Introduction to Cosmology

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1) The Big Bang model
2) Content of the Universe
3) **Cosmological probes**
4) Large Scale Structure: from SDSS to DESI
5) The Hubble constant tension

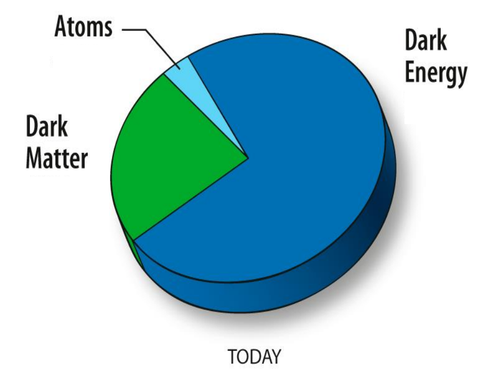
Cosmological probes

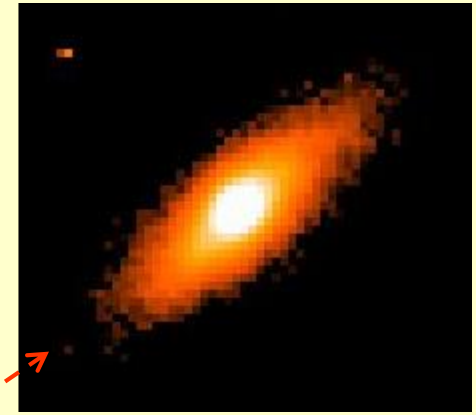
Observations and interpretation

$$1 = \Omega_m(t) + \Omega_r(t) + \Omega_k(t) + \Omega_\Lambda(t)$$

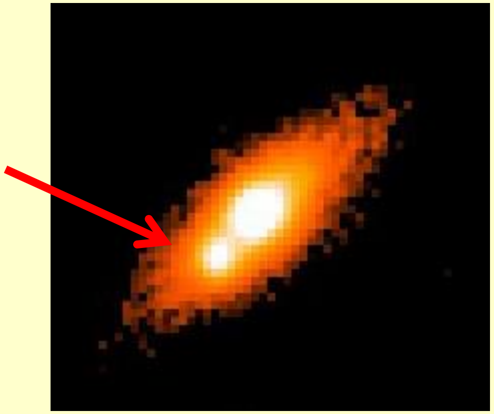
negligible today

- Type Ia supernovae (SNe Ia)
- Cosmic Microwave Background (CMB)
- Baryonic Acoustic Oscillations (BAO)
- Large Scale Structure formation (LSS)

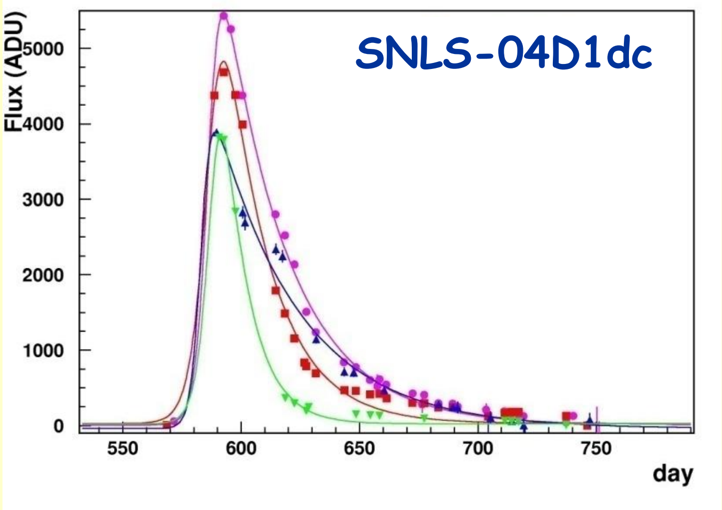




before explosion



SN light curve

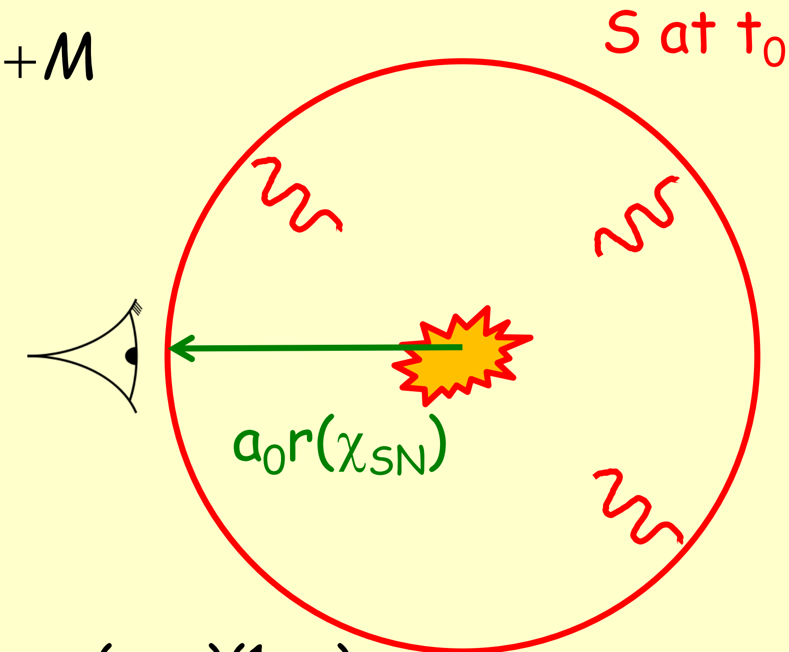


Cosmology with type Ia SNe

- Light curves $\Rightarrow$ apparent peak magnitude:

$$m_B^* = -2.5\log\frac{\Phi}{\Phi_{cal}} = -2.5\log\frac{L}{4\pi d_L^2} + M$$

- Luminosity distance:



emission: $L = \frac{N_g E_E}{Dt_E}$

observation: $F = \frac{N_g E_0}{Dt_0 S}$

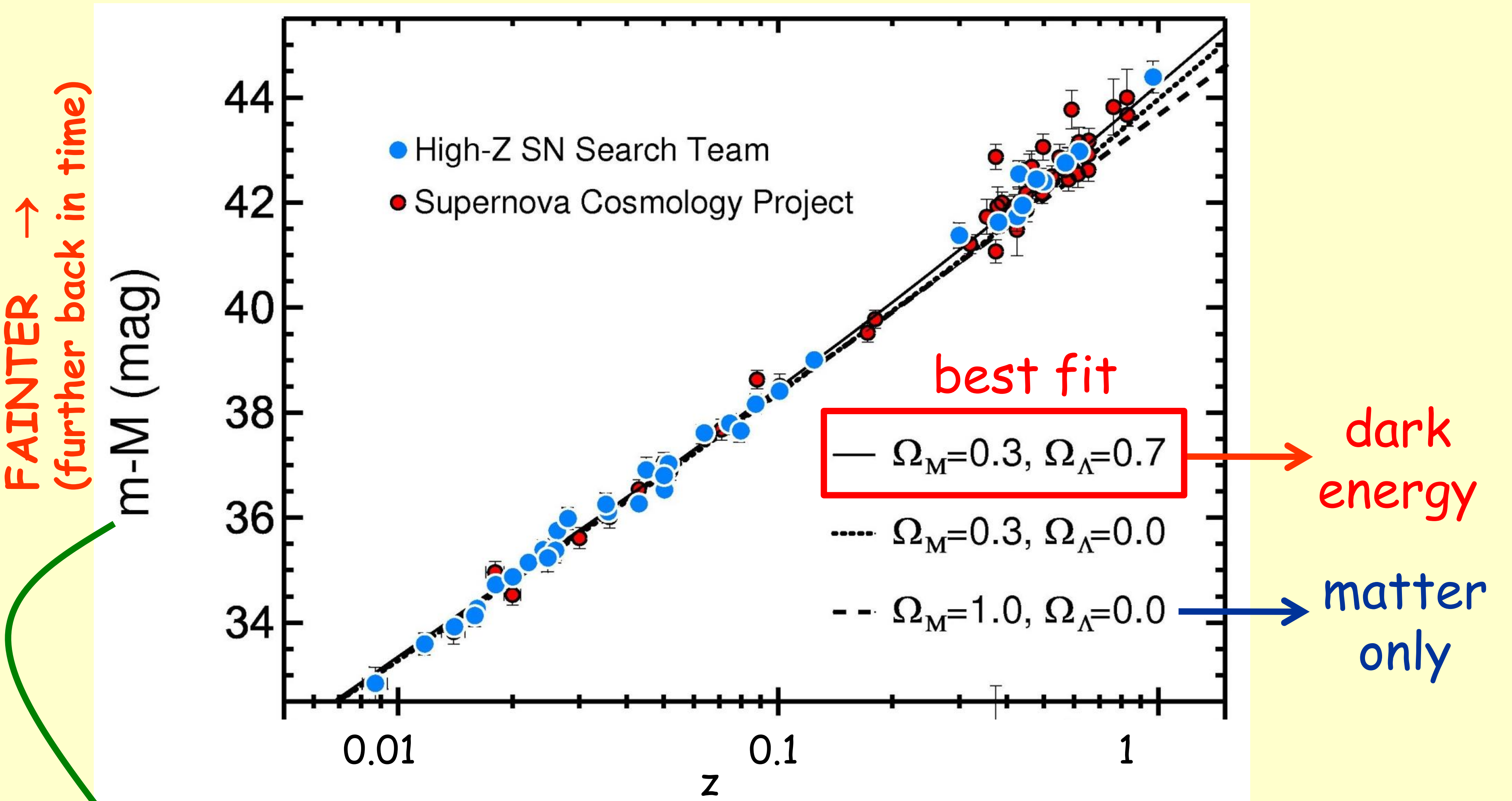
$$\Rightarrow F = \frac{N_g E_E}{Dt_E (1+z)^2 4p(a_0 r(c_{SN}))^2} \equiv \frac{L}{4pd_L^2} \Rightarrow d_L = a_0 r(c_{SN})(1+z)$$

$$\Rightarrow d_L = (1+z)\frac{c}{H_0 A}\begin{Bmatrix}\sin\\ 1\\ \sinh\end{Bmatrix}\left(A\int_0^z \frac{dz'}{\sqrt{W_m^0(1+z')^3 + W_r^0(1+z')^4 + W_k^0(1+z')^2 + W_L^0}}\right)$$

with $A = \sqrt{|W_k^0|}$ *for* $k = -1, 1$ *and* $A = 1$ *for* $k = 0$

here, dark energy = Λ

Accelerated expansion : Type Ia SNe, 1998



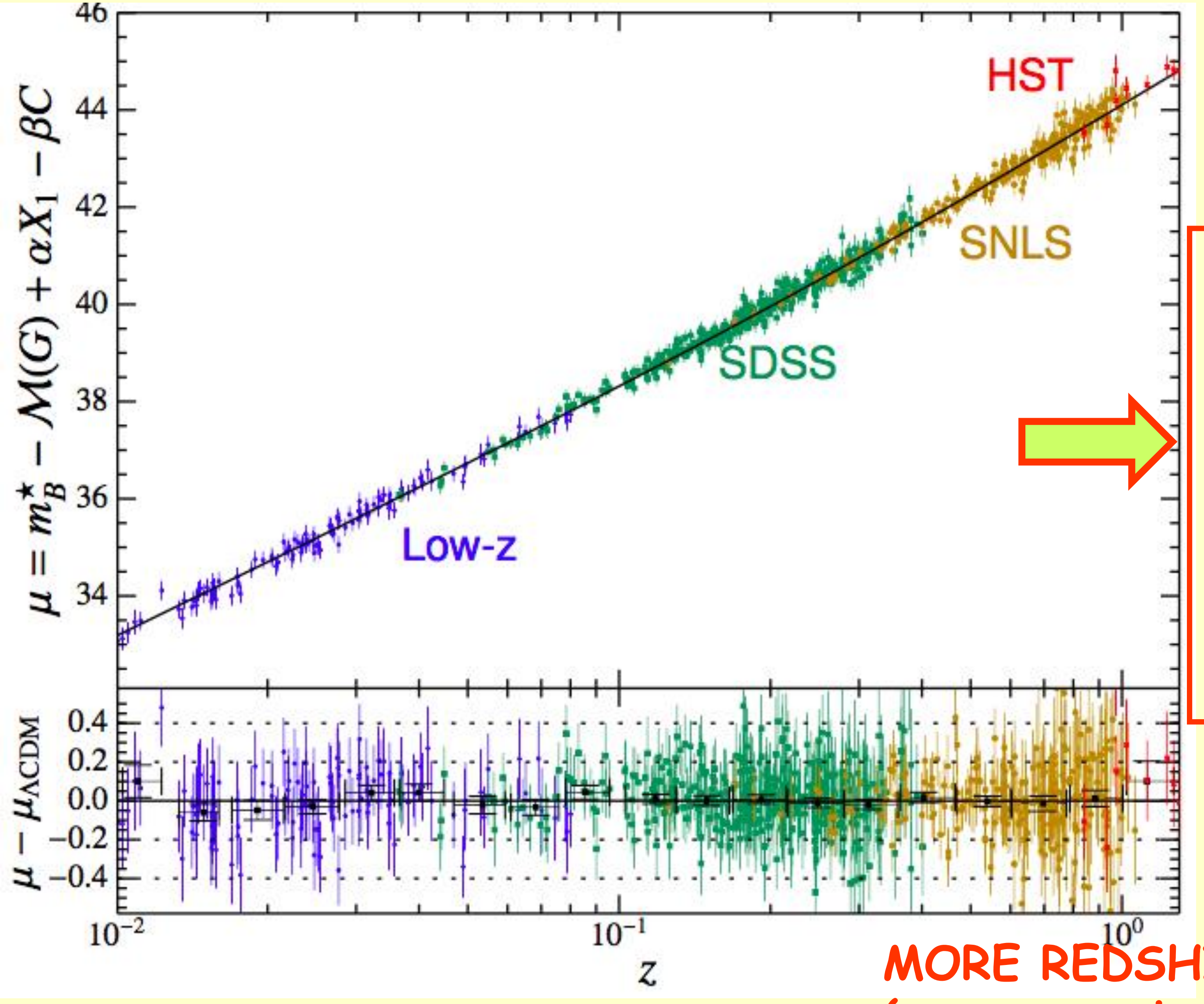
~ apparent magnitude
$= -2.5\log_{10}(\mathcal{L}/4\pi d_L^2)$

MORE REDSHIFT→
(more expansion since explosion)

S.Perlmutter et al., 1999, ApJ, 517, 565 & A.Riess et al., 1998, AJ, 116, 1009

More recent SNIa result, 2014

High quality data for **740** SNeIa



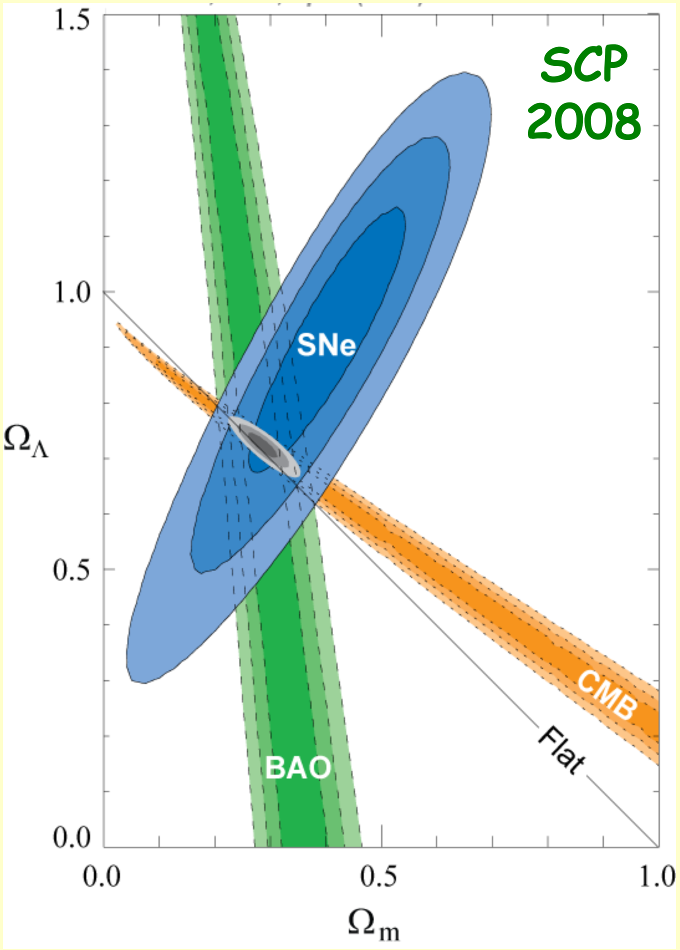
FAINTER (further back in time) →

flat Universe
Λ_{CDM} best-fit:
Ω_m=0.30±0.03
accelerated
expansion
confirmed from
SNe Ia alone
(>99.9%CL)

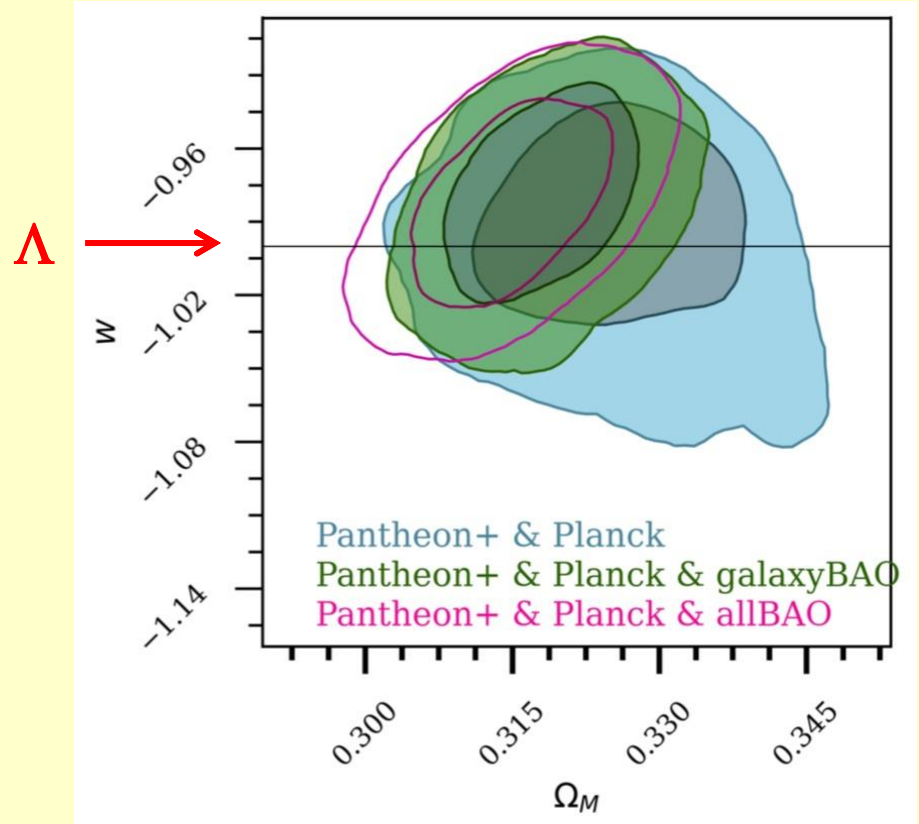
MORE REDSHIFT→
(more expansion since explosion)

M.Betoule et al., 2014, A&A, 568, A22c

Cosmological constraints from CMB+BAO+SNIa data



In a flat Universe with a dark energy component of constant $w \equiv P/\rho$:



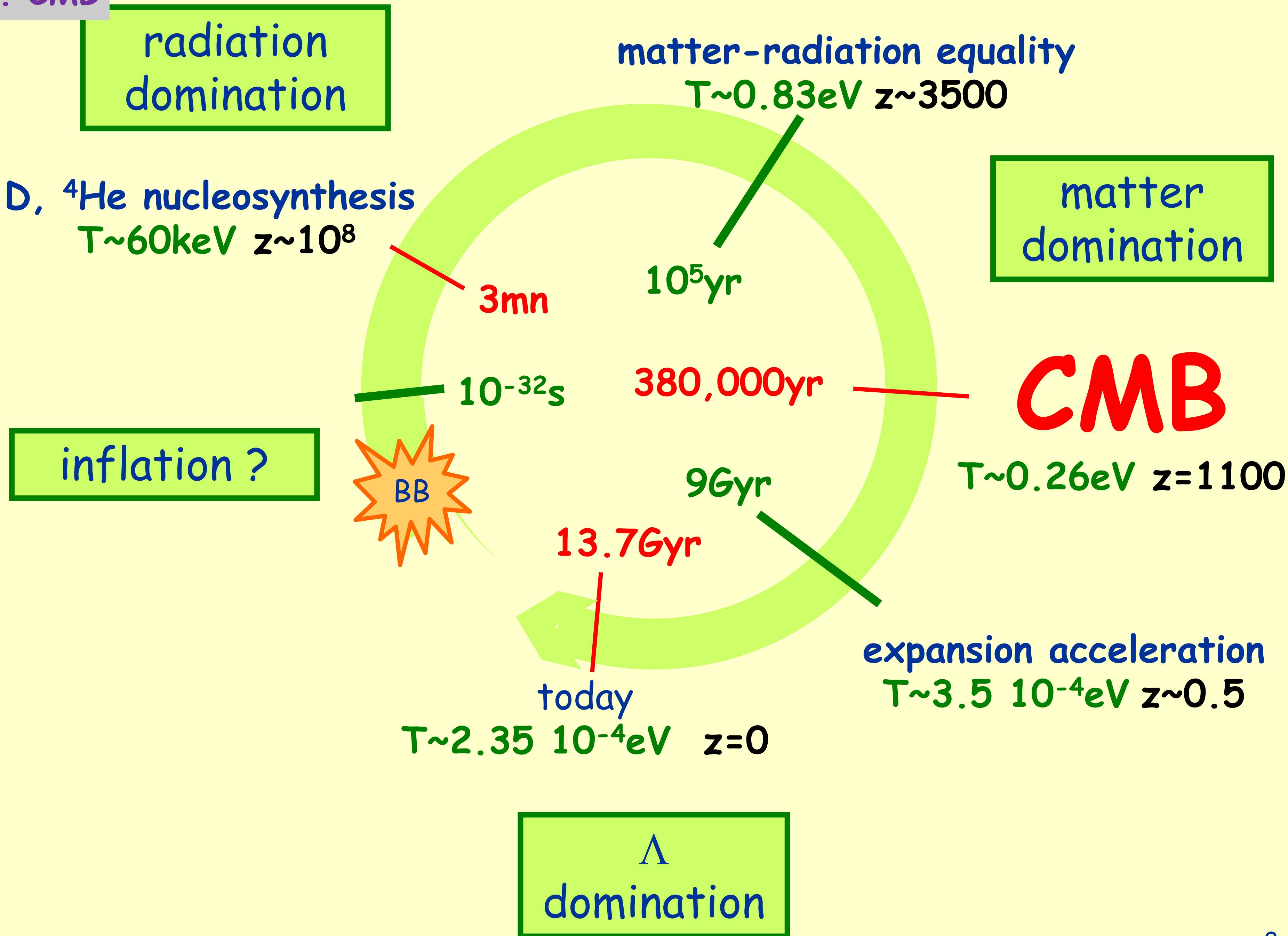
⇨ Universe is flat, Λ or dark energy needed

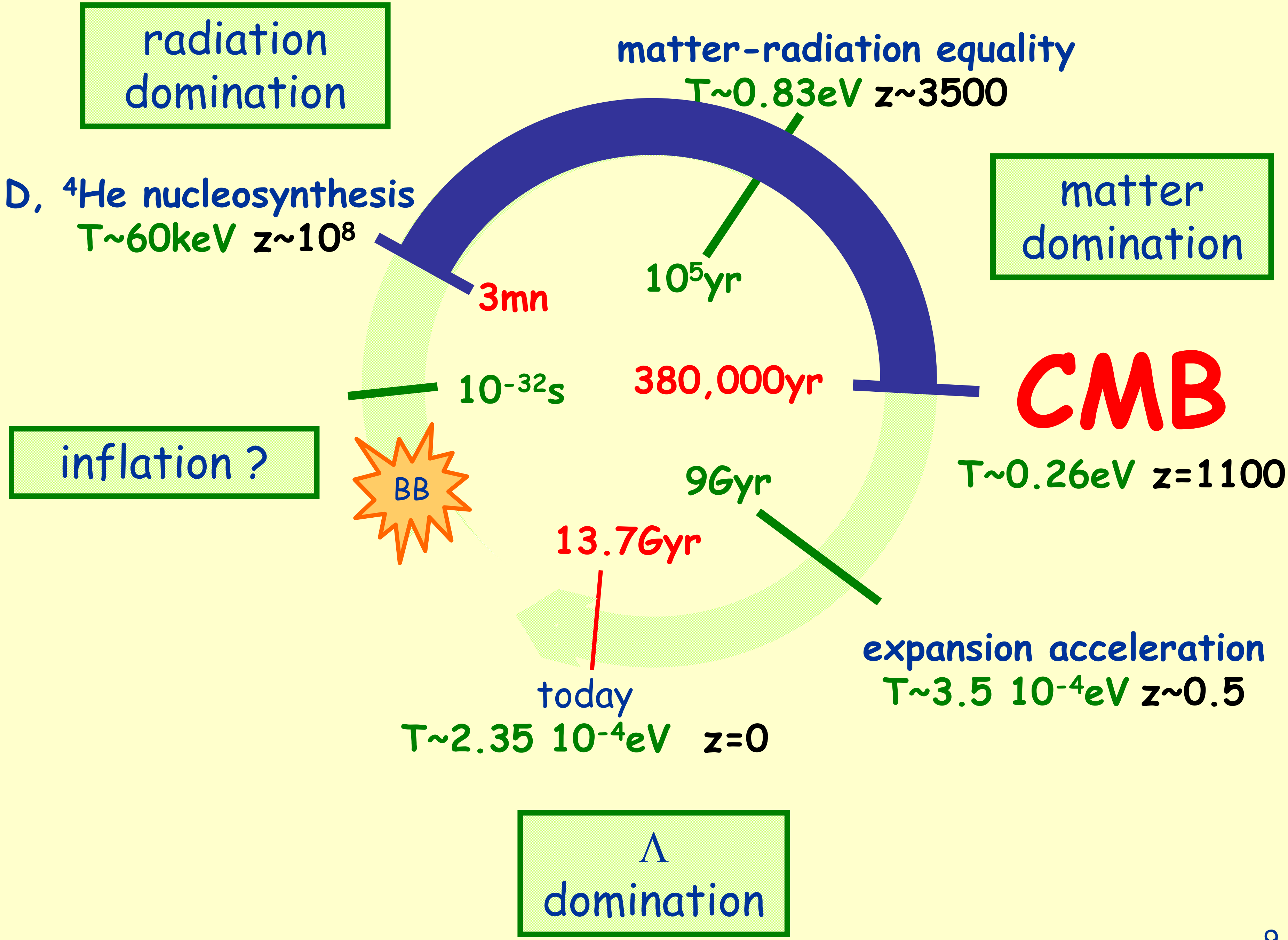
M. Kowalski et al., 2008, ApJ, 686, 749

D. Brout et al., 2022, arXiv:2202.04077

$\Omega_m^0 = 0.316^{+0.005}_{-0.008}$ $(\delta_{stat} \oplus \delta_{syst})$

$w = -0.978^{+0.024}_{-0.031}$ ⇨ Λ OK


radiation domination
matter-radiation equality
T~0.83eV z~3500
D, ⁴He nucleosynthesis
T~60keV z~10⁸
matter domination
3mn
10⁵yr
10⁻³²s
380,000yr
CMB
inflation ?
BB
9Gyr
T~0.26eV z=1100
13.7Gyr
today
T~2.35 10⁻⁴eV z=0
expansion acceleration
T~3.5 10⁻⁴eV z~0.5
Λ domination


radiation domination
matter-radiation equality
T~0.83eV z~3500
matter domination
D, ^{4}He nucleosynthesis
T~60keV z~10^8
3mn
10^5yr
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380,000yr
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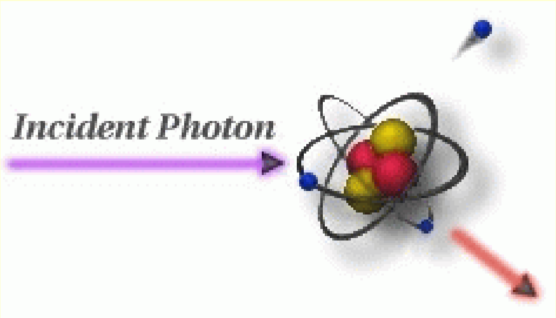
expansion acceleration
T~3.5 10^{-4}eV z~0.5
today
T~2.35 10^{-4}eV z=0
Λ domination

The plasma after primordial nucleosynthesis

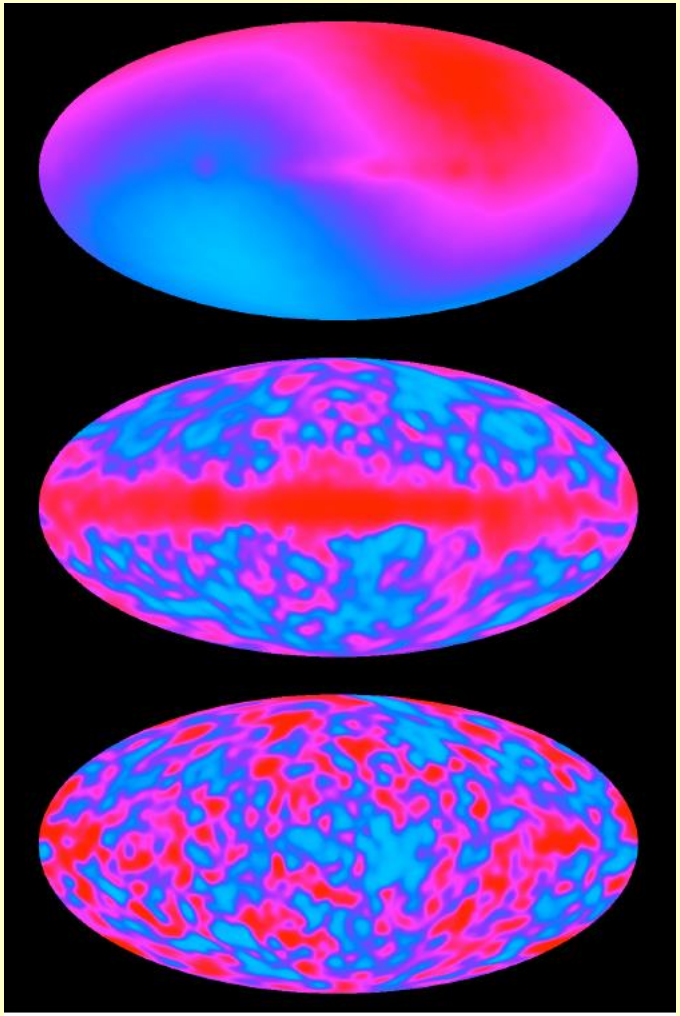
- γ and **e**, **nuclei** ($\equiv$ionized baryons) in thermal equilibrium



atom formation $\leftrightarrow$ Compton scattering : as long as $\Gamma_{Compton} > H(t)$

- end of equilibrium: T~0.26 eV (3,000K) $z \sim 1100 \equiv z_*$
  - neutral H, He atoms form (baryonic matter "recombination")
  - $\sigma_{\gamma\text{-matter}}$ drops, the Universe becomes transparent (matter-radiation "decoupling" after "last-scattering")
  - CMB radiation propagates freely with a blackbody spectrum, T decreases due to expansion (cf. lecture 1)

Sky map of the CMB

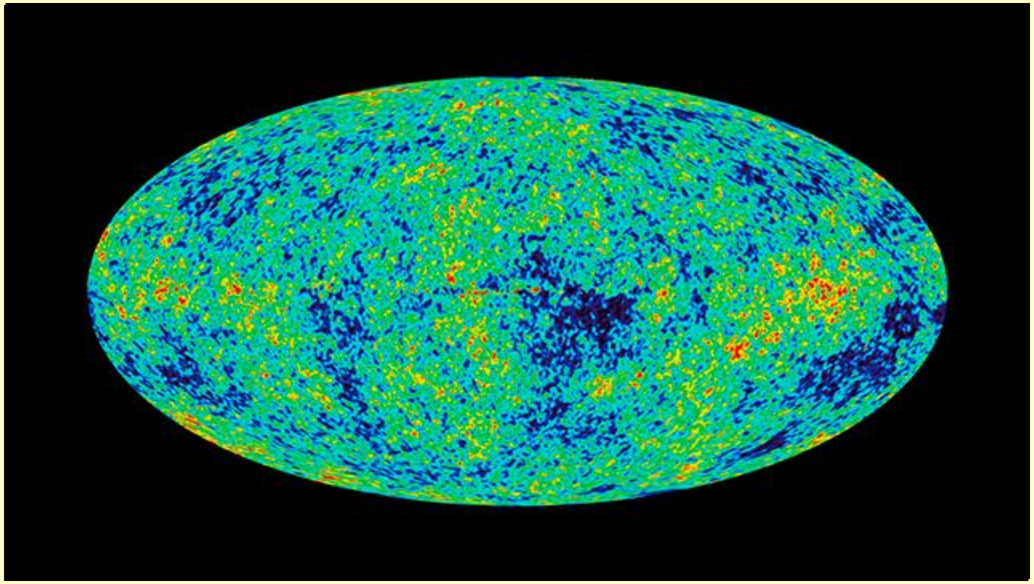


COBE (1993)

red: hotter blue: cooler

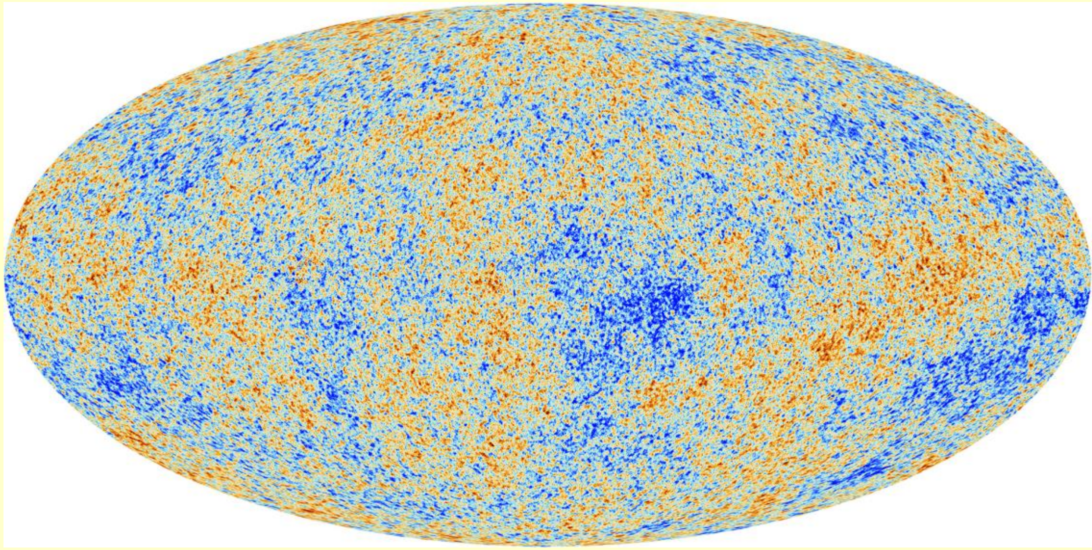
- <T> subtracted: dipole anisotropy (relative Earth/CMB motion) is visible.
- Dipole subtracted : Milky Way emission clearly visible
- Milky Way emission subtracted: primordial temperature fluctuations are visible => density fluctuations in the primordial plasma

COBE (1993) WMAP 7 years (2008)



Sky map, all foregrounds subtracted

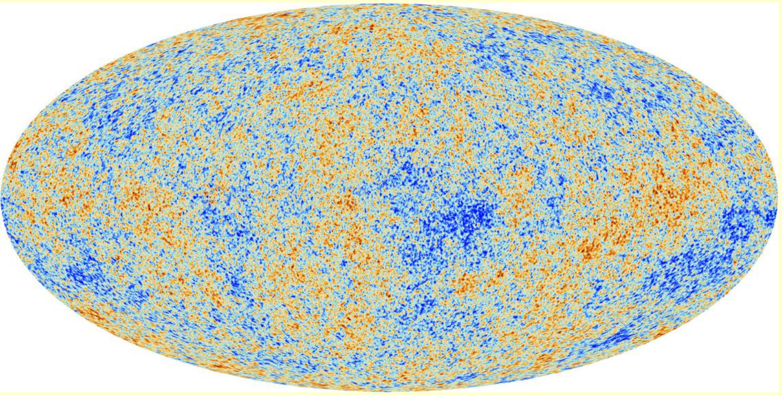
Planck (2013)



- CMB: anisotropies are very small:

$$\Delta T \sim 18\mu K \Rightarrow \Delta T / T \sim 10^{-5}$$

@WMAP and Planck web sites



Analysis of T anisotropies

- Angular fluctuation spectrum:

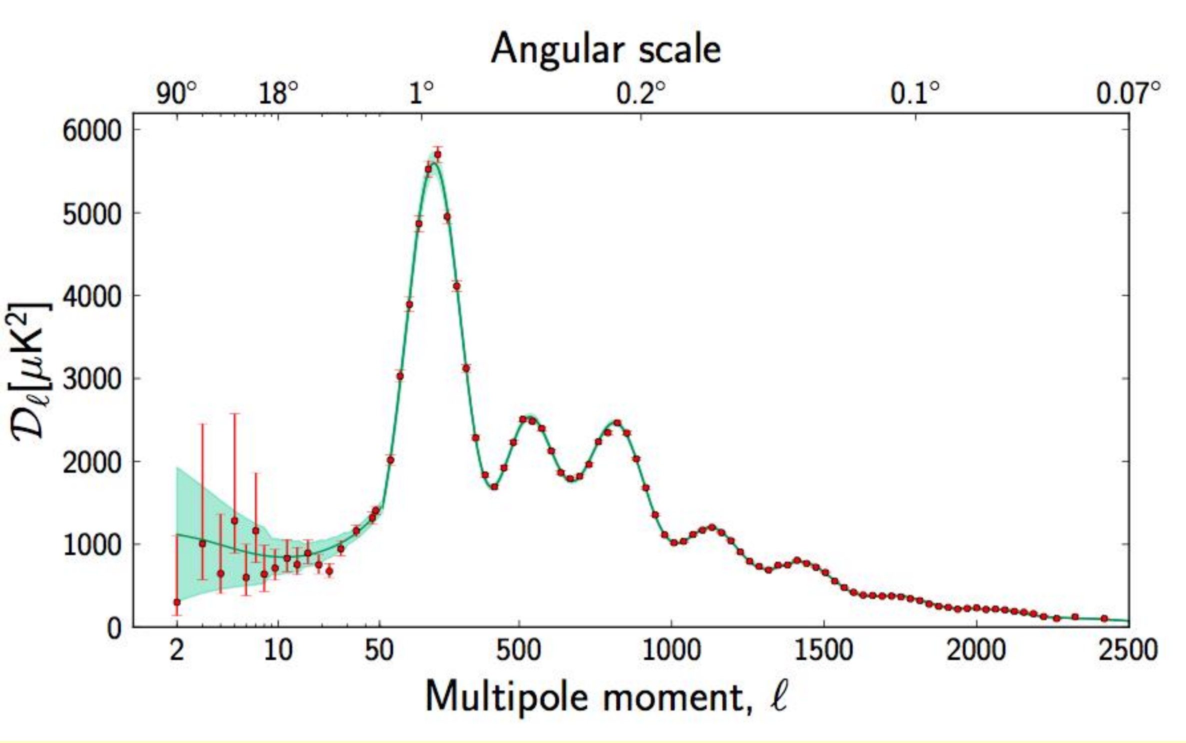
strength of T fluctuations (hot and cold spots) vs angular size of the sky patch on which the measurement is made

- First peak:
  preferred angular size of ~1° ($l_{1st\ peak}$~200)

$$Dq \approx \frac{p}{l} \approx \frac{s_*}{D_*}$$

s_* = distance traveled by sound since t=0 (sound horizon)

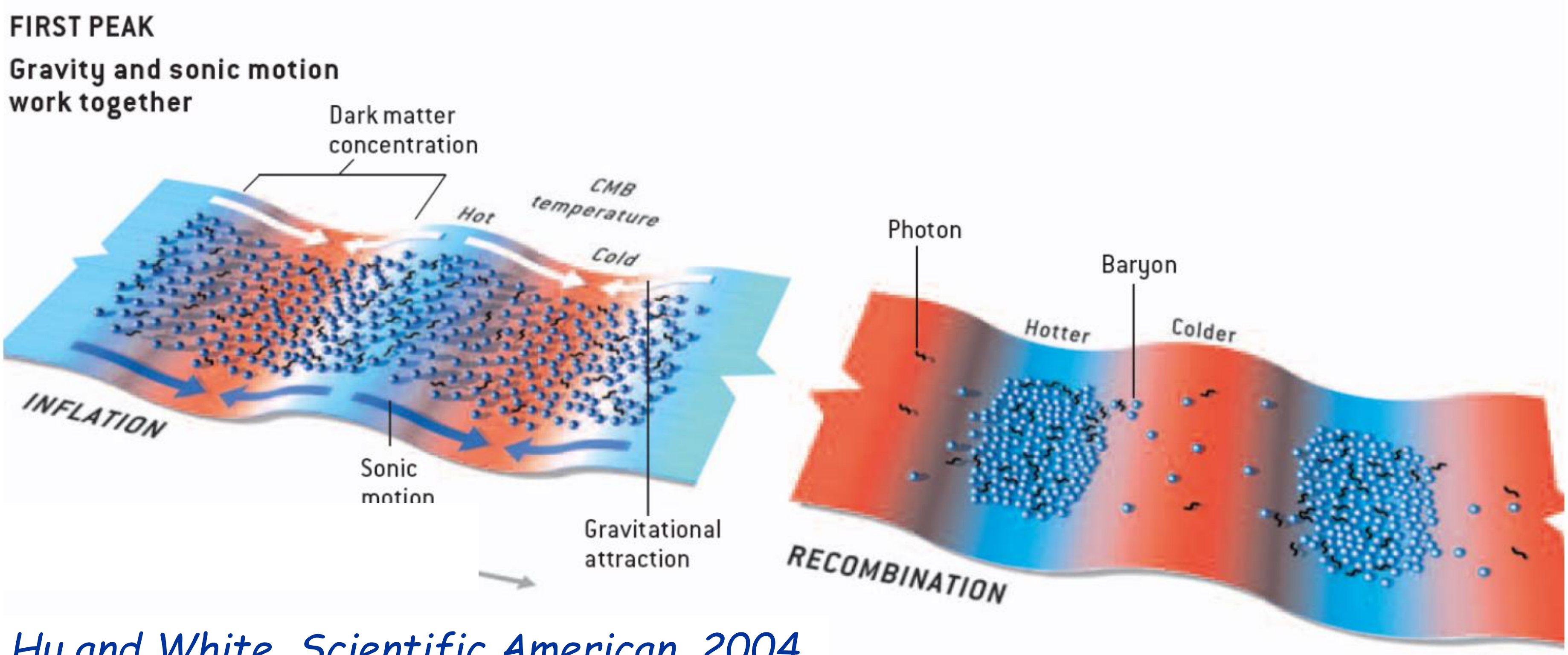
D_* = comoving distance to z_* (angular diameter distance)



Planck (2013)

Origin of temperature anisotropies

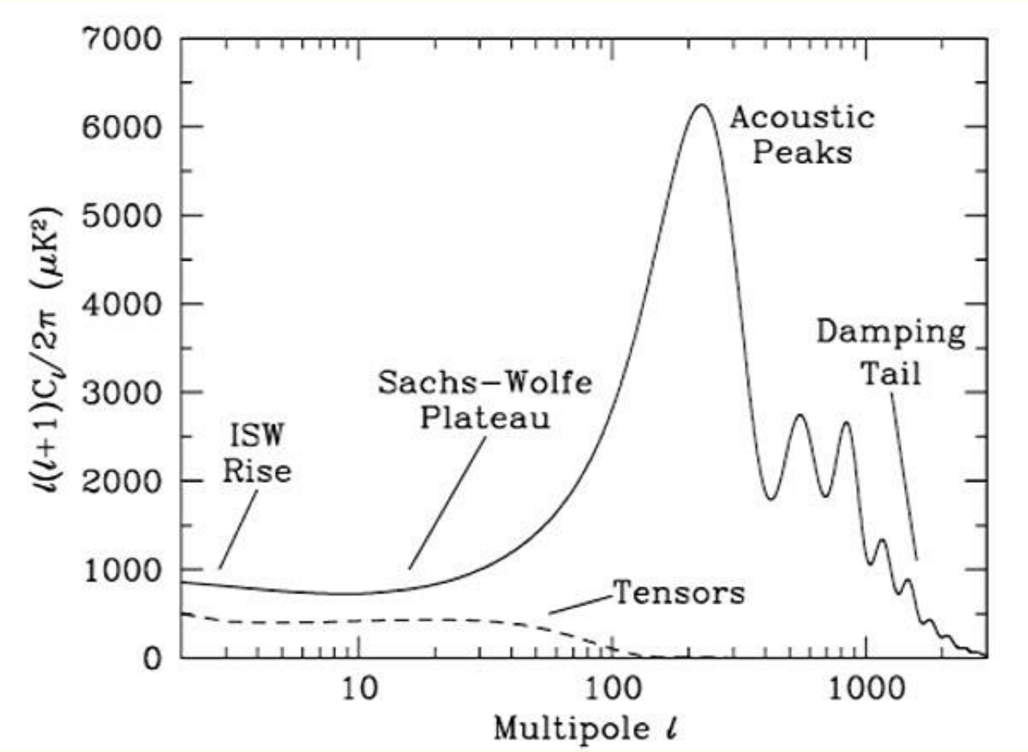
- dark matter collapse increases over-densities, making the photon-baryon plasma to oscillate into and out of these over-densities : 'acoustic oscillations' in primordial plasma
- At decoupling: oscillation pattern is frozen ⇒ imprint in CMB spectrum (and matter spectrum)



© Hu and White, Scientific American, 2004

Features of temperature anisotropy spectrum

- variations in the density or velocity of the plasma at the last scattering surface (pressure waves): 'acoustic' peaks
- variations in the gravitational potential at the LSS or along the photon path: low multipole plateau (large scales)



propagation speed of pressure wave in primordial plasma

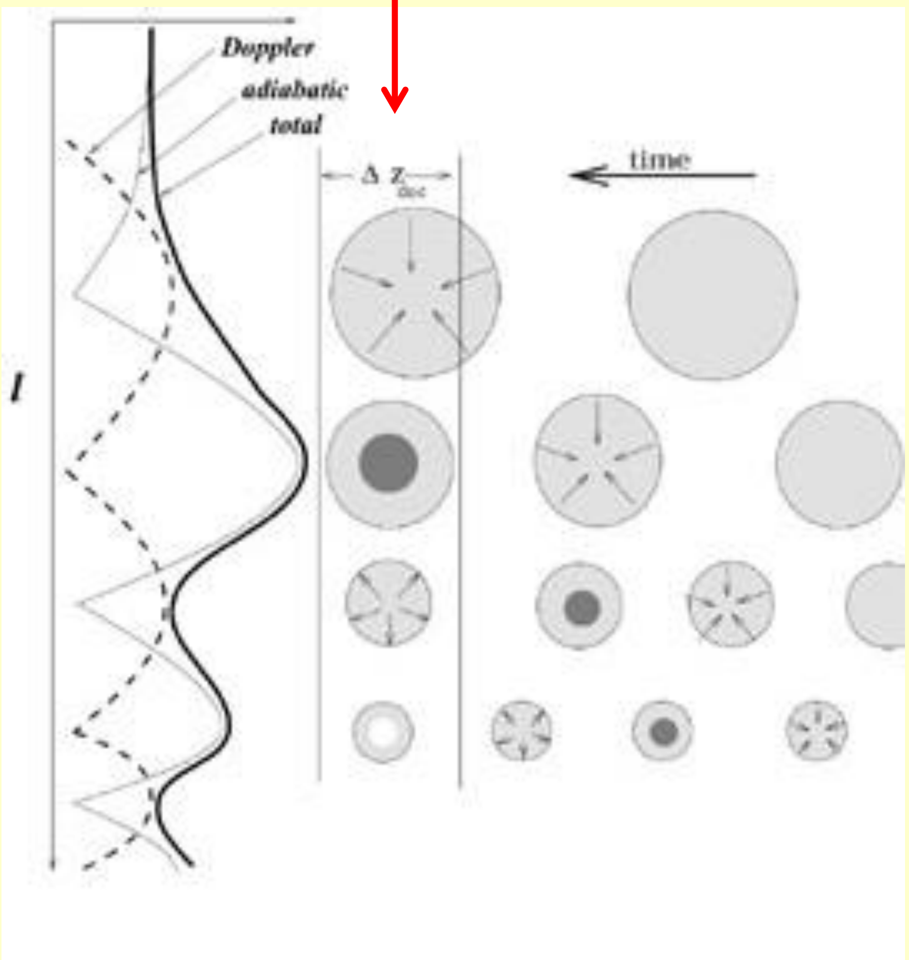
$$v \approx c/\sqrt{3}$$

<u>1st peak</u> : s_* = distance traveled by 'sound' since t=0 until decoupling (sound horizon)

More on oscillation peaks and troughs

CMB spectrum

decoupling



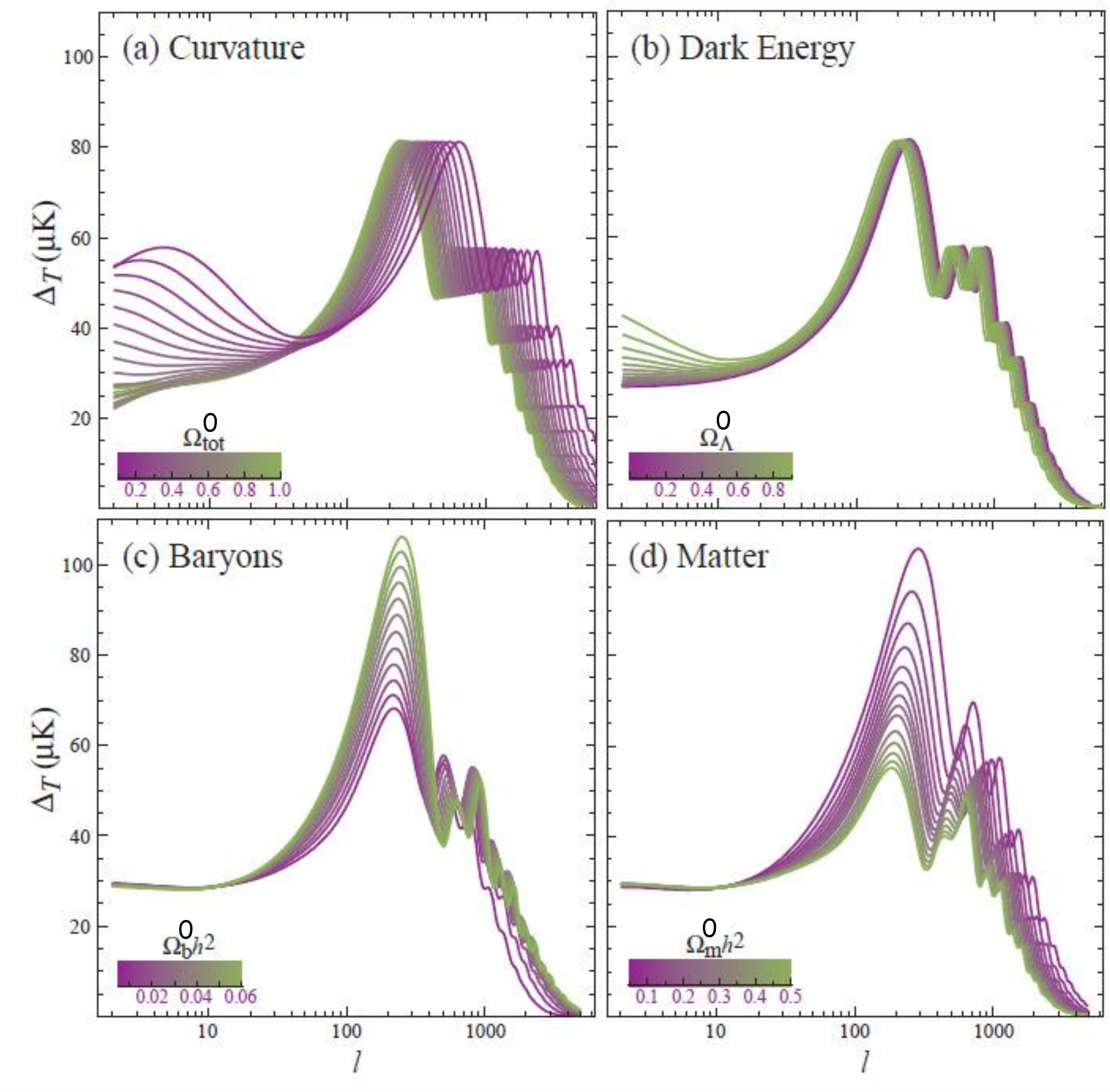
Oscillations of fluctuations at decoupling:

- largest scale fluctuation: maximum velocity
- smaller scale fluctuation: compression and density at maximum : 1st peak
- even smaller scale: expanding, maximum velocity, 1st trough
- smallest one: maximal rarefaction: 2nd peak

⇒ density extremum = peak   velocity maximum = trough

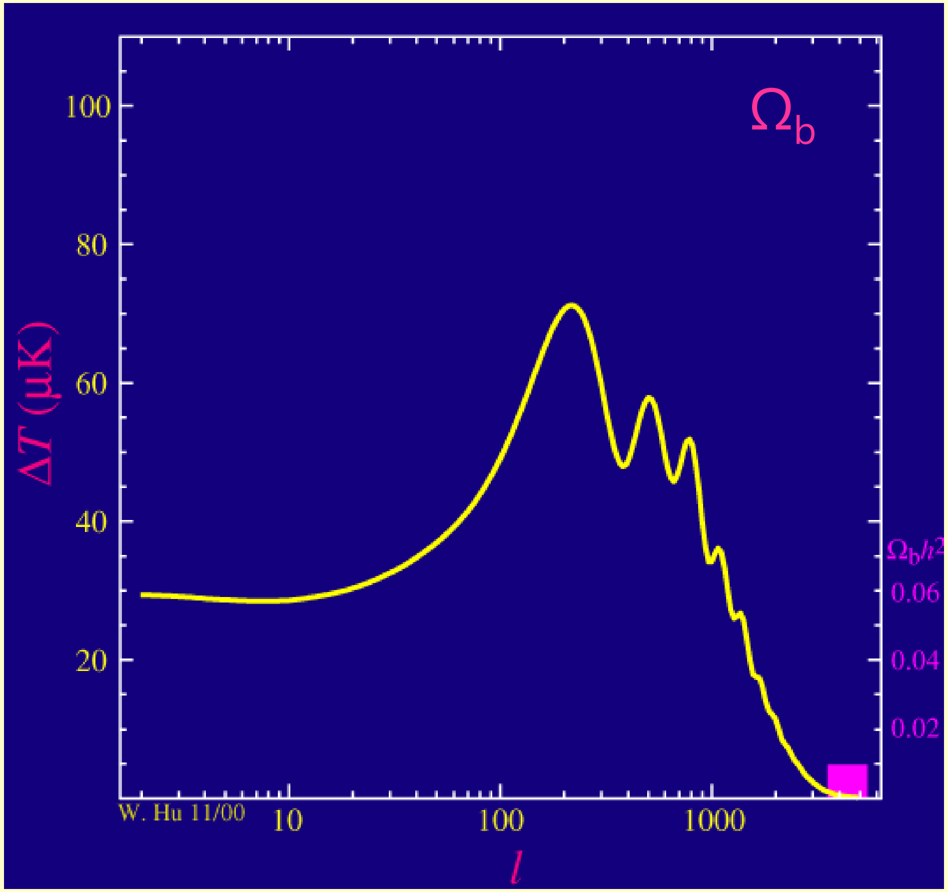
Sensitivity to cosmology parameters

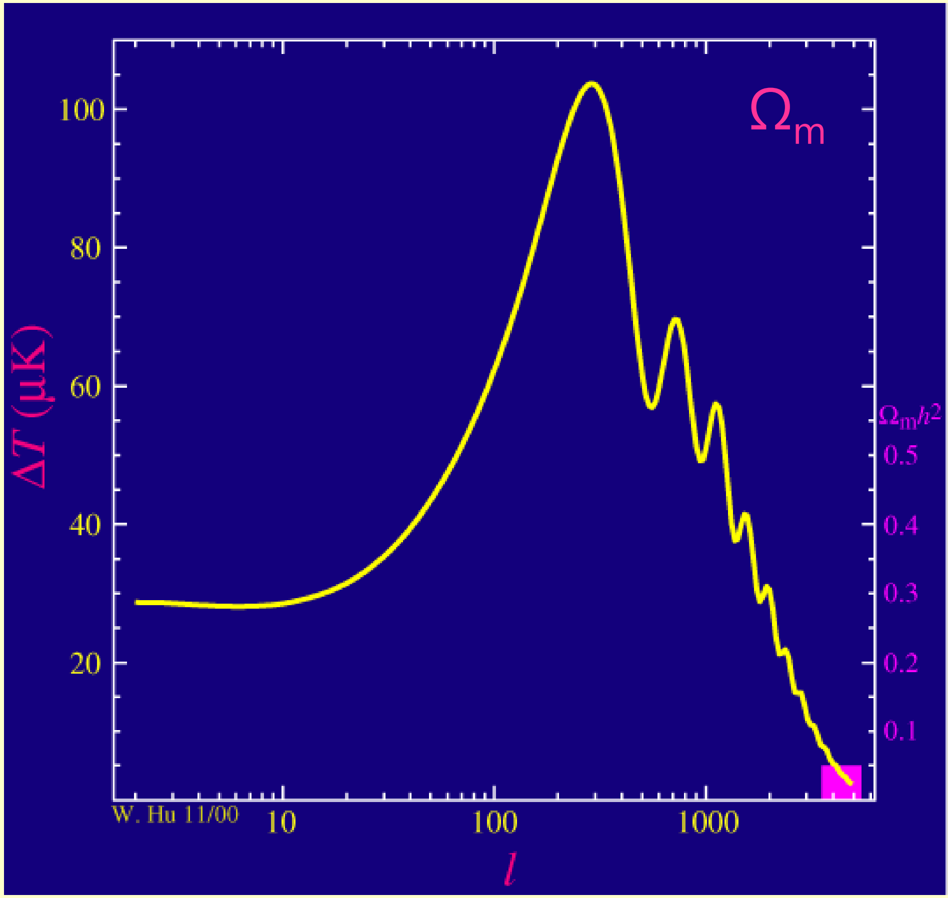
- Ω^0_m from 1st peak position and height
- Ω^0_b from 2nd to 1st peak ratio



Hu and Dodelson, 2002, ARAA 40, 171

Sensitivity to cosmology parameters





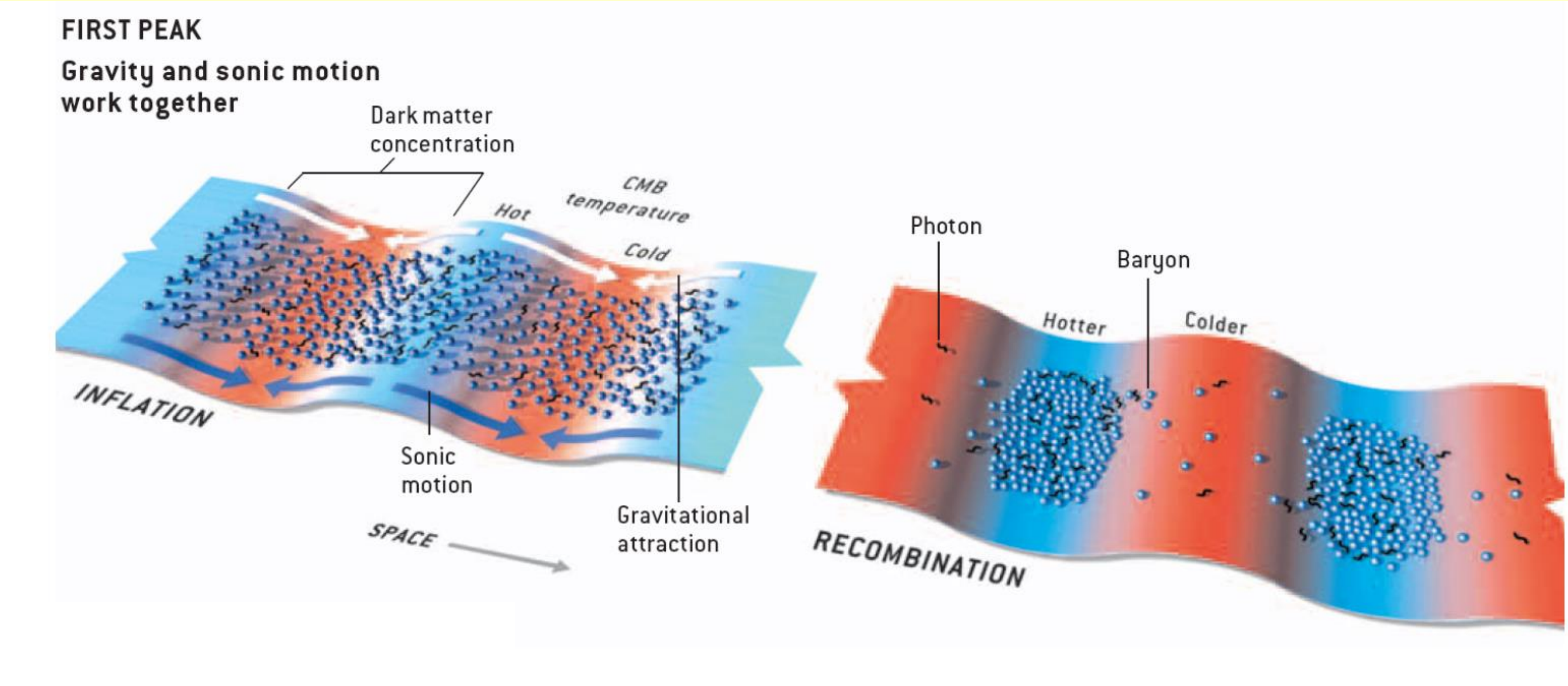
➔ Ω_b^0 from 2nd to 1st peak ratio

➔ Ω_m^0 from 1st peak position & height

@ W. Hu CMB tutorials e.g. http://background.uchicago.edu/~whu/metaanim.html

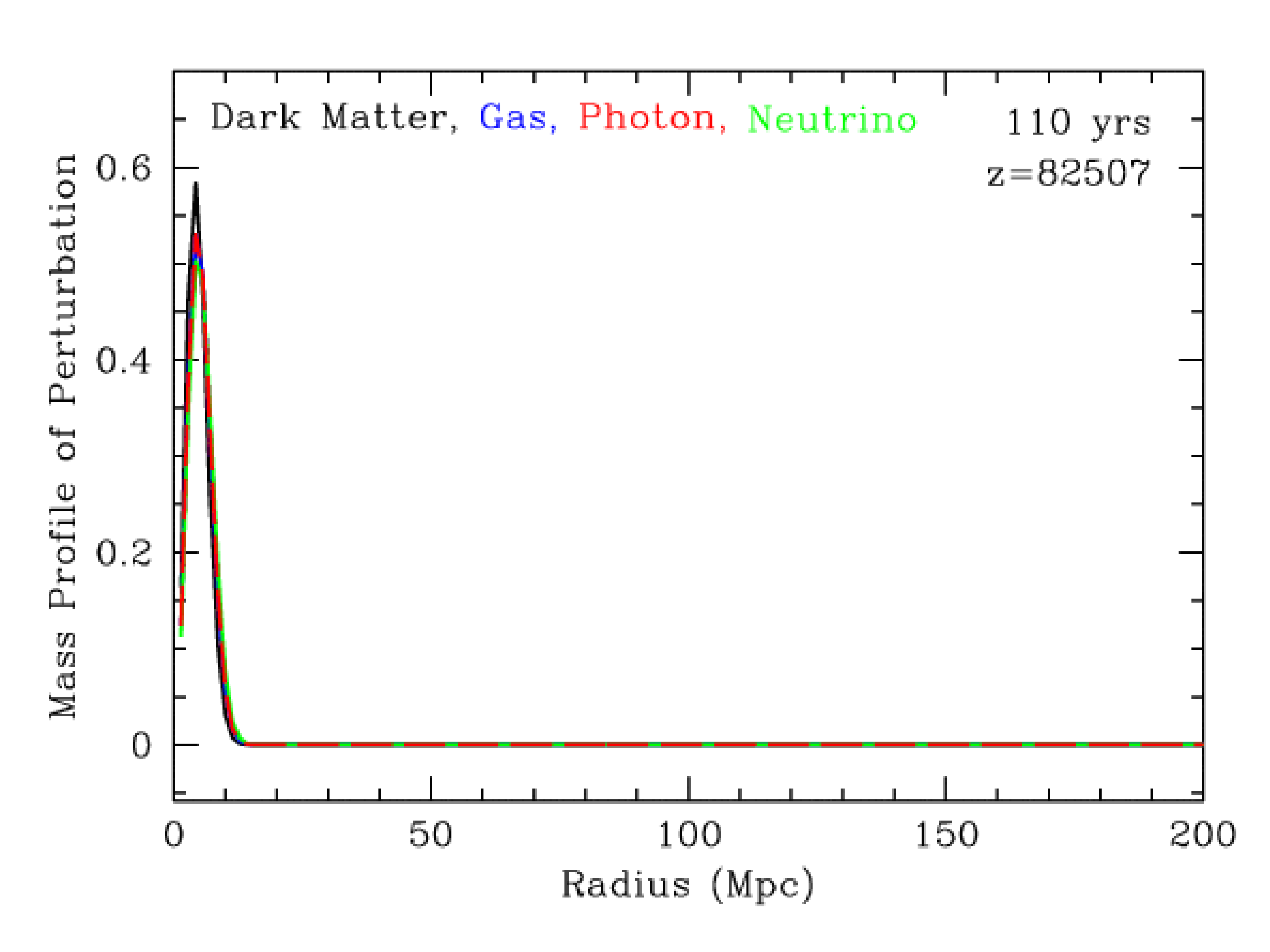
Baryon acoustic oscillations

- in primordial plasma (γ, e, nuclei) : acoustic oscillations
- at decoupling: oscillation pattern is frozen $\Rightarrow$ imprint in matter spectrum (as in CMB spectrum)

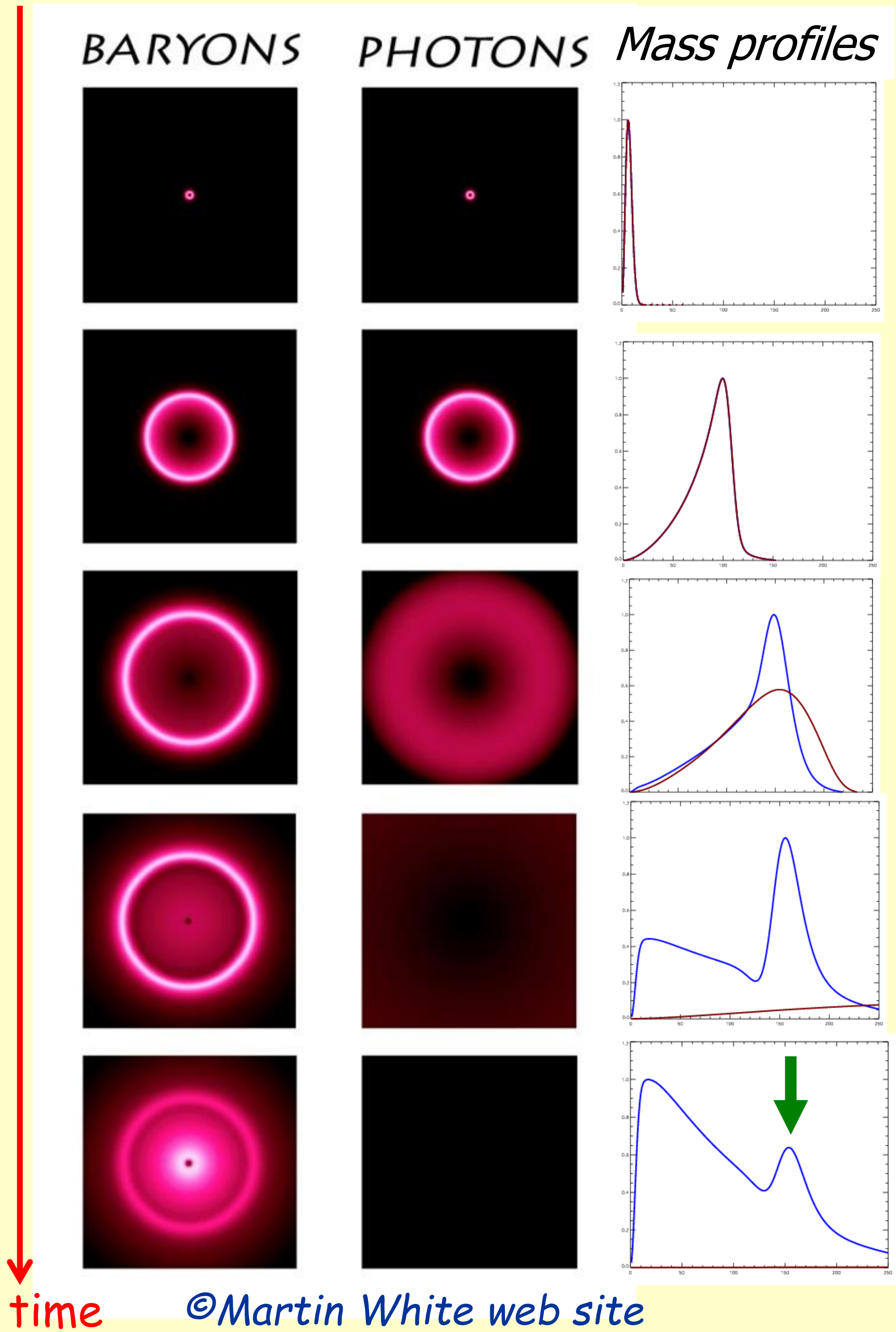


© Hu and White, Scientific American, 2004

Evolution of a single overdensity with time



http://online.kitp.ucsb.edu/online/primocosmo-c13/eisenstein/vid/acoustic_anim.gif



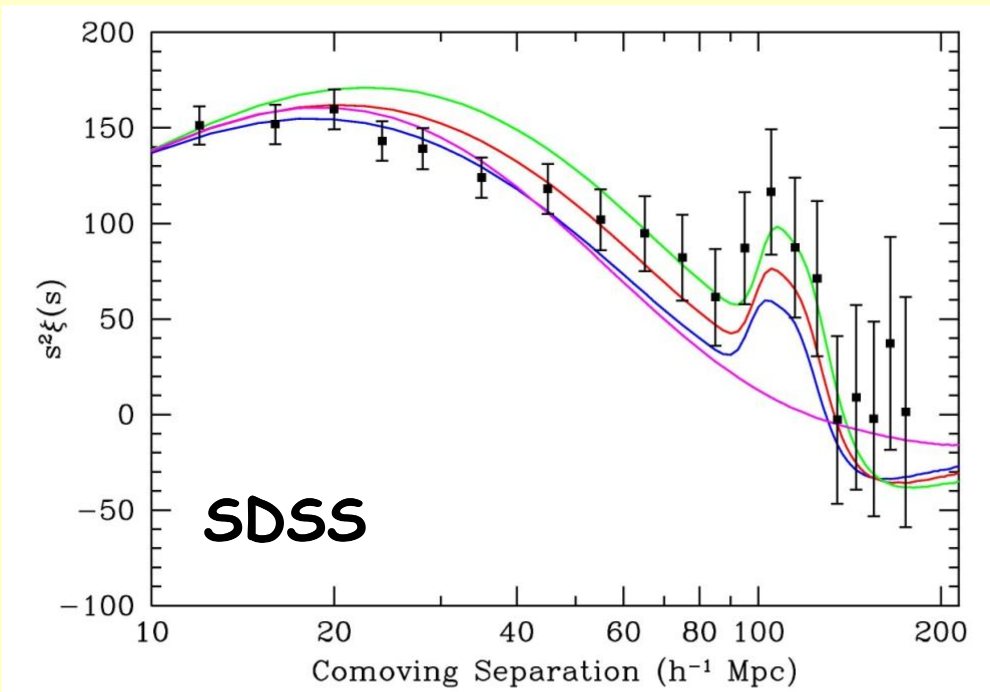
- one single overdensity in the plasma, moving outward
- γ and baryons move together, for 10^5 years
- recombination: γ decouple from baryons and stream away, leaving the baryon peak stalled
- γ ~uniform, baryons remain overdense in a shell ~150Mpc in radius (sound horizon)
- matter attracted by central DM pot. well -> residual shell at 150Mpc, observable today in the matter distribution

Galaxy distributions

First evidence for BAO signal: 2005

D.Eisenstein et al., 2005, ApJ, 633, 560

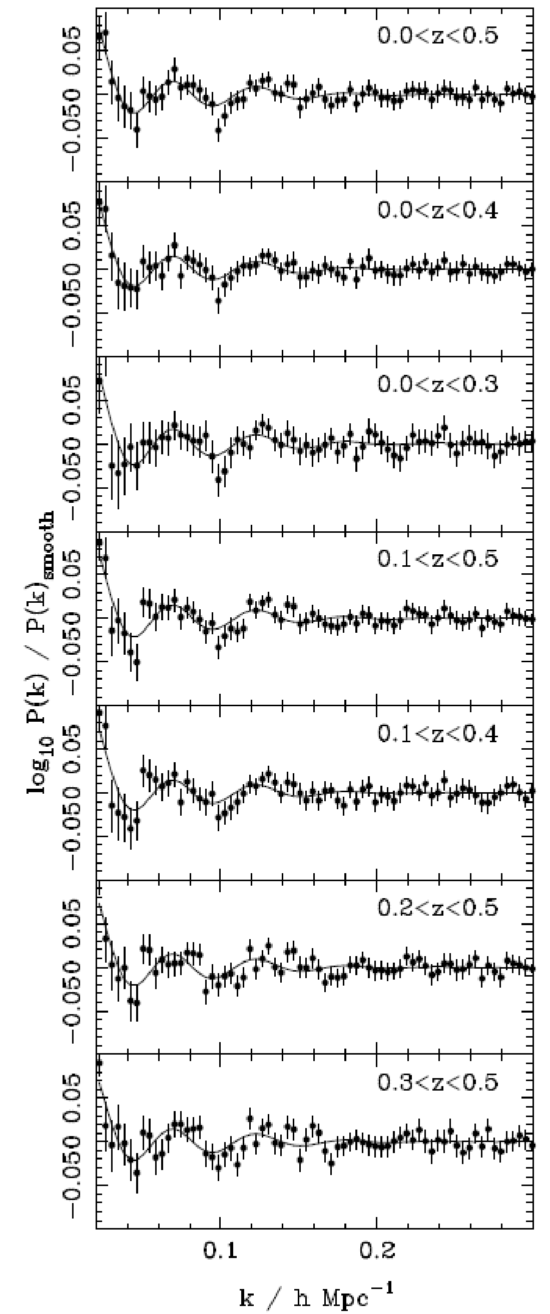
Galaxy correlation function



preferred comoving separation ~150Mpc

(h~0.7)

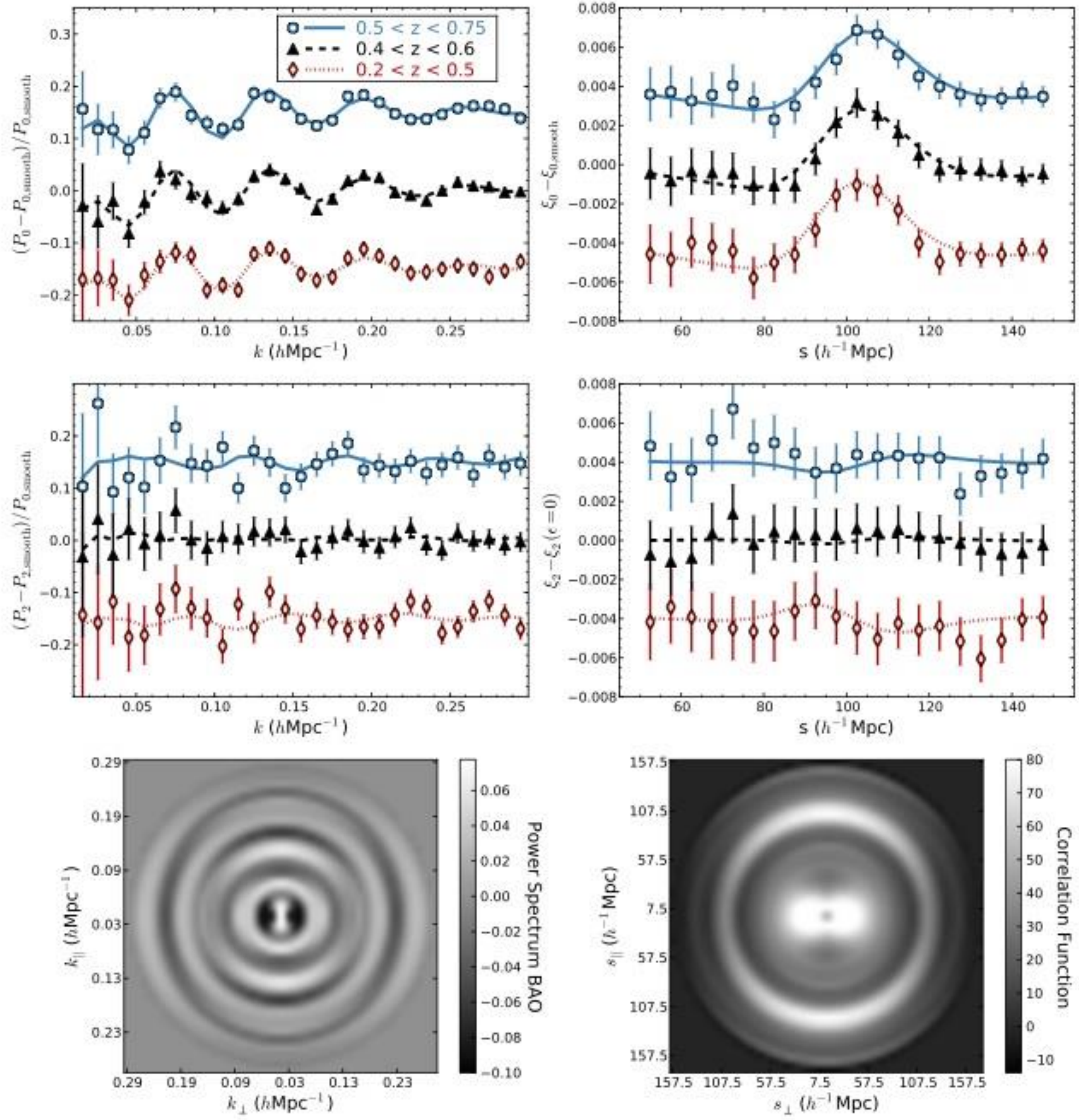
Galaxy power spectrum



W.Percival et al., 2010, MNRAS, 401, 2148

Final SDSS-III results

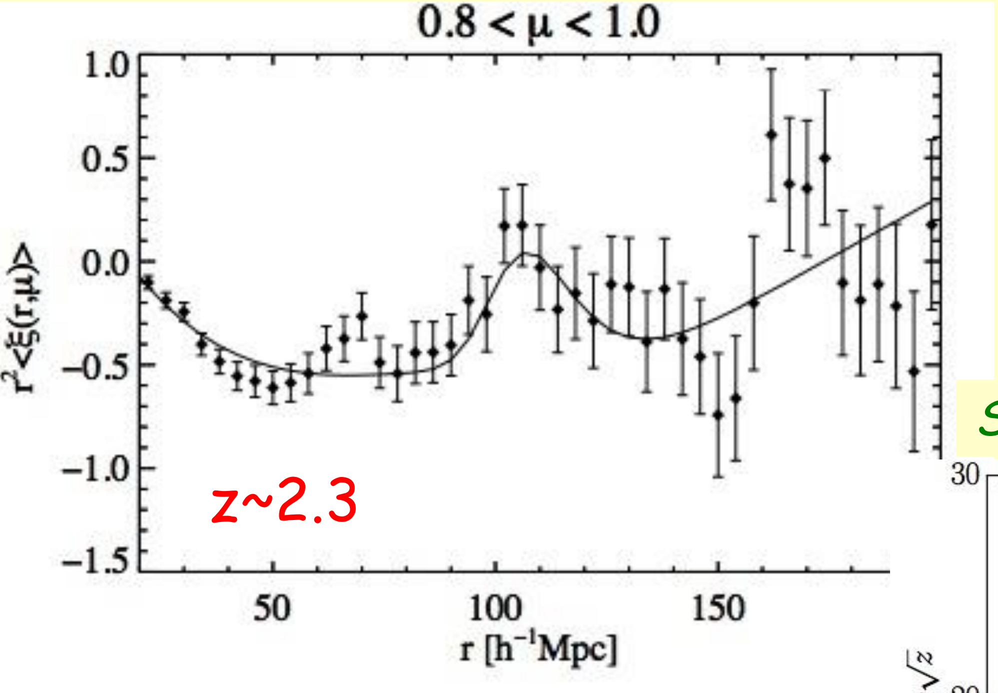
S. Alam et al., 2017, MNRAS,470, 2617A



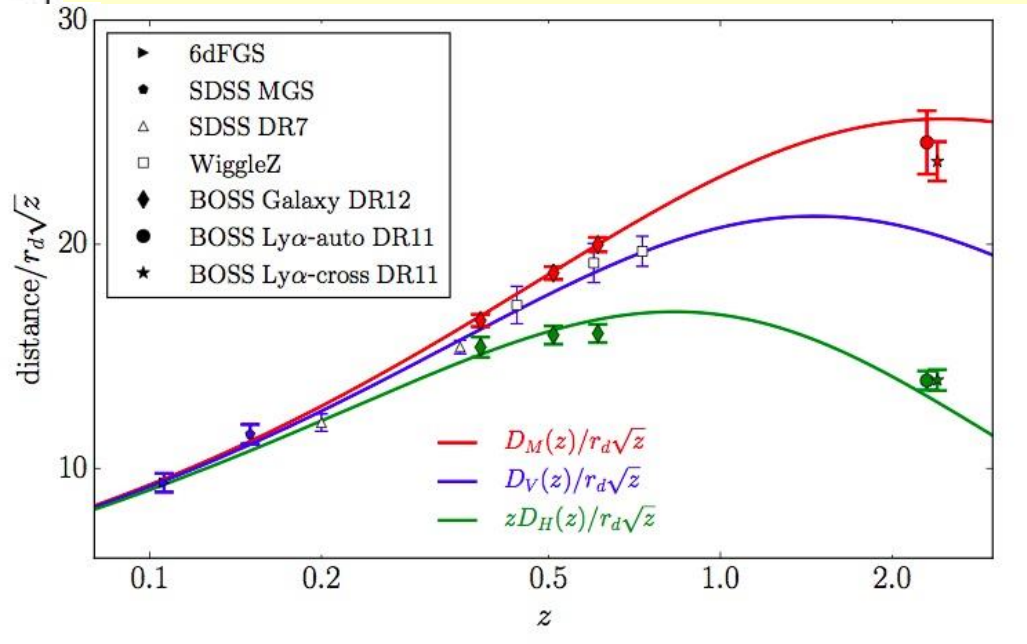
Beyond galaxies

2013: BAO signal detected in intergalactic H distribution (via absorption lines in quasar spectra)

N. Busca et al., 2013, A&A, 552A, 96B



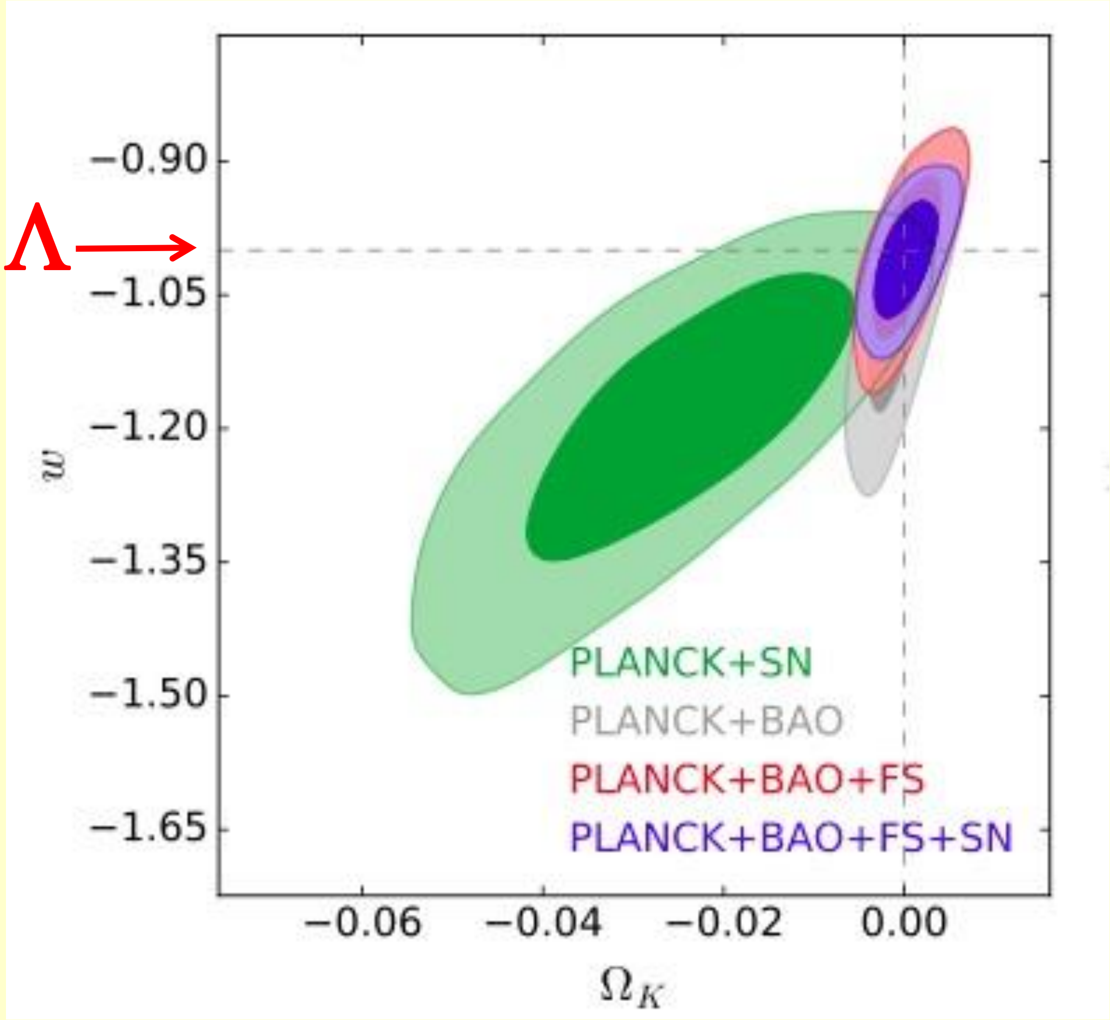
S. Alam et al., 2017, MNRAS,470, 2617A



2016: BAO signal seen in quasar distribution (in cross-correlation with Lyα signal)

Cosmological constraints

- Dark energy component of constant $w \equiv P/\rho$ (Λ <-> $w=-1$):



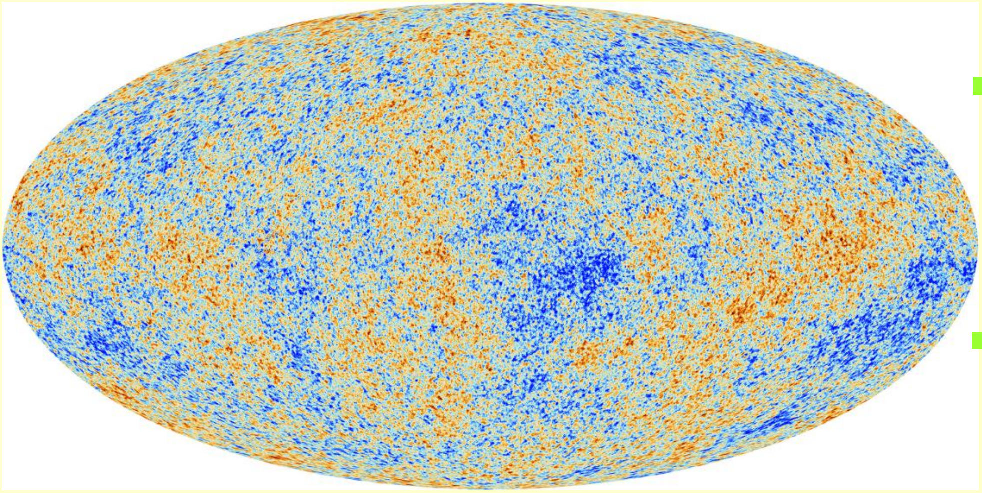
S. Alam et al., 2017, MNRAS,470, 2617A

CMB+BAO+FS+SNe:

Universe is flat ($\Omega_k \sim 0$) and

$w = -1.01 \pm 0.04$

($\delta_{stat} \oplus \delta_{syst}$)



Planck (2013), all foregrounds subtracted

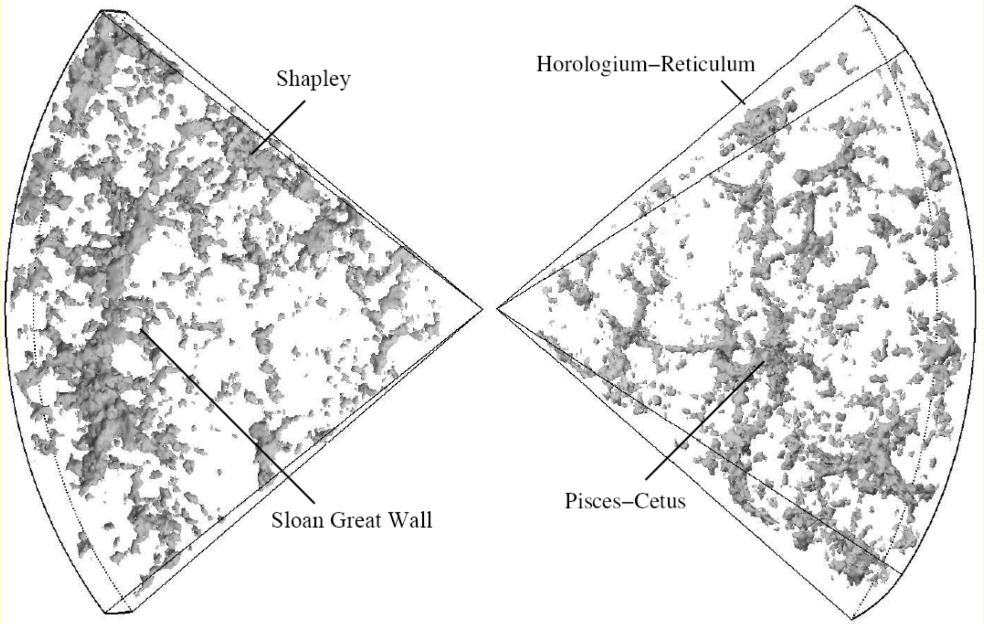
Observational facts

- CMB: very small anisotropies

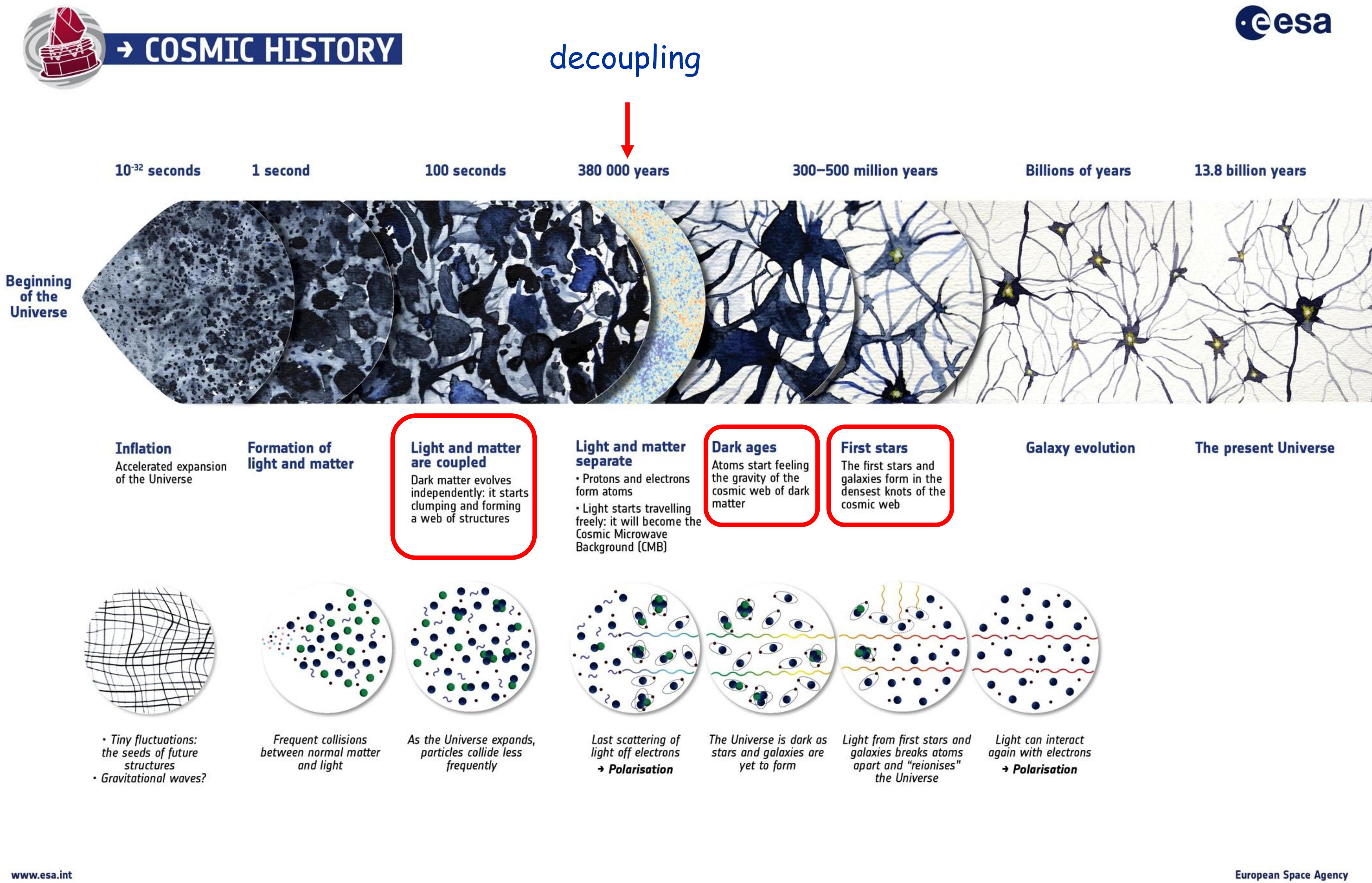
$$\Delta T / T = 10^{-5}$$

- matter density inhomogeneities, amplified by gravitation after decoupling → structures

- Large scale structures today: galaxies, clusters, superclusters, voids and filaments
- Formation of structures: cold dark matter mandatory

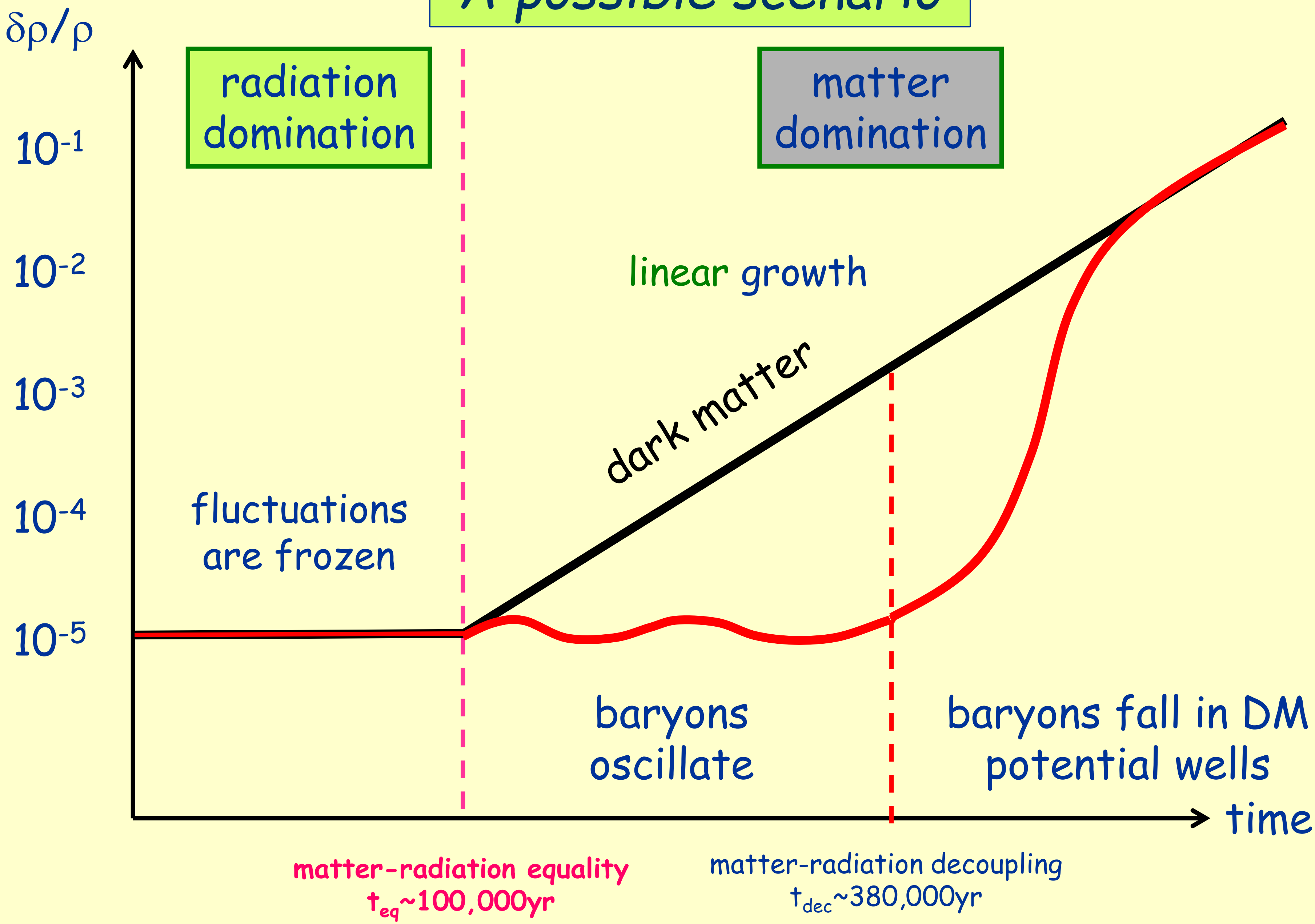


2dF Galaxy Redshift Survey, (2007)



→ COSMIC HISTORY
esa
decoupling
Beginning of the Universe
10^{-32} seconds
1 second
100 seconds
380 000 years
300–500 million years
Billions of years
13.8 billion years
Inflation
Accelerated expansion of the Universe
Formation of light and matter
Light and matter are coupled
Dark matter evolves independently: it starts clumping and forming a web of structures
Light and matter separate
• Protons and electrons form atoms
• Light starts travelling freely: it will become the Cosmic Microwave Background (CMB)
Dark ages
Atoms start feeling the gravity of the cosmic web of dark matter
First stars
The first stars and galaxies form in the densest knots of the cosmic web
Galaxy evolution
The present Universe
• Tiny fluctuations: the seeds of future structures
• Gravitational waves?
Frequent collisions between normal matter and light
As the Universe expands, particles collide less frequently
Last scattering of light off electrons
→ Polarisation
The Universe is dark as stars and galaxies are yet to form
Light from first stars and galaxies breaks atoms apart and "reionises" the Universe
Light can interact again with electrons
→ Polarisation
www.esa.int
European Space Agency

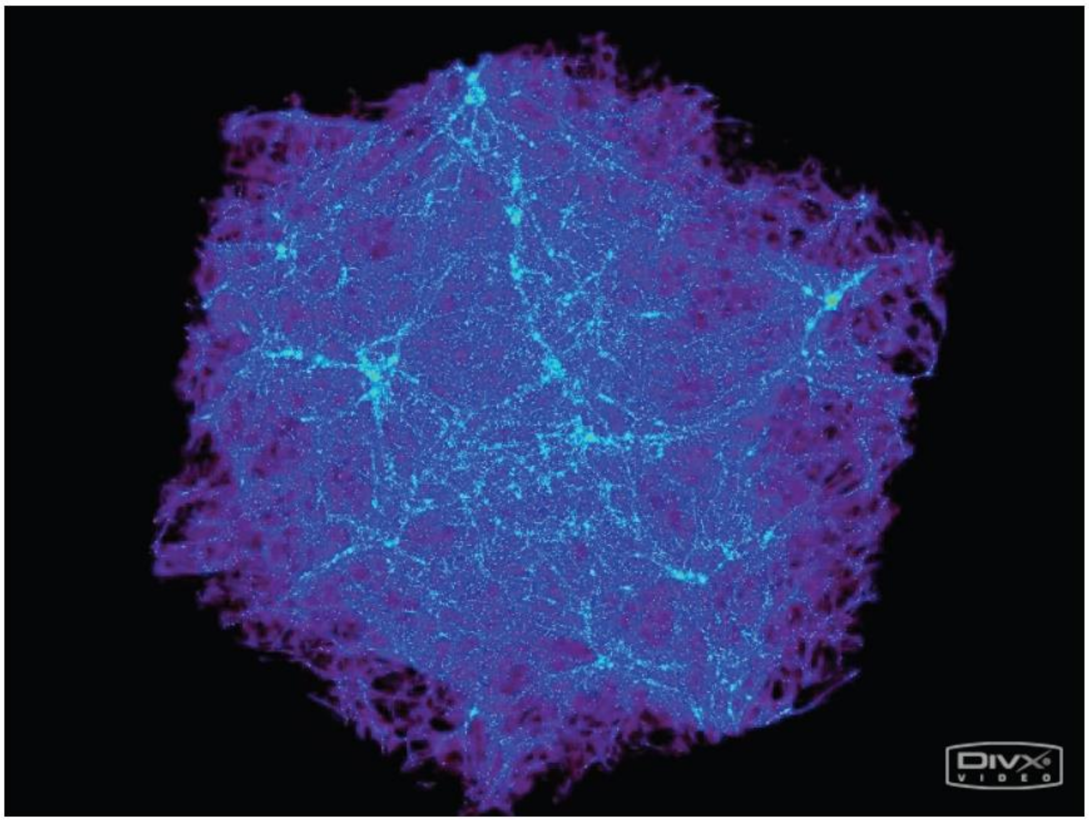
A possible scenario



Numerical simulations, examples

Needed to describe the non-linear regime of structure growth (galaxies, clusters….)

Mare Nostrum Simulation (Horizon Project)

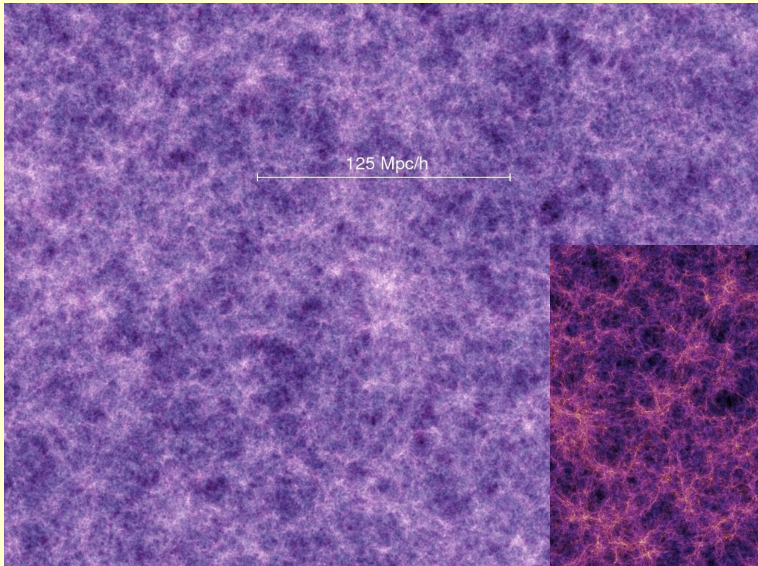


1024^3
50 Mpc/h
2048 processors

Gravity
+
hydro
+
stars
+
SN
+
metals

Numerical simulations, examples

z=18.3 (t=0.21 Gyr)

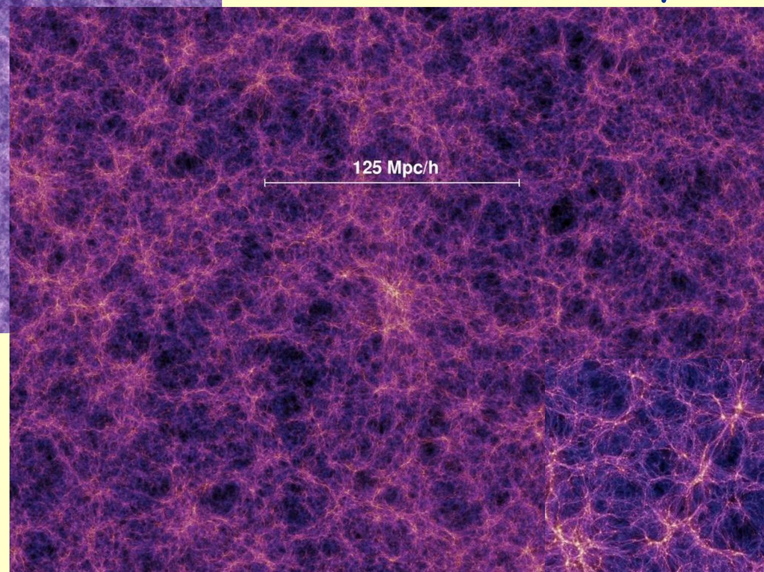


500 Mpc/h

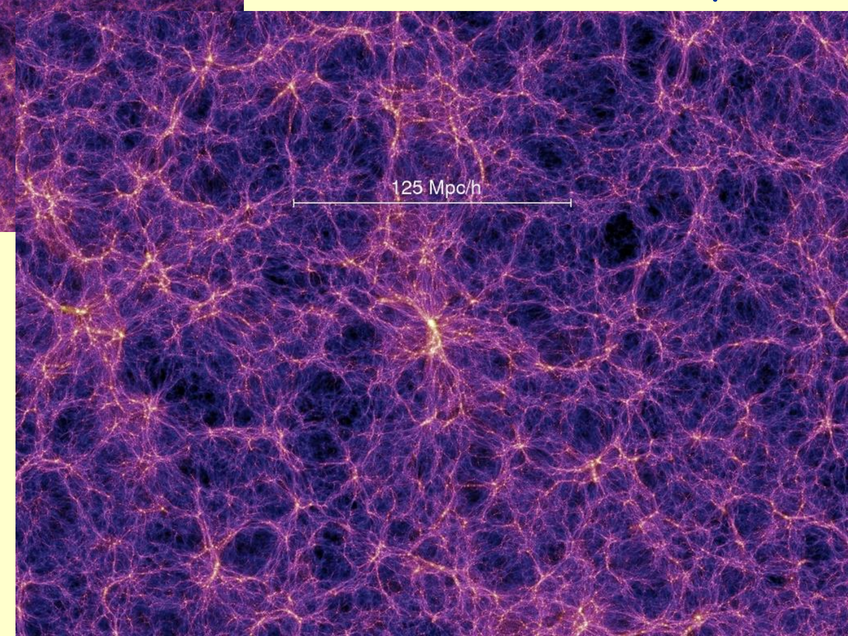
DM only

2160^3 particles

z=5.7 (t=1.0 Gyr)



z=1.4 (t=4.7 Gyr)



low density contrast

high density contrast:
structures

Millennium simulation project, Springel et al. (2005)

Structure formation ?

- Numerical simulations of large scale structure formation (down to galaxy dense halos) from cold dark matter :

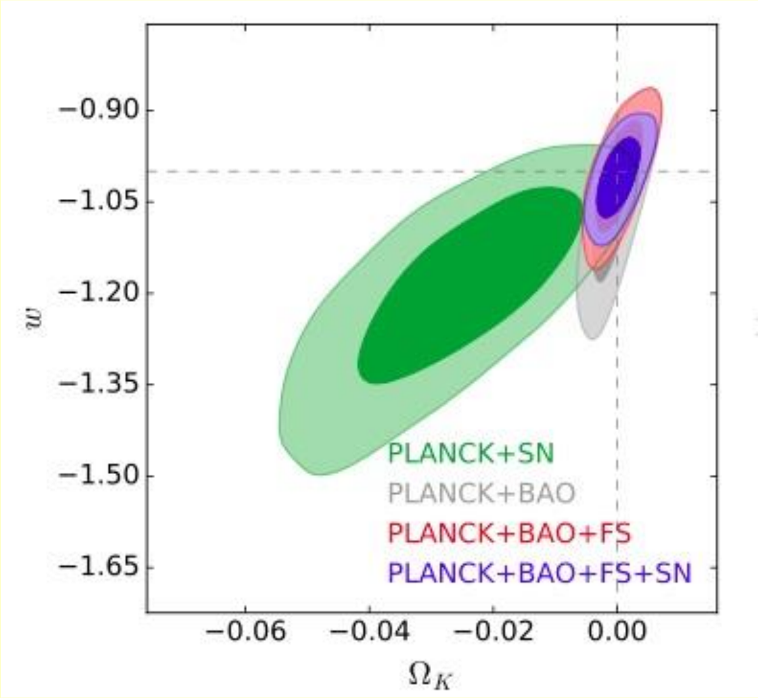
  voids and filaments (the cosmic web) well reproduced

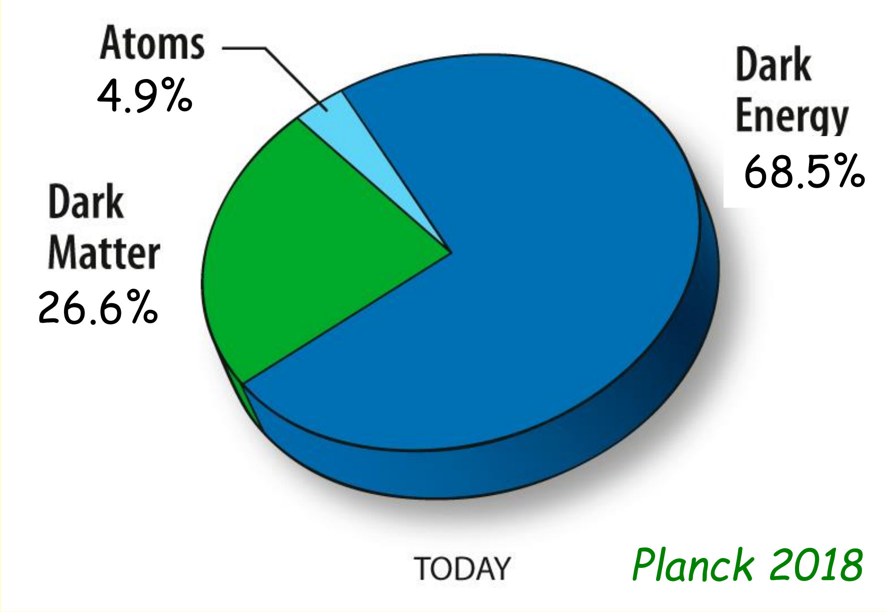
Evolution of matter distribution from numerical simulations

- Current status :
  - Large scale success: two-point correlation function and high z luminosity function correctly reproduced
  - Small scale issues: too many DM satellites expected, expected DM halo profile too cuspy in galaxy cores, galaxy rotation curves do not agree with data
  - By-product : link with particle physics through constraints on neutrinos from large scale structure data (N_ν, Σm_ν)

CONCLUSIONS (3)

- Cosmological measurements today: CMB, SNeIa, BAO.



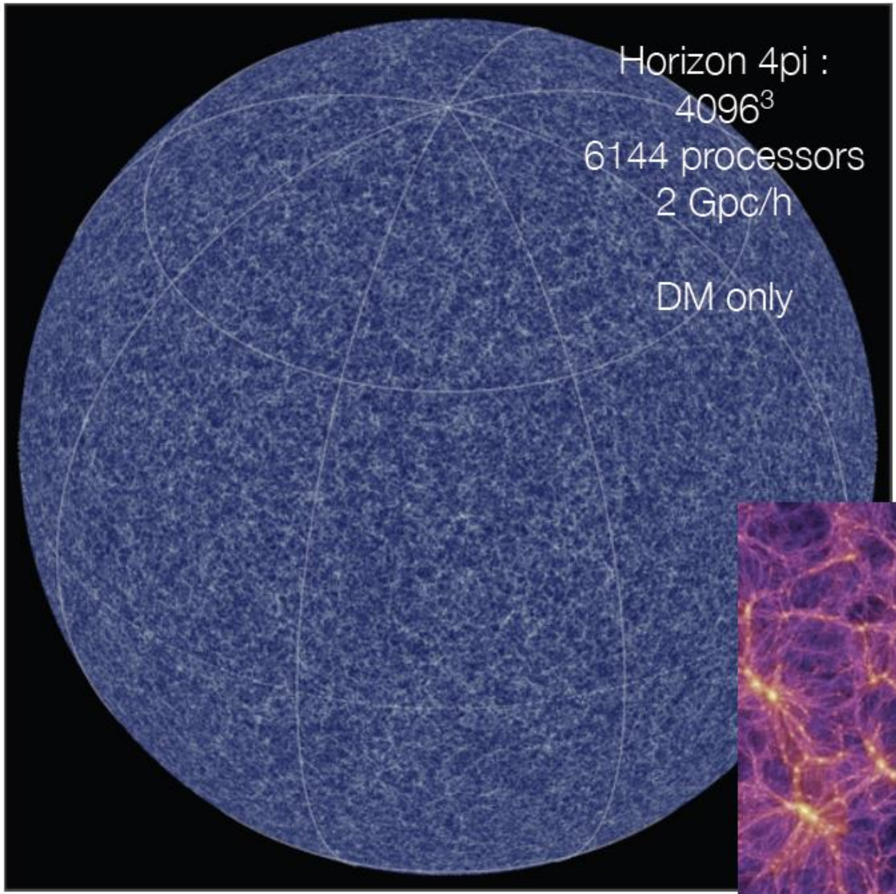


Concordance model = Λ_{CDM}

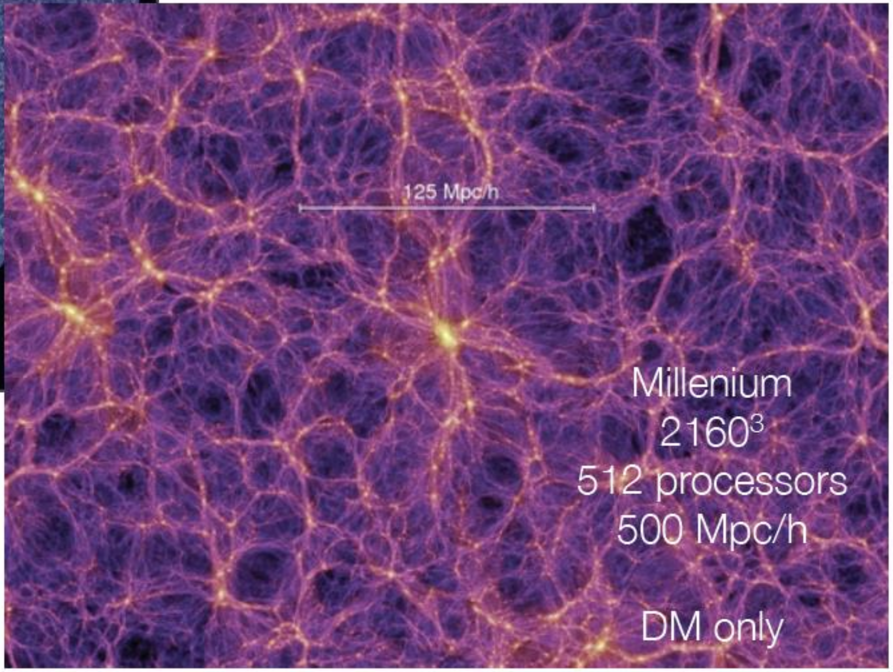
- Future: full power spectrum of ordinary matter, 3D tomography of dark matter with weak lensing, galaxy clusters
- Pending questions: origin of dark energy, understand structure formation at all scales, identify dark matter

BACK UP SLIDES

Numerical simulations, examples



Needed to describe the non-linear regime of structure growth (galaxies, clusters….)



B. Aubert, European Summer Campus, 2012

Numerical simulations, examples

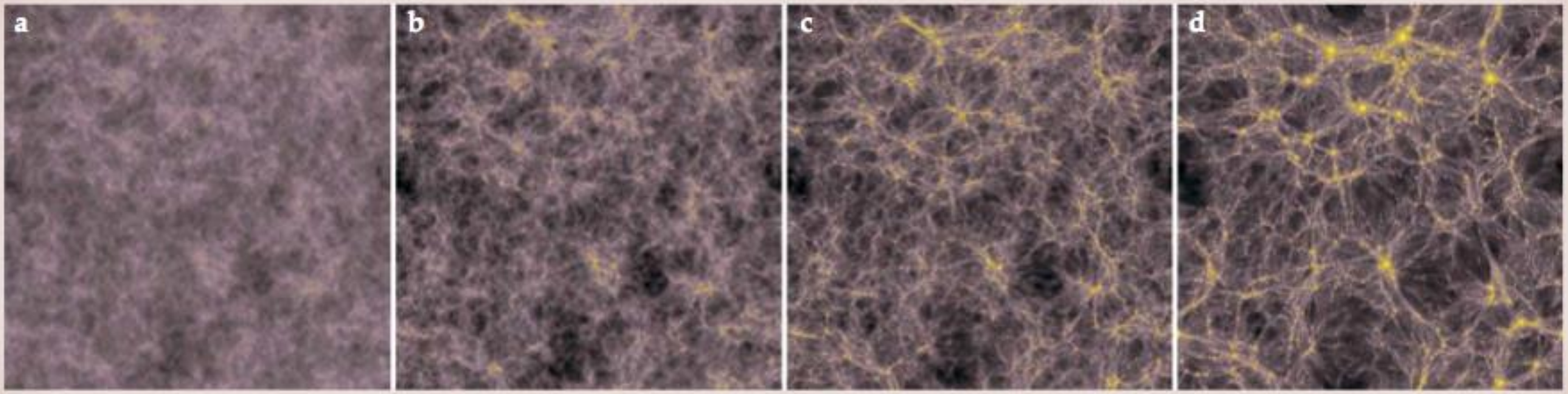
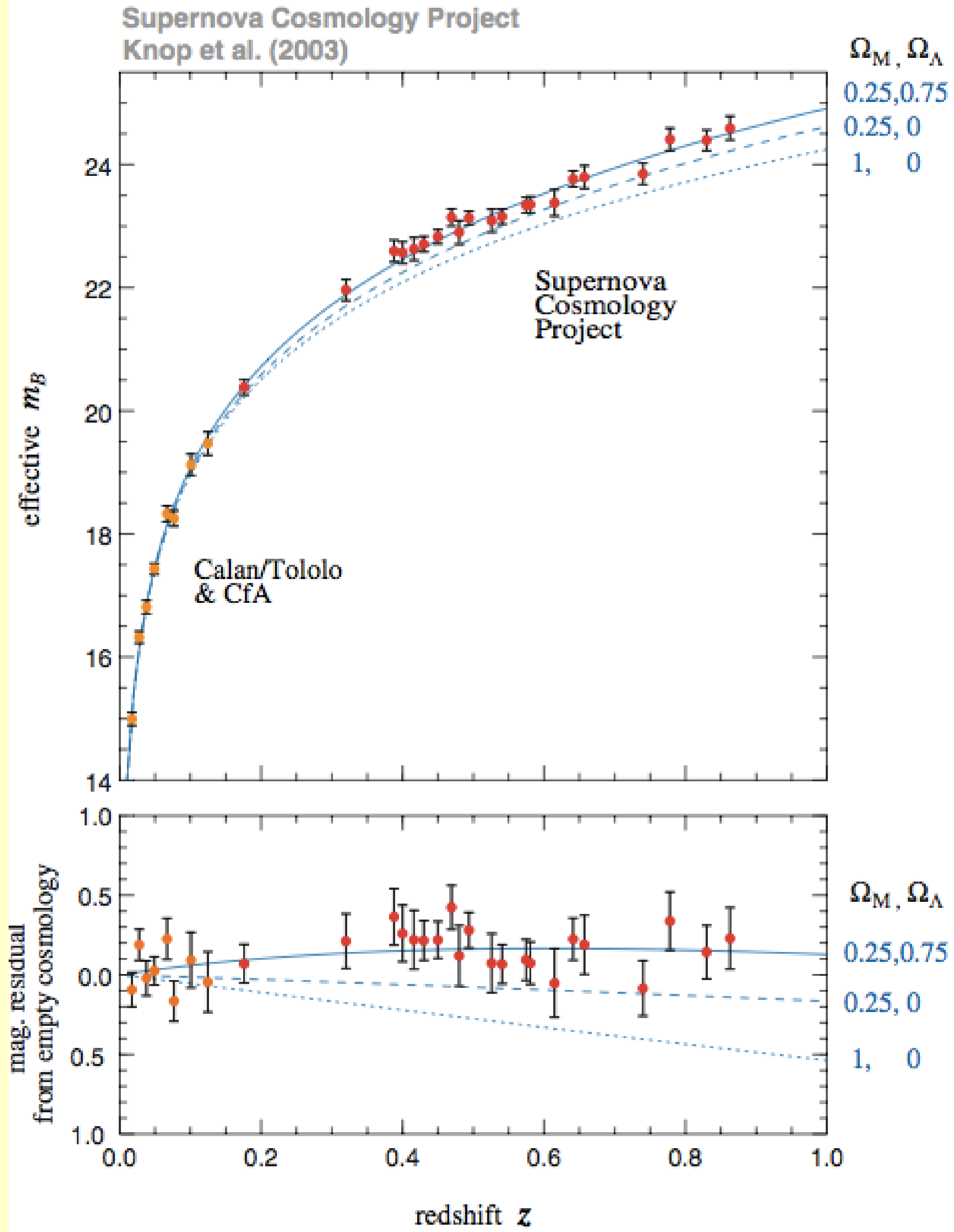


Figure 1. Computer simulation of the ever-increasing clustering of matter (dark plus baryonic) due to gravity in the post-plasma universe. Despite the overall Hubble expansion, initial low-contrast density perturbations **(a)** become more pronounced as overdense regions attract matter away from underdense regions. The result in recent times **(d)** is structures such as superclusters of galaxies and voids that extend over hundreds of millions of light-years. Yellow indicates regions of highest density. (Adapted from M. White et al., *Astrophys. J.* **579**, 16 (2002).

Accelerated expansion : Type Ia SNe, 1998

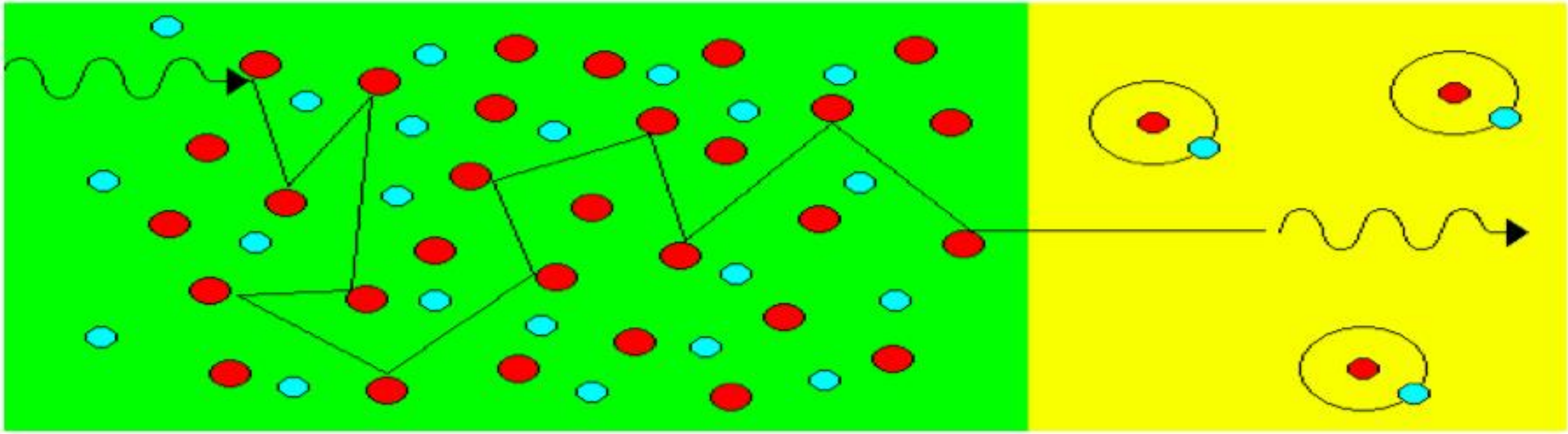
Dark Energy required with P(ΩΛ>0)>0.99

Knop, R. A., et al., 2003, ApJ, 598, 102



Last Scattering Epoch

As the Universe cooled, the free electrons and protons could finally bond togther to form hydrogen atoms. At the same time, the Universe went from a rich plasma to a gas of neutral hydrogen.



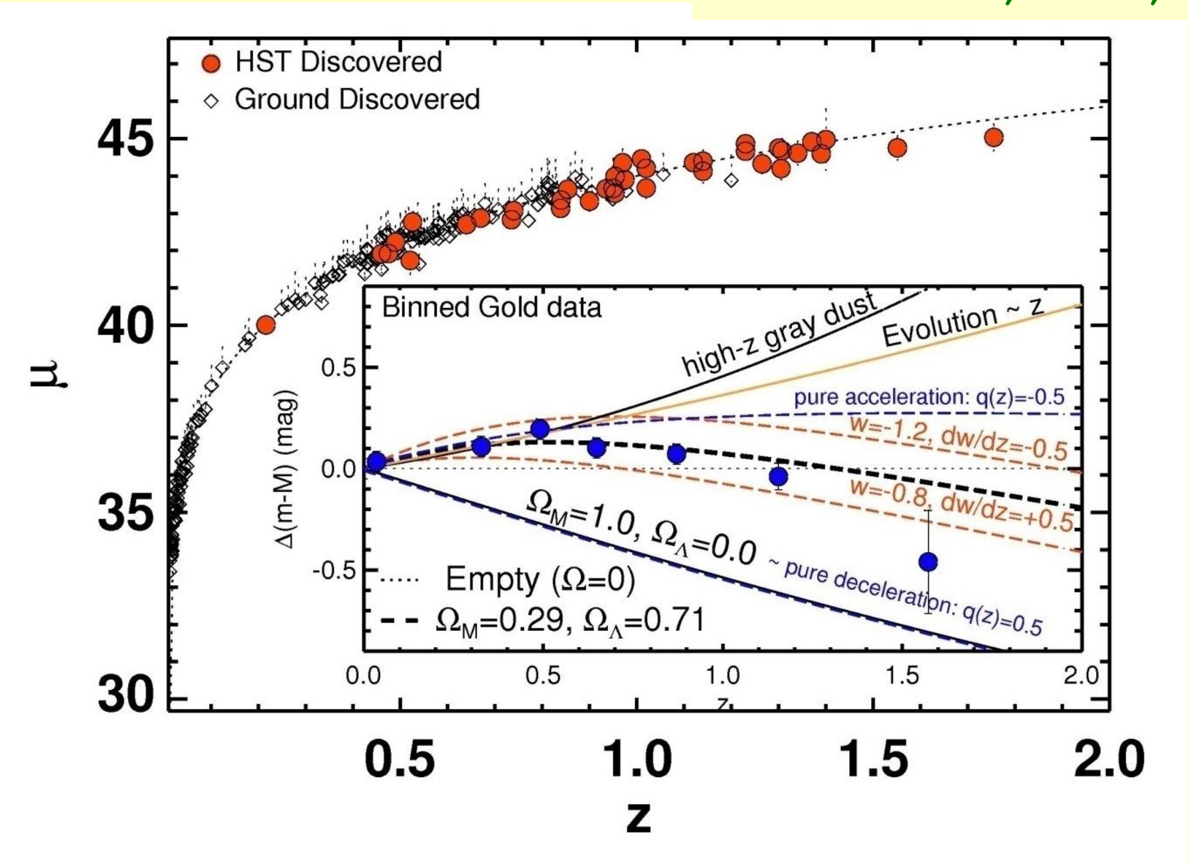
hydrogen plasma

atomic hydrogen

In a plasma, the mean free path of a photon is very short. In a gas of atomic hydrogen, the mean free path is very long, as long as the size of the Universe. Thus, the transition from the early plasma to atomic hydrogen is the epoch of last scattering, the point in time when the photons became free to travel without hindrance.

Reliability of SNe Ia as cosmological probes

A.Riess et al., 2007, ApJ, 659, 98



SNIa dimming of astrophysical origin ?

Simplest models of extinction by intergalactic dust or SNIa evolution ruled out by high-z SNIa data.

Dust scenarios also limited by other astrophysical data.

- Expliquer mieux les scénarios de formation de structure envisagés, rôle de la DM
- rôle des neutrinos, hiérarchie ou non *(now in L3)*
- Il manque : inflation *(now in L3)*, lensing gravitationnel
- Animation évolution d'une sur-densité *(now in L2)*
- Mettre les résultats cosmo du CMB seul (Planck+highL+lensing+WP) Univers plat ?
- Expliquer mieux les différents modèles de dark energy (simple constante cosmo ou modèle avec équation d'état changeant dans le temps)