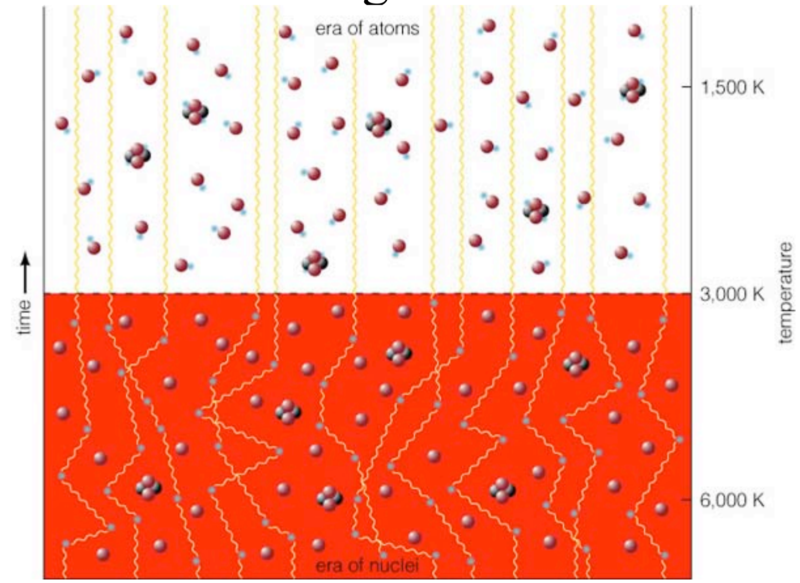
Plasma Universe

- As we go back in time, temperature goes up.
  - $T=2.73(1+z)$ K
- At $z\sim1100$, $T\sim3000$ K
  - About the same temperature as M-dwarfs
- Ionization of hydrogen atoms
  - H + photon → p + e^-
    - Inverse process: recombination p + e^- → H + photon
- Electrons scatter photons in all directions
  - Similar to the interior of the Sun
  - Photons cannot travel freely
  - The universe becomes "opaque"
- Therefore, $z\sim1100$ is the edge of the "visible universe"
  - We cannot look back beyond this epoch using light
  - The epoch called the ***decoupling epoch***.

The origin of CMB



Radiation Era

- In the present universe, radiation energy/matter energy is about 1/3300.
  - At the decoupling epoch, this ratio is about 1/3.
  - The Universe is moderately dominated by matter at the decoupling epoch.
- At $z\sim3300$, the radiation energy equals the matter energy – the matter-radiation equality
  - $z>3300$: Radiation Era
  - $z<3300$: Matter Era
- In the radiation era,
  - $\rho t^2 \sim 10^6$
  - $tT^2 \sim 10^{20}$
    - ρ in g/cm^3, t in seconds, and T in Kelvin.
- The radiation era ends at age about 30,000 years.
  - The decoupling epoch is ~380,000 years.

Nucleosynthesis

- The origin of helium
  - About 24% of the mass of atoms in the universe is helium.
    - 86% is hydrogen
  - Where did helium come from?
  - Stars fuse hydrogen into helium
    - This is incredibly inefficient process.
    - Stars could fuse **only 2%** of all hydrogen in the universe into helium – not enough.
- The first three minutes
  - $T\sim1$ billion K
  - The universe was a very efficient nuclear reactor
  - "Big-bang nucleosynthesis"

Synthesize Helium

- n + p → D + photon
  - When T>1 billion K, photo-dissociation process
    - D + photon → n + p

    also occurs frequently and destroys the formed deuterium
  - One has to wait until temperature drops below 1 billion K: t~100 seconds
- D + D → T + p
  - T: tritium (^{3}H; one proton & two neutrons)
- T + T → ^{4}He + n

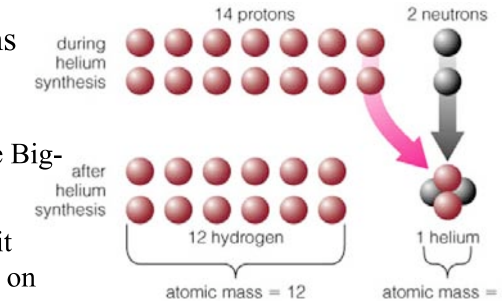
Consumption of Neutrons

- To form D, both n and p are required
  - However, n slowly decays via the process called β-decay:
    - n → p + e^{-} + ν_e
  - Therefore, n is outnumbered by p, and the amount of helium synthesized is essentially determined by the amount of neutrons
    - **n:p = 1:7**
- This n/p ratio explains

  He:H=1:3

•This is one of the most important predictions of the Big-bang model

•The prediction is robust – it does not depend very much on cosmological parameters

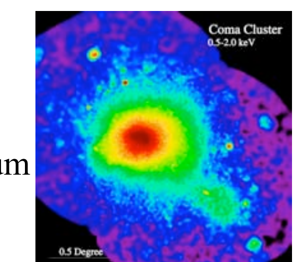


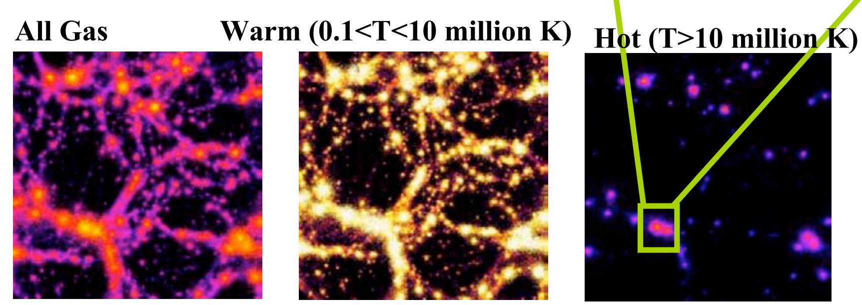
Deuterium

- The amount of deuterium depends on density of nuclei, or Ω_{atoms}. How?
- Low Ω_{atoms}
  - Collision of deuterium, **D + D → T + p**, does not occur frequently
  - A larger fraction of D survives
- High Ω_{atoms}
  - More collision → A smaller fraction survives

Weighing Atoms

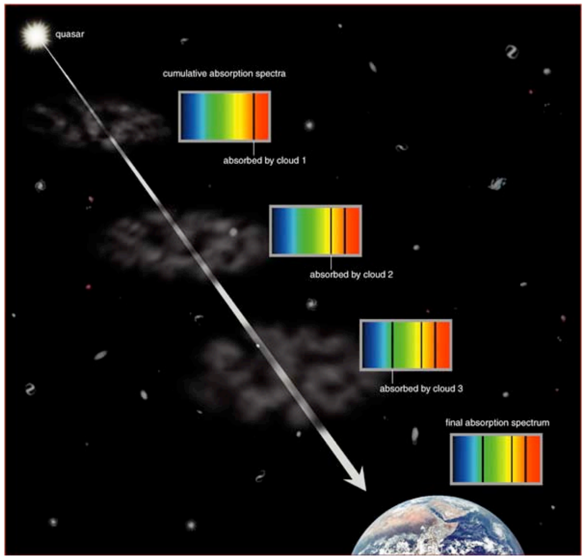
- Where are atoms?
  - Hot gas in clusters of galaxies
  - Warm gas in the intergalactic medium
  - Cold gas in hydrogen clouds



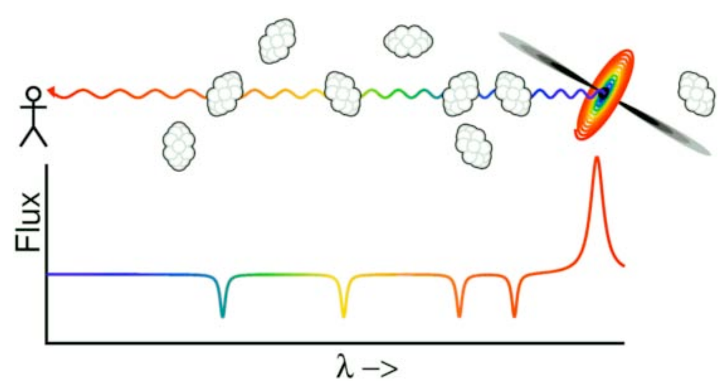


Cold Clouds

- “Cold” (T<0.1 million K) hydrogen clouds absorb background light.
  - They appear as “dark clouds”
  - They are also called the “Lyman-alpha clouds”

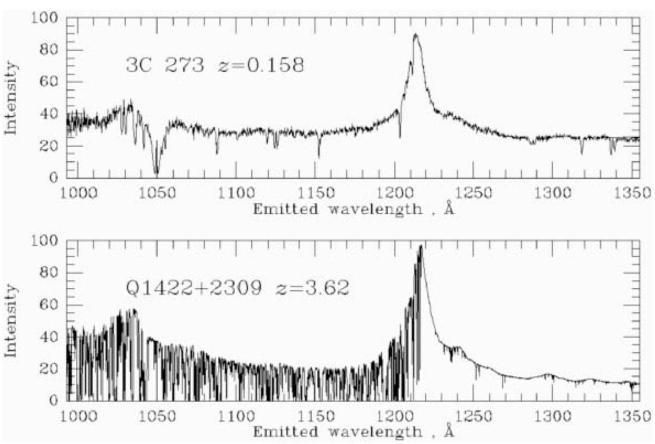


Lyman-alpha Forest



- Quasars are so bright that they can be used as a “lighthouse” which sheds light on Lyman-alpha clouds.

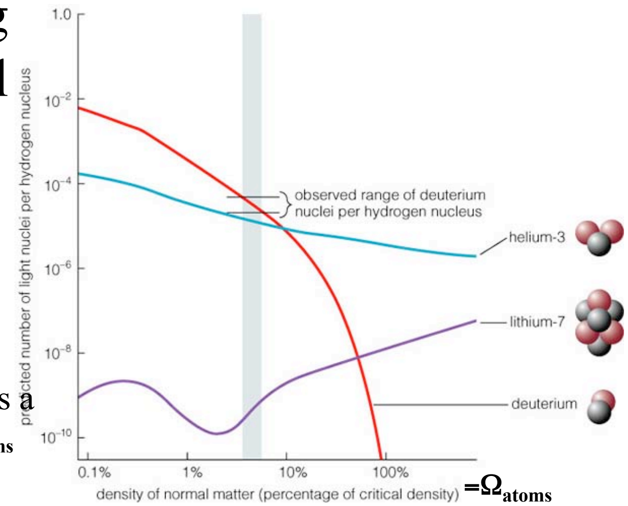
Lyman-alpha Forest



- Quasars at larger distances have more substantial Lyman-alpha forests.

Measuring Primordial Gas

- The Big-bang theory makes definitive predictions for abundances of light elements as a function of Ω_{atoms}



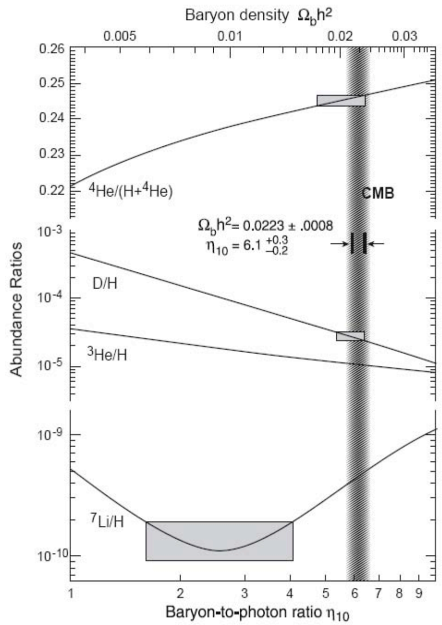
- Comparing the measured abundance with theory, $\mathbf{\Omega_{atoms} = 0.04}$ has been obtained.

"Baryon" is the name for materials made of quarks.

High baryon density implies low deuterium abundance and high helium abundance.

The cosmic microwave background can also be used to determine the baryon density.

Both measurements imply that baryons occupy only 4% of the total energy of the universe.



…yet we need stars…

- The Big-bang nucleosynthesis cannot synthesize any elements heavier than Lithium.
  - Density of nuclei was too low
- The initial proposal of the BBN was abandoned because of this "failure"
- Later it was realized that heavier elements must be synthesized by fusion in stars
  - Although temperature is low (10 million K vs 1 billion K), density is high (100 g/cm^3 vs 20 μg/cm^3)

Pair Creation of Particles

- Mass energy: $E=mc^2$
  - Mass can be converted into energy
- Energy can also be converted into mass
  - Energy can create particles.
- Creation of particles always occurs in pairs:
  - Energy → Particle + Anti-particle
  - Particle and anti-particle have the same masses
  - Required energy: $E = mc^2 + mc^2 = \mathbf{2}mc^2$
- Pair annihilation
  - Particle + Anti-particle → Energy: $E=2mc^2$

Pair Creation in the Early Universe

- A lot of energy out there – but, particles are not so easy to create!
  - As we go back in time, photons get more energy
  - The lightest (hence easiest) particles to create from photons are electrons
  - Pair creation occurs in pairs: *electrons* and *positrons*
- The mass of electrons=$9.11\text{x}10^{-31}$ kg
  - E=$2mc^2$=$1.6\text{x}10^{-13}$ joules → About **10 billion K**

The Lepton Era

- Leptons
  - Electron, positron
  - Muon, anti-muon
  - Tauon, anti-tauon
  - Electron-neutrino, Anti-electron-neutrino
  - Muon-neutrino, Anti-muon-neutrino
  - Tauon-neutrino, Anti-tauon-neutrino
- Leptons are minorities at T<10 billion K (1 second)
  - T>10 billion K: a lot of electrons and positrons will be created
  - The mass of muons = 207 times the mass of electrons
  - The mass of tauons = 3500 times the mass of electrons
  - **The era of leptons**
- Neutrinos?
  - Neutrinos are almost massless (they do have masses, but very small)
  - However, photons cannot create neutrinos

Decoupling of Neutrinos

- Like photons get scattered by electrons, neutrinos also get scattered by the corresponding "—ons".
  - They don't travel freely until the scattering by the corresponding "—ons" have annihilated
  - **Neutrino decoupling**
  - (c.f.) Photon decoupling (z~1100)
- Electron-neutrino decoupling (z~4x10^9)
- Muon-neutrino decoupling (z~4x10^{11})
- Tauon-neutrino decoupling (z~10^{13})
- **Cosmic Neutrino Background** allows us to "see" through the universe in much earlier epochs.
  - The neutrino background is slightly cooler: 1.96 K

Hadrons

- Hadrons can interact via the *strong forces*
- *Baryons*
  - Proton, Anti-proton
  - Neutron, Anti-neutron
  - Lambda, Anti-lambda
    - A lot of others
- *Mesons*
  - Pions, Anti-pions
  - K-ons, Anti-K-ons
    - A lot of others

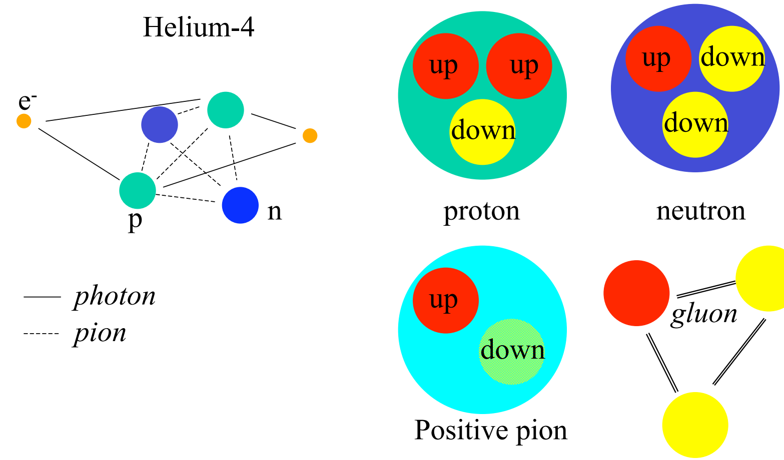
The Hadron Era

- Baryons are heavy:
  - The mass of protons ~ 2000 times the mass of electrons
- At T>20 trillion K (~1/10,000 seconds), the pair-creation of protons and neutrons occurs.
  - **The era of hadrons**
    - Energy → Protons + Anti-protons
    - Energy → Neutrons + Anti-neutrons

Baryon Annihilation Riddle

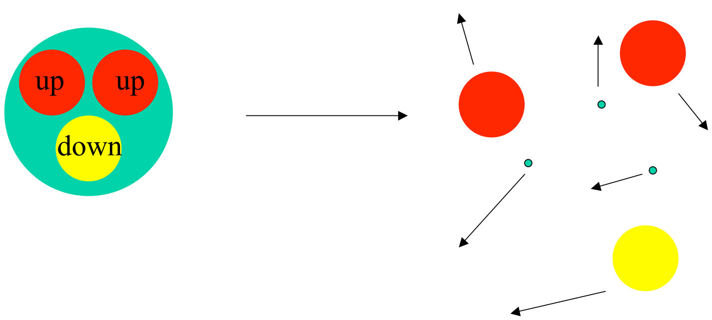
- At T<20 trillion K, protons and neutrons annihilate away
  - Protons + Anti-protons → Energy
  - Neutrons + Anti-neutrons → Energy
- Have all the protons and neutrons annihilated?
  - Of course not: if they had, we weren't born…
- Apparently, there was more matter than anti-matter: WHY?
  - Even more puzzling:
    - 1,000,000,001 protons for 1,000,000,000 anti-protons
    - The required excess of matter is *tiny*!! WHY??
- **Baryogenesis** – challenge for the final theory

Quarks



The Era of Quarks

- $t<10^{-10}$ seconds; $T>10^{15}$K
  - C.f. the era of hadron: $t<10^{-4}$ seconds; $T>10^{13}$K



What's next?

- Unification of forces of nature has been a driver for the progress in physics.
  - Electric force + Magnetic force = Electromagnetic force (James Clerk Maxwell, 1864)
  - Light = Electromagnetic waves
- **Four forces of nature**
  - **EM, Weak, Strong, Gravity**
  - EM+Weak = **Electroweak Force** (*Steven Weinberg, Sheldon Glashow, Abdus Salam*, 1960s)
    - $t\sim10^{-10}$ seconds; $T\sim10^{15}$K
  - Electroweak + Strong = **Hyperweak Force** (*Sheldon Glashow*, *Howard Georgi*, 1974)
    - $t\sim10^{-36}$ seconds; $T\sim10^{28}$K
    - Grand Unification – not fully understood yet
  - Hyperweak Force + Gravity = **Unified Force** (*John H. Schwarz*, *Joel Scherk*, *Ed Witten*, and lot of others, since 1970s)
    - $t\sim10^{-44}$ seconds; $T\sim10^{32}$K [Planck Epoch]
    - Superstring Theory

Superstrings

- The smallest unit is a string.
  - Different oscillating patterns correspond to different particles, including a particle of gravity, *graviton*.
  - Superstring theories require 10-dimensional spacetime
    - In order to explain many particles by oscillations, strings need to oscillate to 10 dimensions.
- M-theory
  - There are many string theories out there…
    - Are they all wrong? Some of them are wrong? What?

  - Ed Witten has shown that different string theories are deeply connected to each other
  - **M-theory** unifies different superstring theories
    - Therefore, M-theory requires one more dimension – 11 dimensions

Beginning of Time

- The barrier of the modern physics
  - Planck Scale
    - Planck Epoch: $t \sim 10^{-44}$ seconds
    - Planck Energy: $T \sim 10^{32}$K
    - Planck Length: $l \sim 10^{-34}$ cm (Planck epoch times c)
  - Gravity and everything else is described by superstrings
    - Spacetime itself is described by dynamics of superstrings