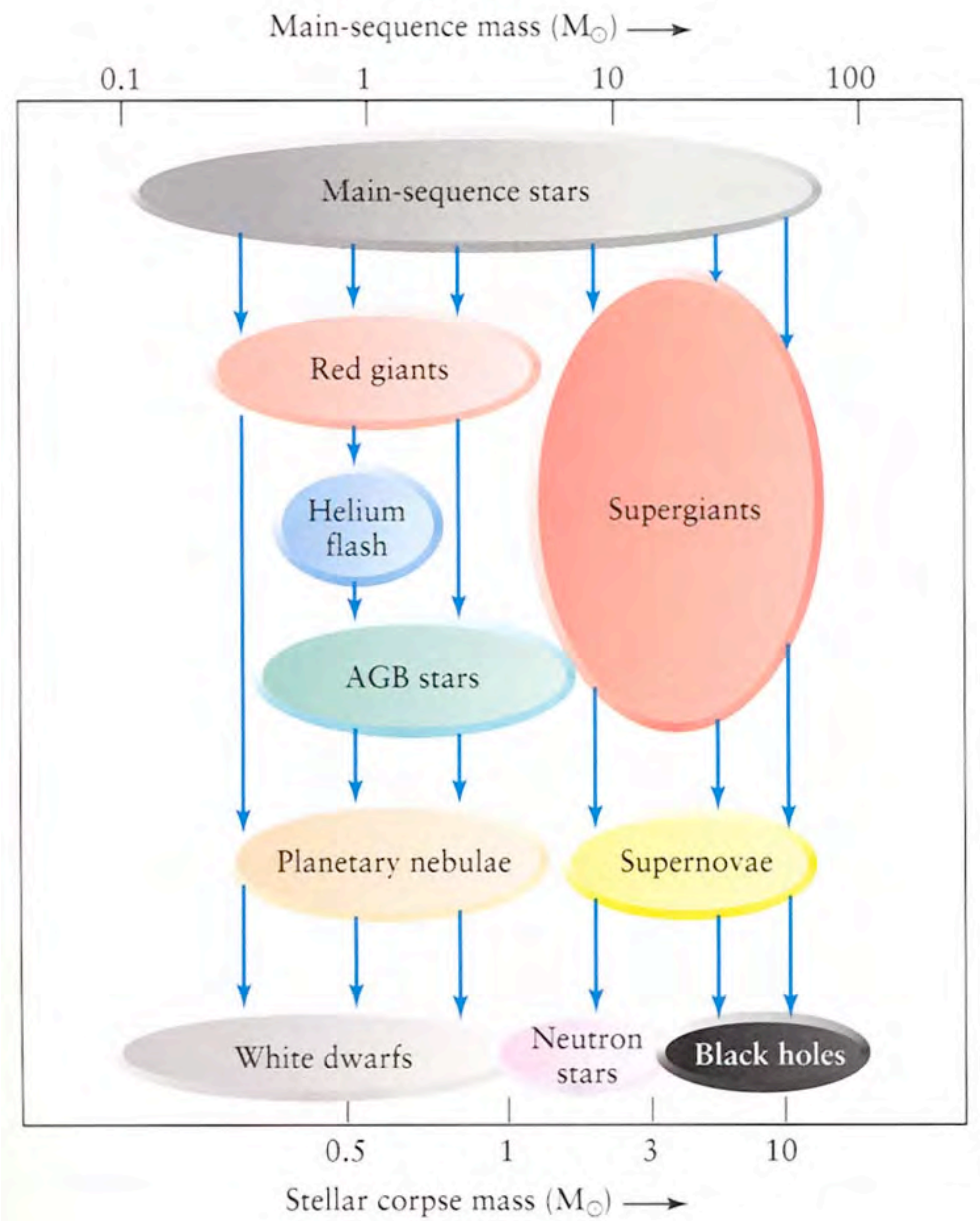
A basic theme: Stars of different mass evolve at different rates, leave different remnants, and dispose of their envelopes differently.

Below: pictorial review of the difference in evolution between low-mass and high-mass stars. **Low-mass stars lose their envelope through a wind and then a planetary nebula, exposing a core that is a white dwarf. For the high-mass stars, the envelope explodes as a supernova (Ch21), but the core probably ends up as a neutron star or a black hole, the subjects of Ch22.**

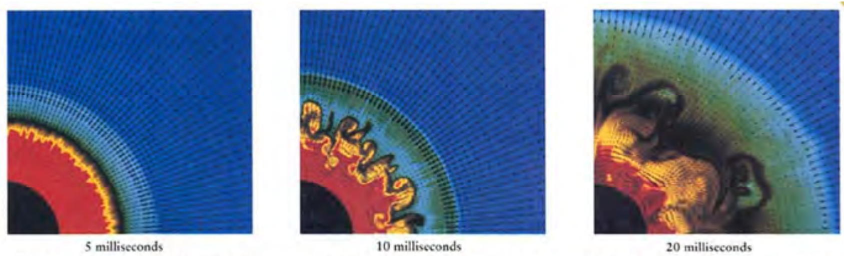
→ What is physical condition that distinguishes between them? That is really a s basic theme: **Electron or neutron degeneracy limits the extent to which a star evolves**. Brown dwarfs become degenerate before they can ignite H, degeneracy saves the cores of some stars from ending up black holes…



Finishing up topics related to supernova explosions

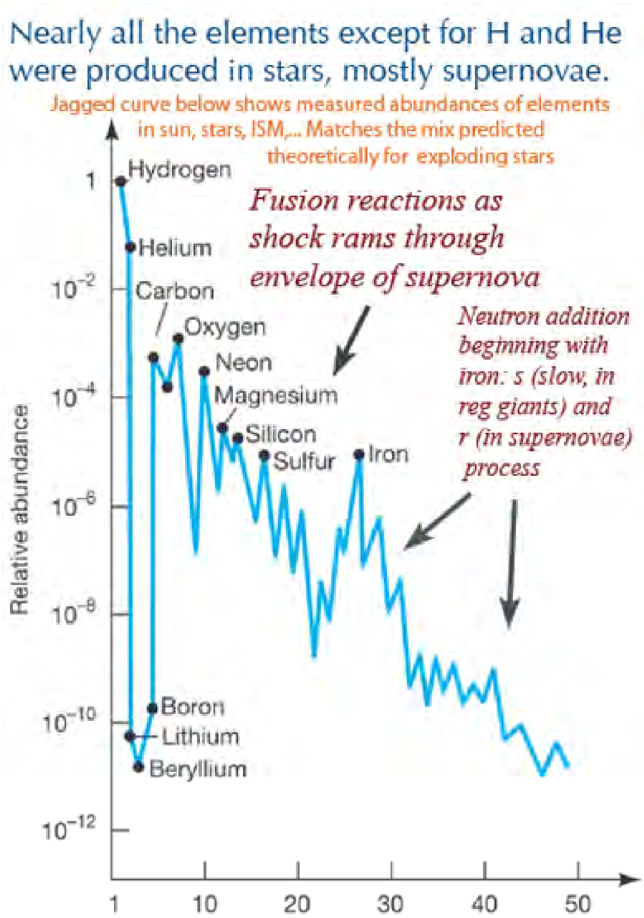
1. Two ways to get a supernova:

- **carbon detonation**: white dwarf accretes mass, is pushed over the *Chandrasekhar limit*, collapses, shock detonates the C + O + ...
  These "Type I" events have light curves that can be used as standard candles (below), and they produce most of the iron in the universe.
- **core collapse** (all massive stars): These leave behind *neutron stars or black holes*, but the shock wave blows off the entire envelope at relativistic speeds.



Collapsing matter bounces off stiff neutron core... producing shock wave that moves out through envelope... heating all the "onion skin" layers (nuclear fusion) and blowing off the envelope (supernova)

Plenty of pictures and reading in text, notes, etc. Simulation of a core-collapse SN shown above, shock processes the "onion skin" envelope...
→ **nucleosynthesis of elements**

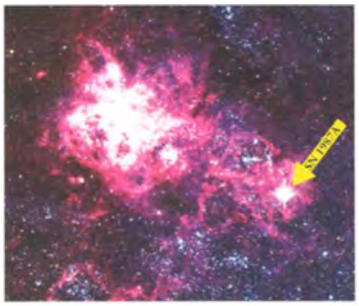


2. Nucleosynthesis (both in core collapse and carbon detonation supernovae). The important graph is shown to the left.

Three main processes account for the observed relative abundances of nearly all the chemical elements in the universe:

- *Helium capture* (C, O, Ne,,…Fe),
- *proton capture* (elements inbetween),
- *neutron capture* (s, r)—elements beyond iron.

3. SN 1987a and detection of SN neutrinos *before* the photons arrived.

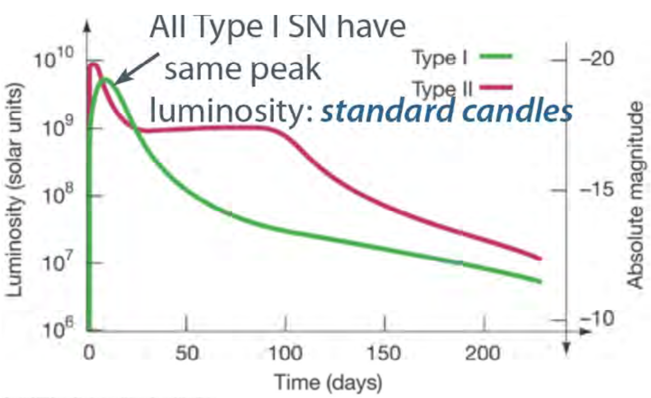


Important and unexpected test of core collapse models for supernovae.

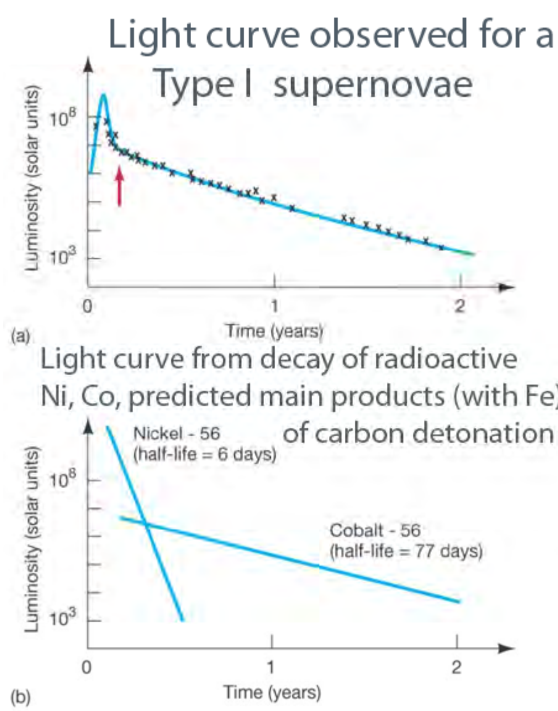
This image shows how 100s of supernovae are discovered in other galaxies, by simple photographs (not neutrinos! 1987a is the only case near enough for that).

4. Supernova light curves:

- Important **standard candles**, will give us distances to objects billions of parces away (Type I)



- Type I supernova light curves also provide strong evidence that carbon detonation is the trigger, since radioactive decay predicted for light curve power source



Neutron stars and pulsars

What remnant is left behind after a supernova explosion?

Carbon detonation: nothing left, no remnant, entire white dwarf explodes, disperses, converted mostly to iron. (Type I supernova light curves)

Core collapse: If remnant is left, it is a neutron degenerate core only a few miles in size ⇒ **neutron star**

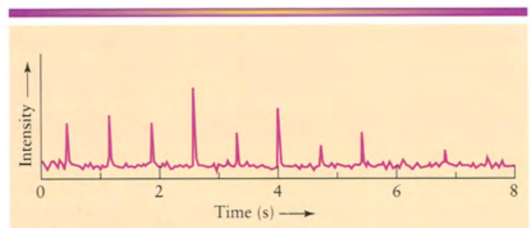
Tiny size → huge density, 100 million tons per cubic centimeter.

→ gravitational force at surface is huge: matter that gets too close heats up and emits x-rays. Accretion disks. (See below).

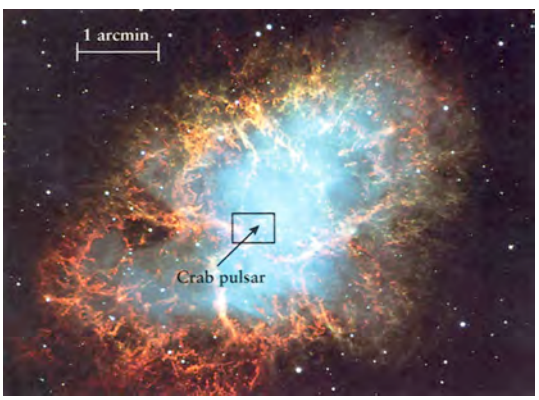
Rotation period → fraction of a second (conservation of angular momentum).

No one thought they could be observed because luminosity would be so small, due to small size. Turned out incorrect.

- 1967: First **pulsar** discovered by accident. By now many hundreds known, pulse period 0.03 to 0.3 sec for most. Hard to explain, until realized that neutron stars would be spinning just this fast.



typical pulsar light curve

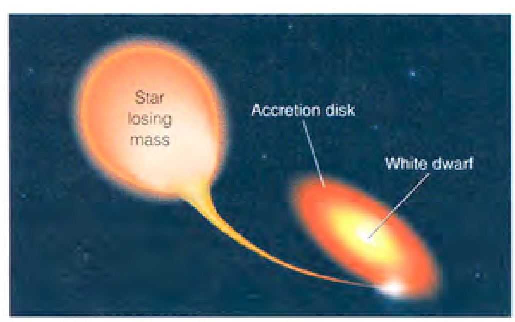


- The pulsar seen at the center of some supernova remnants, especially the Crab Nebula, is very strong evidence that **pulsars are neutron stars, are remnants of supernova explosions.**

- But not *all* supernova remnants have detectable pulsar. And why are they pulsing??

b This artwork likens a pulsar (top) to a lighthouse (bottom). If a pulsar's radiation beams are not aligned with its rotation axis, they will sweep through space. Each time one of these beams sweeps across Earth, we see a pulse of radiation.

Neutron stars as pulsars: Lighthouse model for beaming.



Matter falling into a compact object forms a whirling accretion disk. Friction and tidal forces can make the disk very hot.

Gamma-ray Bursts

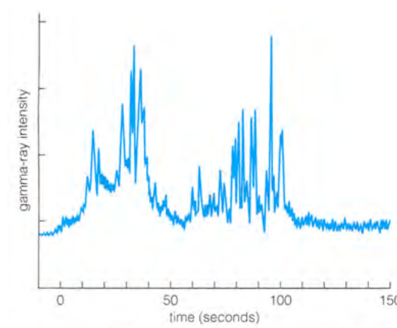
- Flashes of gamma ray light, brief (seconds) and highly irregular

- Until about 1995, completely mysterious because distance unknown: Nearby faint (in our solar system?), or distant luminous (huge energy releases in other galaxies)?

  Good example of need for *standard candles*!

- *Isotropic* (same in all directions) distribution in sky suggested not in our Galaxy, but then they would be brighter than supernovae, and with their energy in the gamma ray part of the spectrum. Seemed impossible.

- 1997 Afterglow emission lines, lines enormously redshifted → this object was 2 billion parsecs away! (Distance from redshift isn't explained until later—take it on faith for now.)



A typical gamma-ray burst light curve, showing dramatic fluctuations in gamma-ray intensity over a period of 2 minutes.

- What are they?? A hint is that they flicker on timescales of a hundredth or thousandth of a second, which means ***they can't be larger than a few hundred kilometers across***. (See p. 578 for the explanation—important reasoning using light travel time.) *How could so much energy be generated in such a small object??*

- *Agreed*: They are relativistic fireball jets.

  Not agreed: What causes the fireball and jet? Leading theories are coalescing neutron stars, and hypernovae (ultraluminous supernovae), although why they are so "hyper" is really not known.