Stellar Death and Black Hole Birth

What is the sun?

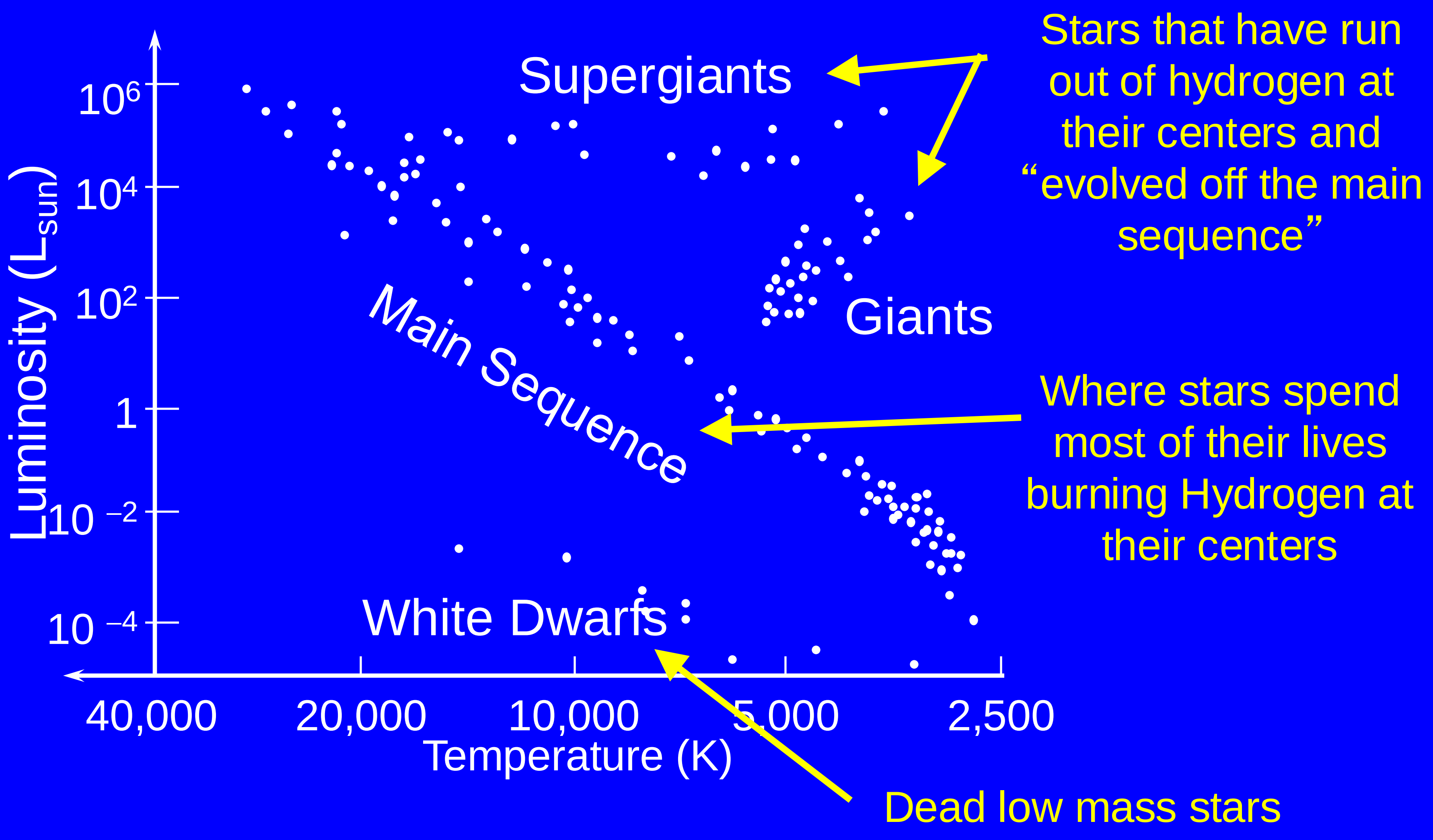
1. A ball of hot gas.
2. Held together by gravity.
3. Supported against gravity by pressure.
4. Radiating energy into space because it is hotter than its surroundings.
5. Replenishing that lost energy by fusing hydrogen into helium in its core.

1-4 apply to all stars. 5 applies to “main sequence” stars, the most common type.

General Properties of Stars

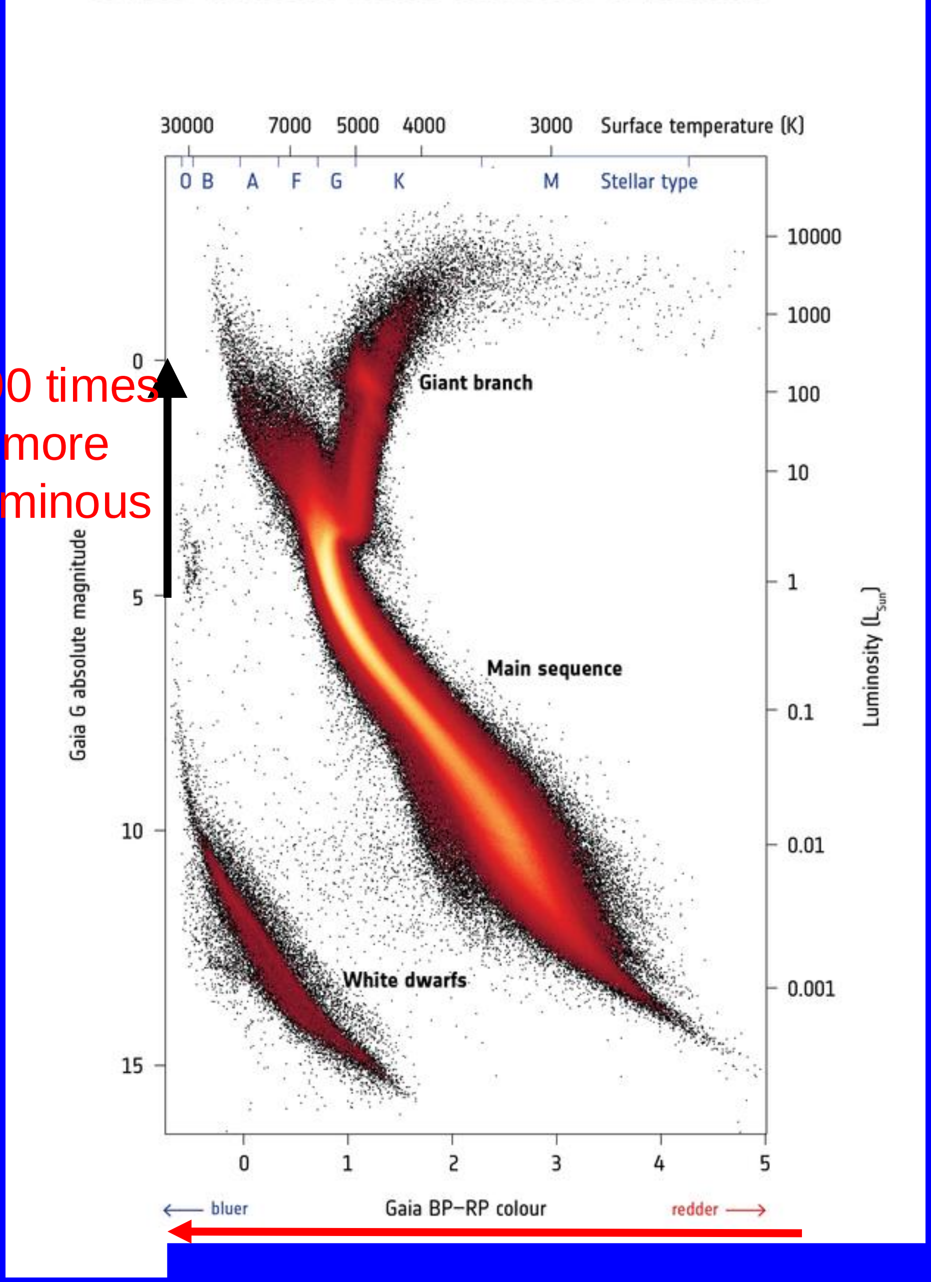
- Stars as you see them can be characterized by a luminosity and a (surface) temperature
- Stars in their physics are controlled by their mass and their age
- There are other variables we will not be worrying about (e.g. initial composition)
- If you look at the distribution of stars in luminosity and termperature, they are not random – they show very strong correlations

Hertzsprung-Russell (HR) Diagram



"Luminosity"

100 times more luminous



temperature

Stars near the Sun as seen by the Gaia satellite

Range of stellar ages

How many included depends on luminosity, temperature and distance – not a completely "fair" sampling of stars

But, can see all the main features

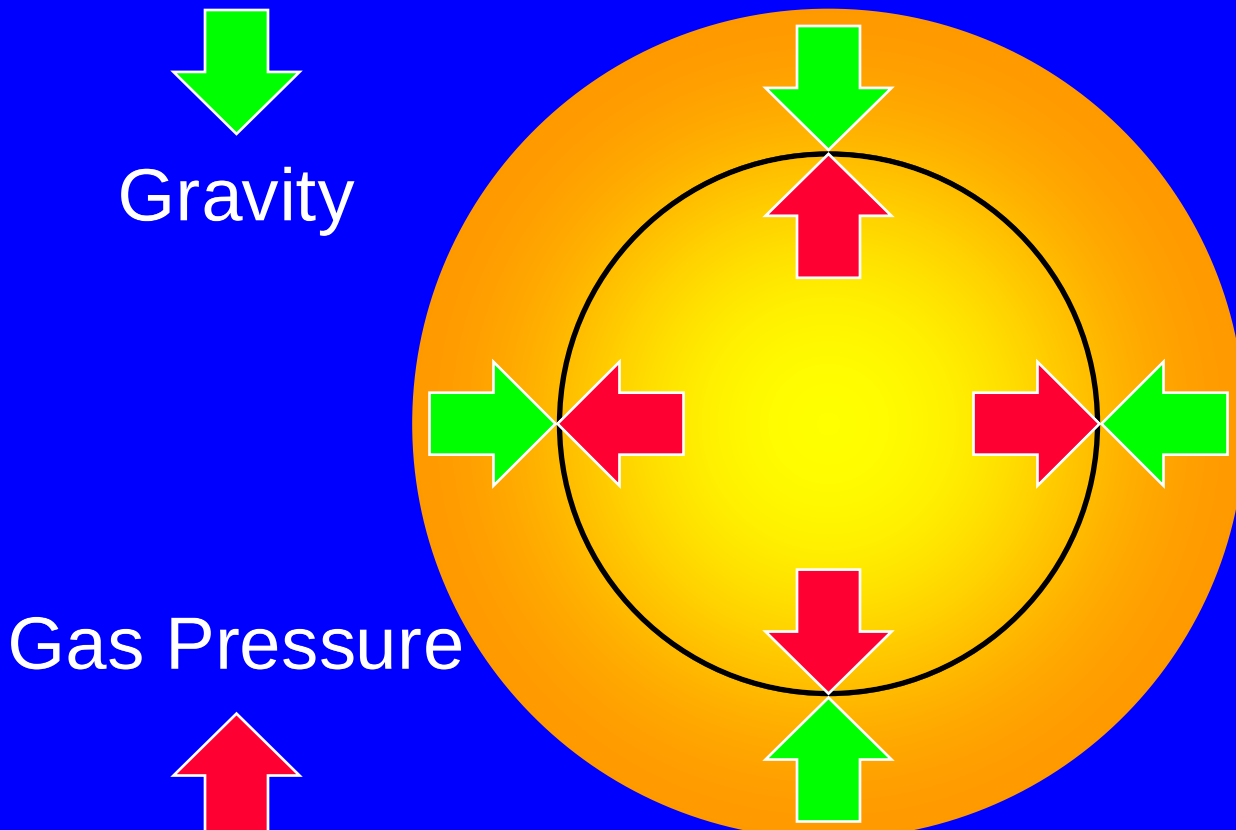
Pressure balance in a star

High pressure in the core of a star supports it against the pull of its own gravity.

Otherwise the star would collapse fairly quickly.

Balance of pressure and gravity is known as hydrostatic equilibrium.

Hydrostatic Equilibrium



Pressure balance in a star

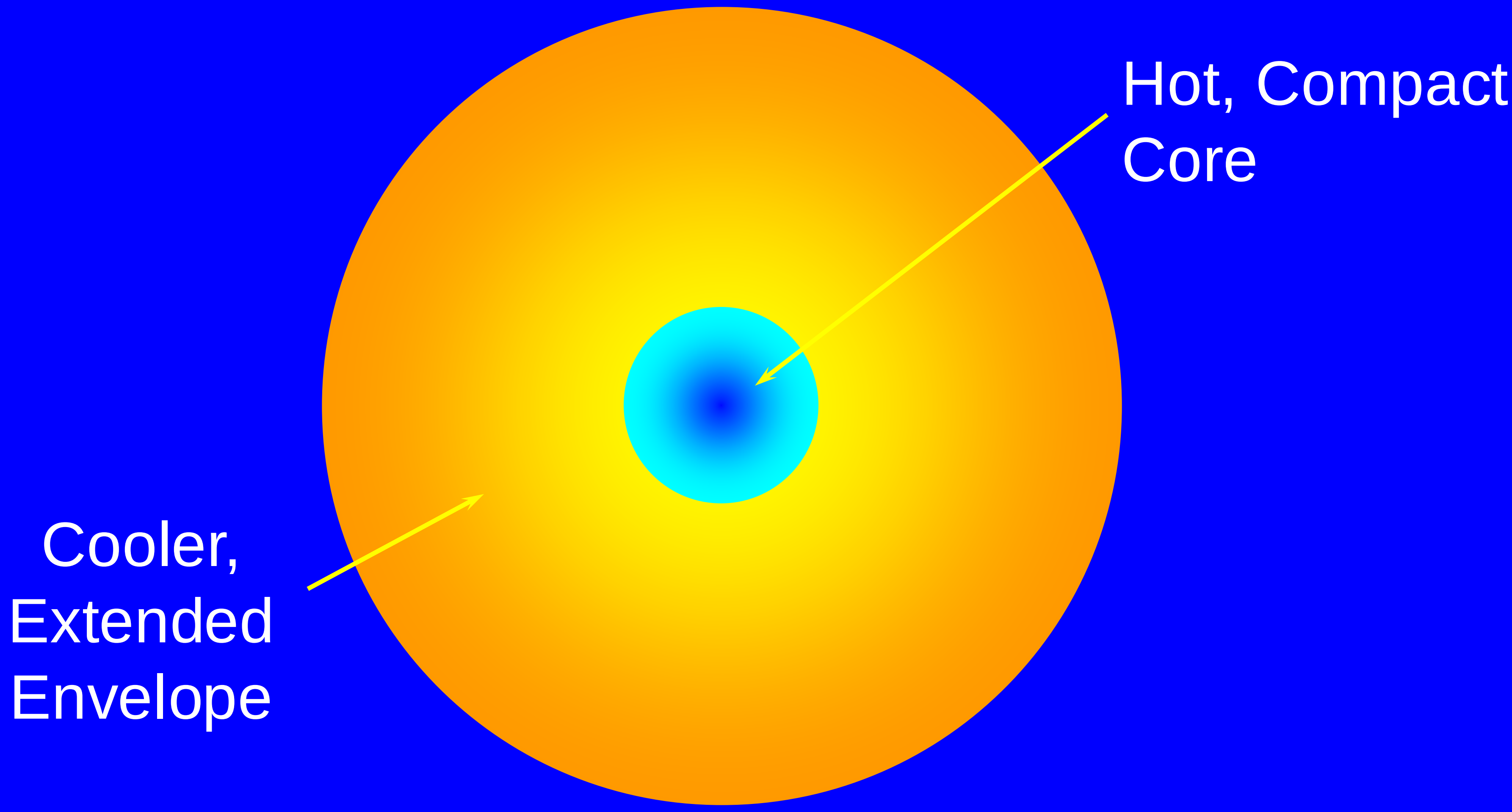
High pressure in the core of a star supports it against the pull of its own gravity.

In the sun and other main sequence stars, that pressure comes from hot atoms.

But stars are always leaking energy into space, which tends to reduce pressure.

In main sequence stars, the leaking energy is replenished by nuclear fusion in the core, which converts hydrogen into helium and releases $E = mc^2$ energy.

Core-Envelope Structure



Example: The Sun

Core:

Radius = 0.25 R_{sun}

T = 15 Million K

Density = 150 times that of water

Near Surface:

Radius = R_{sun} = 700,000 km

T = 5800 K

Density = 10^{-7} that of water

Technically at the surface of the star, the density and pressure, but not the temperature, become zero

Stellar evolution: the basic rules

- Rule #1 -- Stars are in “hydrostatic equilibrium” – gravity is balanced by pressure
- Rule #2 – Stars slowly adjust their structure so that the luminosity they generate with fusion reactions exactly equals the luminosity they are losing by radiation
- Rule #3 – You cannot satisfy these rules forever

The Essential Tension

Comes from Rule #2

Stars are always losing energy – they have a lot of heat energy, they have a surface, the surface has a temperature, and they basically radiate like black bodies

As they burn their fuel in fusion reactions, the amount and location of the energy generated changes

The star must slowly adjust its structure to keep the energy generated equal to the energy radiated

The rate of energy generation depends strongly on the mass of the star

Thermal Time Scale

Thermal time scale is how long it would take to radiate all the heat energy in the Sun

(heat energy)/(luminosity)~30 million years for the Sun

→ Thermal or "Kelvin-Helmholtz" time scale

This was a puzzle before the discovery of fusion reactions as the source of energy

Rule #3 – You Cannot Win

- Stars must always lose energy by radiating it – either you balance it by generating energy or you start to shrink → stars must evolve
- After hydrogen in the core runs out, a star can live for a while as a red giant, by fusing hydrogen outside the core and by fusing helium into heavier elements (carbon, oxygen, etc.)
- But fusing iron into heavier elements does not release energy, so this can't go on indefinitely.

ALL STARS MUST DIE

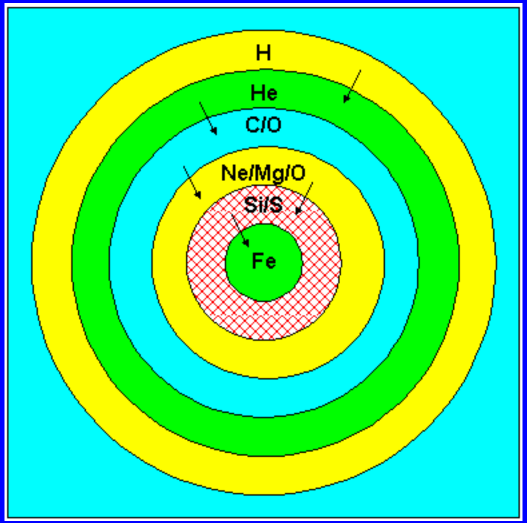
Three possible outcomes

A white dwarf star (Thorne ch. 4, more next week)
The final state of stars that have birth mass $M < 8M_{sun}$

A neutron star (Thorne, chs. 5 and 6, more next week)

A black hole

Supernova

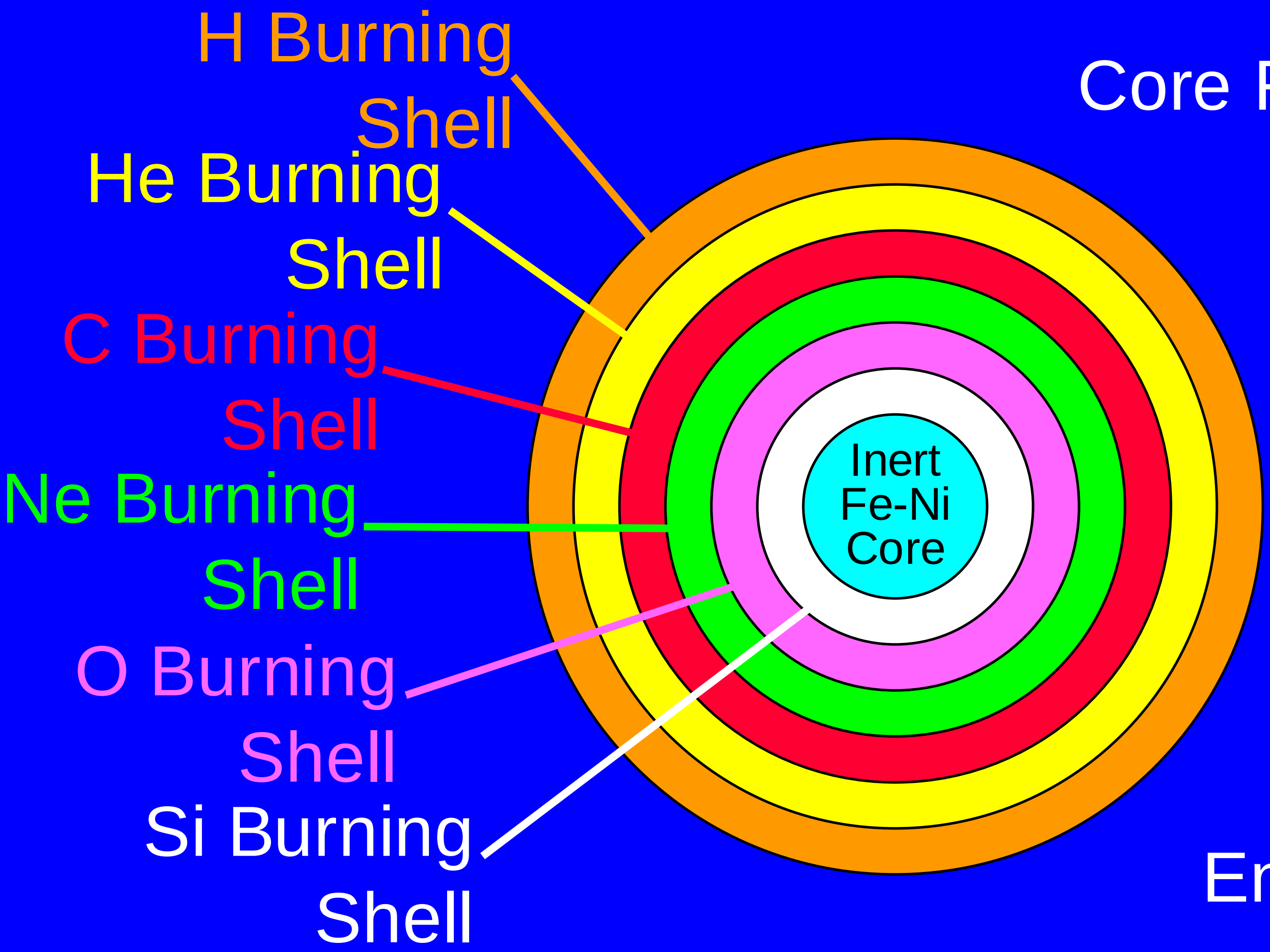


Near the end of its life, a massive star has built up a core of iron that cannot produce more energy from fusion.

When the core collapses under its own gravity, the gravitational energy is enough to explode the star, if it can be coupled into driving an explosion.

A supernova explosion is relatively easy to spot, though you have to monitor galaxies to see them.

End of Silicon Burning



Core Radius: ~1 R_{earth}

Envelope: ~ 5 AU

Iron Core Collapse

Iron core grows to a mass of 1.2–1.4 M_{sun}

- Starts to collapse and heat up
- T>10 Billion K & density ~10^{10} times water

Two energy *consuming* processes kick in:

- Heavy nuclei photodisintegrate into He, p & n
- Protons & electrons combine into neutrons & neutrinos
- Neutrinos escape & carry off energy

Makes the core collapse faster…

Catastrophic Collapse

Start of Iron Core collapse:

- Radius ~ 6000 km (~R_{earth})
- Density ~ 10^{11} kg/m^3

1 second later...

- Radius ~50 km
- Density ~10^{17} kg/m^3
- Collapse Speed ~0.25 c !

Core Bounce

Core collapses until its density is ~2.4×10^{14} times that of water, the density of an atomic nucleus!

Then, the *Strong Nuclear Force* comes into play

Inner $0.7M_{sun}$ of the core:

- comes to a screeching halt
- overshoots & springs back a bit (*bounces*)

Infalling gas hits the bouncing core head-on

Post-Bounce Shockwave

Shockwave starts to blast out into the star:

- Kinetic Energy is ~10^{51} ergs

After 25-40 milliseconds:

- Traffic jam between infalling & outflowing gas
- Tremendous energy losses as the energy from the shock breaks up heavier nuclei back into lighter nuclei
- Shockwave *stalls*

Post-Bounce Shockwave

Meanwhile, <u>neutrinos</u> pour out of the core:

- A few get trapped by the dense surrounding gas
- This leads to rapid heating of the gas
- This in turn leads to violent convection

Almost all the energy of a supernova emerges in neutrinos – but neutrinos interact very, very weakly with matter, so it is very hard to use the biggest energy source in a supernova to actually drive an explosion

Reviving the Shock

In most cases (but not all) the shock “revives” and starts blasting outward again after about 300 milliseconds

- Not fully understood
- Partly due to absorbing a small amount of the energy in the neutrinos
- Partly due to the complex, turbulent fluid motions

New, Improved Shockwave

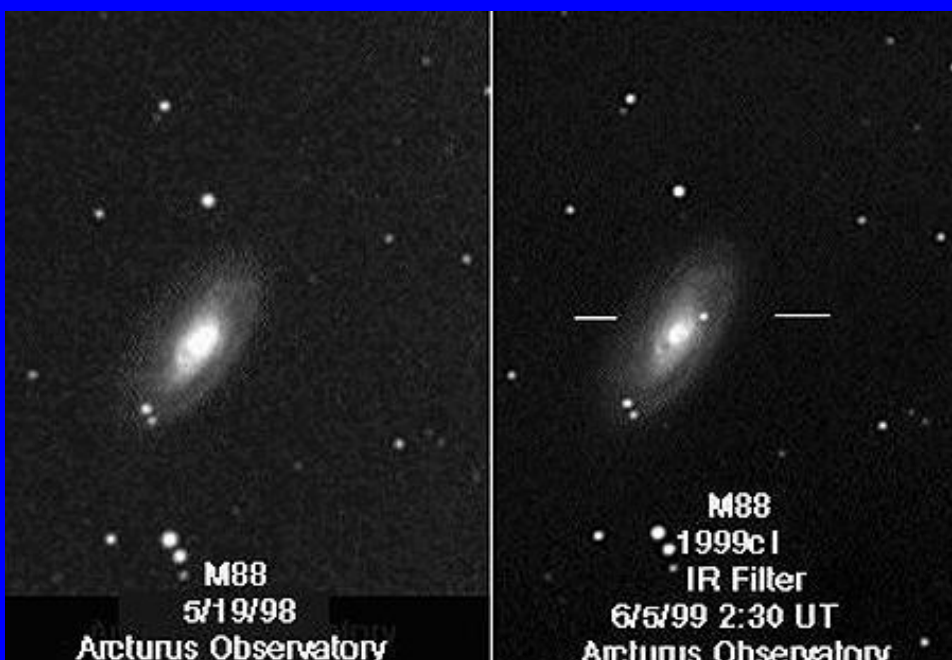
As the shock smashes out through the star:

- Explosive nuclear fusion in its wake produces more heavy elements
- Heats up and accelerates the envelope

Shock breakout a few hours later

- peak speeds ~0.1c!
- All material outside the Iron core/Silicon Shell is ejected, average speed ~5000 km/s

Two supernovae in nearby galaxies

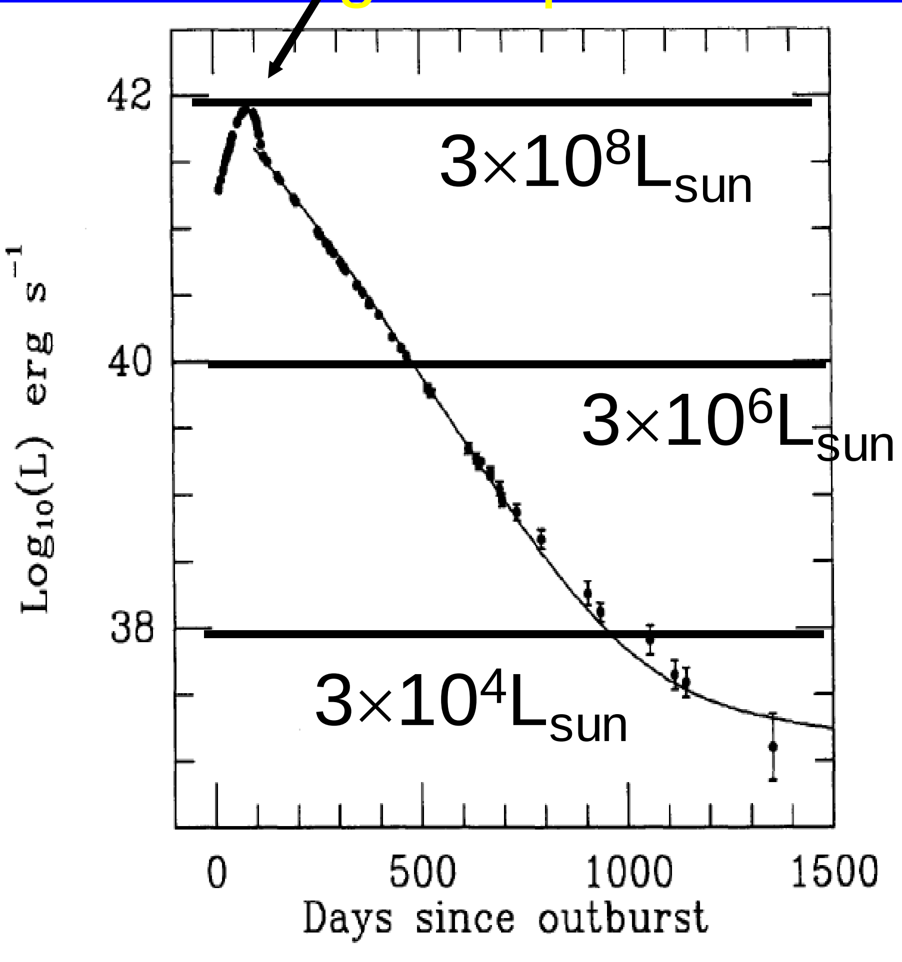


The Crab Nebula, remnant of a Milky Way supernova seen in the year 1054

Fades Away Over a Few Months

- Initial peak is a combination of the atoms becoming neutral and radioactive decay
- The slower fading at late times is energy from the the decay of radioactive Nickel and Cobalt made in the explosion

This (SN1987a) is not a terribly bright supernova



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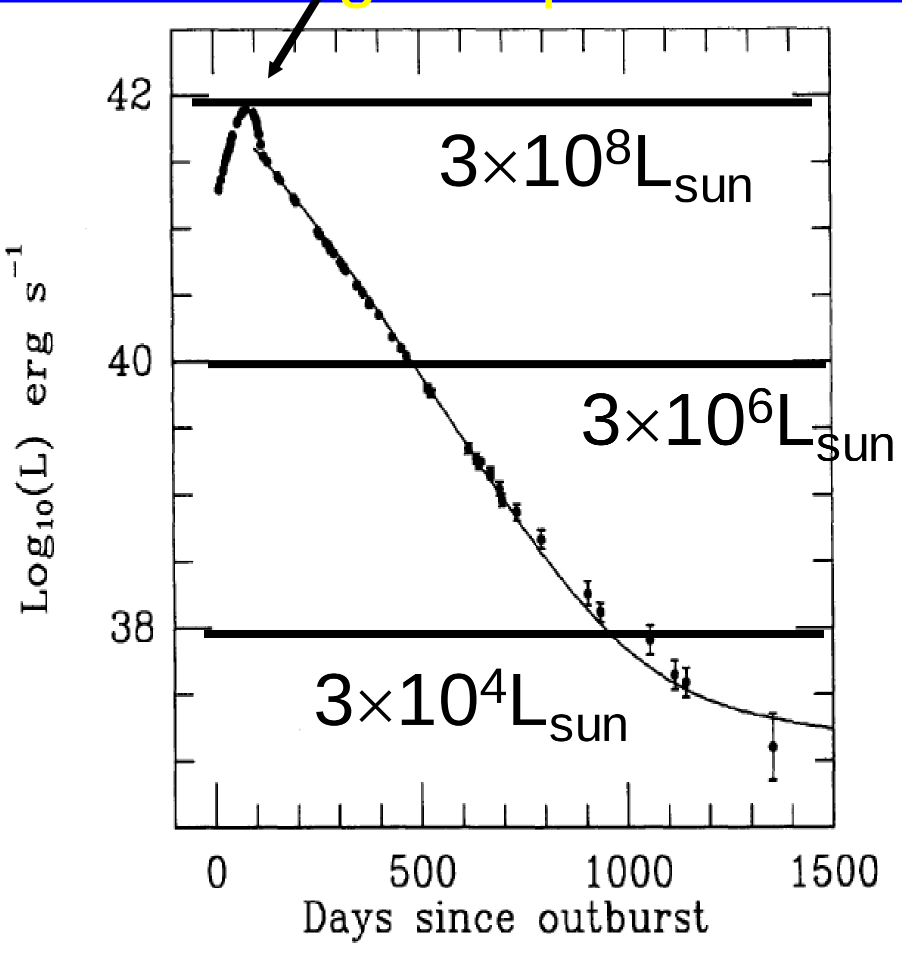
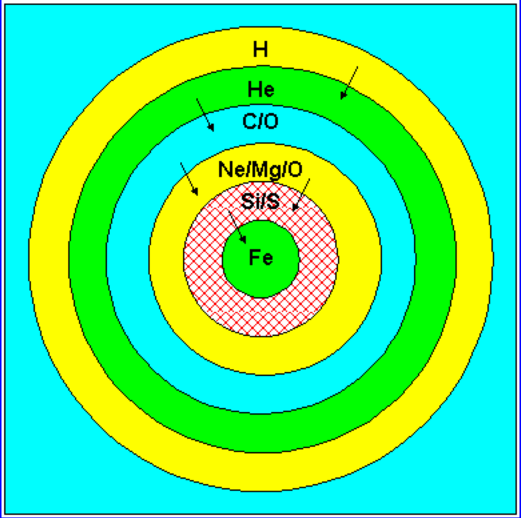


Supernova or quiet collapse?



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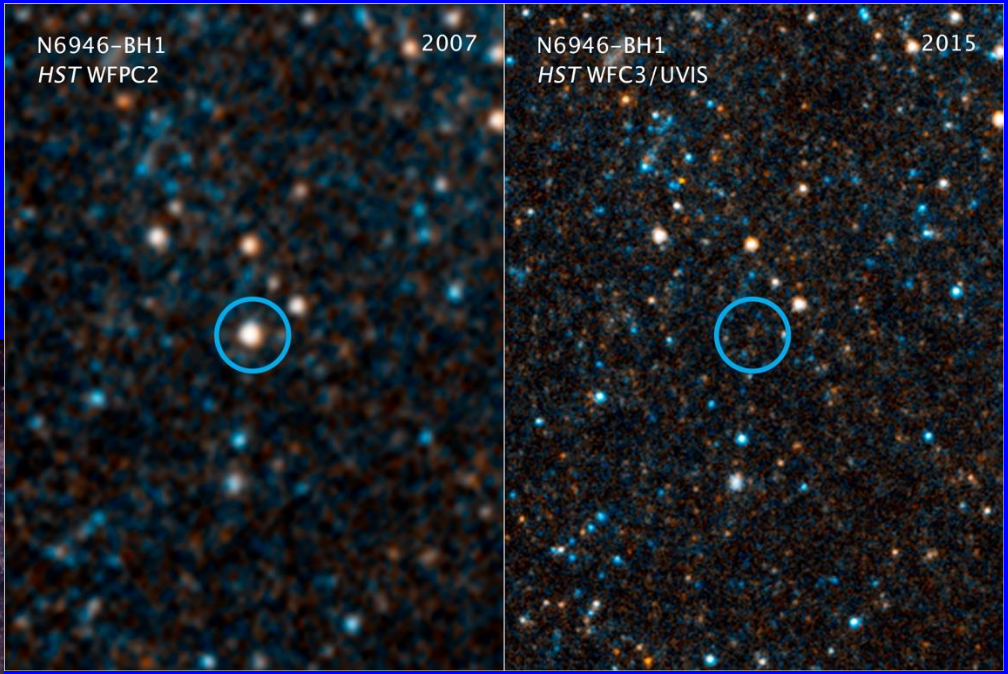
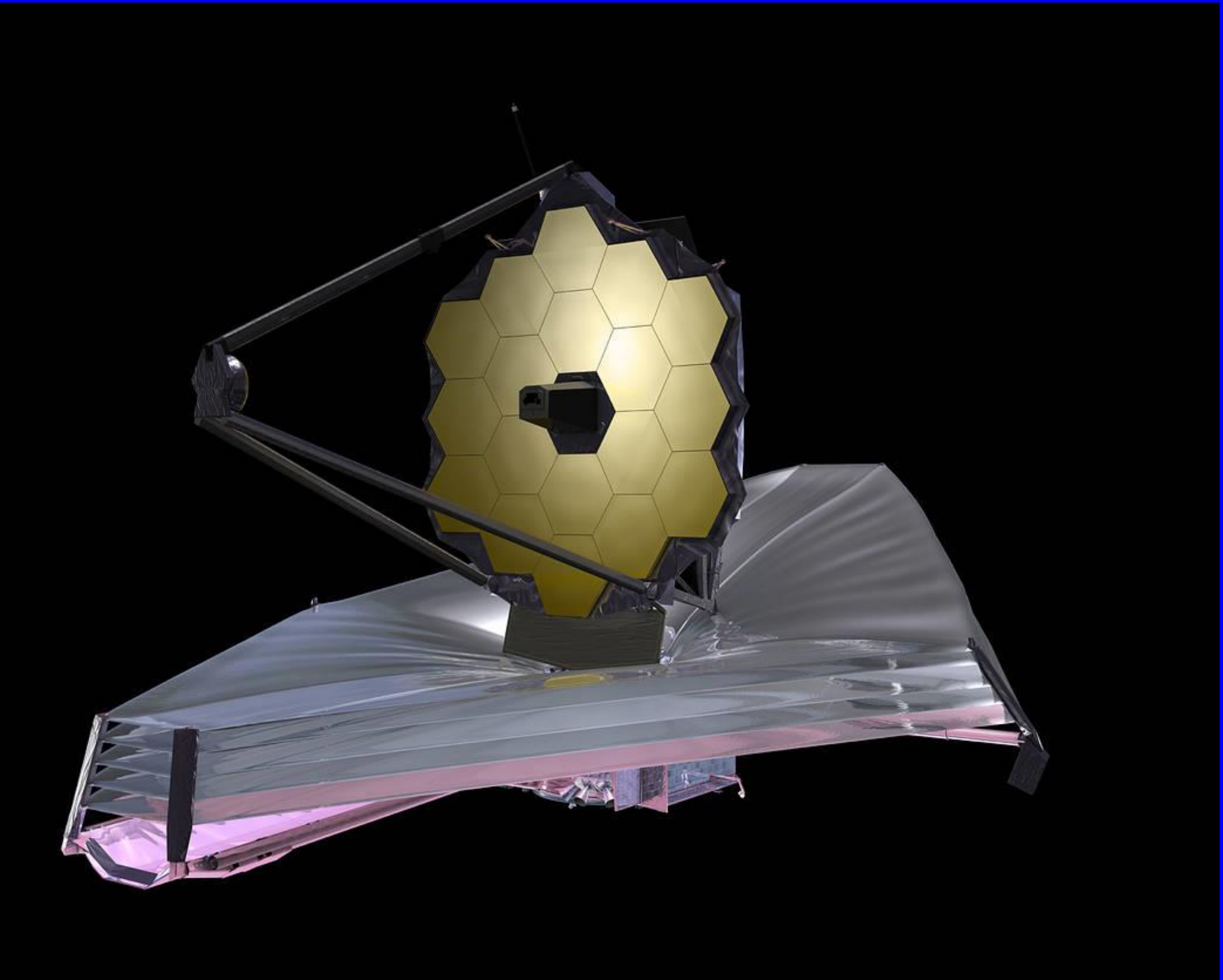
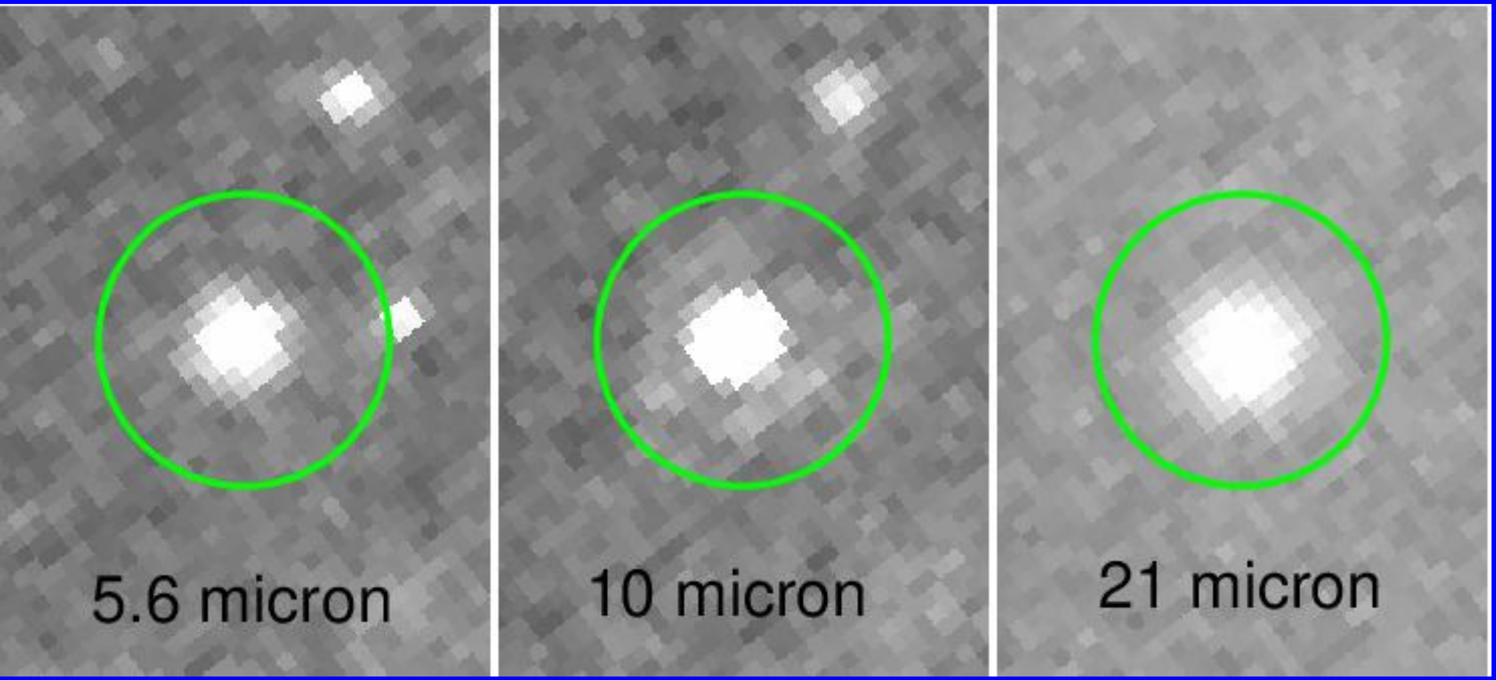
But what if the shock fails and there is no explosion?

Disappearance of a massive star: apparently, collapse to a BH



Or is it just hiding……?





There is a dusty source – but has only 10% of the luminosity of the progenitor star

In our scenario this is powered by material falling onto the newly formed black hole