Astroparticle Physics (1/3)

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CERN Summer Student Lectures, August 2006

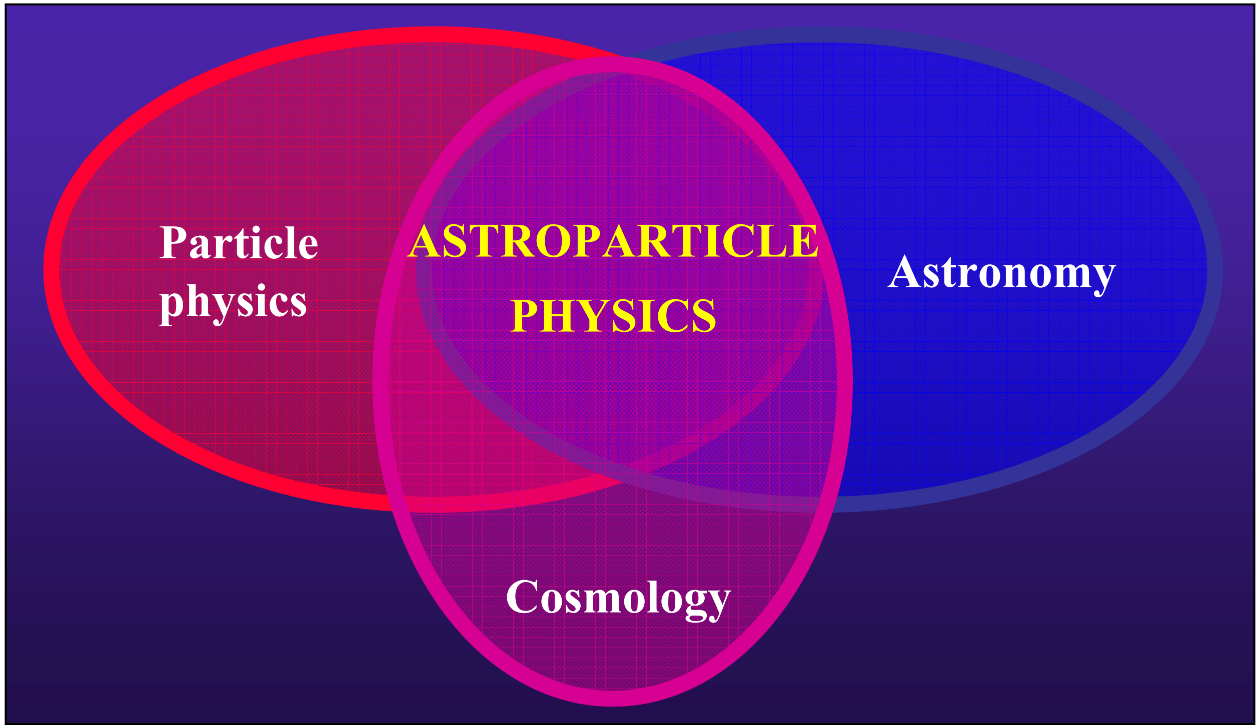
1) **What is Astroparticle Physics ?**
   Big Bang Nucleosynthesis
   Cosmic Microwave Background

2) Dark matter, dark energy

3) High energy astrophysics

Astroparticle Physics?

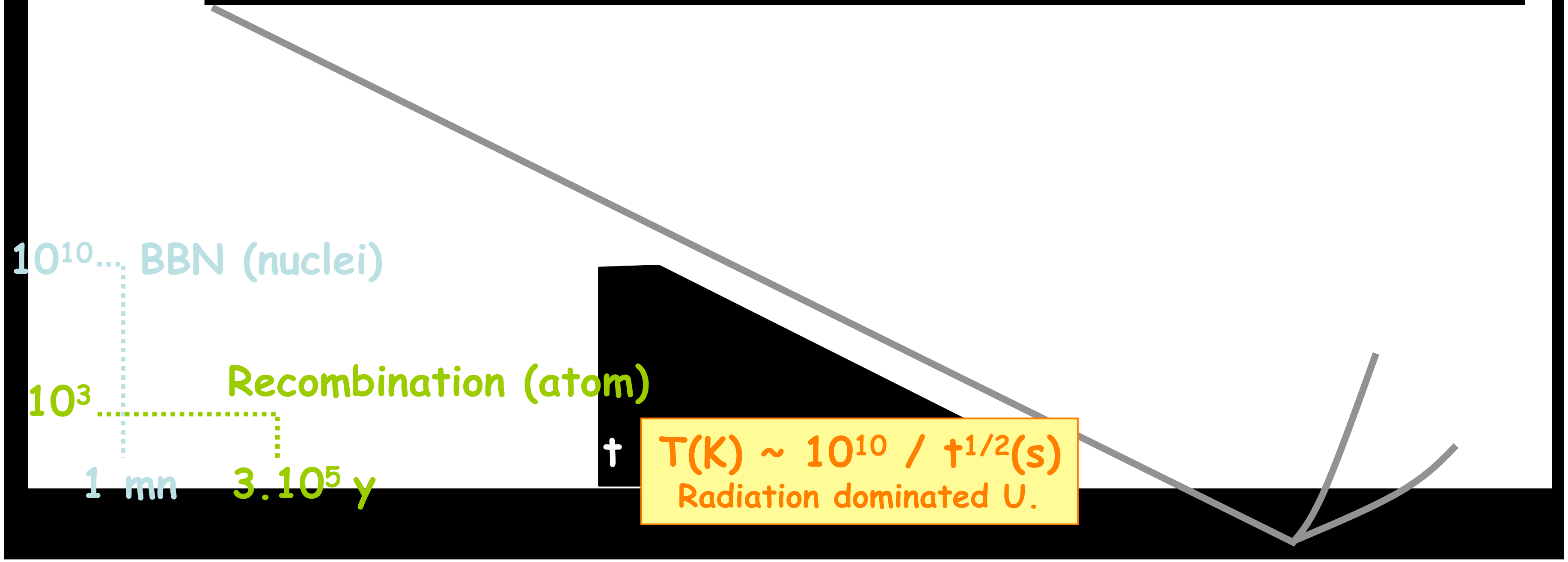
- Composition of the Universe ?
- Evolution of the Universe ?
- Extreme phenomena ?



Evolution of the Universe

Time →

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	$3x10^5$ yr	$3x10^9$ yr	$14x10^9$ yr
Superstring era (?)	GUT era	Inflation era	Electroweak era	Particle Era	Recombination era	Galaxy & star formation	Present era

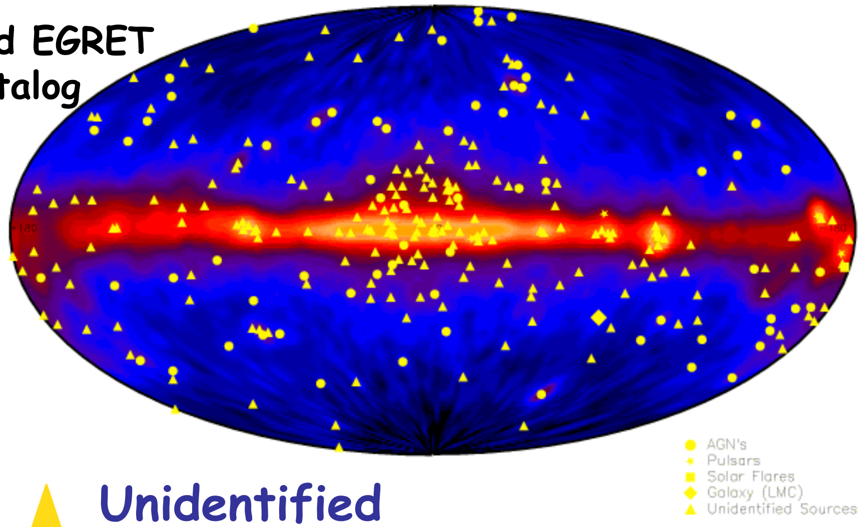


Today's universe

Astroparticle → high energy phenomena, cosmic accelerators

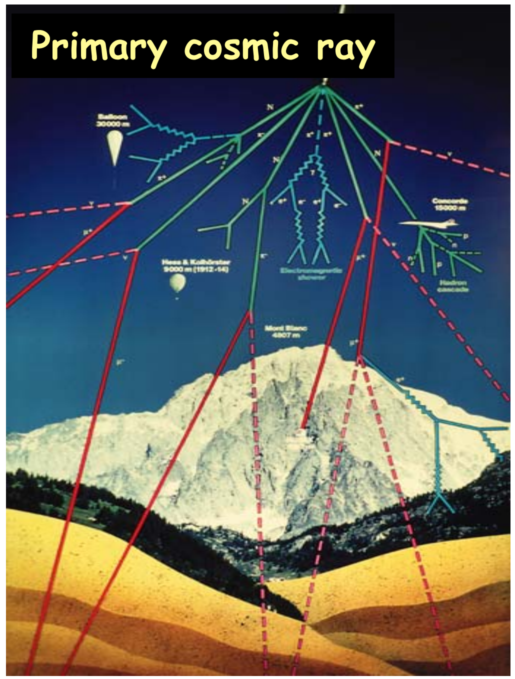
Gamma rays

3rd EGRET catalog



Unidentified sources

Cosmic rays

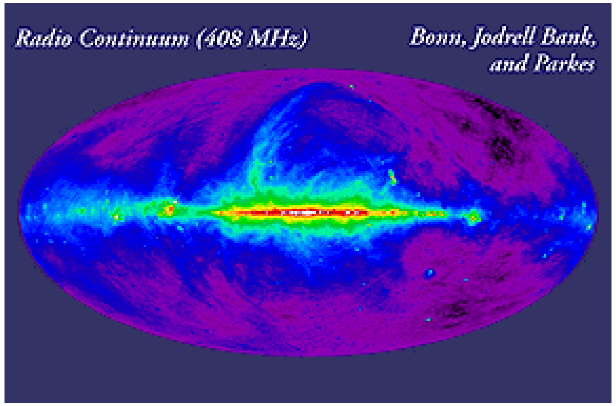


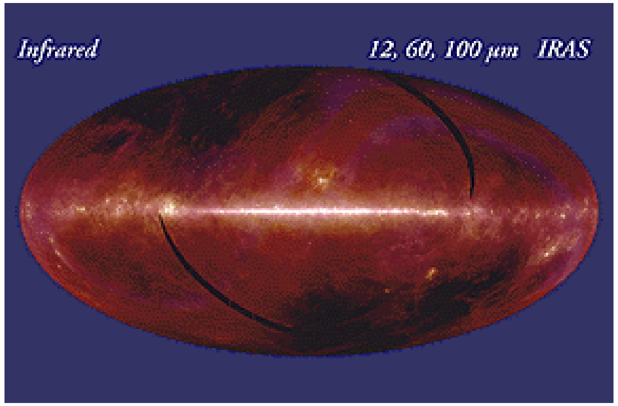
Neutrinos

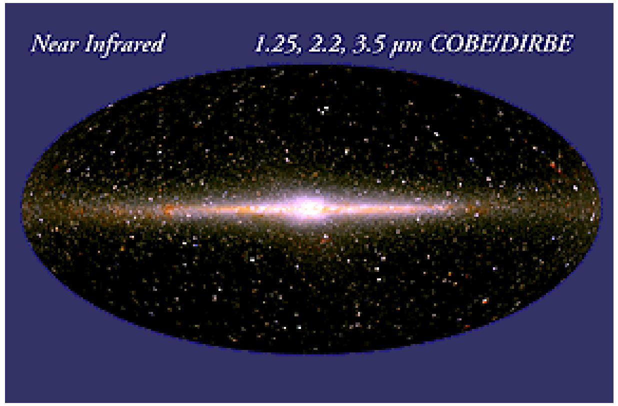
many astrophysical sources (sun, galactic center, AGN...)

⇒ Lecture 3

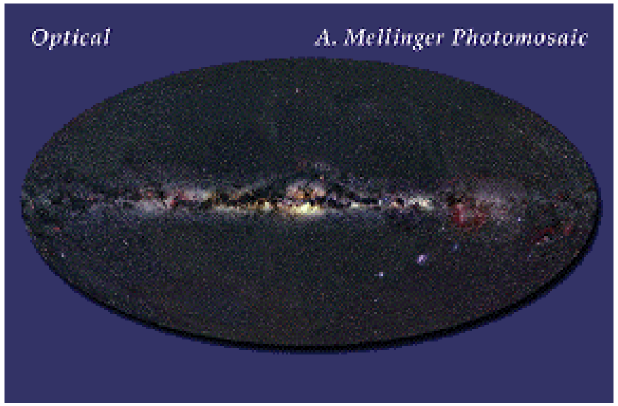
Multi-wavelength universe

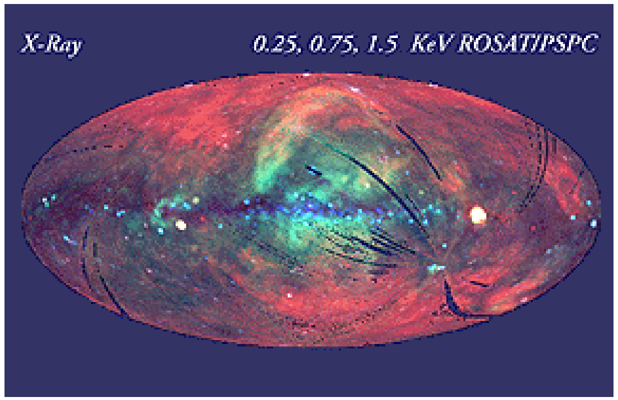


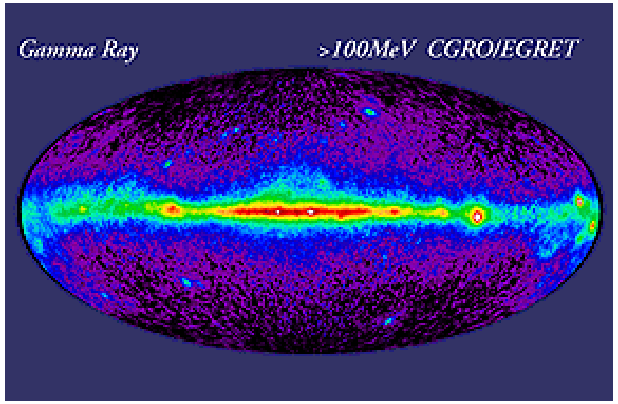




The different faces of the Milky Way

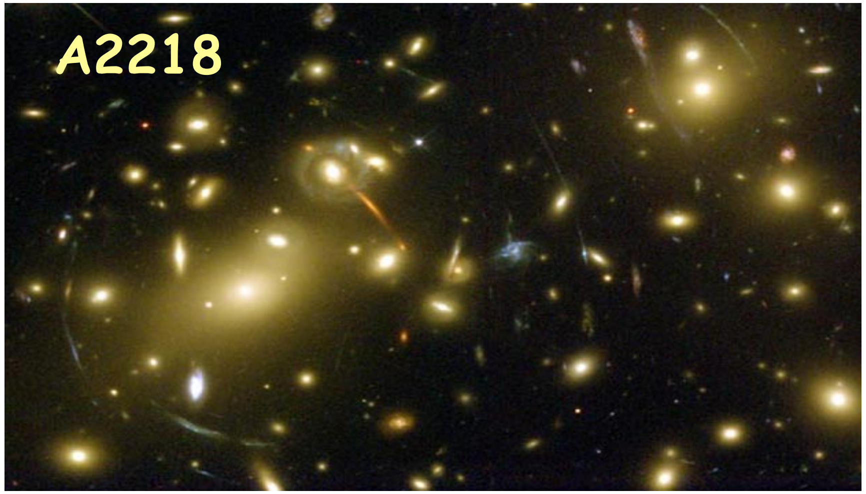


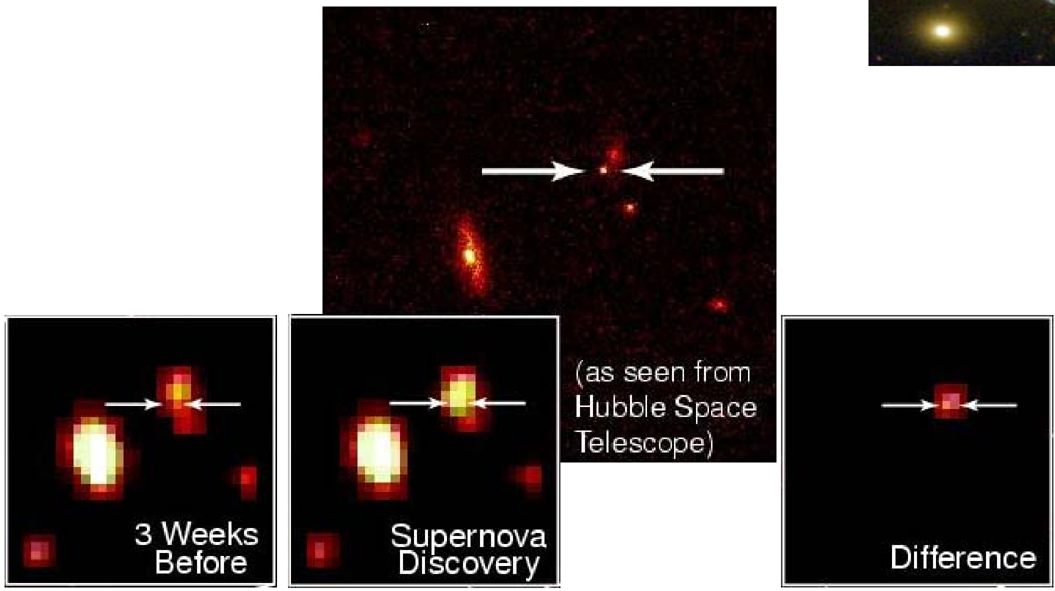




Content of the universe

Dark matter





⇒ Lecture 2

Dark energy

Evolution of the Universe

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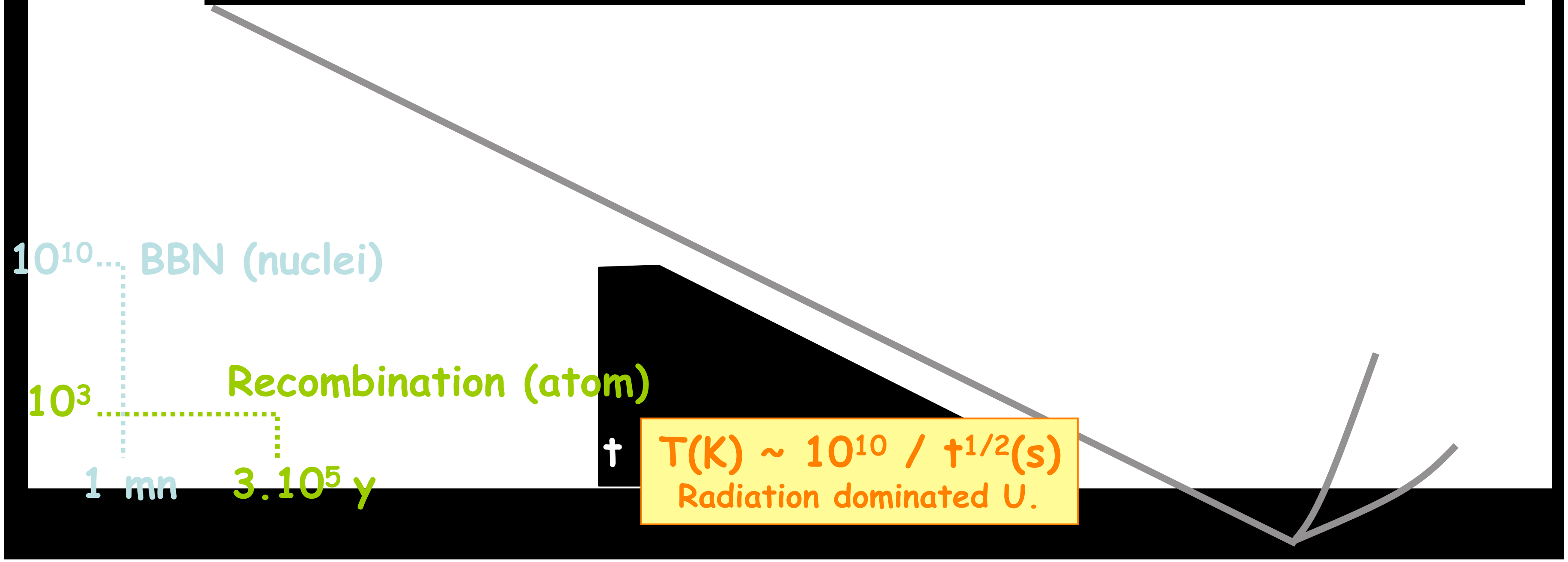

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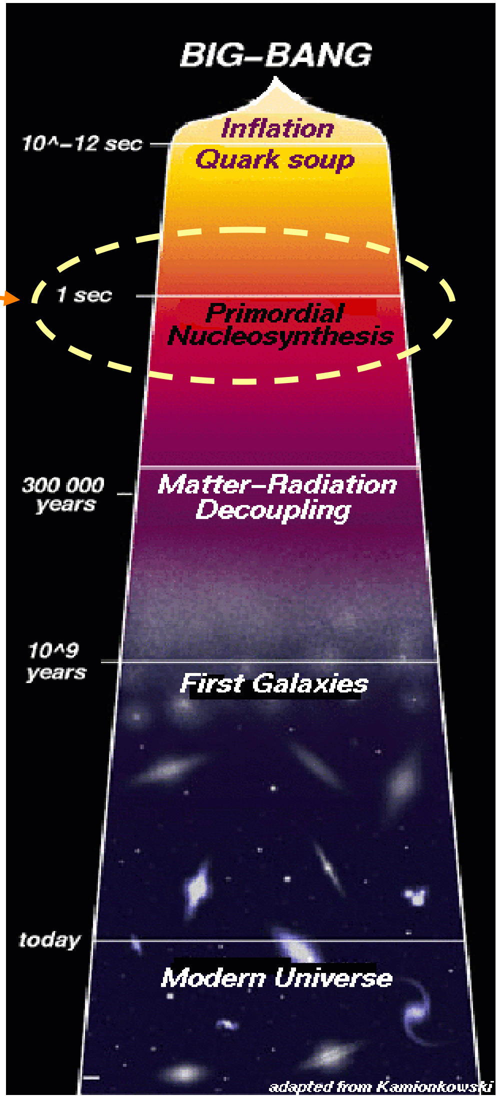
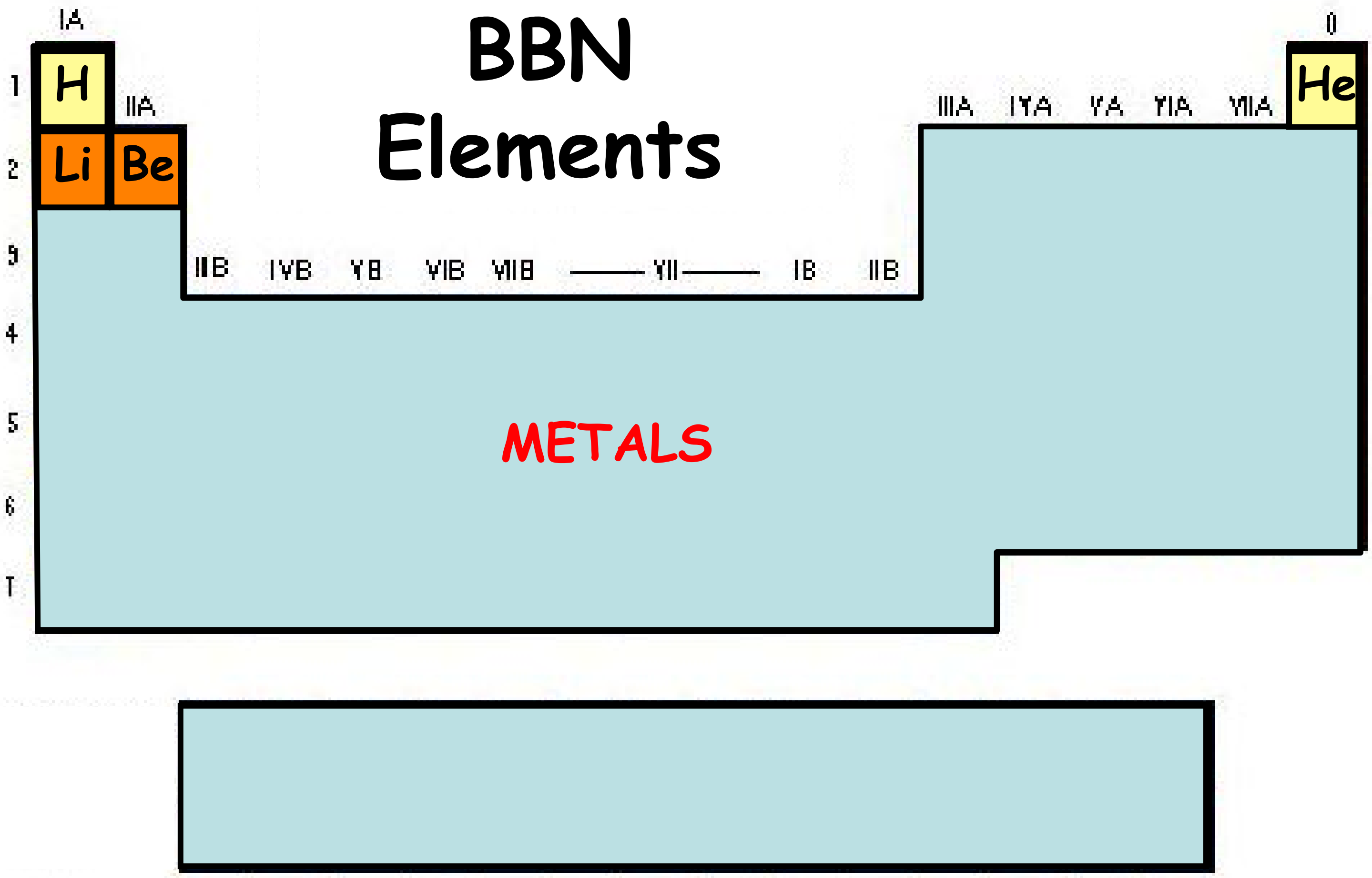
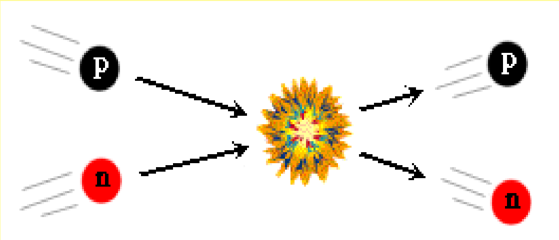


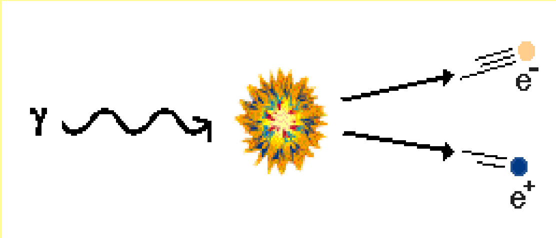
Which elements ?

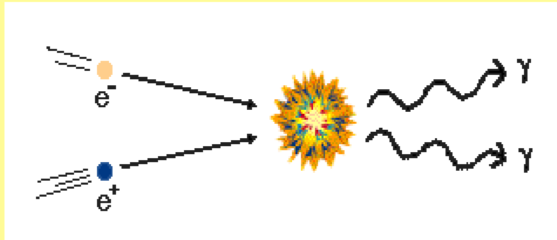


Age < 1s, T > 1 MeV

Collisions maintain thermal equilibrium







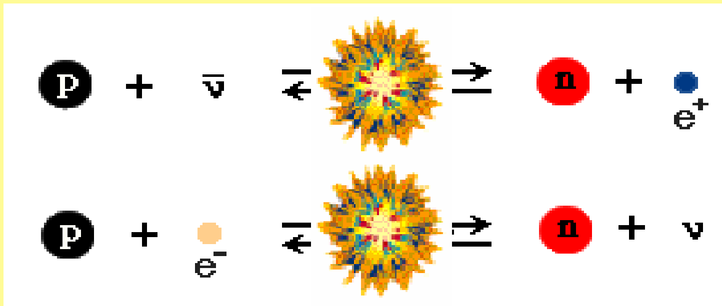
Proton - neutron conversion

Maxwell-Boltzmann distribution :

$$N \propto m^{3/2} \exp\left[-\frac{mc^2}{k_B T}\right]$$

$$\frac{n}{p} = \frac{N\,(\text{neutron})}{N\,(\text{proton})} \sim e^{-\Delta mc2/kT} \sim 1$$

(Δm = 1.3 MeV)



$\frac{n}{p} \rightarrow 0$ as $T \rightarrow 0$ **BUT freeze-out**

n-p freeze-out

- Weak reaction $n \leftrightarrow p$ rate:

  $\Gamma_{weak} = n\sigma|v| \propto G_F^2\, T^5$ (n $\propto T^3$ and $\sigma \propto G_F^2\, T^2$)

- Expansion rate:

  $H = \dot{a}/a \propto \rho^{1/2}$ with $\rho \propto g_* T^4$ (Stefan's law)

  so $H \propto g_*^{1/2}\, T^2$

- Freeze-out when $\Gamma_{weak} \sim H$ with $\dfrac{\Gamma_{weak}}{H} \sim \left(\dfrac{T}{0.8\ \text{MeV}}\right)^3$

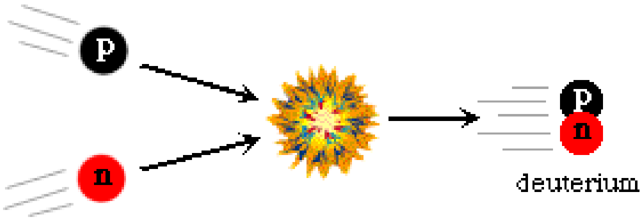
$\Rightarrow$ drop-out of equilibrium at T ~ 0.8 MeV

$$\frac{n}{p} = e^{-\Delta m/kT} = e^{-(1.3\ \text{MeV}\ /\ 0.8\ \text{MeV})} \sim 0.2$$

Deuterium bottleneck

- n_B small $\Rightarrow$ 2-body reactions only

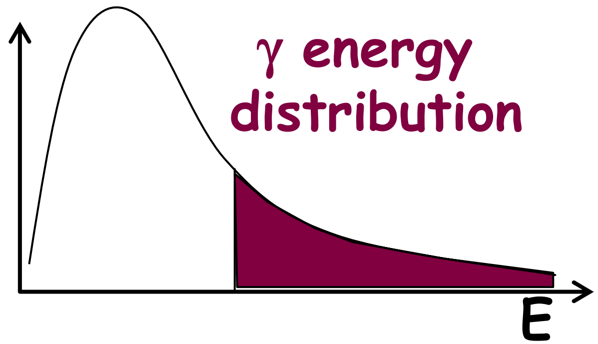
- Formation of D



- Binding Energy (D) = 2.2 MeV

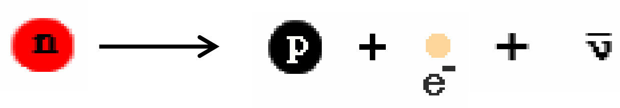
  $n_B / n_\gamma \sim 10^{-10}$

  $\Rightarrow$ D photo-disintegrated



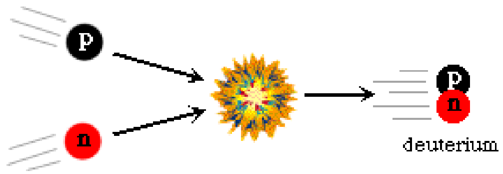
Tail of high energy photons prevents formation of Deuterium until T ~ 0.1 MeV

t=1-3 mn, T=0.3-0.1 MeV

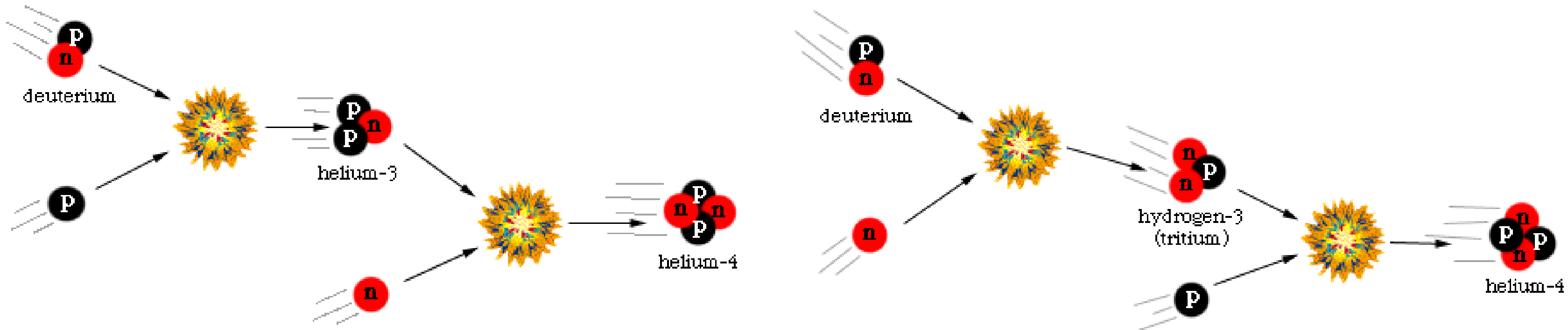
- neutron decay: 

$\Rightarrow$ $n/p \sim (n/p)_0\, e^{-(\Delta t/\tau)}$

$n/p \sim 1/7$

- Deuterium (all n): 

- Helium (all D ie. all n + equal number of p):



Helium abundance ~ $\dfrac{2n}{n+p}$ ~ 0.25

H abundance ~ 0.75

$\eta = n_B/n_\gamma \downarrow \Rightarrow$ D bottleneck lasts less $\Rightarrow n/p \downarrow \Rightarrow$ He $\downarrow$

Heavier elements - BBN

No A=5, A=8 stable nuclei
+
2-body reactions only

$Li^5 \to He^4 + p$
$He^5 \to He^4 + n$
$Be^8 \to He^4 + He^4$

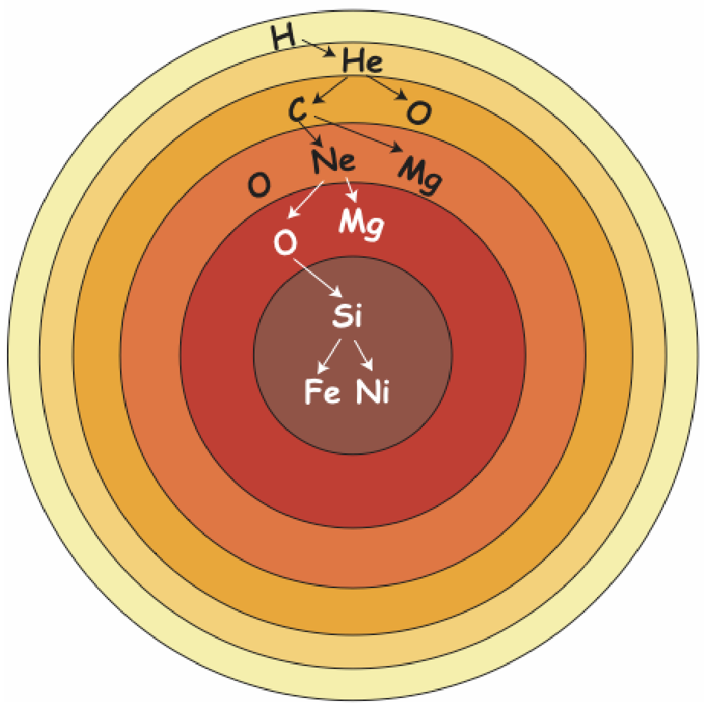
BBN essentially STOPS at He^4

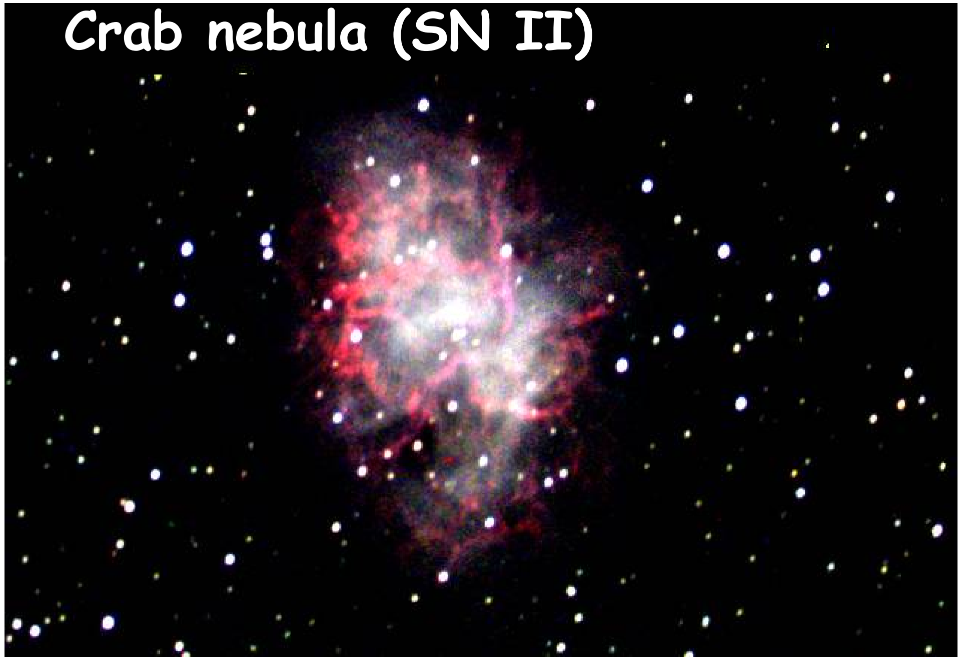
Trace amounts of ${}_3Li^7$, ${}_4Be^7$:

$He^4 + H^3 \to Li^7 + \gamma$
$He^4 + He^3 \to Be^7 + \gamma$
$Be^7 + \gamma \to Li^7 + p$

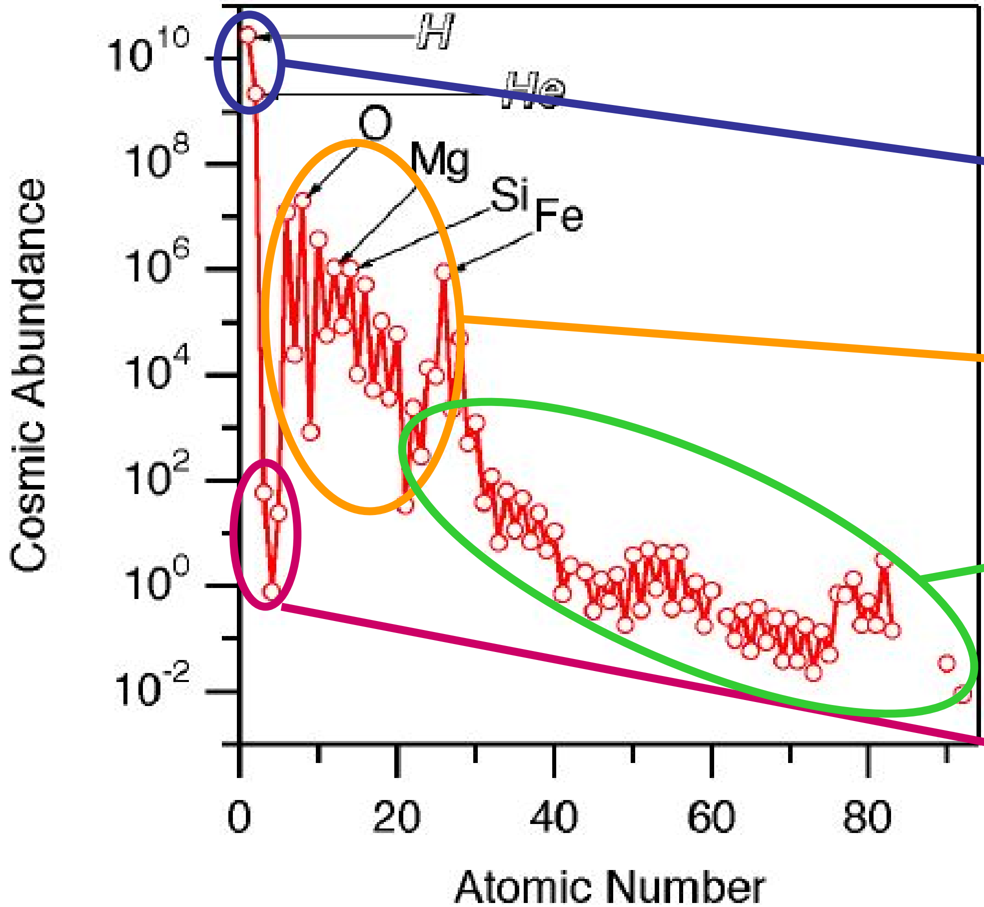
Heavier elements - Stars

Produced in stars
(high densities ⇒ triple alpha reactions allowed)
Spread in ISM by SN explosions





Origin of elements



formed in:

Big Bang Nucleosynthesis

Hot stars

Supernova explosions

Cosmic-ray interactions on inter-stellar medium

Observational constraints

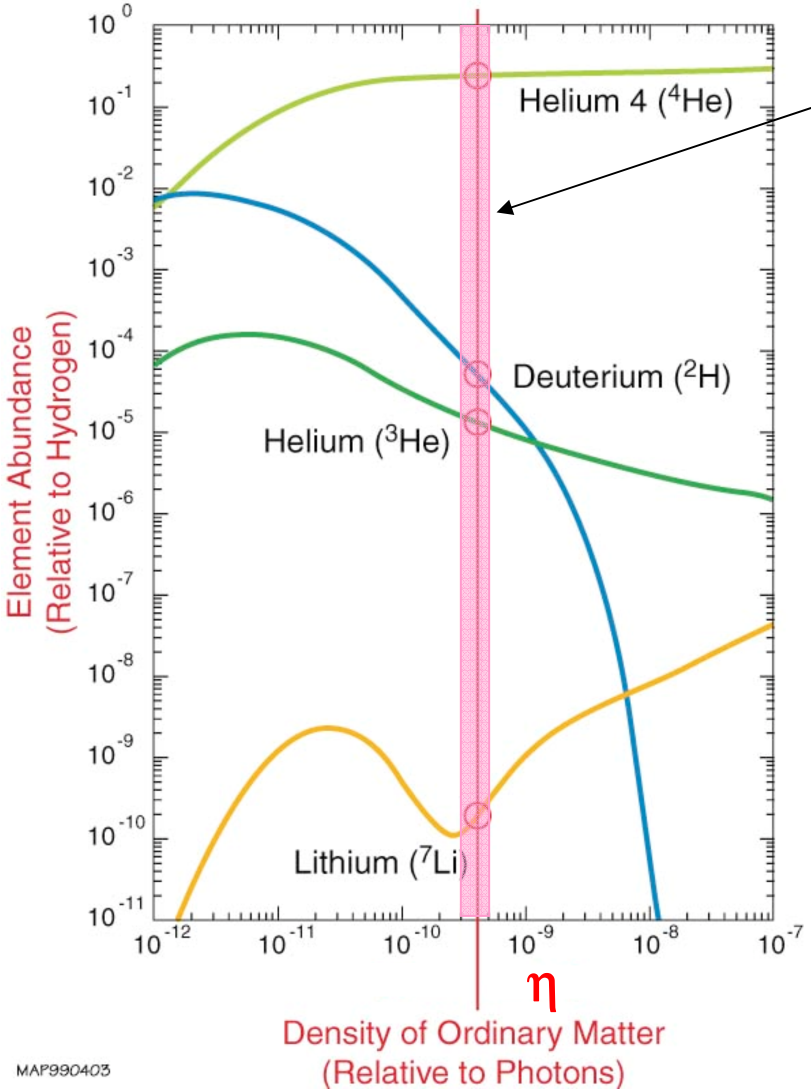
- Stars are net producers of He^4 and metals
  - $\Rightarrow$ use metal poor stars
  - upper limit on primordial abundance of He^4 (and on η)

- D weakly bound
  - $\Rightarrow$ measure in ISM
  - lower limit on primordial abundance of D (upper limit on η)

- D burnt to He^3 and He^3 produced by stars
  - $\Rightarrow$ $D+He^3$ increases with time
  - upper limit on $D+He^3$ ie lower limit on η

- Li^7 very fragile, burnt in stars
  - $\Rightarrow$ use old metal poor stars, require Li^6 (more fragile)

Abundances



Observational concordance

Agreement of abundances over 10 orders of magnitude

⇓

Major success of Big-Bang

CMB: $n_\gamma = 411 \text{ cm}^{-3}$

$\eta = n_B/n_\gamma = (4\pm1).10^{-10}$

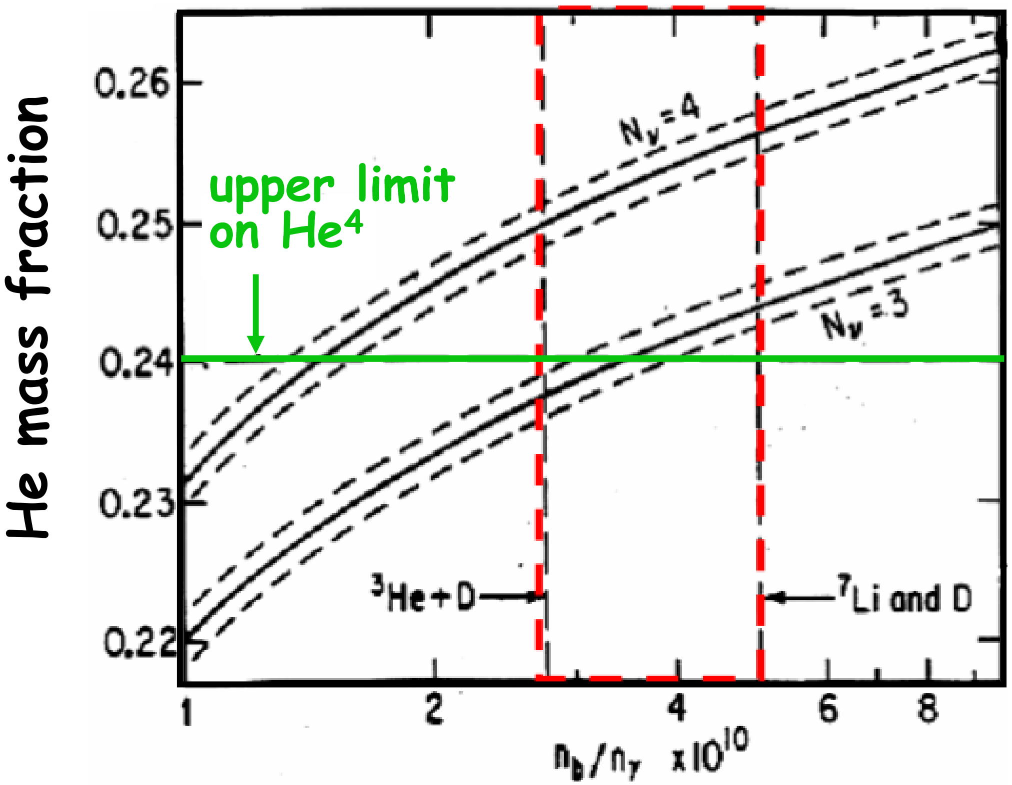
$$\Omega_B = \frac{\rho_B}{\rho_c} = \frac{n_B m_B}{3H^2/8\pi G}$$

$\Omega_B\, h_{70}^2 \sim 0.04$

BBN and neutrinos

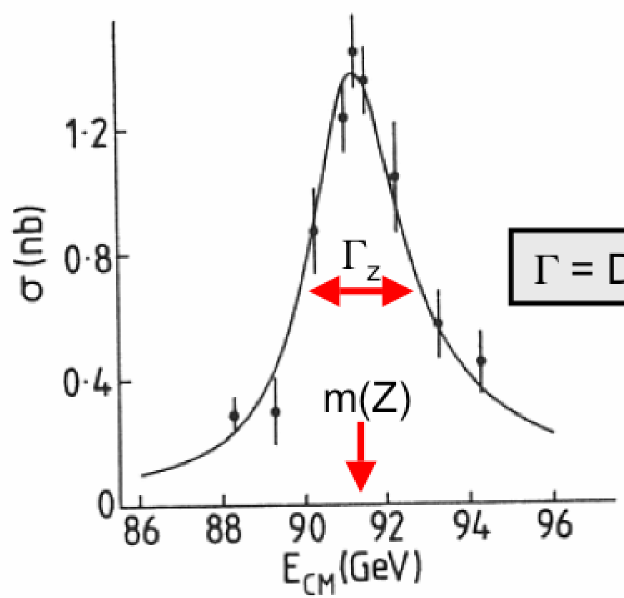
$H \propto g_*^{1/2} T^2$ (remember?) where g_* includes relativistic ν's

so N_ν ∀ ⇒ H ∀ ⇒ sooner freeze-out ⇒ n/p ∀ ⇒ He^4 ∀

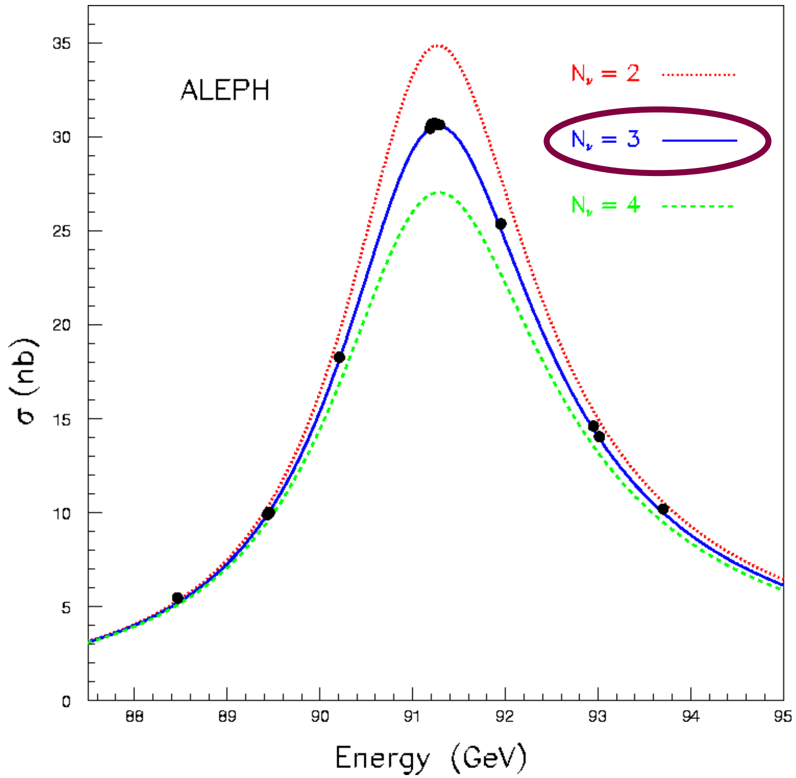


$N_\nu = 3$

LEP and light neutrinos



Γ = Decay rate



N_ν = 2.994 ± 0.012

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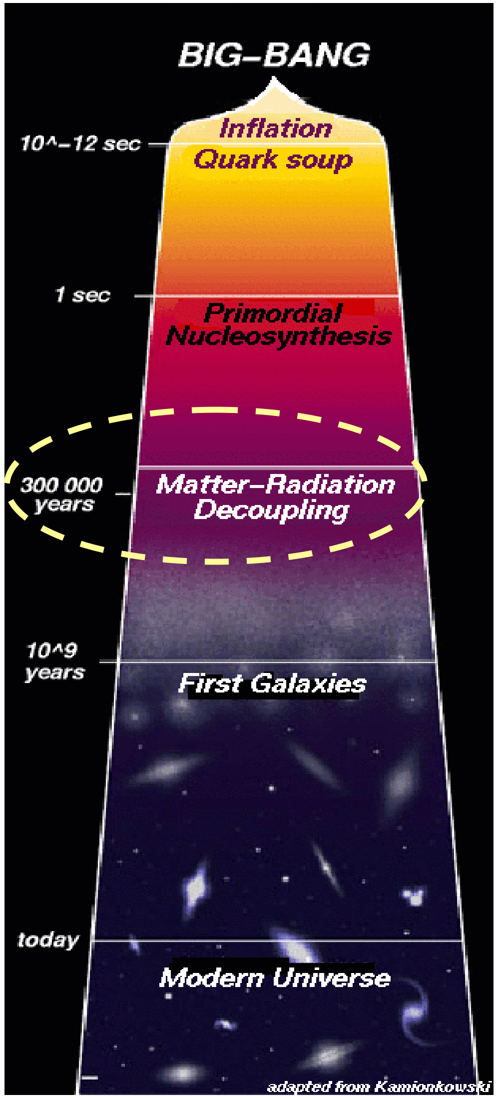


Back to thermal history

$t = 10^{-35}$ s — Density perturbations (inflation?)

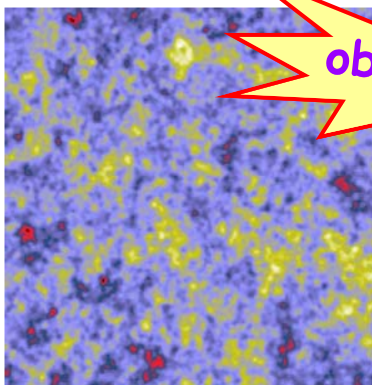
t ~ 2000 yrs — Matter domination

t ~ 300000 yrs — Recombination: $p + e^- \rightarrow H + \gamma$

Matter: Gravitational collapse

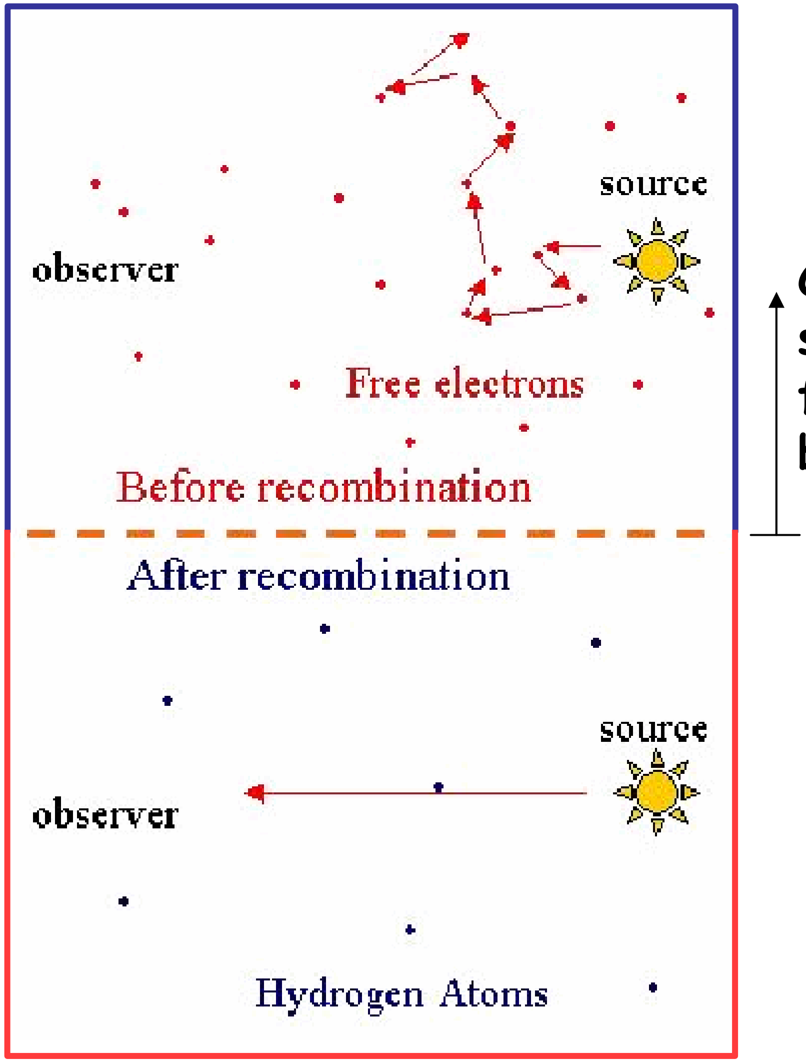
Photons: Free propagation

Galaxies, clusters



CMB

End of opaque Universe



Cannot see further back

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

"Uniform" background at $T_0 = 2.7$ K

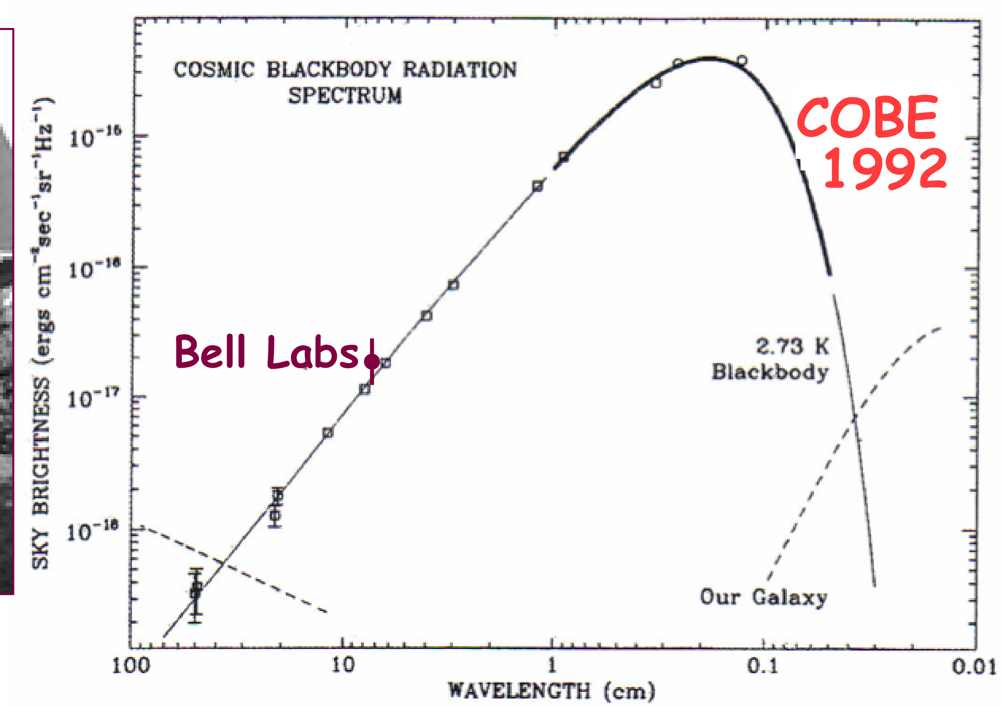
Discovery

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

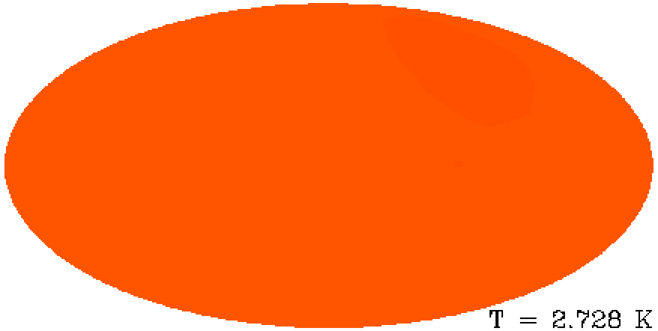
Wilson Penzias

(+ Robert Dicke)

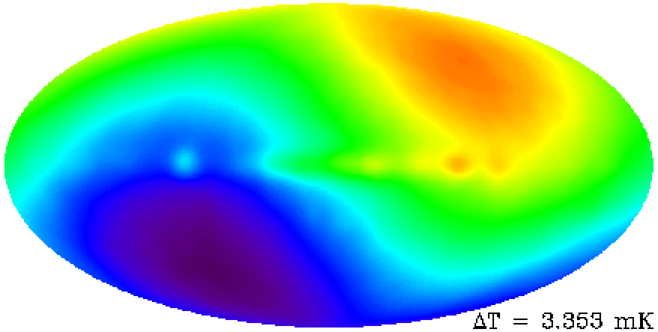
25 years later



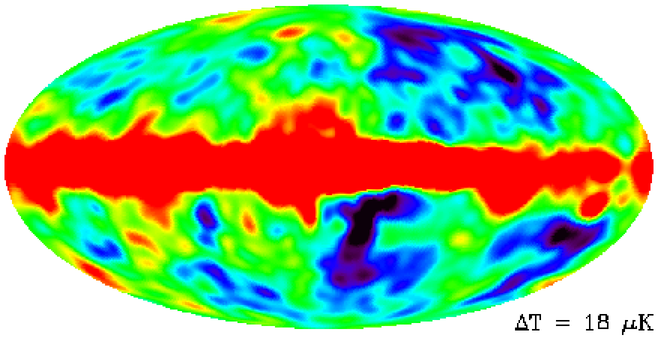
COBE sky maps



T = 2.7 K

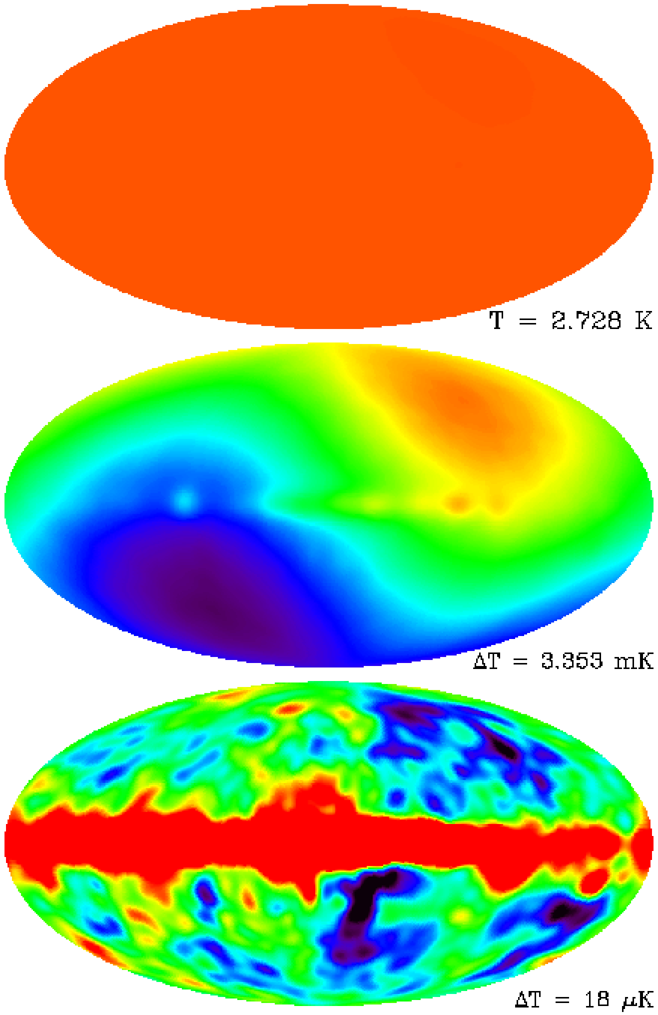


ΔT = 3.4 mK
(after subtraction of constant emission)



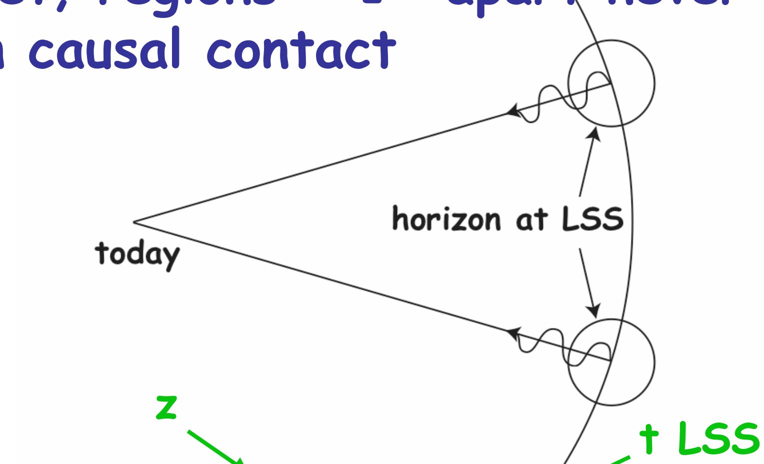
ΔT = 18 μK
(after subtraction of dipole)

COBE sky maps



scale 0-4 K: very homogeneous
→ cosmological origin

Yet, regions > 1° apart never in causal contact

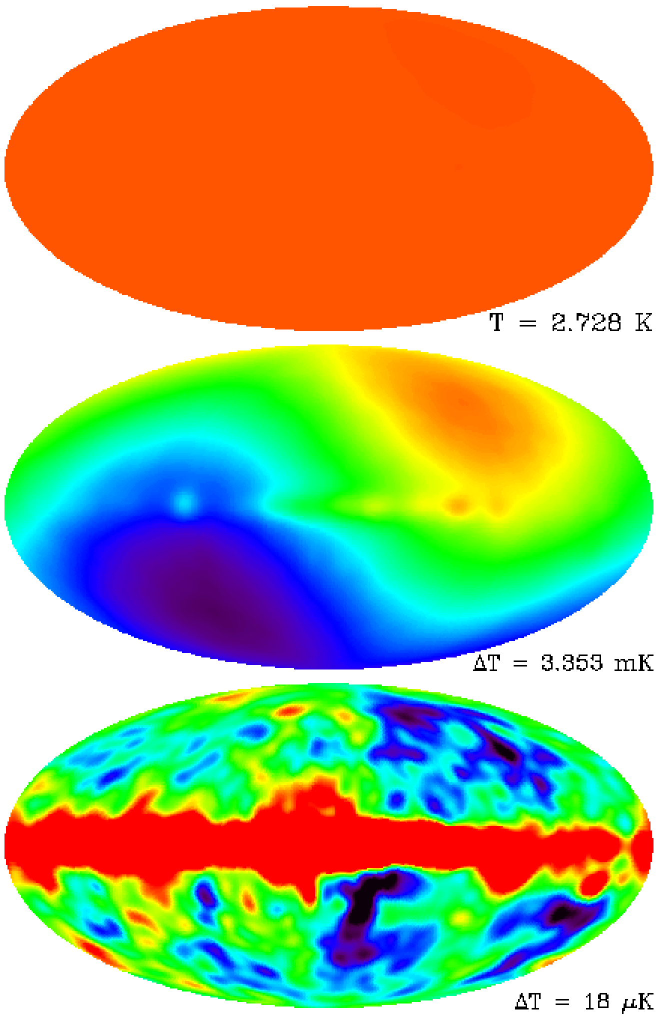


z — t LSS — t now

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

Inflation ?

COBE sky maps



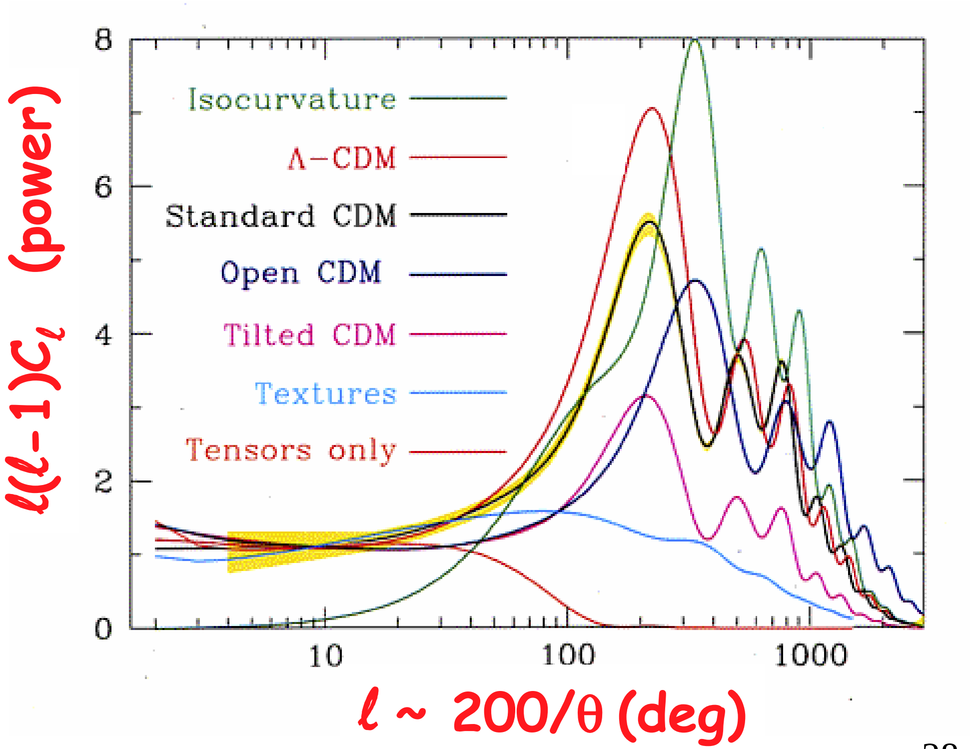
Doppler effect due to motion of Earth w.r.t. CMB
(v = 370 km/s towards Virgo)

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

Anisotropies

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

cosmology



Anisotropies

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$\ell(\ell-1)C_\ell$ (power)

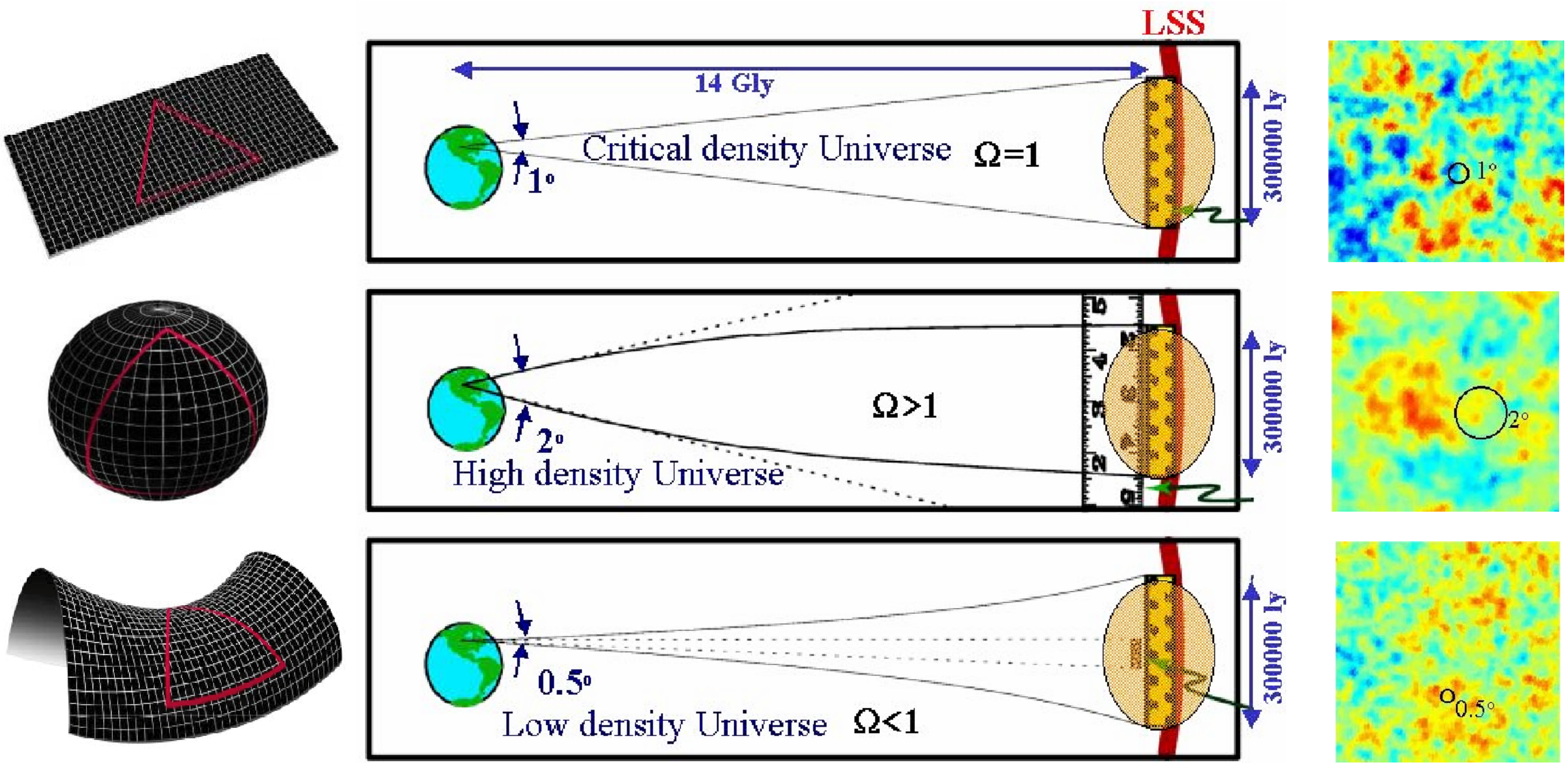
QuickTime™ et un
décompresseur GIF
sont requis pour visionner cette image.

cosmology

$\ell \sim 200/\theta$ (deg)

Max. scale of anisotropies

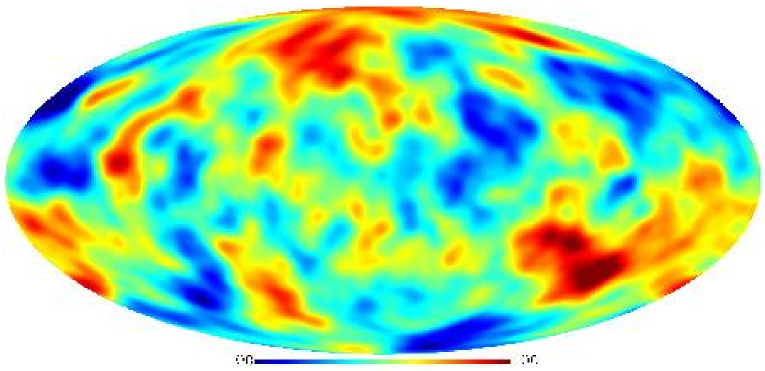
Limited by causality (remember?) $\rightarrow$ maximum scale



$\Rightarrow$ Max scale relates to total content of Universe Ω_{tot} (= $\Omega_M + \Omega_\Lambda$)

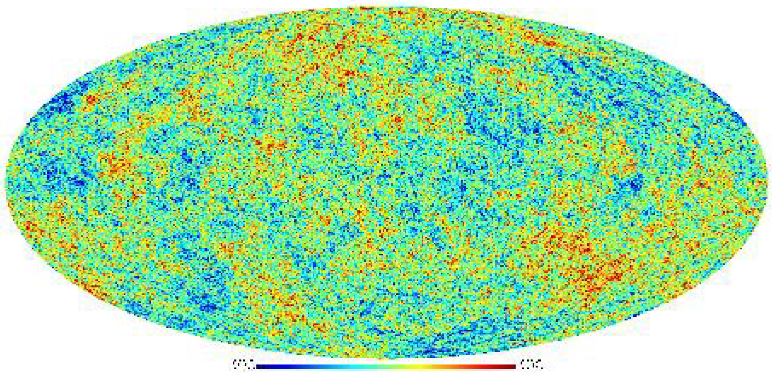
2nd generation satellite

COBE
(7 degree resolution)



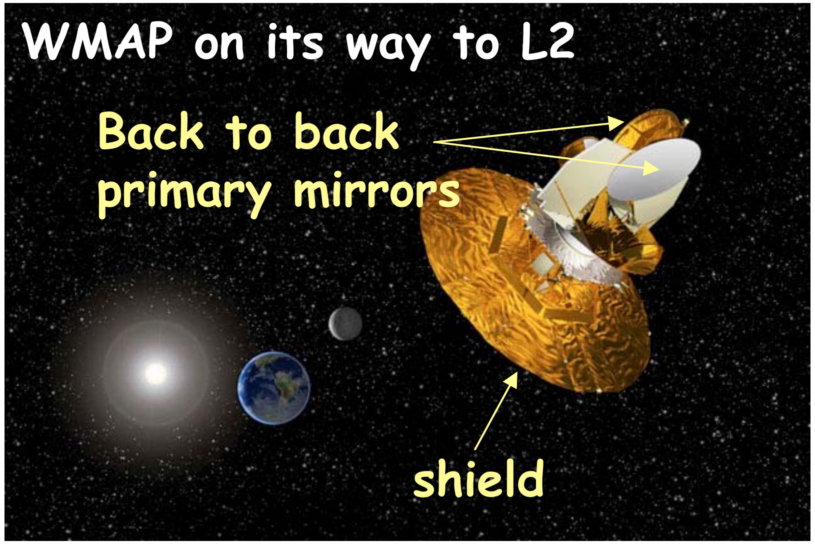
(ℓ < 20)

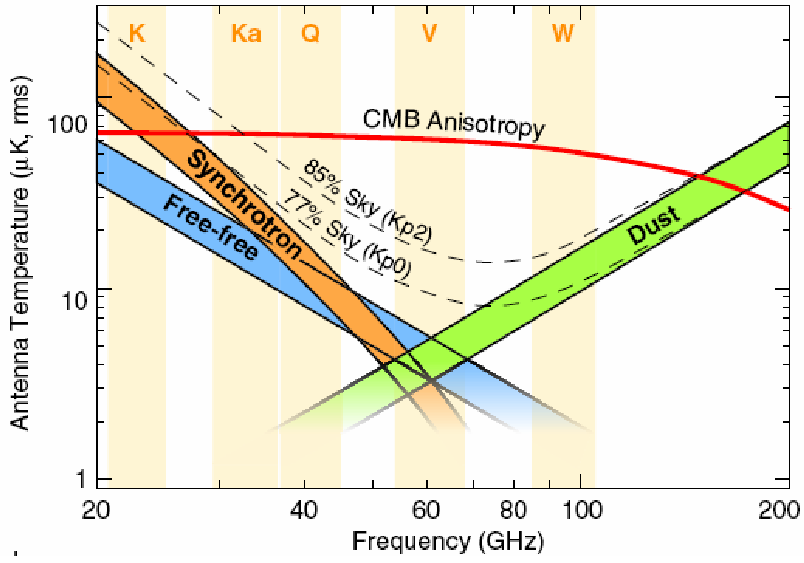
WMAP
(0.25 degree resolution)



(ℓ < 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)

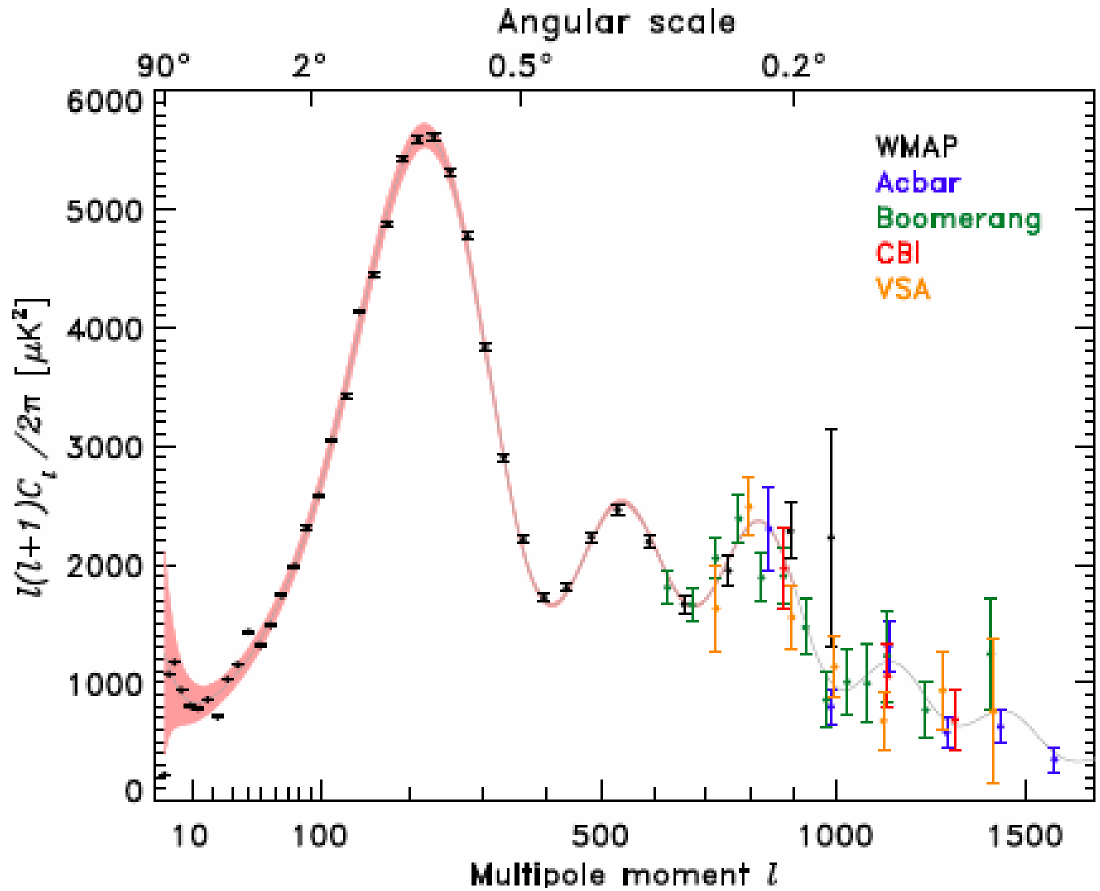
Launch: Jun. 2001
First results: 2003

Cosmological parameters

□□□□Λ□□□□□□□□□□

$\Omega_b\ h^2$	=	0.0223 +/-0.001
$\Omega_m\ h^2$	=	0.13 +/-0.01
h	=	0.73 +/- 0.03
…		…
n_s	=	0.95 +/- 0.02
σ_8	=	0.74 +/- 0.06

Typically ± 5-10%



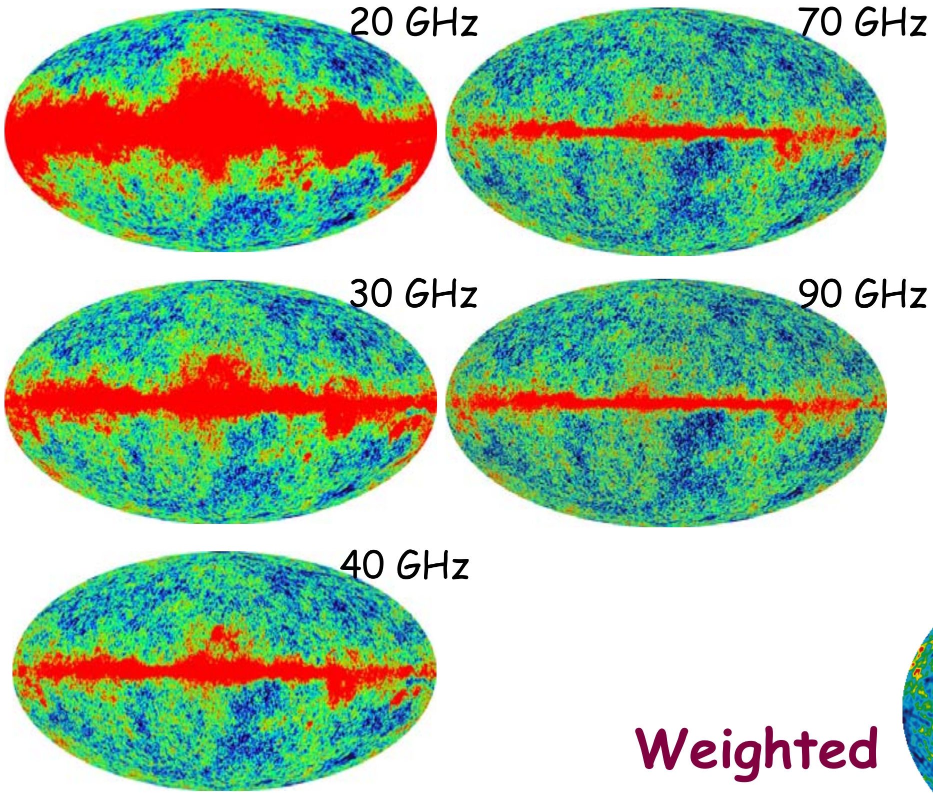
+ H_0 from HST

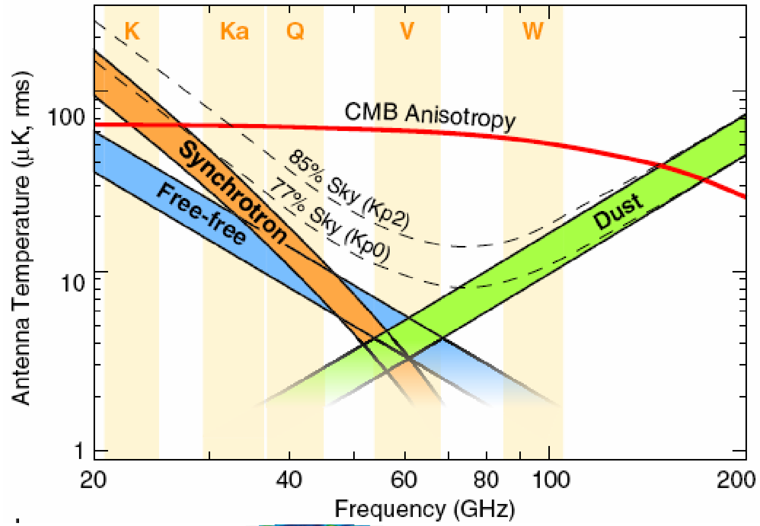
Ω_m	=	0.24 +/- 0.04
Ω_Λ	=	0.72 +/- 0.04

Beyond WMAP

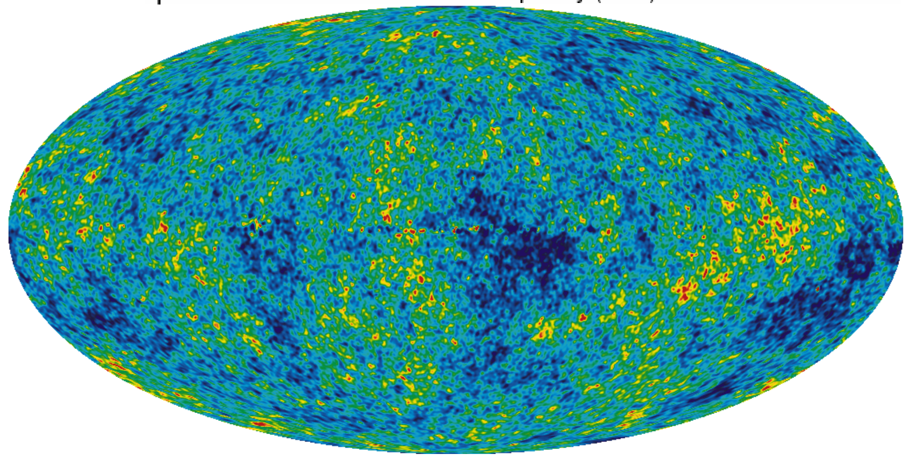
- More frequency channels
- Improved resolution

} I[illegible]ound removal



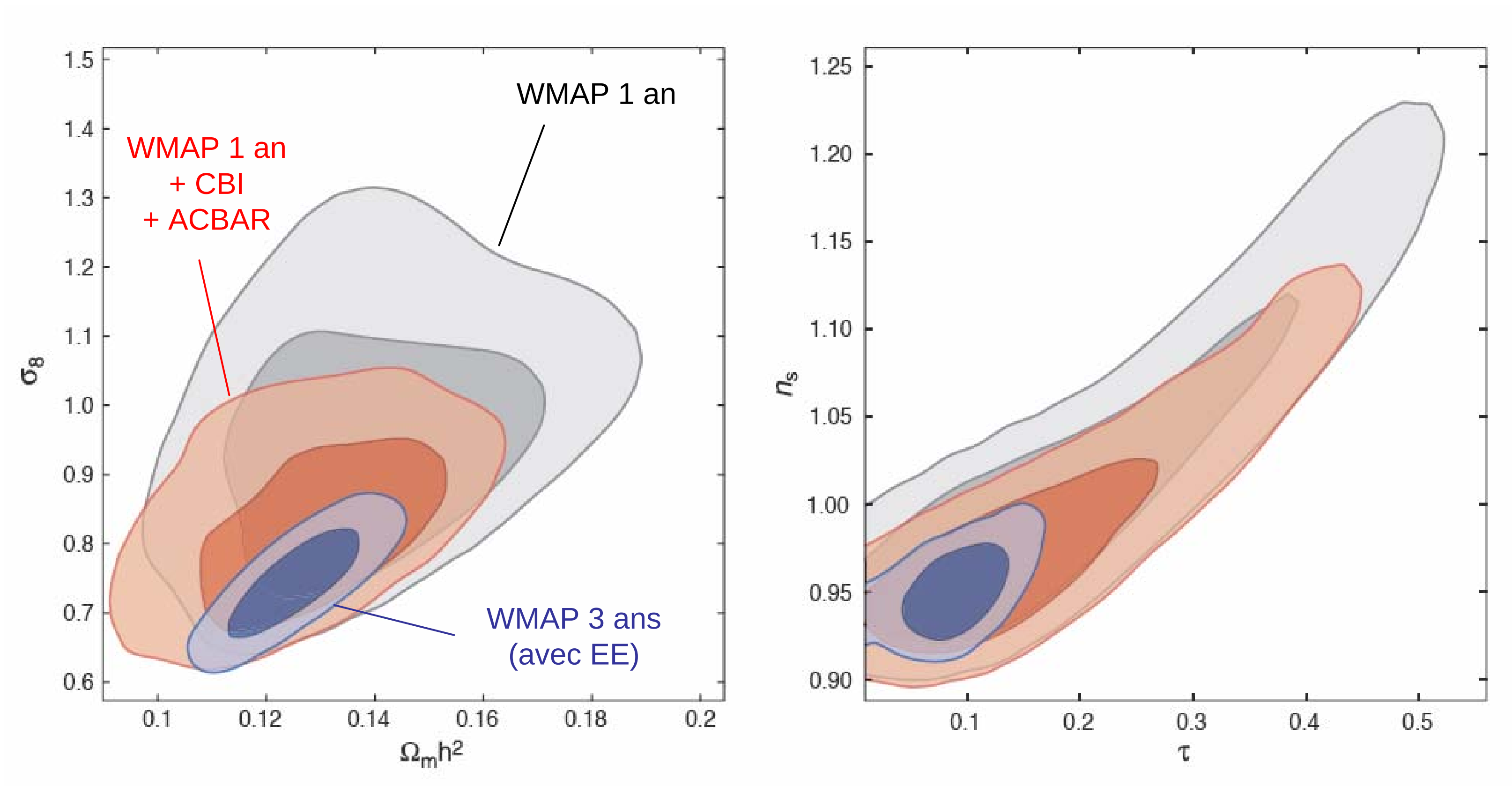


Weighted sum



Beyond WMAP

- More frequency channels
- Improved resolution
- Polarization



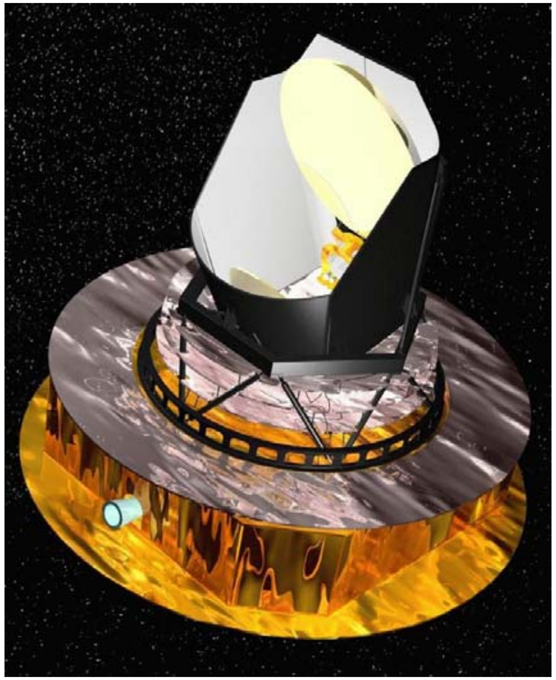
Planck

- [illegible] LFI & HFI
  - HEMTS
  - Bolometers

- Freq coverage from 30 to 850 GHz (9 channels)

- Polarization sensitive

- Launch foreseen spring 2008



Conclusions…

- Determinations of Ω_B (~ 4%) from
  BBN (age ~ 1 mn) and
  CMB (age ~ 300 000 yrs)
  agree !

- Ω_B (~ 4%) < Ω_m (~ 28%)
  ⇒ Non baryonic matter

- Ω_m (~ 28%) < Ω_{tot} (~ 1)
  ⇒ Confirmation of Ω_Λ

Next lecture !