Astroparticle Physics (1/3)

Nathalie PALANQUE-DELABROUILLE
CEA-Saclay
CERN Summer Student Lectures, August 2004

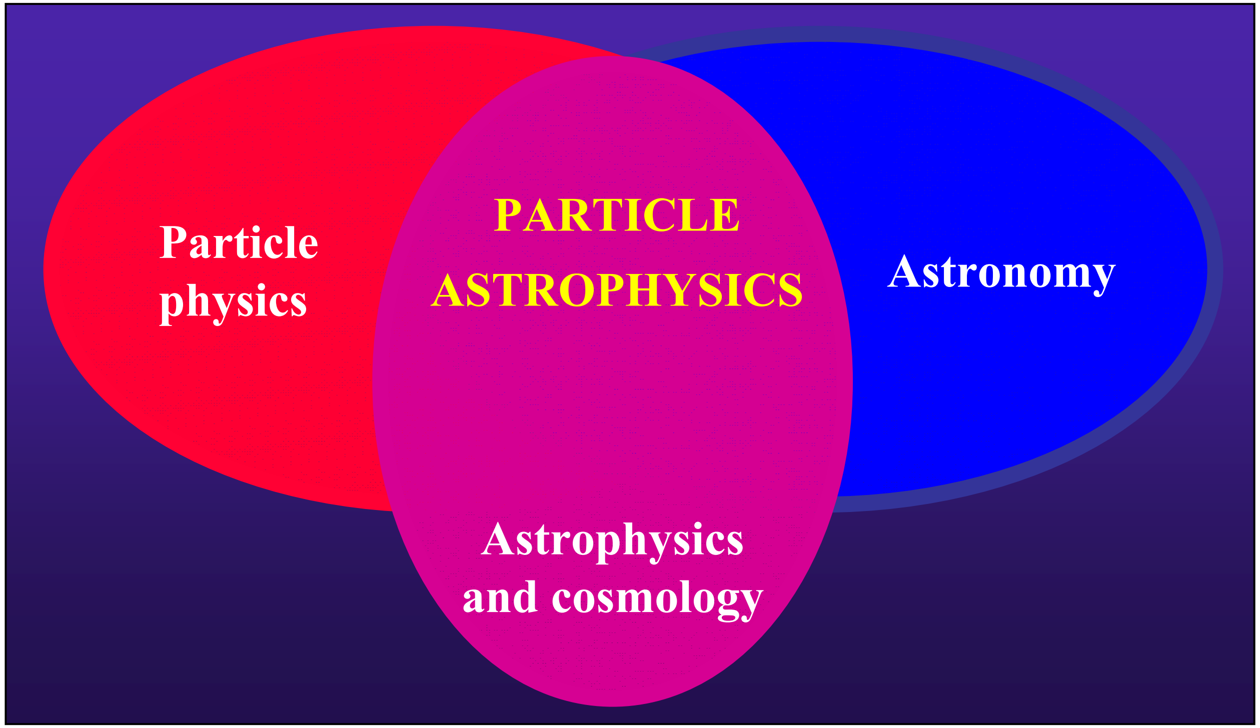
1) What is Astroparticle Physics ?
   Big Bang Nucleosynthesis
   Cosmic Microwave Background

2) Dark matter, dark energy

3) High energy astrophysics

Astroparticle Physics?

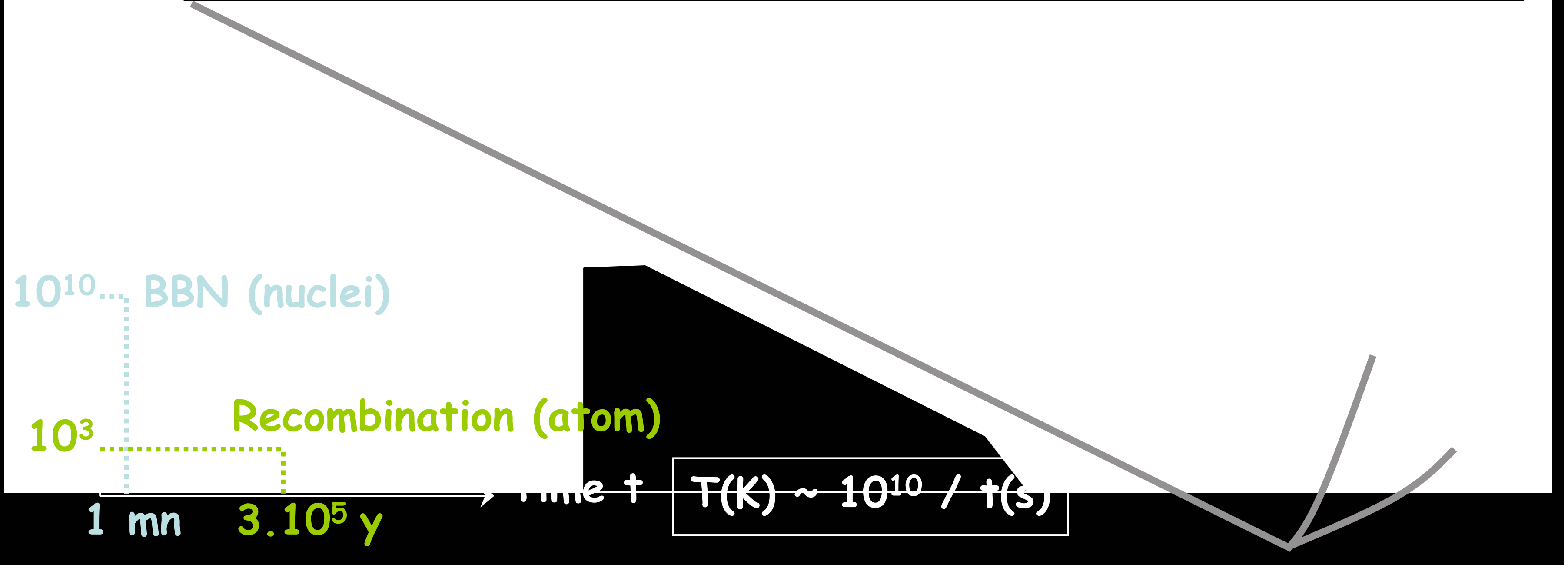
Understanding structure and evolution of Universe using
- subatomic particles (→ Big Bang model, dark matter)
- techniques from particle physics (→ analyses)
- outer space (→ CMB, neutrinos, dark matter)



Development of 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	300 s	$3\text{x}10^{5}$ yr	$3\text{x}10^{9}$ yr	$15\text{x}10^{9}$ yr
Superstring era (?)	GUT era	Inflation era	Electroweak era	Particle Era	Recombination era	Galaxy & star formation	Present era



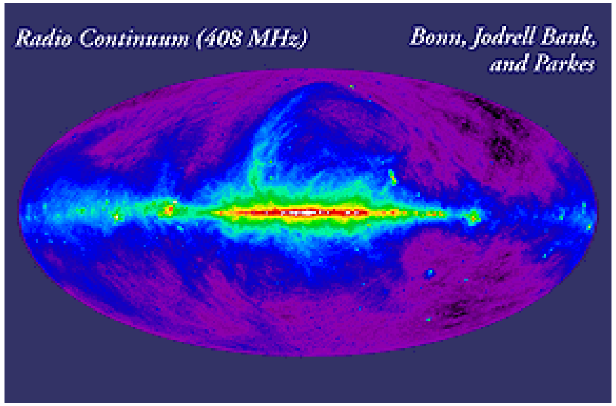
Optical Telescopes

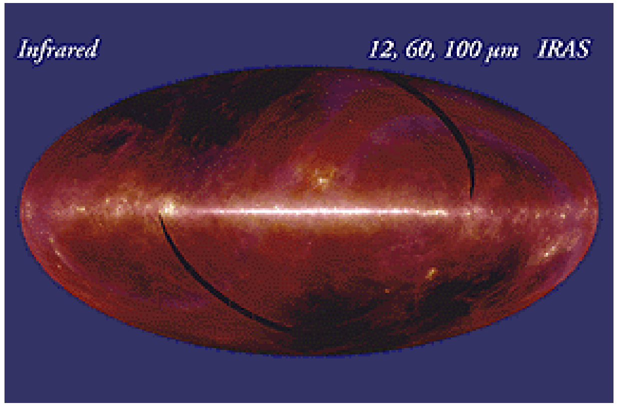
Galileo, 1564 - 1642

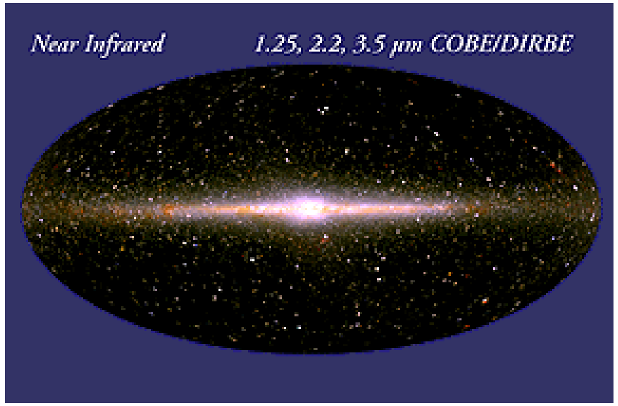
Hubble telescope, 2001

⇒ **Lecture 2**

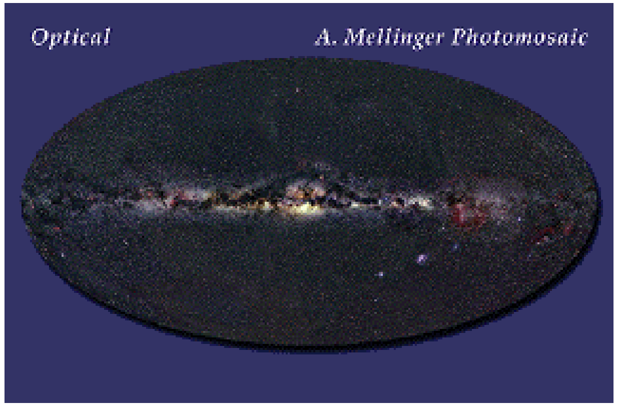
Multi-wavelength universe

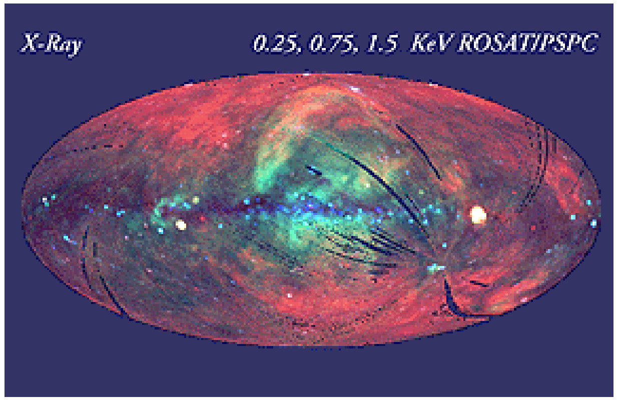


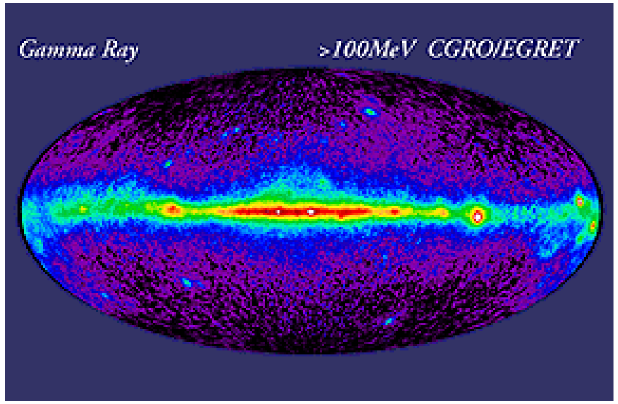




The different faces of the Milky Way

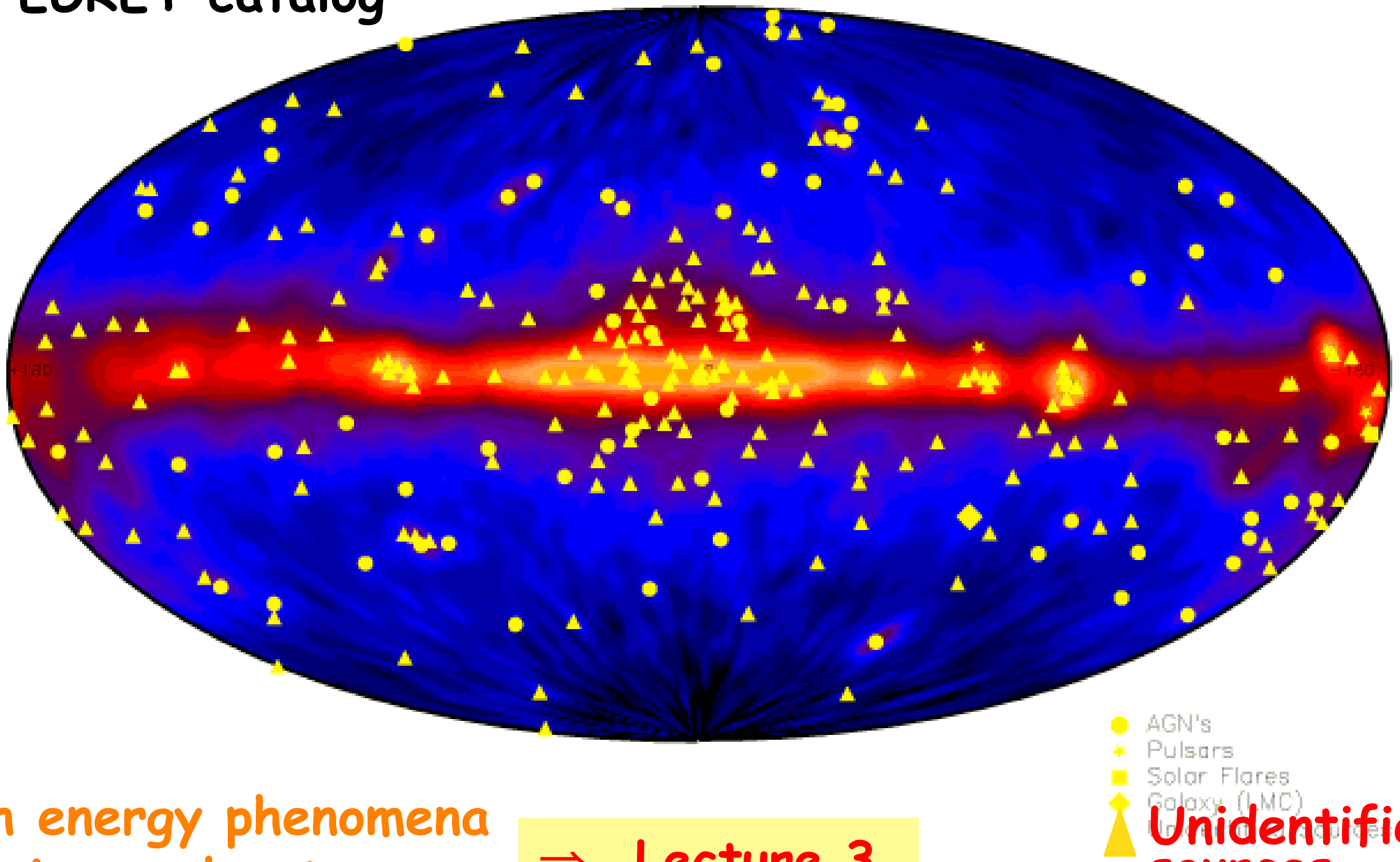






Gamma-ray astronomy

3rd EGRET catalog



Unidentified sources

High energy phenomena
Cosmic accelerators

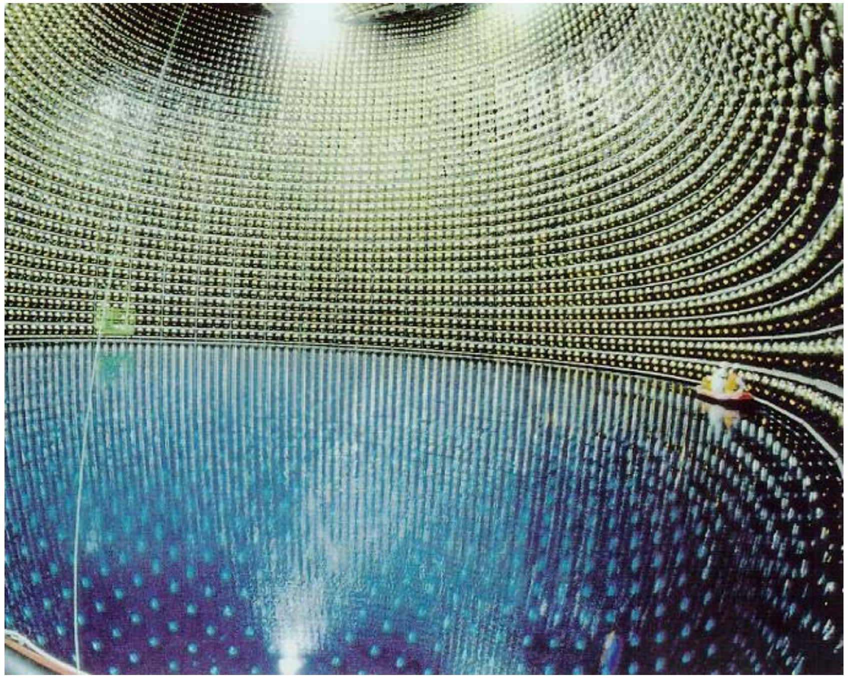
⇒ Lecture 3

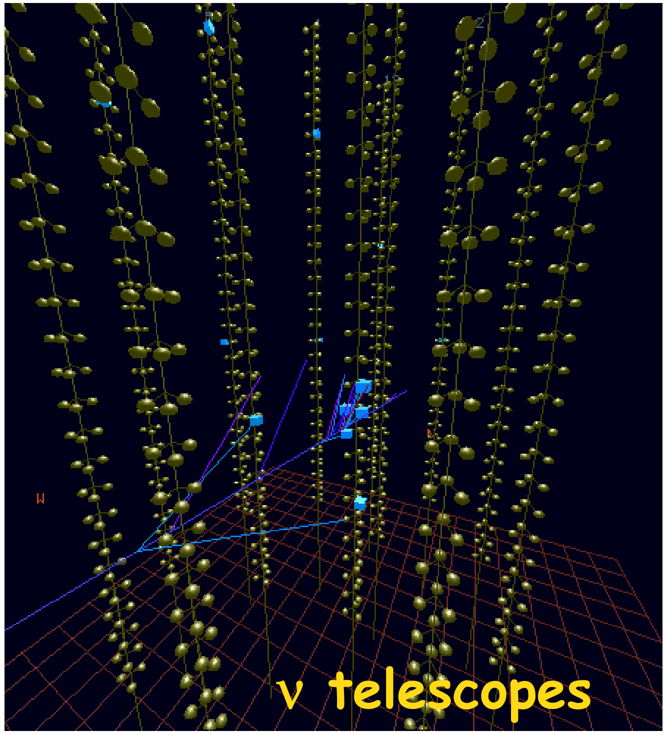
Neutrino astronomy

Numerous astrophysical neutrino sources
sun, galactic center, AGN…

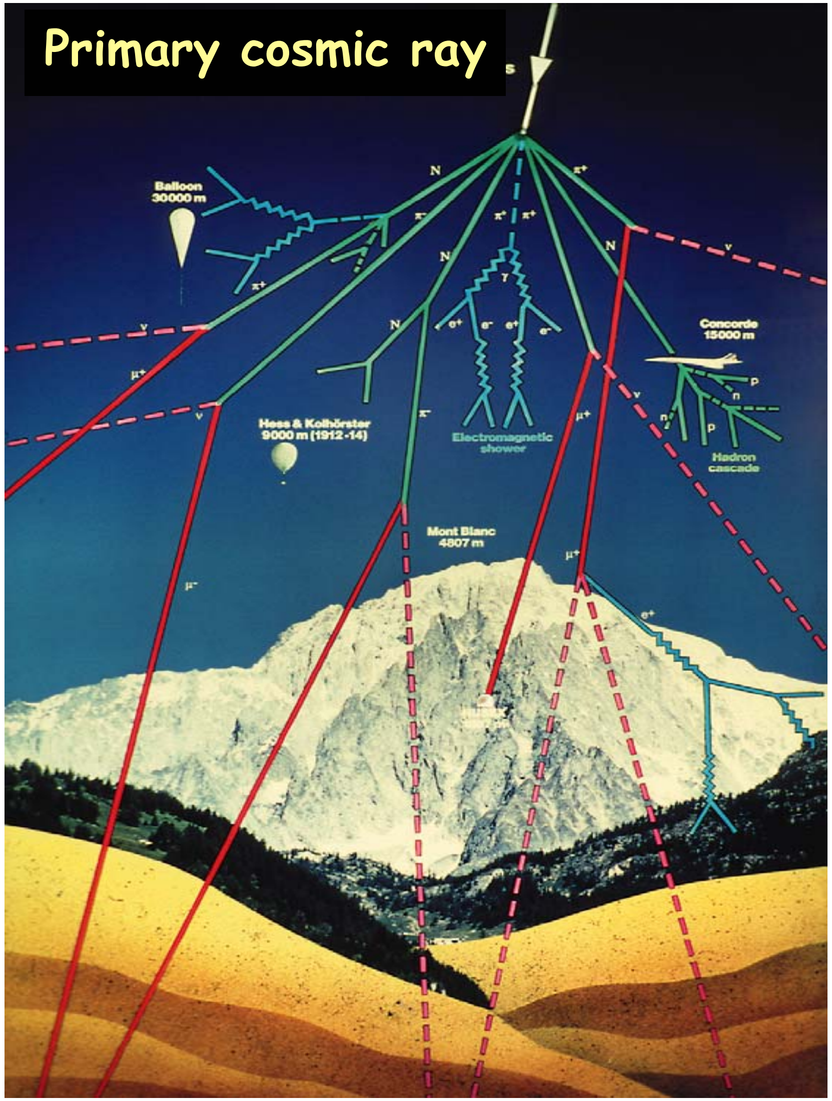
⇒ Lecture 3

Super-Kamiokande





Cosmic Rays



In space (>50 km)
p and nuclei (anti?)
1 particle per $m^2.s$:
small detectors

On ground
μ, ν
1 particle per $m^2.yr$ (per $km^2.yr$)
huge detectors, long duration

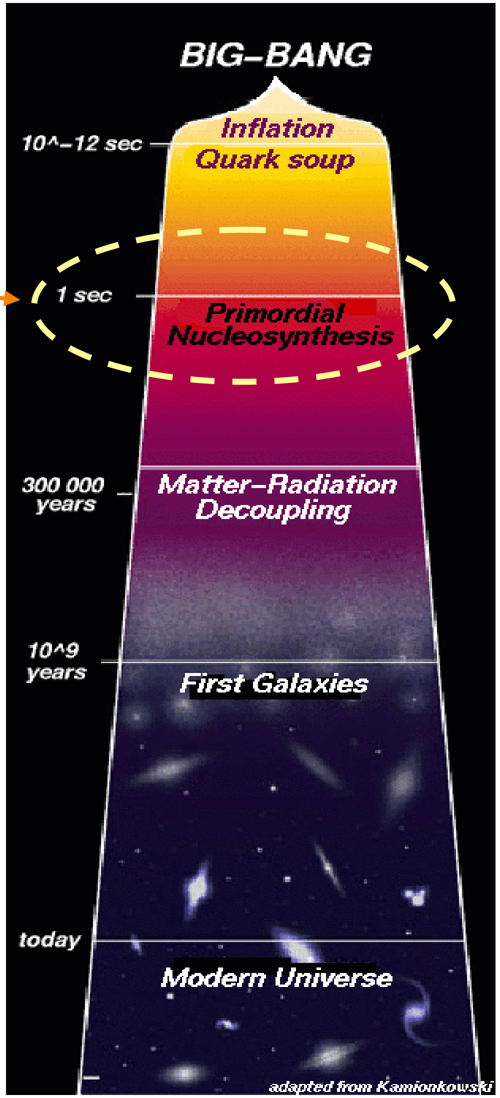
$\Rightarrow$ Lecture 3

Lecture outline

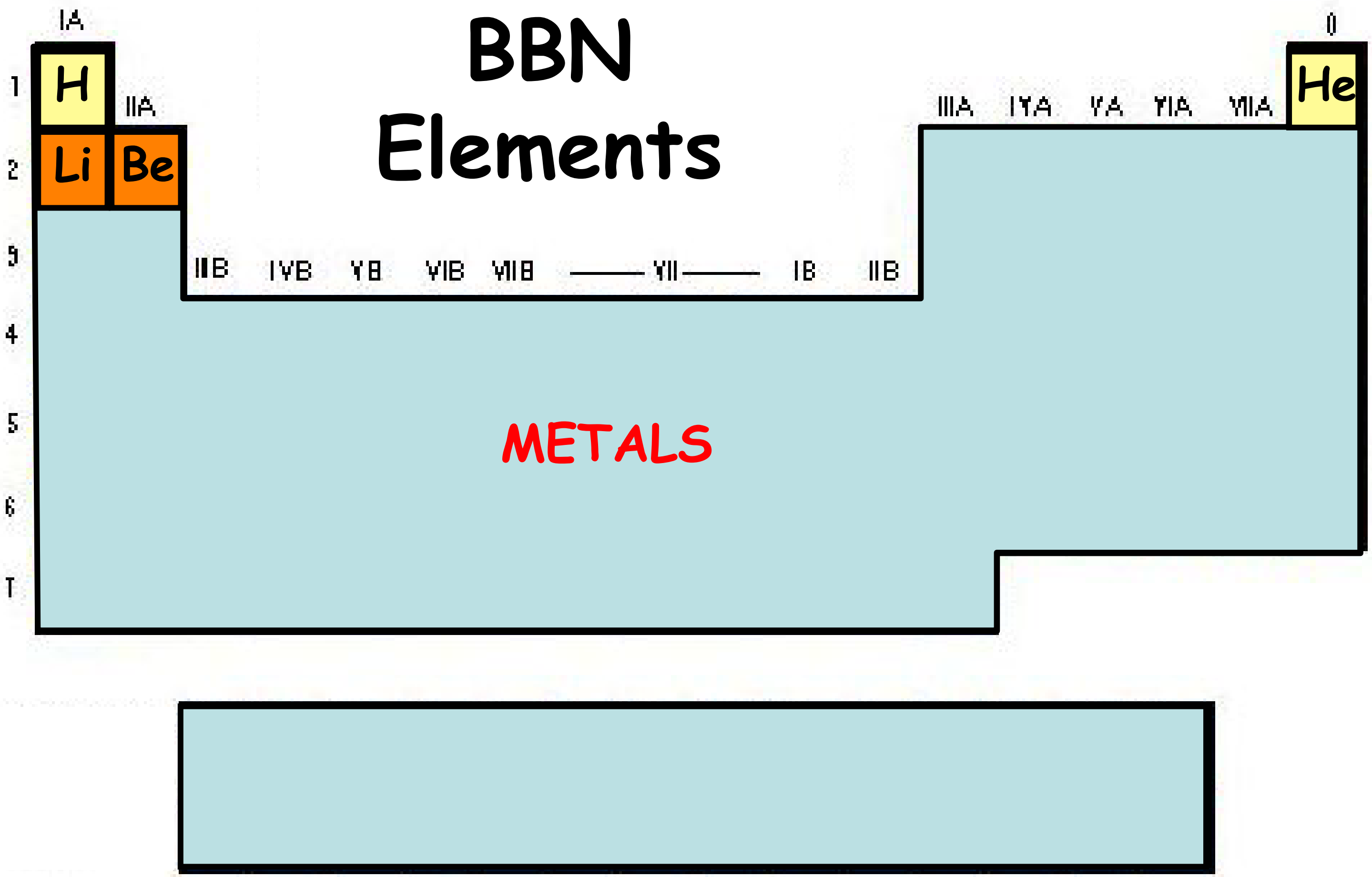
1) What is Astroparticle Physics ?
   Big Bang Nucleosynthesis
   Cosmic Microwave Background

2) Dark matter, dark energy

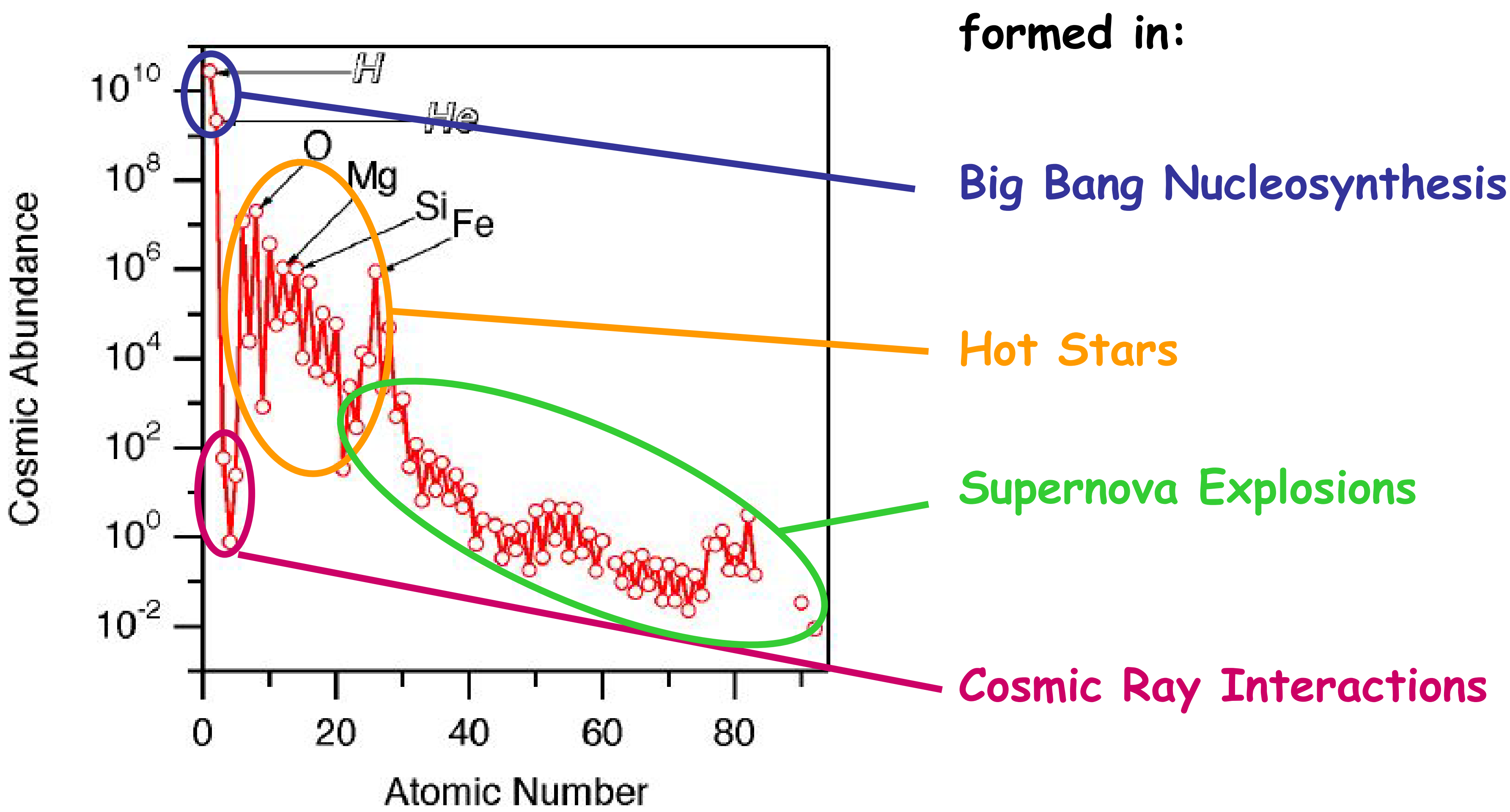
3) High energy astrophysics



Which elements ?



Origin of elements



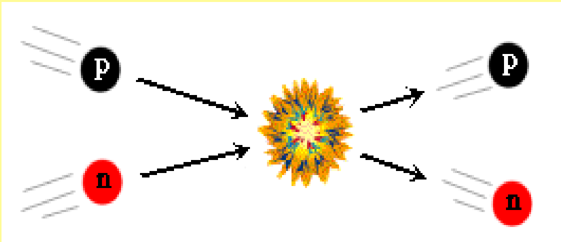
Thermal history

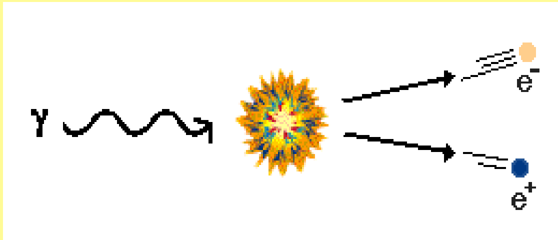
- 10^{-43} s / 10^{19} GeV — GUT ? Ultra-relativistic part. domination: $\rho \propto T^4$
- 10^{-35} s / 10^{15} GeV — Inflation ? GUT symmetry broken

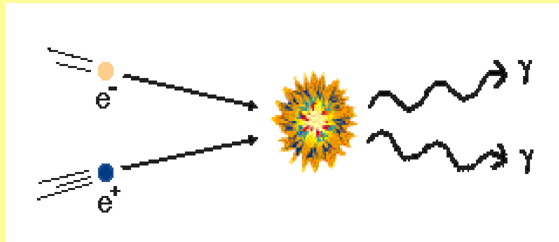
- 10^{-10} s / 10^{2} GeV — EW symmetry breaking
- 10^{-5} s / 300 MeV — Quarks → Hadrons
- 1 s / 1 MeV — Statistical equilibrium b/w particles breaks
- 1 mn / 0.3 MeV — Nucleosynthesis starts
  in a few hours, hadrons → 24% H, 76% He
- 10^{4} yrs / 10^{5} K — (non-relativistic) matter domination: $\rho \propto T^3$
- 10^{5} yrs / 4000 K — Recombination, Universe becomes transparent
  Can't see further back!
- 10^{9} yrs / 10 K — Star and galaxy formation, SN → heavy elements
- 10^{10} yrs / 3 K — Today!

Age < 1s, T > 1 MeV

Collisions maintain thermal equilibrium

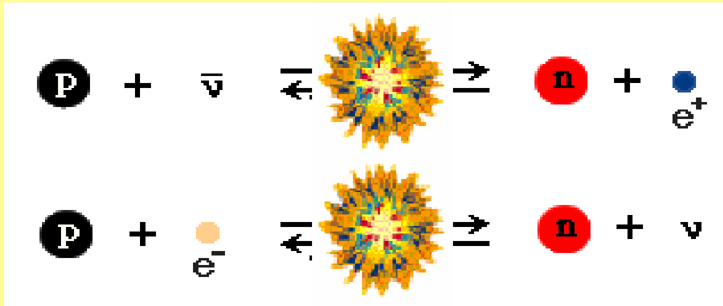






Proton - neutron conversion

(Δm = 1.3 MeV)



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

$\frac{n}{p} \rightarrow 0$ 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:

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

so $H \propto N_\nu^{1/2}\, T^2$

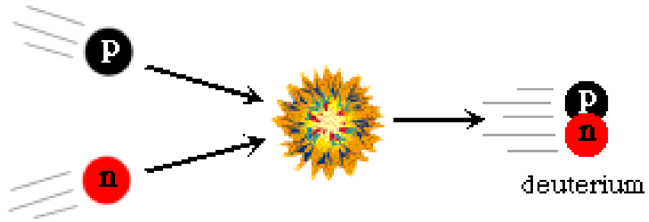
- Freeze-out when $\Gamma_{weak} \sim H$ with $\dfrac{\Gamma_{weak}}{H} \sim \left(\dfrac{T}{0.8\ \text{MeV}}\right)^3$

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

$$\frac{n}{p} = e^{-\Delta m/kT} = 0.18$$

Deuterium bottleneck

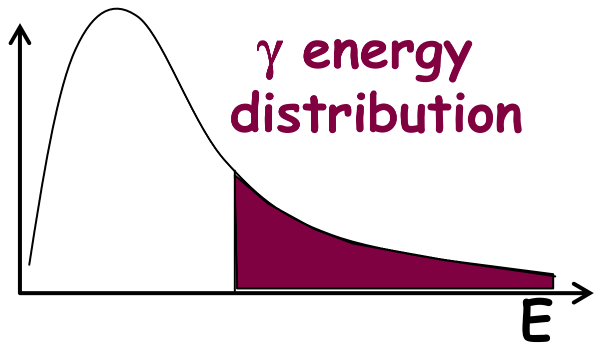
- Formation of D



- 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

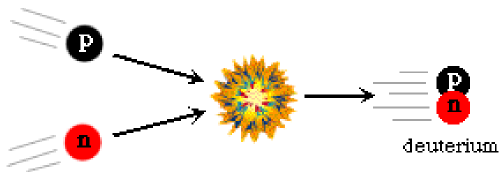
- n_B small $\Rightarrow$ 2-body reactions only

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

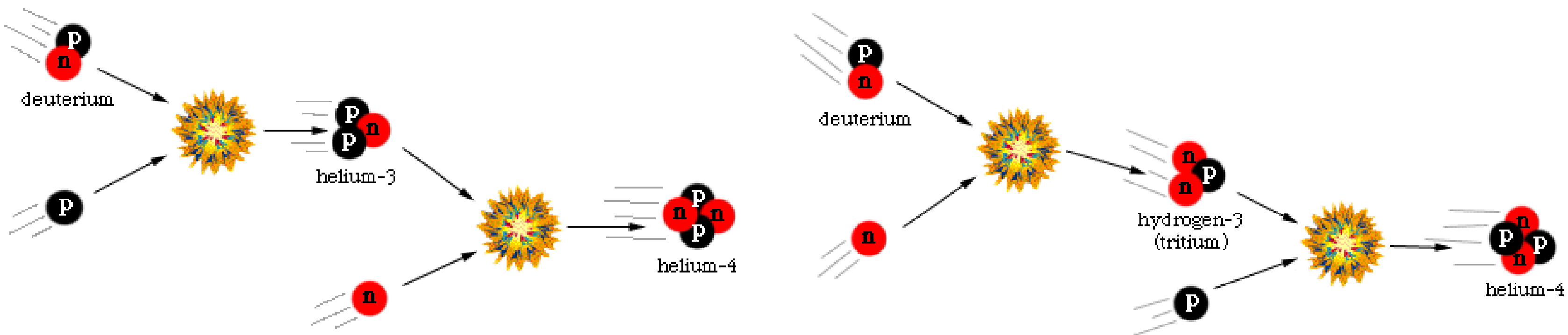
- neutron decay: 

⇒ n/p ~ 1/7

- Deuterium (all n):



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



Helium abundance ~ $\frac{2n}{n+p}$ ~ 0.25	H abundance ~ 0.75

$\eta = n_B/n_\gamma$ ❁ ⇒ D bottleneck lasts less ⇒ n/p ❁ ⇒ He^4❁

Heavier elements - BBN

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

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

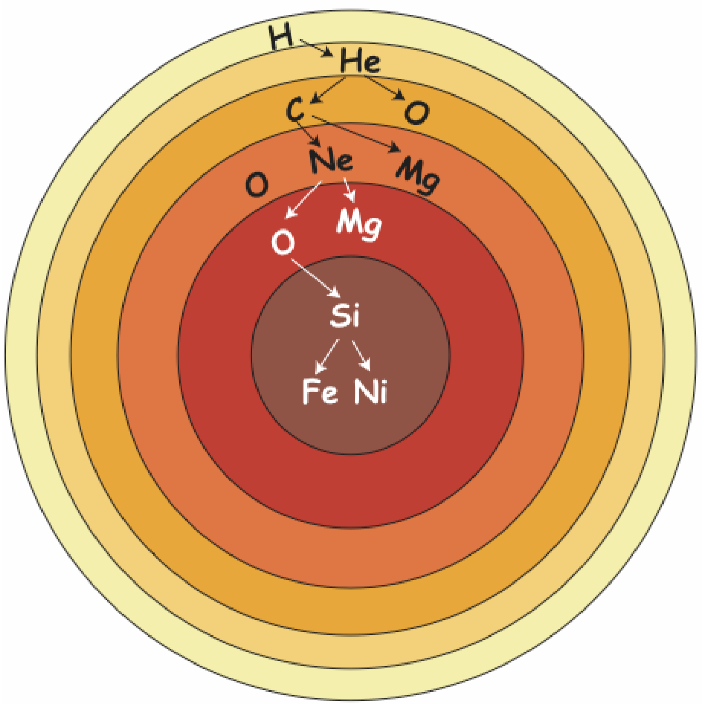
BBN essentially STOPS at He^4

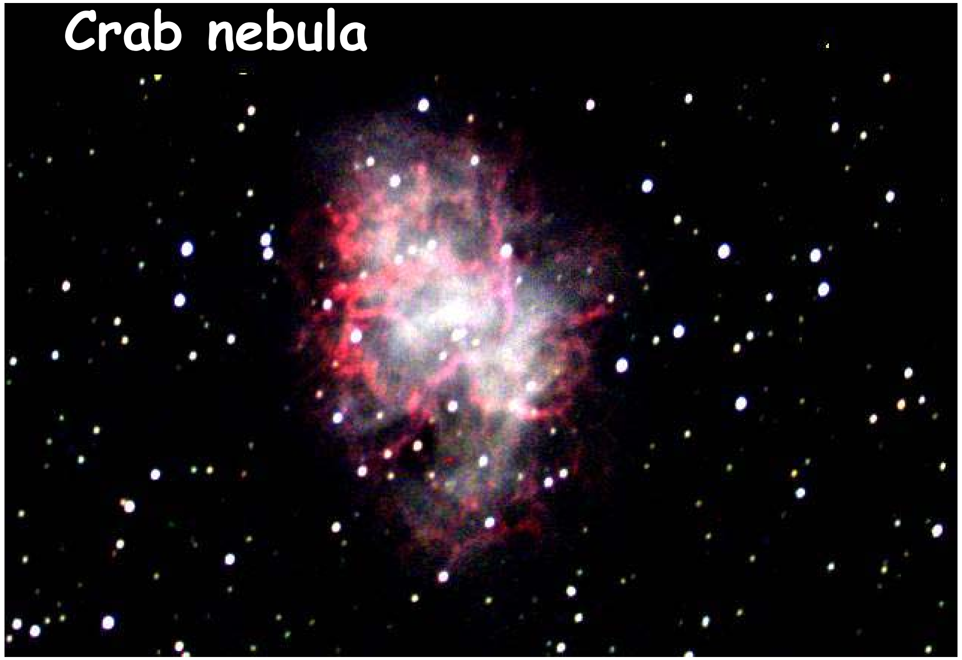
Trace amounts of ${}_3Li^7$, ${}_4Be^7$:

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

Heavier elements - Stars

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





Observational constraints

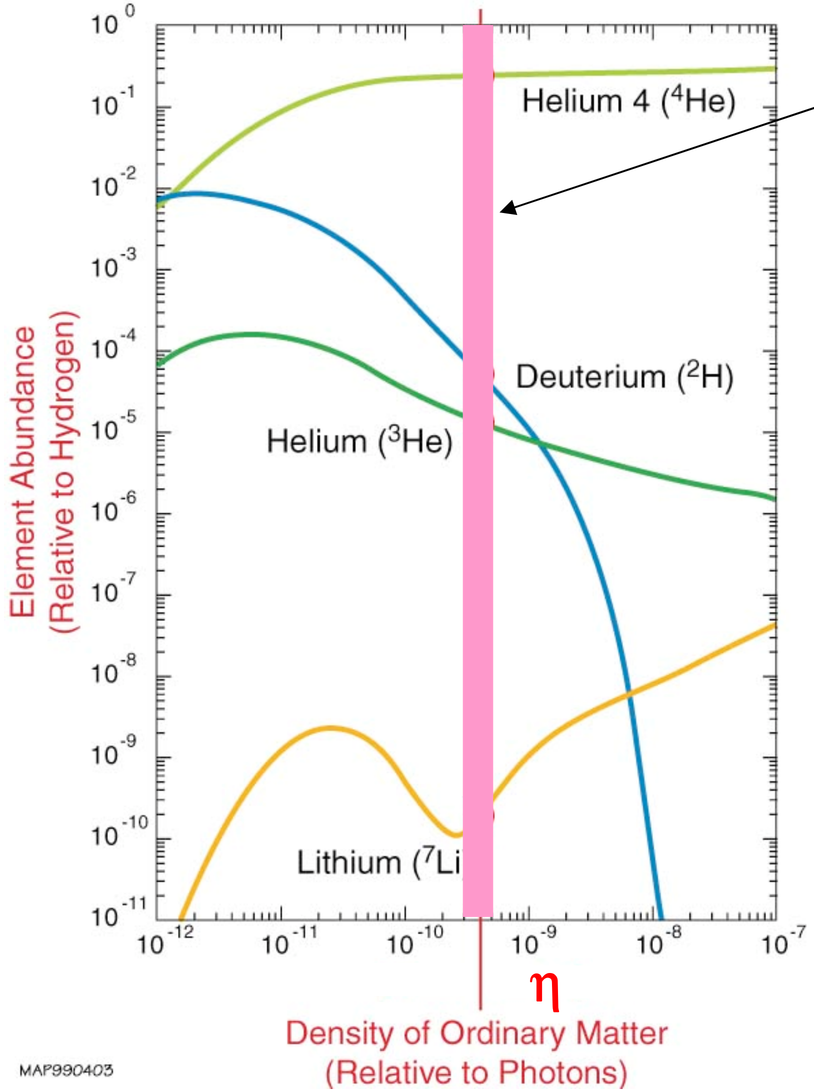
- Stars are net producers of He^4 and metals
  ⇒ use metal poor stars
  upper limit on primordial abundance of He^4 (and on η)

- D weakly bound
  ⇒ 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
  ⇒ $D+He^3$ increases with time
  upper limit on $D+He^3$ ie lower limit on η

- Li^7 very fragile, burnt in stars
  ⇒ 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

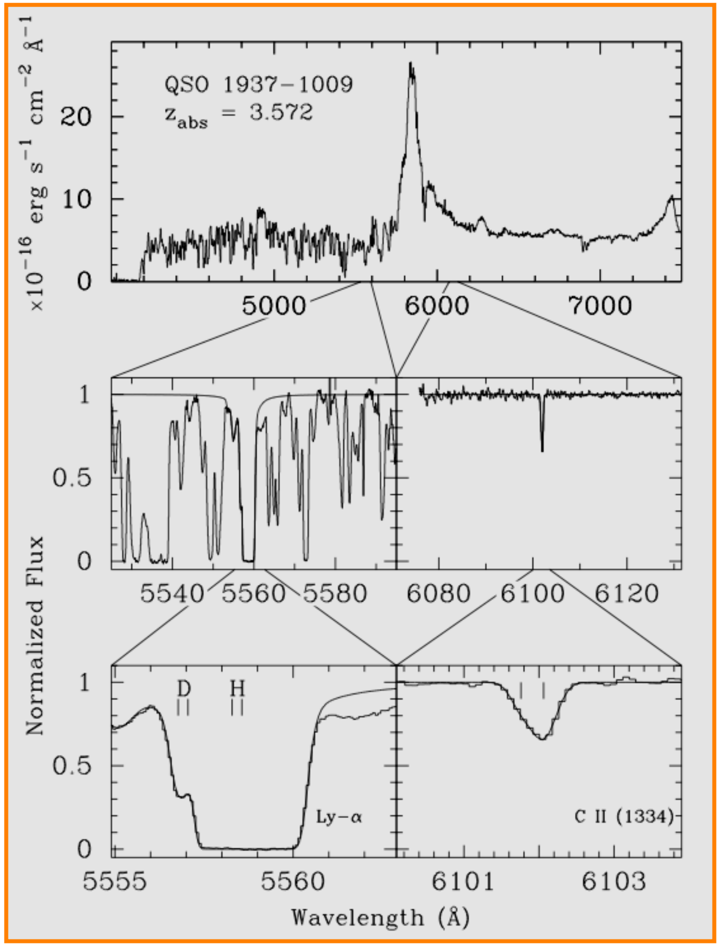
CMB: $n_\gamma = 411\ \text{cm}^{-3}$

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

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

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

D controversy



$\lambda/\lambda_{Li\alpha} = (1+z_{cloud}) / (1+z_{qso})$

Precise measurement from absorption of quasar light by intervening gas clouds (1994-2000)

Hogan, Rugers et al.
High D (low η)
Interlopers at appropriate z?

Tytler et al.
Low D (high η)
OK with BBN

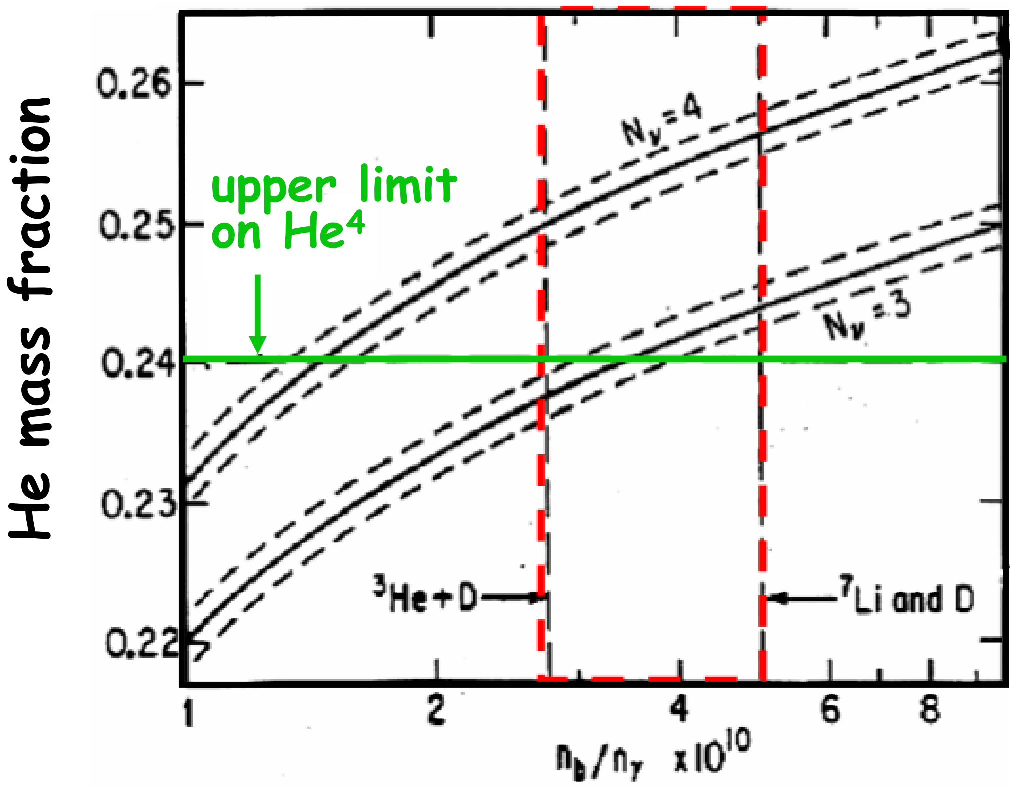
Inconsistent D measurements

(solved by CMB)

BBN and neutrinos

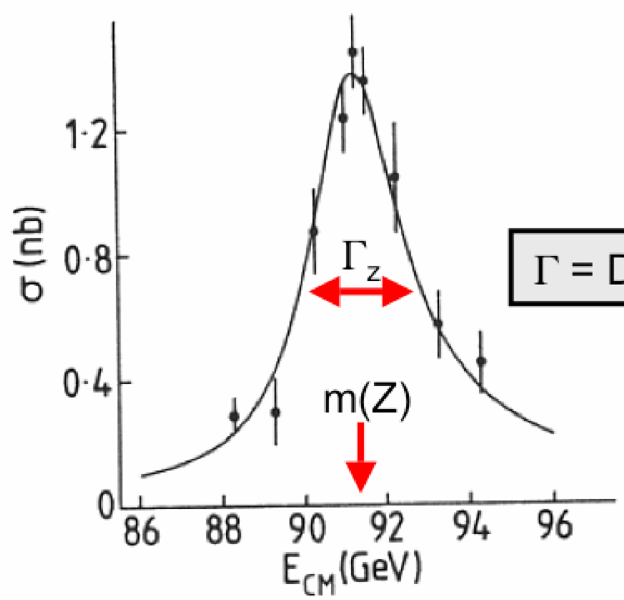
$H \propto N_\nu^{\,1/2}\, T^2$ (remember?)

so N_ν ❁ $\Rightarrow$ H ❁ $\Rightarrow$ sooner freeze-out $\Rightarrow$ n/p ❁ $\Rightarrow$ He^4 ❁

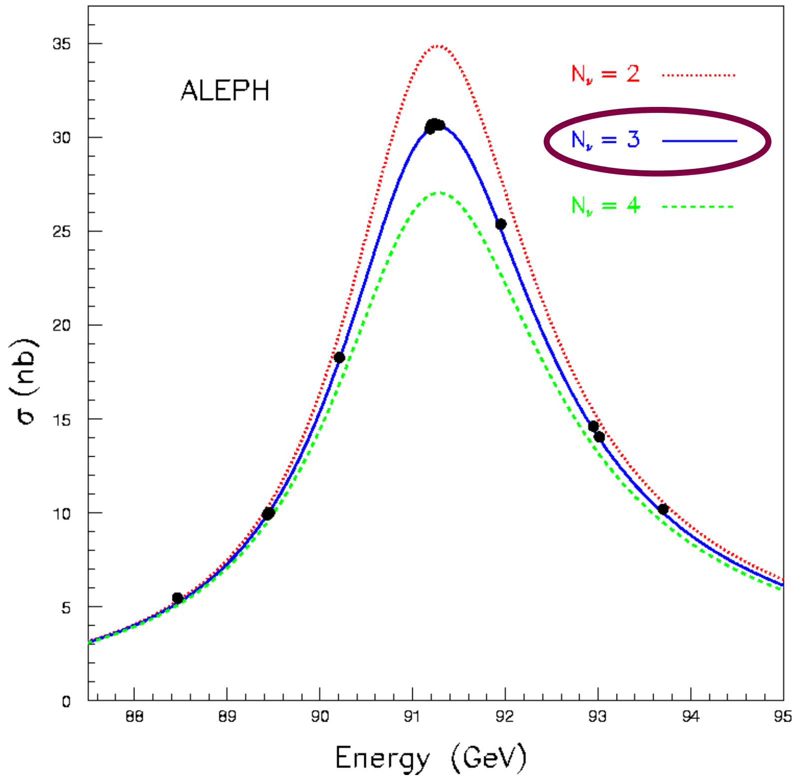


$N_\nu = 3$

LEP and light neutrinos



Γ = Decay rate



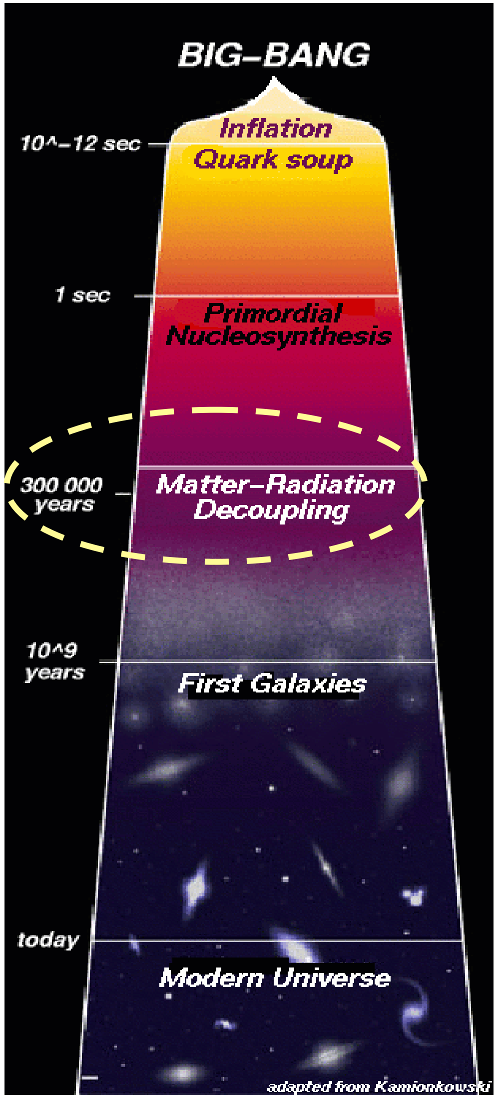
$N_\nu = 2.994 \pm 0.012$

Lecture outline

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

2) Dark matter, dark energy

3) High energy astrophysics



Back to thermal history

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

$t \sim 1$ mn — Nucleosynthesis

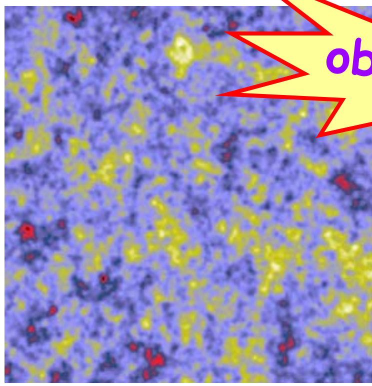
$t \sim 300000$ yrs — Recombination: $p + e^- \rightarrow H + \gamma$

Matter:
Gravitational collapse

Photons:
Free propagation

observable

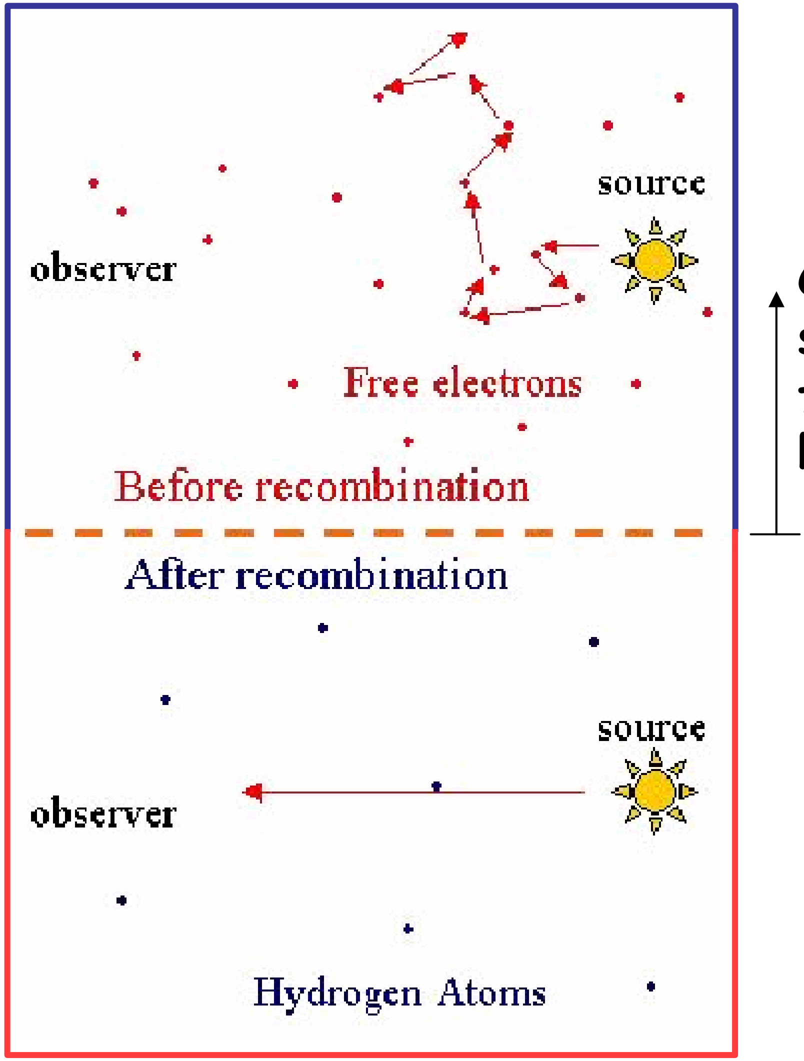
Galaxies, clusters



observable

CMB

End of opaque Universe



Cannot see further back

Multiple scatterings of γ on e- produces "thermal" spectrum at $T = 3000$ K ($z \sim 1000 = R_0 / R_{rec}$)

"Uniform" background at $T_0 = 2.7$ K

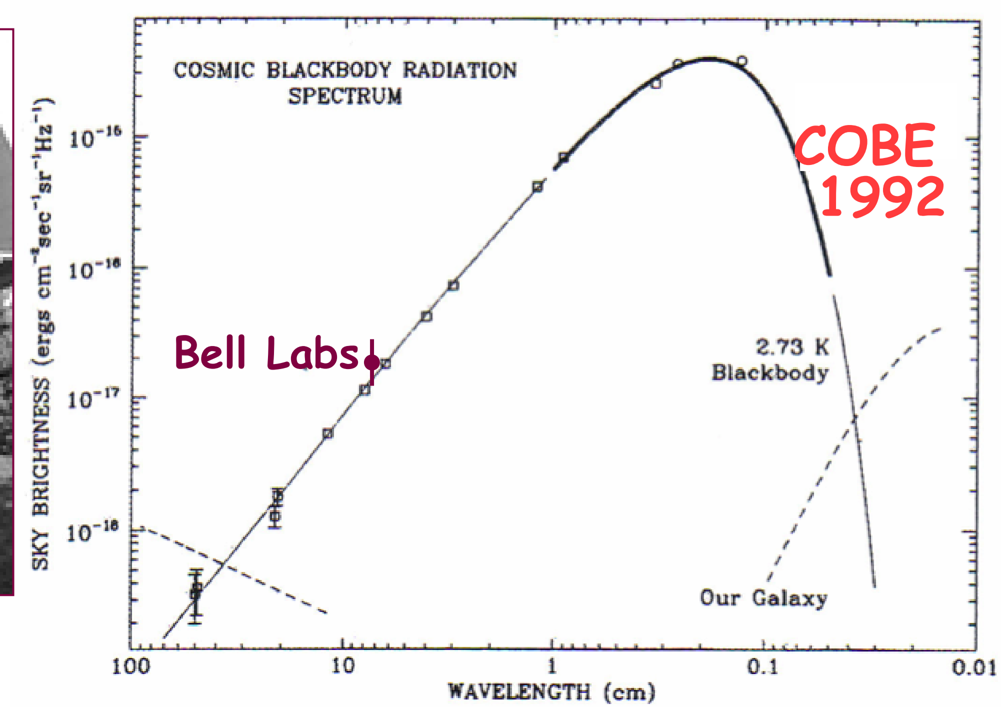
Discovery

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

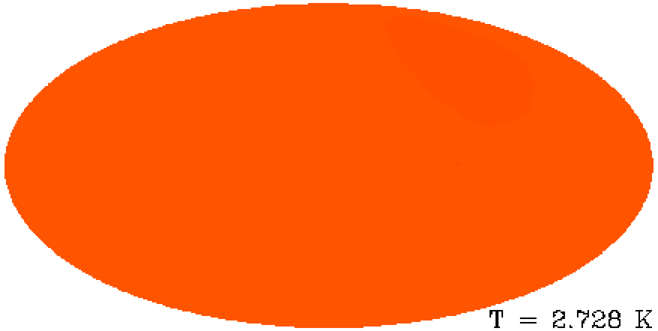
25 years later

Wilson Penzias

(+ Robert Dicke)

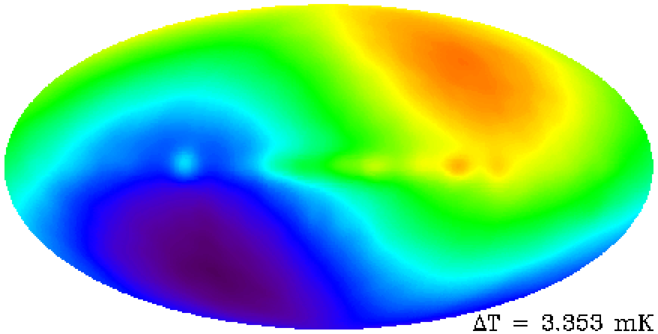


COBE sky maps



$T = 2.728$ K

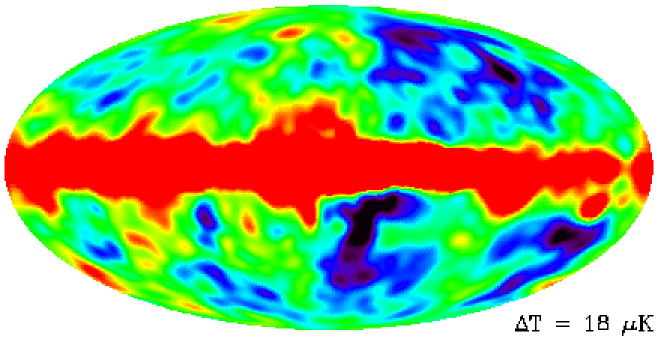
T = 2.7 K



$\Delta T = 3.353$ mK

ΔT = 3.4 mK

(after subtraction of constant emission)

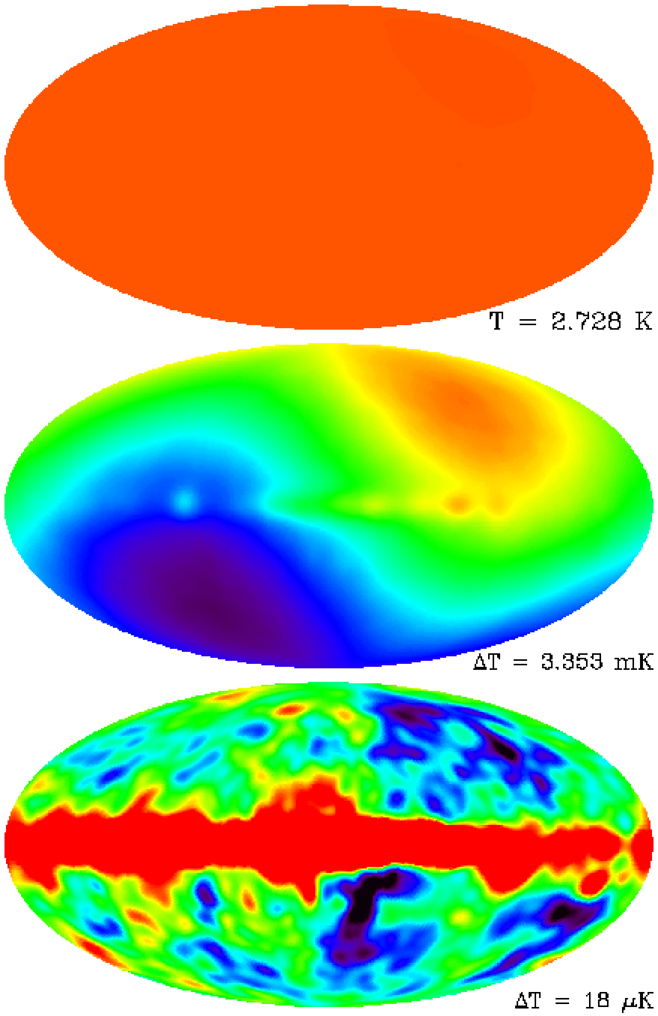


$\Delta T = 18\ \mu K$

ΔT = 18 μK

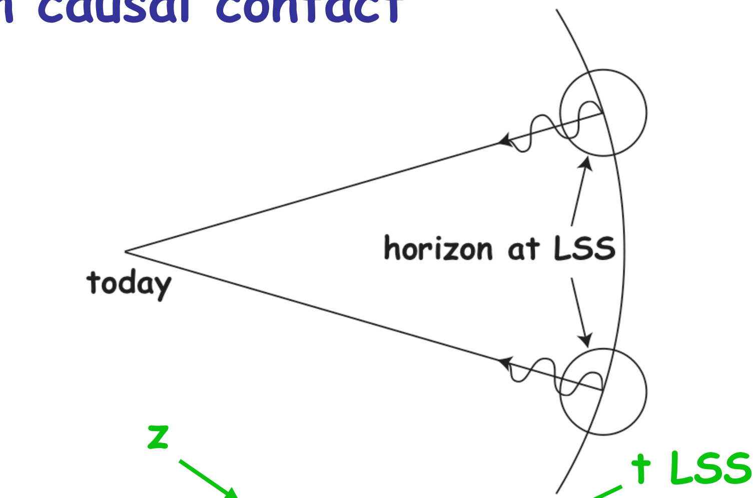
(after subtraction of dipole)

COBE sky maps



scale 0-4 K: very homogeneous!

Yet, regions > 1° apart never in causal contact

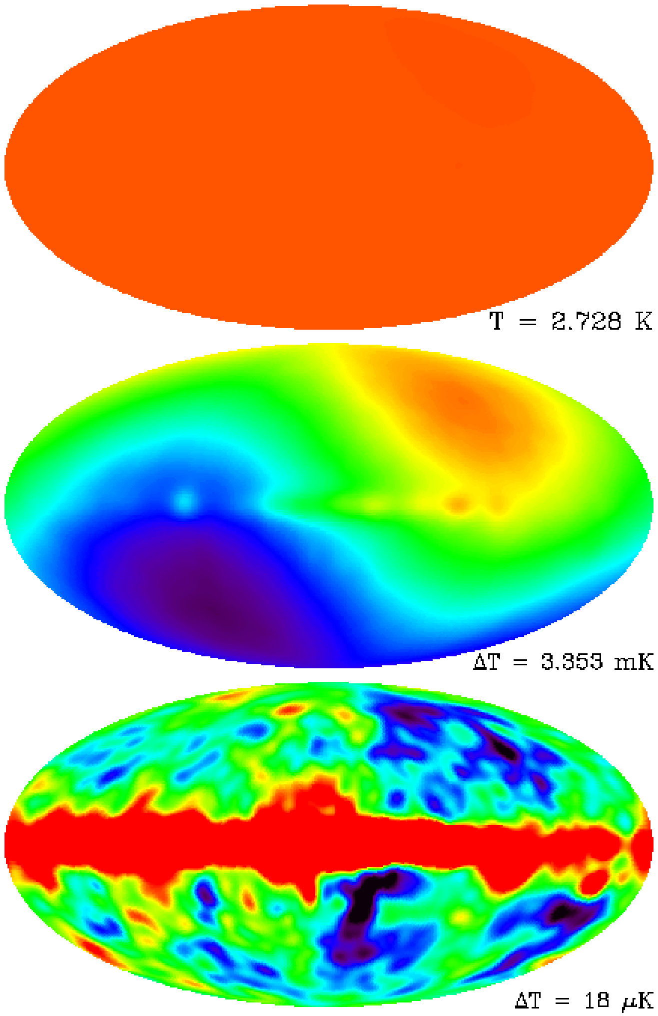


z → 10^3; t LSS → 3.10^5; t now → 14.10^9

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

Inflation ?

COBE sky maps

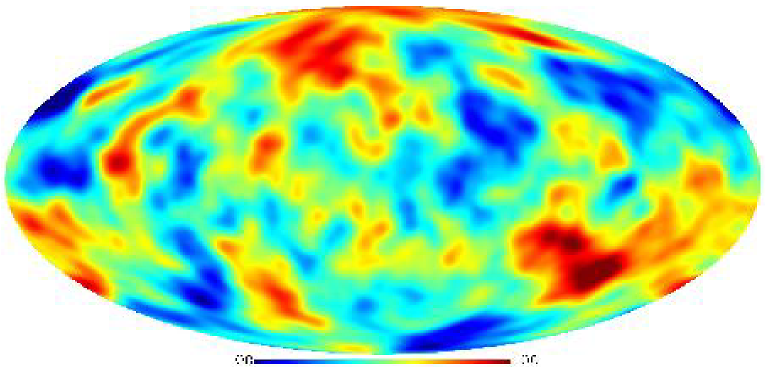


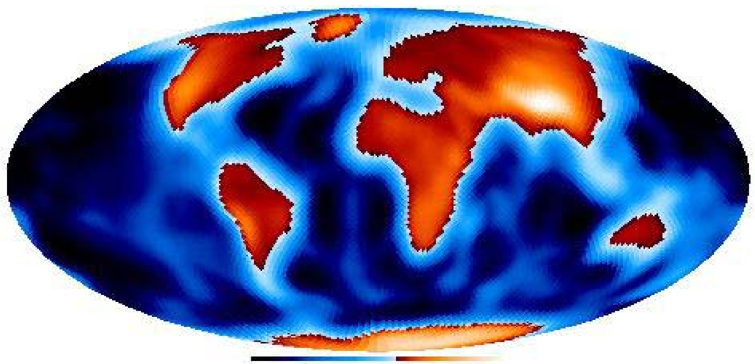
Doppler effect due to motion of Earth w.r.t. CMB
(v = 370 km/s towards Virgo)

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

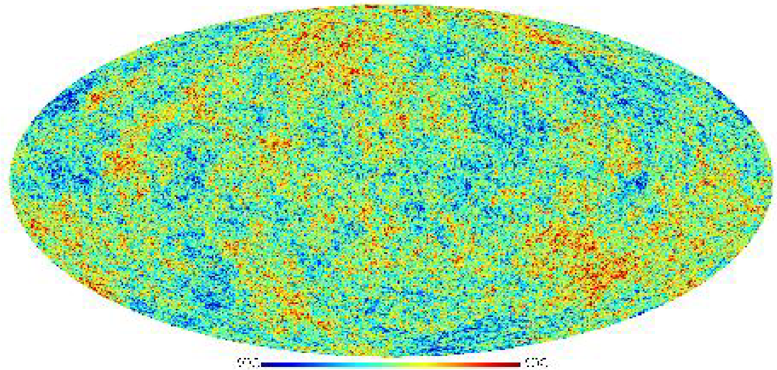
Resolution

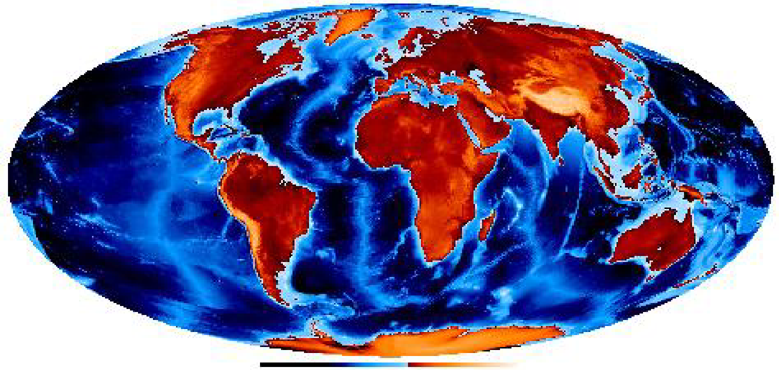
COBE
(7 degree resolution)





WMAP
(0.25 degree resolution)





WMAP

Launched in Jun. 2001
First results in 2003

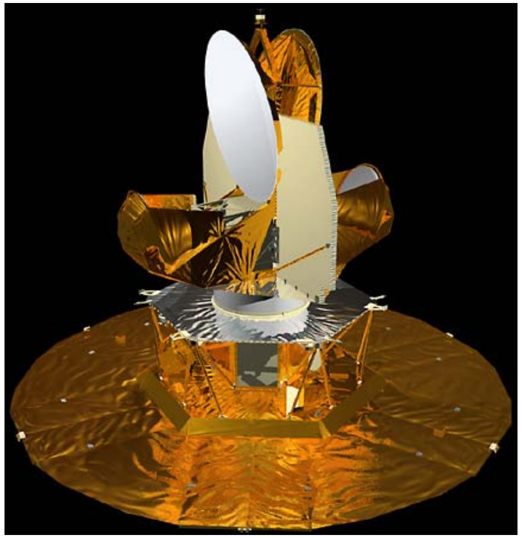
- Lagrange point L2: position of co-rotation with Earth
  ⇒ Stability of conditions
- Very low temperature signal
  ⇒ Need shielding from Sun, Earth, Moon, (Jupiter)
- Dual system to measure T differences
- 5 frequency channels (foreground removal)

Detectors

2 techniques

HEMTS

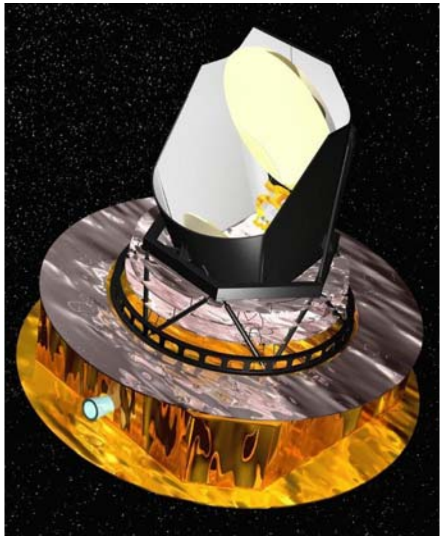
- \+ Easier to use
- \+ No heavy cryogeny (10 K)
- \+ Cheaper
- \- limited to f<90GHz



WMAP

Bolometers

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



Planck

Archeops

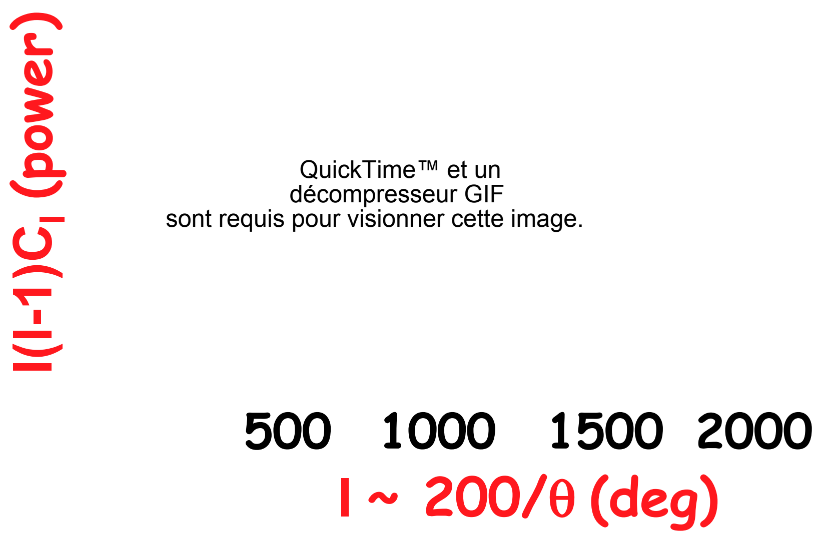
Fluctuations in CMB

- Before recombination, Universe = plasma of free e^- and protons

- Oscillations due to opposite effects of
  - gravity
  - pressure

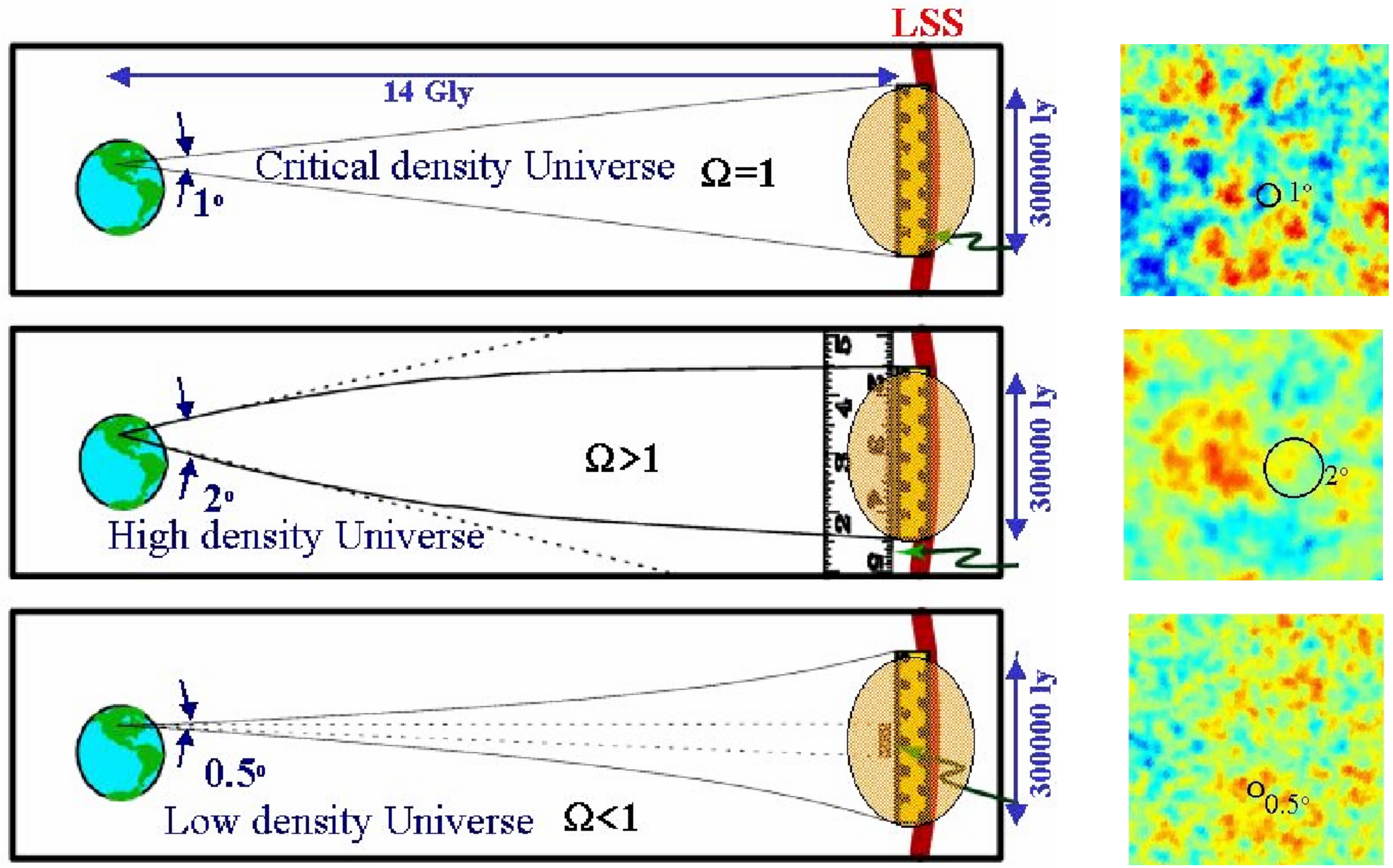
- Power spectrum at various scales

- More baryons
  → greater compression of fluid
  in potential wells



Max. scale of anisotropies

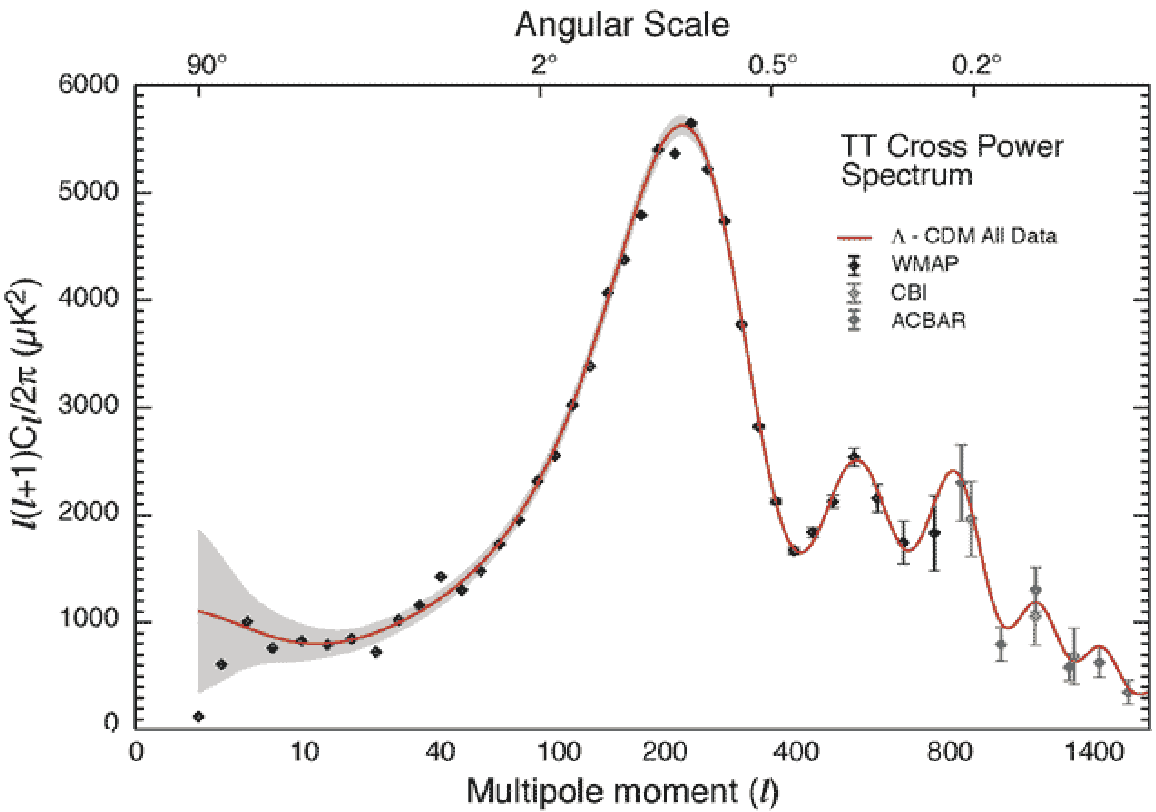
Limited by causality (remember?) → maximum scale



⇒ 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%)
$\Rightarrow \Sigma m_\nu < 3 \times 23$ eV



Consequences...

- 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 !