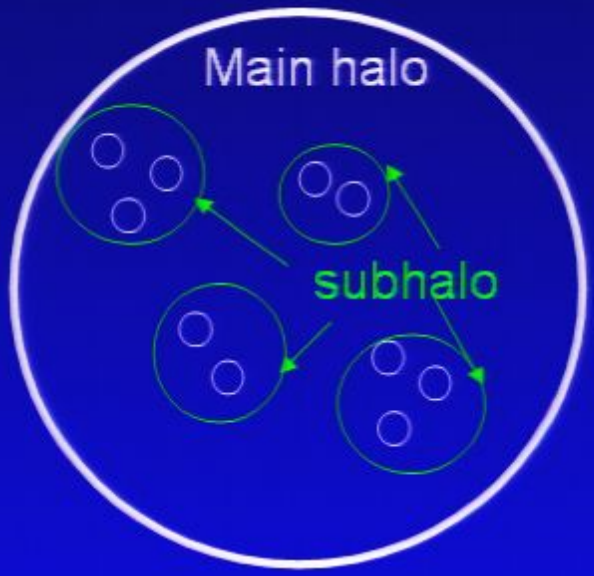


The Magellanic Clouds

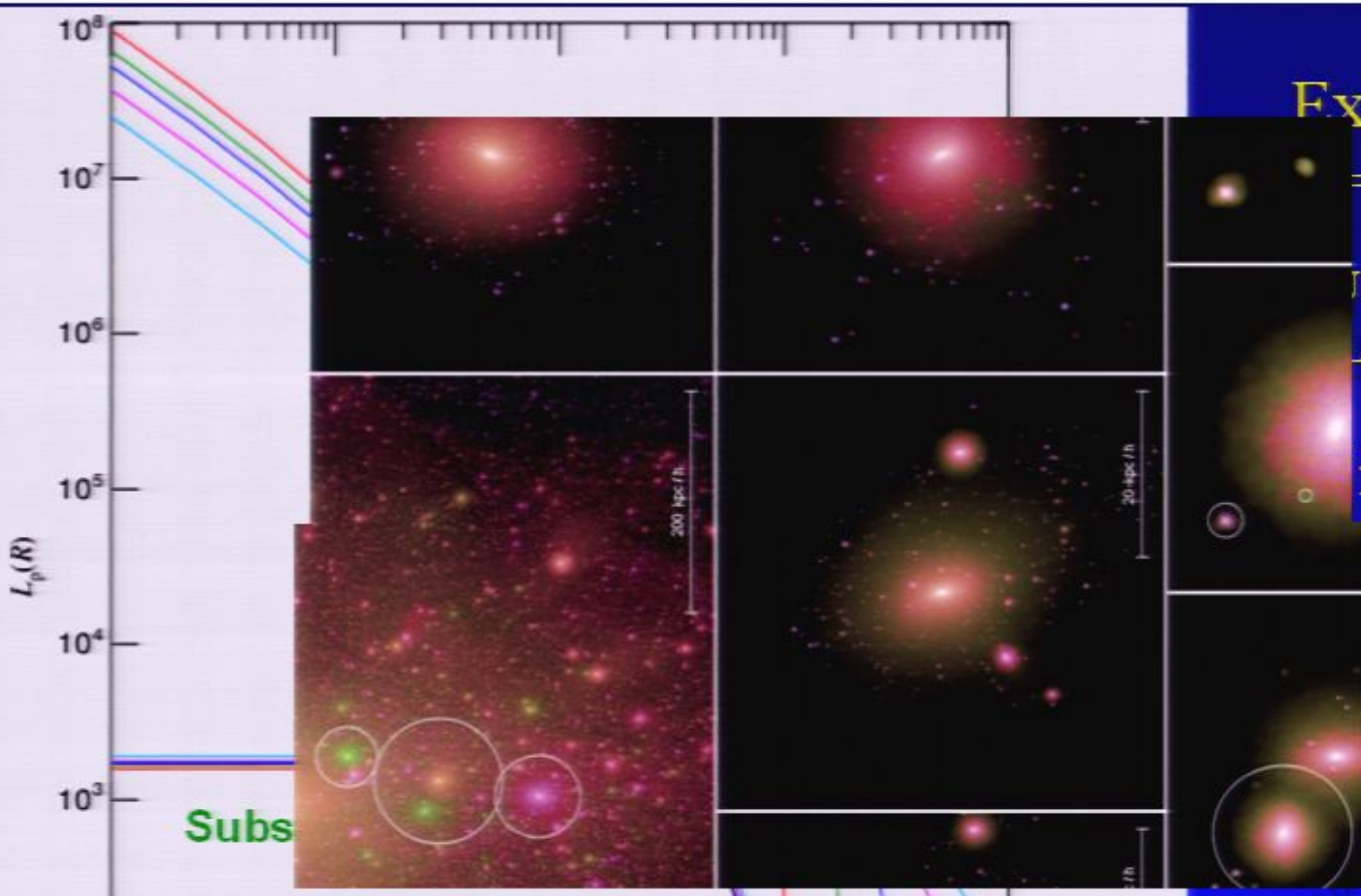
A blueprint for detecting halo CDM annihilation radiation

To calculate the annihilation luminosity from a dark matter halo (L) we need to consider the contribution from 4 components:



1. Smooth emission from main halo (MainSmooth)
2. Smooth emission from resolved subhalos (SubSmooth)
3. Emission from unresolved subhalos in main halo (MainUnres)
4. Emission from substructure of subhalos (SubSub)

Projected annihilation radiation profile

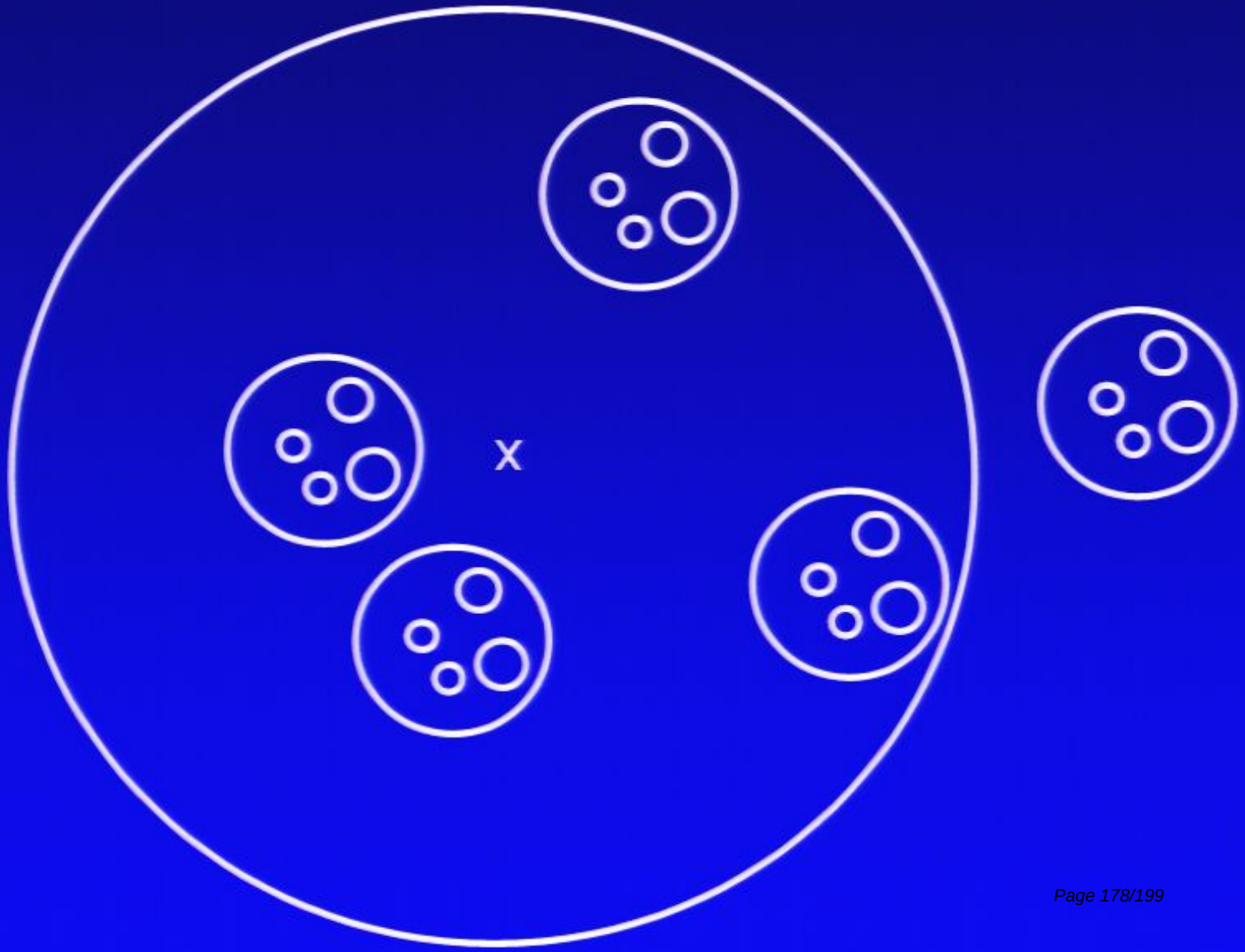


Extrapolating to
$=10^{-6}$ M_{sun} yields
BSMOOTH ~ 200
MAINSMOOTH

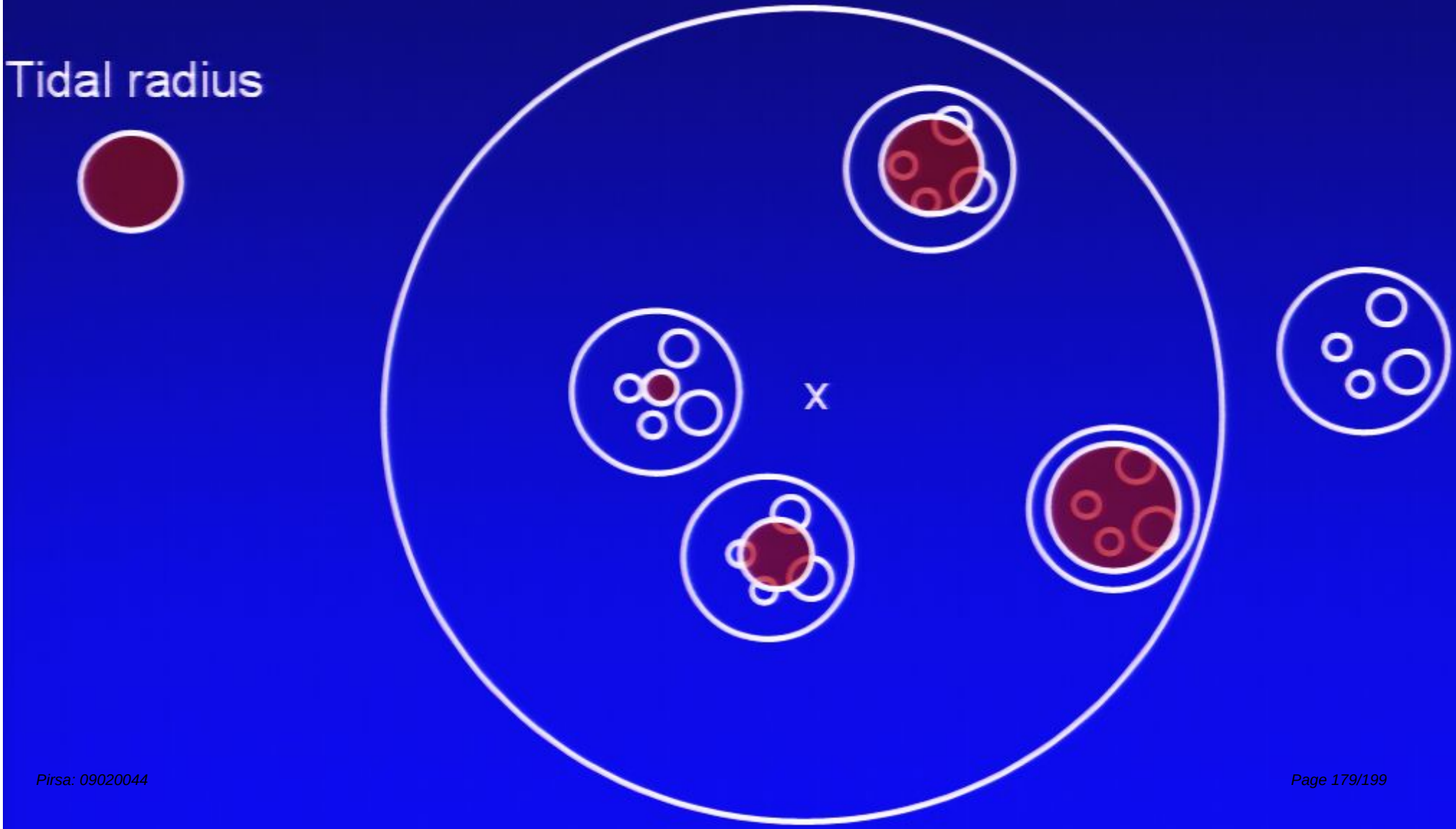
is what would be
n by a distant
observer

total flux from
BSMOOTH and
MAINSMOOTH are
actually similar for an
observer near the Sun.

A “fractal” distribution of nested substructures?

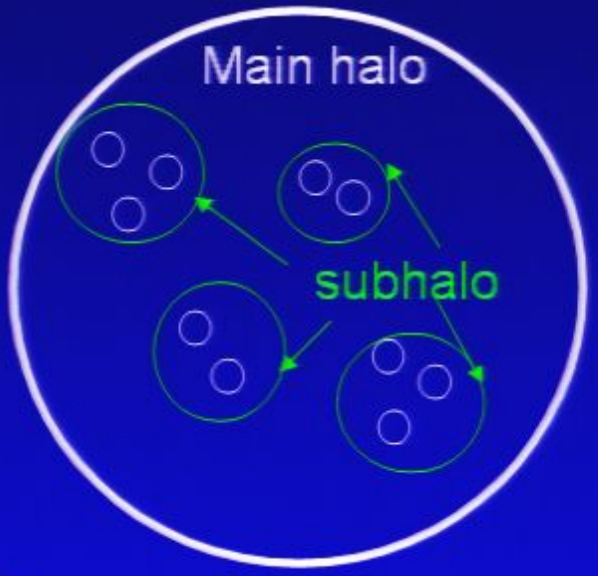


Tidal effects on sub-substructures



Substructures within substructures

•Sub-substructure abundance in subhalos is NOT, in general, a scaled-down version of that in the main halo

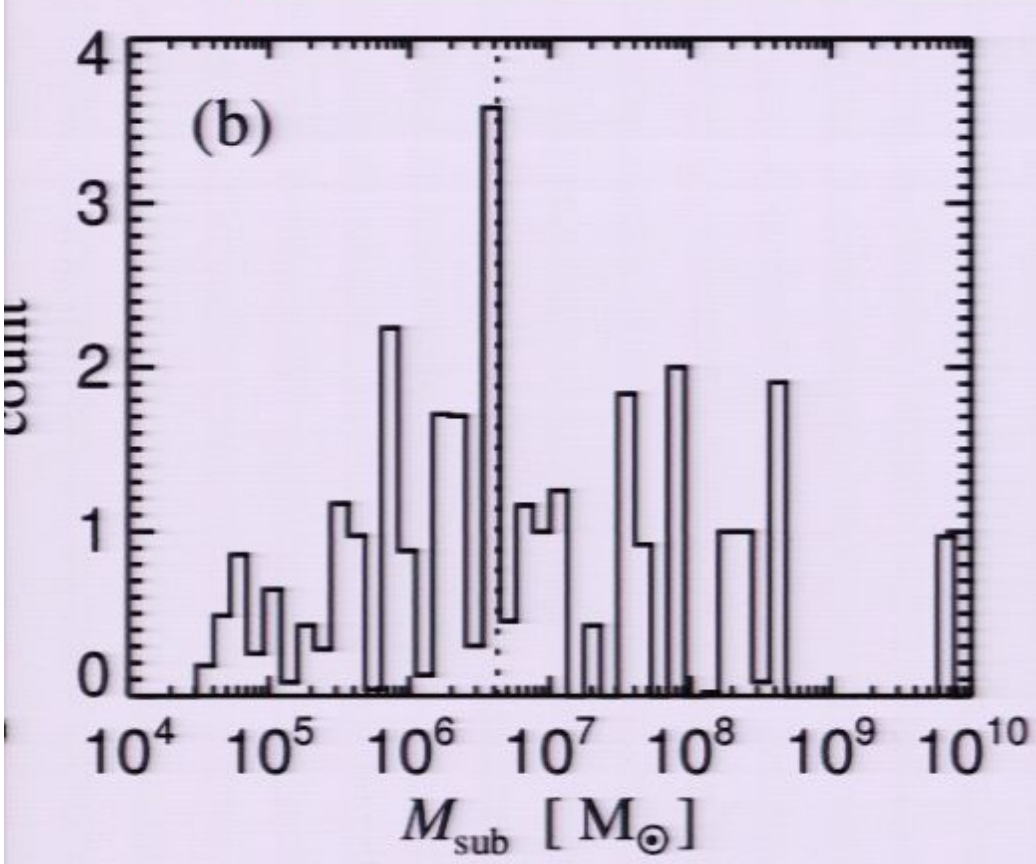


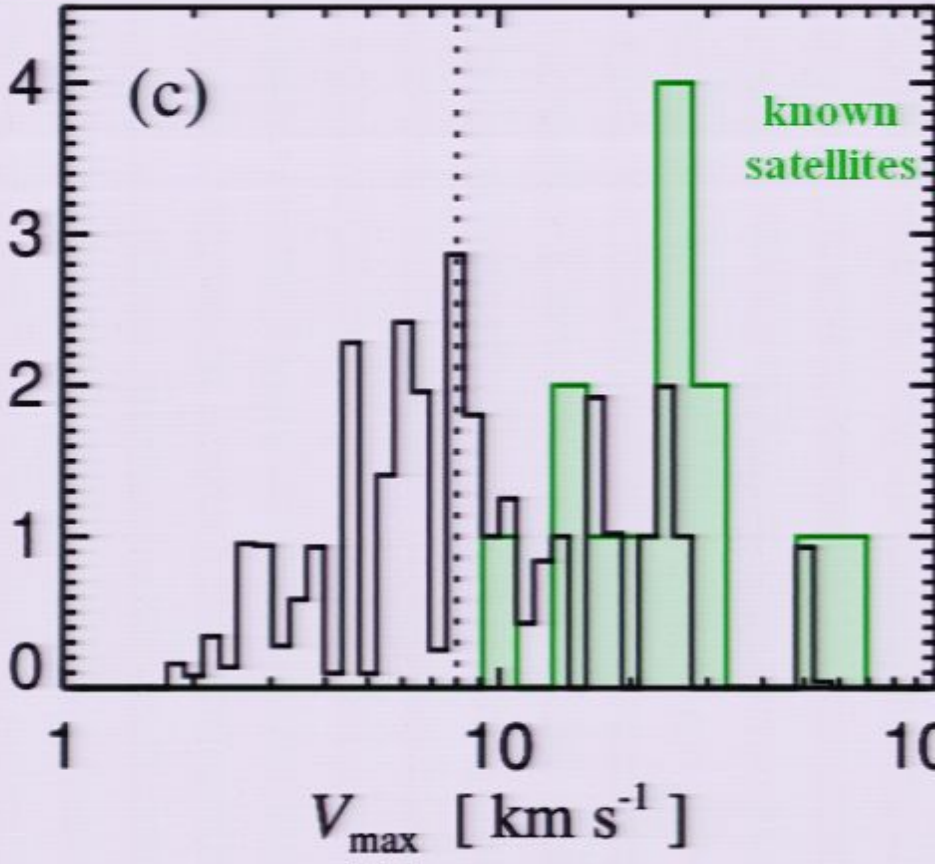
because:

- substructure abundance reduced by tidal truncation
- sub-subhalos continue to loose mass through tides
- sub-subhalos not replenished by infall of fresh halos

$\Rightarrow$ Distribution of sub-substructure is NOT self-similar

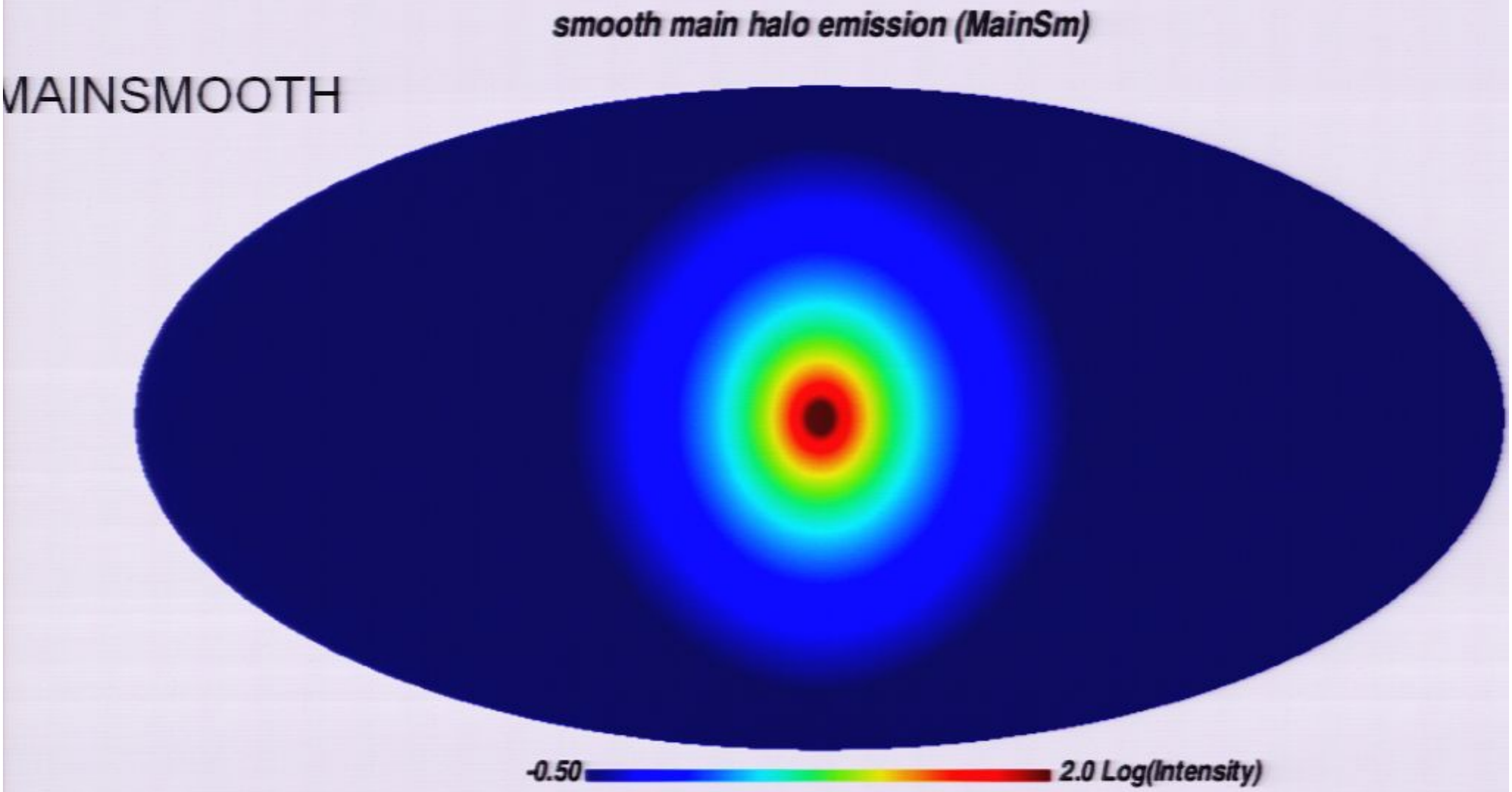
Mass and circular velocity of most detectable substructure





- Highest S/N subhalos have masses well below those inferred for known Milky Way satellites

The gamma-ray sky lit by annihilation radiation



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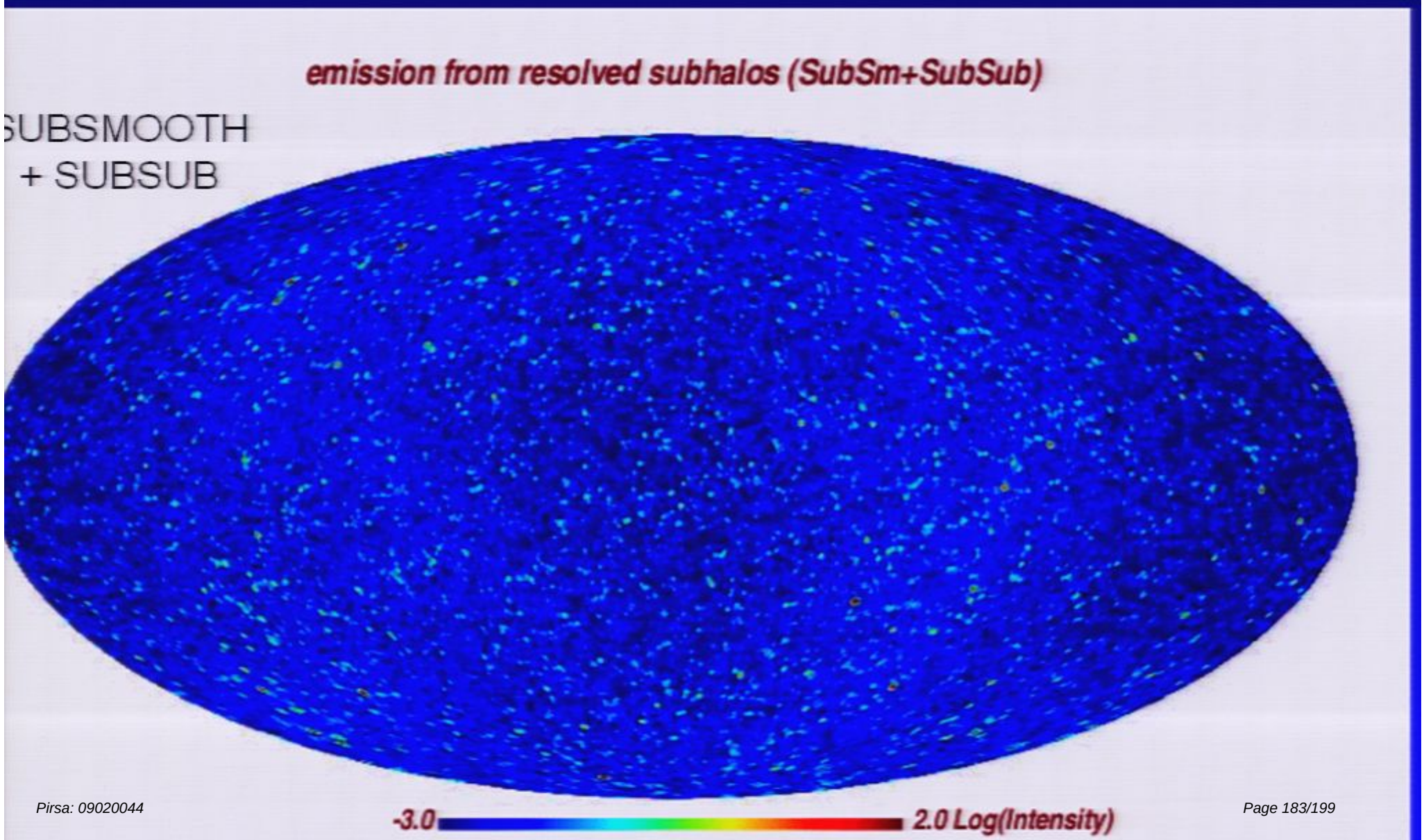

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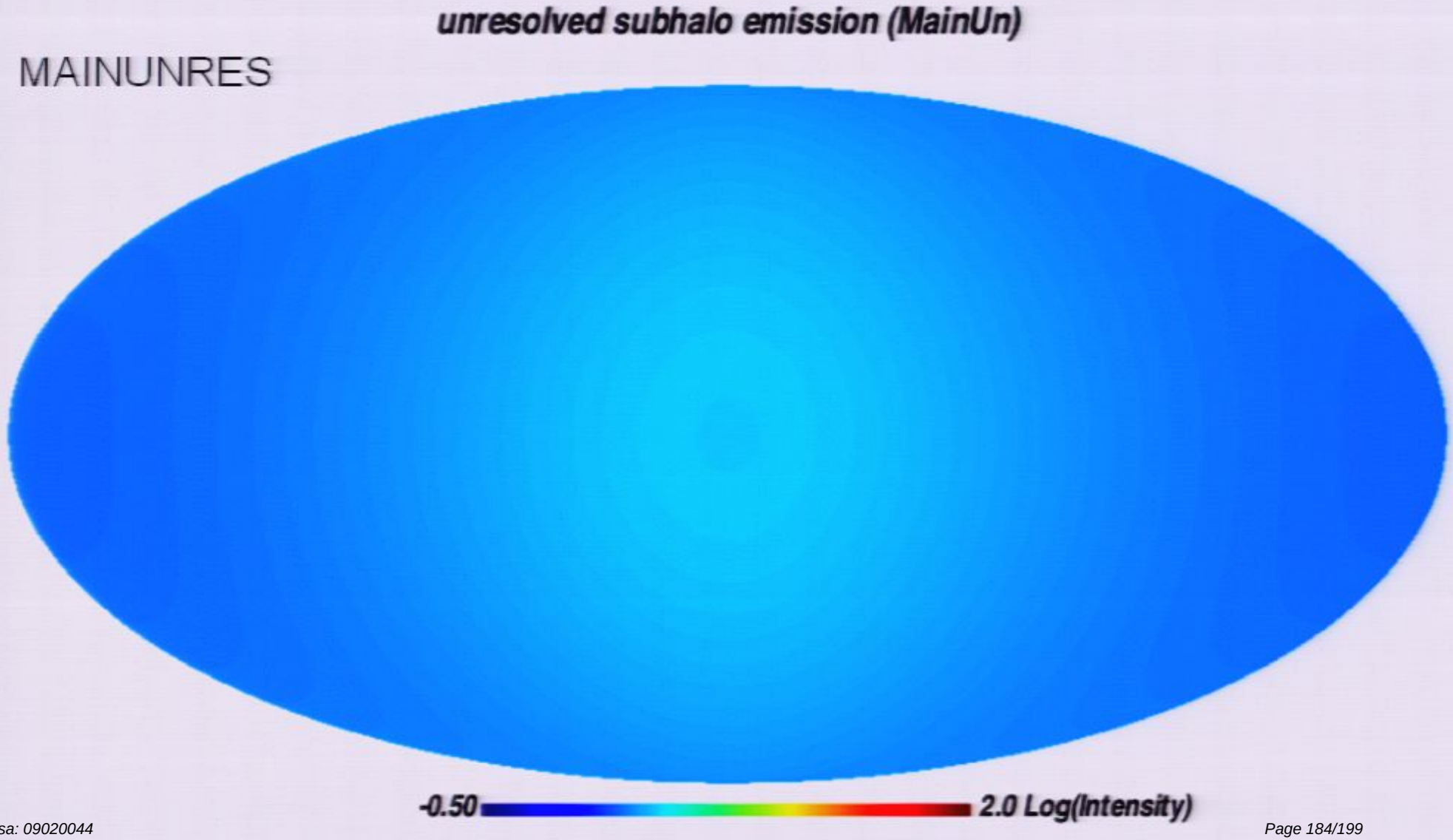

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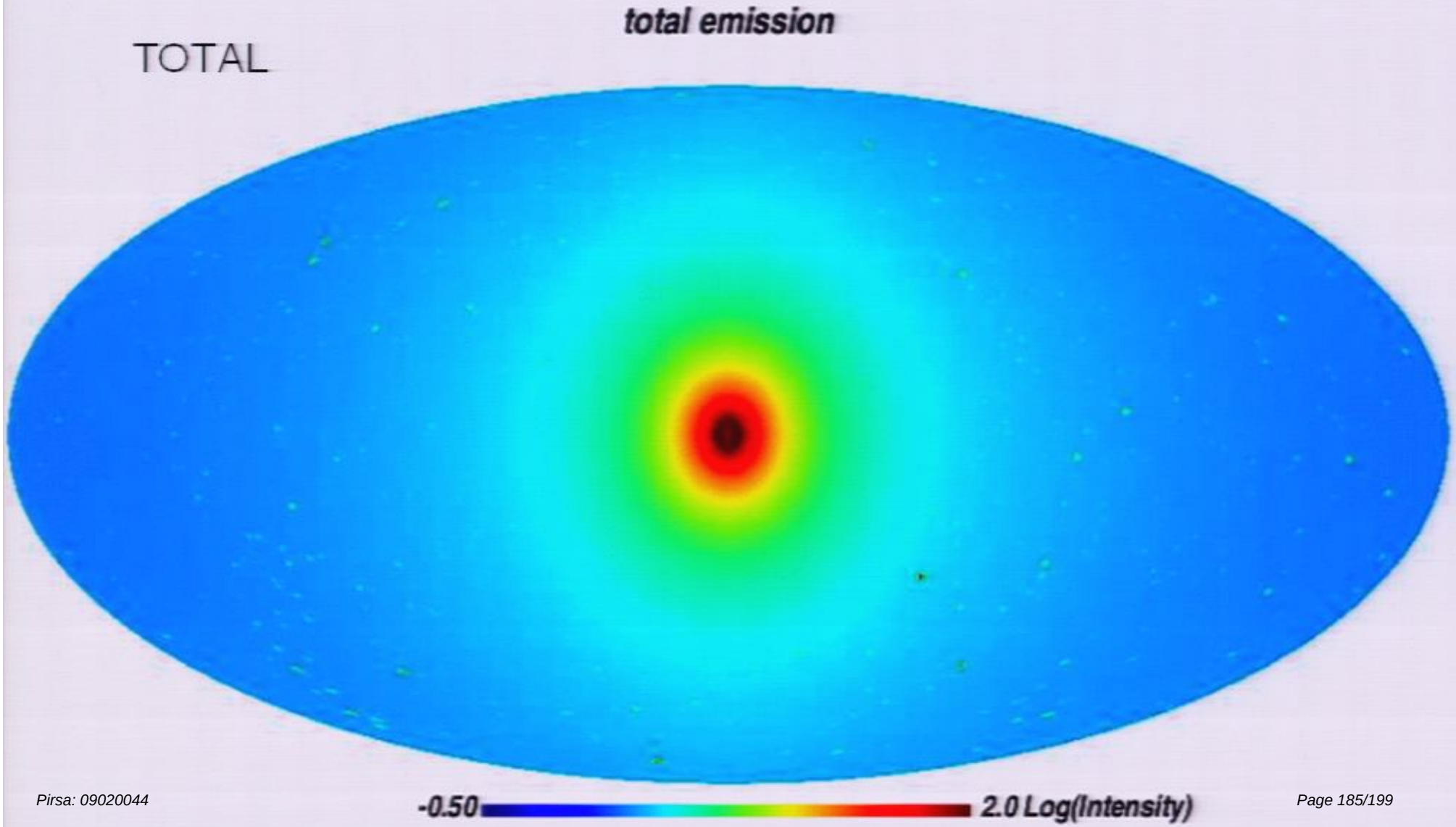

Myths about Cold Dark Matter halo substructure and annihilation signal

- Halo DM is mostly in small (e.g. Earth mass) clumps
- Small (Earth-mass) clumps should dominate DM annihilation signal observable from Earth
- Dwarf spheroidals/luminous satellites are the best targets for detecting DM annihilation signal
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- N-body simulations of ΛCDM predict:
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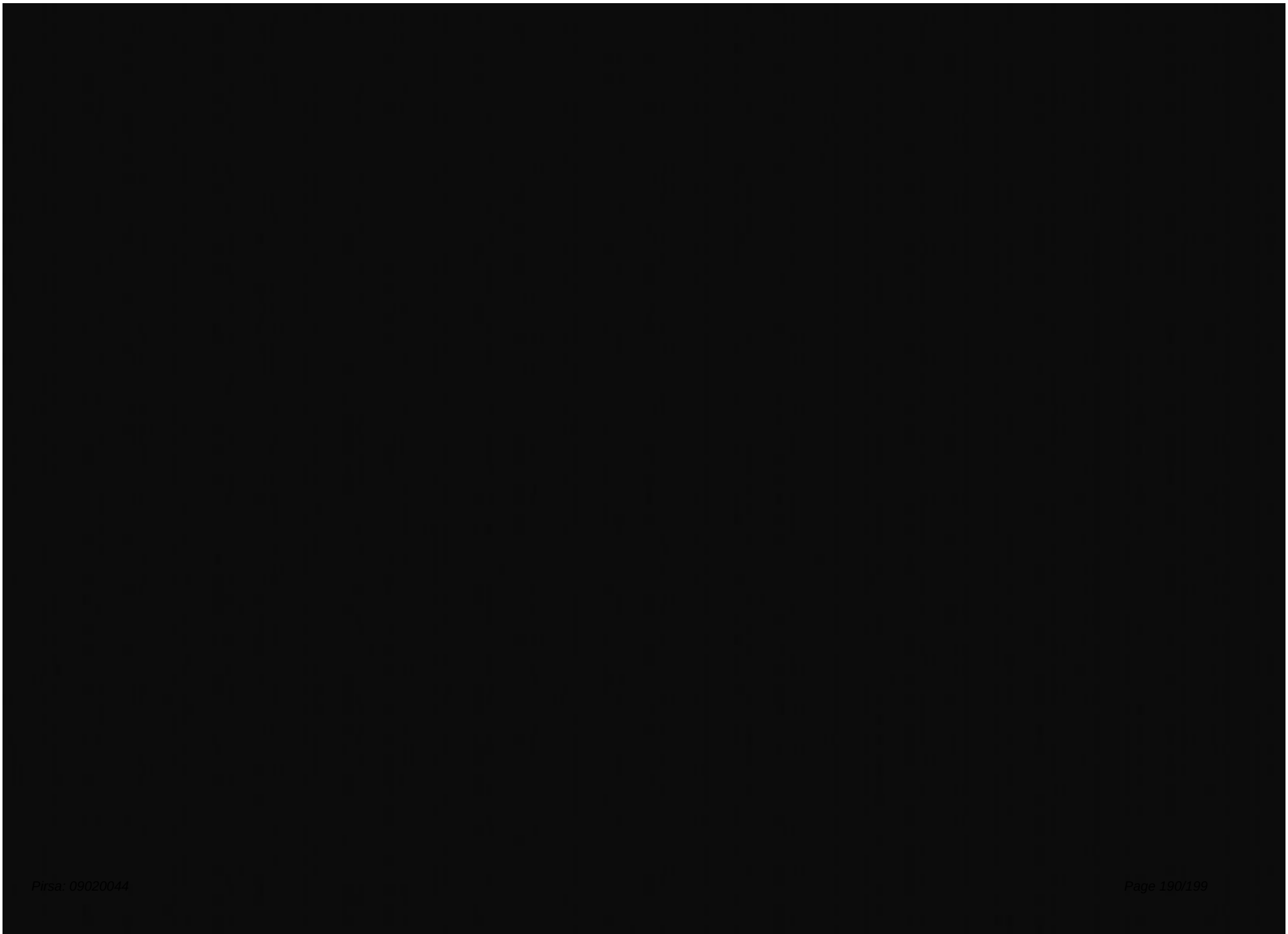

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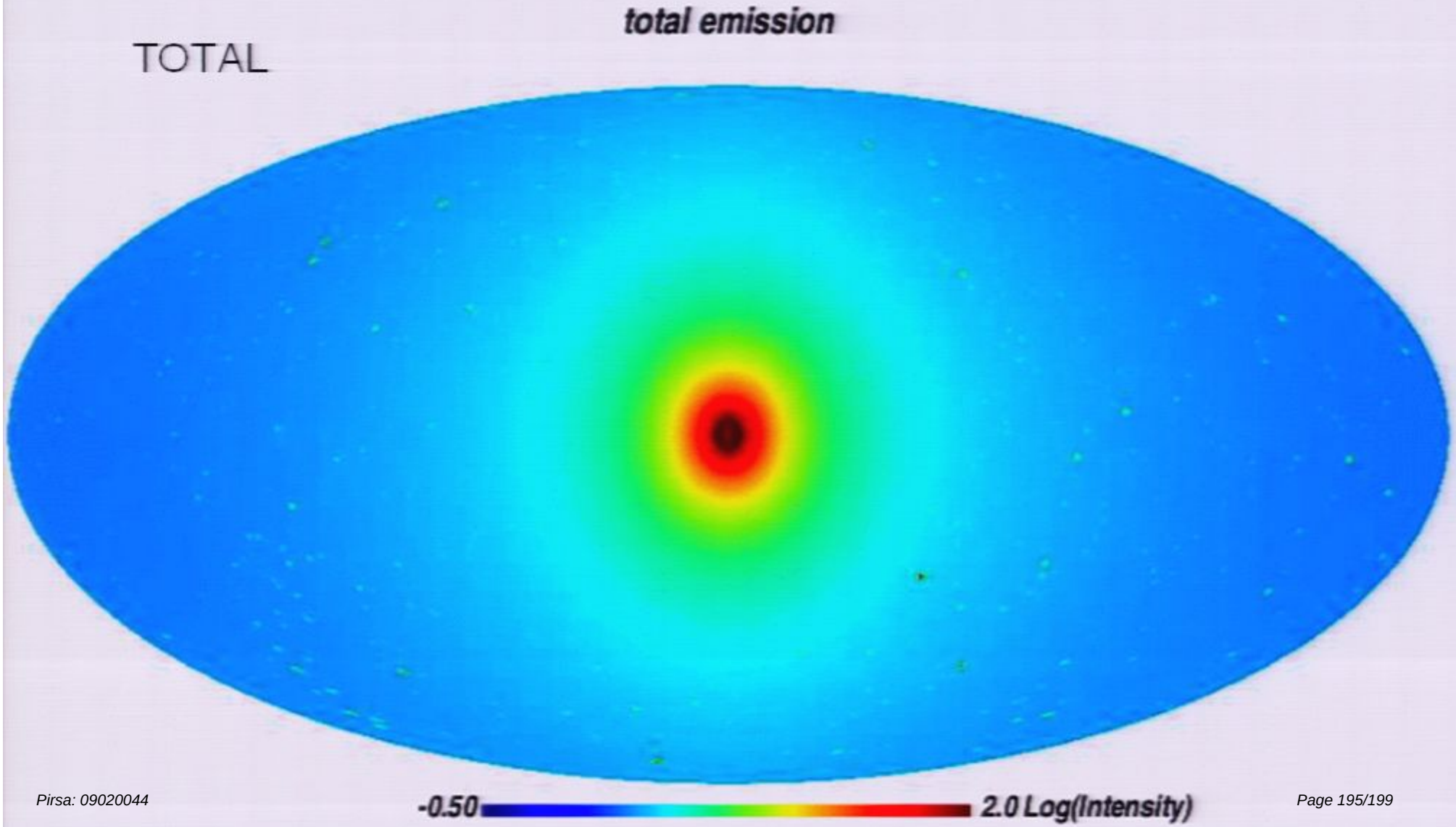

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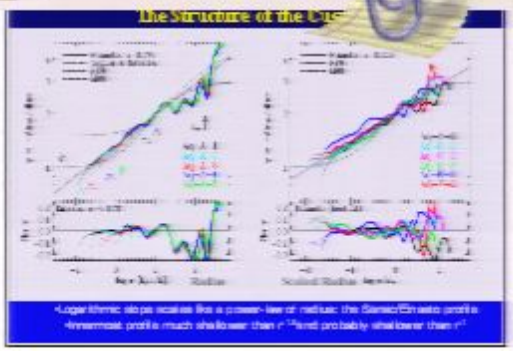

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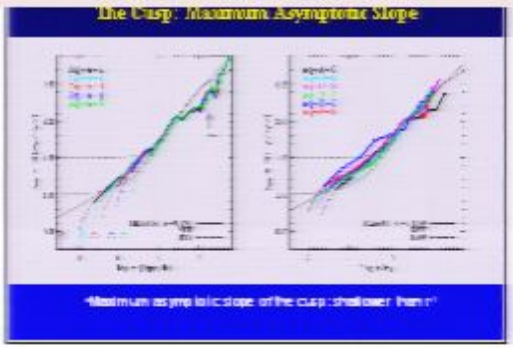

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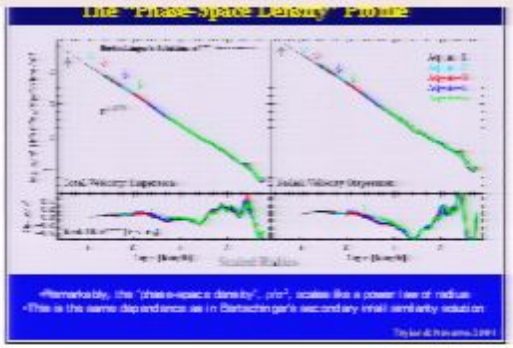

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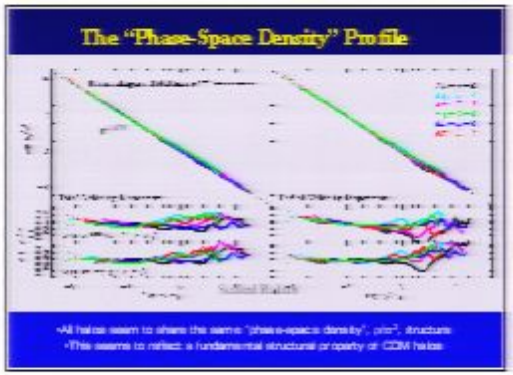

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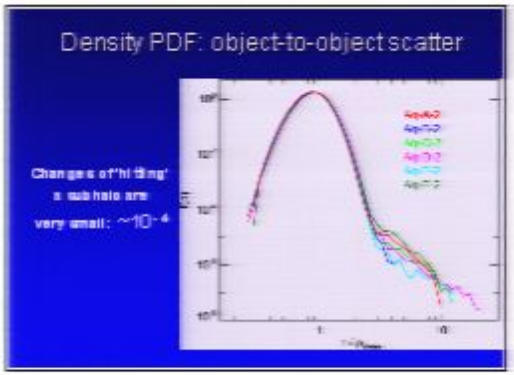

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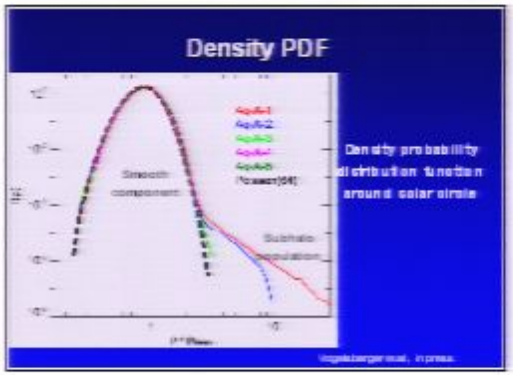

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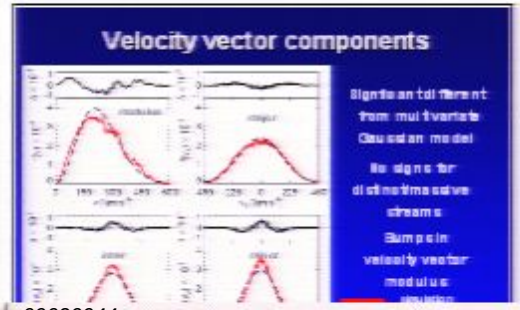

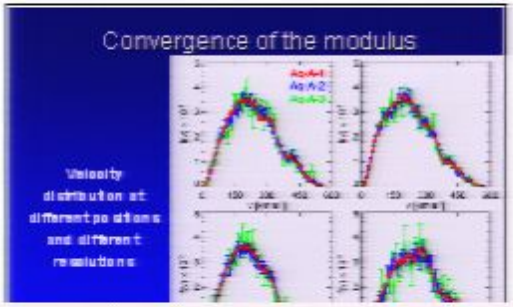

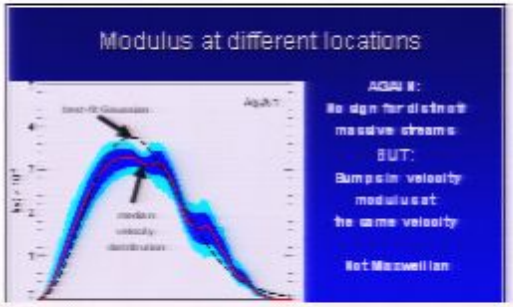

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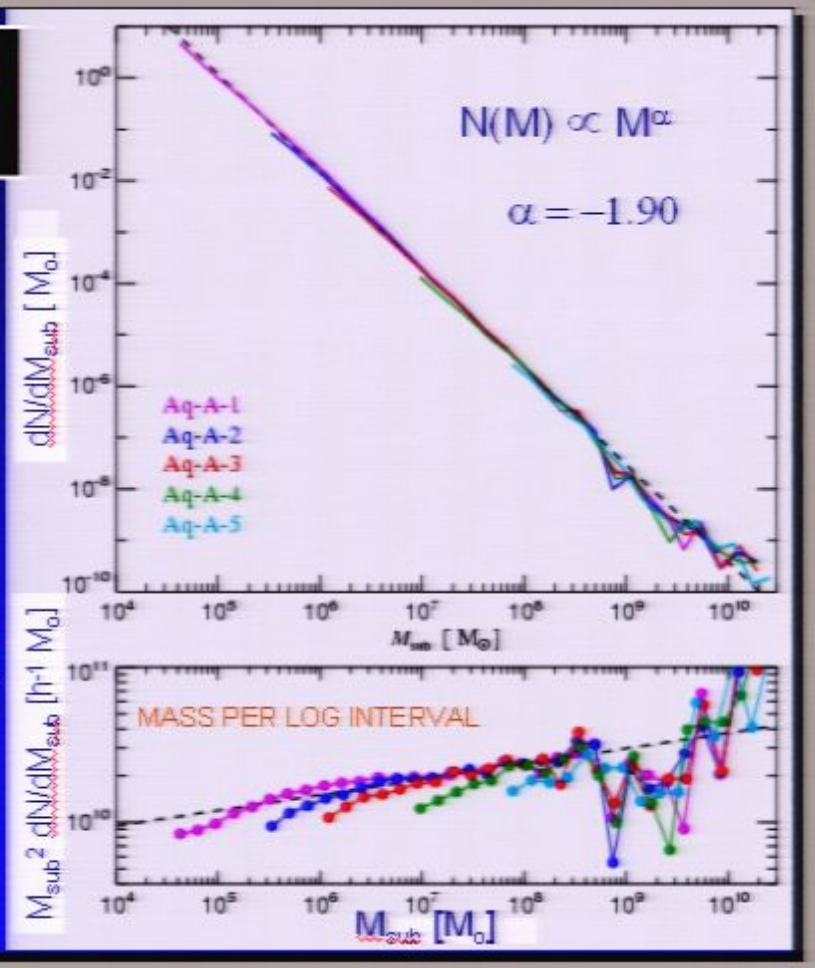

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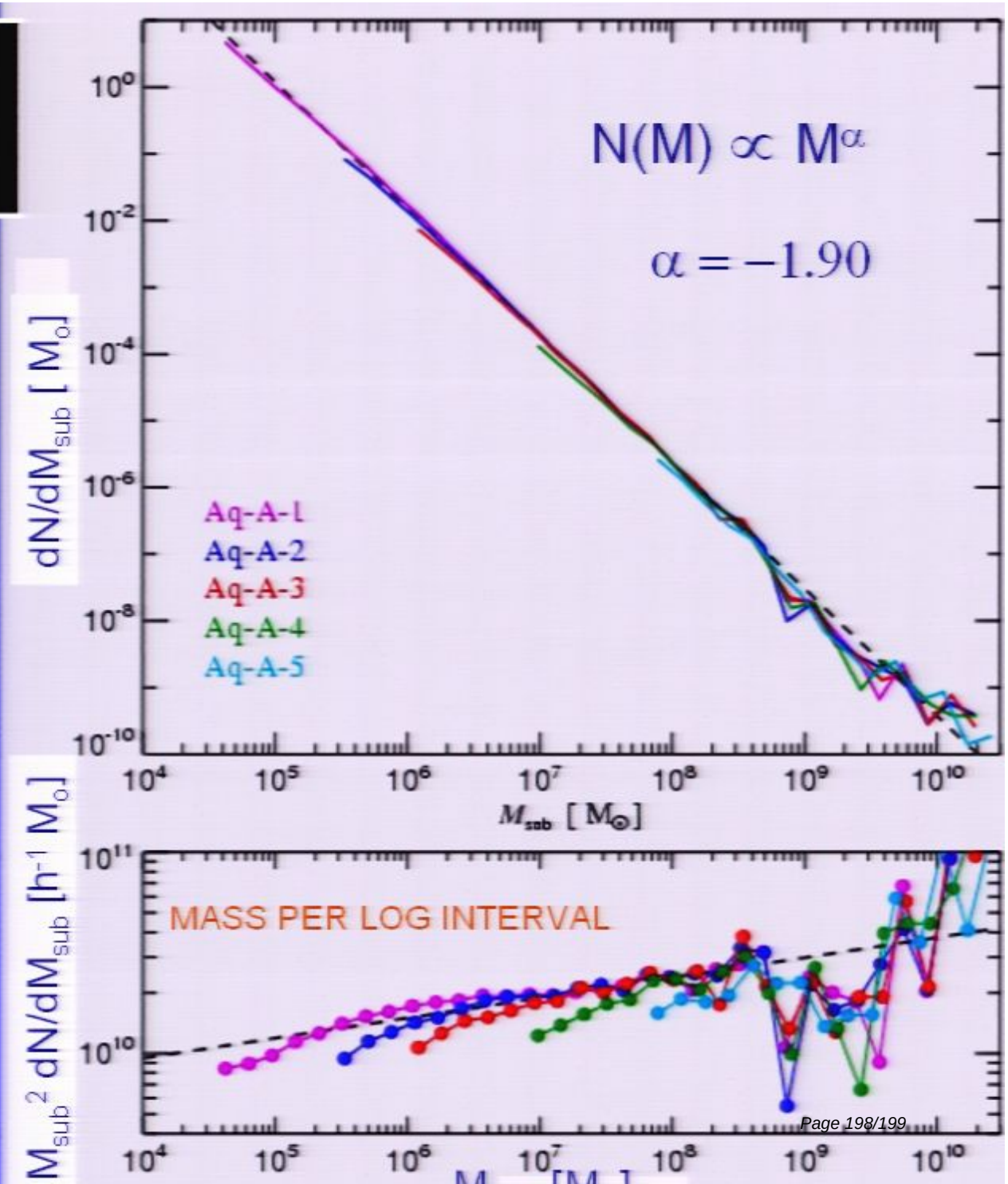

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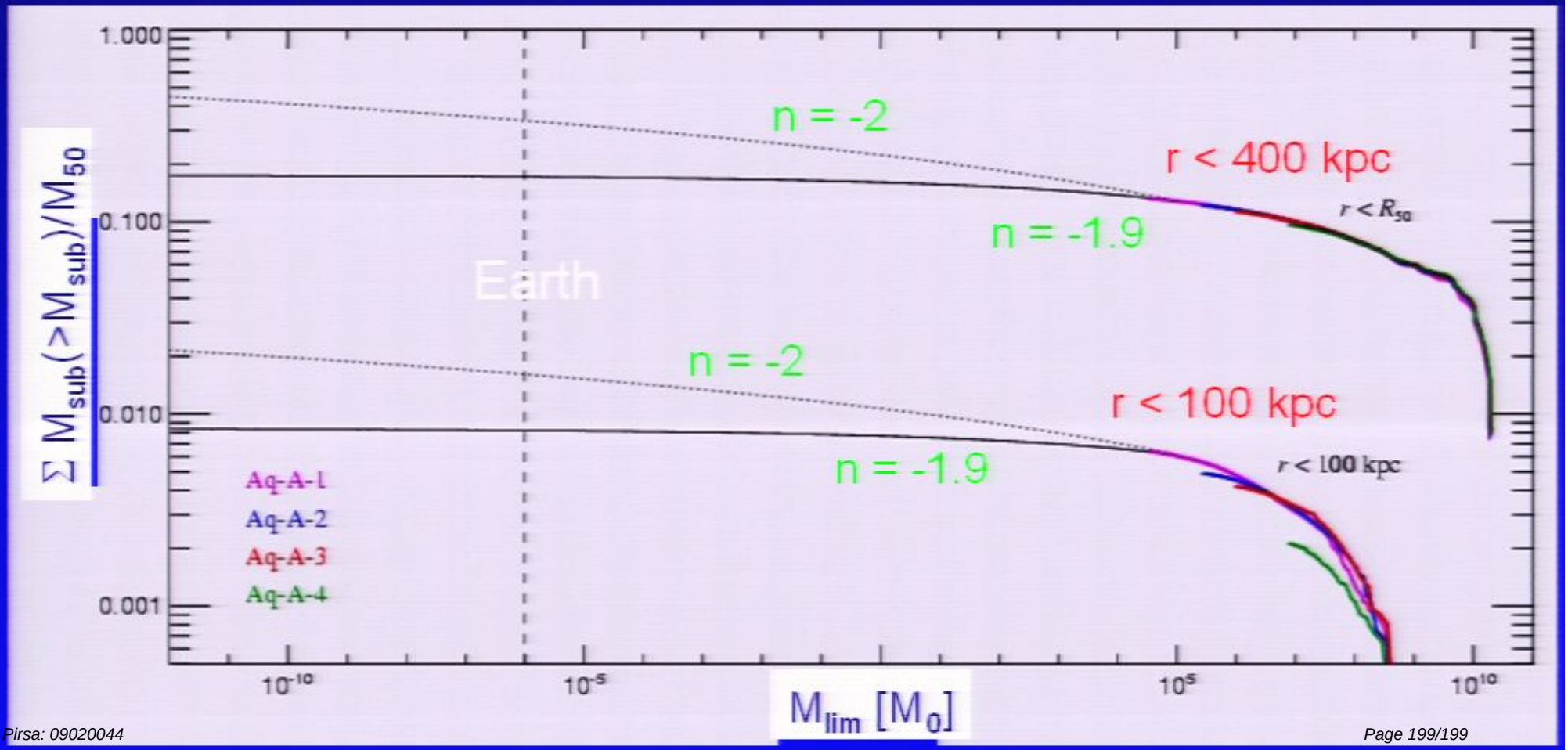

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