CONSTRAINTS ON THE EQUATION OF STATE FROM NEUTRON STAR OBSERVATIONS

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Helmholtz International Summer School
Dubna - July 18, 2017

Sciences

EN IMAGES Les défis de la traduction automatique

SCIENCES | Vidéos | Archéologie | Supplément partenaire : Les Prix EDF Pulse | Affaire de logique | Astronomie | Biologie | Cerveau | Géophysique

ÉDITION ABONNÉS

Dubna : chez les chasseurs russes des nouveaux atomes

Quatre nouveaux éléments, les plus lourds jamais produits, viennent d'être officiellement baptisés. A Dubna, le temple soviétique de la science explore depuis soixante ans les confins de la matière.

LE MONDE SCIENCE ET TECHNO | 10.07.2017 à 17h47 • Mis à jour le 11.07.2017 à 09h30 |

Par Vahé Ter Minassian (Dubna (Russie), envoyé spécial)

Réagir Ajouter

Au Centre international des conférences de Dubna, petite cité de 70 000 habitants aux allures de ville de vacances sur les rives du canal de la Volga, à 120 kilomètres de Moscou, les festivités du « banquet-anniversaire » des soixante ans du Laboratoire Flerov des réactions nucléaires (FLNR) battent leur plein. La vodka aidant, le brouhaha des conversations a rapidement augmenté. Et bientôt, en suivre une devient excessivement difficile. Sans regrets inutiles : il est déjà évident qu'on ne

Visite de la demeure romaine découverte à Auch

Sur les sites du groupe Le Monde.

Dix ans après la crise financière, la finance mondiale renoue avec les...
Le Monde

Pierre Vimont : « Le nationalisme turc permet au régime de trouver une forme...

Neutron stars: general aspects

Constraints from mass measurements

Constraints from radius measurements

Others. . .

Neutron stars: general aspects

Discovery of neutron stars (NSs)

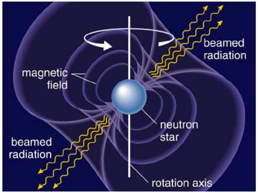
Yakovlev et al., arXiv:1210.0682 (2012); Haensel et al.'s book (2007)

From theoretical predictions . . .

- Feb. 1931: anticipation of the idea of NSs by Lev Landau.
- Jan. 1932: experiments by Chadwick and discovery of the neutron.
- Dec. 1933: Baade & Zwicky: "*supernovæ represent the transitions from ordinary stars to neutron stars, which in their final stages consist of extremely closely packed neutrons*".

. . . to observations

- 1967: observation by chance by Bell (Hewish's graduate student) of very stable radio pulses with $P = 1.3373012$ s. The source is called "pulsar" meaning "Pulsating Source of Radio".
- 1974: Nobel Prize to Hewish (only) for the discovery of pulsars.
- May 1968 : Gold, Nature : pulsar = rotating NS.



Lighthouse model

Period of the pulses = spin period P of the pulsar.
All PSRs are NSs but not all NSs are seen as PSRs.

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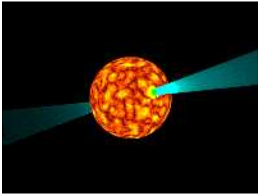

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What is a neutron star?

Origin

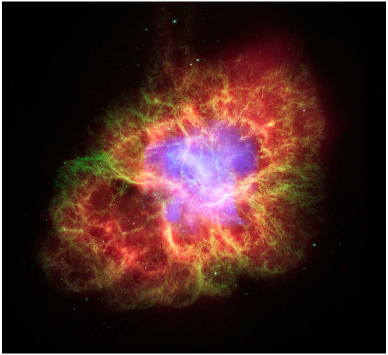
Remnant from the gravitational collapse of a $\sim$ 10 $M_\odot$ star during a Type II, Ib, Ic supernova event.

Properties

- mass $M \sim 1.4\ M_\odot$ ($M_\odot = 10^{30}$ kg),
- radius $R \sim 10$ km,
- compactness $\frac{GM}{Rc^2} \sim 0.2$,
- average density $\bar{\rho} \sim 10^{18}$ kg m^{-3}.

$\Rightarrow$ relativistic objects sustained by the strong interaction.

Crab Nebula hosting a pulsar



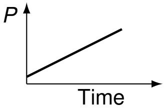
Credits : NASA/ESA.

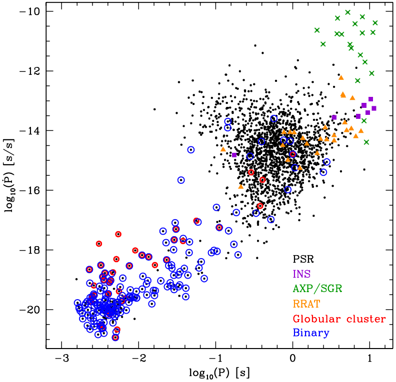
Observations

$\sim$ 3000 NSs from radio to γ-rays, a majority as radio pulsars.
$\sim$ 5% of them in a binary with a companion star.

Pulsar population

NSs undergo a regular spin-down ie. an increase $\dot{P}$ of their spin period P :





$P - \dot{P}$ diagram.
Data from ATNF pulsar catalog.

Several types of emission

- PSR: radio or γ-ray pulsars,
- INS: X-ray pulses, no radio pulses,
- AXP/SGR: bursts observed in X- or γ-rays,
- RRAT: radio bursts.

Toy model

Magnetic dipole :

- spin-down due to emission of electromagnetic radiation.

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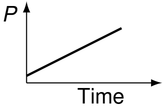

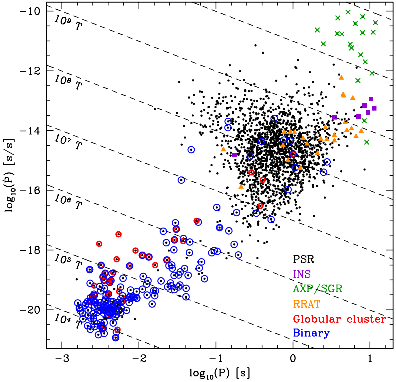

$P - \dot{P}$ diagram.
$I = 10^{45}$ g cm^2, $R = 10$ km.

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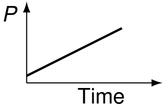

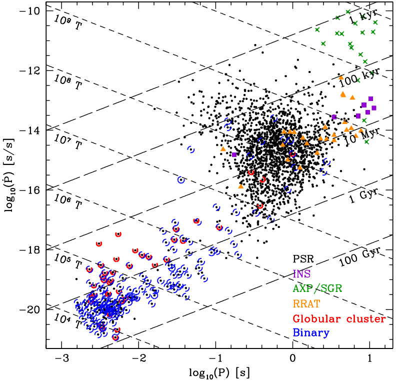

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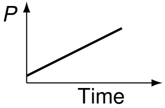

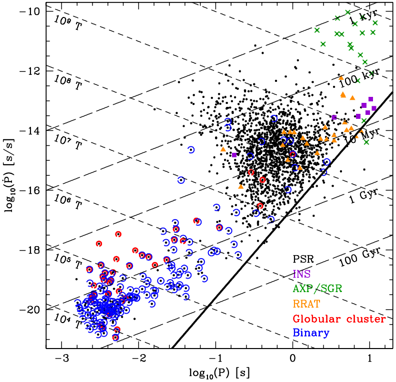

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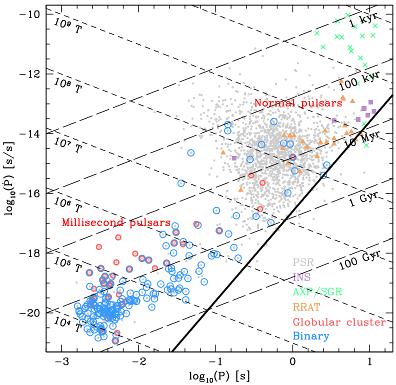
- (model-dependent) death line : below the line, electromagnetic emission stops.

Pulsar population



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Two main types of pulsars

	Normal	Millisecond (MSP)
P (s)	1	0.03
B (T)	10^8	10^4
τ (yrs)	10^7	10^9

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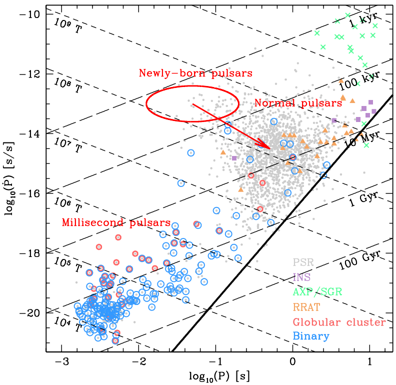

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Normal pulsars

NSs born fastly rotating, spun down by the radio emission until they cross the death line.

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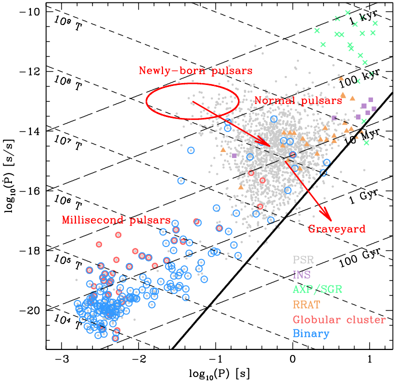

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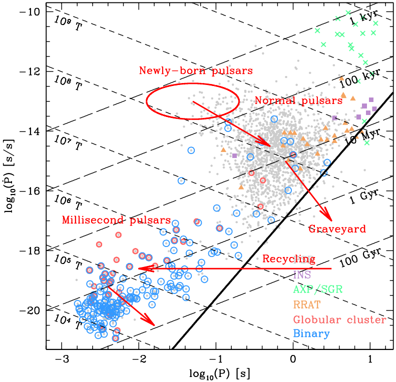

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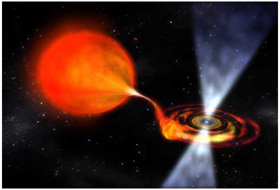
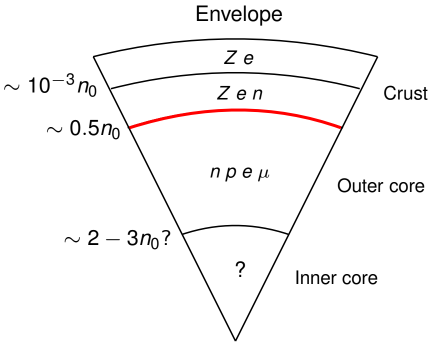
Millisecond pulsars

Old pulsars rejuvenated by the accretion of matter from a binary companion.



Structure



Nuclear saturation density: $n_0 = 0.16 \text{ fm}^{-3}$

Problem

NS matter not accessible in terrestrial laboratories . . .

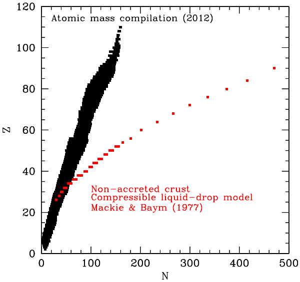
Envelope

- Plasma whose composition determines the spectrum of the NS emission.

Crust

- Gas of electrons,
- lattice of neutron-rich ions,
- at larger densities free neutrons (superfluid?).

Nuclei in lab. vs. NS crust



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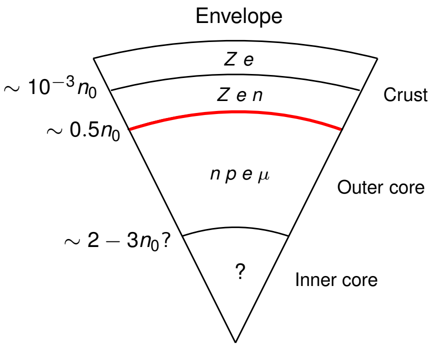


Nuclear saturation density: $n_0 = 0.16\ \text{fm}^{-3}$

?=

- nucleons,
- hyperons (baryons with a least one *s* quark),
- quark matter (deconfined *d*, *u* and *s*),
- pion or kaon condensation, . . .

Envelope

- Plasma whose composition determines the spectrum of the NS emission.

Crust

- Gas of electrons,
- lattice of neutron-rich ions,
- at larger densities free neutrons (superfluid?).

Outer core

- Free neutrons and protons (superfluid?),
- electrons,
- muons.

Inner core

- ?

Equation of state

Mystery : equation of state (EoS)

- Describes the composition and properties of NS matter;
- $P(n)$ with P the pressure and n the baryon density.

NS matter

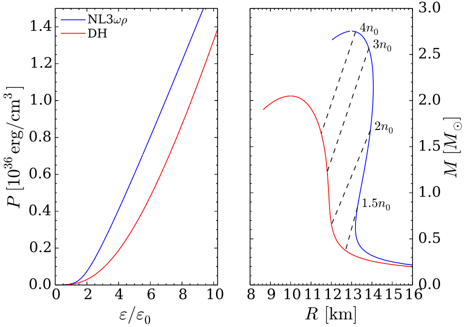
Many-body system of strongly-interacting particles (e, p, n, μ, more?) at zero temperature (thermal energy $\ll$ nucleon Fermi energy).

Two approaches:

- phenomelogical models with effective interactions with parameters adjusted to nuclear and astrophysical quantities,
- ab-initio approaches: 'solving' the many body problem starting with 2 (and 3)-body interactions.

Mass-radius diagram

An EoS + Tolman and Oppenheimer & Volkoff (TOV) equations for hydrostatic equilibrium in GR $=$ a specific mass-radius relation.



Equation of state

General relativity constraint

GR imposes that the radius of a neutron star is larger than the Schwarzschild radius:

$$R > 2\frac{GM}{c^2}.$$

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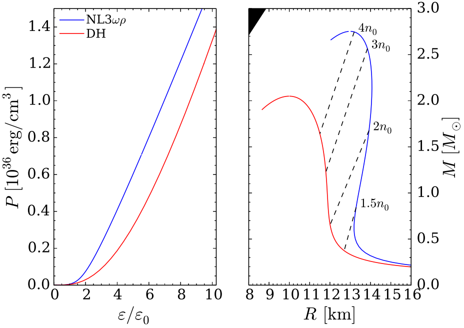

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Finite pressure constraint

For a uniform density profile inside a neutron star, finite pressure imposes:

$$R > \frac{9}{4}\frac{GM}{c^2}.$$

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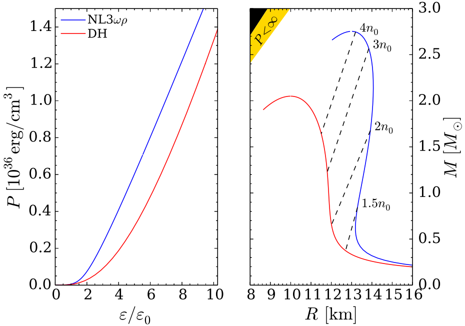

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Subluminal speed of sound implies:

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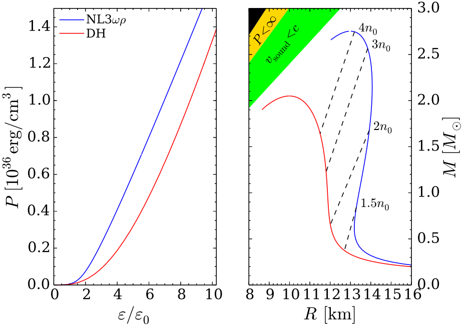

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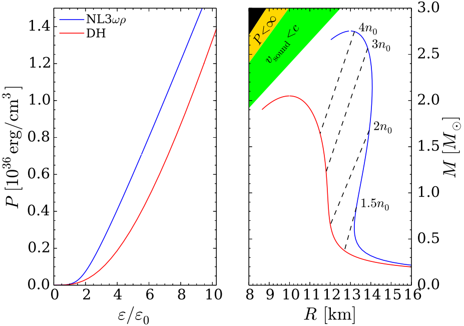


Key point

How to constrain the EoS and thus the properties of the nuclear interaction at large densities thanks to NS observations ?

Constraints from mass measurements

Mass

See eg. Özel & Freire, ARAA (2016)

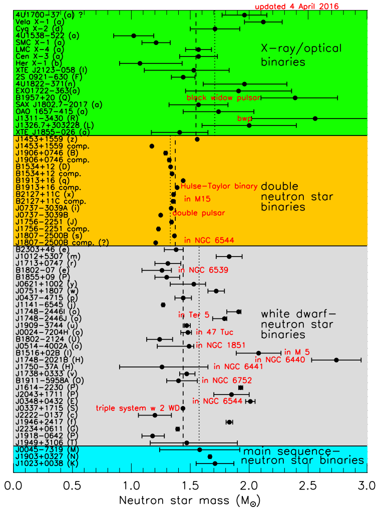
Keplerian orbital elements

- orbital period,
- time of periastron passage,
- eccentricity,
- projected semi-major axis,
- angle of periastron;

$\Rightarrow$ mass function $f_1(M, m_c, i)$.

+ 2 additional quantities

- Post Keplerian parameters:
  - precession of periastron,
  - orbital decay,
  - Einstein delay,
  - Shapiro delay;
- Spectroscopy:
  - orbital velocity,
  - H lines in the white dwarf atmosphere;
- Eclipse modeling.



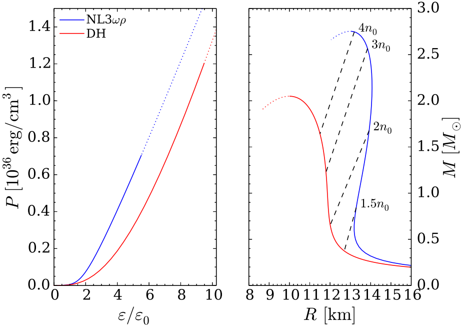
https://stellarcollapse.org/nsmasses

Maximum mass

Theory

- each EoS has a maximum mass $M_{\rm max}$;
- $M_{\rm max} \geq M_{\rm max}^{\rm obs}$.

Mass-radius diagram



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PSR J1614-2230

Fonseca et al., ApJ (2016)
Shapiro delay parameters:

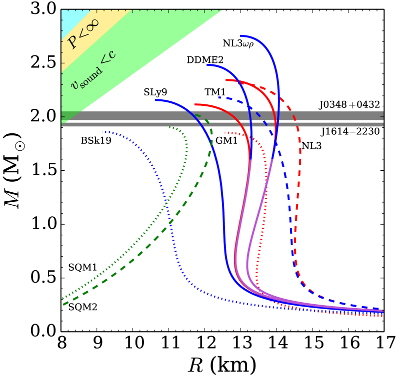
$$M_{\rm max}^{\rm obs} = 1.928 \pm 0.017\ \mathrm{M}_\odot.$$

PSR J0348+0432

Antoniadis et al., Science (2013) WD spectroscopy:

$$M_{\rm max}^{\rm obs} = 2.01 \pm 0.04\ \mathrm{M}_\odot.$$

Mass-radius diagram



EoSs for nucleonic matter (blue), exotic matter (pink) and strange quark matter (green).

Constraints from radius measurements

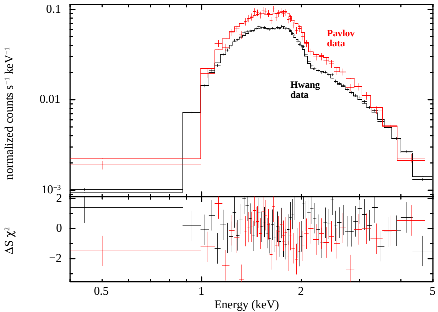
Isolated NSs

Thermal emission

Modeling of the X-ray spectra using atmosphere models.
Determination of the radius observed at infinity :

$$R_\infty = \frac{R}{\sqrt{1-2GM/(Rc^2)}}$$

Cas A NS (Ho & Heinke, Nature 2009)



Composition	H	He	C
R_{emission} (km)	4	5	12

No pulsation → emitting region = whole NS.
→ NS with a C atmosphere.

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Limitations:

- unknown chemical composition of the envelope,
- distance to the source,
- magnetic field B,
- ...

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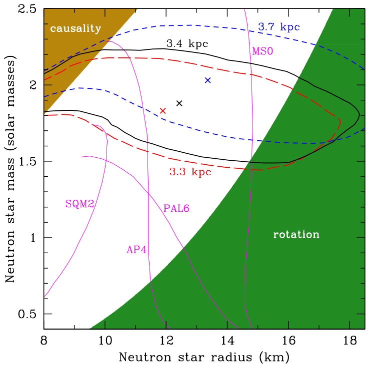

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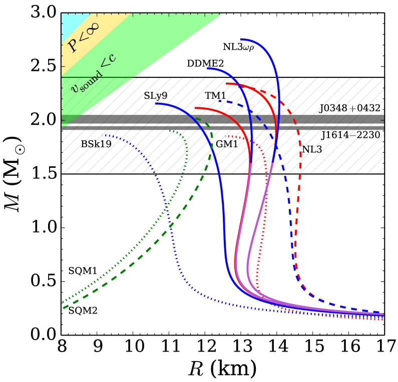


Quiescent thermal emission of accreting NSs

Properties

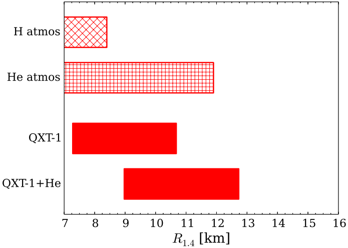
- Low B
- accreted atmosphere $\rightarrow$ H, He
- if NS in a globular cluster, distance accurately known.

Results

- NGC 6397: H atmosphere vs. He atmosphere
  Heinke et al., MNRAS (2014)
- QXT-1: based on 6 objects, only H atmosphere
  Guillot & Rutledge, ApJ (2014)
- QXT-1+He: possibility of He atmosphere for NGC 6397

Limitations

- H or He atmosphere?
- Large uncertainty in the interstellar absorption ($N_{\rm H}$ parameter).
- Undetected hot spots (Elshamouty et al., ApJ 2016)
- Lack for precise distance measurements. Athena and Gaia may help.

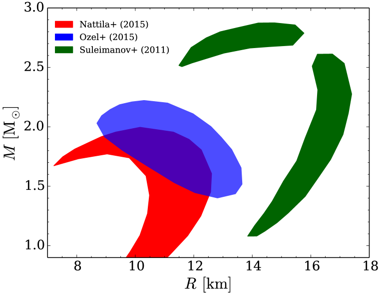


X-bursts from accreting NSs

Photospheric radius expansion bursts

Strong enough to lift up the outer layers of the NS.

4U 1724-307



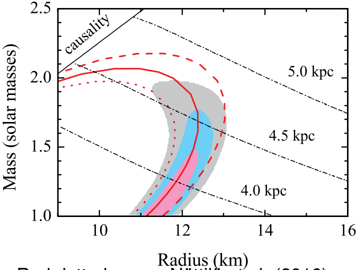
Limitations

eg. Steiner et al., EPJA (2016)
Suleimanov et al., EPJA (2016)
Özel et Freire, ARAA (2016)

- uncertainties in the modelling of the burst, the burst selection, and the composition of the atmosphere.

SAX J1810.8-2609

Suleimanov et al., MNRAS (2017)



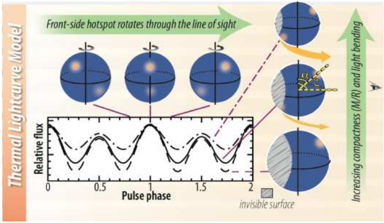
Red dotted curve: Nättilä et al. (2016).

Modeling the X-ray pulse profile of . . .

radio millisecond pulsars

PSR J0437−4715 (Bogdanov, ApJ 2013)

- ▸ pulsations due to magnetic polar caps
- + mass known from radio observations: $M = 1.76 \pm 0.2\ M_\odot$.
- → $R > 12.29$ km (2σ)
- ▸ new mass measurement from Reardon et al., MNRAS (2016): $M = 1.44 \pm 0.07\ M_\odot$



accreting millisecond X-ray pulsars

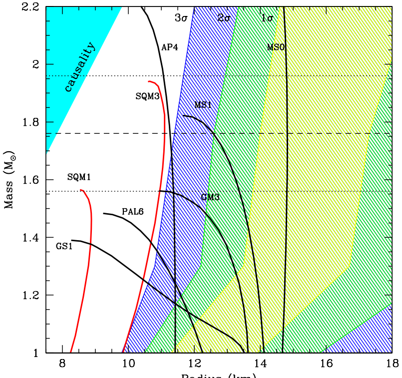
e.g. SAX J1808.4-3658 (Morsink & Leahy, ApJ 2011)

- ▸ pulsations due to accretion onto the NS magnetic poles

Limitations

Özel et Freire, ARAA (2016)

- ▸ hot spot modeling (shape)
- ▸ geometry of the system



Modeling the X-ray pulse profile of . . .

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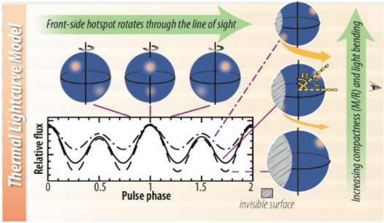

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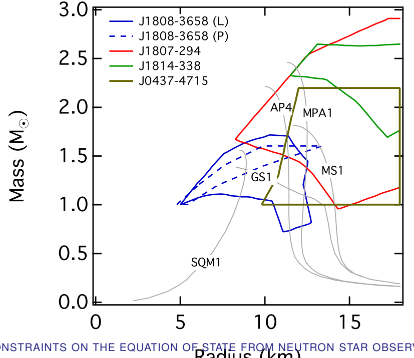
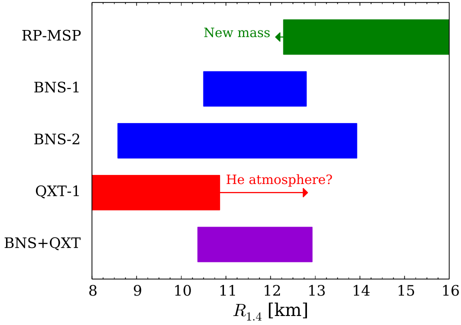


Radius

Fitting the spectrum of

- X-ray emission from radio millisecond pulsars (RP-MSP);
- the quiescent thermal emission of accreting NSs (QXT);
- X-bursts from accreting NSs (BNS).



Summary

Based on most recent publications.
Adapted from Fortin et al. A&A (2015)

- RP-MSP: Bodganov, ApJ (2013)
- BNS-1: Nättilä et al. arXiv:1509.06561
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- BNS+QXT: Steiner et al., ApJ (2013)

Conclusion

- inconsistency (see QXT-1 and RP-MSP),
- many remaining uncertainties in the modelling,
- inclusion of rotation: effect $\simeq$ 10%.

Current consensus

$$R = 9 - 14 \text{ km}.$$

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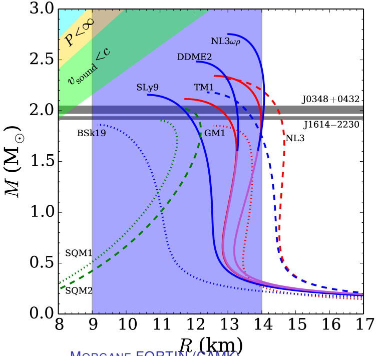

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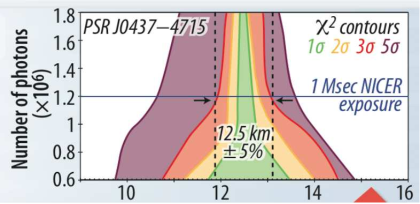
Perspectives

NICER

- Neutron star Interior Composition ExploreR Mission
- NASA project
- On the ISS
- Launch on June 3
- First light yesterday
- Rotating hot spots from non-accreting MSPs
- $M-R$ constraints with a precision of $\sim 5\%$ for ~ 3 NS.



Athena

- Advanced Telescope for High ENergy Astrophysics
- ESA project
- L2 point
- in 2028
- X-ray emission from MSPs;
- quiescent thermal emission of accreting NSs;
- PRE bursts from accreting NSs.

$M-R$ measurements

- rule out EoS
- reconstruct the EoS (see H. Grigorian's talk).

Others...