Cosmology

TUM WS 2019/2020

Lecture 7

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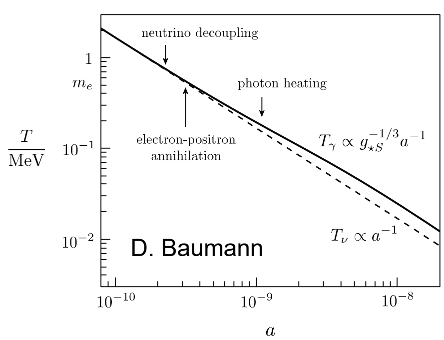
(http://www.eso.org/~bleibund/Cosmology)

Recap of previous lecture

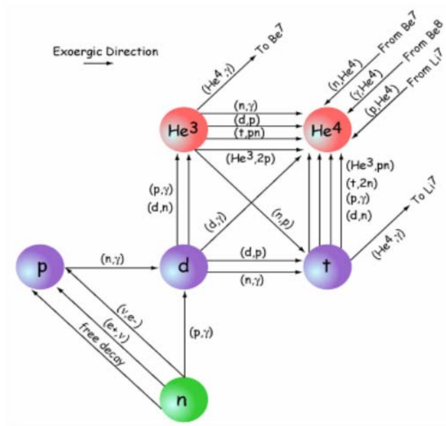


T(K)	***t (seconds)***	X_n
10^{12}	0.0001	0.4962
$3\ 10^{11}$	0.0011	0.4875
10^{11}	0.0099	0.4626
$3\ 10^{10}$	0.1106	0.3798
10^{10}	1.008	0.2386
$3\ 10^{9}$	12.67	0.1654
$1.3\ 10^{9}$	91.09	0.1458
$1.2\ 10^{9}$	110.2	0.1425
$1.1\ 10^{9}$	135.1	0.1385
10^{9}	168.1	0.1333
$9\ 10^{8}$	212.7	0.1268
$8\ 10^{8}$	274.3	0.1182
$7\ 10^{8}$	362.6	0.1070
$6\ 10^{8}$	496.3	0.0919
$3\ 10^{8}$	1980	0.0172
10^{8}	17780	$3.07\ 10^{-10}$

Nucleus	Binding Energy (MeV)
neutron	1.29
Deuterium D (or ^2H)	2.22
Tritium (^3H)	6.92
Helium (^3He)	7.72
Helium (^4He)	28.3

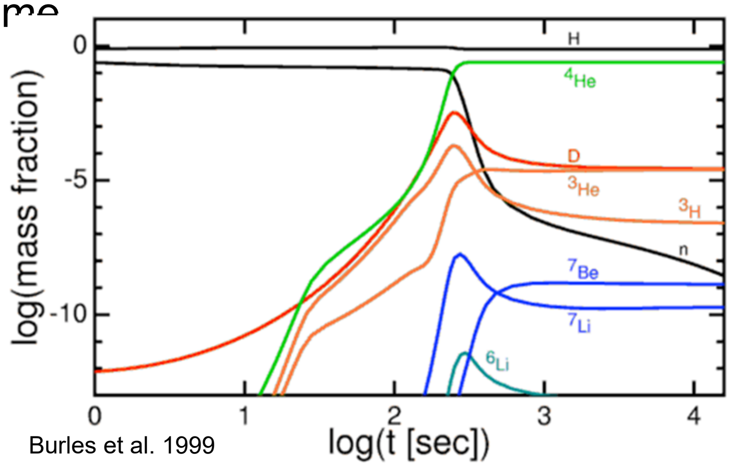
pp-reaction chain

- Formation of D, He and Li



Nucleosynthesis

Formation of elements as a function of time



Burles et al. 1999

Big Bang Nucleonsynthesis

Summary of the expected abundances of light elements formed in the Big Bang

- He (Y)
- D and ^{3}He
- ^{7}Li

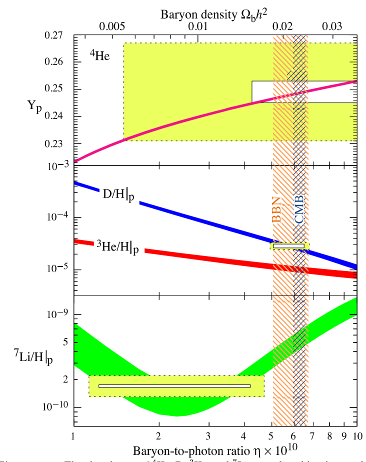
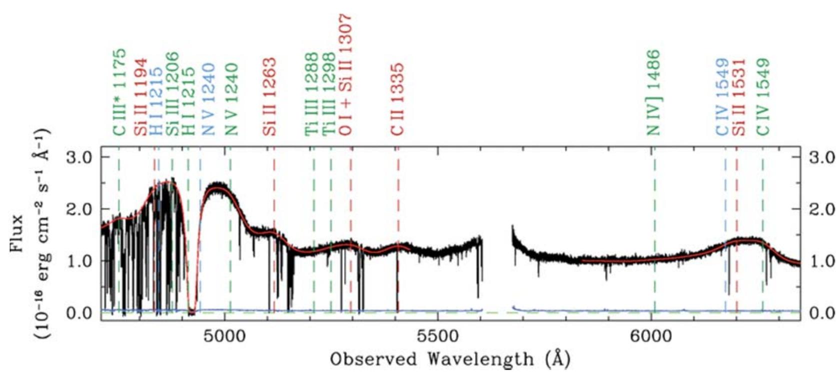


Figure 22.1: The abundances of ^{4}He, D, ^{3}He, and ^{7}Li as predicted by the standard model of Big-Bang nucleosynthesis [14] – the bands show the 95% CL range. Boxes indicate the observed light element abundances (smaller boxes: $\pm 2\sigma$ statistical errors; larger boxes: $\pm 2\sigma$ statistical *and* systematic errors). The narrow vertical band indicates the CMB measure of the cosmic baryon density, while the wider band indicates the BBN concordance range (both at 95% CL).

Measuring Deuterium

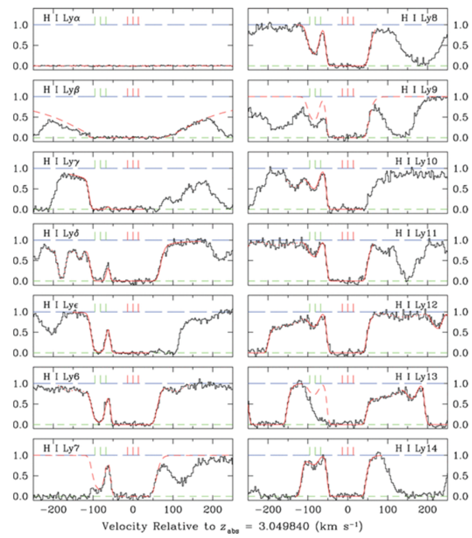
Done in damped Lyman-α systems



Pettini & Cooke 2012

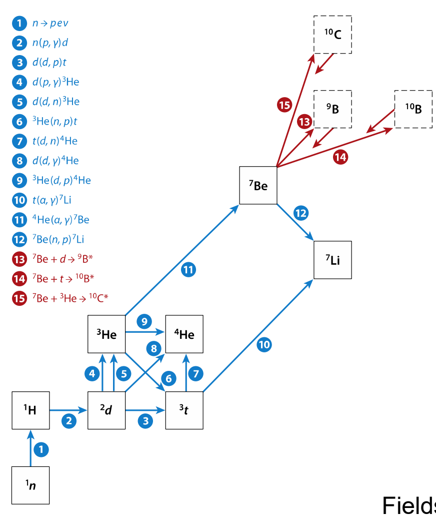
Measuring Deuterium

Slight wavelength offset due to different nucleus mass



pp-reaction chain

- Formation of D, He and Li

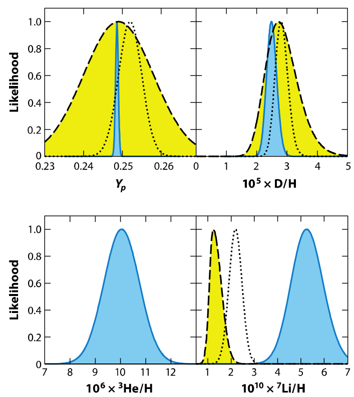


Fields 2011

Figure 1

Simplified big bang nucleosynthesis nuclear network. Shown are 12 normally important reactions (*blue*) and 3 proposed or tested new reactions (*red*).

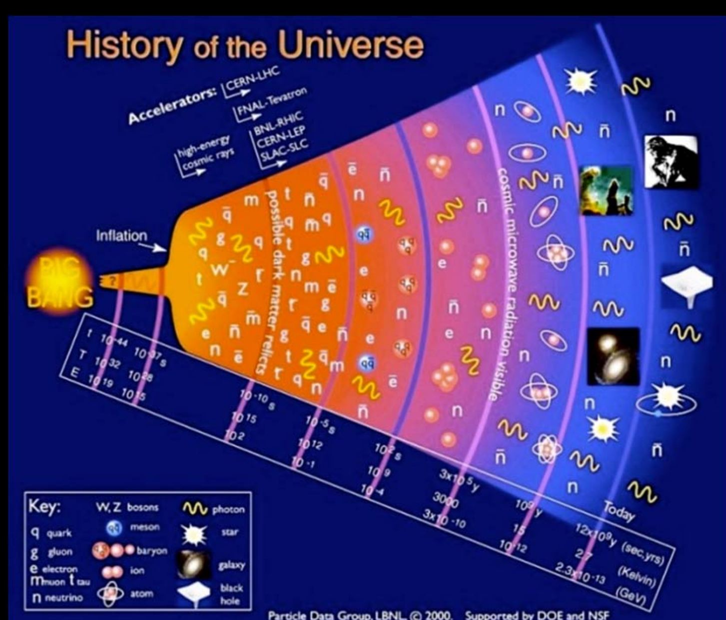
Lithium Problem



Fields 2011

Figure 5

Comparison of big bang nucleosynthesis (BBN)+WMAP predictions and observations. Shown are the likelihood distributions for light-element abundances. The blue curves represent the theory likelihoods predicted for standard BBN through the use of the cosmic baryon density determined by WMAP (63). The yellow curves represent the observational likelihoods based on primordial abundances (see Section 2.2). The dotted curves represent the observational likelihoods for different analyses of abundance data; the difference between these and the yellow curves gives a sense of the systematic errors. Note the spectacular agreement of the ratio of deuterium to hydrogen and, in contrast, the strong mismatch between ^{7}Li theory and data, which constitutes the lithium problem. Reproduced from Reference 30.



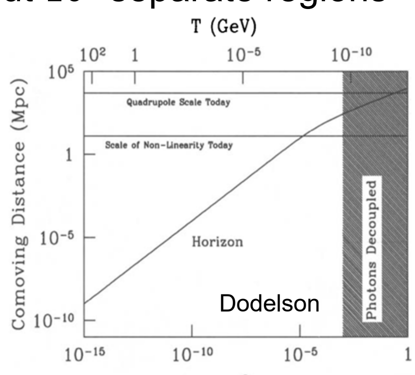
Baryogenesis

- What could create this imbalance?
- Sakharov: 3 conditions required
  1. violate conservation of baryon (and lepton) number
  2. violate the invariance of C (charge) and CP (charge and parity), maintain CPT (charge, parity, time) invariance
     - observed in the K (kaon) decays and B meson decays
     - time invariance is violated by expansion
  3. violate thermal (and chemical) equilibrium
     - can happen at phase transitions

Horizon problem

Structures observed today were not causally connected in the early universe

- there should be about 10^4 separate regions in the sky
- $D_H \approx H_0^{-1}(1+z)^{-\frac{3}{2}}$
- $D_A \approx H_0^{-1}(1+z)^{-1}$
- $\frac{D_H}{D_A} \approx (1+z)^{-\frac{1}{2}}$
- at z=1100 this corresponds to ~1.6° on sky!

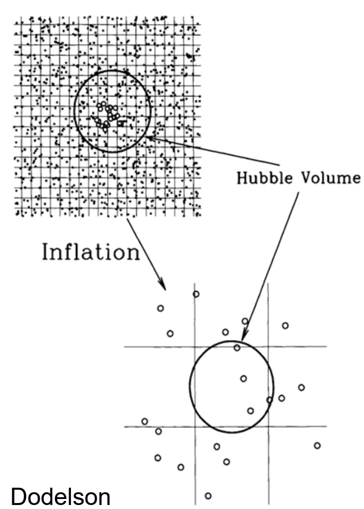


Flatness and Monopole problems

- Curvature today close to 0
  - not 10^5 or some other large number
- Since Ω_K goes with a^{-2} at early times the space has had to be exceedingly flat to maintain this until today
- Symmetry breaking in grand unified theories should leave local topological defects
  - about one monopole per nucleon

"Solution"

- Rapidly expand ("inflate") the space
  - removes monopoles
  - creates flat geometry
  - solves horizon problem
- Inflation is based on the fact that the expansion in a constant density universe is $a(t) \propto e^{Ht}$



Dodelson

Inflation

- Comoving horizon (see lecture 2)

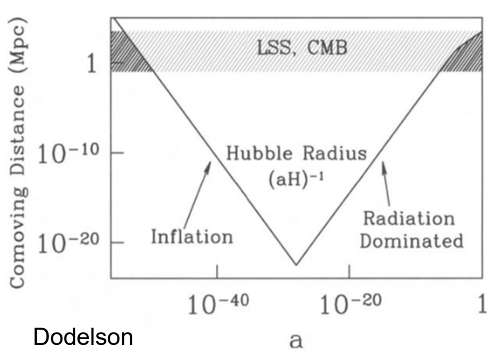
$$\eta = \int_0^a \frac{da'}{a'} \frac{1}{a' H(a')}$$

- Hubble radius $(aH)^{-1}$ defines causally connected region
- To decrease the Hubble radius $\frac{d^2 a}{dt^2} > 0$, i.e. an accelerated expansion
- Expansion rate since the early universe (ignore matter dominated for the moment)

$$a_e \approx \frac{T_0}{10^{19}}\ GeV \approx 10^{-28}$$

Inflation

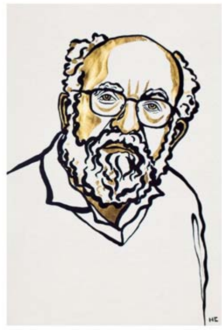
- The current universe is 10^{28} comoving Hubble radii larger than in the early universe. Corresponds to 60 e-foldings.



Dodelson

The Nobel Prize in Physics 2019

Ill. Niklas Elmehed. © Nobel Media.
James Peebles
Prize share: 1/2



Ill. Niklas Elmehed. © Nobel Media.
Michel Mayor
Prize share: 1/4

Ill. Niklas Elmehed. © Nobel Media.
Didier Queloz
Prize share: 1/4

“New perspectives on our place in the universe”

Peebles: “for theoretical discoveries in physical cosmology”

Mayor & Queloz: “for the discovery of an exoplanet orbiting a solar-type star”

Let the festivities begin…

THE NOBEL PRIZE

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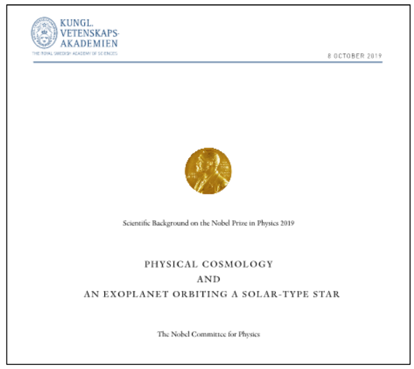
Nobel Prize award ceremony at Konserthuset Stockholm, 10 December 2018. © Nobel Media. Photo: N. Adachi

Nobel Week in Stockholm and Nobel Peace Prize events in Oslo 2019

Share this

The official programme of Nobel Week in Stockholm begins on 6 December with an informal get-together for the 2019 Nobel Laureates at the Nobel Prize Museum. During the following days, the laureates will give press conferences and hold their Nobel Lectures. The week culminates in the Nobel Prize award ceremony and banquet on 10 December and ends with visits to the Nobel Foundation. The Nobel Peace Prize is awarded in Oslo, Norway.

Nobel Explanations


KUNGL.
VETENSKAPS-
AKADEMIEN
8 OCTOBER 2019

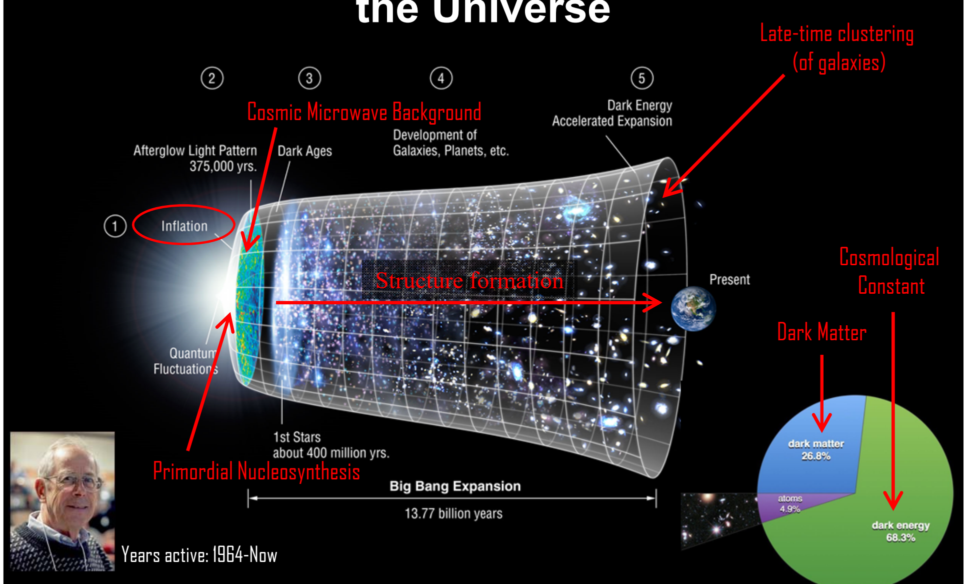
Scientific Background on the Nobel Prize in Physics 2019

PHYSICAL COSMOLOGY
AND
AN EXOPLANET ORBITING A SOLAR-TYPE STAR

The Nobel Committee for Physics

https://www.nobelprize.org/uploads/2019/10/advanced-physicsprize2019-3.pdf

Our current picture of (the history of) the Universe



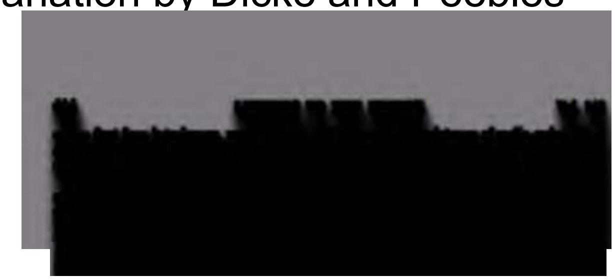
Cosmic Microwave Background

Discovery by Penzias and Wilson (1965)

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE
AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations (July, 1964–April, 1965). A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter in this issue.

Explanation by Dicke and Peebles



Thermal history in 1965

He abundance

[redacted]

He abundance

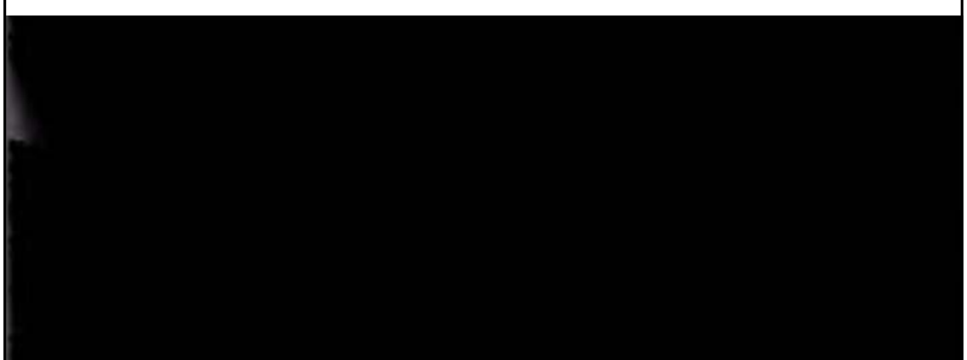
[redacted] eebles 1966

Fluctuations

Fluctuations

(Cold) Dark Matter

Matter/Baryon Density



Cosmological Constant