Cosmology W13

Lecture 8: February 11 2013

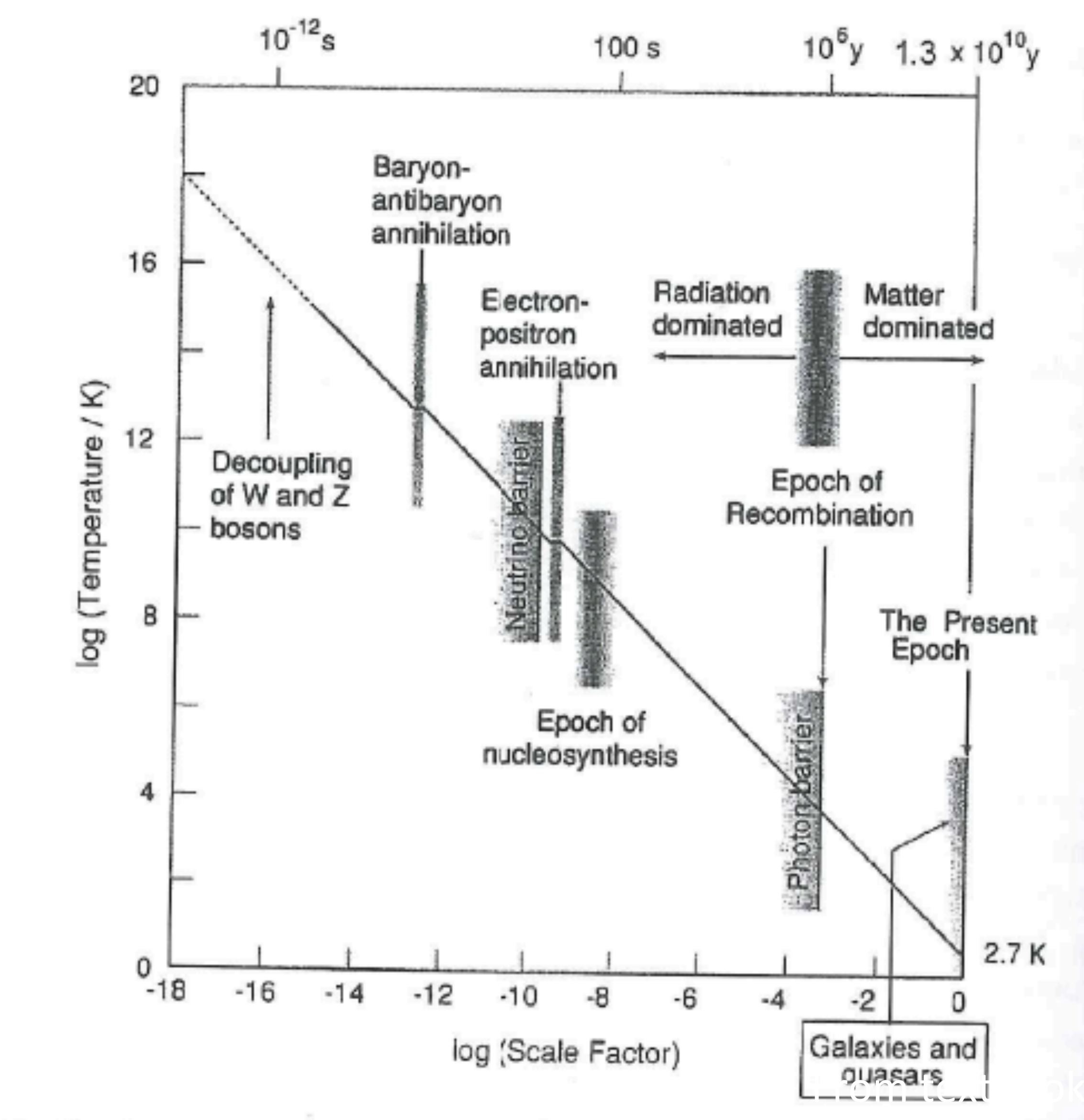
The first few minutes

- General considerations in the limit $KT>>mc^2$
- Neutrino abundance and decoupling (1s 1MeV ~10^{10} K)
- Electron positron annihilation
- Primordial nucleosynthesis (100s 0.1Mev 10^9 K)
- Measured abundances
- Particle freeze out
- Baryons and antibaryons

Key concepts

- Entropy density is conserved
- Particles are in equilibrium with each other as long as interaction rate Γ is > H
  - Their abundance is given by thermal distributions
- When Γ<<H particles freeze out and they decouple from others. If they are frozen n ~1/V

Basic thermal history



From textbook

Basic Thermodynamics Recap

- Relativistic case (KT>>mc^2; kT>>μ)

$$n_b = \frac{g\zeta(3)}{\pi^2}\left(\frac{2\pi kT}{hc}\right)^3 \qquad [BOSE]$$

$$n_f = \frac{3}{4}\frac{g\zeta(3)}{\pi^2}\left(\frac{2\pi kT}{hc}\right)^3 \qquad [FERMI]$$

Neutrinos-electrons-photons

- Relativistic case (KT>>mc^2; kT>>μ)

$$\text{photons} \quad g = 2 \quad \epsilon = aT^4$$

$$\text{electrons} - \text{positrons} \quad g = 2 \quad \epsilon = \frac{7}{8} aT^4$$

$$\text{neutrinos} - \text{antineutrino} \quad g = 1 \quad \epsilon = \frac{7}{16} aT^4$$

When they are all in equilibrium

$$\epsilon = \chi a T^4$$

$$\chi = 1 + 2 \times \frac{7}{8} + 2N_\nu \times \frac{7}{16}$$

$$\epsilon = \frac{3c^2}{32\pi G} t^{-2}$$

$$T = \left(\frac{3c^2}{32\pi G \chi a} \right)^{\frac{1}{4}} t^{-\frac{1}{2}}$$

But neutrino interactions are weak!

$$\Gamma = \sigma_{\mathrm{weak}} n c$$

$$\sigma_{\mathrm{weak}} = \approx 10^{-49} (E/mc^2)^2 m^2$$

$$\Gamma \propto T^5$$

$$H = \frac{\dot{a}}{a} = \left(\frac{8\pi G \epsilon}{3c^2} \right)^{\frac{1}{2}} \propto T^2$$

By t~1s and KT~1Mev neutrino decouple

Soon after… kT~0.5MeV

- Pair production is suppressed:
    - e-e+annhilate and mostly disappear
- Entropy associated with electron positrons is deposited in to the CMB increasing its temperature [blackboard]
- Temperature of CMB higher than that of neutrino background
- Energy density after that time is

$$\epsilon = aT_{\mathrm{CMB}}^4 + 3 \times \frac{7}{8} aT_\nu^4 = 1.68 aT_{\mathrm{CMB}}^4$$

More or less at the same time…

- Rate of weak interactions governing balance between neutron protons and neutrinos falls below H
- Ratio p/n is given by Boltzmann equation with T of CMB [kT<<mc^2]

$$n/p = e^{-\frac{m_n c^2 - m_p c^2}{kT}}$$

$$kT\ 1MeV \rightarrow n/(n+p) \approx 0.21$$

- Then neturons start to decay… but slowly ~1000s

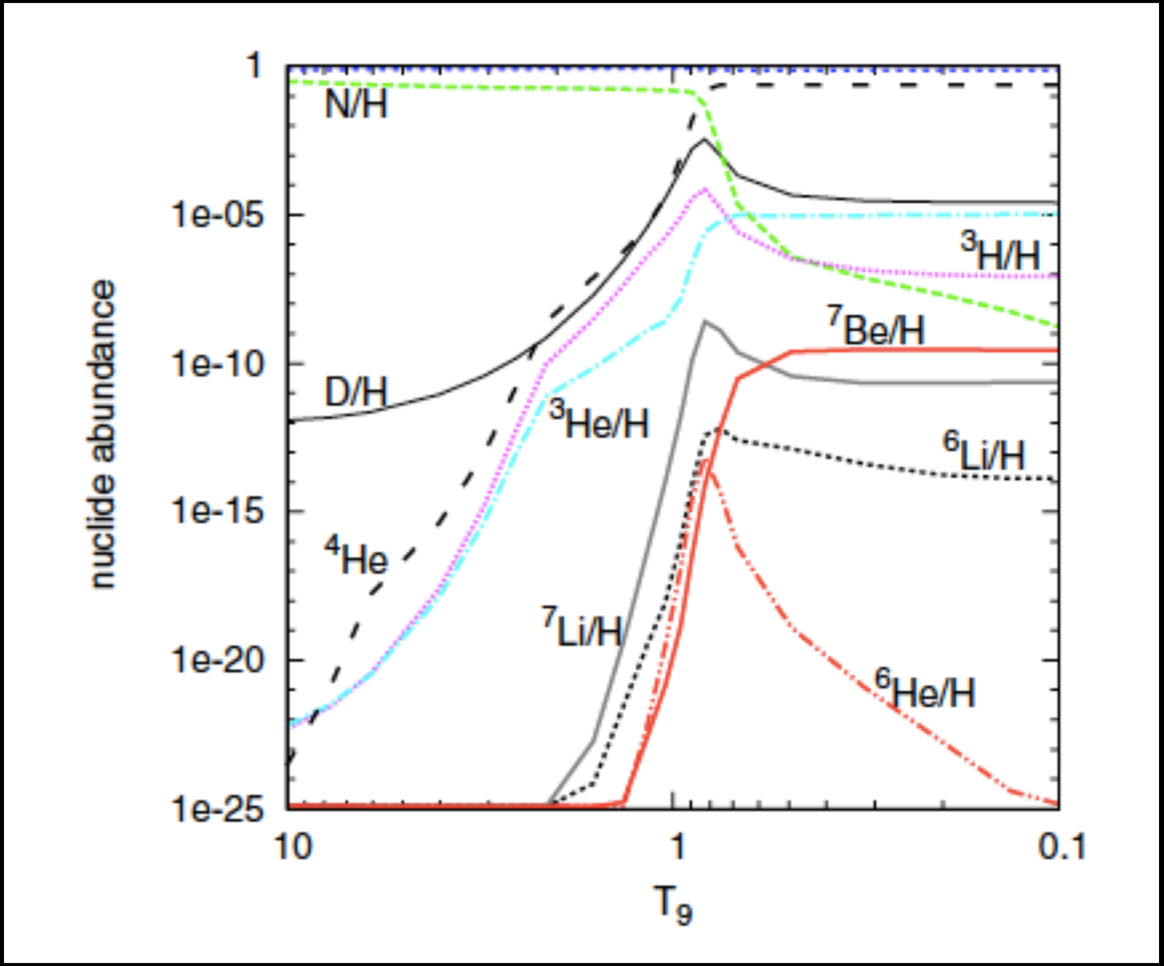
And nucleosynthesis starts..

- As soon as p+n->D+gamma starts tilting toward D
- Very similar to recombination calculation
- There are lots of photons so the high energy tail is sufficient to destroy D even if they kT<binding energy of D~2MeV
- Only when kT~0.1 Mev you have enough D to start chain of nucleosynthesis [Blackboard]

Key concepts

- Coulomb barrier stops chain at light elements
- He^4 is stable
  - He abundance is given by n/p ratio with correction for decay. He/H+He~2n/(e+p)=0.24
- Reactions involving He^3 and D are slow "bottleneck"
  - Increasing baryon density -> reduces abundance of He^3 and D
- Tritium decays with timescale of years

Recent calculations

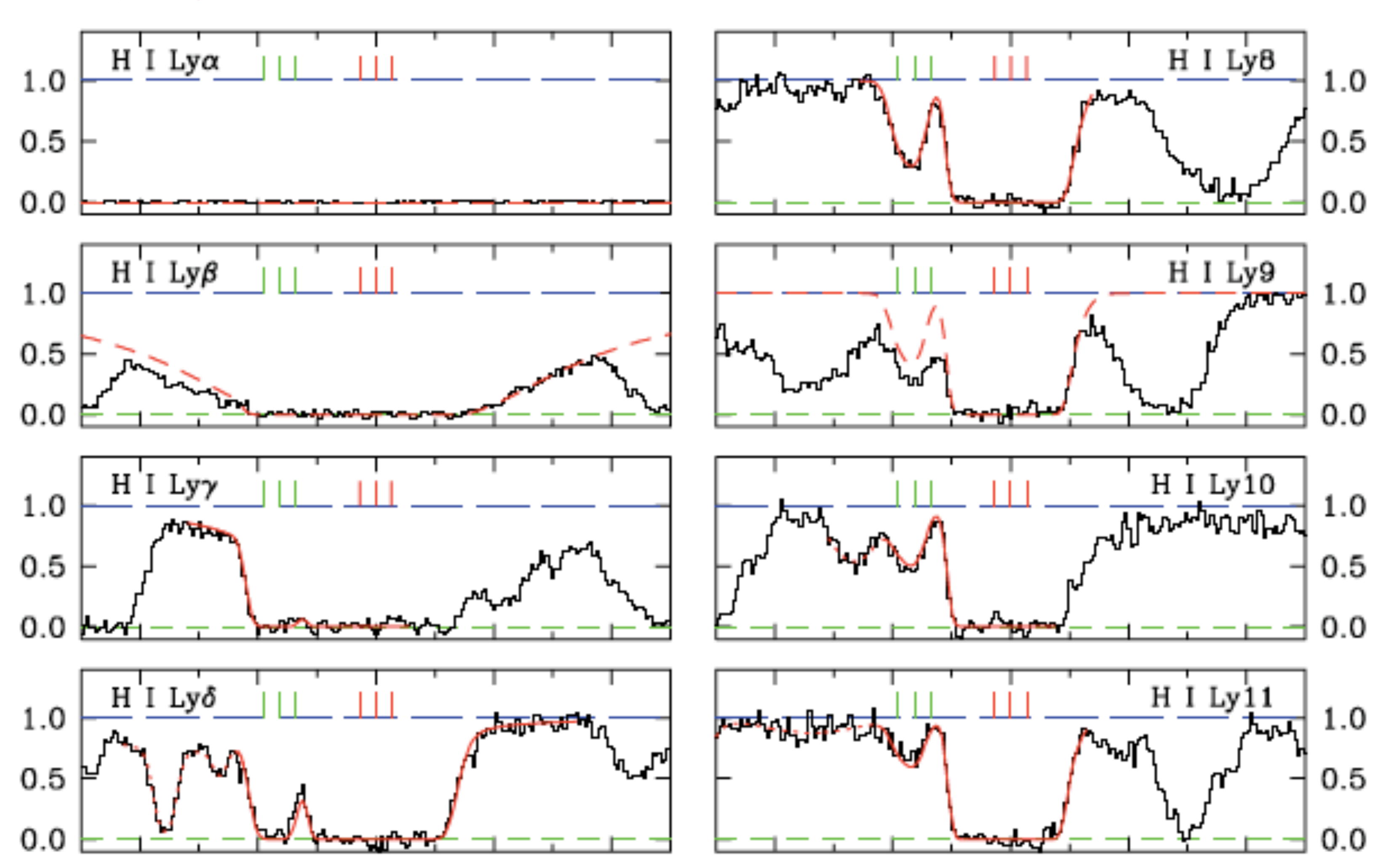


Boyd et al. 2010, PRD, 82, 105005

Measuring BBN: the deuterium case

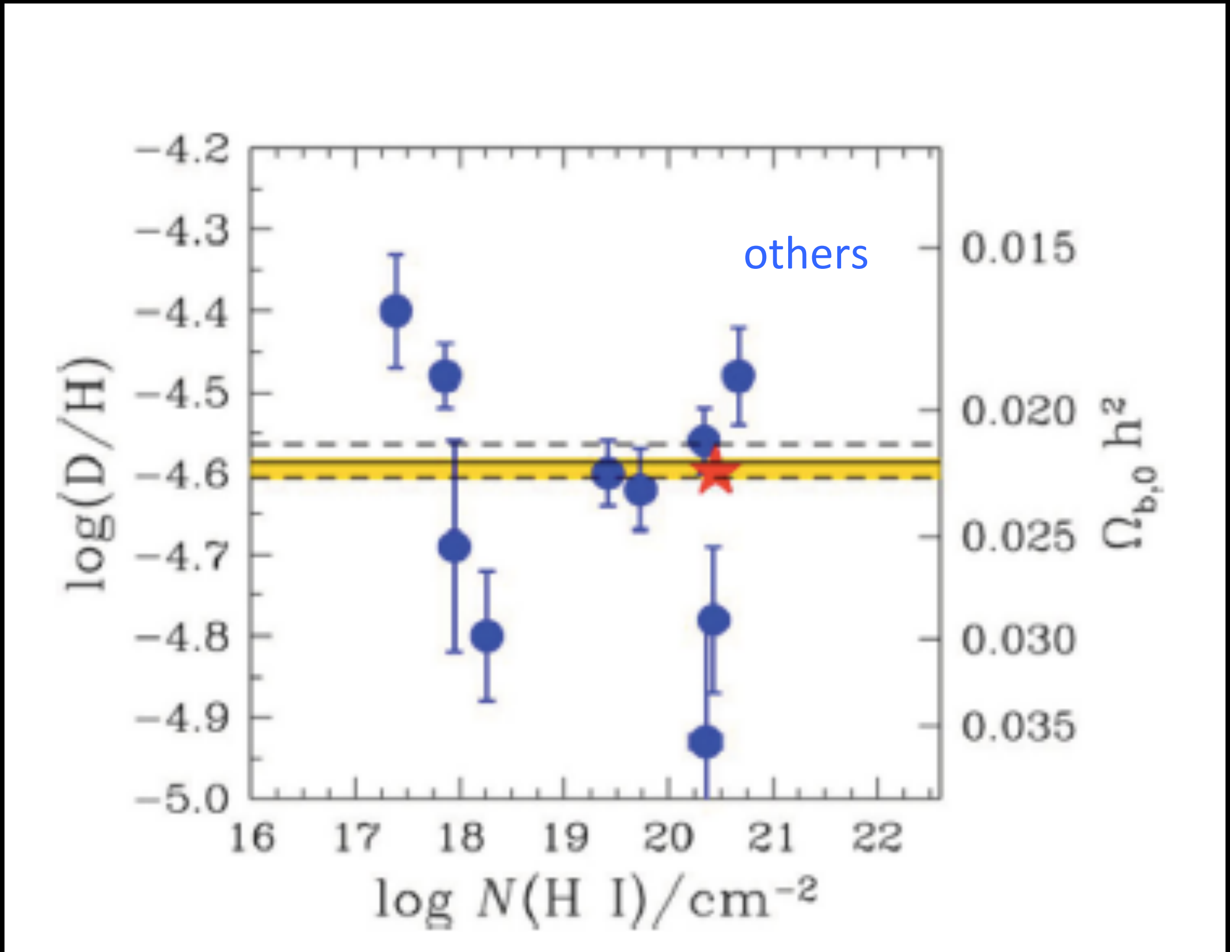
Pettini & Cooke 2012, MNRAS, 425, 247

Hydrogen Deuterium



D should only be destriyed by stars, so high-z is important

Measuring BBN: the deuterium case

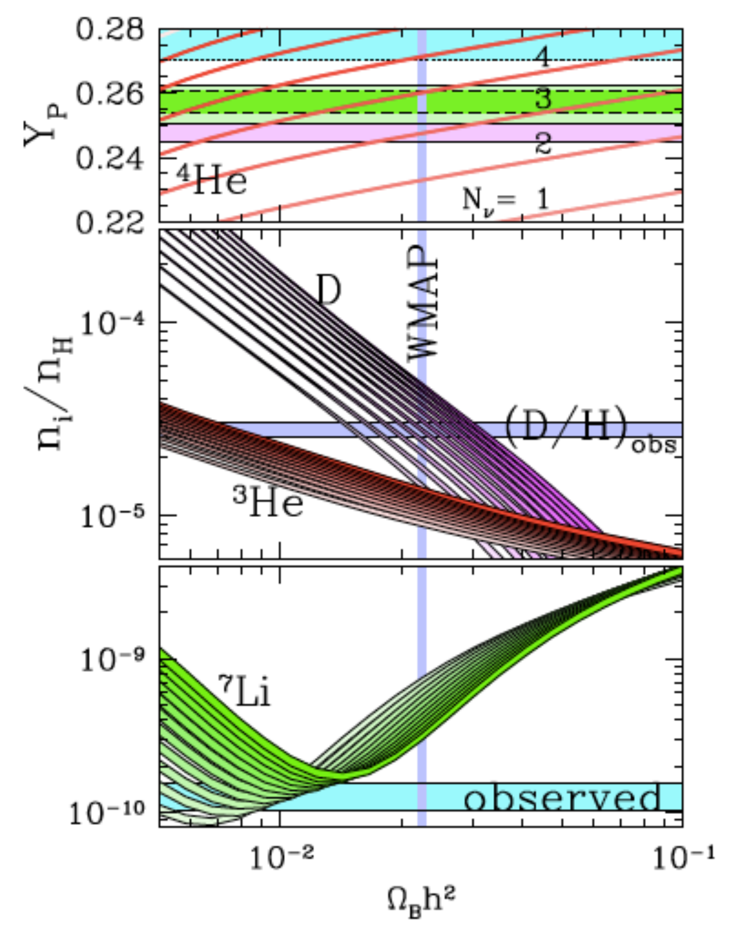


CMB

others

Pettini & Cooke 2012, MNRAS, 425, 2477

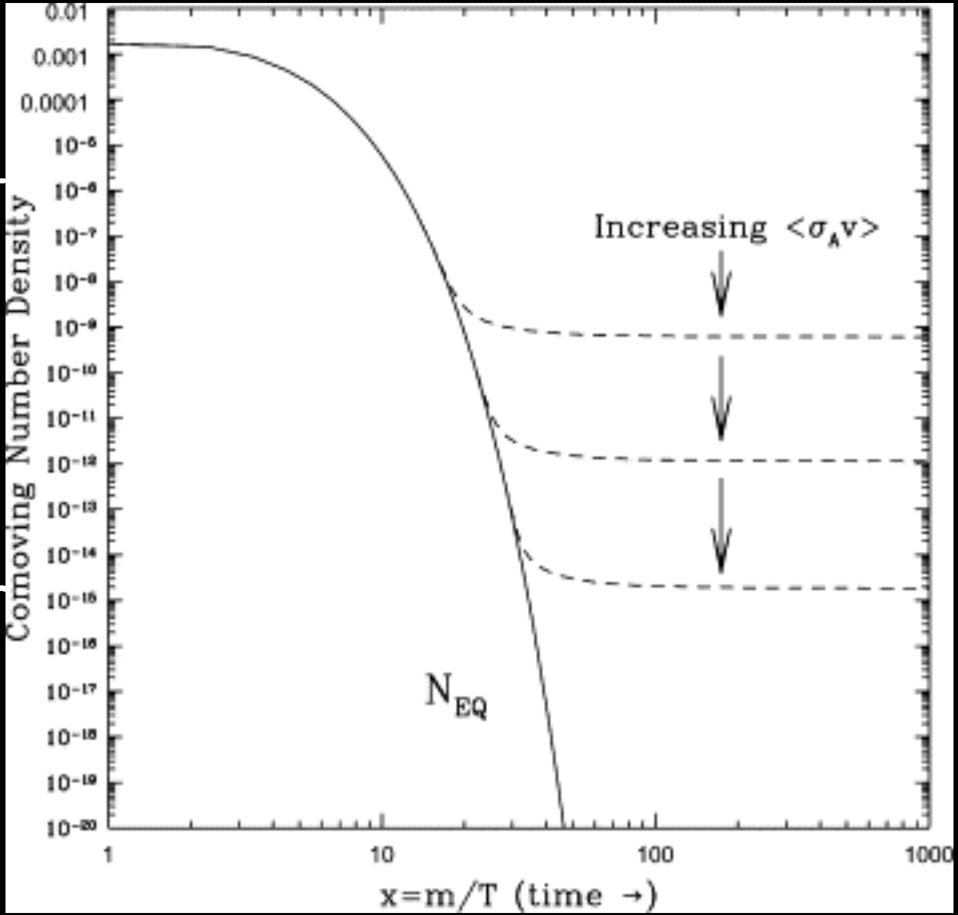
Using BBN to infer physics



Nollett & Holder 2011, arXiv:1112.2683

Particle freeze-out

- If particles were in equilibrium with CMB once they become non-relativistic their abundance drops exponentially
- However, once they decouple, their number density is conserved
- Reaction rate sets abundance



Turner & Kolb 1990

The ineresting case of baryons

- Assume baryon symmetry: p+p- are present in equal number
- One can compute the expected abundance of them:
  - [blackboard]
- Present day abundance of p+ is much higher, no anti-p. What happened?

Freeze-out of hot thermal relics
The case of massive neutrinos

- Neutrino decouple when kT~1Mev>>neutrino mass
- Their abundance is set at decoupling

$$n_b = \frac{g\zeta(3)}{\pi^2}\left(\frac{2\pi kT}{hc}\right)^3 \qquad [BOSE]$$

$$n_f = \frac{3}{4}\frac{g\zeta(3)}{\pi^2}\left(\frac{2\pi kT}{hc}\right)^3 \qquad [FERMI]$$

- Then number is conserved. So we can compute exactly the abundance and mass density of neutrinos today. [blackboard]

The end