# Final Exam

Tuesday, December 17, 2019, 9 am – noon
room 110 (i.e. regular room)

Format: 8 midterm-style problems

**Content**

1/4 of problems on topics covered since midterm #3:
Stellar evolution, H-R diagram, white dwarfs, supernovas, creation of heavy elements, neutron stars, black holes, Special Relativity, General Relativity.

~ 1/4 of problems on midterm #3 topics.

~ 1/4 of problems on midterm #2 topics.

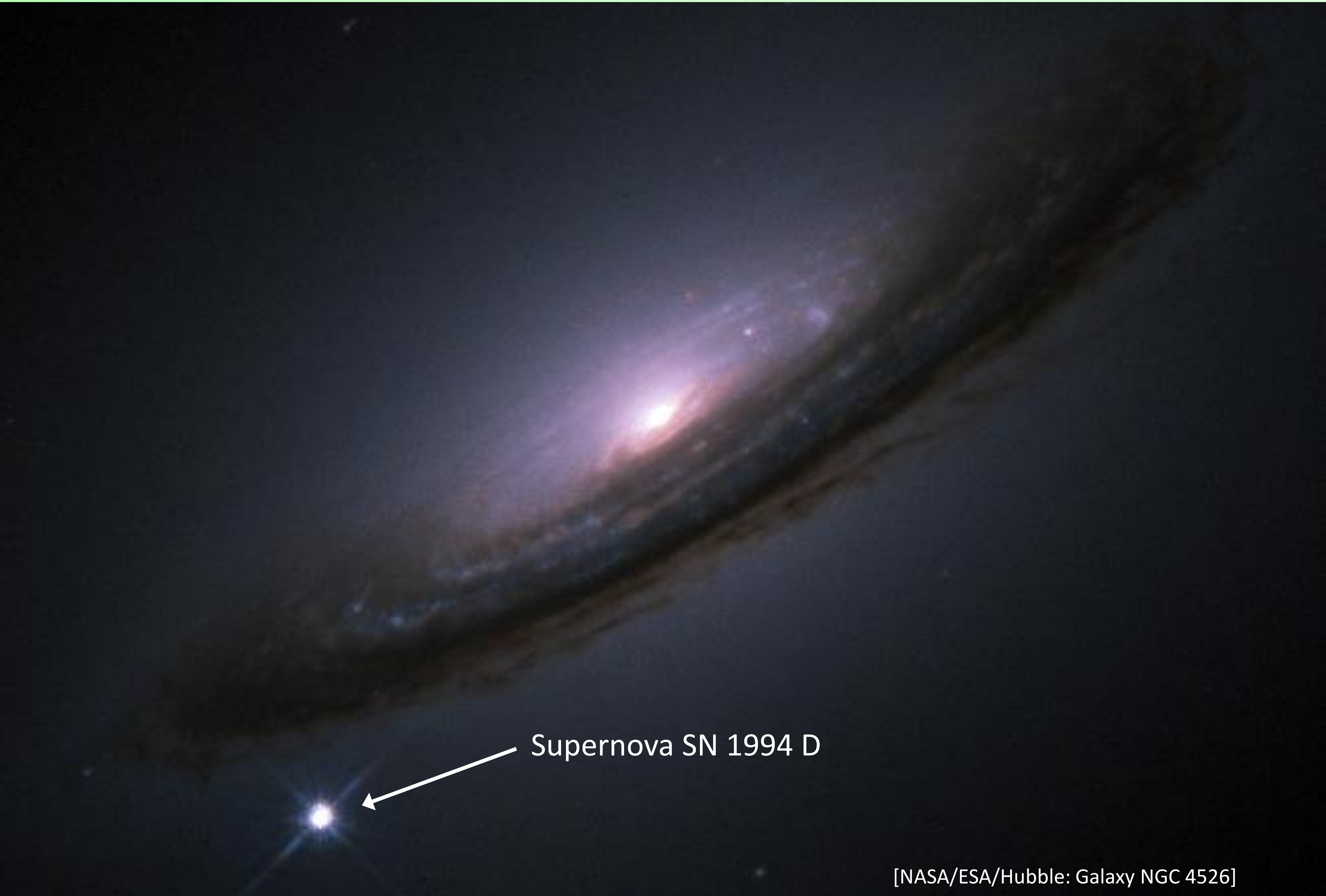
~ 1/4 of problem on midterm #1 topics.

# Today's Topics

Friday, December 6, 2019 (Week 14, lecture 33) – Chapter 24.

1. Type II supernovas.
2. Neutron stars & pulsars.
3. Black holes.

# Supernovas can be as bright as a galaxy




[NASA/ESA/Hubble: Galaxy NGC 4526]

# 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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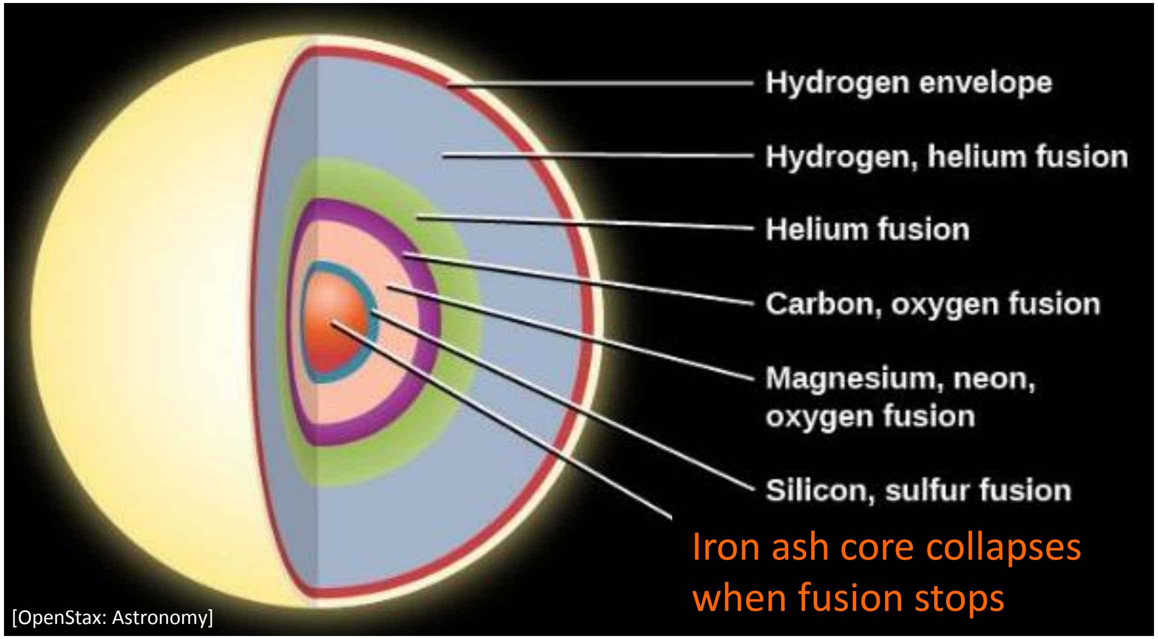
**Type II supernova**

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

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

Note: No neutron star has been detected yet !

# Type II Supernova: *Core Collapse*



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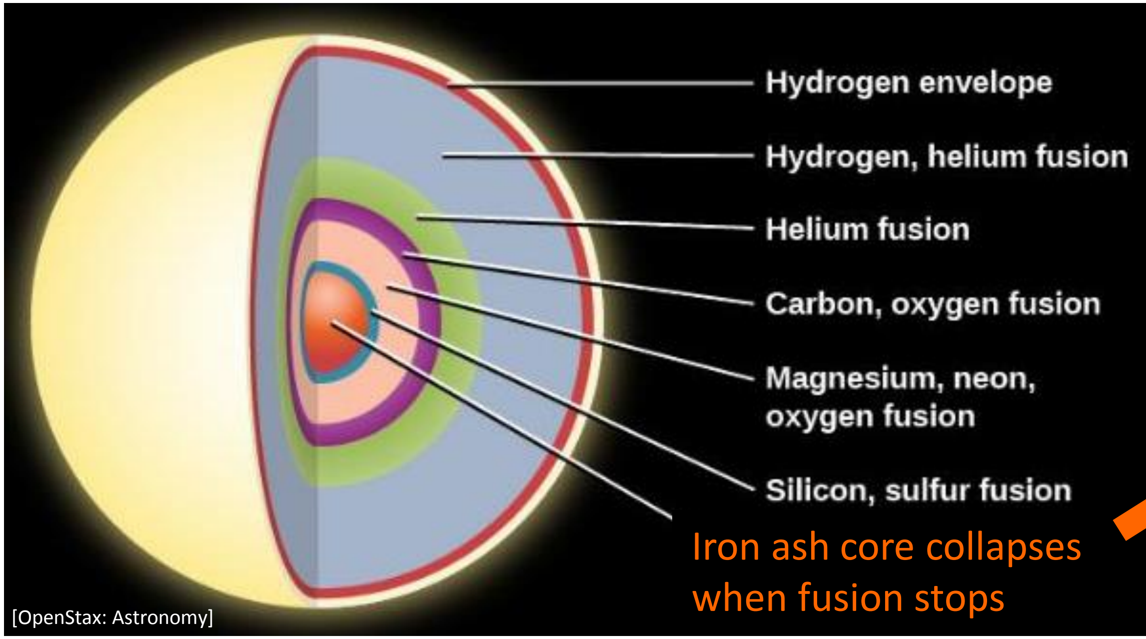


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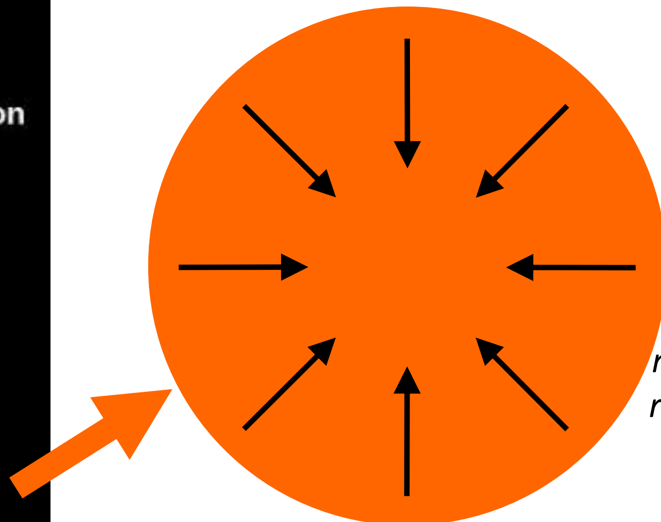

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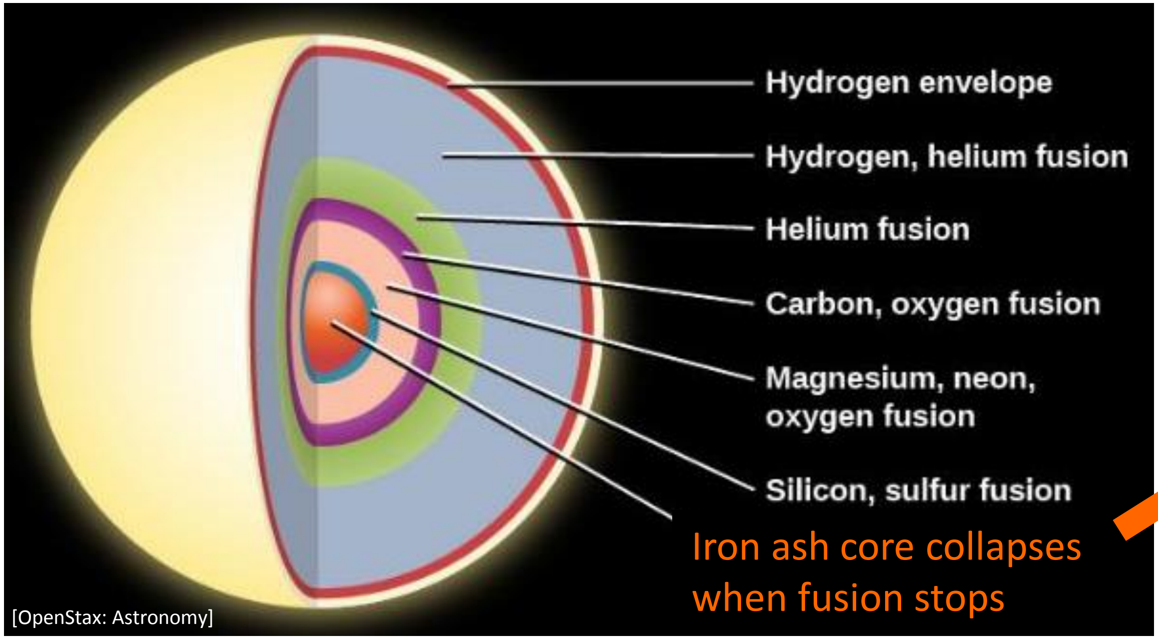


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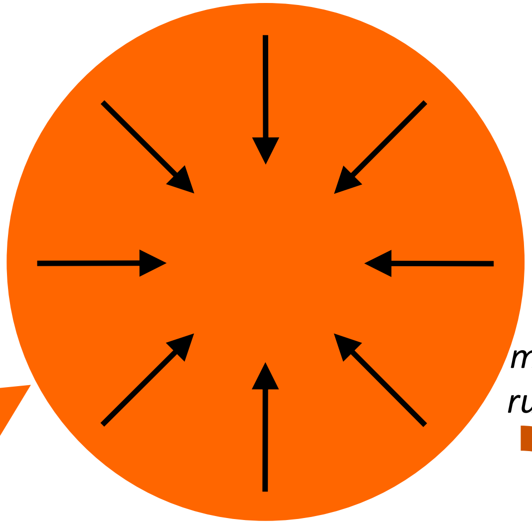
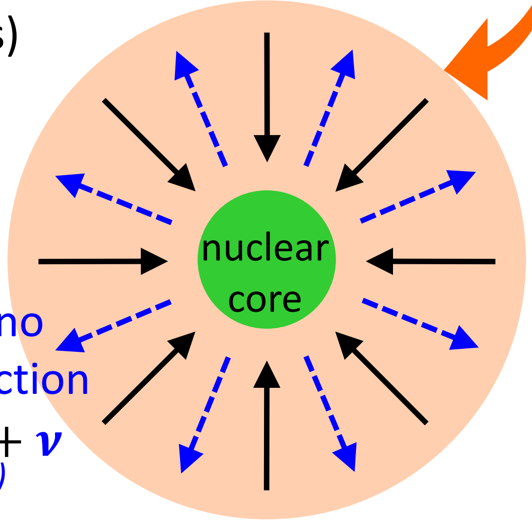


*Core material rushes in*

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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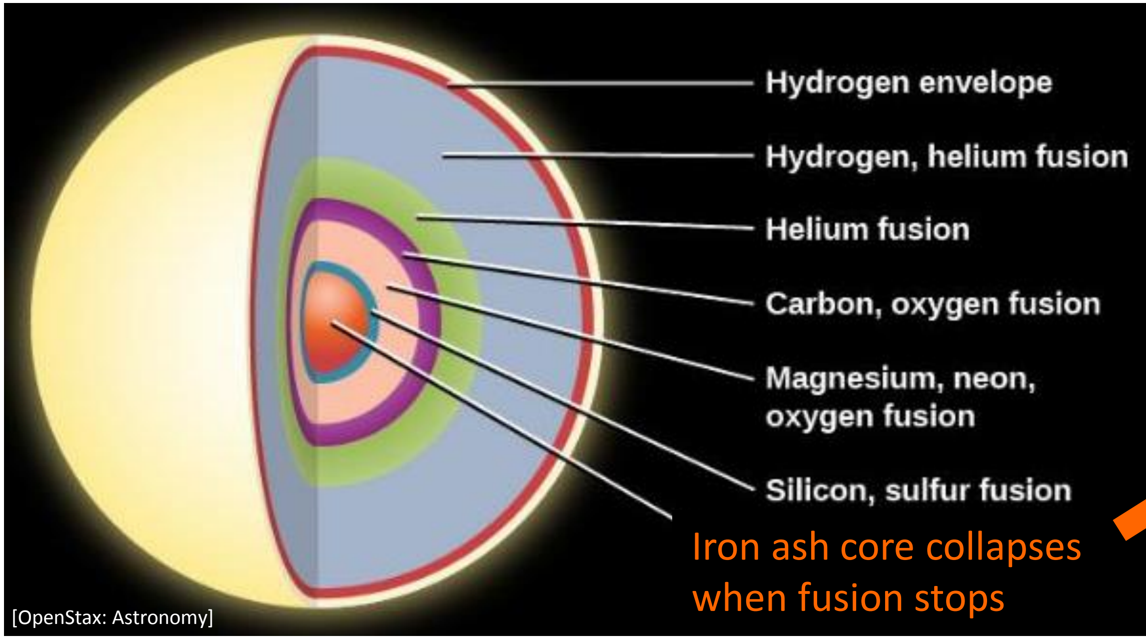


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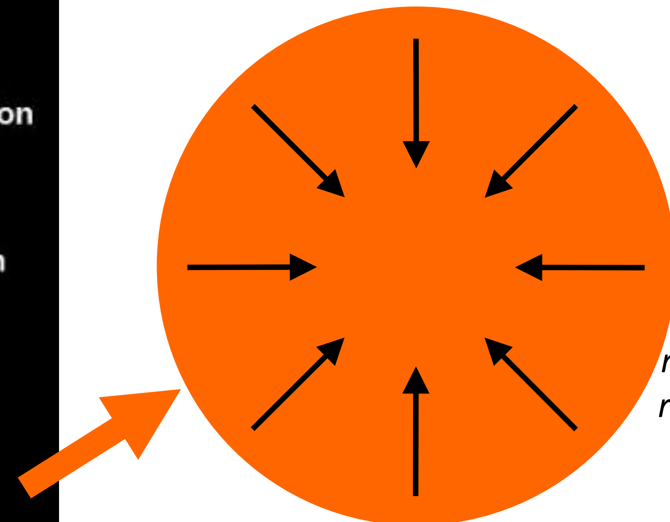


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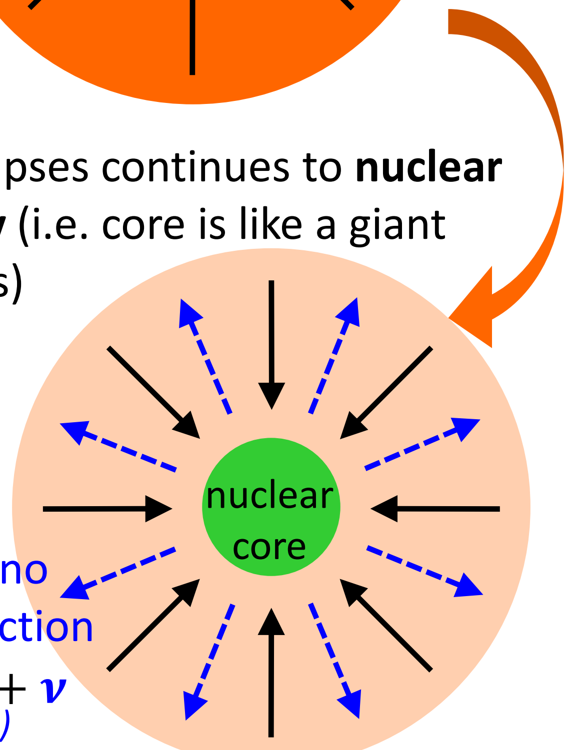
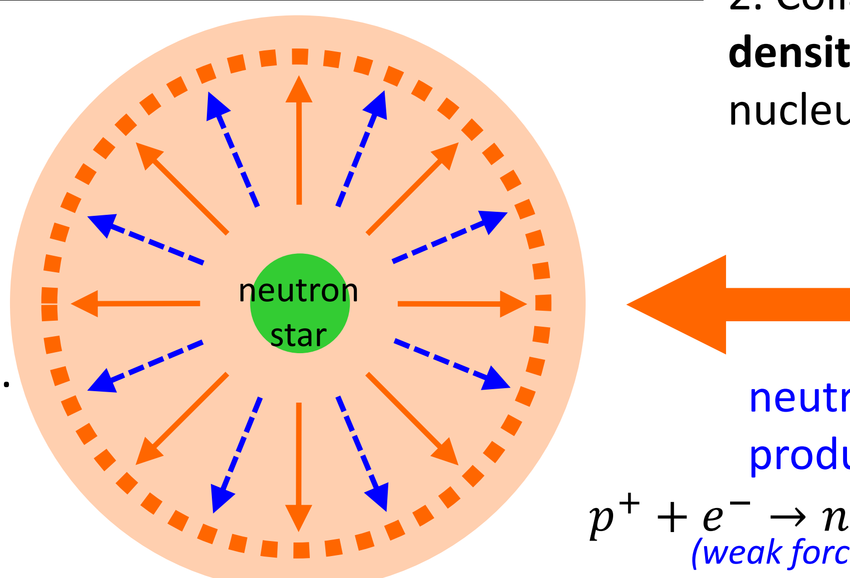



$p^+ + e^- \to n + \boldsymbol{\nu}$
*(weak force)*

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



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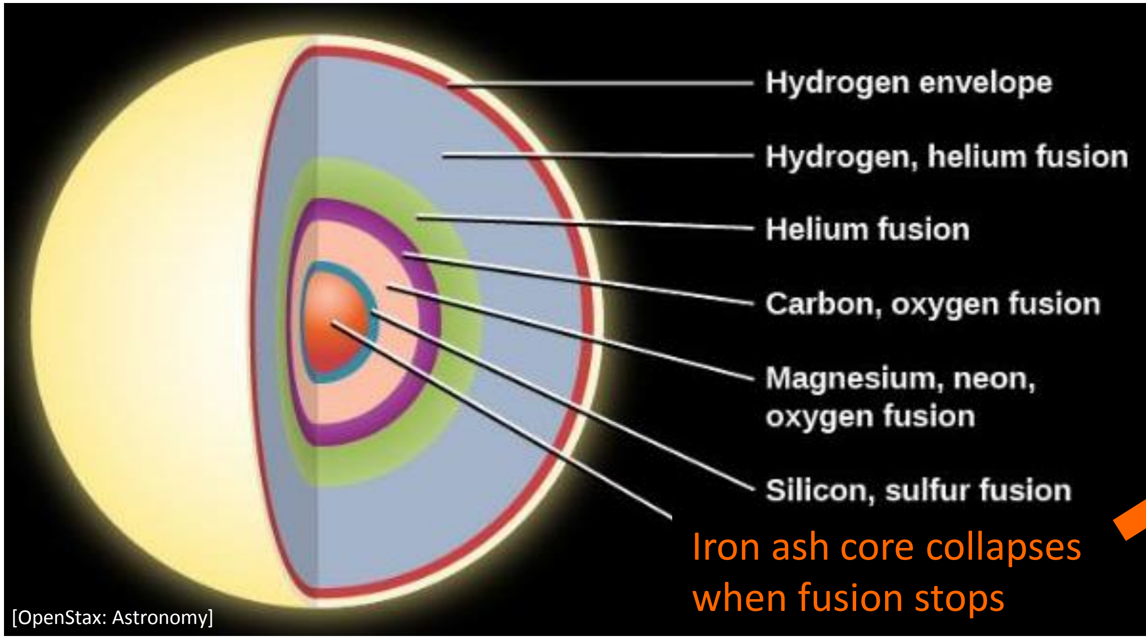


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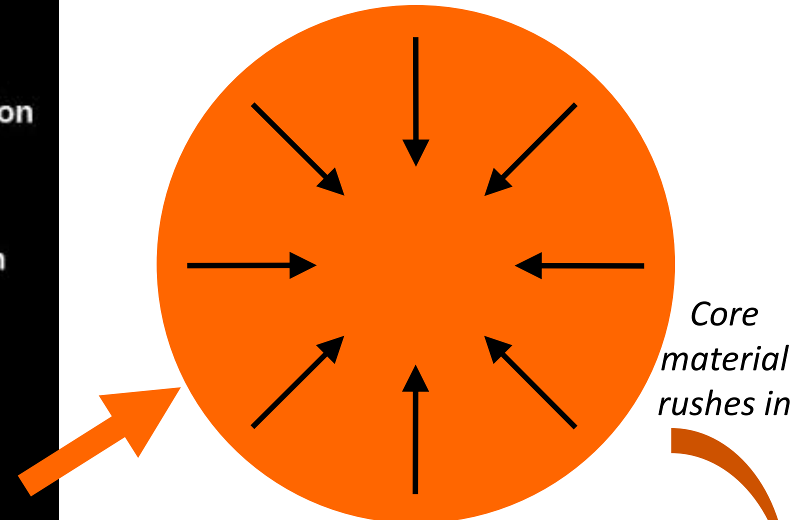


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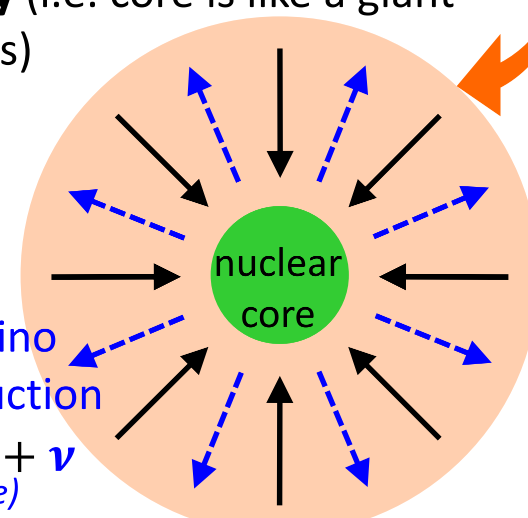


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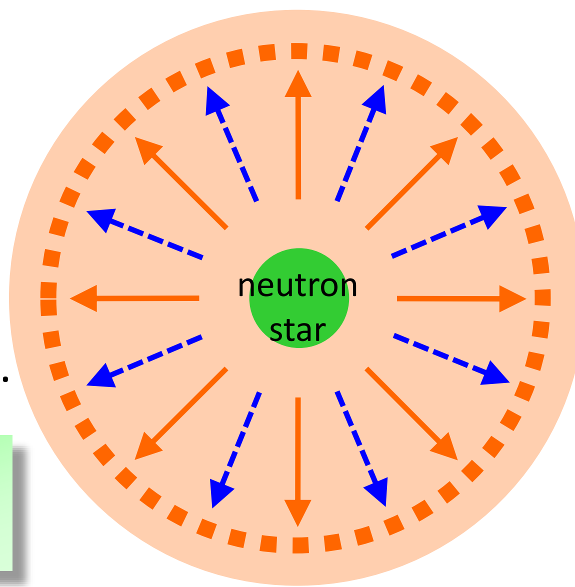


**Note:** entire process takes a few seconds.

# 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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## 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**

=

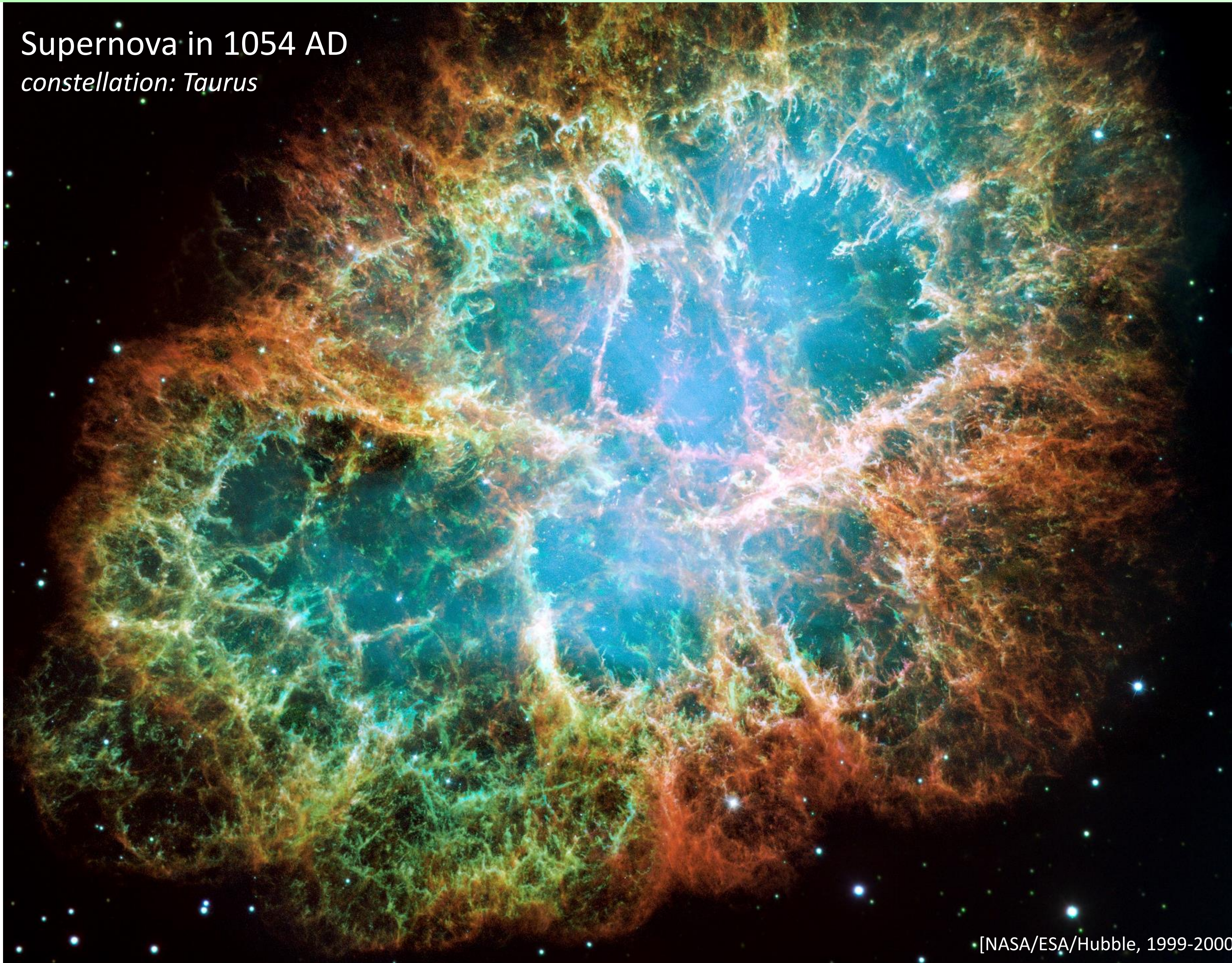
gravity powered neutrino explosion of a massive star

# 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.

# Crab Nebula: Supernova Remnant



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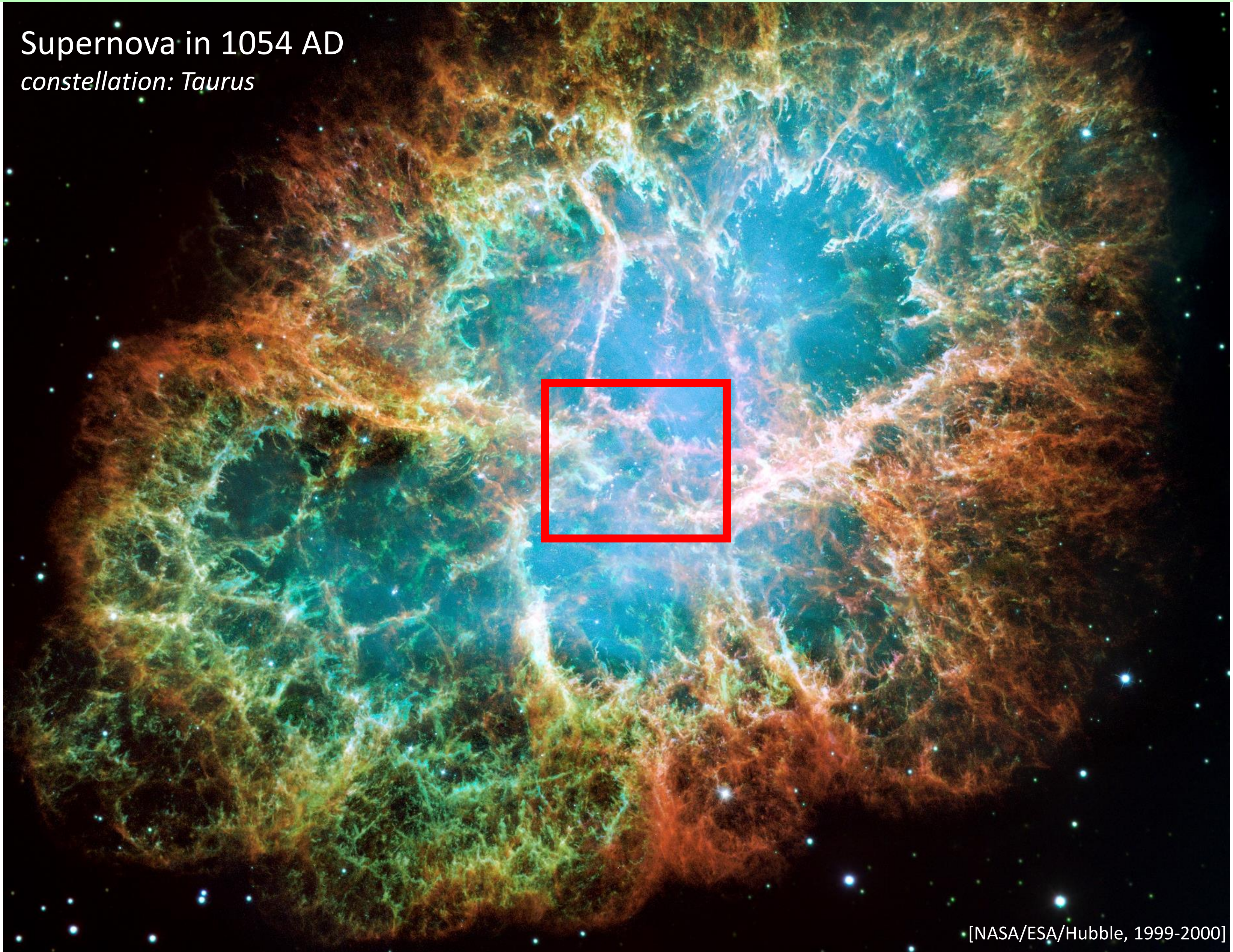
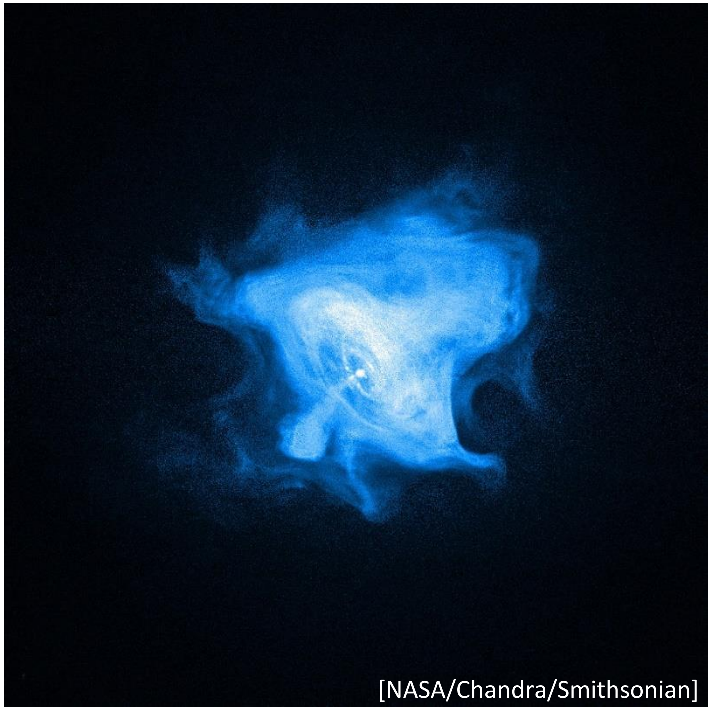
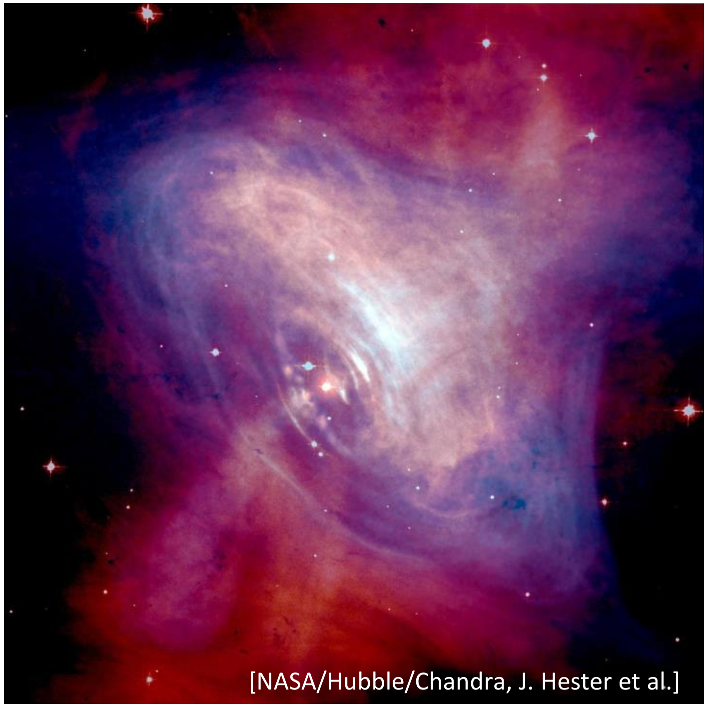


# Crab Nebula: Neutron Star




X-ray image of Crab Nebula neutron star, 2008




X-ray + optical images of Crab Nebula neutron star

# Neutron Stars

[Table 23.3, OpenStax: Astronomy]

| Property | White Dwarf | Neutron Star |
|---|---|---|
| Mass (Sun = 1) | 0.6 (always <1.4) | Always >1.4 and <3 |
| Radius | 7000 km (Earth size) | 10 km (city size) |
| Density | $8 \times 10^5$ g/cm$^3$ | $10^{14}$ g/cm$^3$ |

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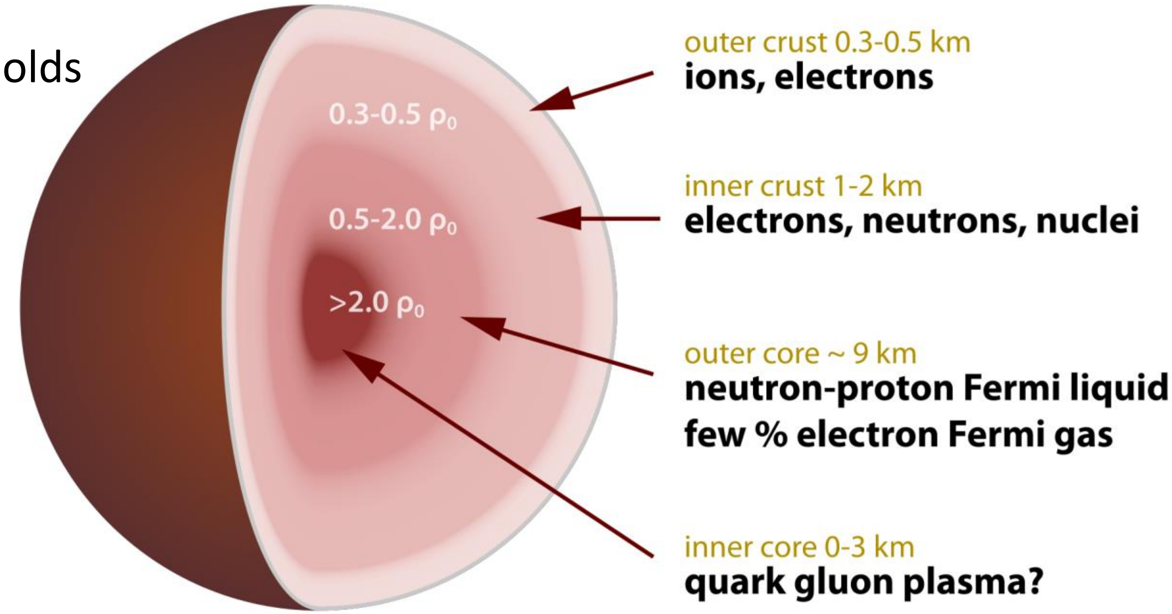


[Wikipedia: Robert Schulze]

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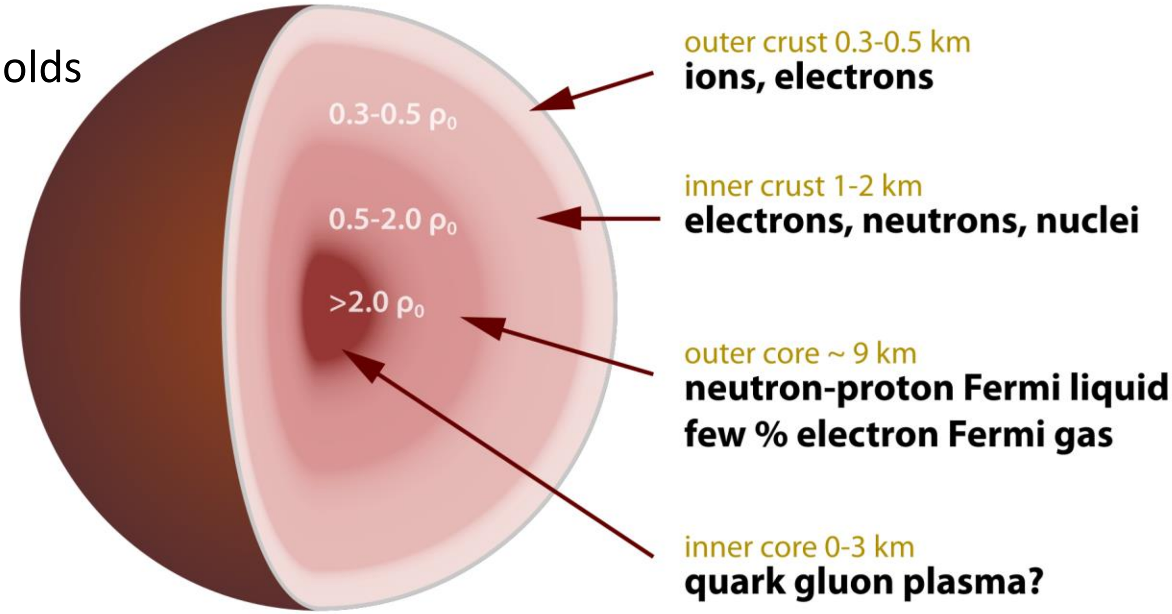
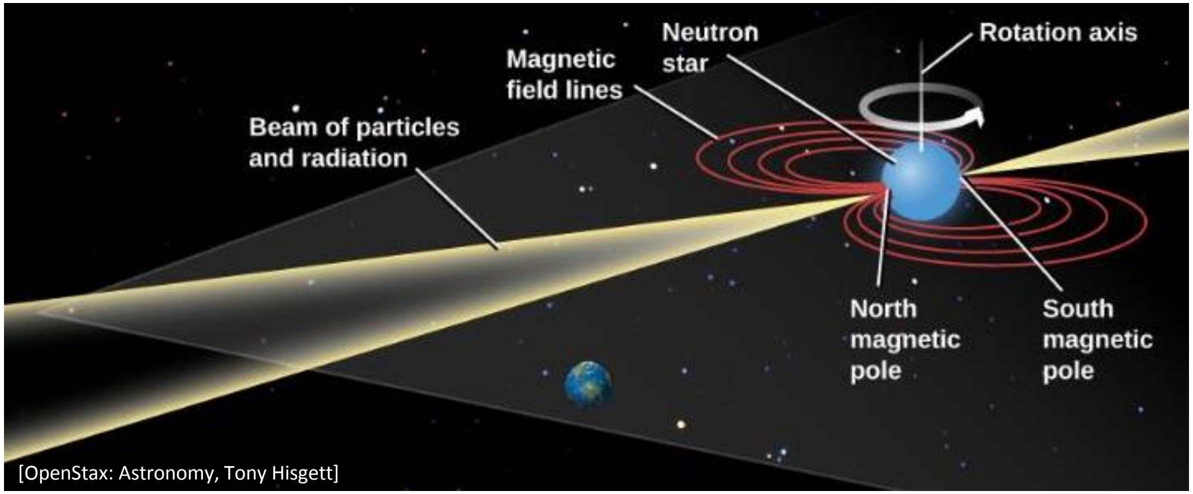
Neutron stars have a **very large magnetic field**: $10^8$ to $10^{15}$ times stronger than Earth's




[Wikipedia: Robert Schulze]

# Pulsars: Rotating Neutron Stars




- **Beams of radiation from the magnetic poles** of a neutron star can give rise to pulses of emission as the star rotates.
- As each beam sweeps over Earth, we see a short pulse of radiation (like a lighthouse).

Jocelyn Bell Burnell
*co-discoverer of pulsars (1967)*

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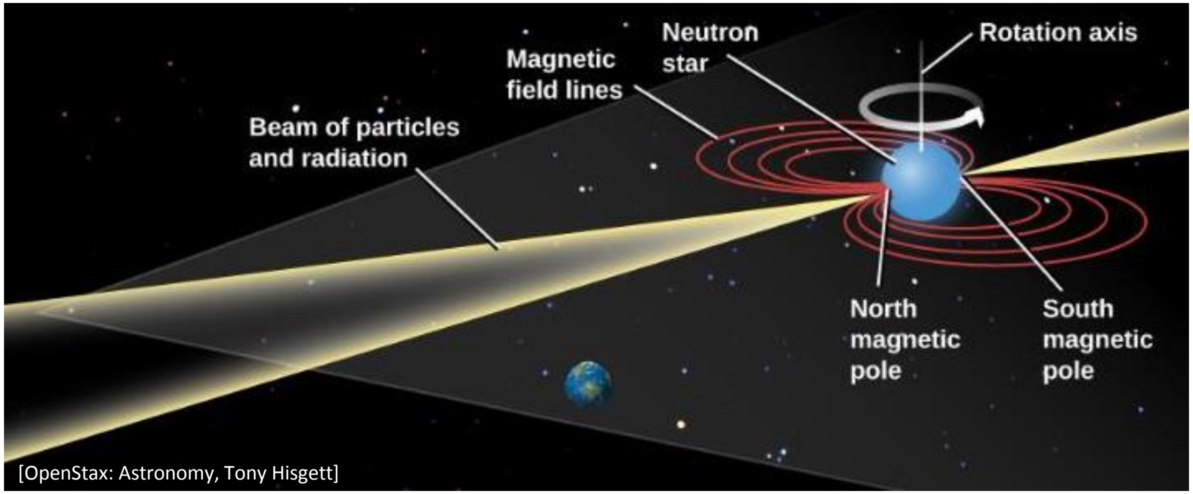

[OpenStax: Astronomy, Tony Hisgett]

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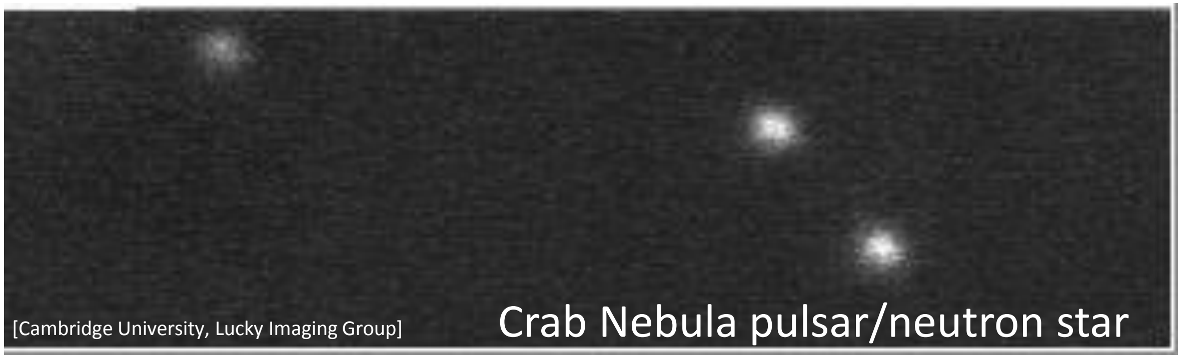
[Cambridge University, Lucky Imaging Group] Crab Nebula pulsar/neutron star


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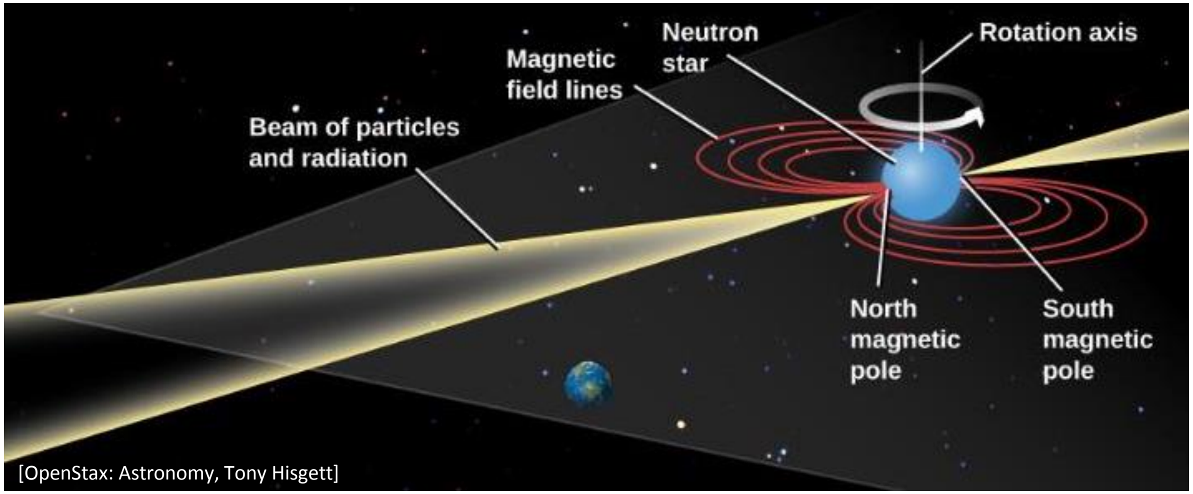


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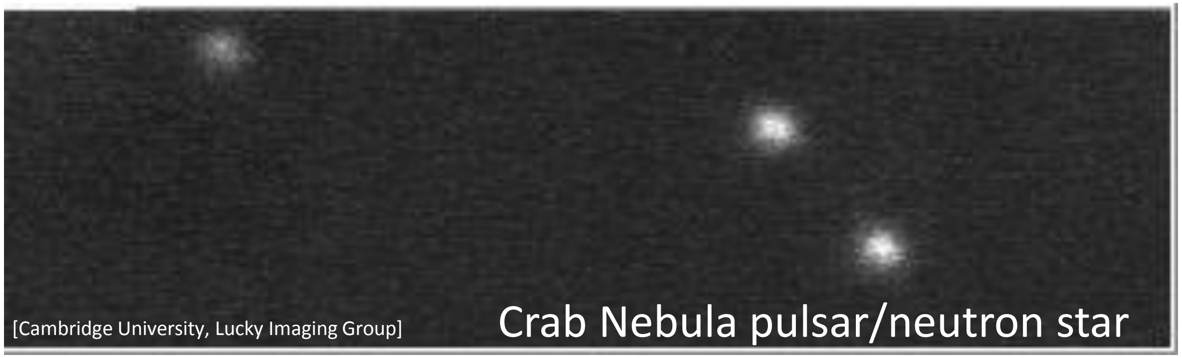

Crab Nebula pulsar/neutron star

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Typical rotation period:
- Very stable.
- ms to seconds.
- Can change abruptly during a "starquake."

# Black Holes

**Black hole**

A celestial object whose gravity is so strong that even light cannot escape from it.

→ Light emitted outside of the **event horizon** (i.e. **Schwarzchild radius**) can escape.

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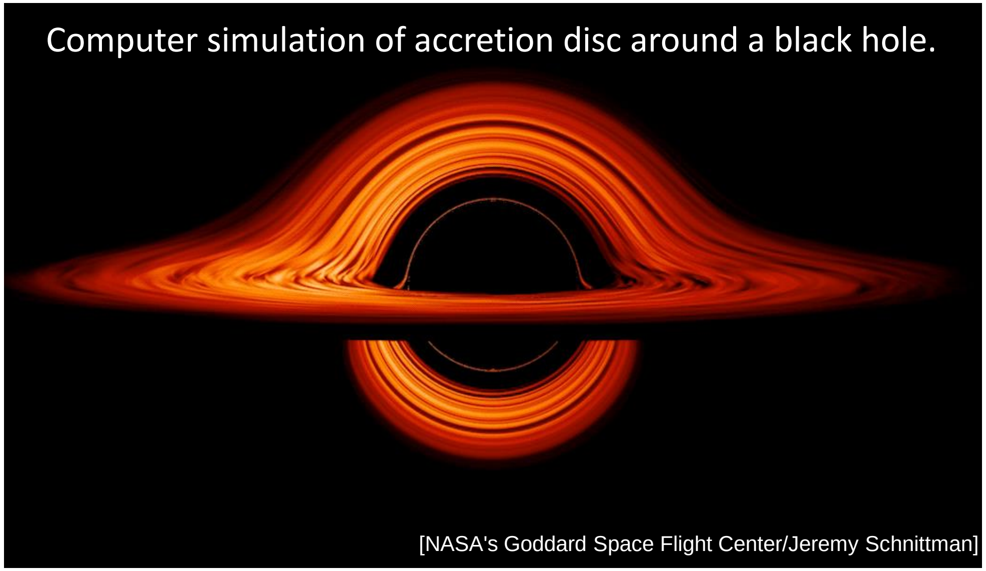
Supermassive black hole at center of M87 galaxy.

[Event Horizon Telescope, www.eso.org, λ=1.3 mm]

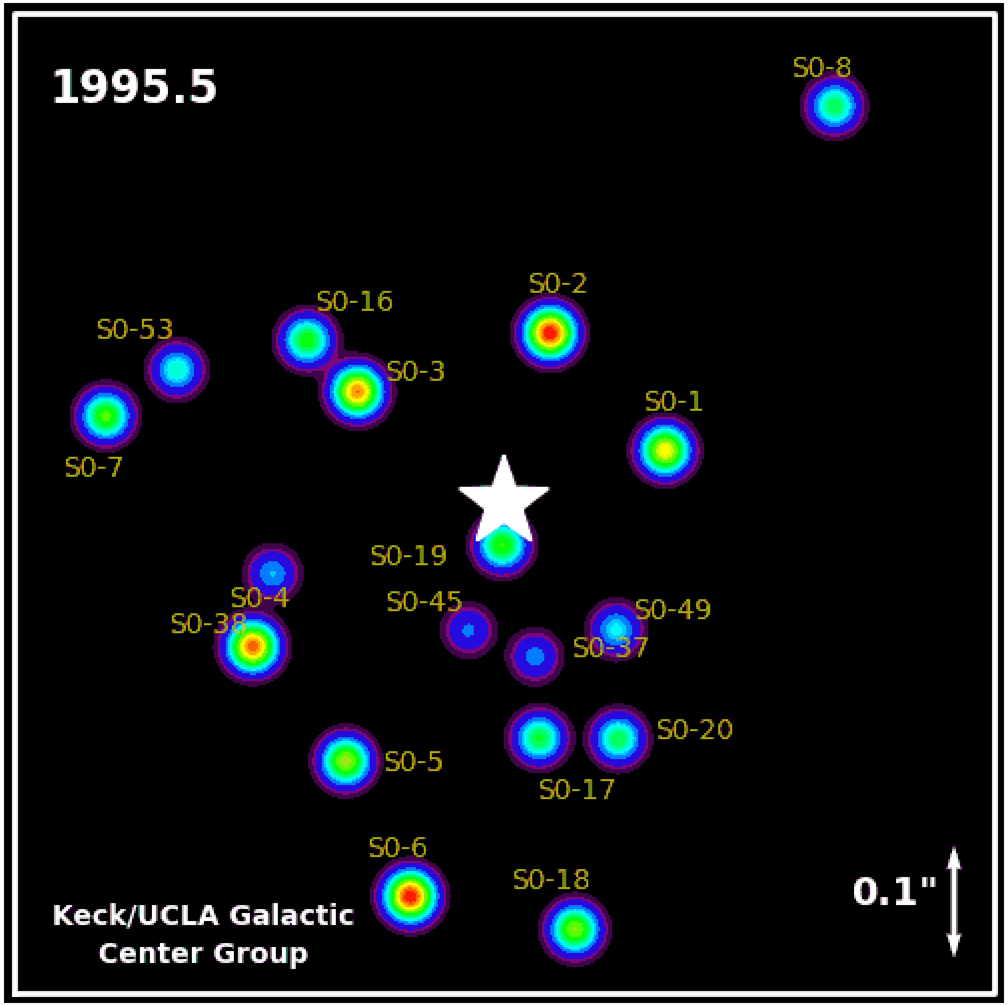


Computer simulation of accretion disc around a black hole.

[NASA's Goddard Space Flight Center/Jeremy Schnittman]

# Black Hole at center of Milky Way

The Sagittarius A* supermassive black hole



# What happens if you fall into a Black Hole?

## Stellar mass black hole

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**Gravitational time dilation:** The object appears to slow down as it gets closer and closer to the event horizon.

→ Very close to the event horizon, the object becomes too redshifted to be well seen and also appears to come to a standstill.
*(note: in frame of object, the object falls into black hole.)*