- Next homework is #7– was due today– last one before exam.

- Exam #2 is in one week! Friday, November 14th!

Want some more extra-credit?

- Watch the Lunar Eclipse this weekend– totality starts around 7:00 pm Saturday Night.
- You can only get extra credit if it was clear, and then you must write 3-4 paragraphs on: What happened? Describe the steps and how it looked. How long in totality? What color was it? Was it cool or lame?
- Worth about 25% of a homework grade.
- Due on Monday Nov 17th at the beginning of class– NO LATE PAPERS WILL BE ACCEPTED!

Outline

- The end of massive stars:
    - Main sequence, red supergiant, helium flash, blue supergaint, red supergiant, supernova, neutron star or…
- Core of a massive star collapses down with so much force that a neutron star is formed.
- Supernova is the shockwave.
- A pulsar is a neutron star that beams us.
- What is Special and General Relativity– Welcome to the world of Einstein.

Exam #2

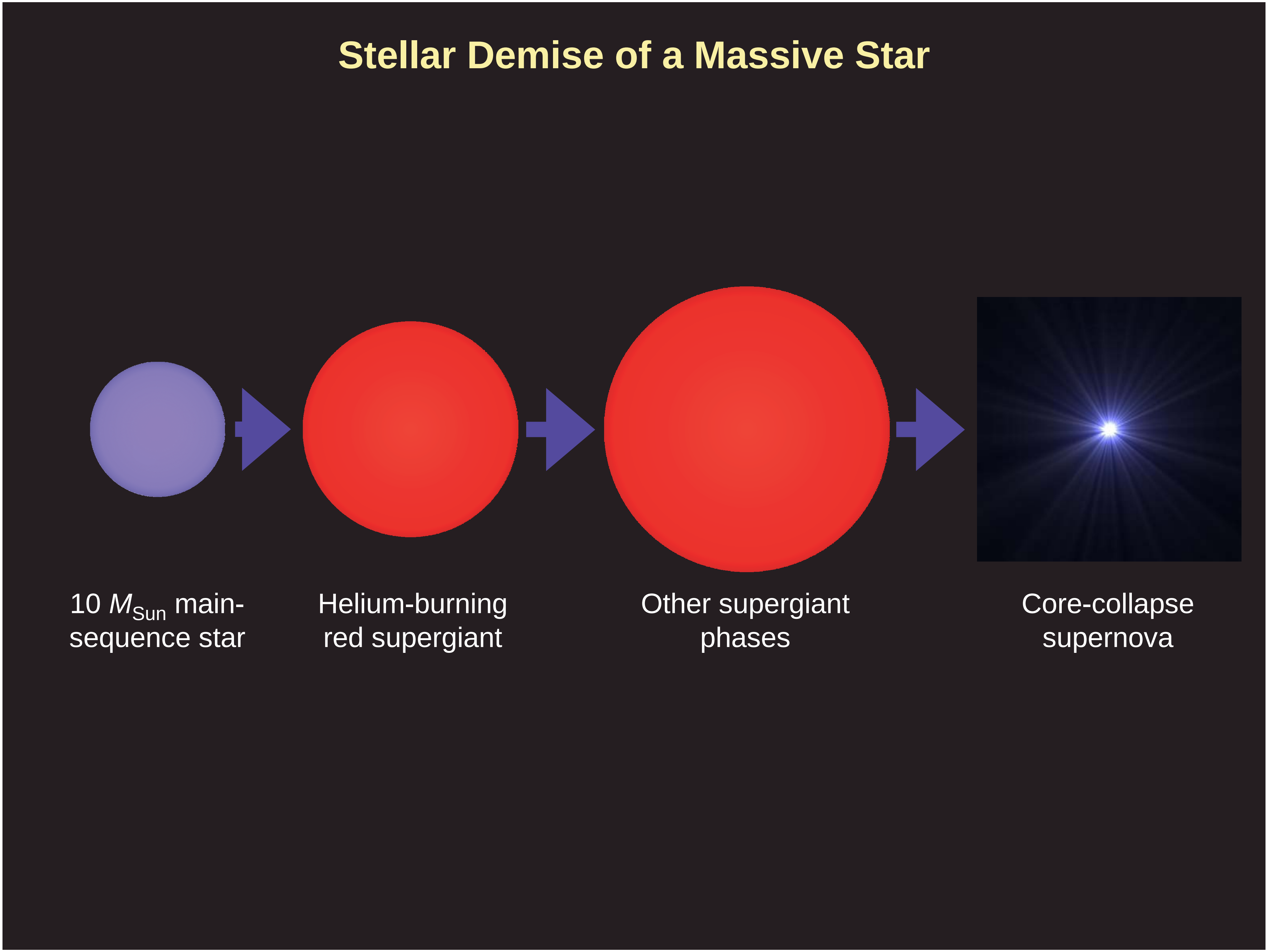
- **Date:** Friday, Nov 14th
- **Place and Time**: In class, at the normal 12:00-12:50 pm time.
- **Format**: 40 multiple choice problems and 2 bonus questions (extra credit).
- **Bring:**
  - Yourself, well-rested and well-studied
  - A #2 pencil
  - On the test you will be given numbers or equations (if any) that you will need. You may **not** use your book or your class notes.

Exam #2

- **Topics included**: All material from the Sun through blackholes. Lecture and reading material are both included. My goal is to test for understanding of the concepts we have discussed, and how they fit together.
- **Study tips.** We have covered a lot of material in a short time, so here are some tips on how to approach your studies for the exam.
  - Topics covered in lectures should be stressed.
  - Homework questions have good examples of questions that may show up on the exam. An excellent way to begin studying is to review the homework problems, particularly those you missed (or got right but were not so sure about). Be sure you understand what the right answer is, and more importantly, **why** it is right.
  - You will need to understand and be able to use any equations that have been introduced in class. Calculations using these equations will be kept simple--it is possible to do the exam without a calculator, but you can bring one if you wish.

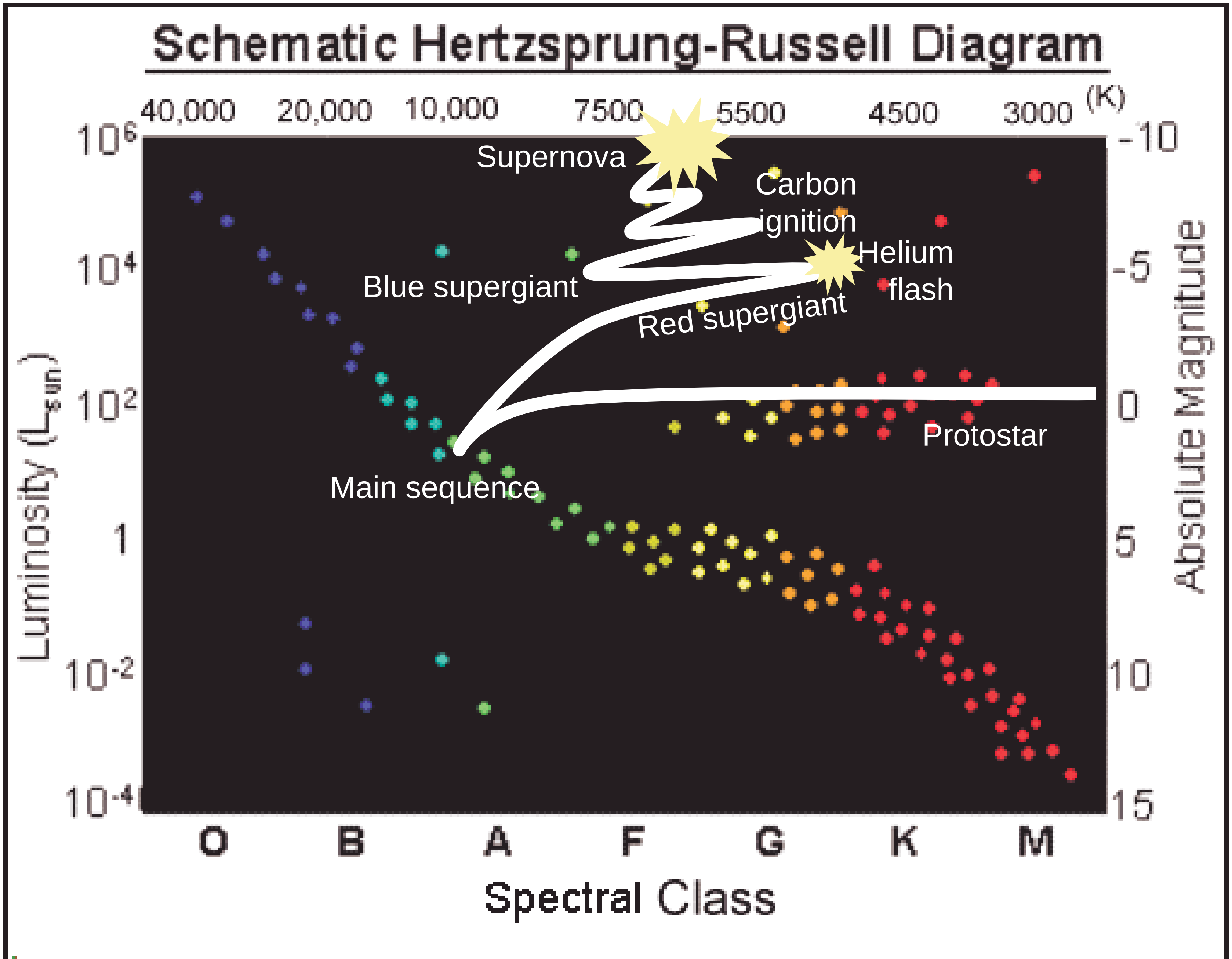
Exam #2

- **In-Class Q and A:** On Wed., Nov. 5th, some time will be allotted in class to ask questions about material on the exam. For example, if there are homework answers you do not understand, this would be an excellent time to ask. To get the most out of this time, you are strongly encouraged to begin studying prior to this class.
- **Out of Class Q and A:** On Thursday, Nov. 13th, I will have office hours from 10:30 to 11:30am and Justin will have TA office hours at 4:00 to 6:00pm. You should bring questions.



Stellar Demise of a Massive Star
10 M_{Sun} main-sequence star
Helium-burning red supergiant
Other supergiant phases
Core-collapse supernova

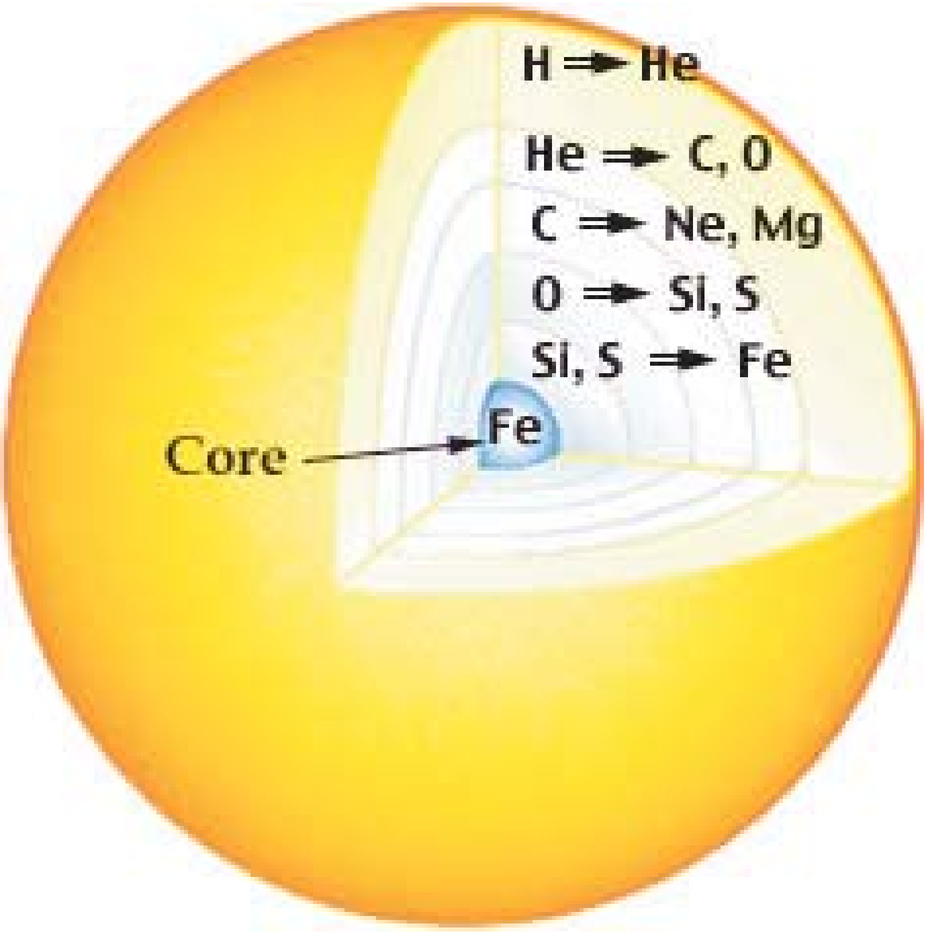
Evolutionary Path of High-Mass Stars: M > 8 M_{Sun}



High Mass Stars

- These are very similar to the intermediate mass stars, but as they have more mass, they can "burn" heavier and heavier atoms in the fusion process.
- Until they create Iron– after that it takes energy to produce heavier atoms
- Nothing left!

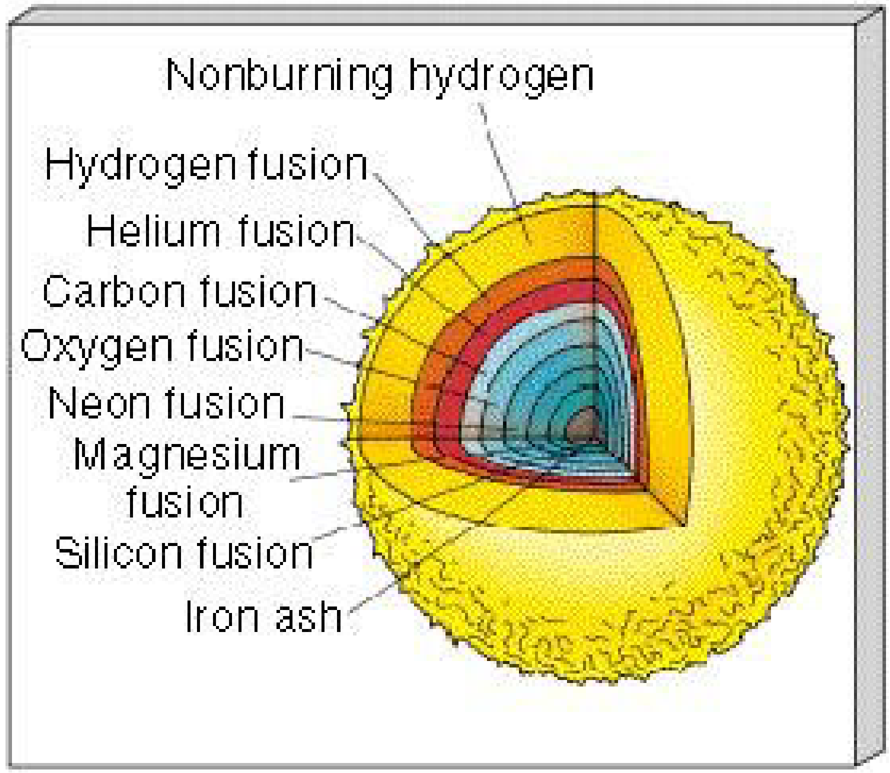
Stage	Temperature (million K)	Duration
H fusion	40	7 million yr
He fusion	200	500,000 yr
C fusion	600	600 yr
Ne fusion	1,200	1 yr
O fusion	1,500	6 months
Si fusion	2,700	1 day



Massive Stars: Late Stages

- Cycles of core contraction, heating, ignition
- Cycles of ash ⇒ fuel
- Burning ever more rapid
- C+He ⇒ oxygen
- O+He ⇒ neon
- ... Up to iron

- Onion-skin structure develops



Core Collapse

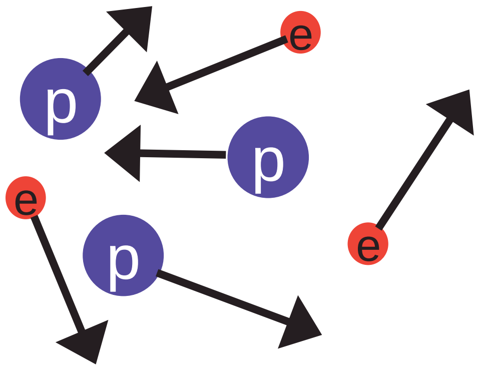
Outer shells collapse rapidly

- Speeds approach *c*
- Just like the white dwarf stage, the core gets compressed to enormous density
- …and high temperature » 10 billion K
- Electrons in core squeezed into protons

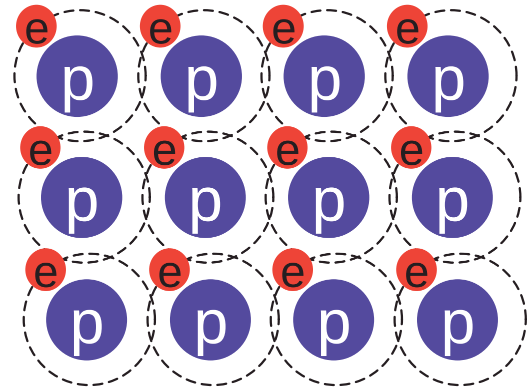
$$p + e \rightarrow n + \nu$$

- Nuclei in core transformed to a sea of neutrons
- Neutrinos released

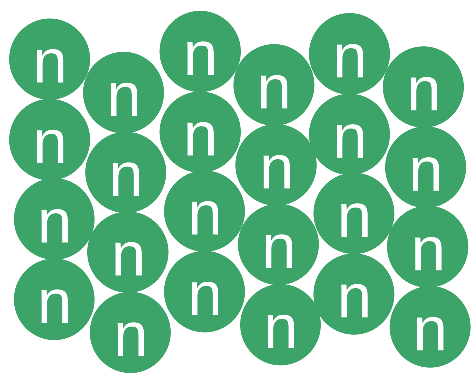
When Electron Degeneracy Just Isn't Enough



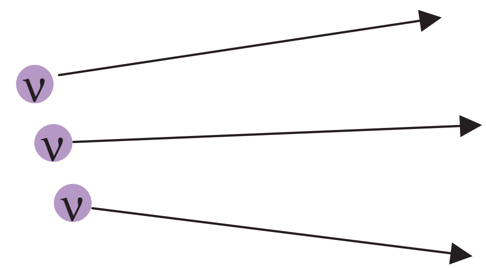
Matter in the core of
a normal star



Electron-degenerate
matter in a white dwarf
1 ton per cubic cm



Neutron-degenerate matter in
a neutron star
400 million tons per cubic cm



Neutrinos produced
as electrons are
forced into nuclei

Massive Star Death: Supernova

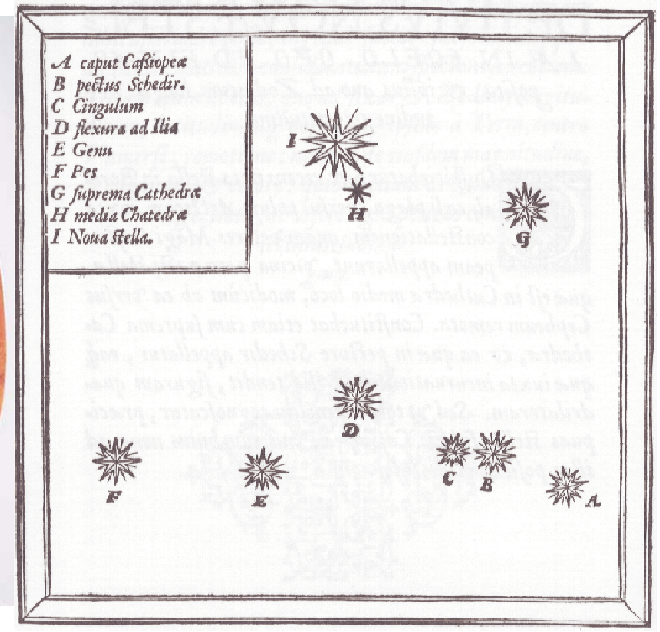
Collapsing outer layers "bounce" off dense neutron core

outward shock wave

- *Demo: Astro Blaster*
- outer layers ejected
- *supernova explosion*

Game Over!

November 11, 1572 Tycho Brahe



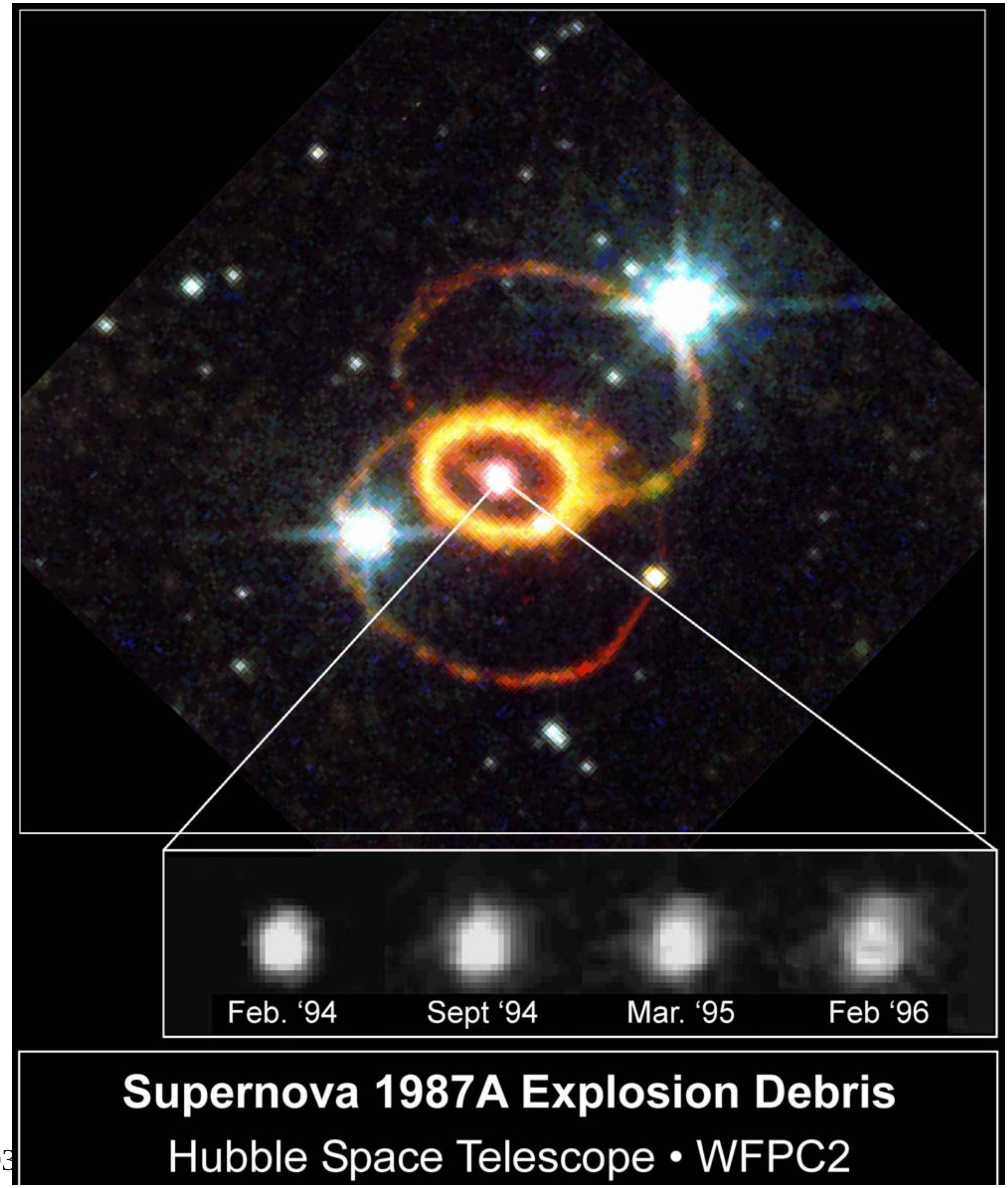
On the 11th day of November in the evening after sunset ... I noticed that a new and unusual star, surpassing the other stars in brilliancy, was shining ... and since I had, from boyhood, known all the stars of the heavens perfectly, it was quite evident to me that there had never been any star in that place of the sky ...

I was so astonished of this sight ... A miracle indeed, one that has never been previously seen before our time, in any age since the beginning of the world.

http://www.hao.ucar.edu/public/education/sp/images/tycho.1.html

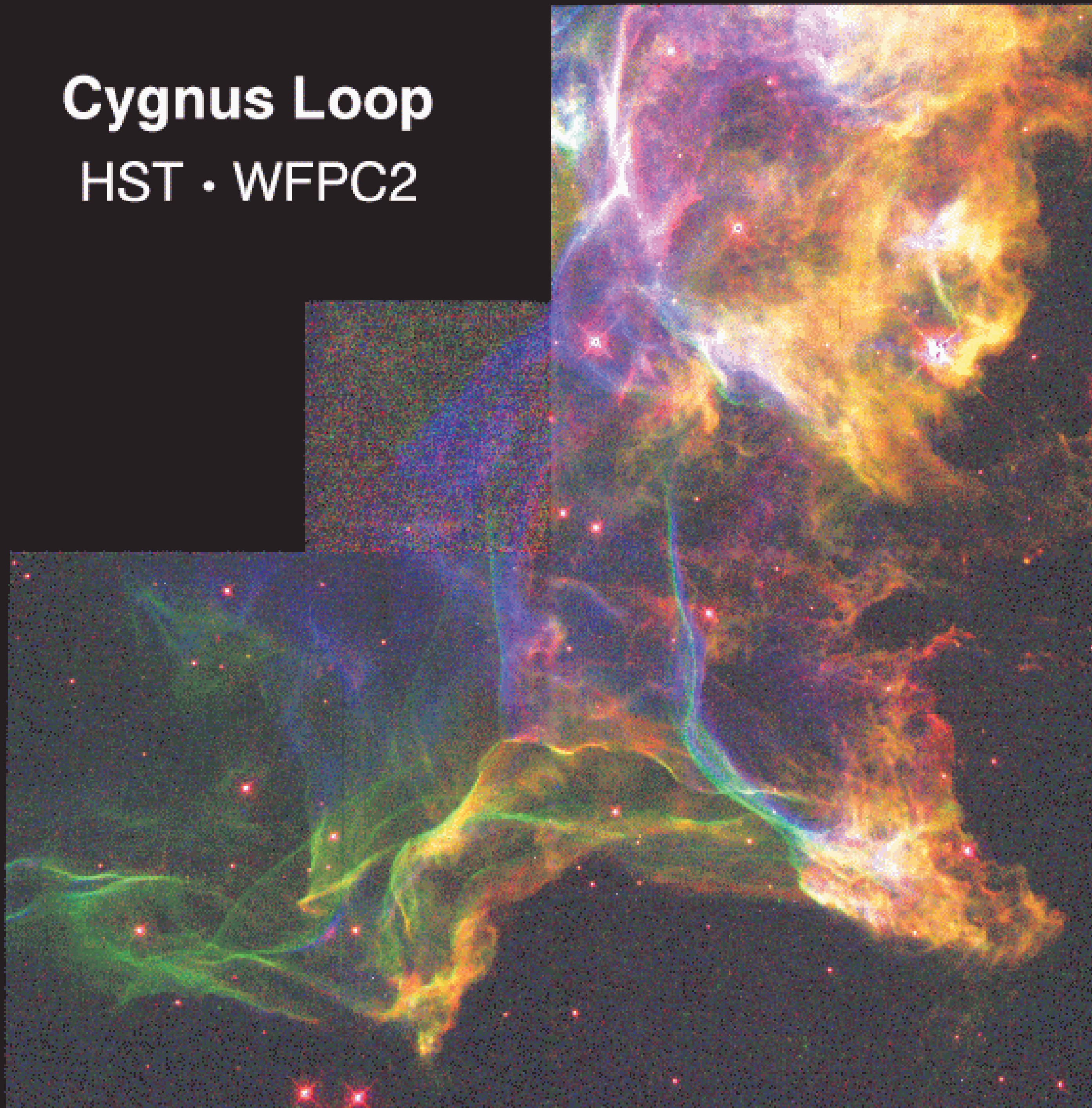
Supernova 1987a

Before   Feb. 23, 1987


Feb. '94
Sept '94
Mar. '95
Feb '96
Supernova 1987A Explosion Debris
Hubble Space Telescope • WFPC2

Cygnus Loop

HST • WFPC2

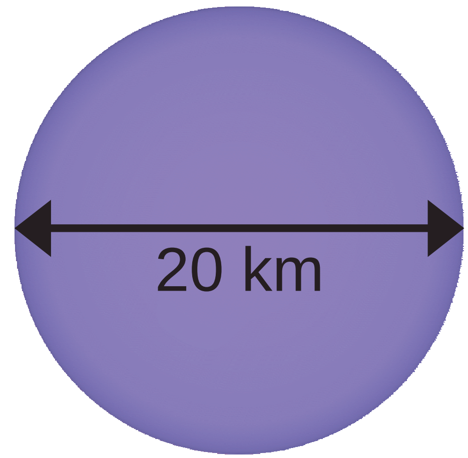


ST ScI OPO PRC95-11 · February 1995 2/14/95 zgl

Neutron Star– Left over Remains of a Supernova!

- Almost like a nucleus–
  very high density 10^{17} kg/m^3
- Supported by neutron degeneracy pressure!
- Teaspoon of neutron star material on Earth would weigh 1 billion tons!!!!
- Gets reduced to very small diameter– around 20 km!
- Escape velocity of half the speed of light

Relative Sizes of Degenerate Compact Stars



Neutron star

What It's Really Like To Be Crushed Flat

- Mass of the Sun in a sphere with radius 10 km
- Surface gravity 200 billion times that on Earth
- Any surface features are crushed to < 1 cm height

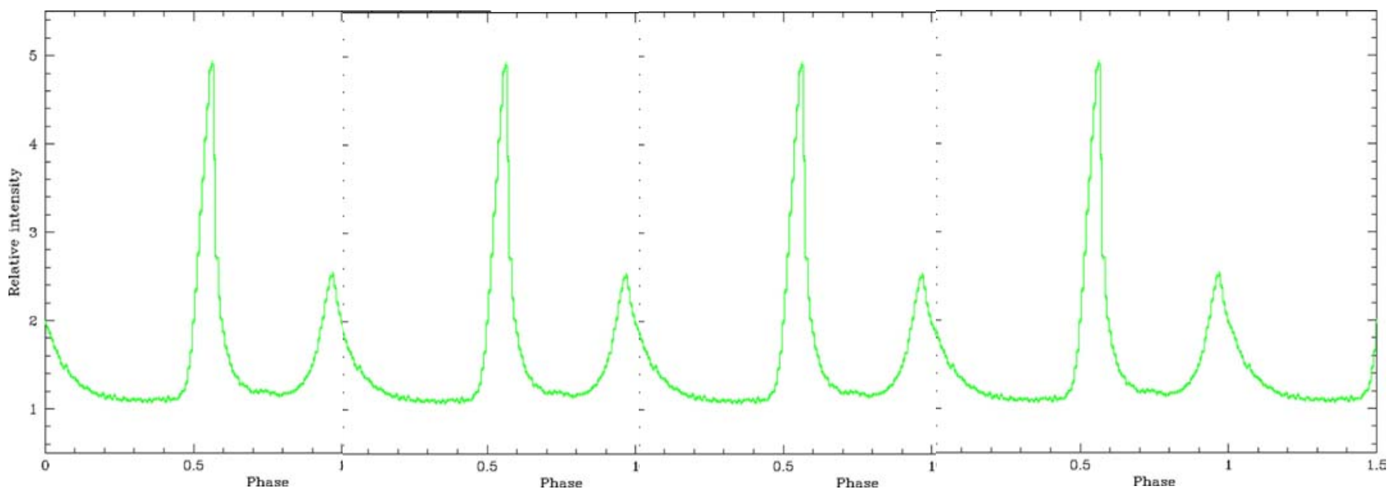
Pulsars

- Neutron stars were thought to be a cool thing that would never been seen– nice theory. But…..
- First discovered through radio observations by Anthony Hewish and Jocelyn Bell in late 1960s
- Actually, Jocelyn (while working as a graduate student) found these radio waves that repeated themselves very regularly
- http://pulsar.princeton.edu/pulsar/multimedia.shtml
- Originally called LGM – Little Green Men

Jocelyn Bell Burnell

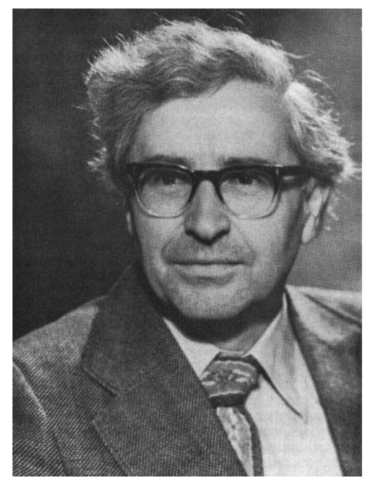
Pulsars

- Accreting, magnetized neutron stars produce regular pulses as their beams sweep past us



Crab Pulsar – Herschel Telescope

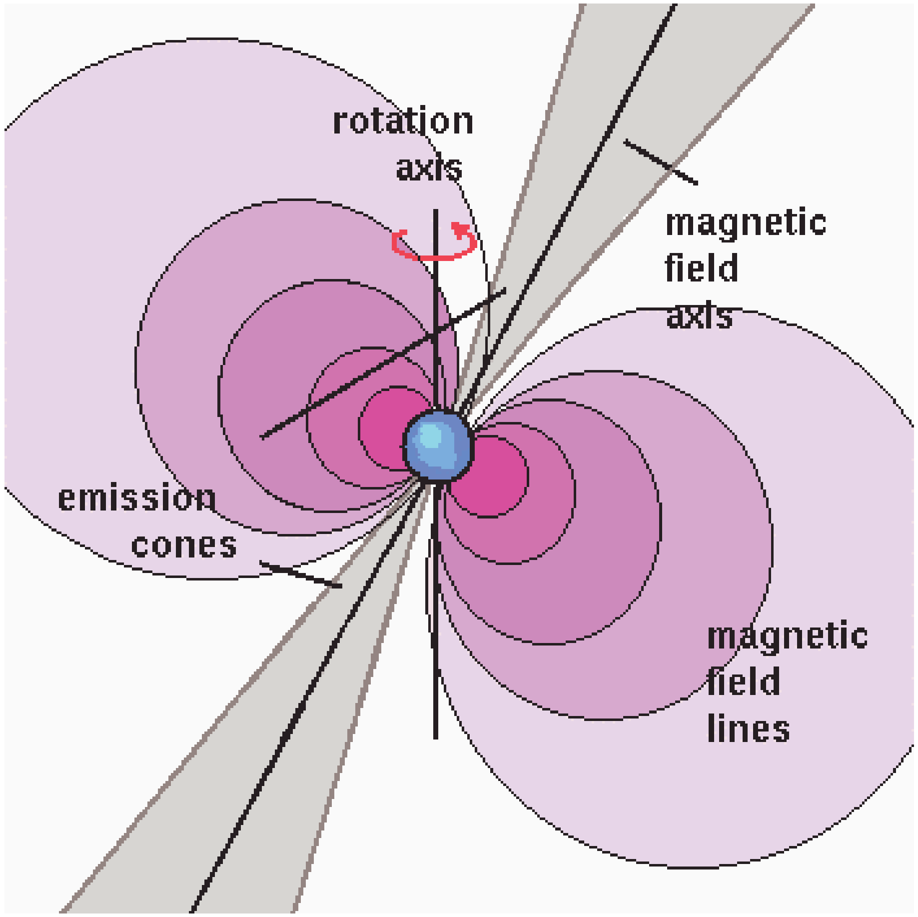
Jocelyn Bell Burnell



Anthony Hewish

What are Pulsars?

- Spin and magnetic field strength of a neutron star are enhanced by collapse
- Typically
  - Surface field strength > 1 trillion times that of the Earth
  - Rotation rate up to 1000 times *per second*
- Spin and magnetic axes are usually not aligned

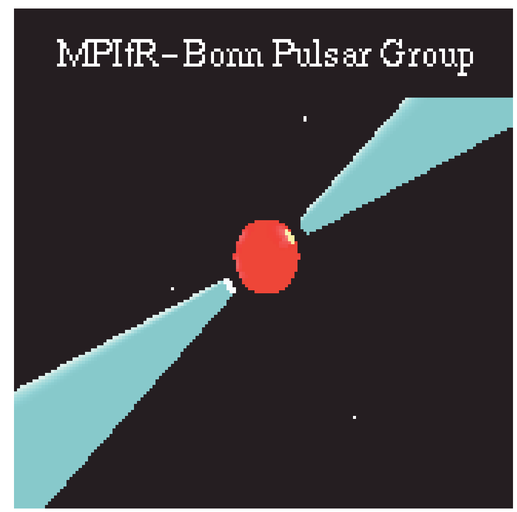


The Pulsar Model: Lighthouse Model

- The pulsar is beaming light at us (mostly in the radio spectrum).
- If the Earth is in the beam, we see the pulsar. If not, we don't see it.

http://chandra.harvard.edu/xray_sources/pulsar_java.html

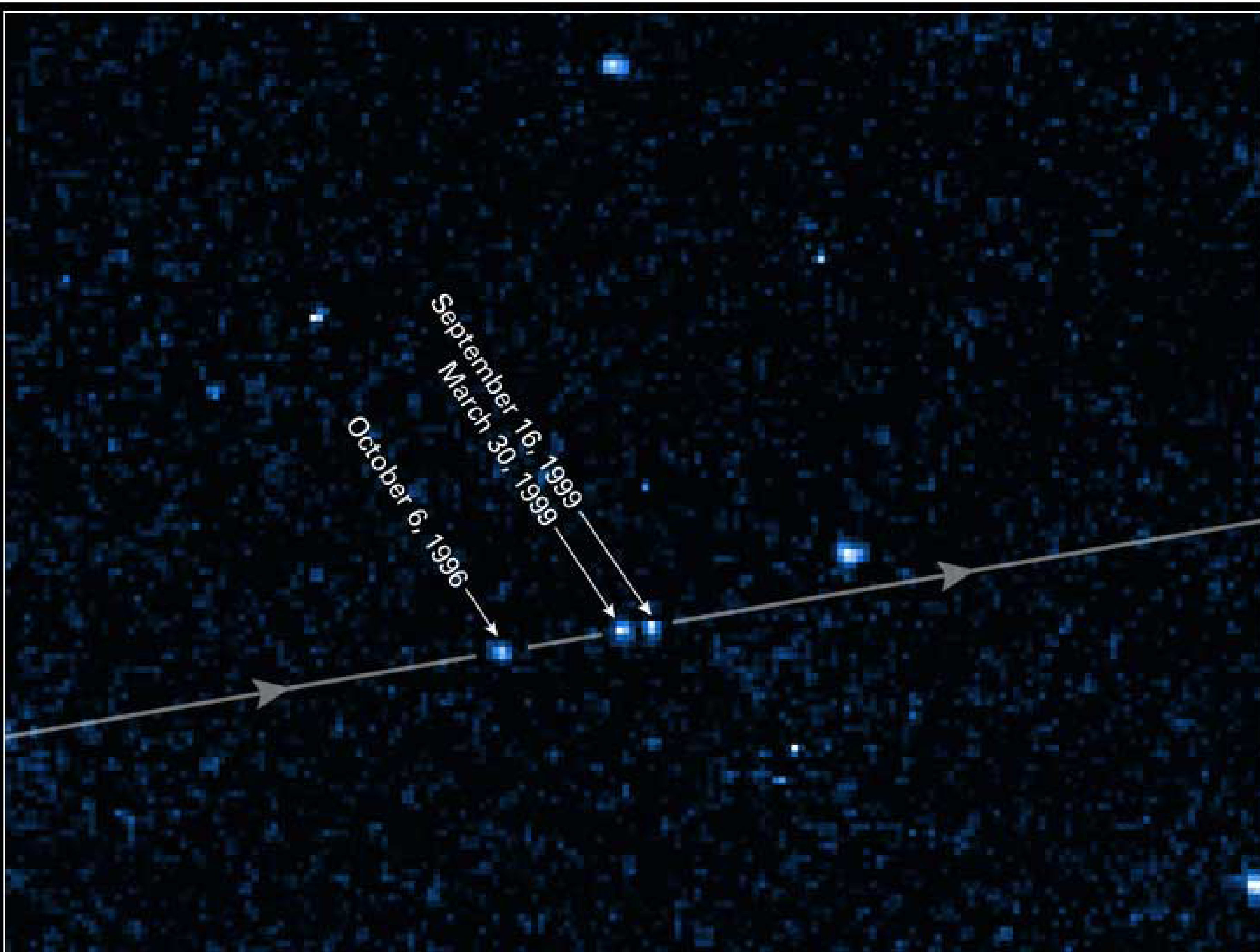
Signature of these strange objects.



Virtual Planetarium

Neutron Star

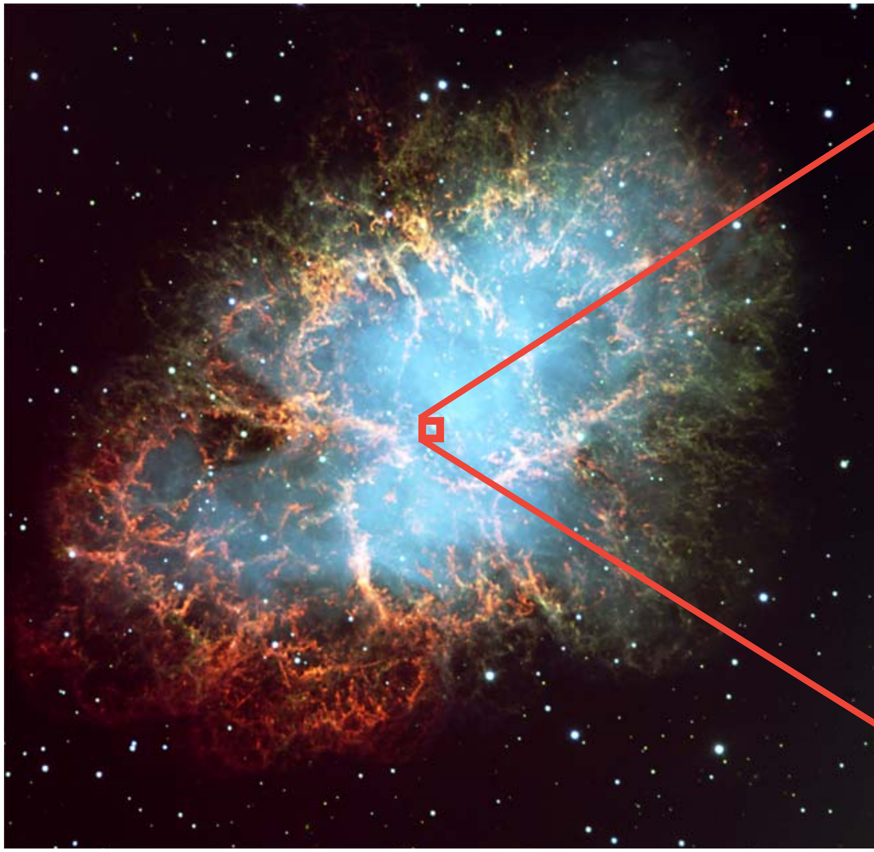
It's as big as Manhattan Island, is 10 trillion times denser than steel, and is hurtling our way at speeds over 100 times faster than a supersonic jet. An alien spaceship? No, it's a runaway neutron star, called RX J185635-3754.



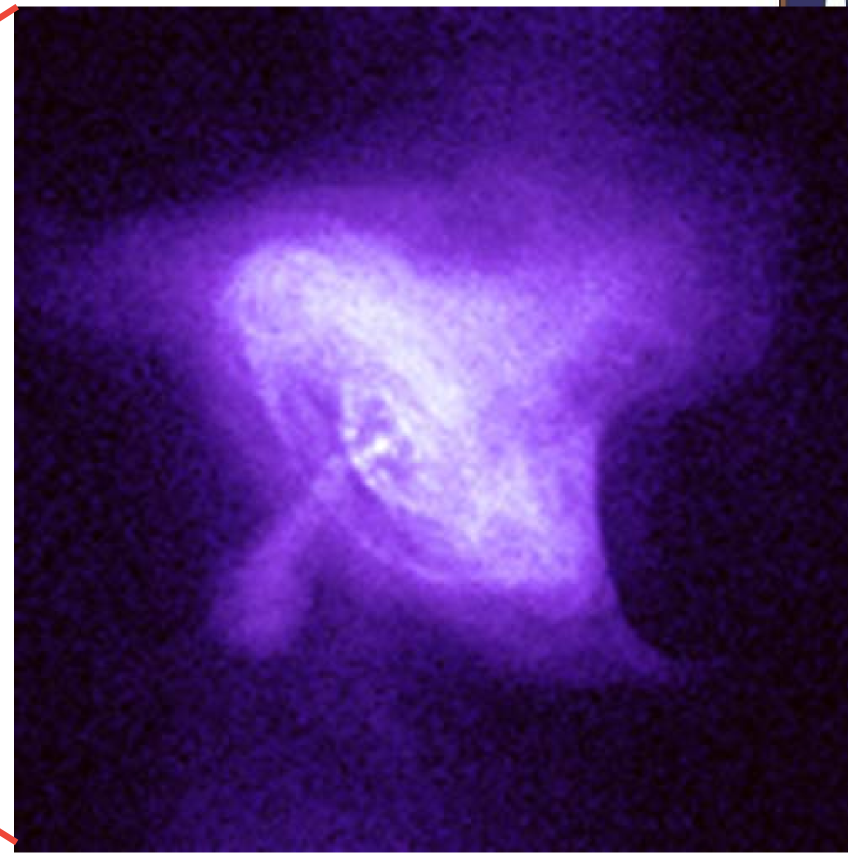
Neutron Star RX J185635-3754 HST • WFPC2

NASA and F. Walter (State University of New York at Stony Brook) • STScI-PRC00-35

Crab Nebula – Remnant of the Supernova of 1054



Optical - ESO



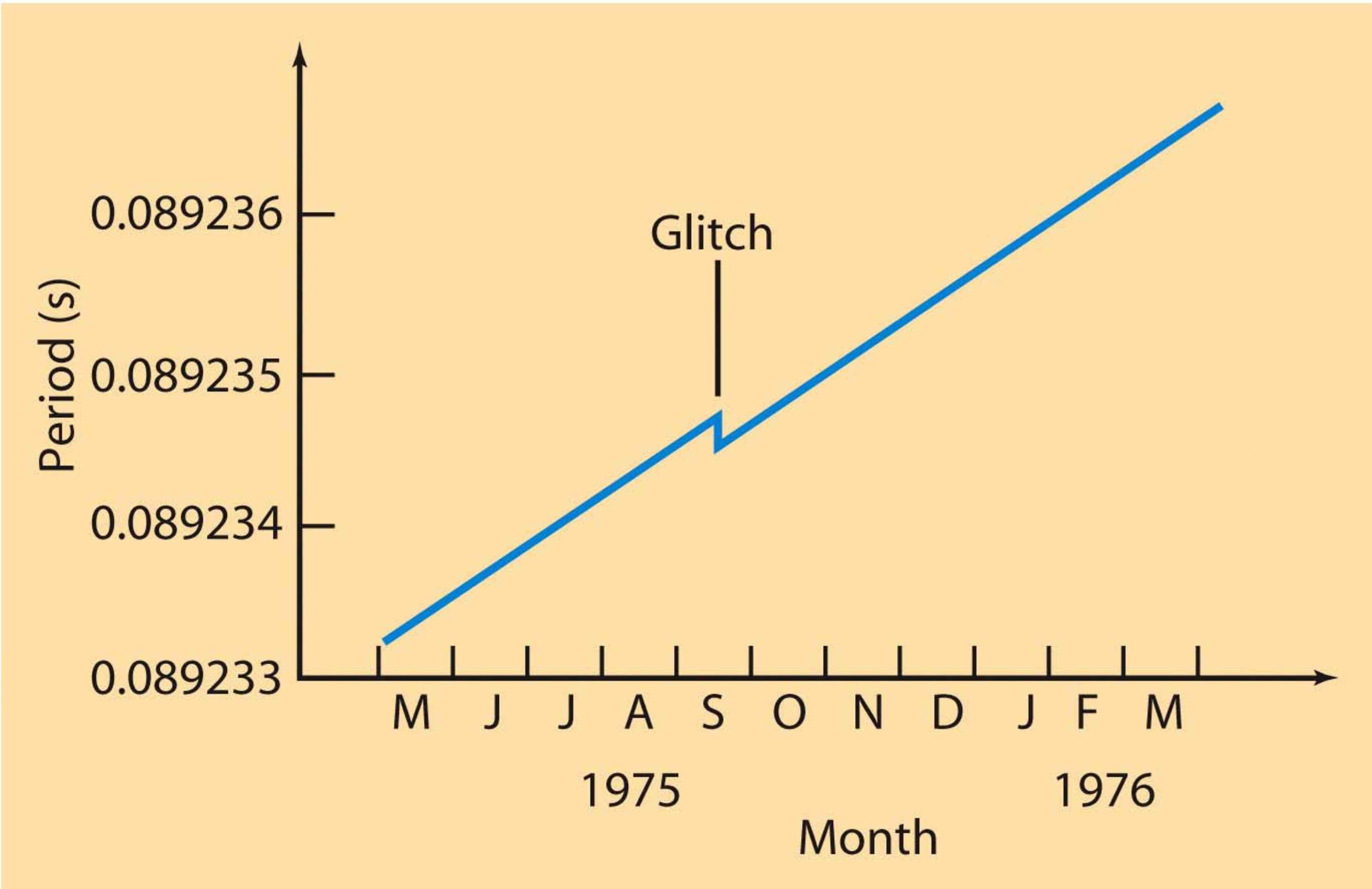
X-ray - Chandra

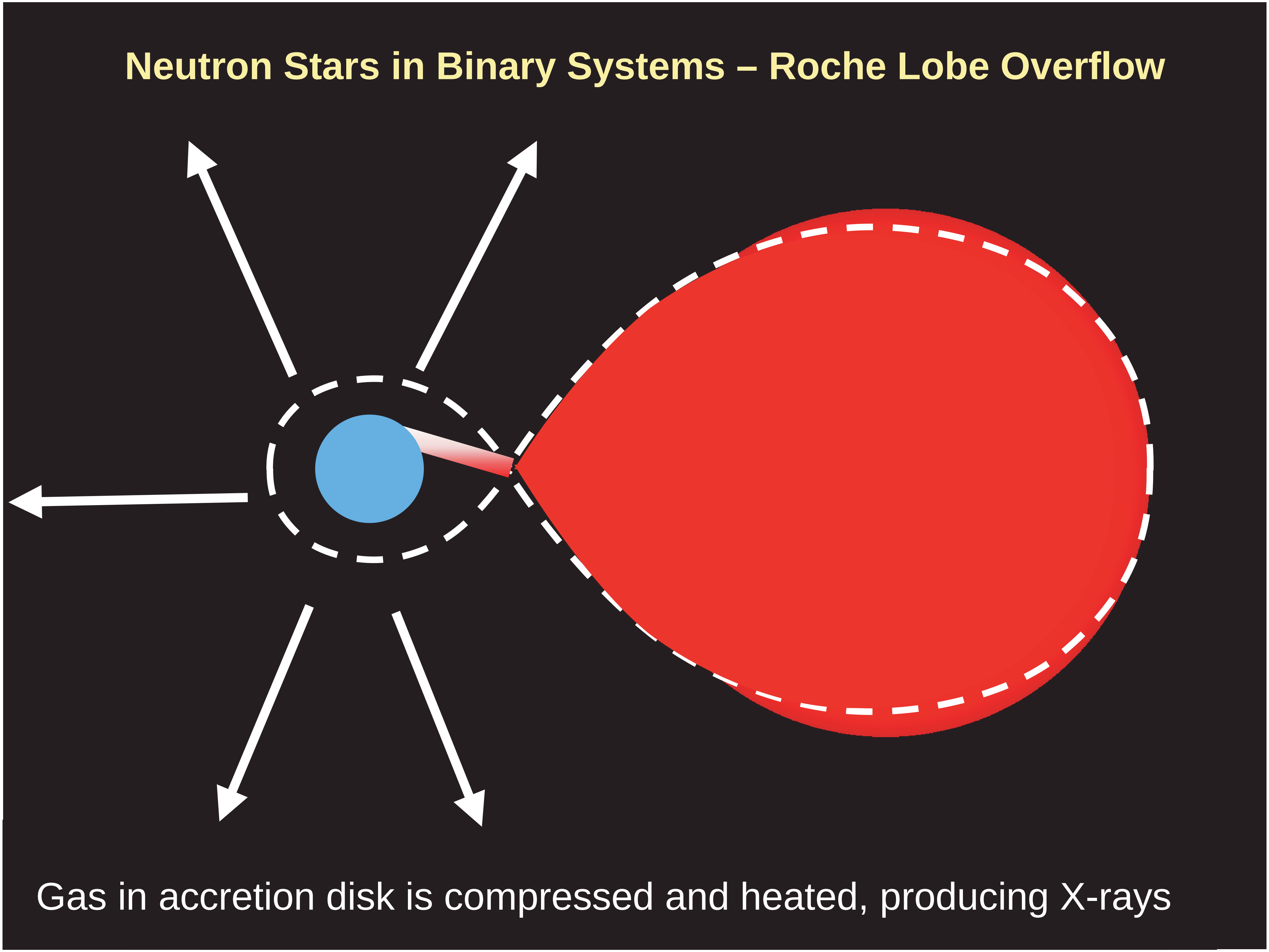
Combined Hubble/Chandra movie

Pulsar wind animation

Pulsar Glitches

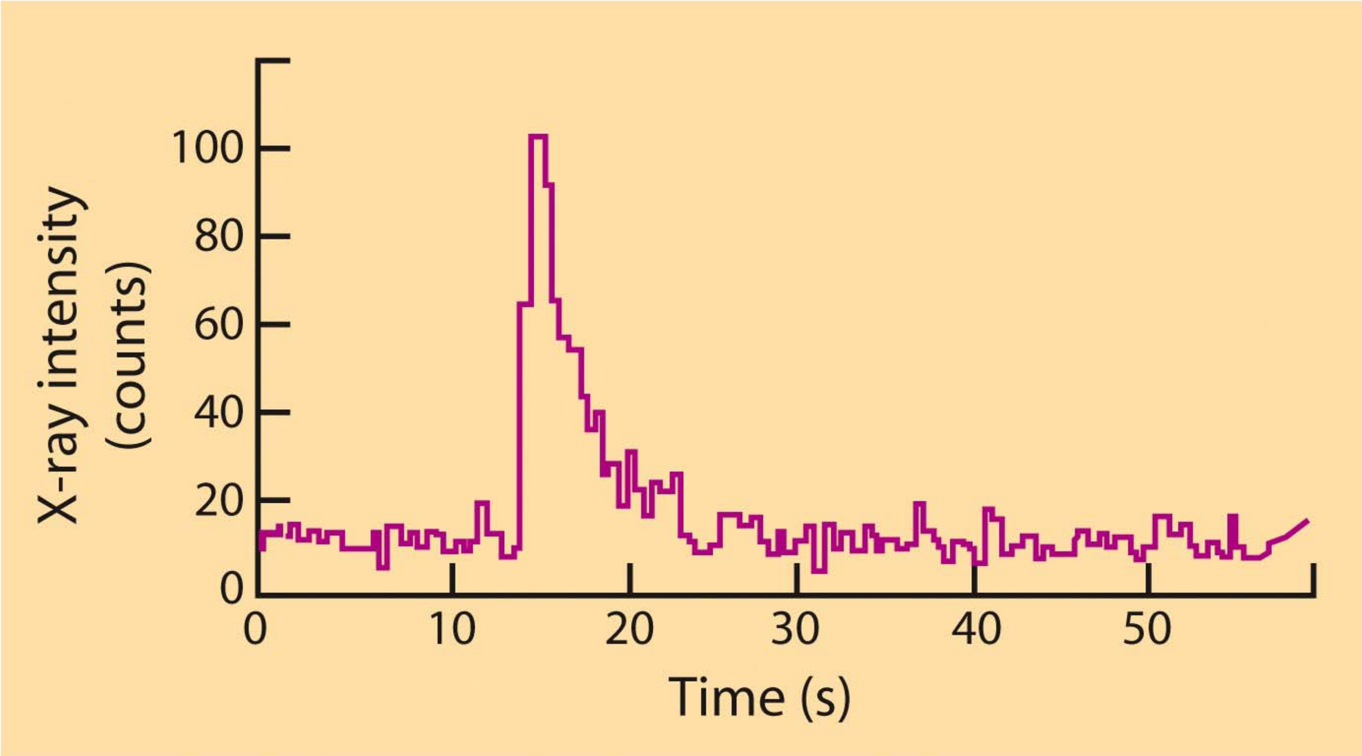
- Pulsars gradually slow down as they radiate energy
- Occasionally this **spin-down** changes abruptly (**glitch**)




Neutron Stars in Binary Systems – Roche Lobe Overflow
Gas in accretion disk is compressed and heated, producing X-rays

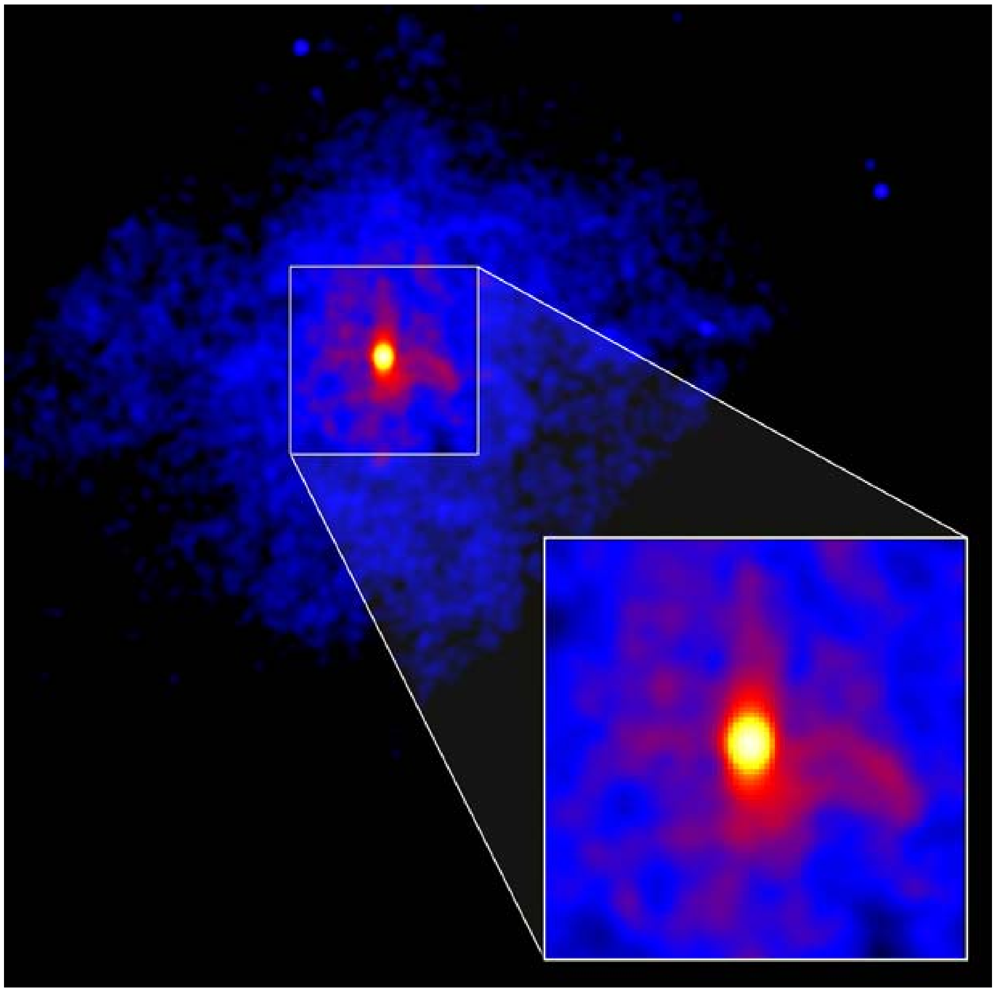
X-Ray Bursts

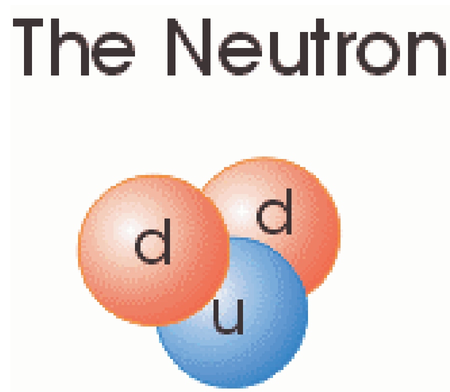
- In binary systems, hydrogen from companion builds up on the neutron star's surface
- Steadily fused to helium
- When accumulates to depth of 1 m, undergoes explosive helium fusion
- Result: intense burst of X-rays

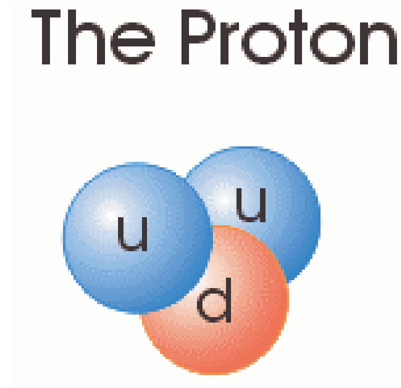


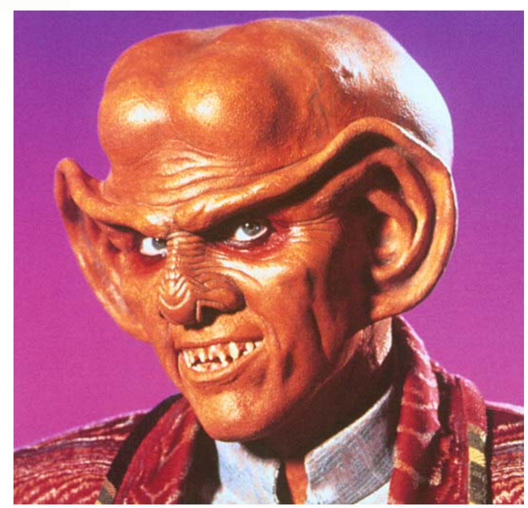
When Neutron Degeneracy Isn't Enough

- Maximum neutron star mass: $3.0M_{Sun}$
- Might be a further stage: **quark stars**
- If not: nothing can halt collapse to a **black hole**









Chandra – 3C58 (X-ray)

Relativity deals with the question:

How do the laws of nature appear to change when you change your state of motion …

Special Relativity

… when your velocity relative to something else is close to the speed of light?

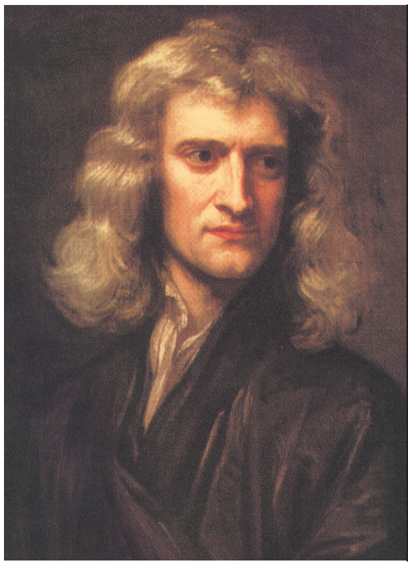
General Relativity

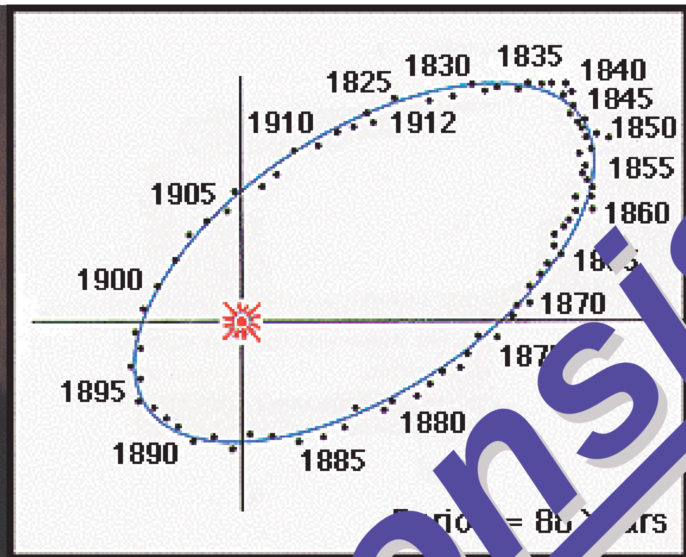
… when you are in a strong gravitational field?

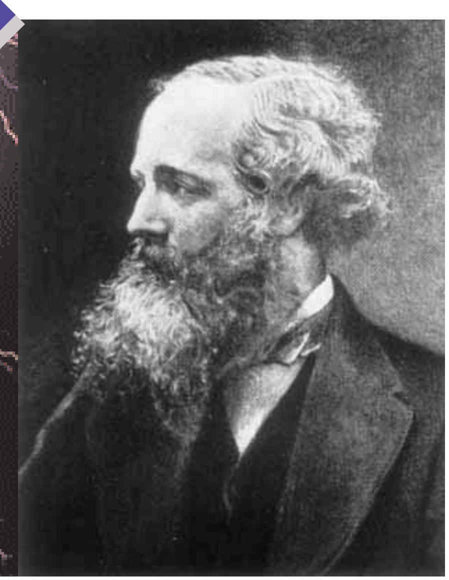
Two Threads of Thought in Physics up to 1900

Mechanics
(Newton's Laws)

Electromagnetism
(Maxwell's Equations)







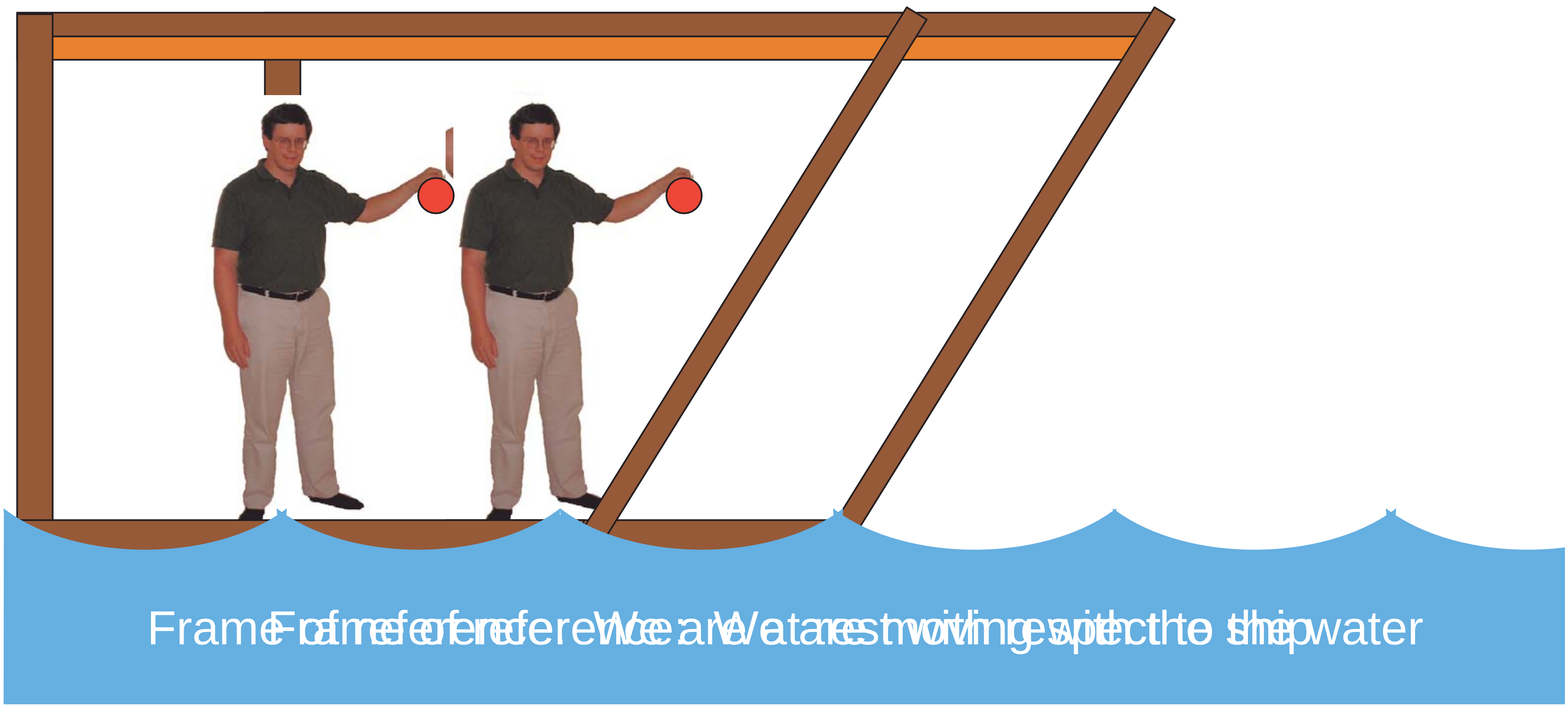
Inconsistent!

All motion is relative
No speed is special

The speed of light is the **same** for all observers

Galileo's ship thought experiment

No experiment within the ship's cabin can detect the ship's motion if the ship moves in the same direction at a constant velocity.



Why Galileo and Maxwell Can't Both Be Right

Consider two locomotives emitting light from their headlamps:

At rest

Moving at some speed *v*

Why Galileo and Maxwell Can't Both Be Right

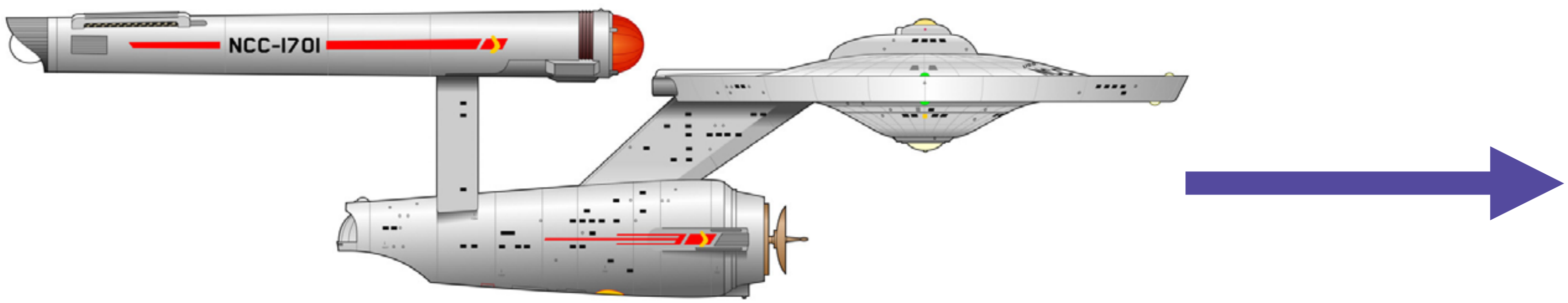
If light emitted by #2 moves relative to #2 at speed c, Galileo says that #1 must see it move at $c + v$.

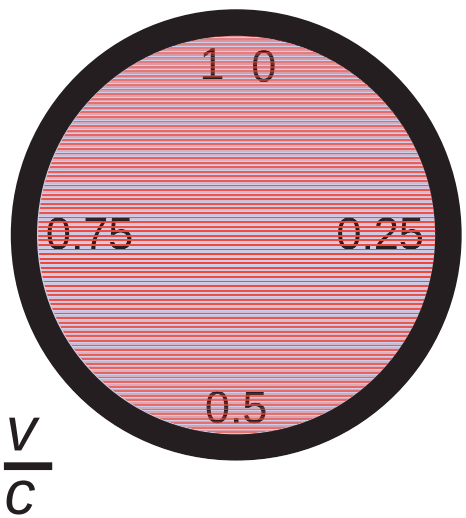
But light emitted by #1 moves relative to #1 at speed c – or at speed $c - v$ relative to #2!

So the speed of light can't be the same for everyone if Galileo – and our intuition – are right. But Maxwell says it is constant!

Counterintuitive Result #1

Moving objects appear shorter in the direction of relative motion (<u>Lorentz contraction</u>)





Fraction of the speed of light	% of original length
0.00	100%
0.001	99.99995%
0.01	99.995%
0.1	99.5%
0.5	86.6%
0.9	43.6%
0.99	14.1%