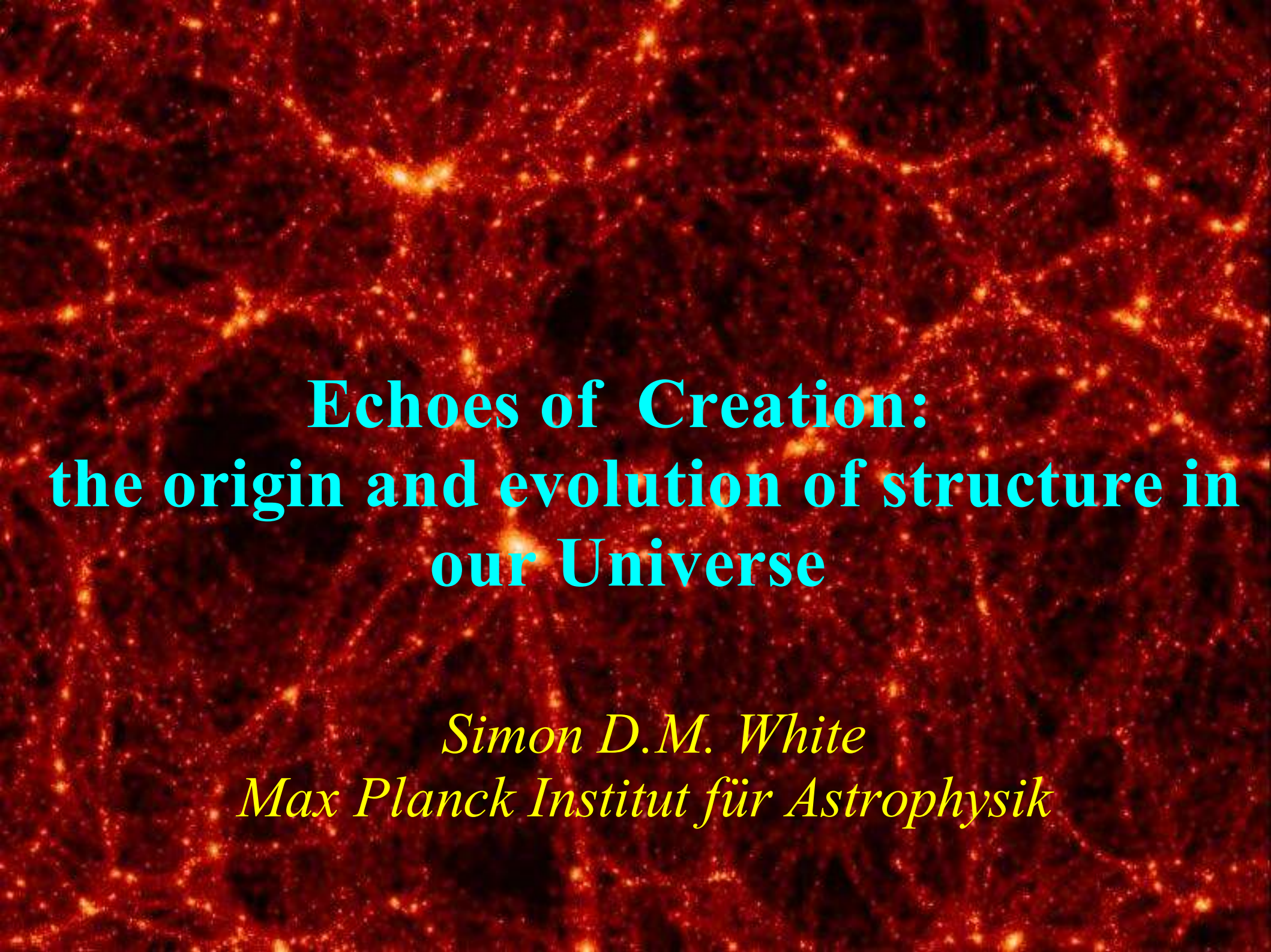


Echoes of Creation: the origin and evolution of structure in our Universe

Simon D.M. White
Max Planck Institut für Astrophysik

The Three Pillars of the Big Bang

I The expansion of the Universe

Eternally unchanging with continual Creation
or
Unending evolution after an instantaneous Creation

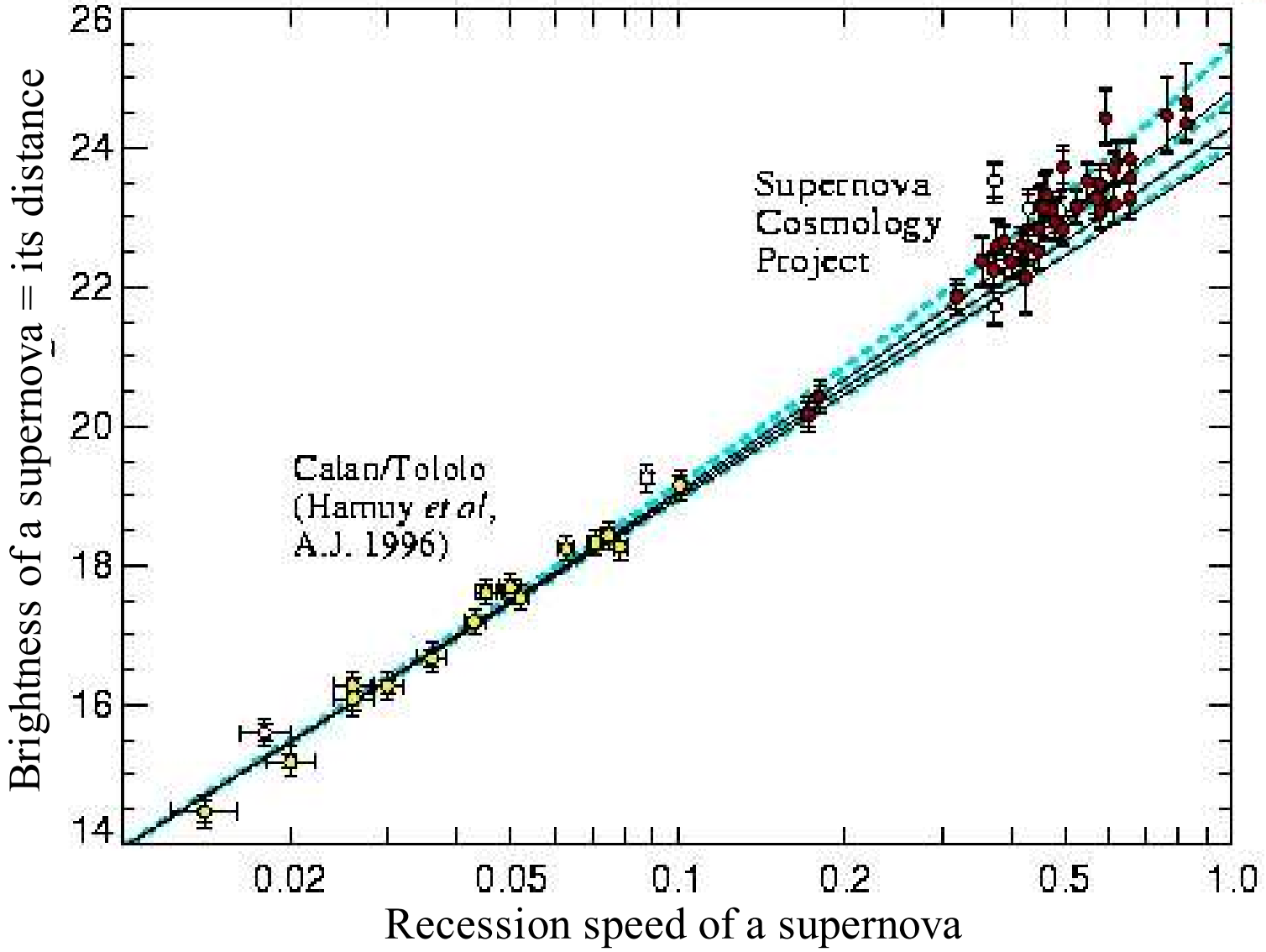
II The abundance of the elements

74% Hydrogen, 24% Helium, 2% `Dirt'
the ashes of the first three minutes and of long-dead stars

III The Cosmic Microwave Background

An all-pervading fossil of our fiery past

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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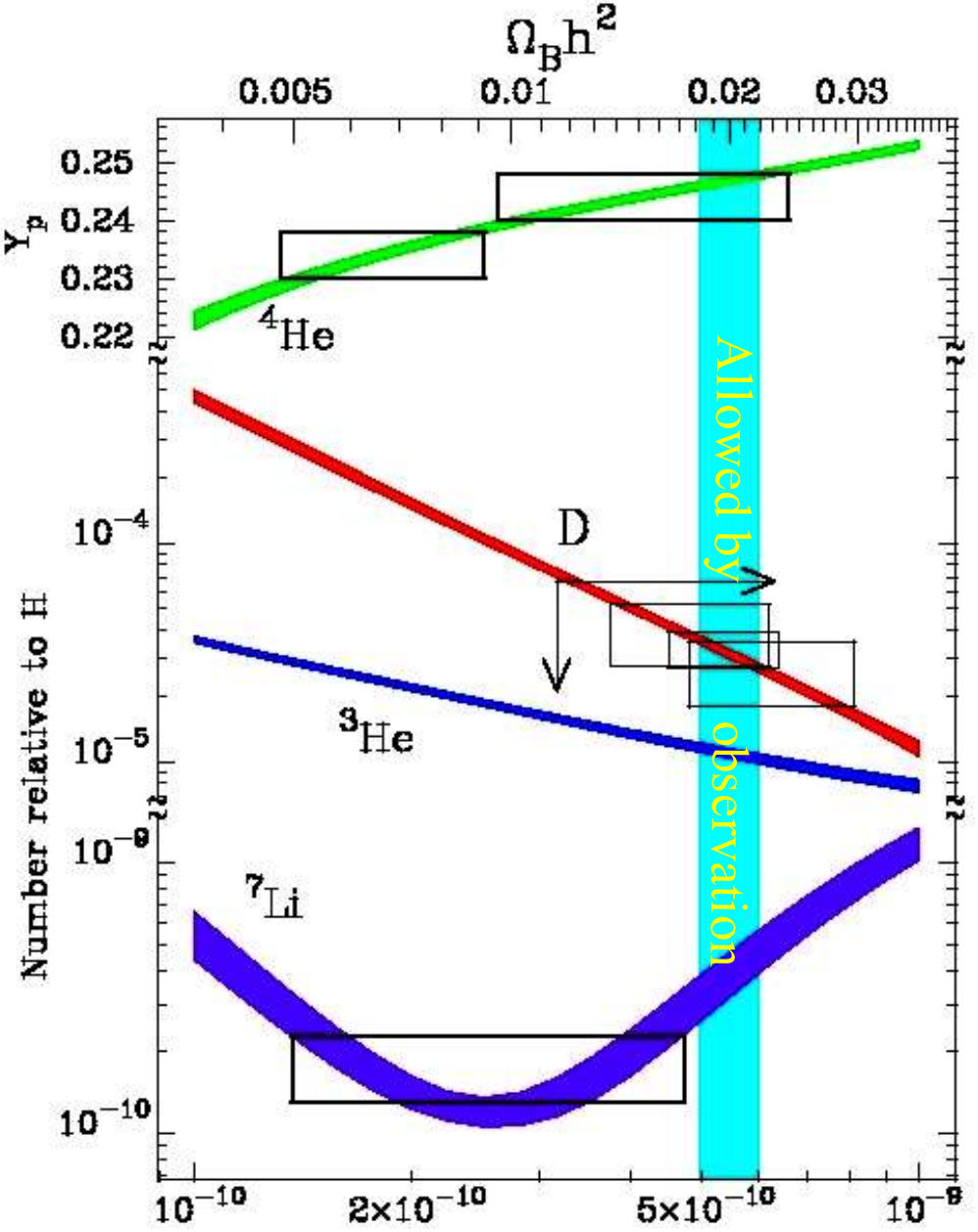
Element formation in the Early Universe

- During the very first 3 minutes the Universe "cools" to 10^9 C
- The nuclei of a few light elements are formed
  - Hydrogen (^{1}H, ^{2}H)
  - Helium (^{3}He, ^{4}He)
  - Lithium (^{7}Li)
- All the other elements formed later through nuclear reactions in stars and stellar explosions

The atoms in our bodies were made in stars



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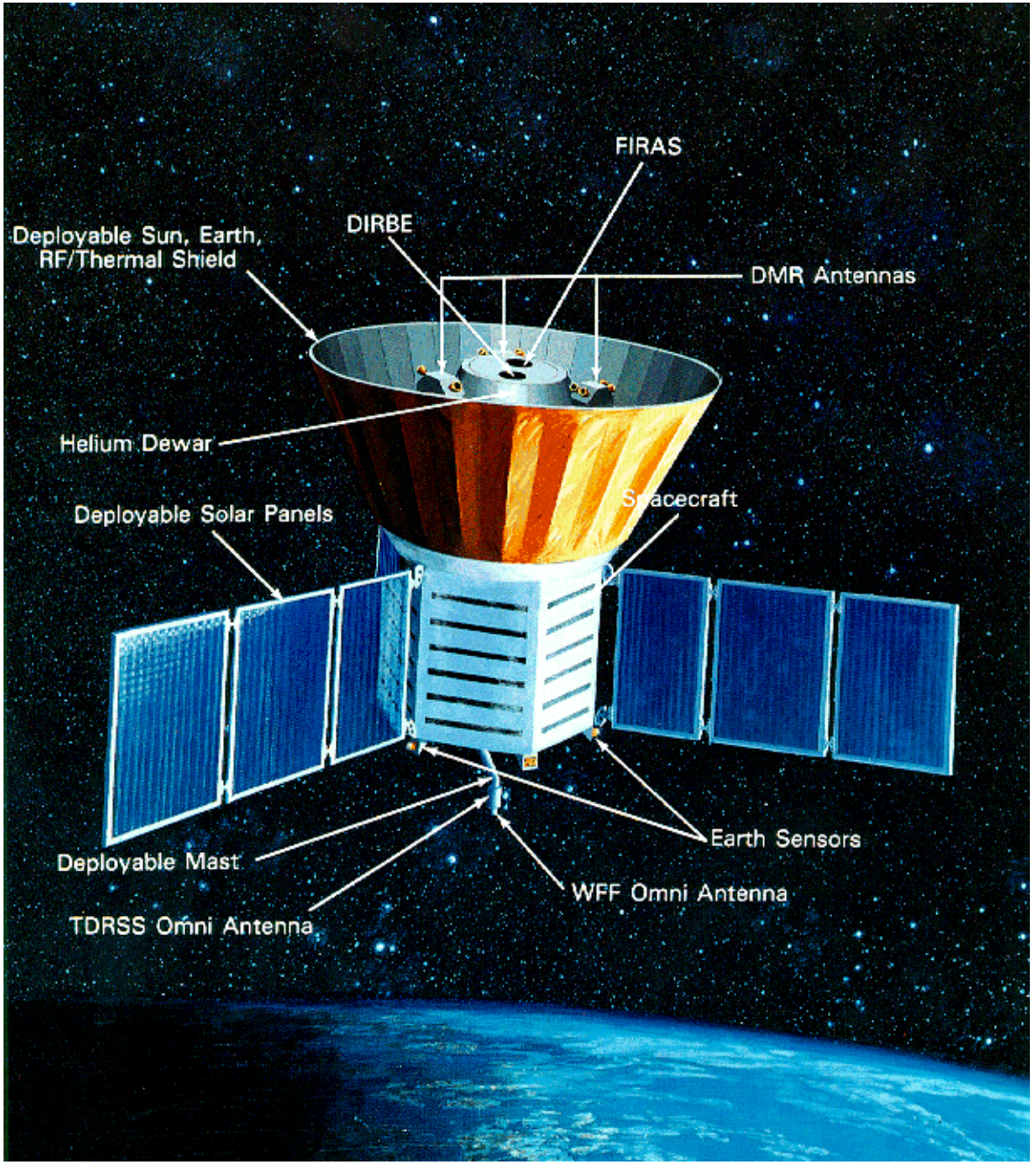
The COBE satellite (1989 - 1993)

- Three instruments

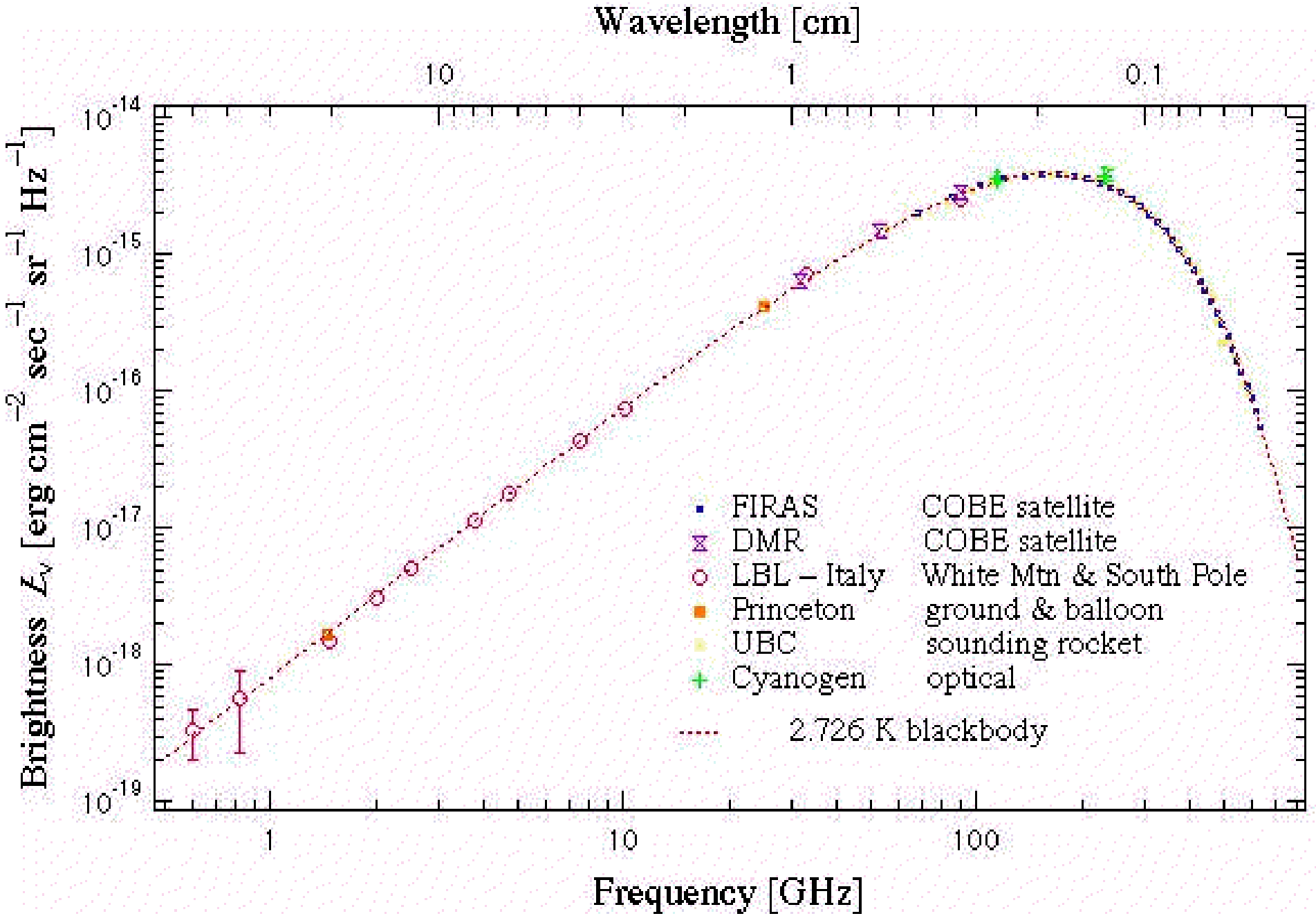
Far Infrared Absolute Spectroph.

Differential Microwave Radiom.

Diffuse InfraRed Background Exp



Spectrum of the Cosmic Microwave Background



What do we learn from the COBE spectrum?

- The microwave background radiation looks like thermal radiation from a `Planckian black-body'. This determines its temperature

  → T = 2.73K

- In the past the Universe was hot and almost without structure

  -- Void and without form --

  At that time it was nearly in thermal equilibrium

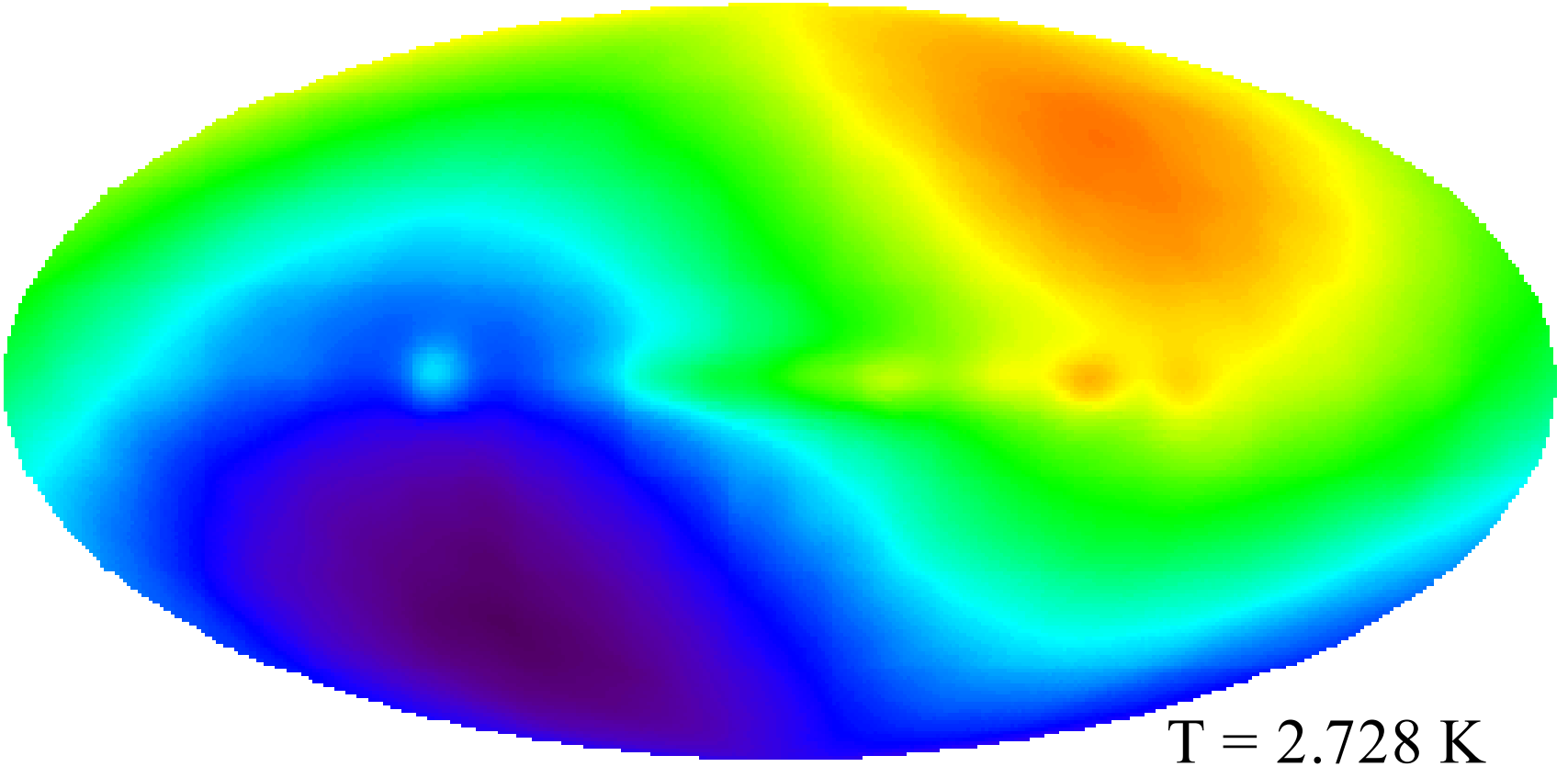
- There has been no substantial heating of the Universe since a few months after the Big Bang itself.

COBE's temperature map of the entire sky

T = 2.728 K

ΔT = 0.1 K

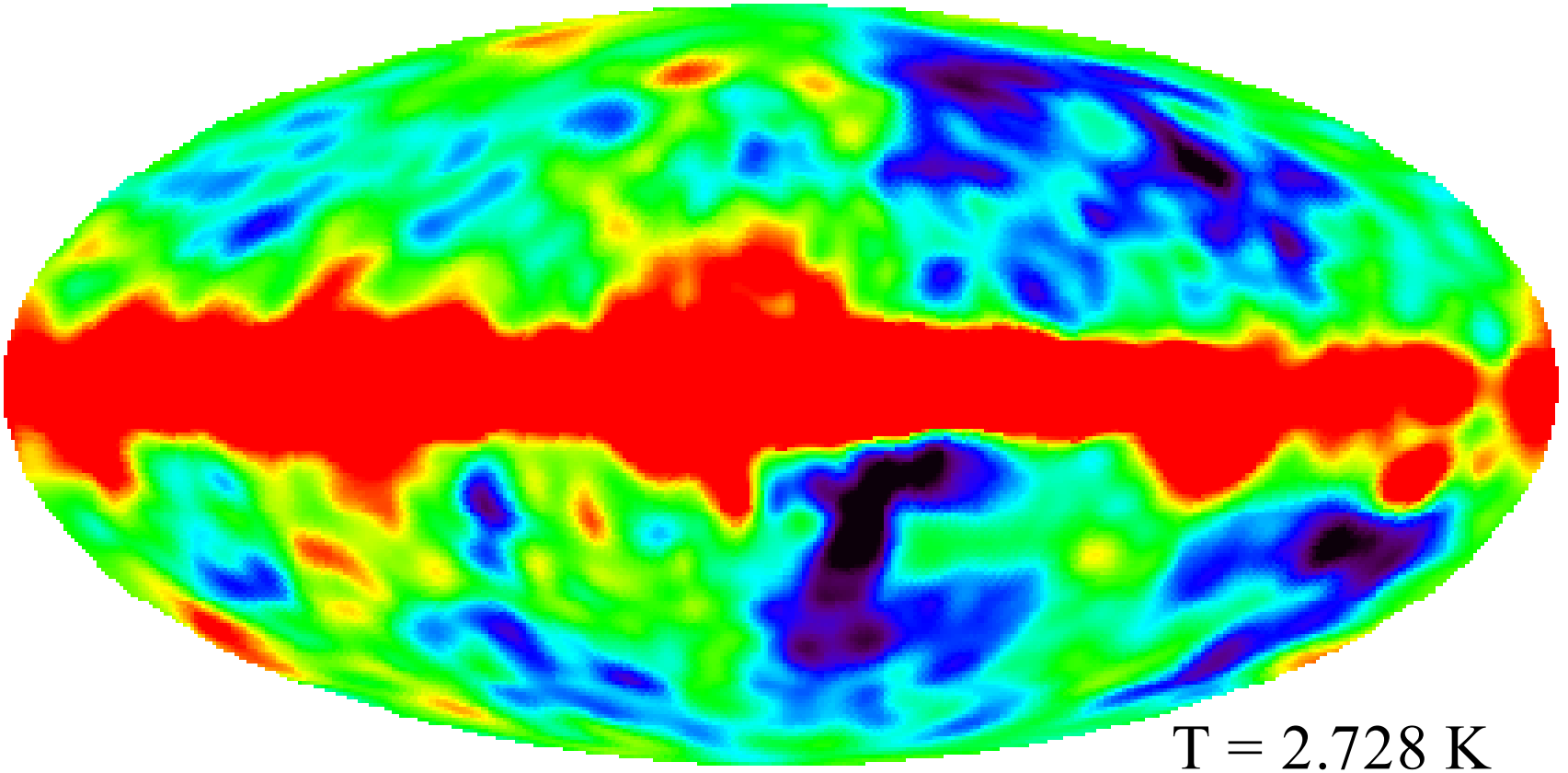
COBE's temperature map of the entire sky



T = 2.728 K

ΔT = 0.0034 K

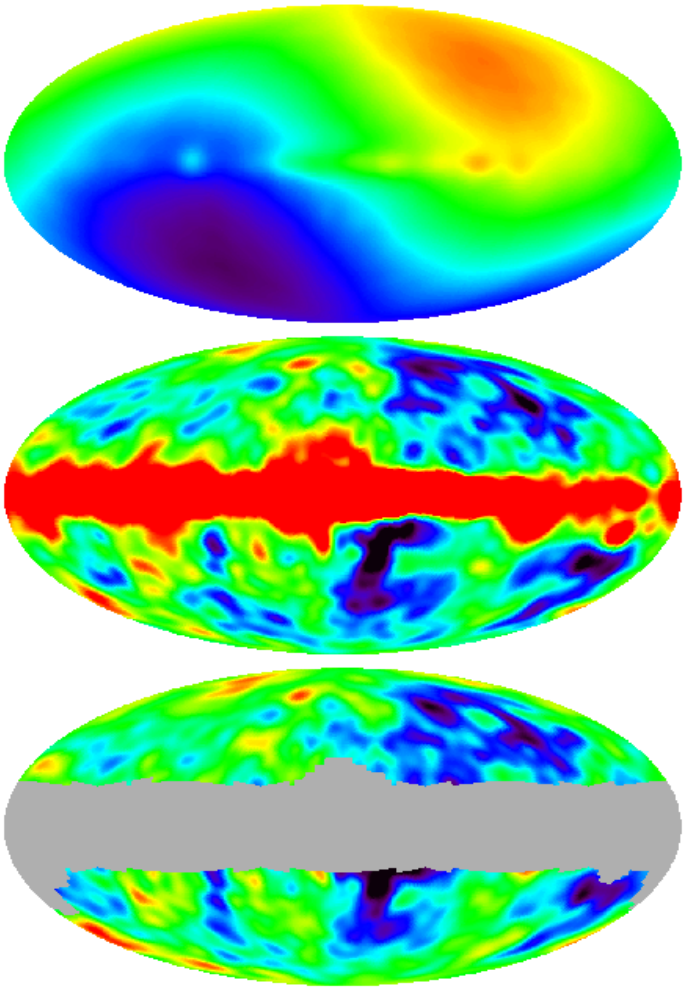
COBE's temperature map of the entire sky



T = 2.728 K

ΔT = 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 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 COBE maps)

When were they made?

A tiny fraction of a second after the Big Bang

What did they turn into?

Everything we see in the present Universe

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 Boomerang balloon flight (1998 - 1999)

A tour of the South Pole

29.12.1998 -- 9.1.1999

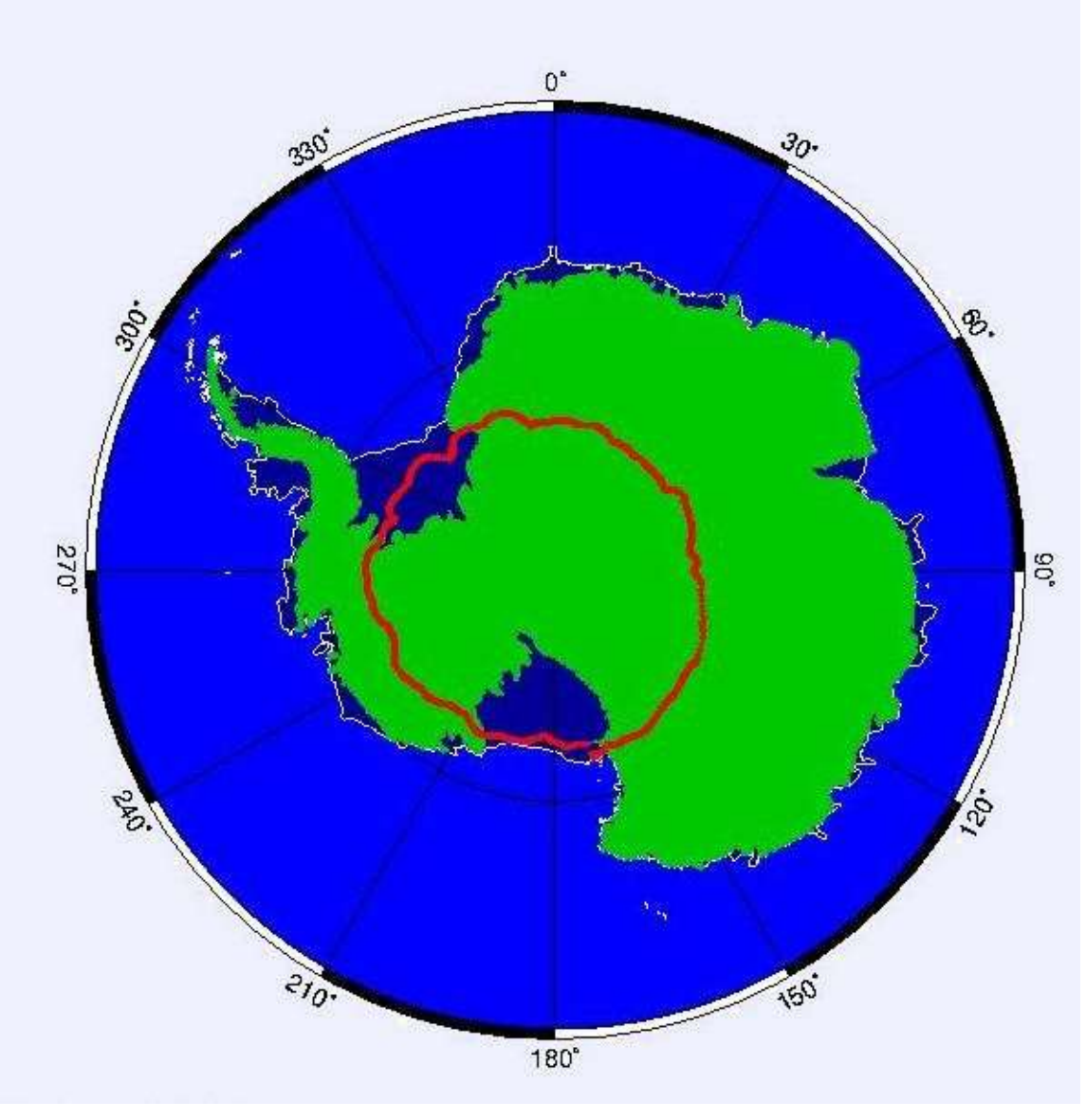
Height 37 km

Weight 1500 kg

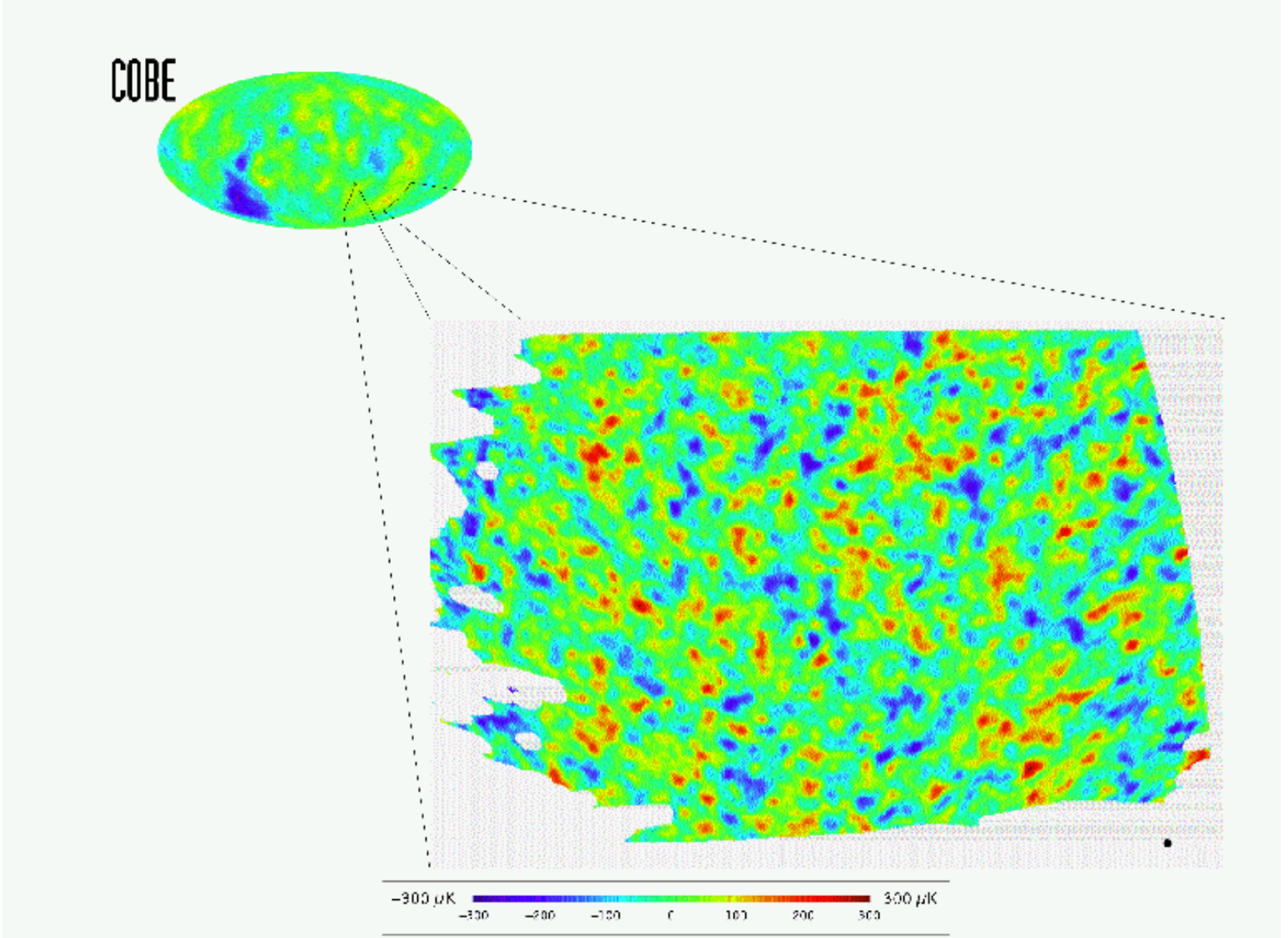
Telescope size 1.2m

Frequ. 90, 150, 240, 400 Ghz

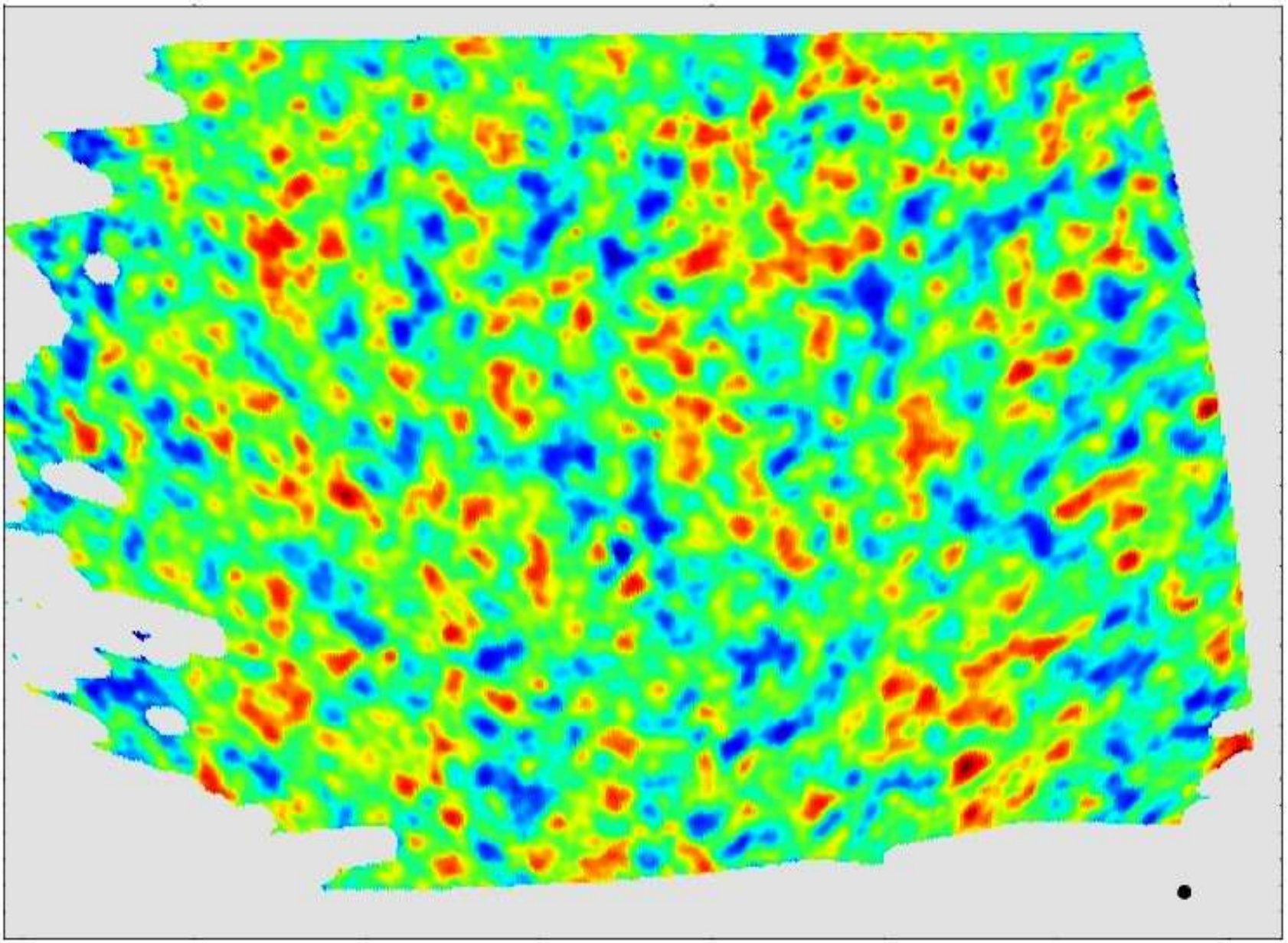
3% of the sky was mapped



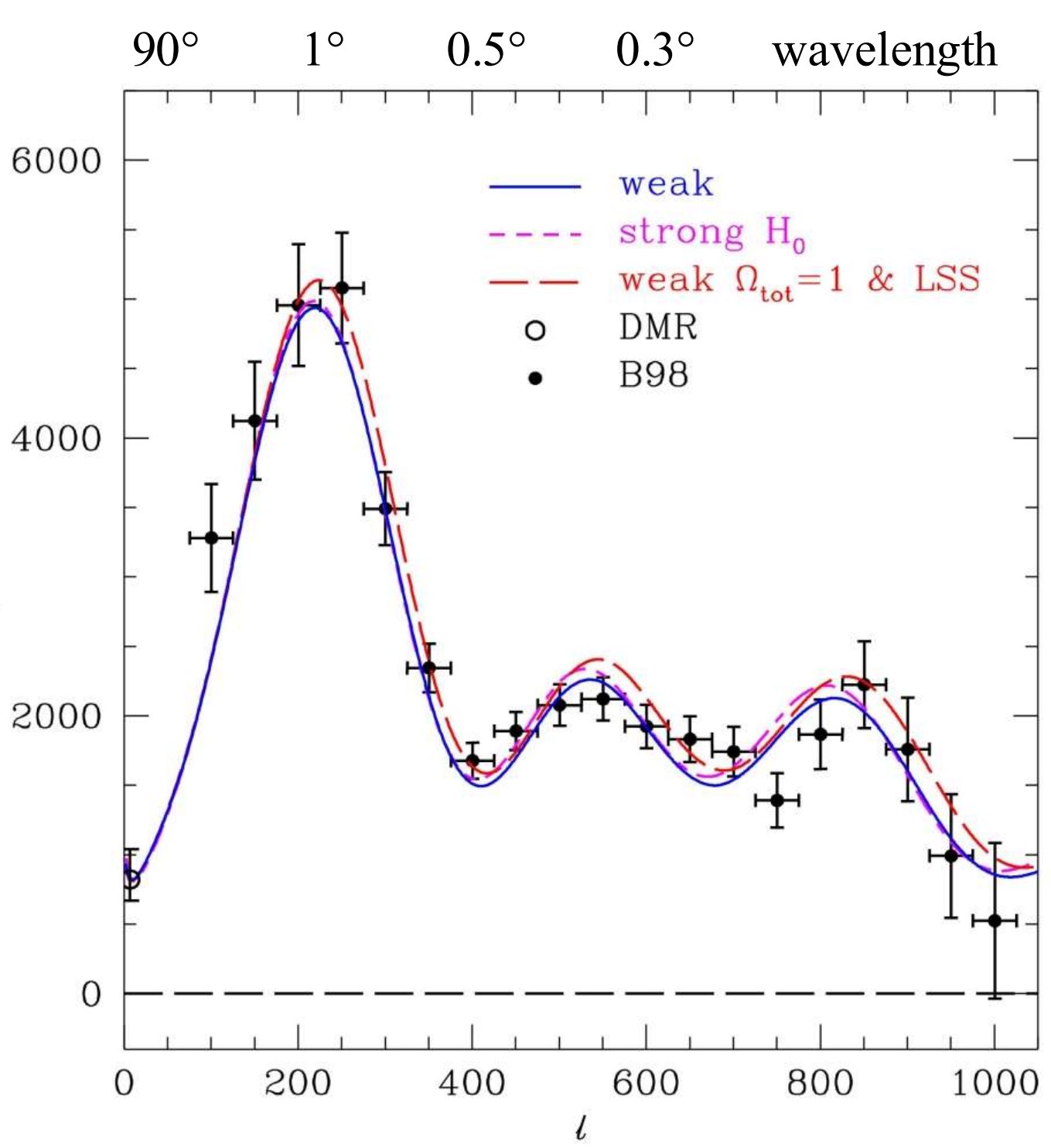
The Boomerang and COBE maps



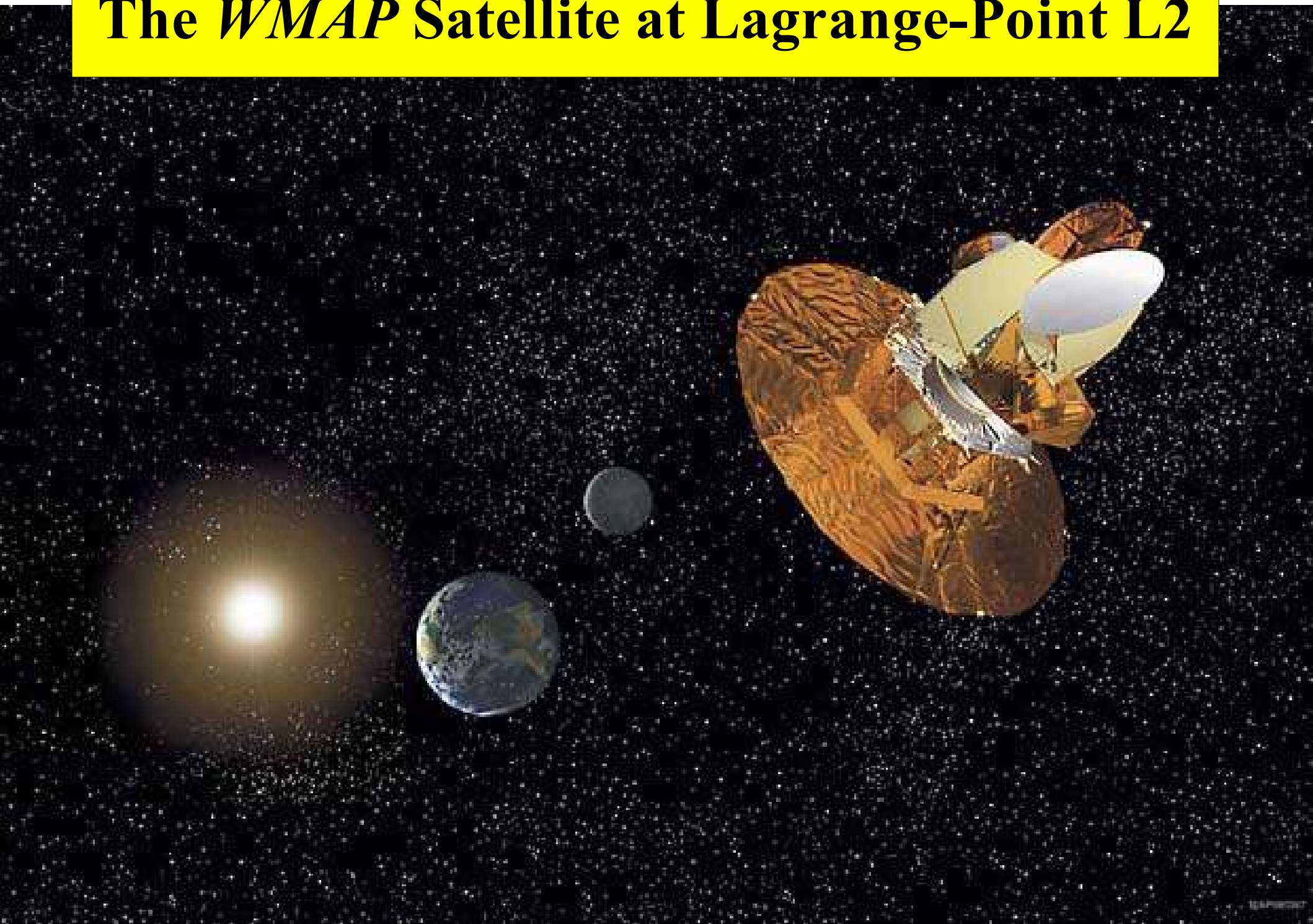
The Boomerang map at 150 Ghz



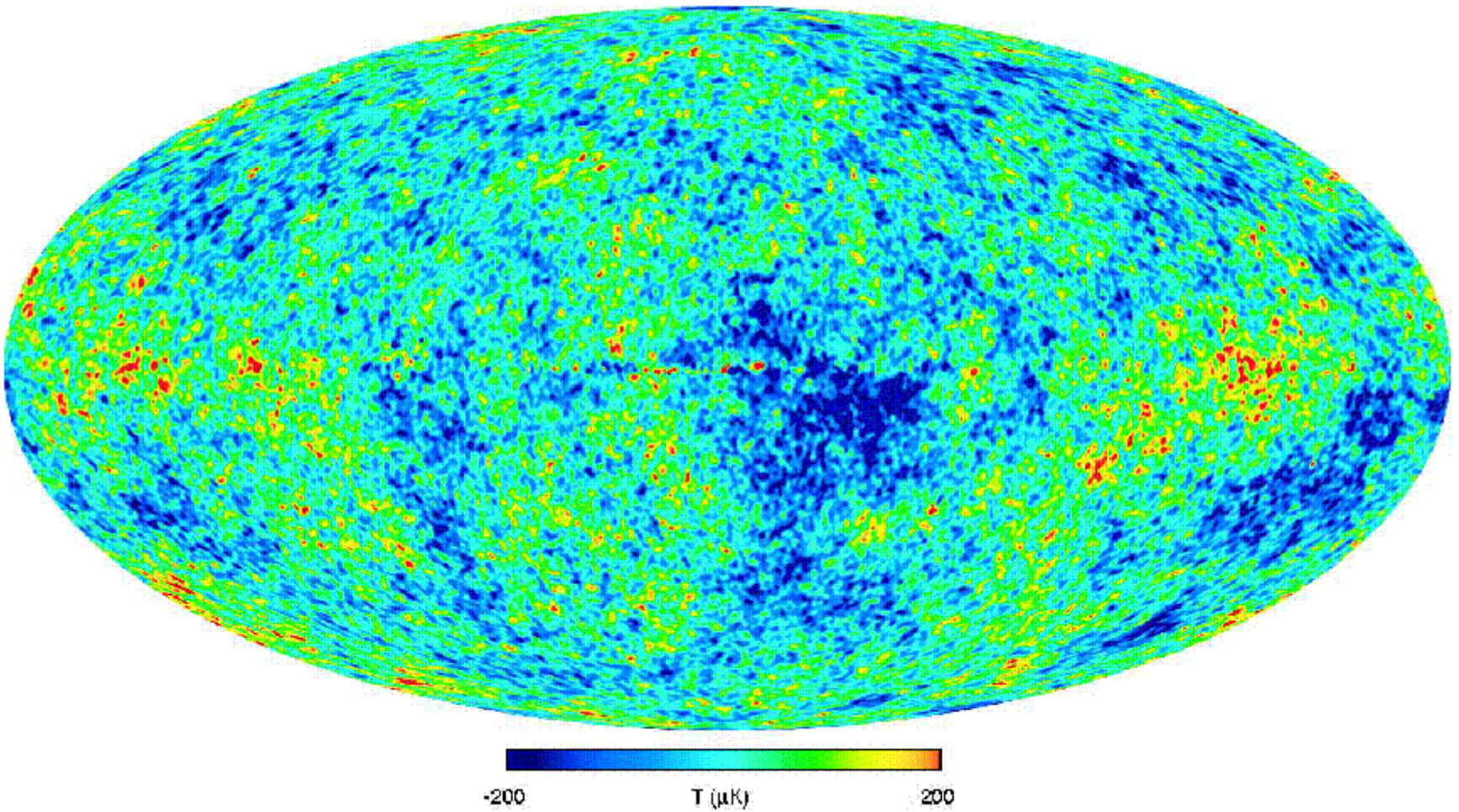
Structure in Boomerang maps of the microwave sky



The *WMAP* Satellite at Lagrange-Point L2

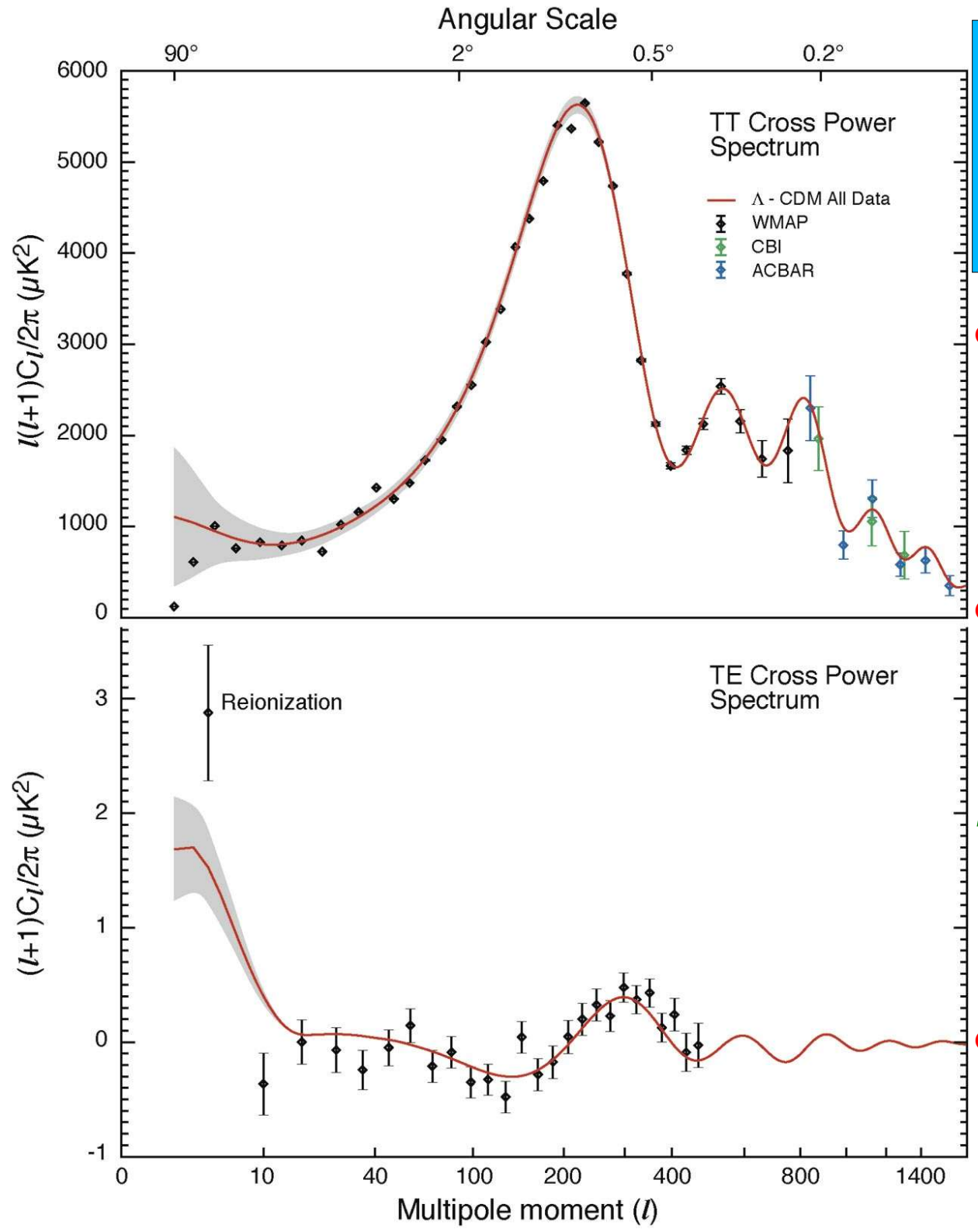


The *WMAP* of the whole CMB sky



Bennett et al 2003

The Emergence of the Cosmic Initial Conditions



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

$t_o = 13.7 \pm 0.2$ Gyr

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

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

$\Omega_b = 0.044 \pm 0.004$

$\tau_e = 0.17 \pm 0.07$

- Parameters in excellent agreement with other astronomical data

What have we learned from Boomerang and WMAP?

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

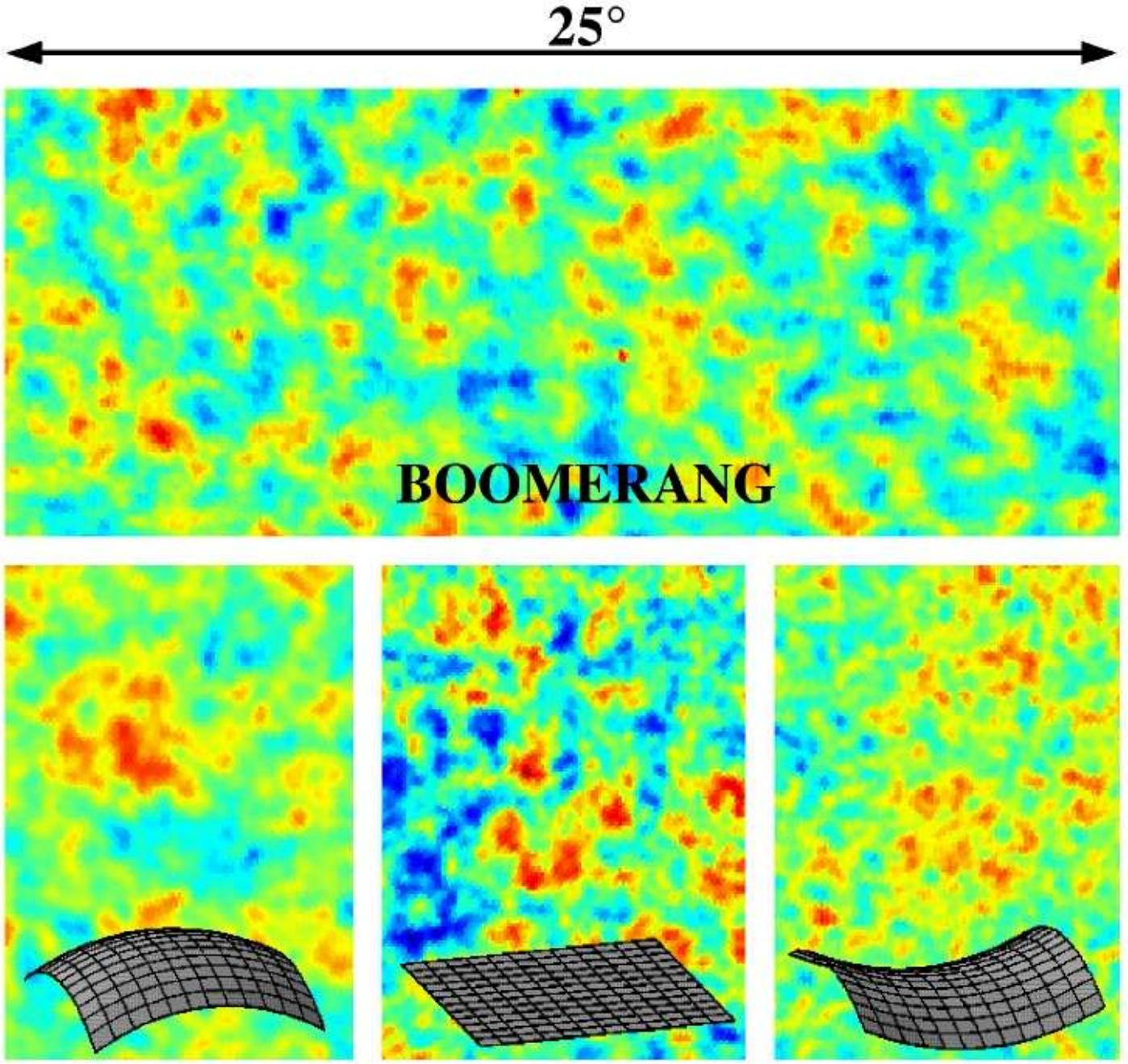
- Only a small fraction of it is made of ordinary matter -- about 4%
  → there is a lot of dark, nonbaryonic matter (about 30%)
  (which can be `seen' through gravitational lensing)

- 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

How Boomerang measured cosmic geometry



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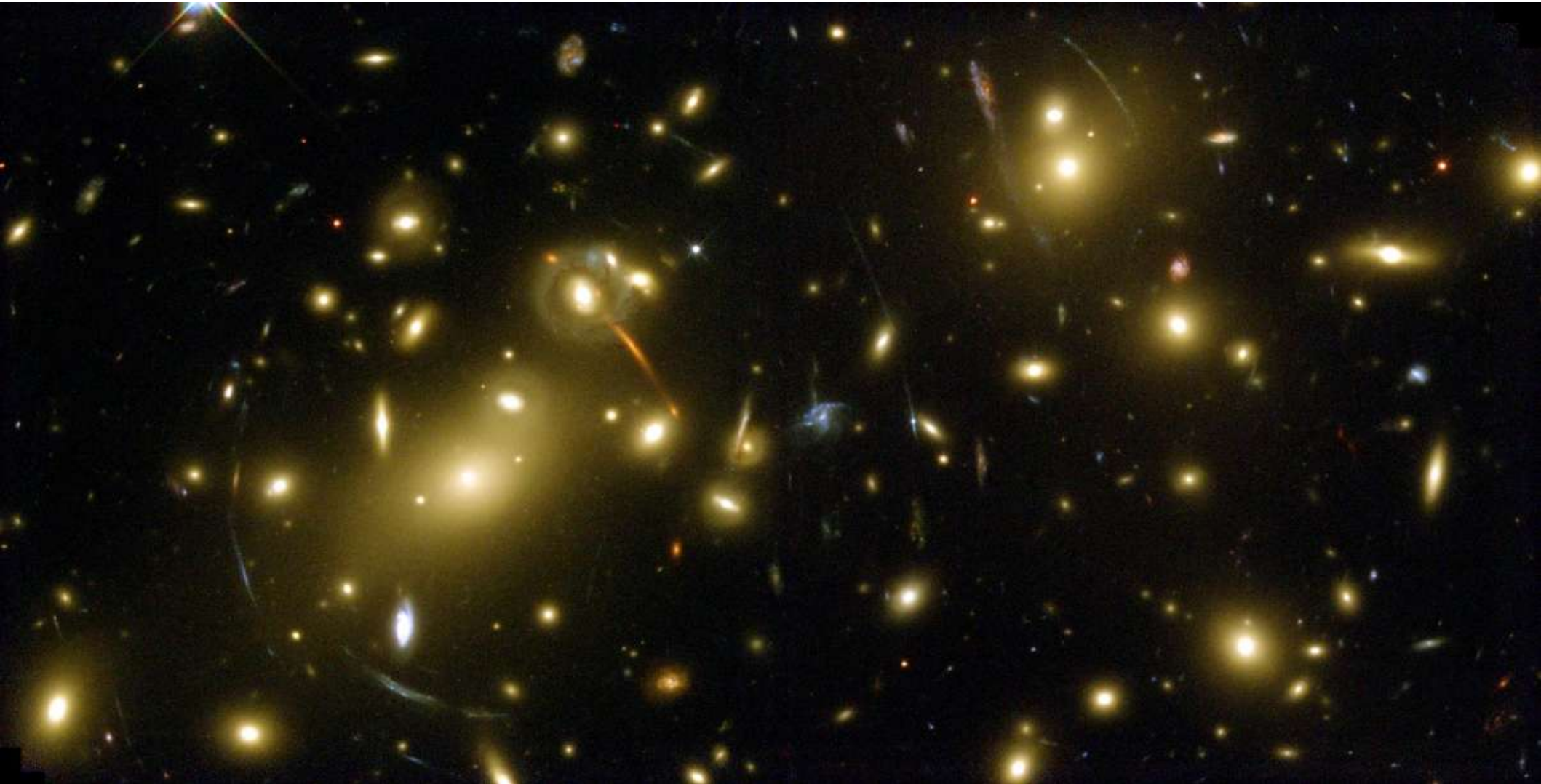
Gravitational lensing by a galaxy cluster

Abell 2218 z=0.17



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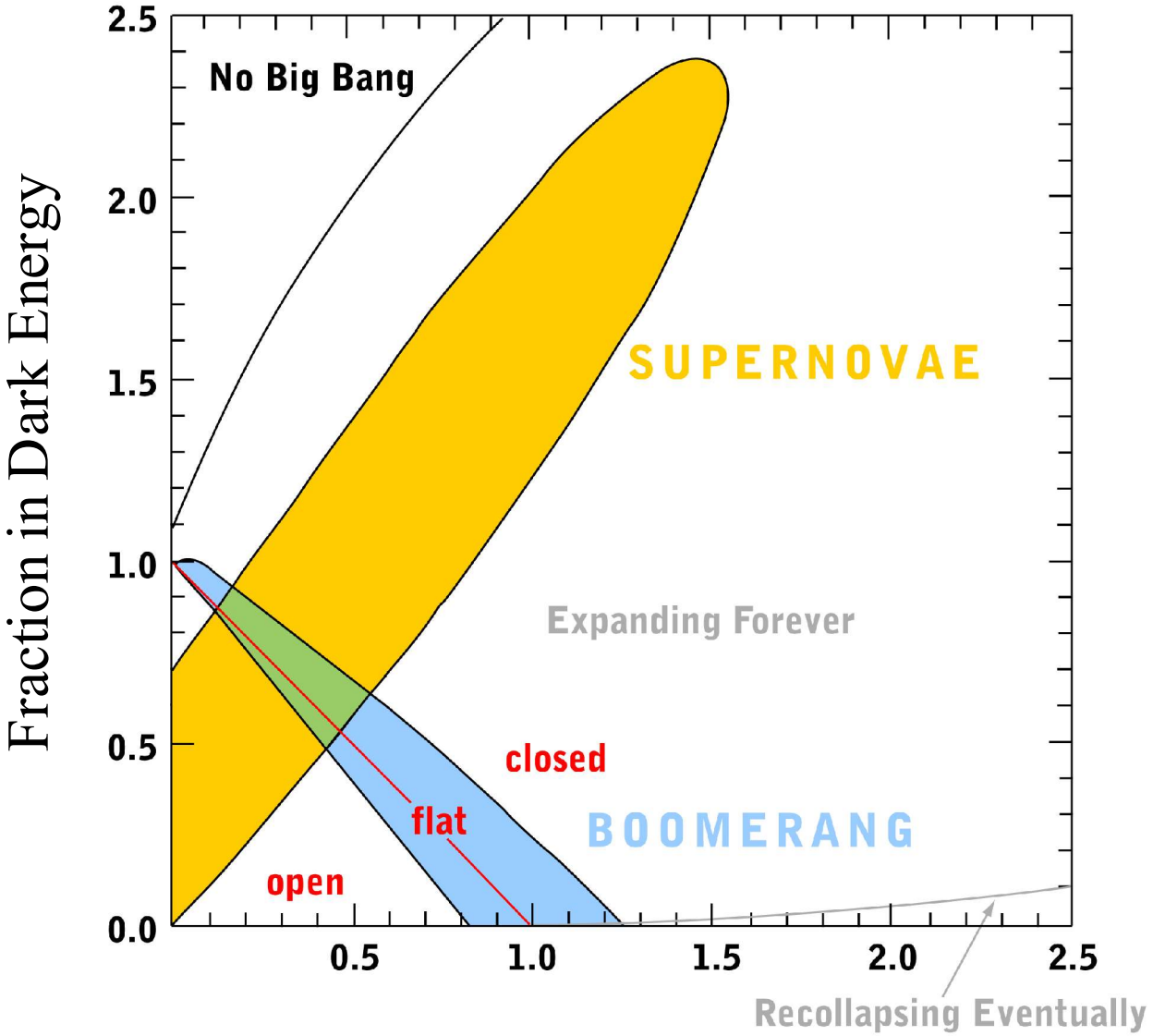
Cosmology after Boomerang and SNIa



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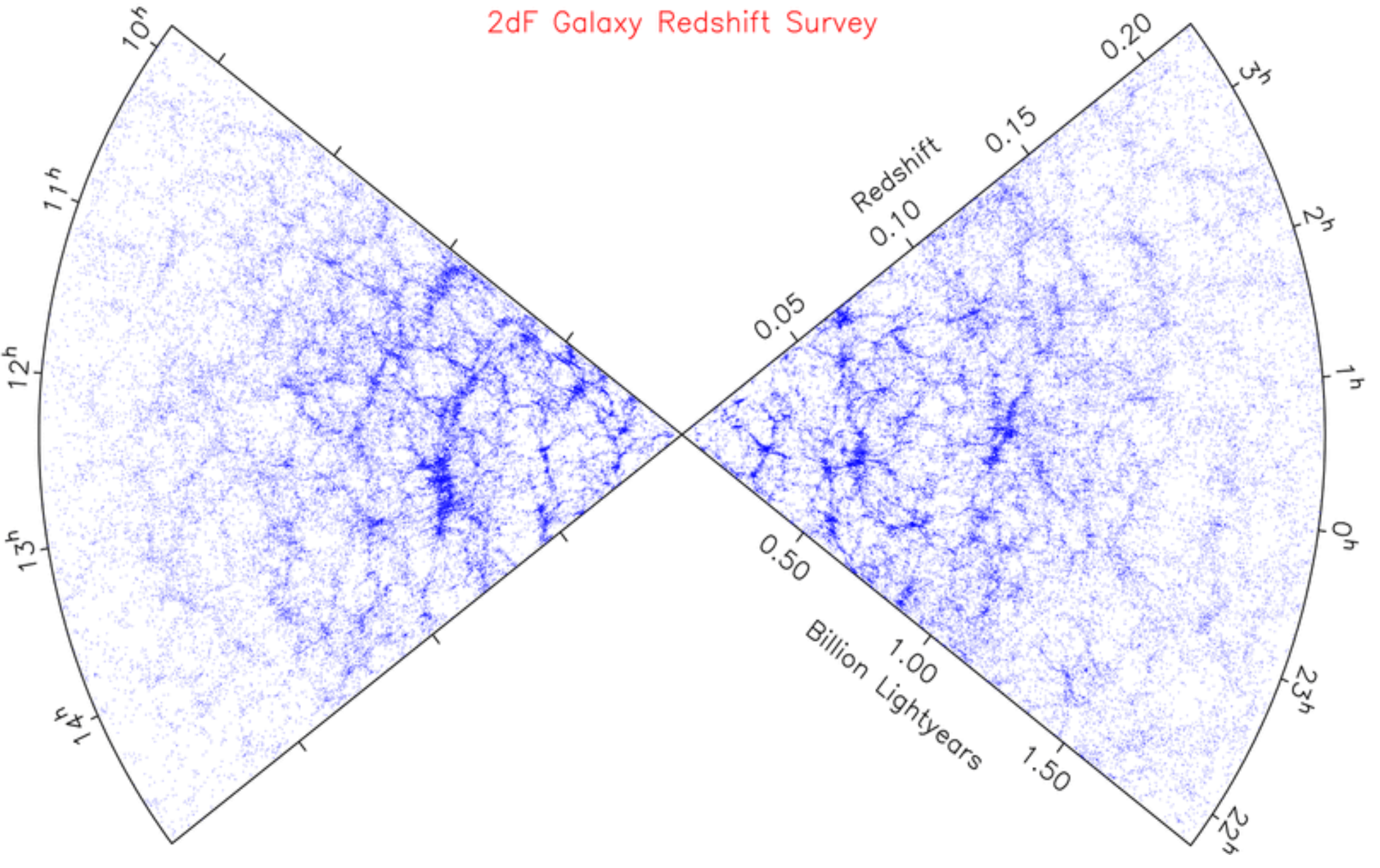
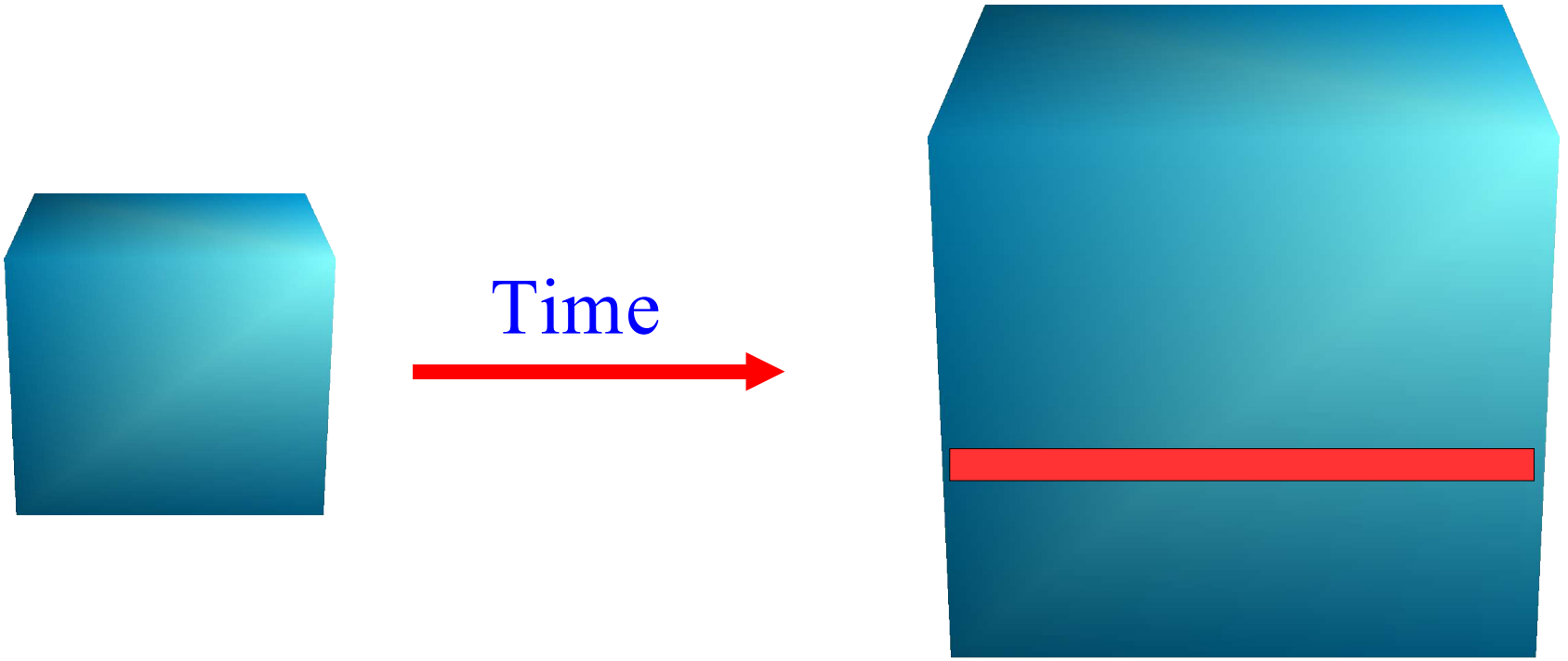
Nearby large-scale structure

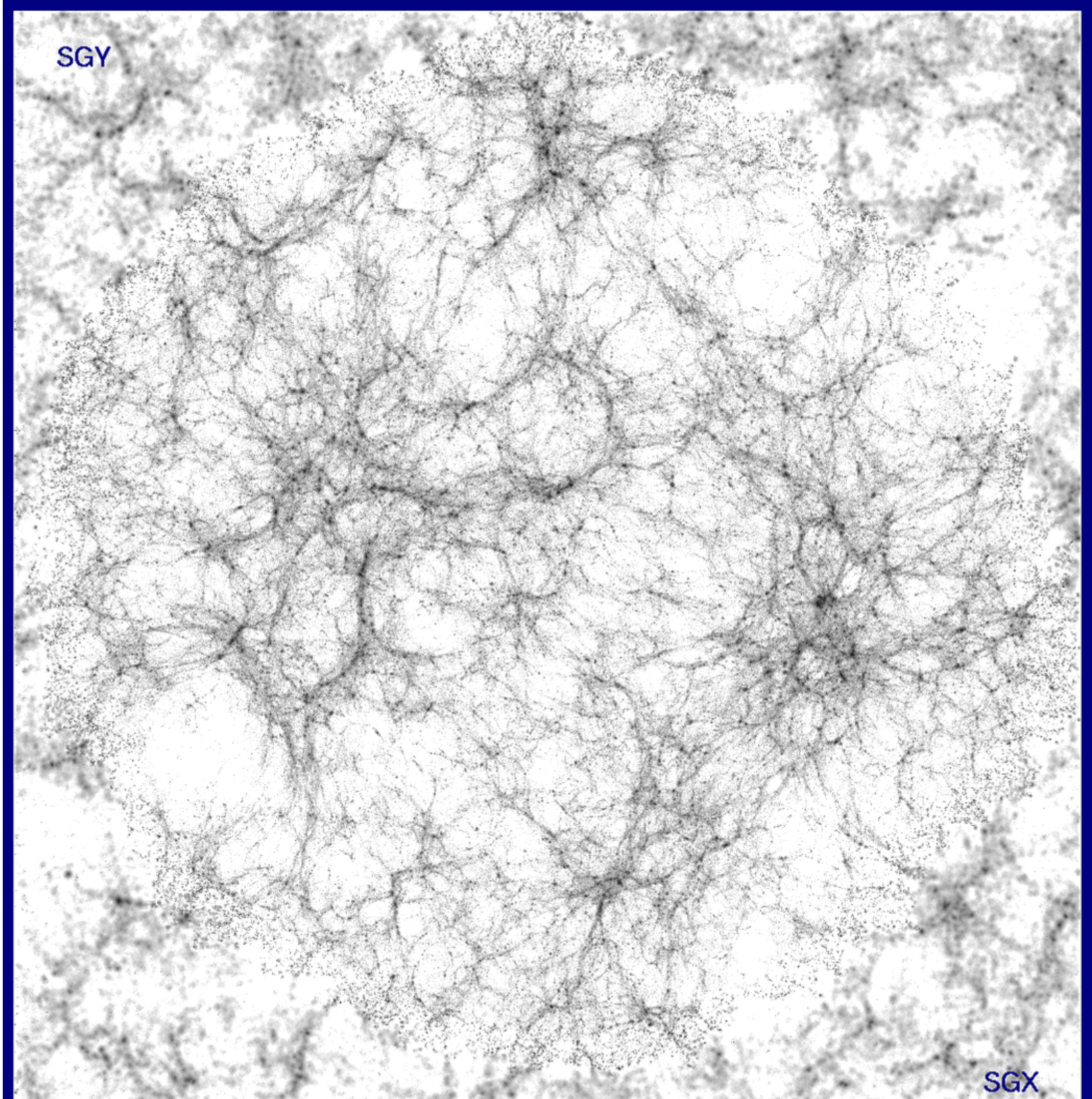


Evolving the Universe in a computer

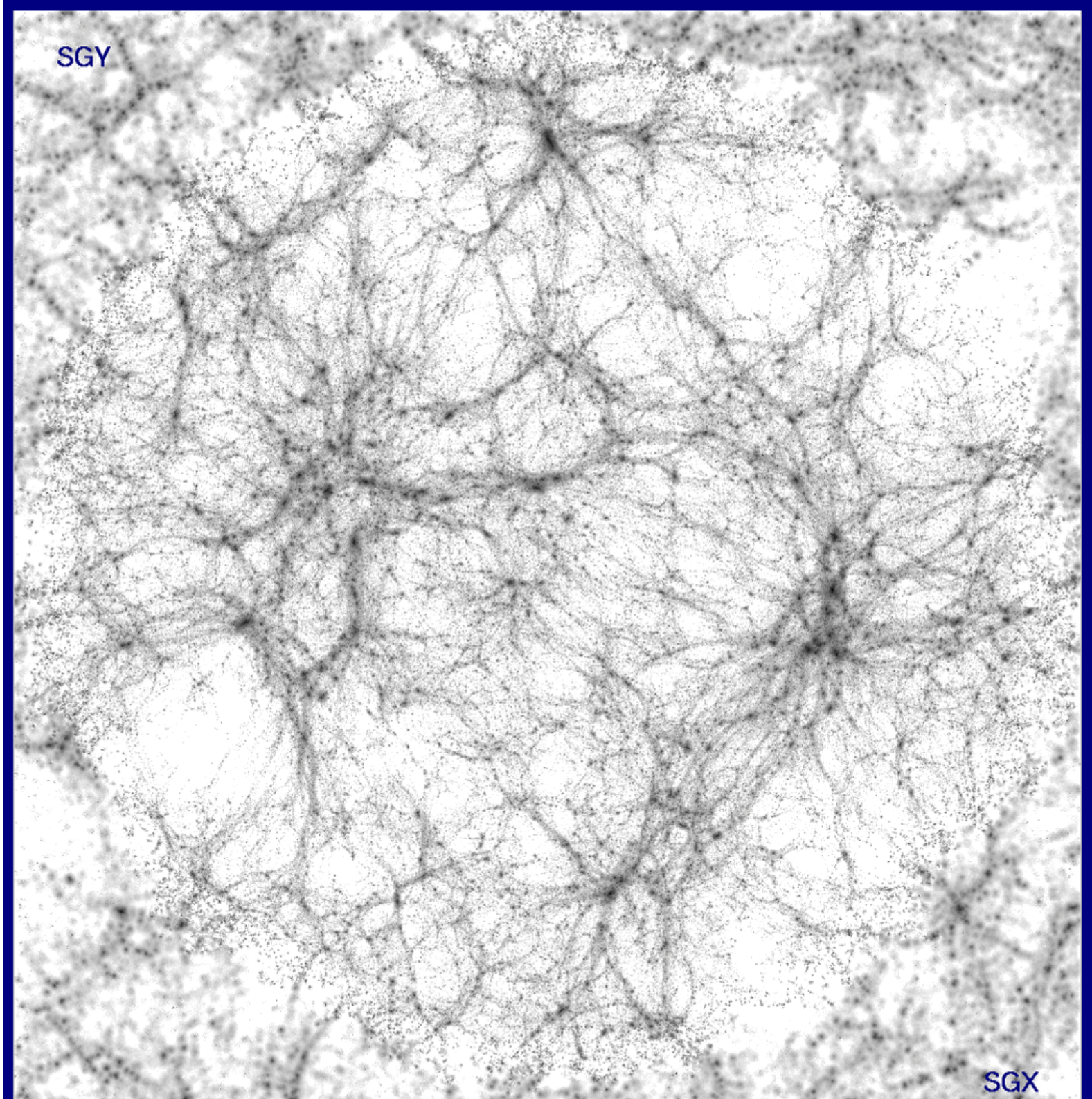


- Follow the matter in an expanding cubic region
- Start 300,000 years after the Big Bang
- Match initial conditions to the observed Microwave Background
- Calculate evolution forward to the present day

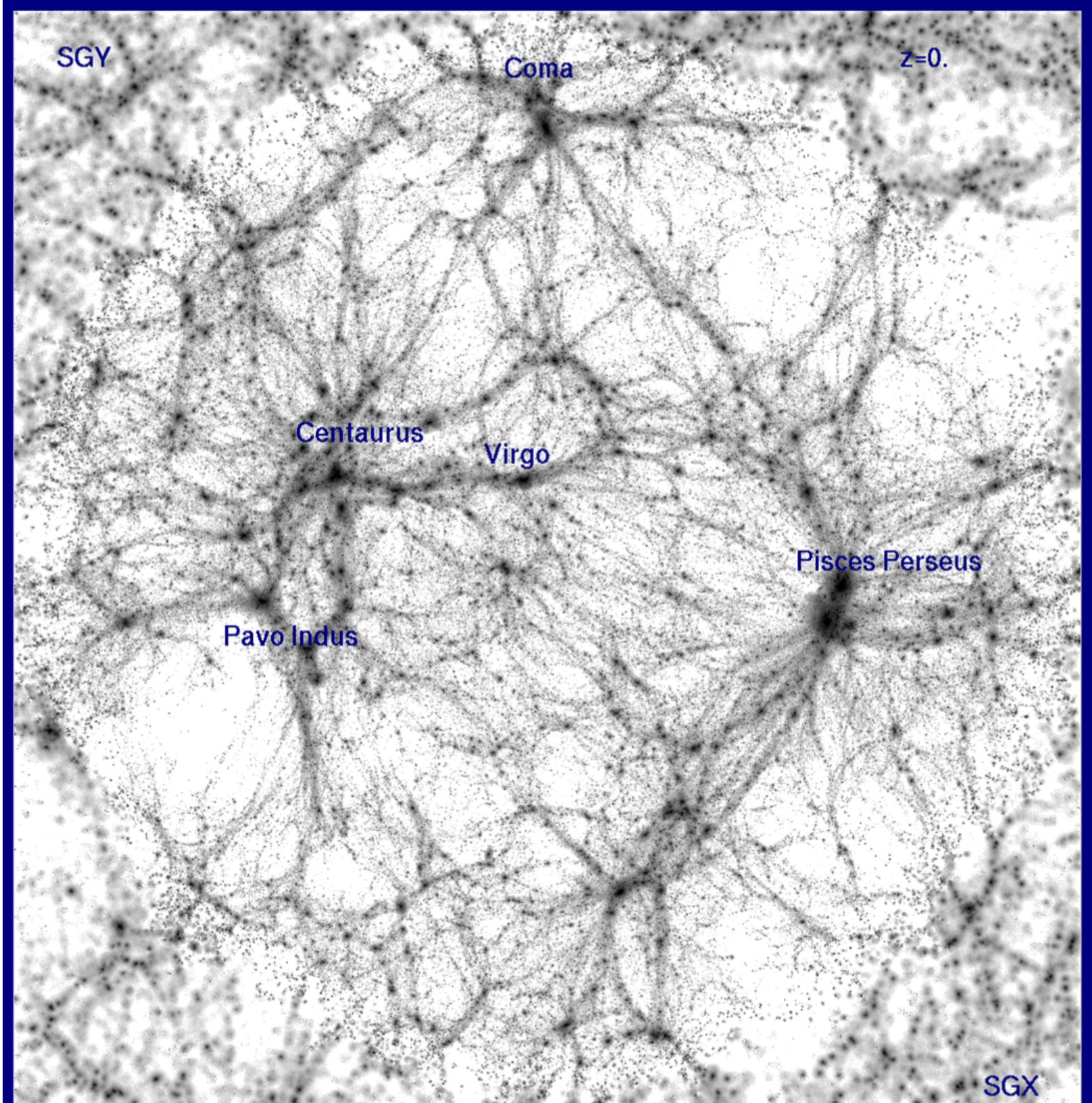
The local Universe at z = 2.4



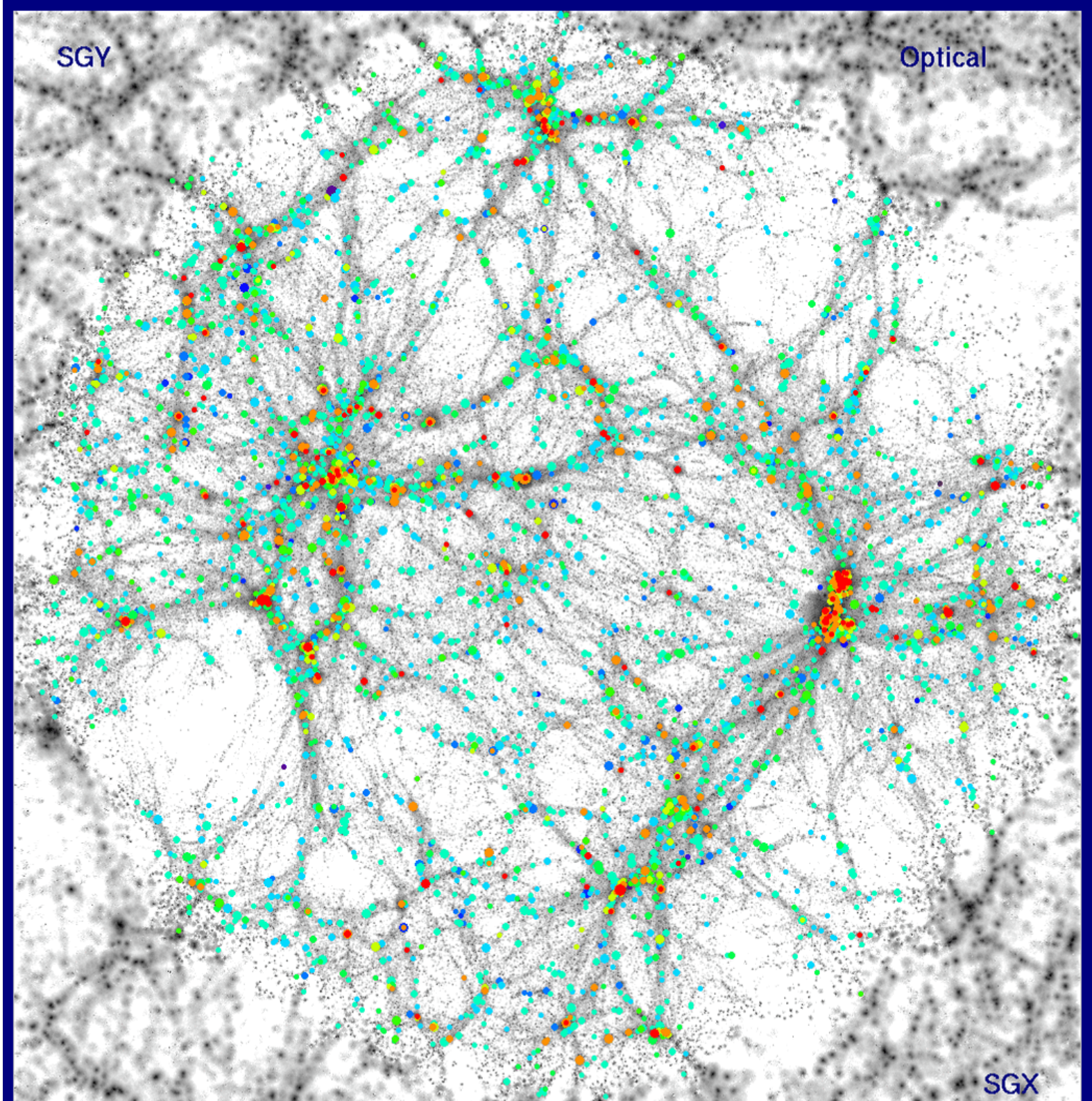
The local Universe at z=0.8



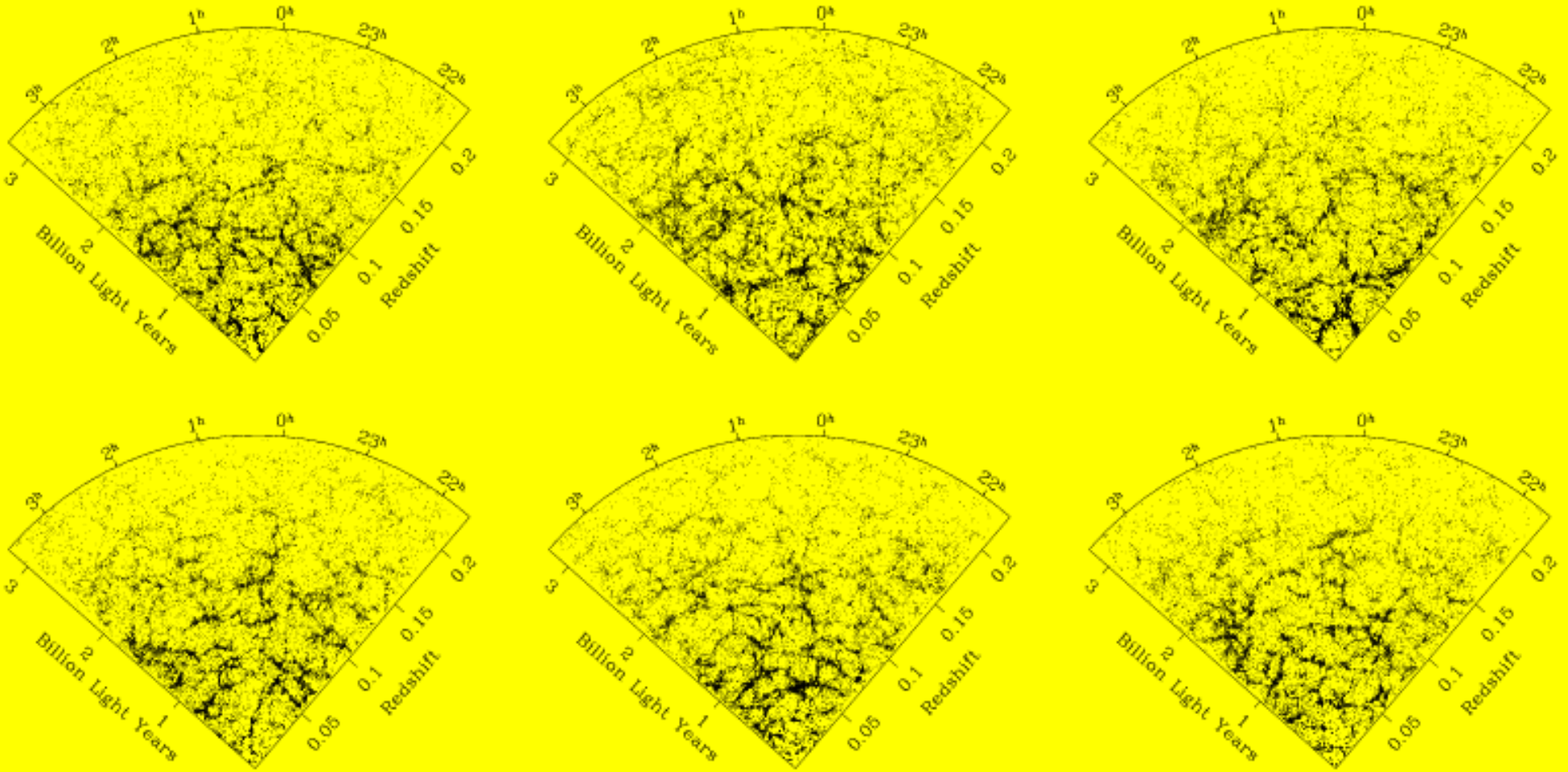
The local Universe today



The local Universe *with* galaxies

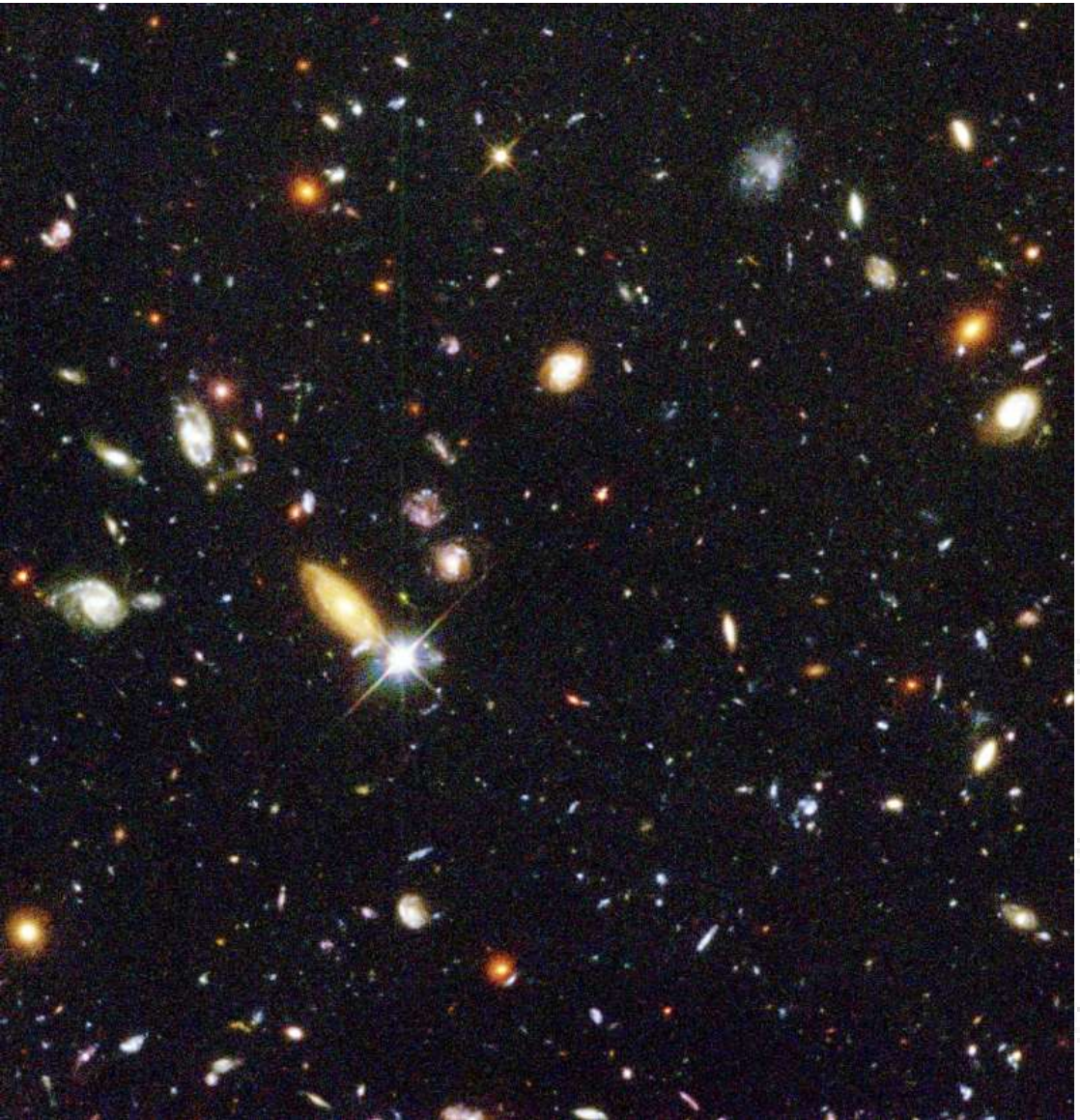


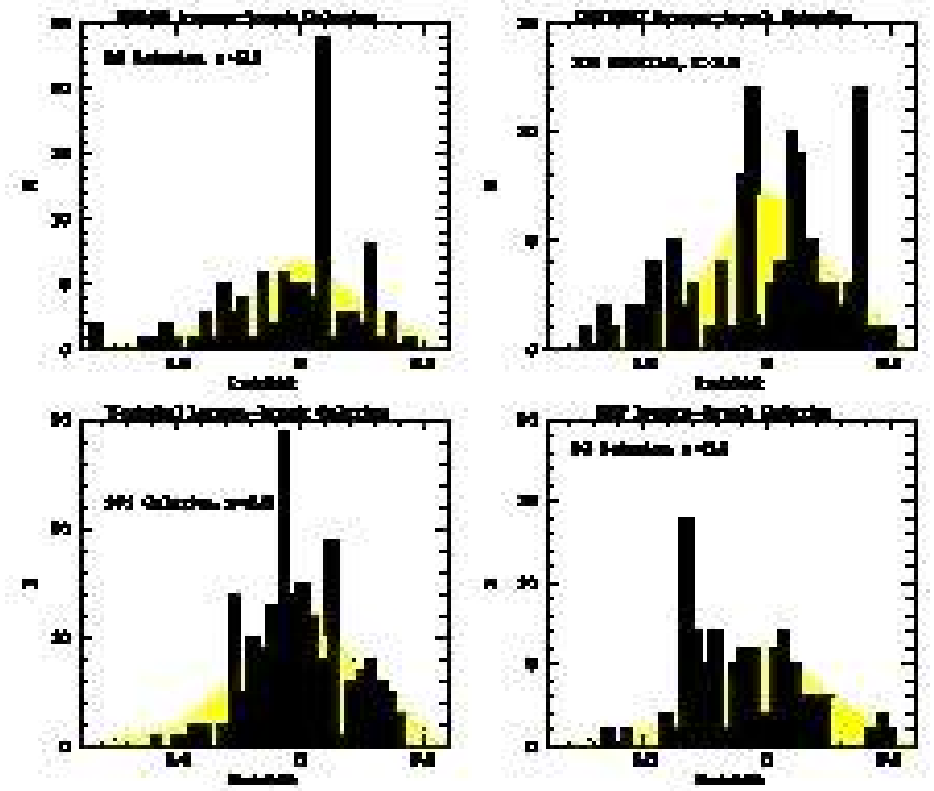
VIRTUAL vs REAL UNIVERSES II

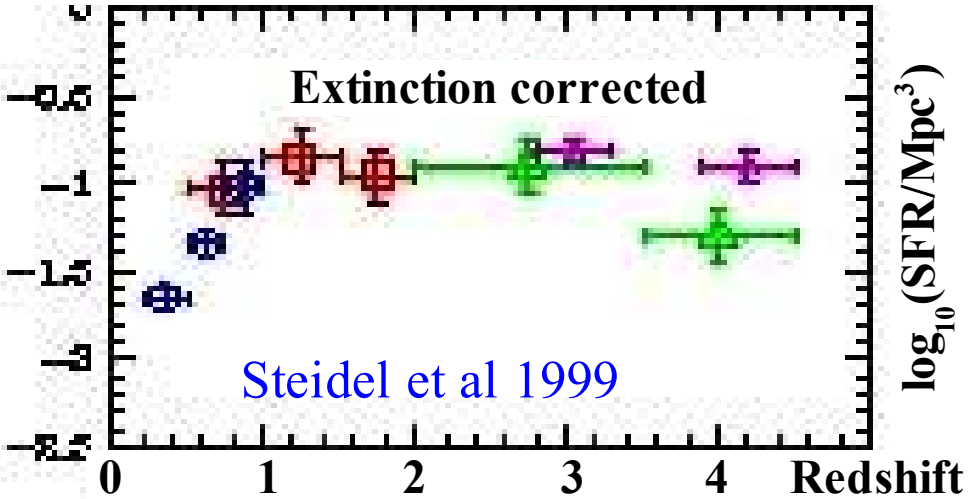


Telescopes as time machines: seeing the past directly

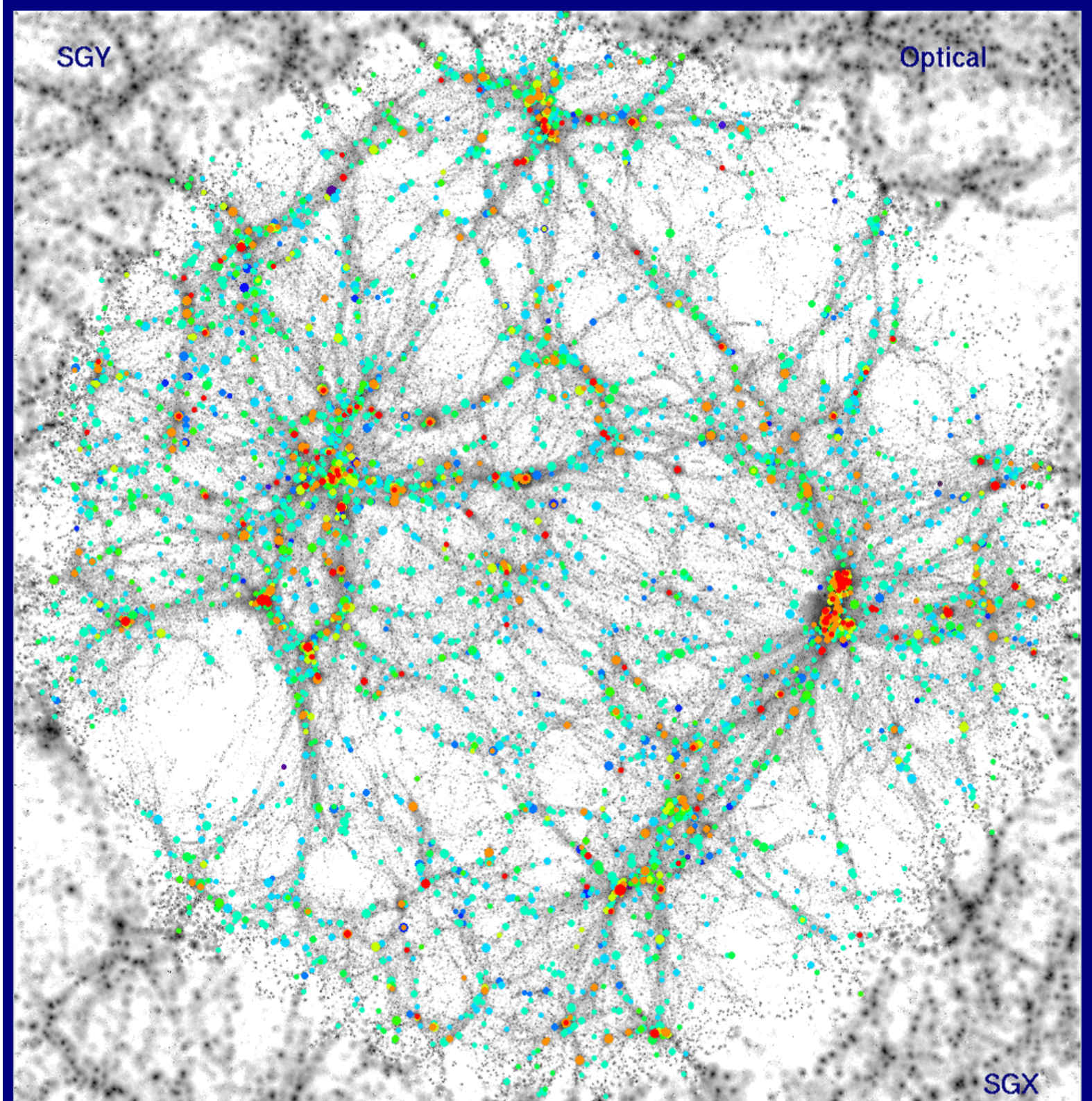
The Hubble Deep Field





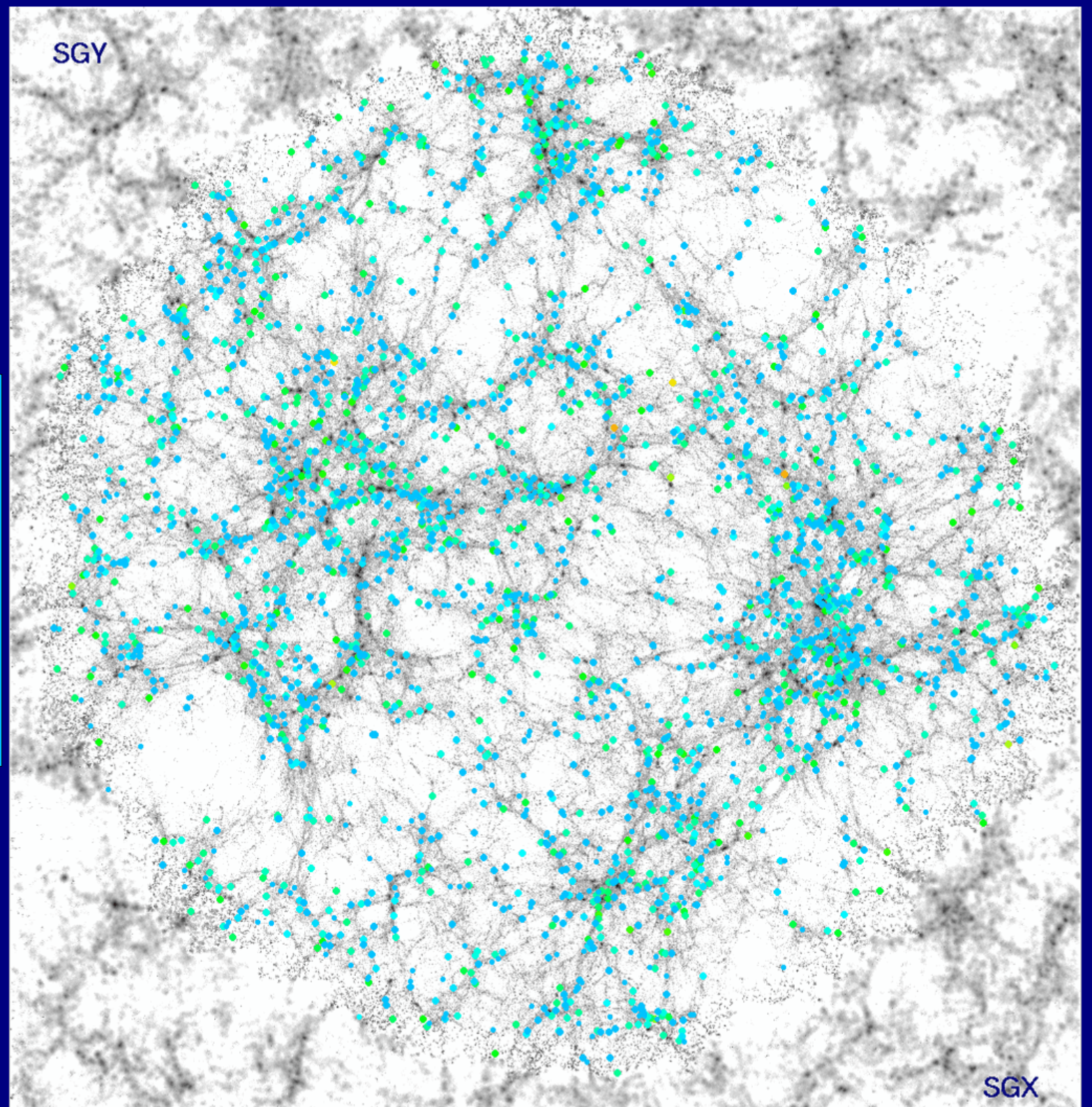


The local Universe *with* galaxies

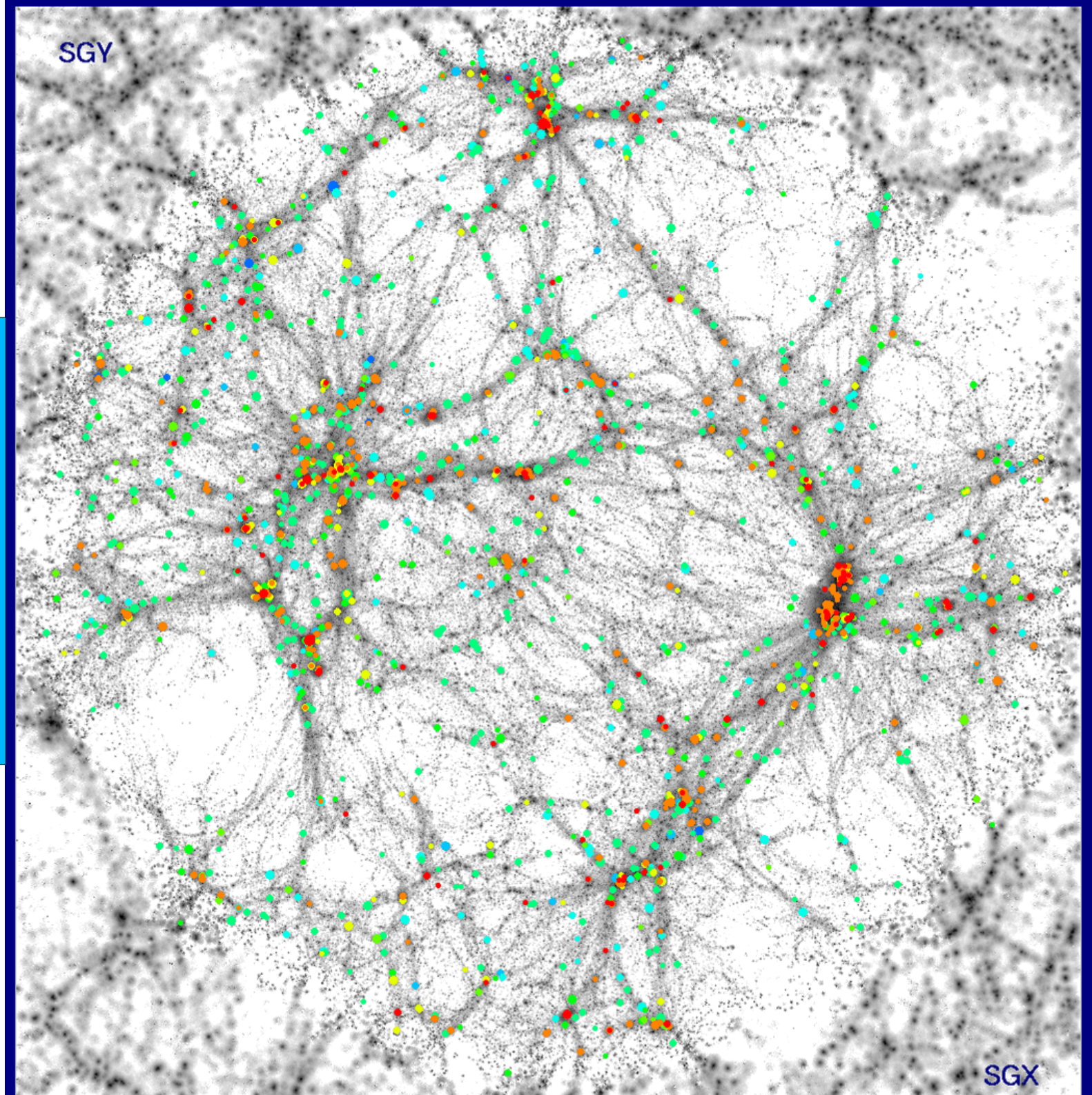


Bright galaxies at redshift $z=2.4$

SFR>5.0



Present-day descendents of bright galaxies from redshift z=2.4



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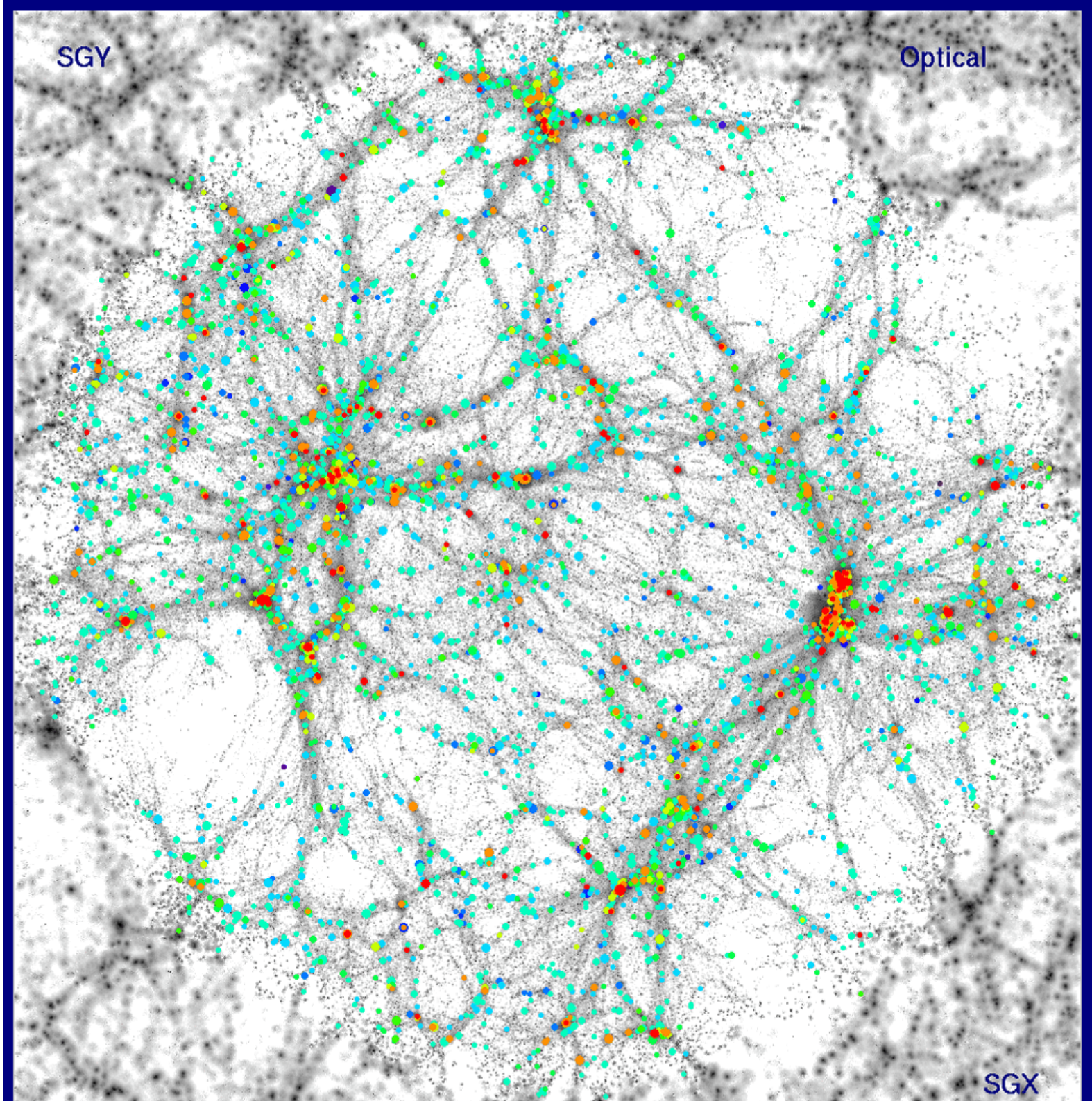

.... and so in summary

- Our Universe began in fire 14 billion years ago
- The expansion is accelerating into an eternal frost
- All structure originated in rolls of the quantum dice
- We are made from the ashes of stars
- Most of the Universe is made of something else, as yet unseen on Earth