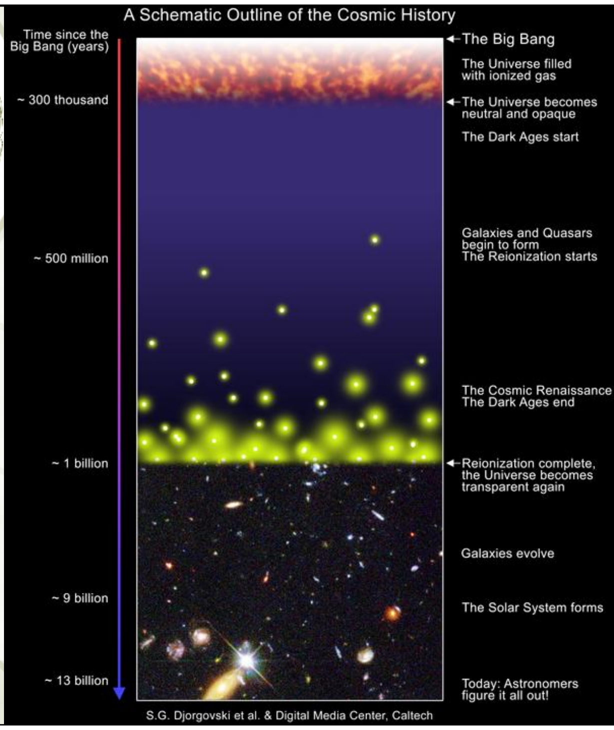
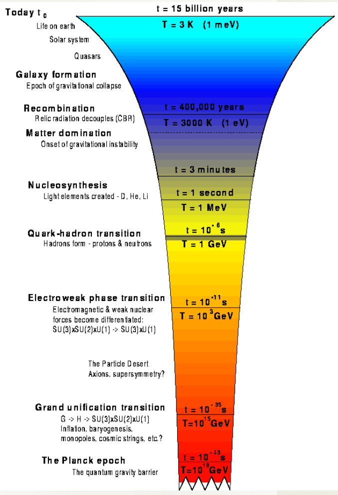
Lecture 18 : *The Early Universe II. Nucleosynthesis*

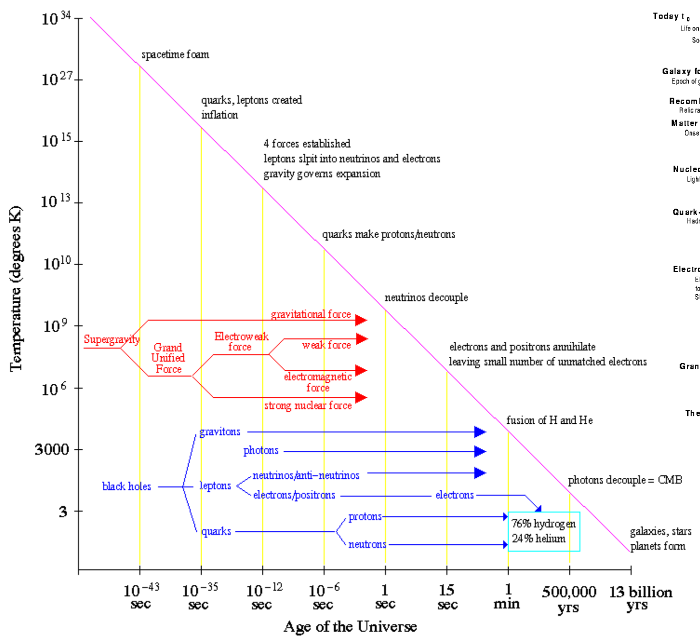
- The structure of “normal” matter
- Nucleosynthesis and the hot big bang
- The density of baryonic matter in the Universe, Ω_B
- Stellar nucleosynthesis
- Recombination and matter/radiation decoupling

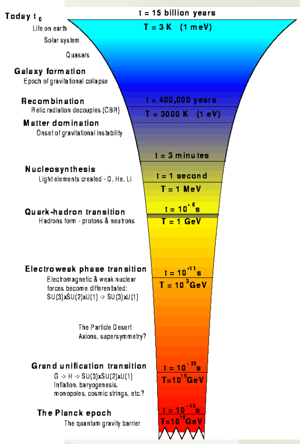


A brief look at the stages of the Universe's life…

- Crude overview:
  - t=0: The Big Bang
  - For first 400,000 yrs, an expanding "soup" of tightly coupled radiation and matter
    - Earliest epochs were "extreme" physics
    - Then more "normal" physics: protons & neutrons form
    - Then came nucleosynthesis
  - After 400,000 yrs, atoms form ("recombination") and radiation and matter "decouple"
  - Following decoupling, matter and radiation evolve independently
  - Galaxies, stars, planets, etc can then form and evolve

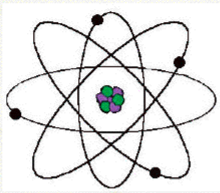






BACKGROUND: THE STRUCTURE OF MATTER

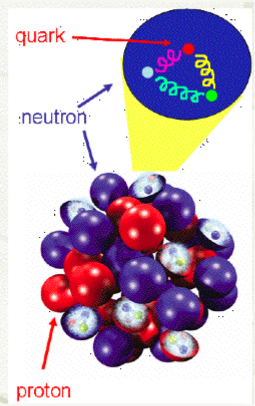
- Atom is made up of…
  - Nucleus (very tiny but contains most off mass)
  - Electrons (orbit around the nucleus)



  - Atom held together by attraction between positively-charged nucleus and negatively-charged electrons.

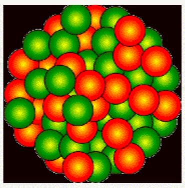
Atomic nuclei

- The nucleus is itself made up of:
  - Protons, **p** (positively charged)
  - Neutrons, **n** (neutral; no charge)
  - Collectively, these particles are known as **baryons**
  - **p** is **slightly** less massive than **n** (0.1% difference)
  - Protons and neutrons bound together by the strong nuclear force (exchange of "gluons")



Elements & isotopes

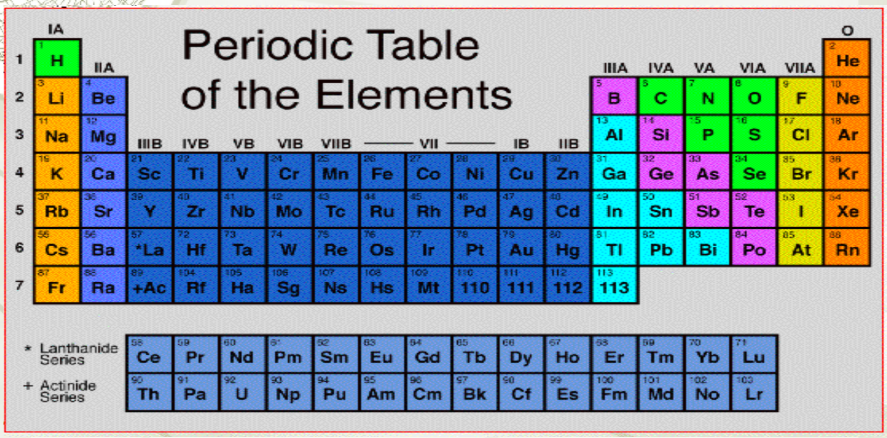
- Number of protons determines element:
  - Hydrogen – 1 proton
  - Helium – 2 protons
  - Lithium – 3 protons
  - Beryllium – 4 protons
  - Boron – 5 protons
  - Carbon – 6 proton
  - …



- Number of neutrons determines the isotope
- e.g., for hydrogen (1 proton), there are three isotopes
  - Normal Hydrogen (H or p) – no neutrons
  - Deuterium (d) – 1 neutron
  - Tritium (t) – 2 neutrons

- There's one more level below this, consisting of quarks…
  - Protons & Neutrons are made up of trios of quarks
  - **Up quarks** & **Down quarks**
  - Proton = 2 up quarks + 1 down quark
  - Neutron = 1 up quark + 2 down quarks
  - There are other kinds of quarks (strange, charm, top, bottom quarks) that make up more exotic types of particles…

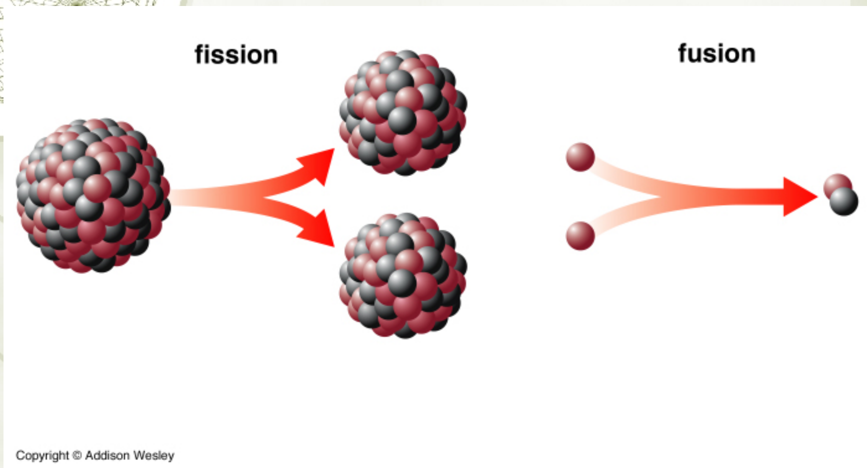
Where did all the nuclei of elements come from?



Nuclear fusion

- Heavier nuclei can be built up from lighter nuclei (or free n, p) by fusion
- Need conditions of very high temperature and density to overcome repulsion of protons
- These conditions are present only in cores of stars and… in the early Universe!
- The original motivation of Gamow, Alpher, & Herman in advocating big bang was that it could provide conditions conducive to nuclear reactions

Fission and fusion



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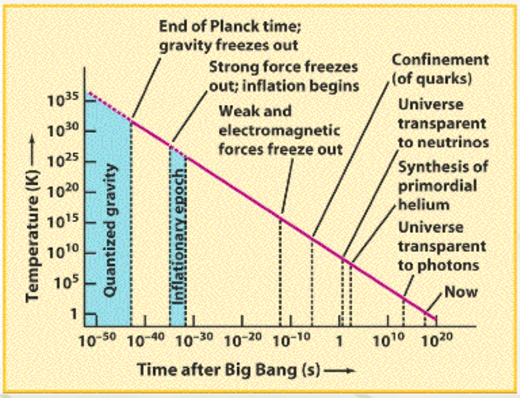
Recall timeline for early Universe…

- At t=1s, neutrinos began free-streaming
- At t=14s, $e^{\pm}$ stopped being created and destroyed
- Temperature continued to drop until protons and neutrons, if they combined, were not necessarily broken apart



NUCLEOSYNTHESIS IN THE EARLY UNIVERSE

- Nucleosynthesis: the production of different elements via nuclear reactions
- Consider universe at t=180s
  - i.e. 3 minutes after big bang
  - Universe has cooled down to 1 billion (10^9) K
  - Filled with
    - Photons (i.e. parcels of electromagnetic radiation)
    - Protons (p)
    - Neutrons (n)
    - Electrons (e)
    - [also Neutrinos, but these were freely streaming]

The first three minutes…

- Protons and Neutrons can **fuse** together to form deuterium (d)

$$n + p \rightarrow D + \gamma$$

- But, deuterium is quite fragile…
- Before t=180s, Universe is hotter than 1 billion degrees.
  - High-T means that photons carry a lot of energy
  - Deuterium is destroyed by energetic photons as soon as it forms

$$D + \gamma \rightarrow n + p$$

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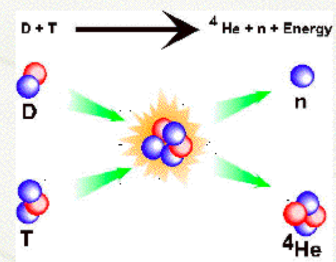
After the first 3 minutes…

- But, after t=180s, Universe has cooled to the point where deuterium can survive
- Deuterium formation is the first step in a whole sequence of nuclear reactions:
  - e.g. Helium-4 (^{4}He) formation:

$$D + D \rightarrow T + p$$

$$T + D \rightarrow {}^4He + n$$



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- An alternative pathway to Helium…

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

- This last series of reactions also produces traces of left over "light" helium (^{3}He)

- Further reactions can give Lithium (Li)

$$ {}^{4}He + T \rightarrow {}^{7}Li + \gamma$$

- Reactions cannot easily proceed beyond Lithium due to the "stability gap"… more about that later

- If this were all there was to it, then the final mixture of hydrogen & helium would be determined by initial number of p and n.
  - If equal number of p and n, everything would basically turn to ^{4}He… Pairs of protons and pairs of neutrons would team up into stable Helium nuclei.
  - Would have small traces of other species
  - But we know that most of the universe is hydrogen… why are there fewer n than p? What else is going on?

Balance of p and n

Protons are more common than neutrons (86% of baryons are p, 14% are n) because:

1. Protons are lower mass thus favored energetically, so they were more abundant to begin with
2. Free neutrons decay quickly

Neutron decay

- Free neutrons (i.e., neutrons that are not bound to anything else) are unstable!
  - Neutrons spontaneously and randomly decay into protons, emitting electron and neutrino

$$n \rightarrow p + e + \overline{\nu}$$

  - Half life for this occurrence is 10.5 mins (i.e., take a bunch of free neutrons… half of them will have decayed after 10.5 mins).

- While the nuclear reactions are proceeding, supply of "free" neutrons is decaying away.
- So, speed at which nuclear reactions occur is crucial to final mix of elements
- What factors determine the speed of nuclear reactions?
  - Density (affects chance of p/n hitting each other)
  - Temperature (affects how hard they hit)
  - Expansion rate of early universe (affects how quickly everything is cooling off and spreading apart).

- Full calculations are complex. Need to:
  - Work through all relevant nuclear reactions
  - Take account of decreasing density and decreasing temperature as Universe expands
  - Take account of neutron decay
- Feed this into a computer…
  - Turns out that relative elemental abundances depend upon the quantity $\Omega_B H^2$
  - Here, Ω_B is the density of the baryons (everything made of protons+neutrons) relative to the critical density.

$$\Omega_B = \frac{\rho_B}{\rho_{crit}} = \frac{\rho_B}{3H_0^2/(8\pi G)}$$

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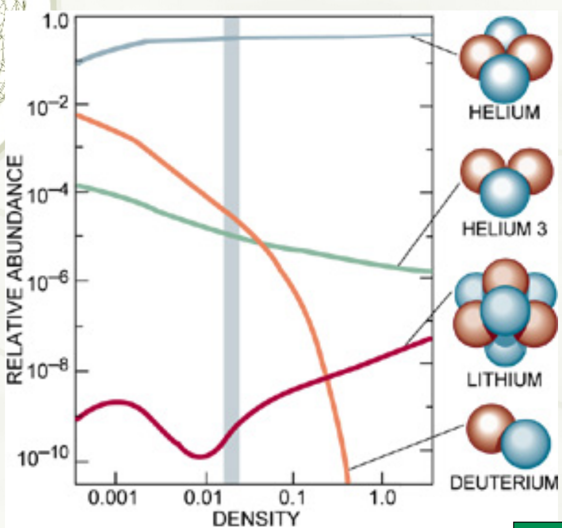
Dependence of abundances on $\Omega_B H^2$

From M.White's webpage, UC Berkeley



$\Omega_B h^2$

$$h = \frac{H_0}{100 km/s/Mpc}$$

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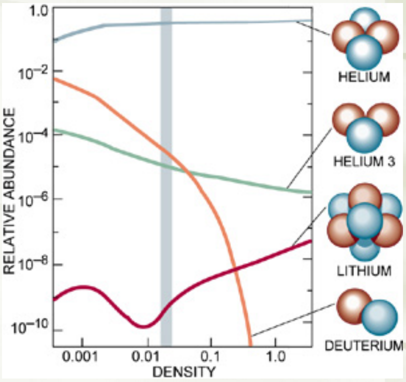
- We can use the spectra of stars and nebulae to measure abundances of elements
  - These need to be corrected for reactions in stars
- By measuring the abundance of H, D, ^{3}He, ^{4}He, and ^{7}Li, we can
  - Test the consistency of the big bang model -- are relative abundances all consistent?
  - Use the results to measure the quantity $\Omega_B h^2$

Results

- All things considered, we have $\Omega_B h^2 \approx 0.019$.
- If H_0=70km/s/Mpc,
  - h=0.70
  - $\Omega_B \approx 0.04$
- This is far below Ω=1!
- Baryons alone would give open universe

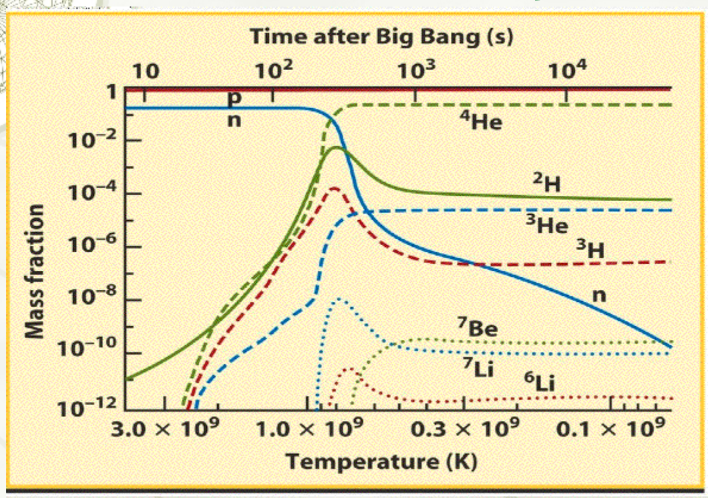


$\Omega_B h^2$

$$\Omega_B \approx 0.049$$

Planck results, 2013

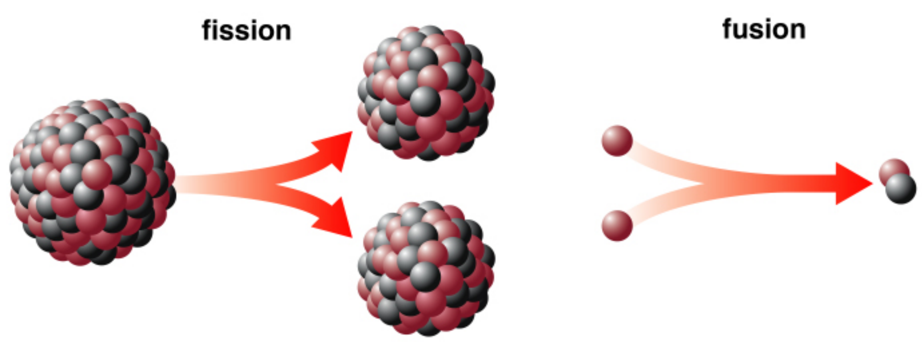
End result of big bang nucleosynthesis



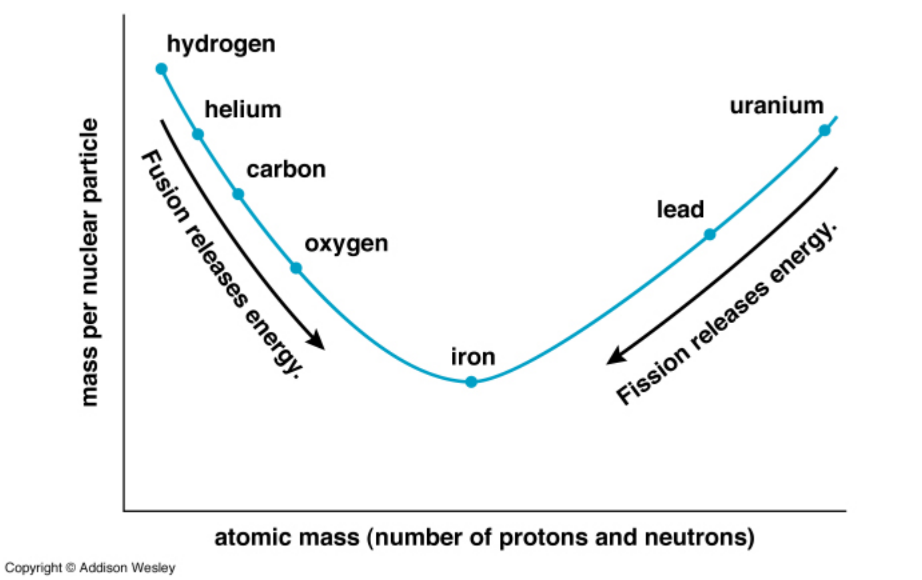
How are other elements formed?

- Big Bang Nucleosynthesis produces most of the hydrogen & helium observed today.
- But what about other elements?
  - There are naturally occurring elements as heavy as Uranium
  - Some elements (e.g., Carbon, Nitrogen, Oxygen) are rather plentiful (1 atom in every 10^5 atoms)
  - Astronomers believe these elements were formed in the cores of stars long after the big bang
    - Theory of stellar nucleosynthesis was first worked out by Burbidge, Burbidge,Folwer, & Hoyle in 1957

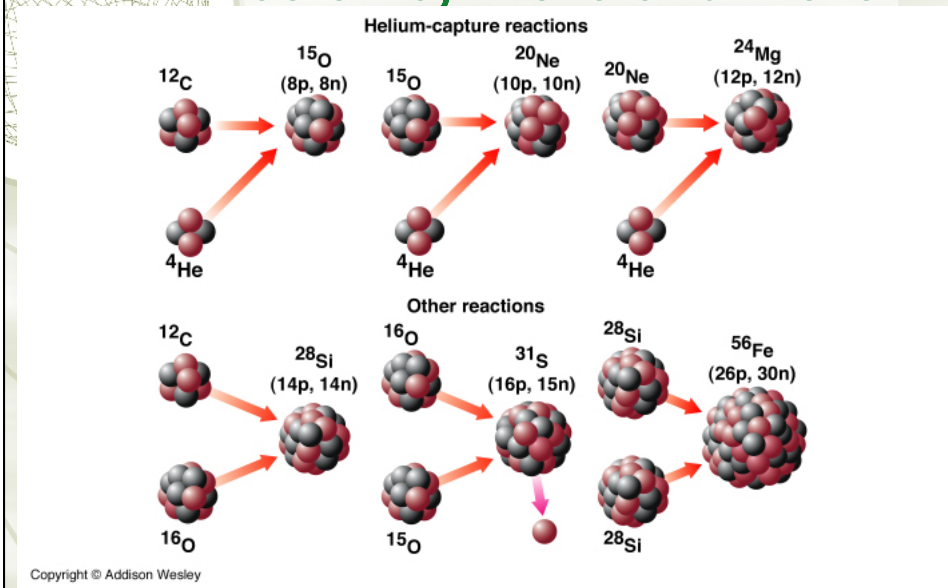
Fission and fusion



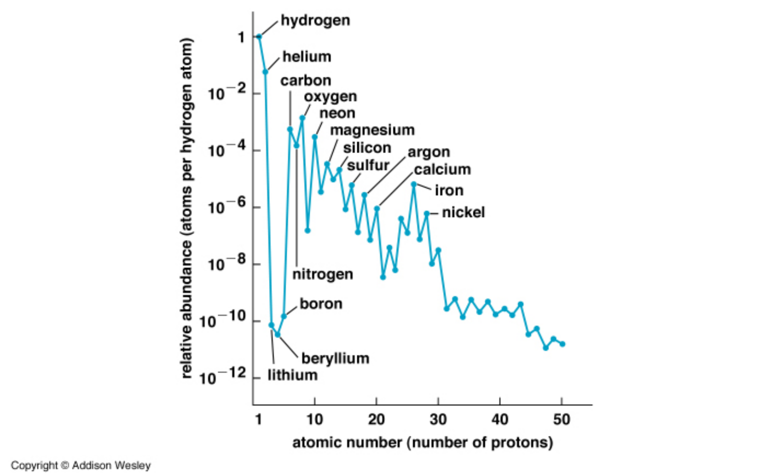
Fission, fusion, and nuclear



Fusion of more and more

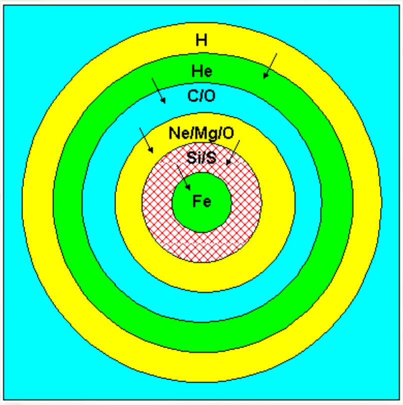


Elemental abundance in the Sun



Stellar "burning"

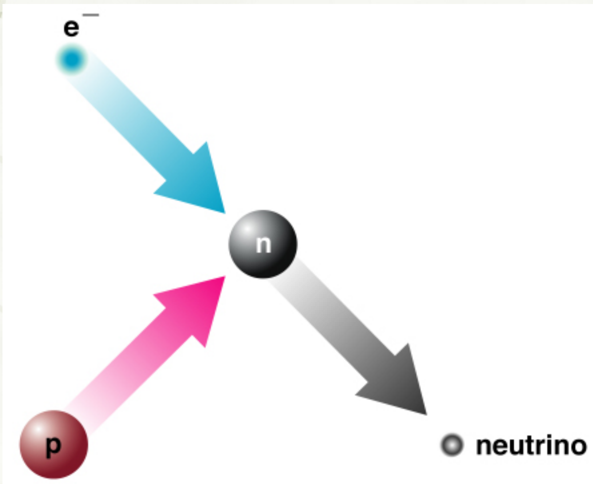
- In the normal life of a star (main sequence)…
  - nuclear fusion turns Hydrogen into Helium
- In the late stages of the life of a massive star…
  - Helium converted into heavier elements (carbon, oxygen, …, iron)
  - "Triple-alpha" process bridges stability gap from Be to C
  - At end of star's life, get an onion-like structure (see picture to right)



Iron, the most stable nucleus

- What's special about iron?
  - Iron has the most stable nucleus
  - Fusing hydrogen to (eventually) iron releases energy (thus powers the star)
  - Further fusion of iron to give heavier elements would require energy to be put in…
  - Can only happen in the energetic environment of a **supernova** explosion

Proton-electron interaction produces a neutron (and other stuff)

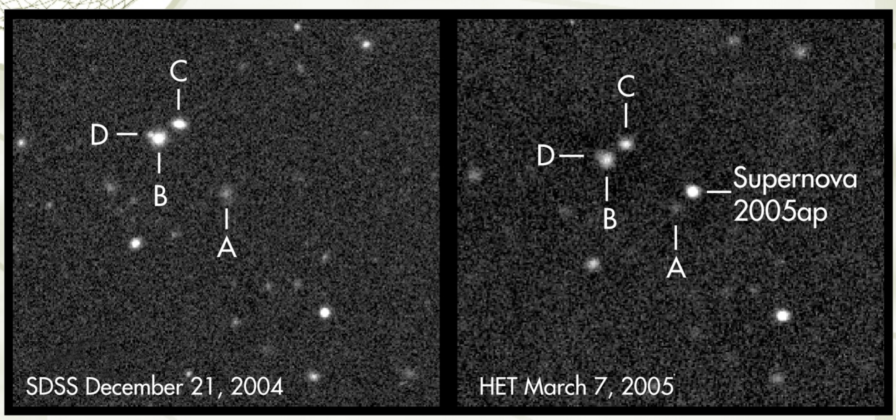


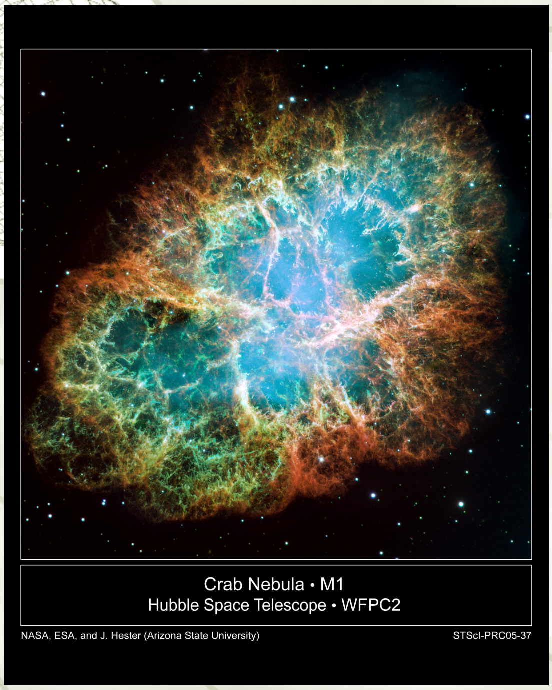
Core collapse

Boom!

(the star explodes)

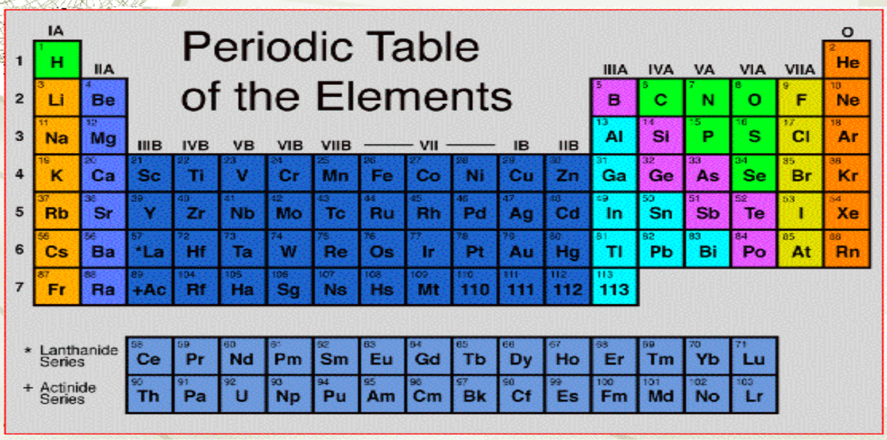
Supernovae briefly outshine their parent galaxies





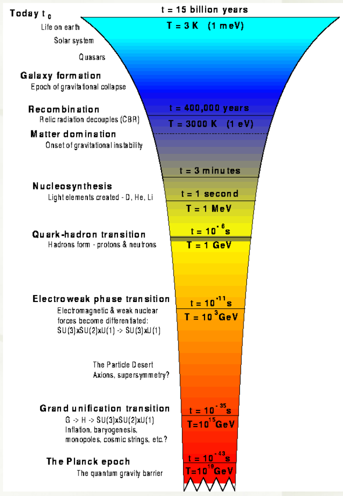
- The Crab Nebula is the remnant of a SN that exploded in 1054 AD
- We directly see a new generation of heavy elements

Where did all the nuclei of elements come from?



After nucleosynthesis

- Nucleosynthesis was essentially completed by t=30min ,with free neutron abundance down to <1%
- Universe continued to expand, with energy density in radiation dropping more rapidly than energy density in matter
- After $t=10^{12}$s (30,000yrs), when ρ_{rad} fell below ρ_{matter} , the Universe ceased to be radiation-dominated era and entered the matter-dominated era
- At this time, the expansion rate of the Universe changed from $R \propto t^{1/2}$ to $R \propto t^{2/3}$
- With faster expansion rate, the radiation temperature began to drop more rapidly



Recombination and beyond

- When radiation temperature reached T=3000K, at t=400,000 yrs, photons were no longer energetic enough to keep electrons from binding to protons
- This marked the time of "recombination": ionized plasma of electrons and protons (with some Helium nuclei) combined into mostly neutral hydrogen atoms (with some Helium atoms)
- Photons interact less with bound electrons than free electrons, so radiation began to stream freely after recombination
- This marked the event of *decoupling of matter and radiation*
- After decoupling, radiation has been freely-streaming through Universe. CBR is the redshifted remnant of radiation that was last "in contact" with matter at z~1100
- Matter also began to evolve freely at that time; when it finally became cool enough, galaxies began to form (more later!)

Next time…

- What do more observations tell us about the parameters for the real Universe?