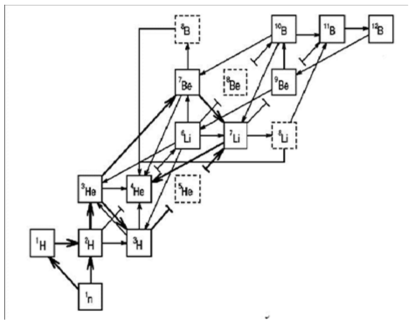
Cosmology 1FA209, 2015
Lecture 8: The early Universe

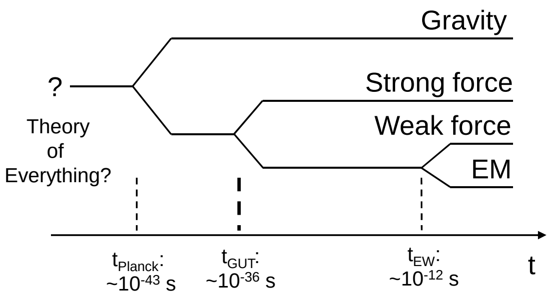


Outline

- Grand unificiation
- Cosmic inflation
- Origin of the elements
- Big Bang Nucleosynthesis
- Measuring elemental abundances

Covers chapters 10 & 11 in Ryden

Grand Unification



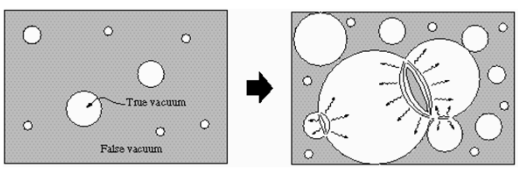
Grand Unification II

- Electroweak unification experimentally confirmed in late 1970s → Nobel prize in physics to Maxwell, Weinberg, Salam & Glashow for electroweak theory
- GUT happens at E_{GUT}~10^{12} TeV
- LHC reaches ~ 10 TeV → Experimental confirmation of GUT is not gonna happen soon…

Phase Transitions

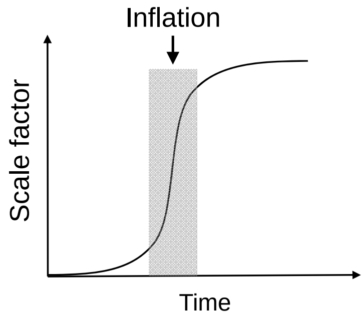
The Universe underwent a phase transition when the temperature dropped below T_{GUT}~10^{28} K
Symmetry between strong and electroweak force lost → Topological defects!

Many GUT scenarios produce magnetic monopoles with mc^2~10^{12} TeV



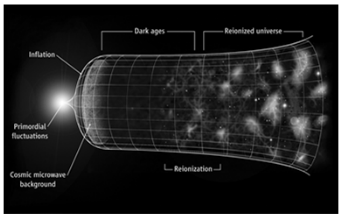
What is cosmic inflation?

A short period of fast expansion, happening very early in the history of the Universe



Why do we need inflation?

- To solve:
  - Flatness problem
  - Horizon problem
  - Magnetic monopole problem
- To provide the seeds for structure formation



The flatness problem I

Observationally:

$|1-\Omega_0| \leq 0.1$

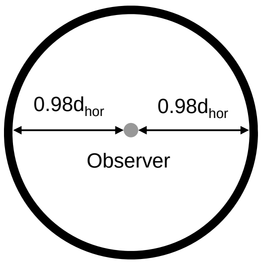
One can show that this implies, at the Planck time:

$|1-\Omega_{\text{Planck}}| \leq 10^{-60}$

Hence, if the Universe is close to flat now, it was extremely close to flat in the past.

Why is the Universe so close to flat?
If this is a coincidence, it very, very improbable!

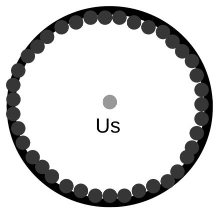
The horizon problem I



How can the CMBR be almost completely isotropic, when opposite sides of the sky have never been in casual contact?

The horizon problem II

$$\theta_{\text{hor}} = \frac{d_{\text{hor}}(t_{\text{lss}})}{d_{\text{A}}} \approx \frac{0.4\text{Mpc}}{13\text{Mpc}} \approx 2 \text{ degrees}$$



● Regions in causal contact
~20000 patches in the CMBR sky

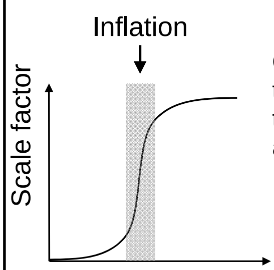
The magnetic monopole problem I

Magnetic monopoles: zero-dimensional objects which act as isolated north or south poles of a magnet

Many GUT models predict huge numbers of these! While subdominant at creation, they would soon come to dominate the energy density of the Universe

Problem: No such objects have ever been observed! Where are the magnetic monopoles?

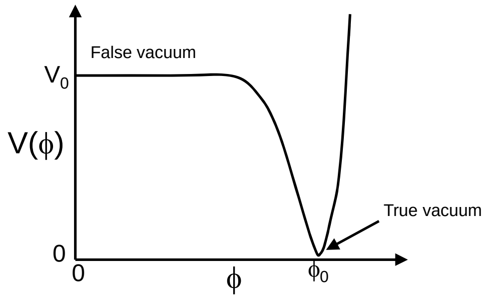
When did inflation occur?



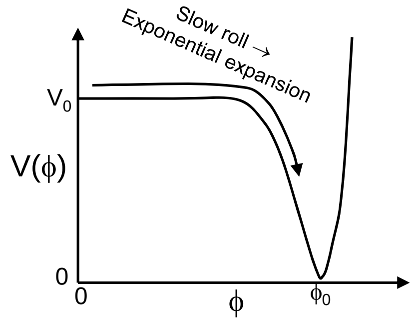
One possible model:
$t_{\text{start}} \sim 10^{-36}$ s after the Big Bang
$t_{\text{stop}} \sim 10^{-34}$ s after the Big Bang
$a(t_{\text{stop}})/a(t_{\text{start}}) \sim e^{100} \sim 10^{43}$

The inflaton field I

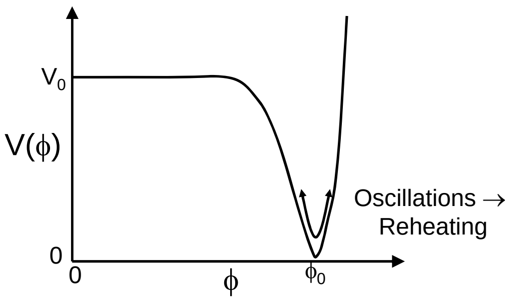
Consider a scalar field $\phi(r,t)$ with potential energy $V(\phi)$



The inflaton field II



The inflaton field III



Slow-roll

$$\varepsilon_{\phi} = \frac{1}{2}\frac{1}{hc^3}\dot{\phi}^2 + V(\phi)$$

$$P_{\phi} = \frac{1}{2}\frac{1}{hc^3}\dot{\phi}^2 - V(\phi)$$

Slow roll:

$$\dot{\phi}^2 << hc^3 V(\phi) \Rightarrow$$

$$\varepsilon_{\phi} \approx -P_{\phi} \approx V(\phi)$$

Negative pressure!
Λ-like expansion!
de Sitter phase!

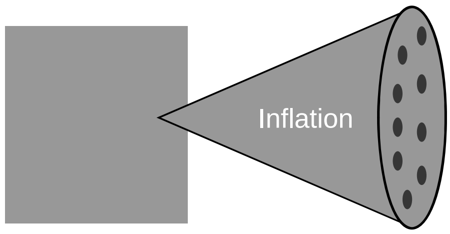
Reheating

If the Universe expands by a factor of $\sim e^{100} \rightarrow$
Temperature drops by e^{-100}
and the radiation energy denstiy gets extremely small

How come it's not small after inflation then?

Oscillations of ϕ around $\phi_0 \rightarrow$
Some of the energy of the inflaton field are
being carried away by radiation
These photons *reheat* the Universe
Hence, no shortage of photons after inflation!

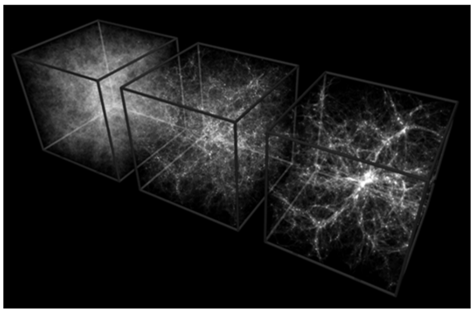
Seeds for structure formation



Prior to inflation:
Microscopic quantum fluctuations
Virtual particles created and annihilated

After inflation:
Quantum fluctuations blow up
to macroscopic scales
act as seeds for structure formation

Seeds for structure formation II



Current Universe
Primordial seeds have generated very complicated structure

Inflation as a solution to the flatness problem I

The acceleration equation:

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}(\varepsilon + 3P)$$

During inflation, the Universe is temporarily dominated by a component with $P < -\varepsilon/3$ (i.e. $w<-1/3$), giving positive acceleration.
One often assumes a *cosmological constant* $\Lambda_{\text{inflation}}$ to be responsible.
Note: This is a constant very different from the Λ driving the cosmic acceleration today.
$\Lambda_{\text{inflation}} \sim 10^{107}\,\Lambda$…

Inflation as a solution to the flatness problem II

Hubble parameter and scale factor during inflation:

$$H_{\text{inflation}} = \left(\frac{\Lambda_{\text{inflation}}}{3}\right)^{1/2}$$

$$a(t) \propto e^{H_{\text{inflation}}\,t}$$

Number of e-foldings during inflation:

$$N = H_{\text{inflation}}(t_{\text{stop}} - t_{\text{start}})$$

$$N \sim 100$$

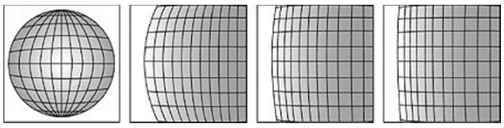
Inflation as a solution to the flatness problem III

$$|1-\Omega(t_{\text{stop}})| = e^{-2N}|1-\Omega(t_{\text{start}})|$$

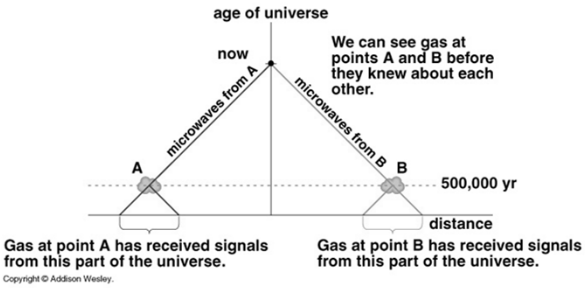
Example:

$$|1-\Omega(t_{\text{start}})| \approx 1 \Rightarrow |1-\Omega(t_{\text{stop}})| \approx 0$$

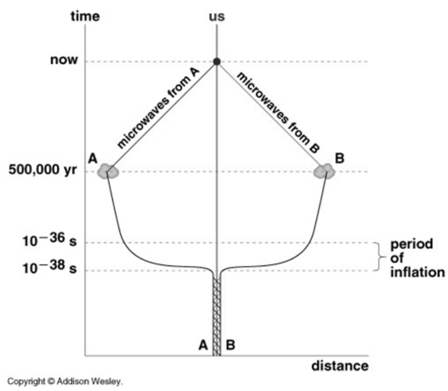
Inflation makes a curved Universe flat!



Inflation as a solution to the horizon problem I



The horizon problem



The solution

Inflation as a solution to the horizon problem II

Horizon before and after inflation:

$$d_{\text{hor}}(t_2) = c\int_{t_1}^{t_2} \frac{\mathrm{d}t}{a(t)}$$

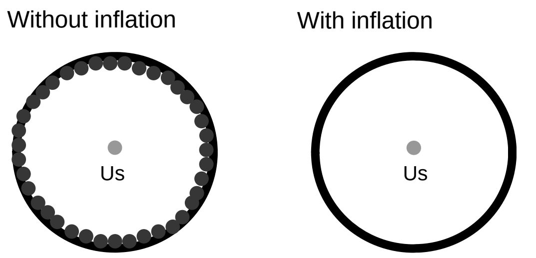
Before inflation :

$$d_{\text{hor}} = 2ct_{\text{start}} \sim 6\times10^{-28}\,\text{m}$$

After inflation :

$$d_{\text{hor}} \approx \mathrm{e}^{N}\,3ct_{\text{start}} \sim 2\times10^{16}\,\text{m}$$

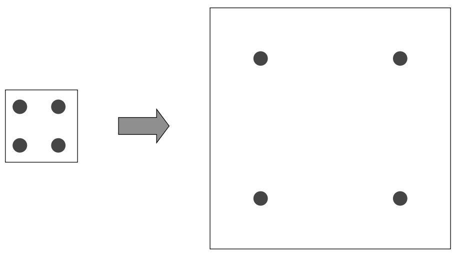
Inflation as a solution to the horizon problem IV



Regions in causal contact
~20000 patches in the CMBR sky

Just one patch in the sky!

Inflation as a solution to the magnetic monopole problem I



Expansion dilutes the number densities of objects, and inflation did this extremely efficiently

Inflation as a solution to the magnetic monopole problem II

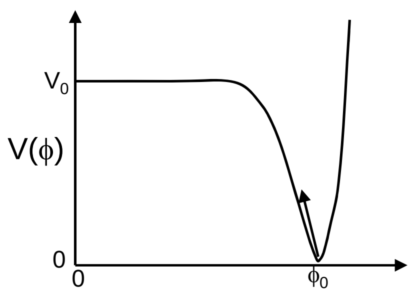
At the end of inflation :

$$n_{\text{monopoles}}(t_{\text{stop}}) \sim e^{-300}\, n_{\text{monopoles}}(t_{\text{GUT}})$$

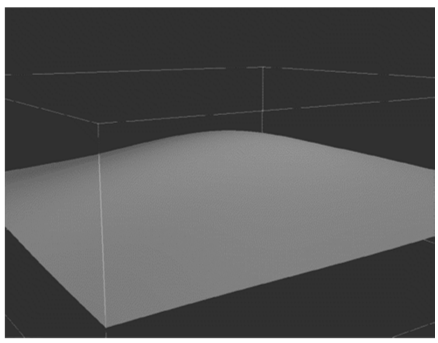
A realistic number density of monopoles at the GUT epoch would correspond to less than one monopole within the volume spanned by the last scattering surface

Eternal inflation I

Once the inflaton field has come to rest at ϕ_0, inflation ends. But in some regions of space equantum fluctuations can make the inflation field move up the potential again → Some regions keep inflating

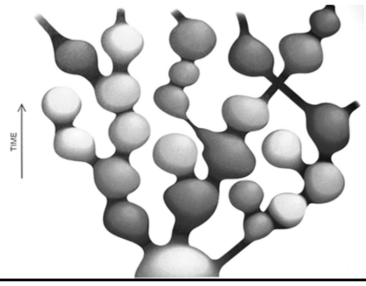


Eternal inflation II



Eternal inflation III

Differently inflated regions may end up with
very different properties ('mutations') → Multiverse
Good 'genes' may promote further expansion
(self-reproducing Universes).



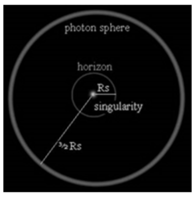
Eternal inflation IV

- Quantum fluctuations in ϕ → *Future-eternal inflation*
  Inflation will always continue (somewhere)
- Past-eternal inflation models also exist:
  Revives the perfect cosmological principle!
  The interior of each inflating bubble may be described by the Big Bang theory, but the multiverse as a whole has been around forever

Stellar Black Holes

Initial mass:	Last stages:	Remnant mass:
$30 < M/M_{solar}$	SN → BH	~ 3—20 M_{solar}

→



Supernova

Stellar Black Hole

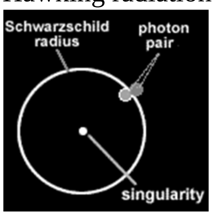
Since the progenitors of stellar black holes are baryonic, these black holes cannot contribute much to the matter density of the Universe

Primordial Black Holes

- High-density regions in the early Universe (t « 1 s) may collapse into primordial black holes
- PBHs could in principle form with masses from M_{Planck} - 10^{15} M_{solar}
- Remains a viable candidate for the cold dark matter: Ω_{PBH} could be ~0.3!
- Example:
  - $M_{PBH} \sim 10^{-8}$ M_{solar} (mass of the Moon) would have a size (event horizon) of R~0.1 mm

Primordial Black Holes II

Hawking radiation:



·Observational constraints:
- BBNS abundances
- Gamma-ray background
- CMBR

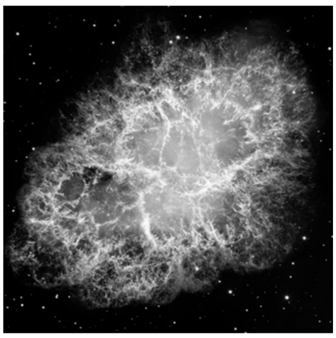
$$\tau_{evap} \sim 9 \cdot 10^{-18} M^3 s$$

$$T_{rad} = \frac{hc^3}{16\pi^2 kGM}$$

Objects with $M > 5\times10^{11}$ kg would still be around!

Unclear what happens at M_{Planck}. Relics may form!

Intermission: What are you made of?



"We are stardust, billion year old carbon
We are golden, caught in a devil's bargain
And we've got to get ourselves back to the garden"
Joni Mitchell: *Woodstock* (1969)

The Elements

Atomic nuclei :
Z = Number of protons
N = Number of neutrons
A = Nucleons = Mass number = Z + N

^{1}H = Normal hydrogen nucleus (proton)
^{2}H = Deuterium (hydrogen isoptope)
^{4}He = Normal Helium

X, Y, Z

- X: Mass fraction of Hydrogen (most common element in the Universe). Here, now: $X \approx 0.71$
- Y: Mass fraction of Helium (second most common element in the Universe) Here, now: $Y \approx 0.27$
- Z: Mass fraction of all heavier elements combined. Also known as "Metallicity". Here, now: $Z \approx 0.02$

Abundances in Astronomy

$$[A/B] = \log_{10}\left(\frac{(\text{number of A atoms / number of B atoms})_{\text{object}}}{(\text{number of A atoms / number of B atoms})_{\text{sun}}}\right)$$

- Common examples:
  - [Fe/H], [O/H] – These two are often carelessly referred to as 'metallicities'
- [Fe/H] = -1 means that the object you're looking at only has 10% Iron (relative to hydrogen) compared to the Sun.

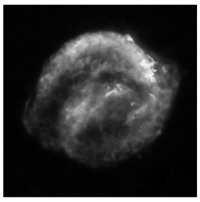
The Light Elements

Created during Big Bang Nucleosynthesis, roughly in the first three minutes after the Big Bang:
- ^{2}H (Deuterium, D), ^{3}H (Tritium)
- ^{3}He, ^{4}He
- ^{6}Li, ^{7}Li
- ^{7}Be, ^{8}Be (Unstable, decays back into Li)

Note: BBNS required to explain abundances of ^{4}He and Deuterium!

The Heavy Elements

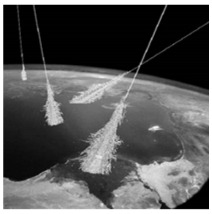
- Essentially all elements with A>7 are created through
  - Stellar nucleosynthesis
  - Supernova nucleosynthesis



Fusion: H $\rightarrow$ He $\rightarrow$ Heavier elements

Cosmic Ray Spallation

- Nucleosynthesis due to high-energy impacts of cosmic rays
- Can form ^{3}He + certain isotopes of Li, Be, B, Al, C, Cl, I and Ne



Important BBNS Reactions I: Proton-neutron freezeout

Consider the Universe at t ≈ 0.1 s…

Pair production:

$\gamma + \gamma \Leftrightarrow e^- + e^+$

n and p are held in equlibrium with each other:

$n + \nu_e \Leftrightarrow p + e^-$

$n + e^+ \Leftrightarrow p + \bar{\nu}_e$

Neutrinos freeze out of these reactions at t ~1 s →
Neutron-to-proton ratio frozen at $n_n/n_p \approx 0.2$
Then follows neutron decay:

$n \Rightarrow p + e^- + \bar{\nu}_e$

Important BBNS Reactions II: Deuterium and Helium synthesis

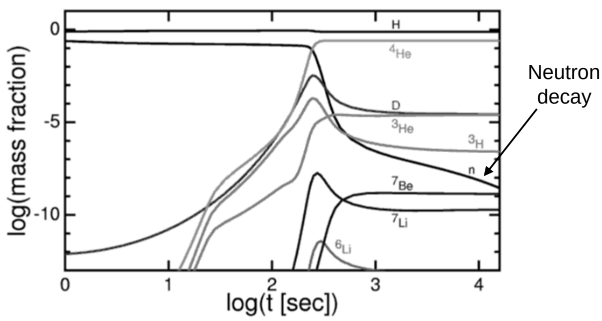
Consider the Universe at t ≈ 2—300 s…

$$p + n \Leftrightarrow d + \gamma$$

The rightward direction starts to dominates once the photon temperature has dropped below the 2.22 MeV binding energy of Deuterium.
Serious production of D does not start until t ≈ 300 s.
Once we have Deuterium, several routes allow the formation of Helium:

$d + n \rightarrow H^3 + \gamma$	$d + d \rightarrow He^3 + n$	$d + d \rightarrow He^4 + \gamma$
$H^3 + p \rightarrow He^4 + \gamma$	$d + d \rightarrow H^3 + p$	
$d + p \rightarrow He^3 + \gamma$	$H^3 + d \rightarrow He^4 + n$	
$He^3 + n \rightarrow He^4 + \gamma$	$He^3 + d \rightarrow He^4 + p$	

The Detailed Solution



The Beryllium Bottleneck

- No stable nuclei with A=8 → Prevents formation of heavier elements during BBNS

Even though you can form:

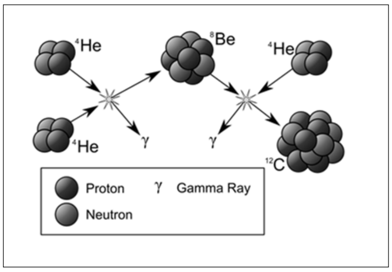
$^4\text{He} + {}^4\text{He} \Rightarrow {}^8\text{Be}$

^{8}Be will decay back into He after just 3×10^{-16} s

Yet we know that the Universe has somehow managed to make heavier elements…

The Beryllium Bottleneck II

How do you make carbon?
Solution: The Triple-Alpha process can take place in stars because of high temperatures (fast fusion of Helium)



The Beryllium Bottleneck III

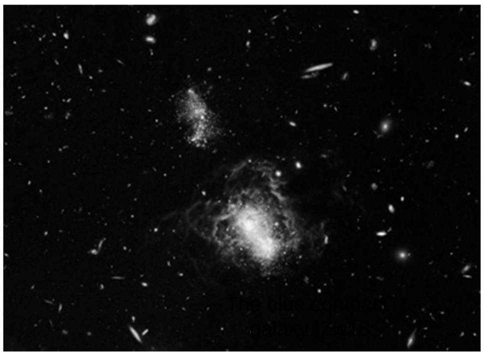
Triple-Alpha works because ^{4}He, ^{8}Be and ^{12}C happen to have finely tuned energy levels.
Fred Hoyle (1950s) predicted a so far unknown excited level of ^{12}C, to explain why Carbon-based entities such as ourselves exist. Experimentalists later proved him right!

Primordial Abundances

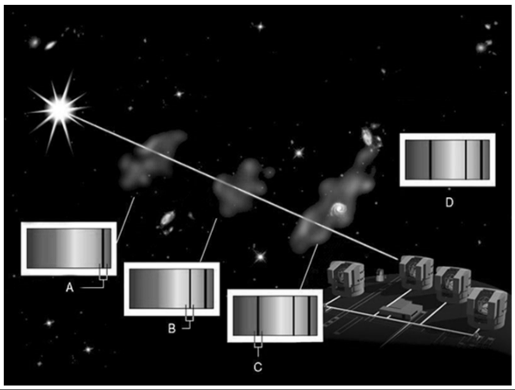
To test BBNS, one needs to measure the primordial abundances of the light elements, i.e. measure the abundances in environments unaffected by chemical evolution

- Helium: Low-metallicity HII regions
- Deuterium: Quasar absorption lines
- Lithium: Low-metallicitiy stars

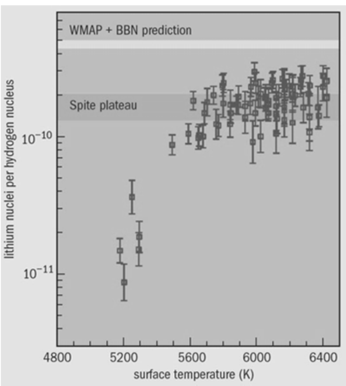
Primordial Helium



Primordial Deuterium



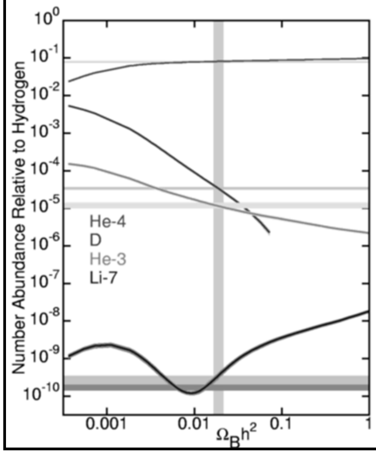
Primodrial Lithium



BBNS – A Big Bang Success Story

- Big Bang explains primordial abundances of the light elements
- The abundances of the light elements agree with predictions over 9 orders of magntiude!
- The resulting Ω_b is in accord with the result from other methods

This is how the success story is usually told – but there may be more to this than meets the eye…



Impressive agreement over 9 orders of magnitude → Big picture probably correct

But beware:
The logaritmic scale hides discrepancies…
And what is the reason for the Li-7 mismatch?