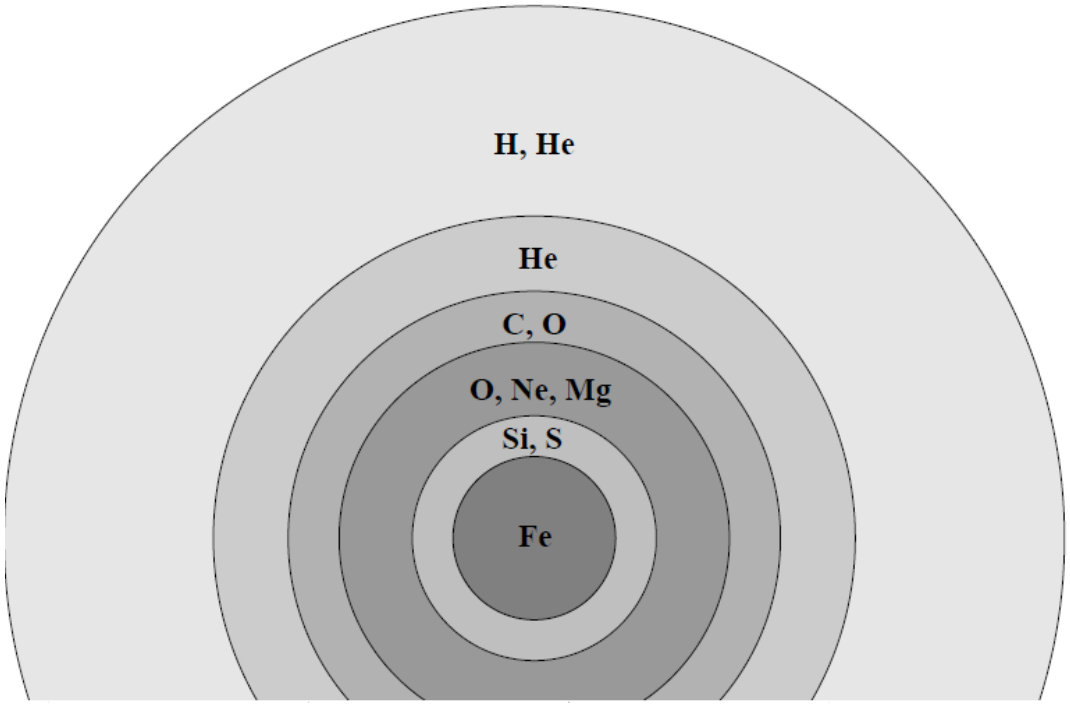
Outline

- Go over problem 4-2
- Core collapse in massive stars
- Properties of neutron stars
- Supernova explosions

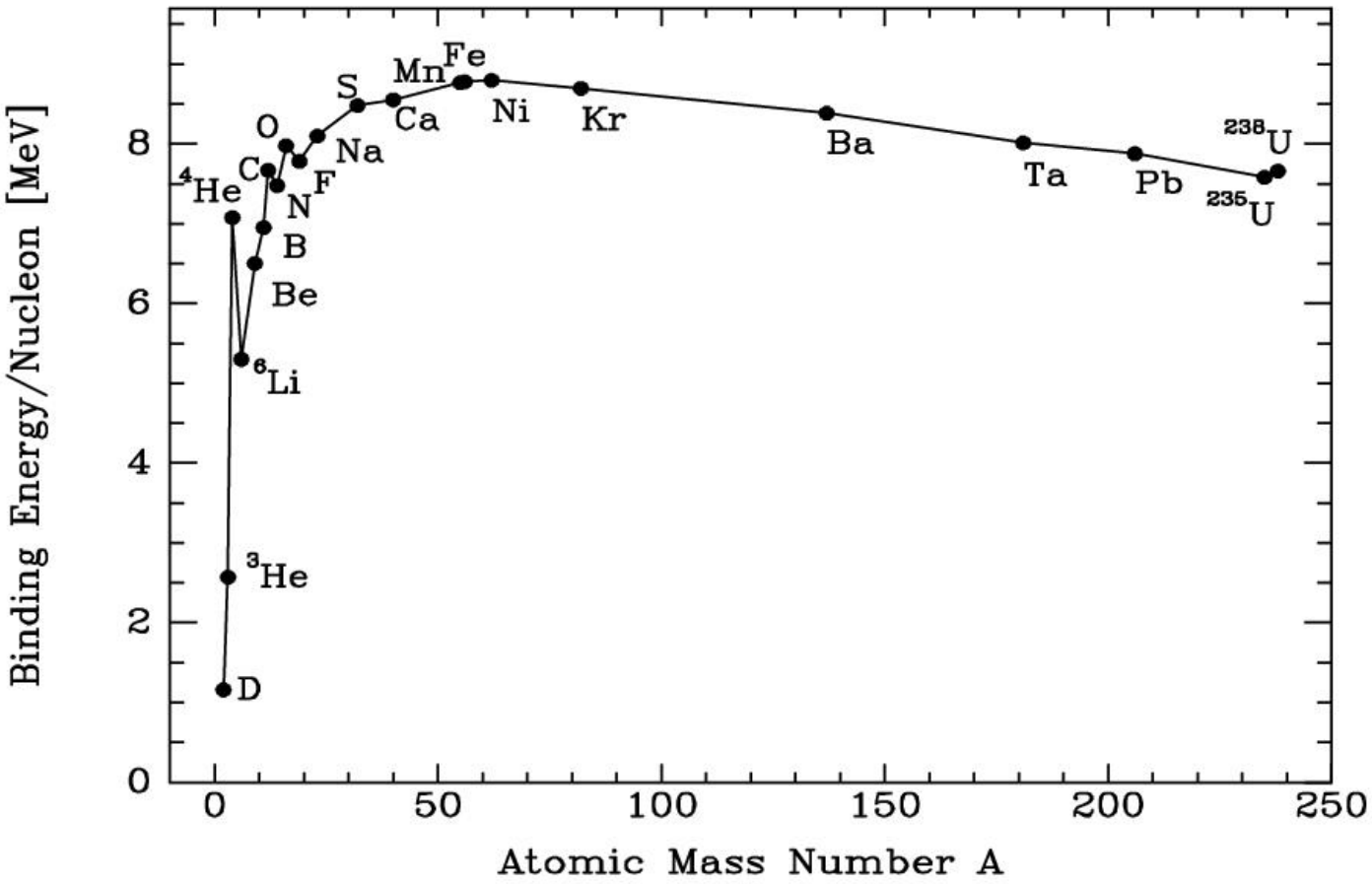
Nuclear Burning in Massive Stars

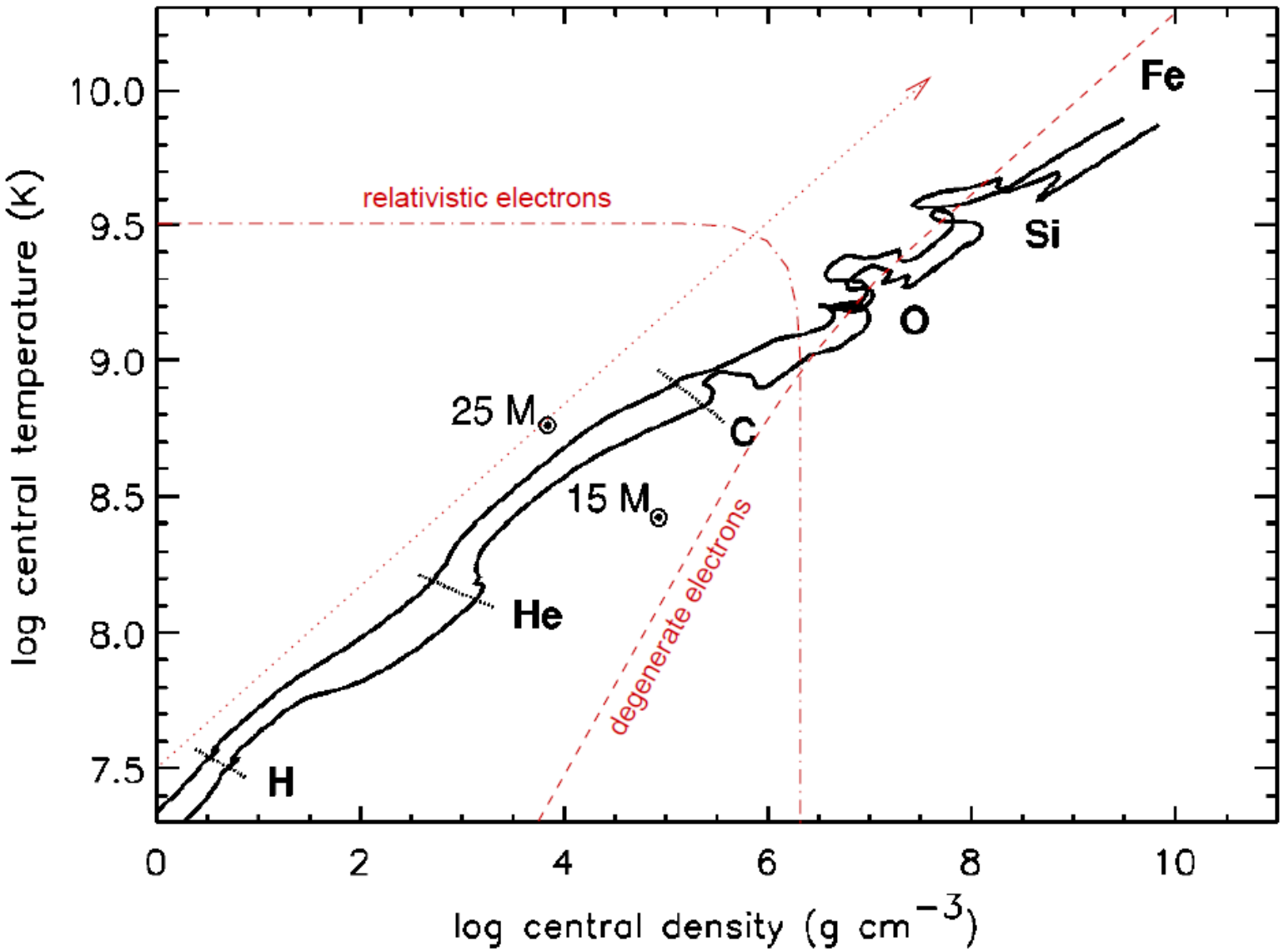
- Core temperature and density is higher in high mass stars
  - Nuclear burning can progress past CNO.
- $^{16}O + {}^{4}He \rightarrow {}^{20}Ne + \gamma$
- $^{12}C + {}^{12}C$ produces mostly ^{20}Ne and ^{24}Mg.
- $^{16}C + {}^{16}C$ produces mostly ^{28}Si and ^{32}S.
- Si burns to ^{56}Fe and some ^{52}Cr.
- Leads to shell structure.
- Burning is very rapid
  - C ~ 500 years
  - Si ~ 1 day



Fusion

- Burning stops releasing energy with Fe because it is the most tightly bound nucleus.





- In final stages, core can no longer produce energy via fusion.
- Core electrons are degenerate and relativistic.
- What happens?

Core Collapse

- Core can no longer support itself by nuclear burning.
- Core collapses, new energy source is gravitational contraction.
- High temperature and density lead to:
- Nuclear photodisintegration:
  - $\gamma + {}^{56}\mathrm{Fe} \rightarrow 13({}^{4}\mathrm{He}) + 4n$ (-124 MeV)
  - $\gamma + {}^{4}\mathrm{He} \rightarrow 2p + 2n$ (-28.3 MeV)
- Neutronization:
  - $e^{-} + p \rightarrow n + \nu_e$
  - $e^{-} + {}^{56}\mathrm{Fe} \rightarrow {}^{56}\mathrm{Mn} + \nu_e$
  - $e^{-} + {}^{56}\mathrm{Mn} \rightarrow {}^{56}\mathrm{Cr} + \nu_e$

Core Collapse

- Energy loss ~ (124 + 13×28.3) MeV/56 ~ 8.8 MeV/nucleon.
- For Chandrasekhar mass of 10^{56} nucleons, release 10^{52} erg.
  - Compare with solar luminosity of 4×10^{33} erg/s.
- Energy is released as neutrinos, leaves the star.
- Core collapses on close to free-fall time scale
  - Core density at end of Si burning $\rho \sim 10^9$ g/cm^3.
  - Free-fall time scale $(3\pi/32G\rho)^{1/2} \sim 0.1$ s
- Density is so high that core is not transparent to neutrinos.
  - Collapse is slowed by outgoing neutrino energy flux and takes a few seconds.
- Most of nucleons (99.5%) are converted to neutrons.
  - Note free neutron lifetime ~ 886 seconds.

Neutron Stars

- Basic physics is degenerate fermion gas, same as white dwarfs, but replace electron mass with neutron mass.
- Also Z/A factor to convert mass to electrons becomes one, since almost all nucleons are neutrons. Then radius is:

$$r = 2.3 \times 10^9 \text{ cm } \frac{m_e}{m_n} \left(\frac{M}{M_{Sun}} \right)^{-1/3} \approx 14 \text{ km } \left(\frac{M}{1.4\, M_{Sun}} \right)^{-1/3}$$

- Star is so compact that general relativity must taken into account. Compare gravitational and rest mass energies:

$$E_{gr} = \frac{G M^2}{2r} \qquad \frac{E_{gr}}{m c^2} = \frac{G M}{r c^2} \approx 0.2$$

- Mass of neutron star measured via Kepler's law is ~20% less than the total mass of the material that formed it.

Neutron Stars

- Average separation between neutrons ~ 2 fm (10-15), but size of neutron ~ 1 fm, so neutron-neutron interactions are important. These are described by the nuclear equation of state, that is not well known at such high densities.
- The effects of general relativity and nuclear interactions modify the predicted radius. Values of 10-12 km are predicted, but the correct value is unknown and efforts to measure it are in progress.
- The limiting mass of a neutron star is also not accurately known. The value lies between 2 solar masses (the heaviest neutron star known) and 3.2 solar masses (Rhoades and Ruffini 1974), which is a limit that can be derived assuming that the speed of sound in nuclear matter does not exceed the speed of light.

Homework

- For next class:
  - Problem 4-3
  - Exam problem #1