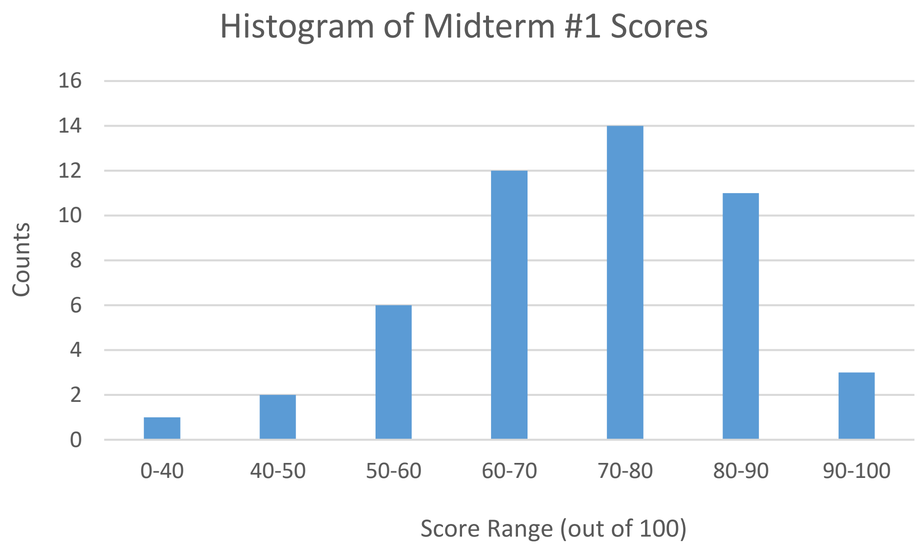
Midterm #1 Results

Average score = 71.8 /100

High score = 99 /100



	Problem #1	Problem #2	Problem #3	Problem #4
average =	22.9 /25	16.8 /25	17.1 /25	15.0 /25

Today’s Topics

Friday, March 21, 2025 (Week 7, lecture 19) – Chapters 22, 23.

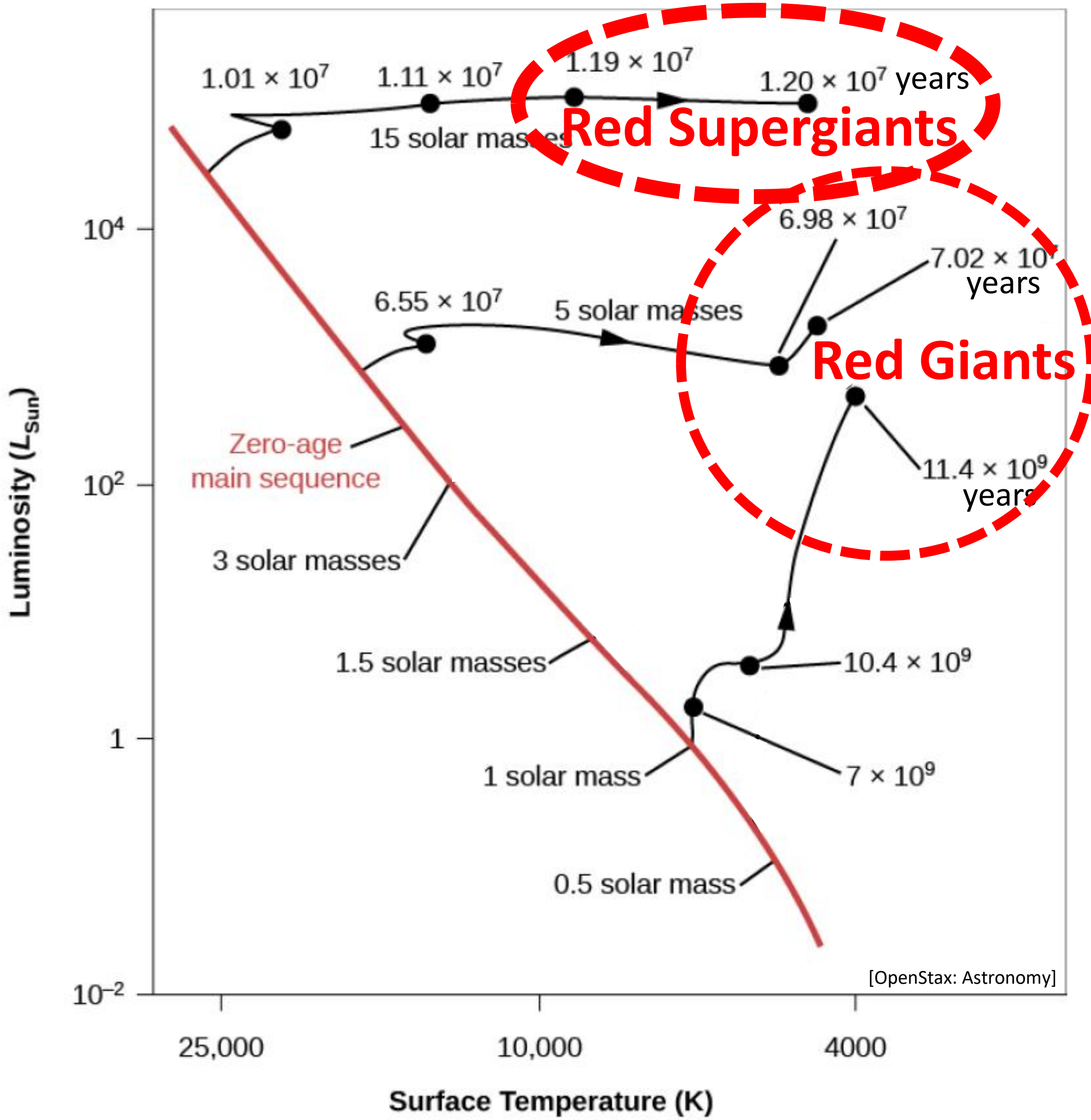
1. Evolution of massive stars.
2. Type II supernovas: images.
3. Type II supernovas: physics.

Interlude 1 Essay is due on Friday, March 28 by 9:00 am

Stellar evolution: on the H-R diagram

Light stars (sun-like & smaller)

- Yellow and red color.
- cooler and dimmer.
- Long lived.
  → > 10 billion years.



Stellar evolution: on the H-R diagram

Heavy stars

- Blue-ish color.
- Hot and very luminous.
- Very short lived.
  → < 1-10 million years.

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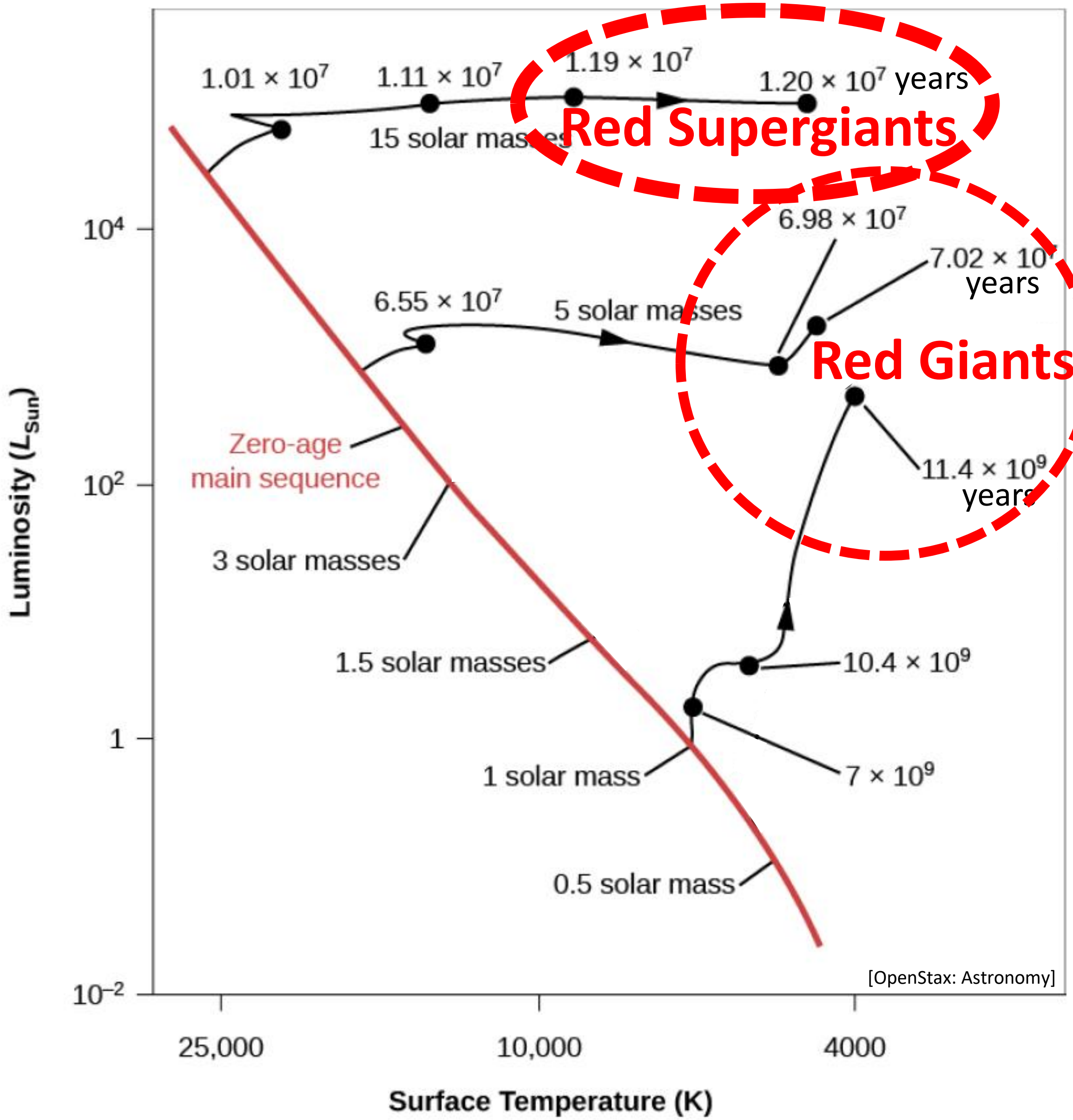

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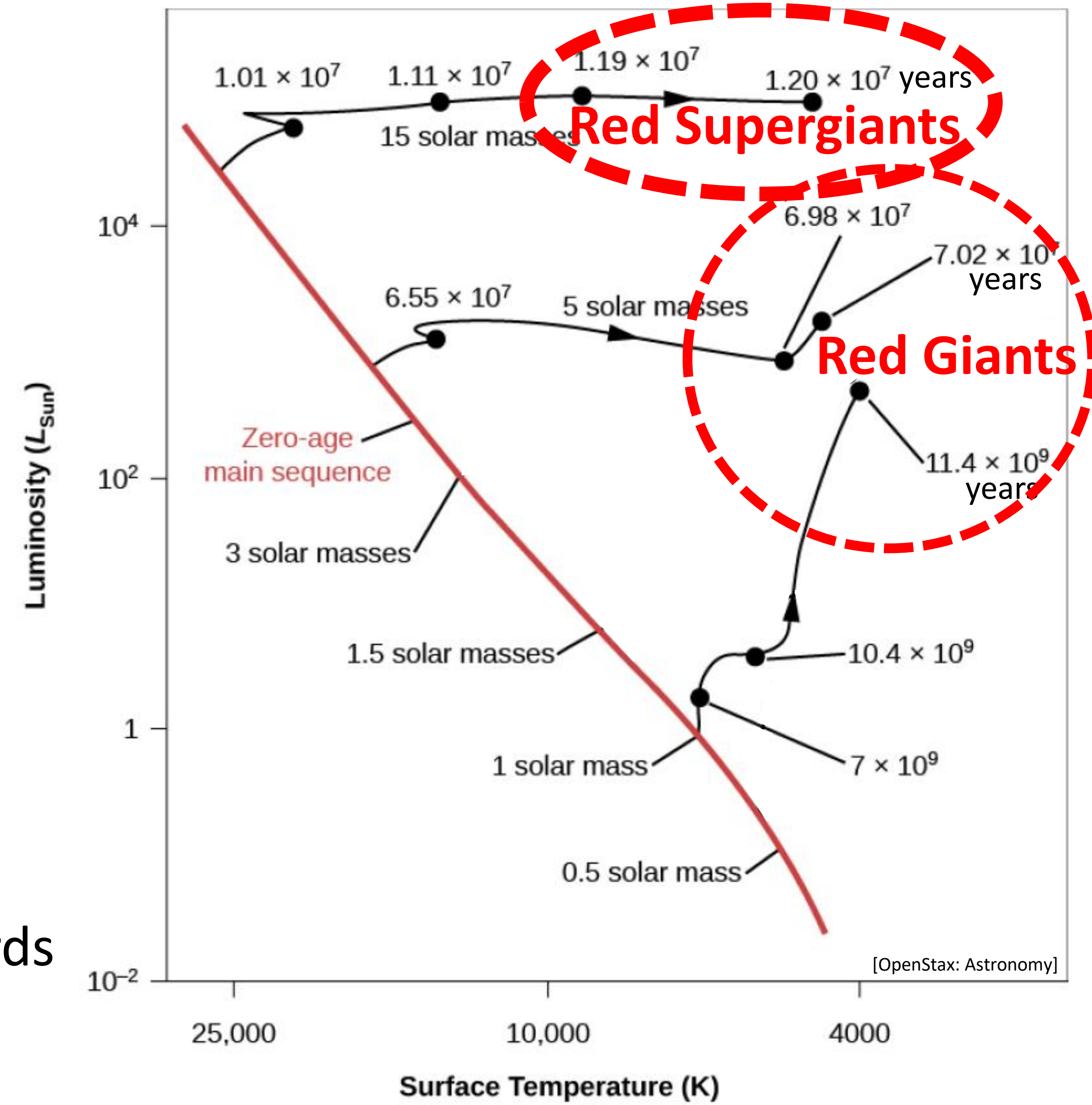
Old age

Stars evolve quickly towards the upper right corner.

→ More luminous, but cooler.



Evolution of Massive Stars

Mass is destiny

Evolution of Massive Stars

- Stars with masses above ~ $8M_{Sun}$ can fuse elements above carbon & oxygen.
- The more massive the star, the more elements can be produced.

  → Most massive elements are produced successively in core of star.
- Above iron & nickel, fusion does not generate energy.

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Alpha-processes

$${}^{12}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{16}_{8}\mathrm{O} \text{ + 7.6 MeV}$$

$${}^{16}_{8}\mathrm{O} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{20}_{10}\mathrm{Ne} \text{ + 4.7 MeV}$$

↓ Mg, Si, S, Ar, Ca, Ti, Cr, Fe

$${}^{52}_{26}\mathrm{Fe} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{56}_{28}\mathrm{Ni} \text{ + 8.0 MeV}$$

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Radioactive decay

$$^{56}_{28}\mathrm{Ni} \rightarrow ^{56}_{27}\mathrm{Co} + e^{-}$$

$$^{56}_{27}\mathrm{Co} \rightarrow ^{56}_{26}\mathrm{Fe} + e^{-}$$

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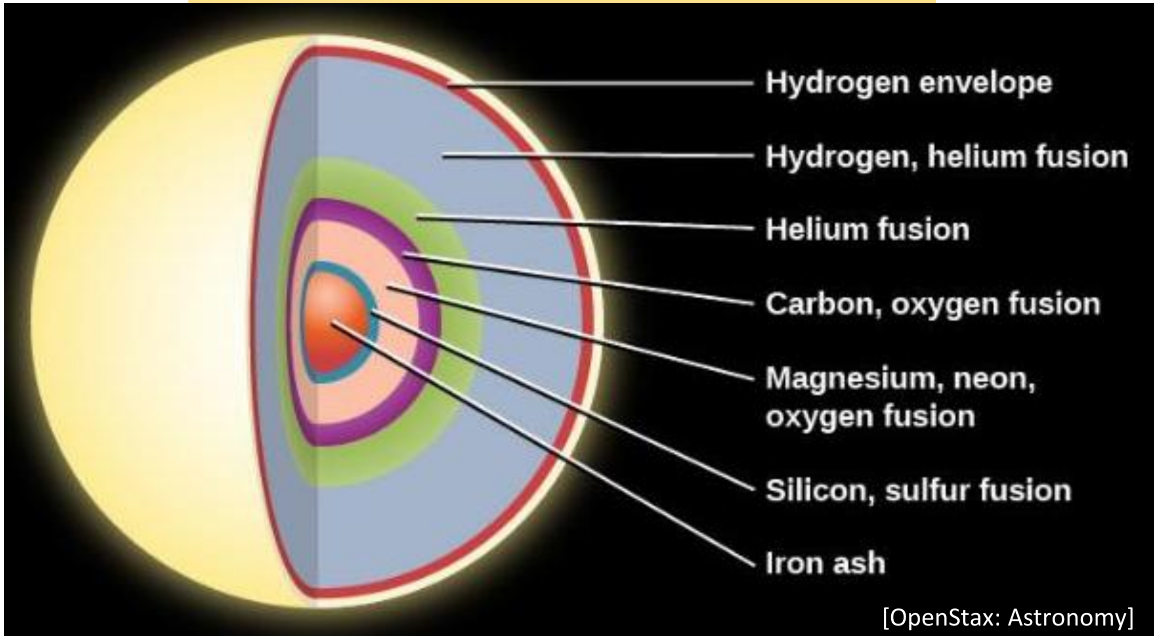
Stellar "onion" of elements



Evolution of Massive Stars
Example: SN 1987A

Mass of SN 1987A $\approx 20M_{Sun}$

Phase	Central Temperature (K)	Central Density (g/cm^3)	Time Spent in This Phase
Hydrogen fusion	40×10^6	5	8×10^6 years
Helium fusion	190×10^6	970	10^6 years
Carbon fusion	870×10^6	170,000	2000 years
Neon fusion	1.6×10^9	3.0×10^6	6 months
Oxygen fusion	2.0×10^9	5.6×10^6	1 year
Silicon fusion	3.3×10^9	4.3×10^7	Days
Core collapse	200×10^9	2×10^{14}	Tenths of a second

type II supernova → neutron star typically (or black hole)

Fusion production of iron & nickel

[Table 23.2, OpenStax: Astronomy]

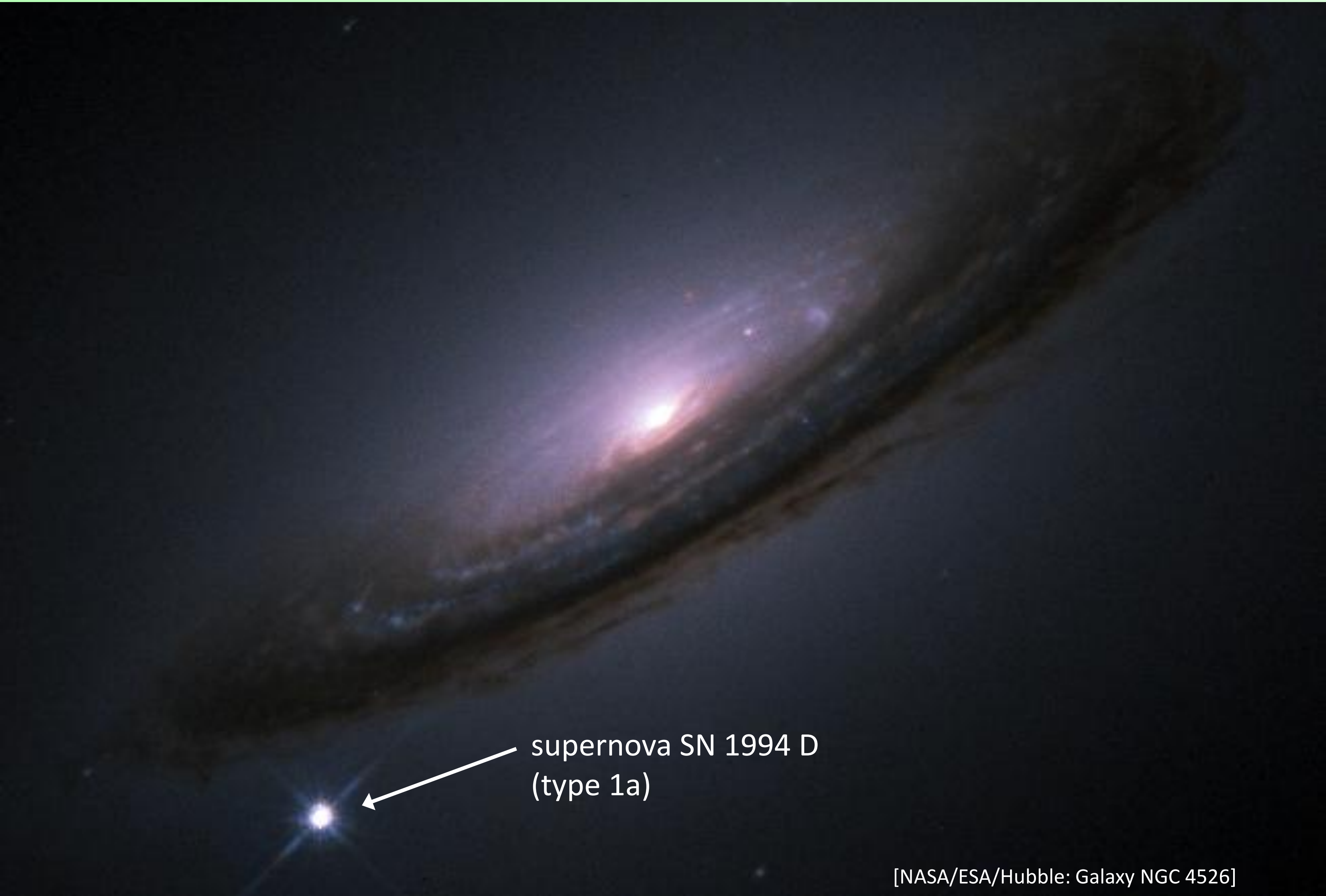
Ultimate Fate of Stars

Initial Mass (Mass of Sun = 1)[1]	Final State at the End of Its Life
< 0.01	Planet
0.01 to 0.08	Brown dwarf
0.08 to 0.25	White dwarf made mostly of helium
0.25 to 8	White dwarf made mostly of carbon and oxygen
8 to 10	White dwarf made of oxygen, neon, and magnesium
10 to 40	Supernova explosion that leaves a neutron star
> 40	Supernova explosion that leaves a black hole

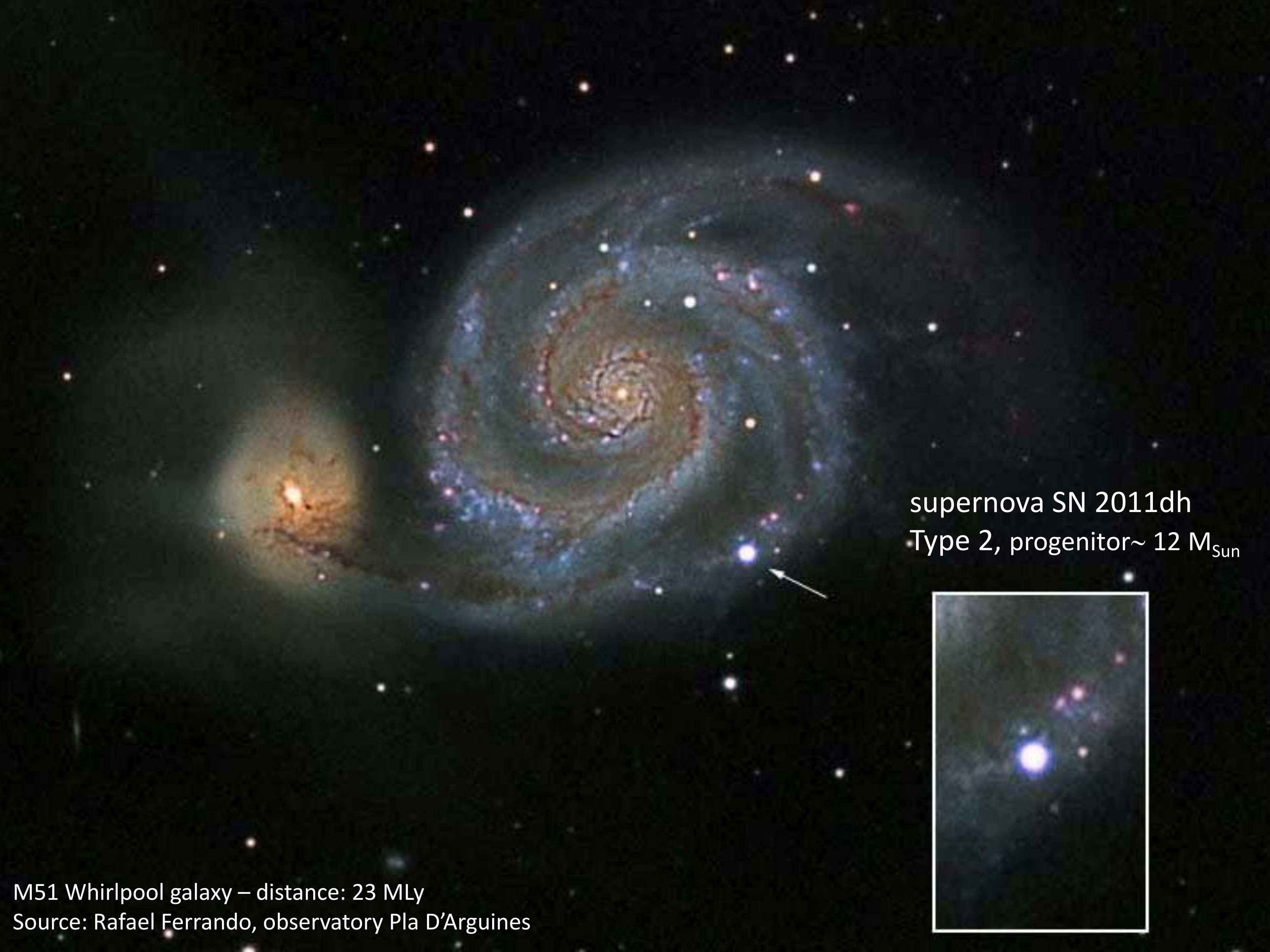
type II supernova

[Table 23.1, OpenStax: Astronomy]

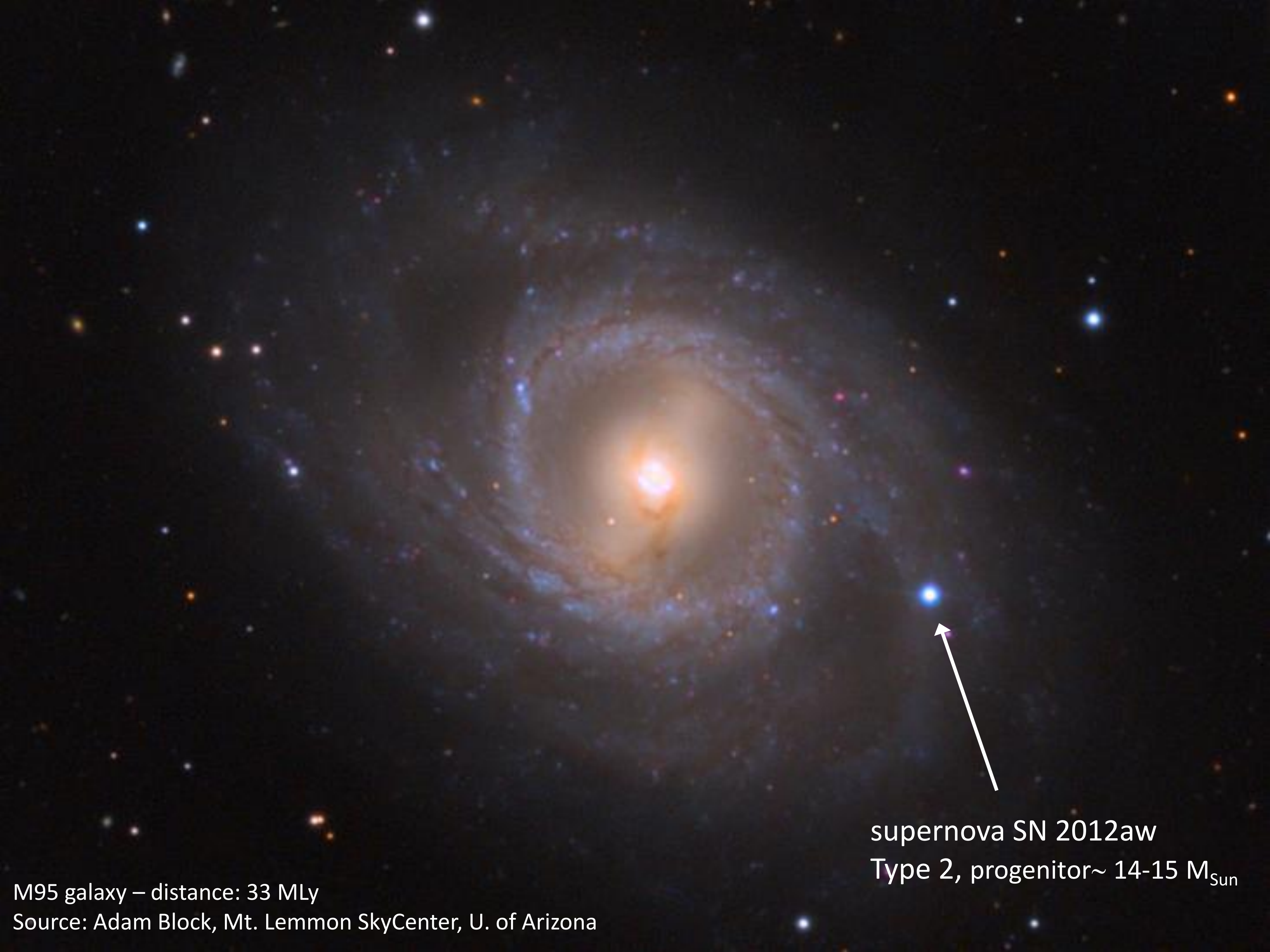
Supernovas can be as bright as a galaxy



[NASA/ESA/Hubble: Galaxy NGC 4526]



M51 Whirlpool galaxy – distance: 23 MLy
Source: Rafael Ferrando, observatory Pla D'Arguines



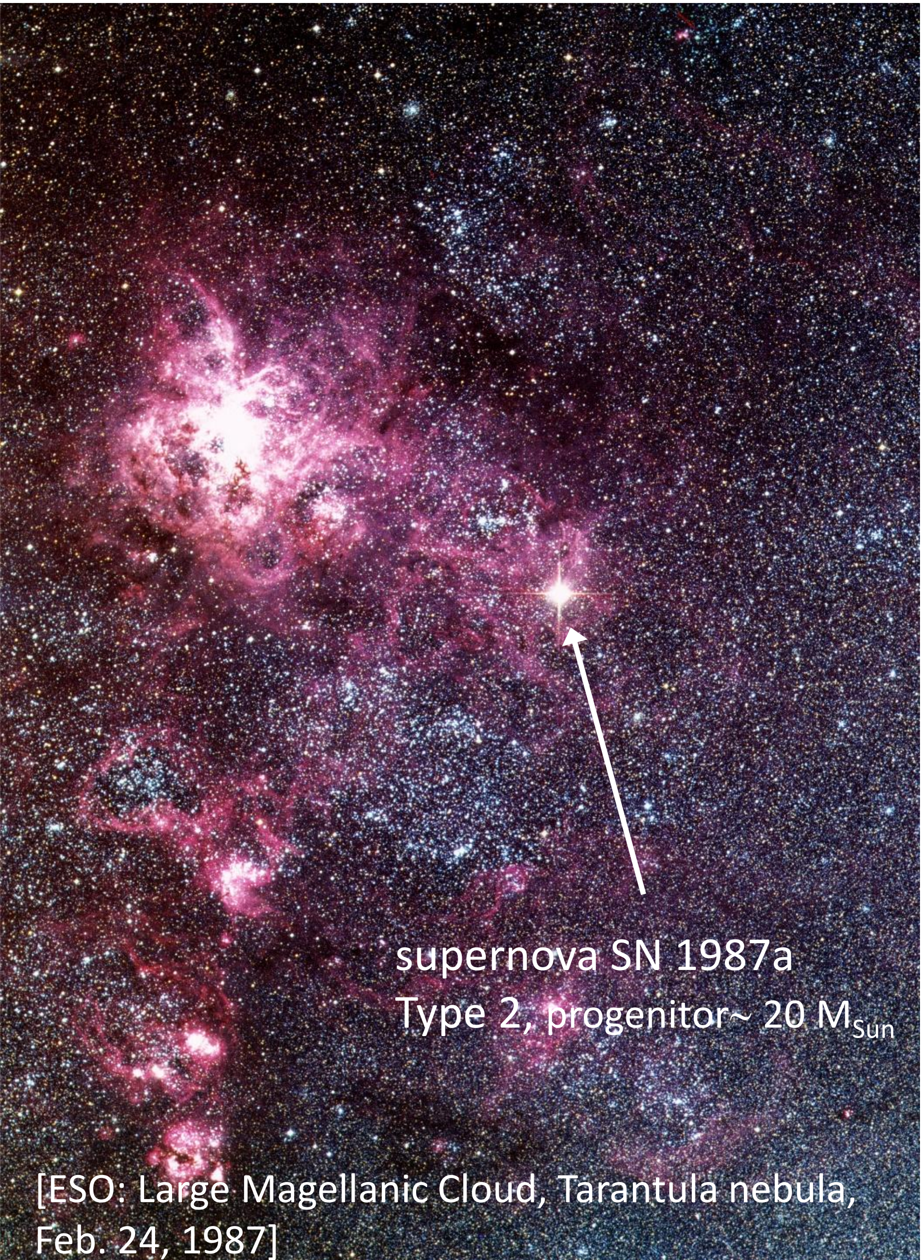
M95 galaxy – distance: 33 MLy
Source: Adam Block, Mt. Lemmon SkyCenter, U. of Arizona

Supernova SN 1987A

[ESO: Large Magellanic Cloud, Tarantula nebula, Feb. 24, 1987]

[NASA, ESA, and R. Kirshner and P. Challis: Jan. 2017]

Supernova SN 1987A



[ESO: Large Magellanic Cloud, Tarantula nebula, Feb. 24, 1987]

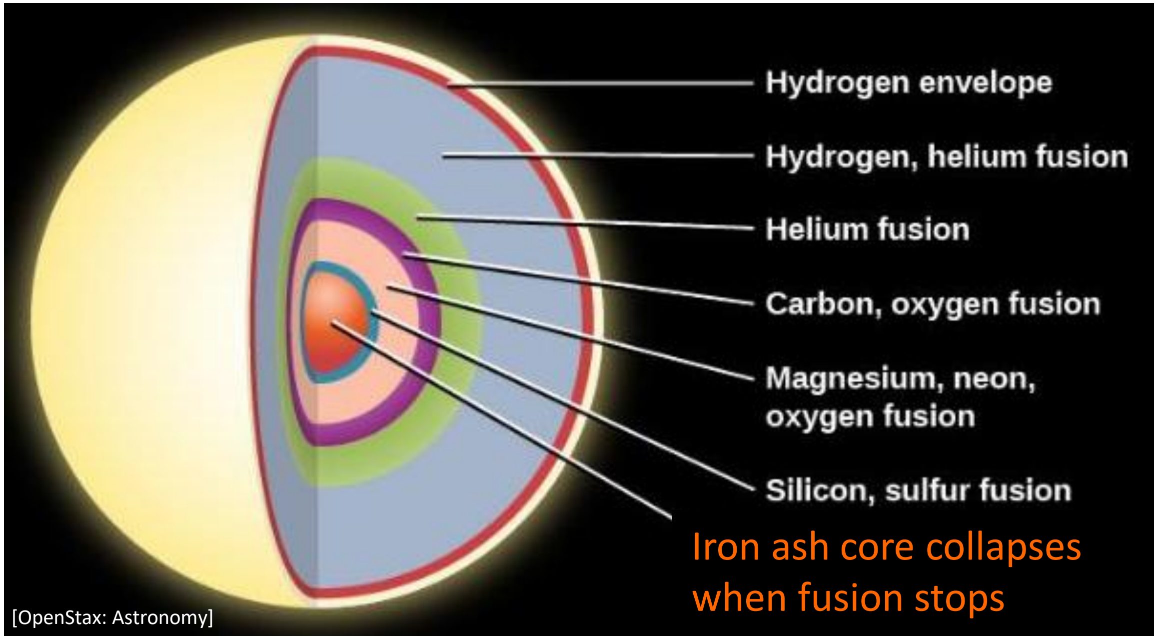
Type II supernova

→ Core collapses under gravity.
→ Produces a neutron star or black hole.

[NASA, ESA, and R. Kirshner and P. Challis: Jan. 2017]

Note: No neutron star has been definitively detected yet !

Type II Supernova: *Core Collapse*



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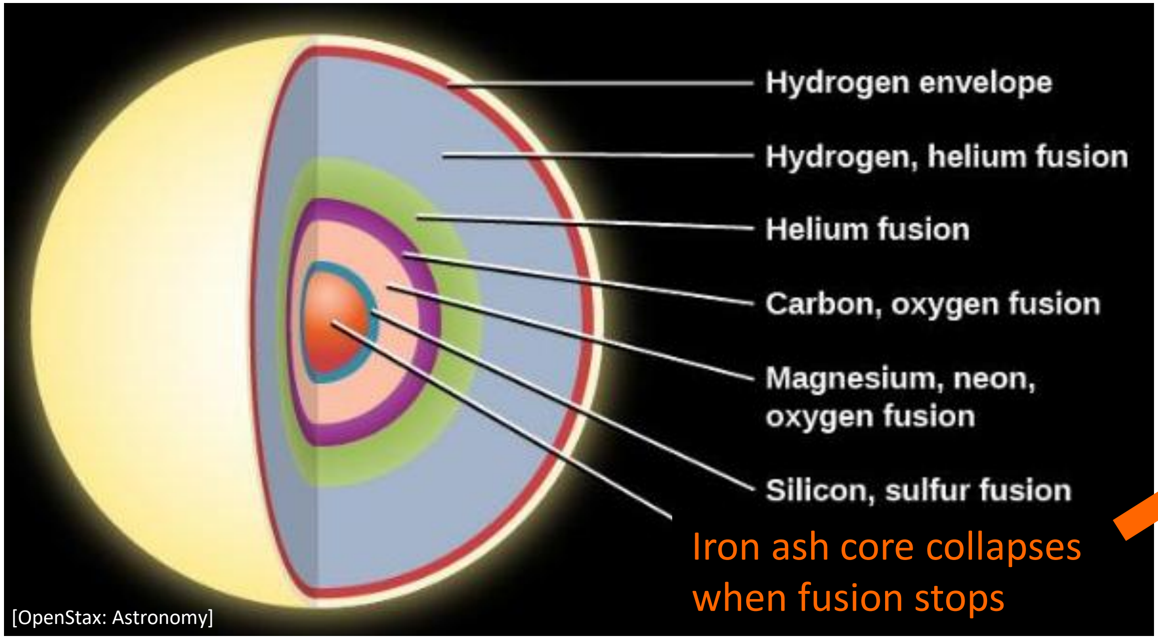
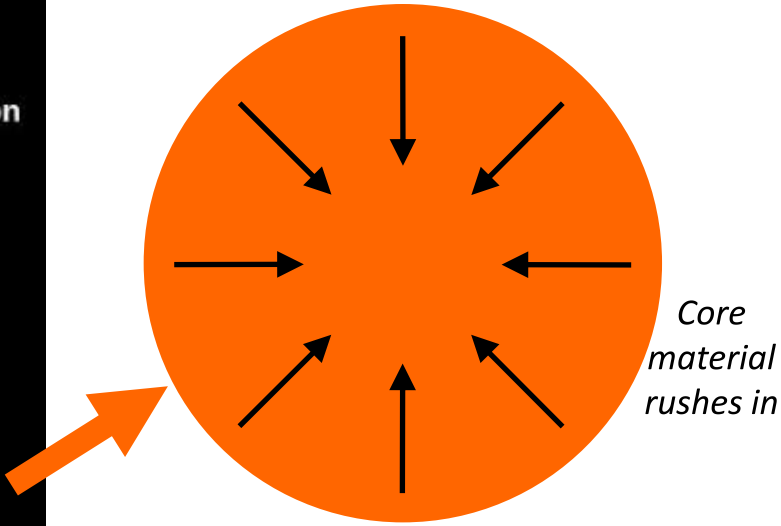


1. **iron core** collapses under gravity



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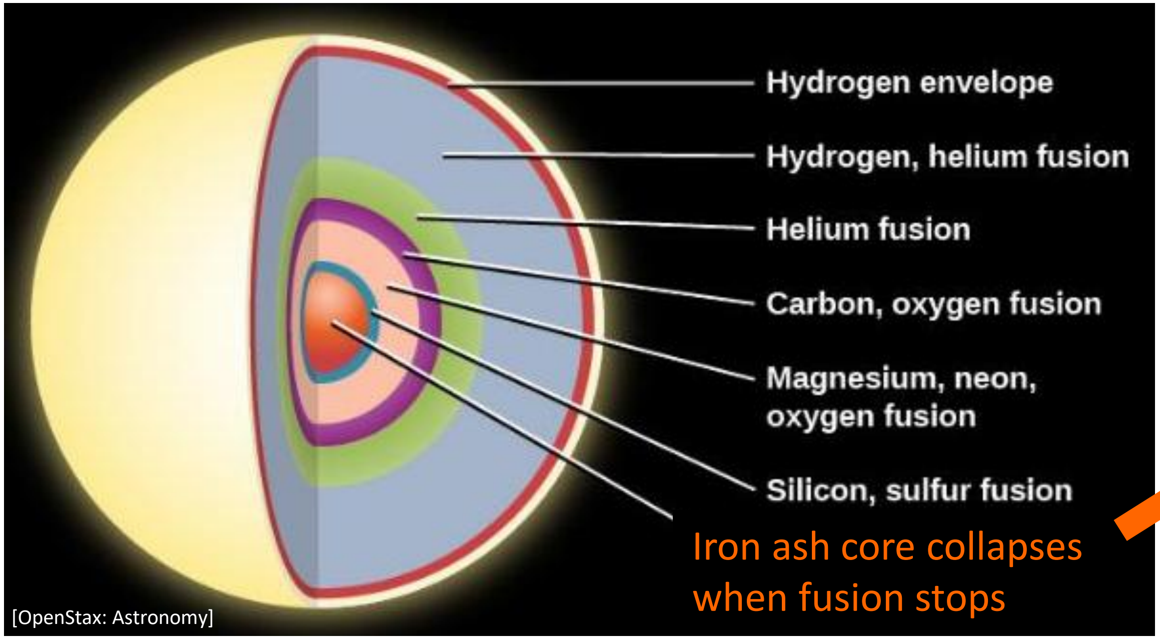

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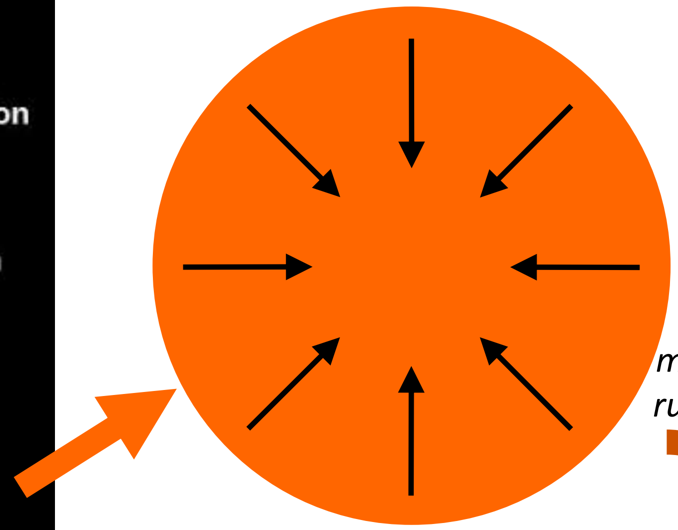
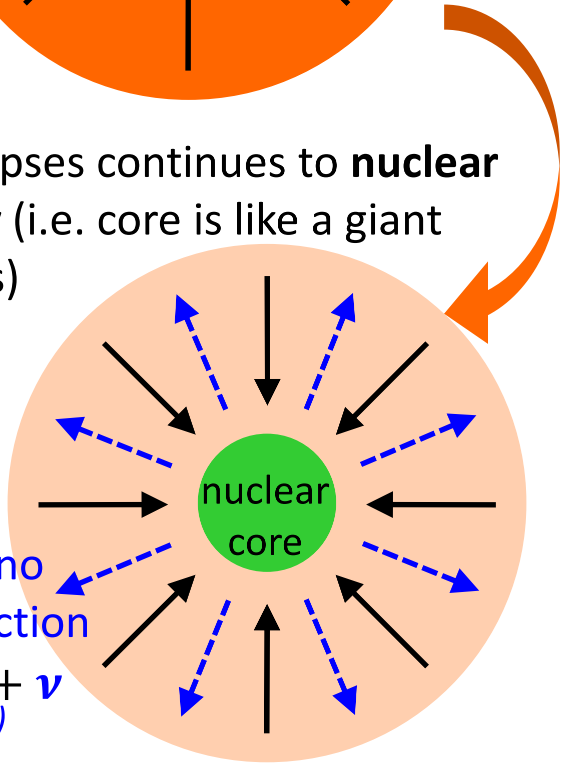


Core material rushes in

2. Collapses continues to **nuclear density** (i.e. core is like a giant nucleus)



neutrino production

$$p^+ + e^- \rightarrow n + \boldsymbol{\nu}$$

(weak force)

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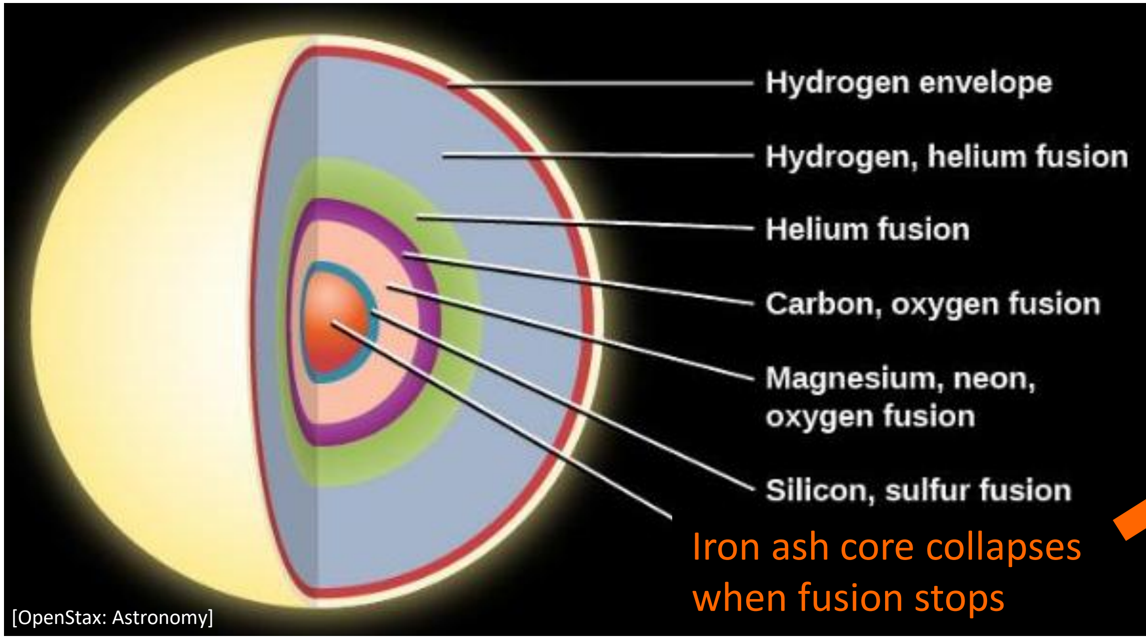

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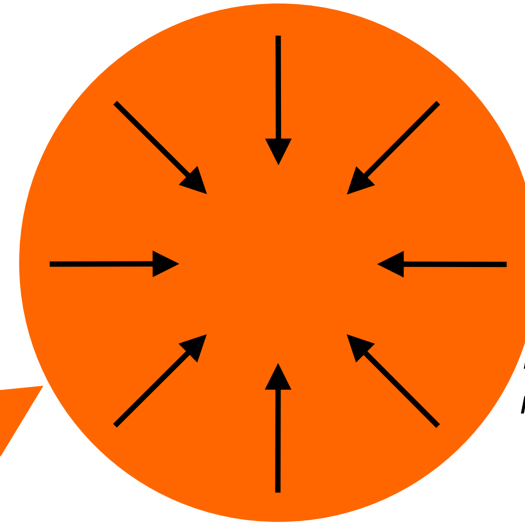

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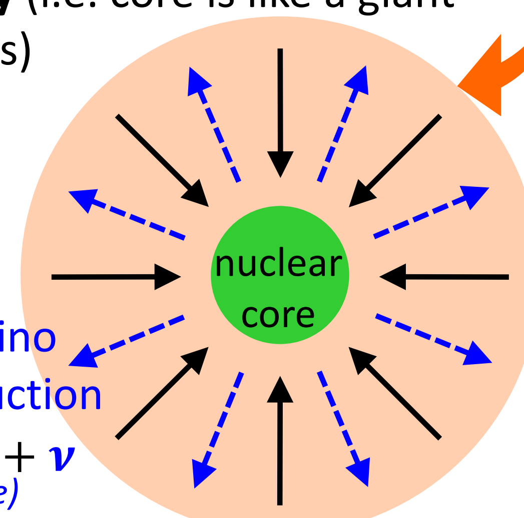

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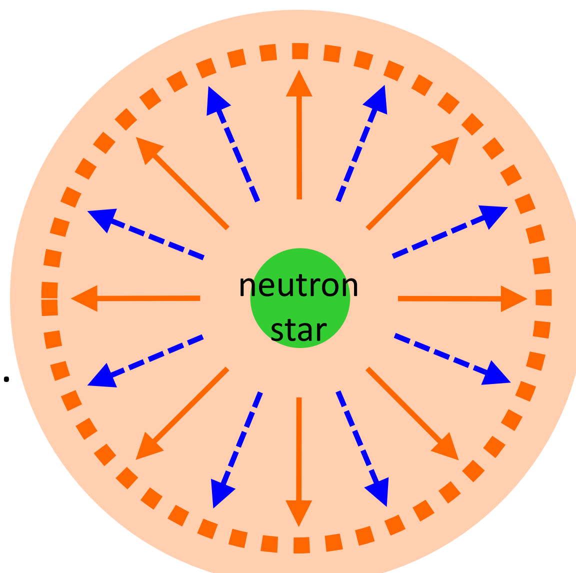
3. In-falling material **rebounds** off **neutron star** core creating an outward moving **shockwave**.

→ Star is blown apart.



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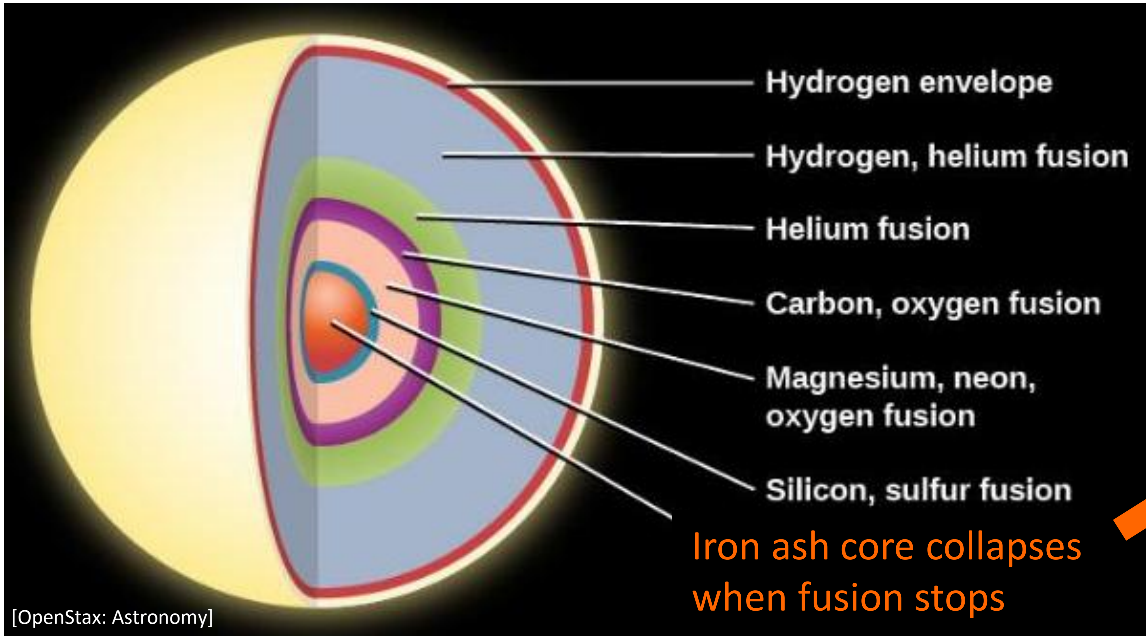

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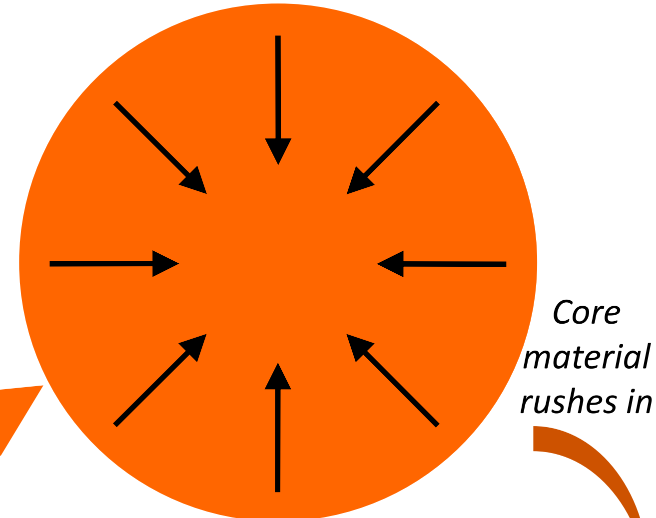

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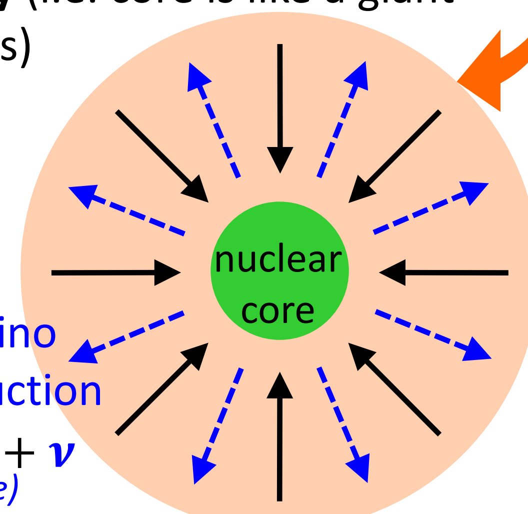

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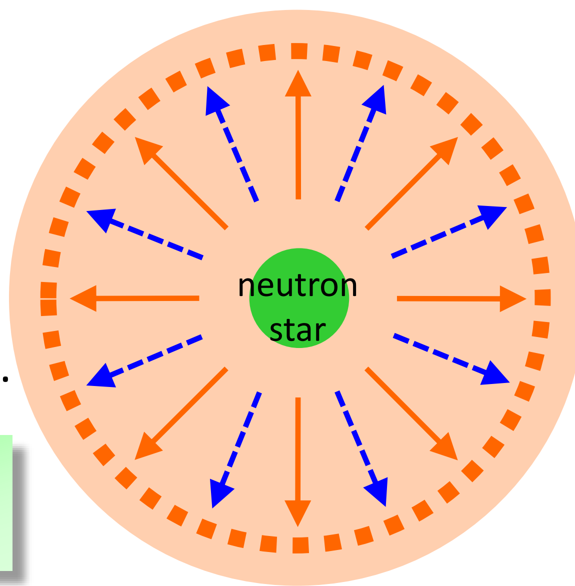

Note: entire process takes a few seconds.

Type II Supernova: *What's produced ?*

Lots of Energy

- Supernovas typically emit about 10^{46} Joules of energy.
  → 100 times more energy than Sun will emit in its lifetime (10^{44} Joules).
- Supernovas shine with a luminosity of 10^9-10^{10} L_{Sun} for a few months.
- This energy comes from **gravitational potential energy** released during the collapse.

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Lots of neutrinos

- When the core collapses, the temperature spikes to 10-100 billion K at nuclear densities.
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- About 20% of the core's mass is converted to neutrinos.
  → Energy: ~ 99% of the energy is released through neutrinos.

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Some light & heavy elements

- About 0.01 % of the supernova's energy is released as electromagnetic radiation (e.g. light).
- Most of the light is emitted due to radioactive decay of heavy elements (primarily Ni).
- Supernovas produce some elements heavier than Fe and Ni (up to Rb).

Supernova

=

gravity powered neutrino explosion of a massive star

Type II Supernova: *What's Left ?*

Initial Star Mass	Outcome	
10-40 M_{Sun}	Supernova → Neutron Star	
40-90 M_{Sun}	Supernova → Black Hole	
>90 M_{Sun}	Direct collapse to Black Hole	(no explosion)

Note: the exact outcome depends on the initial composition (metallicity) star.

Skipping the supernova ? Giant star → black hole