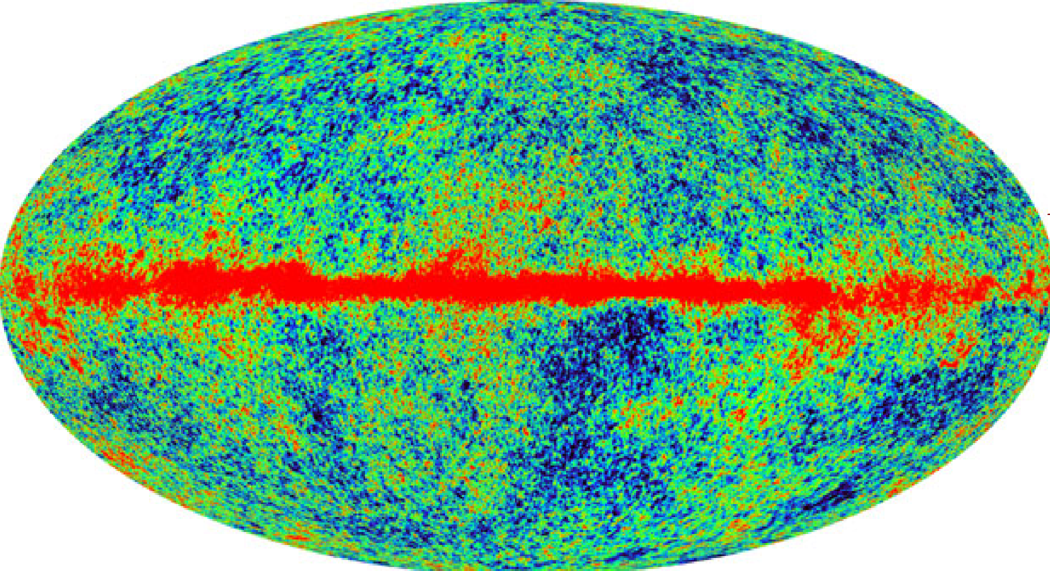
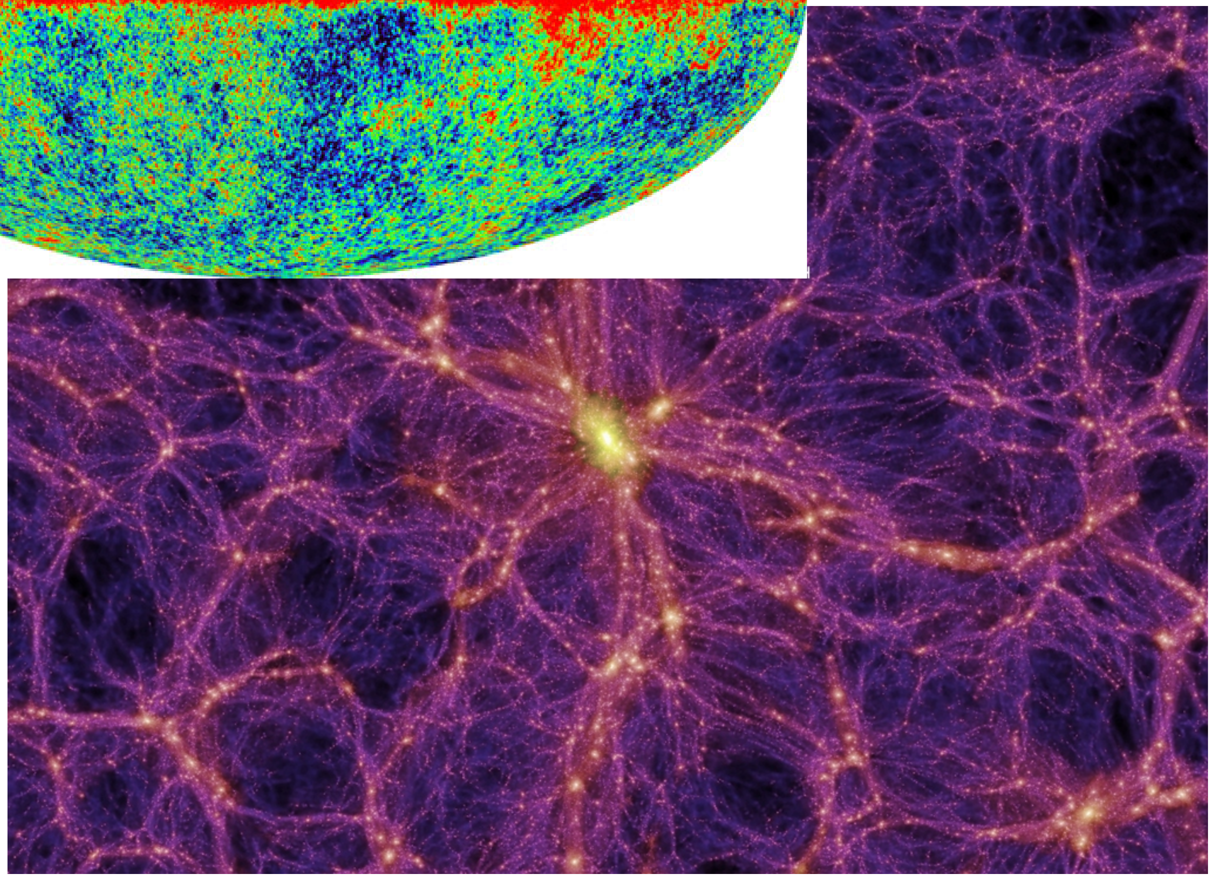
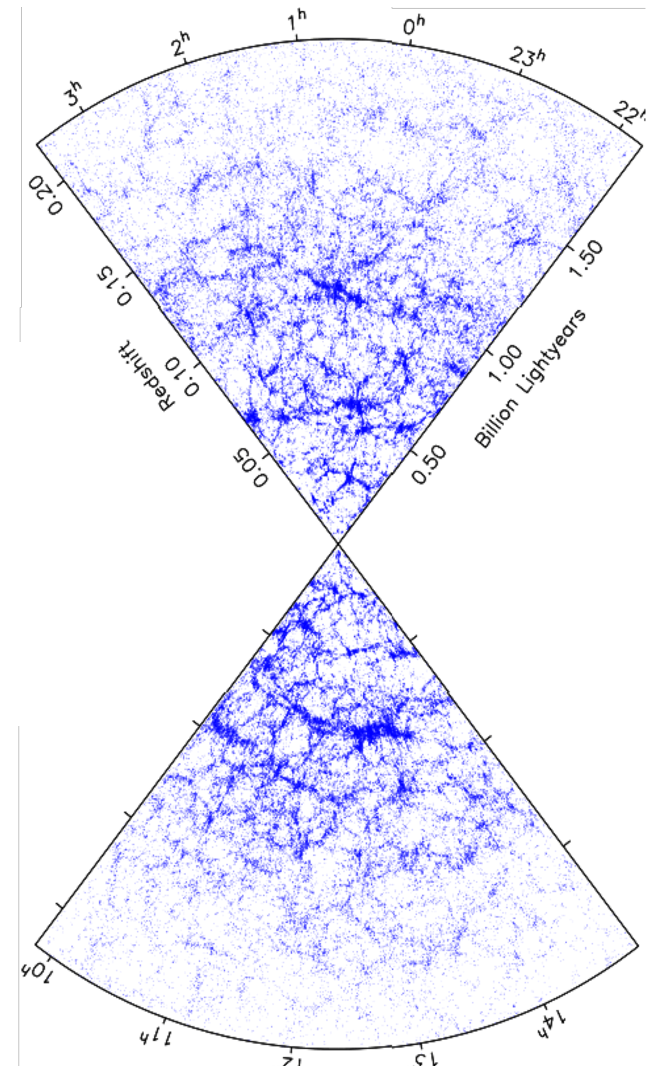


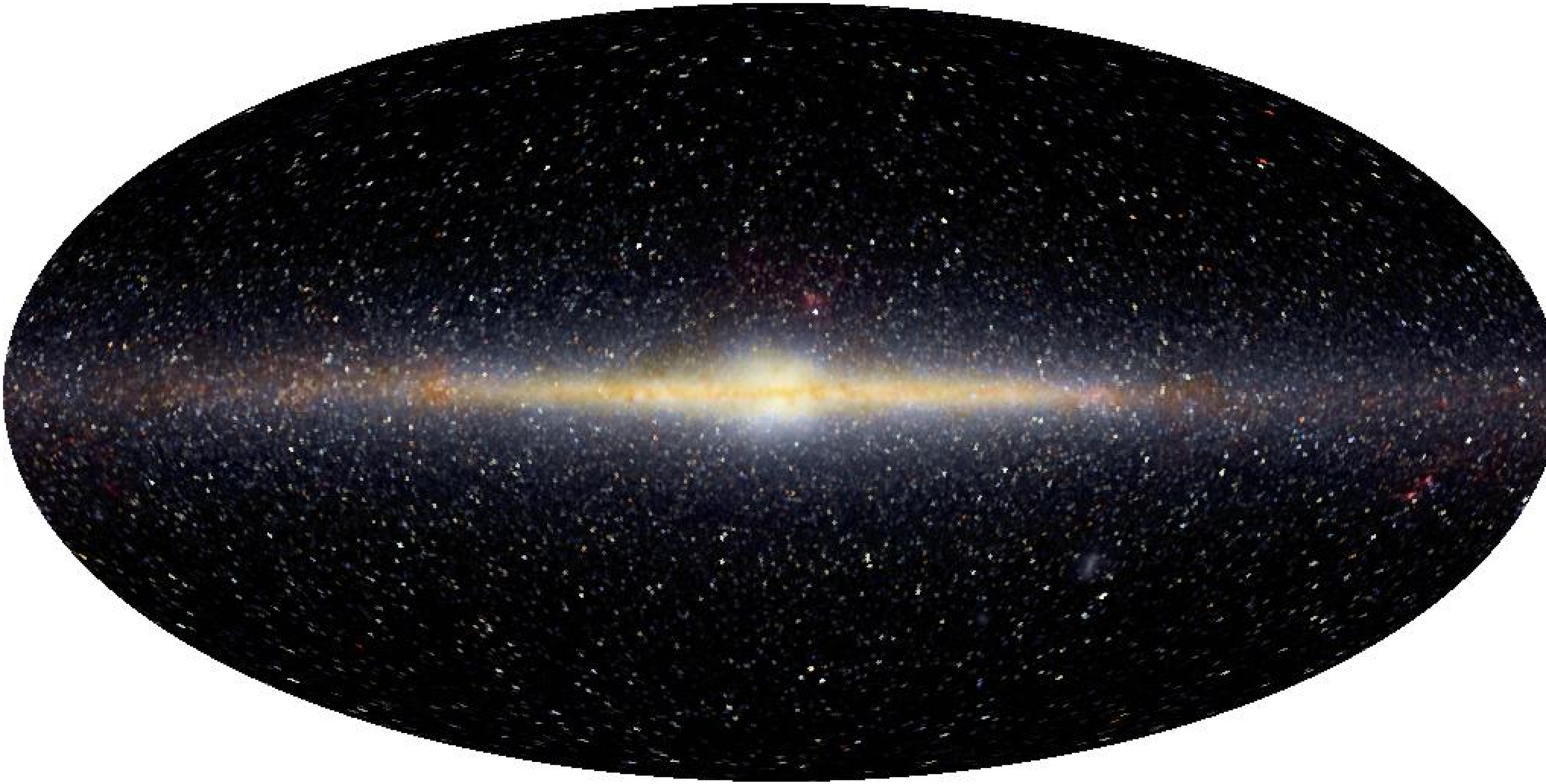
Simon White
Max Planck Institute for Astrophysics

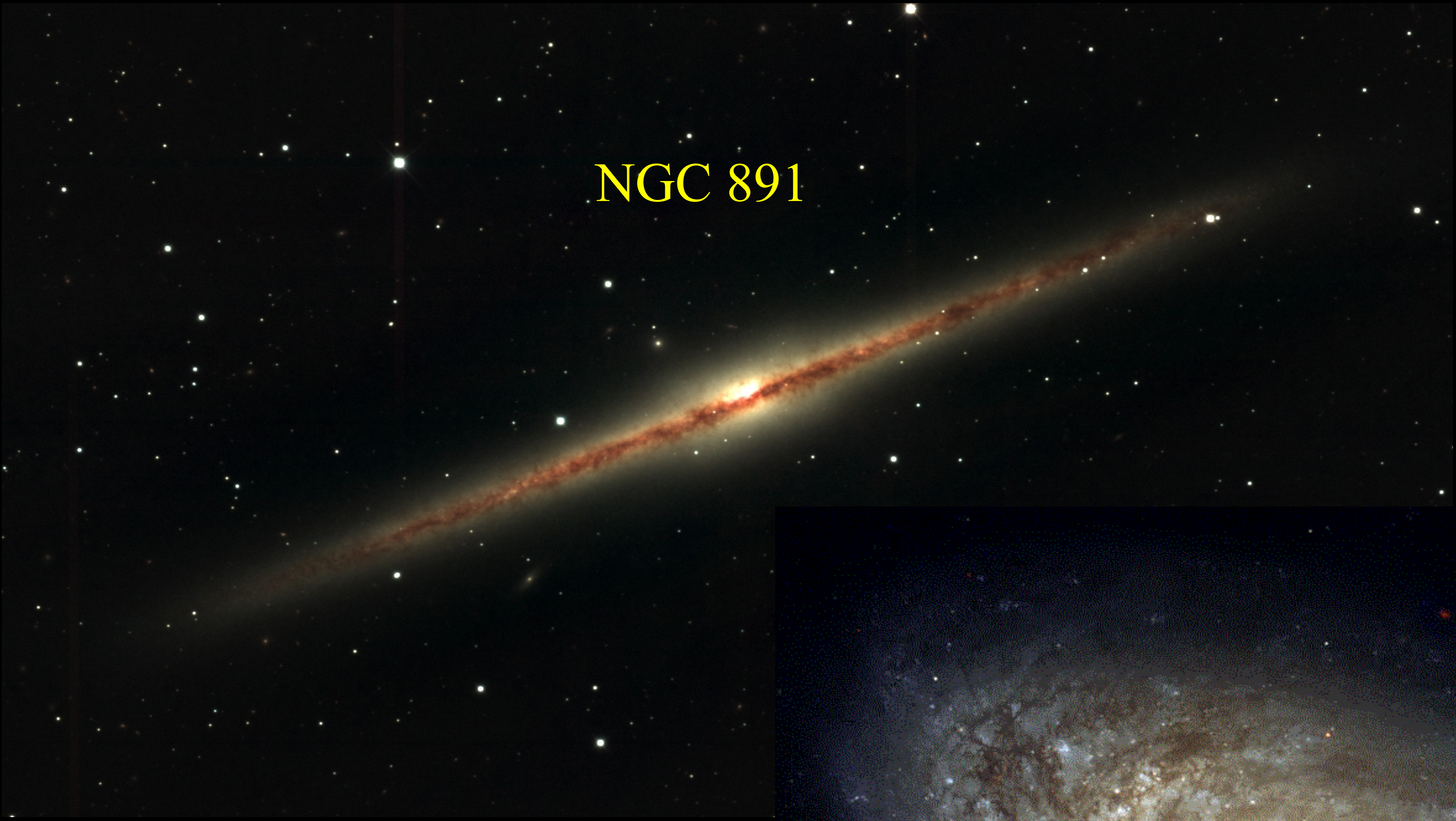




The evolution of cosmic structure

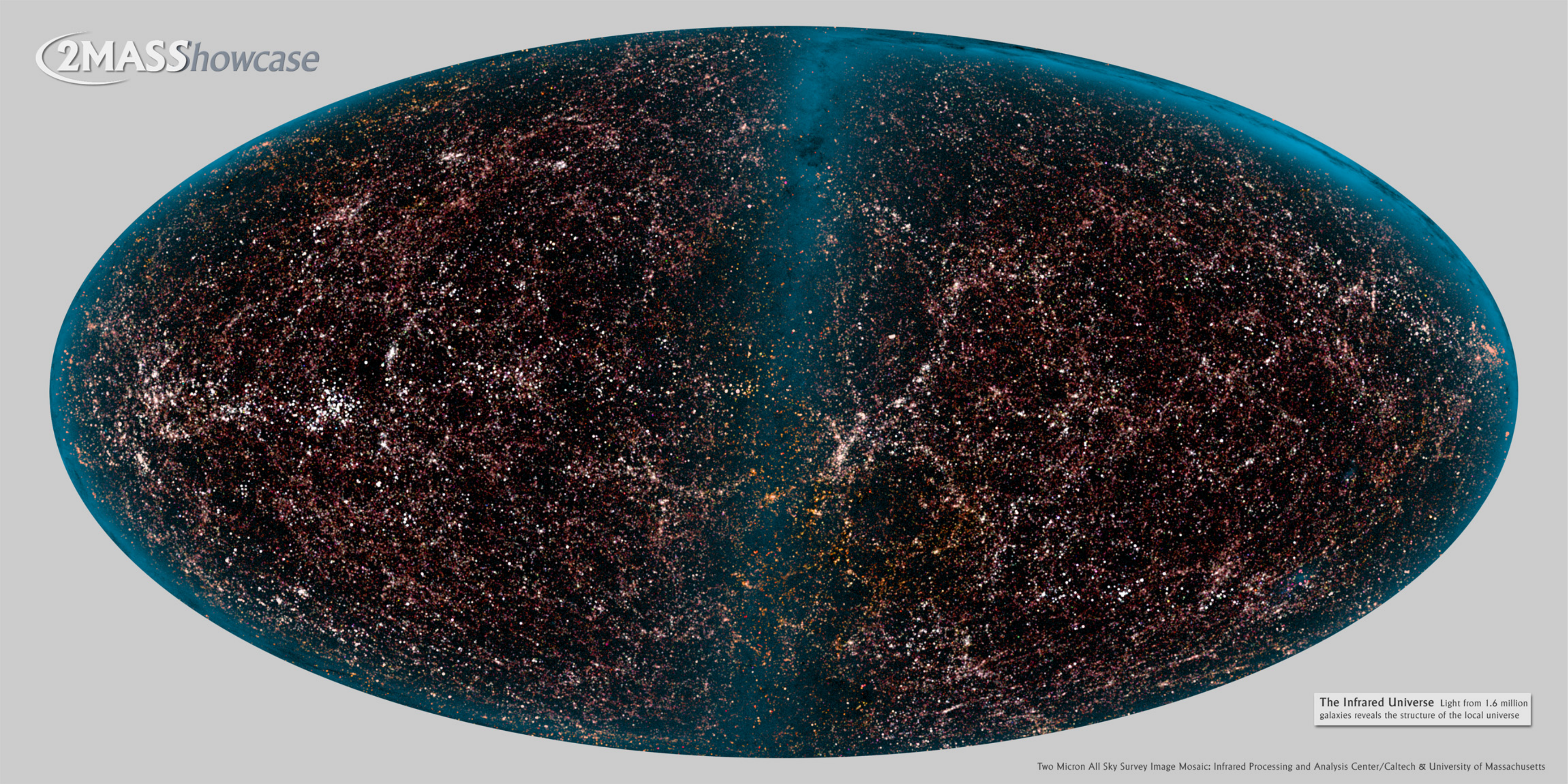
COBE's near-infrared map of the whole sky



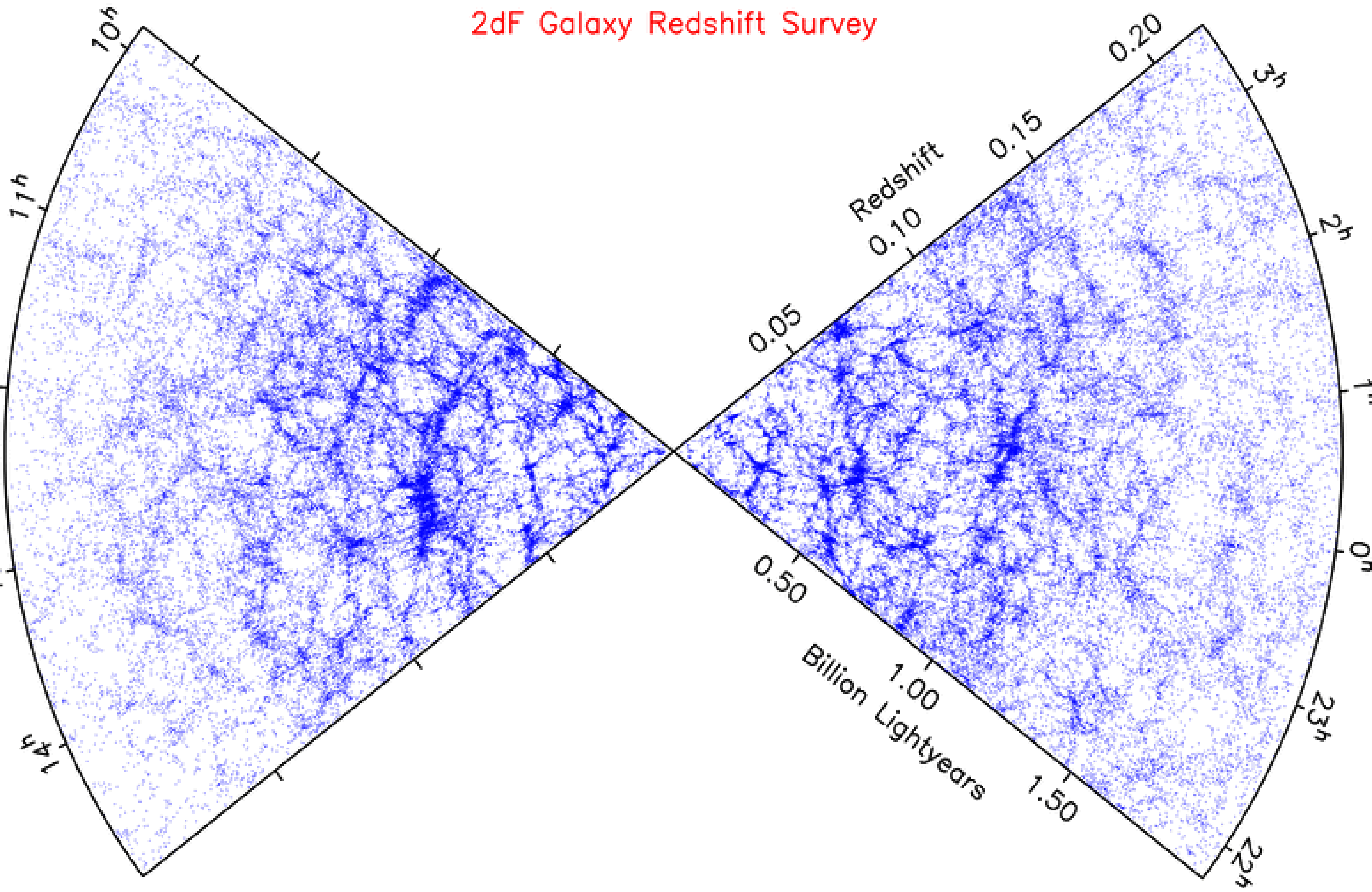


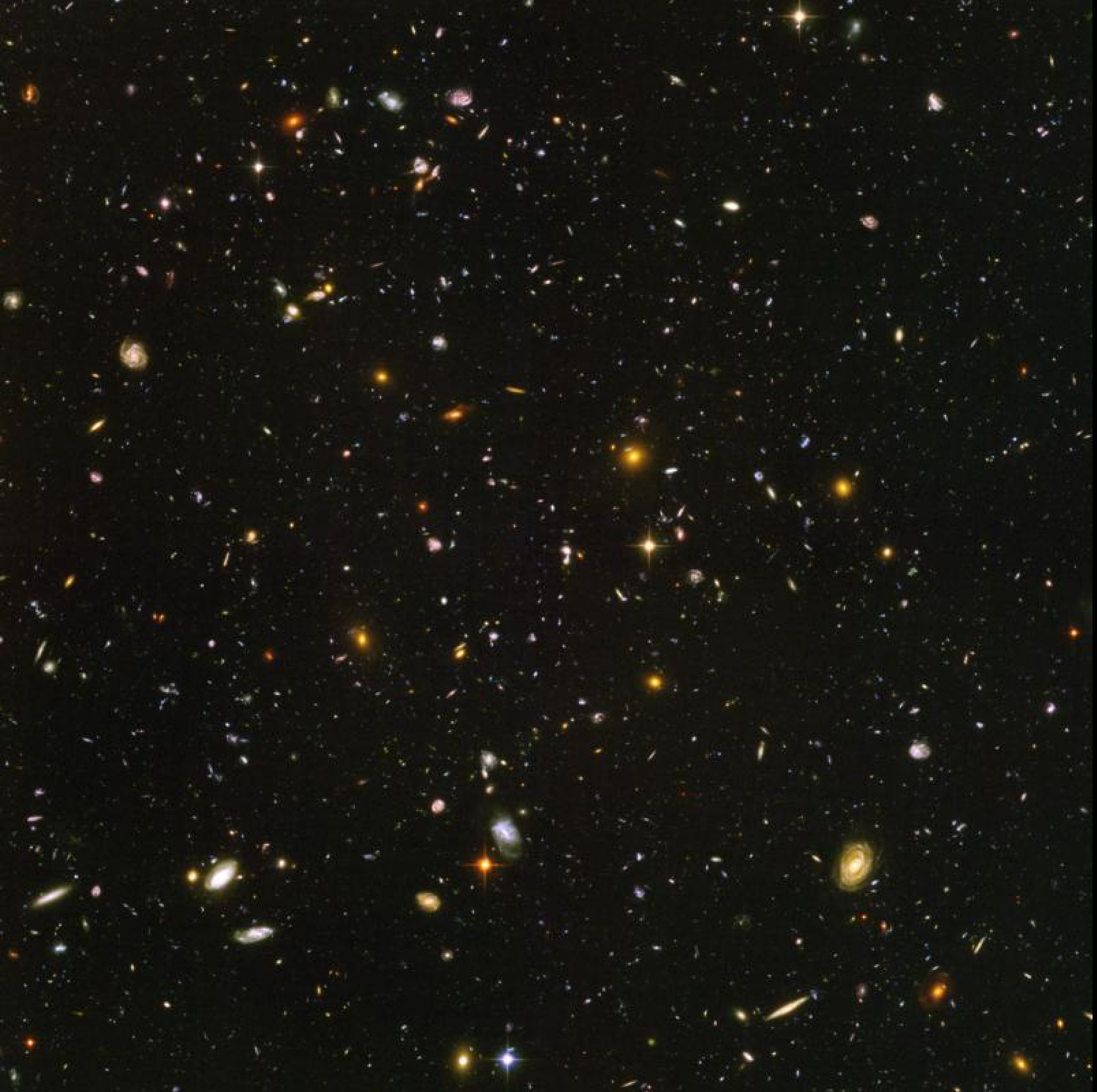
Spiral galaxies like our own

Galaxy map of the whole sky



"Nearby" large-scale structure





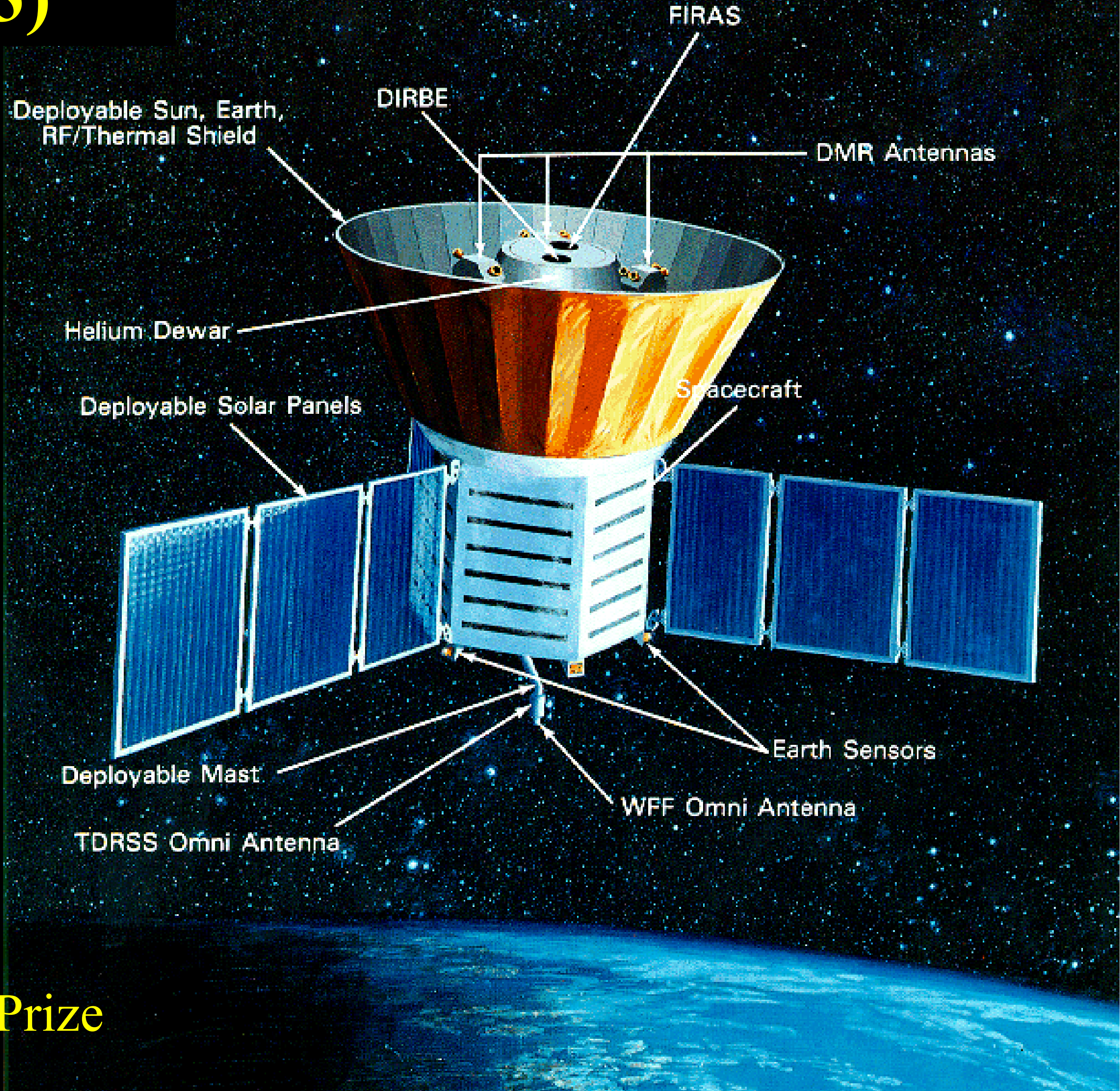
The deepest photo ever made

A 300 hour exposure with the Hubble Space Telescope

Galaxies visible at z>6 when $t < 0.1\ t_o$

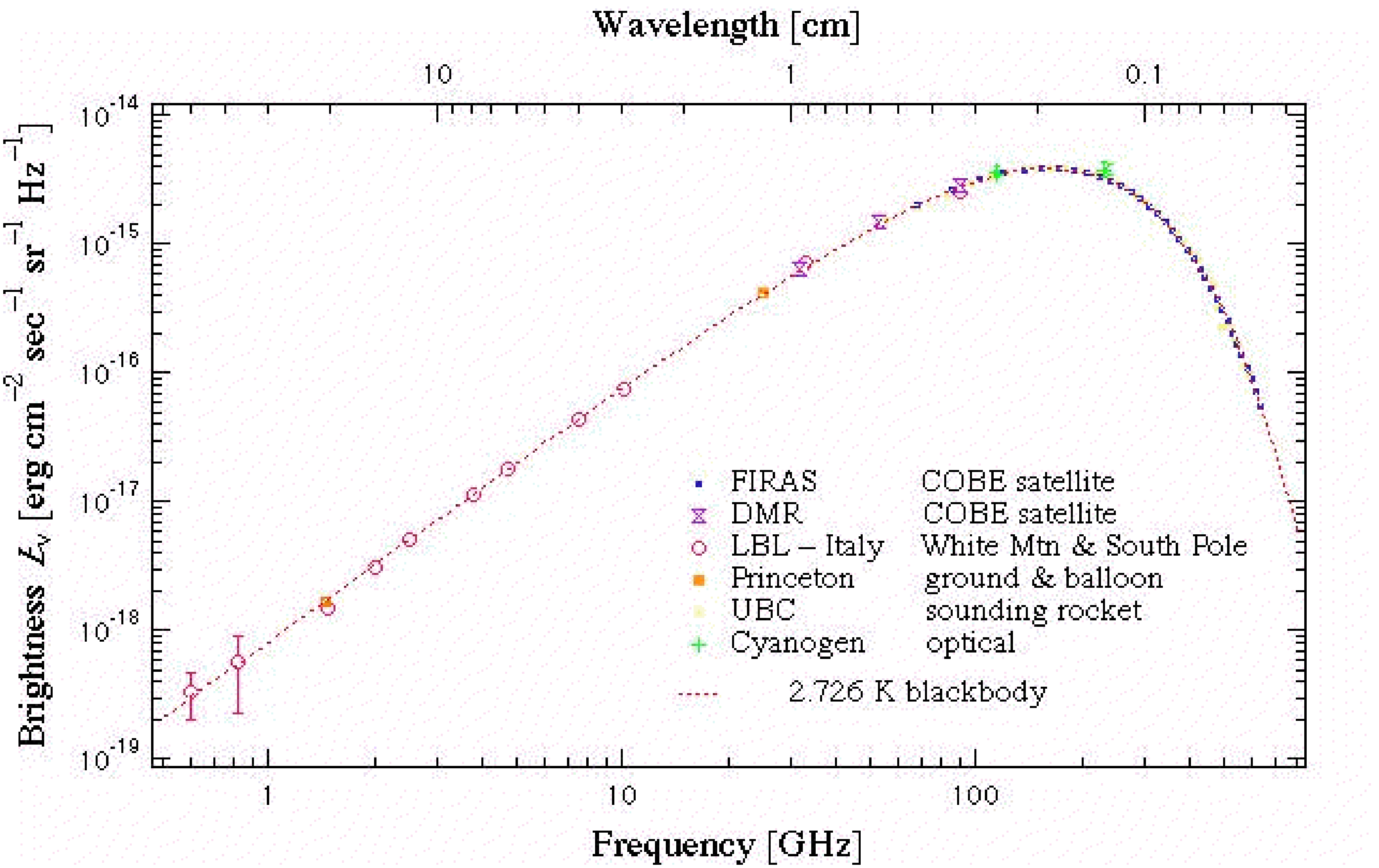
The COBE satellite (1989 - 1993)

- 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

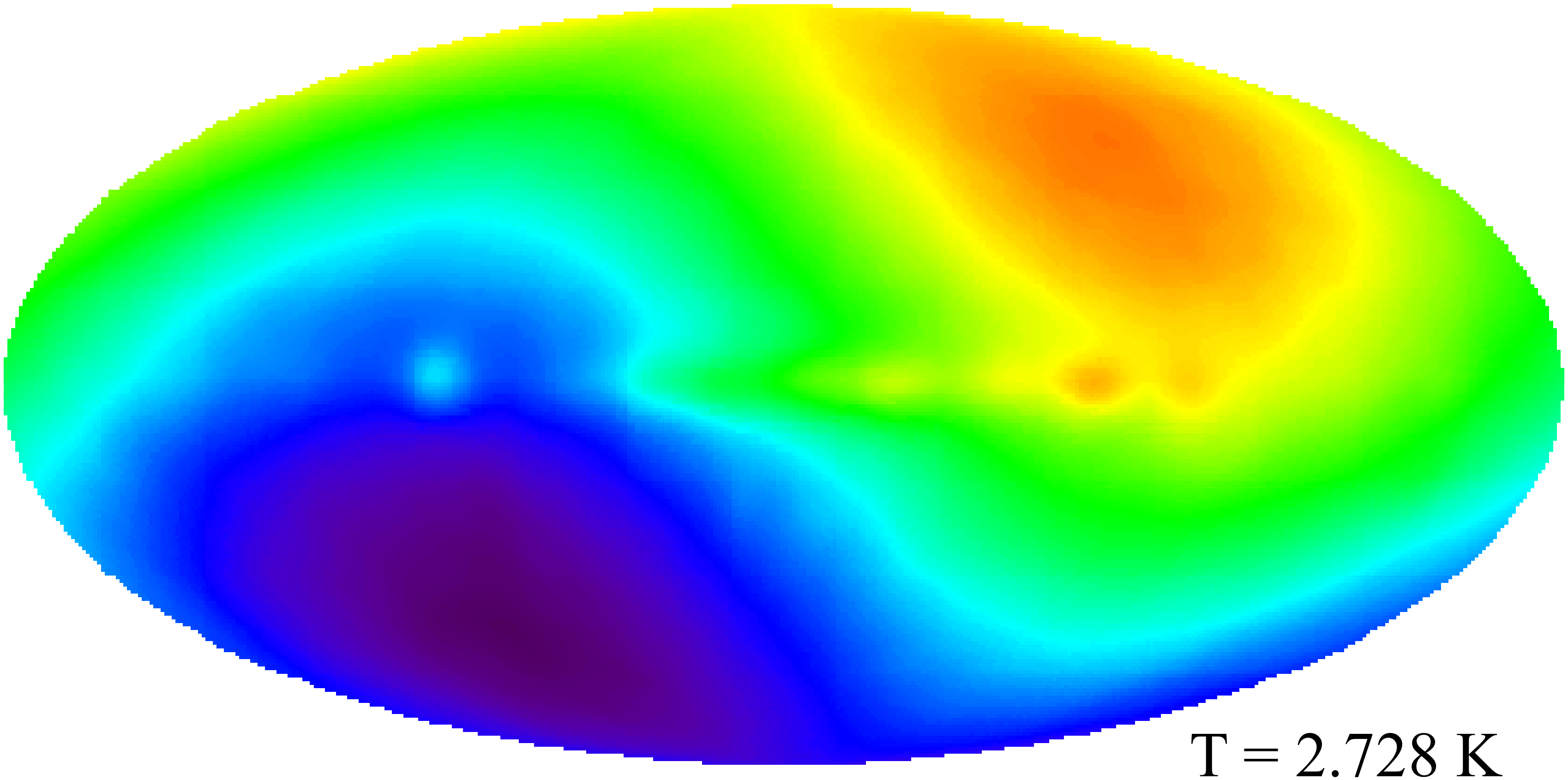


- Spectrum matches a Planckian black-body to better than 1 in 10^4
- The early universe was hot, smooth and in thermal equilibrium
- No significant energy input later than ~1 month after the Big Bang

COBE's temperature map of the entire sky

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

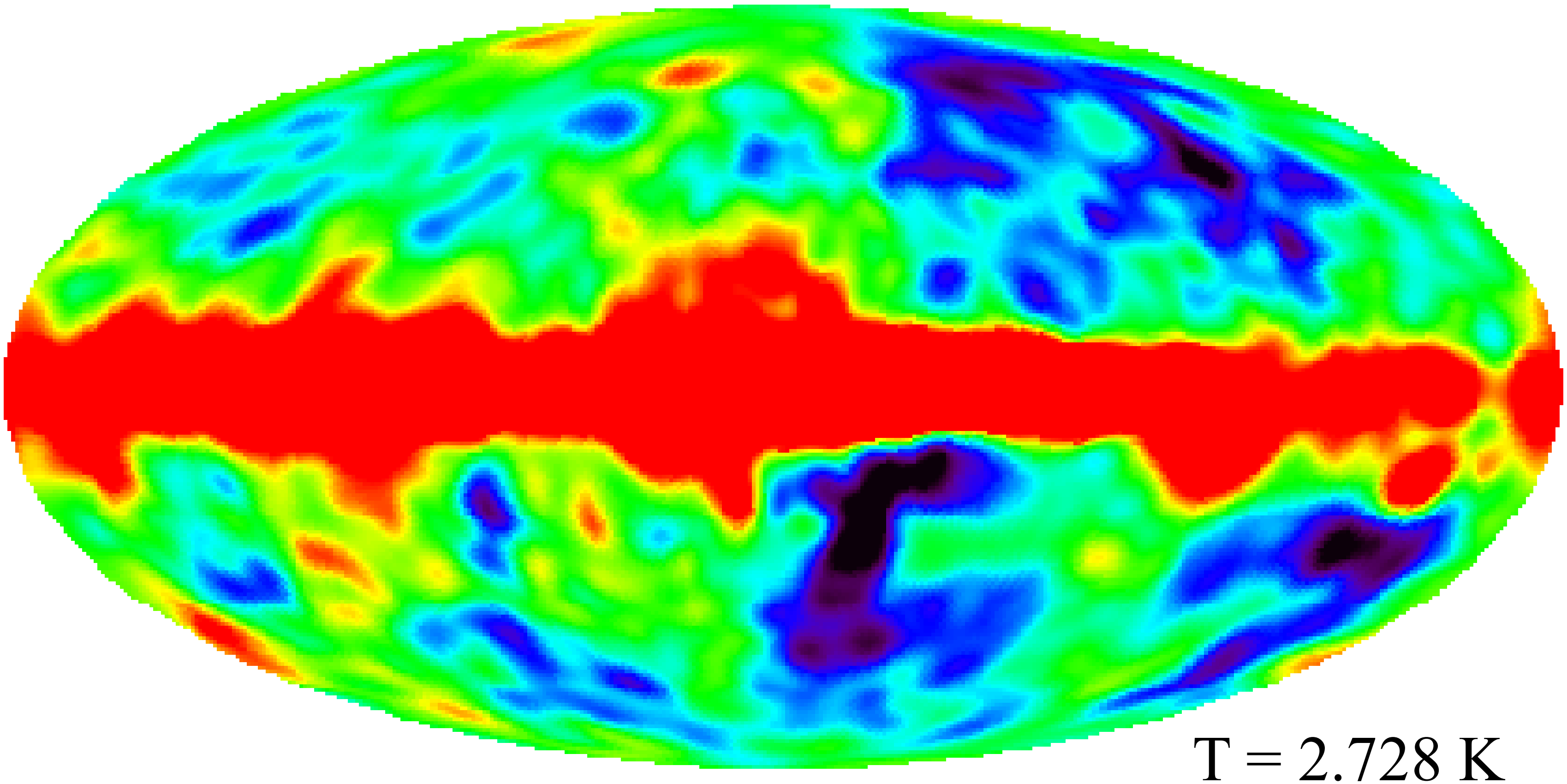
COBE's temperature map of the entire sky



T = 2.728 K

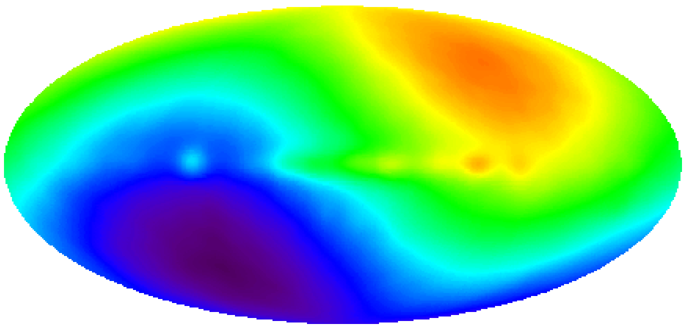
ΔT = 0.0034 K

COBE's temperature map of the entire sky



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

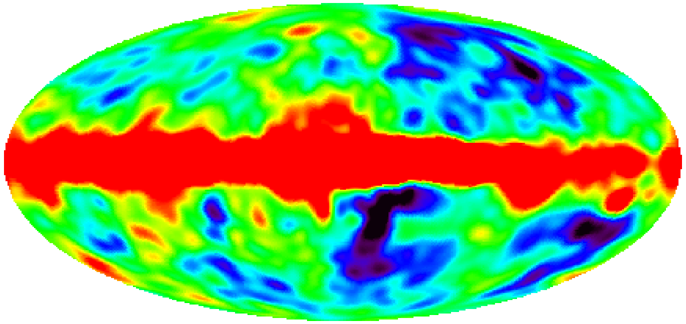
Structure in the COBE map



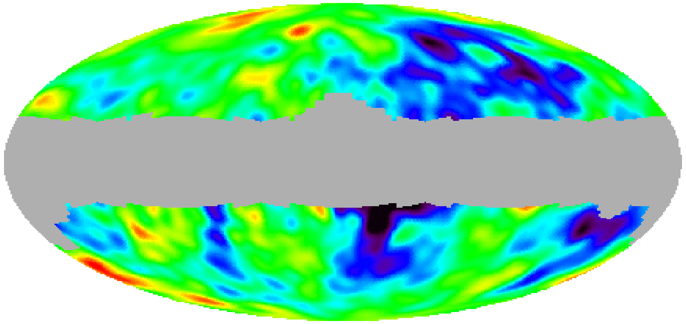
- One side of the sky is `hot', the other is`cold'

➡ 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

- 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

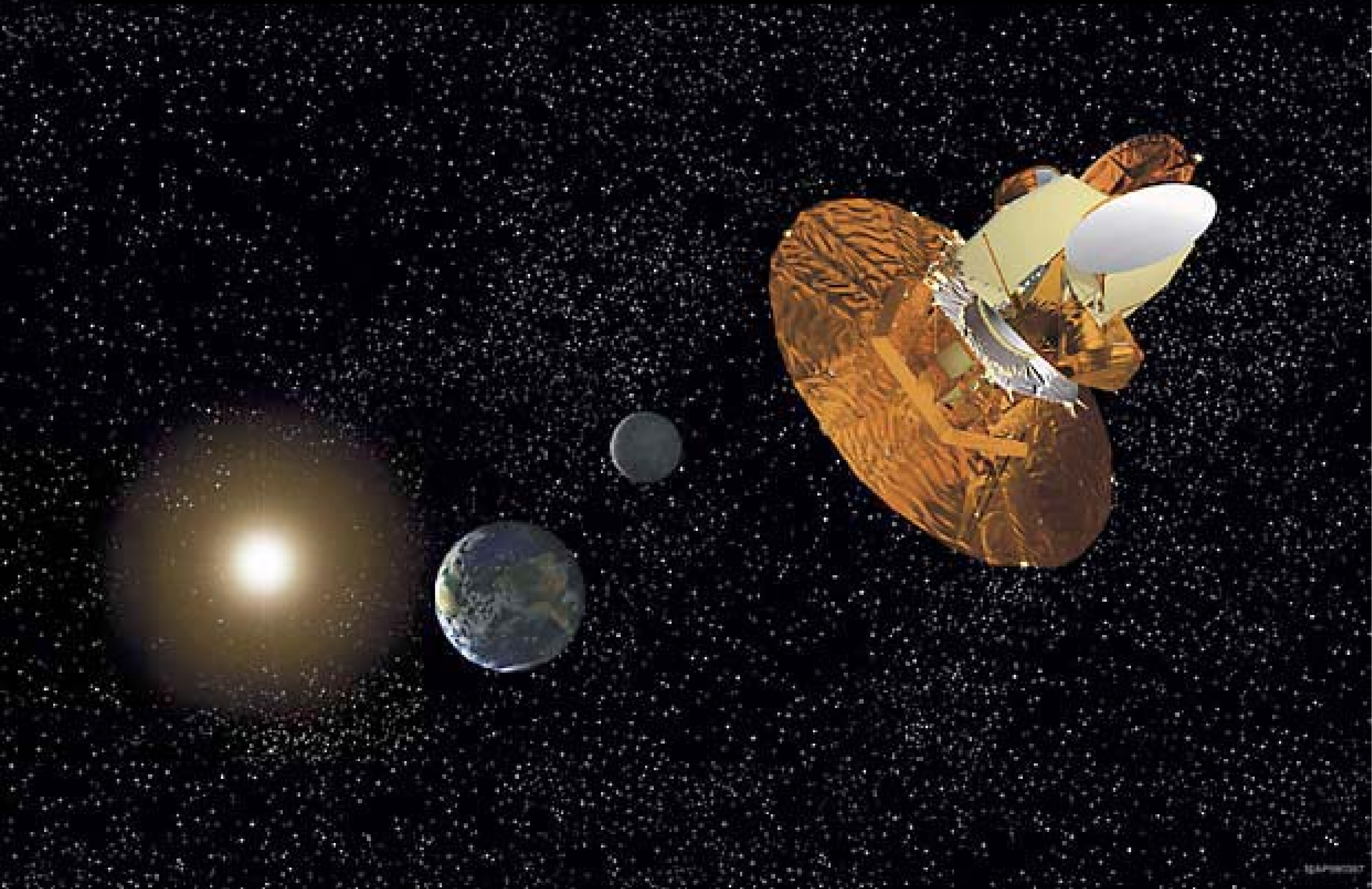
The *pattern* of structure reflects

A: The global geometry and topology of the Universe

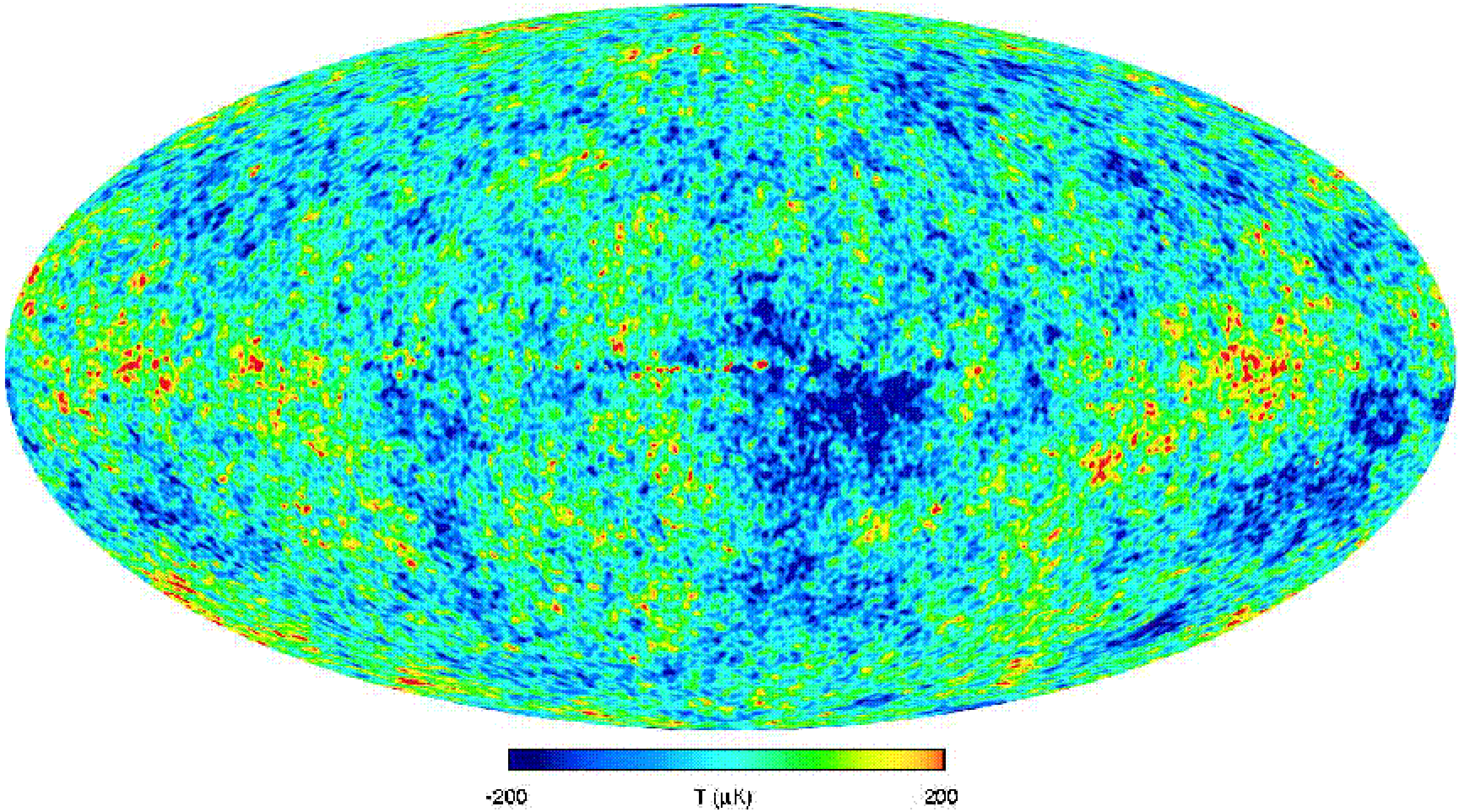
B: The constituents and thermal evolution of the Universe

C: The process which generated the structure

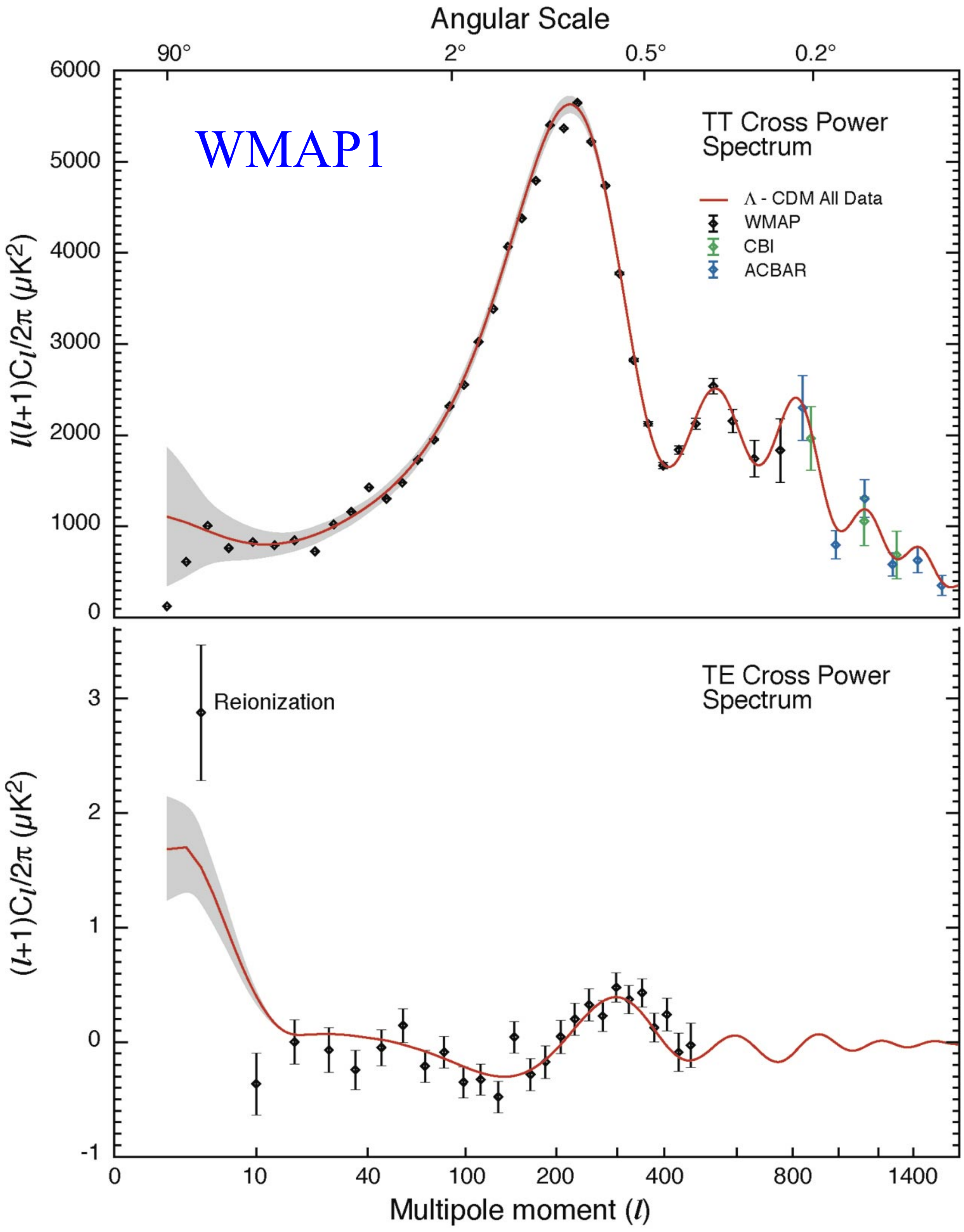
The *WMAP* Satellite at Lagrange-Point L2



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

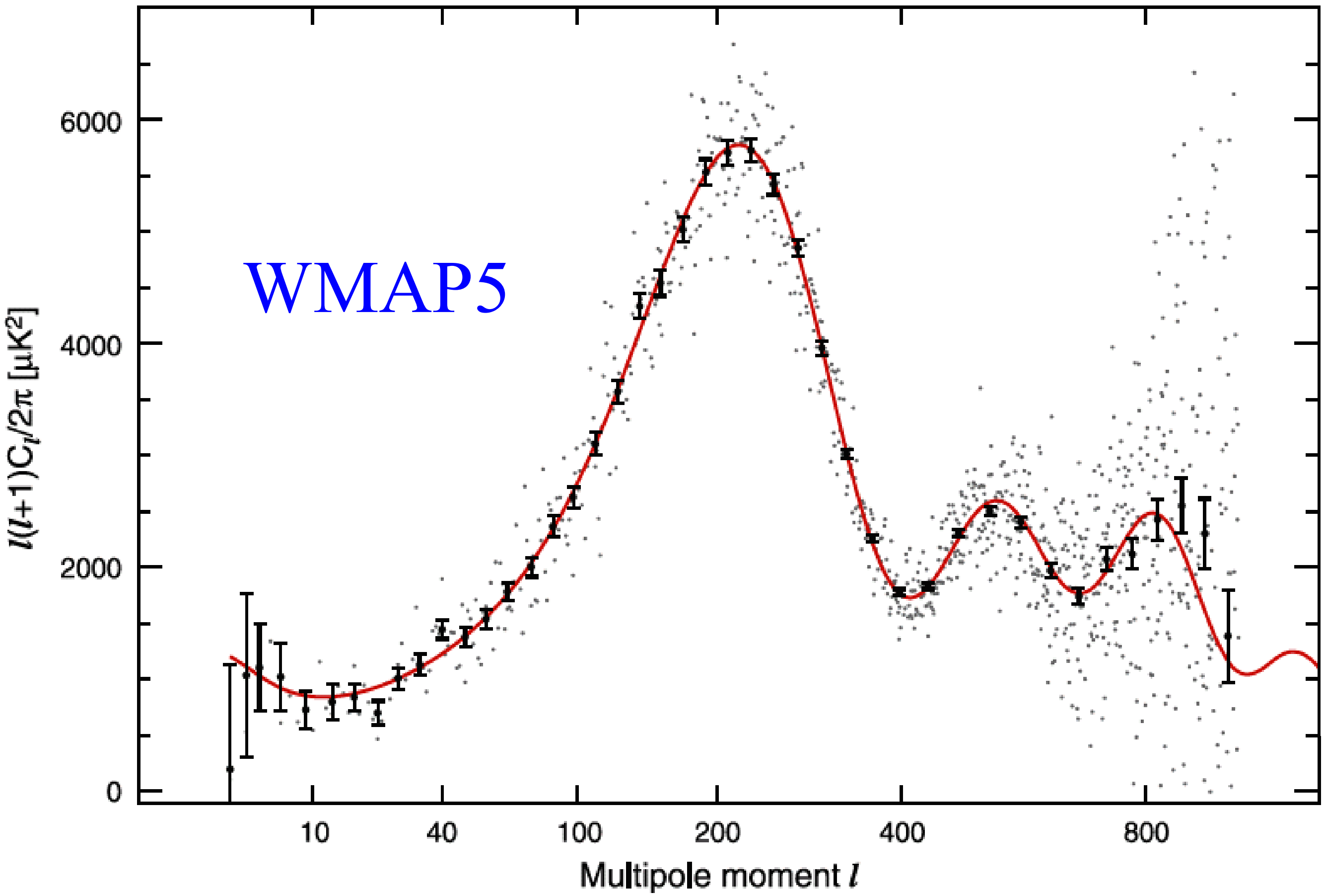
$h = 0.71 \pm 0.03$ $\sigma_8 = 0.84 \pm 0.04$

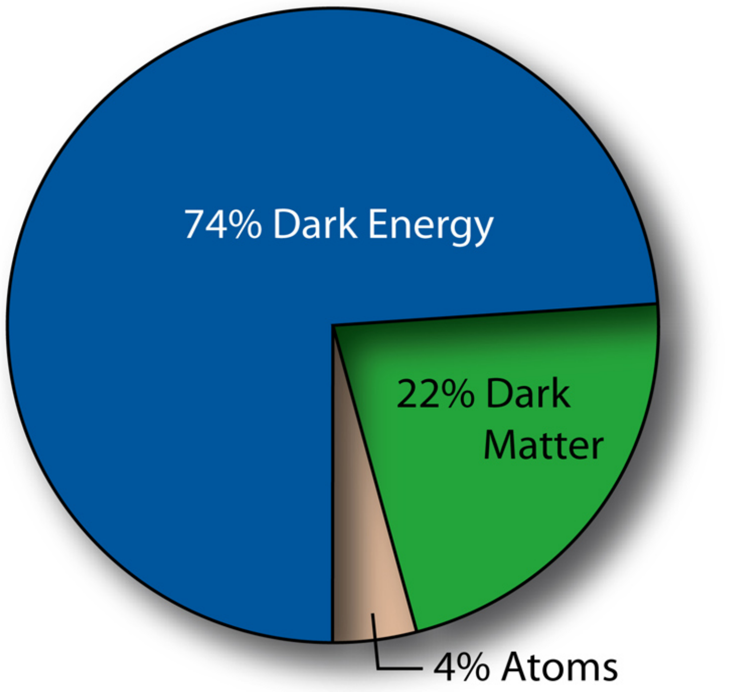
$\Omega_t = 1.02 \pm 0.02$ $\Omega_m = 0.27 \pm 0.04$

$\Omega_b = 0.044 \pm 0.004$

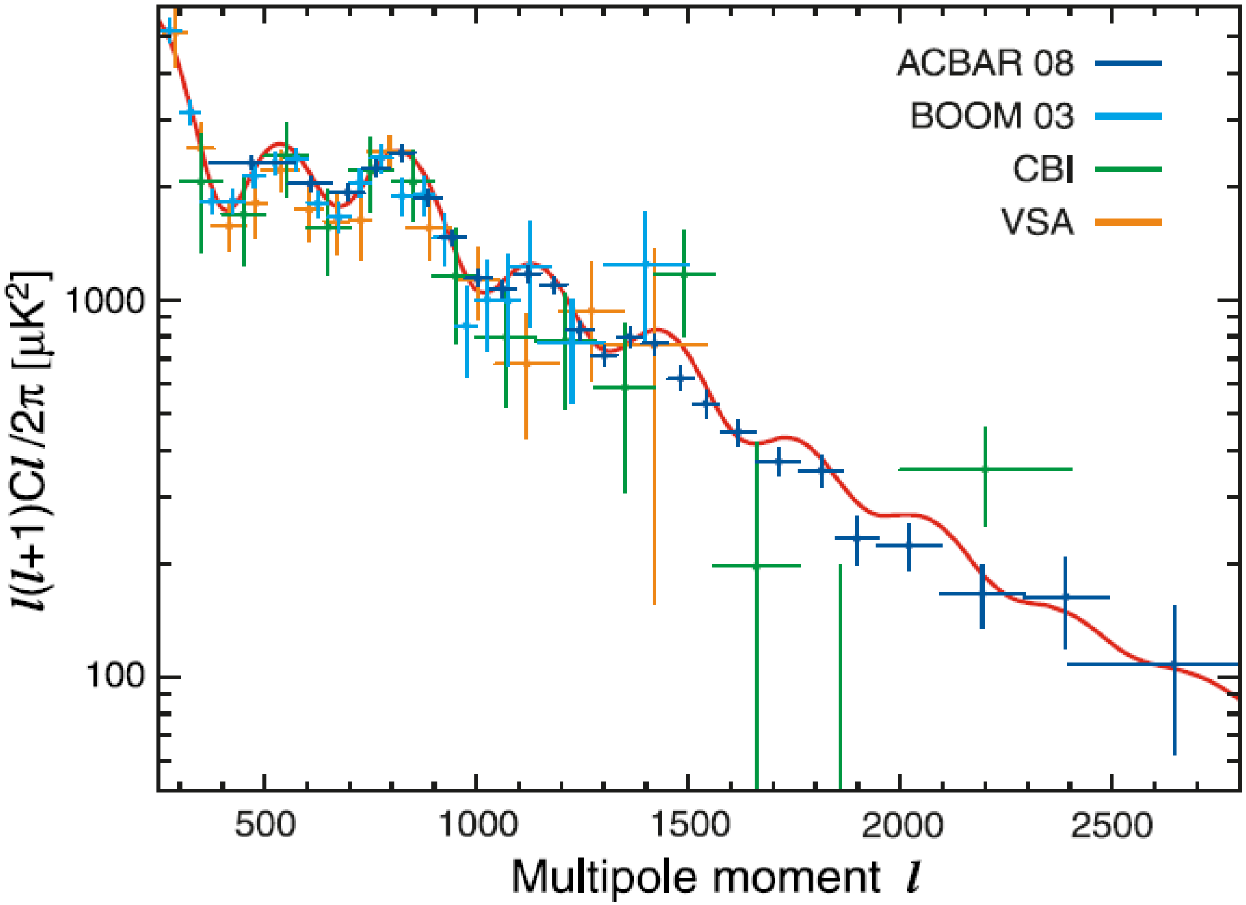
$\tau_e = 0.17 \pm 0.07$

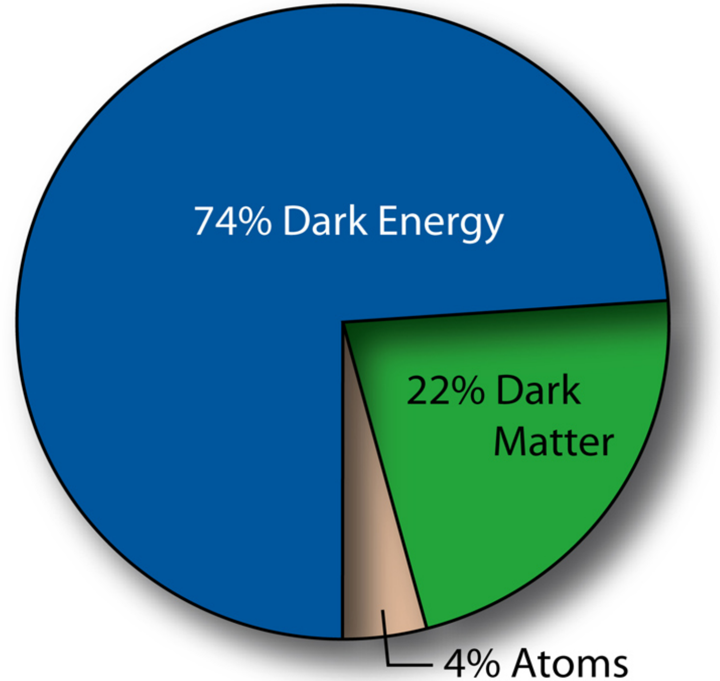
- Parameters in excellent agreement with other astronomical data





parameter	symbol	WMAP-5 alone	WMAP-5 + BAO + SNe	comment
CMB temperature	$T_{\rm CMB}$	2.728 ± 0.004 K	–	from (Fixsen *et al.* 1996)
total matter density	$\Omega_{\rm tot}$	$1.099^{+0.100}_{-0.085}$	1.0052 ± 0.0064	
matter density	$\Omega_{\rm m0}$	0.258 ± 0.03	0.279 ± 0.015	assuming spatial flatness
baryon density	$\Omega_{\rm b0}$	0.0441 ± 0.0030	0.0462 ± 0.0015	here and below
cosmological constant	$\Omega_{\Lambda 0}$	0.742 ± 0.03	0.721 ± 0.015	
Hubble constant	h	$0.719^{+0.026}_{-0.027}$	0.701 ± 0.013	
power-spectrum normalisation	σ_8	0.796 ± 0.036	0.817 ± 0.026	
age of the Universe in Gyr	t_0	13.69 ± 0.13	13.73 ± 0.12	
decoupling redshift	$z_{\rm dec}$	1087.9 ± 1.2	1088.2 ± 1.1	
reionisation optical depth	τ	0.087 ± 0.017	0.084 ± 0.016	
spectral index	$n_{\rm s}$	$0.963^{+0.014}_{-0.015}$	$0.960^{+0.014}_{-0.013}$	





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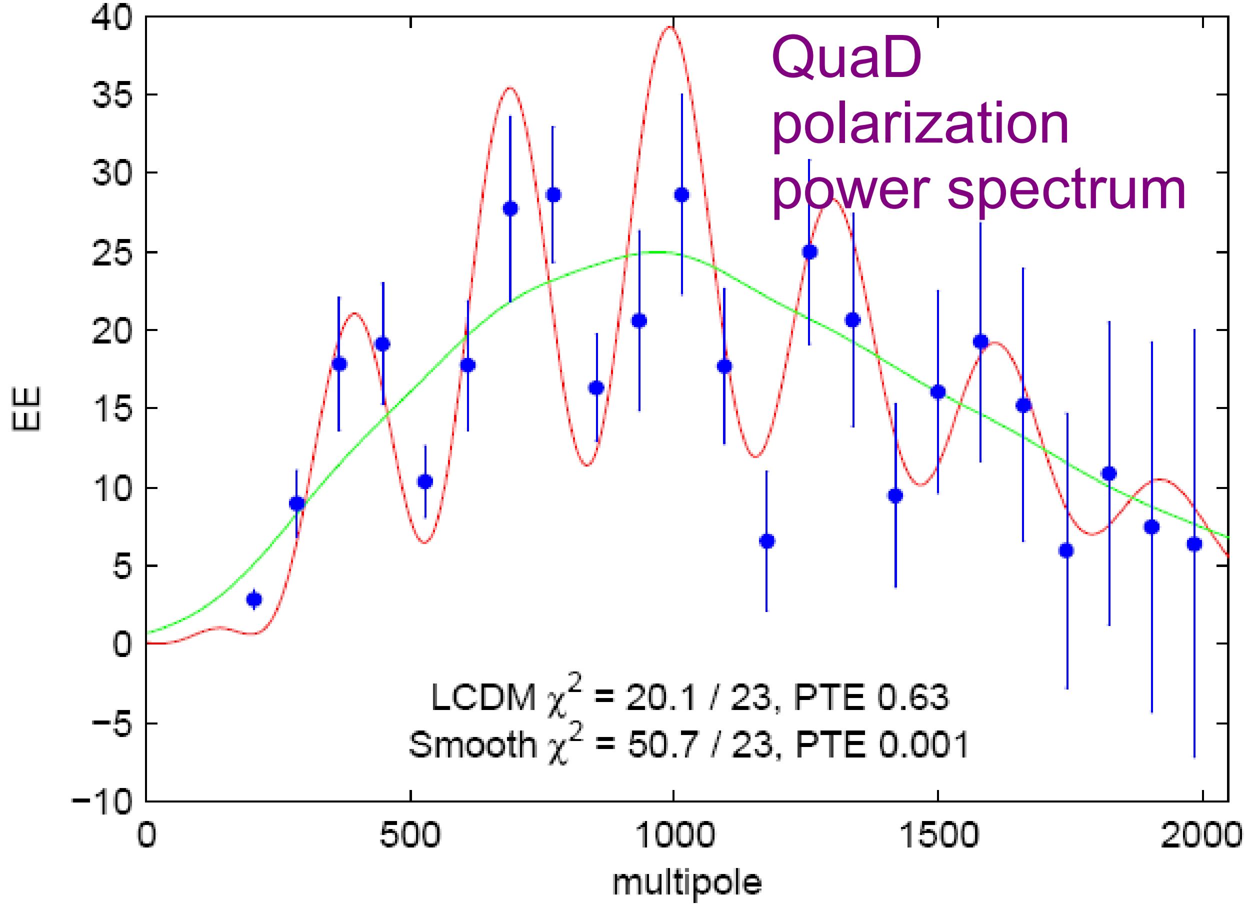

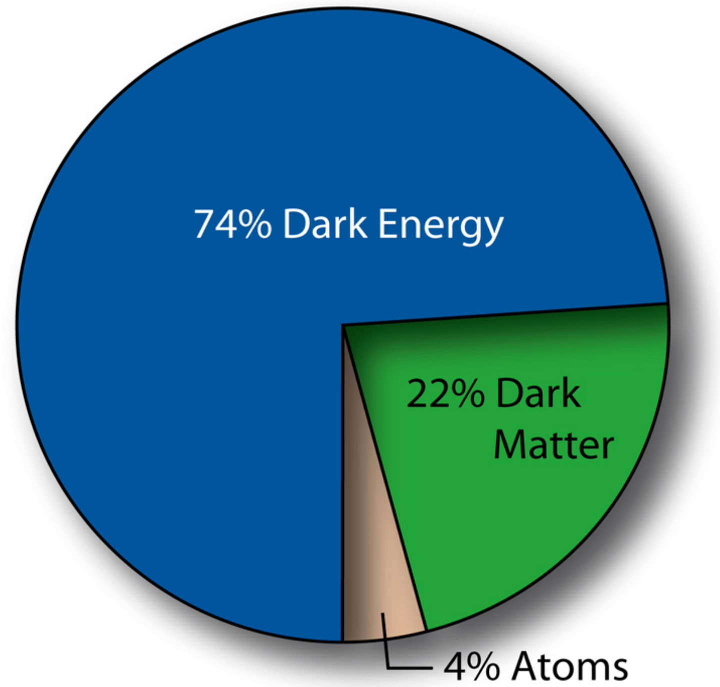

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What have we learned from WMAP?

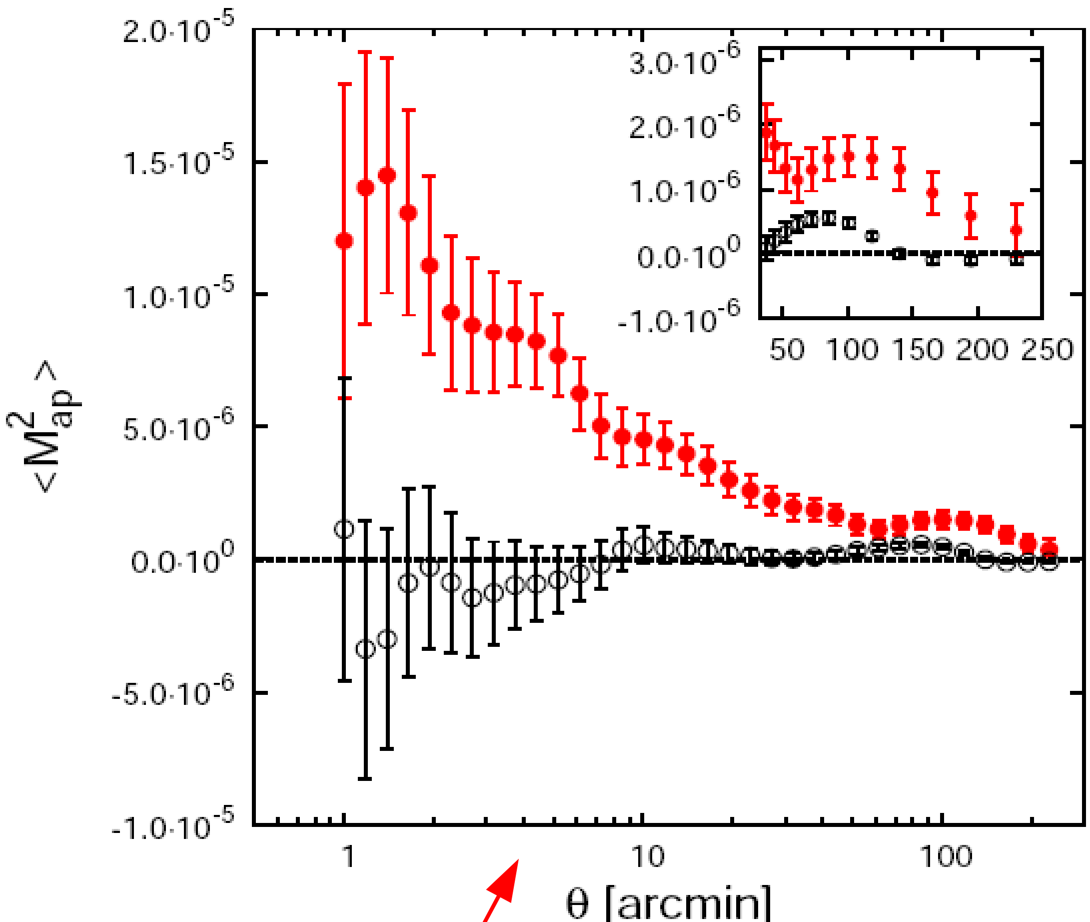
- Our Universe is flat -- its geometry is that imagined by Euclid
- Only a small fraction of it is made of ordinary matter -- about 4.5%
  → there is a lot of dark, nonbaryonic matter (about 23%)
  (which can be "seen" through gravitational lensing)
- Most of it must be a new kind of dark energy (perhaps 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

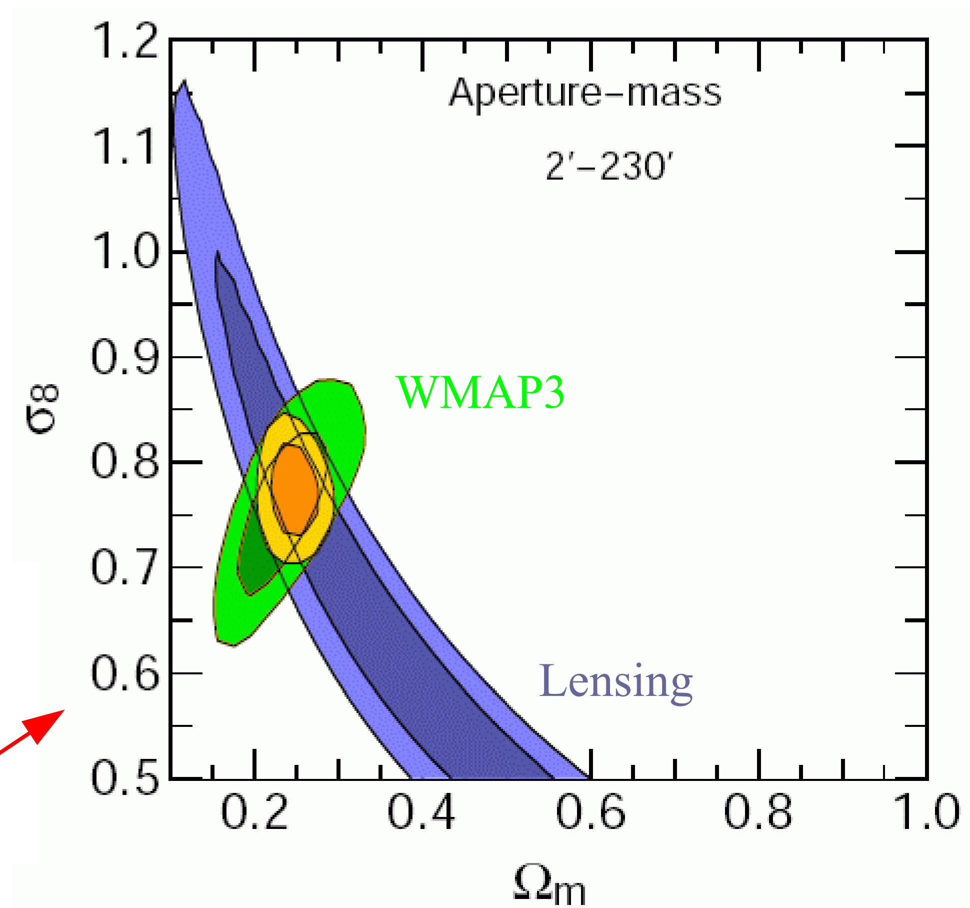
Gravitational lensing by a galaxy cluster

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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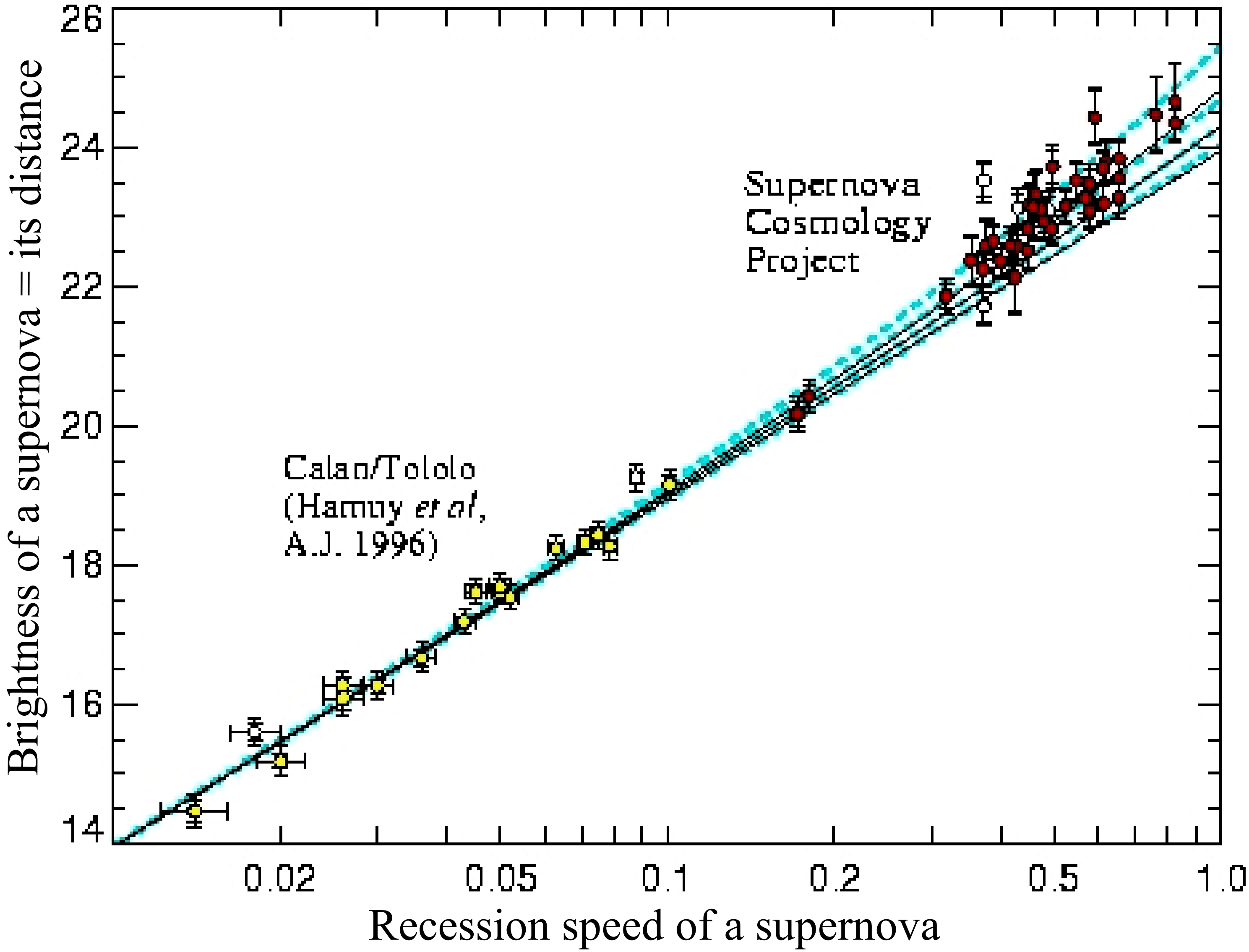
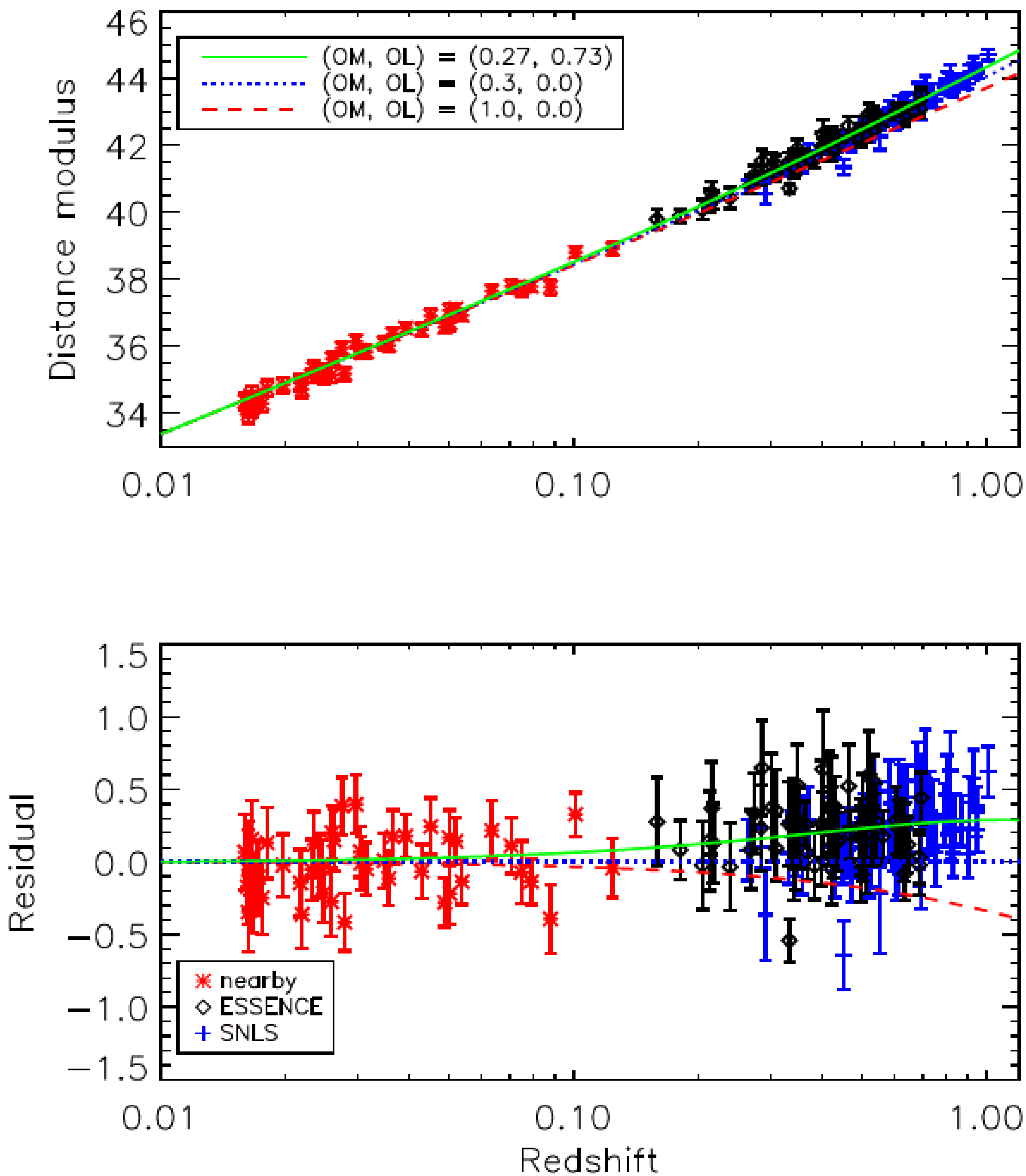
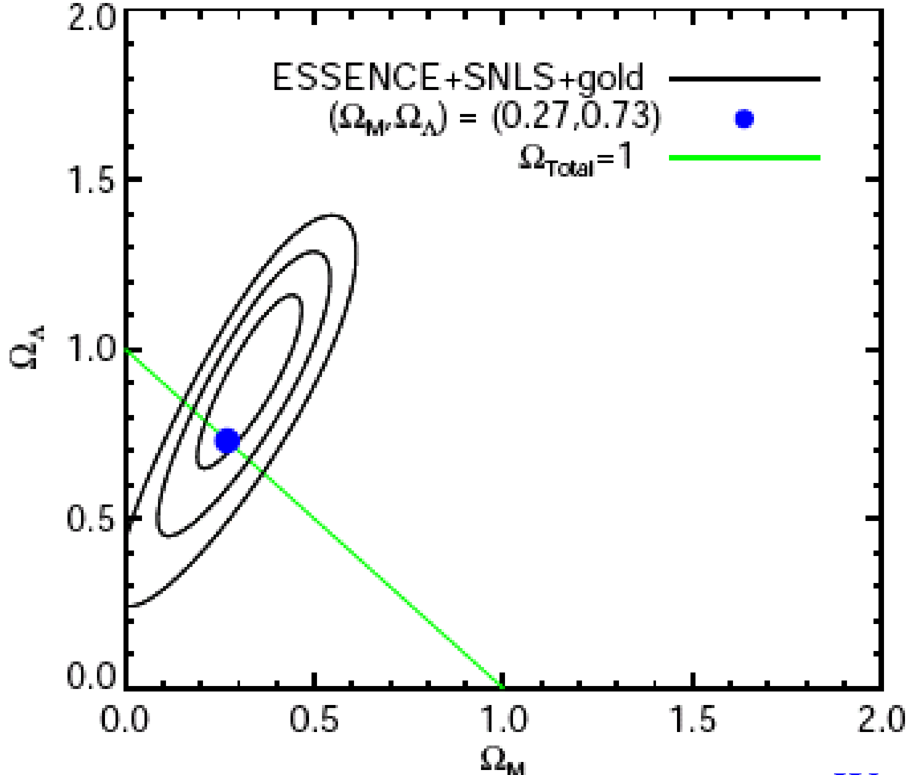
Hubble's “Law” and the expansion history

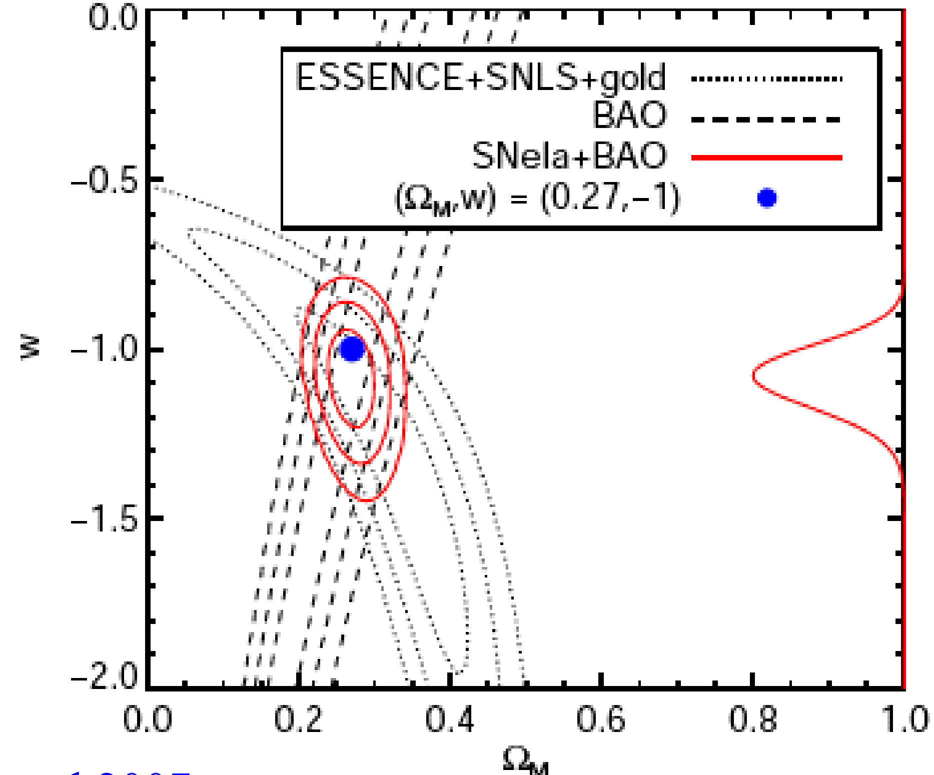


An accelerating Universe! The return of Einstein's "Eselei" or perhaps the discovery of a new form of mass/energy -- the Dark Energy.



The ESSENCE Survey
Wood-Vasey et al 2007





Wood-Vasey et al 2007

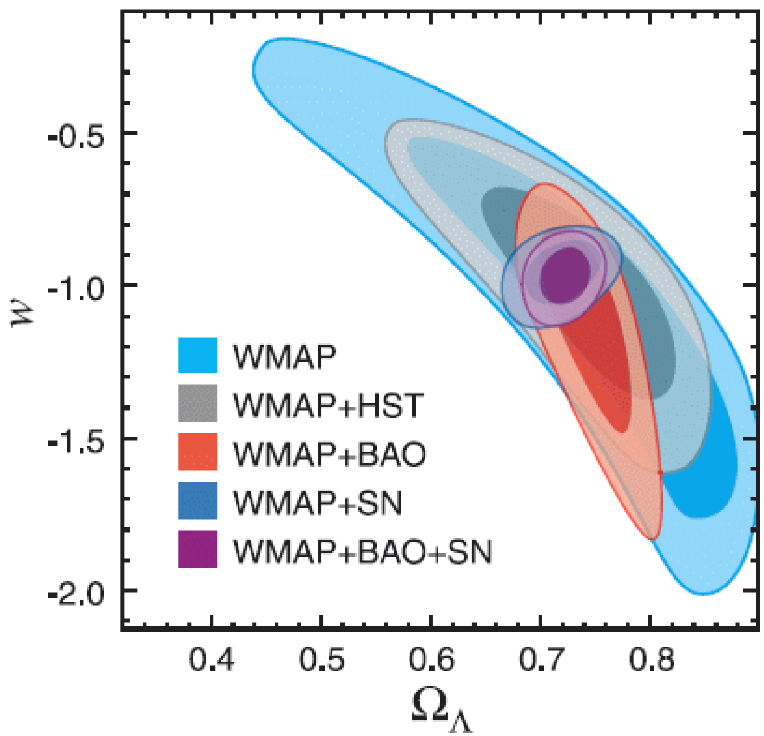
- The SN data require an accelerated expansion today
- With large-scale structure data, they imply a flat Universe with DE
- The DE appears to behave “like” a cosmological constant, w ≈ –1
- The implied parameters agree with those obtained independently from the cosmic microwave background

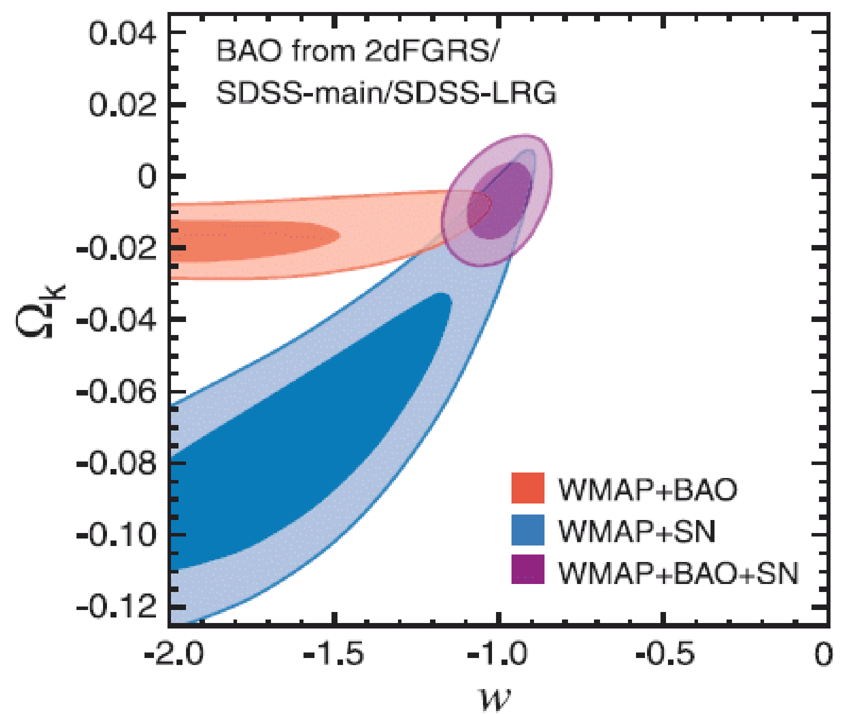
Putting it all together

Class	Parameter	*WMAP*+BAO+SN Mean
Primary	$100\Omega_b h^2$	2.265 ± 0.059
	$\Omega_c h^2$	0.1143 ± 0.0034
	Ω_Λ	0.721 ± 0.015
	n_s	$0.960^{+0.014}_{-0.013}$
	τ	0.084 ± 0.016
	$\Delta^2_{\mathcal{R}}(k_0{}^e)$	$(2.457^{+0.092}_{-0.093}) \times 10^{-9}$
Derived	σ_8	0.817 ± 0.026
	H_0	70.1 ± 1.3 km/s/Mpc
	Ω_b	0.0462 ± 0.0015
	Ω_c	0.233 ± 0.013
	$\Omega_m h^2$	0.1369 ± 0.0037
	$z_{\rm reion}{}^f$	10.8 ± 1.4
	$t_0{}^g$	13.73 ± 0.12 Gyr

Assuming a flat universe

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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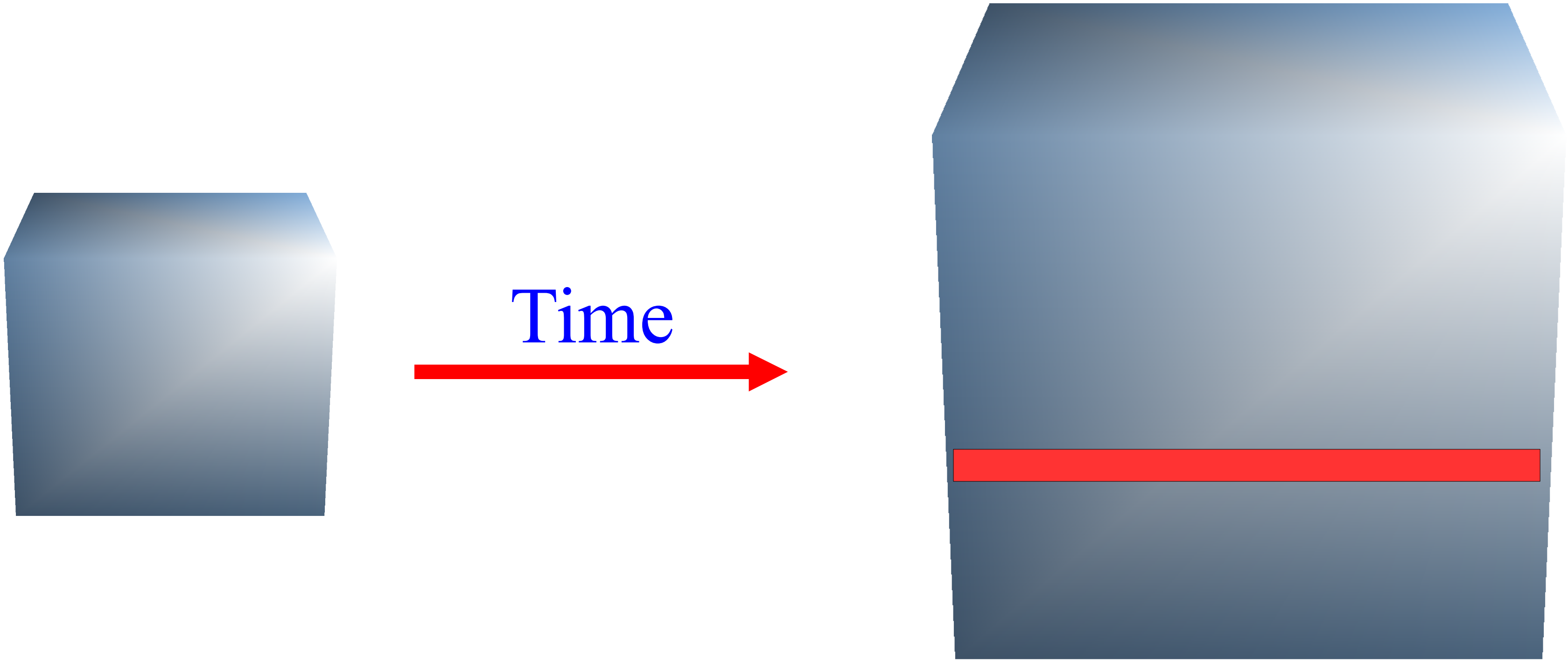
Everything has formed from nothing

The next step...

The Planck satellite has just reached L2 and both instruments are currently functioning nominally

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

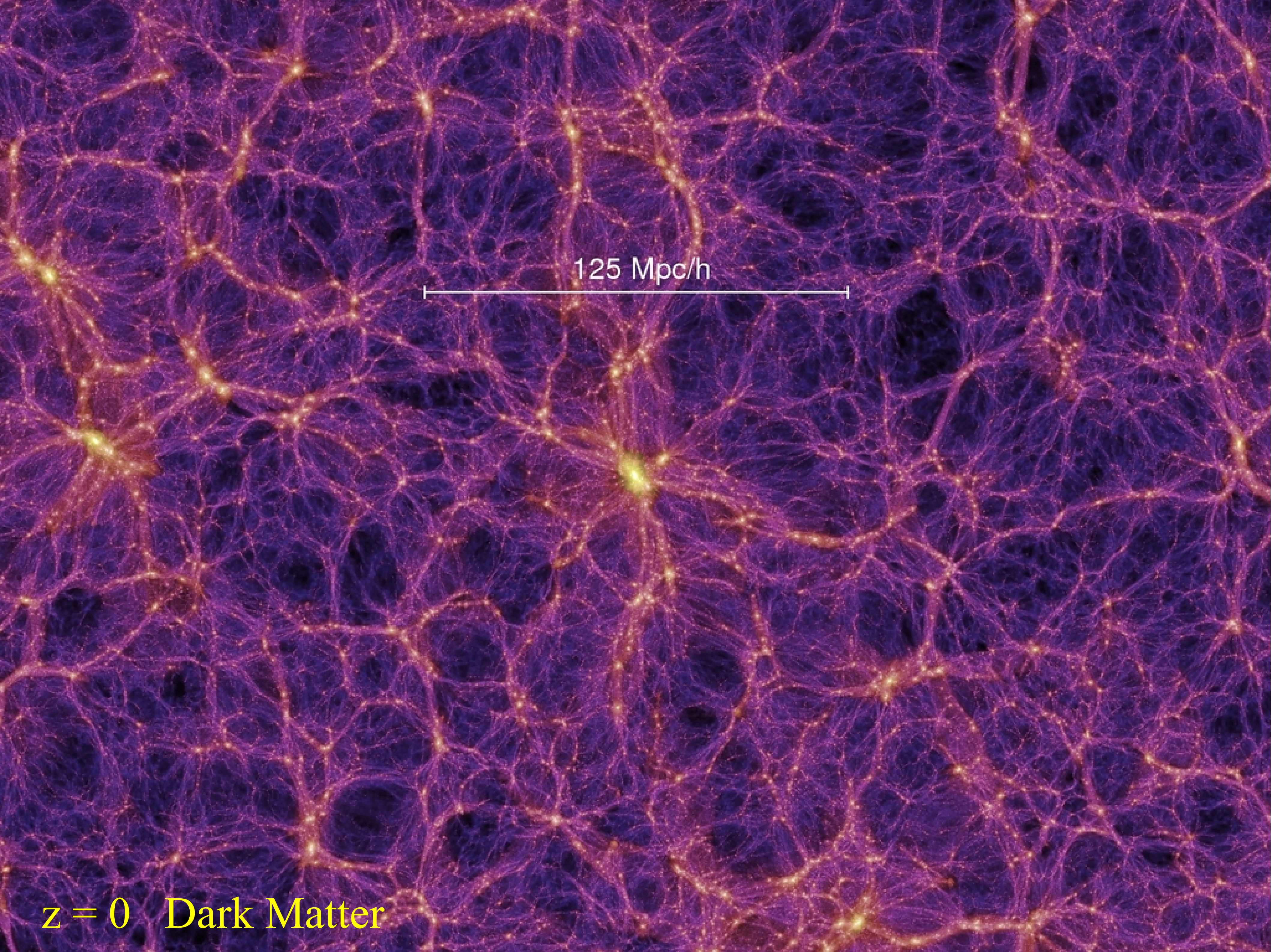
- The growth of dark matter structures in a thin slice

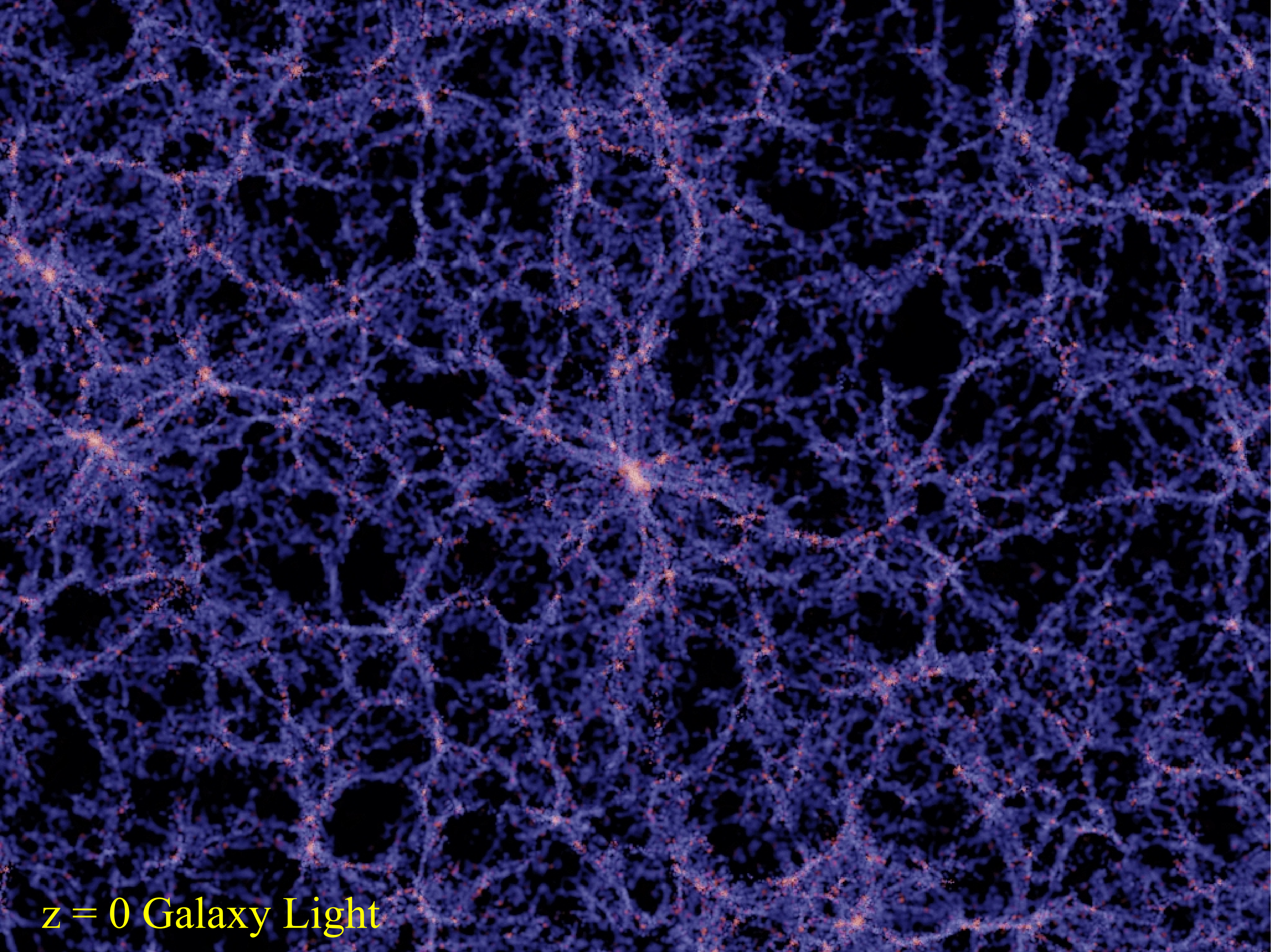
- A flight through the dark matter distribution

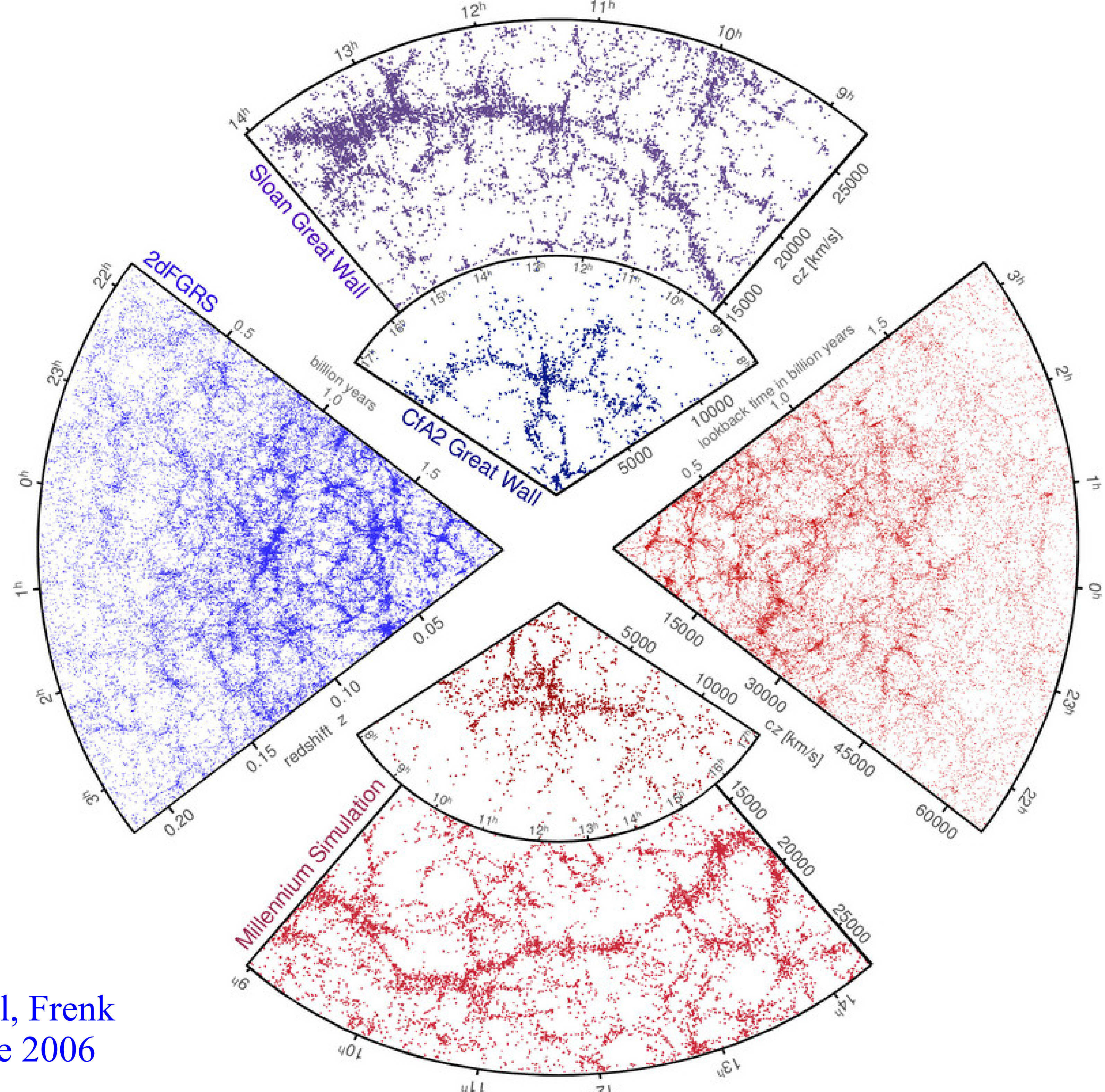
- The assembly of the Milky Way's halo

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 evolution/death
- 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

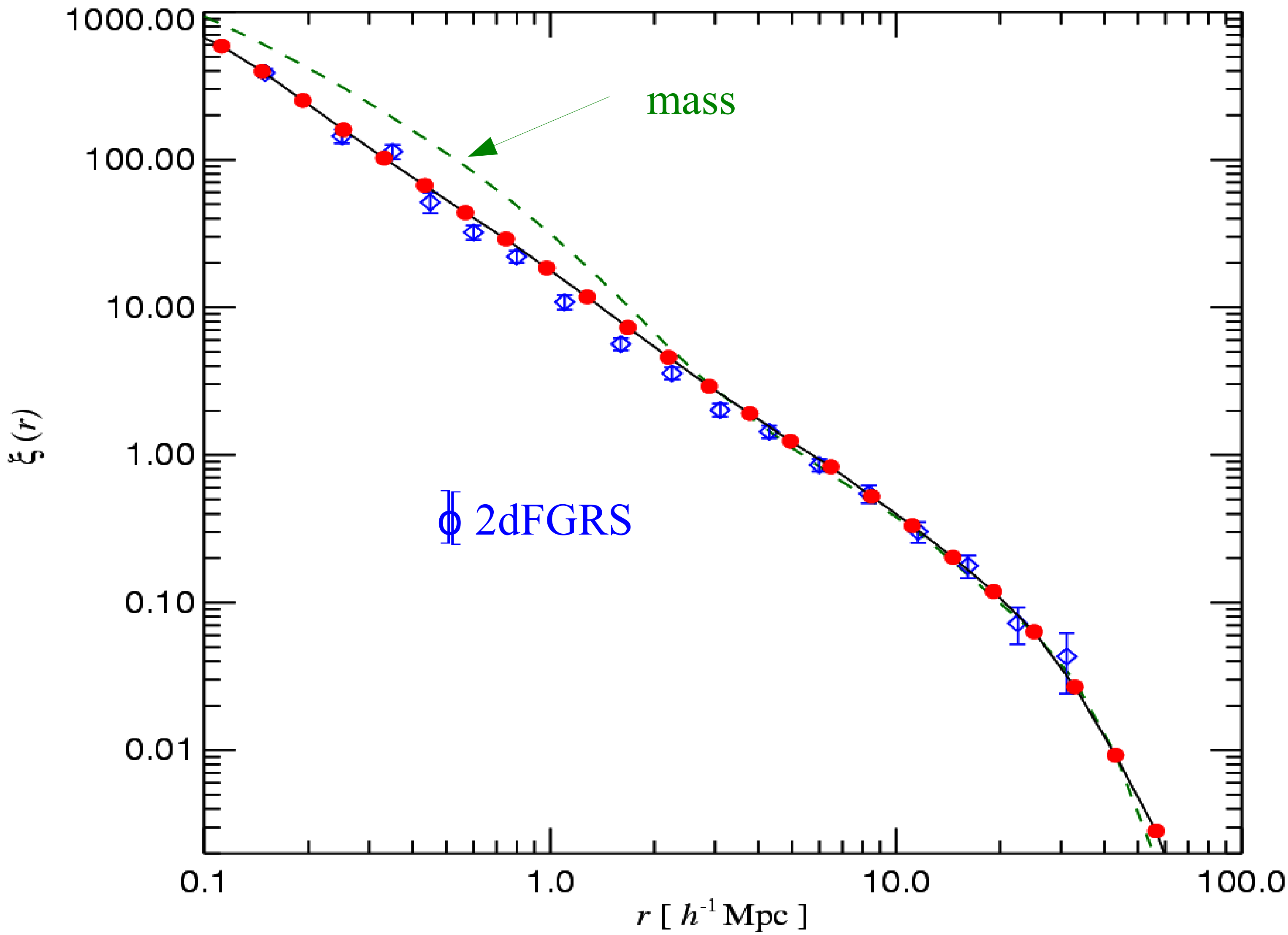

z = 0 Galaxy Light



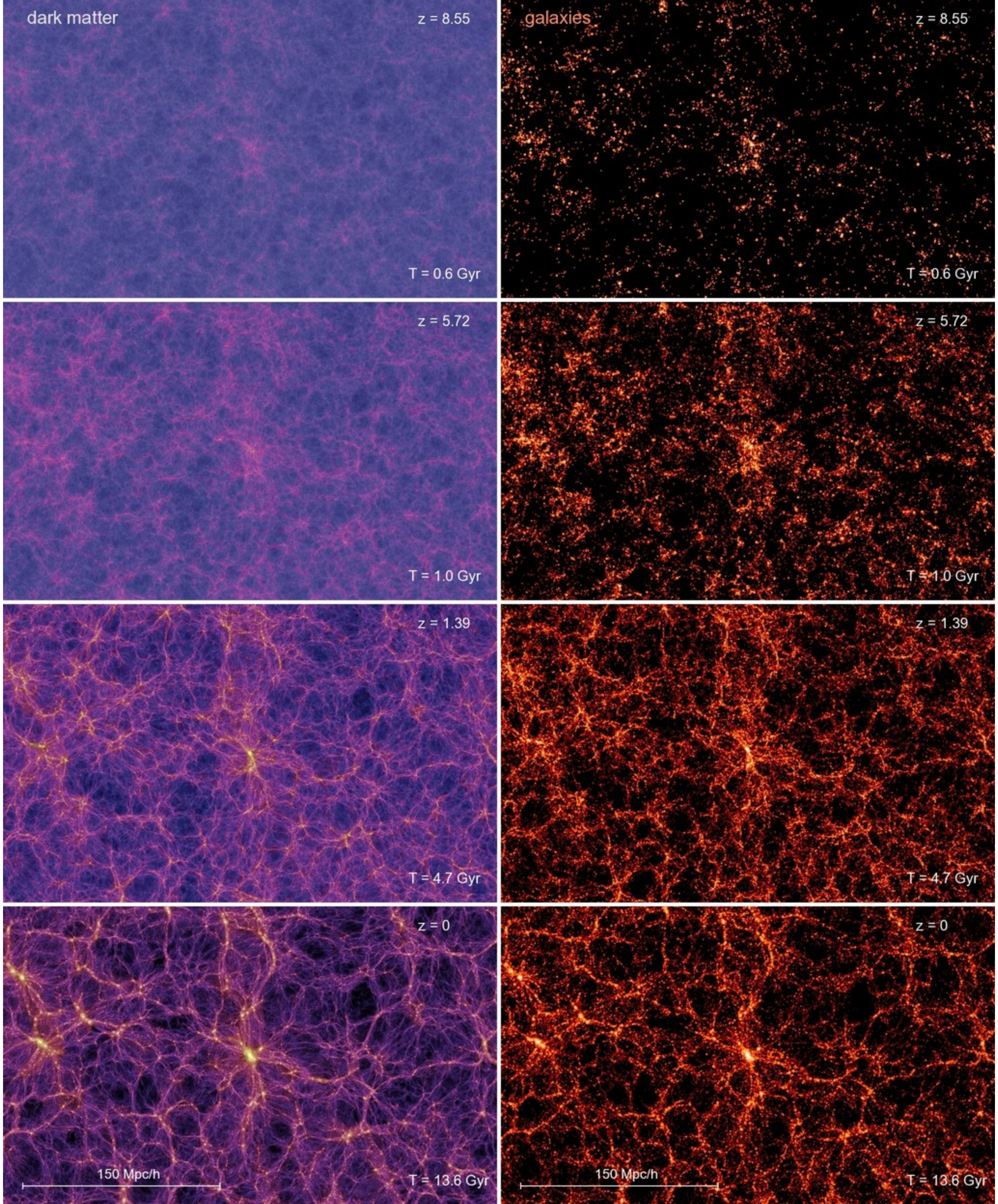
Springel, Frenk
& White 2006

Galaxy autocorrelation function

Springel et al 2005; the Millennium Simulation



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



Large-scale structure at high redshift

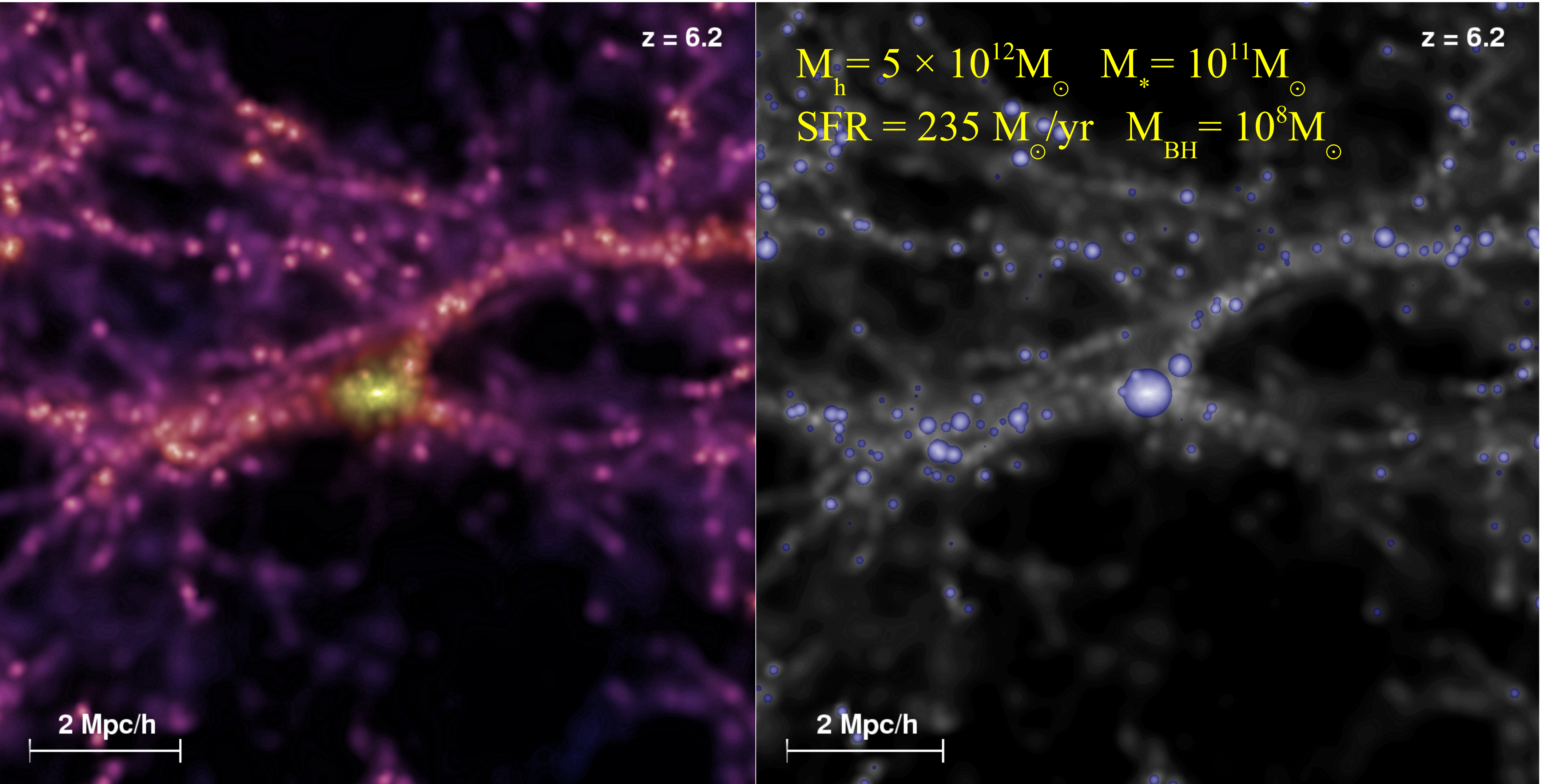
Springel, Frenk & White 2006

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

It is as strong at z=8.5 as at z=0, even though only 1% of all z=0 stars have formed

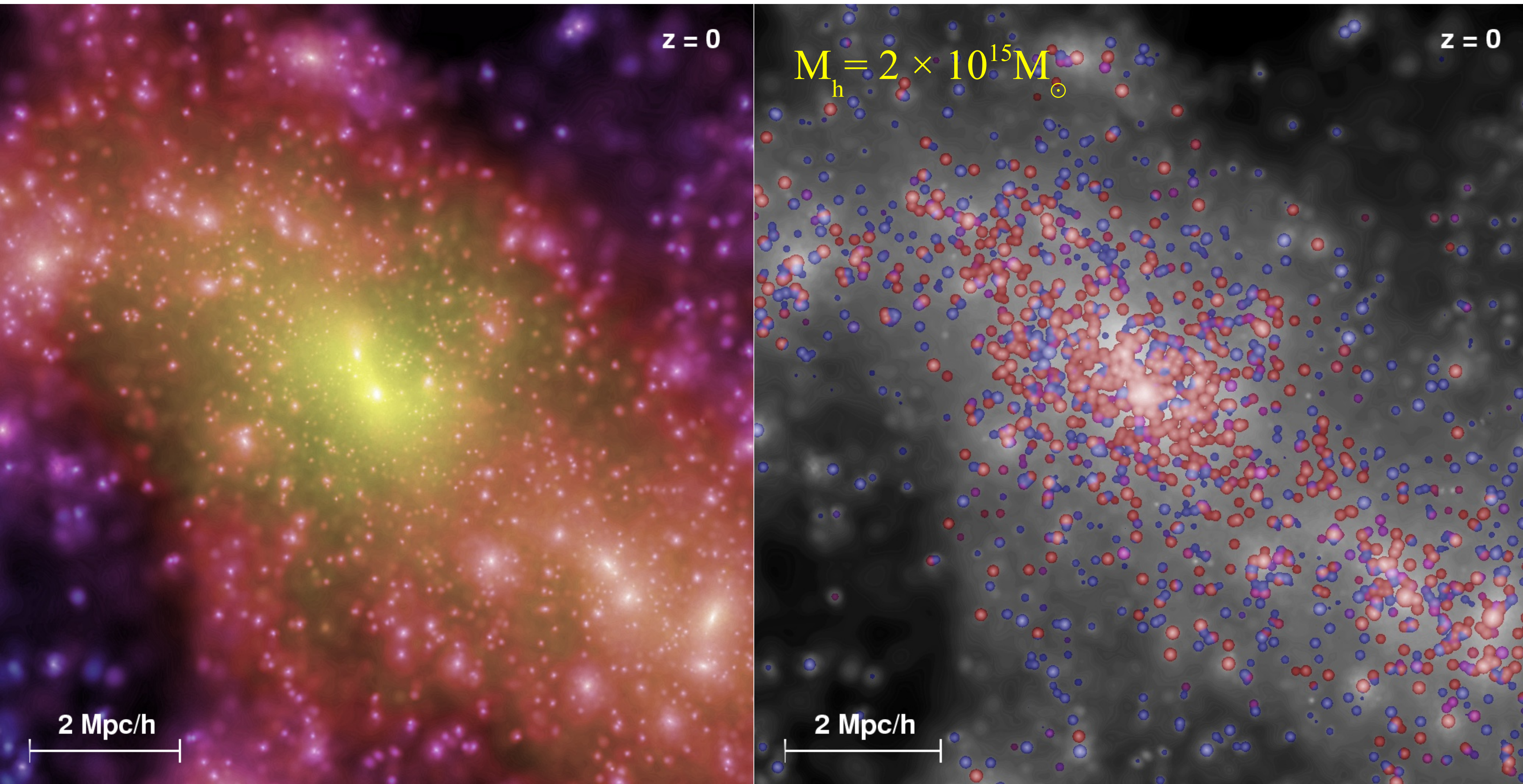
A bright quasar and its surroundings at 1 billion years

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

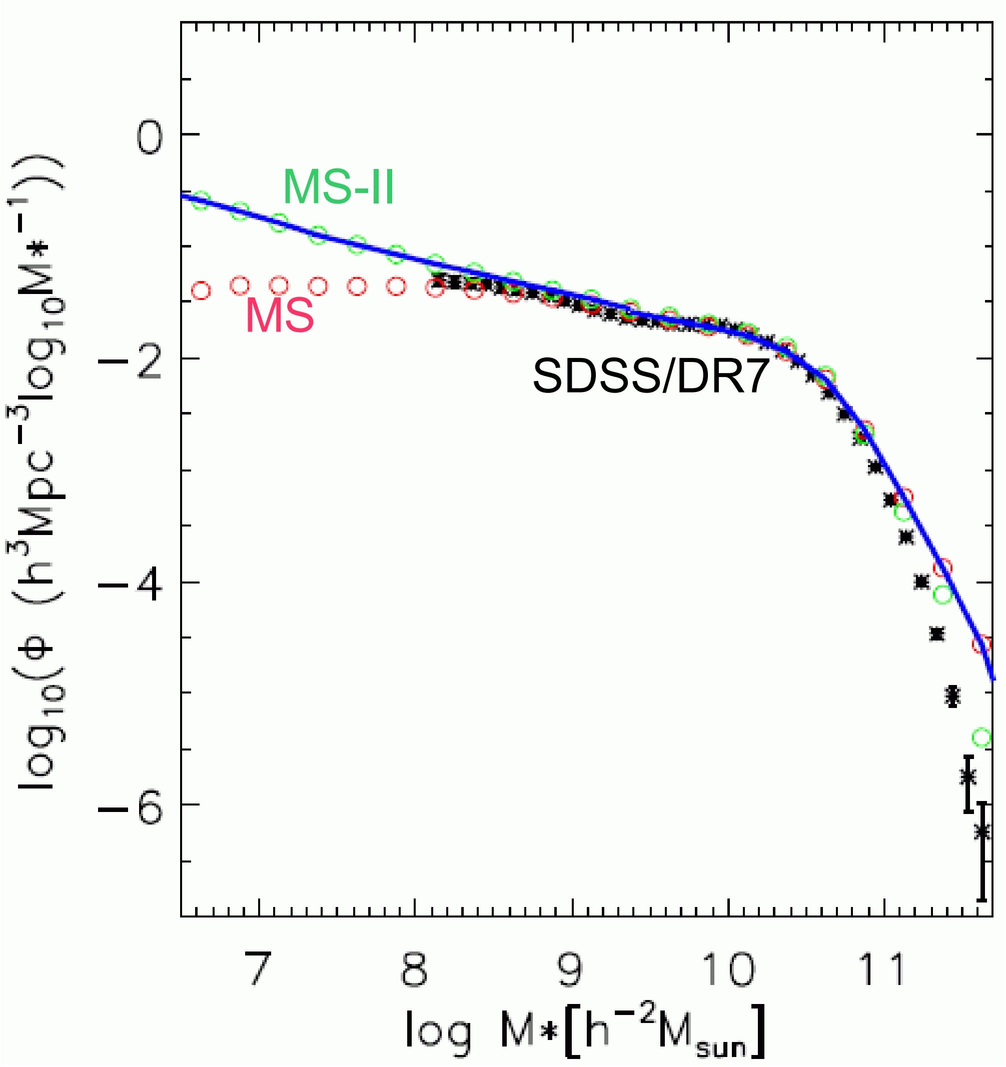
One of the most massive galaxy clusters. The quasar's descendant is part of the central massive galaxy of the cluster.



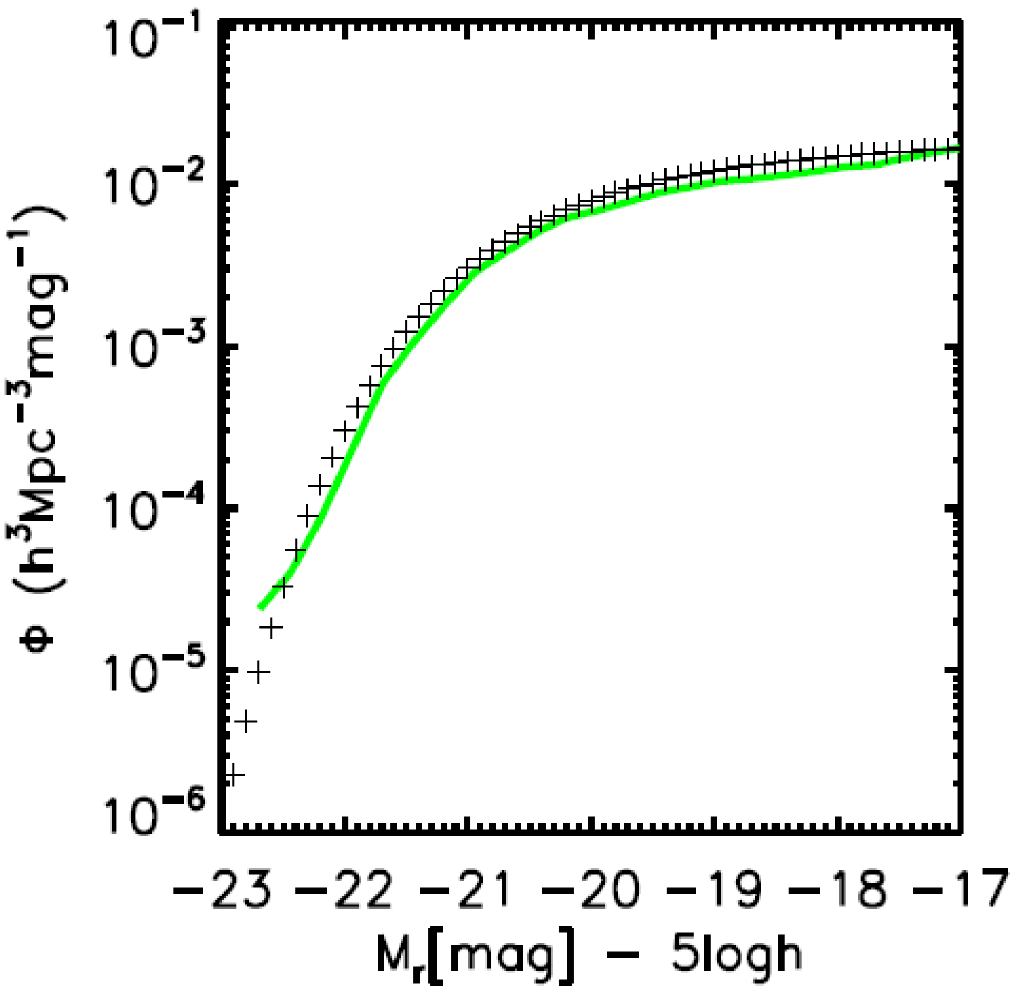
Galaxy formation simulations fit the full low-z population

Guo et al 2009

The stellar mass function of galaxies

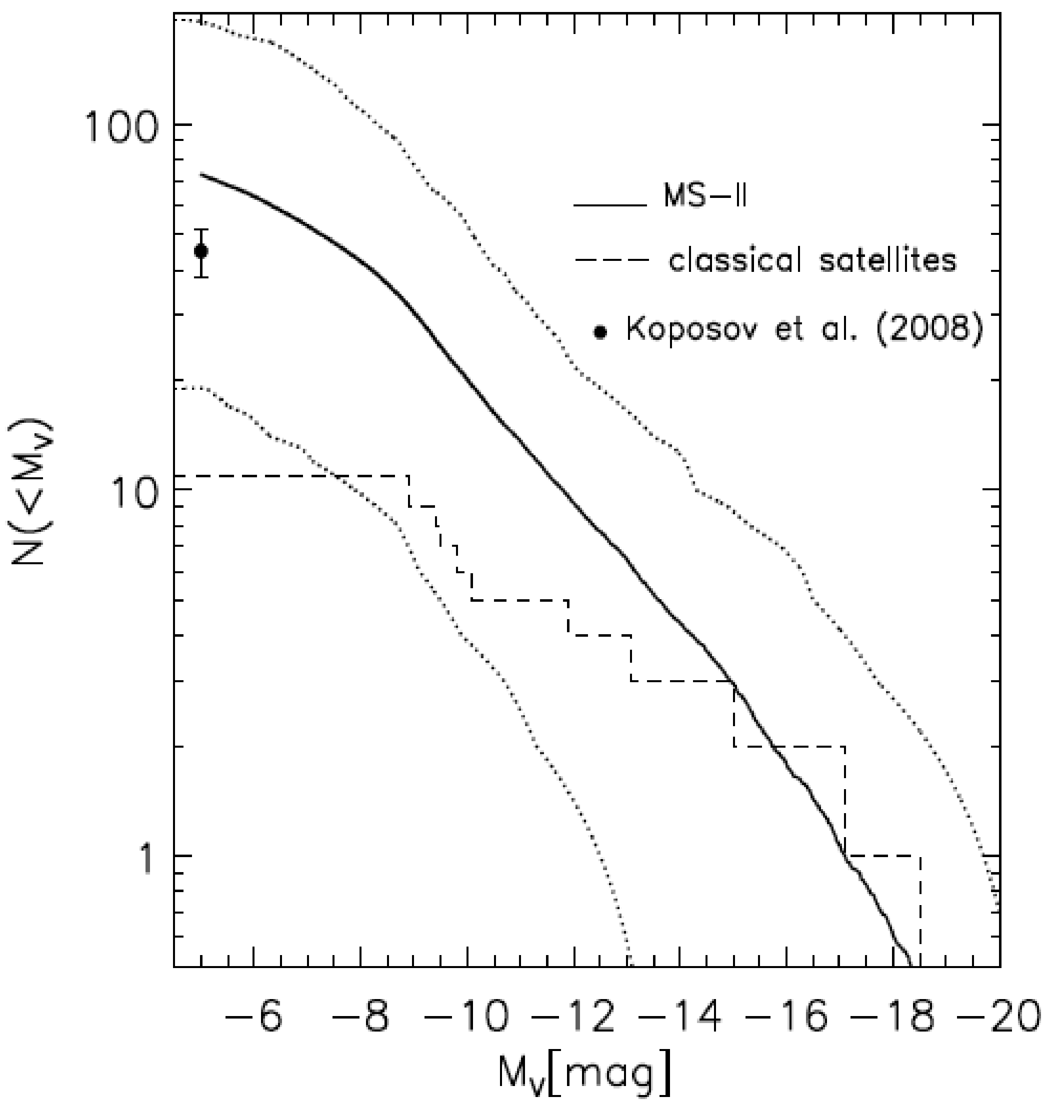


r-band luminosity function of galaxies



....even the ultrafaint satellites of the Milky Way

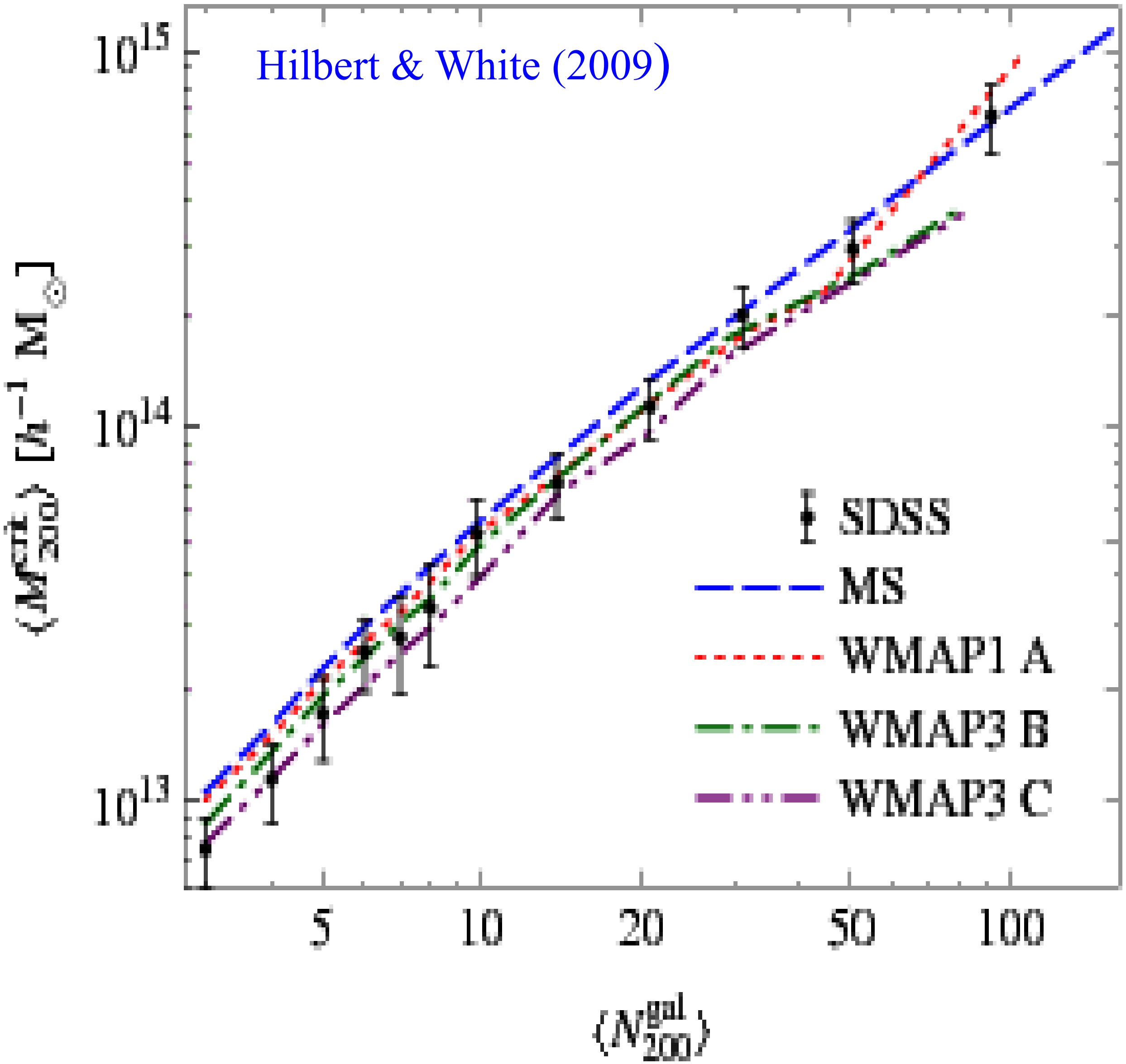
Guo et al 2009



The *same* model reproduces the abundance of small satellite galaxies around the Milky Way.

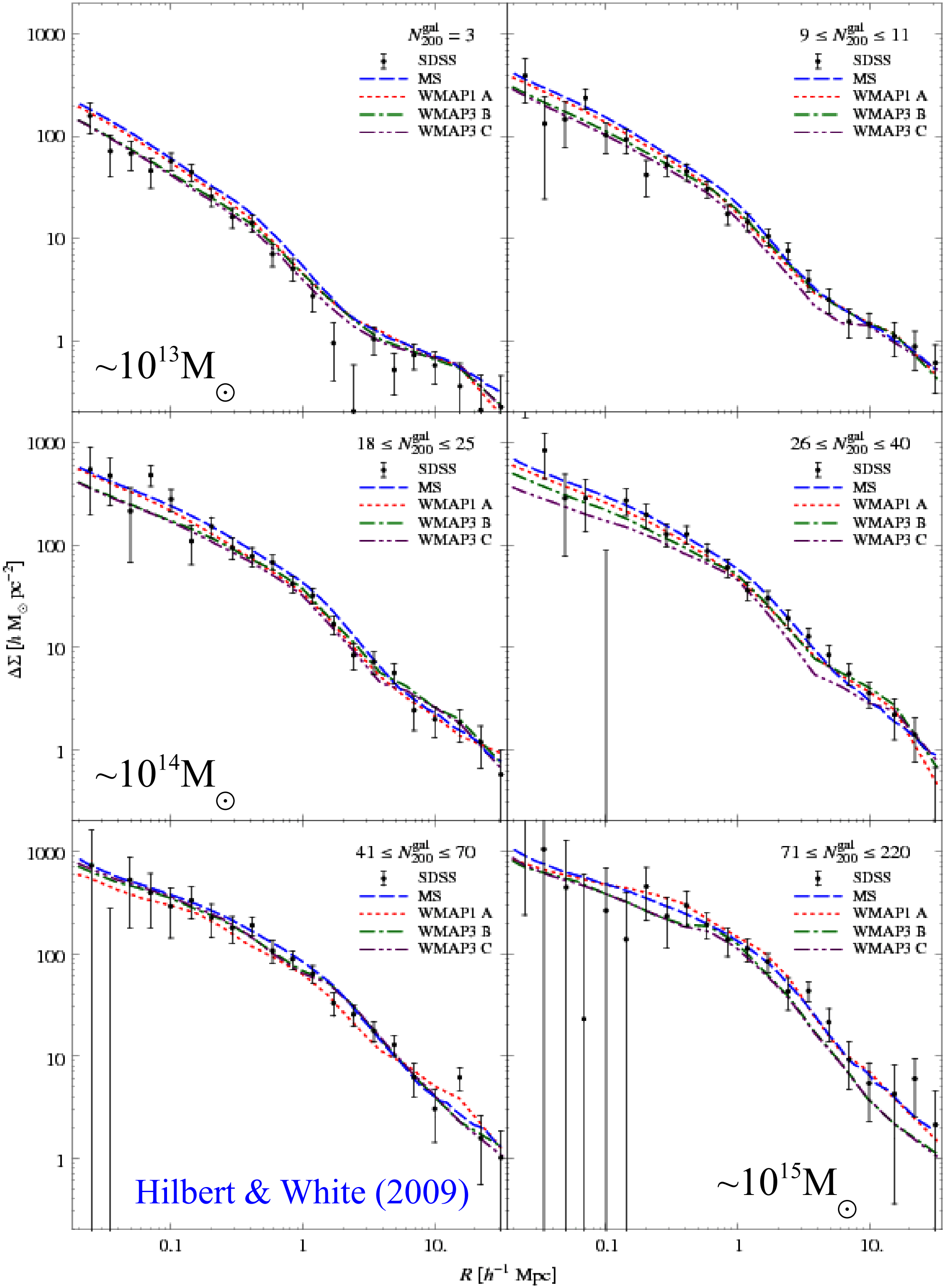
Reionisation is significant in suppressing formation of the faintest systems

Galaxy formation simulations fit low-z groups and clusters



Average dynamical mass of galaxy clusters as a function of the number of red galaxies within them

Observational data from the SDSS/maxBCG catalogue (Johnson et al 2007)



Galaxy formation simulations fit low-z groups and clusters

The simulated cluster population fits the *detailed* shape of the mean mass profile of groups and clusters as a function of richness

This holds for total masses
$10^{13}\ M_\odot \leq M_{200} \leq 10^{15}\ M_\odot$

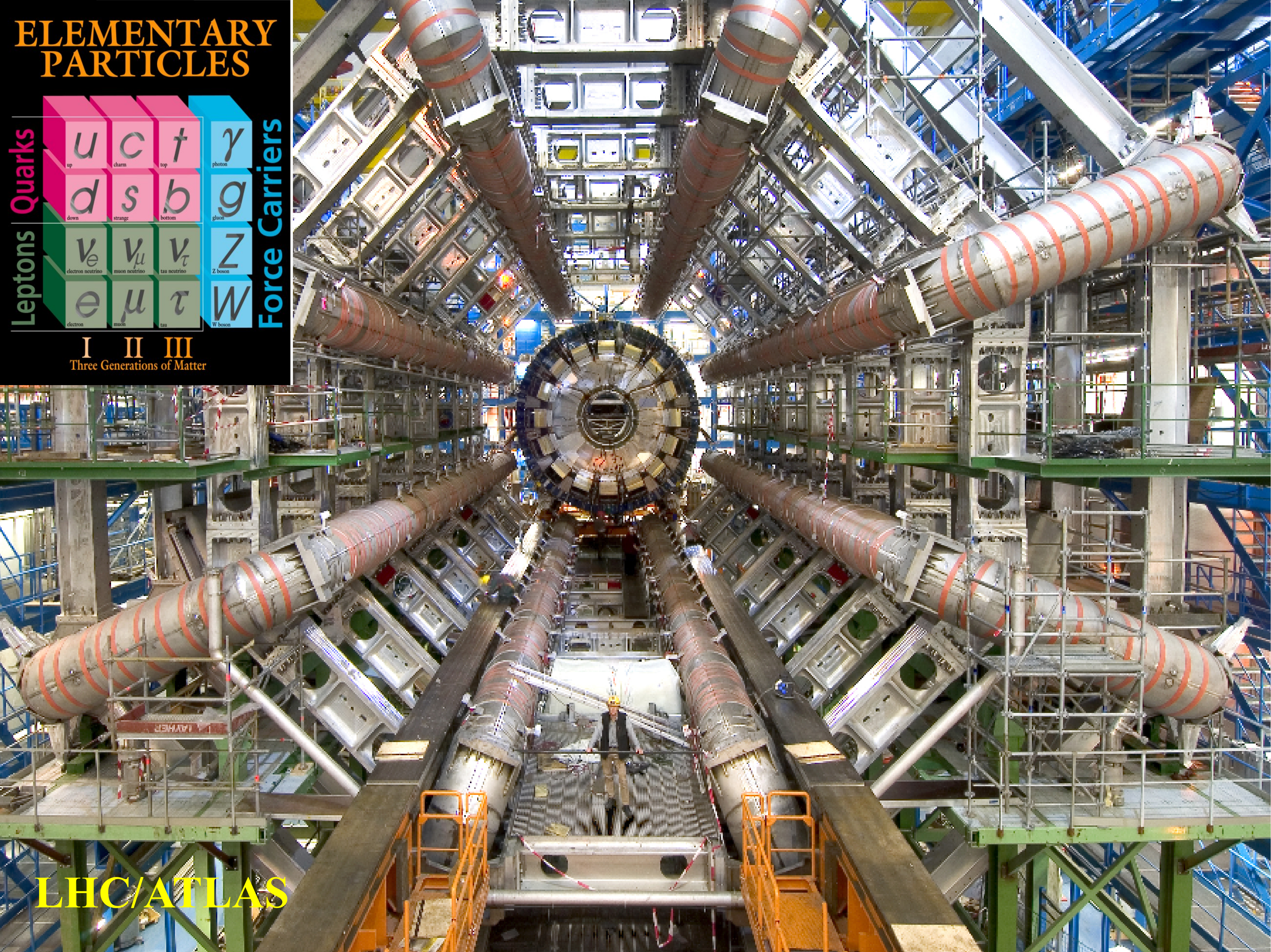
Lensing data from SDSS/maxBCG
(Sheldon et al 2007)

Goals for "late-time" structure formation studies

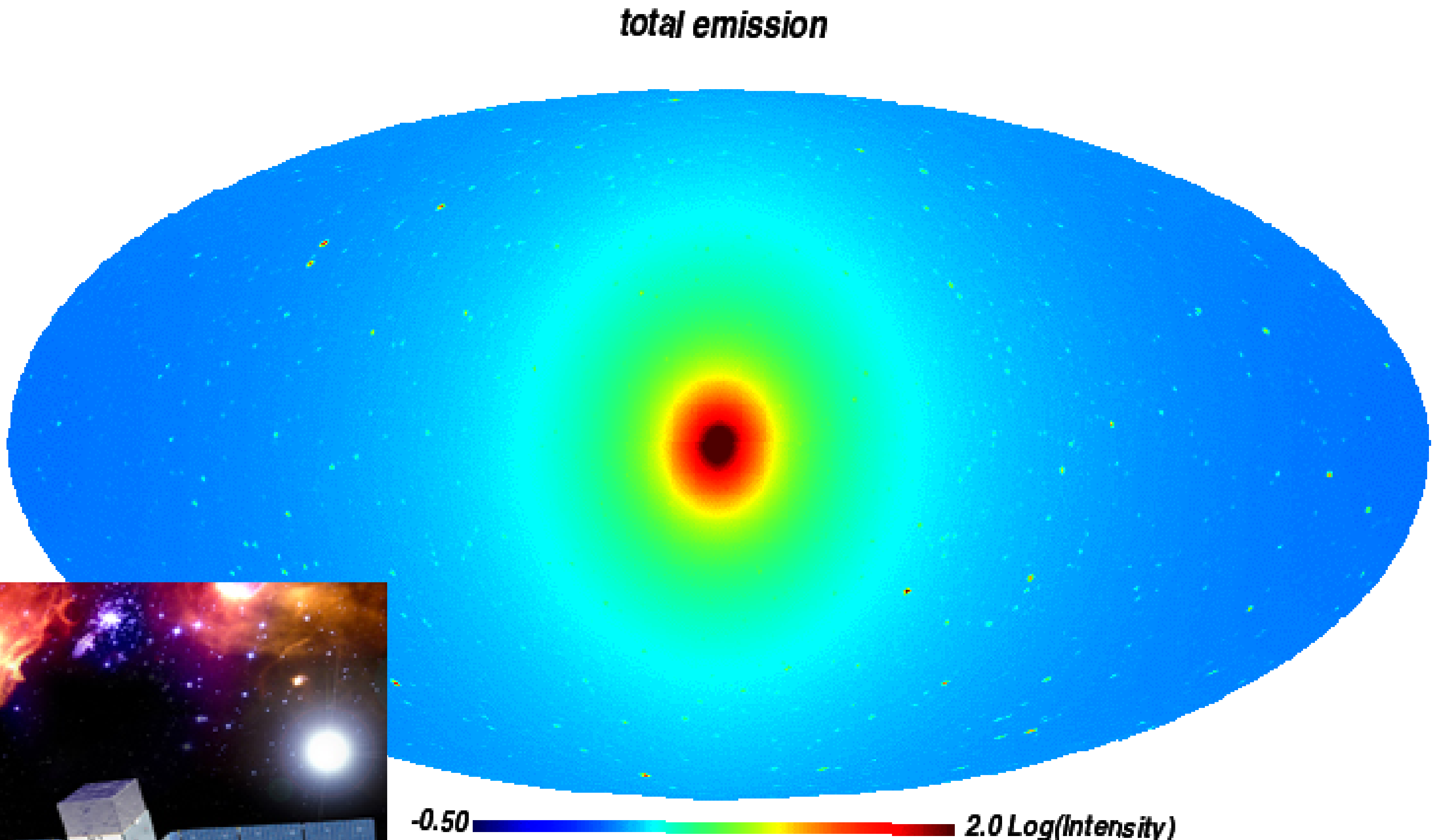
- Linking the linear early Universe with today's nonlinear world

- 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

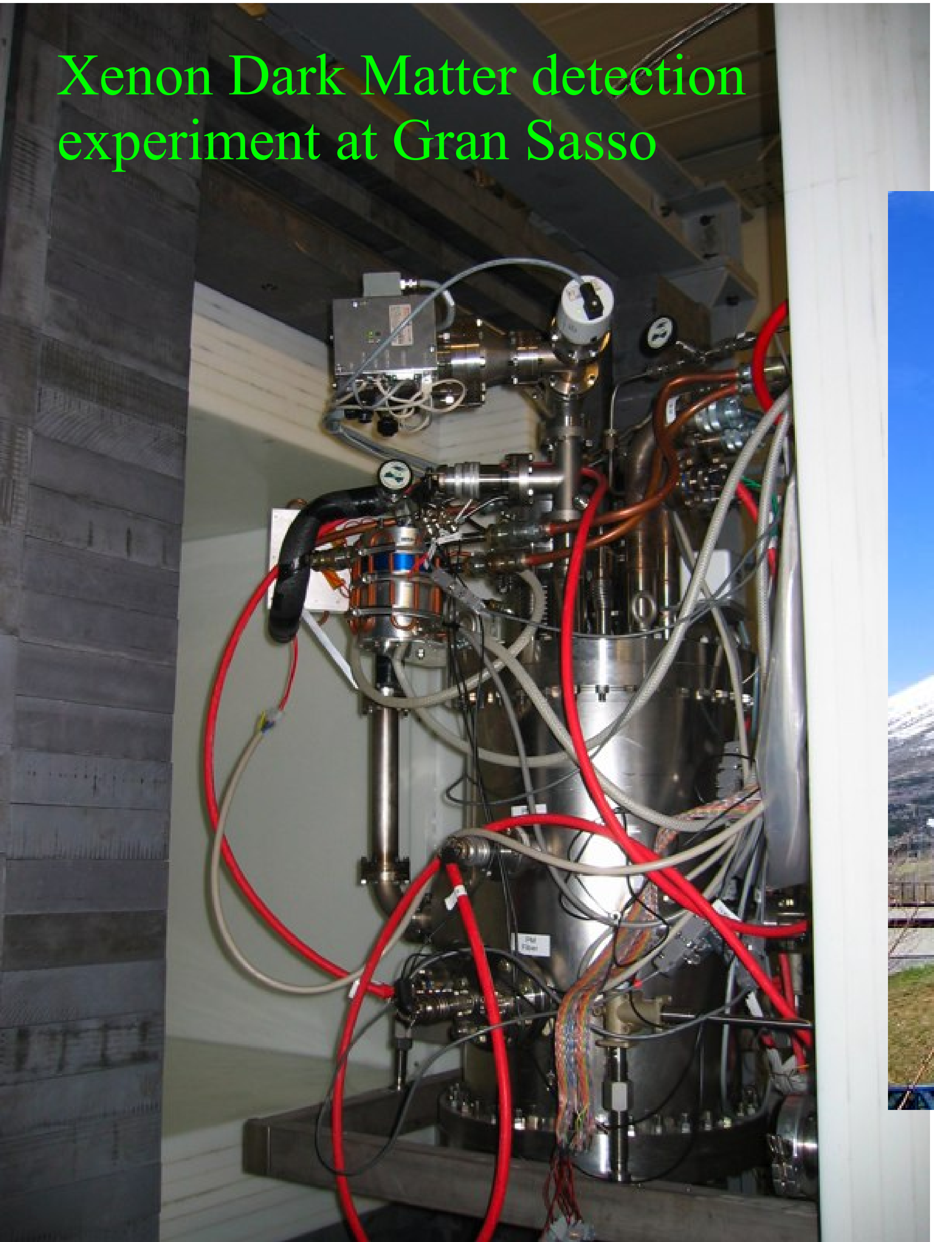

ELEMENTARY PARTICLES
Quarks
Leptons
Force Carriers
u c t γ
up charm top photon
d s b g
down strange bottom gluon
ν_e ν_μ ν_τ Z
electron neutrino muon neutrino tau neutrino Z boson
e μ τ W
electron muon tau W boson
I II III
Three Generations of Matter
LHC/ATLAS


Dark Matter around the Milky Way?



Maybe the annihilation of Dark Matter will be seen by Fermi?

Maybe Dark Matter can be detected in a laboratory



Current understanding of the dark side

- **Dark Matter** appears to account for more than 80% of all the material in and around galaxies and galaxy clusters
- It is also needed to explain how today's cosmic structure grew from that seen in the microwave background
- It cannot be made of “ordinary” baryonic matter
- It is currently only detected by its gravitational effects
- It might be possible to see its annihilation radiation or to detect it in a laboratory on Earth

Current understanding of the dark side

- **Dark Energy** is needed to explain the accelerated expansion of today's universe

- Observed structure in the Cosmic Microwave Background implies that the Universe is flat but that only 25% of the necessary mass-energy can be in baryons+Dark Matter The other 75% must be Dark Energy

- Dark Energy does not clump and is apparently detectable <u>only</u> by its effects on the cosmic expansion, thus only by *astronomical* observations

- We don't have a clue what it is or how it is related to the rest of physics. It appears to behave like the "cosmological constant" in Einstein's theory of gravity