The physics of structure formation in the Universe

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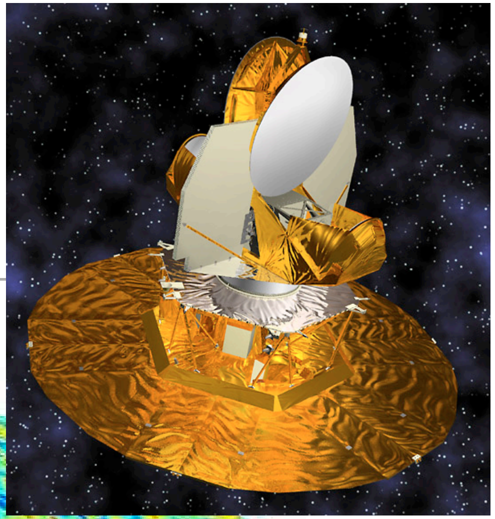
Why do cosmological simulations?

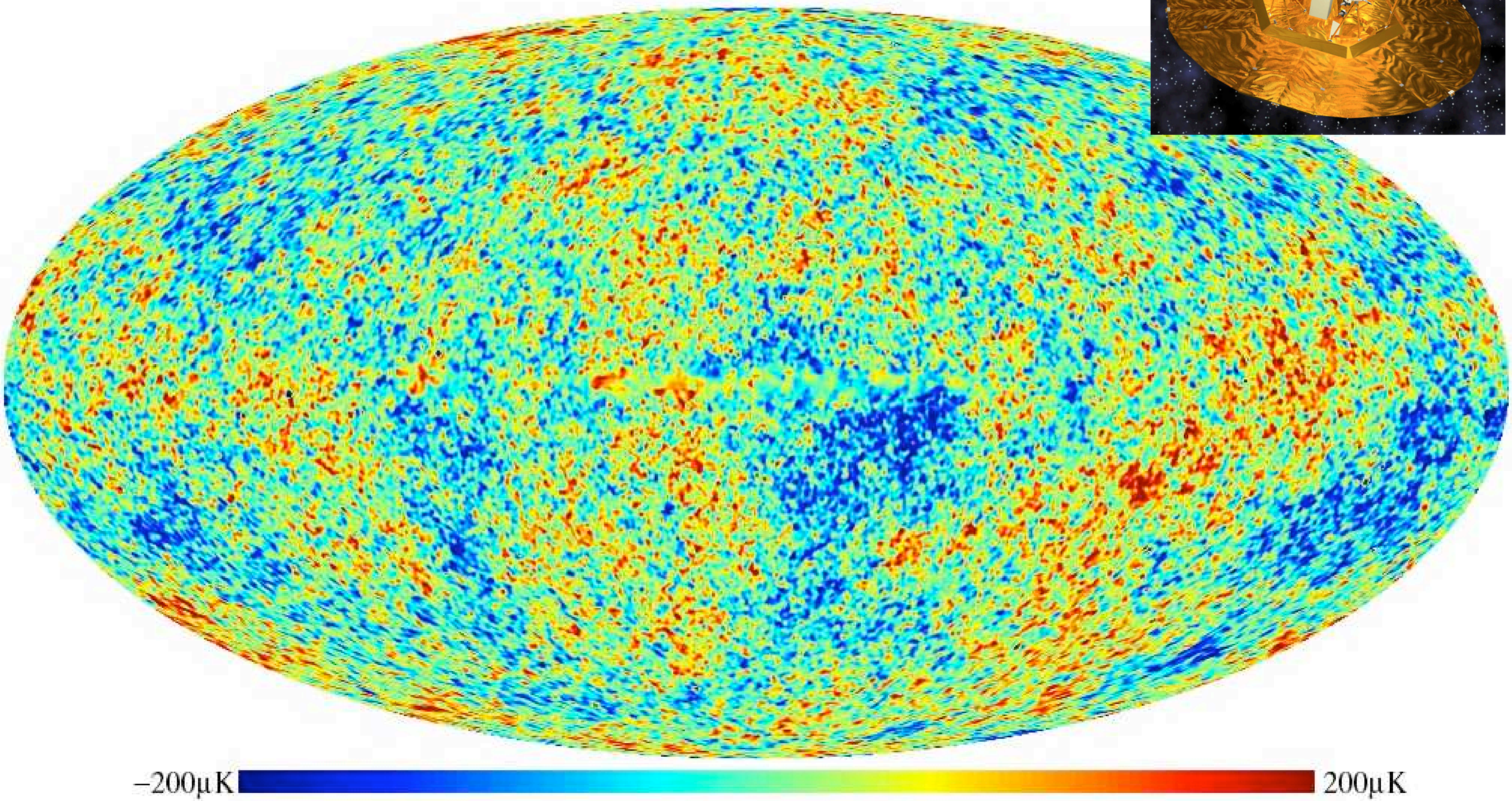
Simple initial conditions

↓

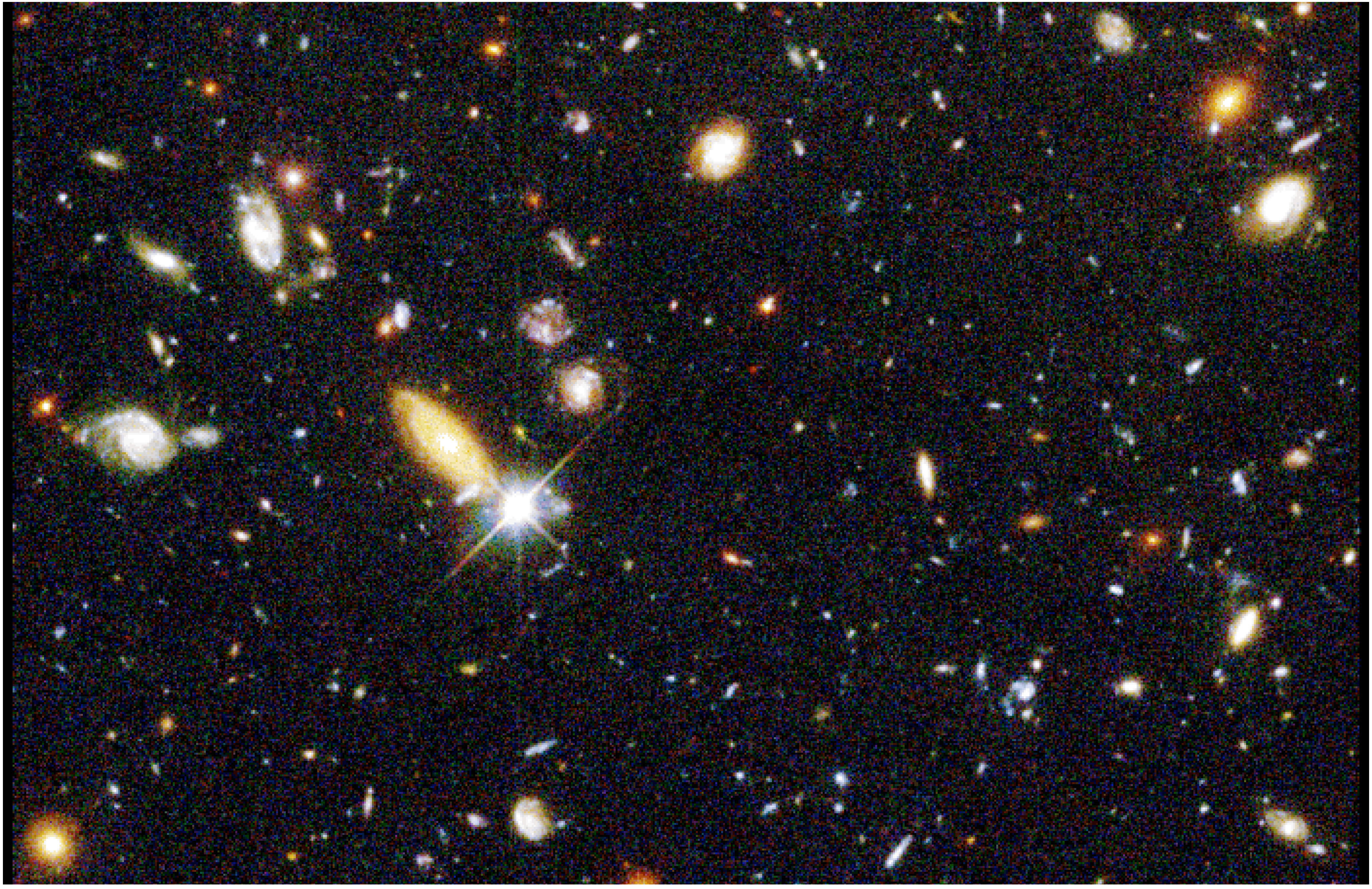
Complex final structure

The cosmic microwave background radiation





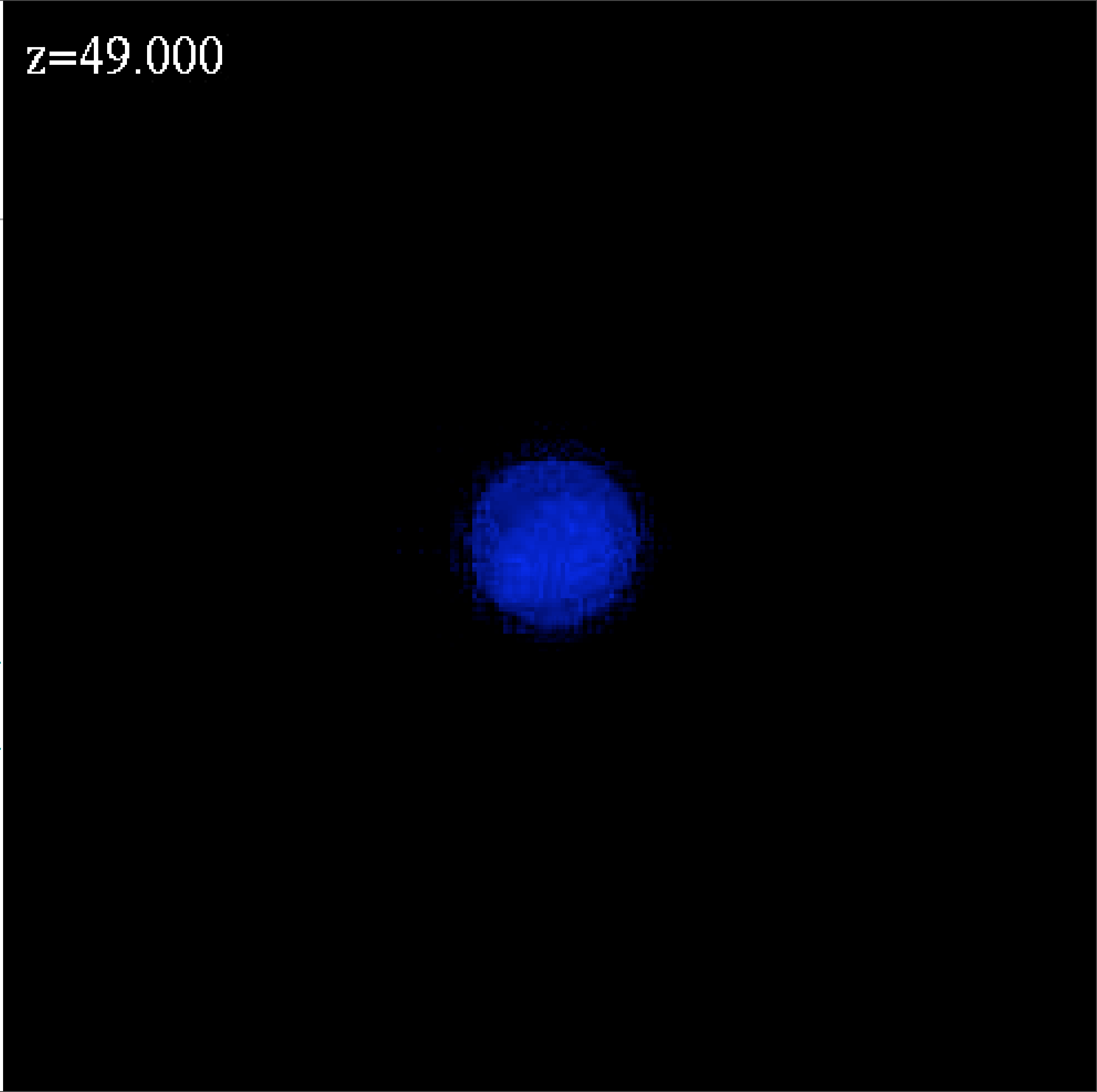
Hubble deep field



The computational challenges

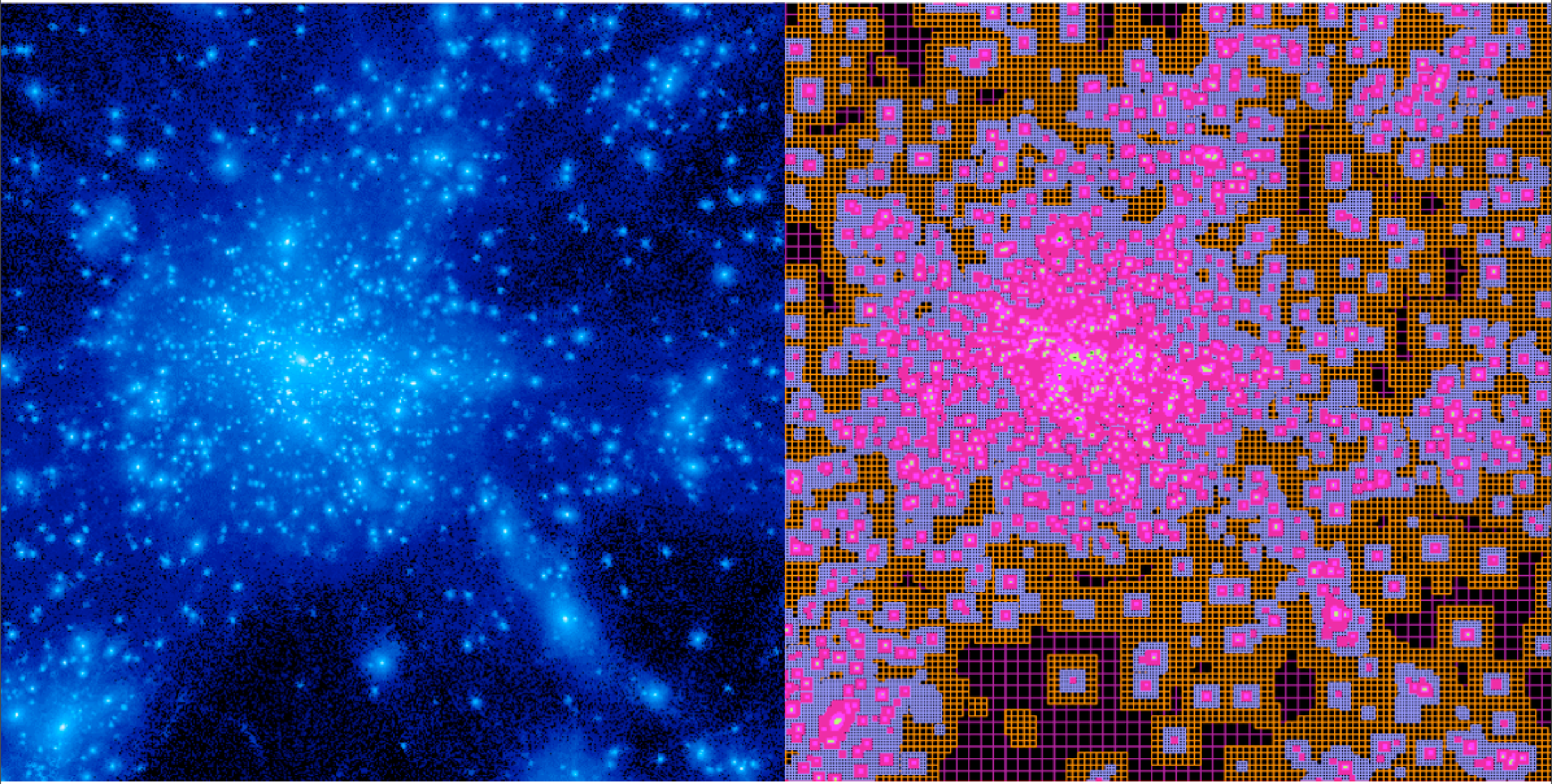
- Changing geometry
- Large dynamic range
- Long-range forces
- Complex astrophysics

Changing Geometry



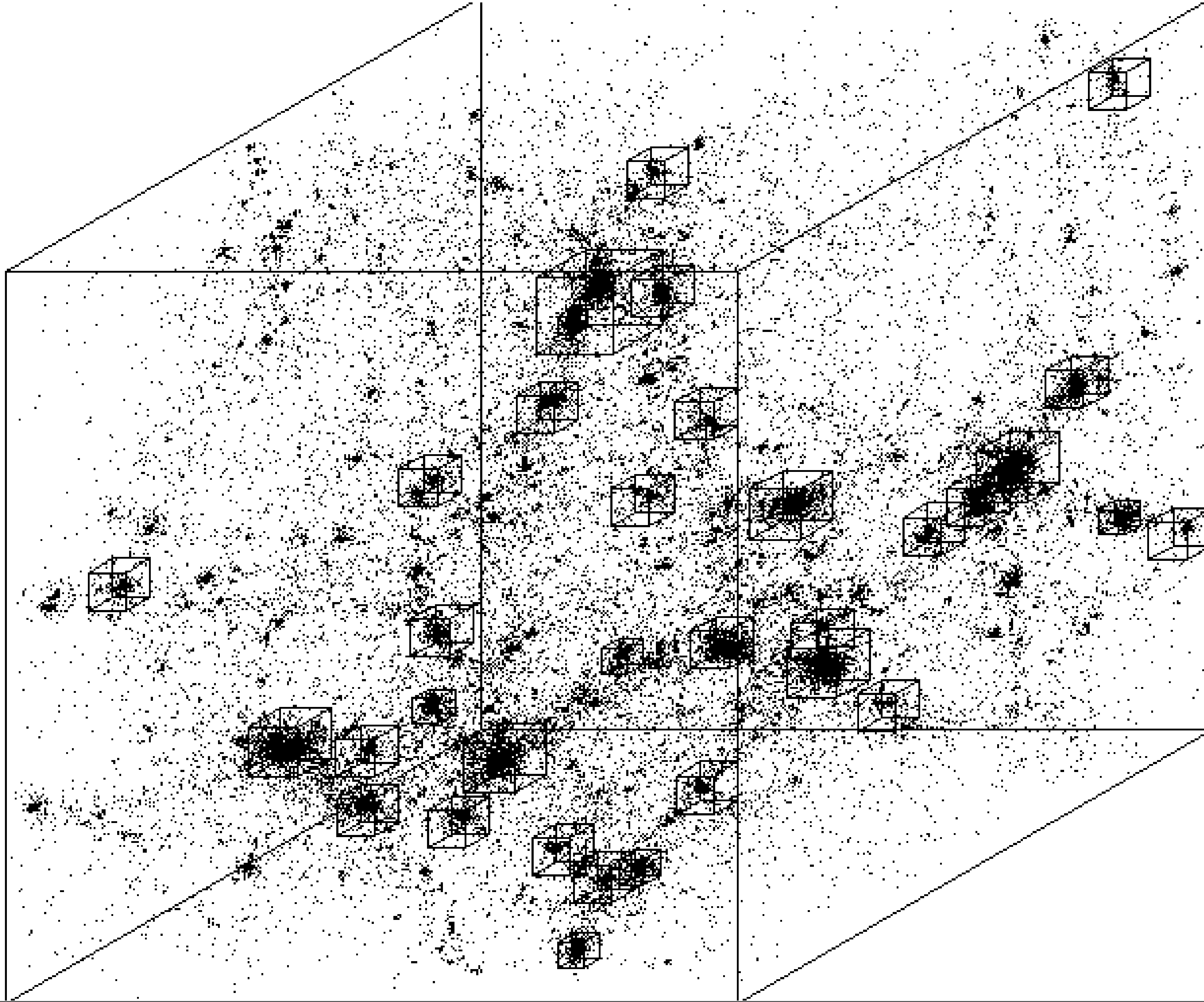
Movie credit: Ben Moore (Zurich)

Adaptive mesh refinement



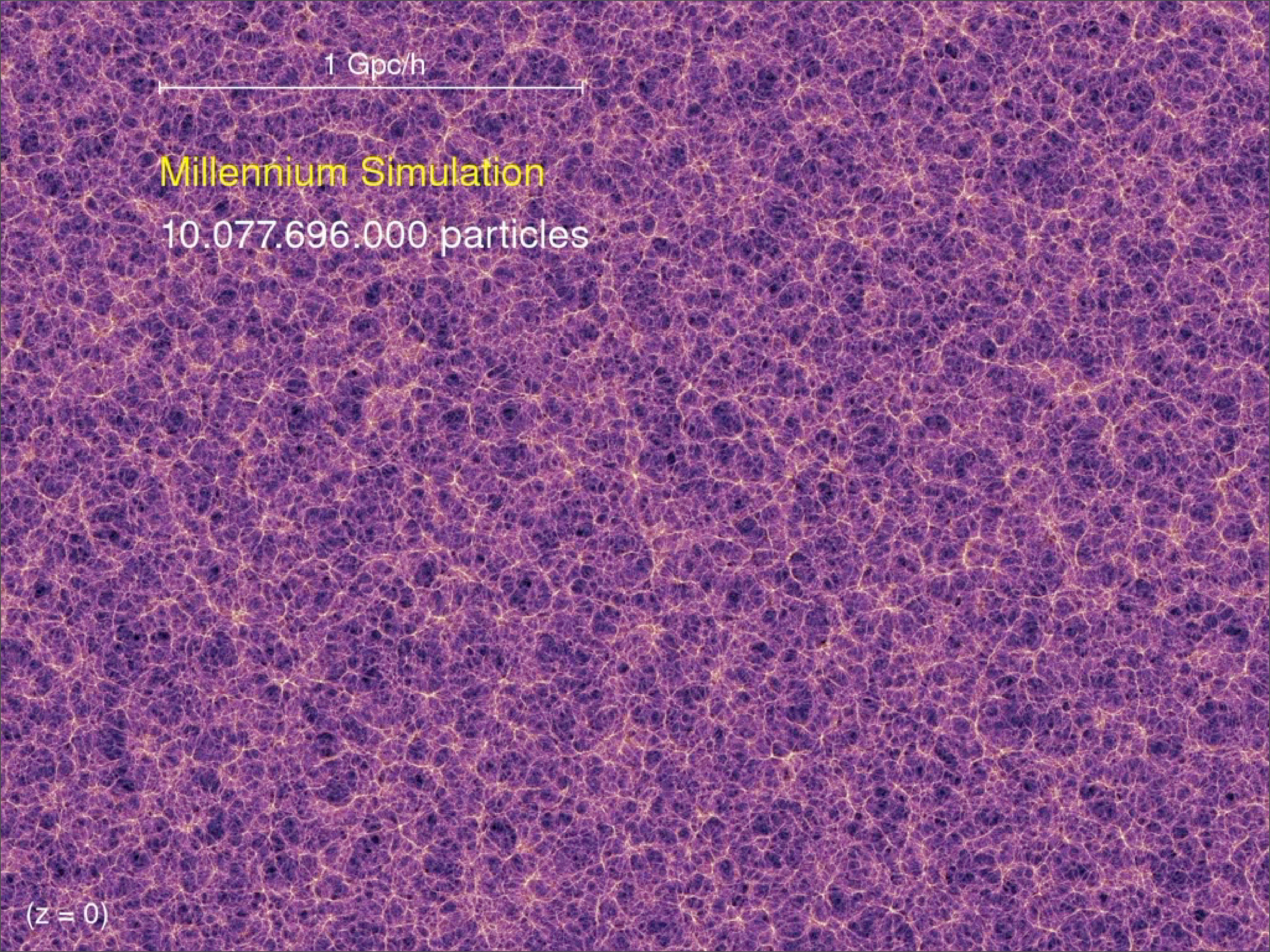
Picture credit: RAMSES code, Romain Teyssier (CEA Saclay)

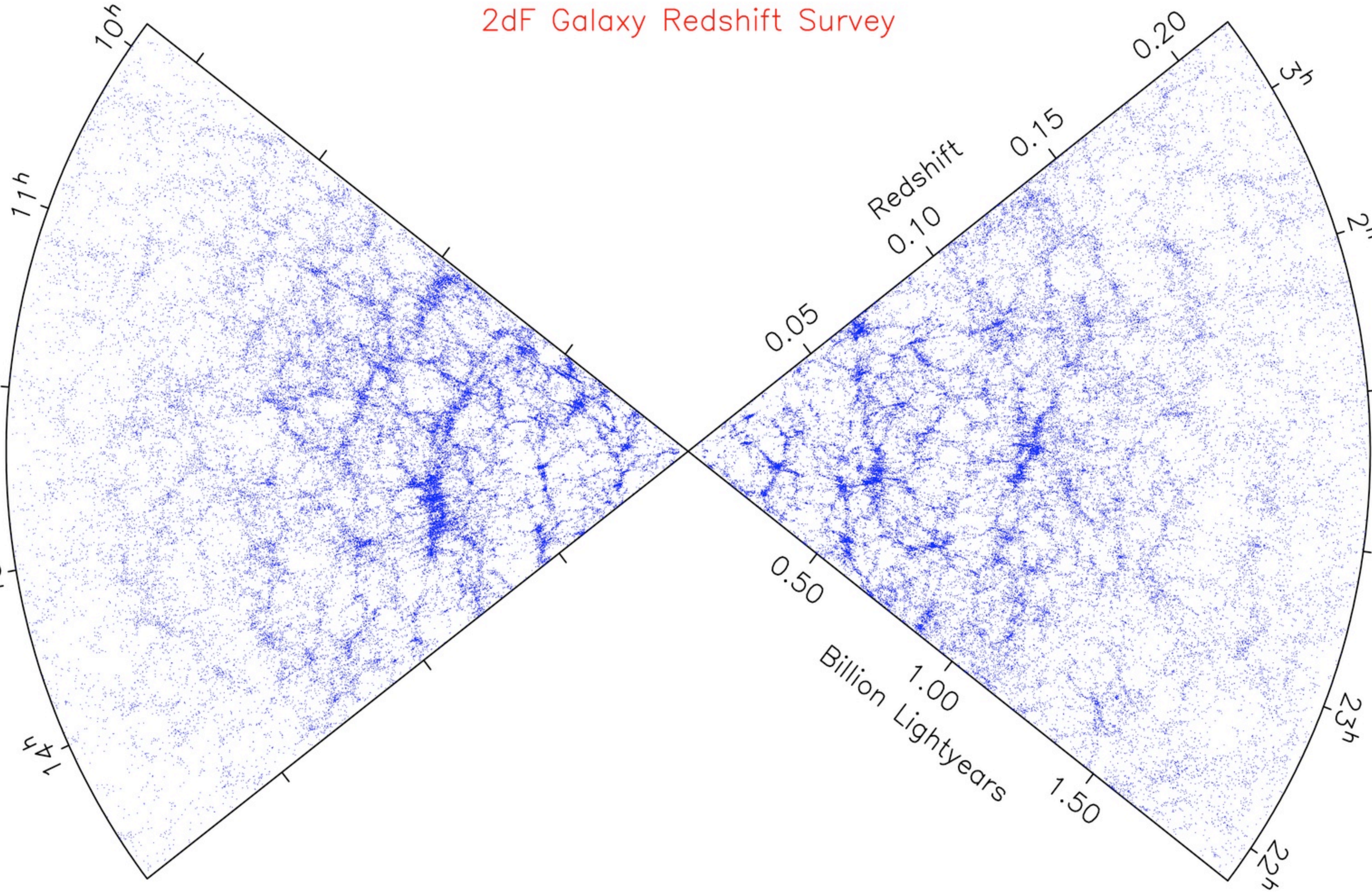
N-body simulations



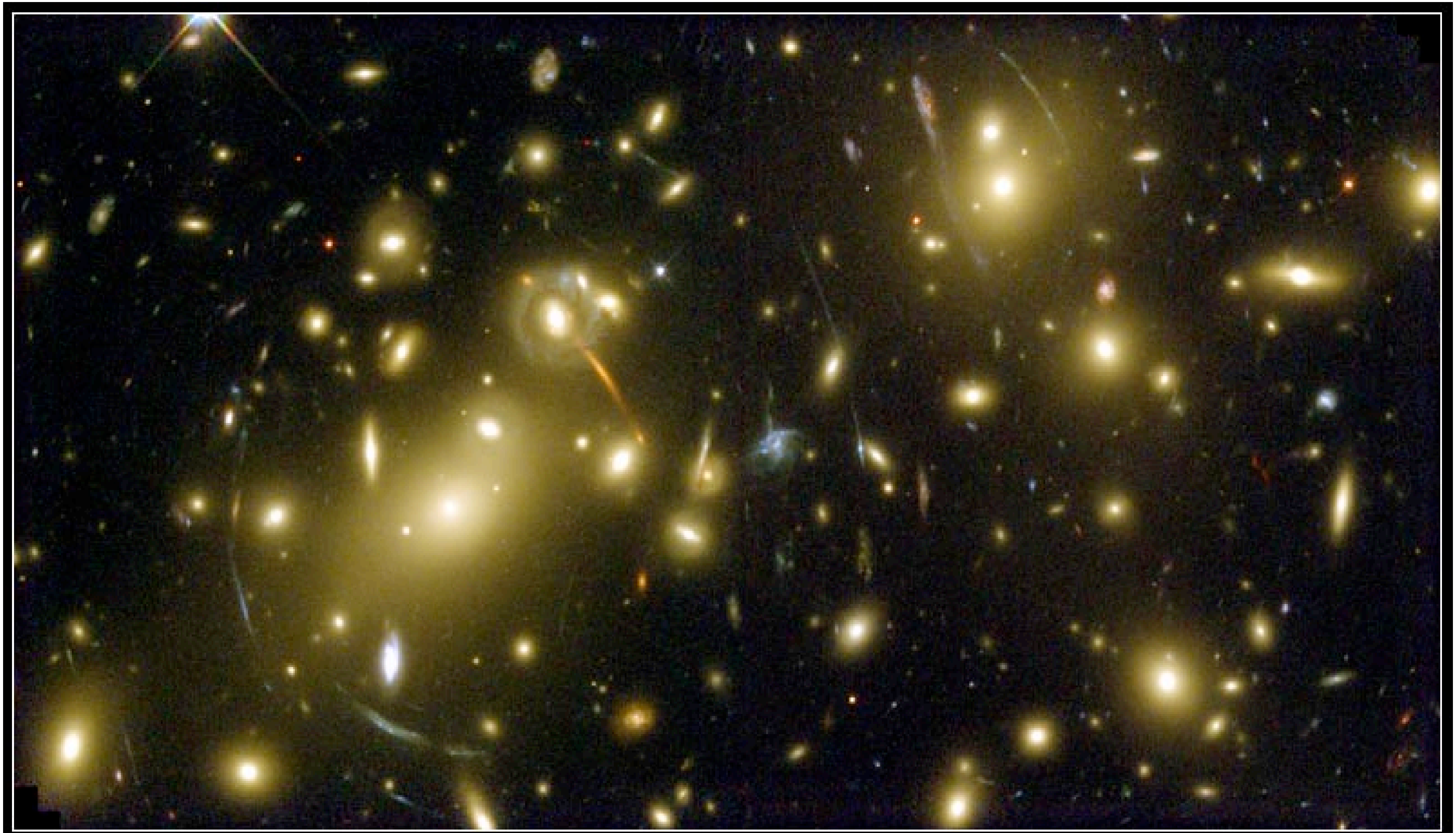
Dynamic range

- Size of the observable Universe: 10 billion light-years (10^{10} lyr)
- Size of large-scale structure: 1 billion light-years (10^{9} lyr)
- Size of a cluster of galaxies: 10 million light-years (10^{7} lyr)
- Size of a galaxy: 10-100 thousand light-years (10^{4-5} lyr)
- Size of a star cluster: 30 light-years ($10^{1.5}$ lyr)
- Size of active galactic nucleus: 3 billion km ($10^{-3.5}$ lyr)
- Size of a star: 10 million km (10^{-7} lyr)


1 Gpc/h
Millennium Simulation
10.077.696.000 particles
(z = 0)



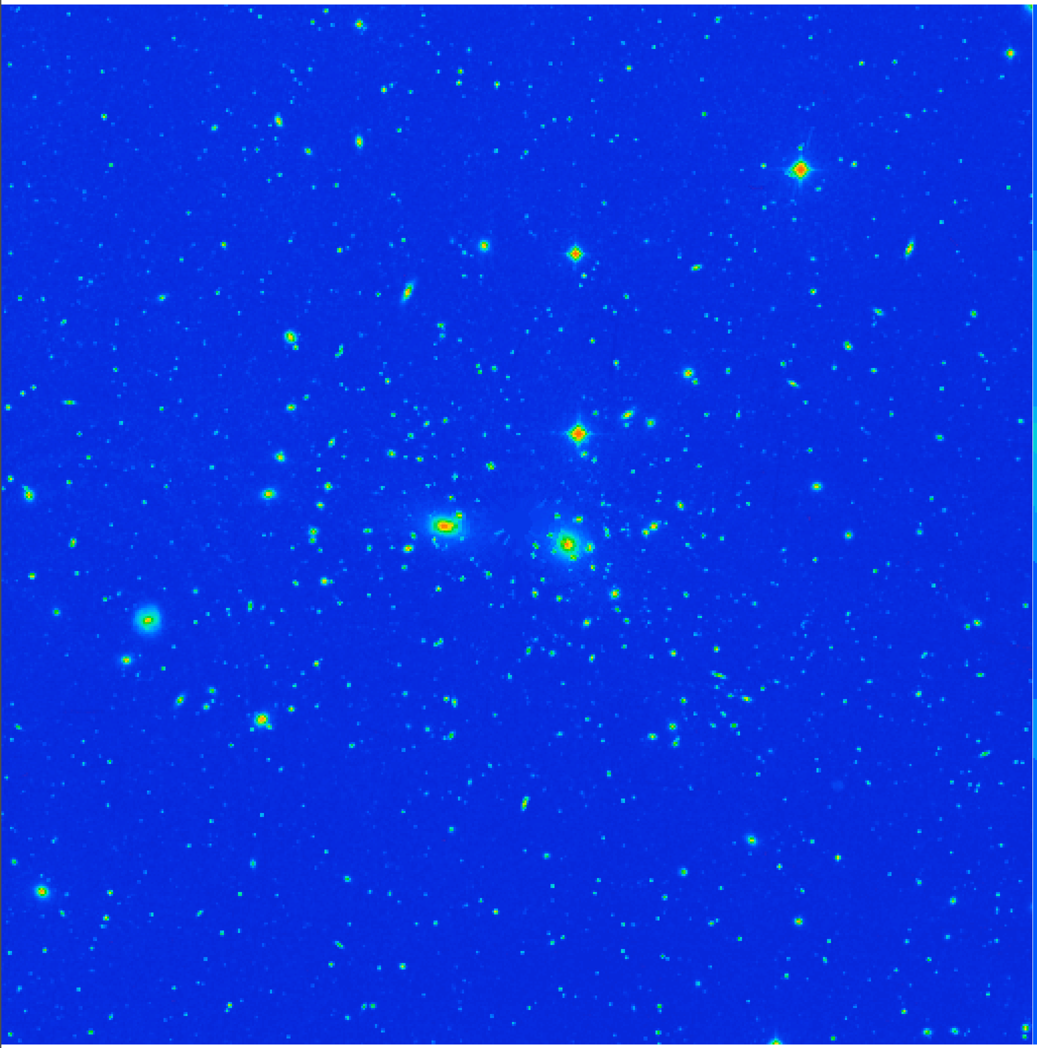
2dF Galaxy Redshift Survey
10h
11h
12h
13h
14h
3h
2h
1h
0h
23h
22h
Redshift
0.05
0.10
0.15
0.20
Billion Lightyears
0.50
1.00
1.50

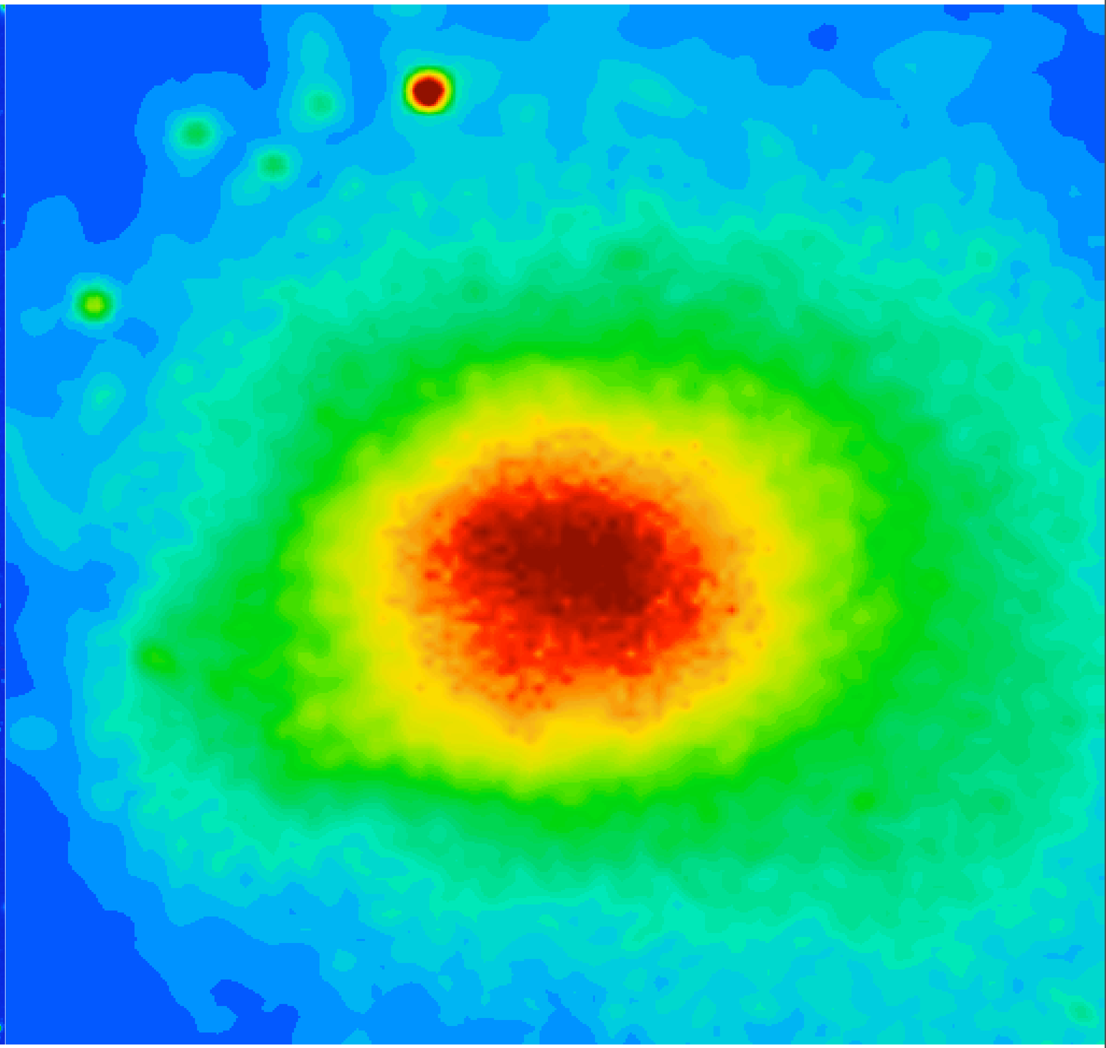


Galaxy Cluster Abell 2218 **HST • WFPC2**

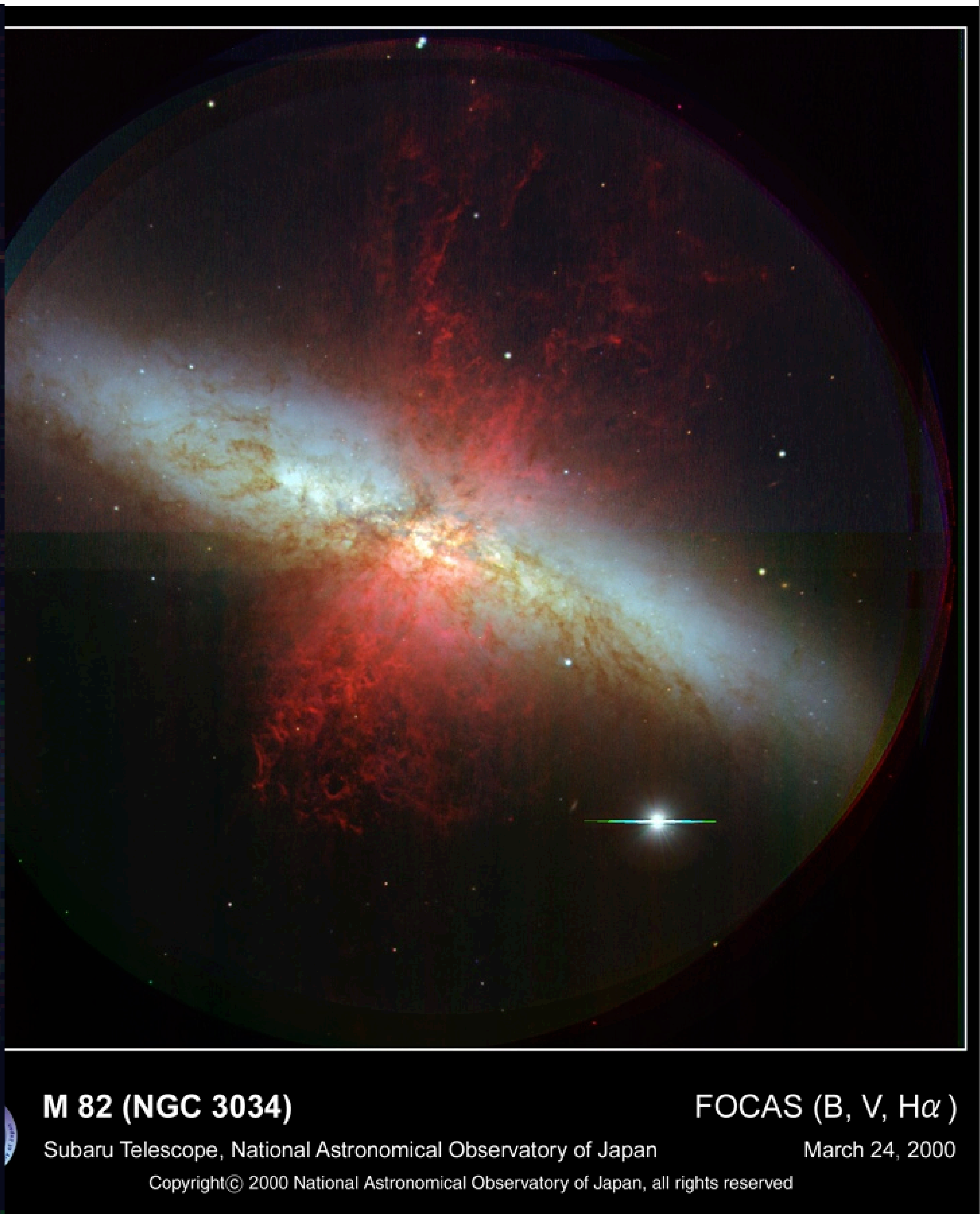
NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

Coma cluster





Galaxies


M 82 (NGC 3034)
FOCAS (B, V, Hα)
Subaru Telescope, National Astronomical Observatory of Japan
March 24, 2000
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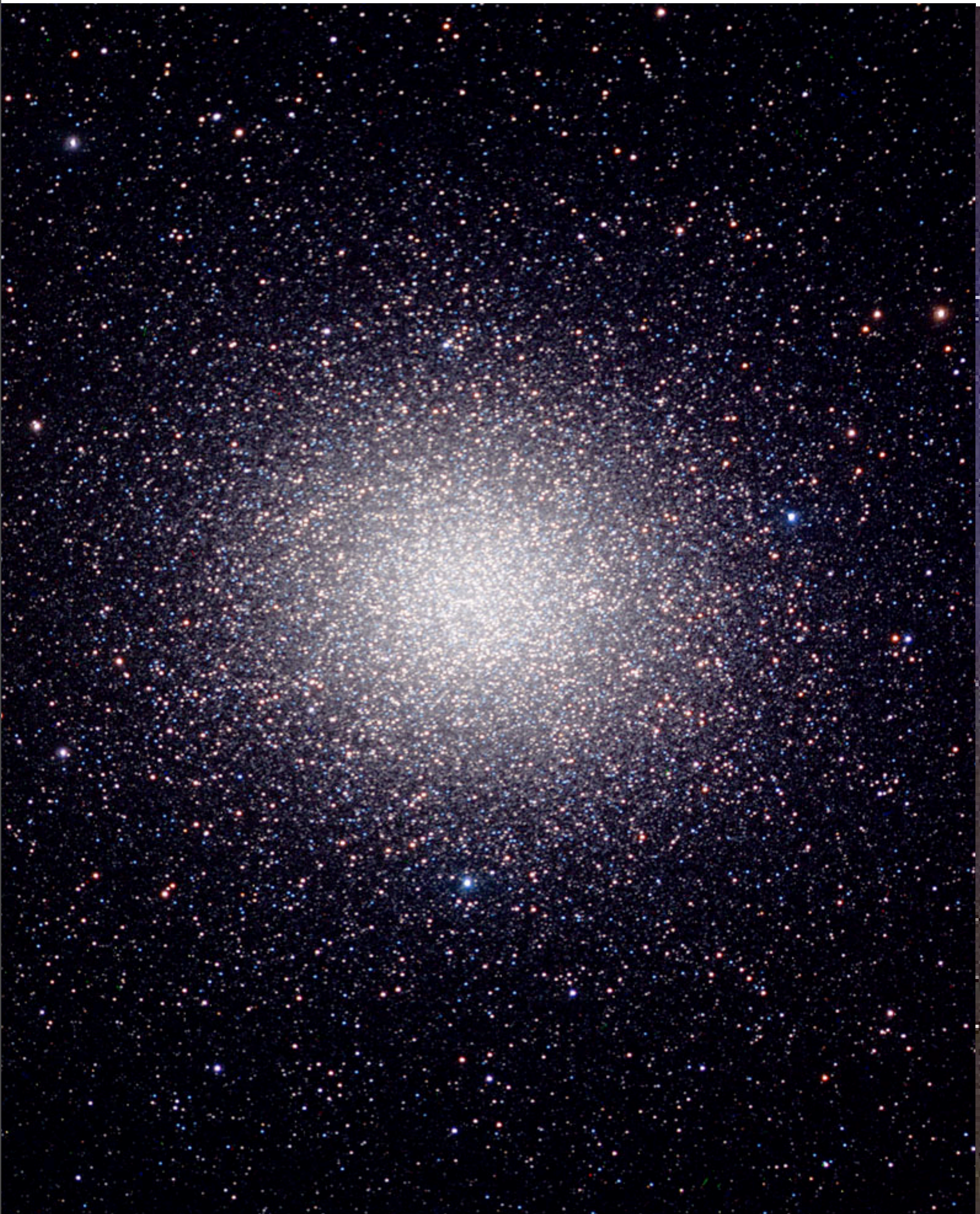
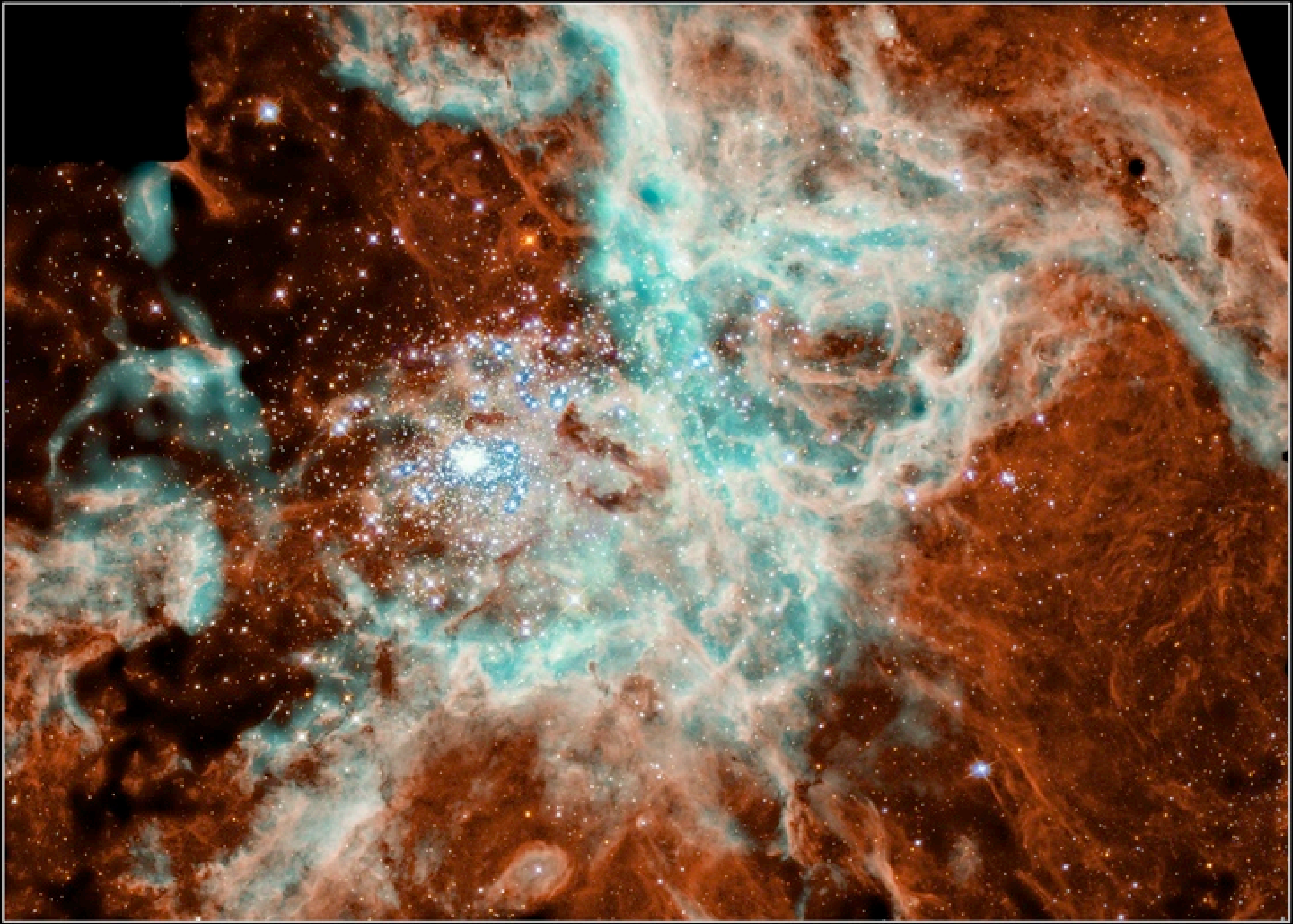
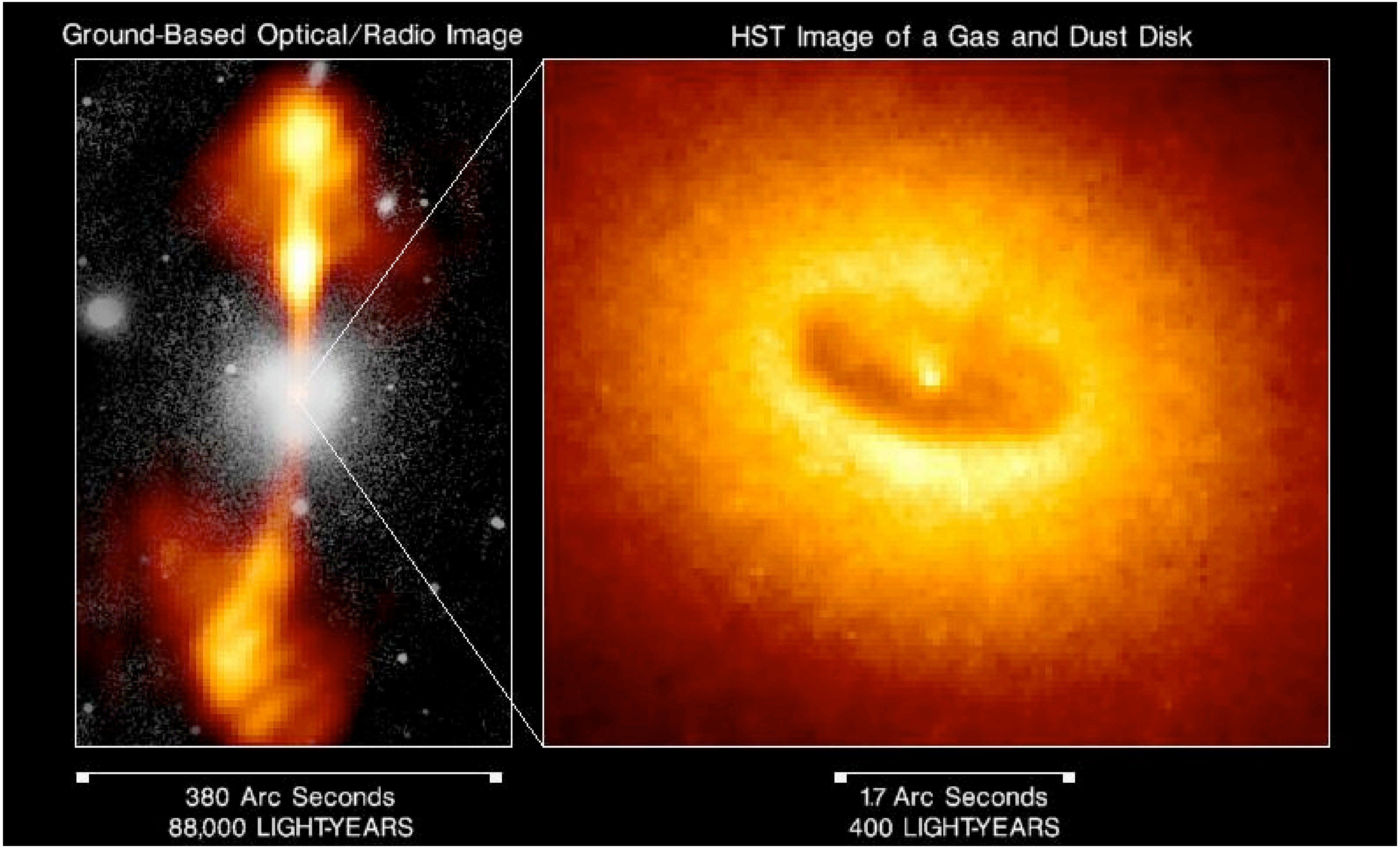
Star clusters



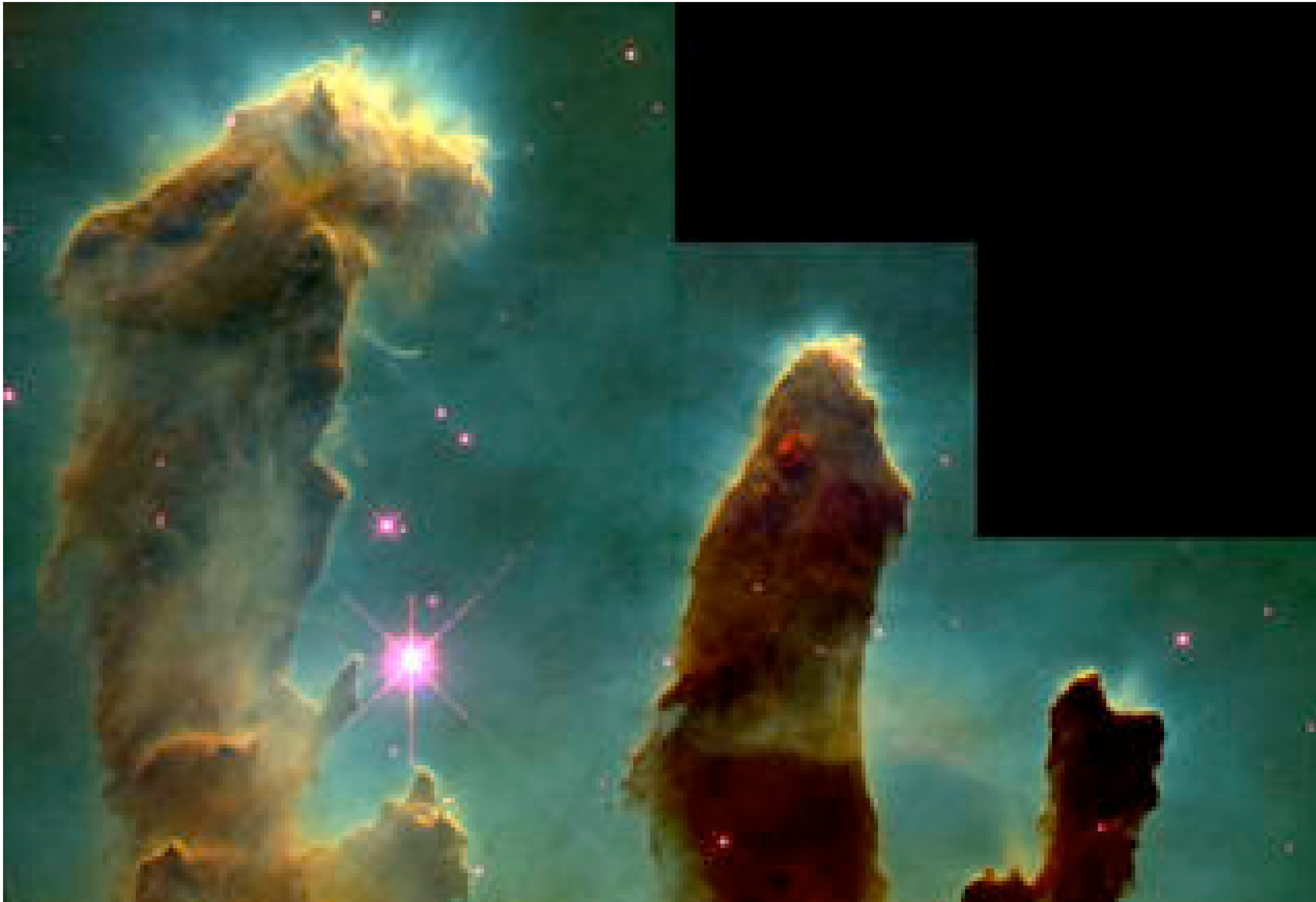


30 Doradus in the Large Magellanic Cloud
Hubble Space Telescope • WFPC2

Active galactic nucleus



Star-forming regions



Planetary nebulae

Supernovae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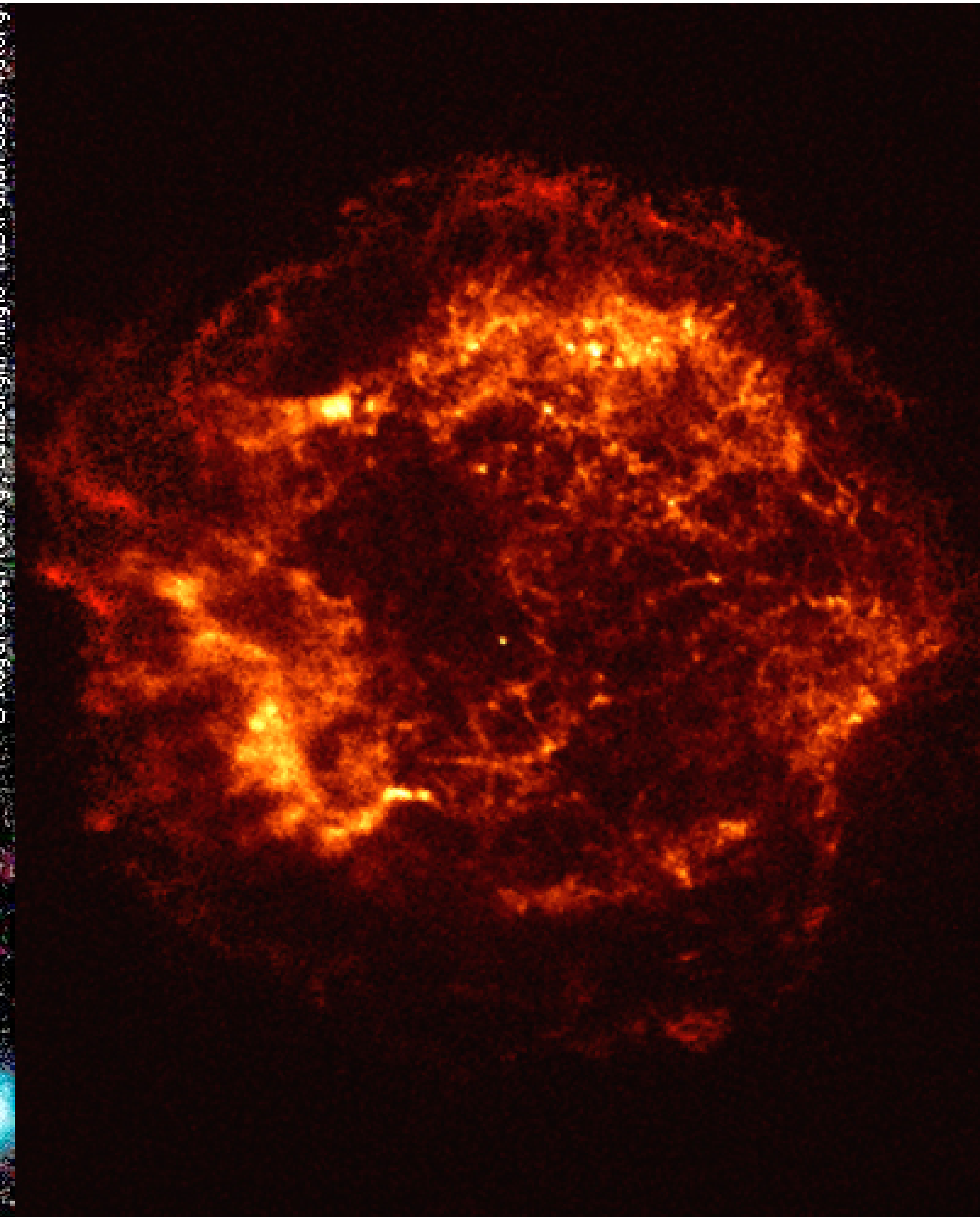


Gravity

- Einstein's equation

$$G_{ab} = \frac{8\pi G}{c^4} T_{ab}$$

- Newton's equation

$$\ddot{r}_i = \sum_j \frac{G m_j (r_j - r_i)}{|r_j - r_i|^3}$$

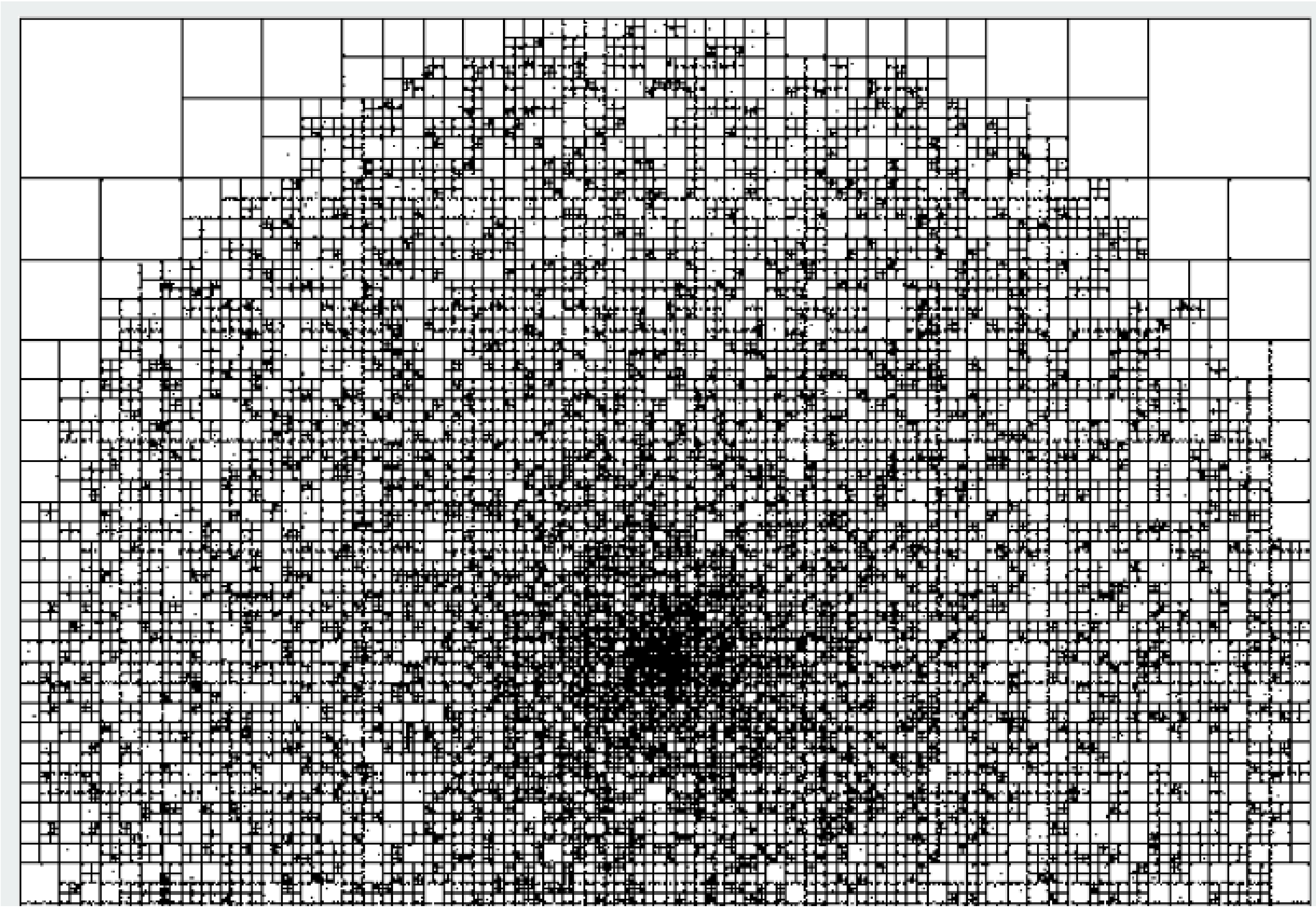
Gravitational N-body methods

- Direct summation: specialised hardware and/or low-N.
- Tree codes: approximate force at large separations.
- Particle mesh (PM) codes: smooth particles onto a grid and use Fast Fourier Transforms (FFT) to solve Poisson equation.
- Particle-particle, particle-mesh (PPPM): combines FFT with direct summation on small scales.
- PM-Tree: combines FFT with a tree on small scales.

Moore's law for cosmological N-body simulations

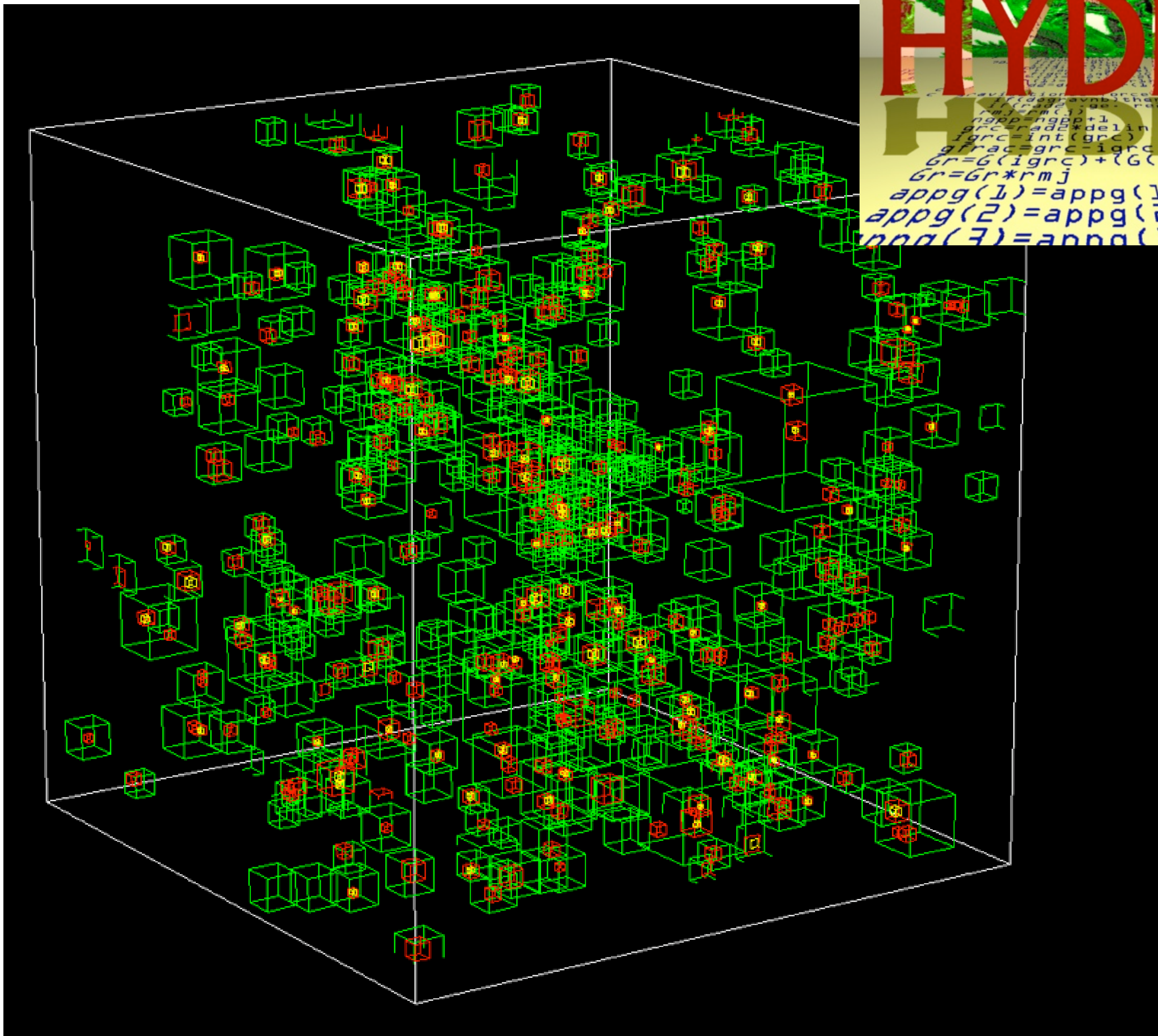
Grape 6a

Tree codes

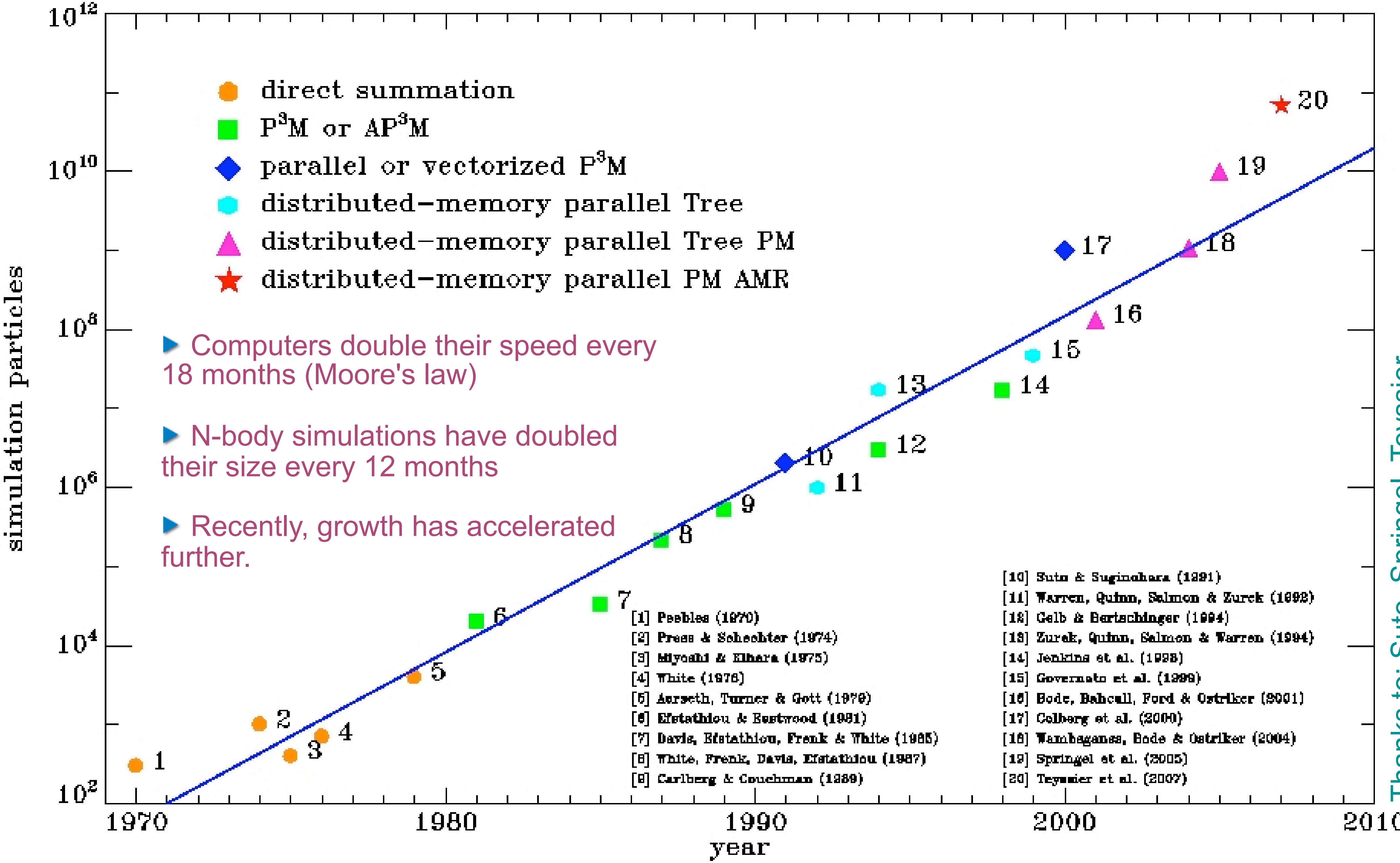


Warren & Salmon

Adaptive P^3M



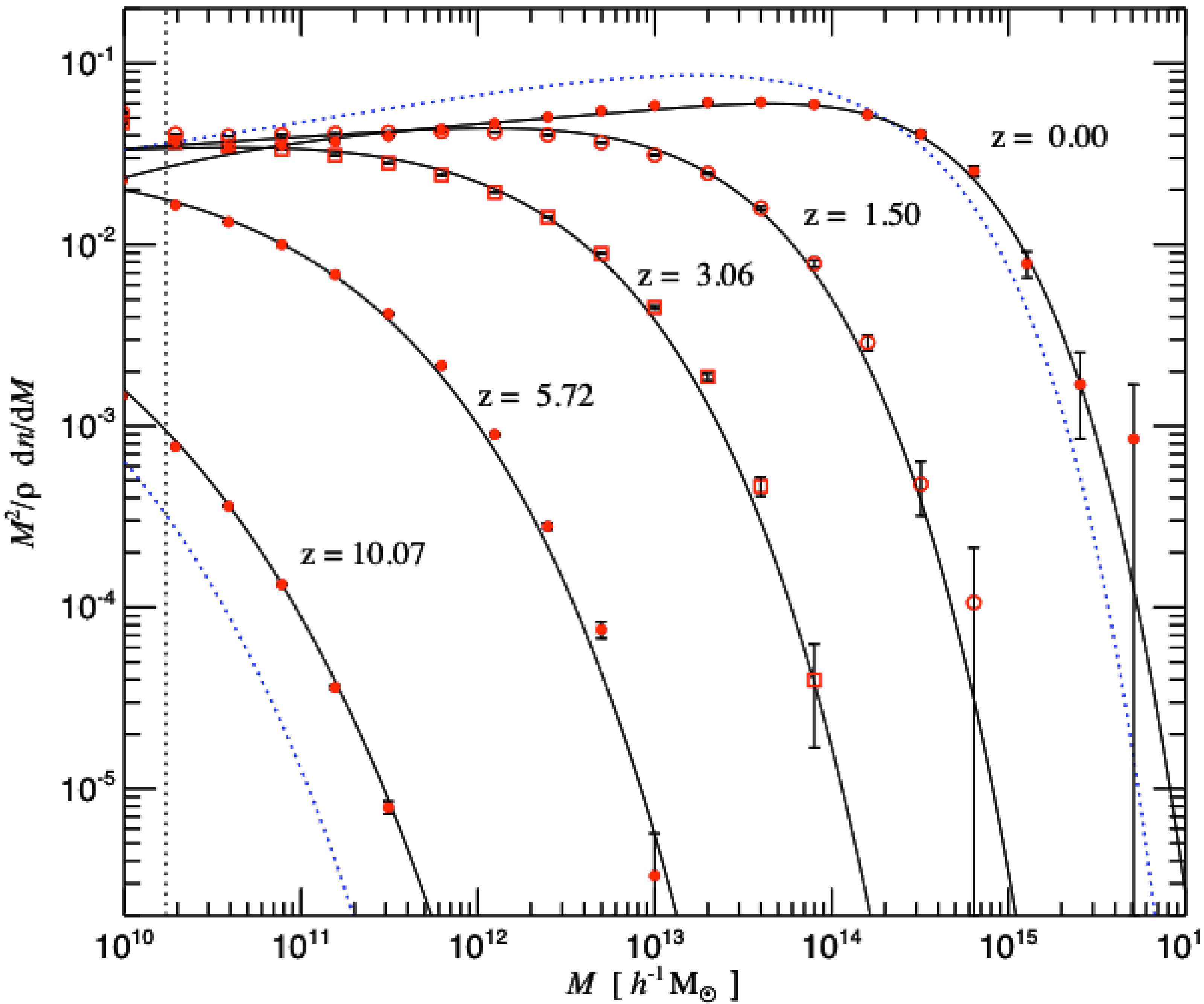
Moore's Law for cosmological N-body simulations



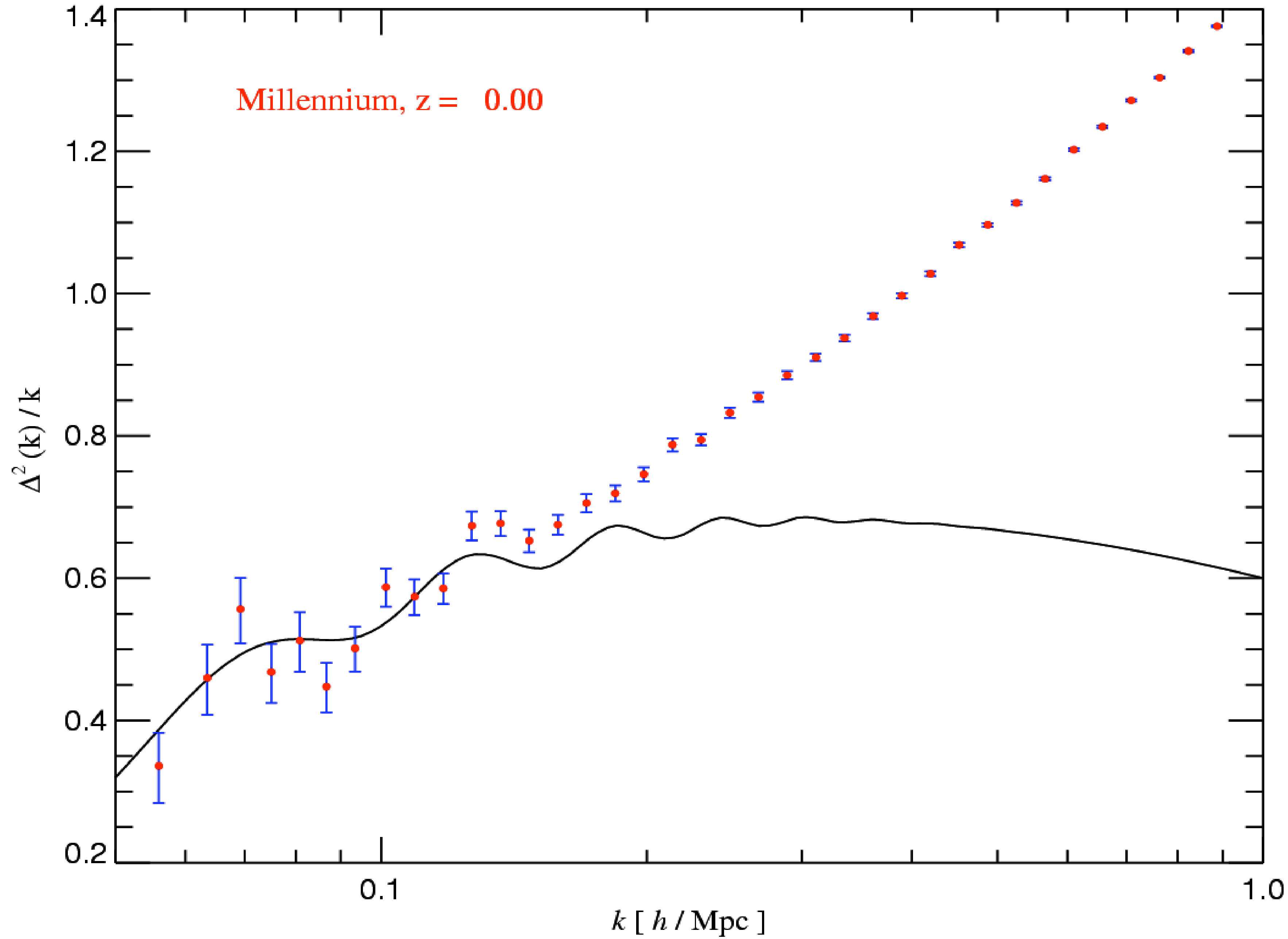
- Computers double their speed every 18 months (Moore's law)
- N-body simulations have doubled their size every 12 months
- Recently, growth has accelerated further.

Thanks to: Suto, Springel, Teyssier

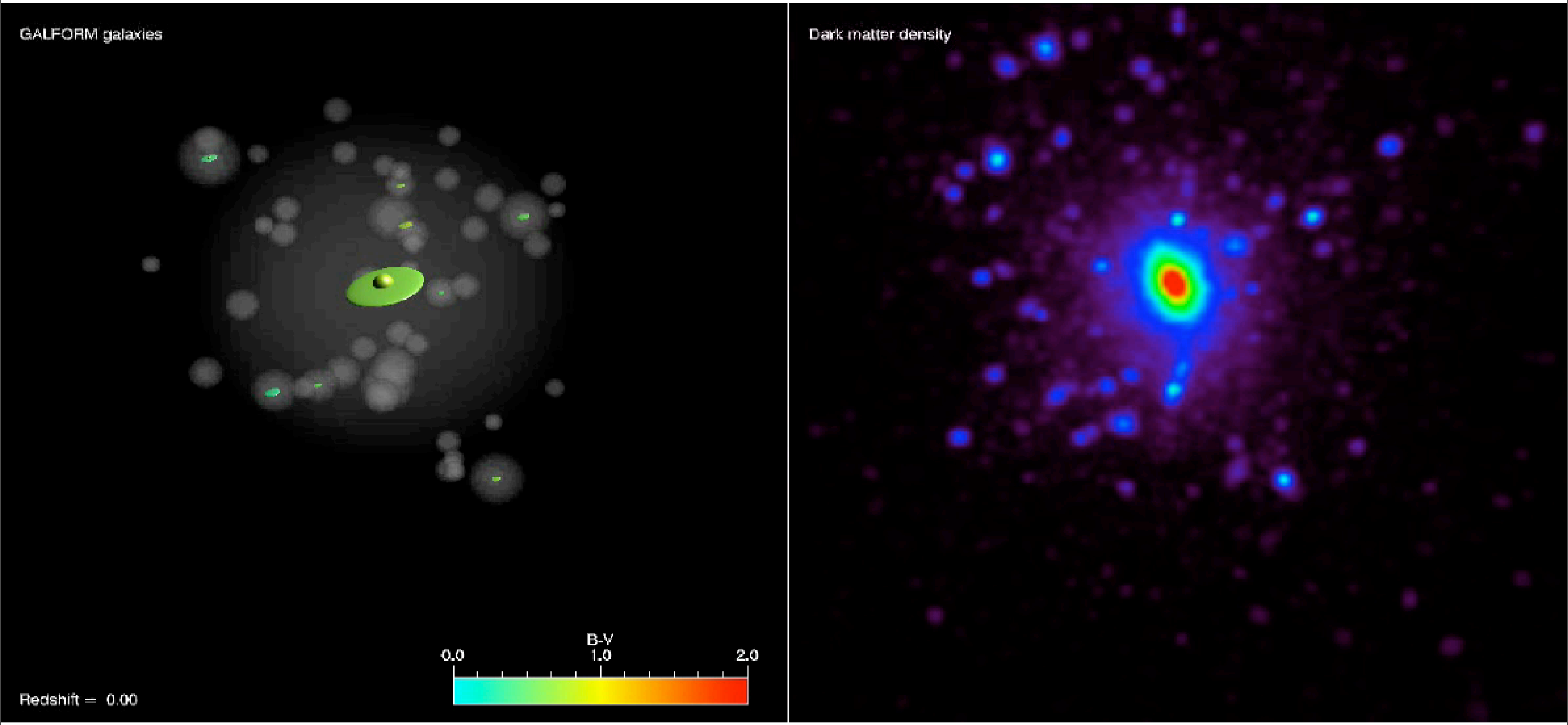
Mass function of halos



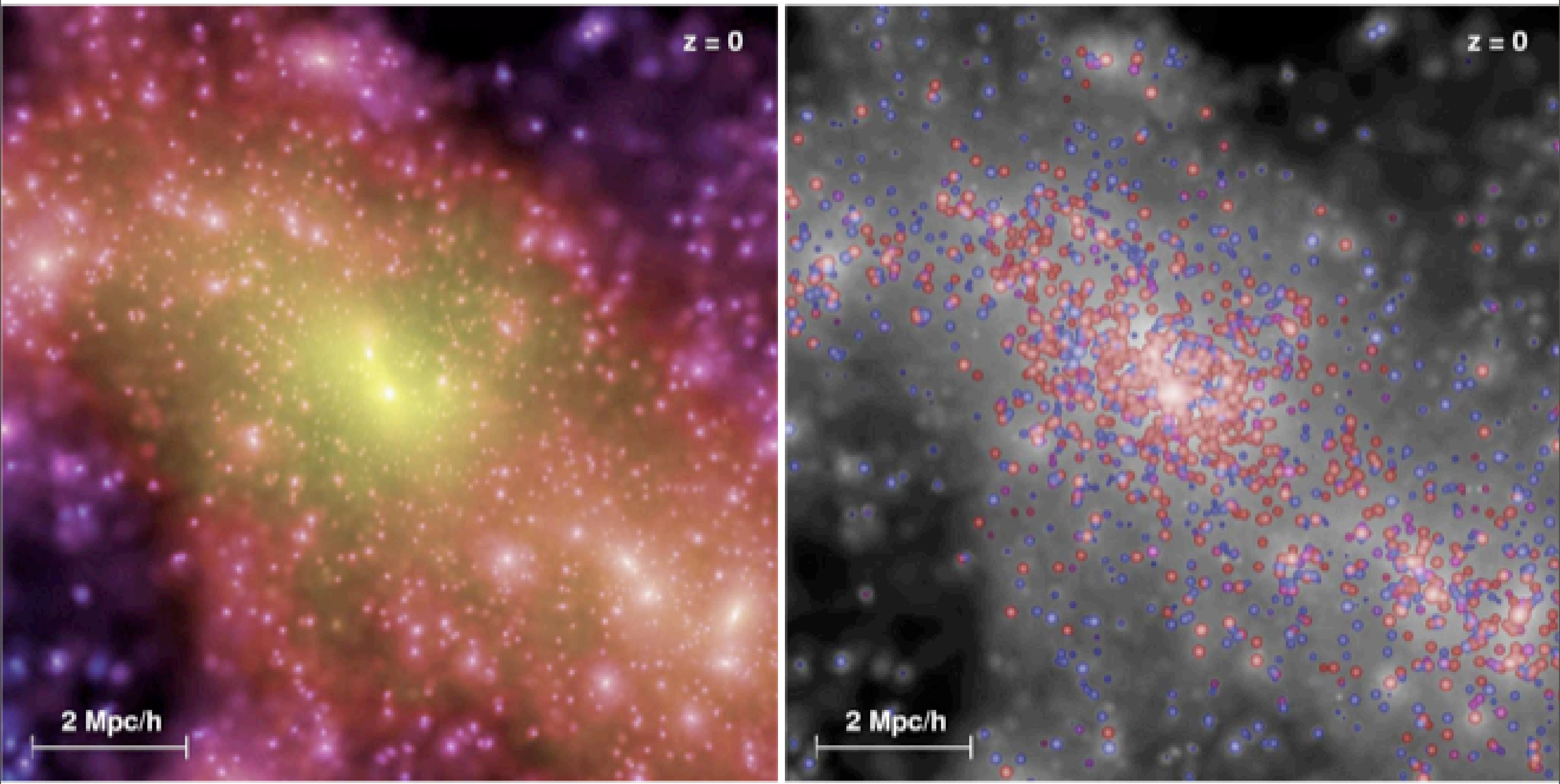
Baryon oscillations



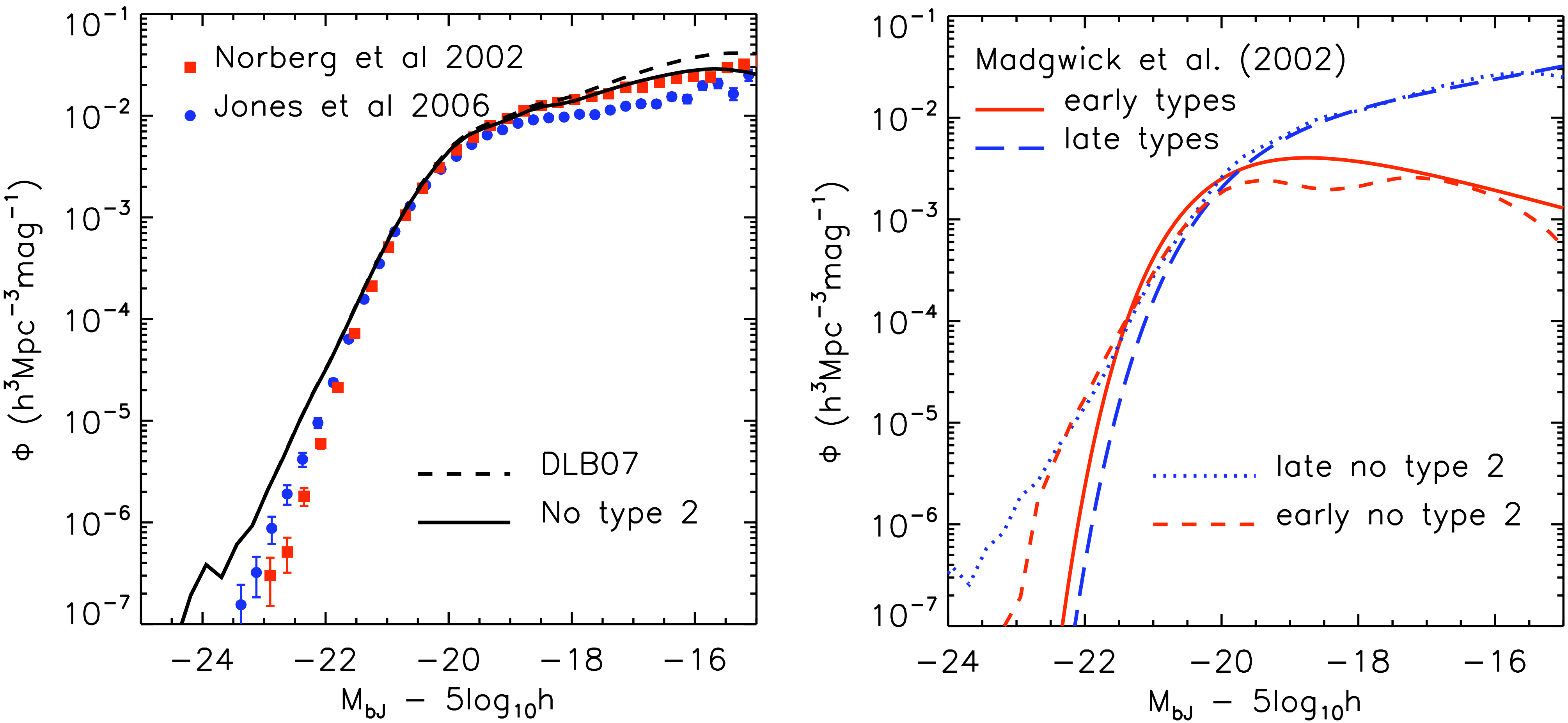
Semi-analytic models



Galaxies in the Millennium Simulation



Luminosity functions of galaxies

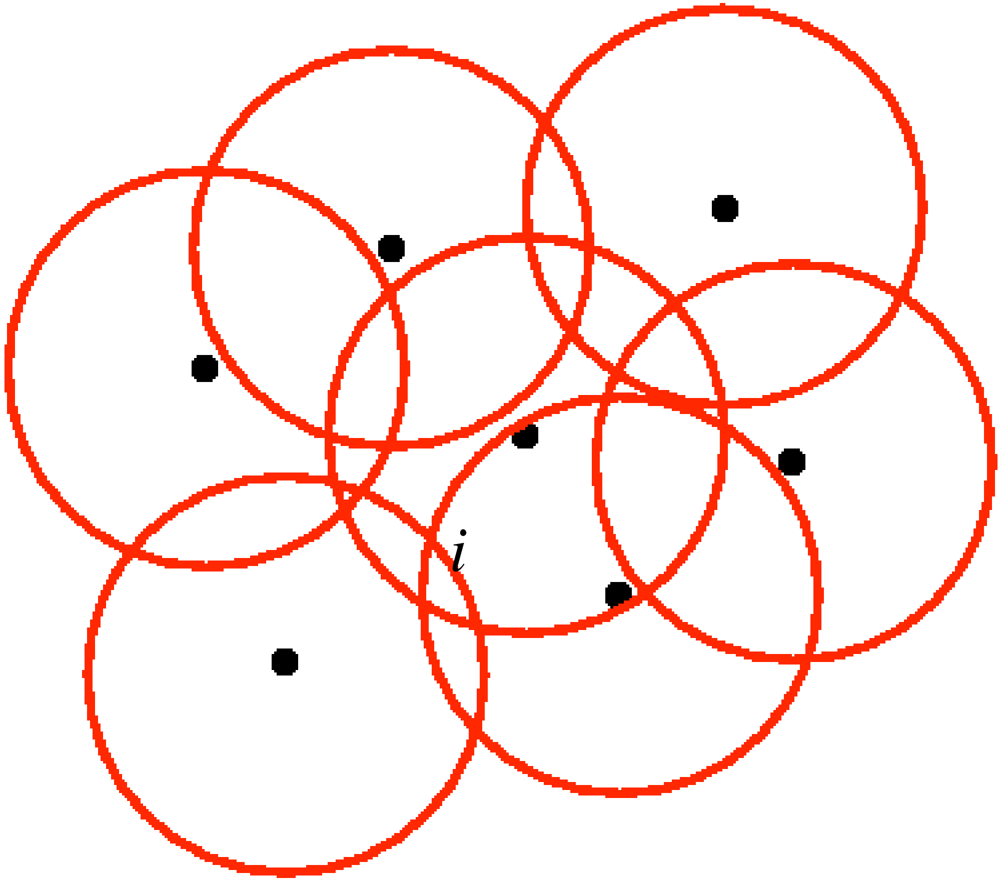


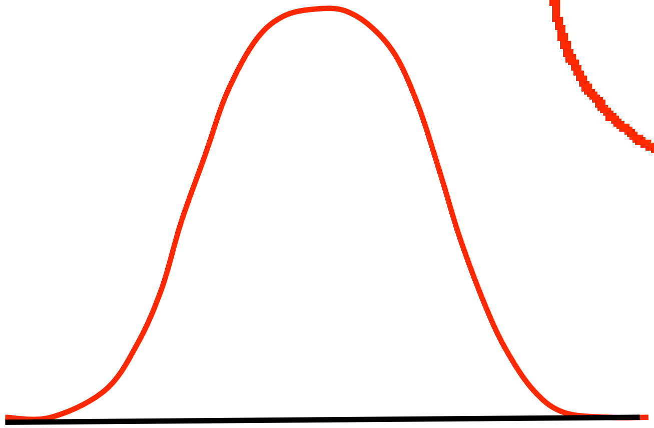
Smoothed particle hydrodynamics

$$\langle A(r)\rangle = \int A(r')W(r'-r)\,\mathrm{d}V$$

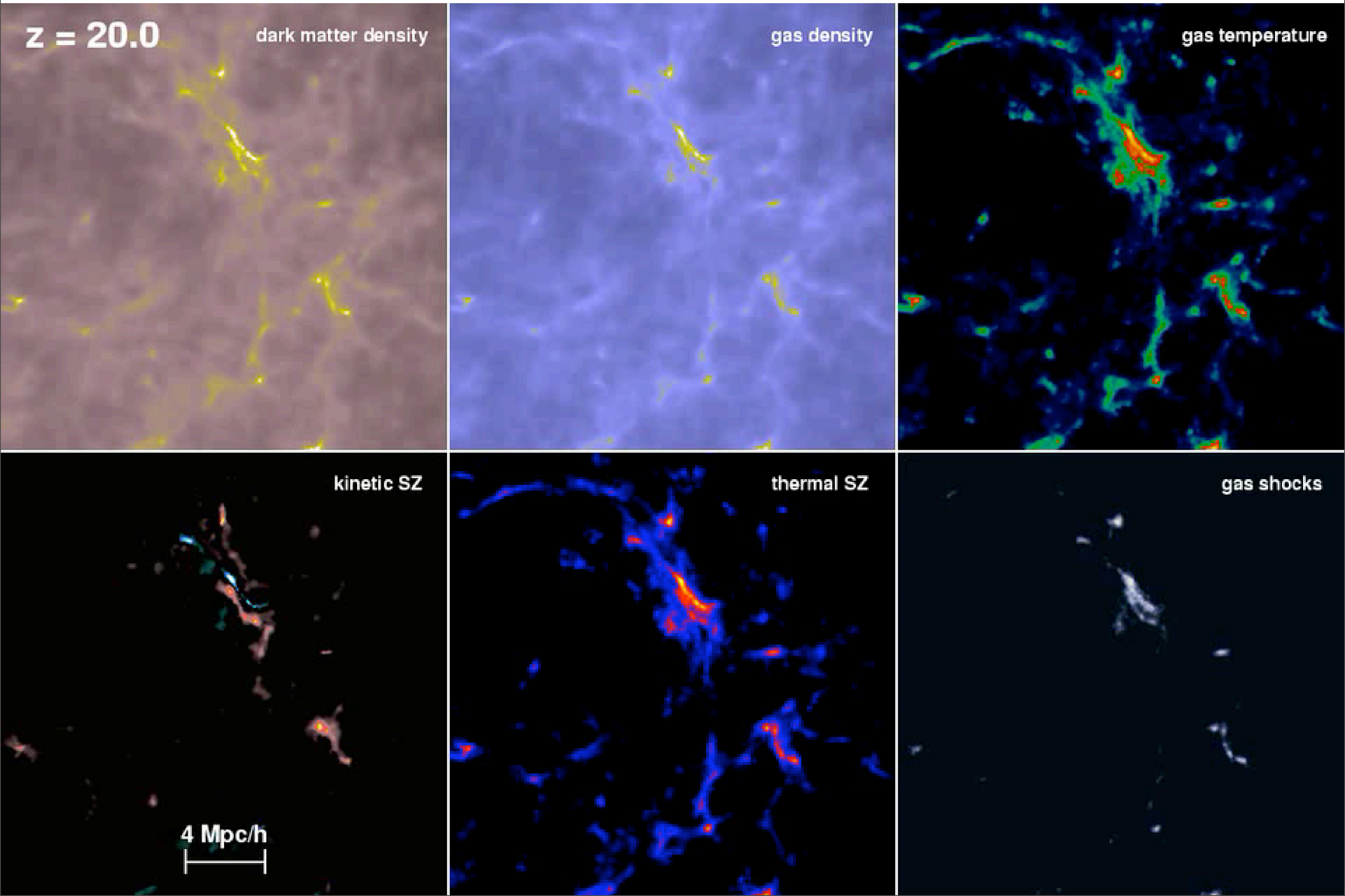
$$\langle A_i\rangle = \sum_j A_j W_{ij} \frac{m_j}{\rho_j}$$

$$\langle \rho_i\rangle = \sum_j W_{ij} m_j$$

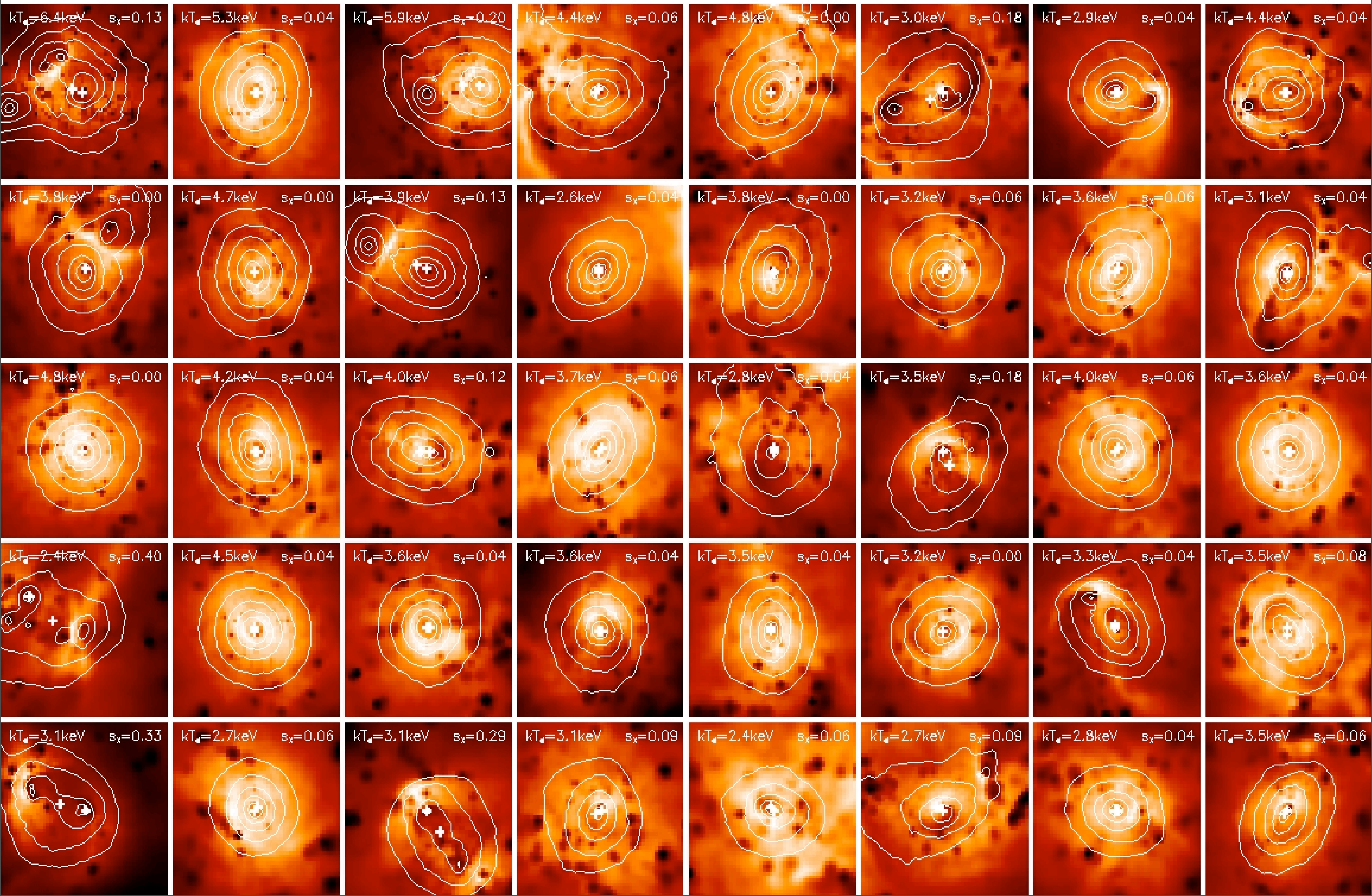




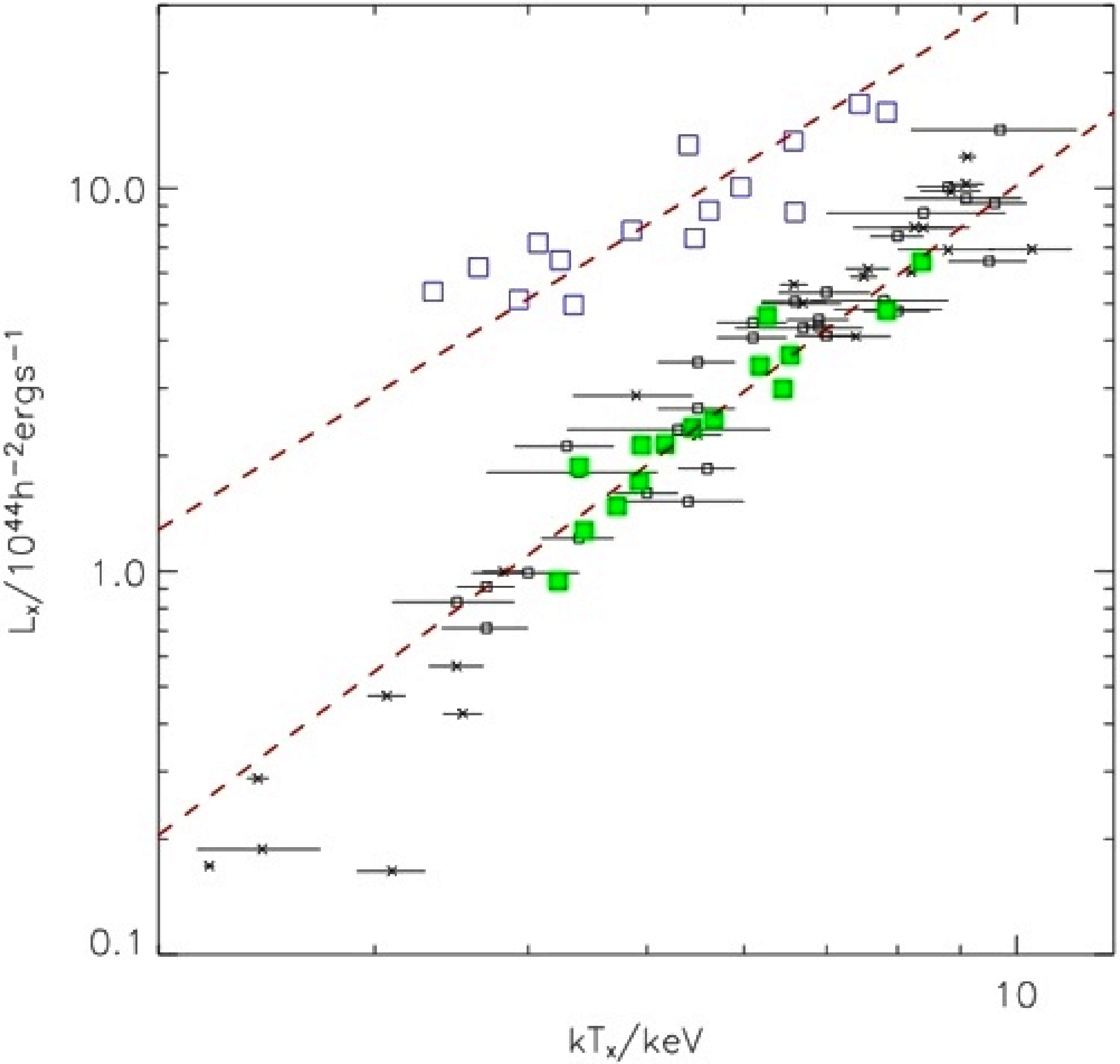
Simulation of a cluster of galaxies with SPH



Simulated cluster catalogues



Luminosity-temperature relation for clusters



The main astrophysical and physical processes to be modelled

- Astrophysical
  - Star-formation, including the first stars
  - Supernova remnants
  - Galaxies, the interstellar medium, galactic super-winds
  - Active galactic nuclei: quasars and radio galaxies
  - The intracluster and intergalactic media, reionization of the Universe
- Physical
  - Atomic and molecular cooling
  - Magnetic fields
  - Cosmic rays (relativistic particles)
  - Radiative transfer

Summary

- The physics of structure formation in the Universe occurs over an enormous range of scales. To model it requires large super-computer simulations.
- The rapidly-changing geometry and long-range forces require special numerical techniques.
- Complex astrophysics on small scales can have a significant impact on the evolution of large-scale structures.