Observational Cosmology: Primordial nucleosynthesis and baryogenesis

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Nucleosynthesis and Baryogenesis

After these lectures, you should be able to:

- Outline the key factors that determine the primordial Helium abundance
- Comment on the expected abundances of the light elements
- Discuss the observed abundances of the light elements
- Describe their implications for the baryon density
- List the Sakharov conditions for baryogenesis
- Explain why they are required and how they might be achieved.

See also:

- Liddle Chapters 12, A4
- http://www.astro.ucla.edu/~wright/BBNS.html
- Kolb in Encyclopedia of Astronomy & Astrophysics, Murdin

Nucleosynthesis: Overview

- The formation of nuclei
  - mostly Helium
  - from protons and neutrons
  - first few minutes after Big Bang
- Universe cools such that photons can no longer dissociate nuclei
- Key questions:
  - How much of each element formed?
  - What determines this?
  - How can we observe it?

Nucleosynthesis

- The number of particles is given by the Maxwell-Boltzmann distribution:
- If the temperature is high the reactions go both ways and there is equilibrium
- As temperature lowers there is a tendency of one reaction to win.
- So we can write the relative number densities with the ratio of these equations:

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

$$n \rightarrow p + e^- + \bar{\nu}_e + 0.8MeV$$

$$\frac{N_n}{N_p} \propto \left(\frac{m_n}{m_p}\right)^{3/2} \exp\left(-\frac{(m_n - m_p)c^2}{k_B T}\right)$$

Nucleosynthesis

$$n + \nu_e \leftrightarrow p + e$$

- $k_B\,T \sim 0.8$ MeV
  - Only $n + \nu_e \rightarrow p + e$ so no new neutrons are formed
  - so $N_n/N_p \sim \exp(-1.3/0.8) \sim 1/5$

Neutrons decay, half life 600s

- $k_B\,T \sim 0.1$ MeV
  - $t \sim 400$ s : reverse reactions ($^4He \rightarrow n$) stop
  - $N_n/N_p \sim 1/5 \times \exp(-\ln 2 \times 400/600) \sim 1/8$
- All remaining neutrons $\rightarrow$ ^4He

$$Y_{He} = 2\,N_n / (N_n + N_p) \sim 0.22$$

- This assumes all other reactions = 0.

$$p + n \leftrightarrow D$$
$$D + p \leftrightarrow {}^3He$$
$$D + D \leftrightarrow {}^4He$$

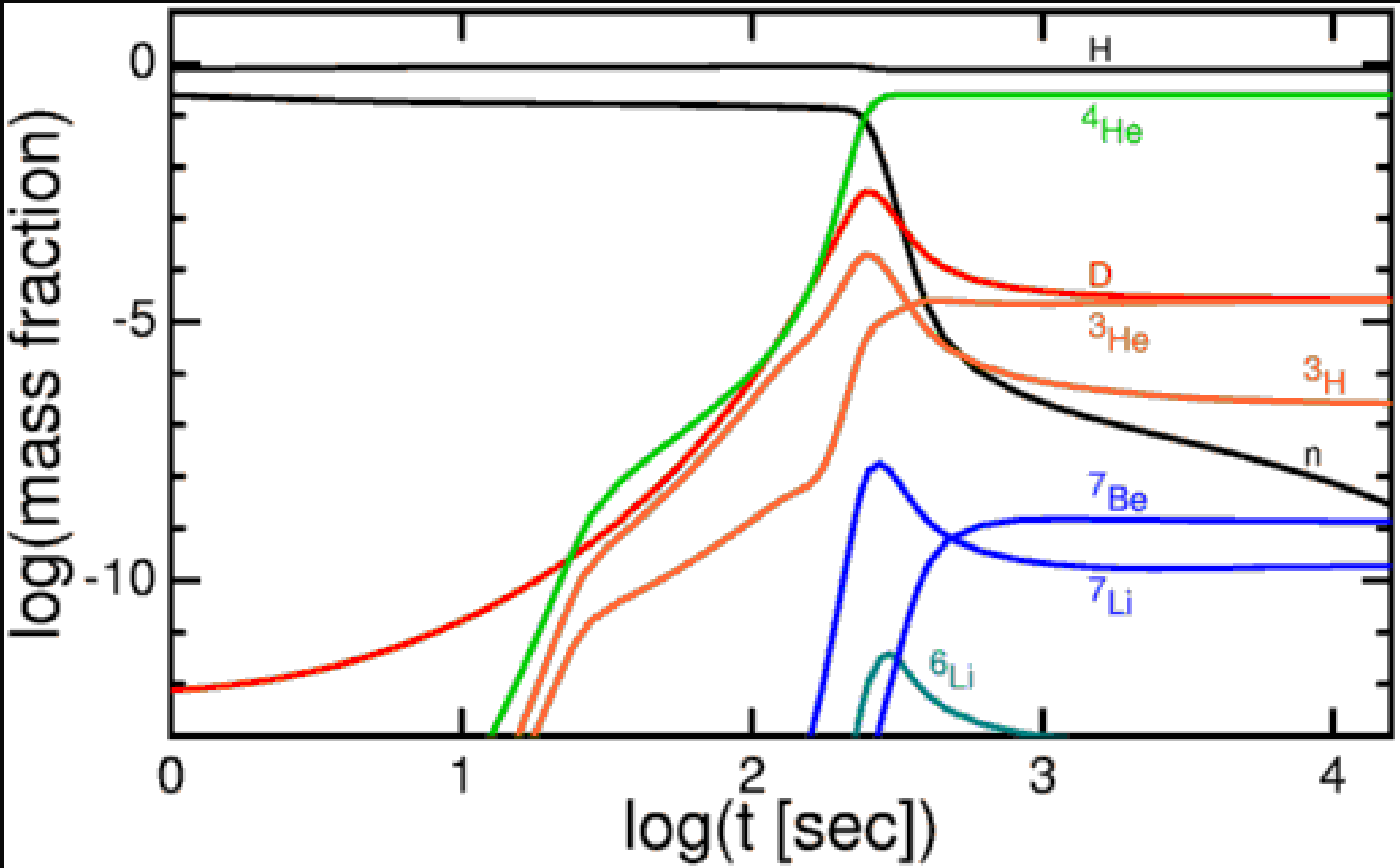
$Y_{He} = 2 N_n / (N_n + N_p) \sim 0.22$

- The mass of Helium is 4 times the mass of the neutron roughly.
- If all neutrons end up in helium 4 then the number of helium 4 particles is half the number of neutrons.
- Therefore

$$Y_4 = \frac{4N_{He}}{N_n + N_p}$$

- So:

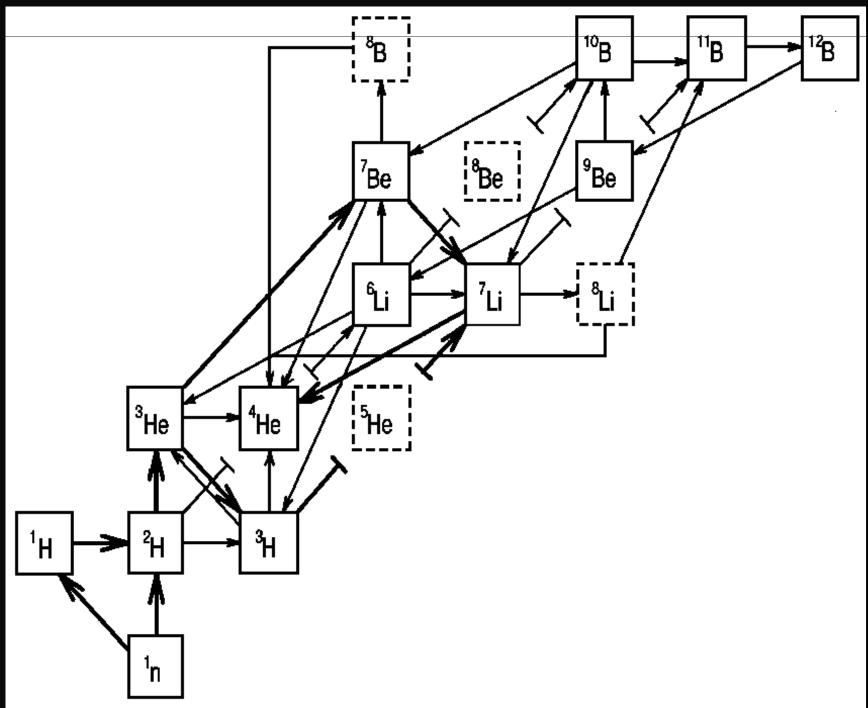
$$Y_4 = \frac{2}{1 + N_p/N_n} \sim 0.22$$



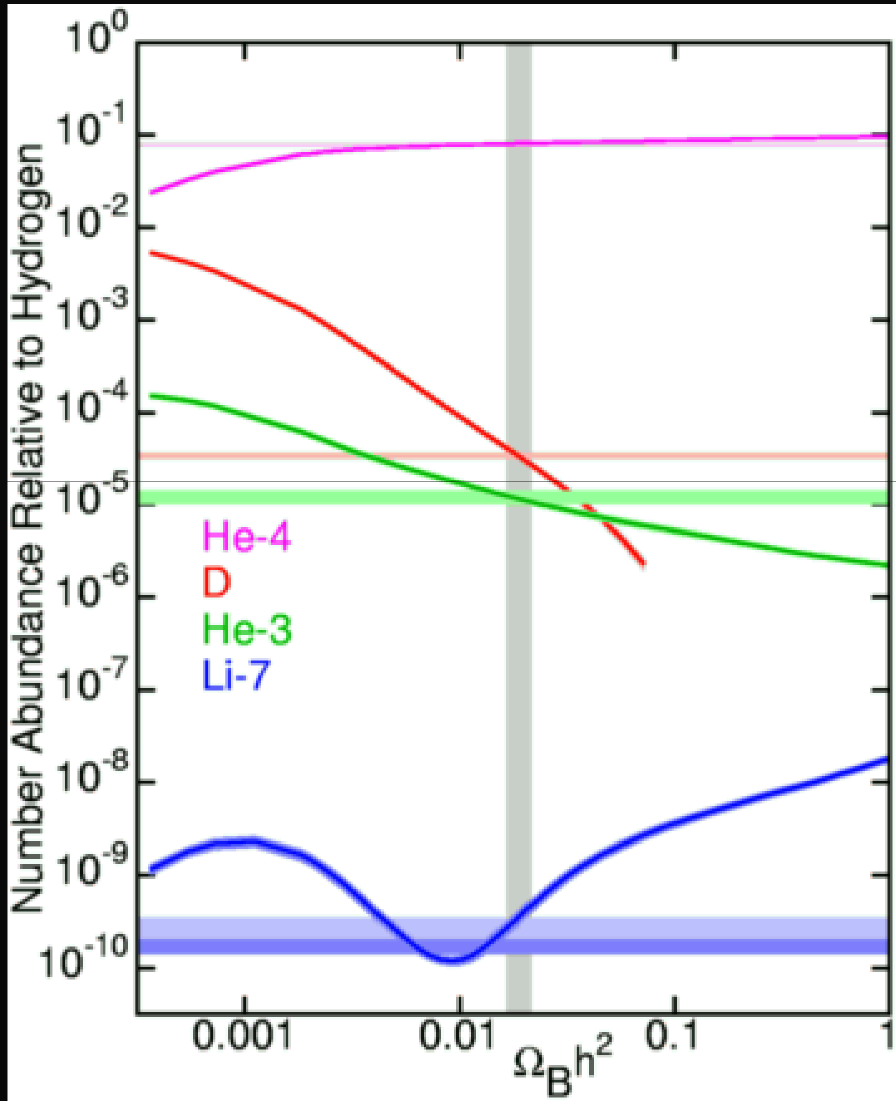
http://www.astro.ucla.edu/~wright/BBNS.html, based on data from Burles, Nollett & Turner (1999)

Effect of baryon density

- Recall chemistry:
  - Reaction rate ∝ density
- Rate of conversion from n to 4He depends on baryon density



http://www.physics.ohio-state.edu/~phillips/bang/bang.html



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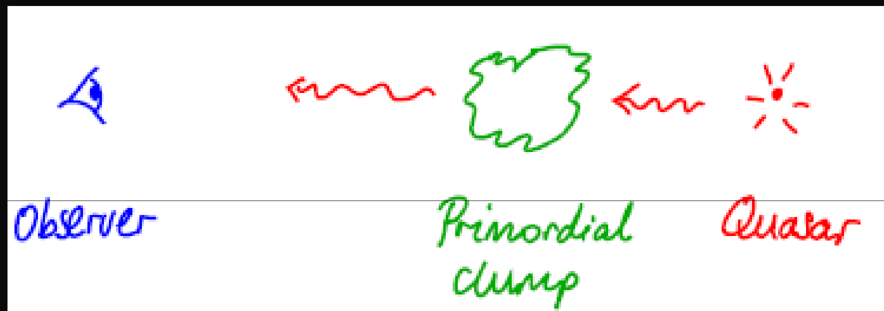
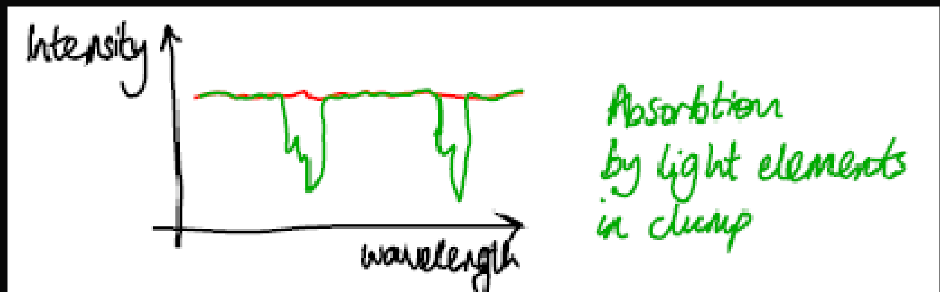
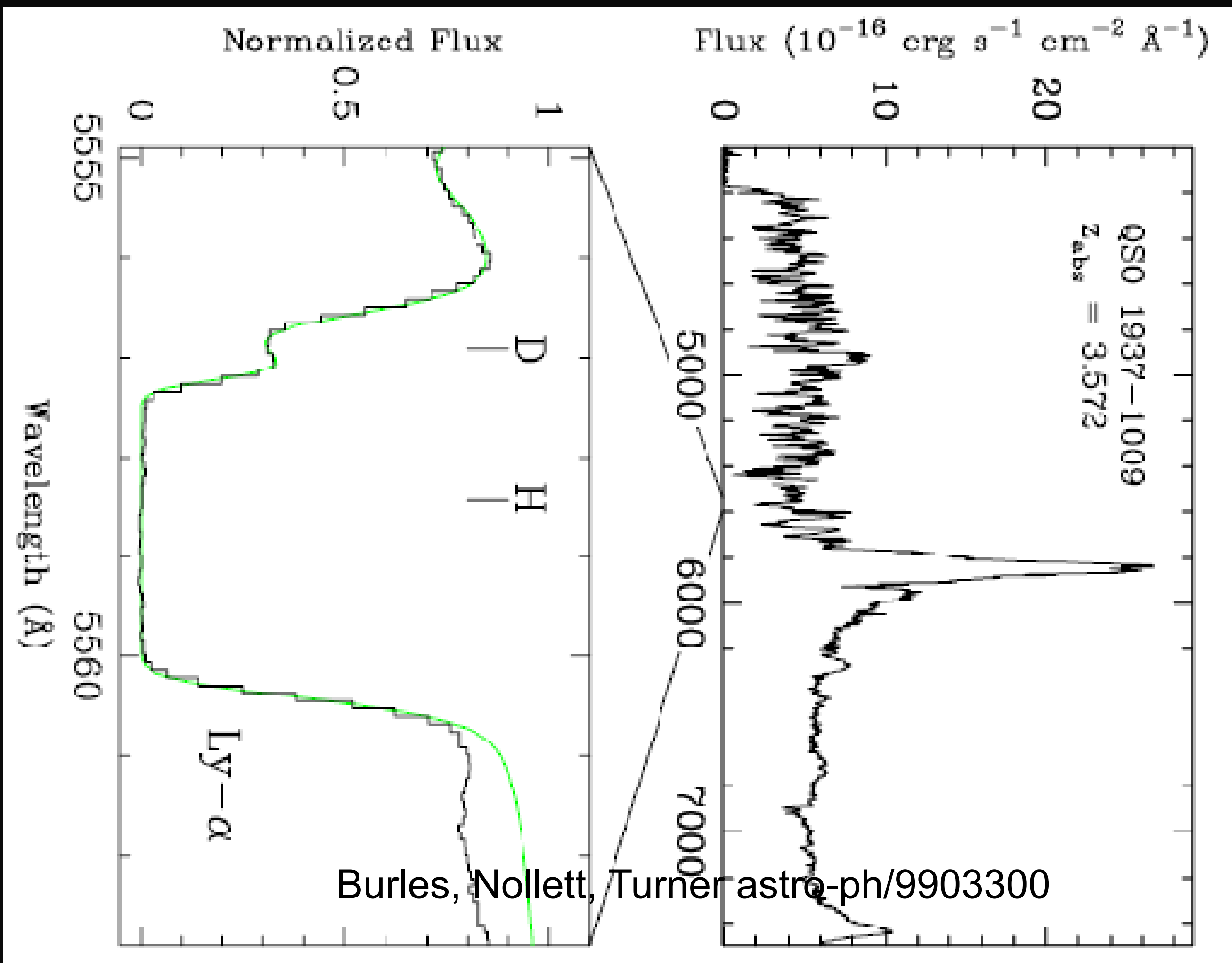
Observations of the abundance of the light elements

- Quasar spectra



- Measure absorption lines





Burles, Nollett, Turner astro-ph/9903300

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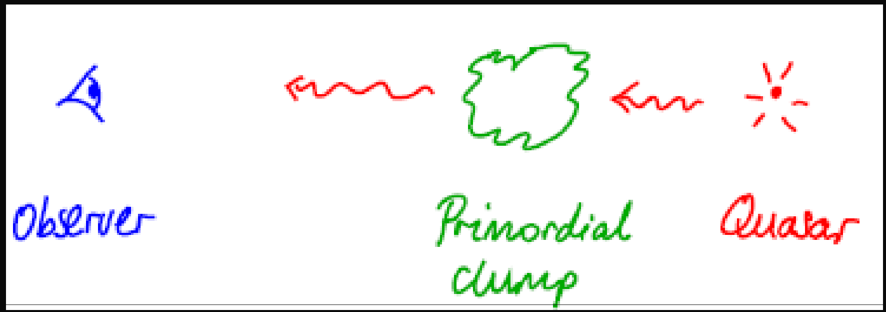
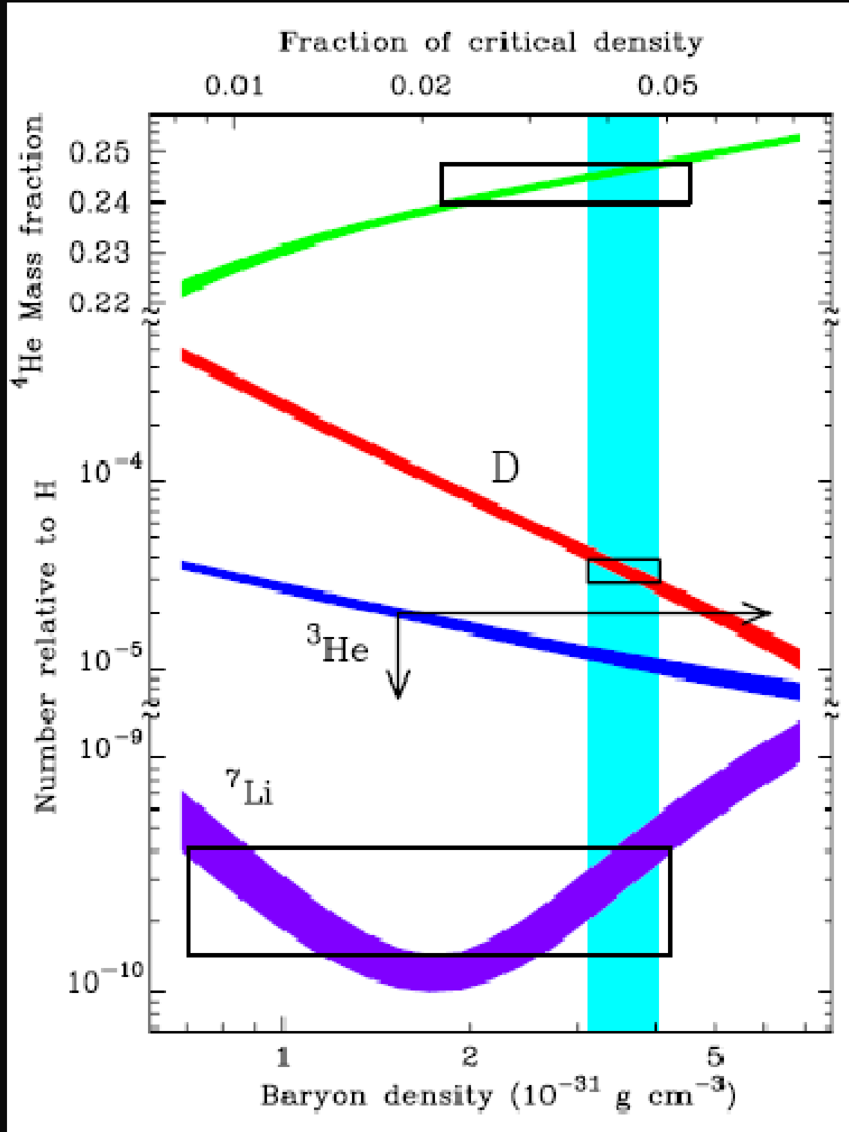


- Measure absorption lines

- Boxes indicate observations
  - Converting gives: $\Omega_b h^2 \sim 0.02$
  - For h=0.72 gives $\Omega_b = 0.04$



Burles, Nollett, Turner astro-ph/9903300

Baryogenesis

The creation of baryons.

- Every particle has an anti-particle
  - positron is antiparticle of electron
  - antiproton is antiparticle of proton
  - baryon number of particle = - baryon number of antiparticle

- Early Universe:
  - 1 billion antiprotons
  - 1billion +1 protons
  - Particle + antiparticle ↔ radiation

- 10^{13}K
  - Particle + antiparticle → radiation
- Universe today = mainly matter

Sakharov conditions

The conditions required for the creation of more matter than anti-matter (Sakharov 1967)

- Baryon number violation
  - Otherwise have same no. of particles and antiparticles
- C and CP violation
  - Parity of antiparticles is opposite to that of particles
- Departure from thermal equilibrium
  - Otherwise all reactions go both ways

Likelihood of Sakharov conditions

- Baryon number violation
  - Never been observed
  - Predicted to occur in several theories.
- C and CP violation
  - CP violation discovered in 1964 (Cronin and Fitch) in interactions of K-mesons (kaons)
- Departure from non-thermal equilibrium
  - Expansion of the Universe

Theories of baryogenesis

1. GUT baryogenesis
2. GUT baryog
3. Baryogenes
4. String scale
5. Affleck-Dine
6. Hybridized A
7. No-scale AD
8. Single field b
9. Electroweak
10. Local EW b
11. Non-local E
12. EW baryog

13. SUSY EW baryogenesis
14. String mediated EW
15. Baryoge
16. Inflation
17. Resonan
18. Spontan
19. Coheren
20. Gravitati
21. Defect m
22. Baryoge
23. Baryoge
24. Baryoge

25. Baryogenesis through collapse of vortons
26. Baryogenesis through axion domain walls
27. Baryogenesis through QCD domain walls
28. Baryogenesis through unstable domain walls
29. Baryogenesis from classical force
30. Baryogenesis from electrogenesis
31. B-ball baryoge
32. Baryogenesis
33. Baryogenesis
34. Baryogenesis
35. Mesoscale bary
36. Axino induced

37. Gravitino induced baryogenesis
38. Radion induced baryogenesis
39. Baryogenesis in large extra dimensions
40. Baryogenesis by brane collision
41. Baryogenesis via density fluctuations
42. Baryogenesis from hadronic jets

http://www.desy.de/desy-th/workshop2004/data/Shaposhnikov.pdf Shaposhnikov DESY 2004

END for now!!!