

Today's Topics

Friday, March 20, 2026 (Week 7, lecture 20) – Chapters 22, 23.

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

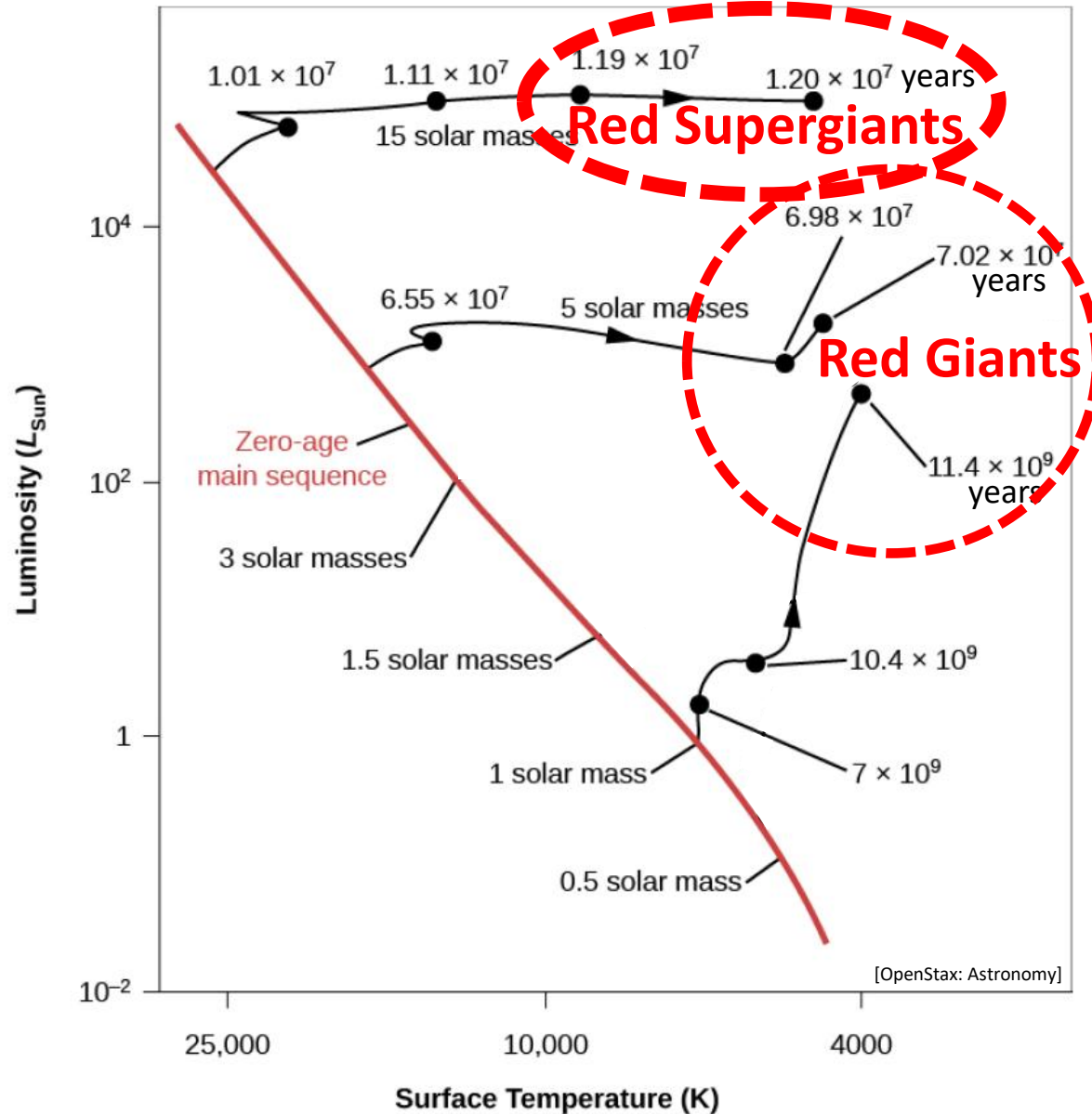
Interlude 1 Essay is due on Monday, March 23 by 9:00 am on Gradescope.

Problem Set #7 is due on Monday, March 30 by 9:00 am on ExpertTA.

Stellar evolution: on the H-R diagram

Light stars (sun-like & smaller)

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



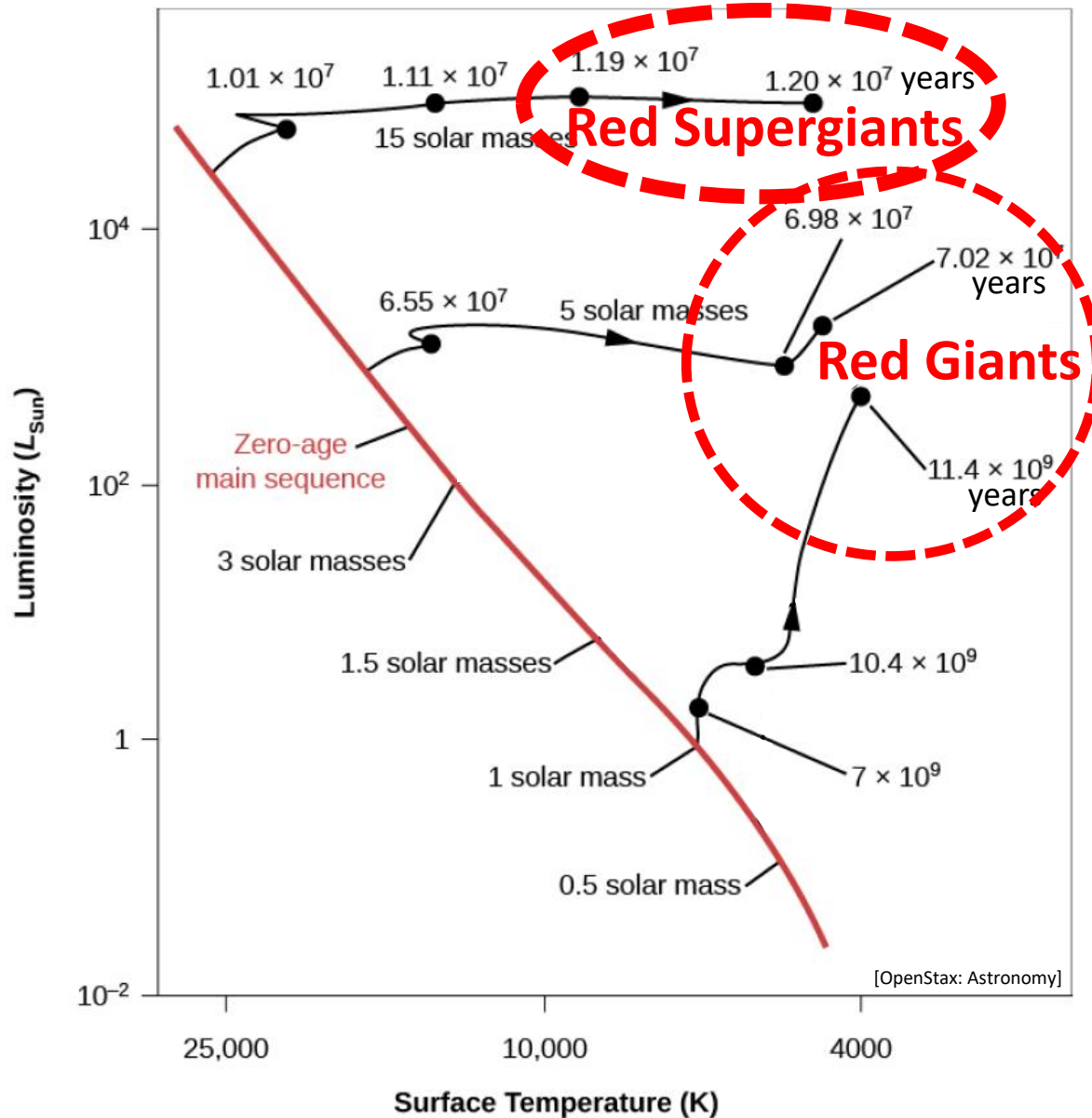
Stellar evolution: on the H-R diagram

Heavy stars

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

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Stellar evolution: on the H-R diagram

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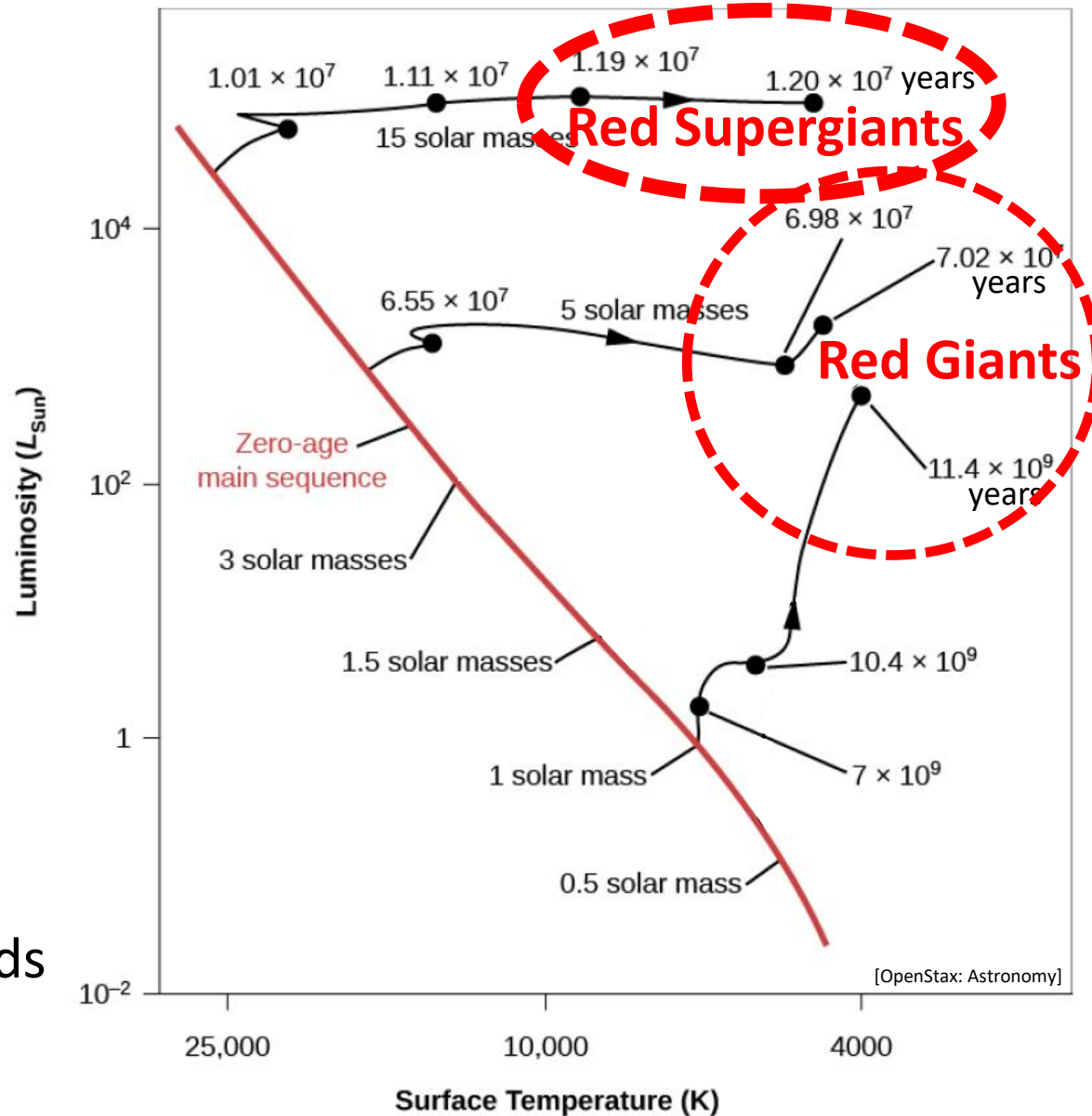
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Light stars (sun-like & smaller)

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Old age

Stars evolve quickly towards the upper right corner.
→ More luminous, but cooler.



[OpenStax: Astronomy]

Evolution of Massive Stars

Mass is destiny

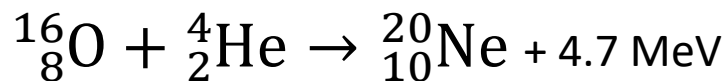
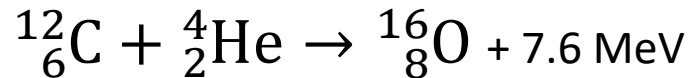
Evolution of Massive Stars

- Stars with masses above $\sim 8M_{\text{Sun}}$ 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.

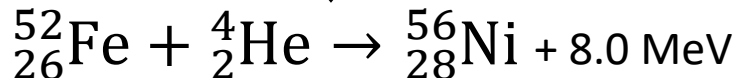
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Alpha-processes



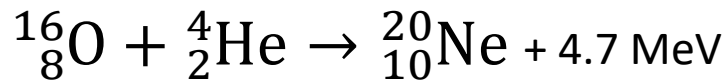
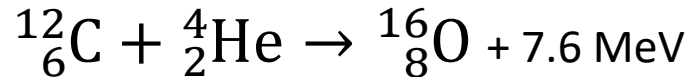
Mg, Si, S, Ar,
Ca, Ti, Cr, Fe



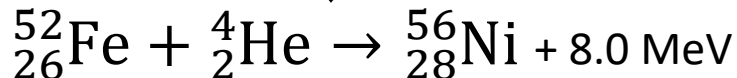
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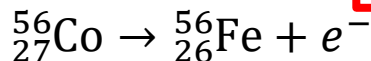
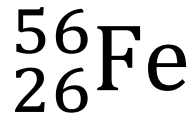
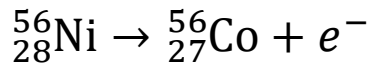
Alpha-processes



↓
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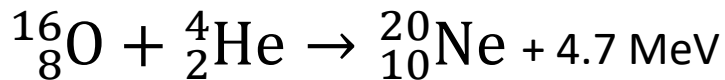
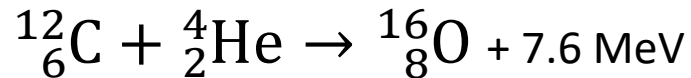
Radioactive decay



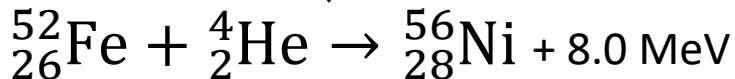
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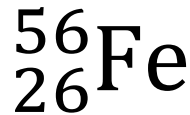
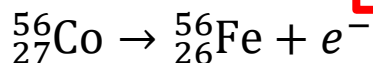
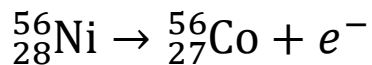
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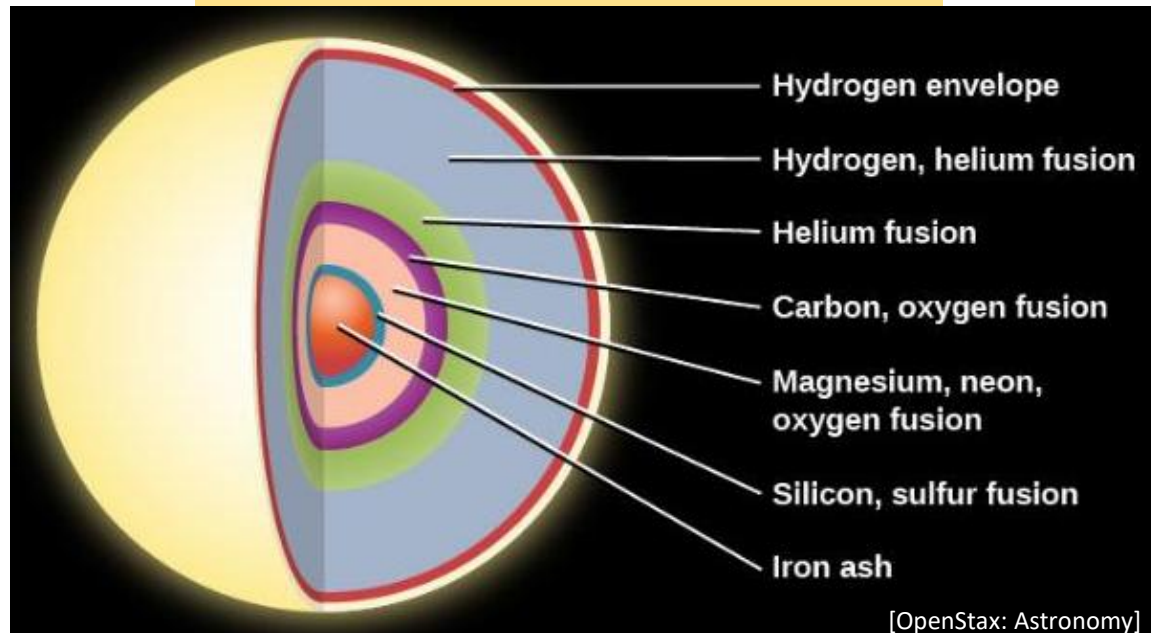
↓
Mg, Si, S, Ar,
Ca, Ti, Cr, Fe



Radioactive decay



Stellar "onion" of elements



Evolution of Massive Stars

Example: SN 1987A

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

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 \rightarrow neutron star typically (or black hole)

Fusion production of iron & nickel

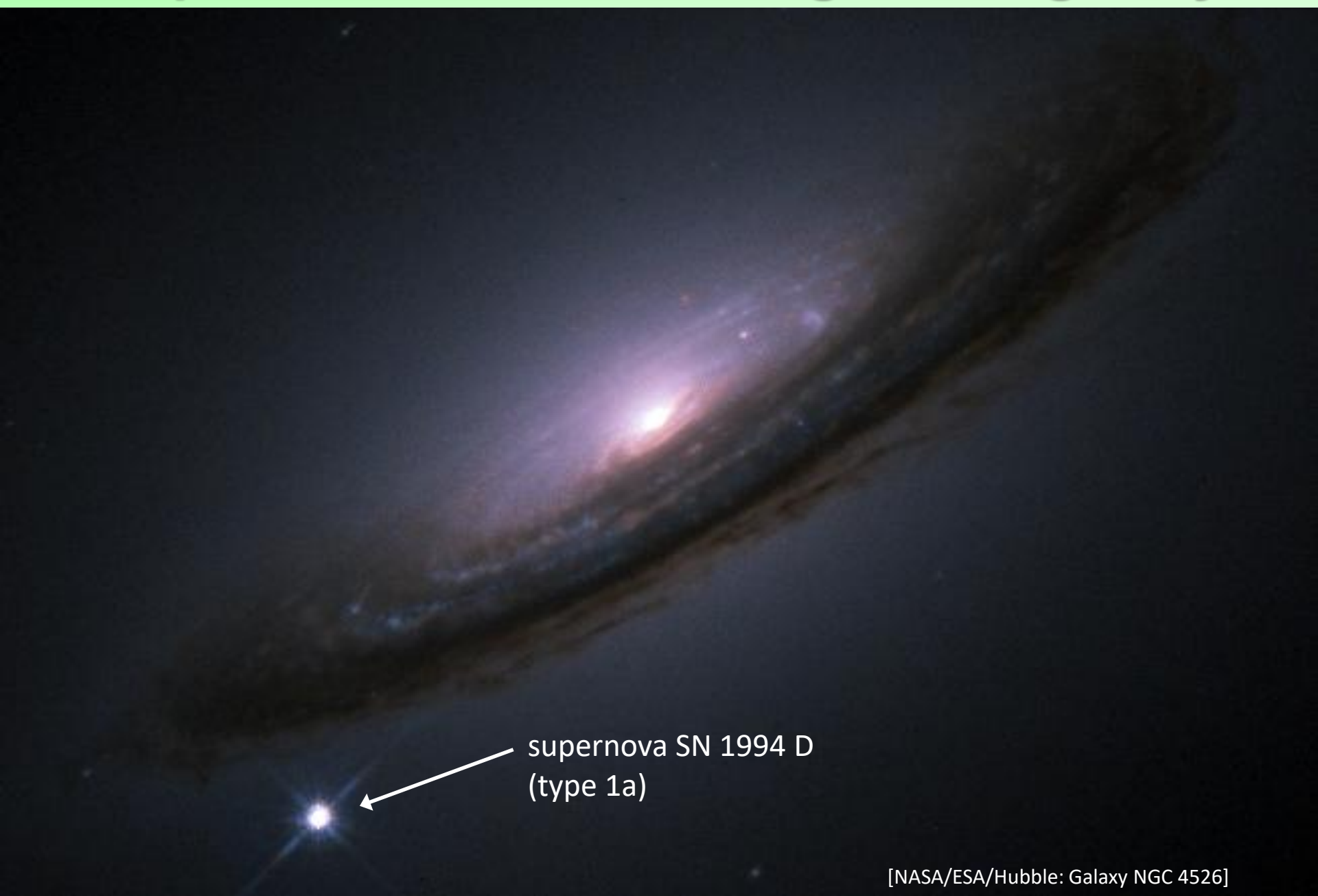
[Table 23.2, OpenStax: Astronomy]

Ultimate Fate of Stars

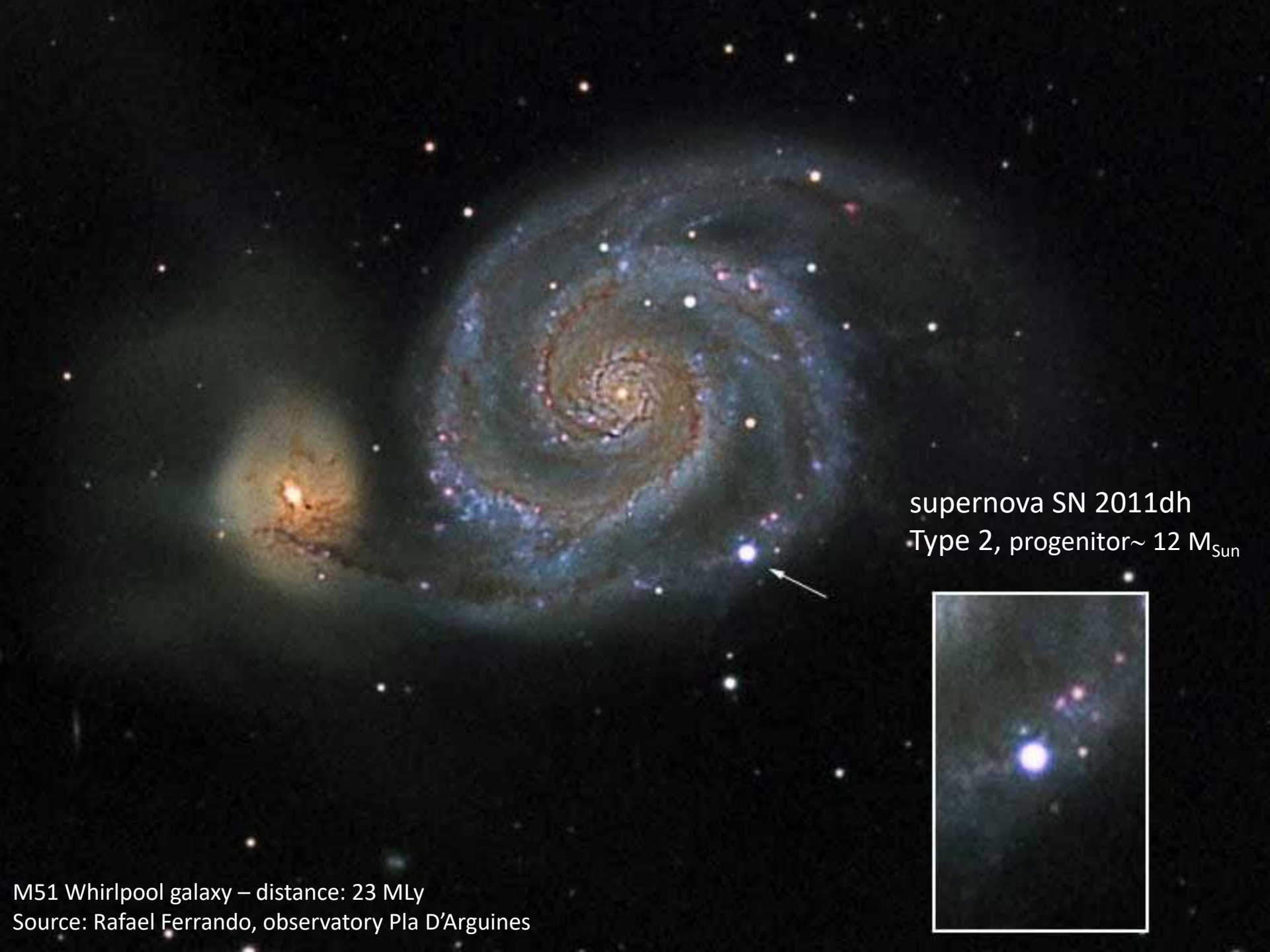
Initial Mass (Mass of Sun = 1) ^[1]	Final State at the End of Its Life
< 0.01	Planet
0.01 to 0.08	Brown dwarf
0.08 to 0.25	White dwarf made mostly of helium
0.25 to 8	White dwarf made mostly of carbon and oxygen
8 to 10	White dwarf made of oxygen, neon, and magnesium
10 to 40	Supernova explosion that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

} type II supernova

Supernovas can be as bright as a galaxy

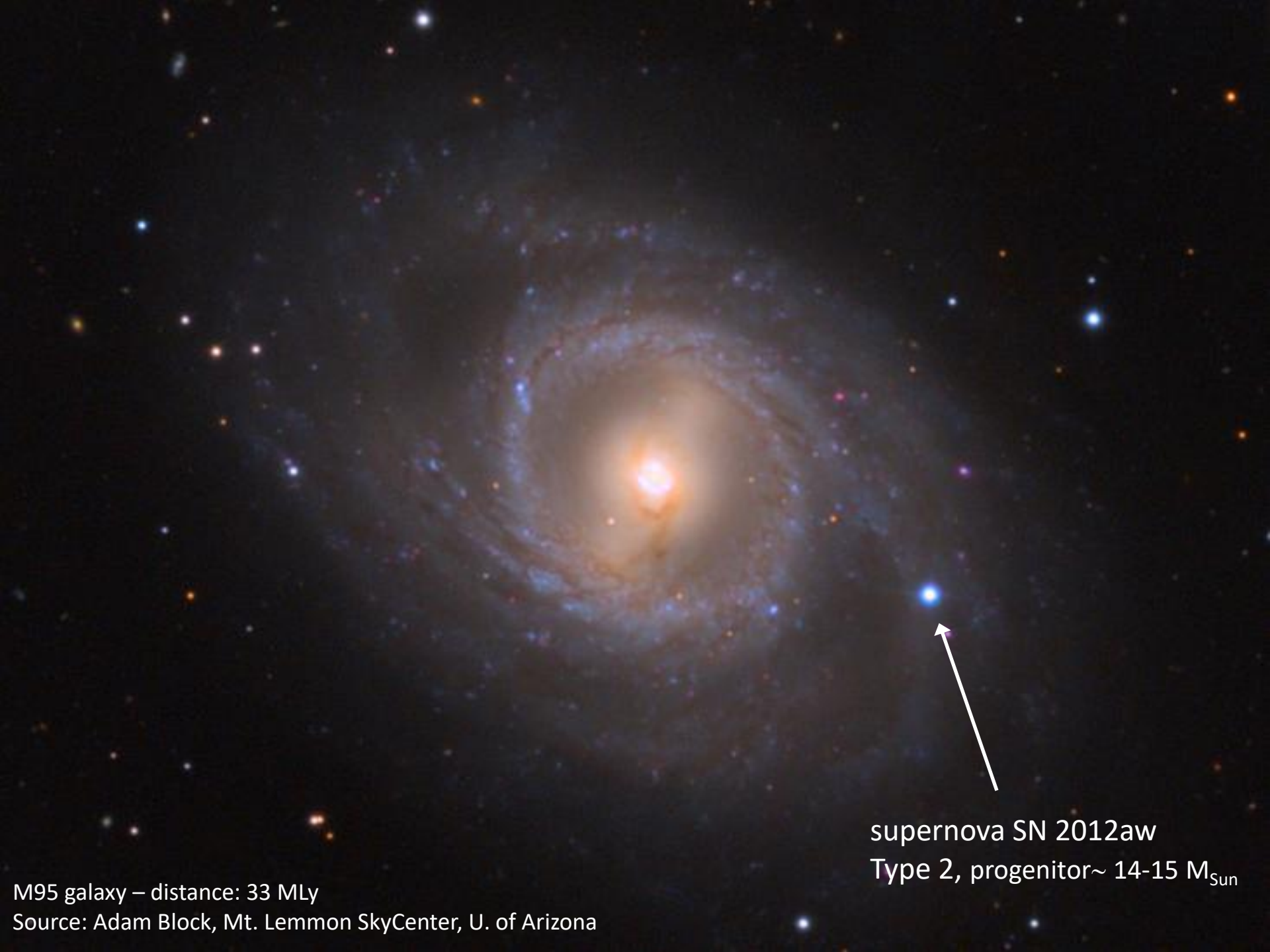


supernova SN 1994 D
(type 1a)



supernova SN 2011dh
Type 2, progenitor $\sim 12 M_{\text{Sun}}$

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



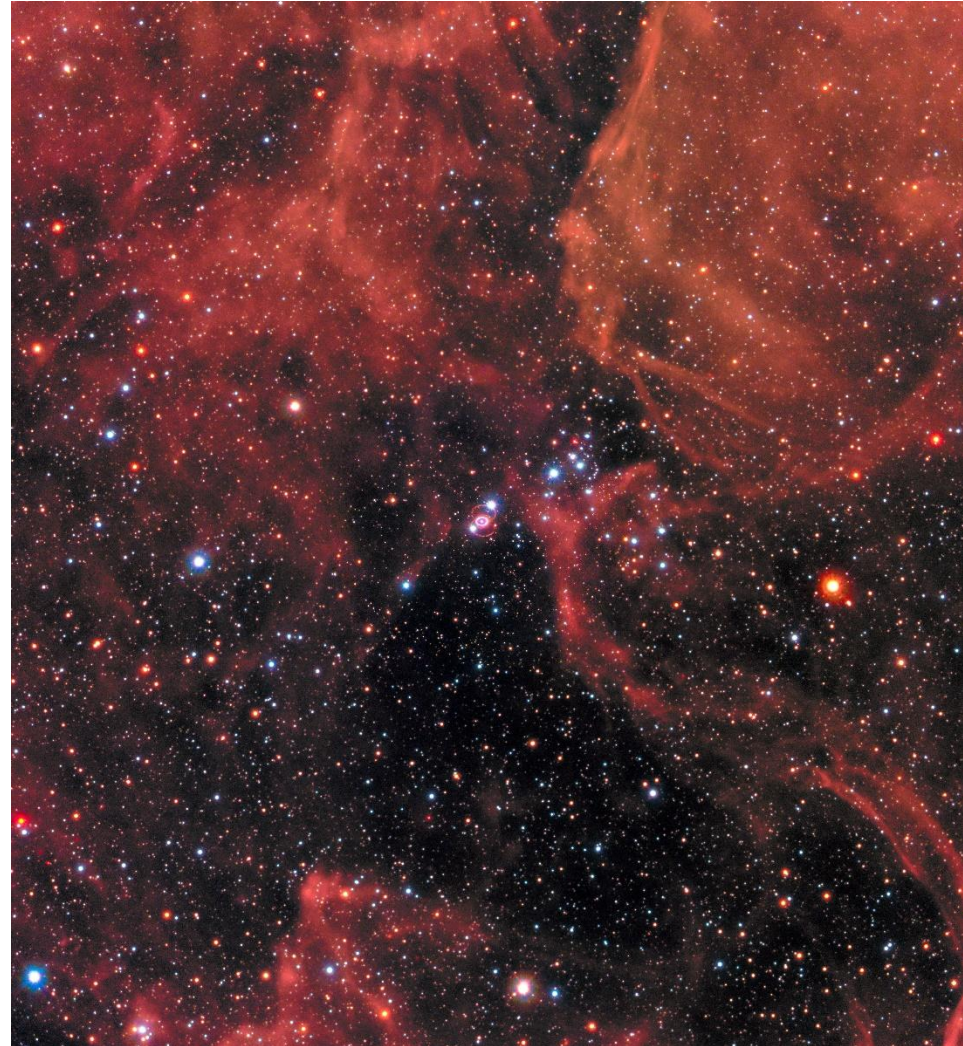
supernova SN 2012aw
Type 2, progenitor $\sim 14-15 M_{\text{Sun}}$

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

Supernova SN 1987A

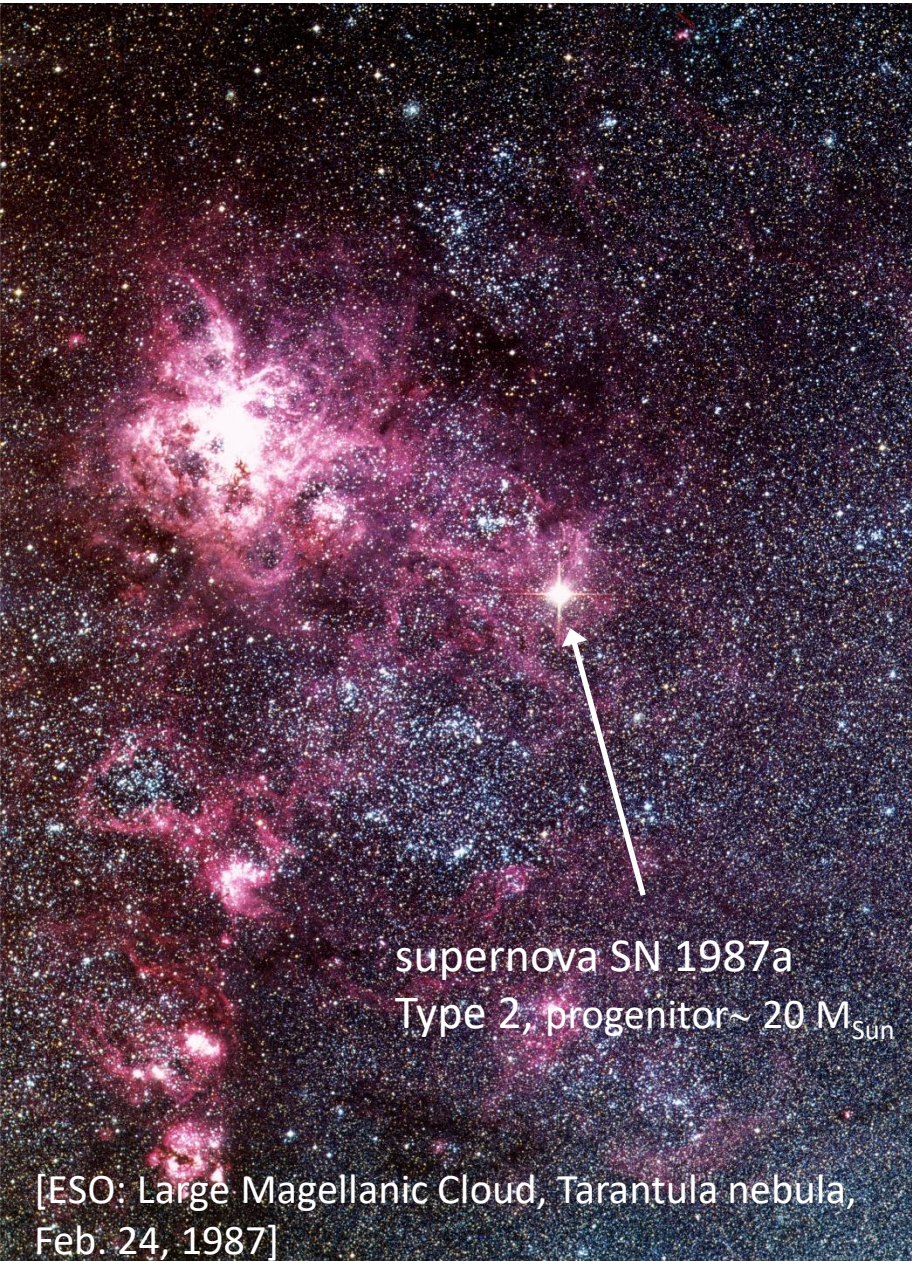


[ESO: Large Magellanic Cloud, Tarantula nebula, Feb. 24, 1987]



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

Supernova SN 1987A



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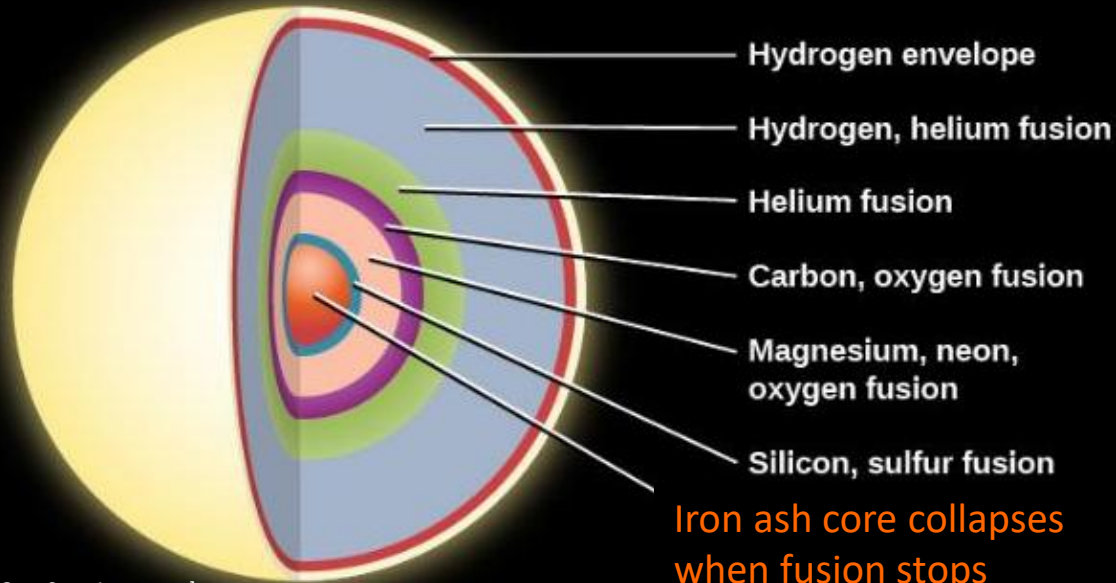
Type II supernova

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



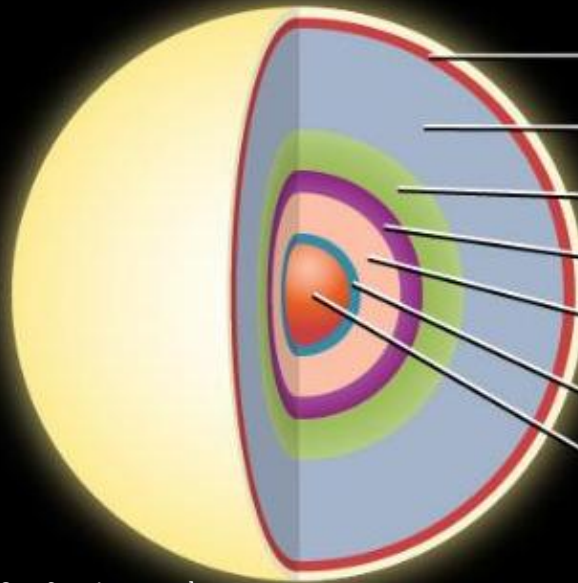
Note: No neutron star has been definitively detected yet !

Type II Supernova: Core Collapse



[OpenStax: Astronomy]

Type II Supernova: Core Collapse



Hydrogen envelope

Hydrogen, helium fusion

Helium fusion

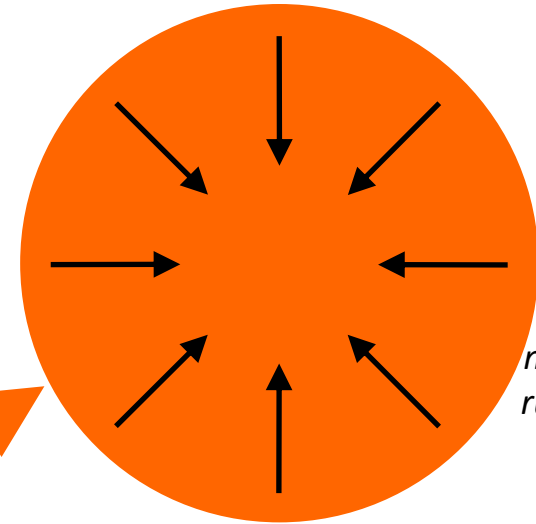
Carbon, oxygen fusion

Magnesium, neon,
oxygen fusion

Silicon, sulfur fusion

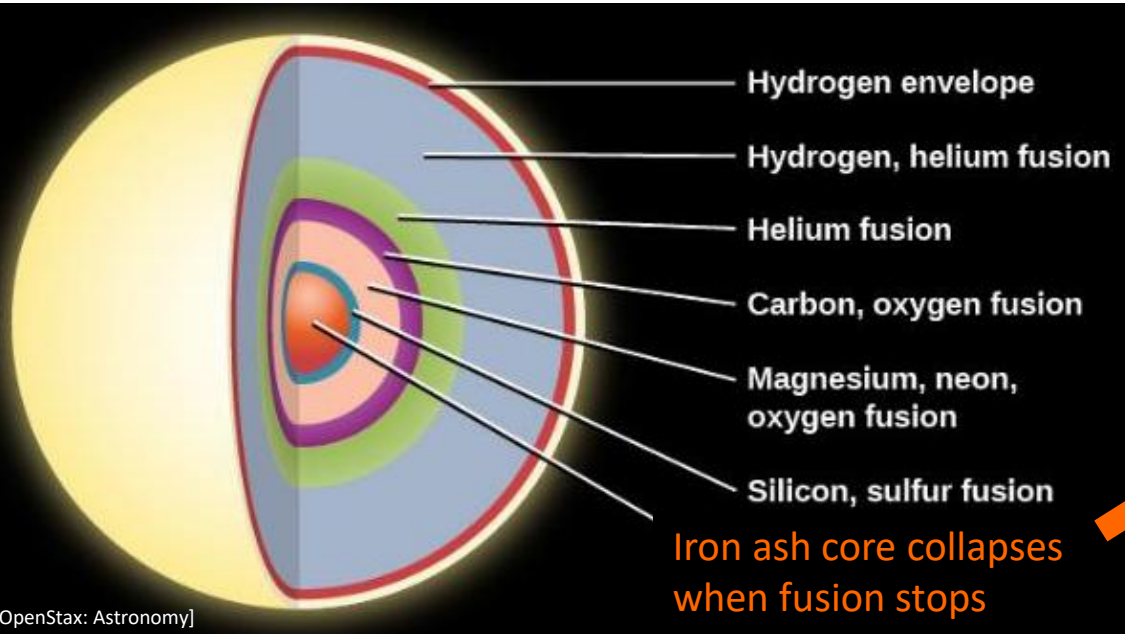
Iron ash core collapses
when fusion stops

1. iron core collapses under gravity

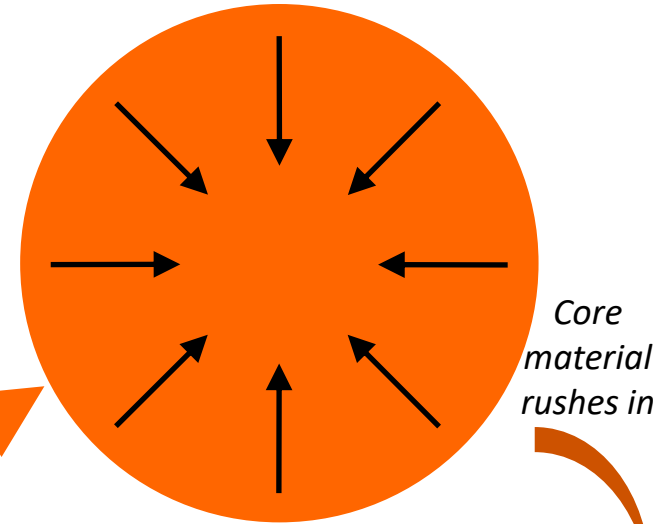


Core
material
rushes in

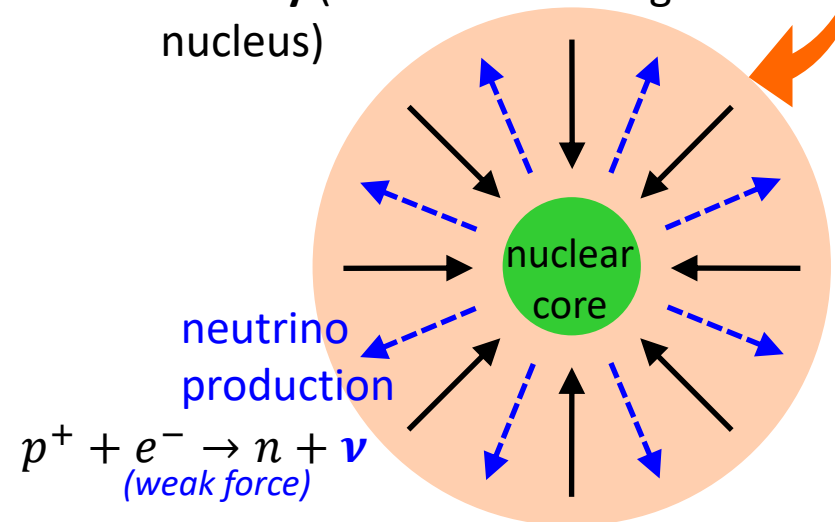
Type II Supernova: Core Collapse



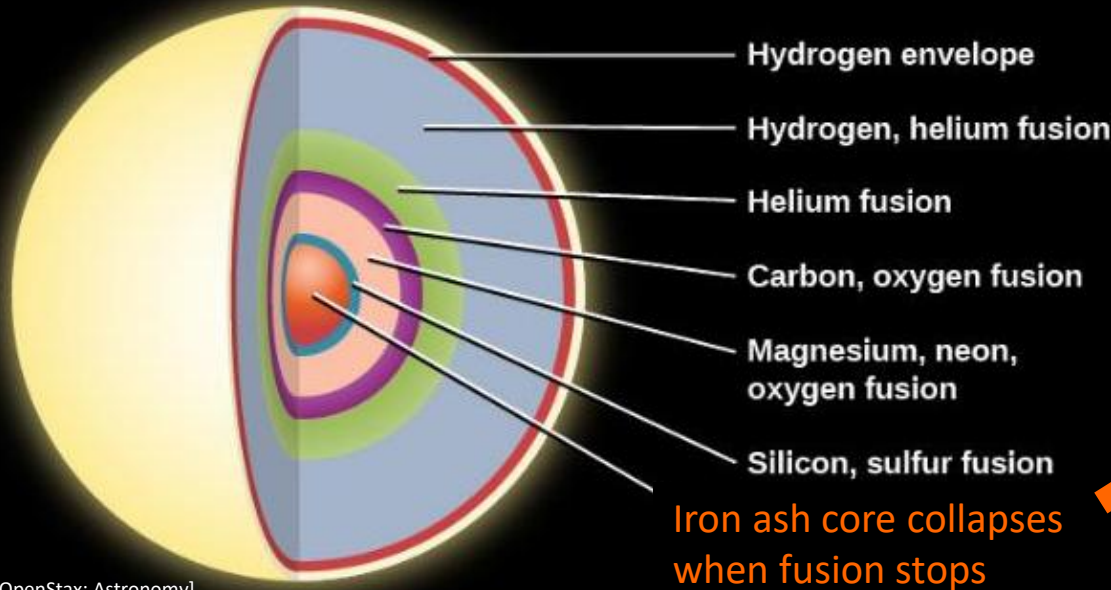
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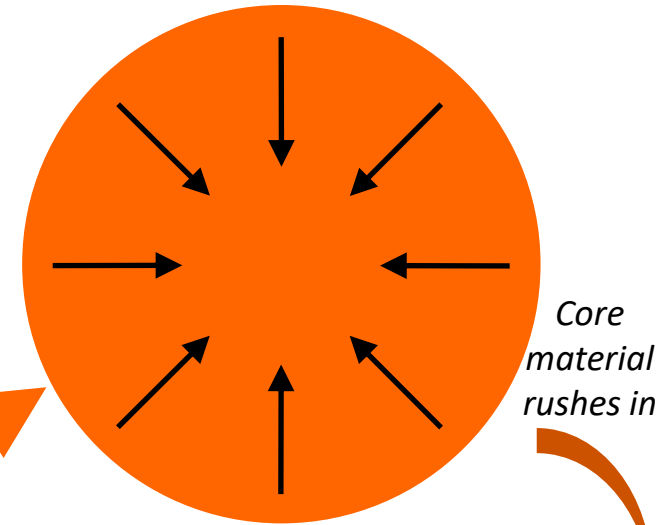
2. Collapses continues to **nuclear density** (i.e. core is like a giant nucleus)



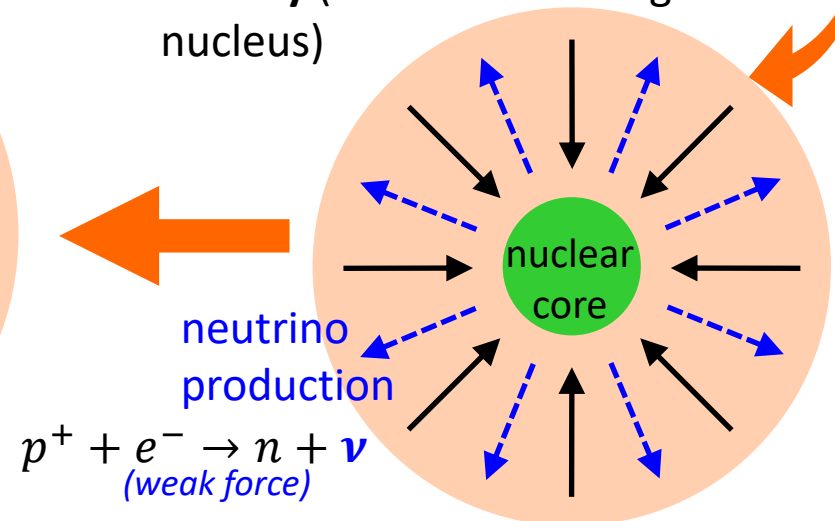
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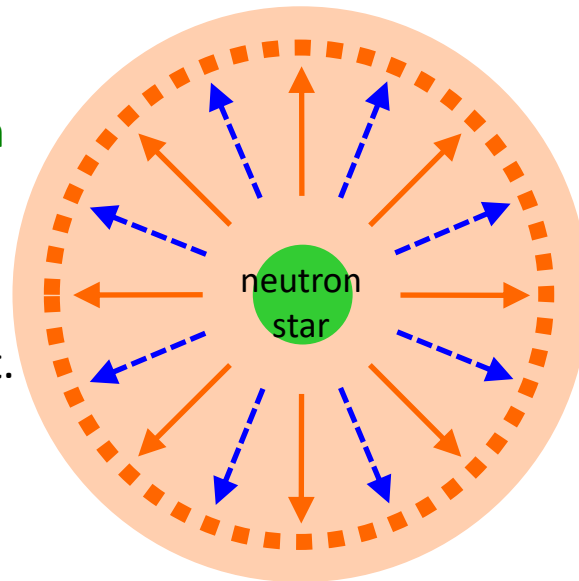
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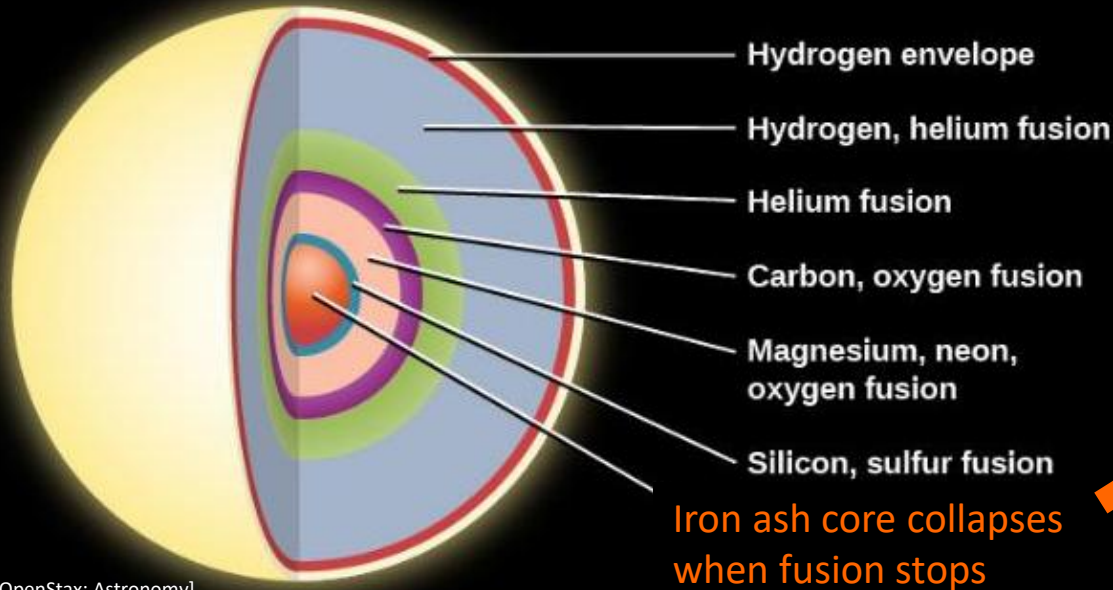
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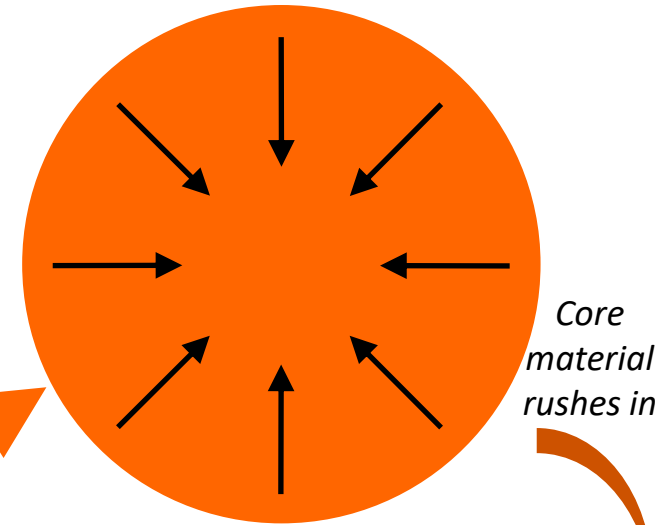
3. In-falling material **rebounds** off **neutron star** core creating an outward moving **shockwave**.
→ Star is blown apart.



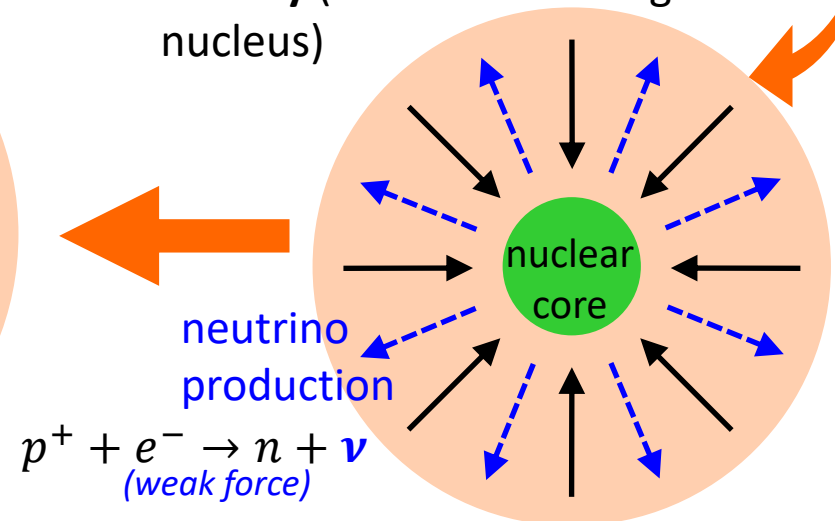
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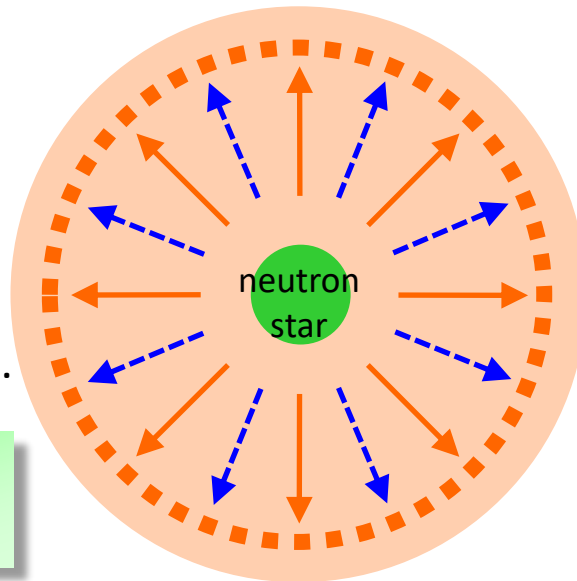


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3. In-falling material **rebounds** off **neutron star** core creating an outward moving **shockwave**.
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Note: entire process takes a few seconds.



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 - $10^{10} L_{\text{Sun}}$ 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.
 - **neutrino** production is favored: $p^+ + e^- \rightarrow n + \nu$.
- 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
10-25 M_{sun}	Supernova → Neutron Star
25-50 M_{sun}	Supernova → Black Hole
>50 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 \rightarrow black hole

N6946-BH1
HST WFPC2

2007



Red supergiant: mass $\sim 18-27 M_{\text{sun}}$
NGC 6946 galaxy -- distance: $\sim 25 \text{ Mly}$

2009: Star brightened briefly to $10^6 L_{\text{Sun}}$

N6946-BH1
HST WFC3/UVIS

2015

