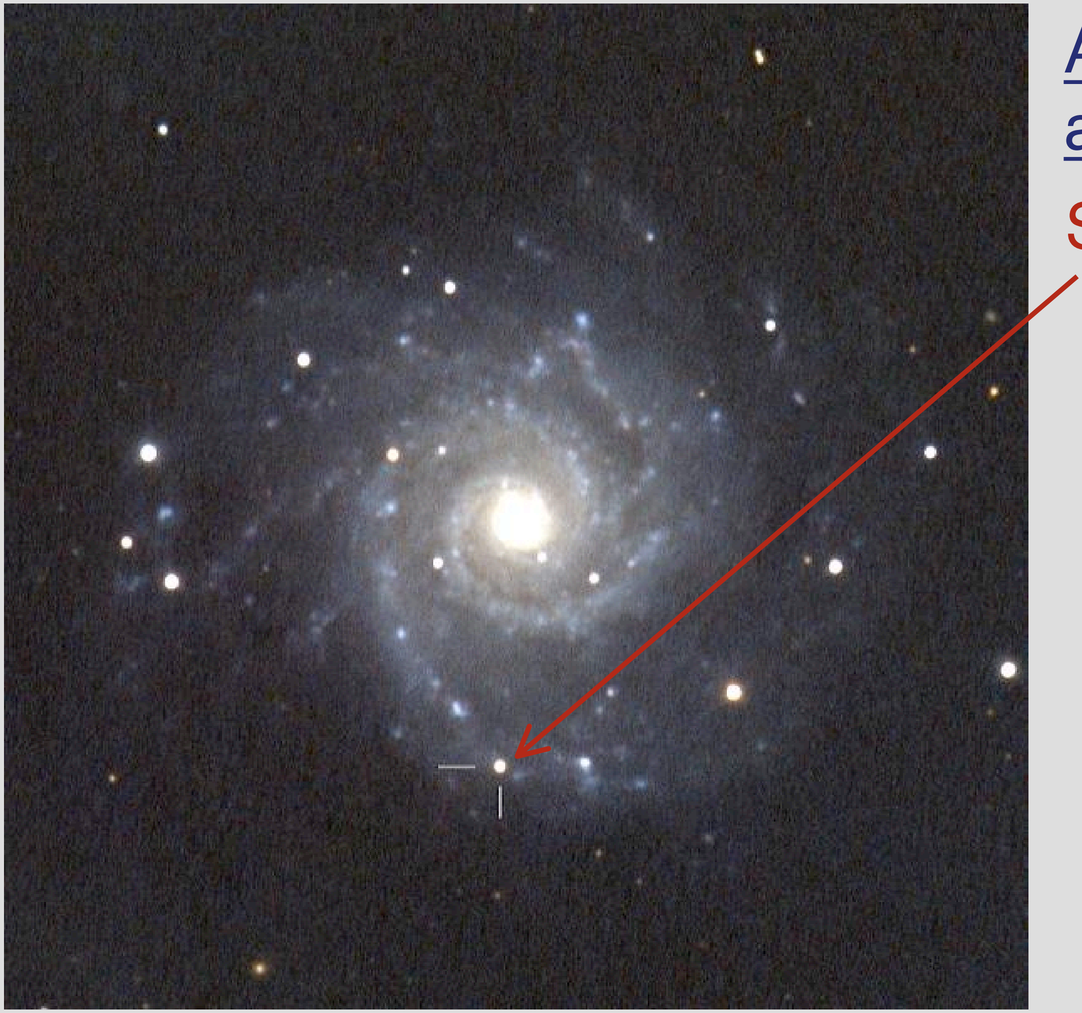
Type II Supernovae

Overwhelming observational evidence that Type II supernovae are associated with the endpoints of massive stars:



<u>Association with spiral arms in spiral galaxies</u>

Supernova in M75

Type II Supernovae

Overwhelming observational evidence that Type II supernovae are associated with the endpoints of massive stars:

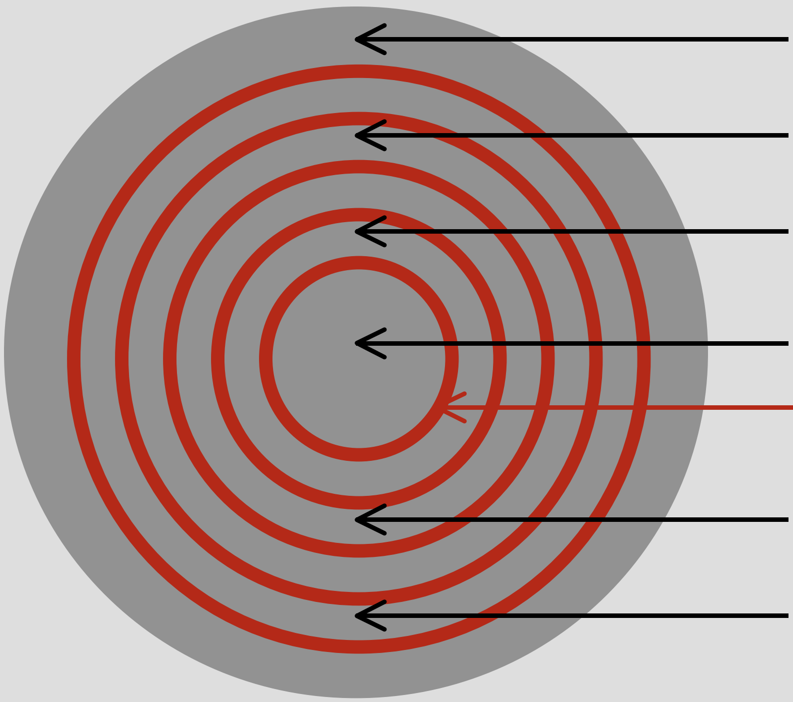
Identification of the progenitors of some core collapse SN

Thought to represent core collapse of massive stars with $M > 8\ M_{sun}$. Type Ib and Type Ic are thought to be similar events in stars that have lost their outer hydrogen envelopes prior to the explosion.

Core collapse in massive stars

In a massive star, core temperature can be high enough that nuclear burning of Si to Fe can occur. Beyond Fe, further fusion is *endothermic*, and will not occur *under equilibrium conditions*. As an iron core develops, other reactions still proceed at larger radii:

`Onion shell' structure



Hydrogen envelope

Carbon shell

Si shell

Iron core

Oxygen shell

Helium shell

Separated by zones in which nuclear fusion is occurring - **shell burning**: e.g. Si burning to Fe just outside the iron core

Eventually iron core becomes too massive to be supported by electron degeneracy pressure:

- Can’t explode like a white dwarf (Type I SN) - the core is *already* made of iron so no more exothermic nuclear reactions possible
- **Core collapses**

Once collapse starts, it proceeds very rapidly:

Photodisintegration

$$^{56}\mathrm{Fe} + \gamma \rightarrow \text{lighter elements}$$

Needs high energy gamma rays

Inverse beta decay

$$e^{-} + p \rightarrow n + \nu_e$$

Needs e^- and p to have enough energy to overcome mass difference between neutron and proton

These processes rob the core of pressure support, accelerate the collapse, and drive the composition toward neutron rich matter.

Once the core reaches nuclear densities - $\rho \sim 10^{15}$ g cm^{-3}, nuclear forces provide a new source of pressure support.

Scale is now: $M = \frac{4}{3}\pi R^3 \rho_{nuc}$

$$R \approx \sqrt[3]{\frac{3M}{4\pi\rho_{nuc}}} \sim 10 \text{ km}$$

Formation of a proto-neutron star stops the collapse, and produces a bounce which sends a shock wave back out into the star.

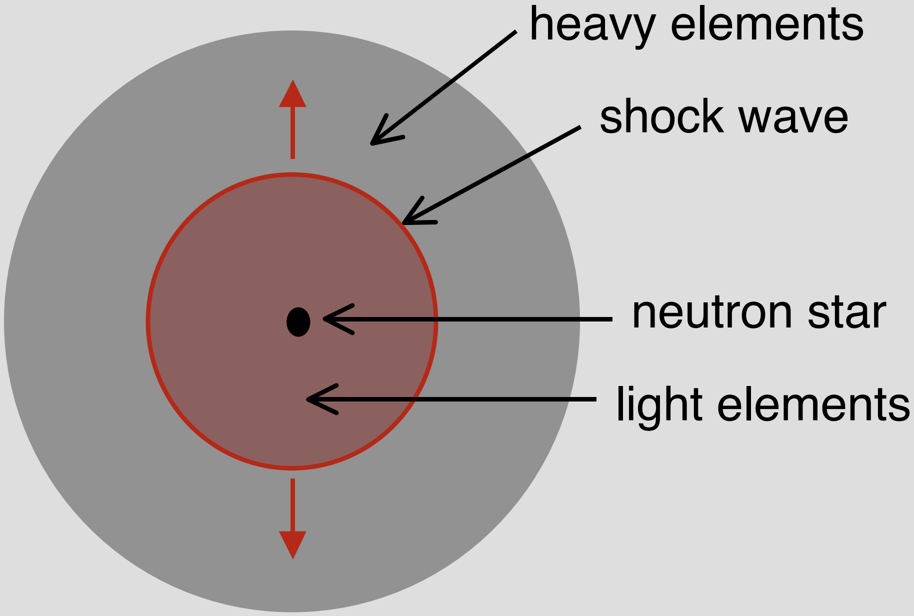
Shock wave can explode the star, *if it can propagate out through the infalling matter*.

Core may leave a neutron star, or if it is too massive, collapse further to form a black hole.

Proven very difficult to ascertain the exact mechanism of Type II supernova explosions:

Problem: the bounce launches a shock wave with an energy that is a fraction of the binding energy of the neutron star - typically ~10^{52} erg.

As the shock propagates through the star, high temperatures break up heavy elements into lighter ones, which absorbs some of the energy:



Energy needed to completely break up heavy elements is about 8 MeV per nucleon:

⇒ 1.6×10^{52} erg M_{sun}^{-1}

`Prompt' mechanism for Type II SN fails…

Neutrino-driven explosions

Neutronization reaction in the core: $e^- + p \rightarrow n + \nu_e$ yields a very large flux of neutrinos, with total energy of a few x 10^{52} erg.

For an interaction cross-section of $\sigma \sim 10^{-44}$ cm^2, mean free path near the neutron star is:

$$l = \frac{1}{\sigma n} \approx 2 \text{ km}$$

(for scattering off nucleons at $\rho = 10^{15}$ g cm^{-3})

i.e. smaller than the size of a neutron star. Most neutrinos will interact with matter as they escape, on a time scale much longer than the free fall time of the core (several seconds).

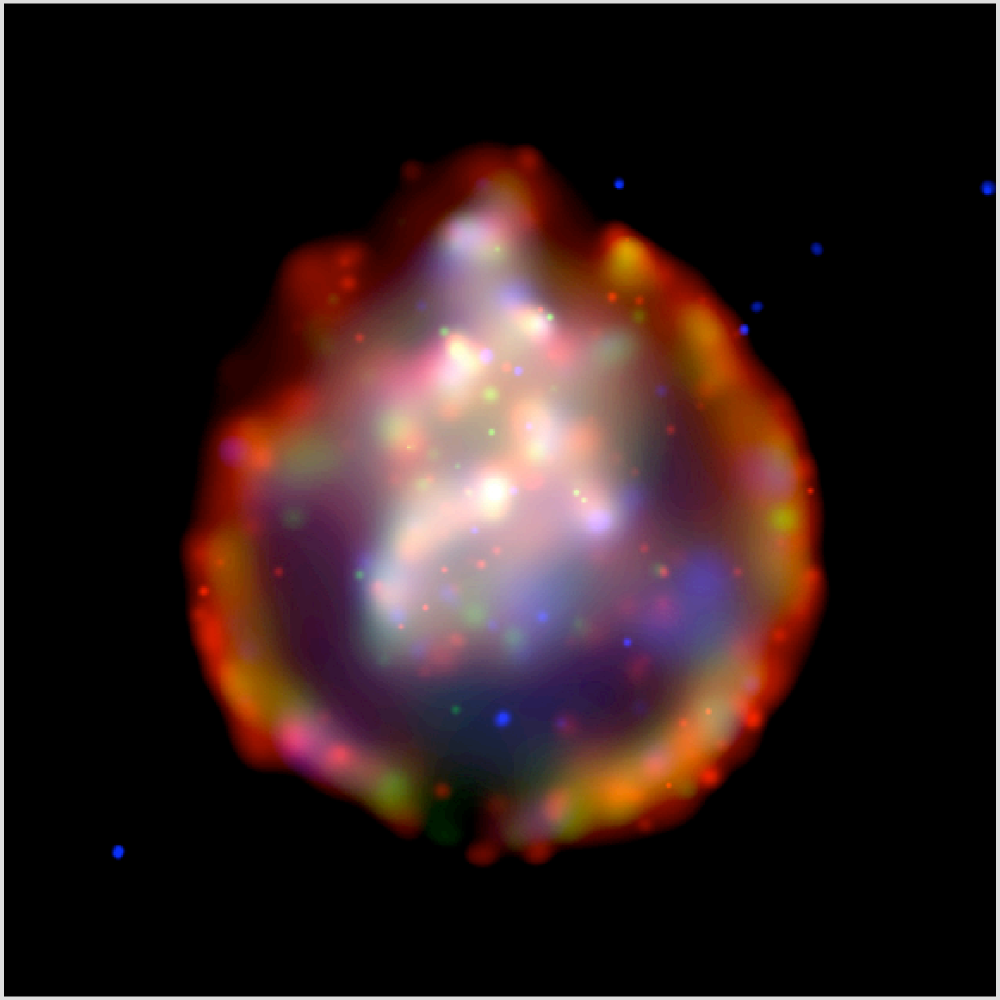
A fraction of the neutrinos will be absorbed by the post-shock matter, heating it and reviving the shock.

Numerical simulations suggest that even with neutrino heating, physics is closely balanced between explosions and fizzles:

- **convection** is widely thought to be essential to achieving robust explosions
- many numerical models fail to explode
- may suggest essential physics is missing or wrong…

Supernova remnants

Explosion ejects outer layers of the star with v ~ 10^4 km s^{-1}. This gas expands and collides with the circumstellar medium producing a supernova remnant.



SNR 0103-72.6

Chandra X-ray image, with colors showing different X-ray energies

Crab pulsar: remnant of a supernova in 1054