Binary Neutron Star Mergers and Nuclear Physics

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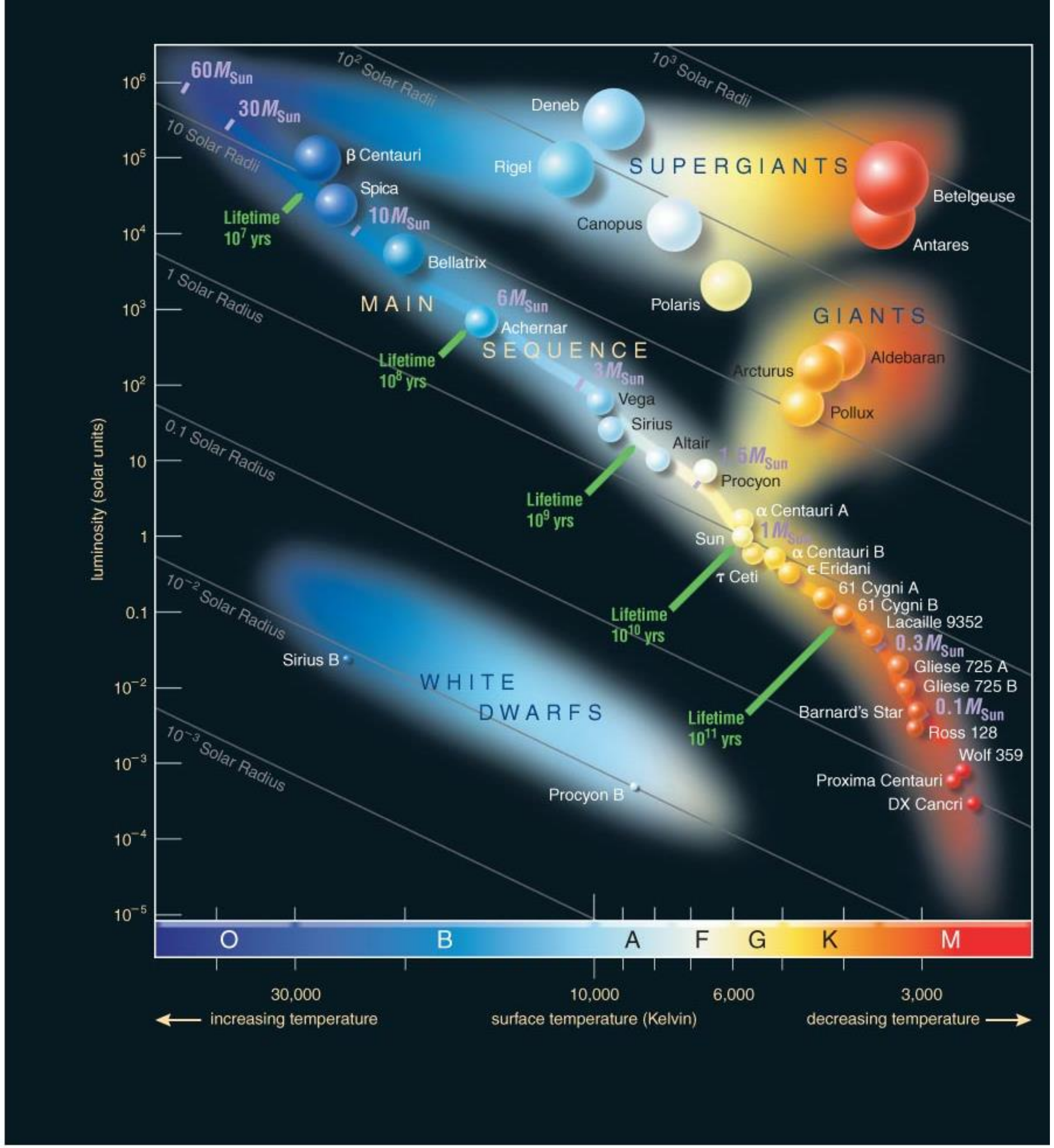
Plan of the Lectures

1. Isolated and Binary Neutron Stars: an Introduction
2. Gravitational Wave Emission from Binary Neutron Star Mergers
3. Electromagnetic Emission from Binary Neutron Star Mergers
4. Observations of Binary Neutron Star Mergers

Compact Objects

Object	Mass ($M_\odot$)	Radius ($R_\odot$)	ρ (g cm^{-3})	$C \equiv \frac{MG}{Rc^2}$
Sun	1	1	~1	10^{-6}
White Dwarf	~0.6	~10^{-2}	~10^{6}	~10^{-4}
Neutron Star	~1.4	~10^{-5}	~10^{14}	~0.2
Black Hole	Any value	$(1-2)\frac{GM}{c^2}$	N/A	0.5-1

$M_\odot \sim 2 \times 10^{33} g$ $R_\odot \sim 7 \times 10^{10}\ cm$



H-R Diagram for Stars

Solar Values

$$M_{\odot} \sim 2 \times 10^{33}\text{g}$$

$$R_{\odot} \sim 7 \times 10^{10}\text{cm}$$

$$L_{\odot} \sim 4 \times 10^{33}\text{erg}\,\text{s}^{-1}$$

$$T_{\text{eff}} \sim 5800\text{K}$$

Note: $1\ \text{erg}\ \text{s}^{-1} = 10^{-7}\text{W}$

$$L = 4\pi R^2 \sigma T^4$$

White Dwarfs

1863: first observation (Sirius B)

1926: Fermi-Dirac Statistics

1930-1931: Chandrasekhar solution for White Dwarfs

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Neutron Stars

1930: discovery of neutron

1934: Baade and Zwicky suggest that SN may produce NS

1939: TOV equations (using Fermi-Dirac statistics estimated a maximum mass of ~0.7 $M_\odot$)

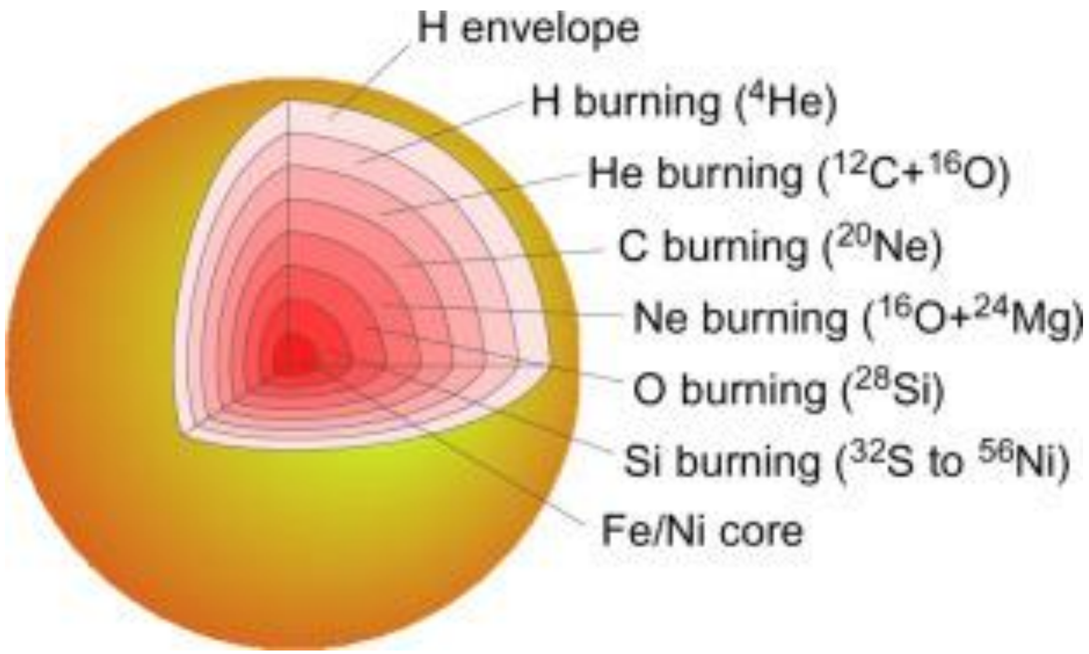
NS Formation

Stage	Time Scale	Fuel or Product	Ash or product	Temperature (10^9 K)	Density (gm/cm^3)
Hydrogen	11 My	H	He	0.035	5.8
Helium	2.0 My	He	C,O	0.18	1390
Carbon	2000 y	C	Ne,Mg	0.81	2.8×10^5
Neon	0.7 y	Ne	O,Mg	1.6	1.2×10^7
Oxygen	2.6 y	O,Mg	Si,S,Ar, Ca	1.9	8.8×10^6
Silicon	18 d	Si,S,Ar, Ca	Fe,Ni, Cr,Ti,...	3.3	4.8×10^7
Iron core collapse[a]	~1 s	Fe,Ni, Cr, Ti,...	Neutron Star	> 7.1	>7.3×10^9

Woosley and Janka 2005

Evolution of a 15-solar-mass star

NS Formation



Yokoyama & Tsujimoto 2021

During the Fe core collapse two main processes take place:

1. Photodisintegration
2. Neutronization

Photodisintegration:

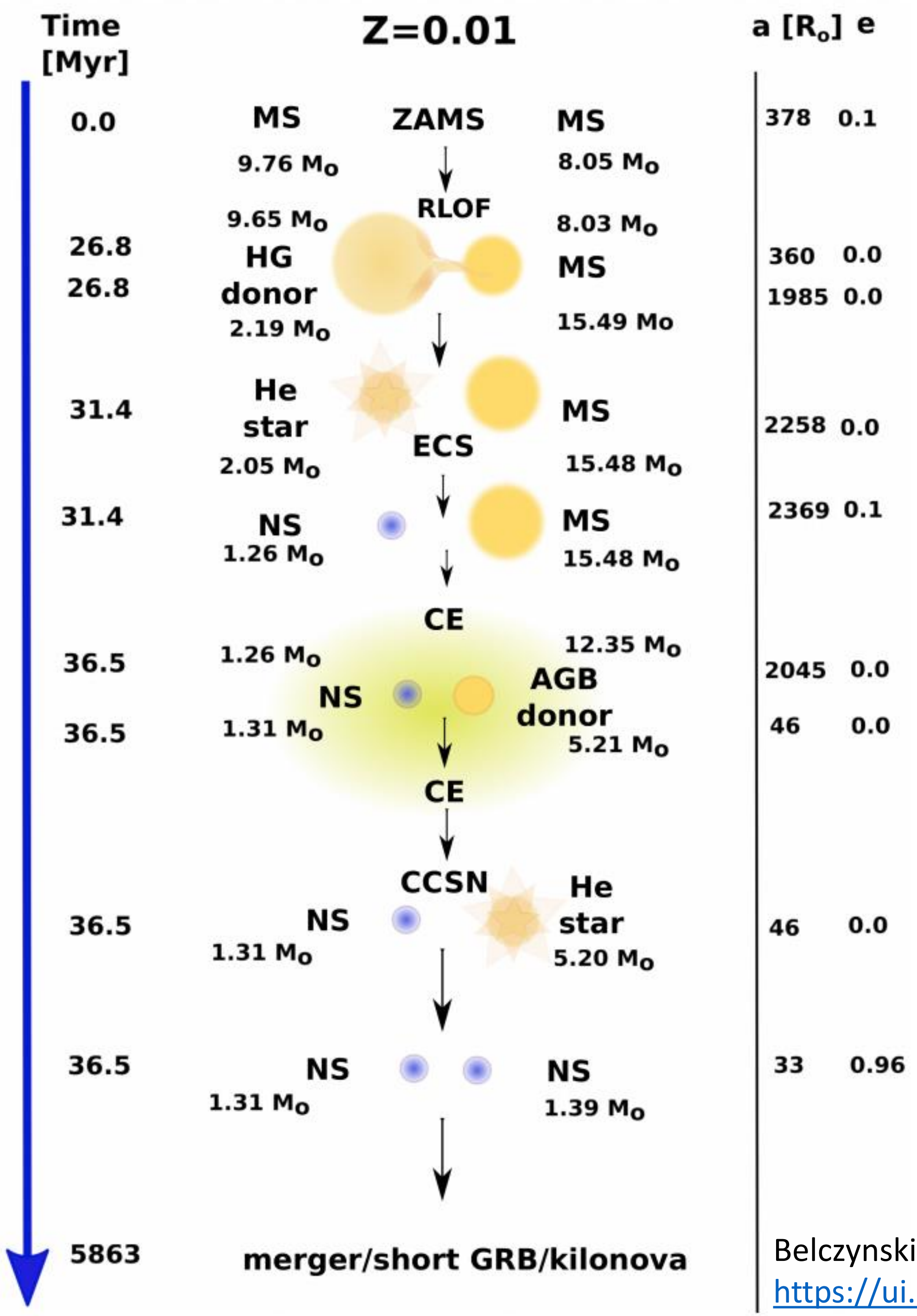
$$\gamma + {}^{56}Fe \rightarrow 13\ {}^{4}He + 4\ n$$
$$\gamma + {}^{4}He \rightarrow 2\ p + 2\ n$$

Neutronization:

$$e^- + p \rightarrow n + \nu_e$$

This produces a neutron reach nucleus and gives birth to a NS.

NS Binary Formation



Several possible formation channels

Requires two stars with masses between ~8 and ~20 $M_\odot$

System needs to survive both SN explosions and common envelope phase

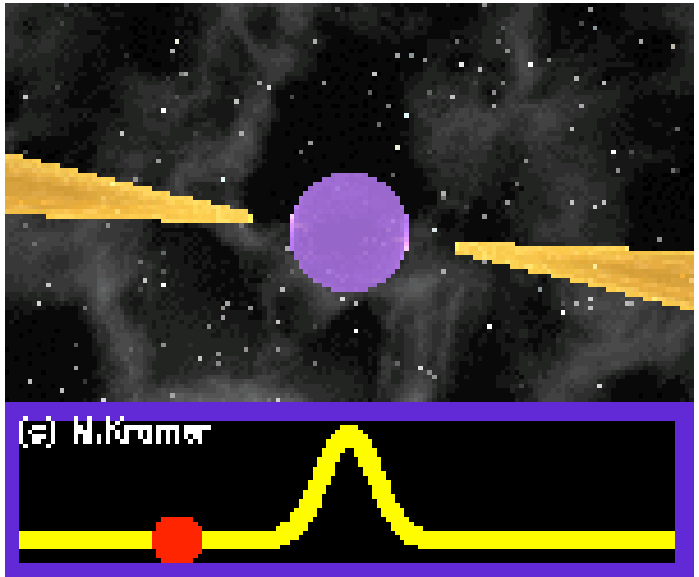
Similar evolution (different progenitors) will lead to NS-BH and BH-BH binaries

Belczynski et al 2018
https://ui.adsabs.harvard.edu/abs/2018A%26A...615A..91B/abstract

NS: DISCOVERY

First NS discovered as a "pulsar" (radio frequencies) in 1967 by PhD student Jocelyn Bell and her supervisor Antony Hewish.

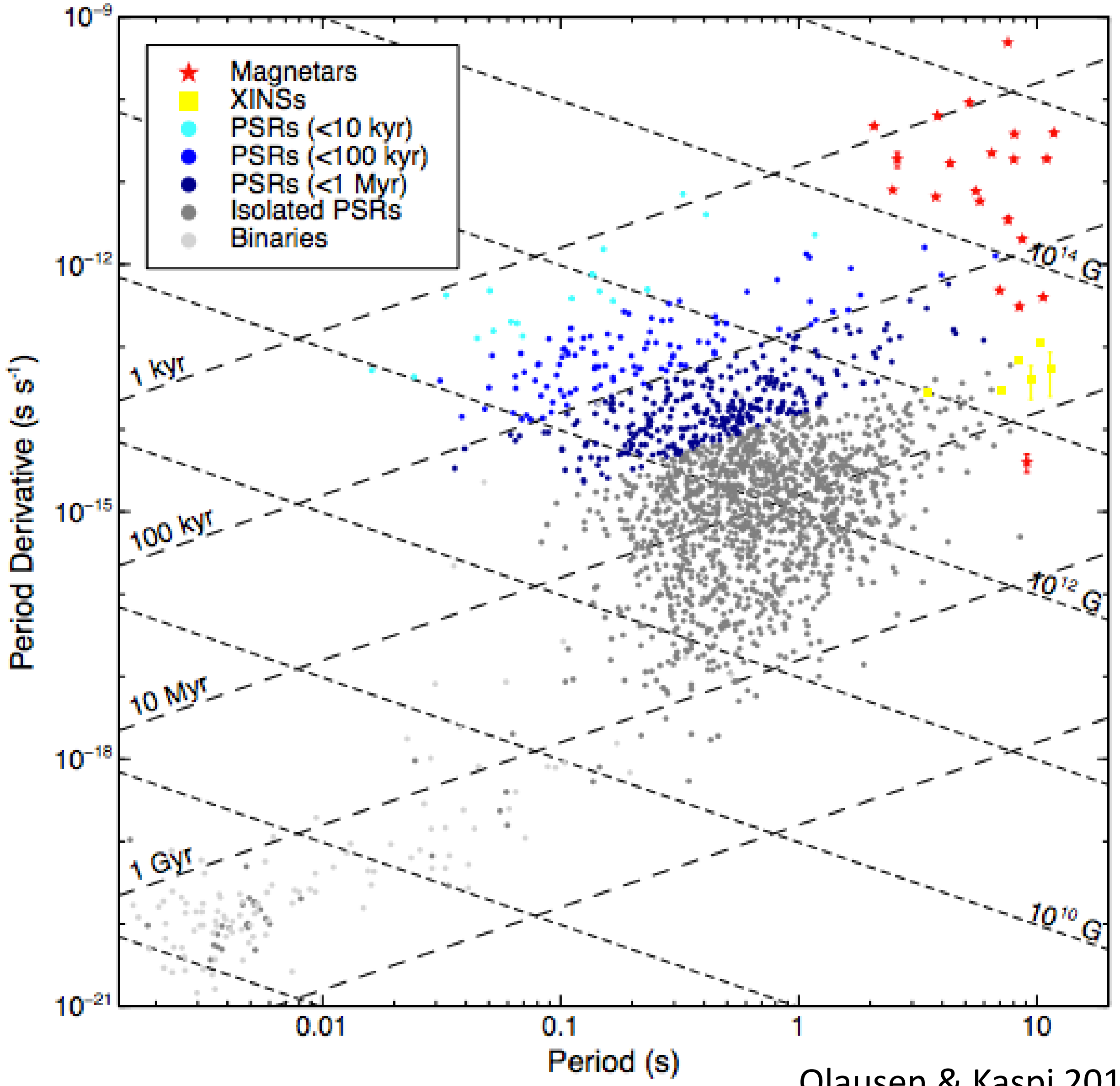
Photo by Daily Herald Archive/SSPL/Getty Images (23/02/1968)



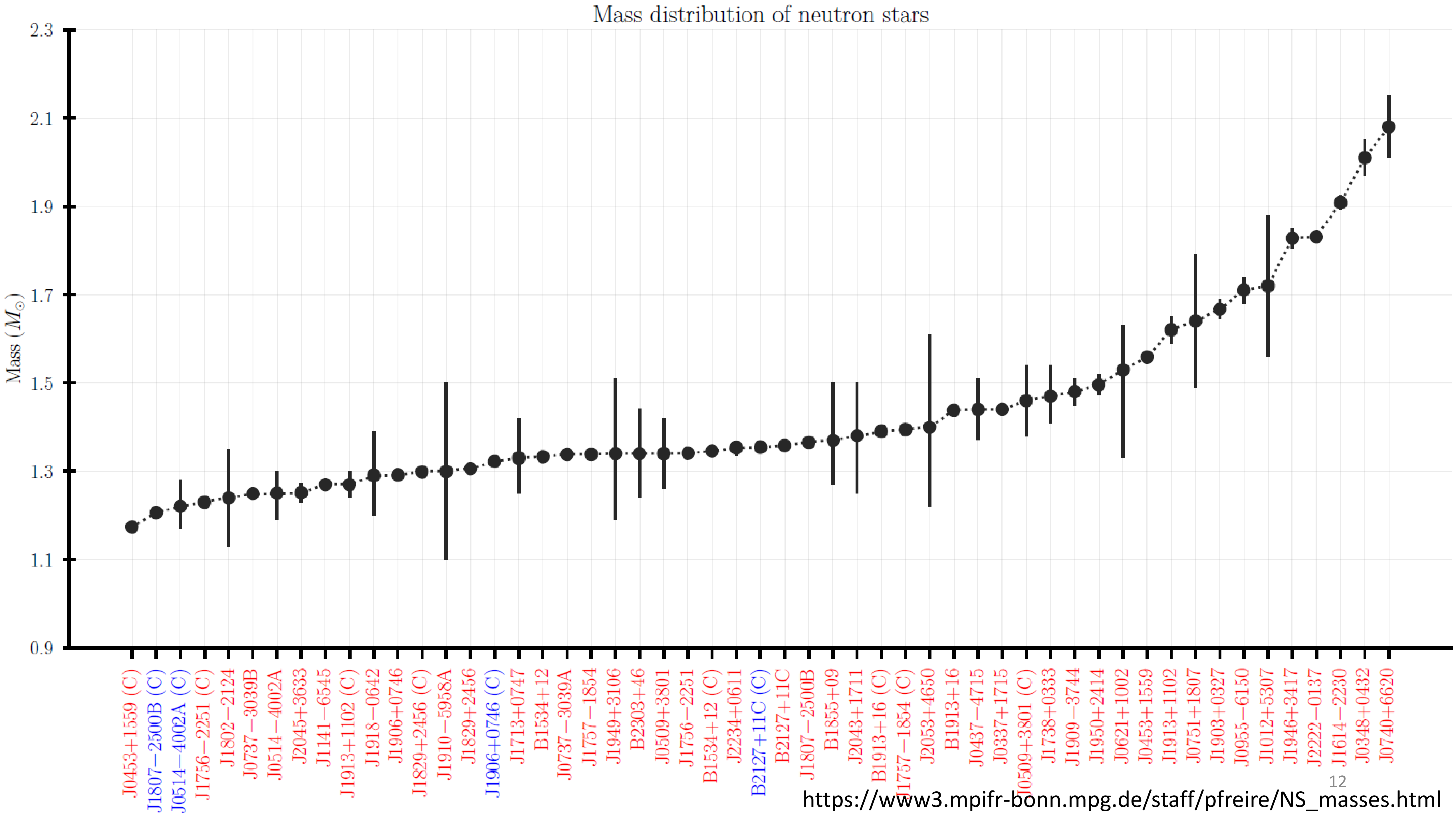
Pulsars are highly-magnetized rotating neutron stars with spins up to ms.

Source: https://link.springer.com/article/10.12942/lrr-2008-8

- Most NSs are observed as pulsars
- We can measure the period and its time derivative
- Not possible to put them in the HR diagram (how do we estimate the radius?)

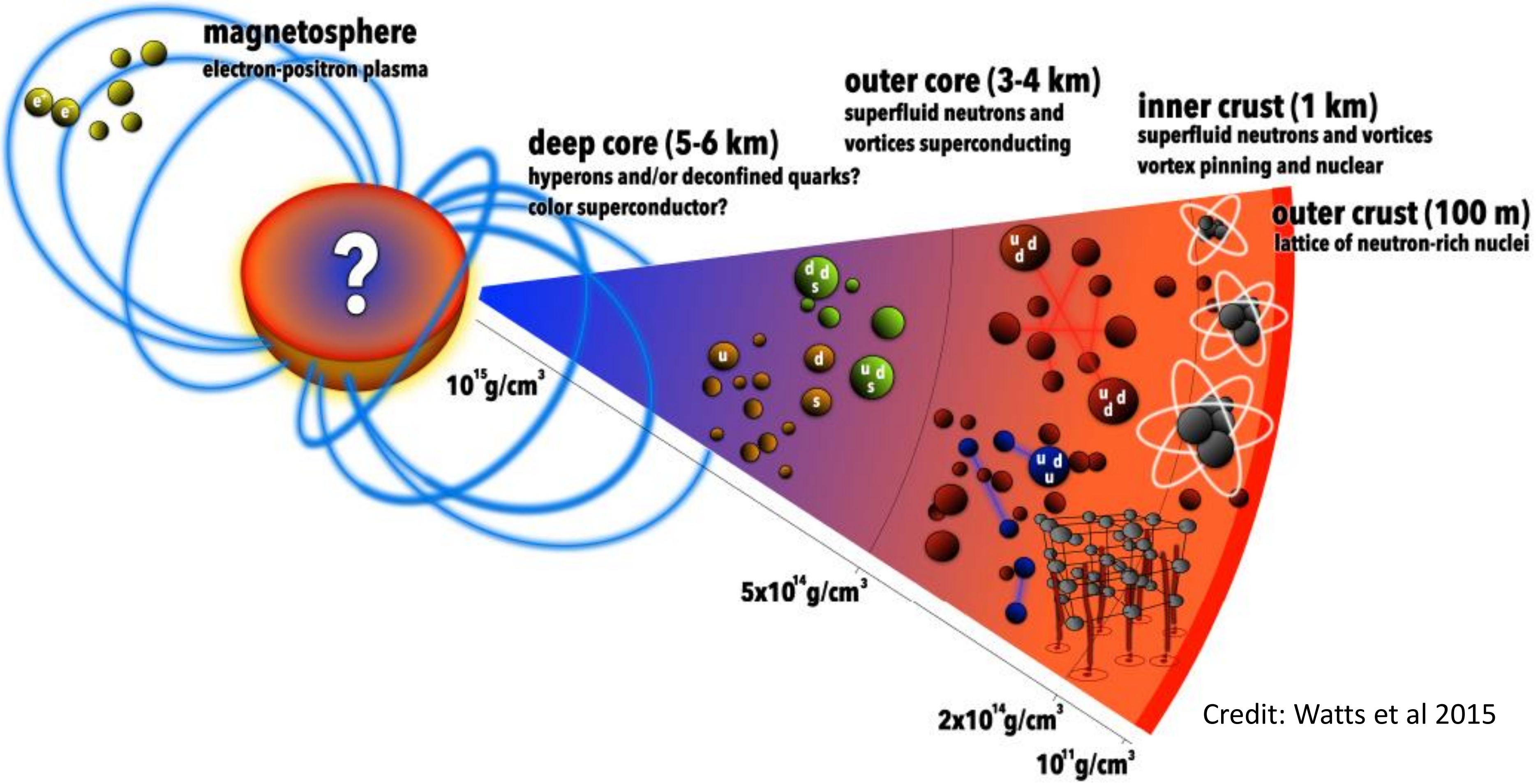


Olausen & Kaspi 2014



https://www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html

Neutron Star Structure



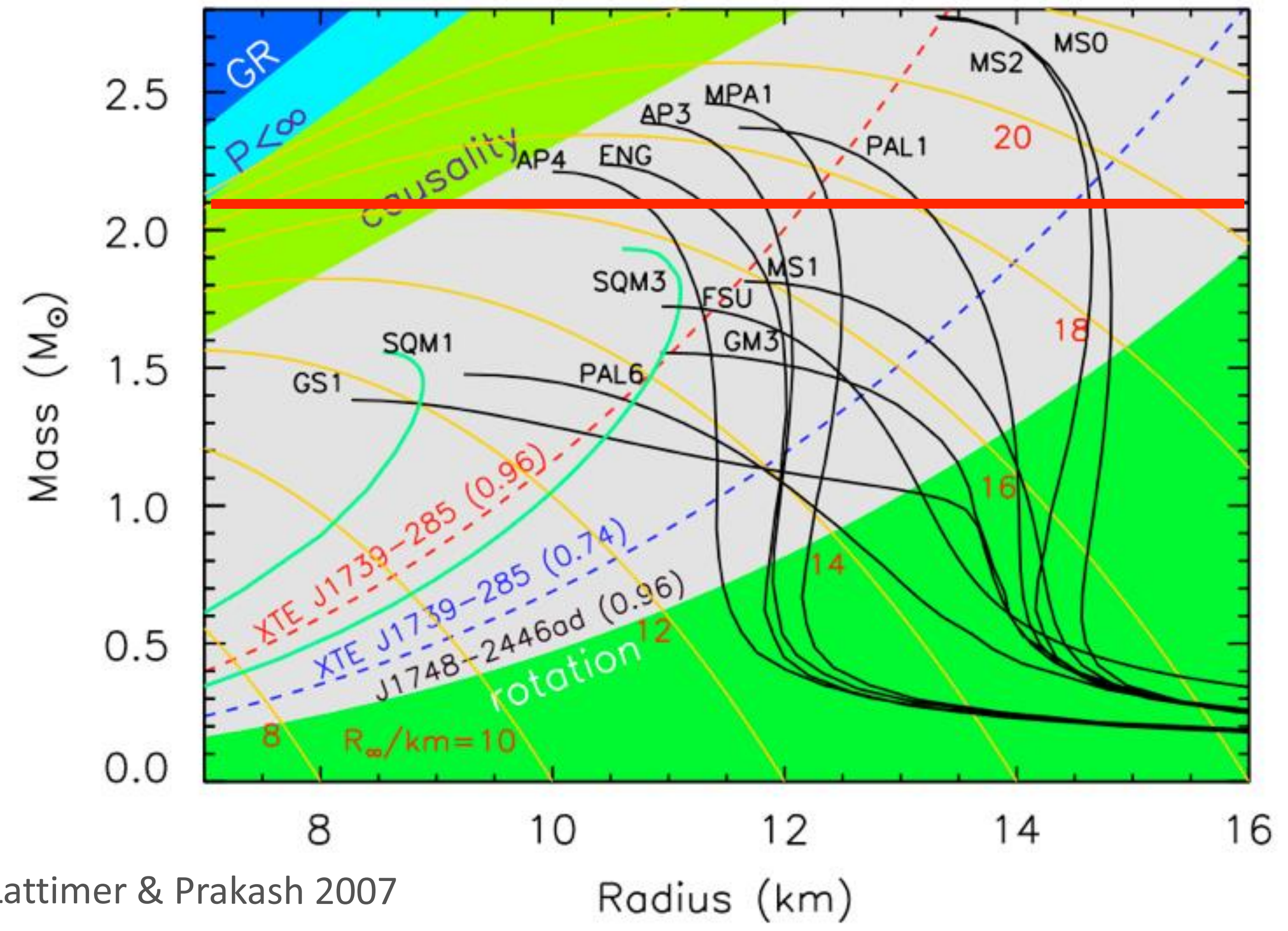
Credit: Watts et al 2015

NSs are more complicated than a "simple" Fermi gas.

Internal structure of NSs is still unknown (how does matter behave at ~10^{15} g cm^{-3}?).

NS EOS THEORY: Mass vs radius

Several different EOSs allow for similar NS masses.



Lattimer & Prakash 2007

Only contemporary measure of Mass and Radius can constraint EOS.