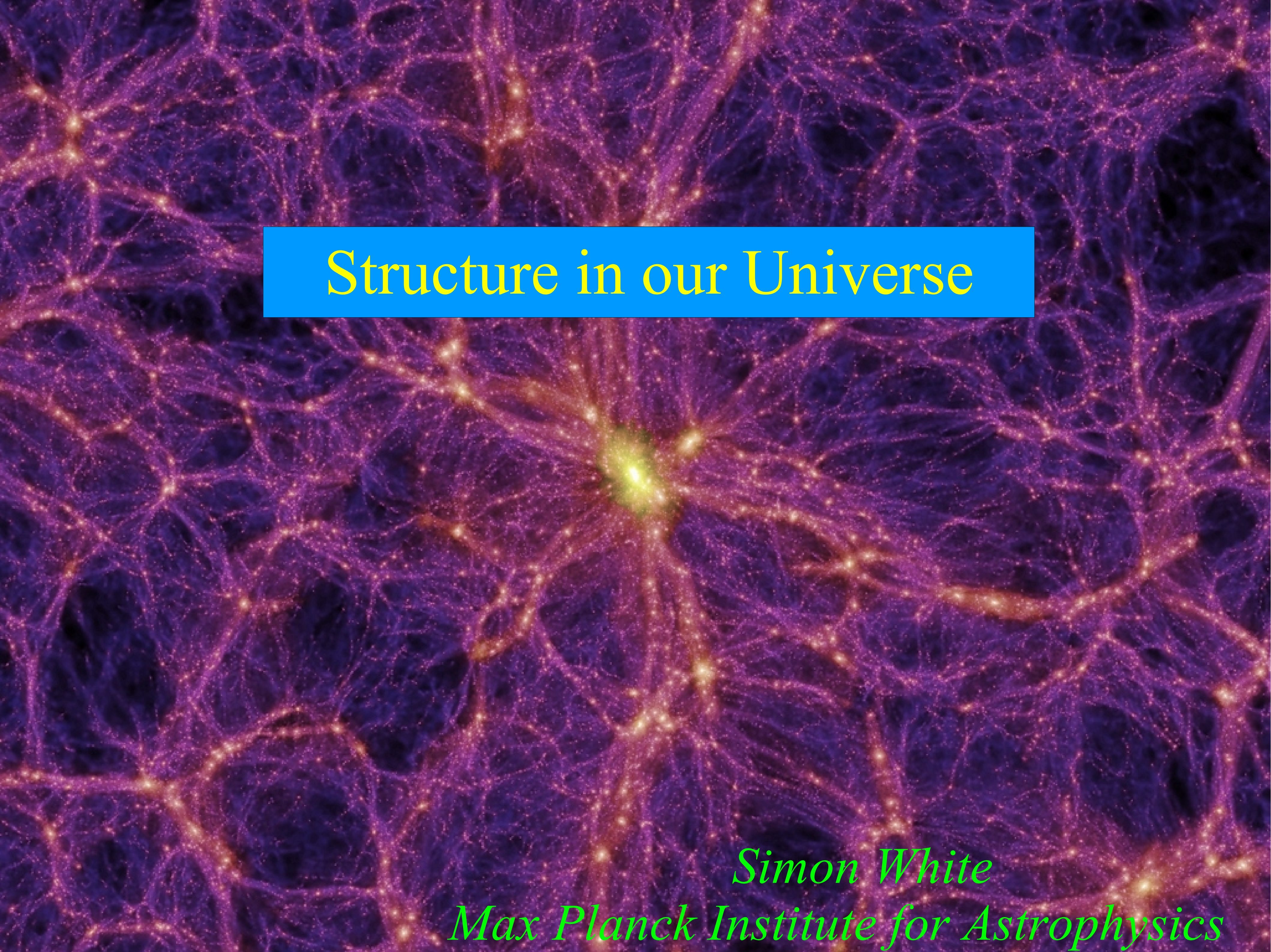
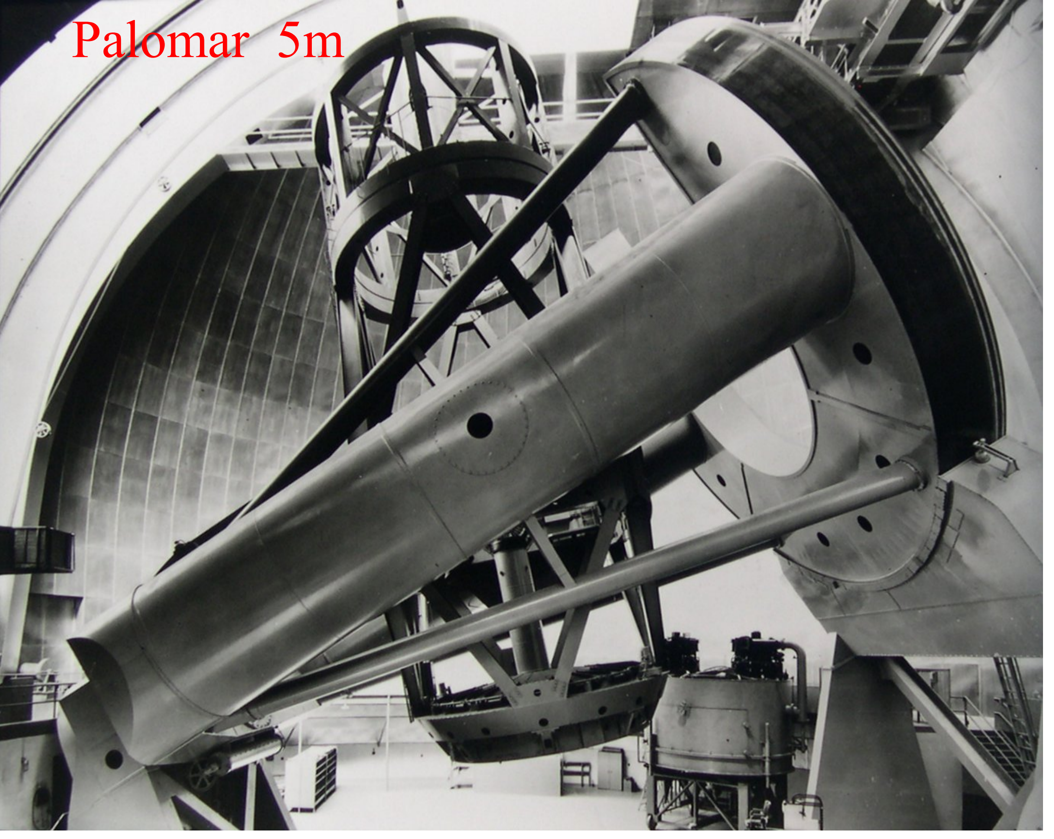
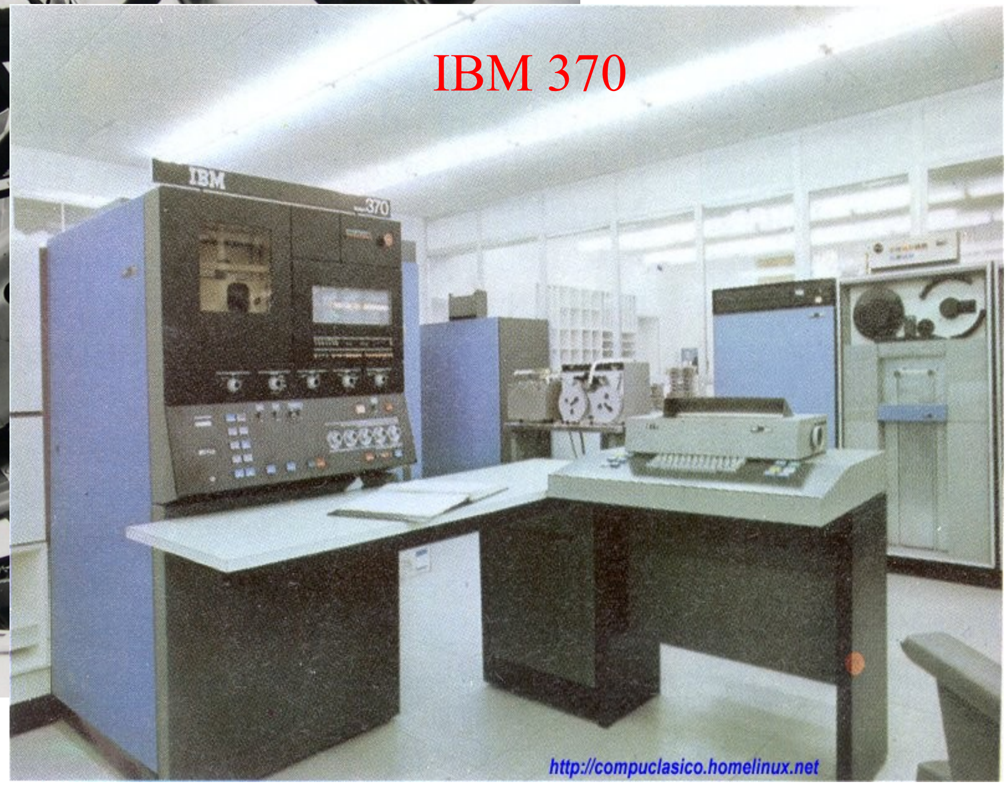
Structure in our Universe



Simon White
Max Planck Institute for Astrophysics

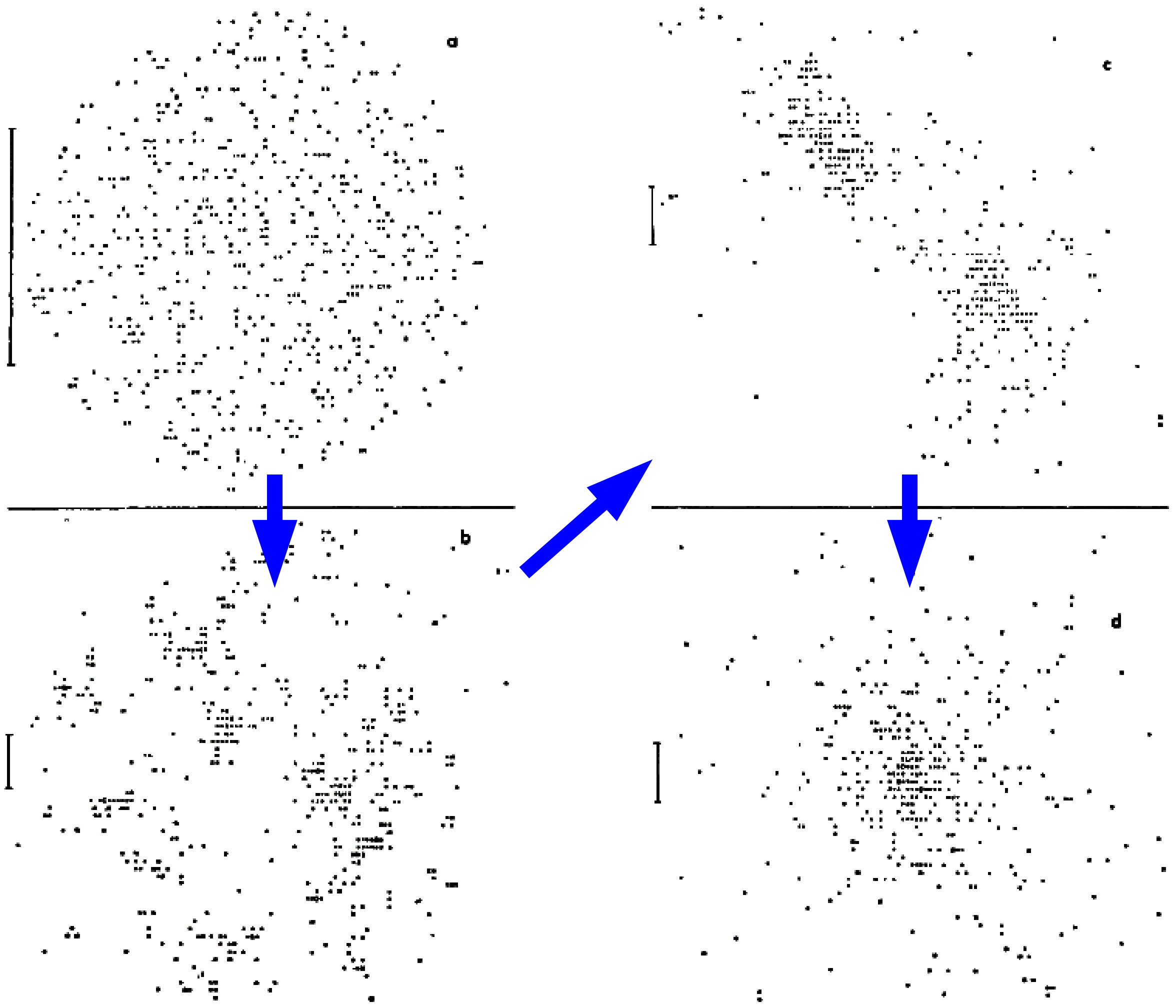

Palomar 5m


Palomar 5m


IBM 370
IBM
370
http://compuclasico.homelinux.net

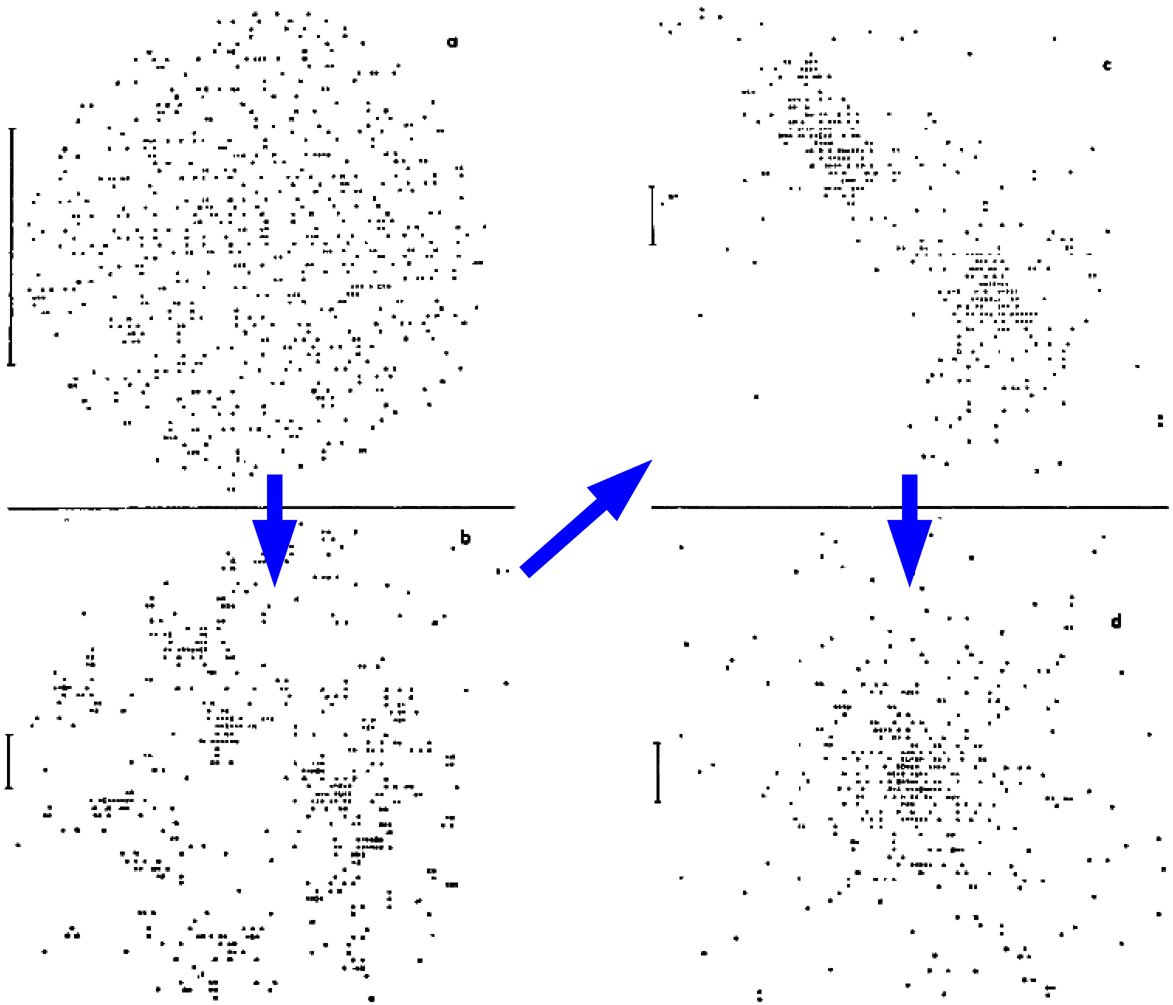

Palomar 5m
IBM 370


Palomar 5m
IBM 370



cluster simulation 1977

N = 700



cluster simulation 1977

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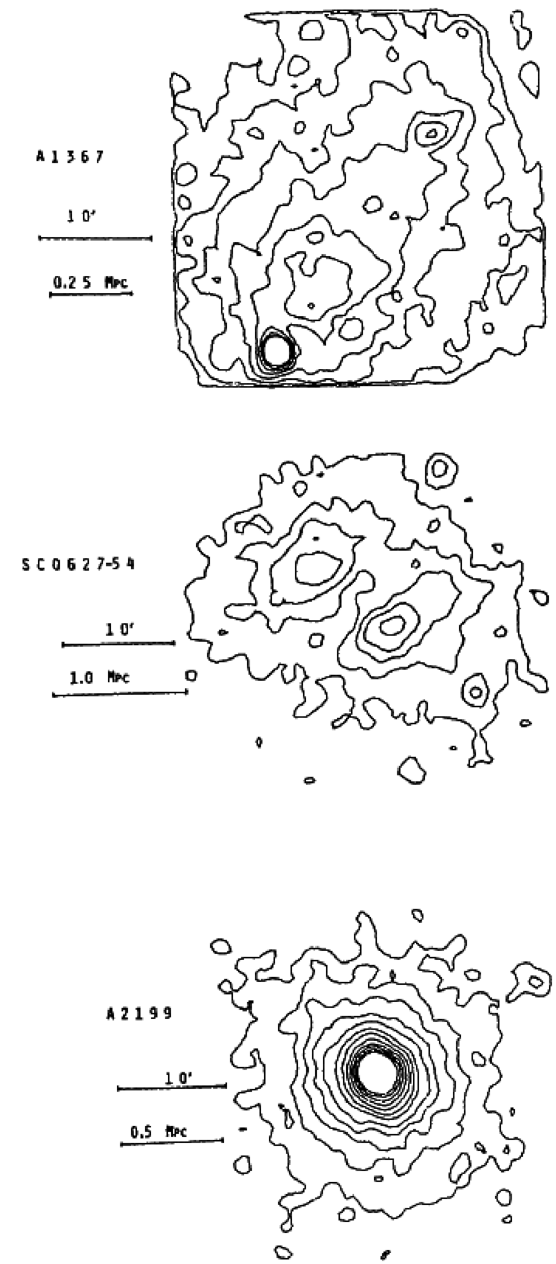
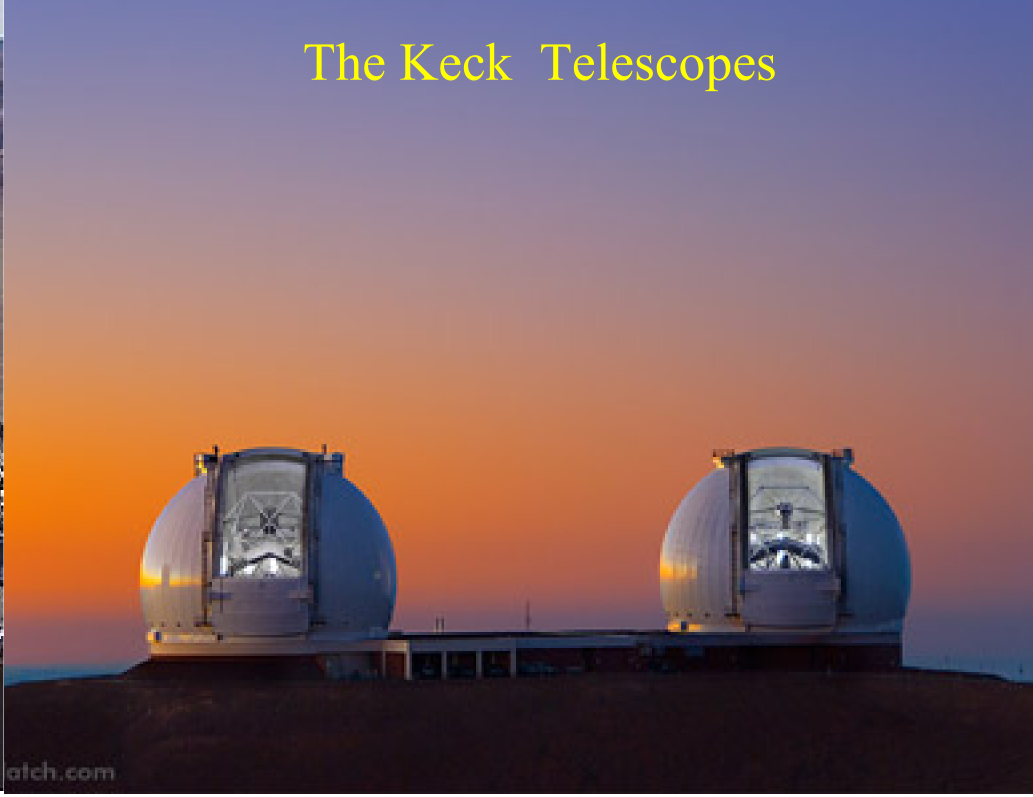
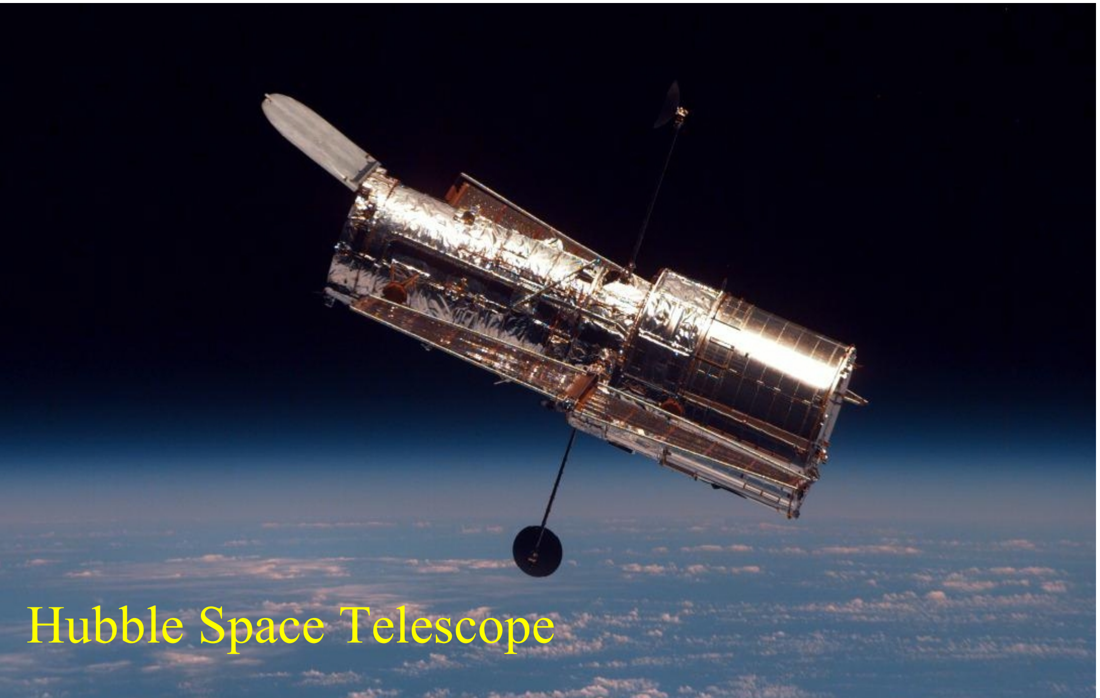
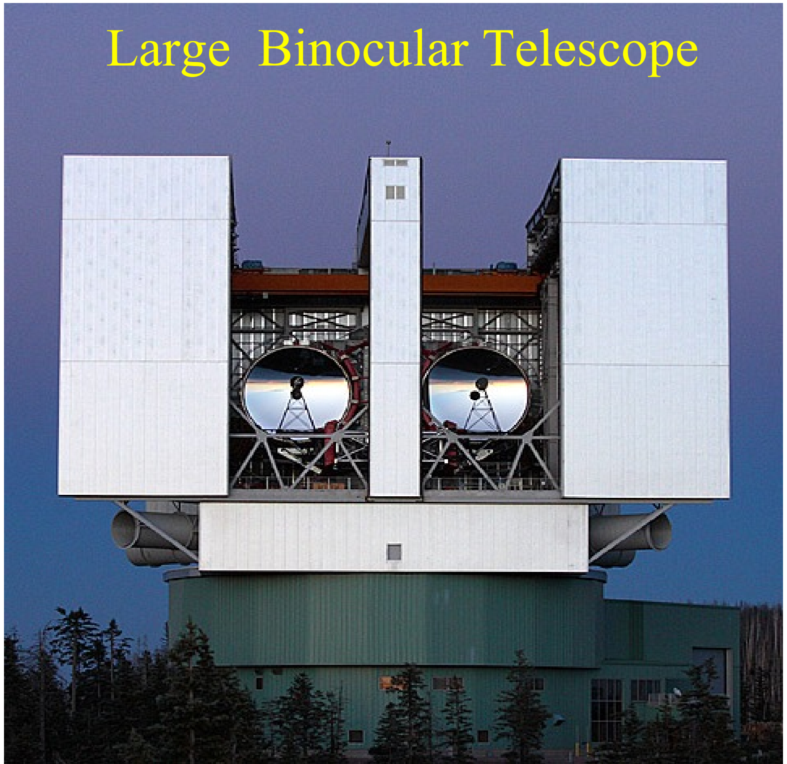


cluster images 1980


Very Large Telescope


The Keck Telescopes
atch.com


Hubble Space Telescope

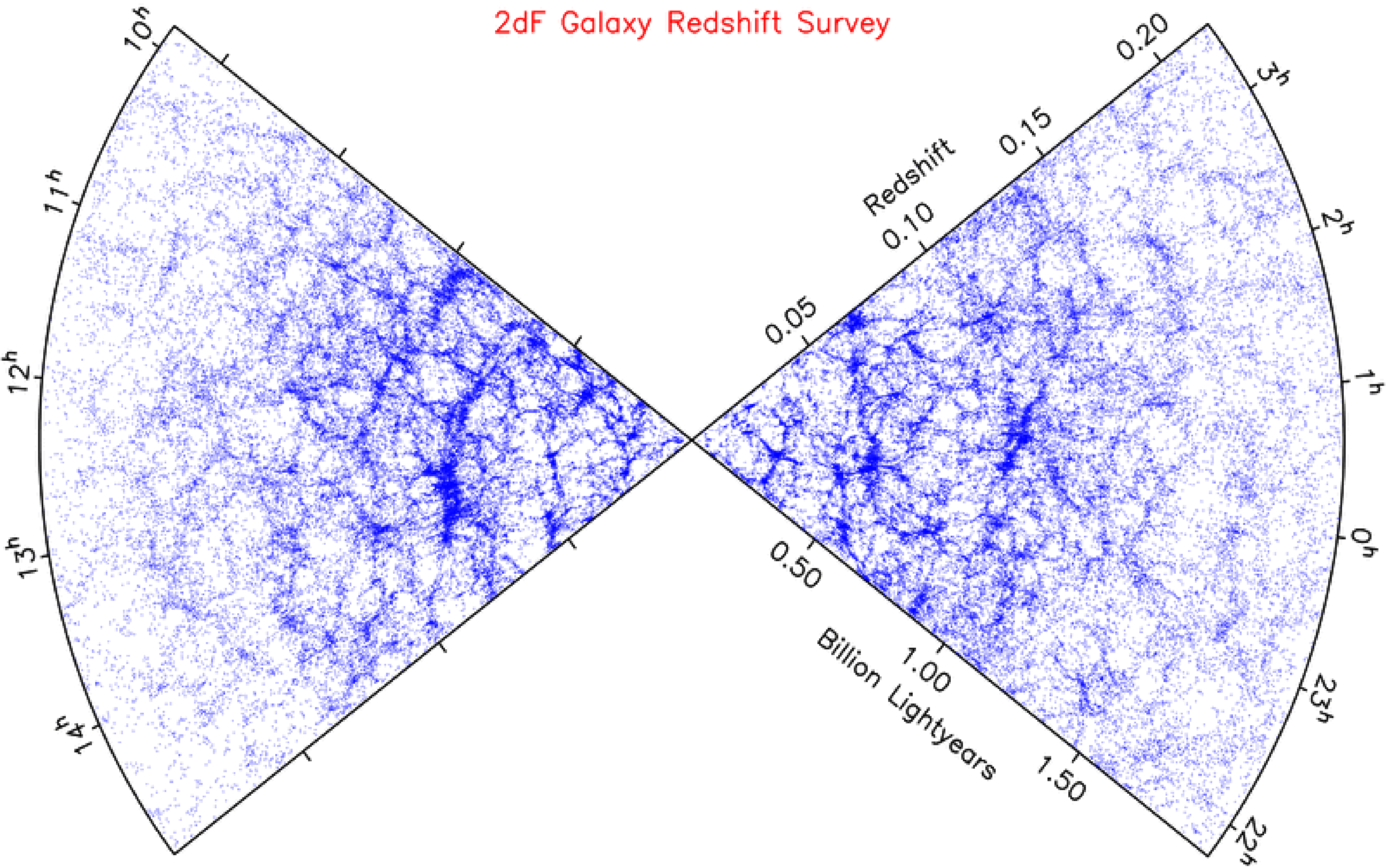

Large Binocular Telescope

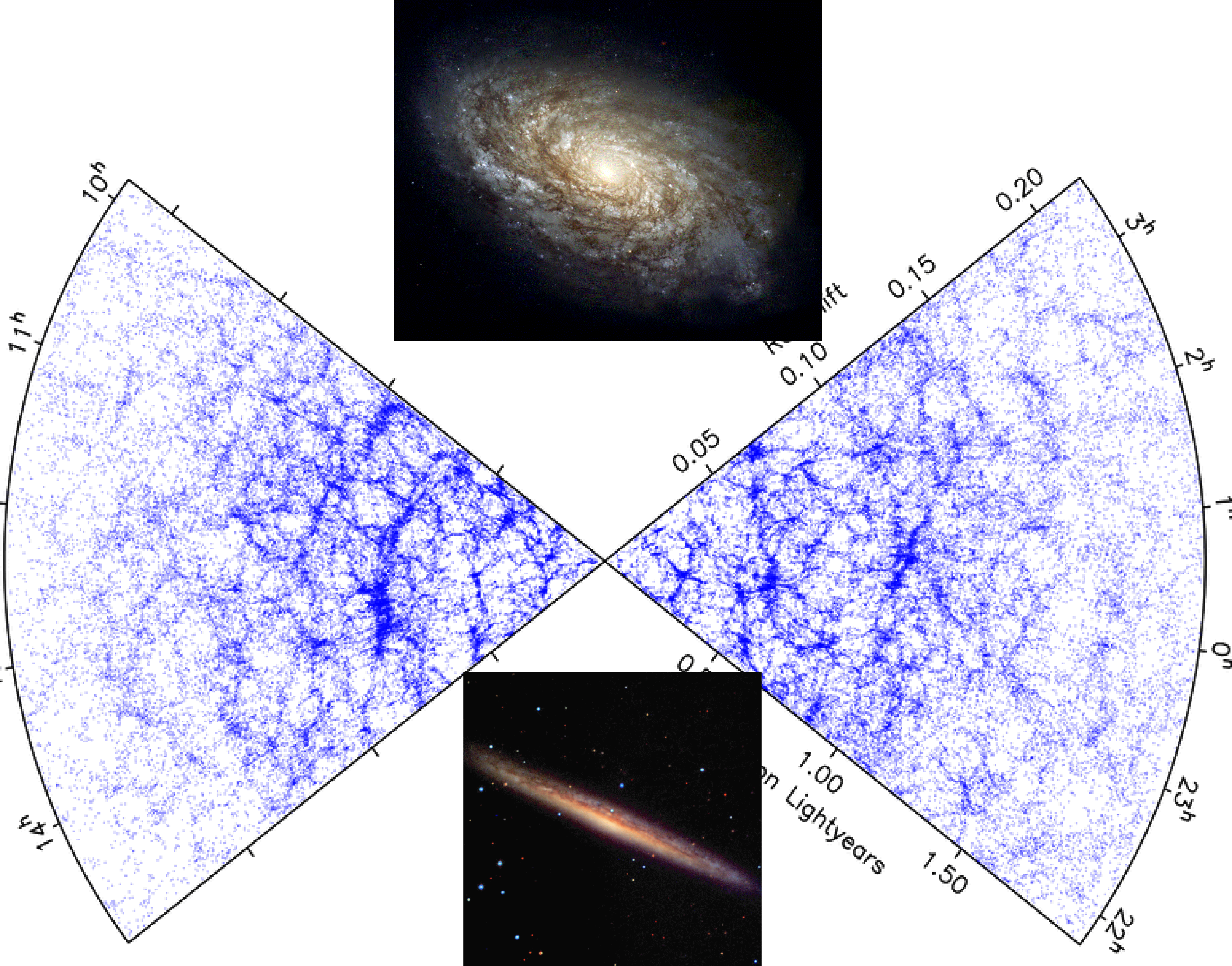
The Coma Galaxy Cluster

Gravitational lensing: “seeing” the dark matter

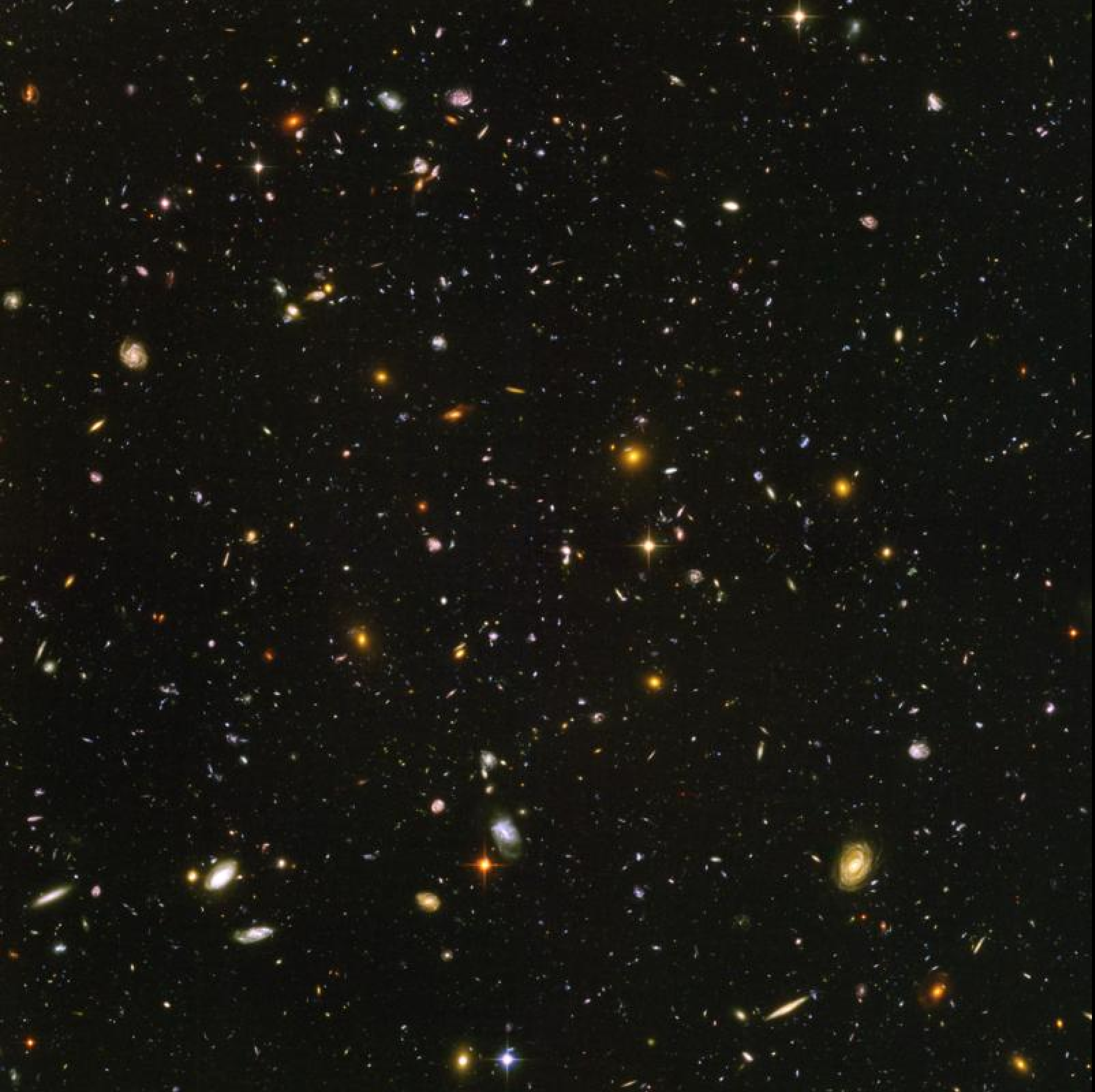
Abell 2218   z=0.17

"Nearby" large-scale structure





10h
11h
12h
13h
14h
0.20
0.15
0.10
0.05
3h
2h
1h
0h
23h
22h
1.00
1.50
Lightyears



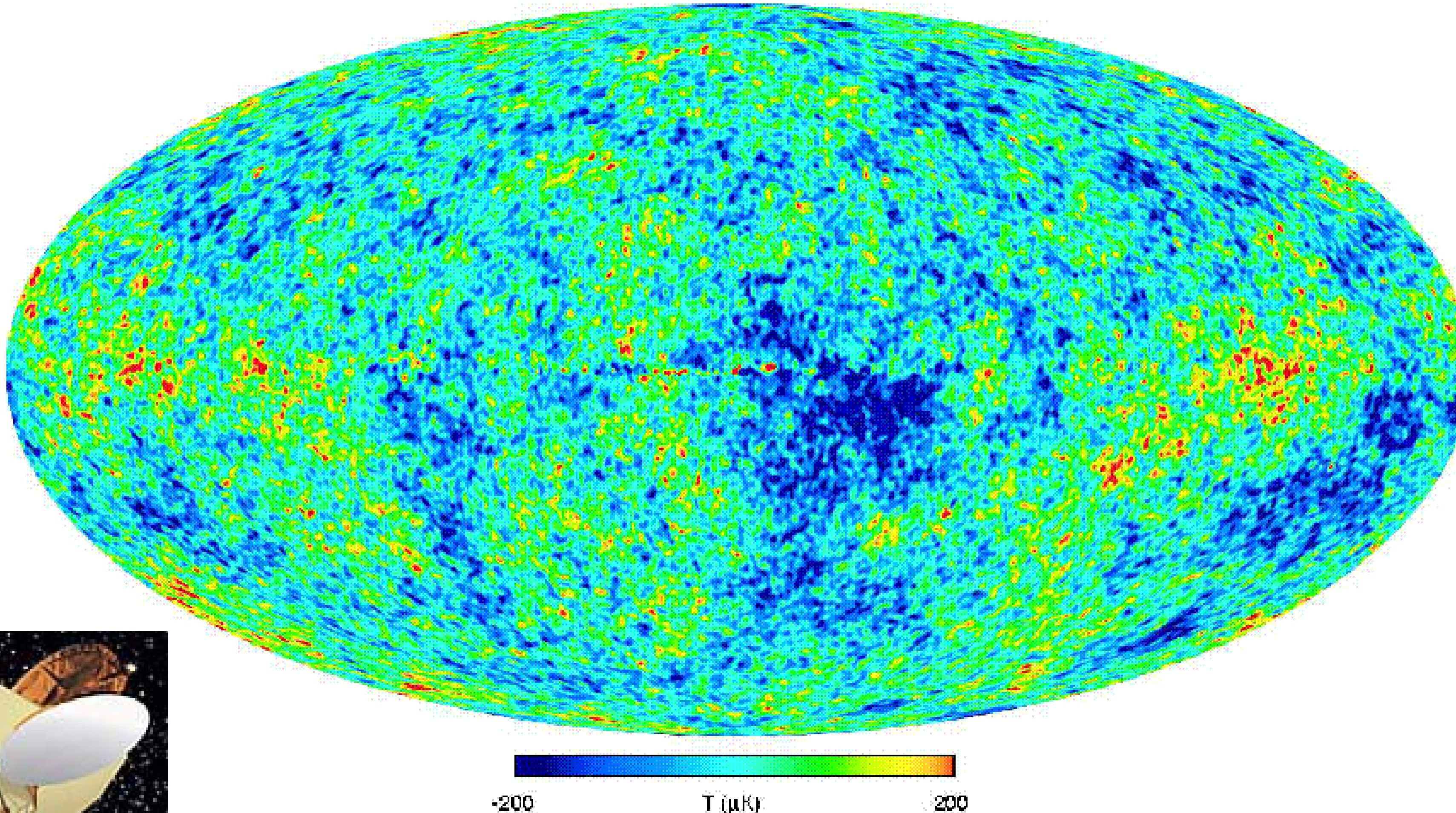
The deepest photo ever made

A 300 hour exposure with the Hubble Space Telescope

Galaxies seen when Universe was a tenth its present age!

Today they are 30,000,000,000 light-yrs away!

The *WMAP* of the whole CMB sky (2003)



Structure in the Microwave Background

- The structure reflects weak sound waves in distant cosmic 'clouds' seen when the Universe was 400,000 years old
- At that time the Universe was near-uniform, and was 1,000 times smaller, 1,000 times hotter than today. There were no heavy elements, no stars, no galaxies, no people

The *pattern* of structure reflects

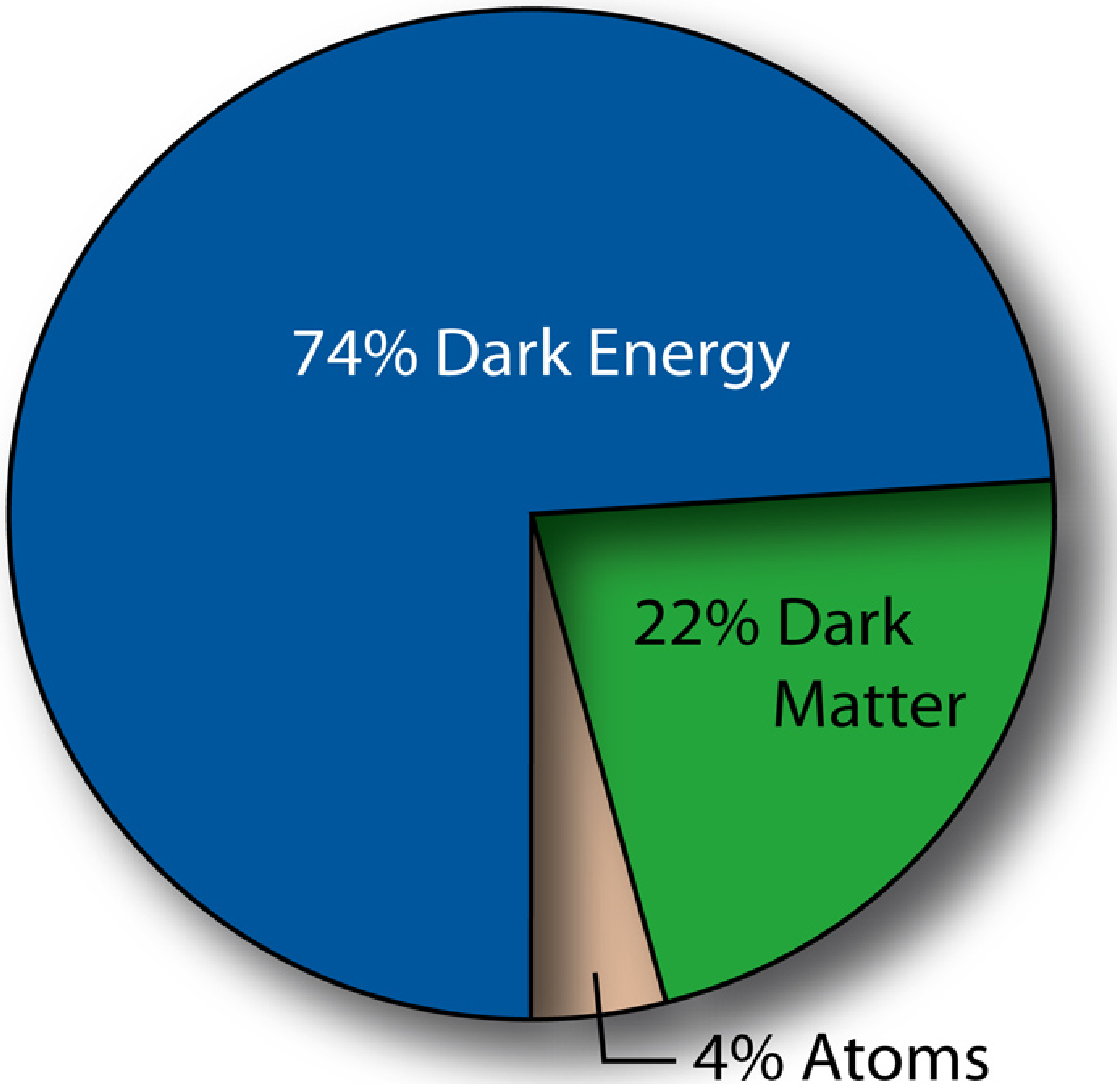
A: The global geometry and topology of the Universe

B: The constituents and thermal evolution of the Universe

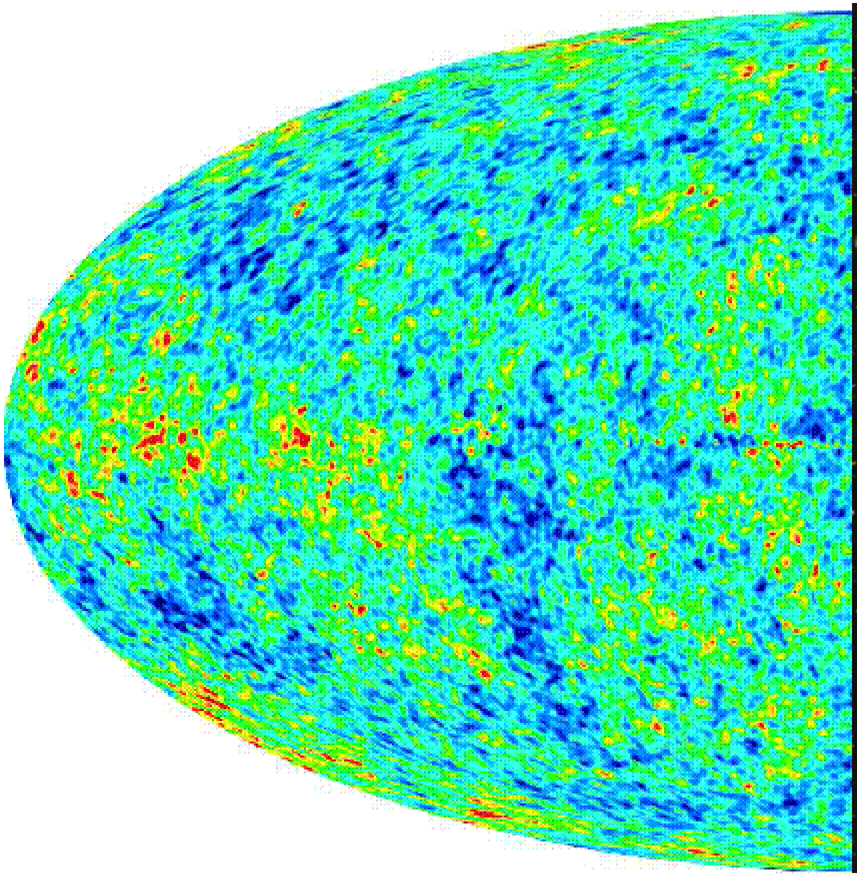
C: The process which originally generated the structure

These ripples grew into ALL present-day structures

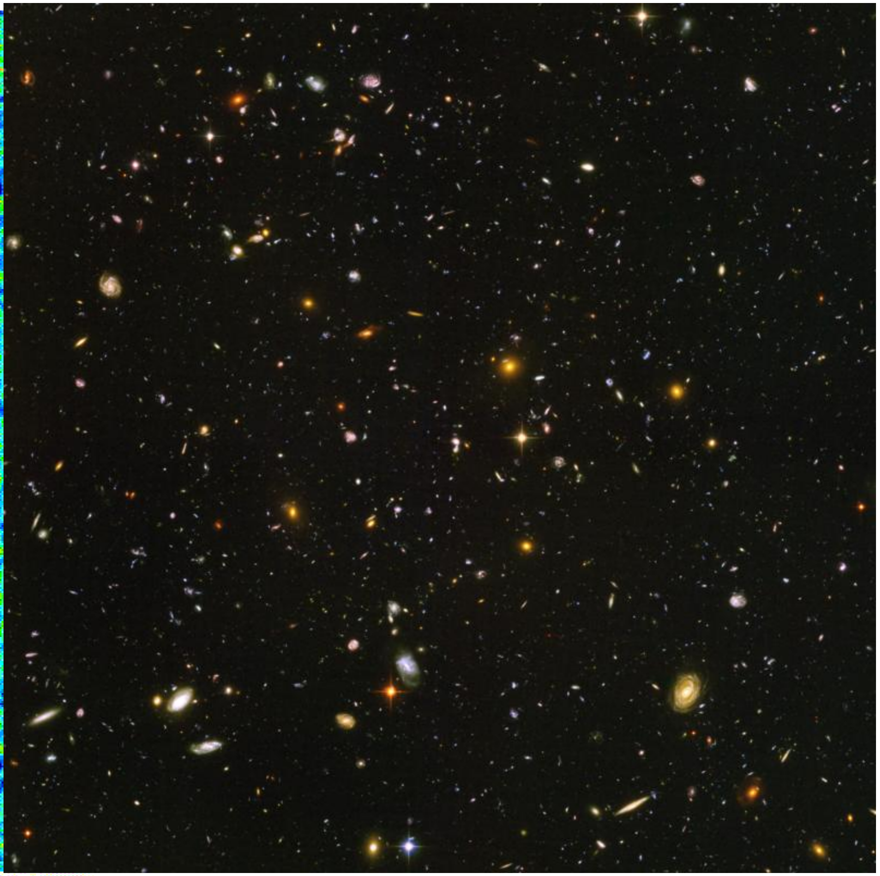
Ordinary matter is a small fraction of today's Universe



Our universe changes with time

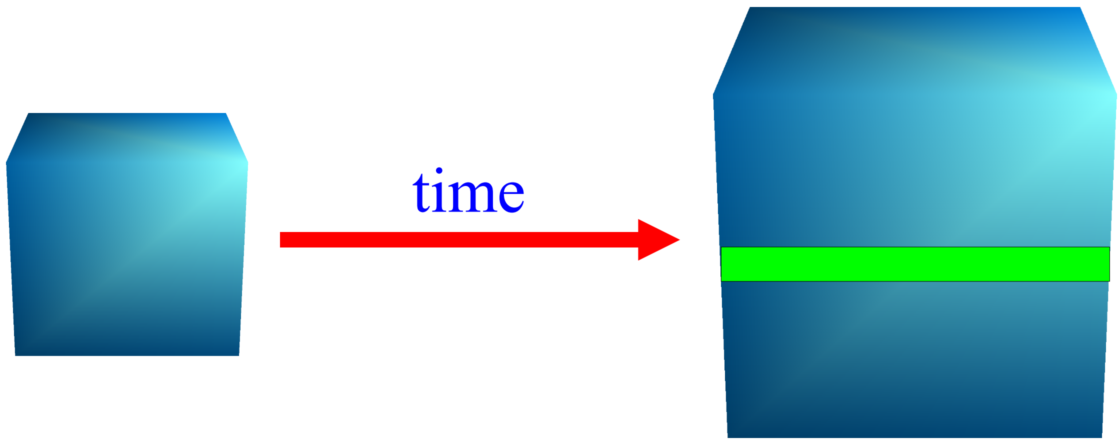


WMAP 2003



The Hubble Ultradeep Field

How structure emerges from the Big Bang



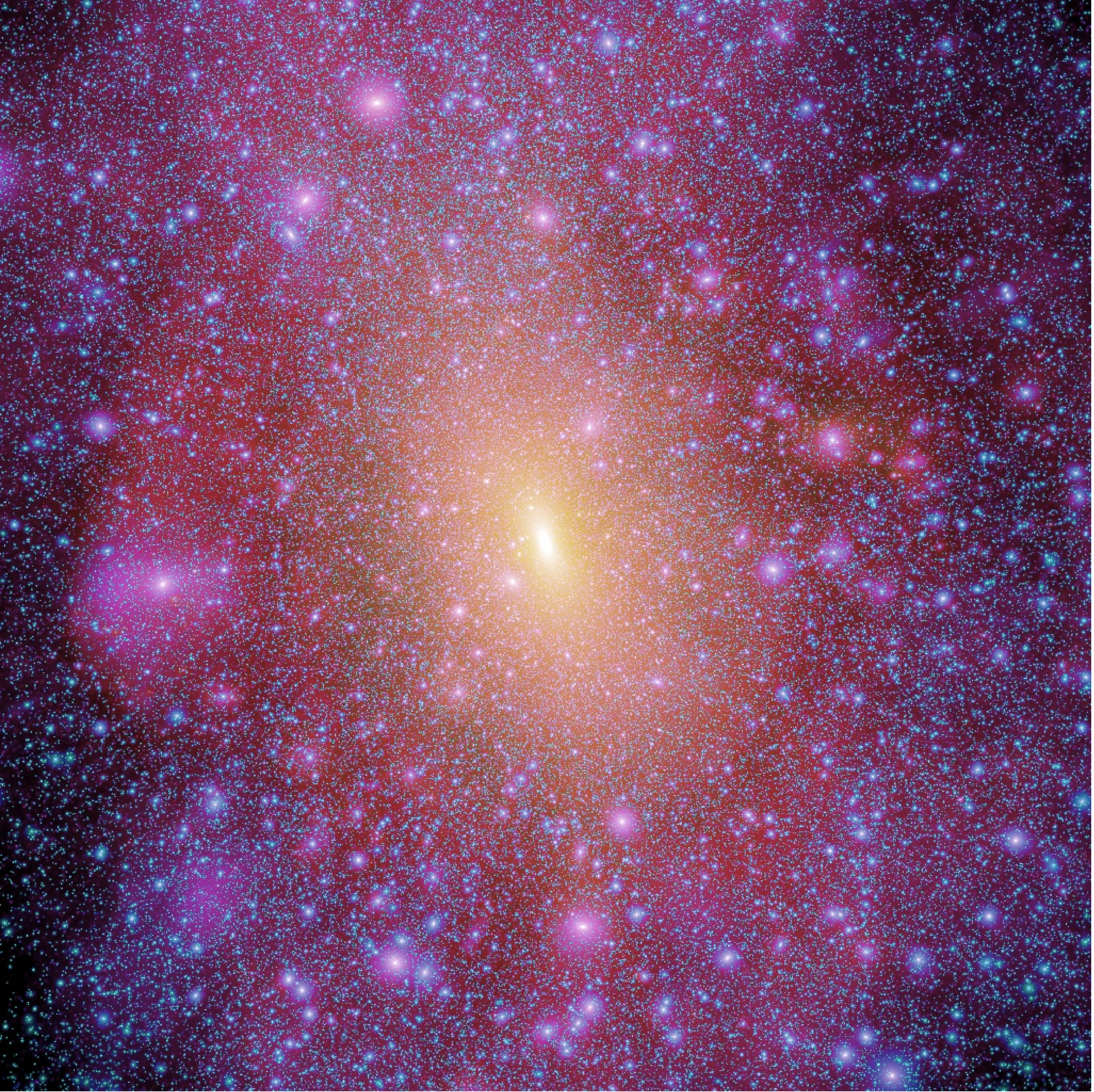
- Start 400,000 years after the Big Bang from the initial conditions seen in the microwave background

- Integrate the equations of motion forwards to the present day in a supercomputer

- The growth of dark matter structures in a thin slice

- A flight through the dark matter distribution

10,000 compute cores
60 Tflop peak speed
40 Tbyte RAM
600 Tbyte fast disk
3.5 MW power



Phoenix-A-1

Gao et al 2010

$N_{200} = 1.1 \times 10^9$

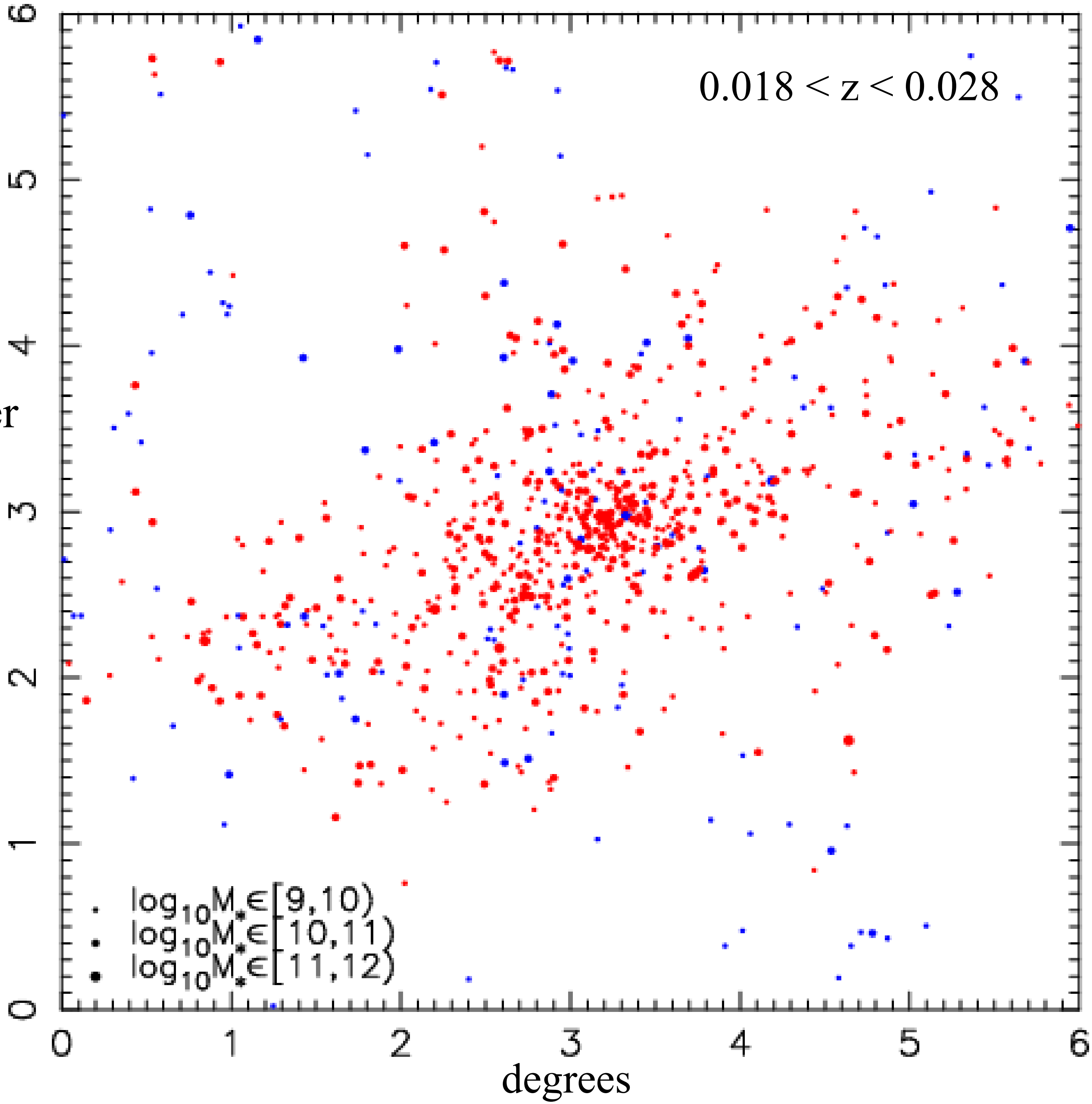
$m_p = 5 \times 10^5 M_\odot$

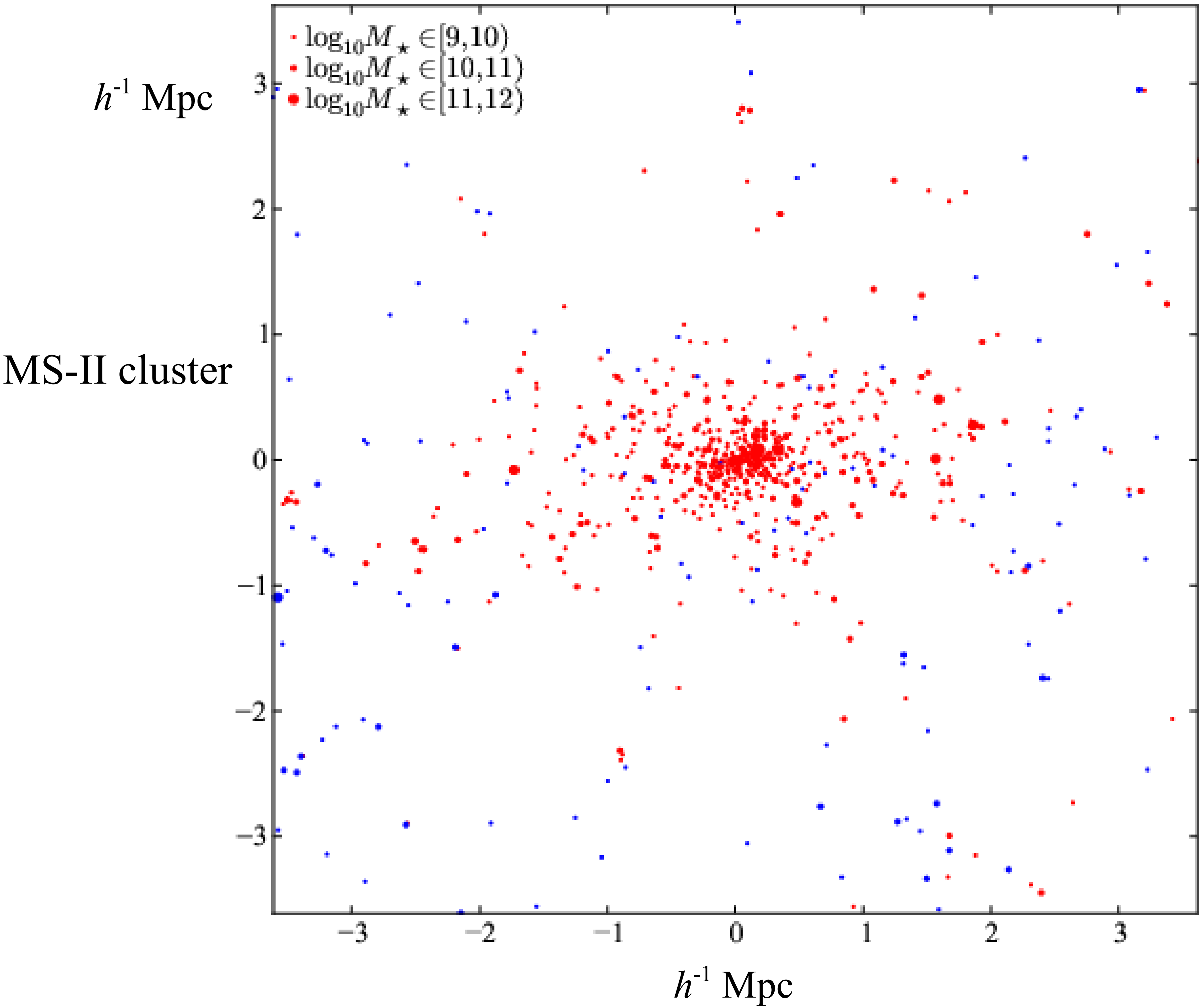
Dark matter *only*!

degrees

Coma cluster

SDSS data

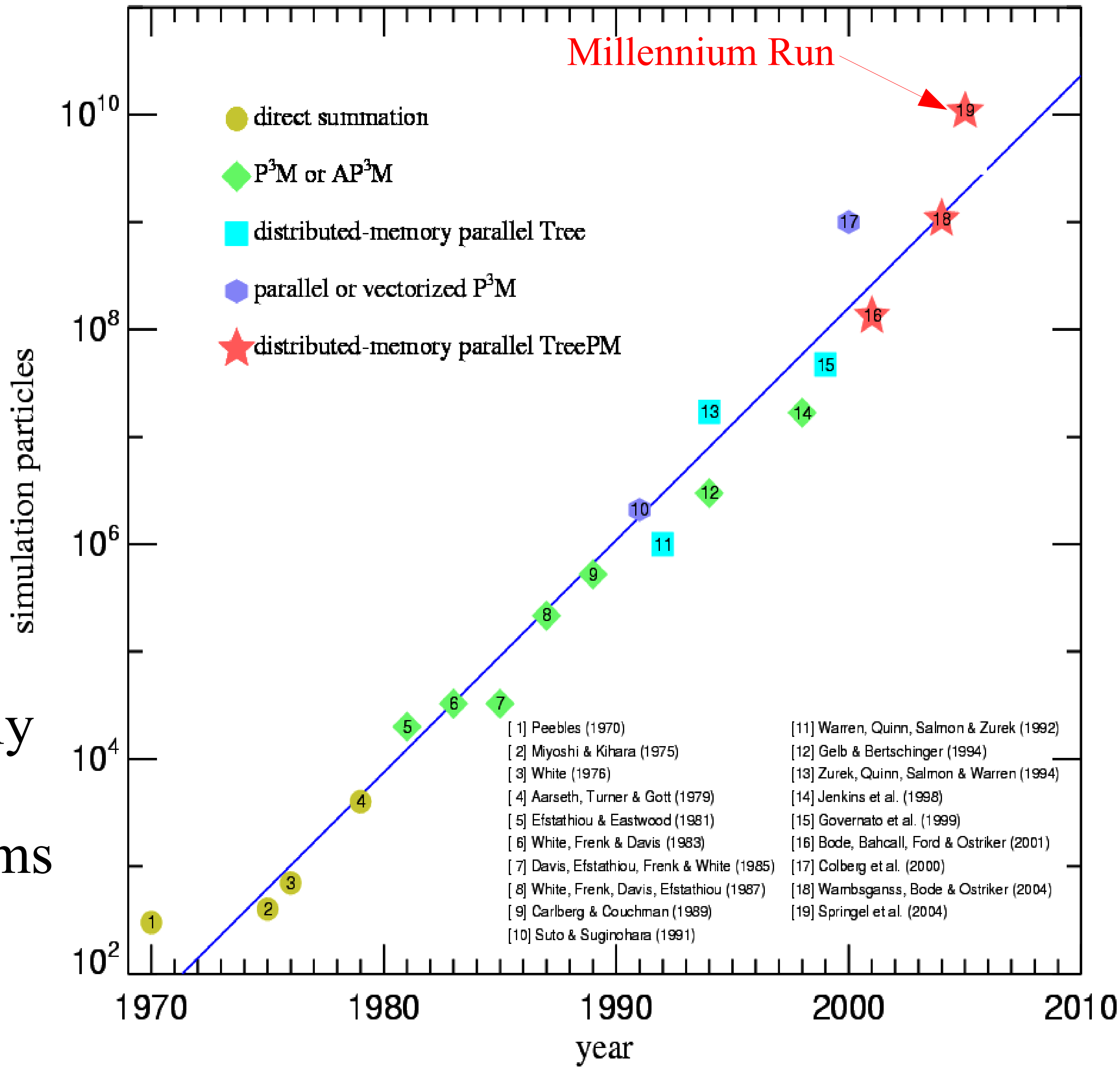




h^{-1} Mpc
MS-II cluster
$\log_{10} M_\star \in [9,10)$
$\log_{10} M_\star \in [10,11)$
$\log_{10} M_\star \in [11,12)$
3
2
1
0
−1
−2
−3
h^{-1} Mpc

Moore's Law for Cosmological N-body Simulations

- Computers double their speed every 18 months
- A naive N-body force calculation needs N^2 op's
- Simulations double their size every 16.5 months
- Progress has been roughly equally due to hardware and to improved algorithms



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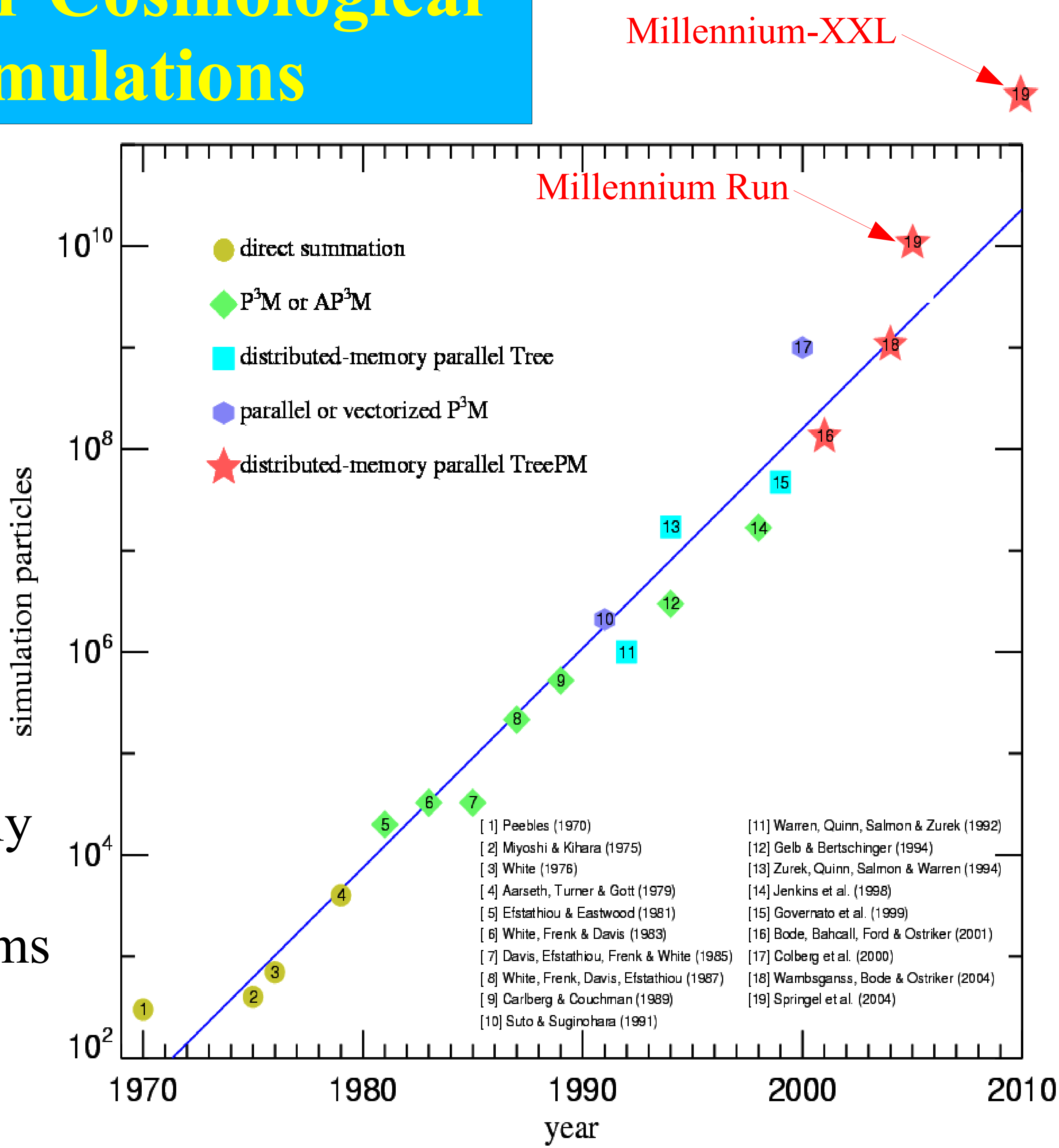
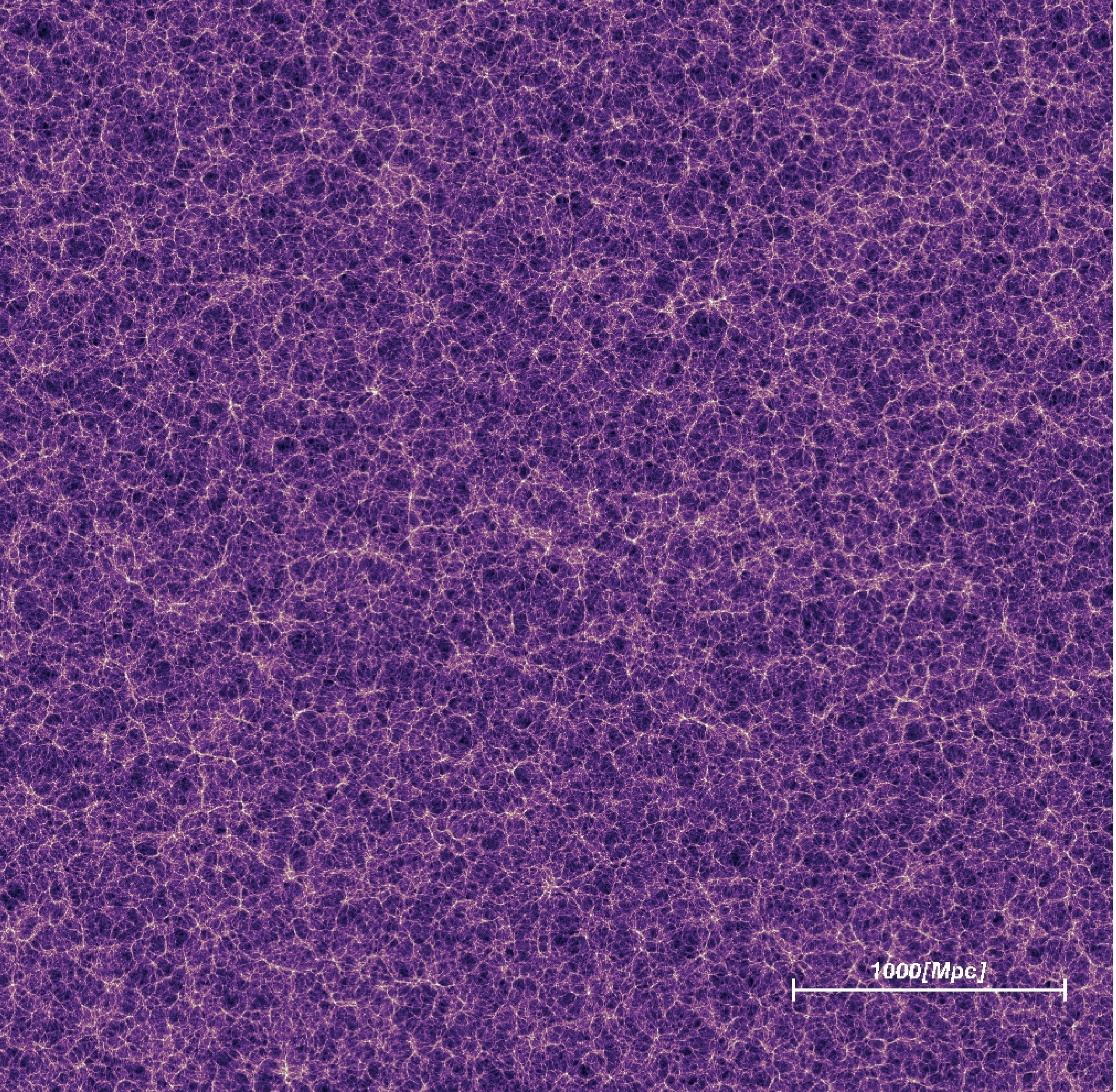




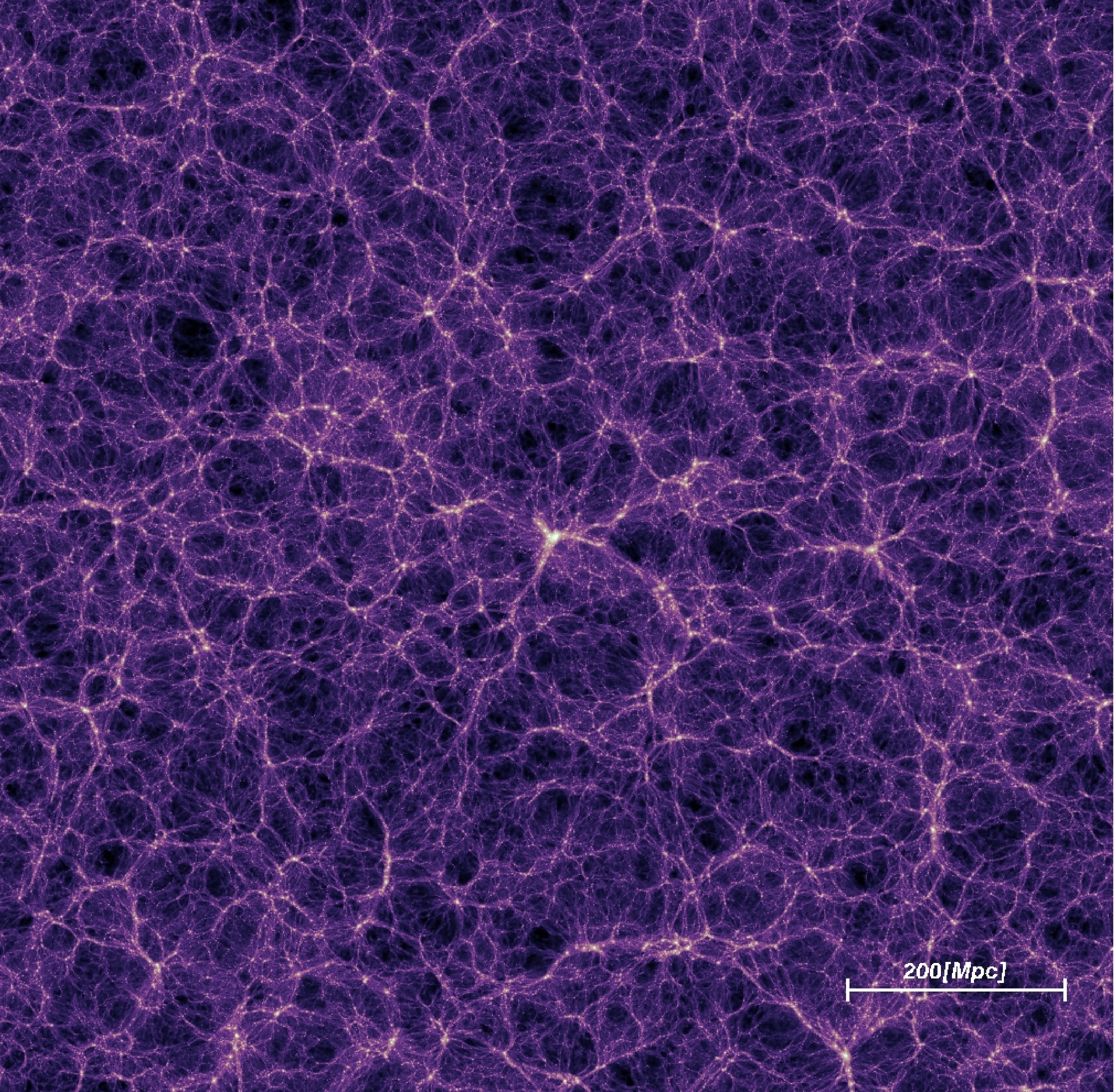
Millennium XXL

Angulo et al 2010

$N = 3 \times 10^{11}$

$m_p = 5 \times 10^{9} M_\odot$

$L = 4.3$ Gpc



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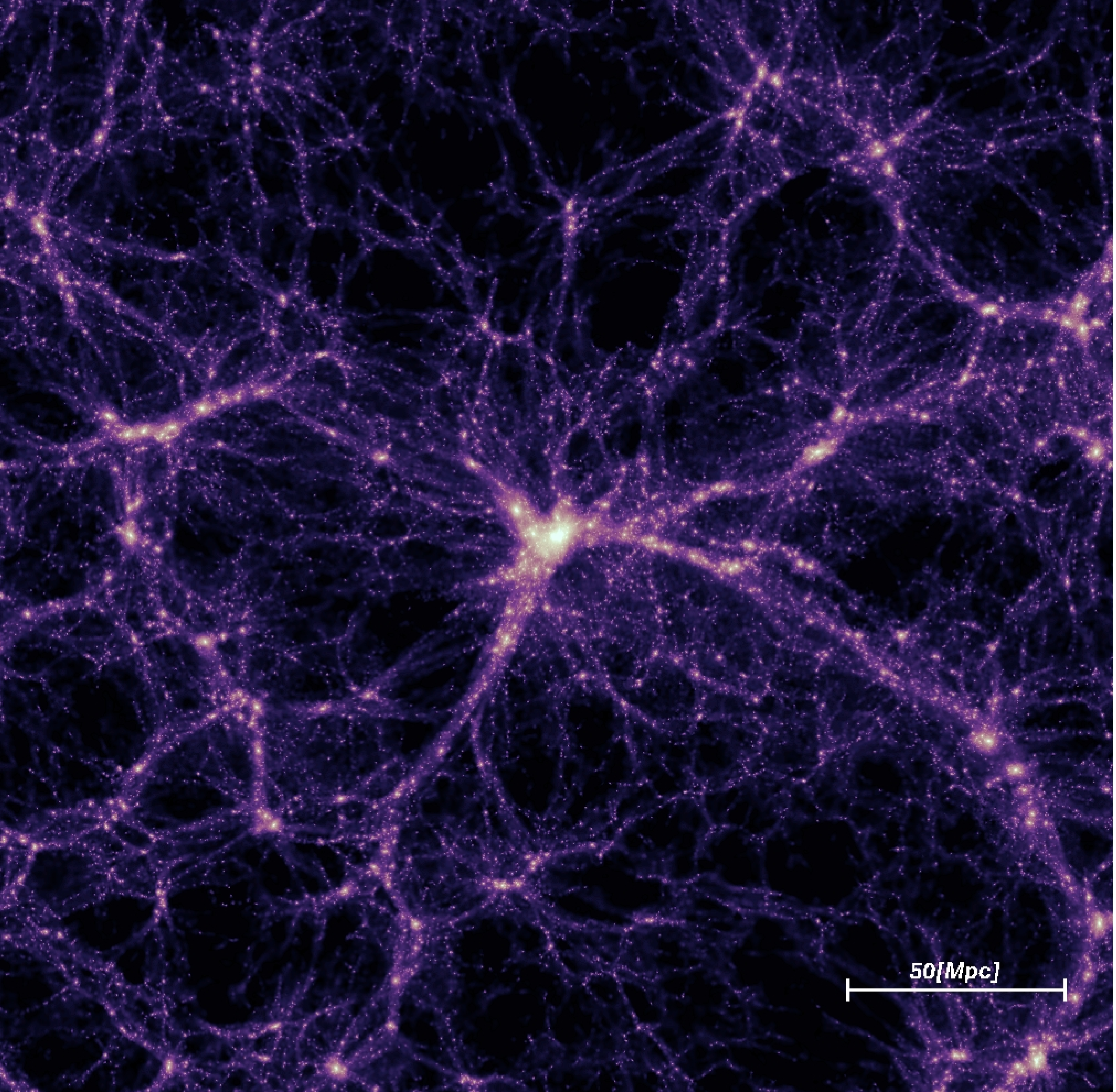

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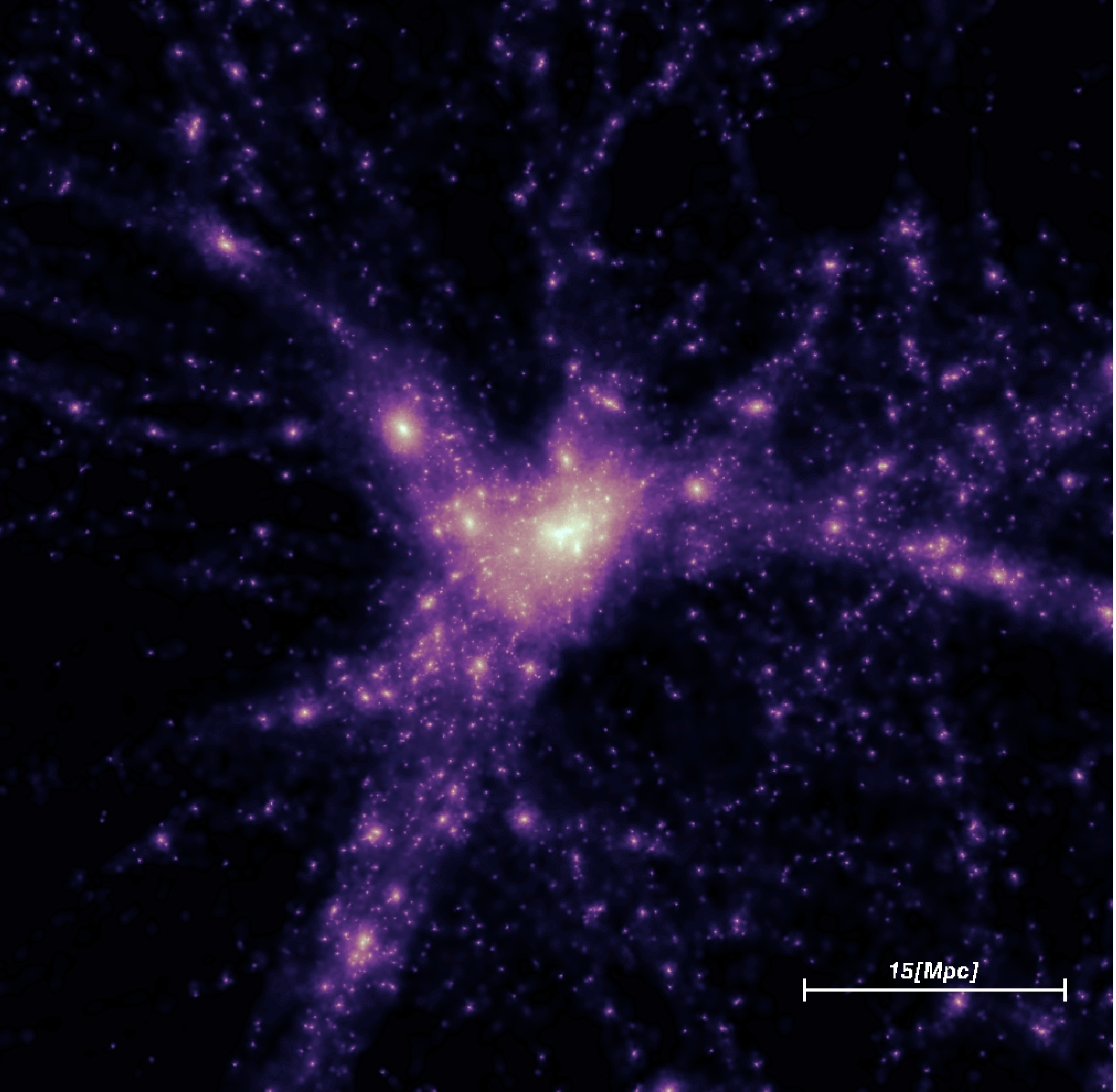

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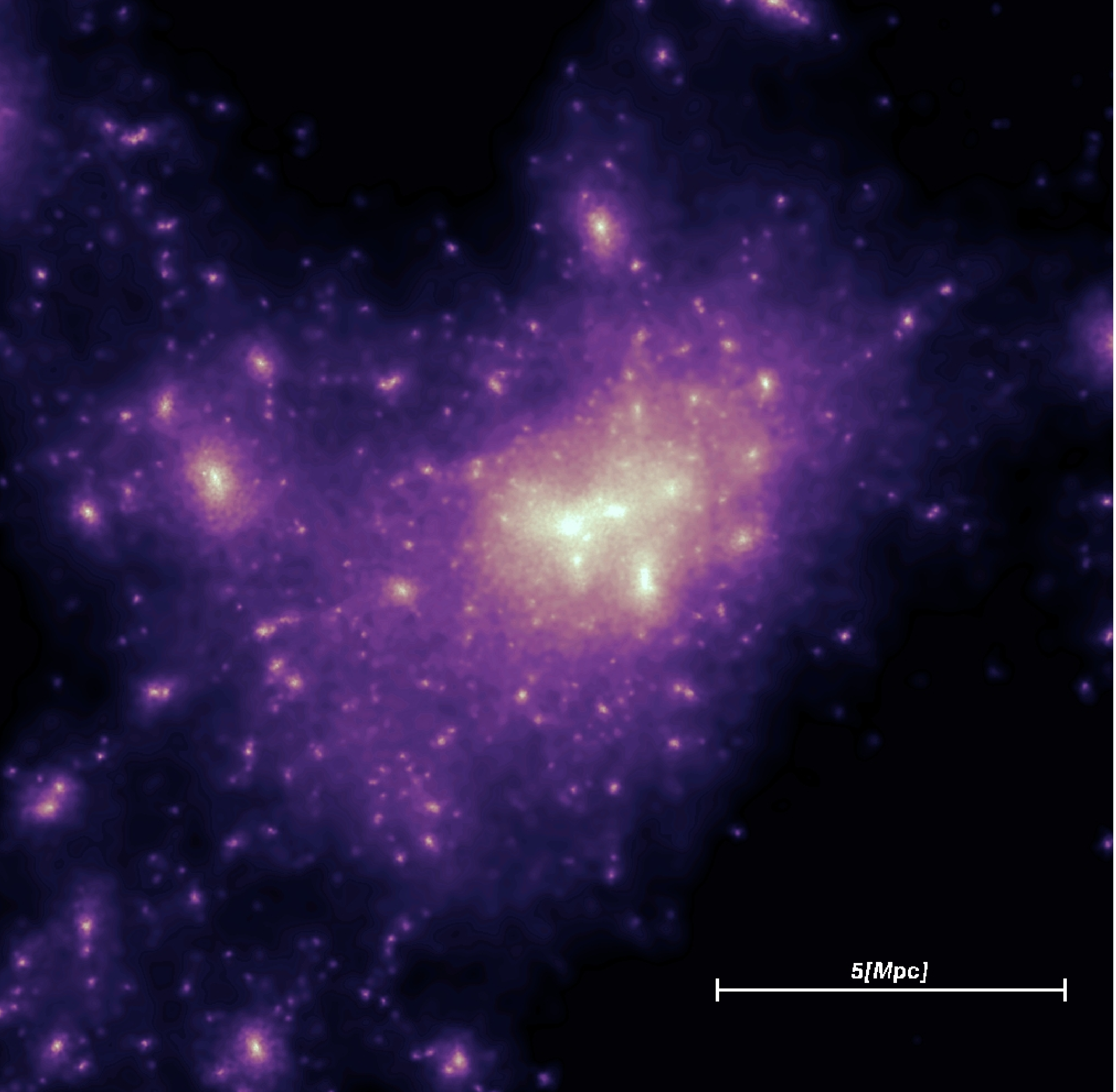

Millennium XXL

Angulo et al 2010

$N = 3 \times 10^{11}$

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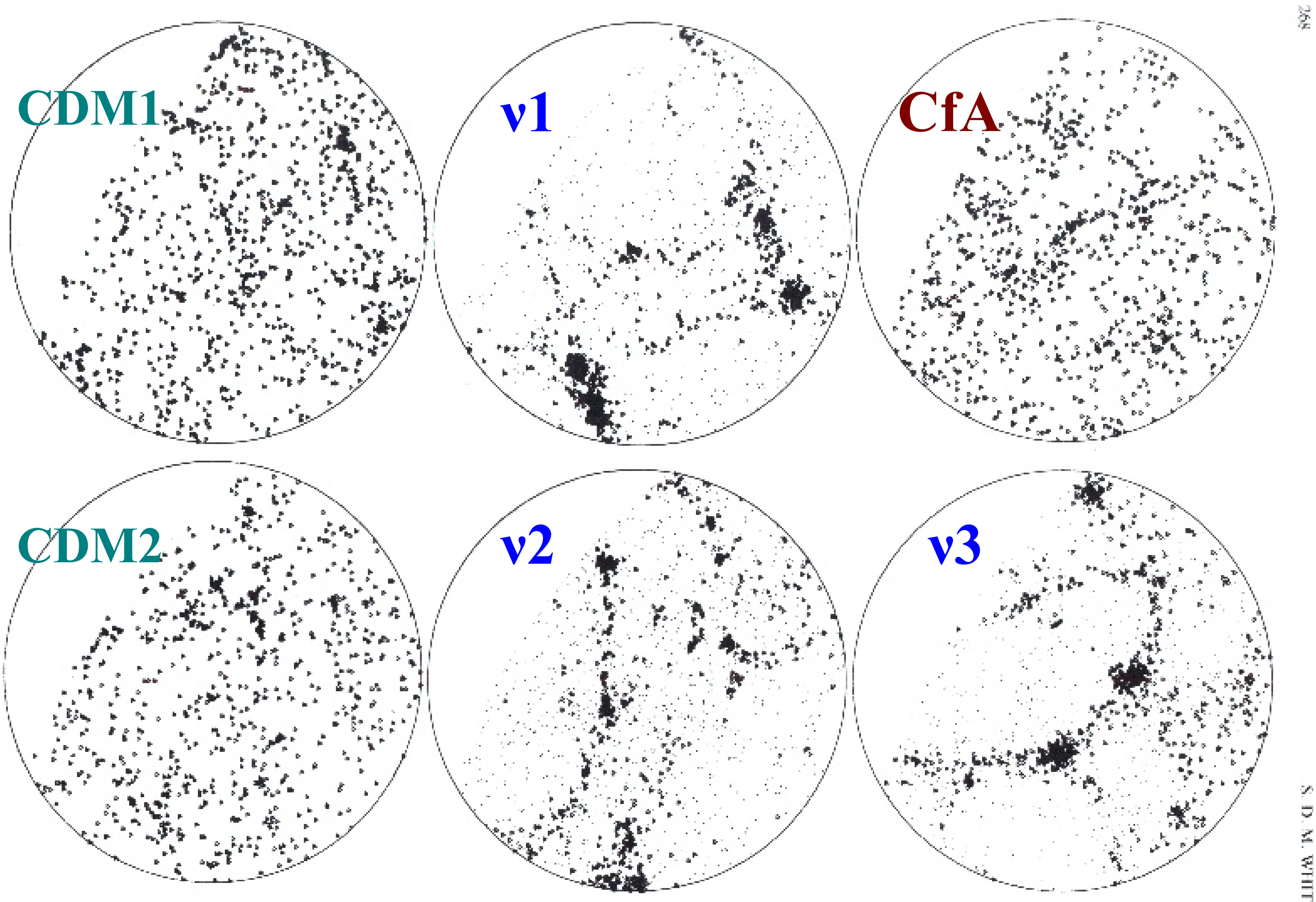
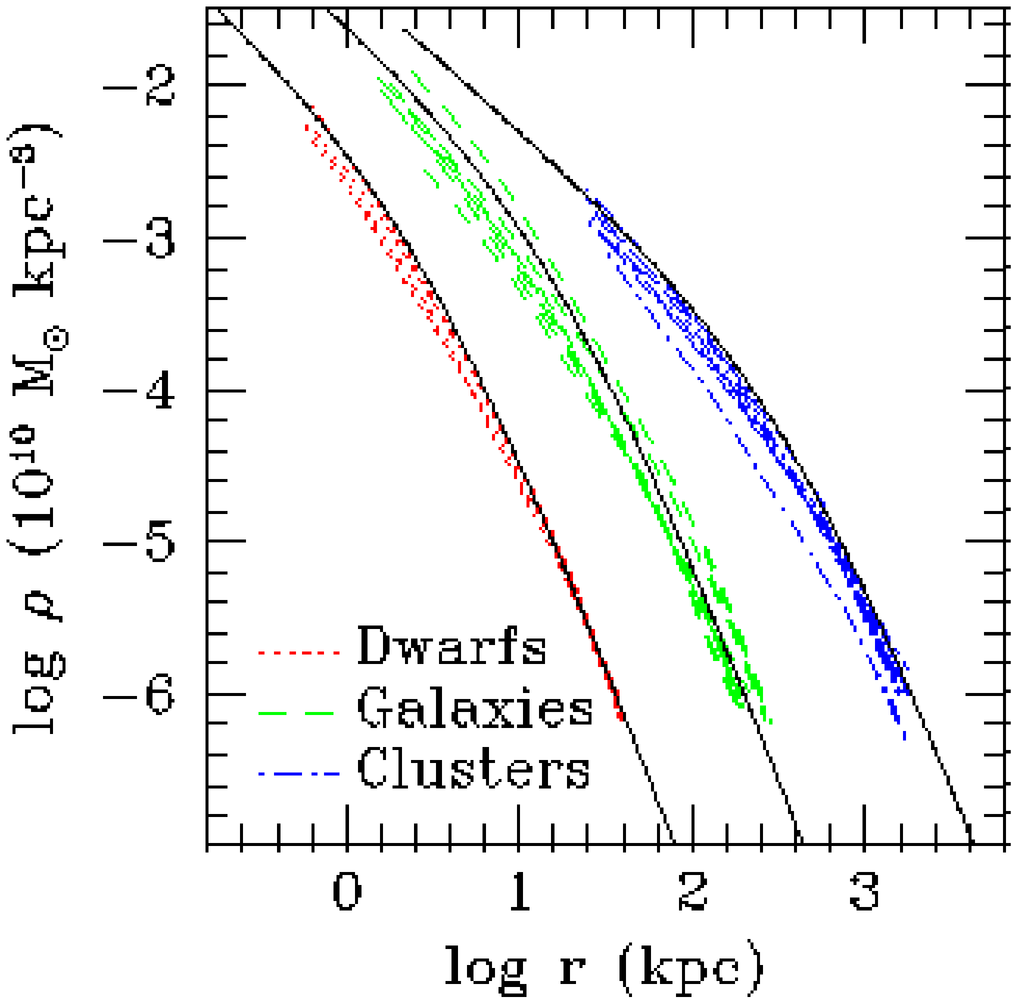
Excluding massive neutrinos as the Dark Matter



Density profiles of dark matter halos

Navarro, Frenk & White 1996



$N_{200} \sim 7 \times 10^3$

The average dark matter density of a dark halo depends on distance from halo centre in a very similar way in halos of all masses at all times in all cosmologies

-- a universal profile shape --

$$\rho(r)/\rho_{crit} \approx \delta \; r_s / r(1 + r/r_s)^2$$

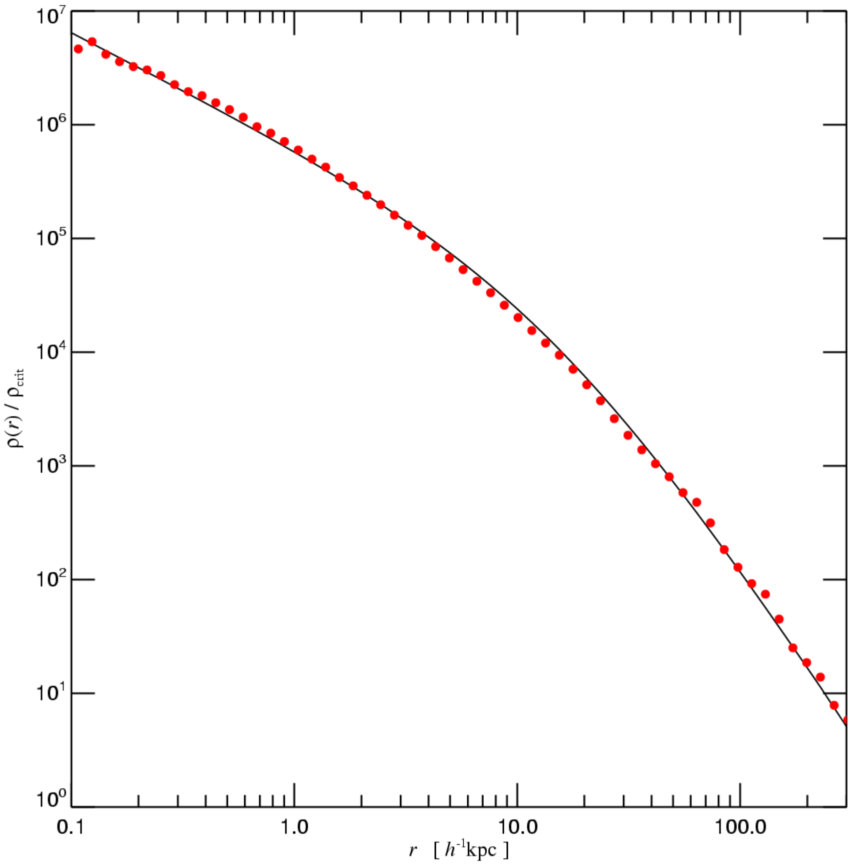
More massive halos and halos that form earlier have higher densities (bigger δ)

A high-resolution Milky Way halo

600 kpc

Navarro et al 2006

$N_{200} \sim 3 \times 10^7$



Dark Matter Halos

- ...are the fundamental nonlinear units of cosmic structure

  50% of all mass is in halos with $M_h > 10^{10} M_\odot$

  60% of all mass is in halos with $M_h > 10^{8} M_\odot$

- ...are triaxial systems with near-universal density structure

  $\rho(r) / \rho_{crit} \approx \delta \; r_s / r \, (1 + r/r_s)^2$

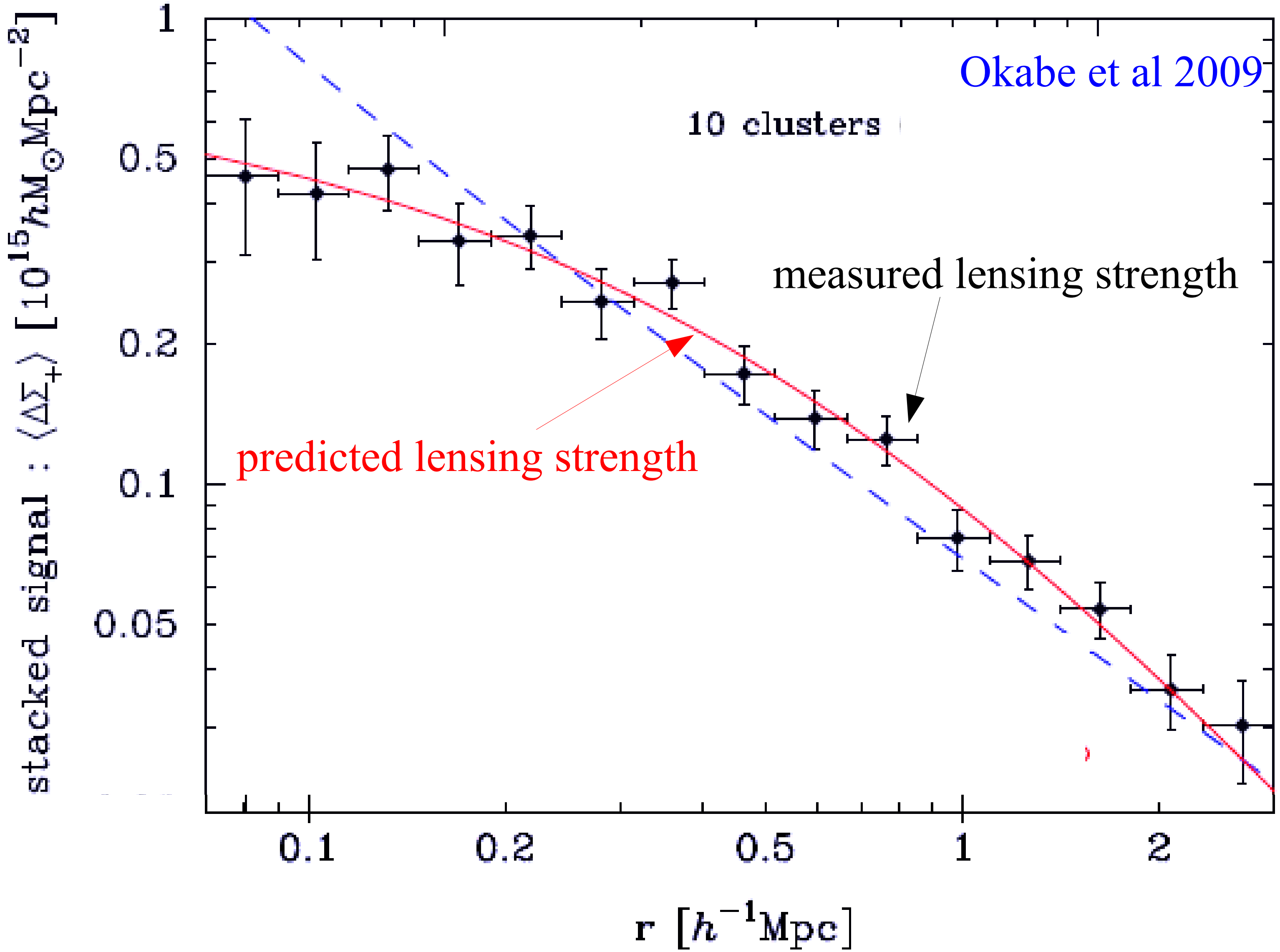
- ...have many subhalos containing ~10% of their mass and

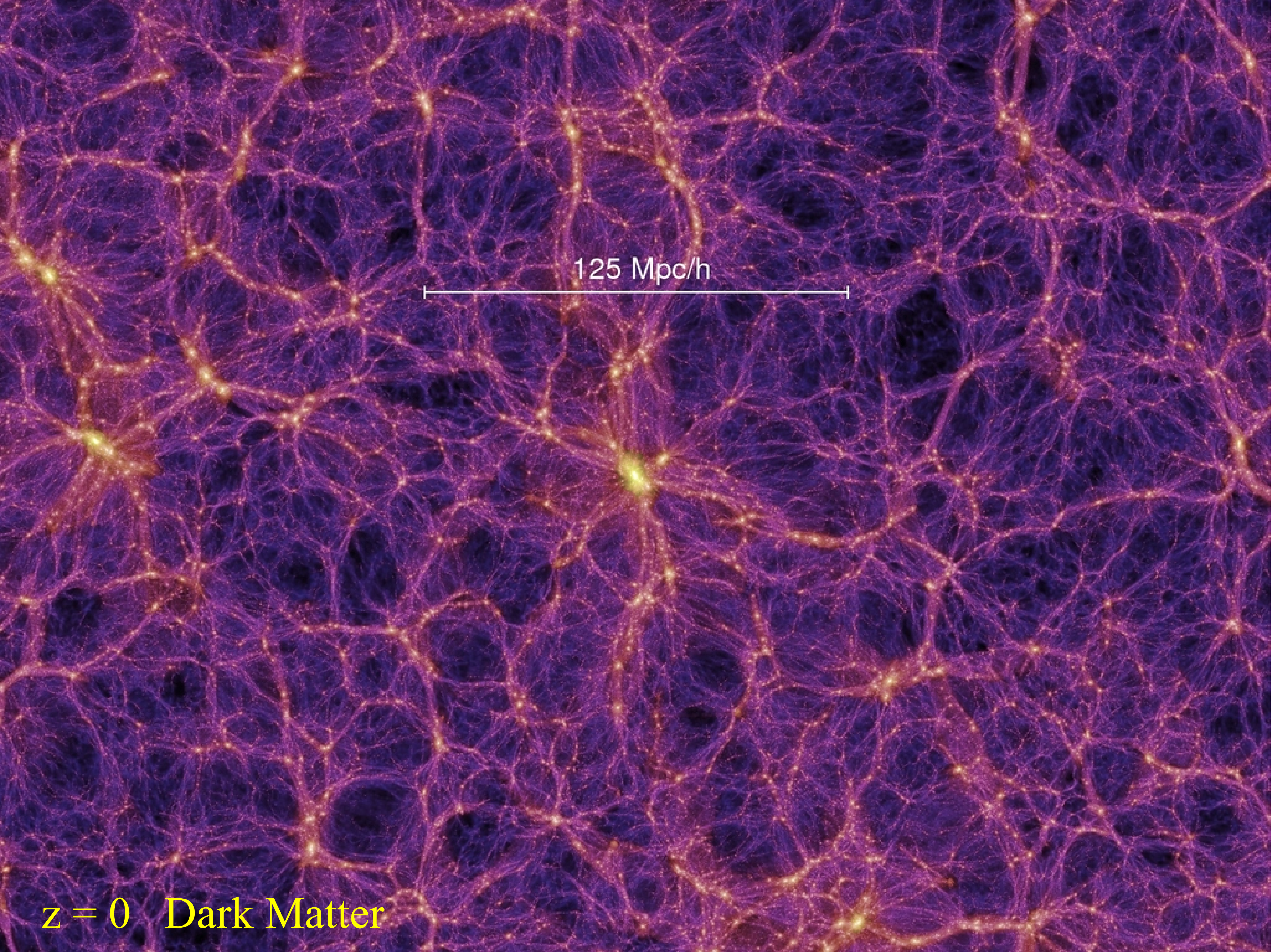
  $dN / dM \sim M^{-1..9}$

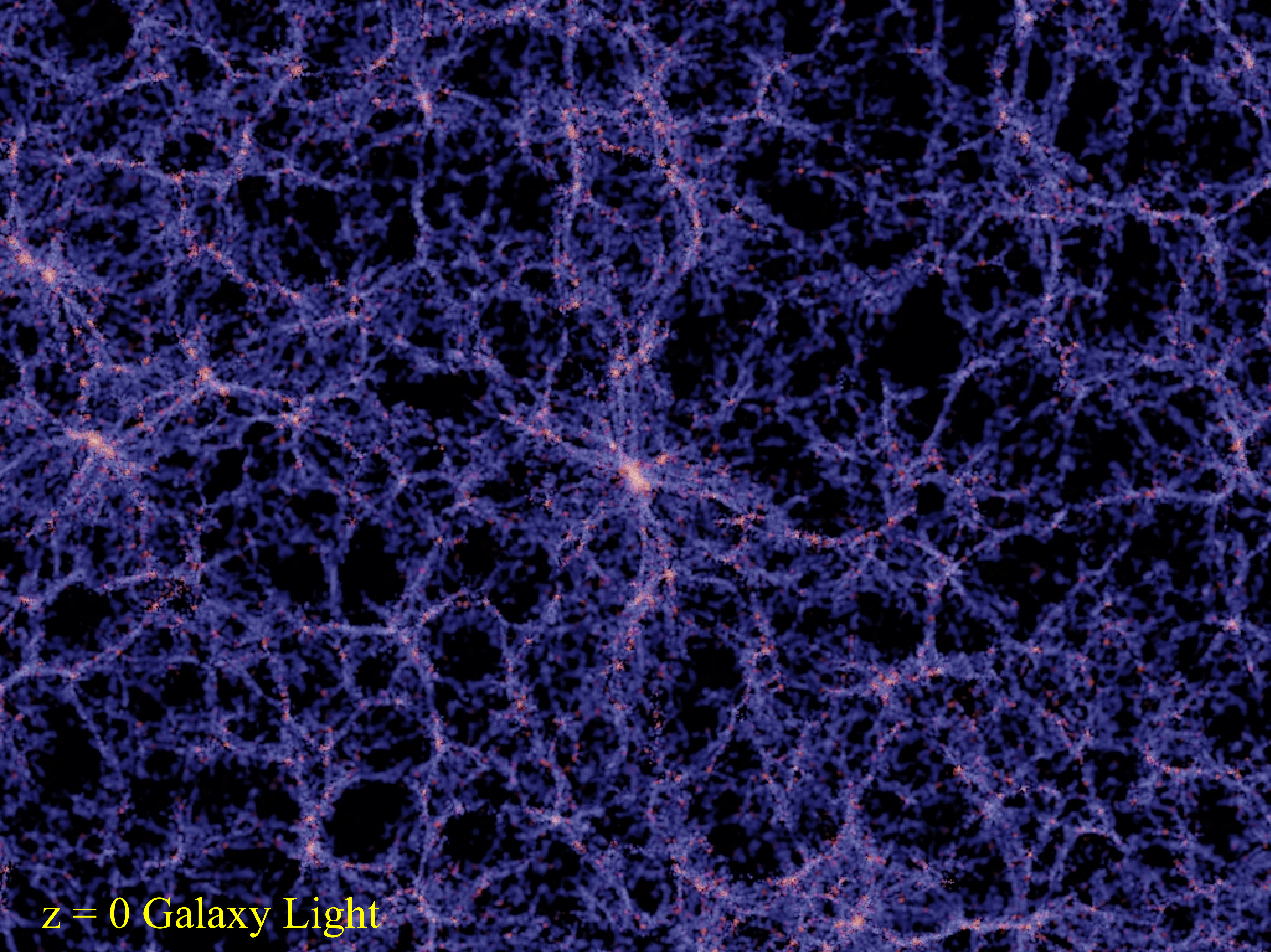
- ...are the sites where galaxies form through the dissipative condensation of baryonic gas

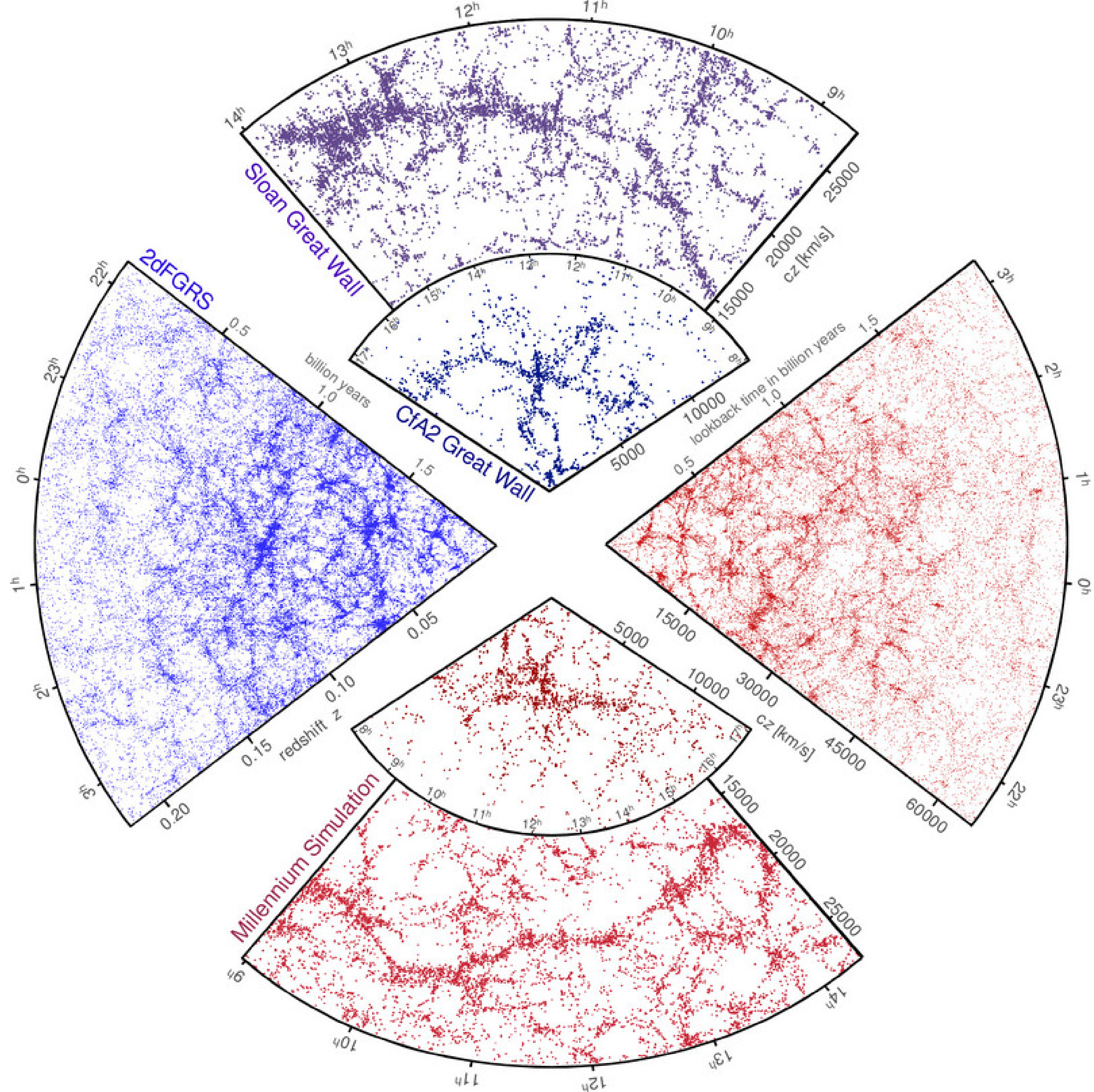
Their properties (abundance, structure, evolution, clustering) have been predicted <u>entirely</u> by numerical simulation

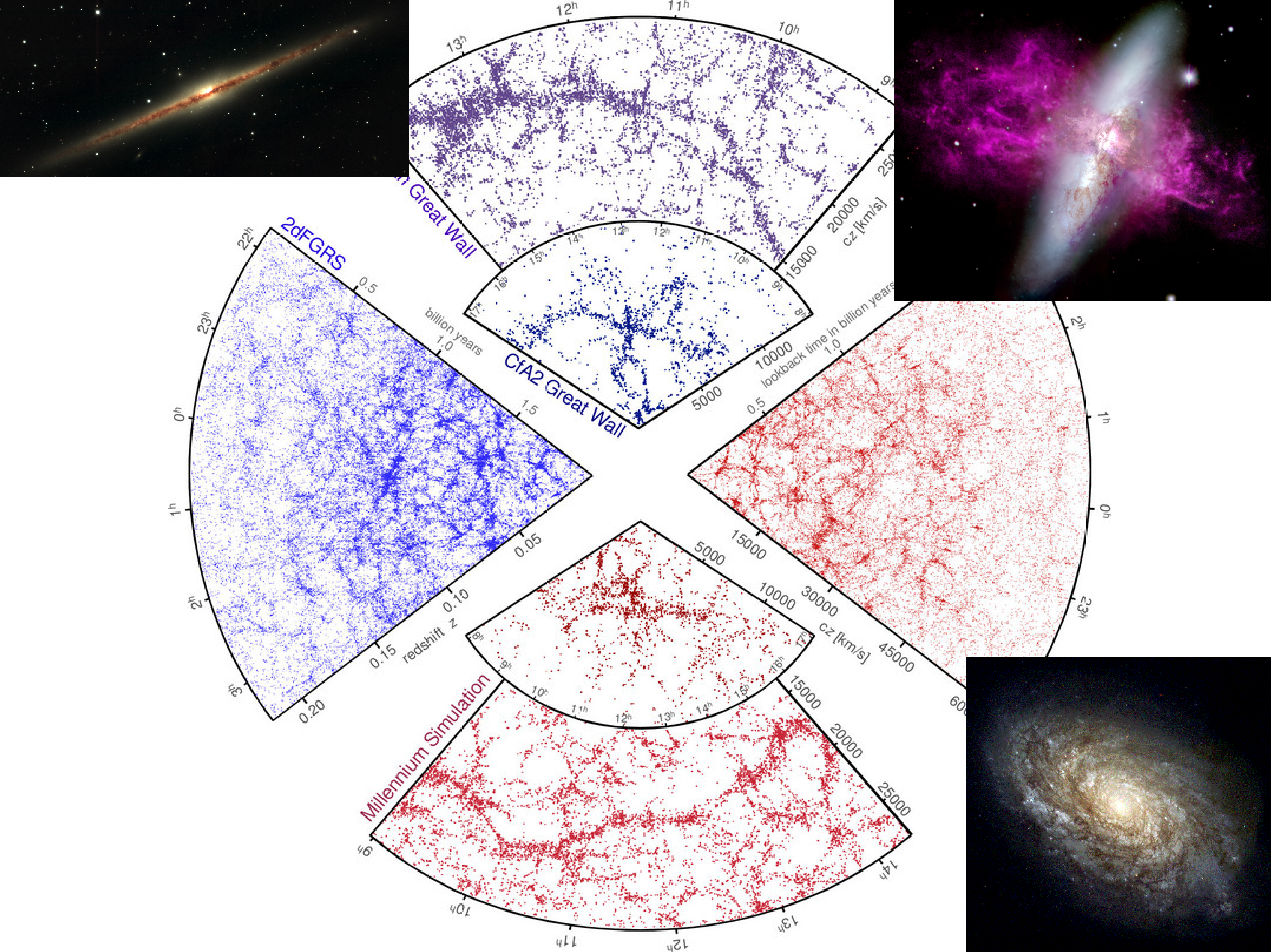
Comparison of lensing strength measured around real galaxy clusters to that predicted by simulations of structure formation




125 Mpc/h
z = 0   Dark Matter

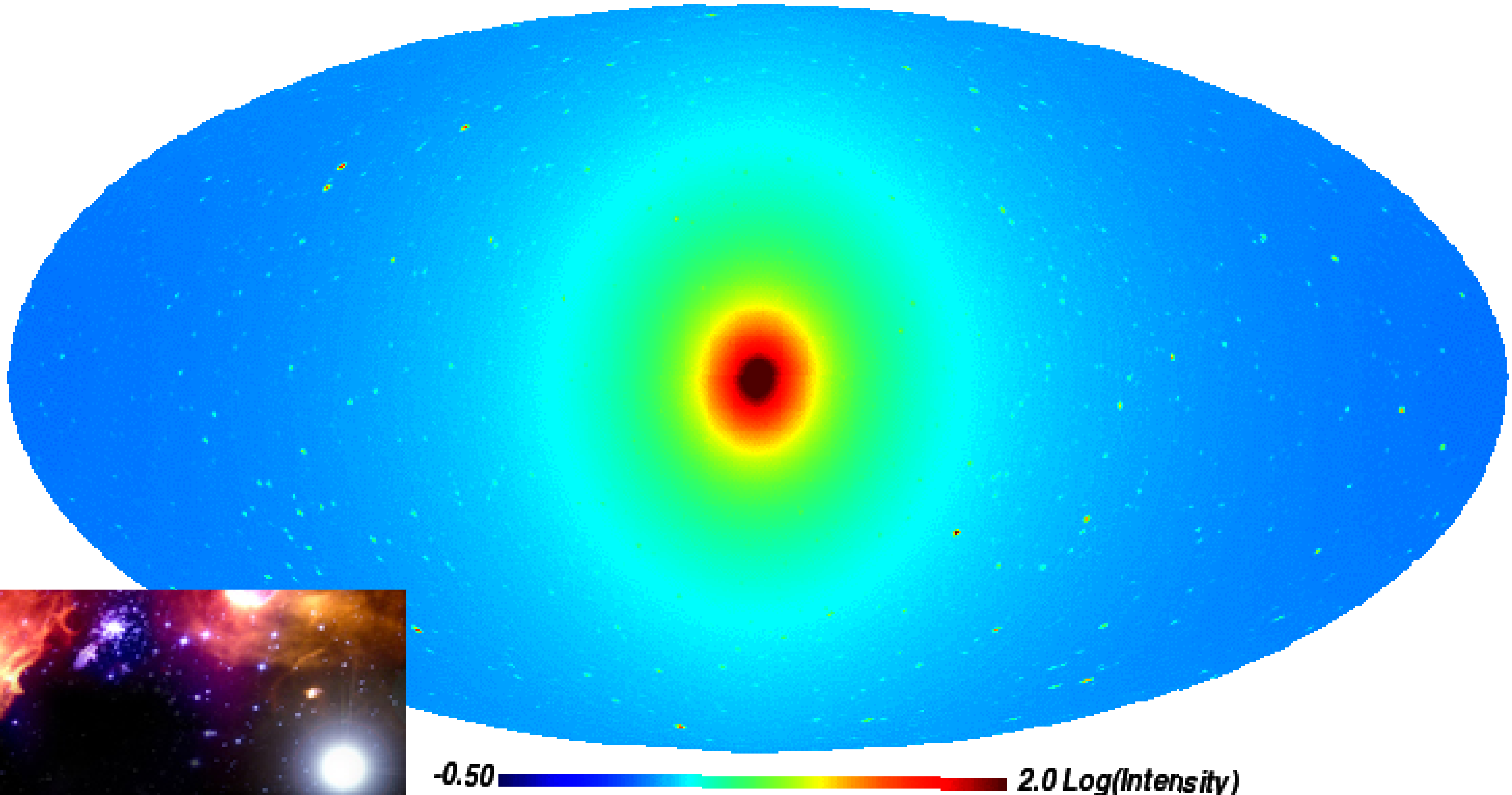

z = 0 Galaxy Light


Sloan Great Wall
2dFGRS
CfA2 Great Wall
Millennium Simulation
cz [km/s]
billion years
lookback time in billion years
redshift z
15000
20000
25000
5000
10000
30000
45000
60000
0.05
0.10
0.15
0.20
0.5
1.0
1.5



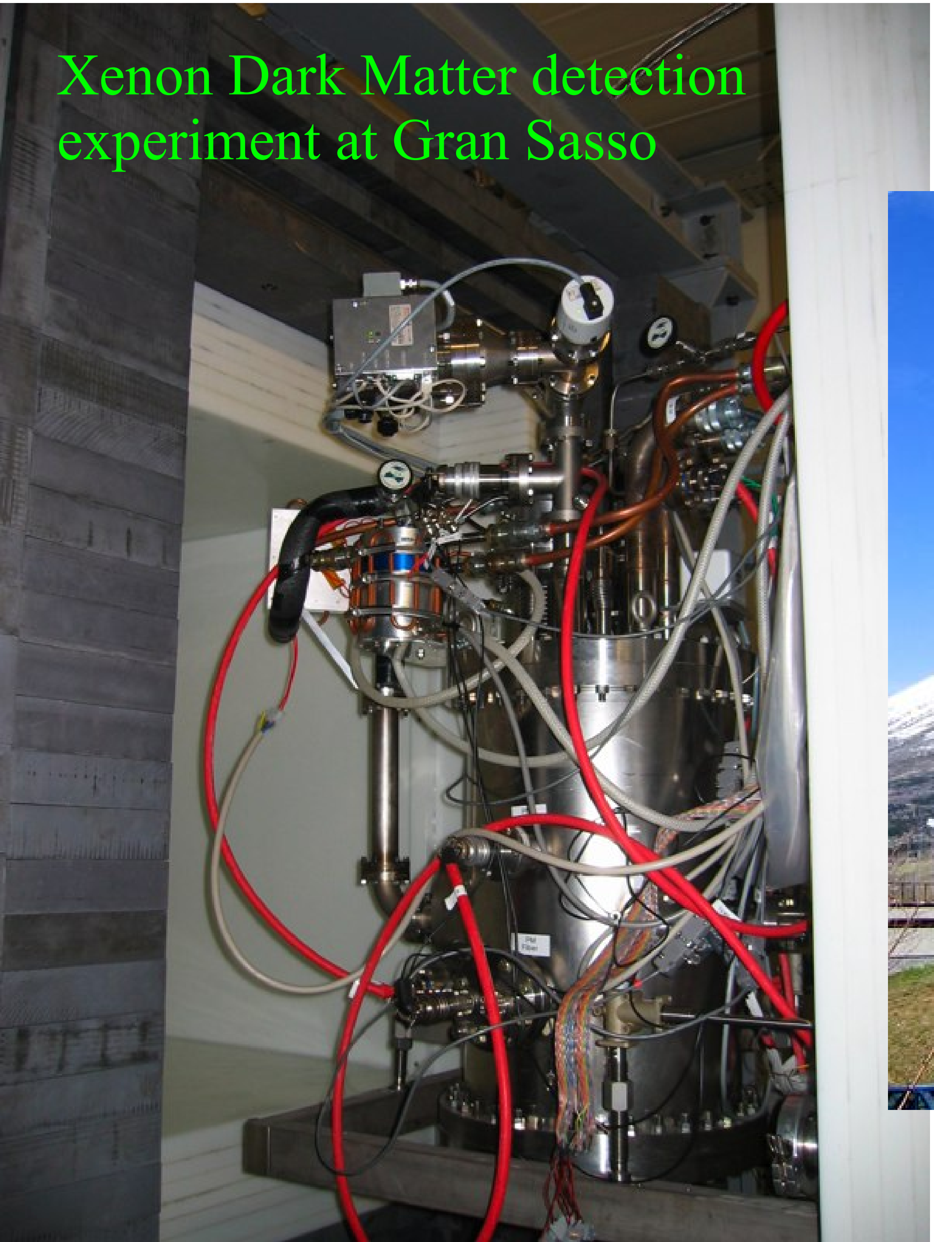
2dFGRS
CfA2 Great Wall
Great Wall
Millennium Simulation
billion years
lookback time in billion years
redshift z
cz [km/s]


Dark Matter around the Milky Way?



Dark Matter as seen by Fermi?

Maybe Dark Matter can be detected in a laboratory



Numerical Simulation in Astrophysics/Cosmology

- Computing power is the fastest growing aspect of astrophysics
- Simulations are now the primary tool for confronting observed objects with theoretical ideas about their nature and origin
- Studies of cosmic structure formation are simplified by the fact that the initial conditions are <u>observed</u> to be simple

  → precise, robust and testable predictions for nonlinear structures when the underlying physics is also simple (e.g. halo structure for comparison with lensing data)

- High quality simulations complement new observations in most proposed tests of the current cosmological paradigm
- For many problems, we are currently limited by (astro)physical understanding, not by computer power