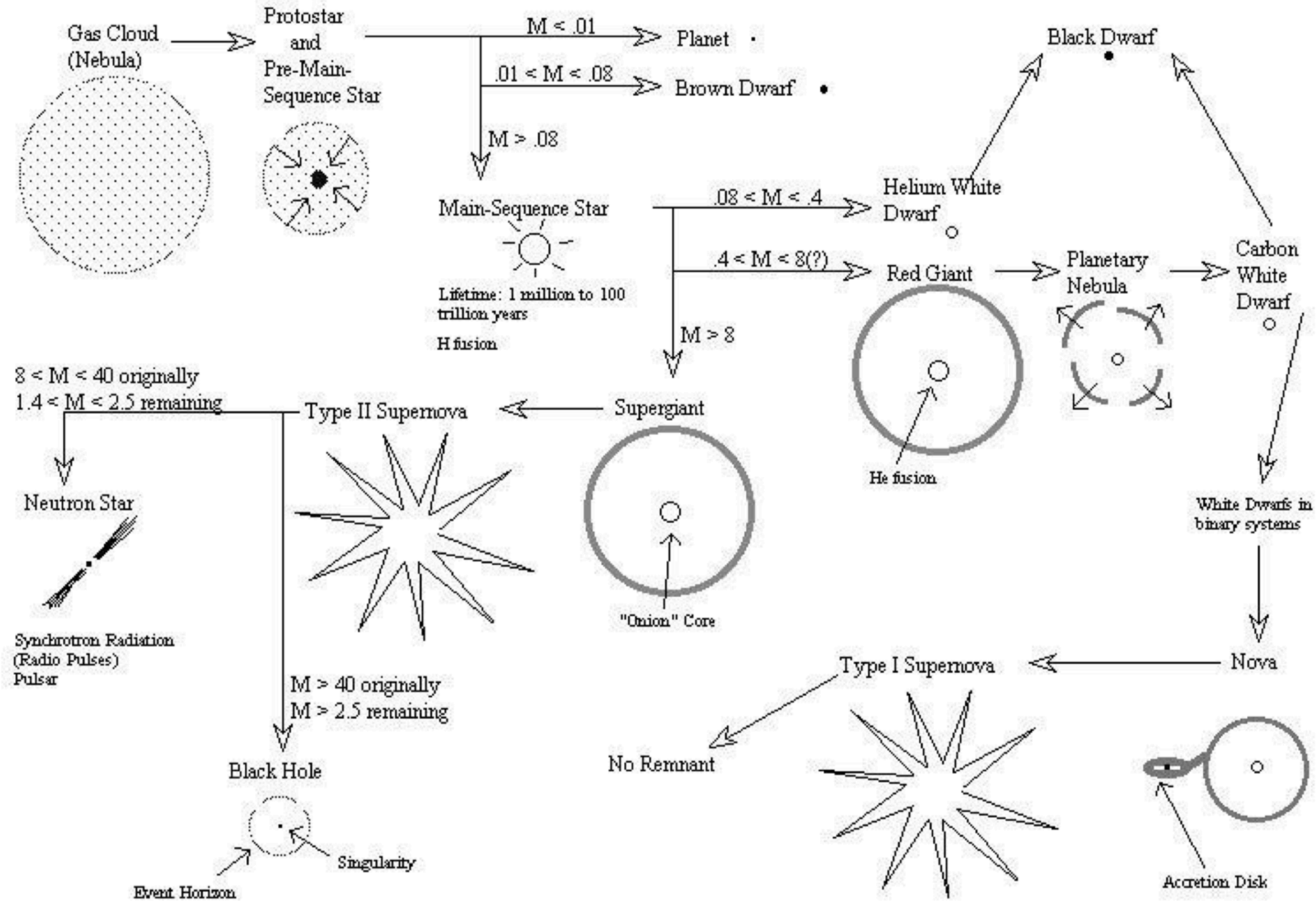
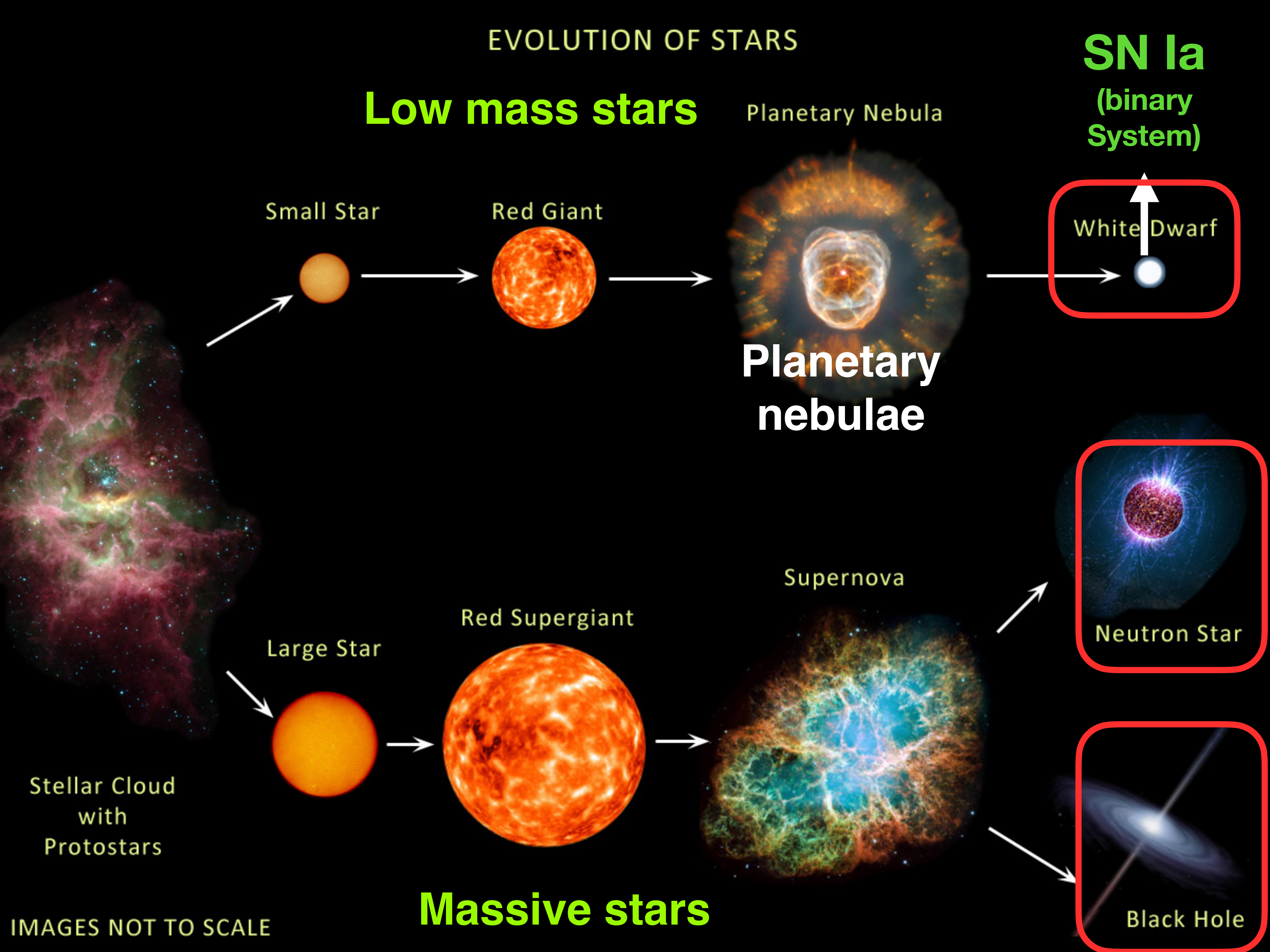
Chapter 18

White Dwarf
Neutron stars
Black holes

Stellar Evolution Review (All masses in units of solar masses.)

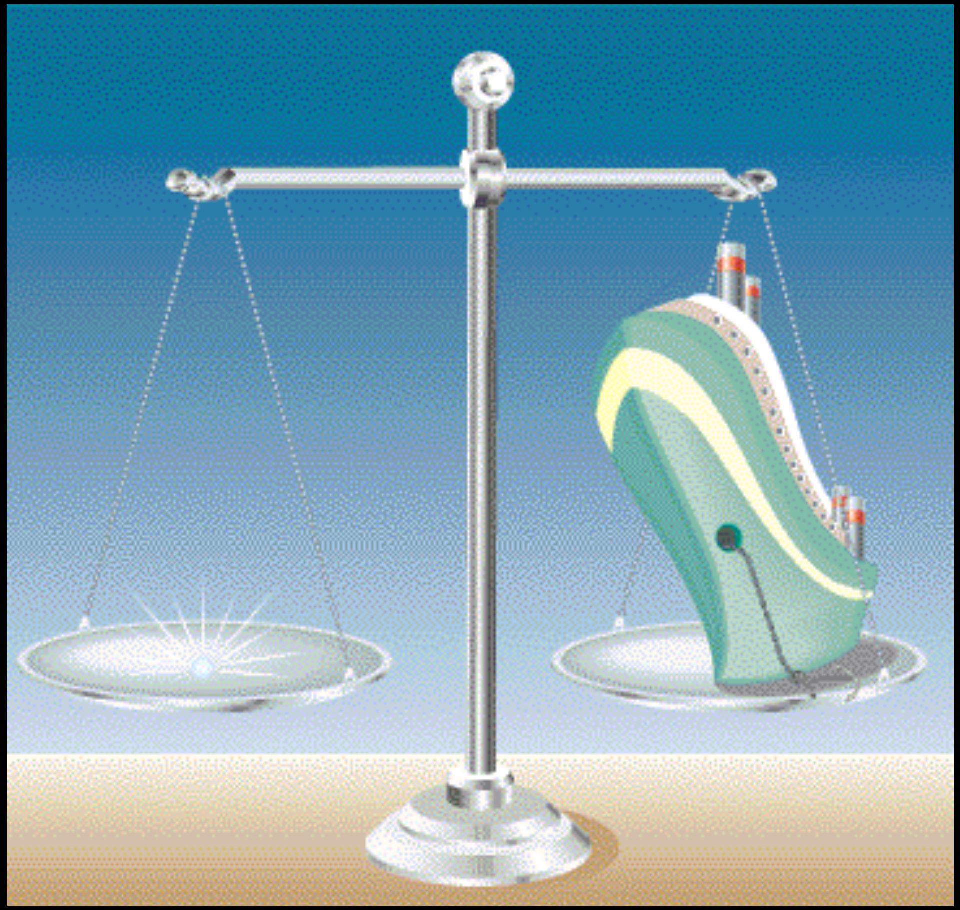



EVOLUTION OF STARS
SN Ia
(binary System)
Low mass stars
Small Star
Red Giant
Planetary Nebula
White Dwarf
Planetary nebulae
Stellar Cloud with Protostars
Large Star
Red Supergiant
Supernova
Neutron Star
Black Hole
Massive stars
IMAGES NOT TO SCALE

White dwarfs are bizarre

- They are very dense

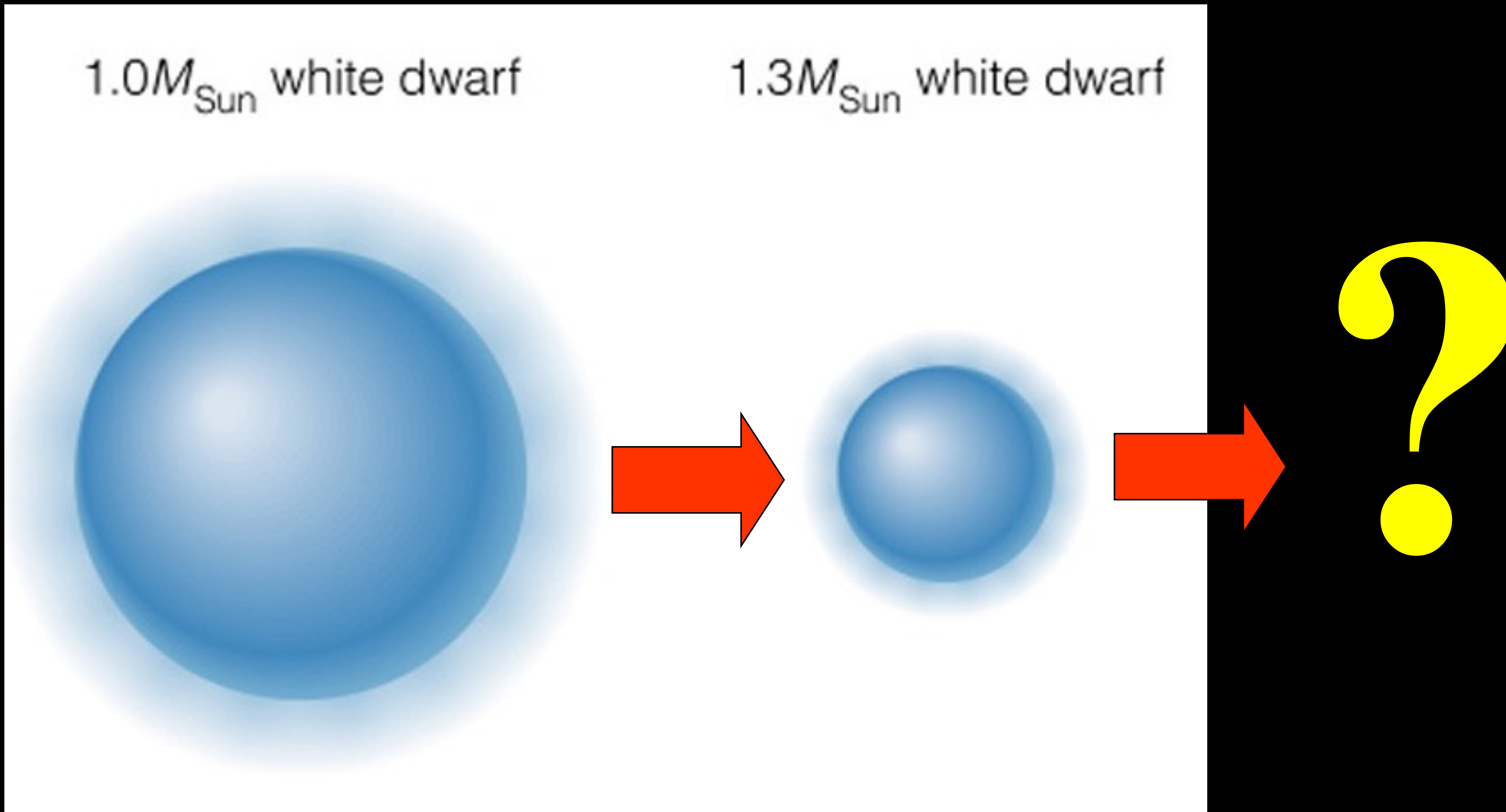
Mass of the Sun compressed into a sphere the size of the Earth!
~2000 kg / cm^3



- They are supported by quantum mechanical effects!

"Electron Degeneracy Pressure"

Massive White Dwarf → Small Size!



Chandrasekhar Limit for White Dwarfs

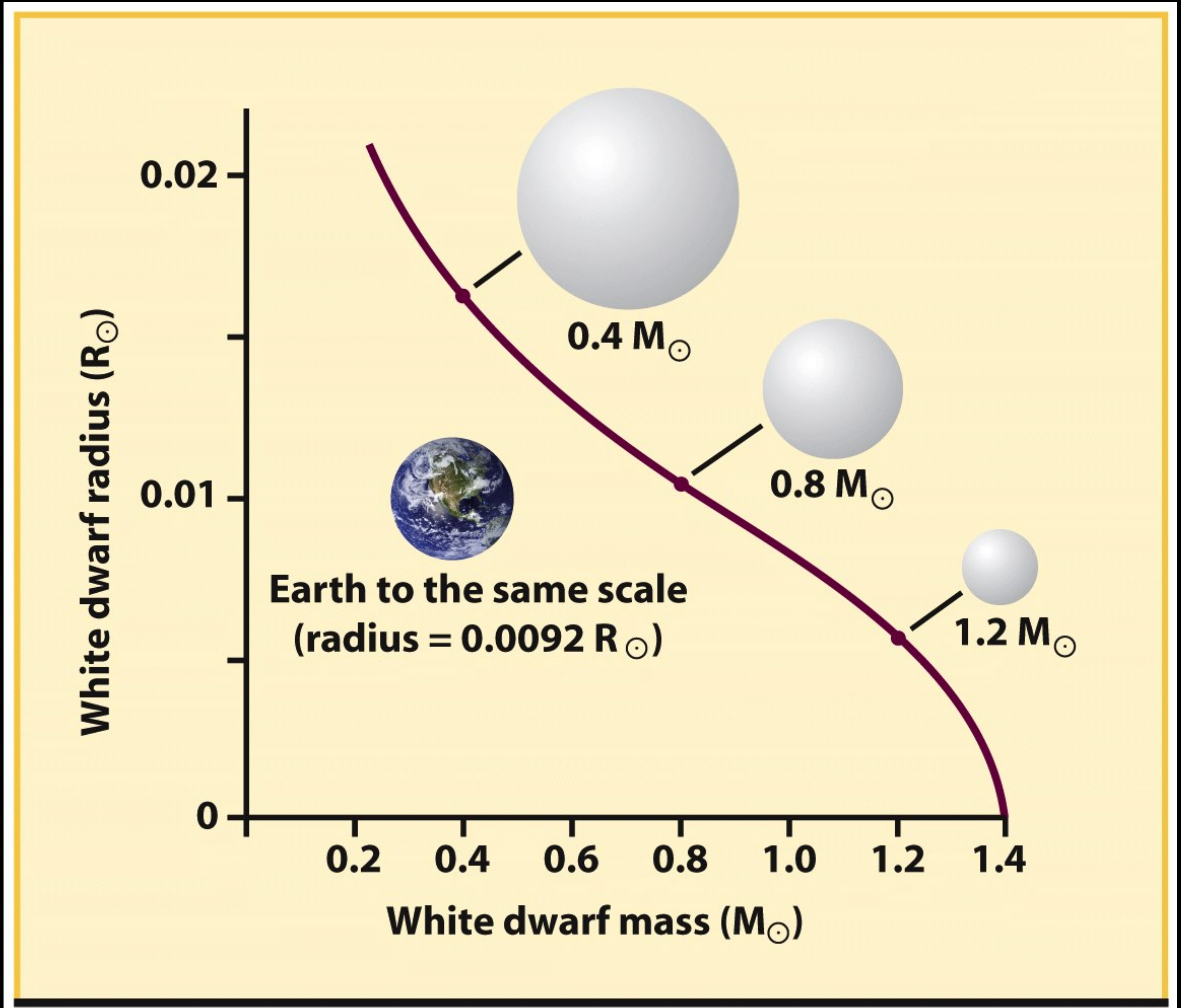


Figure 20-9
Universe, Eighth Edition
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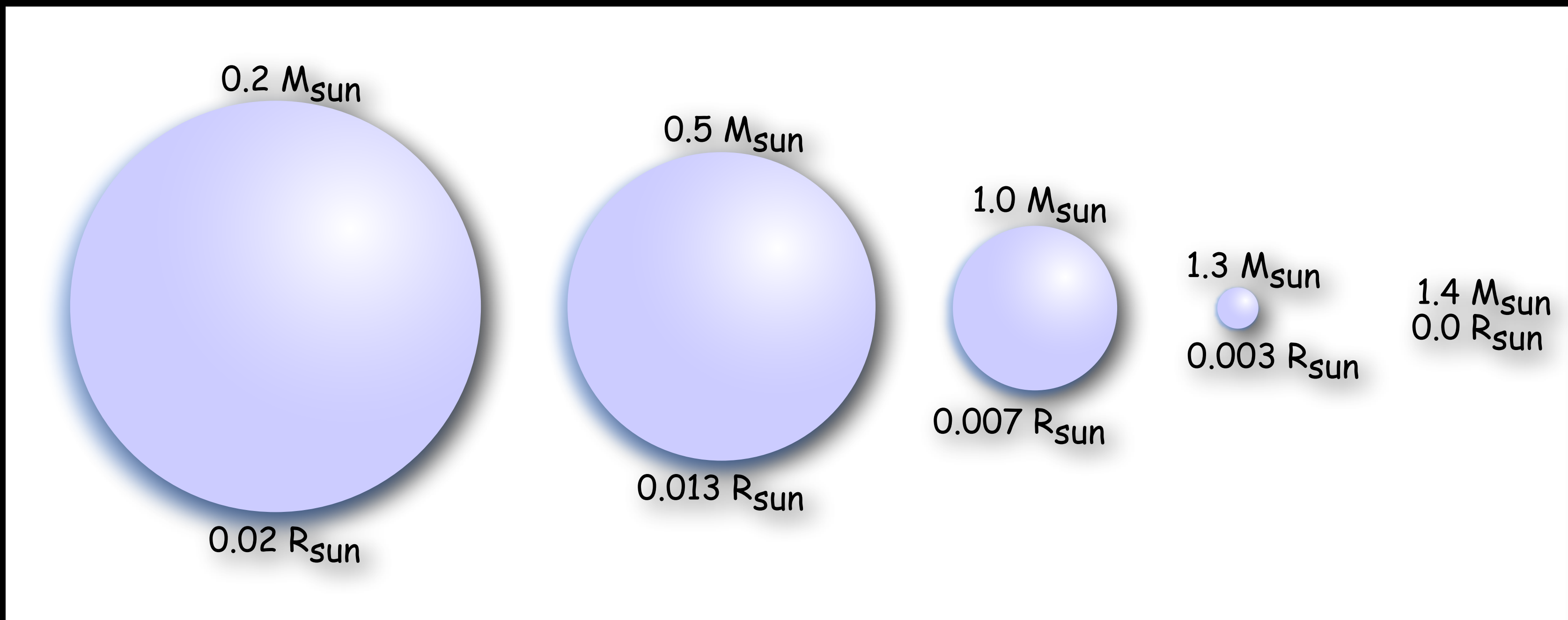
Chandrasekhar Limit for White Dwarfs



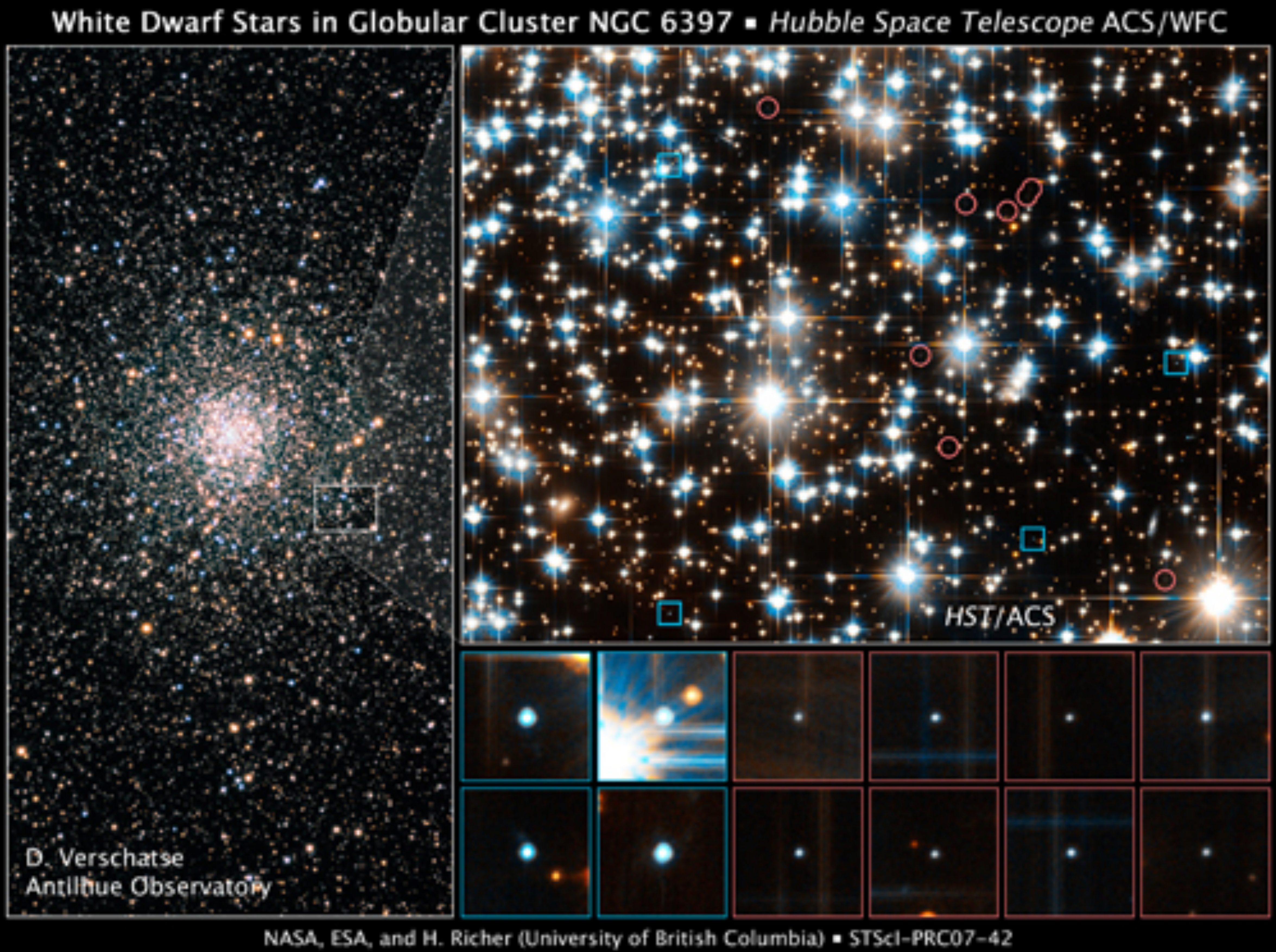
Subrahmanyan Chandrasekhar
1910-1995
(India/U.K./U.S.)

$$M_{ch} = 1.456(\frac{2}{\mu_e})^2 M_{\odot}$$

Worked out the upper mass of white dwarfs limit while sailing from India to England in 1930 (age 20!) to attend Cambridge University (Newton's school).

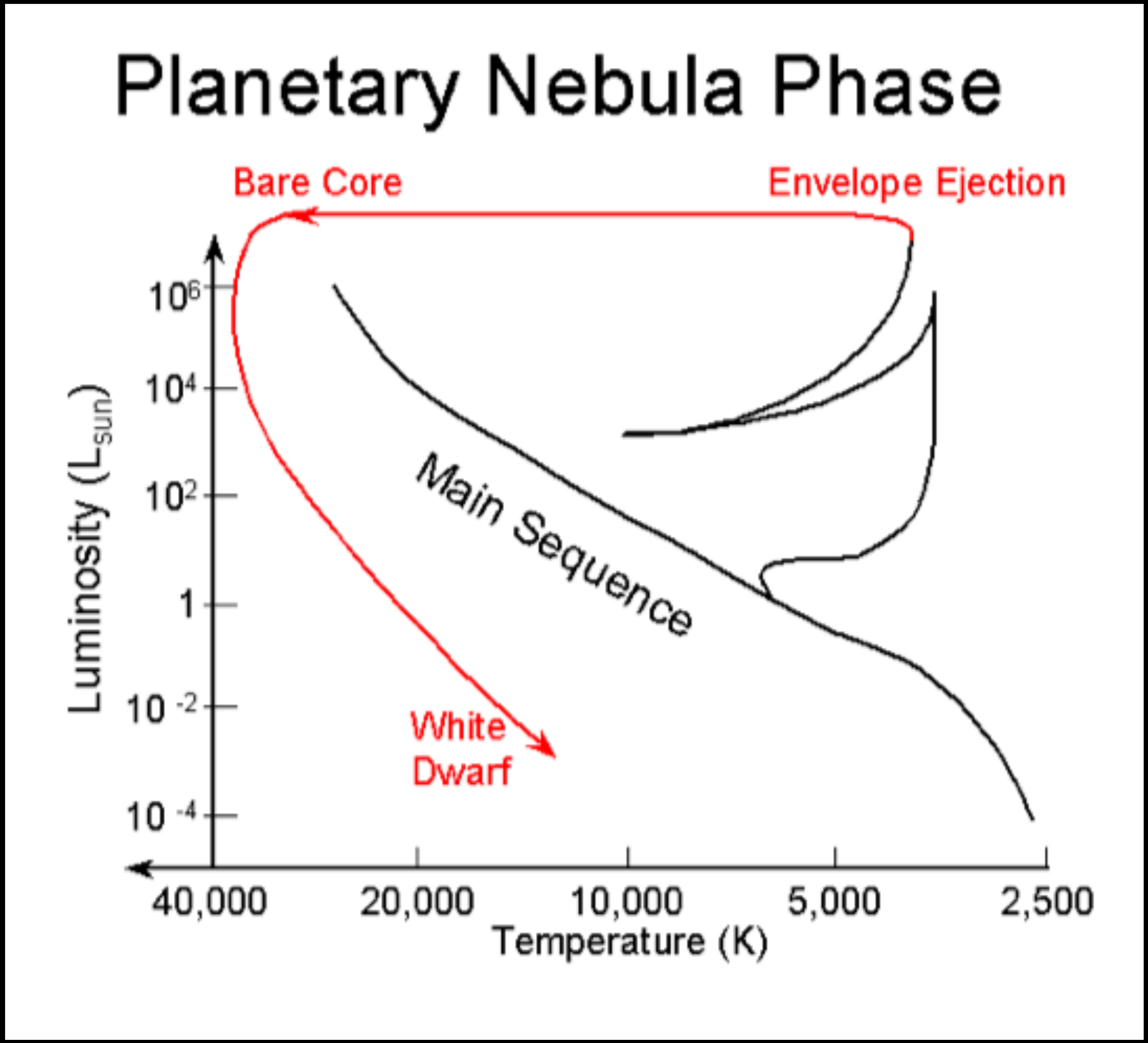
The maximum mass of a white dwarf before collapse is ~1.4 solar masses
All observations of white dwarf masses confirm the ~1.4 solar mass limit

White Dwarf



White Dwarf Stars in Globular Cluster NGC 6397 ▪ *Hubble Space Telescope* ACS/WFC
D. Verschatse
Antilhue Observatory
HST/ACS
NASA, ESA, and H. Richer (University of British Columbia) ▪ STScI-PRC07-42

White Dwarf



White dwarf contract very little while they are cooling down therefore they evolve almost at constant radius

$$L = 4\pi R^2 T_{eff}^4$$

$$L \propto T_{eff}^4$$

White Dwarf

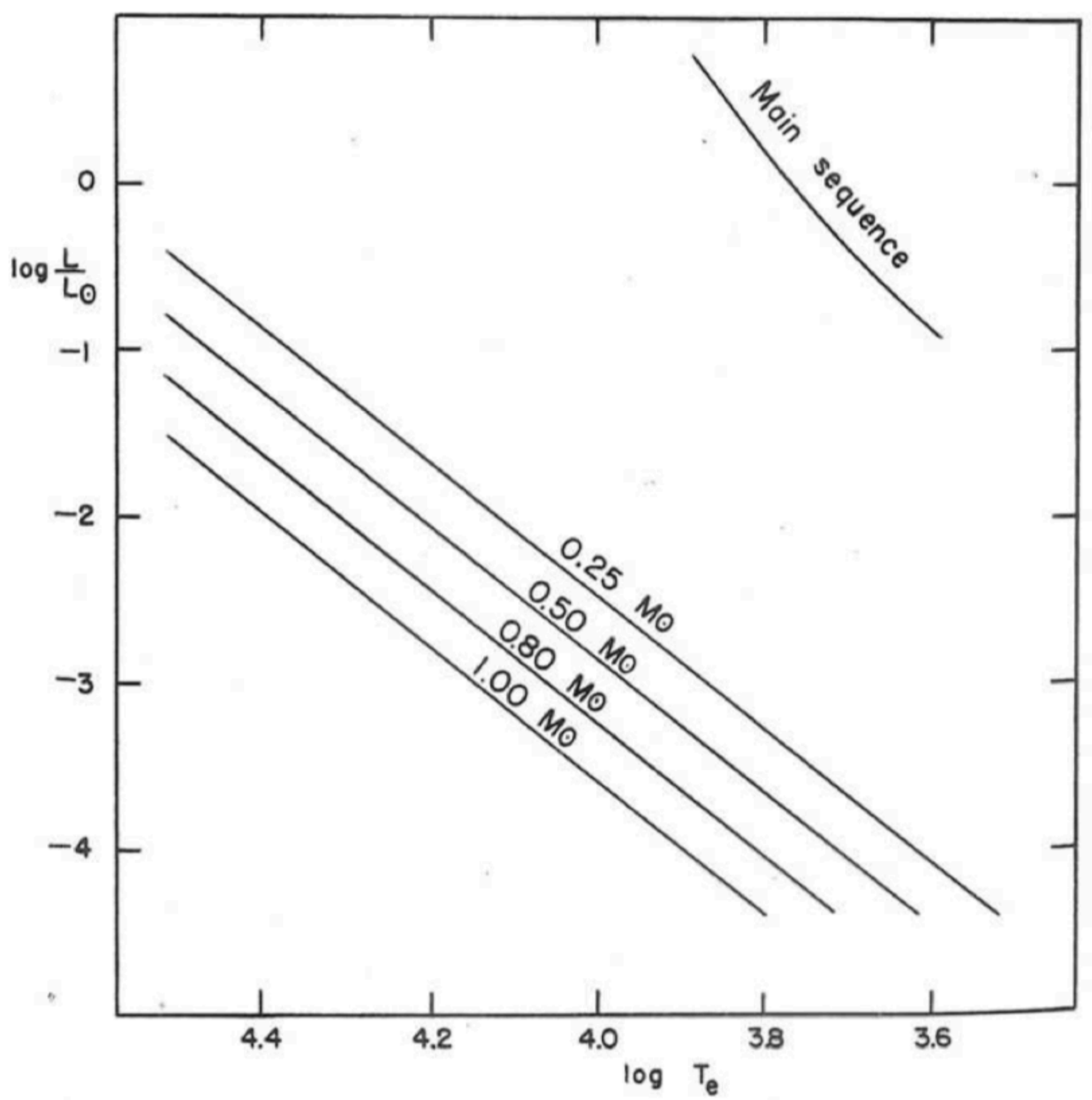


Fig. 26.1. Theoretical Hertzsprung-Russell diagram for the white dwarfs.

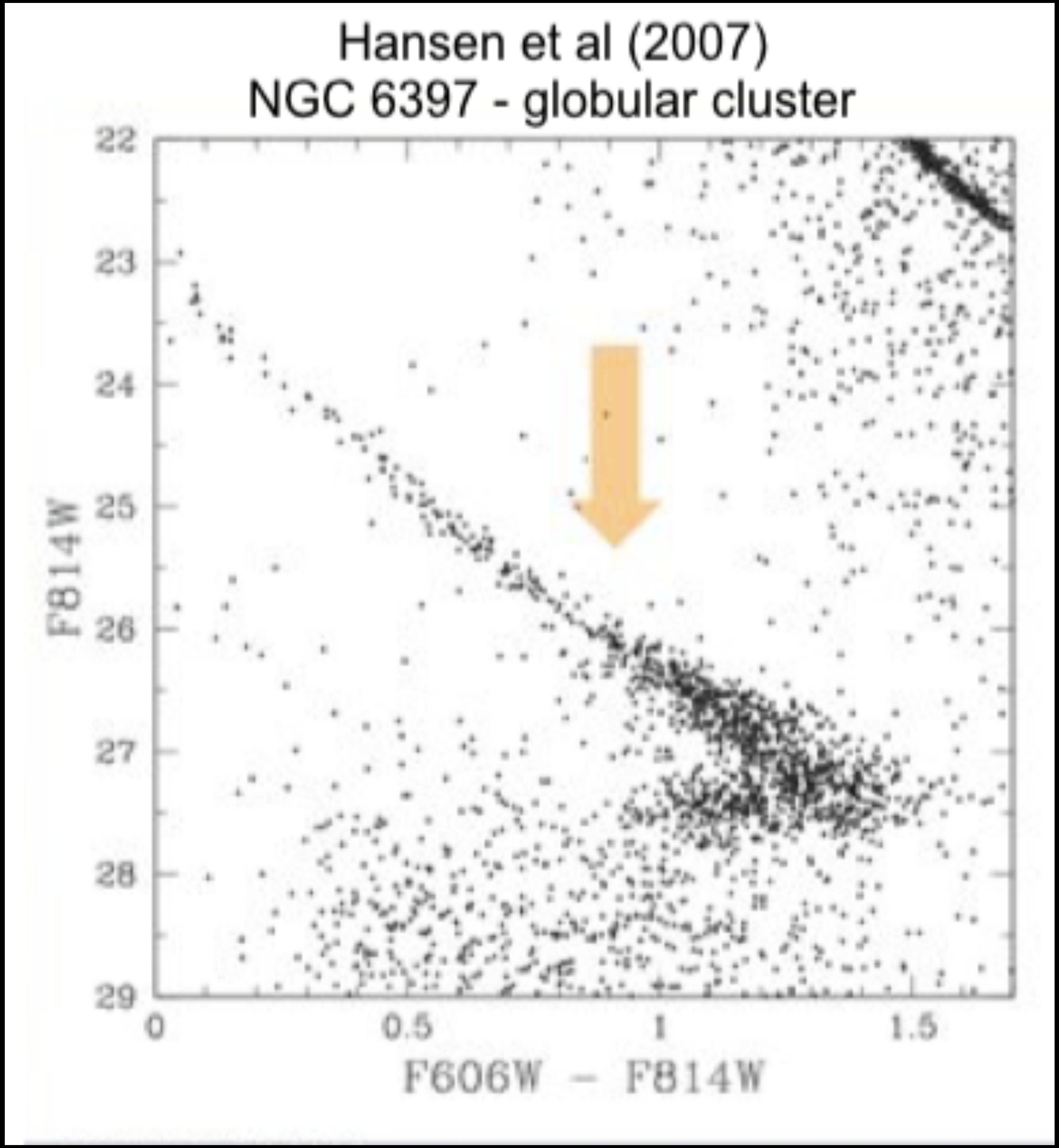
White dwarf contract very little while they are cooling down therefore they evolve almost at constant radius

$$L = 4\pi R^2 T_{eff}^4$$

$$L \propto T_{eff}^4$$

White Dwarf

When the interior temperature declines to ~5000 K, the carbon and oxygen start to crystallize into a lattice. This crystallization releases energy and provides a source of luminosity that slows the cooling.



Eventually the white dwarf will become a "black dwarf", but the Universe is still not old enough to from black dwarf (WD cold enough to stop emitting significant light)

Neutron Star

Theoretically envisioned in the 1930s by Walter Baade and Fritz Zwicky, a neutron star has the following properties:

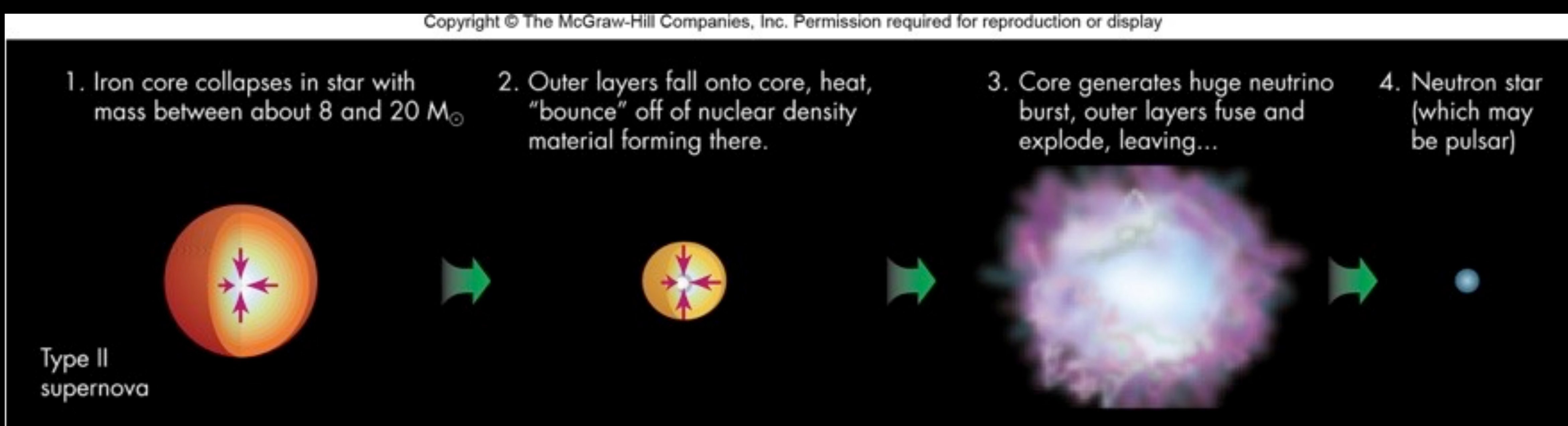
- Radius about 10 km
- Mass between 1 solar mass and a maximum of about 2-3 solar masses
- Upper mass limit about 3 solar masses

Walter Baade

1893 – 1960
(Germany/U.S.)

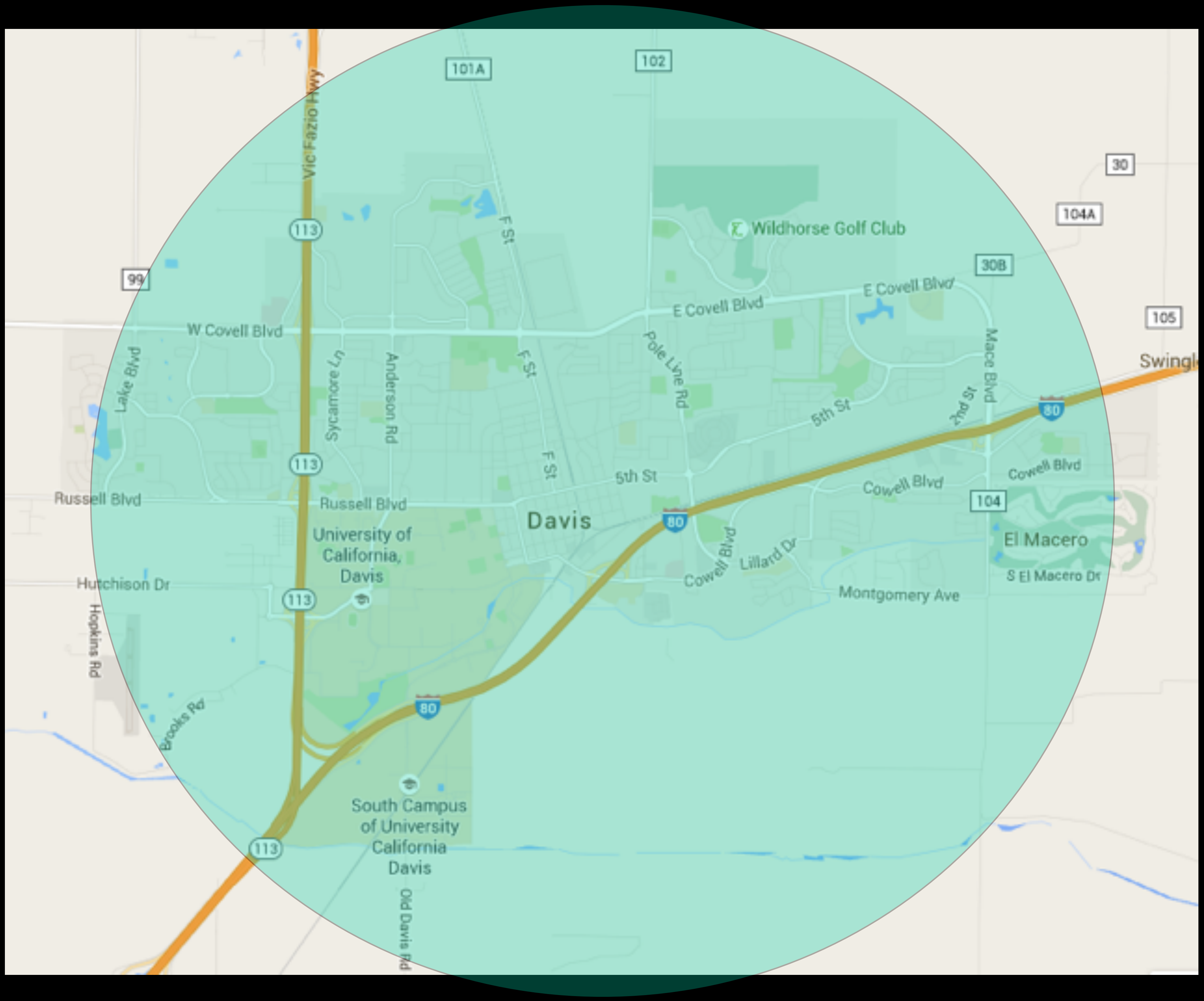
Fritz Zwicky

1898 – 1974
(Switzerland/U.S.)



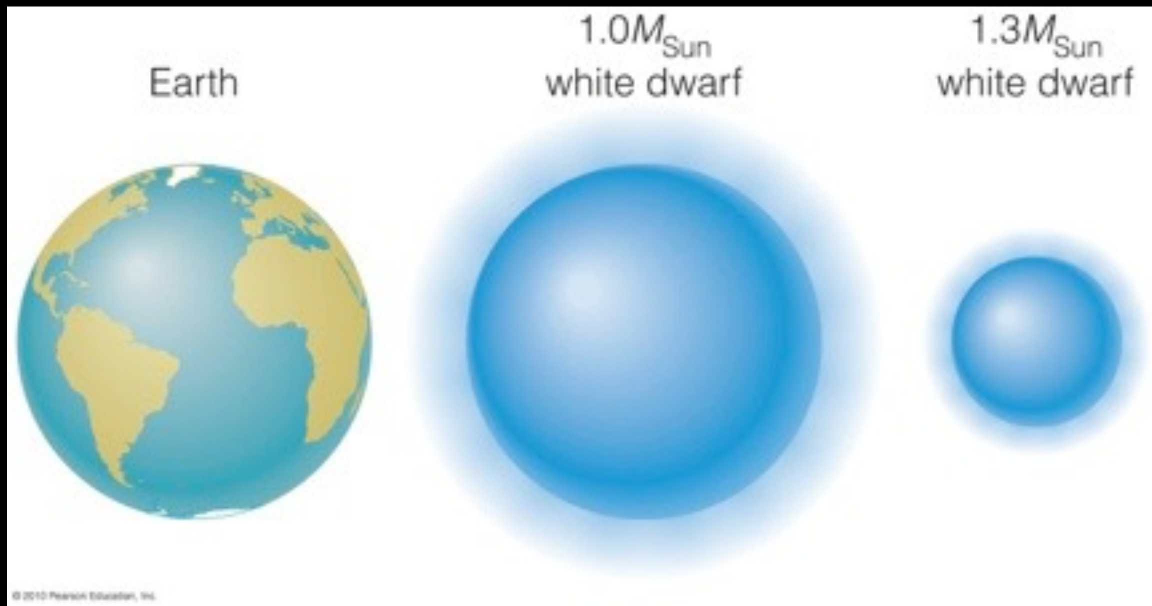
Neutron Star

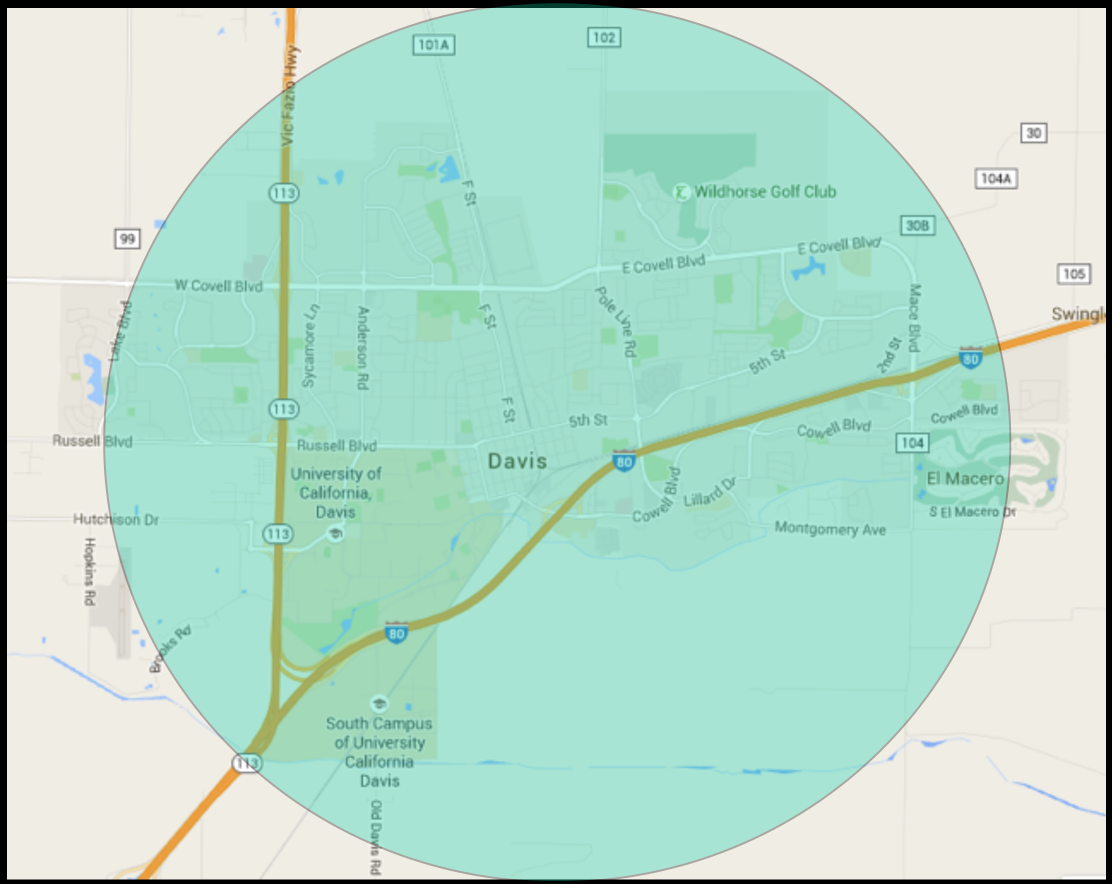
This image shows a 1-solar-mass neutron star, about **10 km** in diameter, compared to Davis, CA:



Density is roughly 10^9 tons per teaspoon!

White Dwarfs and Neutron Stars





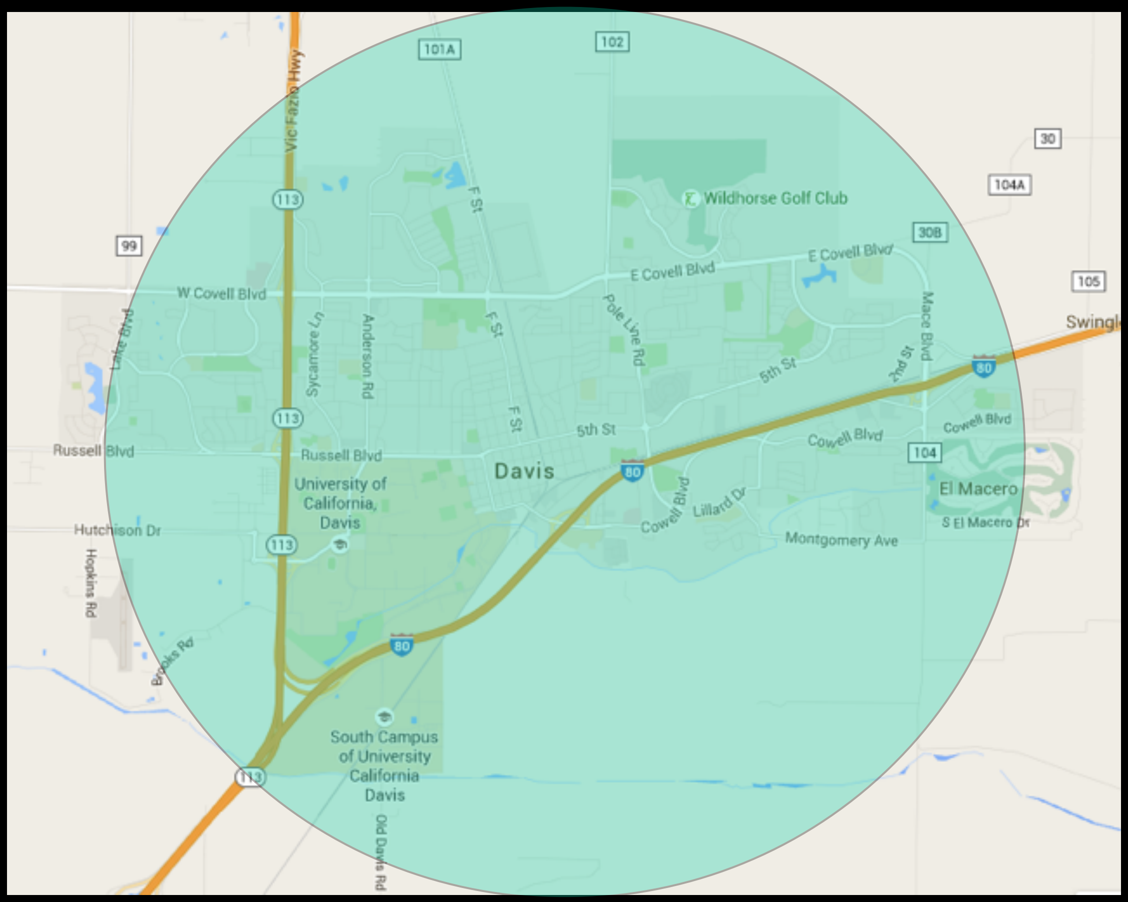
- White Dwarfs
- 0.5 to 1.4 solar masses
- Density is roughly 1 ton per teaspoon!
- About the size of the Earth
- Leftover carbon core of a Sun-like star that ejects a planetary nebula (the fate of the Sun)
- Upper limit of 1.4 solar masses, supported by electron pressure

- Neutron stars:
- up to about 3 solar masses
- Density is roughly 10^9 tons per teaspoon!
- Only about 10 km in diameter
- Ball of neutron created in supernova explosion of a massive star with > 8 solar masses
- Upper limit of about 3 solar masses, supported by neutron pressure

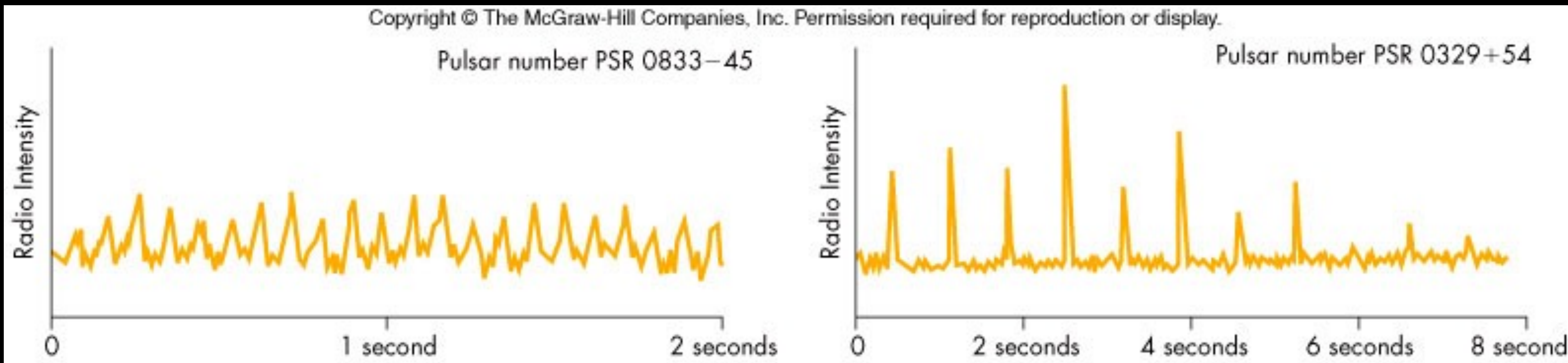
White Dwarfs and Neutron Stars

Other important properties of neutron stars (beyond mass and size):

- Rotation as the parent star collapses, the neutron core spins very rapidly, conserving angular momentum. Typical periods are fractions of a second.
- Magnetic field again as a result of the collapse, the neutron star's magnetic field becomes enormously concentrated and strong.
- Because of the small size, neutron stars were thought to be unobservable... until...



Pulsars



In 1967, Jocelyn Bell, a graduate student of Anthony Hewish, detected an odd radio signal at Jodrell Bank Observatory (England) with a rapid pulse rate of one burst per 1.33 seconds.

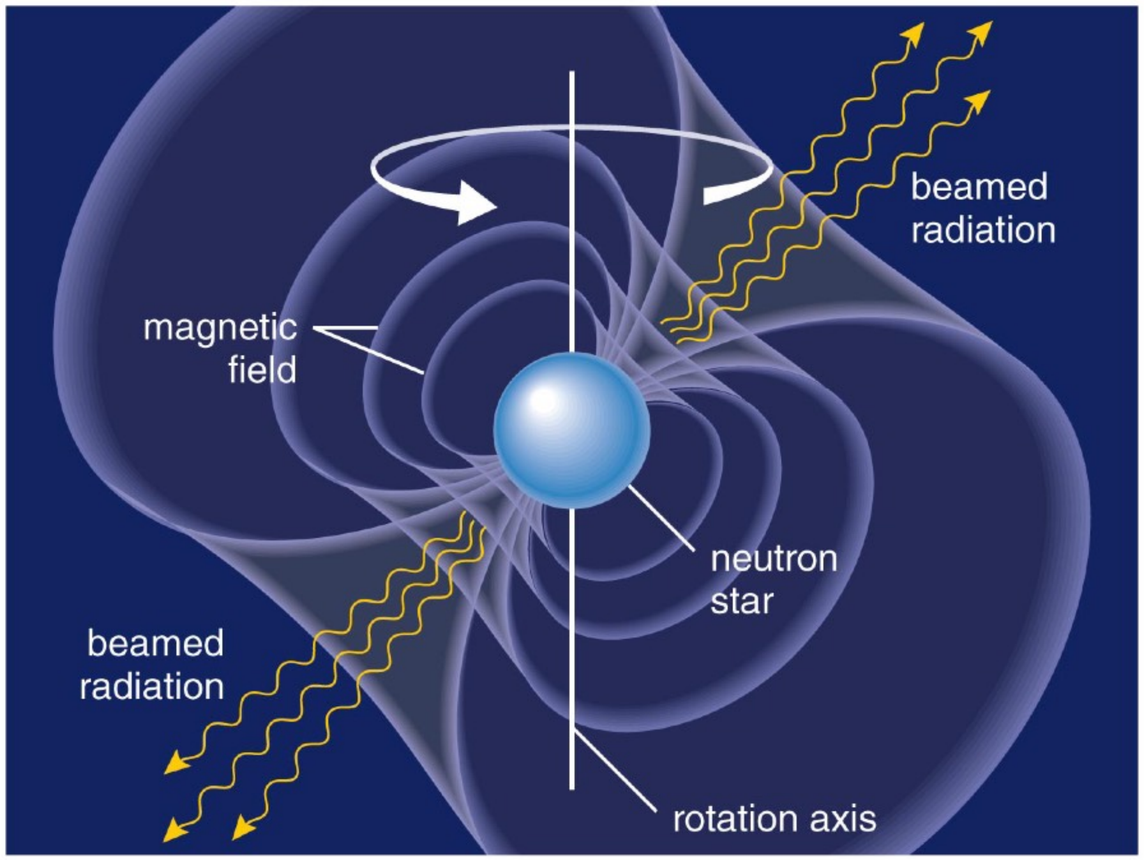
Over the next few months, more pulsating radio sources were discovered and eventually were named pulsars.

Nobel Prize 1974 went to Hewish and another British radio astronomer, Martin Ryle, for interferometer and discovery of pulsars.

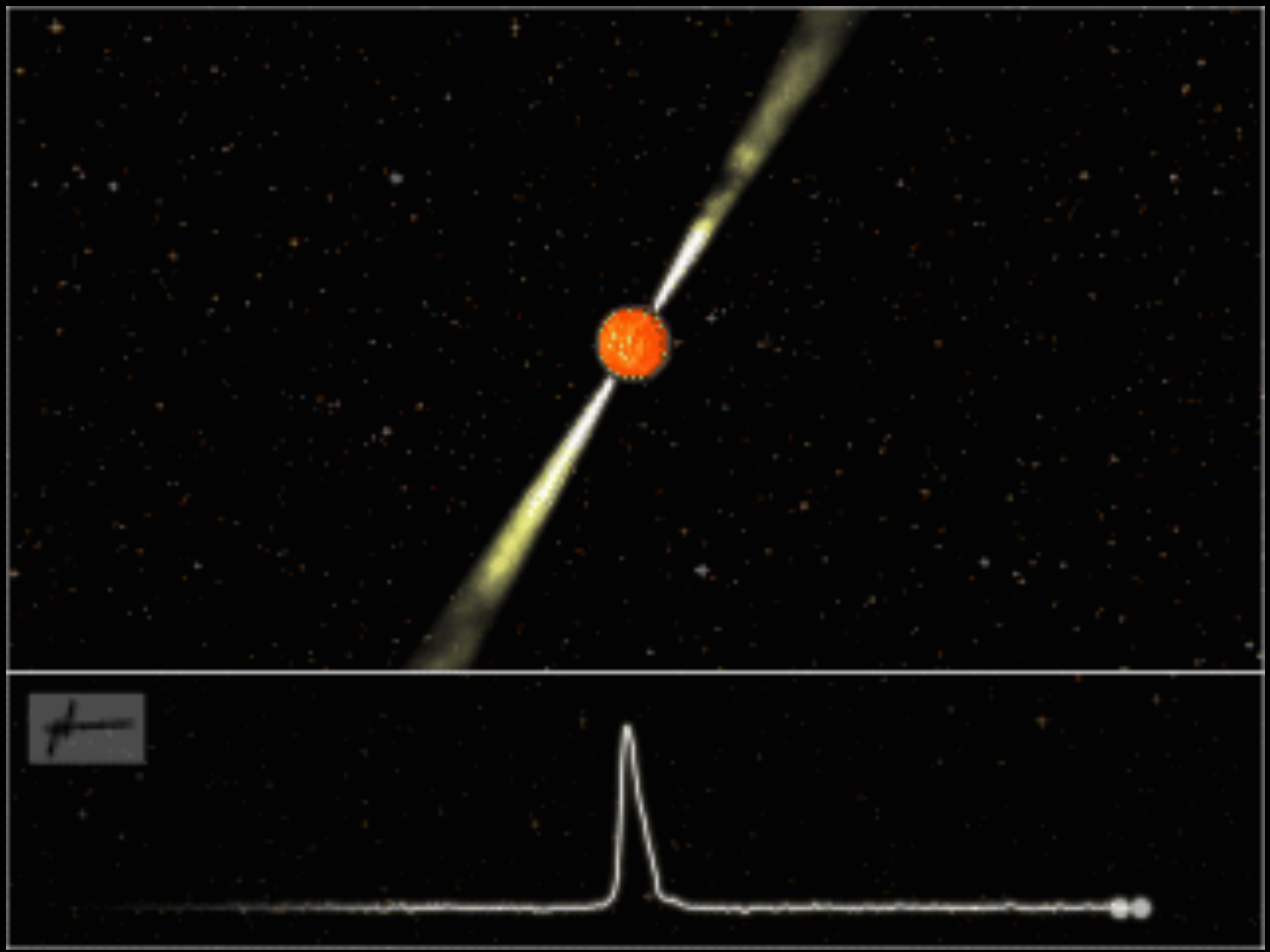
Pulsars: rapidly spinning neutron stars!

- What happens when a massive star collapses to a very small size?
- Recall **conservation of angular momentum**:
  - $L = M \times v \times R$ (mass × velocity × distance from center)
    - Conservation means that **v** goes up if **R** goes down: **L** constant
  - Sun has R ≈ 10^6 km and rotates once every 24.5 days
  - If it shrank to R ≈ 10 km = size of a neutron star, it would rotate once every 2 seconds!
- **Neutron stars are born to spin!**

Why does a Pulsar pulse?

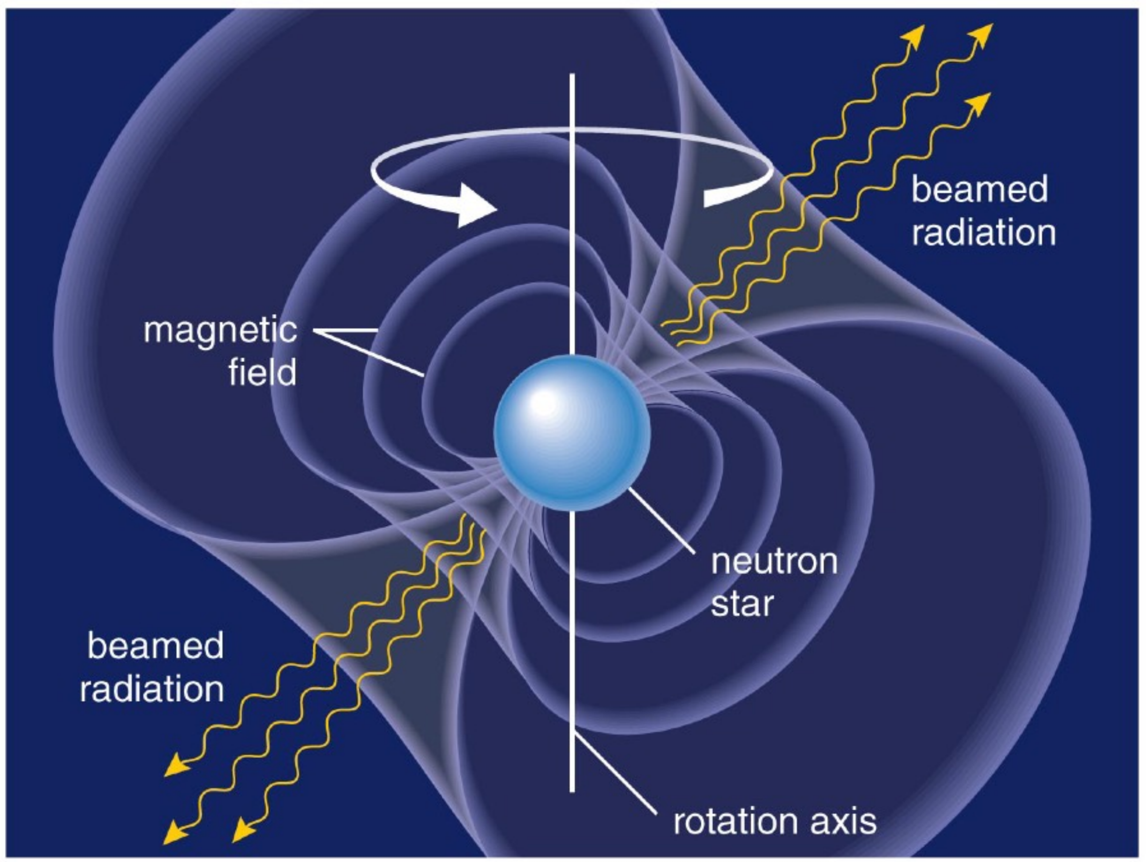


a A pulsar is a rotating neutron star that beams radiation along its magnetic axis.



- Pulsars spin rapidly because of angular momentum conservation
- They emit beams of radiation from their magnetic poles
  - Magnetic axis is not necessarily aligned with rotation axis
  - Radiation beams “sweep” through space, like a lighthouse
  - We observe these as regular pulses

Why Pulsars must be neutron stars



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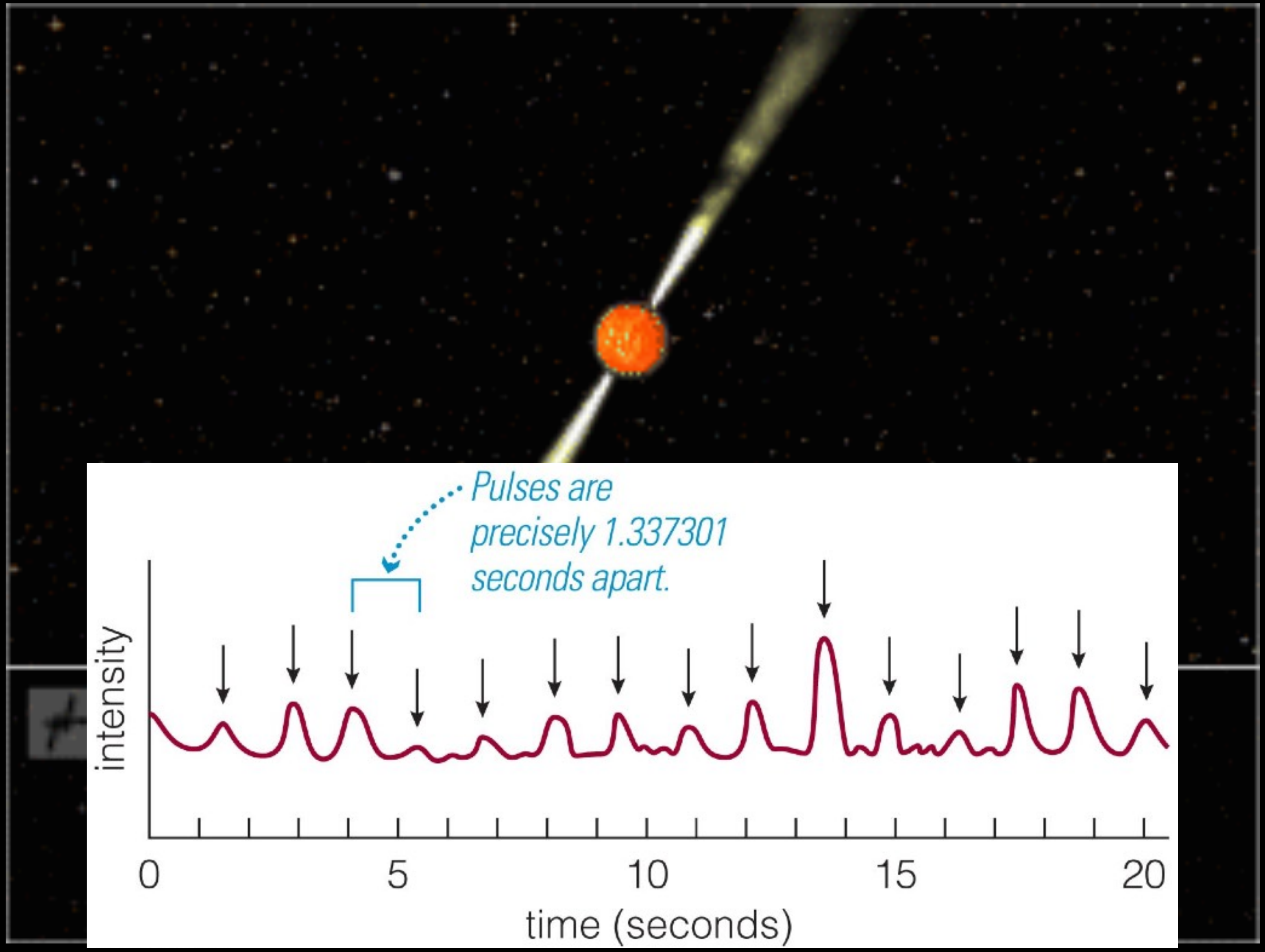
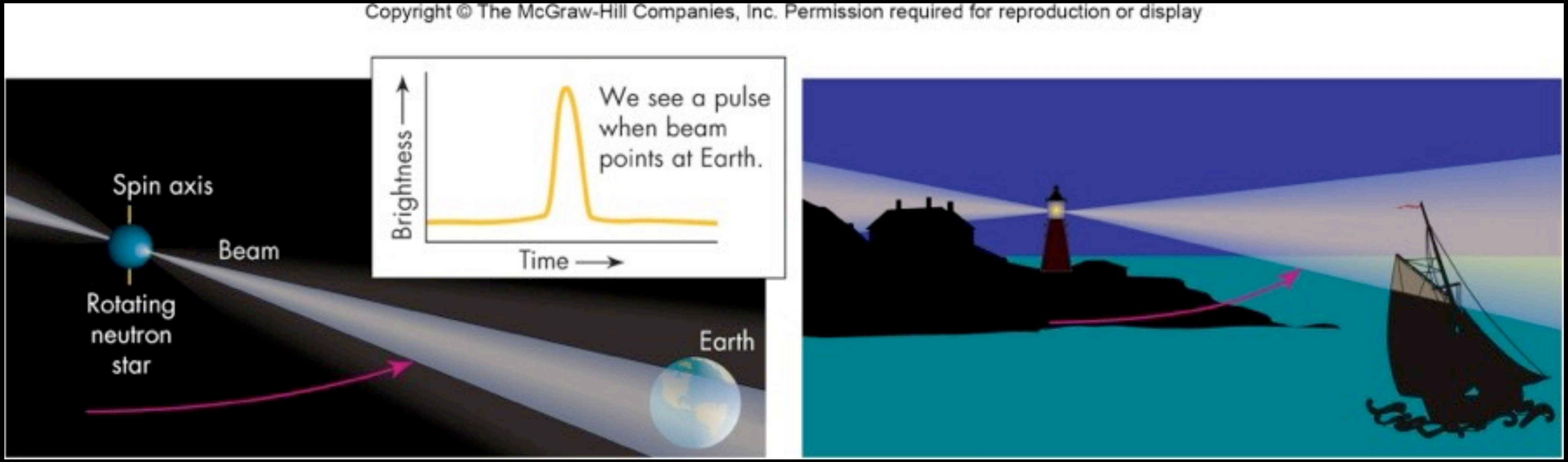


- Spin rates can be as high as 1000 times per second!
  - Neutron star R ≈ 10 km: rotating at **v = 0.2 c**
    - 20% of the speed of light!
  - White dwarf R ≈ 7,000 km: would be rotating 150× faster than speed of light. Not possible!
- Anything other than a neutron star would be ripped apart!

Radiation from Pulsars



- The apparent pulsation of a pulsar that we see is the result of one of the radio beams sweeping across the Earth (sizes and distances in illustration not to scale!)

Evidence that neutron stars are created in supernovae

Credit: Cambridge University Lucky Imaging Group

The Crab Nebula

- Leftover from the supernova of 1054

The Crab Pulsar

- Neutron star located in the center of the supernova remnant
- Rotates 30 times/second!

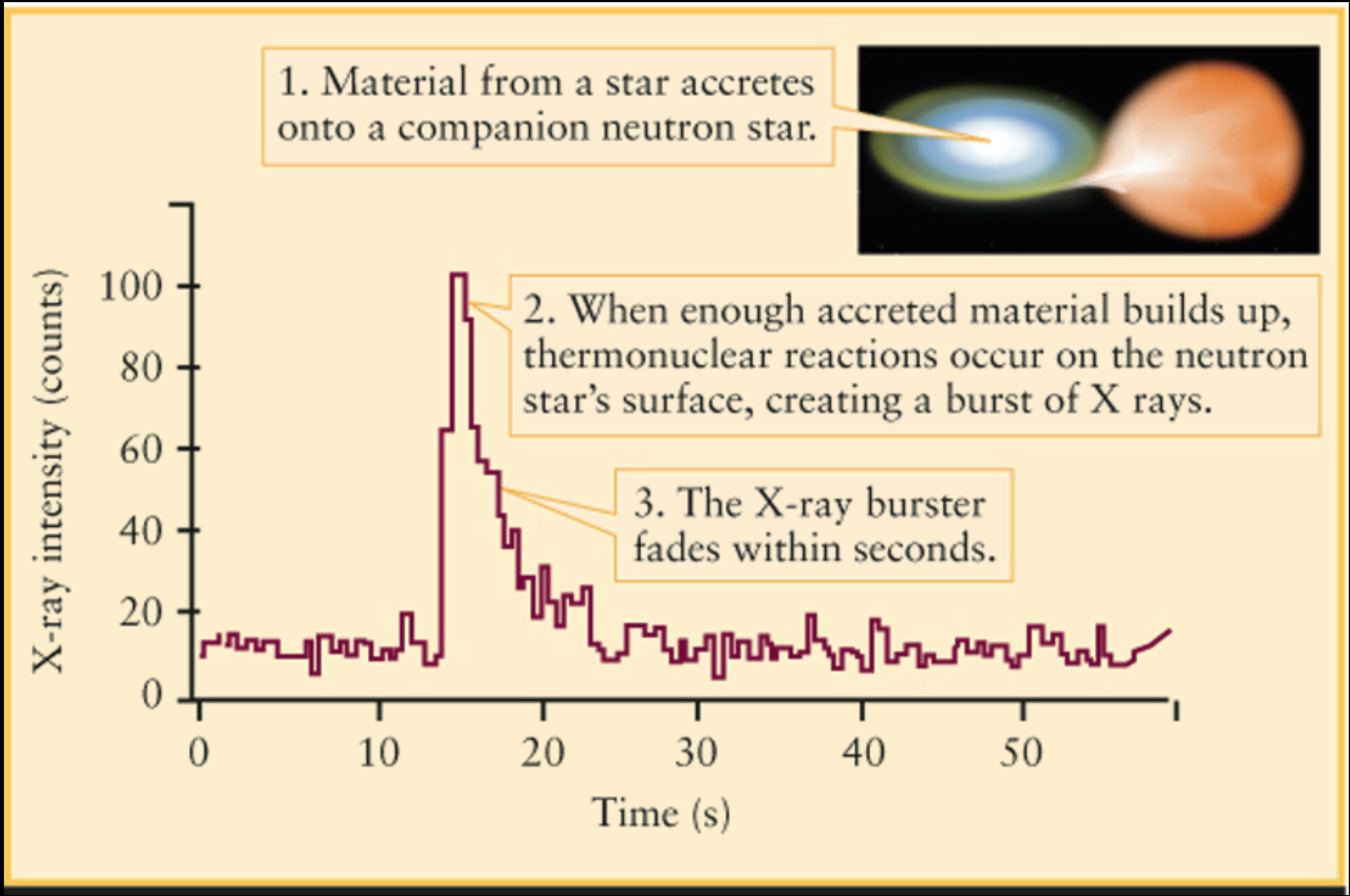
https://www.youtube.com/watch?v=fFLQNzAzLEk

Binary Systems

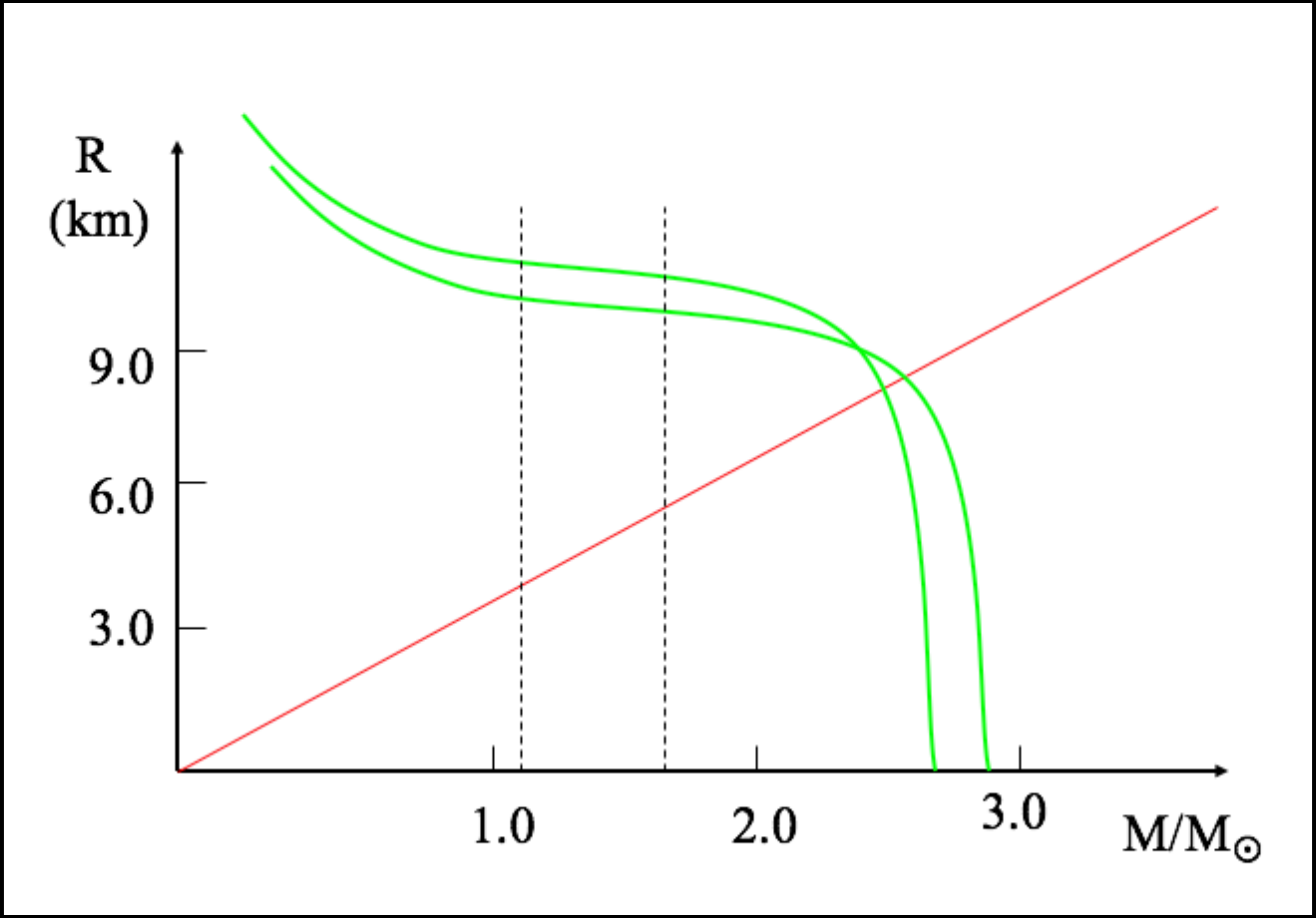
- White Dwarf in binary system
  - Novae
  - SNe Ia

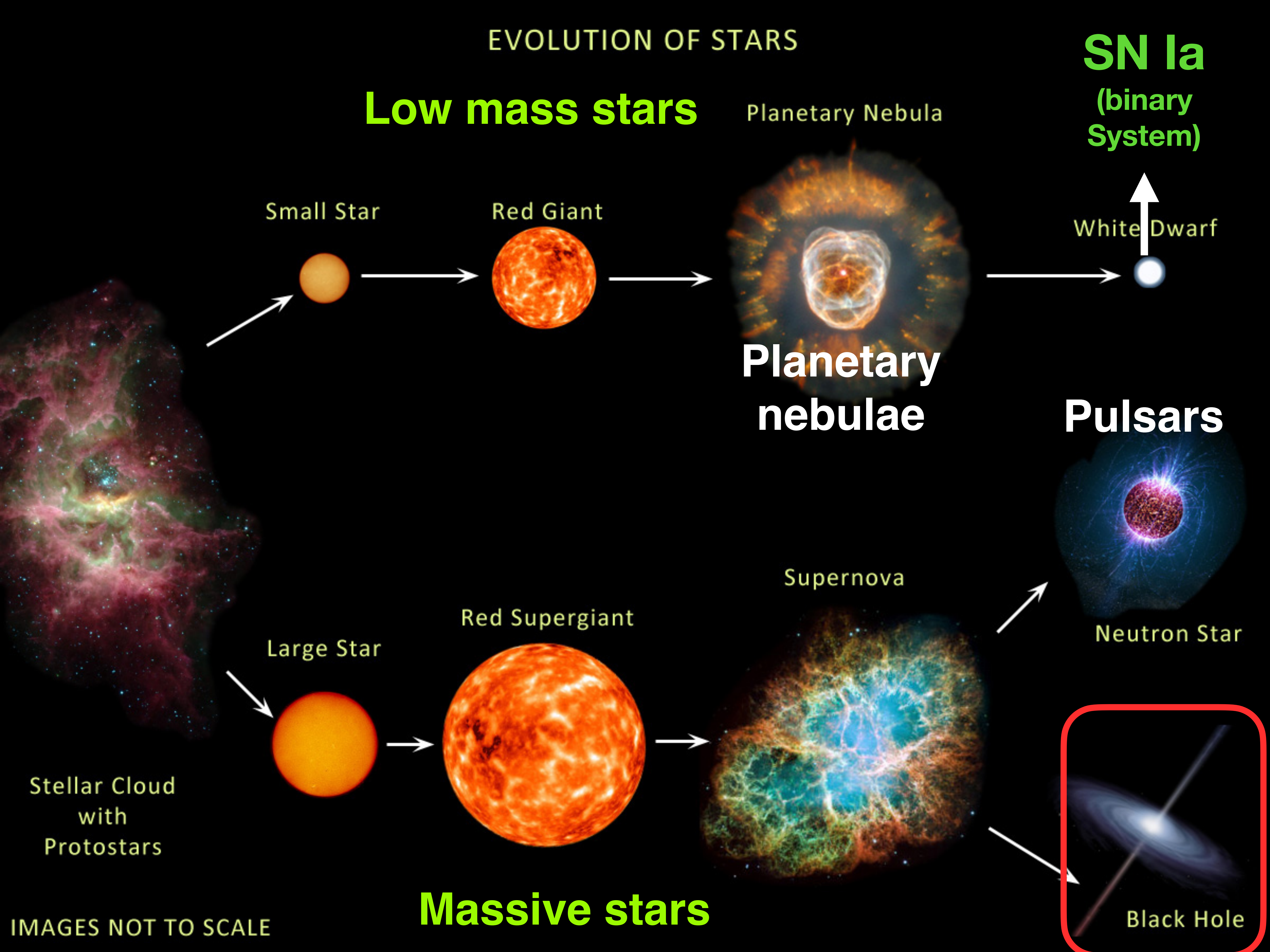
- Neutron stars in binary system
  - X-ray Bursters

X-ray Bursters



Maximum Neutron Star Mass

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White Dwarf
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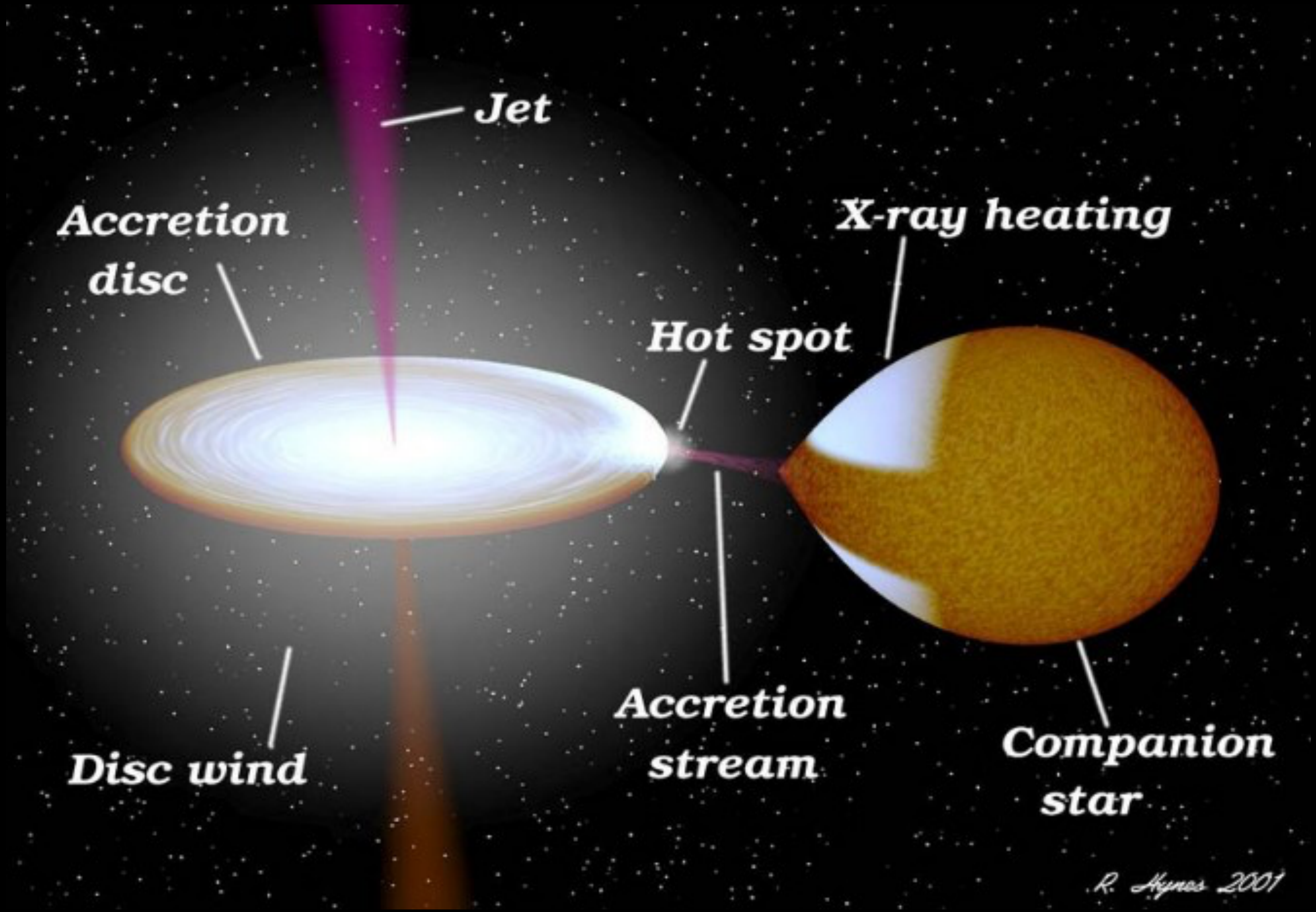
Pulsars
Supernova
Neutron Star
Red Supergiant
Large Star
Stellar Cloud with Protostars
Black Hole
Massive stars
IMAGES NOT TO SCALE

Black hole

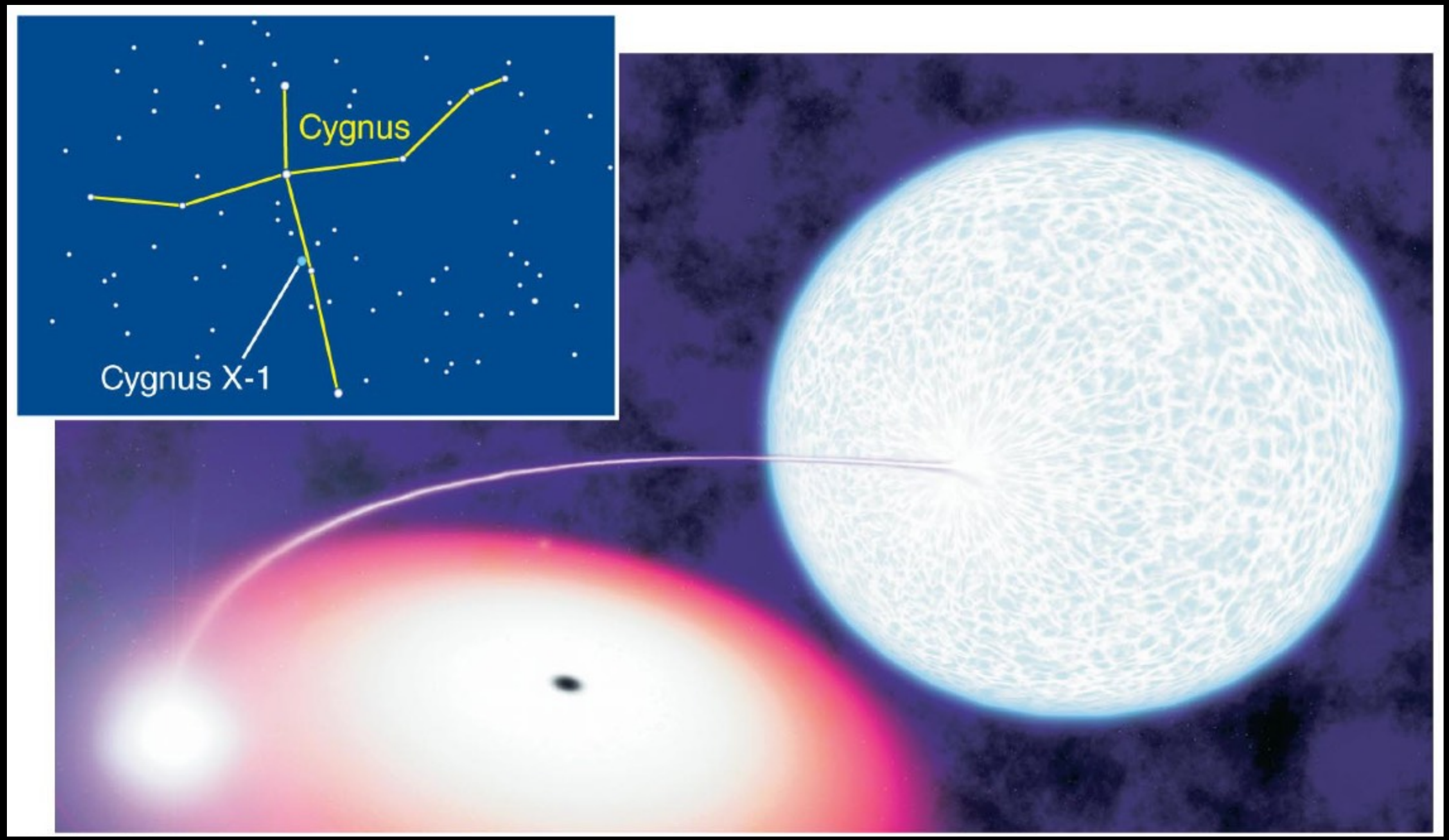
A black hole is a place in space where gravity pulls so much that even light can not get out !

Schwarzschild radius $= 2GM/c^2$

Black Hole in binary system



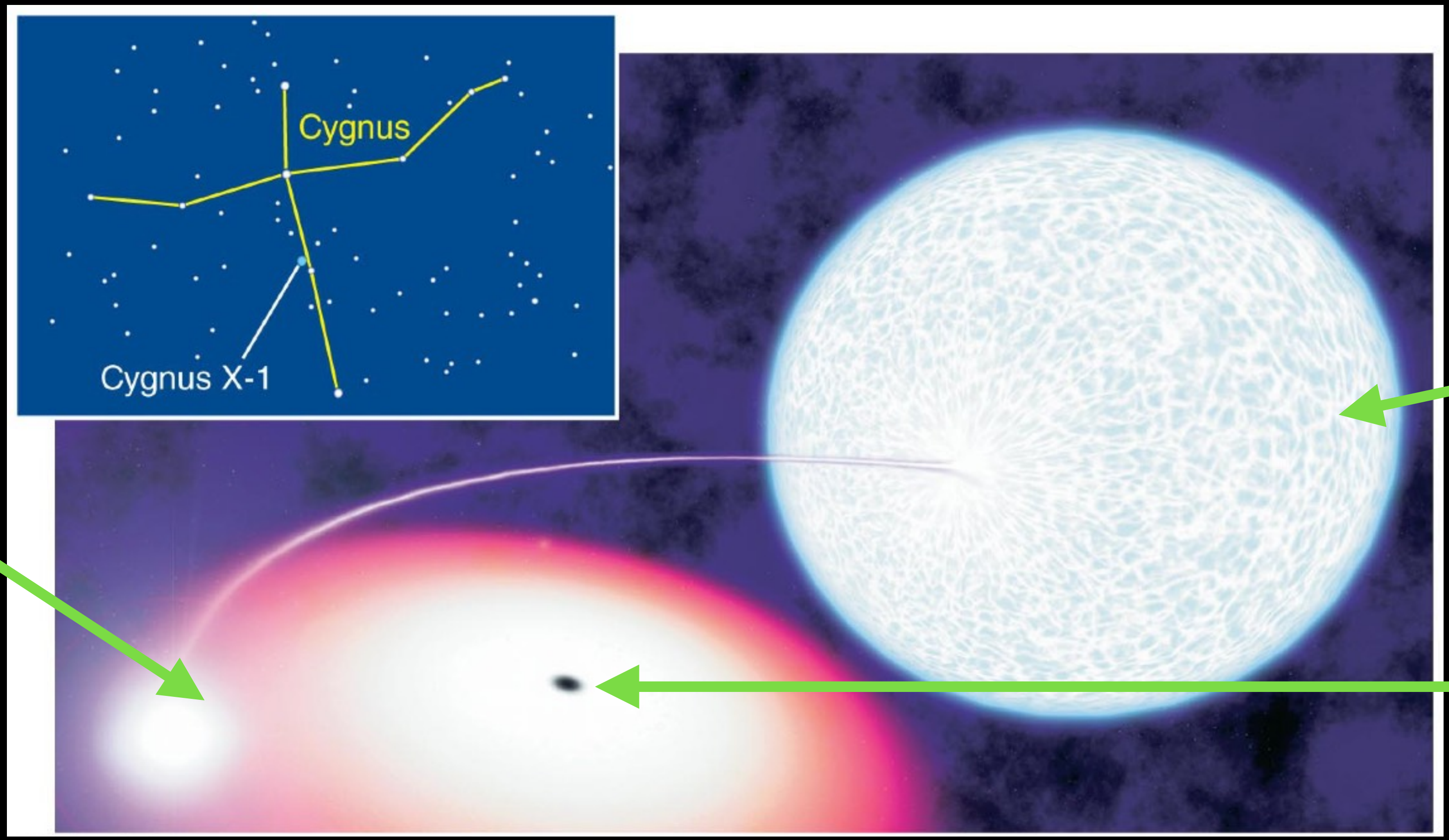
Evidence that black holes exist



- To verify existence of black holes, we need to measure mass within a small volume (event horizon)
- Measure mass using **gravity**: usually with an orbiting companion star
  - Same way we measure masses of stars
- If it's not a star, and its mass exceeds the neutron star limit, then it's likely a black hole

Evidence that black holes exist

Hot gas, falling onto companion object



Massive star

Compact object with $M = 10\text{-}15\ M_{\odot}$

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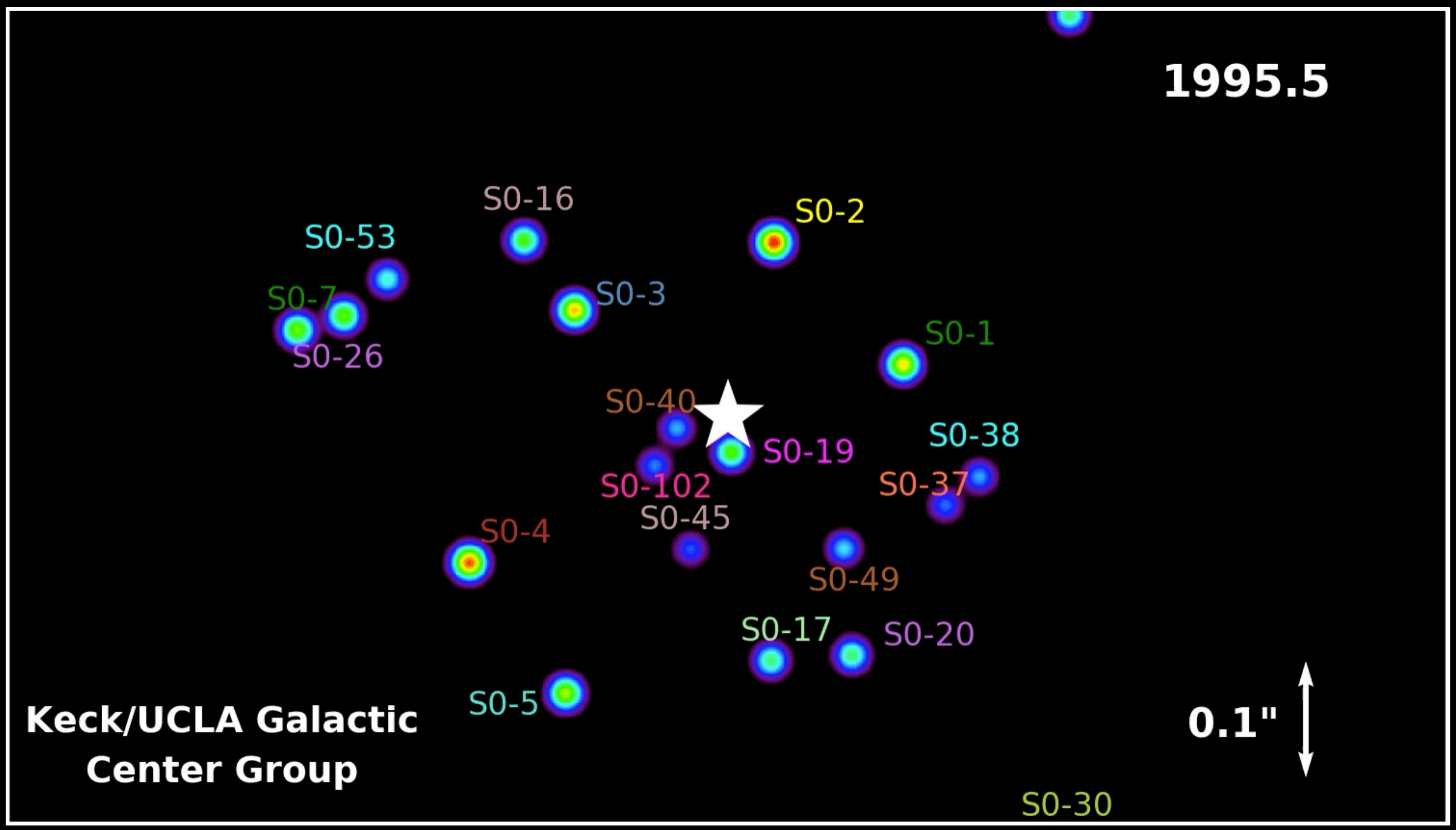
Likely Black Hole Candidates

- Orbits the companion star very rapidly → small & massive
- Too massive to be a neutron star or white dwarf

Six Black-Hole Candidates

OBJECT	LOCATION	COMPANION STAR	ORBITAL PERIOD	MASS OF COMPACT OBJECT
Cygnus X-1	Cygnus	O Supergiant	5.6 days	10-15 M
LMC X-3	Dorado	B3 main-seq	1.7 days	4-11 M
V616 Mon	Monocerotis	K main-seq	7.75 hrs	3.3-+4.2 M
V404 Cygni	Cygnus	K main-seq	6.47 days	8-15 M
J1655-40	Scorpius	F-G main-seq	2.61 days	4-5.2 M
QZ Vul	Vulpecula	K main-seq	8 hours	5-14 M

"Supermassive Black Holes"

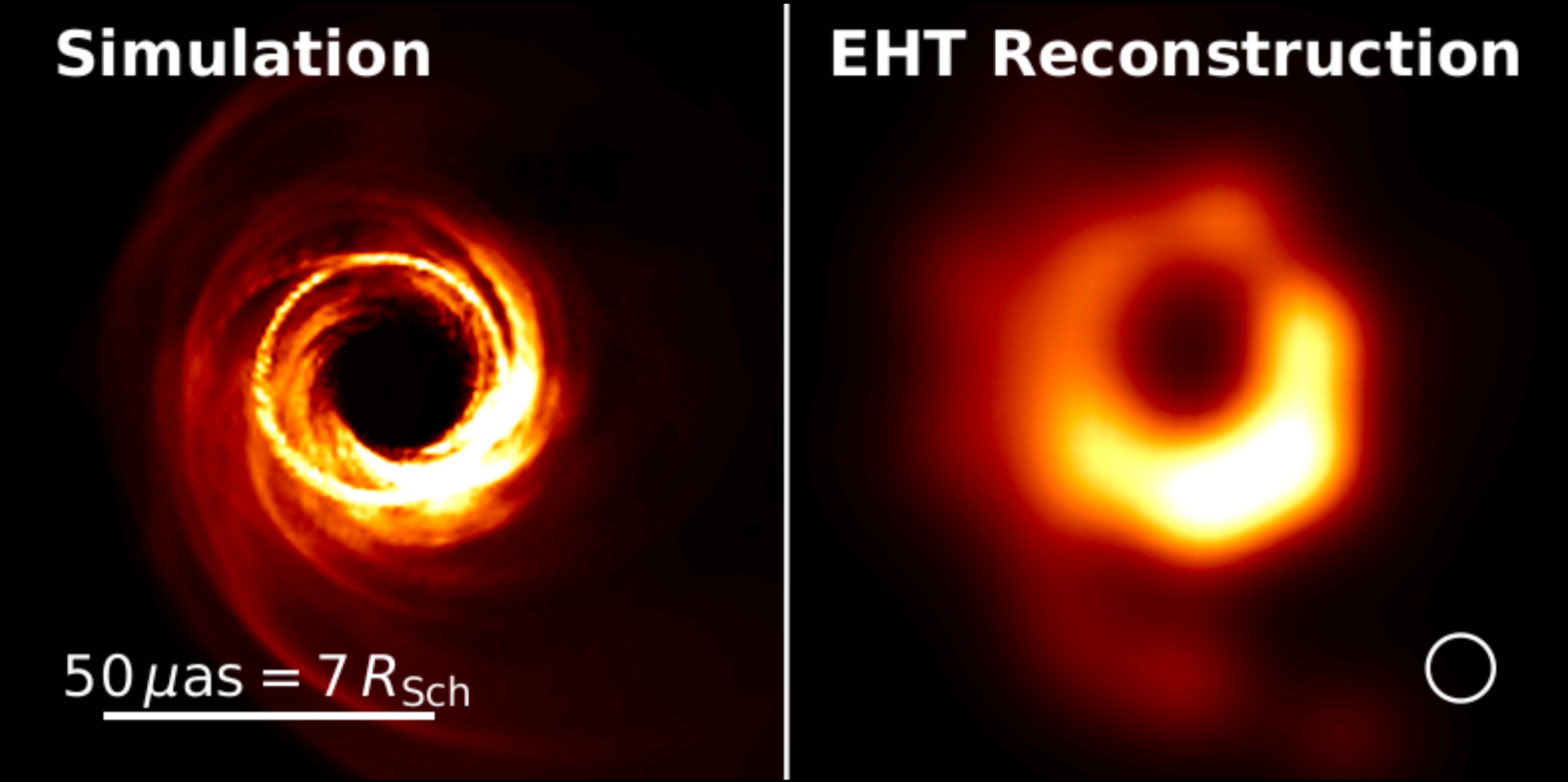


Stars orbiting a massive unseen object in the center of our Milky Way galaxy

- We find evidence for black holes in the centers of galaxies
- Huge masses! 10^6 - 10^9 $M_\odot$
- **Not** the result of supernovae. These objects form in a different way.

First direct image of a black hole in 2019!

- Supermassive black hole in the center of galaxy M87
- Taken by the Event Horizon Telescope (using interferometry)
- Ring of emission around the black hole is from gas moving at very high speeds. Collisions heat the gas, so it emits light.
  - Hot gas is orbiting a mass = $6.5\times10^{9}\ M_{\odot}$!!!


Simulation
EHT Reconstruction
50 μas = 7 R_Sch

Recap: what have we learned?

- **What evidence do we have that neutron stars exist?**
  - Pulsars: massive, rapidly spinning objects
  - Must be very small because of their rapid rotation
    - Neutron stars are the only known objects of this size
  - Some are found in centers of supernova remnants

- **What evidence do we have that black holes exist?**
  - We observe massive compact objects orbiting in binary systems with visible stars
    - Masses are too large to be neutron stars
  - Evidence of “supermassive” black holes in centers of galaxies

More evidences that black holes exist?

We need to go back to gravity …..