Today

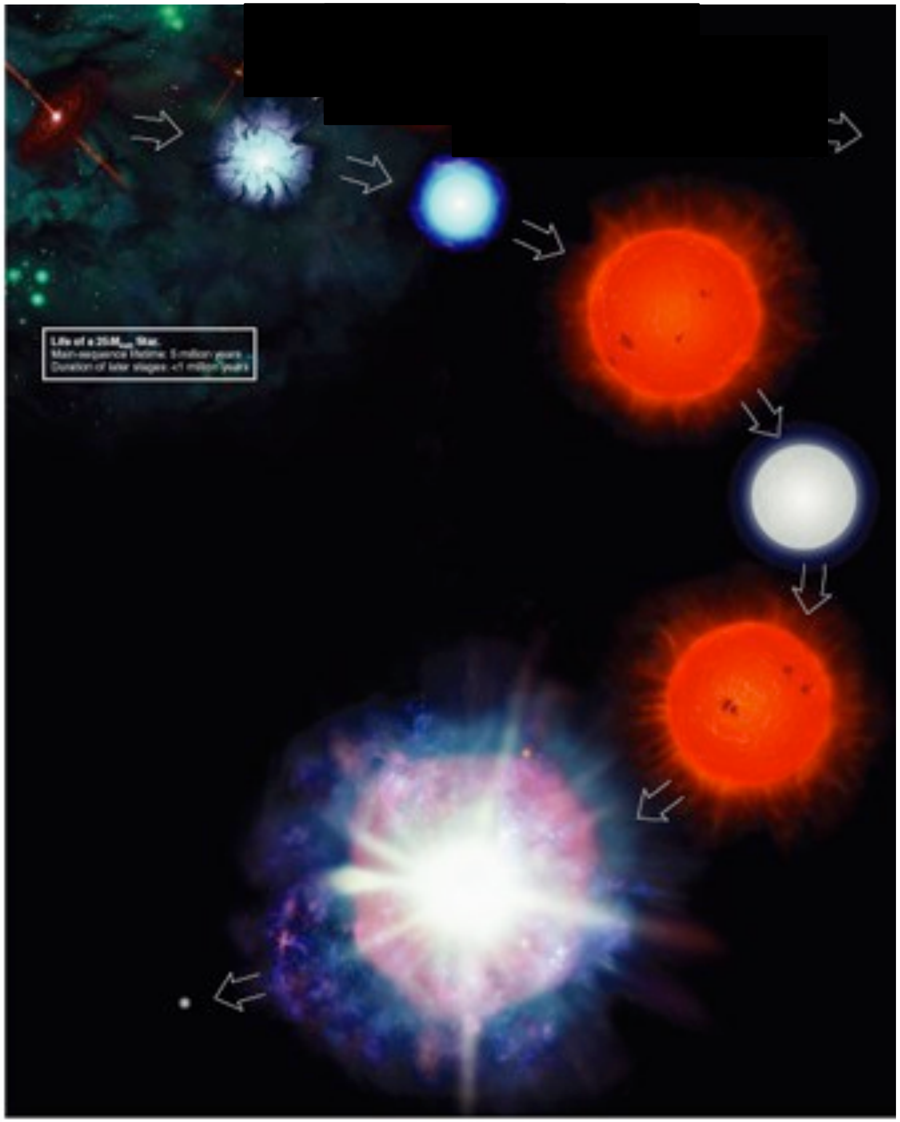
- Stellar Remnants
  - White Dwarfs
    - Type Ia Supernovae
  - Neutron Stars
  - Black Holes

NO SECTIONS NEXT WEEK
(WEEK OF THANKSGIVING)

THERE IS LECTURE TUESDAY (AND A HOMEWORK IS DUE)

Role of Mass

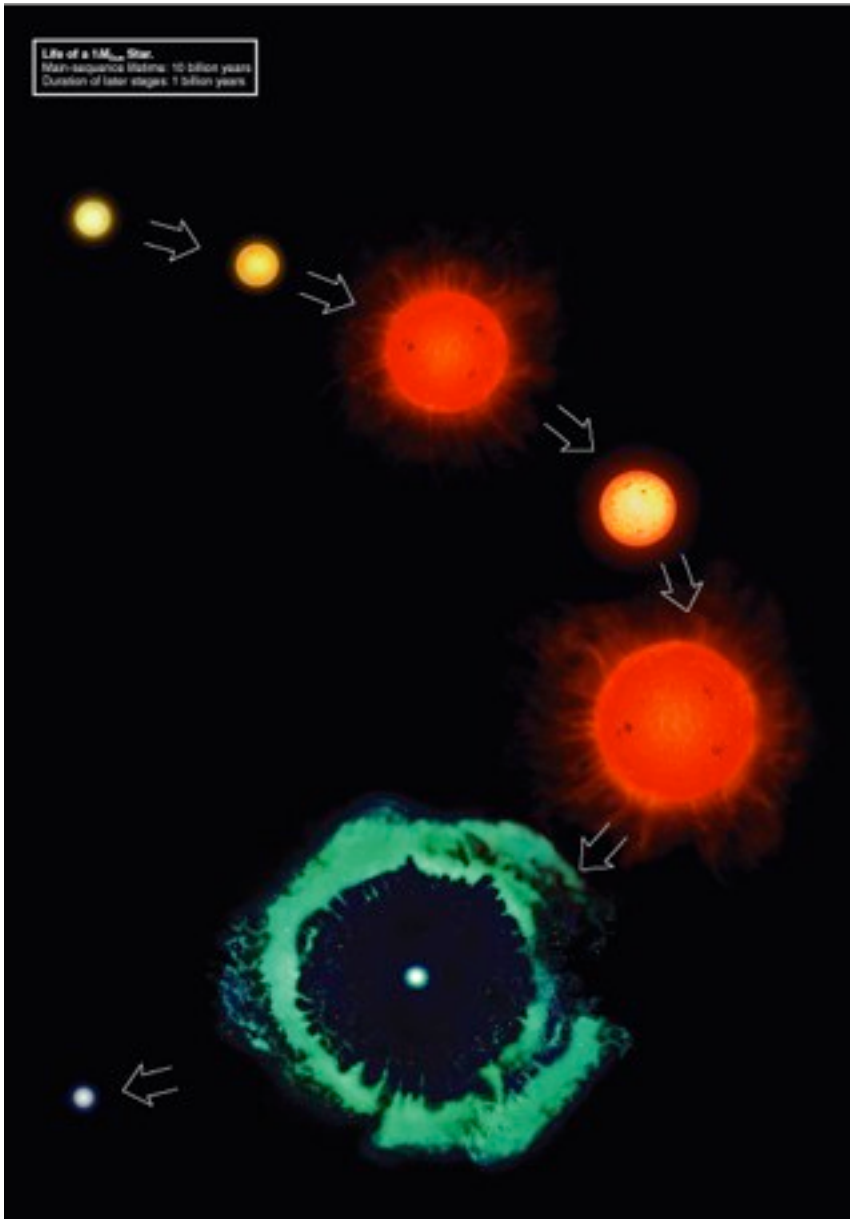
- A star's mass determines its entire life story because it determines its core temperature.
- High-mass stars have short lives, eventually becoming hot enough to make iron, and end in supernova explosions.
- Low-mass stars have long lives, never become hot enough to fuse beyond carbon nuclei, and end as white dwarfs.



Not to scale!

Life Stages of High-Mass Star

1. Main Sequence: H fuses to He in core
2. Red Supergiant: H fuses to He in shell around He core
3. Helium Core Burning: He fuses to C in core while H fuses to He in shell
4. Multiple-Shell Burning: many elements fuse in shells
5. Supernova leaves neutron star behind



Not to scale!

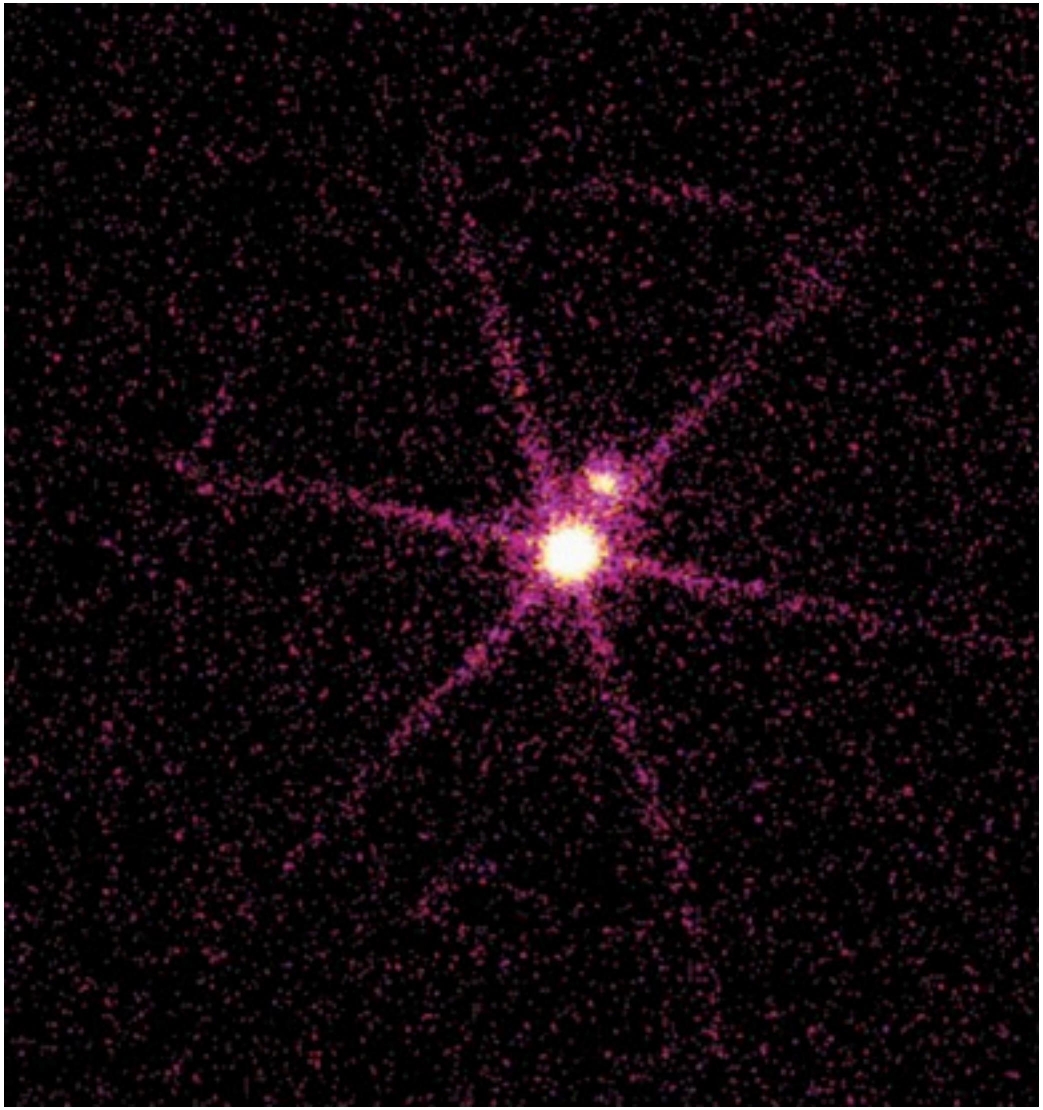
Low-Mass Star Summary

1. Main Sequence: H fuses to He in core
2. Red Giant: H fuses to He in shell around He core
3. Helium Core Burning: He fuses to C in core while H fuses to He in shell
4. Double-Shell Burning: H and He both fuse in shells
5. Planetary Nebula: leaves white dwarf behind

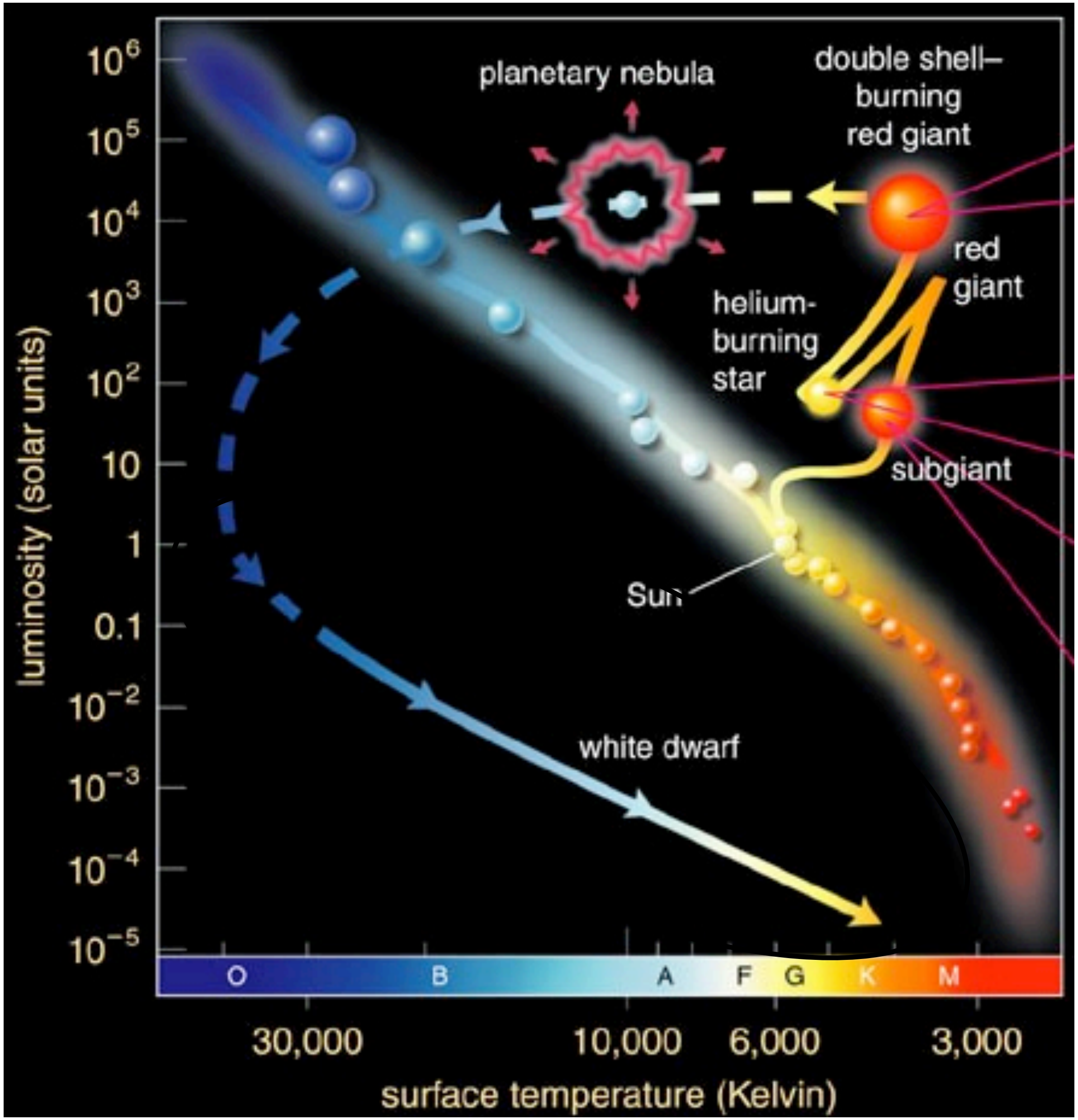
Dead Stars leave corpses

- 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



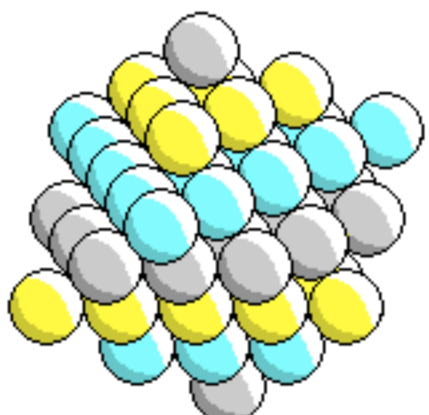
- White dwarfs are the remaining cores of dead stars.
- Electron degeneracy pressure supports them against gravity.



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:

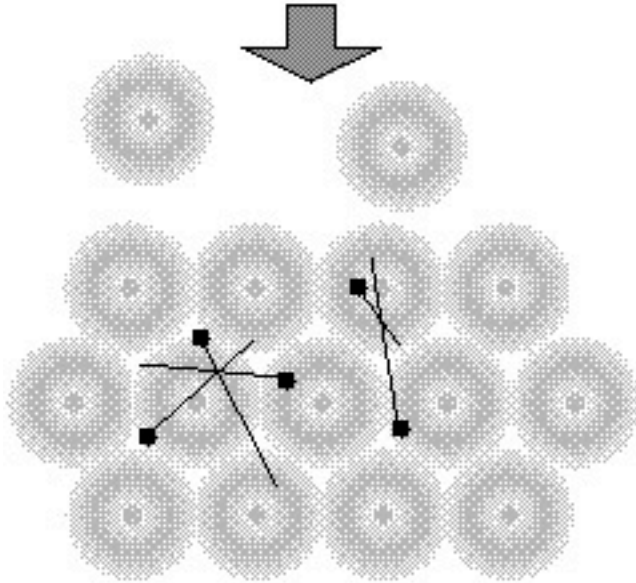
$$\Delta x \Delta p \geq \Box$$

- 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



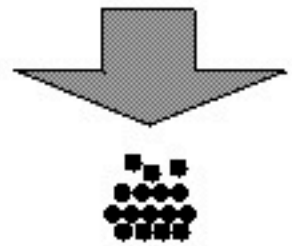
White Dwarf

Electrons run out of room to move around. Electrons 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

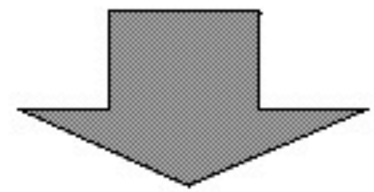


Neutron Star

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

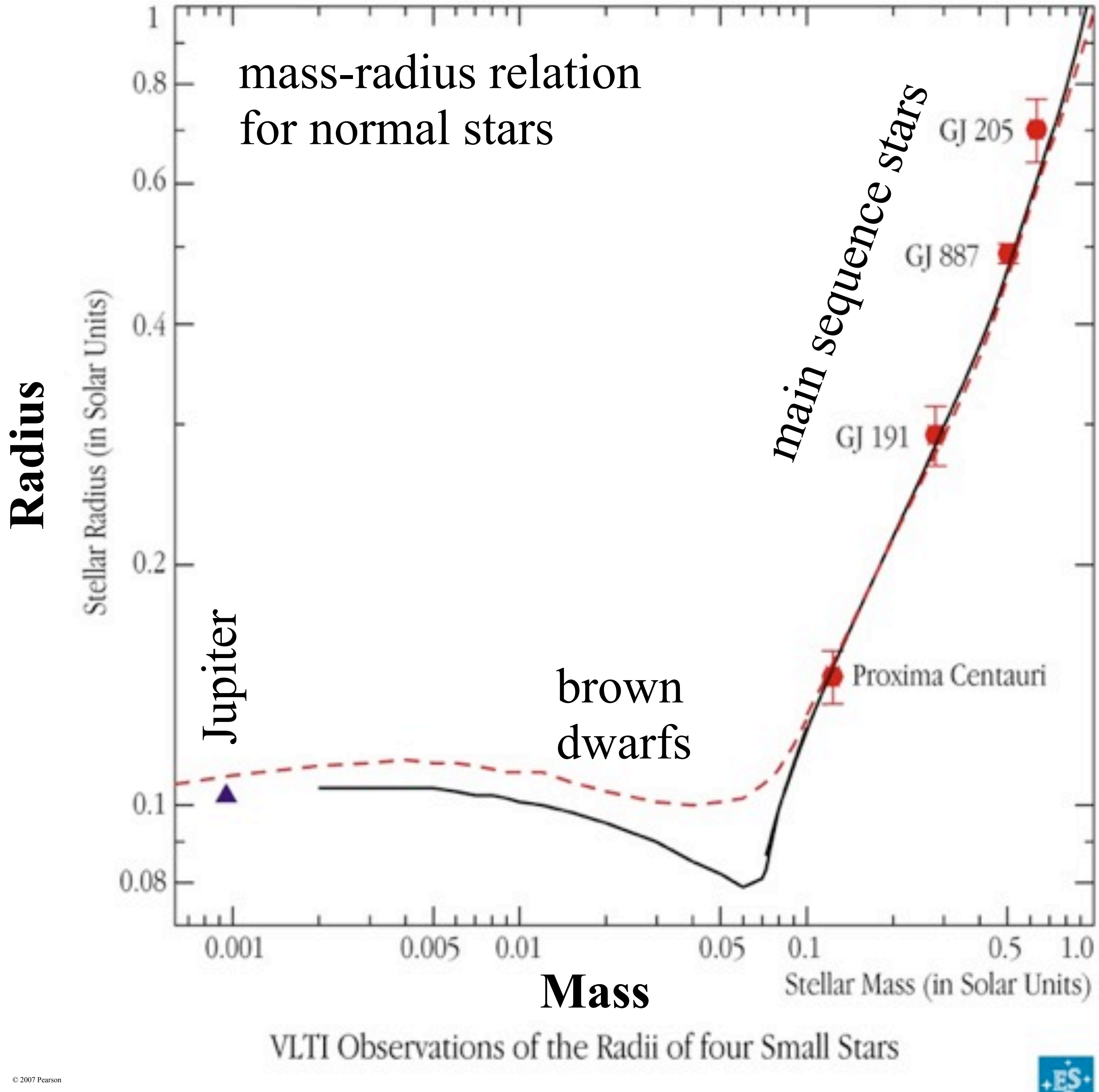
Mass > 3 solar masses

GRAVITY



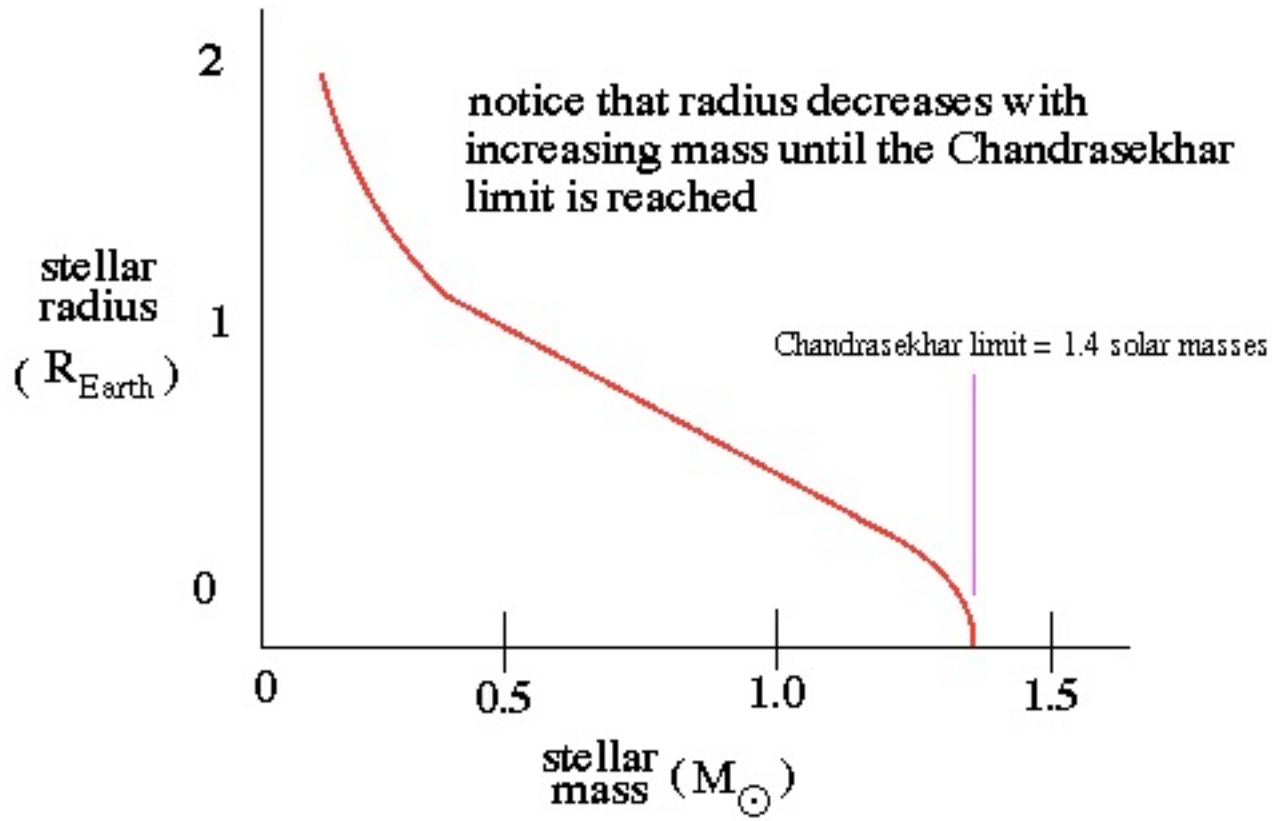
Black Hole

Gravity wins! Nothing prevents collapse.

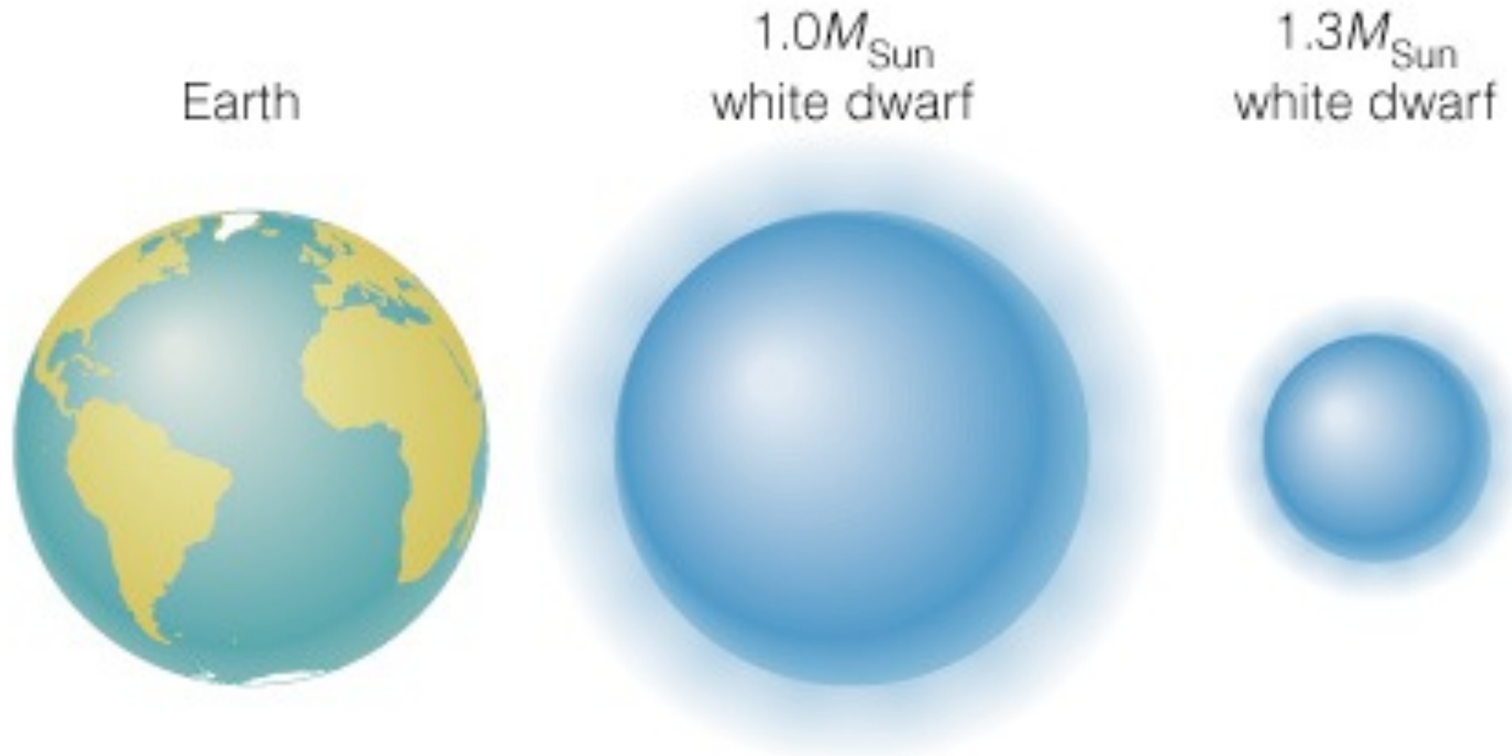


mass-radius relation
for normal stars
main sequence stars
Radius
Stellar Radius (in Solar Units)
1
0.8
0.6
0.4
0.2
0.1
0.08
GJ 205
GJ 887
GJ 191
Proxima Centauri
brown
dwarfs
Jupiter
0.001
0.005
0.01
0.05
0.1
0.5
1.0
Mass
Stellar Mass (in Solar Units)
VLTI Observations of the Radii of four Small Stars

Mass–Radius Relation for White Dwarfs



Size of a White Dwarf



- 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 more dense than water

atomic density

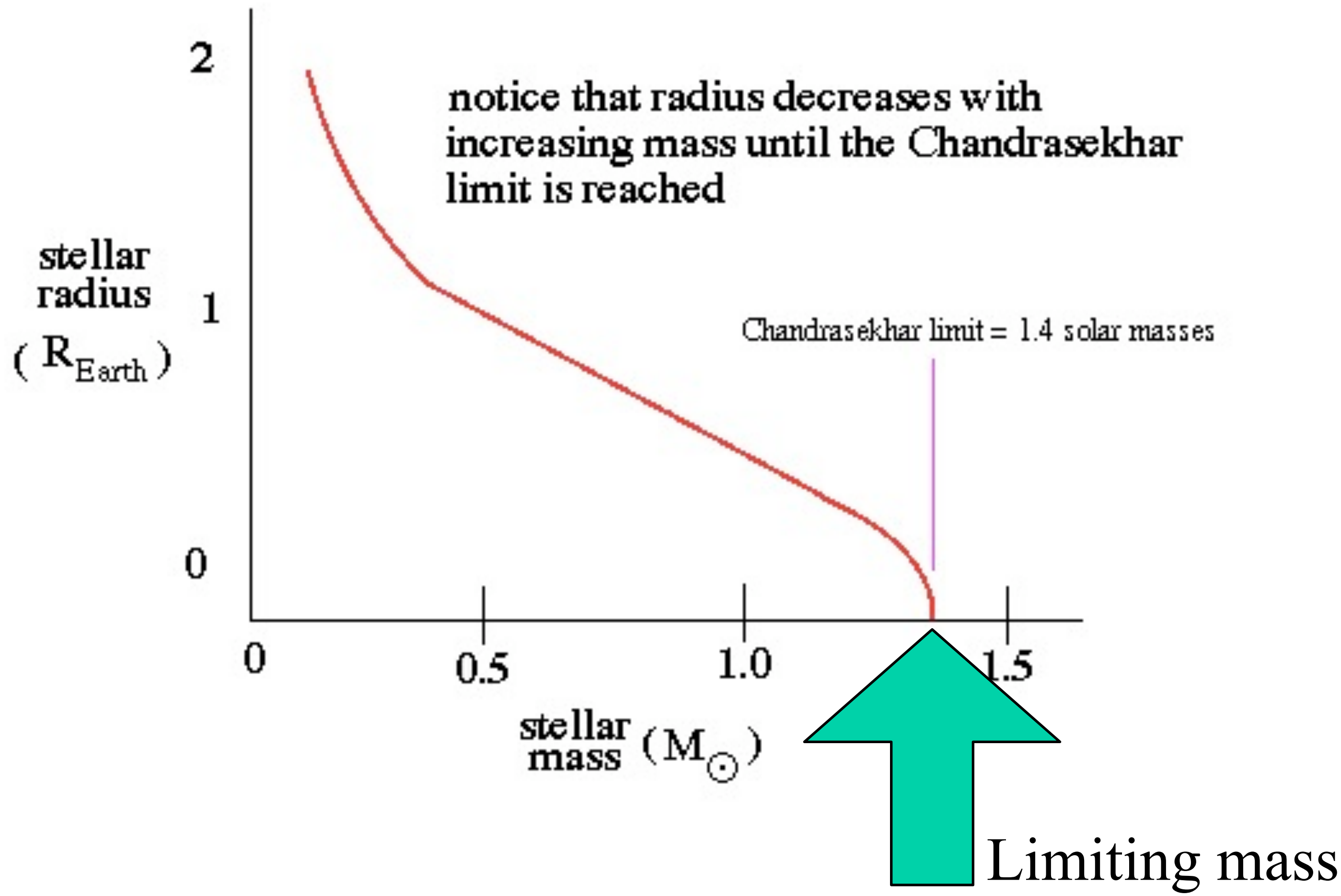
  - instead of weighing a gram, an ice cube block of white dwarf material would weigh a ton.

The White Dwarf Mass Limit

i.e., the ***Chandrasekhar limit***

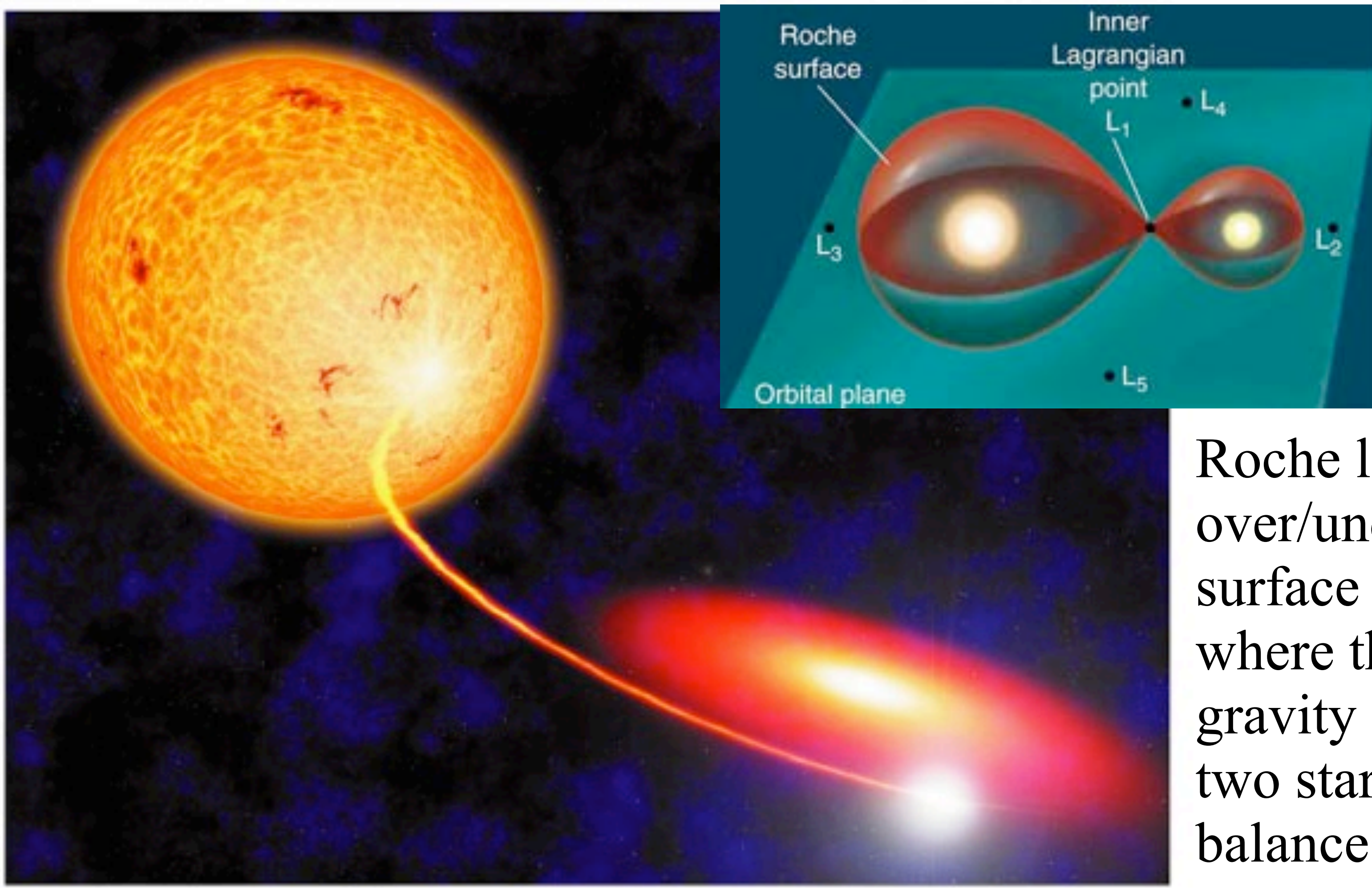
- Quantum mechanics says that electrons must move faster as they are squeezed into a very small space.
- As a white dwarf's mass approaches $1.4M_{Sun}$, its electrons must move at nearly the speed of light.
- Because nothing can move faster than light, a white dwarf cannot be more massive than $\mathbf{1.4}\boldsymbol{M}_{\mathbf{Sun}}$ -
- This is known as the ***Chandrasekhar limit***.

Mass–Radius Relation for White Dwarfs



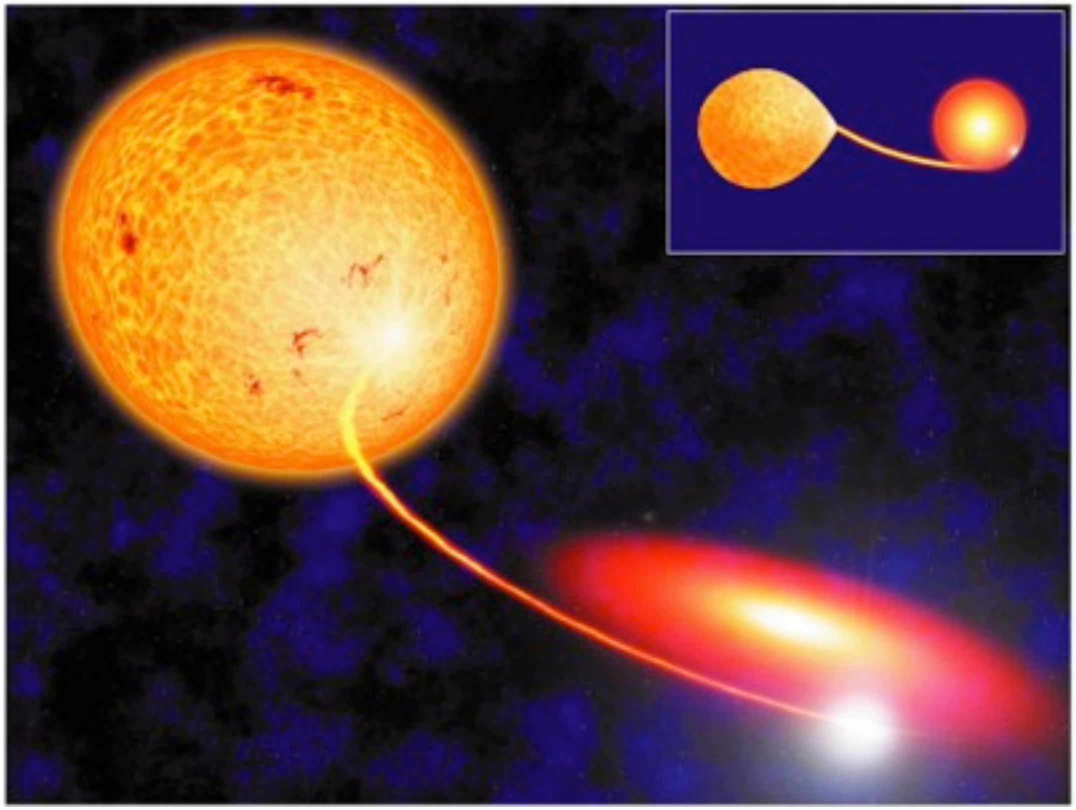
What happens if you add mass to a white dwarf?

White dwarf in a close binary



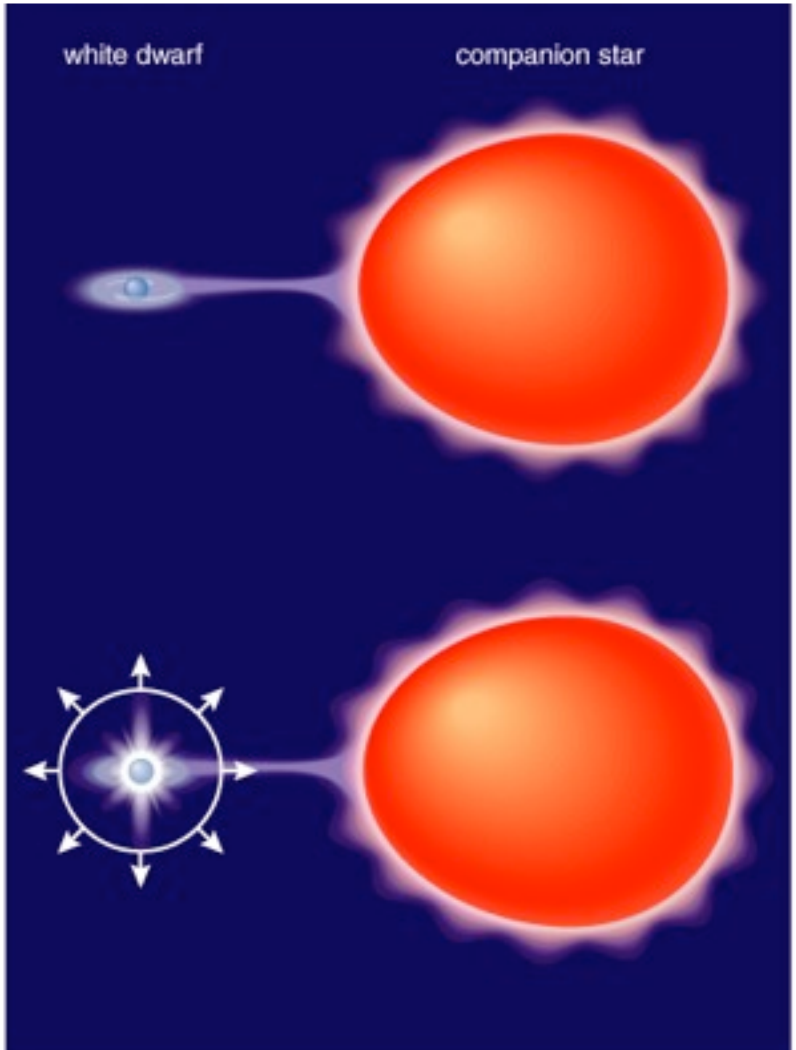
Roche lobes: over/under surface where the gravity of two stars balance.

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.*

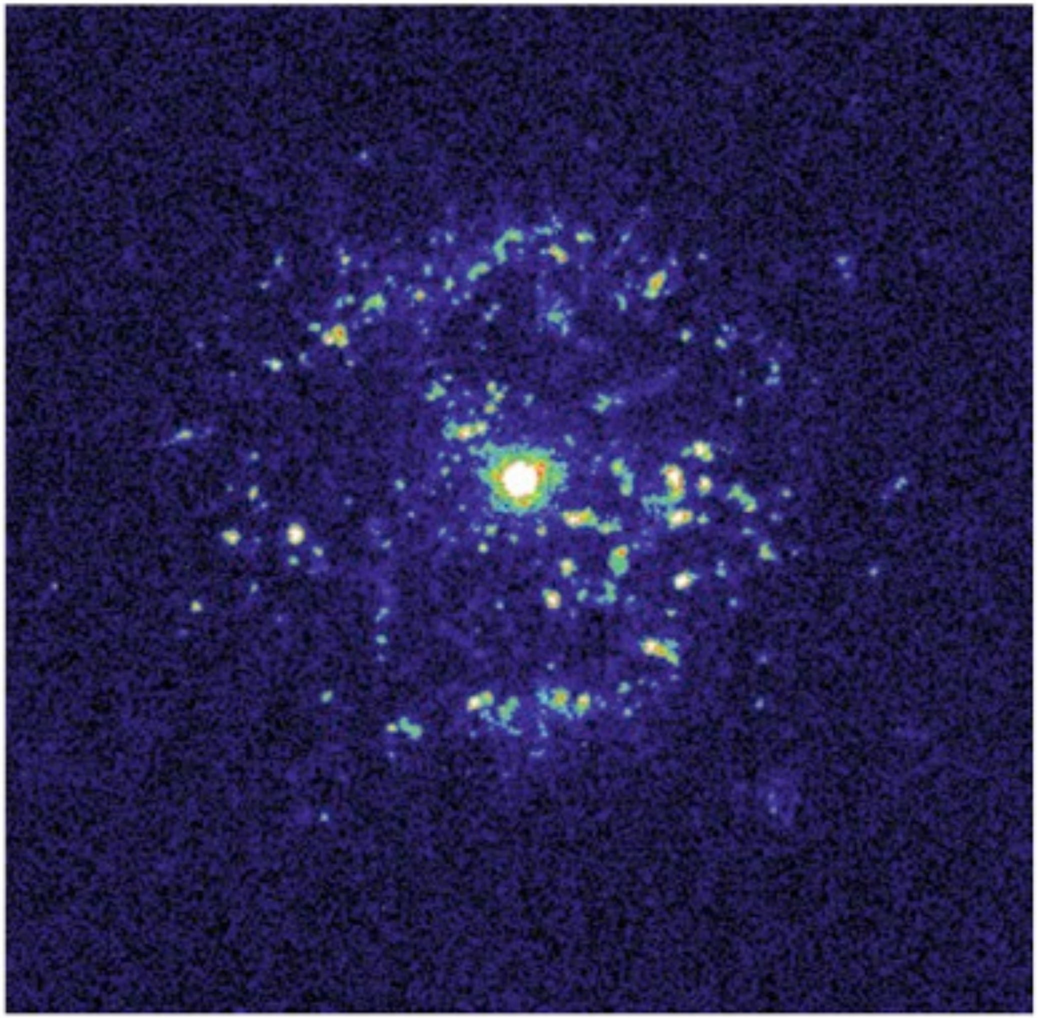
Nova



- 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



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

Only the surface is affected...

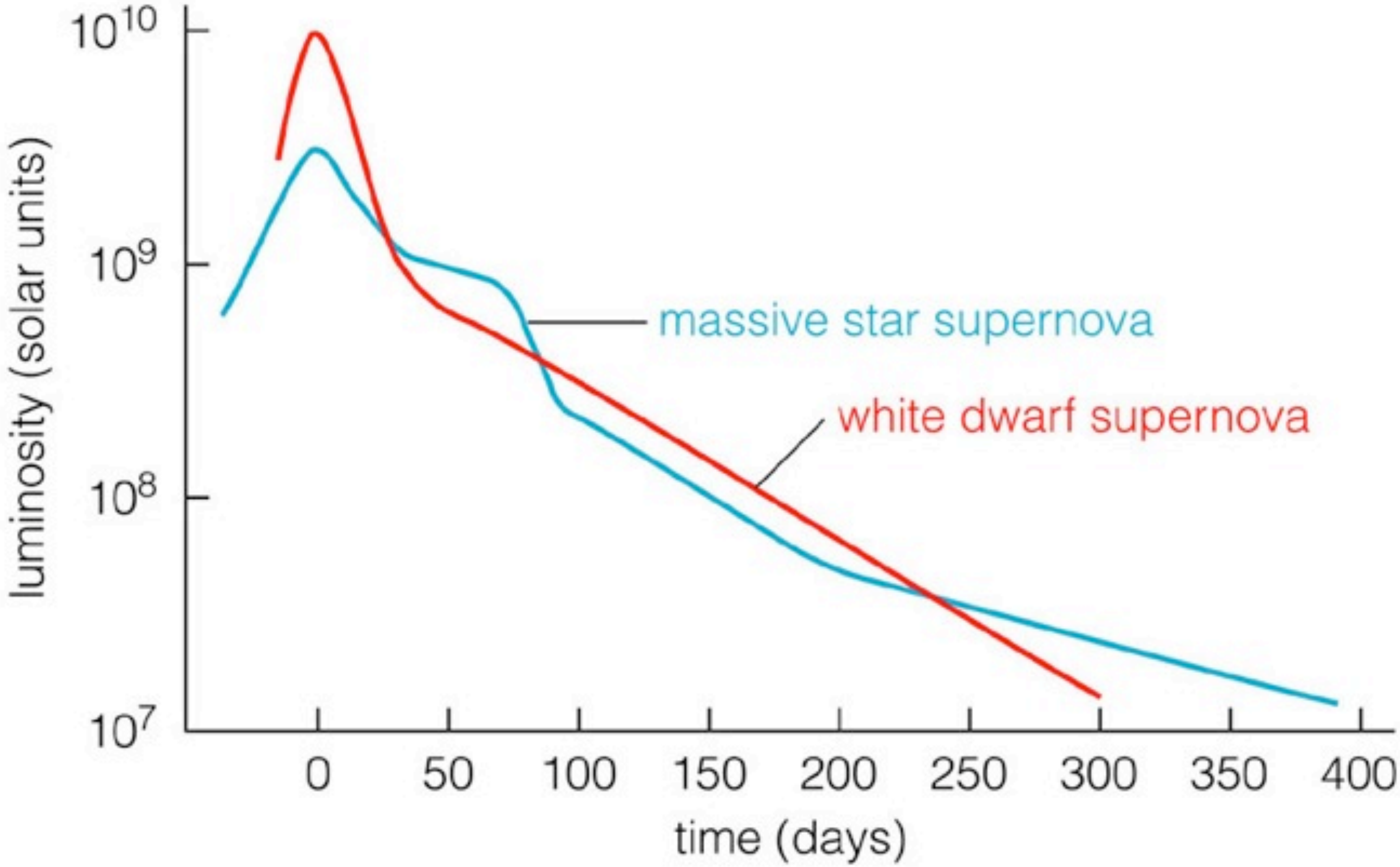
Two Types of Supernova

Massive star supernova: **Type II**

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

White dwarf supernova: **Type Ia**

Carbon fusion suddenly begins as white dwarf in close binary system reaches the Chandrasekhar limit, resulting in an explosion that disrupts the entire white dwarf.



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

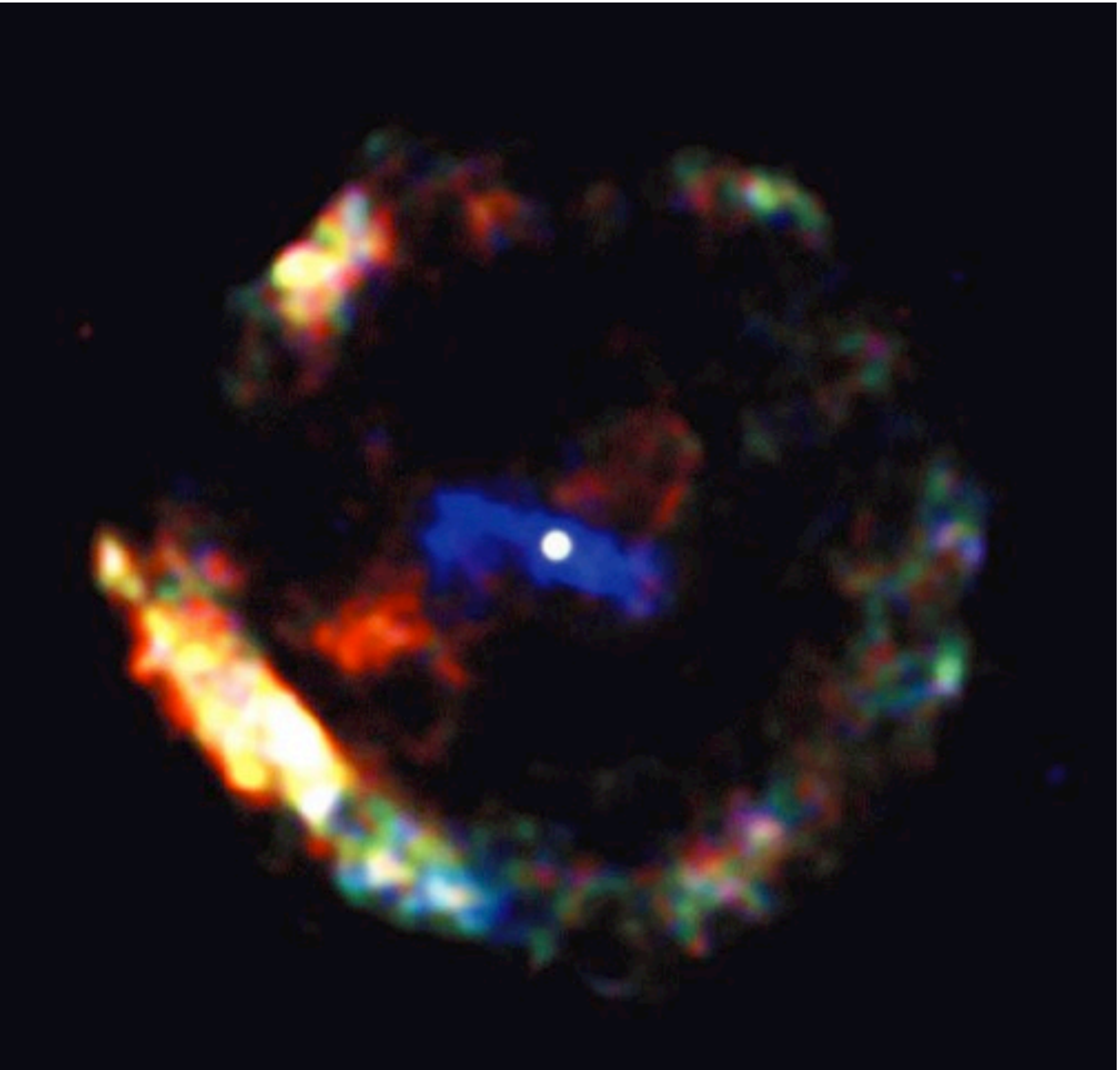
Nova or Supernova?

- 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
  - Type Ia spectra lack hydrogen
    - no exterior “unburnt” layers
  - Type II spectra have hydrogen
    - most of outer star still unburnt

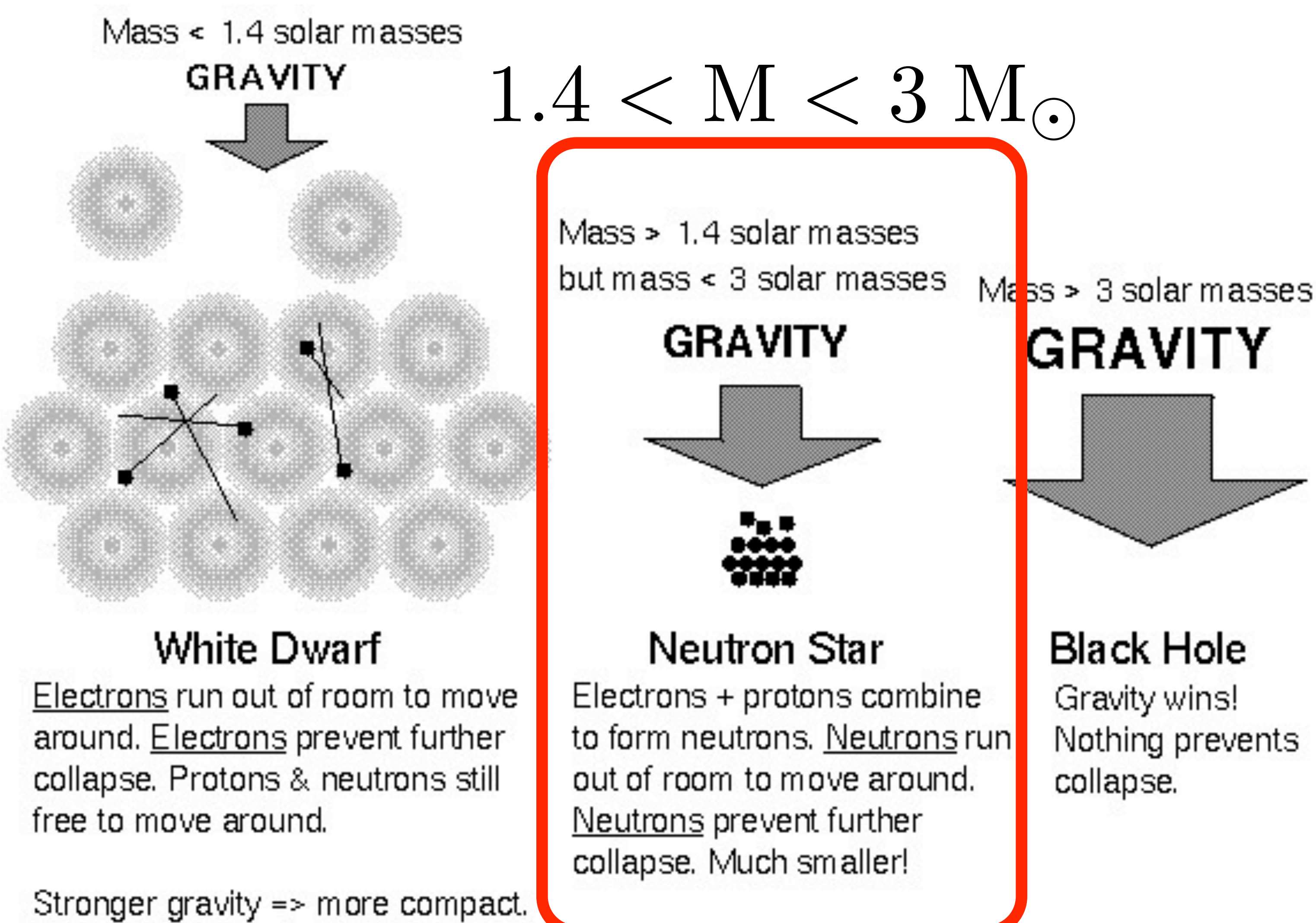
Neutron Stars

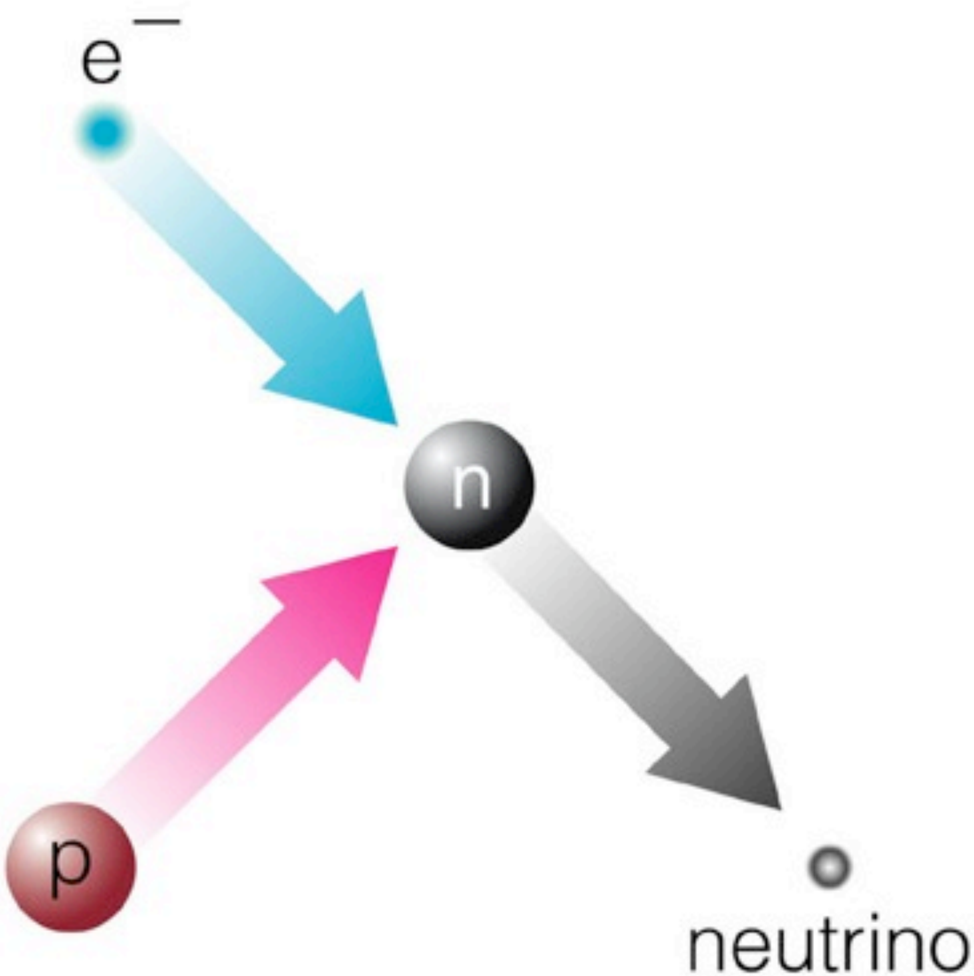


A neutron star is the ball of neutrons left behind by a massive-star supernova.

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

$$1.4 < M < 3\ M_\odot$$

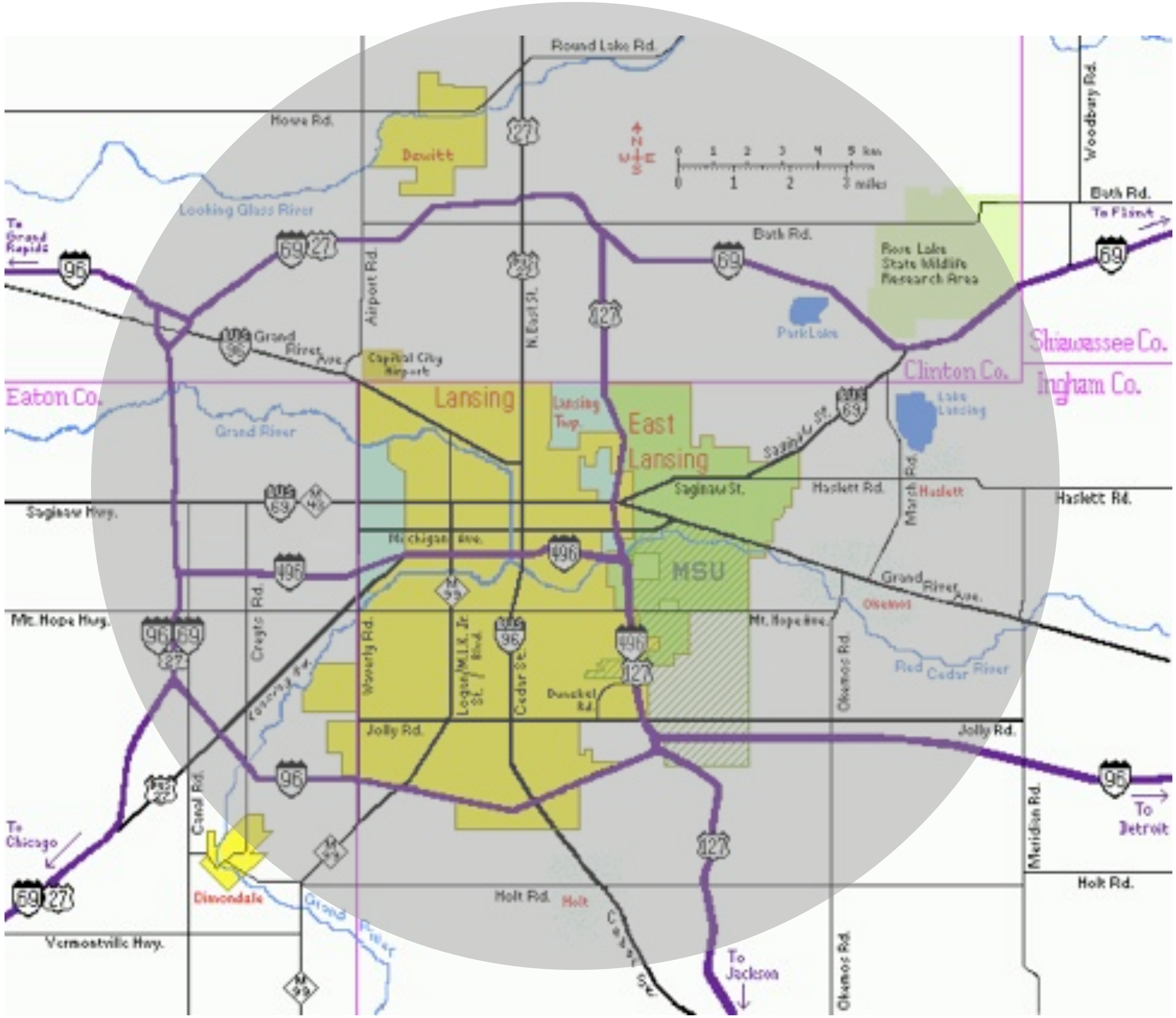

Mass < 1.4 solar masses
GRAVITY
White Dwarf
Electrons run out of room to move around. Electrons prevent further collapse. Protons & neutrons still free to move around.
Stronger gravity => more compact.
Mass > 1.4 solar masses
but mass < 3 solar masses
GRAVITY
Neutron Star
Electrons + protons combine to form neutrons. Neutrons run out of room to move around. Neutrons prevent further collapse. Much smaller!
Mass > 3 solar masses
GRAVITY
Black Hole
Gravity wins! Nothing prevents collapse.



When electron degeneracy pressure fails, electrons combine with protons, making neutrons and neutrinos.

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

Supported by neutron degeneracy pressure.



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

Neutron Star Density

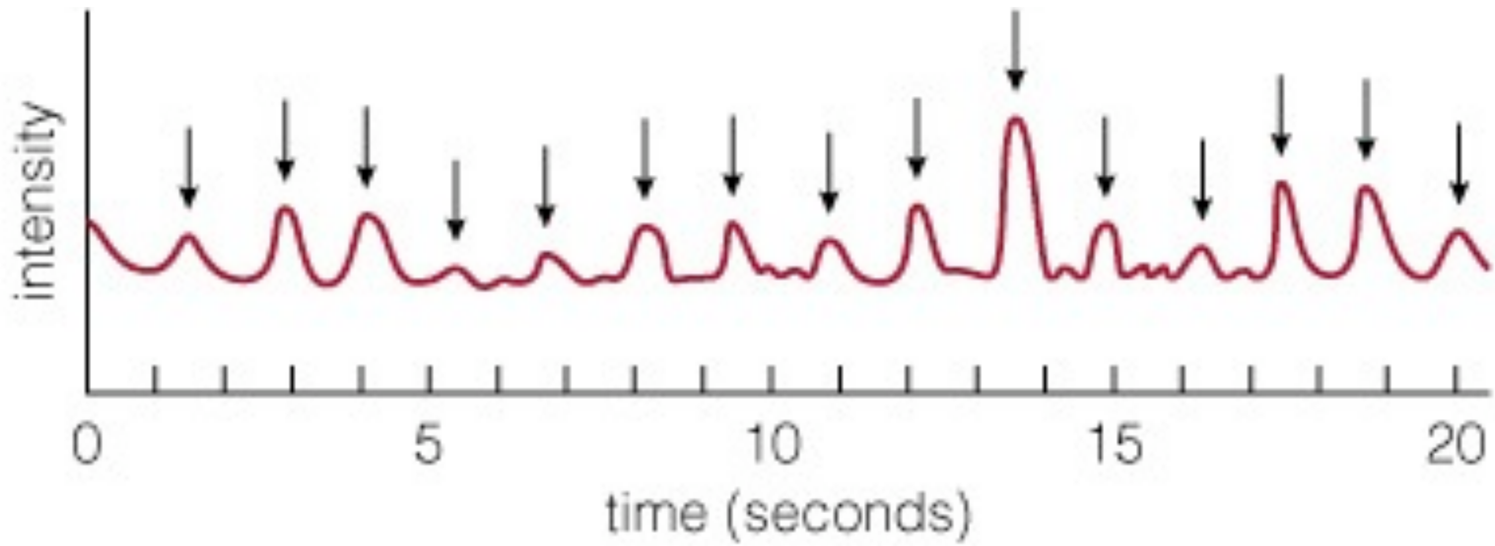
- size R ~ ten kilometers
- mass M ~ mass of stars
- density extra-absurdly high:

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

nuclear density

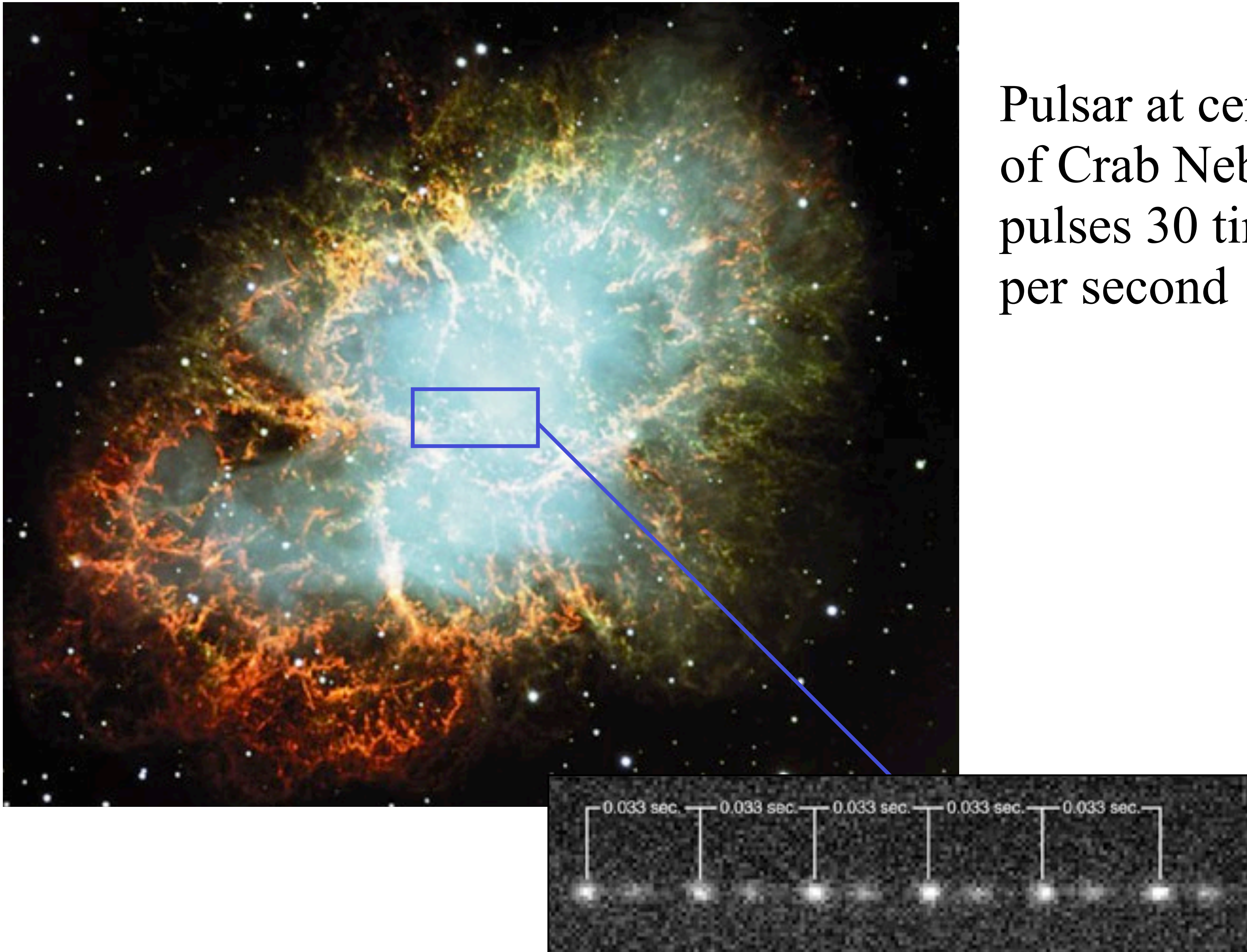
  – equivalent to the entire mass of the earth being stuffed into this building.

Discovery of Neutron Stars

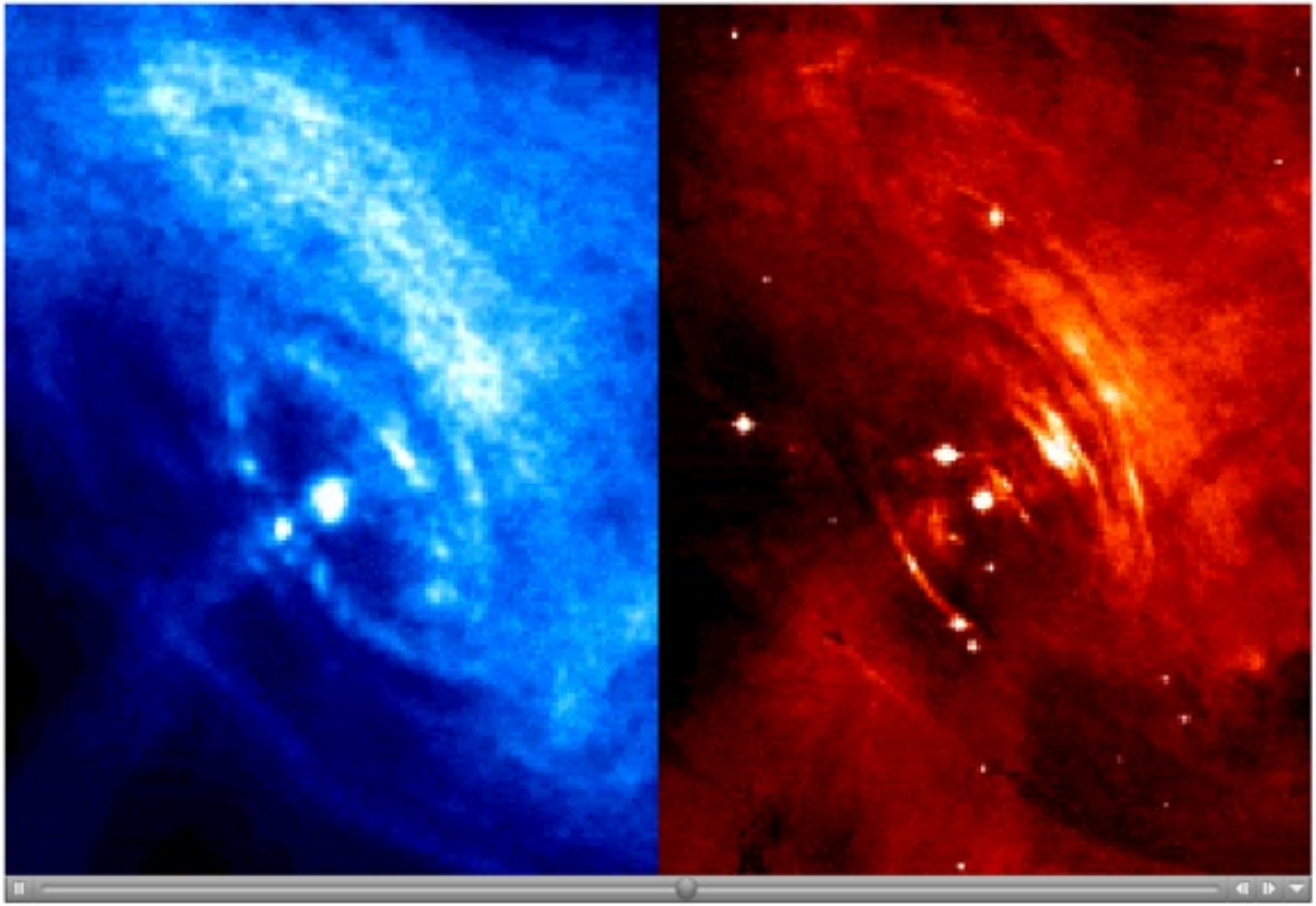


- Using a radio telescope in 1967, Jocelyn Bell noticed very regular pulses of radio emission coming from a single part of the sky.
- The pulses were coming from a spinning neutron star—a *pulsar*.

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



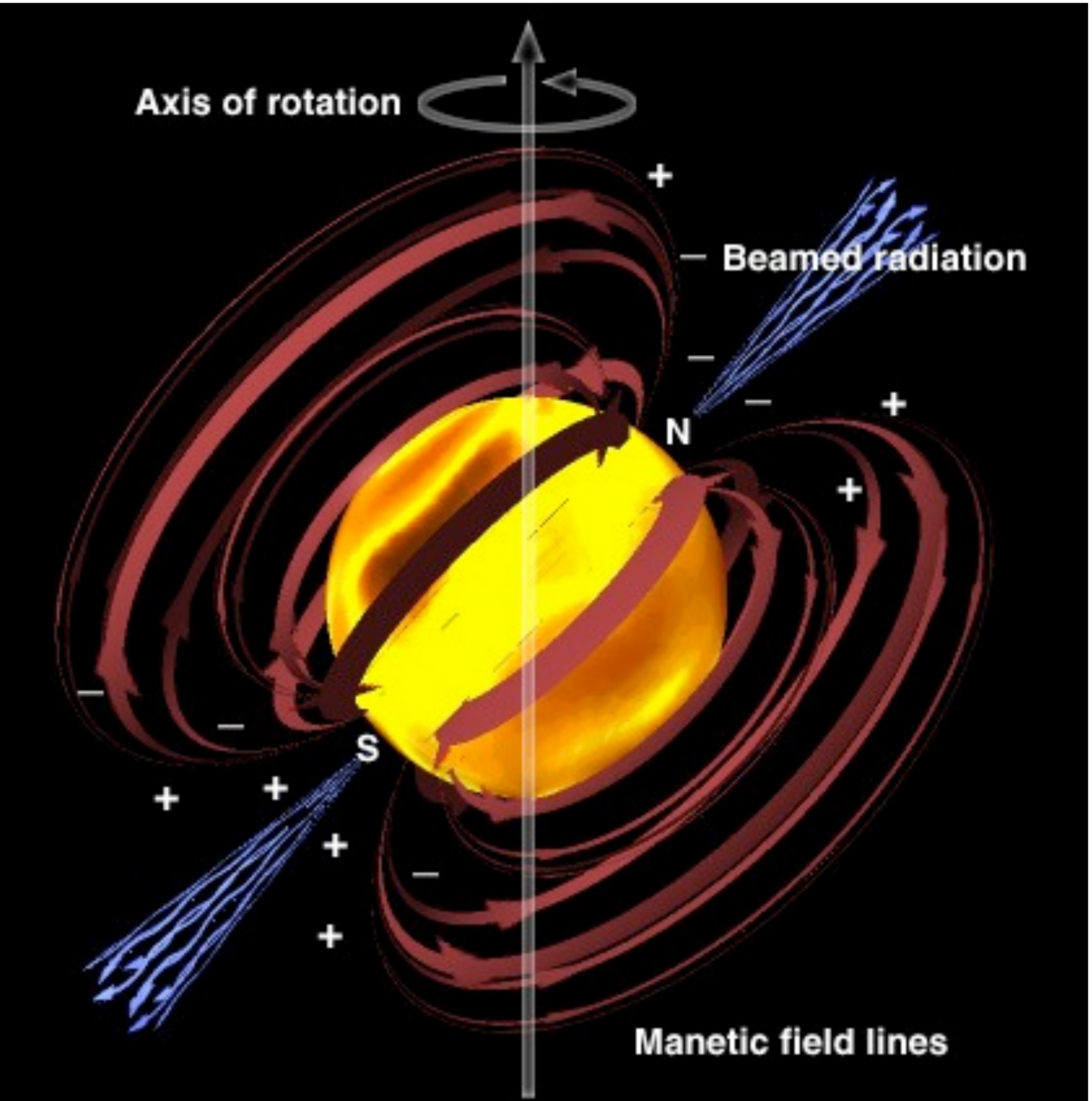
Pulsar at center of Crab Nebula pulses 30 times per second



X-rays Visible light

Crab Nebula Pulsar (close up)

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.

Why Pulsars Must Be Neutron Stars

Circumference of Neutron Star = 2π (radius) ~ 60 km

Spin Rate of Fast Pulsars ~ 1,000 cycles per second

Surface Rotation Velocity ~ 60,000 km/s
~ 20% speed of light
~ escape velocity from NS

Anything else would be torn to pieces!

Neutron Star Limit

- Neutron degeneracy pressure can no longer support a neutron star against gravity if its mass exceeds about 3 M_{Sun}.