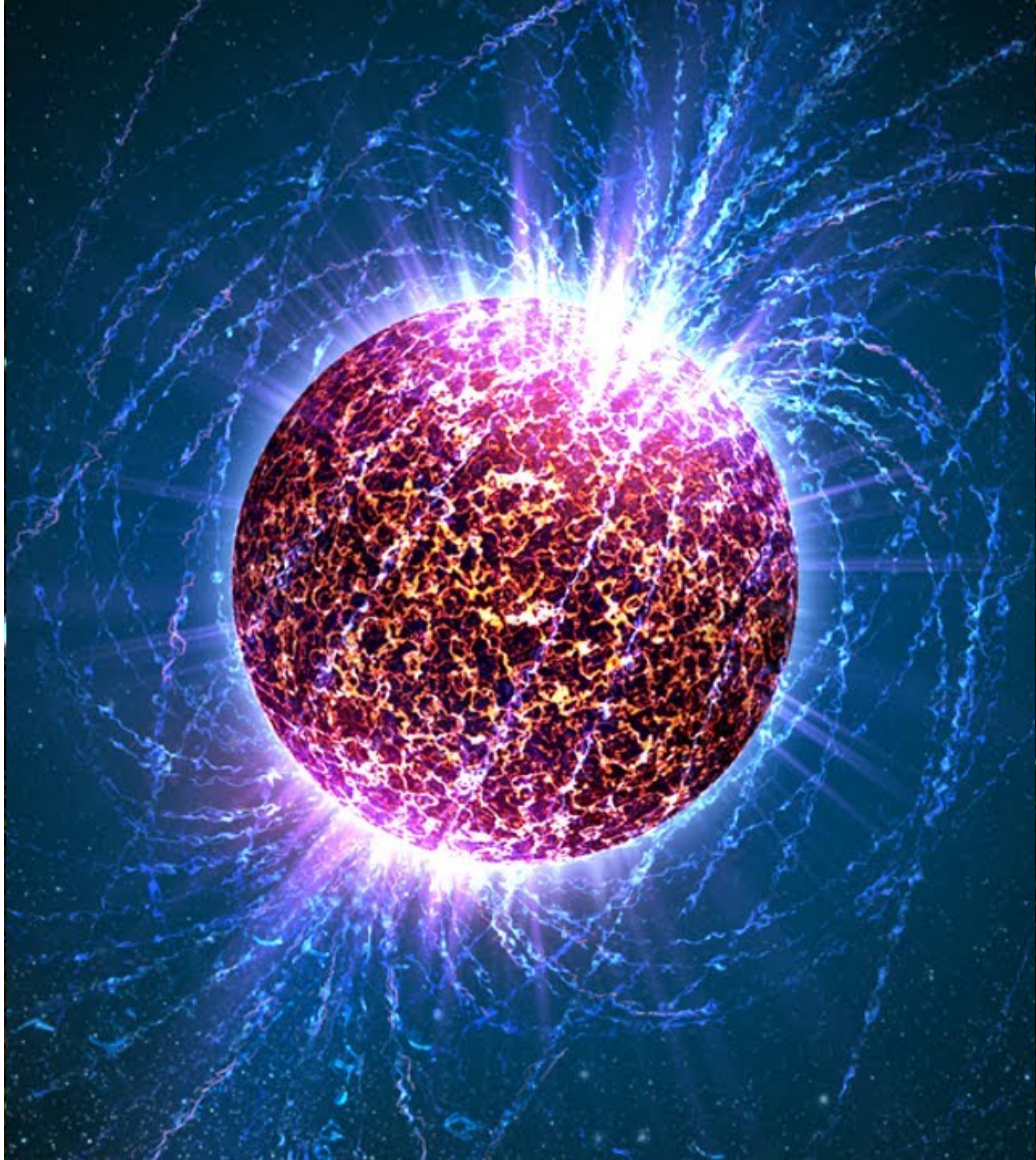
PHY 4905 | Modern Astrophysics

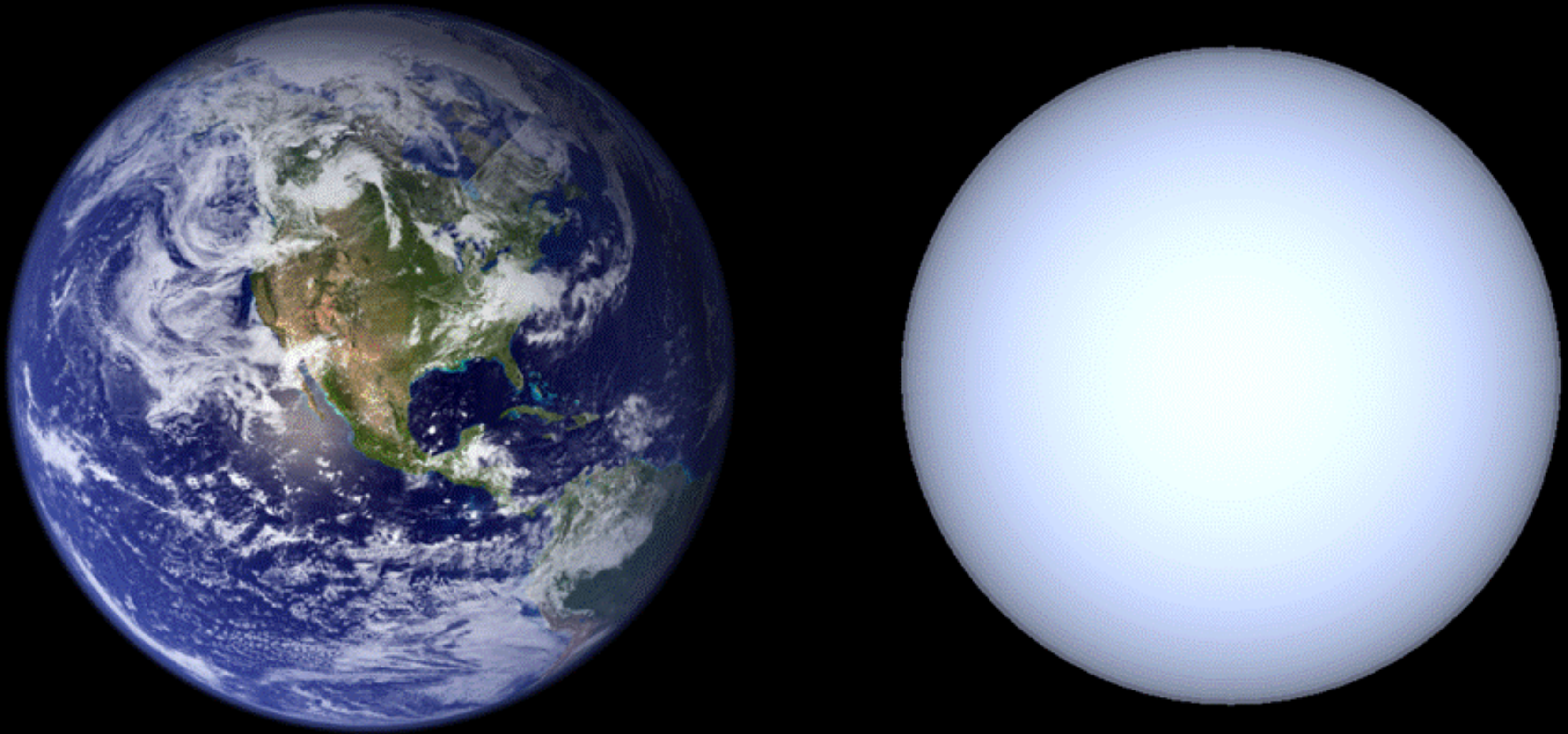
Lecture VI.

Neutron stars

UNIVERSITY of FLORIDA

Imre Bartos | Fall 2019

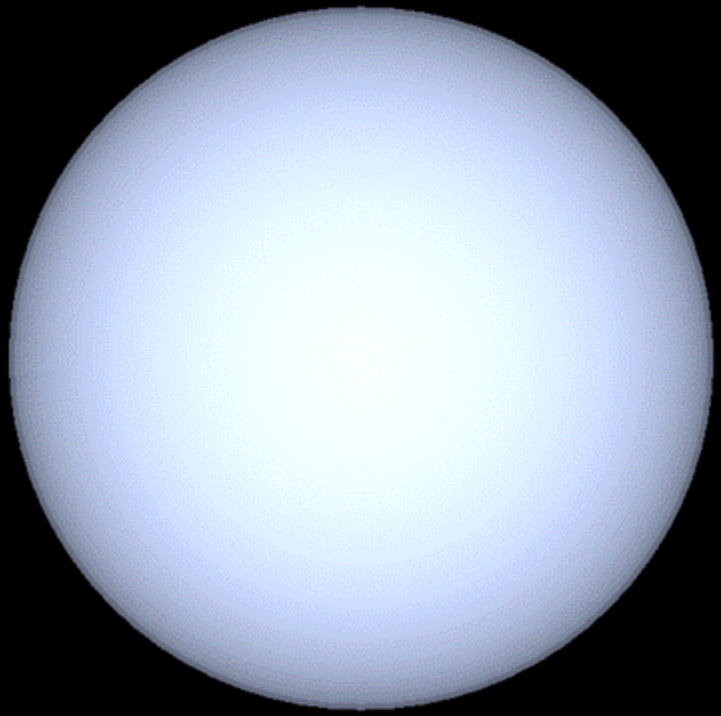




$M \approx 1.0\ M_{sun}$

$R \approx 5800\ km$

$V_{esc} \approx 0.02c$



$M \approx 1.0\ M_{sun}$

$R \approx 5800$ km

$V_{esc} \approx 0.02c$

$$T = 2\pi\sqrt{\frac{a^3}{G\left(M_1 + M_2\right)}}$$

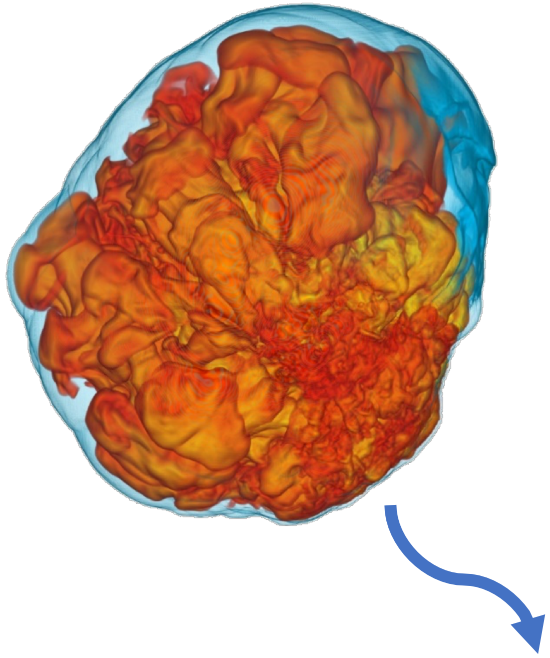
Gravitational wave production

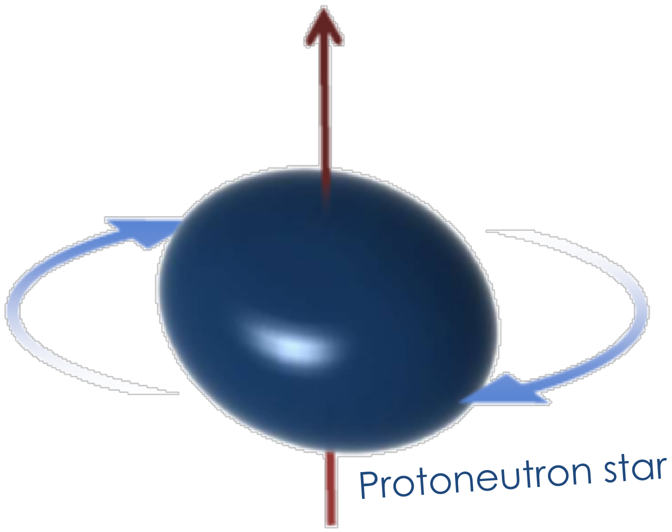
Process	Typical $\lvert h \rvert$ (at 10 kpc)	Typical f (Hz)	Duration Δt (ms)	E_{GW} ($10^{-10} M_{\odot} c^2$)	Limiting Factors or Processes
Prompt Convection	$10^{-23} - 10^{-21}$	$50 - 1000$	$0- \sim 30$	$\lesssim 0.01 - 10$	Seed perturbations, entropy/lepton gradient, rotation
	(Emission characteristics depend on seed perturbations.)				
PNS Convection	$2 - 5 \times 10^{-23}$	$300 - 1500$	500 – several 1000	$\lesssim 1.3(\frac{\Delta t}{1s})$	rotation, BH formation, strong PNS g-modes
Neutrino-driven Convection and SASI	$10^{-23} - 10^{-22}$ (peaks up to 10^{-21})	$100 - 800$	$100- \gtrsim 1000$	$\gtrsim 0.01(\frac{\Delta t}{100ms})$ $\lesssim 15(\frac{\Delta t}{100ms})$	rotation, explosion, BH formation

Unclear, but likely only detectable from the Milky Way

Ott 2008

Rapidly rotating core





Bartos, Brady, Marka 2013

GWs from rapidly rotating cores?

Relevant distance scale:

Low-luminosity GRB / CCSN with jets: 10^2-10^3 Gpc^{-3} yr^{-1}

(Guetta & della Valle 2006; Soderberg+ Nature 2010)

(Beaming factor ~ 10)

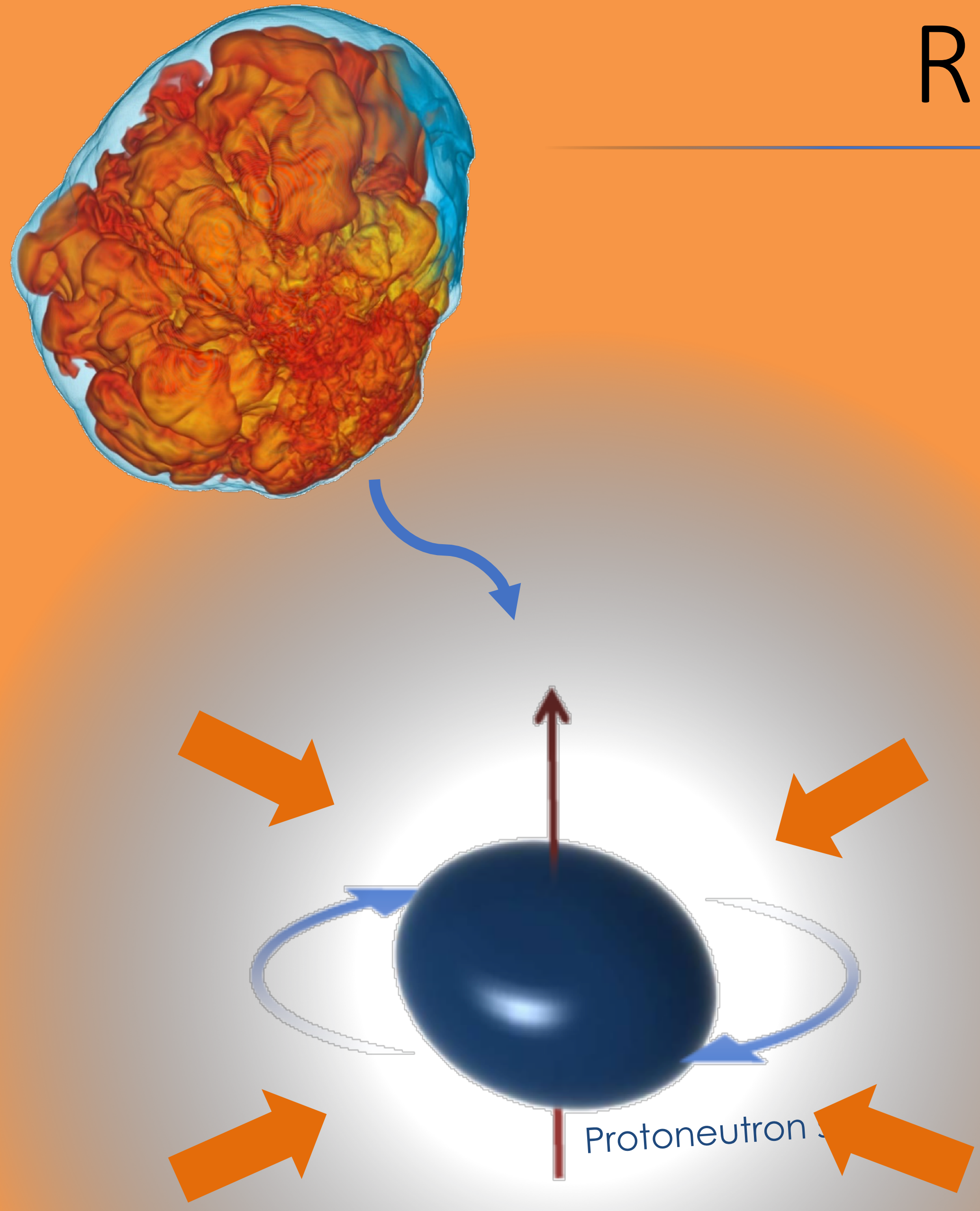
→ 50-100 Mpc

Differential rotation (e.g. Corvino+ 2010)

- **Dynamical instabilities** *(shorter time scale)*
- **Secular instabilities** *(longer time scale)*
- **Magnetic distortion**

$$E_{\rm GW} \approx 10^{-2} M_{\odot} c^2 \left(\frac{\epsilon}{0.2}\right)^2 \left(\frac{f}{2\,\rm kHz}\right)^6 \left(\frac{M}{1.4\,M_{\odot}}\right) \left(\frac{R}{12\,\rm km}\right)^2 \left(\frac{\tau}{0.1\,\rm s}\right)$$

Rapidly rotating core



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Fallback accretion? *(Piro, Thrane, 2012)*

$$E_{\rm GW} \approx 10^{-2} M_{\odot} c^2 \left(\frac{\epsilon}{0.2}\right)^2 \left(\frac{f}{2\,\mathrm{kHz}}\right)^6 \left(\frac{M}{1.4\,M_{\odot}}\right) \left(\frac{R}{12\,\mathrm{km}}\right)^2 \left(\frac{\tau}{0.1\,\mathrm{s}}\right)$$

Homework

$$E_{\rm GW} \approx 10^{-2} M_\odot c^2 \left(\frac{\epsilon}{0.2}\right)^2 \left(\frac{f}{2\,{\rm kHz}}\right)^6 \left(\frac{M}{1.4\,M_\odot}\right) \left(\frac{R}{12\,{\rm km}}\right)^2 \left(\frac{\tau}{0.1\,{\rm s}}\right)$$

Assume realistic dependence of epsilon on f.

What will be the gravitational waveform?

History

Background & detals: Shapiro & Teukolsky
Black Holes, White Dwarfs, Neutron strars

Proposed by Baade and Zwicky as formed in supernovae
(Baade and Zwicky coined super-novae in 1931!)

First neutron star models: Oppenheimer & Volkoff 1939

Expected to be small and hence undetectable via thermal radiation → no interest for ~30 years.

This changed with the discovery of high-energy (X-ray, 1962) emission

General acceptance: discovery of pulsars in 1967
https://www.newyorker.com/tech/elements/the-astronomer-jocelyn-bell-burnell-looks-back-on-her-cosmic-legacy

Chandrasekhar limit by Landau 1932 --- 1.5 Msun

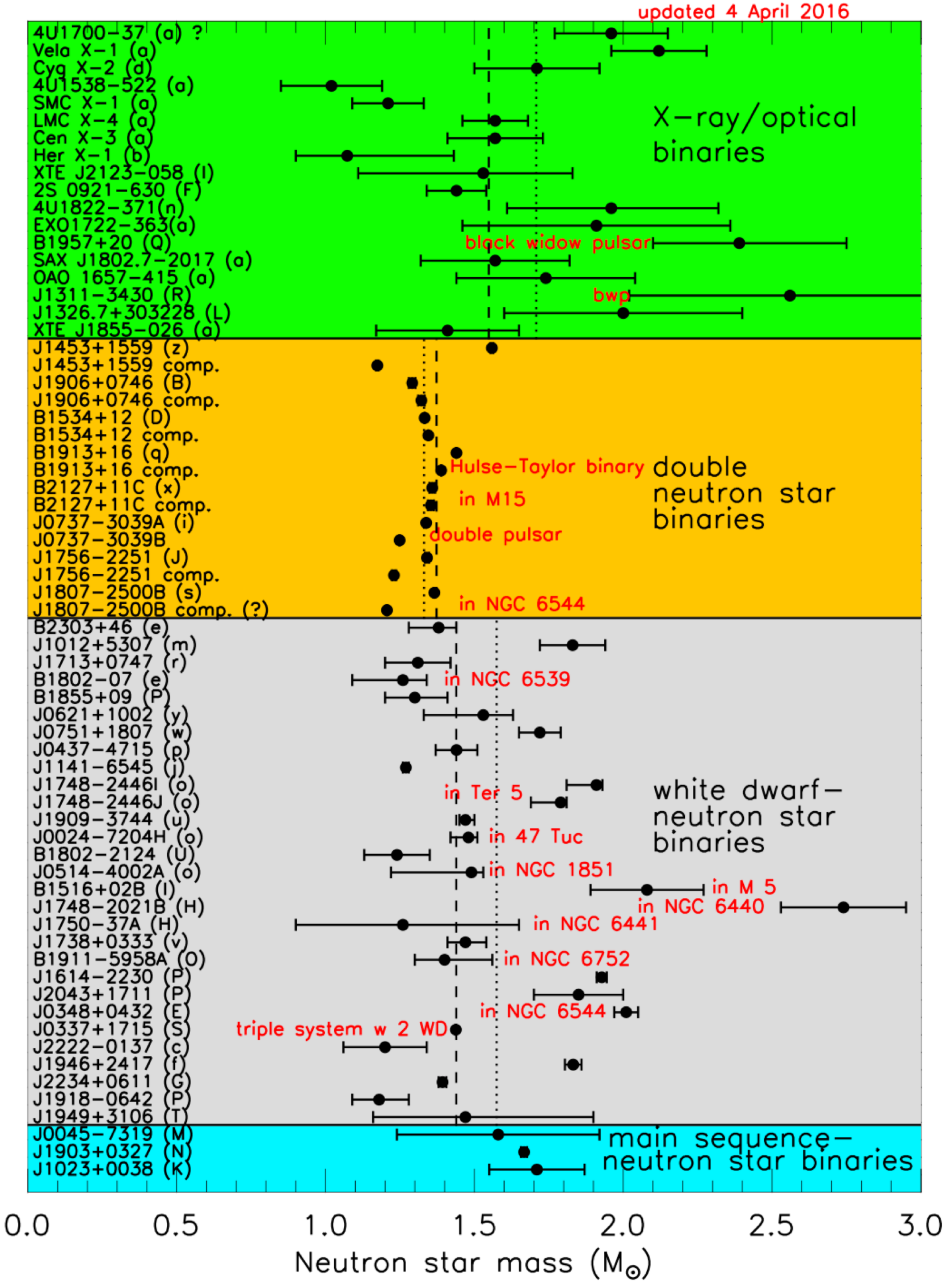
Properties - Mass

There should be a lower limit just from formation. ---   1.1 Msun

Maximum observed mass   ---   ~2 Msun

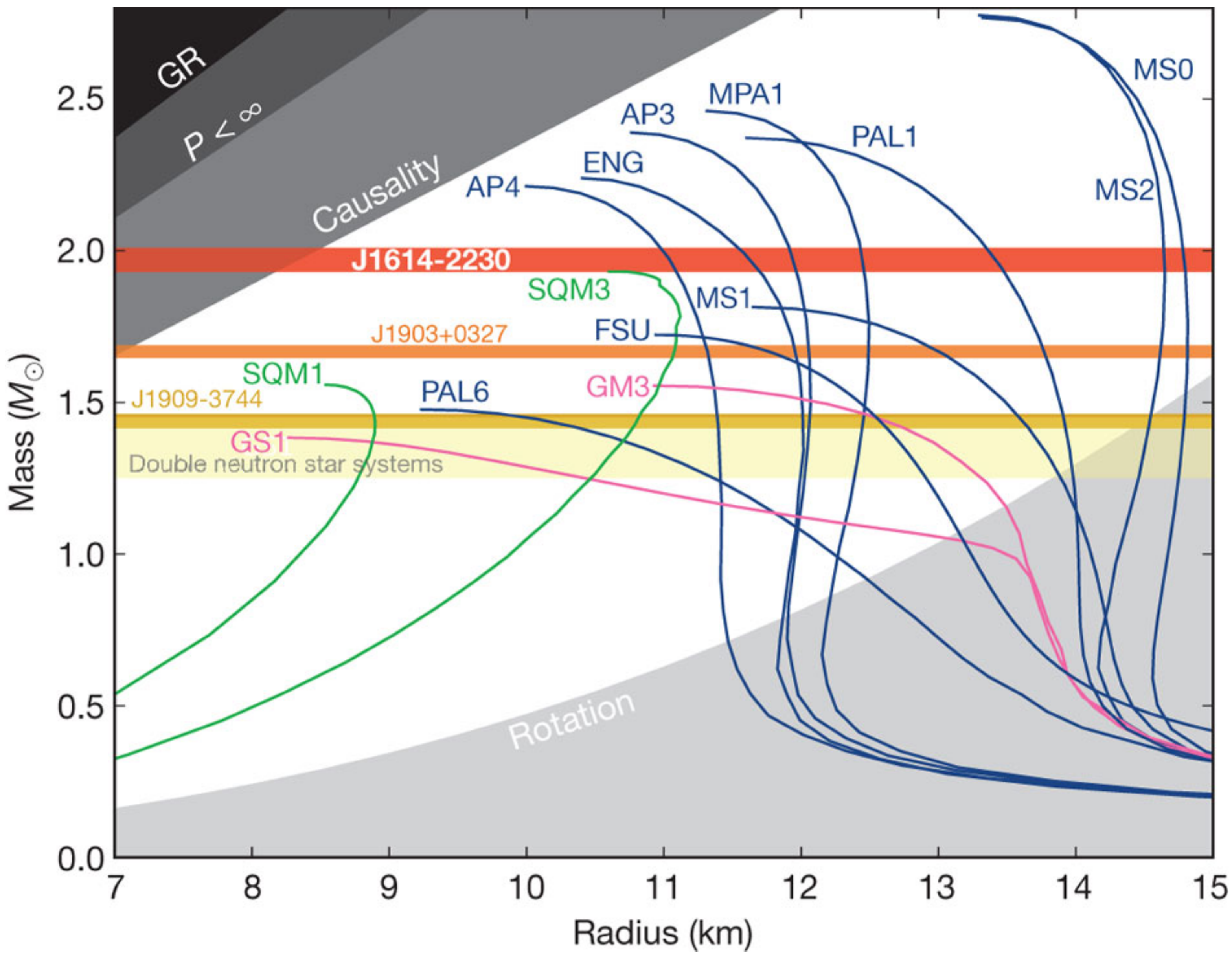
Maximum mass from GW170817 --- 2.17 Msun

Mass distribution depends on NS companion



https://stellarcollapse.org/nsmasses

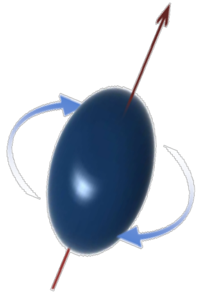
Properties – Equation of state



Magnetic field

Typically 10^4-10^{11} T

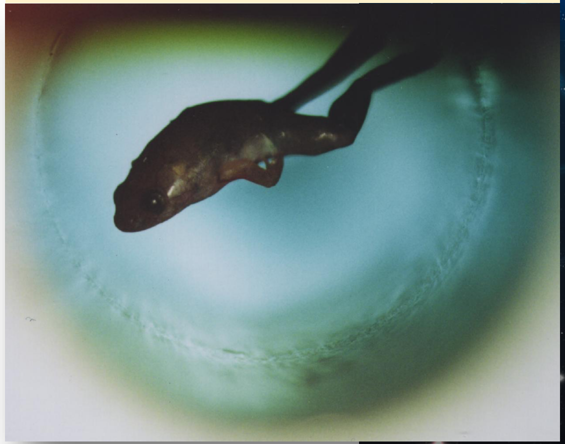
Newly born magnetars --- 10^{15} T



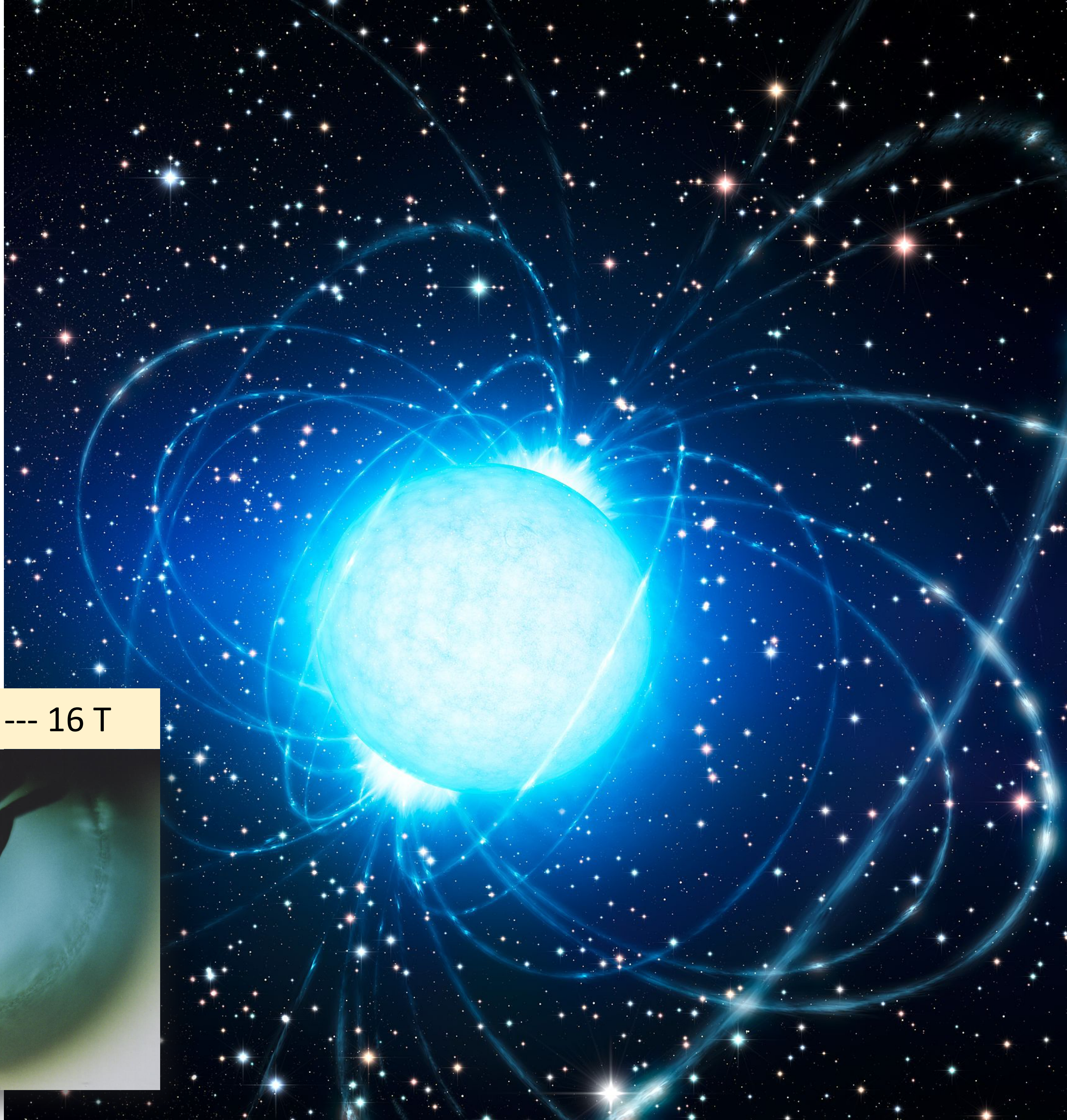
Can make NS prolate

After formation → dynamo effect
→ loss of angular momentum
←→ competing effect with GWs

Frog levitation --- 16 T



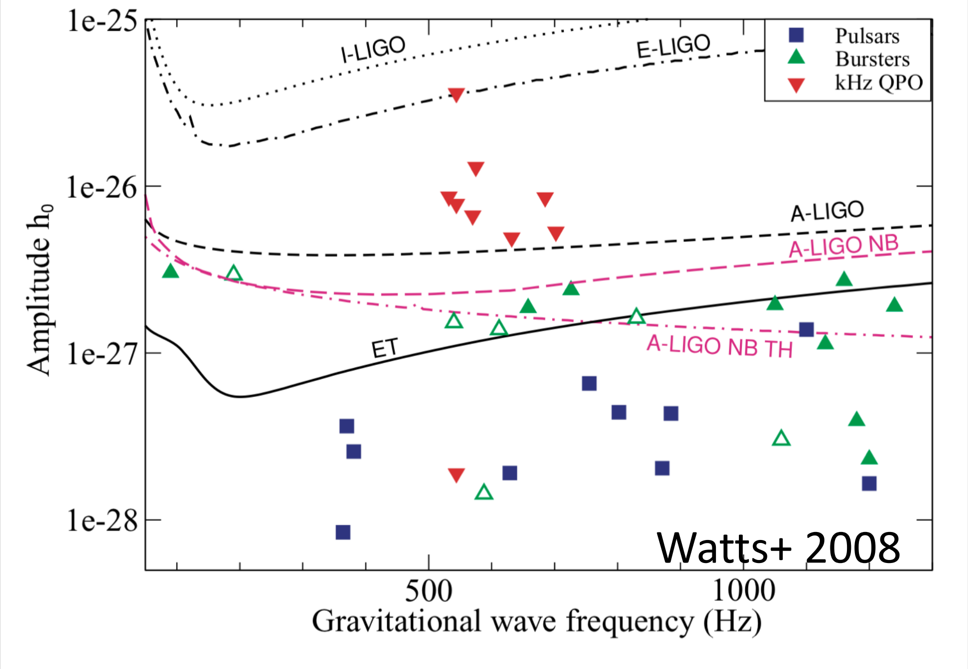
NS slowly loses magnetic fields
→ weak during BNS merger

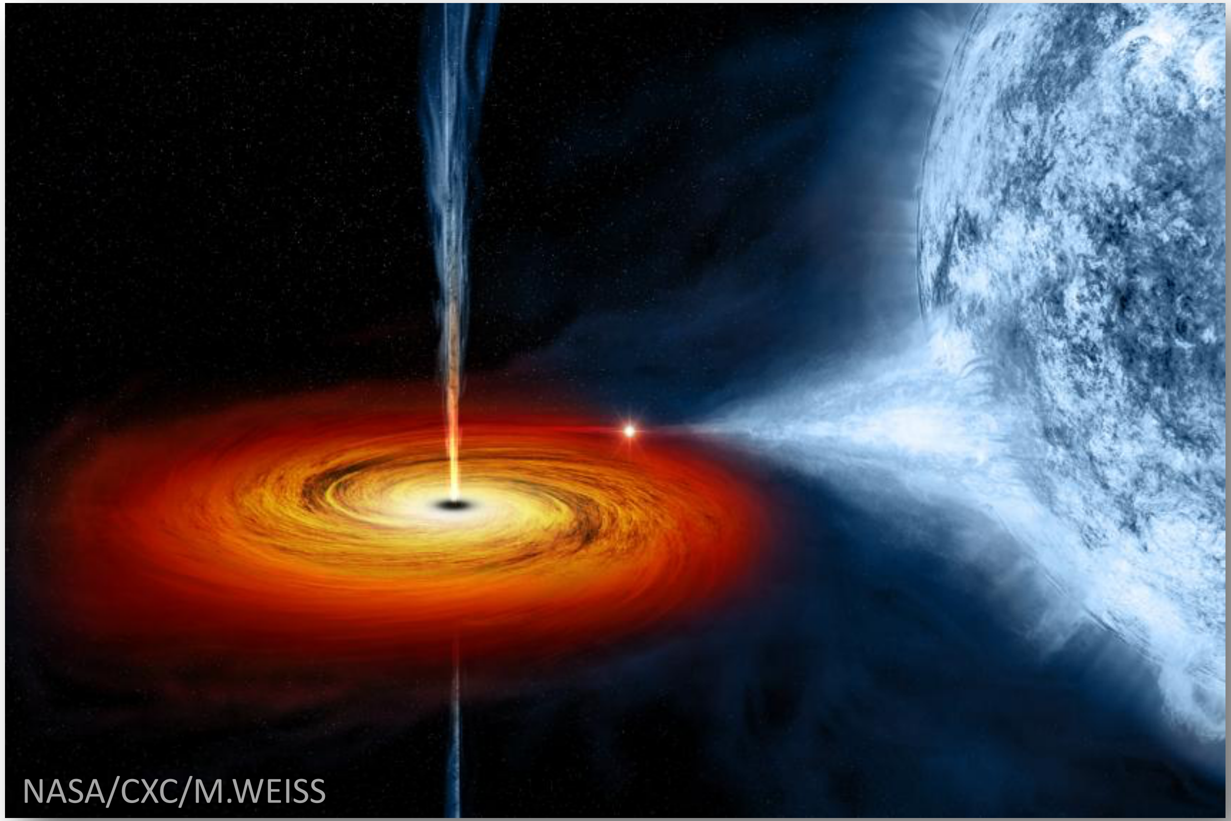


Accretion and spindown

Many accreting NSs rotate around 300 Hz

Maybe GW emission?





Bildsten ApJ Lett 1998

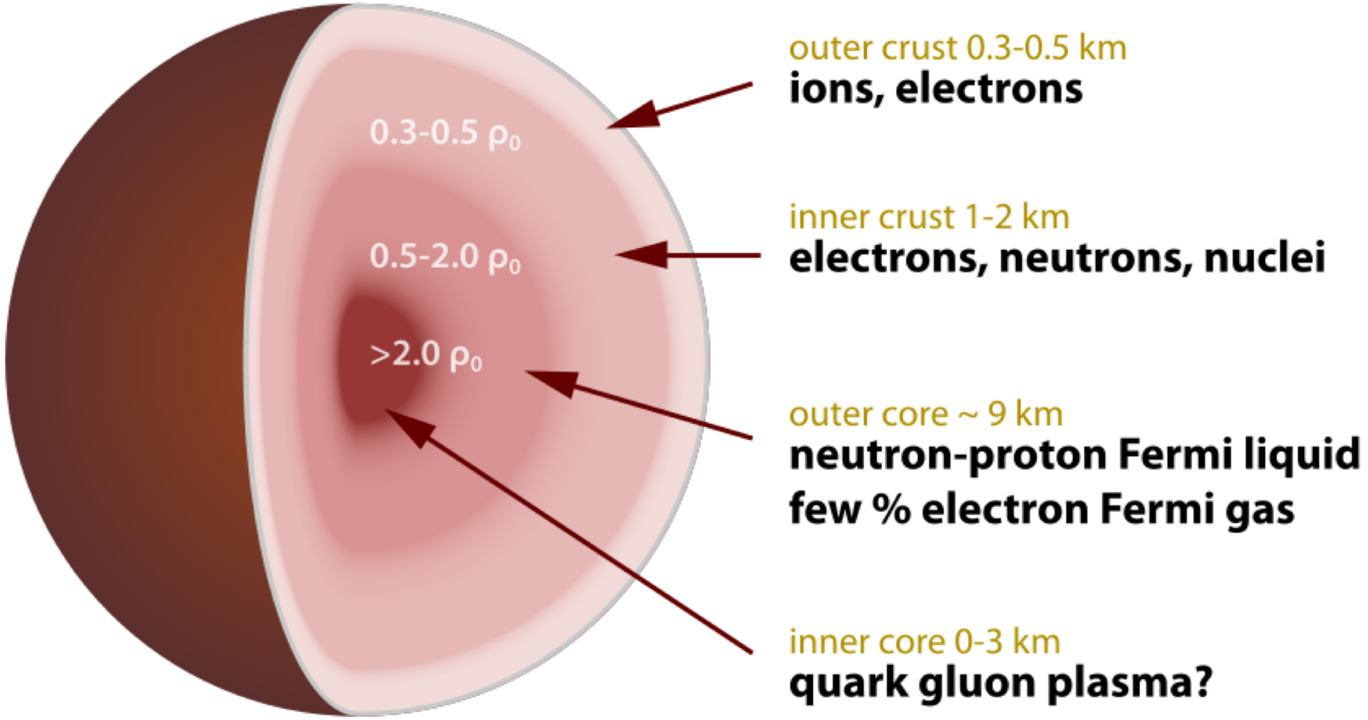
Structure

Mostly unknown

There is likely a NS "crust"

There is likely a core

Quark-gluon plasma in core?



Robert Schulze

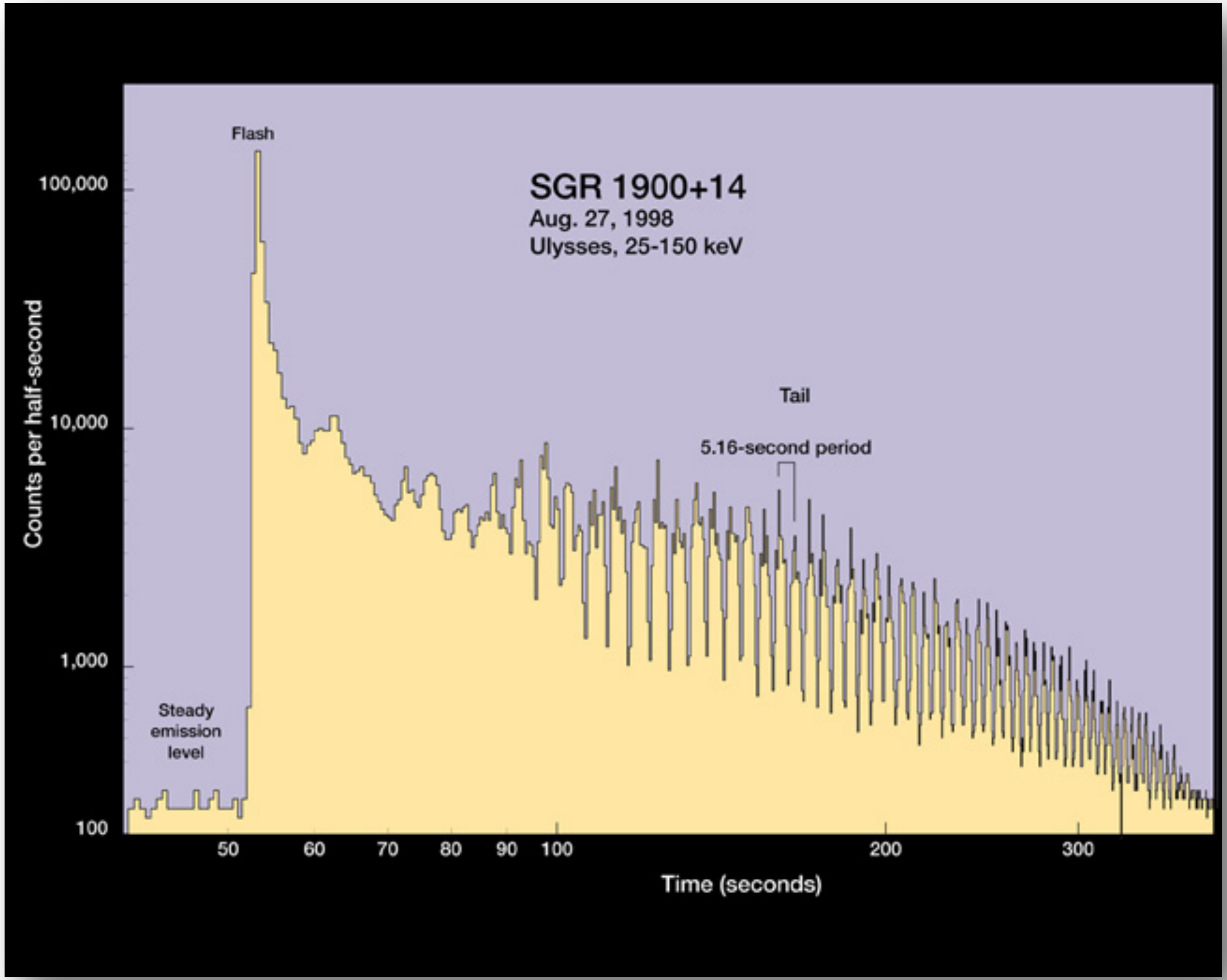
Soft gamma repeaters

Occasional outbursts of gamma rays

Quasi-periodic oscillations

Starquakes??

Magnetic field reorganization?



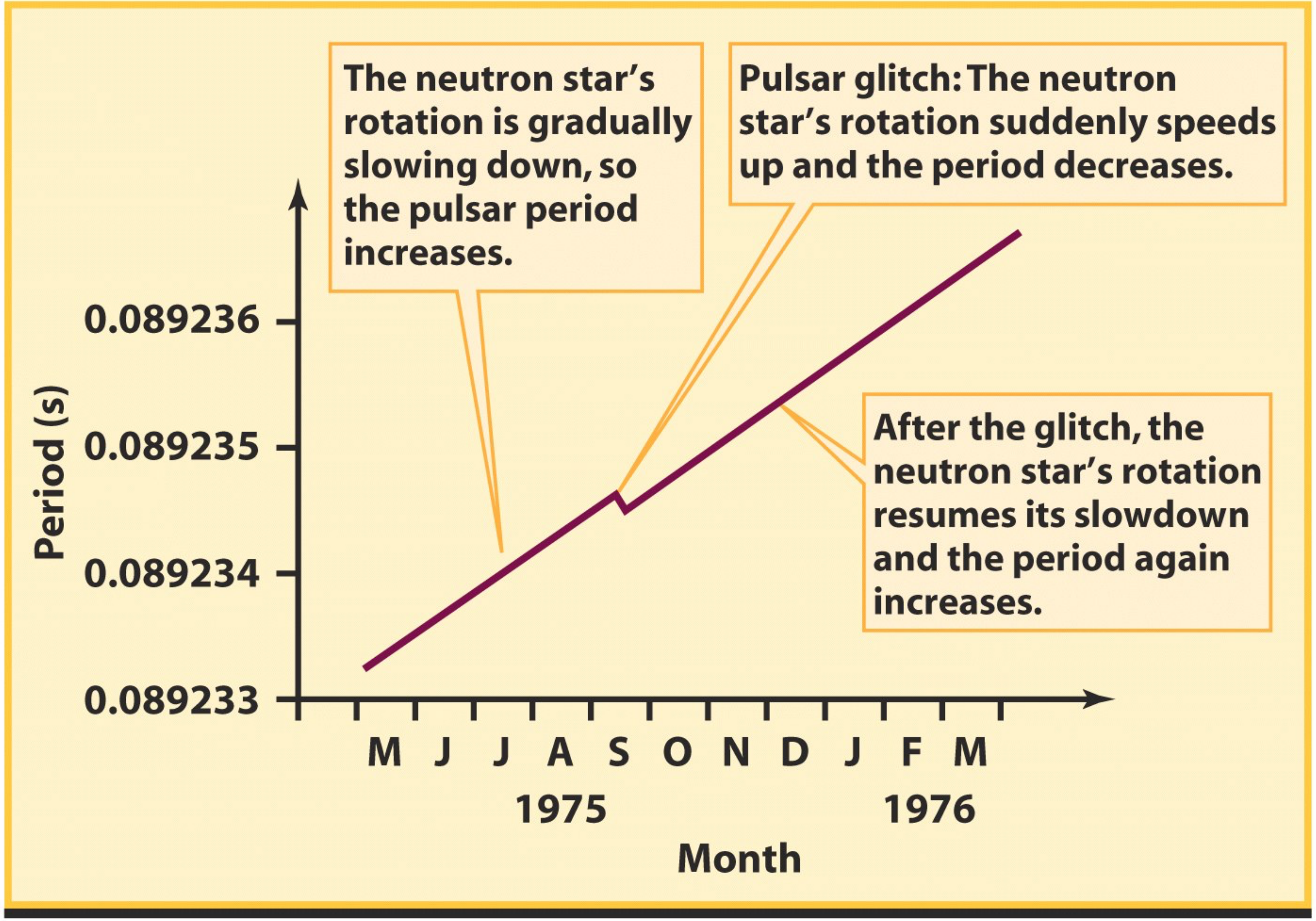
Glitches

Starquakes?
NS crust ruptures
→ radius decreases
→ faster rotation

Core reorganization that releases energy?

Anti-glitches
Unclear??

Bad for pulsar timing



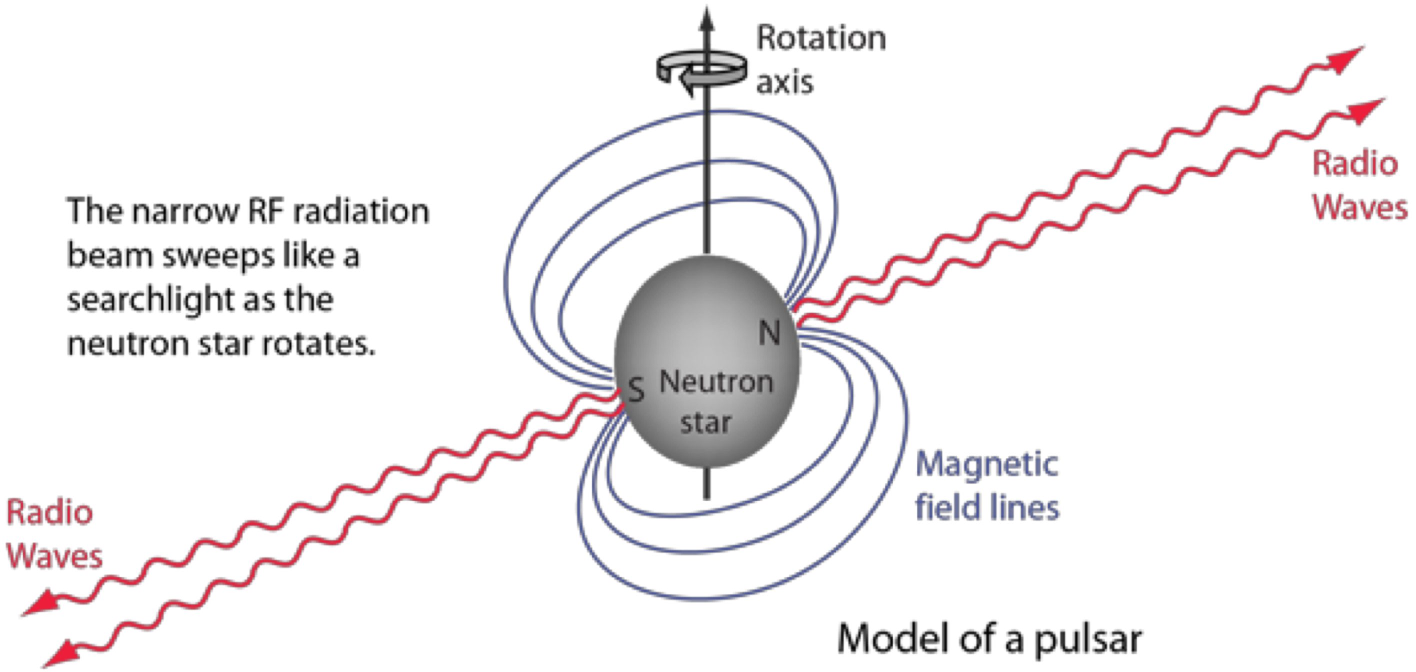
Pulsars

Very regular period

Formed in a supernova

After sufficient slowdown the radio pulsar mechanism is turned off.

Energy source:
- Rotation
- Accretion
- Magnetic fields



http://hyperphysics.phy-astr.gsu.edu