# Astroparticle Physics (1/3)

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CERN Summer Student Lectures, August 2008

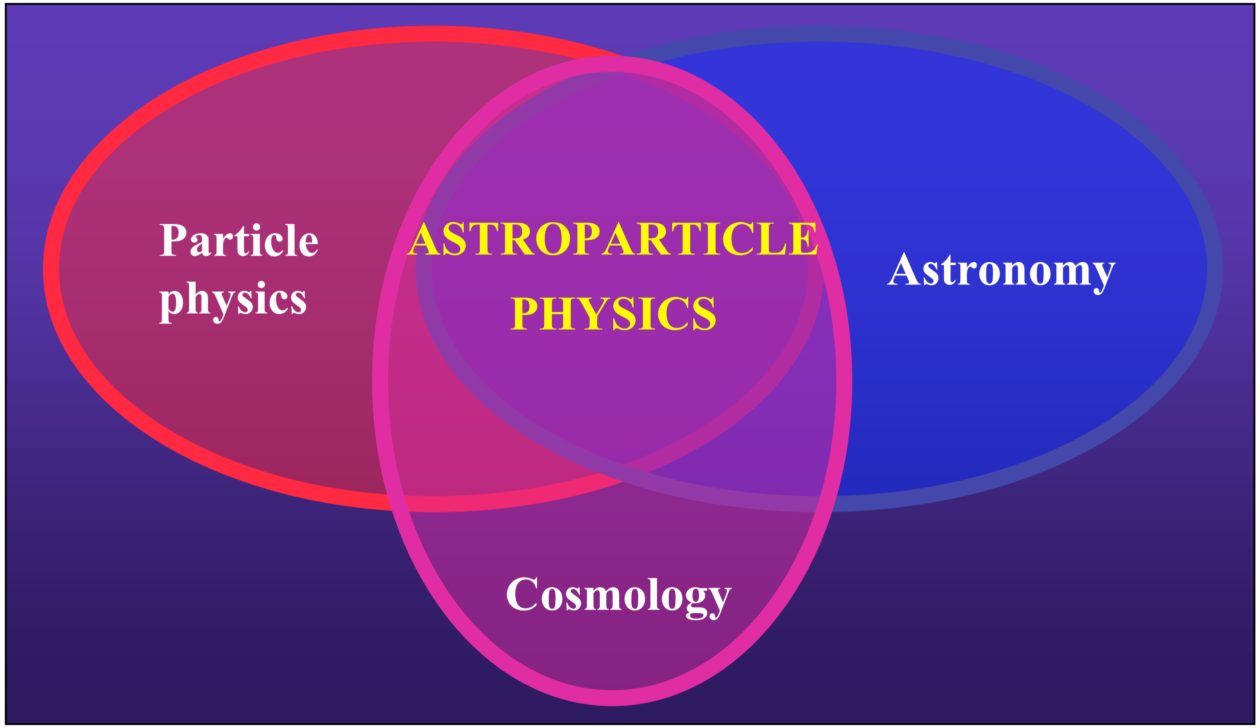
1) What is Astroparticle Physics ?
   Cosmic Microwave Background
   Dark energy

2) Dark matter

3) High energy astrophysics

# Astroparticle Physics?

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

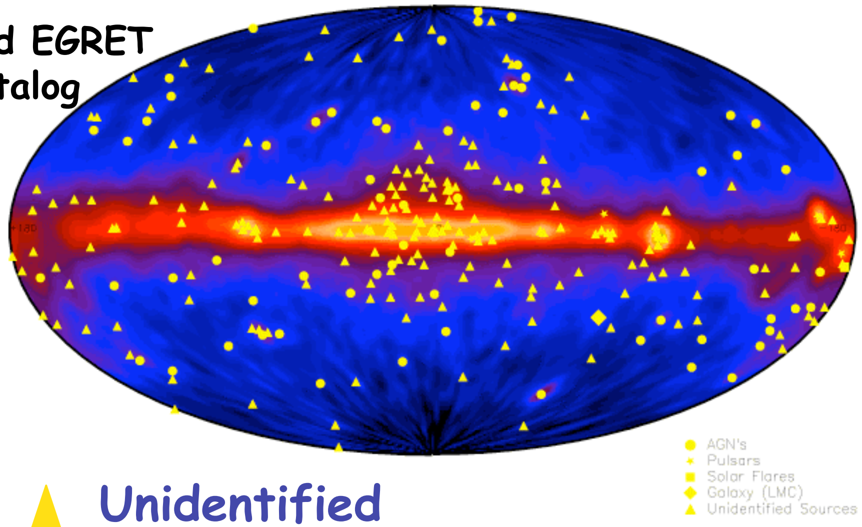


# Today's HE universe

Astroparticle → high energy phenomena, cosmic accelerators

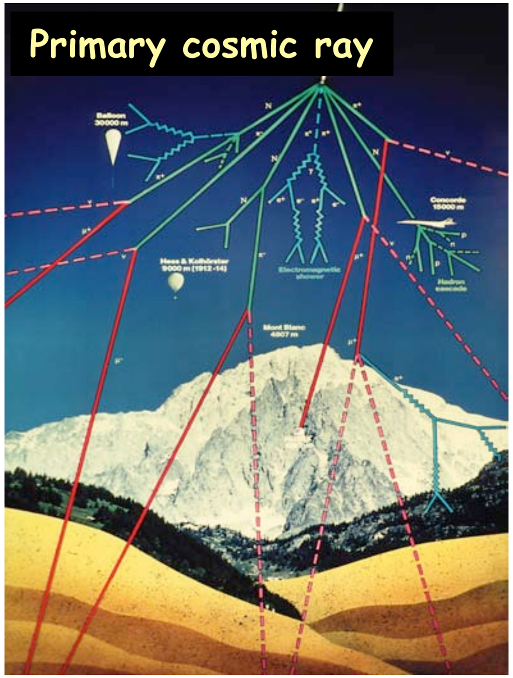
## Gamma rays

3rd EGRET catalog




▲ Unidentified sources

## Cosmic rays

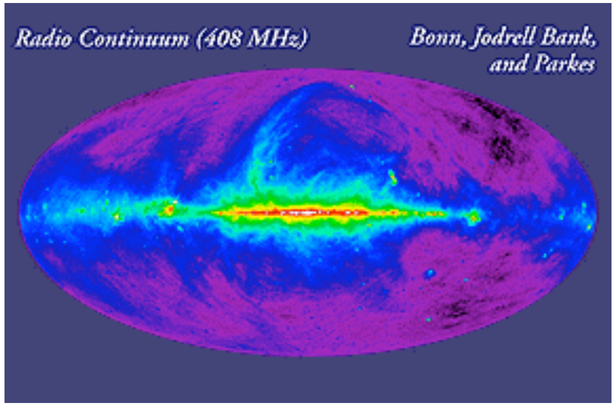


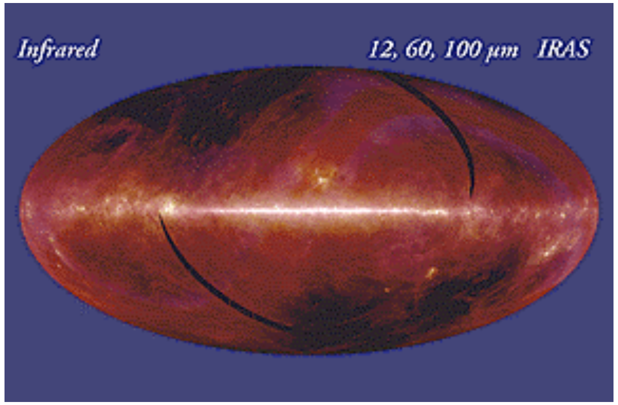

## Neutrinos

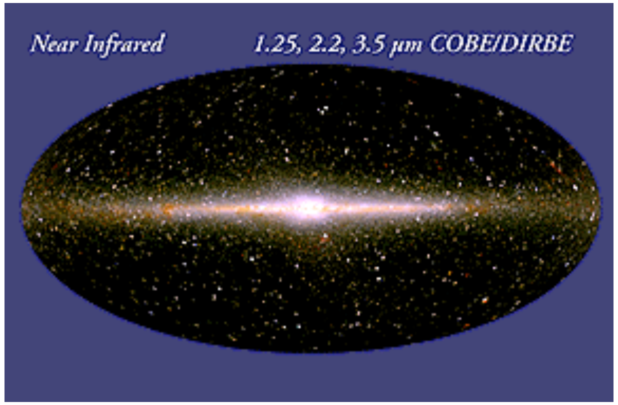
many astrophysical sources (sun, galactic center, AGN…)

⇒ Lecture 3

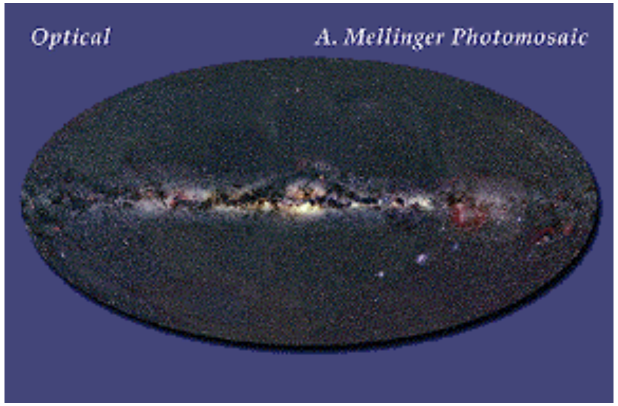
# Multi-wavelength universe

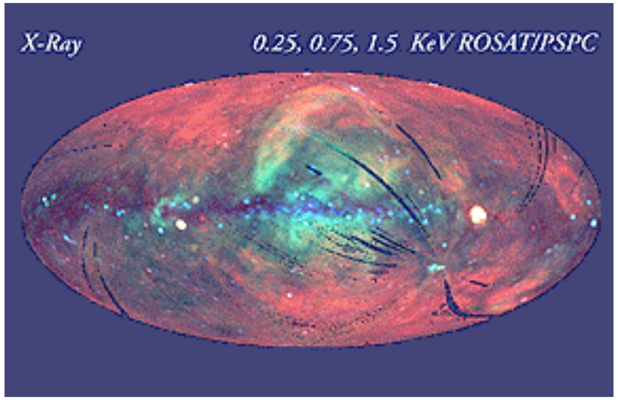


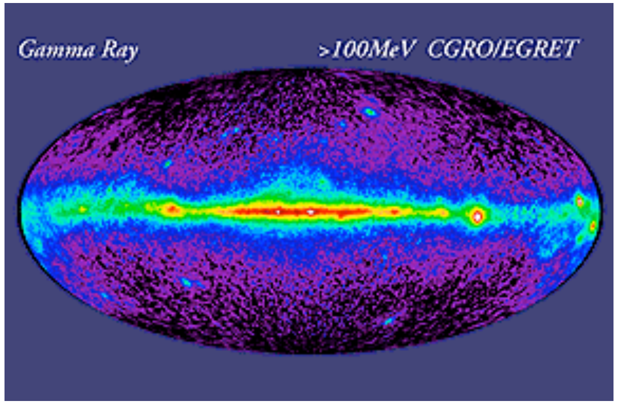




## The different faces of the Milky Way



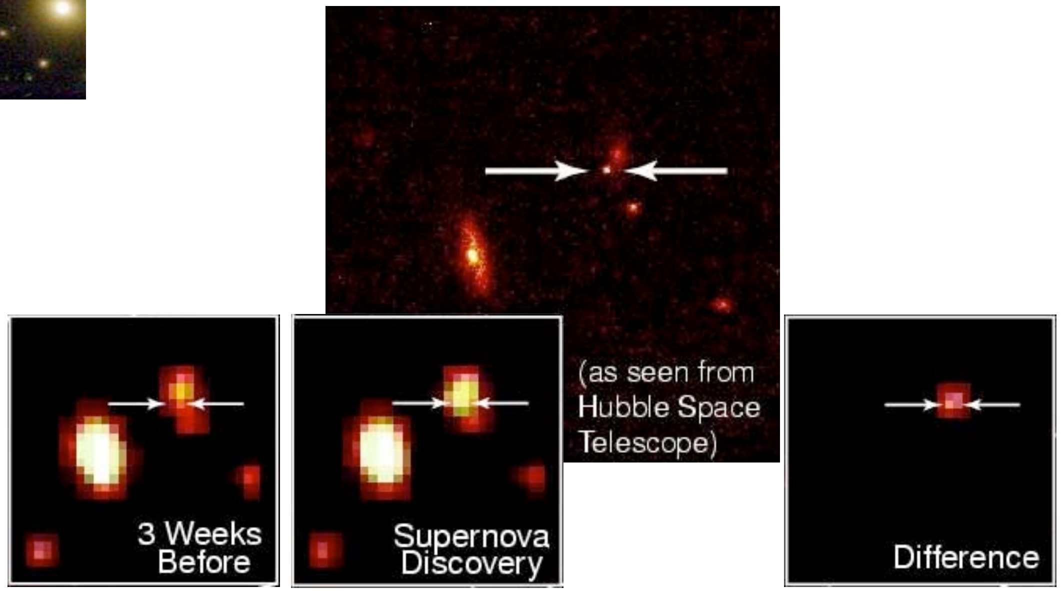



# Content of the universe


Dark matter

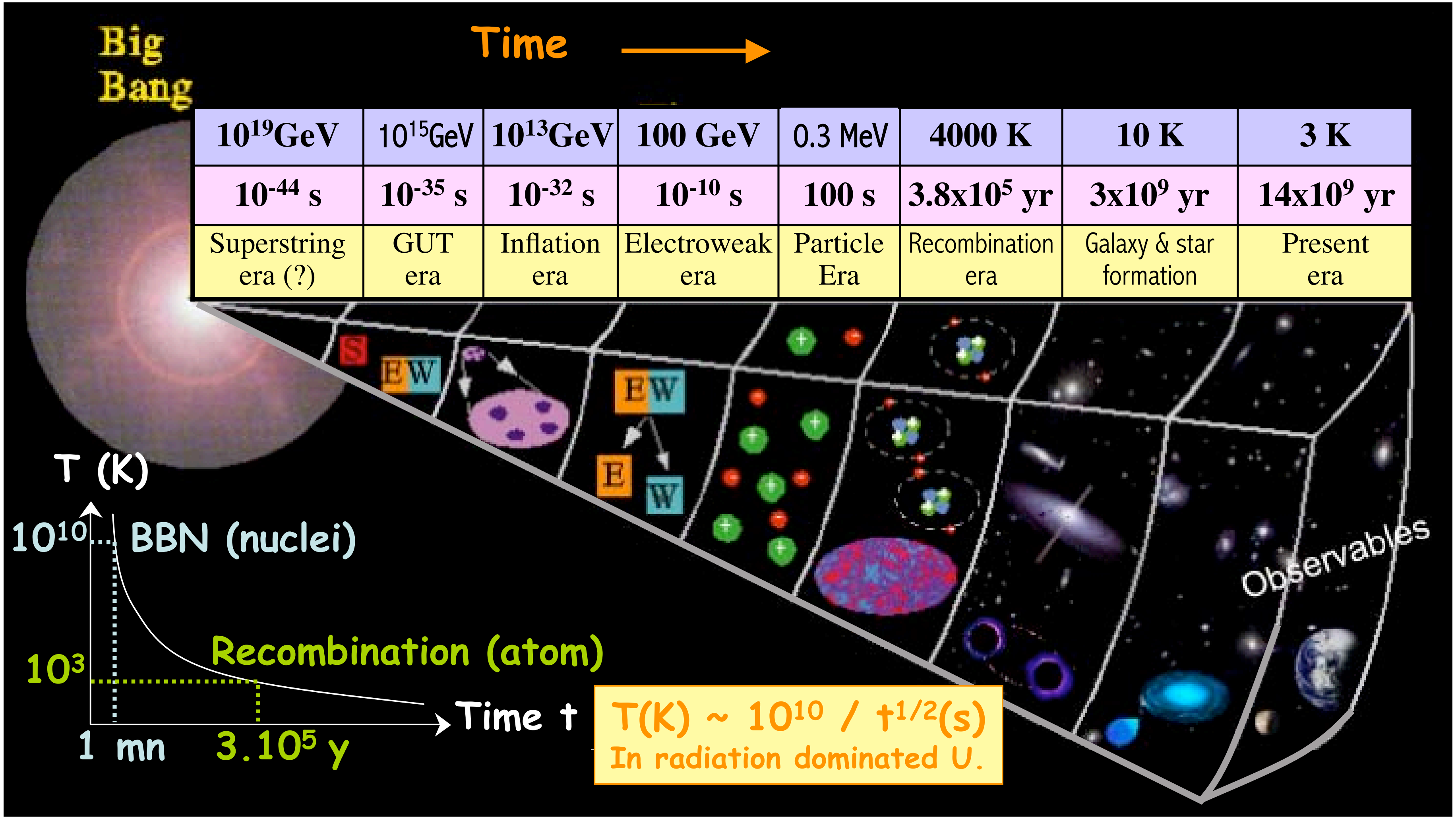
⇒ Lecture 2




Lecture 1 ⇐

Dark energy

# Evolution of the Universe



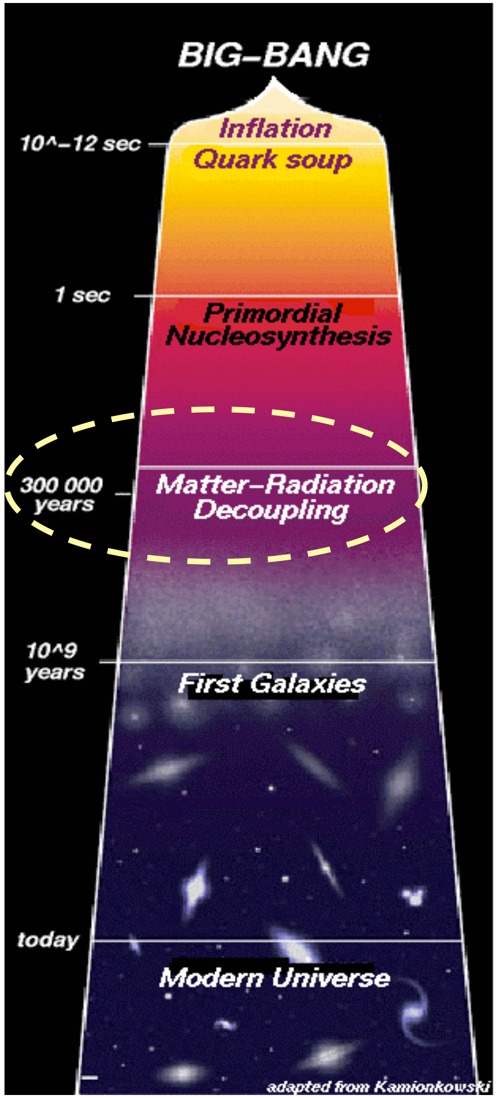

| $10^{19}$GeV | $10^{15}$GeV | $10^{13}$GeV | 100 GeV | 0.3 MeV | 4000 K | 10 K | 3 K |
|---|---|---|---|---|---|---|---|
| $10^{-44}$ s | $10^{-35}$ s | $10^{-32}$ s | $10^{-10}$ s | 100 s | $3.8 \times 10^5$ yr | $3 \times 10^9$ yr | $14 \times 10^9$ yr |
| Superstring era (?) | GUT era | Inflation era | Electroweak era | Particle Era | Recombination era | Galaxy & star formation | Present era |

# Lecture outline

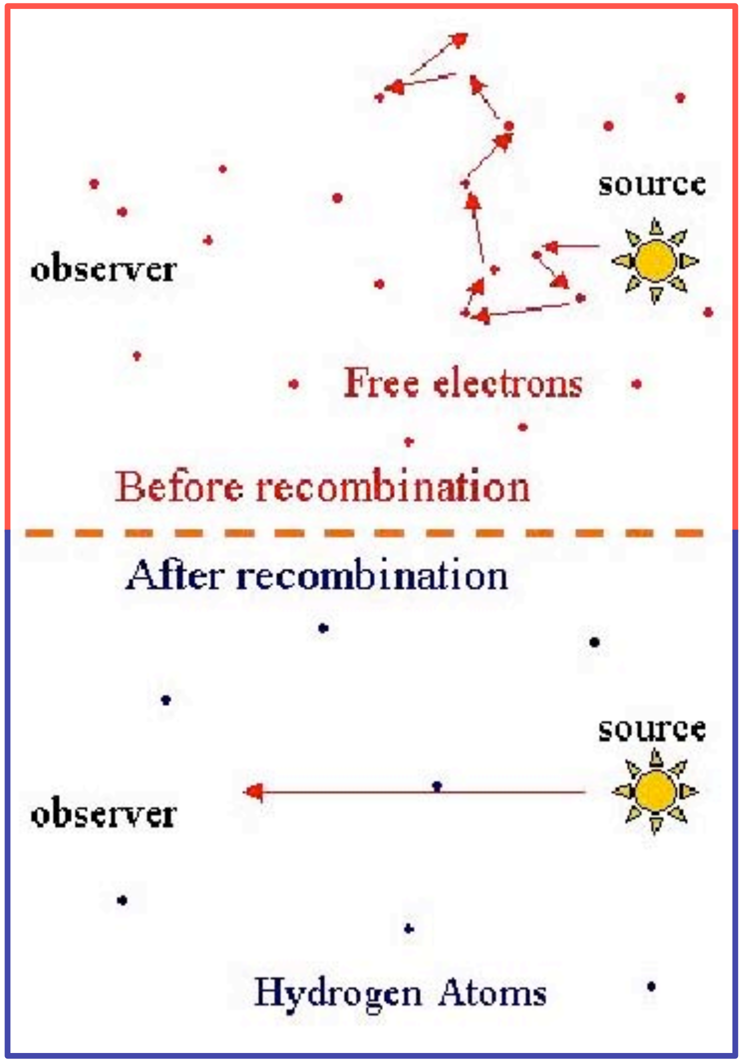
1) What is Astroparticle Physics ?
   Cosmic Microwave Background
   Dark energy

2) Dark matter

3) High energy astrophysics



# End of opaque Universe




Cannot see further back

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

"Uniform" background at $T_0 = 2.7$ K

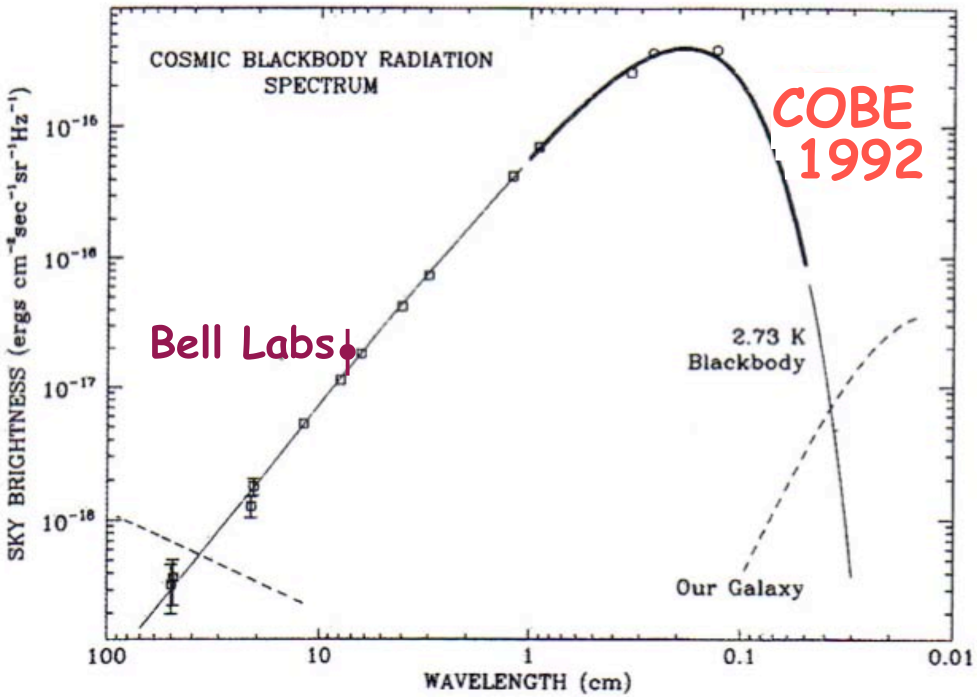
# Discovery

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

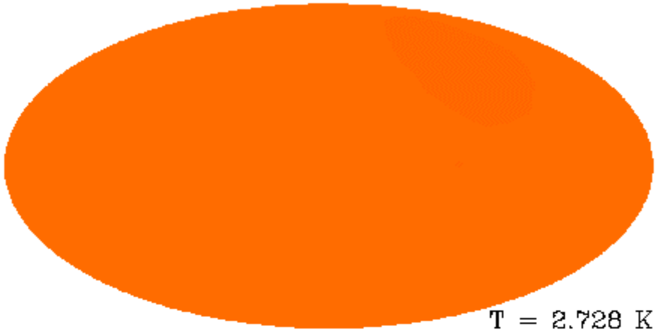
25 years later


Wilson Penzias

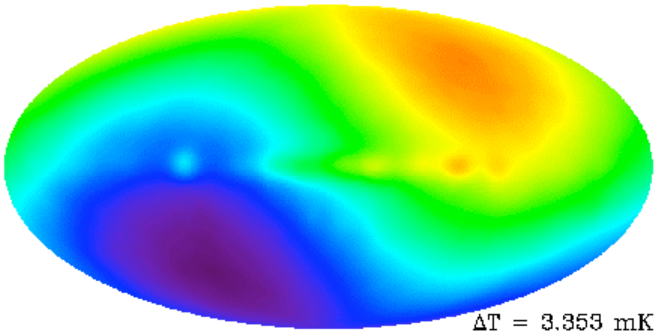
(+ Robert Dicke)



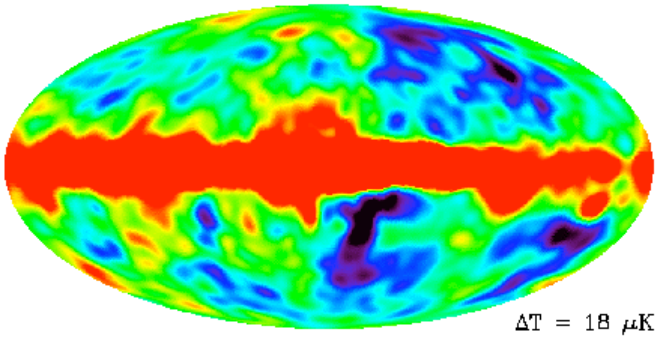
# COBE sky maps




T = 2.7 K

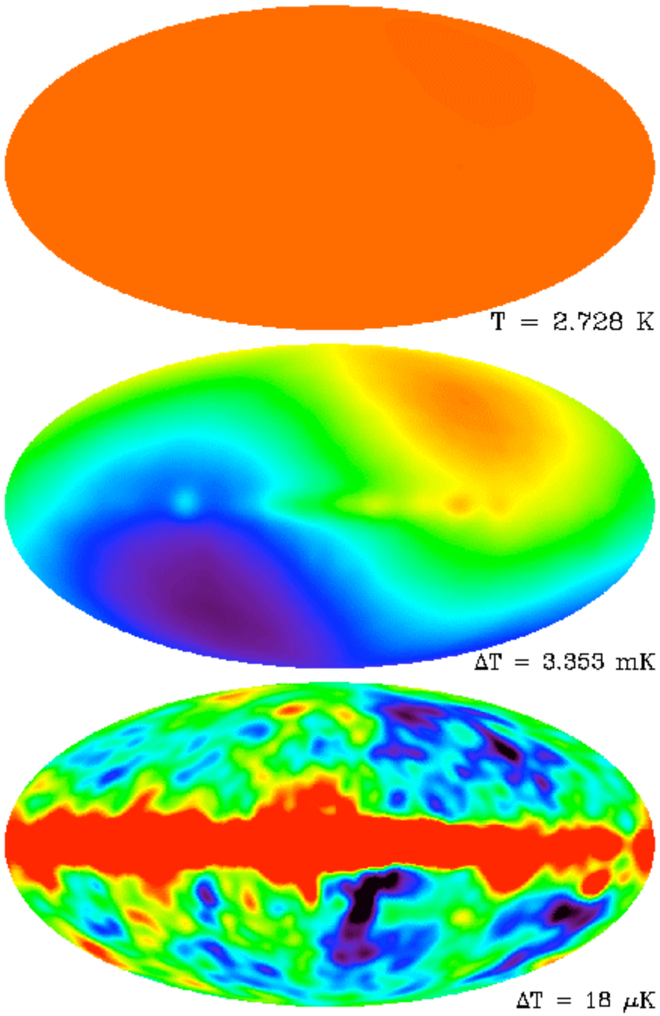



ΔT = 3.4 mK
(after subtraction of constant emission)



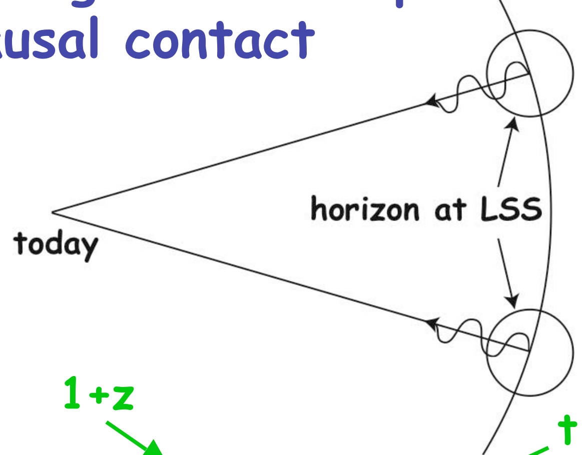

ΔT = 18 μK
(after subtraction of dipole)

# COBE sky maps




scale 0-4 K: very homogeneous
→ cosmological origin

Yet, regions > 1° apart never in causal contact



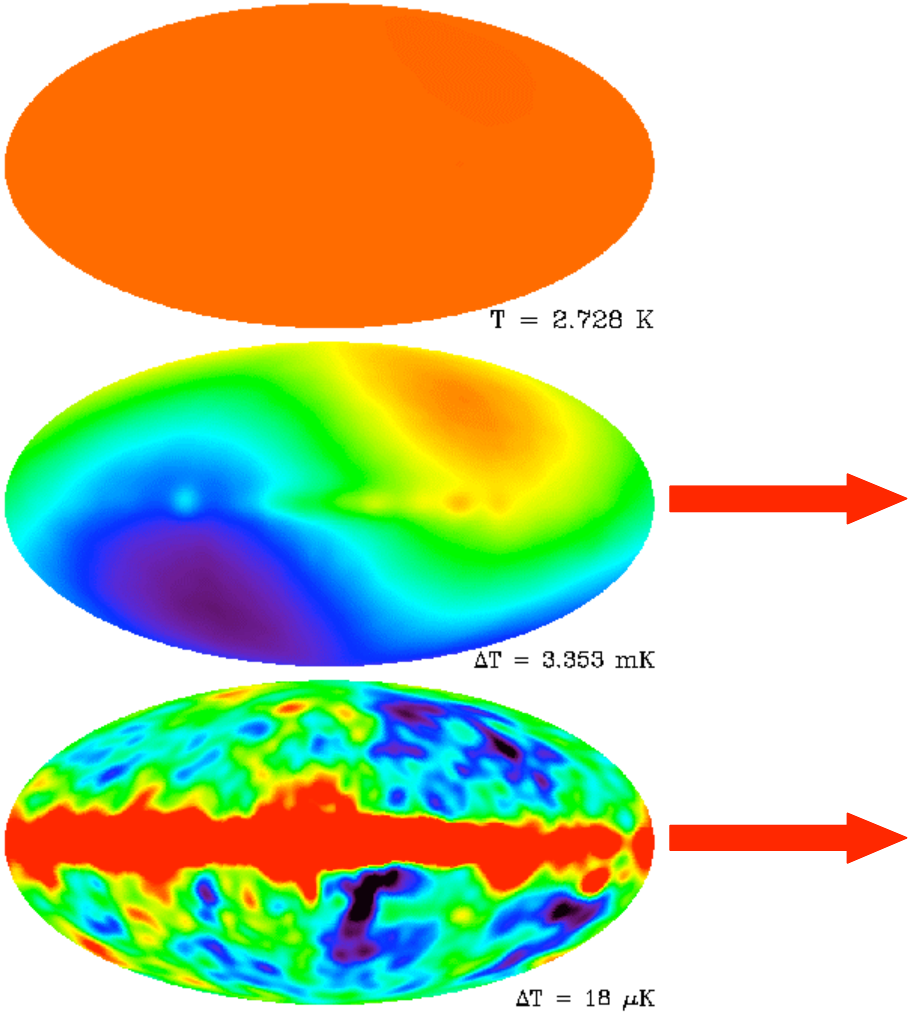

1+z
t LSS

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

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)

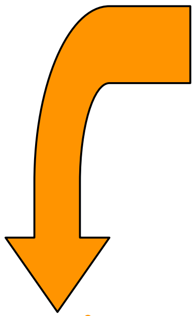
# Anisotropies

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

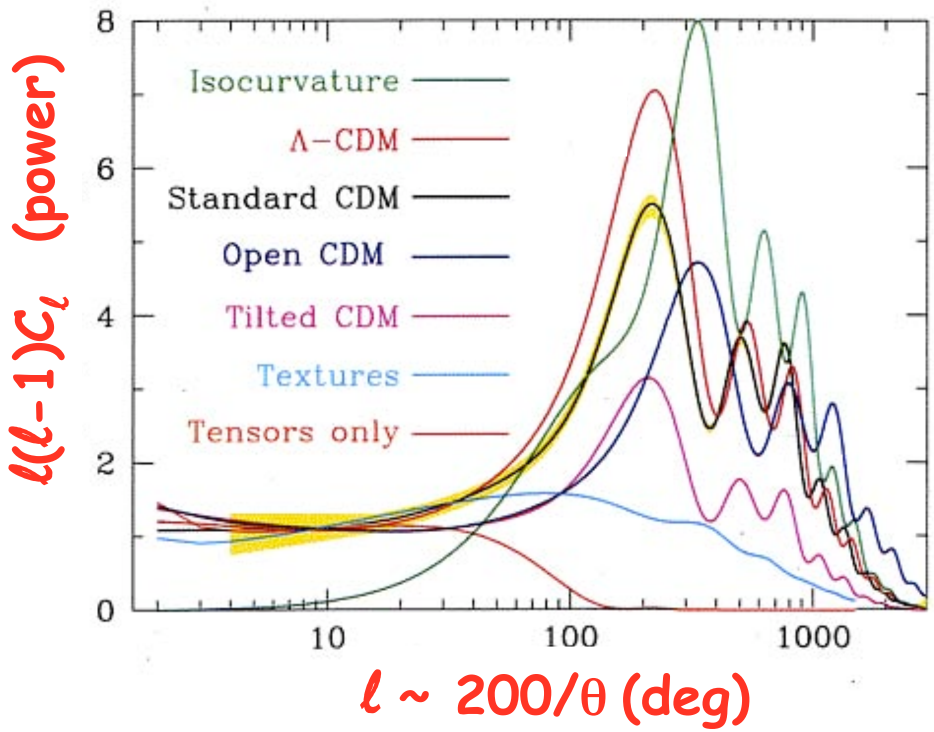
As far out as the sound horizon at recombination

- Presented as a power spectrum

  multipole $\ell$
  amplitude $a_{\ell m}$
  power ~ $|a_{\ell m}|^2 \sim C_\ell$

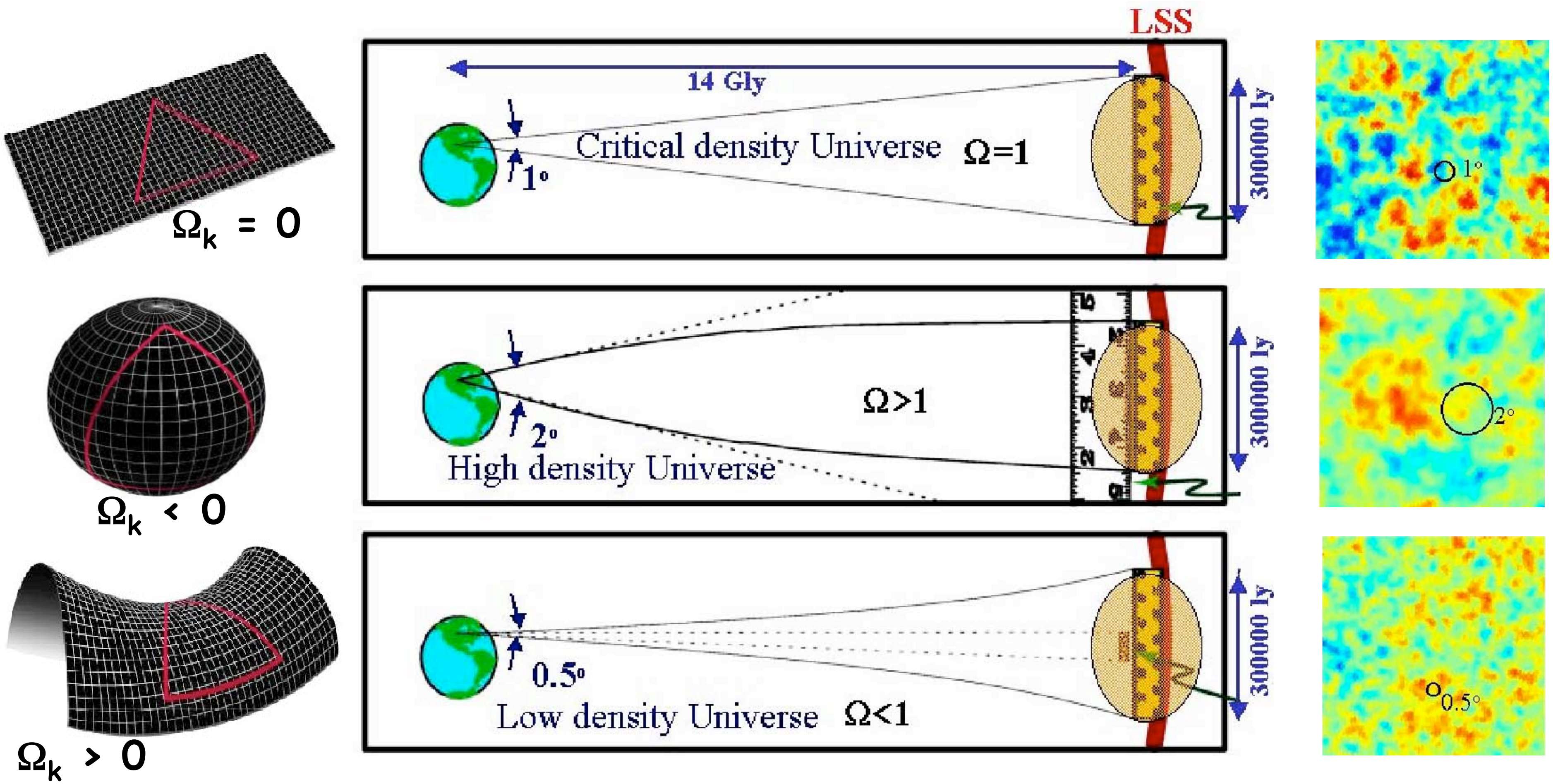


cosmology



# Sound horizon at recombination

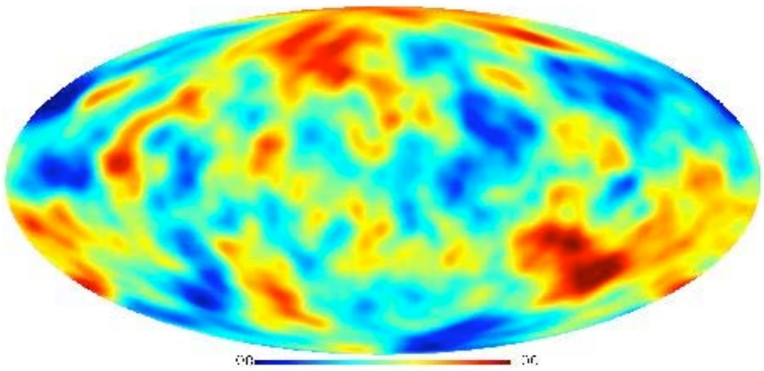
Limited by causality → maximum scale




⇒ Max scale relates to curvature $\Omega_k$ of the universe

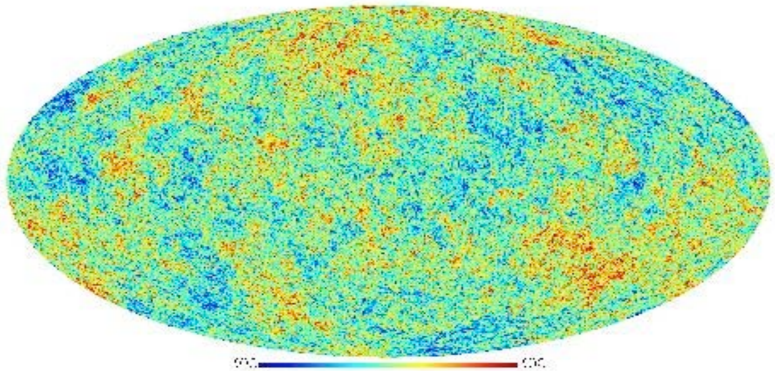
# 2nd generation satellite

COBE
(7 degree resolution)



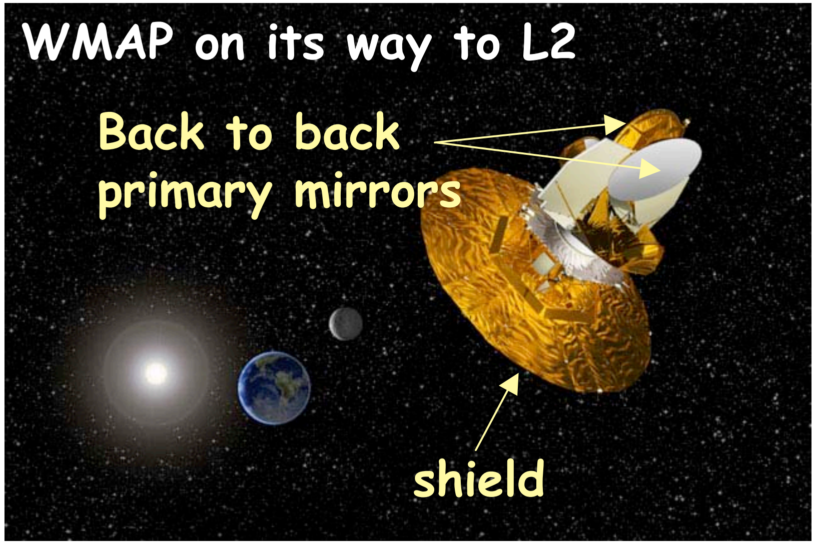
($\ell < 20$)

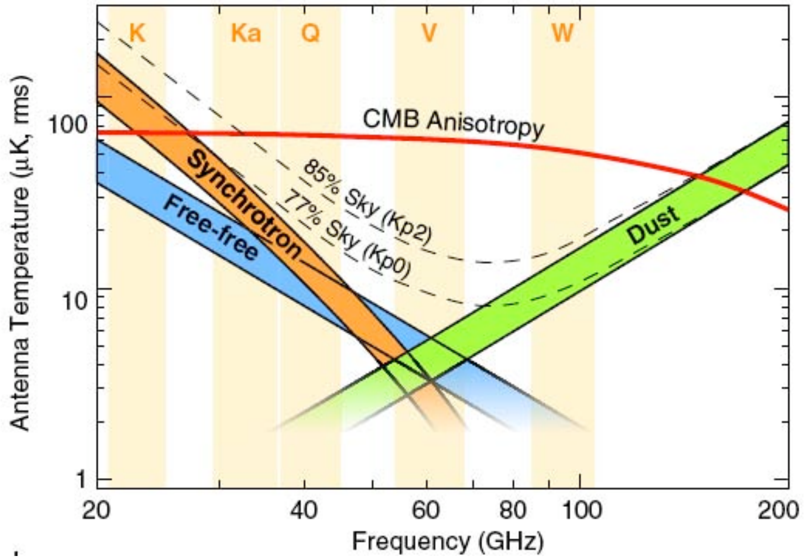
WMAP
(0.25 degree resolution)



($\ell < 700$)

# WMAP

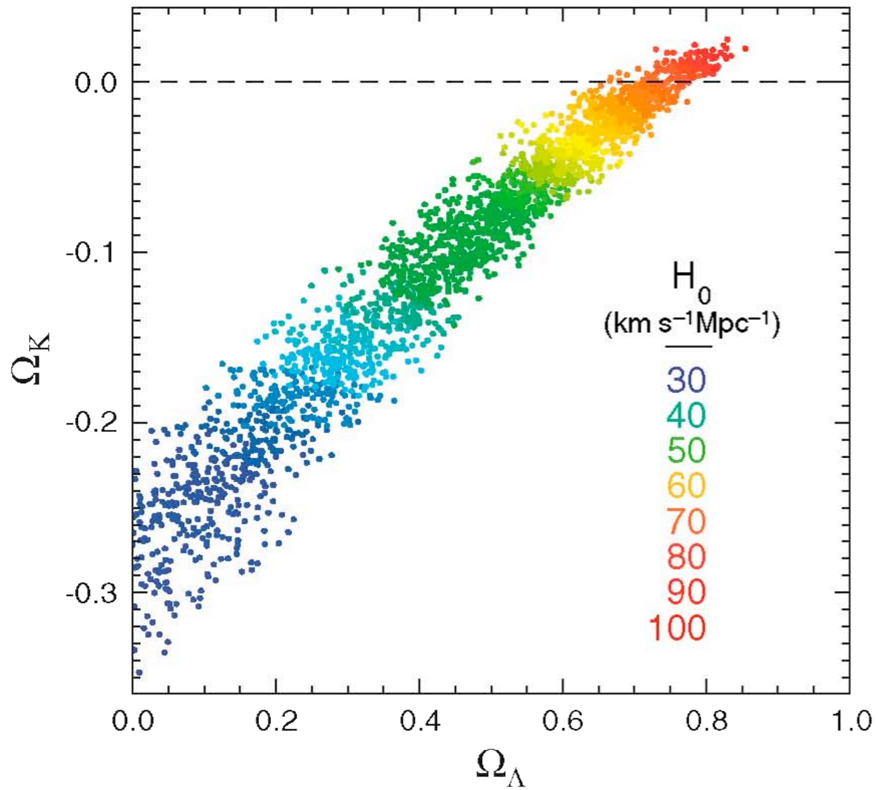



- Very low temperature signal
  ⇒ Need shielding from
  Sun, Earth, Moon, (Jupiter)
- Lagrange point L2: position of co-rotation with Earth
  ⇒ Stability of conditions
- Measure of T differences
- 5 frequency channels
  Foreground removal (<90 GHz)

Launch: Jun. 2001
First results: 2003

# "Concordance model"




Curvature of the Universe (95% CL)

WMAP5 only:
$-0.063 < \Omega_k < 0.017$

WMAP5 + SN + BAO:
$-0.018 < \Omega_k < 0.009$

Komatsu et al., astro-ph/0803.0547v1

$H_0$ from HST = 72 ± 8 km/s/Mpc

Dunkley et al, astro-ph/0803.0586v1

# "Concordance model"

$\Omega_i = \rho_i / \rho_c$
$\Omega_{tot} = 1$ for $\Omega_k = 0$

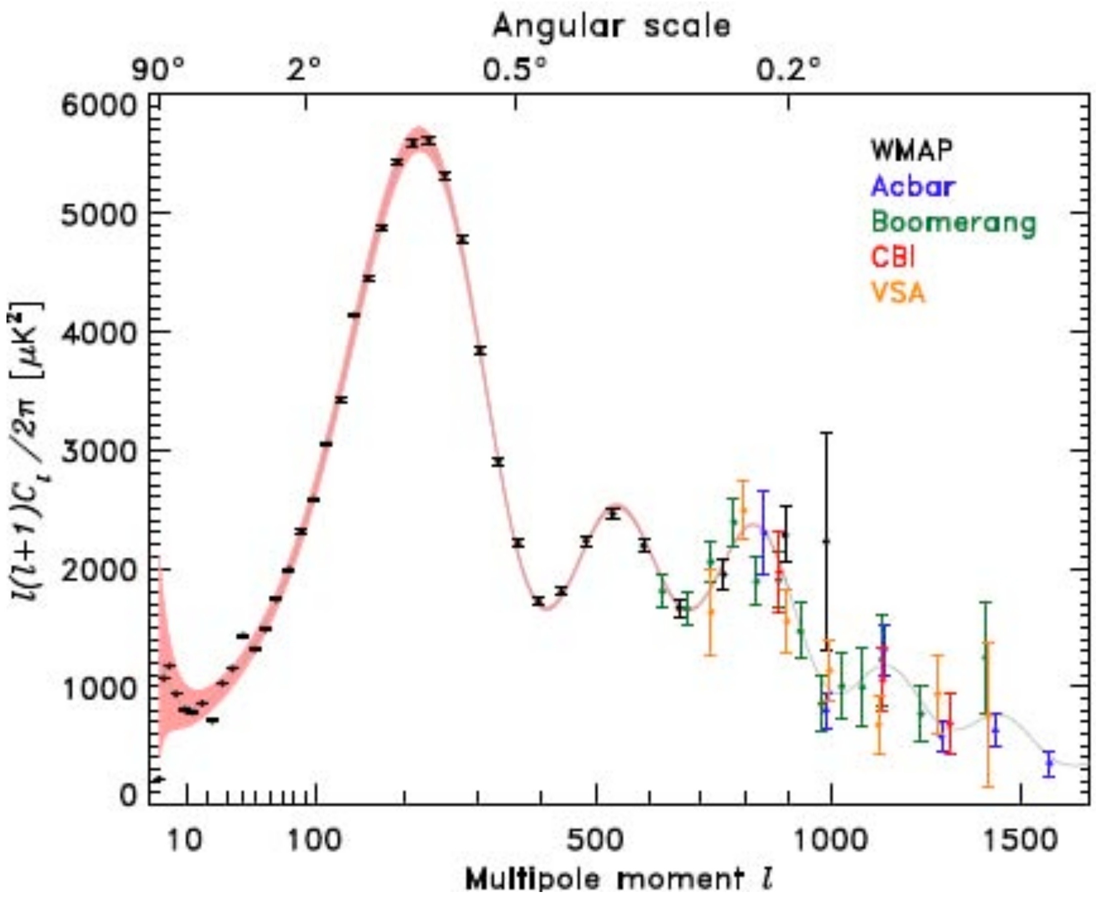
**WMAP alone**
(flat ΛCDM model)

| | | |
|---|---|---|
| $H_0$ | = | 0.74 +/- 0.03 |
| $\Omega_b$ | = | 0.044 +/- 0.003 |
| $\Omega_m$ | = | 0.26 +/- 0.01 |
| $\Omega_\Lambda$ | = | 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

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

Planck mission

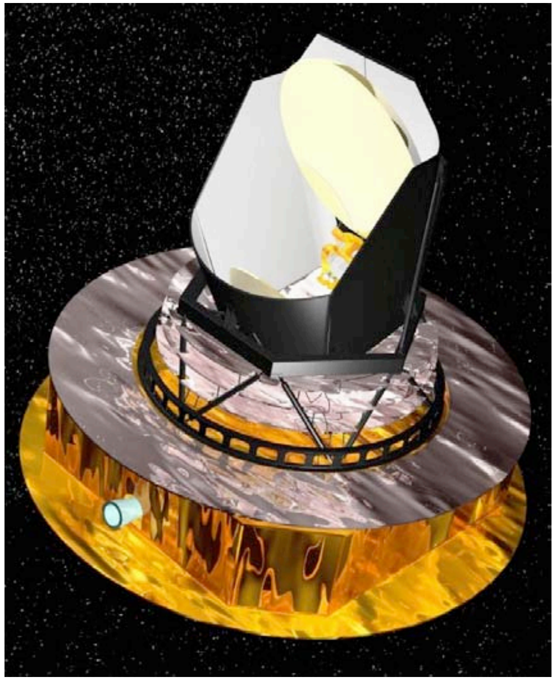
2 instruments LFI & HFI

- LFI → HEMTS
- HFI → Bolometers

Freq coverage from 30 to 850 GHz (9 channels)

Polarization sensitive

Launch foreseen early 2009



# Lecture outline

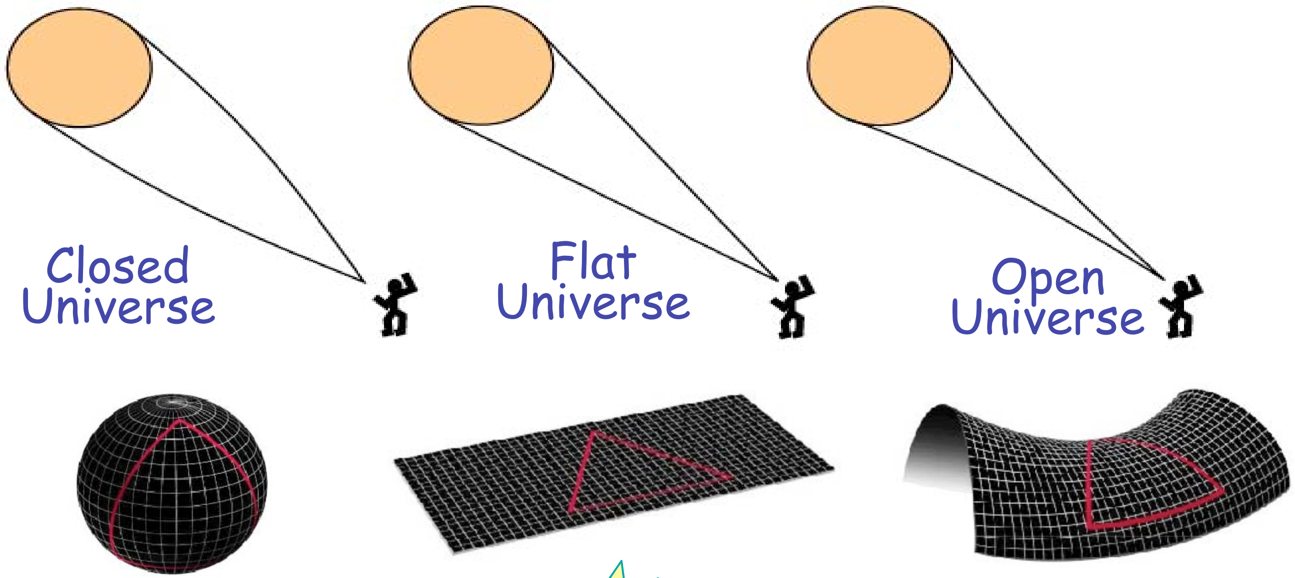
1) What is Astroparticle Physics ?
   Cosmic Microwave Background
   Dark energy
      Supernovae searches
      Baryon acoustic oscillations

2) Dark matter

3) High energy astrophysics

# Measurement of the geometry

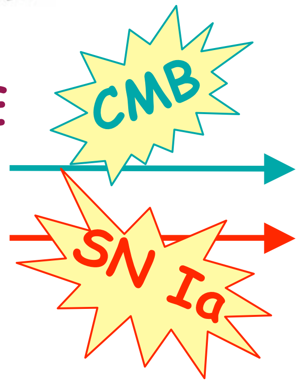
$$1 - \Omega_k(t) = \sum\Omega_x(t) + \Omega_\Lambda(t)$$




AT A GIVEN DISTANCE

Known physical size

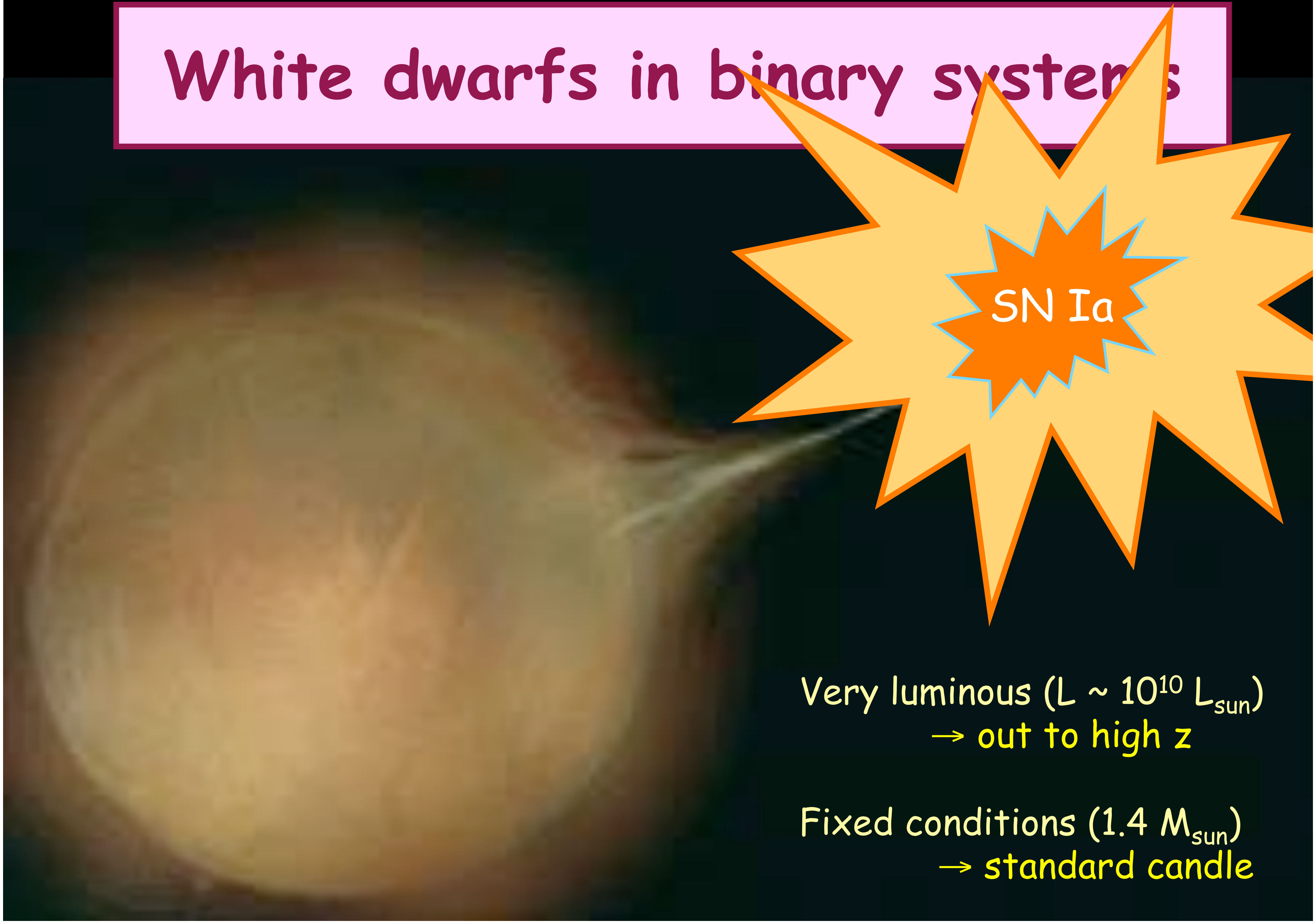
Known luminosity




angle depends on geometry

flux depends on geometry

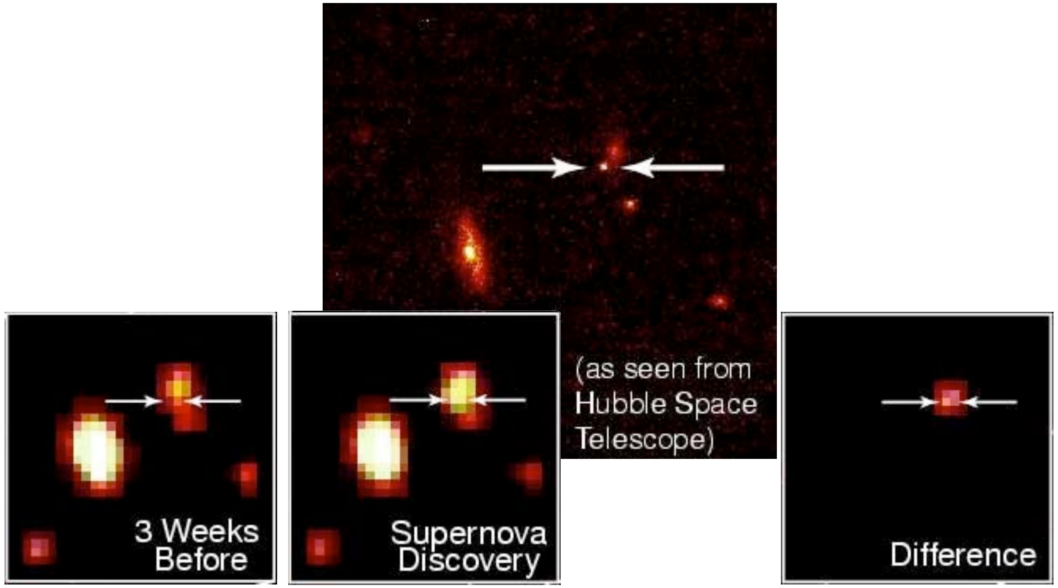
# White dwarfs in binary systems



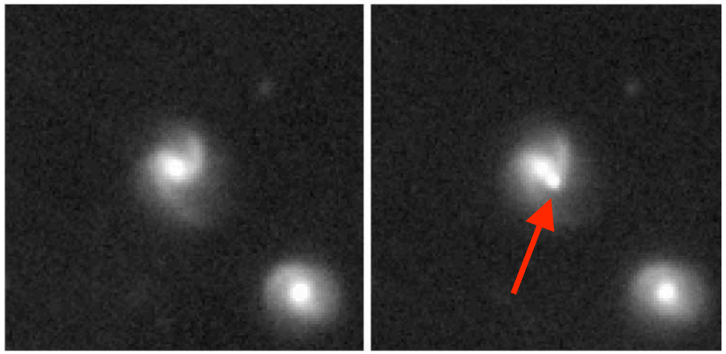

Very luminous ($L \sim 10^{10}\ L_{sun}$)
→ out to high z

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

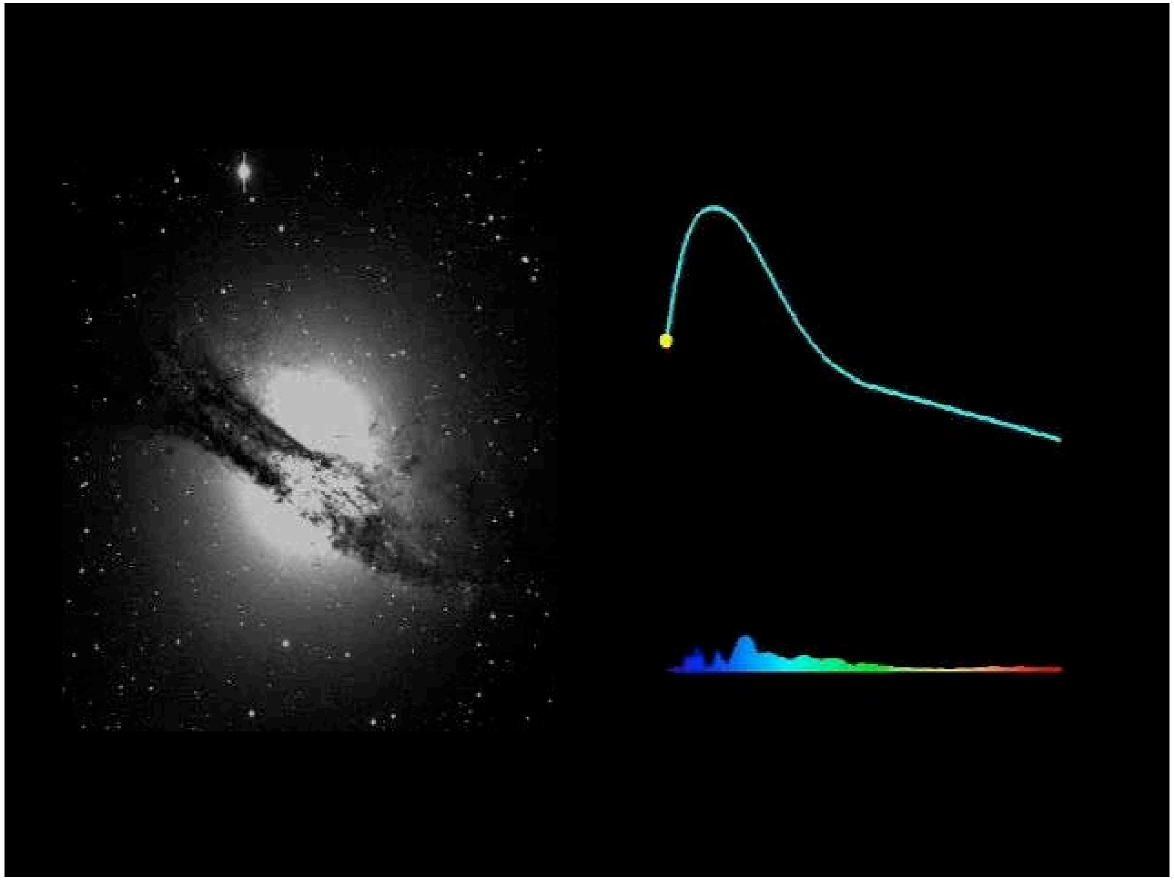
# Type Ia searches




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

# CCD detectors at CFHT

RCA1 1981-1986
1 CCD, 320 x 512
champ 2′ x 3.5′

RCA2 1986-1995
1 CCD, 640 x 1024
champ 2′ x 3.5′

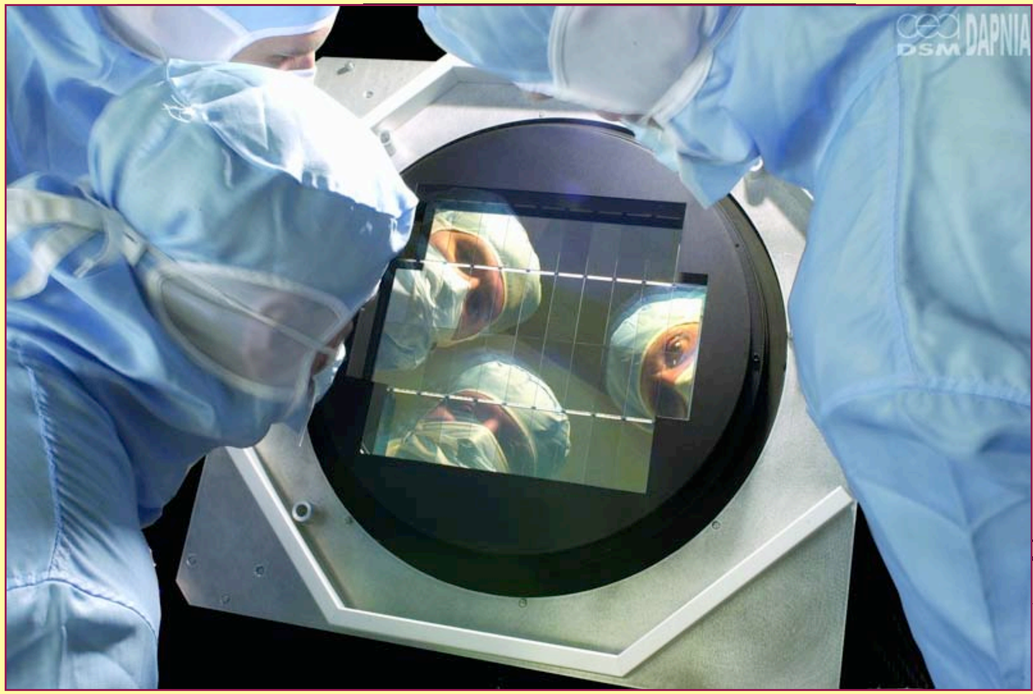
SAIC1 1990
1 CCD, 1K x 1K
champ 4.2′ x 4.2′

Lick2 1992
1 CCD, 2K x 2K
champ 7′ x 7′

MOCAM 1994
4 CCDs, 4K x 4K
champ 14′ x 14′

UH8K 1996
8 CCDs, 8K x 8K
champ 28′ x 28′

2K 1999
, 12K x 8K
42′ x 28′



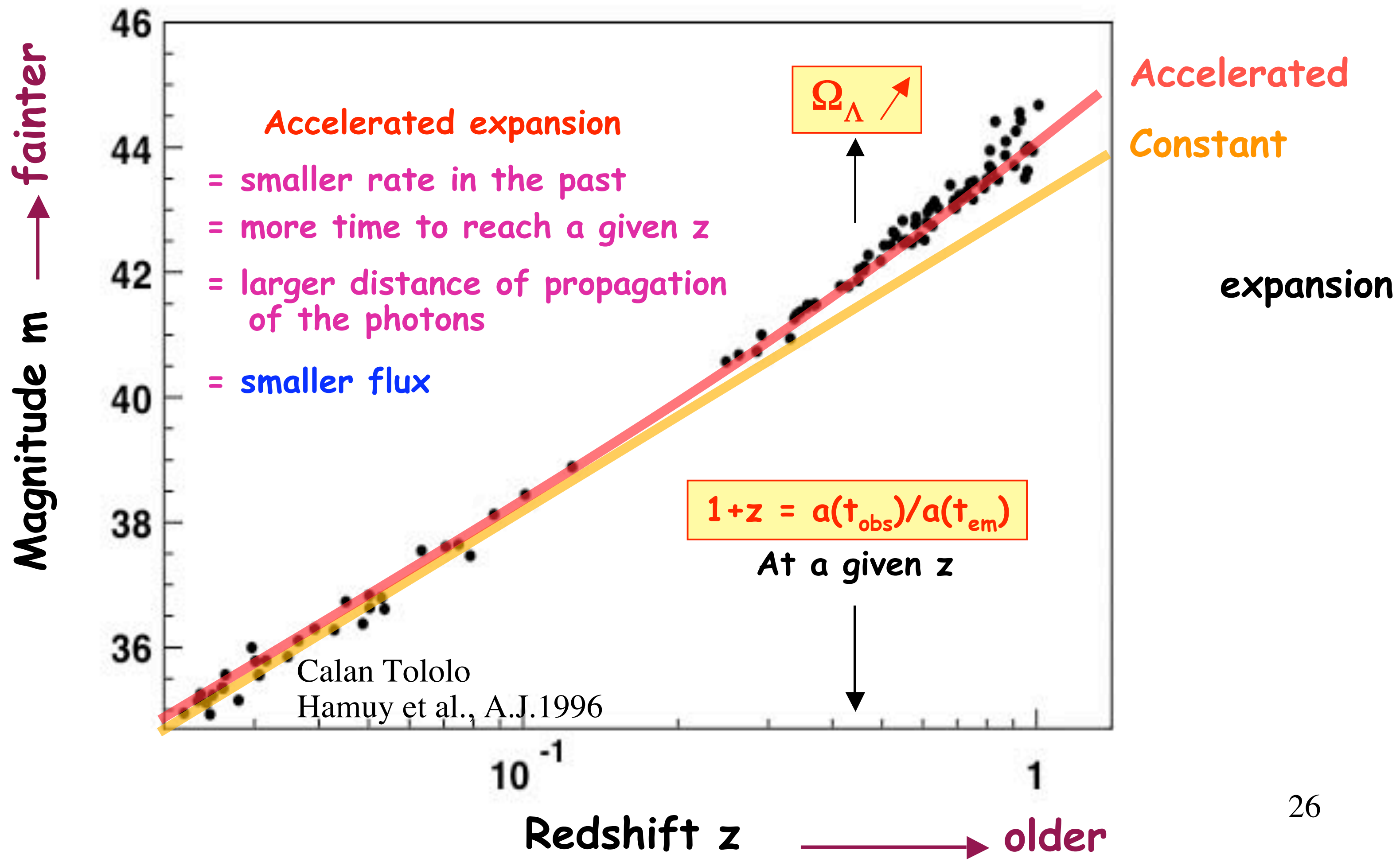

MegaCam 2002
40 CCDs, 20K x 18K
champ 1° x 1°

# Hubble diagram

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

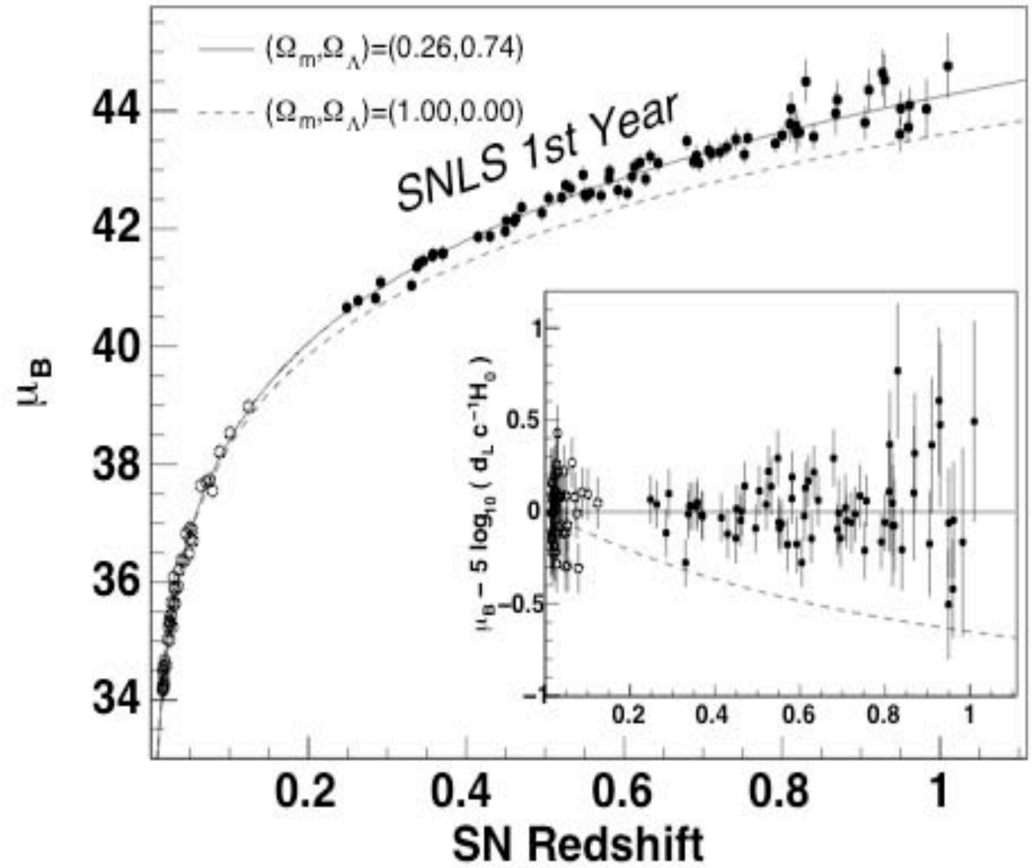
$\Phi \cong \mathcal{L} / 4\pi d_L^2$

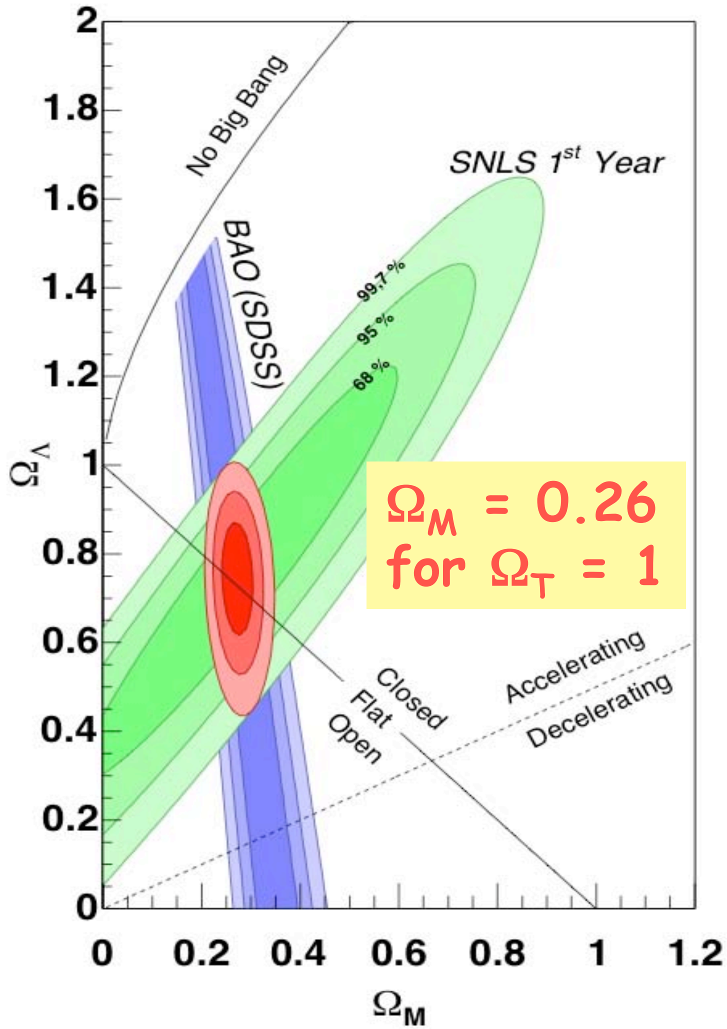
where $d_L(z, H_0, \Omega_M, \Omega_\Lambda, w, ..)$



# SNLS 2006

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



# Beyond $\Omega_\Lambda$...

Cosmological cst

- $\rho_v$ incompatible with a possible $\rho_v$ from particle physics
  - $\Omega_\Lambda = 0.7 \rightarrow \rho_v = \Omega_\Lambda \times \rho_c \sim 10^9$ eV m$^{-3}$
  - $\rho_v$ 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

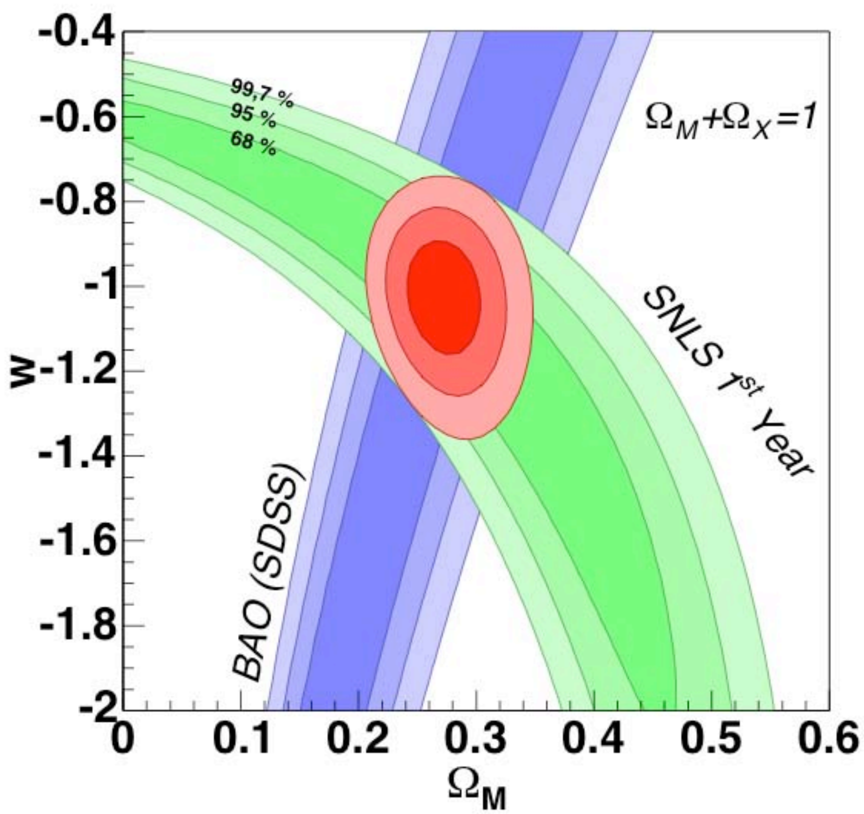
# Equation of state of DE

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

Time evolution of dark energy density $\rho_{de}$ 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)

w = -1.02 ± 0.10

# Standard ruler

Standard candles : supernovae

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

Standard rulers

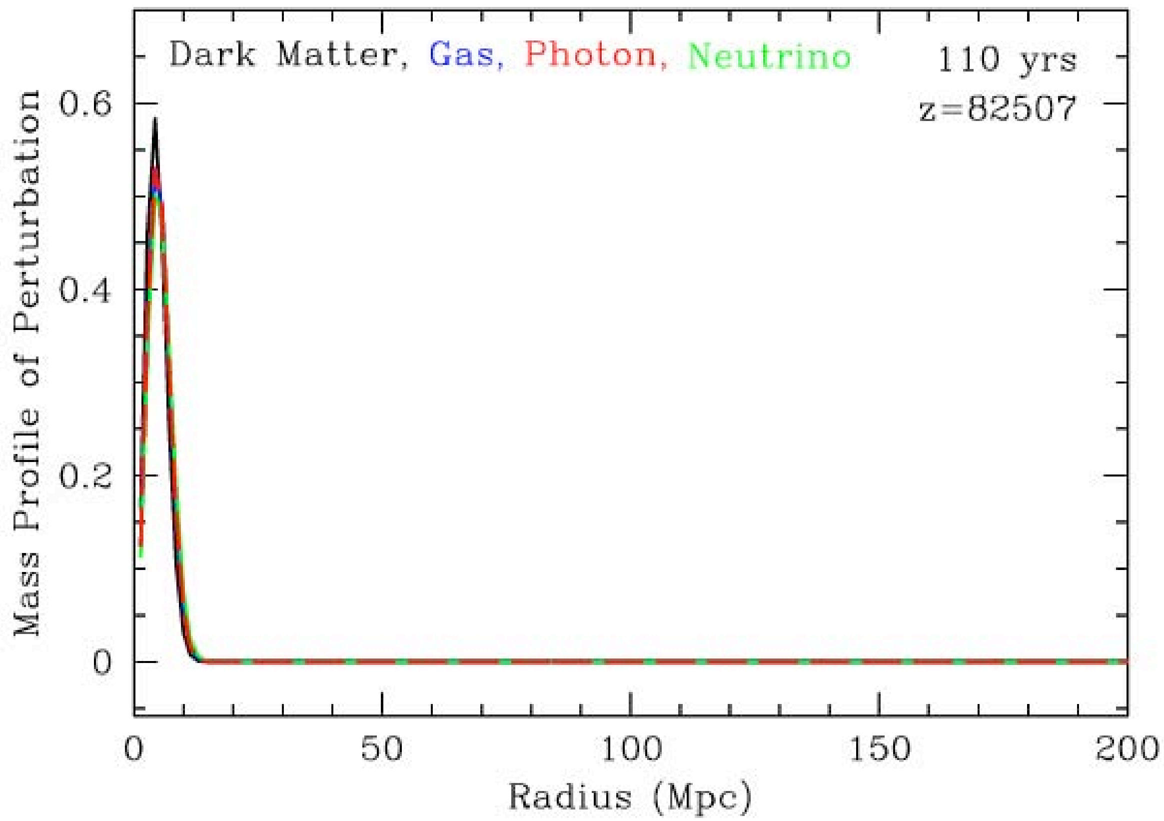
- almost no systematics !

Sound horizon at recombination

Photon distribution
(CMB)

Galaxy distribution
(BAO)

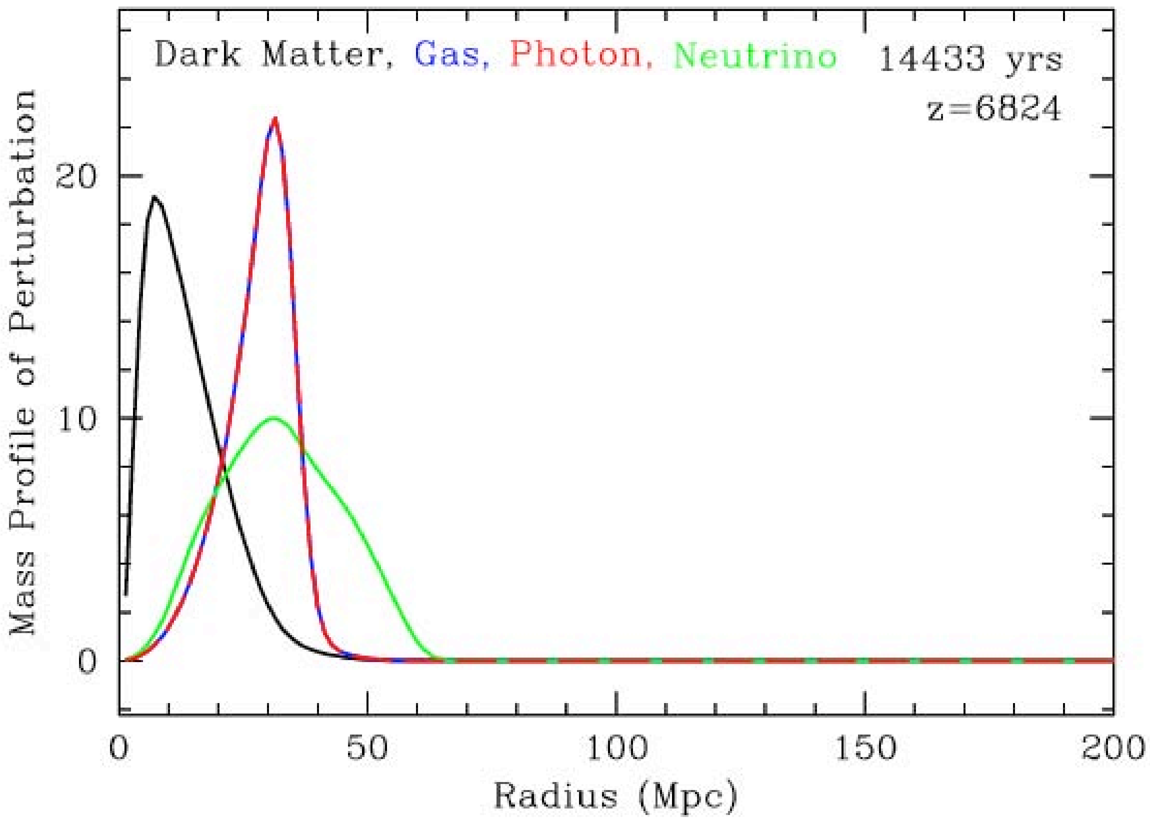
# Imprint on galaxies




**Universe very close to smooth + tiny perturbations**

**Mass profile = ρ $R^2$ R = comoving radius**

# Imprint on galaxies



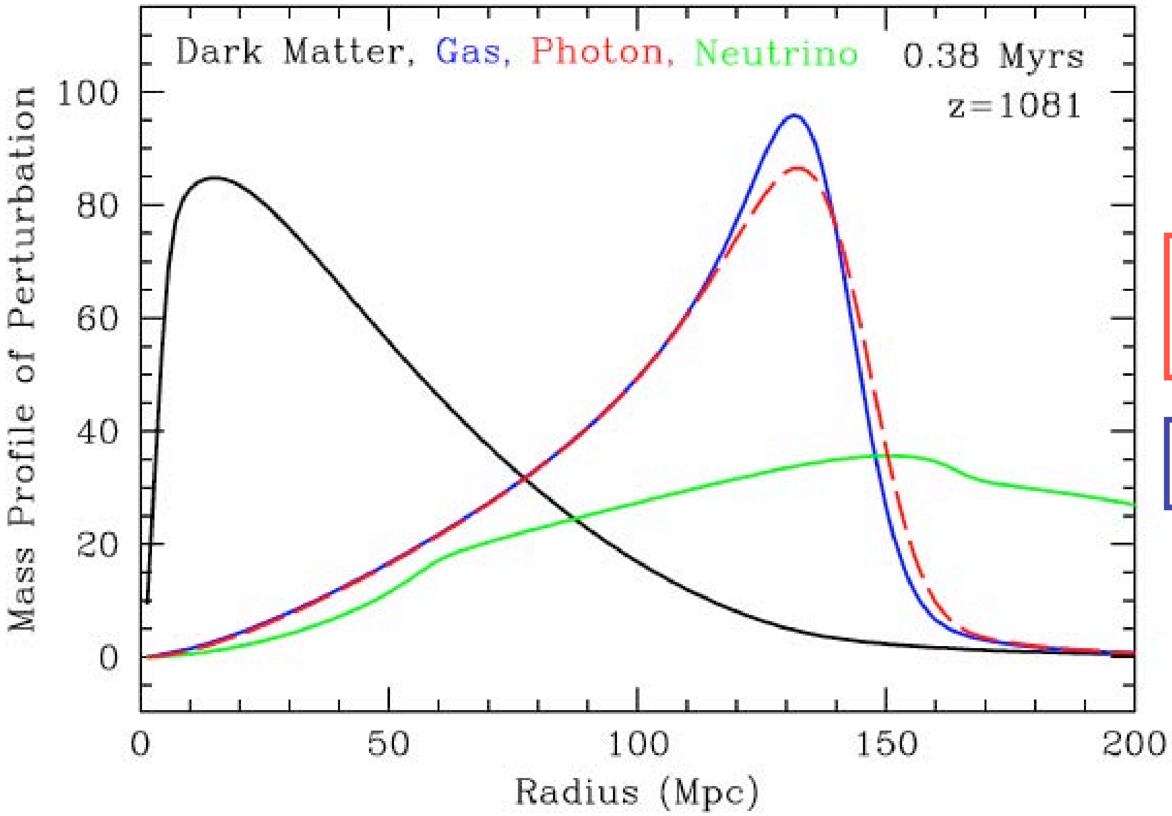

ν's don't interact
→ stream away

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

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

**Mass profile = ρ $R^2$**

# Imprint on galaxies



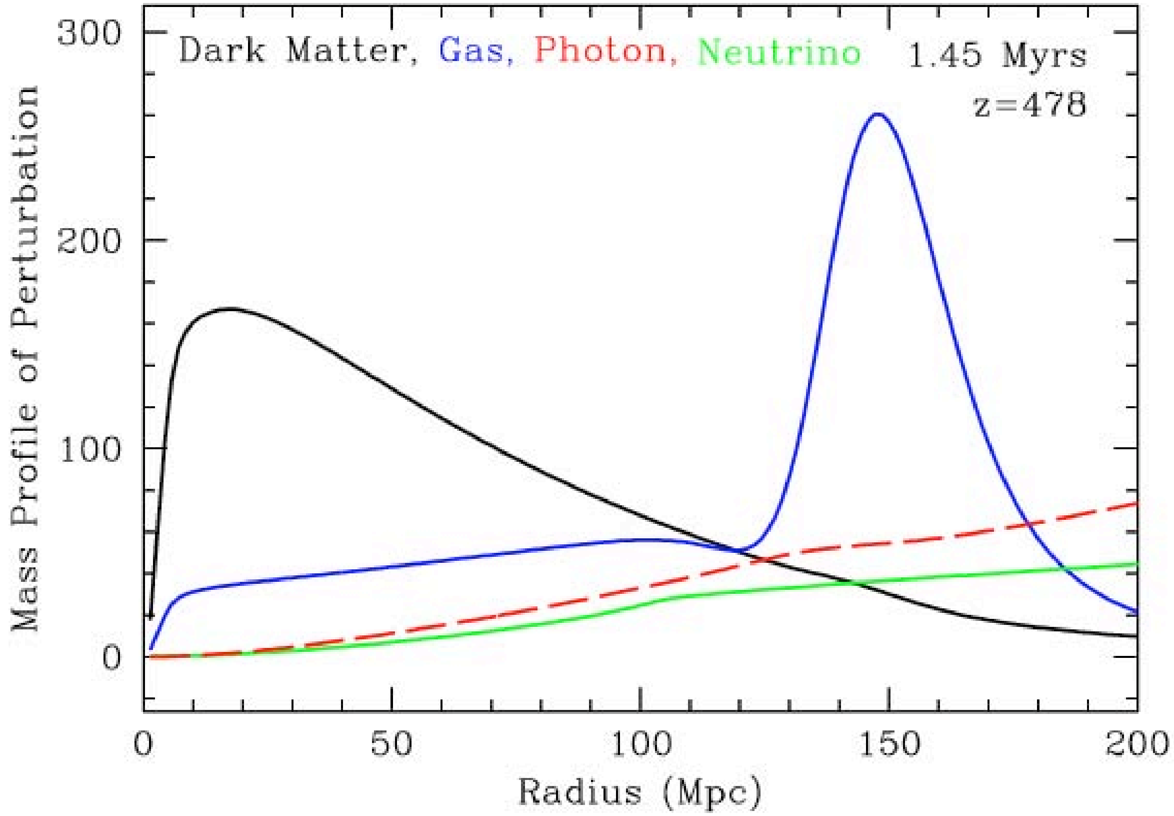

Recombination $e^+e^- \rightarrow p$
(t = 380.000 yrs)

Photons stream past gas particles

Gas wave slows down

Mass profile = $\rho R^2$

# Imprint on galaxies

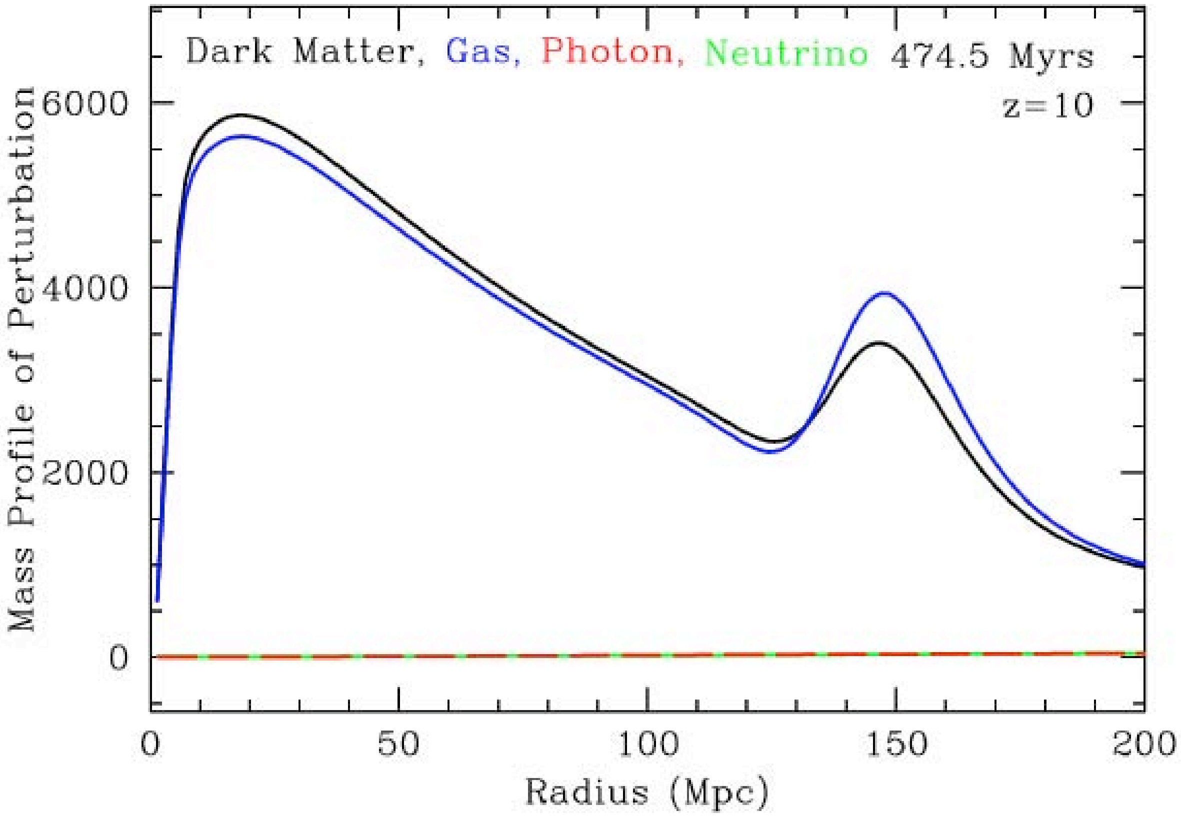



a CDM perturbation at center

a gas perturbation 150 Mpc away

**Mass profile = $\rho R^2$**

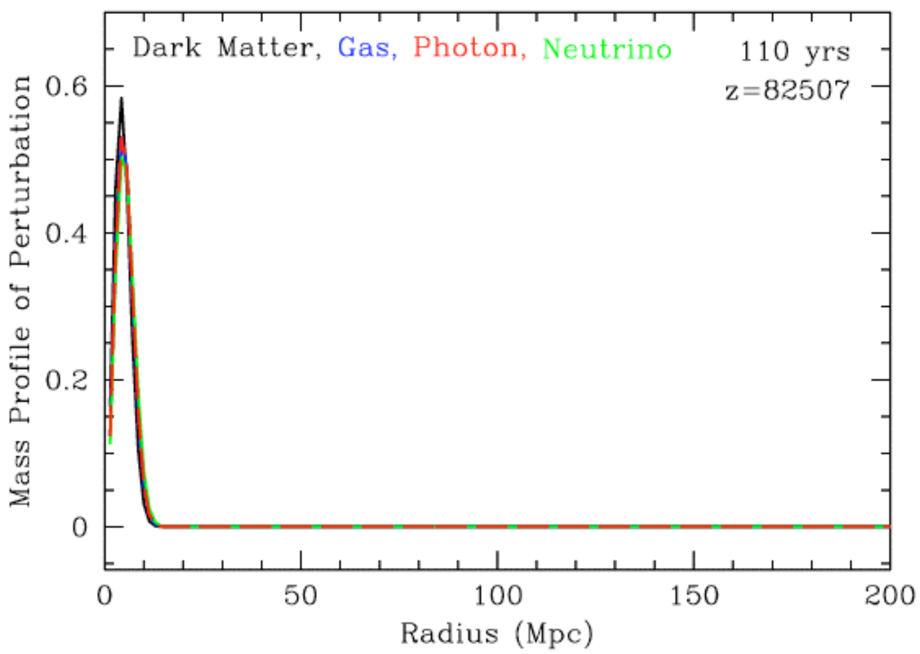
# Imprint on galaxies

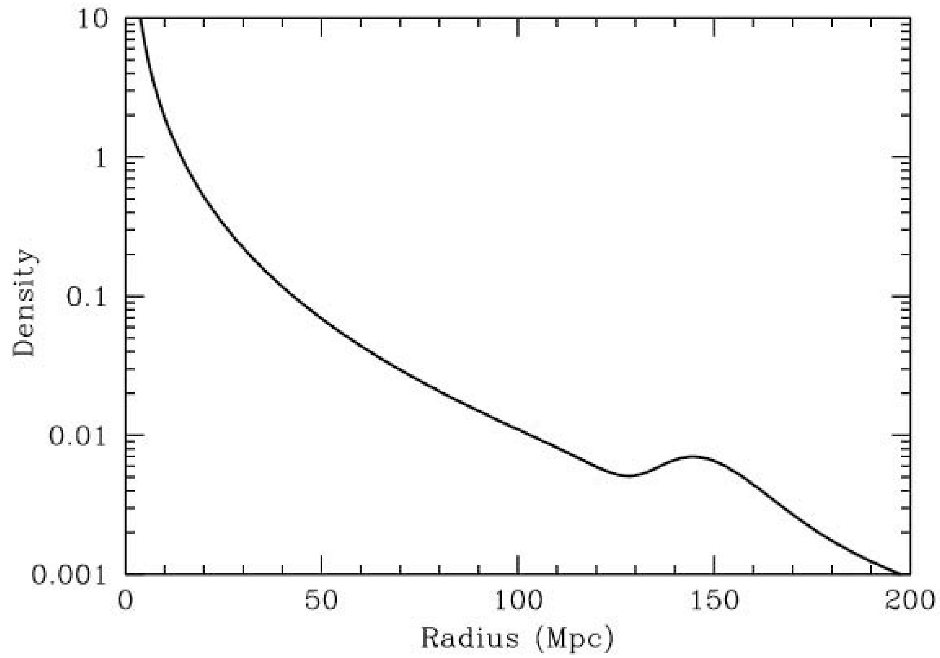



**Acoustic peak decreases relative to original because CDM outweighs gas 5 to 1**

**Mass profile = $\rho$ $R^2$**

# Imprint on galaxies



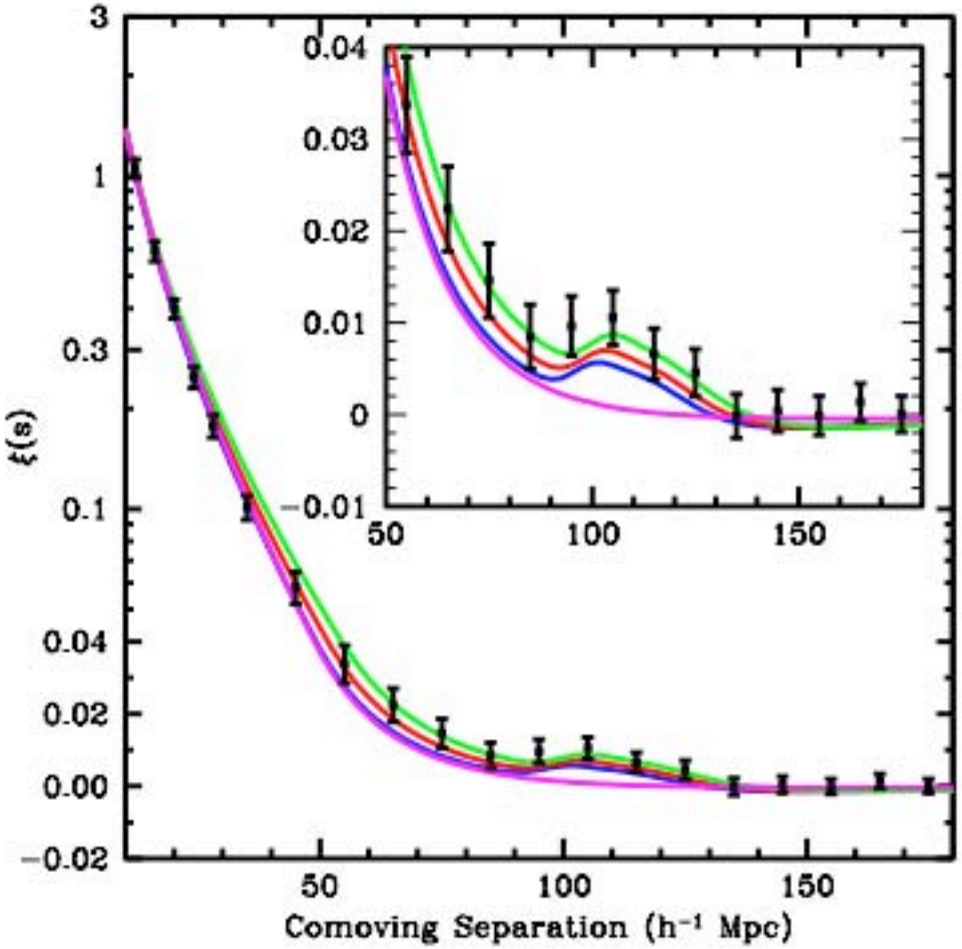




**Mass profile = ρ $R^2$**

**Density = ρ**

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

# Sloan Digital sky Survey




**Position of acoustic peak :**

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

$$\approx \frac{c}{\sqrt{3}} \frac{2/3}{H(z=1100)} (1+z)$$

$$\approx \frac{c}{\sqrt{3}} \frac{2/3\,(1+z)}{H_0\sqrt{\Omega_M (1+z)^3}} \propto \frac{1}{\sqrt{\Omega_M}}$$

**SDSS (z ~ 0.3)**

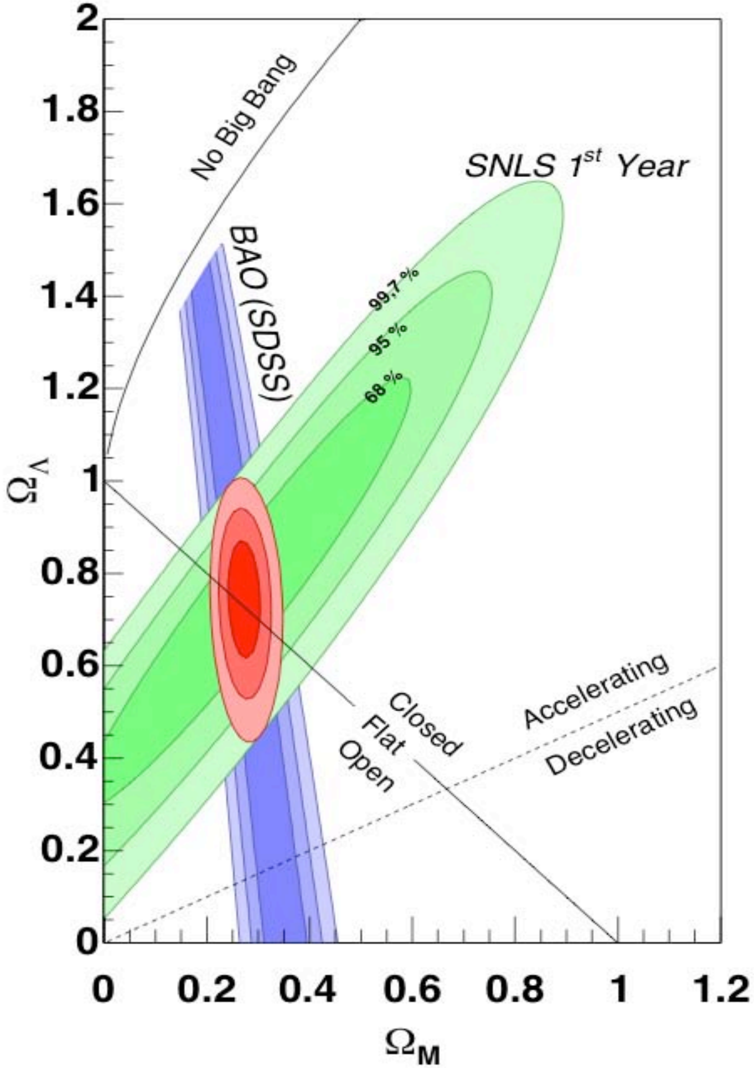
Eisenstein et al, Ap.J. 633 (2005) 560

⇓

$\Omega_{cdm} + \Omega_b = 0.273 \pm 0.025$

$+ 0.123(1+w) + 0.137(1-\Omega_T)$

# Conclusions




Energy content of the Universe

Concordance model