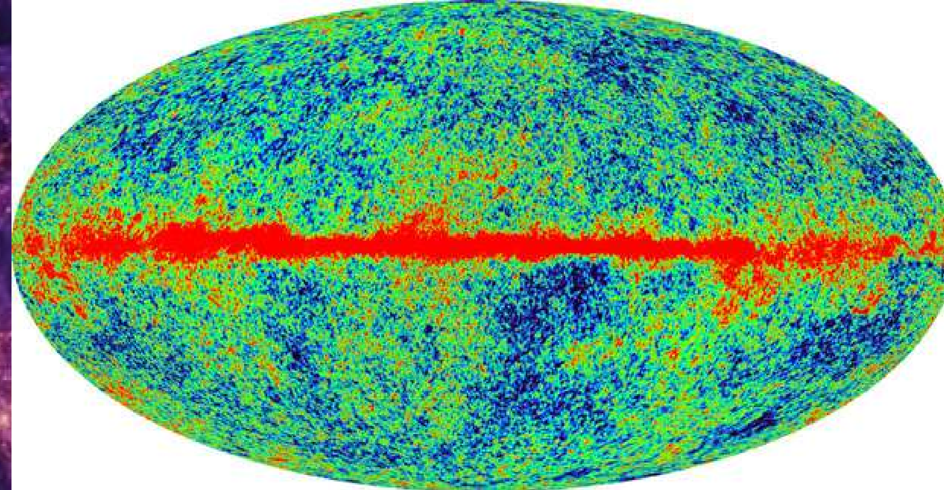
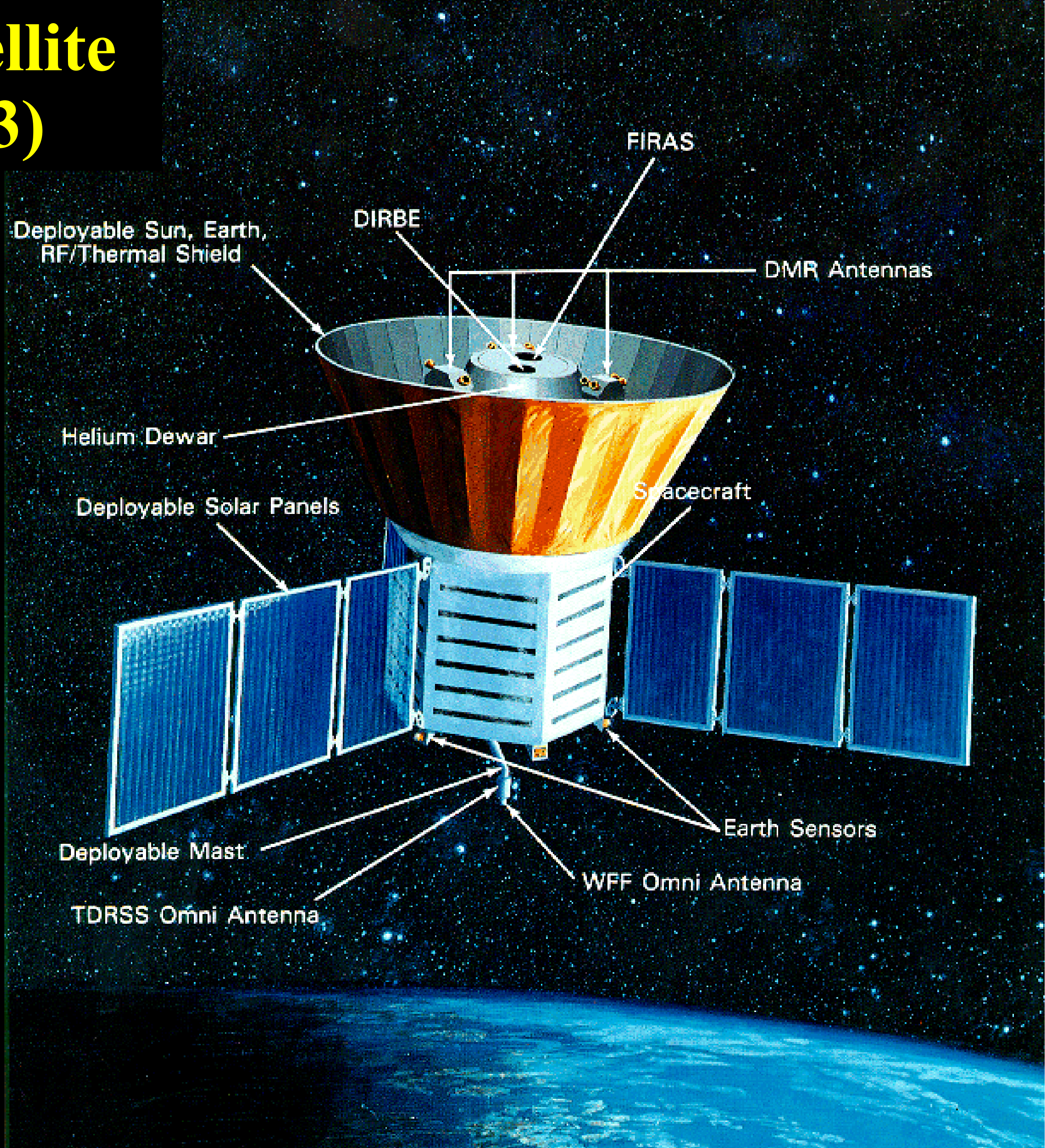


The Millennium Simulation: cosmic evolution in a supercomputer

Simon White
Max Planck Institute for Astrophysics

The COBE satellite (1989 - 1993)

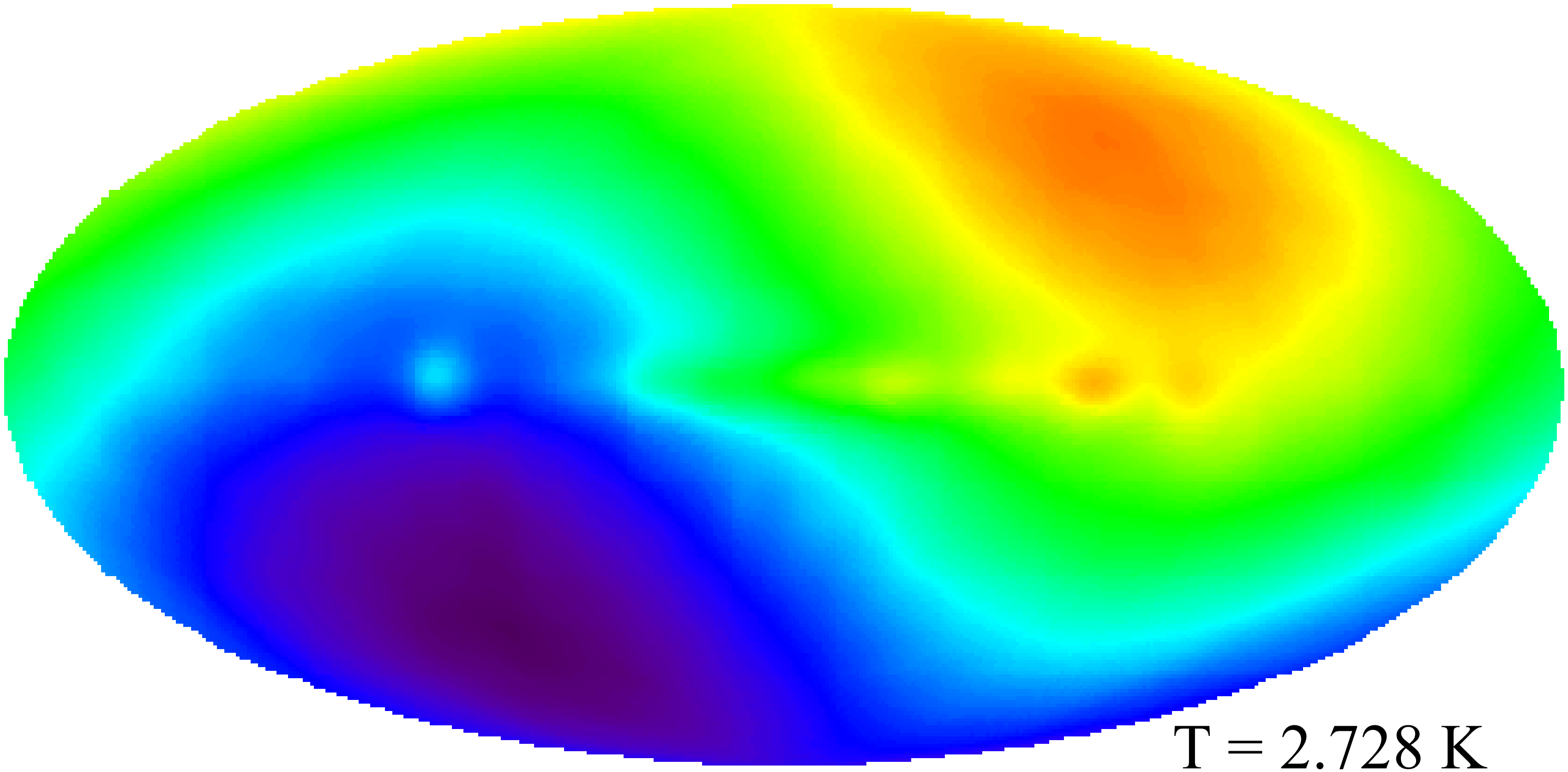
- Two instruments made maps of the whole sky in microwaves and in infrared radiation
- One instrument took a precise spectrum of the sky in microwaves



COBE's temperature map of the entire sky

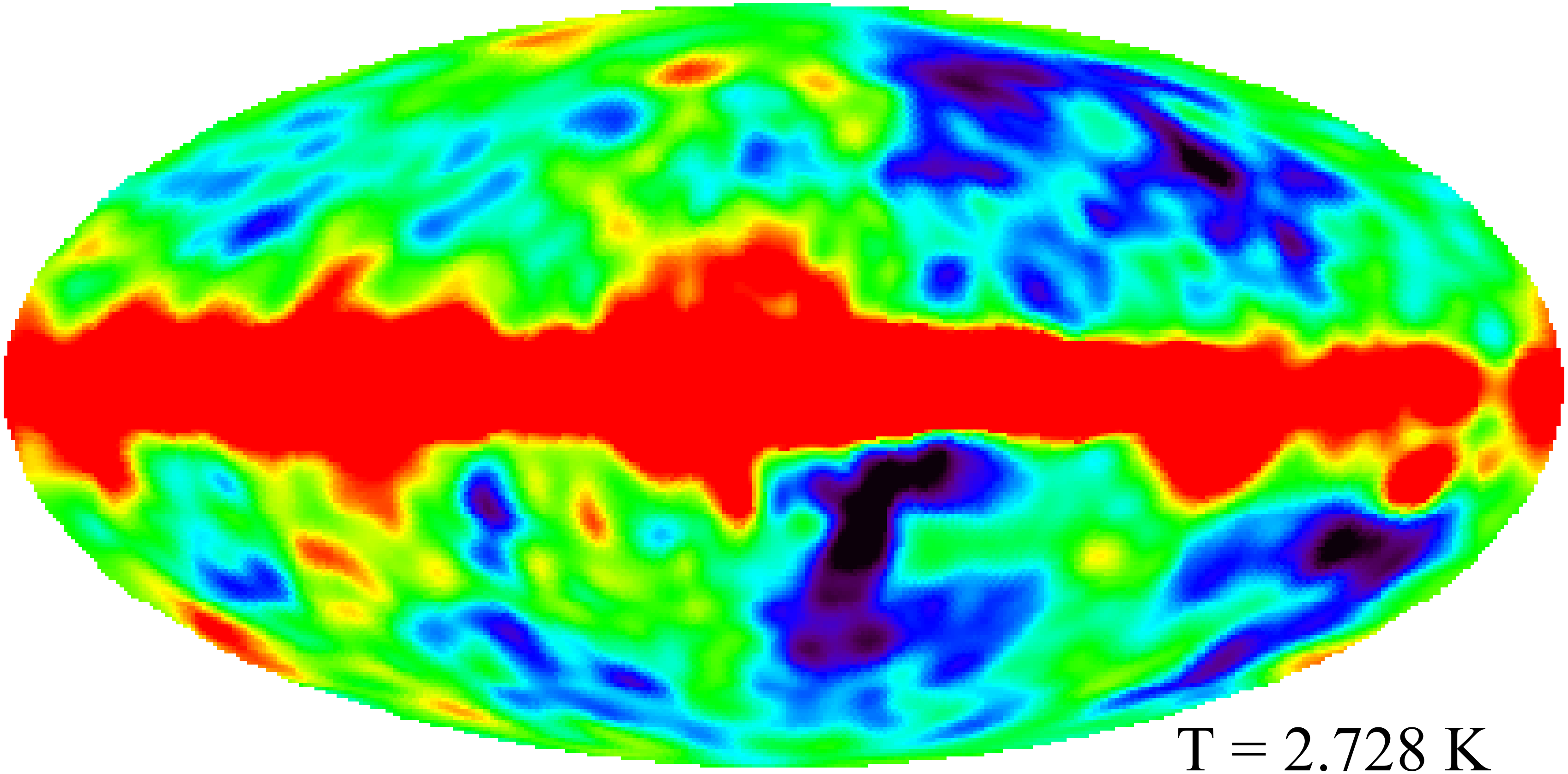
T = 2.728 K
ΔT = 0.1 K

COBE's temperature map of the entire sky



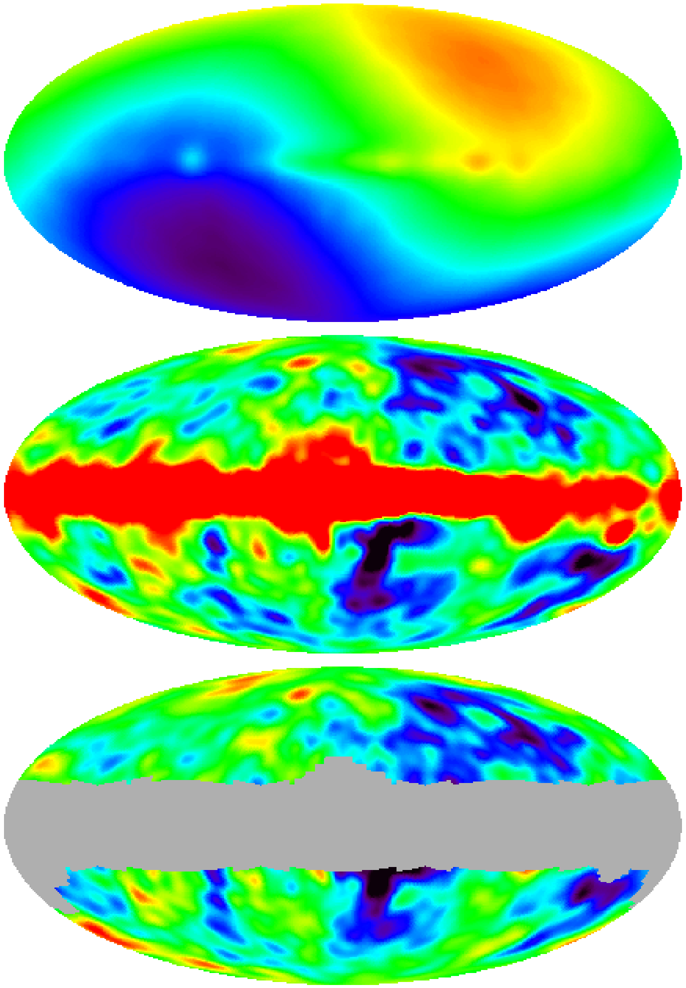
T = 2.728 K
ΔT = 0.0034 K

COBE's temperature map of the entire sky



$T = 2.728$ K
$\Delta T = 0.00002$ K

Structure in the COBE map



- One side of the sky is `hot', the other is `cold'

  → the Earth's motion through the Cosmos

  $V_{\text{Milky Way}} = 600$ km/s

- Radiation from hot gas and dust in our own Milky Way

- Structure in the Microwave Background itself

Structure in the Microwave Background

Where is the structure?

In the cosmic “clouds”, 40 billion light years away

What are we seeing?

Weak gravito-sound waves in the clouds

When do we see these clouds?

When the Universe was 400,000 years old, and was 1,000 times smaller and 1,000 times hotter than today

How big are the structures?

At least a billion light-years across (in the COBE maps)

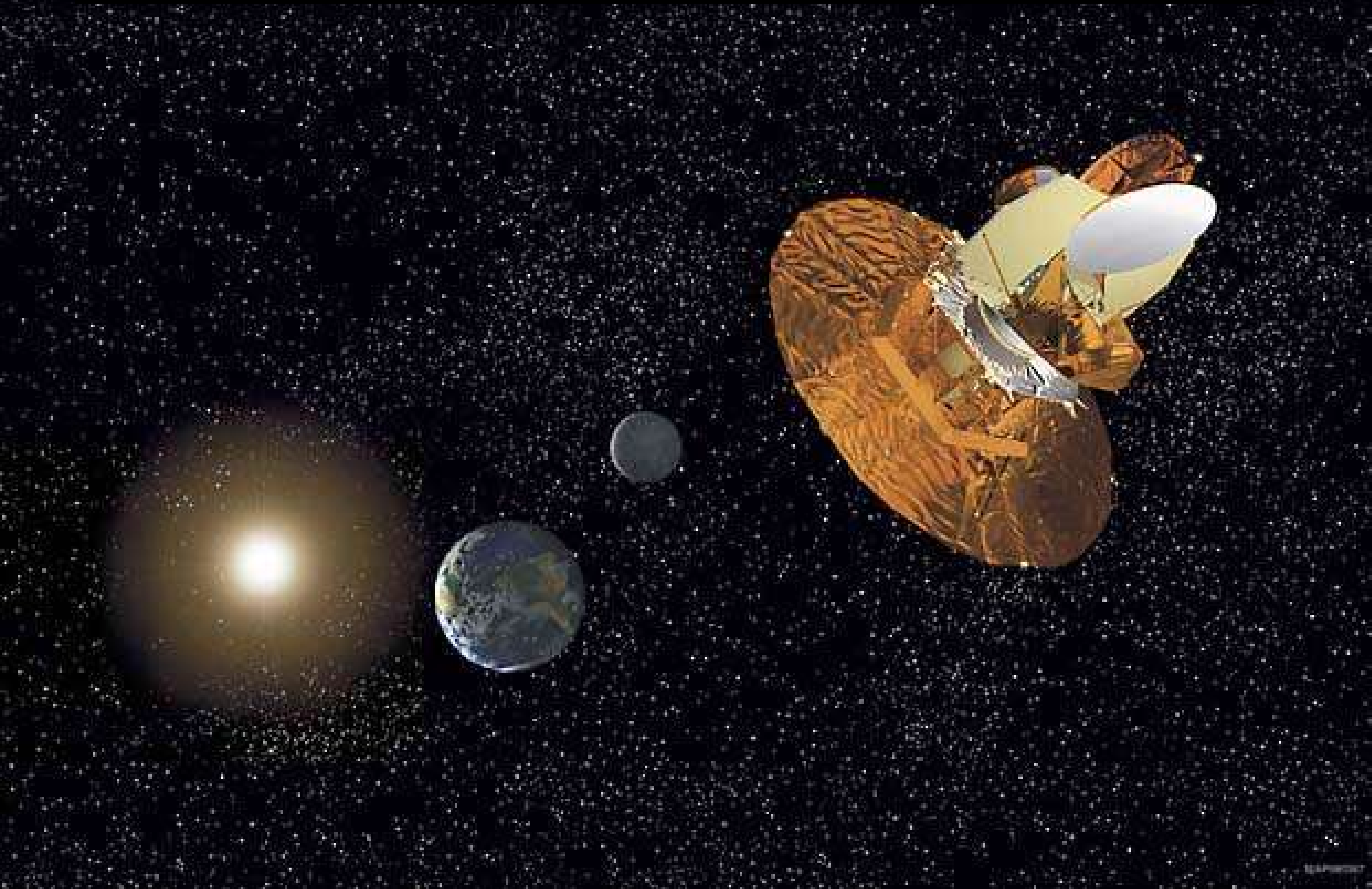
When were they made?

During inflation, perhaps 10^{-30}sec. after the Big Bang

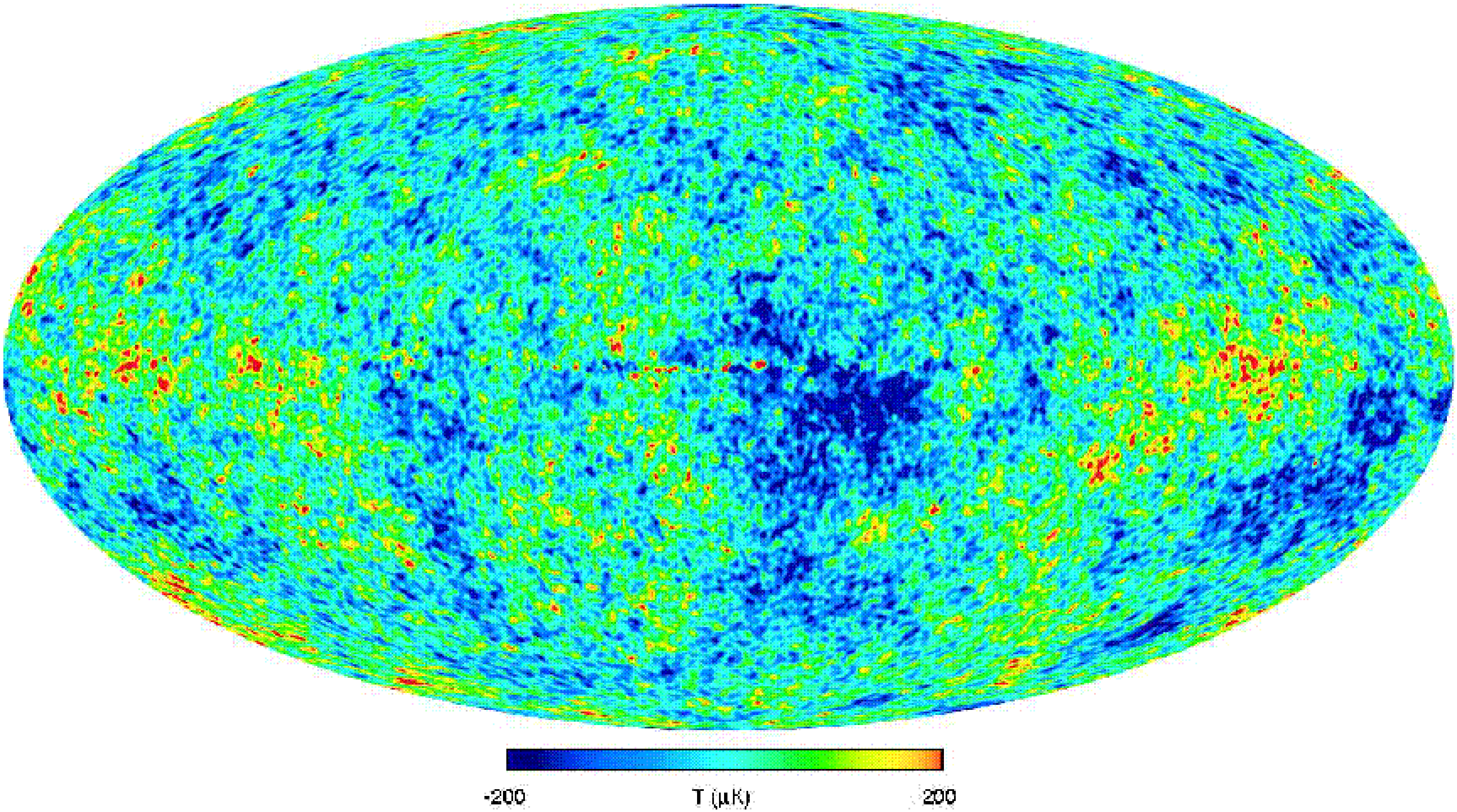
What did they turn into?

<u>Everything</u> we see in the present Universe

The *WMAP* Satellite at Lagrange-Point L2



The *WMAP* of the whole CMB sky



Bennett et al 2003

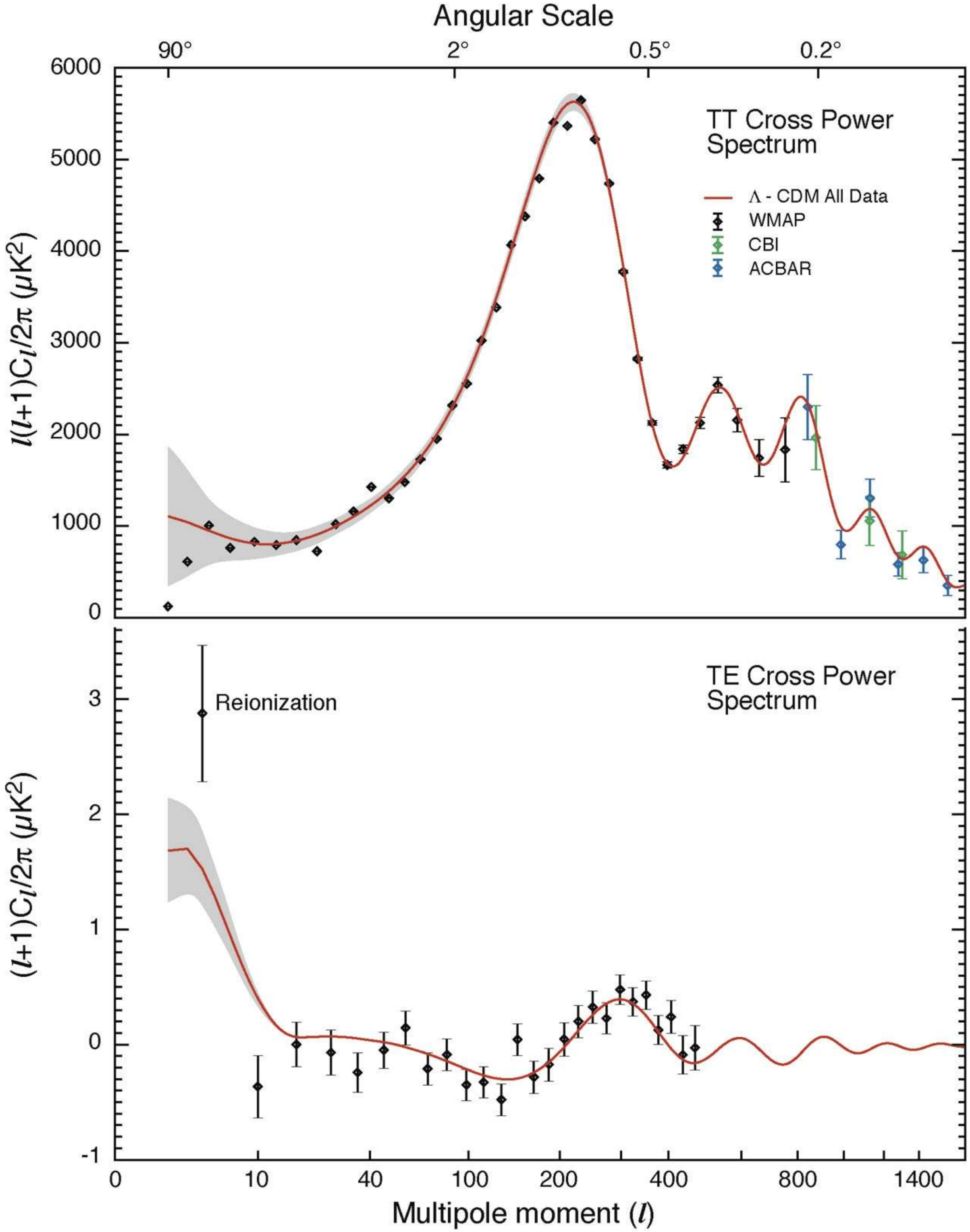
What can we learn from these structures?

The pattern of the structures is influenced by several things:

--the Geometry of the Universe
- finite or infinite
- eternal or doomed to end

--the Content of the Universe: its fractions in
- normal (baryonic) matter
- non-baryonic Dark Matter
- unseen radiation (neutrinos?)
- Dark Energy - a cosmological constant?

--the process which created the structure
- Quantum effects during early inflation?
- Topological knots from an early phase transition?



The Emergence of the Cosmic Initial Conditions

- Temperature-temperature and temperature-polarisation power spectra for *WMAP* and interferometers
- Best ΛCDM model

$$t_o = 13.7 \pm 0.2 \text{ Gyr}$$

$$h = 0.71 \pm 0.03 \qquad \sigma_8 = 0.84 \pm 0.04$$

$$\Omega_t = 1.02 \pm 0.02 \qquad \Omega_m = 0.27 \pm 0.04$$

$$\Omega_b = 0.044 \pm 0.004$$

$$\tau_e = 0.17 \pm 0.07$$

- Parameters in excellent agreement with other astronomical data

What have we learned from WMAP?

- Our Universe is flat -- its geometry is that imagined by Euclid

- Only a small fraction of it is made of ordinary matter -- about 4%
  → there is a lot of dark, nonbaryonic matter (about 25%)
  (which can be "seen" through gravitational lensing)

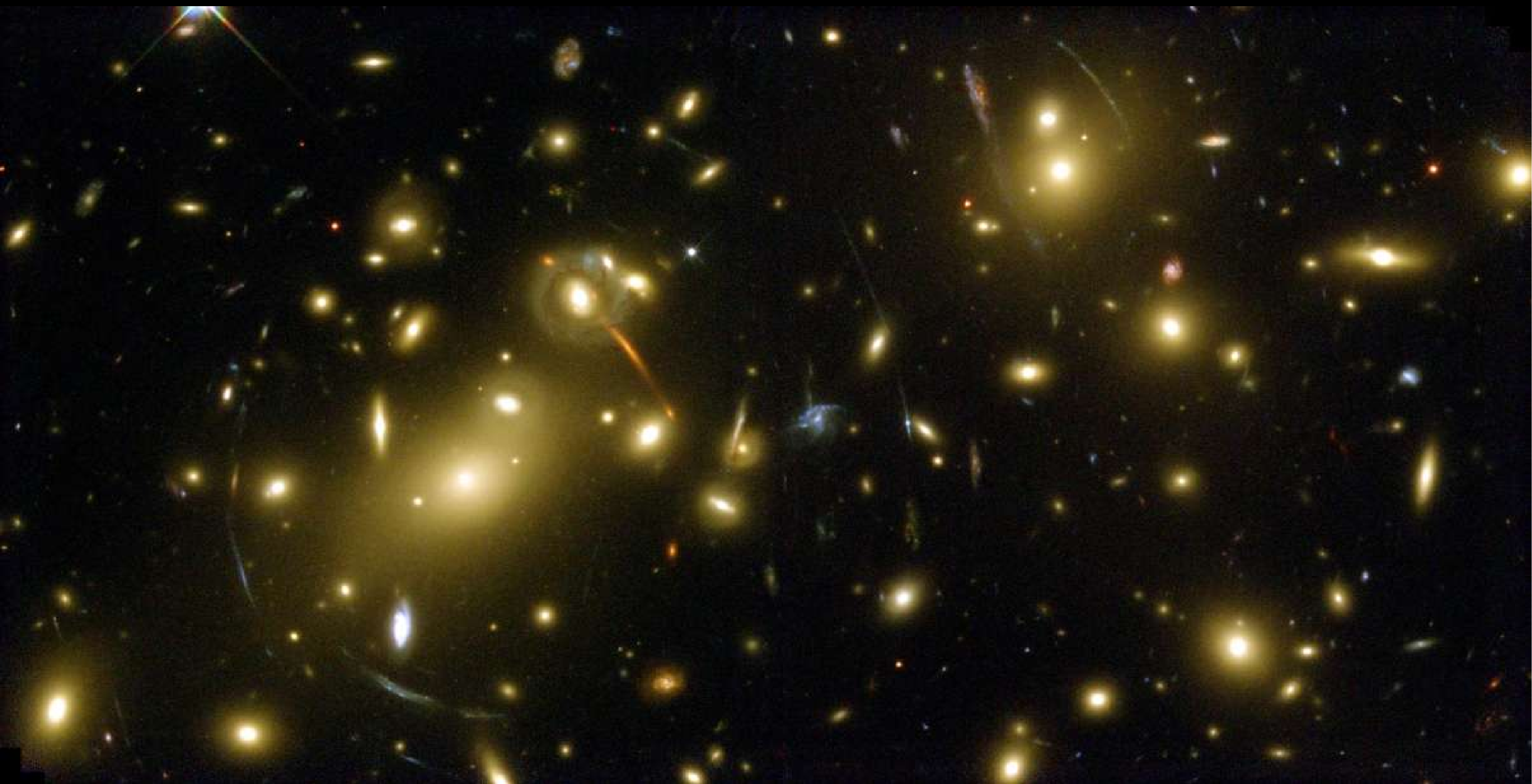
- Most of it must be a new kind of dark energy (perhaps a cosmological constant) as also inferred from the apparently accelerating expansion

- All structure in the Universe originated as quantum zero-point fluctuations of the *vacuum*, perhaps 10^{-30} s after the Big Bang!

Everything has formed from nothing

Gravitational lensing by a galaxy cluster

Abell 2218 z=0.17



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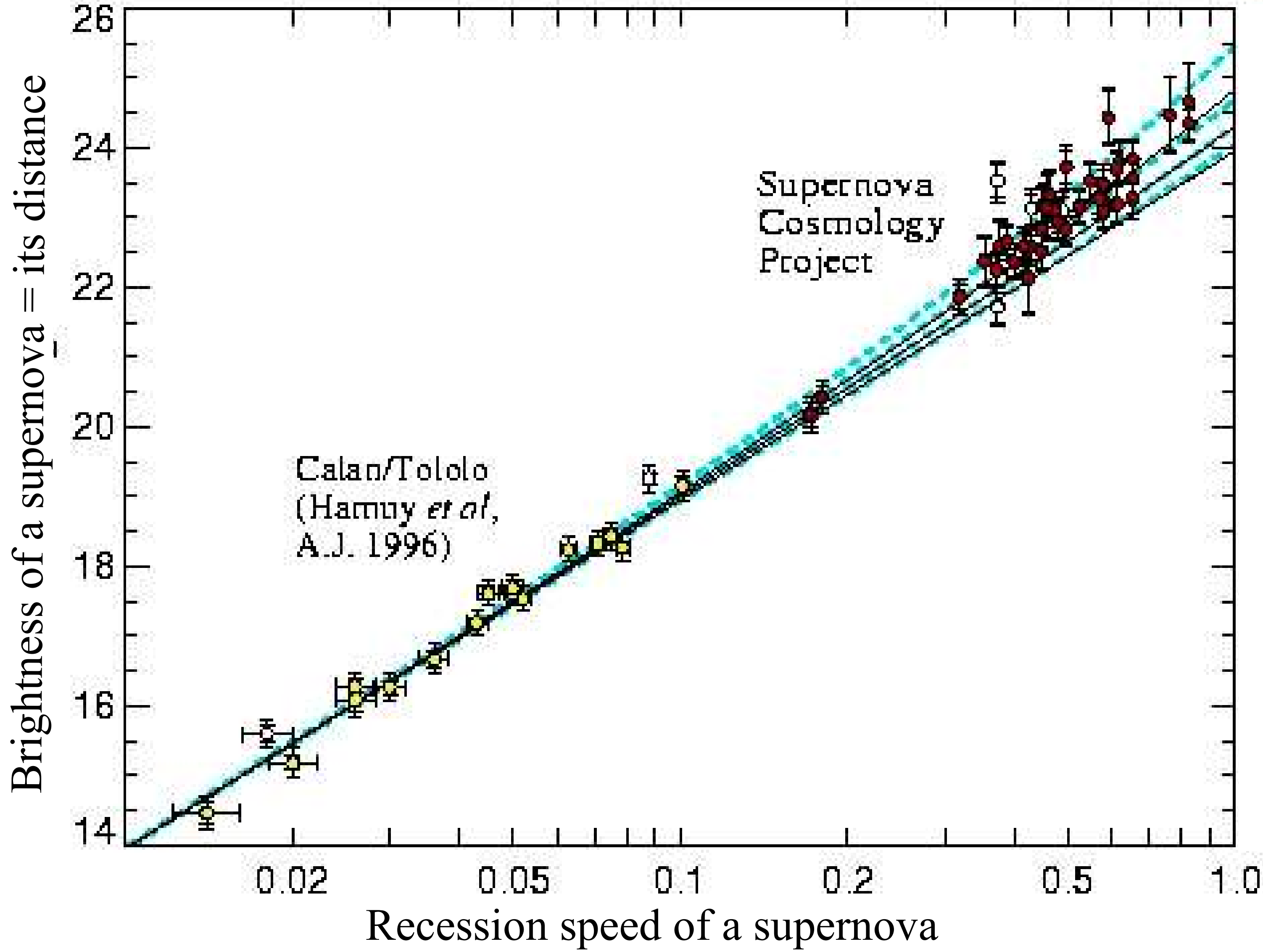
Hubble's Law rules the Cosmic Expansion



An accelerating Universe? The return of Einstein's "Eselei" or the discovery of a new form of mass/energy -- the Dark Energy?

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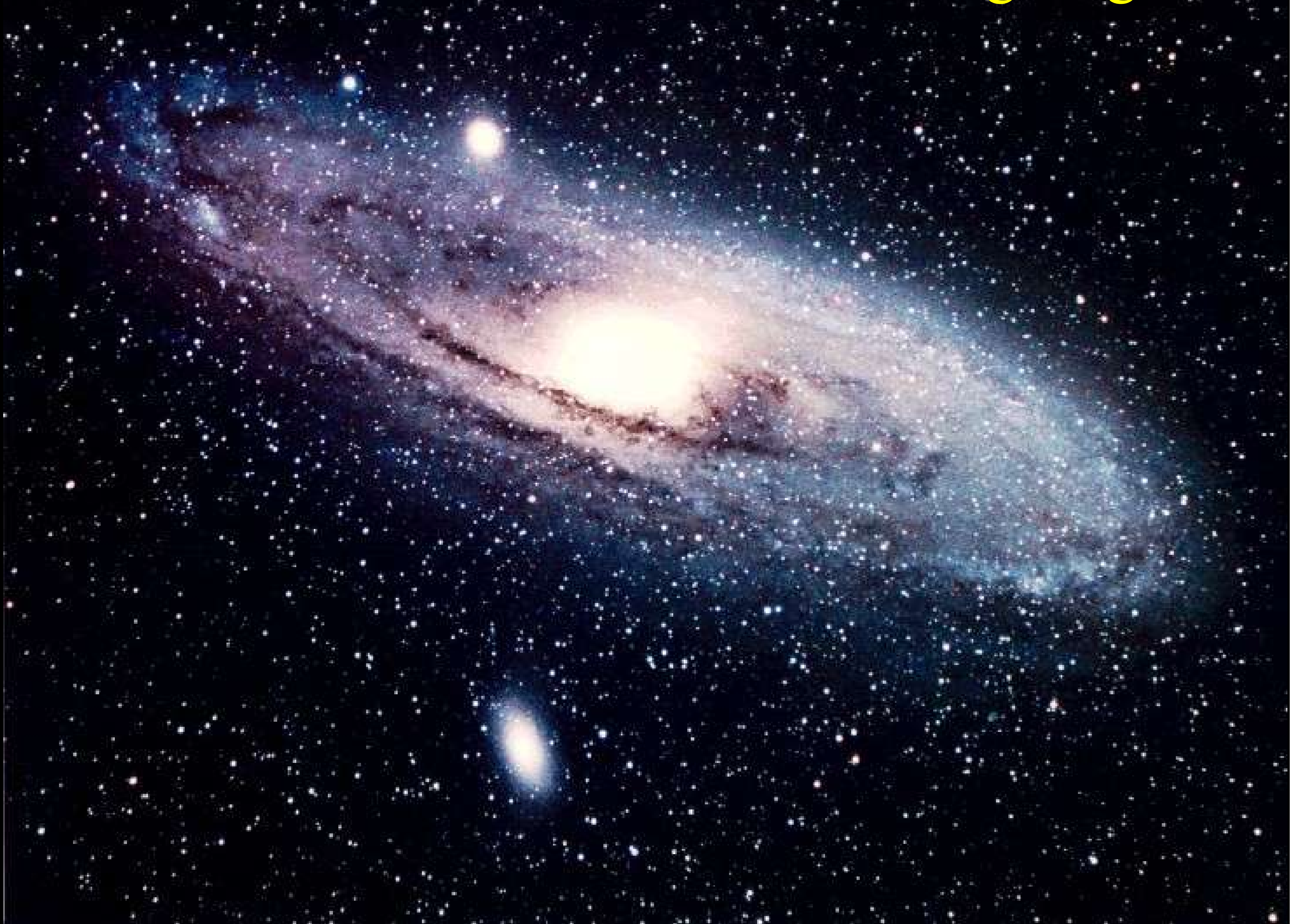
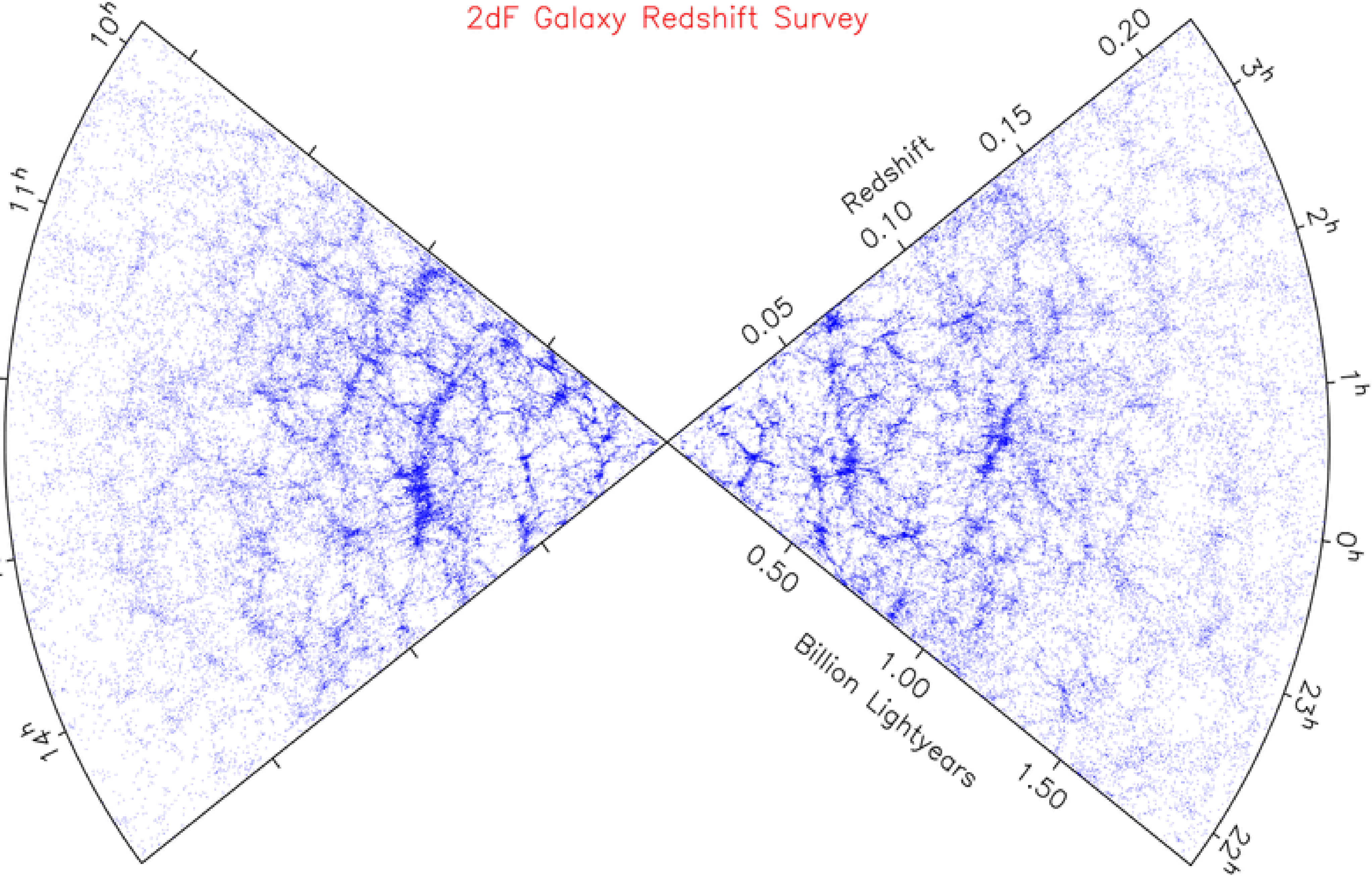
<u>Everything</u> has formed from nothing

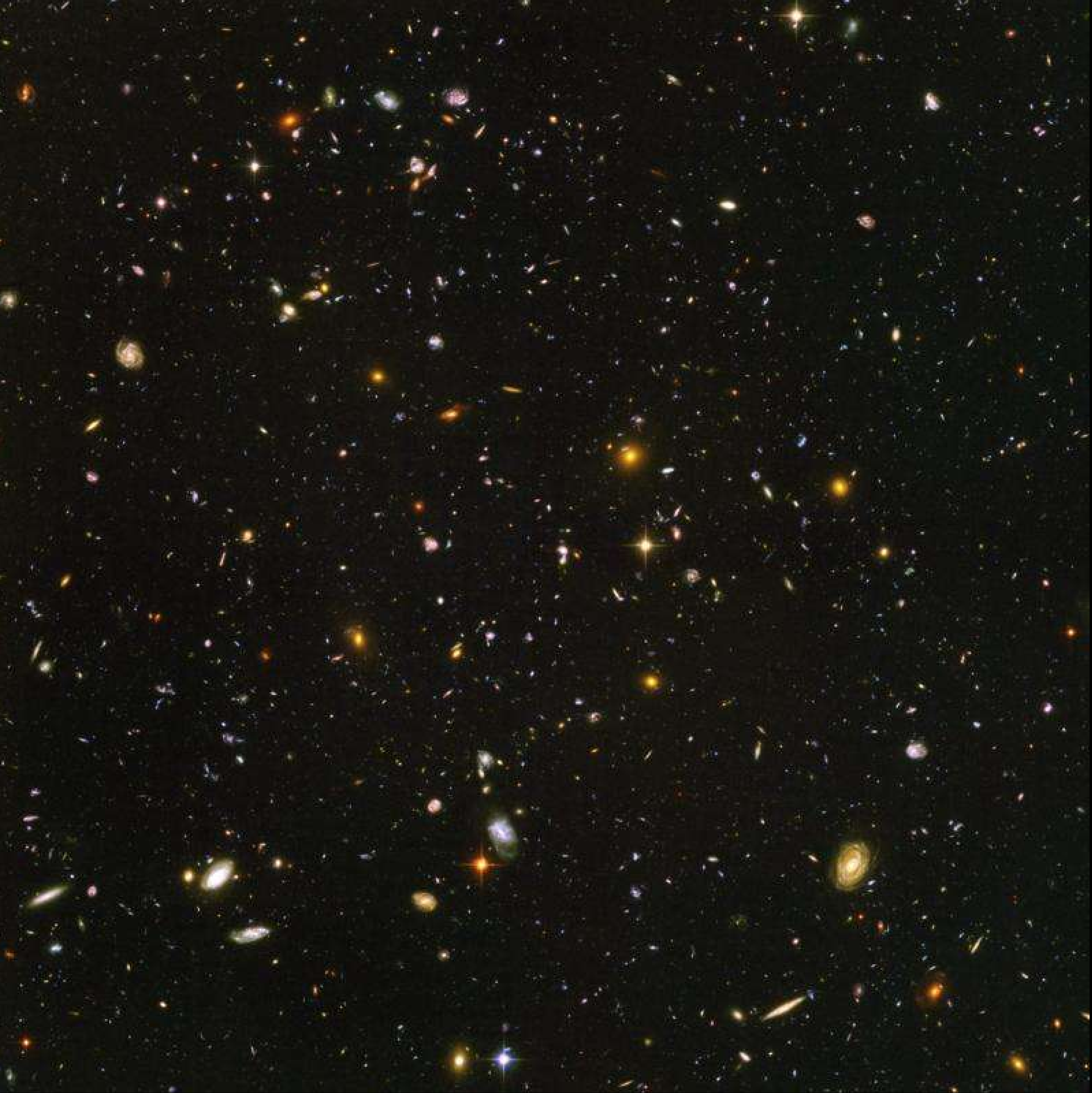
The Andromeda Nebula: our nearest big neighbor



NGC 4414 -- a galaxy like our own

Nearby large-scale structure

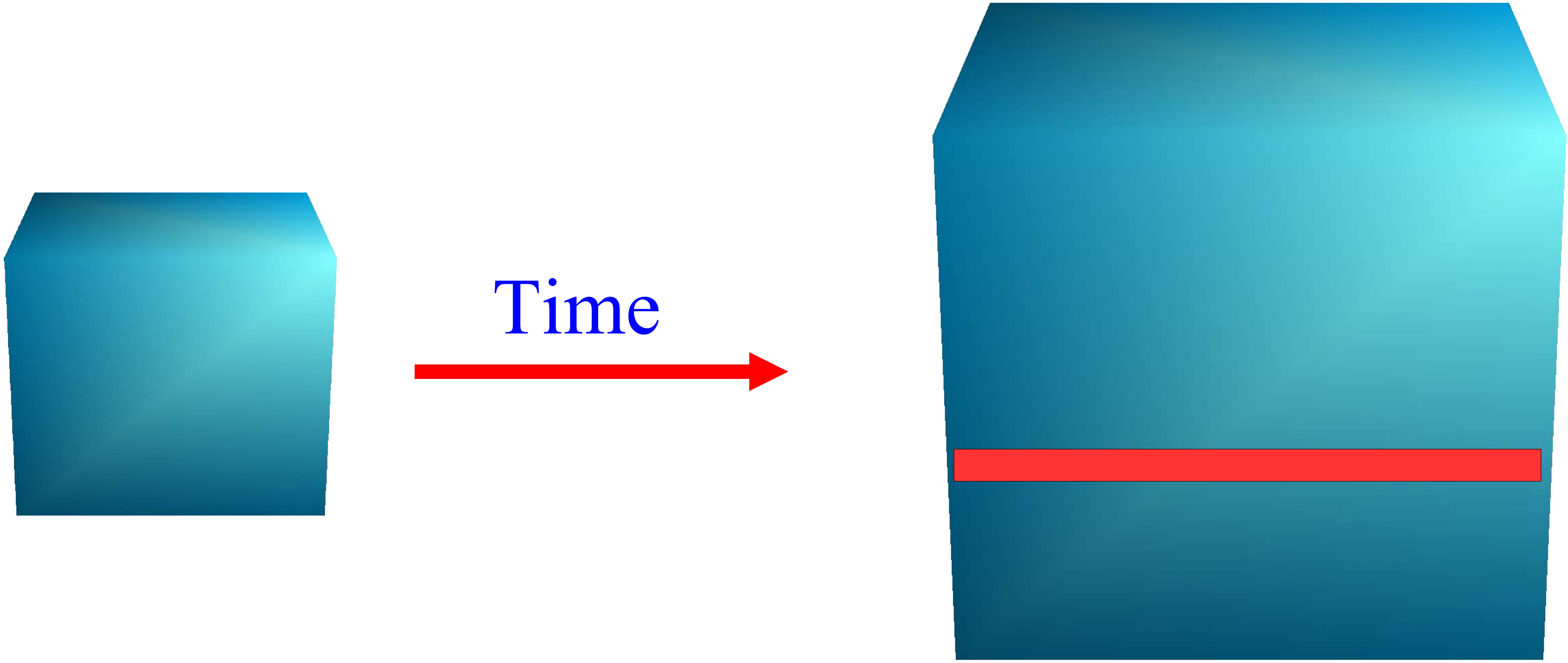




The deepest photo ever made

A 300 hour exposure with the Hubble Space Telescope

Evolving the Universe in a computer



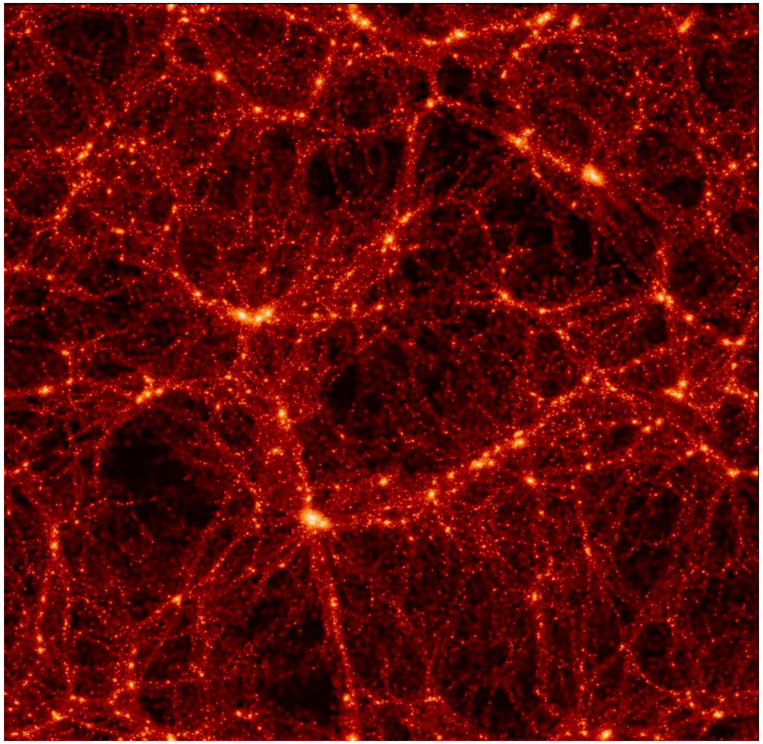
- Follow the matter in an expanding cubic region
- Start 400,000 years after the Big Bang
- Match initial conditions to the observed Microwave Background
- Calculate evolution forward to the present day

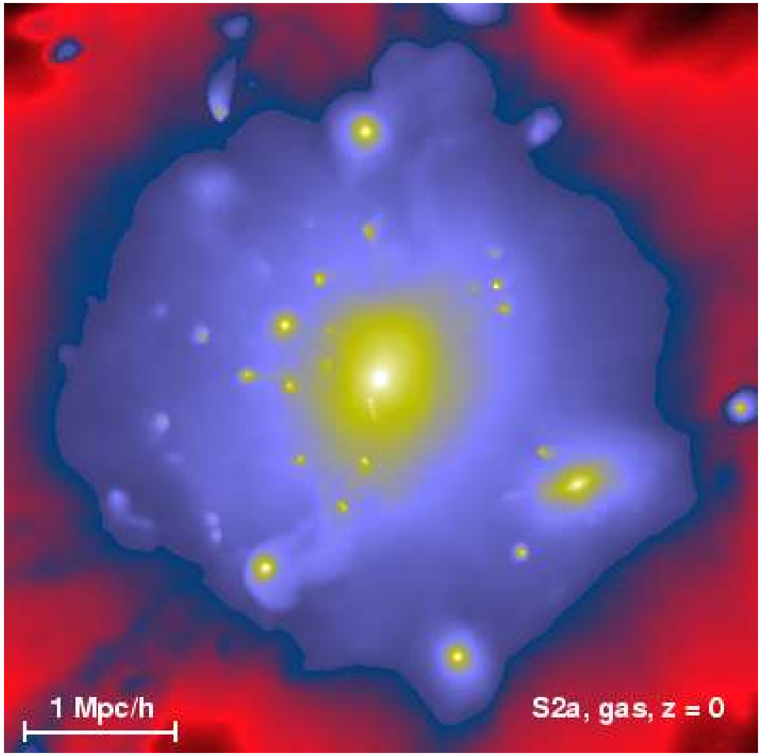
Structure evolution in the standard paradigm

...can be simulated reliably for the dark matter

...and also in the baryons when cooling is neglected...

...but not including cooling, star formation and related processes.





Goals for a model of galaxy/AGN evolution

- Explore the physics of galaxy formation
- Understand the links between galaxy and SMBH formation
- Clarify why galaxy properties are related to clustering
- Determine how environment stimulates galaxy activity
- Interpret new multi-wavelength surveys of galaxies
- Check if such surveys can provide precision tests of and parameter estimates for the standard ΛCDM paradigm

Physics for Galaxy Formation Modelling

Gas Cooling and Condensation

Sensitive to metal content, phase structure, UV background...

Star Formation

No *a priori* understanding -- efficiency? IMF?

Stellar Feedback

SF regulation, metal enrichment, galactic winds

Stellar Aging

Population synthesis → luminosities, colours, spectra, (dust?)

AGN physics

Black hole formation, feeding, AGN phenomenology, feedback

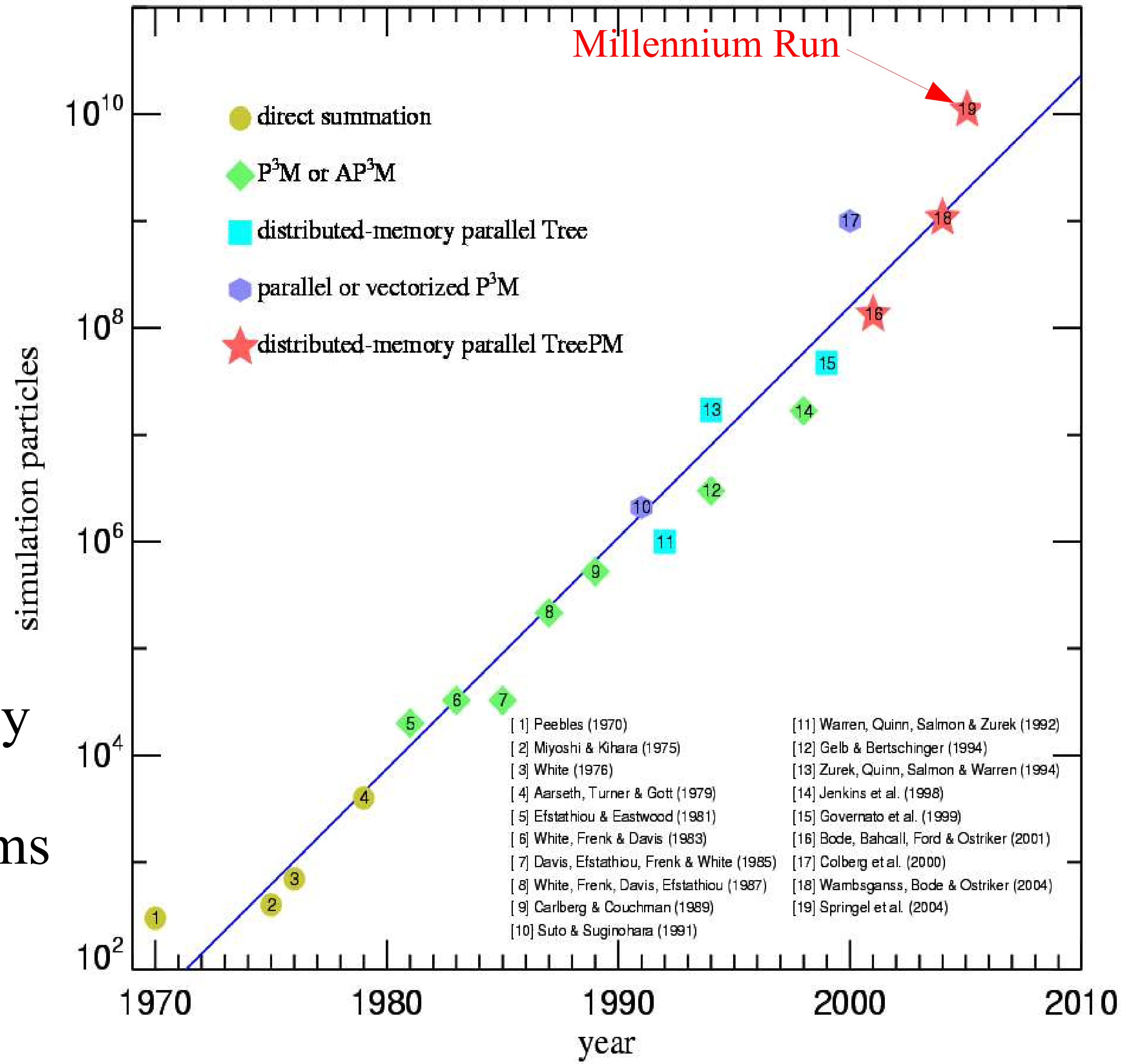
Environment interactions

Galaxy mergers, tidal effects, ram pressure effects

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

Springel et al 2005



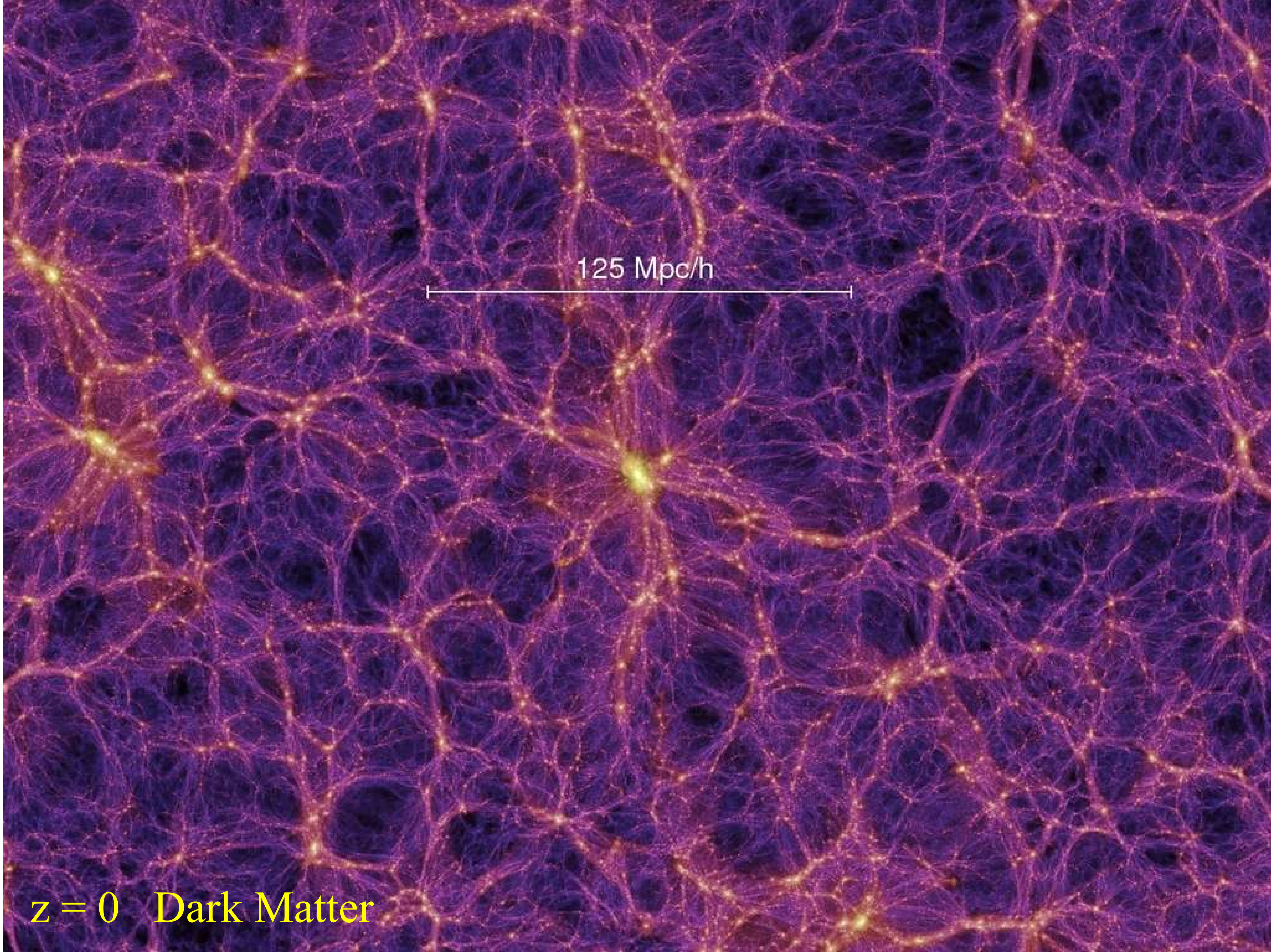
Millennium Run Statistics

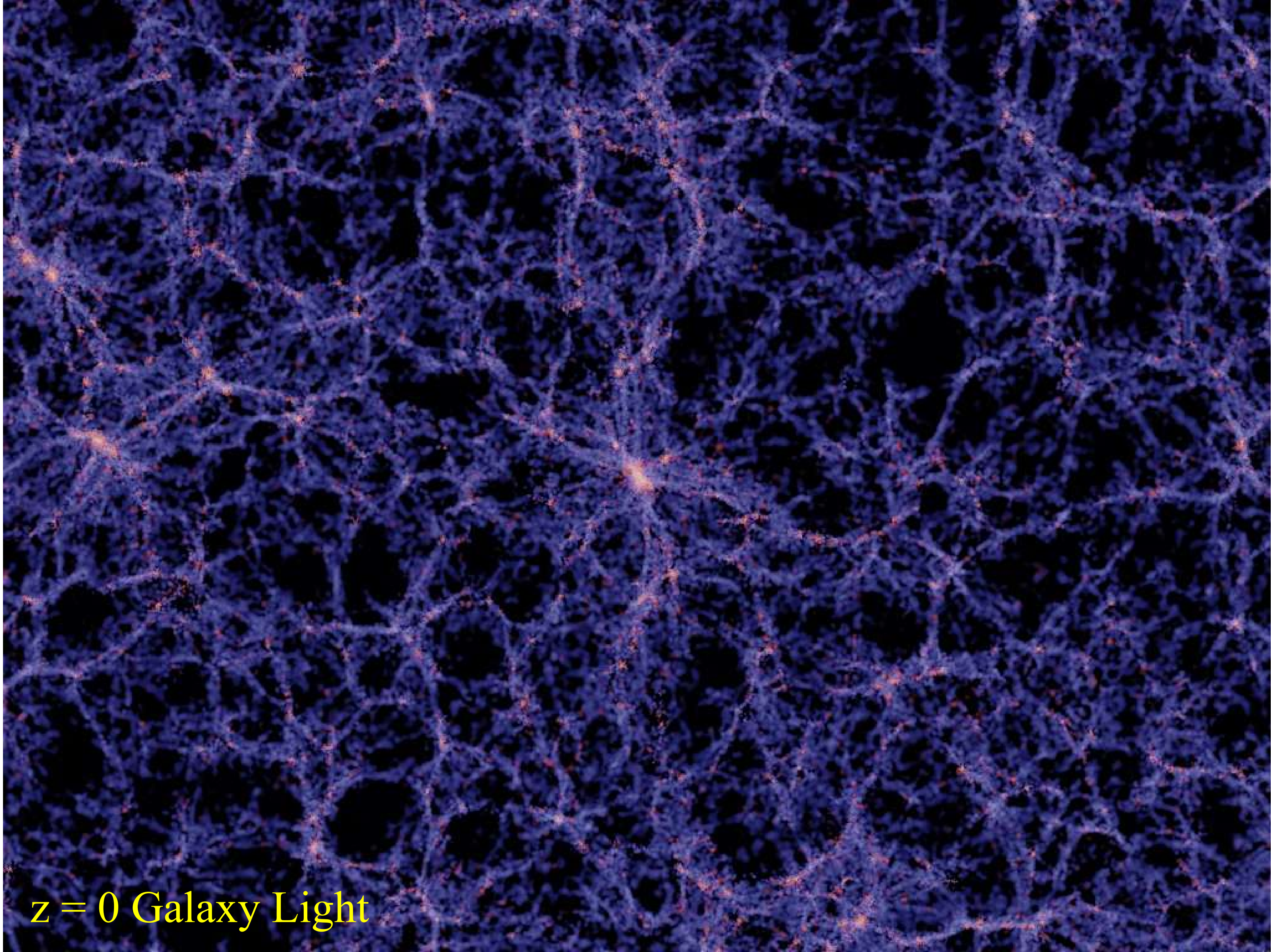
Springel et al 2005: The Virgo Consortium

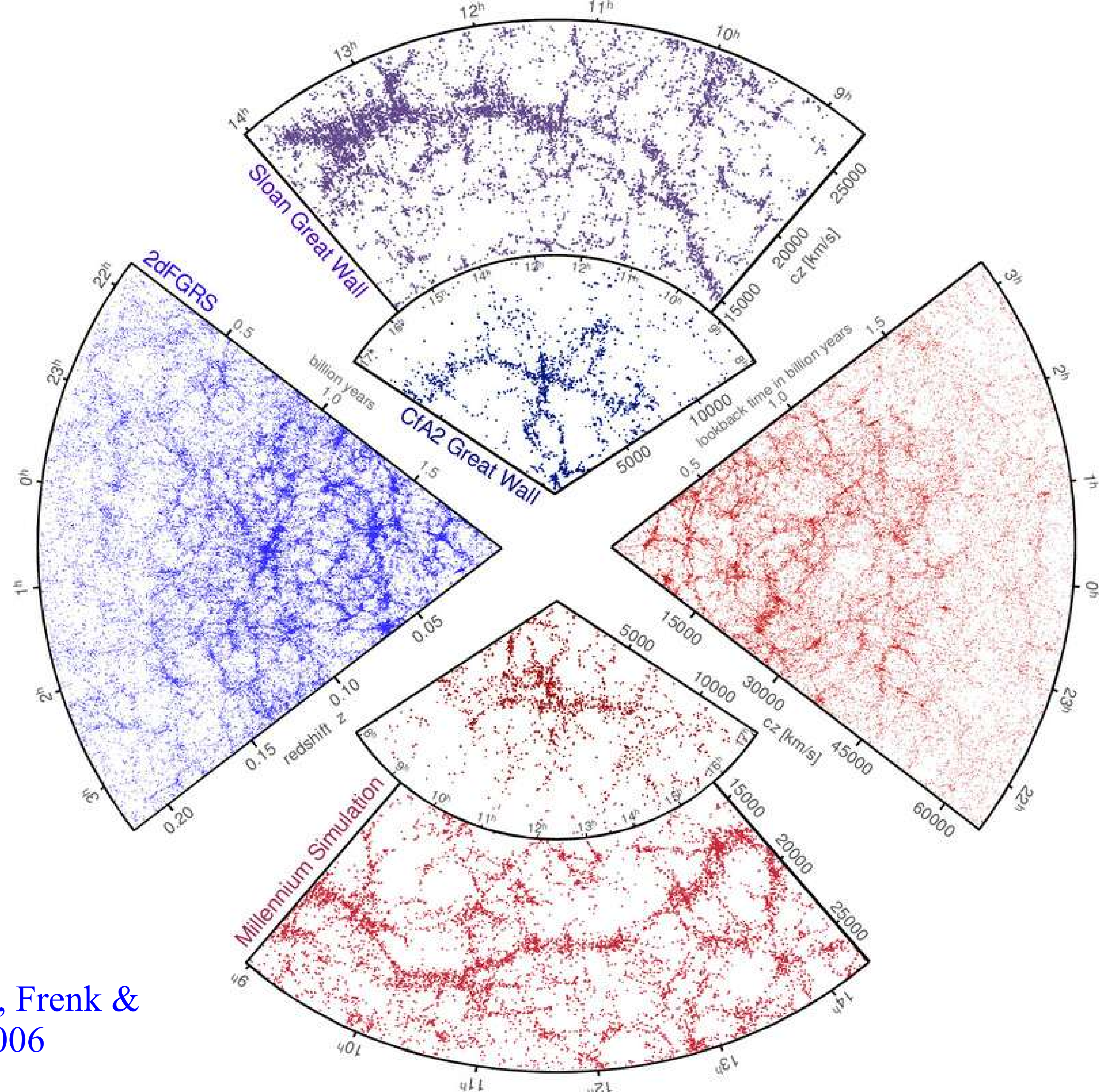
- Particle number: $N = 2160^3 = 10{,}077{,}696{,}000 \approx 10^{10}$
- Box size: $L = 500$ Mpc/h, Softening: $\epsilon = 5$ kpc/h $\longrightarrow$ $L/\epsilon = 10^5$
- Initial redshift: $z_{init} = 127$
- Cosmology: $\Omega_{tot}=1$, $\Omega_m=0.25$, $\Omega_b=0.045$, $h=0.73$, $n=1$, $\sigma_8=0.9$
- 343,000 processor-hours on 512 nodes of an IBM Regatta
  (28 machine days @ 0.2 Tflops using 1 Tbyte RAM)
- Full raw and reduced data stored at 64 redshifts

$\longrightarrow$ **27 Tbytes of stored data**

A <u>testbed</u> for studying galaxy formation models


125 Mpc/h
z = 0   Dark Matter

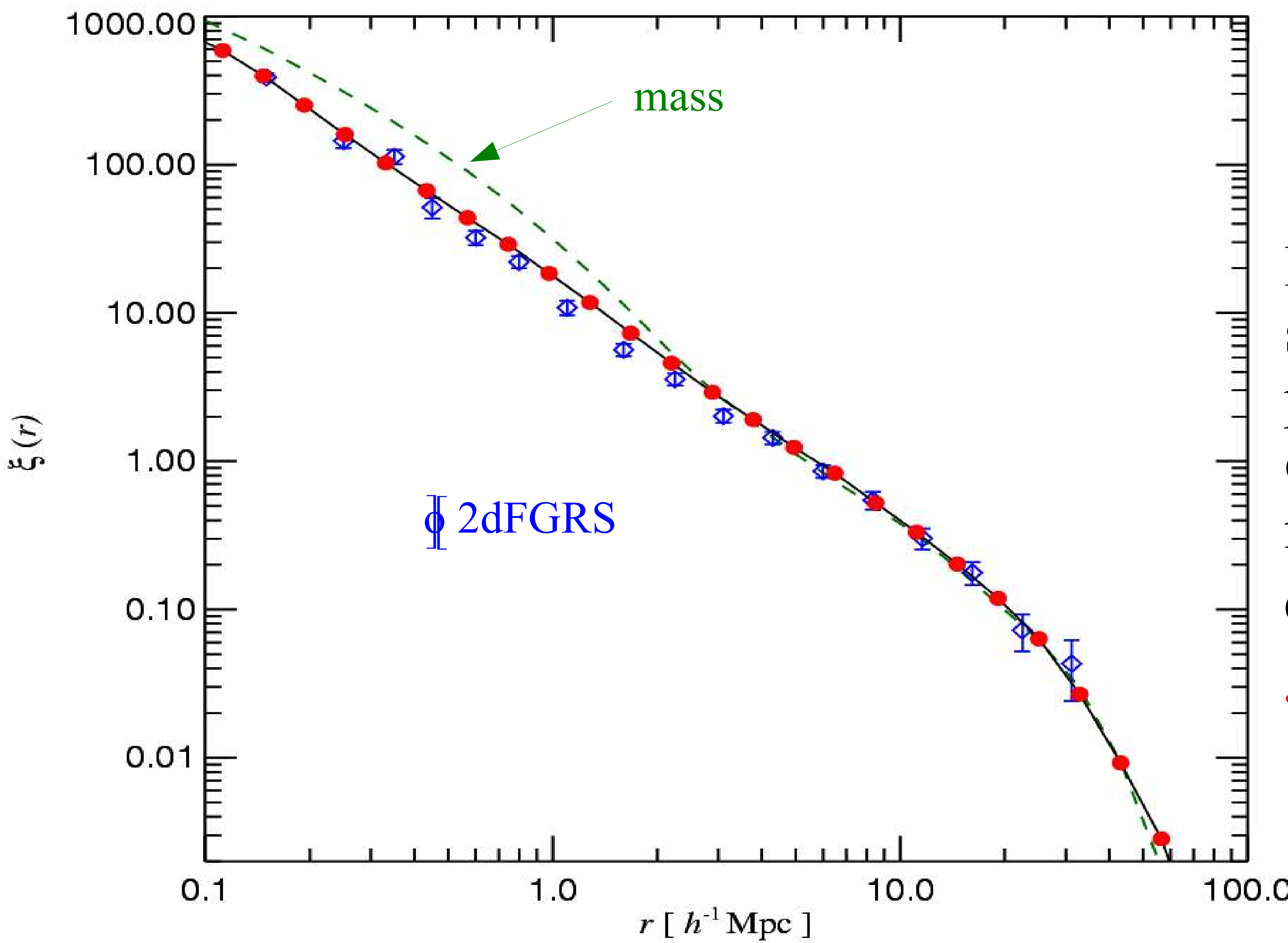

z = 0 Galaxy Light



Springel, Frenk &
White 2006

Galaxy autocorrelation function

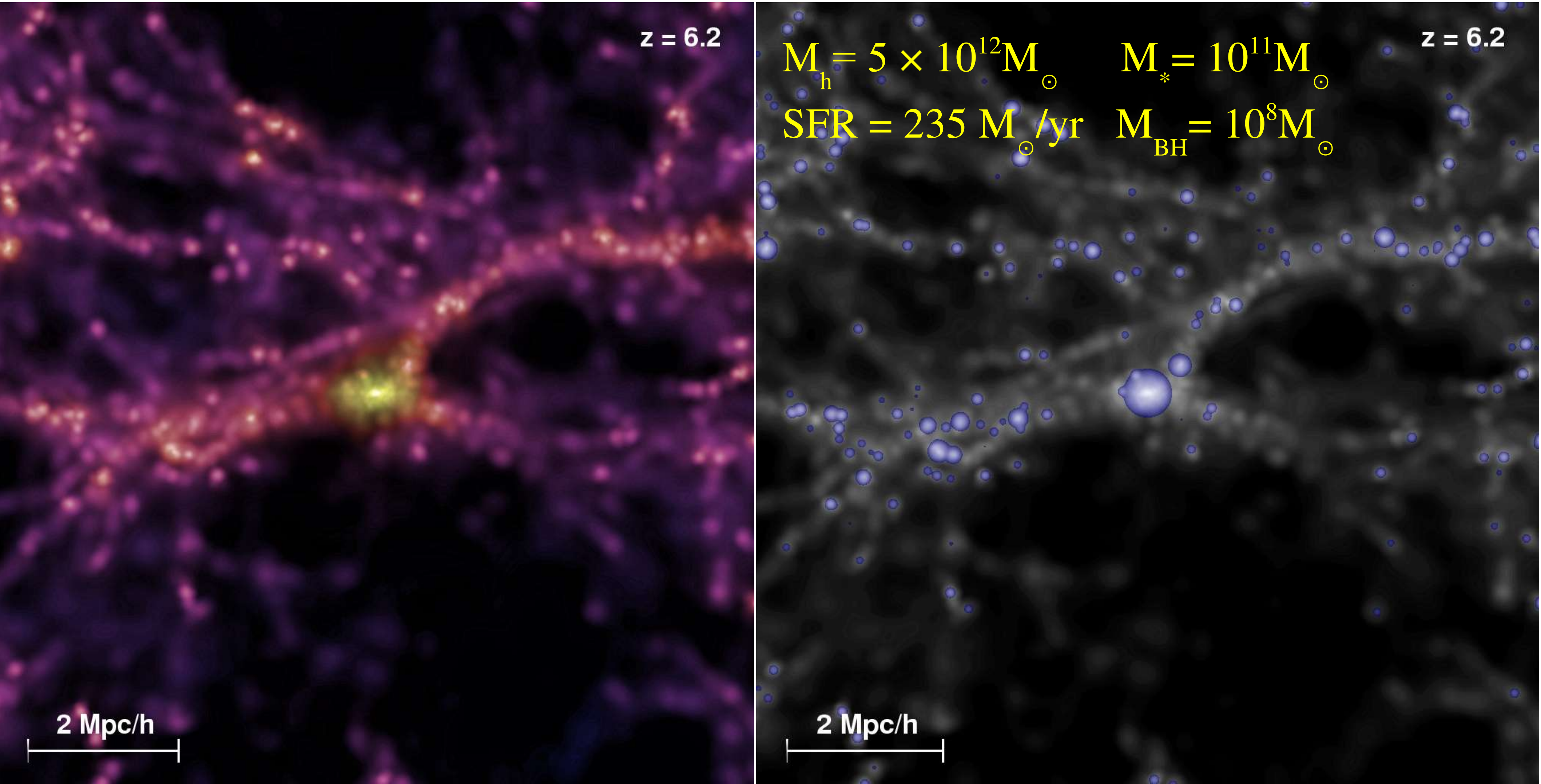
Springel et al 2005



For such a large simulation the purely statistical error bars are negligible on ξ even for the galaxies

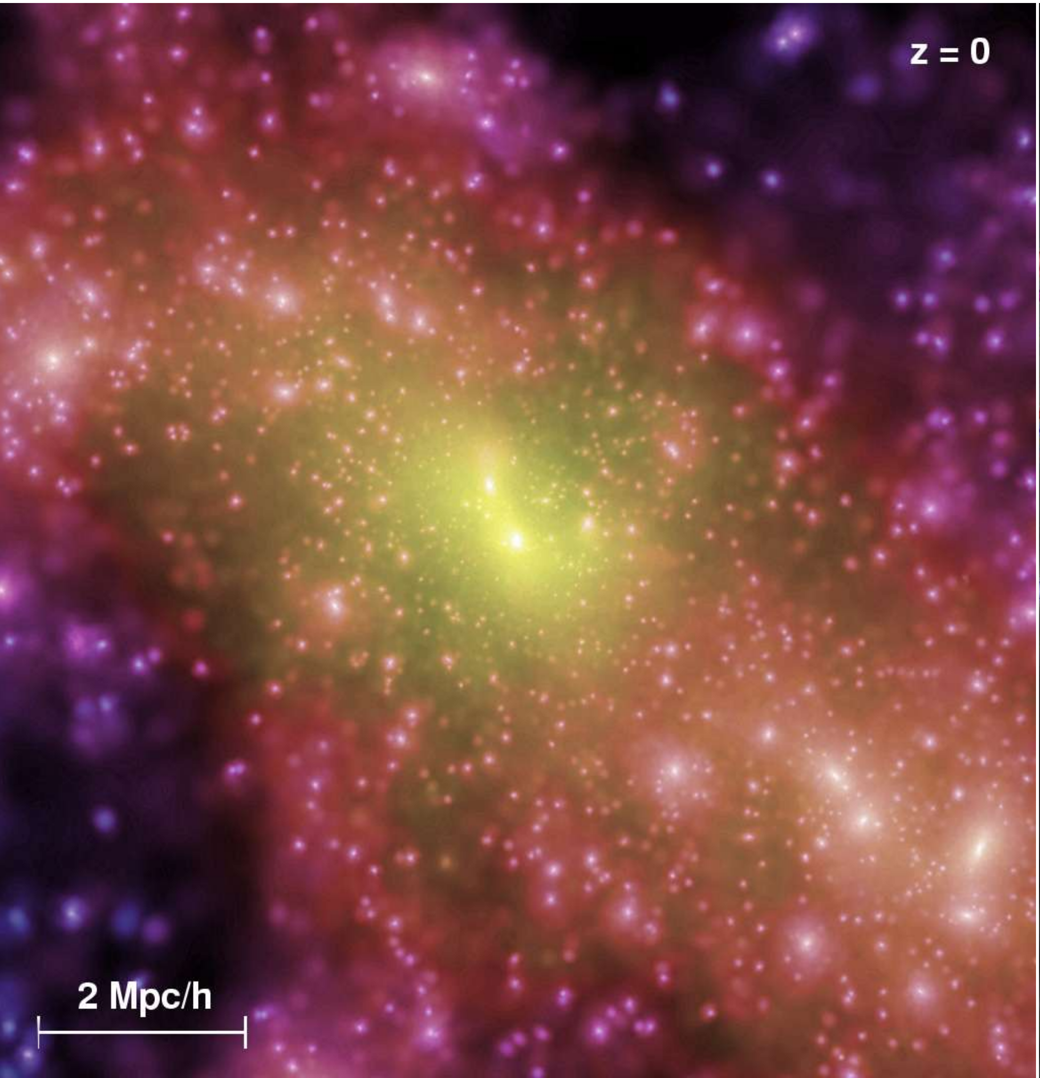
A bright quasar and its surroundings at 1 billion years

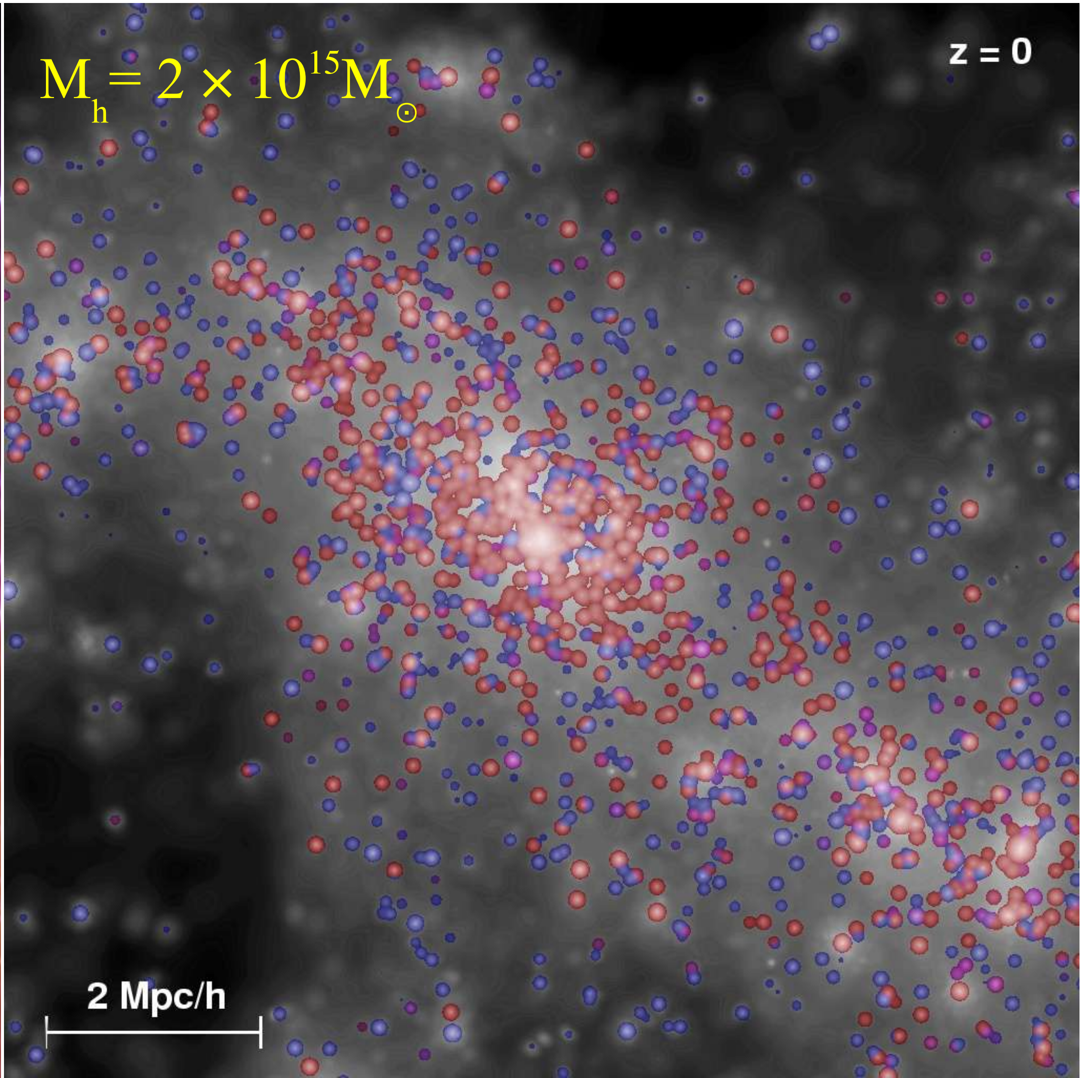
One of the most massive dark matter clumps, containing one of the most massive galaxies and most massive black holes.

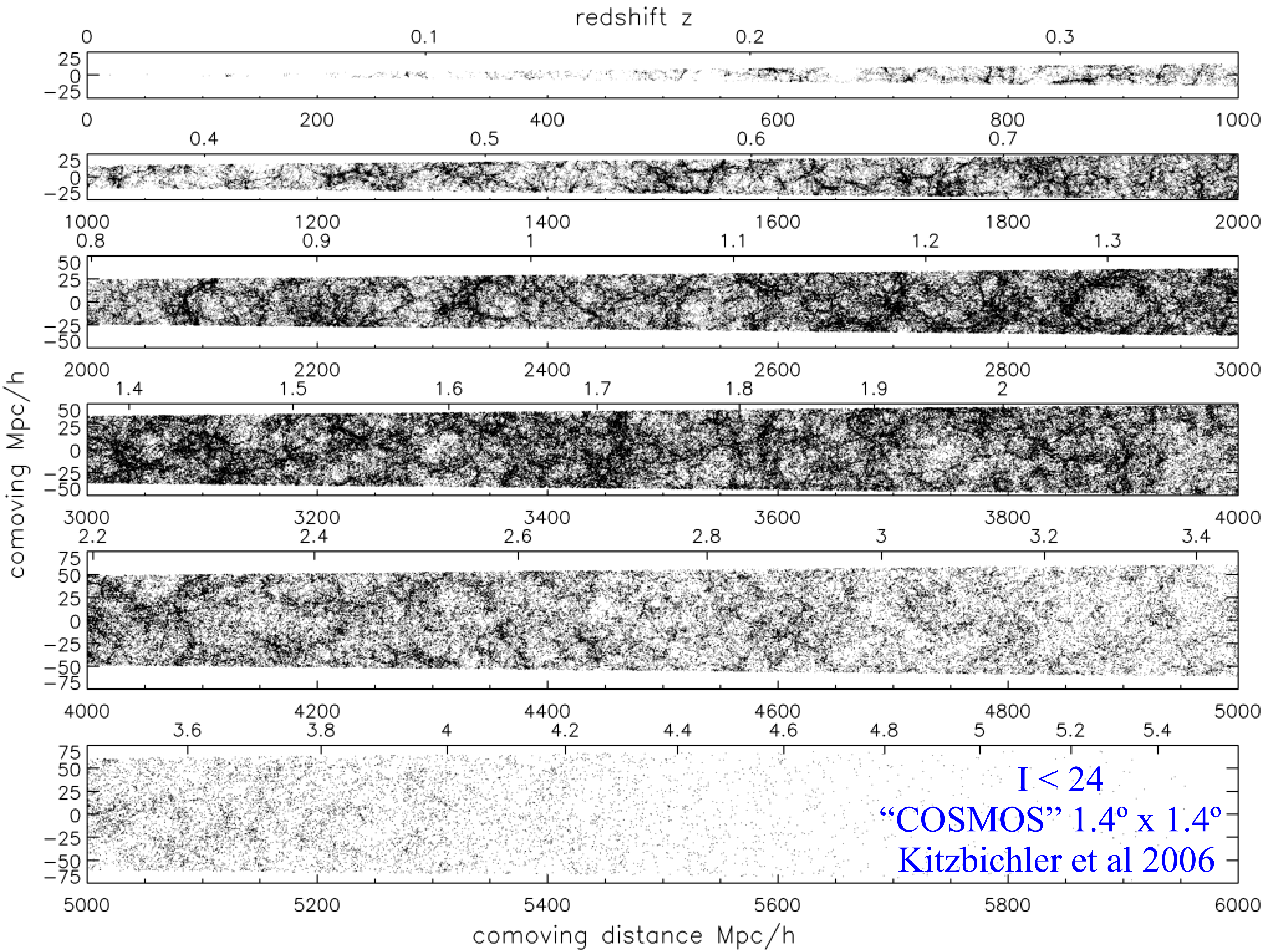


The quasar's descendant and its surroundings today, at t = 13.7 billion years

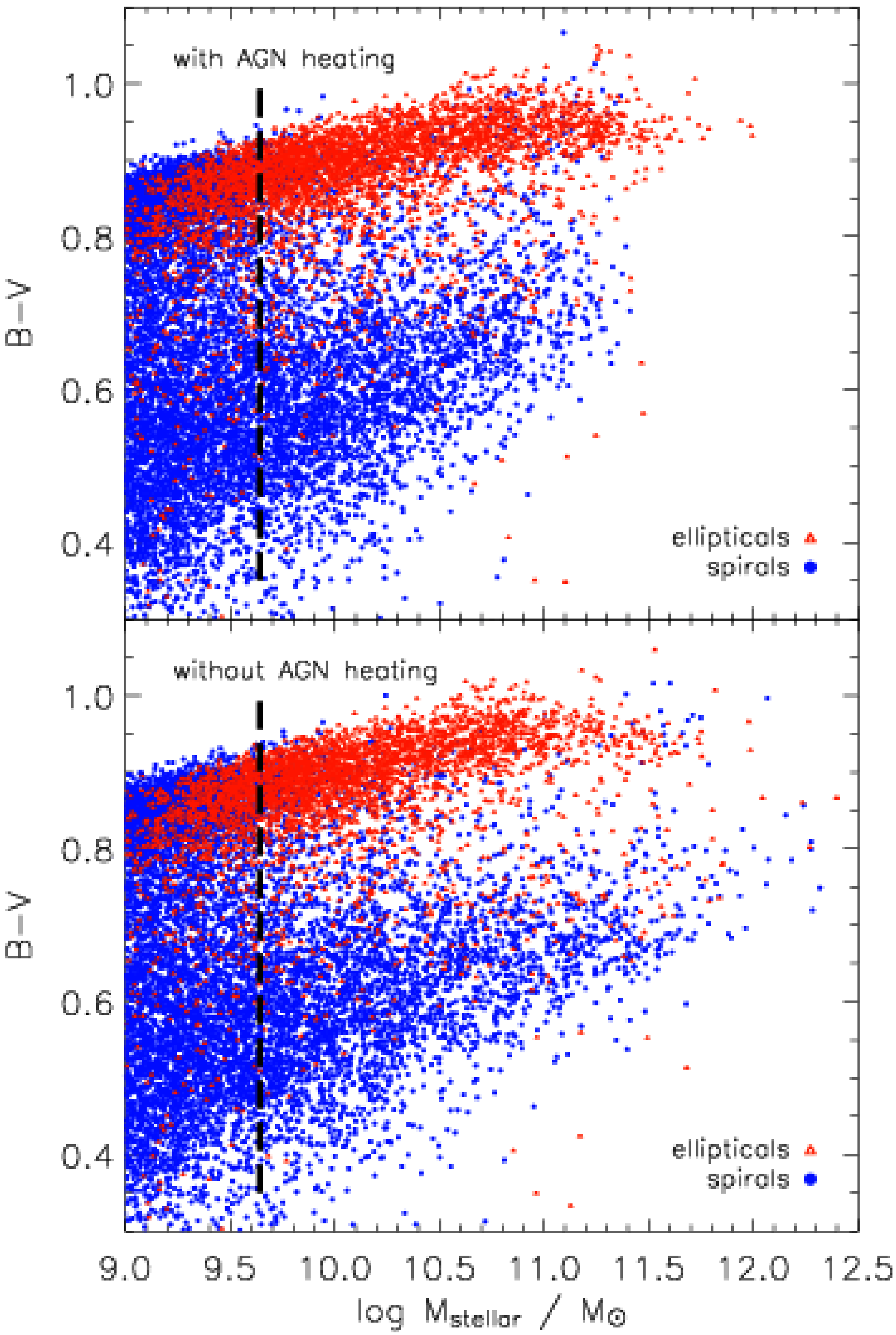
One of the most massive galaxy clusters. The quasar's descendant is part of the central massive galaxy of the cluster.







redshift z
comoving Mpc/h
comoving distance Mpc/h
I < 24
“COSMOS” 1.4º x 1.4º
Kitzbichler et al 2006



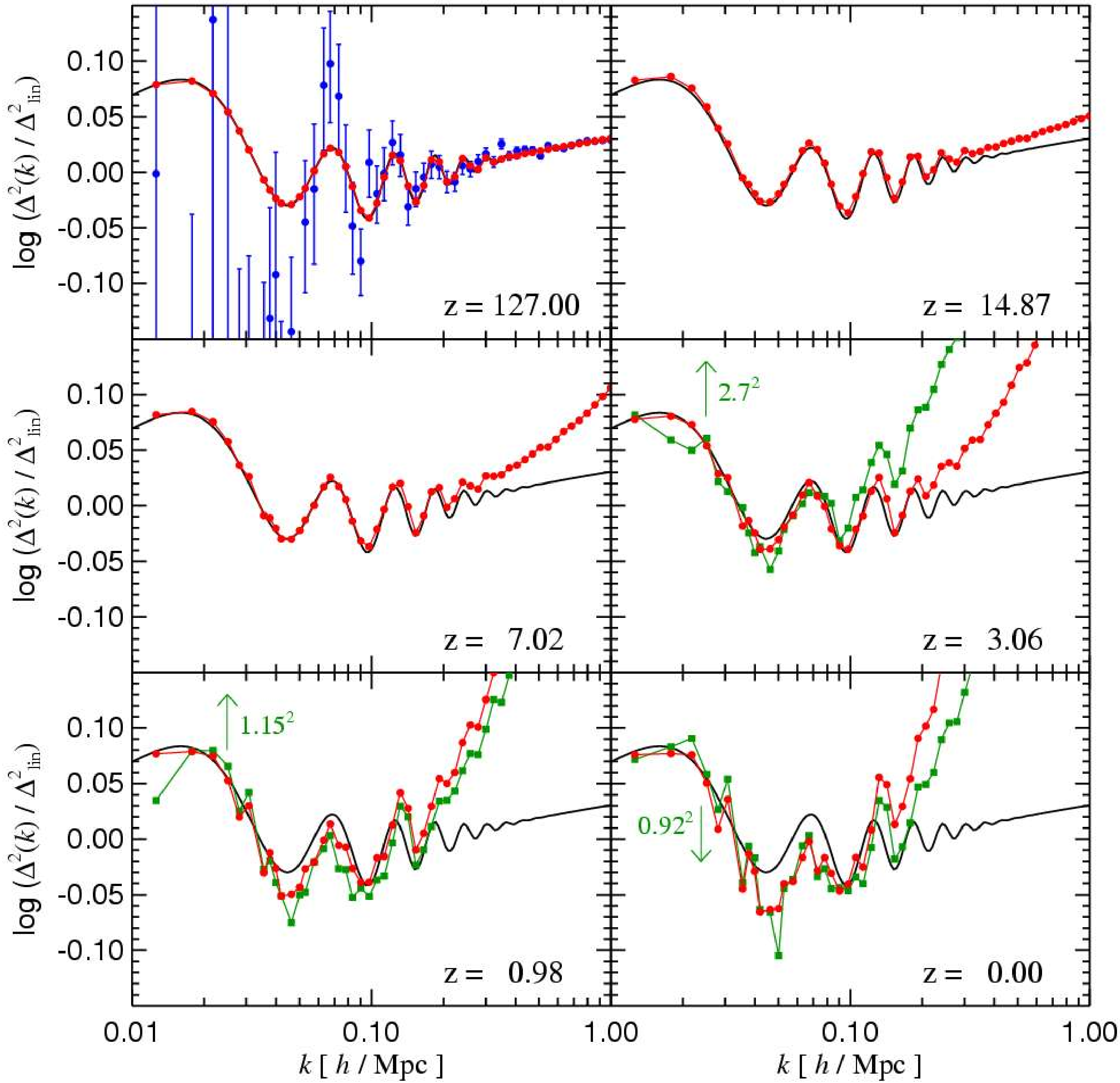
The effects of "radio mode" feedback on z=0 galaxies

Croton et al 2005

- In the absence of a "cure" for the cooling flow problem, the most massive galaxies are:
  - too bright
  - too blue
  - disk-dominated

- With cooling flows suppressed by "radio AGN" these galaxies are
  - less massive
  - red
  - elliptical

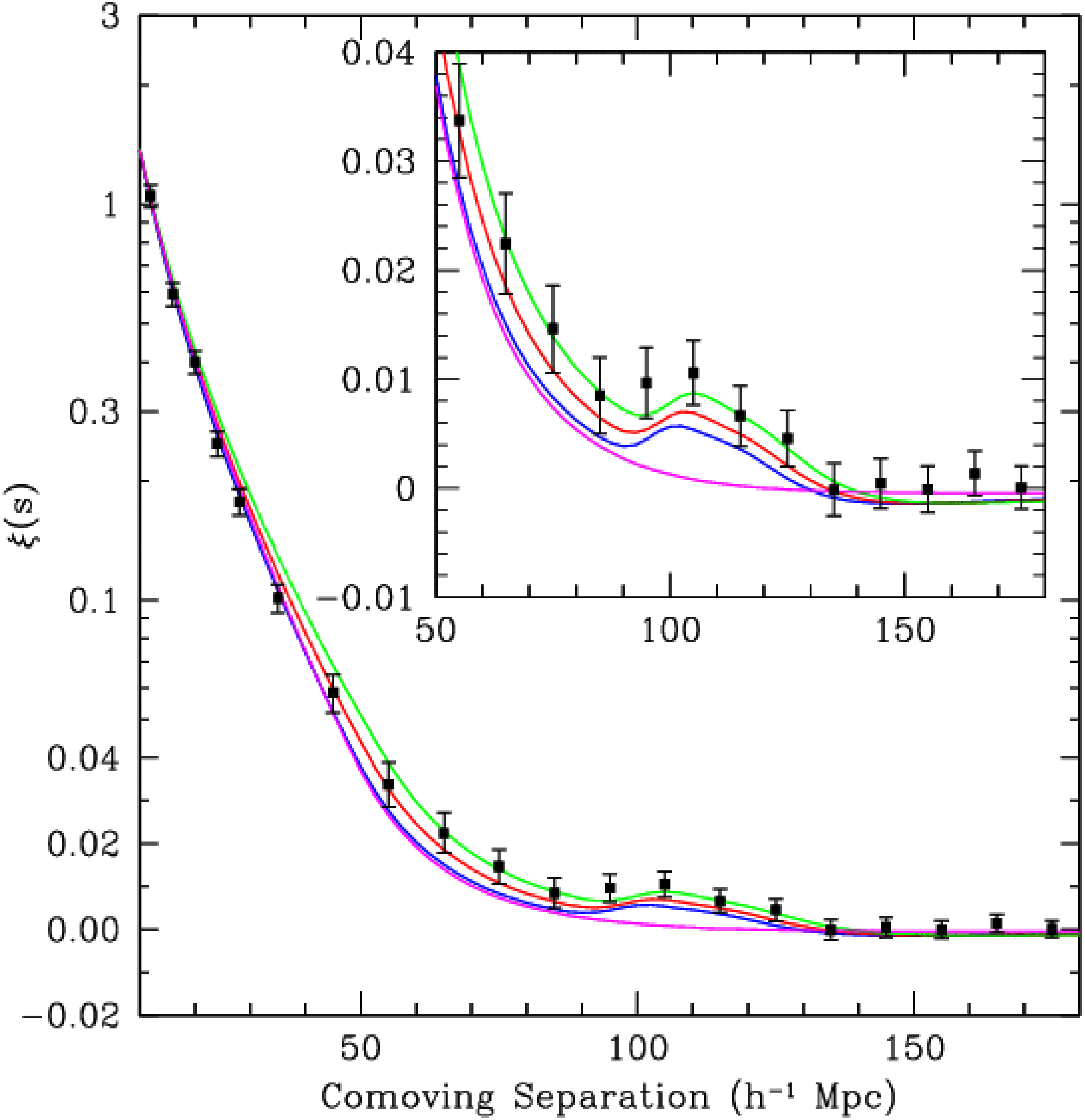
Baryon wiggles in the *galaxy* distribution



Springel et al 2005

Power spectra from the Millennium run divided by a baryon-free ΛCDM spectrum

Galaxy samples are matched to plausible large observational surveys at given z



Baryon wiggles in the *galaxy* distribution

Eisenstein et al 2005

Galaxy autocorrelation for the SDSS luminous red galaxy survey (65,000 galaxies with ‹z› ~ 0.3).

A rod to survey the Universe?

→ constraints on the nature of Dark Energy?

To conclude.....

- The Universe emerged 13.7 billion years ago from a hot, dense and almost uniform explosion -- The Big Bang
- All structure grew from quantum fluctuations of the vacuum -- Everything has grown from nothing
- Normal material is only 4% of the content of the Universe
- About 25% is made of as yet unidentified Dark Matter
- About 70% is an as yet unidentified energy field which accelerates the cosmic expansion today – Dark Energy
- Galaxies and galaxy clusters, stars and planets formed from the primordial gas through the effects of Gravity
- In 2060 we should be able to simulate the whole visible Universe with a resolution equal to the mass of the Sun