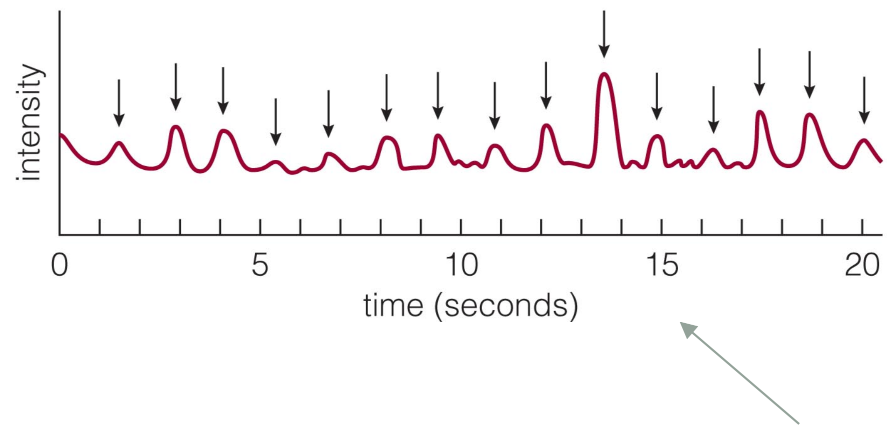
[08] Neutron Stars and Pulsars (2/20/18)

Upcoming Items

1. Read Ch. S2 for next class and do the self-study quizzes
2. First midterm two weeks from today!
3. Question for a later class: how many of you have taken a course on probability? Statistics?



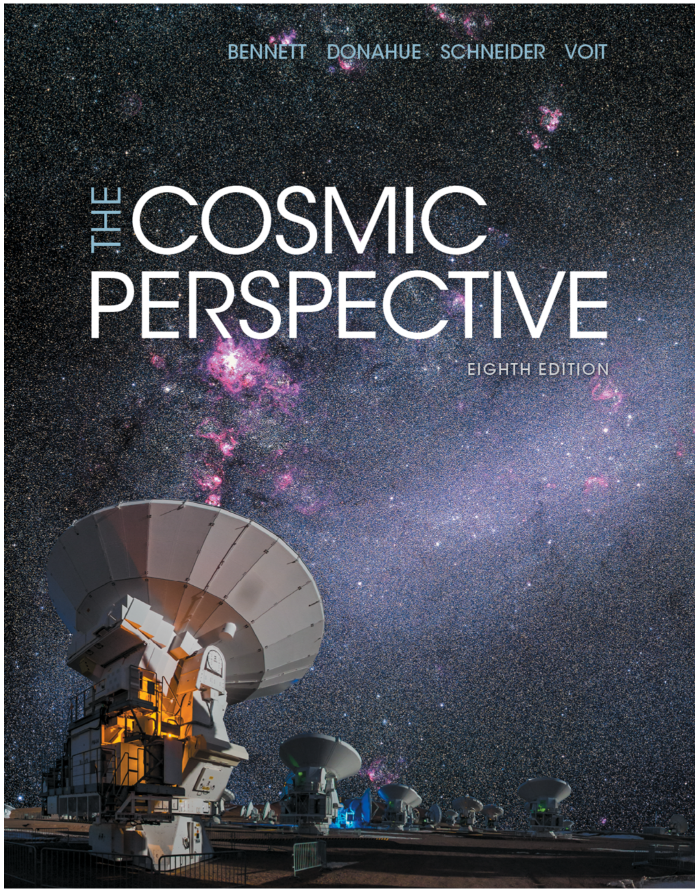
LEARNING GOALS

Ch. 18.2

For this class, you should be able to…

… *describe how neutron stars form, and describe what happens if mass is accreted onto such objects;*

… *explain why some neutron stars appear as pulsars to us, and why the spin rate of pulsars implies they are very dense.*



Any astro questions?

Neutron Stars and Pulsars

- Neutron stars.
  - Cooling ball of mostly neutrons supported by neutron degeneracy.
  - Ridiculously dense material.
  - Accretion results in continuous fusion and X-ray bursts.
- Pulsars. (Note: they are NOT pulsing! Instead, they rotate)
  - Spinning neutron stars with radiation beams that sweep toward us.

Exotic Matter, Part II…

- A paper clip of neutron star matter would weigh more than Mt. Everest!
- A neutron star is even denser than a white dwarf:

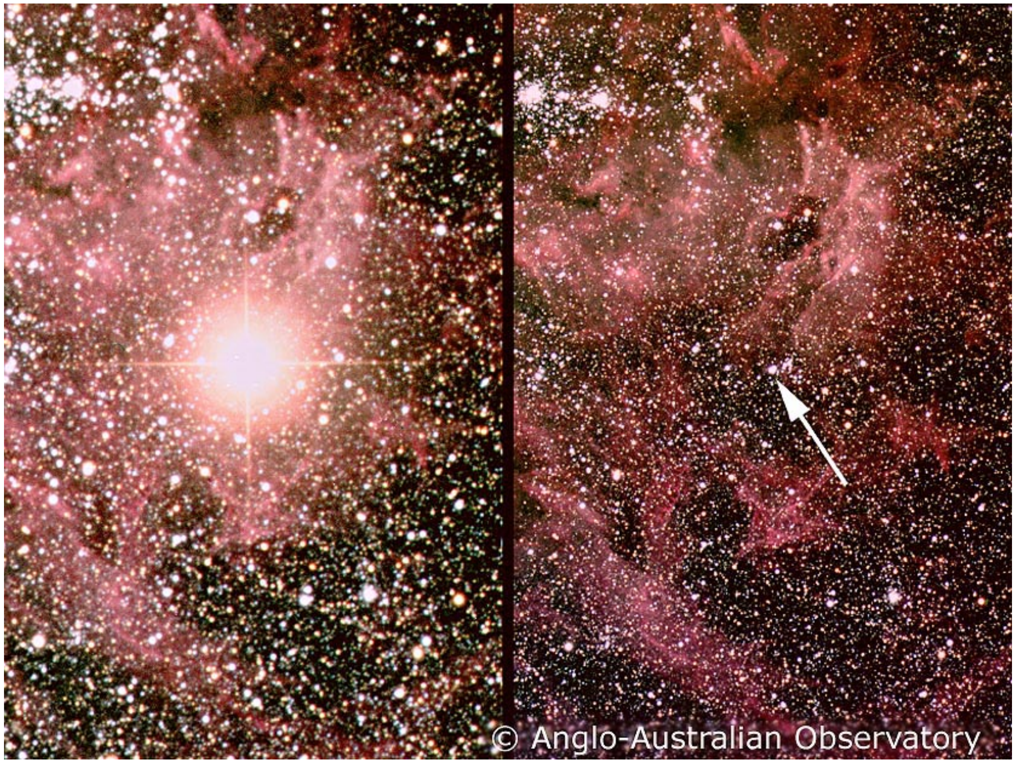
  Density = (mass) / (volume)

  = $(5 \times 10^{30}$ kg$) / ((4/3)\ \pi\ (1 \times 10^{4}$ m$)^3)$

  = 10^{18} kg/m^3 (billion times denser than a white dwarf!).
- In fact, the density is comparable to an atomic nucleus.
  - Surface gravity is so strong that any mountain higher than 1 mm is squashed flat, and any gas on surface quickly differentiates (H on top, then He, then C,…, heavy elements on bottom).
  - At the core of a neutron star there may be "new" and exotic states of matter (new particles, quark soup, etc.).

Star Fall Down, Go Boom

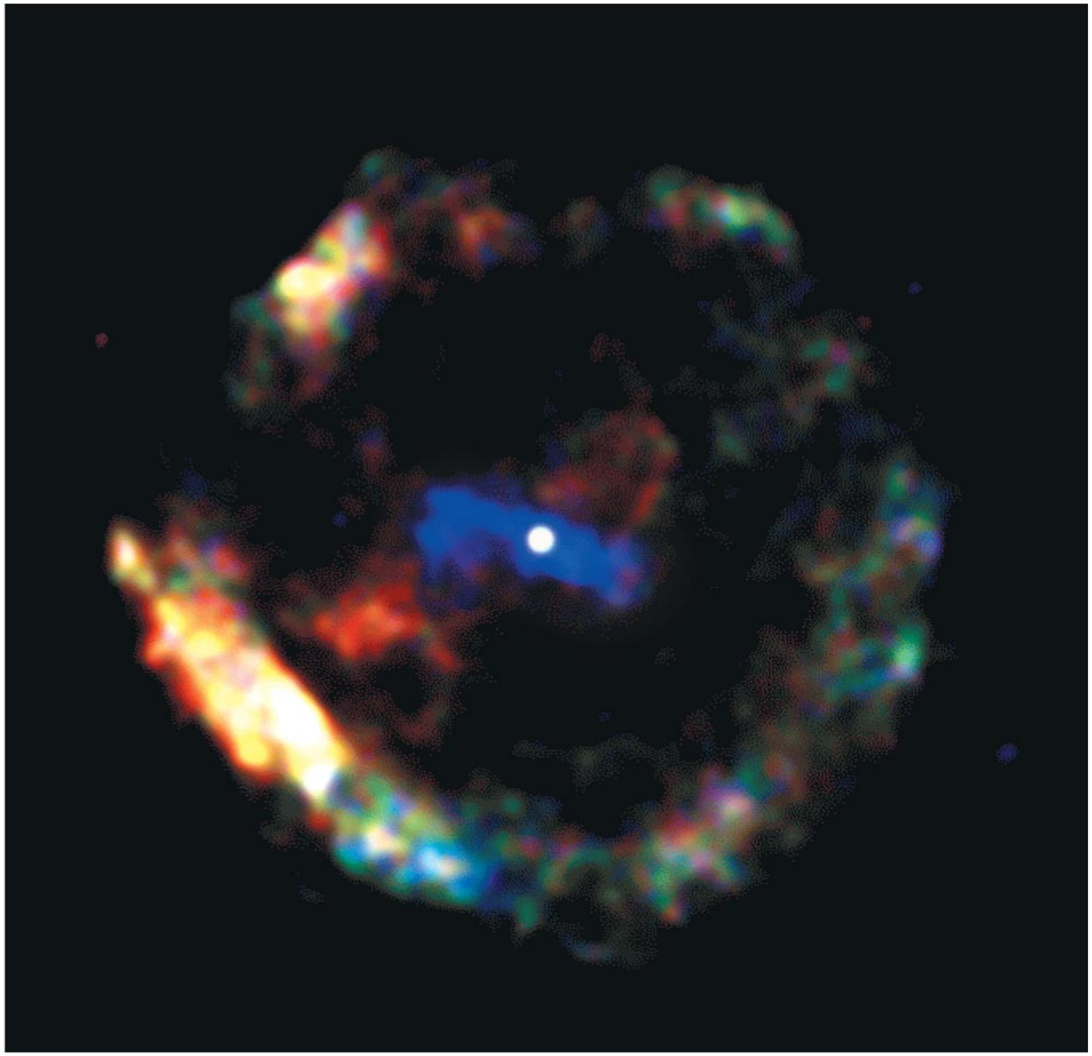
- Big stars: live fast, die young, leave a beautiful corpse!
- H fuses into He, then C, O, ..., but when it gets to iron, the game's up; it can't support itself
- Core collapses, then explosion!



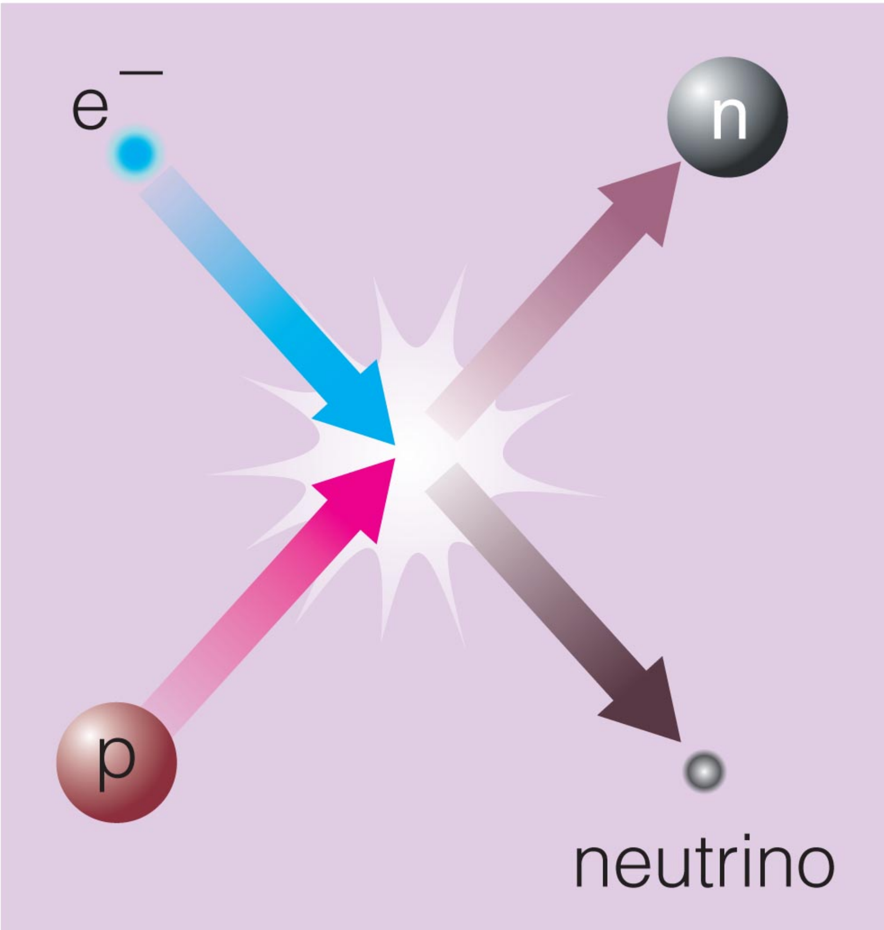
What is Left Behind?

- Fritz Zwicky, irascible Caltech prof: SN might leave behind very compact *neutron star*

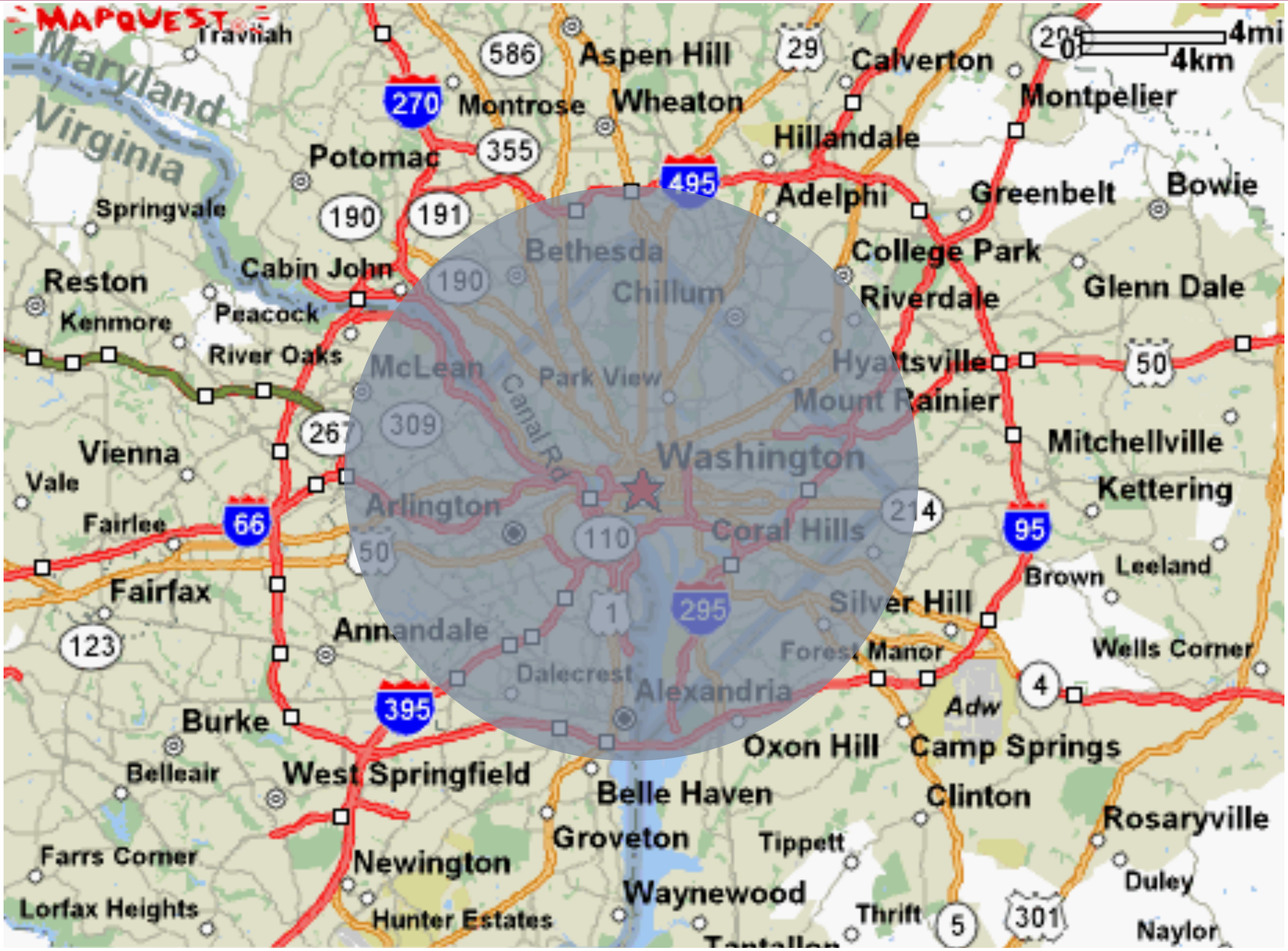
Neutron Stars



- A neutron star is the ball of neutrons left behind by a massive-star supernova.
- Degeneracy pressure of neutrons supports a neutron star against gravity.



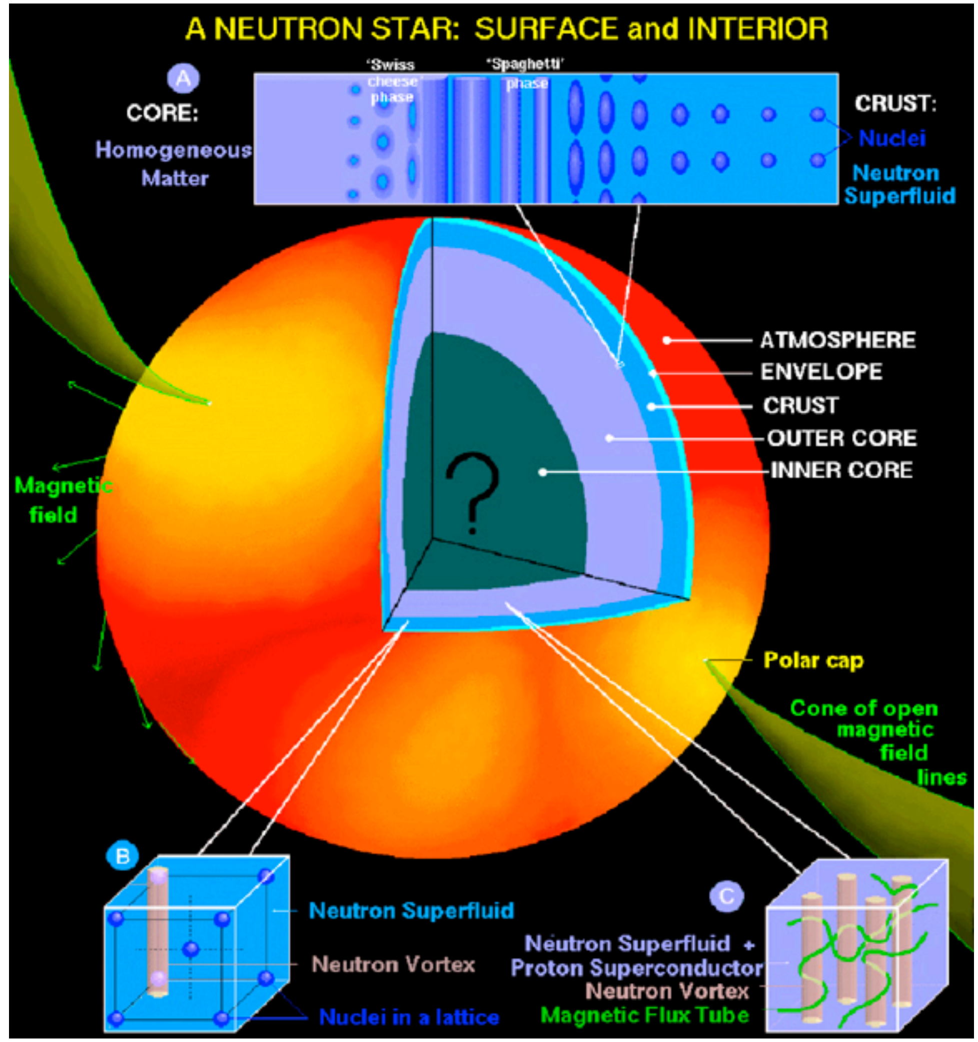
- Electron degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos.
- Neutrons collapse to the center, forming a **neutron star**.
- Neutron stars are ~90% neutrons, probably (rest are protons, electrons,...)
- What properties do we expect of the star?



- A neutron star is about the same size as a small city.
- Expect ~1.2-2 times mass of Sun in ball 10-15 km in radius
- All 7.6 billion people on Earth, crammed into a teaspoon!

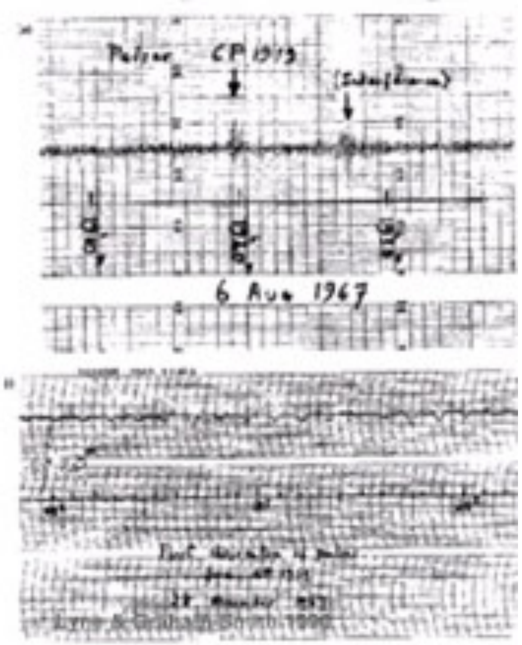
In the Belly of the Beast

- Other highlights
- Magnetic fields on NS surfaces are roughly a billion to a quadrillion times the fields at the Earth's surface(!)
  Atomic shape is quasi-cylinders, not quasi-spheres
- Superconducting superfluid
- Unknown core: neutrons, or weirder stuff?
  Part of my research to find out
- But NS are so small; how could we detect them?



Serendipity

- Graduate student Jocelyn Bell, 1967
- Looking for quasars but found regular signals
- What could these be?

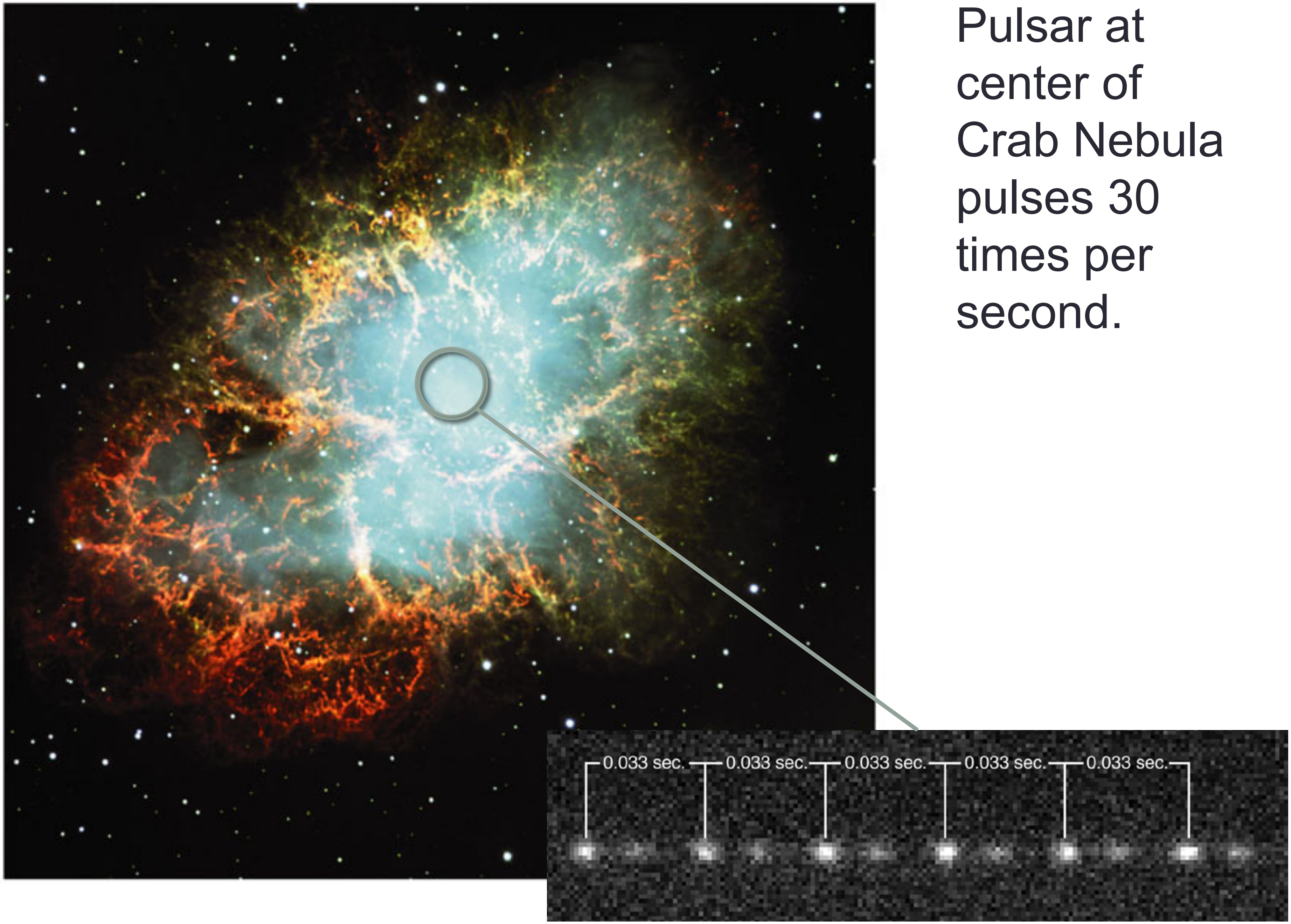


Group Q: What Could Pulsars Be?

- Observational hints circa 1968:
  Known periods in range 0.03 seconds to 4 seconds
  Extraordinarily regular intervals of signals
  Over long time, periods *increase*, never decrease
- Three possible sources: WD, NS, BH
  WD: average density up to ~10^{11} kg m^{-3}
  NS: average density ~10^{18} kg m^{-3}
  BH: effective average density ~10^{19} kg m^{-3} and lower
  Minimum period from any mechanism $P_{min} \sim \pi/(G\rho)^{1/2}$

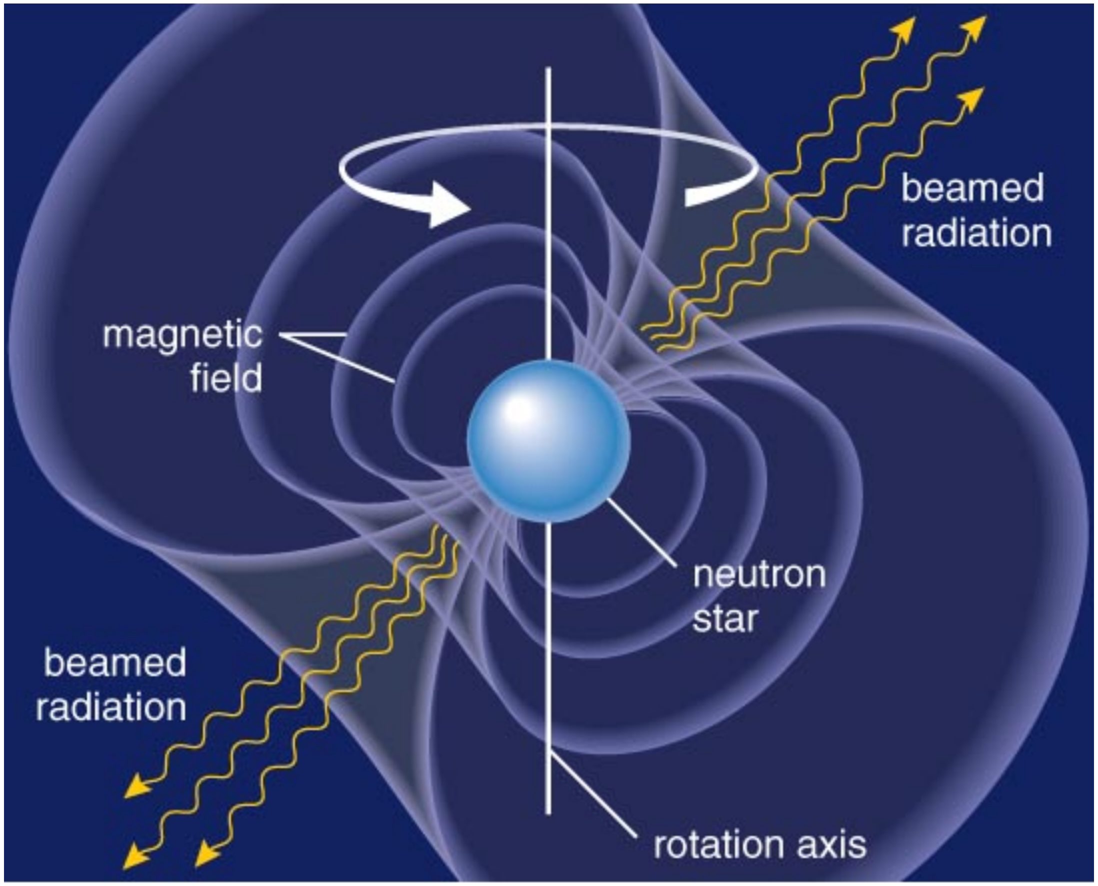
Note:
$G=6.67 \times 10^{-11}$ in
our usual SI units

- Three mechanisms: rotation ($>P_{min}$), pulsation (at P_{min}), and orbits ($>P_{min}$, and orbit shrinks with time due to grav. waves)
- Only one combination of source and mechanism works; in your groups, rule out the other combinations!
  BH are the toughest challenge here...



Pulsar at center of Crab Nebula pulses 30 times per second.

Pulsars



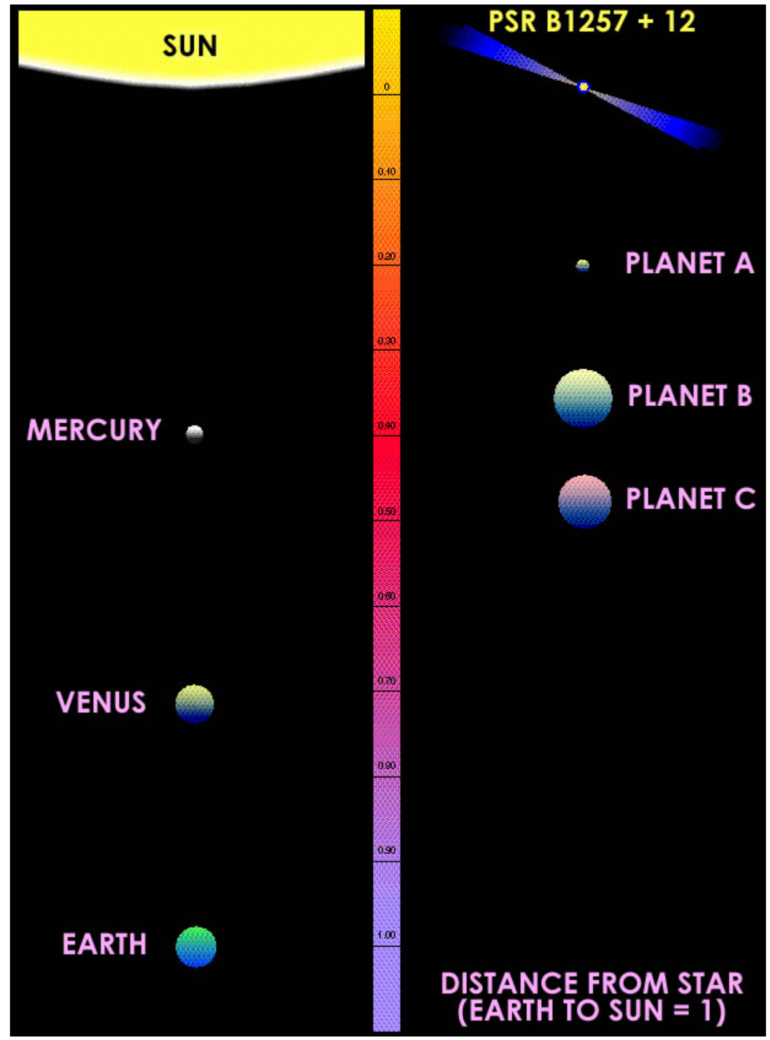
- A pulsar is a neutron star that beams radiation along a magnetic axis that is not aligned with the rotation axis.

Pulsars

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

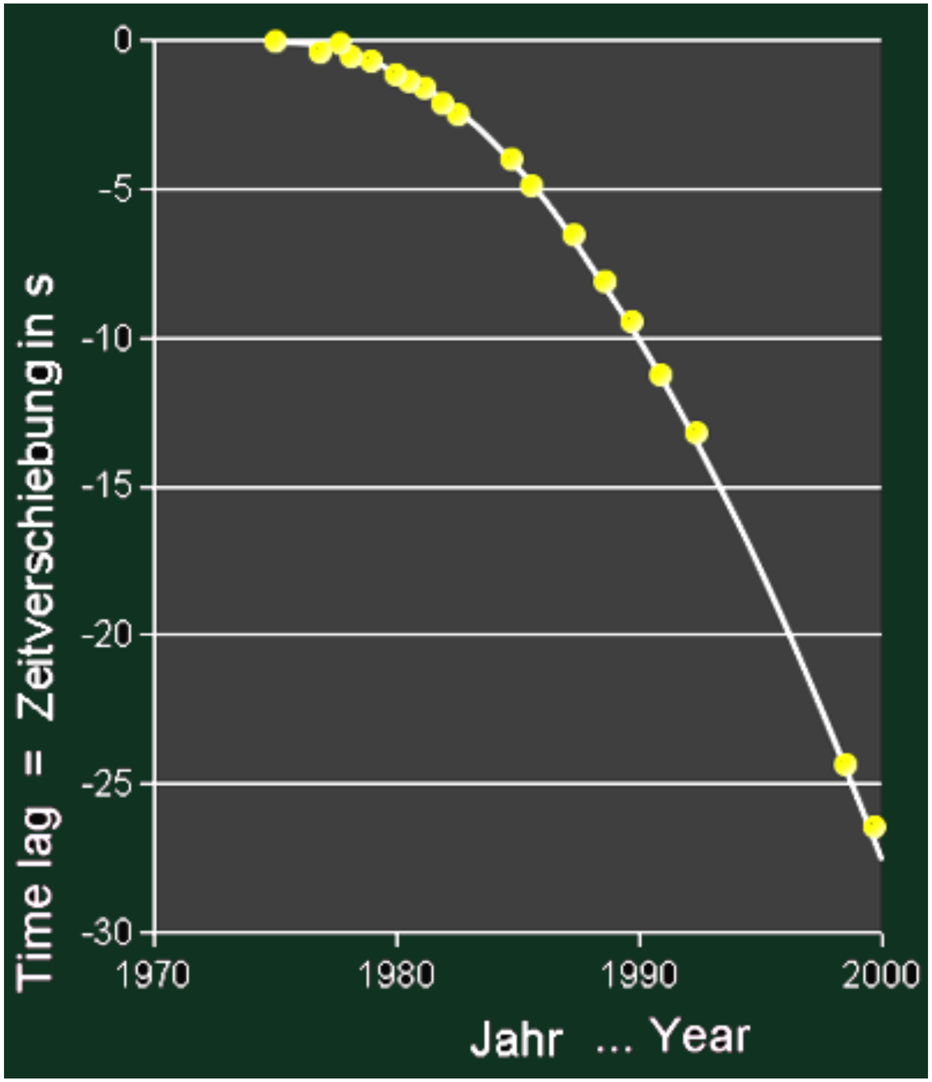
Pulsar Planets

- Pulsars are incredibly good clocks
- Great timing means first extrasolar planets (and still the smallest) were detected around a pulsar!



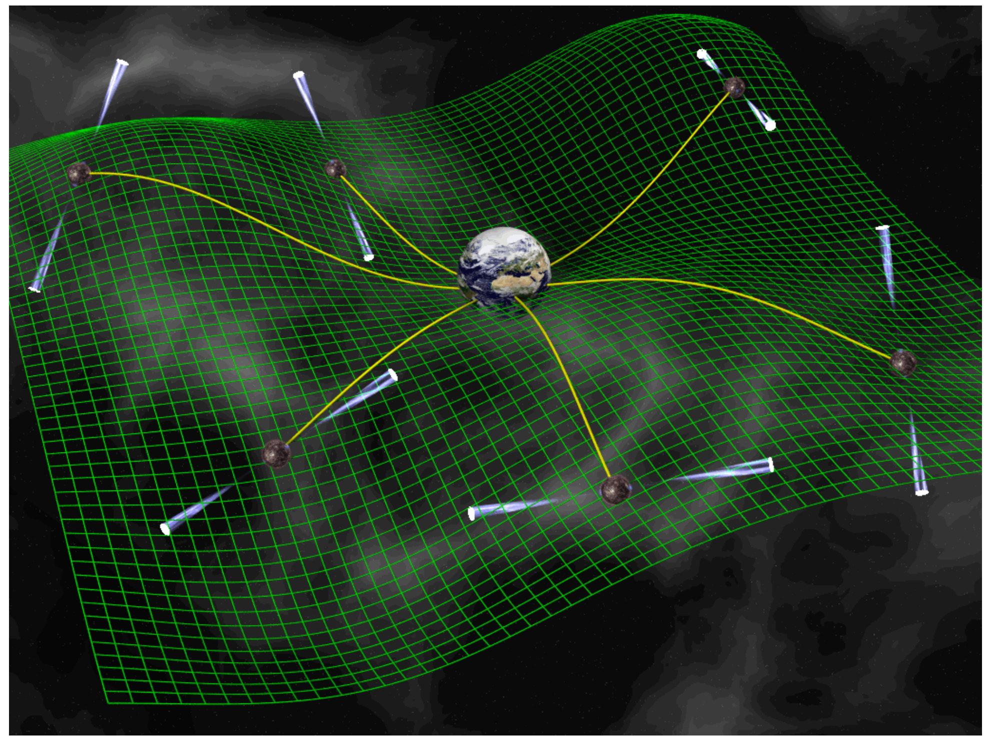
Testing Einstein

- Einstein's theory of gravity predicts that orbits will decay slowly Gravitational waves
- 1974-now: tests with double neutron star systems
- Passes test with flying colors!



Pulsar Timing Arrays

- Future use: time many pulsars, detect ripples in spacetime!
- From binary supermassive black holes
- Who knows what else pulsars can do!

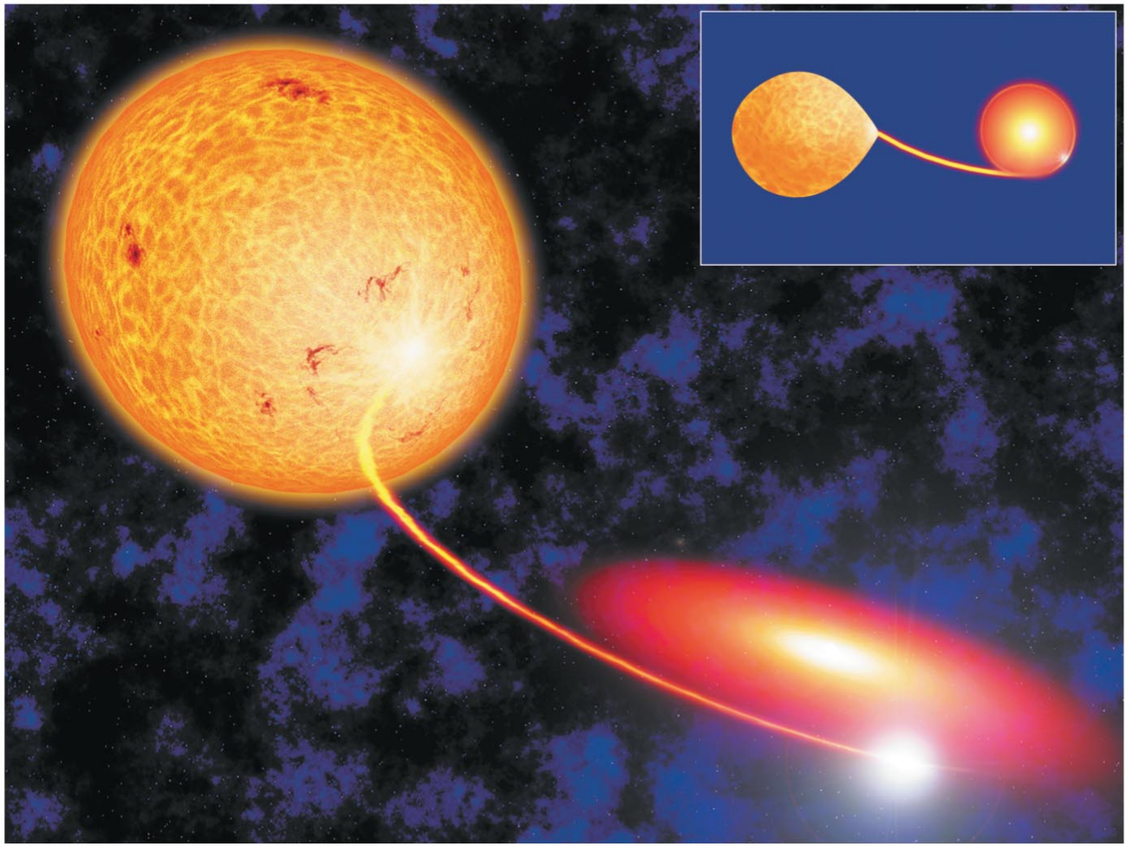


A common ***story*** is that pulsars spin fast because a stellar core's spin speeds up as it collapses into a neutron star.

Makes sense... but the reality is more complicated.

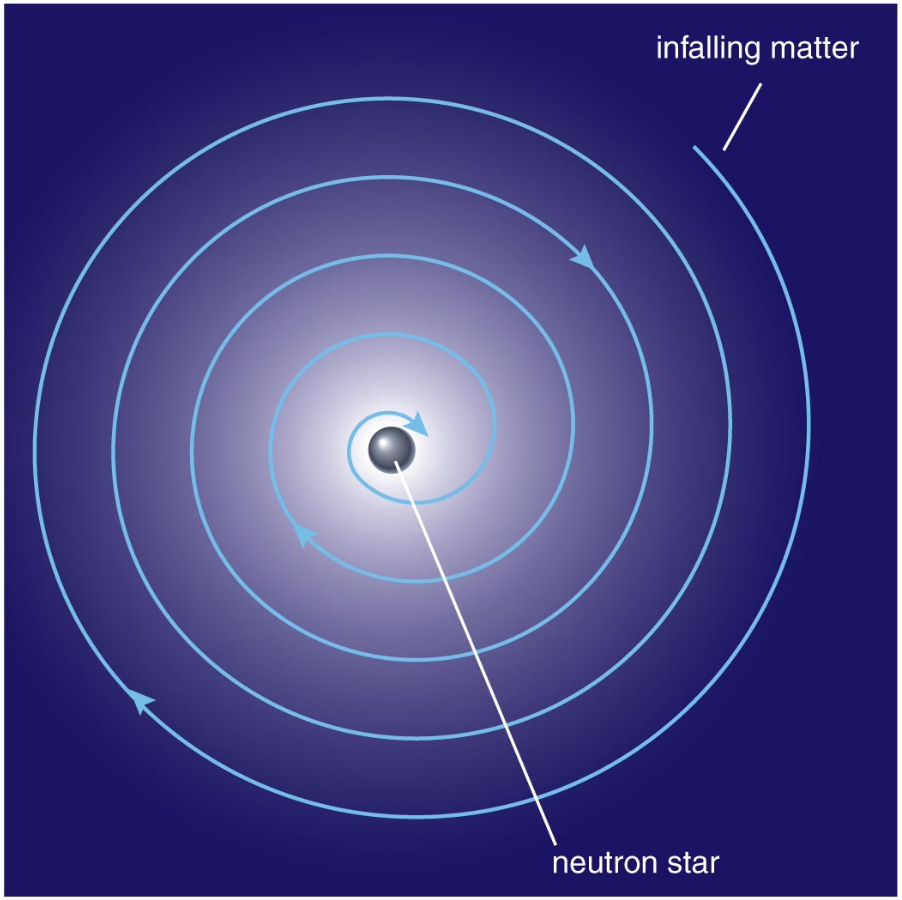
More likely: SN produces a ”kick” that is somewhat off-center, leading to spin

Neutron Star Binaries



Matter falling toward a neutron star forms an accretion disk, just as in a white dwarf binary.

But because a NS is so much more compact than a WD, matter spiraling close to the NS moves much faster, and is thus much hotter: can be 10 million K, and emit in X-rays!



Accreting matter adds angular momentum to a neutron star, changing its spin.

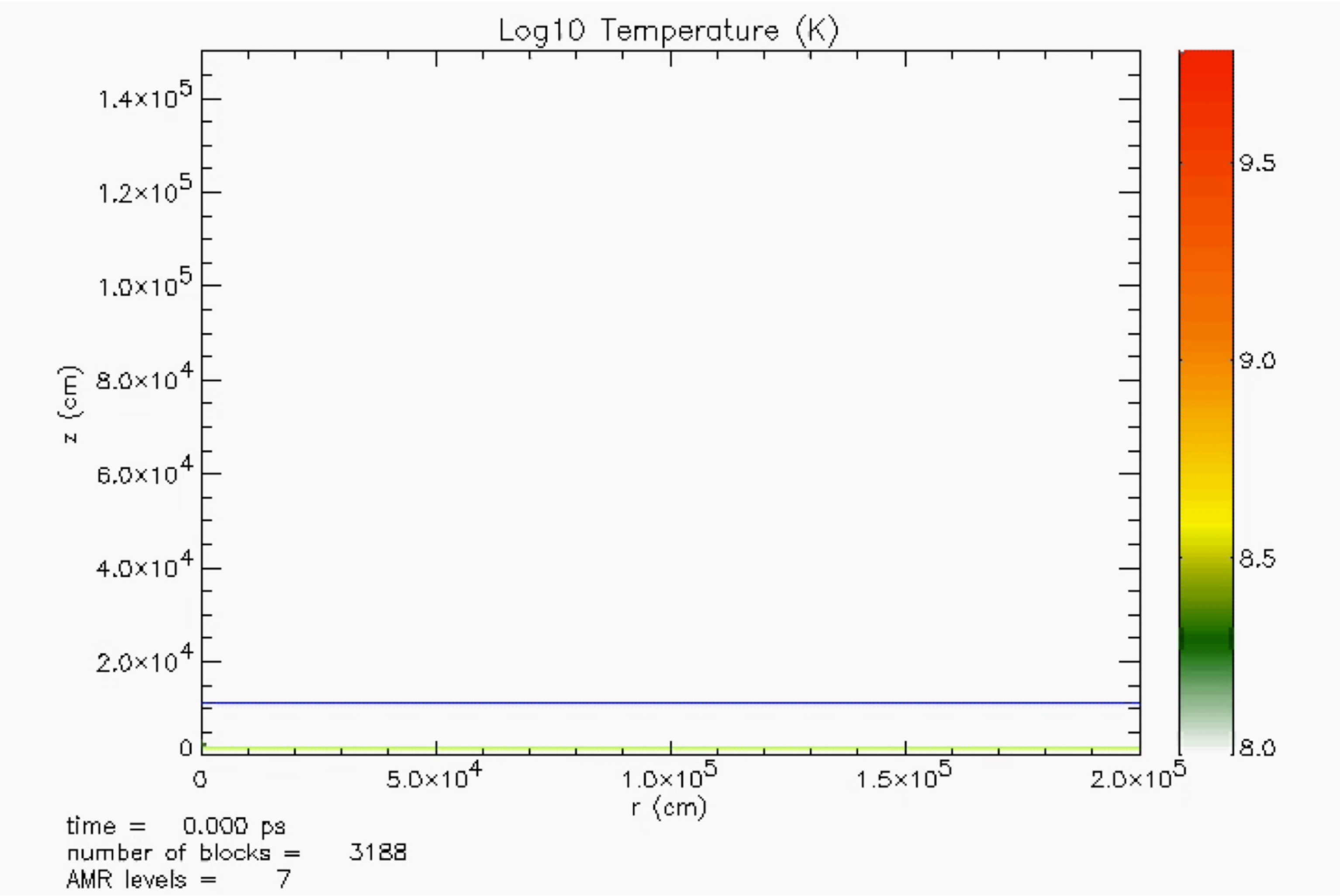
If the matter can get close enough, it can spin the star up very fast indeed; record-holder spins 735 times per second!

Because of the intense gravity, dropping a brick onto a neutron star would release as much energy as an atomic bomb!

Blowing Stuff Up

- Matter flowing from companion piles up
- Can go through fusion flash
- Like all nuclear weapons on Earth, in 10s, per postage stamp area!

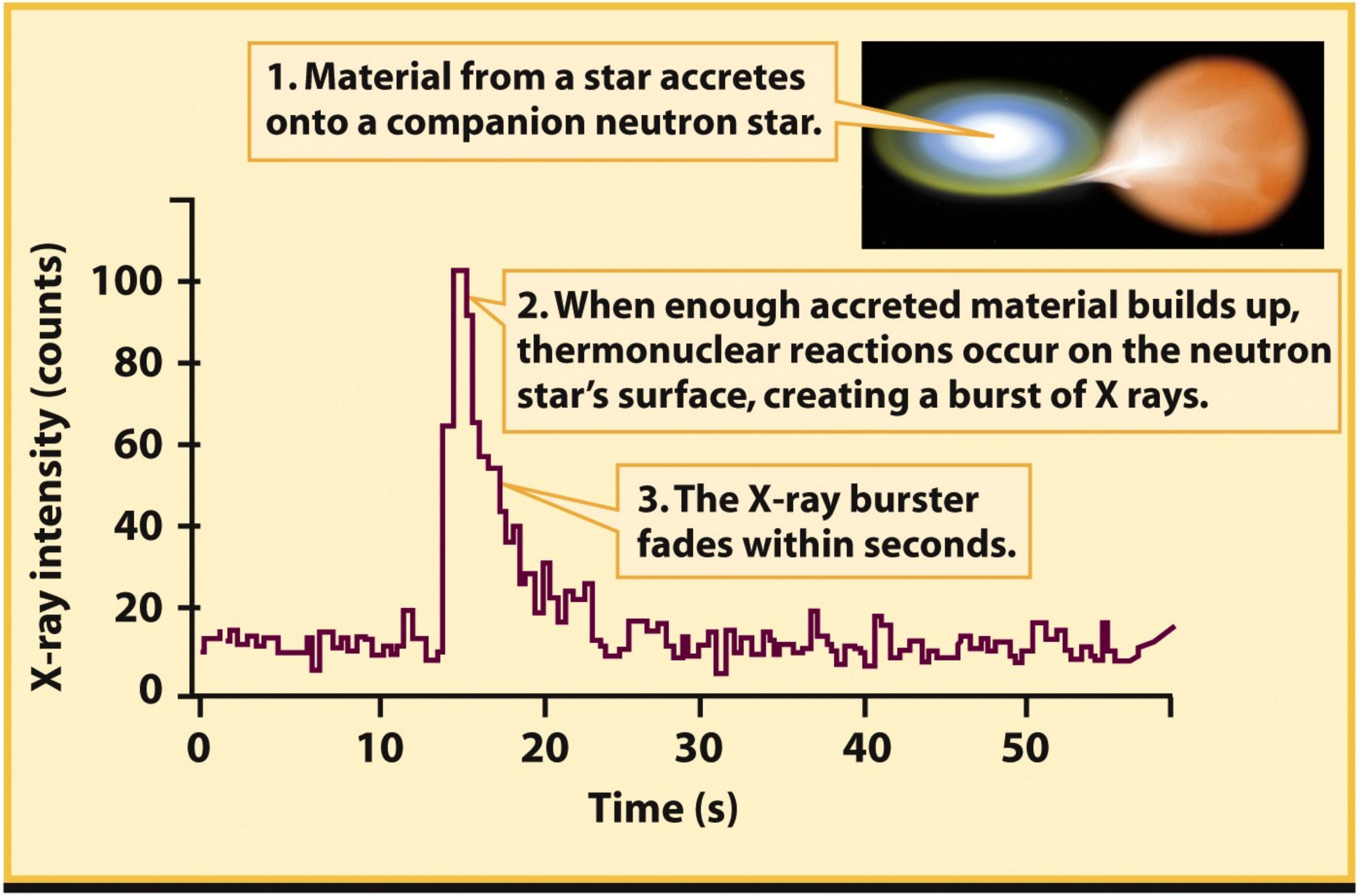
Thermonuclear X-ray Bursts



NS in close binary can accrete from companion.

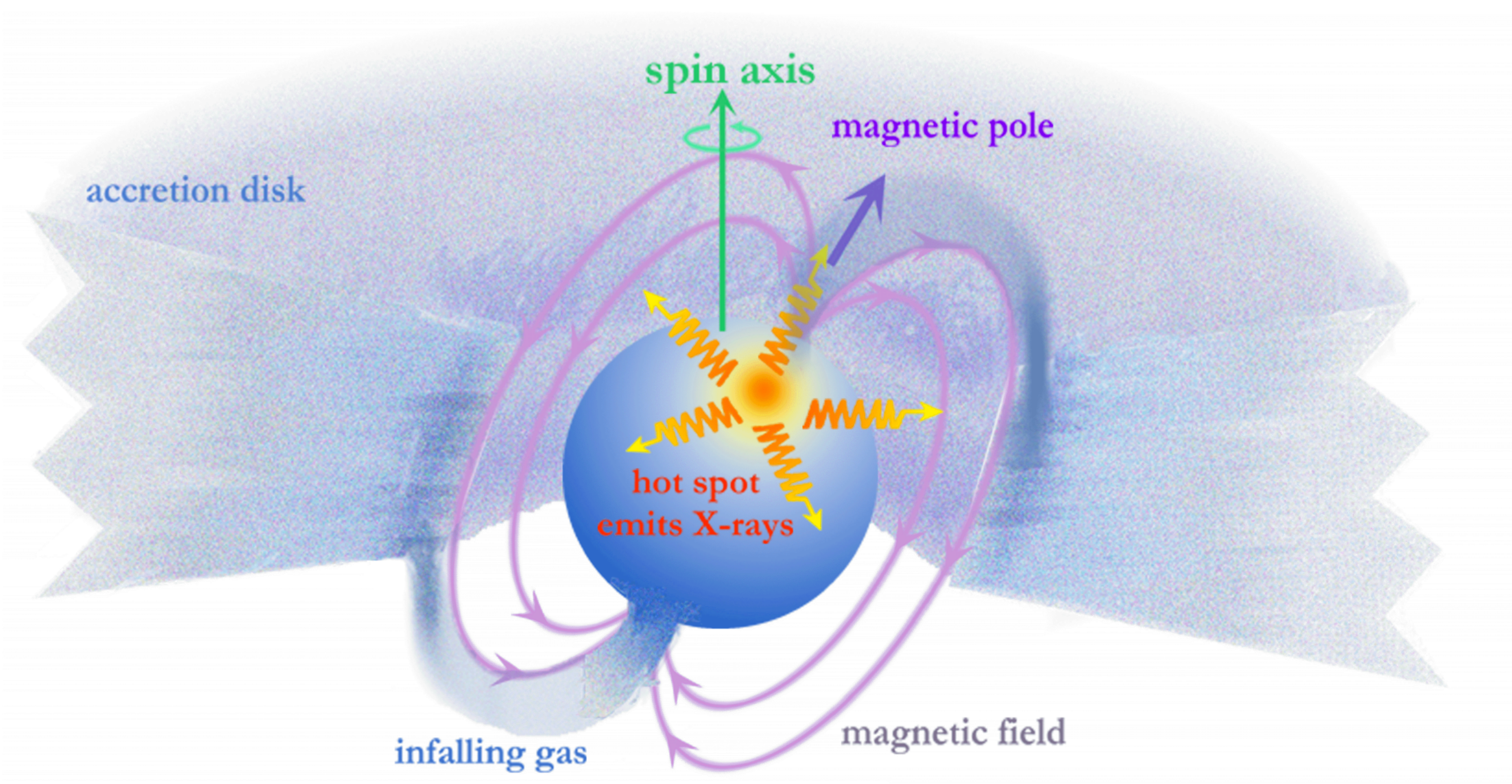
Pileup of H, He can be unstable to fusion.

Mike Zingale: ASC Center for Thermonuclear Flashes


1. Material from a star accretes onto a companion neutron star.
2. When enough accreted material builds up, thermonuclear reactions occur on the neutron star's surface, creating a burst of X rays.
3. The X-ray burster fades within seconds.
X-ray intensity (counts)
0
20
40
60
80
100
0
10
20
30
40
50
Time (s)

X-ray Pulsars

- Requires a *strongly* magnetized rotating neutron star accreting matter from a companion.
- Matter flows down field lines and strikes the magnetic poles of the neutron star: causes X-ray bright "*hotspots*."
- In hotspots, temperatures get high enough to fuse the incoming hydrogen to helium (continuously).
- As poles spin around, the hot-spots flash in and out of view: get an ***accretion-powered X-ray pulsar***.


spin axis
magnetic pole
accretion disk
hot spot
emits X-rays
infalling gas
magnetic field

Magnetars

- In general, neutron stars possess the strongest magnetic fields of any known object.
- But there's a particular class of neutron stars (magnetars) than possess extremely strong fields (10^{15} G or 10^{10} T).
  - Sometimes, these enormous magnetic fields "snap," leading to very intense explosions.
  - Dramatic example… the December 27, 2004 event:
    - During a period of 0.2 s, it produced 100$\times$ the luminosity of our galaxy.
    - It produced a major disturbance on our upper atmosphere (despite being on the other side of our galaxy!).
    - Every X-ray/gamma-ray satellite detected it (even if it wasn't looking!).
    - The blast probably ripped away the top 50 m of the magnetar crust.
  - Good thing it wasn't closer!!!