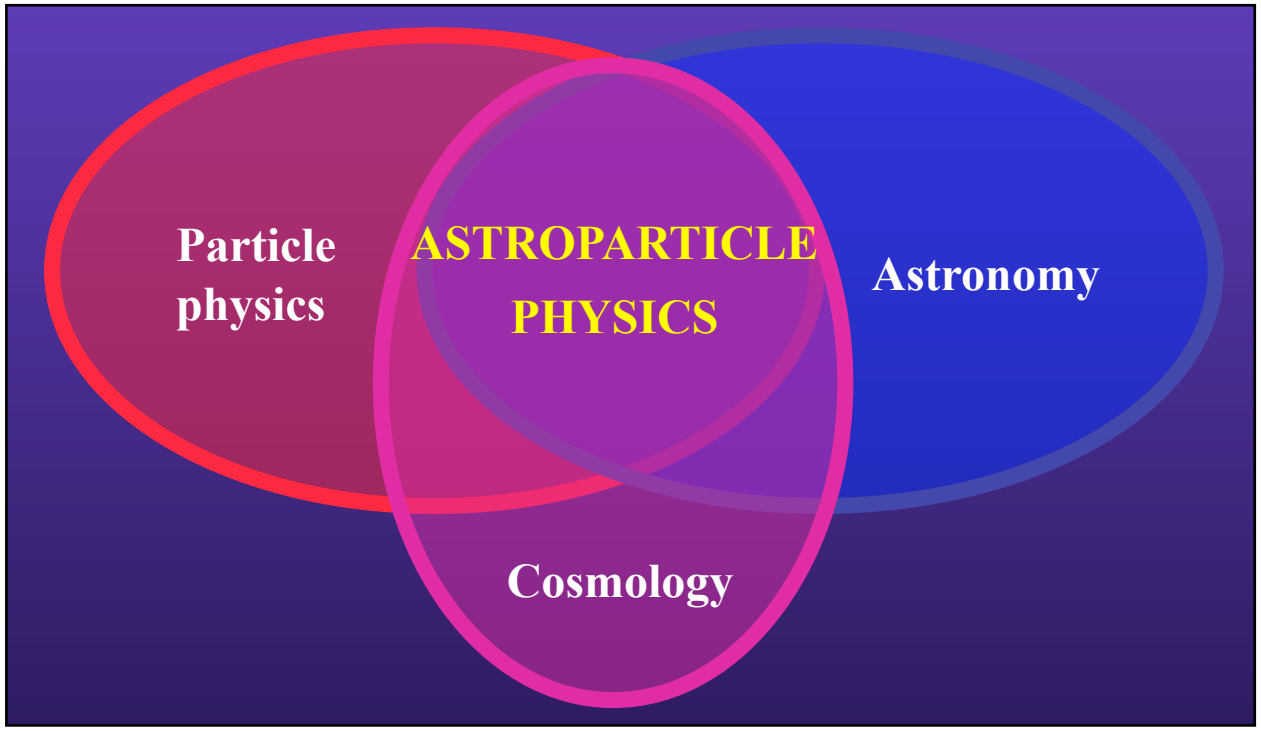
Astroparticle Physics

Nathalie PALANQUE-DELABROUILLE
CEA-Saclay

CERN Summer Student Lectures, August 2009



- Composition of Universe ?
- Evolution?
- Extreme phenomena ?

Astroparticle Physics (1/3)

Nathalie PALANQUE-DELABROUILLE
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1) What is Astroparticle Physics ?
   Cosmic Microwave Background
   Dark energy

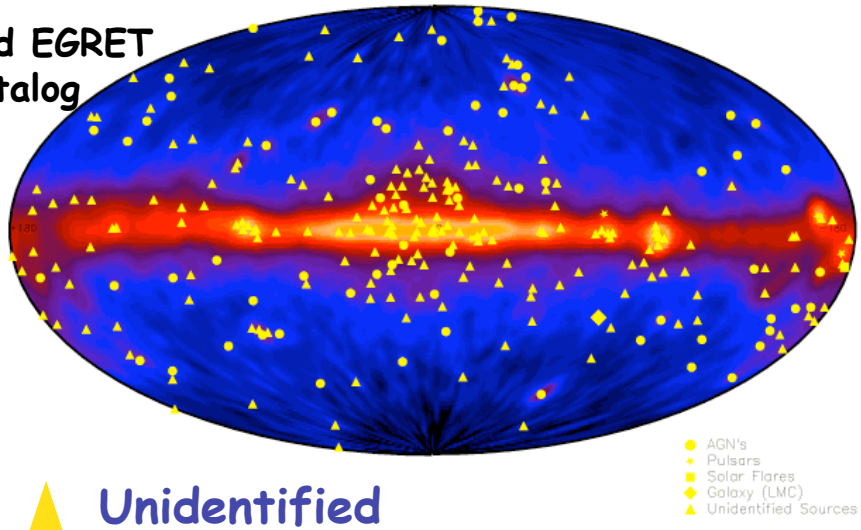
2) Dark matter

3) High energy astrophysics

Today's HE universe

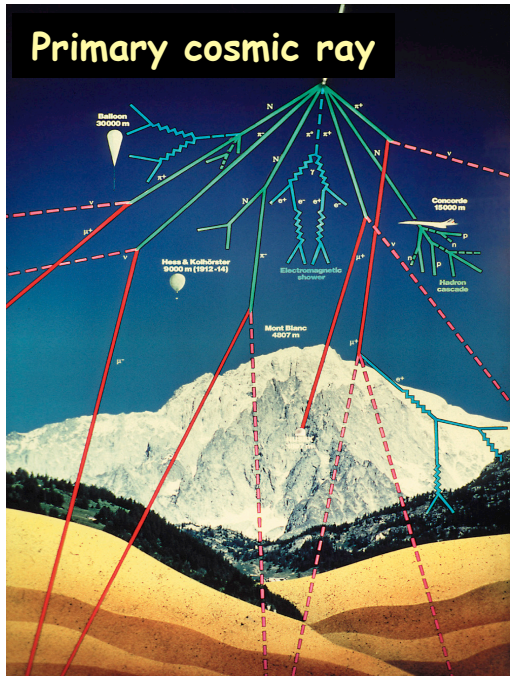
Astroparticle → high energy phenomena, cosmic accelerators

Gamma rays



Unidentified sources

Cosmic rays



Neutrinos

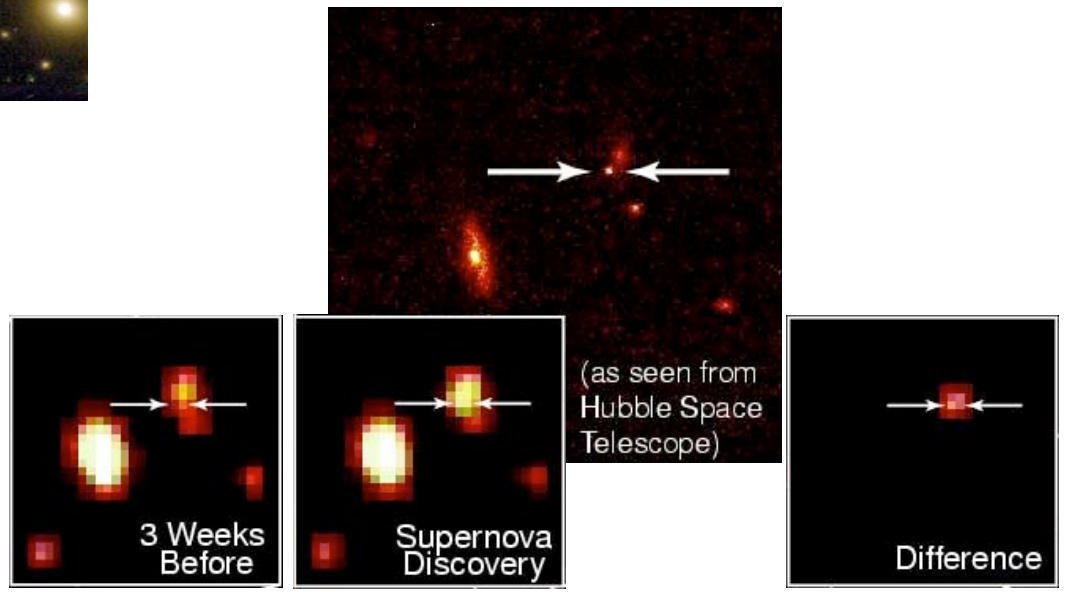
many astrophysical sources
(sun, galactic center, AGN…)

⇒ Lecture 3

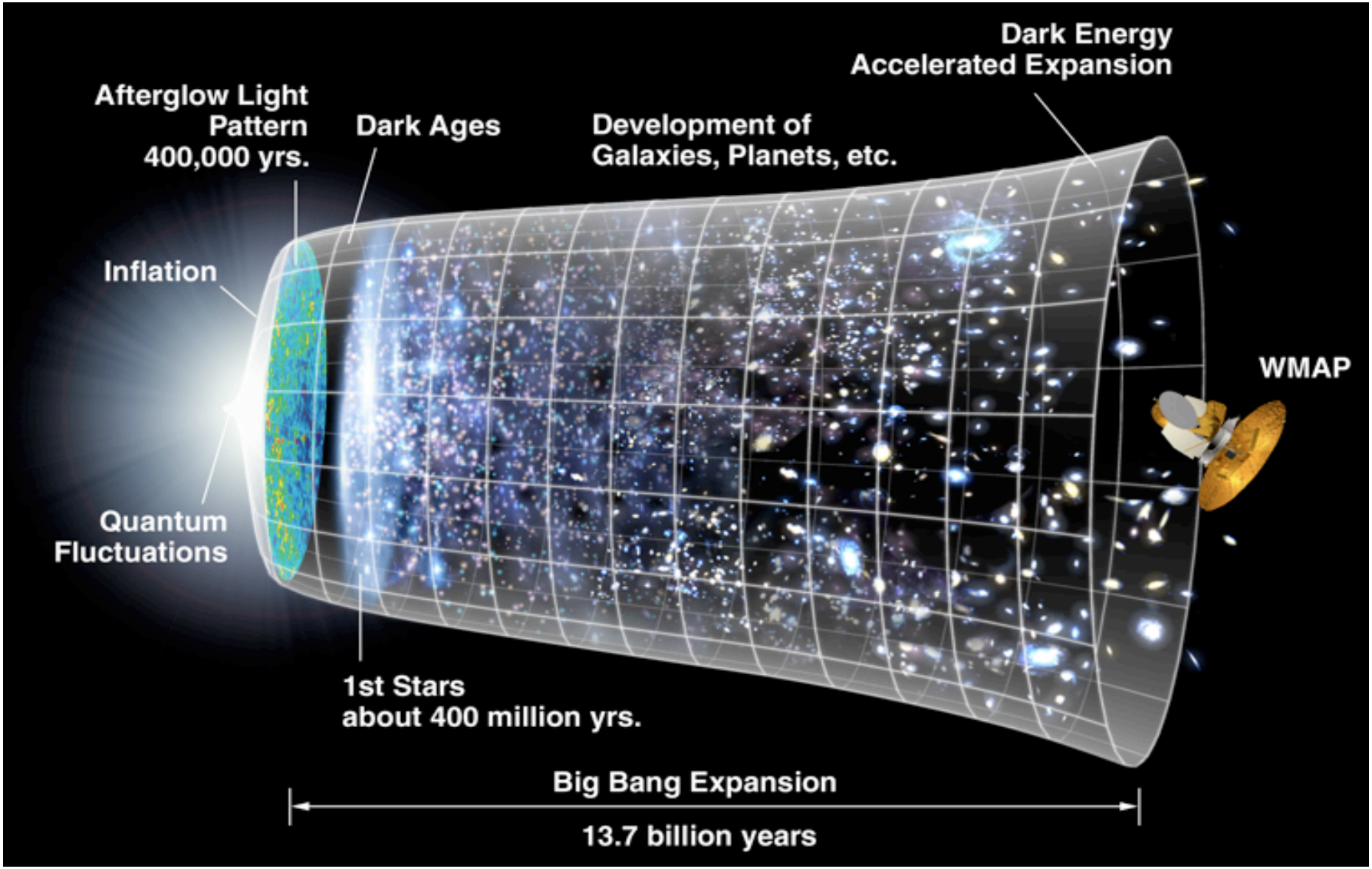
Content of the universe

Dark matter ⇒ Lecture 2

Lecture 1 ⇐ Dark energy



Evolution of the Universe

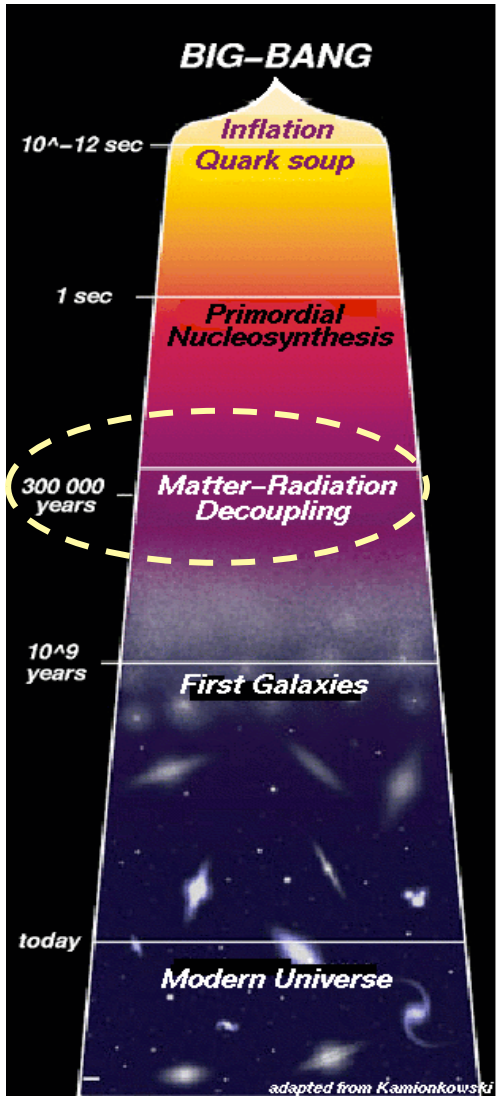


Lecture outline

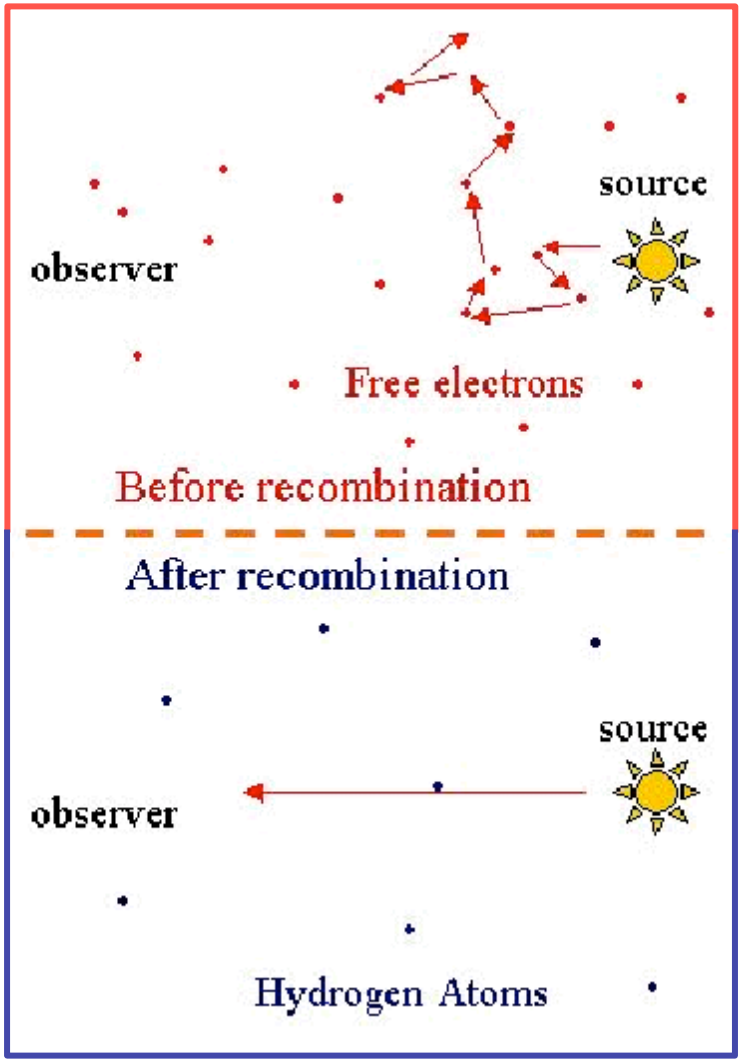
1) What is Astroparticle Physics ?
   Cosmic Microwave Background
   Dark energy

2) Dark matter

3) High energy astrophysics



End of opaque Universe



Cannot see further back

Multiple scatterings of γ on e- produces "thermal" spectrum at T = 3000 K ($z \sim 1100 = a_0 / a_{rec}$)
t = 380 000 yrs

"Uniform" background at $T_0 = 2.7$ K

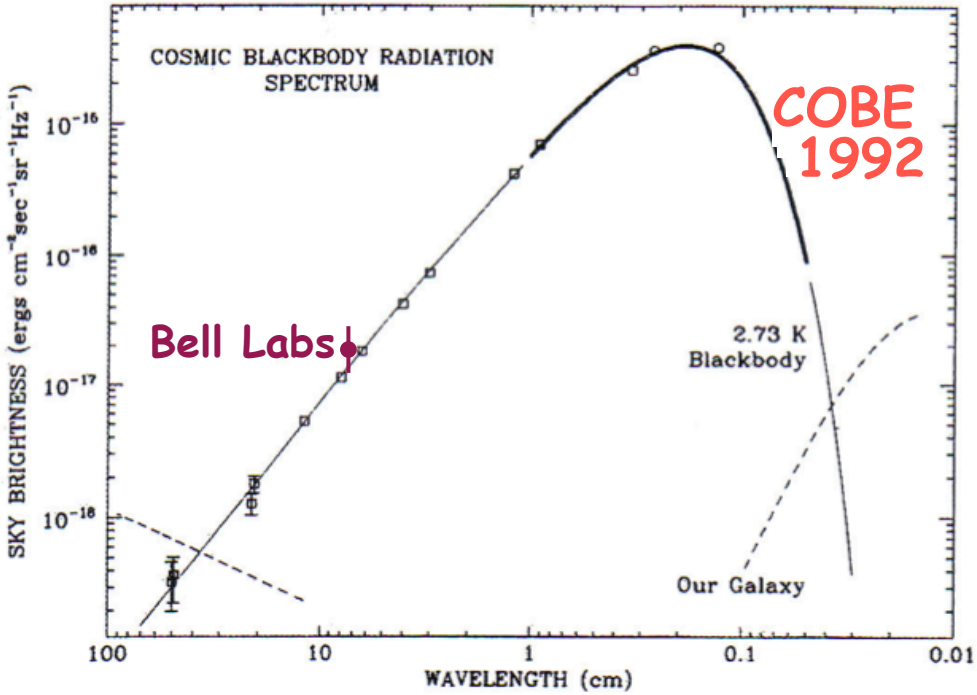
Discovery

Discovered in 1965
as "excess noise"
(Nobel Prize in 1978)

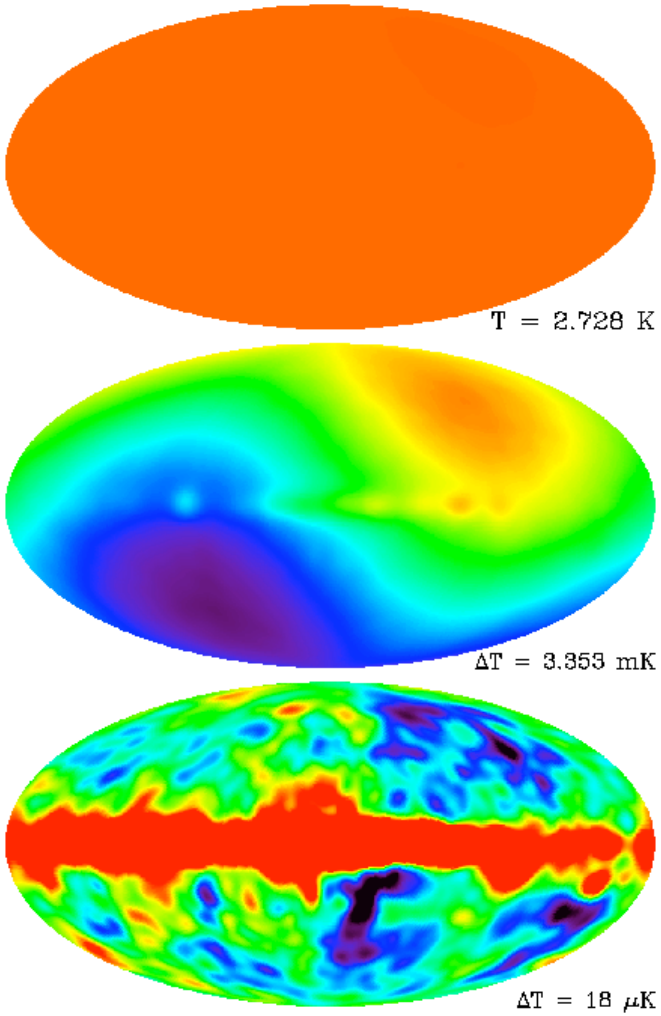
Wilson Penzias

(+ Robert Dicke)

25 years later



COBE sky maps

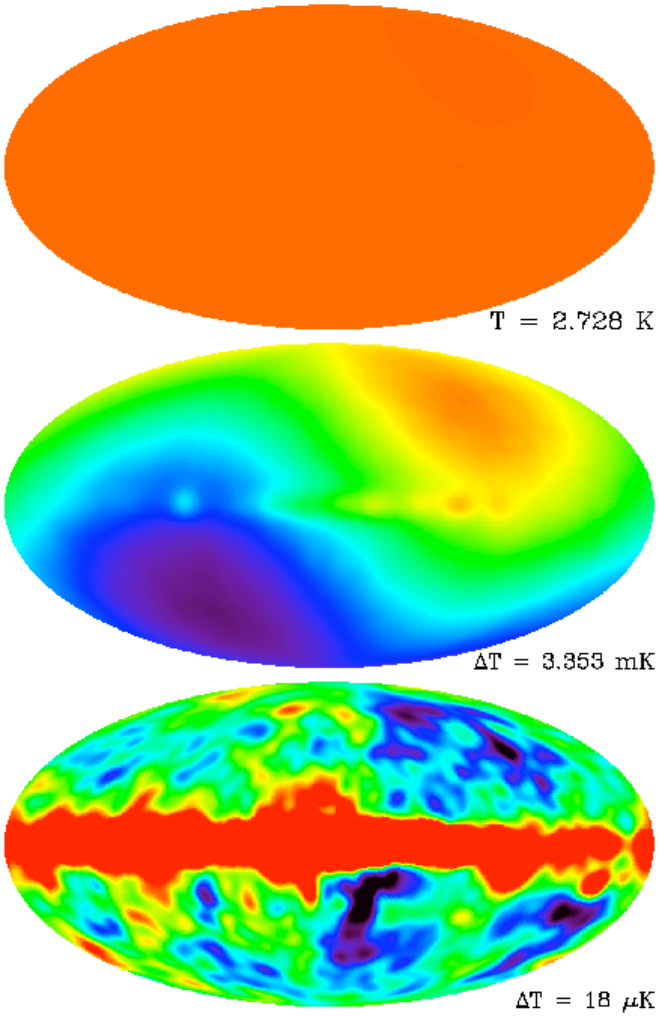


T = 2.7 K

ΔT = 3.4 mK
(after subtraction of constant emission)

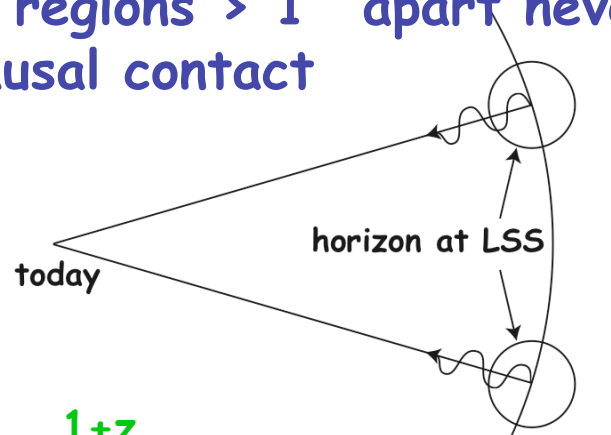
ΔT = 18 μK
(after subtraction of dipole)

COBE sky maps



scale 0-4 K: very homogeneous
→ cosmological origin

Yet, regions > 1° apart never in causal contact



$$\theta_{LSS} \sim \frac{10^3 \times 3.10^5}{14.10^9} \text{ rad} \sim 1°$$

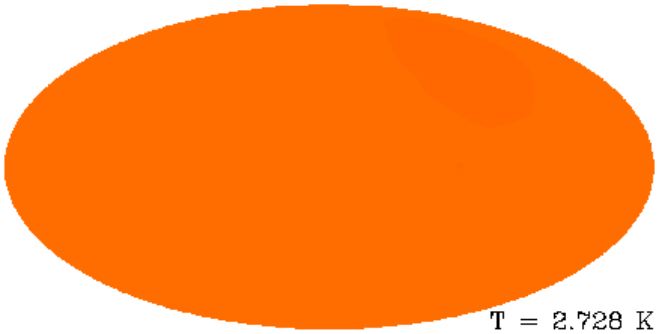
1+z

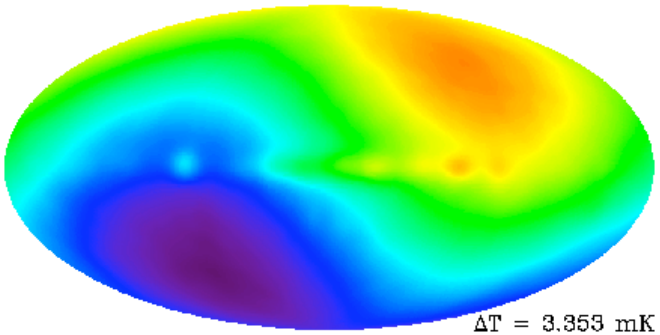
t LSS

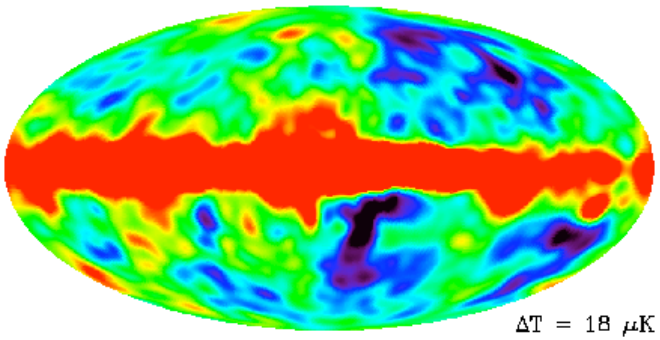
t now

Inflation ?

COBE sky maps







Doppler effect due to motion of Earth w.r.t. CMB
(v = 370 km/s towards Virgo)

Anisotropies : potential wells
Early gravitational seeds for structure formation?
(+ foregrounds)

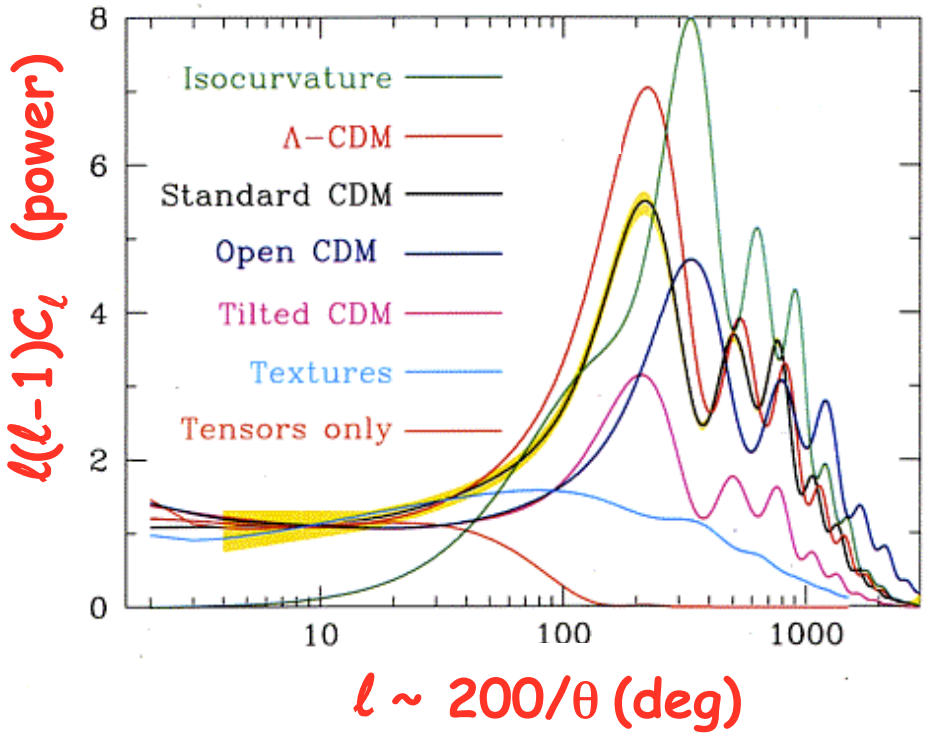
Anisotropies

- Before recombination, Universe = plasma of free e^- and protons
- Oscillations due to opposite effects of
  - gravity
  - pressure

As far out as the sound horizon at recombination

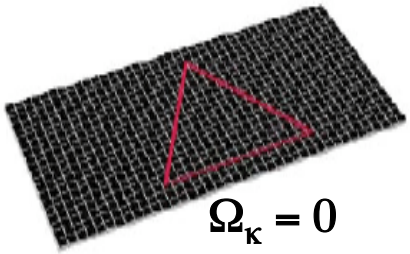
- Presented as a power spectrum
  - multipole ℓ
  - amplitude $a_{\ell m}$
  - power ~ $|a_{\ell m}|^2 \sim C_\ell$

cosmology

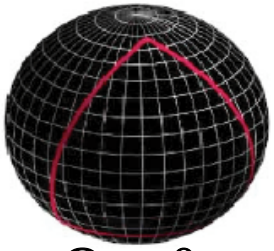


Sound horizon at recombination

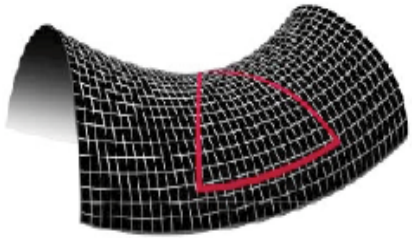
Limited by causality → maximum scale



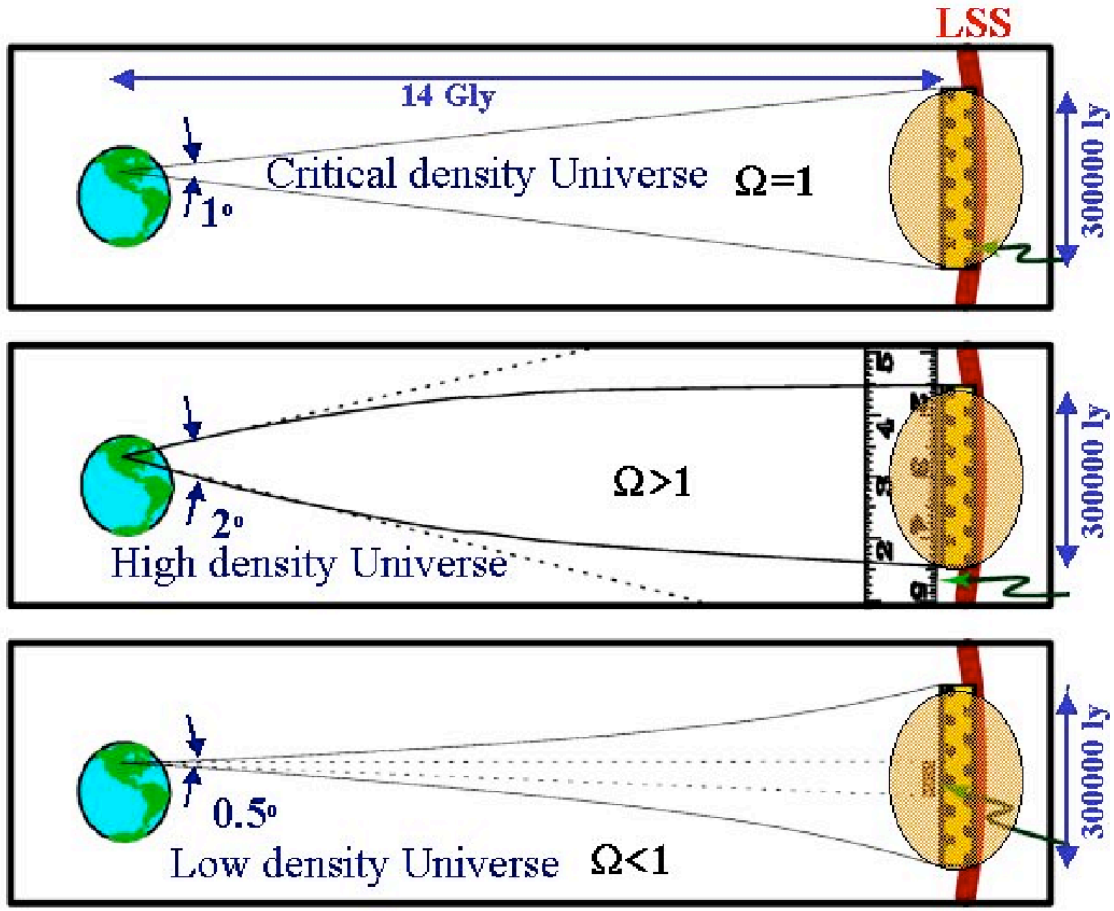
$\Omega_\kappa = 0$

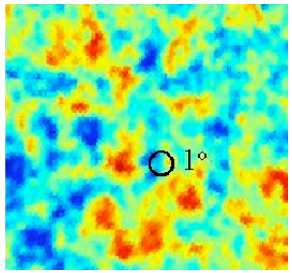


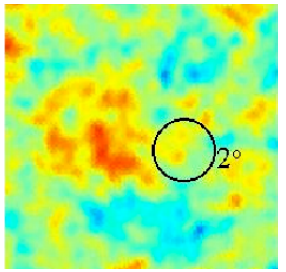
$\Omega_\kappa < 0$

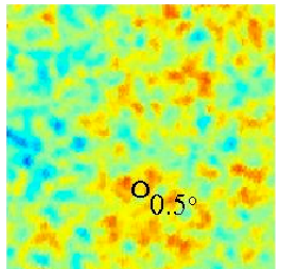


$\Omega_\kappa > 0$





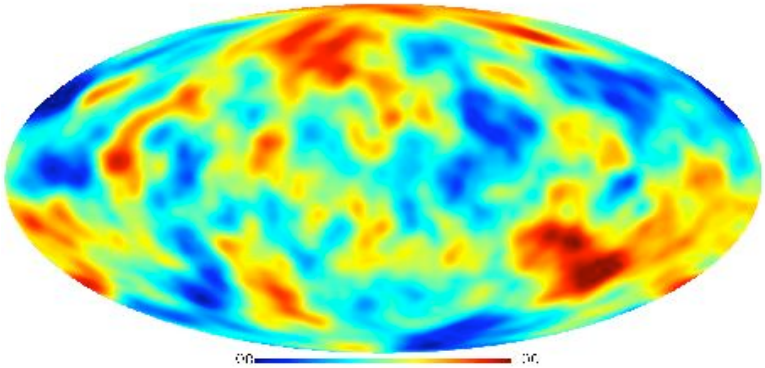




⇒ Max scale relates to curvature Ω_k of the universe

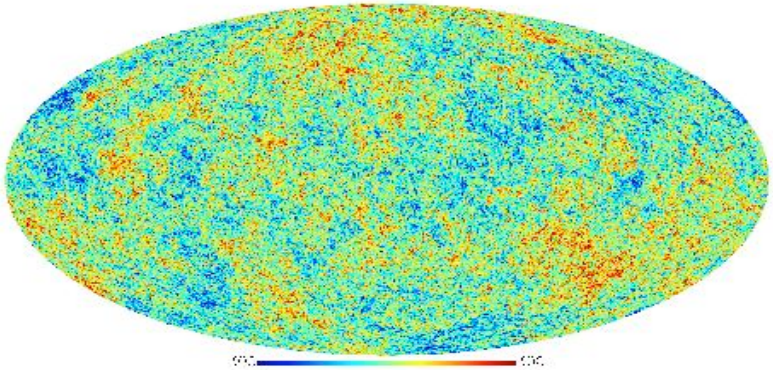
2nd generation satellite

COBE
(7 degree resolution)



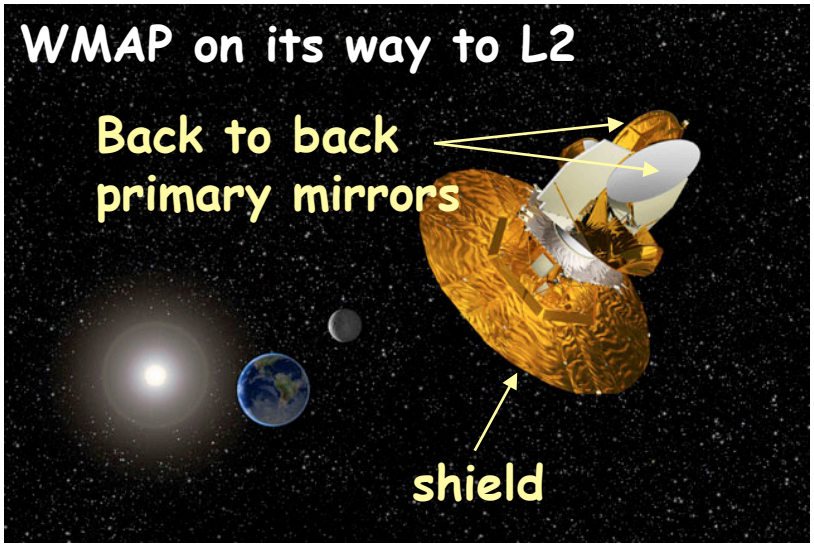
($\ell < 20$)

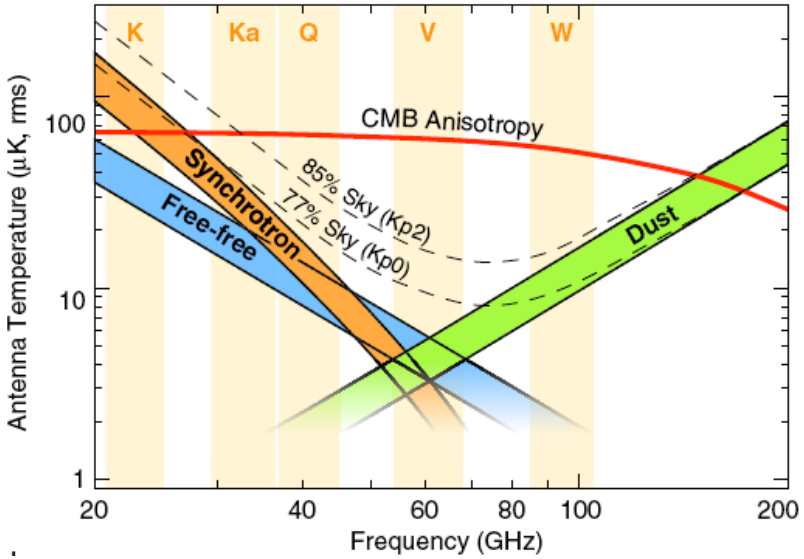
WMAP
(0.25 degree resolution)



($\ell < 700$)

WMAP

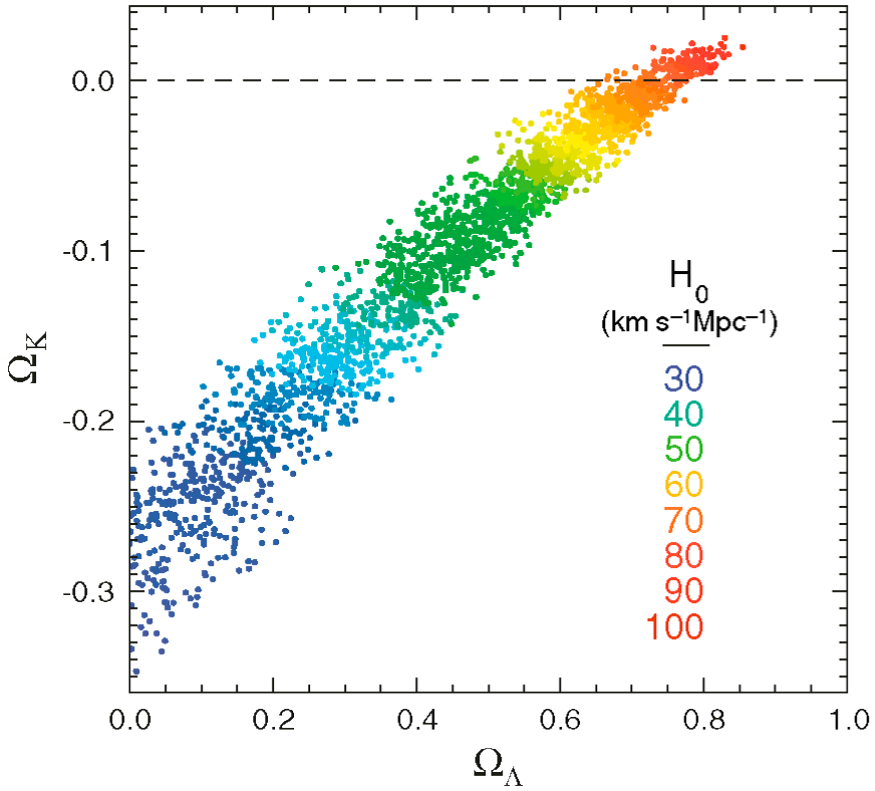




- Very low temperature signal
  ⇒ Need shielding from
  Sun, Earth, Moon, (Jupiter)
- Lagrange point L2: position
  of co-rotation with Earth
  ⇒ Stability of conditions
- 5 frequency channels
  Foreground removal (<90 GHz)

Launch: Jun. 2001
First results: 2003

"Concordance model"



Dunkley et al, astro-ph/0803.0586v1

Curvature of the Universe (95% CL)

WMAP5 only:
$-0.063 < \Omega_\kappa < 0.017$

WMAP5 + SN + BAO:
$-0.018 < \Omega_\kappa < 0.009$

Komatsu et al., astro-ph/0803.0547v1

H_0: present expansion rate of Universe
H_0 from HST = 72 ± 8 km/s/Mpc

"Concordance model"

$\Omega_i = \rho_i / \rho_c$

$\Omega_{tot} = 1$ for $\Omega_k = 0$

WMAP alone

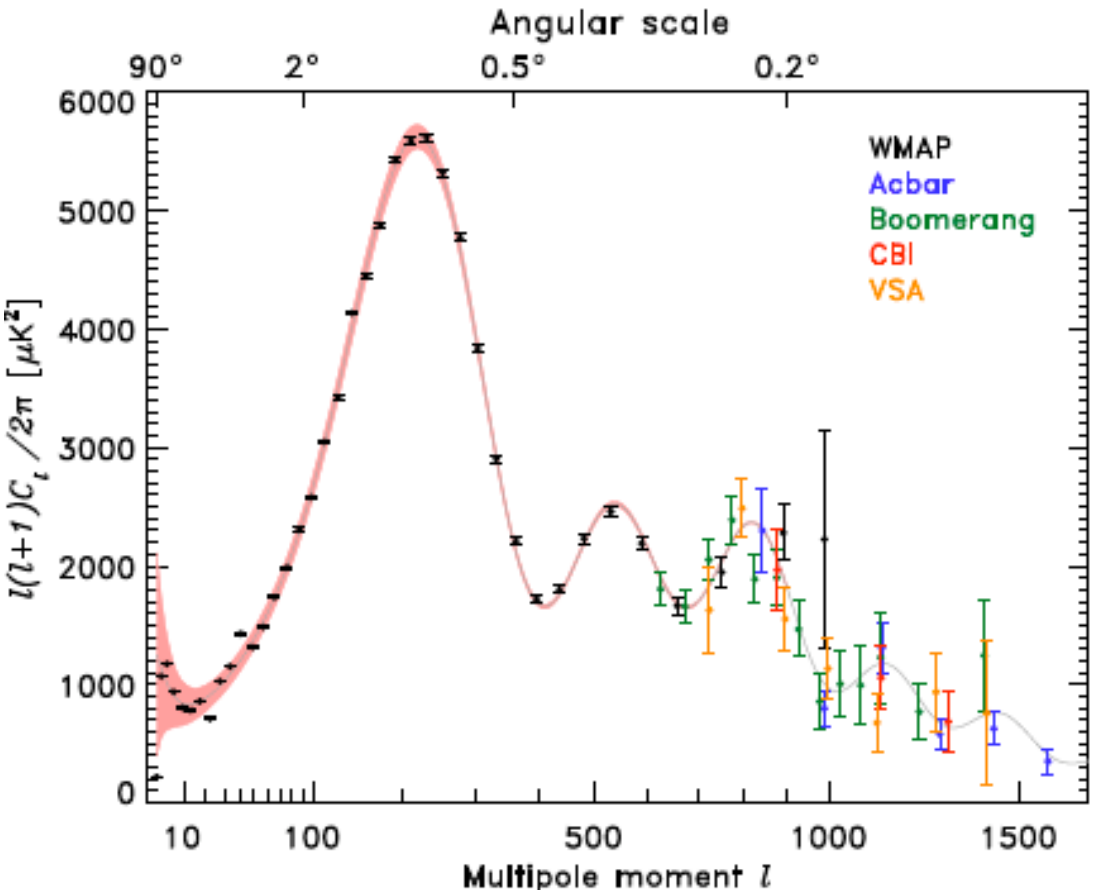
(flat ΛCDM model)

H_0	=	0.74 +/- 0.03
Ω_b	=	0.044 +/- 0.003
Ω_m	=	0.26 +/- 0.01
Ω_Λ	=	72 +/- 3 km/s/Mpc
…		…

compatible w/ H_0 from HST (72 +/- 8 km/s/Mpc)

factor 2 improvement when combining with SN & BAO

Komatsu et al, astro-ph/0803.0547v1



Bennett et al, Ap.J. Suppl. 148 (2003) 97

Beyond WMAP

- More frequency channels
- Improved resolution
- Polarization

→ Planck mission

Probe of inflation (10^{-35} s after Big Bang)
(gravity wave-induced polarization)

Planck mission

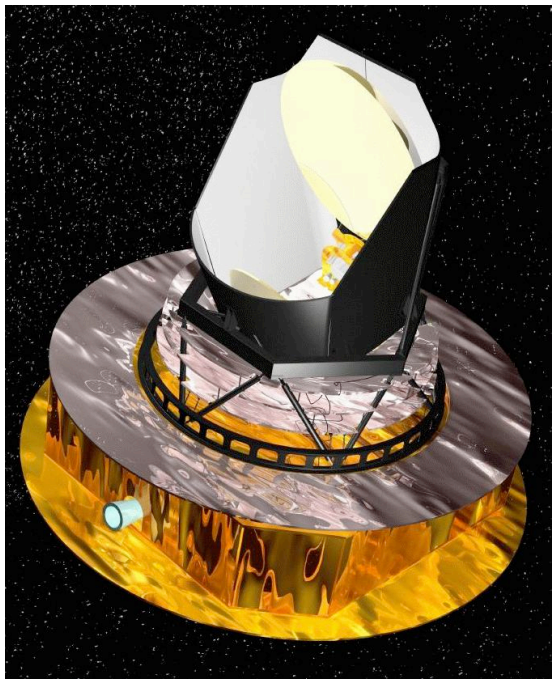
2 instruments LFI & HFI

HEMTS Bolometers

Freq coverage from 30 to 850 GHz
(9 channels)

Polarization sensitive

Launch successful (June 2009)



Lecture outline

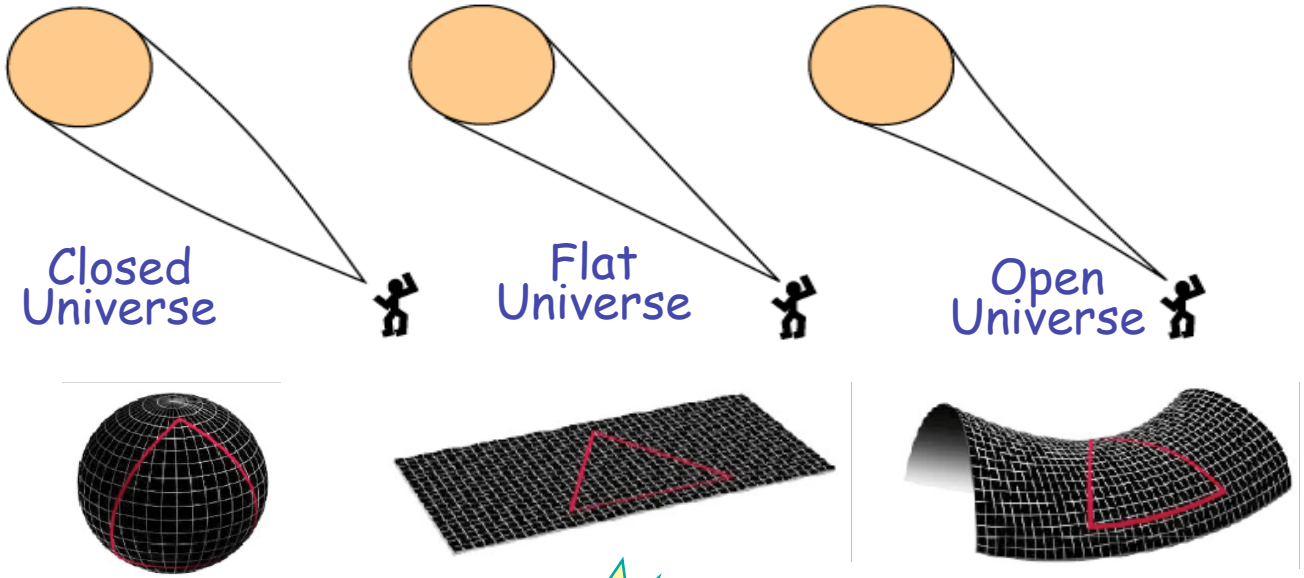
1) What is Astroparticle Physics ?
   Cosmic Microwave Background
   Dark energy
      Supernovae searches
      Baryon acoustic oscillations

2) Dark matter

3) High energy astrophysics

Measurement of the geometry

$$1 - \Omega_k(t) = \sum \Omega_x(t) + \Omega_\Lambda(t)$$



AT A GIVEN DISTANCE

Known physical size — CMB — **angle** depends on geometry

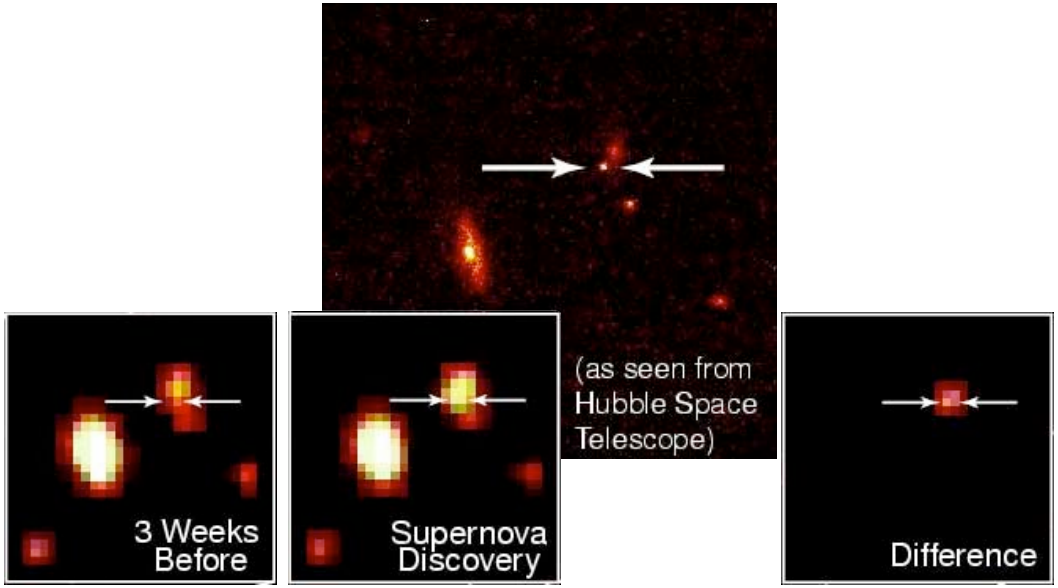
Known luminosity — SN Ia — **flux** depends on geometry

White dwarfs in binary systems

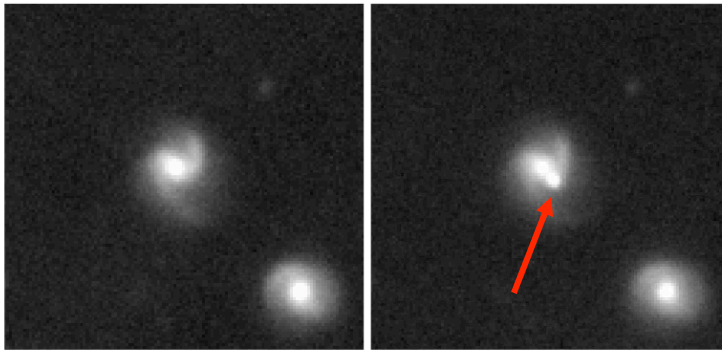
Very luminous ($L \sim 10^{10}\ L_{sun}$)
→ out to high z

Fixed conditions ($1.4\ M_{sun}$)
→ standard candle

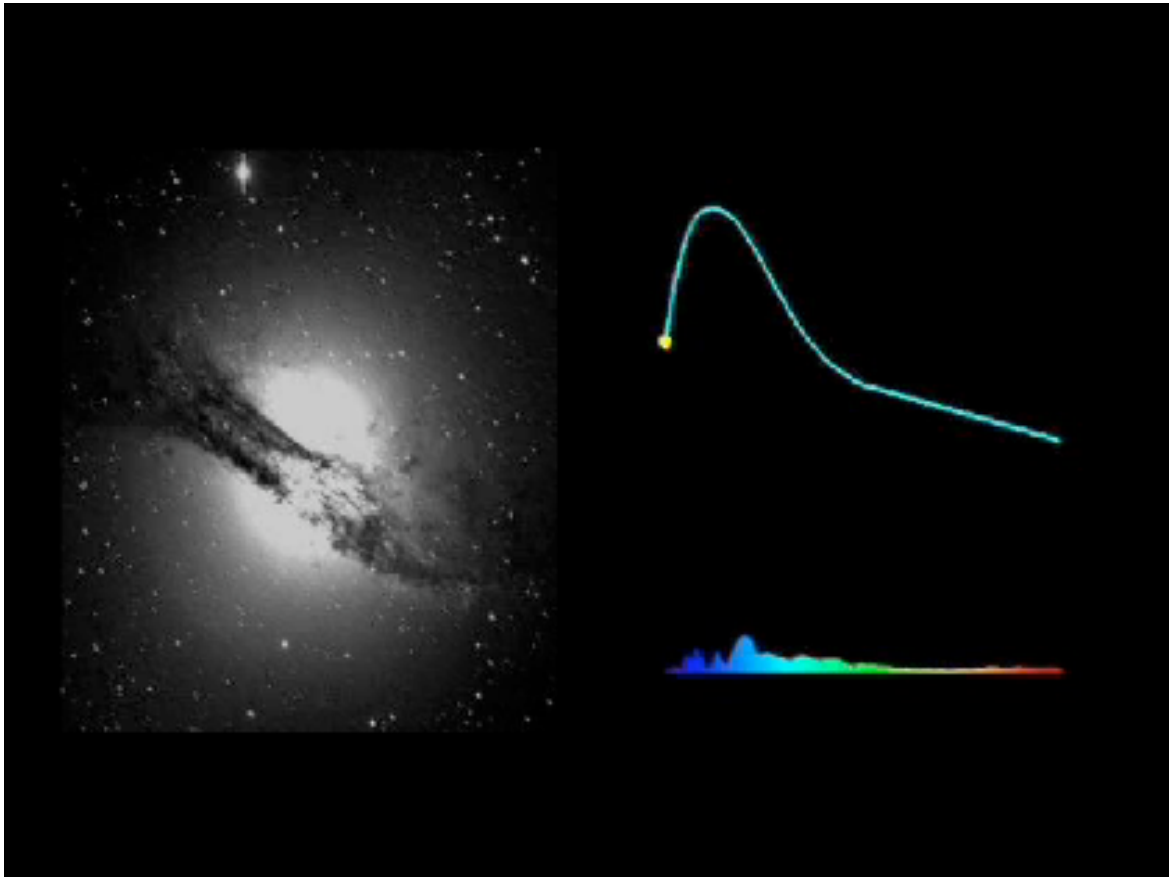
Type Ia searches



3 steps
- discovery (differential photometry)
- identification (spectrum)
- photometric follow-up → light curve



Study of a supernova



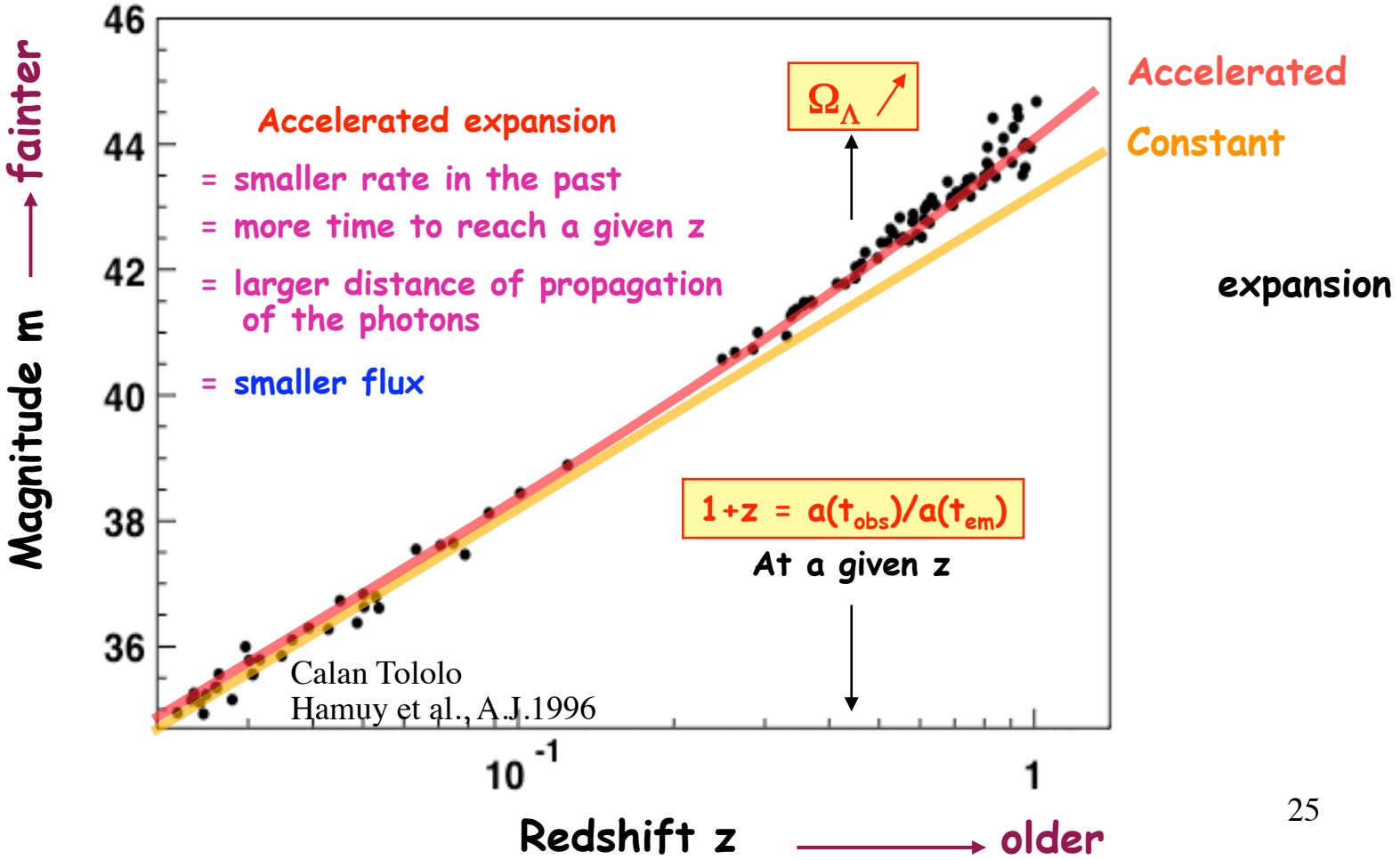
Photometry
→ light-curve
→ max flux
→ distance

Spectrum
→ SNIa
→ redshift z

Hubble diagram

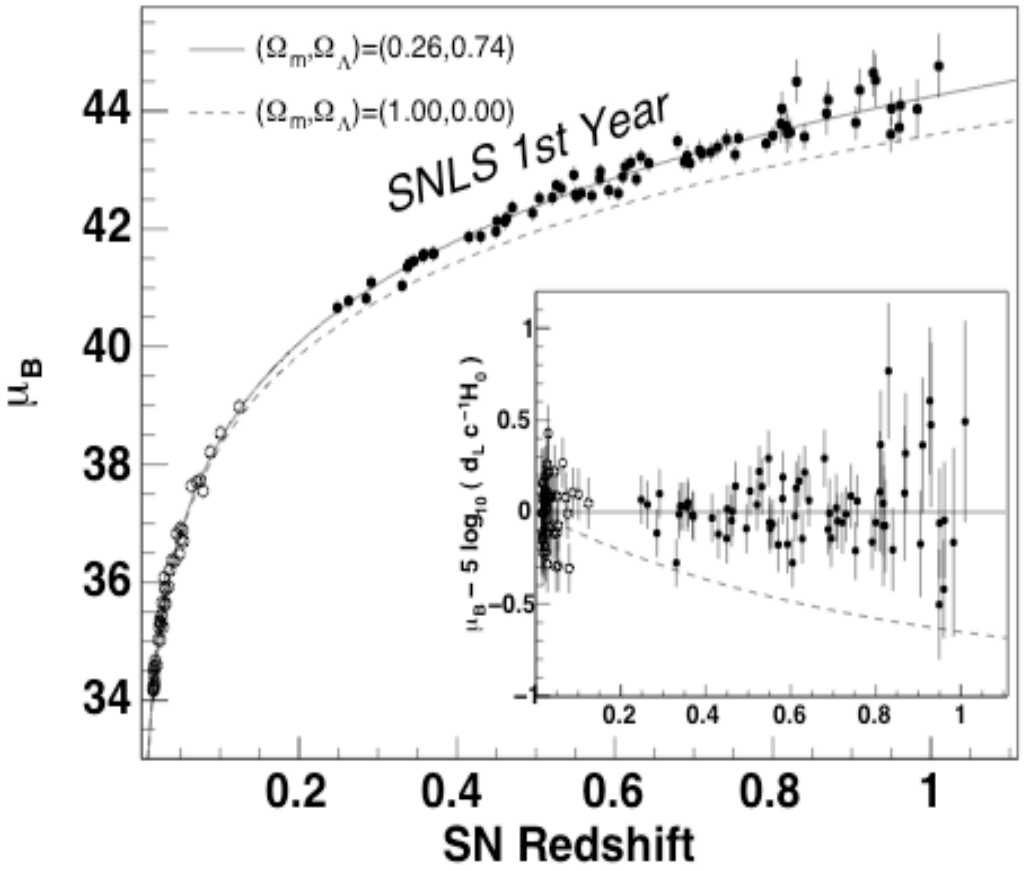
$m = -2.5 \log\Phi + cst$

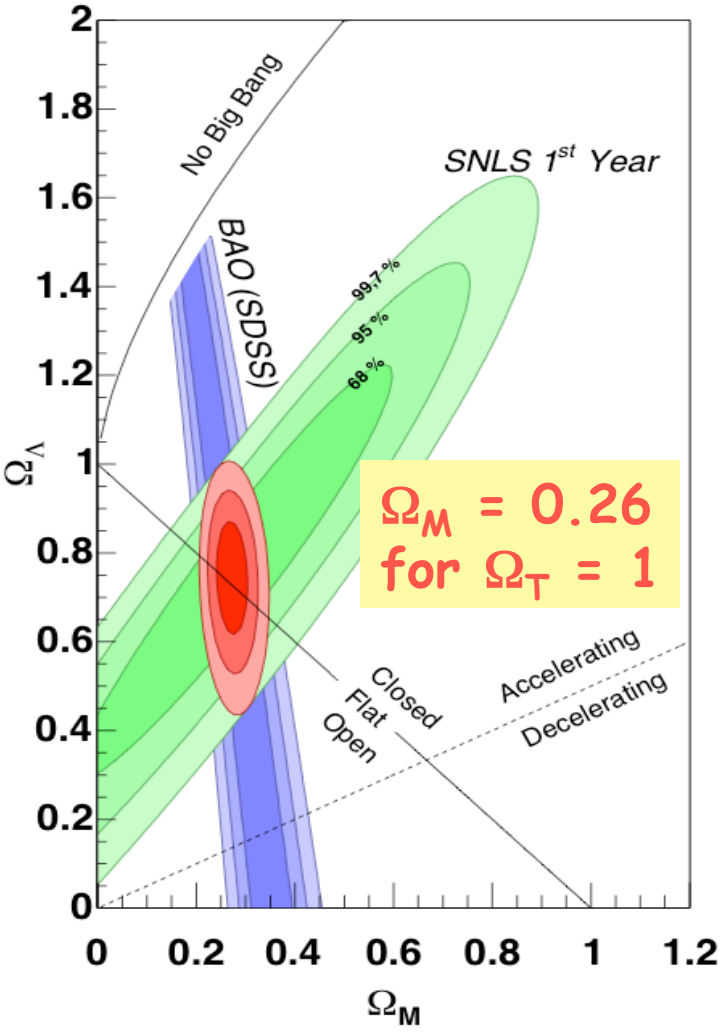
$\Phi \cong \mathcal{L} / 4\pi d_L^2$
where $d_L(z, H_0, \Omega_M, \Omega_\Lambda, w, ..)$



SNLS 2006

Astier et al., A&A 447 (2006) 31A





Beyond Ω_Λ...

Cosmological cst

- ρ_v incompatible with a possible ρ_v from particle physics
  - $\Omega_\Lambda = 0.7 \rightarrow \rho_v = \Omega_\Lambda \times \rho_c \sim 10^9$ eV m^{-3}
  - ρ_v from quantum field theory : $\rho_v \sim M^4 / (hc)^3$
    taking $M = M_{pl} \rightarrow \rho_v \sim 10^{132}$ eV m^{-3}

- Coïncidence problem

  $\Omega_\Lambda = 0.7$, $\Omega_M = 0.3$ yet different evolution with time

Dynamical DE

- quintessence ?

$w = p/\rho$ {
- w = 0 for matter
- w = 1/3 for radiation
- w = -1 for cosmological constant
- w > -1 for "quintessence", dynamical DE

Equation of state of DE

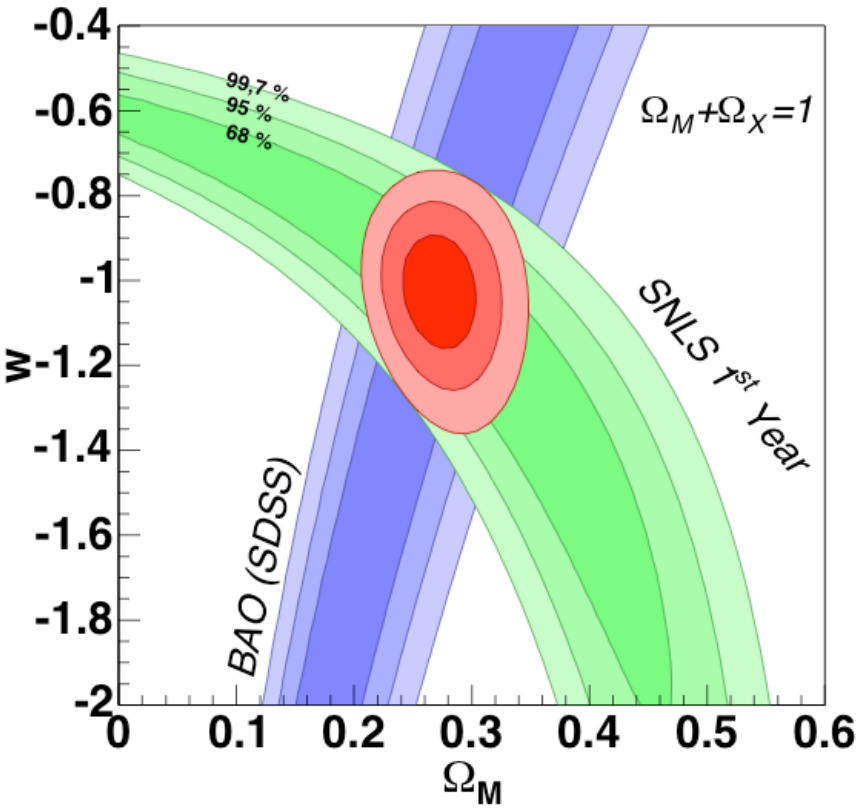
Time evolution of dark energy density ρ_{de} determined by w

$$w = \frac{p_{de}}{\rho_{de}} \qquad \frac{1}{\rho_{de}}\frac{d\rho_{de}}{dt} = -3H(1+w)$$

w = -1	cosmological constant
w = 0	matter
w = 1/3	relativistic matter, radiation

No evidence so far for w ≠ -1
(and no serious theory)

Astier et al., A&A 447 (2006) 31A



w = -1.02 ± 0.10

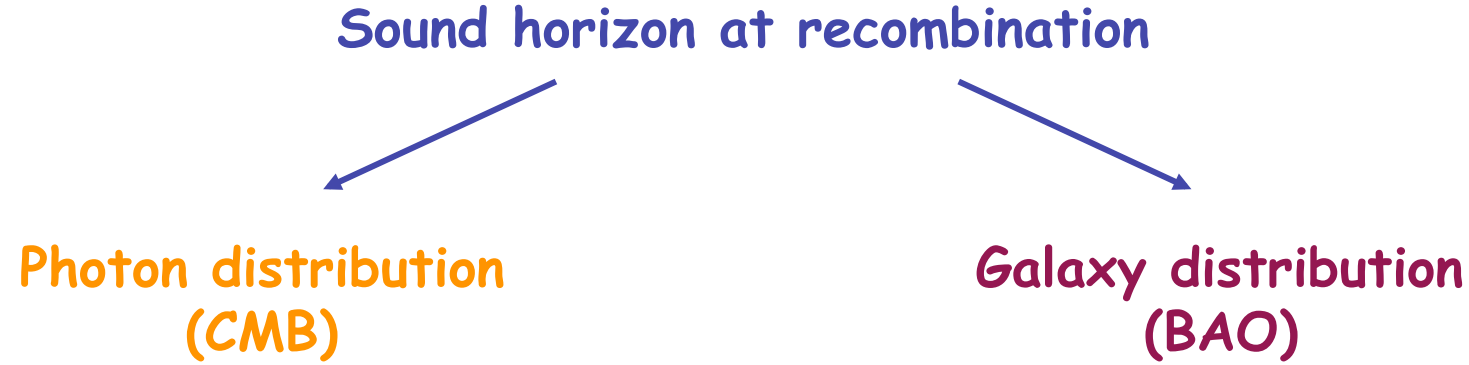
Standard ruler

Standard candles : supernovae

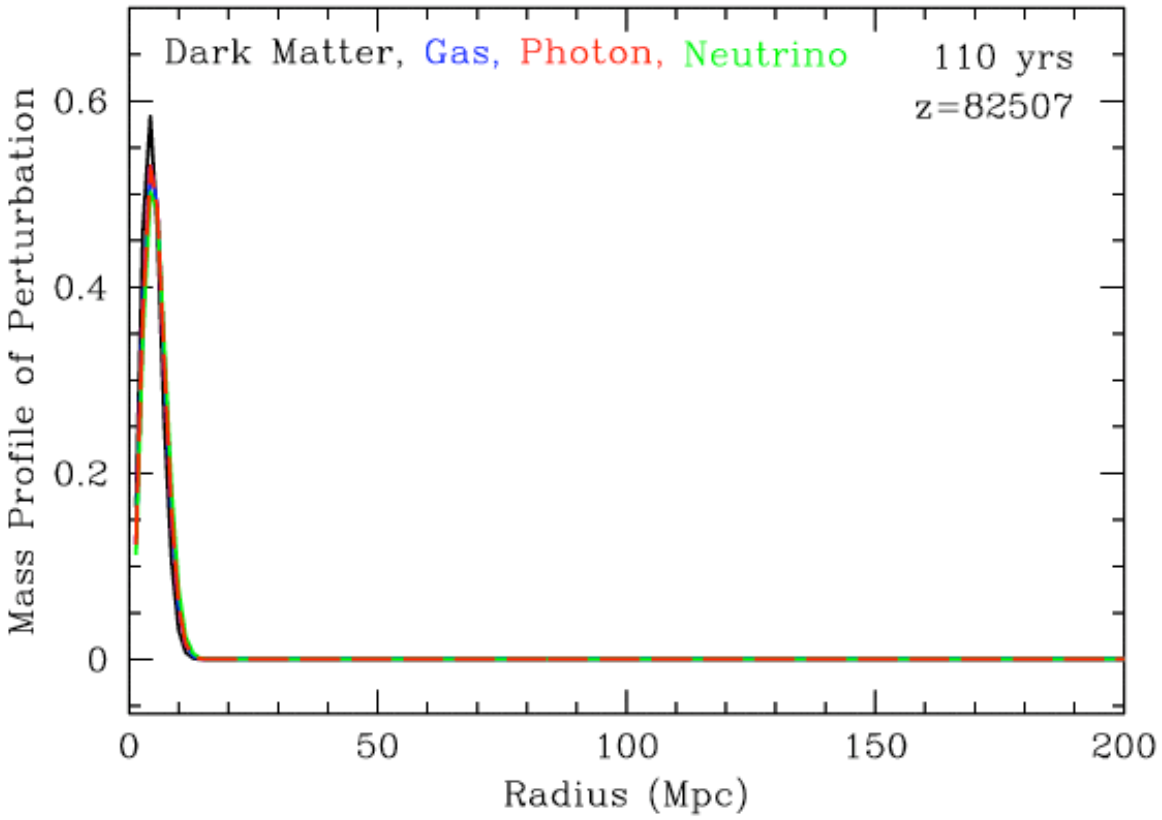
- evolution (variation of flux) and impact on cosmology?
- dust?

Standard rulers

- almost no systematics !



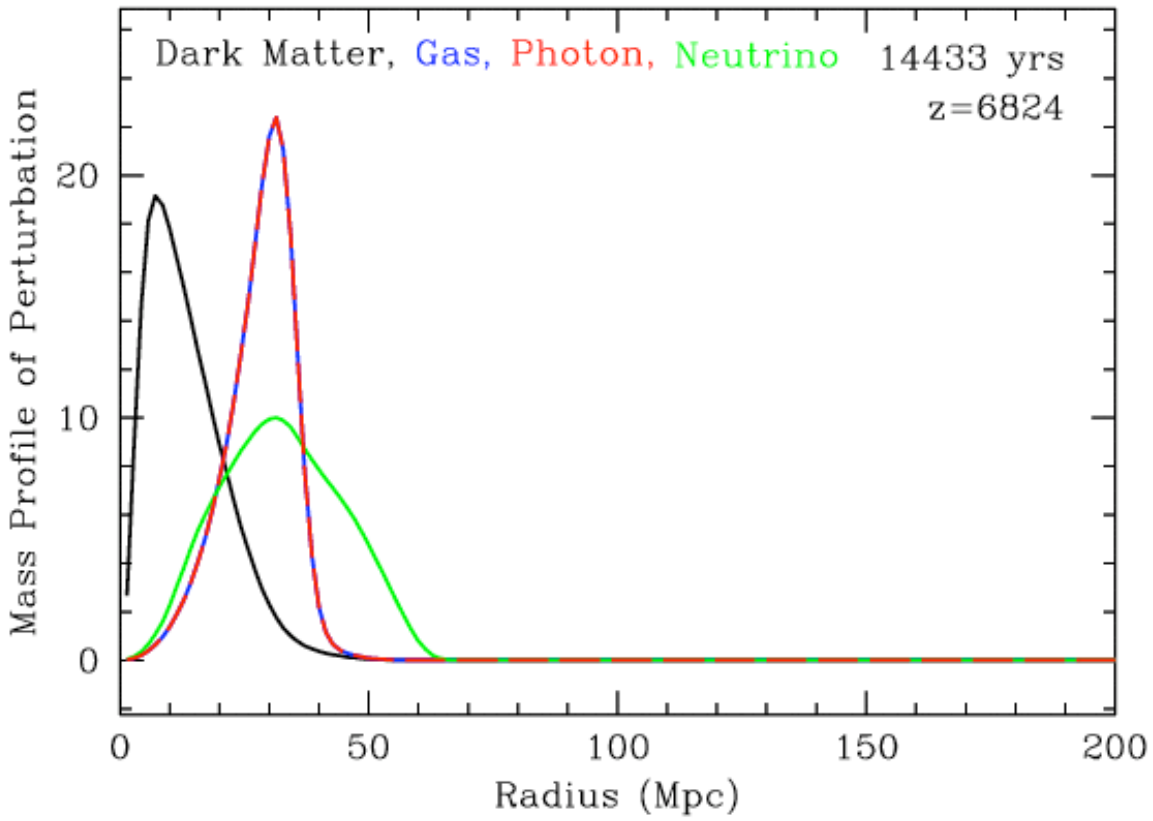
Imprint on galaxies



Universe very close to smooth + tiny perturbations

Mass profile = ρR^2 **R = comoving radius**

Imprint on galaxies



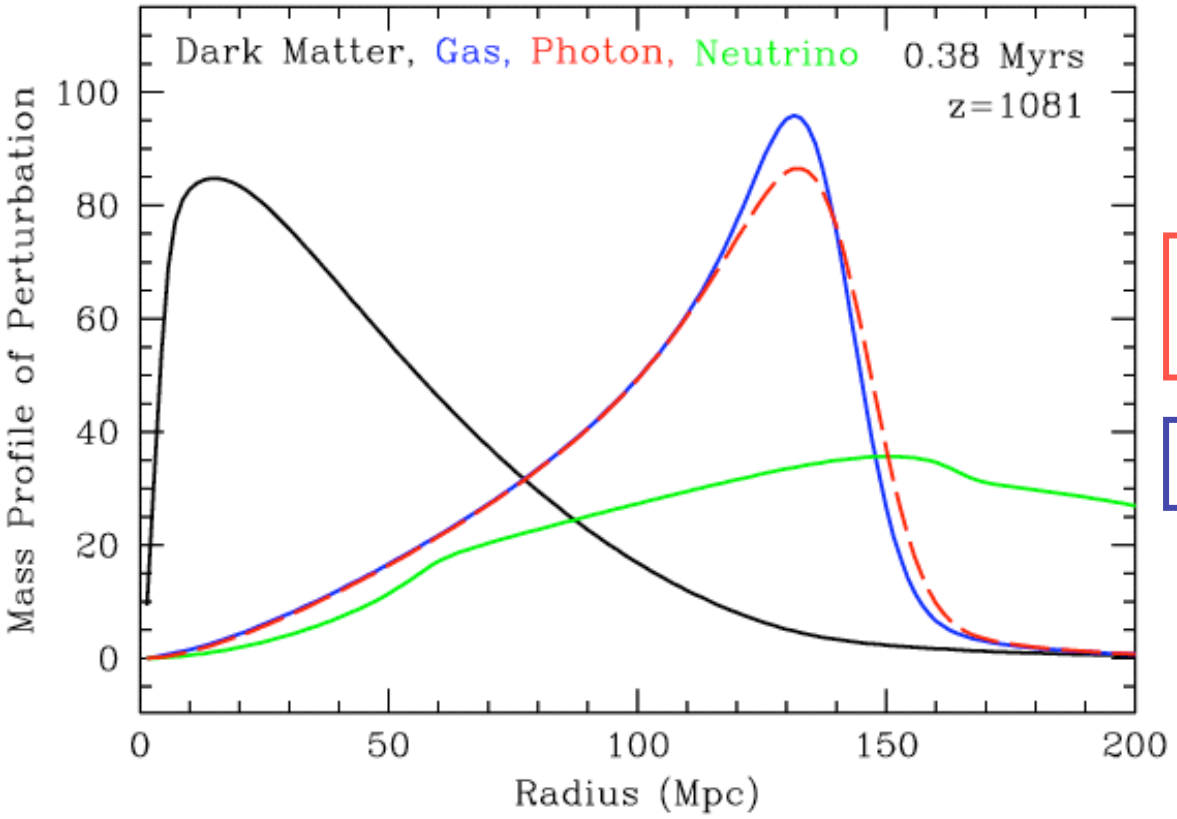
ν's don't interact
→ stream away

Gas hot & ionized
→ photon/e- plasma
with huge pressure
→ expanding
sound wave

CDM no pressure
→ sits still &
accretes surroundings
(overdense)

Mass profile = ρR^2

Imprint on galaxies



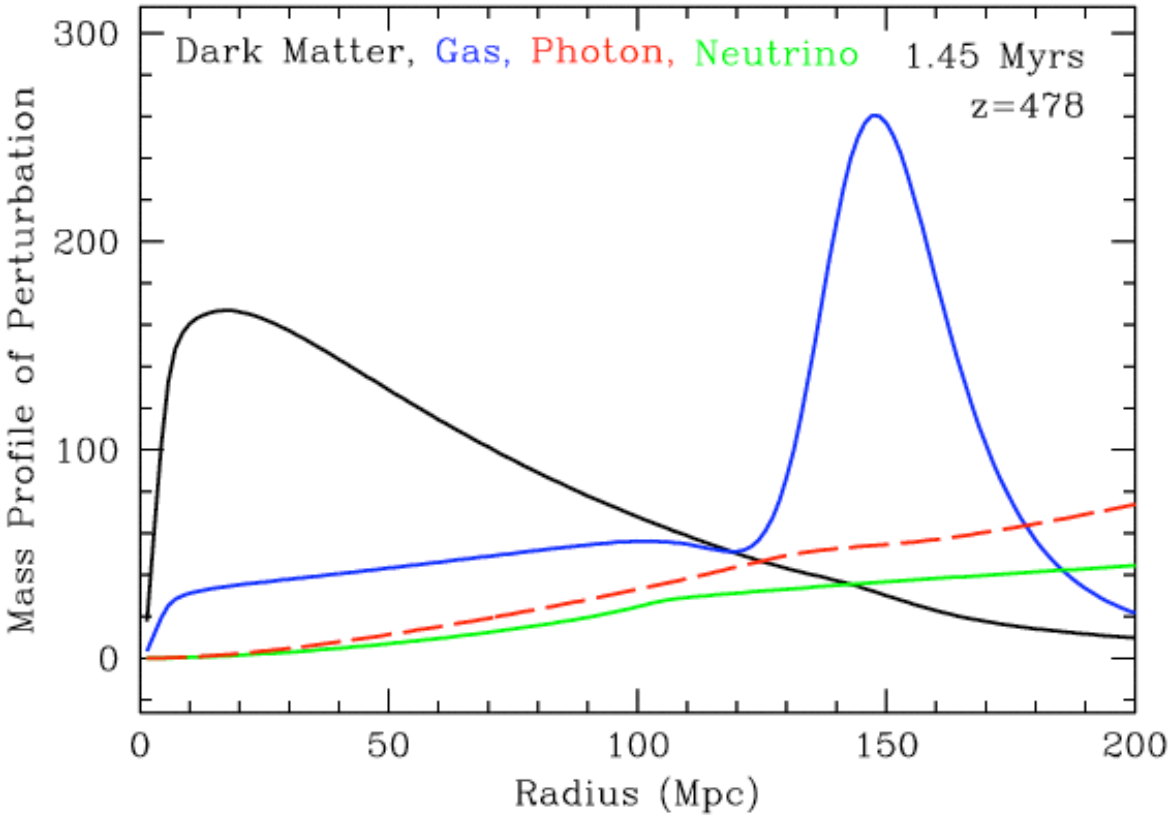
Recombination $e^+e^- \rightarrow p$
(t = 380.000 yrs)

Photons stream past gas particles

Gas wave slows down

Mass profile = ρR^2

Imprint on galaxies

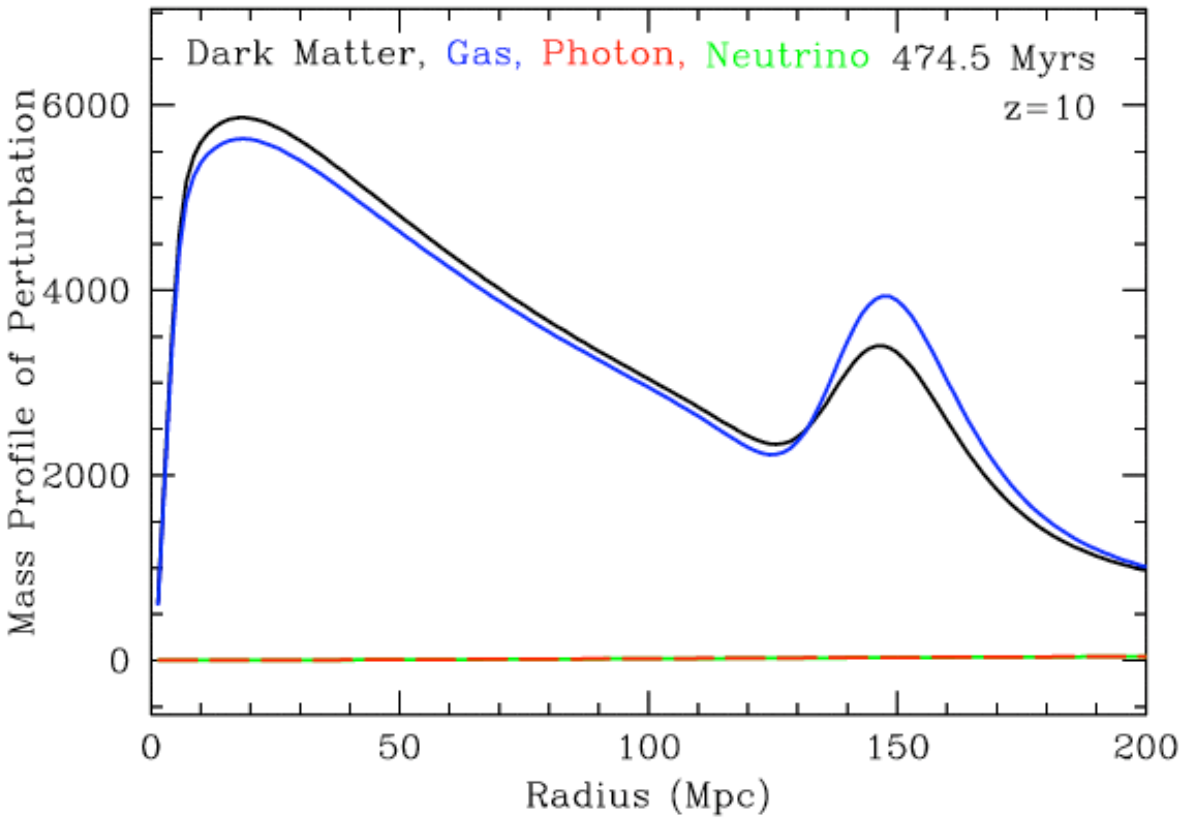


a CDM perturbation at center

a gas perturbation 150 Mpc away

Mass profile = ρR^2

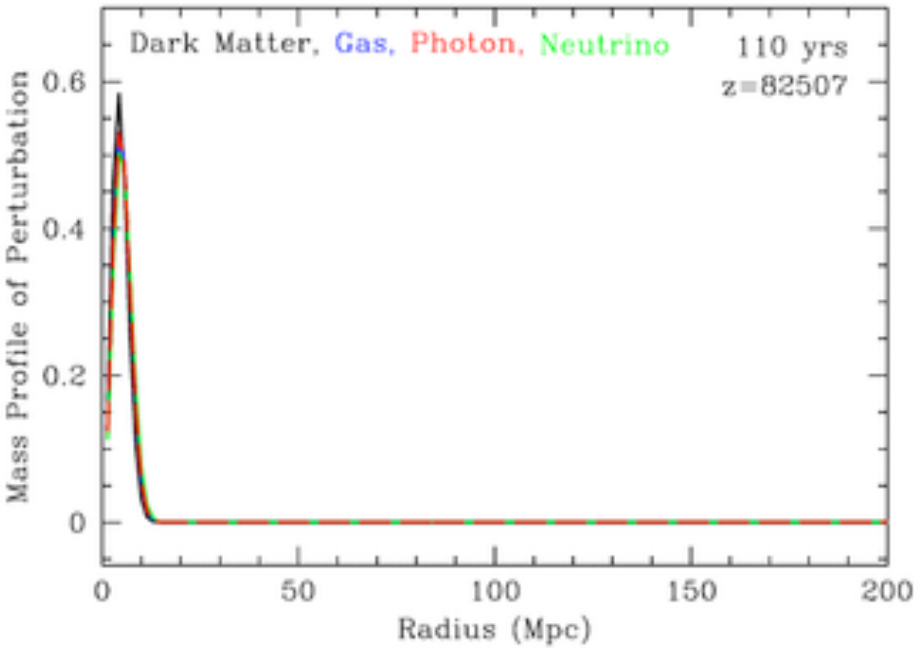
Imprint on galaxies

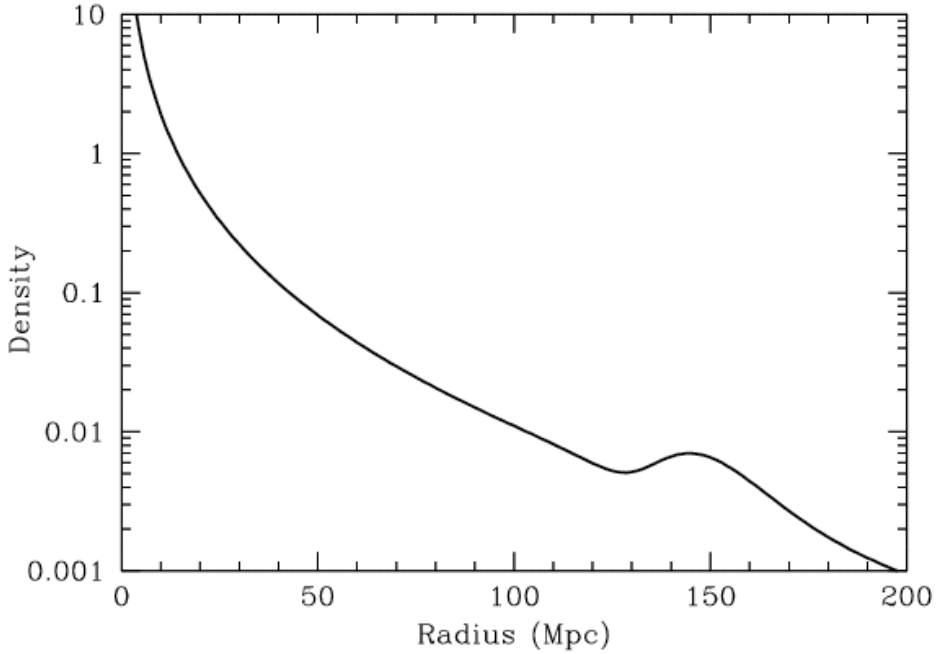


Acoustic peak decreases relative to original because CDM outweighs gas 5 to 1

Mass profile = ρR^2

Imprint on galaxies



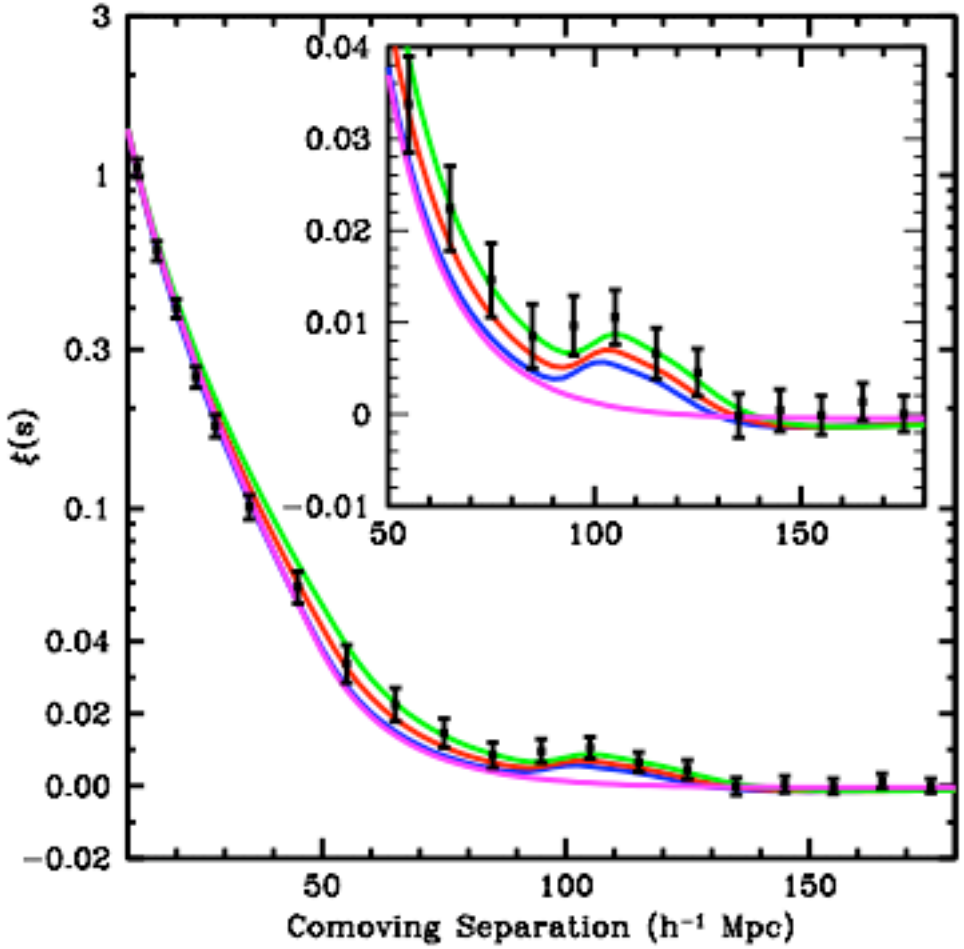


Mass profile = ρR^2

Density = ρ

⇒ small excess in galaxy-galaxy correlation function at 150 Mpc

Sloan Digital sky Survey



Position of acoustic peak :

$$s \approx c_s \, t(z=1100)\,(1+z)$$

$$\propto \frac{1}{H(z=1100)}$$

$$\boxed{\propto \frac{1}{\sqrt{\Omega_M}}}$$

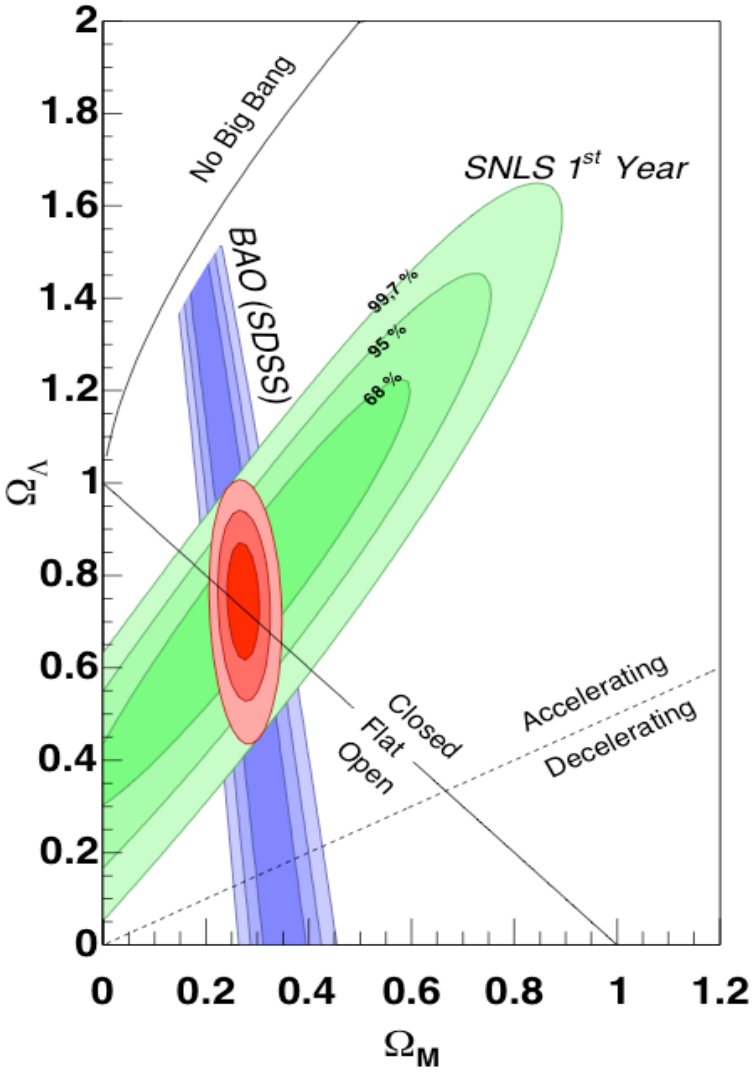
SDSS (z ~ 0.3)

Eisenstein et al, Ap.J. 633 (2005) 560

⇓

$\Omega_{cdm} + \Omega_b = 0.273 \pm 0.025 + 0.123(1+w) + 0.137(1-\Omega_T)$

Conclusions



Energy content of the Universe
Concordance model