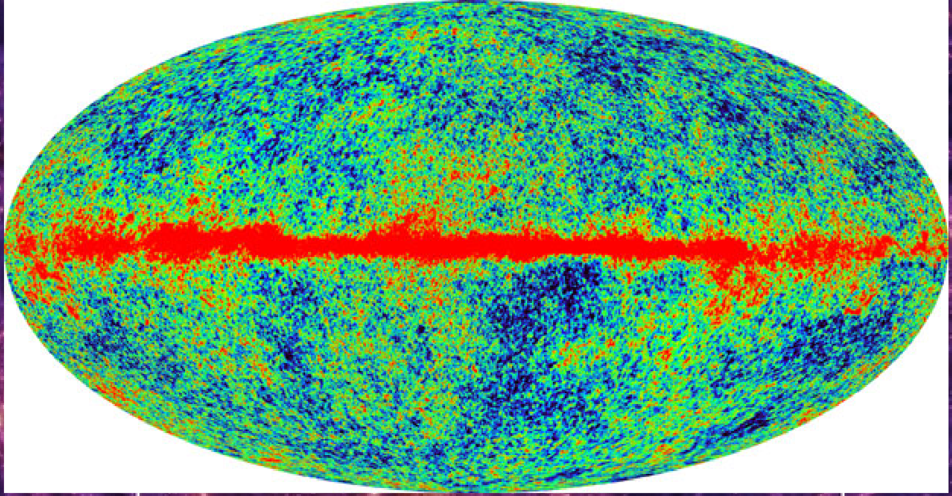
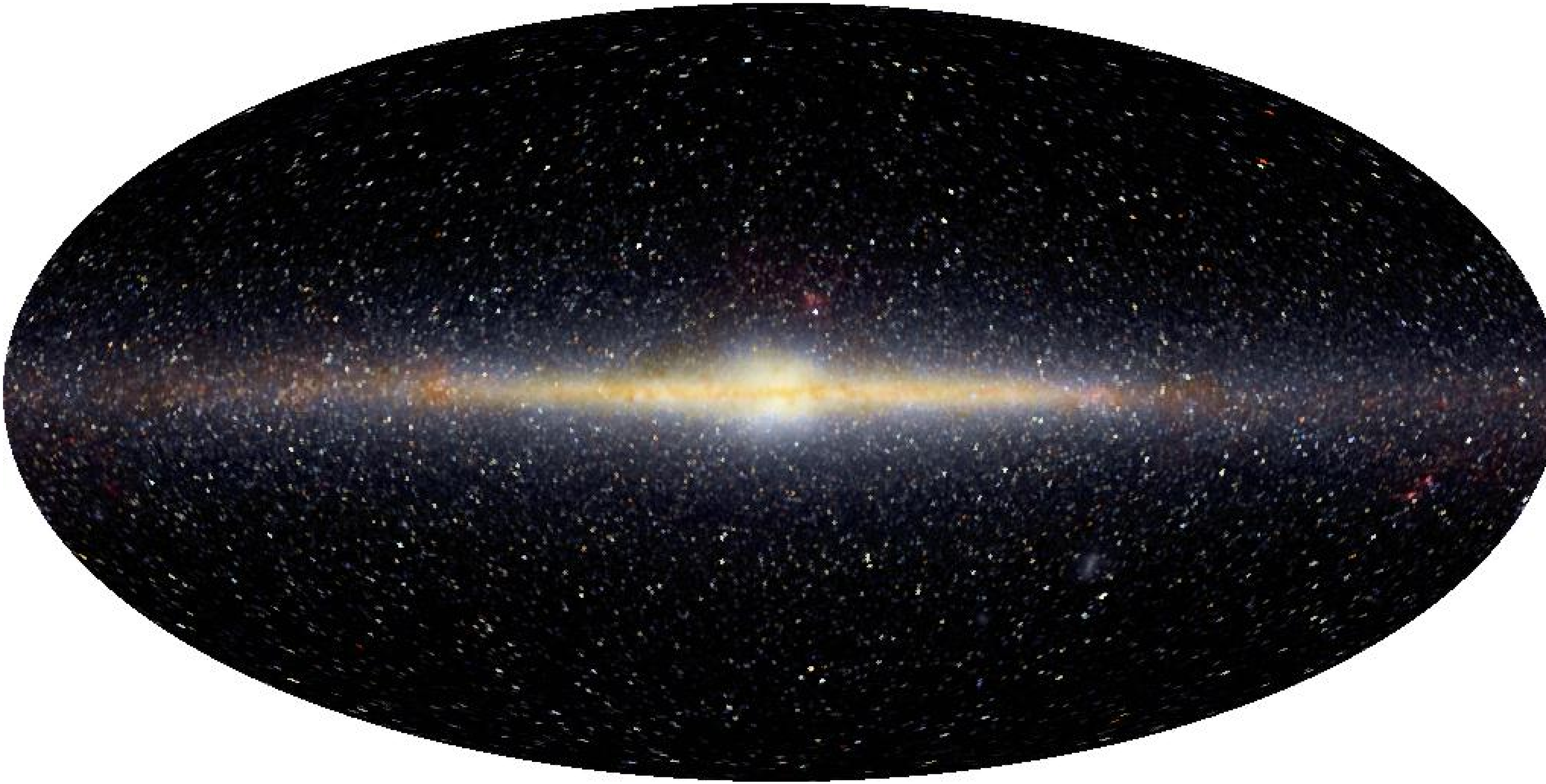
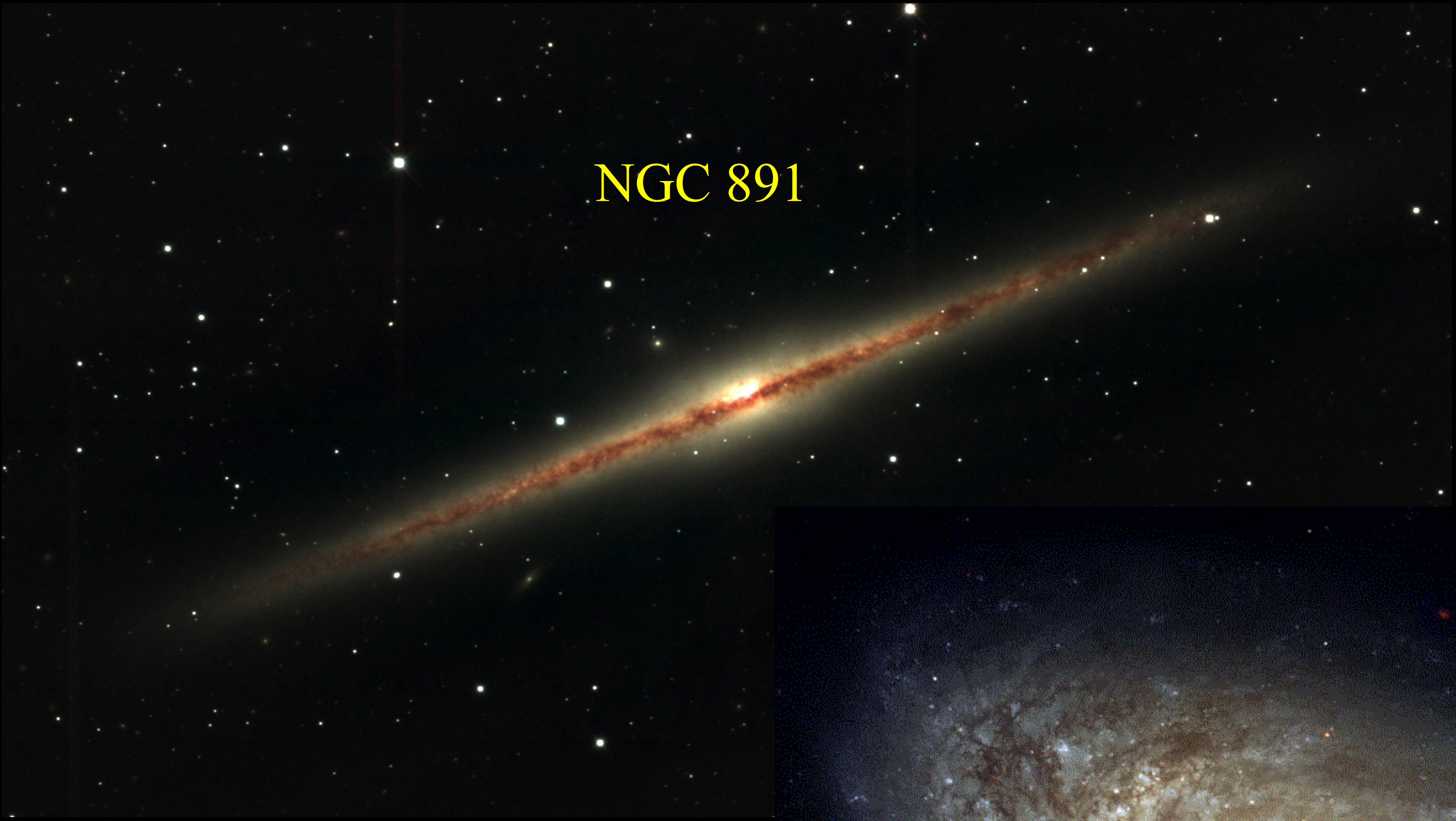


The evolution of cosmic structure

Simon White
Max Planck Institute for Astrophysics

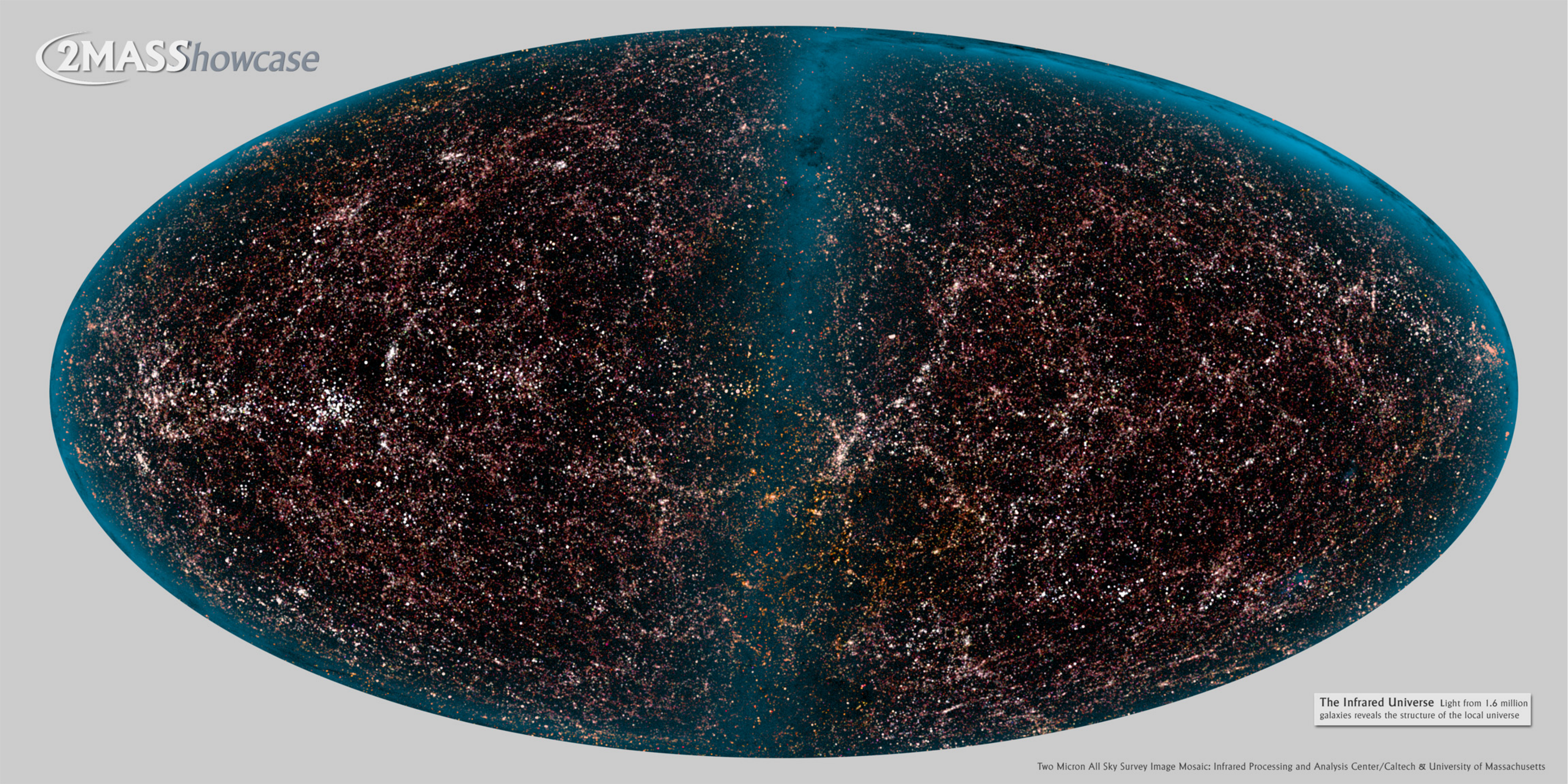
COBE's near-infrared map of the whole sky



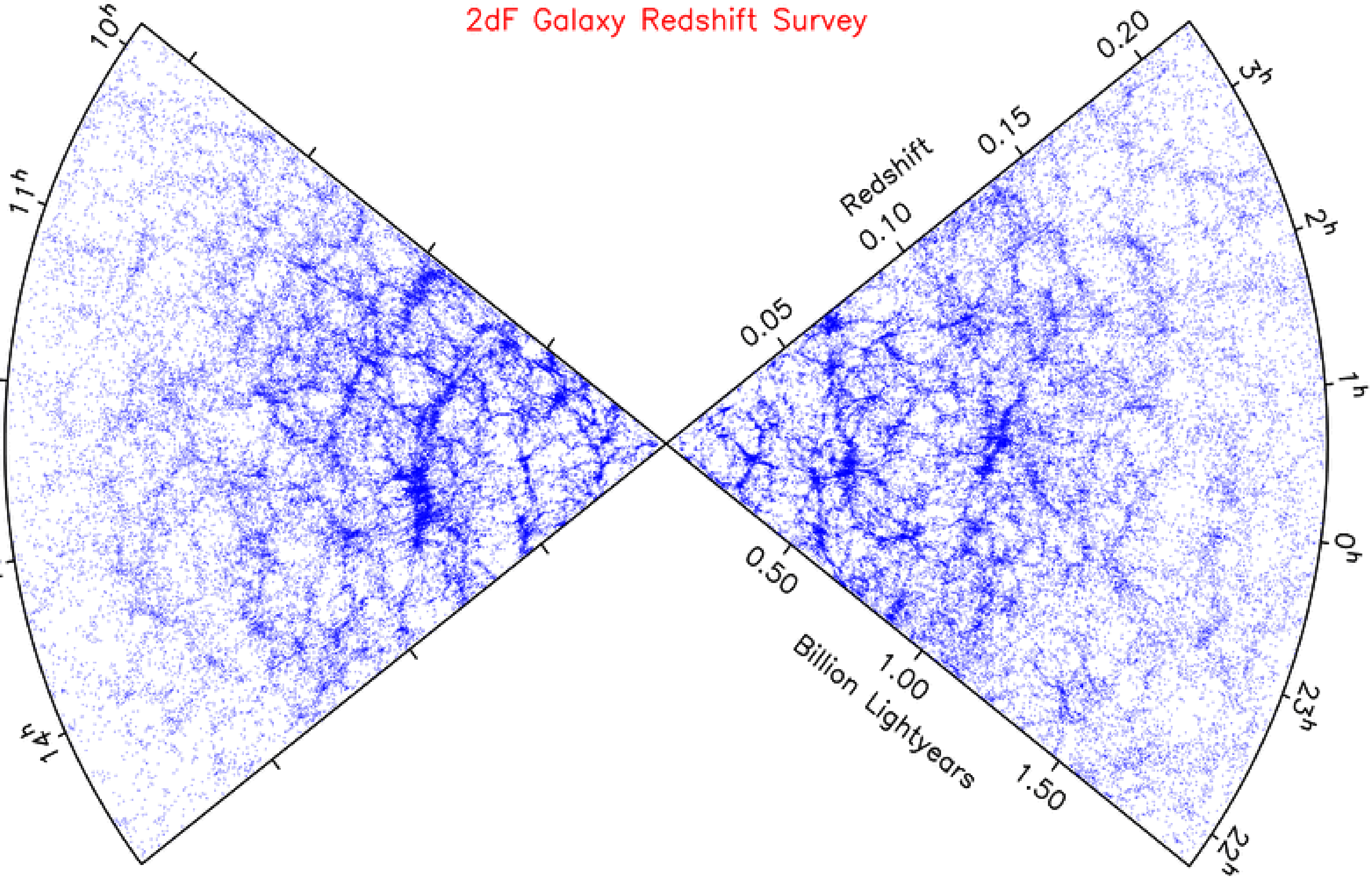


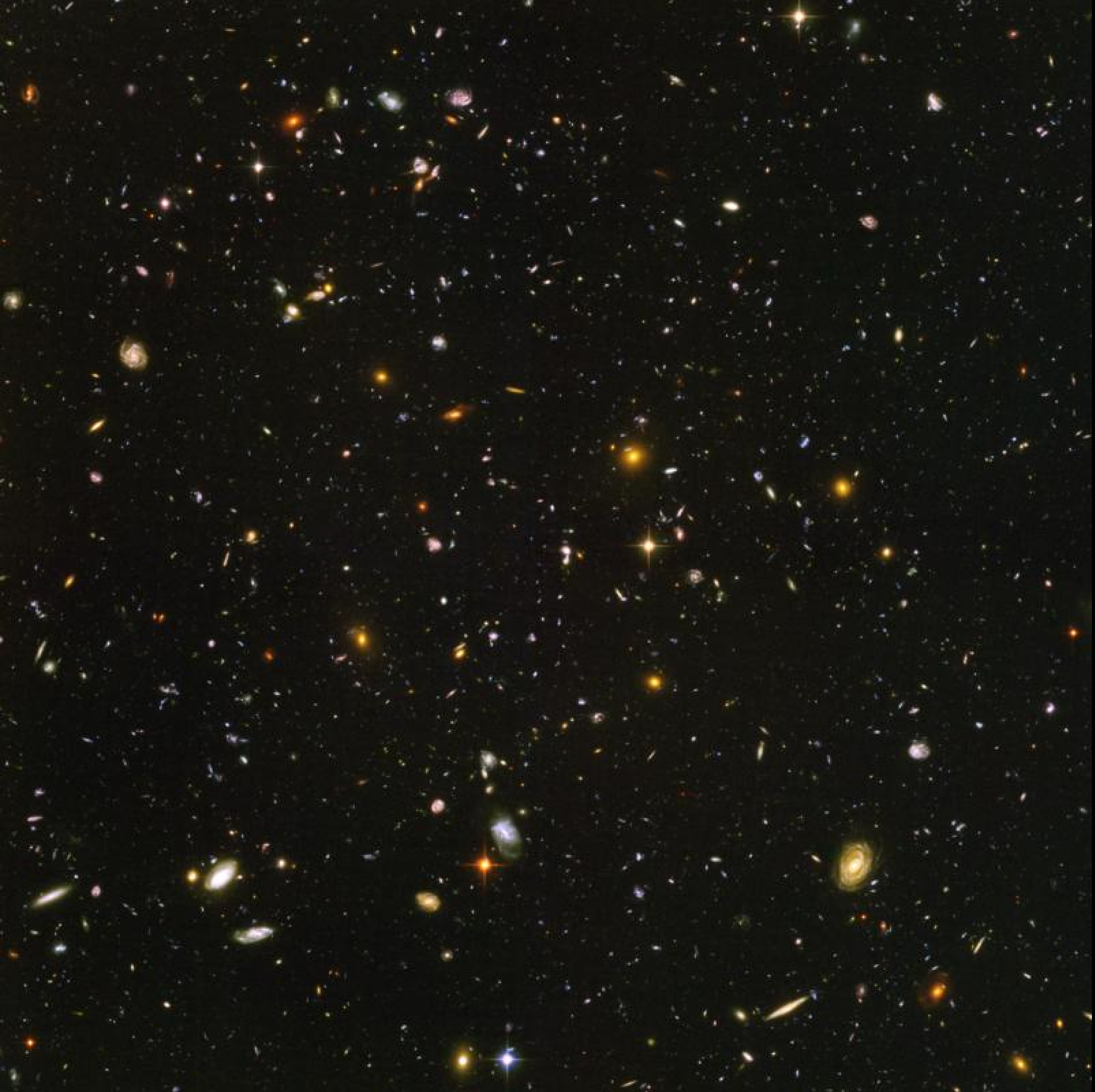
Spiral galaxies like our own

Galaxy map of the whole sky



“Nearby” large-scale structure



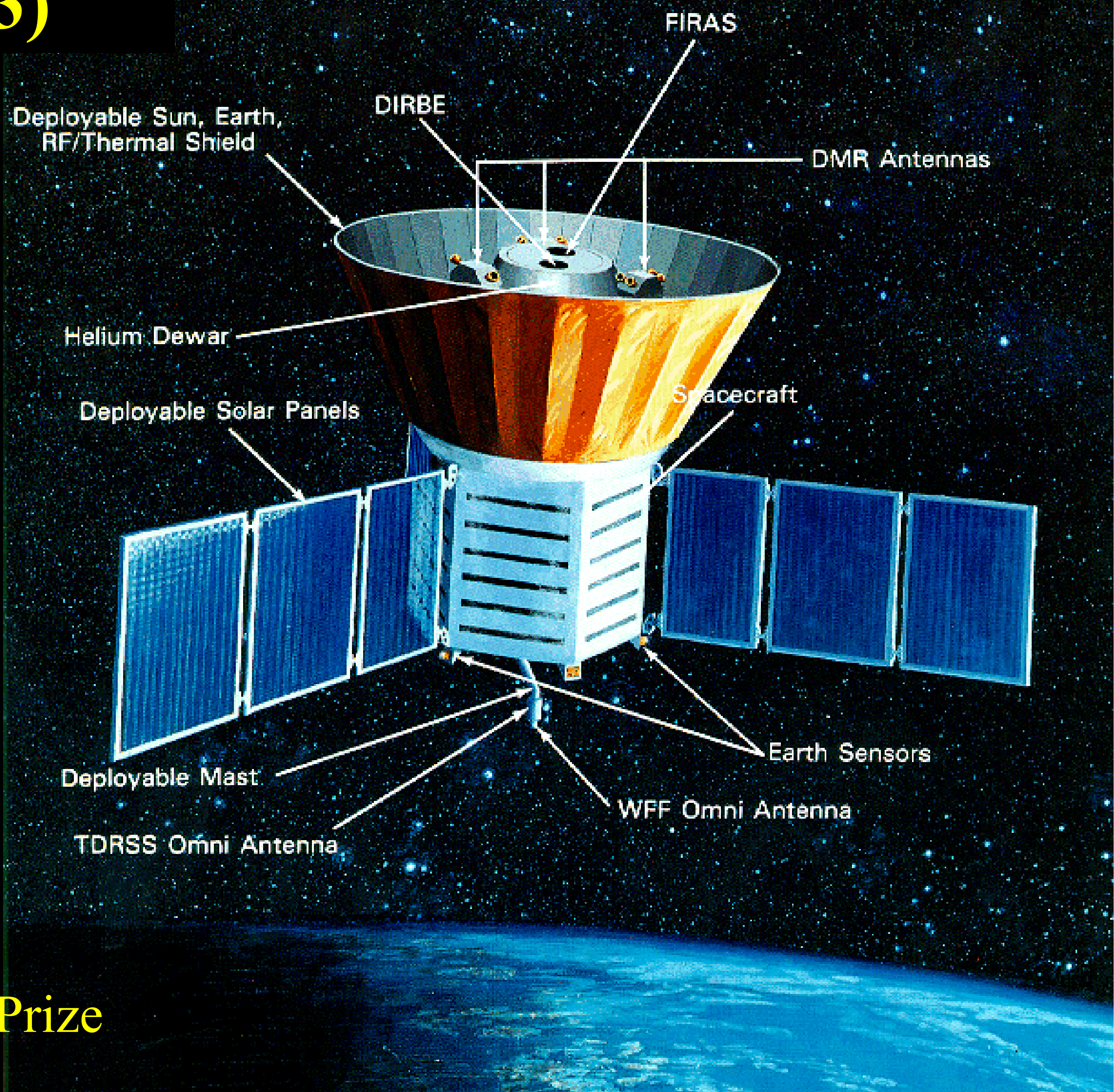


The deepest photo ever made

A 300 hour exposure with the Hubble Space Telescope

Galaxies visible at $z>5$ when $t < 0.1\ t_o$

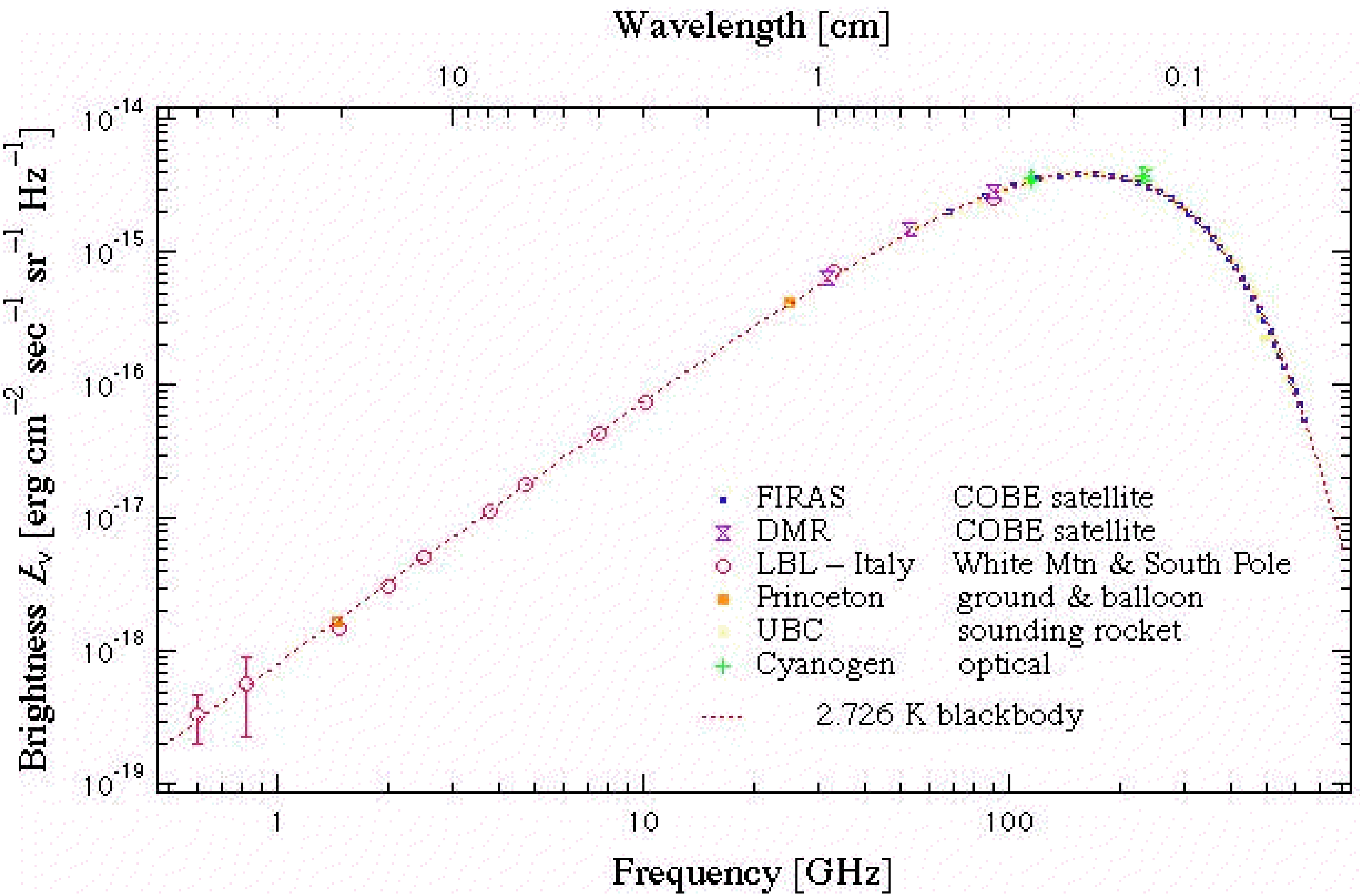
The COBE satellite (1989 - 1993)



- 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

2006 Physics Nobel Prize

Spectrum of the microwave background

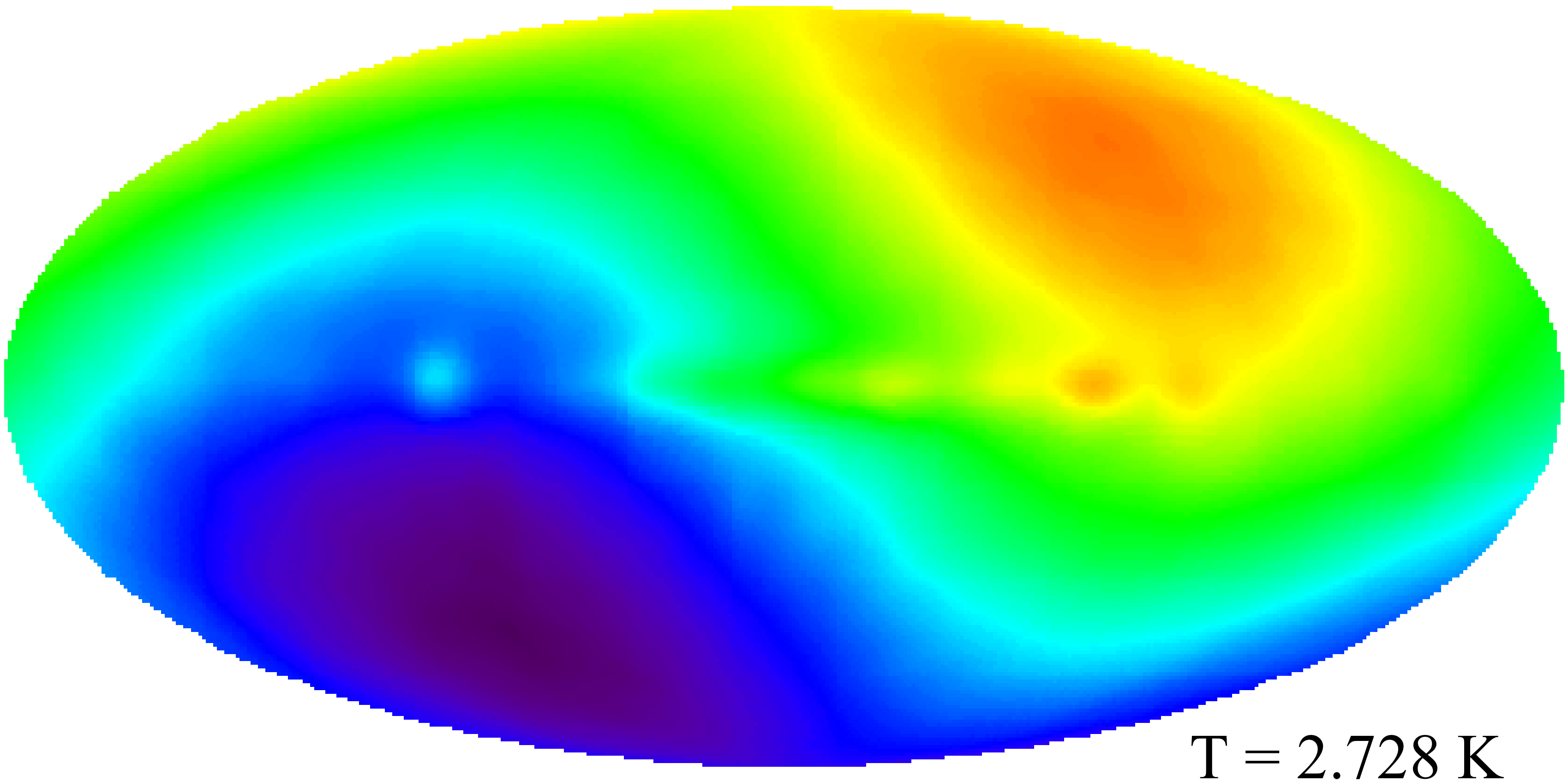


- Spectrum matches a Planckian black-body to better than 1 in 10^{-4}
- The early universe was hot, smooth and in thermal equilibrium
- No significant energy input later than ~1 month after the Big Bang

COBE's temperature map of the entire sky

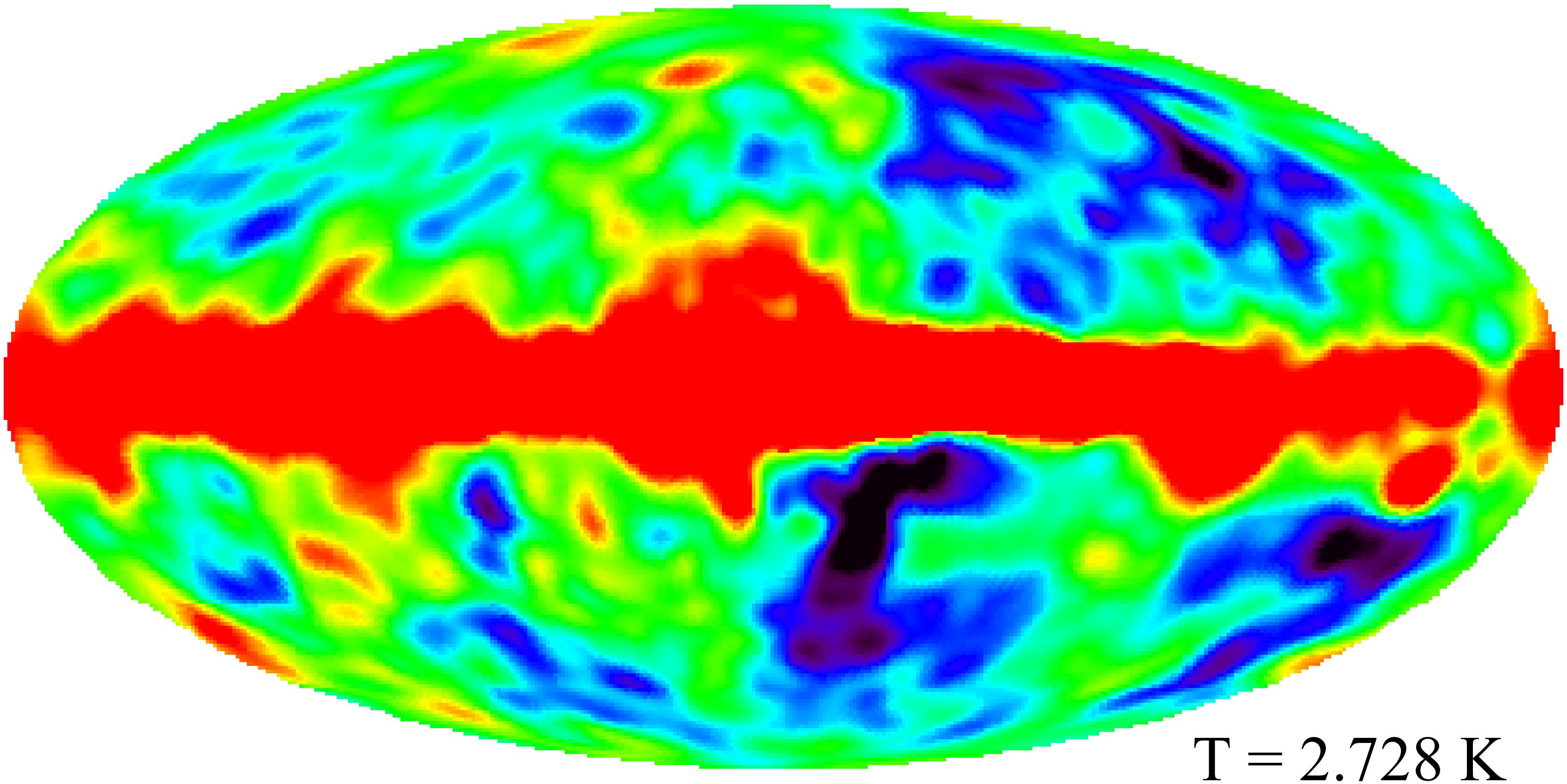
$T = 2.728$ K
$\Delta T = 0.1$ K

COBE's temperature map of the entire sky



T = 2.728 K
ΔT = 0.0034 K

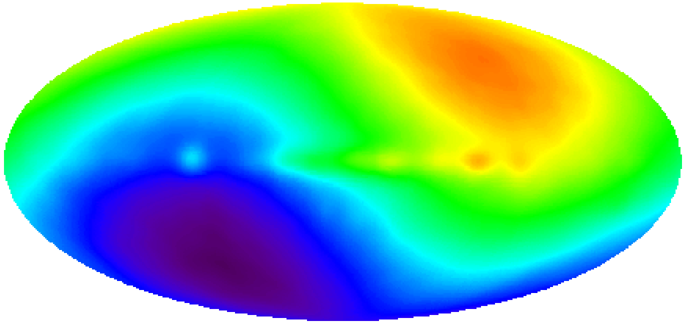
COBE's temperature map of the entire sky



T = 2.728 K

ΔT = 0.00002 K

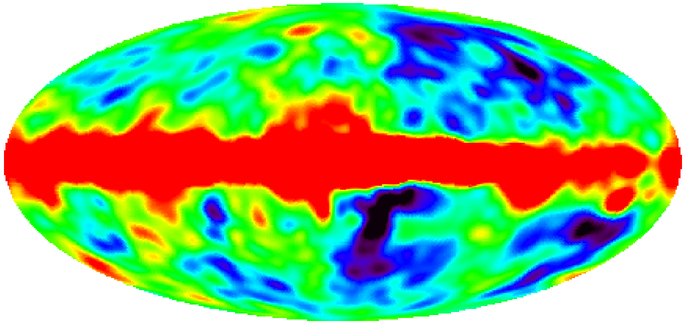
Structure in the COBE map



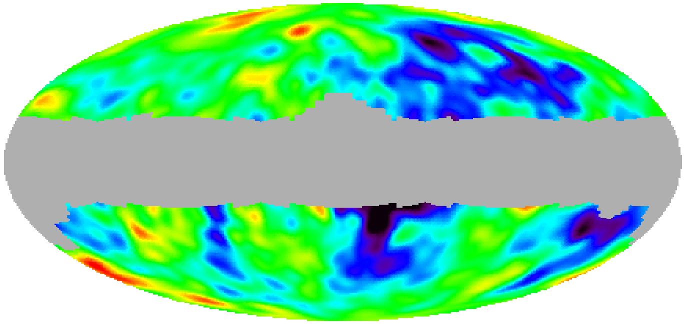
- One side of the sky is `hot', the other is`cold'

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

- The structure lies in cosmic 'clouds', ~ 4 10^{10} l-yrs away
- It reflects weak "sound" waves, A ~ 10^{-4}, in the clouds
- At the time the Universe was only 400,000 years old, and was 1,000 times smaller and 1,000 times hotter than today

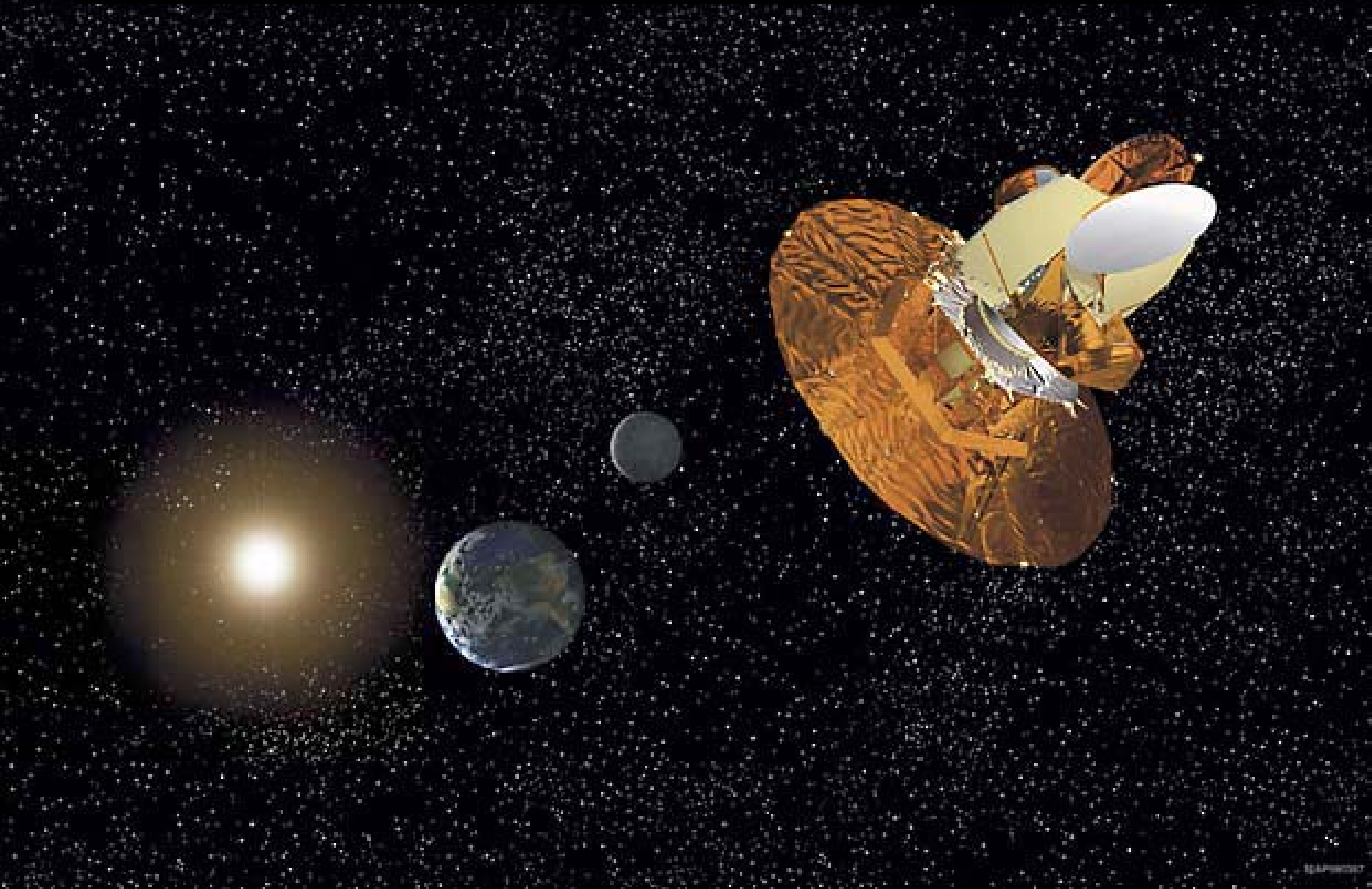
The *pattern* of structure reflects

A: The global geometry and topology of the Universe

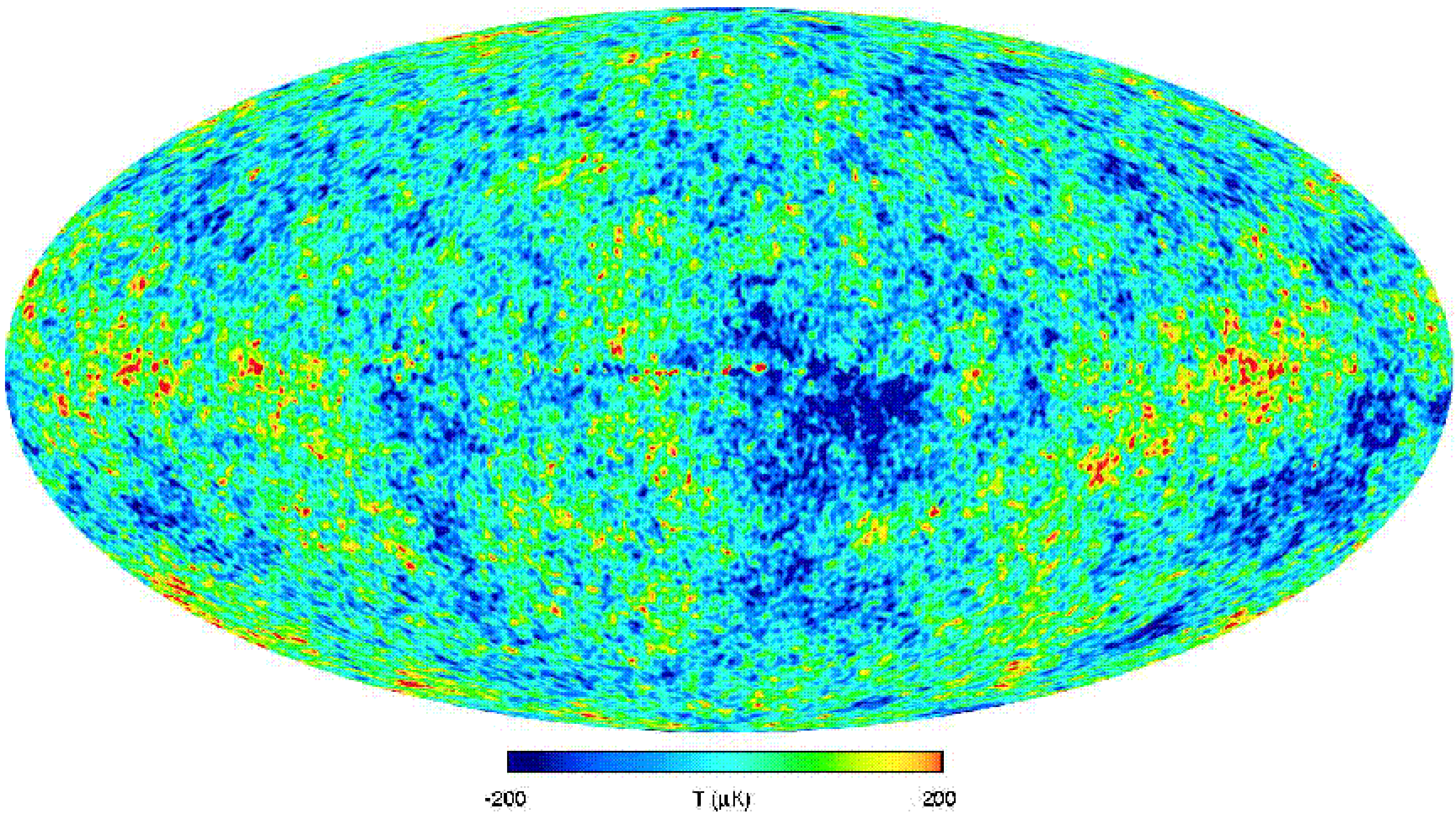
B: The constituents and thermal evolution of the Universe

C: The process which generated the structure

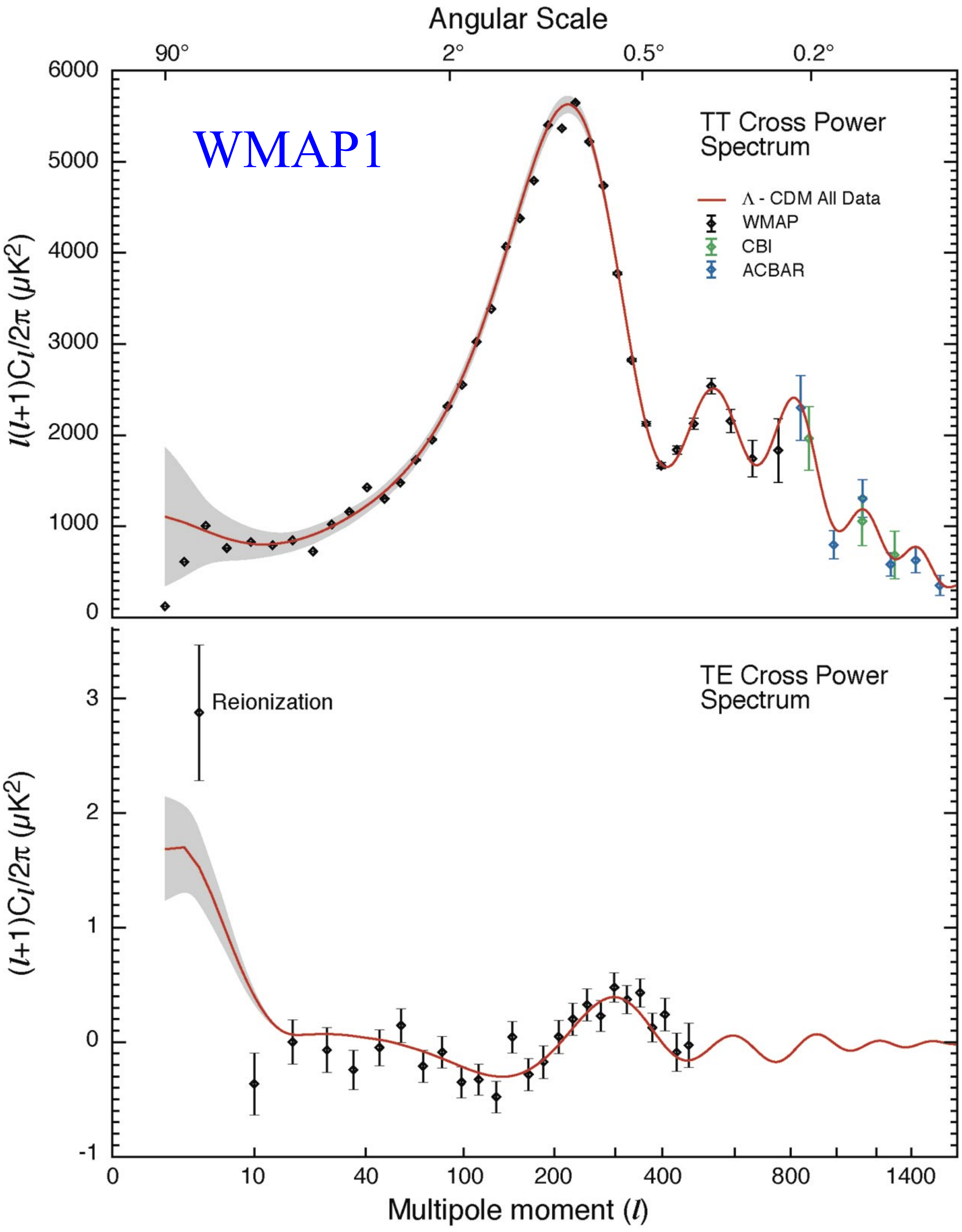
The *WMAP* Satellite at Lagrange-Point L2



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

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

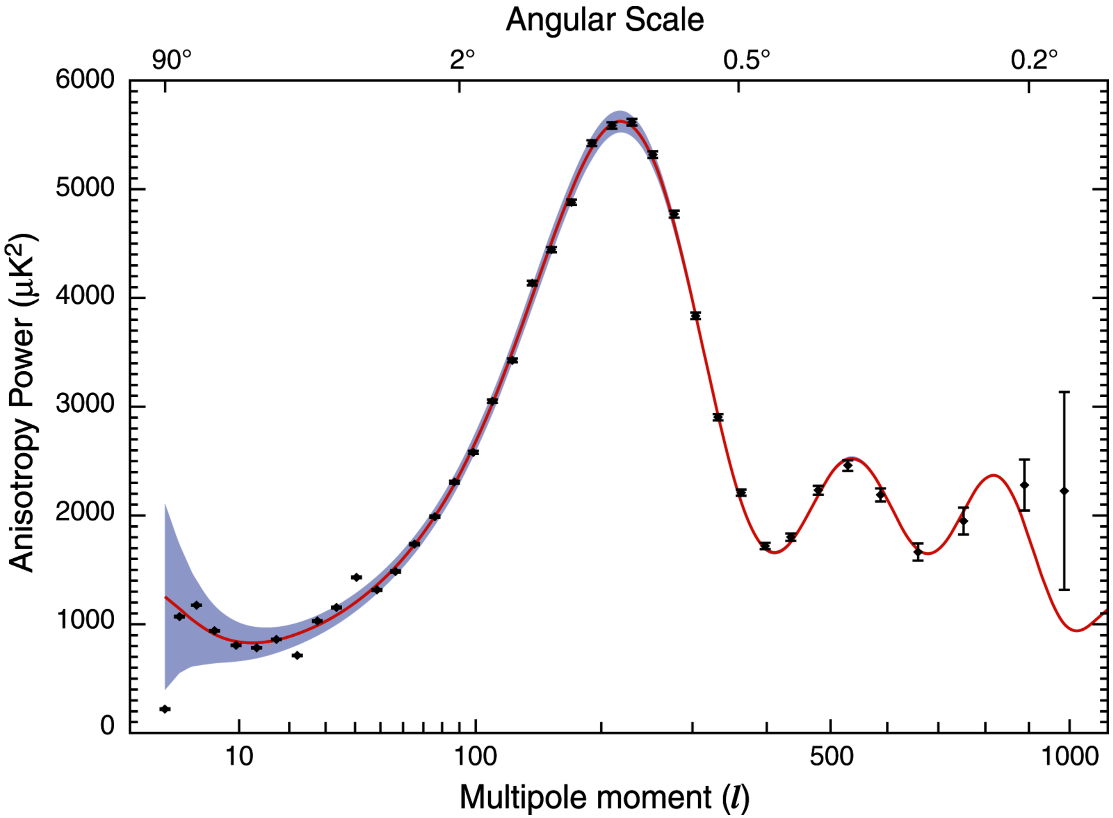
$\Omega_t = 1.02 \pm 0.02$ $\Omega_m = 0.27 \pm 0.04$

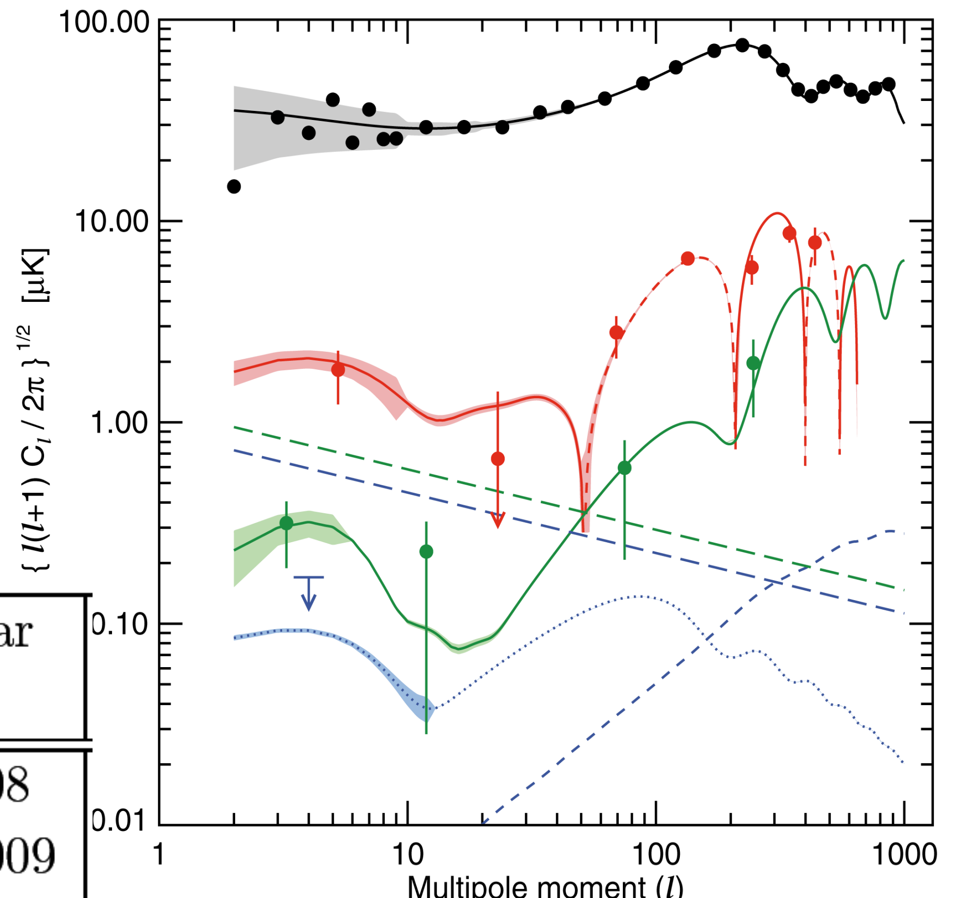
$\Omega_b = 0.044 \pm 0.004$

$\tau_e = 0.17 \pm 0.07$

- Parameters in excellent agreement with other astronomical data

WMAP3

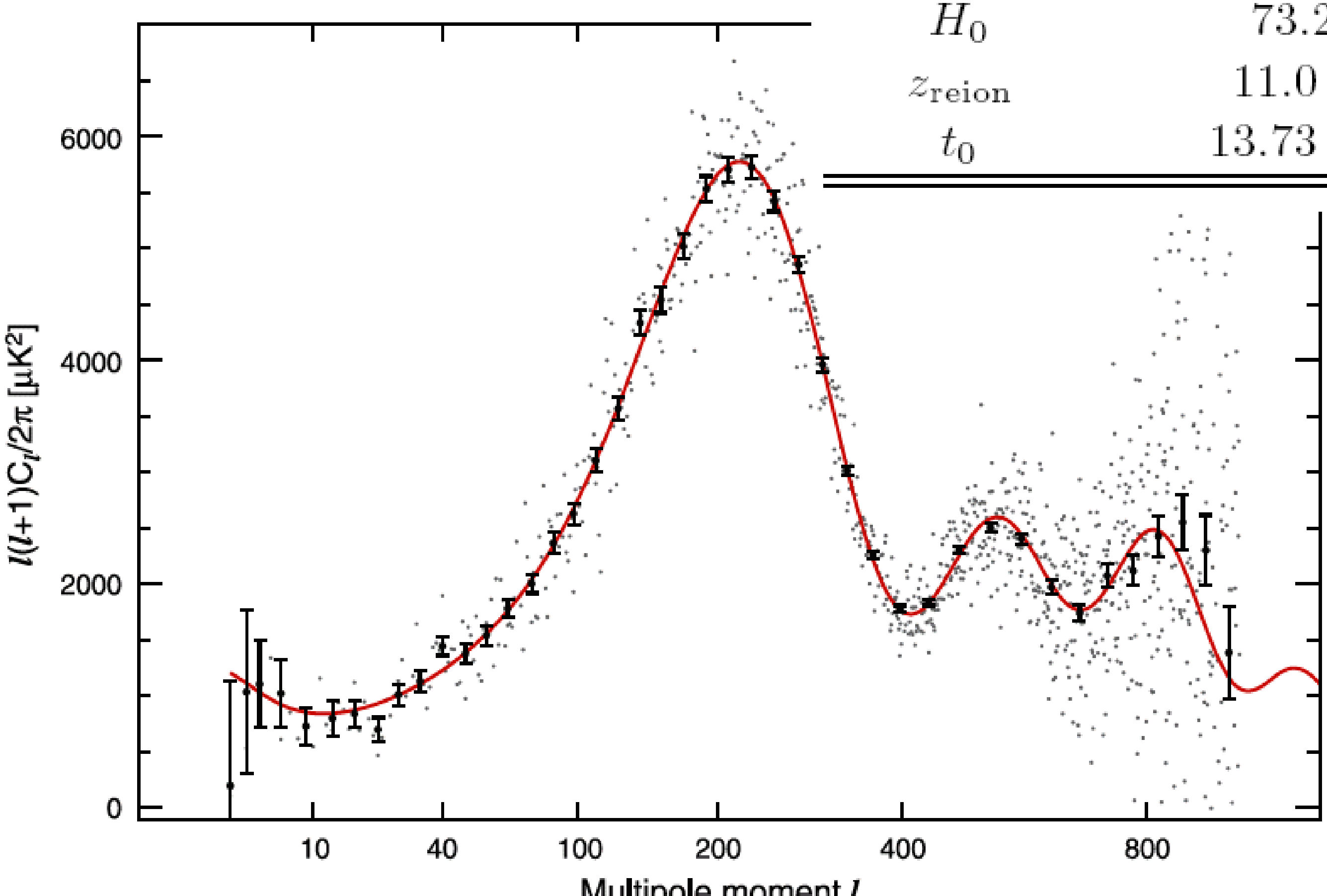




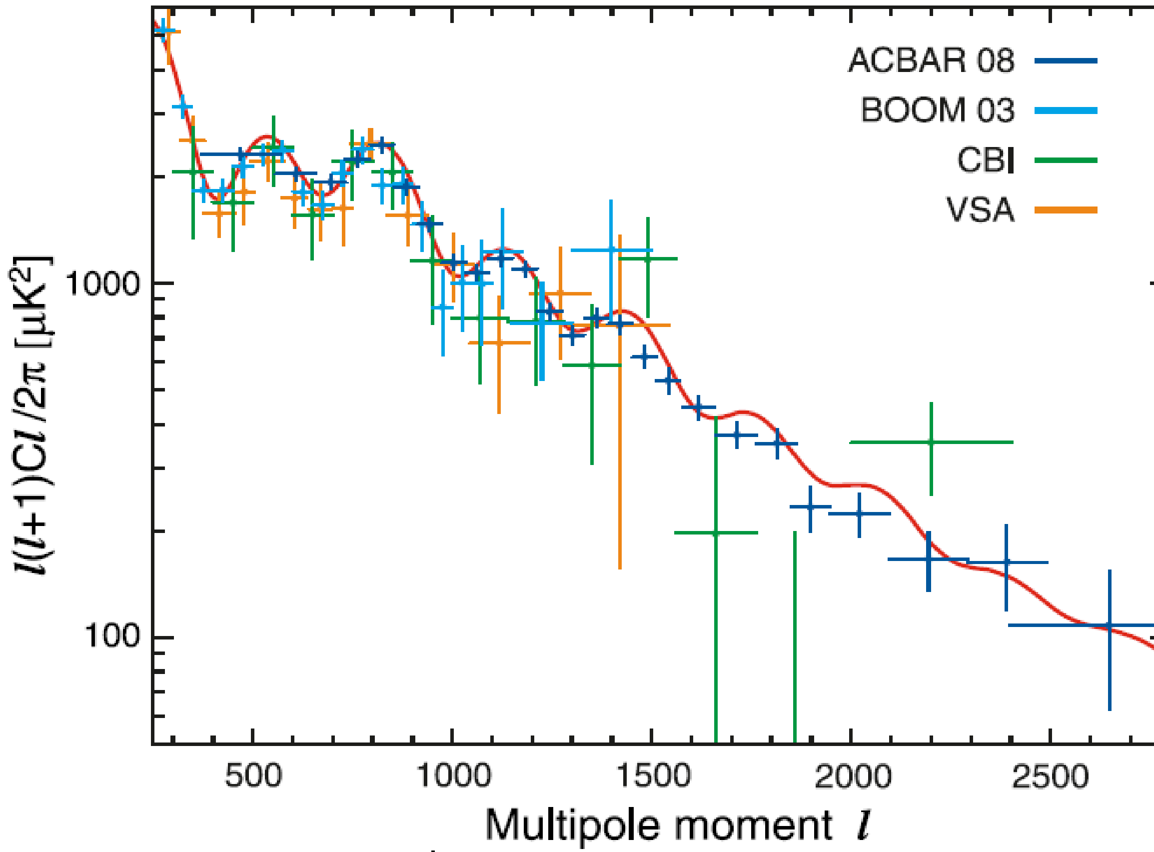
Parameter	First Year Mean	WMAPext Mean	Three Year Mean
$100\Omega_b h^2$	$2.38^{+0.13}_{-0.12}$	$2.32^{+0.12}_{-0.11}$	2.23 ± 0.08
$\Omega_m h^2$	$0.144^{+0.016}_{-0.016}$	$0.134^{+0.006}_{-0.006}$	0.126 ± 0.009
H_0	72^{+5}_{-5}	73^{+3}_{-3}	74^{+3}_{-3}
τ	$0.17^{+0.08}_{-0.07}$	$0.15^{+0.07}_{-0.07}$	0.093 ± 0.029
n_s	$0.99^{+0.04}_{-0.04}$	$0.98^{+0.03}_{-0.03}$	0.961 ± 0.017
Ω_m	$0.29^{+0.07}_{-0.07}$	$0.25^{+0.03}_{-0.03}$	0.234 ± 0.035
σ_8	$0.92^{+0.1}_{-0.1}$	$0.84^{+0.06}_{-0.06}$	0.76 ± 0.05

WMAP5

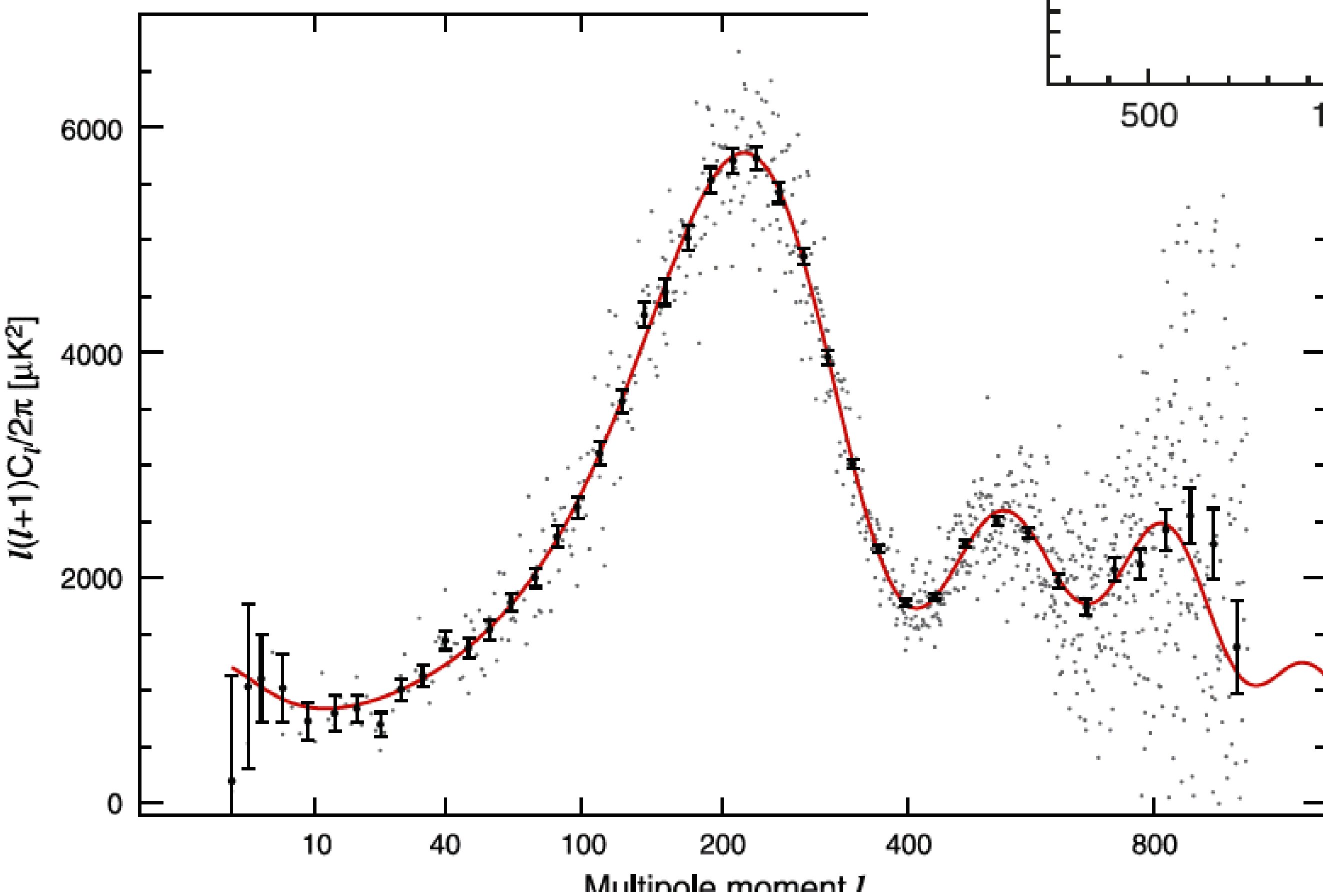
Parameter	3 Year Mean	5 Year Mean
$100\Omega_b h^2$	2.229 ± 0.073	2.273 ± 0.062
$\Omega_c h^2$	0.1054 ± 0.0078	0.1099 ± 0.0062
Ω_Λ	0.759 ± 0.034	0.742 ± 0.030
n_s	0.958 ± 0.016	$0.963^{+0.014}_{-0.015}$
τ	0.089 ± 0.030	0.087 ± 0.017
$\Delta^2_{\mathcal{R}}$	$(2.35 \pm 0.13) \times 10^{-9}$	$(2.41 \pm 0.11) \times 10^{-9}$
σ_8	0.761 ± 0.049	0.796 ± 0.036
Ω_m	0.241 ± 0.034	0.258 ± 0.030
$\Omega_m h^2$	0.128 ± 0.008	0.1326 ± 0.0063
H_0	$73.2^{+3.1}_{-3.2}$	$71.9^{+2.6}_{-2.7}$
$z_{\rm reion}$	11.0 ± 2.6	11.0 ± 1.4
t_0	13.73 ± 0.16	13.69 ± 0.13



WMAP5



ACBAR 08
BOOM 03
CBI
VSA
1000
100
500
1000
1500
2000
2500
$l(l+1)Cl/2\pi$ [μK^2]
Multipole moment l



6000
4000
2000
0
10
40
100
200
400
800
$l(l+1)C_l/2\pi$ [μK^2]
Multipole moment l

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 4.5%
  → there is a lot of dark, nonbaryonic matter (about 23%)
  (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

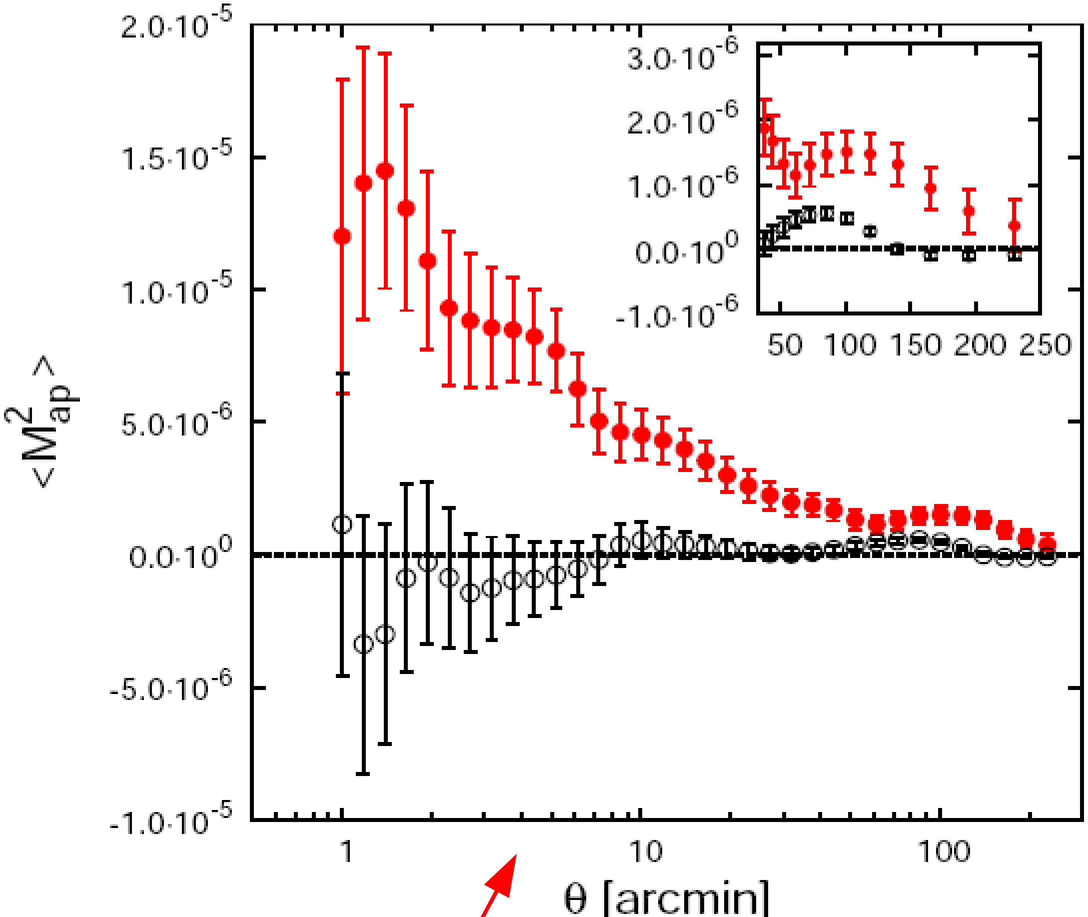
- All structure in the Universe originated as quantum zero-point fluctuations of the *vacuum*, perhaps 10^{-30} s after the Big Bang!

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

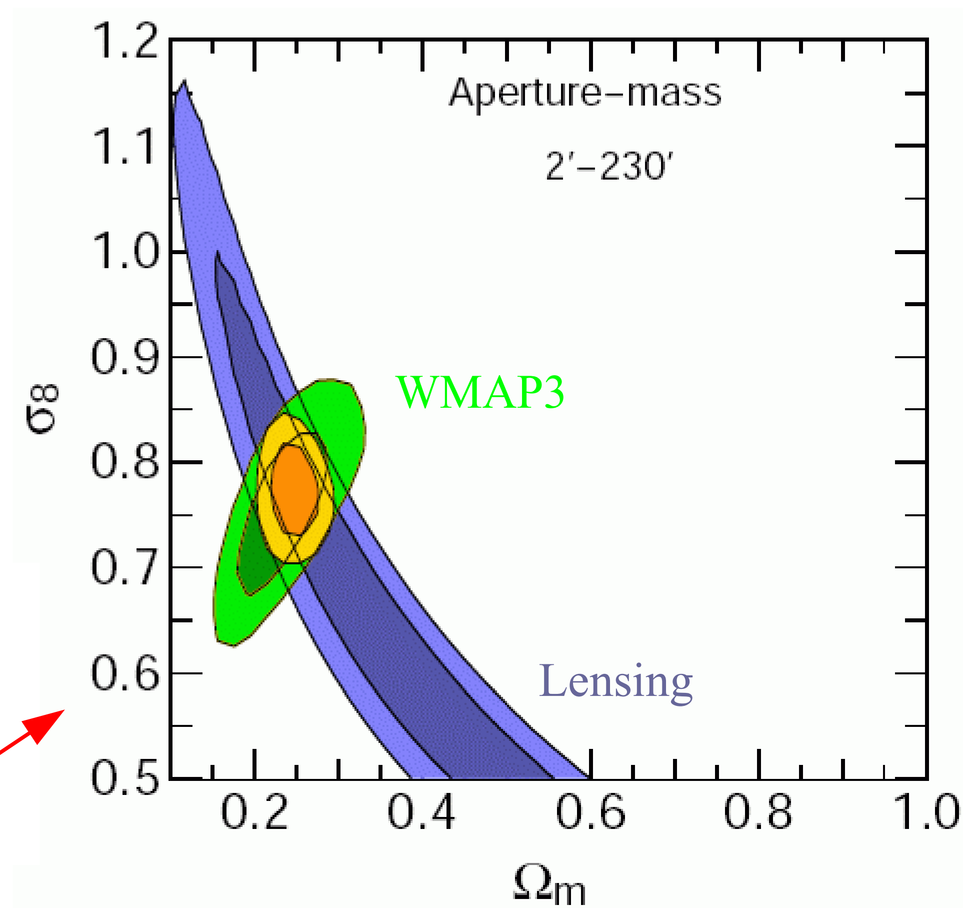
Gravitational lensing by a galaxy cluster

Abell 2218 z=0.17

Large-scale structure from weak lensing



Fu et al 2008



rms mass fluctuation in a compensated circular aperture

implied parameter constraints

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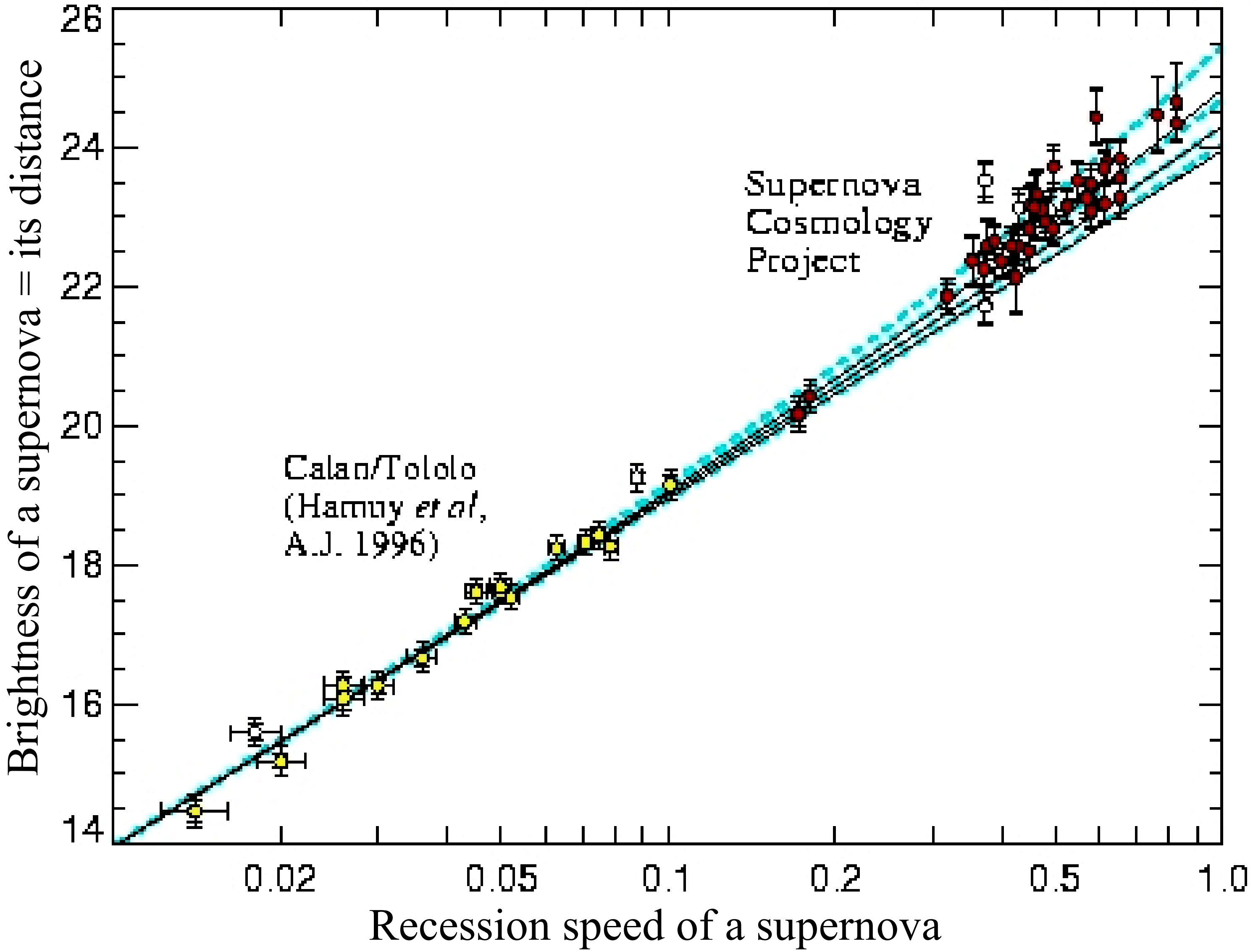
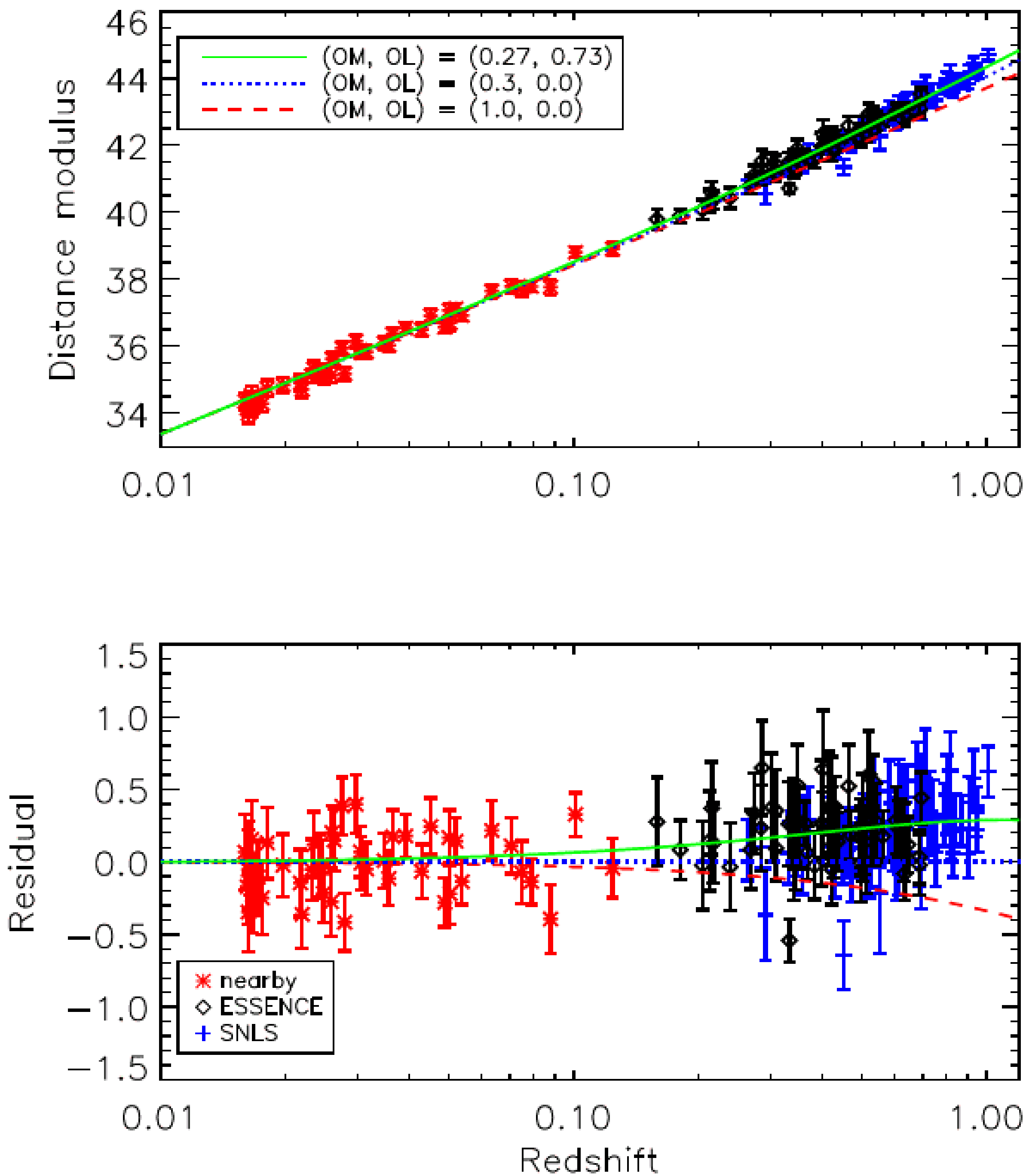
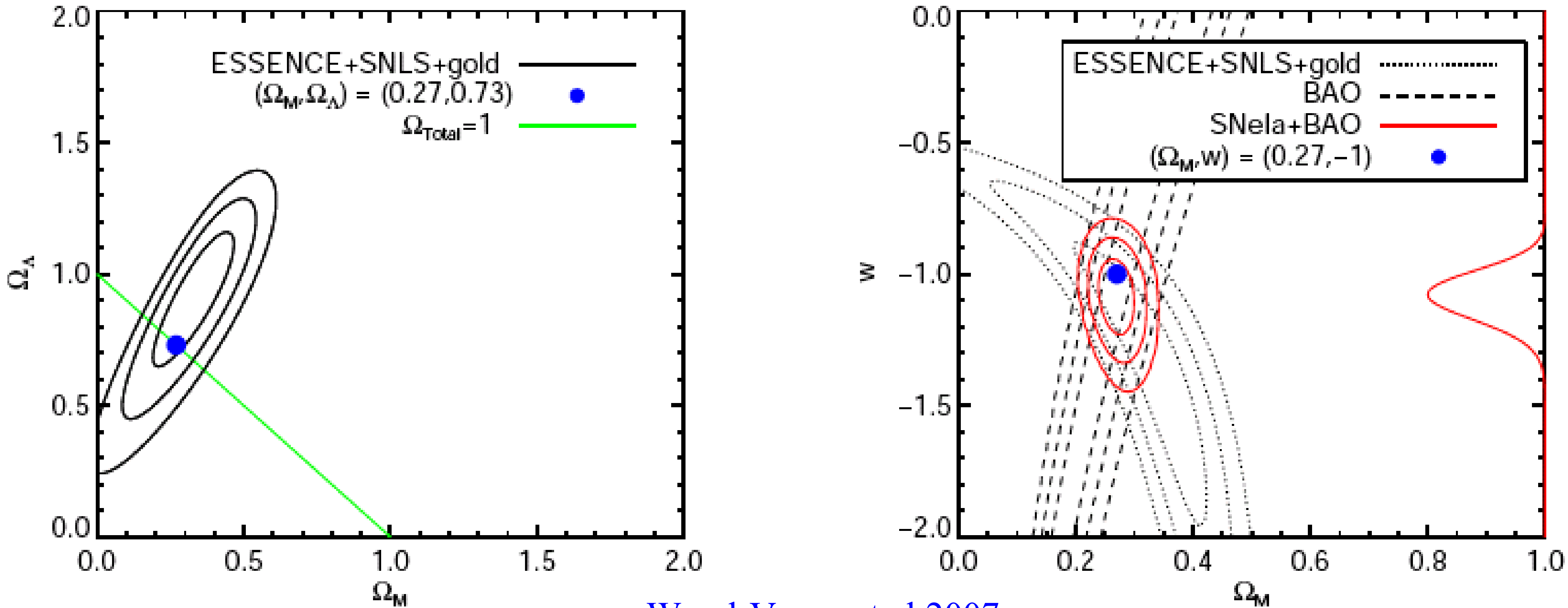
Hubble's “Law” and the expansion history



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



The ESSENCE Survey
Wood-Vasey et al 2007



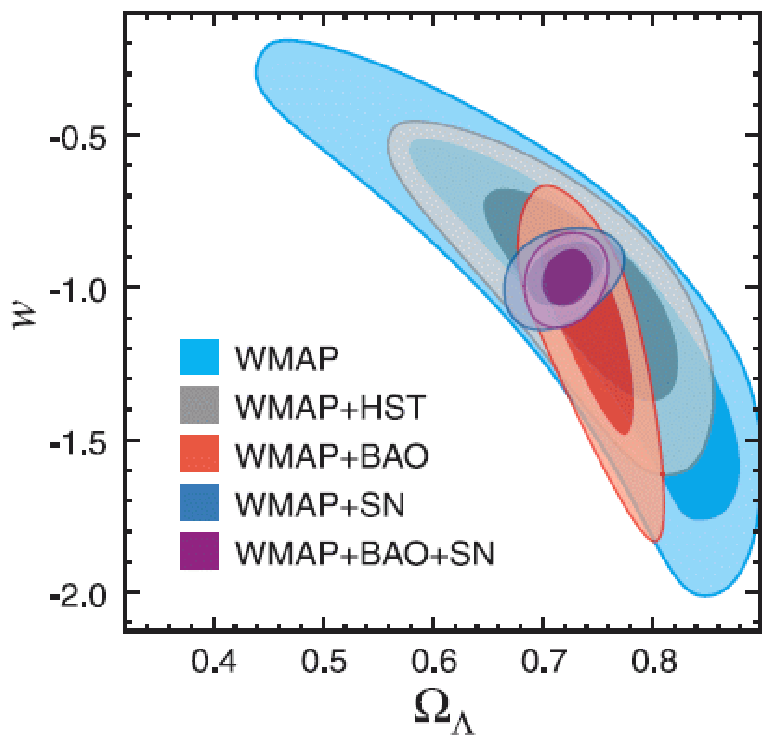
Wood-Vasey et al 2007

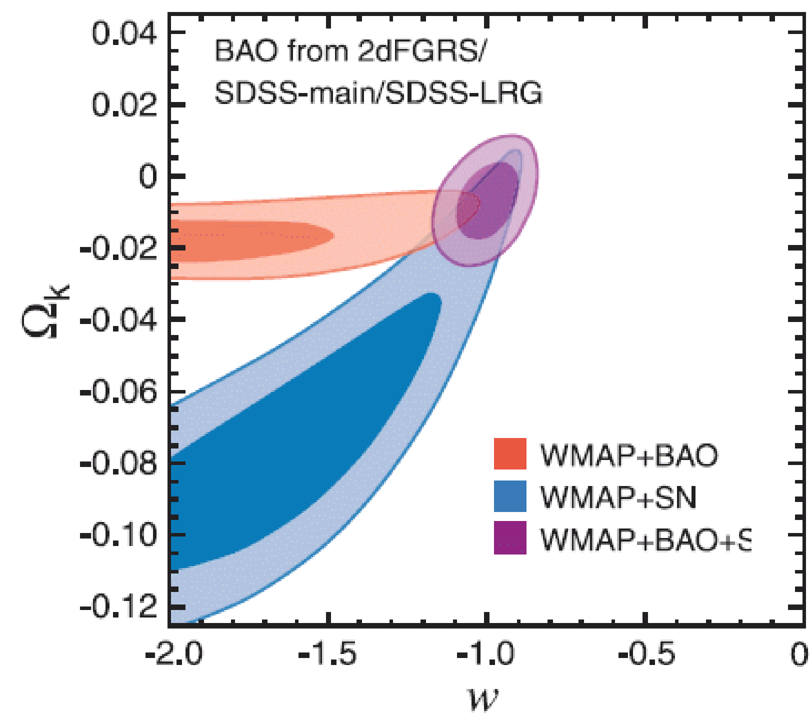
- The SN data require an accelerated expansion today
- With large-scale structure data, they imply a flat Universe with DE
- The DE appears to behave "like" a cosmological constant, $w \approx -1$
- The implied parameters agree with those obtained independently from the cosmic microwave background

Putting it all together

Class	Parameter	*WMAP* 5-year Mean[b]	*WMAP*+BAO+SN Mean
Primary	$100\Omega_b h^2$	2.273 ± 0.062	2.265 ± 0.059
	$\Omega_c h^2$	0.1099 ± 0.0062	0.1143 ± 0.0034
	Ω_Λ	0.742 ± 0.030	0.721 ± 0.015
	n_s	$0.963^{+0.014}_{-0.015}$	$0.960^{+0.014}_{-0.013}$
	τ	0.087 ± 0.017	0.084 ± 0.016
	$\Delta^2_{\mathcal{R}}(k_0$[e]$)$	$(2.41 \pm 0.11) \times 10^{-9}$	$(2.457^{+0.092}_{-0.093}) \times 10^{-9}$
Derived	σ_8	0.796 ± 0.036	0.817 ± 0.026
	H_0	$71.9^{+2.6}_{-2.7}$ km/s/Mpc	70.1 ± 1.3 km/s/Mpc
	Ω_b	0.0441 ± 0.0030	0.0462 ± 0.0015
	Ω_c	0.214 ± 0.027	0.233 ± 0.013
	$\Omega_m h^2$	0.1326 ± 0.0063	0.1369 ± 0.0037
	z_{reion}[f]	11.0 ± 1.4	10.8 ± 1.4
	t_0[g]	13.69 ± 0.13 Gyr	13.73 ± 0.12 Gyr

Komatsu et al 2008





“Explanations” for Dark Energy

- A cosmological constant (i.e. another constant of gravity)
- Dynamical Dark Energy, e.g. quintessence
- A result of “leakage” from higher dimensions
- A reflection of the need to extend/modify General Relativity
- A consequence of the nonlinear behaviour of GR
- The result of systematics in the SN data

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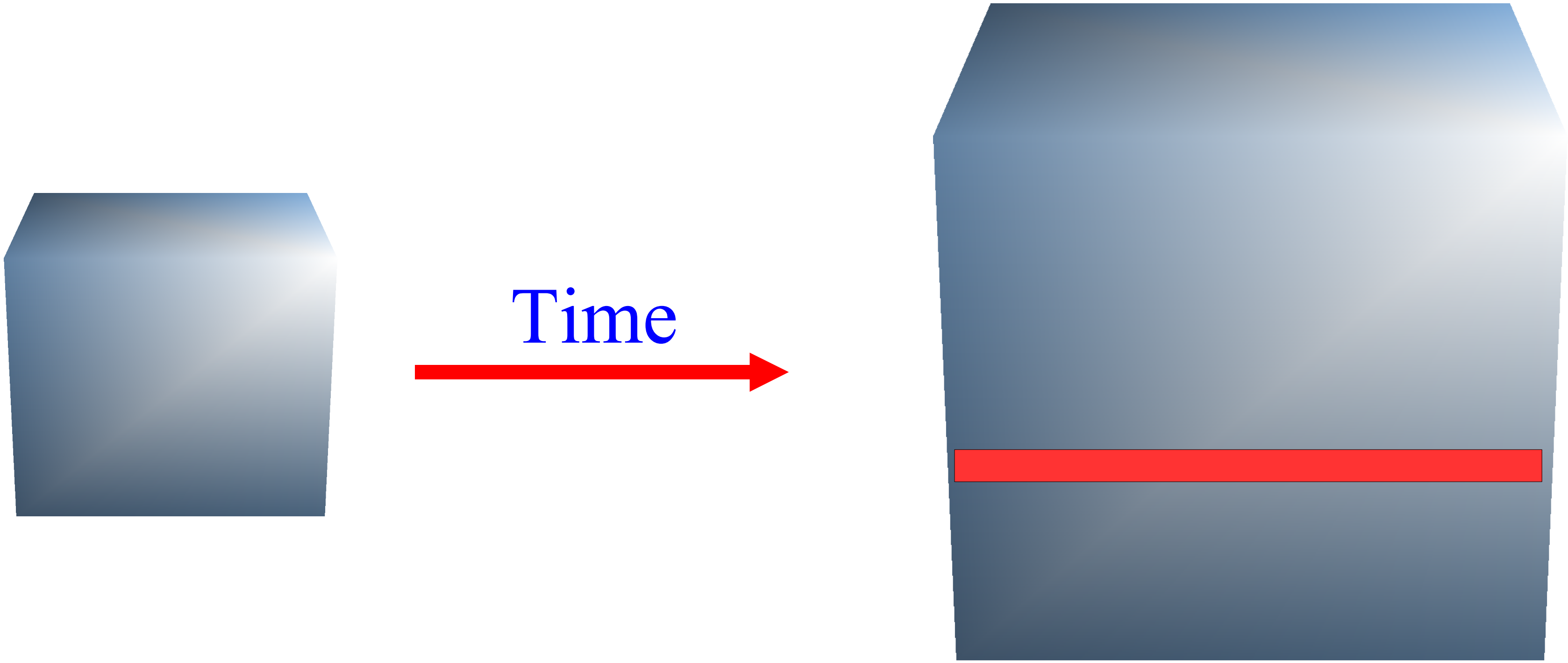
Evolving the Universe in a computer



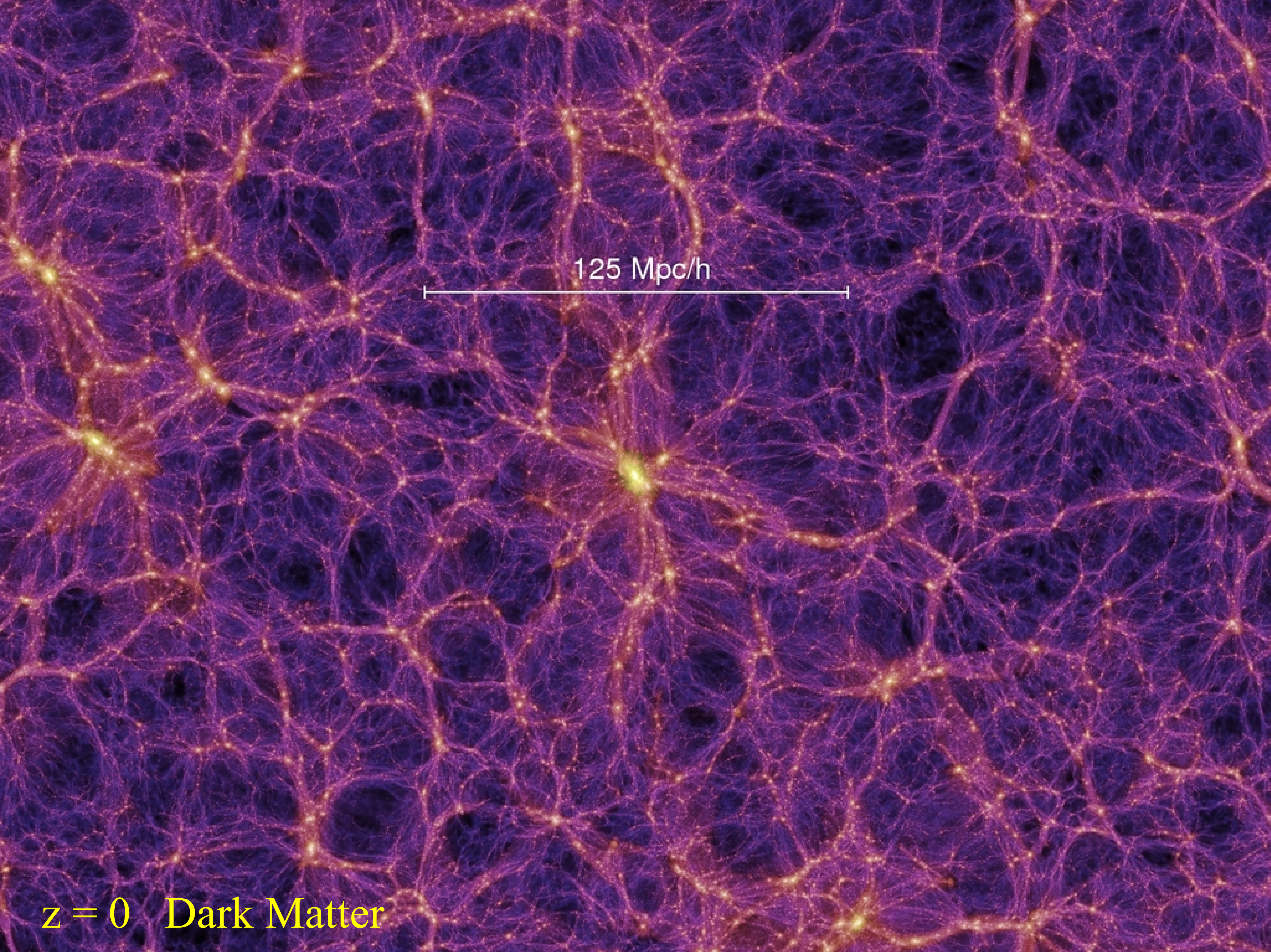
- Follow the matter in an expanding cubic region
- Start 400,000 years after the Big Bang
- Match initial conditions to the observed Microwave Background
- Calculate evolution forward to the present day

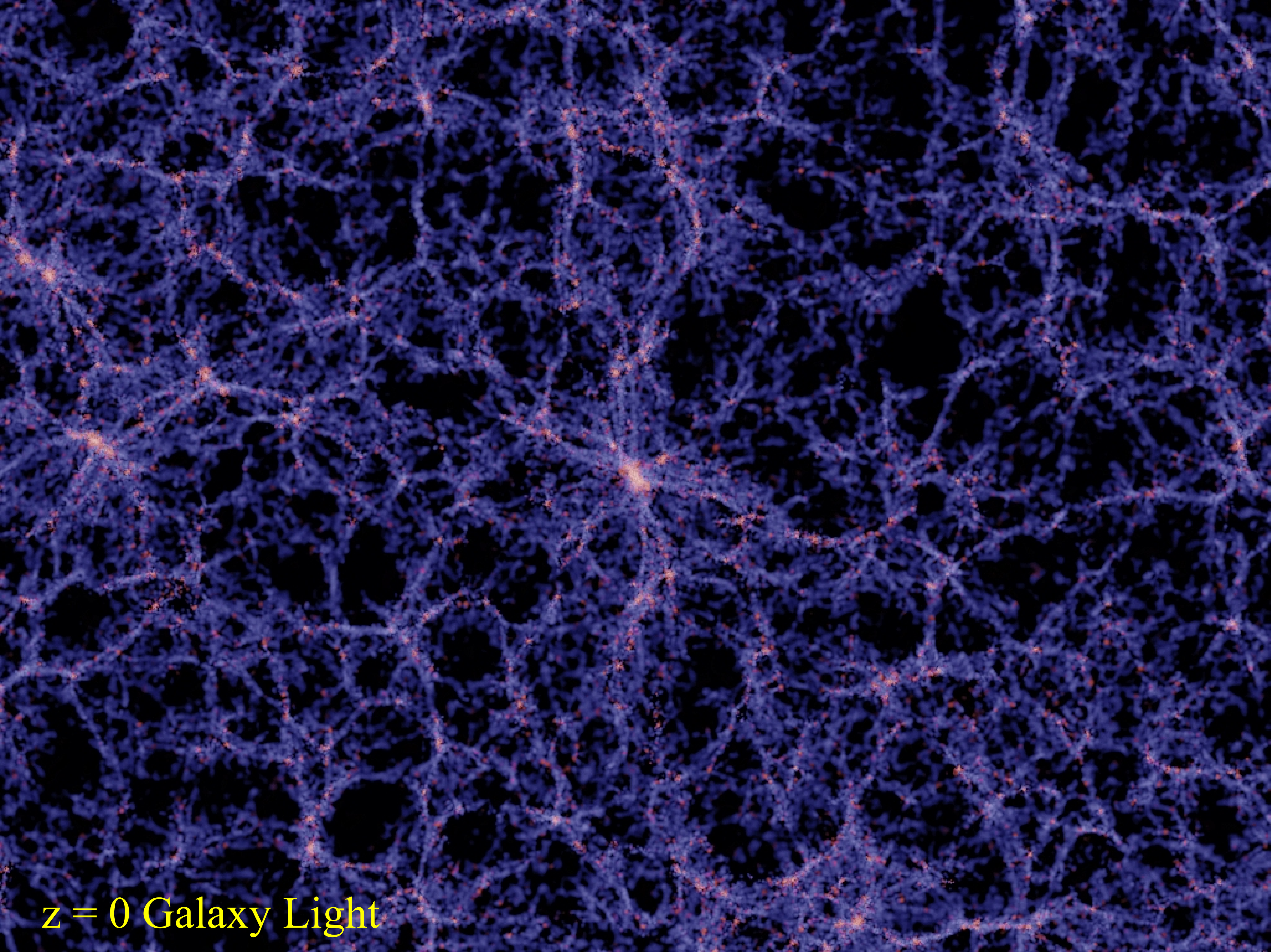
Views of the dark matter in a Virtual Universe

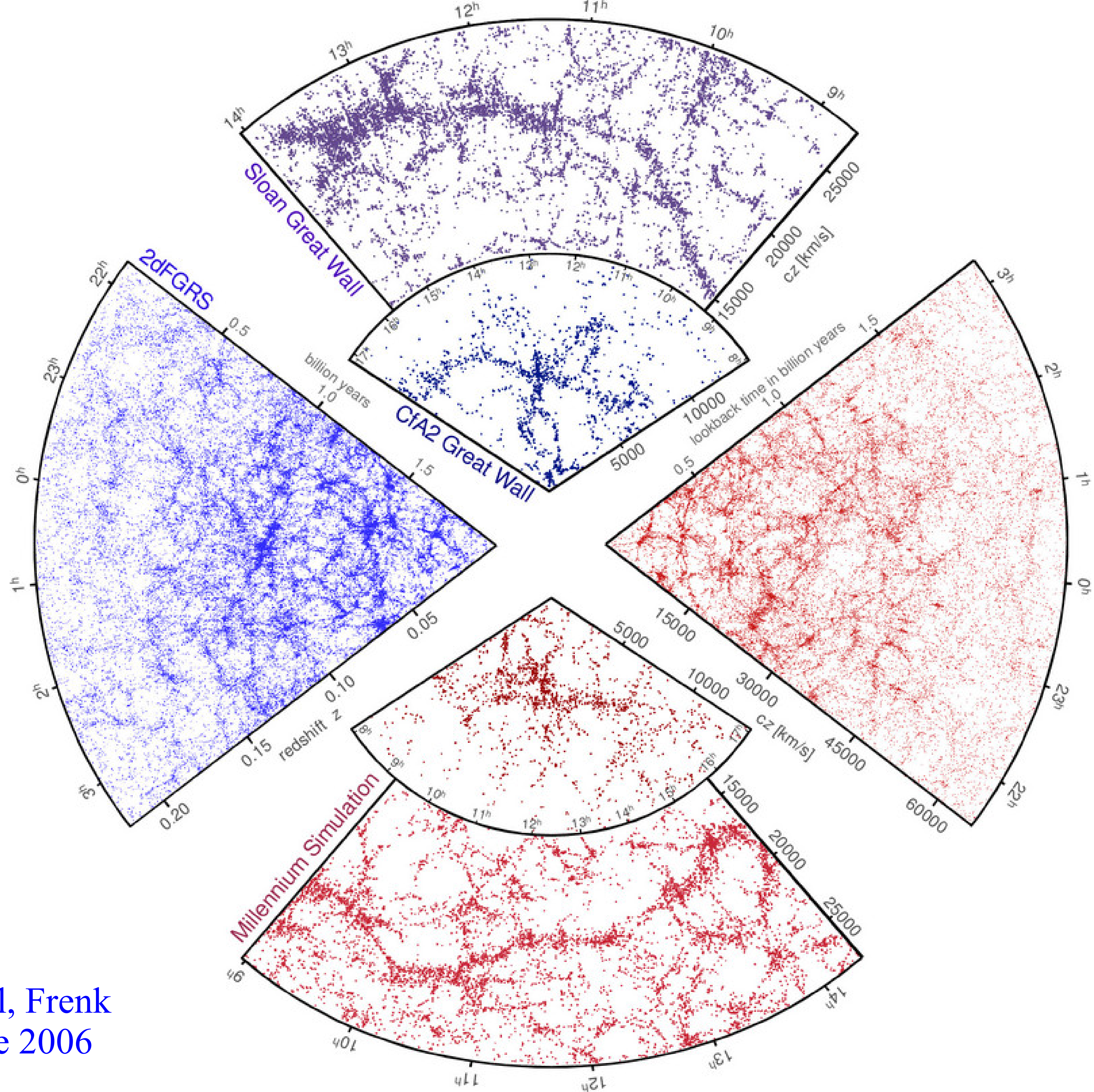
- The growth of dark matter structures in a thin slice
- A zoom from the whole visible Universe into a galaxy cluster
- A flight through the dark matter distribution
- The assembly of the Milky Way's halo

Processes shaping the *visible* Universe

- Shock-heating, radiative cooling and gravitational condensation of gas in DM potential wells
- Star formation and stellar evolution
- Energetic and chemical feedback from star death/supernovae
- Black hole formation and feedback from Active Galactic Nuclei
- Collisions and merging of galaxies
- Condensation and distribution of dust


125 Mpc/h
z = 0 Dark Matter

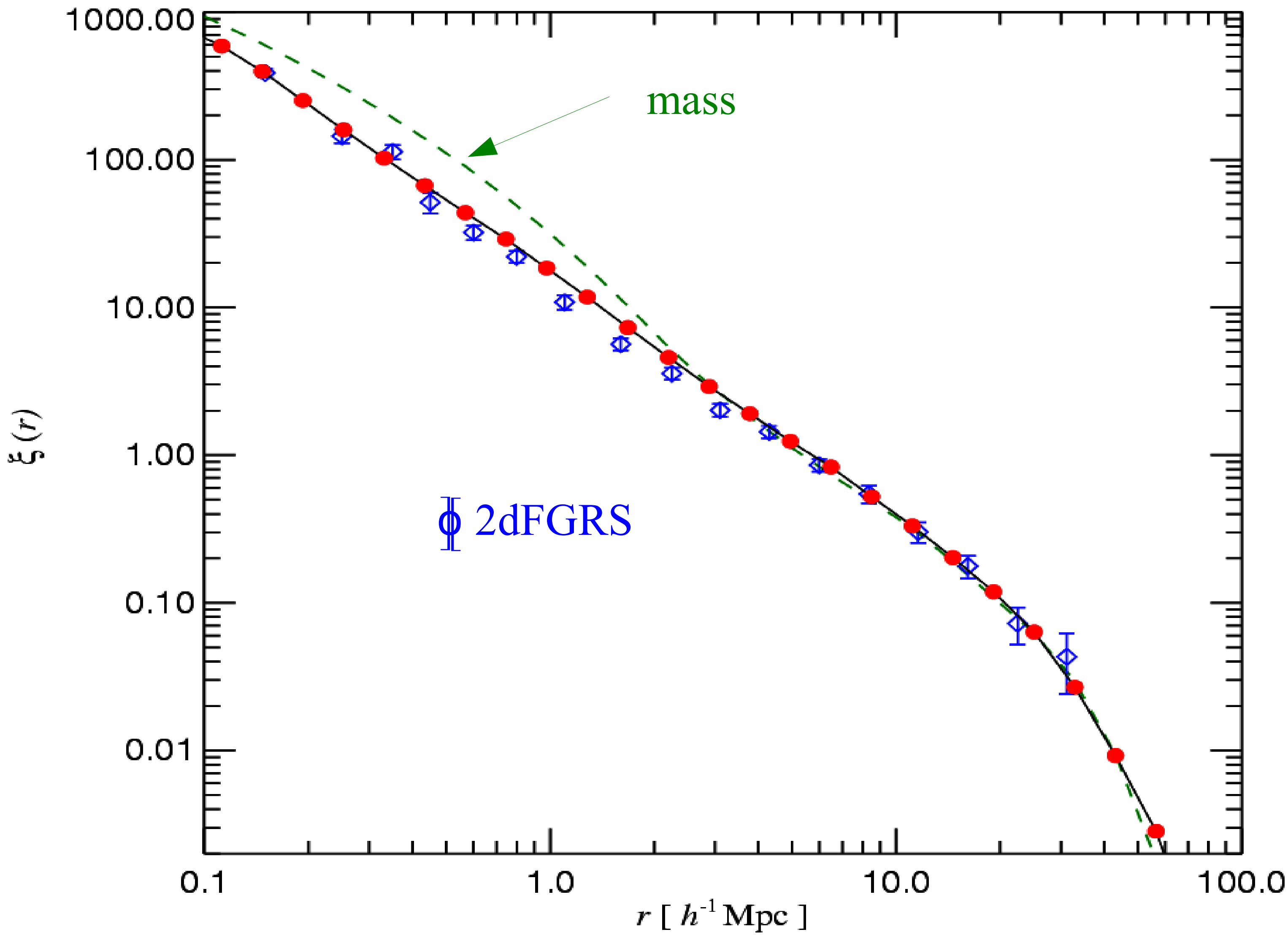

z = 0 Galaxy Light



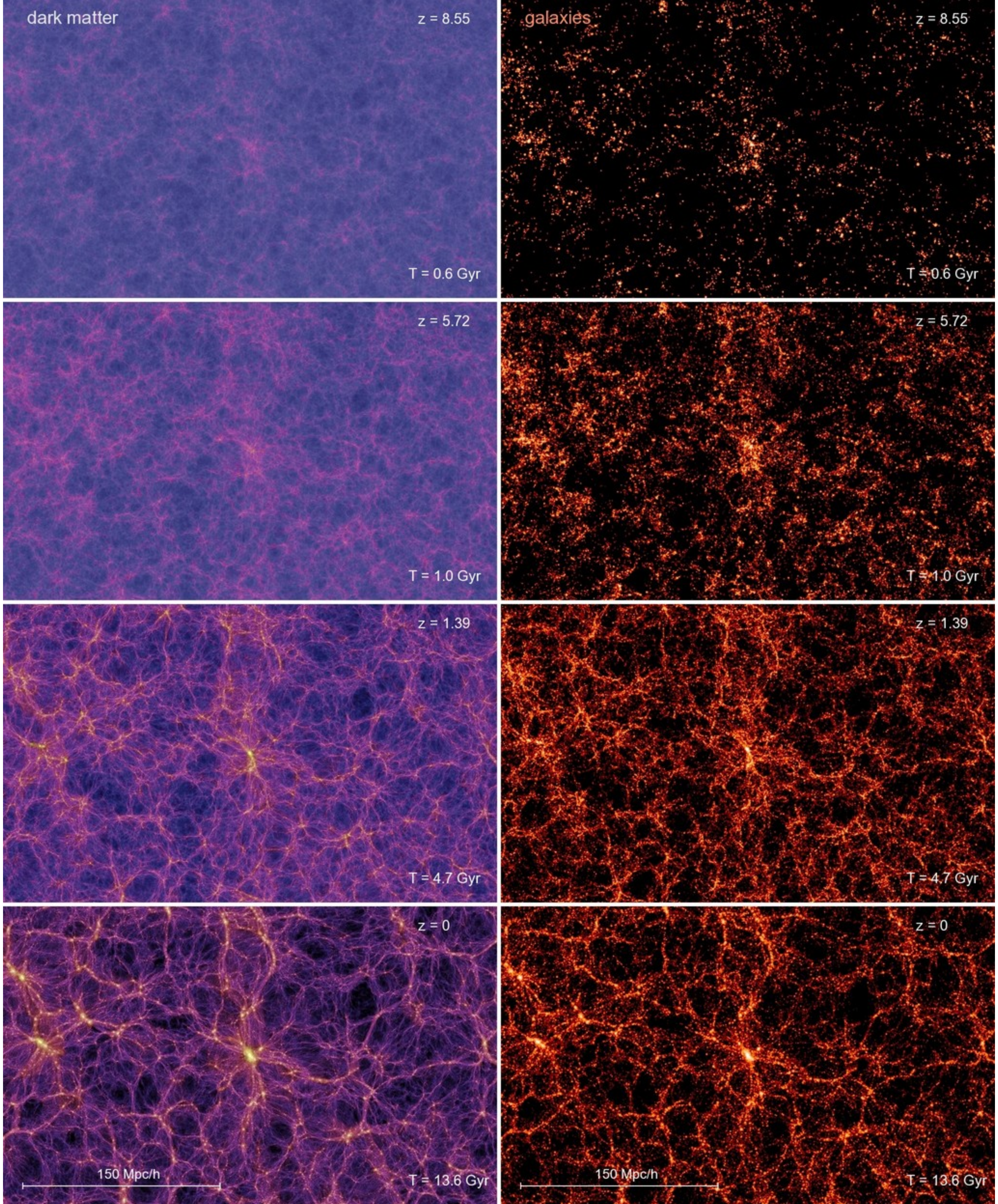
Springel, Frenk
& White 2006

Galaxy autocorrelation function

Springel et al 2005



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



Large-scale structure at high redshift

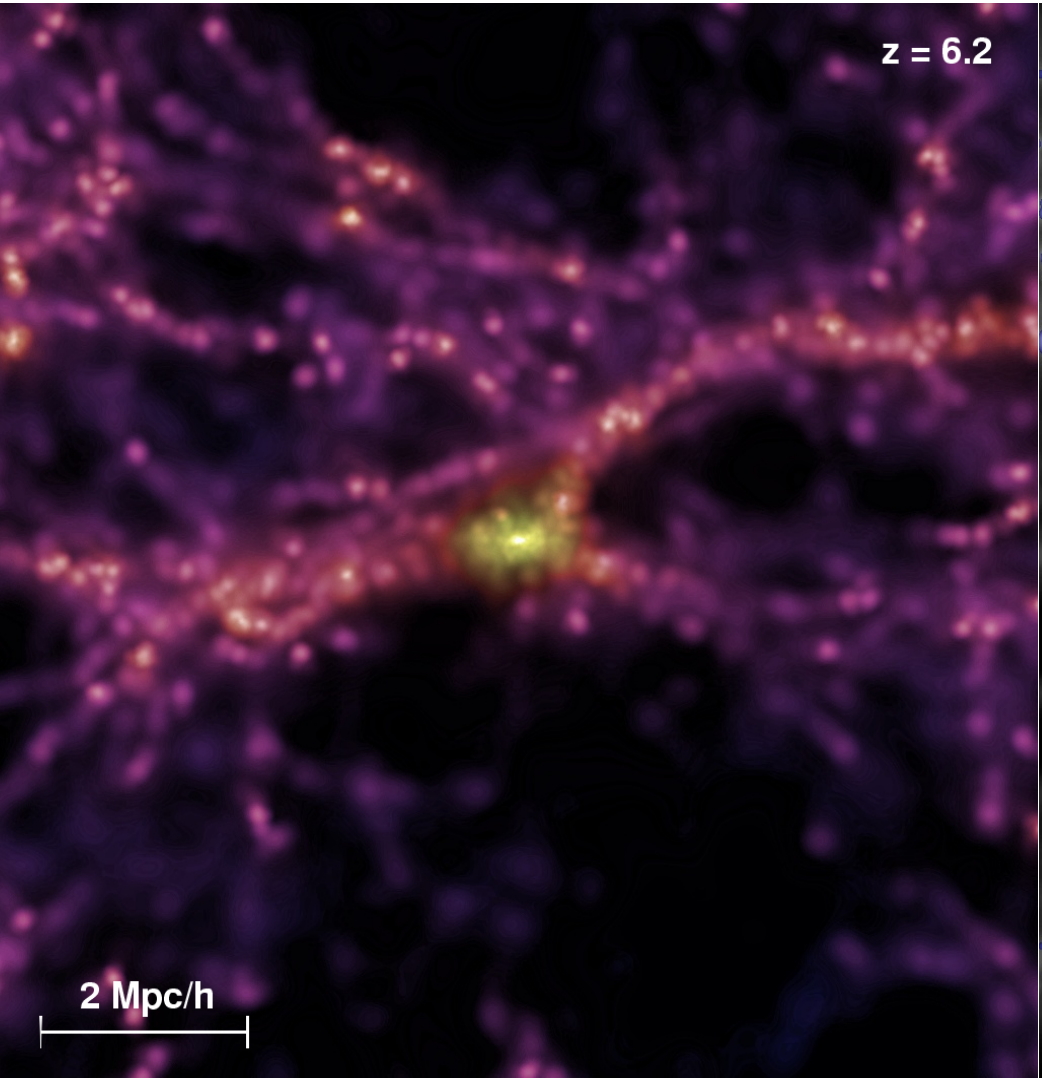
Springel, Frenk & White 2006

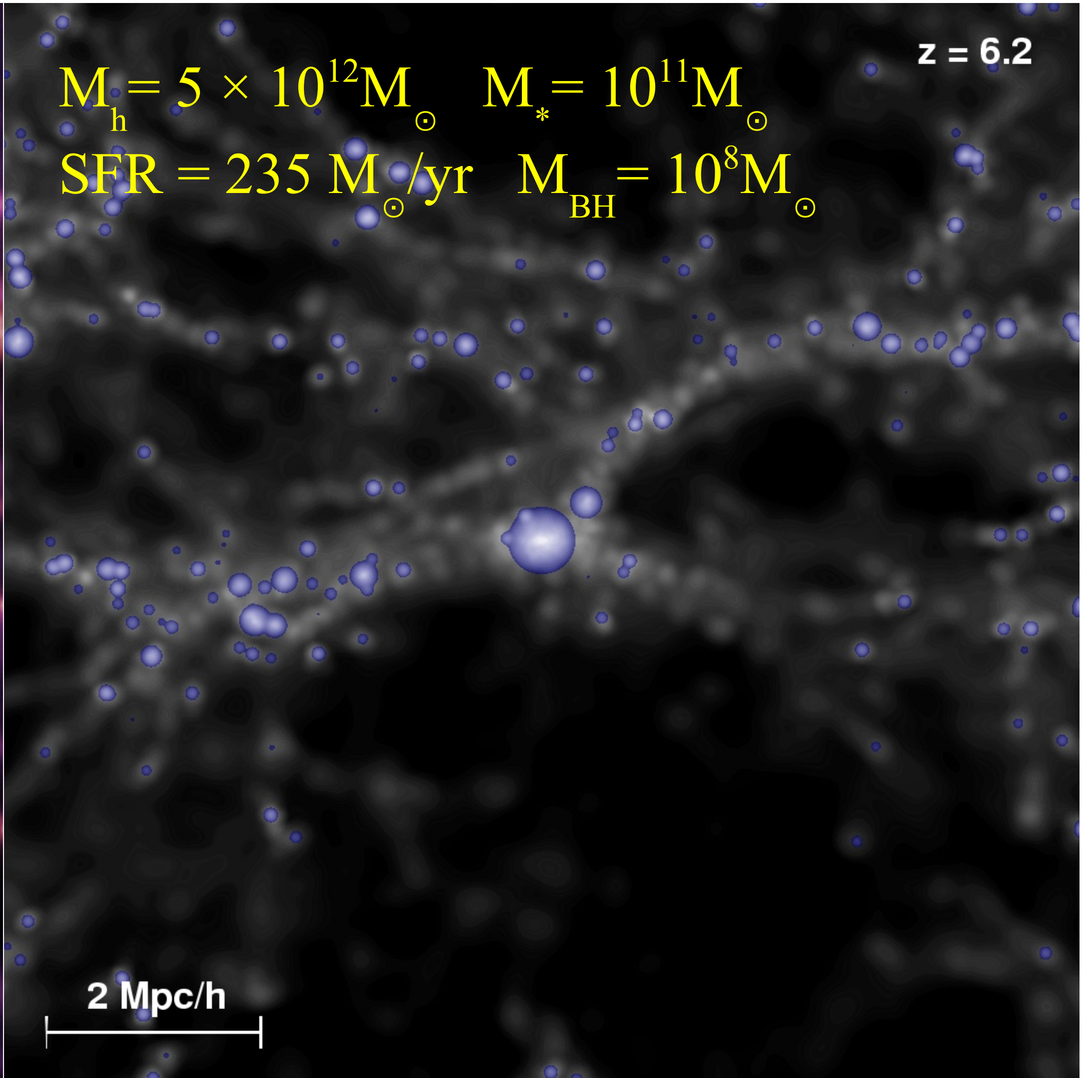
Large-scale structure in the galaxy distribution evolves very little with redshift

It is as strong at z=8.5 as at z=0

A bright quasar and its surroundings at 1 billion years

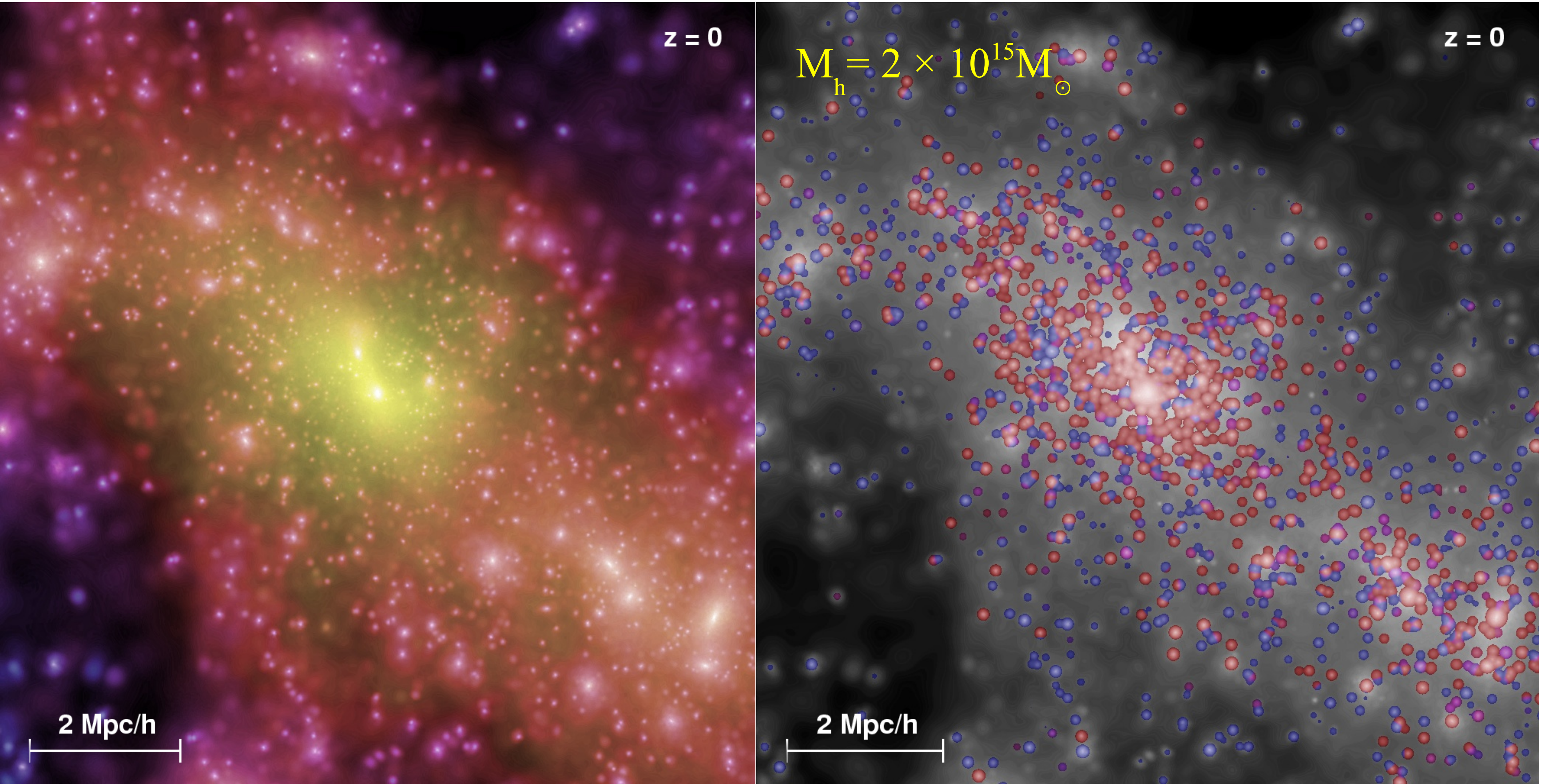
One of the most massive dark matter clumps, containing one of the most massive galaxies and most massive black holes.



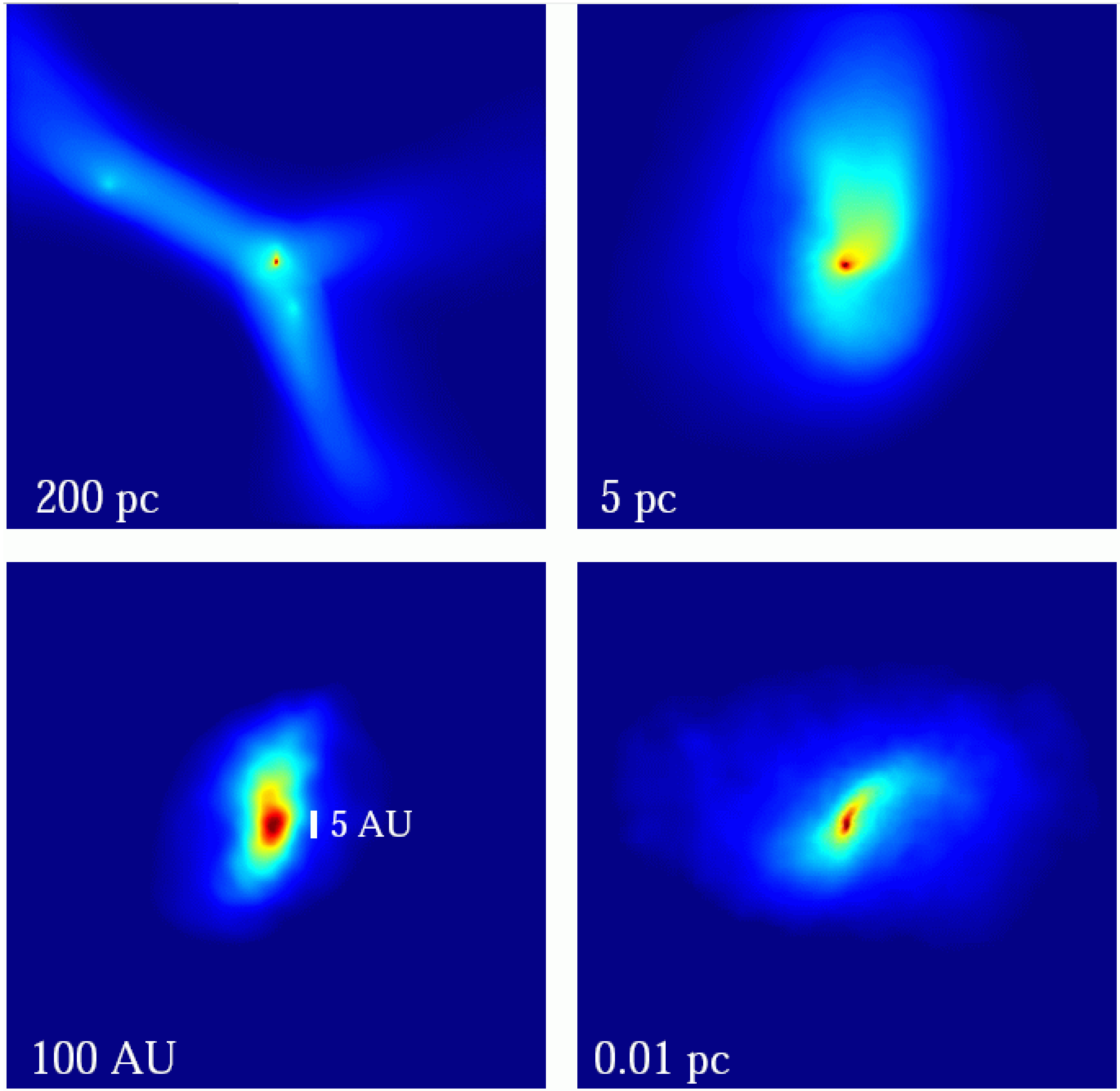


The quasar's descendant and its surroundings today, at t = 13.7 billion years

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



Formation of the "first"star in the Universe



Yoshida et al 2006

- ΛCDM cosmology
- z = 19
- Coherent collapse of "primordial" gas in a $\sim 10^6\, M_\odot$ halo
- Formation of a single star of $\sim 60 - 100\, M_\odot$
- Objects that reionized the Universe?

Goals for “late-time” structure formation studies

- Linking the linear early Universe with today's nonlinear world

- Understanding the (coupled) formation and evolution
  of the first nonlinear objects
  of galaxies, stars and planets
  of the central black holes in galaxies
  of element abundances
  of large-scale structure

- Clarifying whether visible cosmic structures retain information about the nature of Dark Matter, Dark Energy or the process which originally generated structure