Today's Topics

Wednesday, March 26, 2025 (Week 8, lecture 21) – Chapters 22, 23, 24.

A. Neutron stars & pulsars.

B. Einstein's Theory of Relativity.

C. Special Relativity.

D. Length contraction.

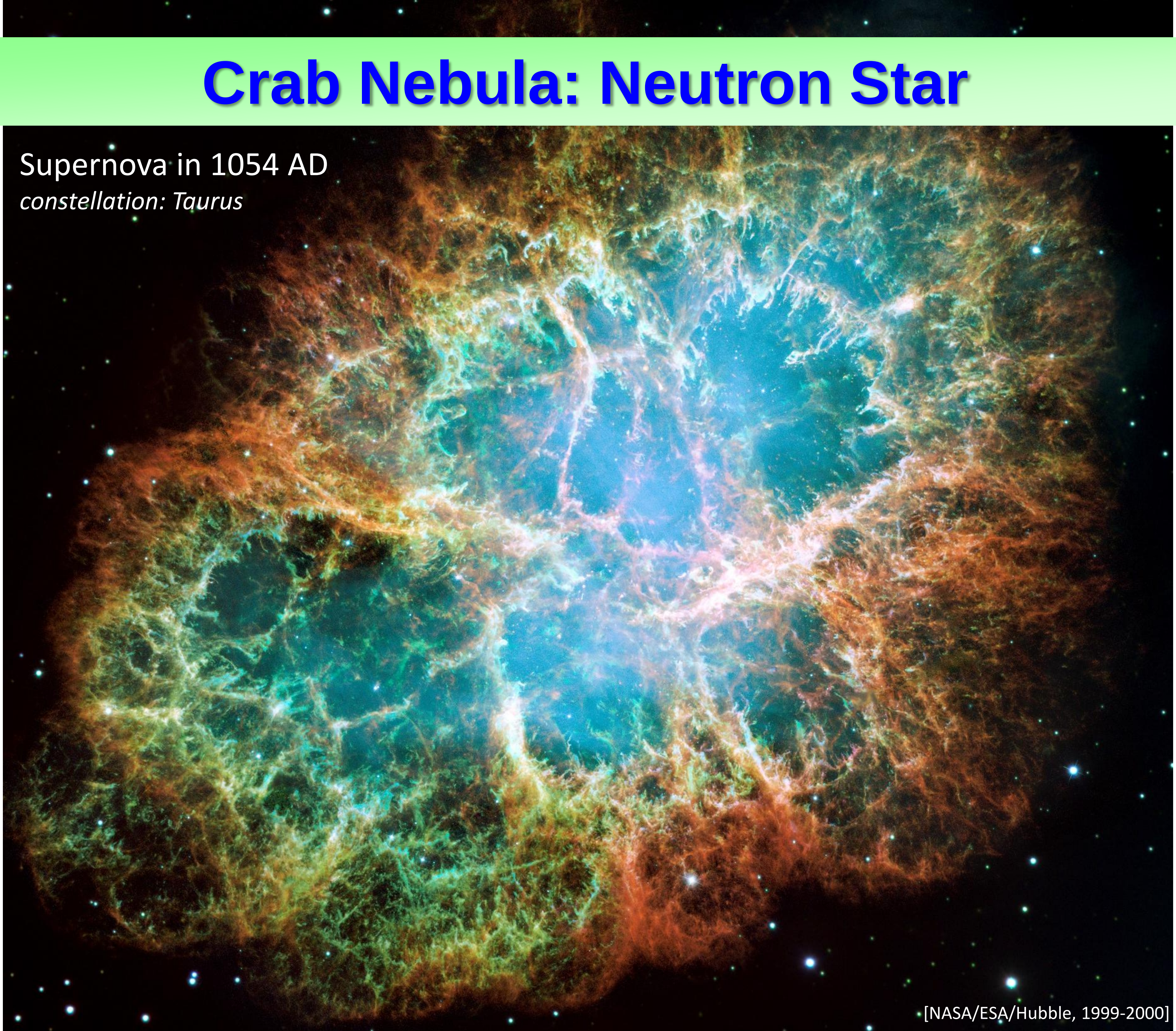
Interlude 1 Essay is due on Friday, March 28 by 9:00 am on Gradescope.

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: Neutron Star



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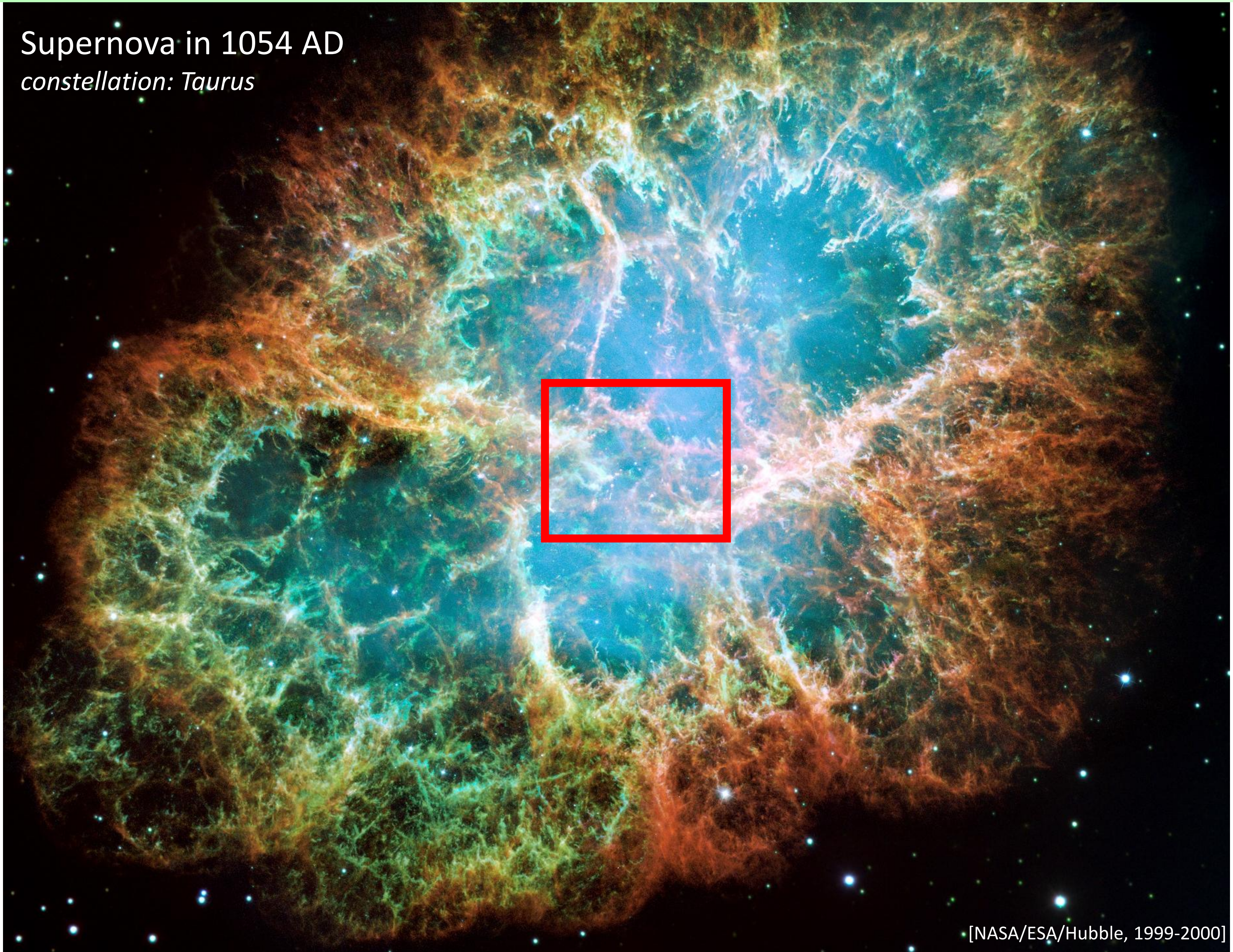

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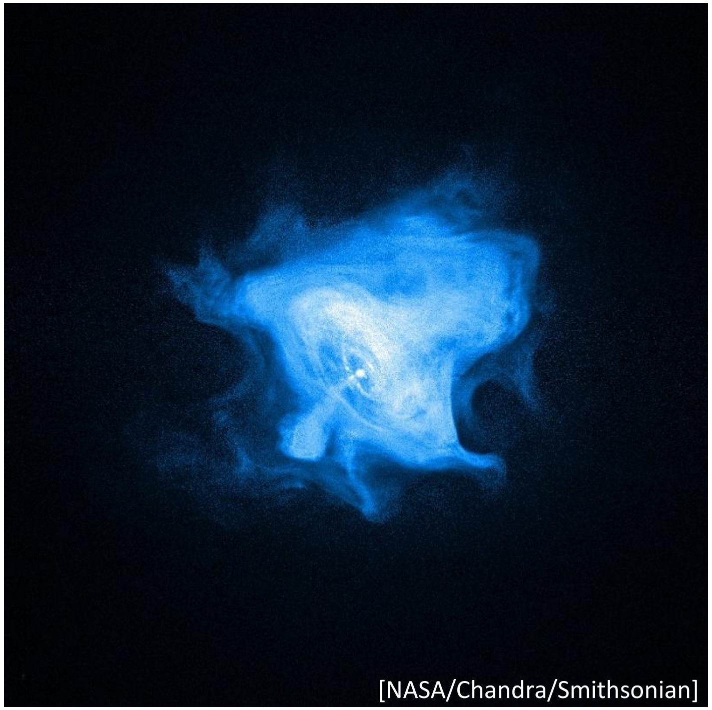
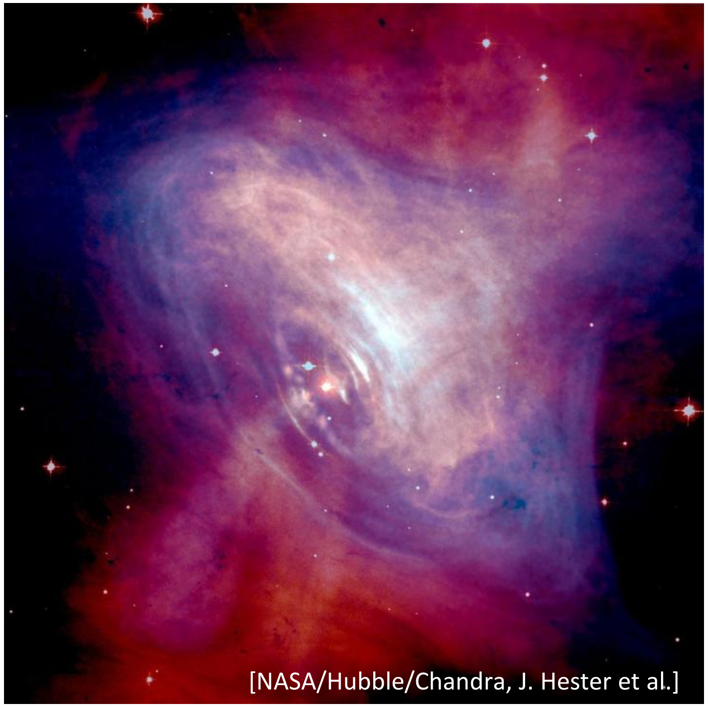


X-ray image of Crab Nebula neutron star, 2008



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	8×10^5 g/cm^3	10^{14} g/cm^3

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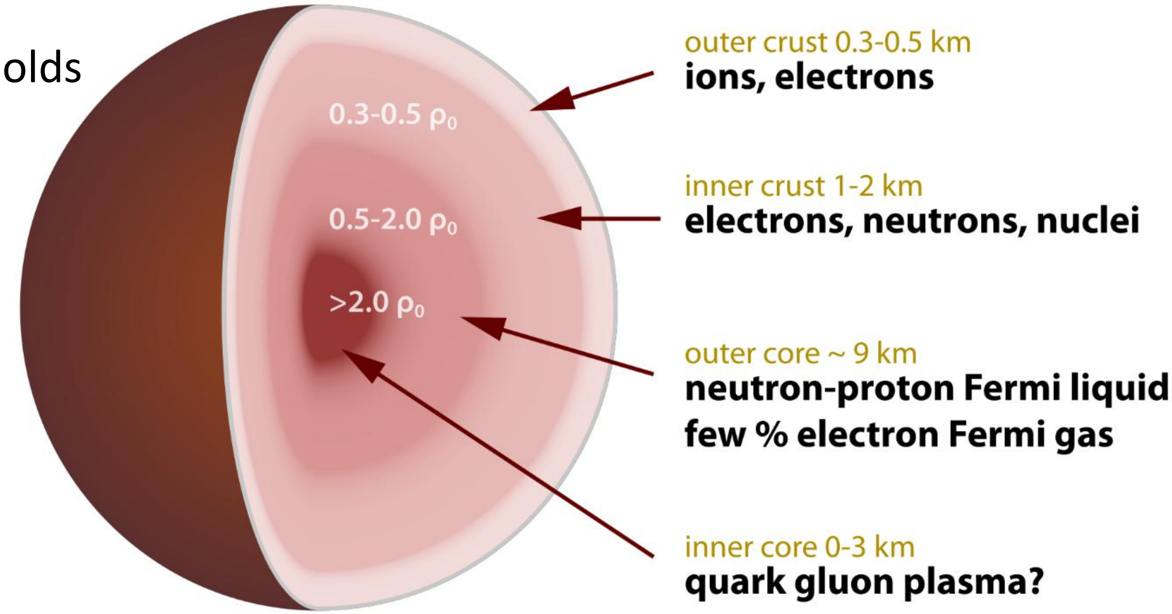

[Wikipedia: Robert Schulze]

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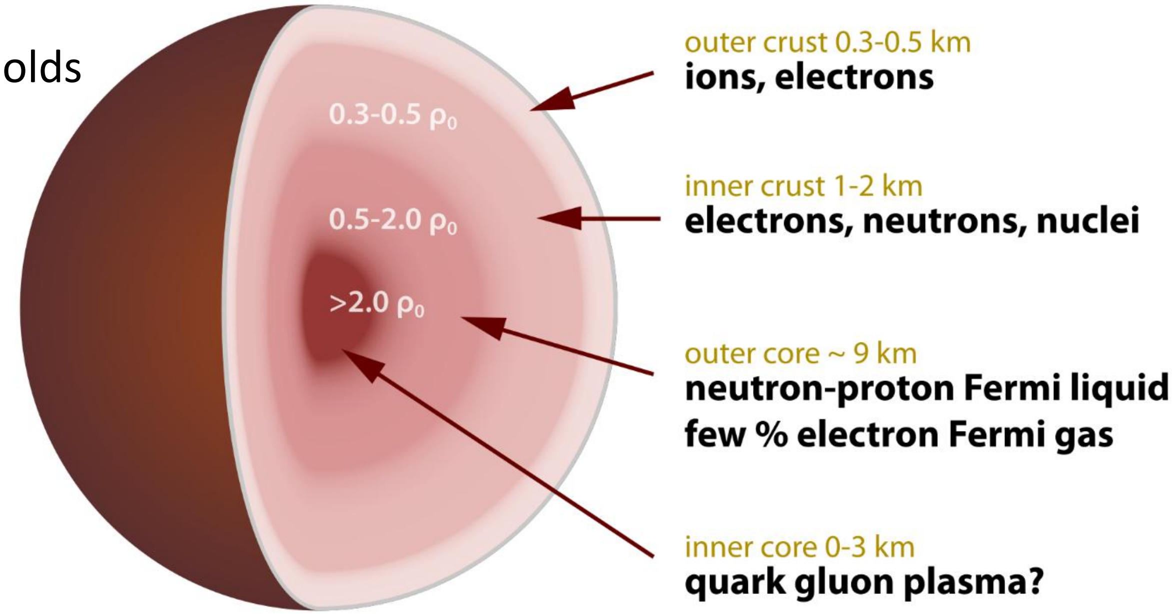
Neutron stars have a **very large magnetic field**: 10^8 to 10^{15} times stronger than Earth's



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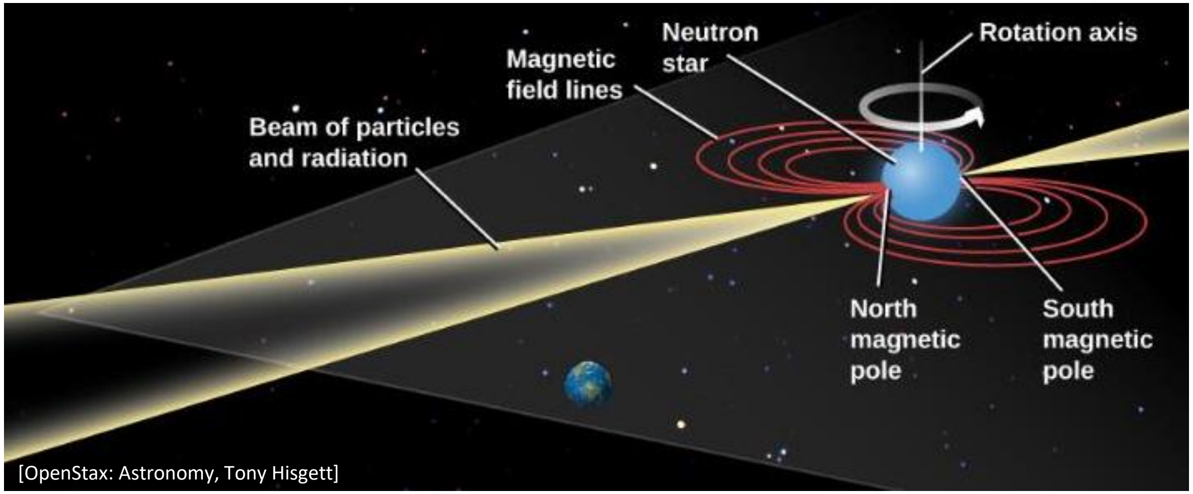
Pulsars: Rotating Neutron Stars

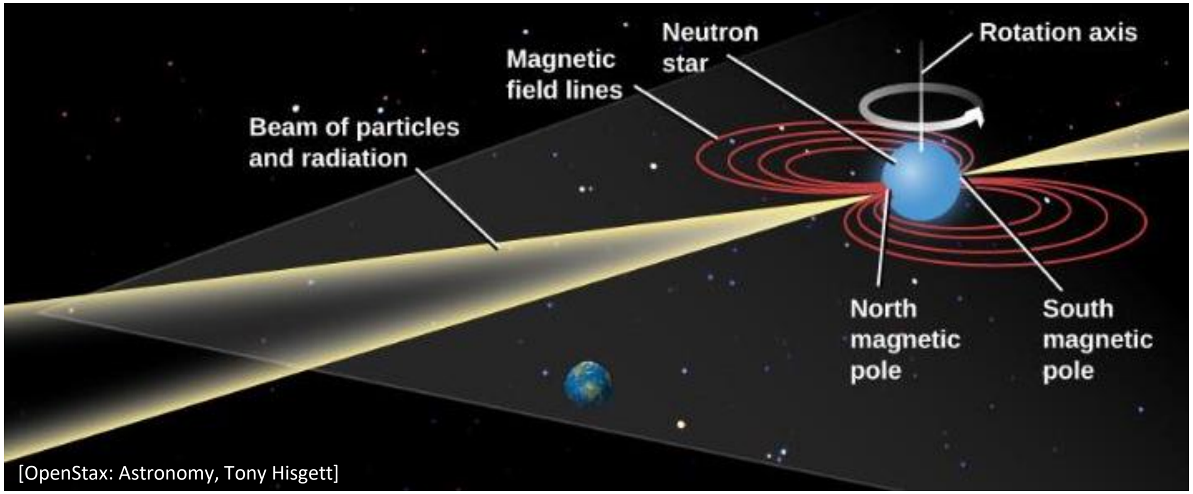


[OpenStax: Astronomy, Tony Hisgett]

Jocelyn Bell Burnell
co-discoverer of pulsars (1967)

- **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).

Pulsars: Rotating Neutron Stars



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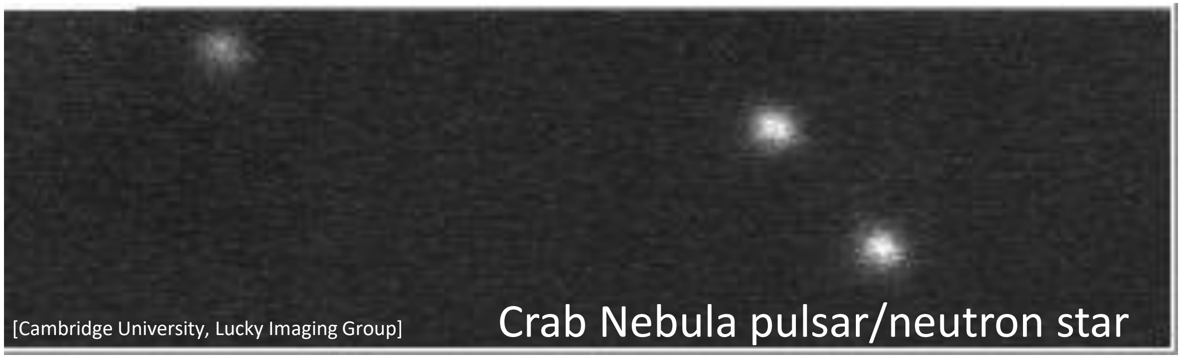
[Cambridge University, Lucky Imaging Group]
Crab Nebula pulsar/neutron star

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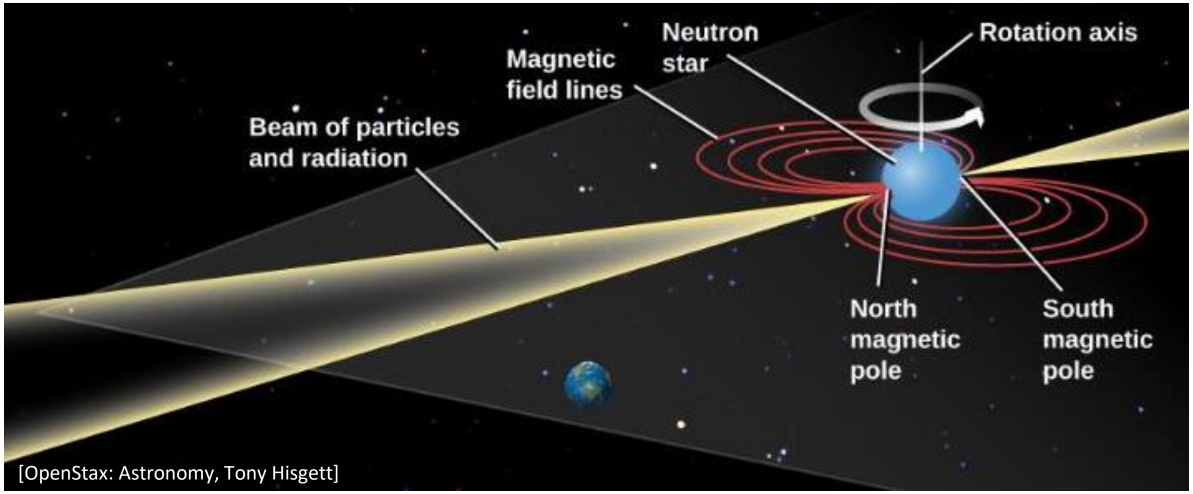

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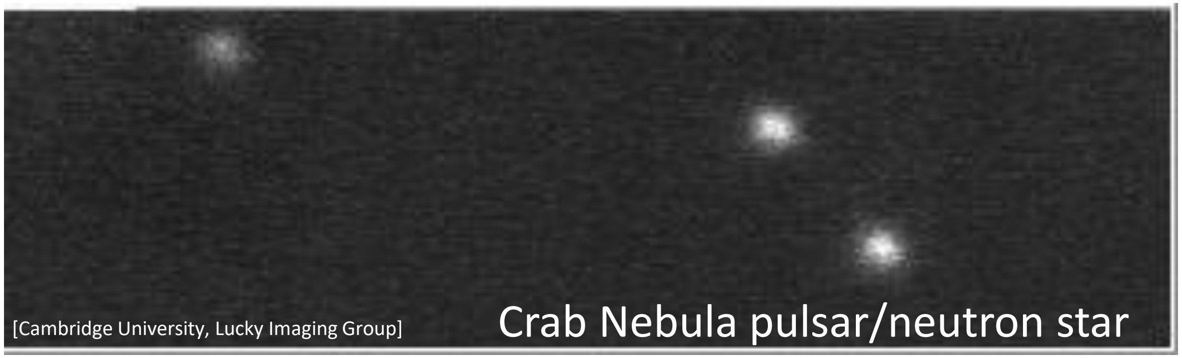
[Cambridge University, Lucky Imaging Group] Crab Nebula pulsar/neutron star


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

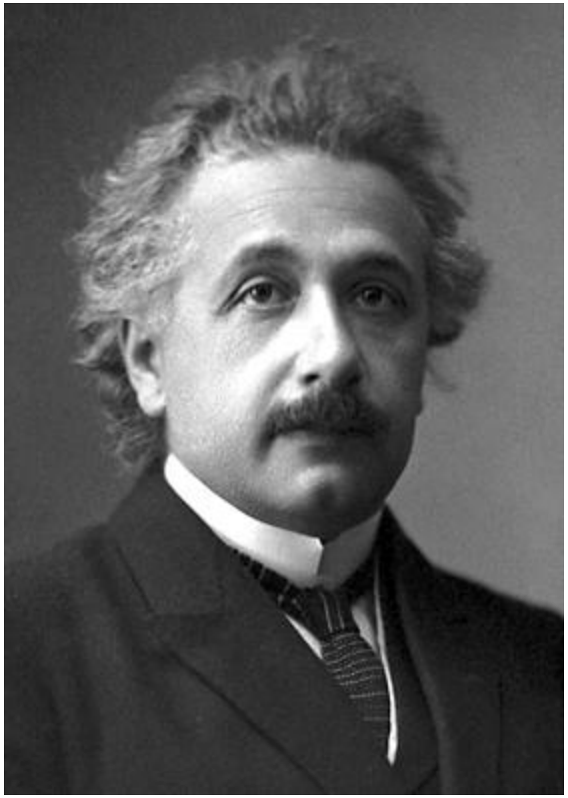
PollEv Quiz: PollEv.com/sethaubin

Einstein’s Theory of Relativity

Einstein's Theory of Relativity

1905: Annus Mirabilis

- Brownian motion (motion of atoms in a gas).
- Photo-electric effect (discovery of the photon, $E = hf$)
- **Special theory of relativity**.
  → Major revision of Galilean relativity.
  → Equivalence of energy and matter: $E = mc^2$



Albert Einstein, 1921.
(1879-1955)

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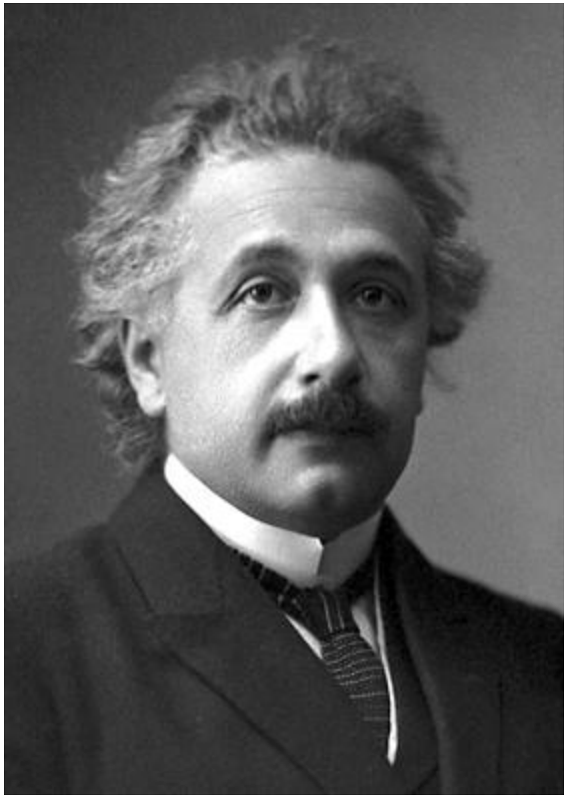
1907-15: General Relativity

Theory of relativity applied to gravity.
→ gravity = curved space-time.



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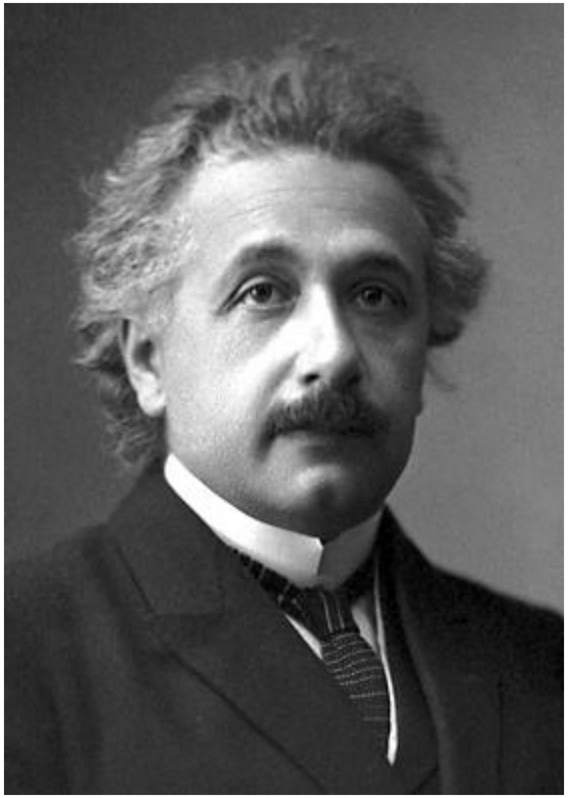

Albert Einstein, 1921.
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1921: Nobel Prize for photo-electric effect.

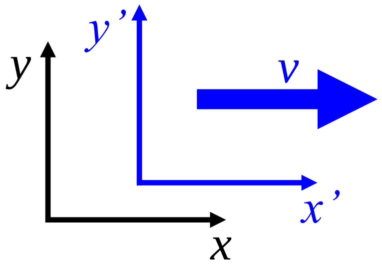
1924: Bose-Einstein Condensation
Predicts the existence of a new type of quantum matter.
→ Builds on the work of Satyendra Bose.
→ First observed in 1995
→ There is a BEC in the basement of Small Hall (room # 069).

Inertial Frames (Galileo & Einstein)

Inertial Frame

Coordinate system at constant velocity in a rest frame.

think of it as a box



Rest Frame

A coordinate system that is not moving.

Note: a rest frame is an inertial frame.

Inertial Frames (Galileo & Einstein)

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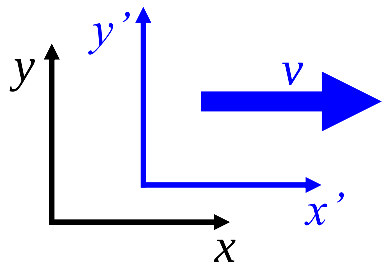

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Important

- **You cannot tell if you are moving** based on local measurements inside your inertial reference frame (the frame attached to you).
- If you are **accelerating/decelerating**, then you can tell based on local measurements (i.e. there is a force on you that you can measure, $F = ma$).

Special Relativity (Einstein)

Principle of Relativity

The laws of physics are the same in all inertial reference frames.

Corollary #1

You cannot tell if you are moving (based on local measurements) in an inertial frame.

Corollary #2: Universal speed of light

The speed of light in vacuum is the same in all inertial frames, regardless of the motion of the source.

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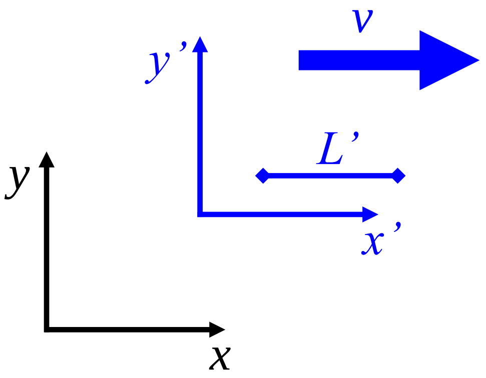
→ Length contraction & time dilation

Special Relativity
Length Contraction

In the x'-y' inertial frame

Consider a rod of length $L' = L_0$, as measured in the x'-y' inertial frame (i.e. the rest frame of the rod).

Note: The rod is aligned with the axis of motion along x'.



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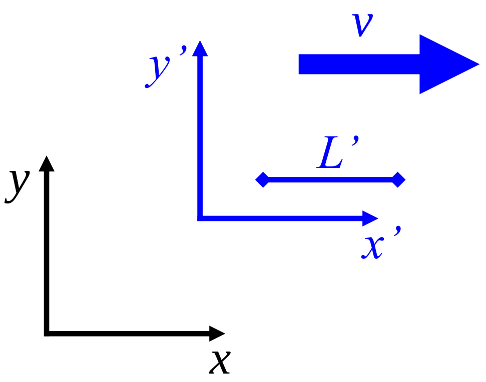


In the x-y inertial frame

If you measure the length of the rod, then you will get a shorter length: $L = \frac{L_0}{\gamma}$.

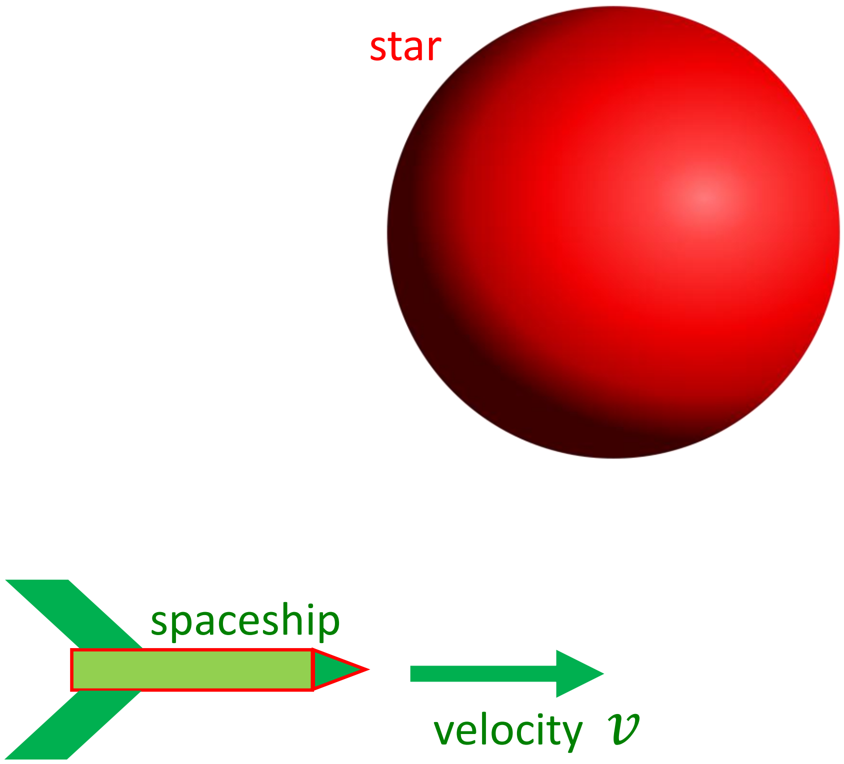
Gamma factor: $\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$

$\gamma \geq 1$

Note: the length contraction is only along the axis of motion. Along axes perpendicular to the motion, there is no change in length.

Length Contraction: Example

Consider a spaceship travelling past a spherical star at 90% of the speed of light.



Question: What is the shape of the star in the frame of the spaceship?

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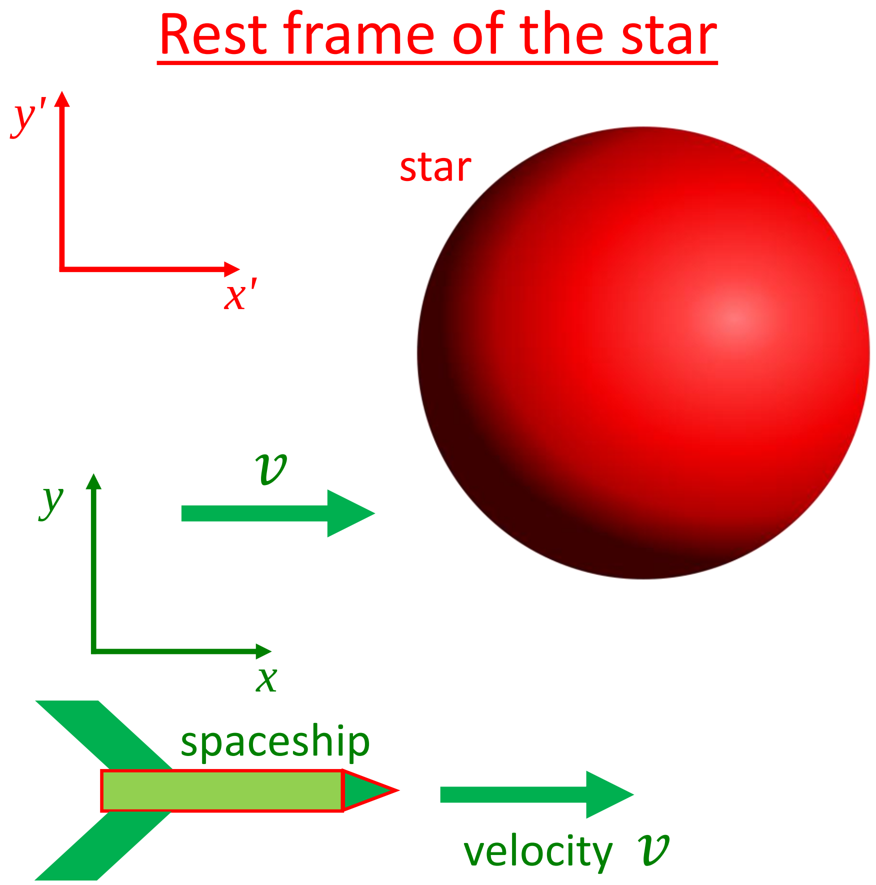

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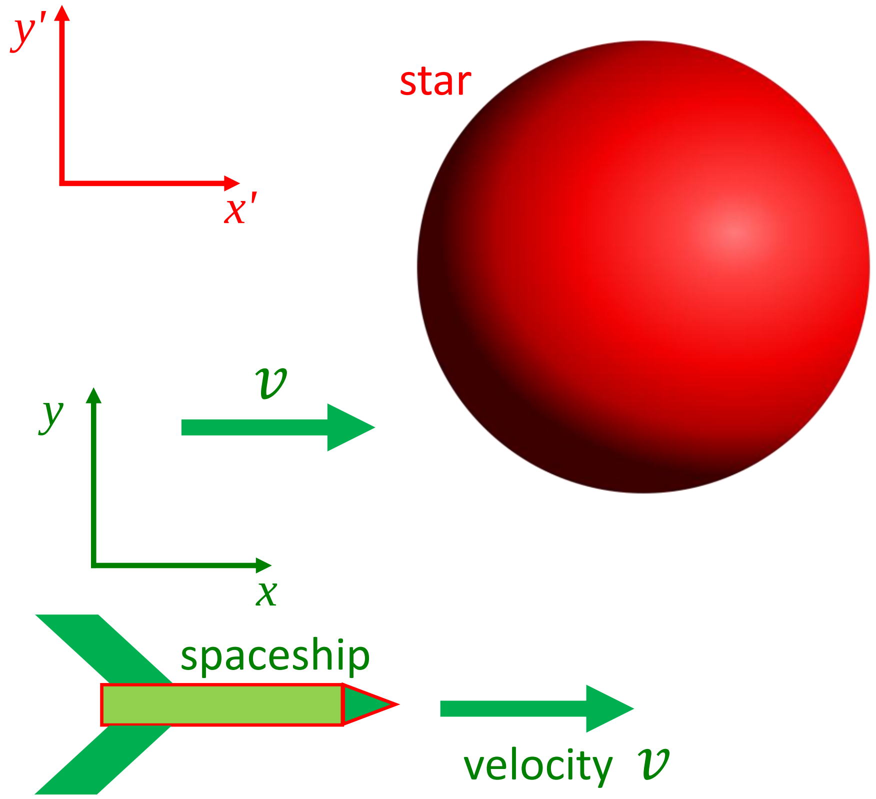

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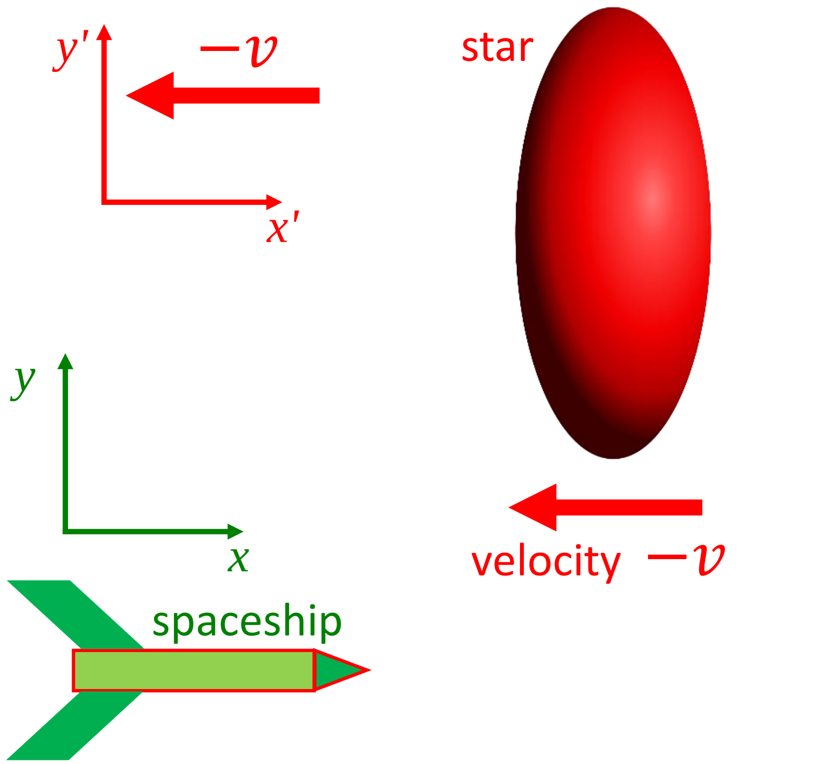

Answer: The star appears/is compressed along the axis of travel.

The transverse directions are unaffected.

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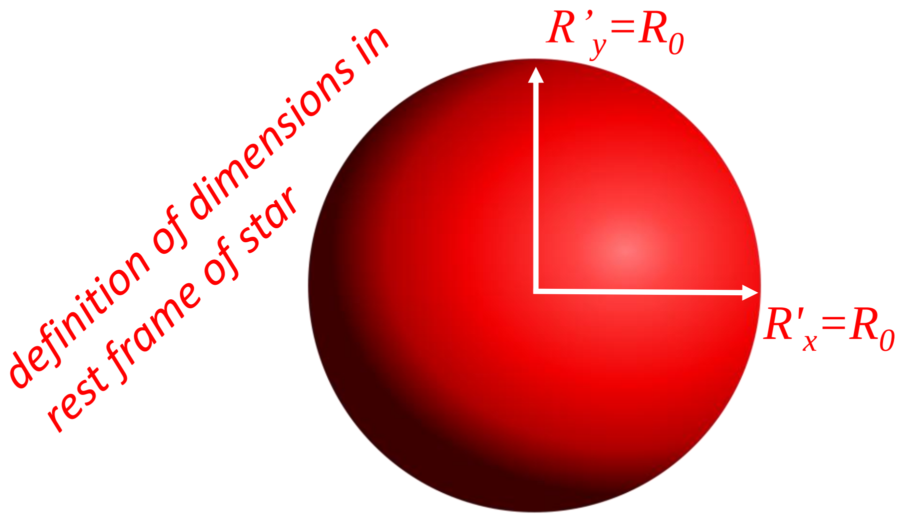
Quantitative answer



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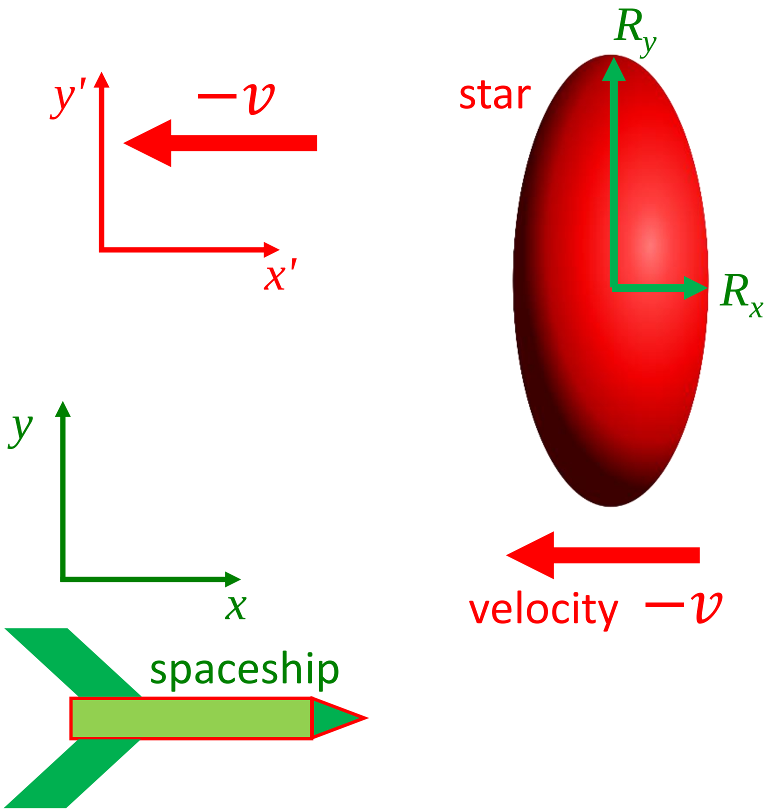

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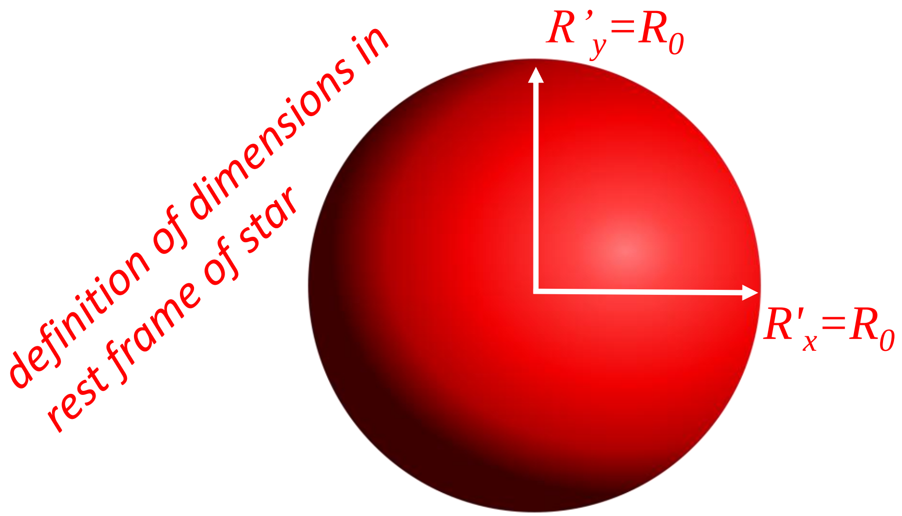

In the rest frame of the spaceship, we have

$$R_x = \frac{R_0}{\gamma} \quad \text{with} \quad \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

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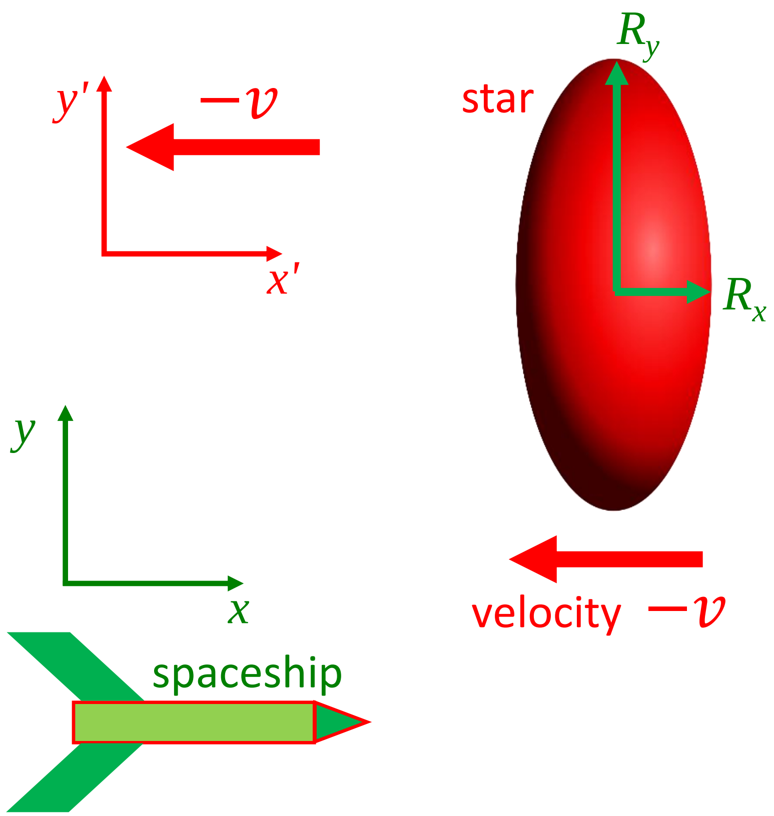

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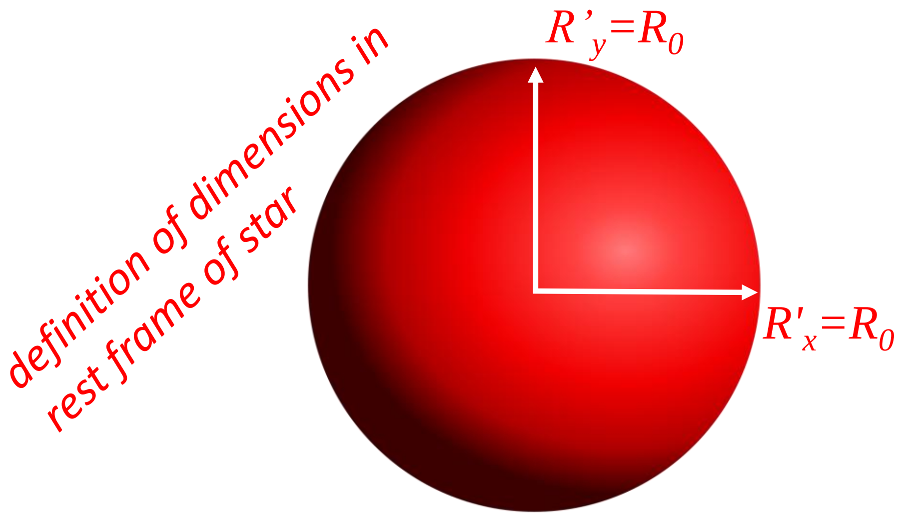

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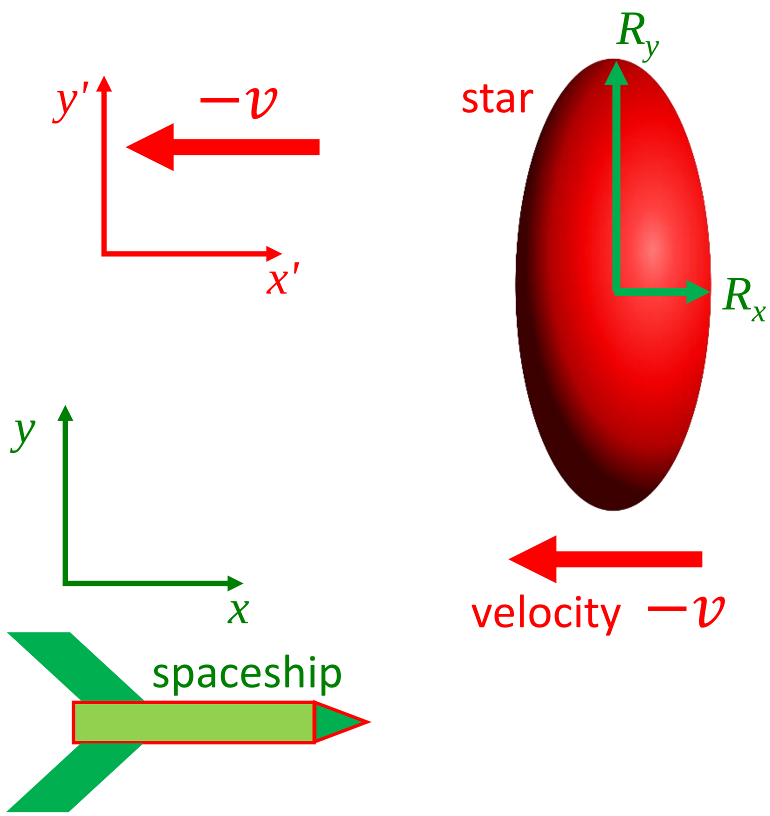
$$R_x = \frac{R_0}{\gamma} \quad \text{with} \quad \gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{1}{\sqrt{1-\frac{(-0.9c)^2}{c^2}}}$$

$$= \frac{1}{\sqrt{1-0.81}} = 2.29$$

Rest frame of the spaceship



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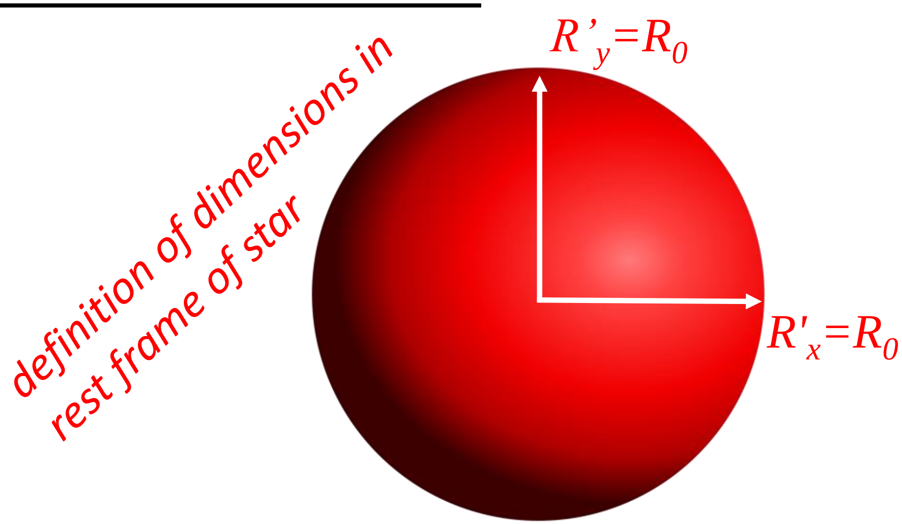
Quantitative answer



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Thus $R_x = \frac{R_0}{2.29} = 0.43 R_0$

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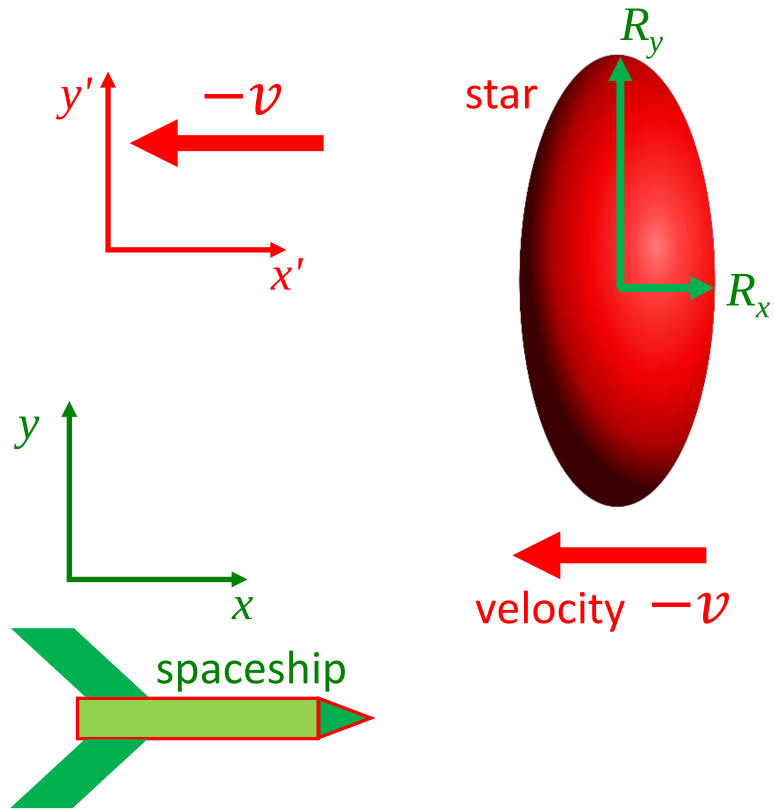

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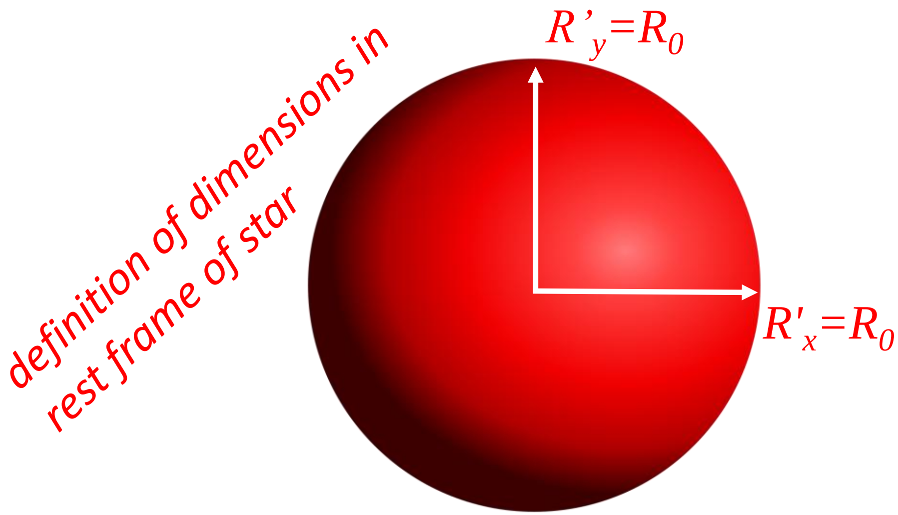
Quantitative answer



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Thus $\boxed{R_x = \frac{R_0}{2.29} = 0.43R_0}$

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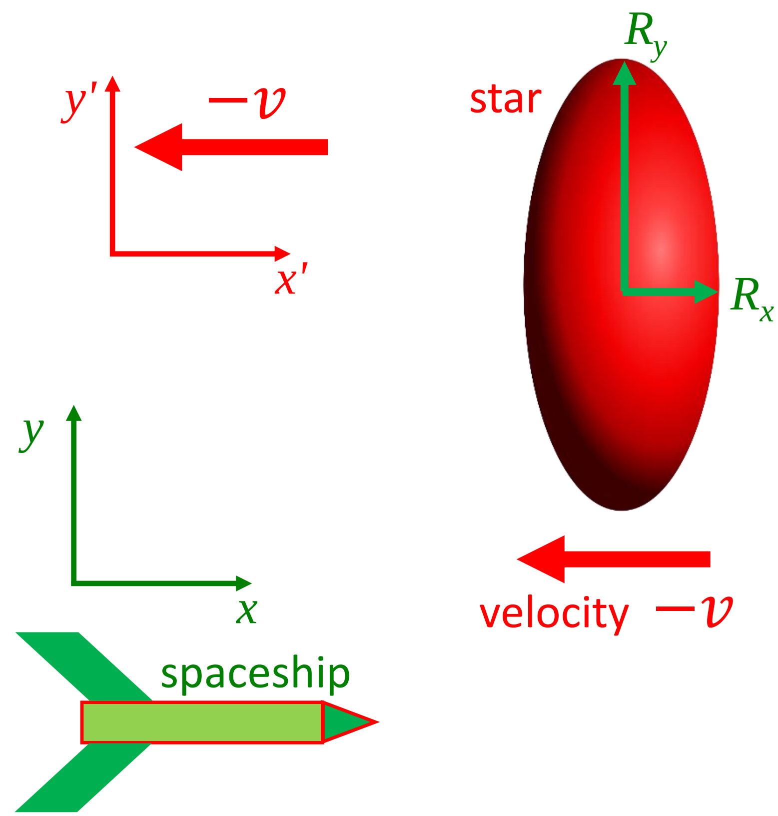

Answer: The star appears/is compressed to 43% of its original size along the direction of travel.
The transverse directions are unaffected.