Comprendre l'infiniment grand

V.Ruhlmann-Kleider
CEA/Saclay Irfu/DPhP

1) Du modèle du Big Bang au contenu de l'Univers
2) **Mesures cosmologiques**
3) Les grandes structures de l'Univers

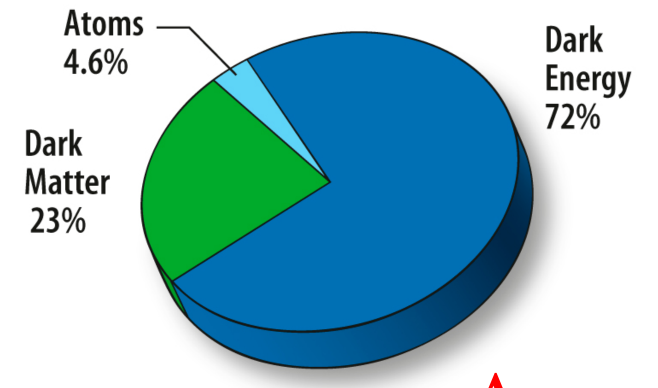
Cosmological probes

Observations and interpretation

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

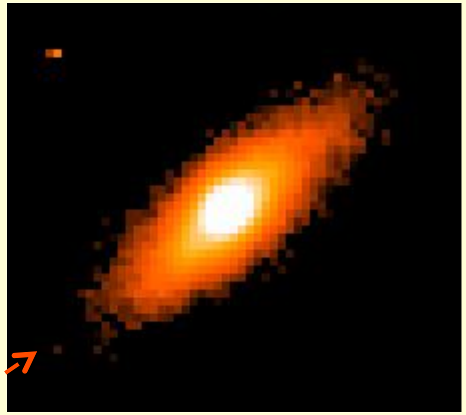
negligible today

- Type Ia supernovae (SNe Ia)
- Cosmic Microwave Background (CMB)
- Baryonic Acoustic Oscillations (BAO)

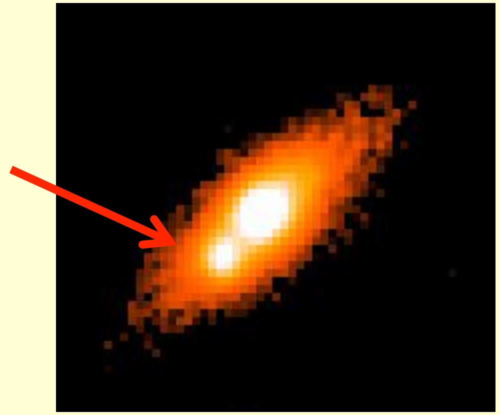


Planck 2018 Λ_{CDM}

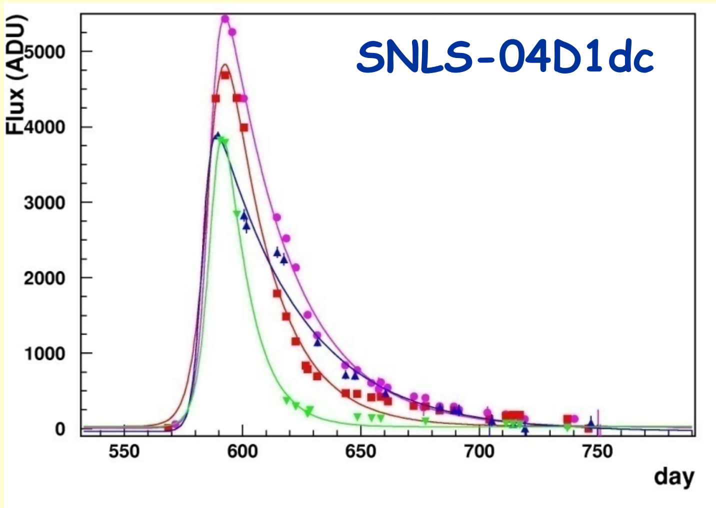
1. SNe Ia



before explosion

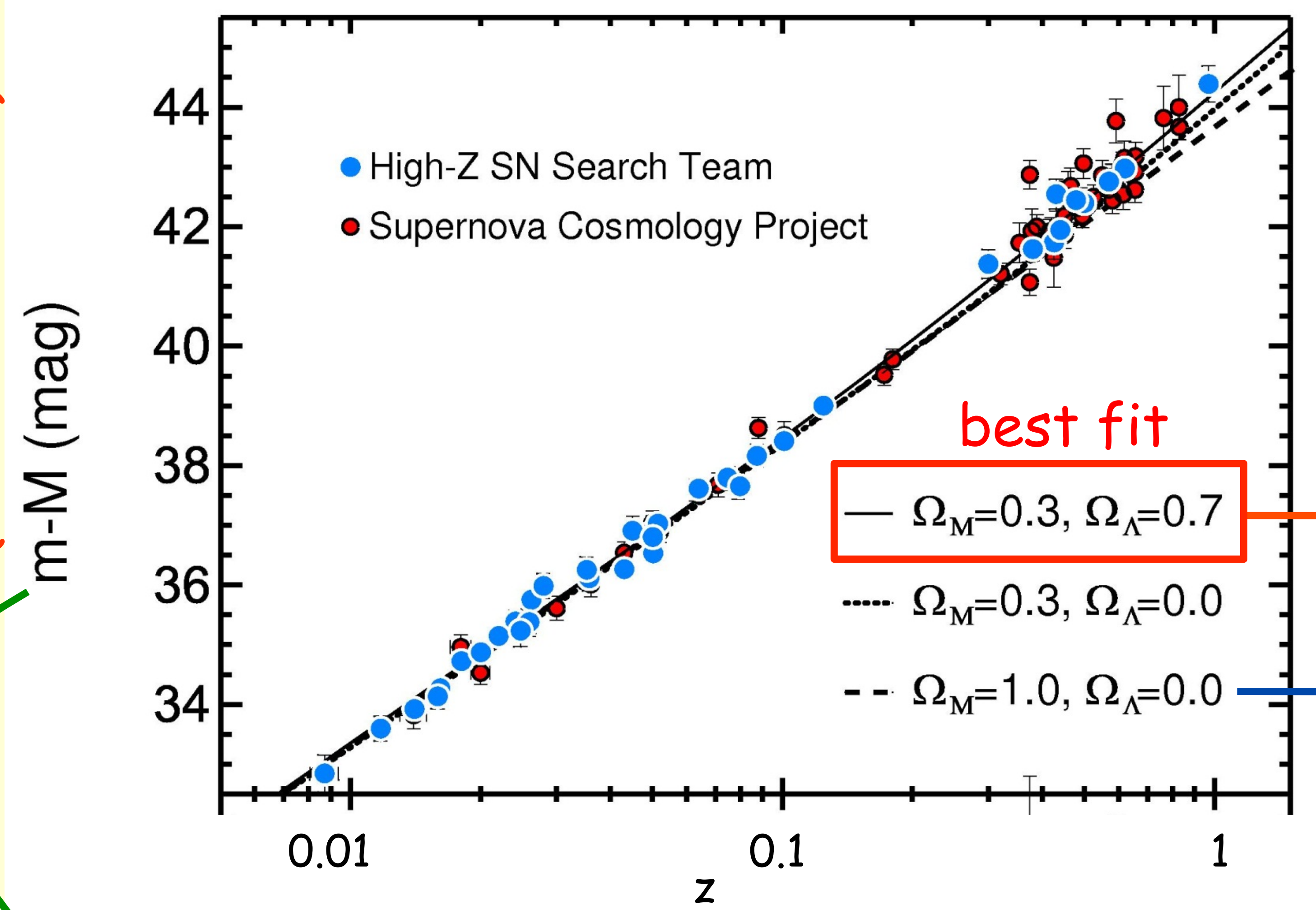


SN light curve



Accelerated expansion : Type Ia SNe, 1998

FAINTER →
(further back in time)



dark energy

matter only

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

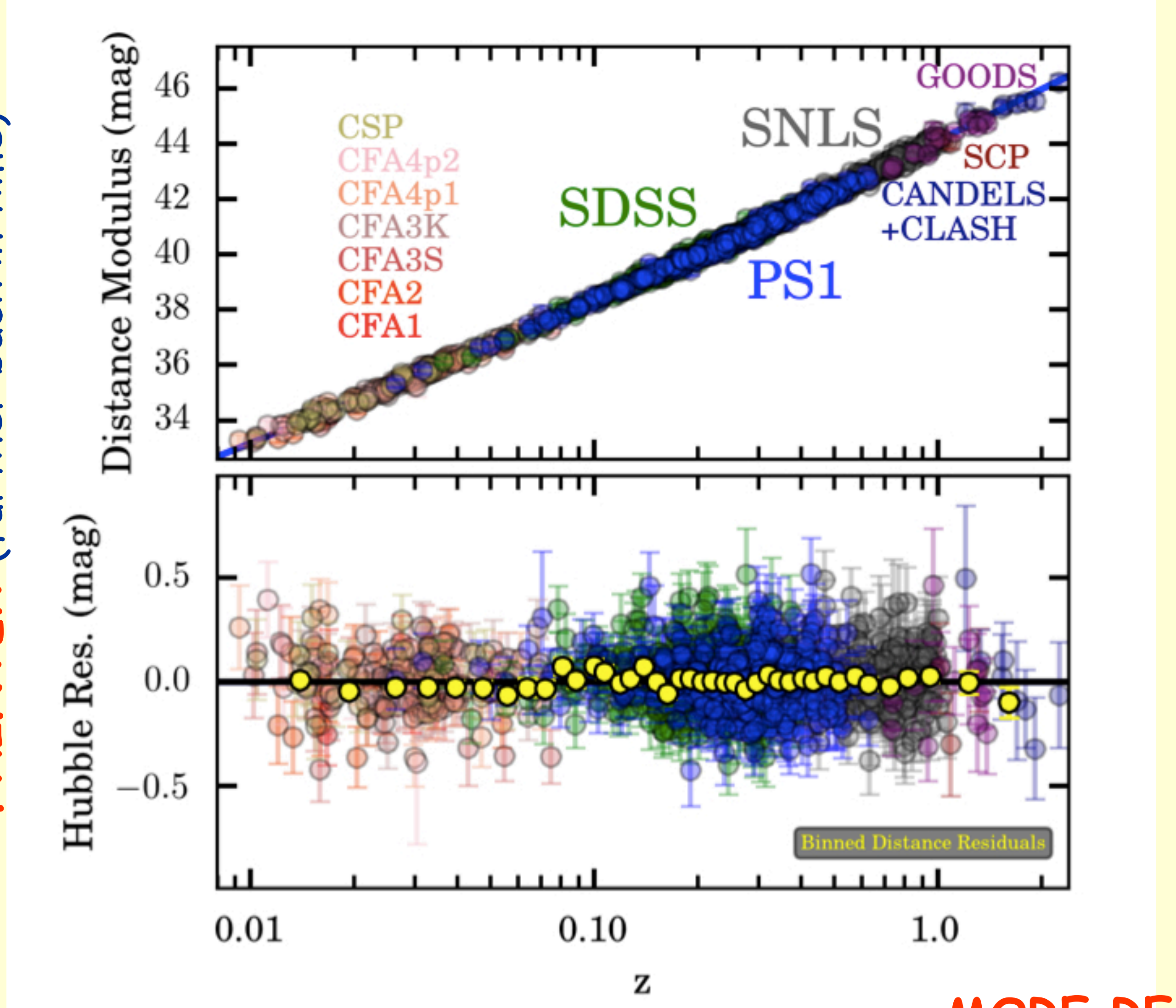
MORE REDSHIFT→
(more expansion since explosion)

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

Most recent SNIa result, 2018

High quality data for **1048** SNeIa, with survey **cross-calibrations**

FAINTER (further back in time) →



Flat Λ_{CDM} fit:

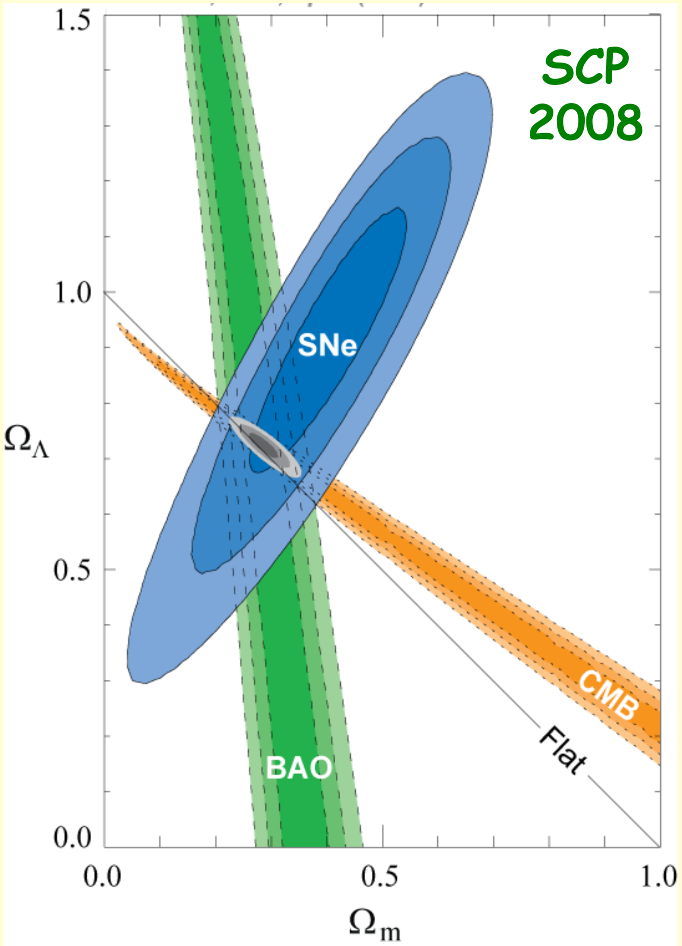
$\Omega_m^0 = 0.298 \pm 0.022$

Accelerated expansion **confirmed** by SNeIa **alone**

MORE REDSHIFT→
(more expansion since explosion)

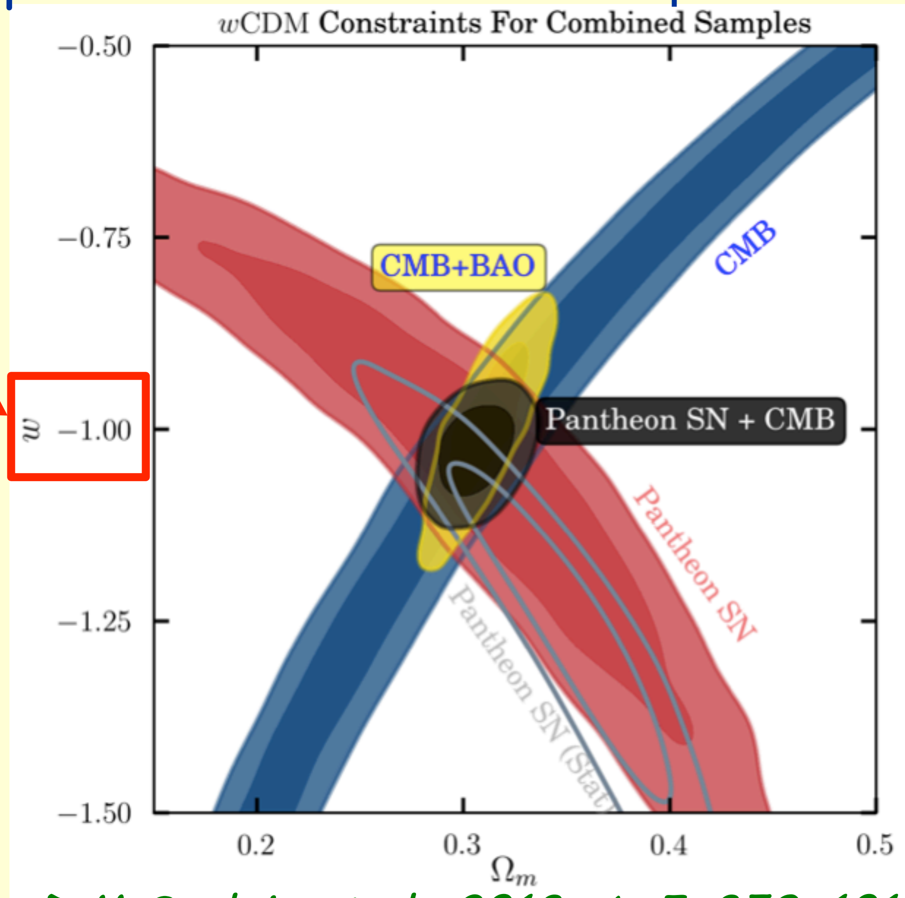
D.M.Scolnic et al., 2018, ApJ, 859, 101S

Cosmological constraints from CMB+BAO+SNIa data



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

Λ



D.M.Scolnic et al., 2018, ApJ, 859, 101S

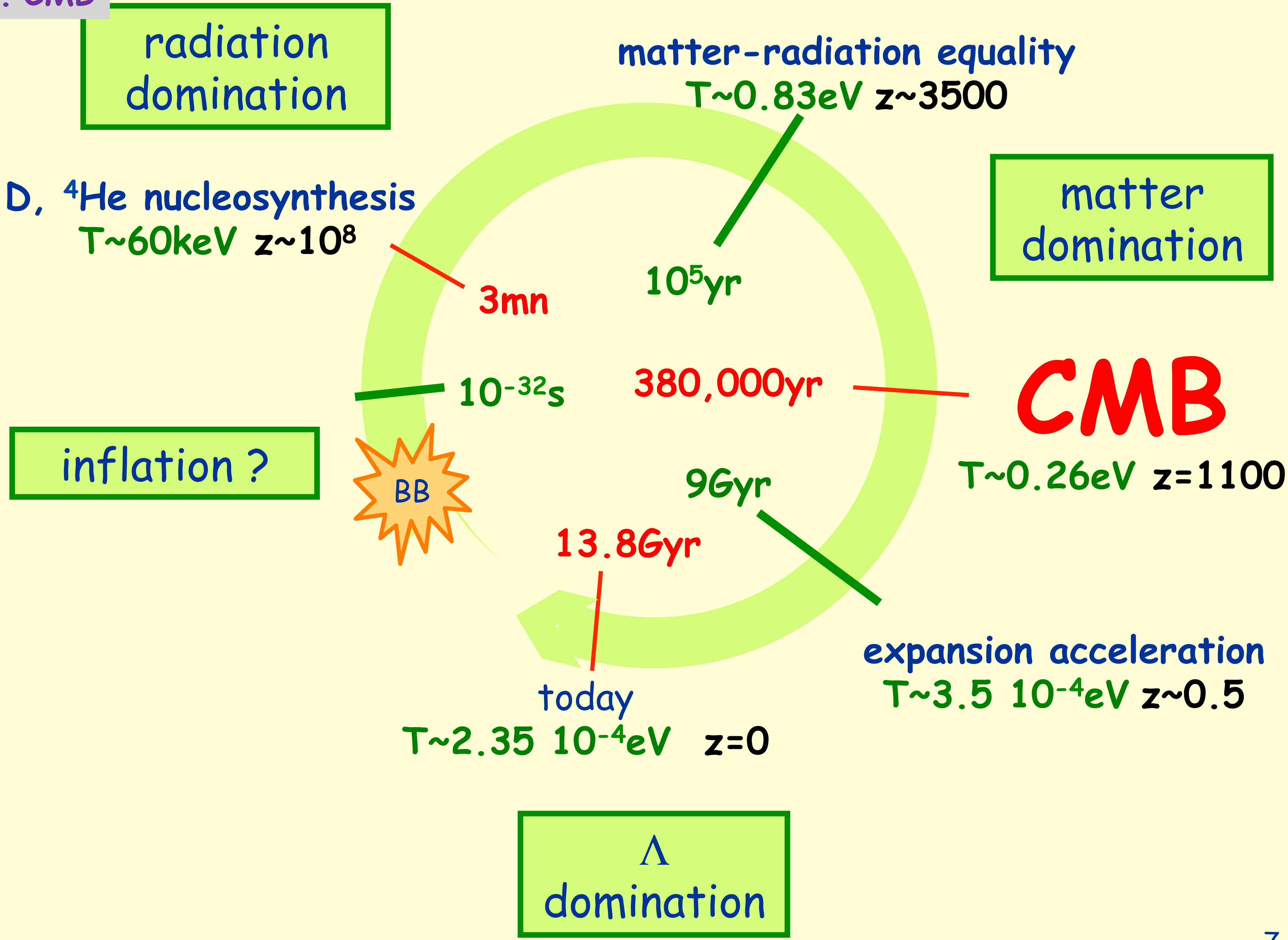
⇨ Universe is flat, Λ or dark energy needed

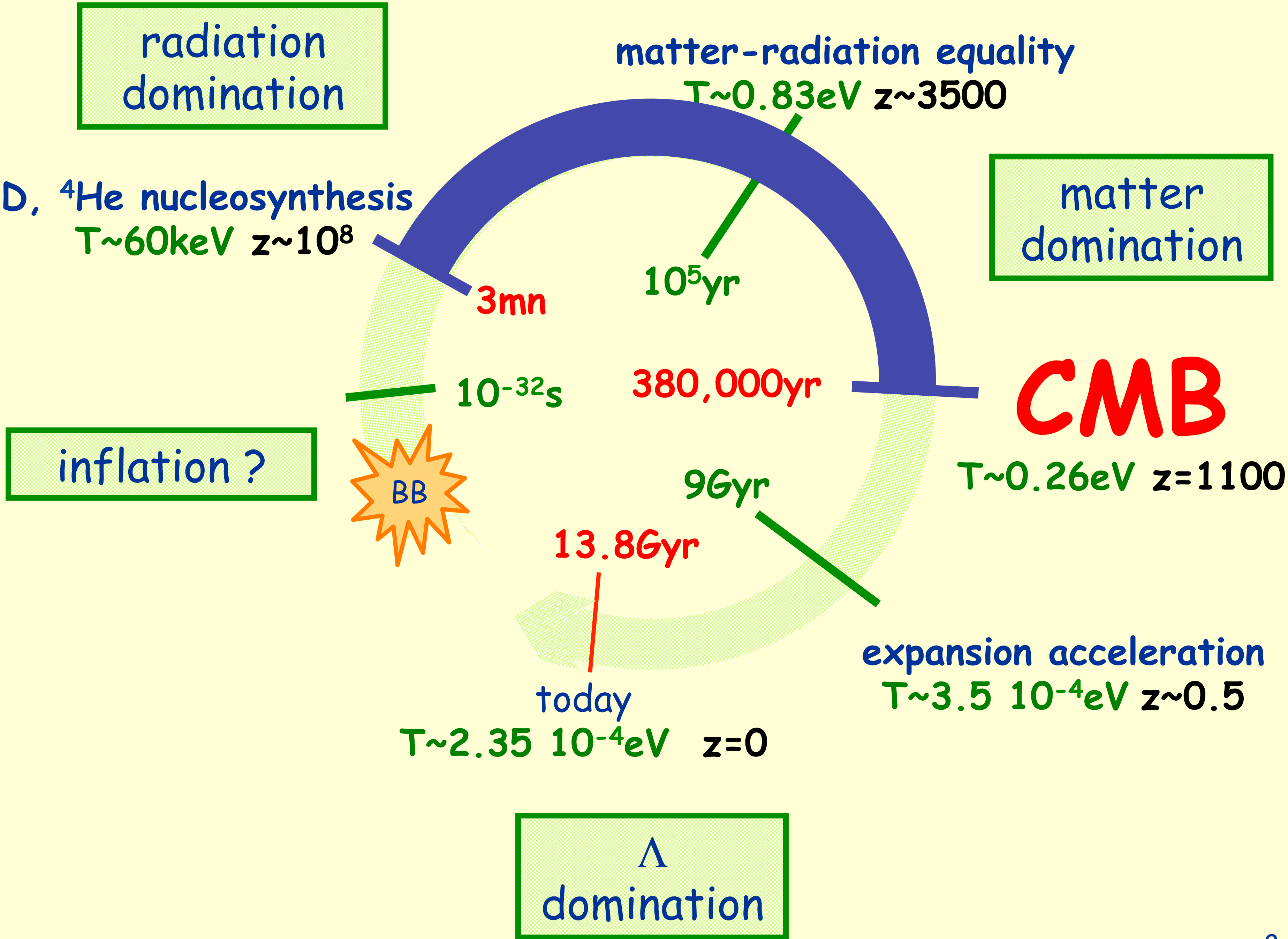
M. Kowalski et al., 2008, ApJ, 686, 749

Ω_m^0=0.307±0.012

w=−1.026±0.041

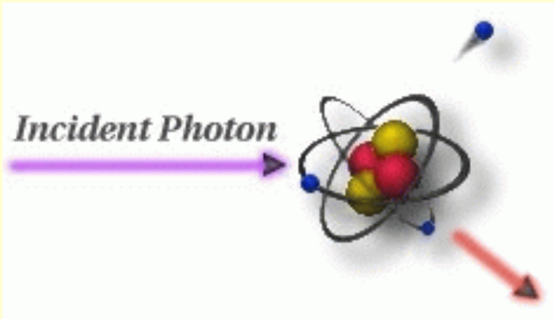
($\delta_{stat} \oplus \delta_{syst}$)


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
T~0.26eV z=1100
inflation ?
BB
9Gyr
13.8Gyr
expansion acceleration
T~3.5 10⁻⁴eV z~0.5
today
T~2.35 10⁻⁴eV z=0
Λ domination


radiation domination
matter-radiation equality
T~0.83eV z~3500
matter domination
D, ⁴He nucleosynthesis
T~60keV z~10⁸
3mn
10⁵yr
10⁻³²s
380,000yr
CMB
T~0.26eV z=1100
inflation ?
BB
9Gyr
13.8Gyr
expansion acceleration
T~3.5 10⁻⁴eV z~0.5
today
T~2.35 10⁻⁴eV z=0
Λ domination

The plasma after primordial nucleosynthesis

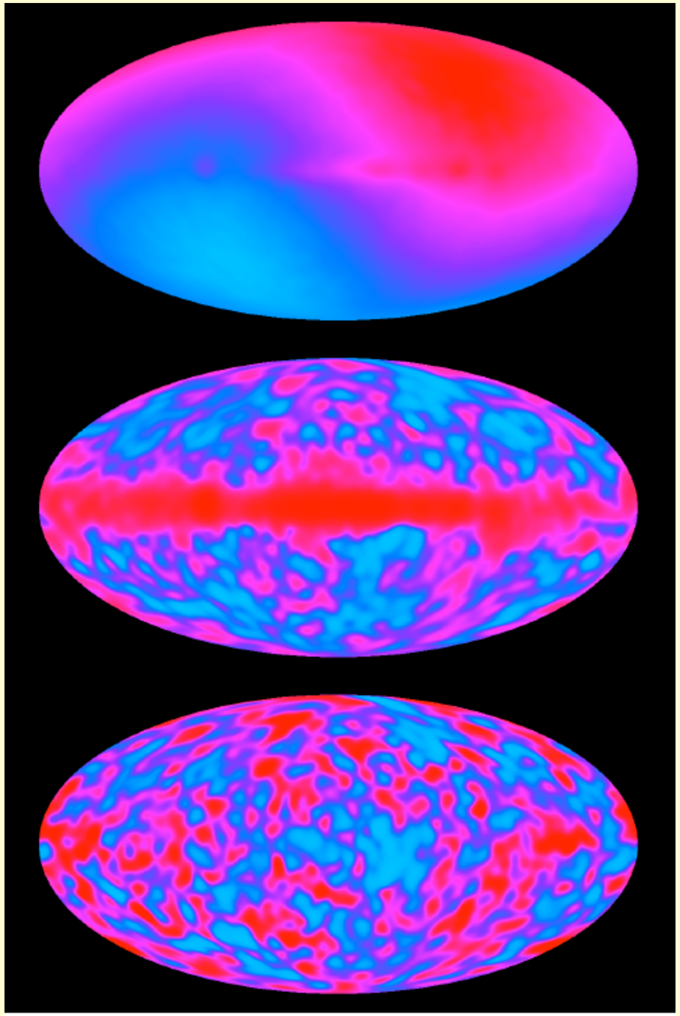
- γ and **e**, **nuclei** (≡ionized baryons) in thermal equilibrium



atom formation ↔ 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

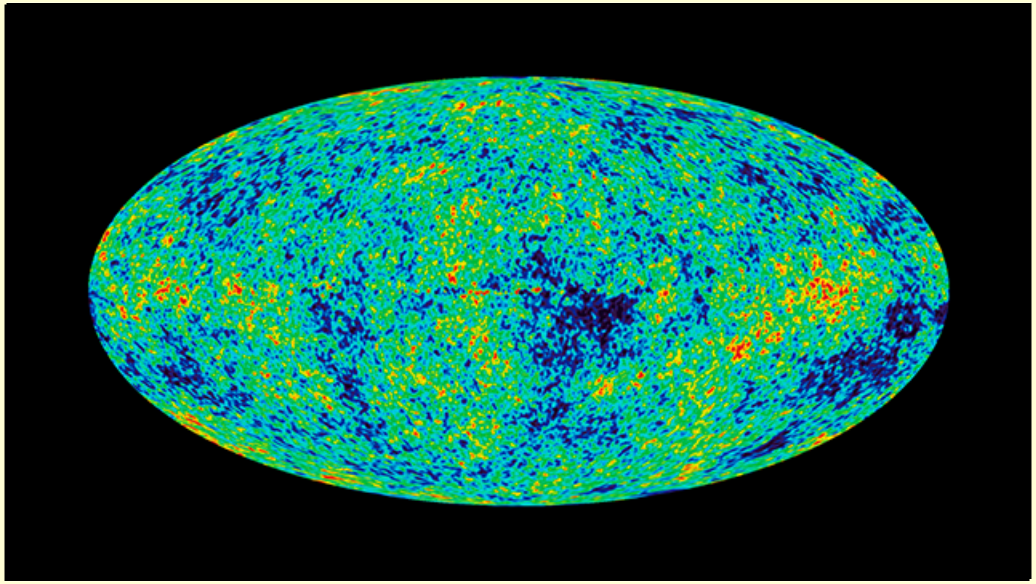


COBE (1993)

red: hotter blue: cooler

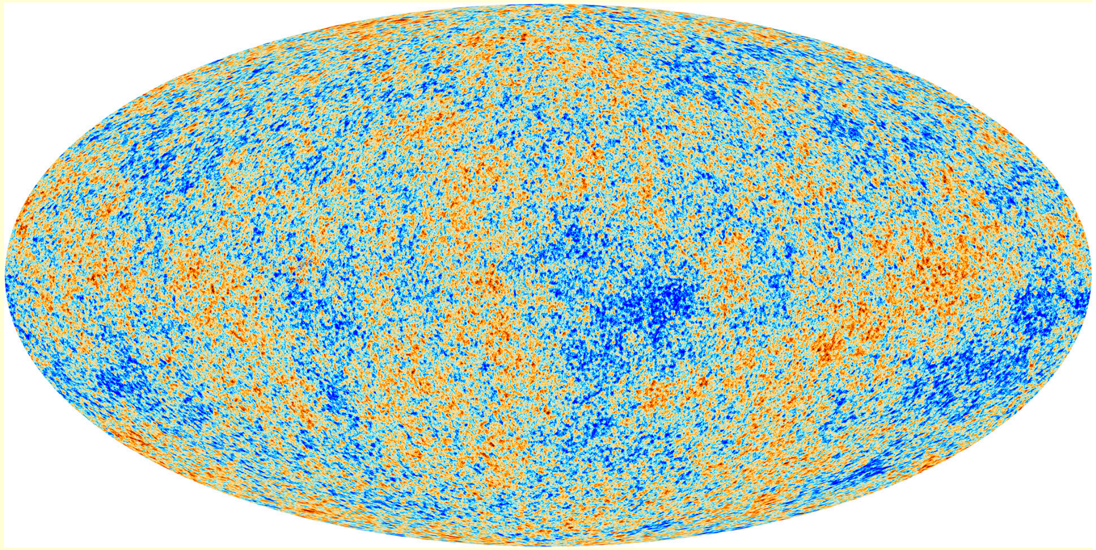
- <T> subtracted: dipole anisotropy (relative Earth/CMB motion) is visible.
- Dipole subtracted : Milky Way emission clearly visible
- Milky Way emission subtracted: primordial temperature fluctuations are visible => density fluctuations in the primordial plasma

COBE (1993) *WMAP 7 years (2008)*



Sky map, all foregrounds subtracted

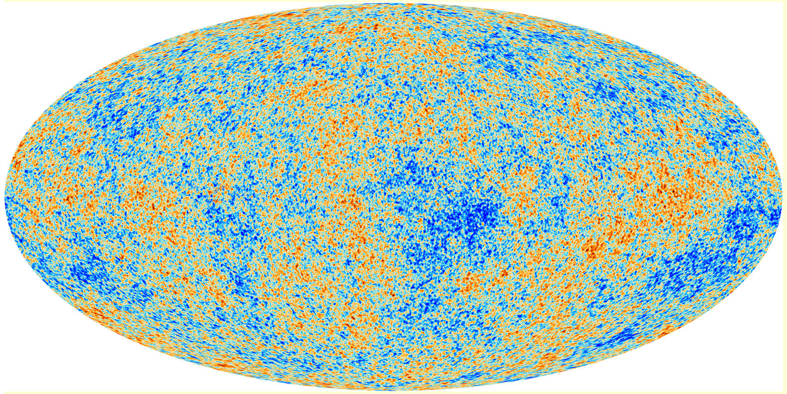
Planck (2013)



- 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:

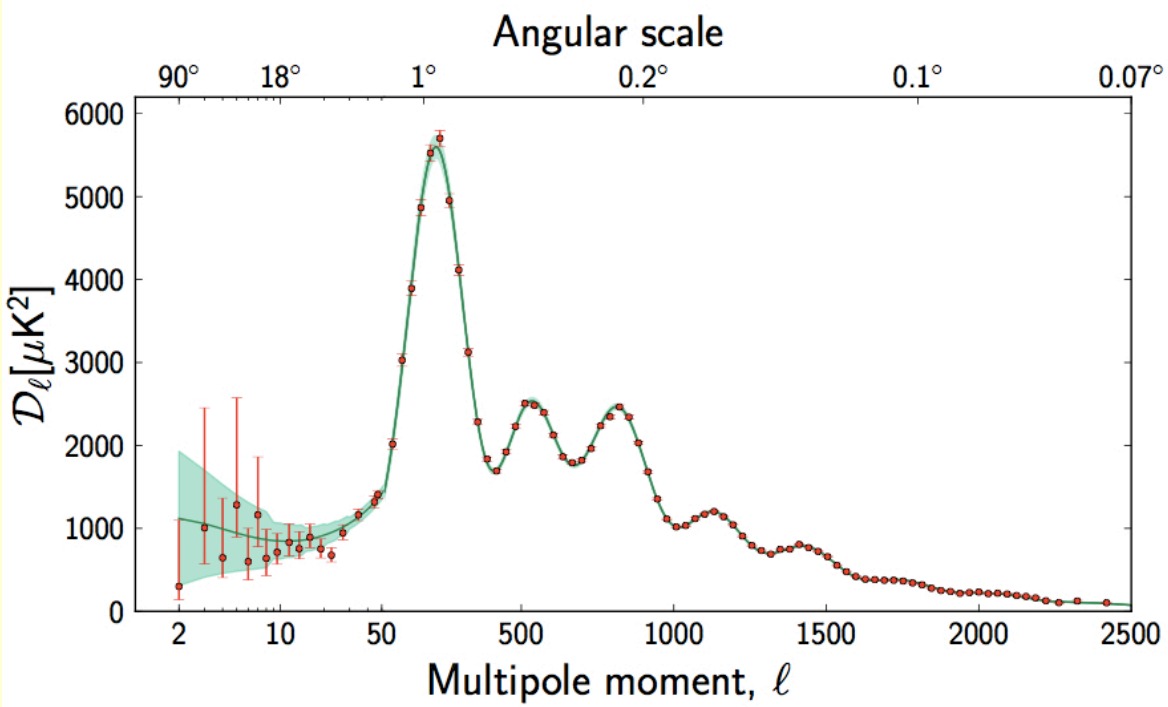
strength of T fluctuations (hot and cold spots) vs angular size of the sky patch on which the measurement is made

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

$$\Delta\theta \approx \frac{\pi}{l} \approx \frac{s_*}{D_*}$$

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

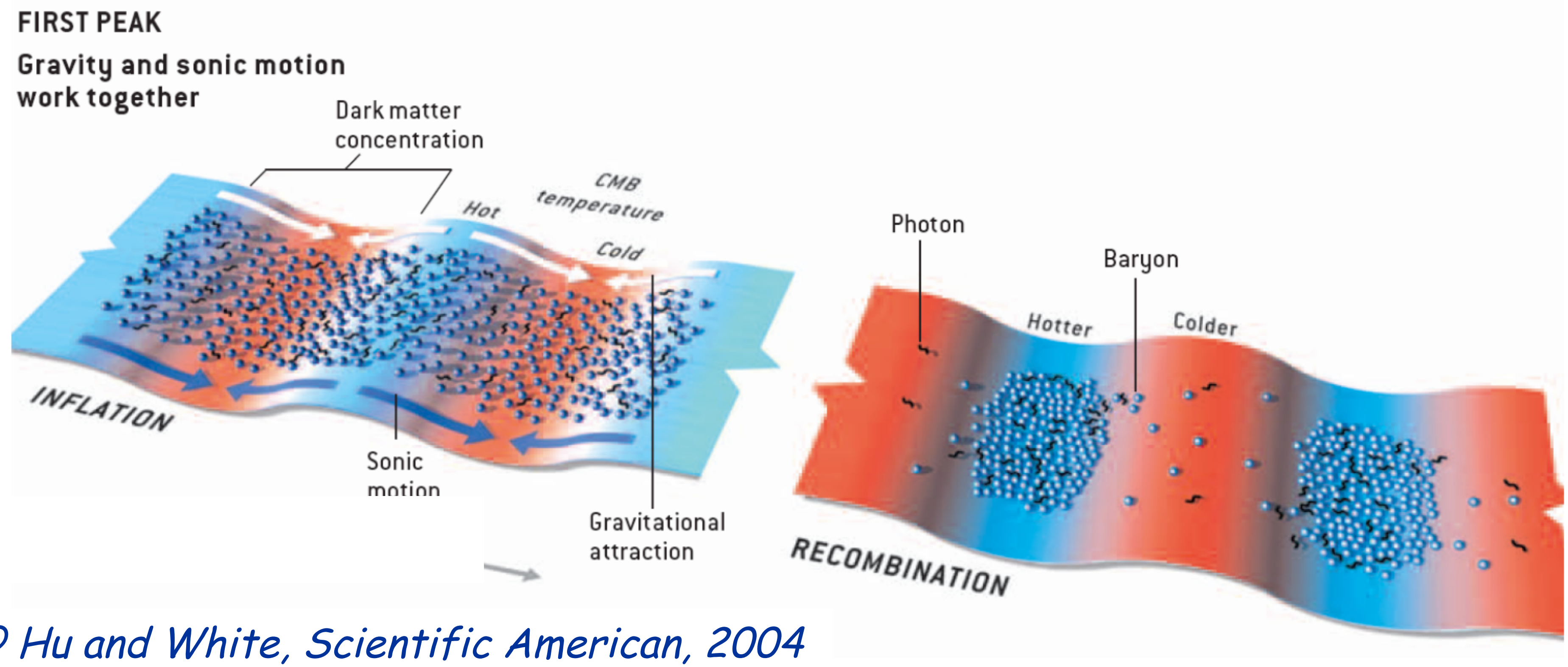
D_* = comoving distance to z_* (angular diameter distance)



Planck (2013)

Origin of temperature anisotropies

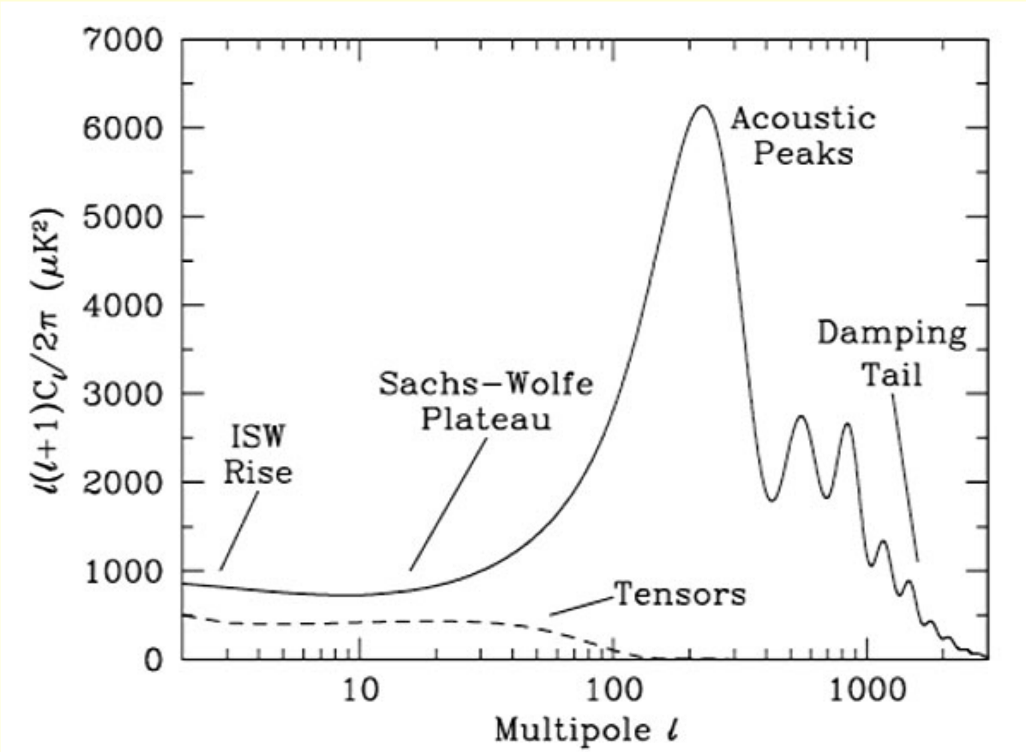
- dark matter collapse increases over-densities, making the photon-baryon plasma to oscillate into and out of these over-densities : 'acoustic oscillations' in primordial plasma
- At decoupling: oscillation pattern is frozen ⇒ imprint in CMB spectrum (and matter spectrum)



© 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

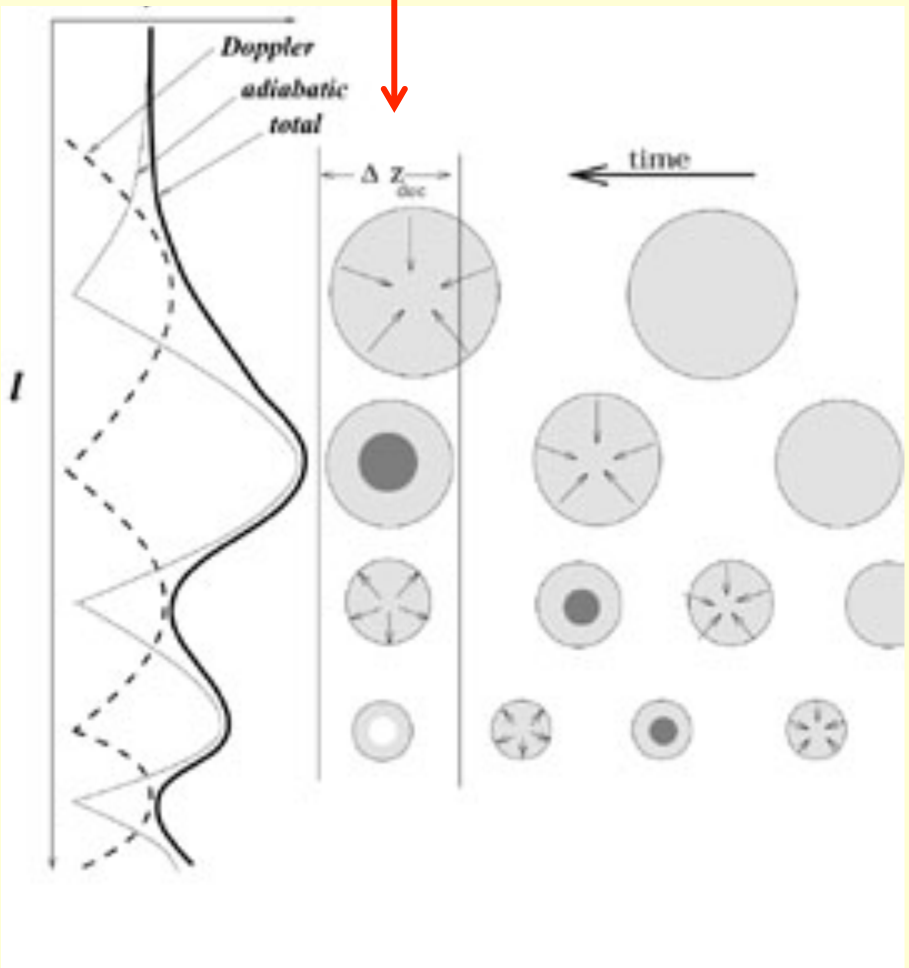
$$v \approx c/\sqrt{3}$$

<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



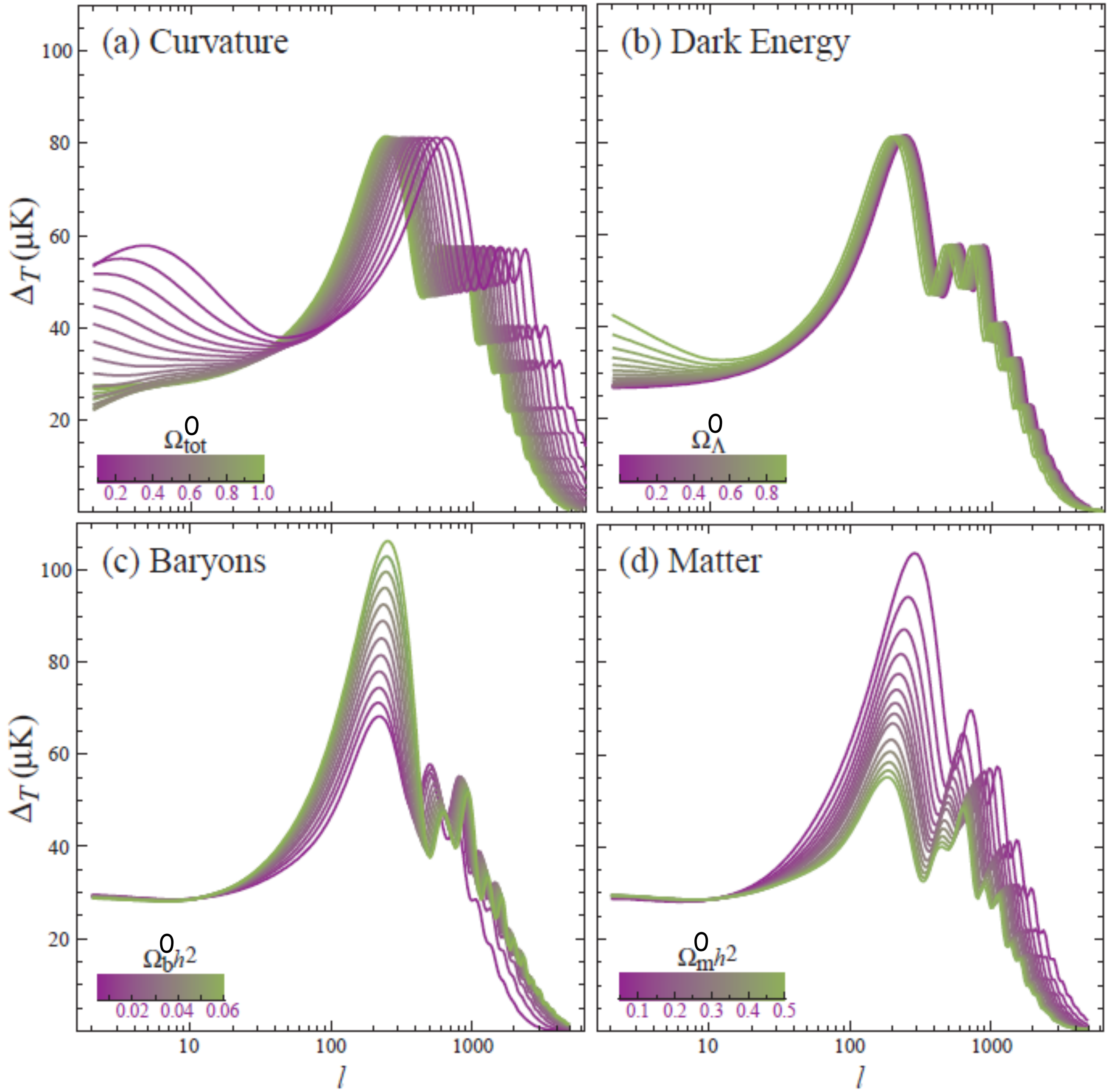
Oscillations of fluctuations at decoupling:

- 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

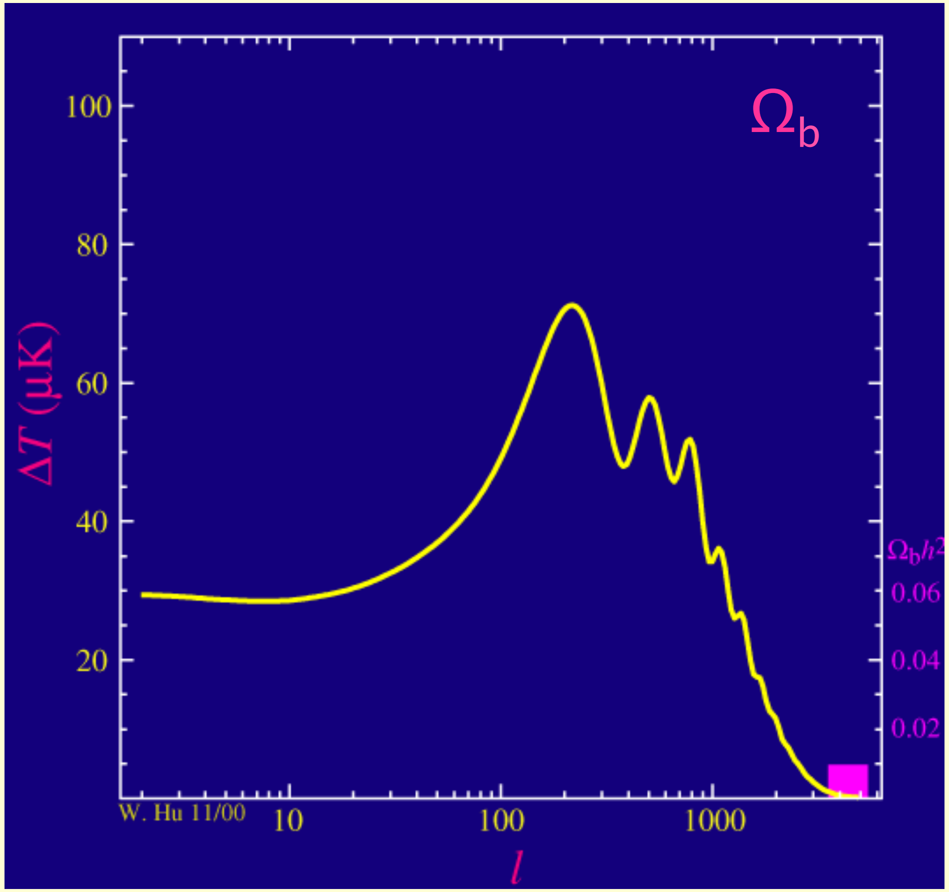
Sensitivity to cosmology parameters

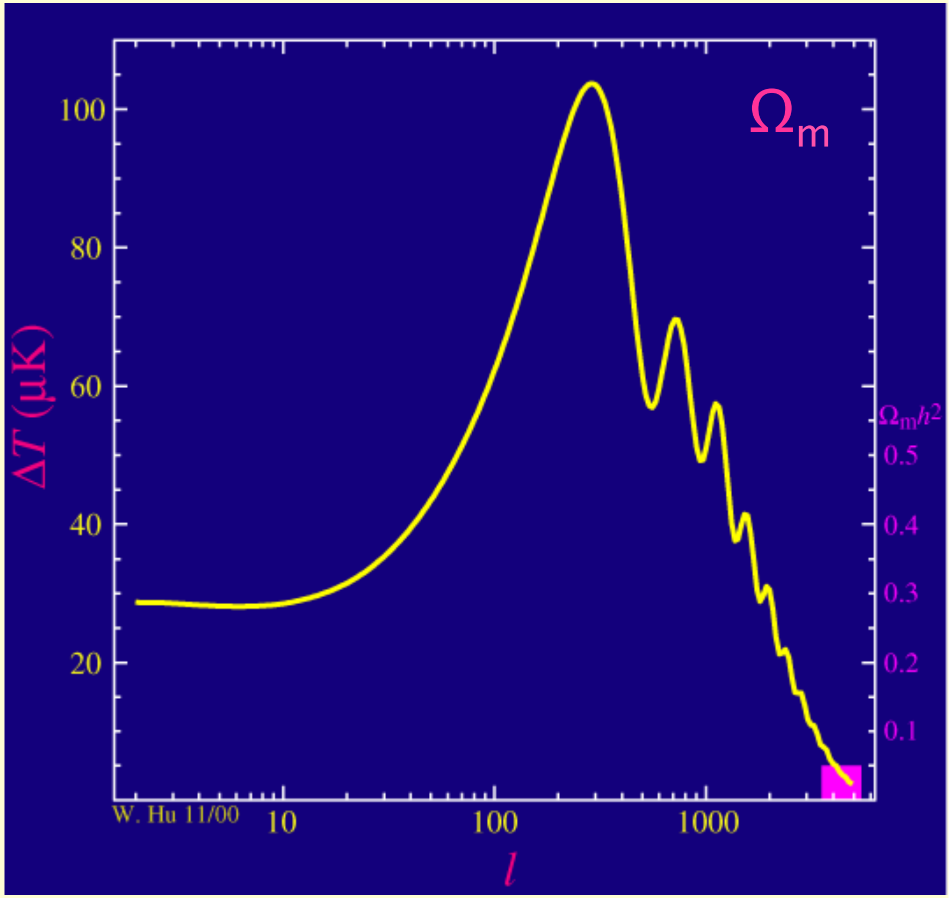
- Ω^0_m from 1st peak position and height
- Ω^0_b from 2nd to 1st peak ratio



Hu and Dodelson, 2002, ARAA 40, 171

Sensitivity to cosmology parameters





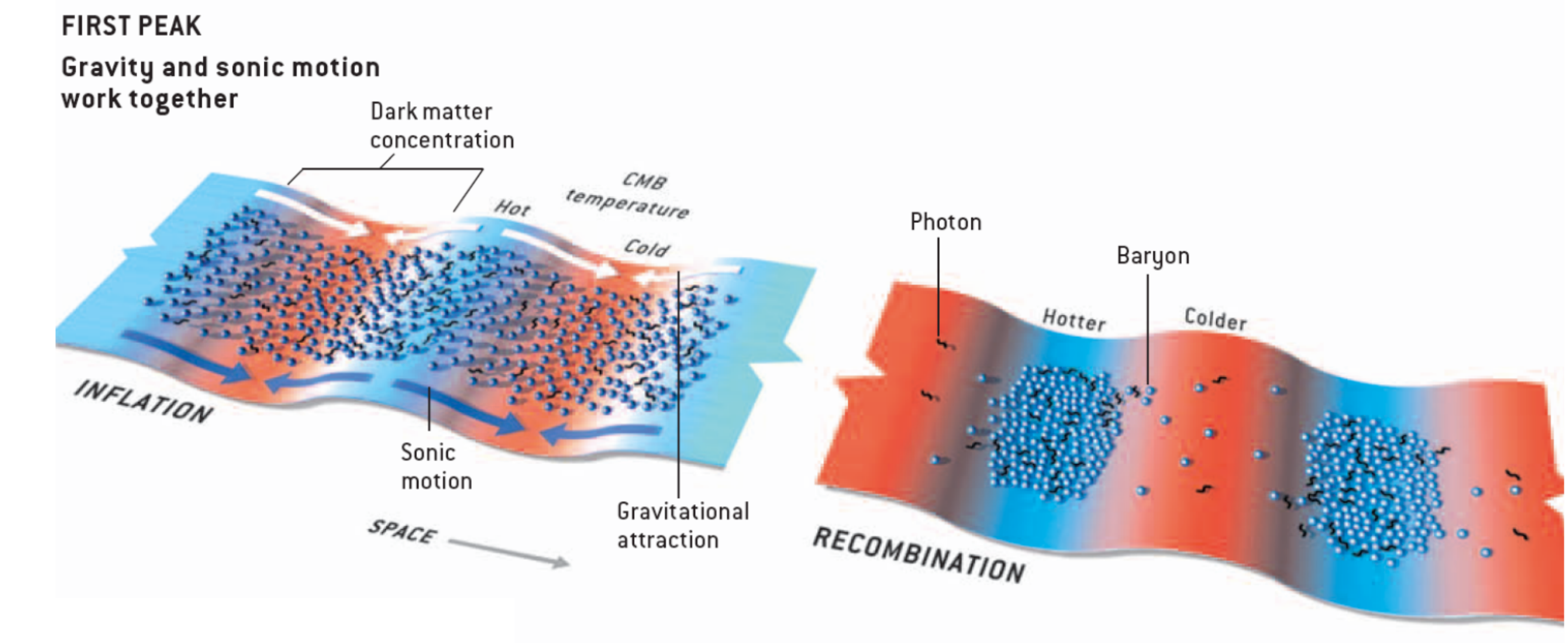
➔ Ω_b^0 from 2nd to 1st peak ratio

➔ Ω_m^0 from 1st peak position & height

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

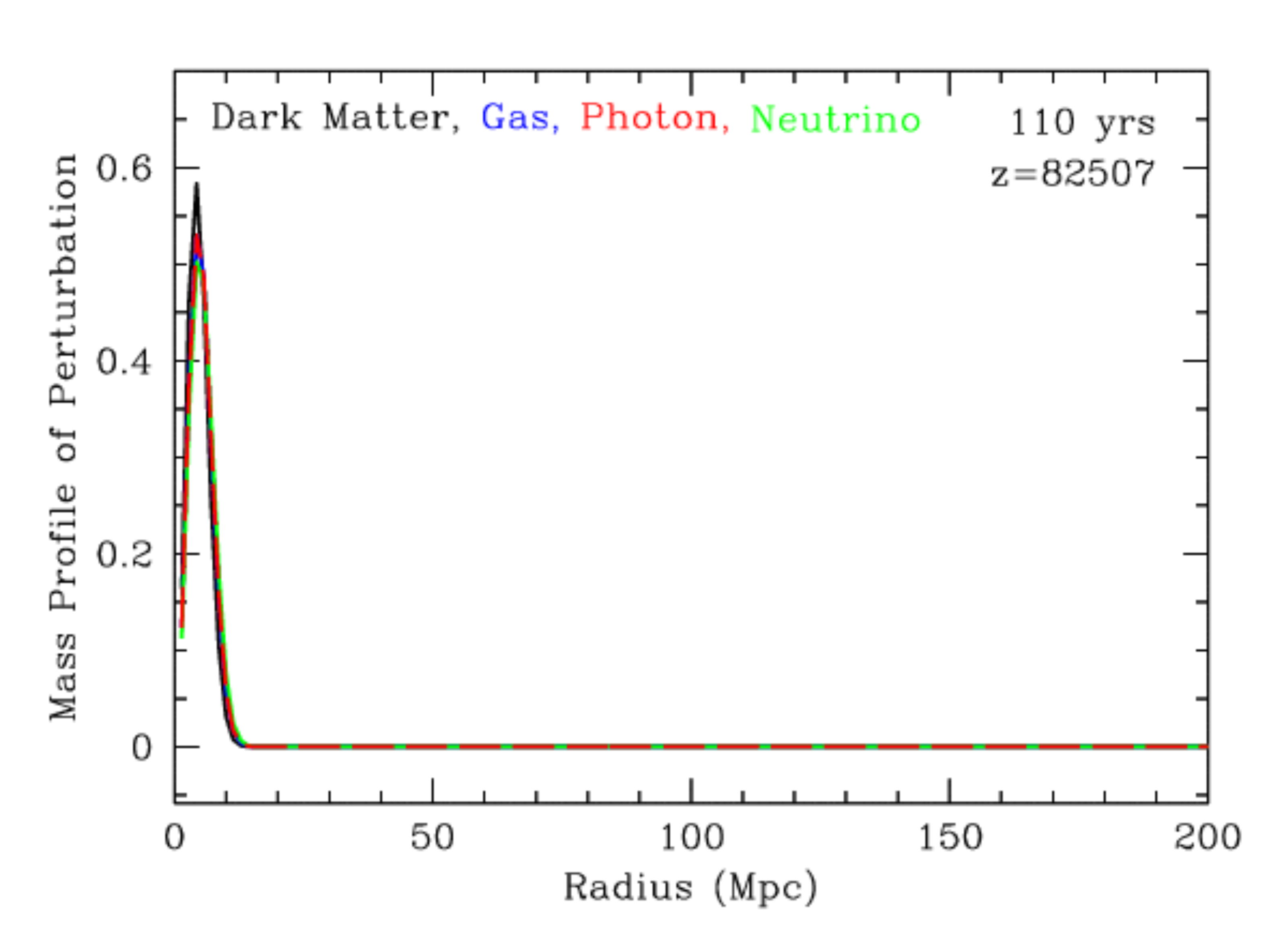
Baryon acoustic oscillations

- in primordial plasma (γ, e, baryons) : acoustic oscillations
- at decoupling: oscillation pattern is frozen ⇒ imprint in matter spectrum (as in CMB spectrum)

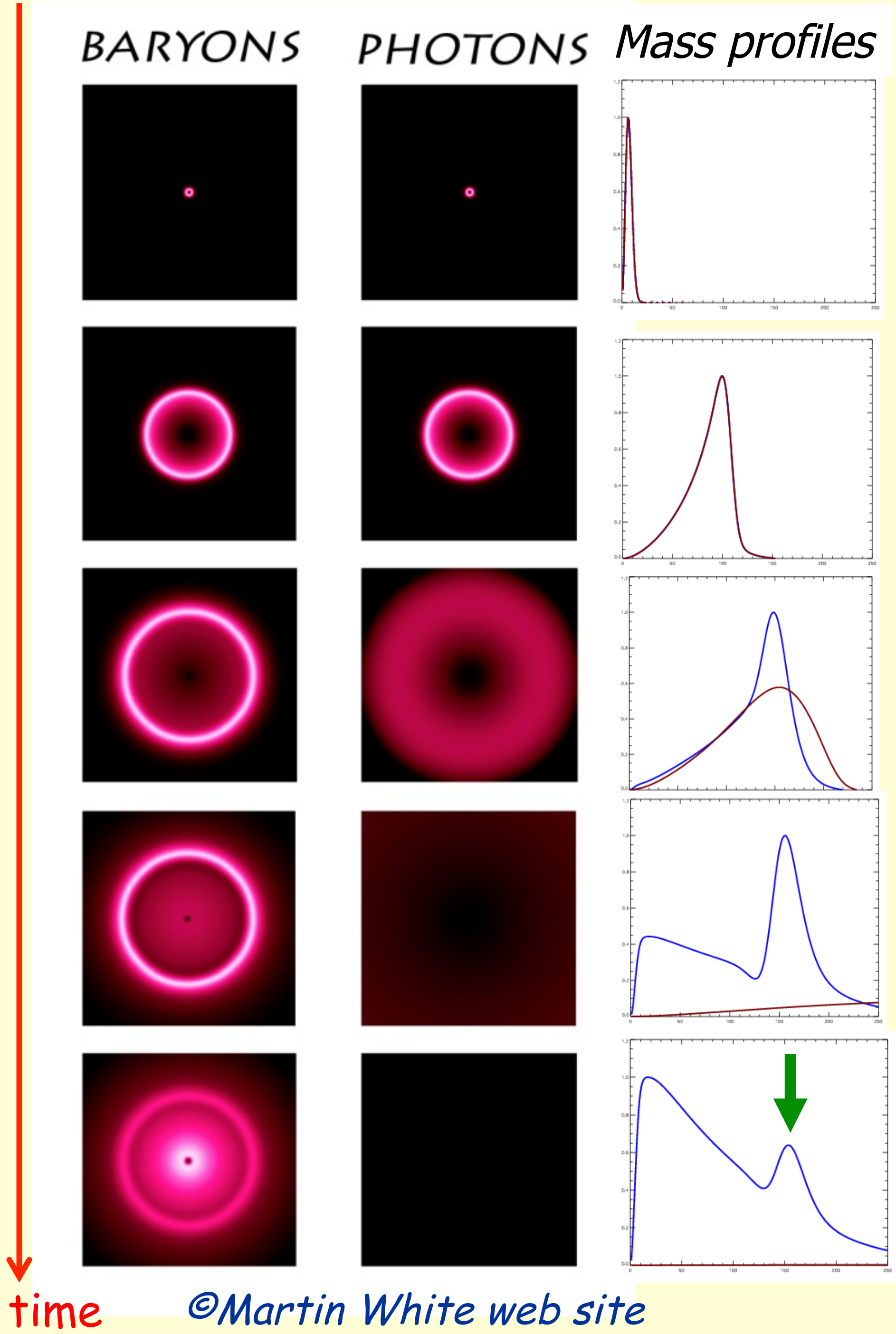


© Hu and White, Scientific American, 2004

Evolution of a single overdensity with time



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



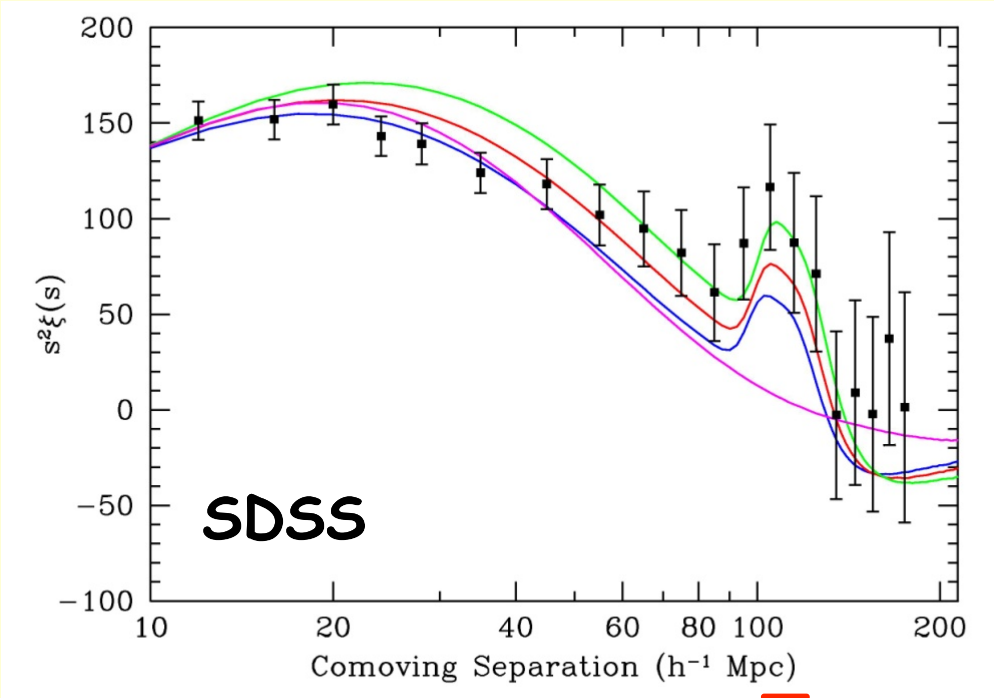
- one single overdensity in the plasma, moving outward
- γ and baryons move together, for 10^5 years
- recombination: γ decouple from baryons and stream away, leaving the baryon peak stalled
- γ ~uniform, baryons remain overdense in a shell ~150Mpc in radius (sound horizon)
- matter attracted by central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

Galaxy distributions

First evidence for BAO signal: 2005

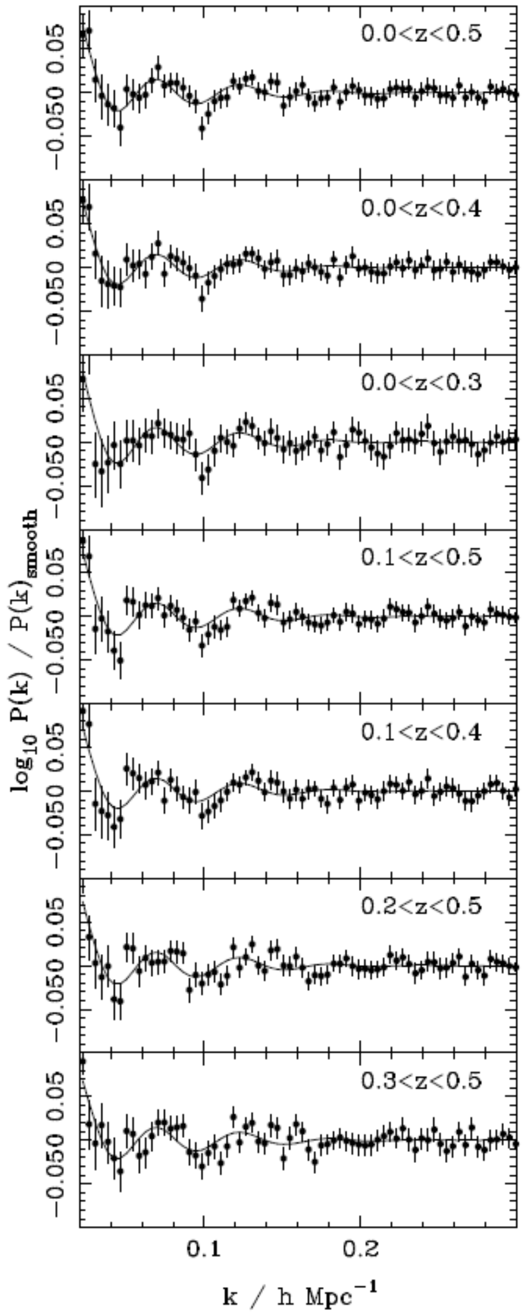
D.Eisenstein et al., 2005, ApJ, 633, 560

Galaxy correlation function



preferred comoving separation ~150Mpc
(h~0.7)

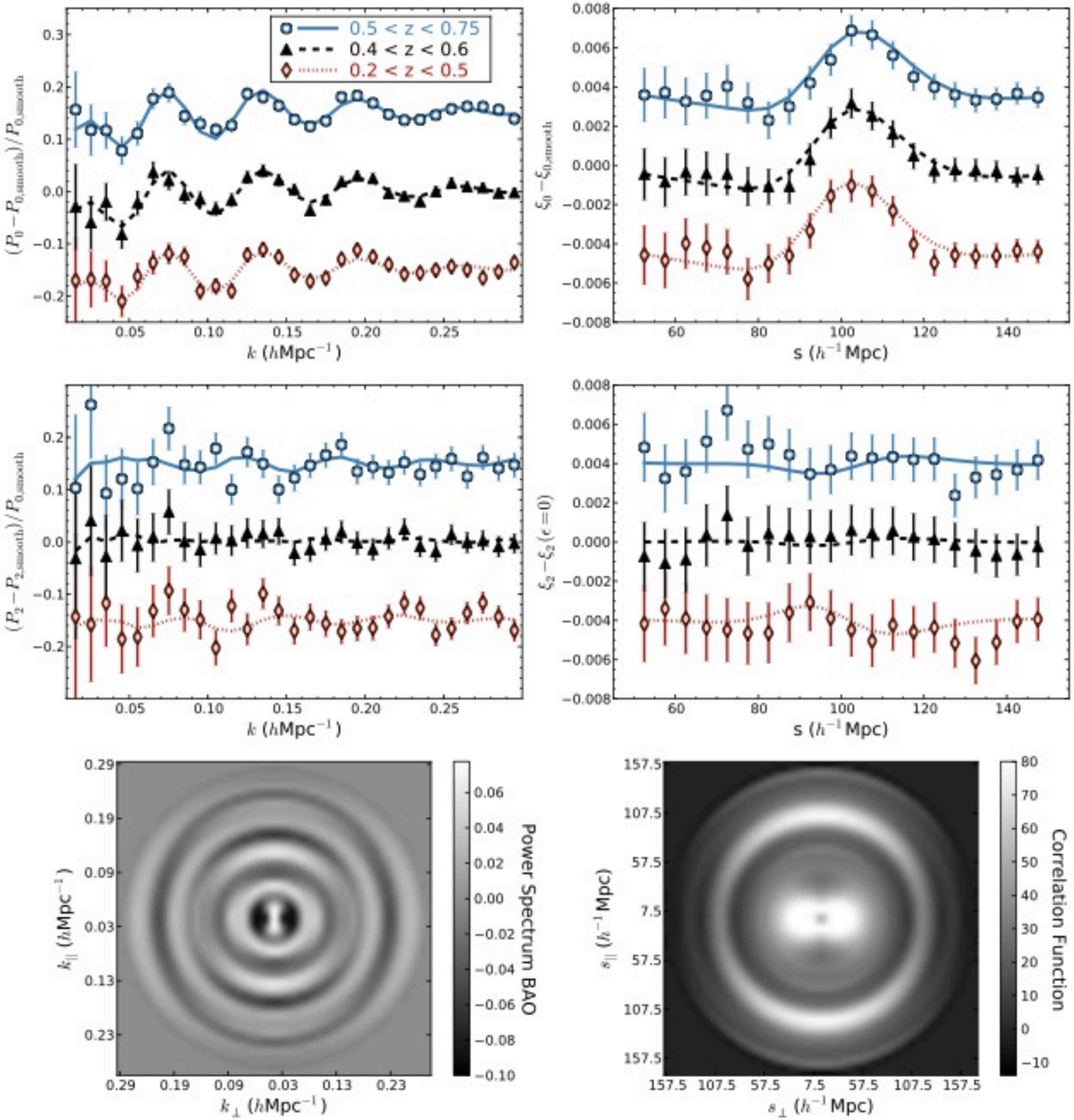
Galaxy power spectrum



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

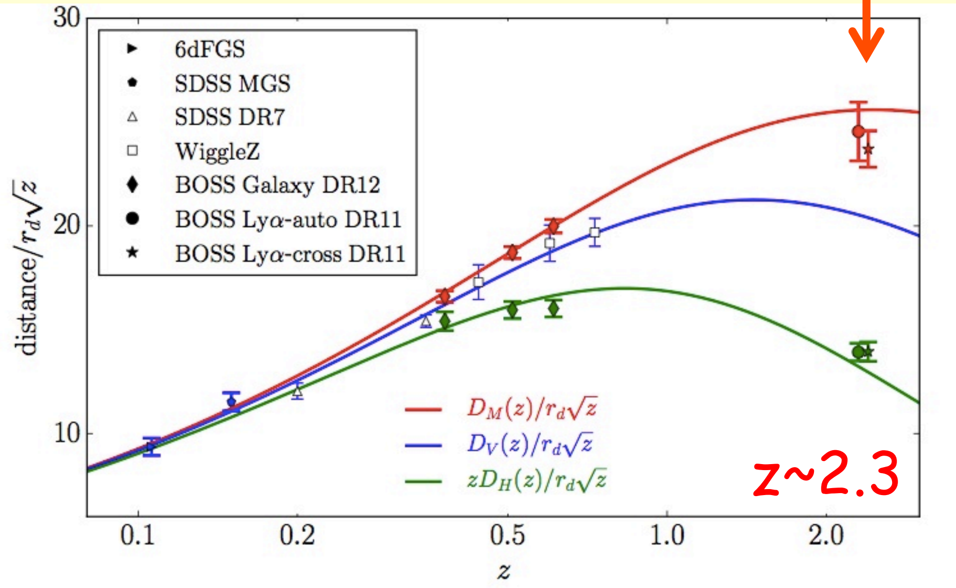
Final SDSS-III results

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



Beyond galaxies

- BAO signal also detected in clustering of intergalactic H clouds (via absorption lines in Lyα forest part of quasar spectra) and quasars.



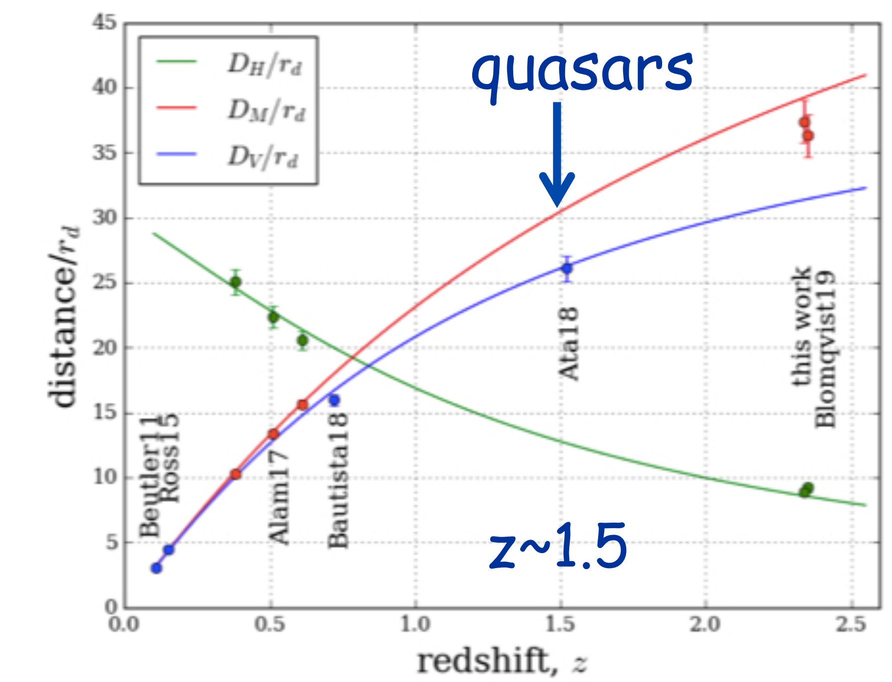
S. Alam et al., 2017, MNRAS,470, 2617A

SDSS-III

Good consistency with Planck-alone Λ_{CDM} fit

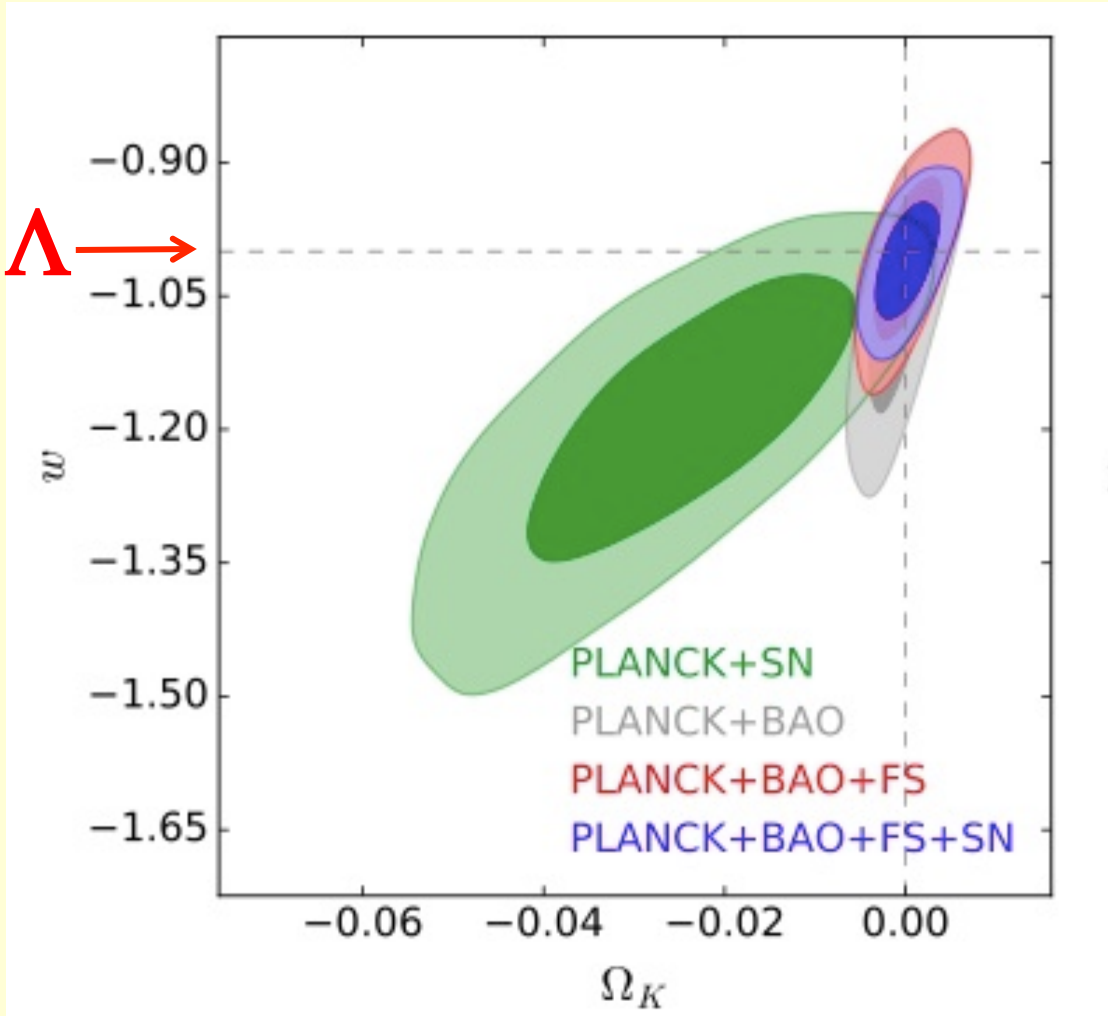
Last update: SDSS-IV

V.de Sainte Agathe et al., arXiv:1904.03400



Cosmological constraints

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



CMB+BAO+FS+SNe:

Universe is flat (Ω_k ~0) and

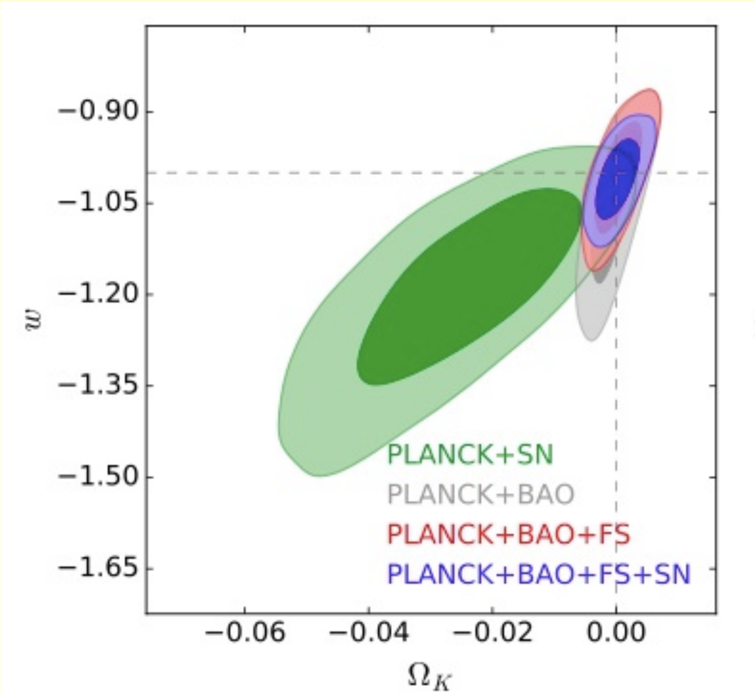
$w = -1.01 \pm 0.04$

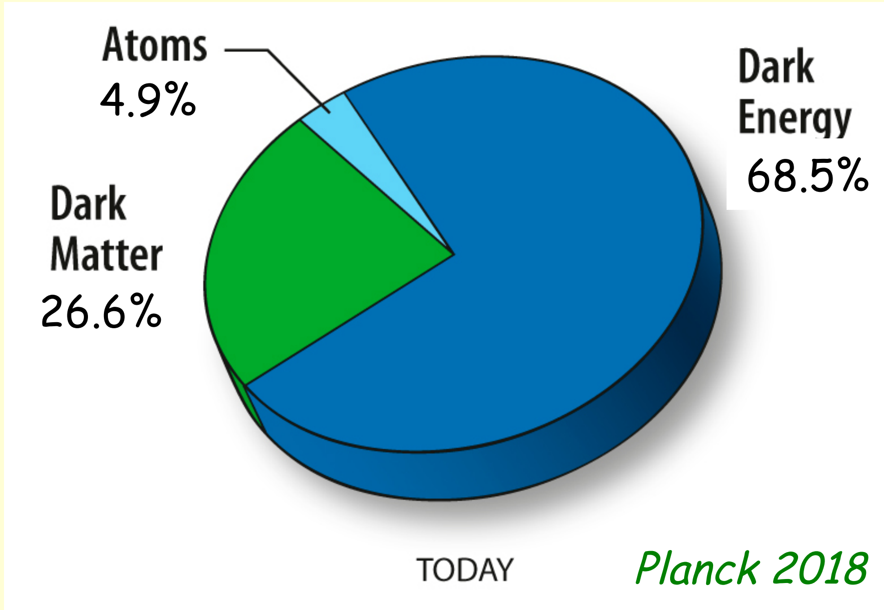
($\delta_{stat} \oplus \delta_{syst}$)

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

CONCLUSIONS (3)

- Cosmological measurements today: CMB, SNeIa, BAO.





Concordance model = Λ_{CDM}

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