Class 11 : Neutron stars and pulsars

ASTR350 Black Holes (Spring 2022)
Cole Miller

This class

- Discovery of pulsars-first direct evidence of neutron stars
- Connection of neutron stars to pulsars
- Exotic nature of neutron stars
- Neutron stars are the 'most' relativistic of all objects OTHER than black holes

RECAP

- Stellar life and death
- Low mass stars ($M<8M_{sun}$)
  - Most of long life on main sequence (H➔He)
  - After exhausting hydrogen in core, enters complex post-MS evolution passing through Red Giant phase
  - End with a White Dwarf ($M>0.4M_{\odot}$)
- High mass stars ($M>8M_{sun}$)
  - Core temperatures are much hotter- short lives
  - Run through H more quickly, then start to fuse other elements.
  - End up with shells of successively heavier elements, ending with an iron core
  - Collapse of iron core produces supernova and may leave a remnant neutron star or black hole

Recap-Origin and Basic Properties

- The collapse of massive stars can end when the degeneracy pressure of neutrons balances the gravitational forces of the matter (ignoring the strong force-baryonic interactions)-produces a neutron star.
  - The term neutron star refers to a star with a mass M on the order of 1.2-2 $M_{\odot}$, radius R of~8-16km, and a central density as high as 5 to 10 times the nuclear equilibrium density
- If the remnant is too massive- collapse to black hole (actually more complex)

Importance of Supernova

- Supernovae are the source of many of the elements of nature
- Their blasts control the structure of the interstellar medium
- They are the origin of most cosmic-rays
- A majority of them give birth to neutron stars and black holes.
- Very luminous and can be seen across the Universe and have been used to determine cosmological parameters

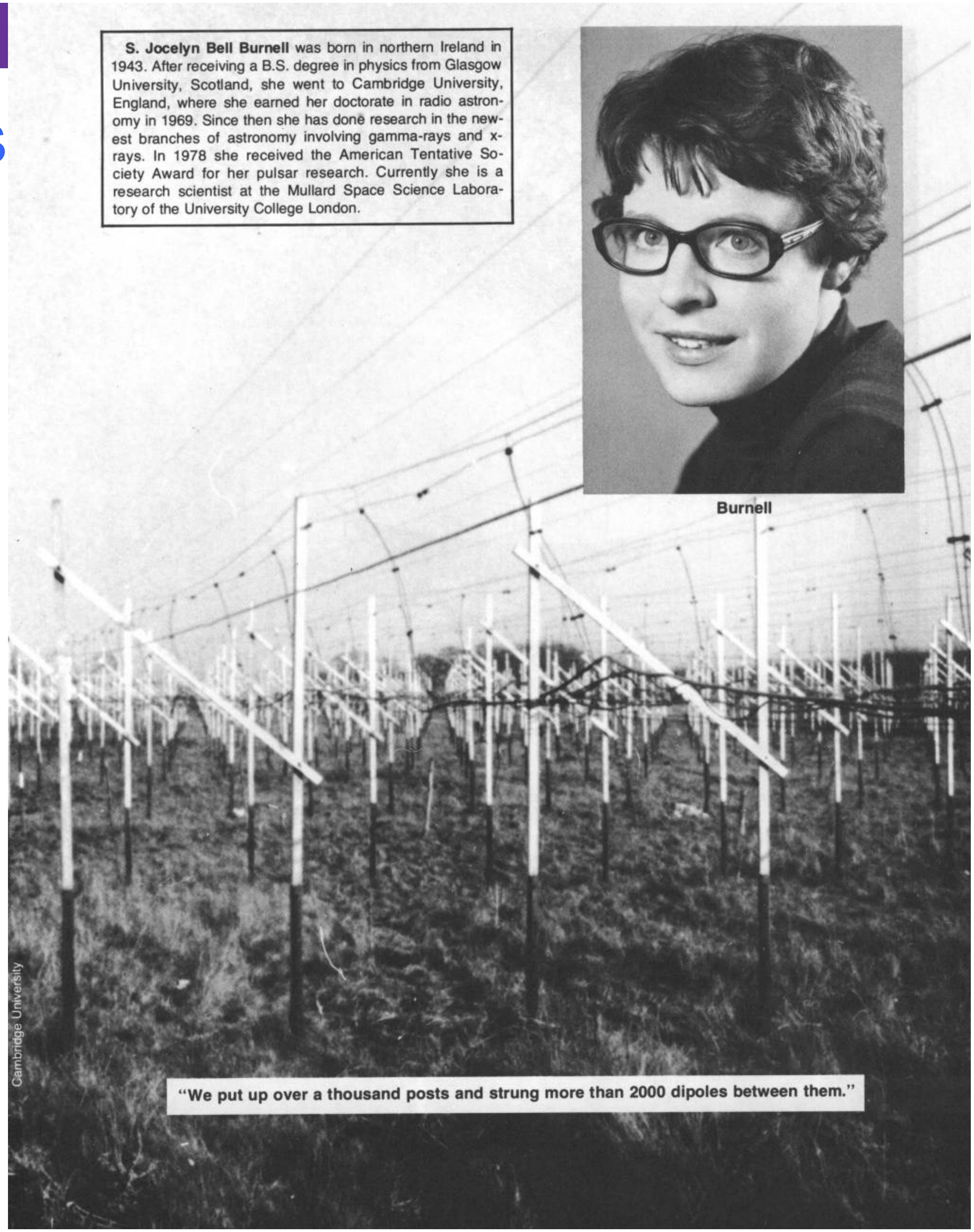
Midterm !!

- **March 15**
- **Closed book, closed notes, calculator needed**
- **On all material through and including March 10 class**
- **Good luck!**

Discovery of pulsars

First discovered by Bell in 1967

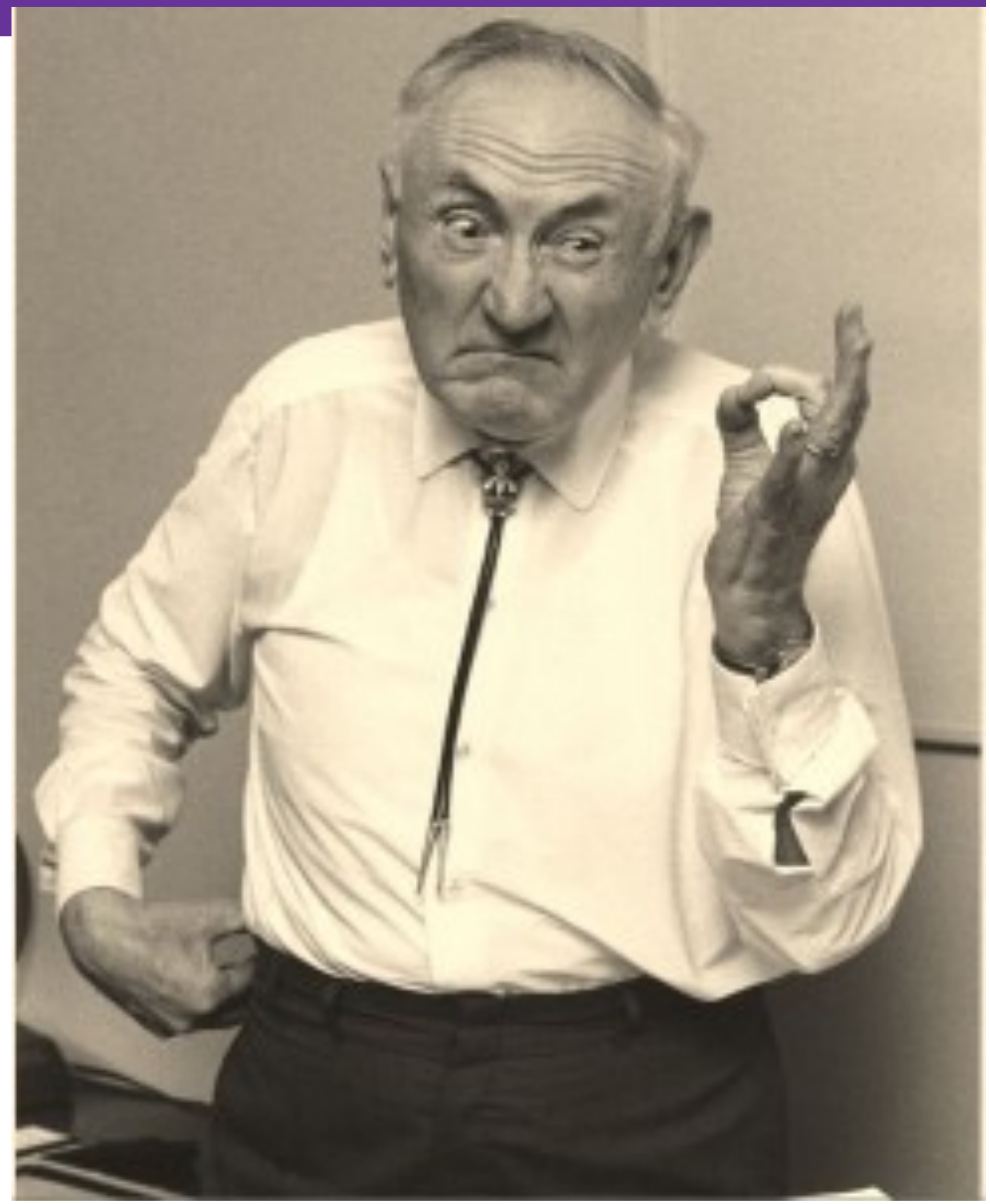
The community rapidly realized that these were neutron stars- idea had been around since the 1930's



Pulsar Sounds

1934, Baade and Zwicky proposed the existence of the neutron star

- 2 years after Chadwick's discovery of the neutron !
- they proposed that the neutron star is formed in a supernova and "consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density."



Fritz Zwicky (1898-1974)

II : Pulsars are rotating neutron stars

- A rotating star will fly apart if the centrifugal force of rotation exceeds its gravitational force… it turns out to be the density of the star that matters-denser objects can rotate more rapidly.
  - Many pulsars rotate so rapidly that even a dense white dwarf would fly apart if it rotated that quickly… need something even higher density
  - This led people to seriously consider the idea of a neutron star

II : Pulsars are rotating neutron stars

- **Pulsars are rotating neutron stars with intense magnetic fields**
  - The pulsed radiation is created by charged particles accelerated in the *spinning magnetic field* which is beamed along the magnetic axis
  - A lot of evidence for this idea now… e.g., can measure the moment of inertia of the central object and we find the expected value for a neutron star

What Does Spinning Fast Tell Us?

$$\frac{v_{\rm rot}^2}{R} < \frac{GM}{R^2}$$

To spin fast object must be dense
To show rapid changes must be small

$$\frac{4\pi^2 R}{P^2} < \frac{GM}{R^2}$$

$$\bar{\rho} \equiv \frac{3M}{4\pi R^3} > \frac{3\pi}{GP^2}$$

- $P=\sqrt{3\pi/G\rho}$

P= period, ρ= density

$P=1s \Rightarrow \rho>1\times10^{11}$ kg/m^3
$P=10^{-1}s \Rightarrow \rho>1\times10^{13}$ kg/m^3
$P=10^{-2}s \Rightarrow \rho>1\times10^{15}$ kg/m^3

Mass of object measured from Kepler's Laws ~1 M_{sun}- **so pulsars must be small and extraordinarily dense**

Observational Intro to Neutron Stars

- Neutron stars are a very diverse population, in their observational properties but narrow range in size and mass.
- Radiate over a broad band but most of their energy is emitted at X-ray and gamma-ray wavelengths

Their electromagnetic emission *can* be powered by

- rotation (spin down)
- accretion
- residual heat
- magnetic fields
- nuclear reactions

Vast number of names for these but all are a subset of the same sort of object

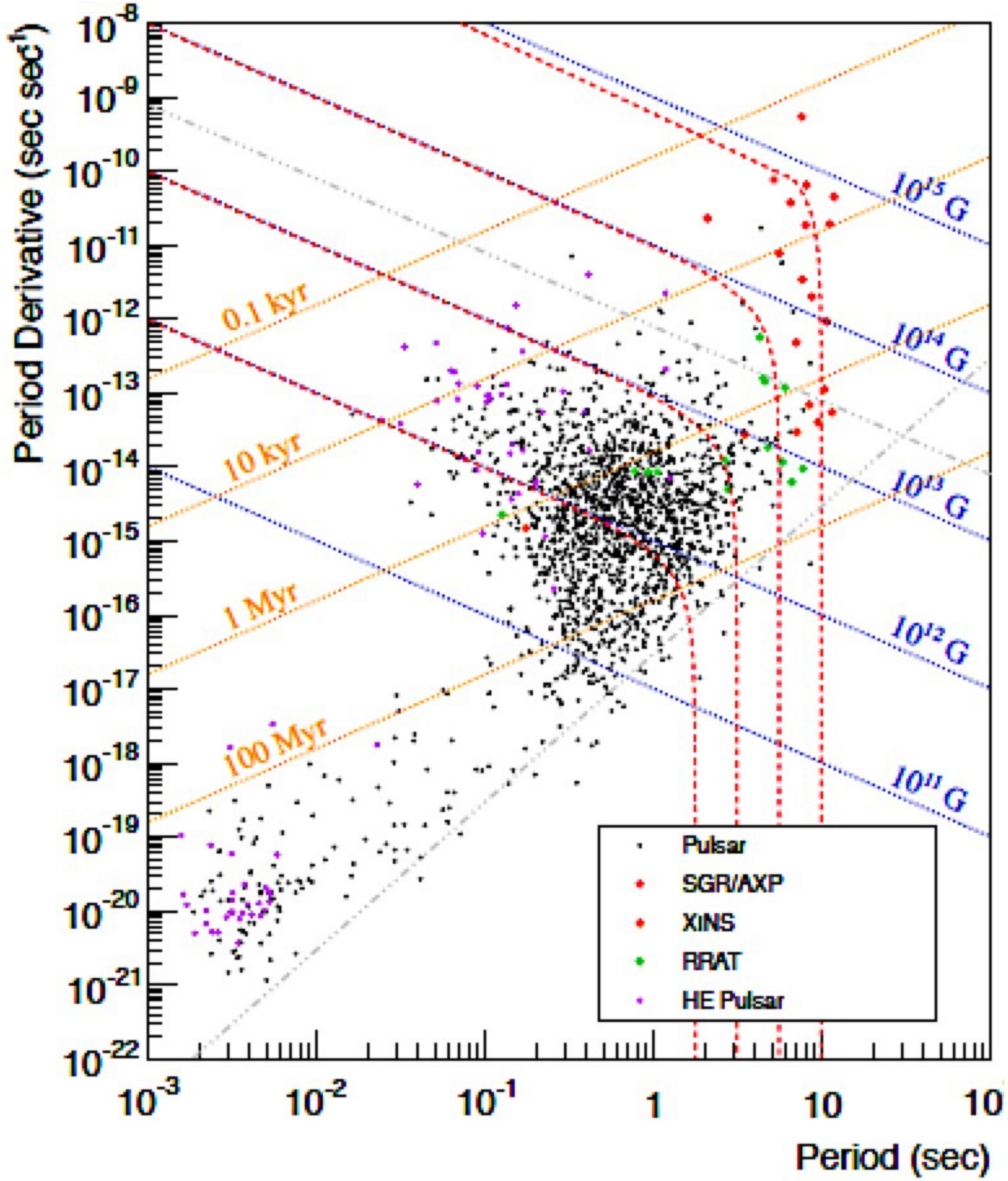
A. Harding 2013

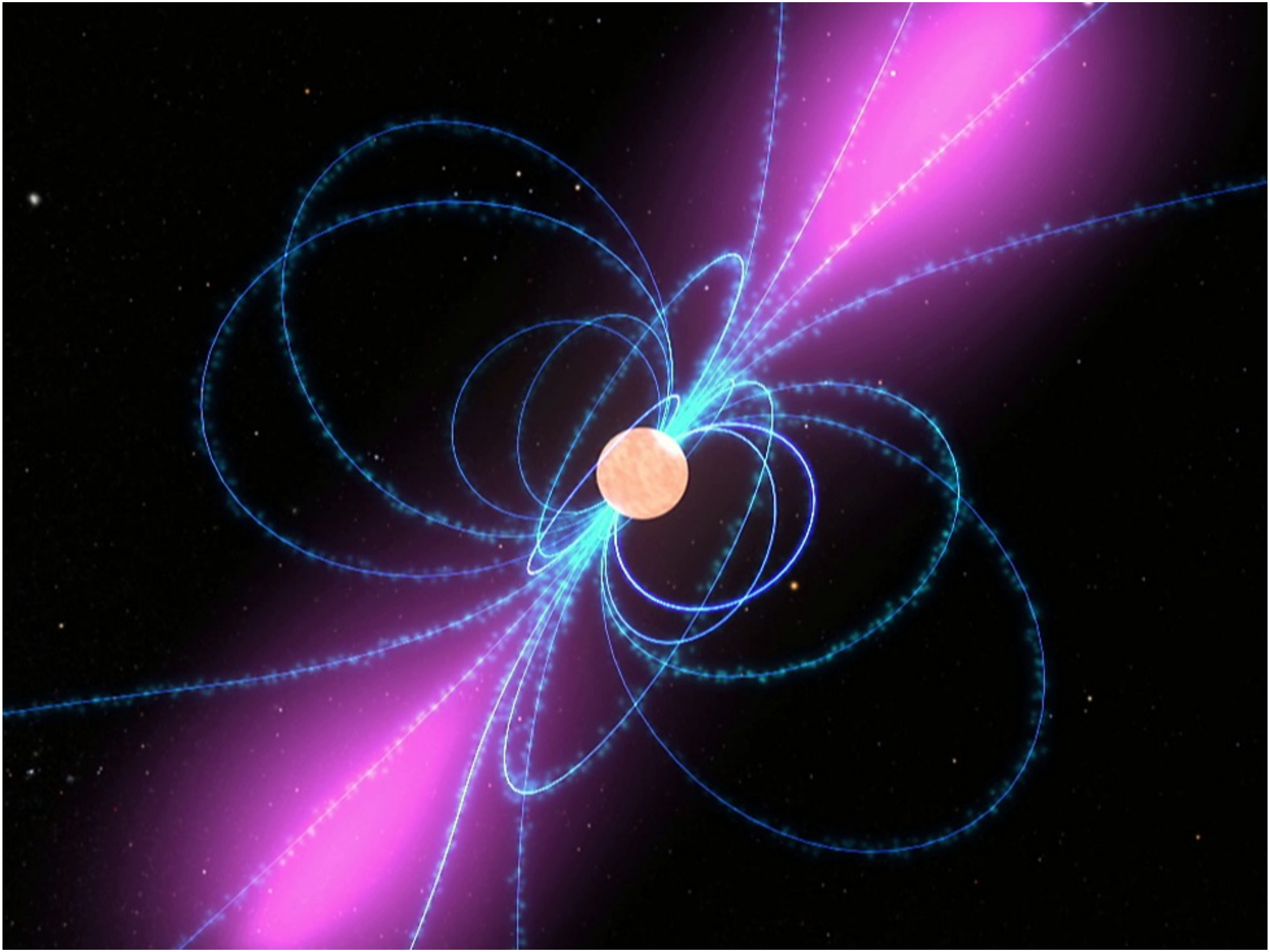
Strong Magnetic Fields

- The most 'common' observational population are non-accreting pulsars (>3000 known, https://www.atnf.csiro.au/people/pulsar/psrcat/)
- Periods (P) from 0.001-100 secs
- 22 orders of magnitude range in dP/dt
- dipole magnetic

$B_s \sim 10^{19}(P/[dP/dt])^{1/2}$

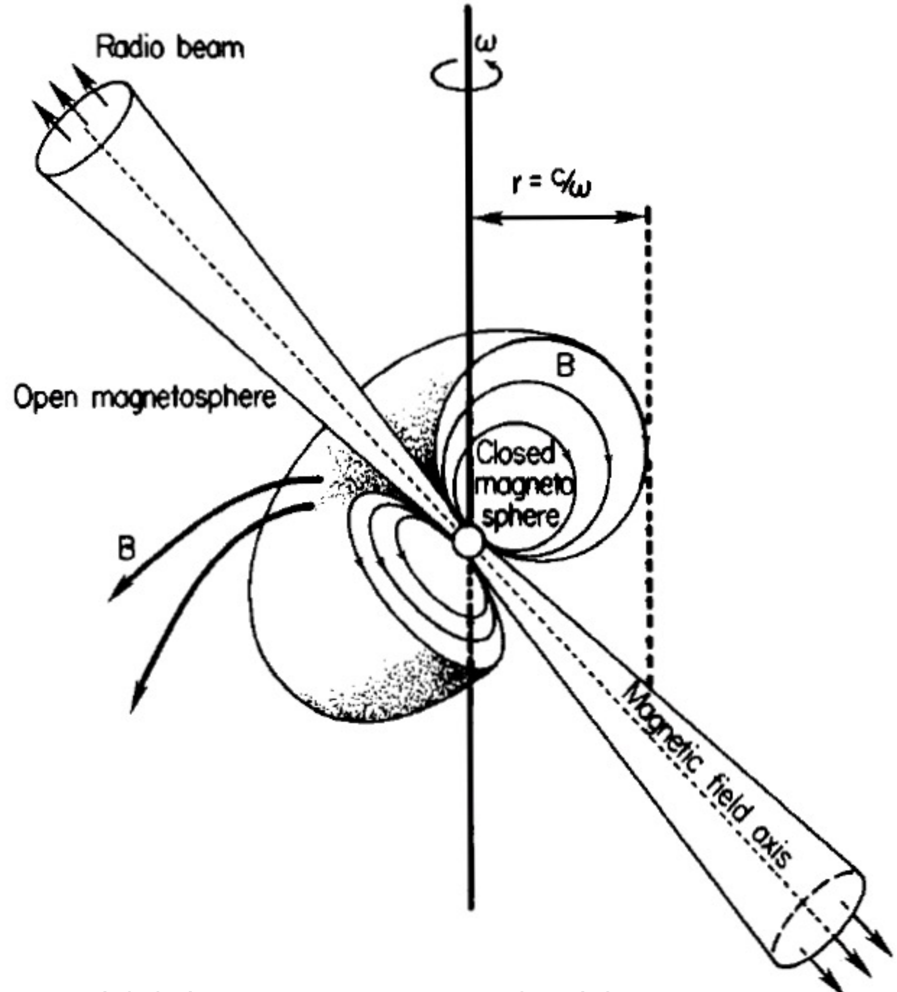
P is in seconds, B in gauss





Isolated Neutron Stars

- In order to produce pulsed radiation from the magnetic poles, the magnetic dipole must be oriented at an angle with respect to the rotation axis
- **Energy loss goes as $\Omega^4 B^2$**
- As they radiate the star spins down- **visible for ~10^7 yrs**



Taylor 1991Proc. IEEE, 79, 1054

For more on neutron stars see http://www.jb.man.ac.uk/~pulsar/Education/Tutorial/tut/tut.html

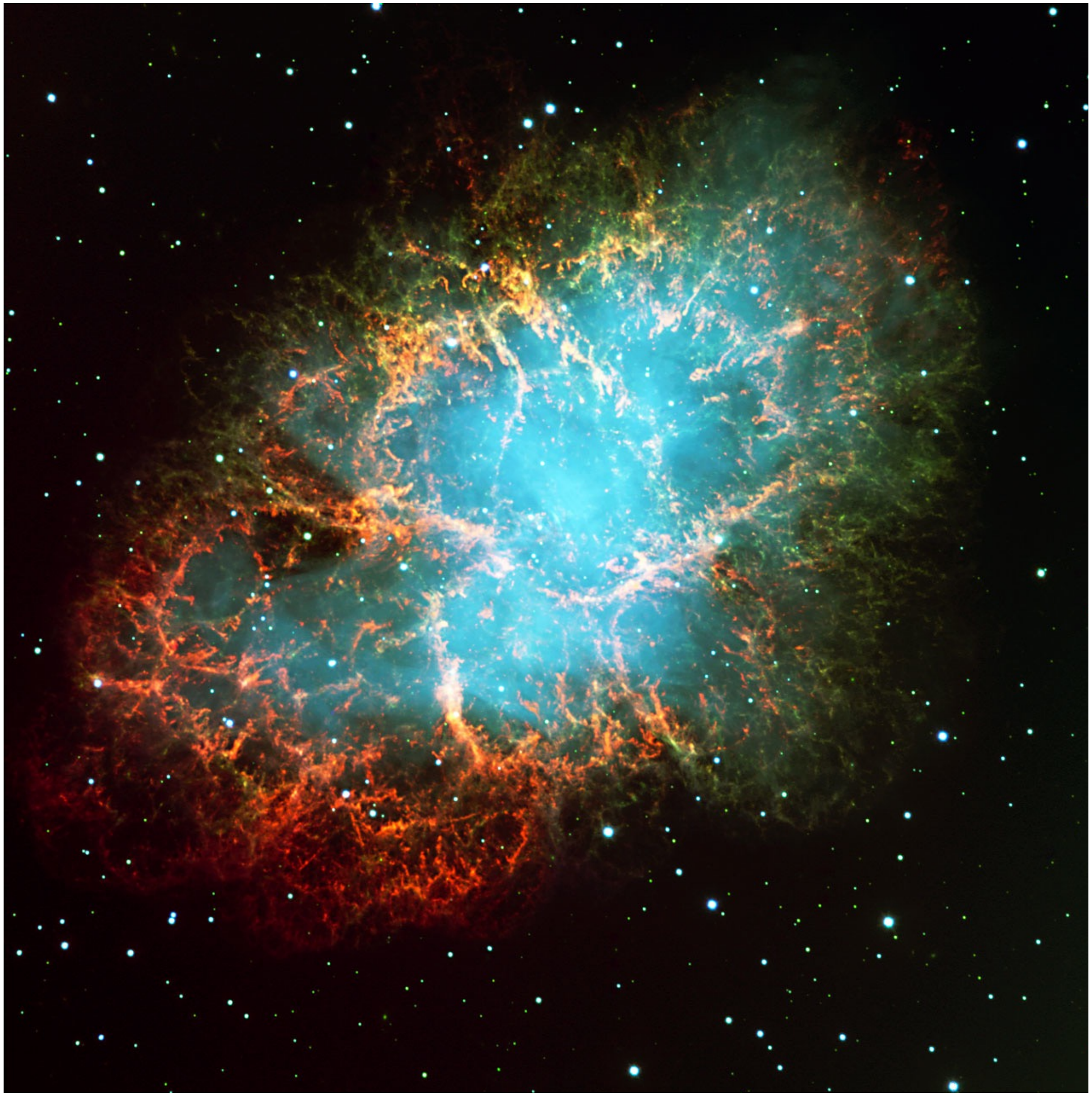
Crab nebula

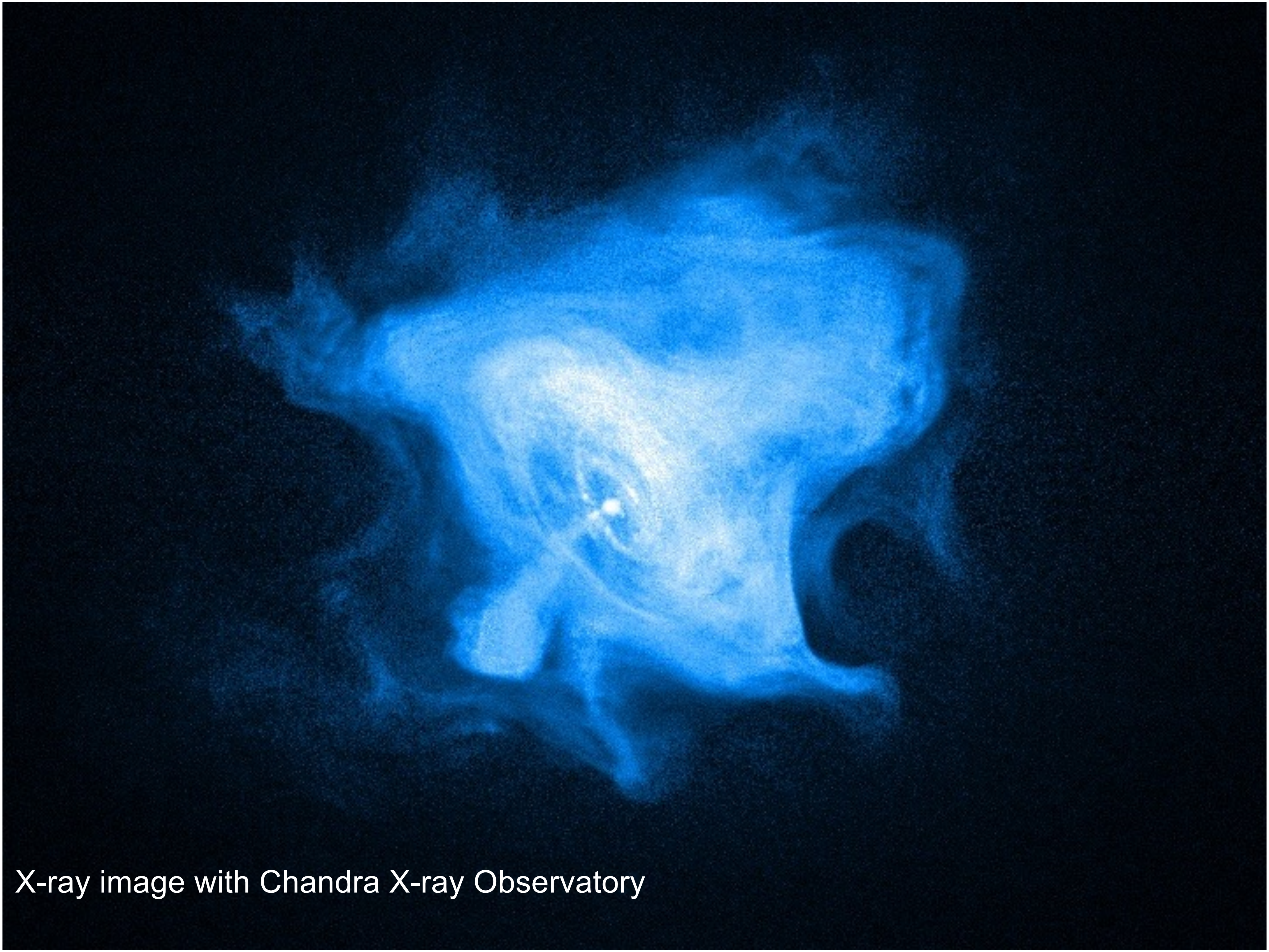
http://www.messier.seds.org/more/m001_sn.html

Result of a supernova detected by Chinese observers in July 1054

was ~4 times brighter than Venus at its brightest and was visible in daylight for 23 days.

The optical image shows hot gas
moving at high velocities (red) and x-ray emission (blue)





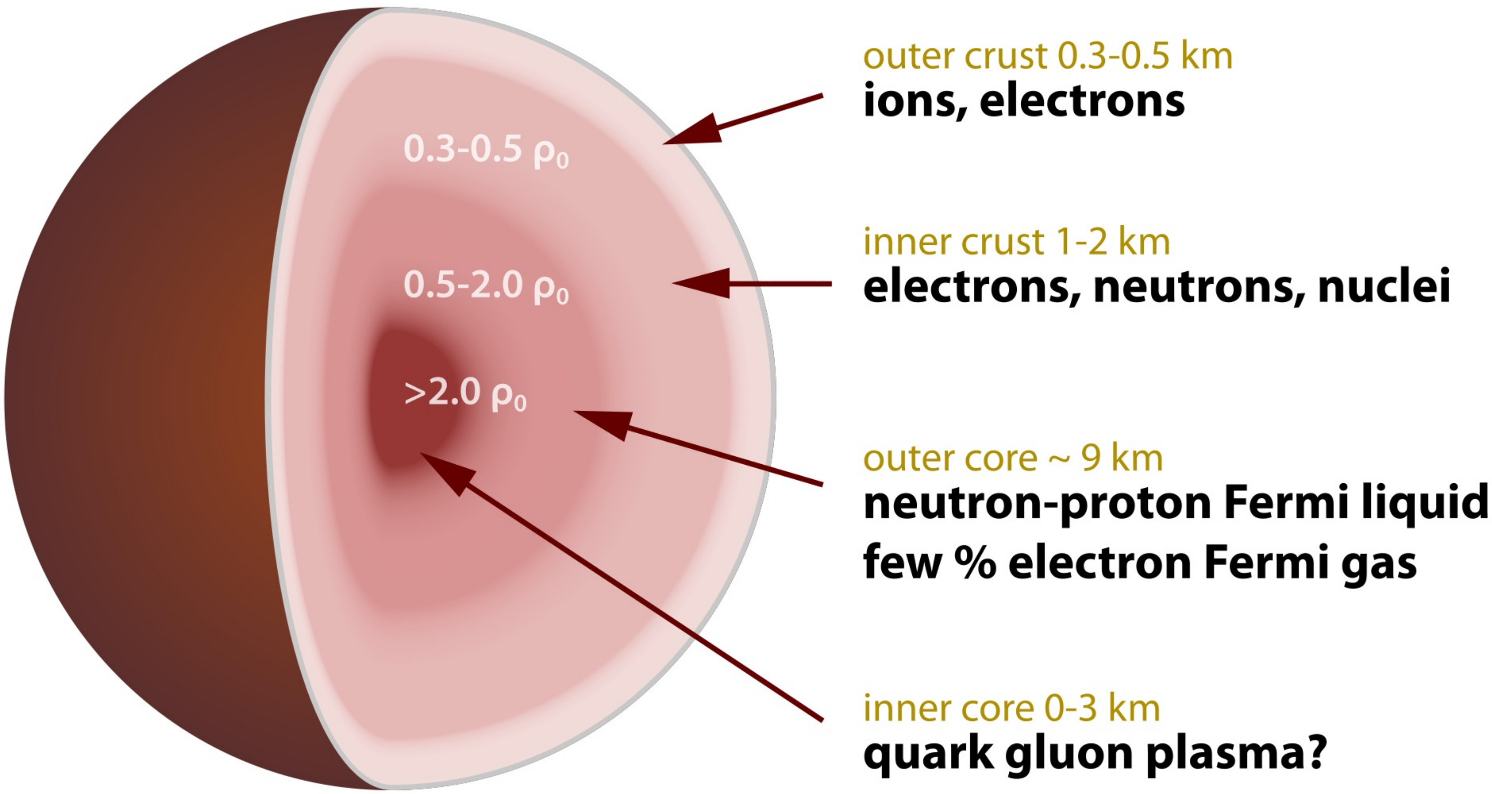
X-ray image with Chandra X-ray Observatory

III : Structure of neutron stars

- Neutron stars are exotic objects
  - Average density is greater than that of an atomic nucleus!
  - Surface gravity is so strong that any mountain higher than 1mm is squashed flat… any gas on surface quickly differentiates (H on top, then He, then C,…, heavy elements on bottom)

- Deeper down, neutron stars have matter in states that we can never obtain in a laboratory…
  - At the core of a neutron star, there may be “new” and exotic states of matter (new particles, quark soup etc.)

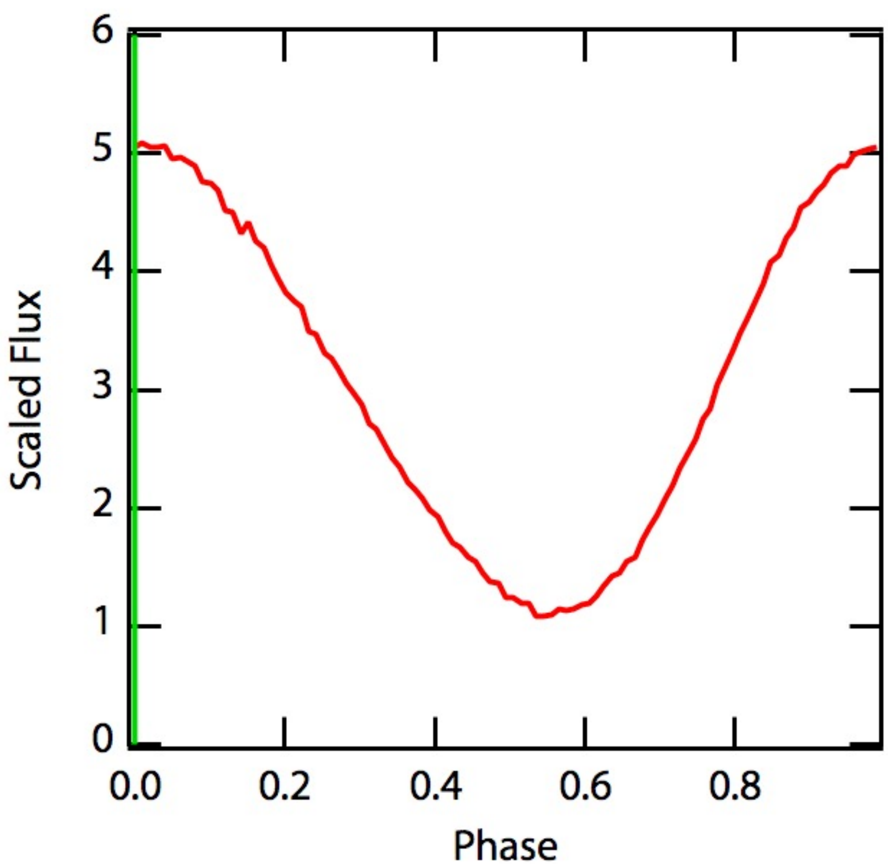
Internal structure of Neutron Stars

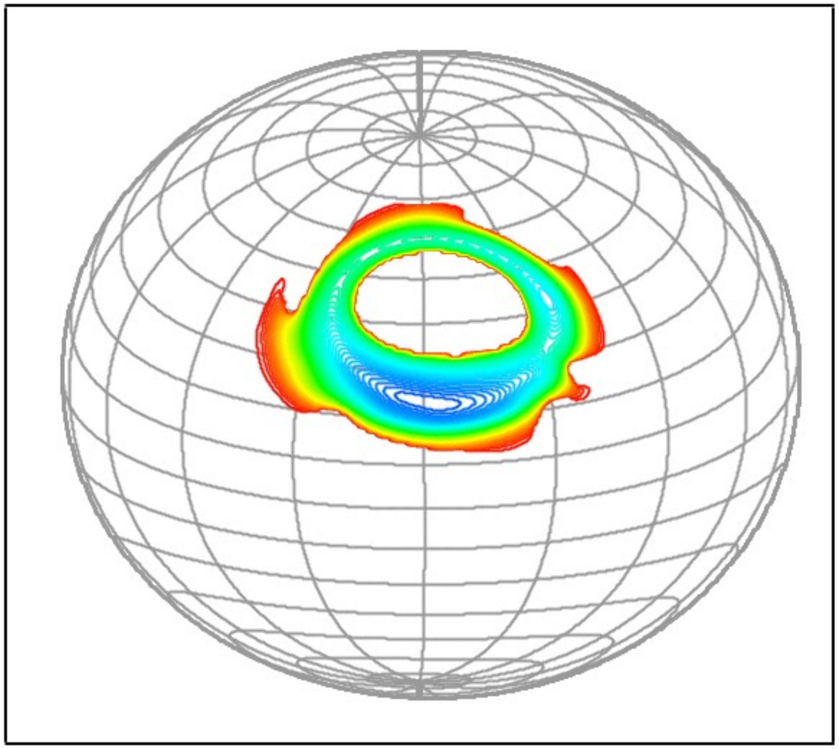


ρ_0=nuclear density- but an atomic nucleus is held together by the strong interaction, whereas a neutron star is held together by **gravity.**

Neutron Stars are Relativistic Objects

- As a testbed for GR, neutron stars have some advantages over black holes
- -they have a surface which can support magnetic fields and can emit X-rays and other radiation
- and their rotation and radius can be measured.
- This has led to detailed study with NICER





Measuring the size of NS

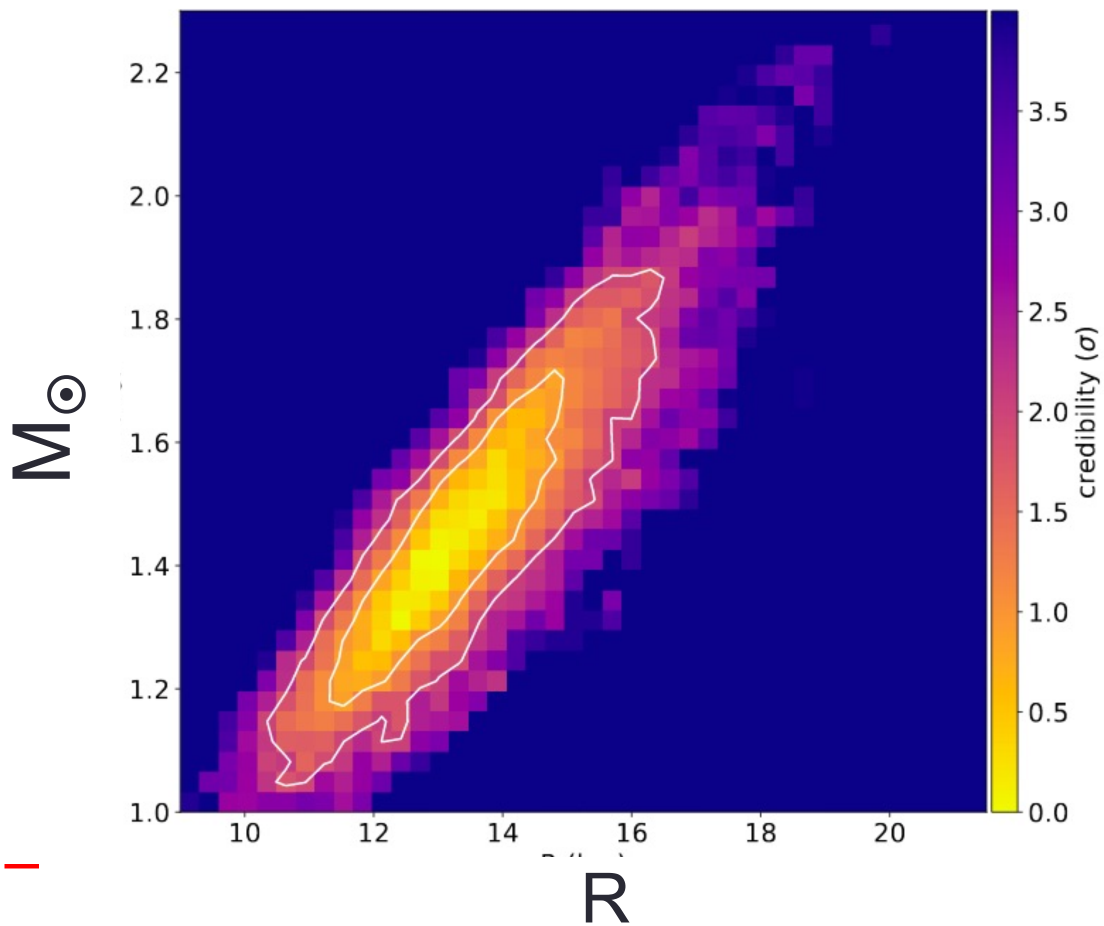
- NS masses are “easy” to measure if they are in binaries
  Basically, use Kepler’s laws
- But radii are really tough
- Using a standard approach with normal stars usually yields absurdly small radii, e.g., <5 km
- Even refining that approach leads to answers with huge possible systematic errors; i.e., you’re not sure you have a reliable answer
- What to do? NASA’s NICER mission!
- *modest cough* I lead one of the two groups within NICER to infer radii from X-ray observations
- Big advances as a result!

Neutron Stars are Relativistic Objects

- The gravitational field at the neutron star's surface is about 2×10^{11} times that of Earth.
- general relativistic correction to hydrostatic equilibrium within a neutron star is very significant

R_{Sch}=4km for M=1.4$M_\odot$, radius of NS is ~12km

e.g light bending, time dilation and gravitational redshift are large effects- allow estimate of mass and radius of NS.



Best estimate and size of a NS –
Miller et al 2019, 2021

Neutron Stars are Relativistic Objects

- Space warping

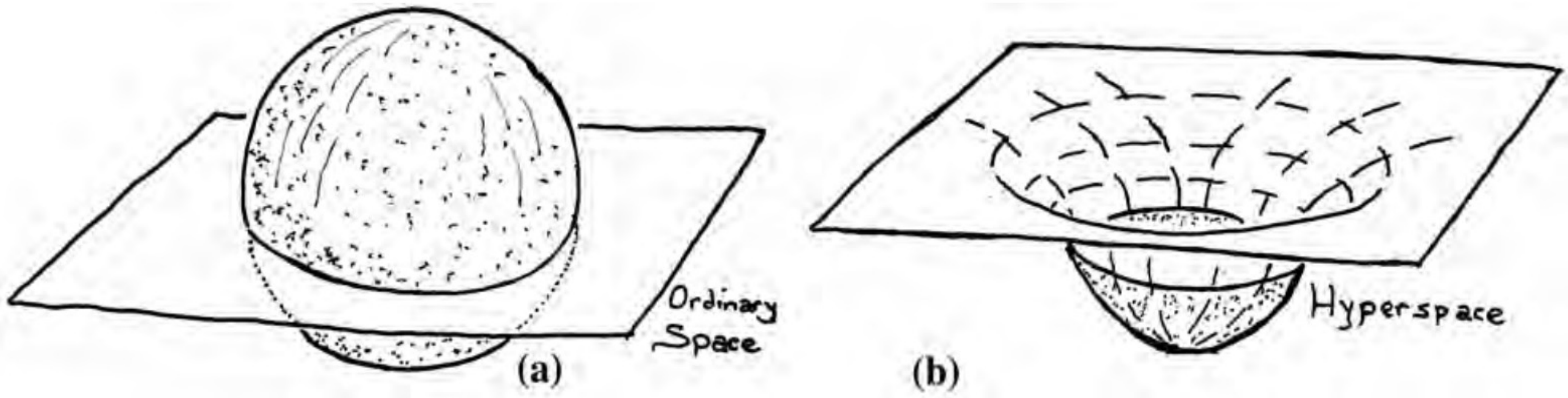


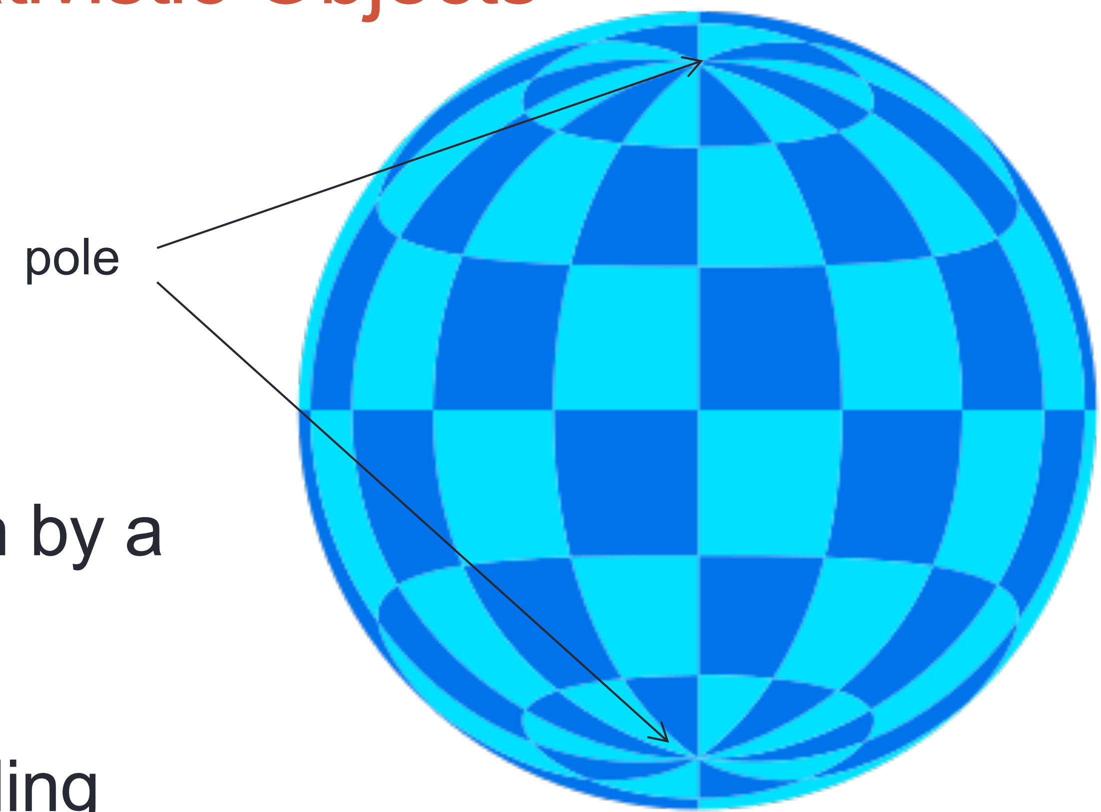
Figure 13: The warpage of space inside and around a neutron star: An equatorial slice through a star [diagram (a)], when osberved from a higher dimensional, flat hyperspace in which our universe is embedded, has the shape shown in diagram (b). The star's circumference may be about twice its diameter rather than π times its diameter.

Due to bending of space the star's circumference is ~4r rather than $2\pi r$ (K. Thorne)

R

Neutron Stars are Relativistic Objects

- Light bending



Gravitational light deflection by a neutron star.

Due to relativistic light bending more than half of the surface is visible to a distant observer- see both poles at same time ($R=2R_S$,M=1 solar mass)

R

IV : 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/10^{11}T)
  - Sometimes, these enormous magnetic fields "snap", leading to very intense explosions
  - Dramatic example… the 27th December 2004 event
    - During a 0.2s period of time, it produced 100x the total luminosity of our galaxy
    - It produced a major disturbance of 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 50m of the magnetar crust!
  - Good it wasn't closer!!!

Magnetars

Have occasional huge outbursts of X-rays and soft-gamma rays, as well as luminosities in quiescence that are generally orders of magnitude greater than their spin-down luminosities.

Magnetars are thought to be young, isolated neutron stars powered by the decay of a very large magnetic field.

Their intense magnetic field inferred via spin-down to be in the range 10^{13}-10^{16}G

'quantum critical field' $B_{QED} \equiv m^2_e c^3/he = 4.4\times10^{13}$G.

In their most luminous outburst magnetars can briefly out-shine all other cosmic soft-gamma-ray sources combined [Kaspi 2010]

Period and Magnetic Field

Notice enormous range of periods 10^{-3}-100 seconds
Magnetars- B~10^{14}-10^{16} Gauss
Above ~$4x10^{13}$Gauss quantum mechanical effects become important

CCO- central compact objects
MSP= millisecond pulsar
LMXBs- low mass x-ray binaries

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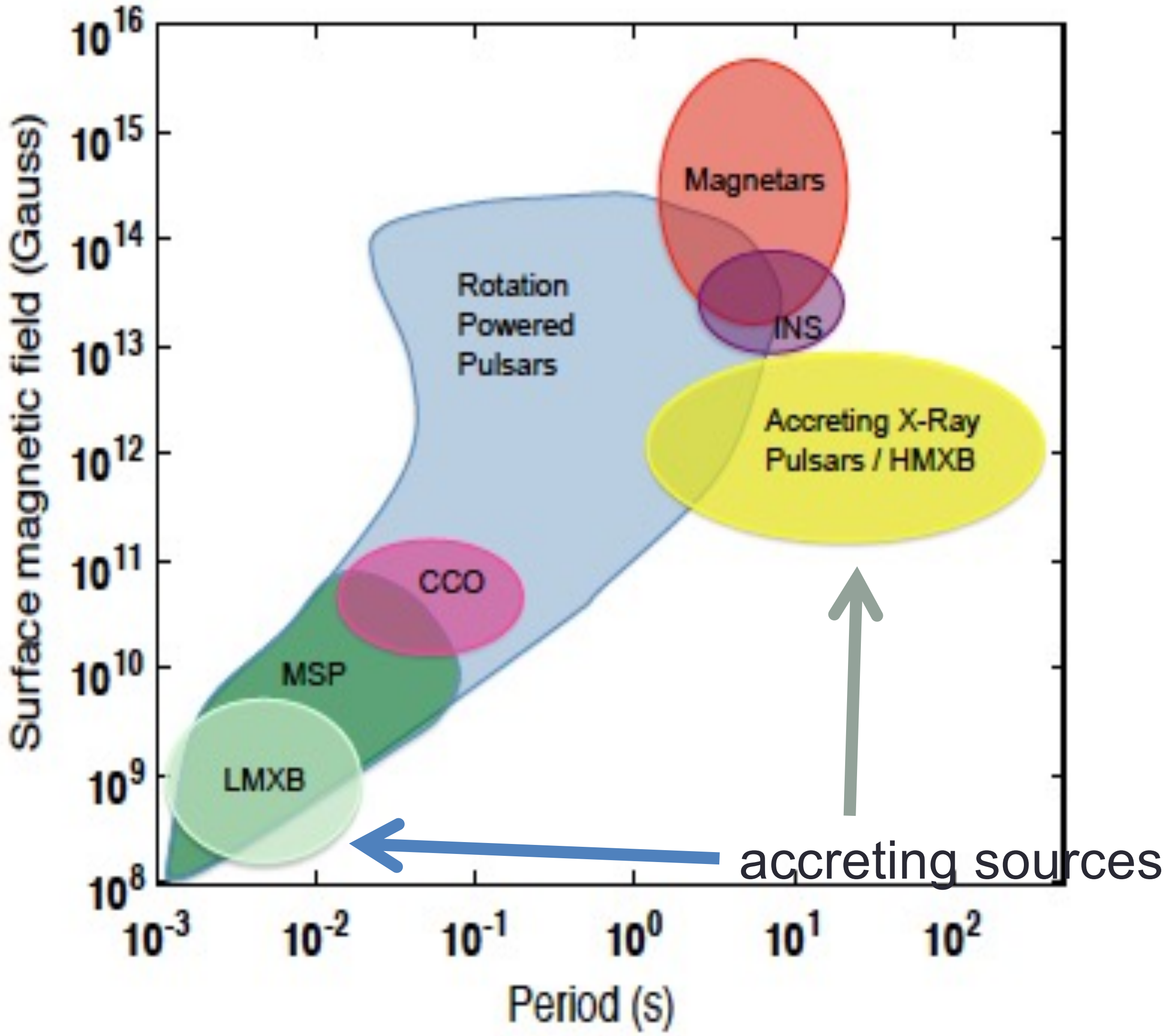
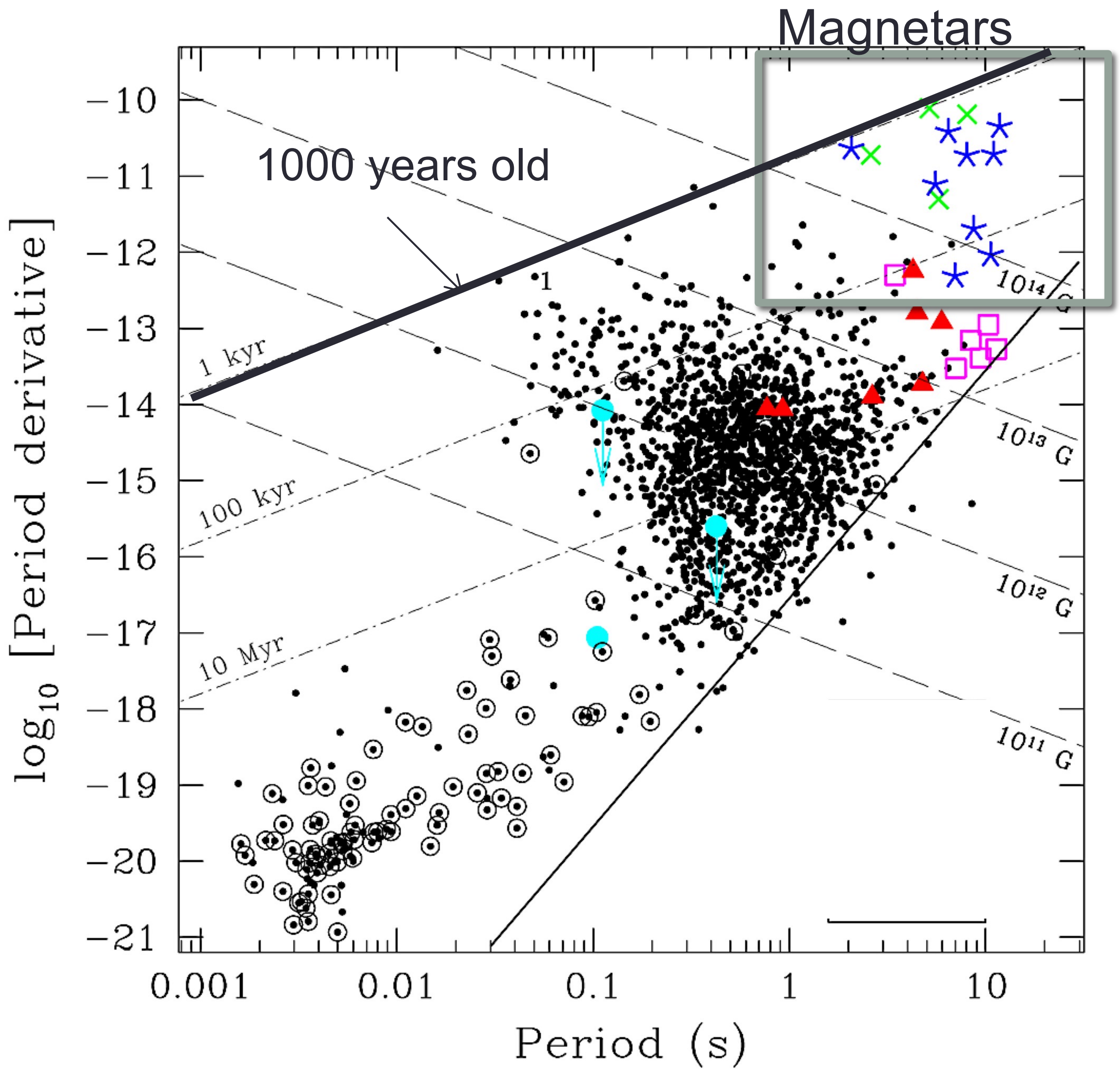


Magnetars

spinning down, with spin-down rates that imply spin-down timescales (~P/ dP/dt) of a few thousand years, suggesting great youth.

Confined to galactic plane

Lines of constant age, magnetic field.
Ignore colors

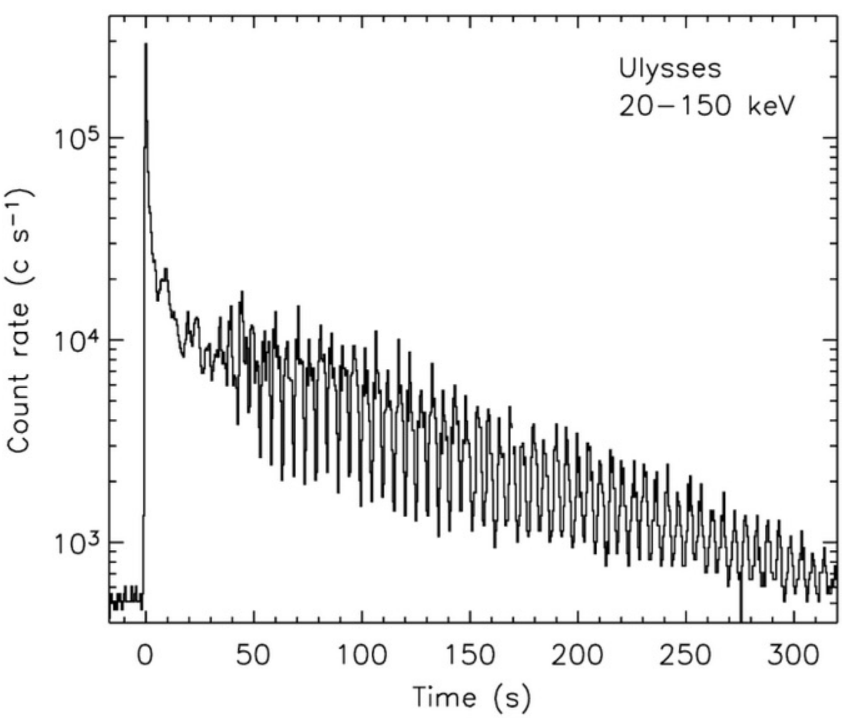


Open circles are in binaries

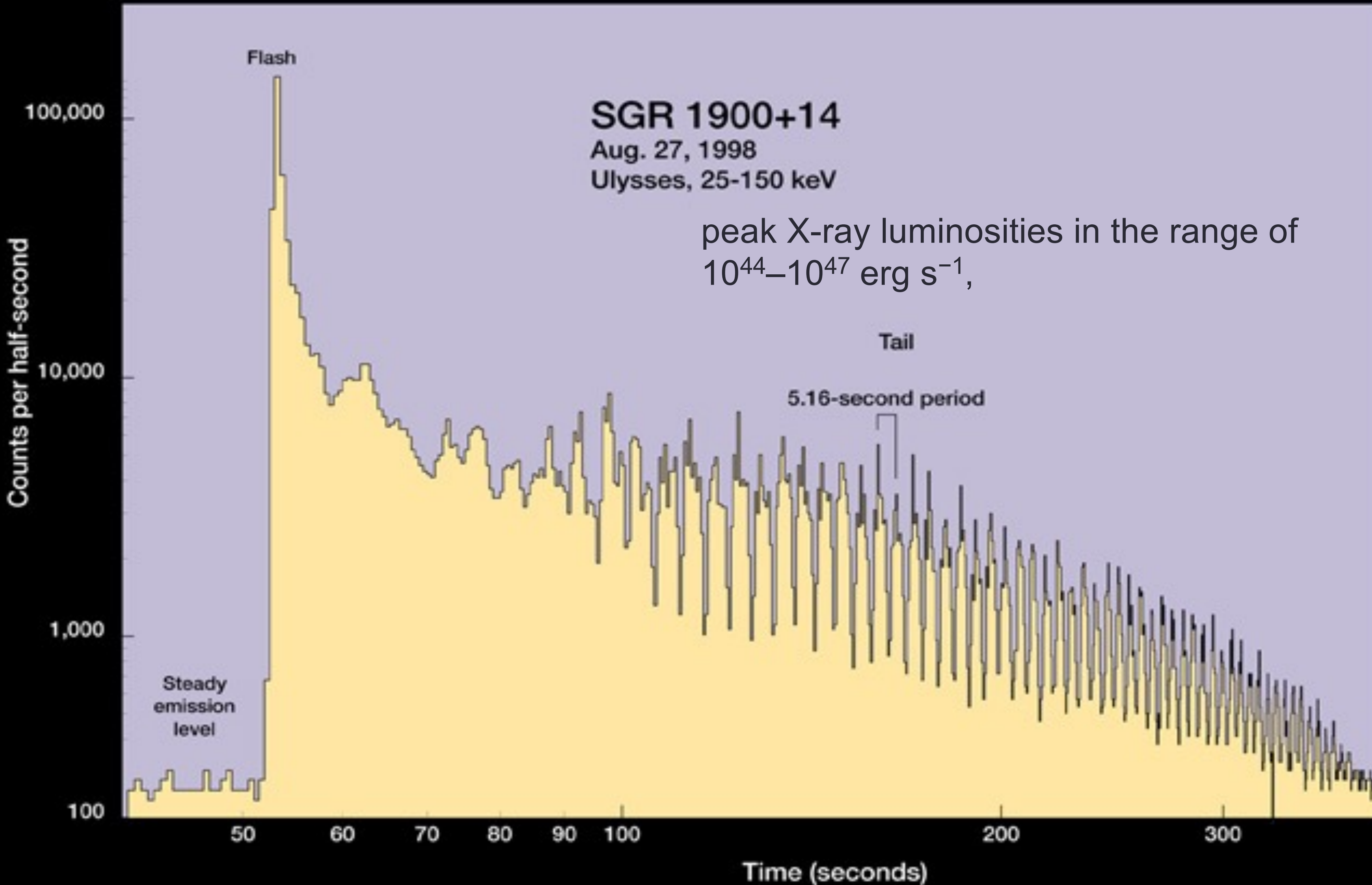
Enormous Burst from Magnetar

A magnetar in the LMC on March 5,1979 was, by a factor of 1000, the brightest source in the x-ray sky for a few seconds – the flux was strong enough to effect the ionosphere!

Total energy was $5x10^{44}$ ergs in x-rays equivalent to 4000 years of solar luminosity



Position (obtained by triangulation) consistent
with a supernova remnant in the LMC



peak X-ray luminosities in the range of 10^{44}–10^{47} erg s^{-1},

What's Happening???

- The behavior of magnetars on the timescales of 1–10 kyr is due to slow evolution of the magnetic field inside the star, which is capable of breaking the solid crust.
- The interior of a neutron star is an excellent conductor, and hence the magnetic field is practically "frozen" in the stellar material (Kaspi and Beloborodov 2017)
- But can have "starquakes"—sudden fractures and displacements of the crust, which shake the magnetosphere and trigger bursts.