Astroparticle Physics (1/3)

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CERN Summer Student Lectures, August 2004

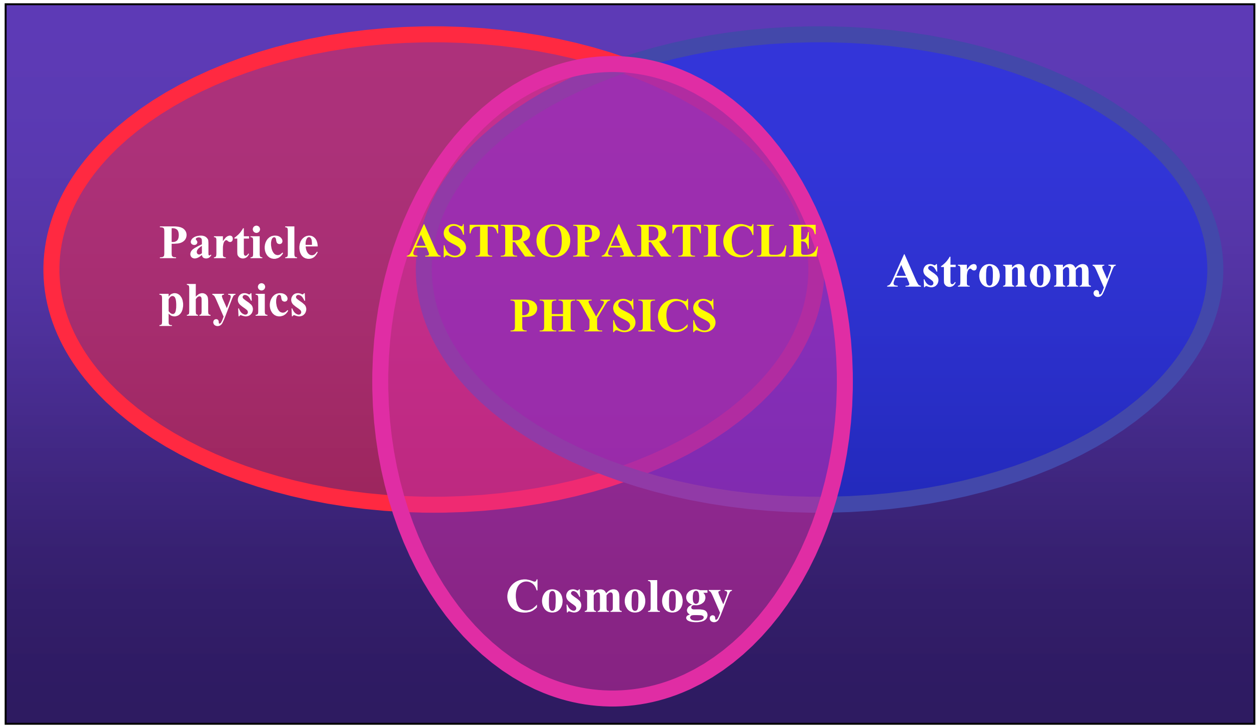
1) What is Astroparticle Physics ?
   Big Bang Nucleosynthesis
   Cosmic Microwave Background

2) Dark matter, dark energy

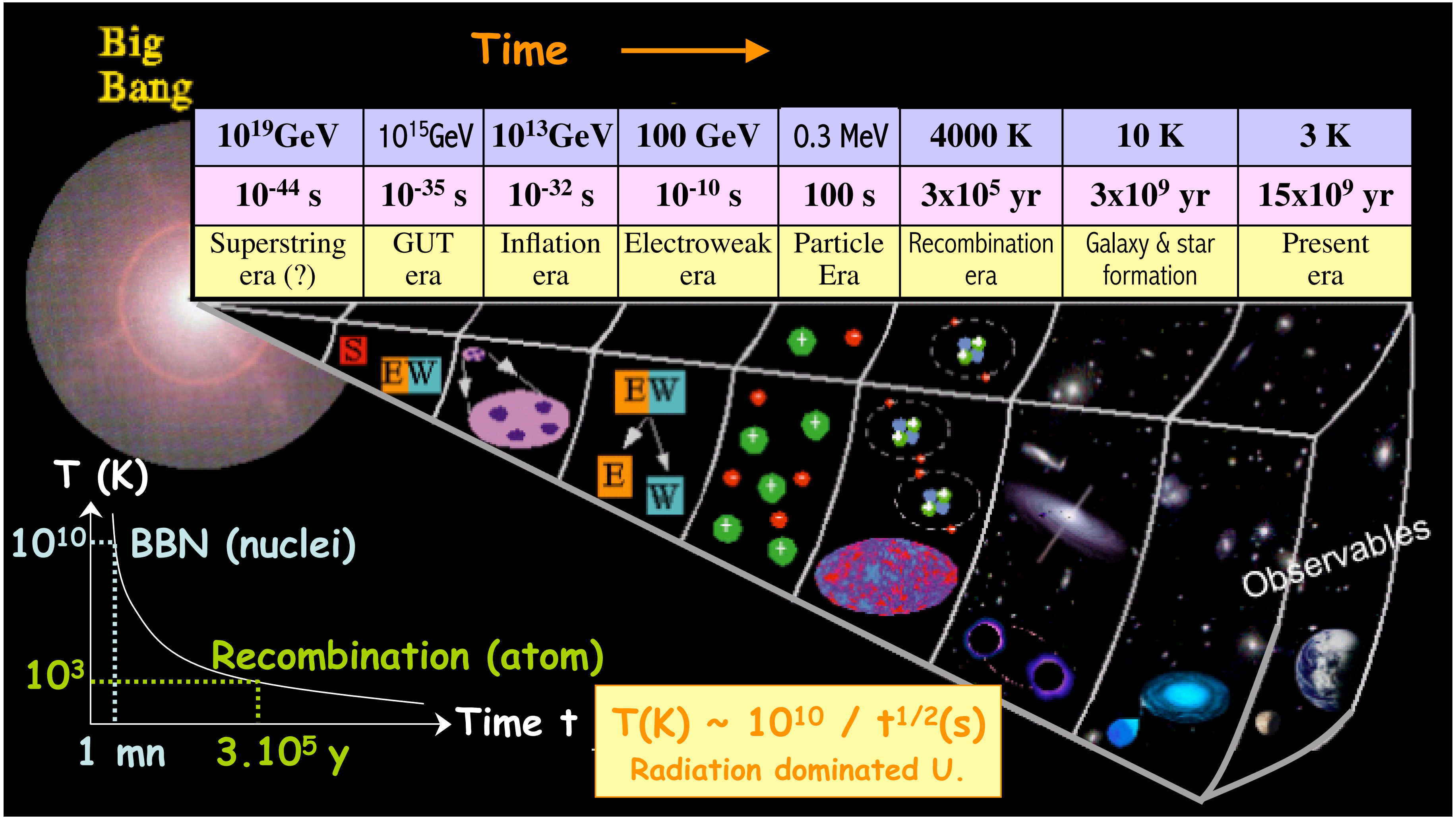
3) High energy astrophysics

Astroparticle Physics?

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



Development of Universe



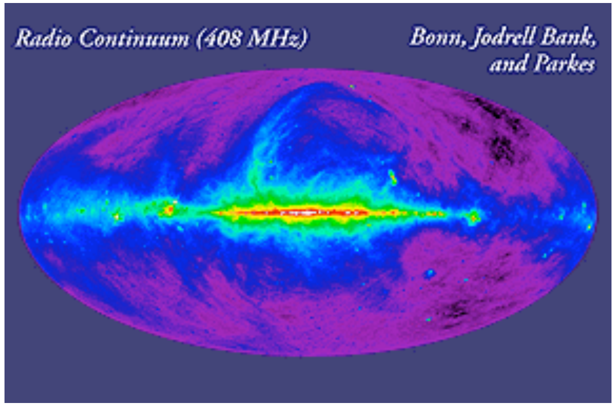
Optical Telescopes

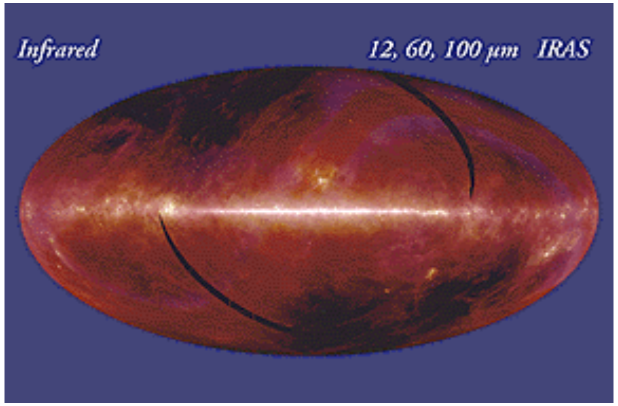
Galileo, 1564 - 1642

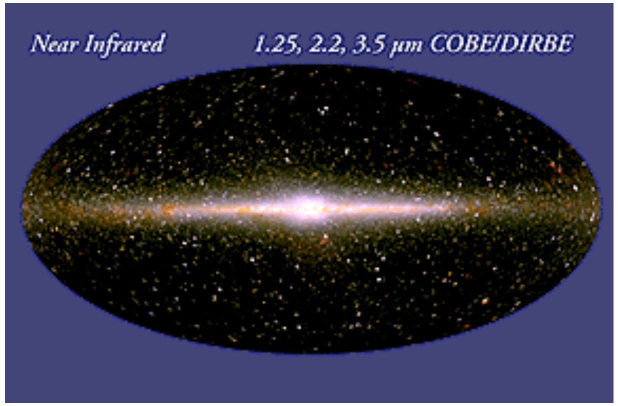
Hubble telescope, 2001

⇒ Lecture 2

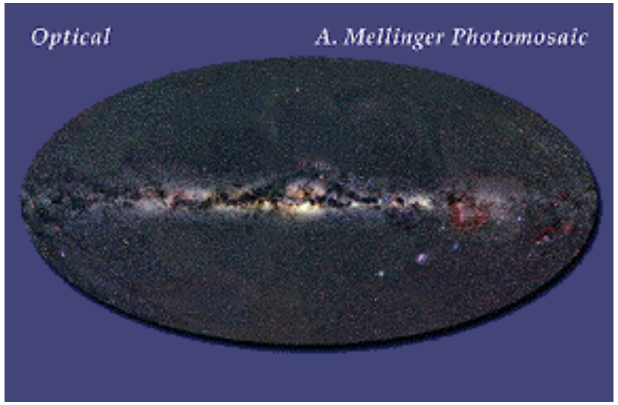
Multi-wavelength universe

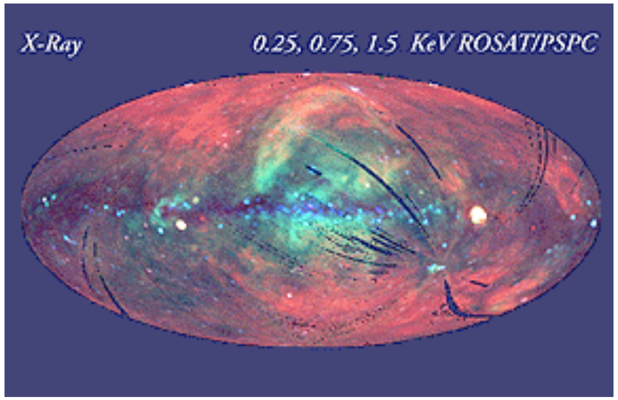


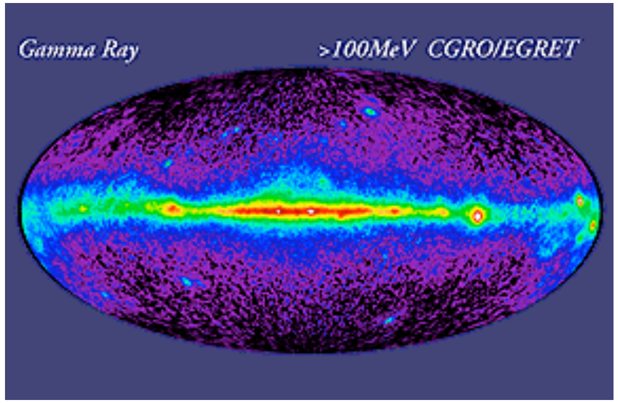




The different faces of the Milky Way

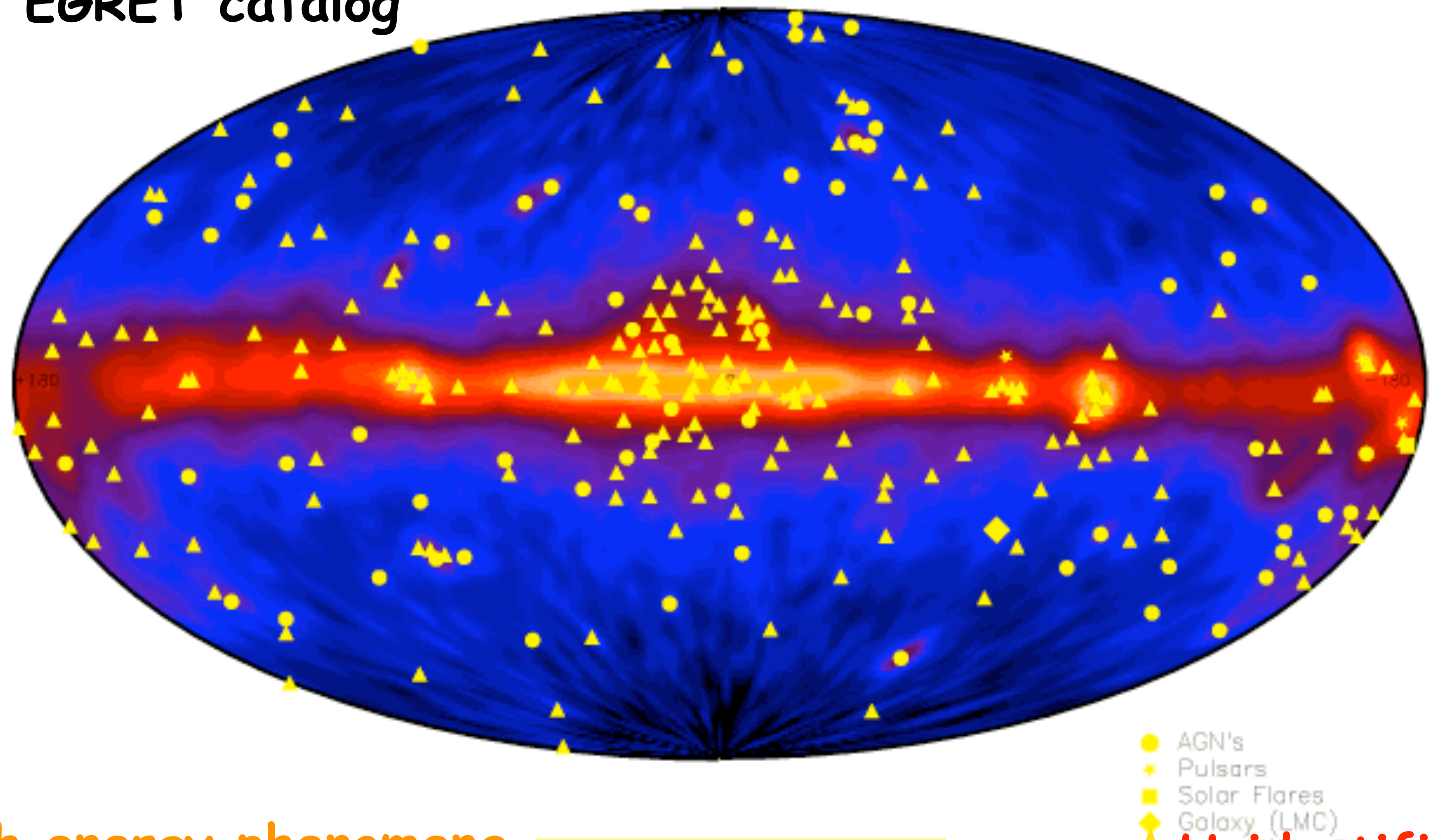






Gamma-ray astronomy

3rd EGRET catalog



High energy phenomena
Cosmic accelerators

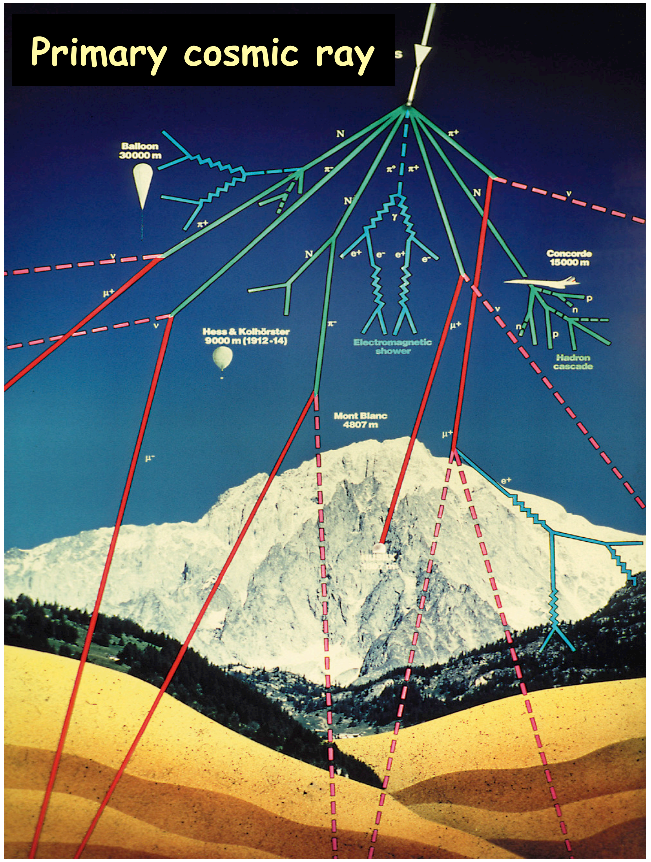
⇒ Lecture 3

Unidentified sources

High Energy astronomy

- **Neutrinos** : numerous astrophysical neutrino sources
  sun, galactic center, AGN...

- **Cosmic Rays** :



In space (>50 km)
p and nuclei (anti?)

On ground
μ, ν

$\Rightarrow$ Lecture 3

Lecture outline

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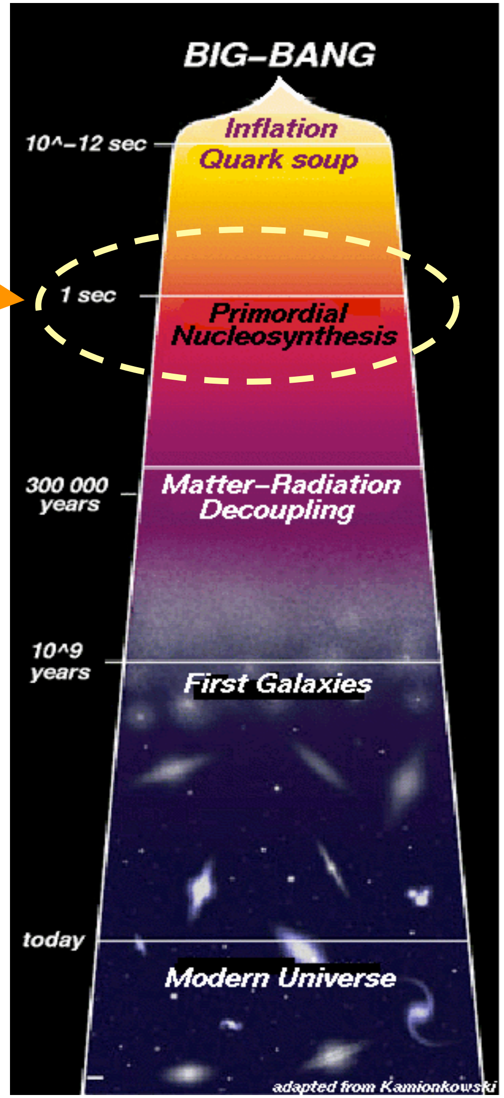
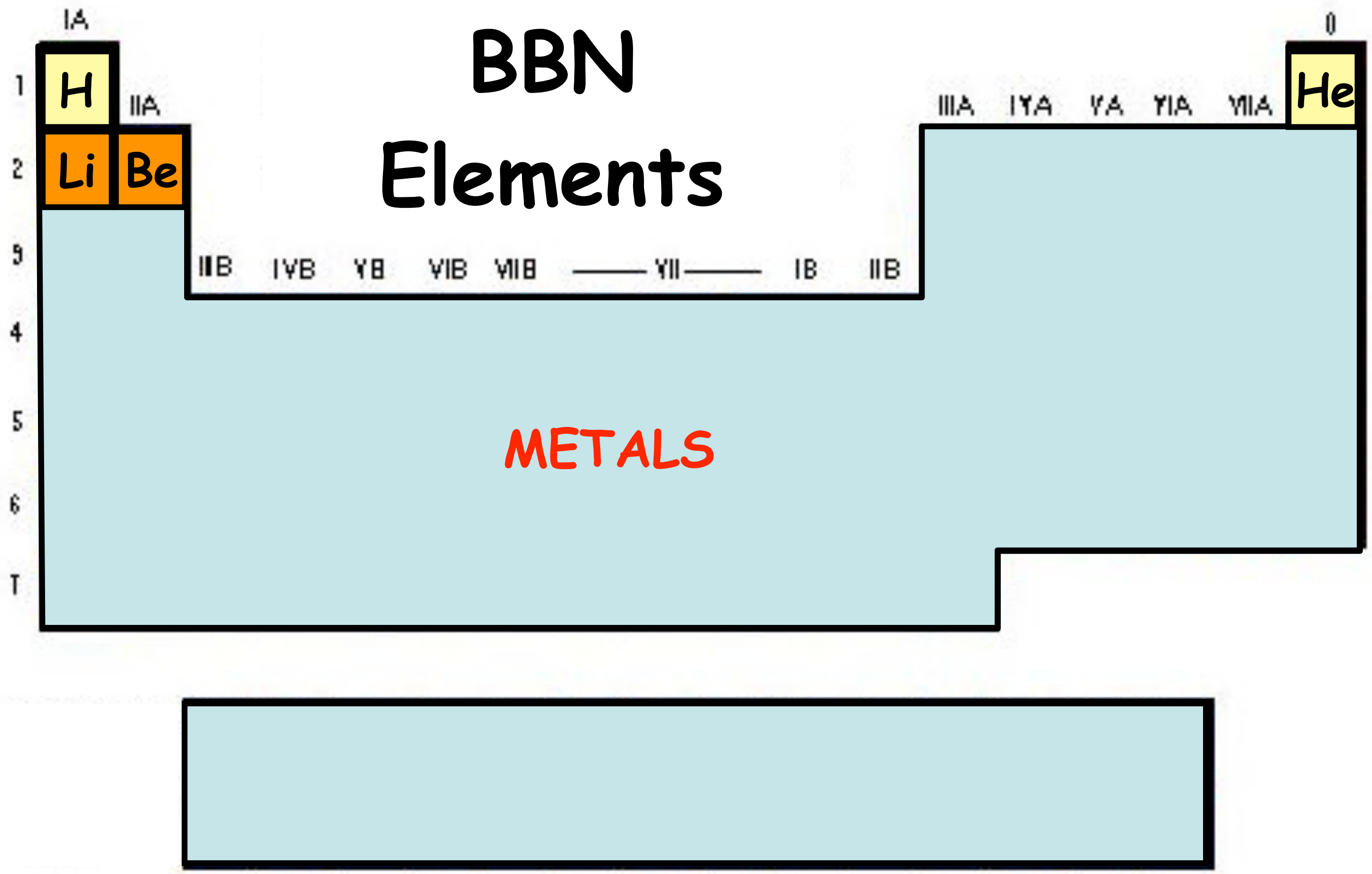
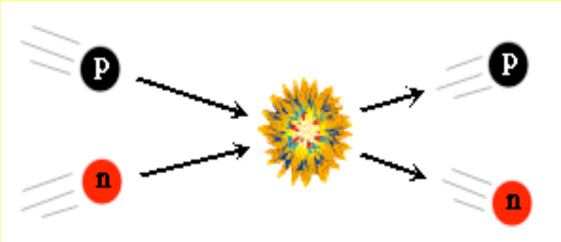


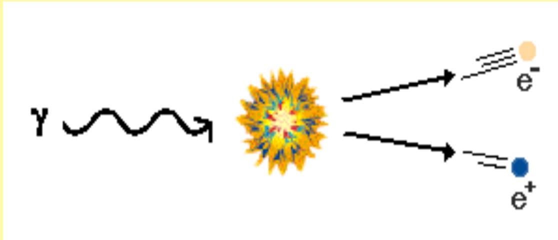
Which elements ?

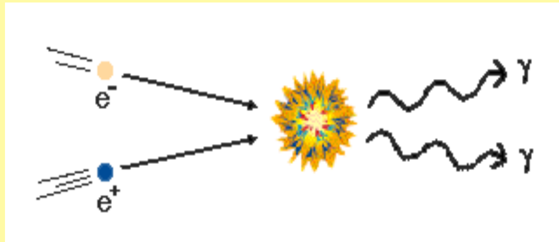


Age < 1s, T > 1 MeV

Collisions maintain thermal equilibrium







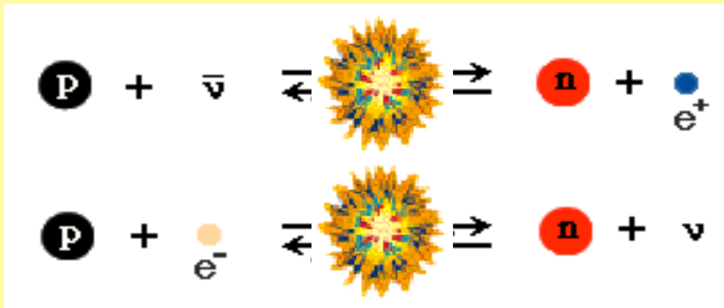
Proton - neutron conversion

Maxwell-Boltzmann distribution :

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

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

($\Delta m = 1.3$ MeV)



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

n-p freeze-out

- Weak reaction $n \leftrightarrow p$ rate:

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

- Expansion rate:

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

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

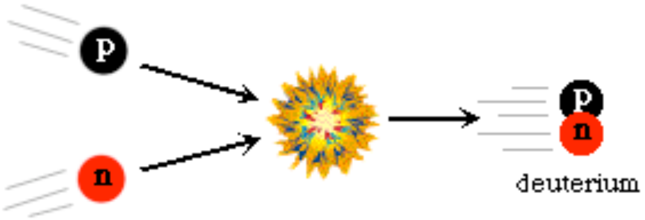
- Freeze-out when $\Gamma_{weak} \sim H$ with $\dfrac{\Gamma_{weak}}{H} \sim \left(\dfrac{T}{0.8\ \text{MeV}}\right)^3$

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

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

Deuterium bottleneck

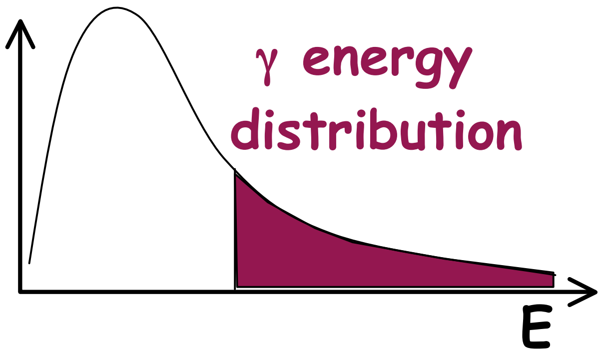
- n_B small ⇒ 2-body reactions only
- Formation of D



- Binding Energy (D) = 2.2 MeV

  n_B / n_γ ~ 10^{-10}

  ⇒ D photo-disintegrated



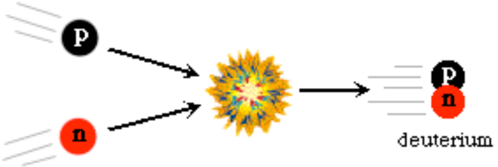
Tail of high energy photons prevents formation of Deuterium until T ~ 0.1 MeV

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

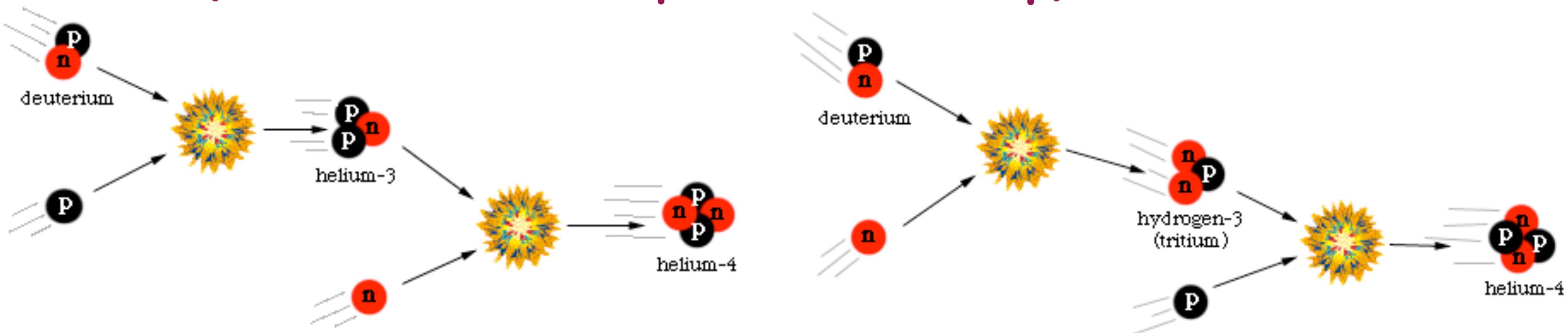
- neutron decay: 

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

$n/p \sim 1/7$

- Deuterium (all n): 

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



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

H abundance ~ 0.75

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

Heavier elements - BBN

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

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

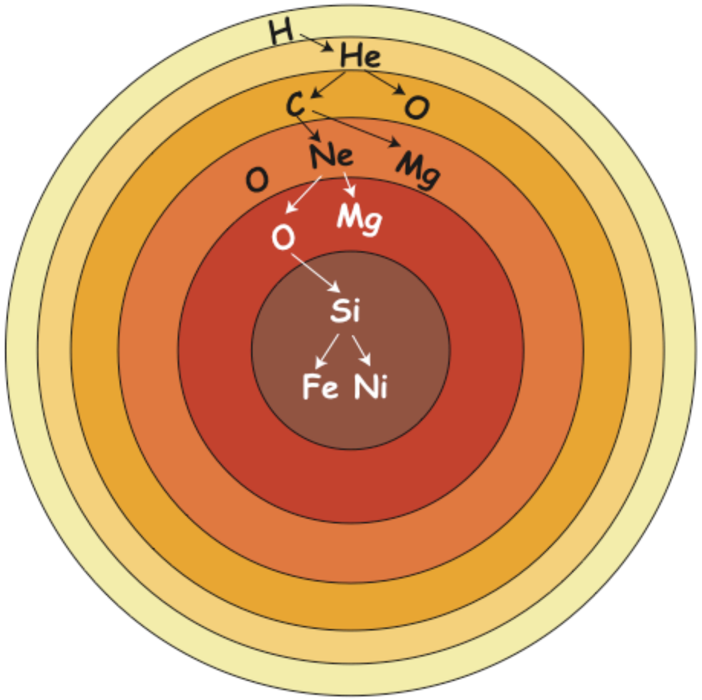
BBN essentially STOPS at He^4

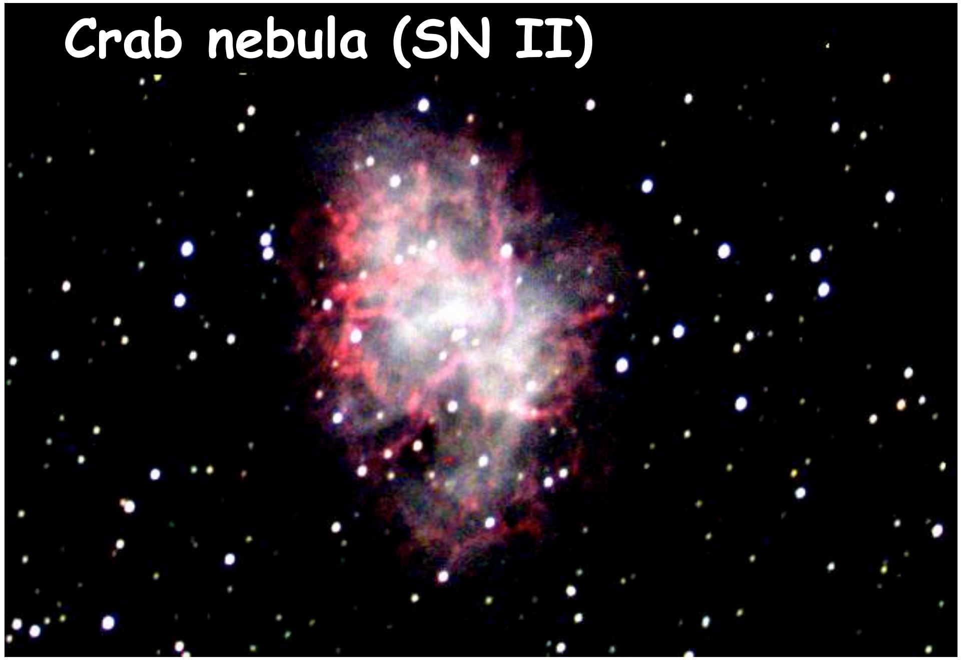
Trace amounts of ${}_3Li^7$, ${}_4Be^7$:

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

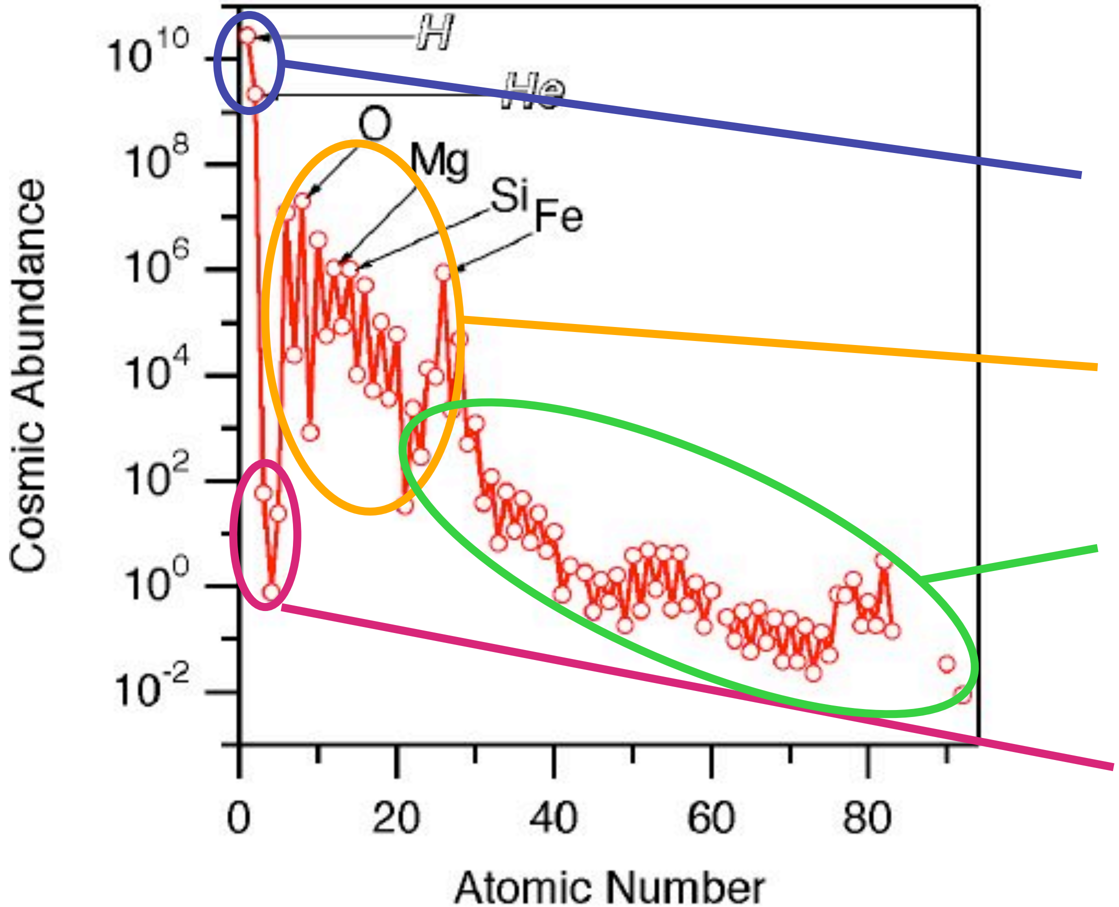
Heavier elements - Stars

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

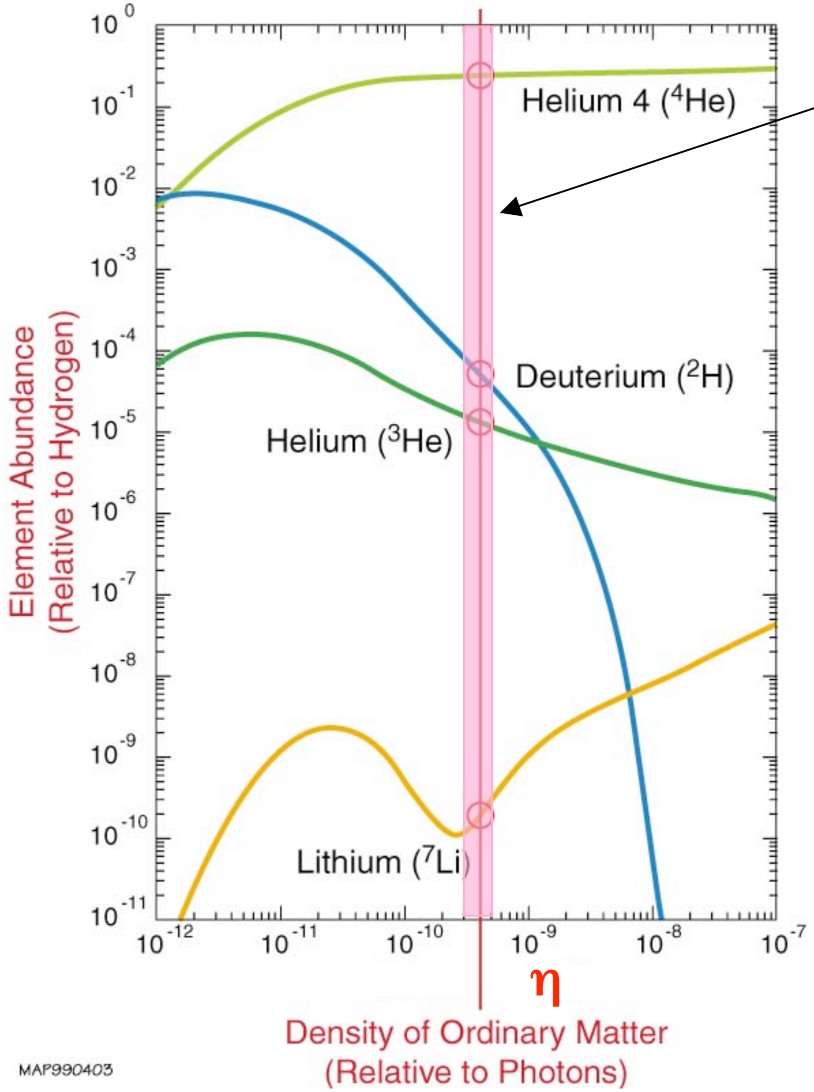
- Stars are net producers of He^4 and metals
  - $\Rightarrow$ use metal poor stars
  - upper limit on primordial abundance of He^4 (and on η)

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

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

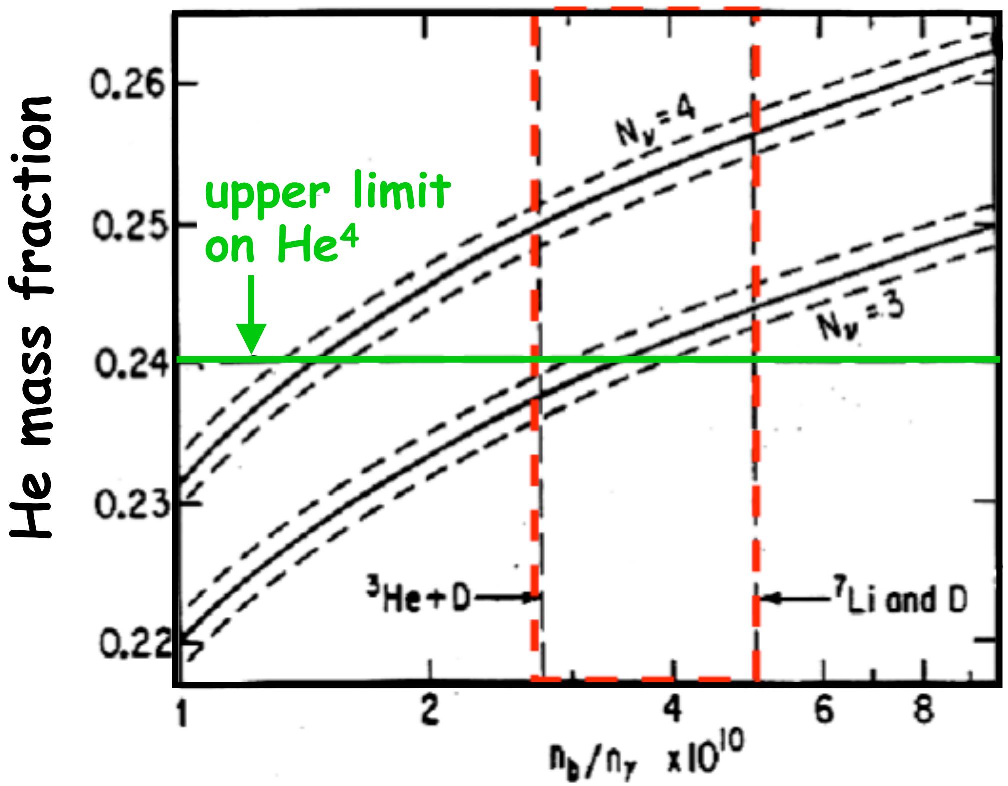
$$\Omega_B = \frac{\rho_B}{\rho_c} = \frac{n_B m_B}{3H^2/8\pi G}$$

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

BBN and neutrinos

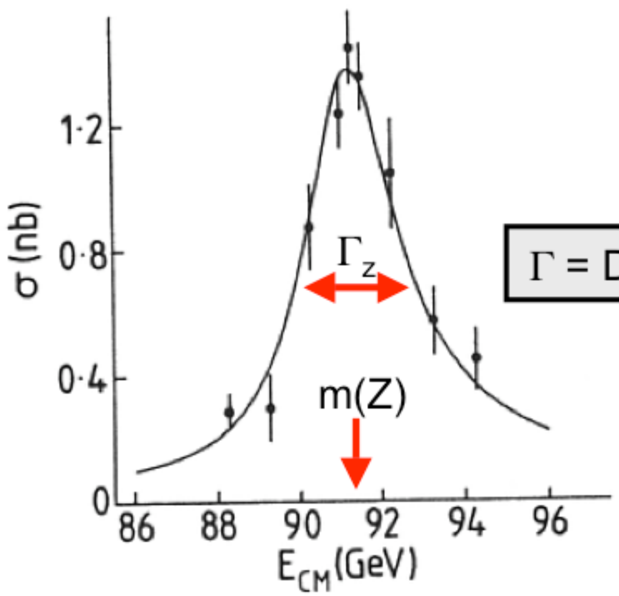
$H \propto g_*^{1/2}\, T^2$ (remember?) where g_* includes relativistic ν's

so $N_\nu \nearrow \Rightarrow H \nearrow \Rightarrow$ sooner freeze-out $\Rightarrow n/p \nearrow \Rightarrow He^4 \nearrow$

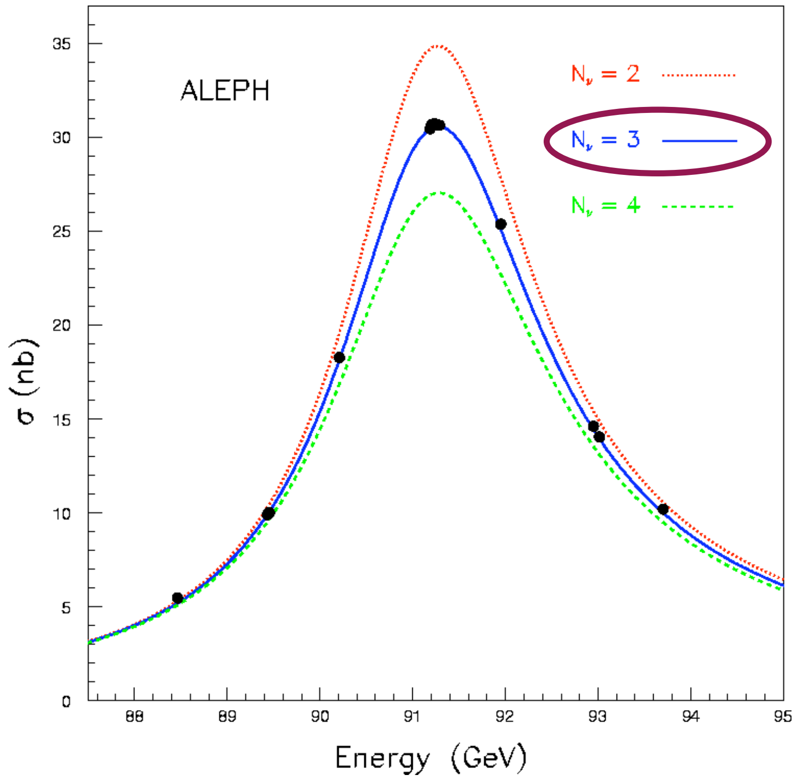


$N_\nu = 3$

LEP and light neutrinos



Γ = Decay rate



$N_\nu = 2.994 \pm 0.012$

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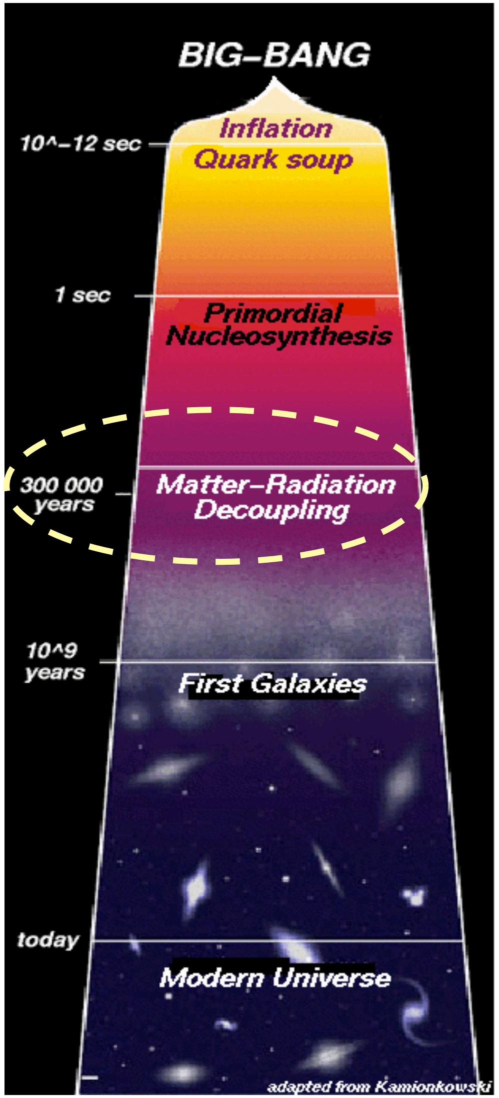


Back to thermal history

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

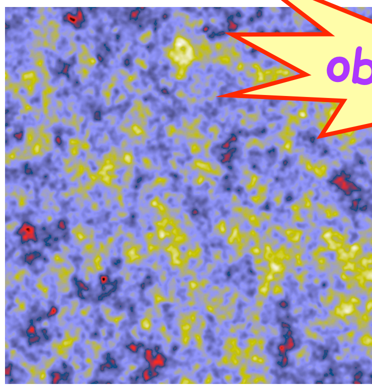
$t \sim 2000$ yrs — Matter domination

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

Matter:
Gravitational collapse

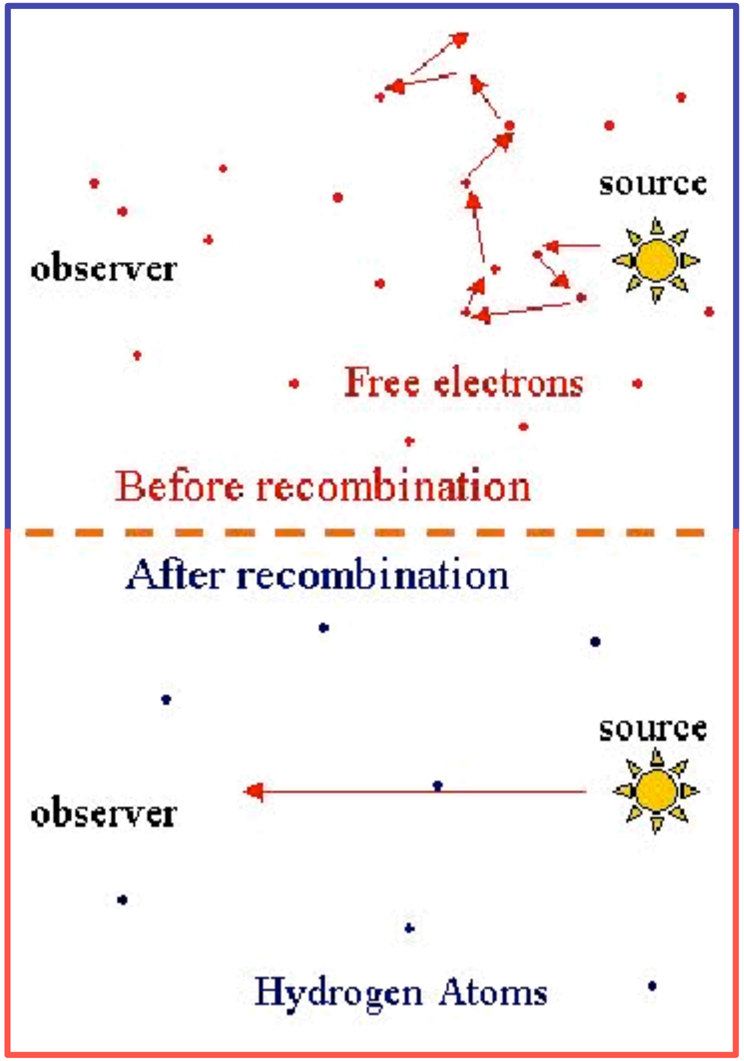
Photons:
Free propagation

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

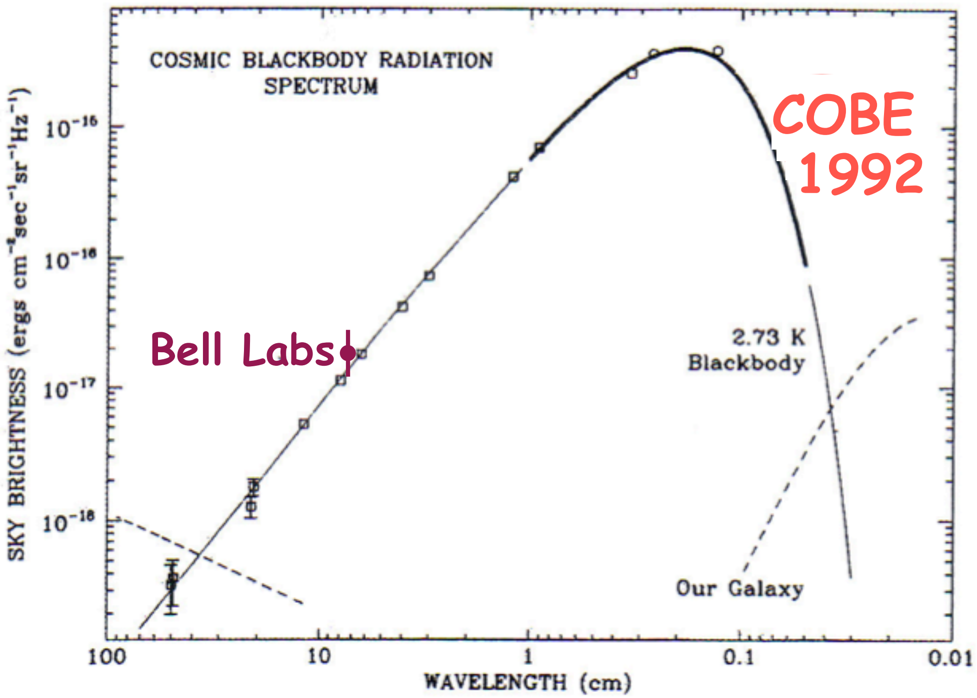
Discovery

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

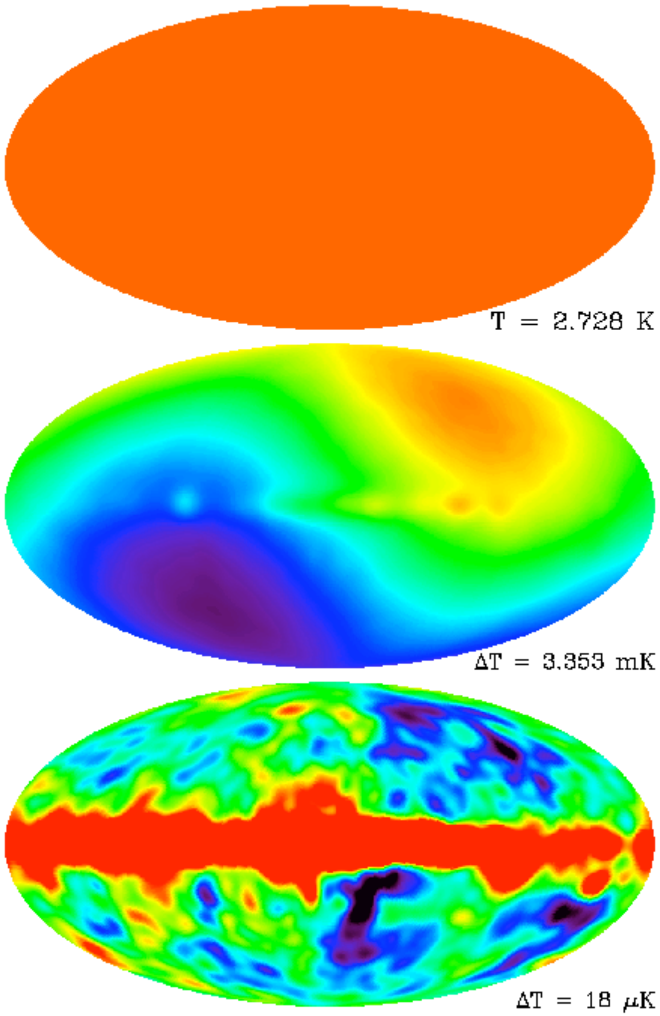
Wilson Penzias

(+ Robert Dicke)

25 years later



COBE sky maps



T = 2.7 K

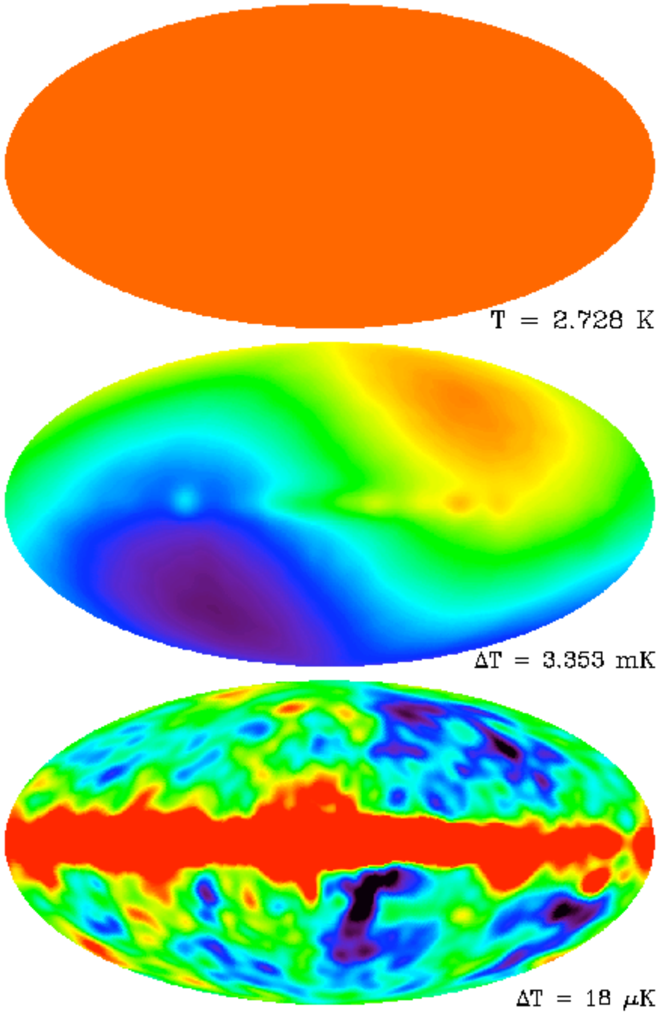
ΔT = 3.4 mK

(after subtraction of constant emission)

ΔT = 18 μK

(after subtraction of dipole)

COBE sky maps



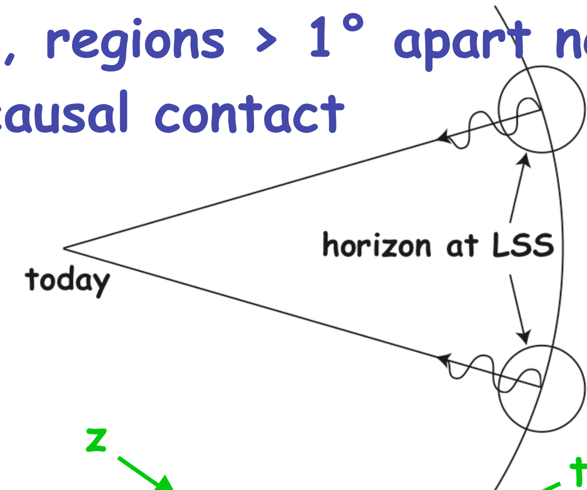
T = 2.728 K

ΔT = 3.353 mK

ΔT = 18 μK

scale 0-4 K: very homogeneous!

Yet, regions > 1° apart never in causal contact



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

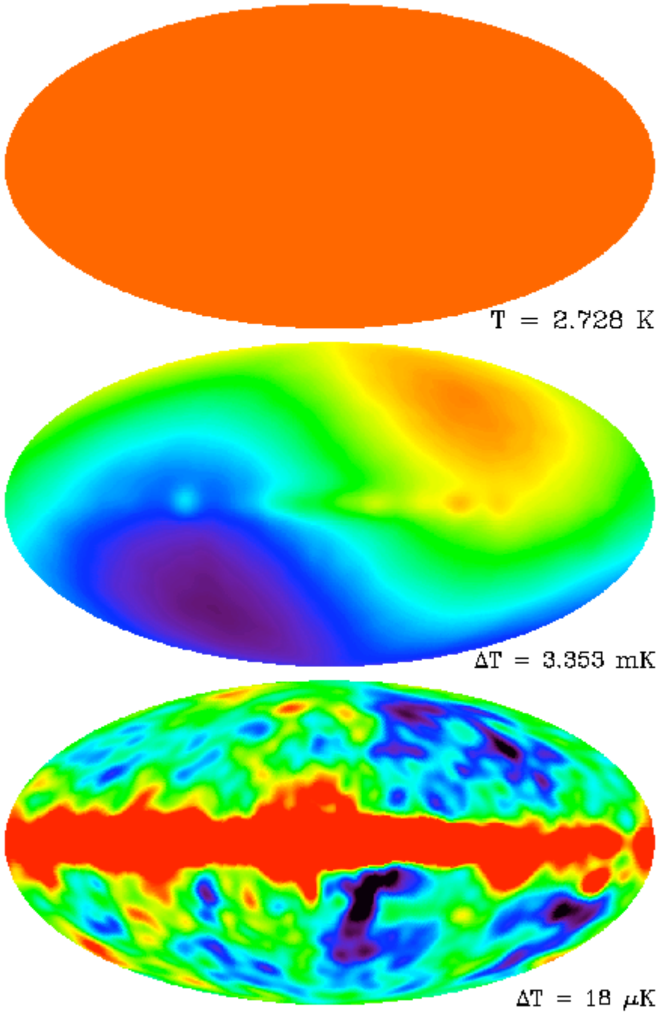
z

t LSS

t now

Inflation ?

COBE sky maps

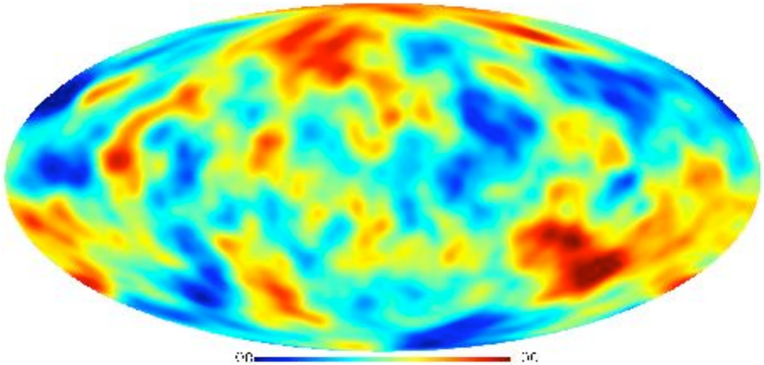


Doppler effect due to motion of Earth w.r.t. CMB
(v = 370 km/s towards Virgo)

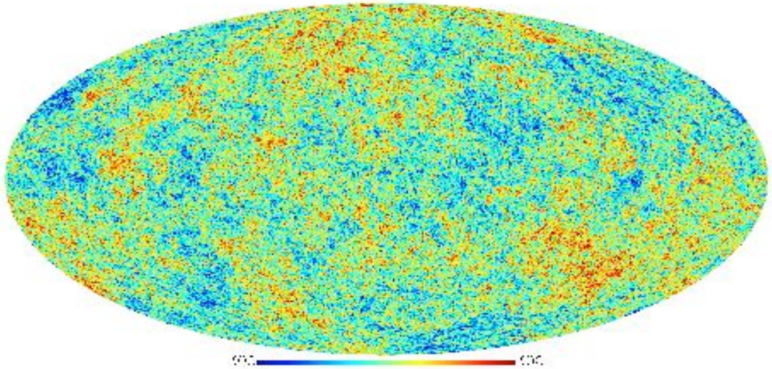
Anisotropies : potential wells
Early seeds for structure formation?
(+ foregrounds)

2nd generation satellite

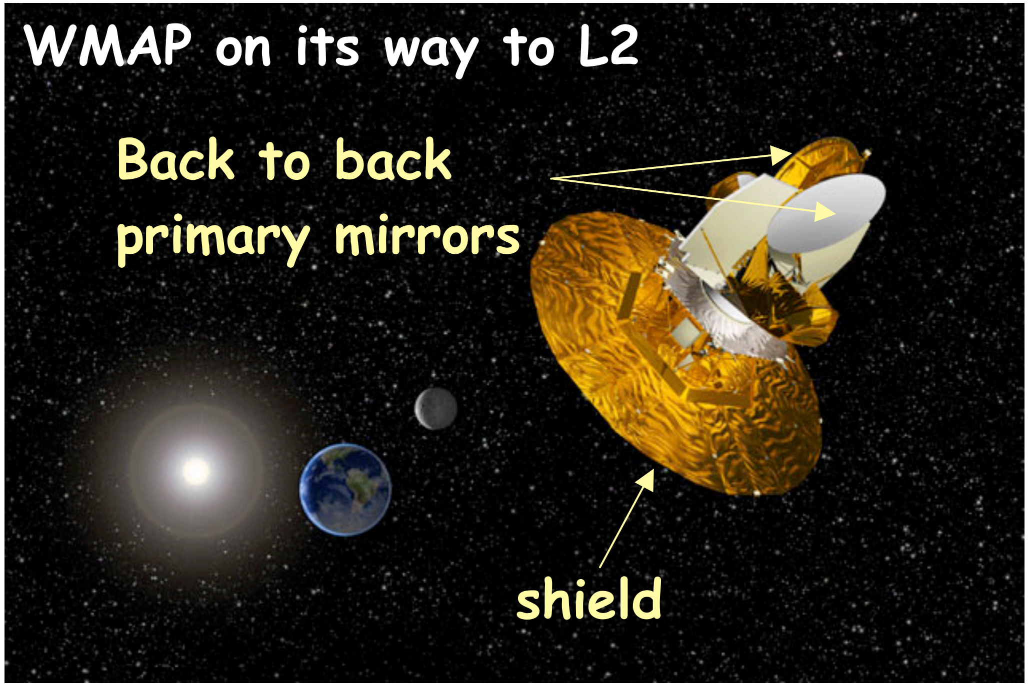
COBE
(7 degree resolution)



WMAP
(0.25 degree resolution)



WMAP



Launched in Jun. 2001
First results in 2003

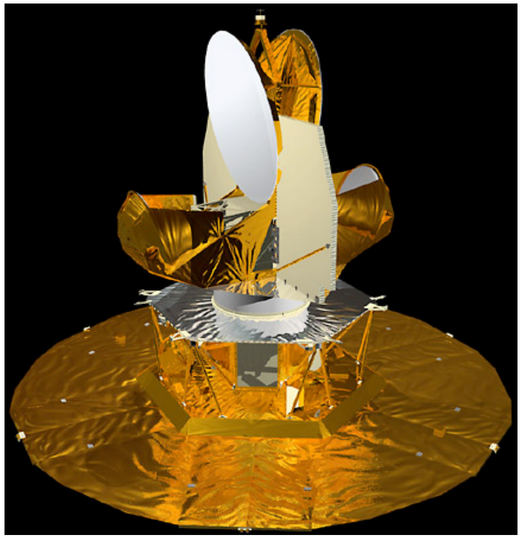
- Lagrange point L2: position of co-rotation with Earth
  ⇒ Stability of conditions
- Very low temperature signal
  ⇒ Need shielding from Sun, Earth, Moon, (Jupiter)
- Dual system to measure T differences
- 5 frequency channels (foreground removal)

Detectors

2 techniques

HEMTS

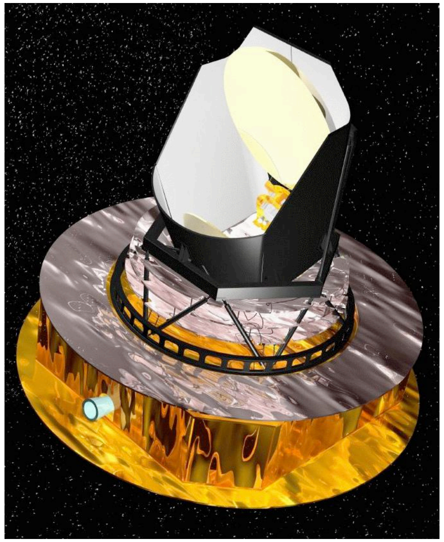
- + Easier to use
- + No heavy cryogeny (10 K)
- + Cheaper
- − limited to f<90GHz



WMAP

Bolometers

- + Better sensitivity (S/N)
- + Larger frequency coverage
- − Cryogeny (100 mK)

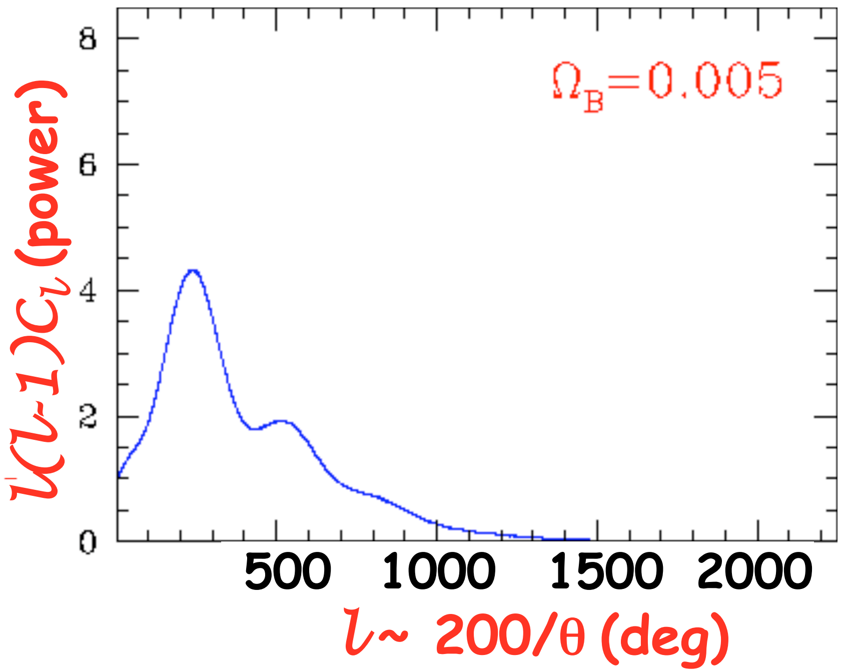


Planck

Archeops

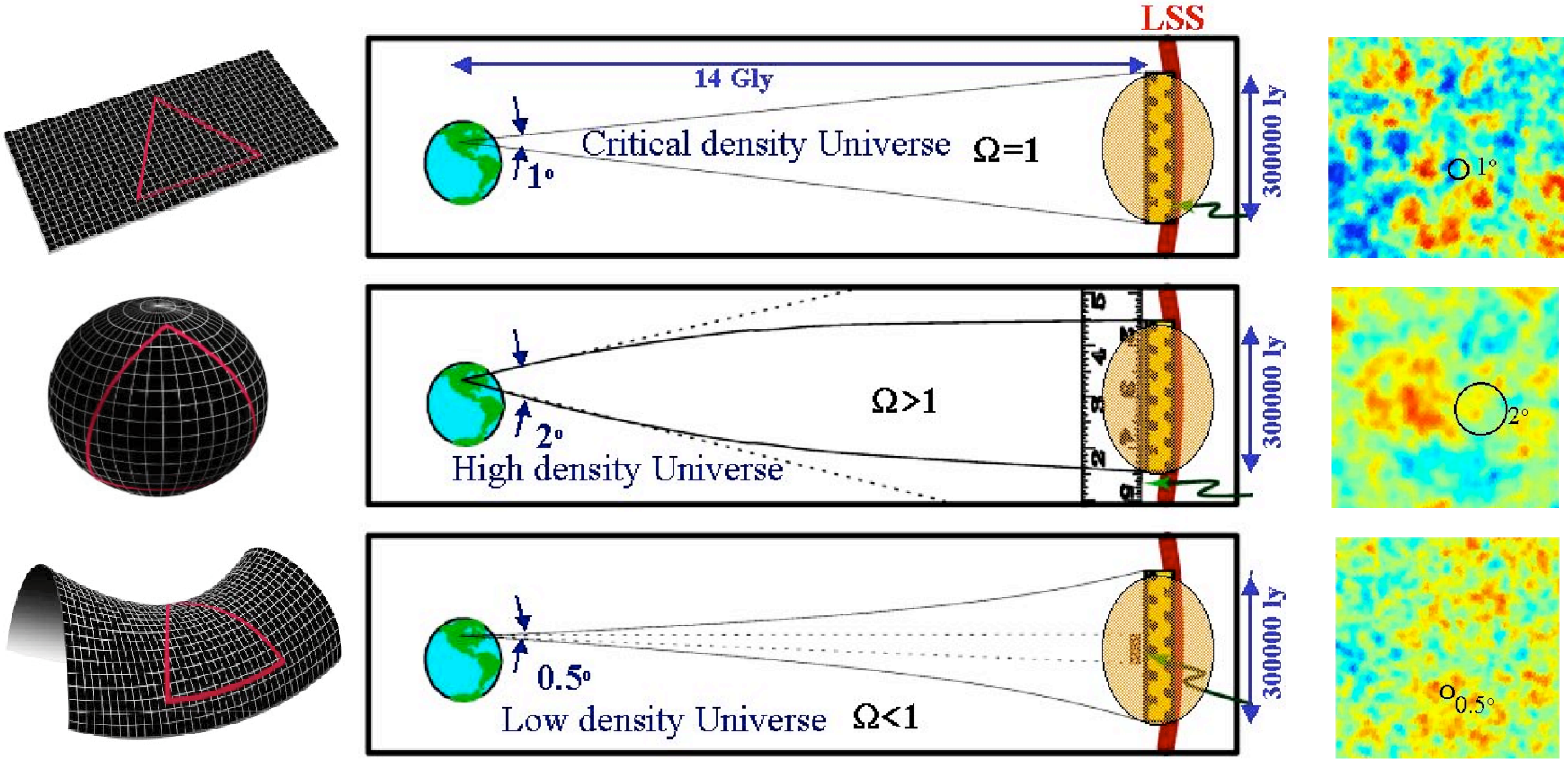
Fluctuations in CMB

- Before recombination, Universe = plasma of free e^- and protons
- Oscillations due to opposite effects of
  - gravity
  - pressure
- Power spectrum on various scales
- More baryons
  → greater compression of fluid in potential wells



Max. scale of anisotropies

Limited by causality (remember?) → maximum scale



⇒ Max scale relates to total content of Universe Ω_{tot}

Power spectrum

$\Omega_{tot} = 1.02 \pm 0.02$

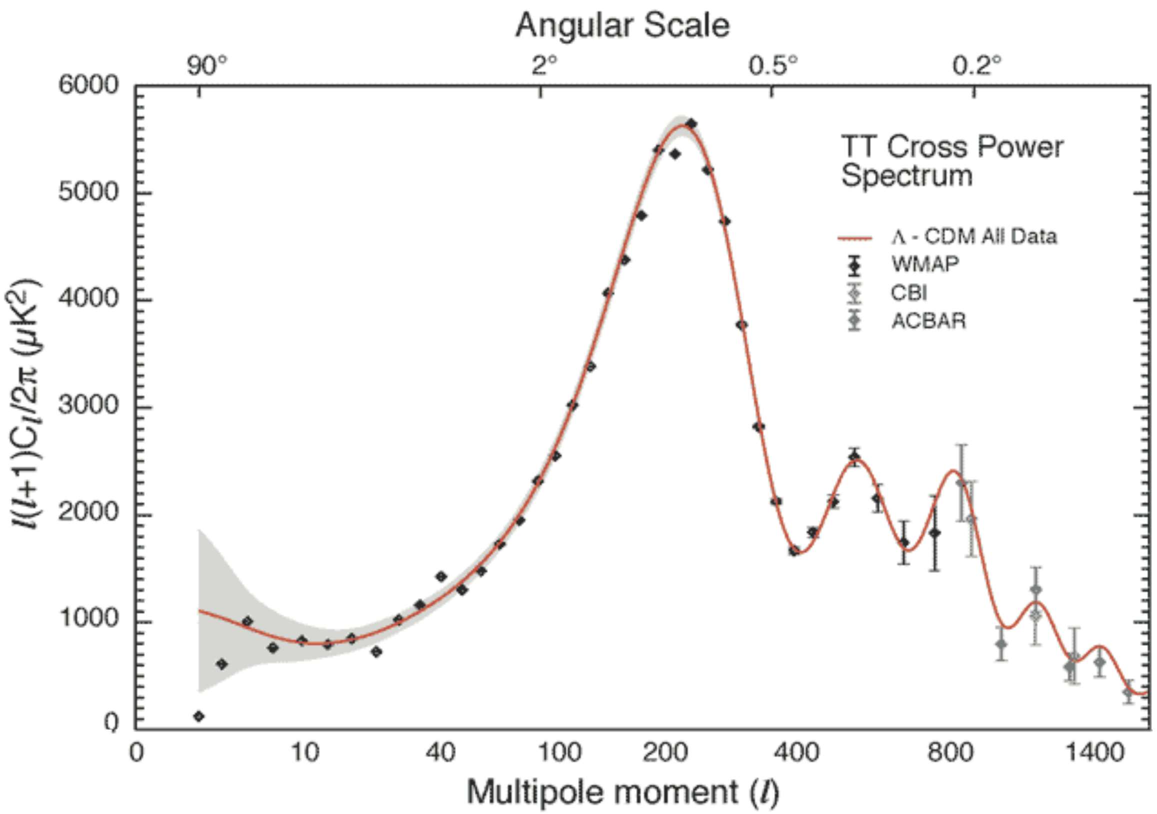
$\Omega_m = 0.28 \pm 0.02$

$\Omega_\Lambda = 0.72 \pm 0.04$

$\Omega_B h_{70}^2 = 0.045 \pm 0.002$

$\Omega_\nu h_{70}^2 < 0.016$ (95% CL)

$\Rightarrow \Sigma m_\nu < 1$ eV



Conclusions…

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

  agree !

- Ω_B (~ 4%) $<$ Ω_m (~ 28%)
  - $\Rightarrow$ Non baryonic matter

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

Next lecture !