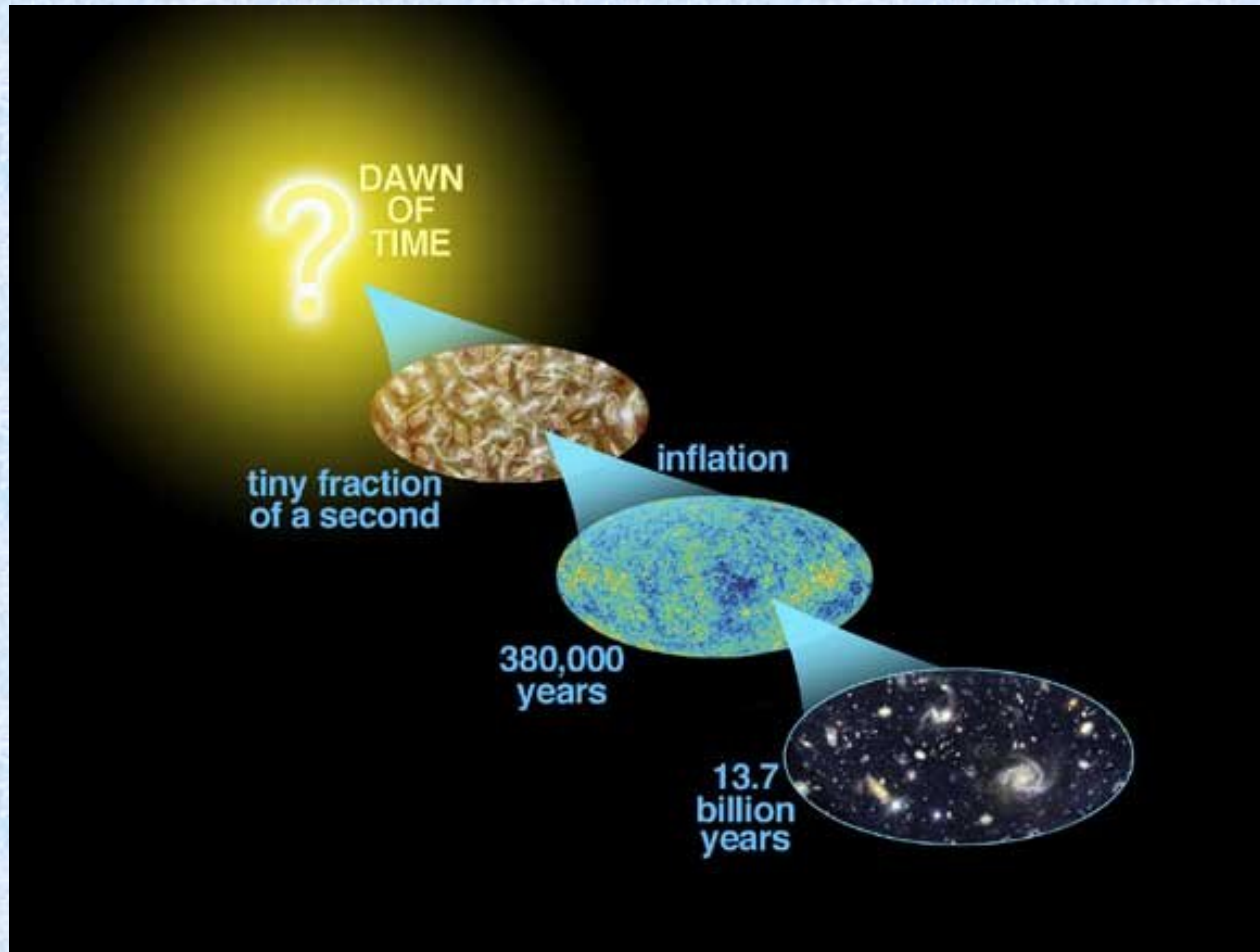


# Physics 133: Extragalactic Astronomy and Cosmology



Lecture 15; March 5 2014

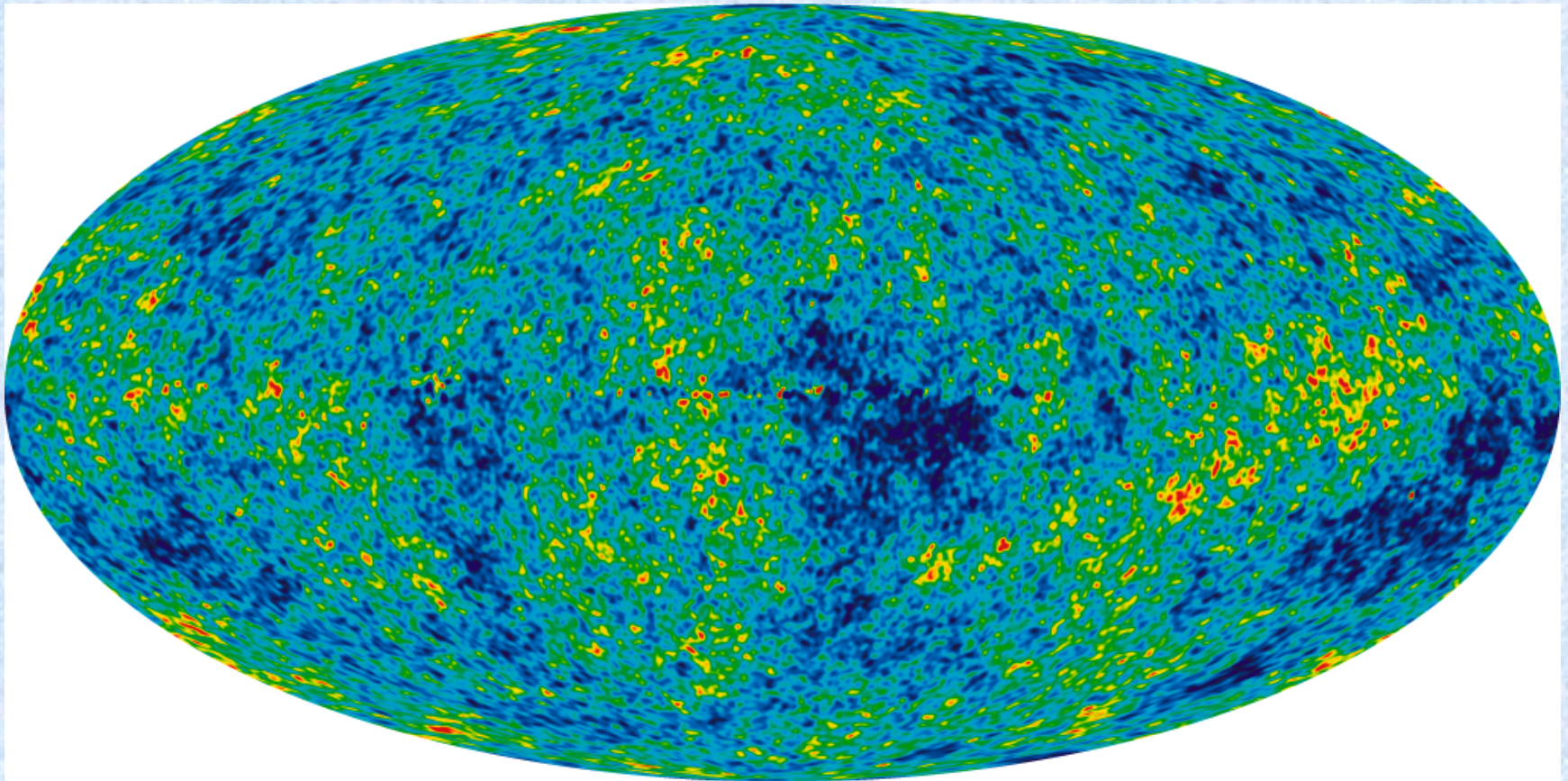
## Previously:

- CMB fluctuations are generated by fluctuations in the gravitational field at the time of last scattering
- The angular scale of the fluctuations gives us information on the content of the universe.

# Outline:

- How about before CMB decoupling?
  - What can be predicted and measured?
- Introduction to nucleosynthesis
  - Neutrons and protons
  - Deuterium
  - Heavy elements and cosmography
- Baryon-antibaryon asymmetry
- Problems of the standard Big Bang model:
  - Flatness Problem
  - Horizon Problem
  - Monopole Problem

# What was before this?

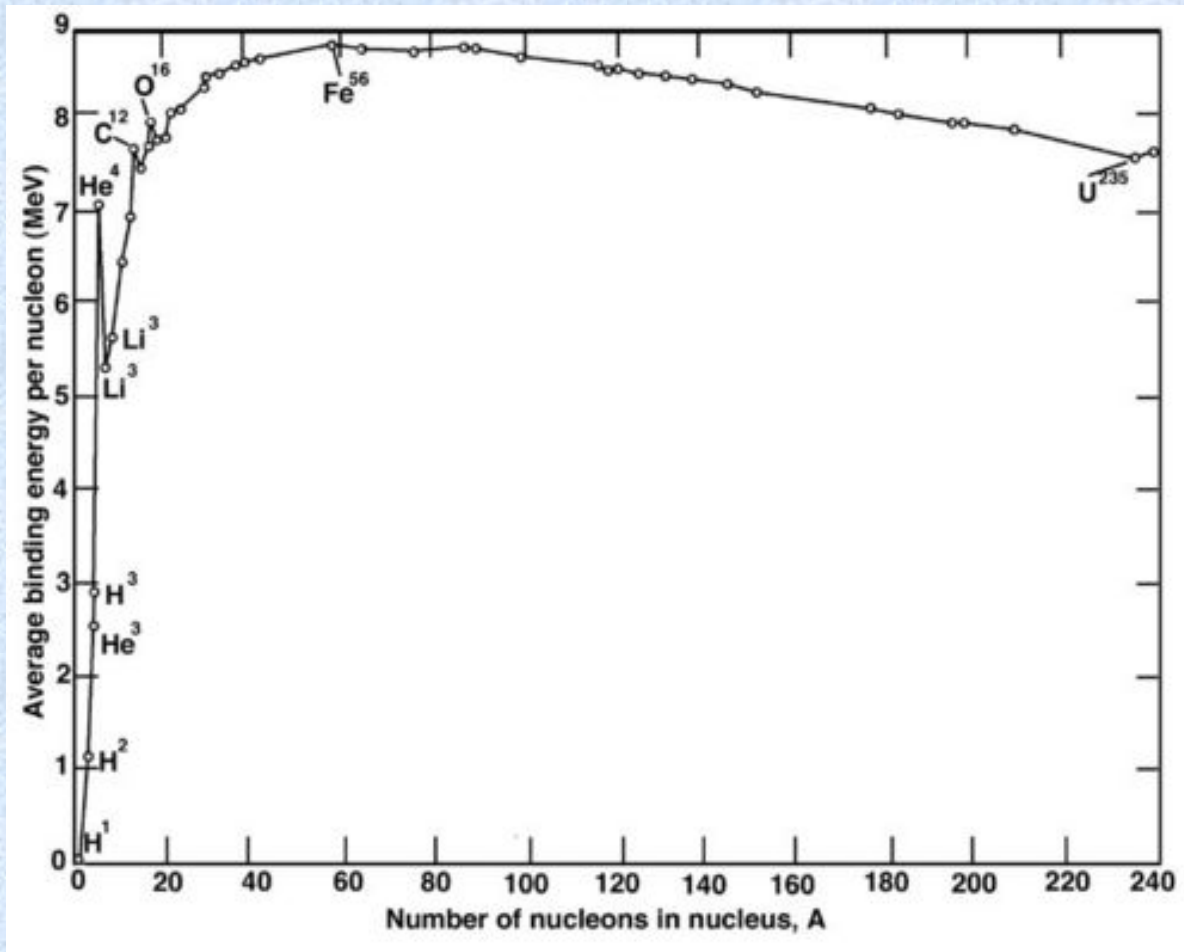


We cannot see, yet we have a way to probe into the time before LS

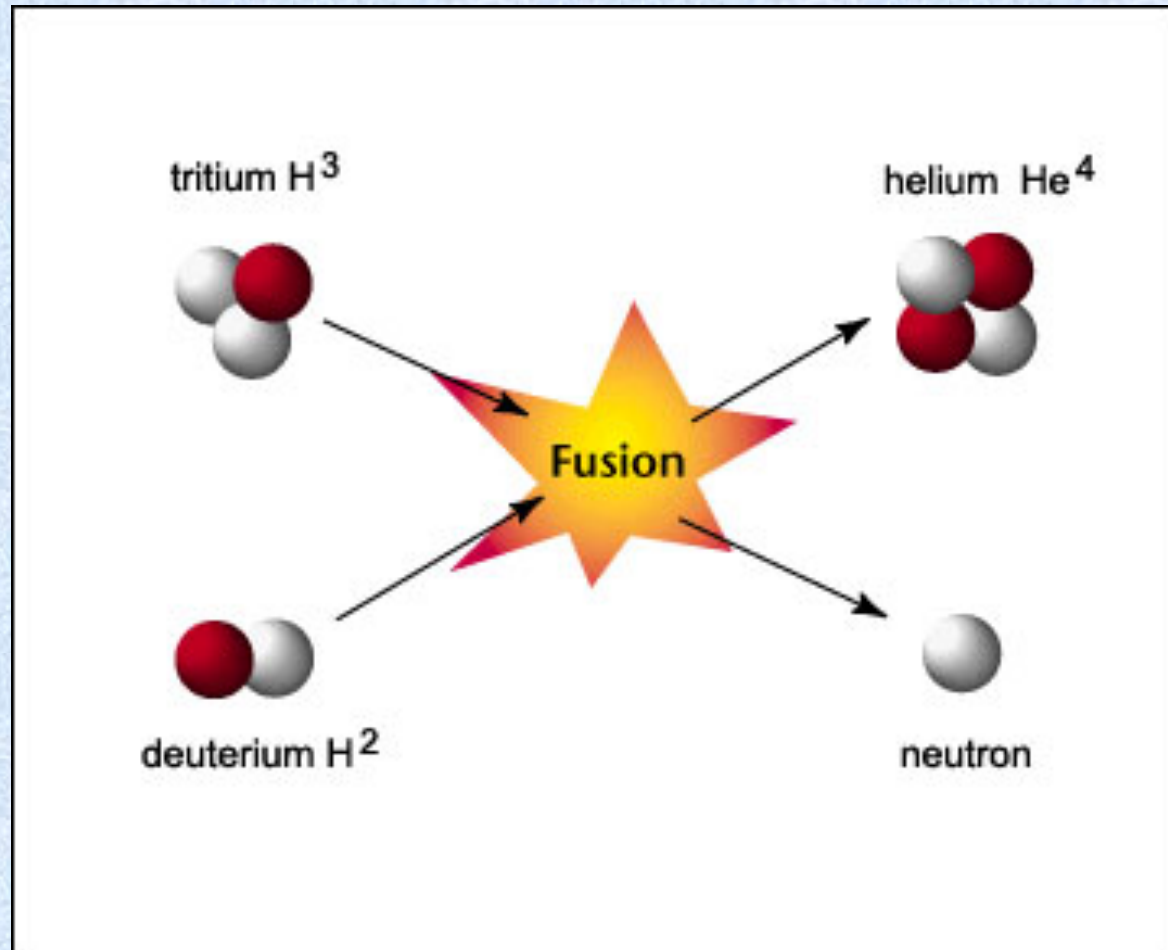
# Scales

- At  $t \ll 47,000$  (what is this?):  $a \propto t^{1/2}$
- $T(t) \sim 10^{10} \text{ K} (t/\text{s})^{-1/2}$ , i.e.  $kT \sim 1 \text{ MeV} (t/\text{s})^{-1/2}$
- MeV is the scale of nuclear binding energies!
- At  $t \sim 1 \text{ s}$  the universe is hot enough to do nuclear reactions!
- At  $t \sim 1 \text{ ps}$ , TeV scales (LHC)!

# Basics of Nuclear fusion/fission

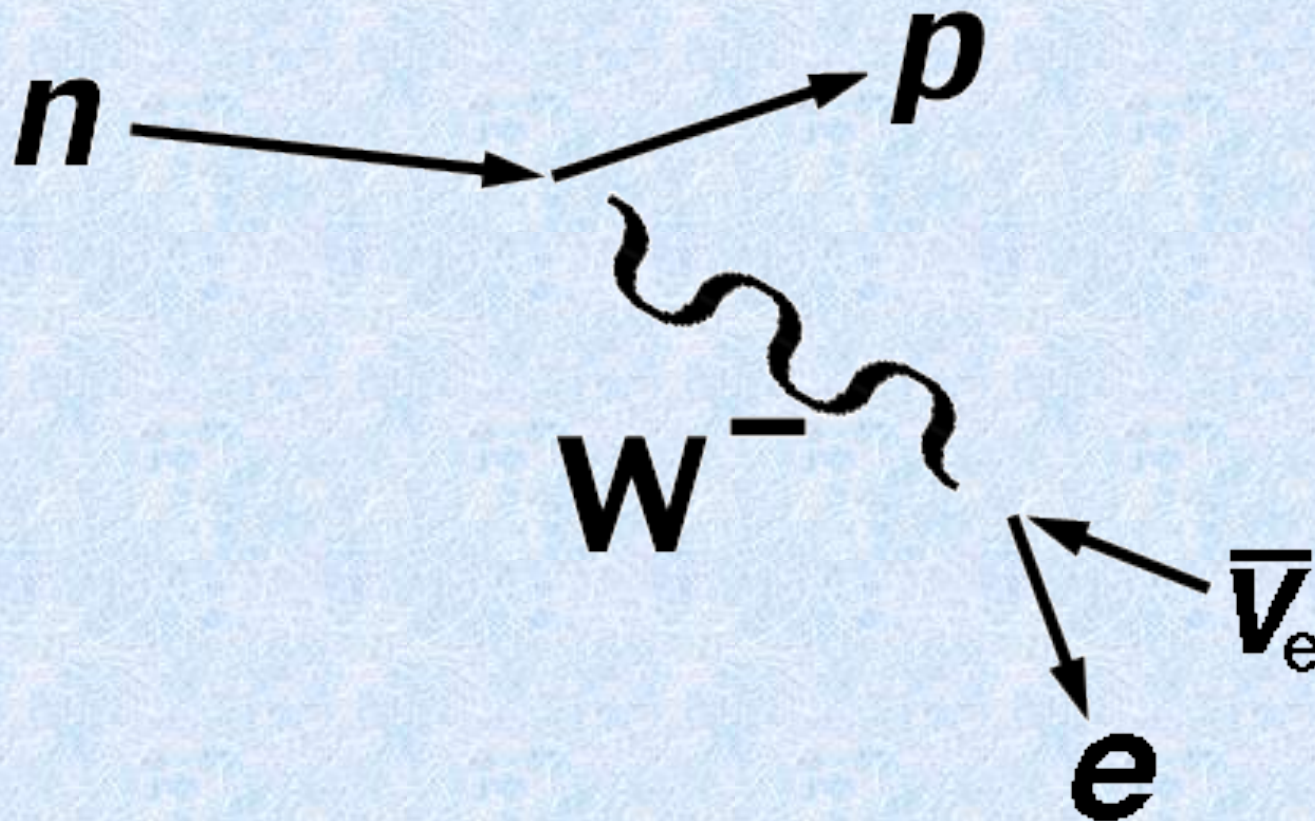


# Example of fusion



Other examples?

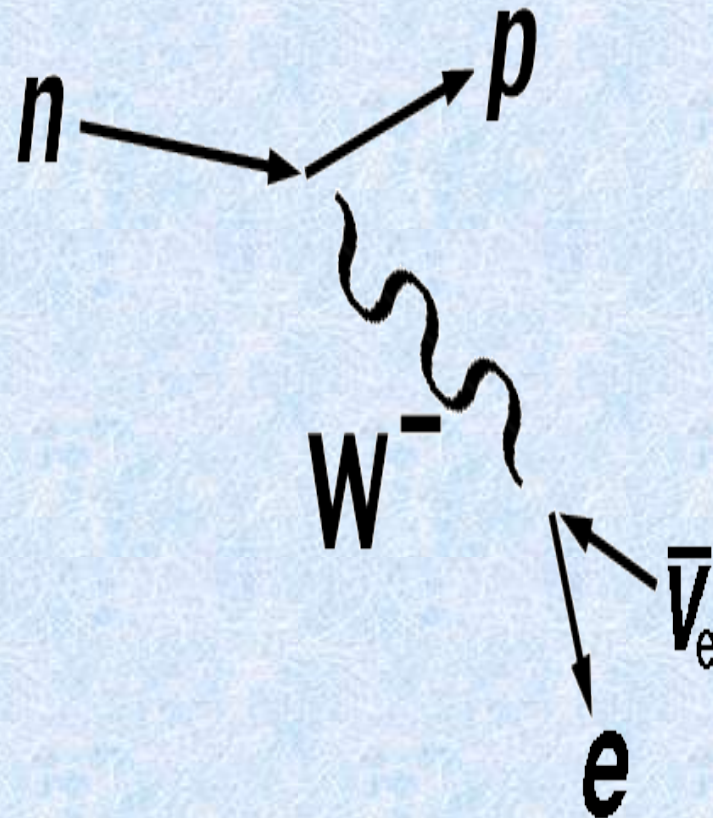
# Neutrons are unstable



Decay time is 890s

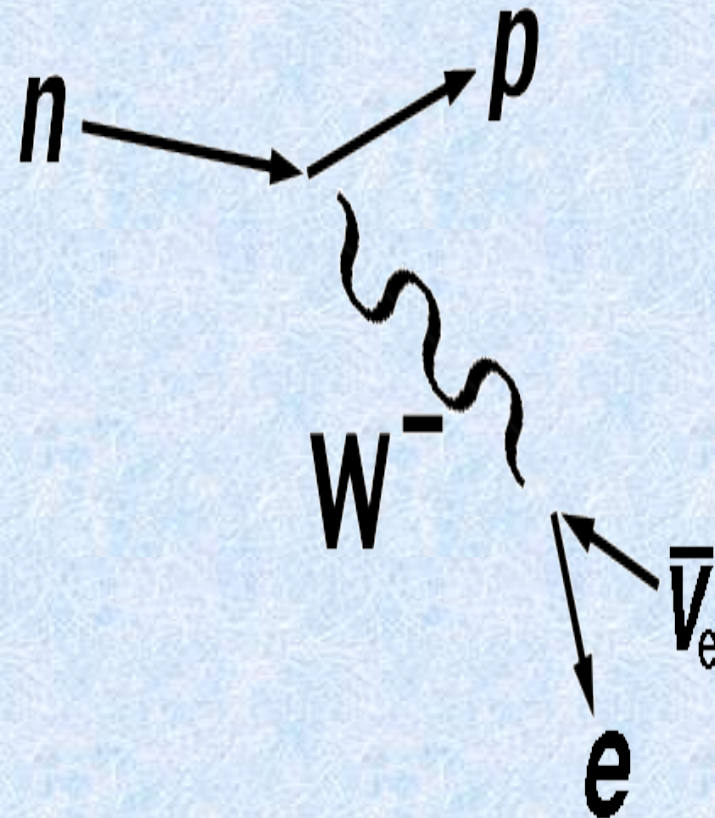
## At first...

- At very early times reaction is in equilibrium ( $\ll 1$ s)  
[enough  $e^-$   $e^+$ ]
- Relative abundances given by Maxwell Boltzmann quation:
  - $N(n)/N(p)=\exp(-Q/KT)$



## ...but then

- Cross section for weak interactions decays very rapidly with temperature
- Eventually interaction rate drops below expansion rate:
  - FREEZE OUT!
- [Blackboard]

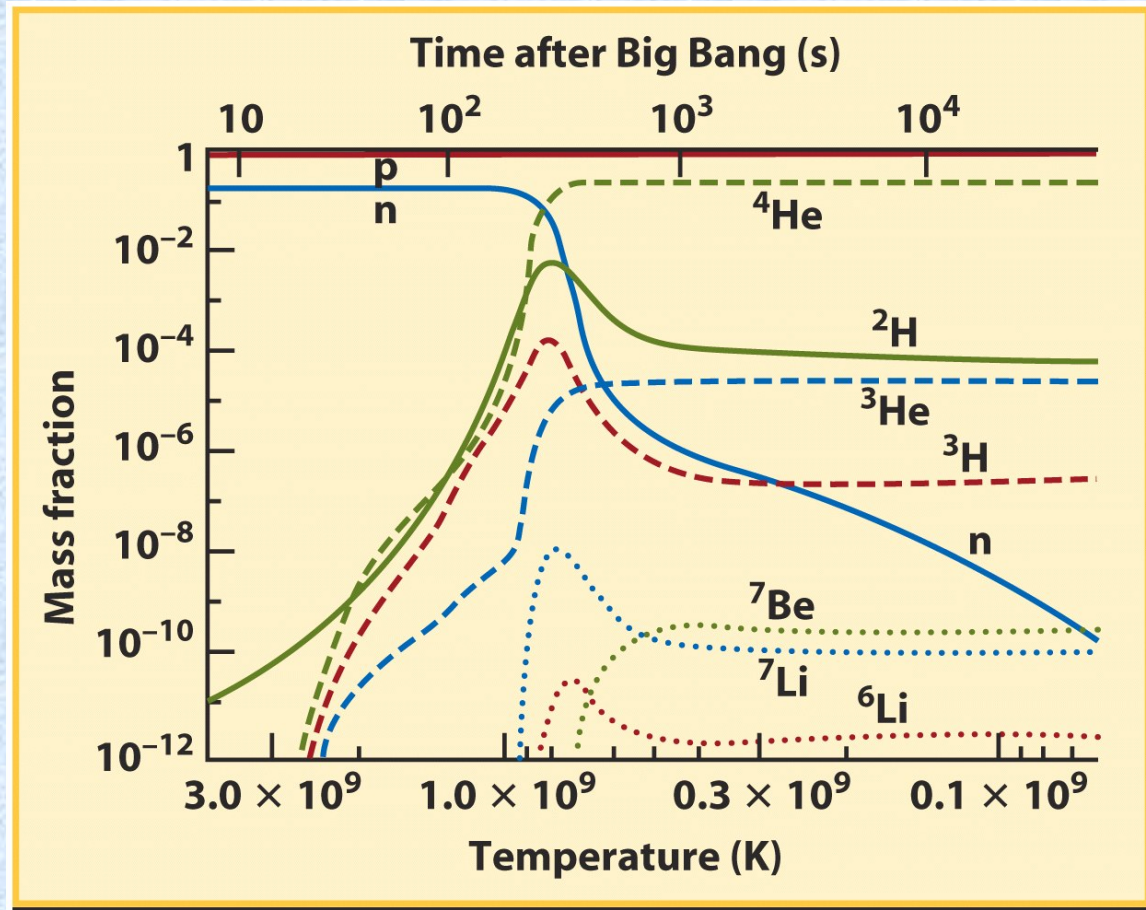


## After freeze out

- Most remaining neutrons get captured by p forming Deuterium [Saha's equation]
- Maximum number of non-H nuclei is set by abundance of n at freeze-out and their decay.
- Most of the non-H nuclei end up as He because it's the most stable nucleus

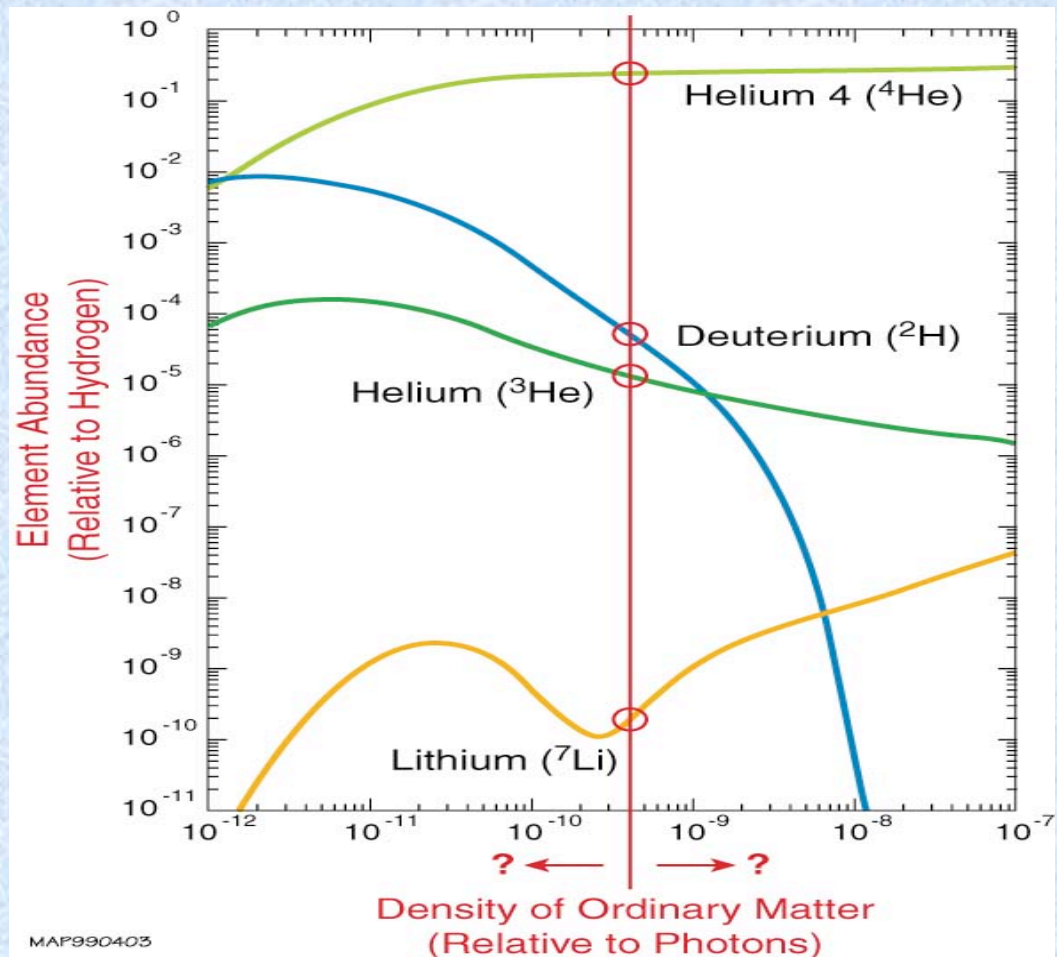
# Final outcome

- Nuclear reactions as long as the expanding universe supports them
- By  $\sim 5\text{m}$  everything is over!



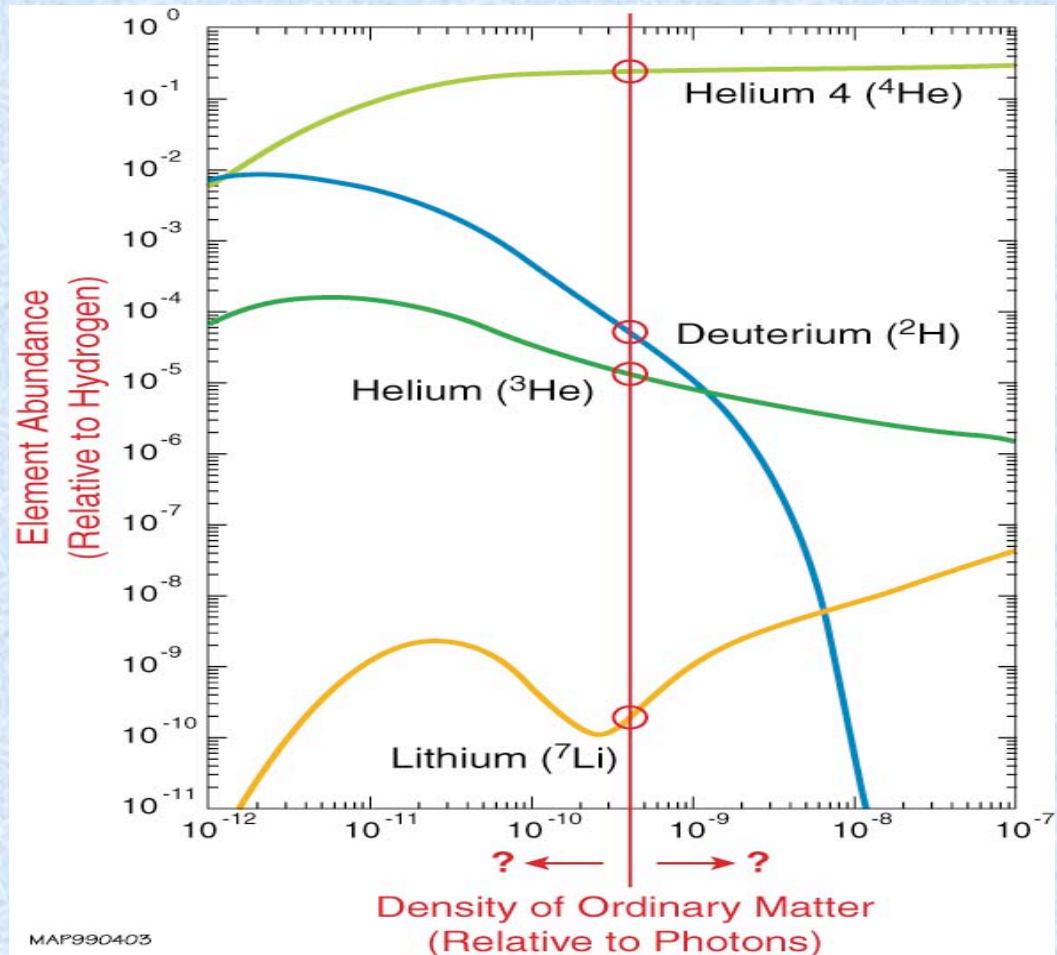
# Critical parameter

- The yield is dominated by  $\eta$  (remember recombination?)
- High  $\eta$  starts BBN early and is more efficient at producing He
- So there are fewer leftovers..
- Li is more complicated since there are competing channels



# BBN + measurement = baryon abundance

- If we measure e.g. D/H we infer  $\eta$ 
  - Best value  $5.5 \pm 0.5 \times 10^{-10}$
- We know  $T(\text{CMB})$ , so we obtain  $n(\text{baryons})!$  At 10%
- How do we measure D/H?



# Baryon-antibaryon asymmetry

- There are much many more photons than baryons
- There are much many more baryons than antibaryons
- What happened?
- [Blackboard]

# **Problems with classic Big Bang**

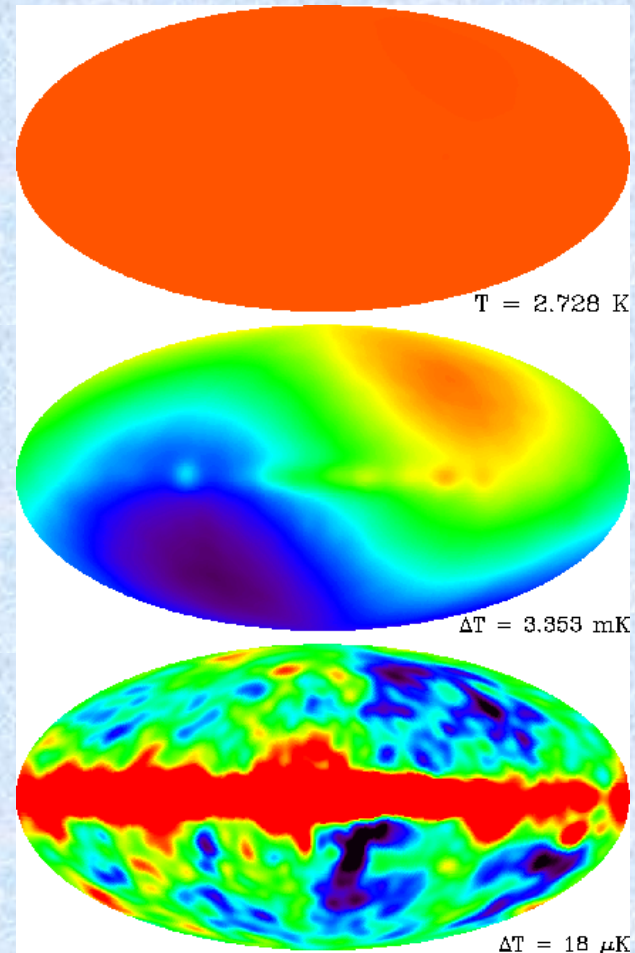
# Flatness Problem

- At present time the universe is very close to flat
- You can consider this as a coincidence... however.. [blackboard]



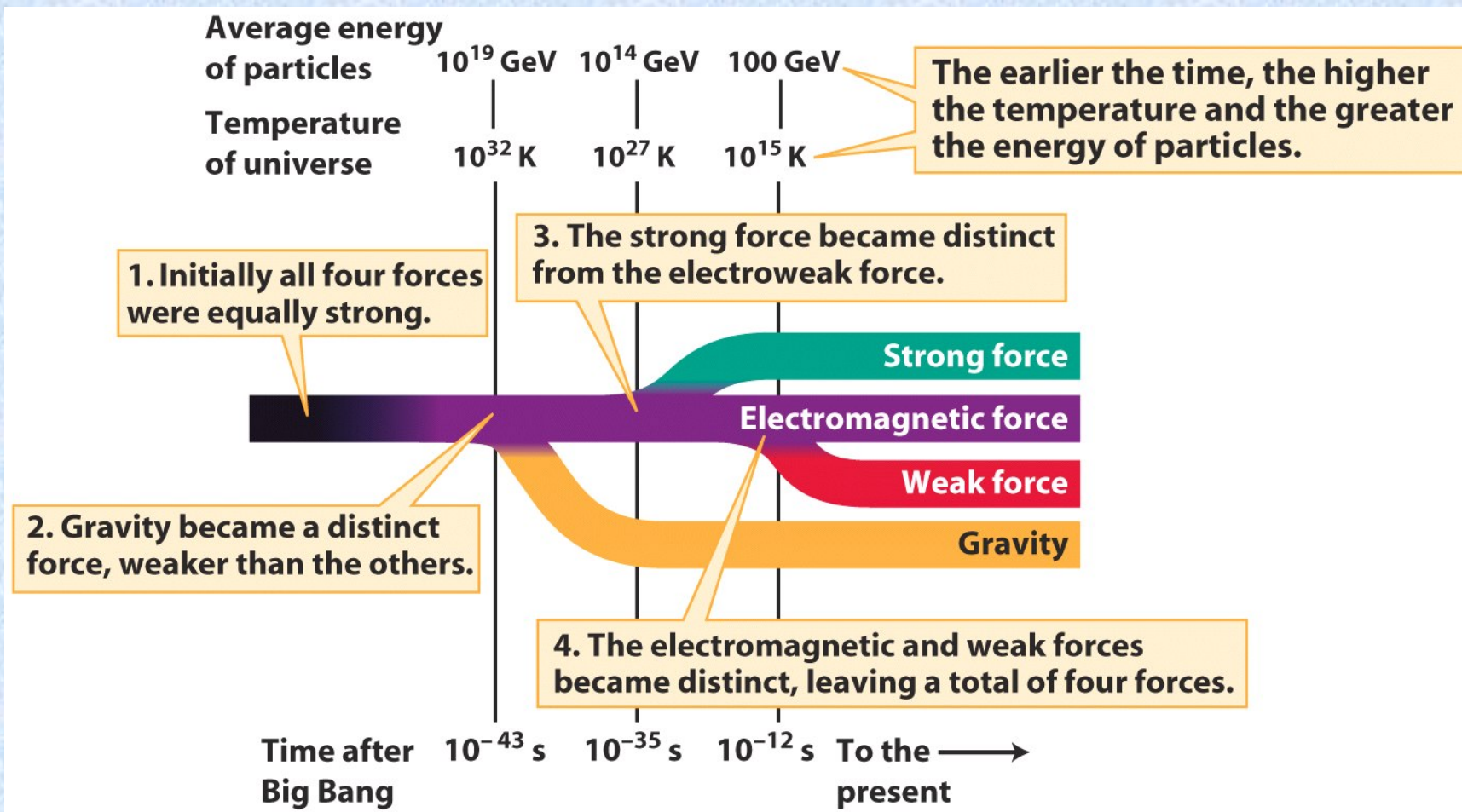
# Horizon Problem

- The CMB is VERY ISOTROPIC!
- Perhaps too isotropic..
- Regions too far on the sky are not causally connected, because their distance is larger than the horizon at the last scattering surface [blackboard]



# Monopole Problem

## Grand unified theories



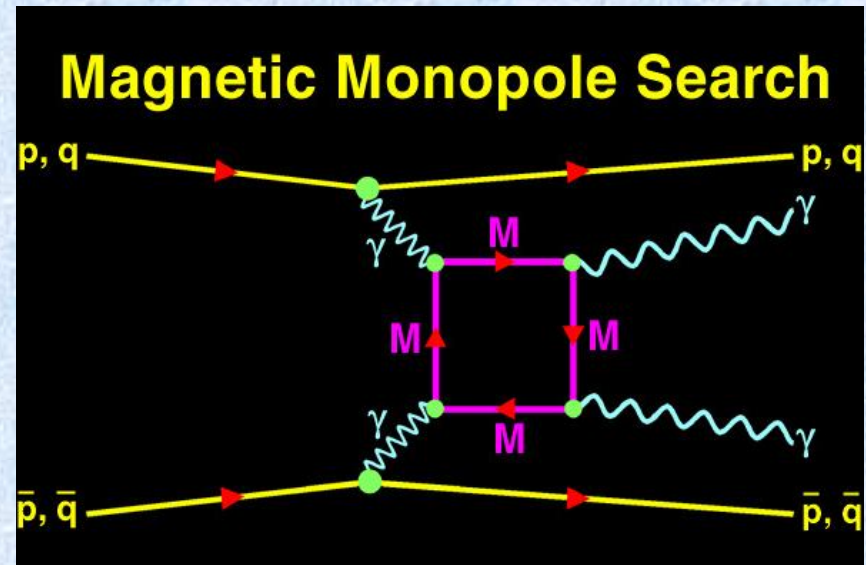
# Phase transitions and symmetry breaking



# Monopole Problem

## Grand unified theories

- When strong and electroweak forces break apart, magnetic monopoles are predicted to be left over with  $E \sim 10^{12}$  TeV
- Monopoles would dominate the energy density of the Universe!
- Monopoles have never been seen!
- [Blackboard]



# Summary I

- Theory of big bang nucleosynthesis predicts the abundance ratios of light elements remarkably well
- So well that it can be used to measure baryon abundance.
  - By the way: this is another piece of evidence for non-baryonic dark matter
- The dominance of matter over antimatter is explained in the standard model by a tiny violation of symmetry

# Summary II:

- In spite of its great successes the classic Big Bang model has three major problems:
  - It's too flat
  - It's too isotropic
  - There are no magnetic monopoles
- The currently favored solution is called “inflation”
- Next time we will see how inflation solves the three problems

**The End**

See you on monday