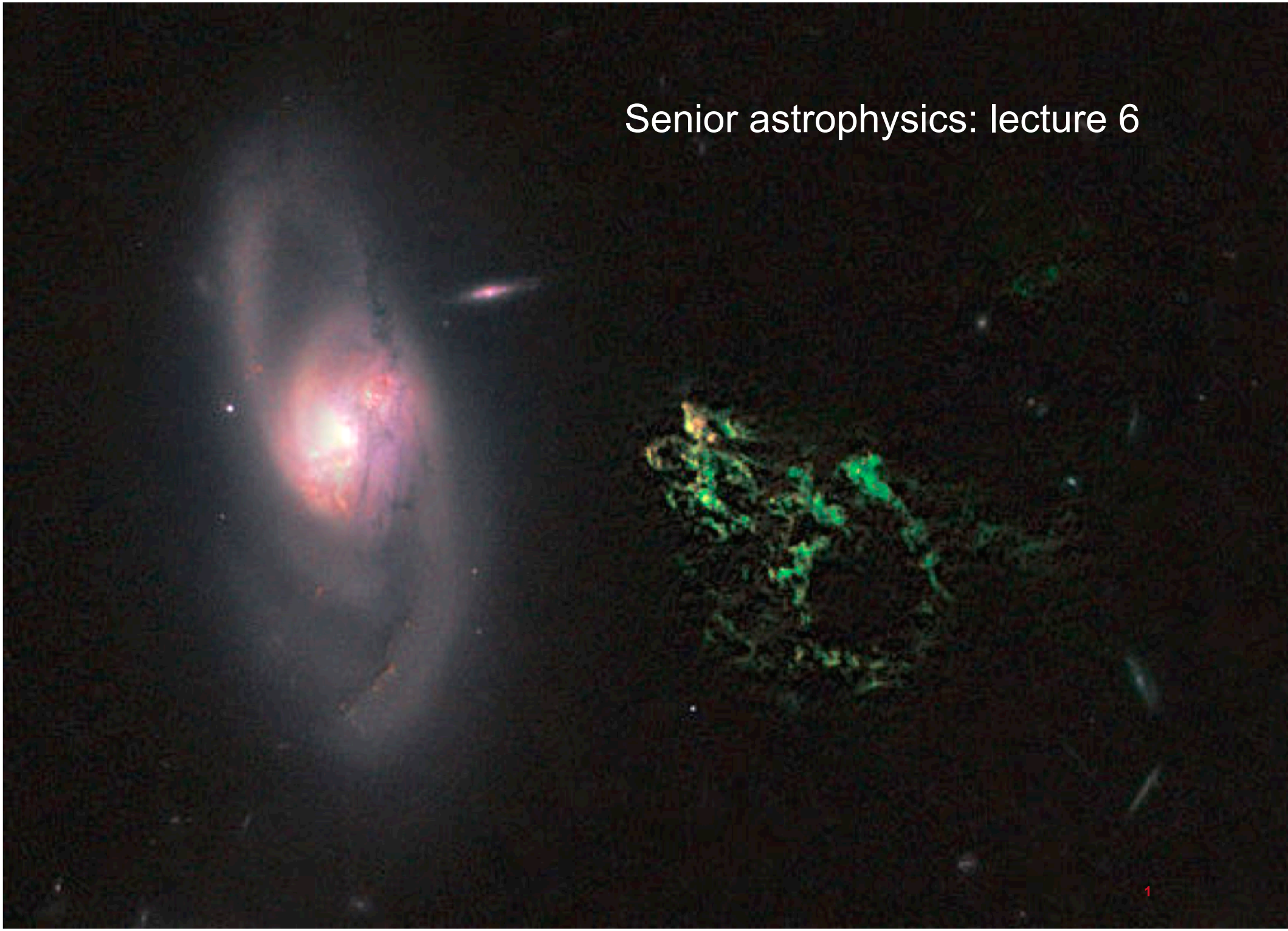
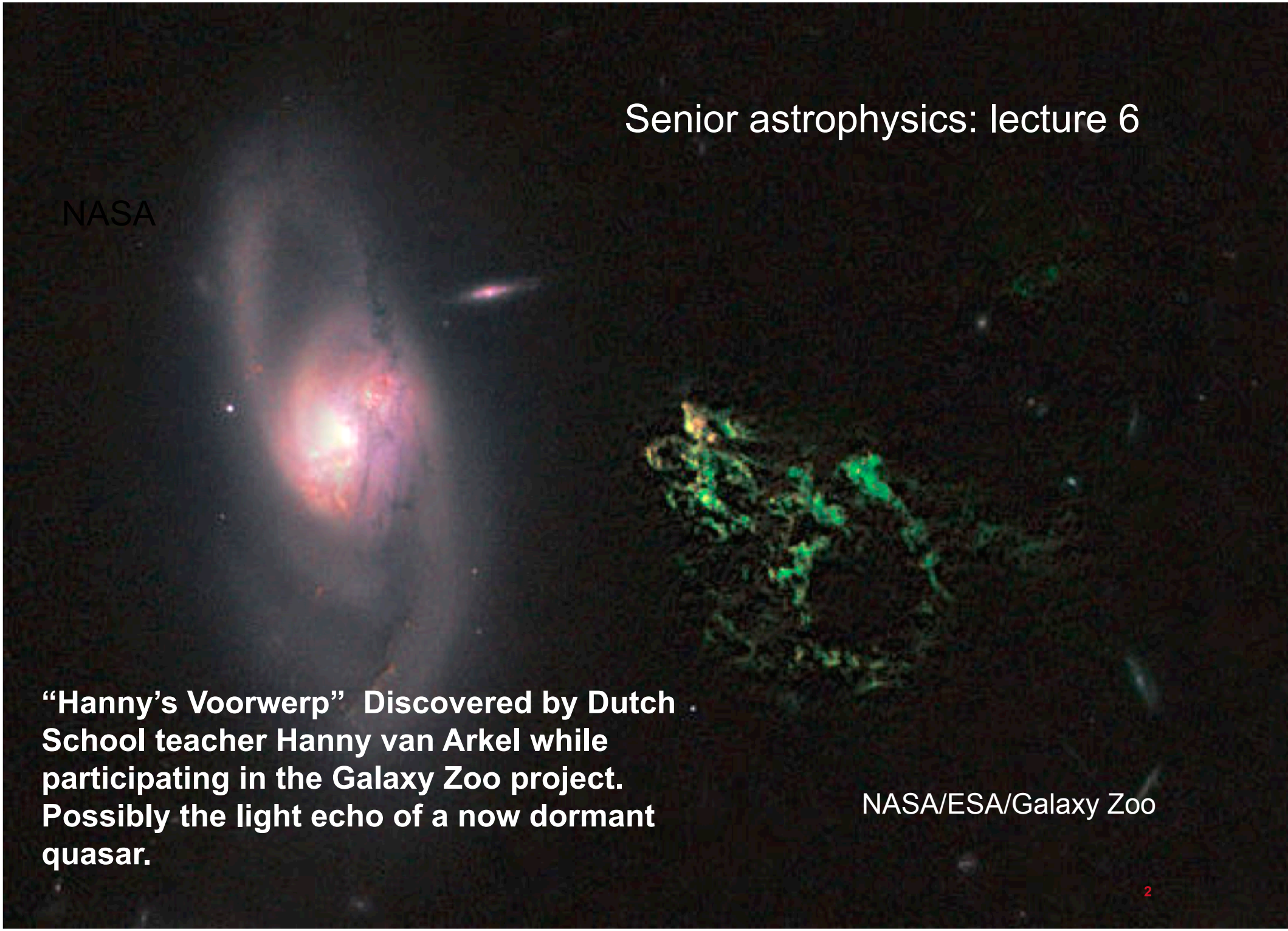

Senior astrophysics: lecture 6



Senior astrophysics: lecture 6

NASA

“Hanny’s Voorwerp” Discovered by Dutch School teacher Hanny van Arkel while participating in the Galaxy Zoo project. Possibly the light echo of a now dormant quasar.

NASA/ESA/Galaxy Zoo

Senior Astrophysics

- Scott Croom: scroom@physics.usyd.edu.au rm 561A
  - Lectures 1 to 9: Cosmology
  - 1st assignment given: 20th September, due 4th October
  - Lecture 9 ADV/REG split (6th Oct).

- Helen Johnston: helenj@physics.usyd.edu.au rm 563
  - Lecture 10 to 19: Stellar evolution and the end states of stars.
  - 2nd assignment given: 13th Oct, due 27th October
  - Lecture 19 ADV/REG split.

Lecture 6: The hot big bang

Revision from lecture 5: distances and the CMB

1. The Helium problem
2. Temperature evolution.
3. Phases in the early Universe
   - Quarks
   - Baryogenesis
4. Nucleosynthesis
5. Observed abundance

Wikipedia: Big bang Nucleosynthesis, big bang, baryogenesis

Books: Liddle: Ch 11, 12 + Adv. Topic 4

Revision: distance

- Comoving distance (d_c)
  - Distance between objects with respect to the expanding metric. I.e. expansion removed.
  - Normalized to now (a_0) so is the proper (physical) distance we could (in principle) measure with a ruler now.
- Luminosity distance (d_L)
  - Distance the photon feels it has travelled.
  - For calculating luminosities.
- Angular diameter distance (d_A)
  - Proper (physical) distance at time of photon emission.
  - For calculating the sizes of bound structures/objects.

$$d_c = a_0 r_1 = (1+z) d_A = \frac{d_L}{(1+z)}$$

- Useful calculators:
  - http://www.astro.ucla.edu/~wright/CosmoCalc.html
  - http://icosmos.co.uk/ - includes graphing facility

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Revision: distance

› In the most general case, we can find the comoving distance by solving:

$$\int_0^{r_1} \frac{dr}{[1-kr^2]^{1/2}} = \frac{c}{H_0 a_0} \int_0^{z} \frac{dz}{\sqrt{\Omega_m (1+z)^3 + \Omega_R (1+z)^4 + \Omega_k (1+z)^2 + \Omega_\Lambda}}$$

› For an Einstein-de Sitter Universe (flat, Ω_M=1, Ω_R=0, Ω_Λ=0):

$$d_c = r_1 a_0 = \frac{2c}{H_0}\left[1 - \frac{1}{(1+z)^{1/2}}\right]$$

› Can define a **Particle Horizon** for z -> infinity. In the EdS case:

$$d_H(t_0) = r(z=\infty)a_0 = \frac{2c}{H_0} = 3ct_0 \text{ and at any time } d_H(t) = r(z=\infty)a(t) = 3ct$$

Proper horizon!!! (=comoving horizon at t_0)

Revision: distance

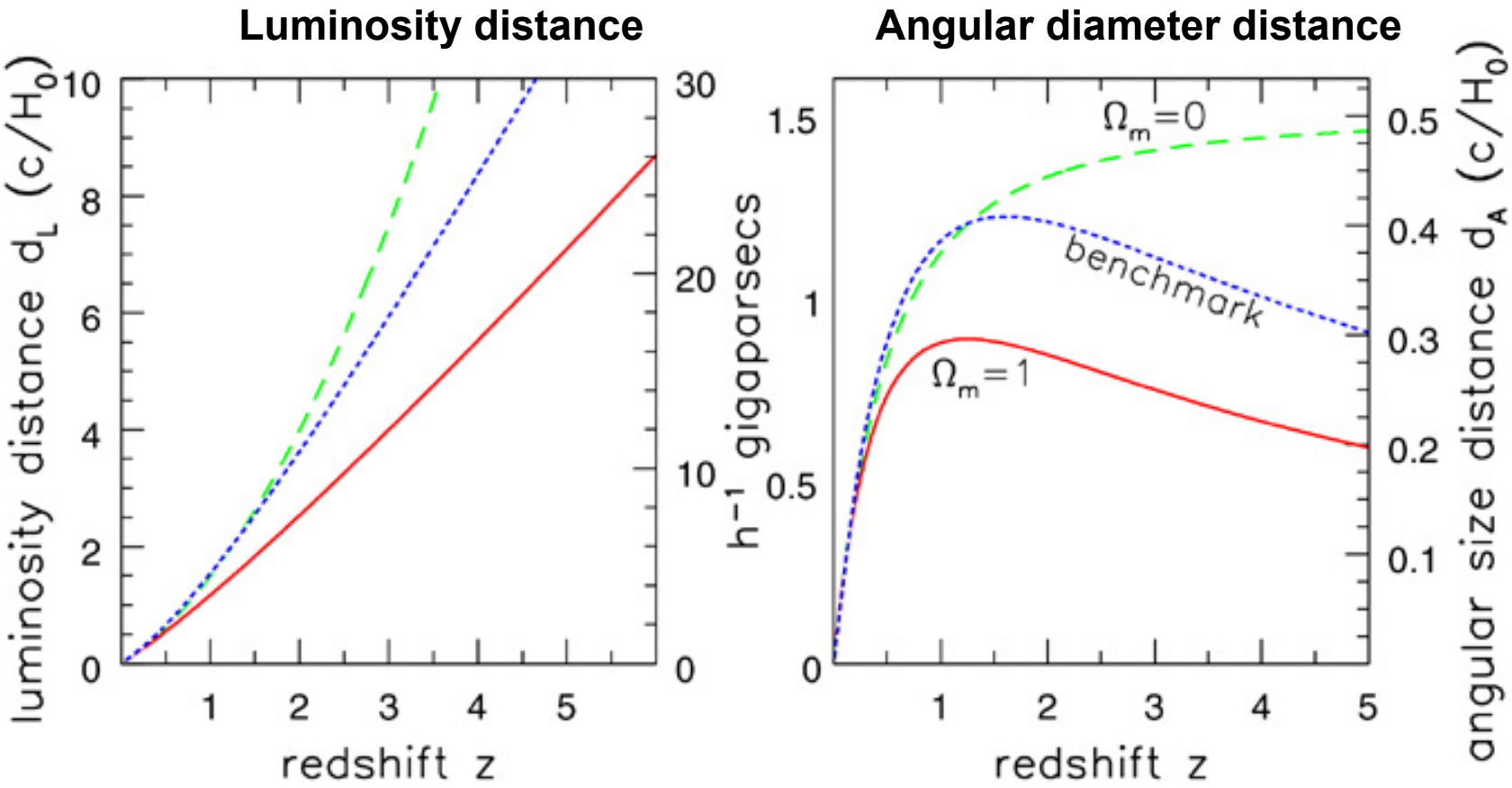


Fig 8.11 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Example flat Universes. Benchmark: Ω_m=0.3, Ω_Λ=0.7 (currently preferred model).

Revision: cosmic microwave background

- Black body integrated energy density is

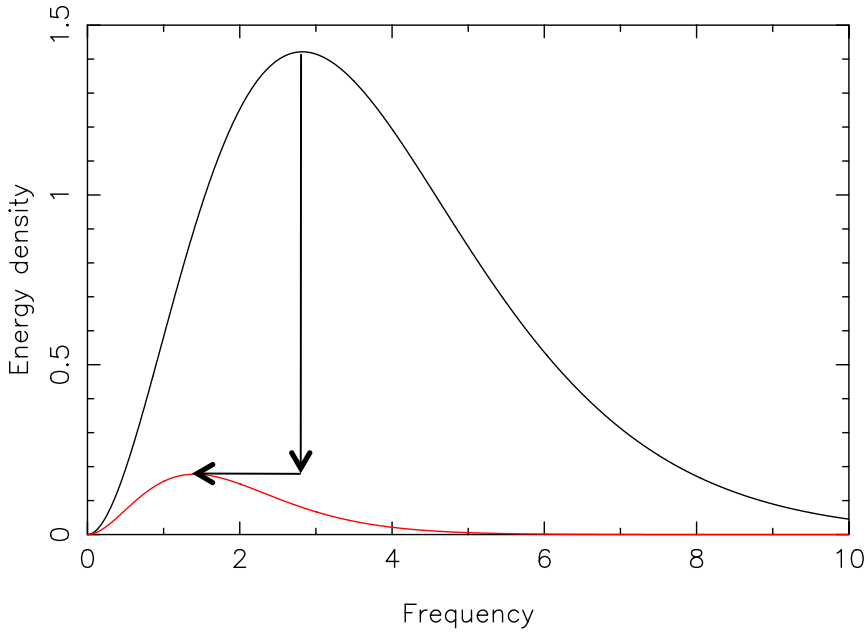
$$\rho_{rad} c^2 = \varepsilon_{rad} = \alpha T^4$$

but ρ_{rad} evolves as

$$\rho_{rad} \propto \frac{1}{a^4}$$

so $$\boxed{T \propto \frac{1}{a}}$$

- BB spectrum maintains its shape as T changes.



$$\varepsilon_\nu d\nu = \frac{8\pi h}{c^3} \frac{\nu^3}{\exp(h\nu / k_B T) - 1} d\nu$$

with expansion: $\mathrm{T} \downarrow \propto \nu \downarrow$

Shape dependent on exponential term only

i.e., $\varepsilon_{\nu_1} d\nu_1 = a^4 \varepsilon_{\nu_o} d\nu_o$

if a is the expansion factor between ν_1 and ν_0

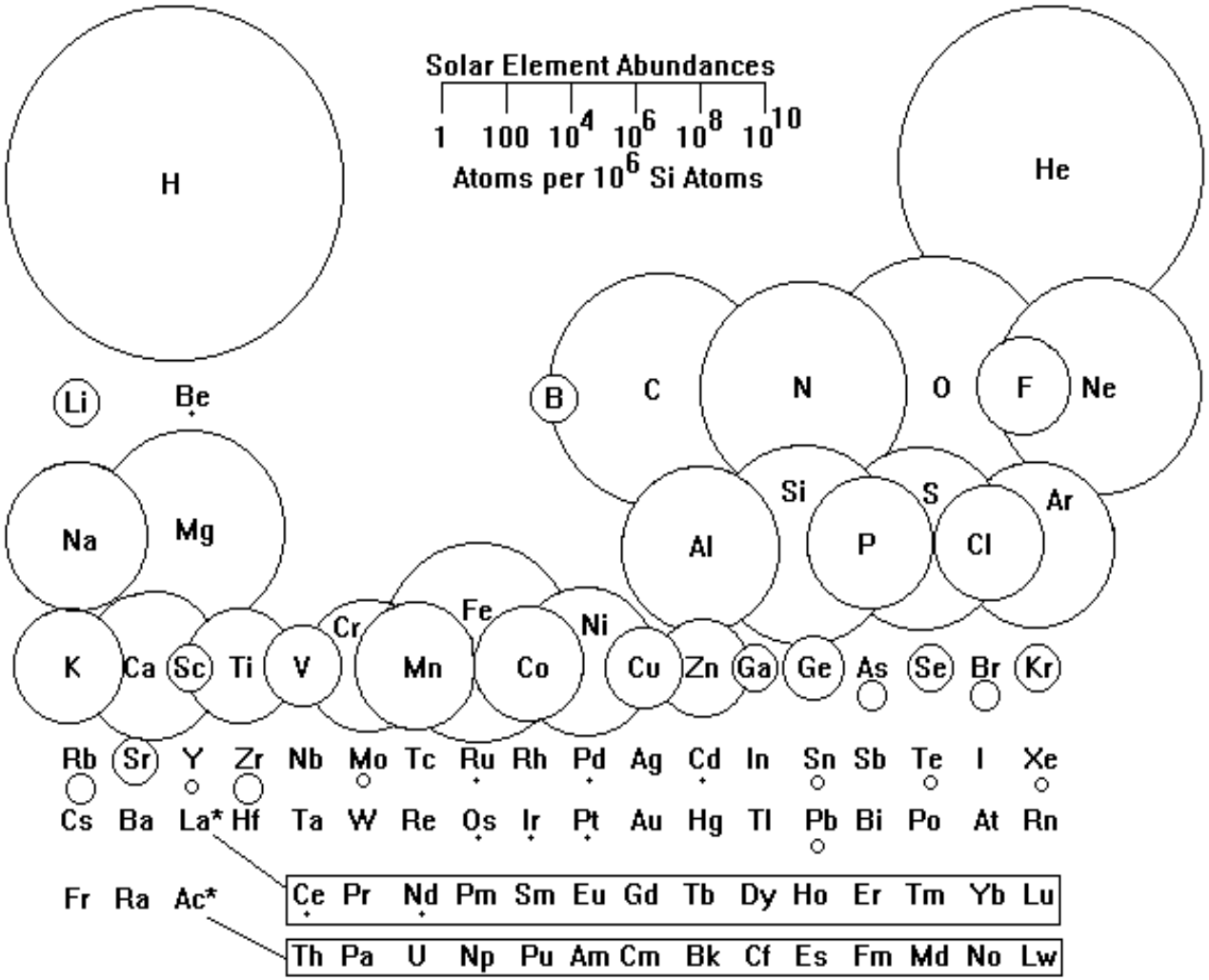
Revision: cosmic microwave background

- At early time Universe is hot and ionized.
- As the Universe cools, the electrons and protons will eventually be able to form stable atoms.
- CMB photons free stream from this point of ***decoupling*** or ***"recombination"*** to us.
- As the photon-to-baryon ratio is so high ~10^9, a temperature much cooler than the ionization temperature of hydrogen will maintain ionization.
- Decoupling finally occurs at $T \approx 3000K$
- What redshift is this?

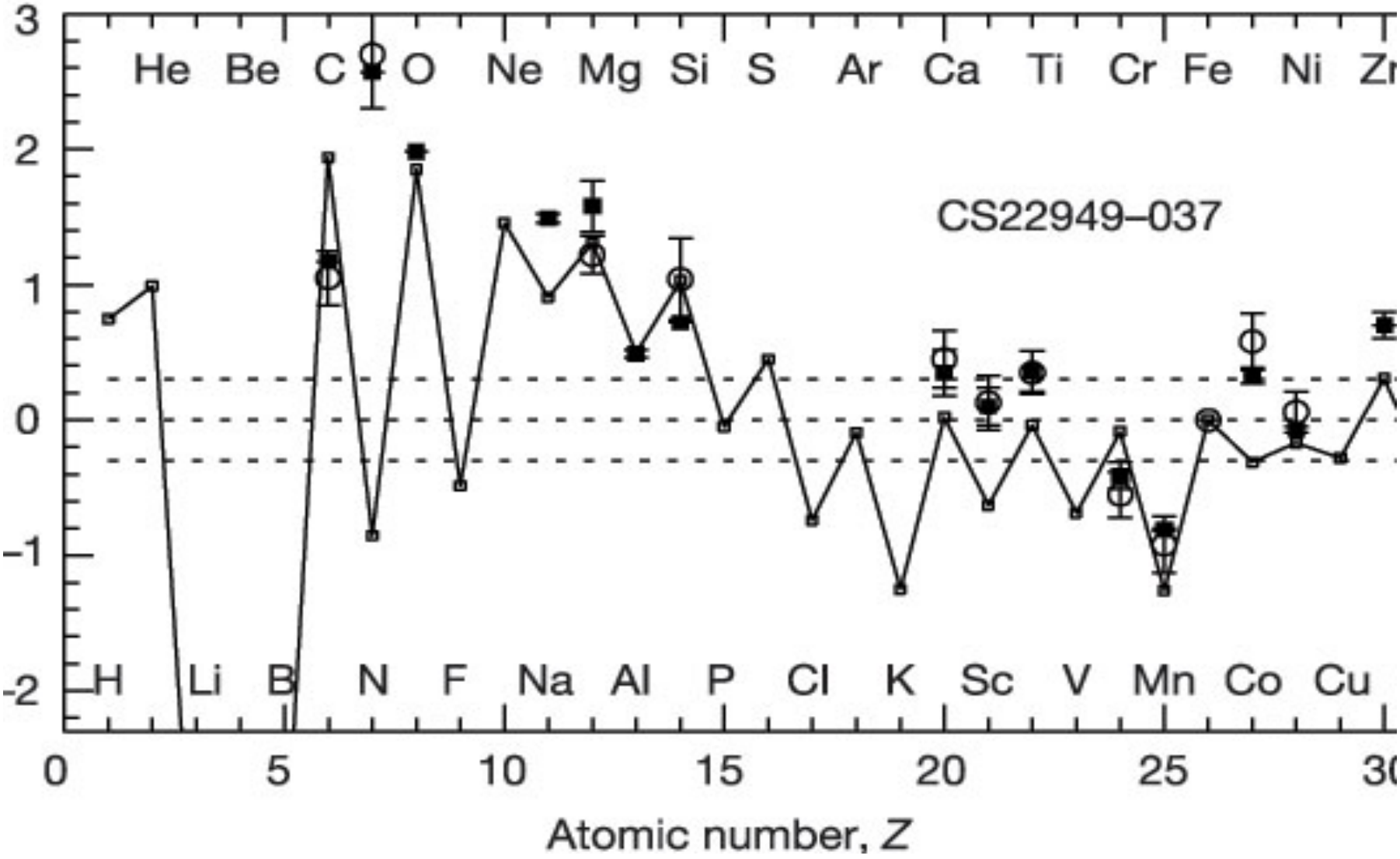
$$\frac{T}{T_0} \approx \frac{3000}{2.725} = \frac{a_0}{a} = (1+z)$$

$$\Rightarrow z_{dec} = 1100$$

6.1 The helium problem

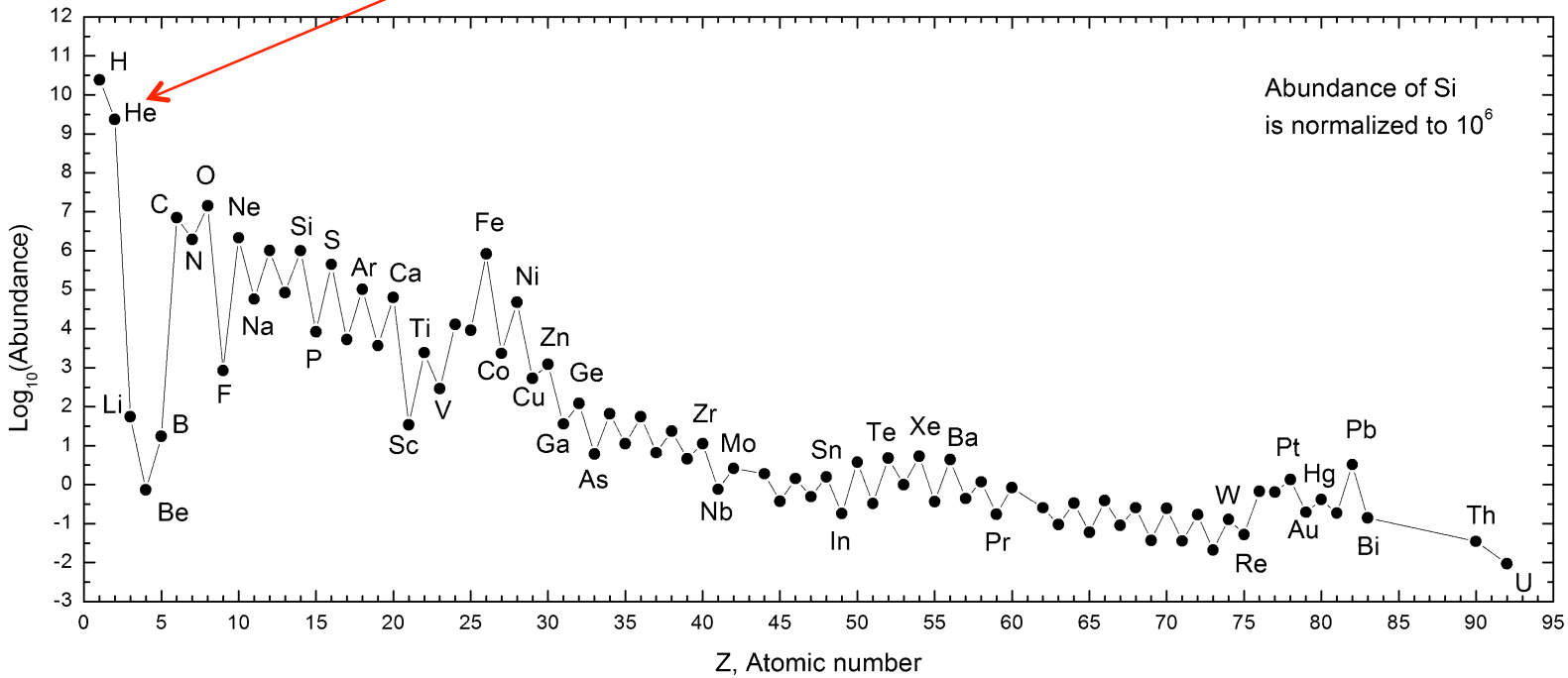


6.1 Yield from Supernovae



6.1 Abundances in the Solar System

Very high Helium abundance
not expected via stellar nucleosynthesis



6.2 Temperature evolution

- The very early Universe is dominated by photons, as their energy density scales as $1/a^4$.

$$a \propto t^{1/2} \quad \Rightarrow \quad \rho_{rad} \propto t^{-2}$$

- Radiation drives the dynamics and Temperature increases towards the big bang:

$$T \propto \rho_{rad}{}^{1/4} \propto a^{-1} \propto t^{-1/2}$$

- When do photons take over?

$$\frac{\Omega_{rel}(a)}{\Omega_m(a)} = \frac{4.15 \times 10^{-5}}{\Omega_{0,m} h^2} \frac{1}{a}$$

$$\Rightarrow a_{eq} = \frac{1}{24000 \Omega_{0,m} h^2} \approx \frac{1}{3500}$$

$$\Rightarrow z_{eq} \approx 3500 \text{ for } \Omega_{0,m} = 0.3, \ h = 0.7$$

Can then show $t_{eq} \approx 60{,}000\, yrs$ (try this...)

6.2 Temperature evolution

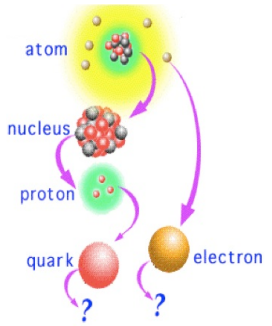
Running the clock backwards:

- Radiation-matter coupling (i.e., ionized) **$t\sim10^{13}$s, T~3000K**
- Radiation starts to dominate dynamics **$t\sim10^{12}$s, T~10^4K**
- Nuclei split apart (D=2Mev, ^{4}He=28MeV) **t~1s, T~10^{10}K**
- Neutrons/protons → Quarks **$t\sim10^{-4}$s, T~10^{12}K**
- Electro-weak symmetry breaking **$t\sim10^{-11}$s, T~10^{14}K**
- GUT scale: strong-weak symmetry breaking **$t\sim10^{-35}$s, T~10^{28}K**

Temperature Increasing, time decreasing

- Smallest time we can contemplate is the Planck time:

$$t_{pl} = \sqrt{\frac{hG}{2\pi c^5}} = 5.39\times10^{-44}\,s \quad \Rightarrow \quad T \approx 10^{32}\,K$$



6.3 Phases in the early Universe

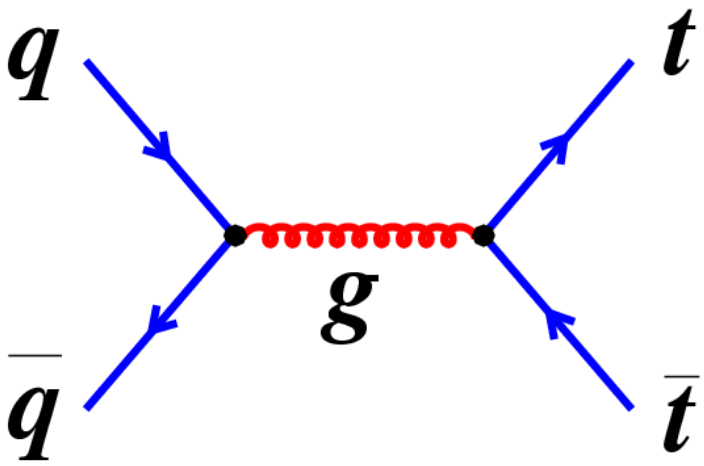
- Once Planck scale is reached gravity expected to have similar strength to other forces. Need A unified model of quantum gravity.
- Large Hadron Collider ~10TeV ~10^{17}K

6.3.1 Quark Soup

› Early Universe, $t<10^{-4}$s, $T > 10^{12}$K

› GUTs suggest that at this temperature all particles should exist in *roughly* equal numbers:

- Sufficient ambient photon energy exists to make all reactions possible
- Reactions proceed in both directions with equal efficiency as energy difference irrelevant compared to ambient photon energy.

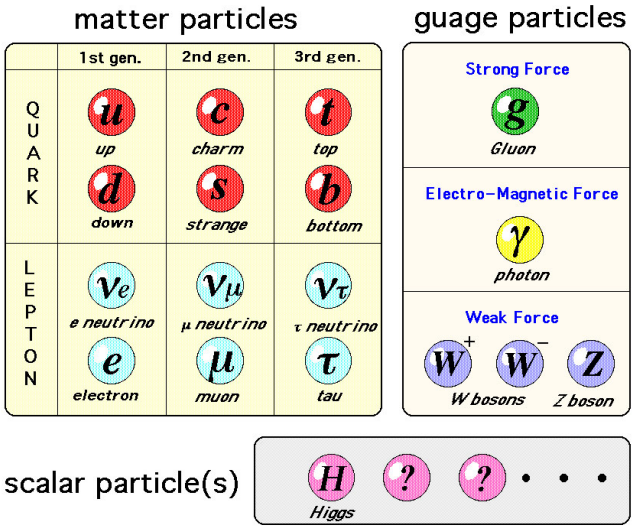


6.3.1 Quarks

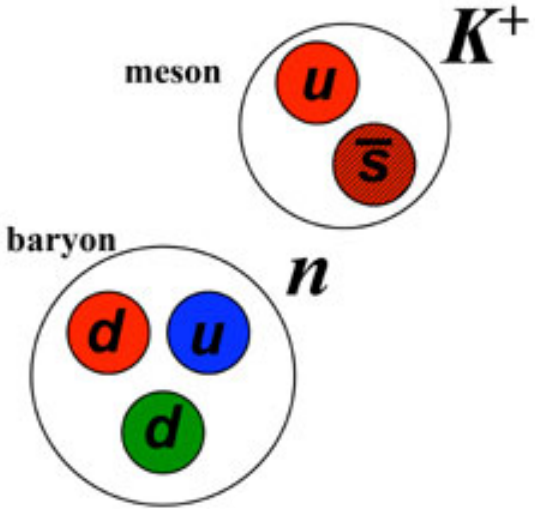
There are six quarks and associated leptons →

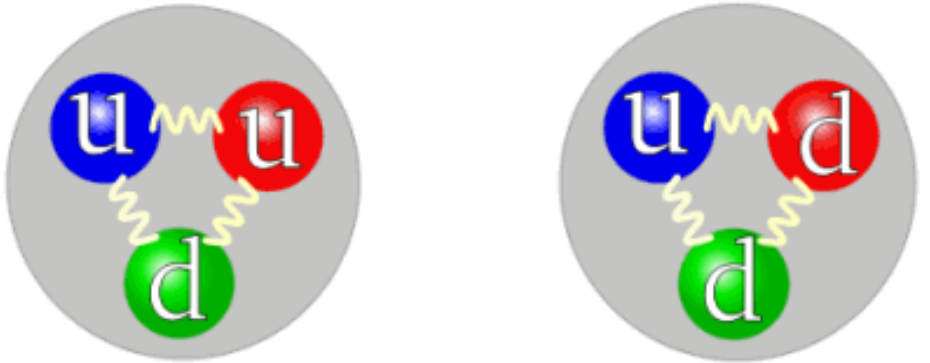
All normal matter (baryons, i.e., protons & neutrons) is made up of combinations of two quarks: uud or udd.

Mesons=quark, anti-quark pairs.



Elements of the Standard Model





Proton Neutron

Quark composition of a proton and a neutron (diagrams from *Wikipedia*)

6.3.1 Sieving the Quark Soup

› As the Universe cools:

- Reactions leading to more massive Quarks no longer allowed (not enough energy).
- More massive Quarks decay to u and d (freeze out)
- Quark soup → u+d, anti-u+d, leptons, photons, gluons and some residual stable heavy particles

Quark	**U D**	**S**	**C**	**T**	**B**
Rest m (GeV)	**0.003**	**0.1**	**1.3**	**171**	**4.2**
Temp	10^{10}	10^{12}	10^{13}	10^{15}	10^{13}

$$E = mc^2 = 2.8k_BT$$

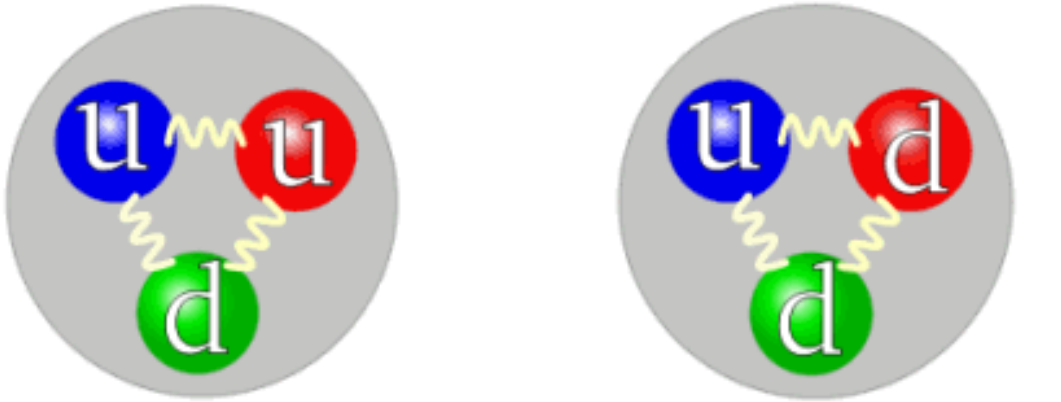
E in units of eV when

$$k_B = 8.619 \times 10^{-5} eVK^{-1}$$

6.3.2 Baryogenesis

1. Quarks bubbling in and out of existence
2. Hadrons form and remain stable once $T<10^{12}K$

Binding energy ~ 939MeV → $T=4x10^{12}K$



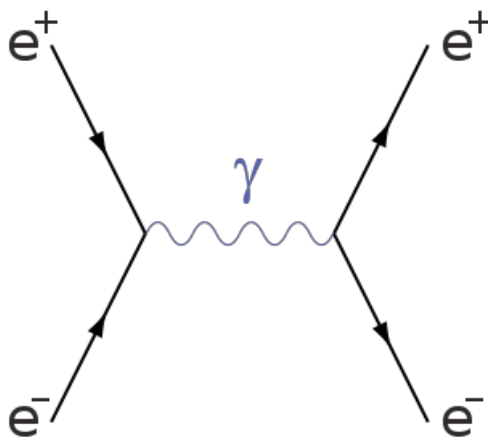
Proton Neutron

Quark composition of a proton and a neutron (diagrams from *Wikipedia*)

3. Hadrons involving other Quarks unstable and quickly decay (seen in collider experiments).

6.3.2 Matter anti-matter asymmetry

- In the very early Universe we would expect to see equal numbers of particles and anti-particles.
- Now we see no evidence of significant anti-matter in the Universe.
- What happened?



- Asymmetry caused by some as yet unknown process.
- Only needs to be a weak asymmetry.
- 1 billion anti-protons + 1billion and 1 protons annihilate to leave 1 proton and 10^9 photons, which is the observed photon to baryon ratio.

6.3.2 The neutron-proton ratio

› Protons stable neutrons decay:

$$n \Leftrightarrow p + e^{-} + \bar{\nu}_e + \gamma\,[0.8\text{MeV}] \text{ when } kt >> 0.8\text{MeV}$$

$$n \rightarrow p + e^{-} + \bar{\nu}_e + \gamma\,[0.8\text{MeV}] \text{ when } kt << 0.8\text{MeV}$$

› While in thermal equilibrium the density of n to p is given by a Maxwell-Boltzmann distribution:

$$\frac{N_n}{N_p} = \left(\frac{m_n}{m_p}\right)^{3/2} e^{-\left[\frac{(m_n - m_p)c^2}{kT}\right]} = \left(\frac{939.6}{938.3}\right)^{3/2} e^{-\left[\frac{(939.6-938.3)}{0.8}\right]} = \frac{1}{5}$$

› Once the ambient energy is below 0.8MeV thermal equilibrium no longer holds and we can no longer use MB eqn to determine ratio.

6.3.2 Neutron decay

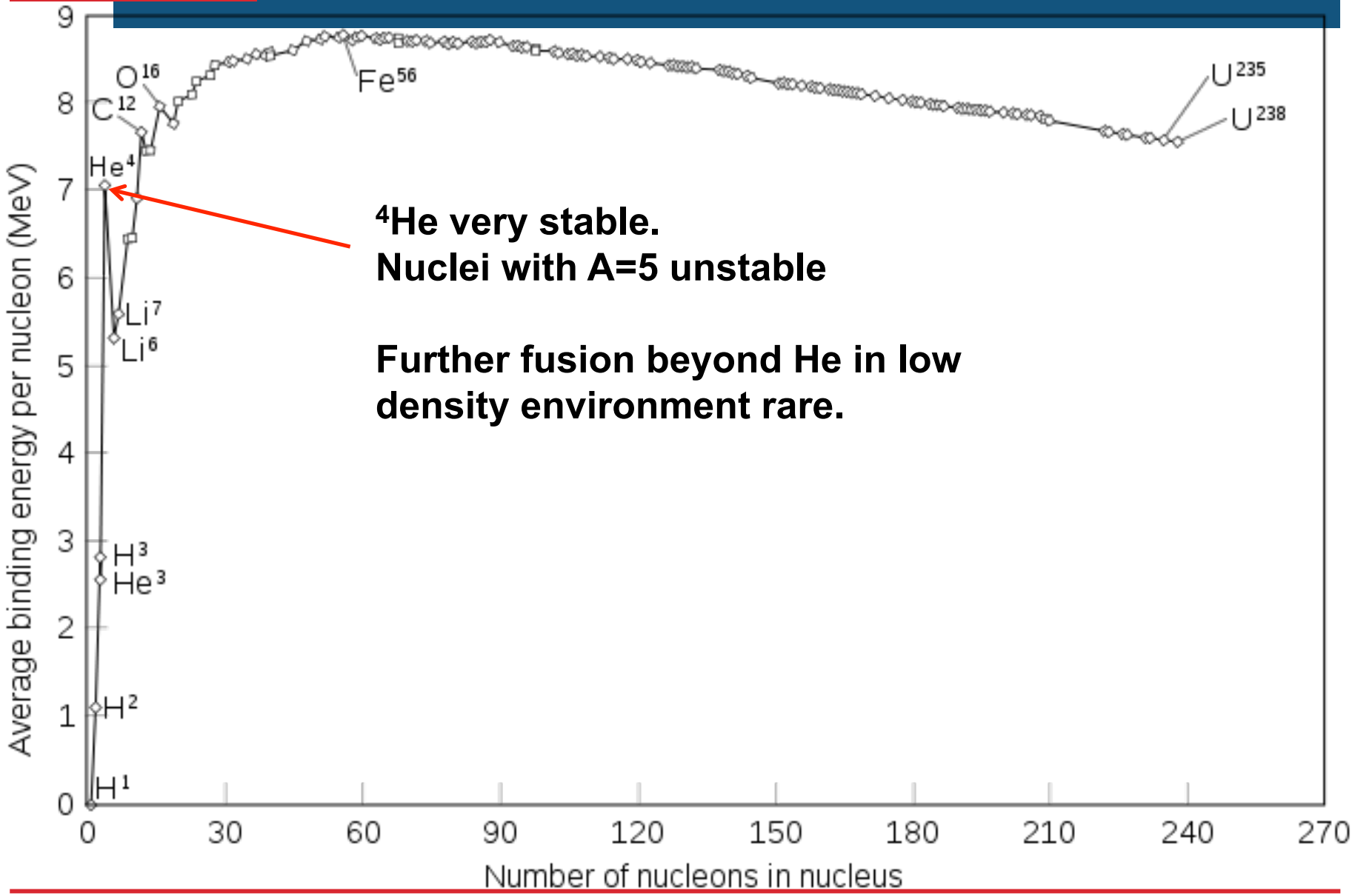
- As U cools below 0.8MeV neutrons spontaneously decay.
- Their half life is given by: t_{half}=611s (mean lifetime=t_{half}/ln(2)=881s)
  - Hence:

$$\frac{N_n}{N_p} \approx \frac{1}{5}\exp\left(\frac{t \times \ln(2)}{611s}\right)$$

- But how long for the Universe to cool from 0.8MeV to when neutrons become bound (stable) inside nuclei?
- Three factors:
  - Binding energy of nuclei (^{2}D=2.2MeV, ^{4}He = 28MeV)
  - Photon to baryon ratio (10^9 photons per baryon)
  - How temperature scales with time ($T \sim t^{-0.5}$)

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6.3.2 Binding energy of nucleons



^{4}He very stable.
Nuclei with A=5 unstable

Further fusion beyond He in low density environment rare.

6.4 Nucleosynthesis

- Given a gas with neutrons and protons and photons, nuclear reactions will take place (fusion).

- But the atoms formed will also be destroyed (fission) by other high energy photons

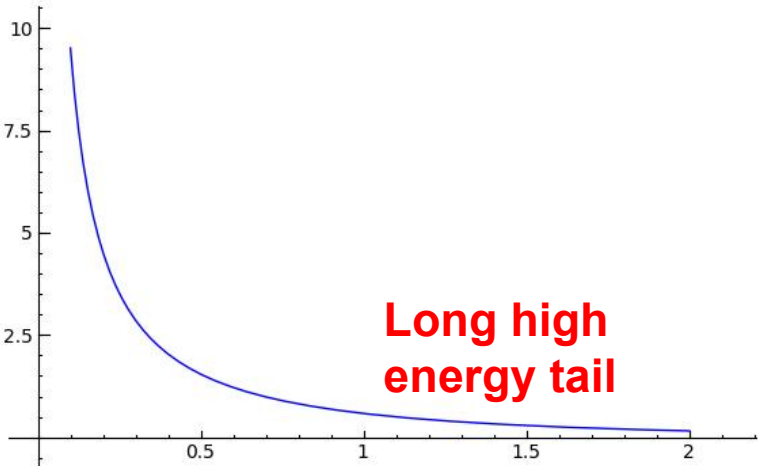
$$p + n \rightarrow^{2} D, \quad D + p \rightarrow^{3} He, \quad D + D \rightarrow^{4} He$$

- Although ^{4}He is stable at 28MeV it cannot form until D is also stable which is at 2.2MeV
  - Deuterium bottleneck (^{4}He waits for D to be stable)
- But hang on 2.2MeV > 0.8MeV
- Why doesn't Deuterium form during n/p thermal equilibrium?

6.4 Nucleosynthesis

› Photons have a Planck distribution:

$$N = \frac{1}{\exp(h\nu / k_B T) - 1}$$



$$N_\gamma(h\nu > E) = \int_{E/h}^{\infty} N_\gamma d\nu \approx N_\gamma e^{\left(-E/k_B T\right)}$$

$$\text{We want}: N_\gamma e^{\left(-E/k_B T\right)} \approx N_b, \text{ at energy E}$$

$$\frac{E}{k_B T} \approx \ln\left(\frac{N_\gamma}{N_b}\right) \approx \ln\left(10^9\right) \approx 20$$

The same argument as the CMB decoupling temperature.

› As photon-baryon ratio is high (1:10^9) when mean temp is 0.8MeV many photons with still have sufficient energy to break deuterium apart.

› Only when ~1:10^9 photons has > 2.2MeV will Deuterium be stable long enough for ^{4}He to form. So expect this to happen at $k_B T$~0.1 MeV.

› In actual fact, a more detailed calculation gives ~0.06 MeV (pretty close!).

6.4 Neutron decay (again)

› Age of Universe at 0.8MeV (n/p last in equilibrium)

- Calibrate: 1s after Big Bang temp was 1.3×10^{10}K

$$t_{0.8MeV} \approx 1\left(\frac{8.619\times10^{-5}.1.3\times10^{10}}{k_BT}\right)^2 \approx \left(\frac{1.1MeV}{k_BT}\right)^2 \approx 2s \qquad \frac{t}{t_o} = \left(\frac{T_o}{T}\right)^2 = \left(\frac{k_BT_o}{k_BT}\right)^2$$

› Age of Universe at 0.06MeV (when high energy photons drop below binding energy of D):

$$t_{0.06MeV} \approx 1\left(\frac{1.3\times10^{10}K}{T}\right)^2 \approx \left(\frac{1.1MeV}{k_BT}\right)^2 \approx 340s$$

› Fraction of decayed neutrons:

$$N_n(t) = N_n(0)e^{-t/\tau} = 0.68$$

$$N_p(t) = N_p + 0.32N_n(0) = 5.32$$

› Final Neutron to proton ratio:

$$\frac{N_p}{N_n} \approx \frac{5.32}{0.68} \approx 7.8$$

6.4 The ^{4}He abundance

› Because ^{4}He peaks in Binding Energy once D bottleneck is overcome most (all) neutrons end up in this form.

› To first order:

$$X_p \equiv \frac{\text{mass in } H}{\text{total mass}} = \frac{N_p - N_n}{N_p + N_n} = 0.77$$

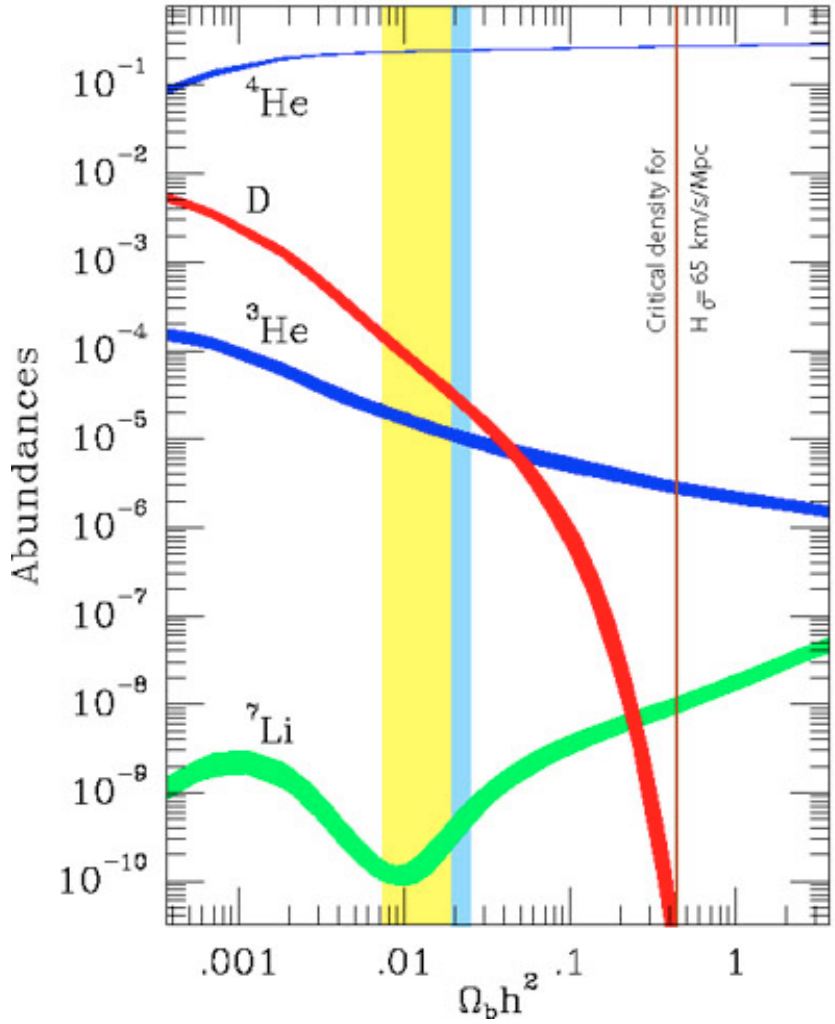
$$Y_p \equiv \frac{\text{mass in He}}{\text{total mass}} = \frac{2N_n}{N_p + N_n} = 0.23$$

› Big Bang Nucleosynthesis predicts that ~23% of the baryonic Universe should be ^{4}He and 77% H

› This provided the first explanation for the high density of ^{4}He seen in nearby stars.

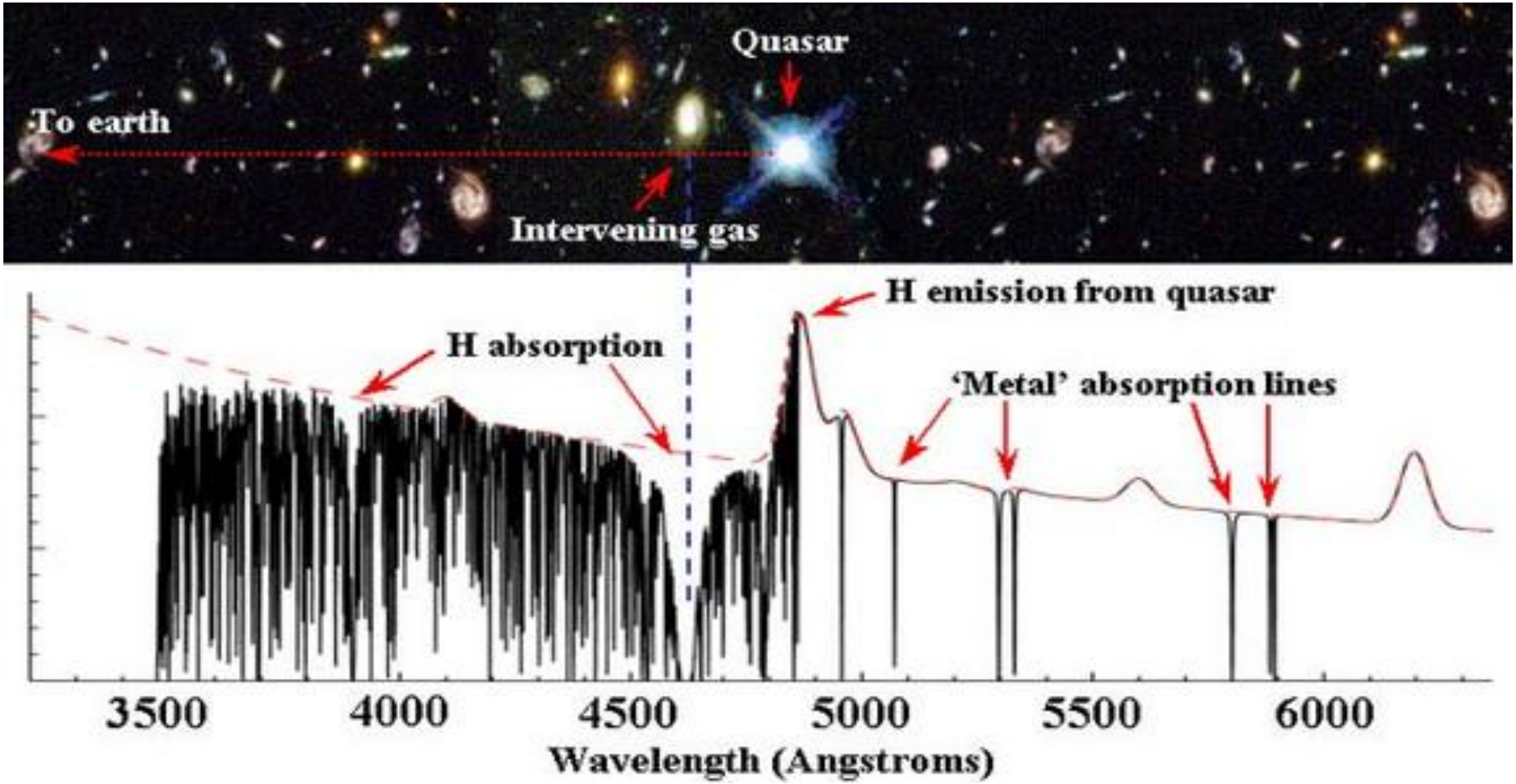
6.5 Observed abundances

- Why strong dependency on density?
- High density: easy for D to find partner to process to Helium
- Low density: hard for D to find partner to process to Helium
- Deuterium therefore a key measurement to define baryon density of Universe

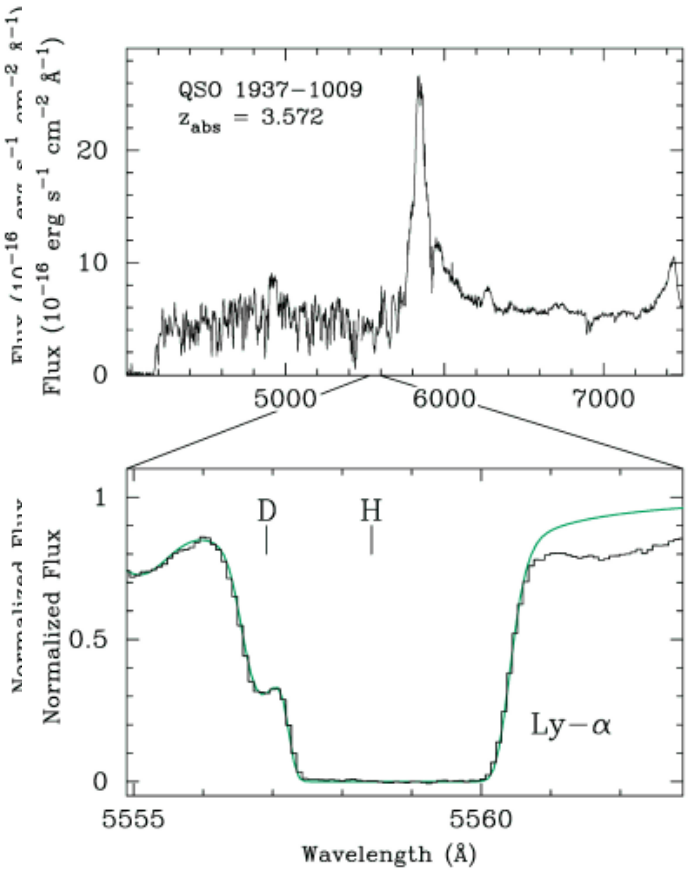


Schramm & Turner (1998)

6.5 Abundances from quasar absorption lines

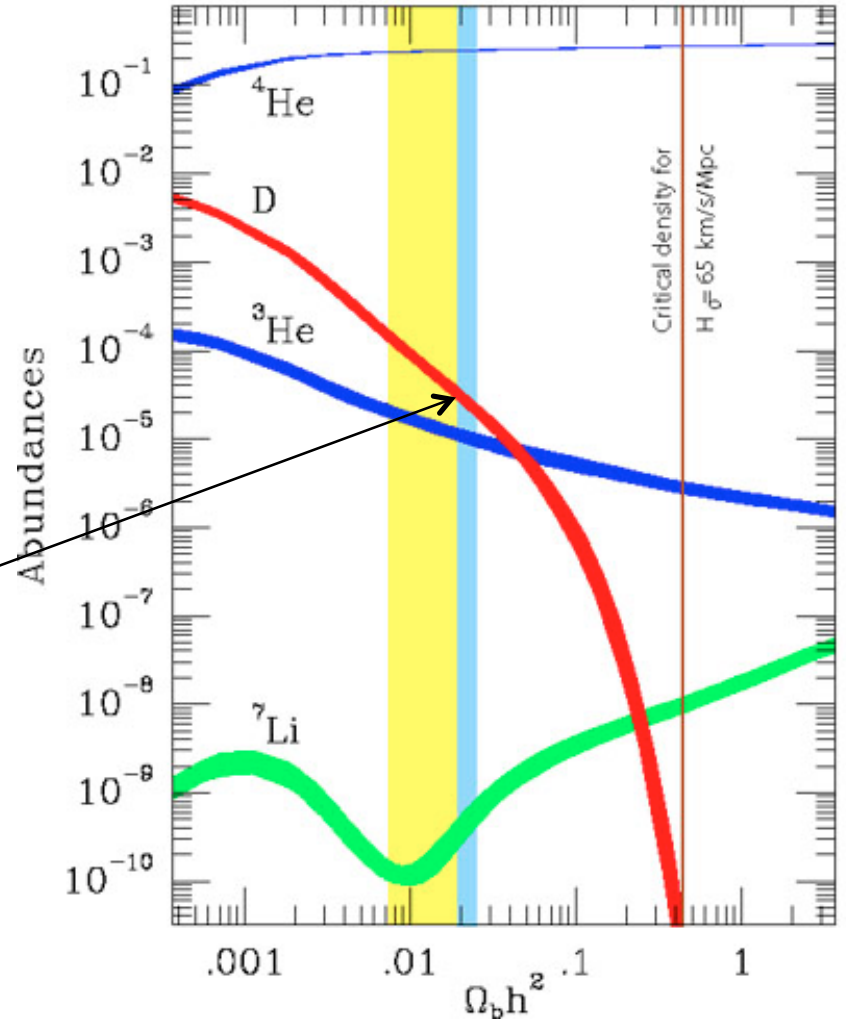


6.5 Deuterium measurements



$$\rho_B \approx 2.0 \times 10^{-28}\ \text{kg m}^{-3}$$

$$\text{or} \quad 0.016 \le \Omega_B h^2 \le 0.024$$



Schramm & Turner (1998)