Neutron Stars

Lecture 1: Some generalities (both theoretical and observational)

Ignacio F. Ranea-Sandoval (Argentina)

Facultad de Ciencias Astronómicas y Geofísicas
UNIVERSIDAD NACIONAL DE LA PLATA

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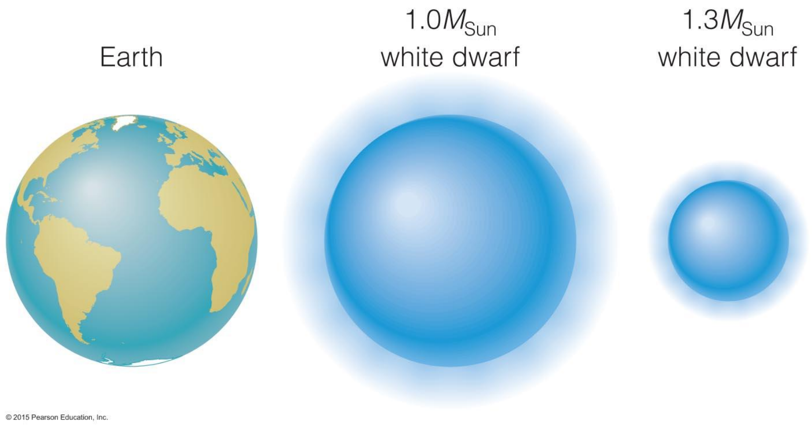
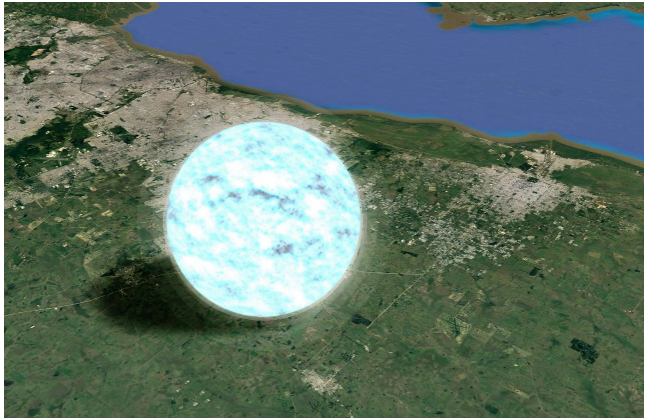
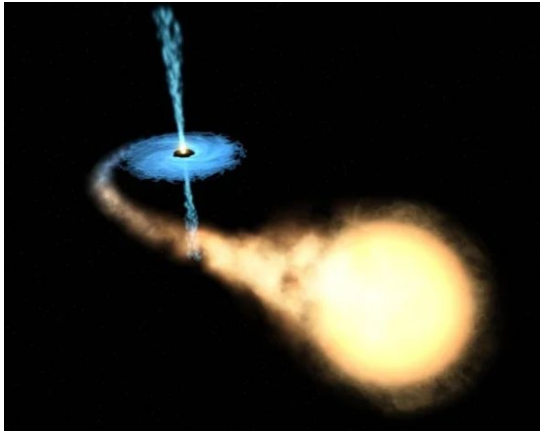
https://arco.fcaglp.unlp.edu.ar/

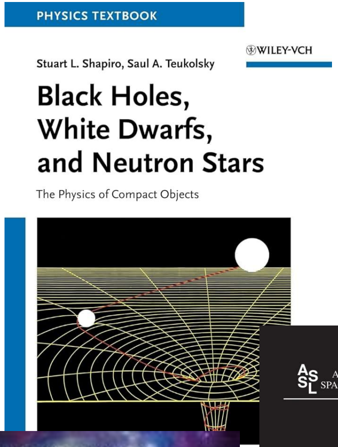
Compact objects in the Universe

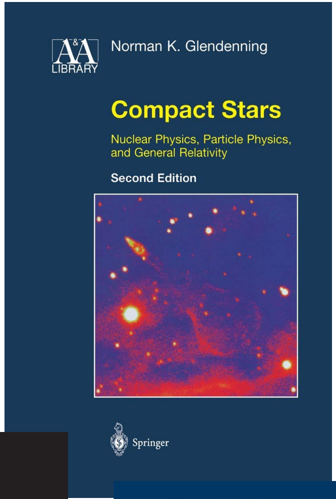


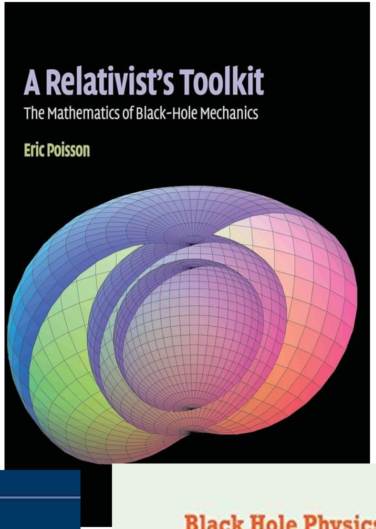




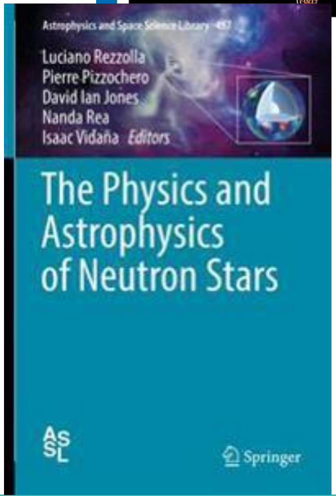
What to read?

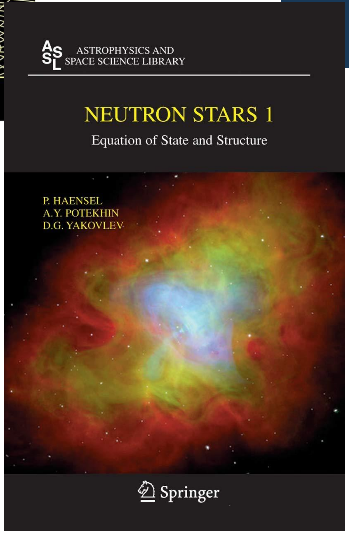


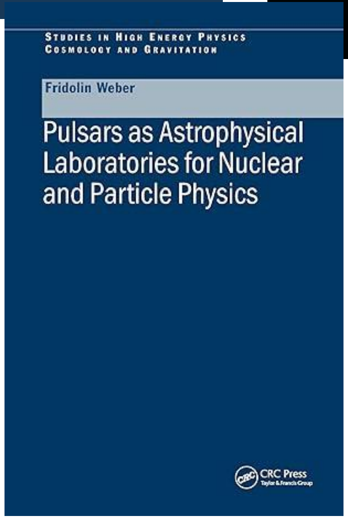


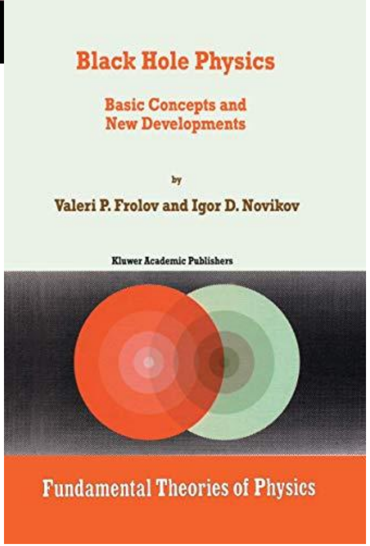


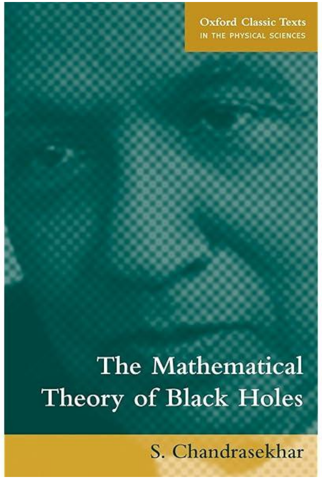
Classical books











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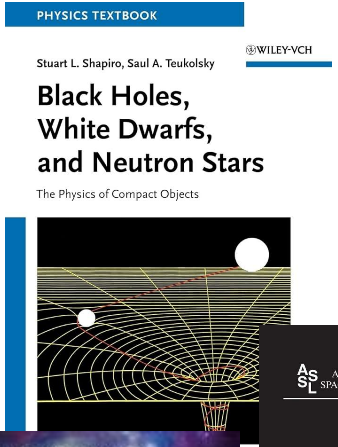
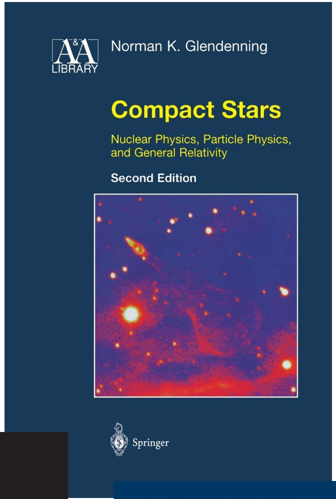
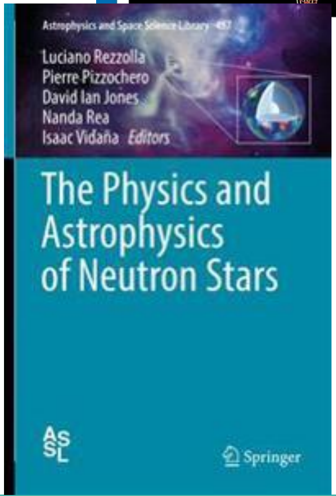
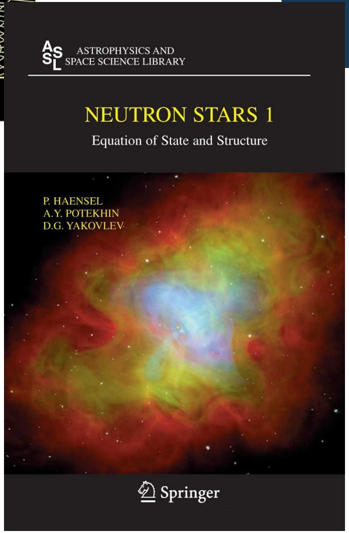
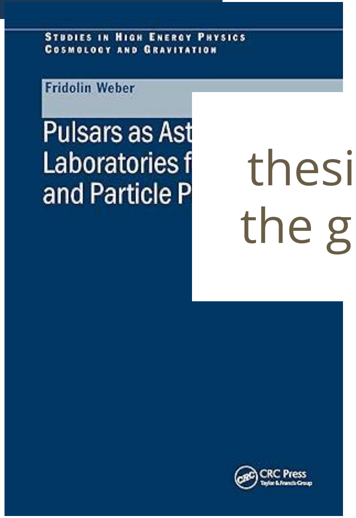
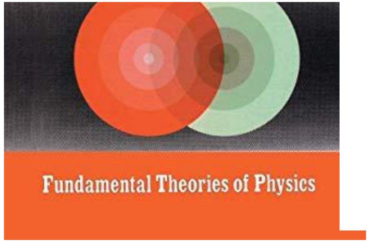


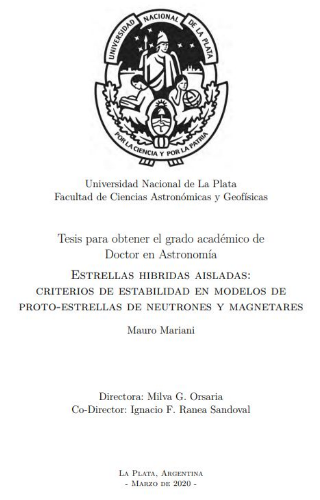












Universidad Nacional de La Plata
Facultad de Ciencias Astronómicas y Geofísicas

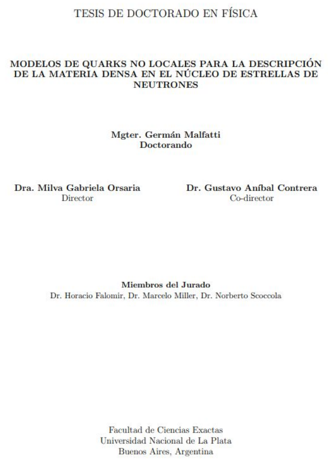
Tesis para obtener el grado académico de
Doctor en Astronomía

ESTRELLAS HIBRIDAS AISLADAS:
CRITERIOS DE ESTABILIDAD EN MODELOS DE PROTO-ESTRELLAS DE NEUTRONES Y MAGNETARES

Mauro Mariani

Directora: Milva G. Orsaria
Co-Director: Ignacio F. Ranea Sandoval

LA PLATA, ARGENTINA
- MARZO DE 2020 -



TESIS DE DOCTORADO EN FÍSICA

MODELOS DE QUARKS NO LOCALES PARA LA DESCRIPCIÓN DE LA MATERIA DENSA EN EL NÚCLEO DE ESTRELLAS DE NEUTRONES

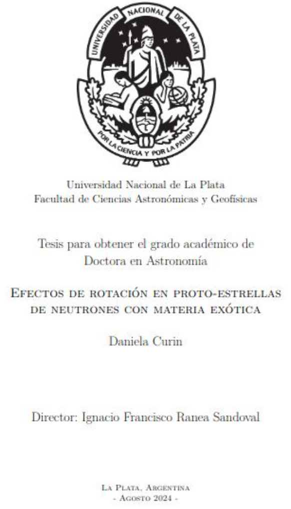
Mgter. Germán Malfatti
Doctorando

Dra. Milva Gabriela Orsaria
Director

Dr. Gustavo Aníbal Contrera
Co-director

Miembros del Jurado
Dr. Horacio Falomir, Dr. Marcelo Miller, Dr. Norberto Scoccola

Facultad de Ciencias Exactas
Universidad Nacional de La Plata
Buenos Aires, Argentina



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Tesis para obtener el grado académico de
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EFECTOS DE ROTACIÓN EN PROTO-ESTRELLAS DE NEUTRONES CON MATERIA EXÓTICA

Daniela Curin

Director: Ignacio Francisco Ranea Sandoval

LA PLATA, ARGENTINA
- AGOSTO 2024 -

thesis done within the group I work in

What to read?

PHYSICS TEXTBOOK

WILEY-VCH

few modern review papers

PROCEEDINGS OF SCIENCE

Astrophysical Black Holes: A Review

Cosimo Bambi*
Center for Field Theory and Particle Physics and Department of Physics, Fudan University, 200438 Shanghai, China
E-mail: bambi@fudan.edu.cn

Astron Astrophys Rev (2024) 32:3
https://doi.org/10.1007/s00159-024-00154-z

REVIEW ARTICLE

Check for updates

Experimental studies of black holes: status and future prospects

Reinhard Genzel[1,2,3] · Frank Eisenhauer[1,4] · Stefan Gillessen[1]

Received: 27 February 2024 / Accepted: 21 March 2024 / Published online: 25 April 2024

Reports on Progress in **Physics**

REVIEW

From hadrons to quarks in neutron stars: a review

Gordon Baym, Tetsuo Hatsuda, Toru Kojo, Philip D Powell, Yifan Song and Tatsuyuki Takatsuka

Published 27 March 2018 • © 2018 IOP Publishing Ltd
ports on Progress in Physics, Volume 81, Number 5
ation Gordon Baym *et al* 2018 *Rep. Prog. Phys.* **81** 056902
I 10.1088/1361-6633/aaae14

IOP Publishing Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. **46** (2019) 073002 (33pp) https://doi.org/10.1088/1361-6471/ab1d81

Topical Review

Phase transitions in neutron stars and their links to gravitational waves

Milva G Orsaria[1,2], Germán Malfatti[1,2], Mauro Mariani[1,2], Ignacio F Ranea-Sandoval[1,2], Federico García[3,4], William M Spinella[5], Gustavo A Contrera[1,6,7], Germán Lugones[8] and Fridolin Weber[7,9]

Masses, Radii, and the Equation of State of Neutron Stars

Feryal Özel[1] and Paulo Freire[2]

[1]Department of Astronomy, University of Arizona, Tucson, Arizona 85721; email: fozel@email.arizona.edu

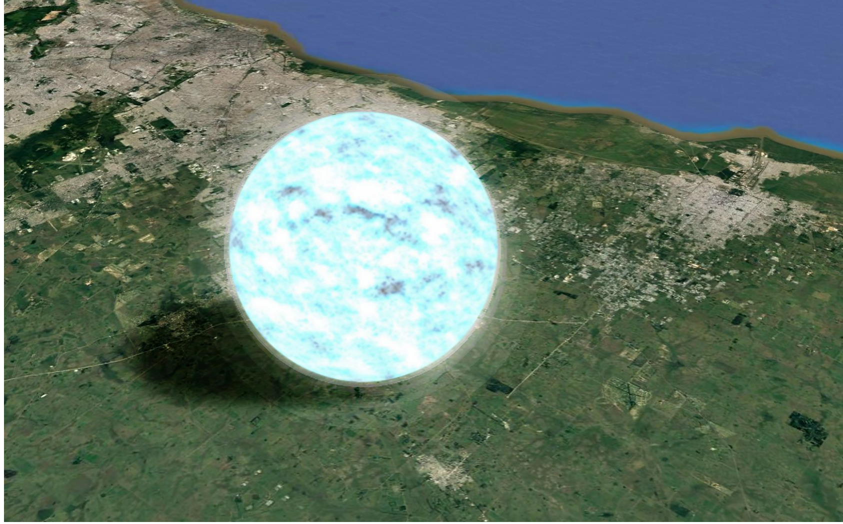
[2]Max-Planck-Institut für Radioastronomie, D-53121 Bonn, Germany; email: pfreire@mpifr-bonn.mpg.de

What are Neutron Stars?

Most compact objects in the Universe

Masses up to $2M_{sun}$ and radii between 10 to 15 km

Huge mean densities! (can anyone make an estimate?)



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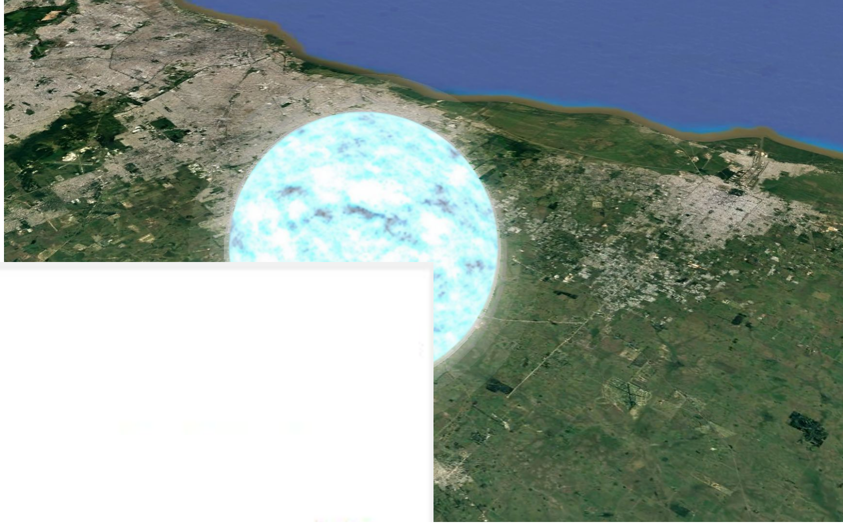

Basic Neutron Star Characteristics

$$R := \frac{10km + 15km}{2}$$

$$M_{Sun} := 1.98892 \cdot 10^{30} kg$$ *Mass of the Sun in kg*

$$M_{NeutronStar} := \frac{1.44 + 2}{2} \cdot M_{Sun}$$

$$\rho := \frac{M_{NeutronStar}}{\frac{4}{3} \cdot \pi \cdot R^{3}}$$ *Density = Mass/Volume.*

$$\rho = 4.181 \times 10^{17} \frac{kg}{m^{3}}$$

$$teaspoon := 4.92892159 \cdot mL$$

$$\rho = 2.272 \times 10^{9} \frac{ton}{teaspoon}$$

The density that I get is about 2 billion tons per teaspoon.

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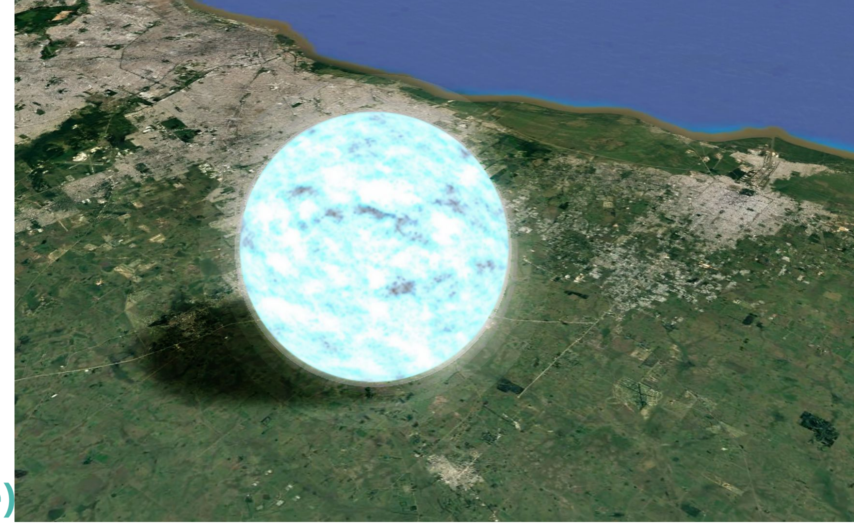
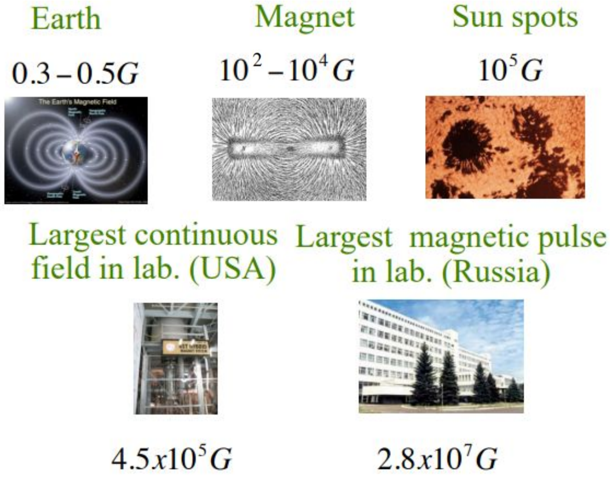
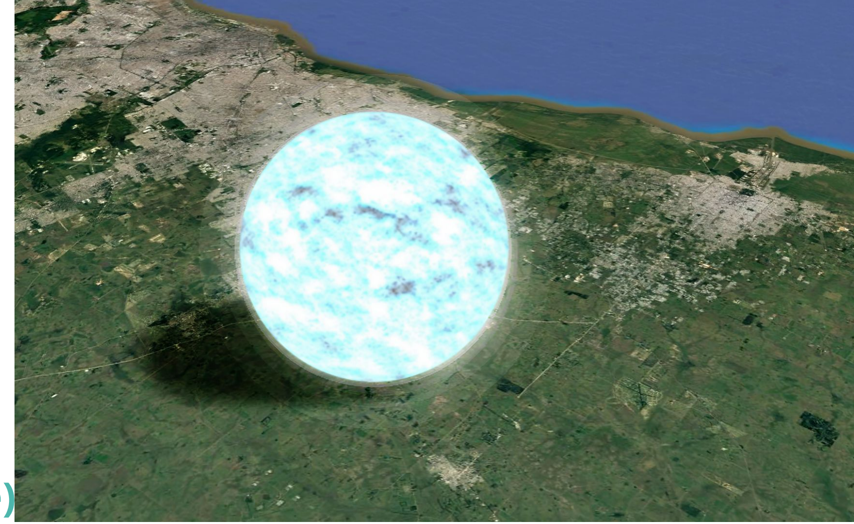
Huge magnetic fields (up to 10^{15} Gauss at the surface)





Magnets of CERN ~8 10^5 G

What are Neutron Stars?



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In particle accelerators, during a collision extremely brief (10^{-23} seconds) magnetic fields of over 10^{18} G has been created in the Brookhaven National Laboratory

Magnets of CERN ~8 10^5 G

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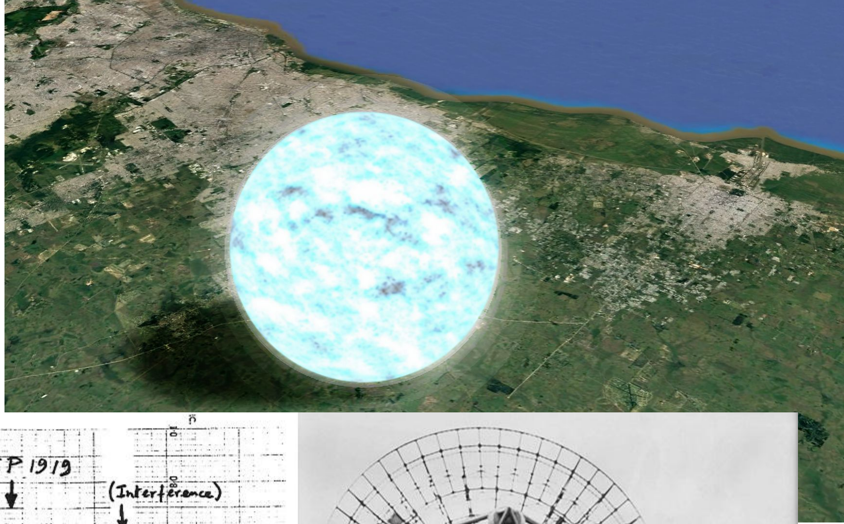
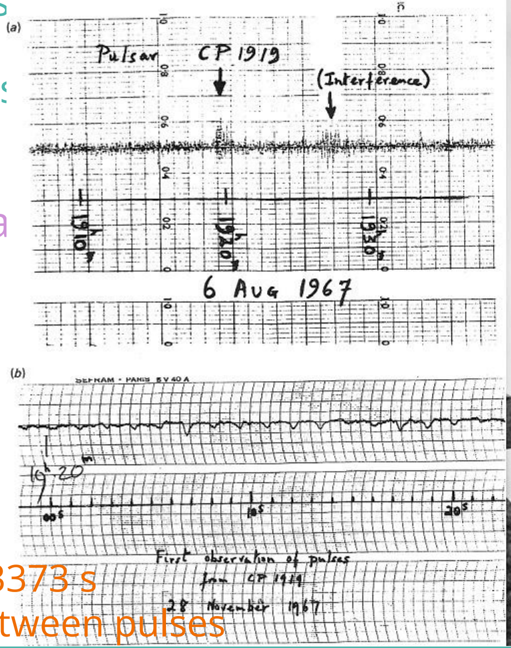
Most observations come from the Milky Wa

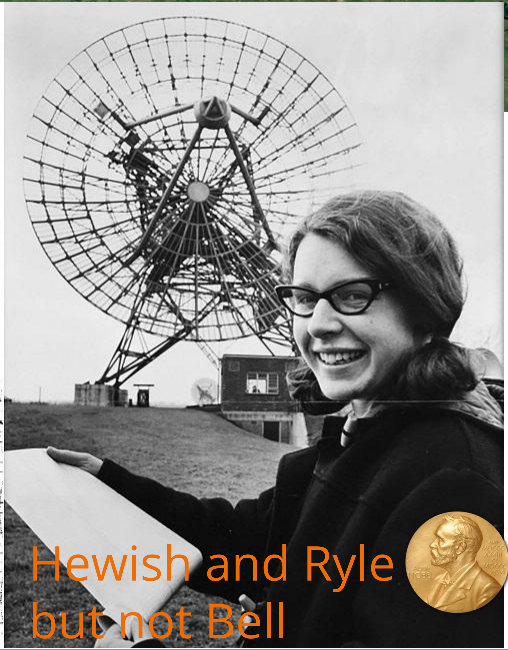
Some from LMC and SMC

Very few from even further away





1,3373 s
between pulses



Hewish and Ryle
but not Bell

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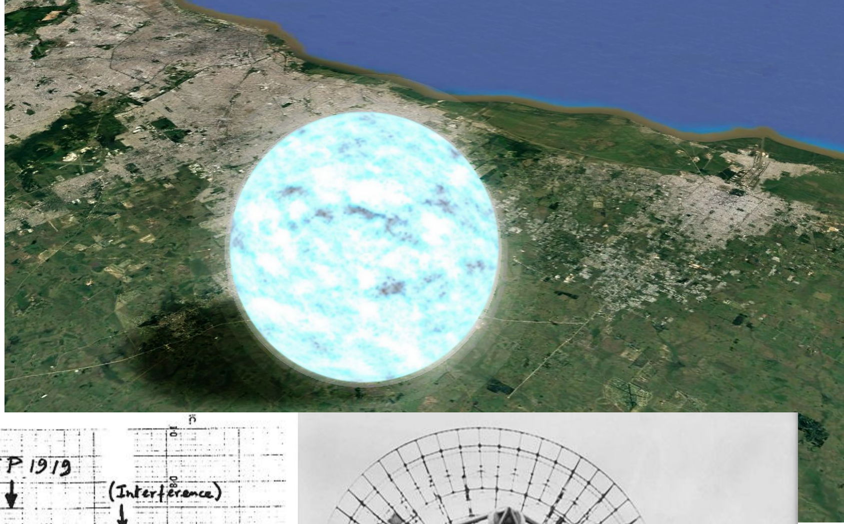
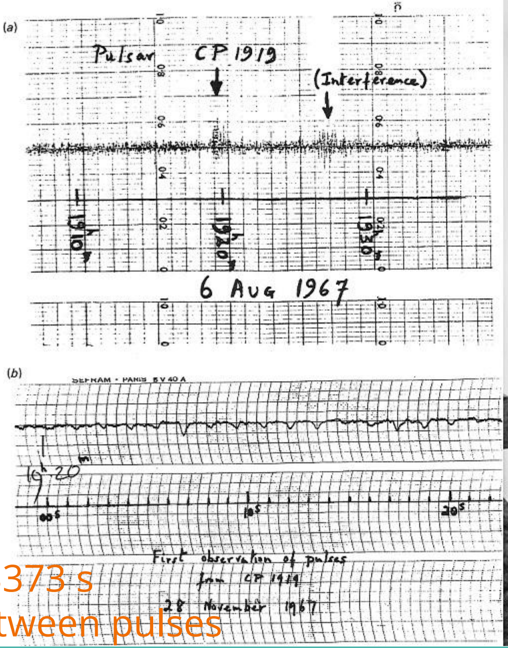
Great to test GR in the strong field regime

(first indirect detection of GWs Taylor

Hulser pulsar)





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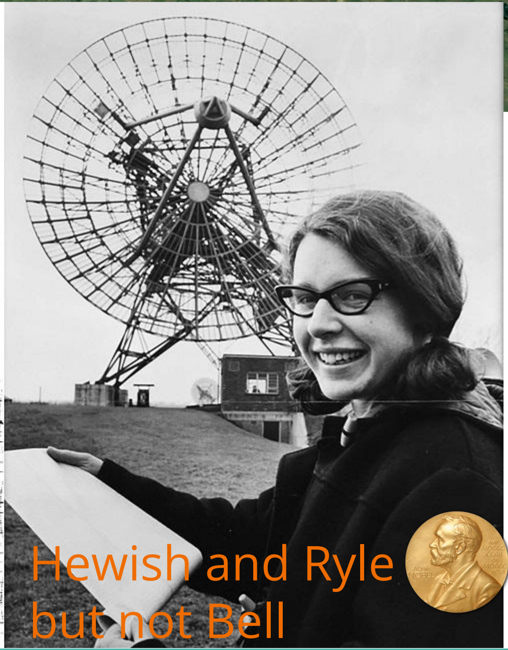
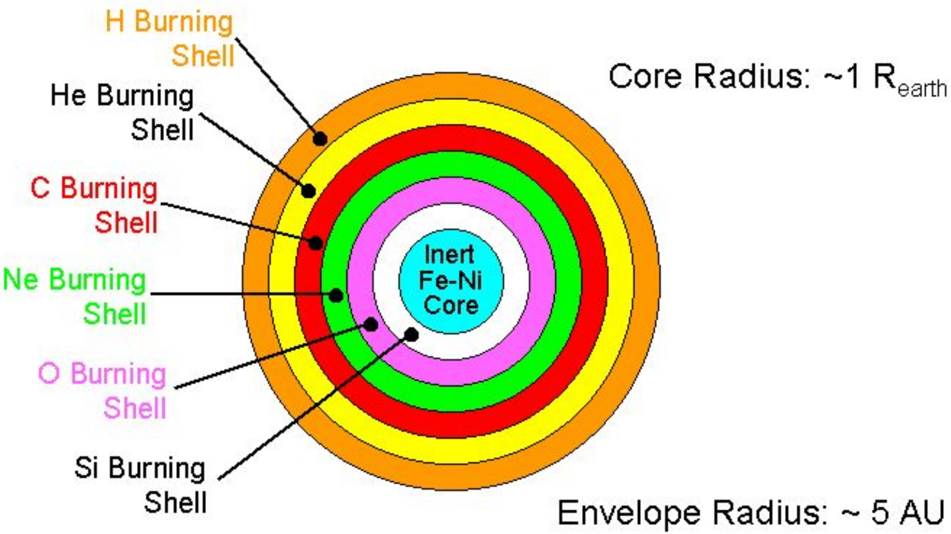


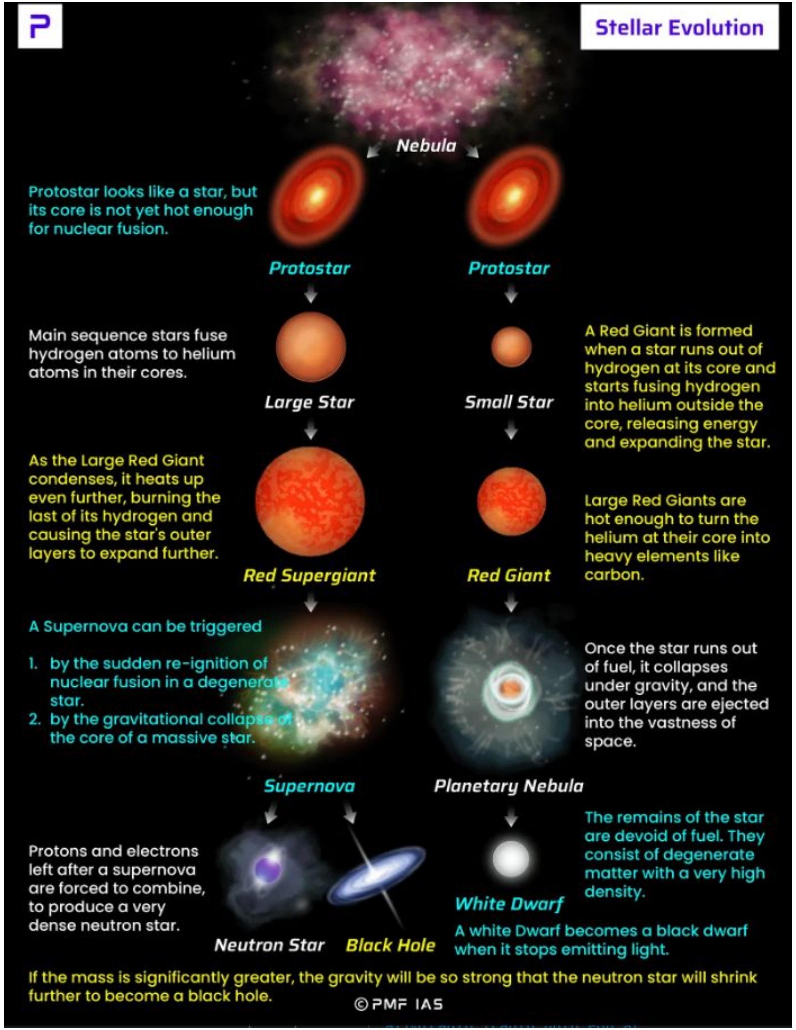
Hewish and Ryle
but not Bell

How are they formed?

A (brief) story about stellar evolution of isolated stars

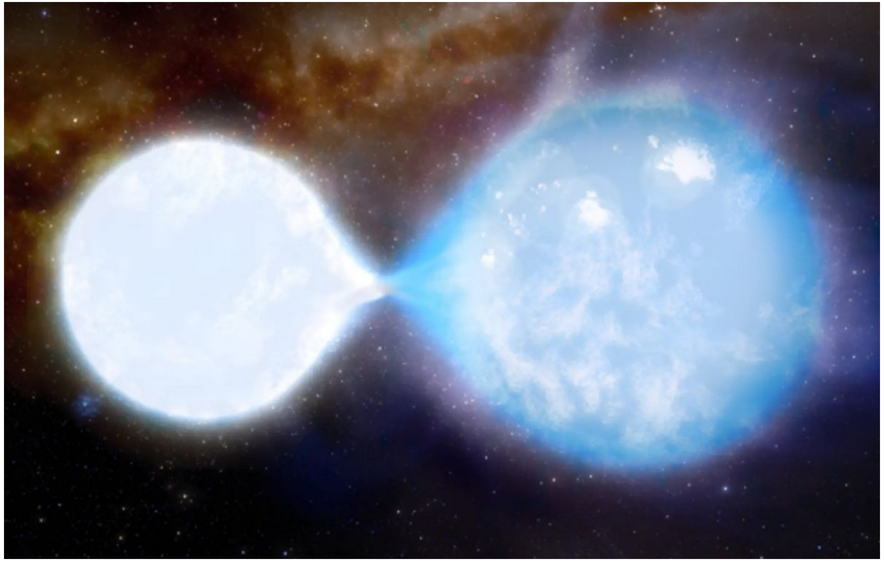
You will see more details of this topic in a different course of the school.

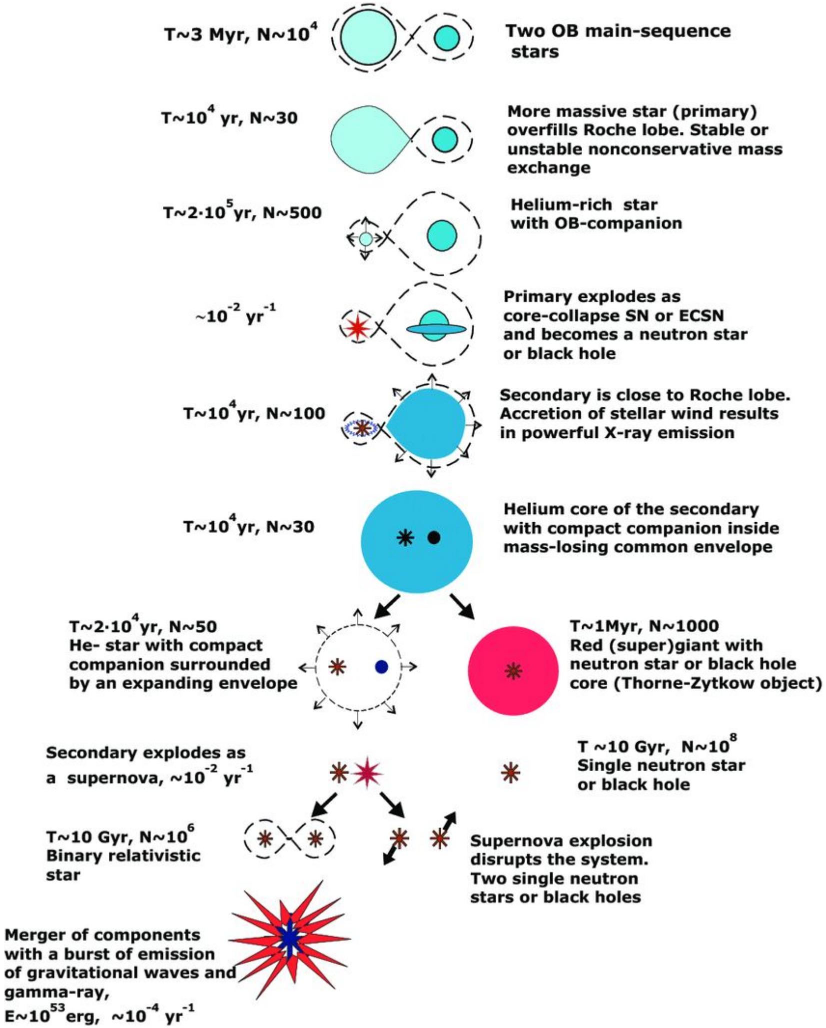




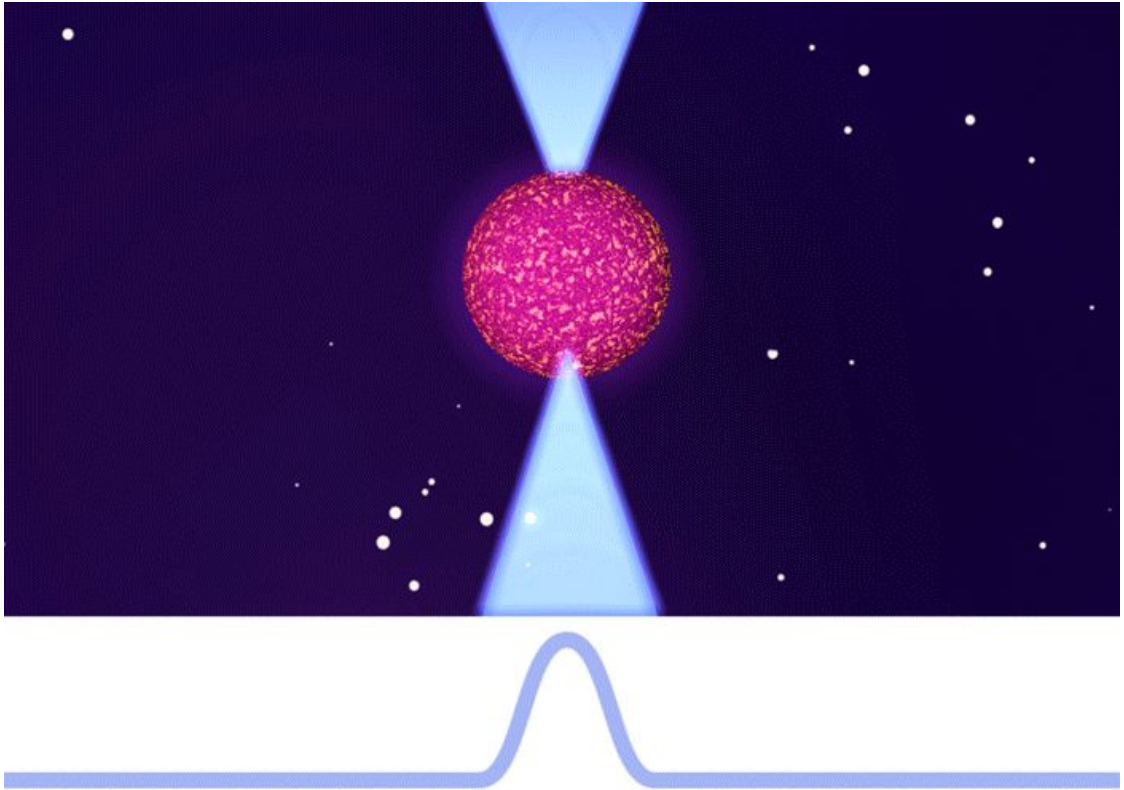
How are they formed?

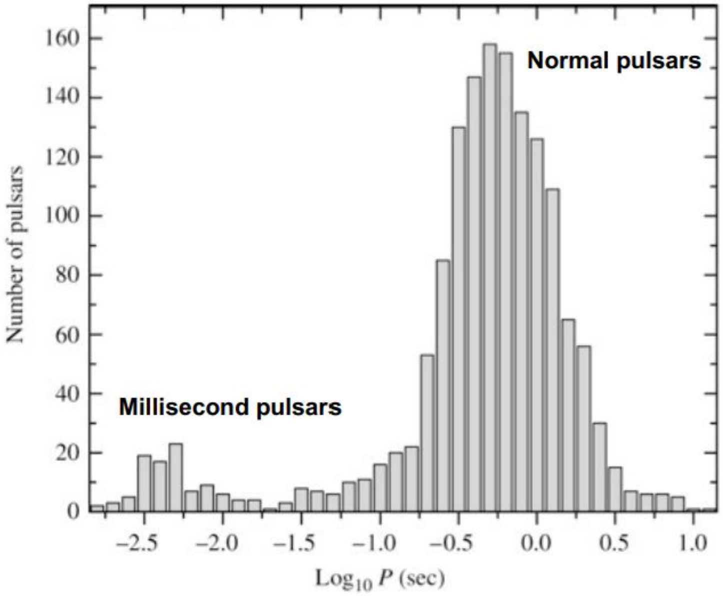
A (brief) story about stellar evolution of binary stars





Pulsars: Atomic Clocks in the Universe

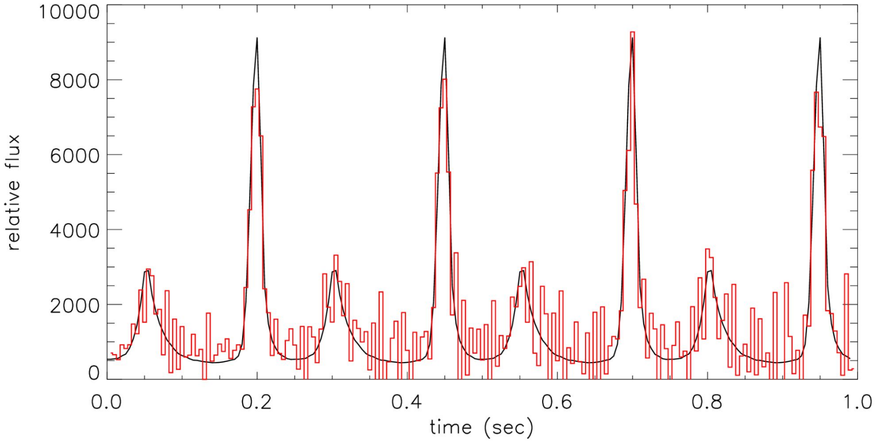




Pulsars: Atomic Clocks in the Universe

Pulsar Timing

- It includes
  - spin (period and time derivatives)
  - astrometry (position, proper motion)



More than 2500 pulsars are know, most of them discovered in radio but can be studied also in the high-energy end of the electromagnetic spectrum

Both isolated and in binary systems

Pulsars: Atomic Clocks in the Universe

Pulsar Timing

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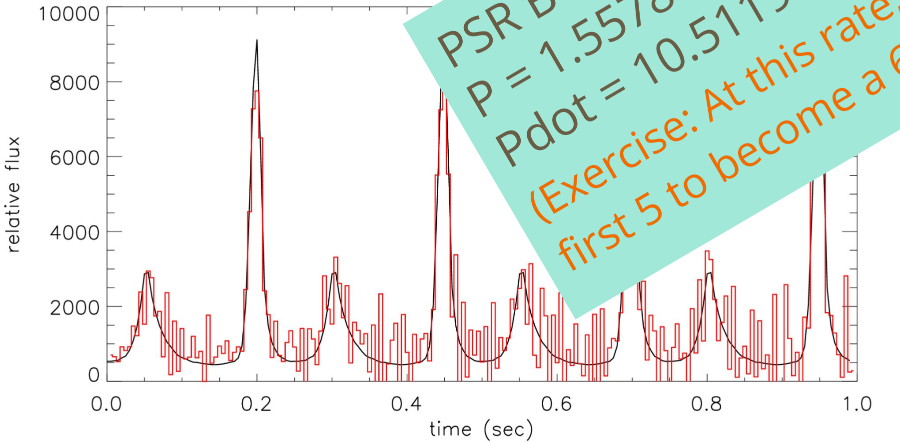

PSR B1973+21 (from Kaspi et al, ApJ, 1994)
P = 1.557806468819794(2)ms
Pdot = 10.51193(2) 10^{-20} s/s
(Exercise: At this rate, how long does it take for the first 5 to become a 6?)

0 pulsars
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spectrum.

Both isolated and in
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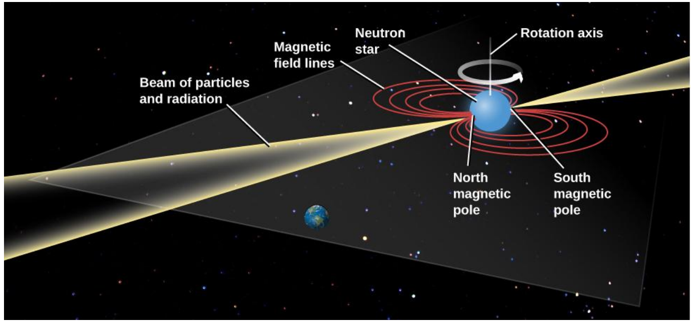
Pulsars: rotating magnetized NSs

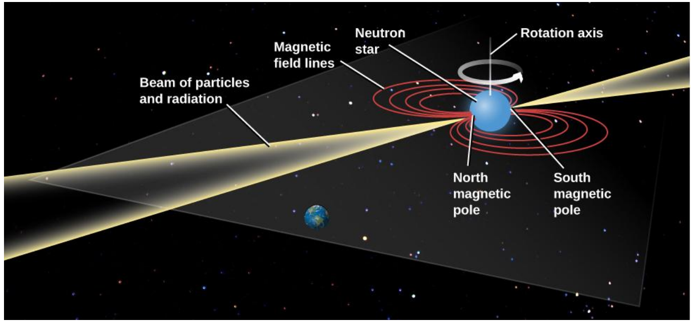


Theoretical background

The Poynting flux (power per unit area)

$$\vec{S} = \frac{c}{4\pi}\vec{E} \times \vec{B} = \frac{c}{4\pi}E^2$$

Pulsars: rotating magnetized NSs



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using the expression for the electrical

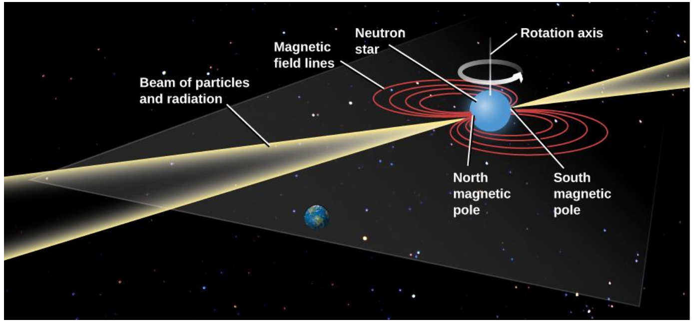
field of a point charge and electromagnetic laws

for a moving particle we can obtain Larmor's formula

$$p_E = \frac{2}{3}\frac{q^2\dot{v}^2}{c^3}$$

Electromagnetic power emitted by a non-relativistic point charge

Pulsars: rotating magnetized NSs



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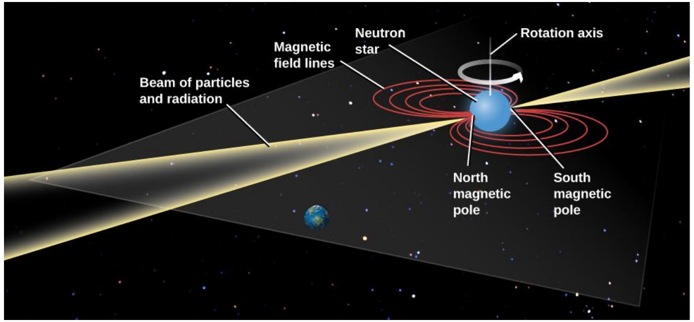
A similar treatment can be performed for a uniformly magnetized sphere of radius R and polar magnetic field B_p that rotates with an angular frequency Ω an whose magnetic and rotation axes are tilted an angle α to obtain the energy loss-rate due to magnetic-dipole radiation

$$\dot{E} = -\frac{B_p^2 R^6 \Omega^4 \sin^2\alpha}{6c^3}$$

Pulsars: rotating magnetized NSs

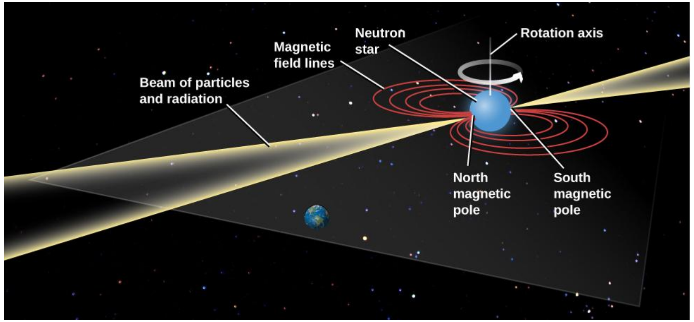


Theoretical background

where is this energy coming from?

$$\dot{E} = -\frac{B_p^2 R^6 \Omega^4 \sin^2 \alpha}{6c^3}$$

Pulsars: rotating magnetized NSs



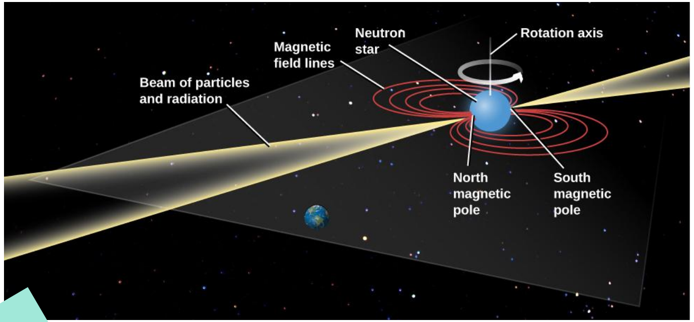
Theoretical background

where is this energy coming from?

$$\dot{E} = -\frac{B_p^2 R^6 \Omega^4 \sin^2 \alpha}{6c^3}$$

Loss of rotational kinetic energy!

$$\dot{E} = \frac{dE_{rot}}{dt} = \frac{d}{dt}\left(\frac{1}{2} I \Omega^2\right) = I \Omega \dot{\Omega}$$



Pulsars: rotating magnetized NSs

Theoretical background

where is this energy coming from?

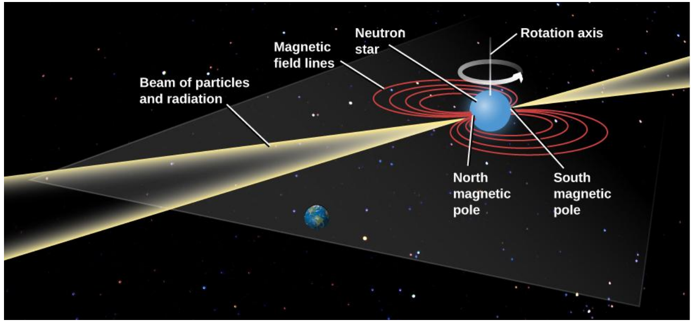
$$\dot{E} = -\frac{B_p^2 R^6}{\cdots}$$

Loss of rotational kinetic energy!

$$\cdots\Big) = I\Omega\dot{\Omega}$$

Can anyone remember how to calculate the moment of inertia, I, of a sphere with uniform density?

Pulsars: rotating magnetized NSs



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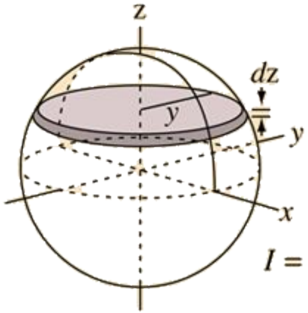
Loss of rotational kineti



$$dI = \frac{1}{2}y^2 dm = \frac{1}{2}y^2 \rho dV = \frac{1}{2}y^2 \rho \pi y^2 dz$$

and the integral becomes

$$I = \frac{1}{2}\rho\pi \int_{-R}^{R} y^4\, dz = \frac{1}{2}\rho\pi \int_{-R}^{R} (R^2 - z^2)^2\, dz = \frac{8}{15}\rho\pi R^5$$

Radius = R

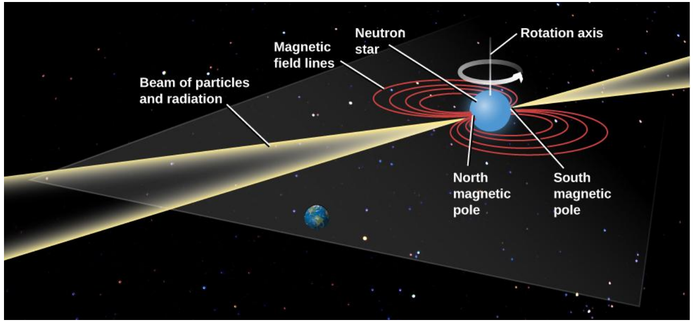
Mass = M

Density $= \rho = \frac{M}{V} = \frac{M}{\frac{4}{3}\pi R^3}$

Substituting the density expression gives

$$I = \frac{8}{15}\left[\frac{M}{\frac{4}{3}\pi R^3}\right]\pi R^5 = \frac{2}{5}MR^2$$

Pulsars: rotating magnetized NSs



Theoretical background

where is this energy coming from?

$$\dot{E} = -\frac{B_p^2 R^6 \Omega^4 \sin^2 \alpha}{6c^3}$$

Loss of rotational kinetic energy!

$$\dot{E} = \frac{dE_{rot}}{dt} = \frac{d}{dt}\left(\frac{1}{2} I \Omega^2\right) = I\Omega\dot{\Omega} = \frac{4\pi^2 I \dot{P}}{P^3}$$

Exercise: Obtain the energy loss-rate for the Crab pulsar that rotates with a period of 0.033 s, that changes with time at a rate of $10^{-12.4}$ s/s. Assume that it has a moment of inertia of 10^{45} g cm^2.

Pulsars: rotating magnetized NSs

Brief summary

$$\tau_c = \frac{P}{2\dot{P}}$$

$$B \simeq 3 \cdot 10^{19} \sqrt{P\dot{P}}\ \mathrm{G}$$

$$-\dot{E} \simeq 10^{47} \frac{\dot{P}}{P^3}\ \mathrm{erg/s}$$

P in seconds

Pulsars: rotating magnetized NSs

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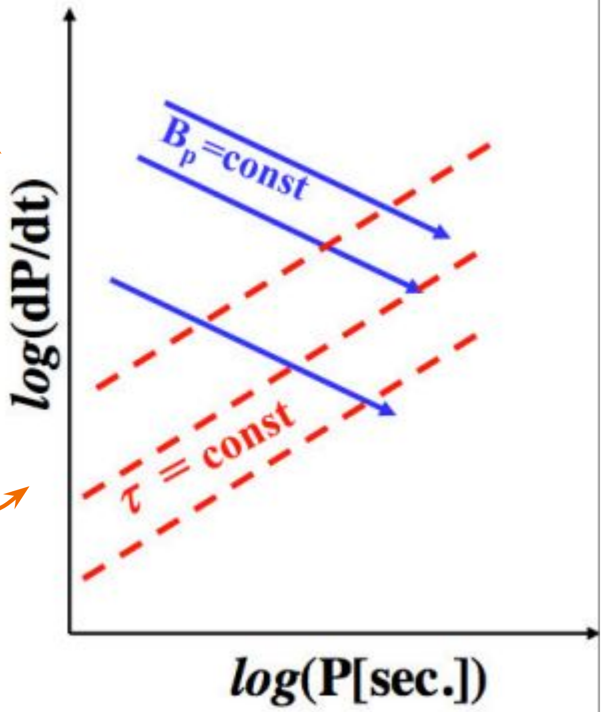

Pulsars: rotating magnetized NSs

P - Ṗ diagram

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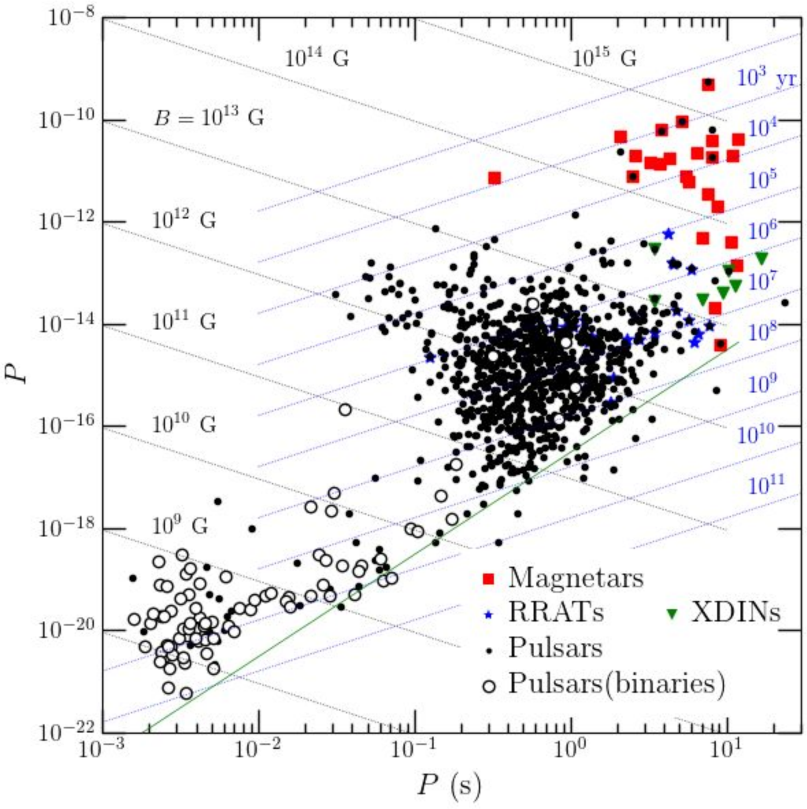
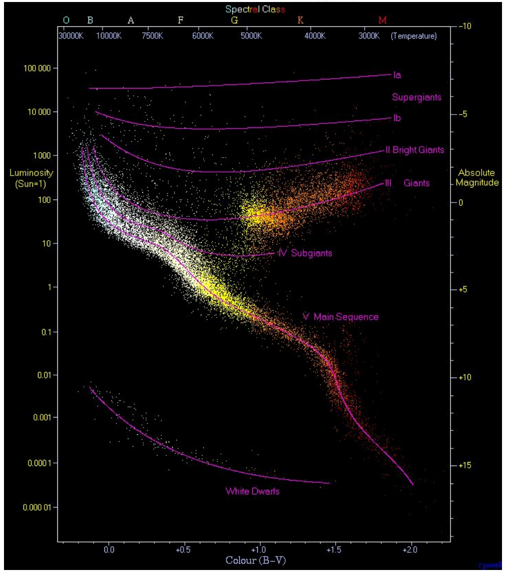
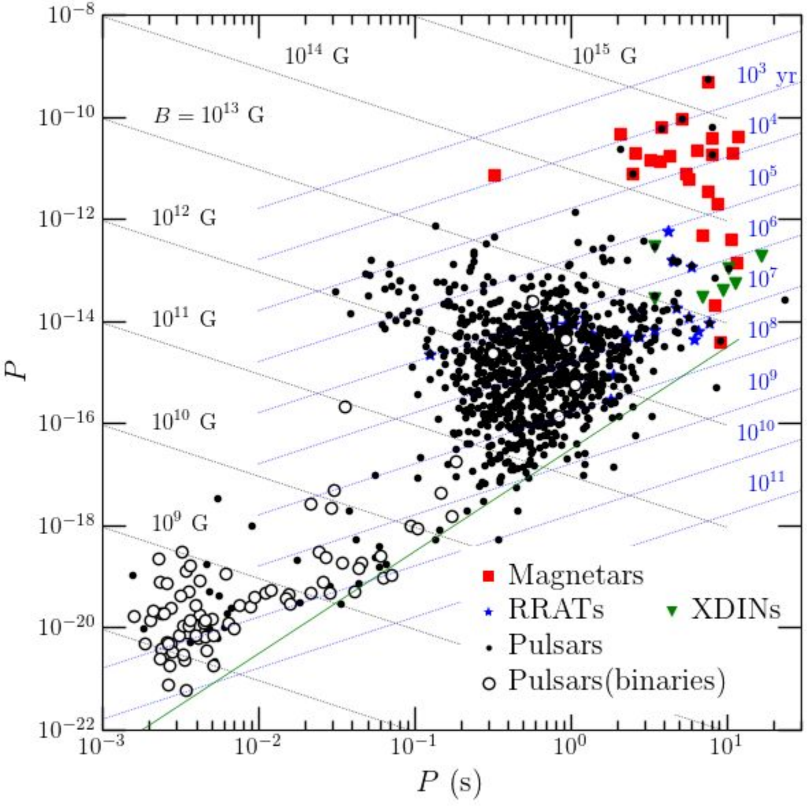


Pulsars: rotating magnetized NSs

Kind of a HR diagram

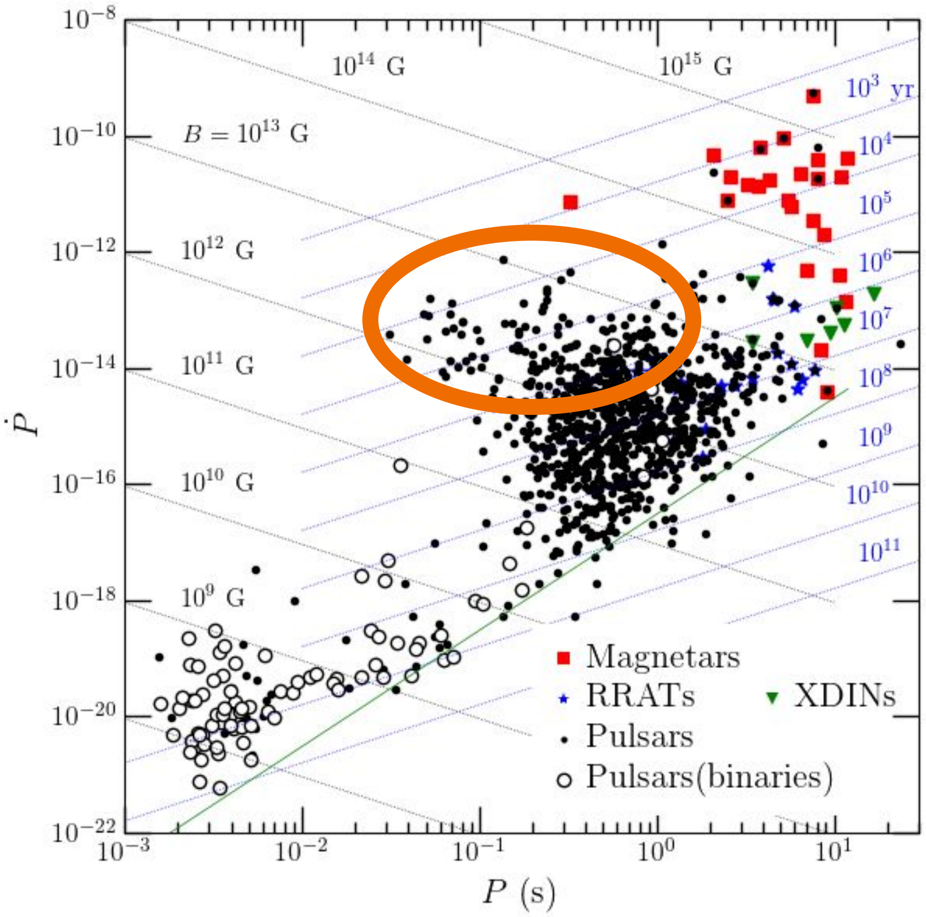




Pulsars flavors and evolution

Young PSR

(high B, fast, very energetic)



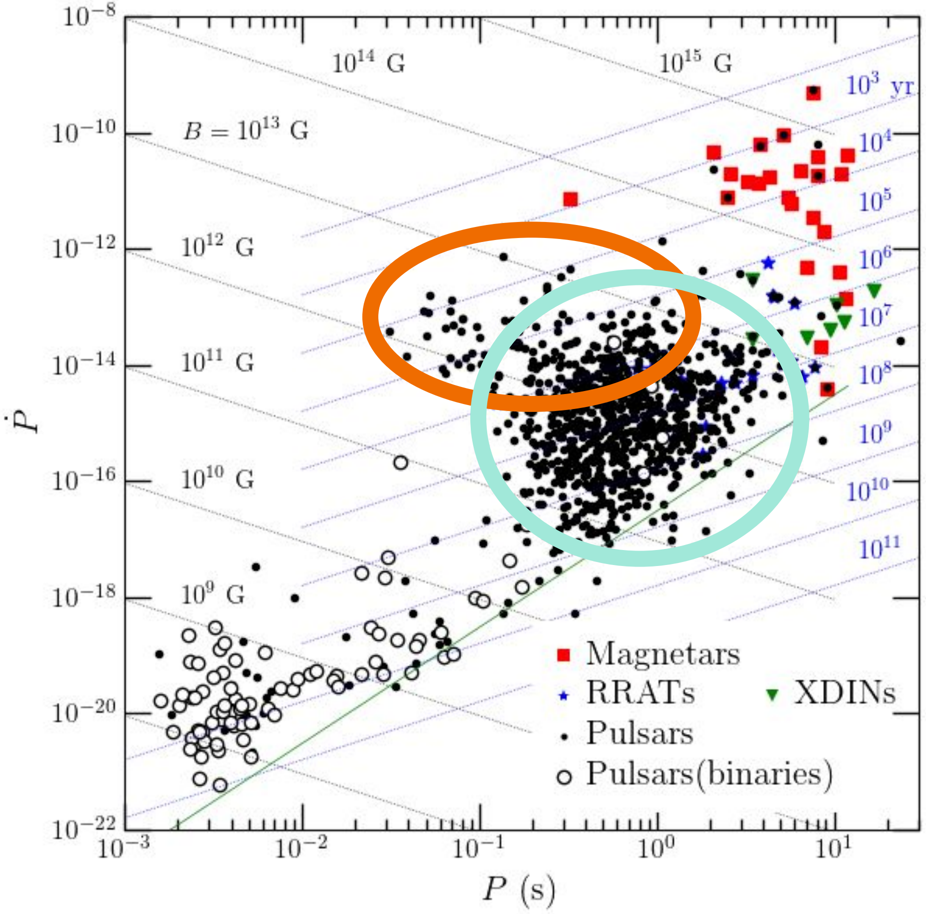
Pulsars flavors and evolution

Young PSR

(high B, fast, very energetic)

Normal PSR

(average B, slow)



Pulsars flavors and evolution

Young PSR

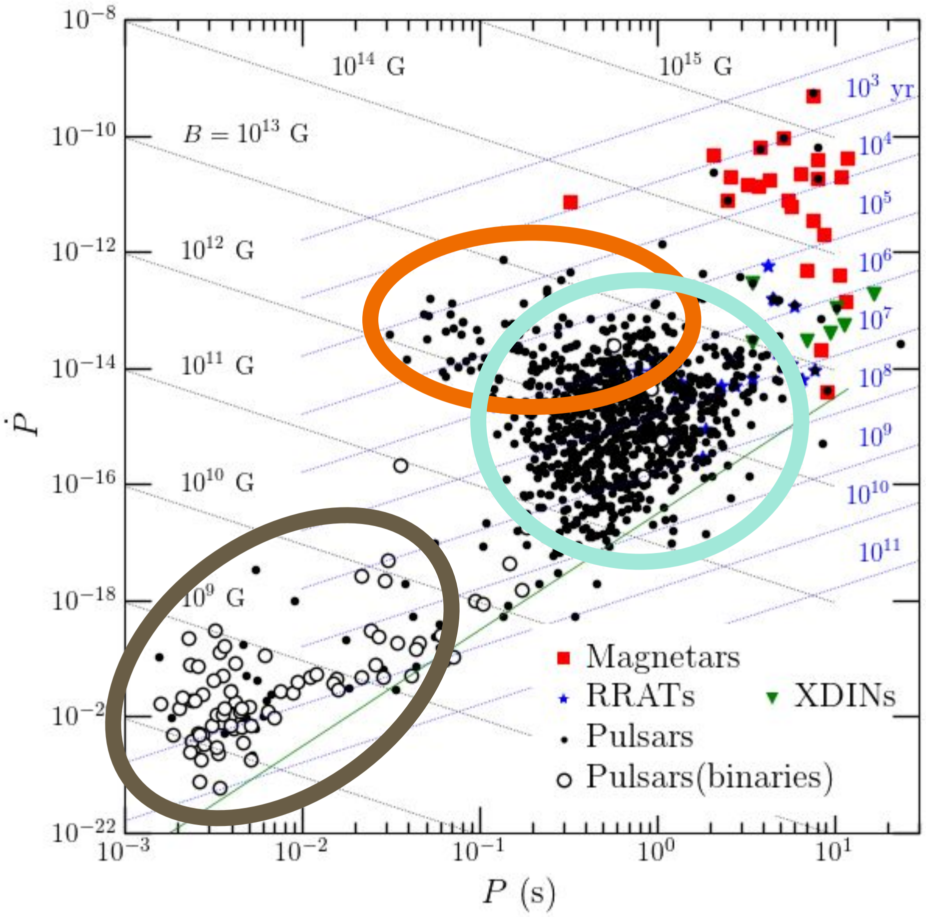
(high B, fast, very energetic)

Normal PSR

(average B, slow)

Millisecond PSR

(low B, very fast, old, recycled by accretion!)



Pulsars flavors and evolution

Young PSR

(high B, fast, very energetic)

Normal PSR

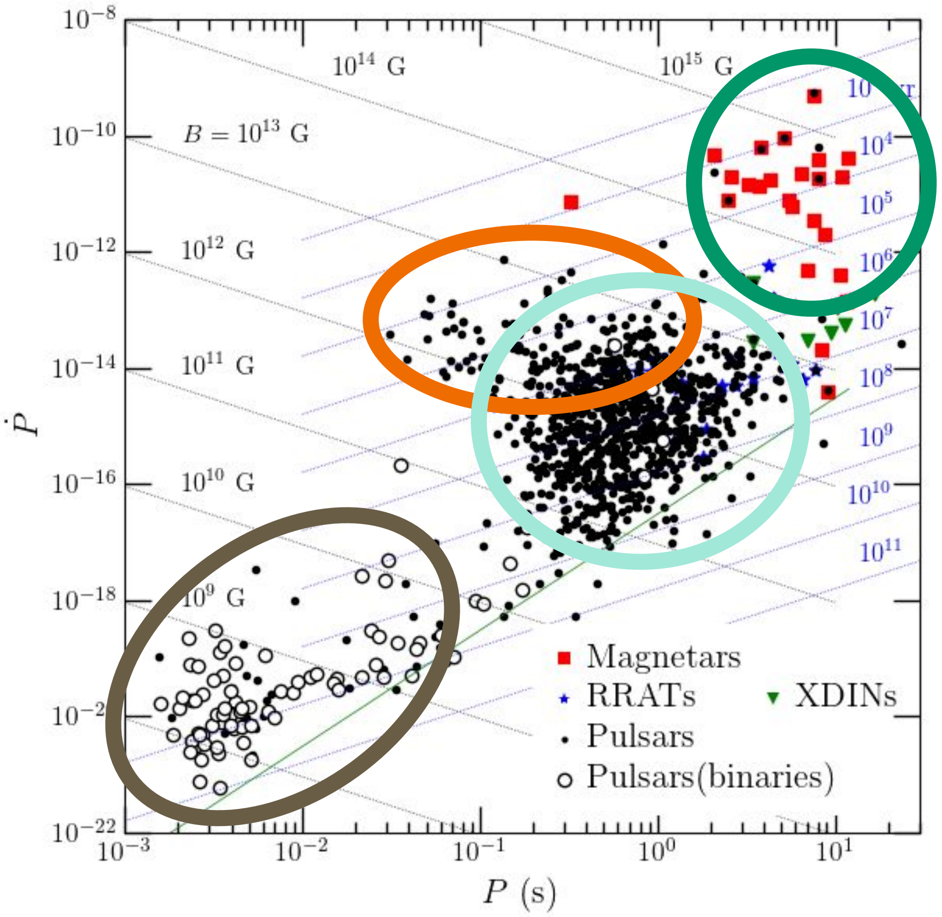
(average B, slow)

Millisecond PSR

(low B, very fast, old, recycled by accretion!)

Magnetars

(extreme B, slow, not powered by rotation!)



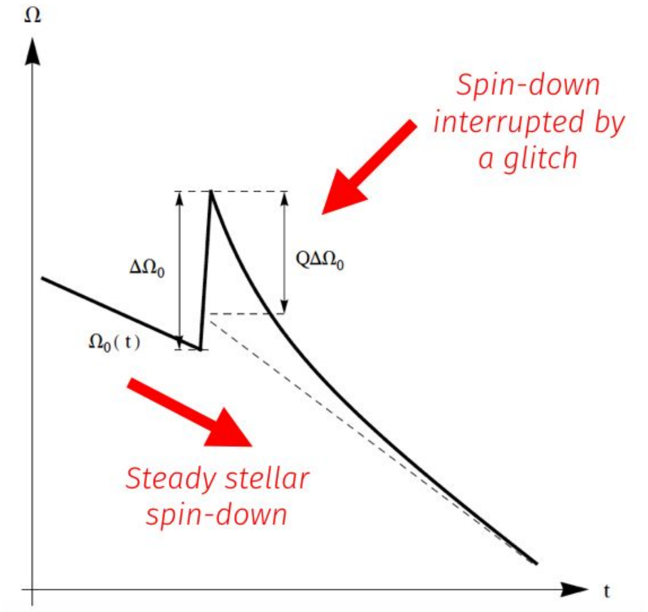
Not everything is so "smooth"

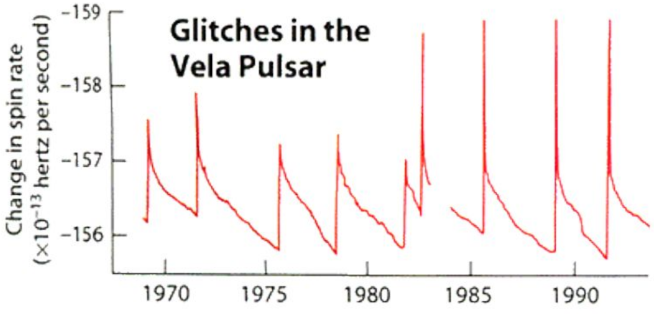
Timing irregularities

Glitches (spin-up events)

719 events in 239 pulsars ~6% of known pulsars

(Zhou et al., 2022)





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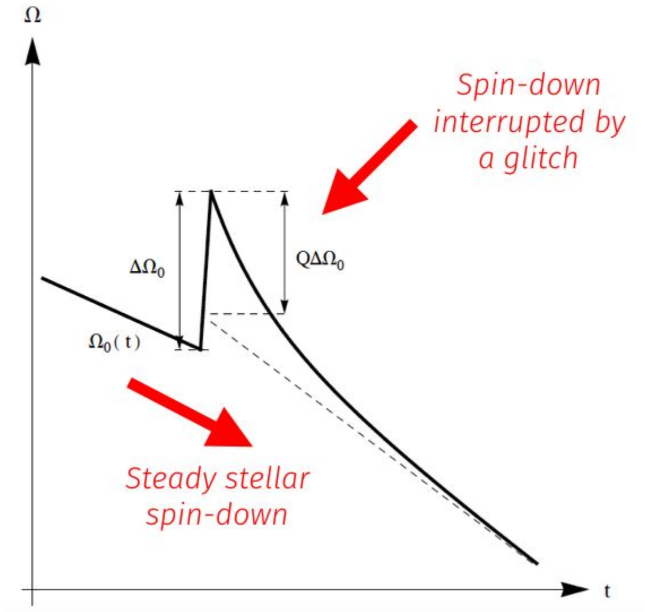
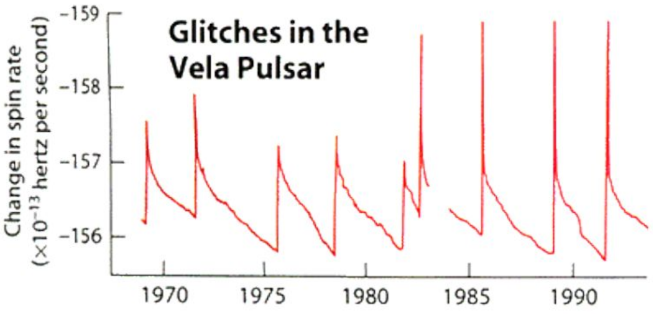




Explanation?

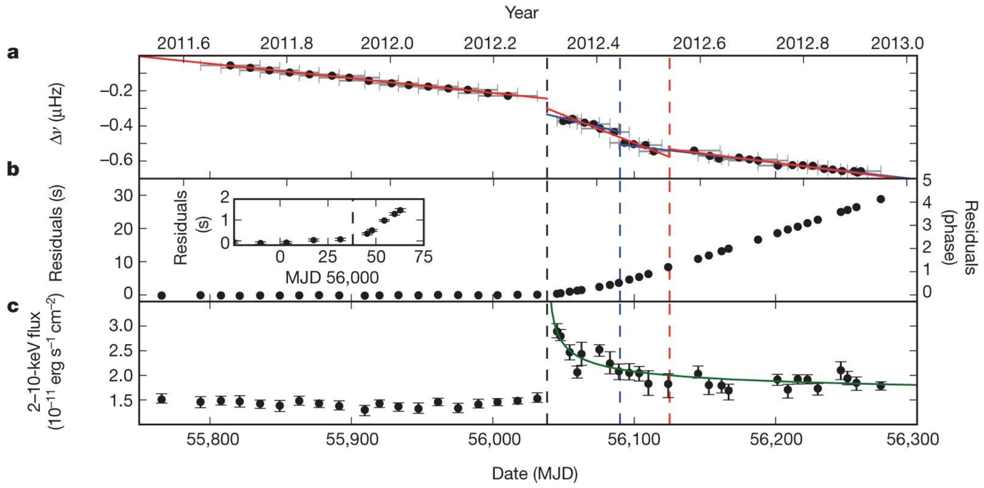
Mainstream idea:
Angular momentum transferred to the crust from superfluid core (Andersson & Itoh, 1975)

Not everything is so “smooth”

Timing irregularities

Anti-glitches (spin-down events)

7 events in 3 magnetars (Zhou et al., 2022)

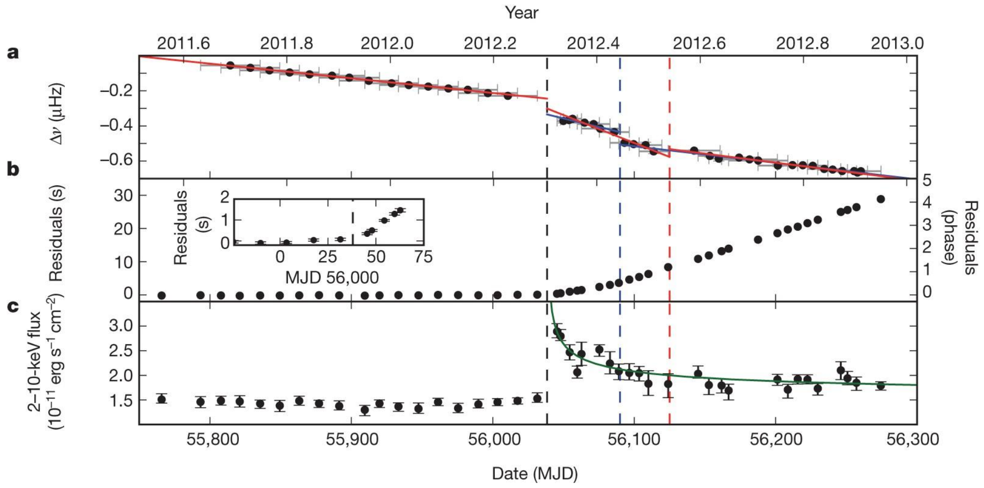


Not everything is so “smooth”

Timing irregularities

Anti-glitches (spin-down events)

7 events in 3 magnetars (Zhou et al., 2022)



Explanation?

Wind braking model (Tong, ApJ 2014)
Starquake after cumulative magnetic field decay (Garcia & Ranea-Sandoval, MNRASL 2015)
Collision with an object (Huang & Geng, ApJL 2014)

No mainstream idea but the we have to rethink the mechanism behind glitching activity

Mass and radii of NSs

Are we able to estimate masses

and radii of these extreme objects?

Mass and radii of NSs

Are we able to estimate masses

and radii of these extreme objects?

This is a major problem in astronomy

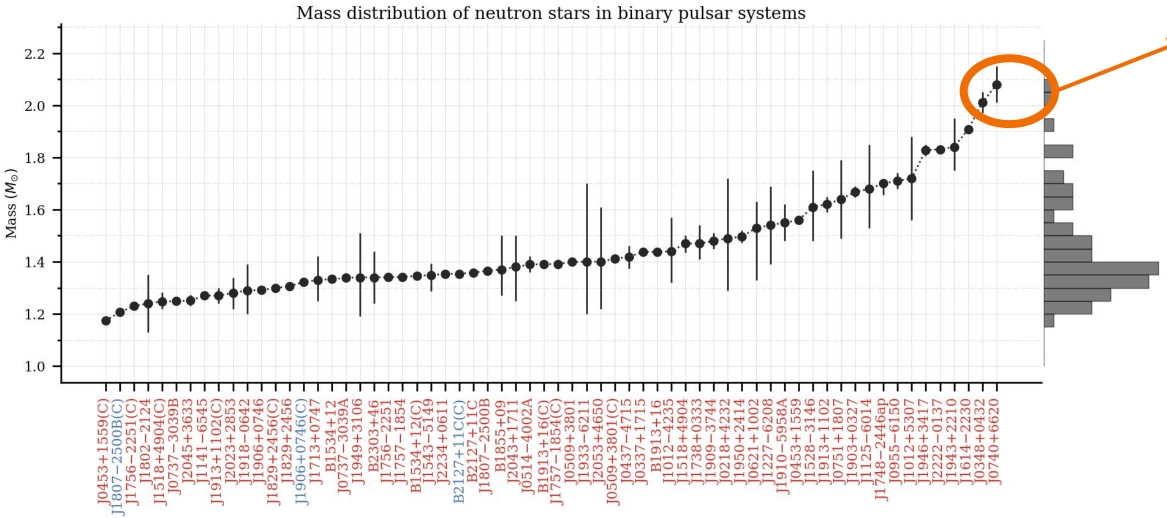
(not only related to compact objects)

This information (we will see later) is of central relevance

to learn about the behavior of matter in the inner depths

of these fascinating objects

How do me know their masses?



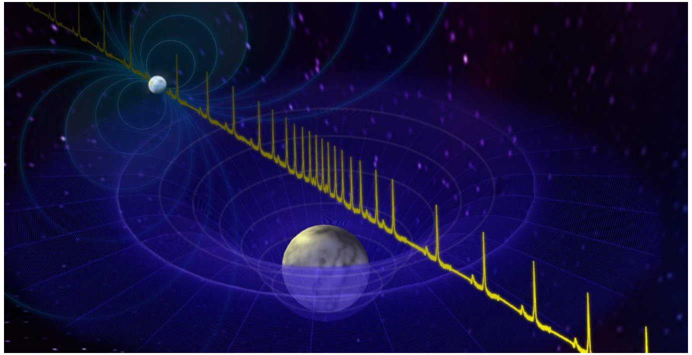
2 Solar mass NSs!!

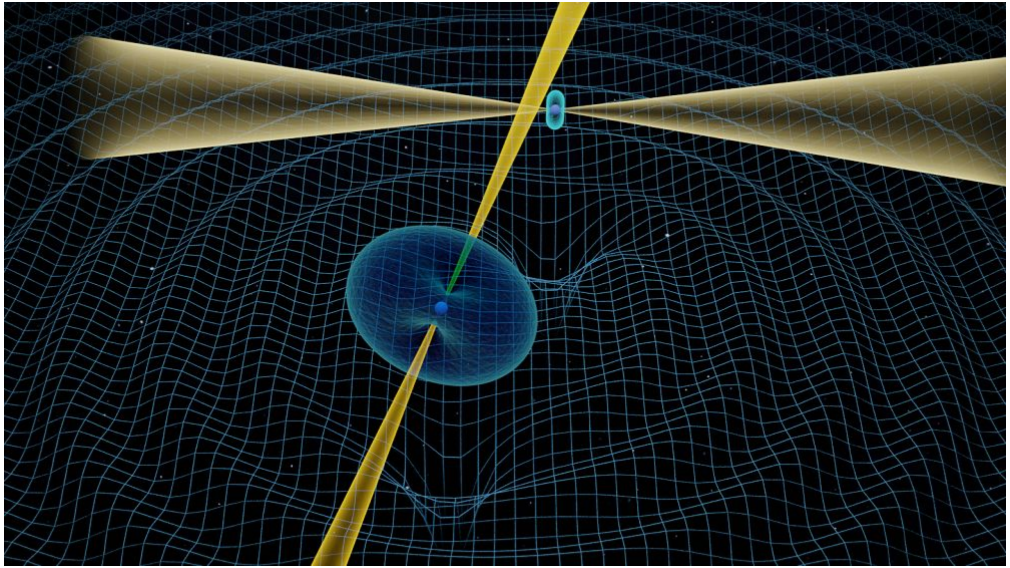
How do we know their masses and radii?

Electromagnetic + General Relativistic effects

Binary Systems of

NS + NS and NS + WD



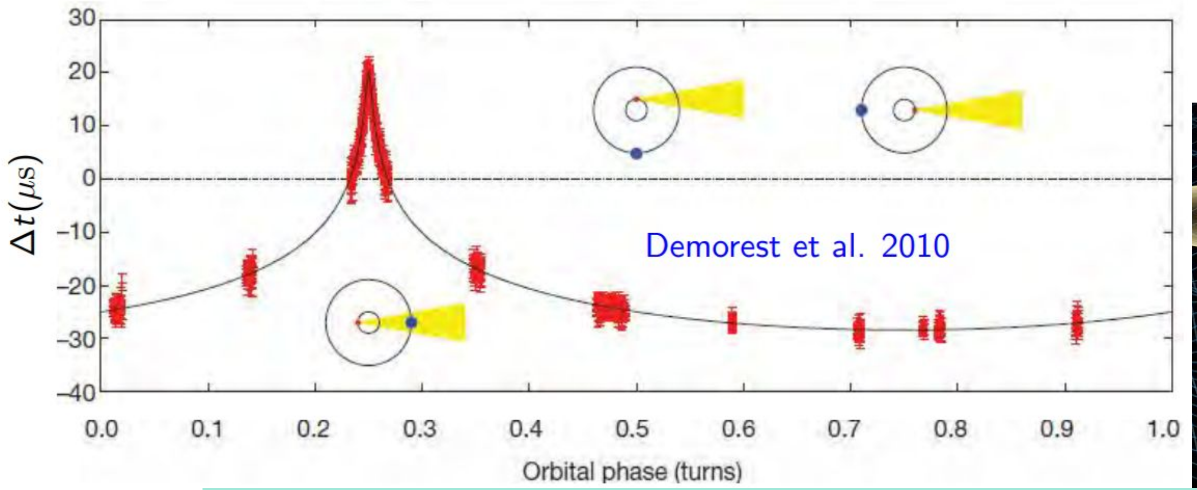


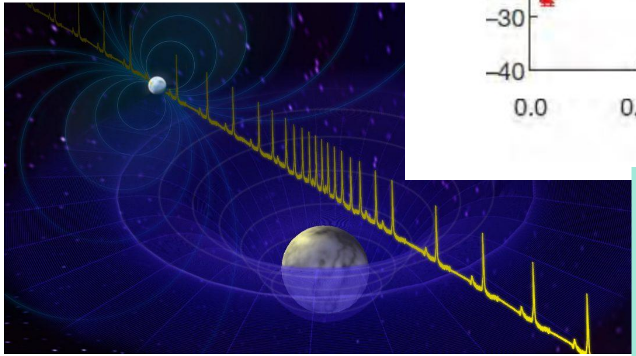
How do we know their masses and radii?

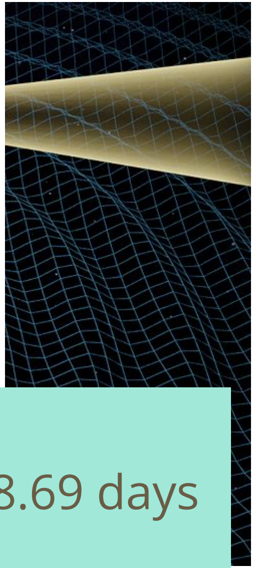
Electromagneti

Binary Systems

NS + NS and NS







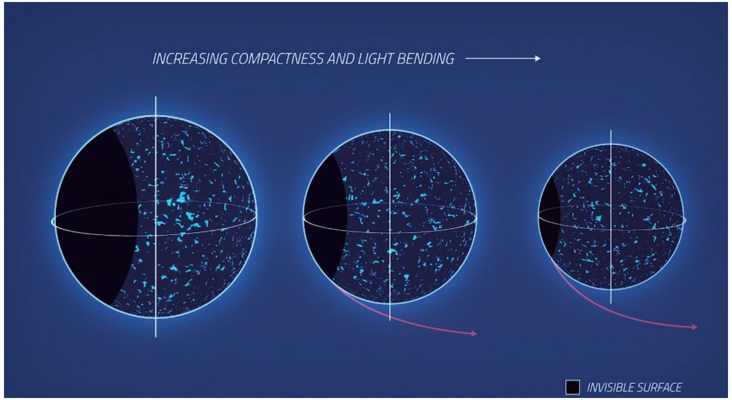
PSR J1614-2230
3.15 ms pulsar orbit half Solar mass WD in 8.69 days
Orbit is highly edge-on sin i = 0.99984
Using Shapiro delay mass can be estimated

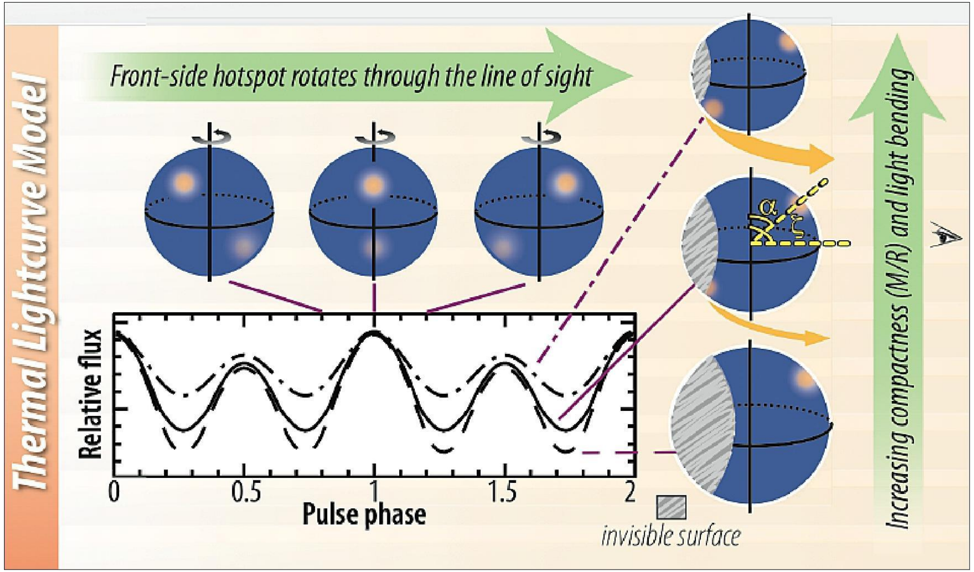
2 Solar mass pulsars

How do we know their masses and radii?

NICER Telescope

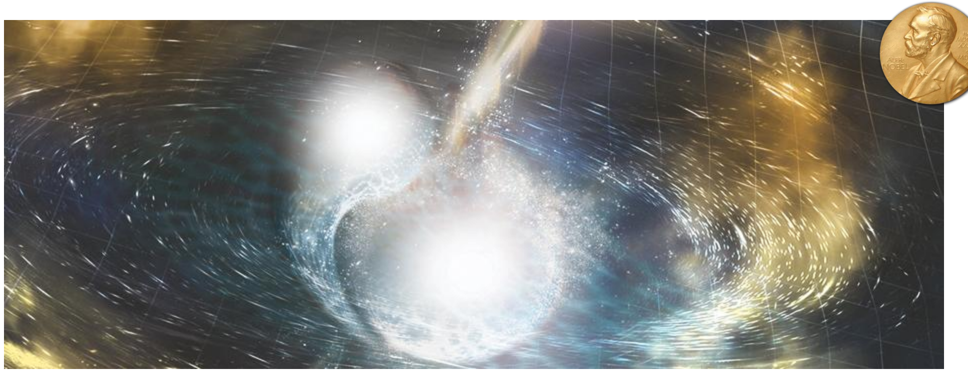
Mass and Radii of ISOLATED NSs!!

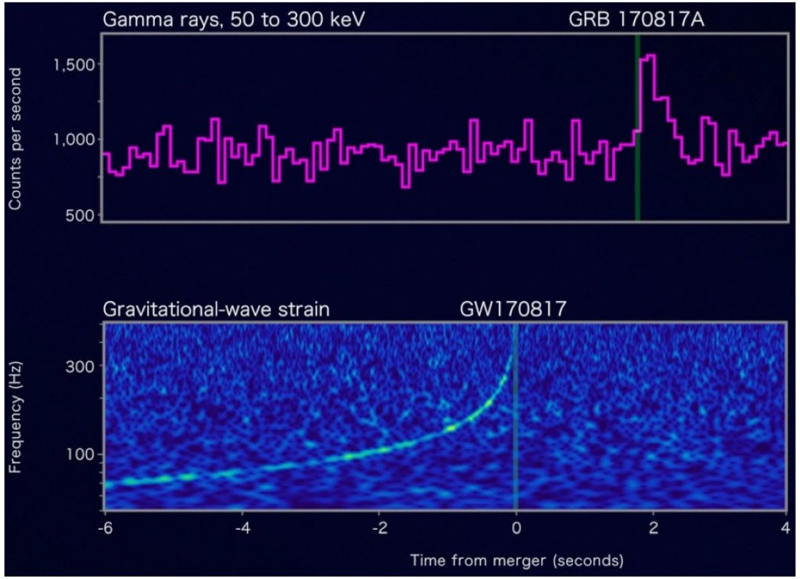




How do we know their masses and radii?

Gravitational waves from NS + NS mergers

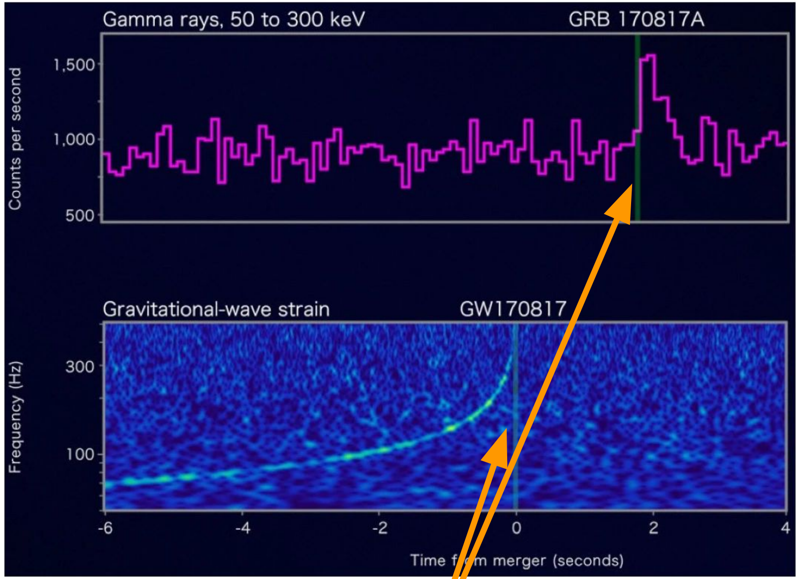




Mass, radius and dimensionless tidal deformability estimated

How do we know their masses and radii?

Gravitational waves from NS + NS mergers

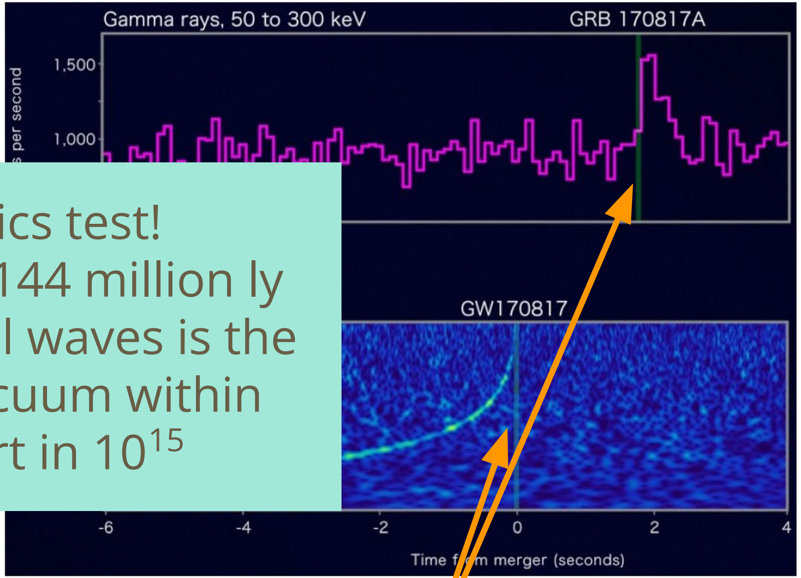


Mass, radius and dimensionless tidal deformability estimated

Link between NS+NS merger and short GRB!!

How do we know their masses and radii?

Gravitational waves from NS + NS mergers

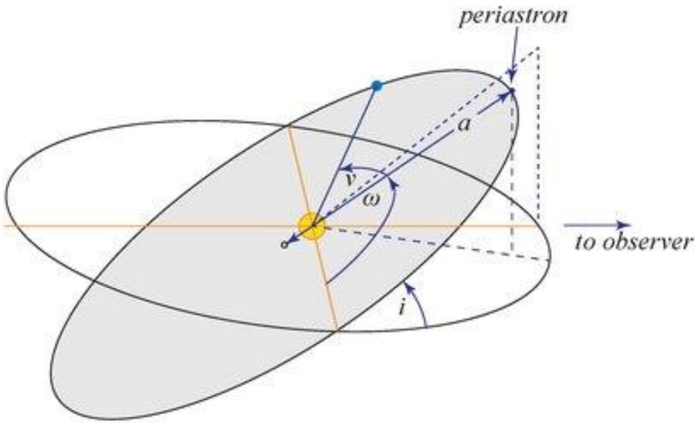


Fundamental physics test!
progenitor is located at 144 million ly
the speed of gravitational waves is the same that of light in vacuum within approximately 1 part in 10^{15}

Mass, radius and dimensionless tidal deformability estimated

Link between NS+NS merger and short GRB!!

How do we know their masses and radii?
A more detailed explanation



The Keplerian parameters

(1) the binary period P_b
(2) the orbital eccentricity e
(3) the projection of the pulsar's semimajor axis a_{psr} onto the observer's line of sight $x_{psr} = a_{psr} \sin(i)/c$ (i angle between the orbital angular momentum and the line of sight)
(4) the time of periastron T_0
(5) the longitude of periastron ω

$$f = \frac{(M_c \sin i)^3}{M_T^2} = \frac{4\pi^2}{T_\odot} \frac{x_{psr}^3}{P_b^2}$$

$GM_\odot/c^3$ ~4.92 microsec

mass of the companion

total mass of the system

How do we know their masses and radii?
A more detailed explanation

Despite the fact that the Keplerian parameters can be measured with high precision we have 3 unknowns and 1 equation

The Kepleria… …ameters

(1) the … …d P_b

(2… …tricity e

… …he pulsar's

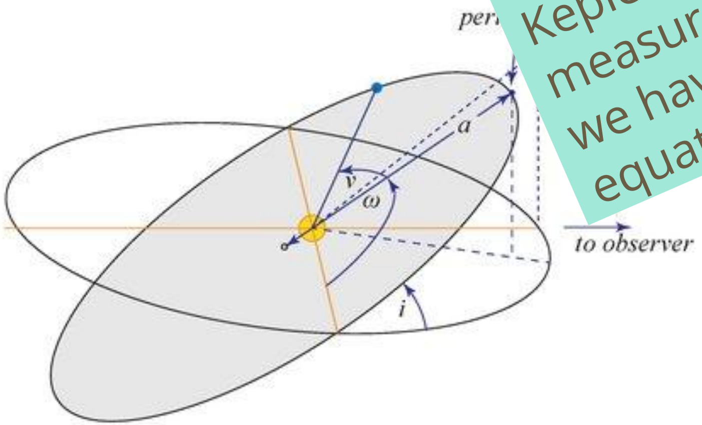
… …to the observer's

… a_{psr} sin(i)/c (i angle between

… …gular momentum and the line of sight)

… …time of periastron T_0

(5) the longitude of periastron ω



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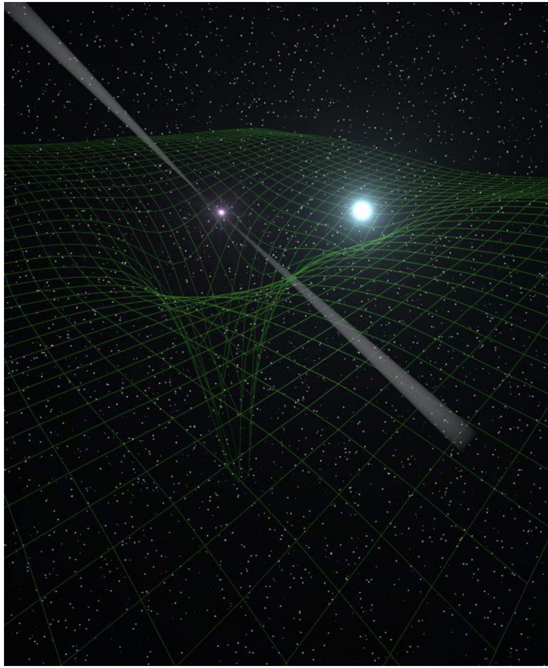
total mass of the system

How do we know their masses and radii?

If the companion (c) is also a pulsar or it is a white dwarf or a main sequence star, one could know both orbits

through timing
via optical spectroscopy

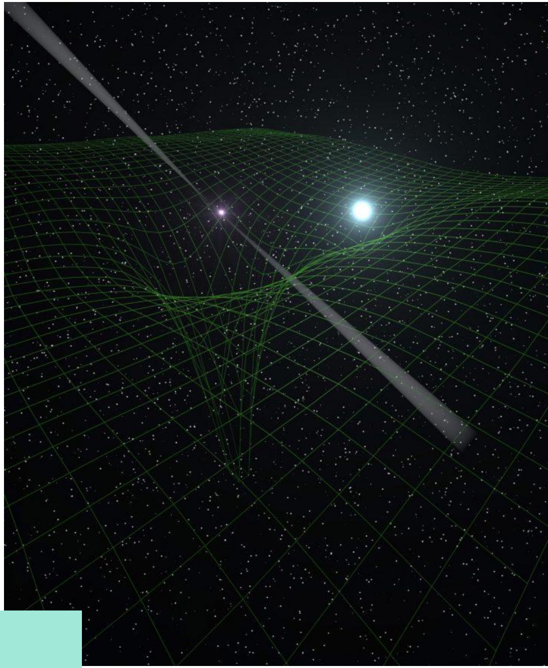


Not easy and is done in a small quantity of binary systems.

How do we know their masses and radii?

If the companion is also a pulsar or it is a white dwarf or a main sequence star, x_c can be measured

via timing
via optical spectroscopy



If in addition the mass of the white dwarf companion can be estimated from its optical spectrum, the mass of the pulsar can be obtained!

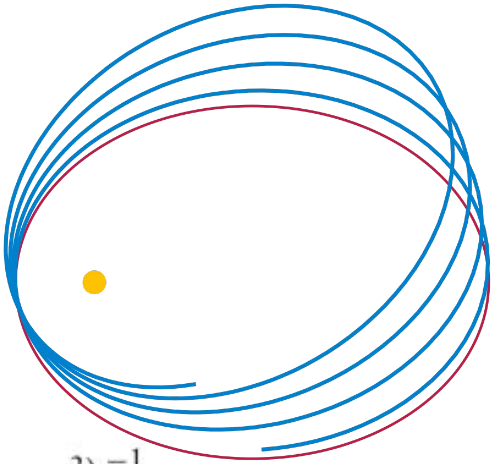
is done in
ity of
s.

How do we know their masses and radii?

Post-Keplerian parameters

In the relativistic environment of close binaries, (small) relativistic effects can be observed in the dynamics of the orbital motion

How do we know their masses and radii?



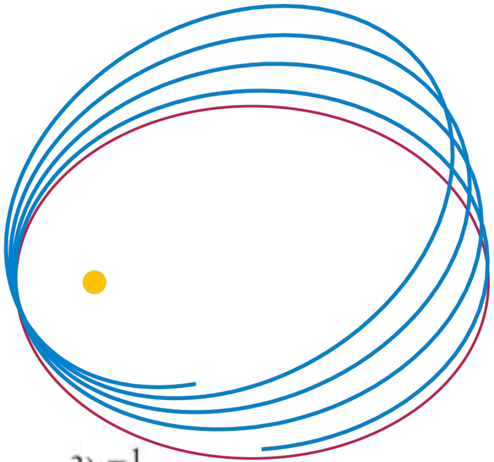
Post-Keplerian parameters

In the relativistic environment of close binaries, (small) relativistic effects can be observed in the dynamics of the orbital motion

$$\dot{\omega} = 3 \left(\frac{P_{\mathrm{b}}}{2\pi} \right)^{-5/3} (T_{\odot} M_{\mathrm{T}})^{2/3} \left(1 - e^2\right)^{-1} .$$

Advance of the periastron

How do we know their masses and radii?



Post-Keplerian parameters

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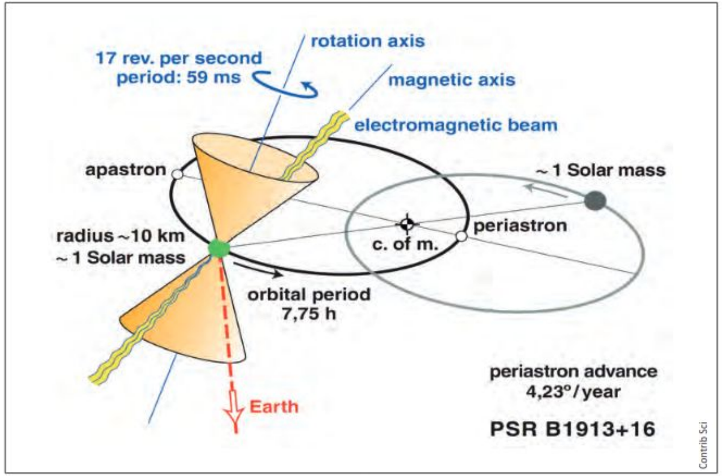
$$\dot{\omega} = 3\left(\frac{P_{\mathrm{b}}}{2\pi}\right)^{-5/3} (T_{\odot} M_{\mathrm{T}})^{2/3} (1 - e^2)^{-1} .$$

Rate of advance of periastron:

For PSR 1913+16 $\Longrightarrow$ $\dot{\omega}$ = 4.2 deg/year (10^5 larger than for mercury).

For PSR J0737-3039 $\Longrightarrow$ $\dot{\omega}$ =16.88 deg/year



How do we know their masses and radii?

In the relativistic environment of close binaries, (small) relativistic effects can be observed in the dynamics of the orbital motion

$$\gamma = e\left(\frac{P_b}{2\pi}\right)^{1/3} T_\odot^{2/3} M_T^{-4/3} M_c \left(M_{psr} + 2M_c\right).$$

Einstein delay comes from considering gravitational redshift and time dilation in an eccentric orbit

How do we know their masses and radii?

In the relativistic environment of close binaries, (small) relativistic effects can be observed in the dynamics of the orbital motion

$$\gamma = e \left(\frac{P_b}{2\pi} \right)^{1/3} T_\odot^{2/3} M_T^{-4/3} M_c \left(M_{psr} + 2M_c \right) .$$

$$\dot{P}_b = -\frac{192\pi}{5} \left(\frac{P_b}{2\pi T_\odot} \right)^{-5/3} \left(1 + \frac{73}{24} e^2 + \frac{37}{96} e^4 \right) \times (1 - e^2)^{-7/2} M_{psr} M_c M_T^{-1/3} .$$

Orbital decay due to energy loss from gravitational wave emission

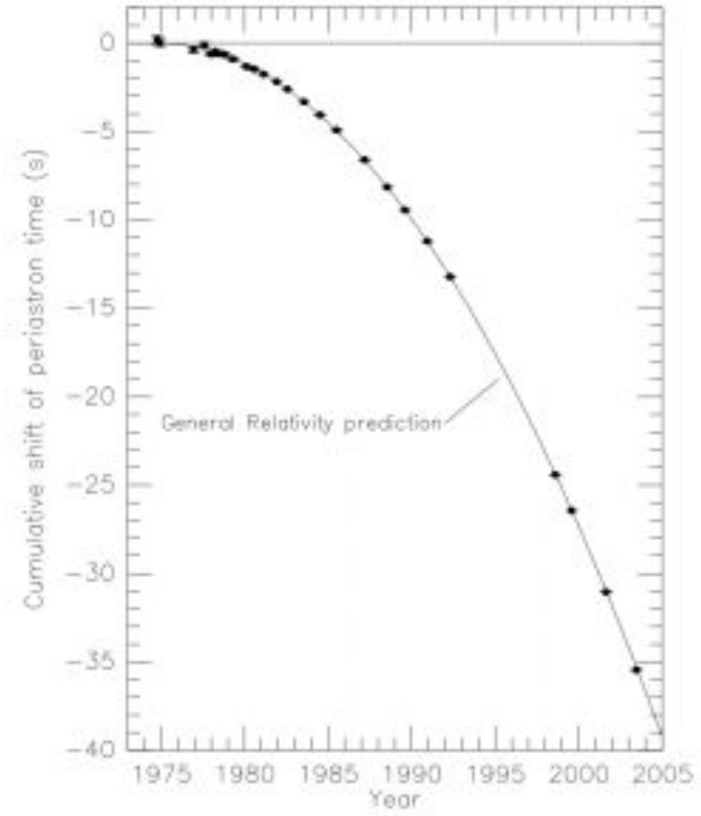
Indirect measurement of gravitational waves!

$$\dot{P}_{\mathrm{b}} = -\frac{192\pi}{5}\left(\frac{P_{\mathrm{b}}}{2\pi T_{\odot}}\right)^{-5/3}\left(1+\frac{73}{24}e^{2}+\frac{37}{96}e^{4}\right)\times(1-e^{2})^{-7/2}\,M_{\mathrm{psr}}M_{\mathrm{c}}M_{\mathrm{T}}^{-1/3}.$$

Hulse and Taylor discovered first pulsar in a binary system in 1975.

Taylor and Weisberg (1982) presented strong evidence of gravitational waves carrying away energy and producing an increase in the period just as the one predicted by General Relativity.

NSs testing fundamental physics



How do we know their masses and radii?

In the relativistic environment of close binaries, (small) relativistic effects can be observed in the dynamics of the orbital motion

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$$\Delta t = -2 M_c T_\odot \ln[1 - \sin i \sin(\Phi - \Phi_0)]$$

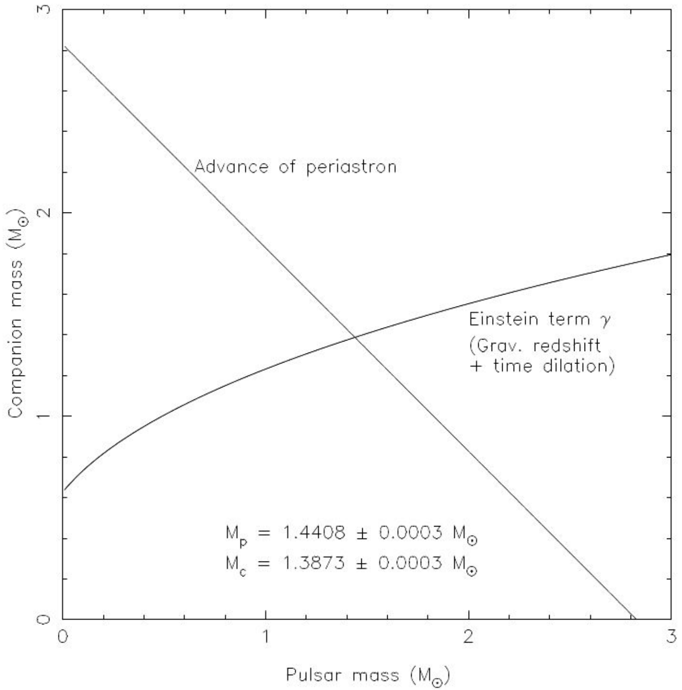
"range" $r = M_c T_\odot$ and the "shape" $s = \sin i$

Φ is the orbital phase in radians, Φ_0 is the phase of the ascending node

Shapiro delay of the reception of radio pulses due to light propagating in curved spacetime of the companion star

How do we know their masses and radii?

An example
PSR B1913+16

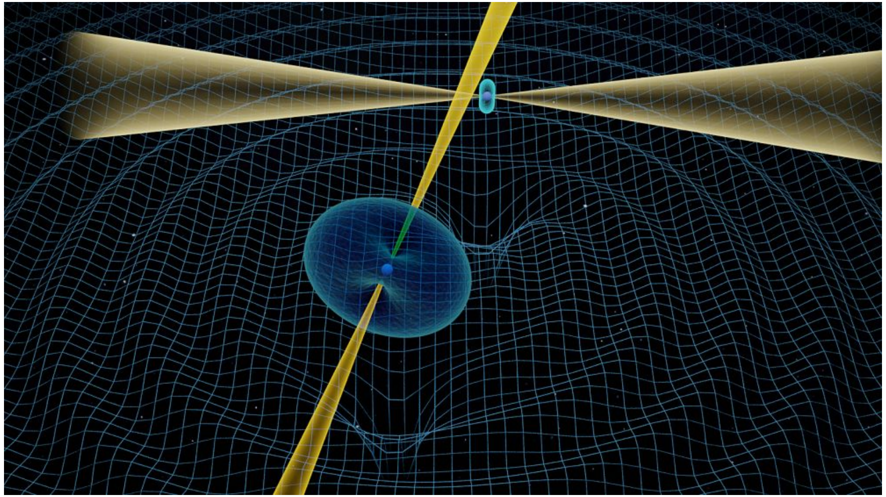


Parameter	Value
Orbital period P_b (d)	0.322997462727(5)
Projected semi-major axis x (s)	2.341774(1)
Eccentricity e	0.6171338(4)
Longitude of periastron ω (deg)	226.57518(4)
Epoch of periastron T_0 (MJD)	46443.99588317(3)
Advance of periastron $\dot{\omega}$ (deg yr^{-1})	4.226607(7)
Gravitational redshift γ (ms)	4.294(1)
Orbital period derivative $(\dot{P}_b)^{obs}$ (10^{-12})	−2.4211(14)

From Weisberg and Taylor 2002
https://iopscience.iop.org/article/10.1086/341803

How do we know their masses and radii?

An example
J0737-3039 double pulsar
the holy grail

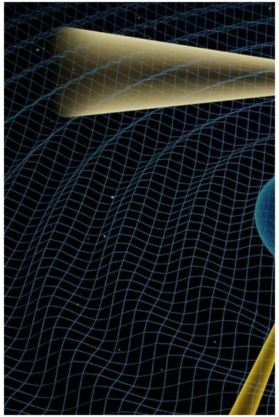


From Kramer et al. 2021

Parameter	Value
Right ascension (R.A.), α (J2000)	$07^{h}37^{m}51^{s}.248115(10)$[a]
Declination (Dec), δ (J2000)	$-30°39'40''.70485(17)$[a]
Proper motion R.A., μ_α (mas yr^{-1})	$-2.567(30)$[a]
Proper motion Dec., μ_δ (mas yr^{-1})	$2.082(38)$[a]
Parallax, π_c (mas)	$1.36(+0.12, -0.10)$[a]
Position epoch (MJD)	55045.0000
Rotational frequency (freq.), ν (Hz)	44.054 068 641 962 81(17)[b]
First freq. derivative, $\dot{\nu}$ (Hz s^{-1})	$-3.4158071(11) \times 10^{-15}$[b]
Second freq. derivative, $\ddot{\nu}$ (Hz s^{-2})	$-2.286(29) \times 10^{-27}$[b]
Third freq. derivative, $\dddot{\nu}$ (Hz s^{-3})	$1.28(26) \times 10^{-36}$[b]
Fourth freq. derivative, $\overline{\nu}$ (Hz s^{-4})	$4.580(86) \times 10^{-43}$ [b]
Timing epoch, t_0 (MJD)	55700.0
Profile evolution, FD parameter c_1	0.0000180(75)
Profile evolution, FD parameter c_2	−0.0001034(10)
Profile evolution, FD parameter c_3	0.0000474(26)
Dispersion measure, DM (pc cm^{-3})	48.917 208
Orbital period, P_b (day)	0.102 251 559 297 3(10)
Projected semimajor axis, x (s)	1.415 028 603(92)
Eccentricity (Kepler equation), e_T	0.087 777 023(61)
Epoch of periastron, T_0 (MJD)	55 700.233 017 540(13)
Longitude of periastron, ω_0 (deg)	204.753 686(47)
Periastron advance, $\dot{\omega}$ (deg yr^{-1}) [c]	16.899 323(13)
Change of orbital period, $\dot{P}_b$	$-1.247920(78) \times 10^{-12}$
Einstein delay amplitude, γ_E (ms)	0.384 045(94)
Logarithmic Shapiro shape, z_s	9.65(15)
Range of Shapiro delay, r (μs)	6.162(21)
NLO factor for signal prop., q_{NLO}	1.15(13)
Relativistic deformation of orbit, δ_θ	$13(13) \times 10^{-6}$
Change of proj. semimajor axis, $\dot{x}$	$8(7) \times 10^{-16}$
Change of eccentricity, $\dot{e}_T$ (s^{-1})	$3(6) \times 10^{-16}$
Derived parameters	
$\sin i = 1 - \exp(-z_s)$	$0.999936(+9/-10)$
Orbital inclination, i (deg)	89.35(5) or 90.65(5)
Total mass, M ($M_\odot$)[d]	$2.587052(+9/-7)$
Mass of pulsar A, m_A ($M_\odot$)[d]	$1.338185(+12/-14)$
Mass of pulsar B, m_B ($M_\odot$)[d]	$1.248868(+13/-11)$
Galactic longitude, l (deg)	245.2357
Galactic latitude, b (deg)	−4.5049
Proper motion in l, μ_l (mas yr^{-1})	−3.066(35)
Proper motion in b, μ_b (mas yr^{-1})	−1.233(31)
Distance from π_c, d (pc)	735(60)
Transverse velocity, v_T (km s^{-1})	11.5(10)

How do we know th

An example
J0737-3039 double pulsar
the holy grail



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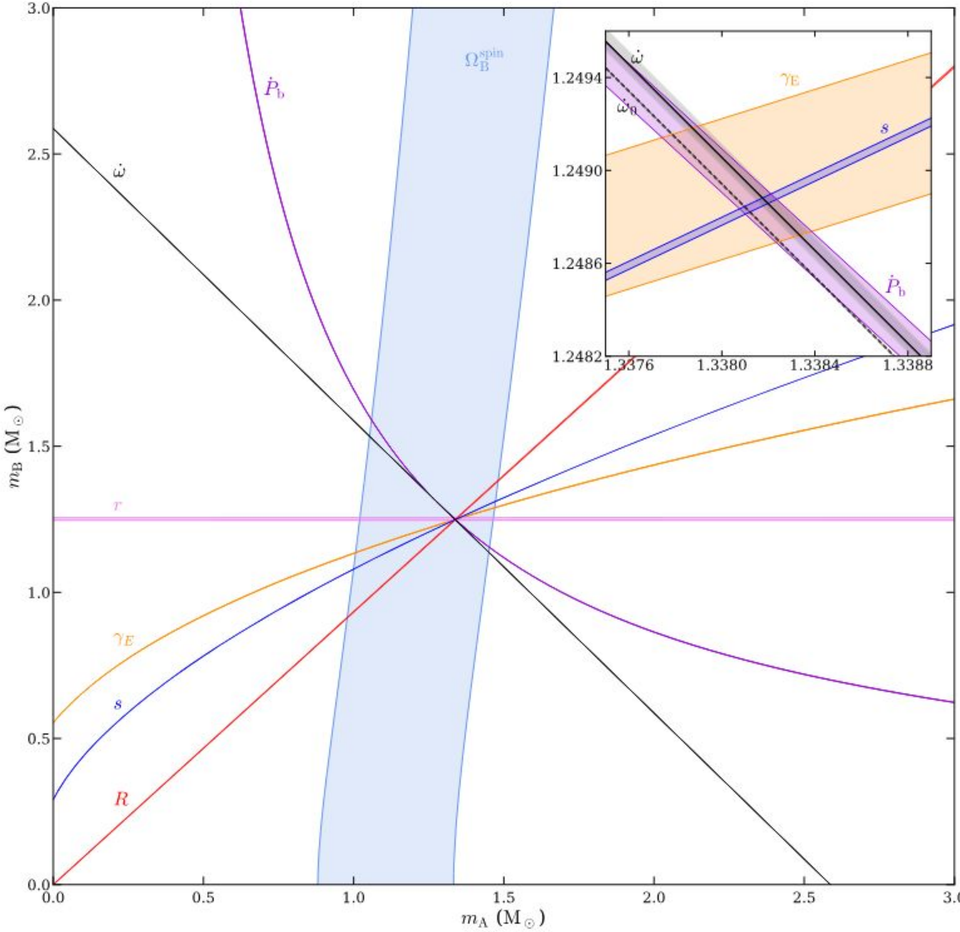
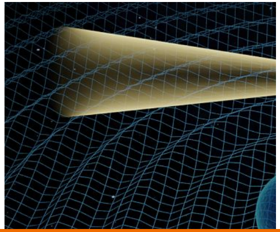


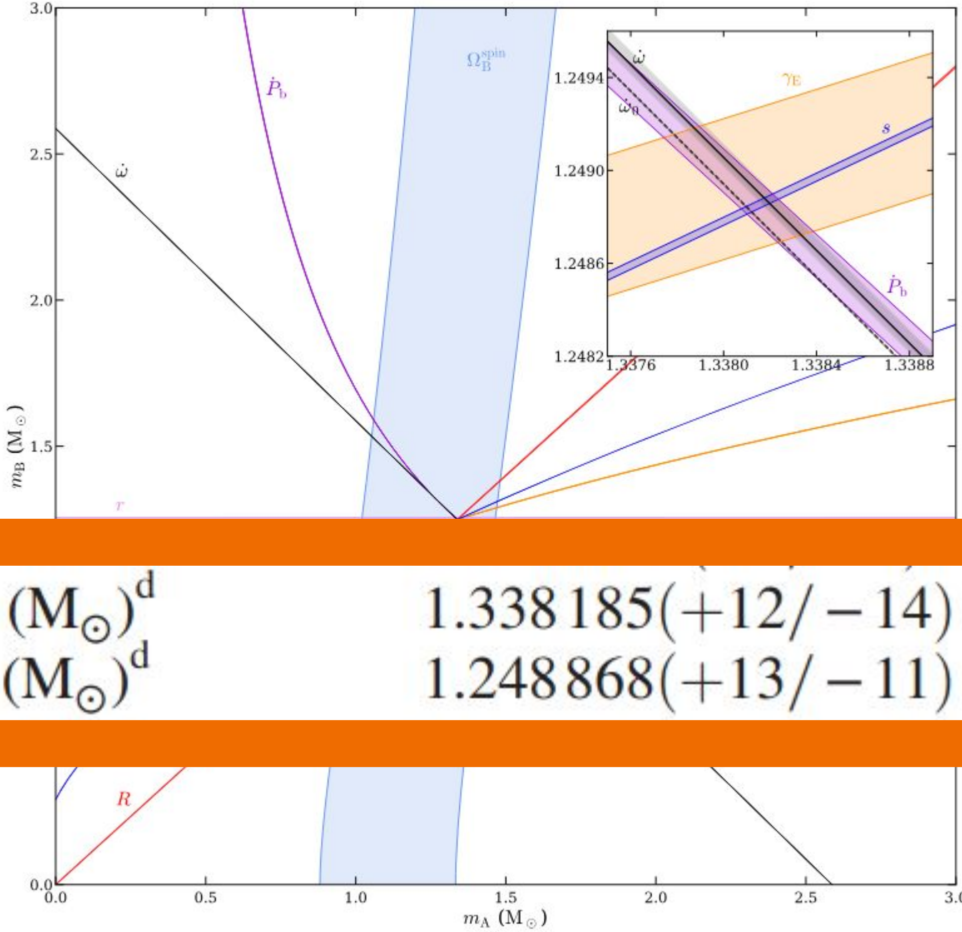
TABLE IV. Timing parameters for PSR J0737–3039A in TDB units (see the text). Except for astrometry and DM, the parameters are derived using Tempo with the 30-s TOA dataset. Numbers in parentheses are 1σ uncertainties referred to the last quoted digit.

Value
ᵐ51ˢ248115(10)[a]
9′40″70485(17)[a]
-2.567(30)[a]
2.082(38)[a]
(+0.12, −0.10)[a]
55045.0000
68 641 962 81(17)[b]
8071(11) × 10⁻¹⁵[b]
86(29) × 10⁻²⁷[b]
3(26) × 10⁻³⁶[b]
0(86) × 10⁻⁴³ [b]
55700.0
0000180(75)
.0001034(10)
0000474(26)
48.917 208
251 559 297 3(10)
5 028 603(92)
37 777 023(61)
.233 017 540(13)
4.753 686(47)
.899 323(13)
7920(78) × 10⁻¹²
384 045(94)
9.65(15)
6.162(21)
1.15(13)
3(13) × 10⁻⁶
5(7) × 10⁻¹⁶
5(6) × 10⁻¹⁶
9936(+9/−10)
5(5) or 90.65(5)
7052(+9/−7)
185(+12/−14)
868(+13/−11)
245.2357
−4.5049
-3.066(35)
-1.233(31)
735(60)
11.5(10)

How do we know th

An example
J0737-3039 double pulsar
the holy grail





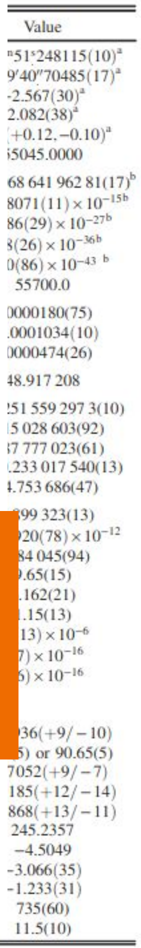


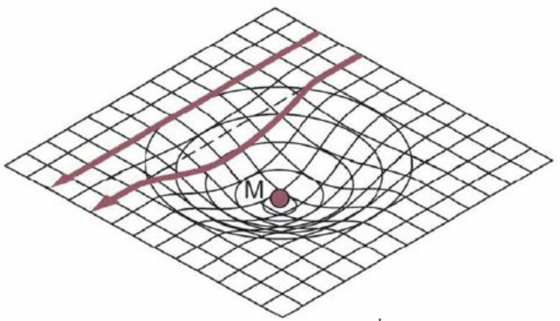
TABLE IV. Timing parameters for PSR J0737–3039A in TDB units (see the text). Except for astrometry and DM, the parameters are derived using Tempo with the 30-s TOA dataset. Numbers in parentheses are 1σ uncertainties referred to the last quoted digit.

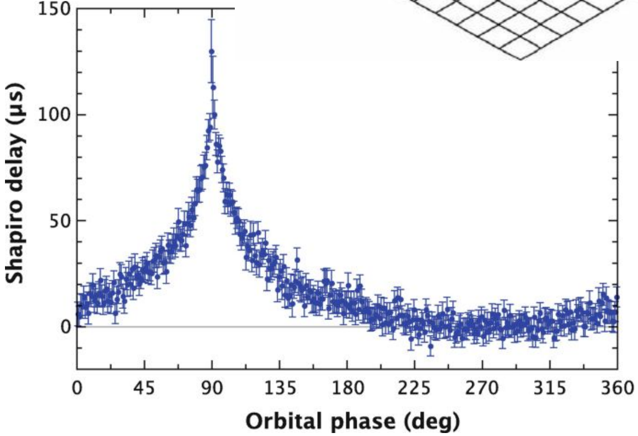
Mass of pulsar A, m_A ($M_\odot$)[d]	1.338 185(+12/ − 14)
Mass of pulsar B, m_B ($M_\odot$)[d]	1.248 868(+13/ − 11)

Fr

How do we know their masses and radii?

Shapiro delay
~2 Solar mass pulsar





Letter | Published: 27 October 2010

A two-solar-mass neutron star measured using Shapiro delay

P. B. Demorest, T. Pennucci, S. M. Ransom, M. S. E. Roberts & J. W. T. Hessels

Nature **467**, 1081–1083 (2010) | Cite this article

9878 Accesses | **3075** Citations | **65** Altmetric | Metrics

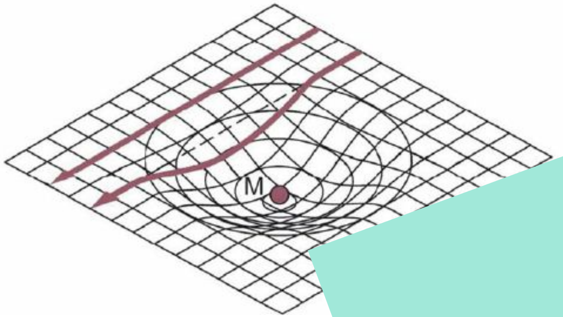
A Massive Pulsar in a Compact Relativistic Binary

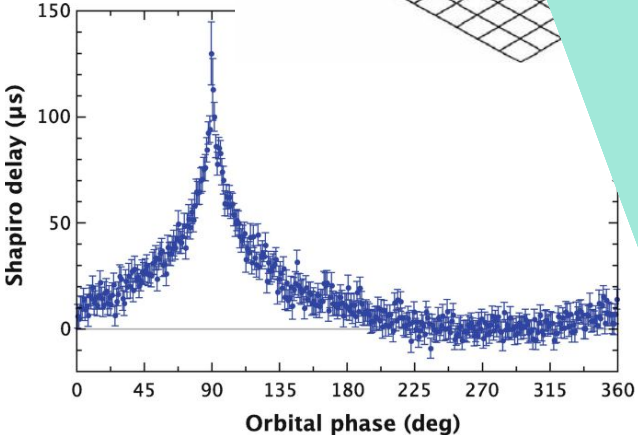
JOHN ANTONIADIS, PAULO C. C. FREIRE, NORBERT WEX, THOMAS M. TAURIS, RYAN S. LYNCH, MARTEN H. VAN KERKWIJK, MICHAEL KRAMER, CEES BASSA, VIK S. DHILLON, [...] , AND DAVID G. WHELAN +12 authors Authors Info & Affiliations

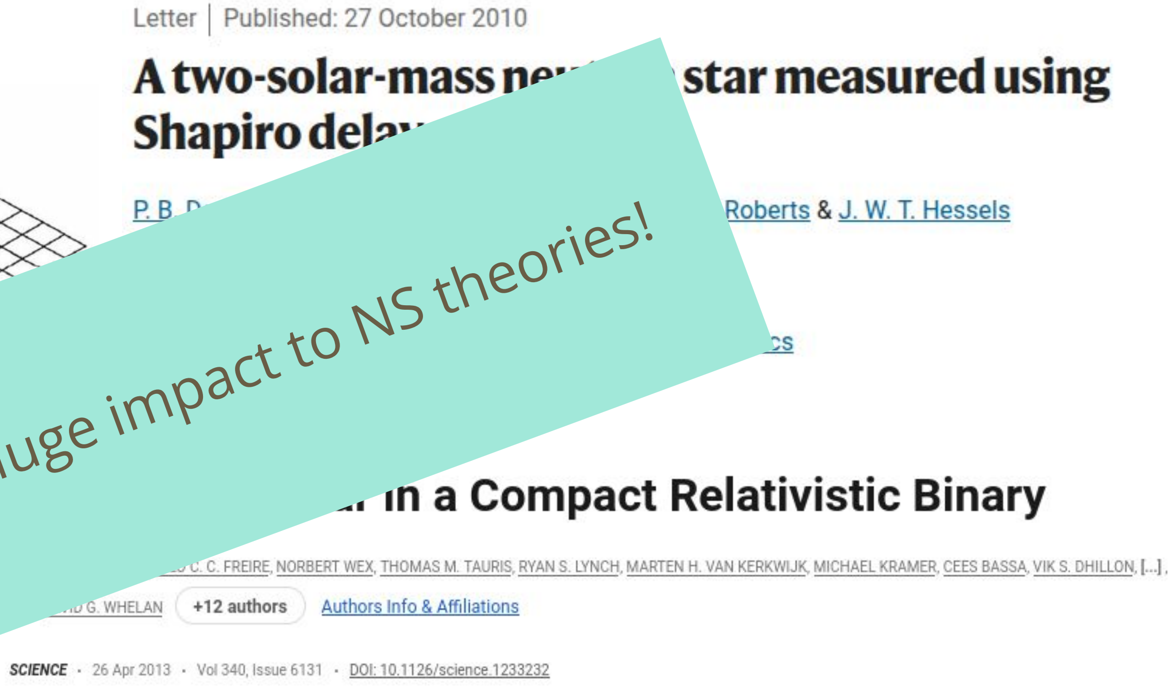
SCIENCE · 26 Apr 2013 · Vol 340, Issue 6131 · DOI: 10.1126/science.1233232

How do we know their masses and radii?

Shapiro delay
~2 Solar mass pulsar





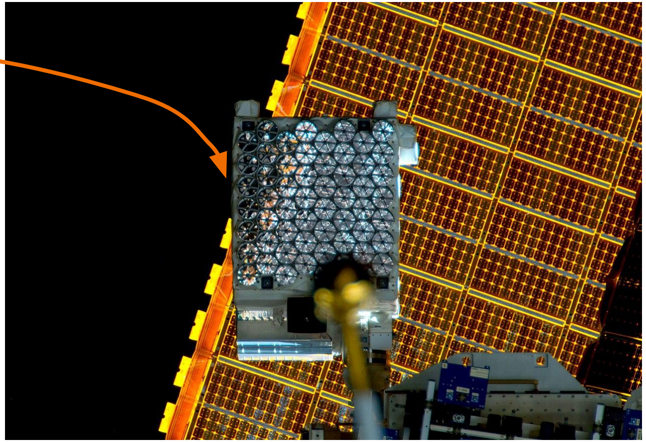


Huge impact to NS theories!

How do we know their masses and radii?

A NICER view

The Neutron star Interior Composition ExploreR is an X-Ray telescope mounted on the International Space Station



How do we know their masses and radii?

A NICER view

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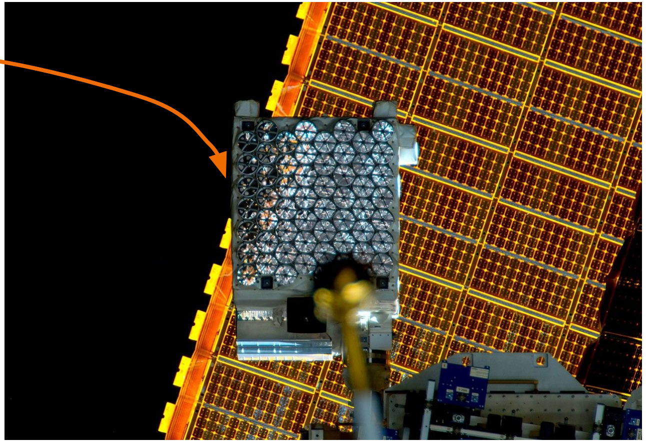
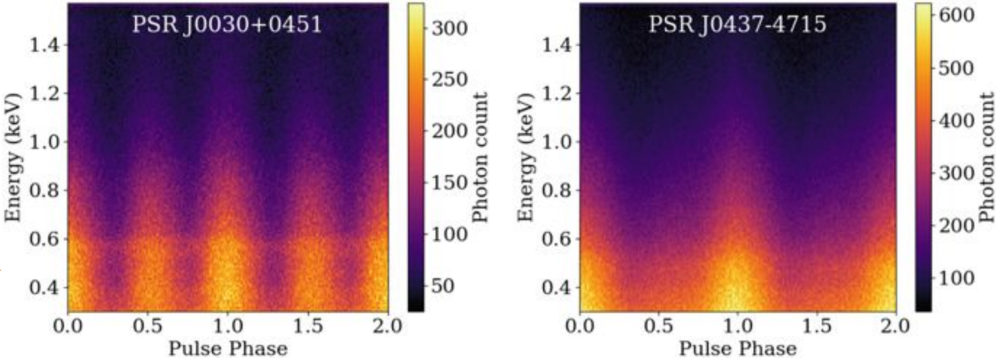


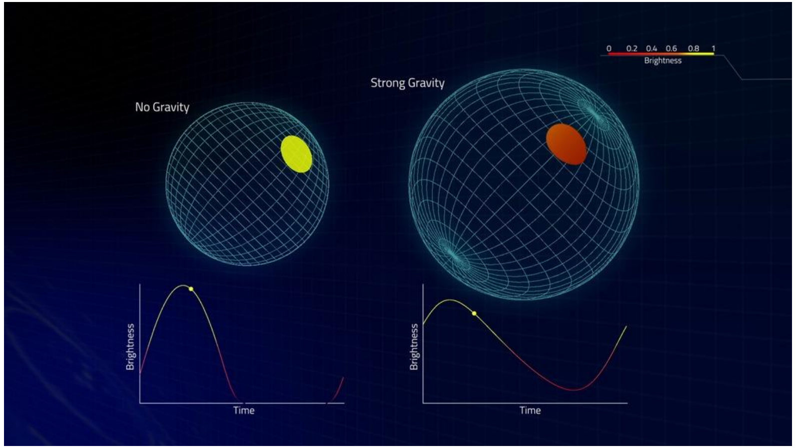
Dedicated to study NSs light curves to estimate mass, radius and other relevant features of these intriguing objects

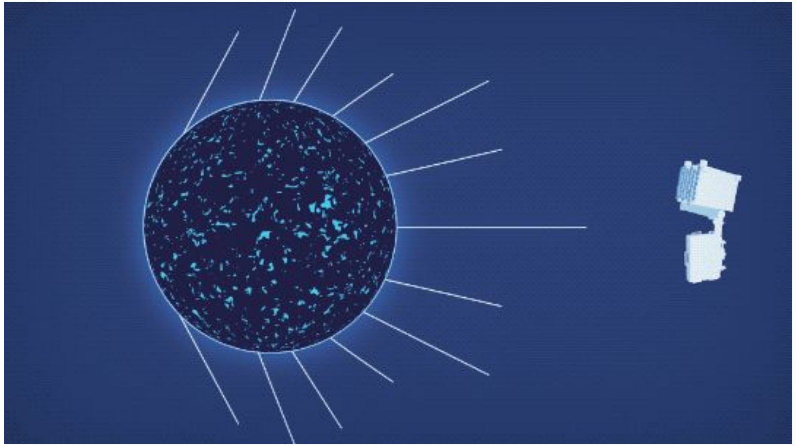


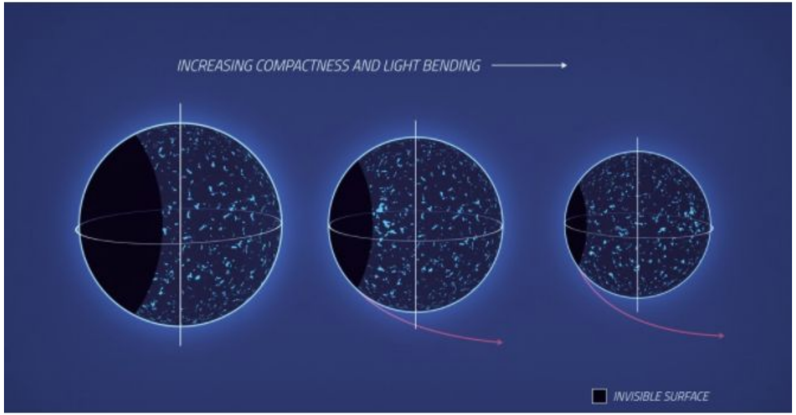
How do we know their masses and radii?

A NICER view

It works using GR effects such as light bending and gravitational redshift



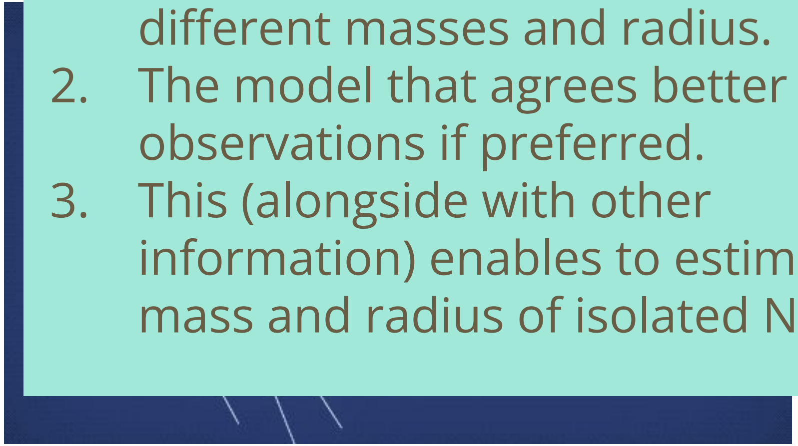


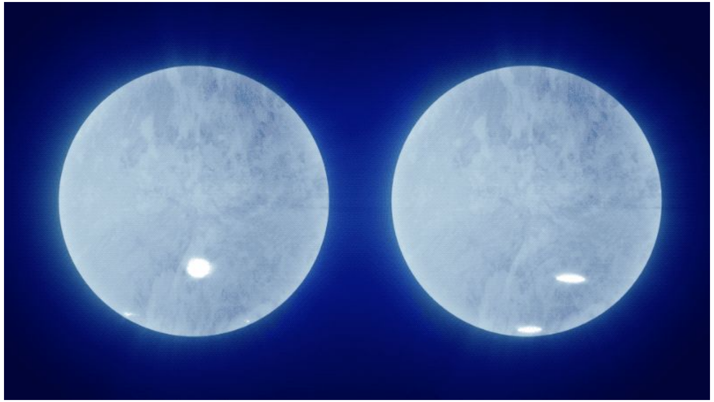


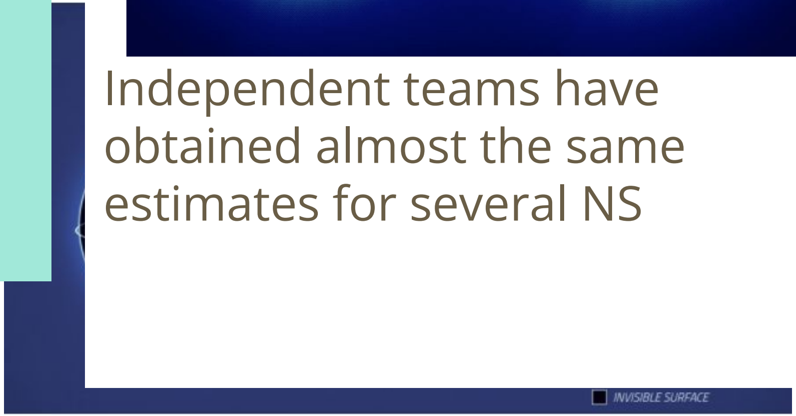
How do we know their masses and radii?

A NICER view

1. The observed light curve is compared to different synthetic models of number and shapes of hot spots in the surface of NSs of different masses and radius.
2. The model that agrees better with observations if preferred.
3. This (alongside with other information) enables to estimate mass and radius of isolated NSs.





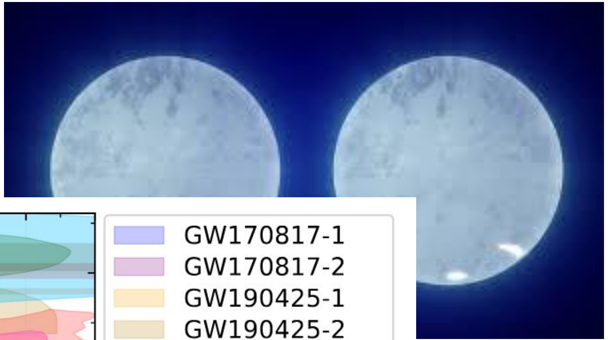


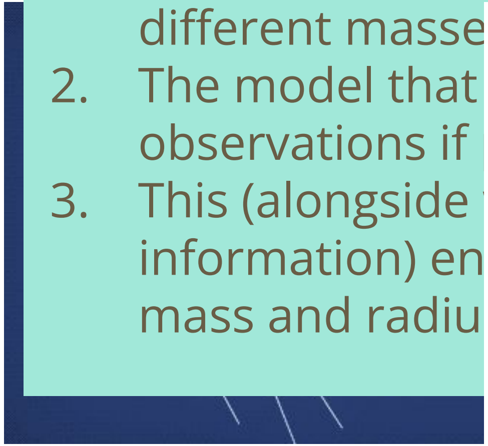
Independent teams have obtained almost the same estimates for several NS

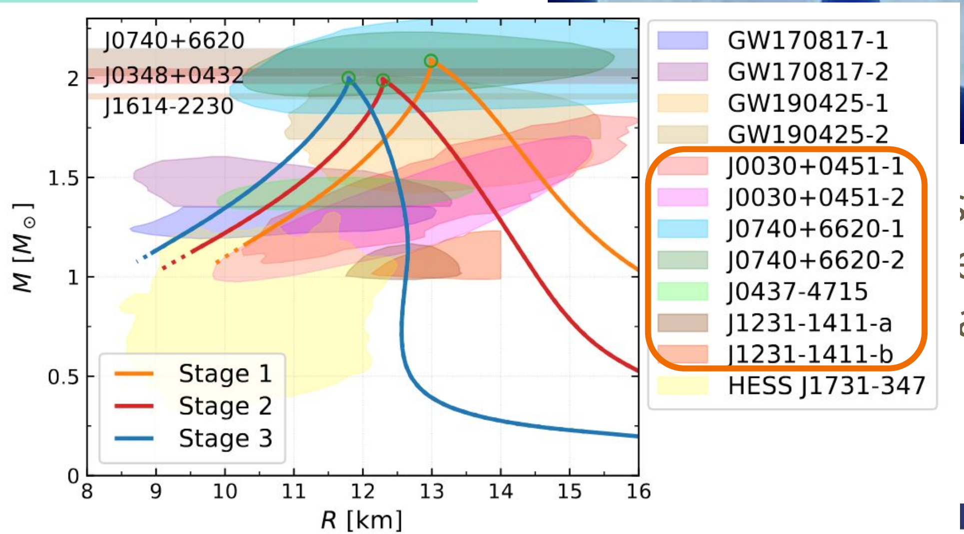
How do we know their masses and radii?

A NICER view

1. The observed light curve is compared to different synthetic models of number and shapes of hot spots in the surface of NSs of different masse
2. The model that observations if
3. This (alongside information) en mass and radiu







; have
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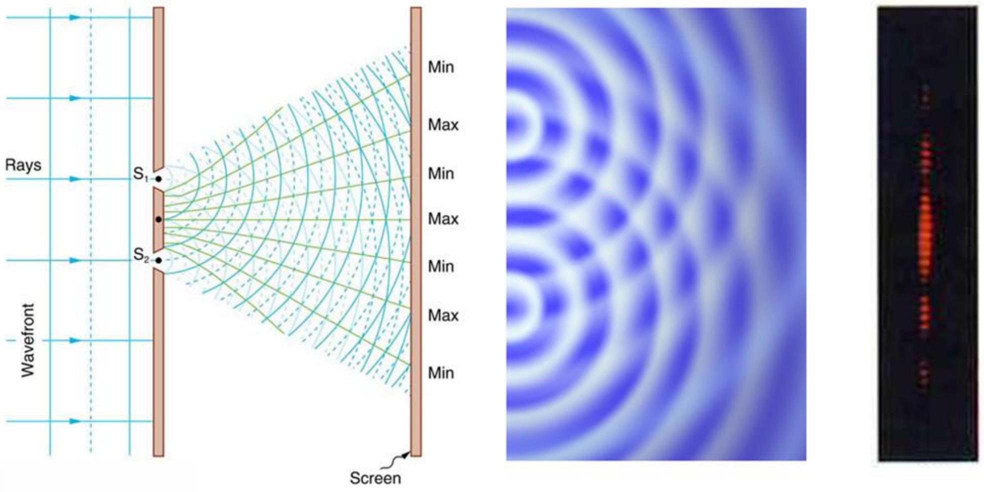
Why do we want to know their masses and radii?

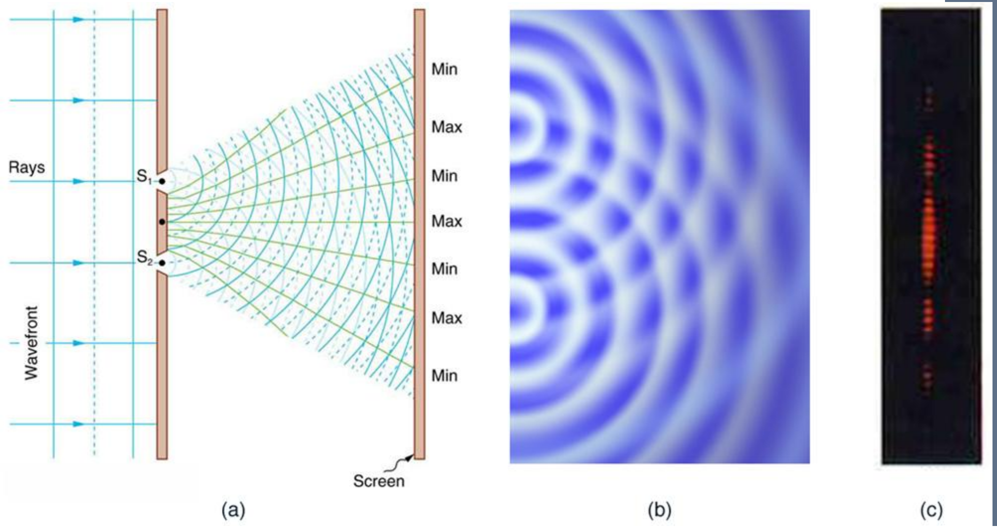
Binary NS mergers!

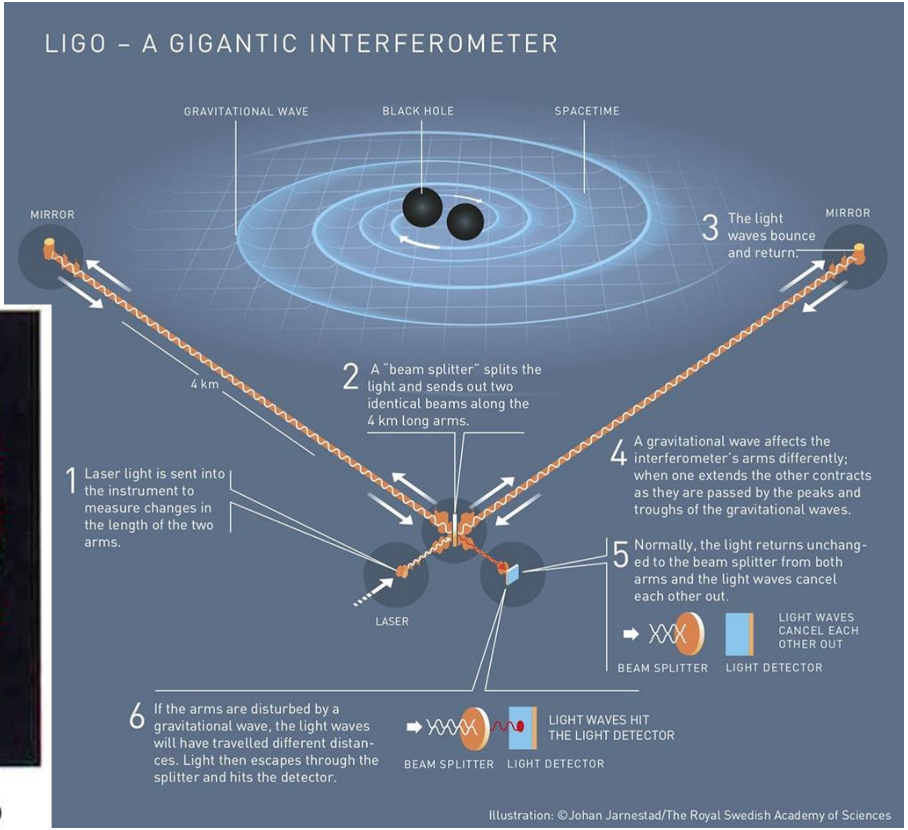


(a) (b) (c)

Why do we want to know their masses and radii?

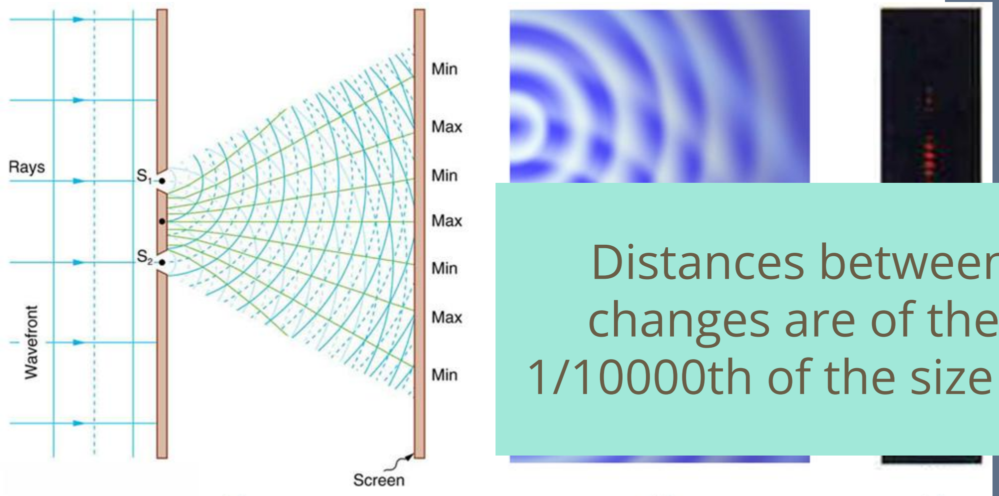
Binary NS mergers!



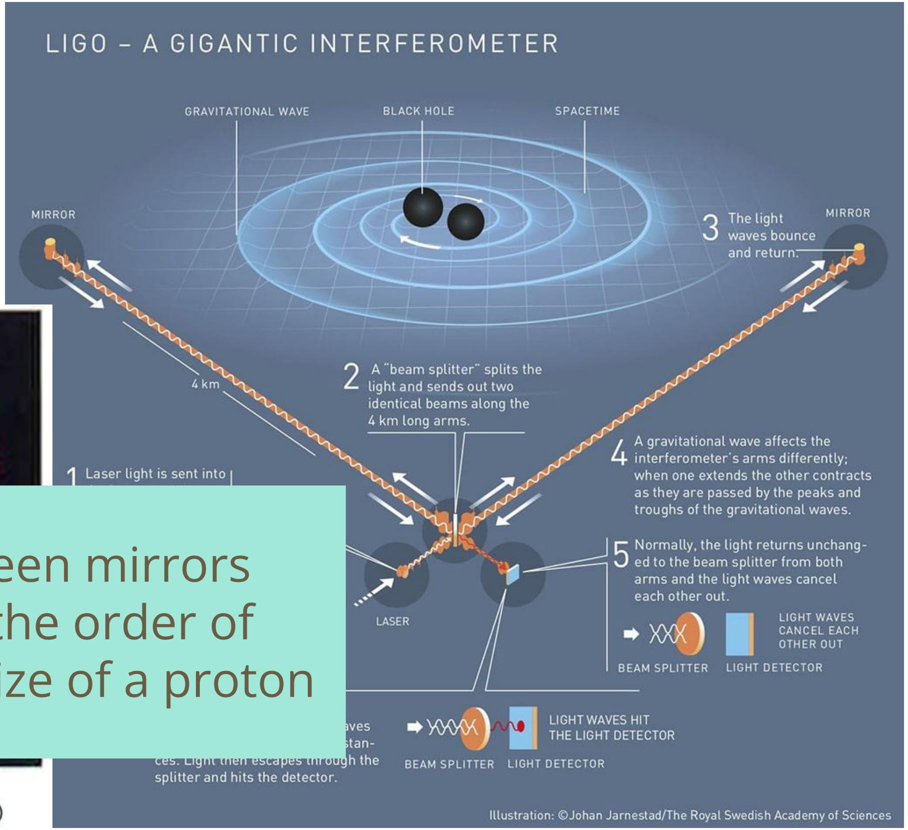


Why do we want to know their masses and radii?

Binary NS mergers!



(a) (b) (c)



Distances between mirrors changes are of the order of 1/10000th of the size of a proton

Why do we want to know their masses and radii?

Binary NS mergers!

GW170817 event

multimessenger astronomy with GWs started!

Why do we want to know their masses and radii?

Binary NS mergers!

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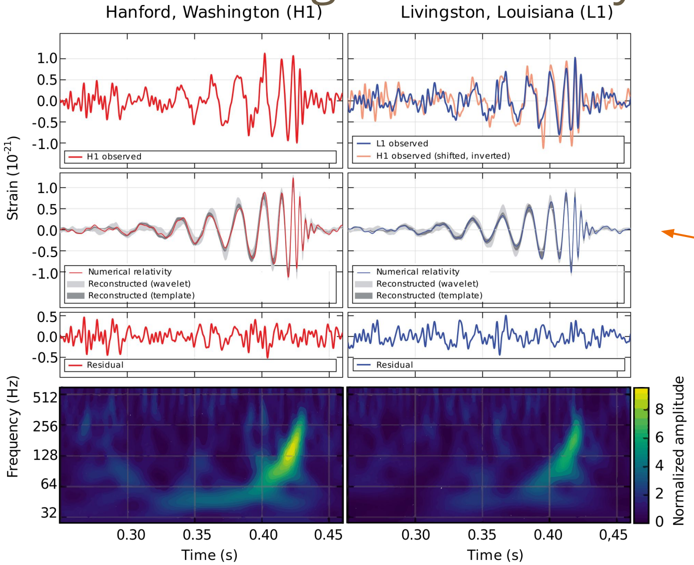
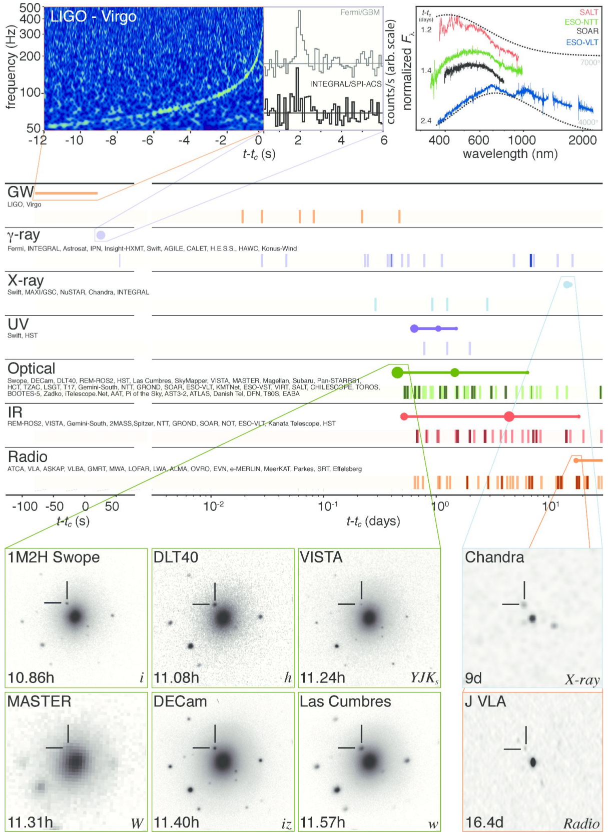


theoretical curves have information of mass and radius



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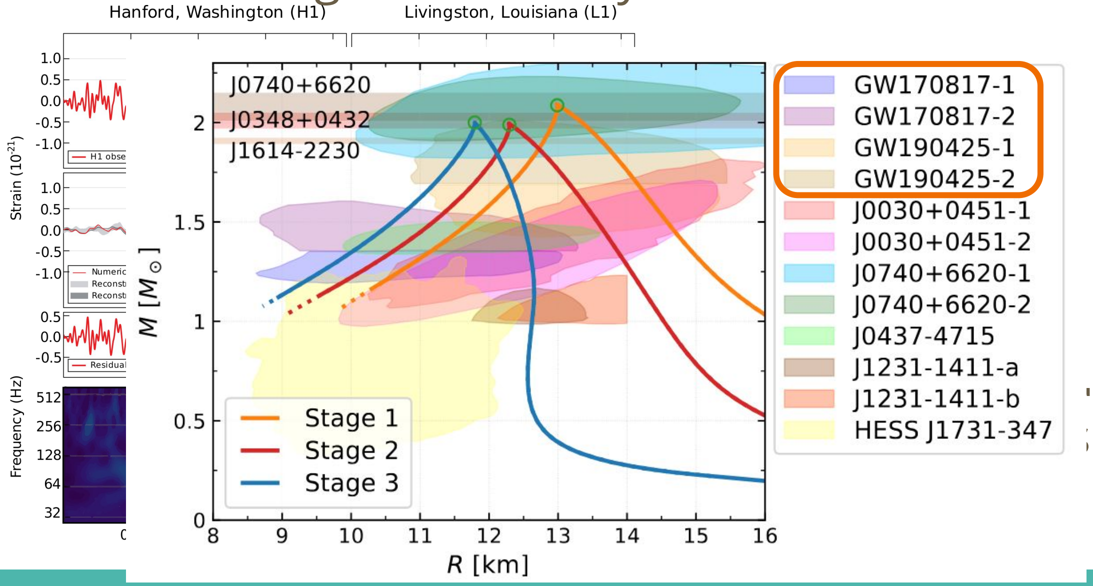
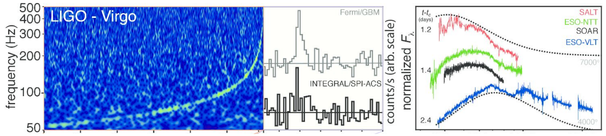
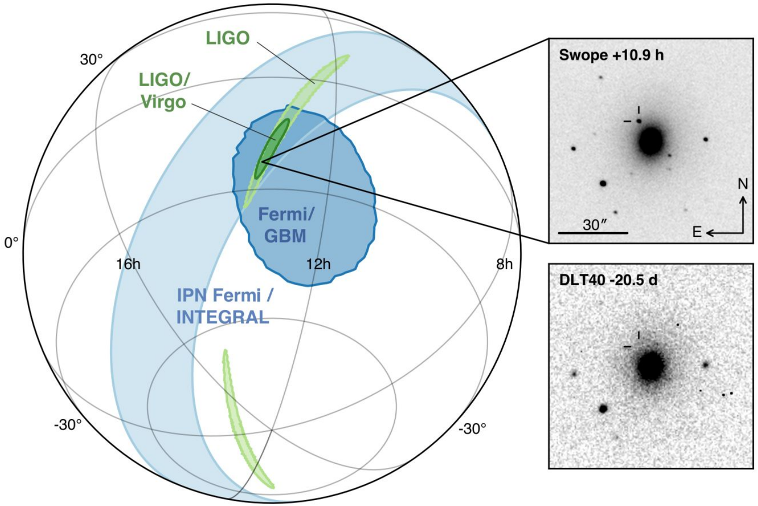
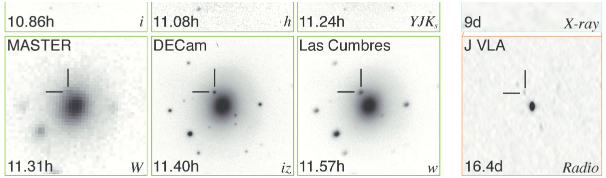


tion

and





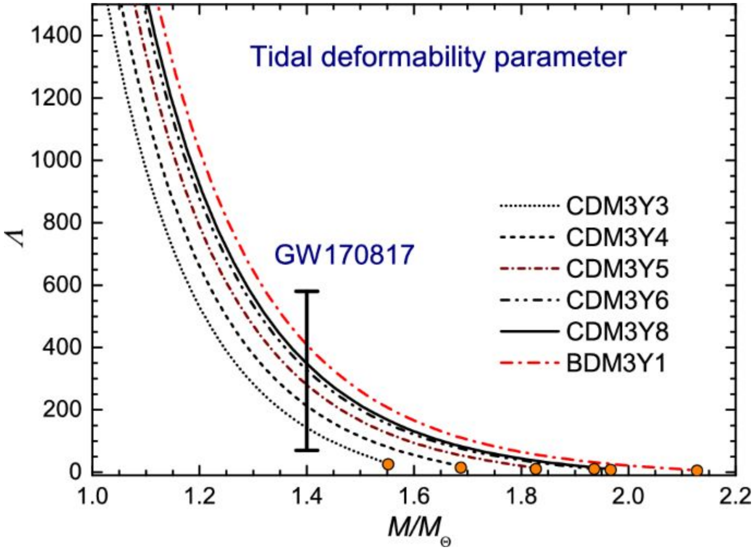


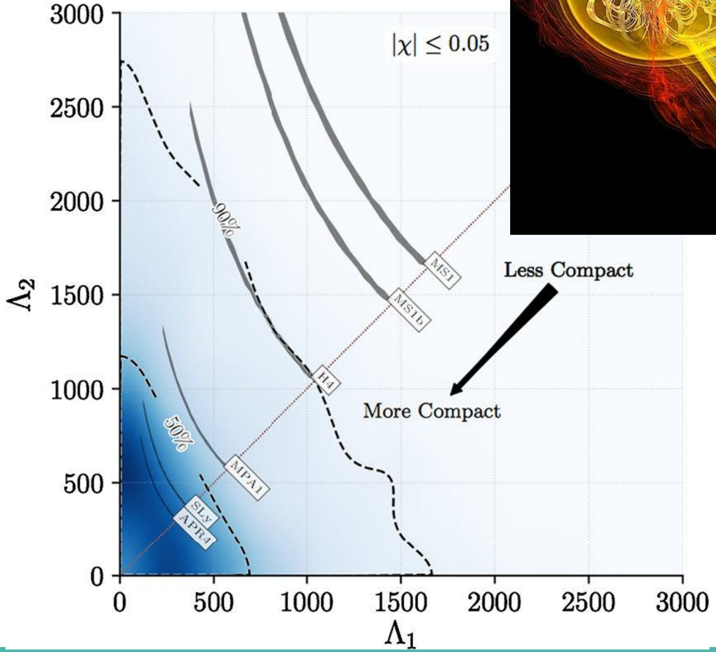
Why do we want to know their masses and radii?

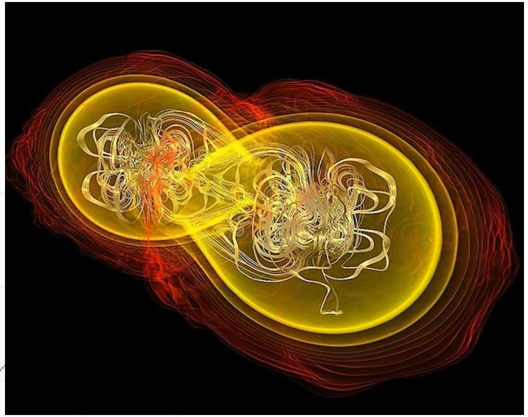
Binary NS mergers!

GW170817 event

Tidal deformability also estimated!





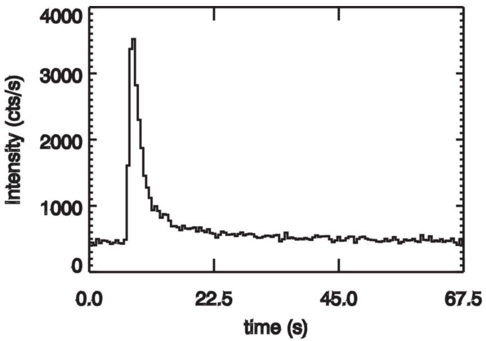


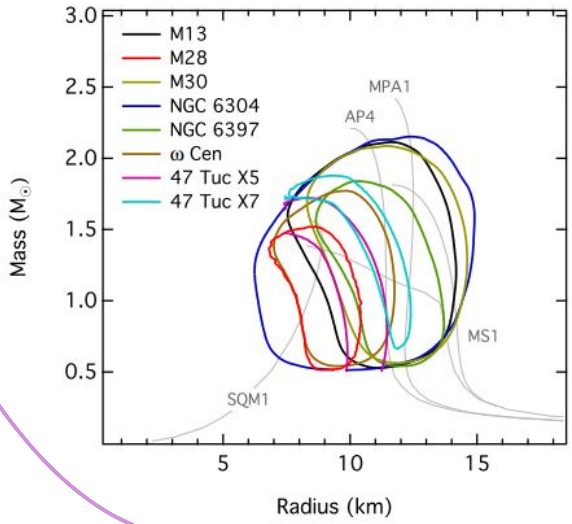
How do we know their masses and radii?

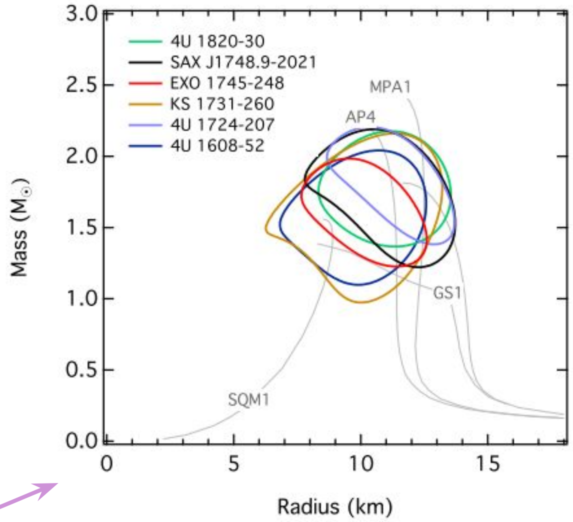
Estimating radii
spectroscopic measurements from LMXBs

Quiescence stage

During burst







From Ozel and Freire 2016

How do we know their masses and radii?

Estimating radii
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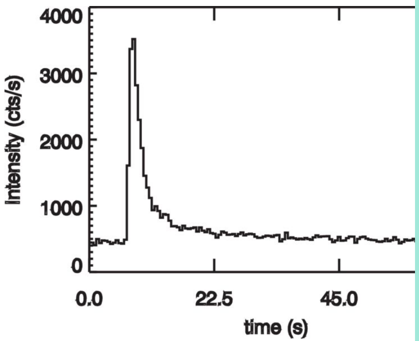
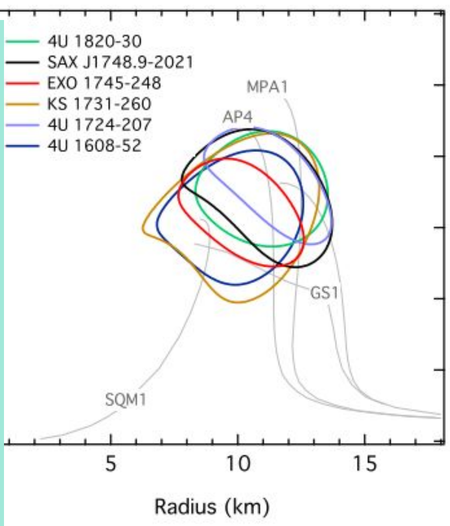
Quiescence stage
During burst



The method relies in measuring the thermal flux of an object with known distance. Model the spectrum as a black body and obtain its effective temperature, then use the Stefan–Boltzmann Law to obtain the radius

$$\frac{R_{obs}}{D} = \left(\frac{F_{bol}}{\sigma_B T_{eff}^4} \right)^{1/2}$$



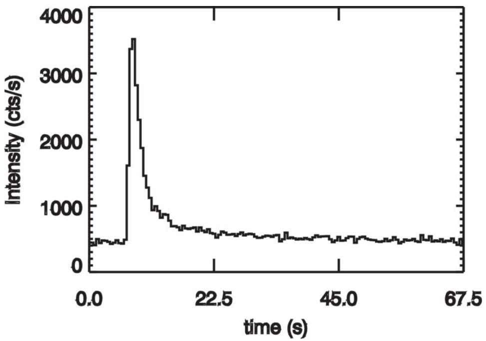
From Ozel and Freire 2016

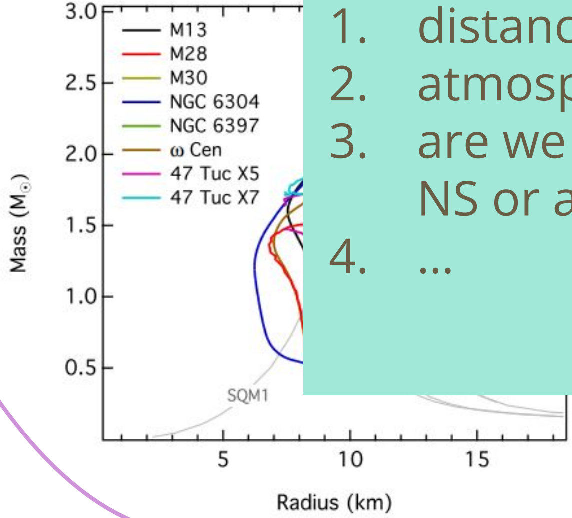
How do we know their masses and radii?

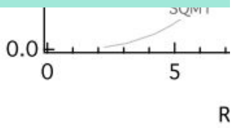
Estimating radii
spectroscopic measurements from LMXBs
Quiescence stage
During burst

It has lots of difficult-to-test hypothesis and the obtained results are highly dependent on them

1. distance determination problems
2. atmosphere models
3. are we estimating the radius of the NS or a different sphere?
4. ...







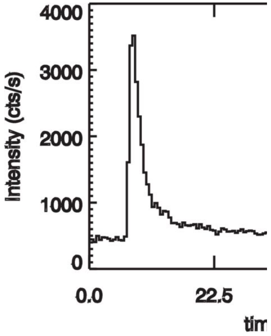
From Ozel and Freire 2016

How do we know their masses and radii?

Estimating radii
spectroscopic measurements from
LMXBs
Quiesce
During b

$$1 + z = \left(1 - \frac{2GM}{Rc^2}\right)^{-1/2} \qquad g = \frac{GM}{R^2}\left(1 - \frac{2GM}{Rc^2}\right)^{-1/2}$$

Can be estimated from a fitting
procedure to the spectroscopic data



How do we know their masses and radii?

Estimating radii
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Quiesce
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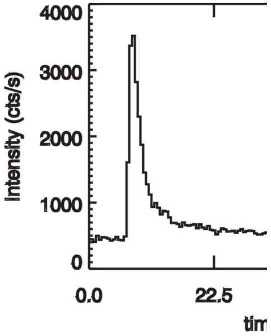
$$g = \frac{GM}{R^2}\left(1 - \frac{2GM}{Rc^2}\right)^{-1/2}$$



Inverting them we get

$$R = \frac{zc^2}{2g}\frac{(2+z)}{(1+z)}$$

$$M = \frac{z^2c^4}{4gG}\frac{(2+z)^2}{(1+z)^3}$$

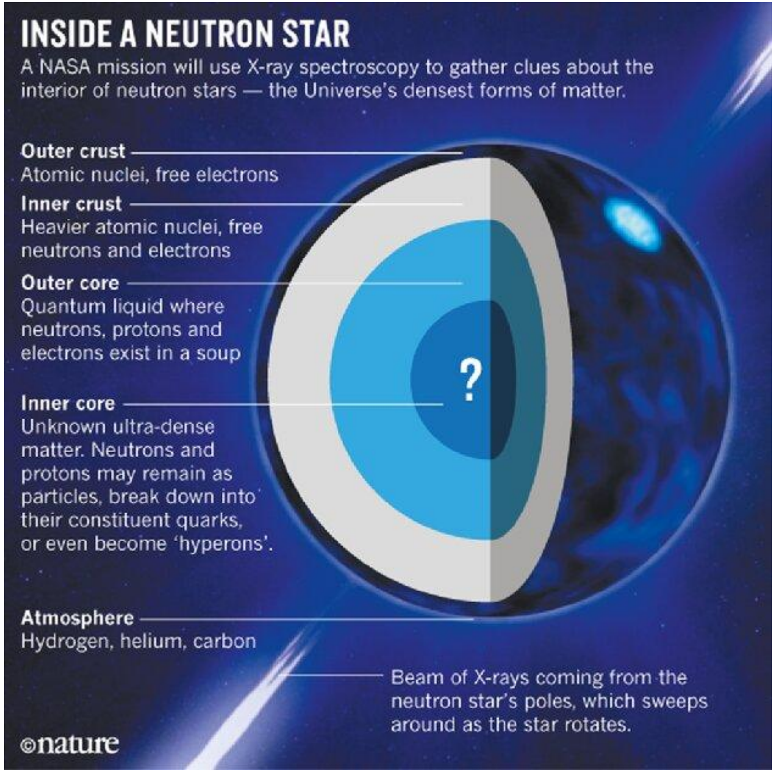
Why do we want to know their masses and radii?

NSs have mean densities of

about 10^{17} kg/m^3

Impossible to reach such conditions

in terrestrial laboratories

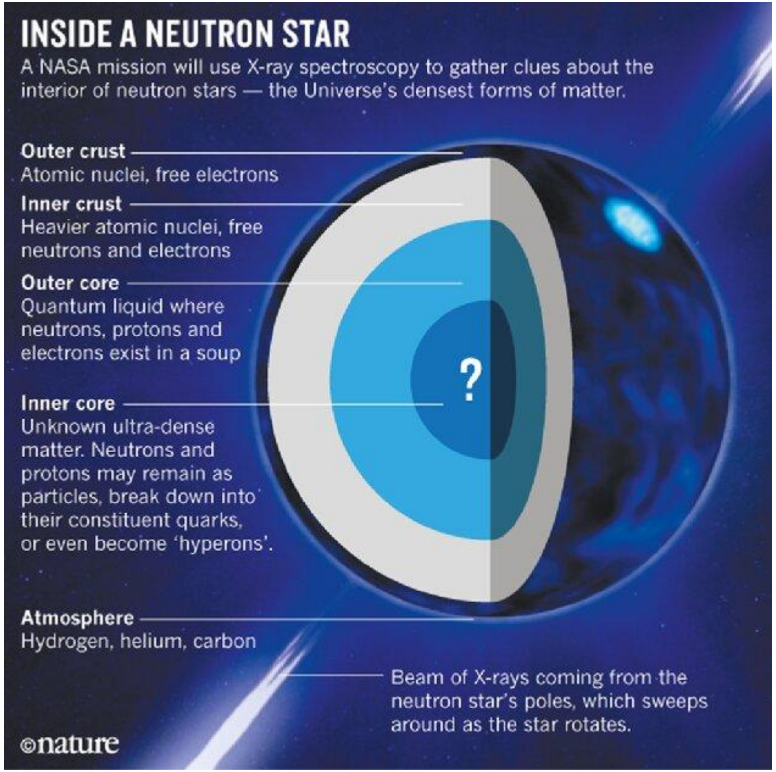


Why do we want to know their masses and radii?

NSs have mean densities of about 10^{17} kg/m^3

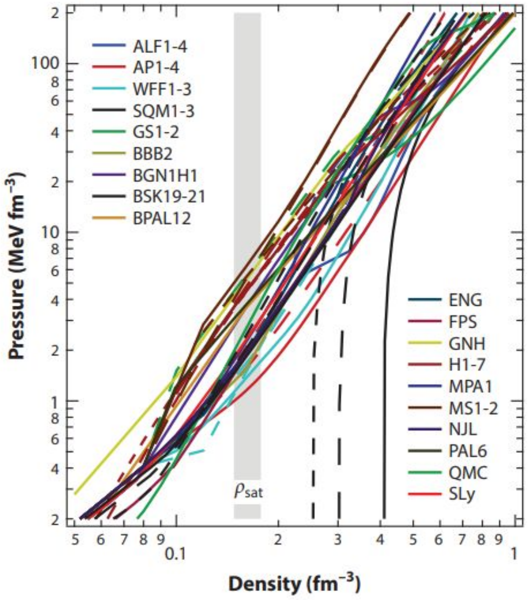
Impossible to reach such conditions in terrestrial laboratories

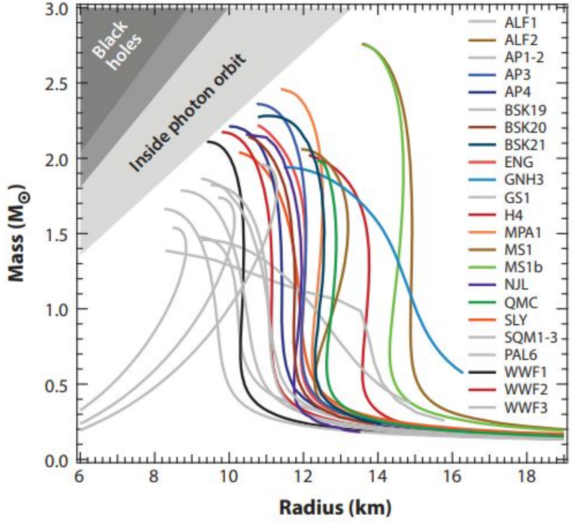
To learn about the behaviour of matter at such conditions, we must understand NSs



Why do we want to know their masses and radii?

In the next classes we are going to learn that there is a one-to-one relationship between the behaviour of matter (described via an equation of state) and the so-called mass-radius relationship of NS





Why do we want to know their masses and radii?

In the next classes we are
going to learn that th
a one-to-one
betw
matte
equati
so-calle
relations of NS

Information in the M-R plane translate into information in the microphysical arena