Perspectives from Astrophysics

Isaac Vidaña, INFN Catania

Meeting Iniziativa Specifica
MONSTRE, May 11th – 12th 2023,
Milano

In this talk I will …

- ✓ Review some of the astrophysical constraints of the nuclear EoS
- ✓ Point out some of the still open questions in neutron star physics
- ✓ Comment briefly upcoming observations of NS & new experimental data on neutron-rich matter

Based on:

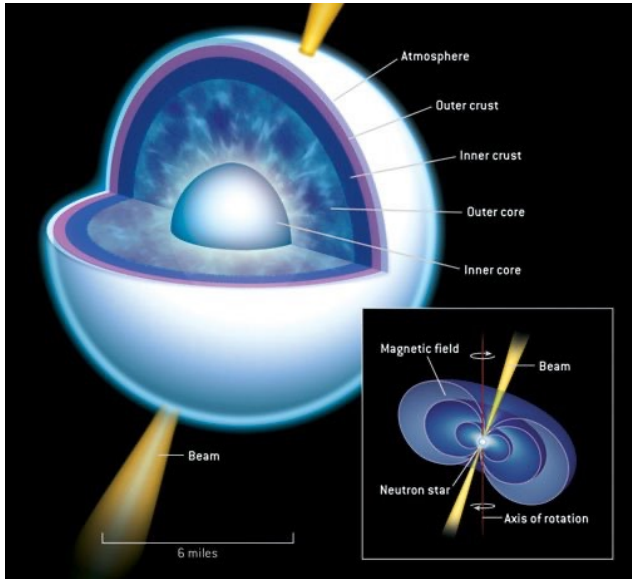
I.V., Nuovo Cimento C 41, 1 (2018)

H. Schatz et al., J. Phys. G: Nucl. Part. Phys. 49, 110502 (2022)

Astrophysical Constraints of the nuclear EoS

- The main astrophysical constraints on the nuclear EoS are those arising from the **observation of neutron stars**

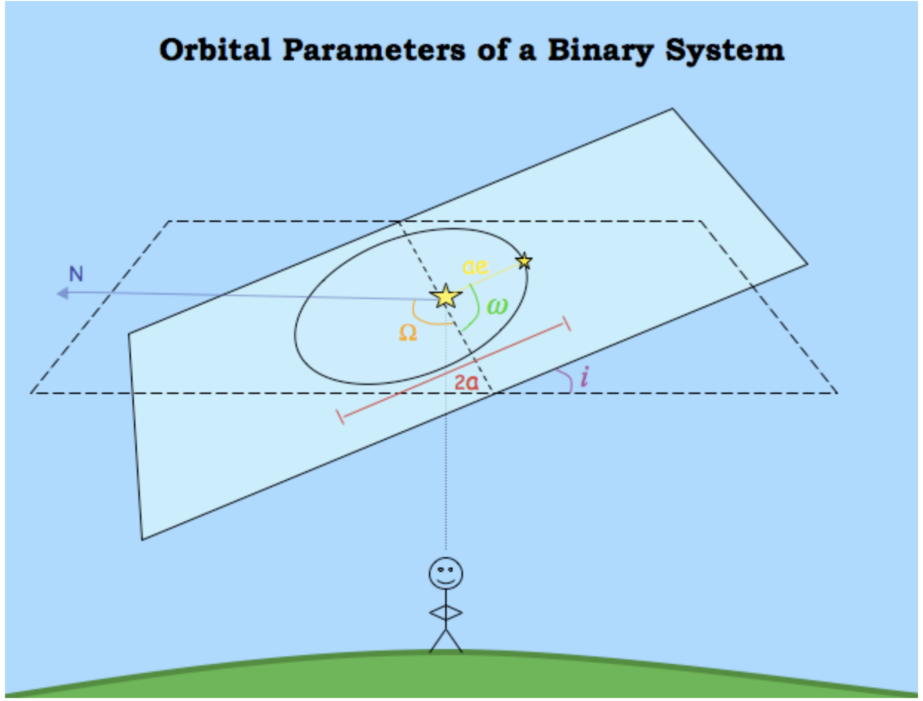
- After more than 50 years of observations we have collected an **enourmous amount of data** on different neutron star observables from which it is possible to infer **valuable information** on the **internal structure** of these objects and, therefore, also on the **nuclear EoS**.



- Masses
- Radii
- Gravitational Waves
- Rotational periods
- Pulsar Glitches
- Surface Temperature / Luminosity
- Magnetic fields
- Gravitational redshift
- Quasiperiodic oscillations
- NS moment of intertia

Neutron Star Masses

NS masses can be inferred directly from
observations of binary systems



- 5 orbital (Keplerian) parameters can be precisely measured:
  - ✓ Orbital period (P)
  - ✓ Projection of semimajor axis on line of sight (a sin i)
  - ✓ Orbit eccentricity (ε)
  - ✓ Time of periastron (T_0)
  - ✓ Longitude of periastron (ω_0)
- 3 unknowns: M_1, M_2, i

Kepler's 3rd law

$$\frac{G(M_1+M_2)}{a^3} = \left(\frac{2\pi}{P}\right)^2 \quad \rightarrow$$

$$f(M_1,M_2,i) \equiv \frac{(M_2 \sin i)^3}{(M_1+M_2)^2} = \frac{Pv^3}{2\pi G}$$

mass function

In few cases small deviations from Keplerian orbit due to GR effects can be detected

Measure of at least 2 post-Keplerian parameters → High precision NS mass determination

$$\dot{\omega} = 3T_{\otimes}^{2/3}\left(\frac{P_b}{2\pi}\right)^{-5/3}\frac{1}{1-\varepsilon}\left(M_p+M_c\right)^{2/3} \longrightarrow$$

Advance of the periastron

$$\gamma = T_{\otimes}^{2/3}\left(\frac{P_b}{2\pi}\right)^{1/3}\varepsilon\frac{M_c\left(M_p+2M_c\right)}{\left(M_p+M_c\right)^{4/3}} \longrightarrow$$

Time dilation & grav. redshift

$$r = T_{\otimes}M_c \longrightarrow$$

Shapiro delay “range”

$$s = \sin i = T_{\otimes}^{-1/3}\left(\frac{P_b}{2\pi}\right)^{-2/3}x\frac{\left(M_p+M_c\right)^{2/3}}{M_c} \longrightarrow$$

Shapiro delay “shape”

$$\dot{P}_b = -\frac{192\pi}{5}T_{\otimes}^{5/3}\left(\frac{P_b}{2\pi}\right)^{-5/3}f(\varepsilon)\frac{M_pM_c}{\left(M_p+M_c\right)^{1/3}} \longrightarrow$$

Orbit decay due to GW emission

Recent Measurements of High NS Masses

- **PSR J164-2230** (Demorest et al. 2010)

✓ binary system (P=8.68 d)

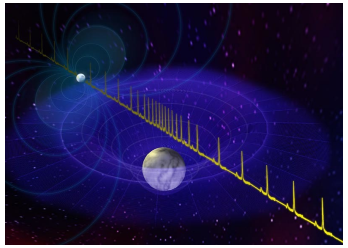
✓ low eccentricity ($\varepsilon = 1.3 \times 10^{-6}$)

✓ companion mass: $\sim 0.5 M_\odot$

✓ pulsar mass: $M = 1.928 \pm 0.017 M_\odot$

In this decade NS with $2M_\odot$ have been observed by measuring Post-Keplerian parameters of their orbits

- Advance of the periastron $\dot{\omega}$
- Shapiro delay (range & shape)
- Orbital decay $\dot{P}_b$
- Grav. redshift & time dilation γ



- **PSR J0348+0432** (Antoniadis et al. 2013)

✓ binary system (P=2.46 h)

✓ very low eccentricity

✓ companion mass: $0.172 \pm 0.003 M_\odot$

✓ pulsar mass: $M = 2.01 \pm 0.04 M_\odot$

- **MSP J0740+6620** (Cromartie et al. 2020)

✓ binary system (P=4.76 d)

✓ low eccentricity ($\varepsilon = 5.10(3) \times 10^{-6}$)

✓ companion mass: $0.258(8) M_\odot$

✓ pulsar mass: $M = 2.14^{+0.10}_{-0.0.9} M_\odot$ (68.3% c.i.)

$M = 2.14^{+0.20}_{-0.018} M_\odot$ (95.4% c.i.)

Formation of Binary Systems

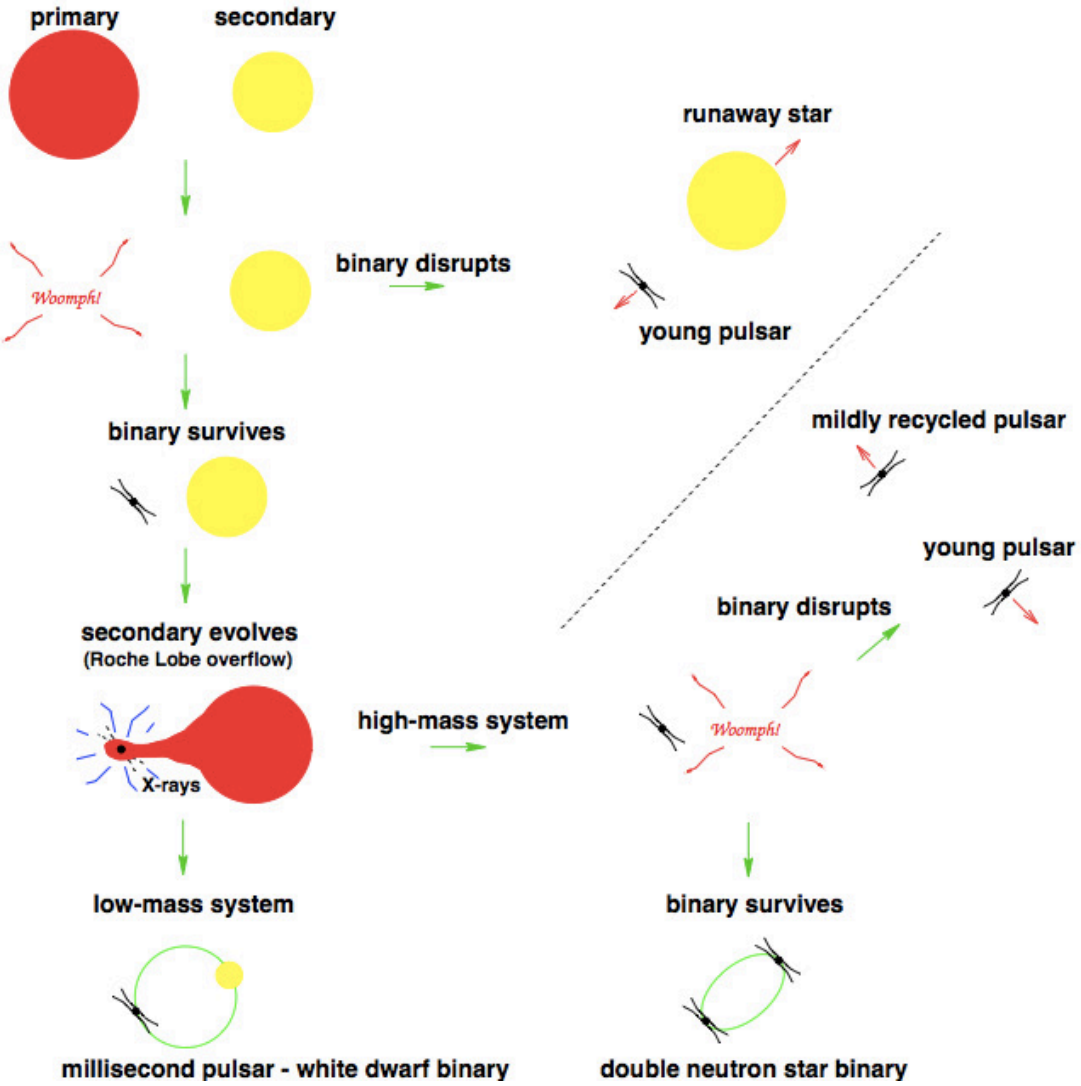
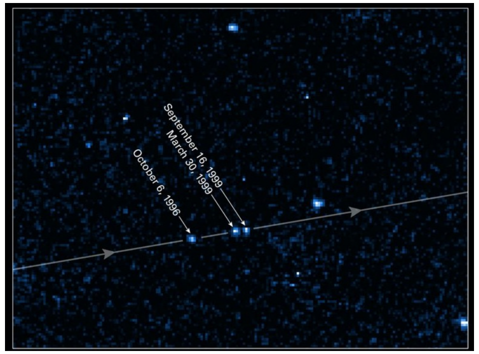


Figure by P.C.C. Freire

The desired measurement of neutron star radii

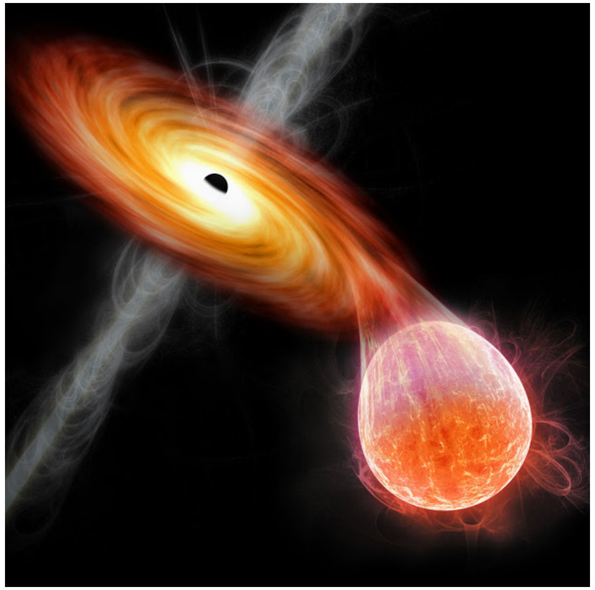
Radii are very difficult to measure because NS:

- ✧ are very small (~ 10 km)
- ✧ are far from us (e.g., the closest NS, RX J185635-3754, is at ~ 200 ly, moving at 100 km/s)



Credit by NASA

A possible way to measure it is to use the thermal emission of low mass X-ray binaries:



NS radius can be obtained from:

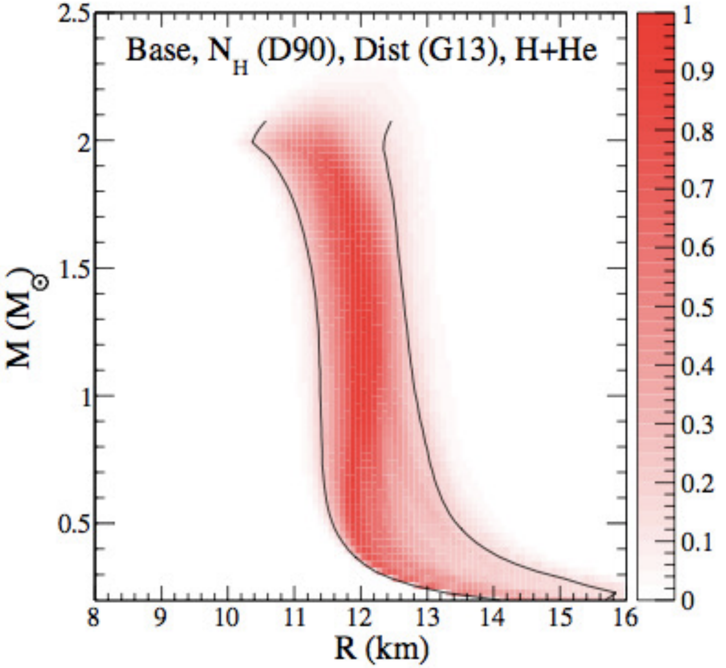
- ✧ Flux measurement +Stefan-Boltzmann’s law
- ✧ Temperature (Black body fit+atmosphere model)
- ✧ Distance estimation (difficult)
- ✧ Gravitational redshift z (detection of absorption lines)

$$R_\infty = \sqrt{\frac{FD^2}{\sigma_{SB}T^4}} \rightarrow R_{NS} = \frac{R_\infty}{1+z} = R_\infty\sqrt{1-\frac{2GM}{R_{NS}c^2}}$$

Estimations of Neutron Star Radii from LMXB

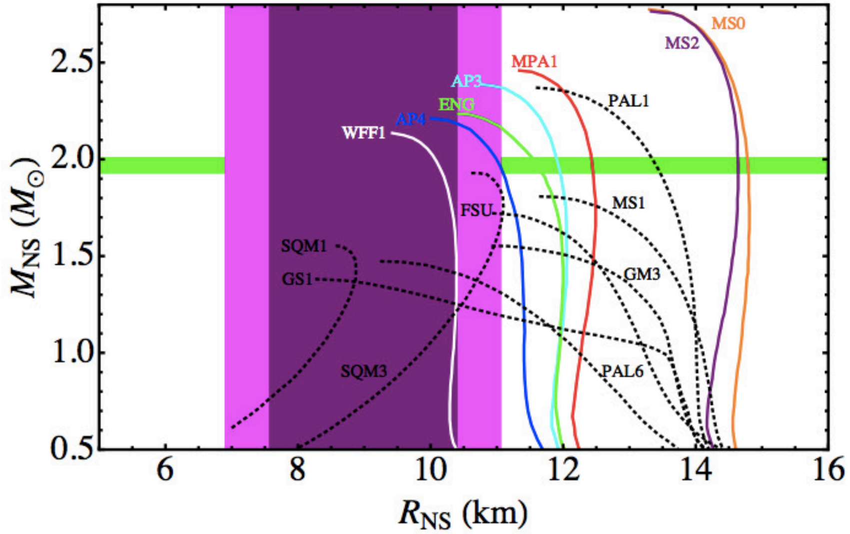
The conclusion from past analysis of the thermal spectrum from 5 quiescent LMXB in globular clusters was controversial

Steiner et al. (2013, 2014)



$$R = 12.0 \pm 1.4 km$$

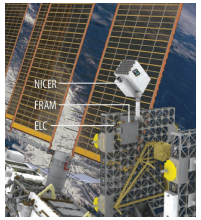
Guillot et al. (2013, 2014)

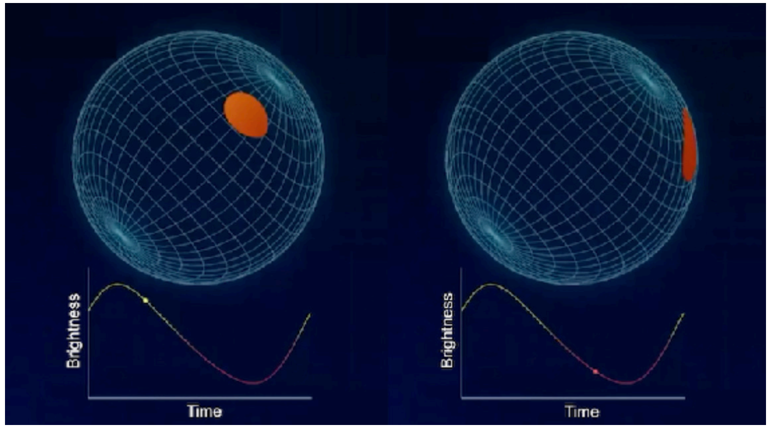


$$R = 9.1^{+1.3}_{-1.5} km$$ 2013 analysis

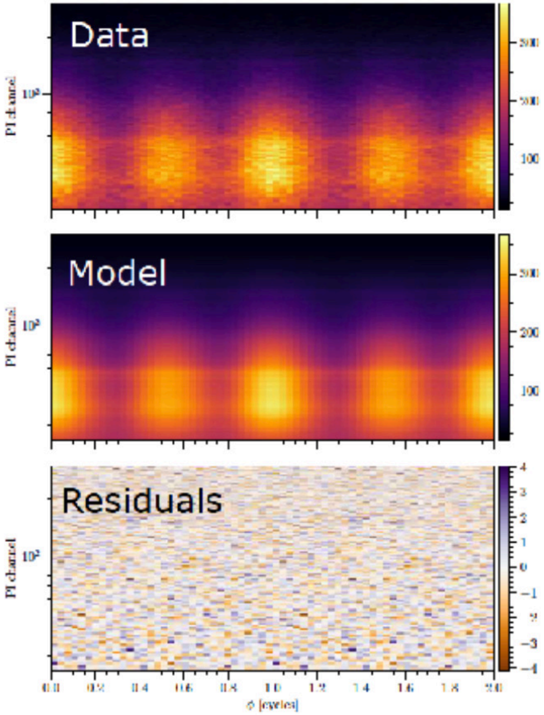
$$R = 9.4 \pm 1.2 km$$ 2014 analysis

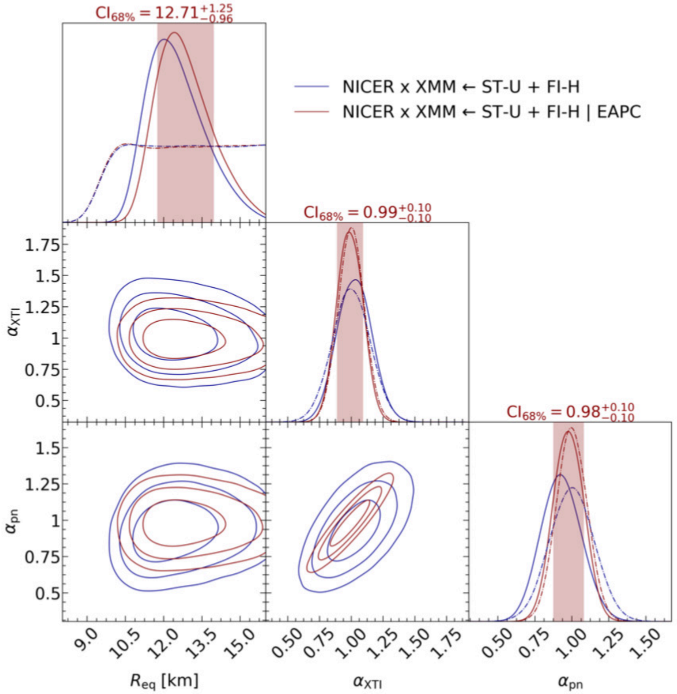
NICER: Neutron Star Interior Composition Explorer





A new way of measuring NS radius by tracking the X-ray emission from "hot spots" on the star's surface as the star rotates. M/R is extracted by modeling the Pulse Profile of the hot spots





- ✧ PSR J0740+6620

$$M = 2.072^{+0.067}_{-0.066} M_{\odot}$$

$R = 13.7^{+2.6}_{-1.5}\ km$ Miller et al., arXiv:2105.06979

$R = 12.39^{+1.30}_{-0.98}\ km$ Riley et al., arXiv:2105.06980

- ✧ PSR J0030+0451

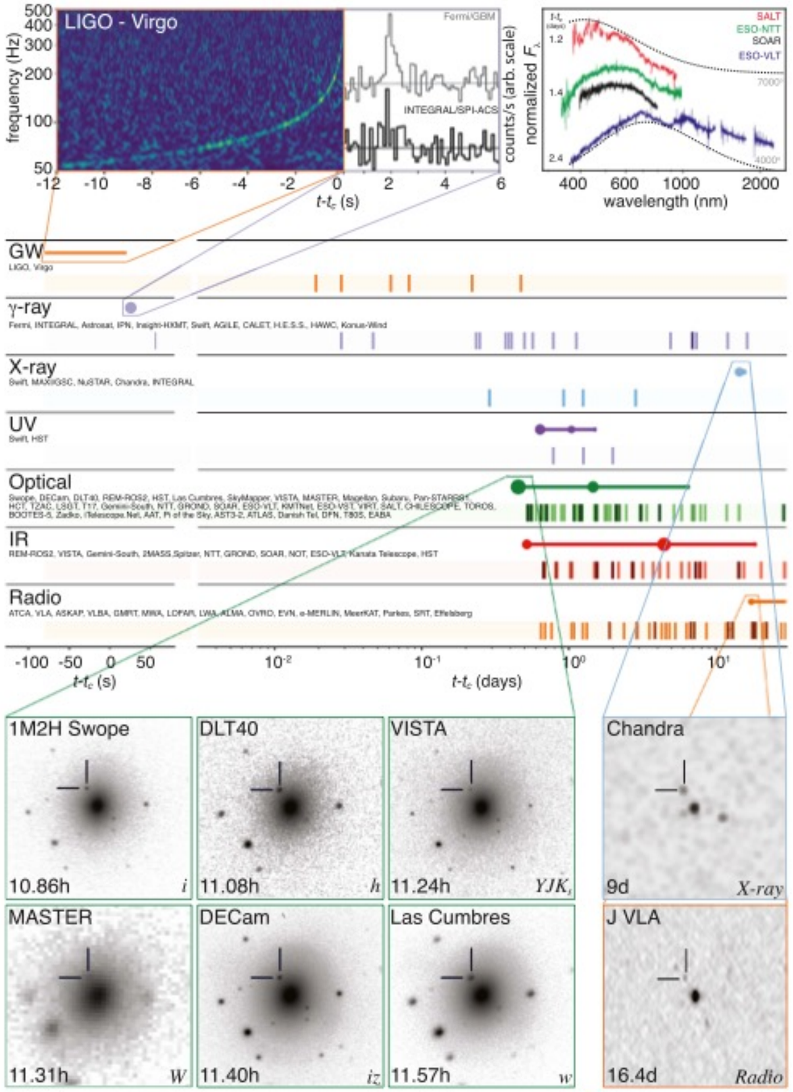
$$M/R = 0.156^{+0.008}_{-0.010}$$

$R = 13.02^{+1.24}_{-1.06}\ km$ Miller et al., ApJ 887 L24 (2019)

$R = 12.71^{+1.14}_{-1.19}\ km$ Riley et al., APJ 887 L21 (2019)

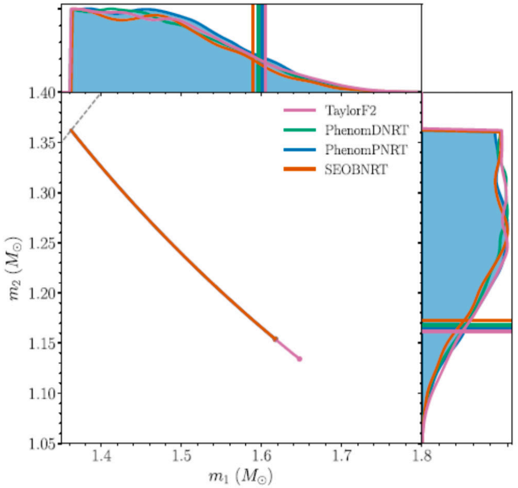
GW170817: the first NS-NS merger

Multi-messenger observations of the event GW170817



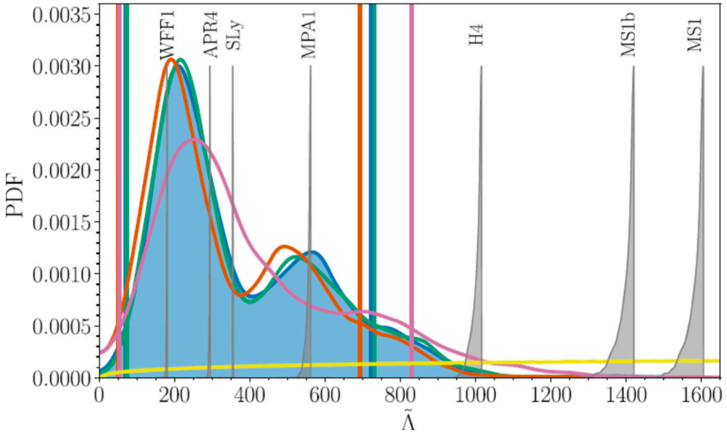
✧ Masses estimated from the chirp mass

$$M_c = \frac{\left(m_1 m_2\right)^{3/5}}{\left(m_1 + m_2\right)^{1/5}}$$



✧ Radius from the tidal deformability

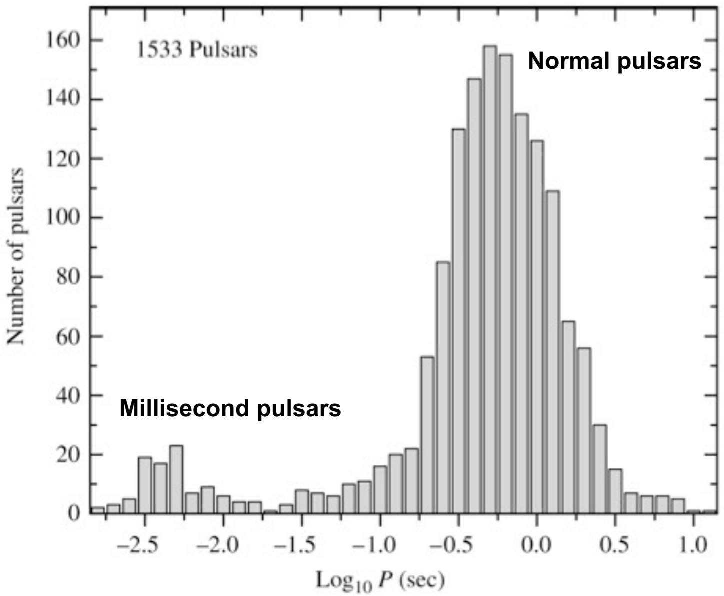
$$\tilde{\Lambda} = \frac{16}{13}\frac{\left(1+12q\right)\Lambda_1 + \left(q+12\right)\Lambda_2}{\left(1+q\right)^5}$$



A $1.36M_{\odot}$ has a radius of 10.4 km (WFF1), 11.3 km (APR4), 11.7 km (Sly), 12.4 km (MPA1), 14.0 (H4), 14.5 (MS1b) and 14.9 km (MS1)

Rotational Periods

- The majority of know NS are observed as pulsars
- The distribution of the rotational period of pulsars shows two clear peaks that indicate the existence of two types of pulsars
  - normal pulsars with P ~ s
  - millisecond pulsars with P ~ ms



Globular cluster Terzan 5

- First millisecond pulsar discovered in 1982 (Arecibo)
- Nowadays more than 200 millisecond pulsars are known
- PSR J1748-2446ad discovered in 2005 is until know the fastest one with P=1.39 ms (716 Hz)

Maximum (Minimum) Rotational Frequency (Period) of a Neutron Star

Rotation of pulsars can be accurately measured. However, pulsars cannot spin arbitrarily fast. There is an absolute maximum (minimum) rotational frequency (period)

Centrifugal Force = Gravitational Force

⬇

Keplerian Frequency Ω_K

(EoS dependent)

Newtonian Gravity

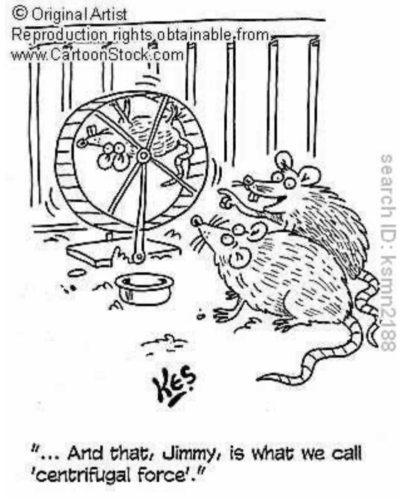
$$P_{\min} = 2\pi\sqrt{\frac{R^3}{GM}} \approx 0.55\left(\frac{M_{sun}}{M}\right)^{1/2}\left(\frac{R}{10km}\right)^{3/2} \quad ms$$

General Relativity

$$P_{\min} = 0.96\left(\frac{M_{sun}}{M}\right)^{1/2}\left(\frac{R}{10km}\right)^{3/2} \quad ms$$

An observed frequency above the Ω_k predicted by a given EoS would rule out that model

Fasted pulsar known: PSR J1748-2446ad (P=1.39595482 ms) cannot allow to put stringent constraints on existing EoS



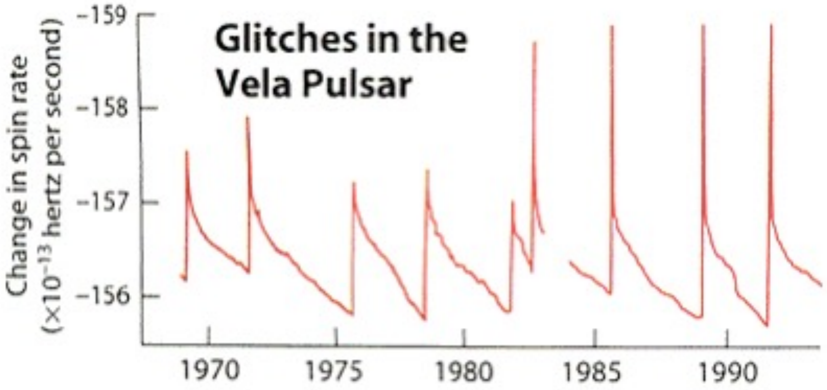
"... And that, Jimmy, is what we call 'centrifugal force'."

Pulsar glitches

Sometimes the period P of a pulsar decreases suddenly. These variations (glitches), although small, are observable

$$\frac{\Delta\Omega}{\Omega} \approx 10^{-9} - 10^{-5}$$

First glitches observed in the Crab & Vela pulsars. Nowadays we know more than 520 glitches in more than 180 pulsars



Vortex lines model:

Glitches result from a sudden transfer of angular momentum from the neutron superfluid to the solid crust caused by the unpinning of many vortex lines or by the cracking of the crust to which vortex lines are pinned.

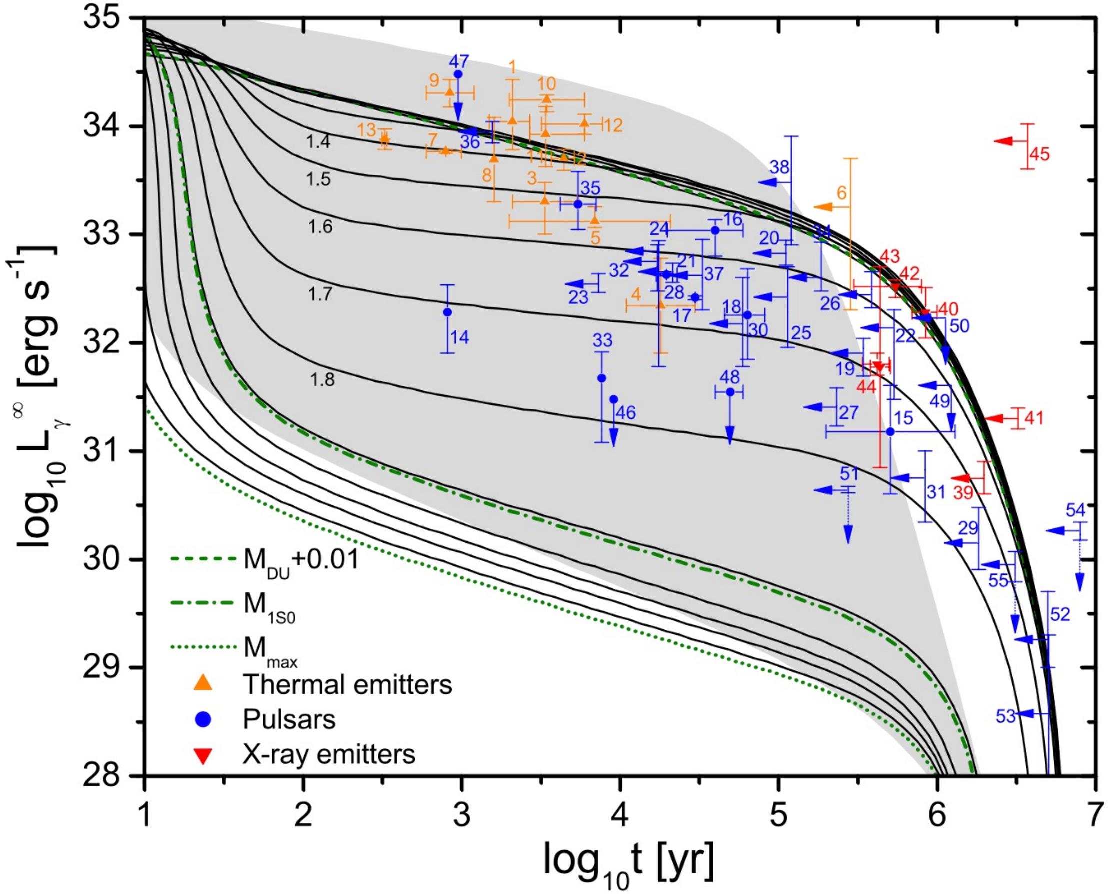
Other models include:

Starquakes between crust & core, magnetospheric instabilities or instabilities in the moion of neutron superfluid

Surface Temperatures / Luminosity

- Detection of thermal photons from the stellar surface in X-ray binaries allows to determine effective surface temperatures of neutron stars by fitting the observed spectra to blackbody ones

- But neutron stars are not blackbodies, because the hydrogen and helium (or even carbon) in their atmospheres modifies the blackbody spectrum. In addition the presence of strong magnetic fields can also modify the surface emission



Cooling calculations require a lot of microphysics

$$\frac{dE_{th}}{dt} = C_v \frac{dT}{dt} = -L_\gamma - L_\nu + H$$

✓ C_v: <u>specific heat</u>
✓ L_γ: <u>photon luminosity</u>
✓ L_ν: <u>neutrino luminosity</u>
✓ H: “heating”

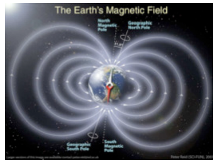
Magnetic Field of a Pulsar

Type of Pulsar	Surface magnetic field
Millisecond	$10^8 - 10^9$ G
Normal	10^{12} G
Magnetar	$10^{14} - 10^{15}$ G

Extremely high compared to …

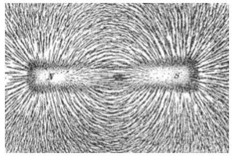
Earth

$0.3-0.5G$



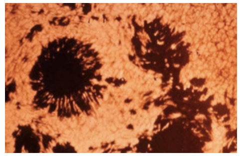
Magnet

10^3-10^4G



Sun spots

10^5G

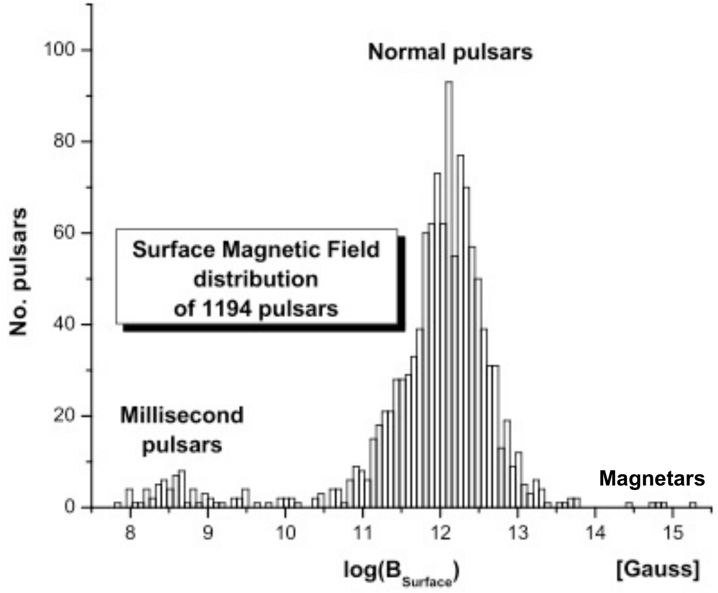


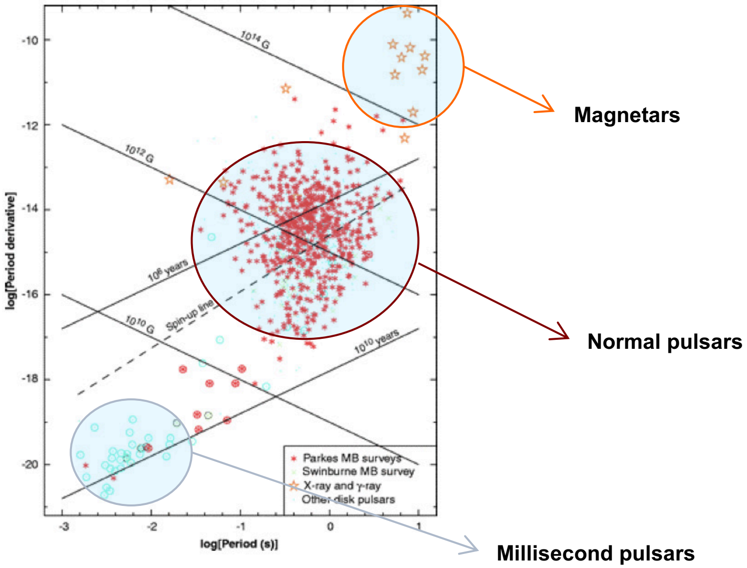
Largest continuous field in lab. (USA)

$4.5x10^5G$

Largest magnetic pulse in lab. (Russia)

$2.8x10^7G$





GravitationS Redshidt,QPOs & NS moment of inertia

Gravitational Redshift:

$$z=\left(1-\frac{2GM}{c^2R}\right)^{-1/2}-1$$

Measurements of z allow to constraint the ratio of M/R

Quasi-periodic Oscillations:

QPO in X-ray binaries measure the difference between the NS rot. freq. & the Keplerian freq. of the innermost stable orbit of matter elements in the accretion disk. Their observation & analysis can put stringent constraints on masses, radii & rotational periods

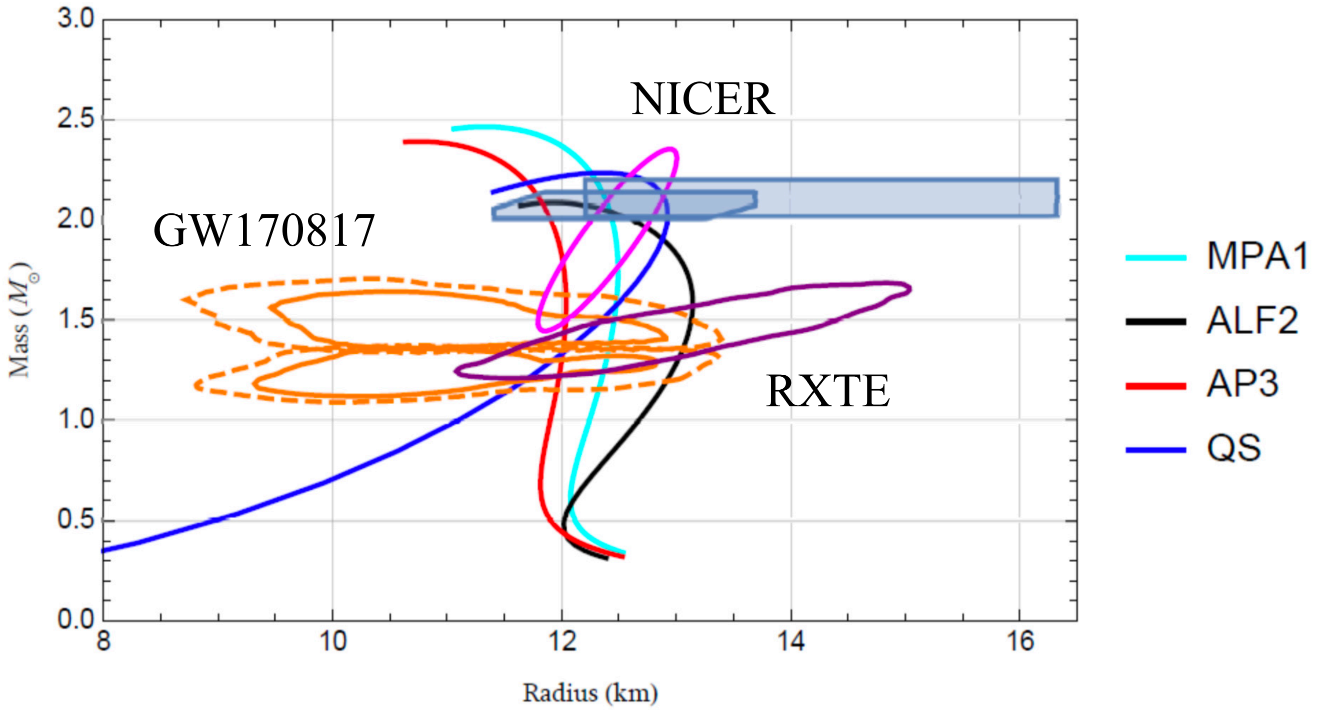
NS moment of inertia:

$$I=\frac{J(\Omega)}{\Omega};\quad J(\Omega)=\frac{8\pi}{3}\int_0^R dr r^4\,\frac{p(r)+\varepsilon(r)}{\sqrt{1-\frac{2M(r)}{r}}}\big(\Omega-\omega(r)\big)e^{-\nu(r)}$$

Measurements of I could also constraint EoS. But not measured yet. Lower bound can be inferred from timing observations of Crab pulsar

Combined analysis of a few astrophysical data

- NICER PSR J0740+6620 & PSR J0030+0451 (bands)
- GW170817 (from tidal deformability, orange solid/dashed lines)
- Rossi X-ray Timing Explorer (RXTE) results for the cooling tail spectra of 4U1702-429 (violet line)



Open Questions

- How robust are different nuclear-physics models in describing the interiors of neutron stars ?. Up to which densities are they sitll applicable ?.

- What particles are present in neutron-star interiors and which states of matter do they form ?.

- How can we best connect experiments with atomic nuclei to the properties of neutron-rich matter in the crust and core of neutron stars ?.

- Do we fully understand the systematic uncertainties in the analyses of radio, x-ray, and gravitational-wave data from neutron stars, and of experimental nuclear structure and heavy-ion collision data ?.

- How can we robustly combine this multitude of constraints spanning widely different scales ?.

Future Perspectives

Upcoming observations of NS & new data on neutron-rich matter from experiments will provide improved uncertainties allowing a more refined picture of NS and tighter constraints on their properties

✧ **NS observation:**

- New x-ray telescopes (Imaging x-ray polarimetry explored (Dec. 2021), XRISM (2023), Athena (2031)) will enable further advances & improve modelling of x-ray sources
- The improvement in the next decade of the sensitivity of LIGO & Virgo detectors will increase the prospects for dense matter science with GW
- Third generation of GW detectors (Einstein Telescope, Cosmic Explorer) in the 2030s will allow the detection of a post-merger GW signal & its electromagnetic countepart
- Future observations of young NS (Cas A or the potential remnant of SN 1987A) will constraint theoretical cooling models & potentially set constraints on energy gaps of superfluid matter.

Future Perspectives

- **Experimental information:**
  - Neutron-skin thickness in heavy nuclei crucial to obtain key information on nuclear matter probed in the outer core of NS
  - Nature of very-neutron rich nuclei at the limits of existence from rare isotope facilities such as FRIB (USA), RIBF (Japan) & FAIR (Germany)
  - Heavy-ion collision experiments at these facilities & others such as NICA (Russia) to probe matter at high densities & neutron-proton asymmetries. Crucial to better understand systematic uncertainties in the analysis of such experiments & improve transport model simulations


MERCI!
THANK YOU!
FRAPAR.