Title: Galaxy Formation: Problems, Solutions and Beyond

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Abstract: Cosmo Seminar

University of Durham

Galaxy Formation, Problems, Solutions and Beyond…

Black holes, their impact on galaxy formation and the next steps

Richard Bower

Ian McCarthy, Andrew Benson

Ian Vernon

& the Galform team

The OWLS project and beyond

Joop Schaye

Craig Booth, Ian McCarthy, Rob Crain

and the OWLS team

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Part I

- The late universe
- How do galaxies form?

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We want to…

- Get from here (t=10^3 yr)

(and before…)

- To here (t=10^{10} yr)

(and beyond…)

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The pieces of the galaxy formation problem

- The Early Universe
  - Seed fluctuations in density
- Gravitational instability
  - The lowest entropy state of a gravitating system is strongly clustered
  - …virialised dark matter halo
- Gas cooling
  - Need to radiate energy for collapse to proceed
  - …cold gas disk supported by angular momentum
- Star formation
  - …but that's not the end of it…

Cosmological model
(Ω_m, Ω_Λ, h); dark matter

↓

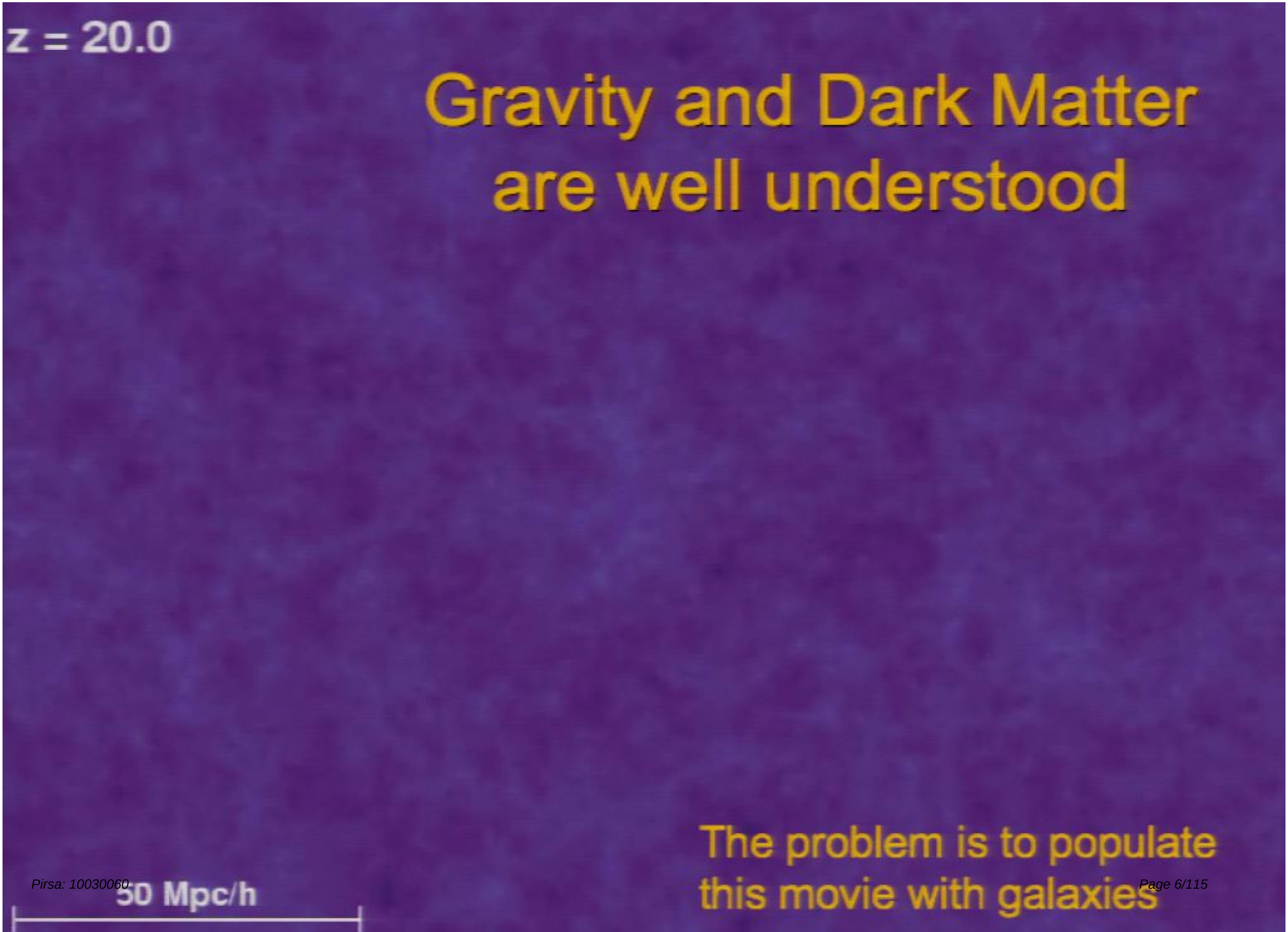
Primordial fluctuations
$\delta\rho/\rho(\mathbf{M}, \mathbf{t})$

↓

Dark matter halos
(N-body simulations)

↓

Gas processes
(cooling, star formation, feedback)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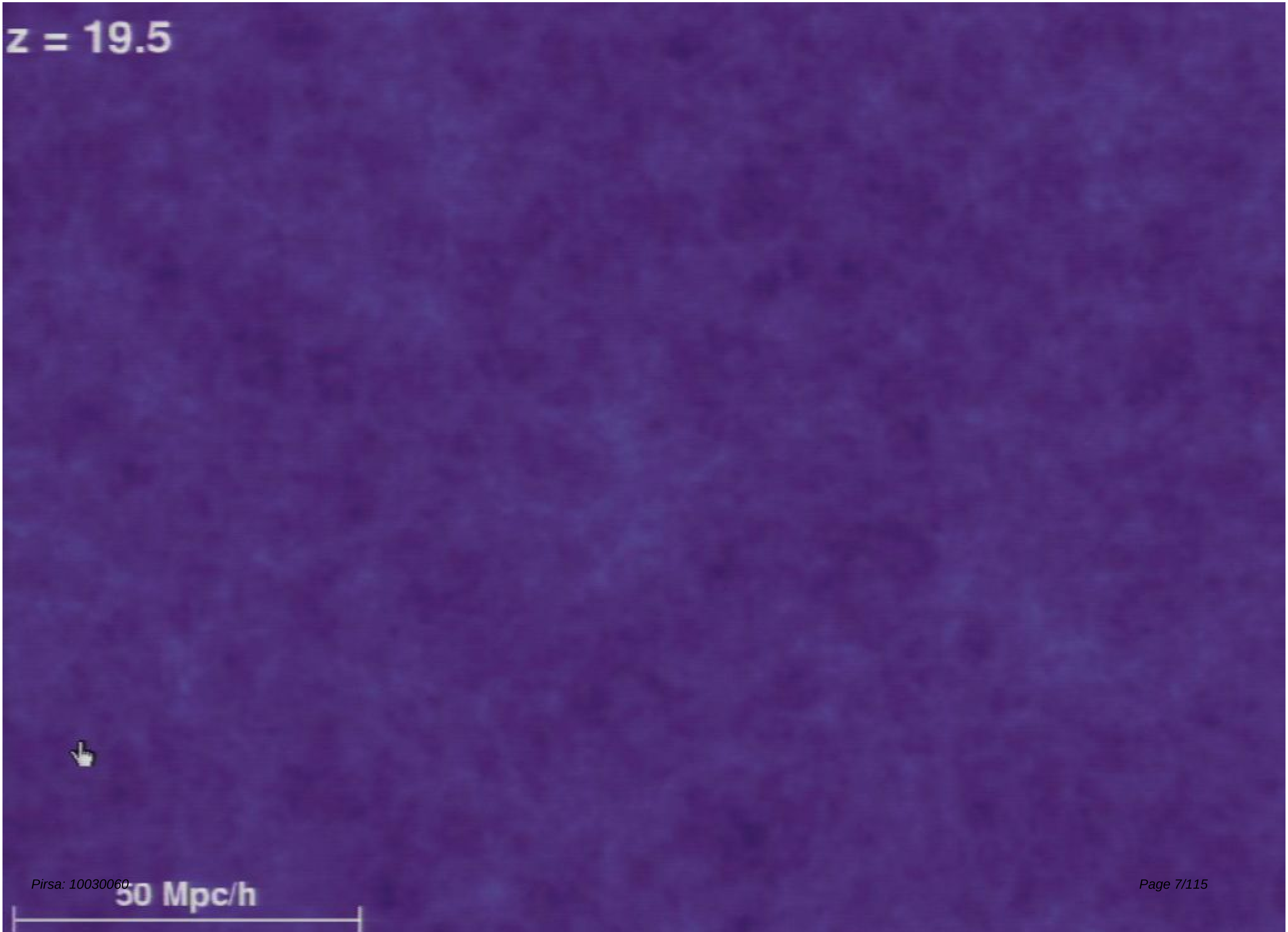
Gravity and Dark Matter are well understood
The problem is to populate this movie with galaxies
50 Mpc/h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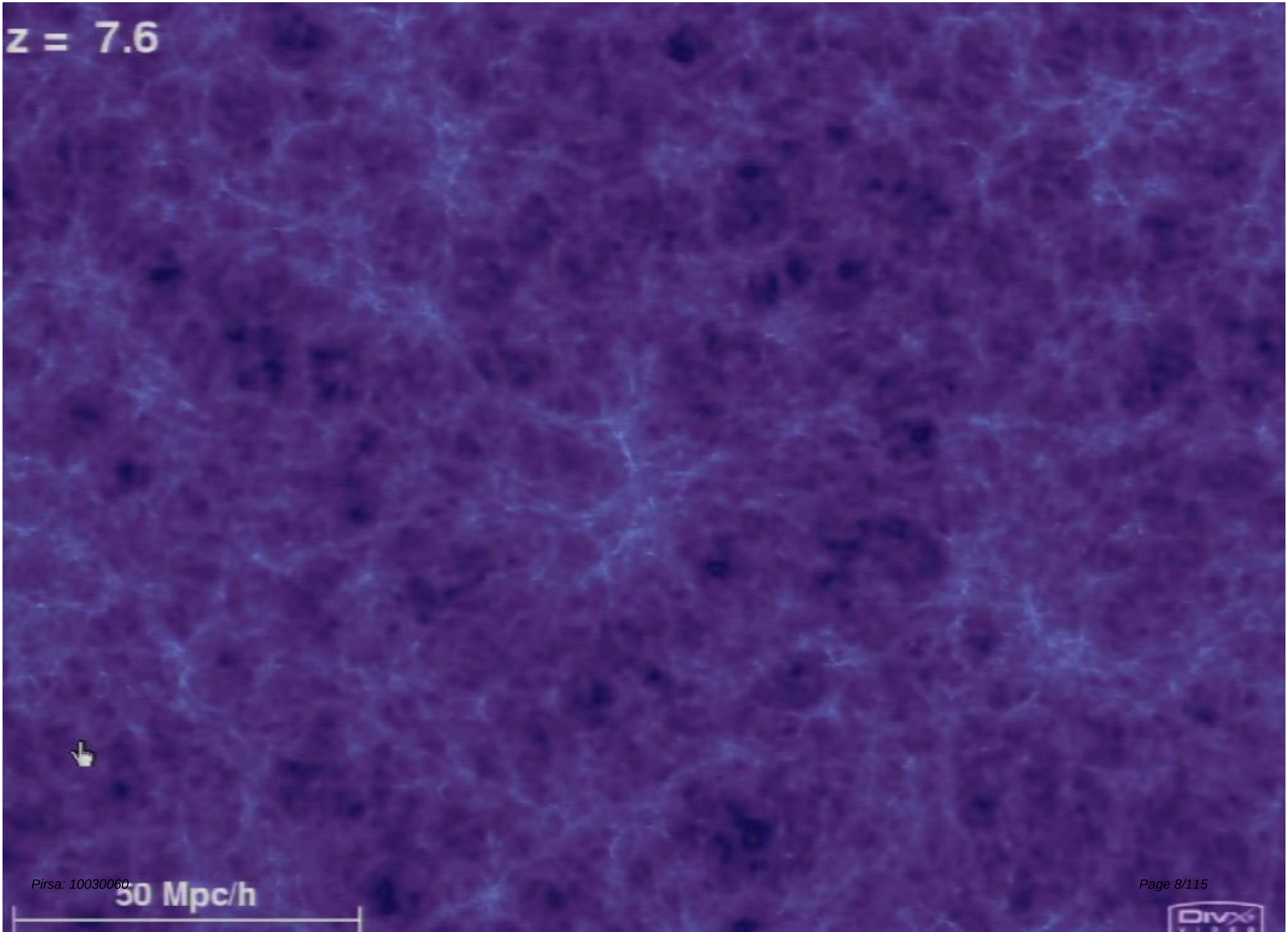
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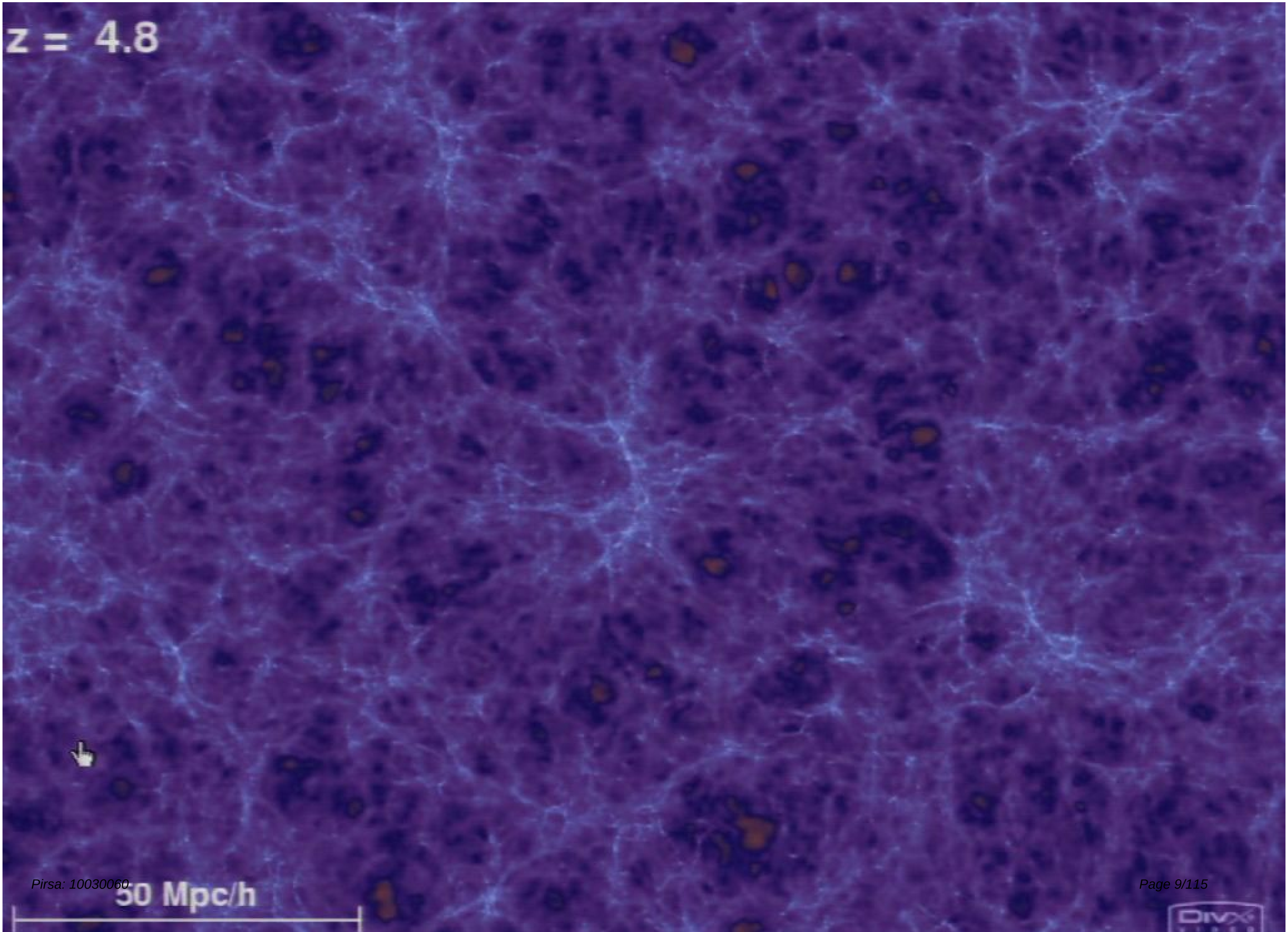
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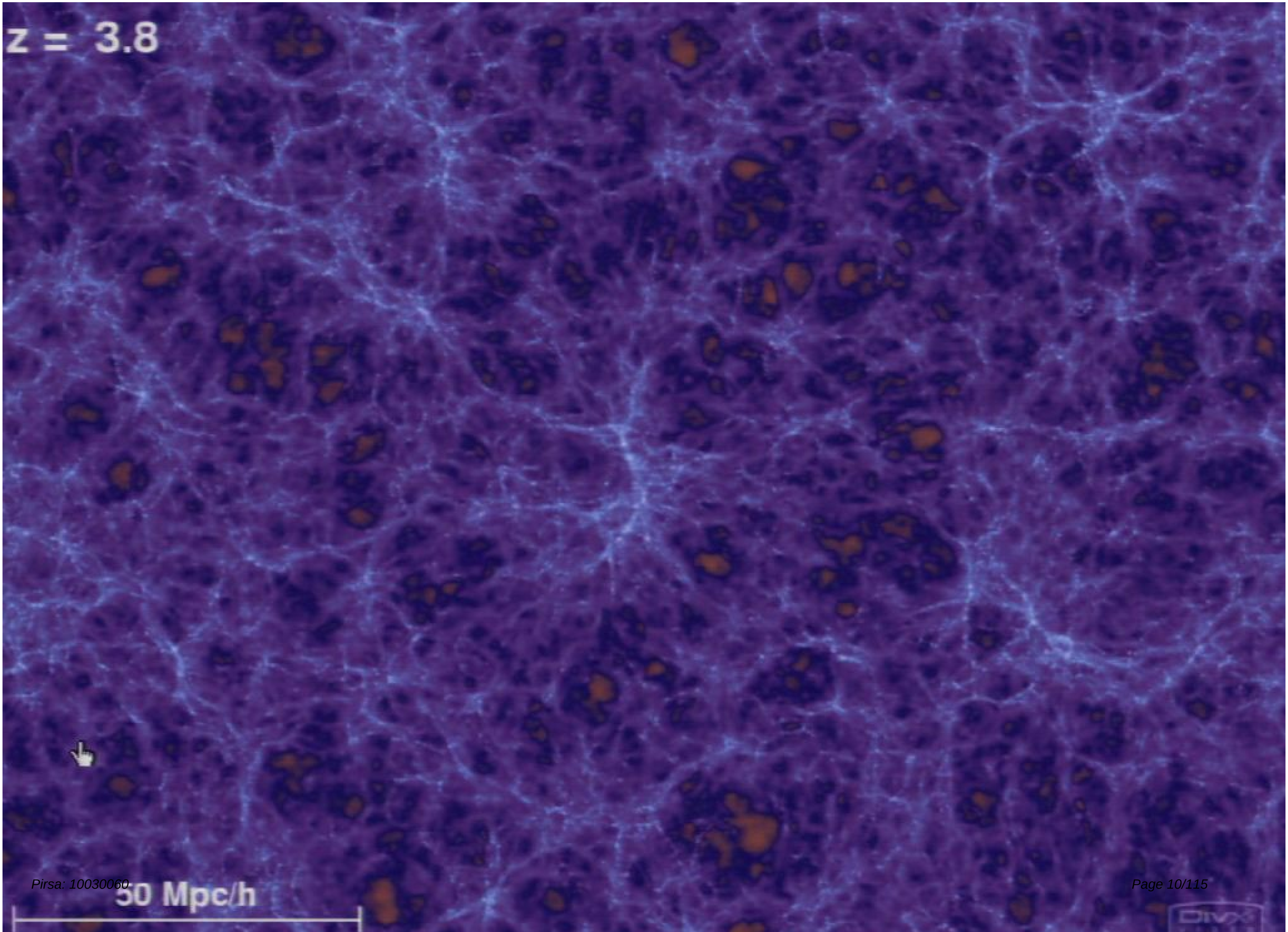
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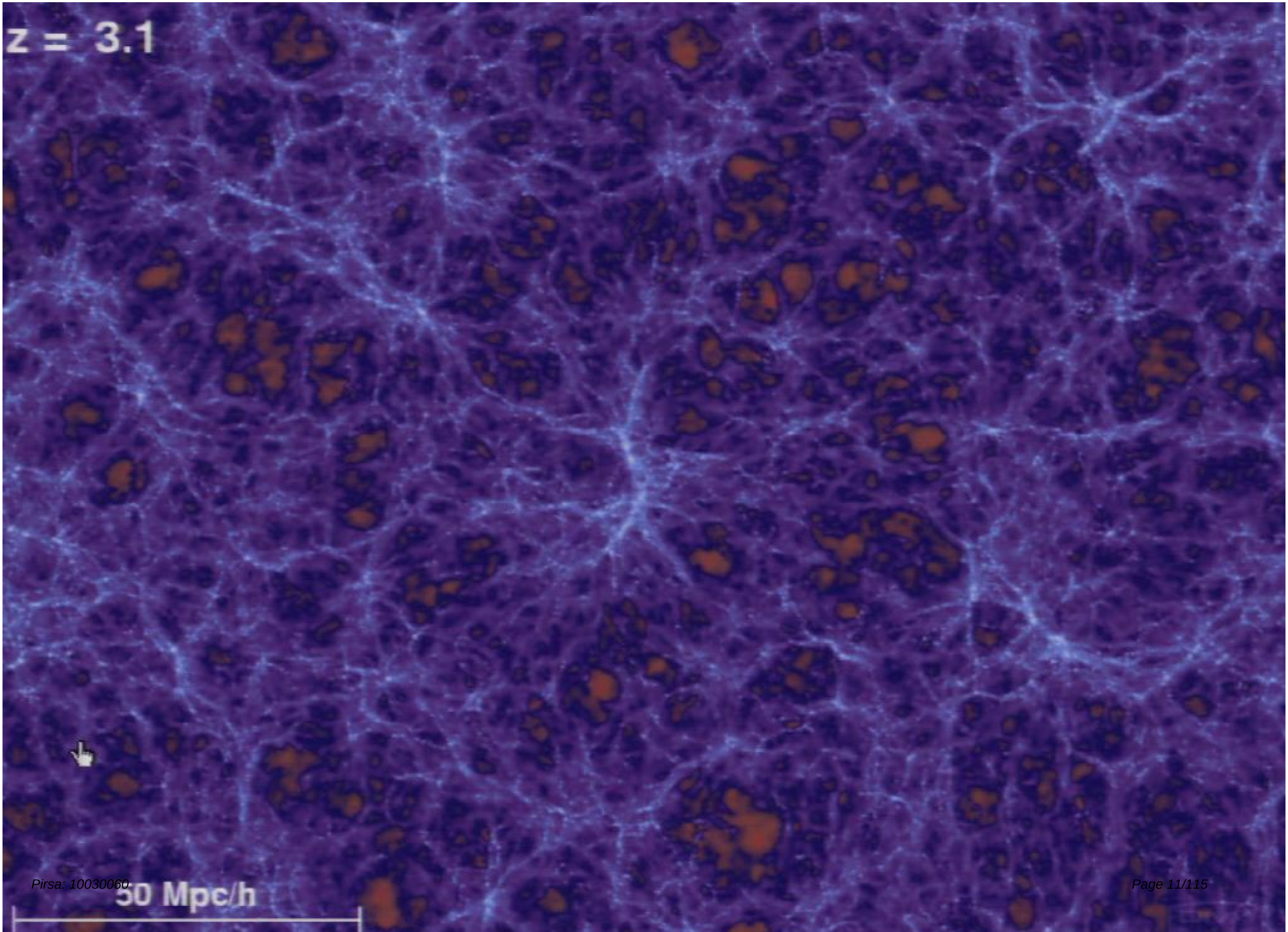
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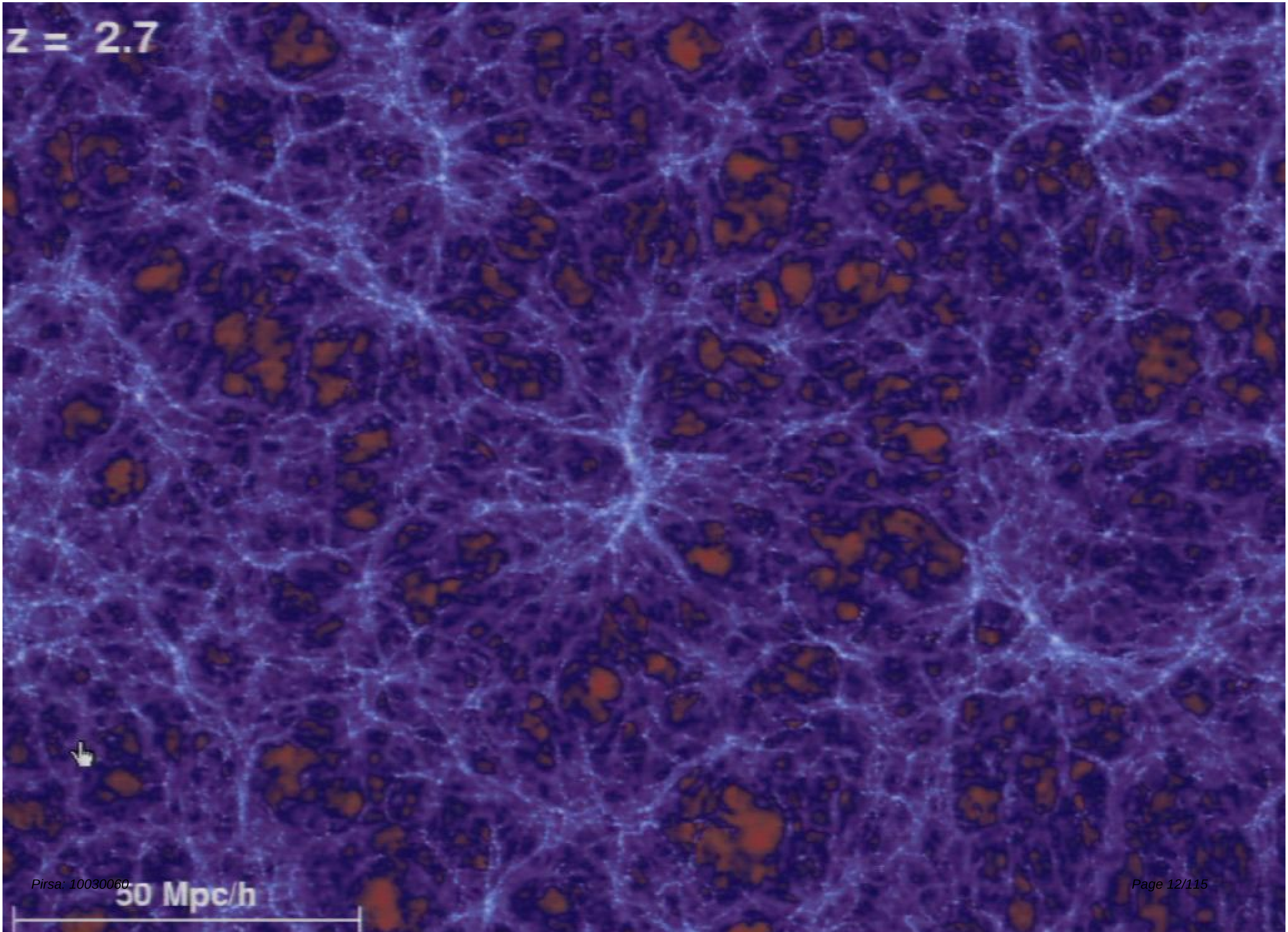
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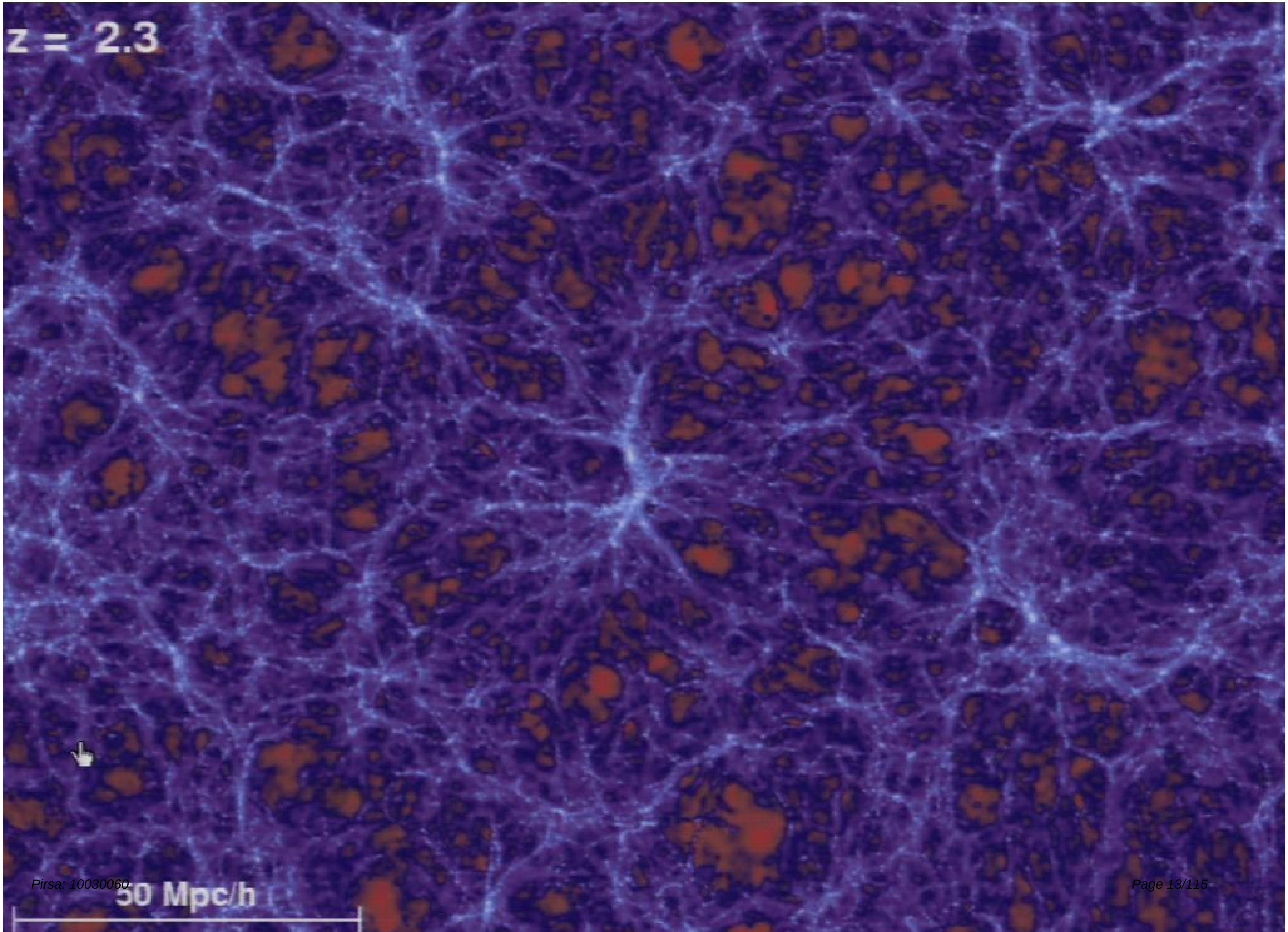
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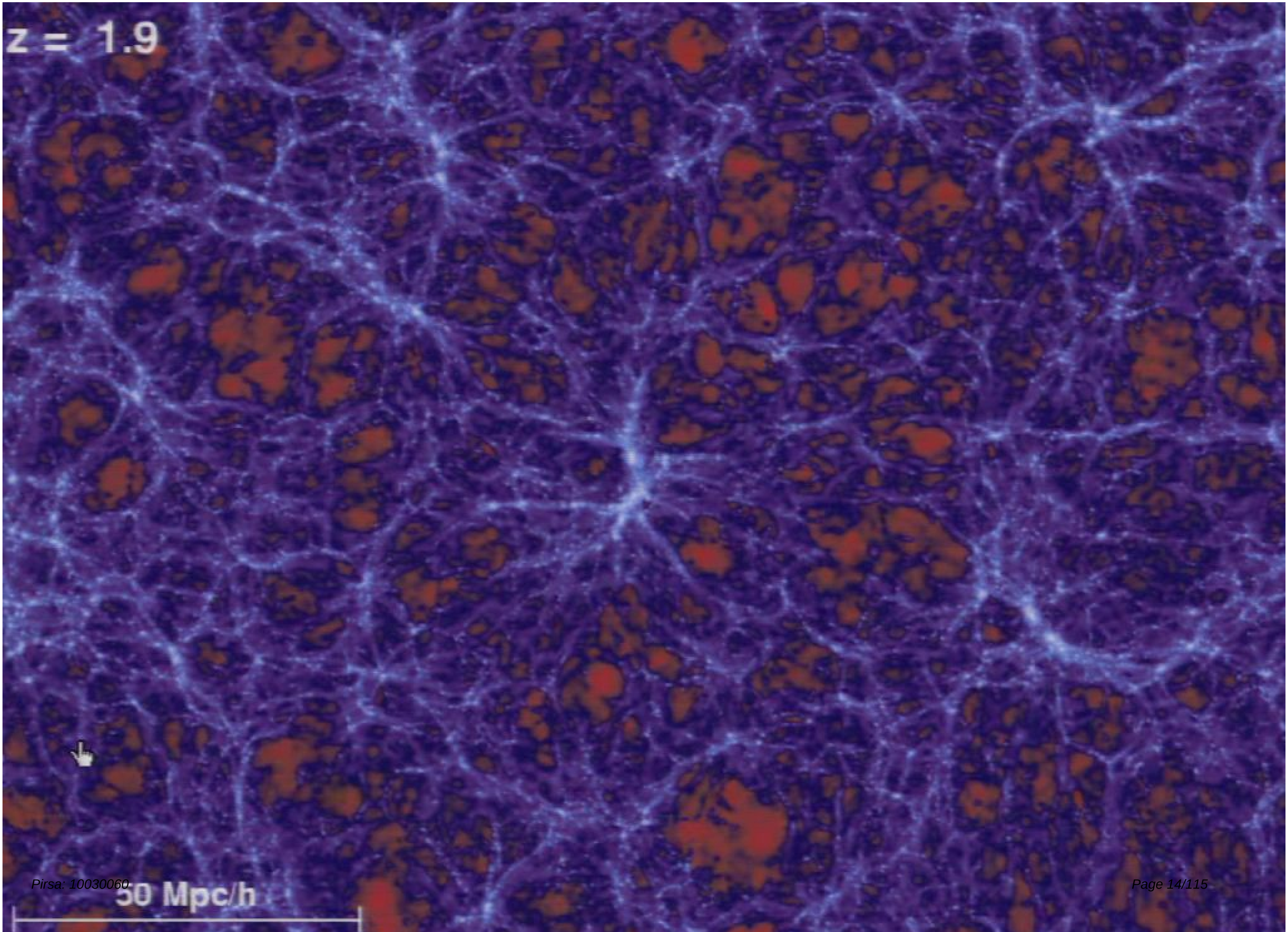
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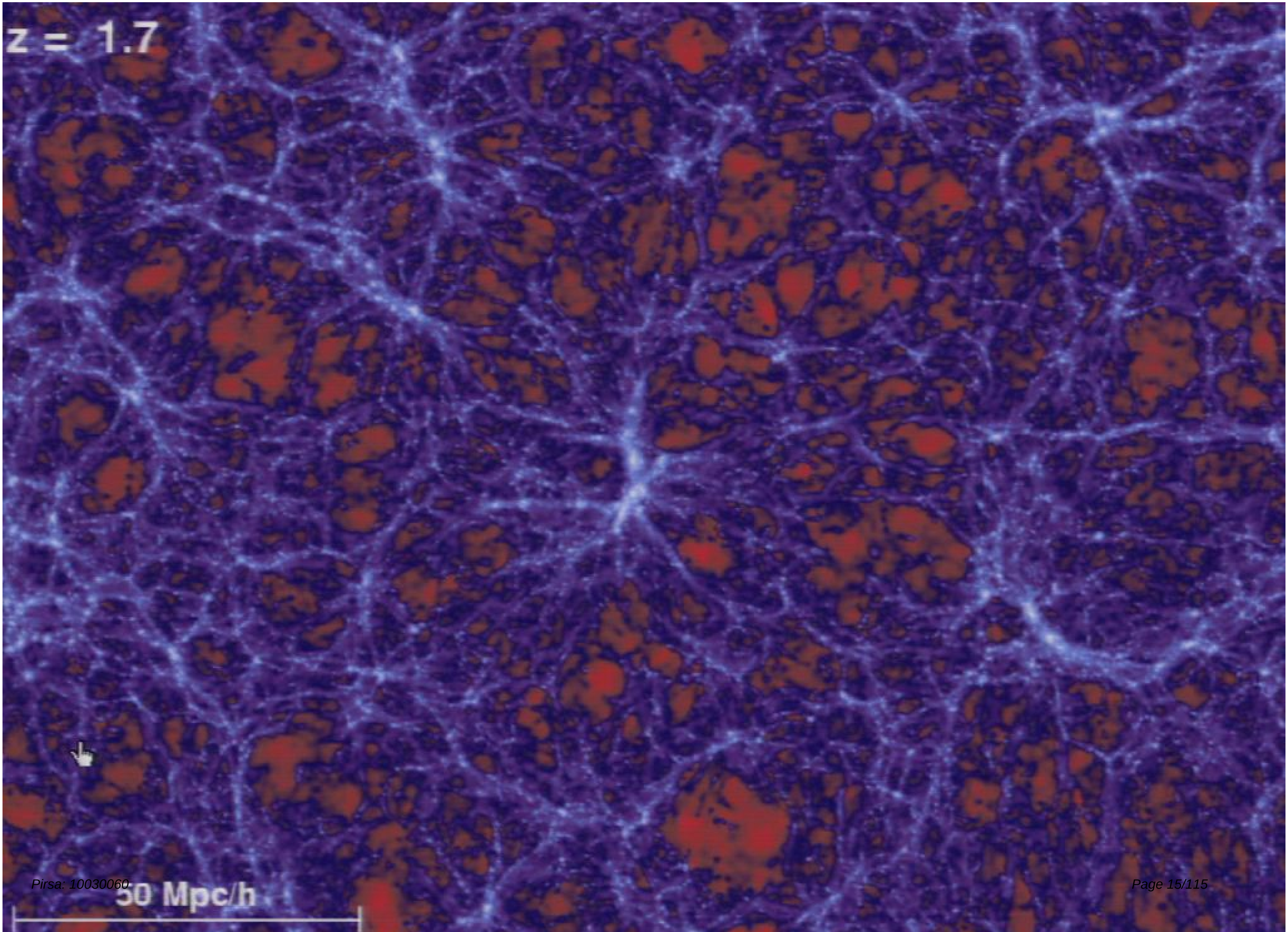
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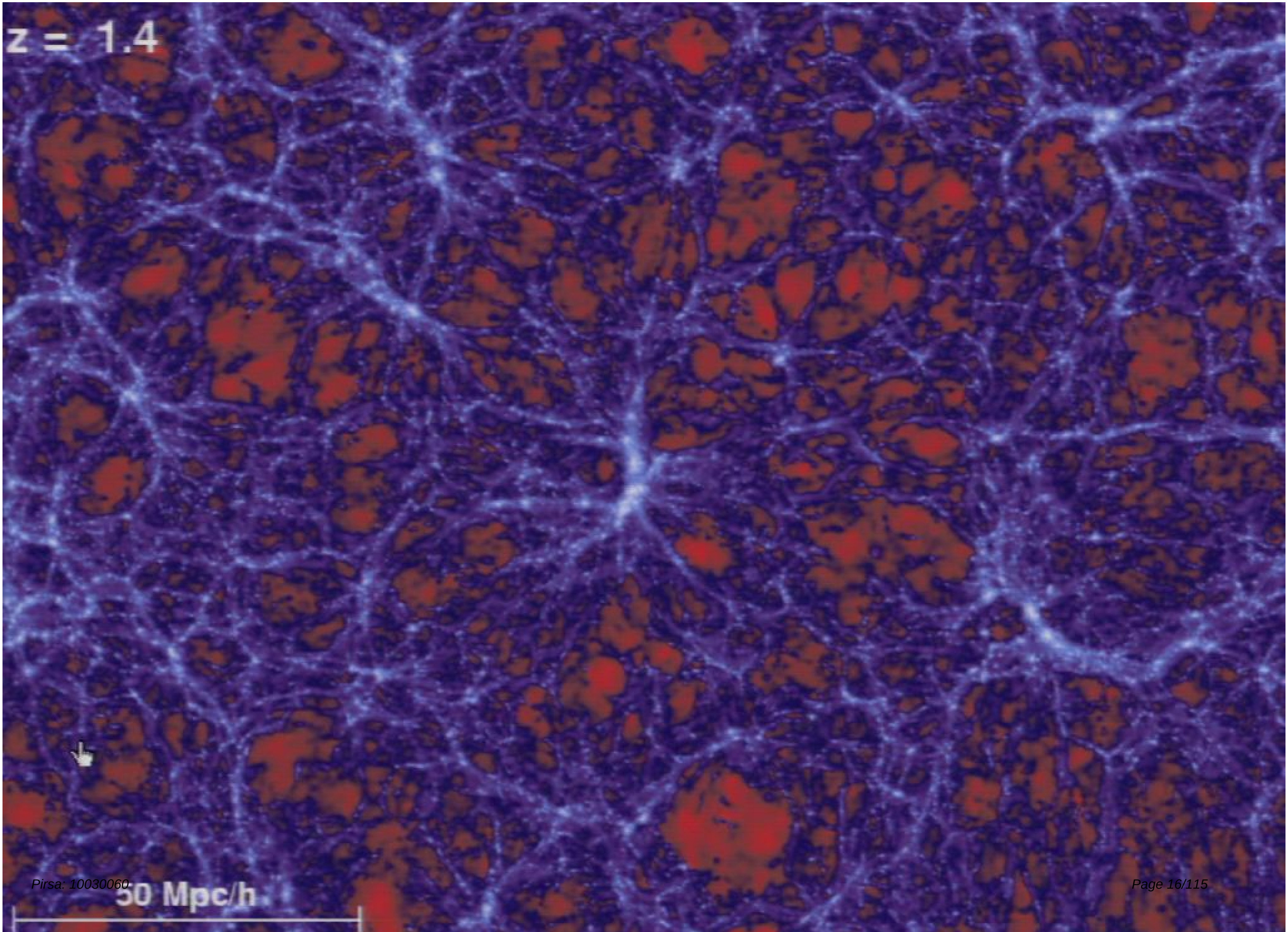
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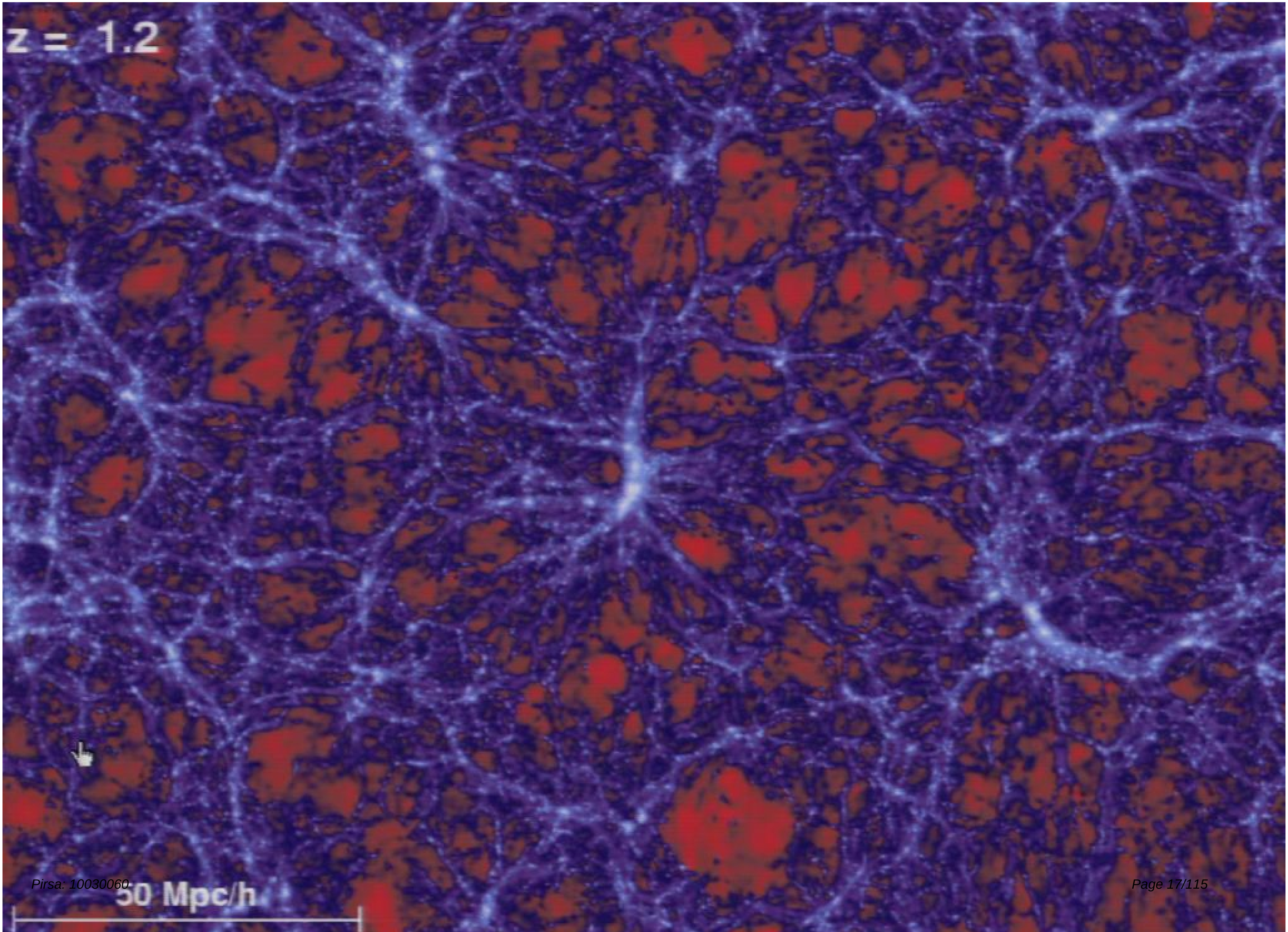
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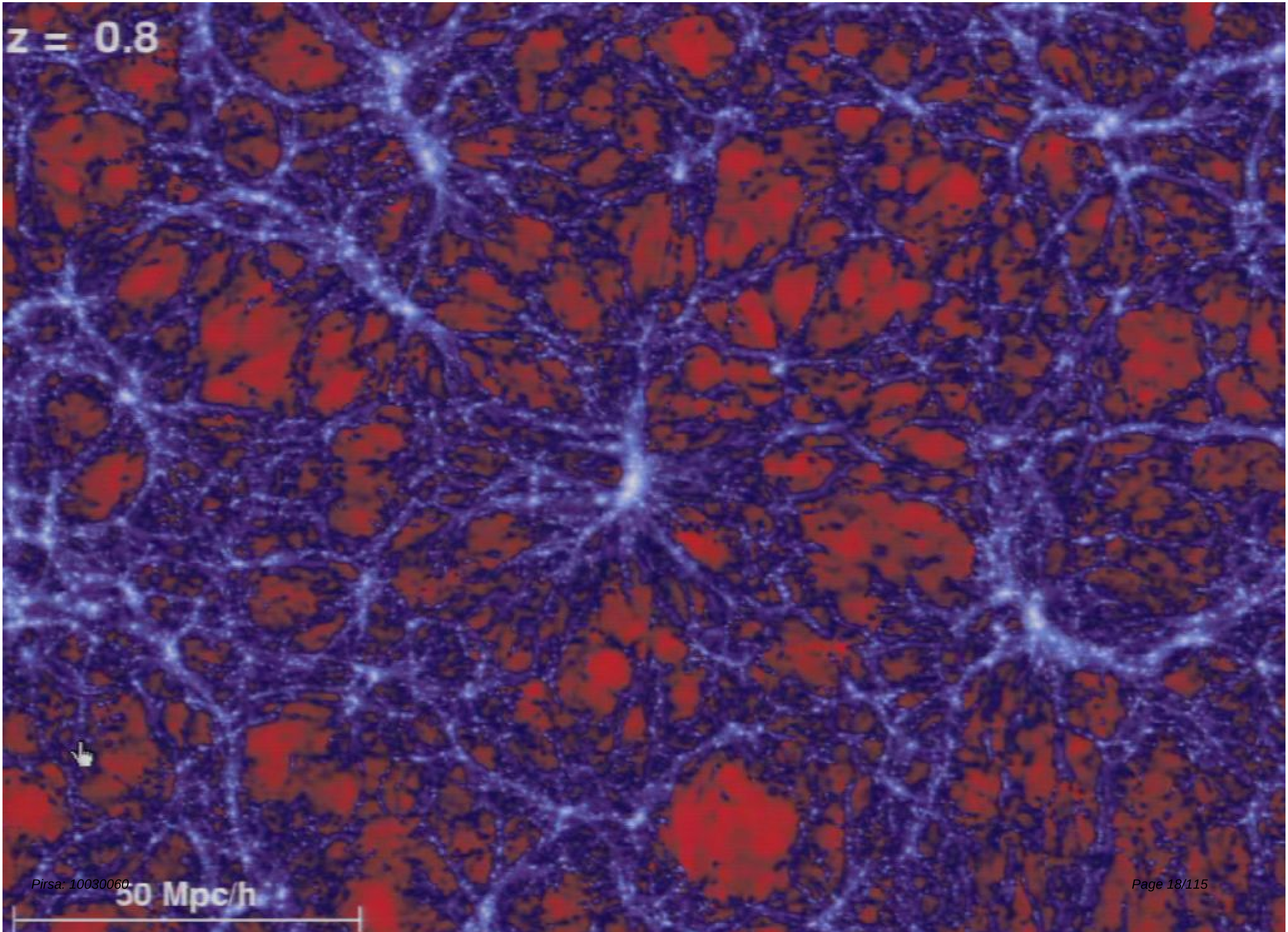
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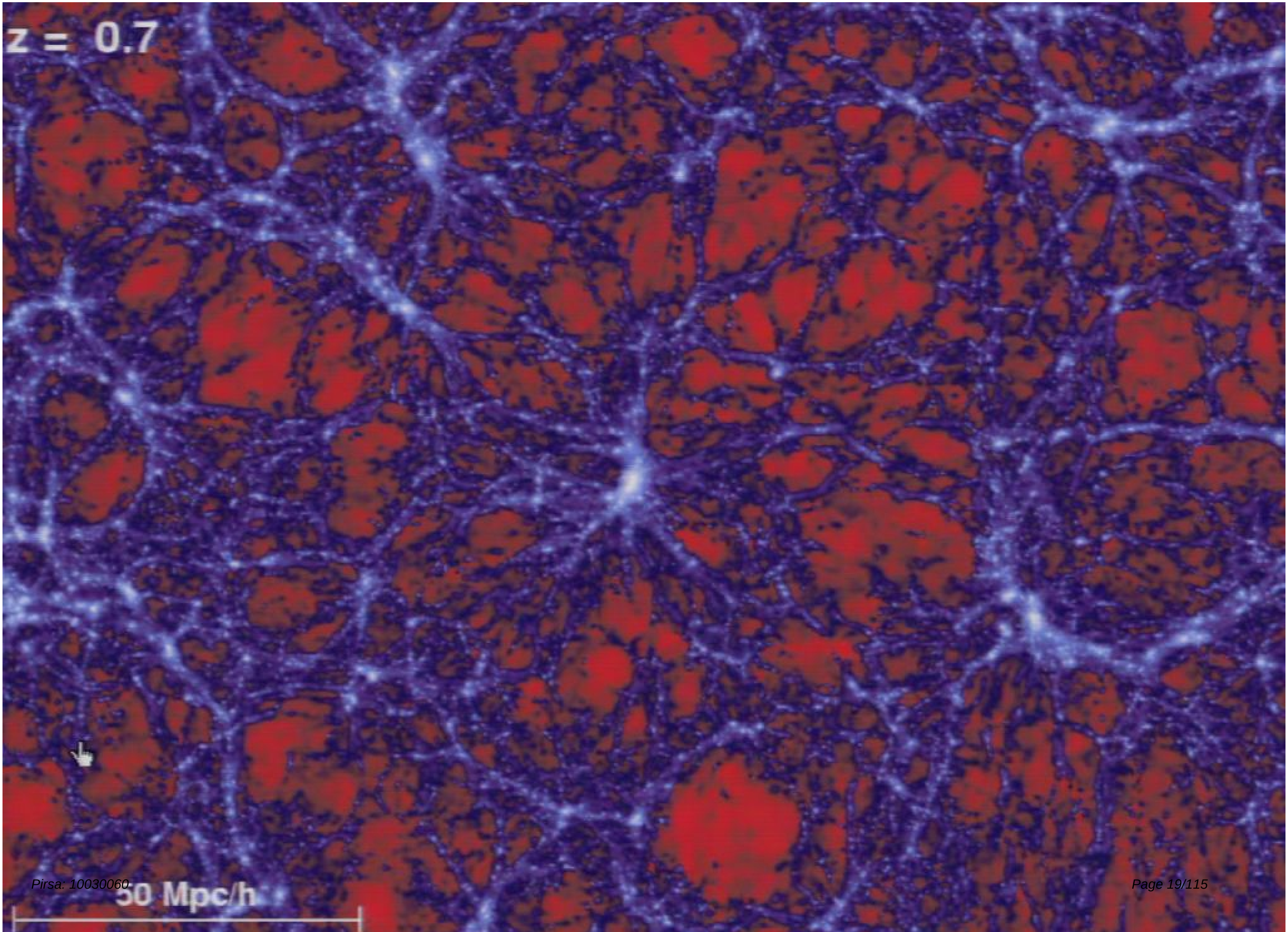
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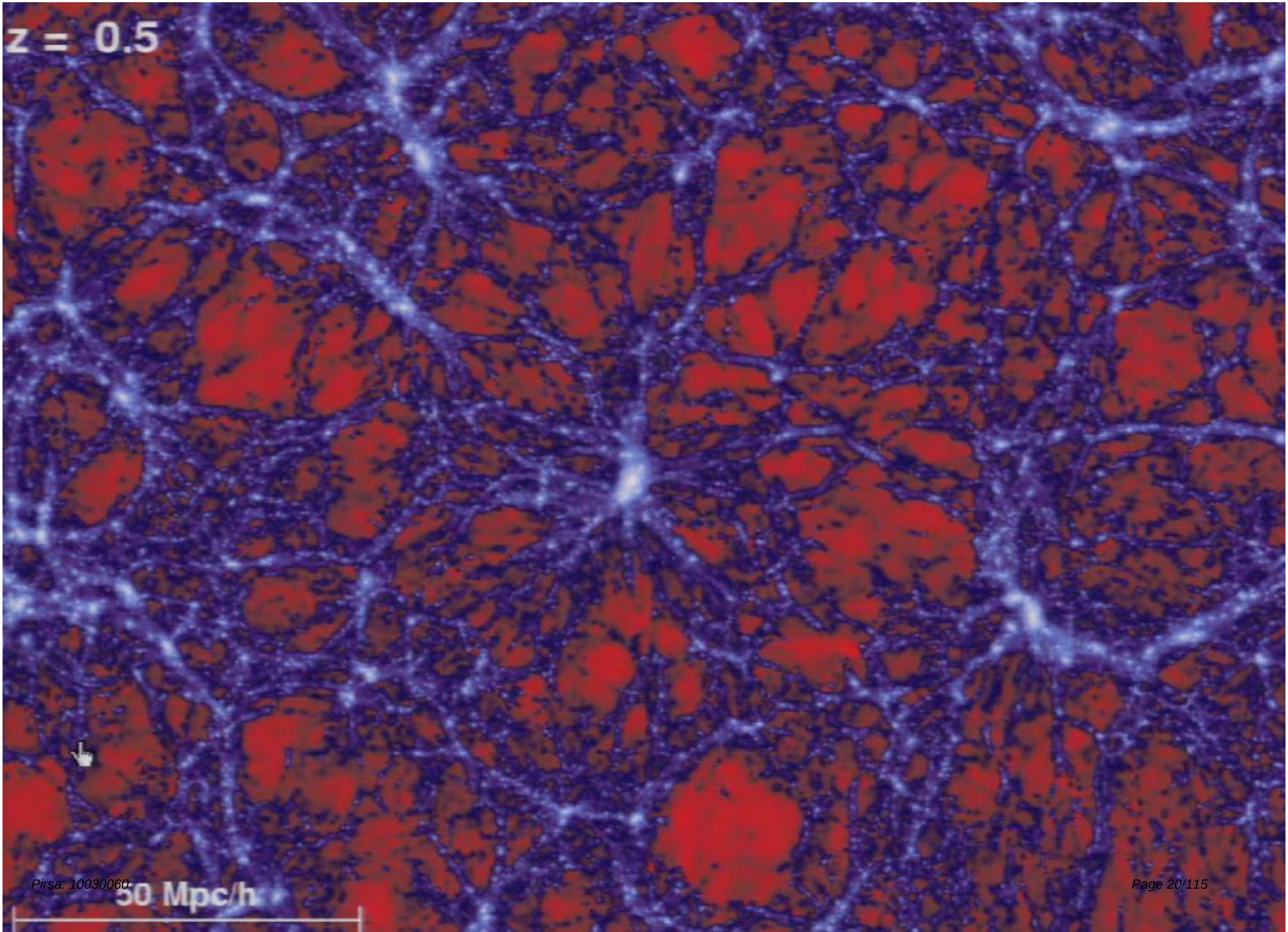
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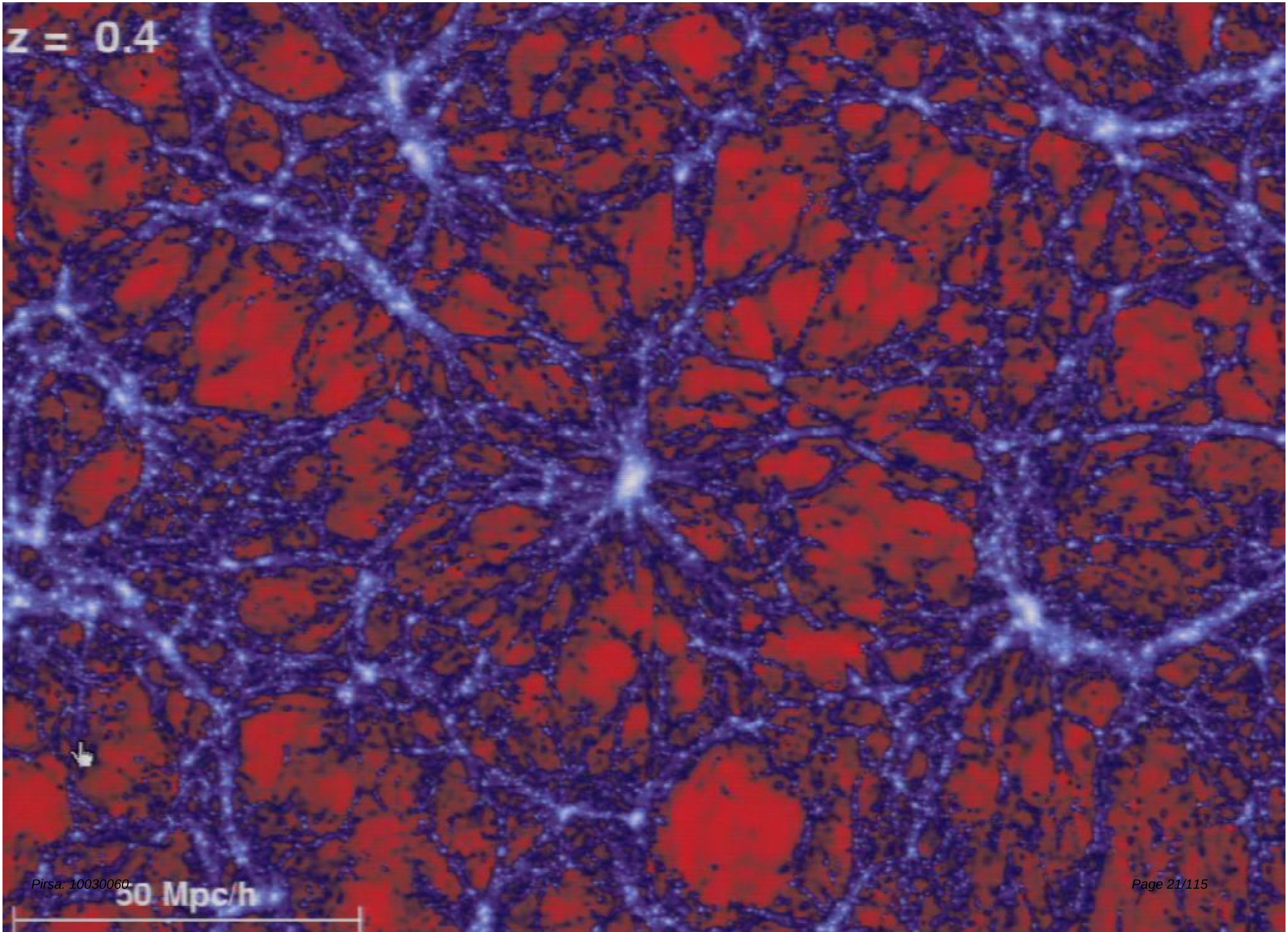
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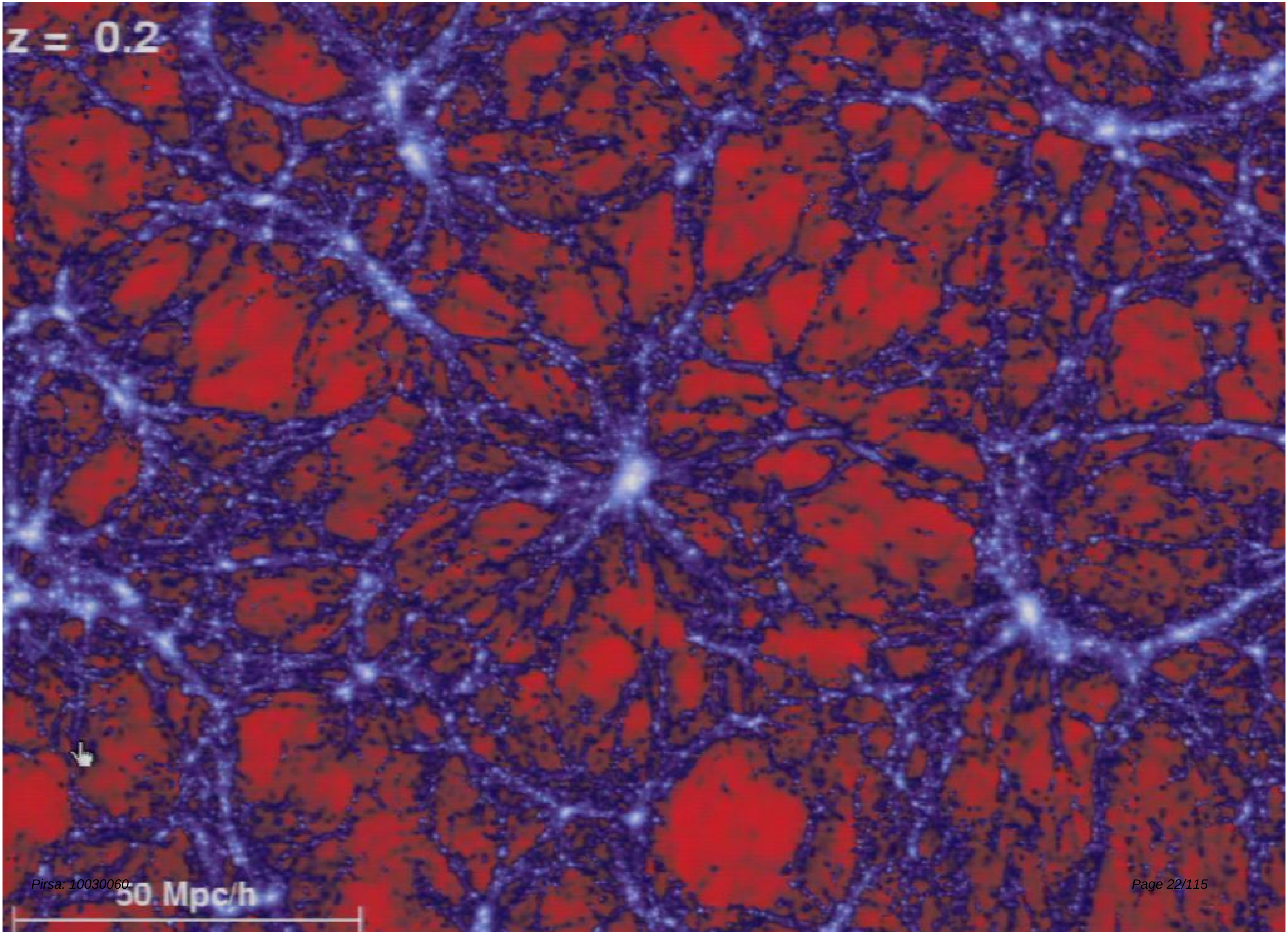
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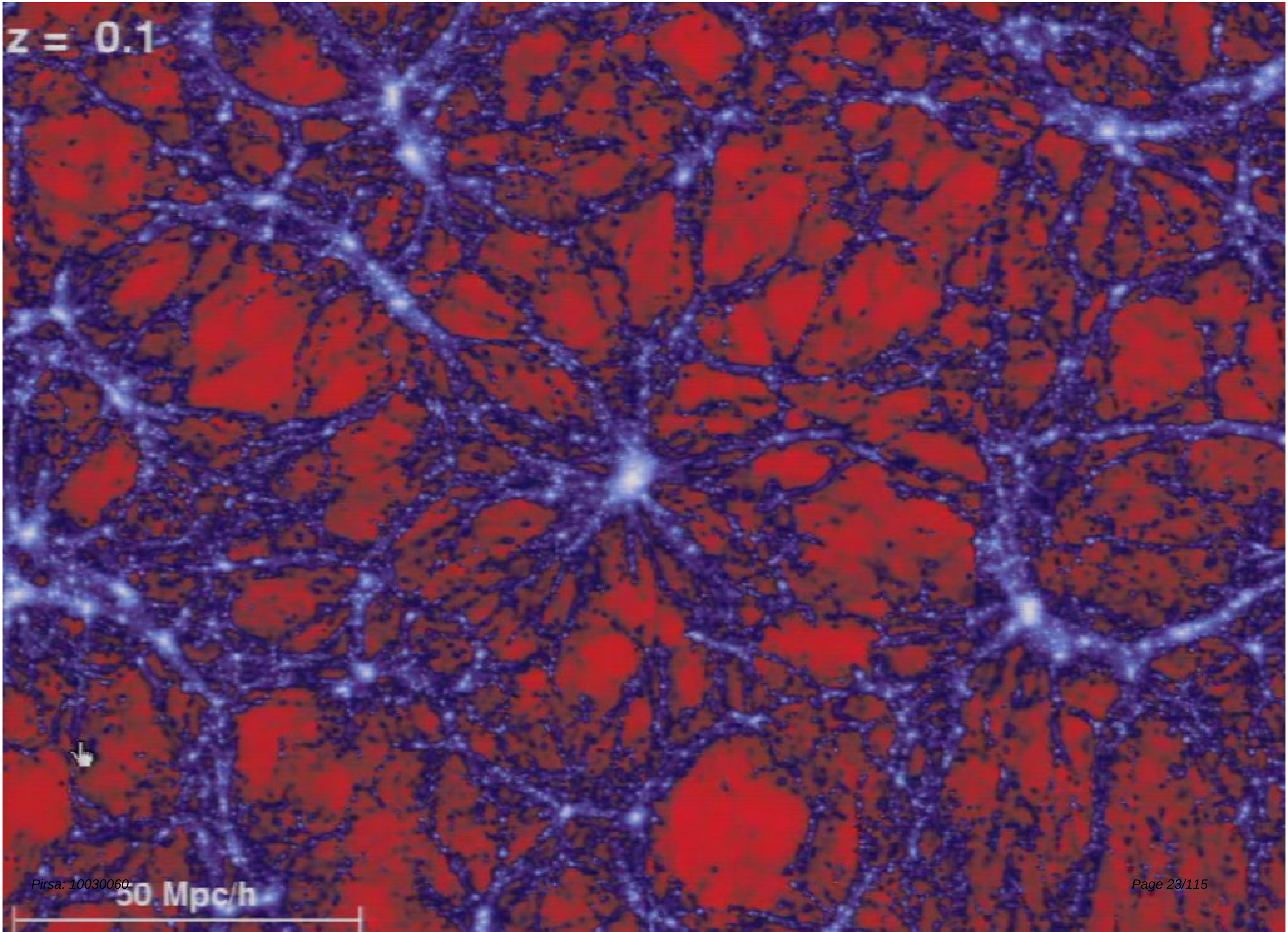
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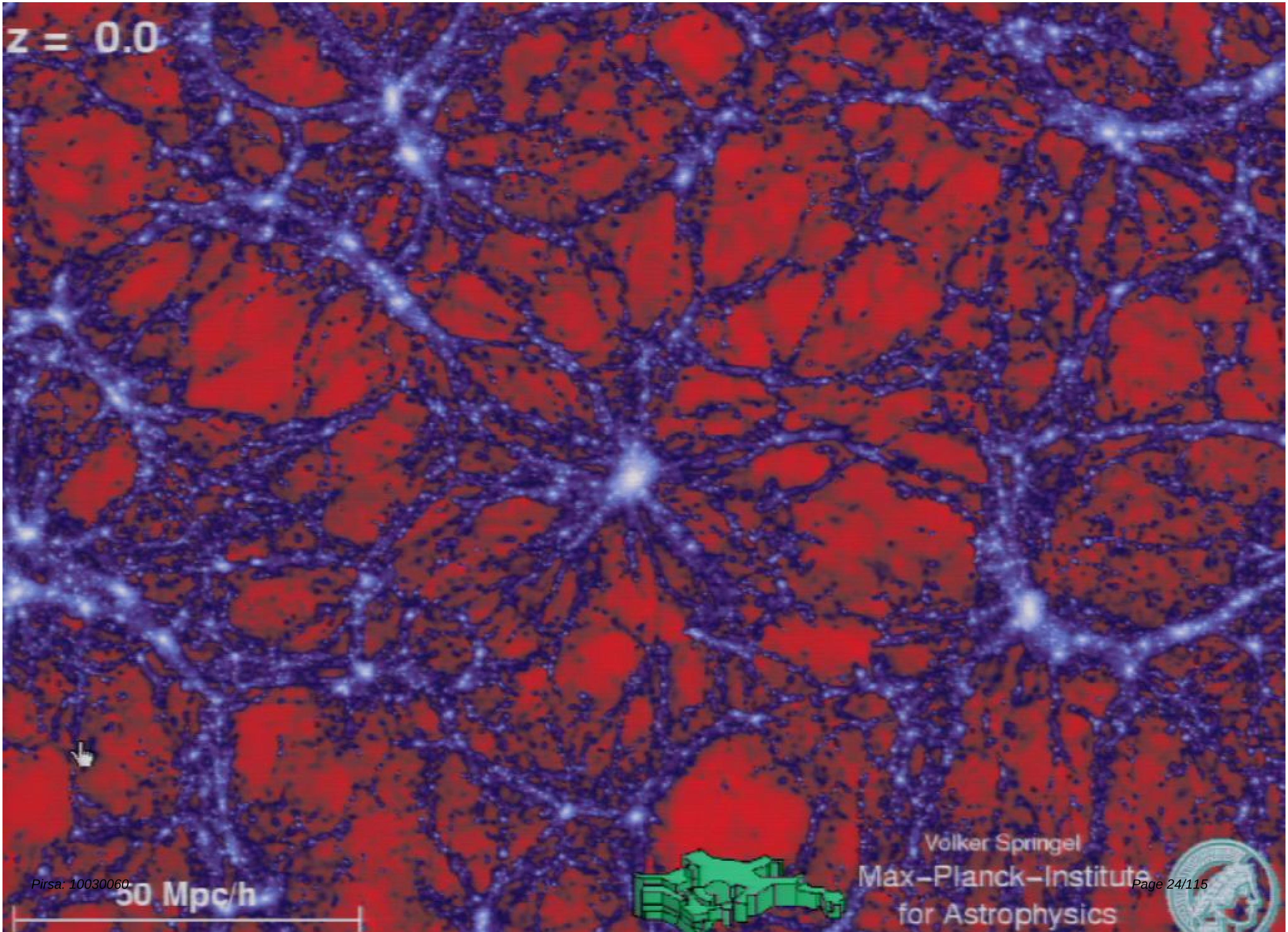
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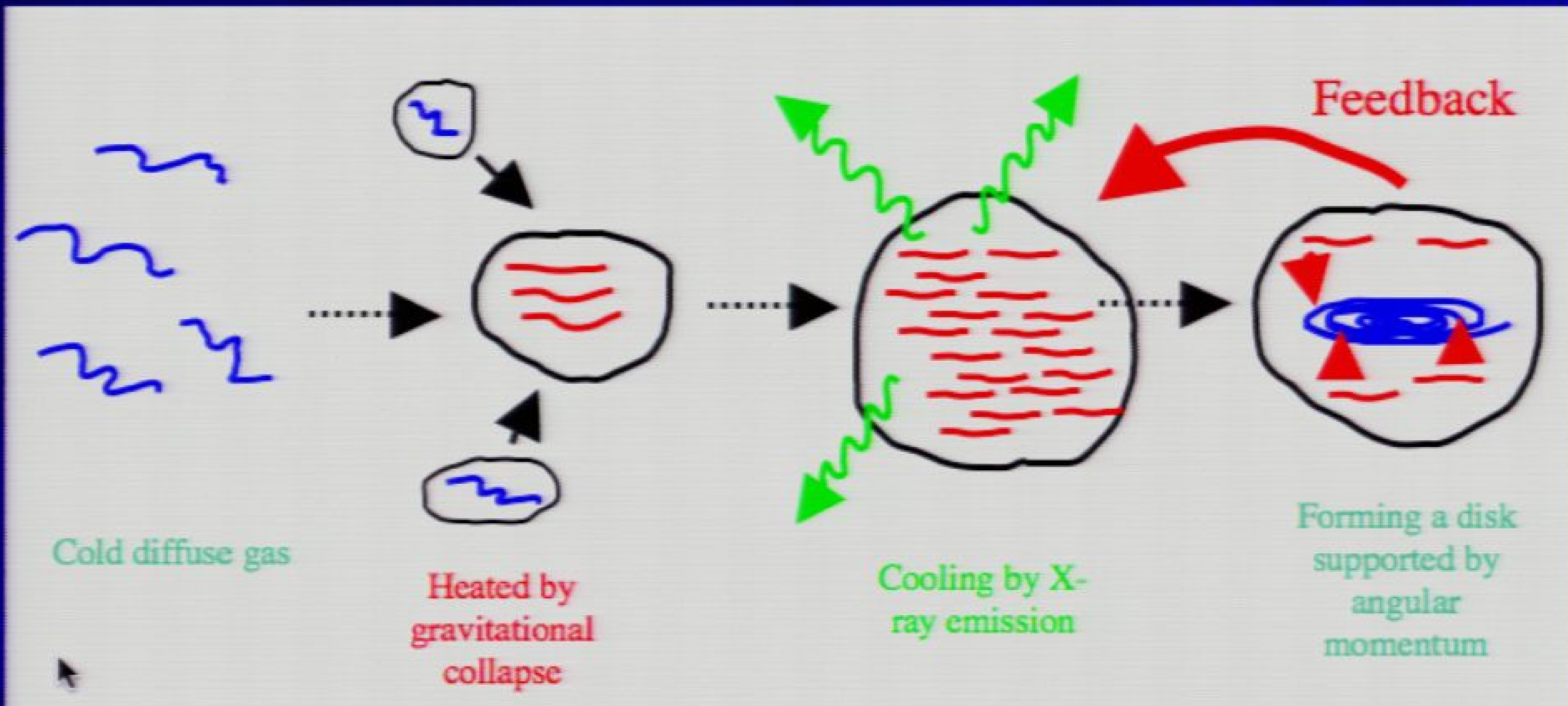
50 Mpc/h
Volker Springel
Max–Planck–Institute
for Astrophysics

A Galaxy Formation Cartoon



Run away cooling is prevented by "feedback"
- but how does feedback work?

Rees & Ostriker, 1978; White & Frenk 1991

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The trouble with galaxy formation

- Galaxies from because gravitating systems have negative specific heat
  - Cooling makes the system hotter and denser
  - Denser -> increased cooling
  - This overpowers the energy feedback from supernovae

...but...

- Galaxy Formation is observed to be very inefficient
  - Only 10% of baryons from into stars
  - Why?
  - What's missing?
    - the ISM is not a simple fluid
    - Black holes play a key role

The trouble with galaxy formation

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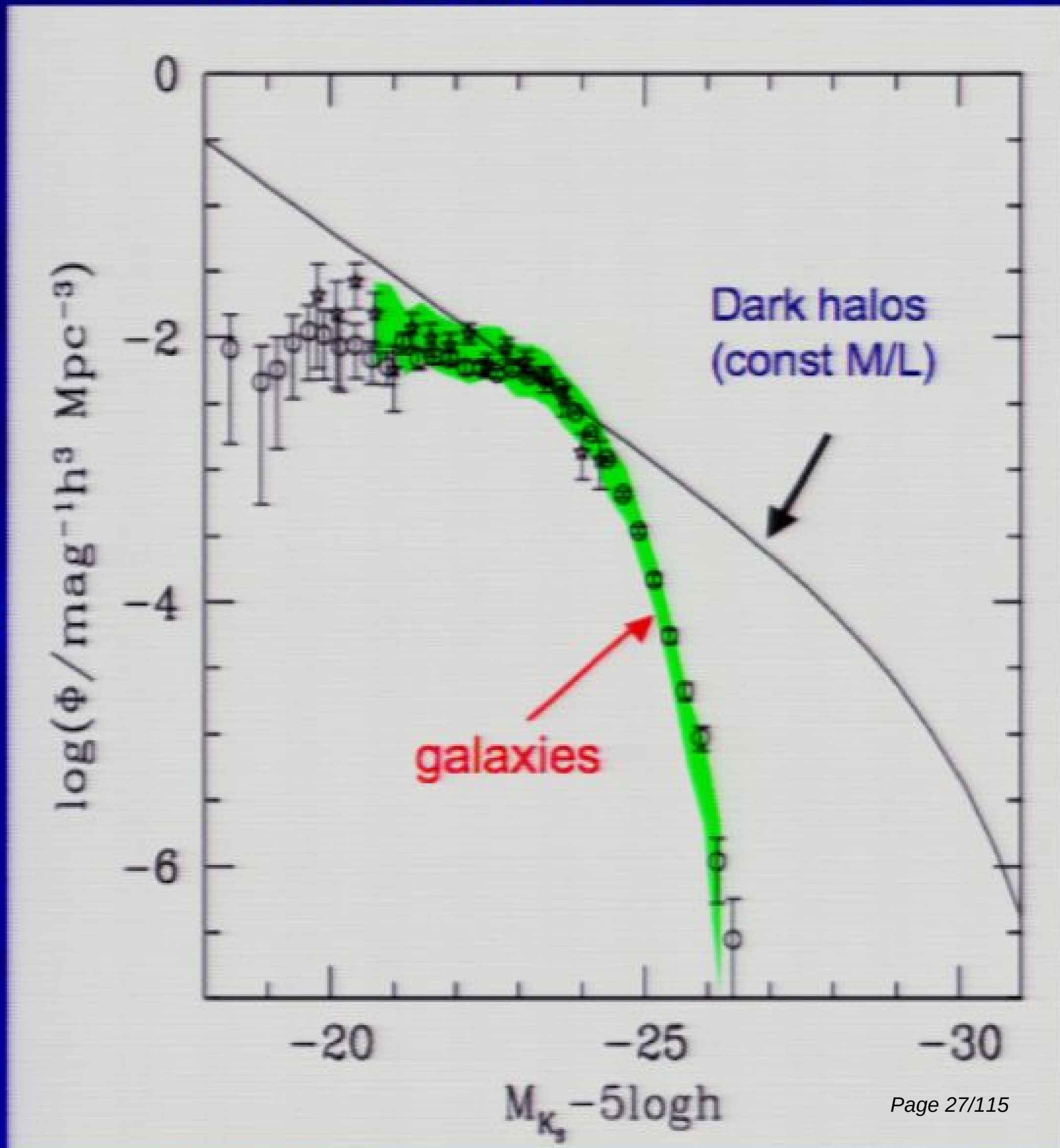
- The ingredients for galaxy formation
  - Dark matter haloes
  - Gas accretion, cooling and heating
  - Star formation
- But to get it to work, you need…
  - "feedback"
  - Supernovae
  - Black holes
  - Metal production and mixing




Multi-wavelength view of the M82 (star-bu

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How to solve the galaxy formation problem

- SPH
  - Smooth particle hydrodynamics
  - A good approach
    - It adapts the integration scale to the density
    - Enforces conservation of energy, entropy and momentum
    - The gas density can never be negative
  - Meshes well with N-body gravitational codes

$$\rho_i = \sum m_j W(r_{ij}, h)$$

$$P_i = K_i \rho_i^{\gamma}$$

$$\left.\frac{dv_i}{dt}\right|_{hydro} = -\sum m_j \left[\frac{P_i}{\rho_i^2}\nabla W_{ij}(h_i) + \frac{P_j}{\rho_j^2}\nabla W_{ij}(h_j)\right]$$

$$\left.\frac{dv_i}{dt}\right|_{visc} = -\sum m_j \Pi_{ij} v_{ij} \quad \text{where } \Pi_{ij} \text{ is a viscosity}$$

$$P_{visc} \approx \tfrac{1}{2}\rho^2 \Pi_{ij}$$

$$\frac{dK_i}{dt} = \frac{1}{2}\frac{\gamma-1}{\rho_i^{\gamma-1}}\sum m_j \Pi_{ij}(v_{ij}\cdot\nabla W_{ij})$$

Note that this isn't a perfect representation of fluid dynamics

How to solve the galaxy formation problem

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- Numerical simulation
  - You know the equations, so solve them
    - SPH
    - AMR
  - Add cooling (OK), star formation (?), supernovae (?), black holes (?)
  - But…
    - Need utlra-high resolution
    - Don't actually know the equations
    - Current computers are far too slow

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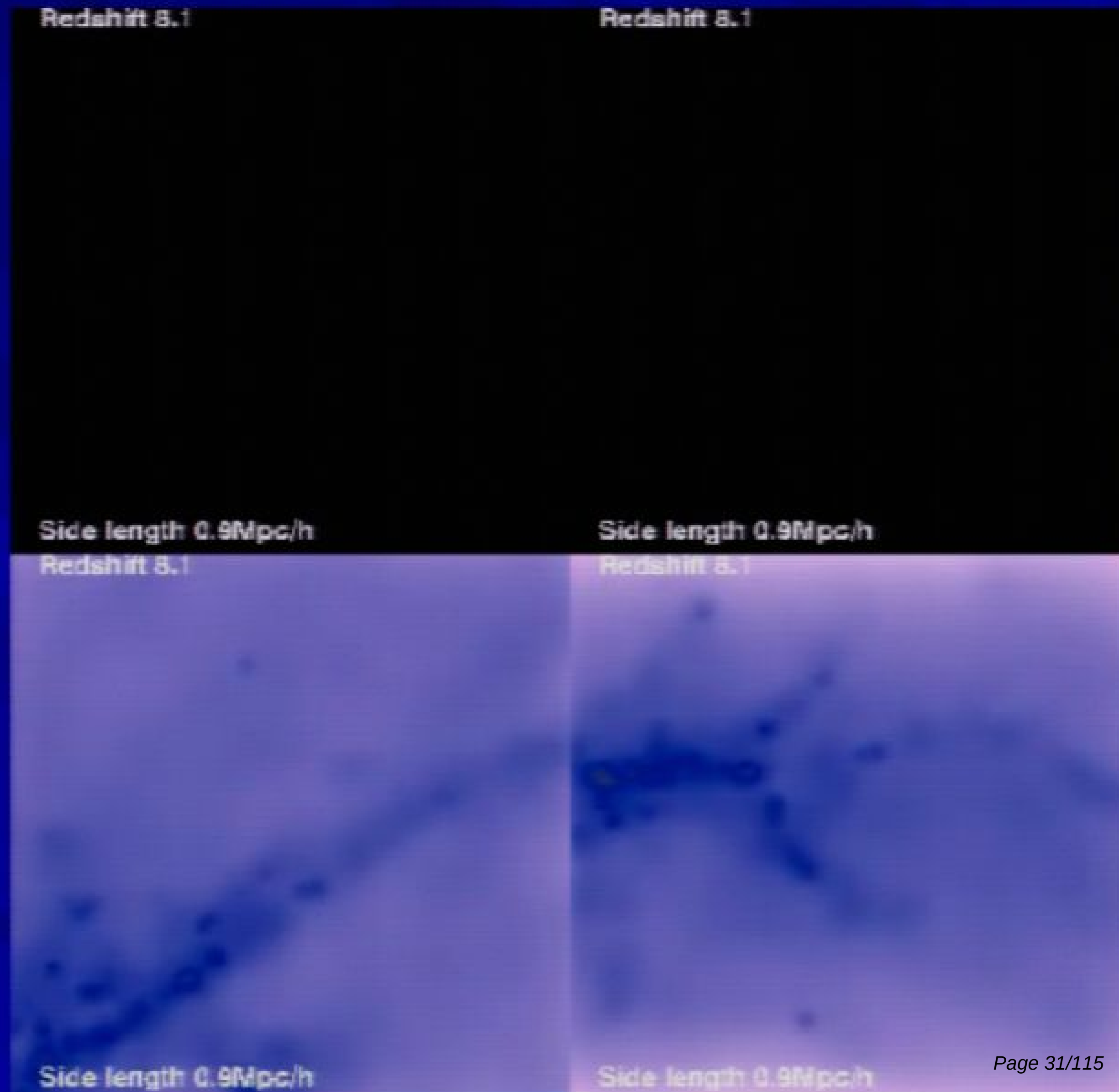
An example simulation

- Pretty picture
- But…
  - Beware of believing that its' reality
  - You need to compare a cosmological volume to the observed universe



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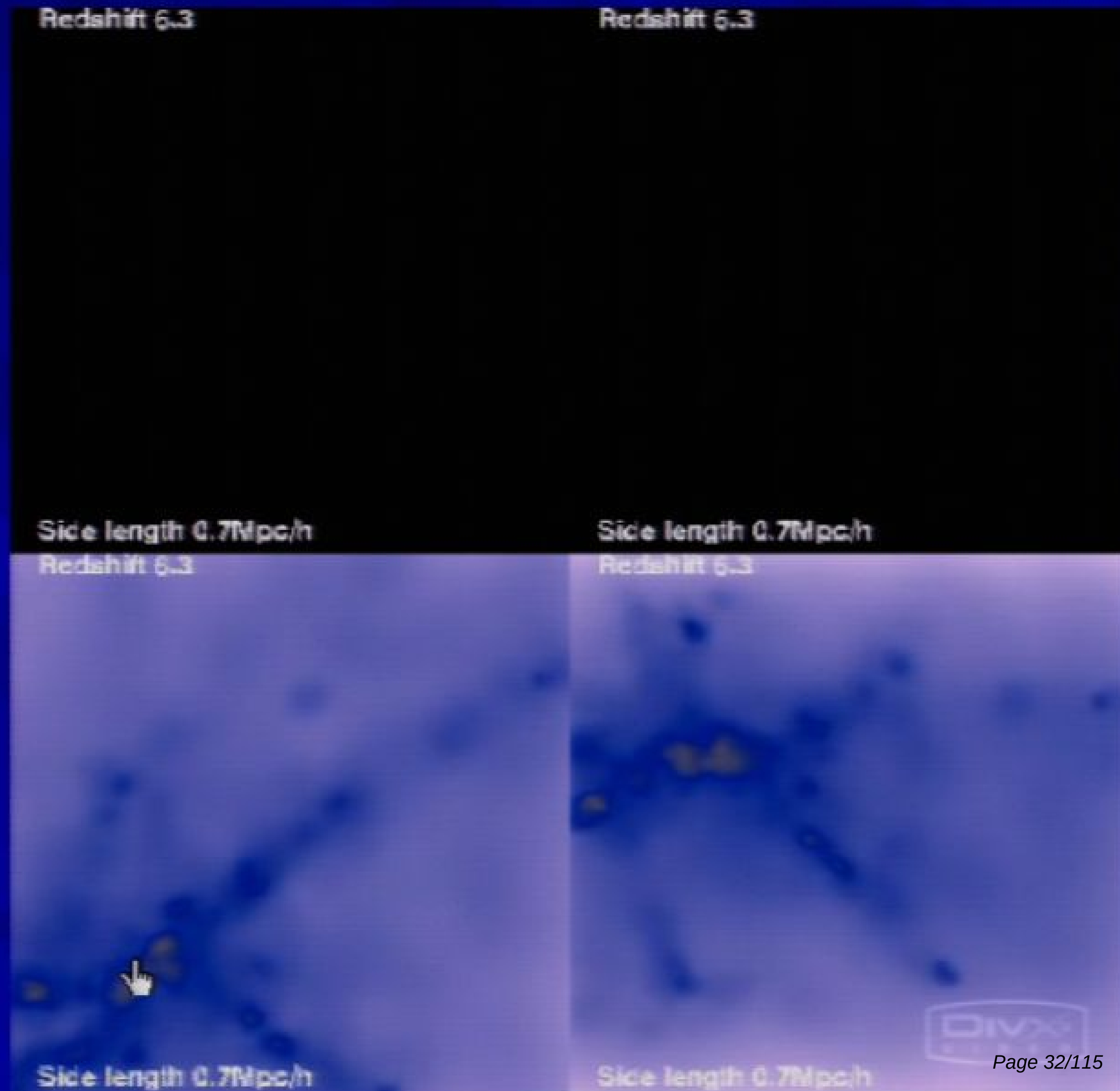

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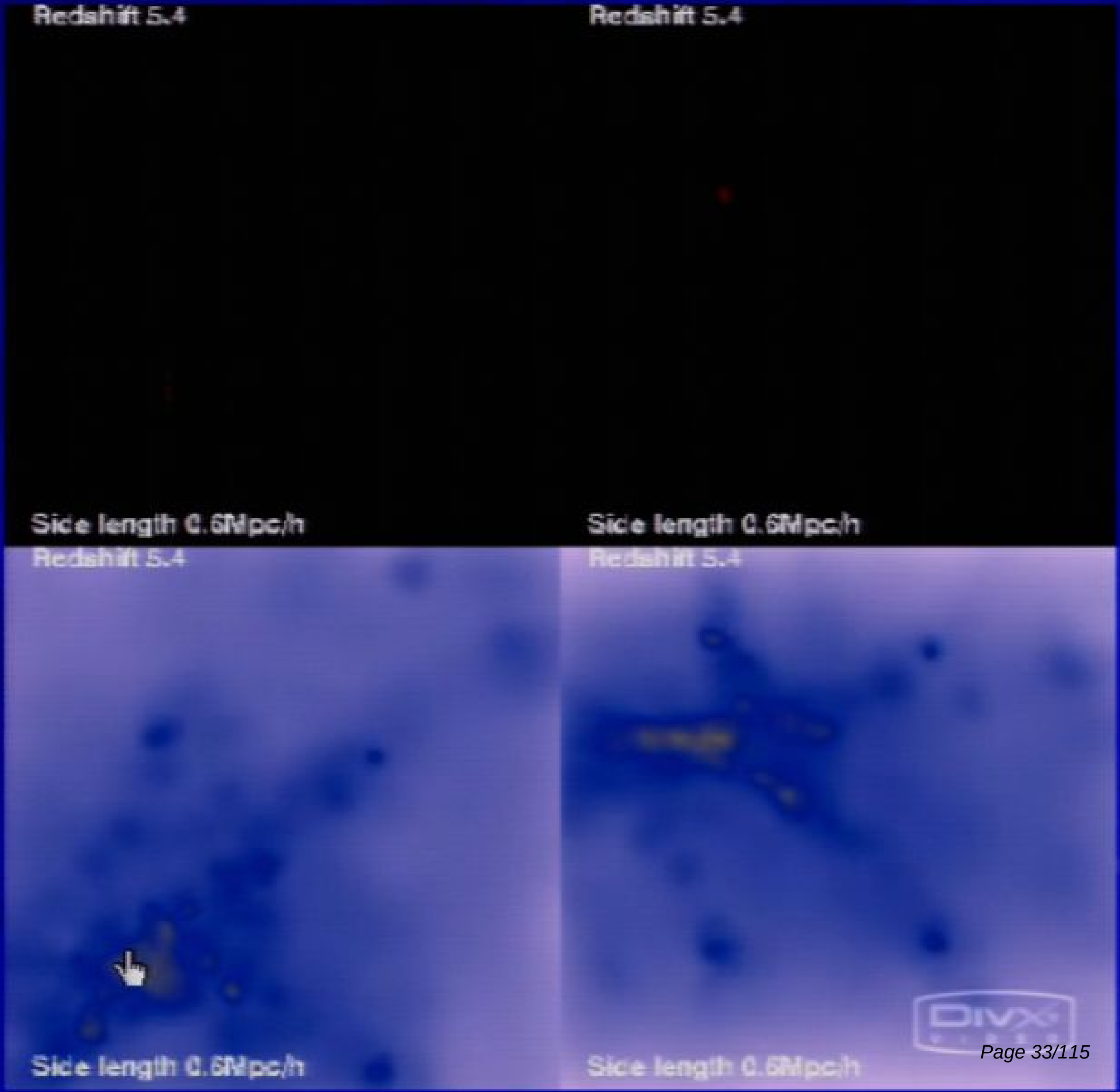

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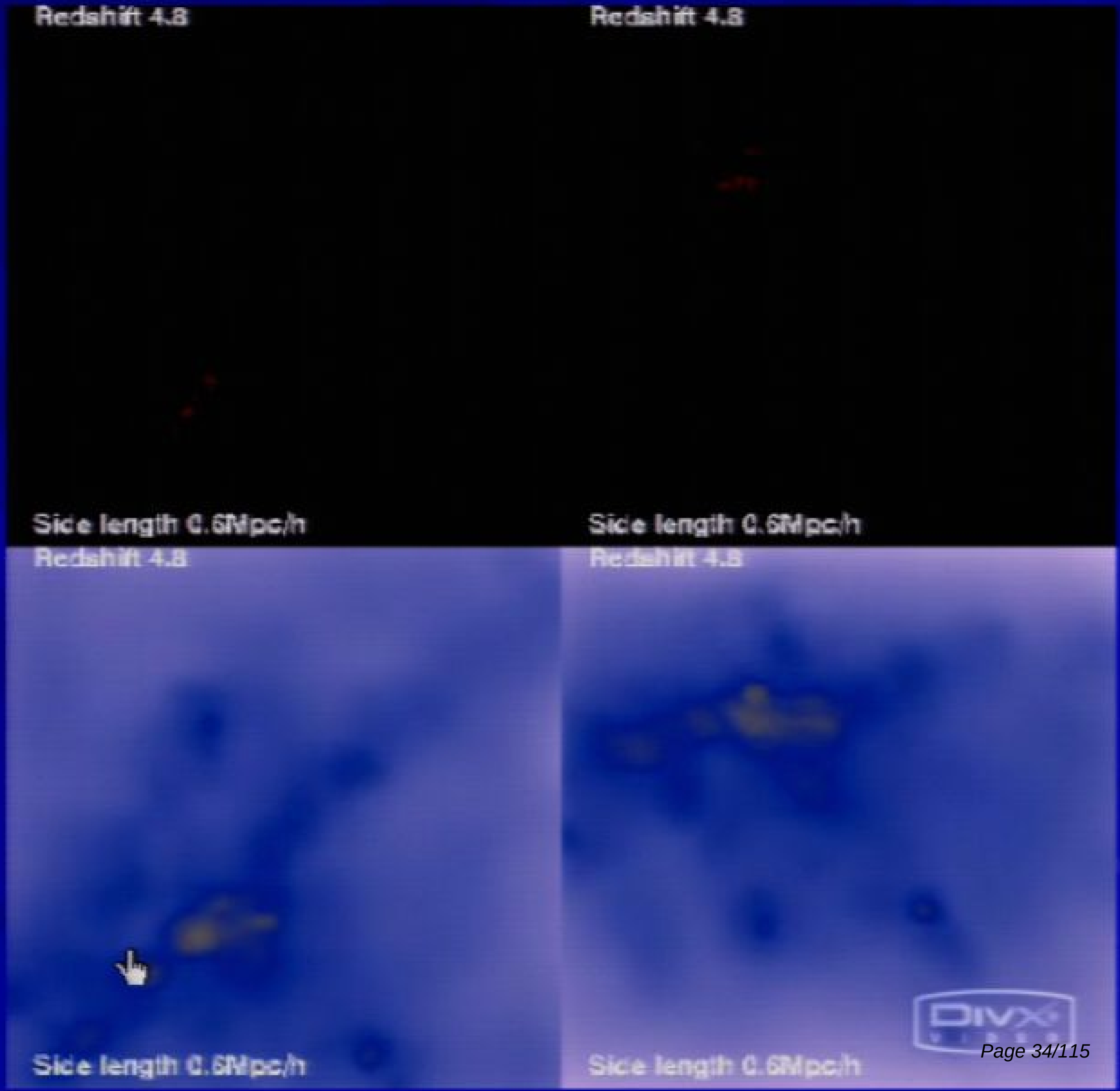

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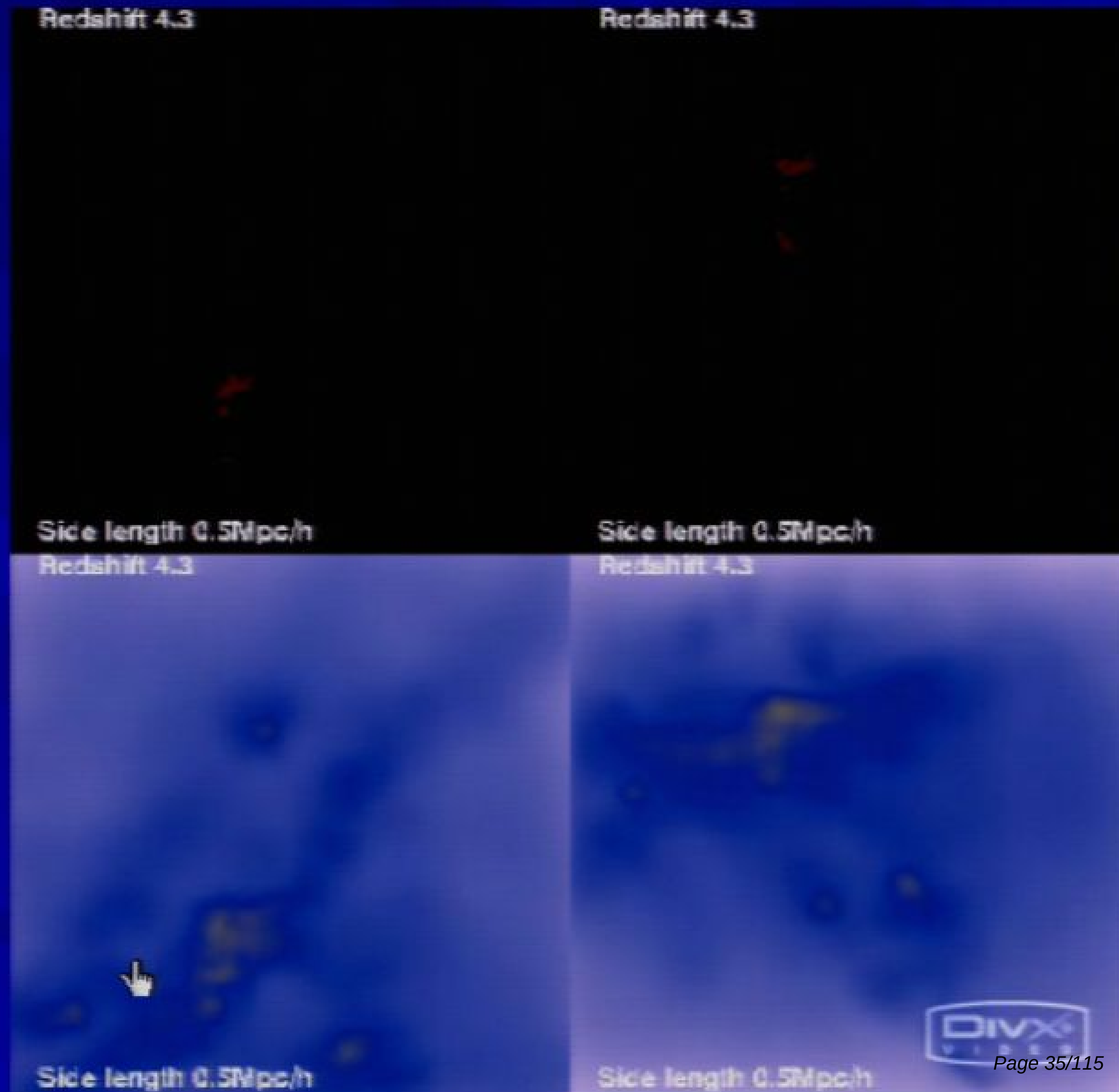

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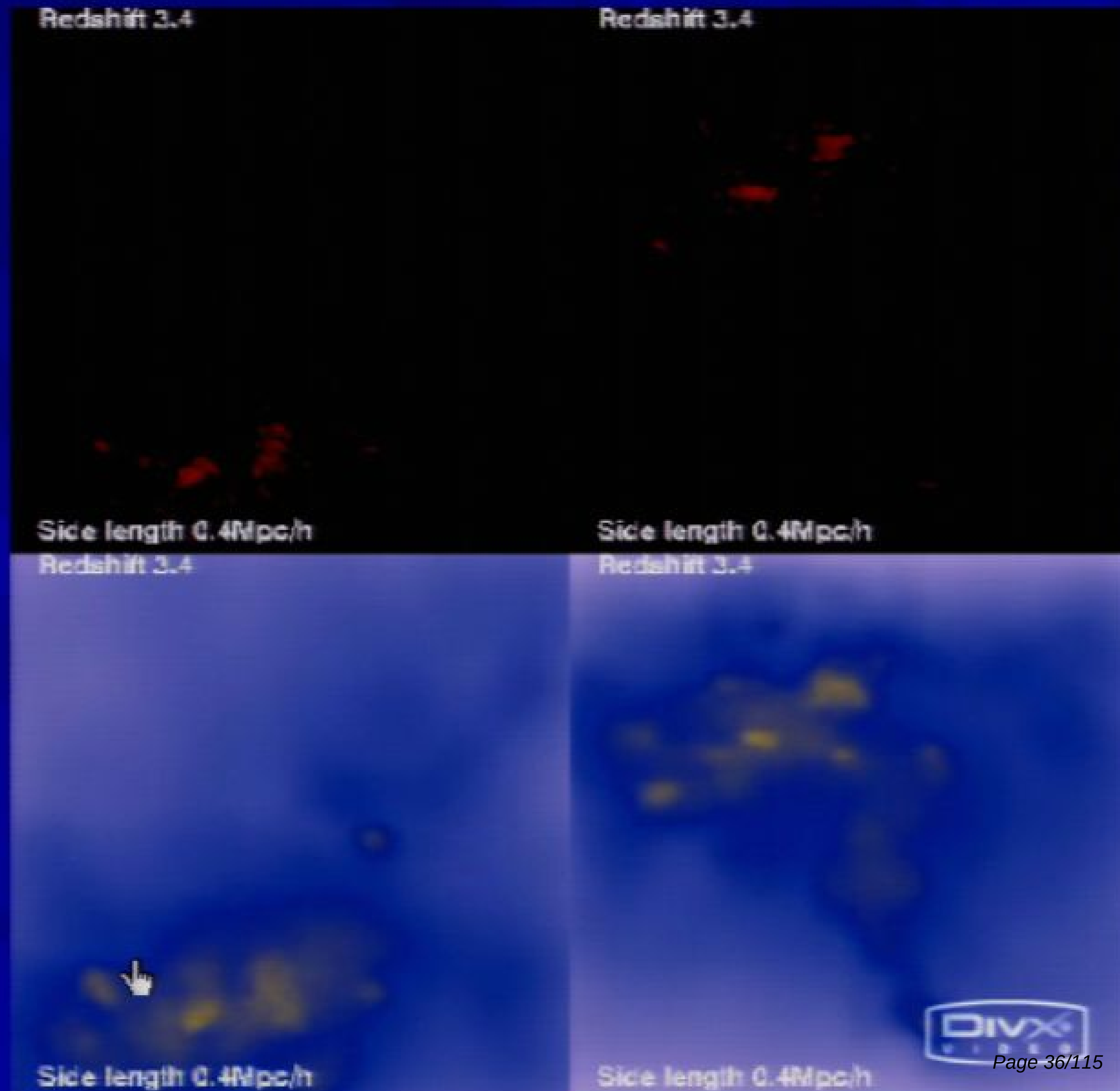

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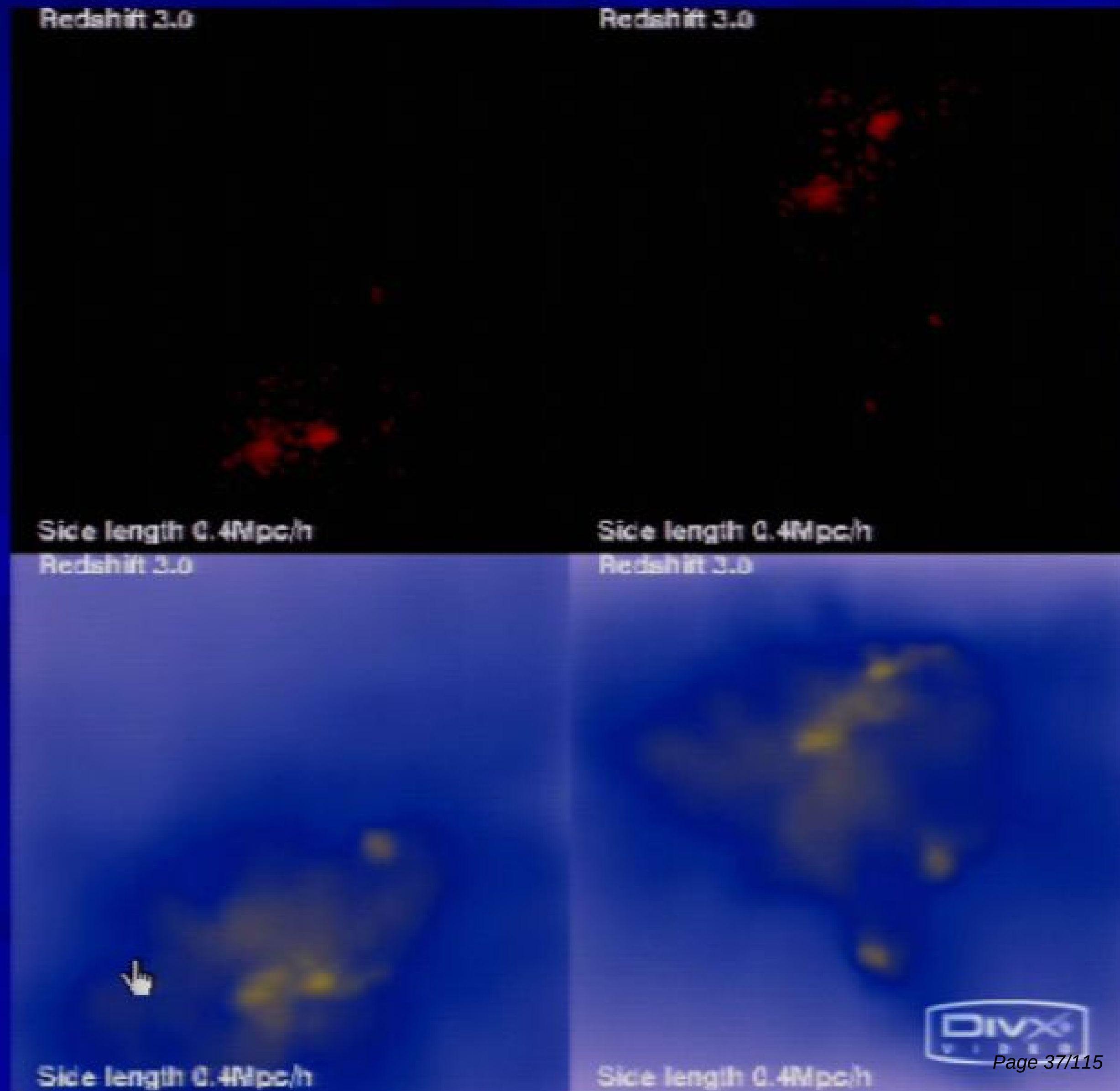

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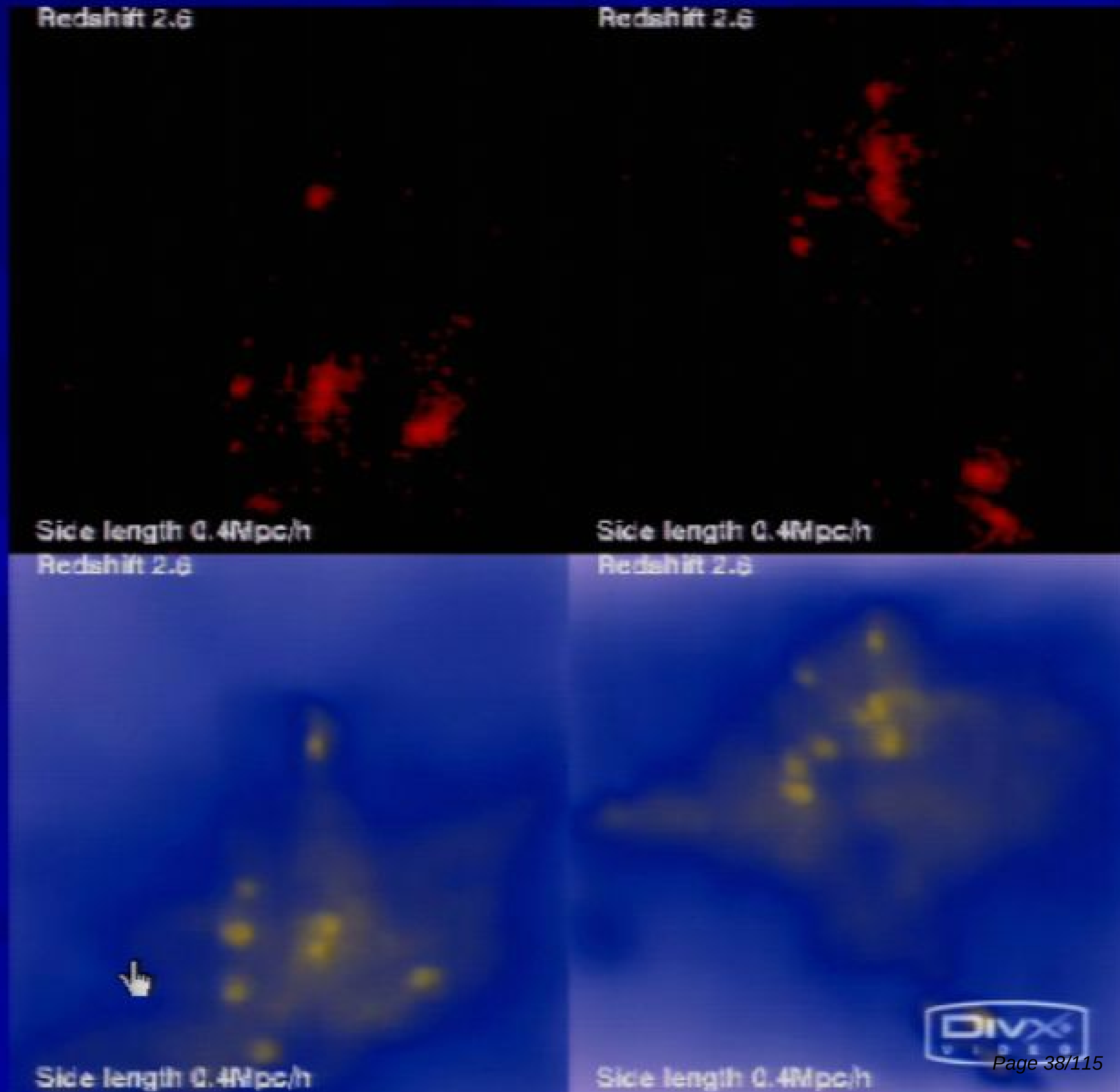

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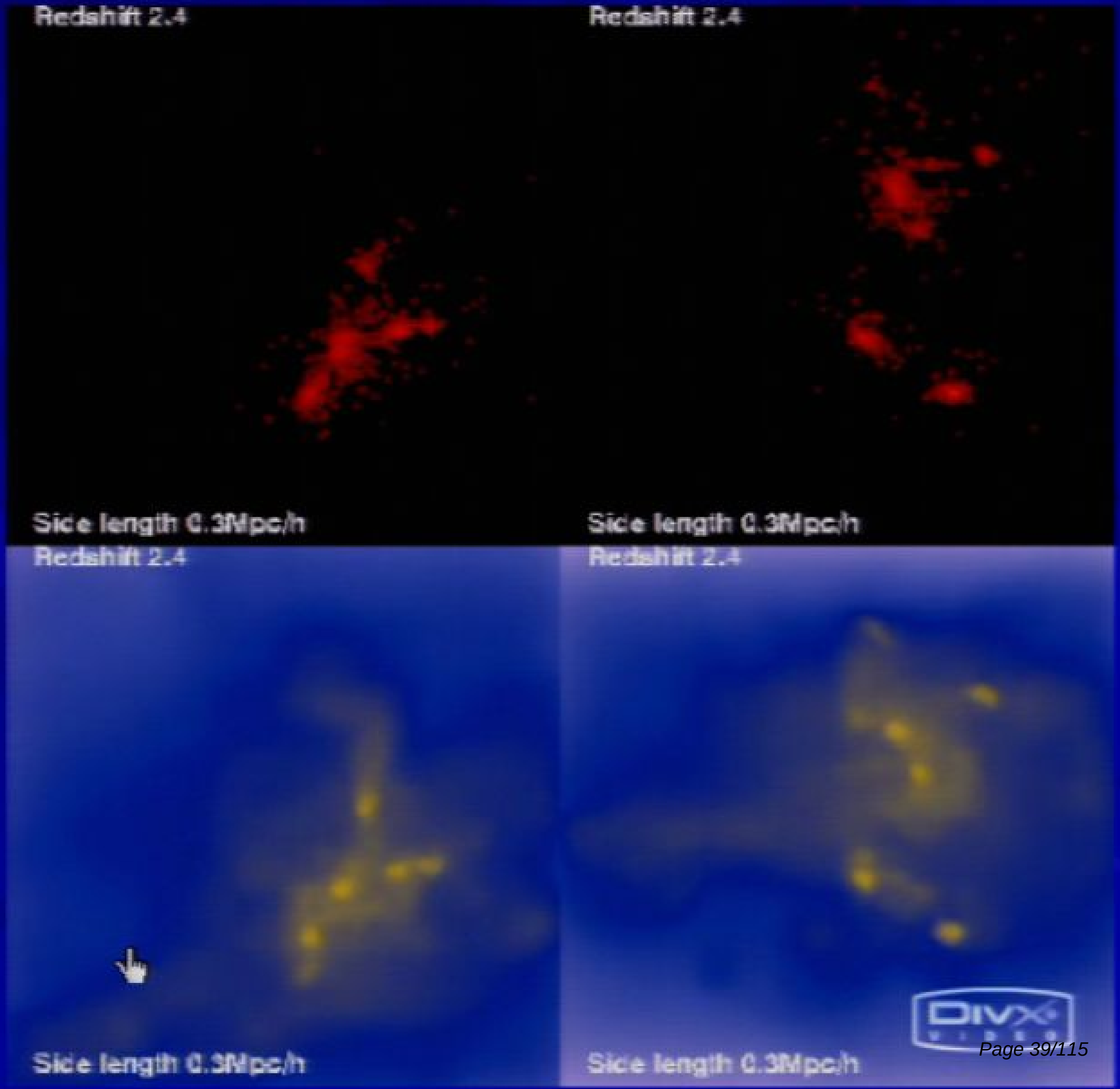

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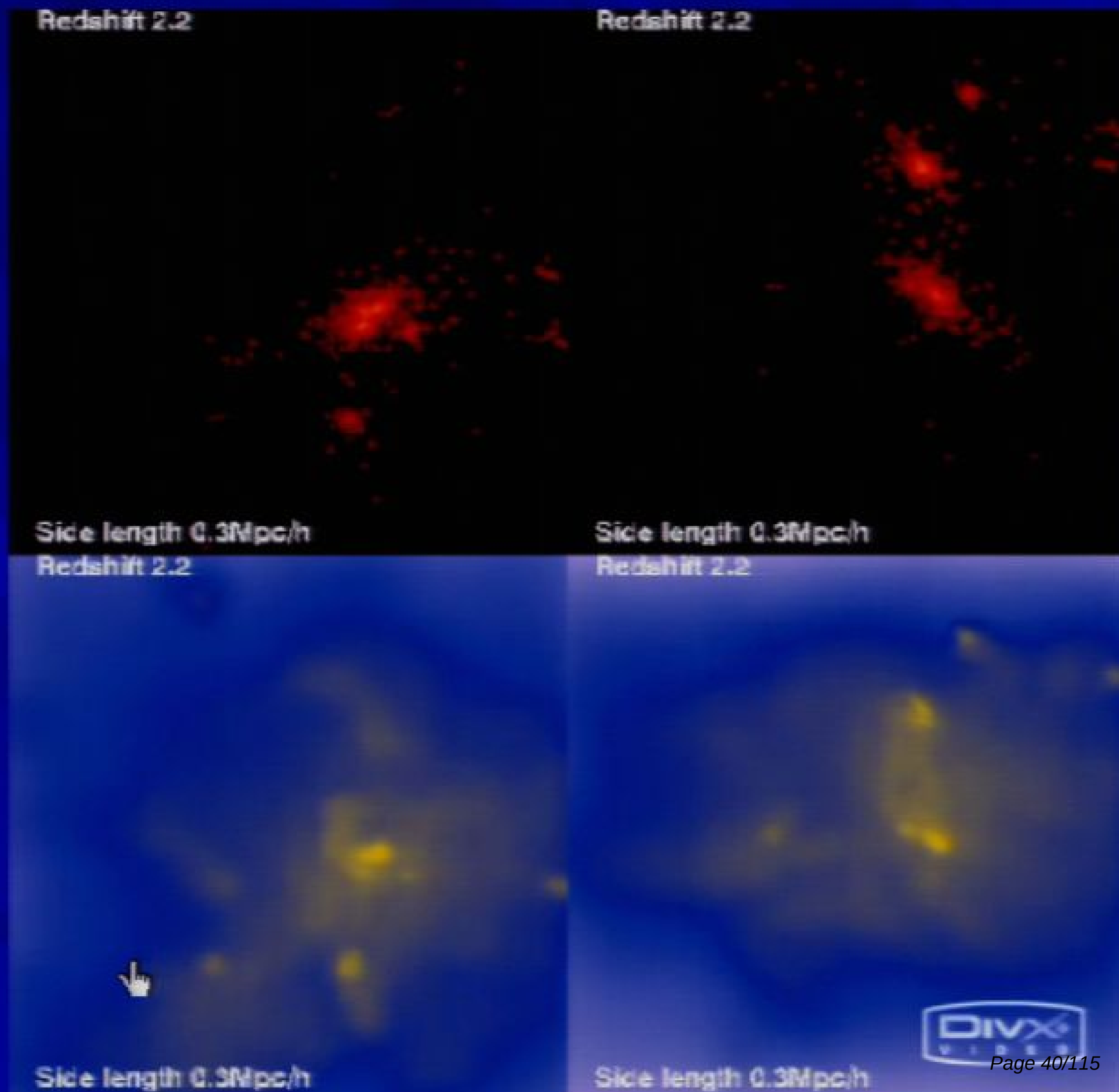

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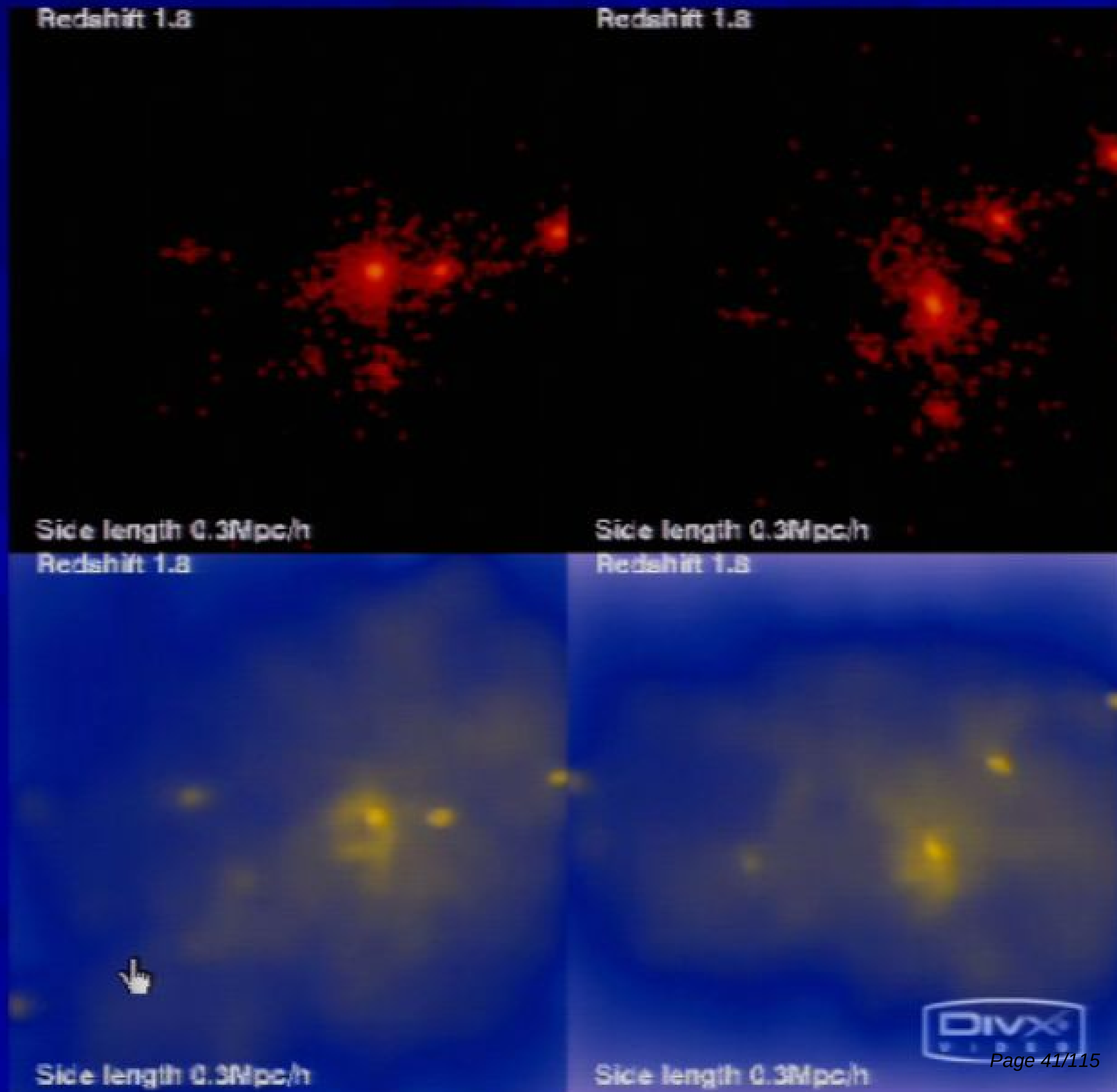

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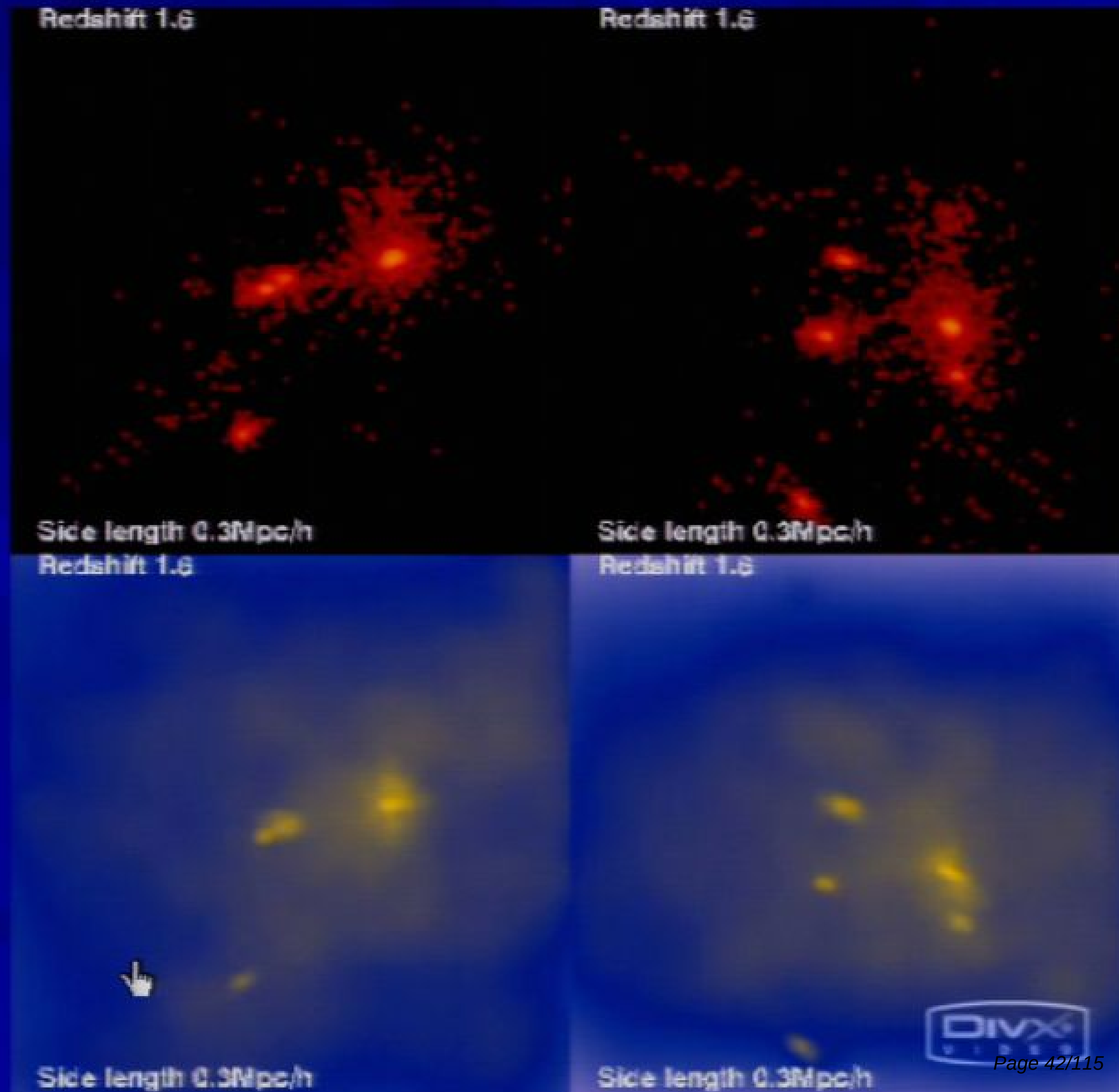

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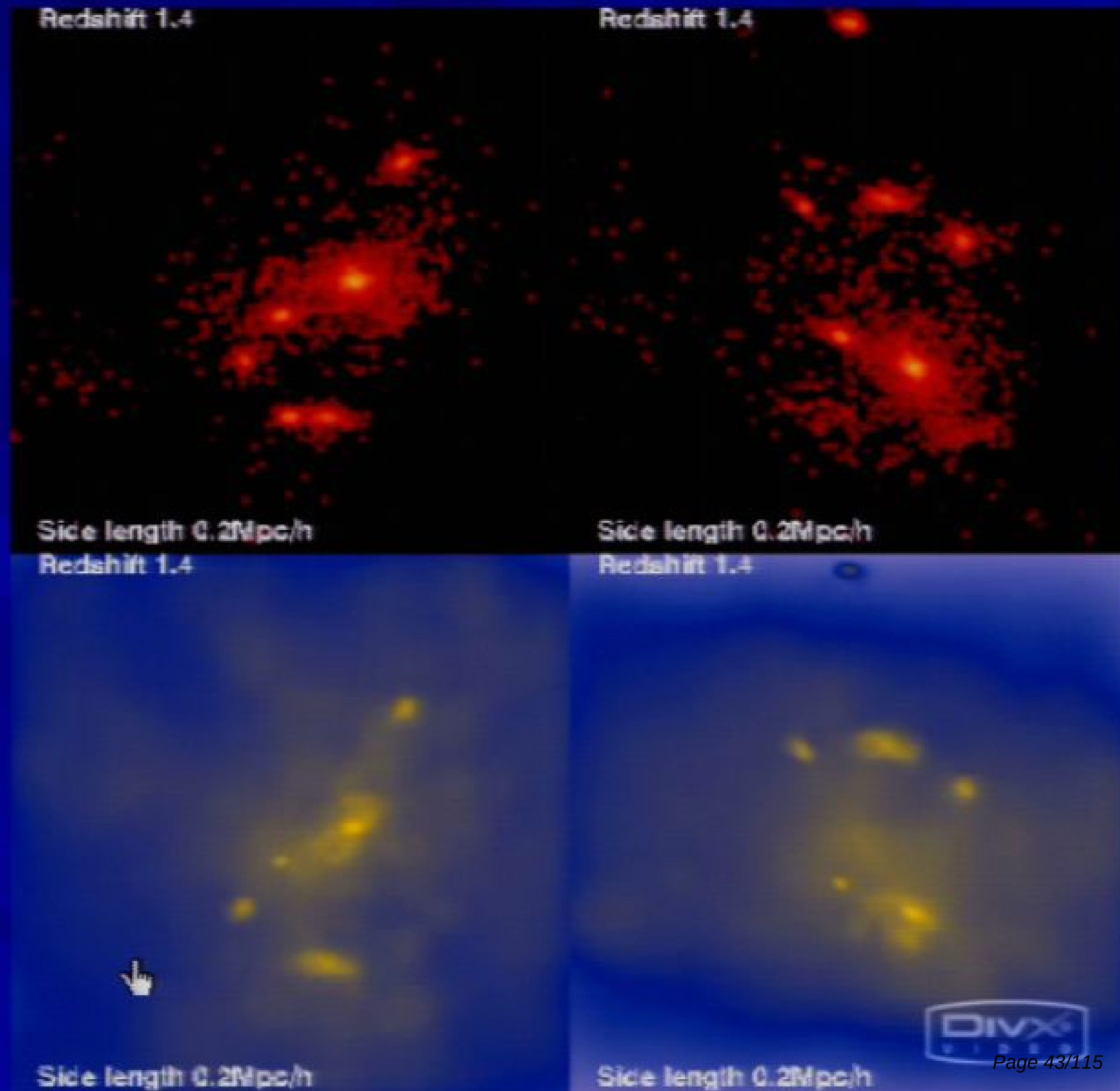

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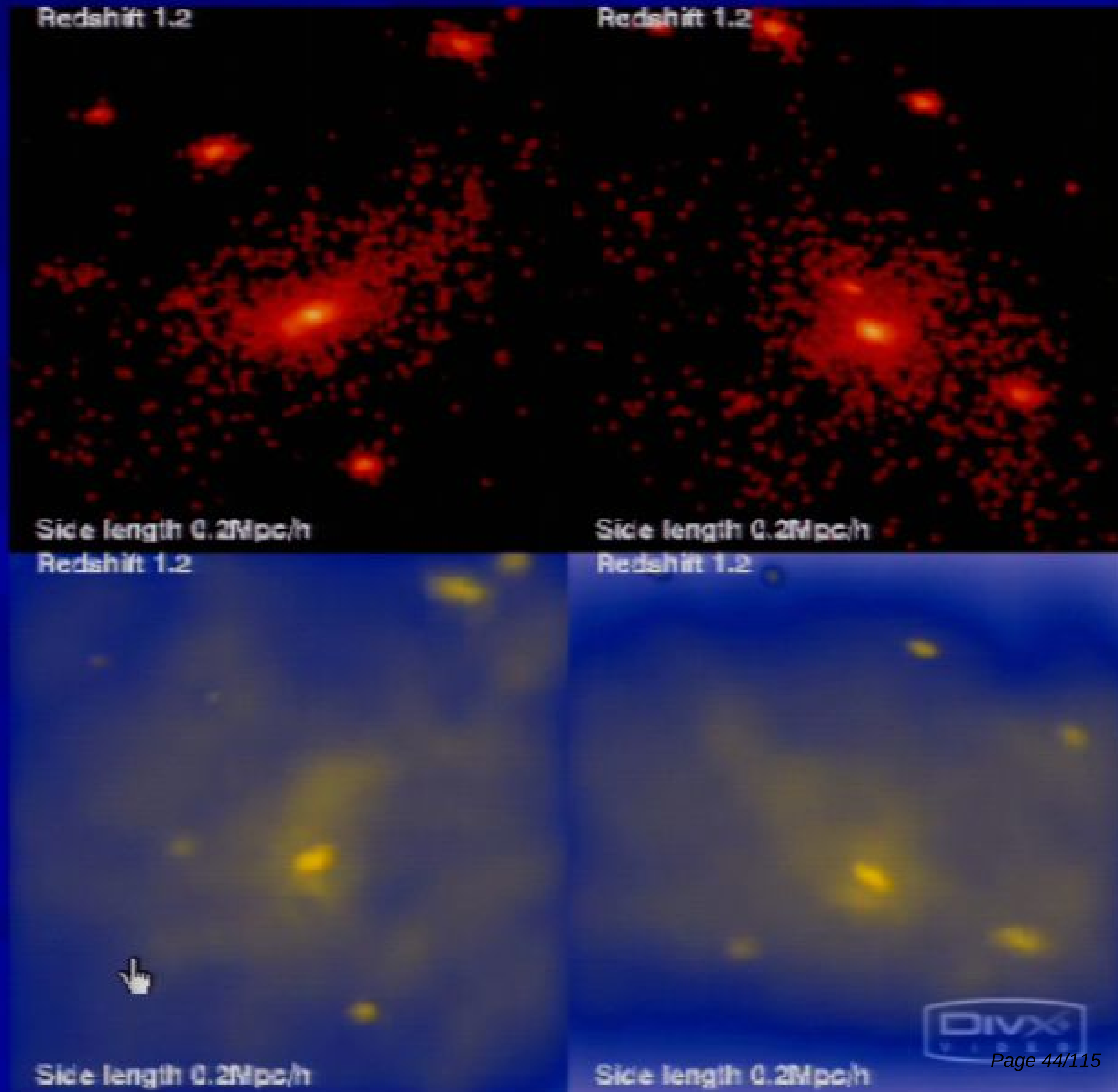

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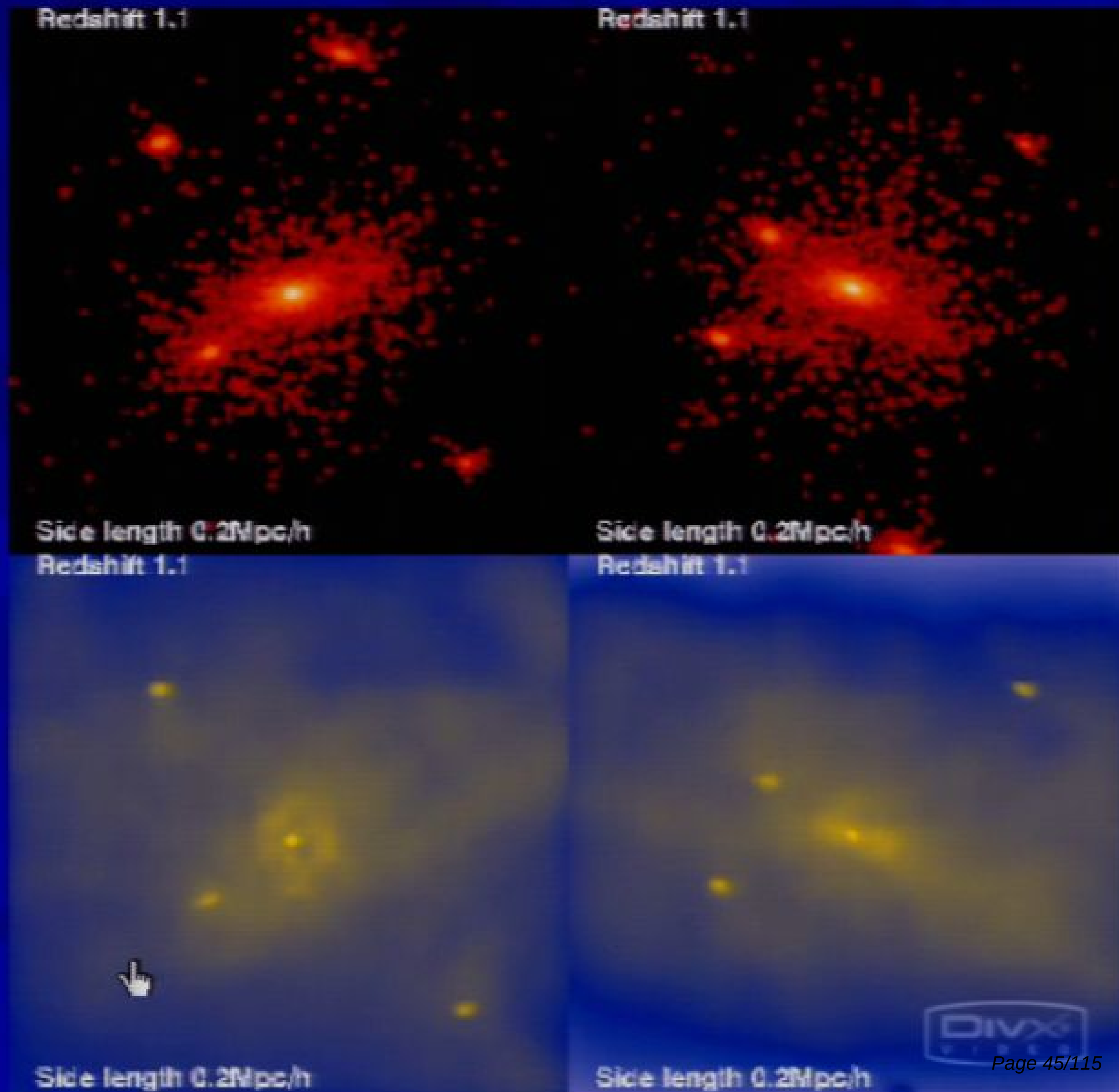

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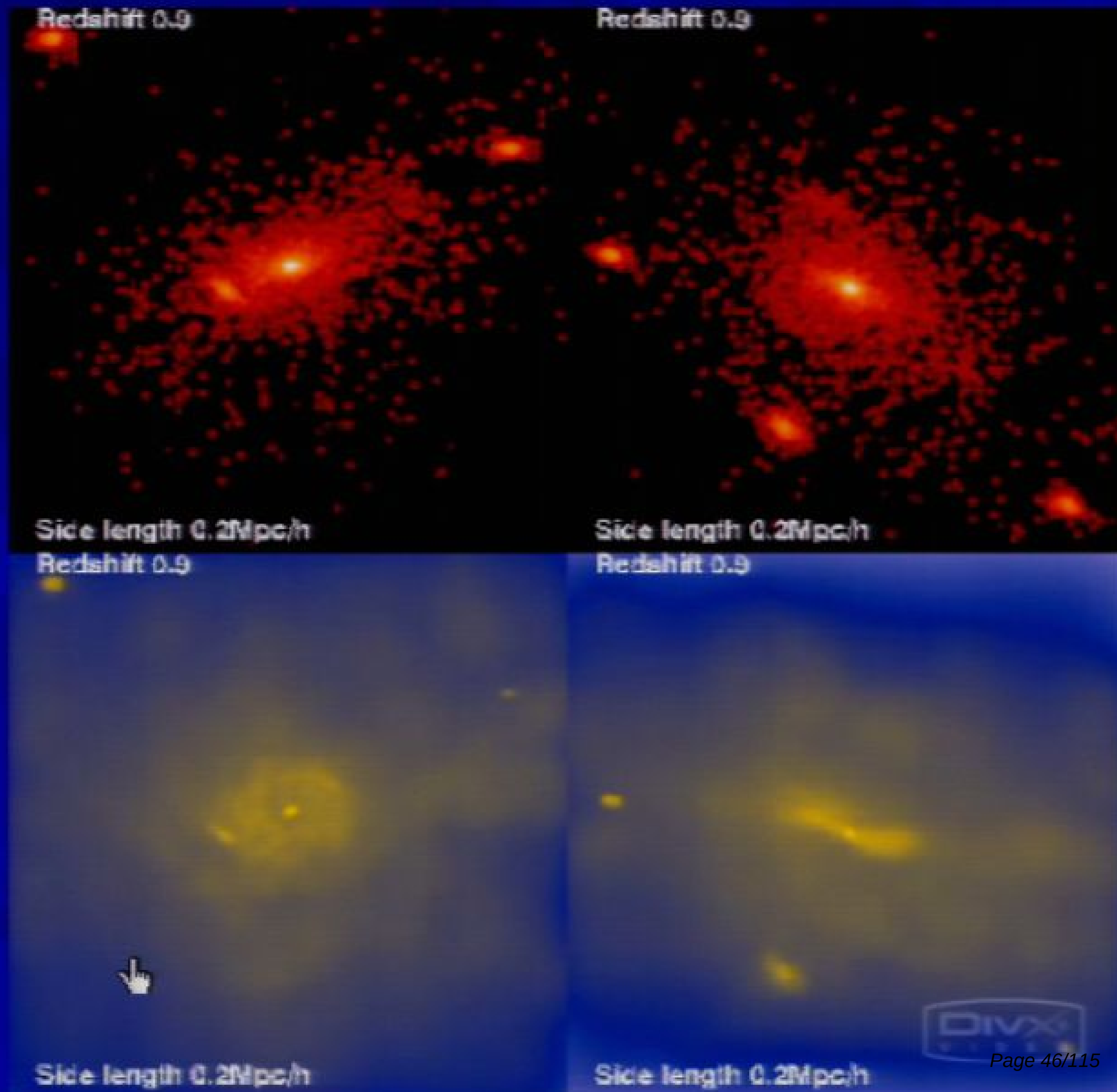

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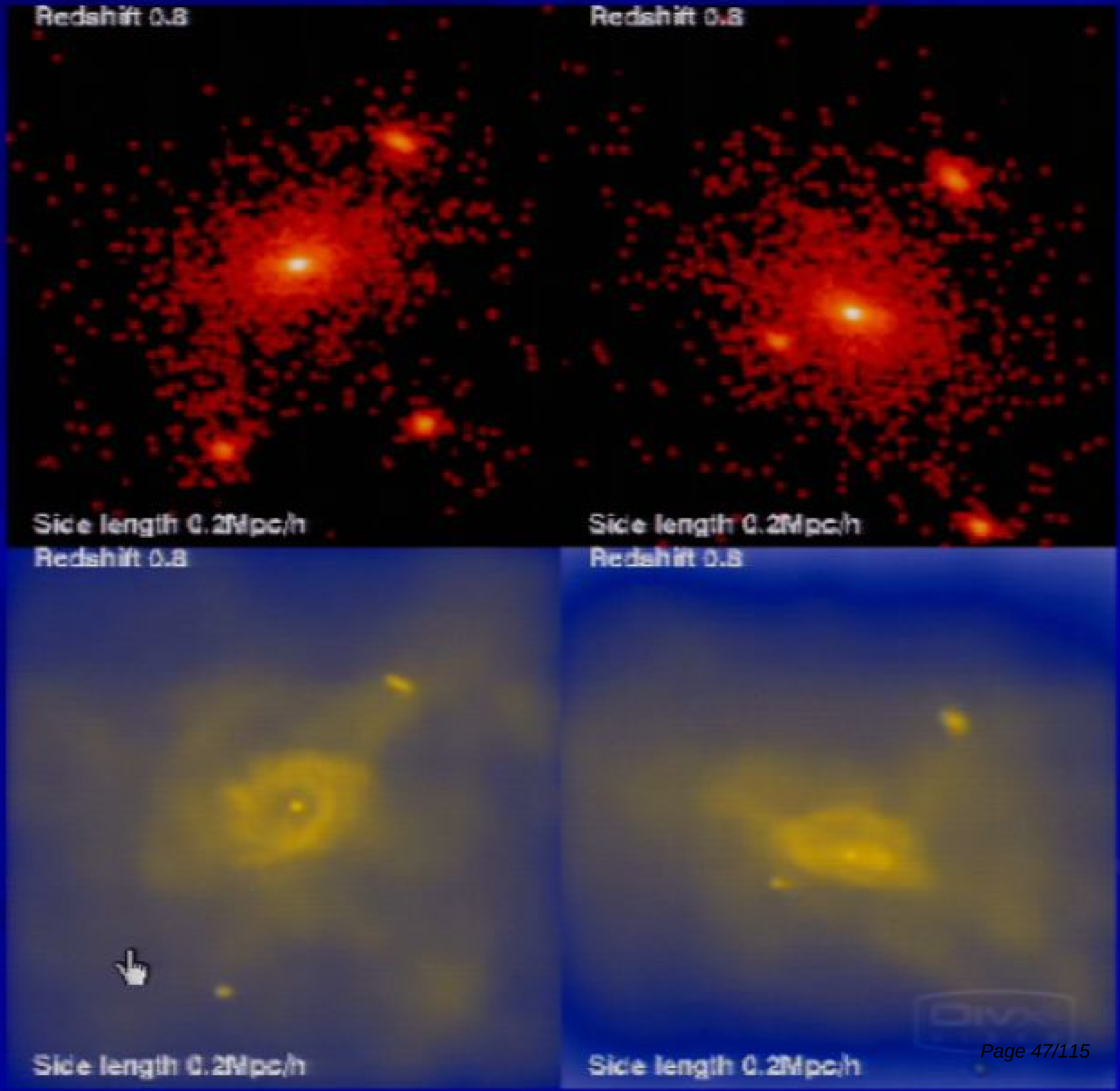

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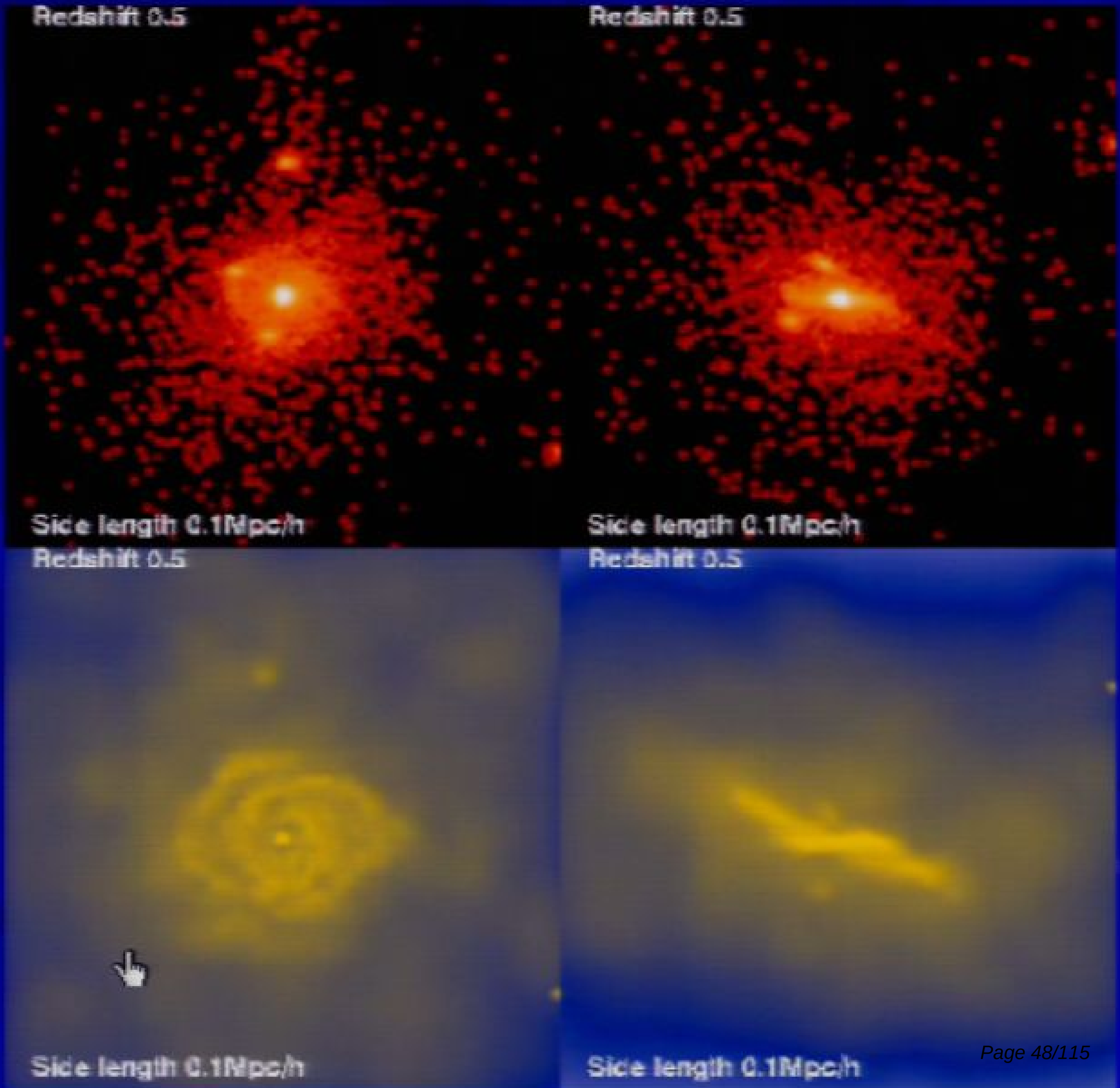

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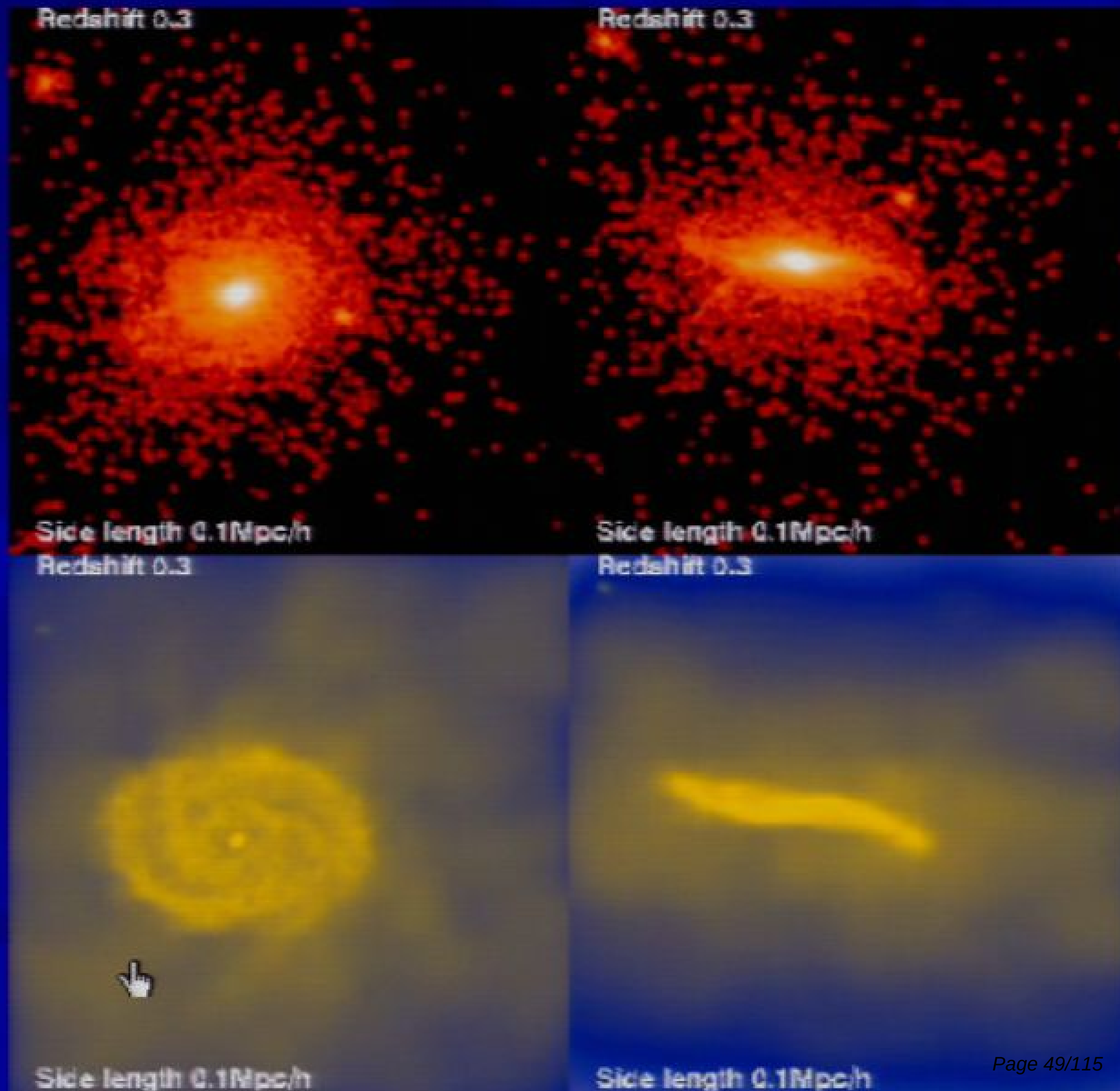

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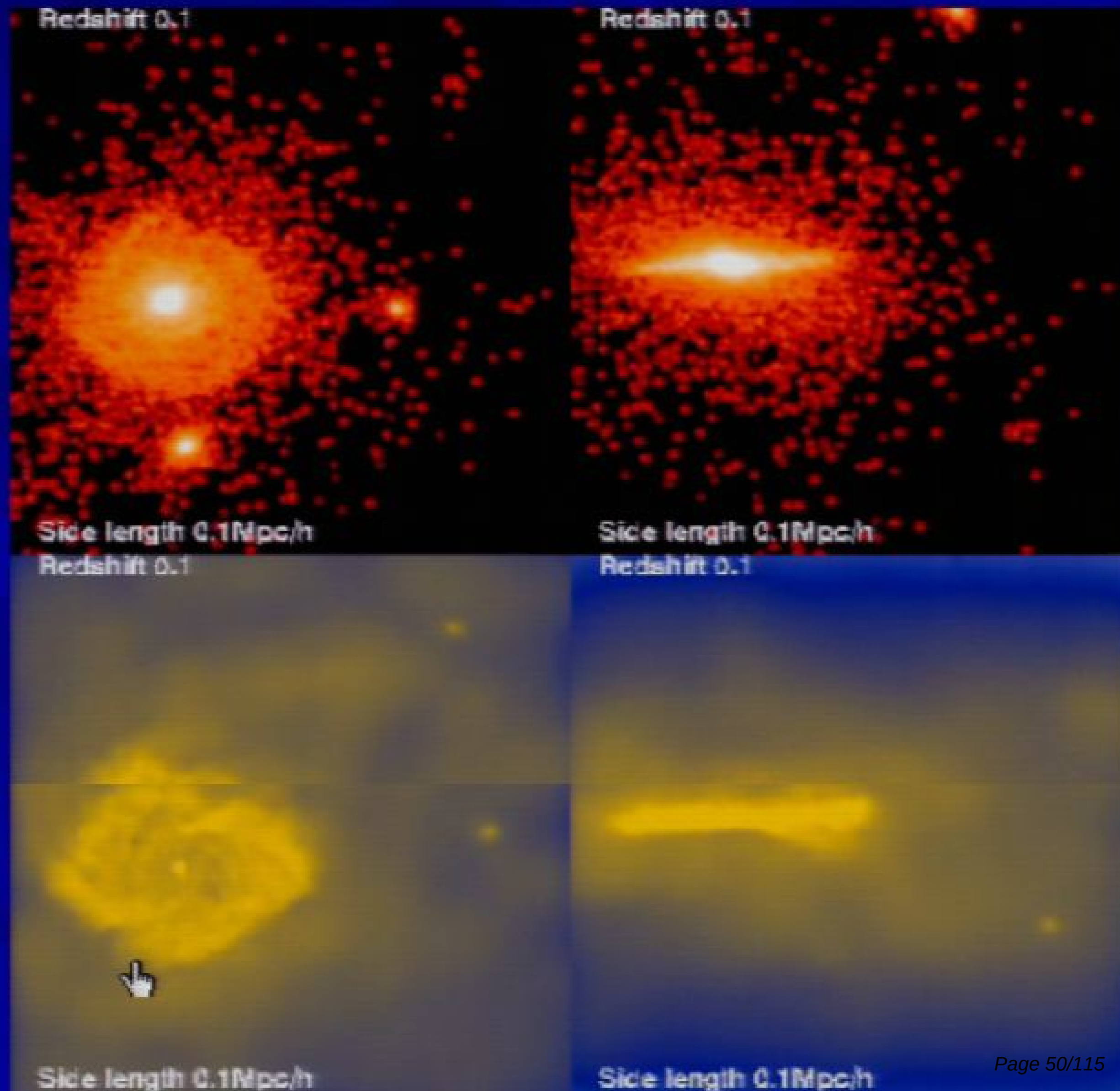

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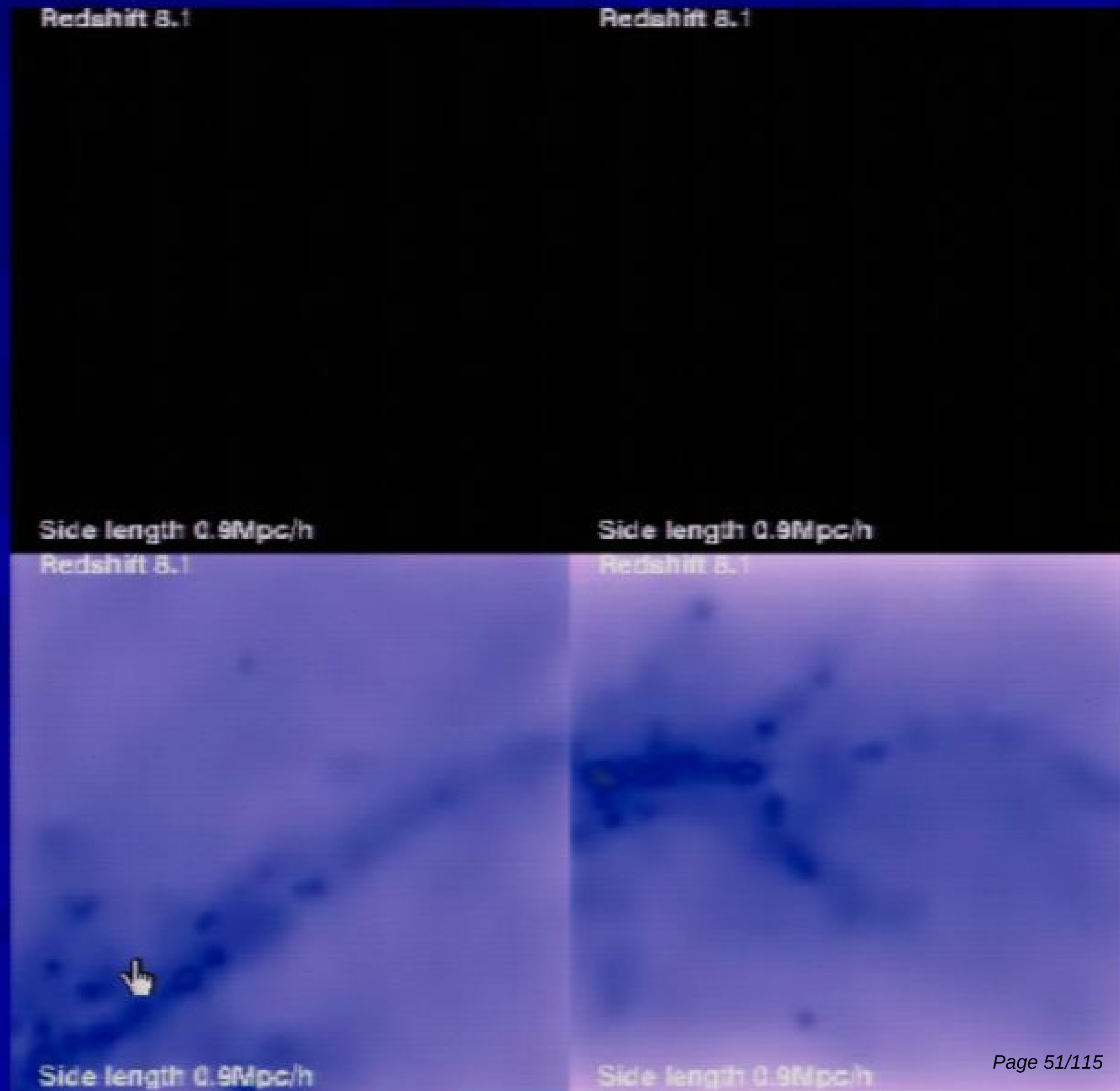

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How to solve the galaxy formation problem

- Numerical simulation
  - You know the equations, so solve them
    - SPH
    - AMR
  - Add cooling (OK), star formation (?), supernovae (?), black holes (?)
  - But…
    - Need utlra-high resolution
    - Don't actually know the equations
    - Current computers are far too slow

- "Semi-analytics"
  - Follow the spirit of the original papers…
  - Reduce the problem to a coupled set of non-linear differential equations
  - You "understand" the physics that's involved
  - Fast
    - Easy to see what happens if you change the assumptions
  - But…
    - only as good as the assumptions you make!

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The “semi-analytic” approach

- Coupled differential equations
- Takes a macroscopic view
- The “sub-grid” physics is described by uncertain parameters
  - These must be determined by comparison to observations
  - The choice of parameterisation should be justified using idealised simulations and physics

$$\frac{\mathrm{d}n}{\mathrm{d}\ln M_{\mathrm{v}}} = \sqrt{\frac{2}{\pi}}\frac{\Omega_0\rho_{\mathrm{crit}}}{M_{\mathrm{v}}}\left|\frac{\mathrm{d}\ln\sigma}{\mathrm{d}\ln M}\right| \times[1+1.047(\omega^{-2p})+0.6G_1+0.4G_2]A'\omega \times\exp\left(-\frac{1}{2}\omega^2-0.0325\frac{\omega^{2p}}{(n_{\mathrm{eff}}+3)^2}\right), \qquad (3)$$

$$\dot{M}_{cool} = 4\pi r_{cool}^{\,2}\rho(r_{cool})\frac{dr_{cool}}{dt}$$

$$t_{\mathrm{cool}}(t) = \frac{3k_{\mathrm{B}}T_{\mathrm{v}}(t)}{2\Lambda(t)n_{\mathrm{H}}}$$

$$\dot{M}_* = \frac{M_{\mathrm{gas}}}{\tau_*} - \dot{M}_{\mathrm{R}}$$

$$\dot{M}_{\mathrm{gas}} = -(1+\beta')\frac{M_{\mathrm{gas}}}{\tau_*} + \dot{M}_{\mathrm{R}} + \dot{M}_{\mathrm{infall}}.$$

$$f_{\mathrm{exp}} = \exp\left(-\frac{\lambda_\phi V^2}{\langle e\rangle}\right),$$

$$\dot{M}_{\mathrm{reheated}} = (1-f_{\mathrm{exp}})\beta'\dot{M}_*.$$

$$f_{\mathrm{acc}} = \exp\left(-\frac{V^2_{\mathrm{max}}}{\langle e\rangle}\right) - \exp\left(-\frac{V^2_{\mathrm{v}}}{\langle e\rangle}\right)$$

This is highly simplified - see Benson & Bower 2010 for a realistic version!

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The "semi-analytic" approach

- Coupled differential equations
- Takes a macroscopic view
- The "sub-grid" physics is described by uncertain parameters
  - These must be determined by comparison to observations
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Parameter	Minimum	Maximum
h_0	0.6750	0.7270
Ω_b	0.04320	0.04920
Λ_0	0.7142	0.7278
σ_8	0.7650	0.8690
n_s	0.9320	0.9880
$V_{\rm cut}/{\rm km\ s^{-1}}$	10.00	50.00
$z_{\rm cut}$	5.000	13.00
$\log_{10}(\alpha_{\rm cool})$	-1.523	0.4771
$\log_{10}(\alpha_{\rm remove})$	-1.523	0.0000
$\log_{10}(a_{\rm core})$	-2.000	-0.5229
$\log_{10}(\epsilon_*)$	-3.523	-1.301
α_*	-4.000	1.000
$V_{\rm hot,disk}/{\rm km\ s^{-1}}$	100.0	550.0
$V_{\rm hot,burst}/{\rm km\ s^{-1}}$	100.0	550.0
$\alpha_{\rm hot}$	1.000	3.700
$\log_{10}(\lambda_{\rm expel,disk})$	-1.523	1.000
$\log_{10}(\lambda_{\rm expel,burst})$	-1.523	1.000
$\log_{10}(\epsilon_\bullet)$	-2.398	-1.000
$\log_{10}(\eta_\bullet)$	-3.000	-1.000
$\log_{10}(F_\bullet)$	-3.000	-1.523
$\log_{10}(\alpha_{\rm reheat})$	-1.523	0.4771
$\log_{10}(f_{\rm ellip})$	-2.000	-0.3010
$\log_{10}(f_{\rm burst})$	-2.000	-0.3010
$\log_{10}(f_{\rm gas,burst})$	-1.523	-0.3010
$B/T_{\rm burst}$	0.0000	1.000
$A_{\rm ac}$	0.7000	1.000
$w_{\rm ac}$	0.7000	1.000
$\epsilon_{\rm d,gas}$	0.7000	1.150
$\log_{10}(\epsilon_{\rm strip})$	-2.000	0.0000

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Part II

The Monster's Fiery Breath

- The buzz about AGN and galaxy formation
- An overview of recent successes

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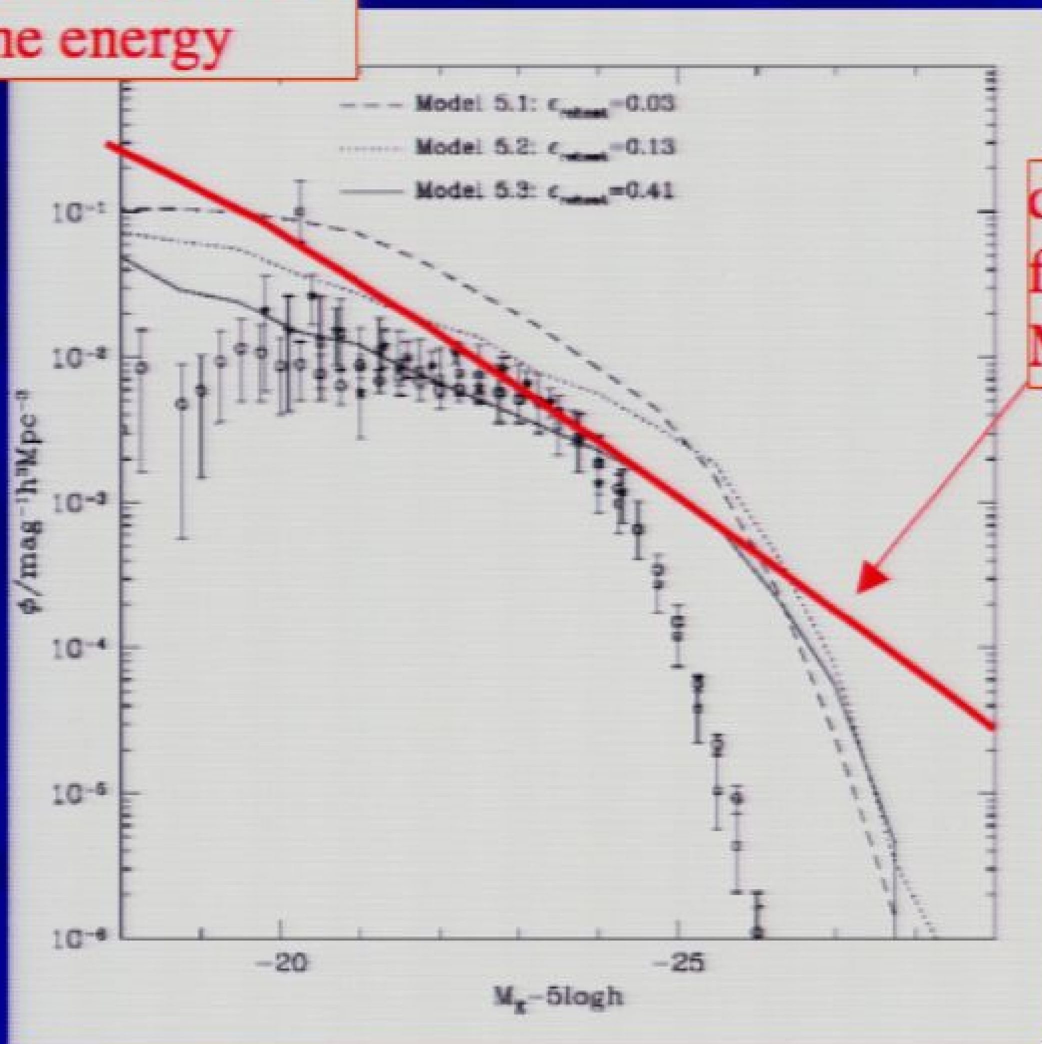
What cooling+feedback need to do!

Formation of faint galaxies supressed by Sne energy



dark matter mass function (fixed M/L)

NB: exacerbated by the high value of WMAP Ω_b

The same problem is seen in simulations: Balogh et al., 2001; Springel & Hernquist 2003

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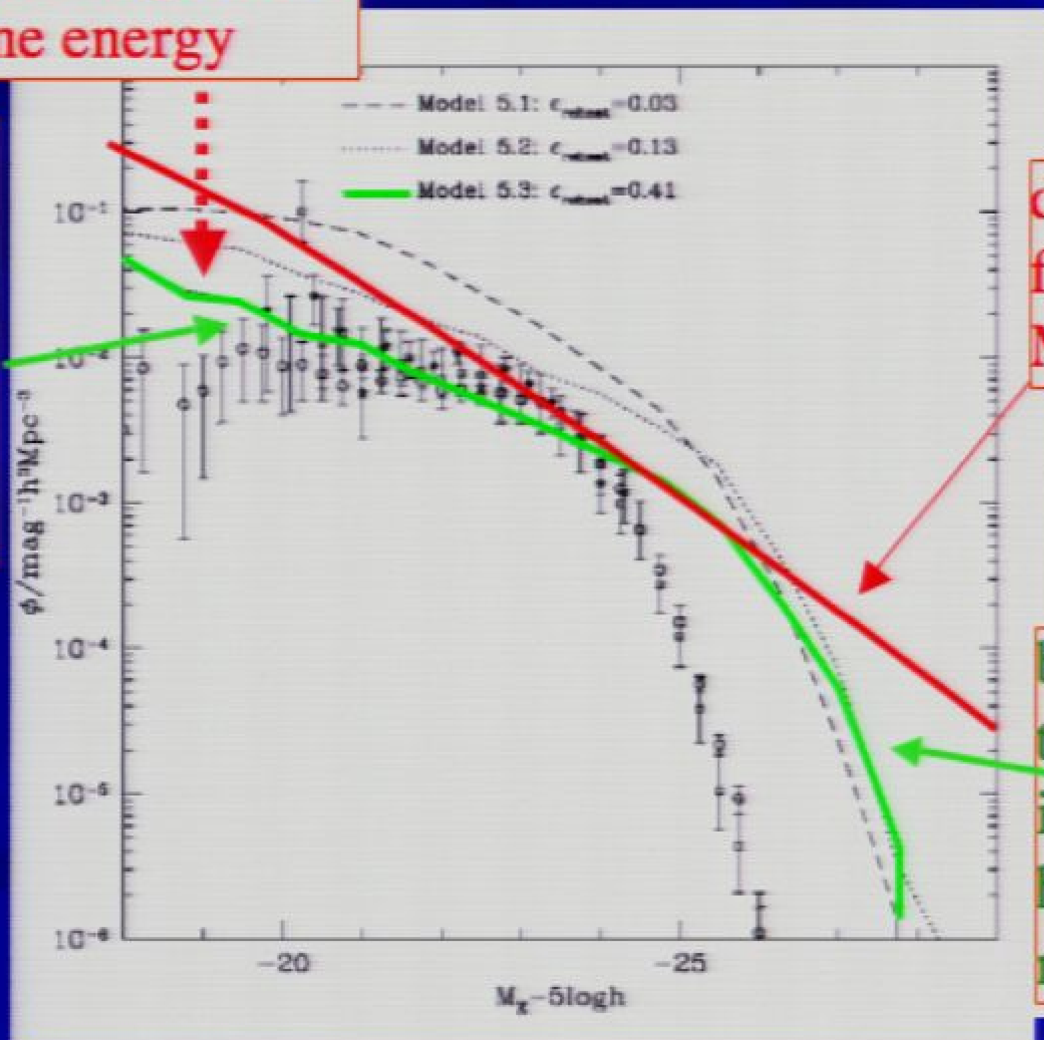

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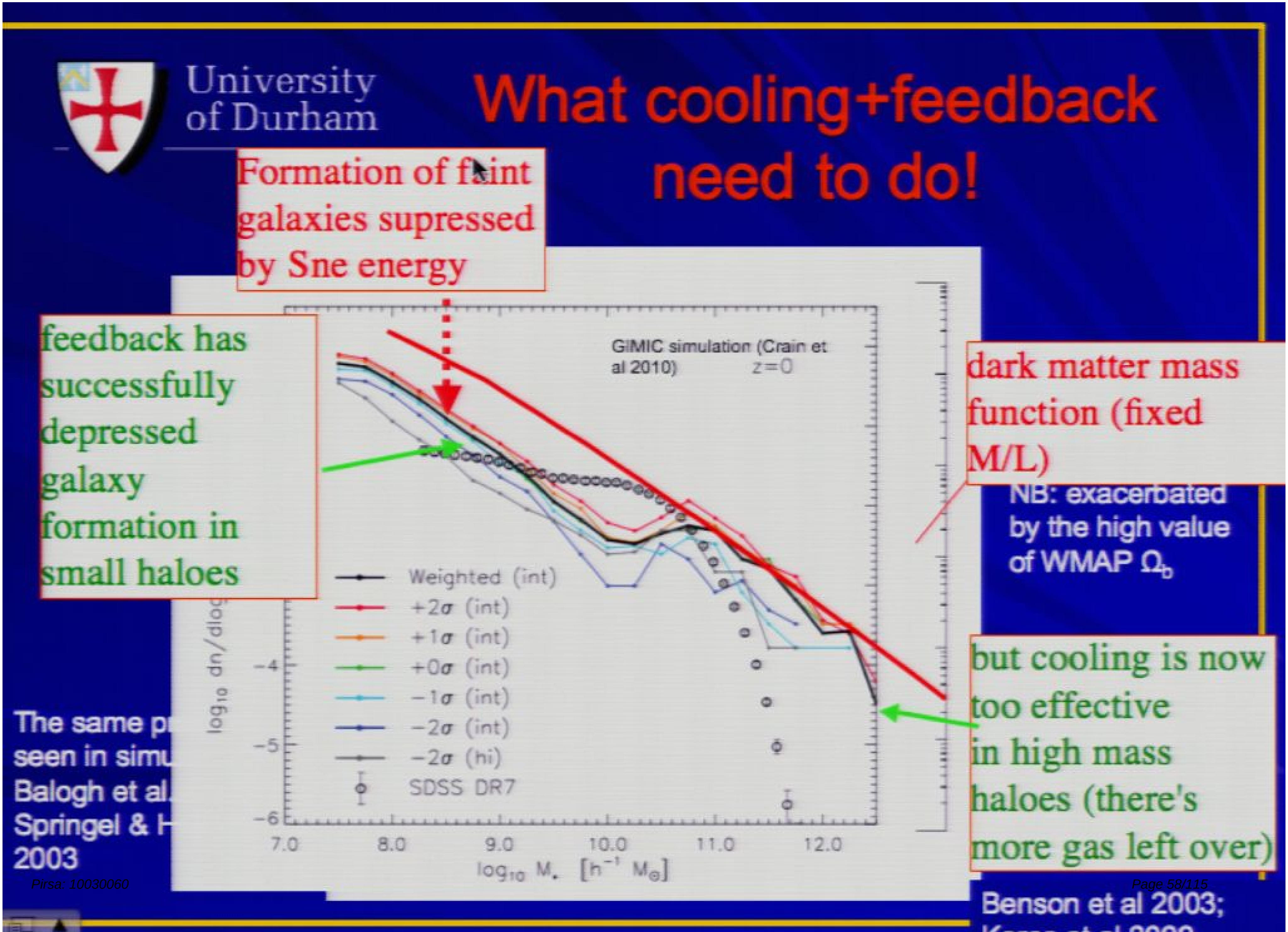
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What cooling+feedback need to do!
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GIMIC simulation (Crain et al 2010)
z=0
dark matter mass function (fixed M/L)
NB: exacerbated by the high value of WMAP Ωb
Weighted (int)
+2σ (int)
+1σ (int)
+0σ (int)
−1σ (int)
−2σ (int)
−2σ (hi)
SDSS DR7
but cooling is now too effective in high mass haloes (there's more gas left over)
The same p
seen in simu
Balogh et al
Springel & H
2003
log10 M* [h^-1 M⊙]
Benson et al 2003;

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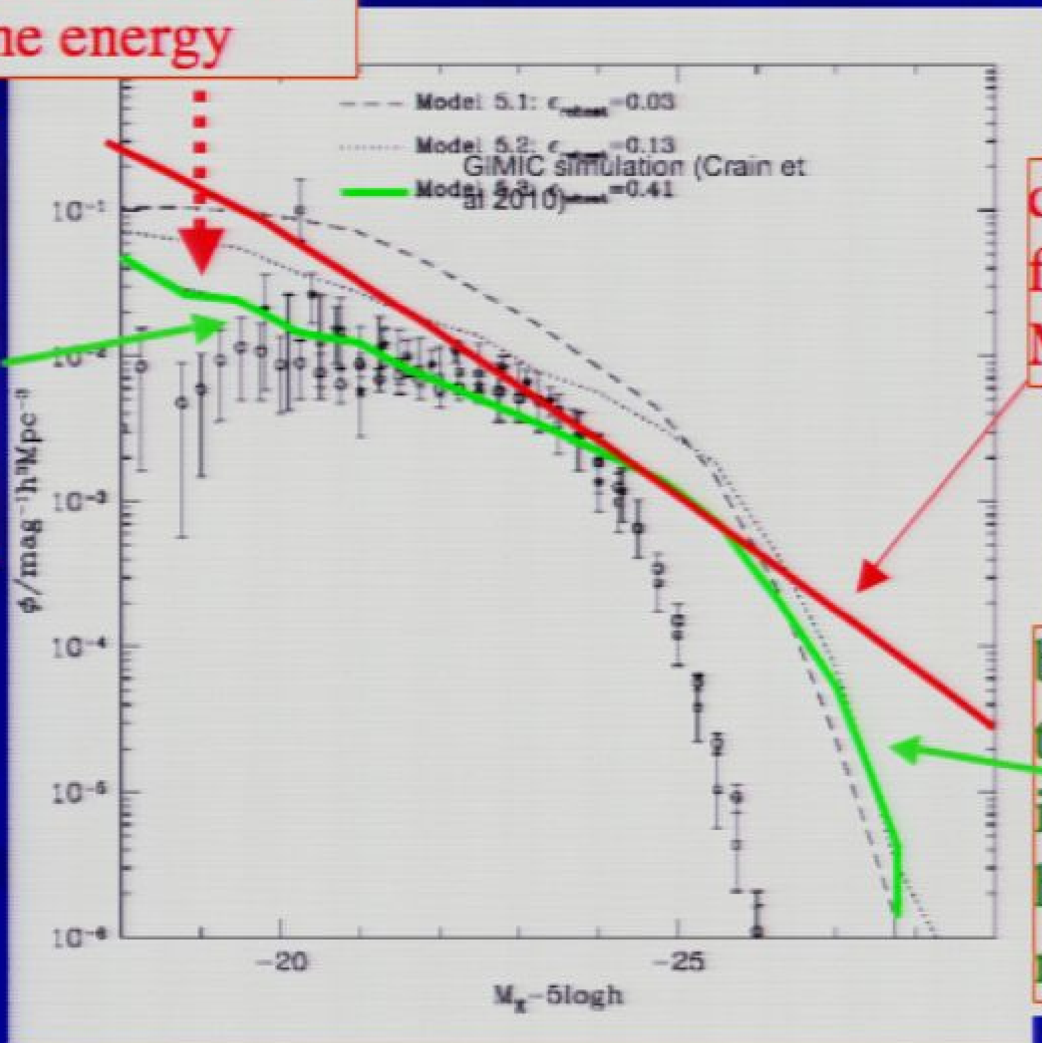

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What cooling+feedback need to do!

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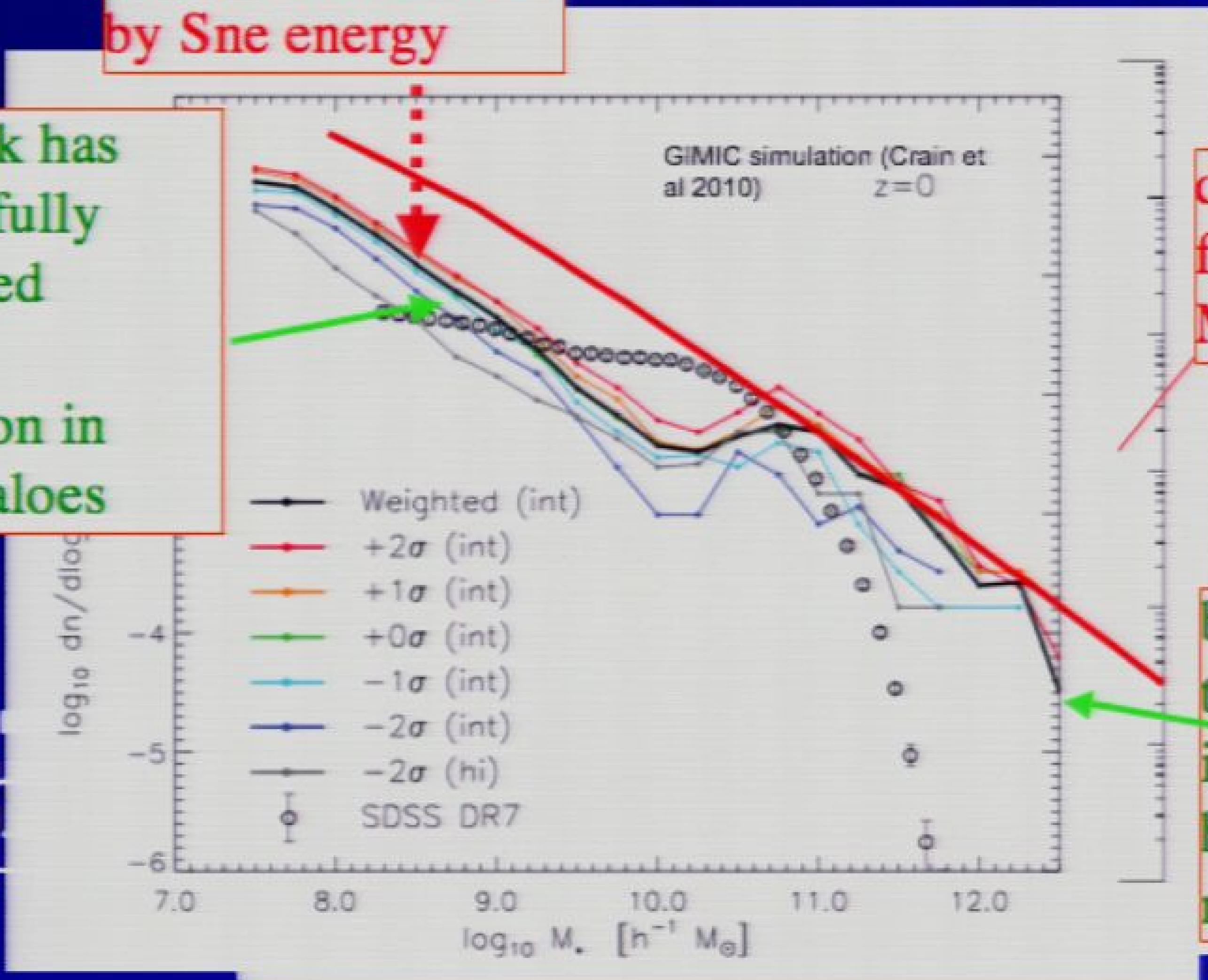

The same p… seen in simu… Balogh et al… Springel & H… 2003

Benson et al 2003;

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The three problems of galaxy formation

1. The bright end of the luminosity function
   - What sets the break in the galaxy luminosity function?
2. The "cooling flow" problem
   - Why don't cooling flows result in bright blue galaxies at the centres of clusters?
3. The "hierarchy" problem
   - Why are the brightest galaxies old and red?

These problems are closely interconnected: do AGN provide the solution?

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   - Why don't cooling flows result in bright blue galaxies at the centres of clusters?
3. The "hierarchy" problem
   - Why are the brightest galaxies old and red?

4. Only 10% of the baryons form into stars!!! Where are the other baryons? what are their properties?

These problems are closely interconnected: do AGN provide the solution?

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The Power of AGN

Comparison of energies:

Thermal energy of a 10^{13} $M_{\odot}$ halo ... 10^{61} erg
Accretion energy of a 10^{9} $M_{\odot}$ black hole ... 2×10^{62} erg

It seems unlikely that AGN are unimportant!

The two forms of AGN feedback

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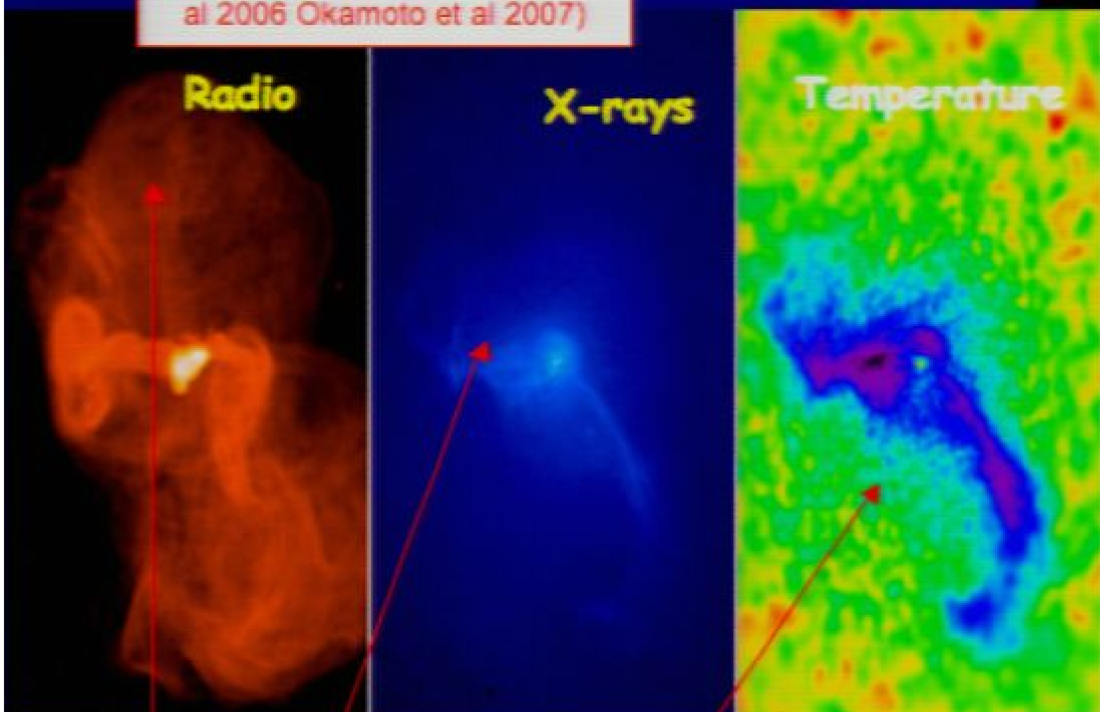
"Radio" mode feedback

(eg. Croton et al 2006, Bower et al 2006 Okamoto et al 2007)



Shock heating

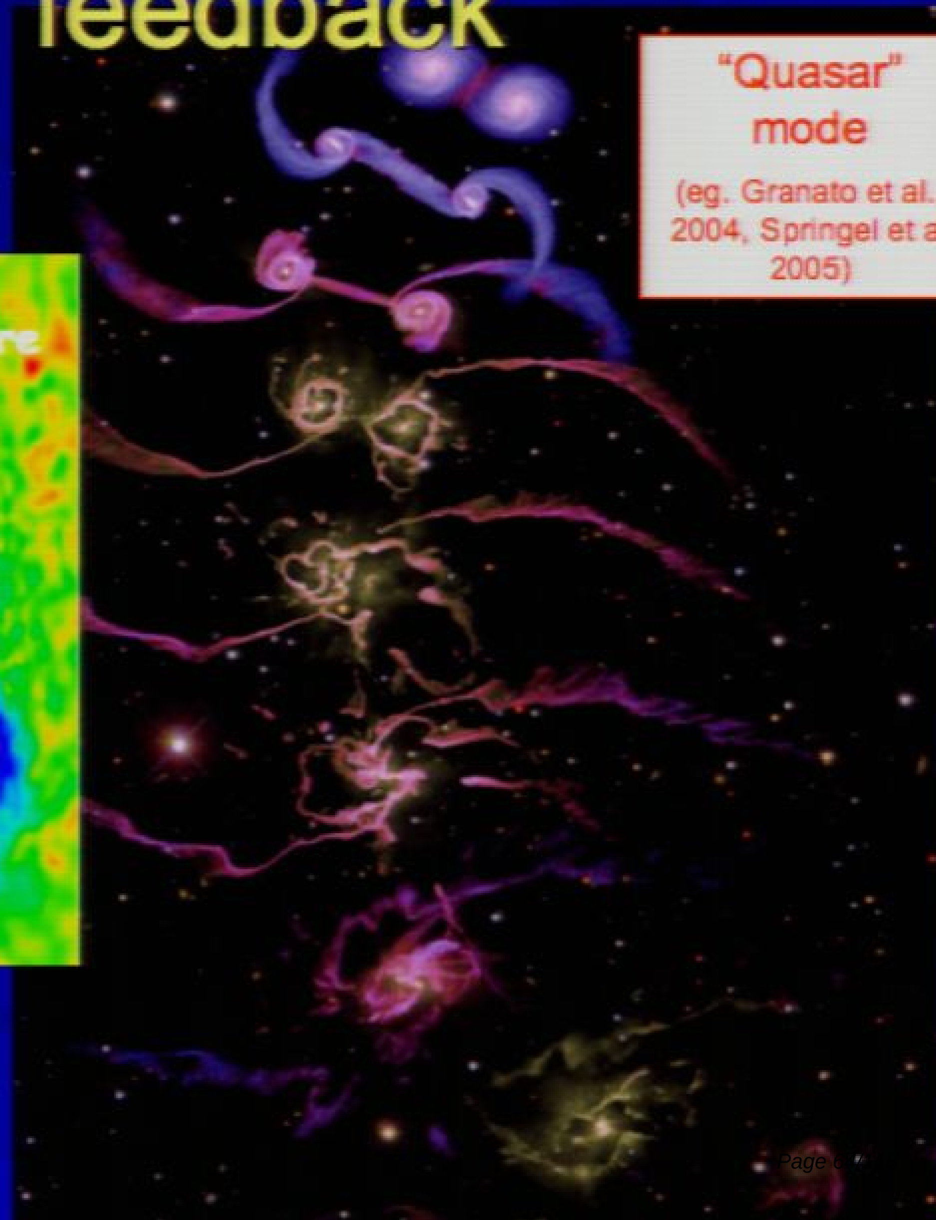
Uplifting matterial?

plasma and ICM?

M87: Forman et al 2006;
Perseus: Fabian et al 2000,

"Quasar" mode

(eg. Granato et al., 2004, Springel et al 2005)



The two modes of AGN feedback

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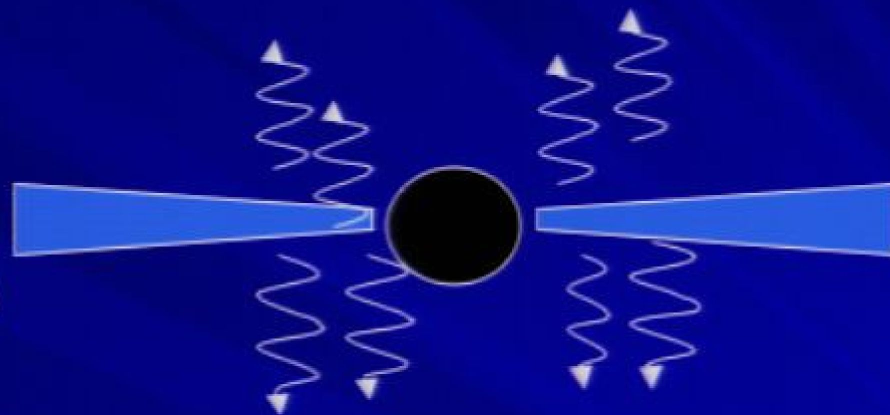
Radiatively efficient flows

- "normal" Shakura-Sunyaev disk
- Geometrically thin
- Heat generated by the flow is radiated
- The disk stays cool and thin



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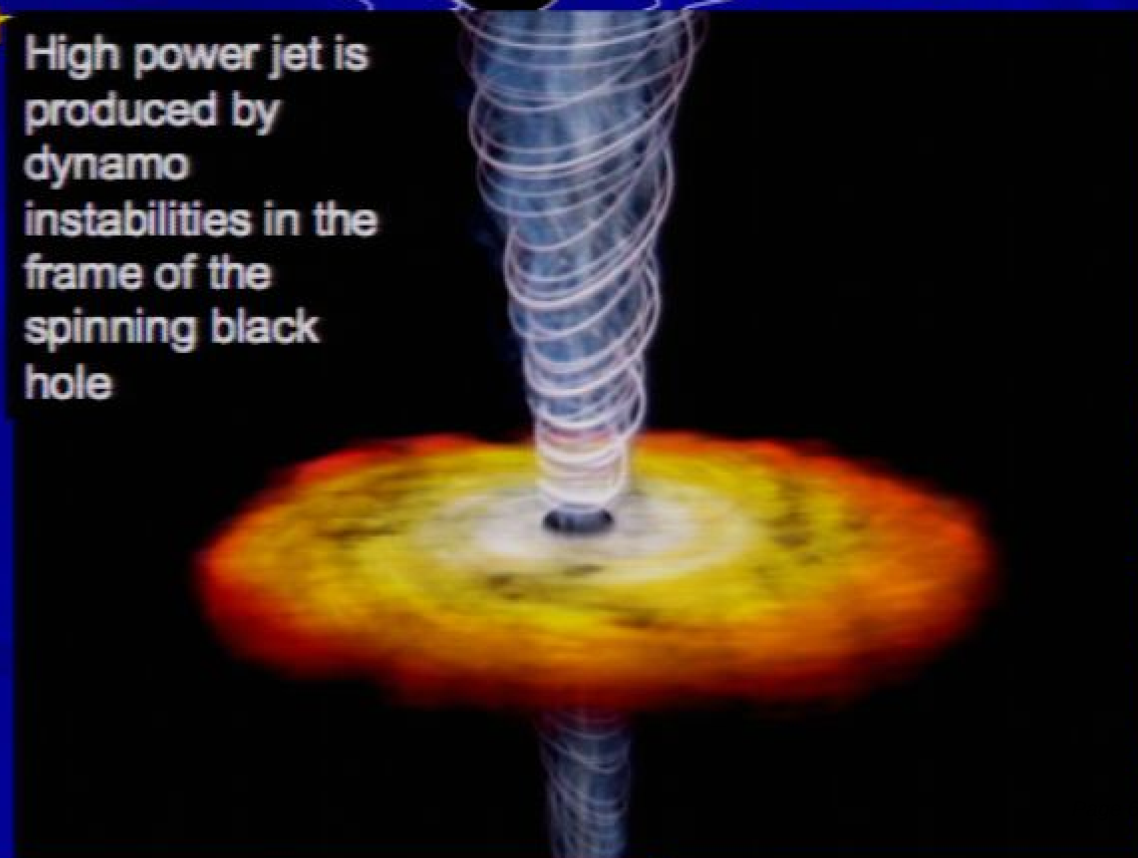
High accretion rate



Radiatively inefficient flows
- •Geometrically thick
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(ADAF: Narayan & Yi 1995; RIAF: Blandford & Begelman 1999)

.ow
cretion
rate

t

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al

1983, Meier 1999, 2001)

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The AGN feedback loop

“radio” mode

$P_{max}=\varepsilon L_{edd}$

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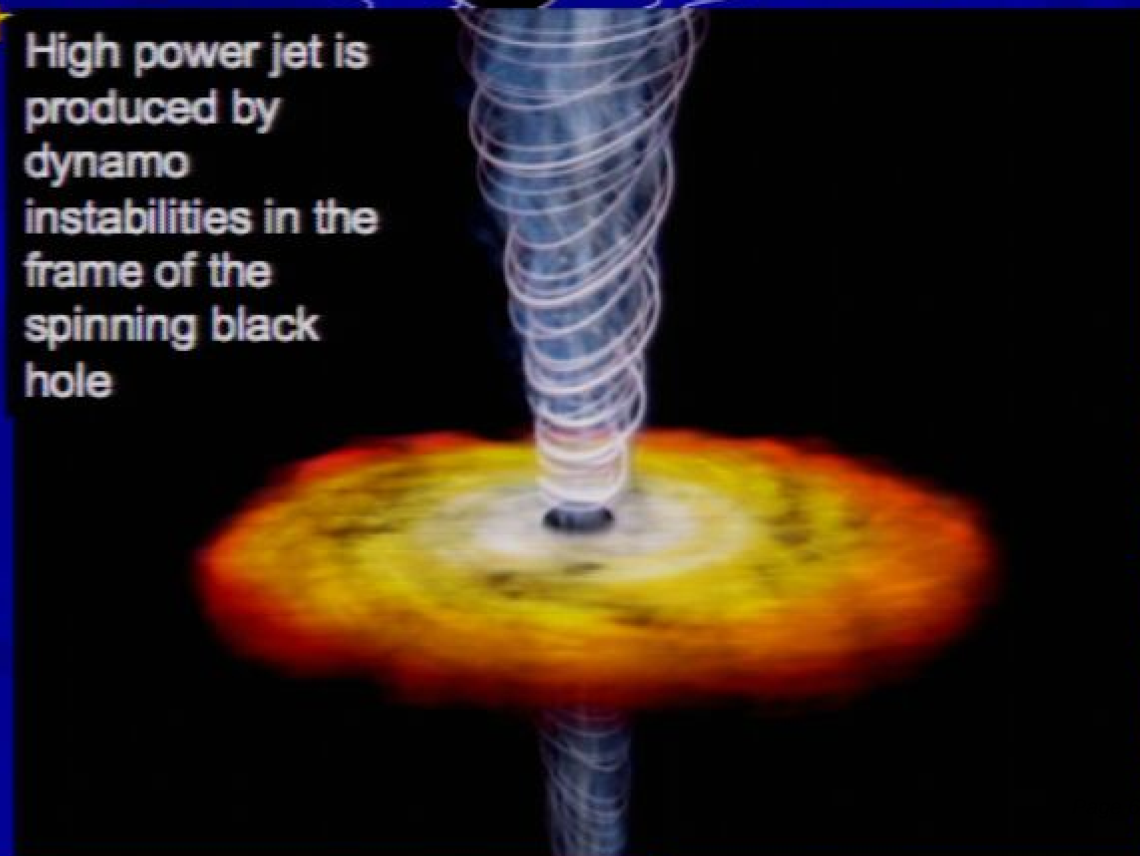

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[L]ow [ac]cretion [r]ate

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The two modes of AGN feedback

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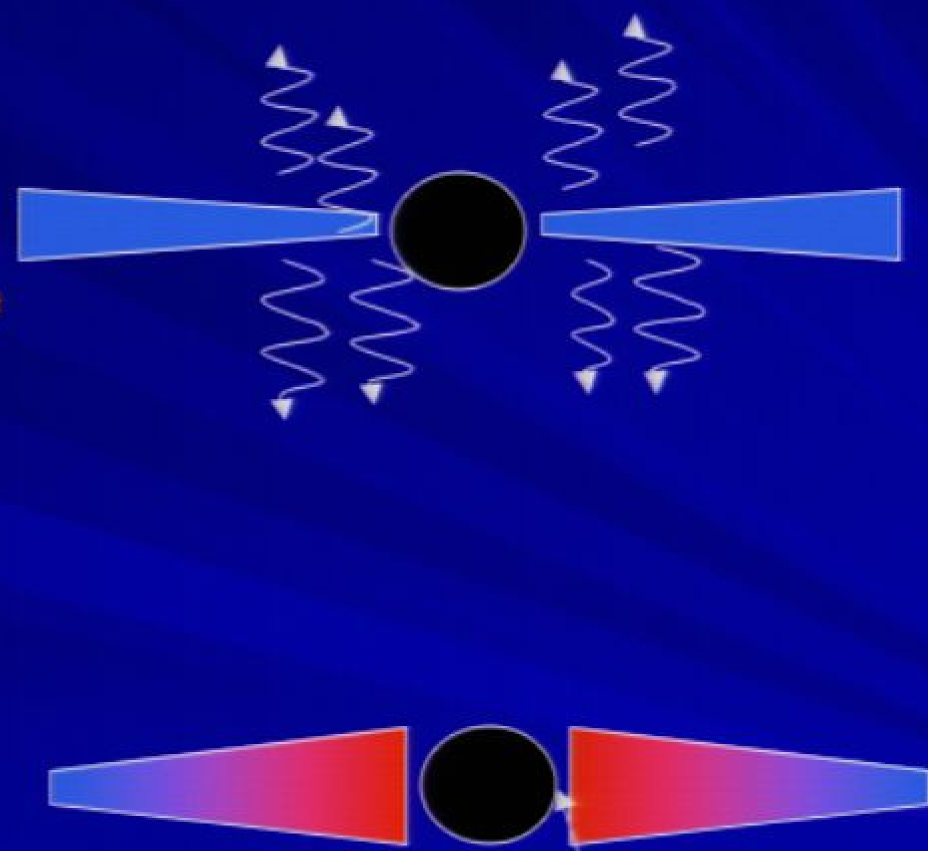

High accretion rate

Low accretion rate

Radiatively inefficient flows
- Geometrically thick
- Heat generated by the flow is trapped and advected into the black hole
- The disk becomes hot and thick

(ADAF: Narayan & Yi 1995; RIAF: Blandford & Begelman 1999)

Large disk scale height leads to magnetic field being stretched into the black hole's space time

(Blandford Znajek 1977, Rees et al 1982, Meier 1999, 2001)

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The two modes of AGN feedback

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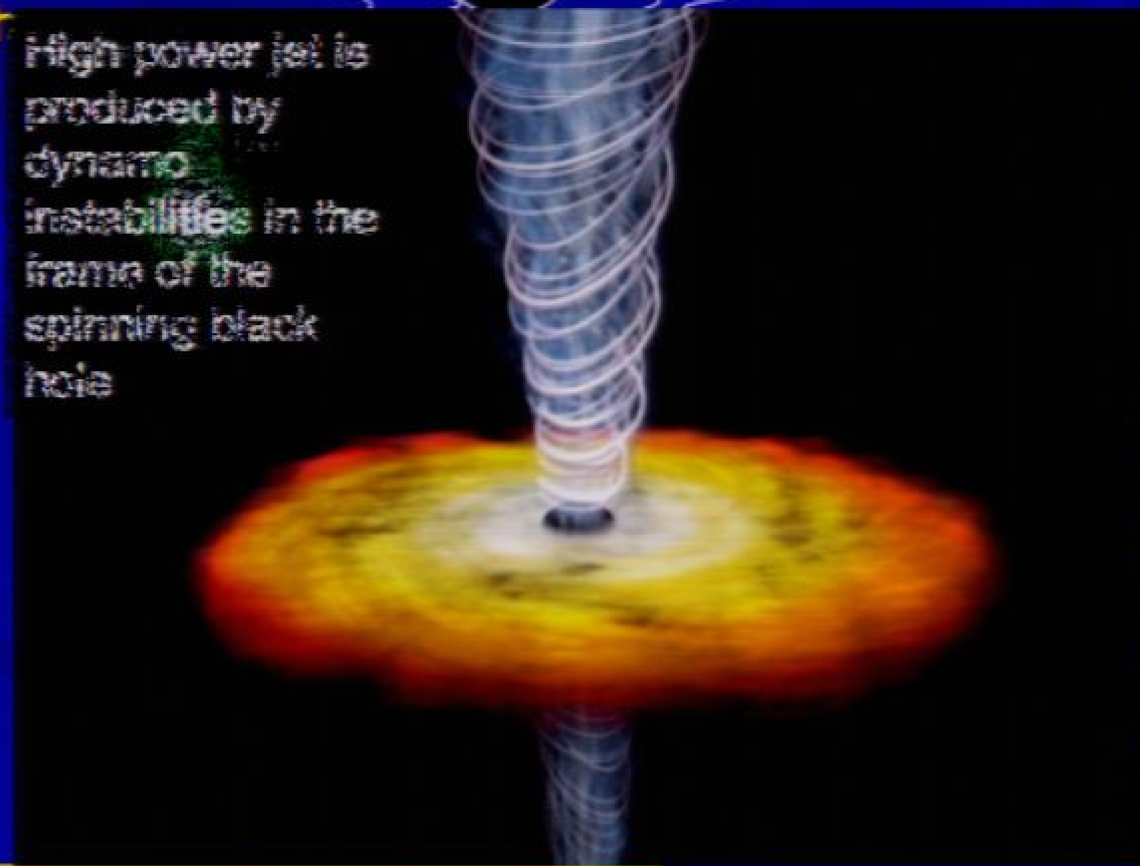

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The AGN feedback loop

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seems unlikely that AGN are unimportant!

Keres et al 2005; Dekel & Birnboim 2005; Binney 2004

The AGN feedback loop (new version)

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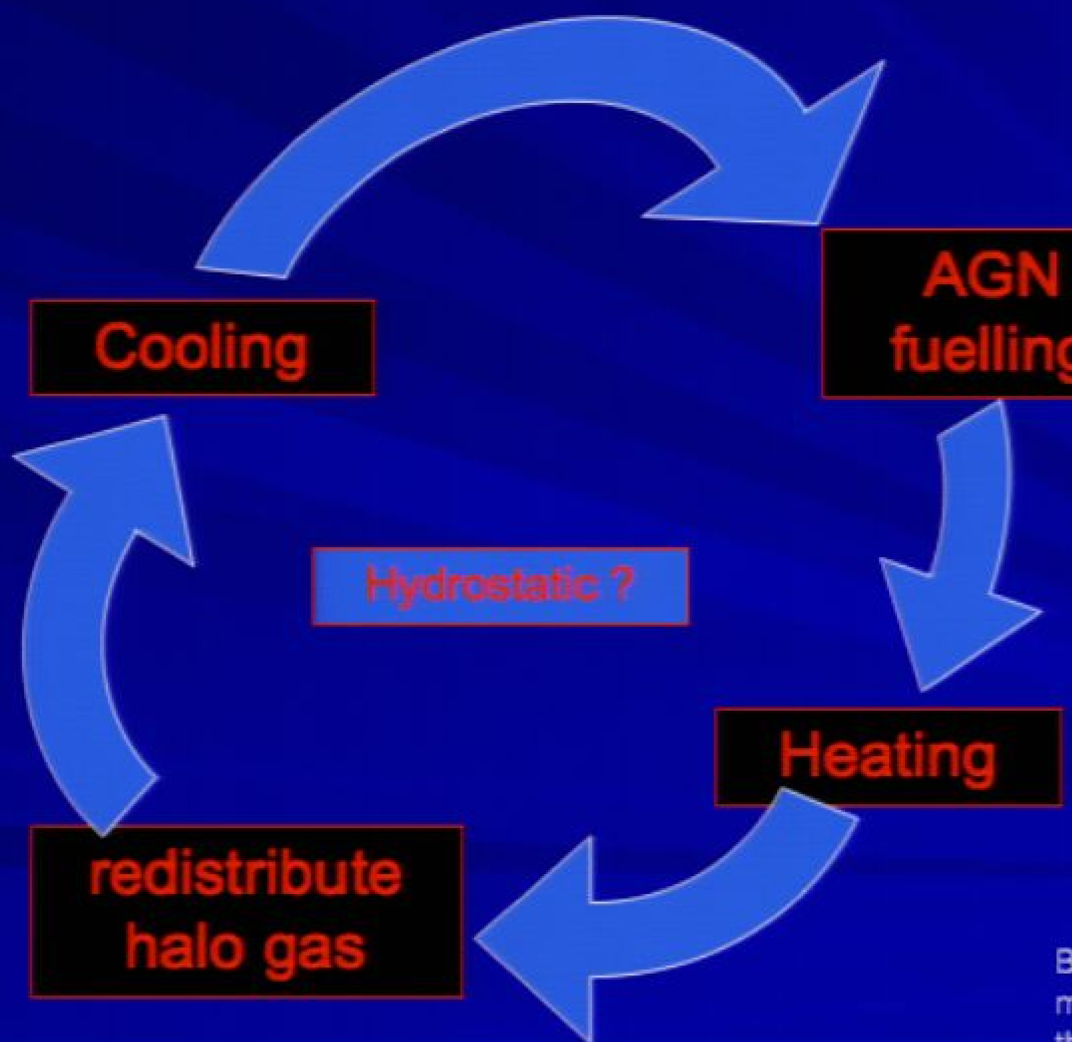

"radio" mode

$P=\min(\varepsilon L_{edd}, \eta \dot{M}_{cool})$

As seen in numerical sims: Puchwein et al 2008; McCarthy et al 20[illegible]

Based on the "excess energy" method (Wu et al 19[illegible]), plus the hydrostatic criterion

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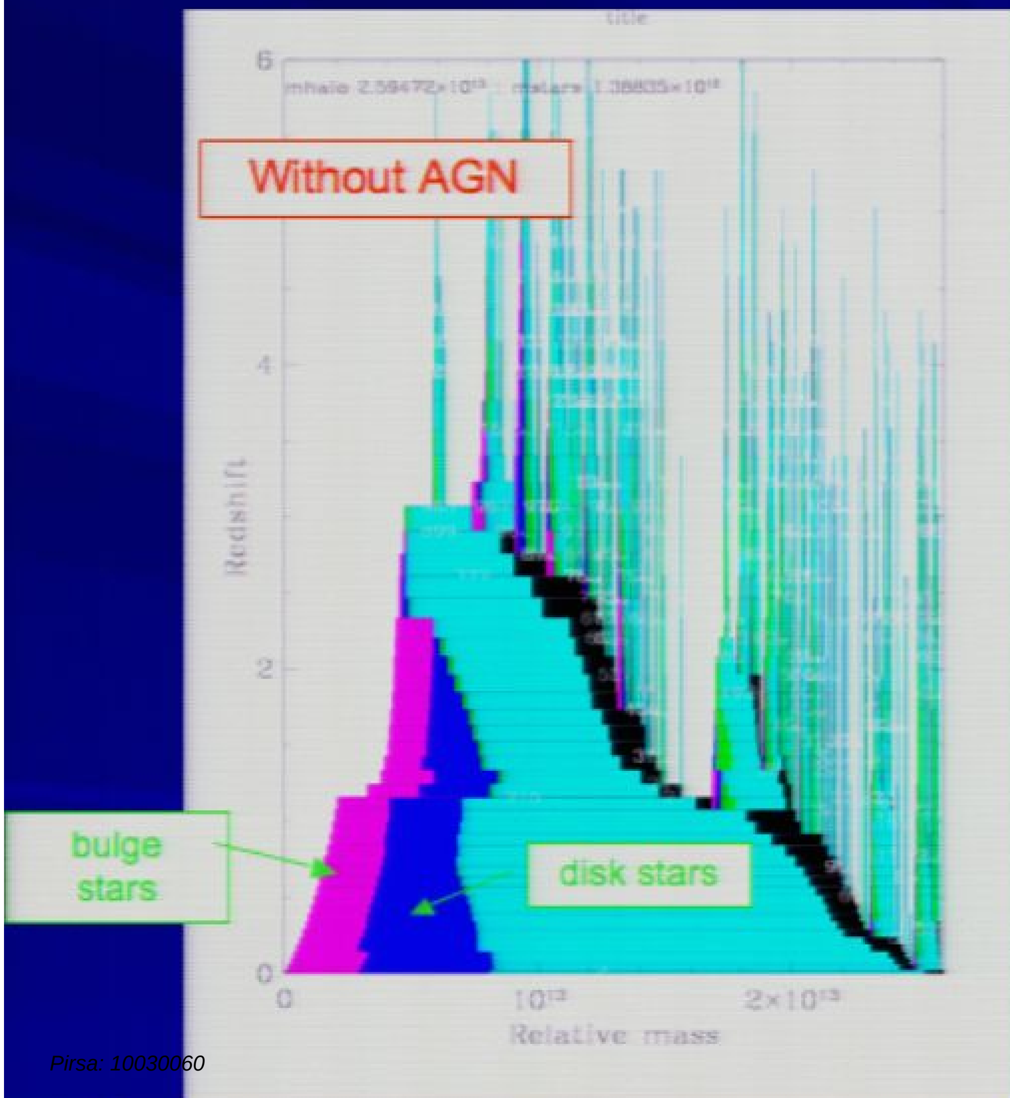
The impact of AGN Feedback: An Example



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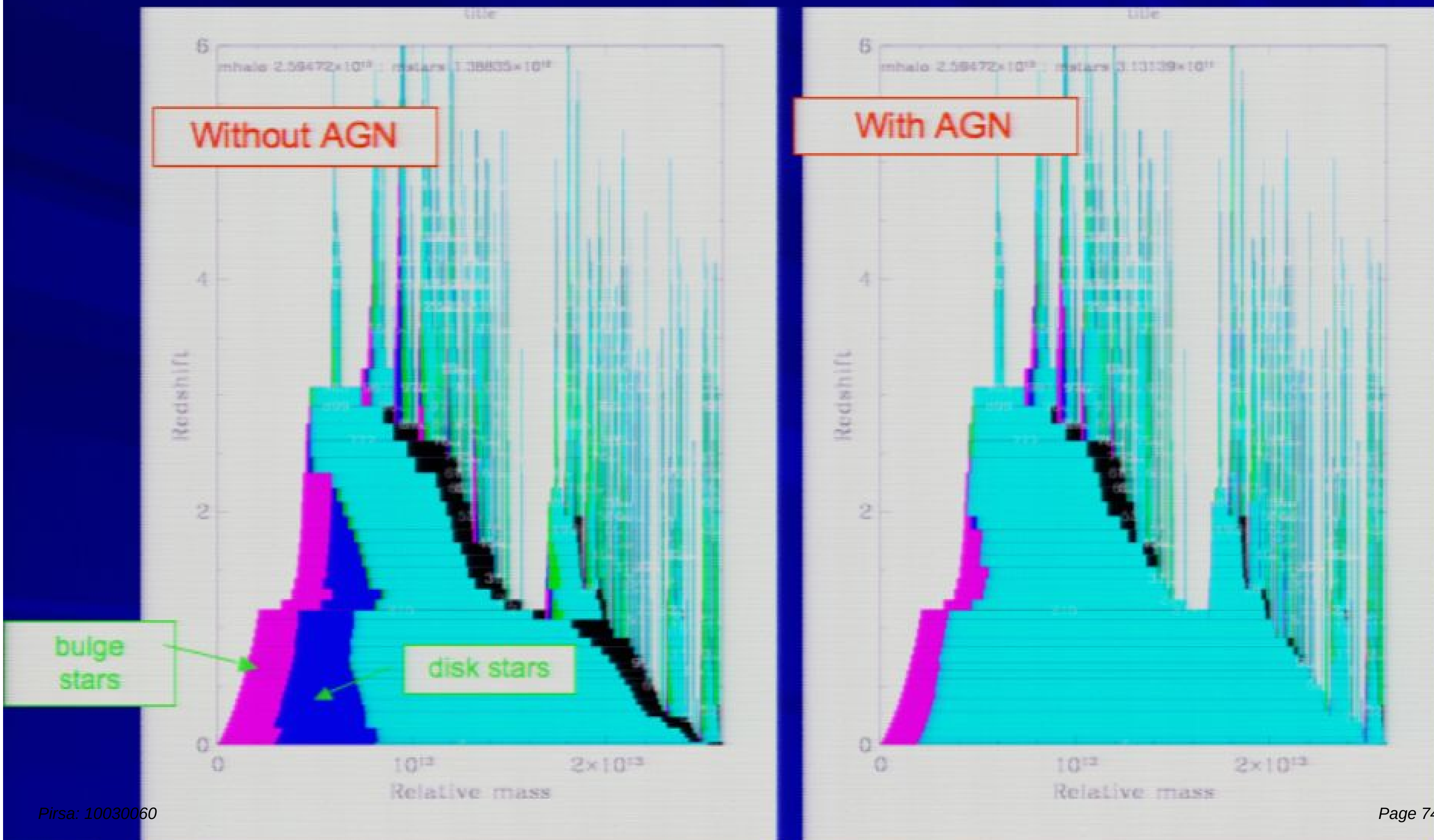

Present-day Galaxies

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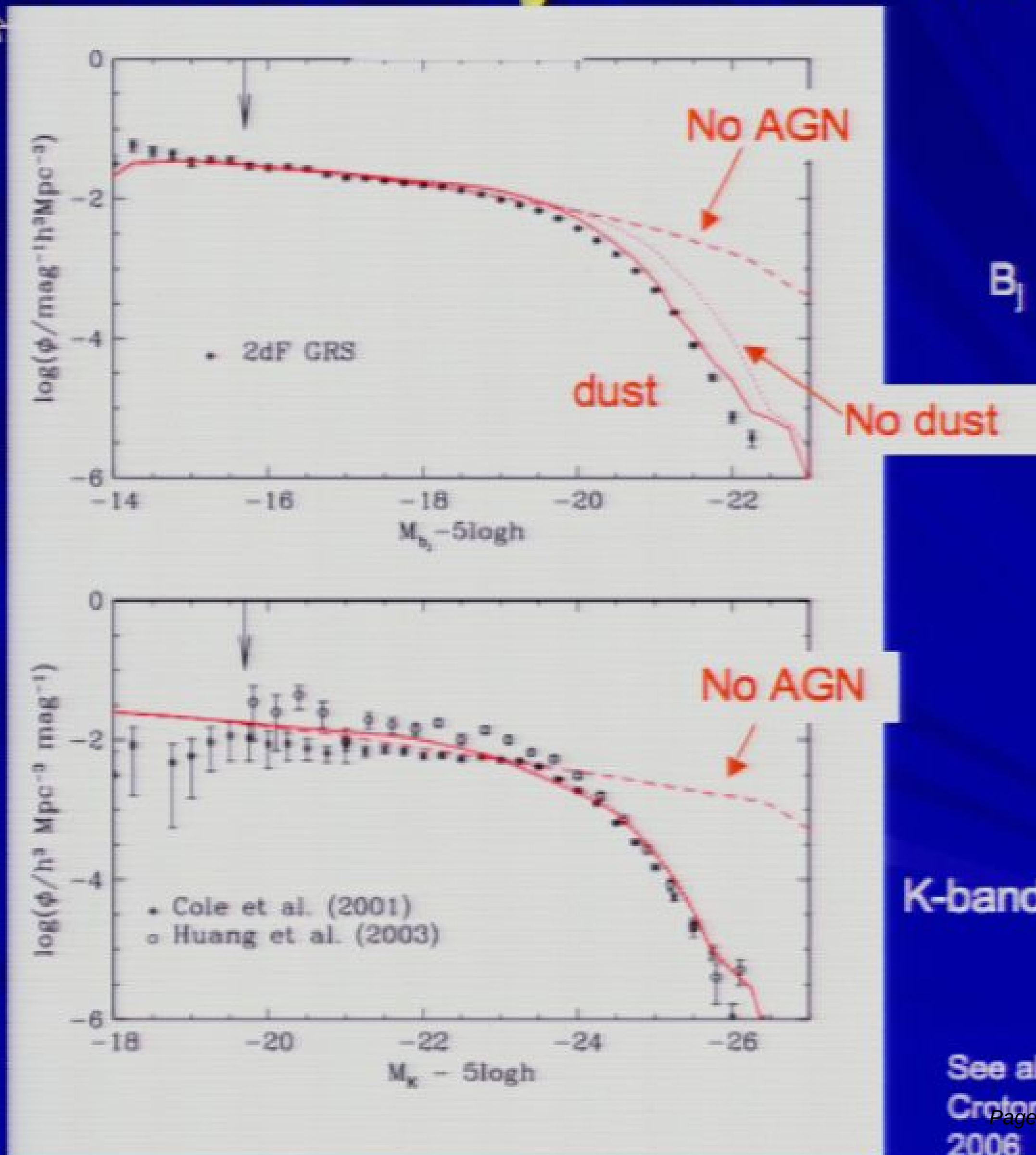
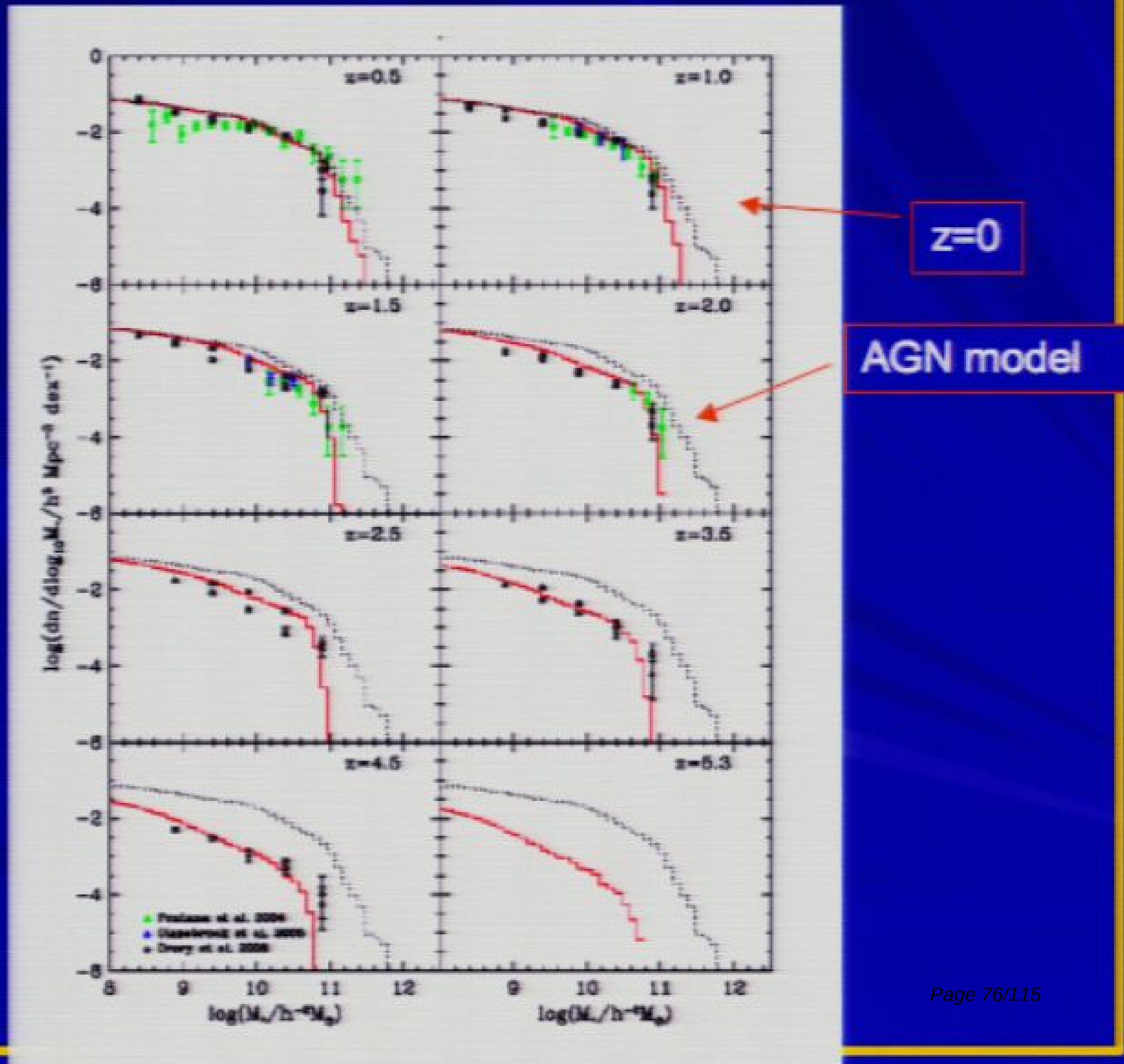
- Bj and K luminosity functions
- Switching "radio" feedback off leads to a population of very bright galaxies formed in cooling flows
- But position of the LF break is set by the division between rapid and hydrostatic cooling haloes.



See also Croton et al., 2006

Evolution of the Stellar Mass Function

- The evolution of the stellar mass function from Drory et al 2005.



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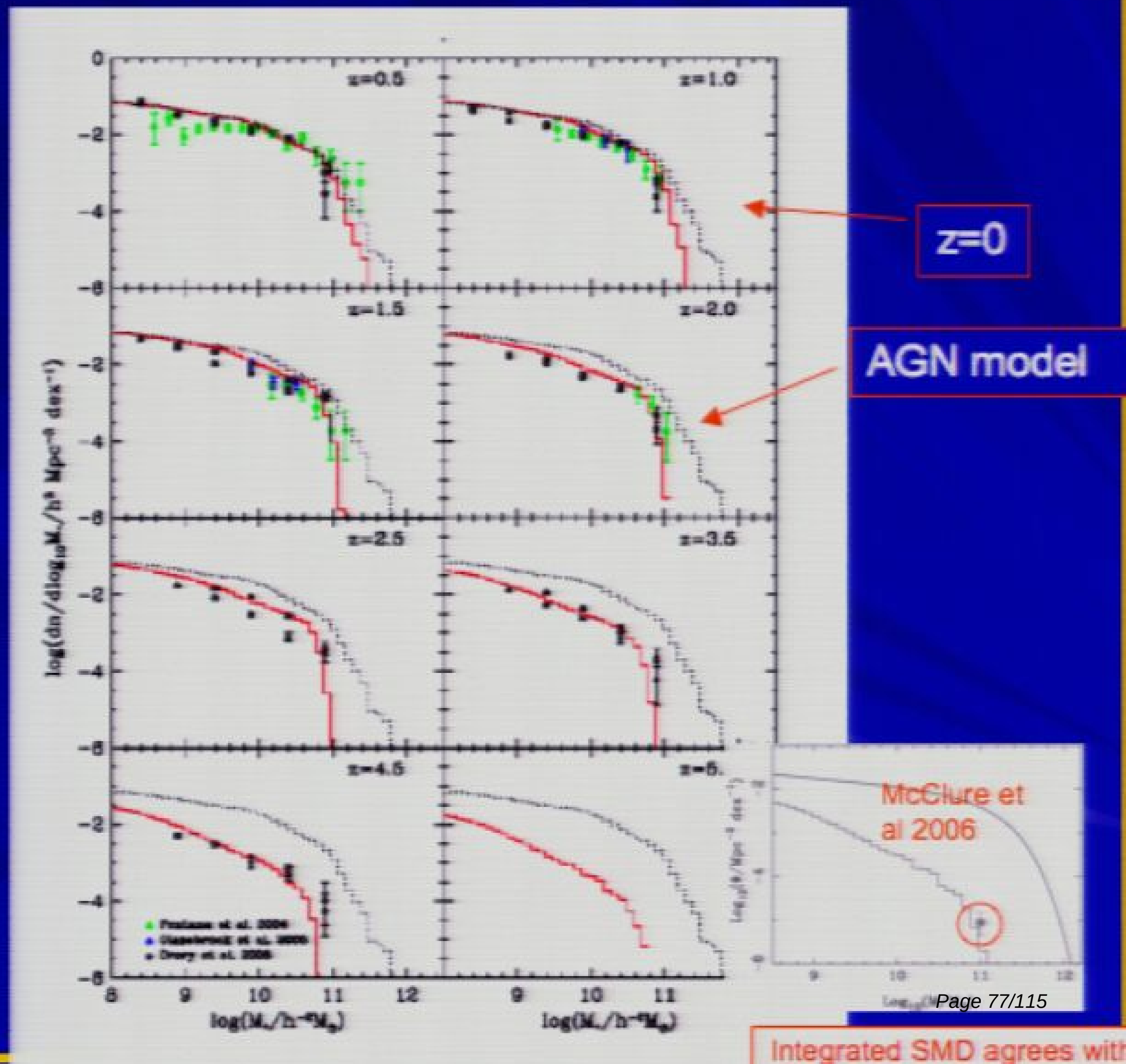

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But there's (a lot) more to the universe than galaxies

Only 10% of the baryons are locked into stars: what about the properties of the rest?

"The flip-side of galaxy formation"

The flip-side of galaxy formation: scaling relations of galaxy clusters

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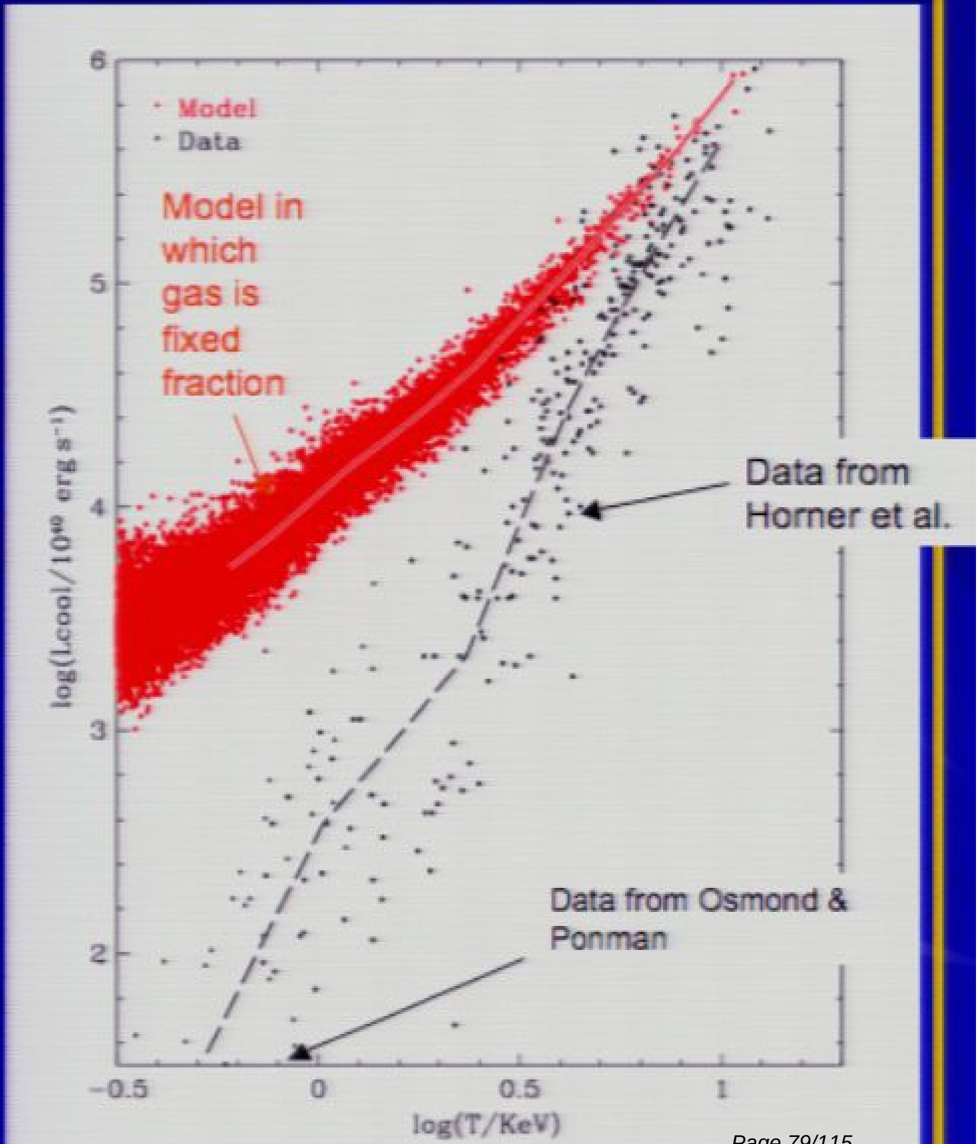
- The gas distribution in groups is puffed-up compared to clusters.
- "Cooling" vs "Preheating" vs "in-situ" heating
  - Cooling: remove the gas and turn it into stars. [Voit & Bryan 01]
  - Preheating: Heat the gas before it falls into gravitational potential: 2nd law prevents it getting dense in groups [Evrard & Henry 91; Kaiser 1991]
  - In-situ heating: we know radio source have a large impact on clusters - do they have an even greater heat impact on groups? [Wu etal 01, Bower etal 08]
- Our aim:
  - Link ICM heating to feedback during galaxy formation. Can we solve the problems of galaxy formation and the ICM in one go? [Scannapieco & Broadhurst 2001; Wu etal 2001; Bower etal 2001]



Voit & Bryan: A Cartoon Model

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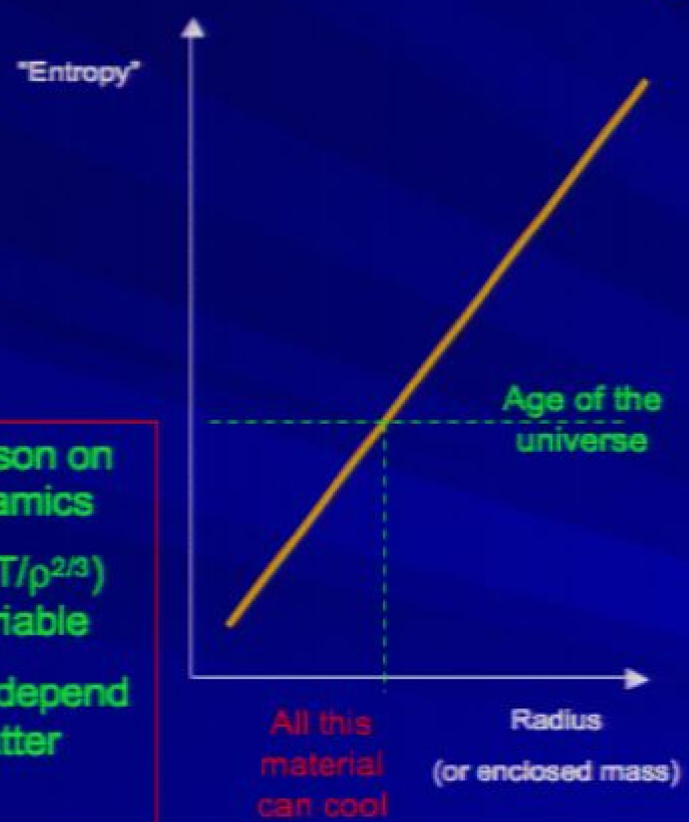

A quick lesson on thermodynamics

"Entropy" ($T/\rho^{2/3}$) is a key variable

- Does not depend on dark matter halo
- Only changed by heating and cooling
- Fixed cooling time ~ fixed entropy

Voit & Bryan 2001; Voit & Ponman 2003

X-ray Emission from Groups and Clusters

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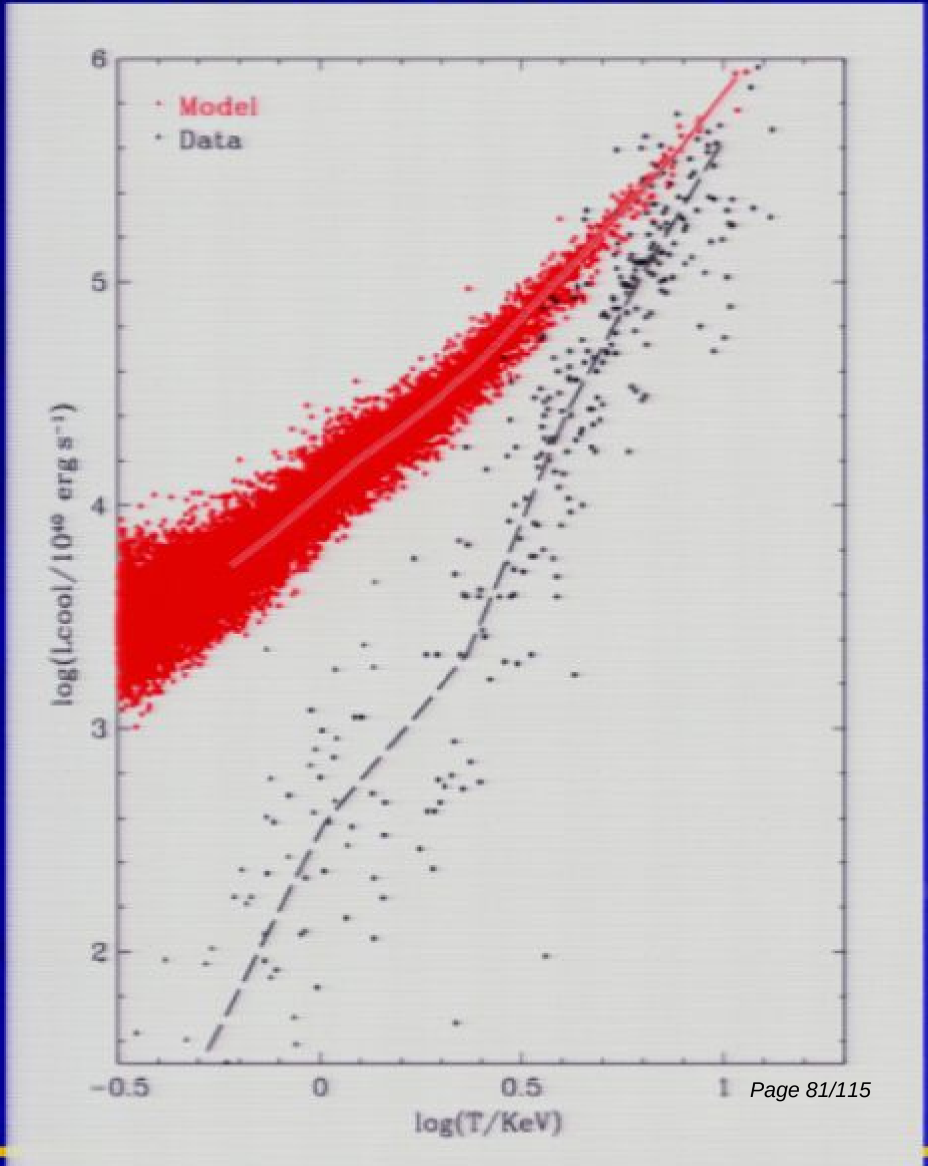
- L-T relation : well known that the self-similar relation fails
- AGN: standard model just prevents cooling
- Revised model, AGN feedback redistributes halo gas until the cooling rate drops and AGN power is cut off



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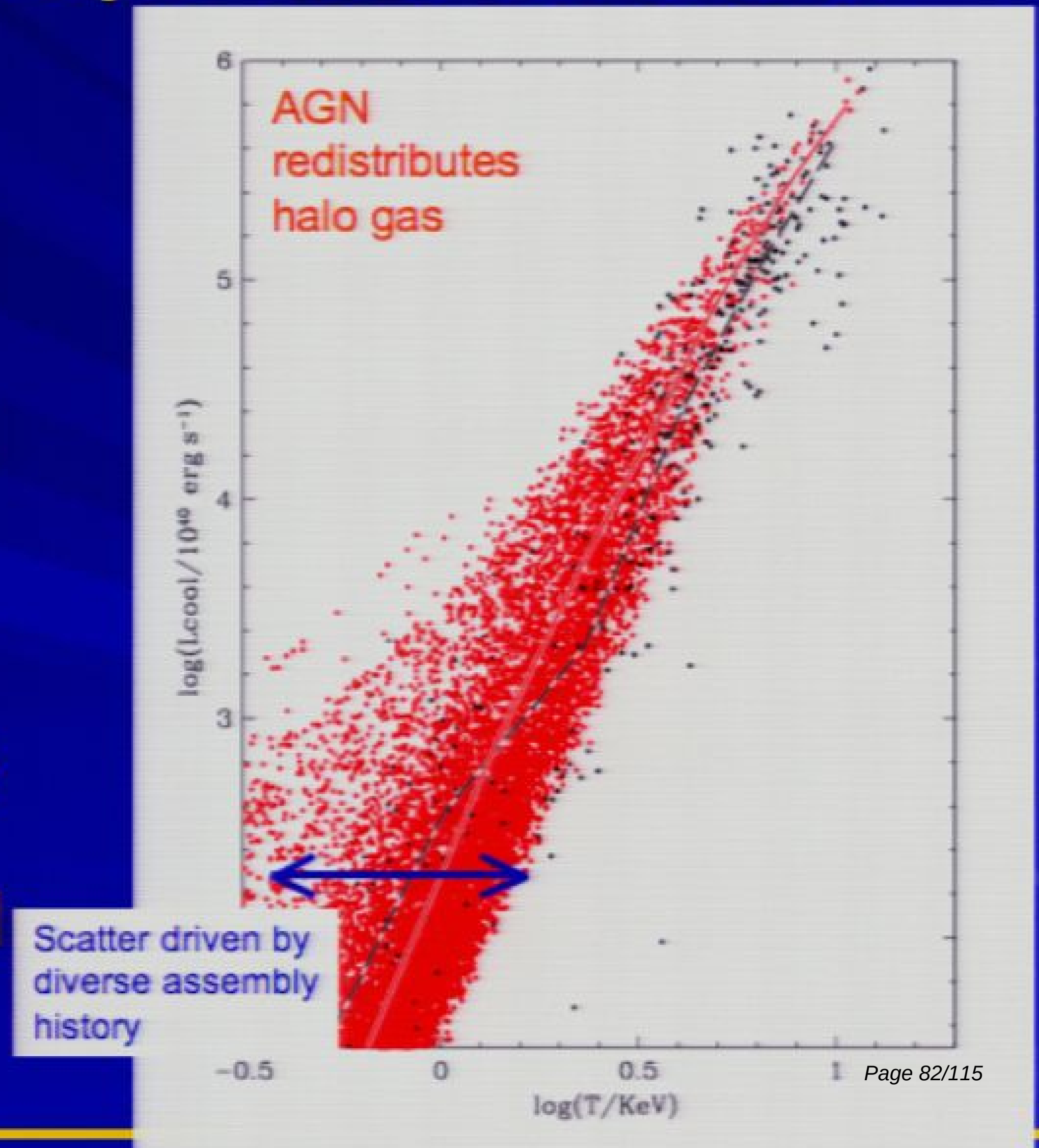

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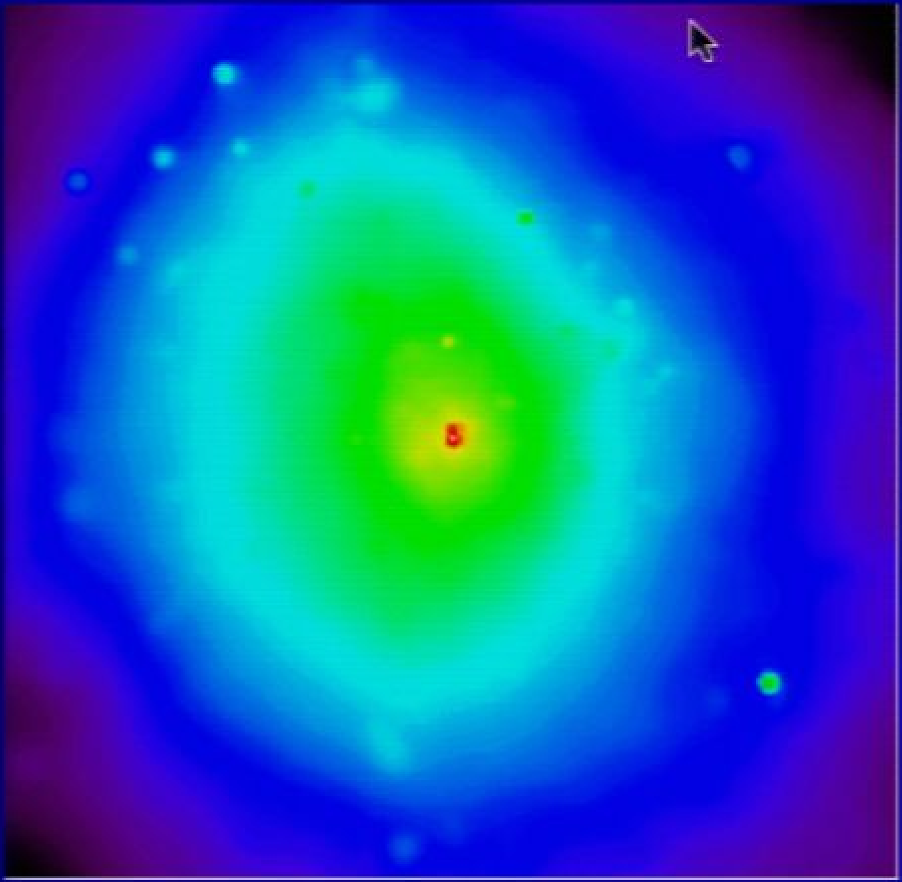
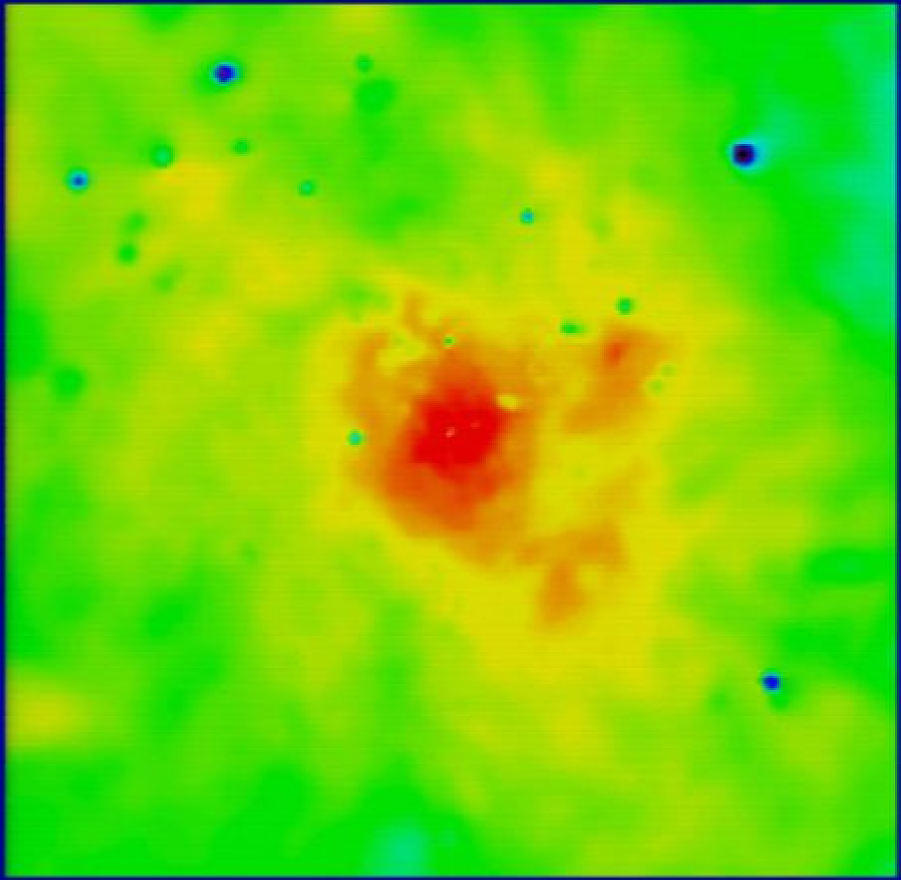
Part III

- But semi-analytic models are highly simplified
- …need numerical simulations to re-inforce these ideas:
  - OWLS - like semi-analytic models, but with numerical simulations [also Dave et al 2008; Puchwein et al. 2008]
  - Fortunately, the “flip-side” is accessible for numerical simulations

OWLS: Mock X-ray observations



X-ray surface brightness map
[0.5-7.0 keV band]



X-ray spectroscopic-like temperature map
[0.5-7.0 keV band]

- Analyse the 70 most massive groups in each 100 h^-1 Mpc OWLS simulation box ($M_{200} > 3 \times 10^{13}$ M_{sun})

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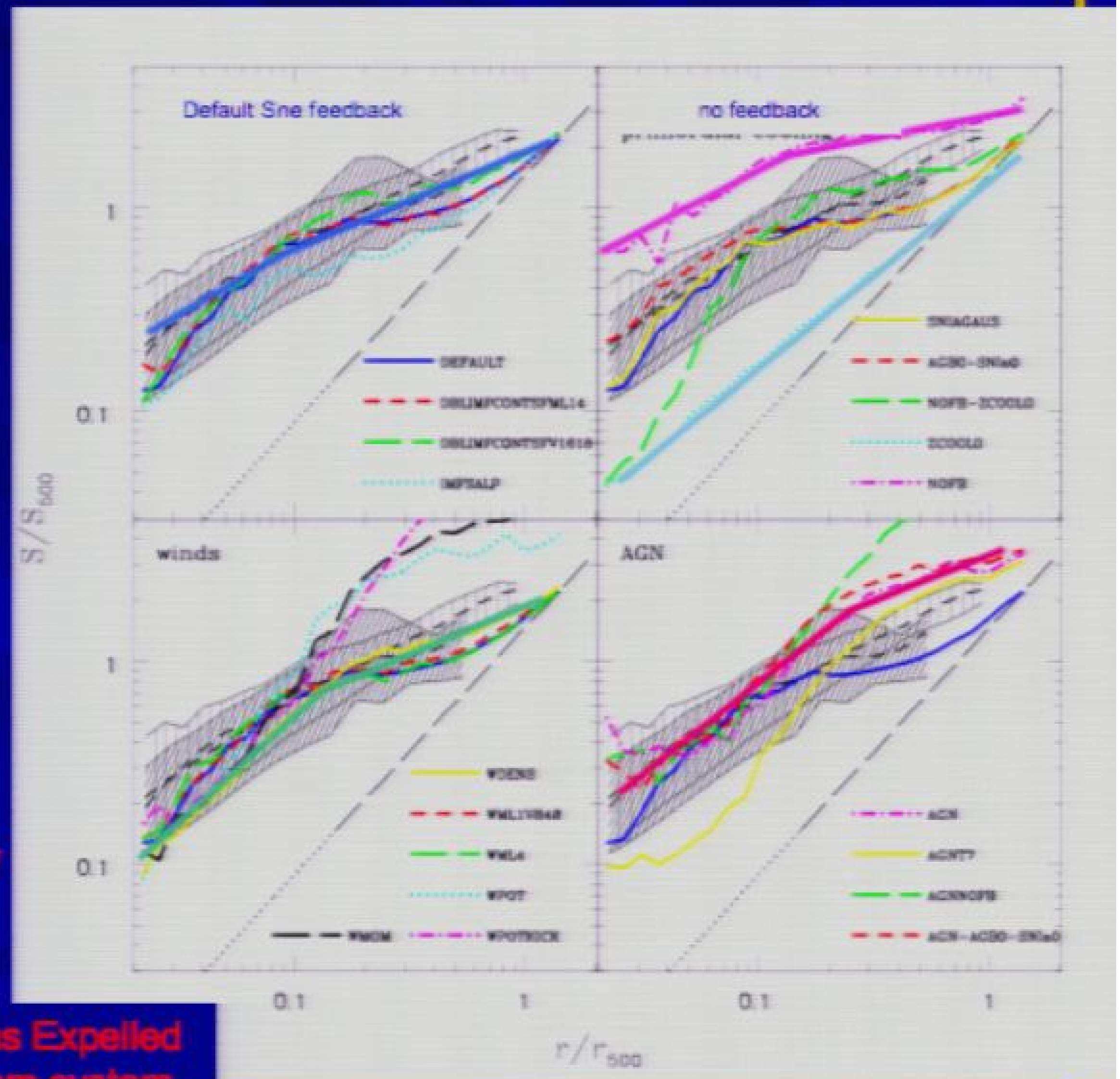
Entropy profiles

- Surprisingly little variation between feedback schemes
- Voit & Bryan process seems to work!
- But where does the low entropy gas go?
  - No feedback
  - default
  - High energy winds
  - AGN driven winds

Too many stars!

Gas Expelled from system



McCarthy et al 2009

Cooled Gas Mass

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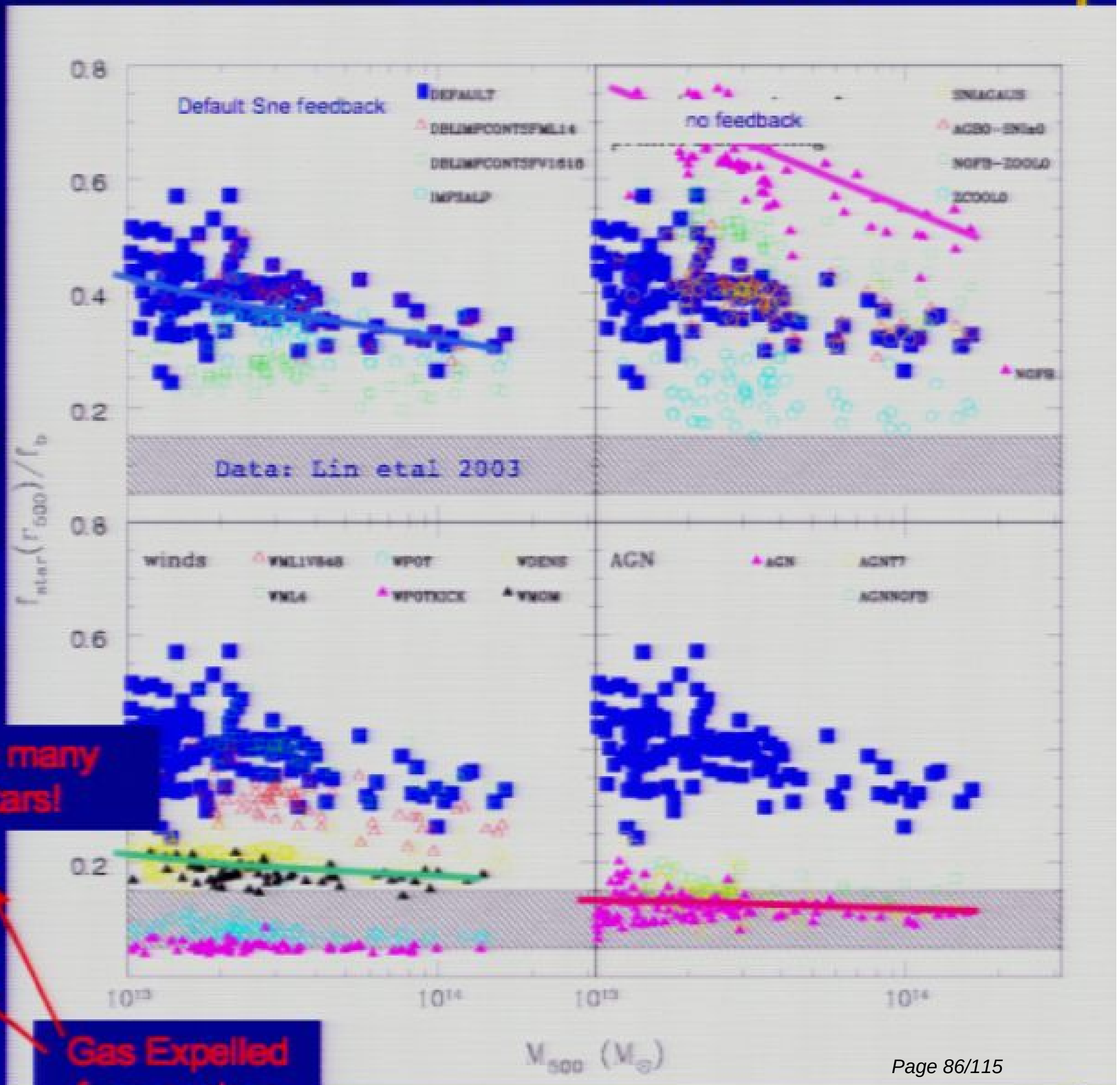
- "star formation efficiency puzzle"
- But where does the low entropy gas go?
  - No feedback
  - default
  - High energy winds
  - AGN driven winds

Too many stars!

Gas Expelled from system



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Part IV

The Future

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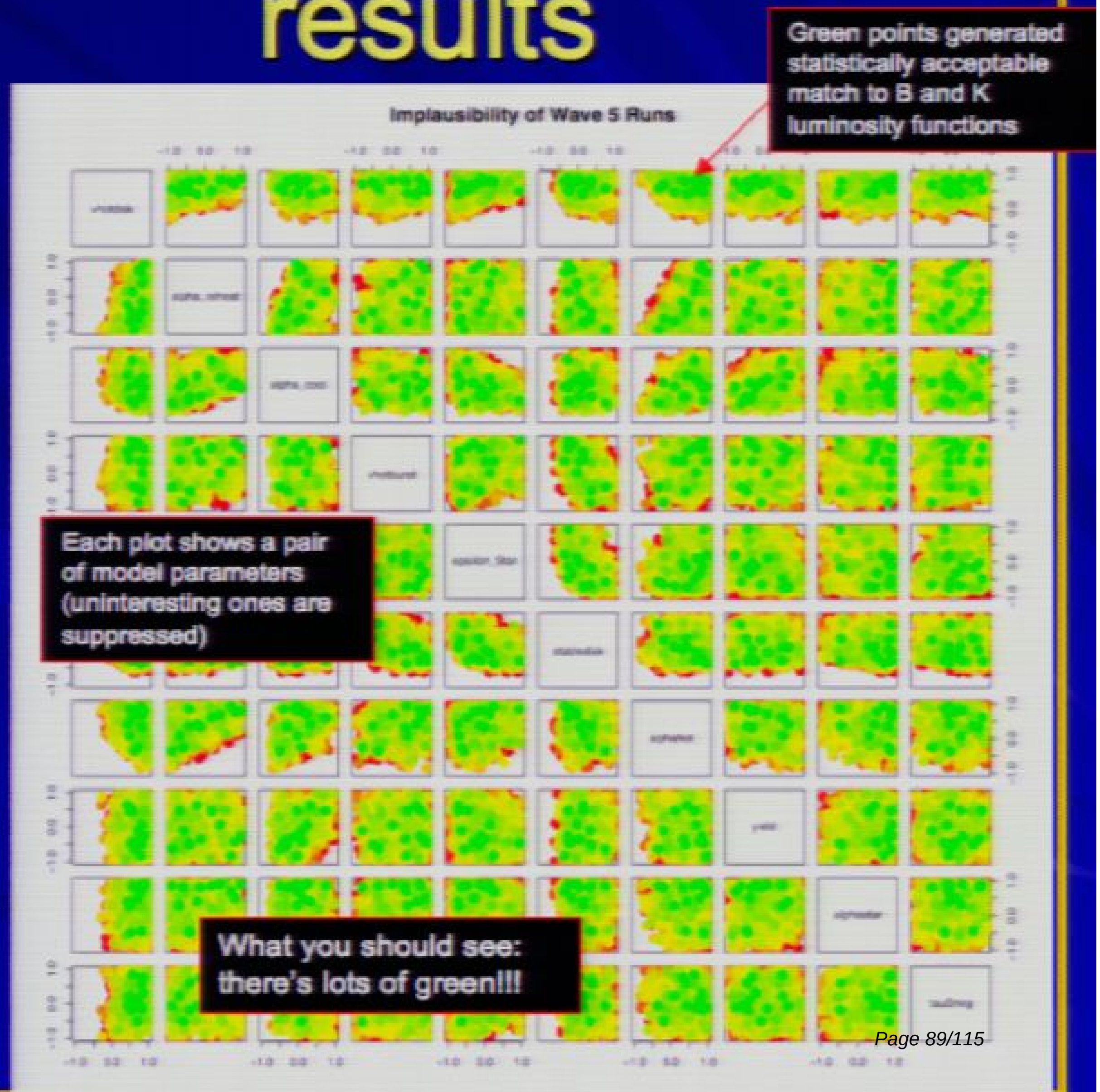
Galaxy Formation in 16-dimensions

- There are 16 parameters in the Galform model
- …but this doesn't mean you can obviously fit the data

- Bower et al 2010 - exploring parameter space with Bayesian emulators.
  - A key part of the idea is "waves of emulation"
  - adapting computational expense to the likelihood of finding an acceptable match to data

Quick summary of the results

- Acceptable luminosity function fits can be found over a wide range of parameter space
- …but this is a projection effect - the acceptable space lies on thin planes (0.05% of volume)



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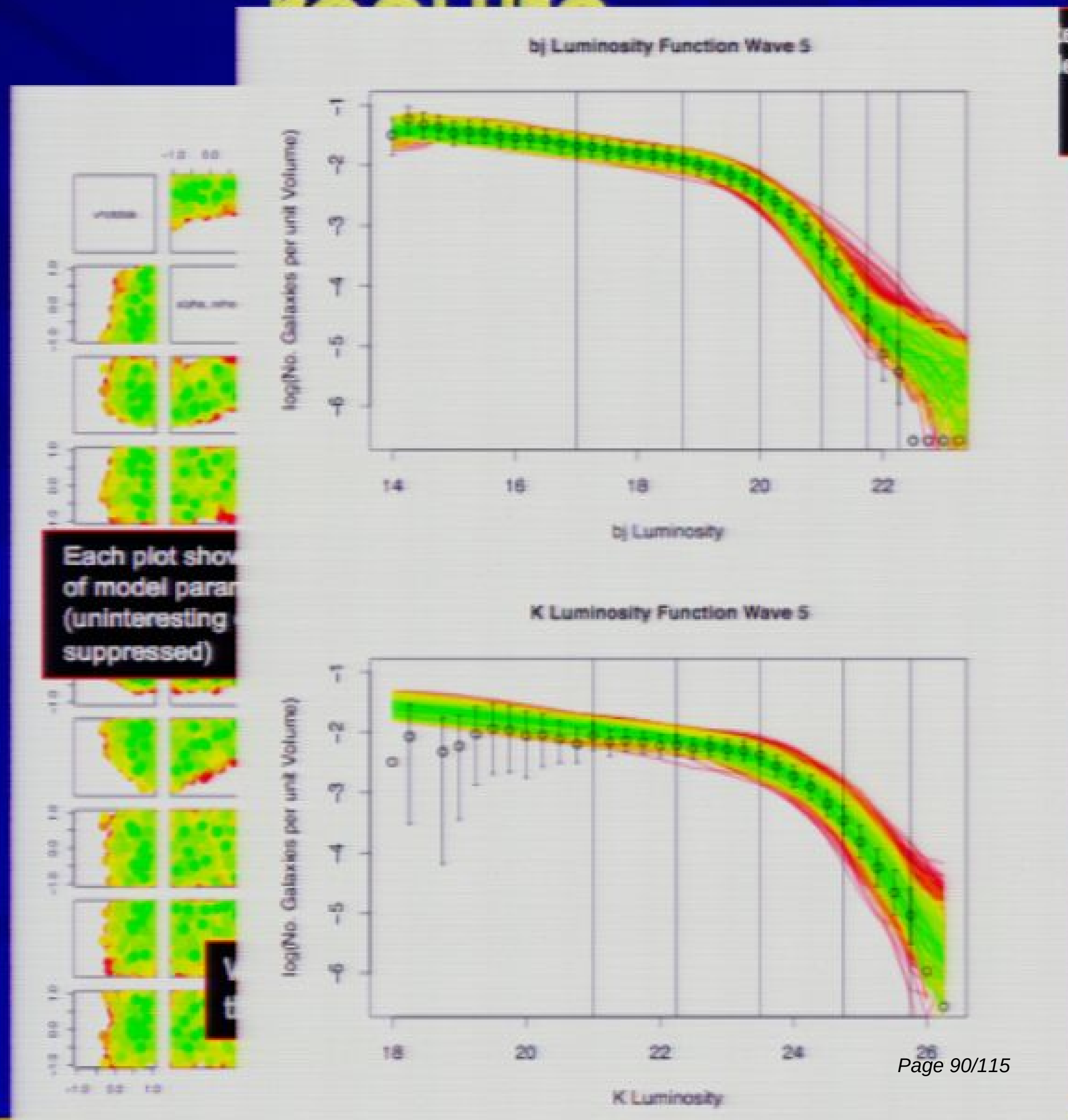

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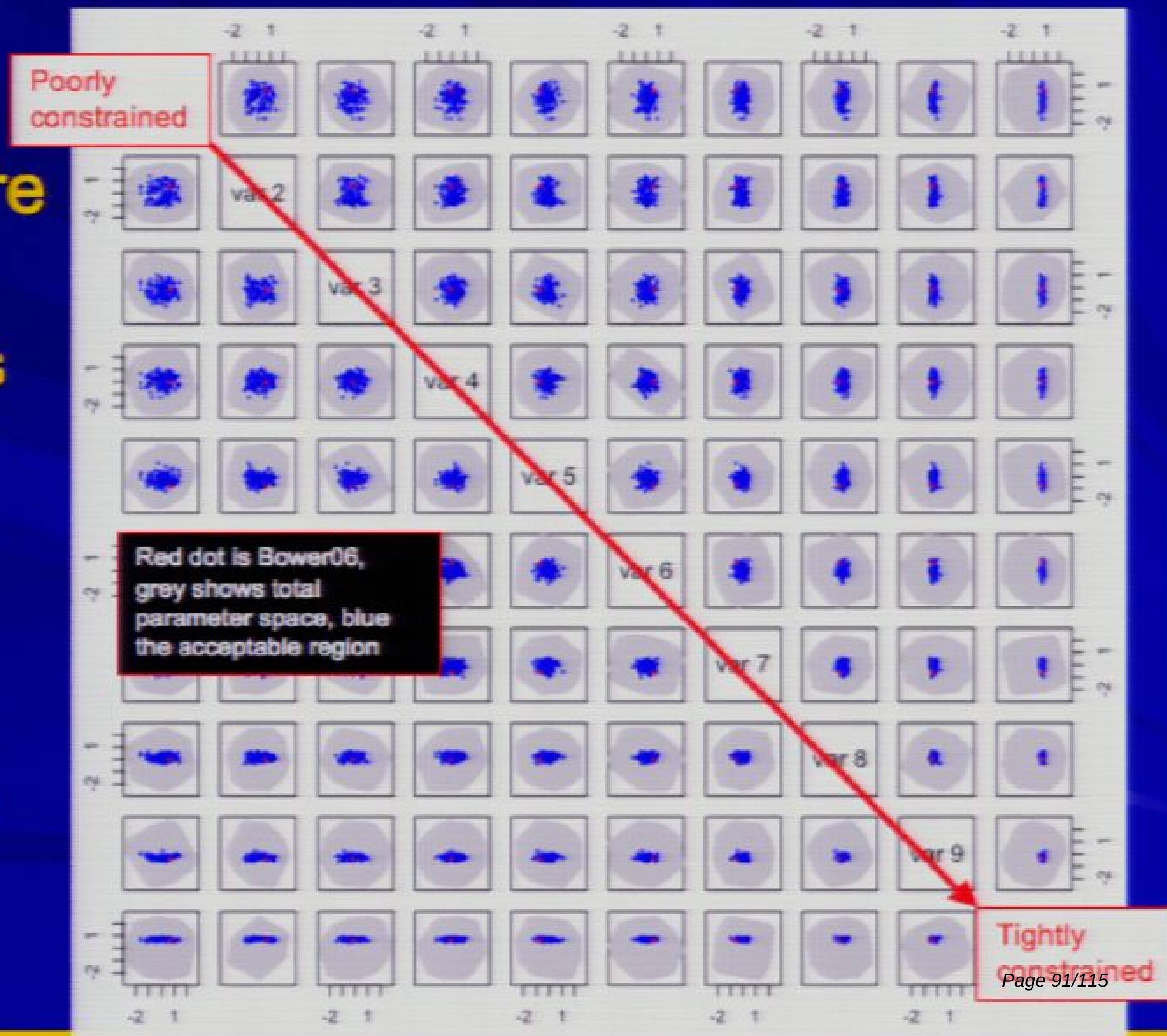
Projection Pursuit:

- how many parameters are there really?
  - PCA analysis of the parameter space - highlights linear trends
- Ans: 4 + a bit



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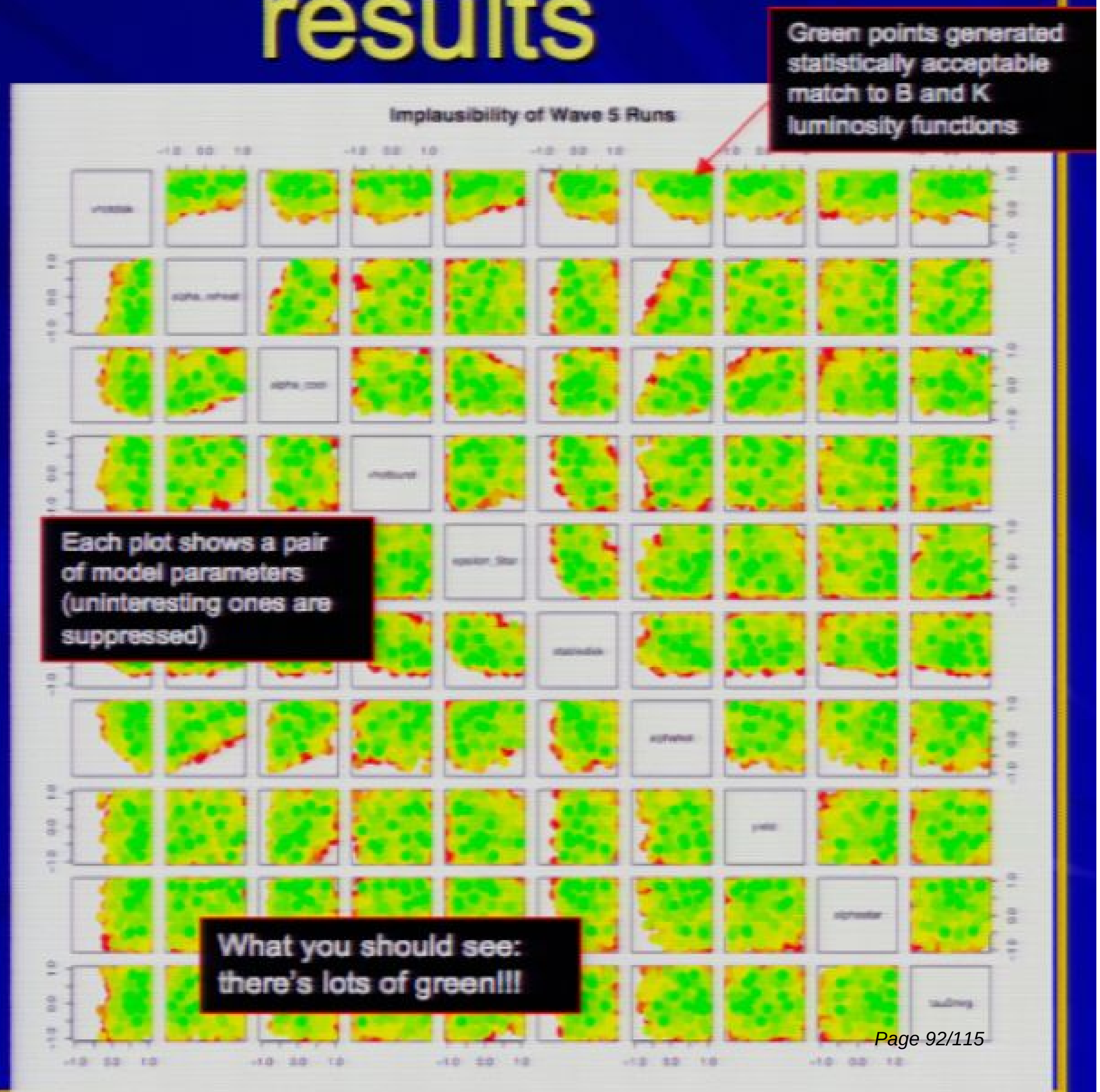

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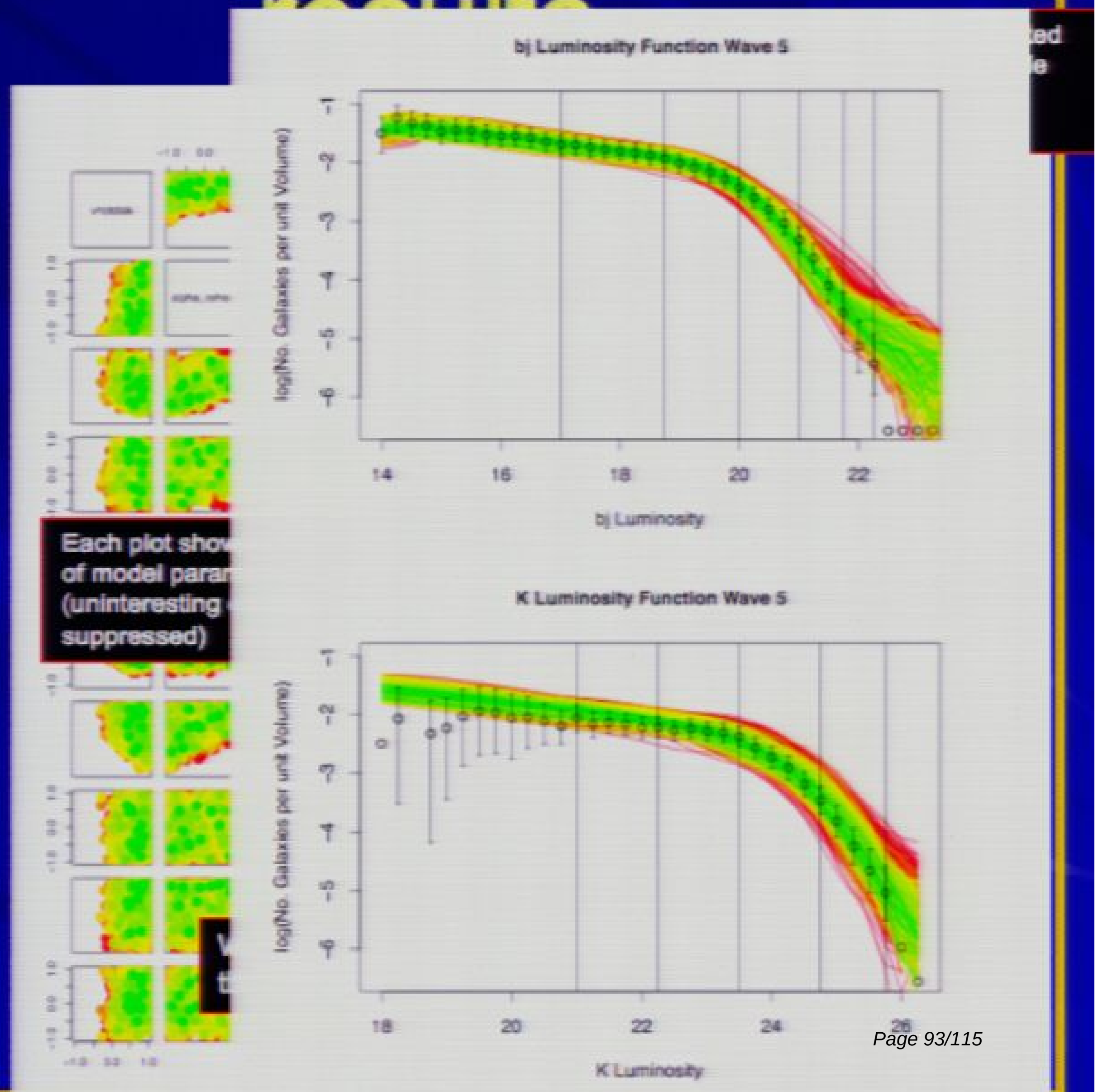

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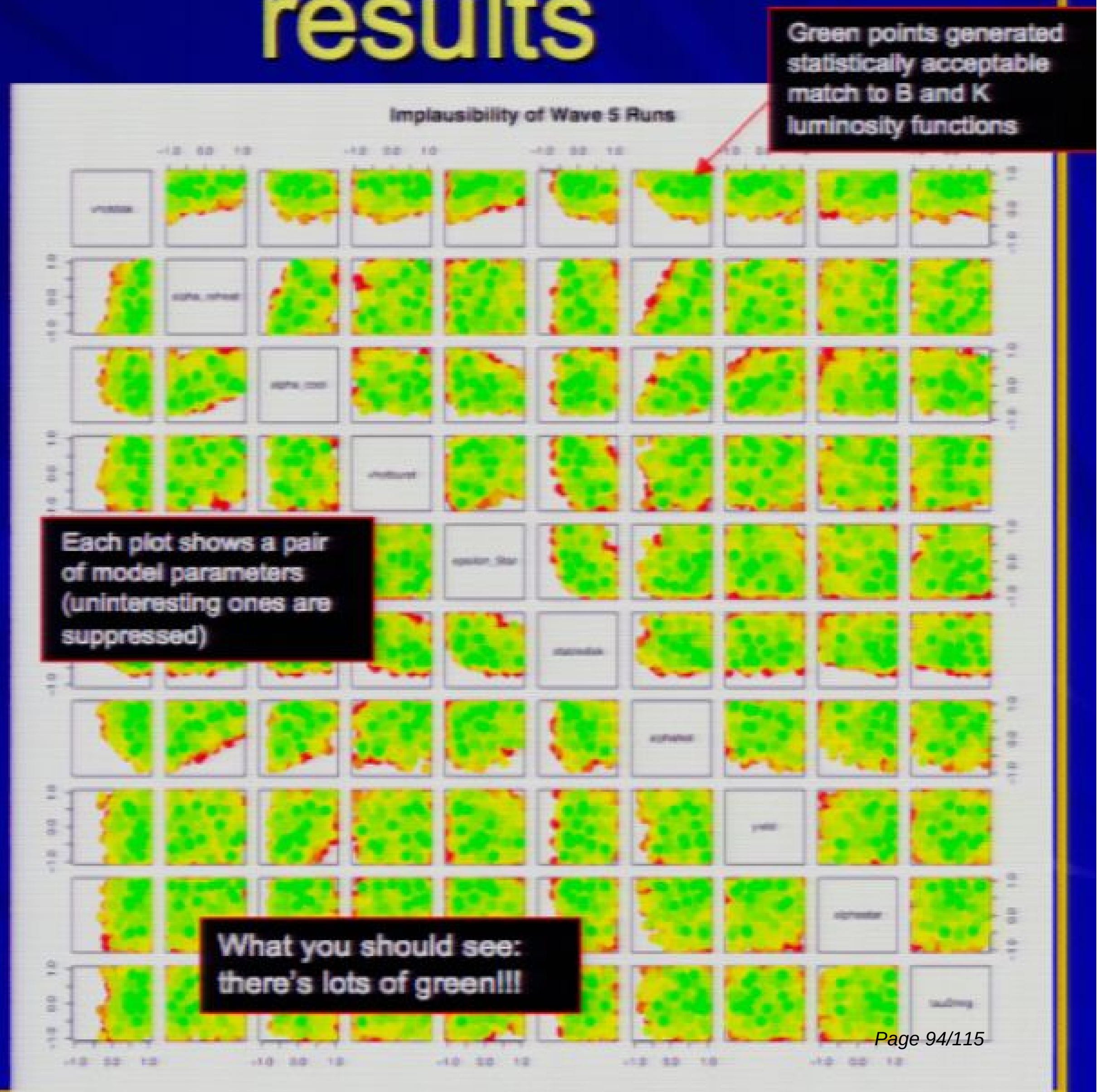

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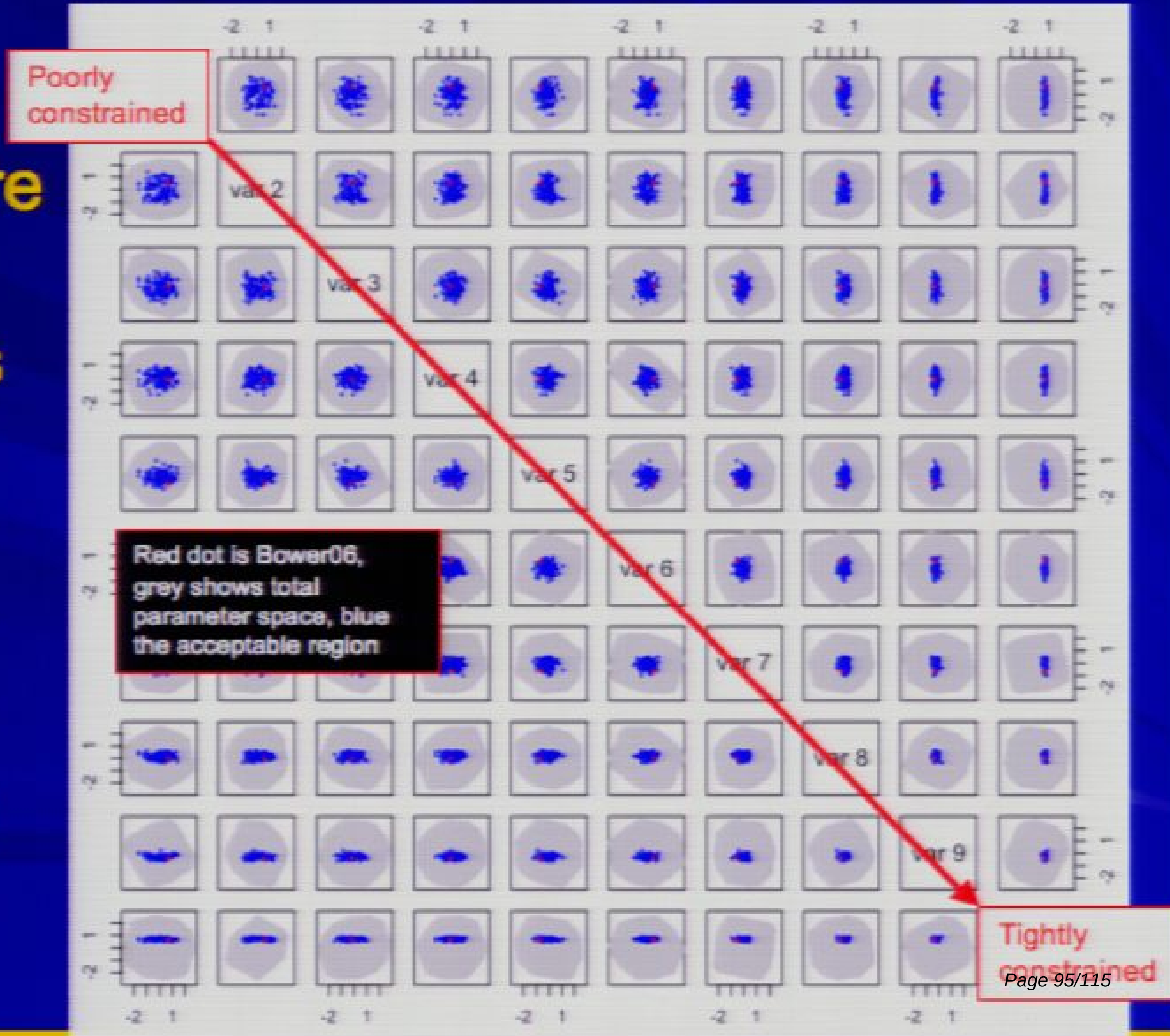

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Going forward with numerical simulations

- The way forward
  - Use numerical simulations to do what they are good at.
    - Shock heating of gas
    - Gas cooling
    - Outflows from galaxies (on macroscopic scales)
    - The macroscopic effect of AGN jets and winds
- Use the semi-analytic approach for the small scale physics
    - Multi-phase ISM
    - Star formation
    - AGN fueling
- A tiered approach to simulations
  - Galaxy patches
    - Sub-grid model for the ISM
  - Individual galaxies
    - Sub-grid model for winds and jets
  - Cosmological Simulations
- Embrace the parameter space!

...pushing the OWLS philosophy further

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Multiscale simulations

Crain et al 2010

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Connecting with the early universe?

A flight of fantasy… supposing we understood galaxy formation…

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Beyond the universe we know

- A key issue is the viability of other universes
- The multiverse suggests our universe is just one of many islands where the physical constants (aka. Parameters) happen to take on particular values
- But we need some measure of the observability of the universe…

- One possibility:
  - Count the number of galaxies
  - …but is this too restrictive?
  - How “big” is the universe?
- Another approach…
  - Measure the entropy generated as galaxies form
- Put another way,
  - given our ability to observe the universe, how special are the initial conditions?

Bousso et al 2007

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We can do this, but do the results make sense?

- Back of the envelope calculation…
  - Entropy due to cooling gas 4×10^{70} Mpc^{-3}
  - Due to supernova feedback 2×10^{70} Mpc^{-3}
  - Due to black hole feedback 2×10^{71} Mpc^{-3}
- These make sense!

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- These make sense!

- But…
  - Entropy due to star light 2×10^{72} Mpc^{-3}
  - Out weighs entropy from cooling or feedback of feedback
  - (Entropy due to black hole horizon 10^{89} Mpc^{-3} …dominates everything! Why is it so different?)
- Does this "explain" our universe? Does it provide a suitable "measure"?

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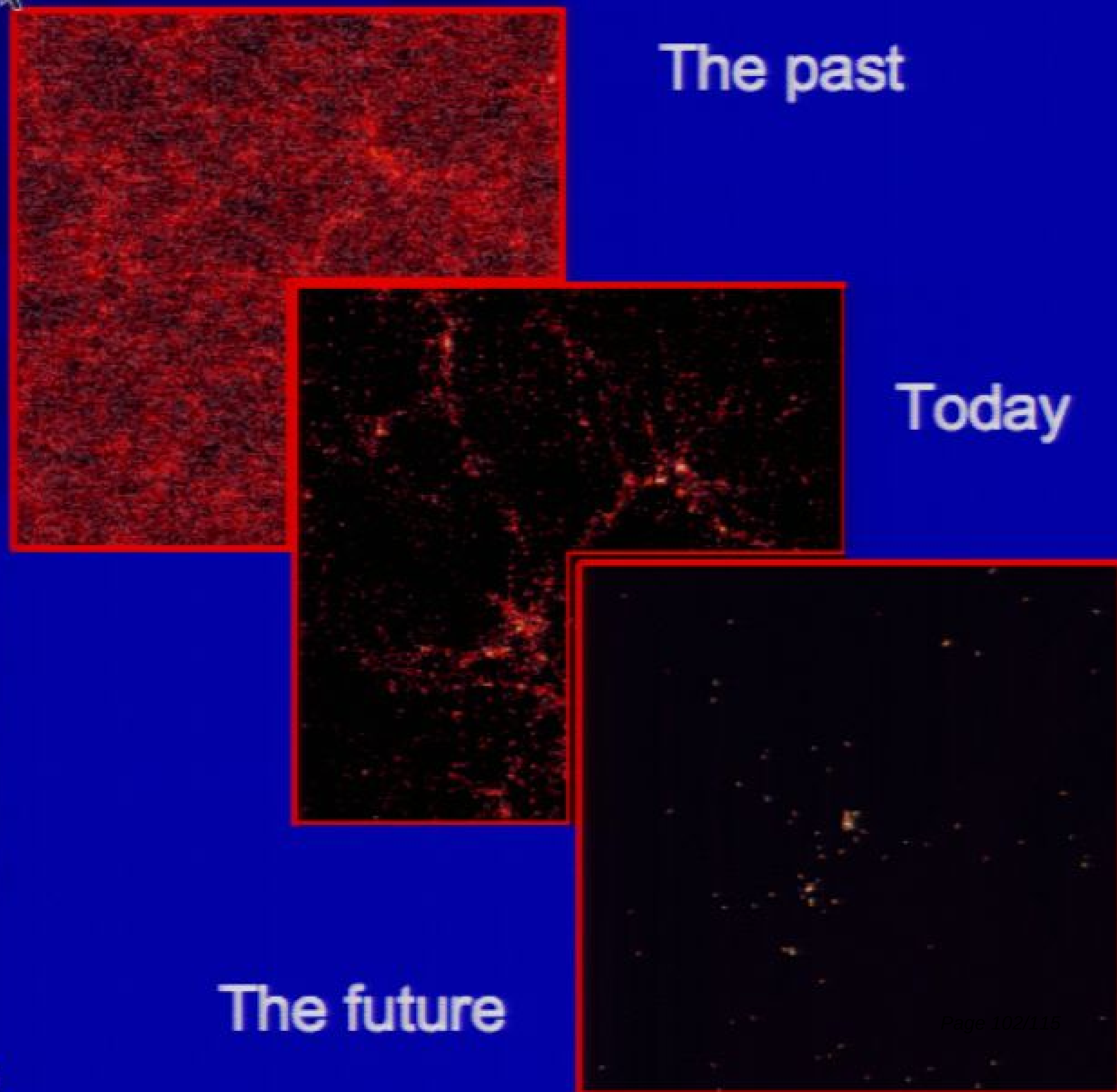
Is this a crazy idea?

- In the near future, the vacuum energy density will dominate over gravity
- Today's clusters will grow only a little.
- While the Milky-Way and andromeda will collide, their "daughter" will remain isolated for ever!
- There will only be one galaxy in the entire visible universe.



The past

Today

The future

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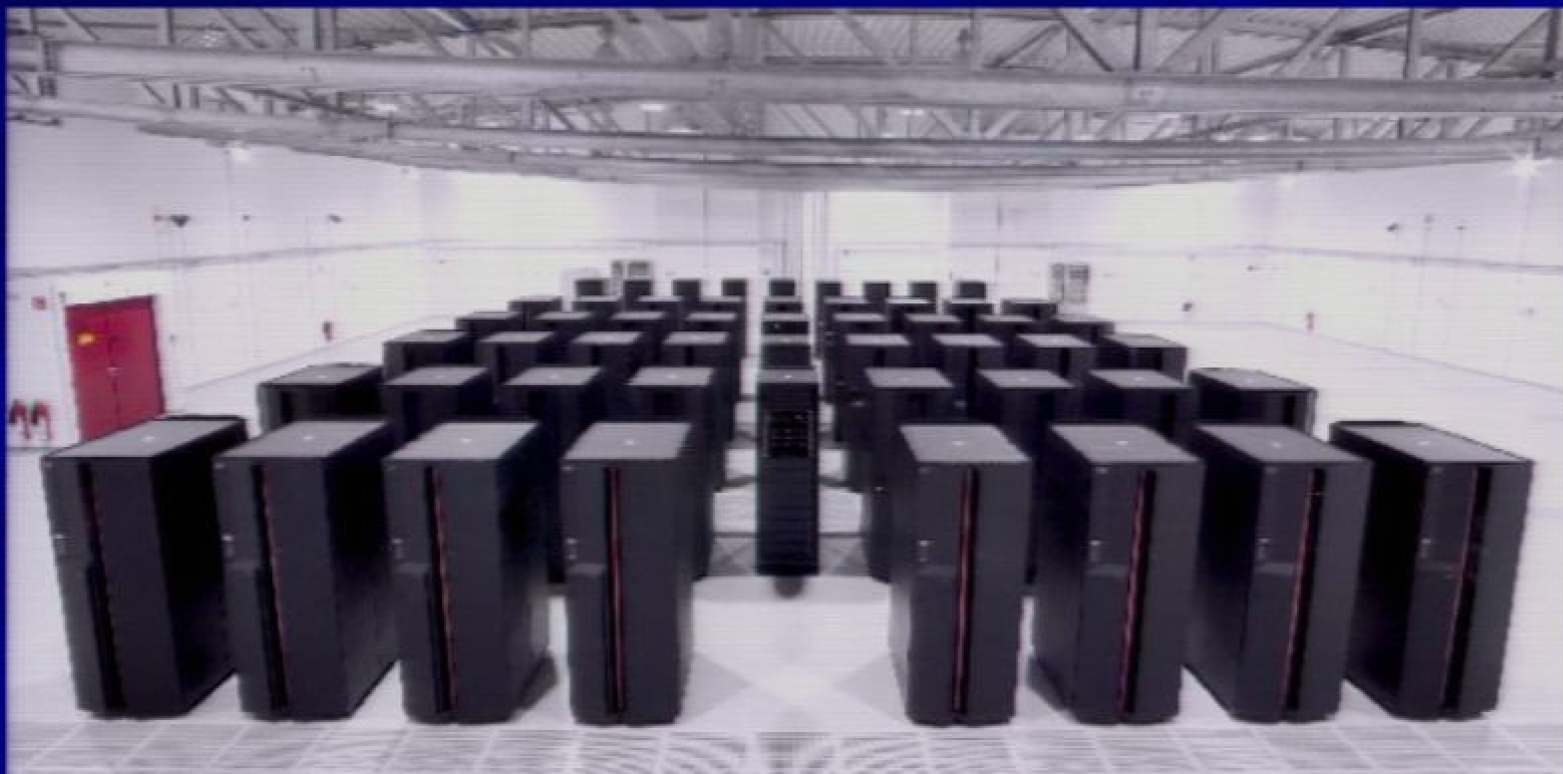
Is this a crazy idea?



In the future, galaxies will only exist as a theoretical possibility glimpsed only inside a computer!

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Conclusions = what you should remember!

- Some past successes
  - The three problems: the luminosity function, cosmic down-sizing, the cooling catastrophe.
  - AGN feedback - pushing gas out of groups (Bower et al 2008)
- Next steps:
  - Applying the "semi-analytic" philosophy to create multi-scale numerical simulations
  - Beyond galaxy formation in our own universe…
  - The universe as a heat engine. A "measure" of our universe.

Coming to an astro-ph server near you:

Benson+RGB 2009 "Galaxy Formation

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Thank you!

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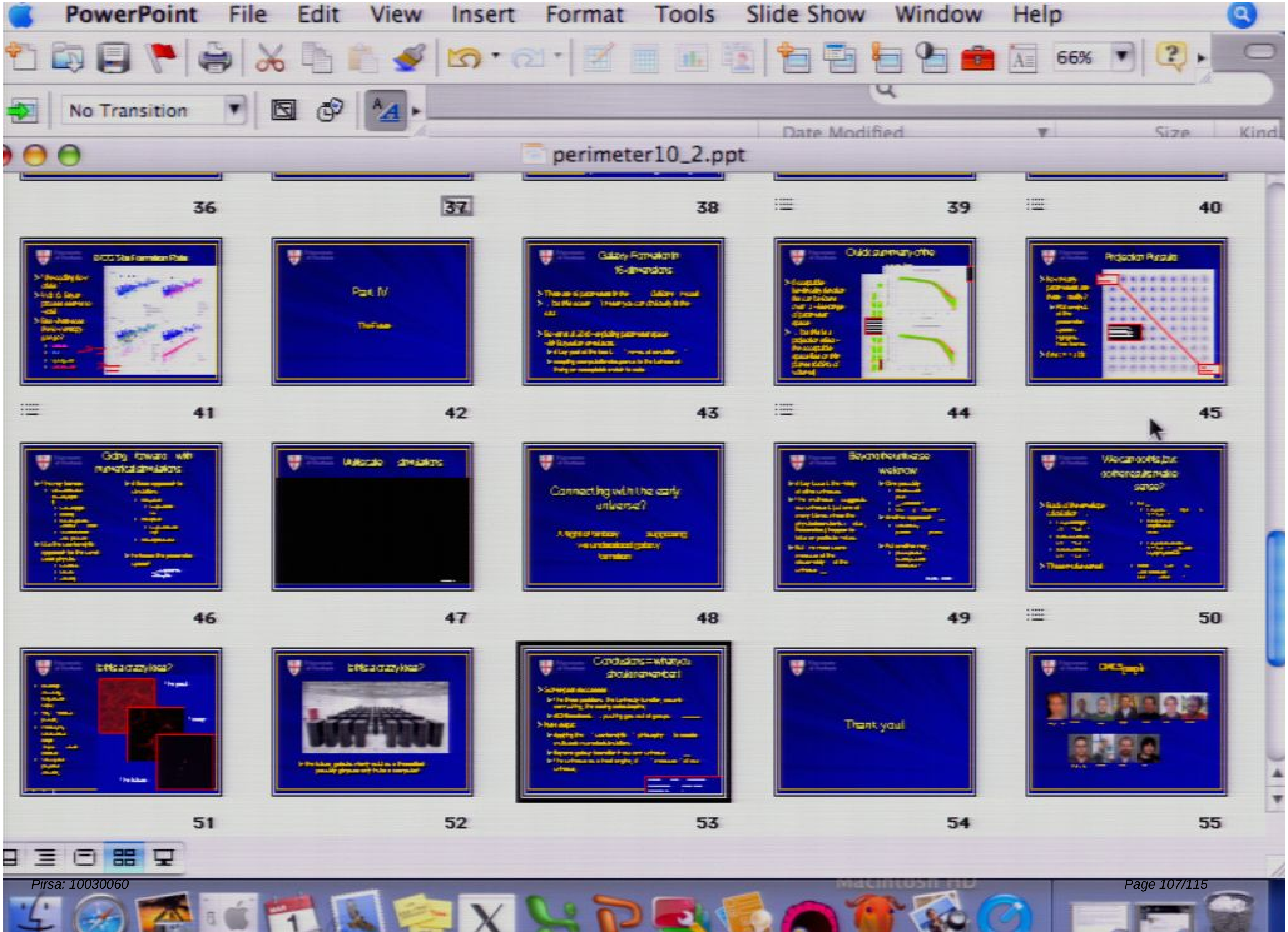
- Some past successes
  - The three problems: the luminosity function, cosmic down-sizing, the cooling catastrophe.
  - AGN feedback - pushing gas out of groups (Bower et al 2008)
- Next steps:
  - Applying the "semi-analytic" philosophy to create multi-scale numerical simulations
  - Beyond galaxy formation in our own universe…
  - The universe as a heat engine. A "measure" of our universe.

Coming to an astro-ph server near you:

Benson+RGB 2009 "Galaxy Formation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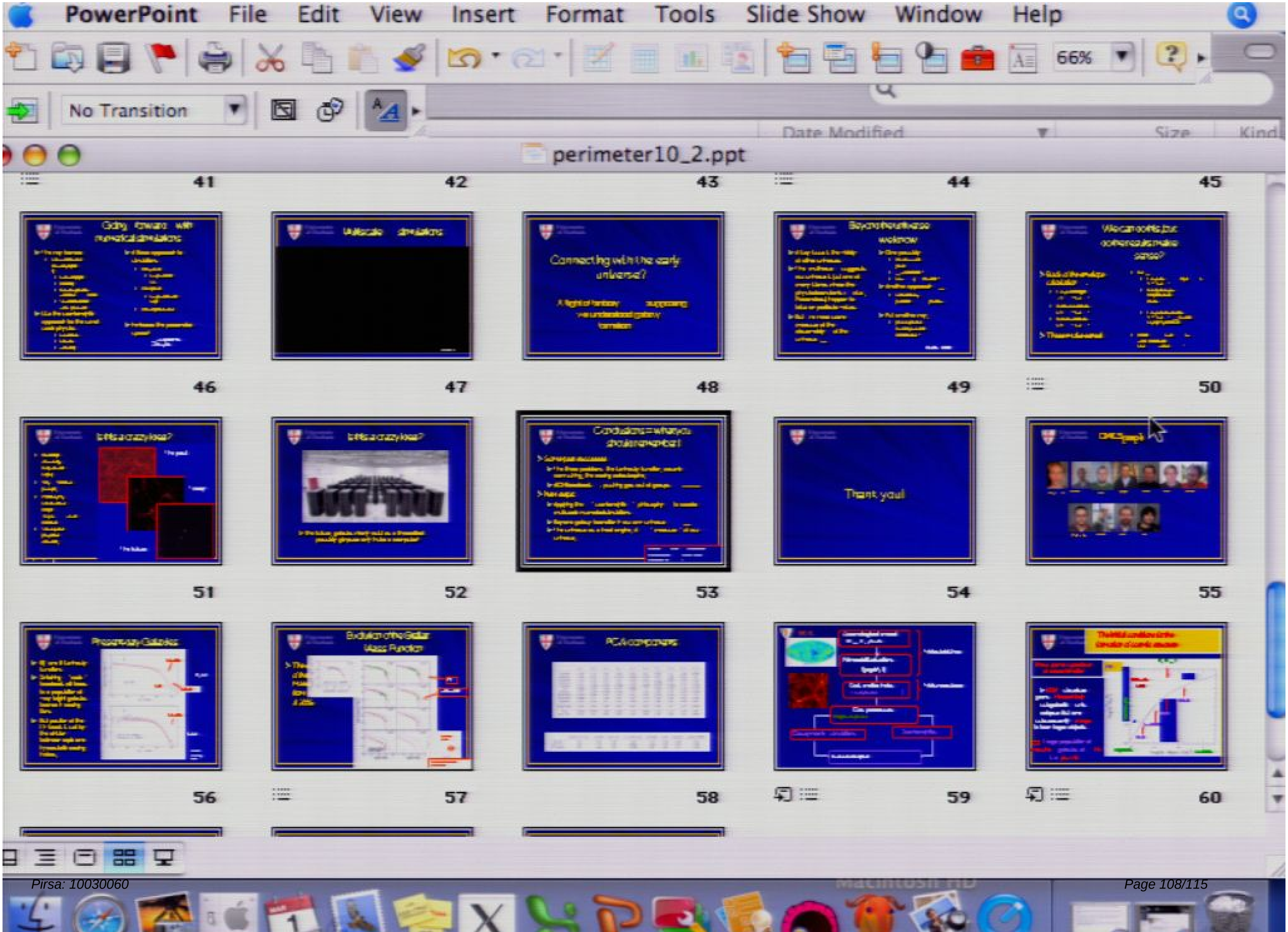
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Connecting with the early universe?
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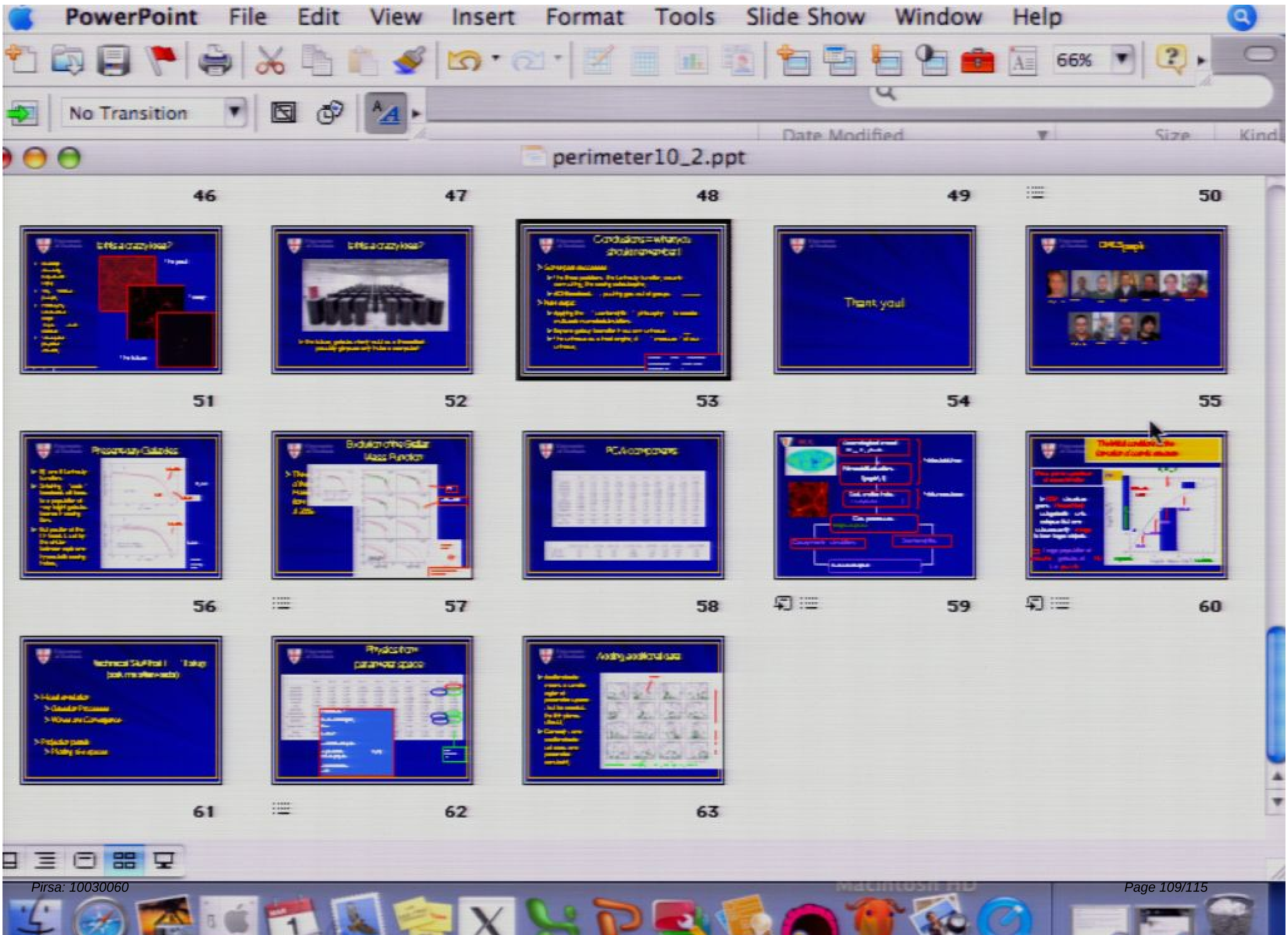
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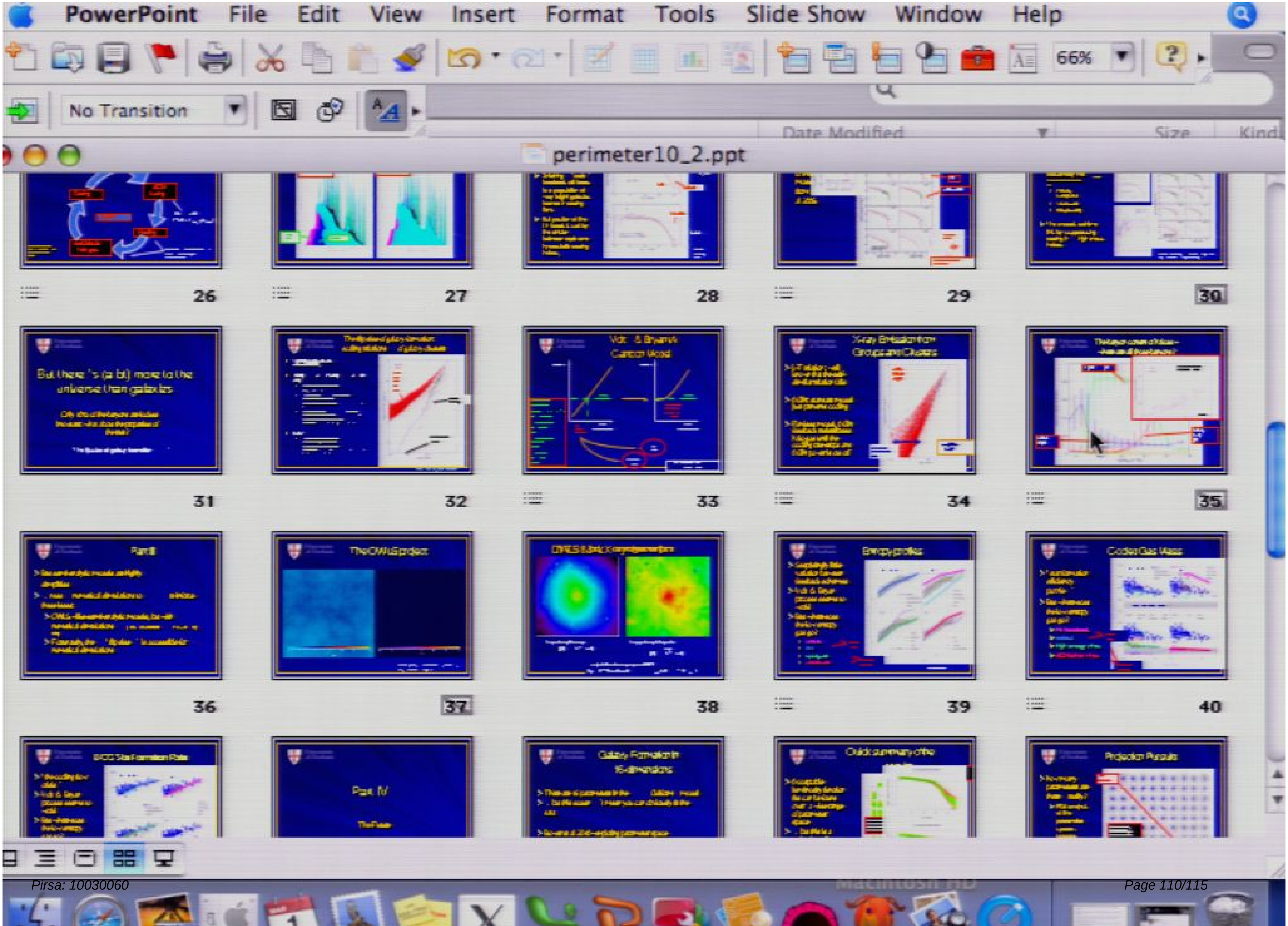

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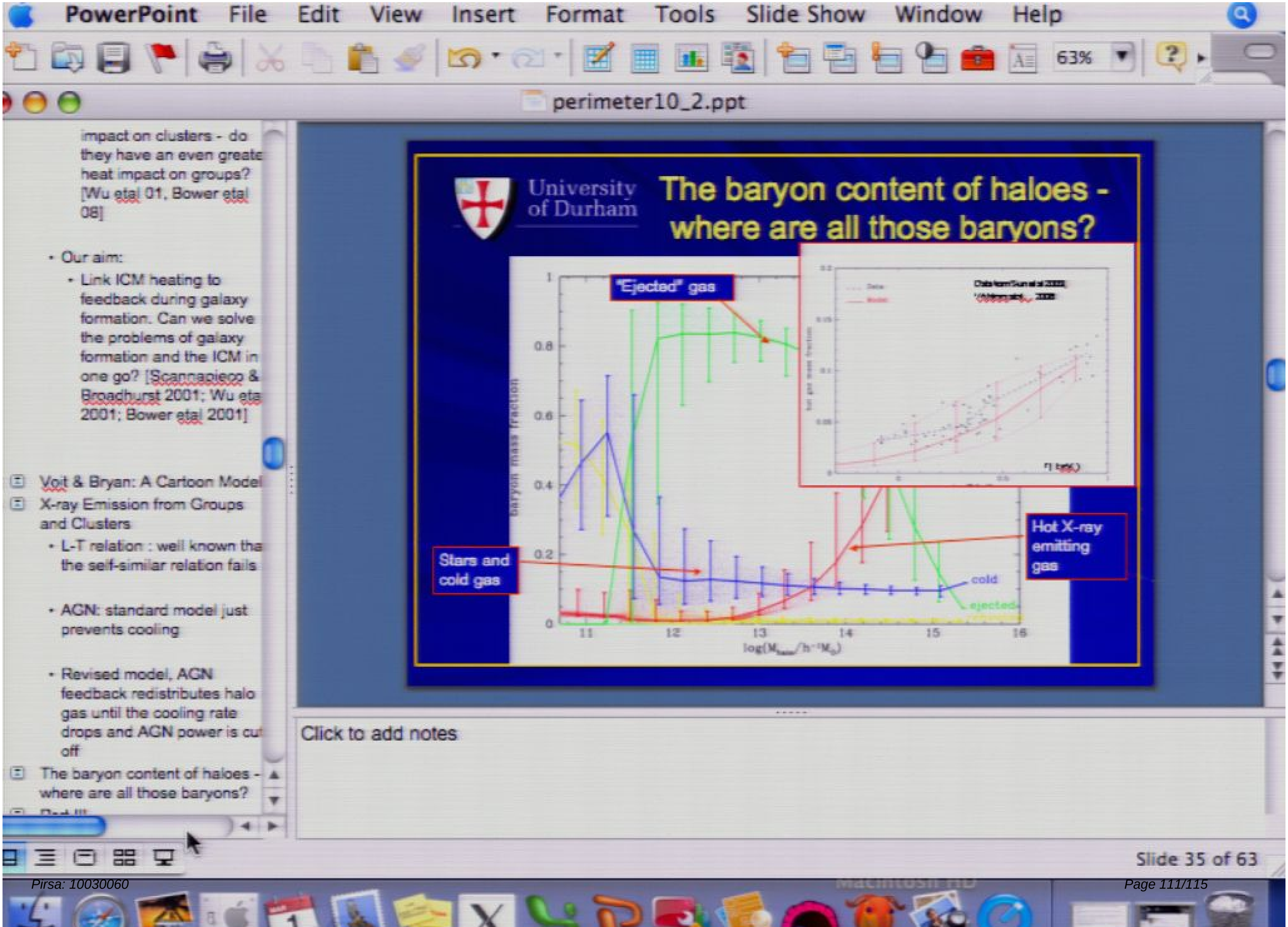
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impact on clusters - do they have an even greate heat impact on groups? [Wu etal 01, Bower etal 08]
• Our aim:
• Link ICM heating to feedback during galaxy formation. Can we solve the problems of galaxy formation and the ICM in one go? [Scannapieco & Broadhurst 2001; Wu eta 2001; Bower etal 2001]
Voit & Bryan: A Cartoon Model
X-ray Emission from Groups and Clusters
• L-T relation : well known tha the self-similar relation fails
• AGN: standard model just prevents cooling
• Revised model, AGN feedback redistributes halo gas until the cooling rate drops and AGN power is cut off
The baryon content of haloes - where are all those baryons?
University of Durham
The baryon content of haloes - where are all those baryons?
"Ejected" gas
Stars and cold gas
Hot X-ray emitting gas
baryon mass fraction
cold
ejected
Click to add notes
Slide 35 of 63

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The baryon content of haloes - where are all those baryons?

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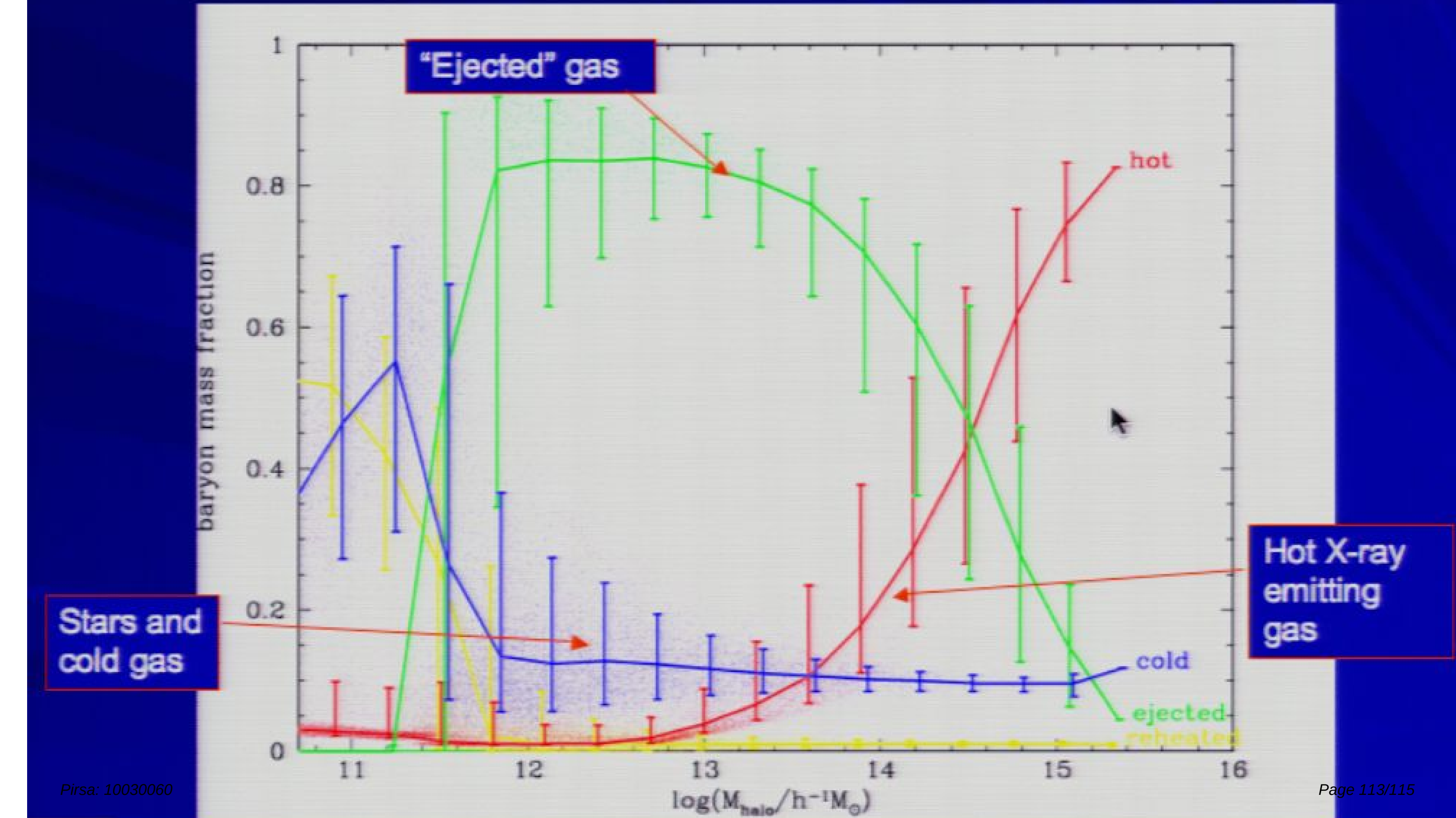

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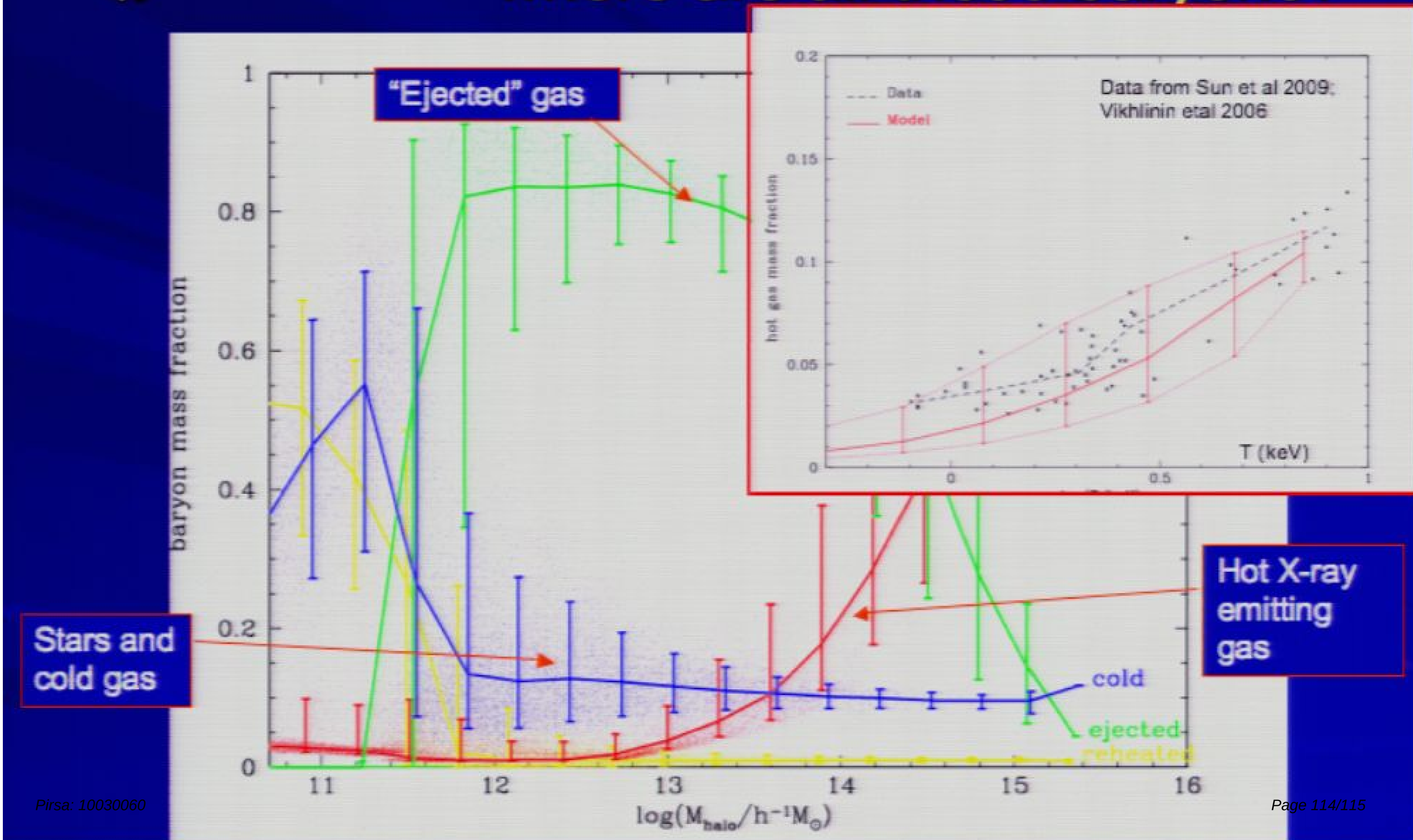
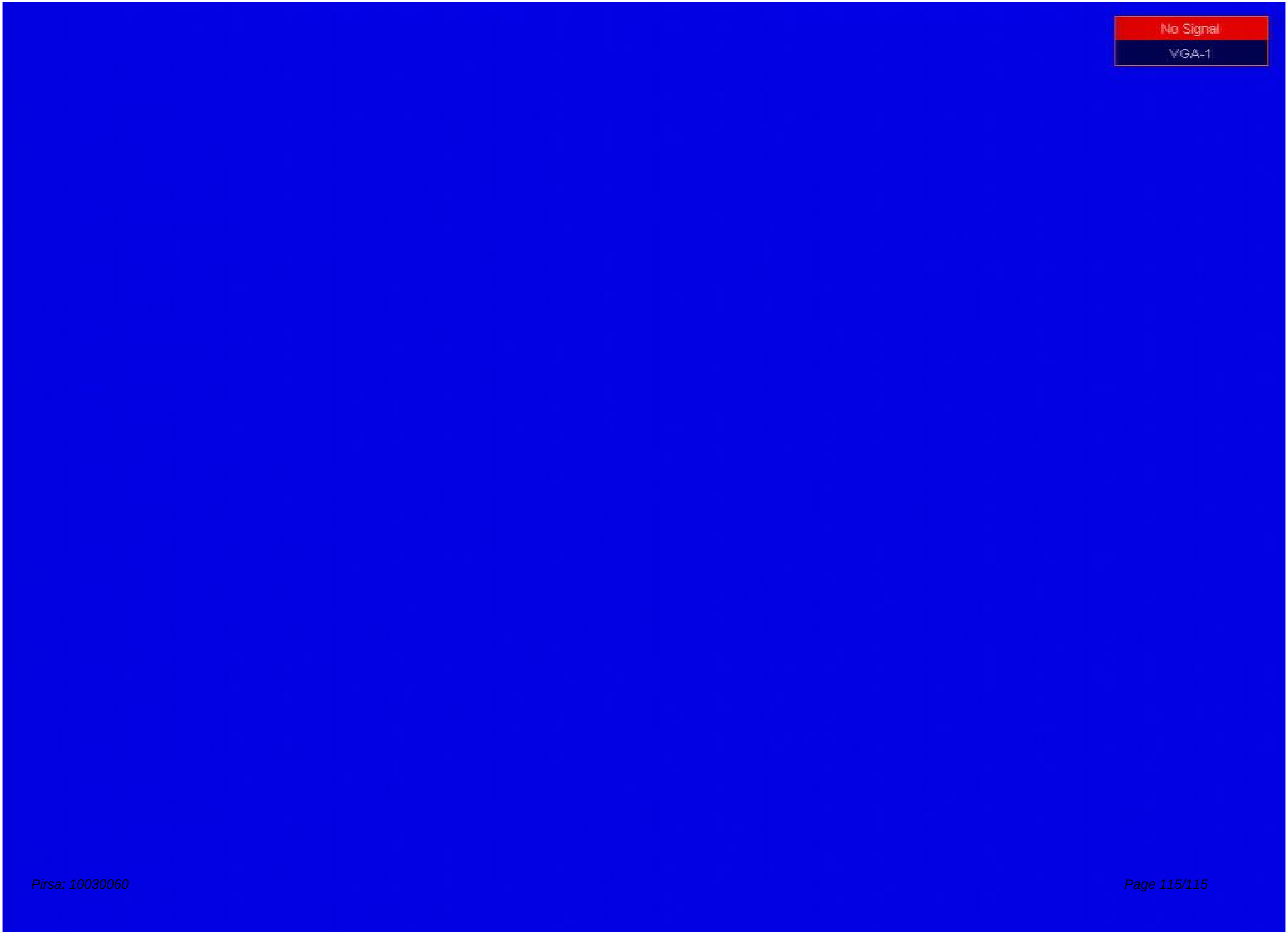
The baryon content of haloes - where are all those baryons?

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