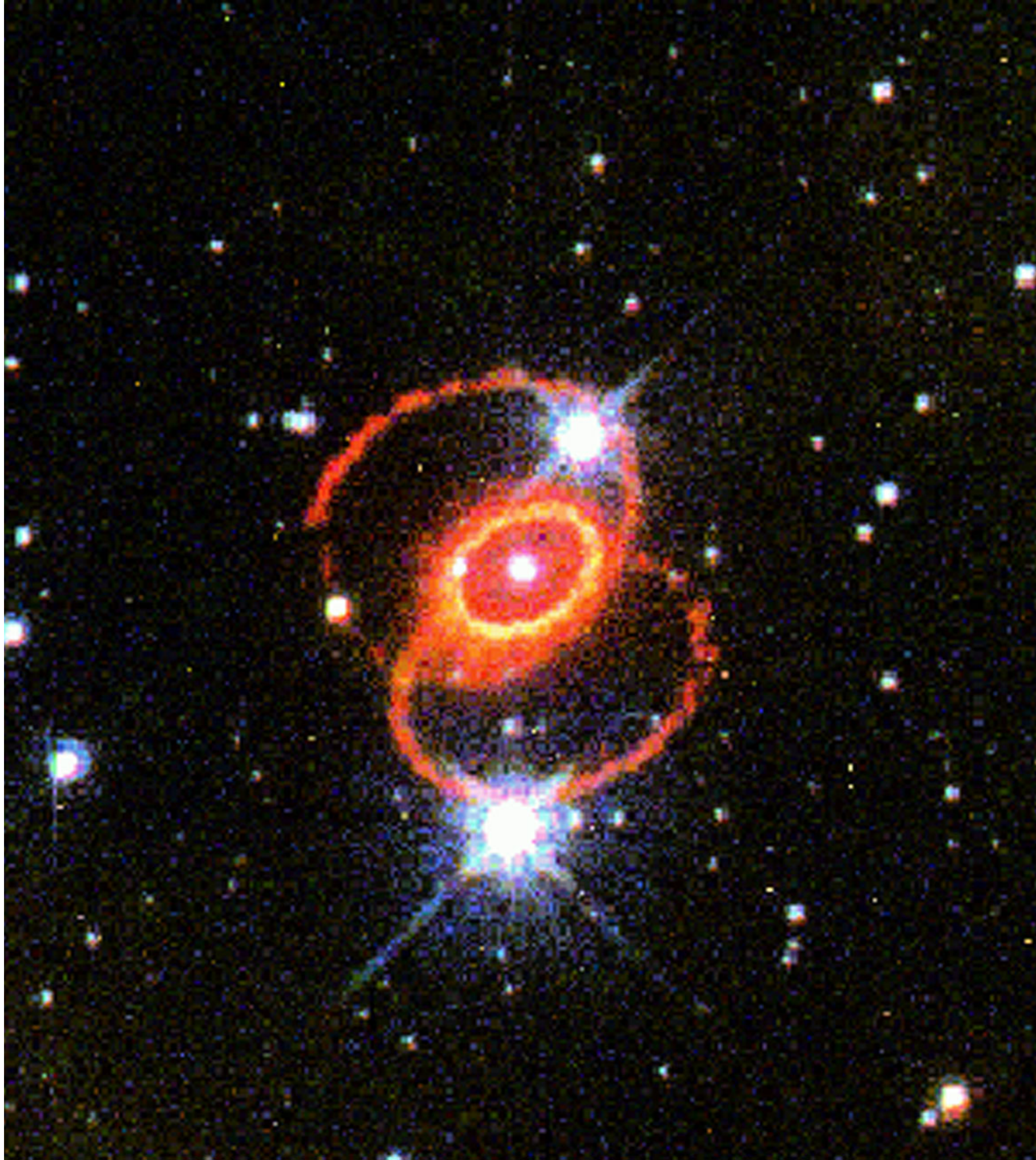
PHY 4905 | Modern Astrophysics

Lecture V.

Supernovae

UF | UNIVERSITY of FLORIDA

Imre Bartos | Fall 2018



Classification

Absorption line and light curve

<table>
<tr><td rowspan="3">Type I
No hydrogen</td><td colspan="3">Type Ia
Presents a singly ionized silicon (Si II) line at 615.0 nm (nanometers), near peak light</td><td>Thermal runaway</td></tr>
<tr><td rowspan="2">Type Ib/c
Weak or no silicon absorption feature</td><td colspan="2">Type Ib
Shows a non-ionized helium (He I) line at 587.6 nm</td><td rowspan="6">Core collapse</td></tr>
<tr><td colspan="2">Type Ic
Weak or no helium</td></tr>
<tr><td rowspan="4">Type II
Shows hydrogen</td><td rowspan="3">Type II-P/L/N
Type II spectrum throughout</td><td rowspan="2">Type II-P/L
No narrow lines</td><td>Type II-P
Reaches a "plateau" in its light curve</td></tr>
<tr><td>Type II-L
Displays a "linear" decrease in its light curve (linear in magnitude versus time).[47]</td></tr>
<tr><td colspan="2">Type IIn
Some narrow lines</td></tr>
<tr><td colspan="3">Type IIb
Spectrum changes to become like Type Ib</td></tr>
</table>

https://en.wikipedia.org/wiki/Supernova

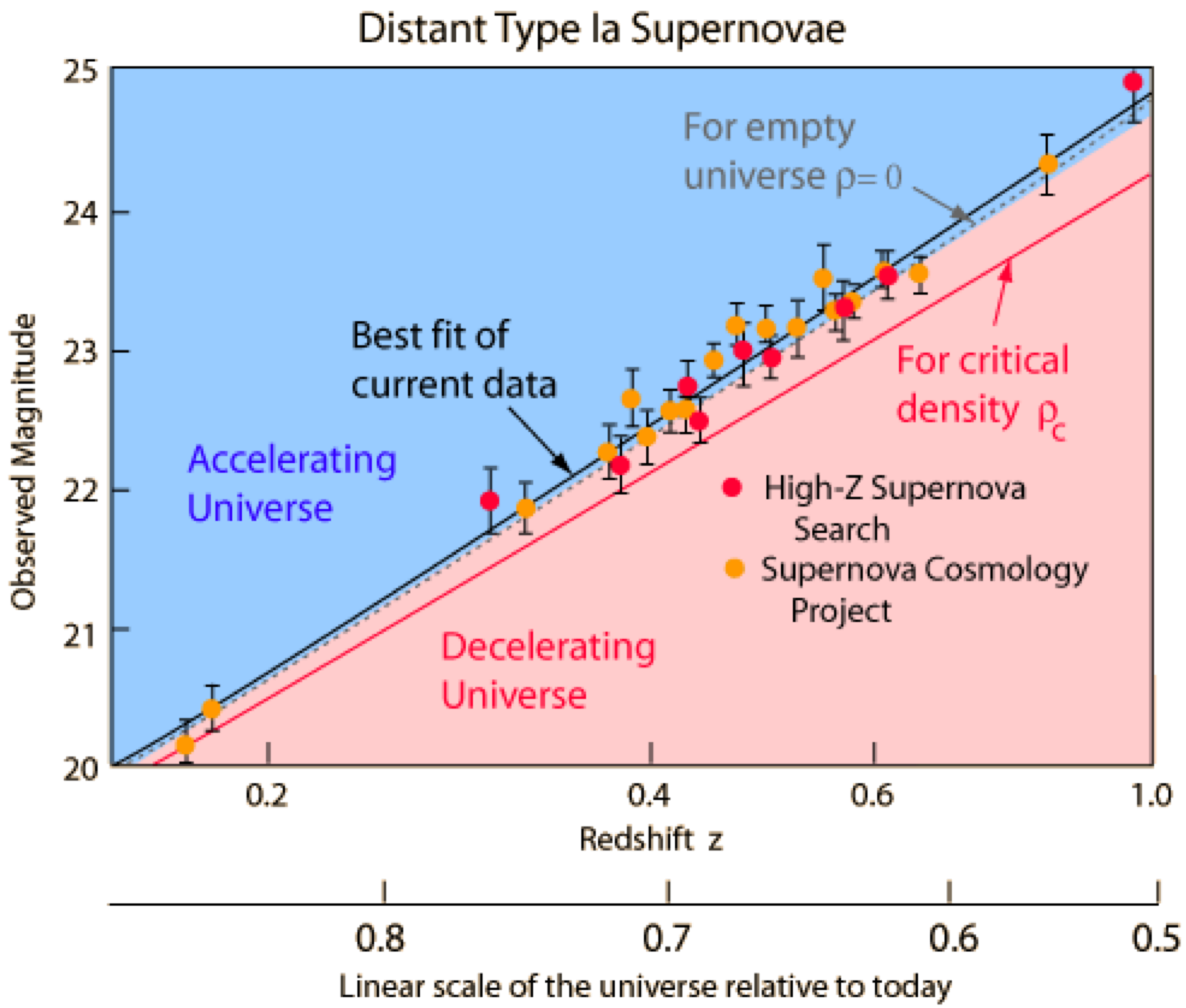
Cosmology with Type Ia Supernovae

"Standard candle"
always the same peak luminosity

Allows reconstruction of
luminosity distance

vs. host galaxy redshift

→ Rate of expansion of the universe



SN 1987A

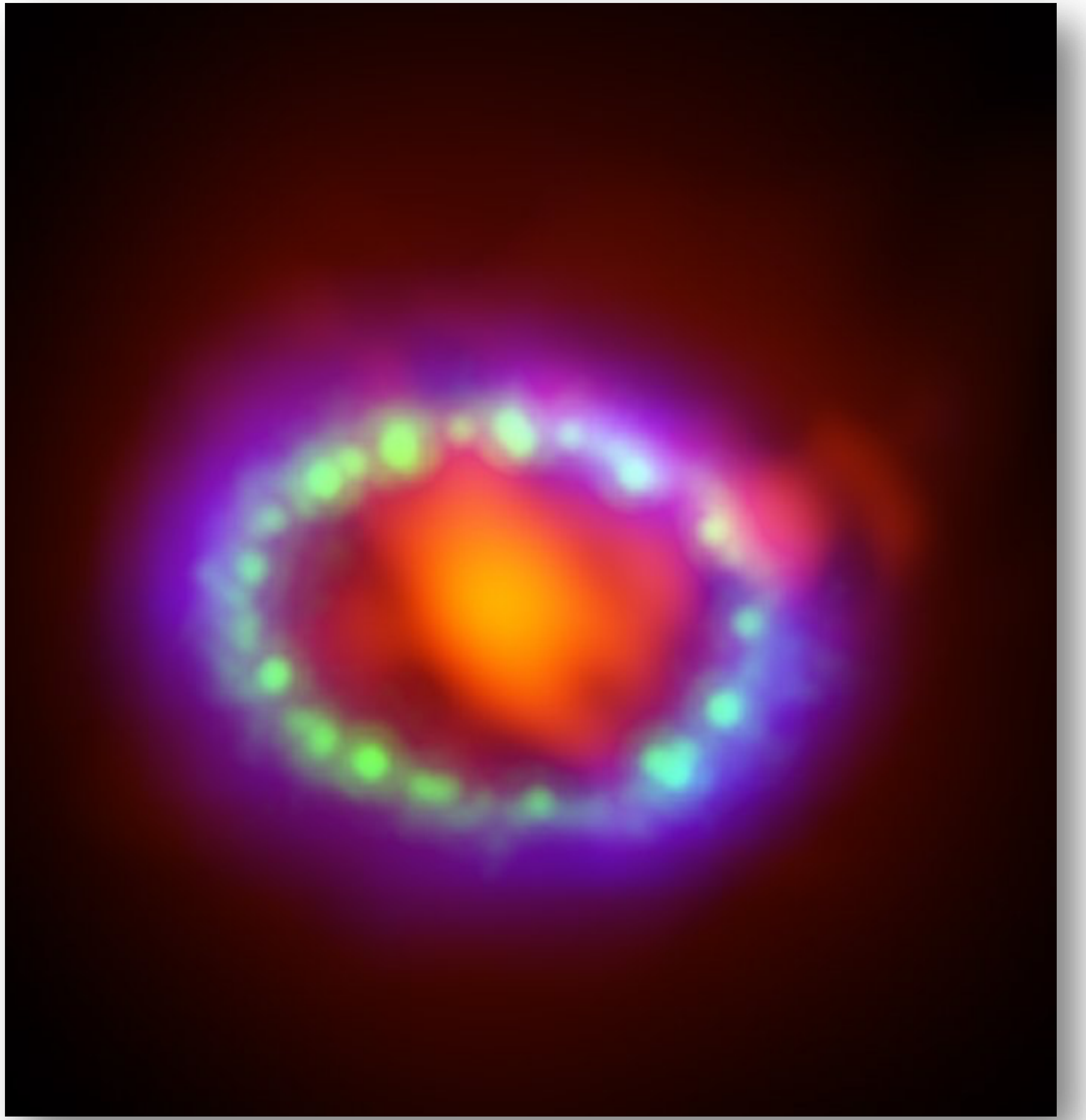
In Large Magellanic Cloud at ~50 kpc

Progenitor star: blue supergiant

Visible to the naked eye from the Southern hemisphere

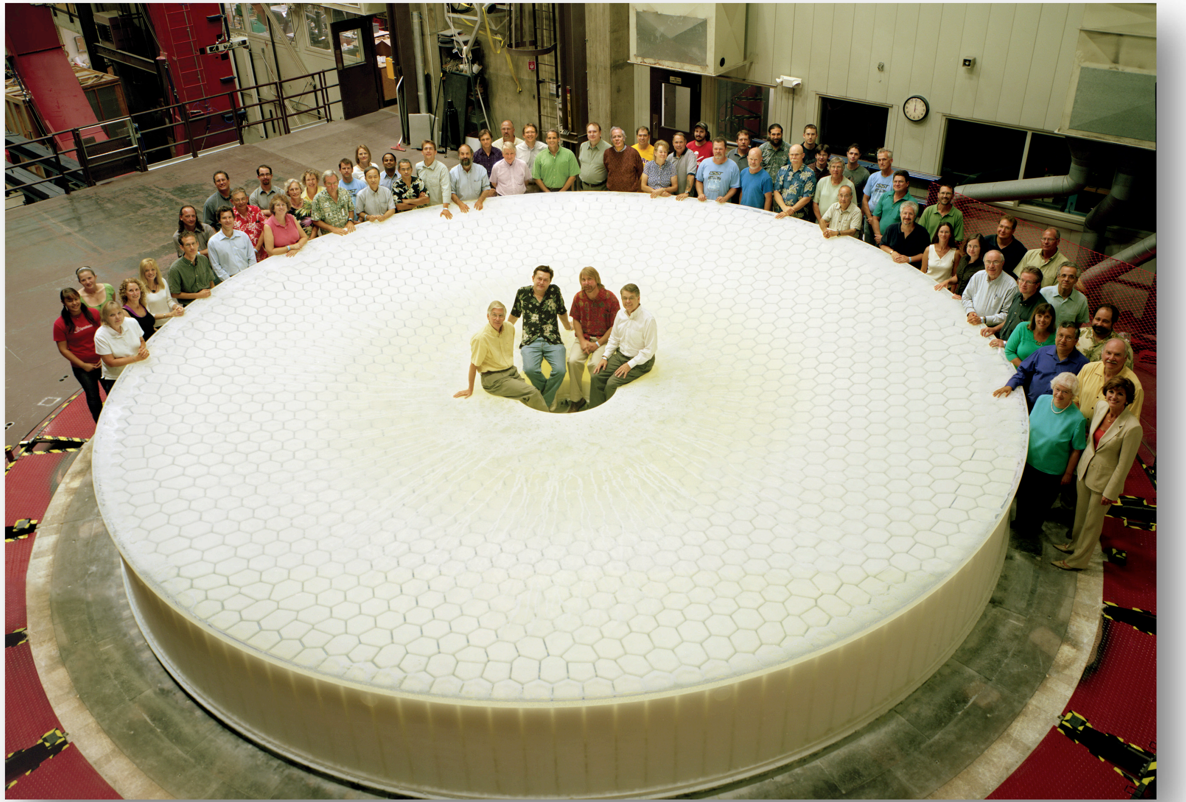
Detection of 25 neutrinos
2-3 hours before the first light was detected

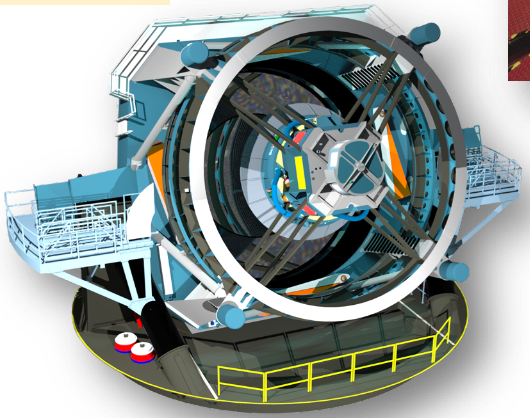
No NS remnant has been observed



Observations

Zwicky Transient Facility (ZTF)
Regular scans of the sky, rapid ToO response

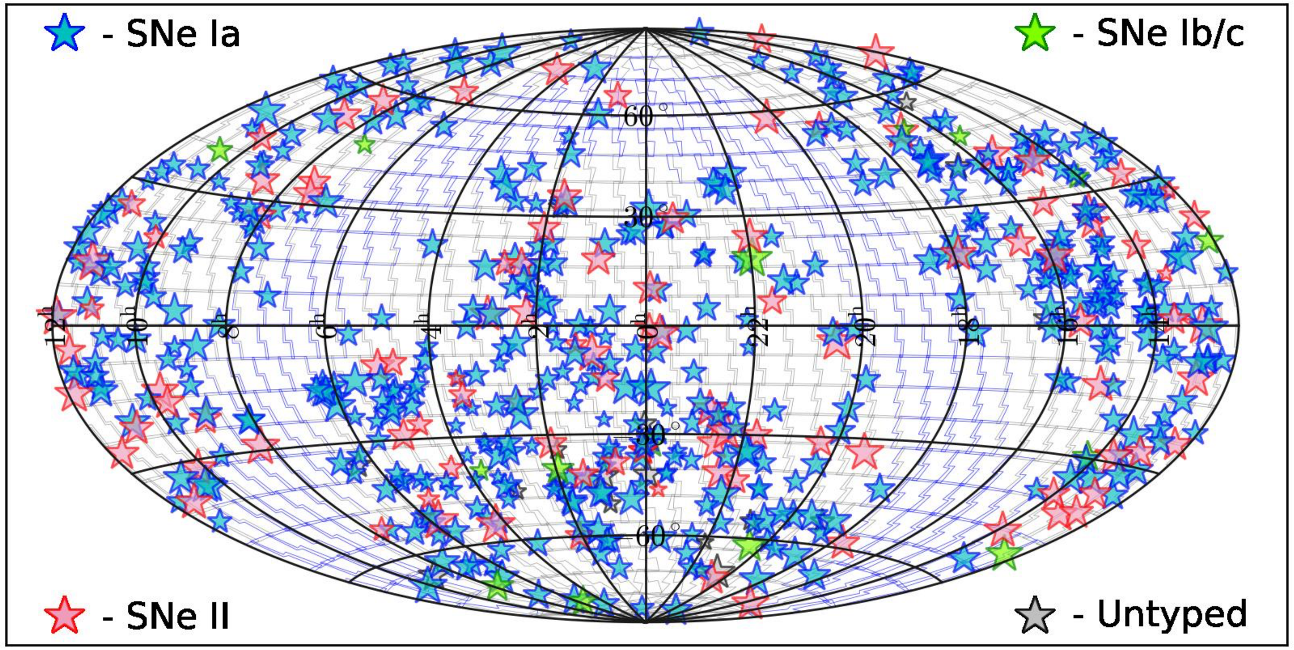




Large Synoptic Survey Telescope (LSST, 2022)
Regular scans of the sky, very high sensitivity (9m)

Observations

ASAS-SN



Multiple, very small telescopes that scan the whole sky every night.

Gravitational waves

"messy" waveform
stochastic with dominant frequency

Emission essentially stars with core bounce

Duration: 10s of ms

Waveform will depend on:
- Mass
- Nuclear equation of state (EoS)
- Rotation
- …

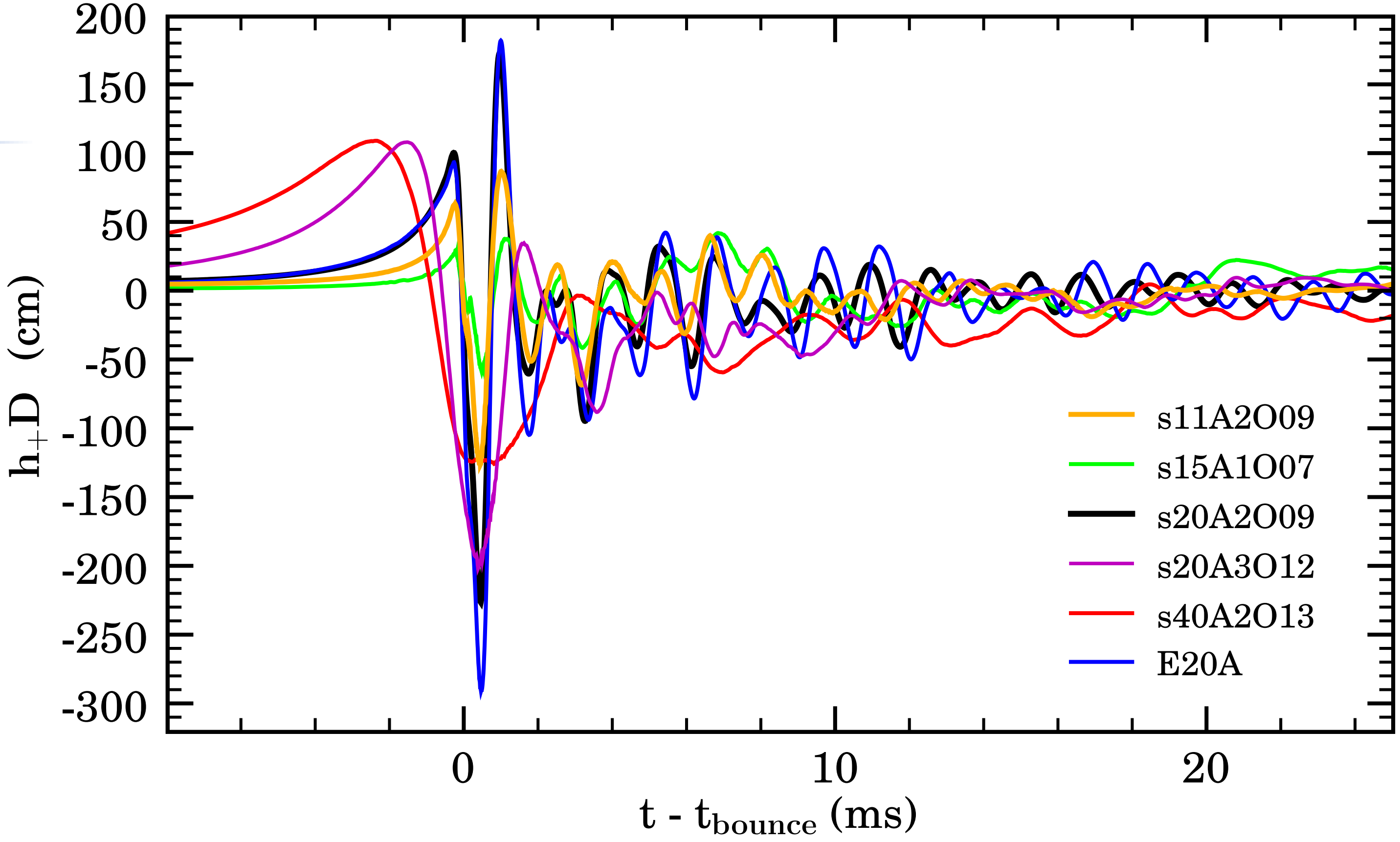


Figure 2. GW signals ($h_+ D$ in units of cm, where D is the distance of the source) for a few examples from the 2D GR model set of Dimmelmeier et al. [108]. The models shown here were computed with the Shen EOS [135, 136] and employ 1D presupernova models of [137], spanning the progenitor mass range from 11.2 $M_\odot$ (s11) to 40 $M_\odot$ (s40). The models were set up with precollapse central angular velocities $\Omega_{\mathrm{c,i}}$ from ~ 1.5 rad s^{-1} to ~ 11 rad s^{-1}. For details of the rotational setup, see [108]. Model E20A uses a 20-$M_\odot$ presupernova model that was evolved by [138] with a 1D prescription for rotation. Note the generic shape of the waveforms, exhibiting one pronounced spike at core bounce and a subsequent ring down. Very rapid precollapse rotation ($\Omega_{\mathrm{c,i}} \gtrsim 6$ rad s^{-1}; models s20A3O12 and s40A2O13 in this plot) results in a significant slow-down of core bounce, leading to a lower-amplitude and lower-frequency GW burst. The GW signal data are available for download from [126].

Ott 2008

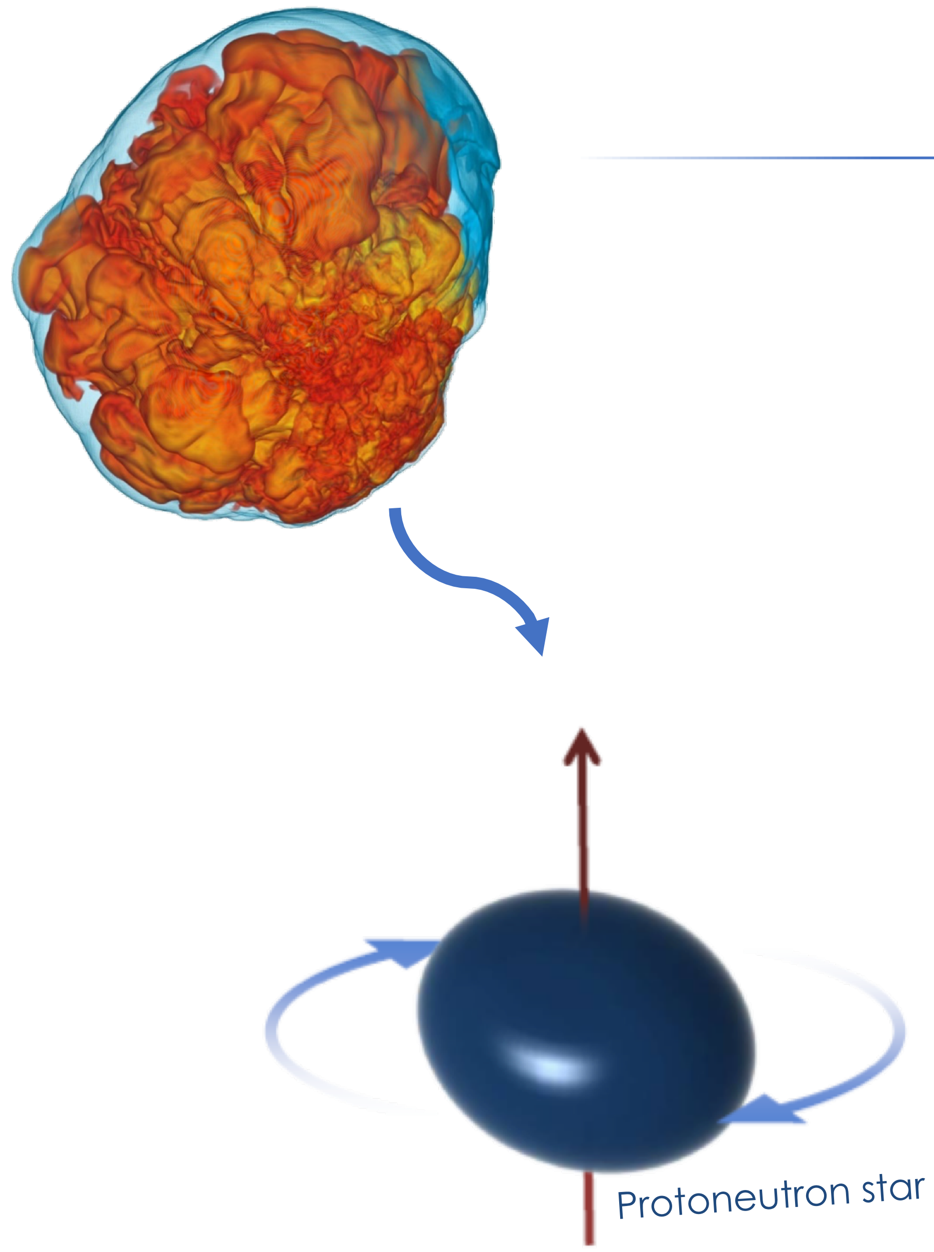
Gravitational wave production

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)

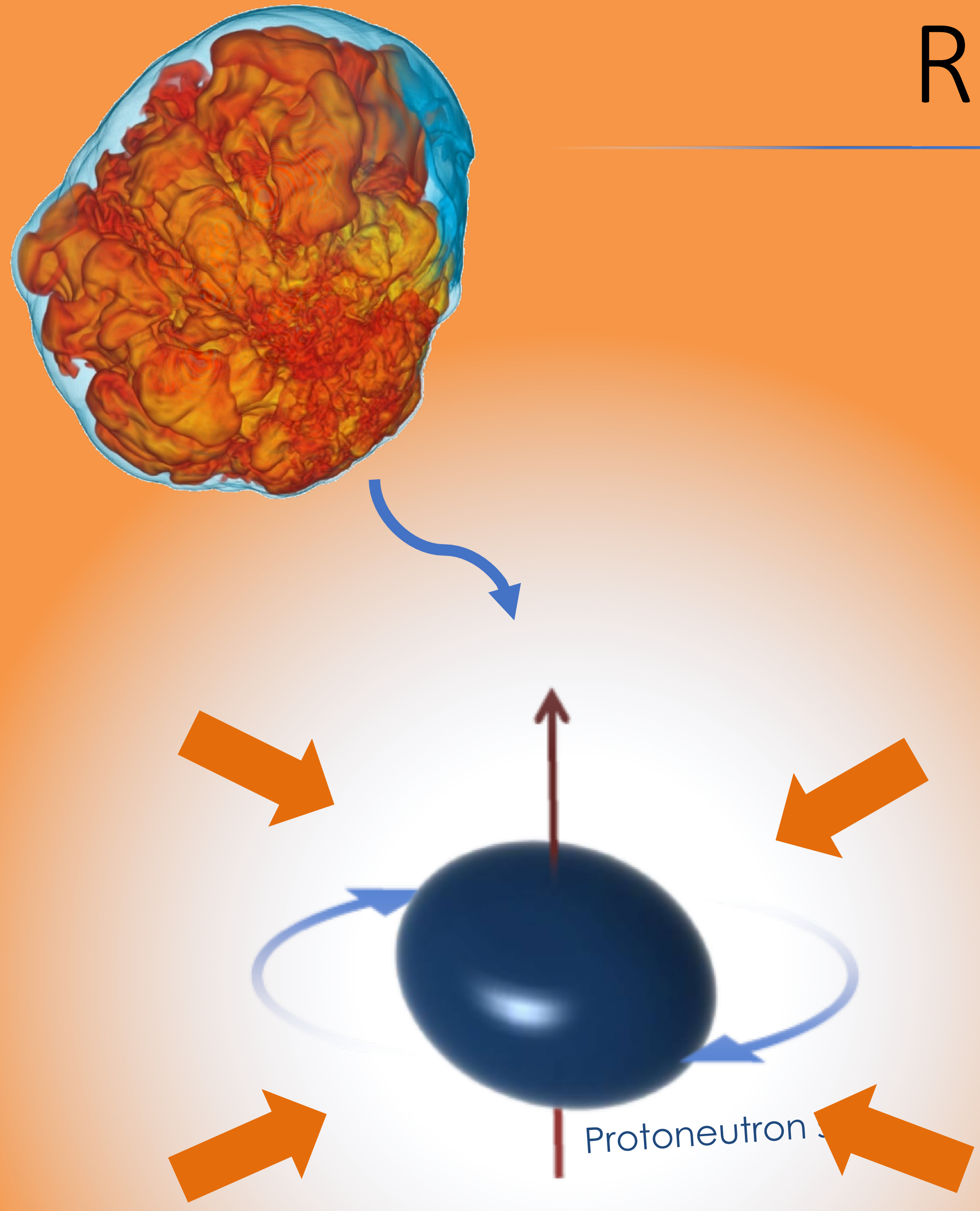
→ 50-100 Mpc

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)*

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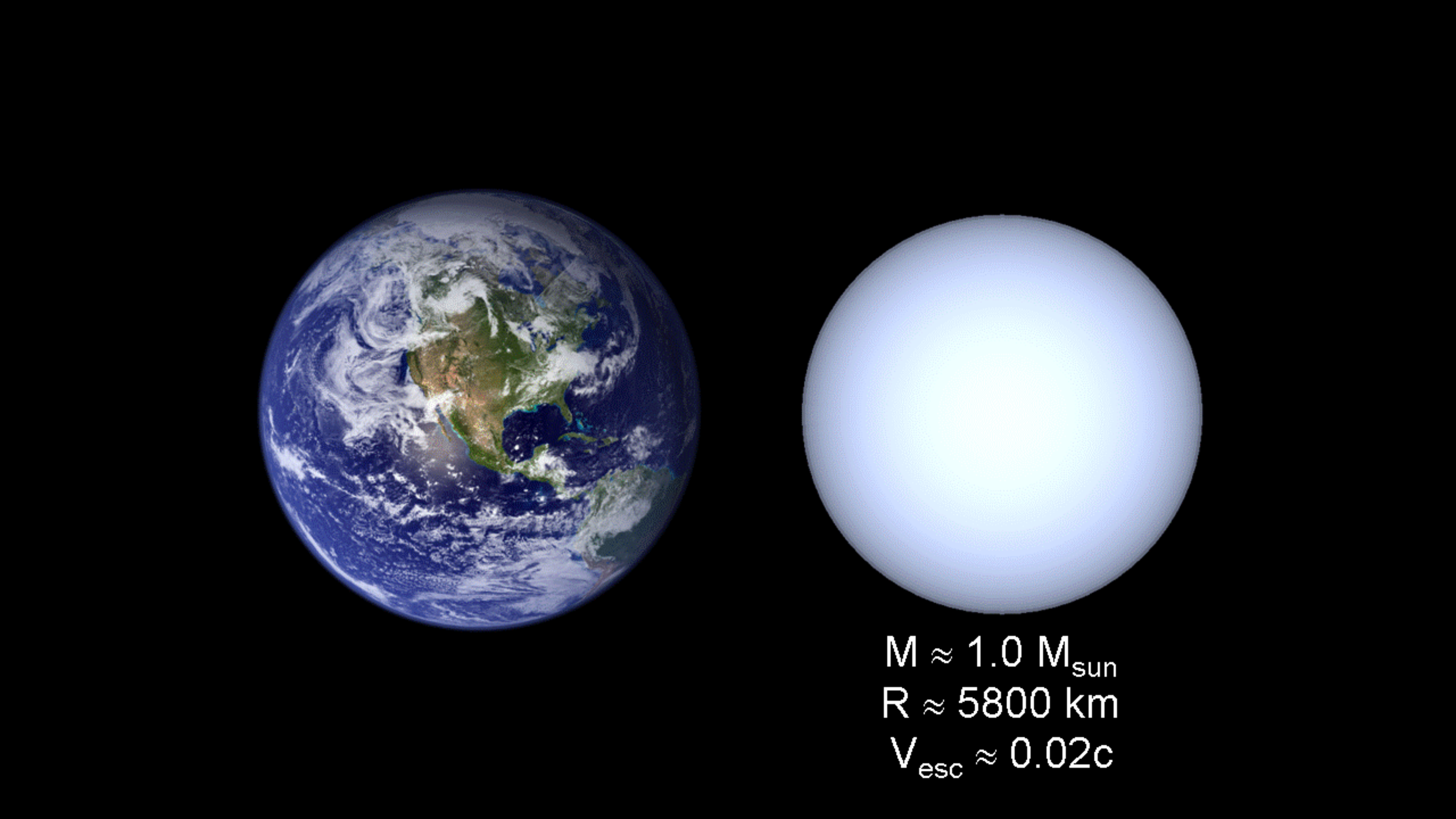
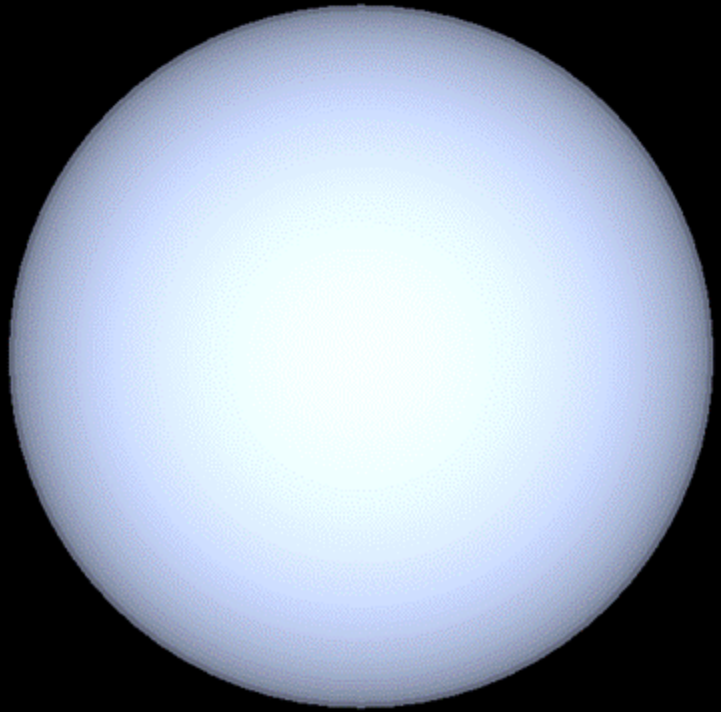
Bartos, Brady, Marka 2013


$M \approx 1.0\ M_{sun}$
$R \approx 5800$ km
$V_{esc} \approx 0.02c$



$M \approx 1.0\ M_{sun}$
$R \approx 5800$ km
$V_{esc} \approx 0.02c$

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

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

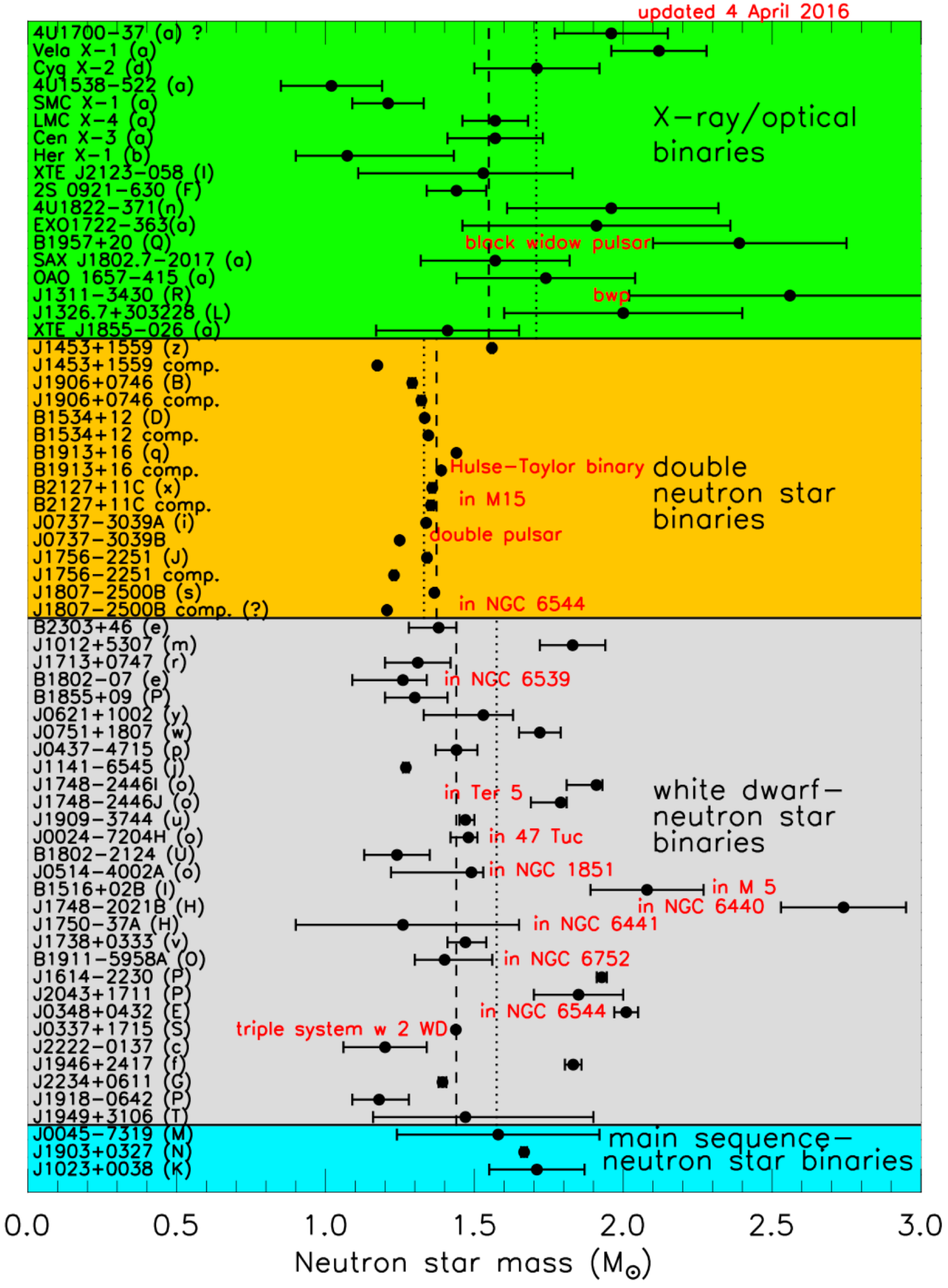
Properties - Mass

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

Maximum observed mass --- ~2 Msun

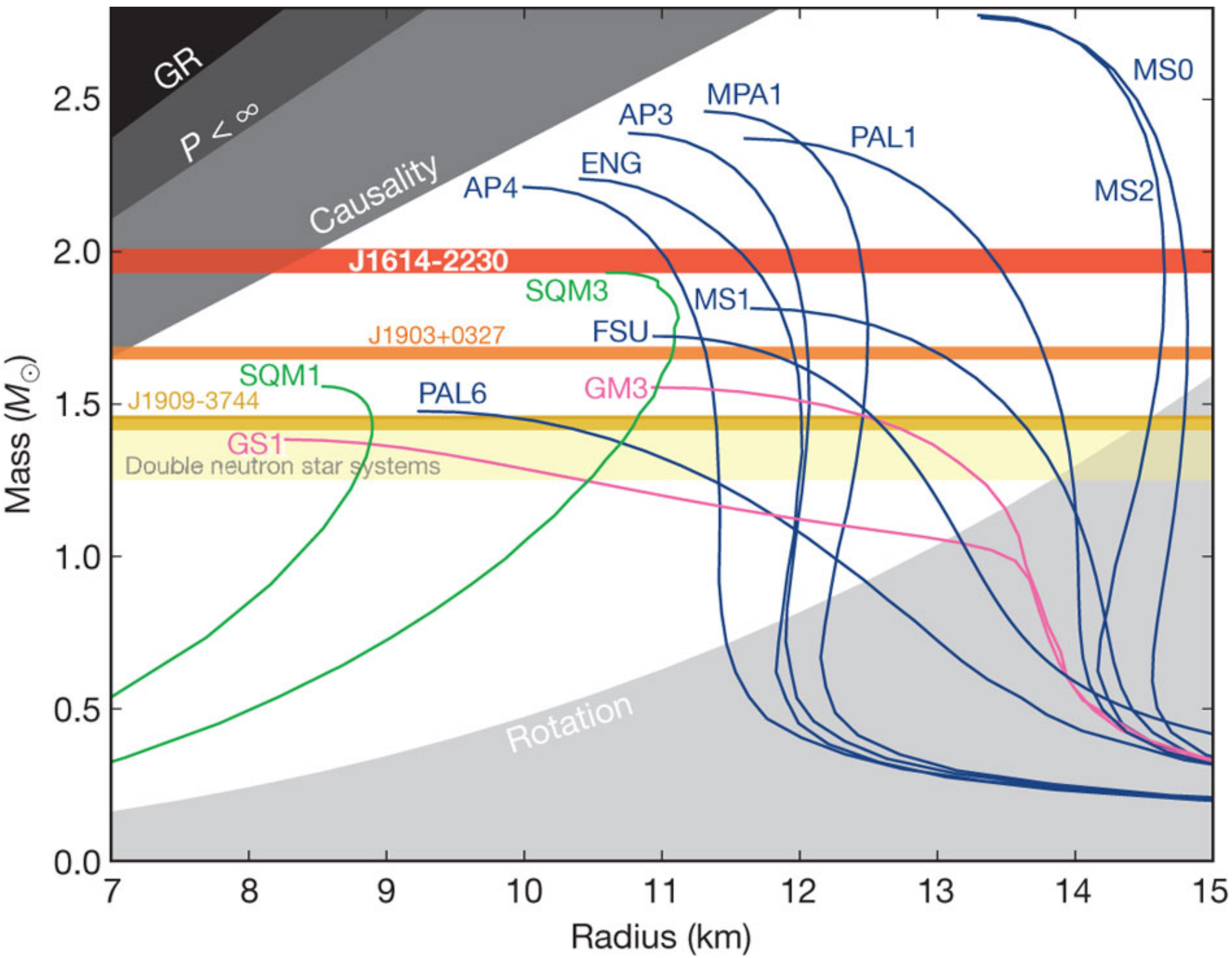
Maximum mass from GW170817 --- 2.17 Msun

Mass distribution depends on NS companion



https://stellarcollapse.org/nsmasses

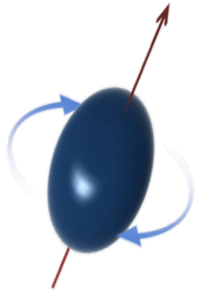
Properties – Equation of state



Magnetic field

Typically 10^4-10^{11} T

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

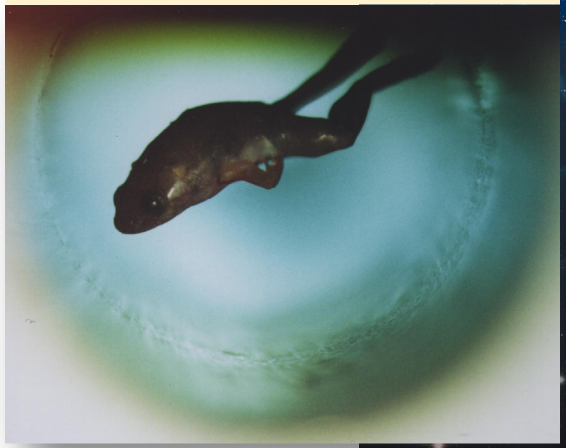


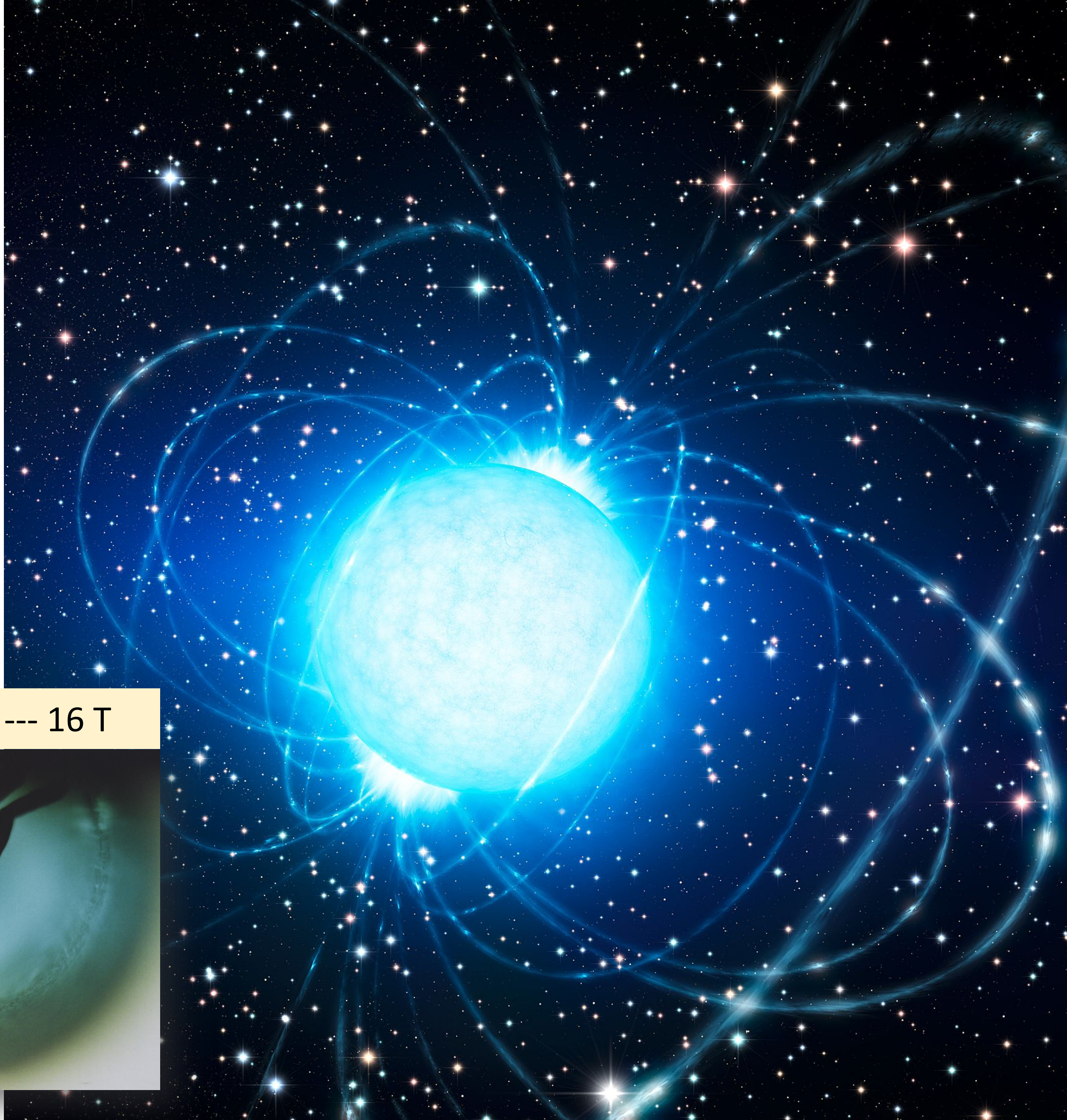
Can make NS prolate

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

NS slowly loses magnetic fields
→ weak during BNS merger

Frog levitation --- 16 T

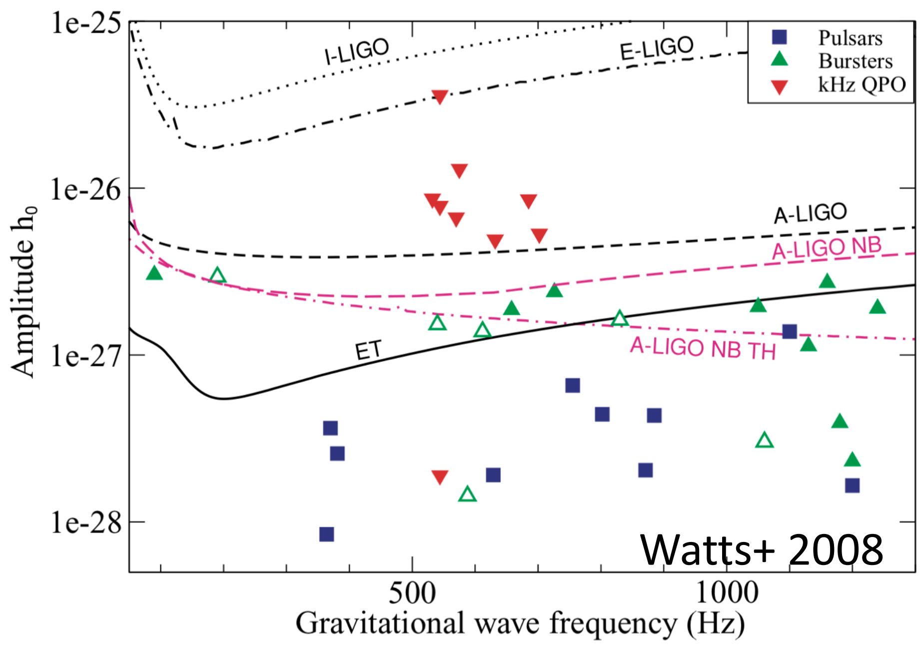


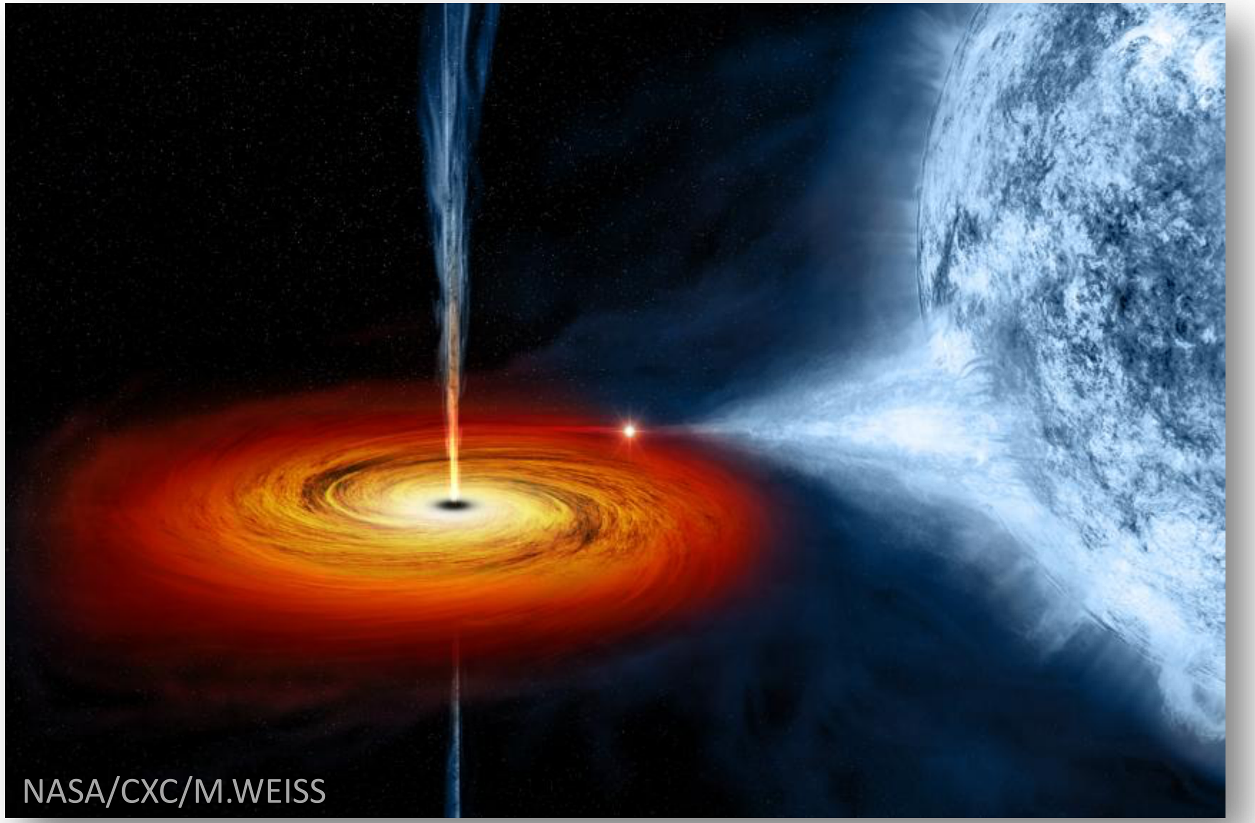


Accretion and spindown

Many accreting NSs rotate around 300 Hz

Maybe GW emission?





Bildsten ApJ Lett 1998

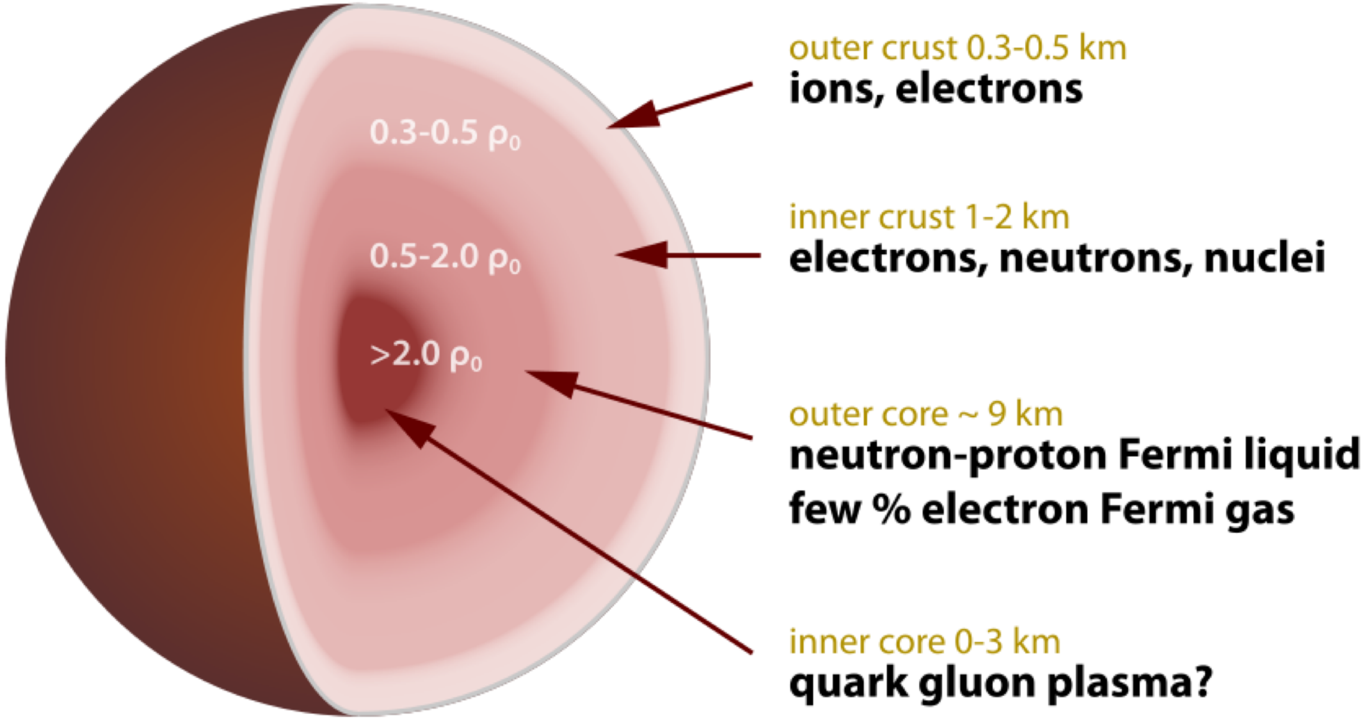
Structure

Mostly unknown

There is likely a NS "crust"

There is likely a NS "crust" and core

Quark-gluon plasma in core?



Robert Schulze

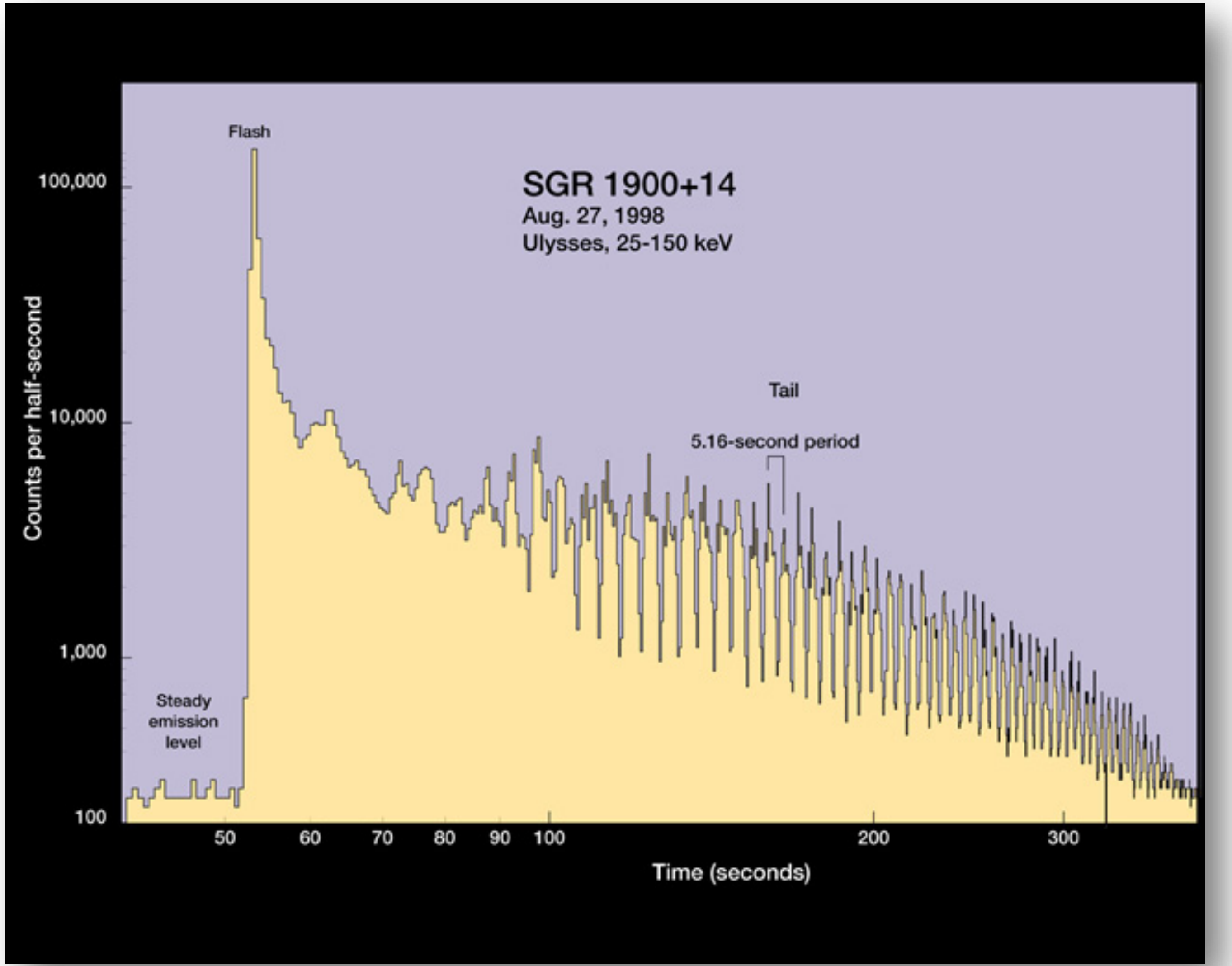
Soft gamma repeaters

Occasional outbursts of gamma rays

Quasi-periodic oscillations

Starquakes??

Magnetic field reorganization?



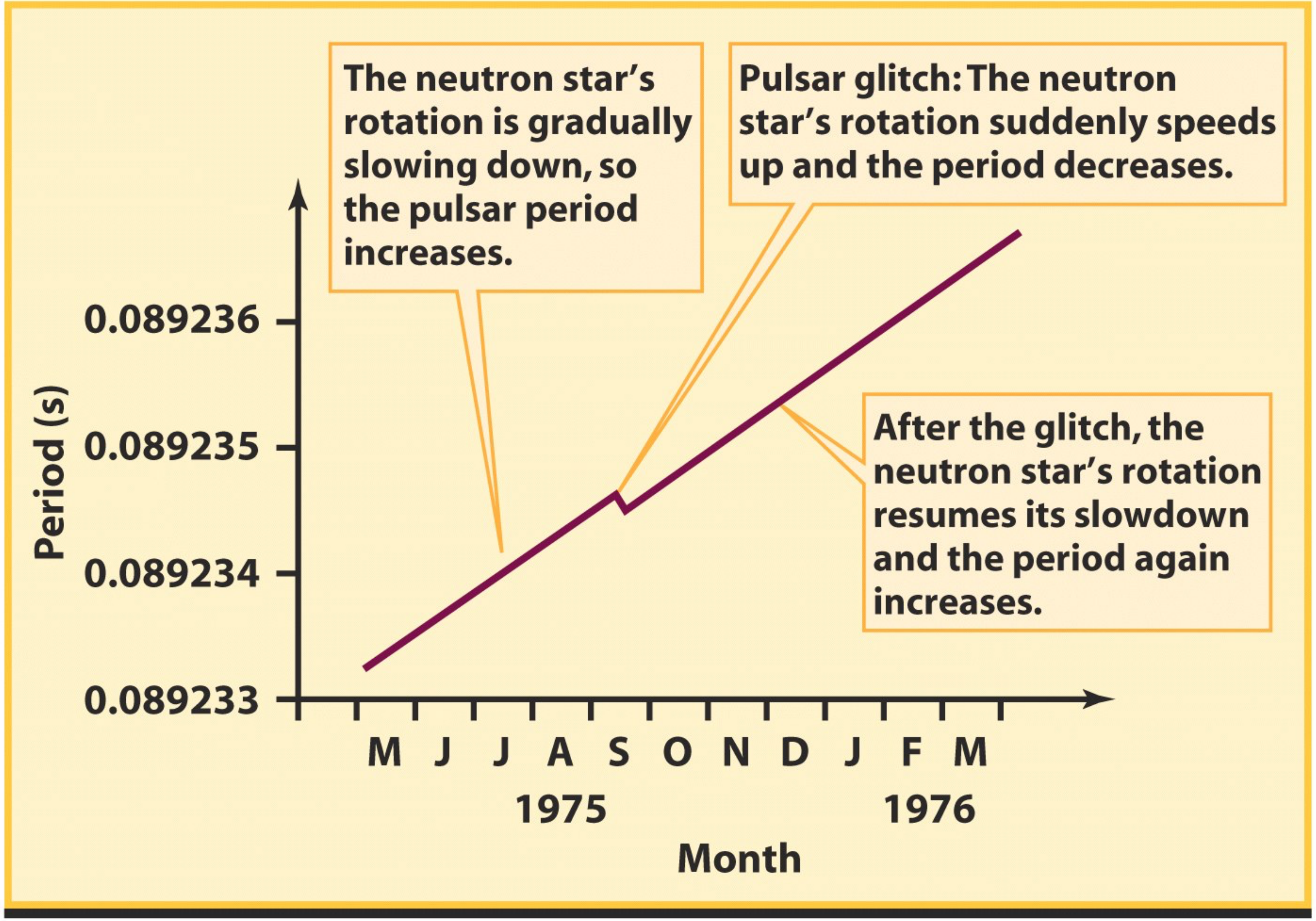
Glitches

<u>Starquakes?</u>
NS crust ruptures
→ radius decreases
→ faster rotation

Core reorganization that releases energy?

<u>Anti-glitches</u>
Unclear??

Bad for pulsar timing



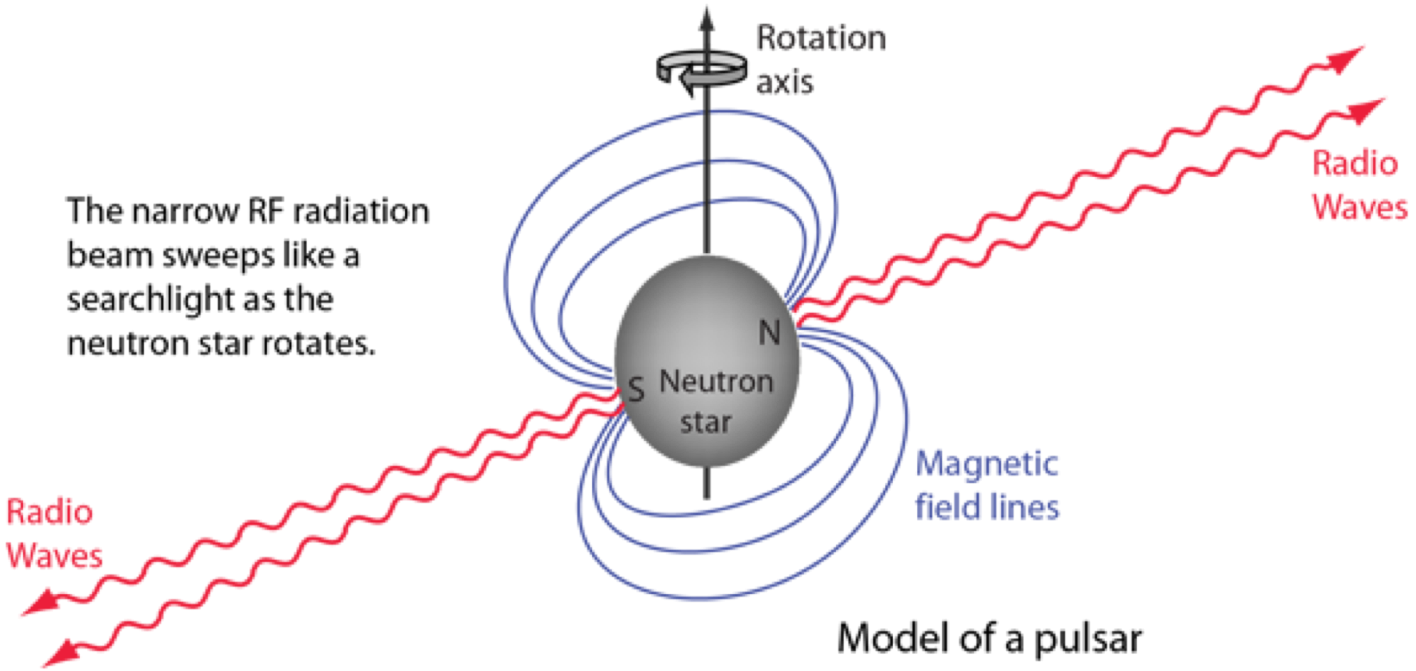
Pulsars

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