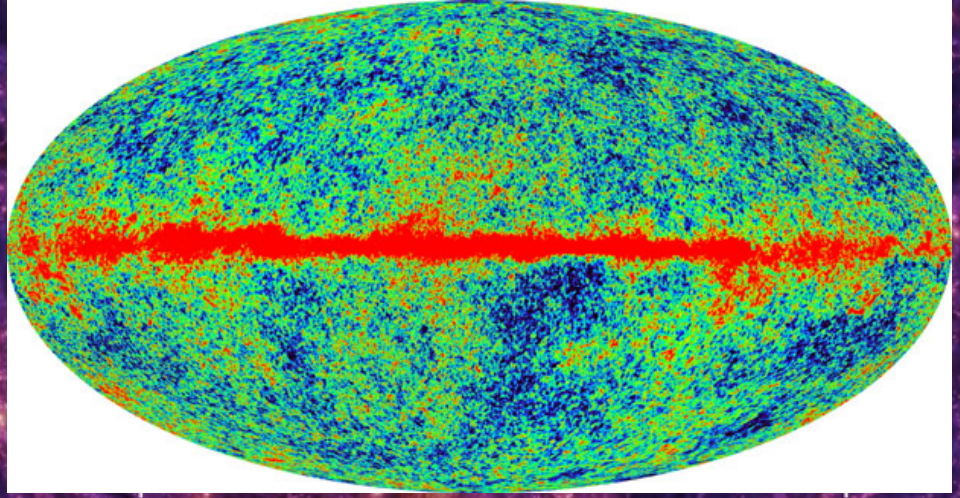
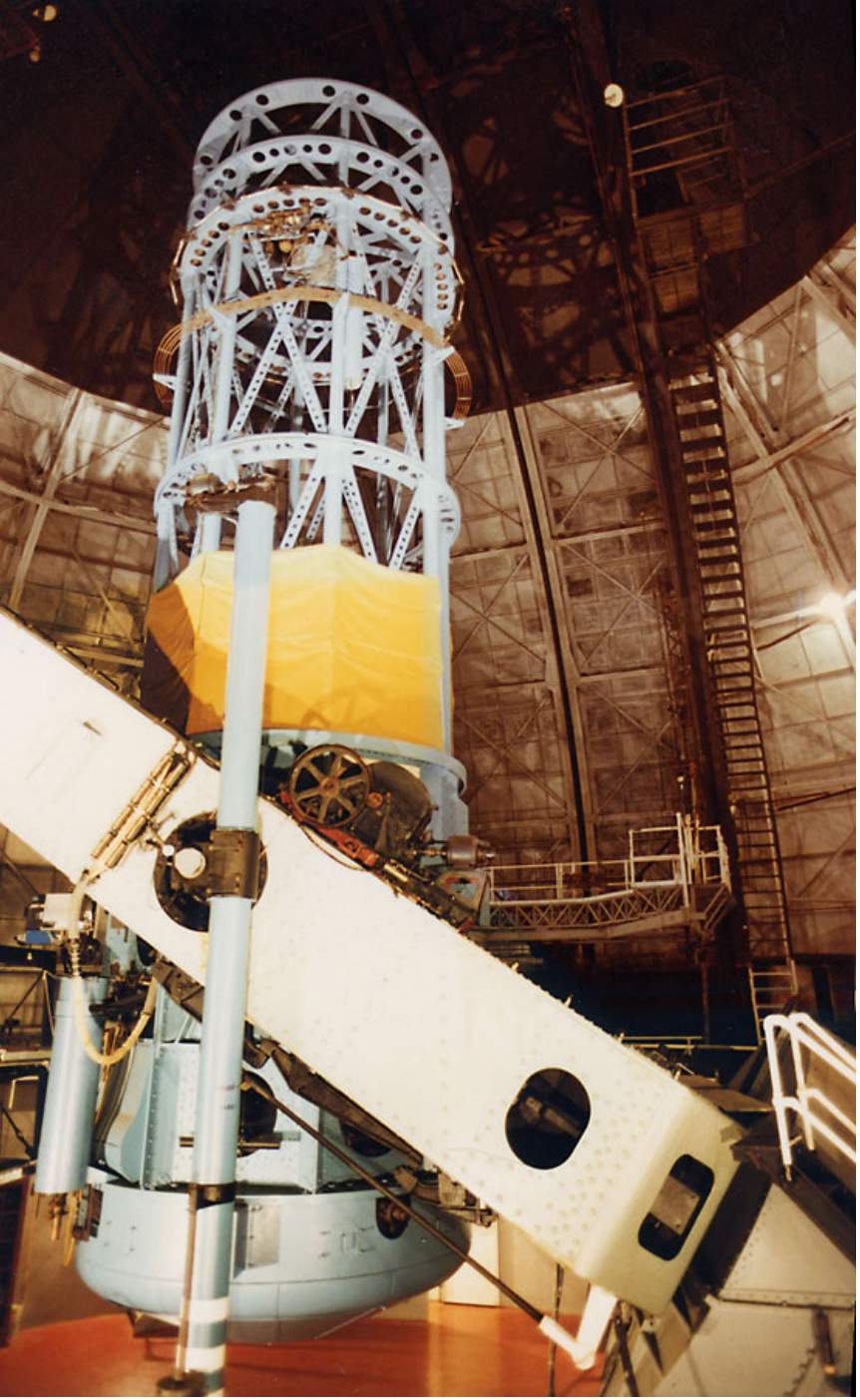


SPIE
Marseille 2008

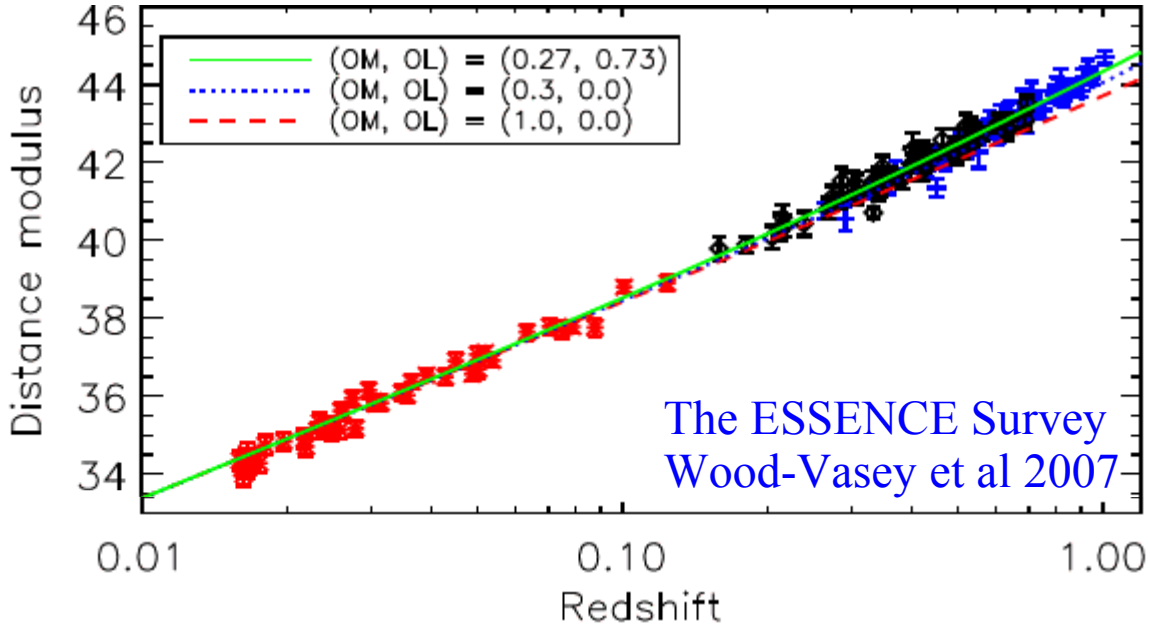
Introduction to the standard cosmological model

Simon White
Max Planck Institute for Astrophysics

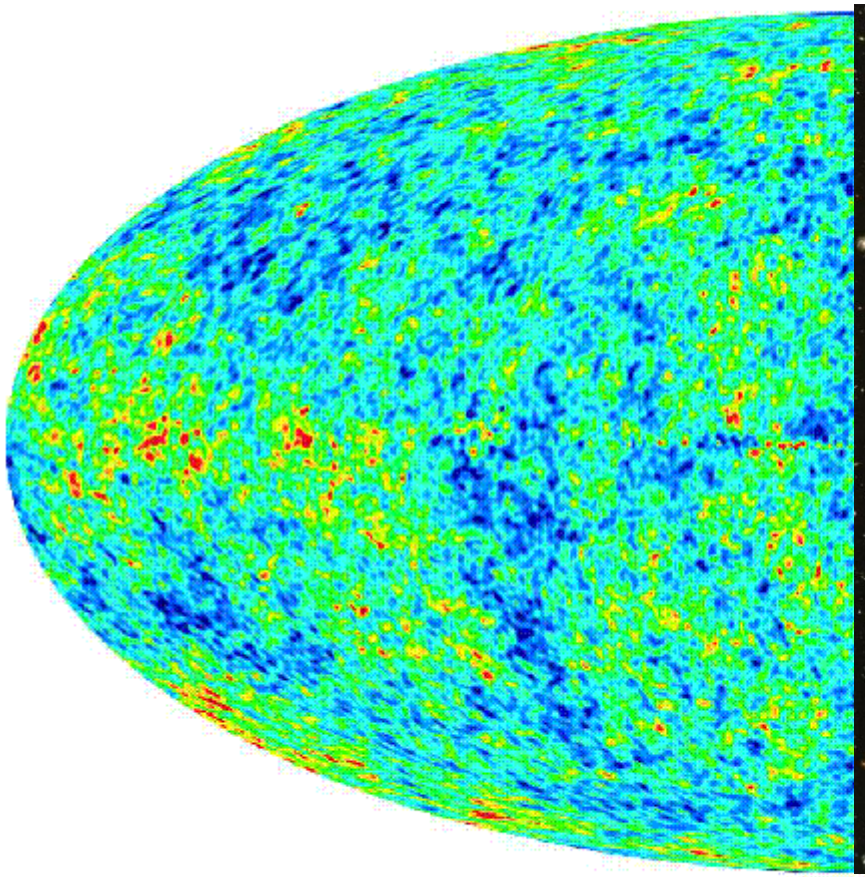


Our universe is expanding

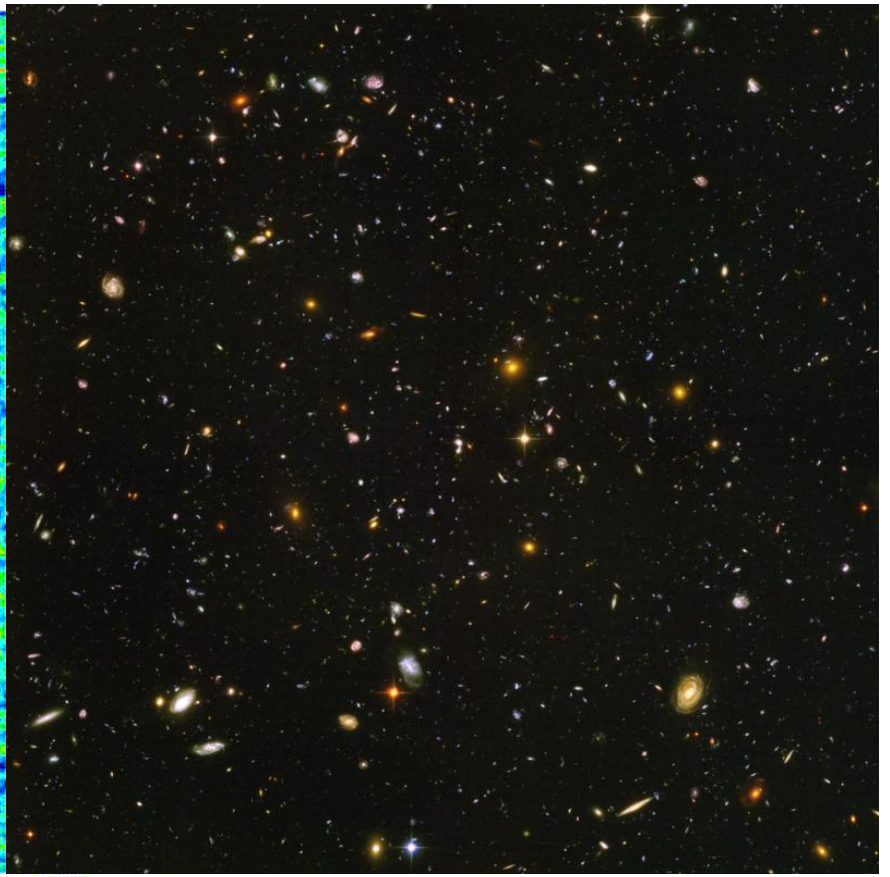
Hubble 1929



Our universe changes with time

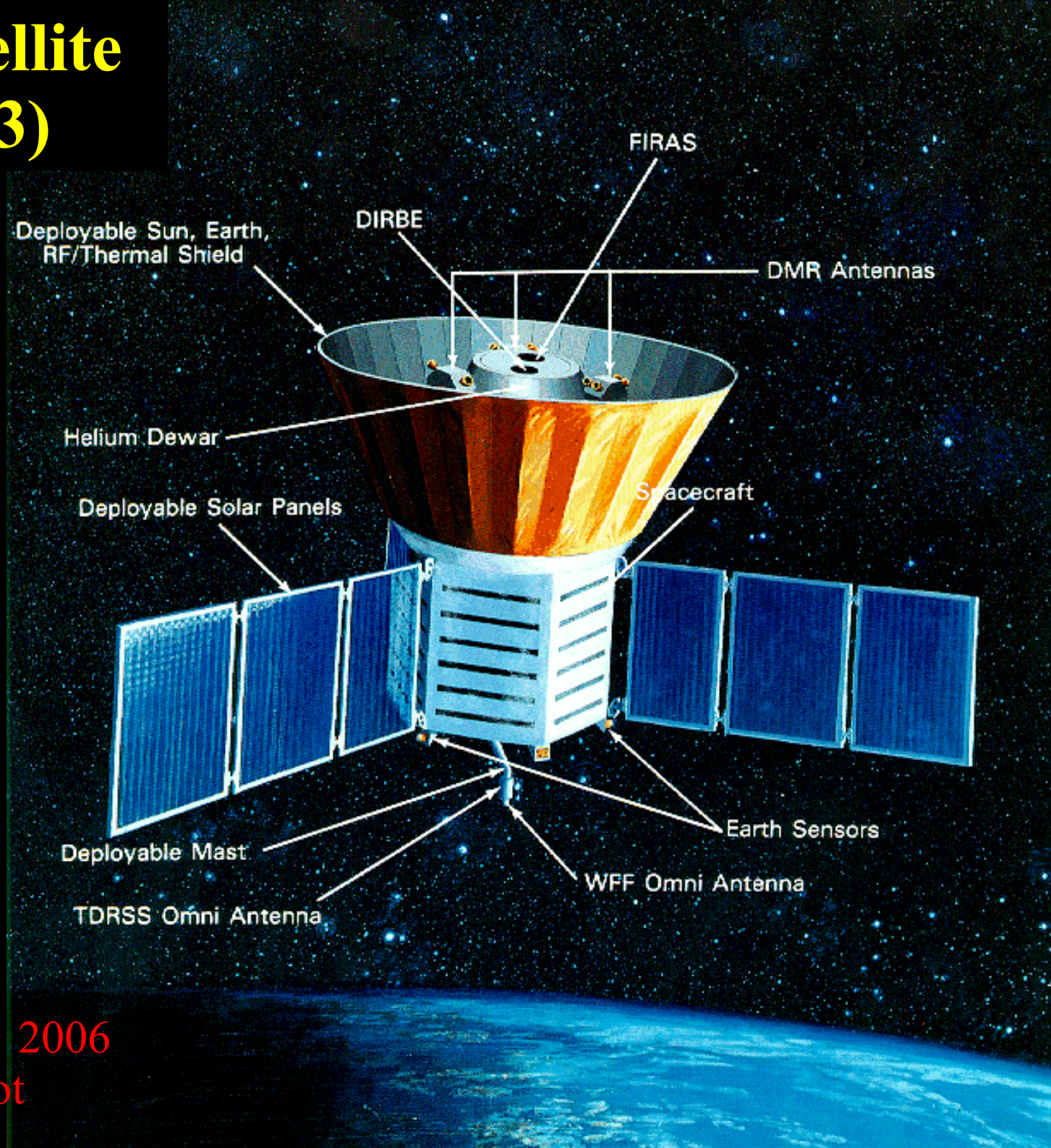


WMAP
Bennett et al 2003



The Hubble Ultradeep Field

The COBE satellite (1989 - 1993)

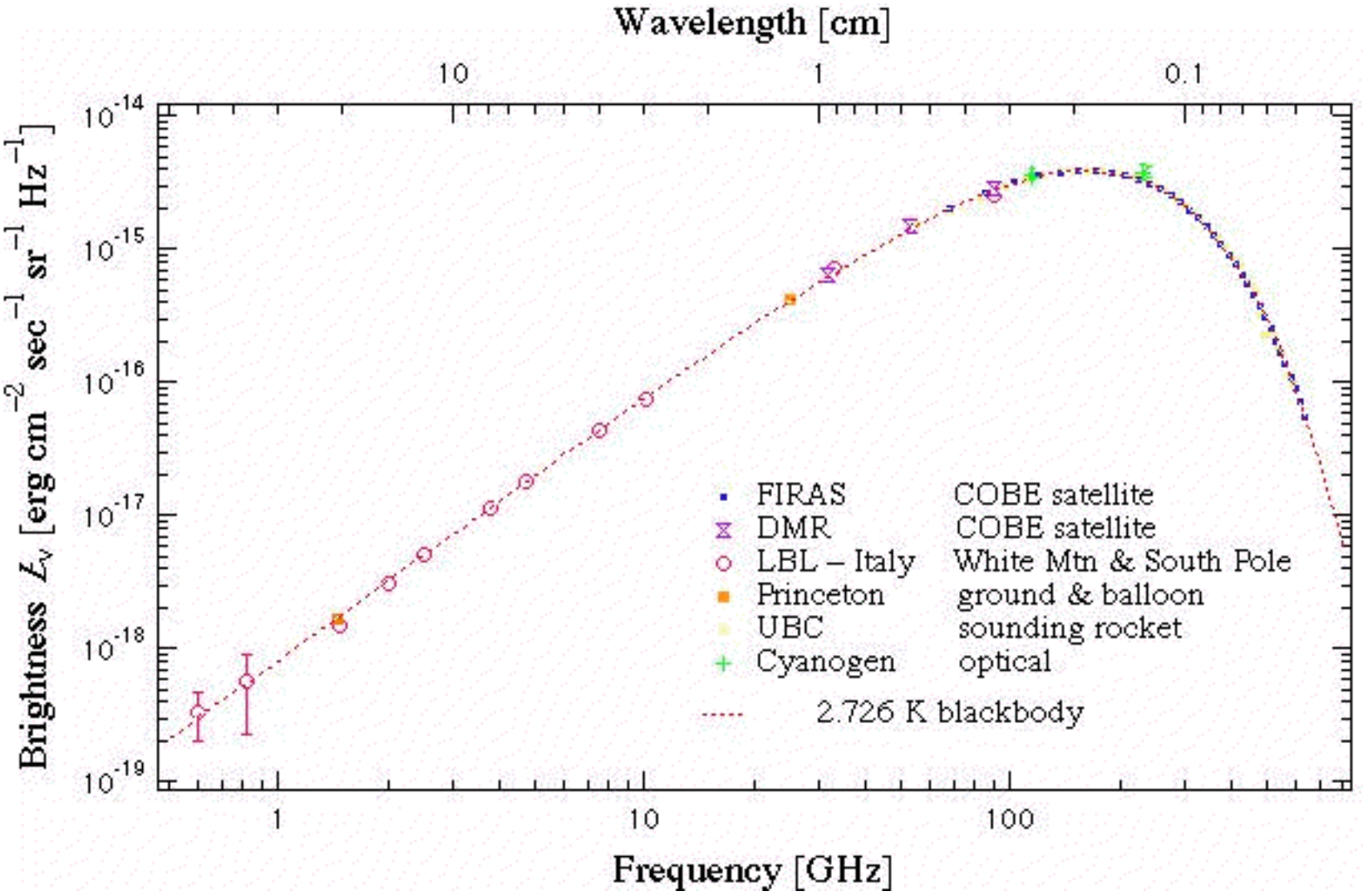


- Two instruments made maps of the whole sky in microwaves and in infrared radiation

- One instrument took a precise spectrum of the sky in microwaves

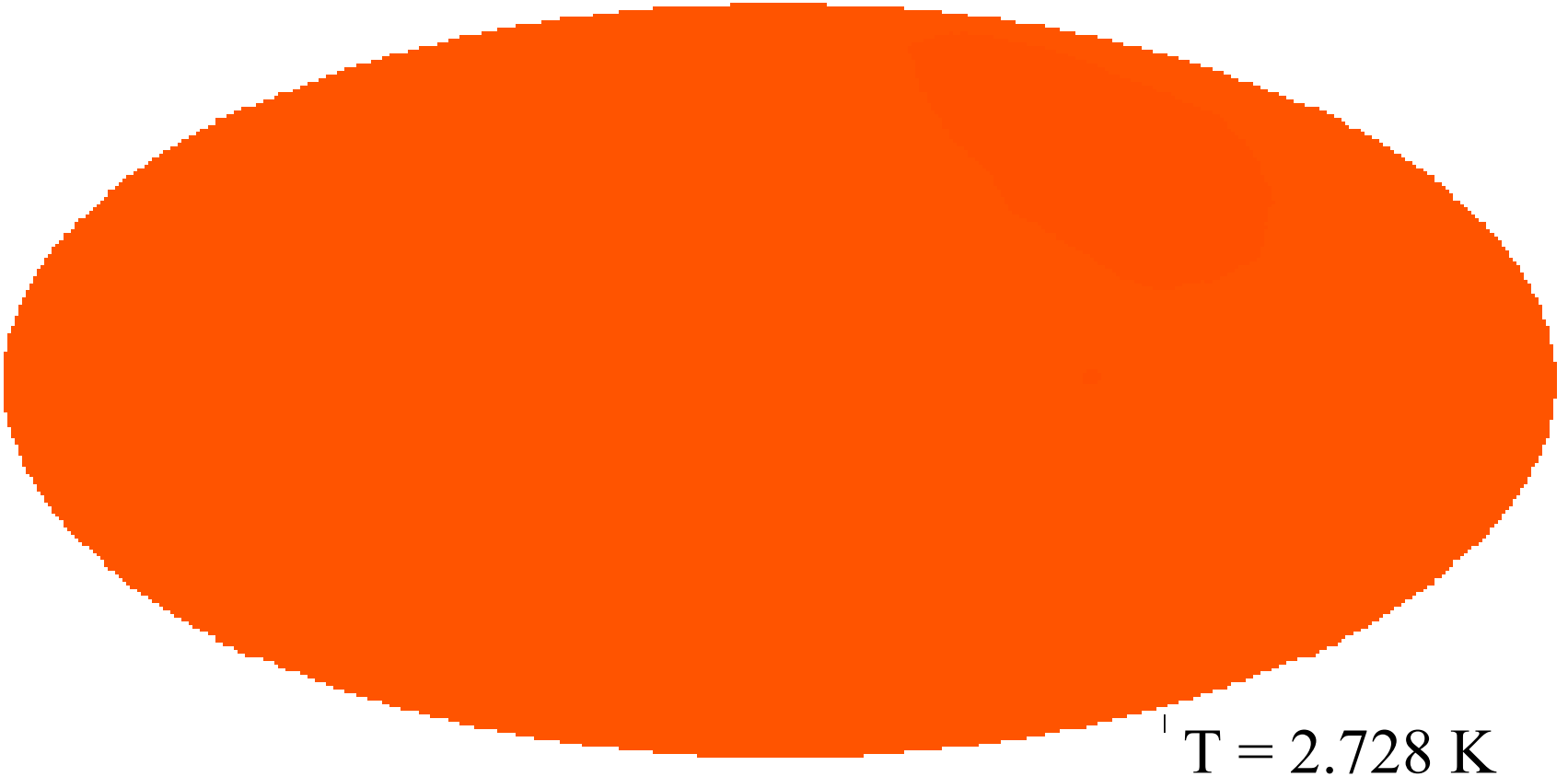
Nobel Prize for Physics 2006
J. Mather & G. Smoot

Our universe was once hot, smooth and in thermal equilibrium



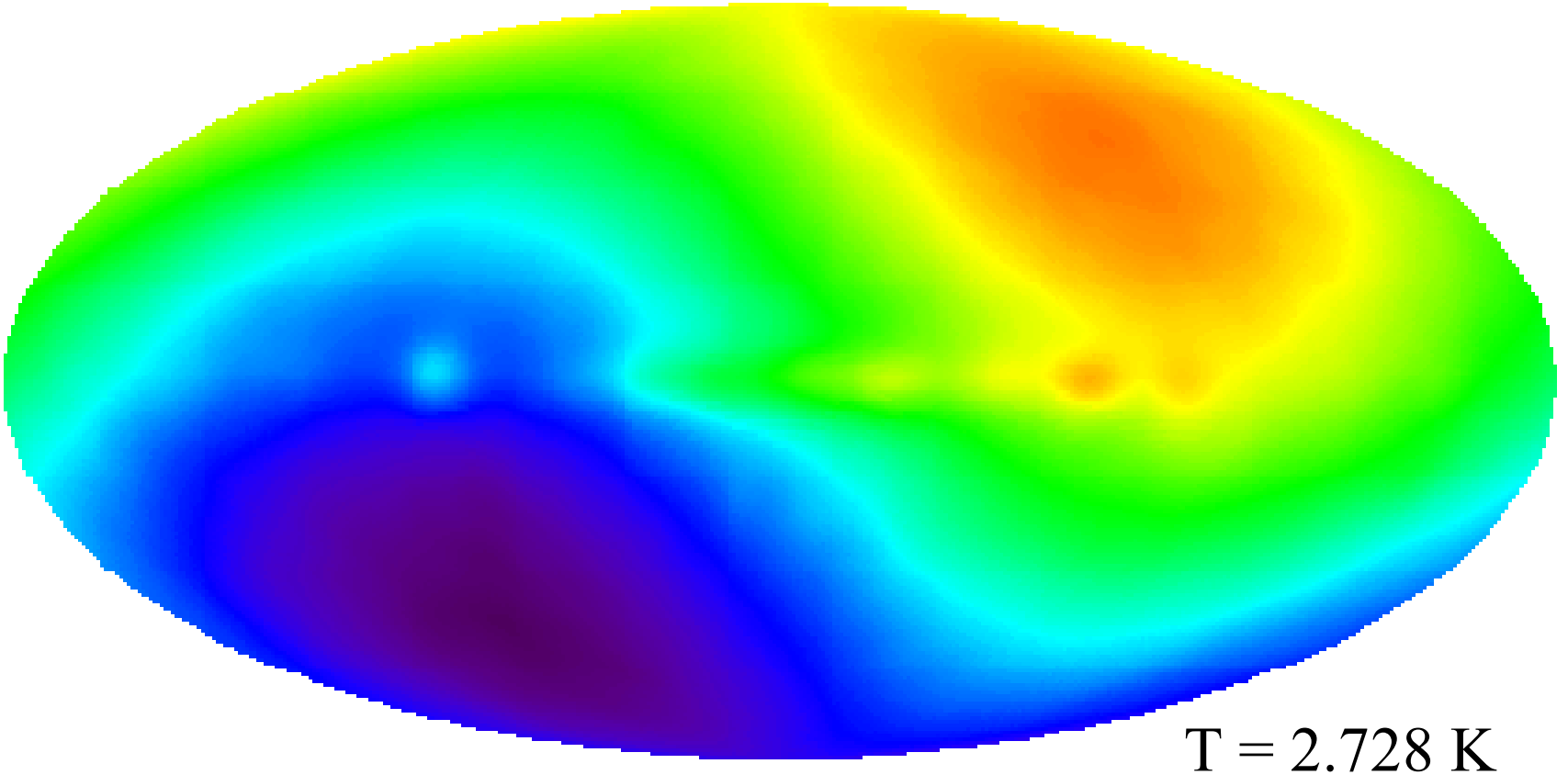
- Photons outnumber protons by a billion to one
- Spectrum matches a Planckian black-body to better than 1 in 10^{-4}
- No significant energy input later than ~1 month after the Big Bang

At 400,000 years the universe was very smooth



At 400,000 years the universe was very smooth

The strongest signal reflects our motion through the CMB



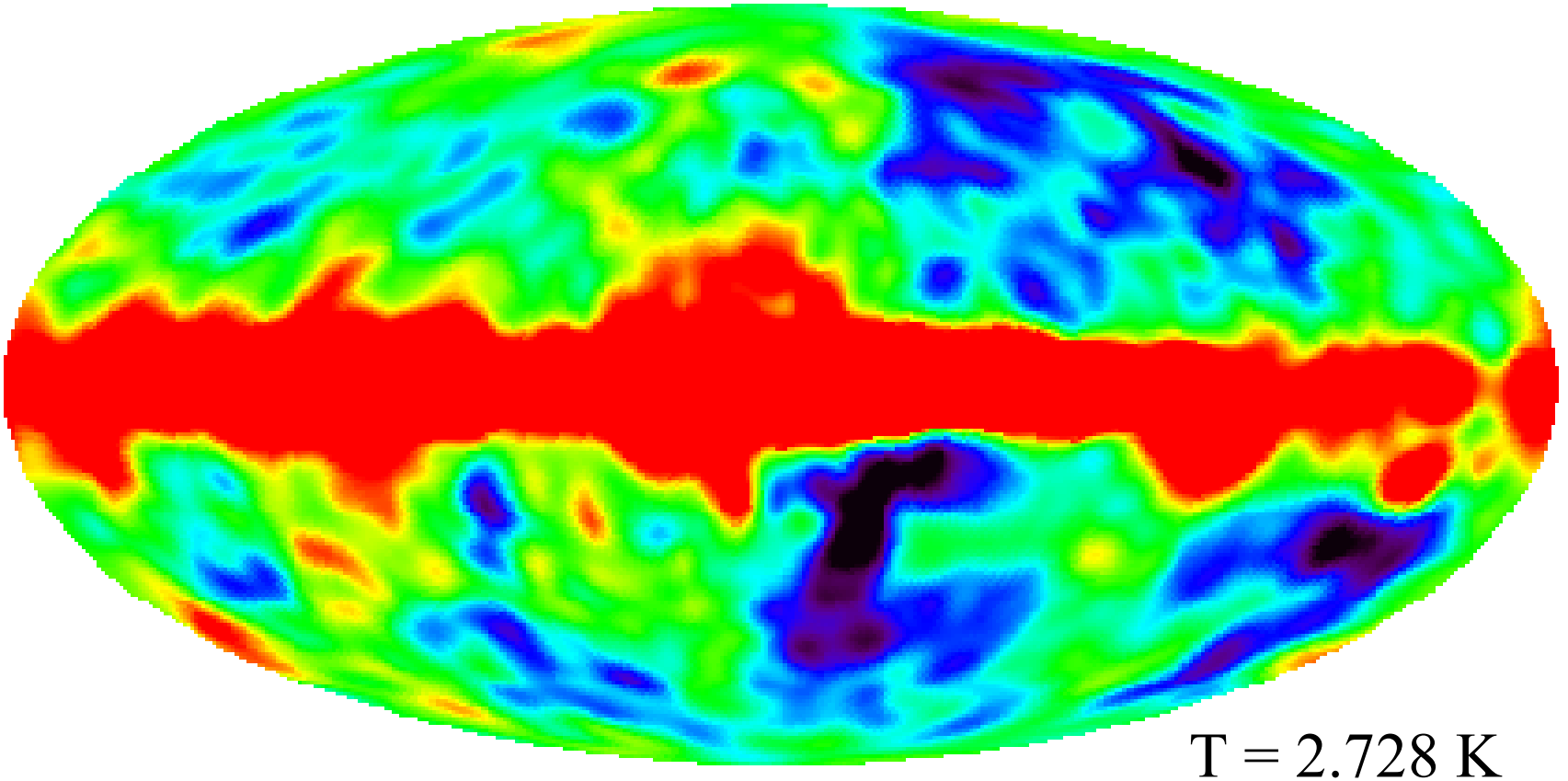
T = 2.728 K

ΔT = 0.0034 K

At 400,000 years the universe was very smooth

The Galactic foreground emission is weak

Structure at z=1000 is even weaker, $\Delta T/T \sim 10^{-5}$ → dark matter!



T = 2.728 K

ΔT = 0.00002 K

Structure in the Microwave Background

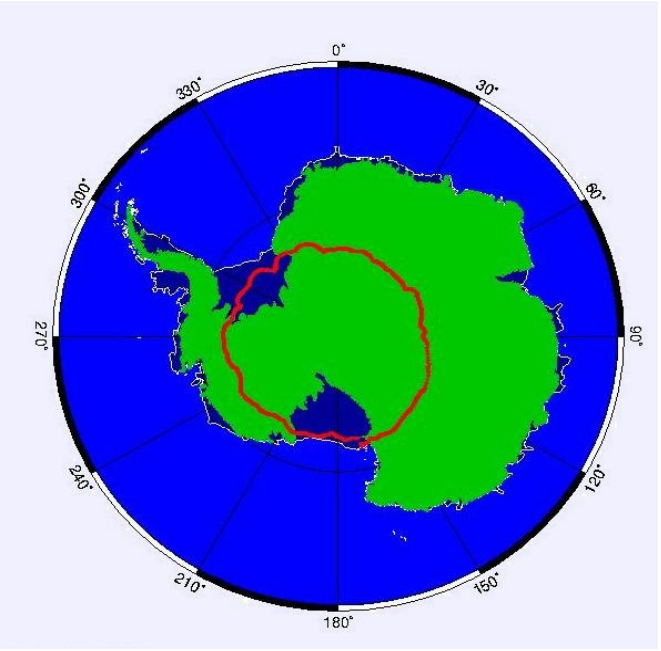
- The structure lies in cosmic 'clouds', ~ 4 10^{10} l-yrs away
- It reflects weak "sound" waves, A ~ 10^{-4}, in the clouds
- At the time the Universe was only 400,000 years old, and was 1,000 times smaller and 1,000 times hotter than today

The *pattern* of structure reflects

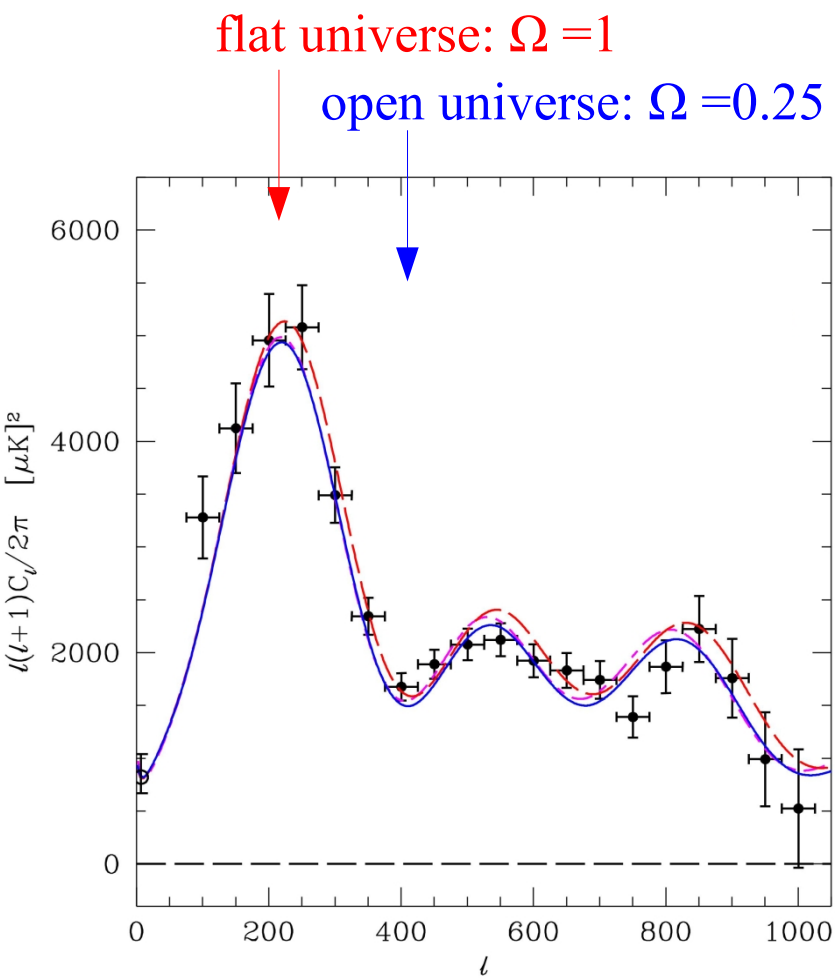
A: The global geometry and topology of the Universe

B: The constituents and thermal evolution of the Universe

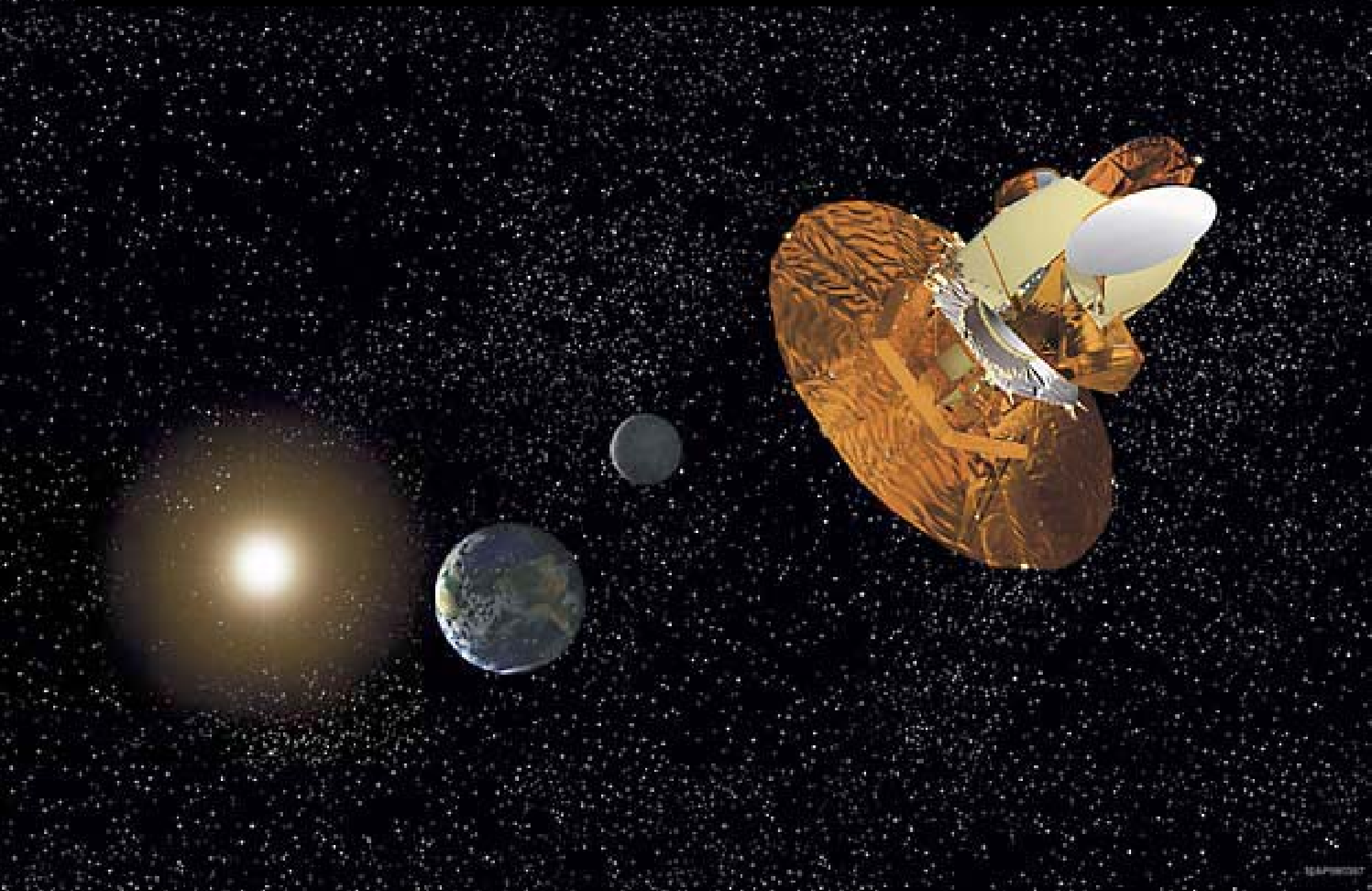
C: The process which generated the structure



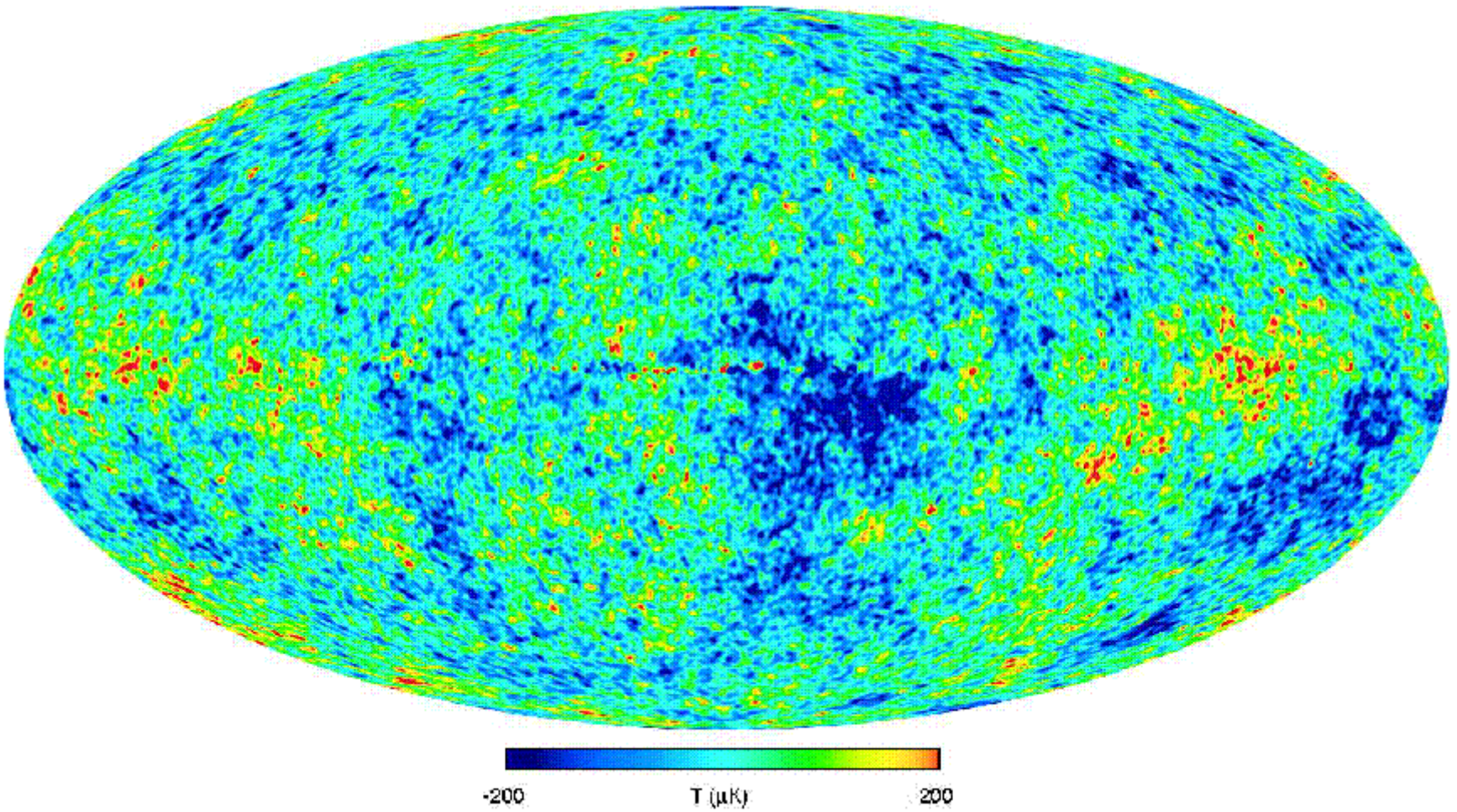
Our universe is flat



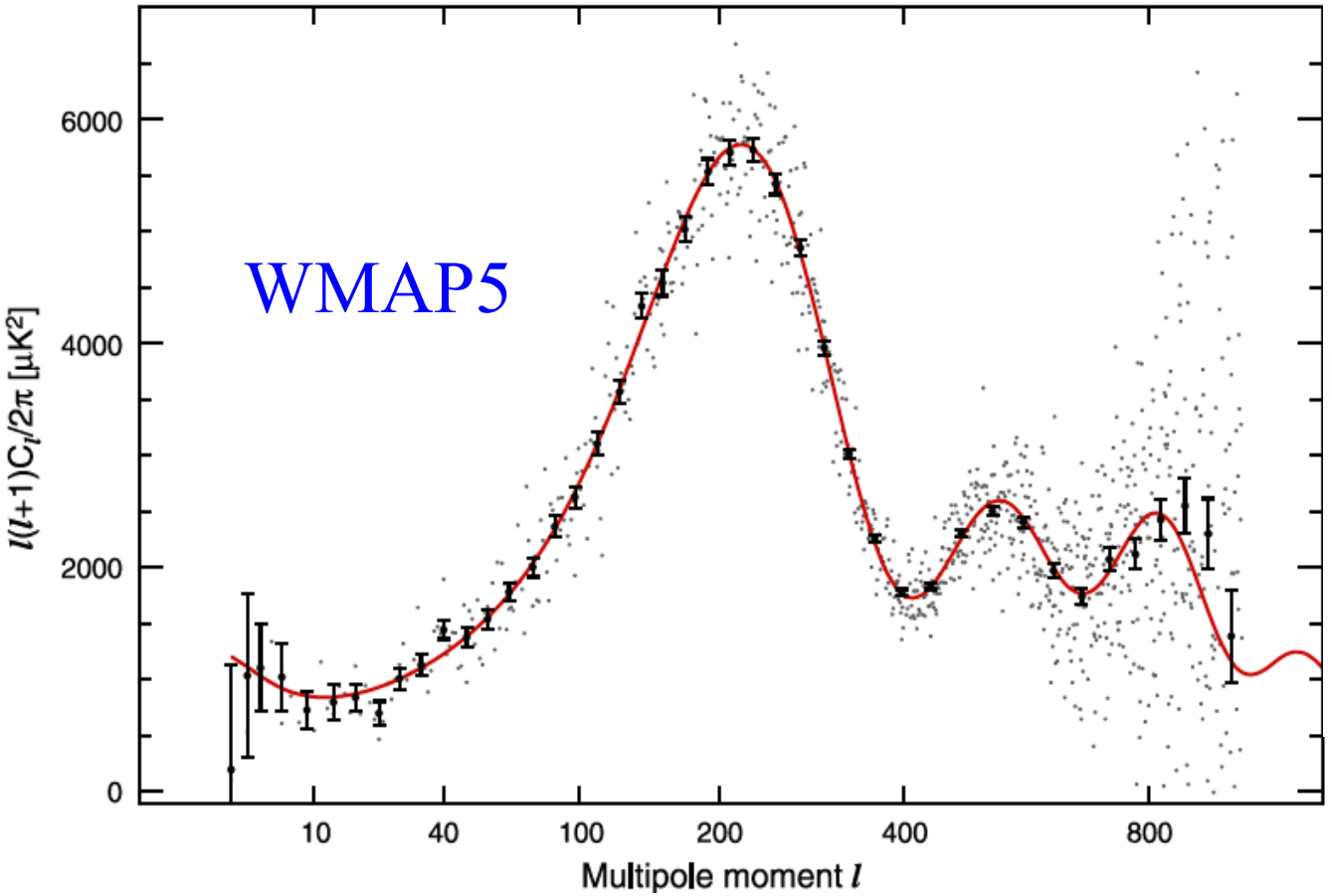
The *WMAP* Satellite at Lagrange-Point L2

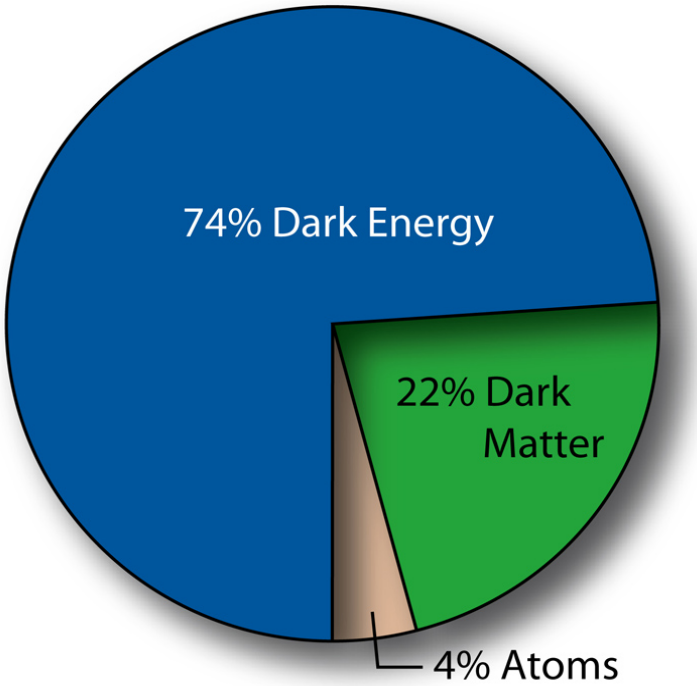


The *WMAP* of the whole CMB sky

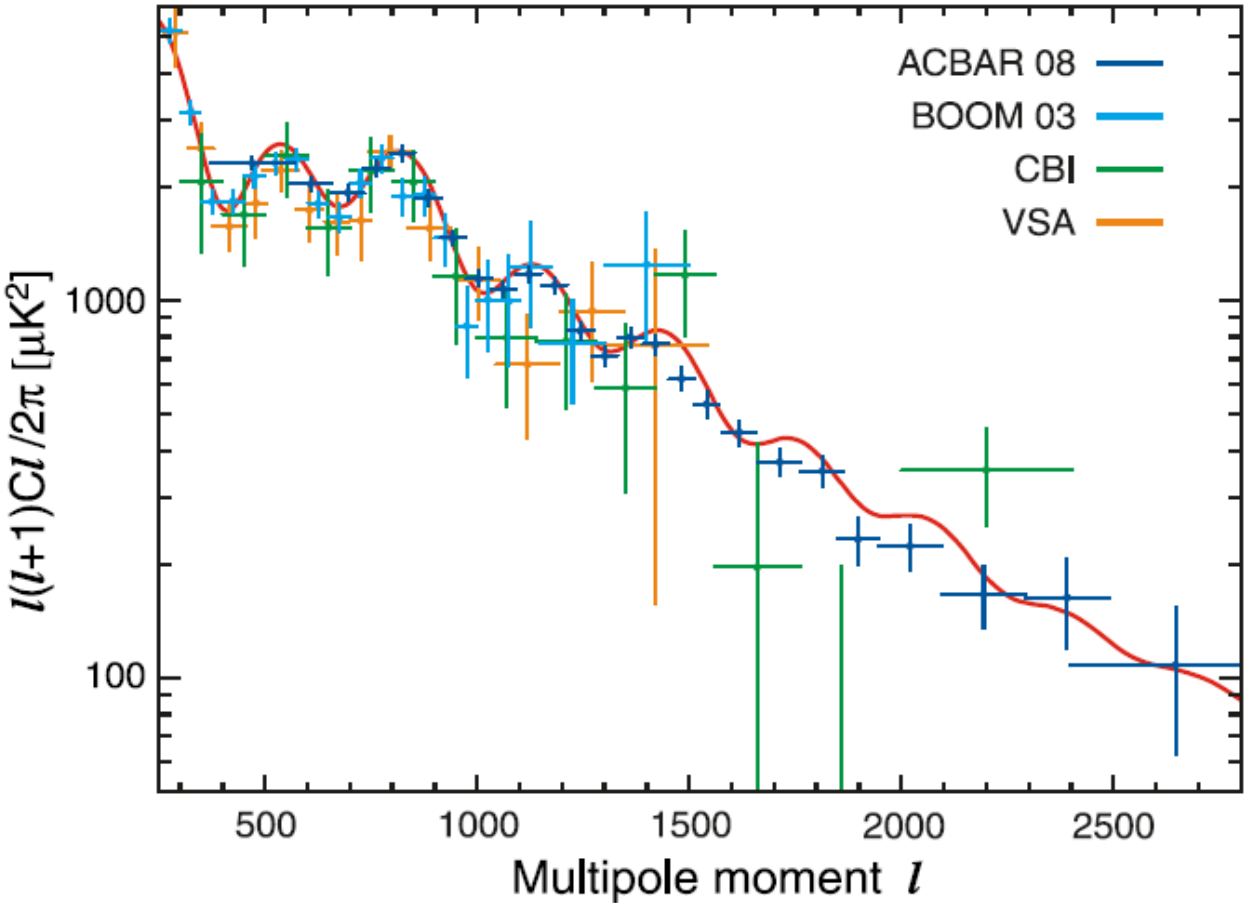


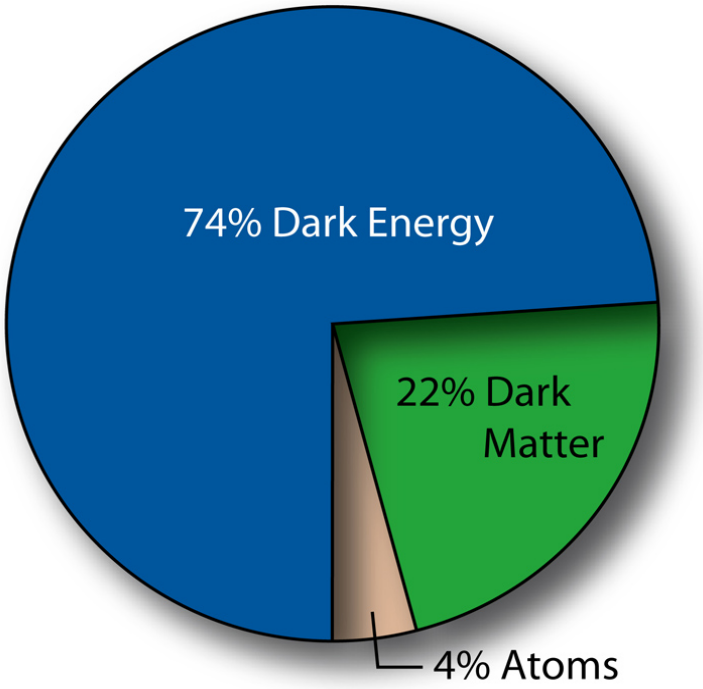
Bennett et al 2003





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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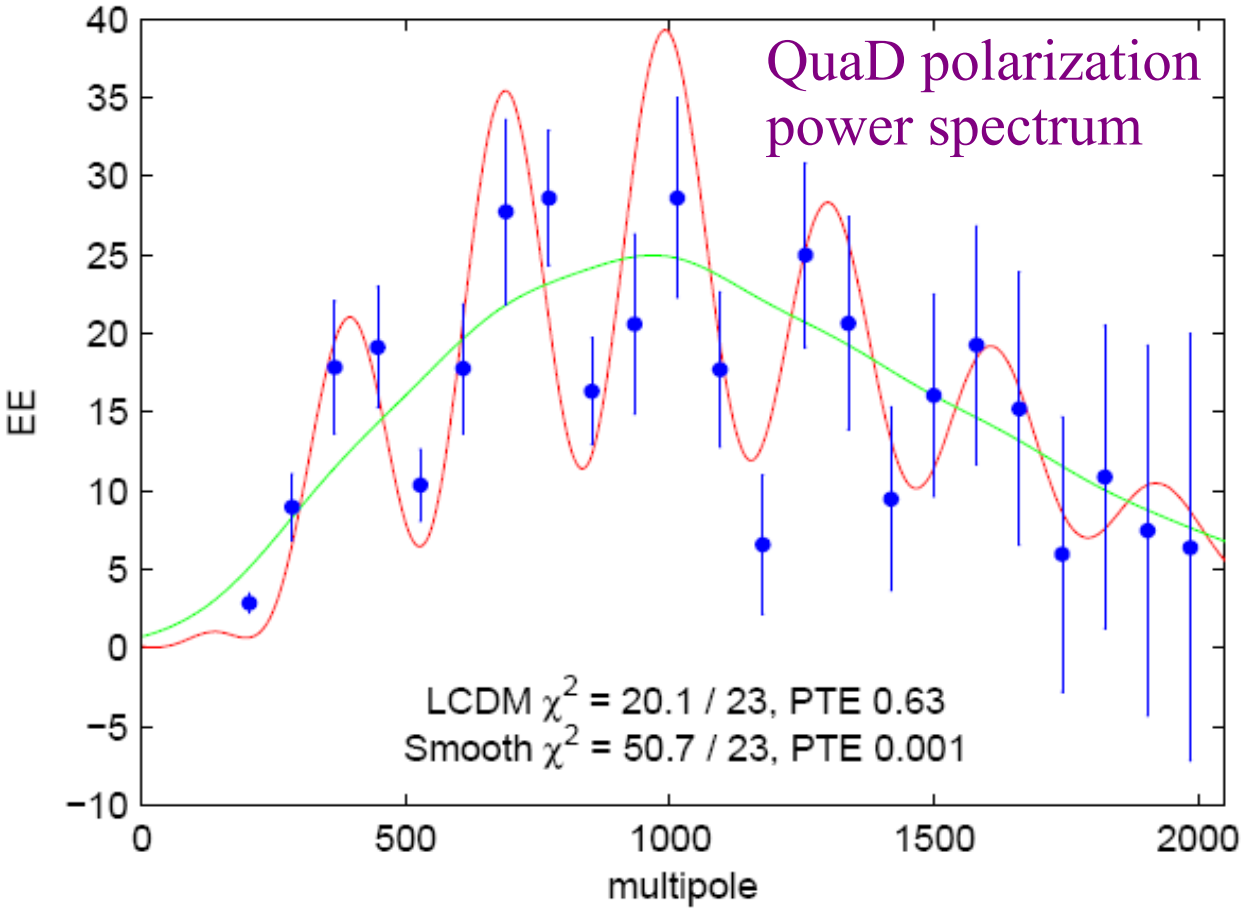

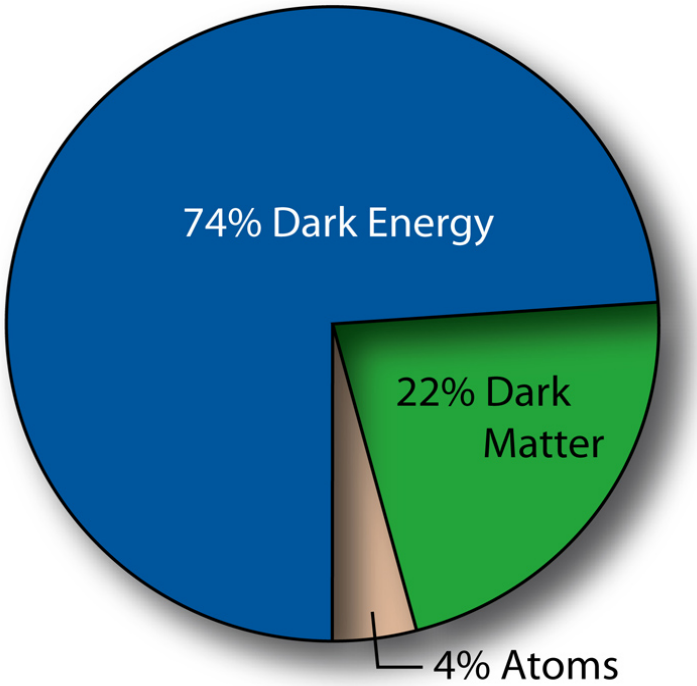

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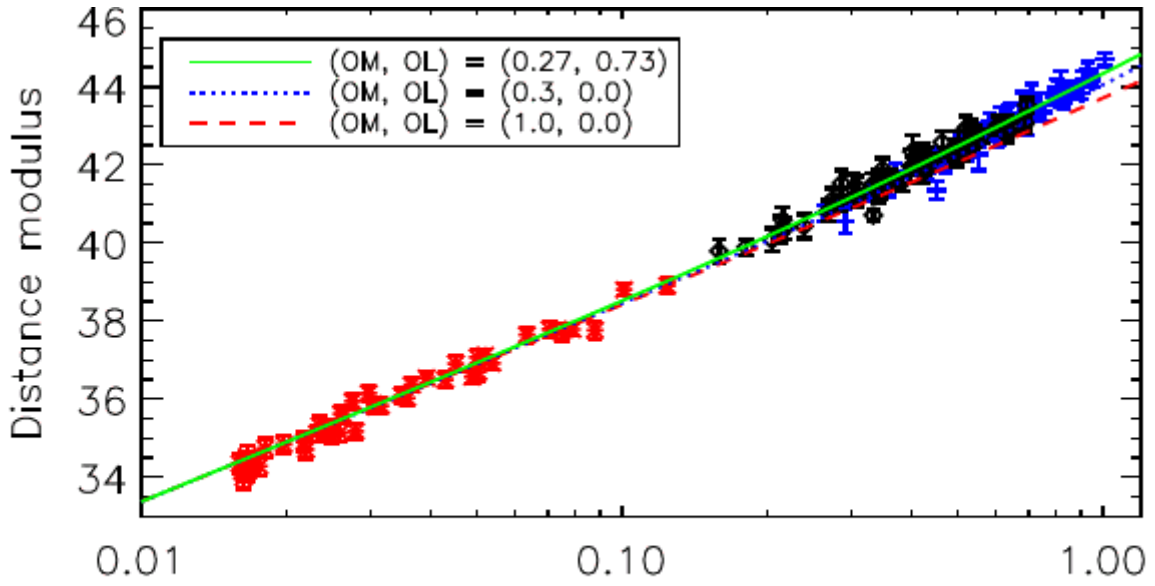
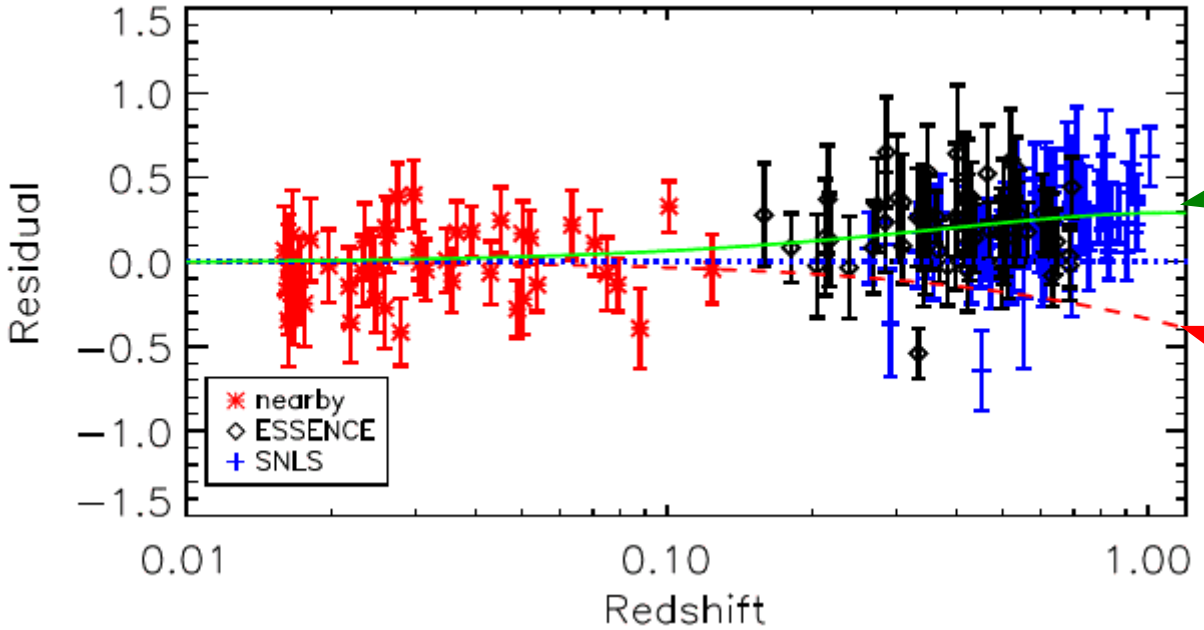
Supernovae show the expansion is accelerating



The ESSENCE Survey
Wood-Vasey et al 2007



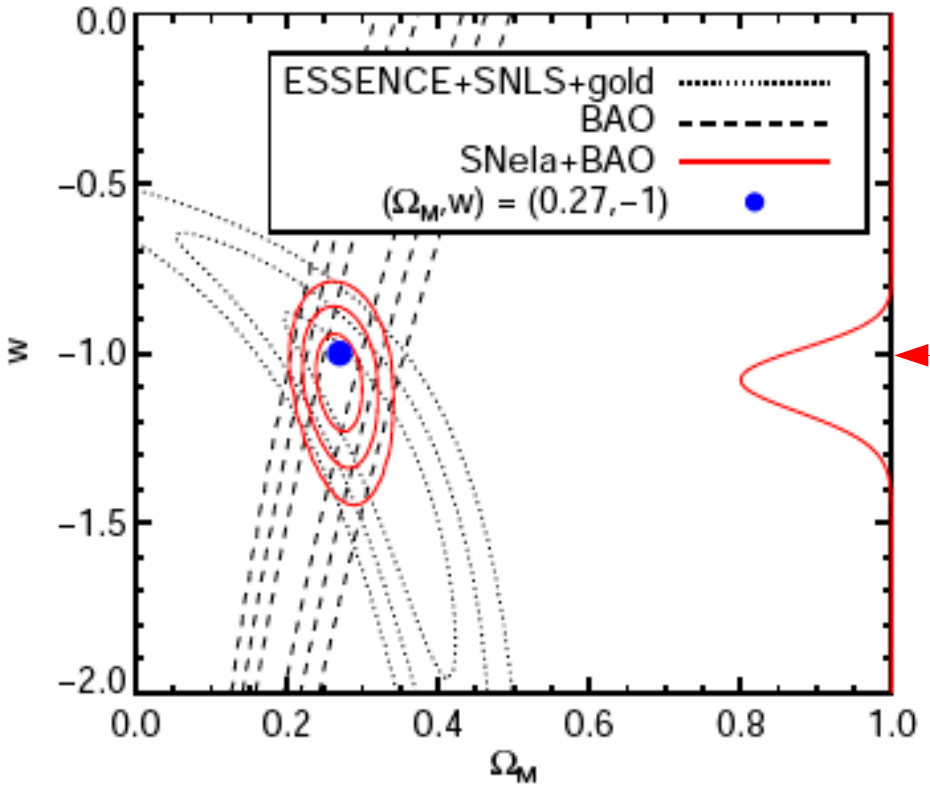
flat dark energy-dominated universe

flat matter-dominated universe

Supernovae show the expansion is accelerating

..and that the Dark Energy behaves like a cosmological constant

The ESSENCE Survey
Wood-Vasey et al 2007



value expected for a cosmological constant

The high redshift universe has shown us..

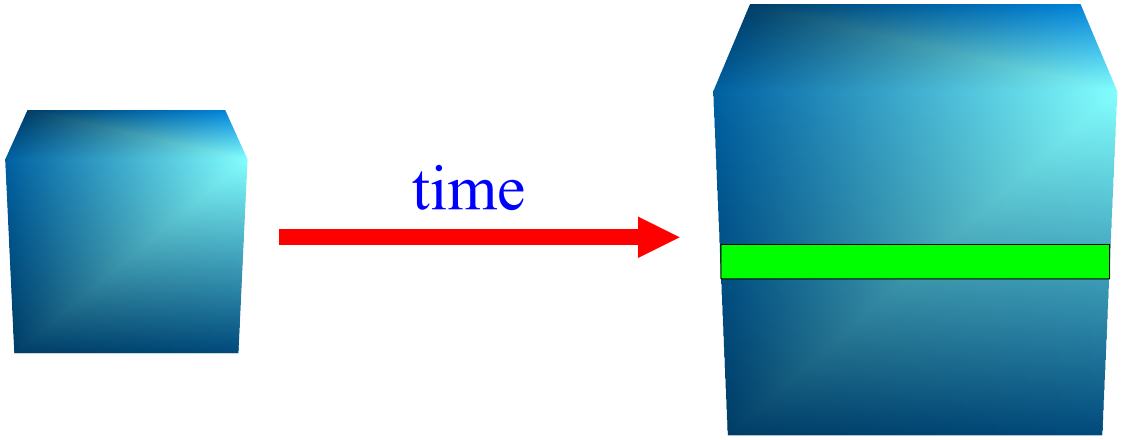
- how our Universe has evolved
  hot → cold, smooth → lumpy
- what its geometry is
  flat – as imagined by Euclid
- what it is made of
  23.5% dark matter(?), 4.5% baryons, 72% dark energy(?)
- how all structure originated
  from quantum fluctuations in the inflationary vacuum(?)

..but it was a very uninteresting place!

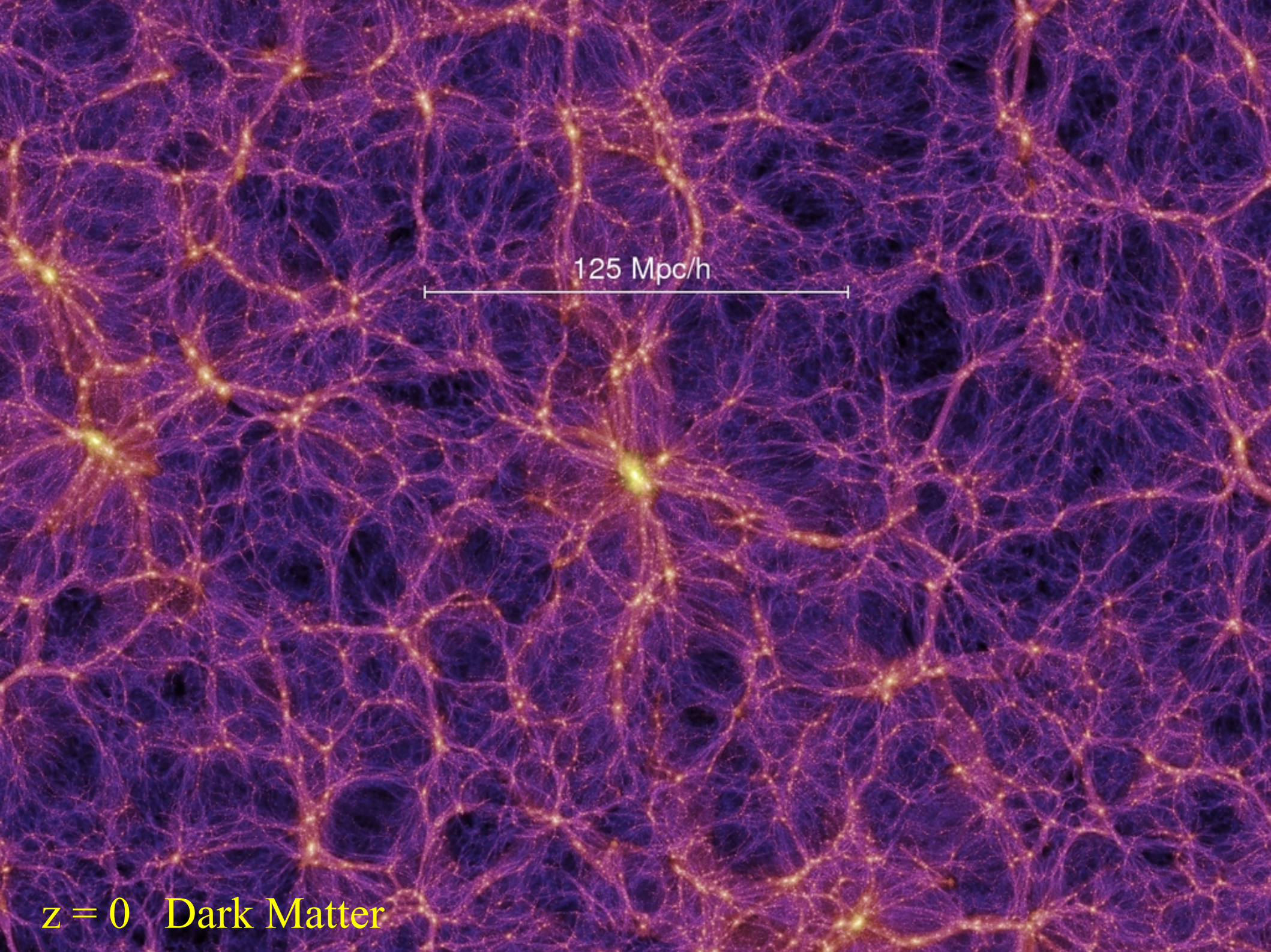
- No galaxies, no stars, no planets, no elements beyond Li !

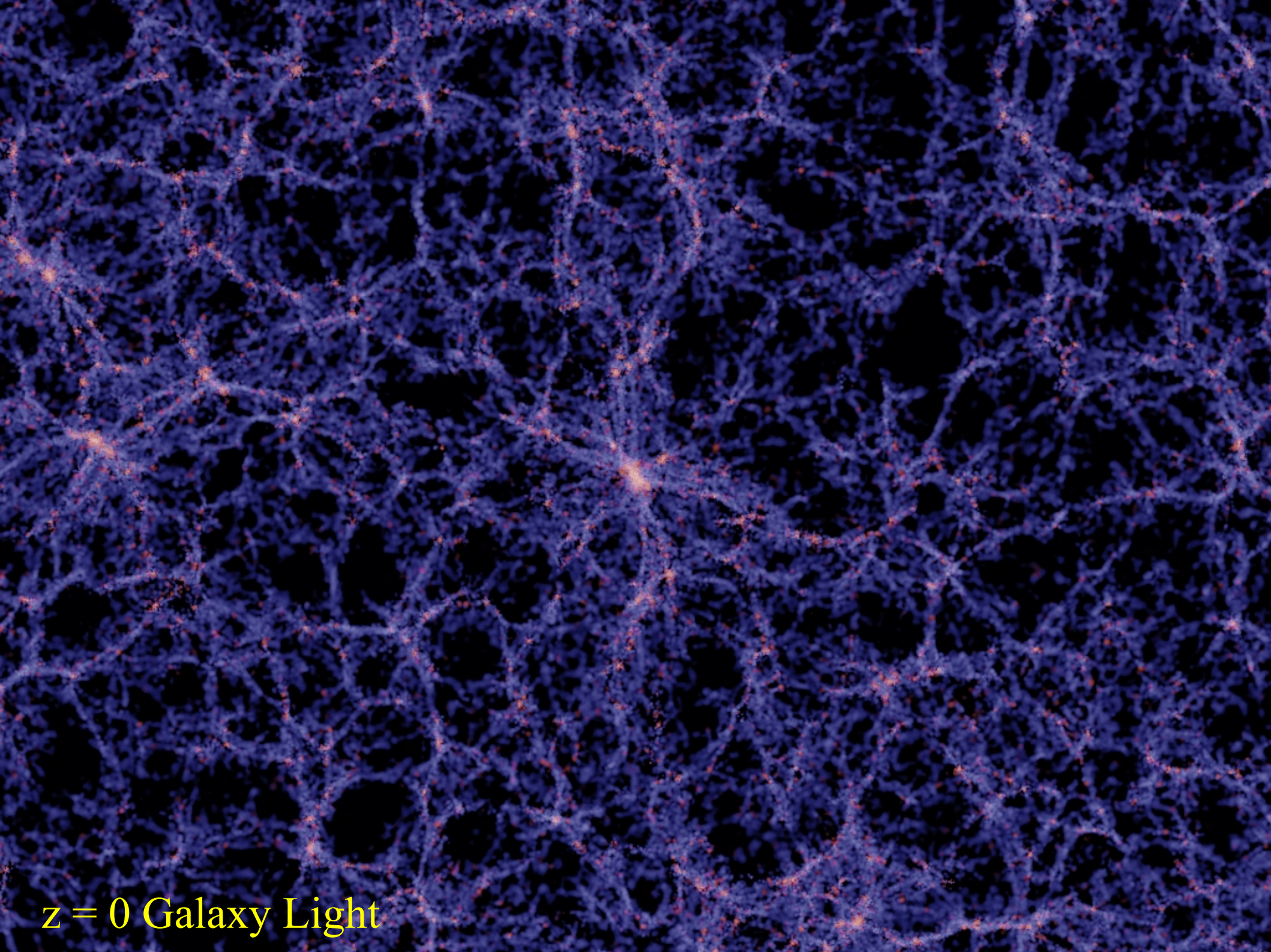
How did today's universe emerge from it?

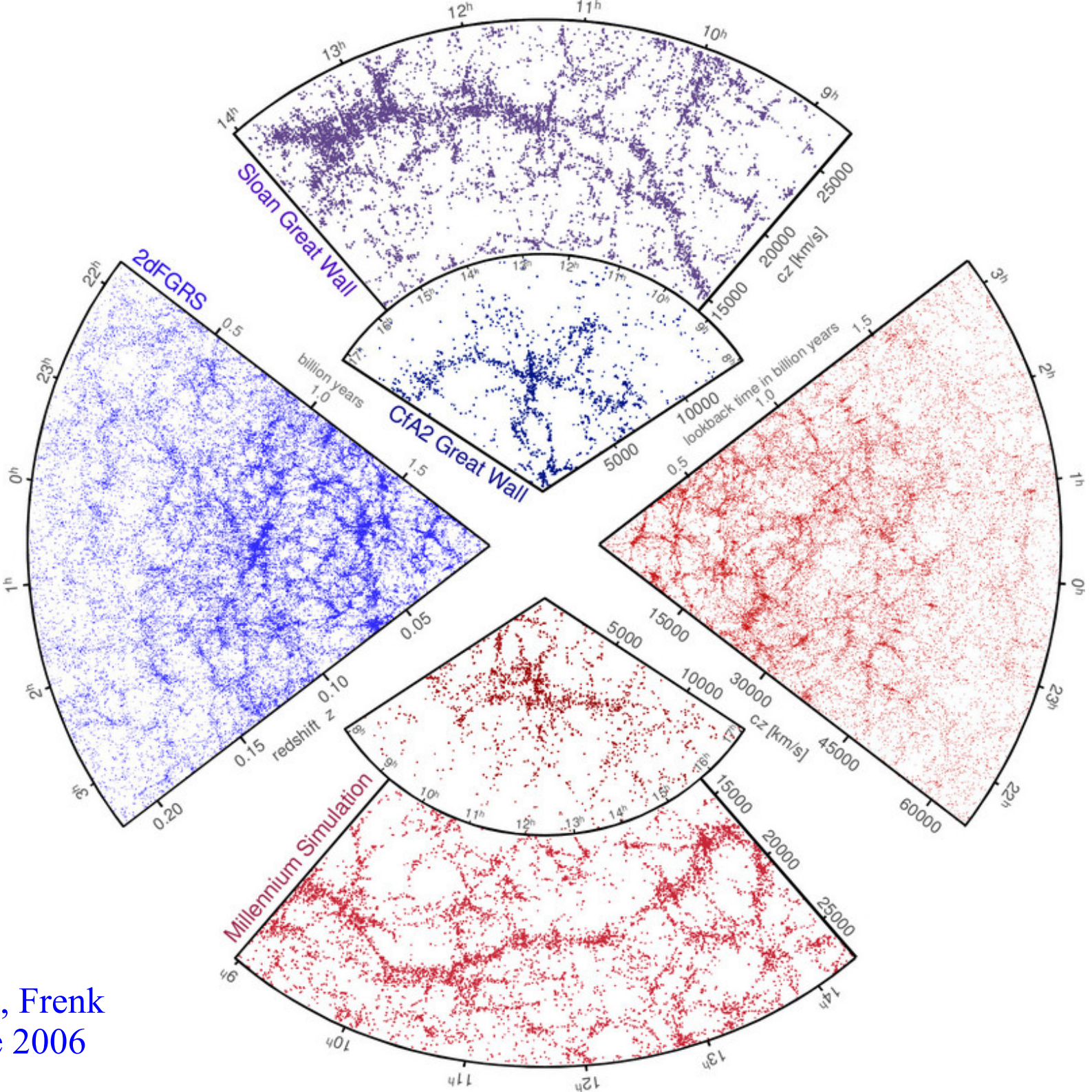
How structure emerges from the Big Bang



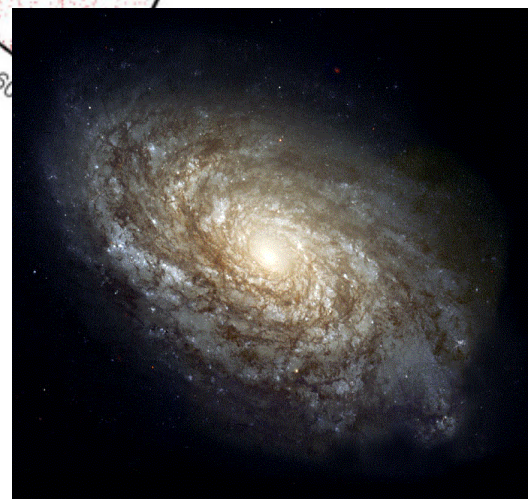
- Start 400,000 years after the Big Bang from the initial conditions seen in the microwave background
- Integrate the equations of motion forwards to the present day in a supercomputer
- The growth of dark matter structures in a thin slice
- A flight through the dark matter distribution


125 Mpc/h
z = 0 Dark Matter


z = 0 Galaxy Light



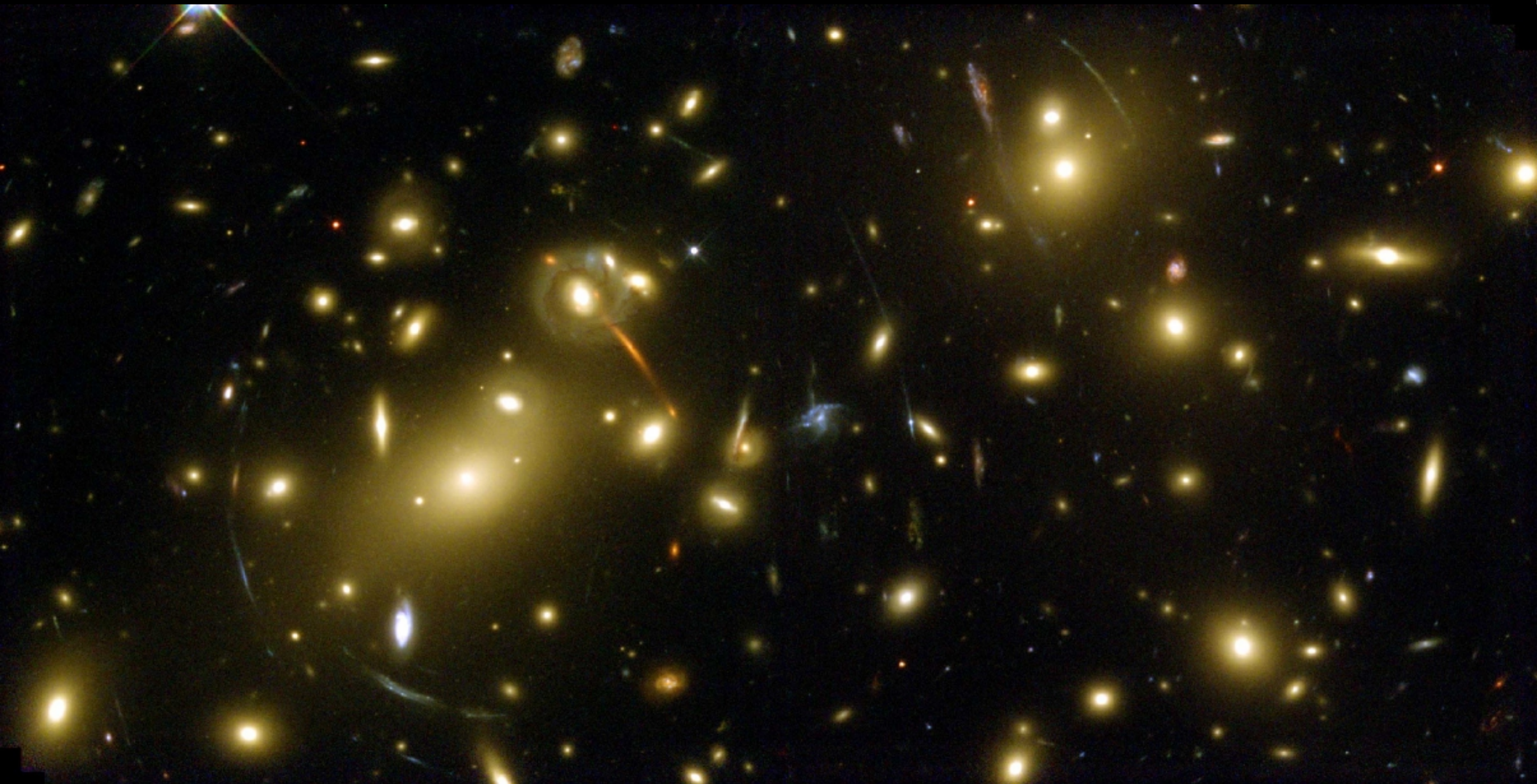
Springel, Frenk
& White 2006



Springel, Frenk
& White 2006

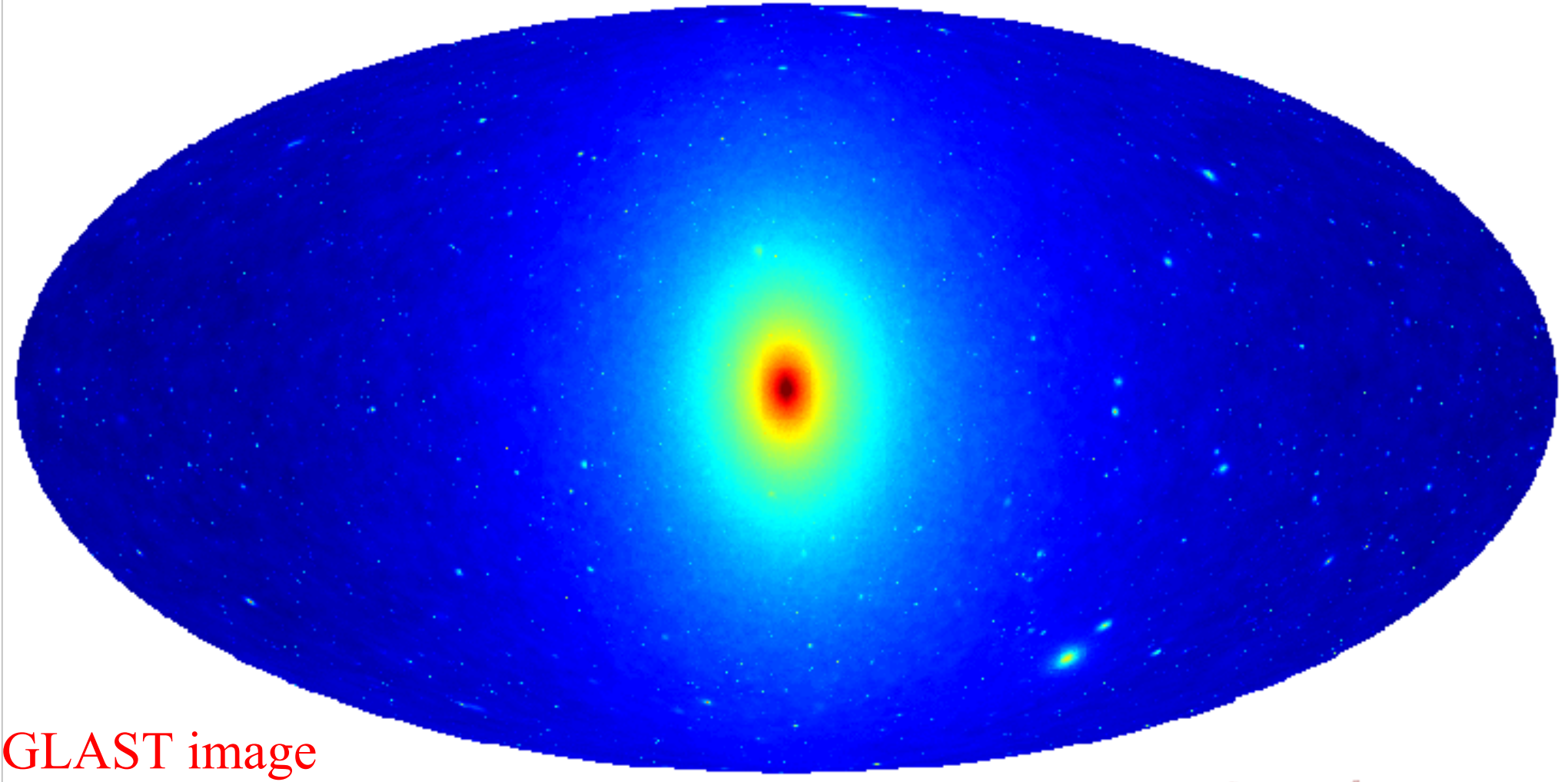
Gravitational lensing: “seeing” the dark matter

Abell 2218 z=0.17



The Milky Way halo in annihilation radiation: gamma-rays from supersymmetric dark matter?

Aquarius simulation: $N_{200} = 1.1 \times 10^9$



GLAST image after 1 year?

What's next in cosmology?

We have been surprised by

- The cosmic expansion
- Dark Matter
- Cosmic evolution
- The microwave background
- Dark Energy
- ..also white dwarfs, pulsars, quasars, γ-ray bursts, neutrino masses, extrasolar planet properties...

We cannot plan major advances, only improve technical abilities

We do not know which technique will reveal the next surprise

→ We must remain opportunistic and open-minded, both scientifically and technically, if we are to continue to find surprises