We Are All Stardust: Nuclear Physics in the Cosmos

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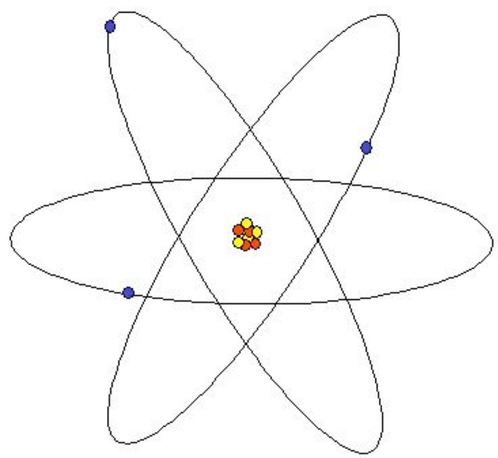
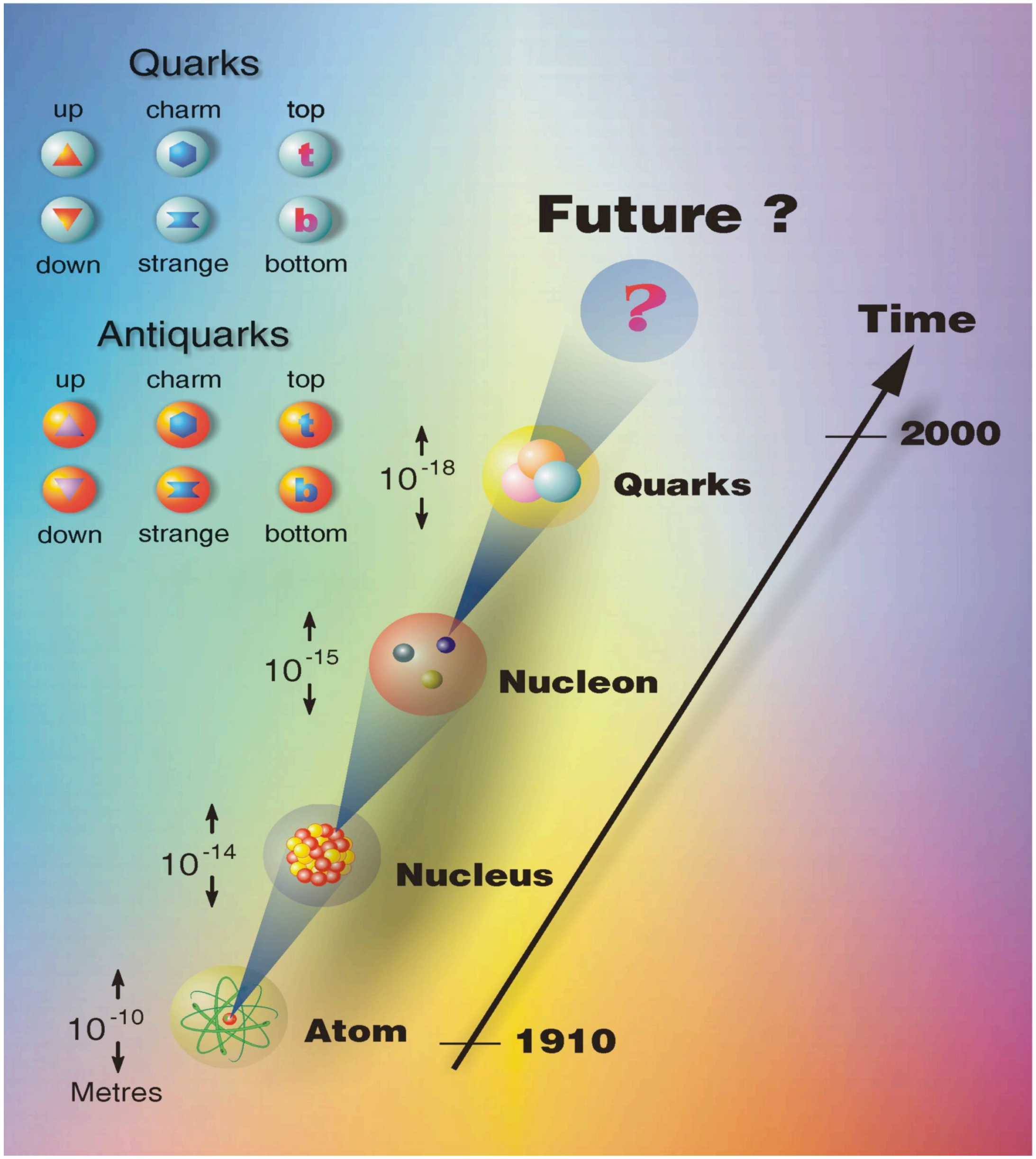
What is our world made of? According to the ancient Greek philosopher Democritus, ATOMS

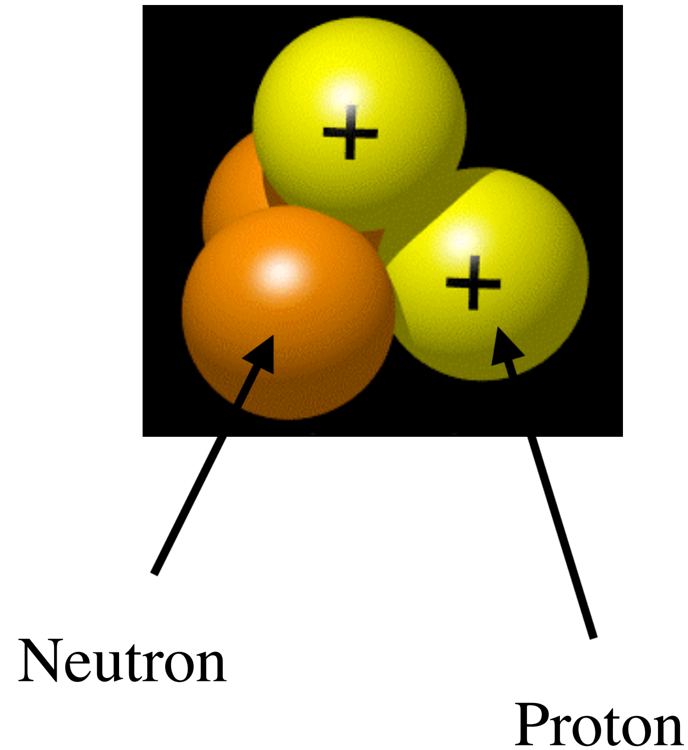


But wait, now we know there is much more to the story. . . atoms are made up of even *SMALLER* particles!

What's in an Atom?

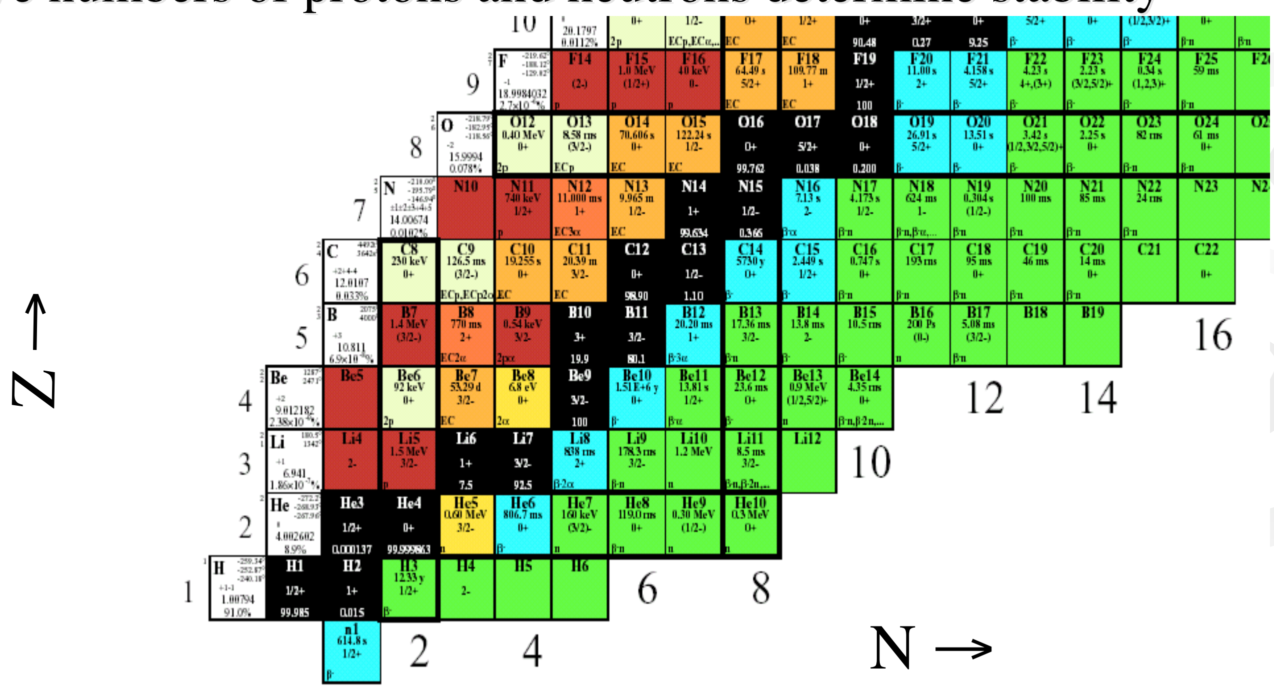


How about a nucleus?

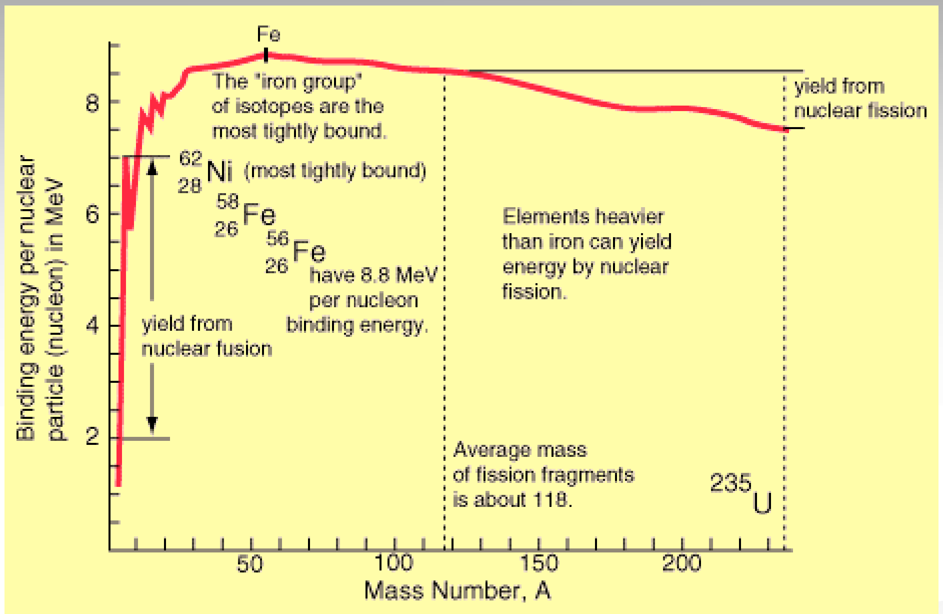


Atomic Nuclei

- Atoms made up of electrons and nuclei
- Nuclei made up of protons and neutrons
- Number of protons, Z, determines element
- Number of neutrons, N, determines isotope
- Z + N = A, the atomic mass
- Nuclei are labeled as ^{A}Ch, where Ch is a symbol for the chemical element; e.g., ^{1}H is hydrogen-1 (a single proton) and ^{4}He is helium-4 (2 protons and 2 neutrons)
- Relative numbers of protons and neutrons determine stability



Nuclear Masses and Binding Energy

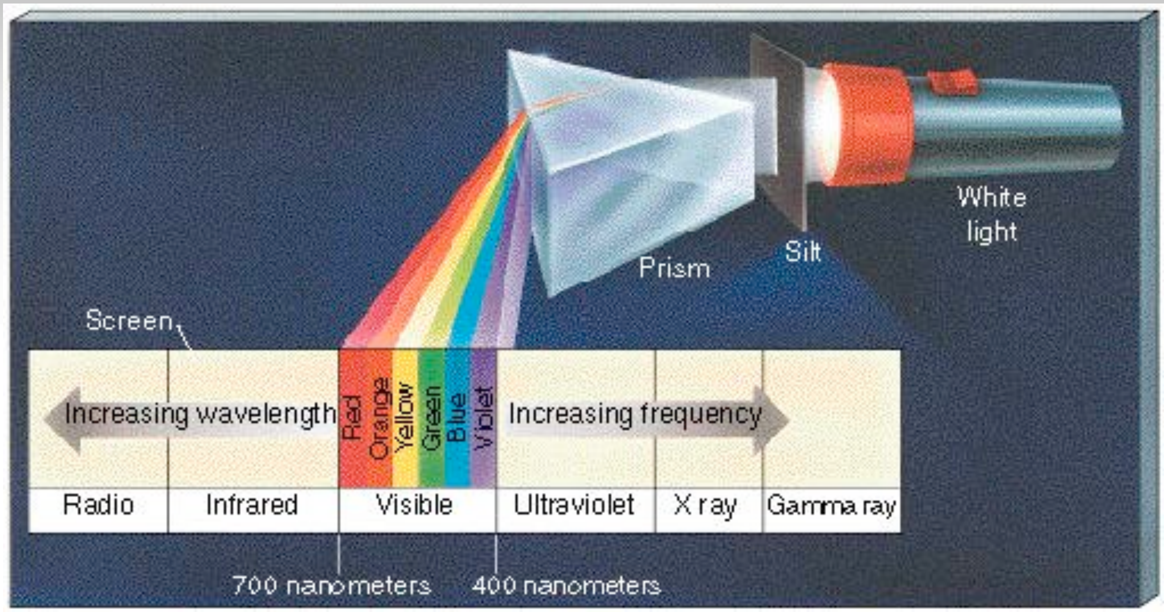


- Einstein: $E_0 = mc^2$, where E_0 is the rest energy
- Nuclei with smaller masses per nucleon are more tightly bound, and have larger binding energy per nucleon
- In nuclear reactions, difference between the rest energies of reacting nuclei and product nuclei is released as kinetic energy
- Fusion of light nuclei & fission of heavy nuclei release lots of energy

Abundances of Atomic Nuclei

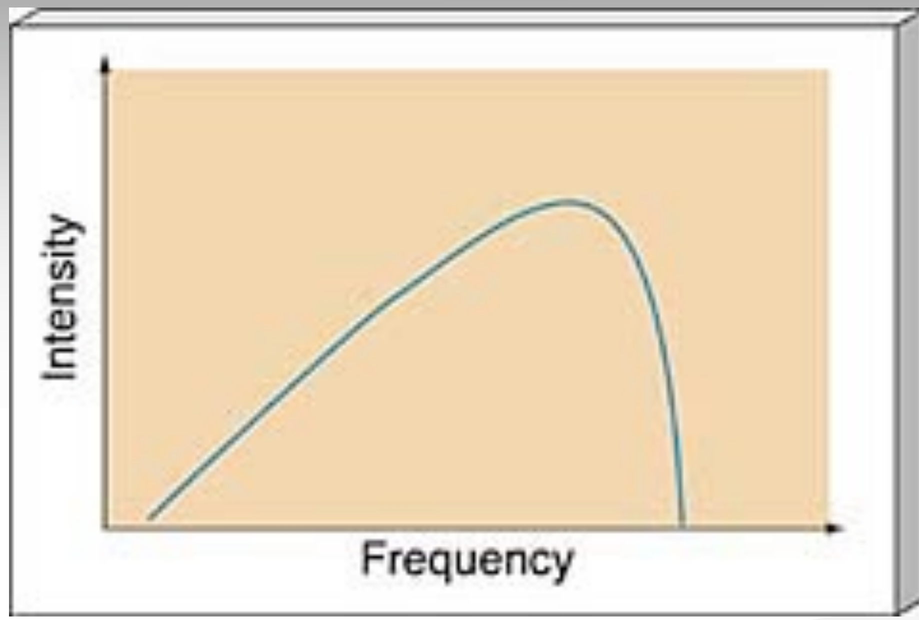
- Which nuclei are found in the universe, and in what amounts?
- 2 sources of information:
  - Starlight (provides elemental abundances)
  - Primitive Meteorites (provide isotopic abundances)
- Once we know the abundances, we can use physical laws to determine the conditions needed to produce them

The Nature of Light



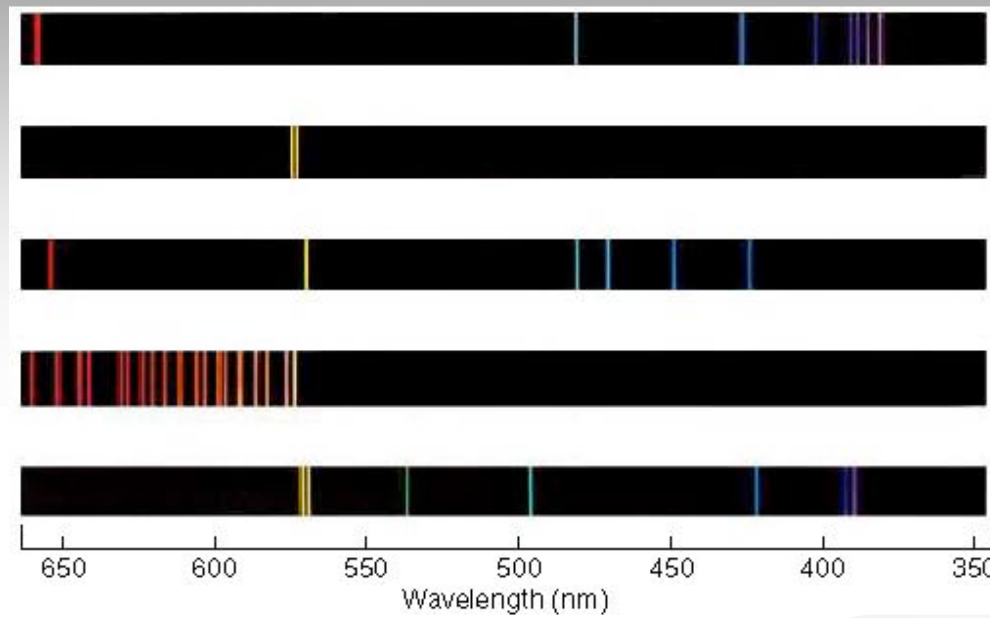
- Light: an electromagnetic wave
- Ordinary white light a mixture of different colours
- Different colours correspond to different wavelengths & frequencies

Light From Hot, Opaque Objects



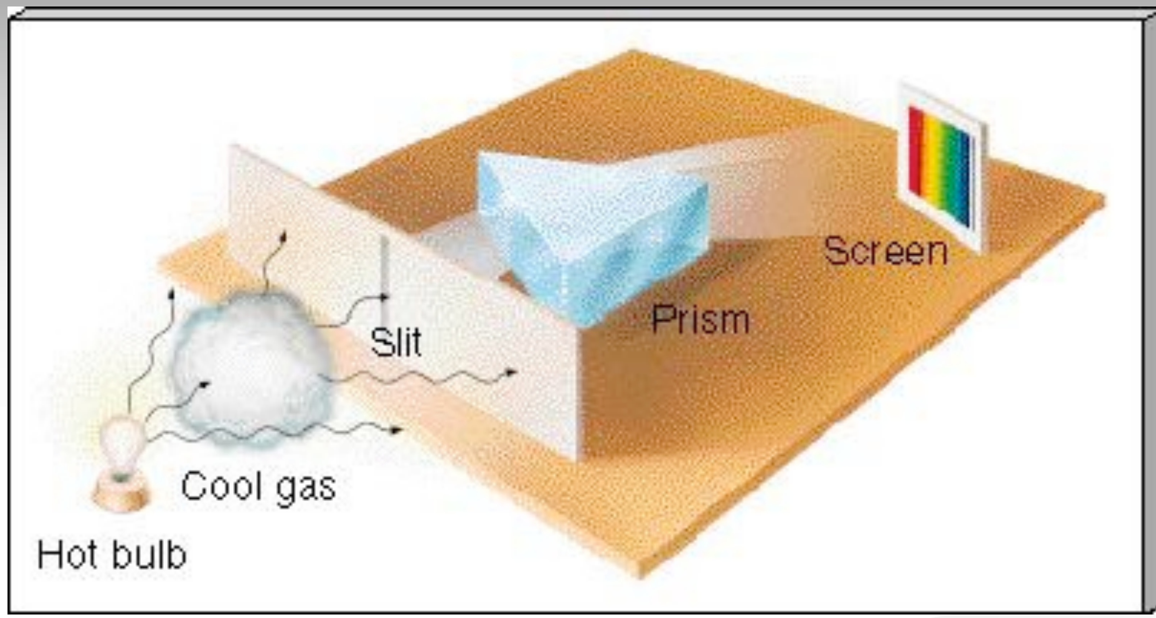
- Every opaque object emits thermal electromagnetic radiation (light)
- Composition of the light is characteristic of the object's temperature
- Intensity is a continuous distribution in frequency (or colour)
- Frequency (colour) of peak of the distribution depends on temperature
- E.g., electric stove, the Sun

Light from Diffuse Gases



- As explained by quantum mechanics, atoms in diffuse (relatively transparent) gases emit and absorb light only at certain frequencies (wavelengths)
- Those wavelengths (colours) are characteristic of the type of atom (chemical element)
- The spectra of all the different naturally occurring chemical elements have been measured in the lab
- E.g., neon signs

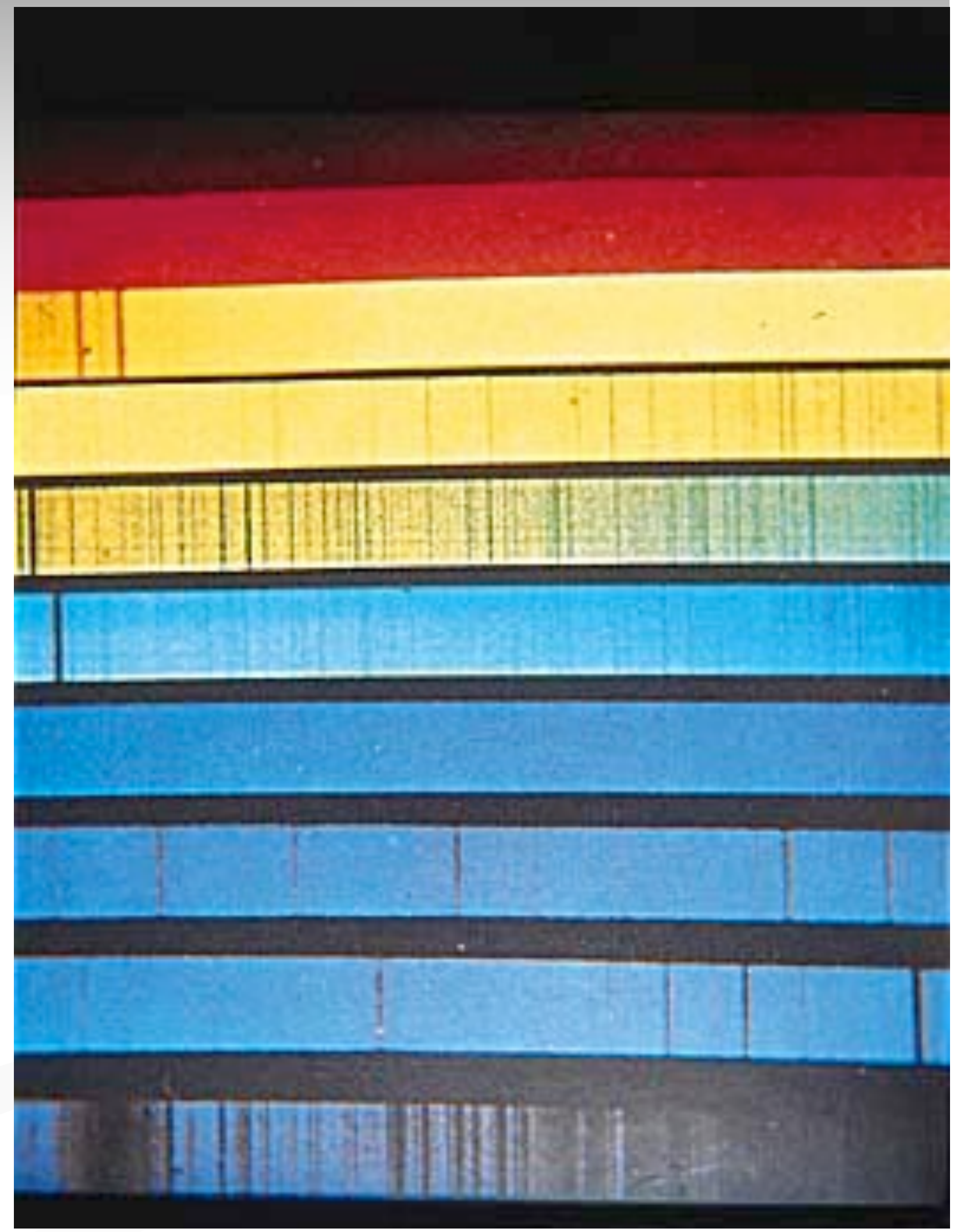
Absorption Lines



- A thermally radiating light bulb viewed from behind a relatively cool gas leads to the continuous spectrum as before, but with dark lines present at certain colours.
- The colours of these absorption lines are uniquely characteristic of the elements in the gas

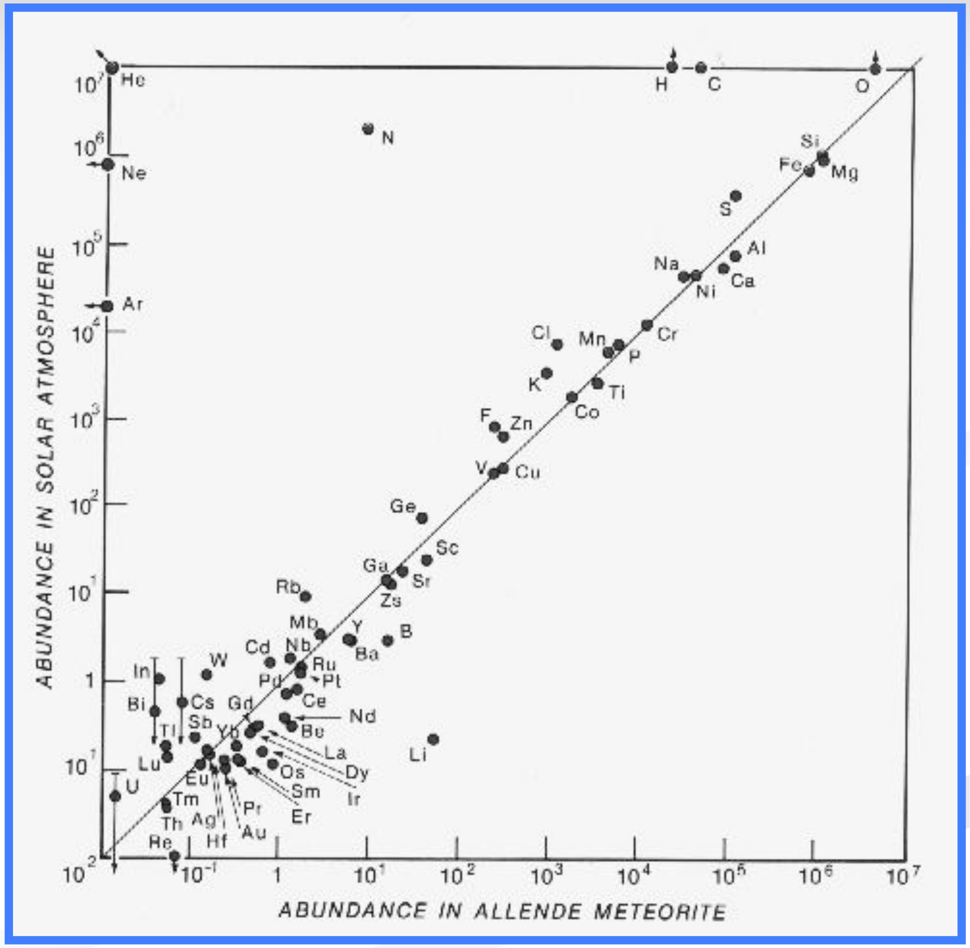
The Solar Spectrum

- Relatively cool, diffuse gas near the Sun's surface absorbs continuous, thermal radiation from the opaque, hot solar interior
- Temperature of surface is 6000 K, and temperature of centre is 16 million K
- Comparing solar absorption lines with laboratory spectra allows determination of elemental abundances in solar atmosphere

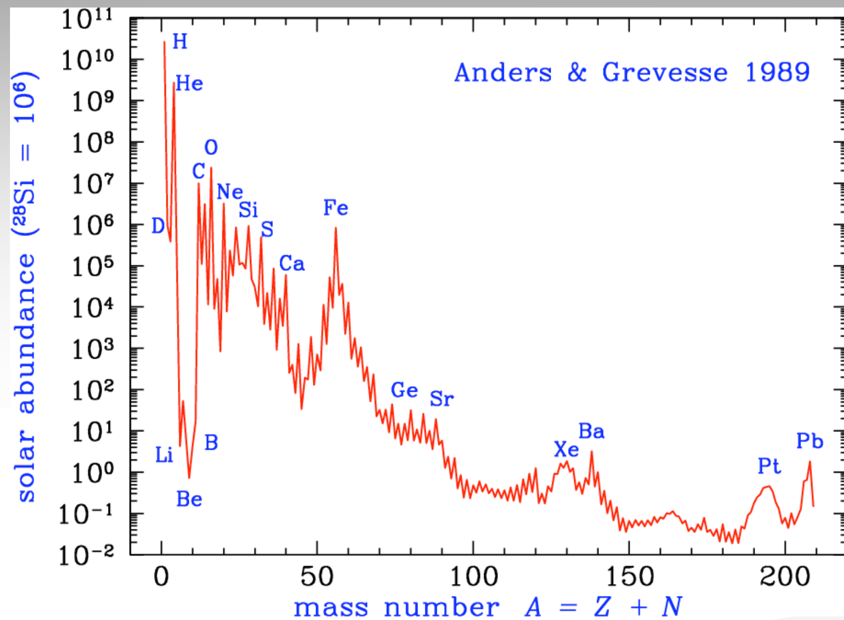


Solar & Meteoritic Abundances

- Solar absorption lines in general yield only chemical information (which element)
- Meteorites can be examined in the lab much more thoroughly and precisely, allowing determination of isotopic abundances too
- Agreement between two sources of abundance information is excellent



Solar System Abundances



- ^1H by far most abundant
- By mass, ^4He second, then ^{16}O, ^{12}C, ^{20}Ne, and ^{56}Fe
- Sun (and therefore, solar system) is 71% hydrogen & 27% helium; all other elements make up only 2% of the mass of the solar system, even though they're all heavier than H and He
- Other stars: 70-75% H, 25-30% He
- This gives a clue to the origin of the lightest elements, that they are produced differently from all the rest

Forces of Nature

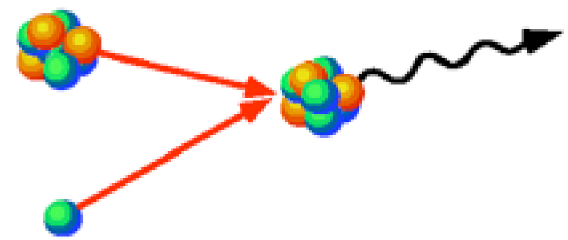
- Gravity:

  affects everything, even light, but only really important in large concentrations of matter such as planets, stars, galaxies, clusters of galaxies, the universe
- Weak Nuclear Force: responsible for radioactive decay & some nuclear reactions
- Electromagnetic Force: electricity, magnetism, felt by all charged particles
- Strong Nuclear Force:

  felt by protons and neutrons, holds the nucleus together; involved in all nuclear reactions

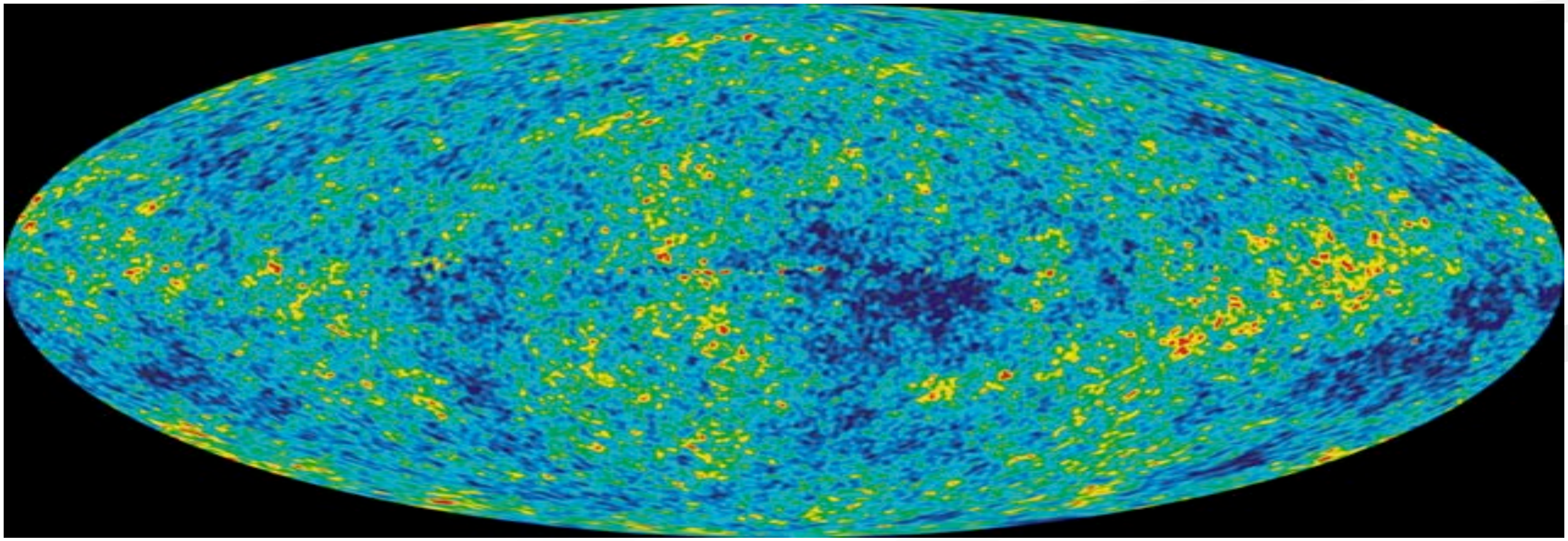
Thermonuclear Fusion Reactions

- Positively charged nuclei repel one another due to electromagnetic force
- If they get close enough together, the dominant strong nuclear force can be felt
- Probability of a reaction depends very strongly on temperature
- Only at very high temperatures of a few million K or higher can fusion occur, for typical pressures

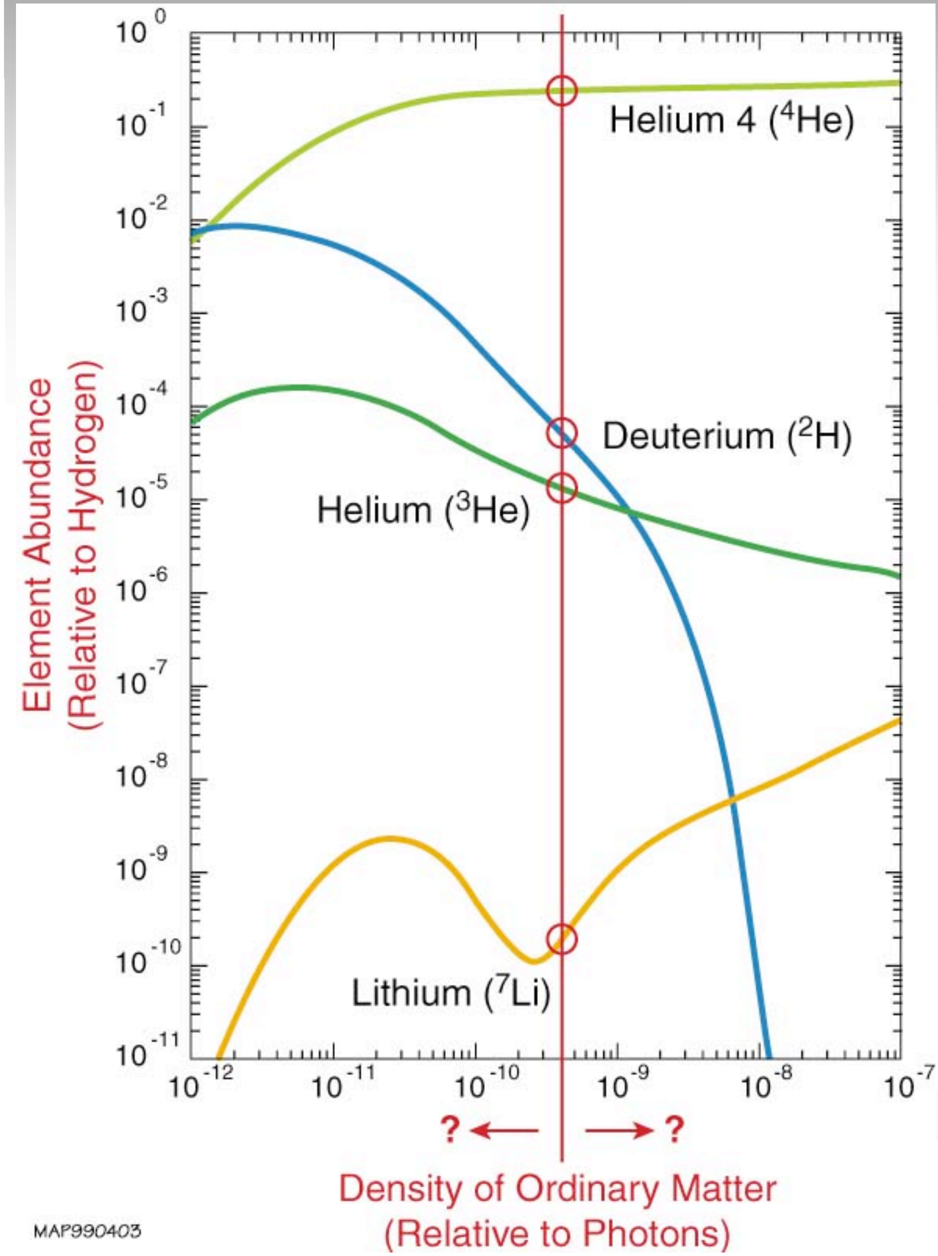


The Big Bang Theory

- Expansion of the universe: distant galaxies are flying away from us at speeds proportional to their distance (the Hubble law)
- There is a cosmic microwave background radiation that has nearly the same intensity in every direction; it is the thermal radiation of the universe, the radiant heat left over from the Big Bang, and corresponds to a temperature of 2.7 K

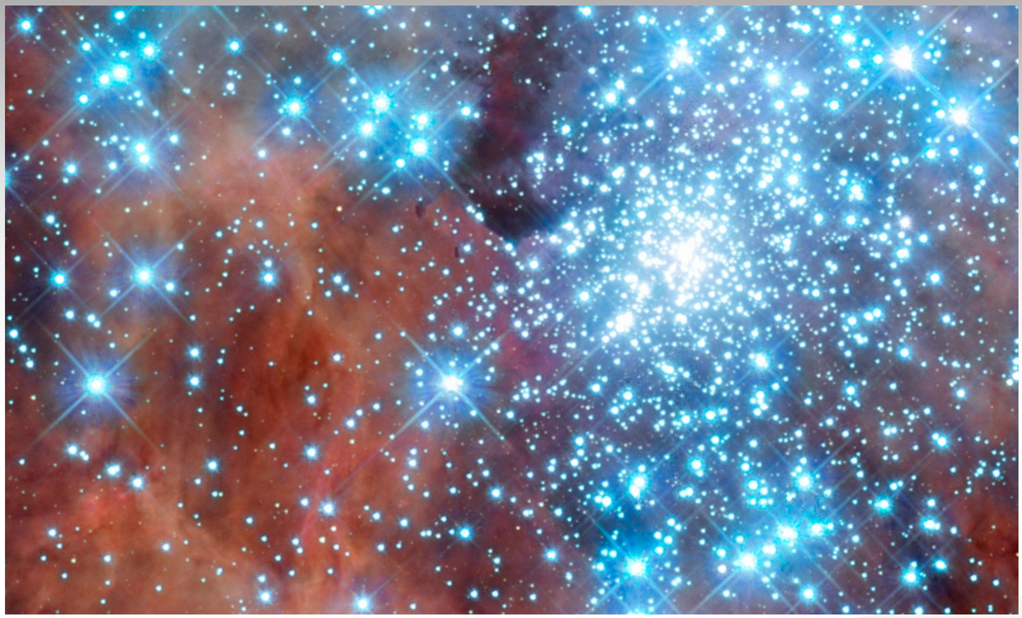


Big Bang Nucleosynthesis



- The abundances of the lightest elements agree with calculations of a period of thermonuclear fusion reactions in the first few minutes after the Big Bang
- Big Bang nucleosynthesis produced H, He, & trace quantities of Li

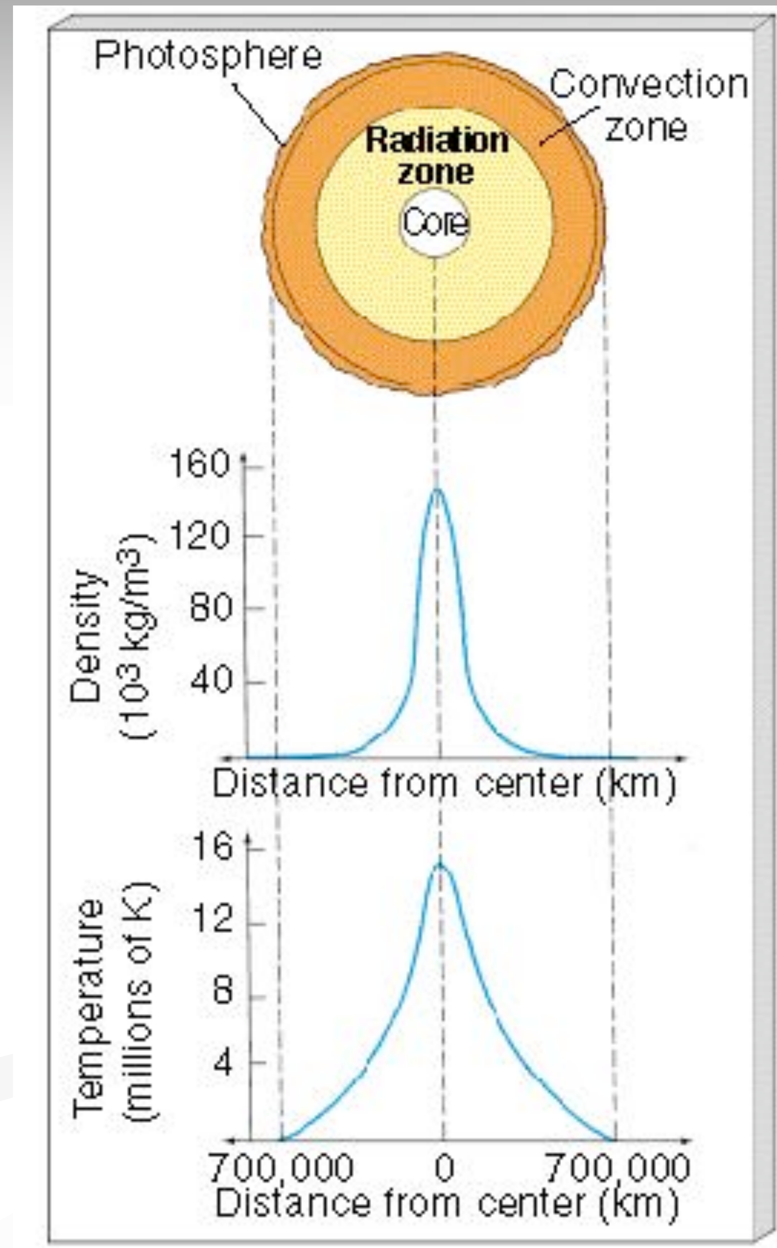
Stars



- Stars are hot balls of gas powered by internal nuclear energy sources
- The pressure at the centre must support the weight of the overlying layers: gravity tends to collapse a star under its own weight; as it shrinks, the pressure, temperature, and density all increase until the pressure balances gravity, and the star assumes a stable configuration
- For gas spheres at least 1/10 the mass of the Sun, the central temperature becomes hot enough to initiate thermonuclear fusion reactions
- Nuclear reactions in the hot, dense core are the power source of the Sun and all other stars

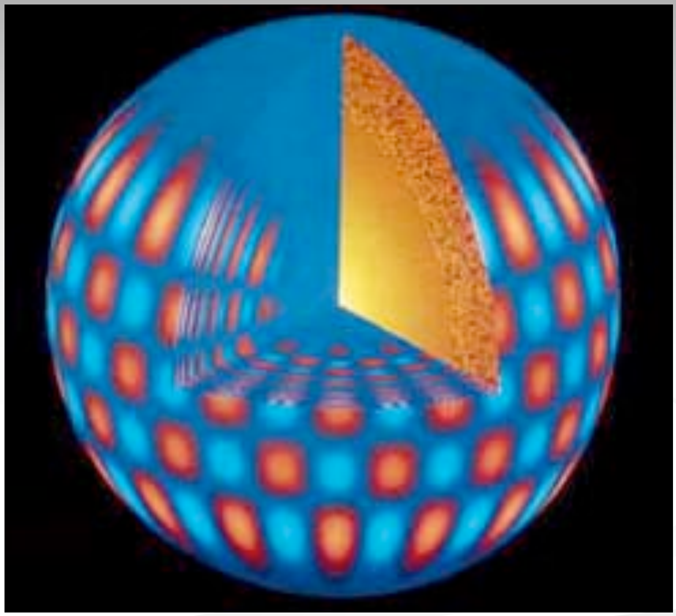
The Sun

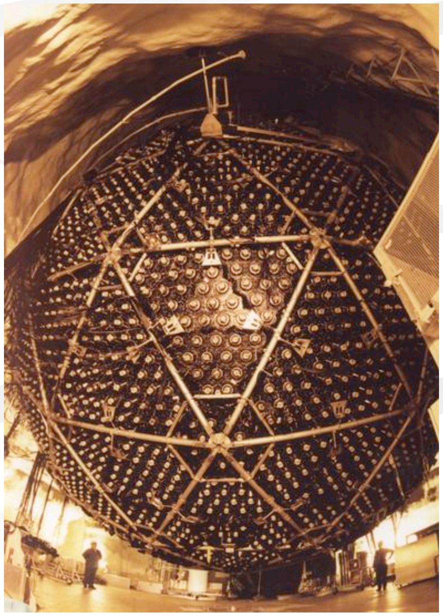
- Solar centre is about 150 times denser than water (8 times denser than heavy metals such as uranium)
- Central pressure is more than 200 billion times atmospheric pressure
- Central temperature is 16 million K
- Light produced in the core requires ~ 40 million years to wend its way to the surface, where it can fly freely



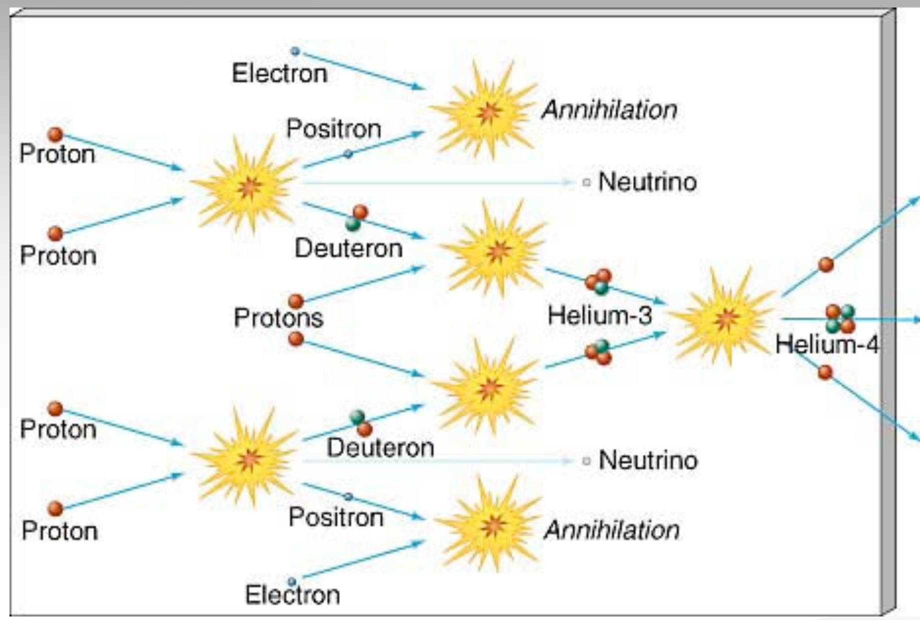
How Do We Know All That?

- Helioseismology (study of surface vibrations of the Sun) allows us to infer solar temperature, density, composition, sound speed, from 5% of solar radius to the surface
- Sudbury Neutrino Observatory and other detectors measure solar neutrinos, weakly interacting particles created in nuclear reactions and radioactive decays in the solar core, which then fly right through the Sun and can be detected on Earth



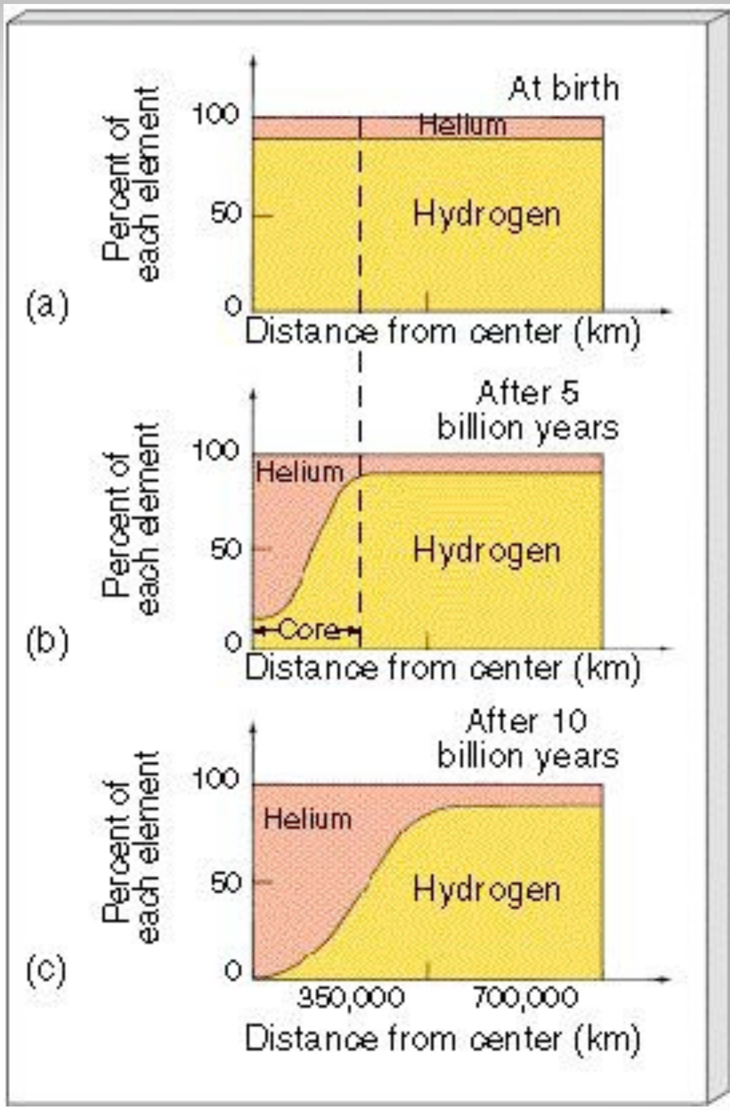


How Does the Sun Generate Energy?



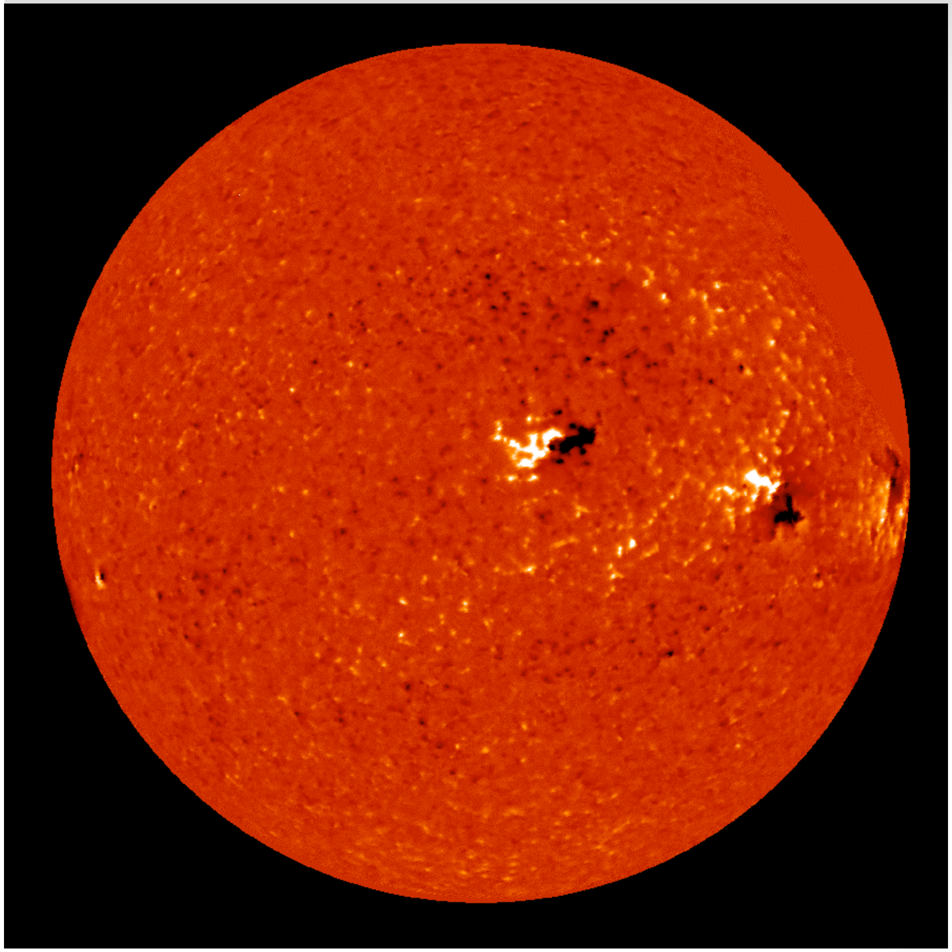
- 4 hydrogen nuclei (protons) are fused into a single ^{4}He nucleus, with the emission of 2 positrons and 2 neutrinos
- This is very efficient, releasing about 1% of the binding energy, an enormous amount of energy
- The vast majority of stars generate energy the similarly, by fusing hydrogen into helium

How Long Can This Go On?



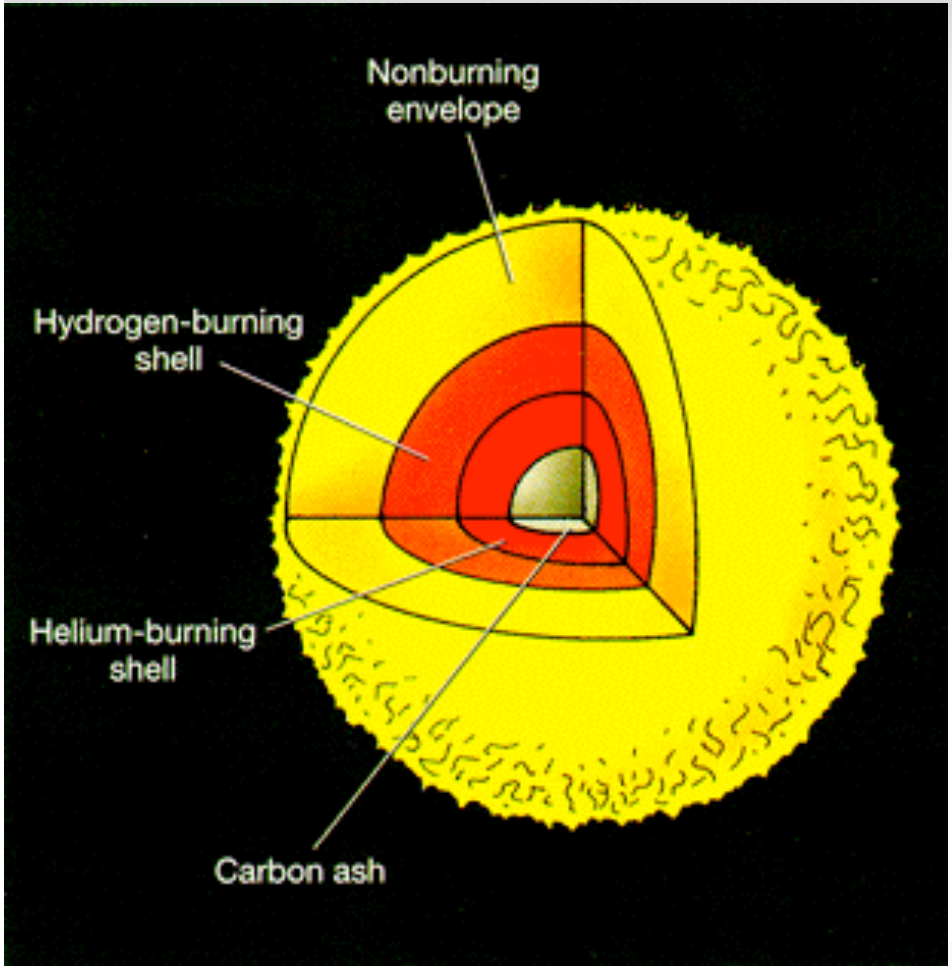
- Sun started as 71% H by mass, 27% He
- Gradually, H in the core is fused into He
- Presently, ~ 4.6 billion years after it started shining, the Sun's core H is about 1/2 gone
- Will continue fusing H into He in the core for another 5 Gyr
- Then what?

Red Giant Phase



- Inert He core contracts, outer layers expand, Sun becomes red giant
- H fuses into He in a shell surrounding the He core
- Size and mass of inert He core continue to expand
- The more massive the core becomes, the more pressure is required to support it and the overlying layers, so temperature rises
- Eventually, becomes hot enough for He to fuse into carbon via 3 alpha reaction ($^4He+^4He+^4He \rightarrow ^{12}C$)
- Some carbon fused into oxygen

After Core Helium Exhaustion

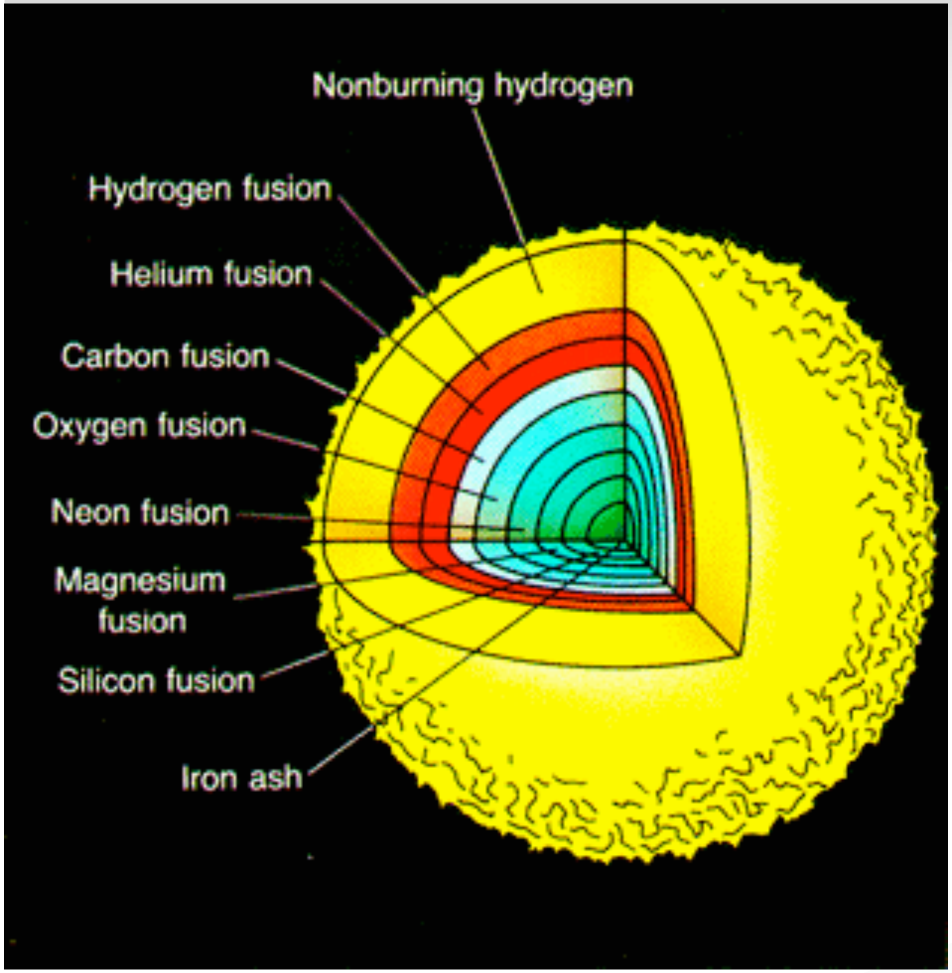


- Inert carbon core (the ashes of helium burning)
- He-burning shell
- He layer (the ashes of hydrogen burning)
- H-burning shell
- Hydrogen-rich envelope
- Core never gets hot enough to burn carbon

Planetary Nebula Phase

- Star ejects outer layers, enriching interstellar medium with elements produced during the star’s life
- The core, composed predominantly of carbon, oxygen, and helium, becomes a white dwarf, a stellar cinder that gradually cools, no longer able to generate energy by nuclear reactions

How About More Massive Stars?



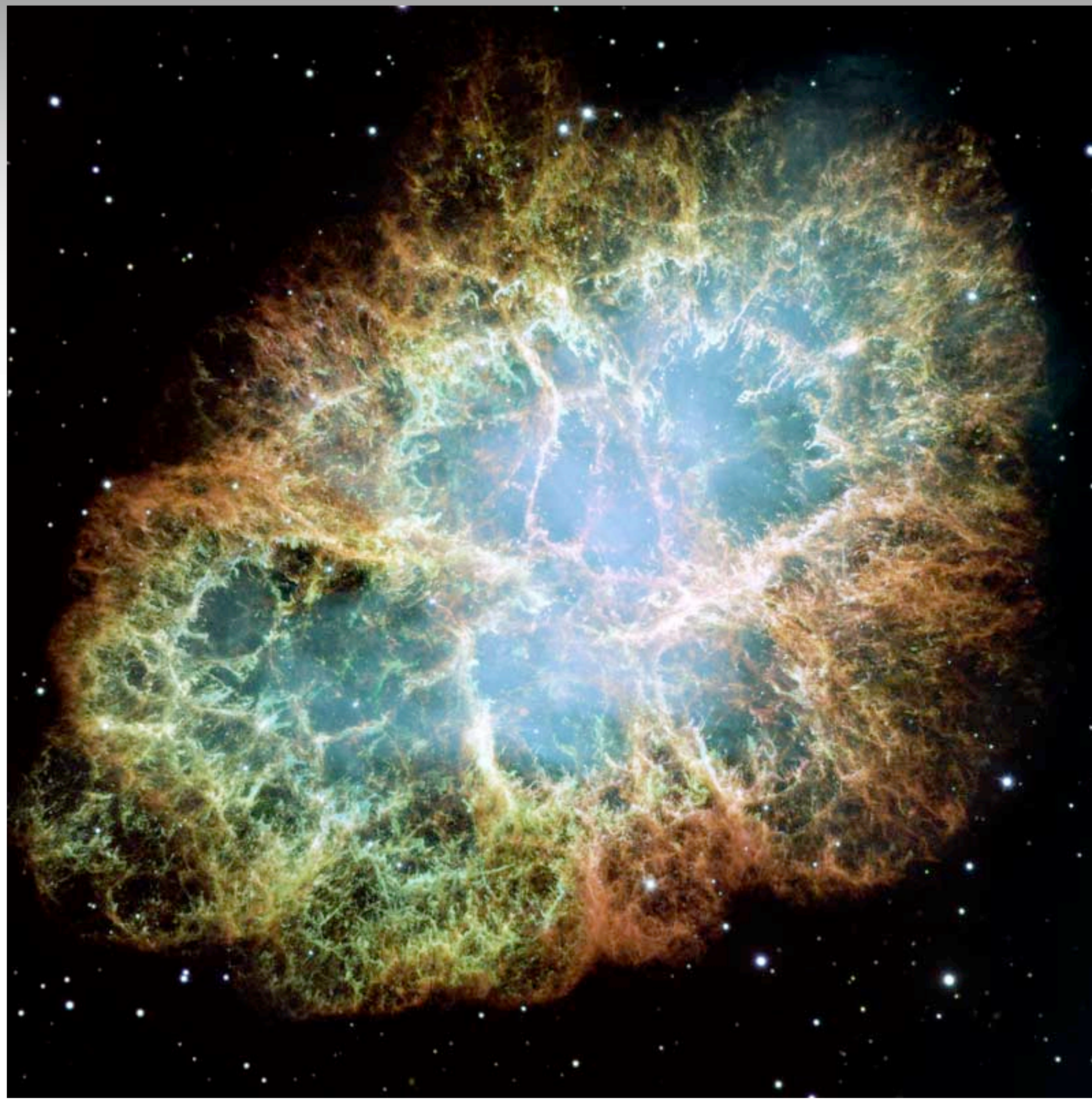
- After core helium fusion comes carbon fusion, oxygen fusion, & silicon fusion
- Creates an onion-like structure, with an inert iron core surrounded by progressively cooler burning shells and a hydrogen-rich envelope

Major Stellar Fusion Processes

Fuel	Major Products	Threshold Temperature (K)
Hydrogen	Helium	4 Million
Helium	Carbon, Oxygen	100 Million
Carbon	Oxygen, Neon, Sodium, Magnesium	600 Million
Oxygen	Magnesium, Sulfur, Phosphorous, Silicon	1 Billion
Silicon	Cobalt, Iron, Nickel	3 Billion

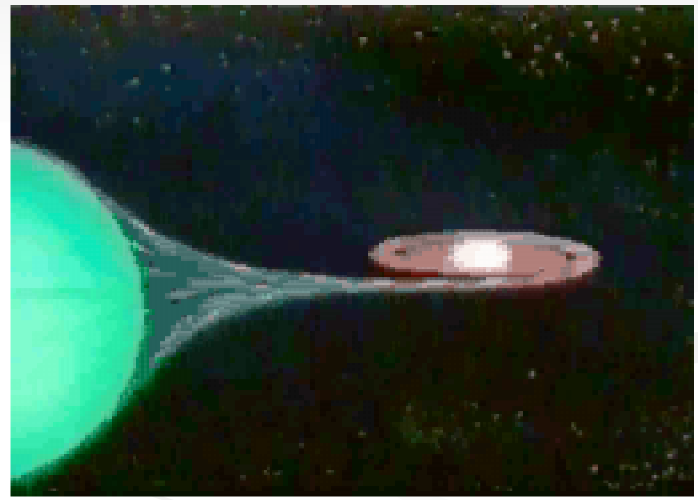
Core-Collapse Supernova

Supernova Remnant

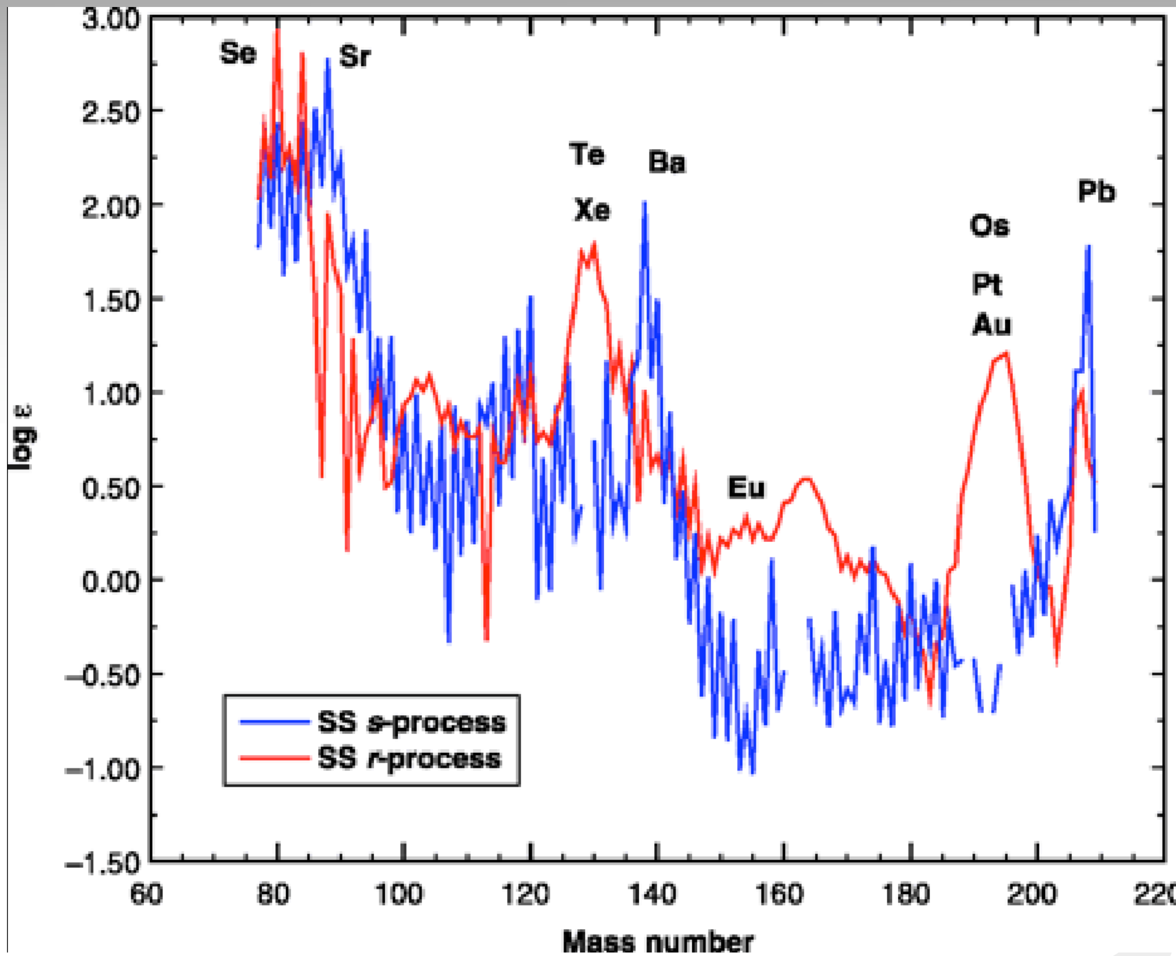


Type Ia Supernovae

- Another type of supernova takes place in binary star systems
- If a white dwarf accretes sufficient matter from its stellar companion, it detonates in a cataclysmic thermonuclear explosion



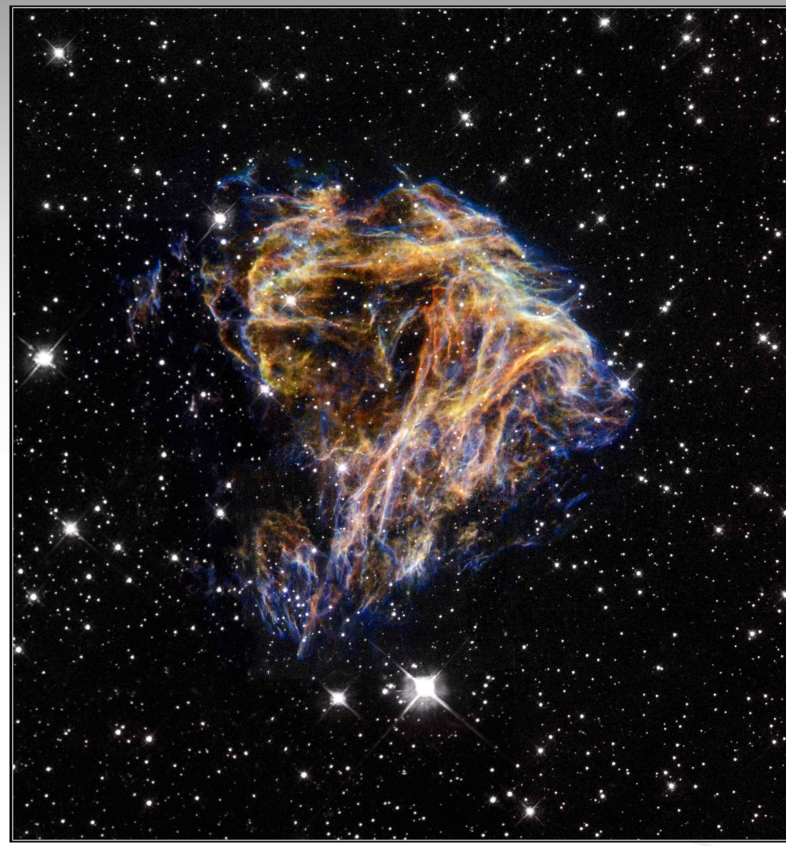
Heavy Element Abundances



~1/2 of chemical elements w/ A > 70 produced in the rapid neutron capture *(r)* process: neutron captures on rapid timescale (~1 s) in a hot (1 billion K), dense environment (>10^{20} neutrons cm^{-3})

The other half are produced in the slow neutron capture process

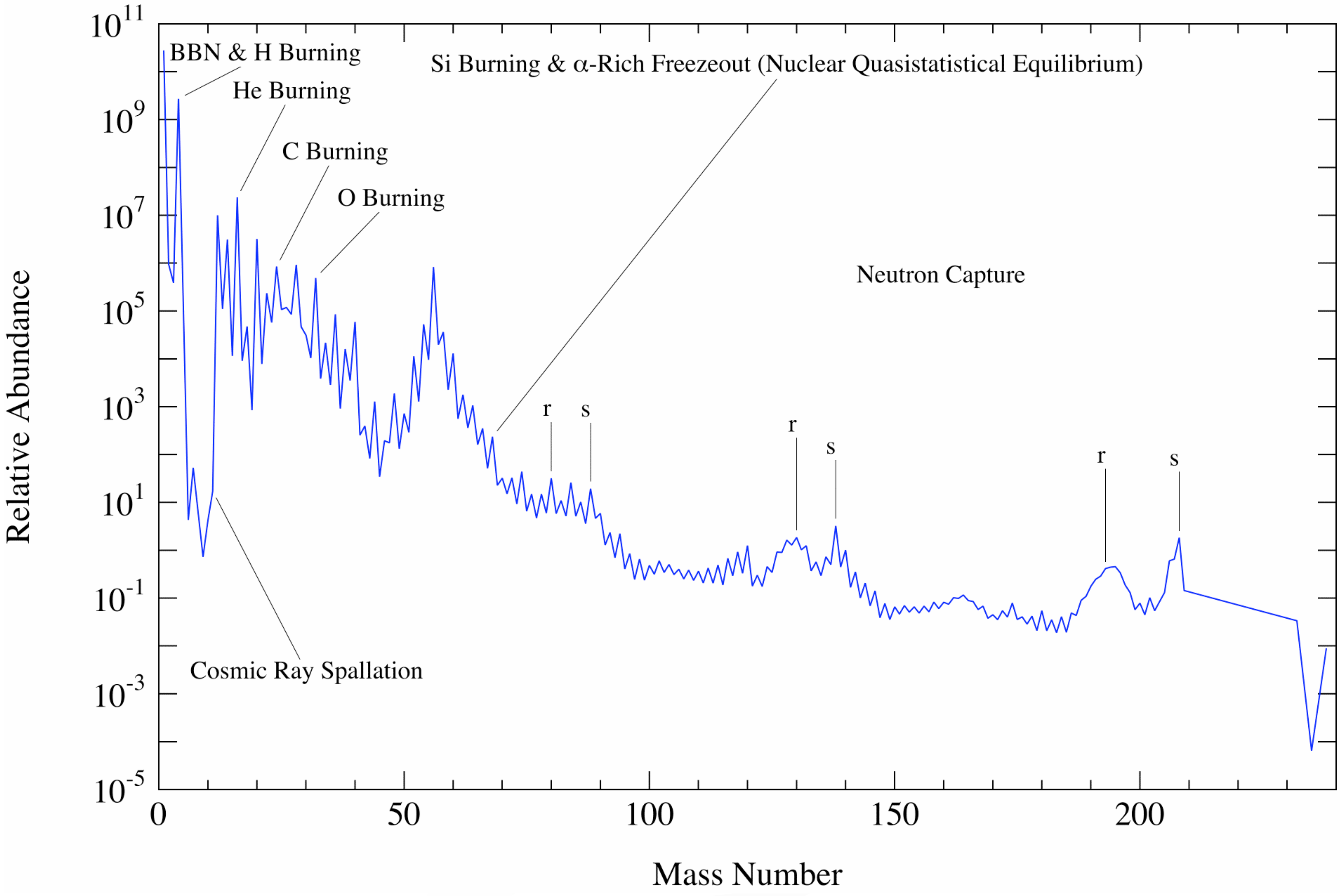
The *r* Process Site?



Core-collapse supernovae favoured astrophysical site; explosion liberates synthesized elements, distributes throughout interstellar medium;

Abundances of *r* process elements in old stars show consistent pattern for $Z > 47$, but variations in elements with $Z \leq 47$, implying at least 2 sites

Solar System Abundances, Revisited



Summary

- Lightest elements, H and He produced in Big Bang
- Li, Be, B: cosmic rays
- C-Ni: made in stars, supernovae
- All elements heavier than Fe, Ni: neutron capture
- Slow neutron capture: formed in giant stars
- Rapid neutron capture process: occurs in supernovae, neutron star mergers, . . .
- TRIUMF leads the world in direct studies of experimental nuclear astrophysics with radioactive nuclear beams