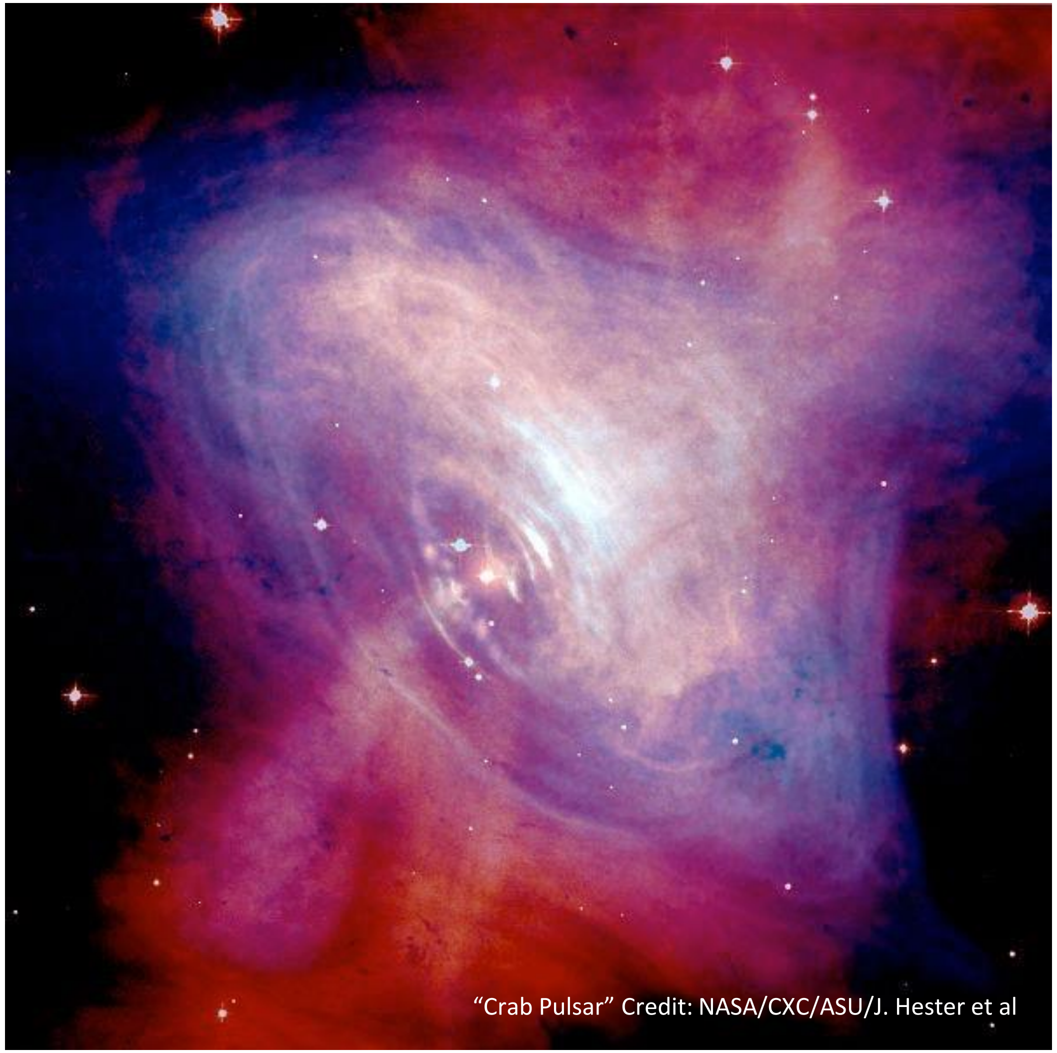
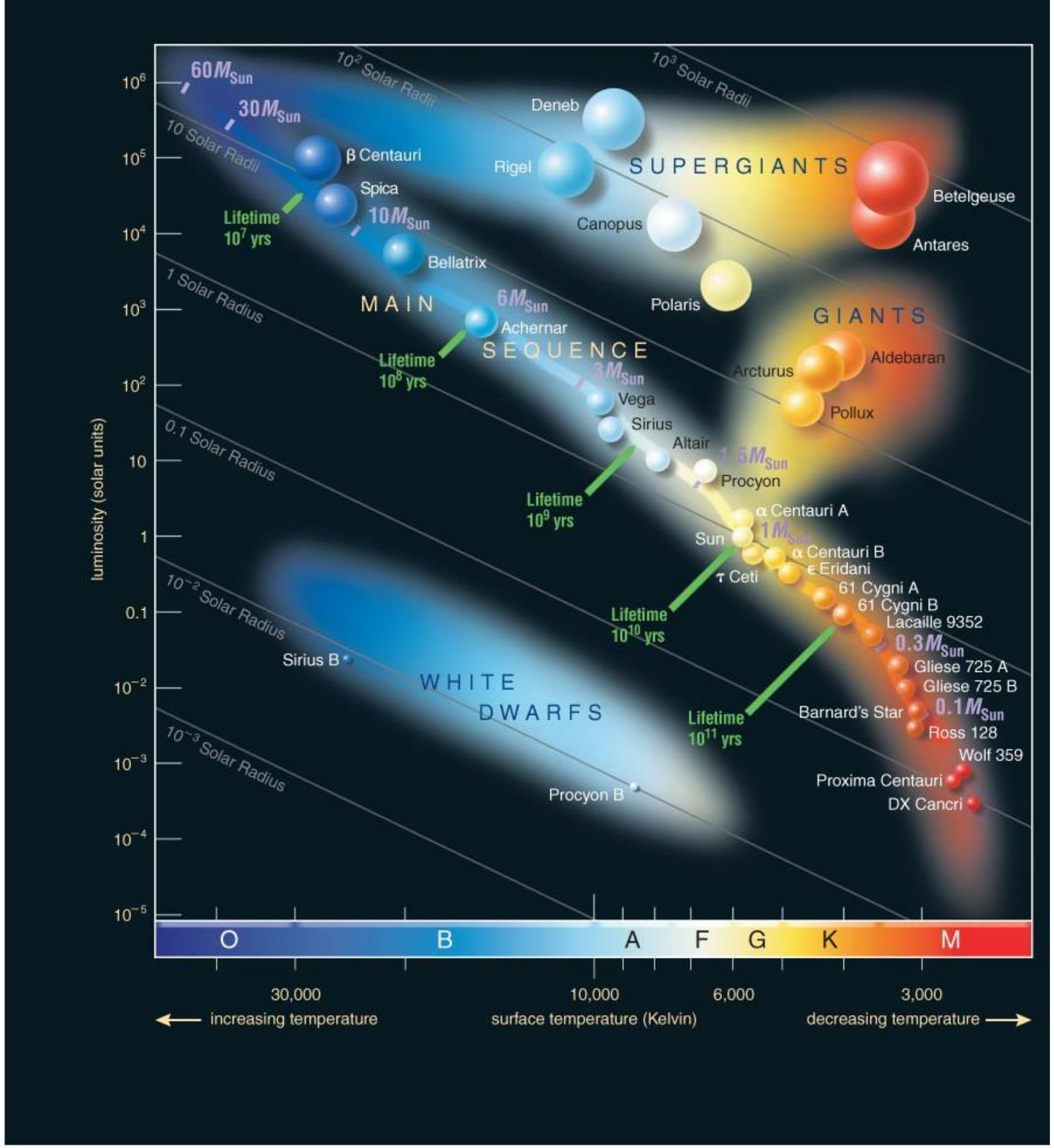
Neutron Stars


“Crab Pulsar” Credit: NASA/CXC/ASU/J. Hester et al

Bruno Giacomazzo

www.brunogiacomazzo.org



H-R Diagram for Stars

Solar Values

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

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

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

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

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

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

Tolman-Oppenheimer-Volkoff (TOV) Equations

Note:

$G = c = 1$

$$\frac{\partial P}{\partial r} = -(e + P)\frac{\partial \phi}{\partial r}$$

$$\frac{\partial m}{\partial r} = 4\pi r^2 e$$

$$\frac{\partial \phi}{\partial r} = \frac{4\pi r^3 P + m}{r(r - 2m)}$$

$$P = P(\rho)$$

$$e = e(\rho)$$

If a polytropic EOS is used then:

$$P = K\rho^{\Gamma}\,, e = \rho + \rho\epsilon = \rho + P/(\Gamma - 1)$$

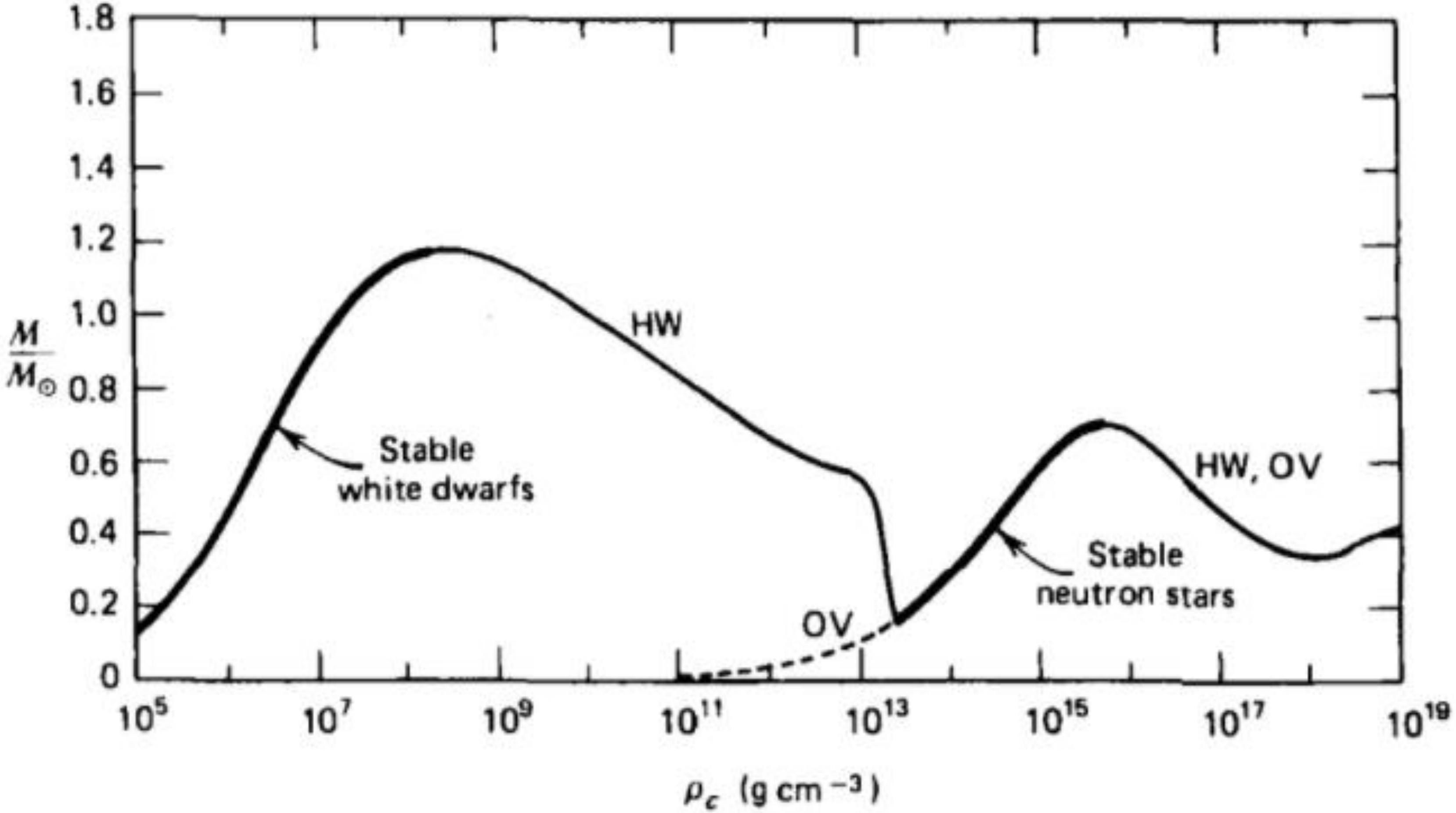


Figure 9.1 Gravitational mass versus central density for the HW (1958) and OV (1939) equations of state. The stable white dwarf and neutron star branches of the HW curve are designated by a *heavy solid* line.

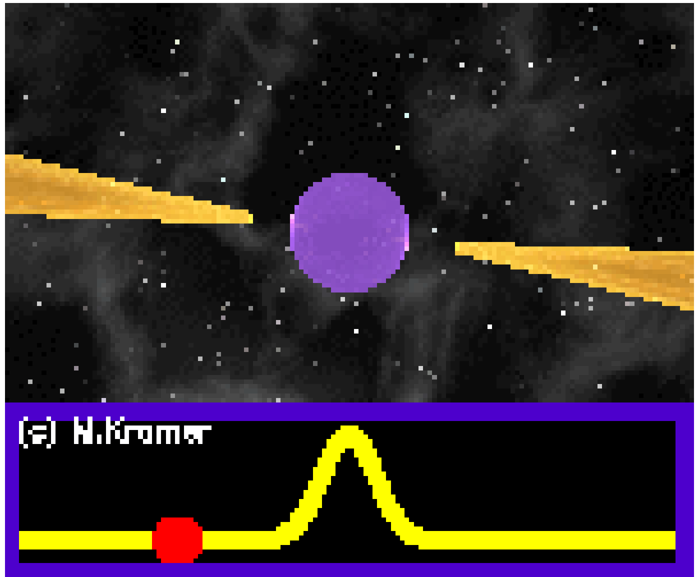
OV = TOV solution with polytropic EOS; HW = solution with Harrison-Wheeler EOS

Credit: S. L. Shapiro and S. A. Teukolsky 1983, “Black Holes, White Dwarfs, and Neutron Stars – The Physics of Compact Objects”, WILEY-VCH Verlag GmbH & Co. KGaA

NS: DISCOVERY

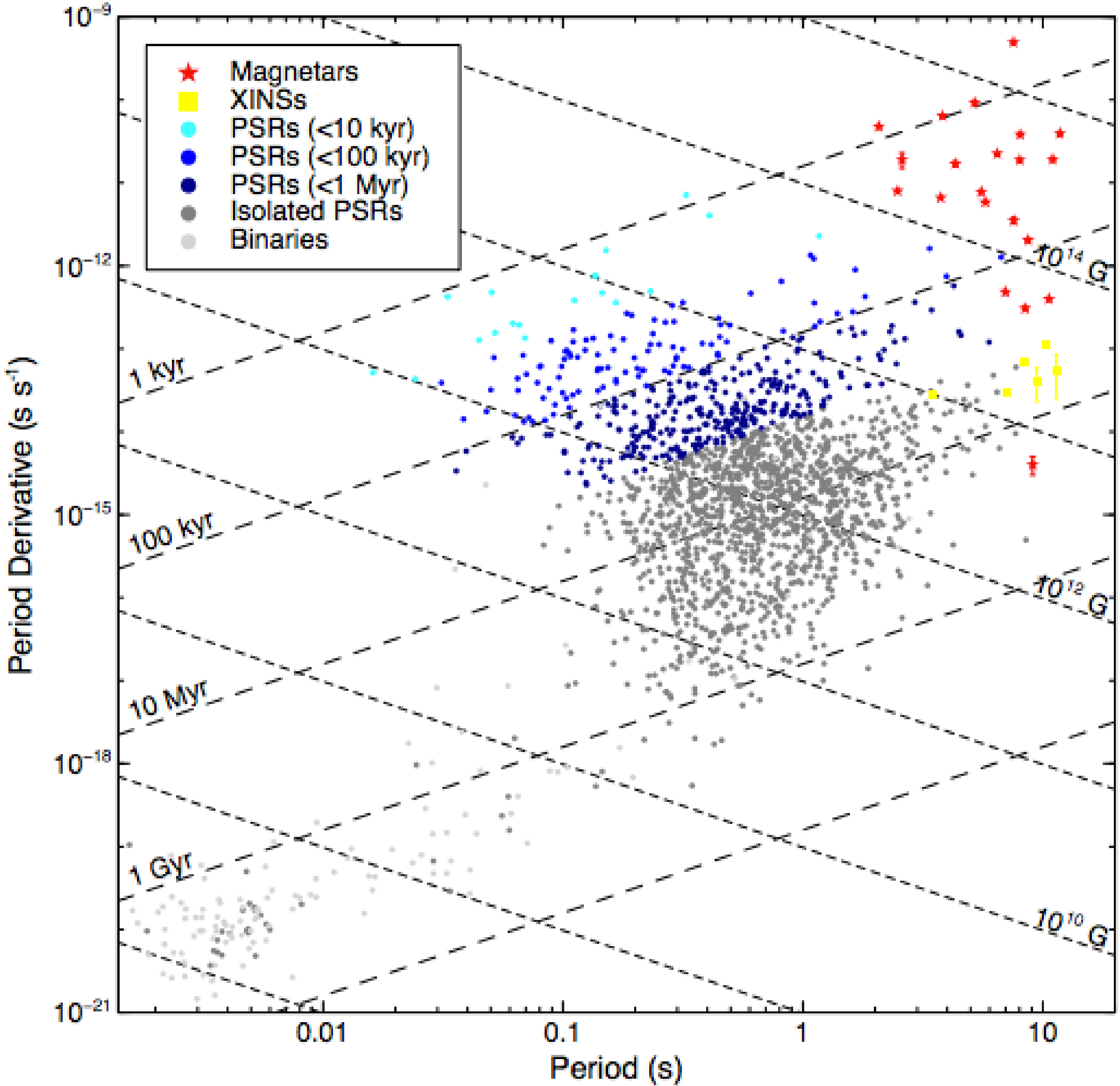
First NS discovered as a "pulsar" (radio frequencies) in 1967 by PhD student Jocelyn Bell and her supervisor Antony Hewish.

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



$$\dot{\omega} = -\frac{B^2 R^6 \sin^2\theta}{6c^3 I}\omega^3 \Rightarrow \dot{\omega} = -C\omega^n$$

Assuming n=3 (n is the “braking index”):

$$B \approx 3.2 \times 10^{19}\sqrt{\frac{P\dot{P}}{1\ s}}\ G$$

Olausen & Kaspi 2014

NS: CRAB PULSAR

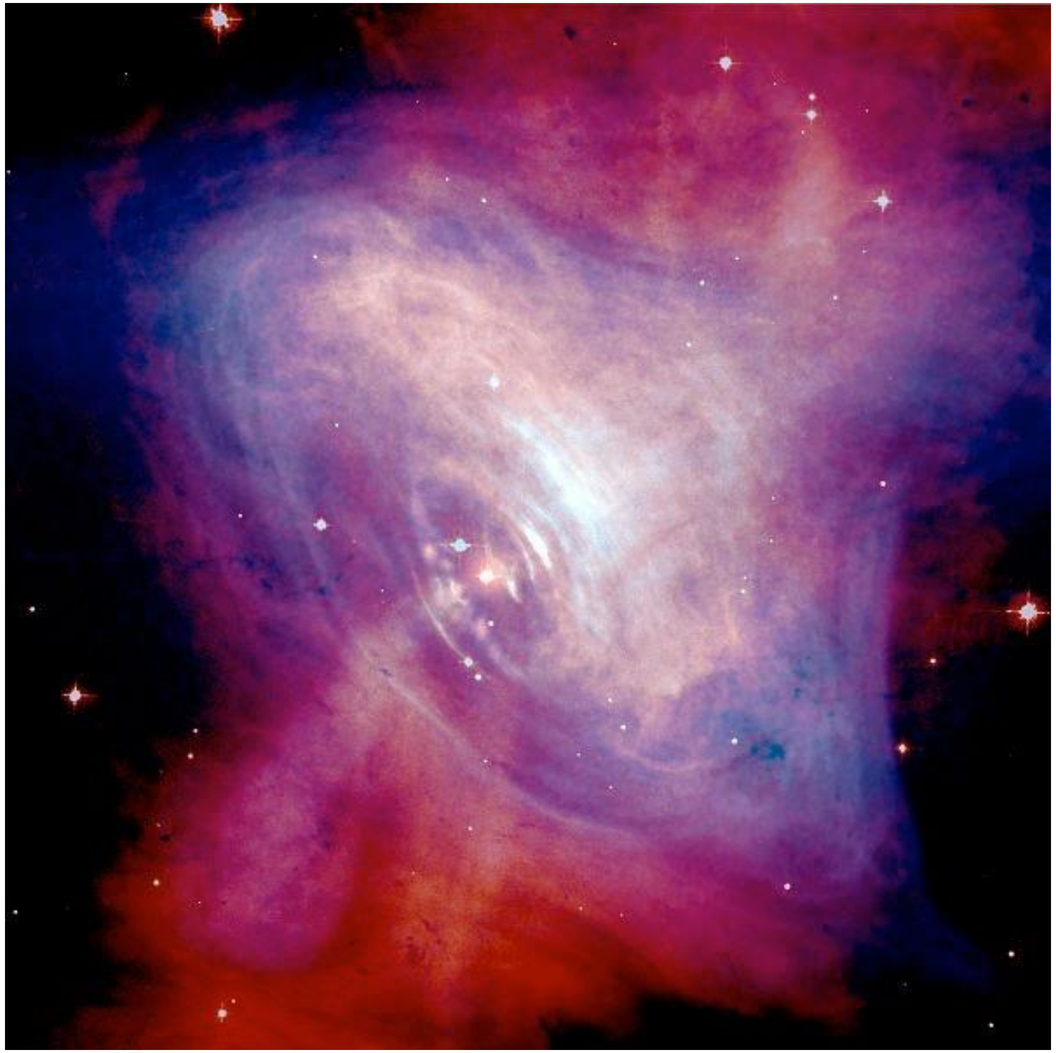
Discovered in 1968

First to be connected to a SN explosion (SN 1054)

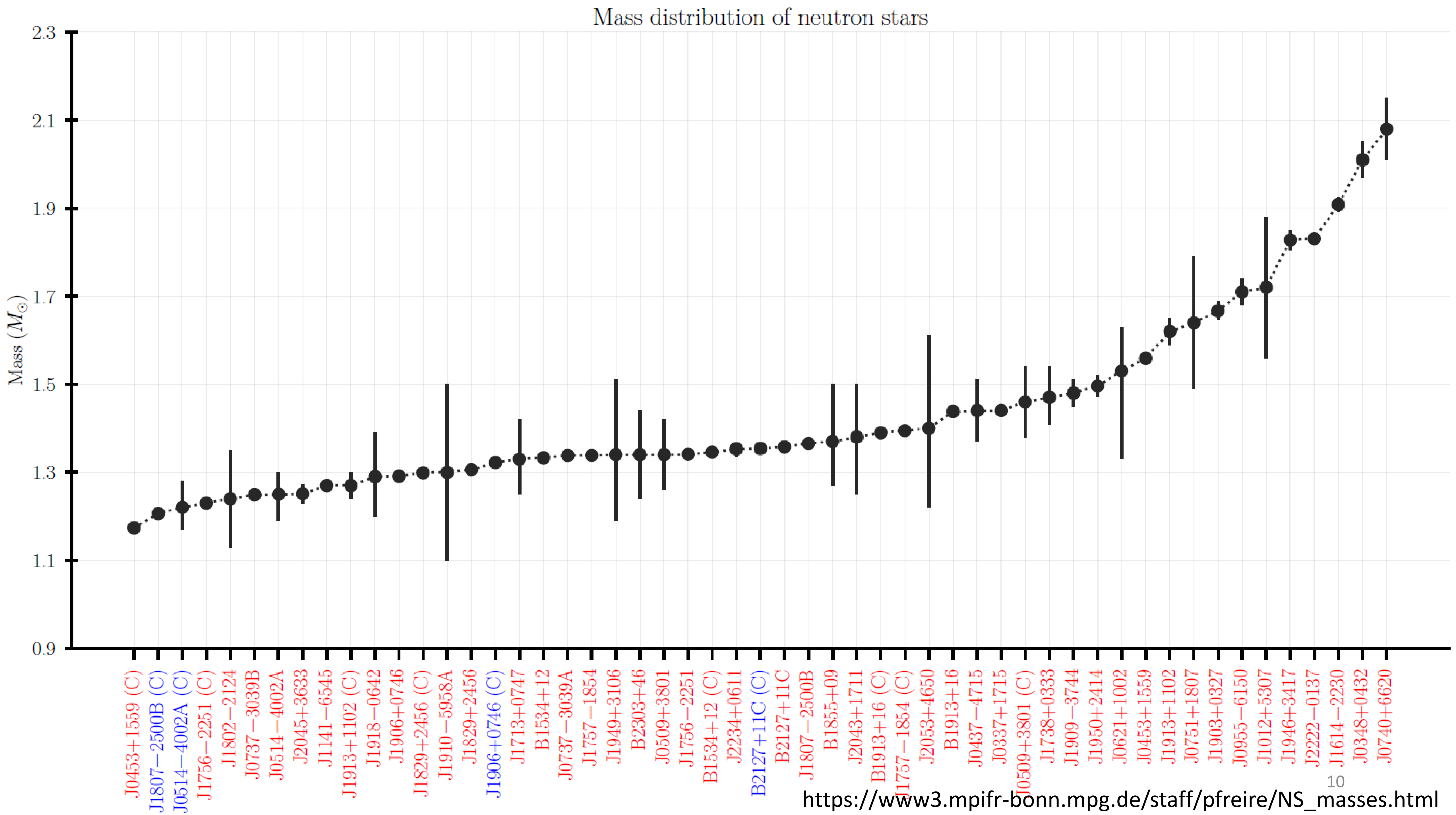
Observed from radio to gamma rays

$P \approx 33.1\text{ms}$ (note $P_{\odot} \approx 27$ days)
$\dot{P} \approx 4.23 \times 10^{-13}\ s\ s^{-1}$
$n = 2.51 \pm 0.01$
(Ho & Andersson 2012, Nature Physics 8, 787)

In observed binary pulsar systems, the fastest pulsar has $P = 22.7\text{ms}$, i.e., $\chi \approx 0.02$ (PSR J0737-3039A).

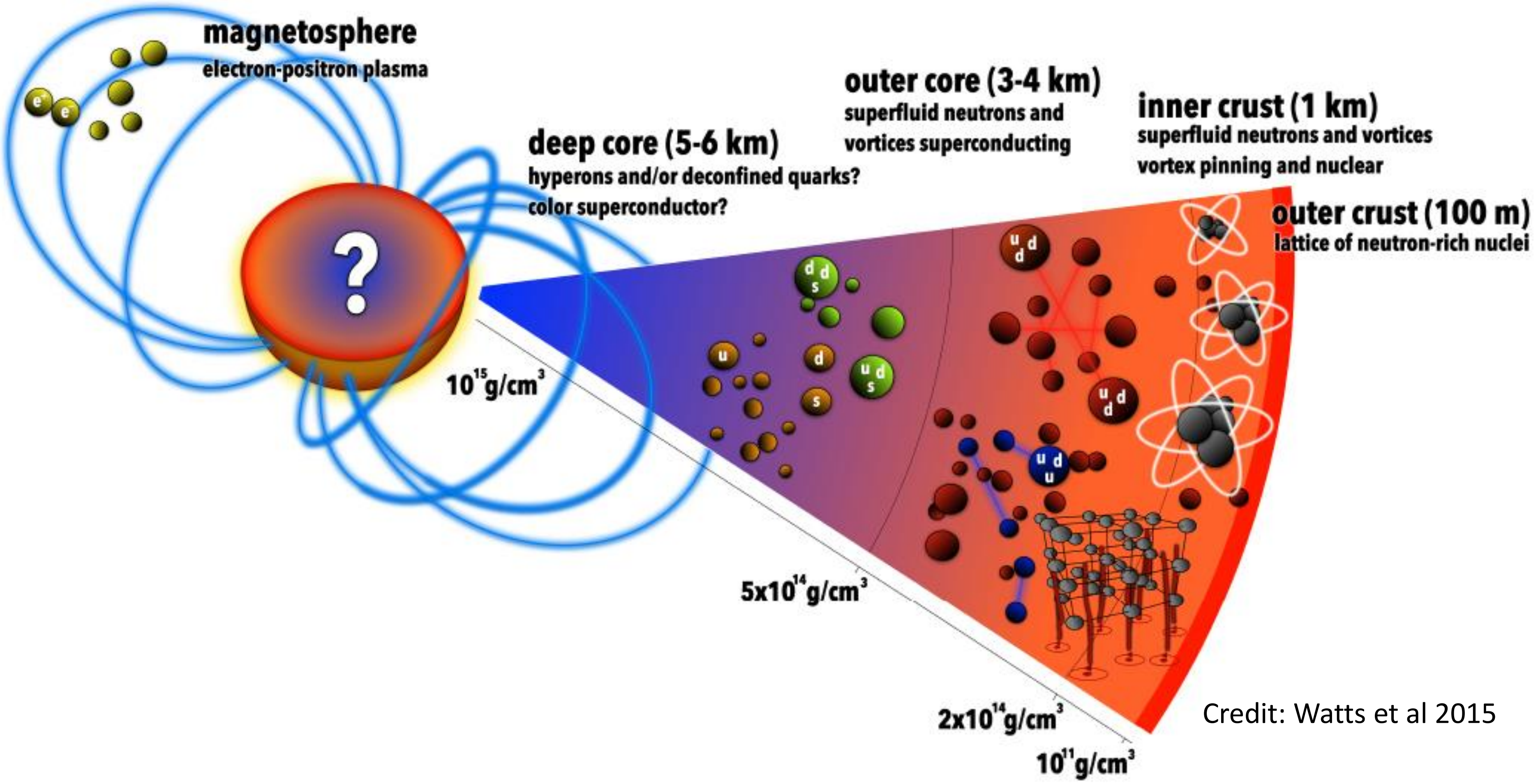


"Crab Pulsar" Credit: NASA/CXC/ASU/J. Hester et al



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

Neutron Star Structure



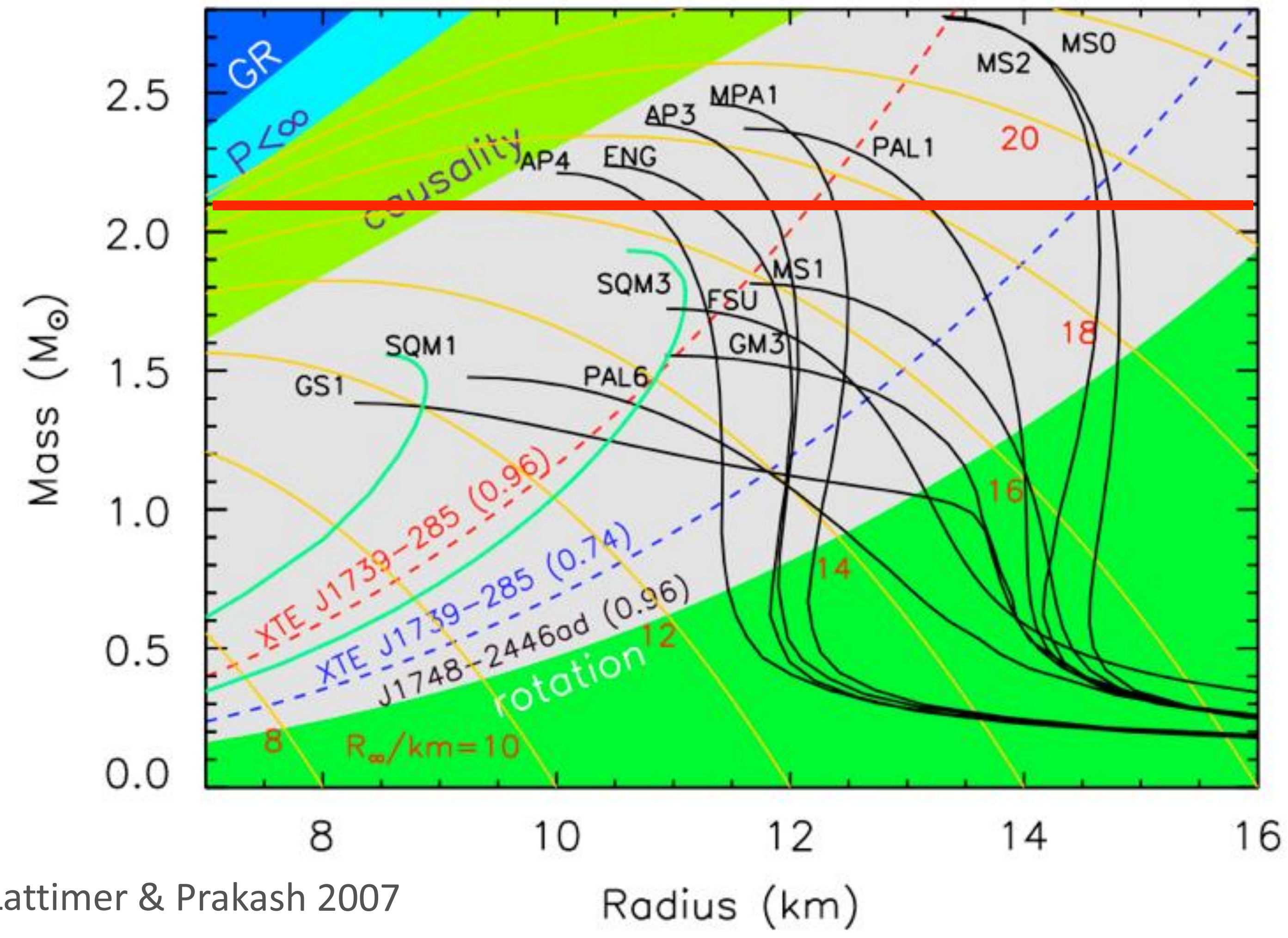
Credit: Watts et al 2015

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.

CompOSE: https://compose.obspm.fr/

- Home
- EoS
  - Overview
  - Families
    - Neutron Matter EoS
      - Statistical model by Hempel et al; Steiner et al; Banik et al
      - G. Shen et al
      - STOS (H_Shen et al)
      - Microscopic calculations
      - All
    - General Purpose EoS
    - Cold Matter EoS
      - STOS (H_Shen et al)
      - Microscopic calculations
      - All
    - Cold Neutron Star EoS
      - Skyrme models
      - Hybrid (quark-hadron) EoS
      - Relativistic mean field models

CompOSE

CompStar Online

Supernovæ Equations of State

comp star

The online service CompOSE provides data tables for different state of the art equations of state (EoS) ready for further usage in astrophysical applications, nuclear physics and beyond.

The cold neutron star EoS tables can be used directly within LORENE to obtain models of (rotating/magnetised) neutron stars, see the eos_compose class.

If you decide to publish work using one or more of the here provided EoS we ask you to cite the given references and would be happy if you acknowledge CompOSE.

Data tables, associated software and the manual can be freely downloaded. Log in is required if you wish to use further utilities, such as graphics and online computations. Please contact "develop.compose(at)obspm.fr" if you wish to have an account.

see also:

- Binary and Millisecond Pulsars: https://link.springer.com/article/10.12942/lrr-2008-8
- A map of known pulsars: http://ishivvers.com/maps/pulsars
- Rotating Stars in Relativity: https://link.springer.com/article/10.1007/s41114-017-0008-x
- NICER Constraints on the Dense Matter Equation of State: https://iopscience.iop.org/journal/2041-8205/page/Focus_on_NICER_Constraints_on_the_Dense_Matter_Equation_of_State