“Creation of the Elements in the Early Universe”

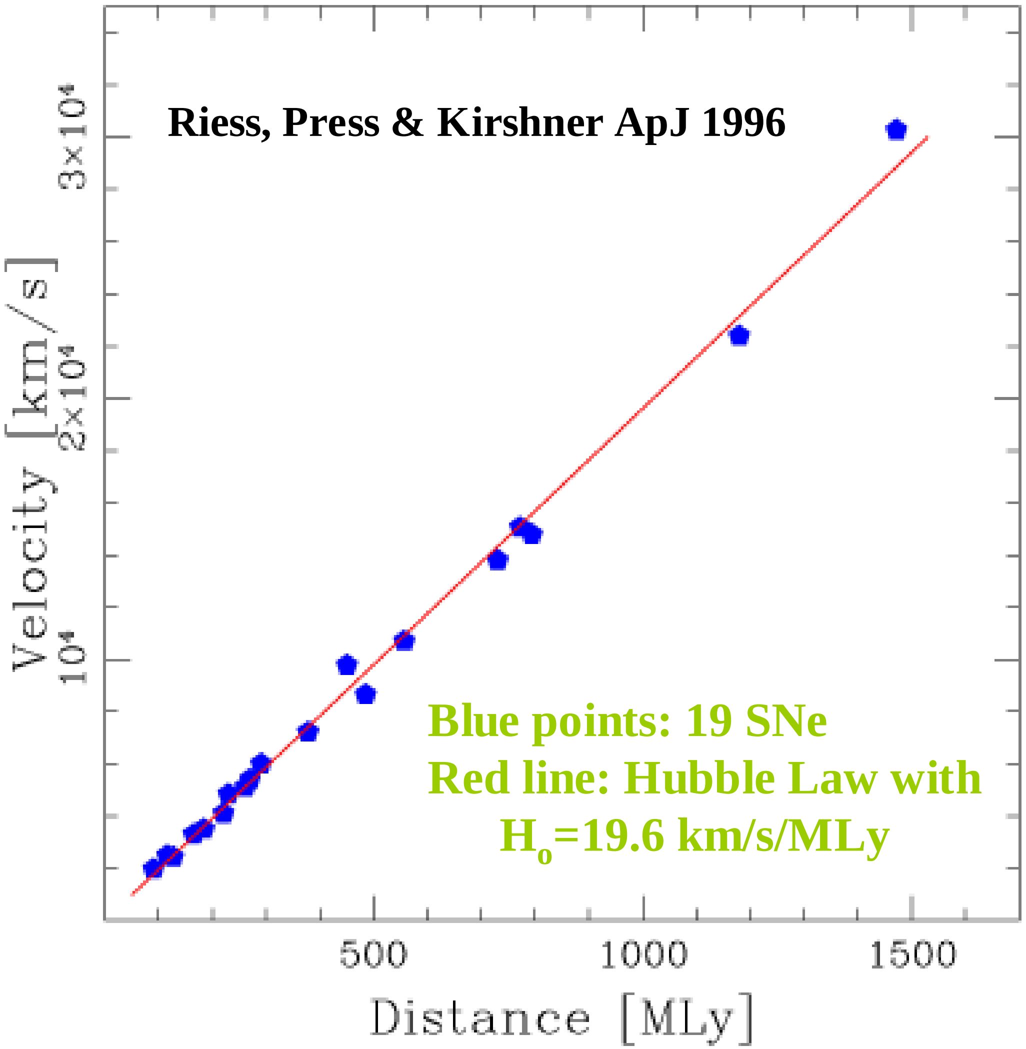
Based partly on lecture by Joe Mohr

Outline

- **1. Fission versus Fusion**
  - As an energy source
  - The right environment
- **2. The Helium Problem**
  - Why 24% Helium is too much
  - Conditions in the early universe
- **3. Primordial Nucleosynthesis**
  - Evolution of early universe
  - Creation of the light elements
  - Observations of light element abundances
- **4 Summary**

The Universe is Expanding

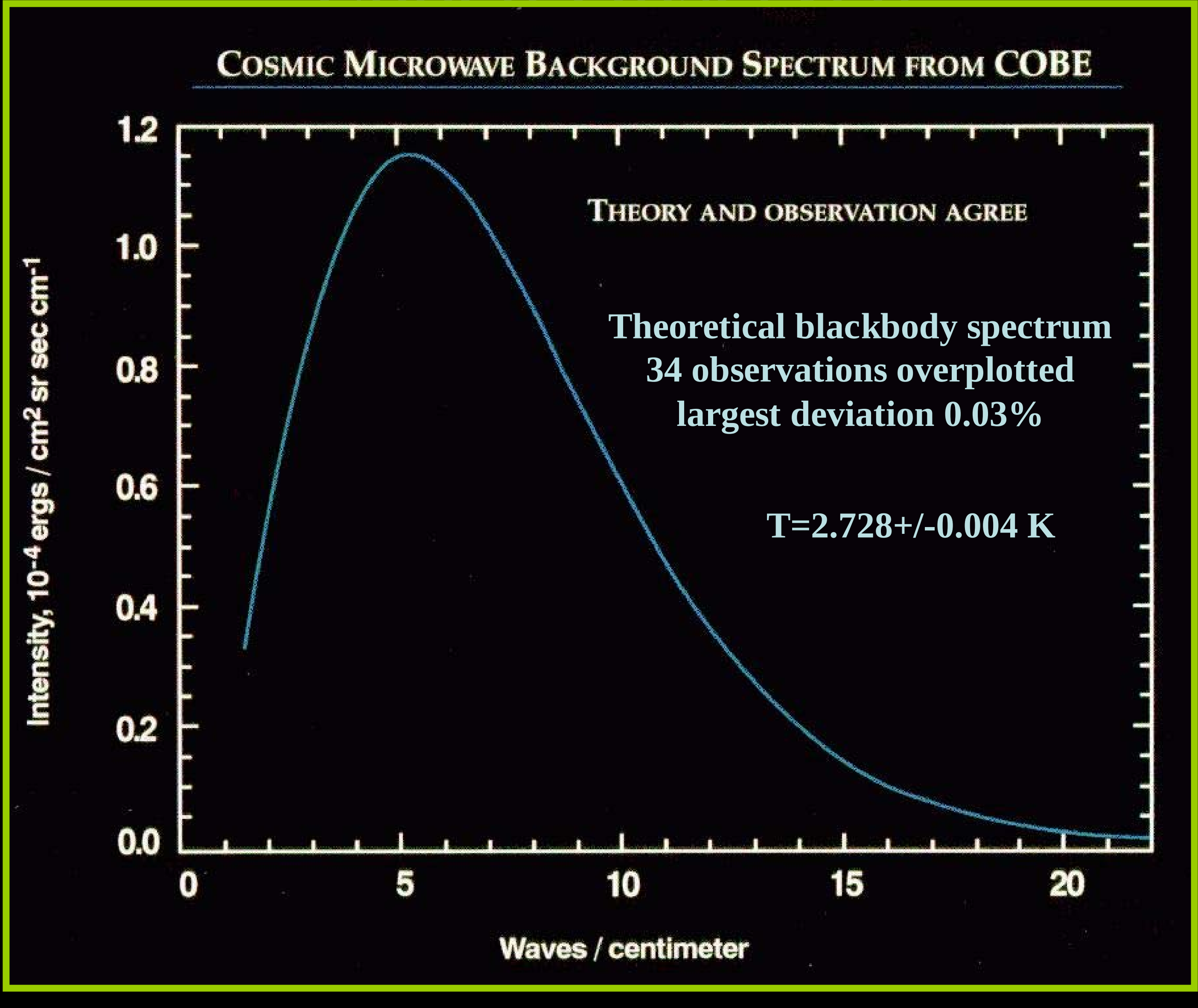
Distance measurements to 19 Type Ia SNe



Type Ia supernovae and every other distance indicator used provides results consistent with the Hubble Law: other galaxies are receding from us, and their recession velocities are proportional to their distances, in other words, the farther away the galaxy, the faster it travels away from us.

$$v_r = H_o d$$

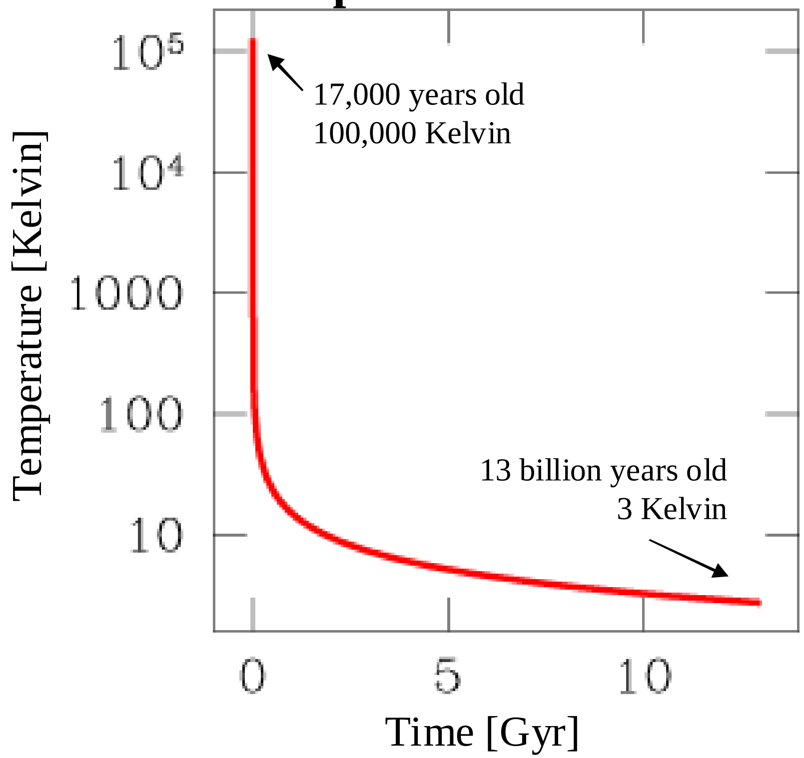
The Relic Radiation of Hot, Dense Epoch Observed



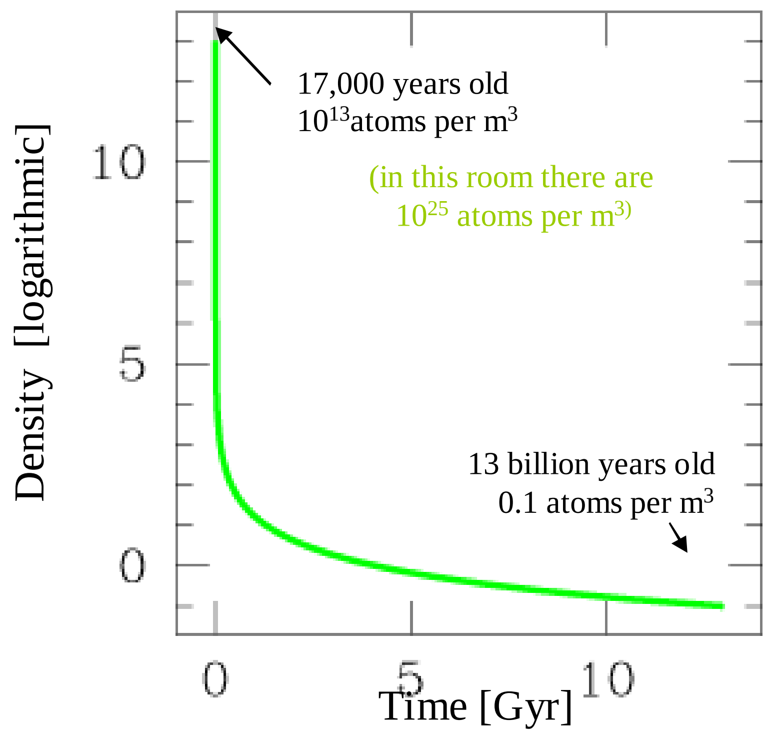
Conditions in Early Universe

- Expansion and CMB imply Universe was hotter and denser in the past
- At some time when the universe was very young, conditions were similar to those in the centers of stars
- Note: temperature and density decrease with time, different behavior from stars
- There exists some window of opportunity during which conditions are favorable for fusion

Temperature versus Time

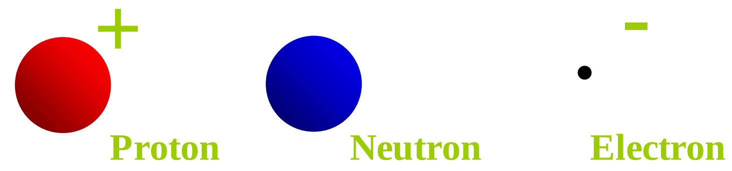


Density versus Time



Atoms, Elements and Isotopes

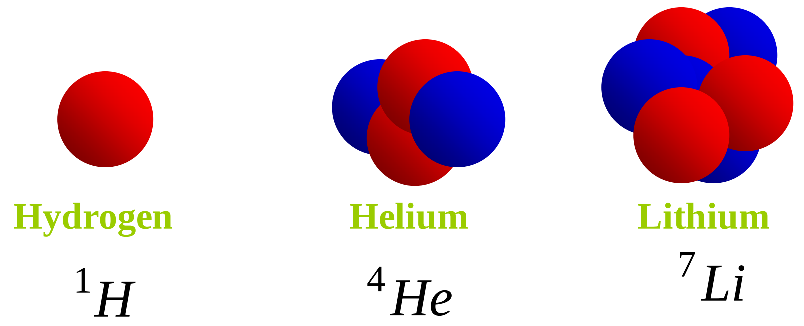
- Hadrons and leptons.



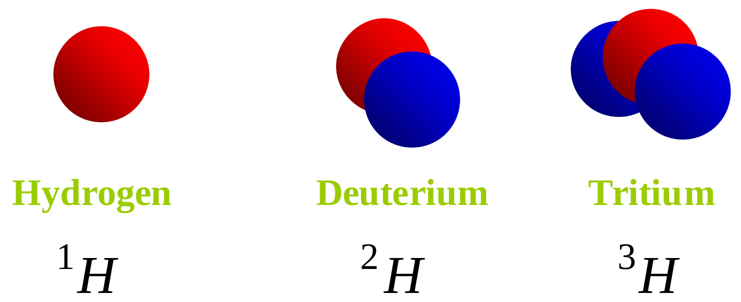
Relative Masses 1 : 1 : 0.0006

Relative Charge +1 : 0 : -1

- key elements: H,He,Li,Be



- Hydrogen isotopes.



Fission versus Fusion

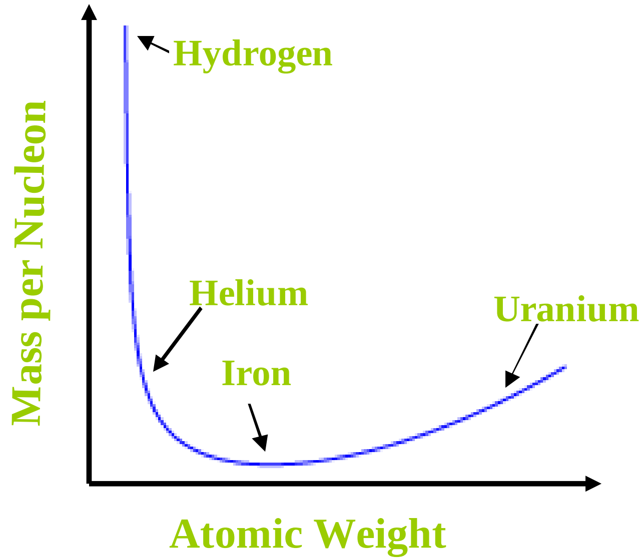
- Fission: splitting a nucleus into two or more parts

$$n + {}^{235}U \rightarrow {}^{236}U \rightarrow 2n + {}^{94}Sr + {}^{140}Xe + \text{Energy}$$

- Fusion : building a new, more massive nucleus by binding two, lower mass nuclei. Hydrogen fusion: $4\ {}^{1}H \rightarrow {}^{4}He + \text{Energy}$

Fusion Converts Mass to Energy $E=mc^2$

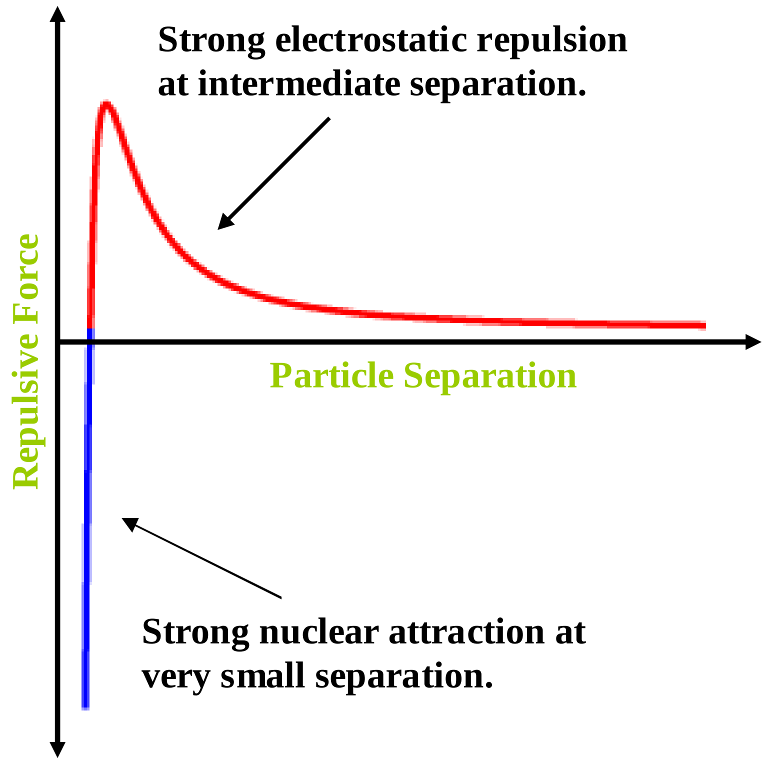
4 H nuclei:	$6.693X10^{-24}$ g
1 He nucleus:	$6.645X10^{-24}$ g
mass difference:	$0.048X10^{-24}$ g
0.07% of mass converted to energy	



Low Z and high Z unstable relative to Iron. Binding energy released both for fusing light elements and splitting heavy ones.

Fusion Requires Extreme Conditions

- Fusion occurs during collisions
  - long range electrostatic repulsion
  - strong binding
  - Fusion is a classic example of quantum tunnelling
- Fusion requires high temperatures: ~10^7K
  - high atomic number means more electrostatic repulsion, thus needs higher temperature
- Fusion requires high densities
  - so that collisions are very common



The Helium Problem

- Observed elemental abundances
  - Hydrogen 75%
  - Helium 24%
  - Everything else ~1%

- Stellar nucleosynthesis
  - Helium efficiently fused into higher mass elements like Carbon
  - Expect roughly as much helium as in all the higher mass elements
  - Ratio: 75% H, 13% He, 12% rest
  - As though universe started out made of Hydrogen and Helium rather than just Hydrogen

- Early Universe
  - Conditions favorable for nucleosynthesis? Yes

	Leptons		Quarks	
First family Normal Matter	Electron	Electron Neutrino	Up chg +2/3	Down chg -1/3
Second family First seconds of big bang and cosmic rays	Muon	Muon Neutrino	Charm	Strange
Third family Earlier in big bang	Tau	Tau Neutrino	Top	Bottom
Bosons integer spin	Photons electro-magnetic force	Gluons Strong force (between quarks)	Intermediate vector bosons Weak Force	Gravitons Gravity

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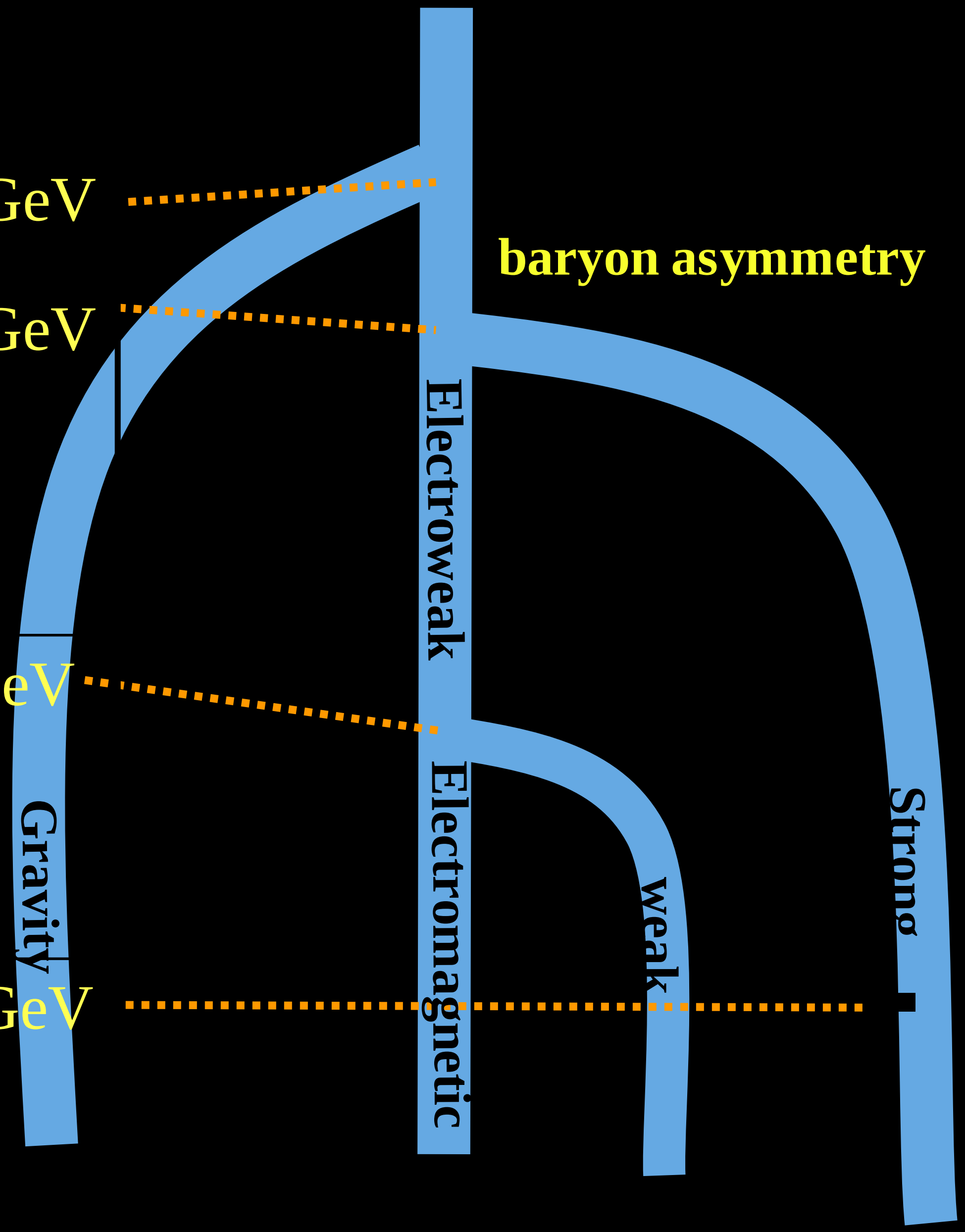
Evolution of the Forces

Gravity	10^{-44} s	10^{19} GeV
Quantum Chromo-dynamics	10^{-36} s	10^{15} GeV
Weak Interaction	10^{-11} s	10^{2} GeV
Quark-hadron transition	10^{-4} s	10^{-1} GeV



The Planck Era:
Quantum Limit of Spacetime

Compton wavelength $$\lambda_c = \frac{h}{mc}$$

Schwartzchild radius $$r_s = \frac{2Gm}{c^2}$$

A black hole for which $\lambda_c > r_s$ is quantum mechanically unstable

- probability that singularity outside event horizon

-quantum breakdown of General Relativity

Set $\lambda_c = r_s$:

$$\frac{h}{mc} = \frac{Gm}{c^2} \Rightarrow m_p = \sqrt{\frac{hc}{G}} = 5.8 \times 10^{-8}\,kg = Planck mass$$

Planck length

$$\lambda_p = \frac{h}{m_p c} = \frac{Gm_p}{c^2} = \sqrt{\frac{Gh}{c^3}}$$

Scale size for quantum foam

Planck Time

$$t_p = \frac{\lambda_p}{c} = \sqrt{\frac{Gh}{c^5}} = 1.35 \times 10^{-43}\,s$$

Eras of the Universe

Planck era	10^{-44} s
Inflation Era	10^{-17} s
Hadron era	10^{-6} s
Lepton era	10^{-2} s
Nucleosynthesis era	1 s
Decoupling	10^{13} s
Radiation dominated	$<3.10^{14}$s
Matter Dominated	$>3.10^{14}$s
Structure formation	10^{15} s
Today	4.10^{17} s
Dark Energy Era	10^{19} s

Expansion of the Early Universe

Hubble law: Universe compact in past.

Friedmann Equations: theoretical equation of motion for isotropic homogeneous universe.

Early universe radiation dominated: ignore matter

Fried

$$T(t) = \left(\frac{3c^2}{2^7 \pi G \sigma} \right)^{\frac{1}{4}} t^{-\frac{1}{2}} = 1.5 \times 10^{10} t^{-\frac{1}{2}} DegKelvin$$

σ = Stefan-Boltzmann constant. Remember hf~3kT

eg: time to cool 10^{10}K-10^{9}K= 231 s-2.31 s ~ 4 min

Temperature evolution depends only on fundamental constants!!

The Hadron Era

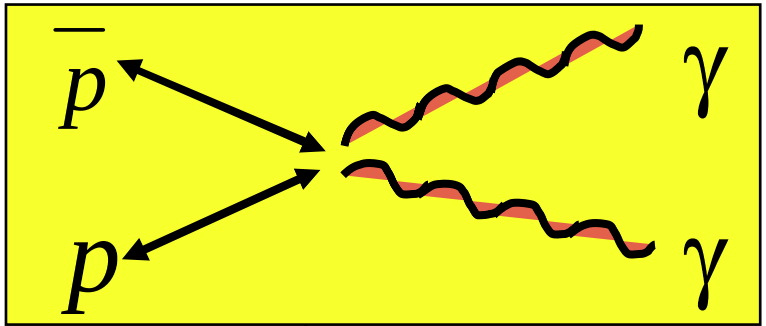
this regime accesible to particle accelerators

Time: 10^{-6} s, quark-gluon plasma, $kT >> M_{hadron}c^2$

Themal gamma rays break up hadrons into quark constituents.

Time 10^{-4} s, $T \sim 10^{12}$ K: temperature and density greater than a neutron star, but not enough to break up hadrons

quark-gluon plasma ⟶ hadron plasma



hadron plasma consists of **p, p⁻, n, n⁻** and their excited states called mesons

proton-antiproton annihilation

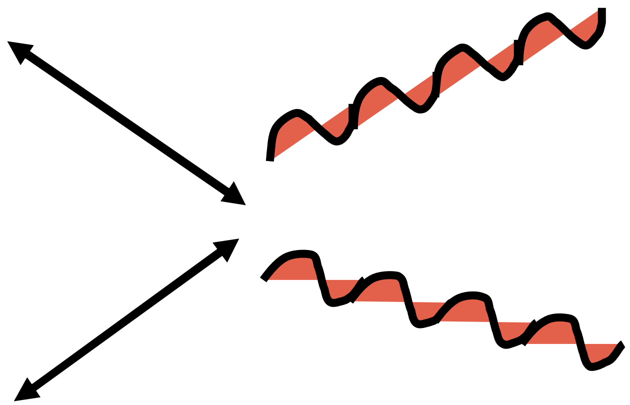
proton-antiproton pair creation

Hadrons in Thermal Equilibrium

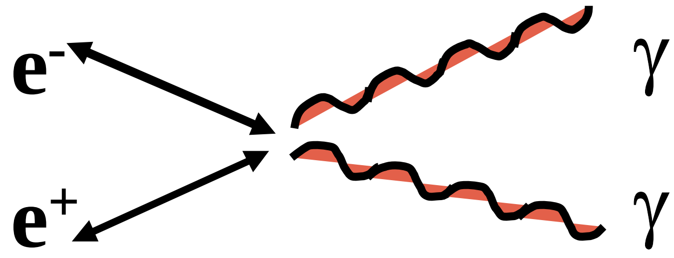
Thermal equilibrium between protons, antiprotons, neutrons, antineutrons and photons.

One photon per baryon

Tiny excess of matter over antimatter negligible and this time but essential to the future universe.



Lepton Era



Energy sufficient for electron-positron pair creation (1000 times less than needed for hadrons)

$$kT < M_{hadron}c^2, \;\; kT > M_{lepton}\, c^2$$

Composition: **(e^-,ν_e), $(\mu\text{-},\nu_\mu)$, (τ^-,ν_τ) + antiparticles + protons + neutrons + photons**

$T=10^{-2}$ s, $T=10^{11}$ K

Neutrino mean free path exceeds horizon scale (10^{-2} light seconds). Thereafter neutrinos propagate with negligible scattering

Nucleosynthesis Era

Neutron is marginally heavier than proton. $(m_n - m_p)c^2 = 1.29\,\mathrm{MeV}$

Protons and neutrons in thermal equilibrium with electrons and neutrinos.

$$p + e^- \longleftrightarrow n + \nu$$

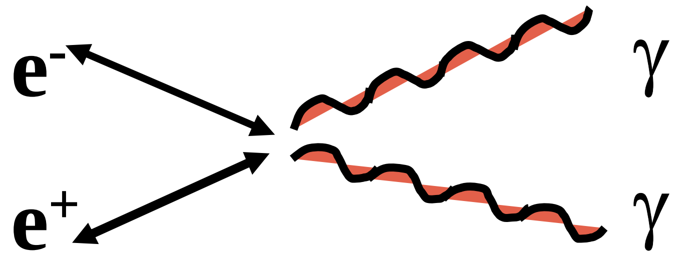
$$p + \nu^- \longleftrightarrow n + e^+$$

thermal equilibrium

$$\frac{N_n}{N_p} = e^{-\frac{(m_n - m_p)c^2}{kT}}$$

As T $\longrightarrow \infty$ expect $N_n/N_p \longrightarrow 1$. Small mass difference ensures $N_n < N_p$ as universe cools and this ensures both H and He in the universe.

Electron-Positron Annihilation



When photon energy falls below electron rest mass of 0.5MeV, $T \sim 5 \times 10^9$K, positron population falls to zero.

$n + e^+ \longrightarrow p + \nu^-$

$p + e^- \longrightarrow n + \nu$

This reaction stops (→ $n + e^+ \longrightarrow p + \nu^-$)

This reaction energetically unfavourable (→ $p + e^- \longrightarrow n + \nu$)

N_n/N_p is now frozen. Use Boltzmann equation

Substitute $m_n - m_p = 1.4 \times 10^{-3} m_p = 1.29$MeV, $T = 5 \times 10^9$K

$\longrightarrow$ **$N_n/N_p = 0.2$** **(*try it yourself*)**

Below 10^9K $n + p \rightarrow D$ **(=2H) Deuterium**

Deuterium Bottleneck and the Hydrogen Helium ratio

Deuterium is fragile! Easily destroyed by

$$D + \gamma \longrightarrow n + p \quad \text{for } T>100\text{keV}$$

So any deuterium that forms is immediately destroyed until T < 100keV, 10^9 K.

Once T < 10^9K can have $D + D \longrightarrow He^4$ **= 2n+2p**

But Nn/Np = 0.2. (2 neutrons for 10 protons)

ie: for every He^4 there must be 8 free protons

ie: $N_{He}/N_H = 1 : 8$

ie: $M_{He}/M_H = 1:2$

ie: 33% He, 66%H

Better estimates allowing for time evolution give 25%

Primordial Nucleosynthesis Baryometer

Estimate baryon mass fraction of universe from these reactions

$$p + n \longrightarrow H^2 + \gamma$$

$$H^2 + H^2 \longrightarrow He^3 + n \longrightarrow H^3 + p$$

$$H^3 + H^2 \longrightarrow He^4 + n$$

Symbol= chemical species. ($D=H^2$)

superscript= atomic weight (N_n+N_p)

Deuterium residue much less in high density universe…more chance of $H^2 + H^2$ reaction

higher density=less deuterium

slower expansion= less deuterium

Measure deuterium and also He^3, Li, Be to determine baryon fraction of universe

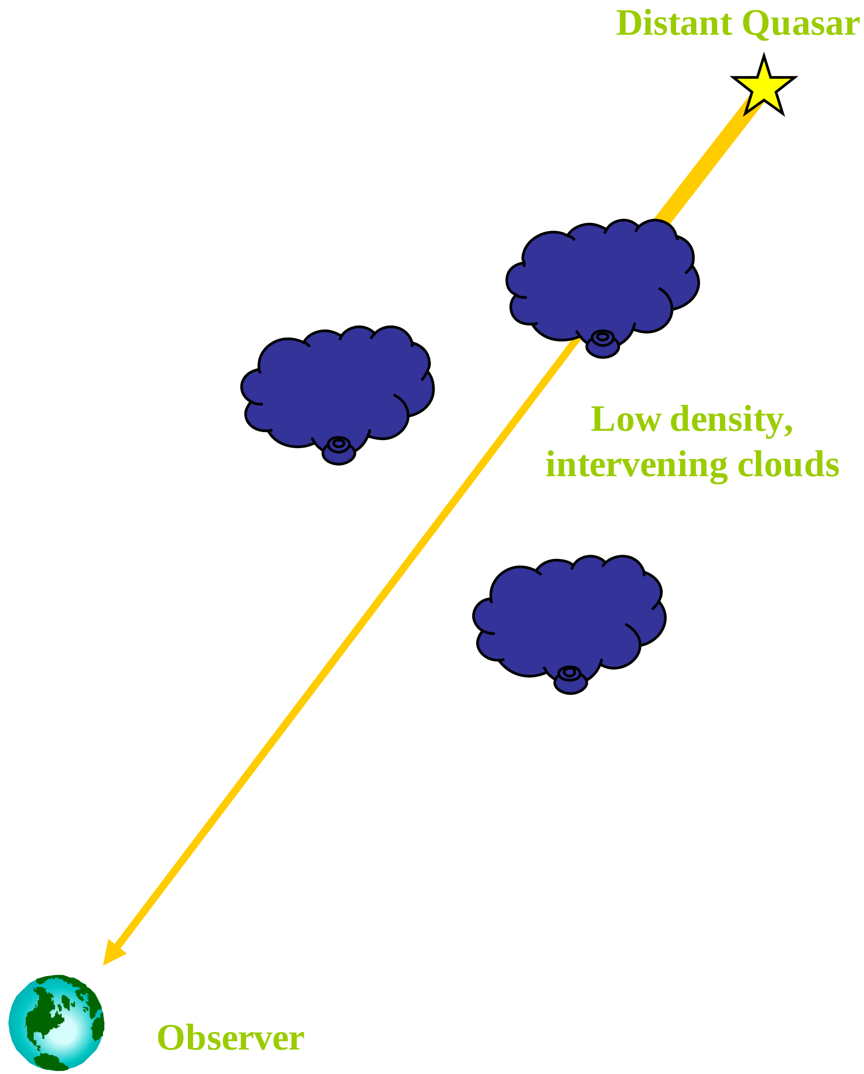
Need to allow for spontaneous decay of free neutrons (890s lifetime), and need to know nuclear reaction rates and cross sections.

Summary of Primordial synthesis

- time<15s, Temperature> 3 billion Kelvin
  - universe is soup of protons, electrons and more exotic matter
  - so hot that nuclei are blasted apart by high energy photons as soon as they form
- time=15s, Temperature=3 billion Kelvin
  - Still too hot for Deuterium to survive
  - Cool enough for Helium to survive, but too few building blocks
- time=3min, Temperature=1 billion Kelvin
  - Deuterium survives briefly after it is fused
  - once it appears, Deuterium is quickly fused into He, but the whole process is slowed by the shortage of Deuterium (deuterium bottleneck)
  - no stable nuclei with 5 or 8 nuclear particles, and this bottleneck restricts formation of elements heavier than Helium
  - trace (but measureable) amounts of Lithium are formed
- time=35min, Temperature=300 million Kelvin
  - nucleosynthesis essentially complete
  - hot enough for Helium fusion, but density too low for appreciable fusion
- Model makes very precise predictions about the relative abundances of the light elements ^2H, ^3He, ^4He and ^7Li. What about observations?

Using Quasars to Probe the Youngest Gas Clouds

- Distant quasar
  - very luminous source that can be seen at large distances
- Low density clouds
  - distant structures still forming
- Observe absorption spectrum
  - positions and strength of absorptions lines tells is
    - cloud composition
    - temperature
    - location



Observations of Deuterium

- Deuterium Abundance
  - easily destroyed in stars
  - look for deuterium in low density clouds of gas that exist as close to the beginning of the universe as currently possible
  - differences between Hydrogen and Deuterium nucleus cause a minor change in the energies of electron transitions, shifting their absorption lines apart and creating a characteristic, bimodal absorption line
  - absorption spectrum at right contains this feature, allowing the Deuterium to Hydrogen ratio to be measured very accurately in this distant gas cloud
  - gas cloud absorbed the quasar light at a time when the universe was only 10% its current age- 1.3 Gyr.
  - these high quality measurements are possible now that very large, 10 m class telescopes exist

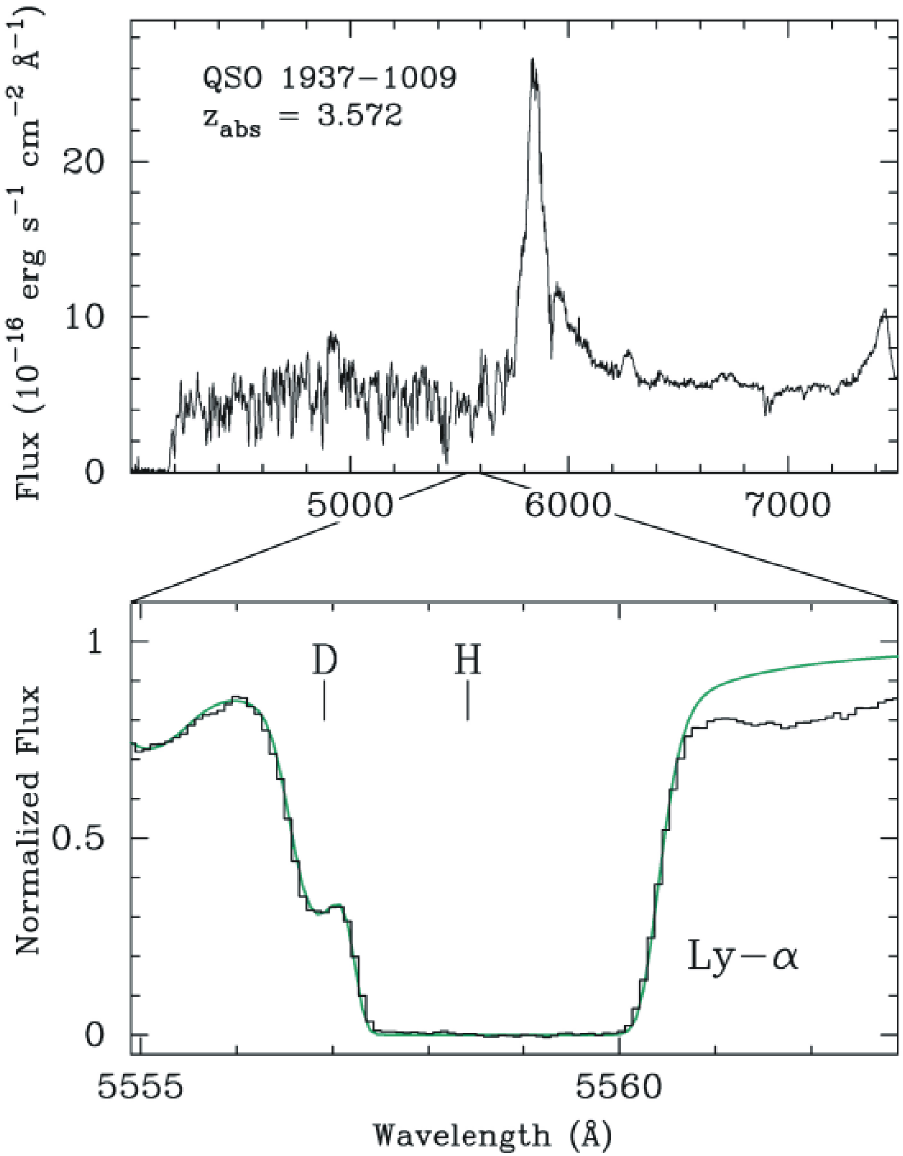
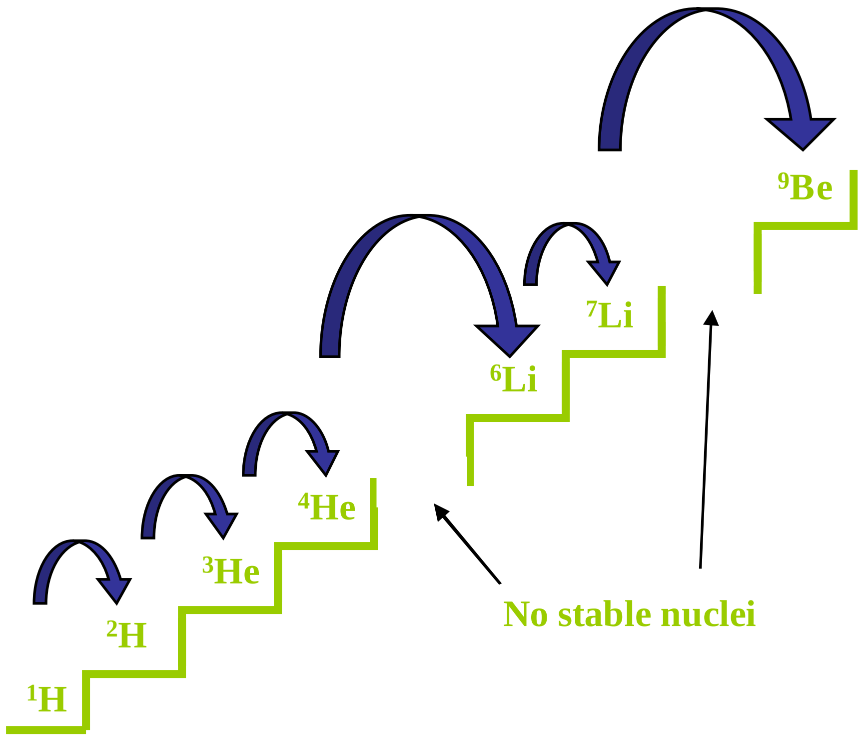


Figure taken from APS poster by Burles, Nollett and Turner

Observations by Tytler and Burles

Primordial Nucleosynthesis versus Stellar Nucleosynthesis

- Timescale
  - Stellar Nucleosynthesis (SN): billions of years
  - Primordial Nucleosynthesis (PN): minutes
- Temperature evolution
  - SN: slow increase over time
  - PN: rapid cooling
- Density
  - SN: 100 g/cm^3
  - PN: 10^{-5} g/cm^3 (like air in this room)
- Photon to baryon ratio
  - SN: less than a single photon per baryon
  - PN: billions of photons to every baryon



The lack of stable elements with masses 5 and 8 make it more difficult for cosmic nucleosynthesis to progress beyond Lithium and even Helium.

Observations of He and Li

- Helium Abundance
  - measured in old stars with lowest observed abundances of heavier elements like Oxygen
  - attempt to find stars which have the smallest levels of contamination from stellar nucleosynthesis
- Lithium Abundance
  - measured in stars
  - Lithium is easily destroyed in stars
  - focus on the transition from low mass stars (lower surface temperature) whose core material is well mixed by convection to higher mass stars (higher surface temperature) where mixing of core materials is not efficient

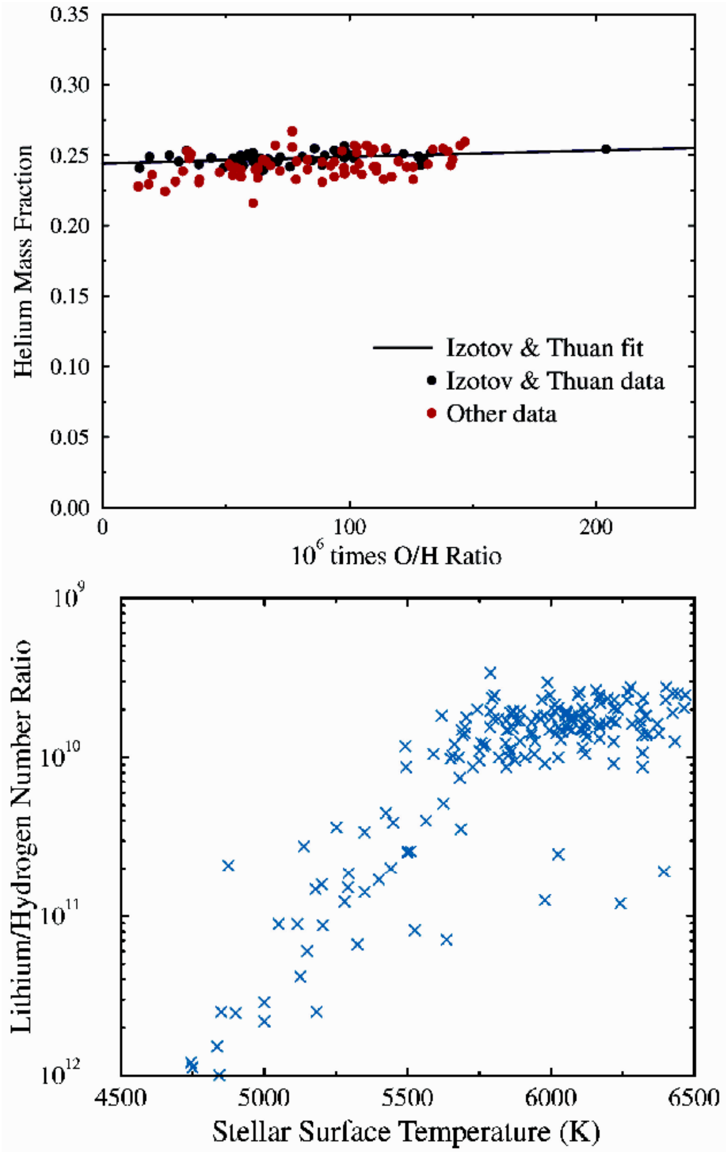


Figure taken from APS poster by Burles, Nollett and Turner

Cosmic Concordance

Primordial nucleosynthesis

explains observed, light element abundances if the density of normal matter (baryons) in the universe lies around 3.5x10^{-31} g/cm^3 or 0.21 hydrogen atoms per cubic meter

Precise observational test

- independent measurements of abundances of four different light elements lead to consistent constraints on the density of normal matter
- provides confidence that primordial or Big Bang nucleosynthesis provides a correct explanation of the formation of the light elements.

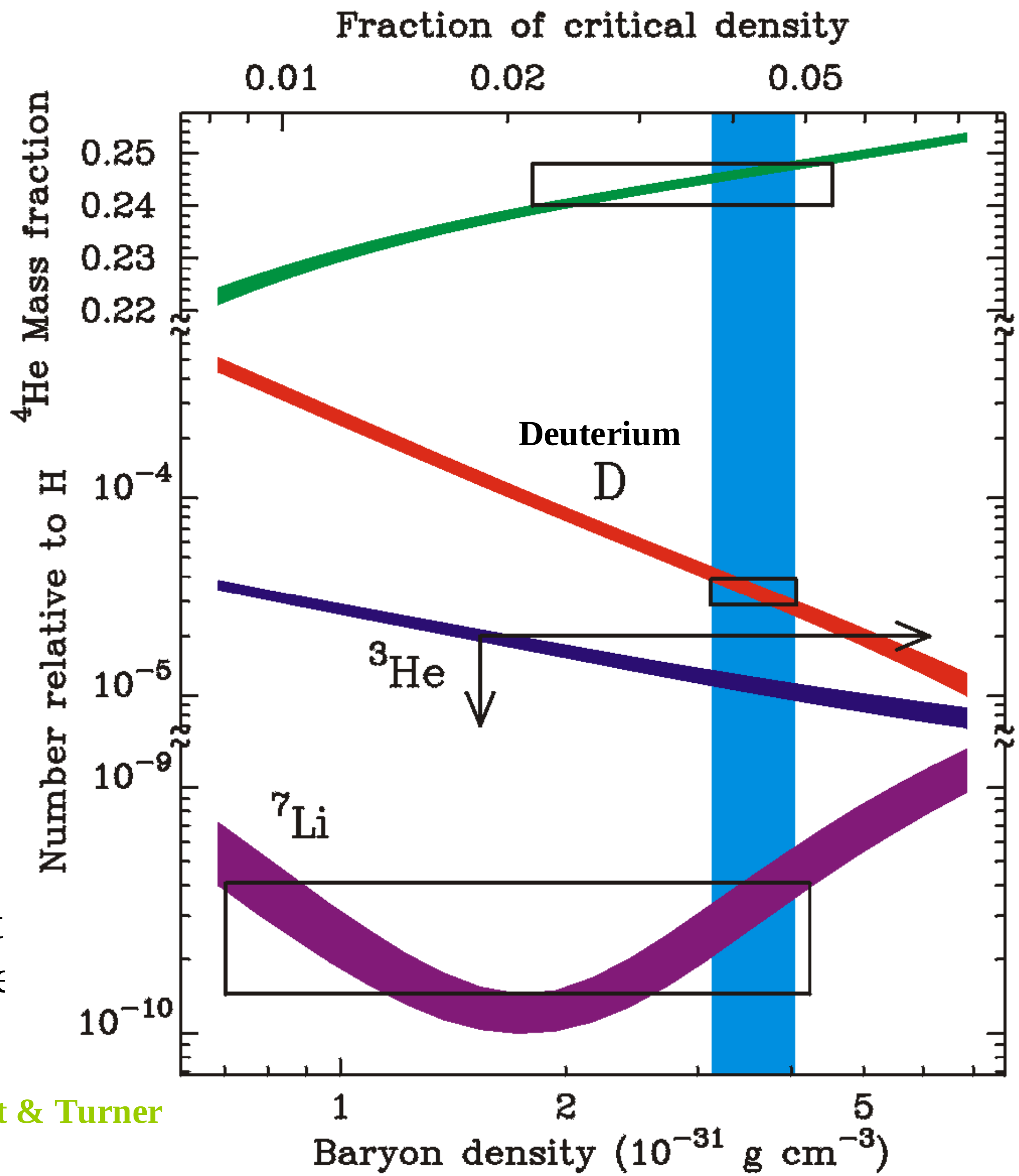


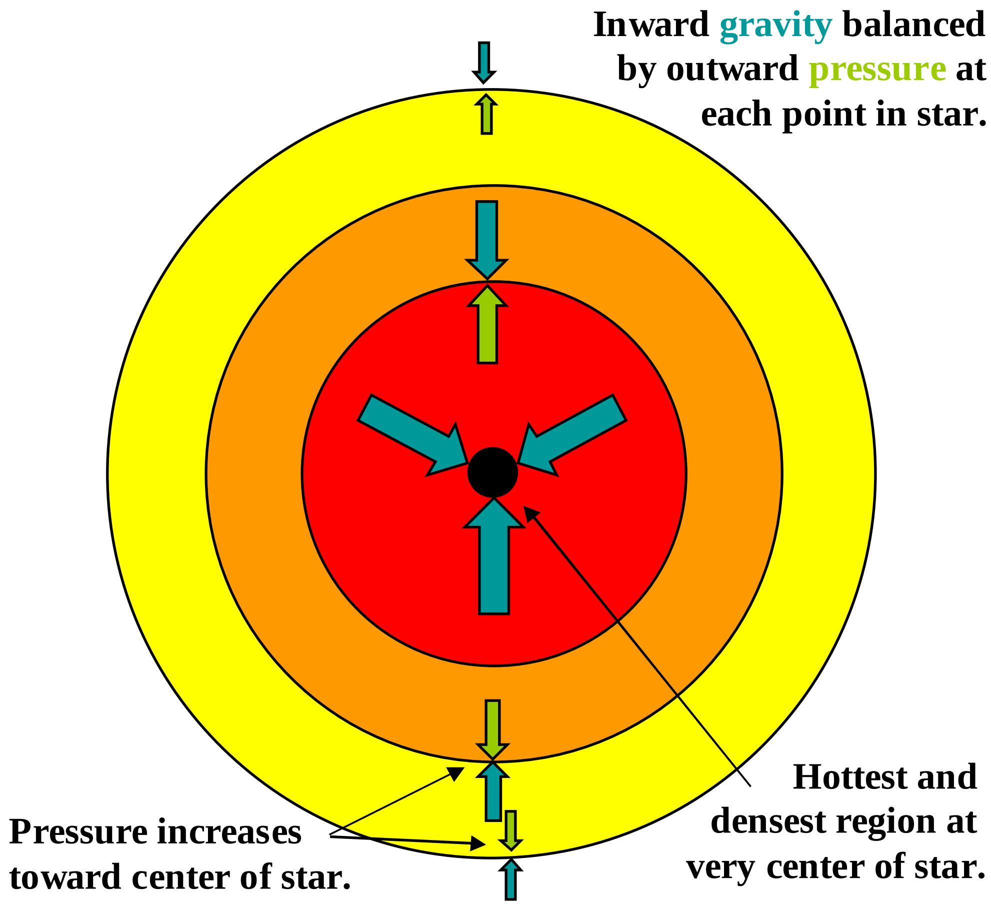
Figure taken from APS poster by Burles, Nollett & Turner

Summary

- Fusion and fission
  - fusion requires extreme conditions- high temperature and density
- The Helium problem
  - Mass fractions: Hydrogen- 75%, Helium- 24%, everything else- 1%
  - stellar nucleosynthesis cannot explain high He abundance relative to heavier elements
- Primordial nucleosynthesis
  - conditions favorable for fusion in early universe
  - universe expands/cools so fast that few elements heavier than ^4He produced
  - observations of light element abundances provide independent, quantitative and consistent constraints on density of normal matter in universe
  - Big Bang provides natural and consistent explanation

Stellar Structure

- Sun is a sphere of hot gas
  - composed of 75% H, 25% He + trace amounts of high mass elements
  - emits blackbody spectrum (with absorption lines) that has effective temperature of ~5,500 K
- Stable system- hydrostatic equilibrium
  - balance between gravitational forces trying to collapse the star and pressure forces trying to blow the star apart
  - each layer must support the weight of all the layers above it, so pressure increases with depth into the star



Fusion Occurs in the Cores of Stars

- Once the star contracts sufficiently, the central temperature and density rise so that hydrogen burning begins, depleting the Hydrogen and creating Helium "ash" in the stellar core (inefficient mixing).
- Eventually the star runs short of Hydrogen, fusion slows, star cools, central pressure falls and then the star contracts, driving up central density and temperature.
- Eventually the temperature rises to ~100 million

Burning Hydrogen into Helium
the proton-proton chain

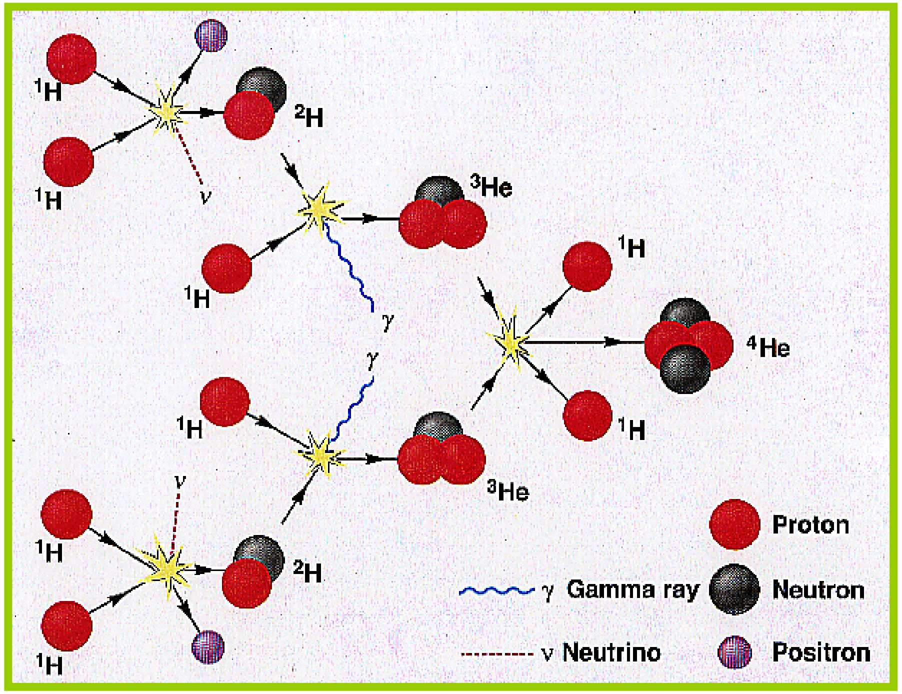


Figure from *Foundations of Astronomy* by M. Seeds

Energetic photons can break fused nuclei apart.

Stellar Evolution and Creation of Elements

- Progression of fusion
  - hydrogen burned into helium
  - helium burned into carbon and oxygen
  - carbon and oxygen burned into silicon
  - silicon burned into iron
  - no more fusion energy available!

- After running out of fuel at each stage, the star contracts and the core temperature and density rise

- At each stage, the "ash" from the