Today

- Stellar Remnants
  - White Dwarfs
    - Type Ia Supernovae
  - Neutron Stars

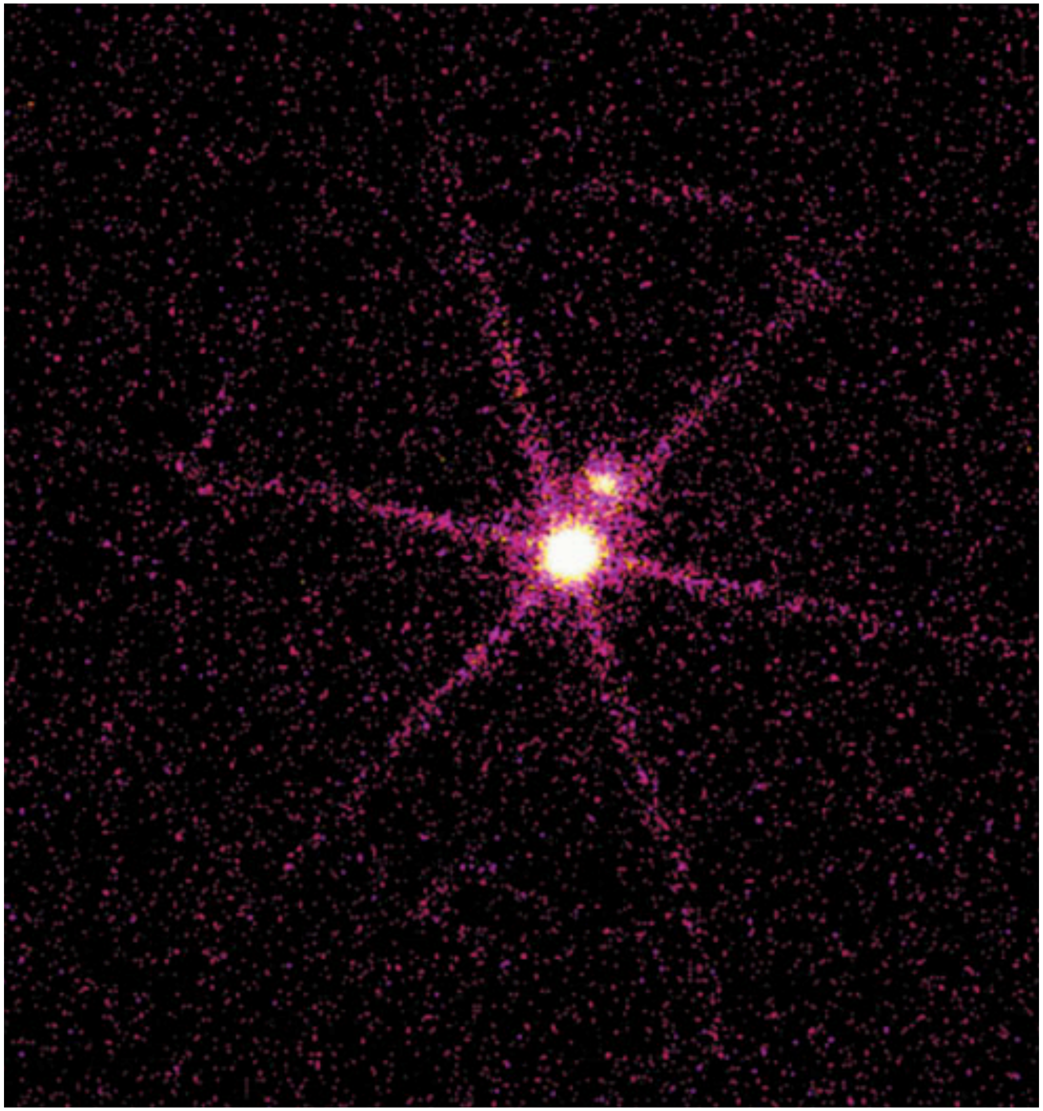
Reminder: Next Homework

- The next homework is due the *Tuesday* after Thanksgiving
- Necessary so we can squeeze in a last homework at the end of class
- I strongly recommend that you start now, so that you don't have to think about it during your break!

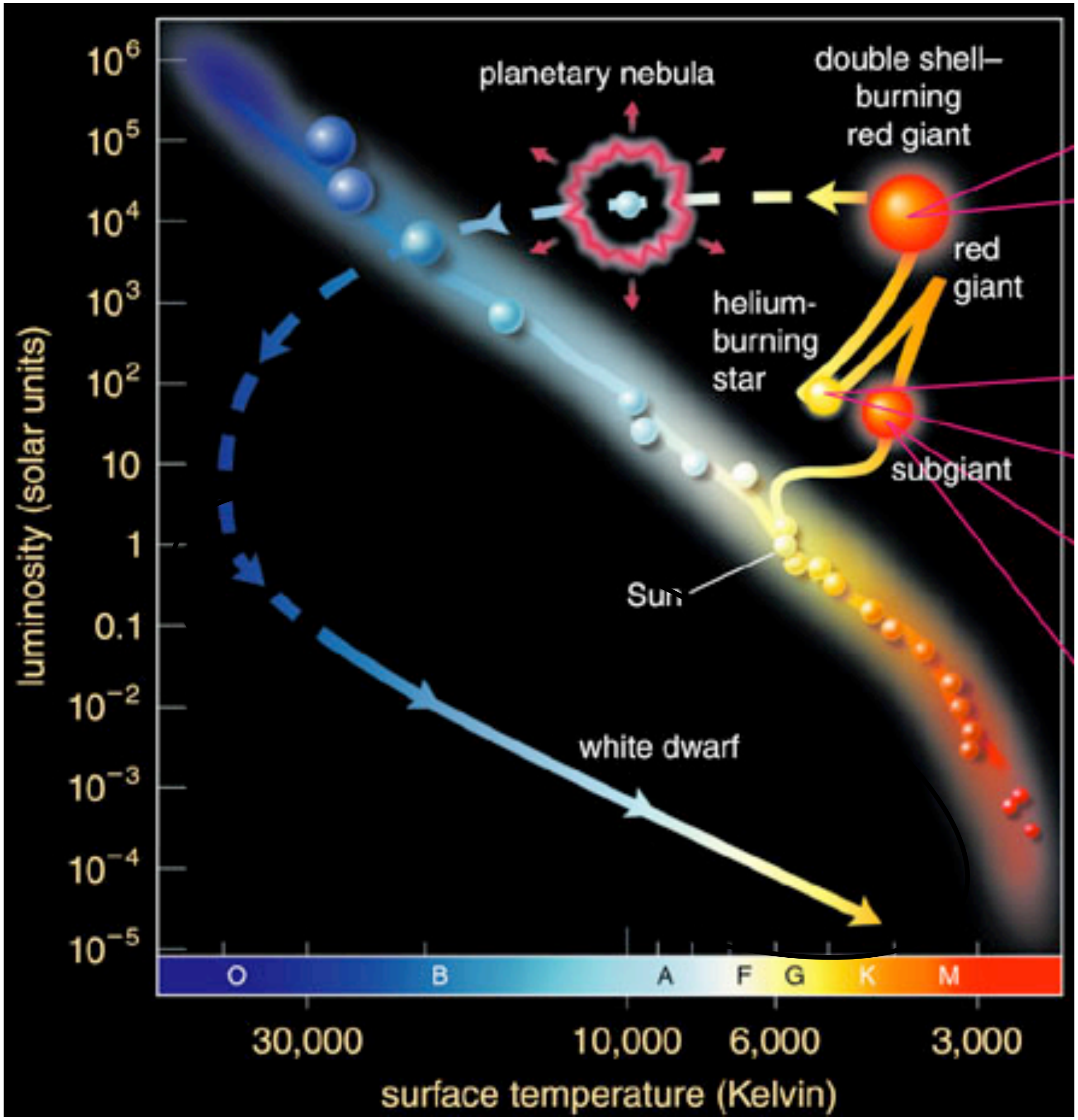
Dead Stars leave corpses

- White dwarfs
  – remnant core of low mass star
  – supported by electron degeneracy pressure
- Neutron stars
  – remnant core of high mass star
  – supported by neutron degeneracy pressure
- Black Holes
  – remnant of some massive stars
  – gravity's ultimate victory

White Dwarfs



- White dwarfs are the remaining cores of dead stars.
- Electron degeneracy pressure supports them against gravity.

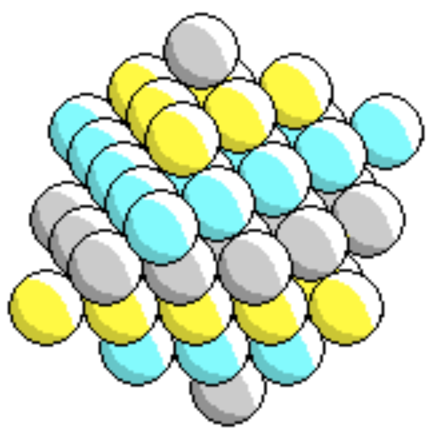


White dwarfs cool off and grow dimmer with time.

Electron Degeneracy

- A white dwarf is the spent fuel of a stellar core. Fusion has ceased. What holds it up?

- Electron degeneracy
  - gravity crushes atoms as close together as possible, so that the electrons "bump" into each other.



Electron Degeneracy

- Electron degeneracy pressure is really a quantum mechanical effect stemming from the Heisenberg Uncertainty Principle:

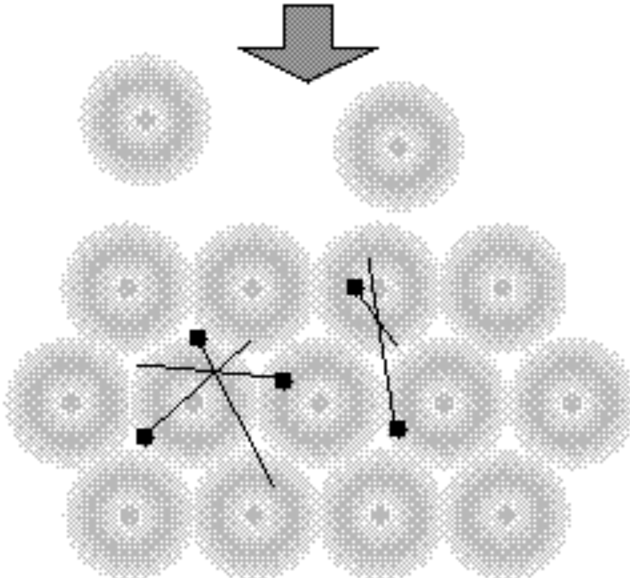
$$\Delta x \Delta p \geq \hbar/2$$

- The position *x* of the electrons becomes very confined, so their momentum *p* - and in sum, their pressure - becomes large.

$M < 1.4\ M_\odot$

Mass < 1.4 solar masses

GRAVITY



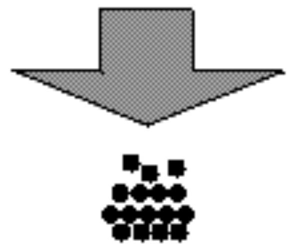
White Dwarf

<u>Electrons</u> run out of room to move around. <u>Electrons</u> prevent further collapse. Protons & neutrons still free to move around.

Stronger gravity => more compact.

Mass > 1.4 solar masses
but mass < 3 solar masses

GRAVITY

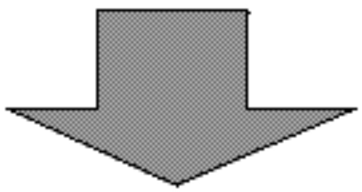


Neutron Star

Electrons + protons combine to form neutrons. <u>Neutrons</u> run out of room to move around. <u>Neutrons</u> prevent further collapse. Much smaller!

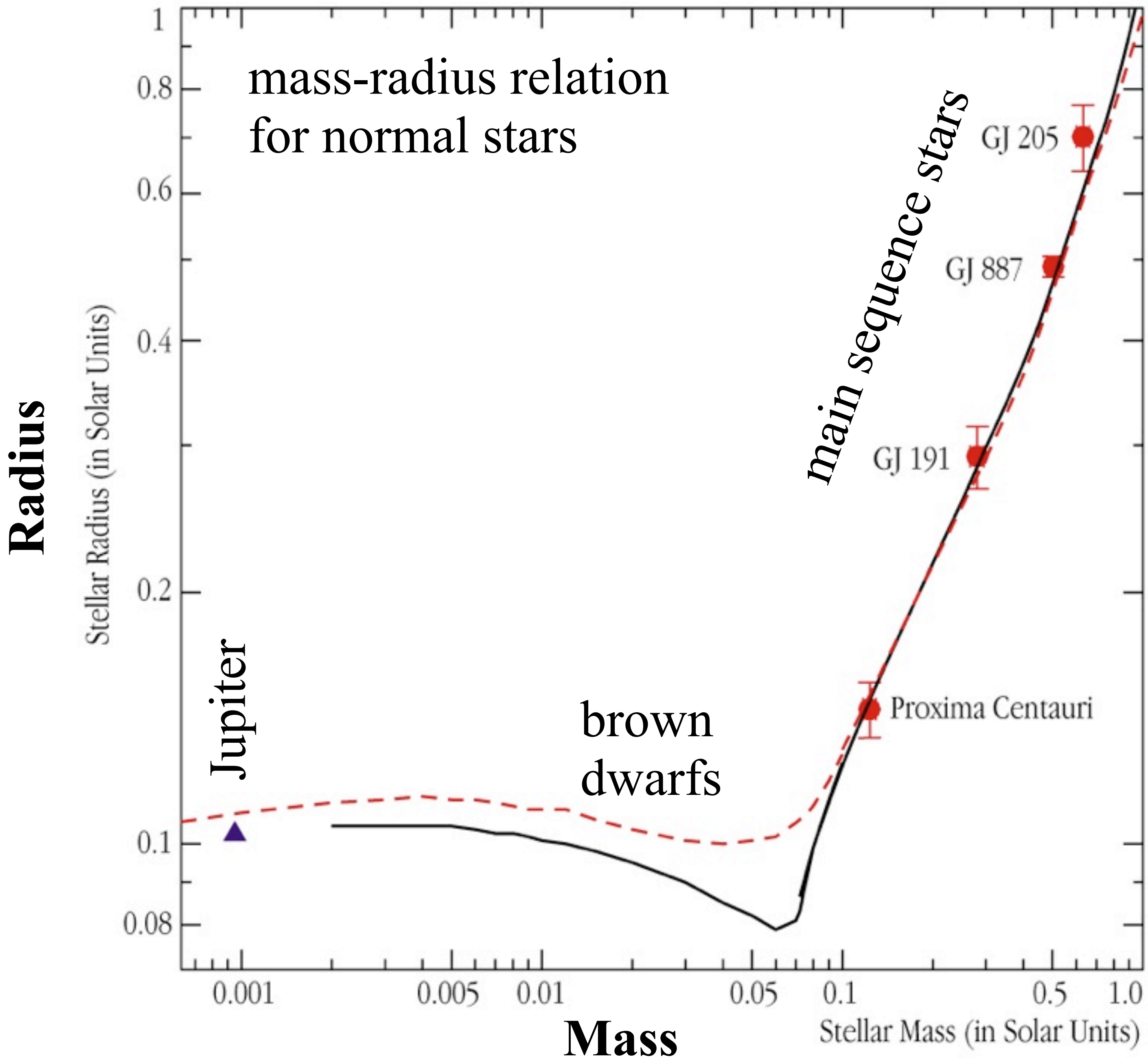
Mass > 3 solar masses

GRAVITY



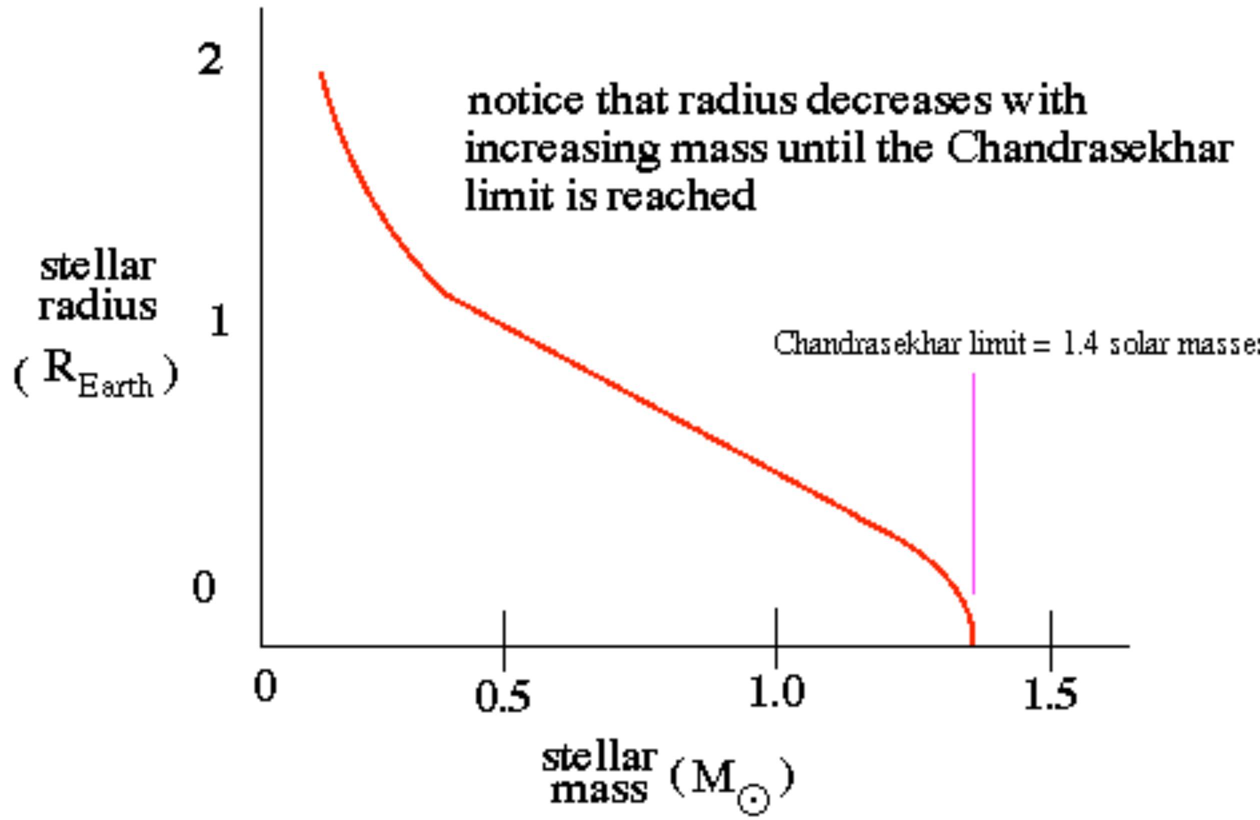
Black Hole

Gravity wins! Nothing prevents collapse.

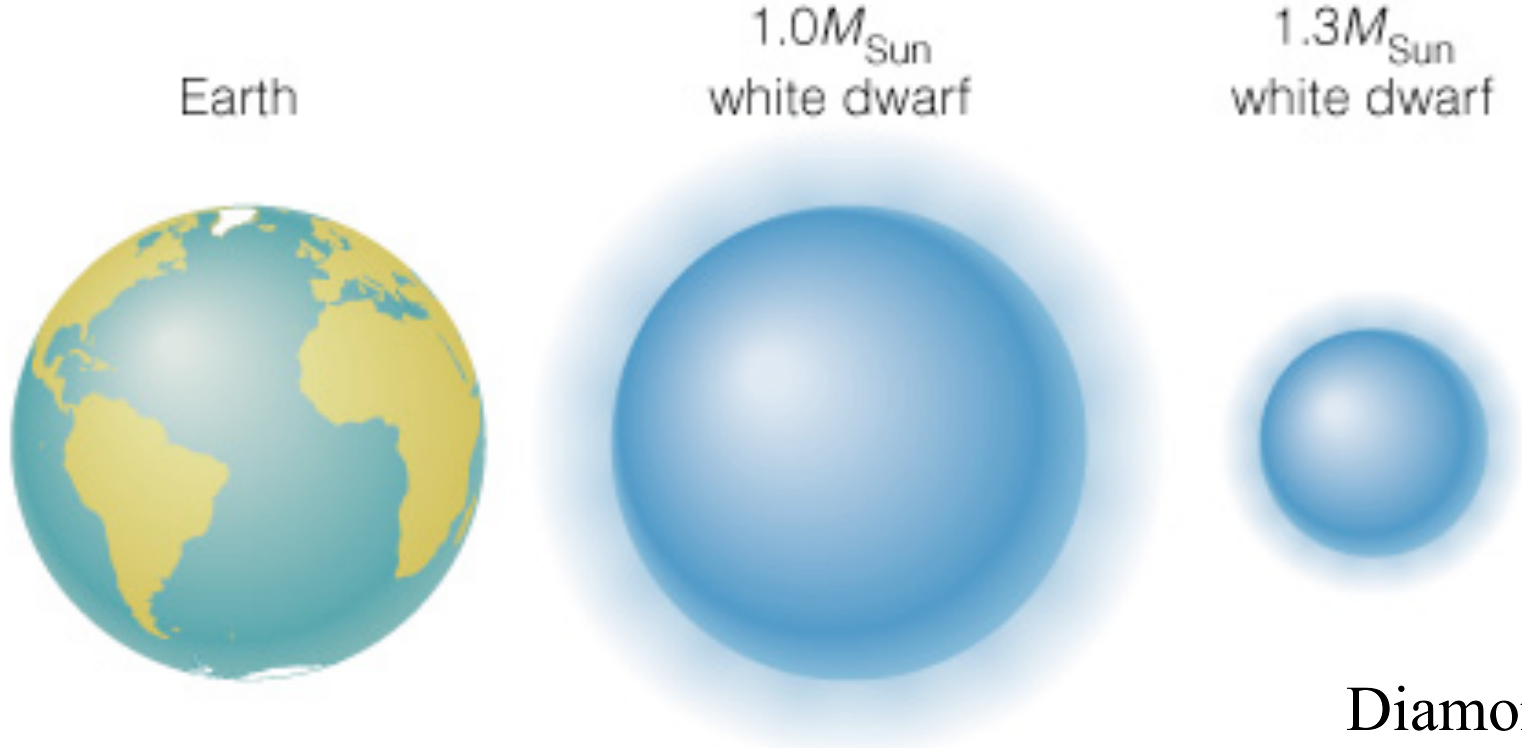


VLTI Observations of the Radii of four Small Stars

Mass–Radius Relation for White Dwarfs



Size of a White Dwarf



Diamond

- White dwarfs with the same mass as the Sun are about the same size as Earth.
- Higher-mass white dwarfs are *smaller*.

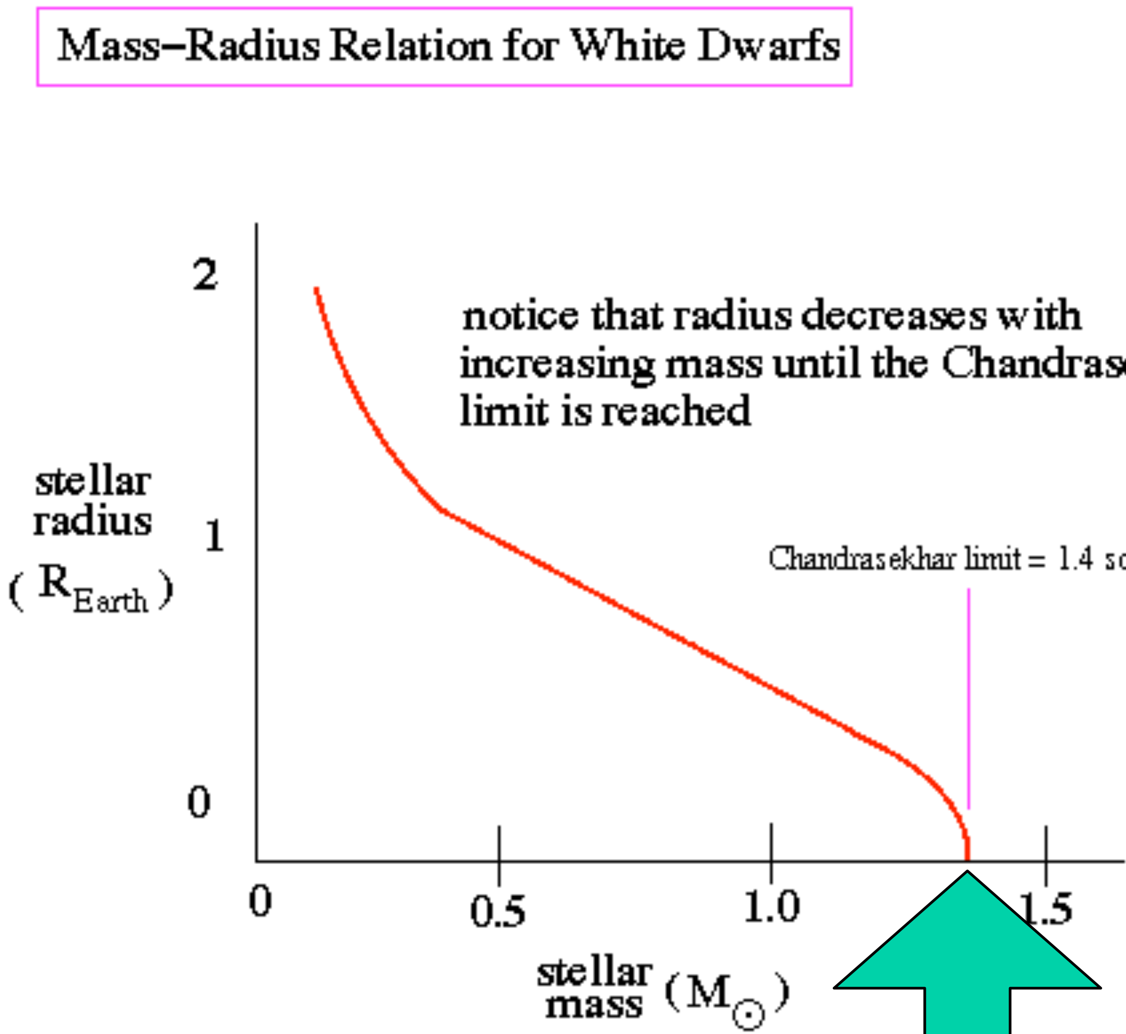
White Dwarf Density

- size R ~ thousands of kilometers
- mass M ~ mass of stars
- density absurdly high:
  - white dwarf matter is roughly a million times denser than water
  - instead of weighing a gram, an ice cube block of white dwarf material would weigh a ton.

The White Dwarf Limit

- *more commonly known as the Chandrasekhar limit*

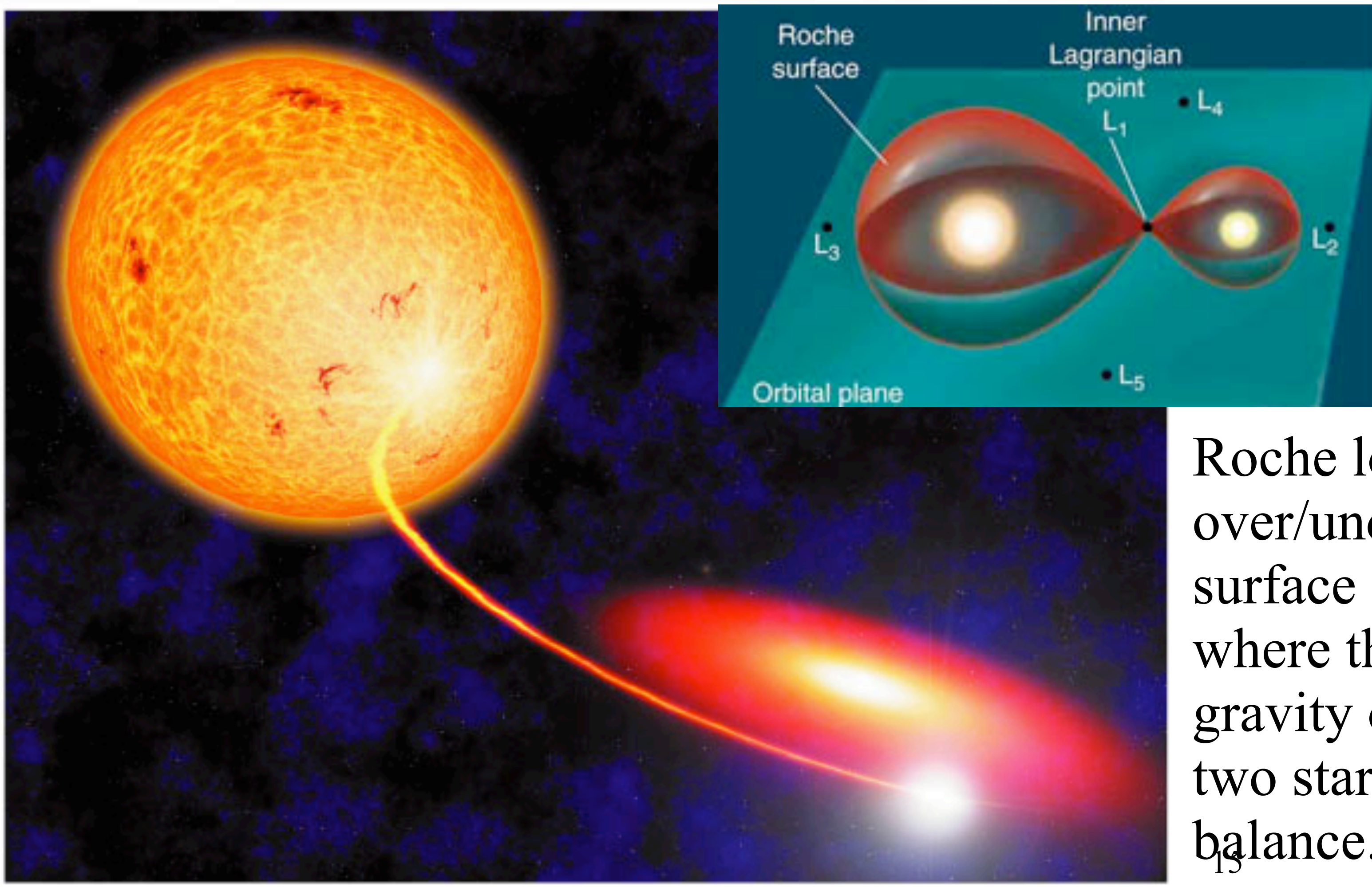
- Quantum mechanics says that electrons must move faster as they are squeezed into a very small space
- As a white dwarf's mass approaches $1.4M_{\mathrm{Sun}}$, its electrons move at a speed approaching that of light.
- This turns out to make the white dwarf unstable; it starts contracting and keeps contracting faster and faster, almost at free fall!
- This is also what allows the cores of massive stars to collapse and lead to massive star supernovae
- Thus white dwarfs cannot be more massive than $\mathbf{1.4}\boldsymbol{M}_{\mathbf{Sun}}$, the *white dwarf limit* (also known as the *Chandrasekhar limit*).



Limiting mass

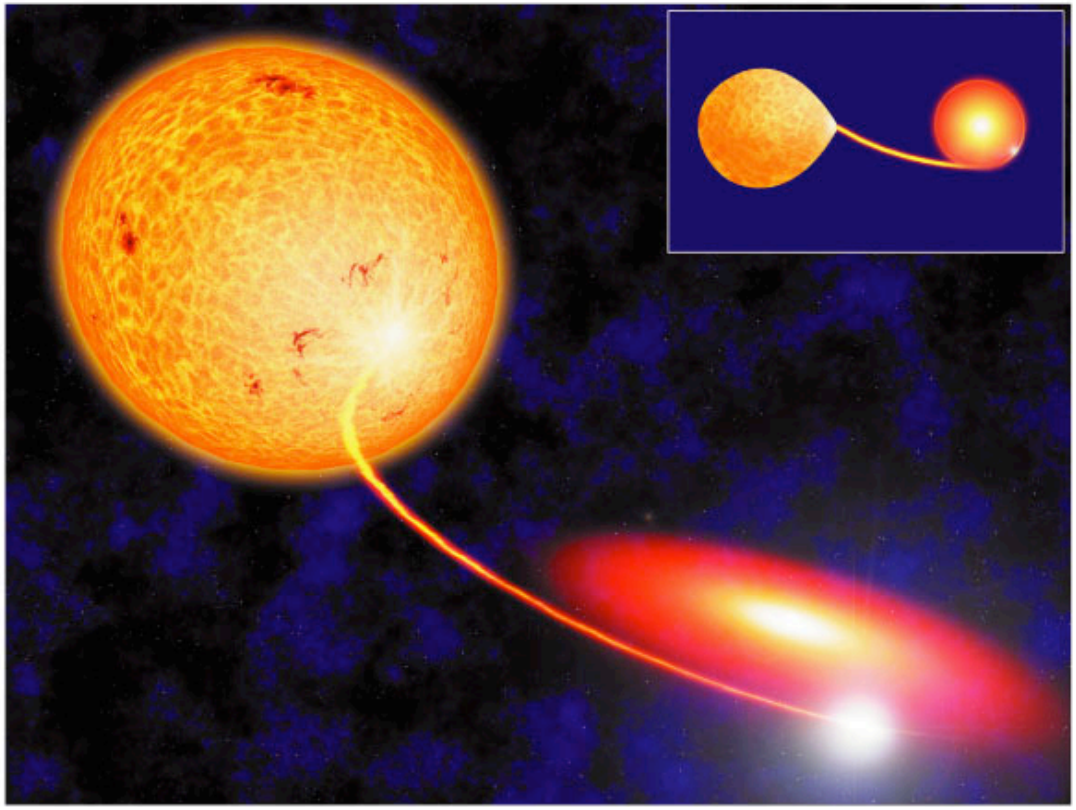
What happens if you add mass to a white dwarf?

White dwarf in a close binary



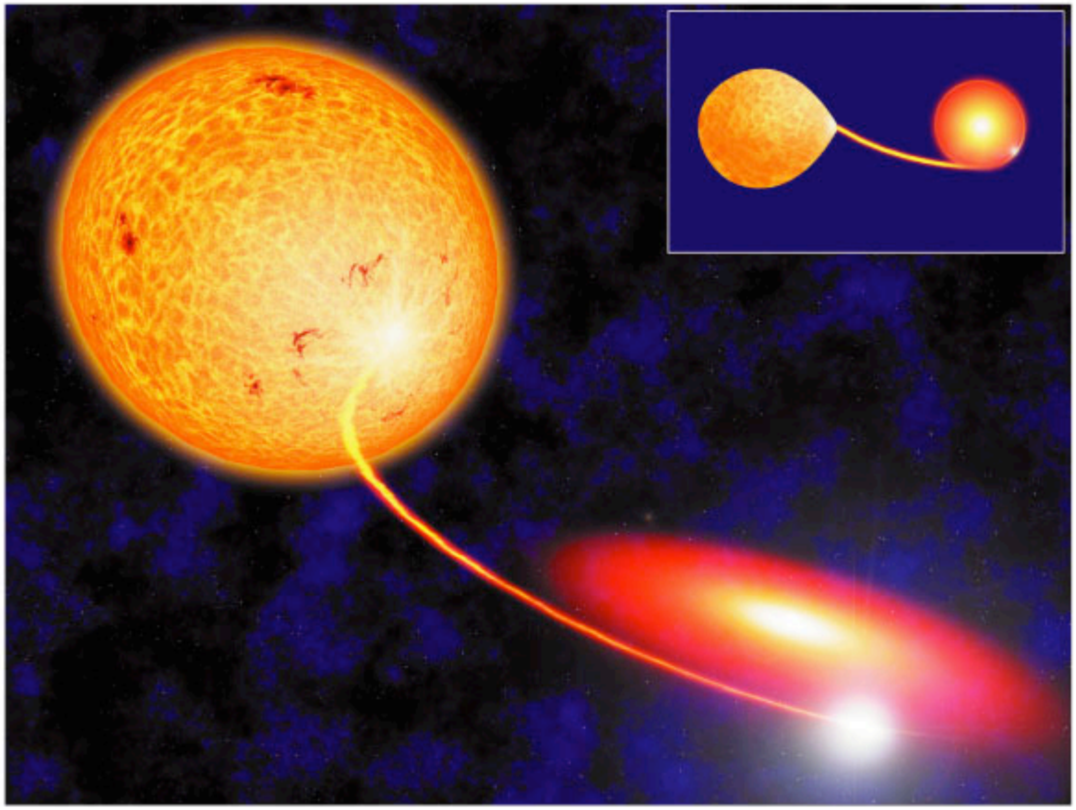
Roche lobes: over/under surface where the gravity of two stars balance.

Accretion Disks



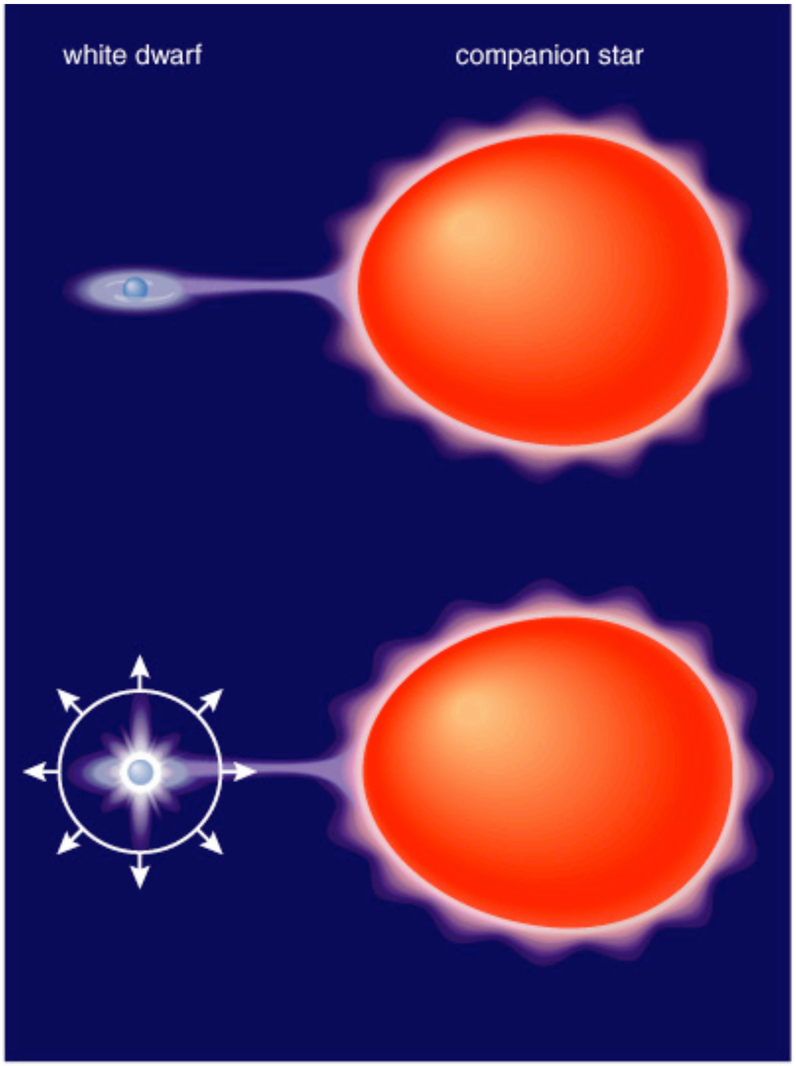
- Mass falling toward a white dwarf from its close binary companion has some angular momentum.
- The matter therefore orbits the white dwarf in an *accretion disk.*

Accretion Disks



- Friction between orbiting rings of matter in the disk transfers angular momentum outward and causes the disk to heat up and glow.

Nova

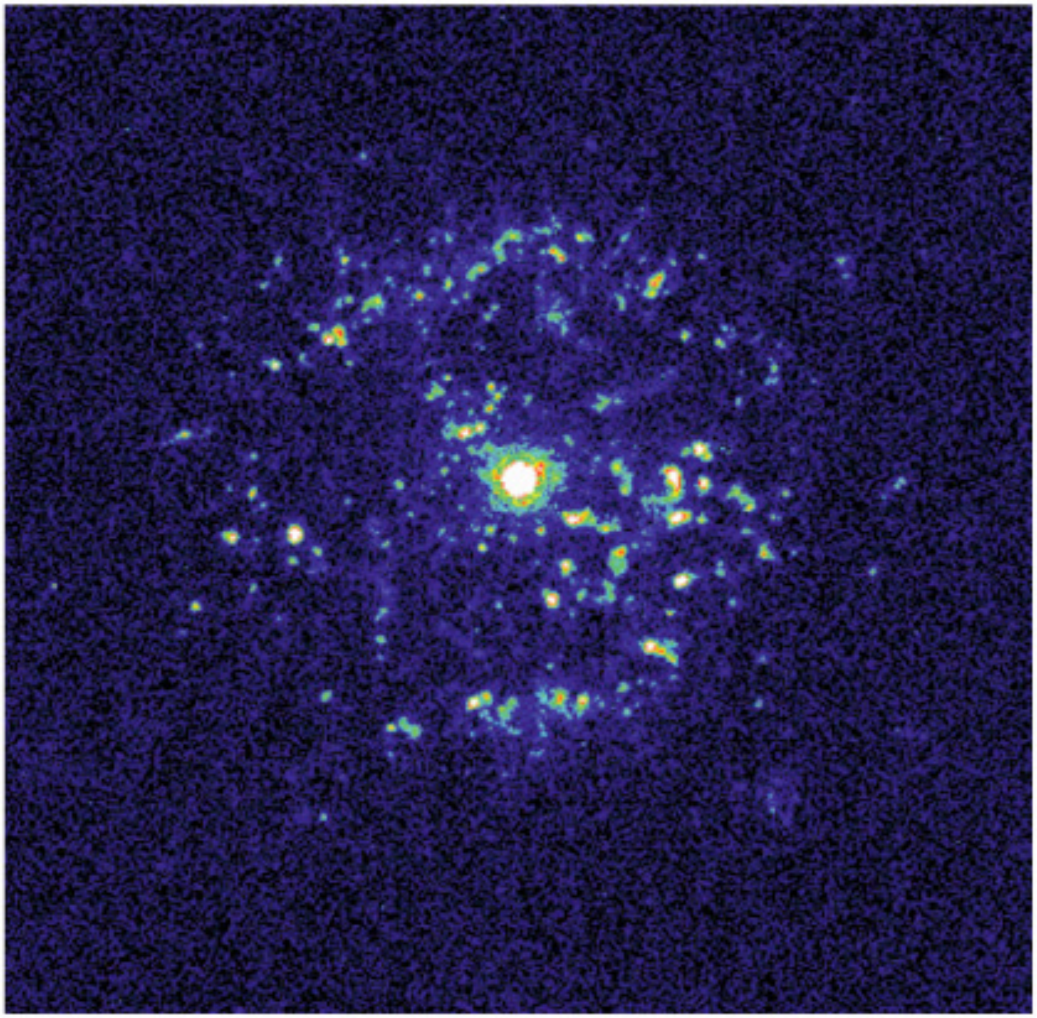


Demo

- The temperature of accreted matter eventually becomes hot enough for hydrogen fusion.
- Fusion begins suddenly and explosively on the *surface* of a white dwarf, causing a *nova*.

Nova

Video



- The nova star system temporarily appears much brighter.
- The explosion drives accreted matter out into space.

Only the surface is affected...

Adding Matter to a WD

Suppose a white dwarf in a binary is just below the Chandrasekhar limit, and more matter falls onto the WD from the companion. What happens?

A. The WD simply gets heavier

B. The WD turns into a normal star

C. The WD collapses

D. The companion starts to take matter from the WD

E. I don't know

Two Types of Supernova

Massive star supernova:

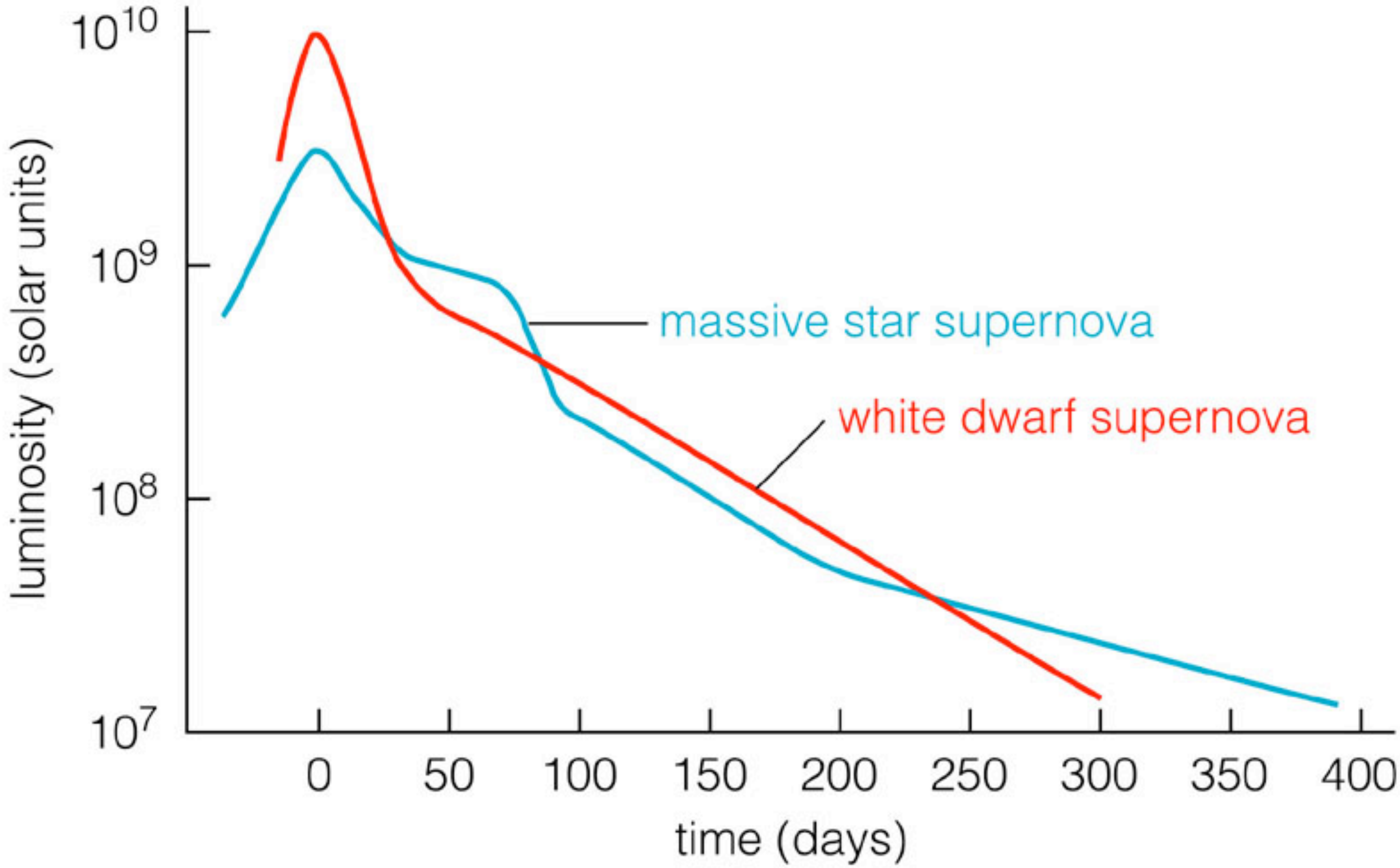
Iron core of massive star reaches white dwarf limit and collapses into a neutron star, causing explosion

White dwarf supernova: **Very important in cosmology!**

Carbon fusion suddenly begins as white dwarf in close binary system reaches white dwarf limit, resulting in total explosion

Simulation

...entire white dwarf is disrupted.



One way to tell supernova types apart is with a ***light curve*** showing how luminosity changes with time.

Nova or Supernova?

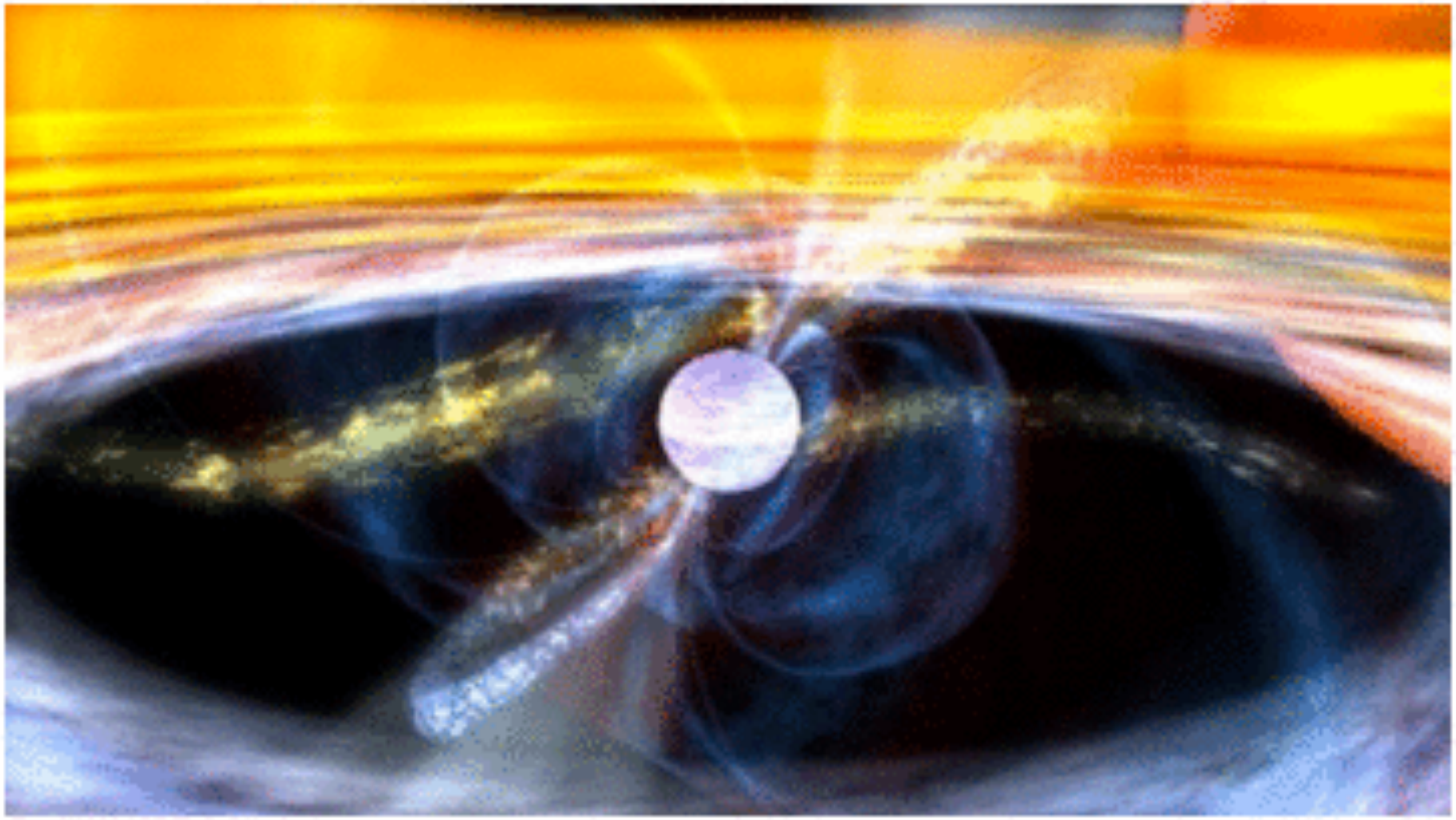
- Supernovae are MUCH MUCH more luminous (about 10 million times) !!!
- Nova:
  - H to He fusion of a layer of accreted matter, white dwarf left intact
- Supernova:
  - complete explosion of white dwarf, nothing left behind

Supernova Type: Massive Star or White Dwarf?

- Light curves differ
- Spectra differ (exploding white dwarfs don't have hydrogen absorption lines)
  - White dwarf supernova spectra lack hydrogen
    - no exterior "unburnt" layers
  - Massive star supernova spectra have hydrogen
    - most of outer star still unburnt

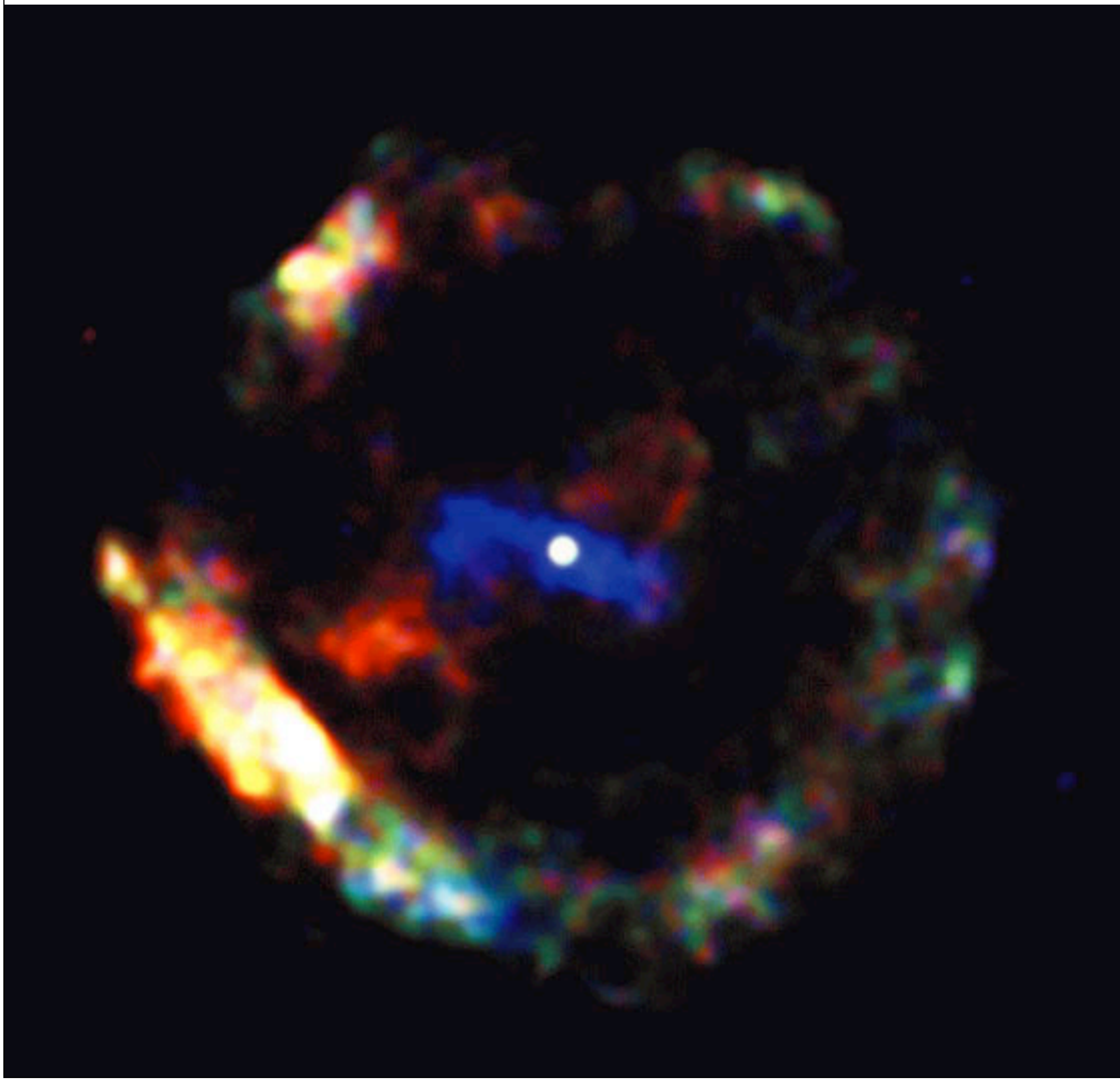
Potential New NASA Mission Would Reveal the Hearts of Undead Stars

Published on ASDNews: Nov 10, 2011



Source / copyright : NASA

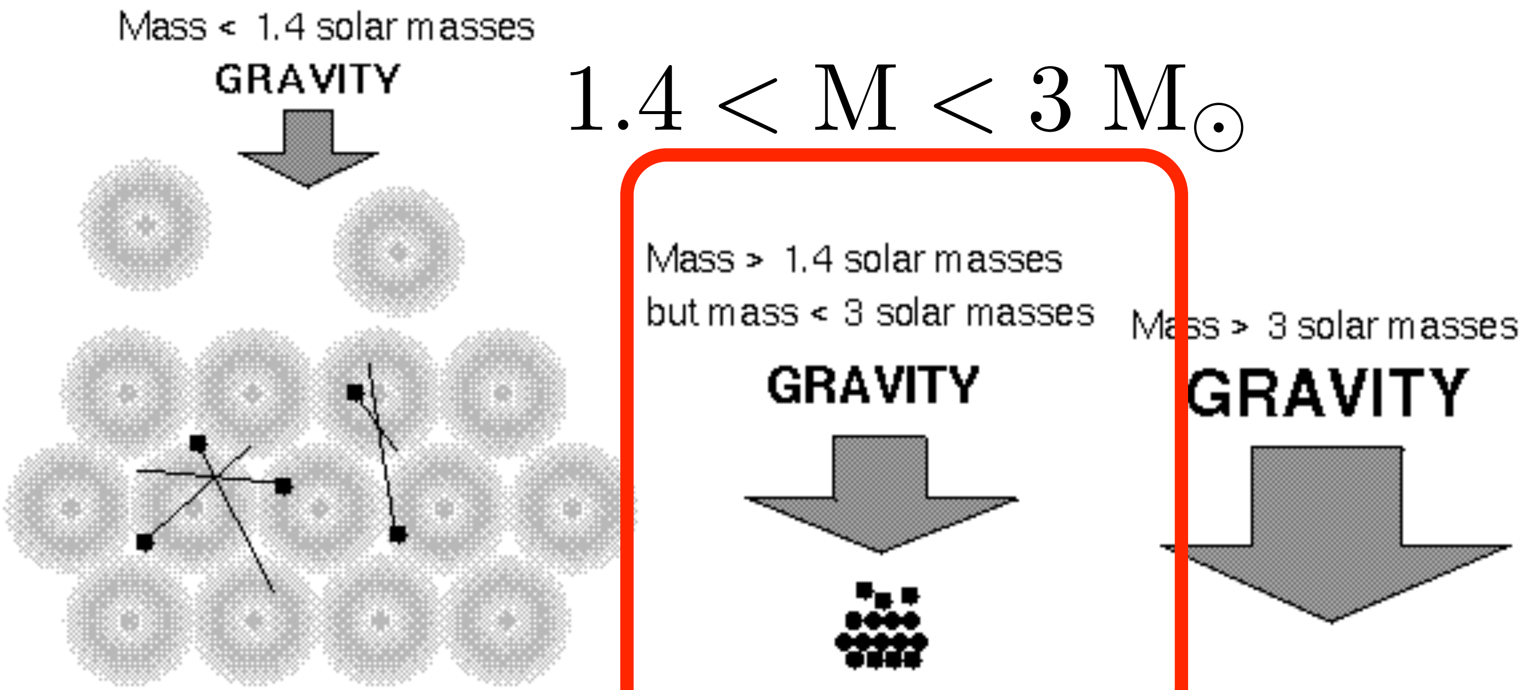
Neutron Stars



A neutron star is the ball of neutrons left behind by a massive-star supernova.

The degeneracy pressure of neutrons supports a neutron star against gravity.

$1.4 < M < 3\ M_\odot$



White Dwarf
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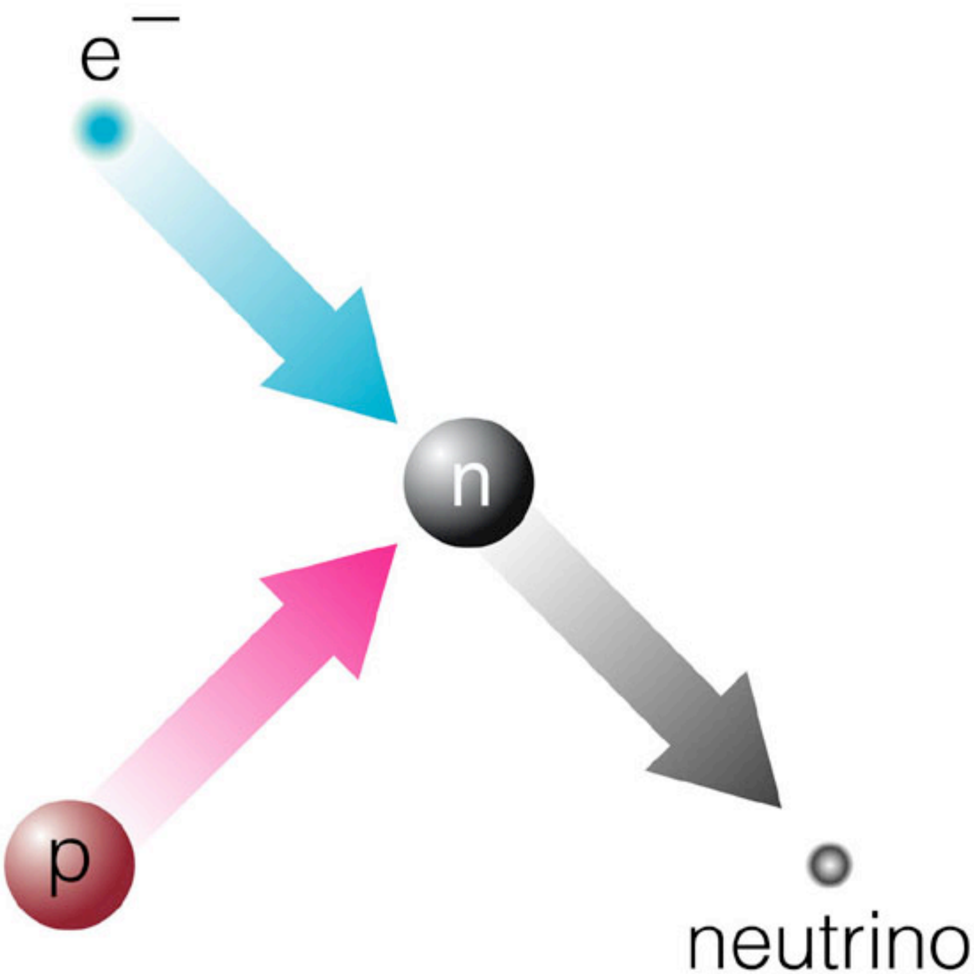
Black Hole
Gravity wins! Nothing prevents collapse.

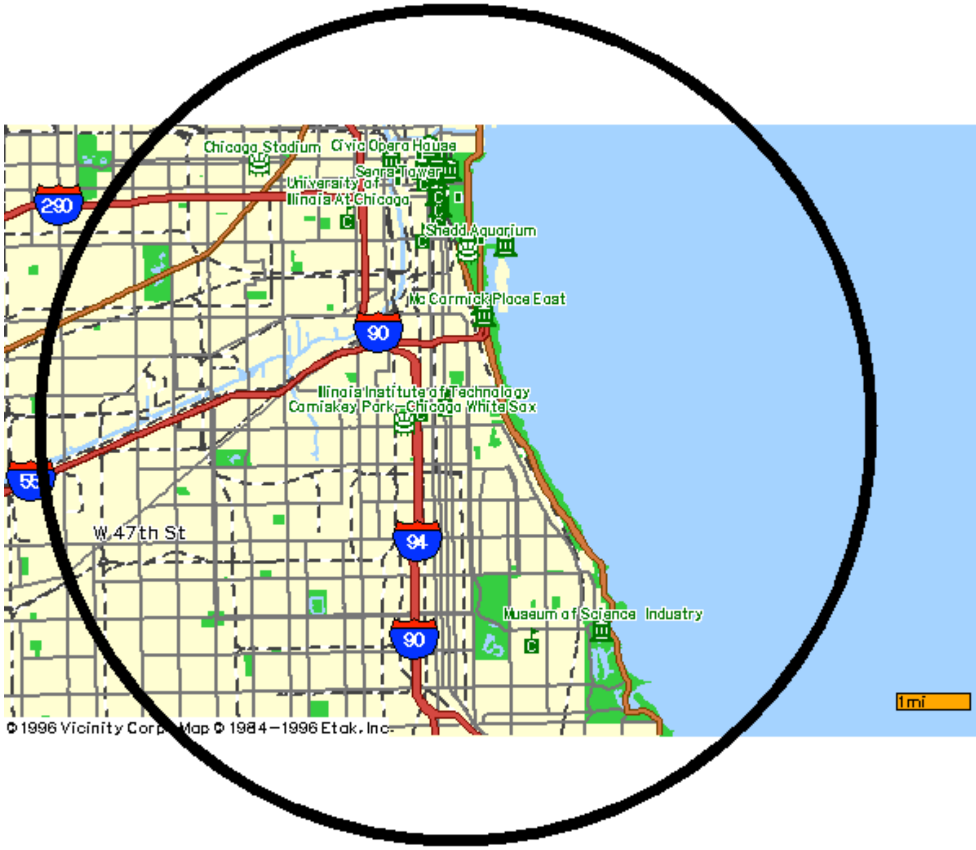


Electron degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos.

Neutrons collapse to the center, forming a ***neutron star.***

Supported by neutron degeneracy pressure.

Neutron star vs. Chicago



From my webpage
http://www.astro.umd.edu/~miller/nstar.html

Mass=1.4 M_{sun}, Radius=10 km
Spin rate up to 38,000 rpm
Density~10^{14} g/cc, Magnetic field~10^{12} Gauss

A neutron star is about the same size as a small city - roughly 10 km.

Neutron Star Density

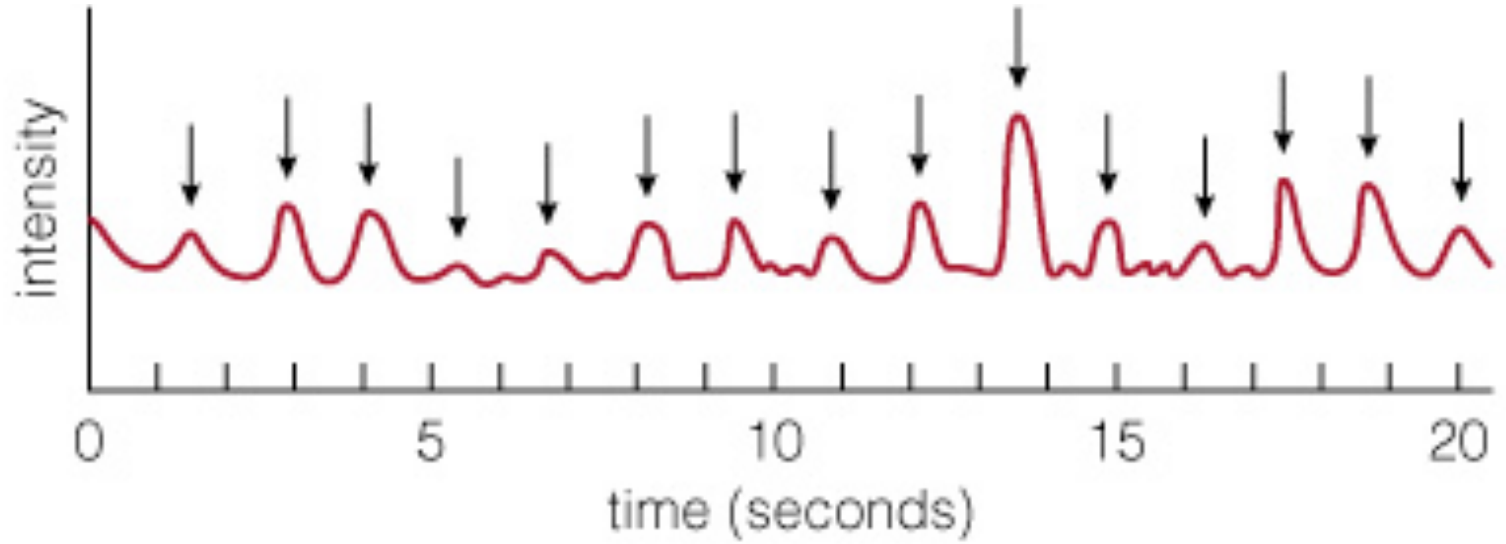
- size R ~ ten kilometers
- mass M ~ mass of stars
- density extra-absurdly high:

$$\text{density} \sim 10^{14}\ \mathrm{g\,cm^{-3}}$$

nuclear density

  – equivalent to the entire mass of the earth being stuffed into this building, or all 7 billion people on Earth being jammed into a teaspoon!

Discovery of Neutron Stars

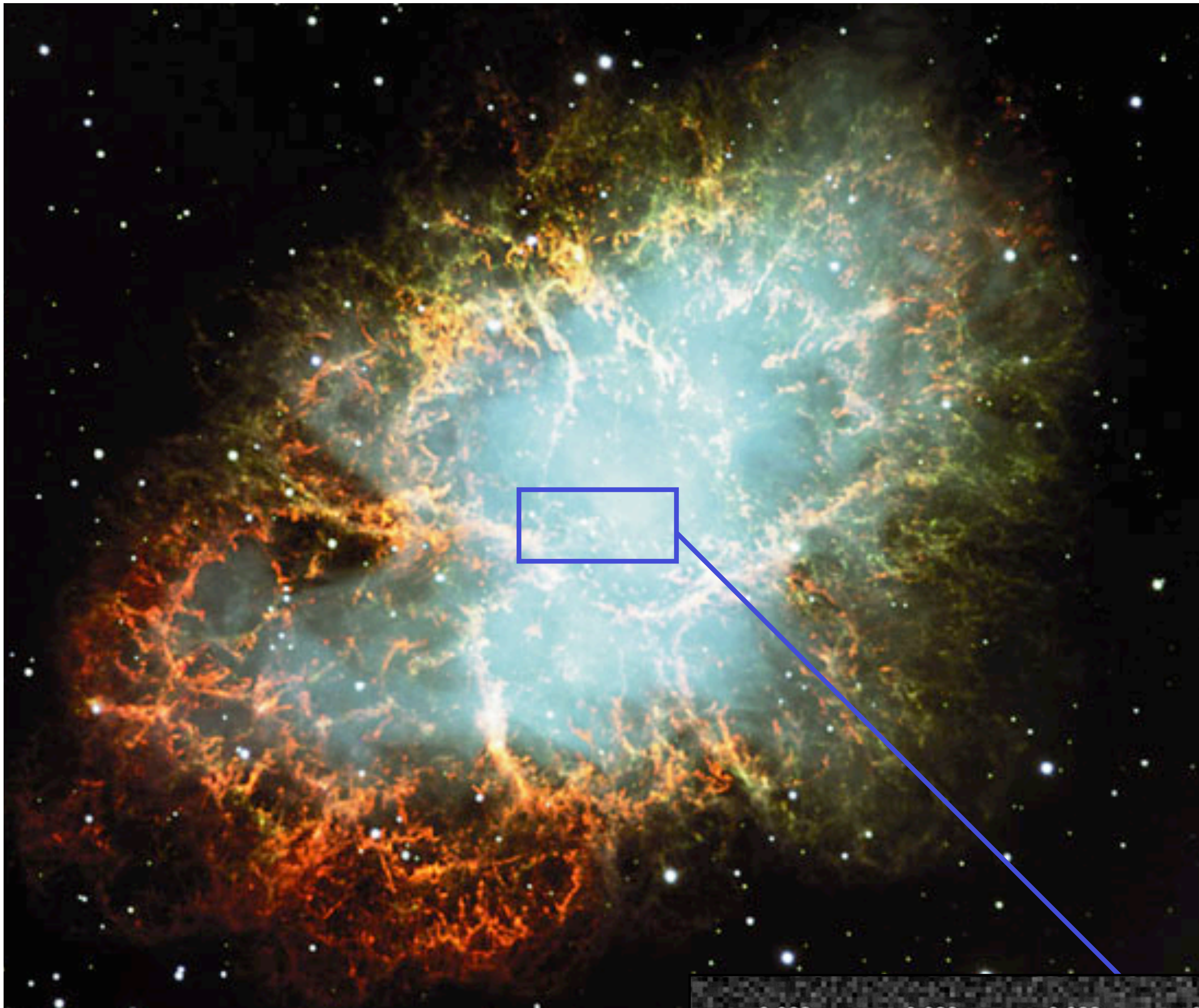


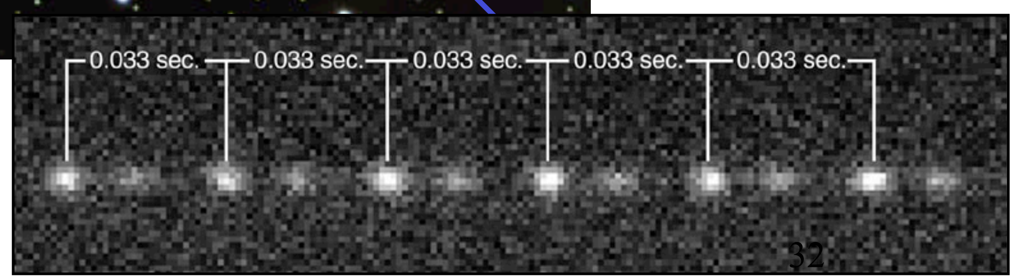
- Using a radio telescope in 1967, Jocelyn Bell noticed very regular pulses of radio emission coming from a single part of the sky.
- The pulses were coming from a spinning neutron star—a *pulsar.*

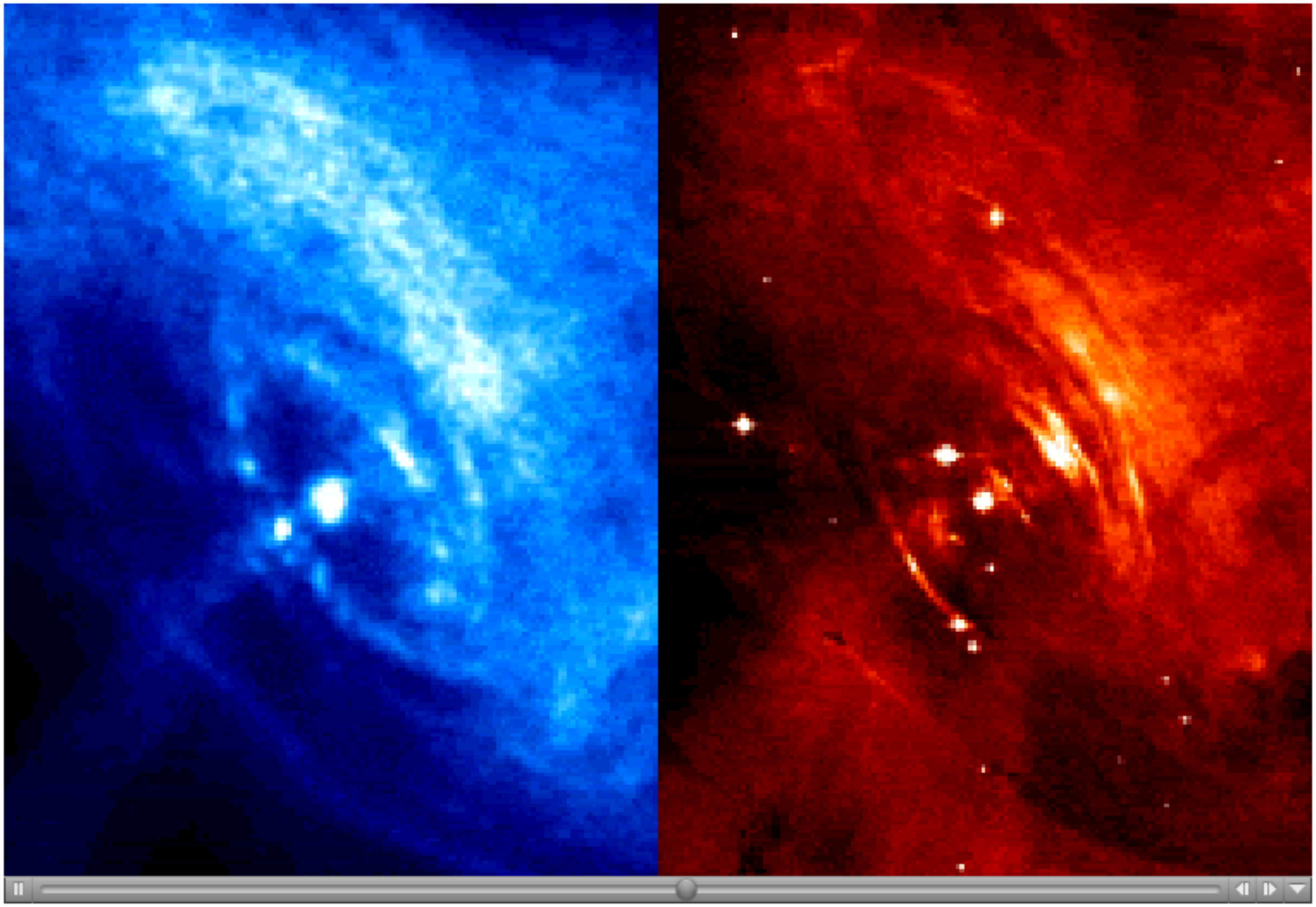
Demo

http://www.jb.man.ac.uk/~pulsar/Education/Sounds/sounds.html

Pulsar at center of Crab Nebula pulses 30 times per second

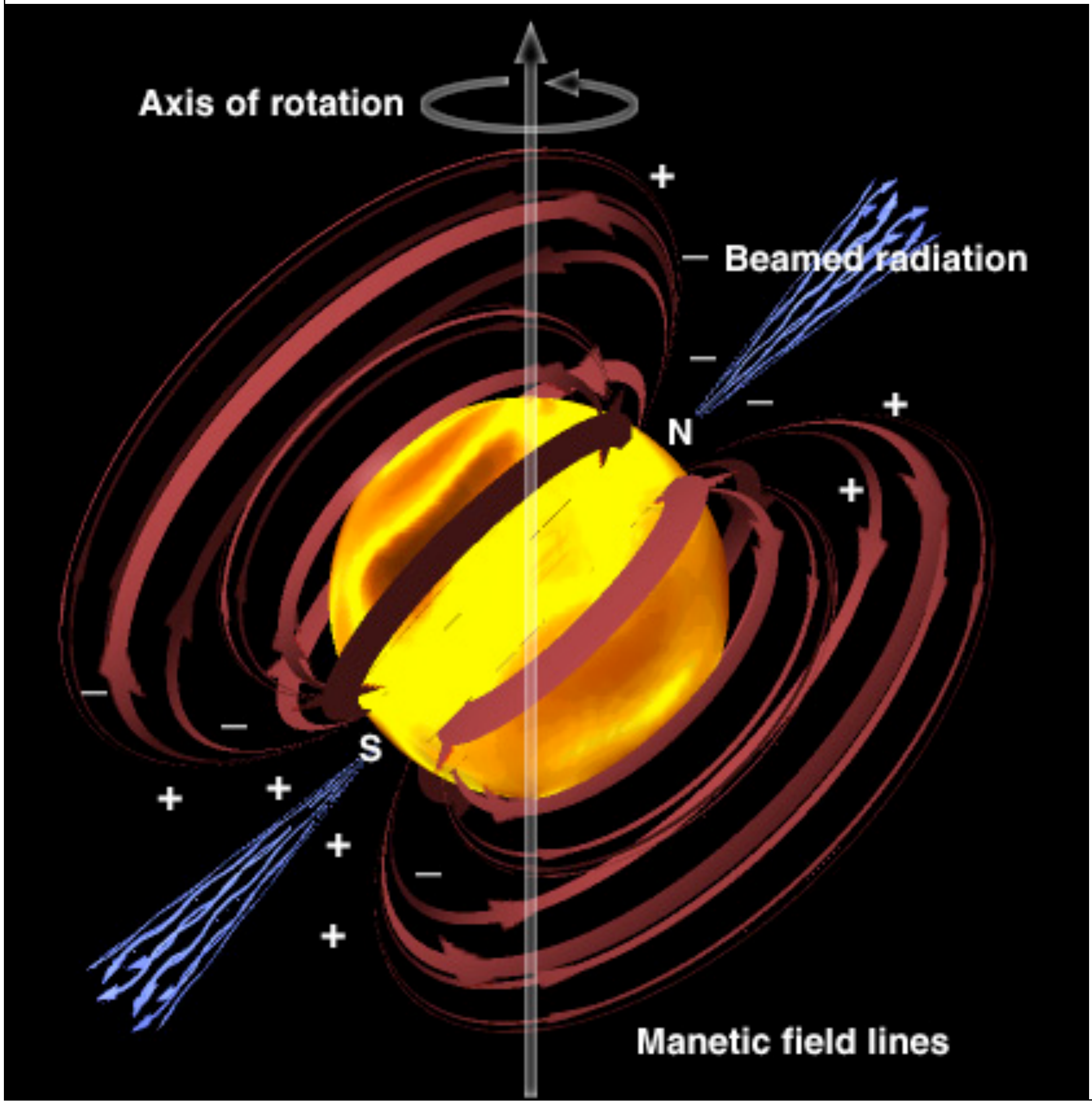






X-rays　　　　　　　　　Visible light

Pulsars



A pulsar is a neutron star that beams radiation along a magnetic axis that is not aligned with the rotation axis.

Pulsars

The radiation beams sweep through space like lighthouse beams as the neutron star rotates.