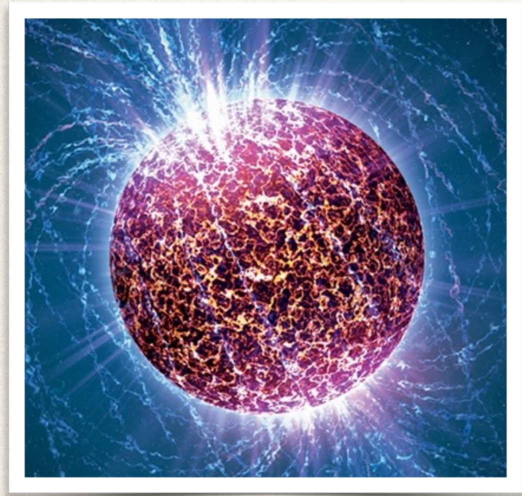
Recent measurements of neutron star masses and radii as probes of nuclear physics

Sebastien Guillot

University of Toulouse III

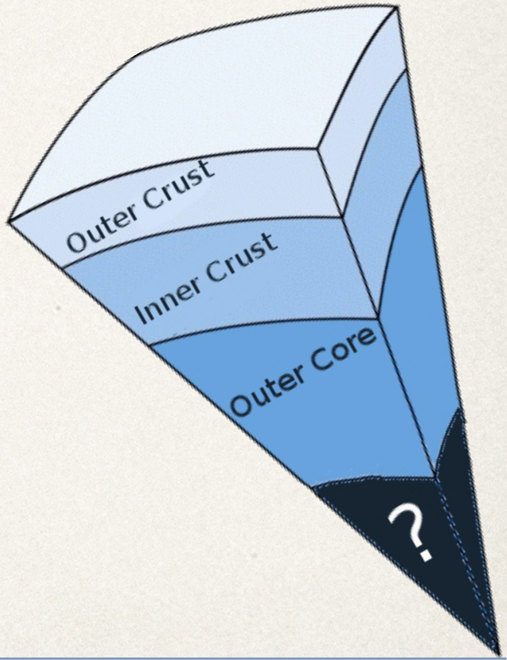


Collaborators

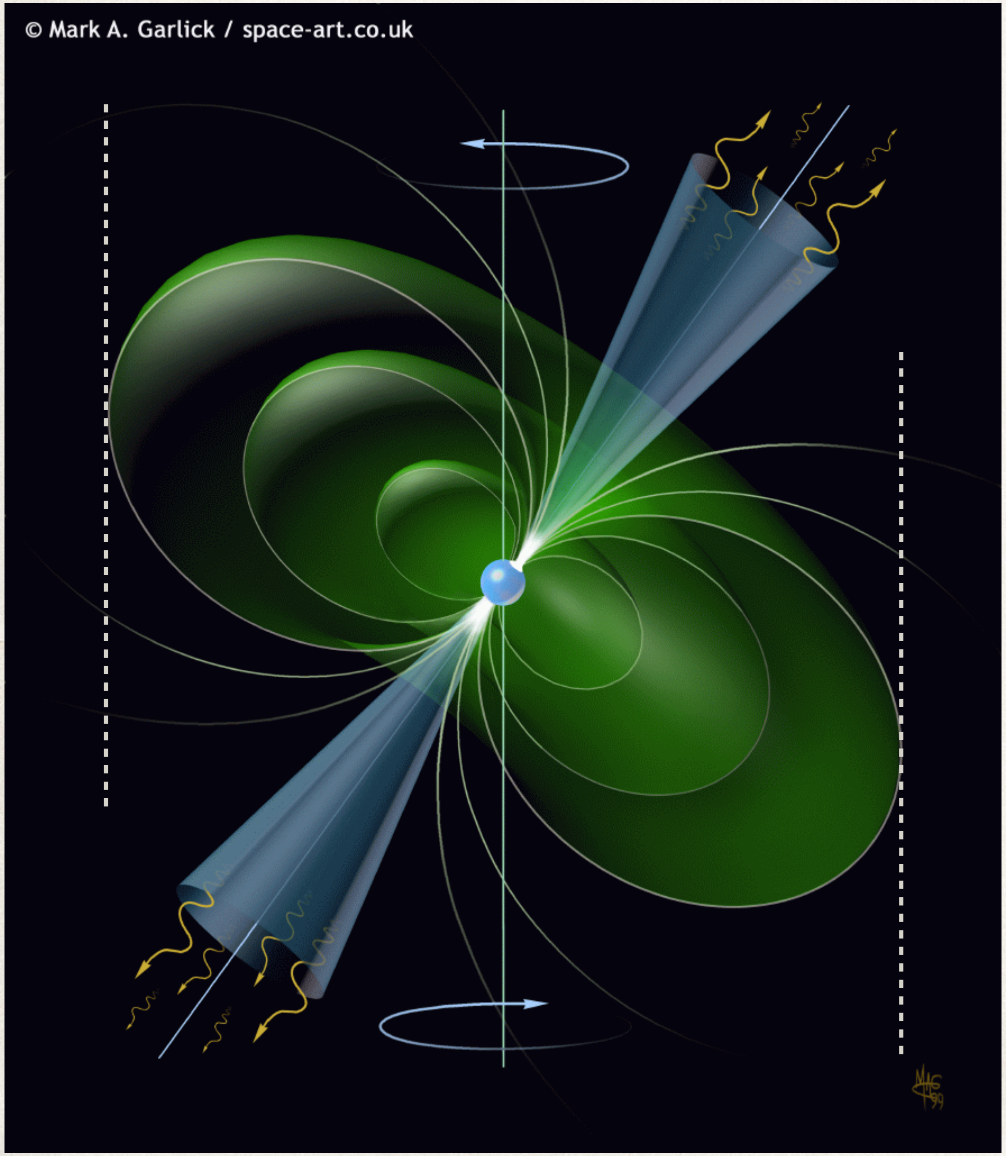
A. Watts, T. Salmi, D. Choudhury, S. Vincinguerra,
And many people in the NICER Science team

at IRAP

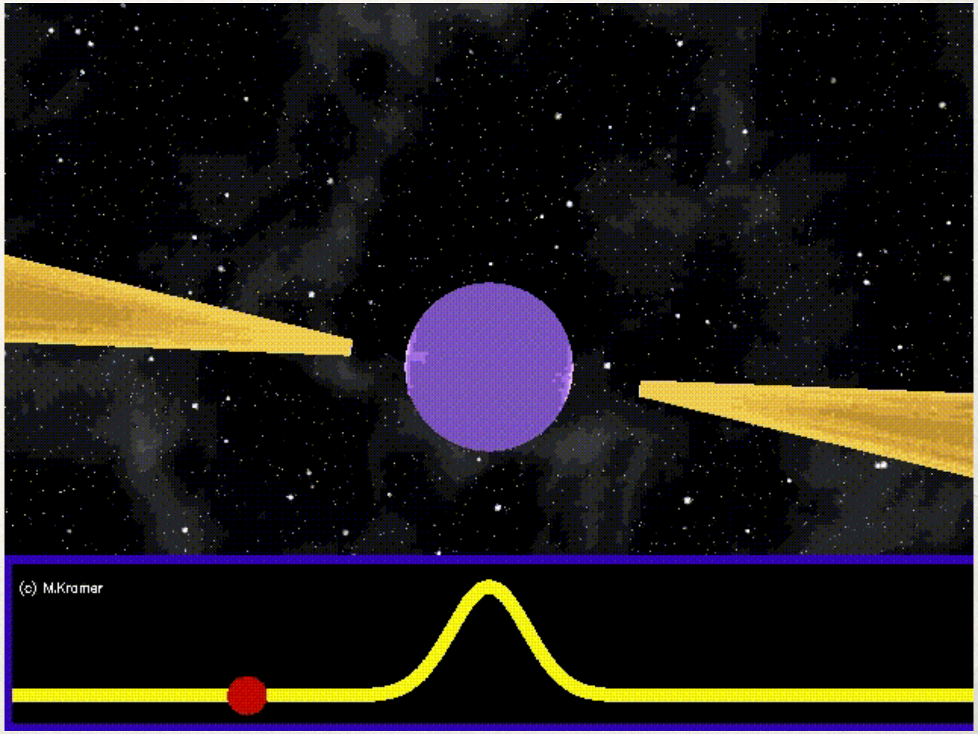
Lucien Mauviard,
Pierre Stammler, Denis Gonzalez



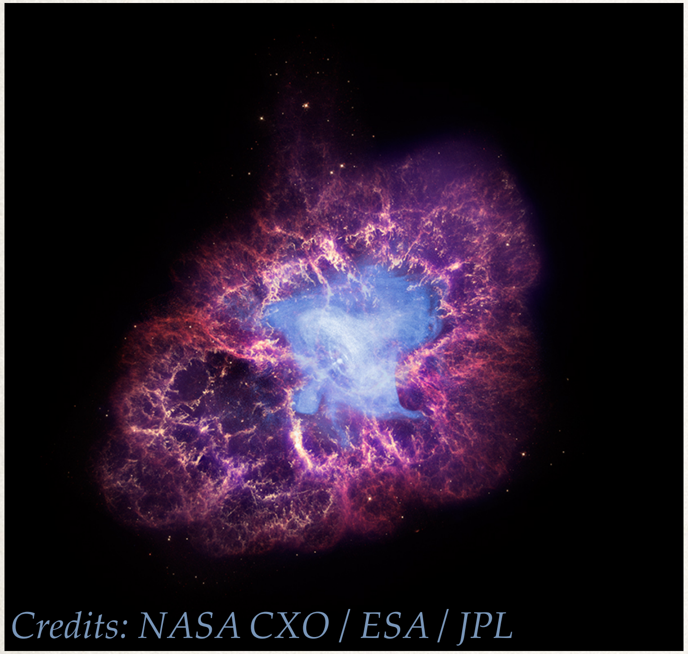
All pulsars are neutron stars, but not all neutron stars are pulsars!



R_{NS} ~ 10 – 15 km
M_{NS} ~ 1.0 – 2.0 $M_{\odot}$
B ~ 10^8 – 10^{15} G
P_{spin} ~ 0.001 – 10 sec



Neutron stars are the remnants of the core-collapse of massive stars.

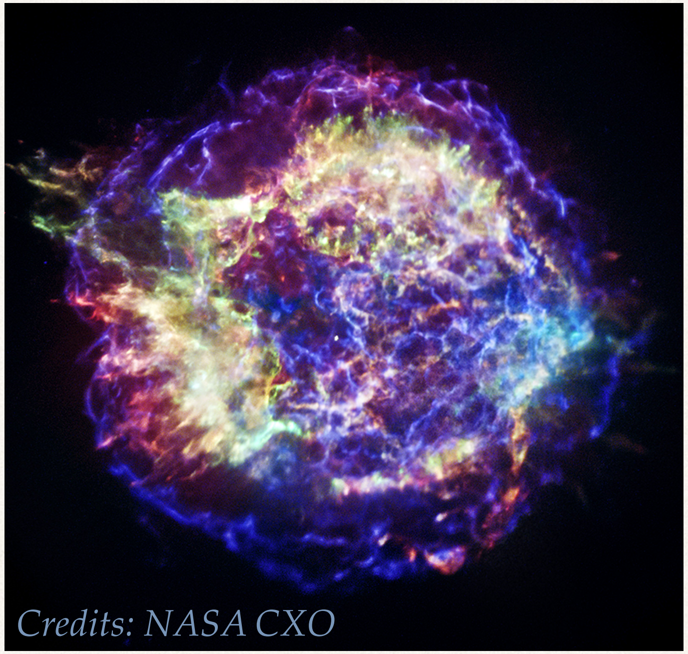


Credits: NASA CXO / ESA / JPL

Crab Nebula

X-ray+IR+Opt

A pulsar, at most wavelengths



Credits: NASA CXO

Cassiopeia A

X-ray

A neutron star without pulsations

Credits: NASA CXO / HST

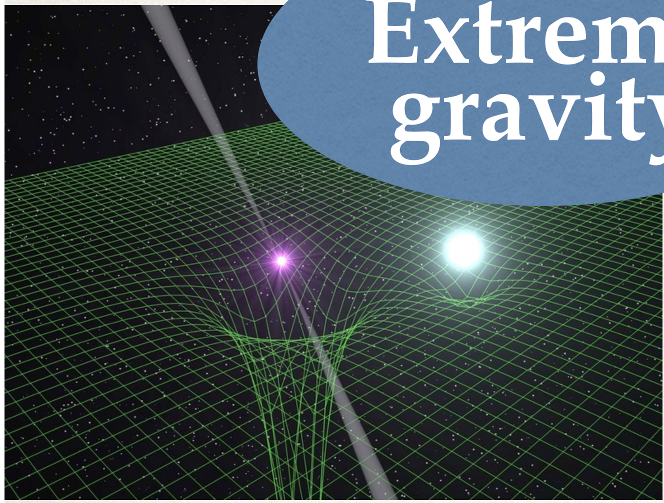
SN 1987 A

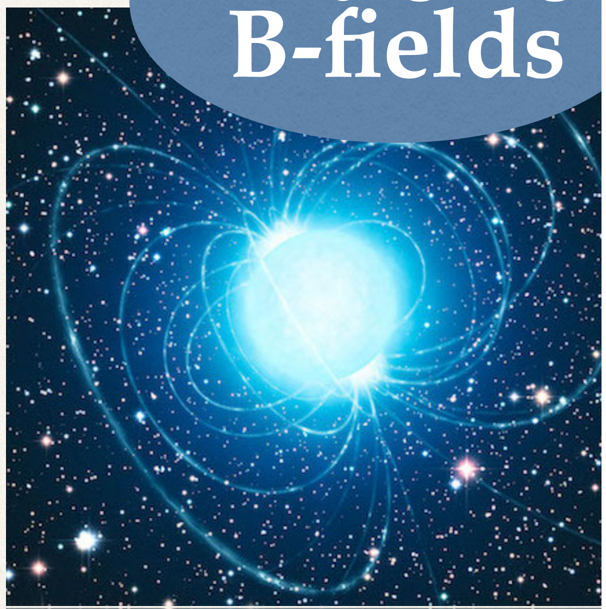
X-ray+Optical

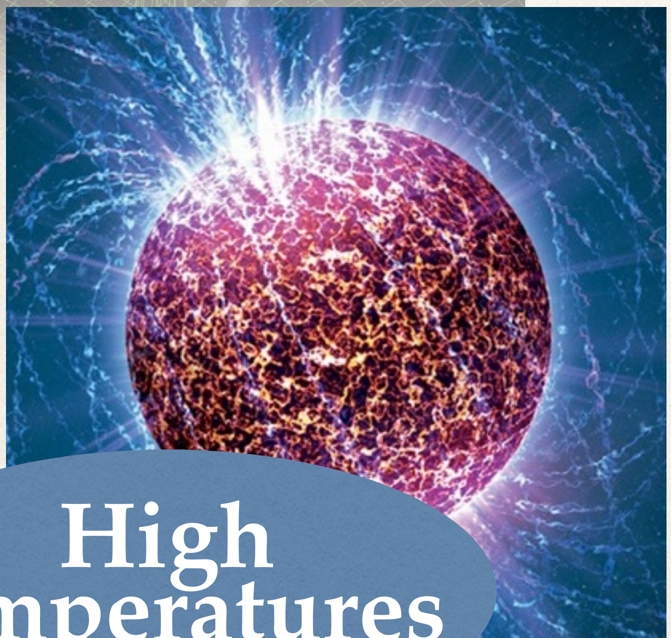
A neutron star, maybe ?

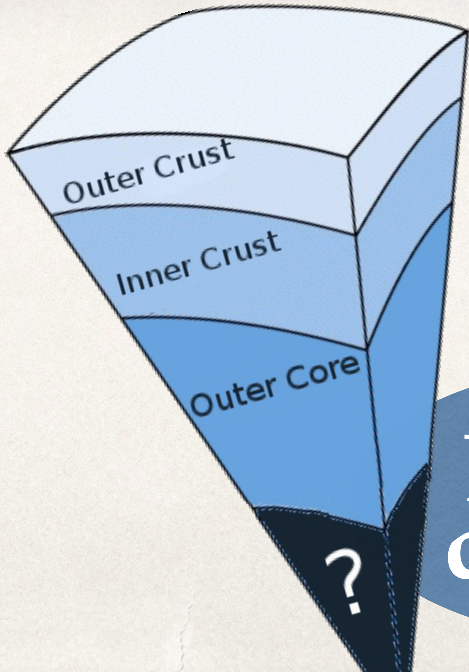
Fransson et al. 2024

Neutron stars are amazing laboratories for extreme physics.

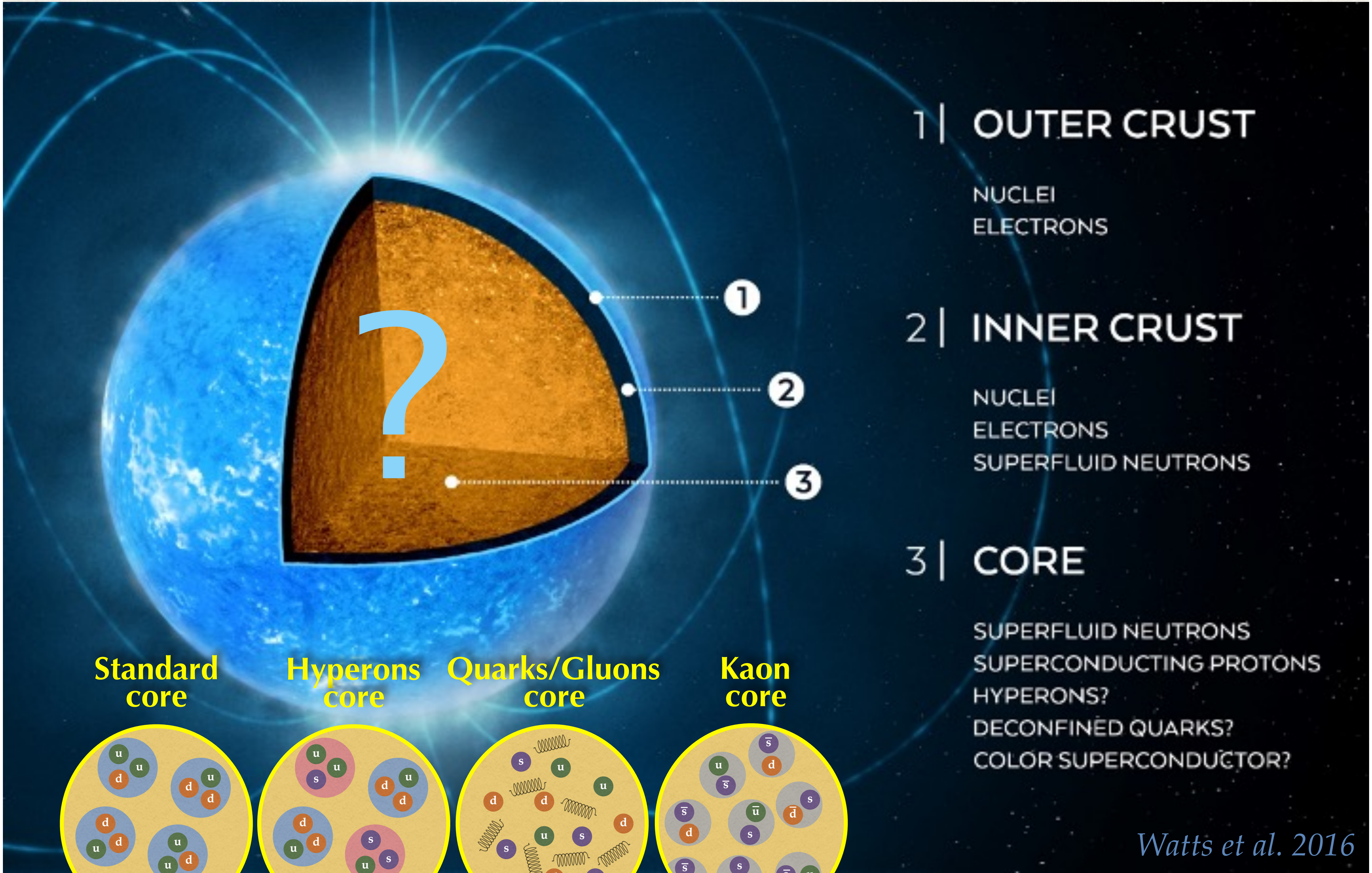






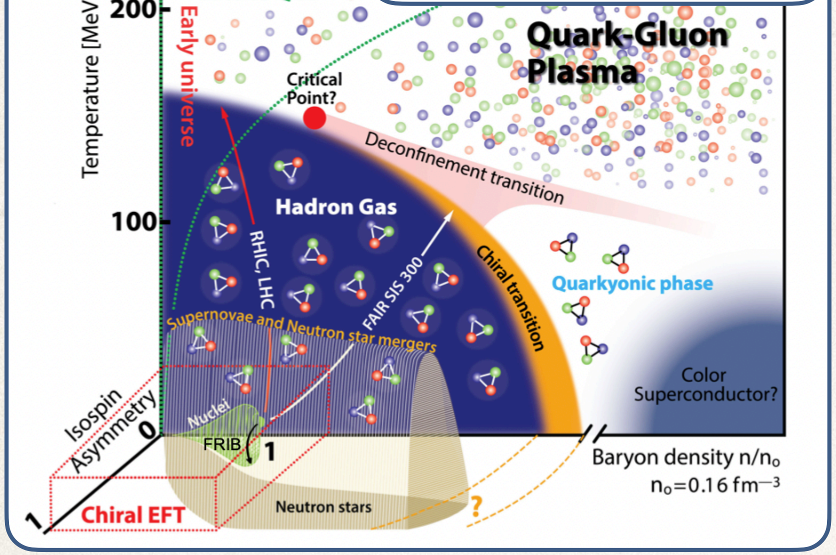


Besides the top ~ 1km, the properties of neutron star interiors are mostly unknown.

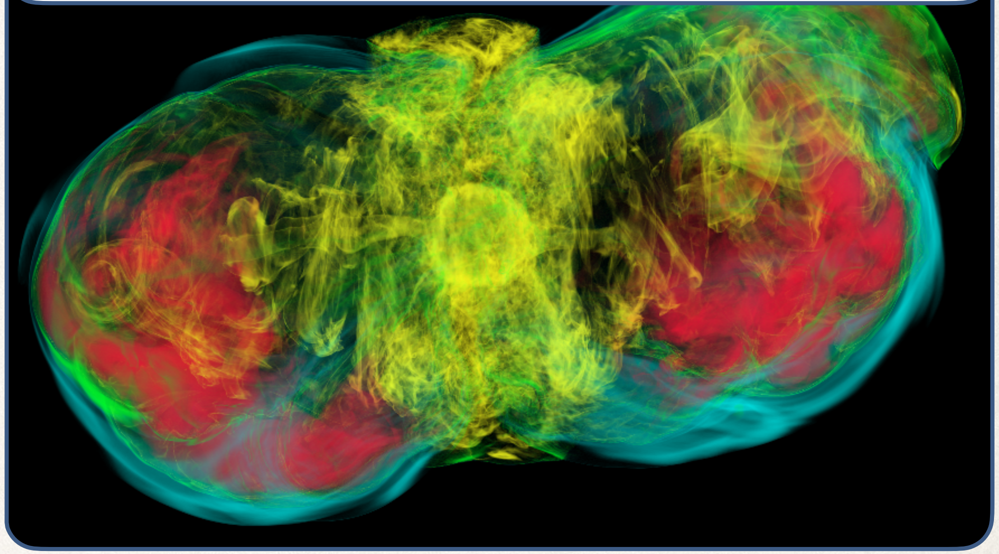


The dense matter equation of state is a key question of fundamental physics and astrophysics

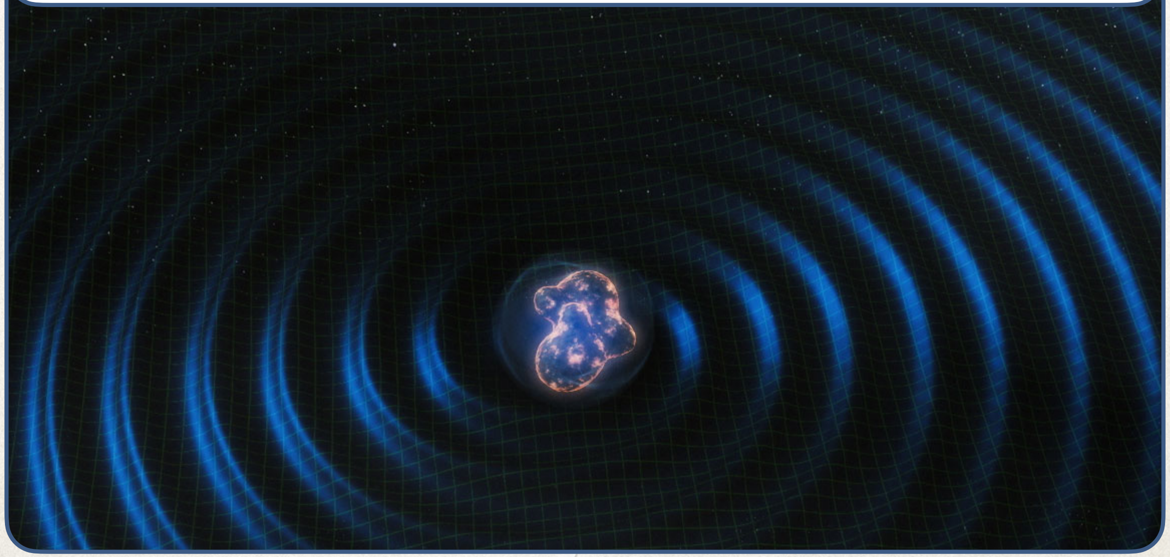
Nuclear physics

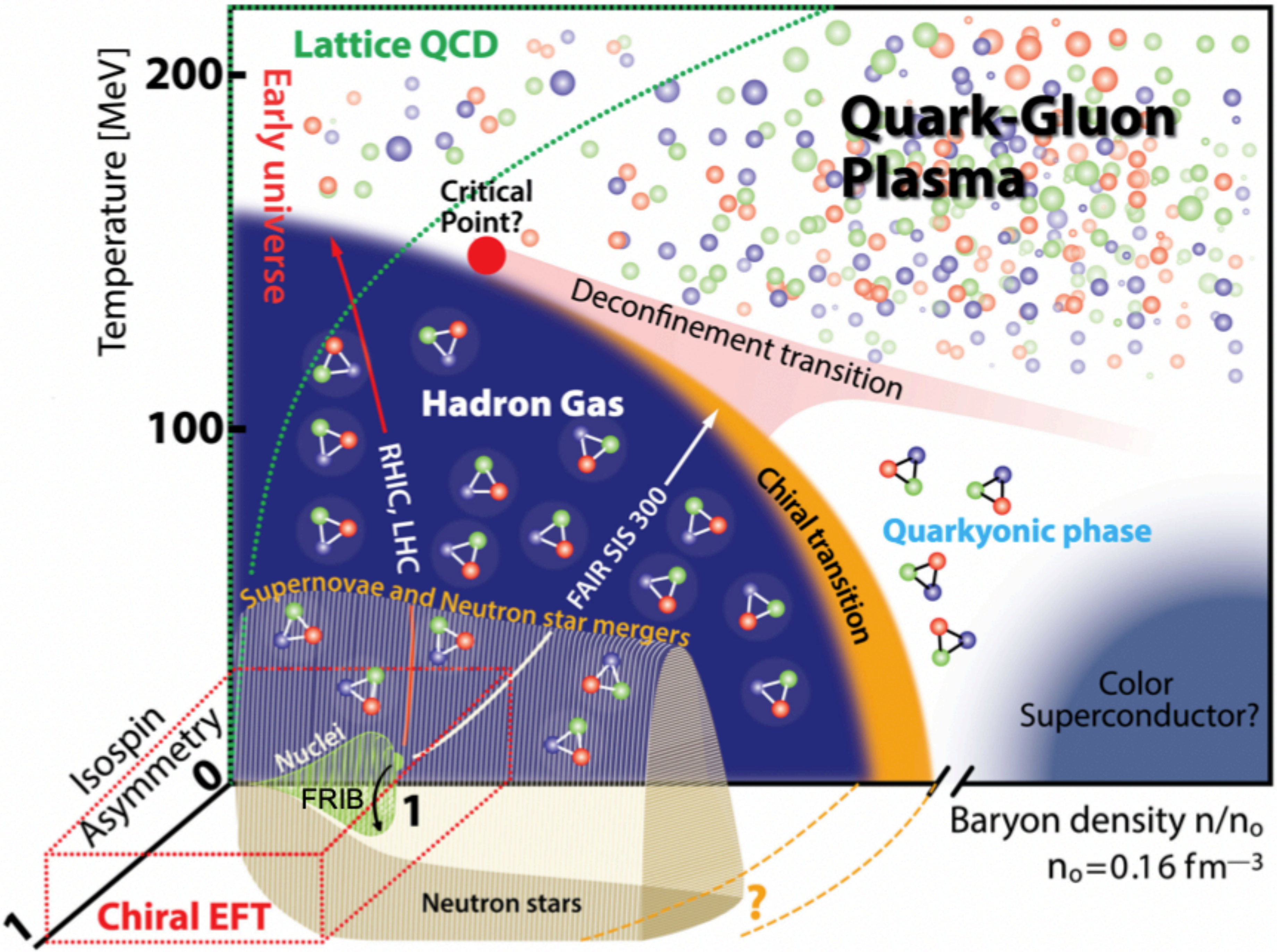


Supernovae mechanisms



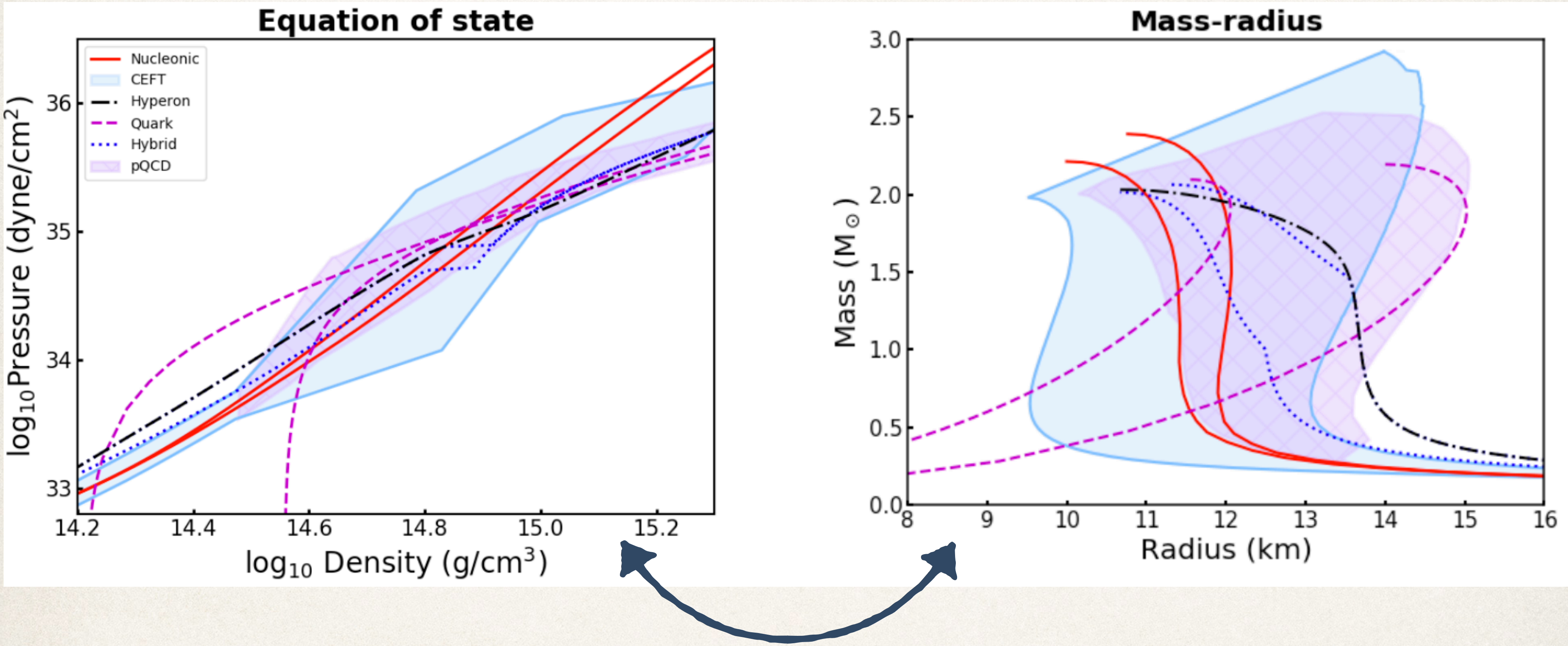
Mergers of compact objects





Lattice QCD
200
100
Temperature [MeV]
Early universe
Critical Point?
Quark-Gluon Plasma
Deconfinement transition
Hadron Gas
RHIC, LHC
FAIR SIS 300
Chiral transition
Quarkyonic phase
Supernovae and Neutron star mergers
Color Superconductor?
Isospin Asymmetry
0
1
Nuclei
FRIB
1
Baryon density n/n₀
n₀=0.16 fm⁻³
Chiral EFT
Neutron stars
?

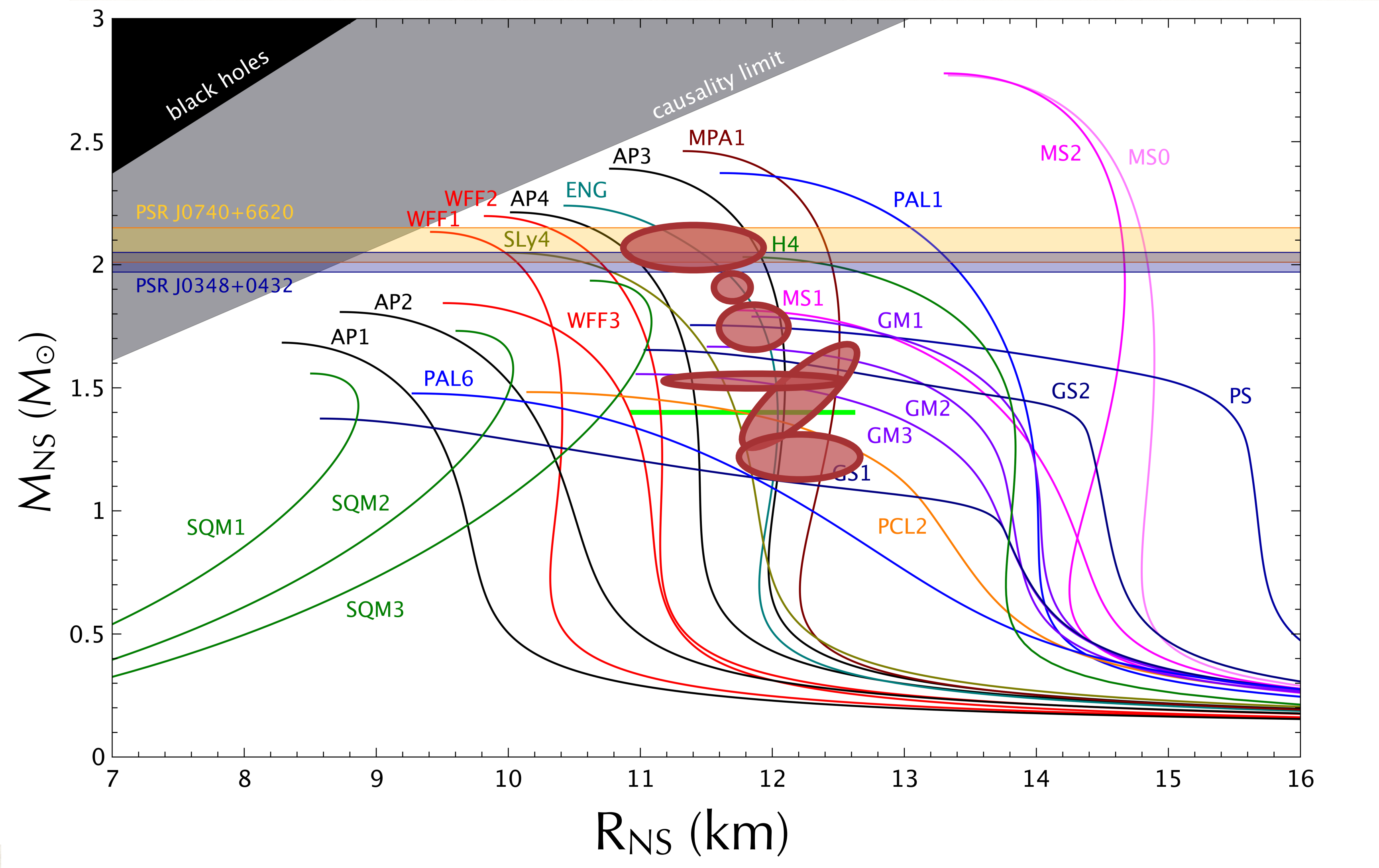
Dense nuclear matter is described by an equation of state P(ρ).



Equations of stellar structure

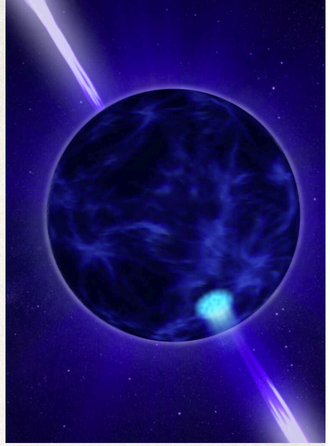
Figure from Watts et al. 2017

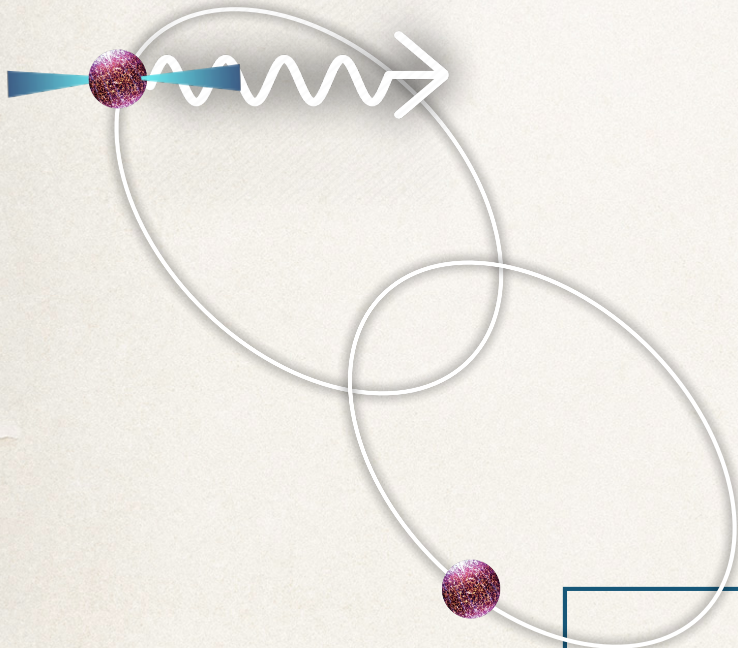
To determine the equation of state P(ρ), one needs to measure M_{NS} and/or R_{NS}.

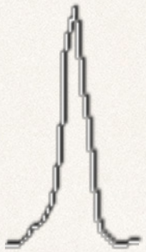


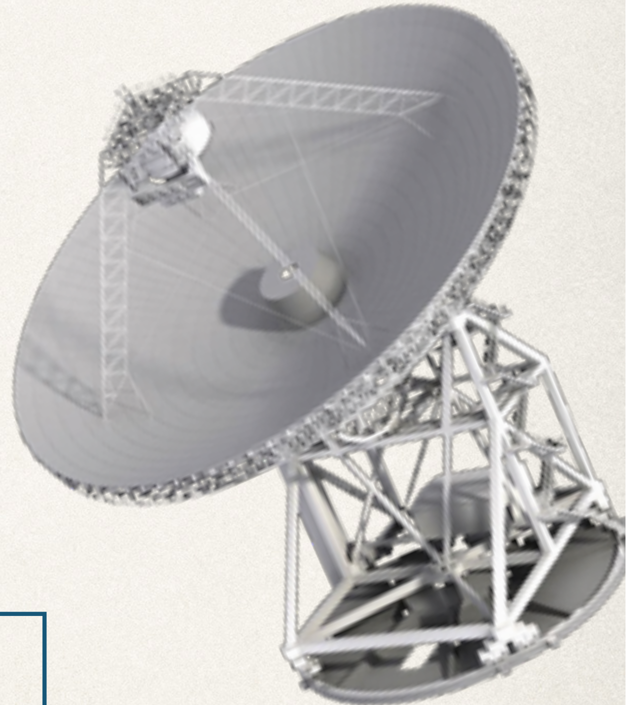
Credits: N. Wex

Radio timing of pulsars in binary systems permits measurements of orbital parameters.







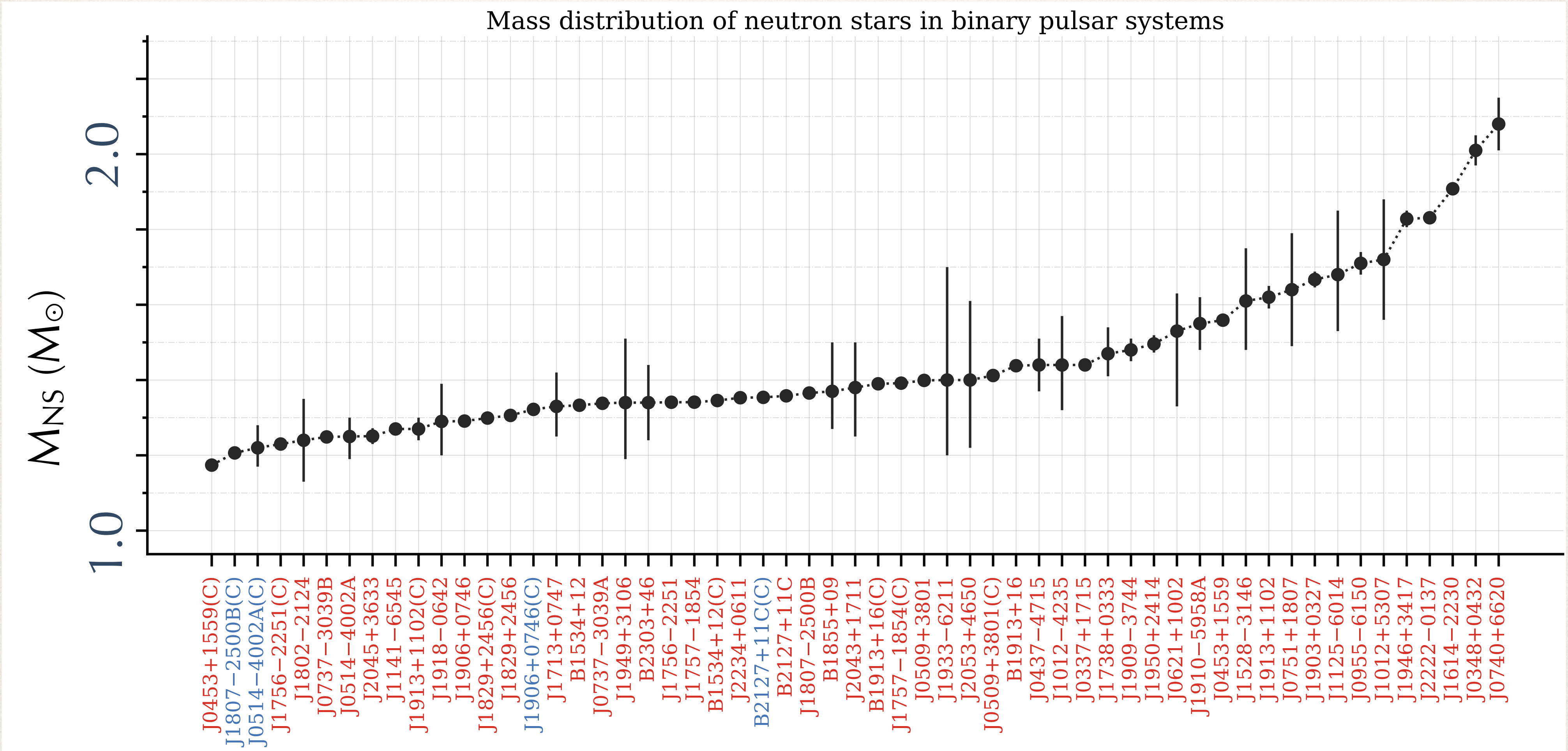


Best M_{NS} measurement
Double-NS system PSR B1913+16
$M_{PSR} = 1.4414 \pm 0.0002\ M_{\odot}$

Weisberg et al. 2005

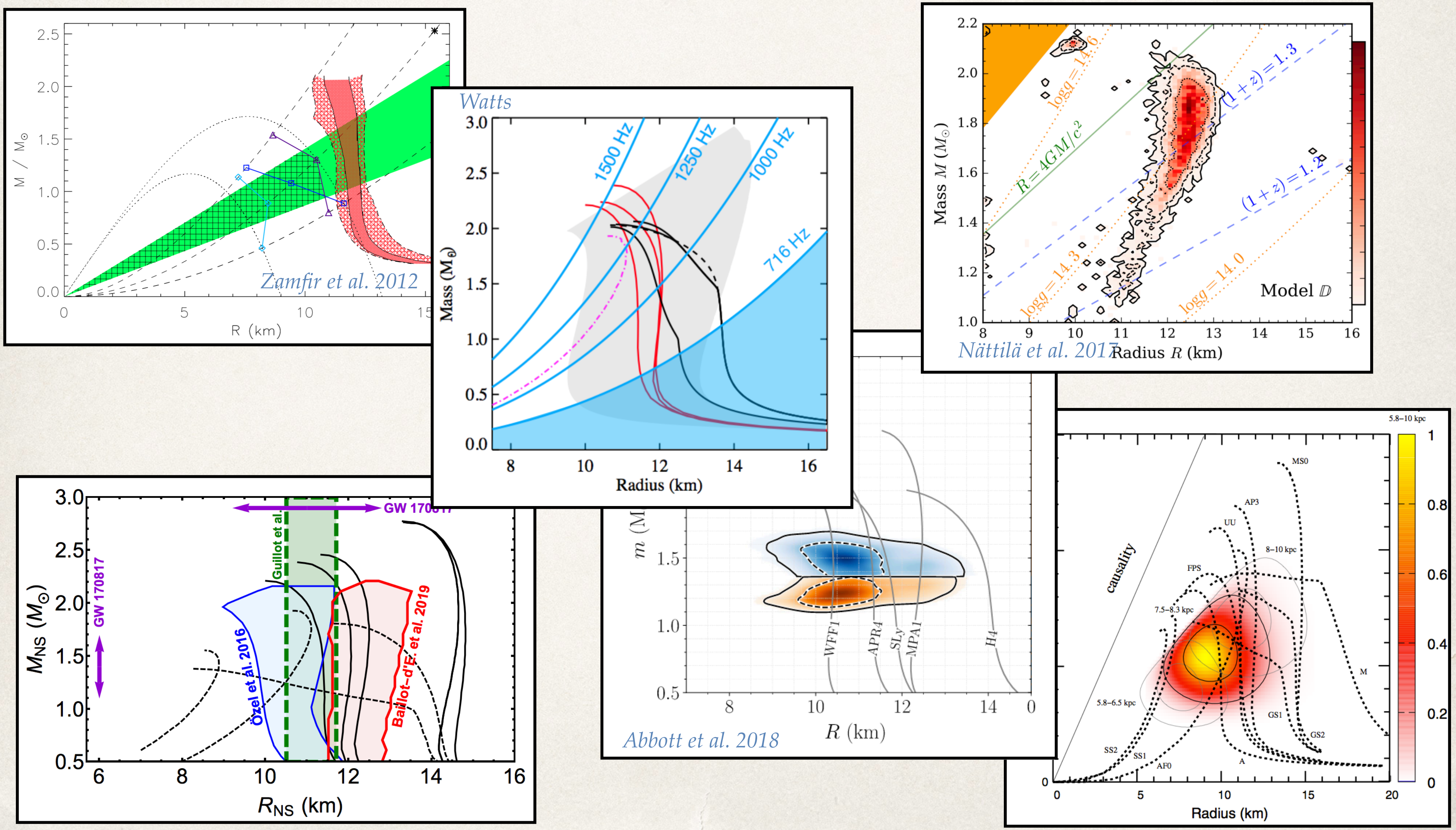
?
Backup slides

Neutron star masses cover a wide range from about 1.2 to 2.0 M☉.



Credits: P. Freire

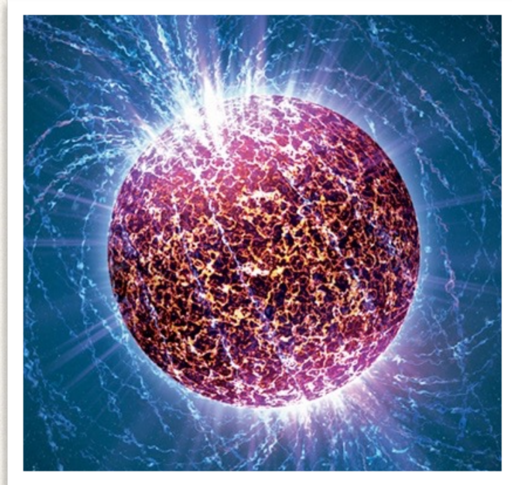
Many complementary methods to measure M_{NS} and R_{NS}, exist, with varying degrees of success.



Measuring the radius with precision is much more difficult.

To measure the radius, we need to:

- observe the surface thermal emission,
- correctly model this emission,
- know the distance independently.



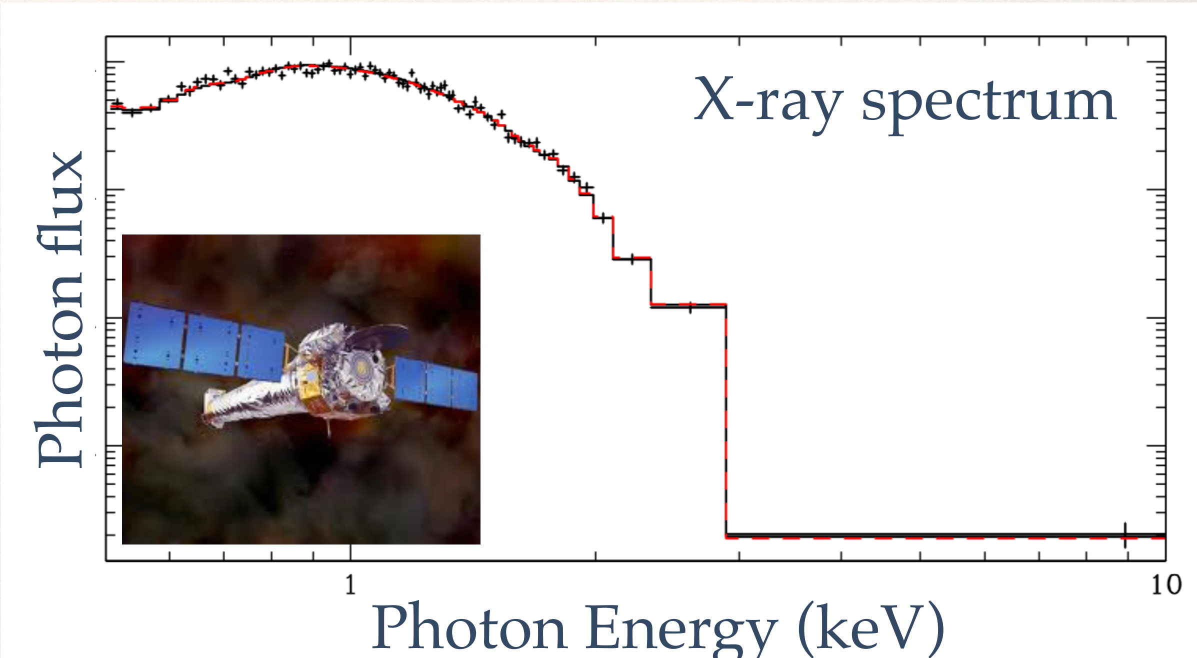
Luminosity

$$L = 4\pi R^2 \sigma T_{\mathrm{eff}}^4$$

$$\downarrow$$

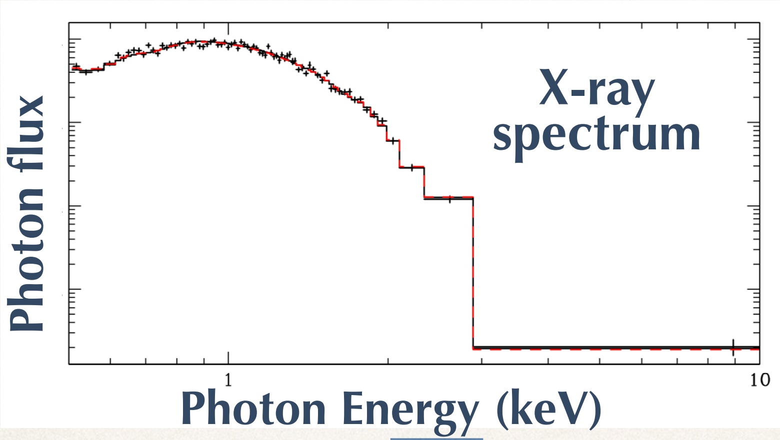
Flux

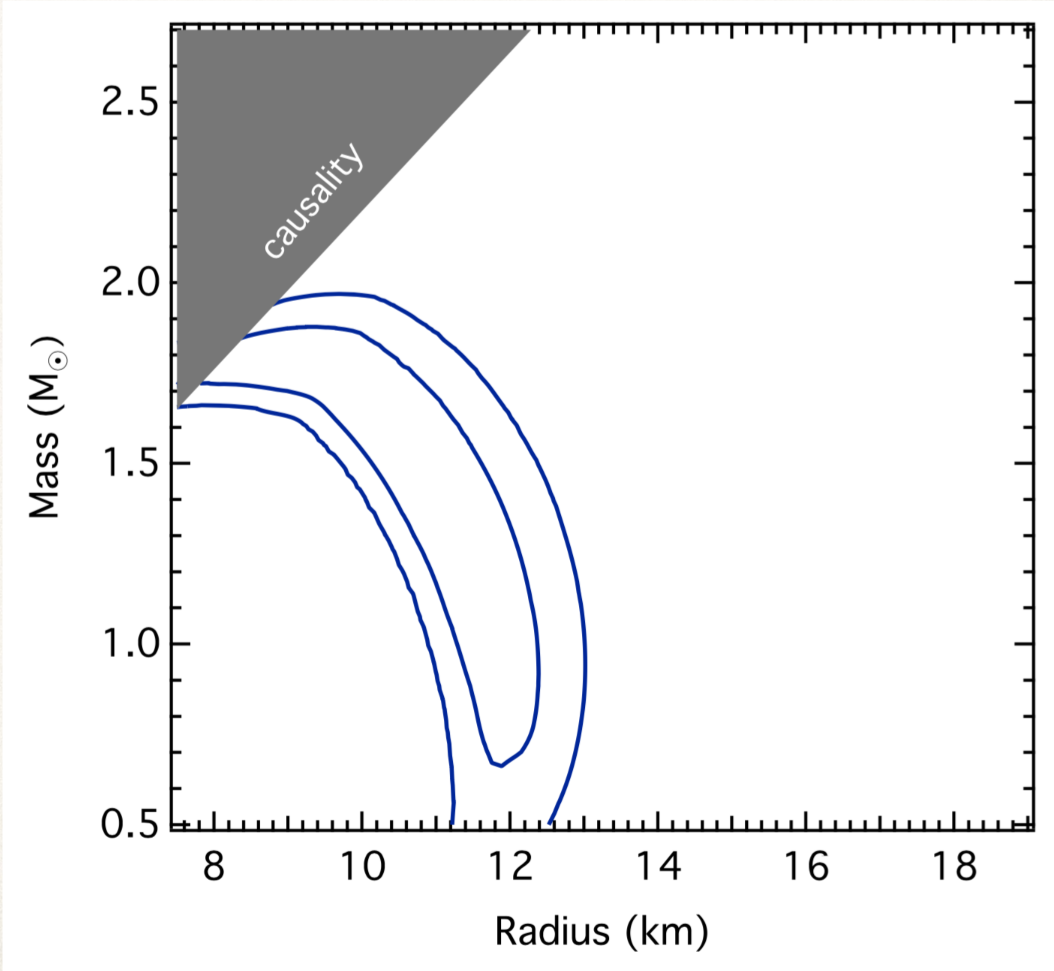
$$F = \left(\frac{R}{D}\right)^2 \sigma T_{\mathrm{eff}}^4$$



Because of gravitational redshift, the radius is degenerate with the mass.

$$R_\infty = R_{\rm NS}\,(1+z) = R_{\rm NS}\left(1 - \frac{2GM_{\rm NS}}{R_{\rm NS}\;c^2}\right)^{-1/2}$$



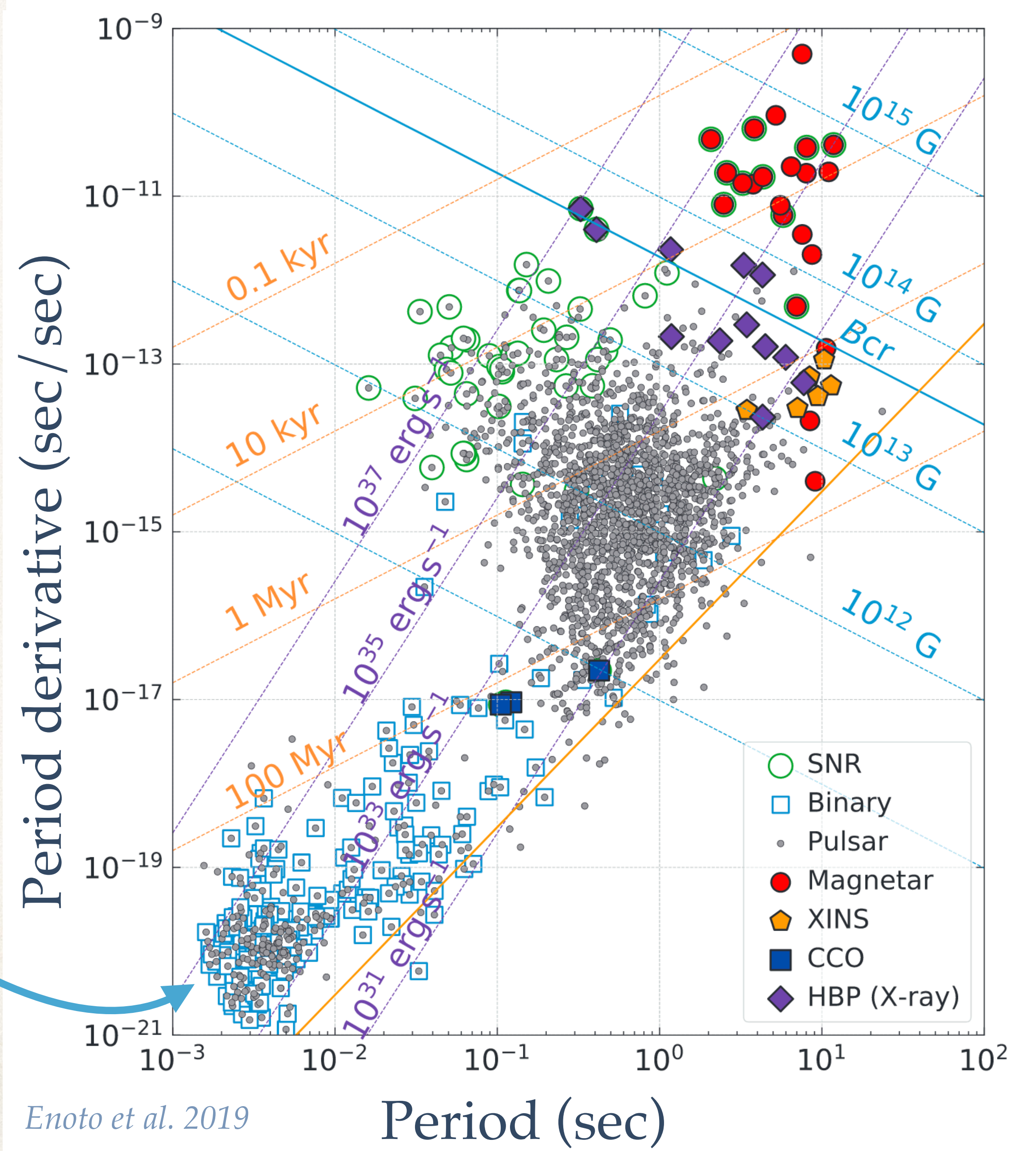


$$F_{\rm X} \propto \left(\frac{R_\infty}{D}\right)^2 \sigma T^4_{\rm eff,\infty}$$

Bogdanov et al. 2016

To measure M_{NS} and R_{NS}, choose your players carefully!

Millisecond pulsars are old and fast rotating neutron stars

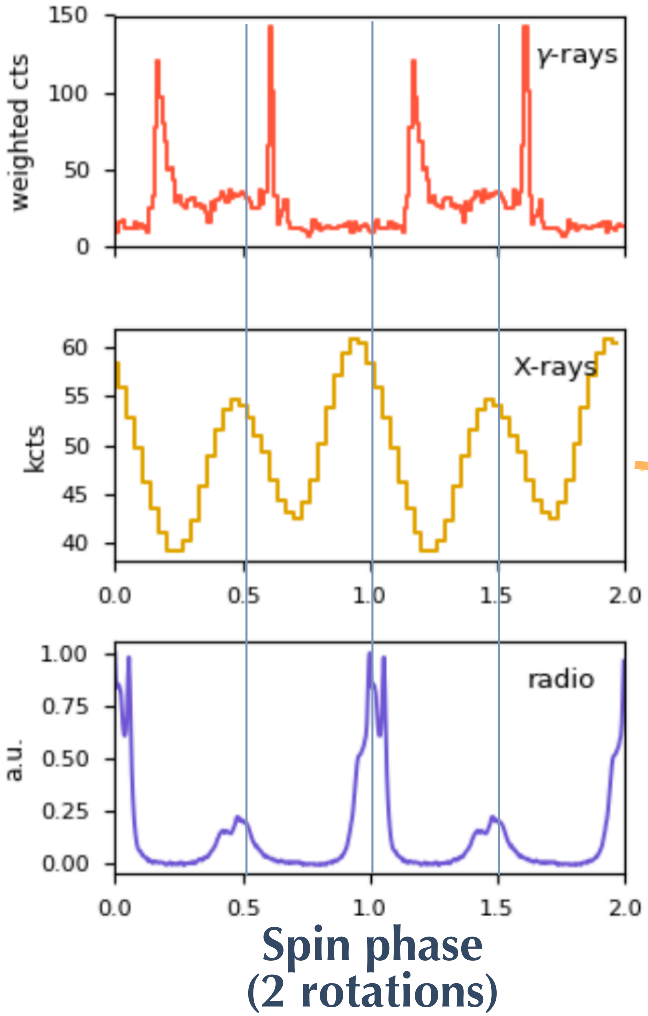


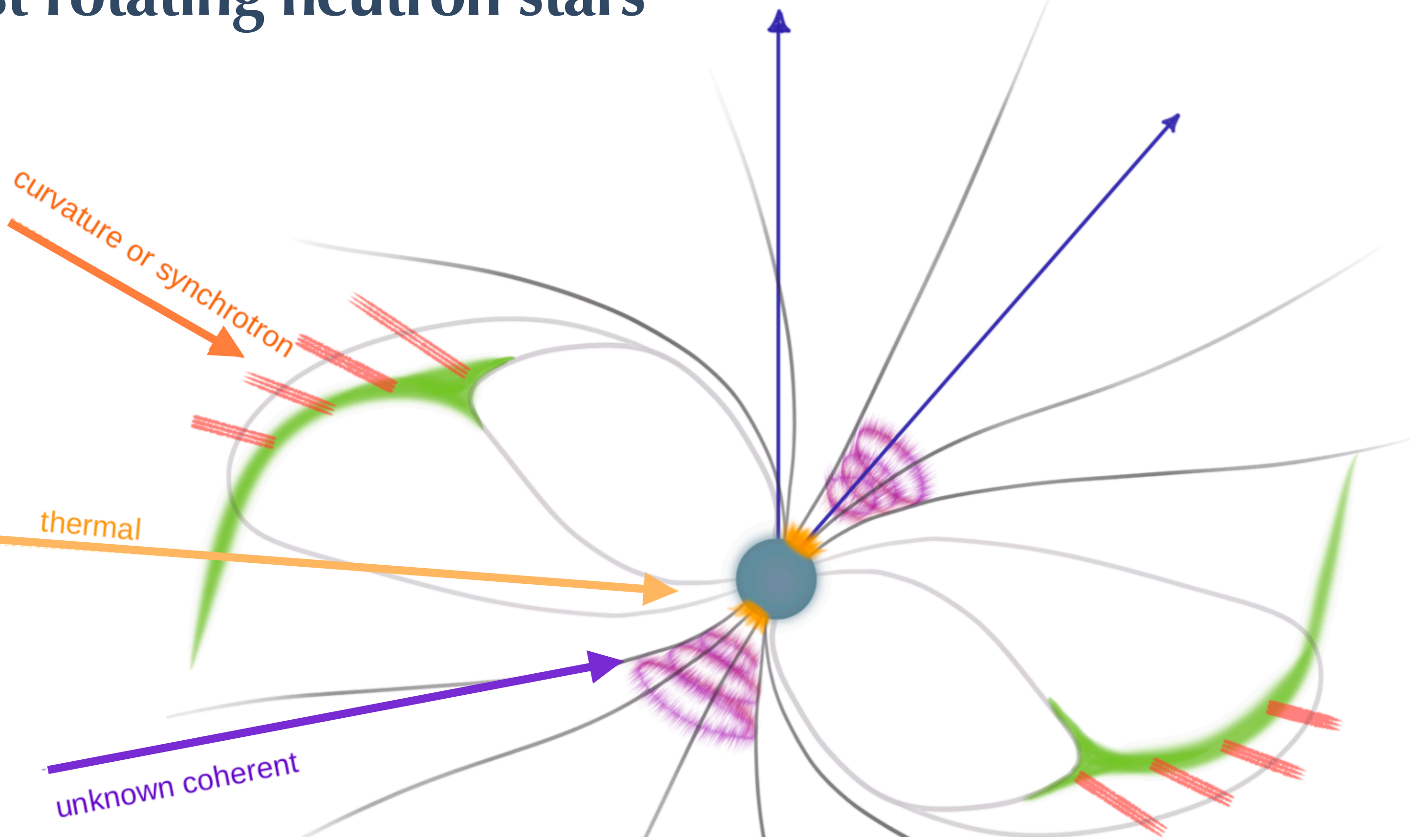
Enoto et al. 2019

X-ray emitting millisecond pulsars can be trusted!

B ~ $10^8 - 10^9$ G
P_{spin} ~ 2 – 5 msec

Old fast rotating neutron stars



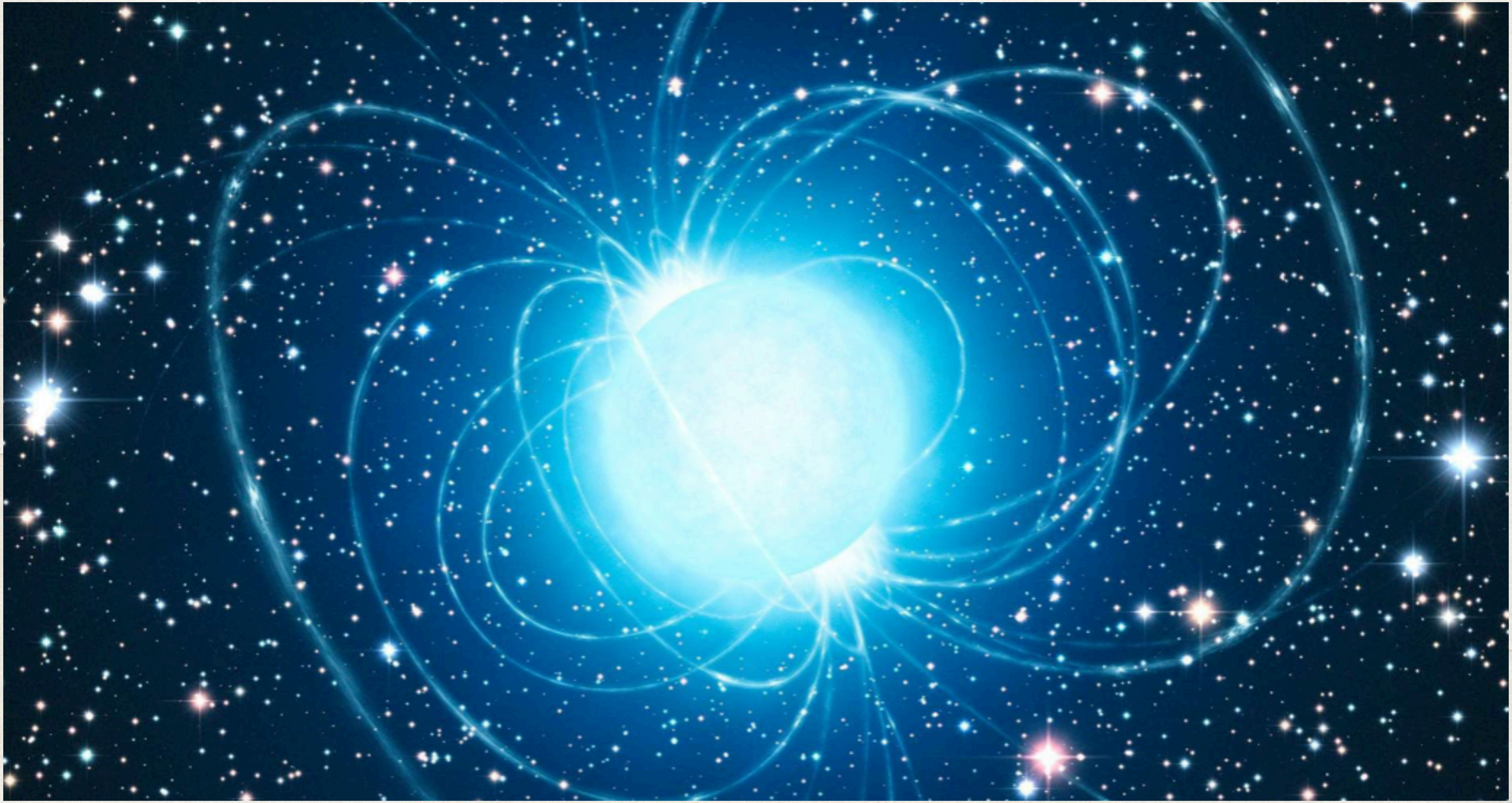


Advantages of millisecond pulsars:

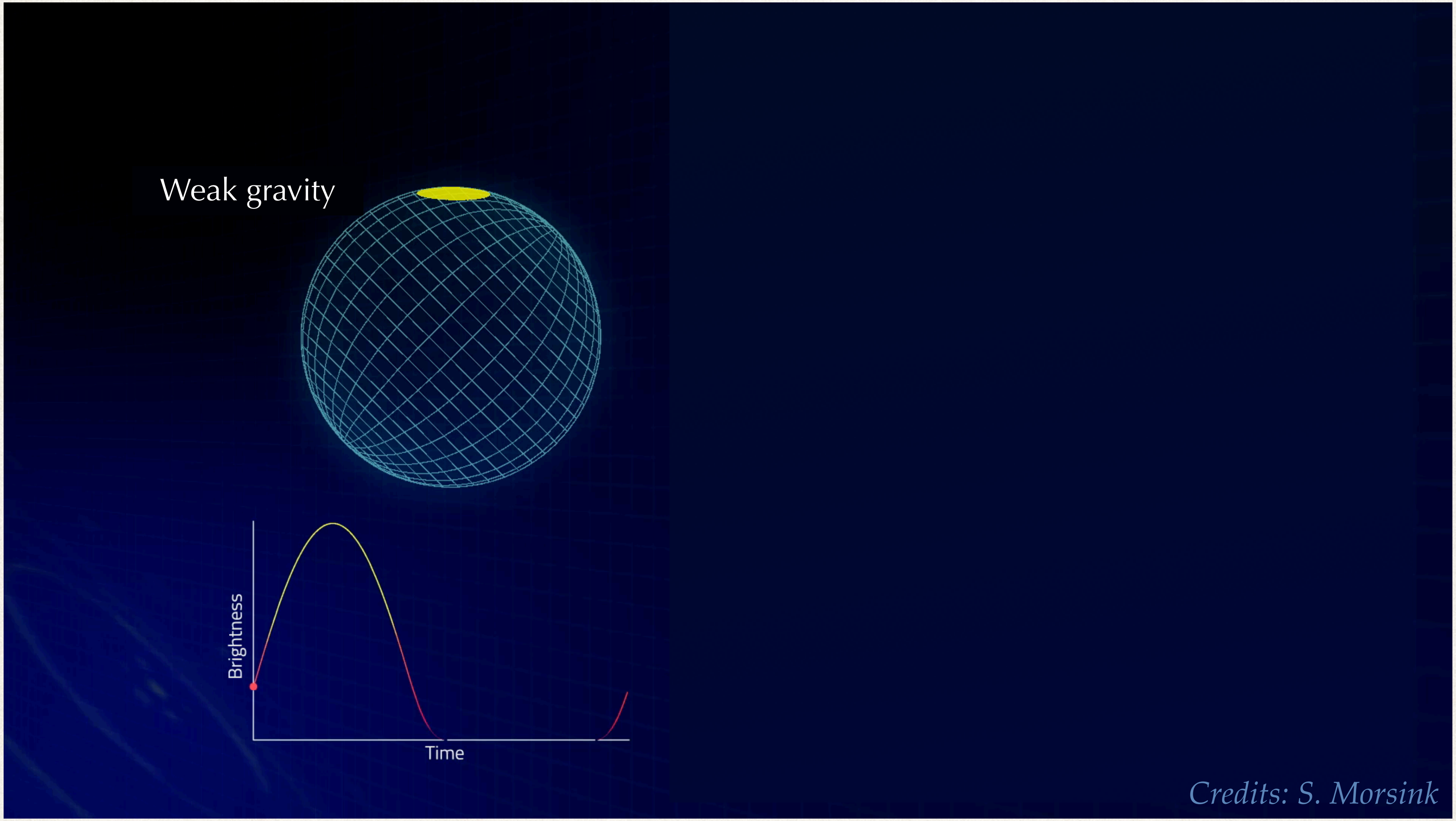
- Very stable on long time scales
- Low B-fields and no accretion
- Purely thermal X-ray emission
- Additional info from radio/gamma

Credits: A. Bilous

The hot X-ray emission of millisecond pulsar comes from e^-/p^+ bombardment of the surface heating the polar caps.

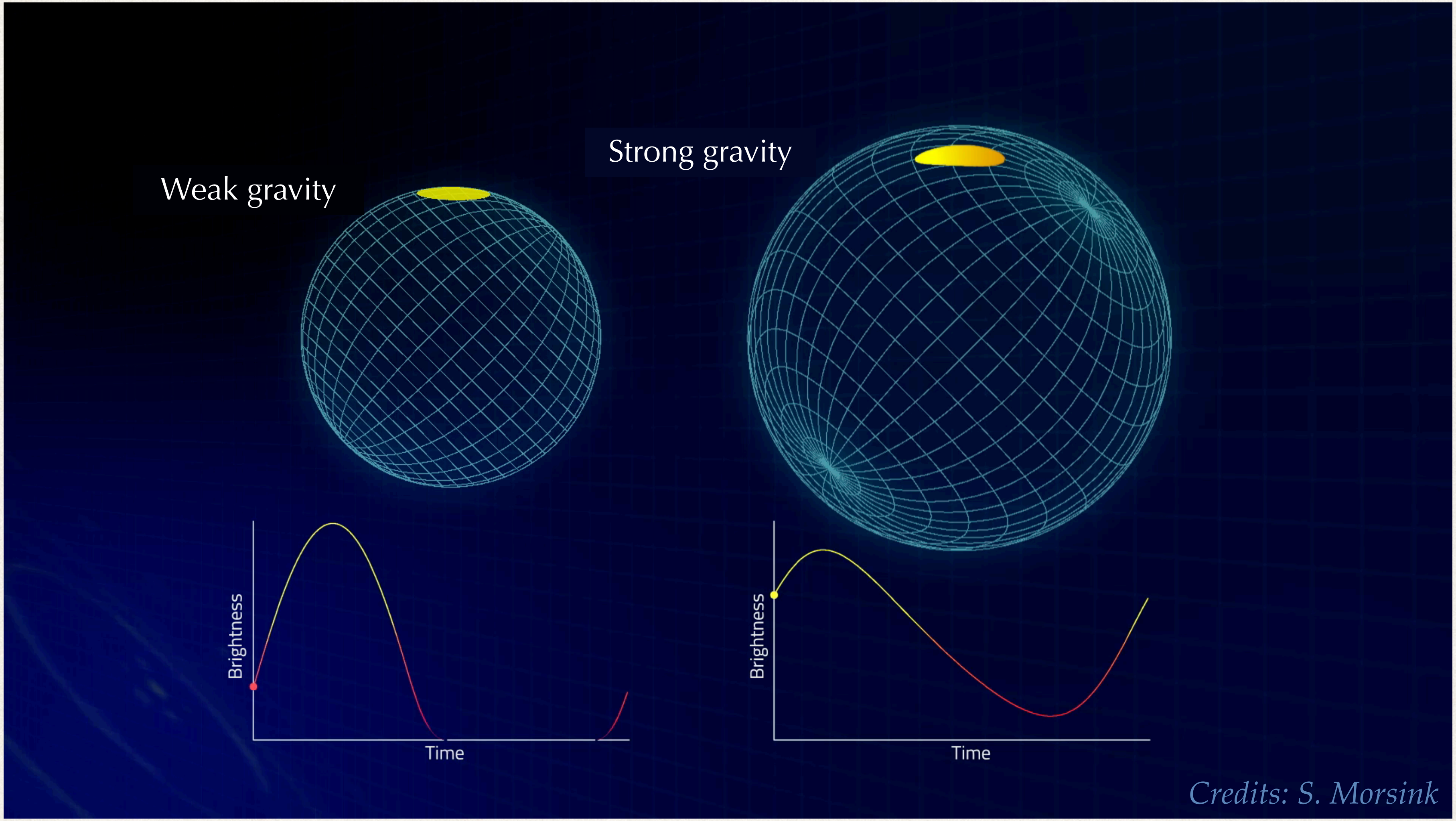


Credits: ESO



Credits: S. Morsink

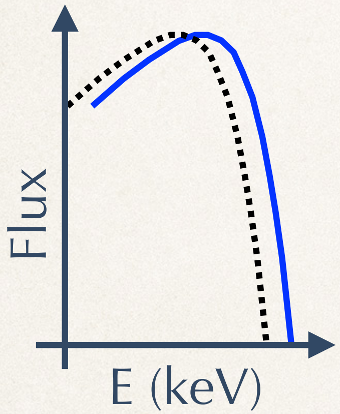
Strong gravity permits seeing beyond the hemisphere of the neutron star.

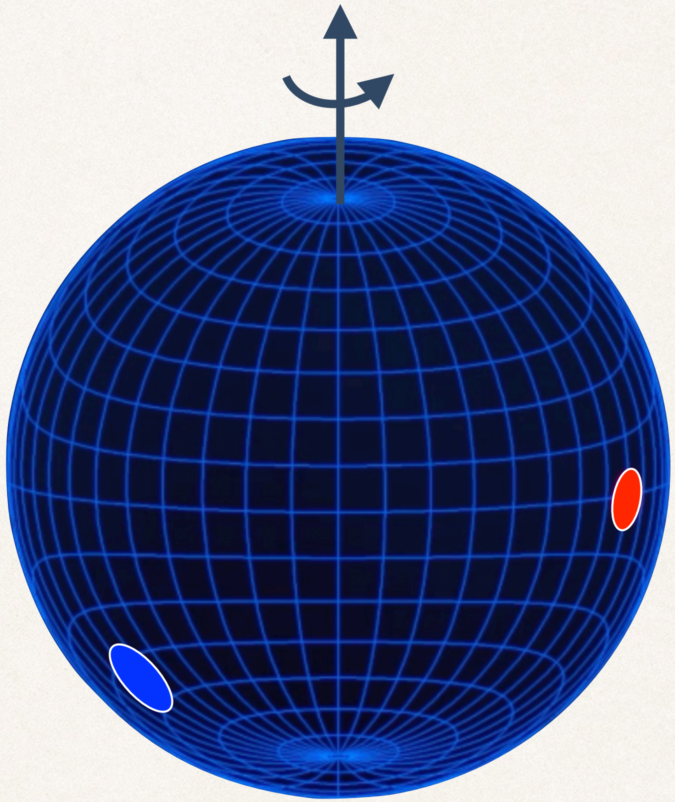


Pulse profile modelling to determine the compactness M_{NS}/R_{NS}

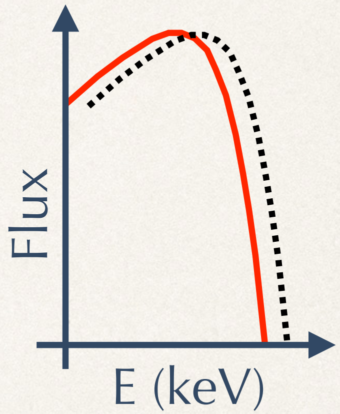
The Doppler effect break the degeneracy between M_{NS} and R_{NS}.

Approaching spot is blue shifted

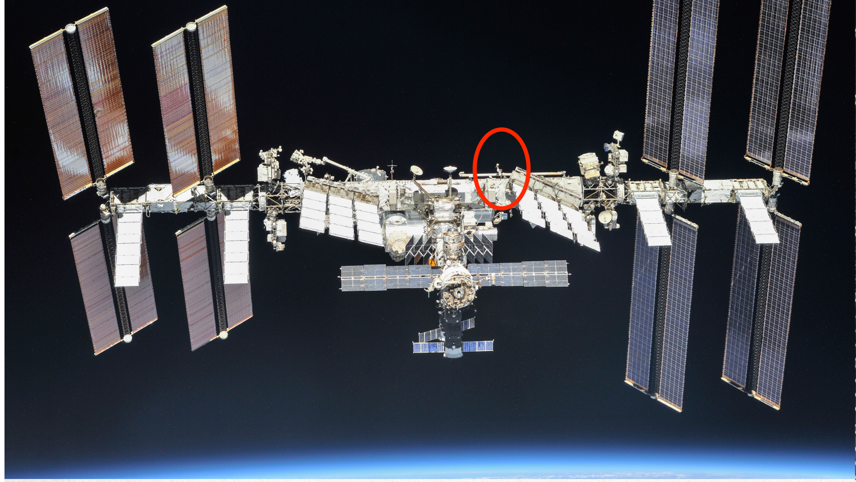


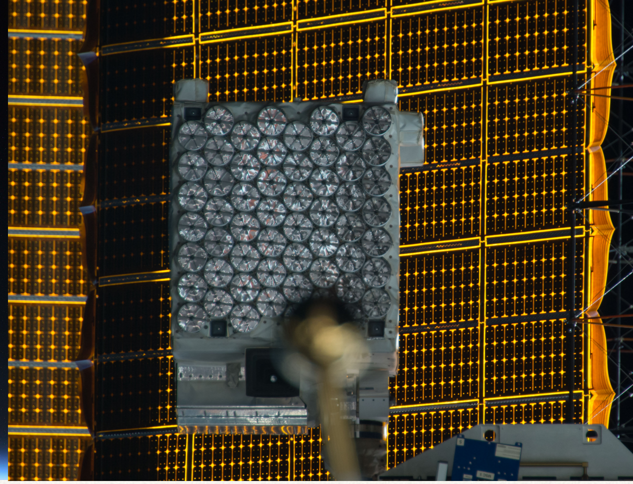


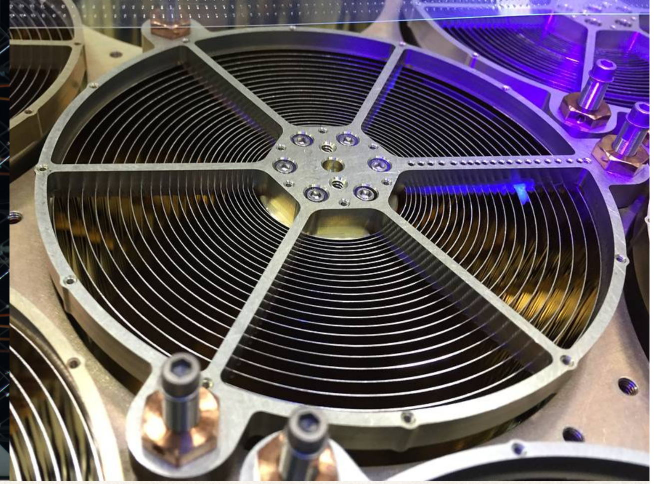
Receding spot is red shifted



The effect depends on the line of sight velocity, i.e., <u>spin frequency</u> and <u>distance from rotation axis</u>

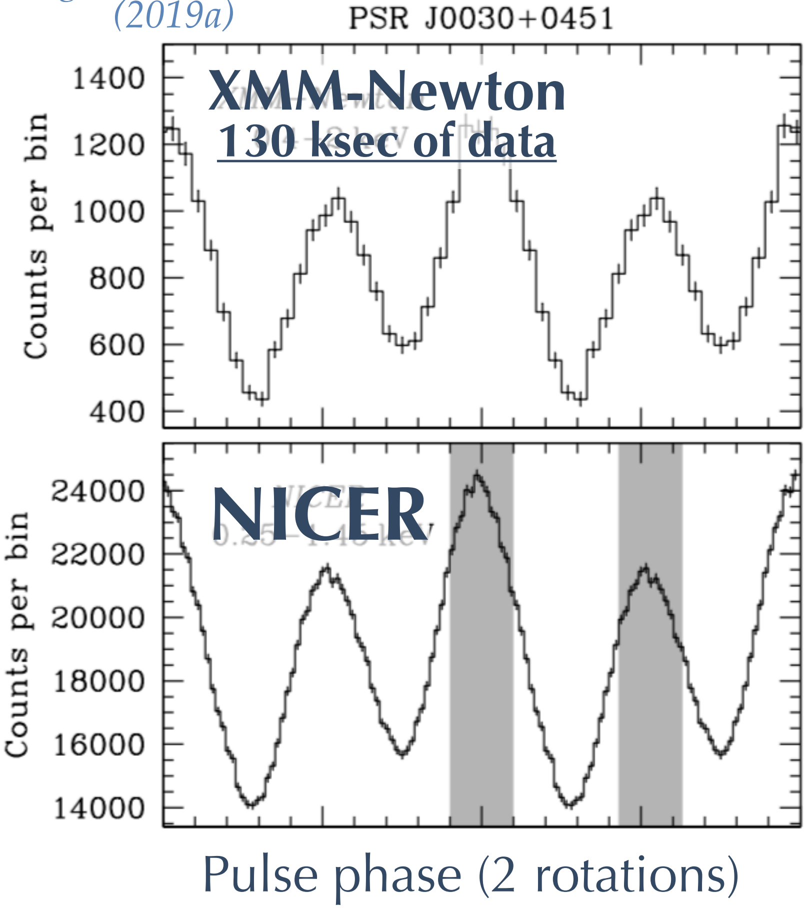


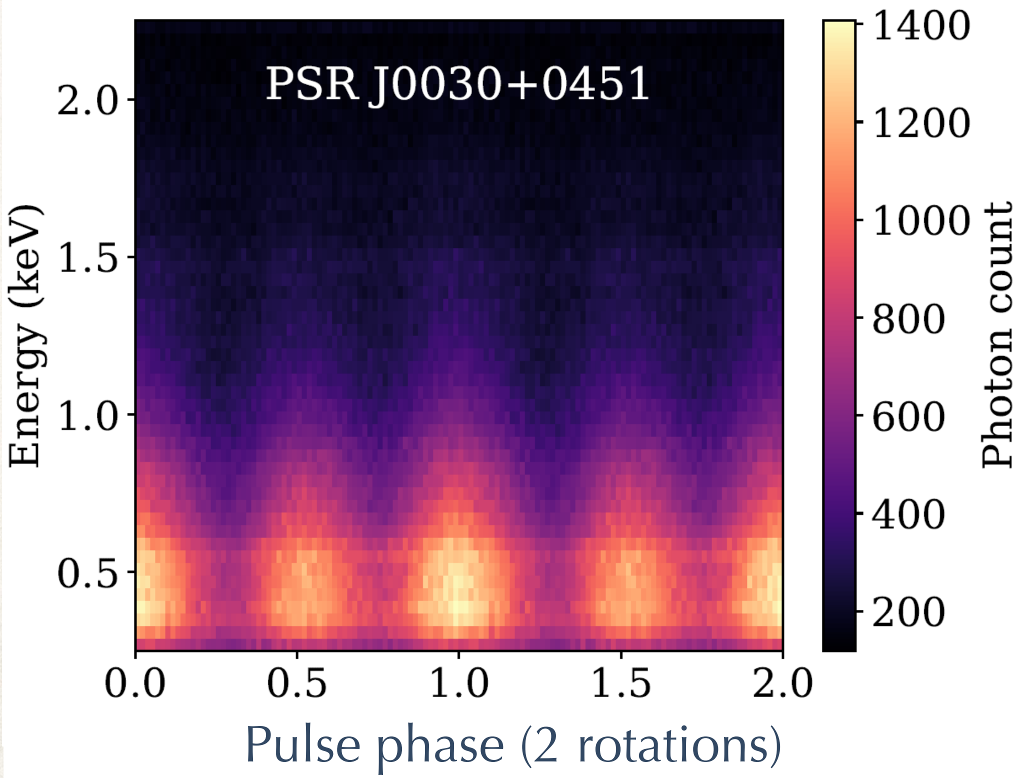


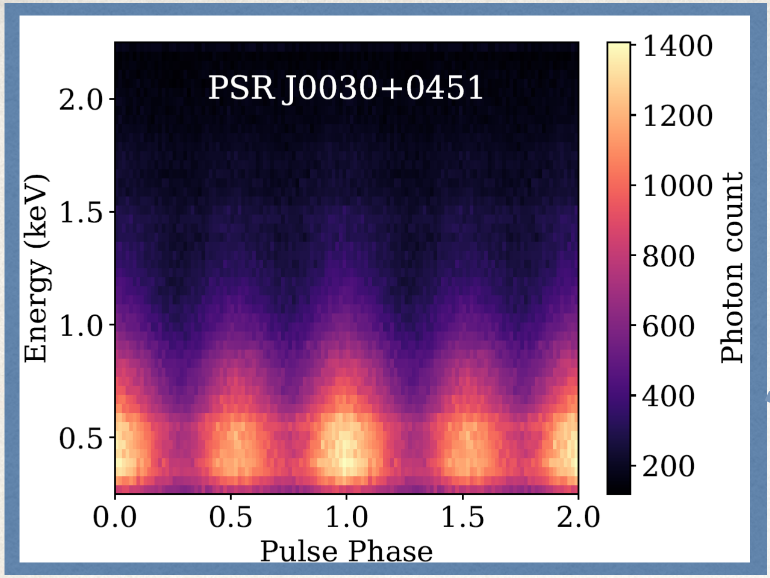


NICER has given us beautiful data sets to perform pulse profile modelling.

Bogdanov, SG et al. (2019a)

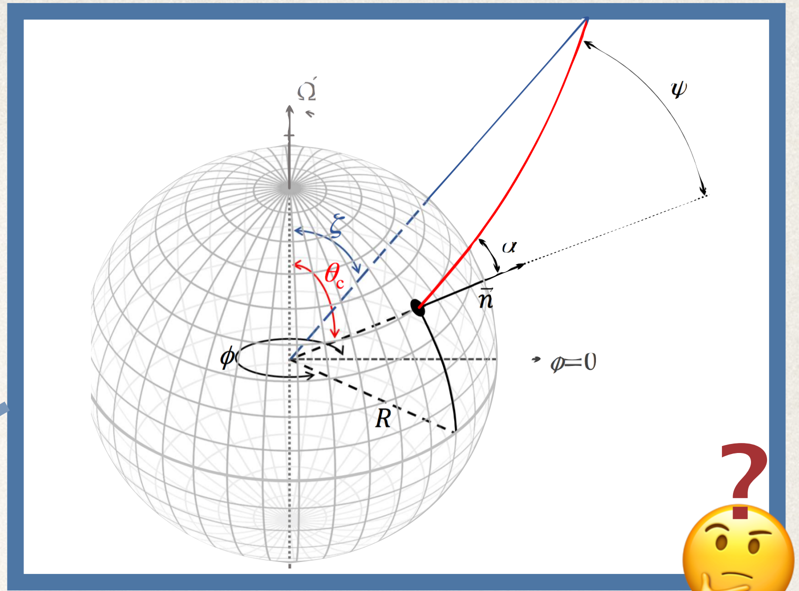






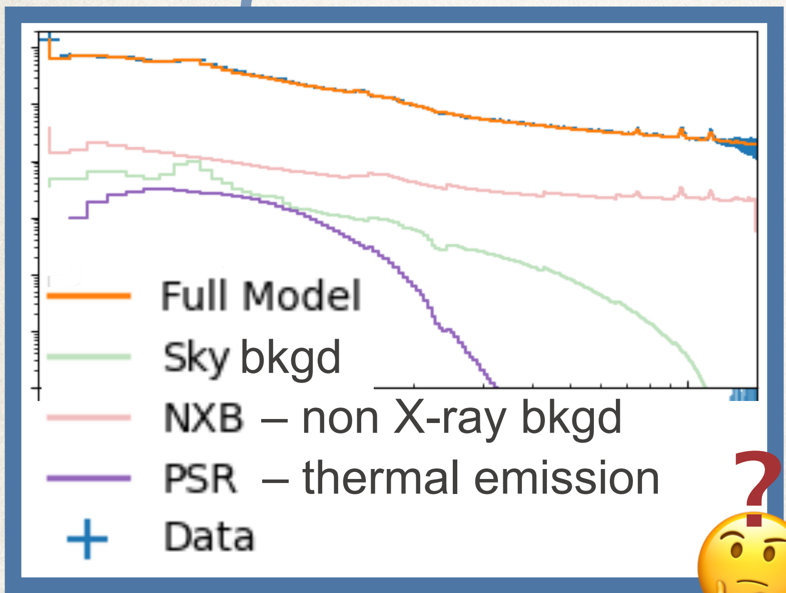
Priors

mass
distance
inclination

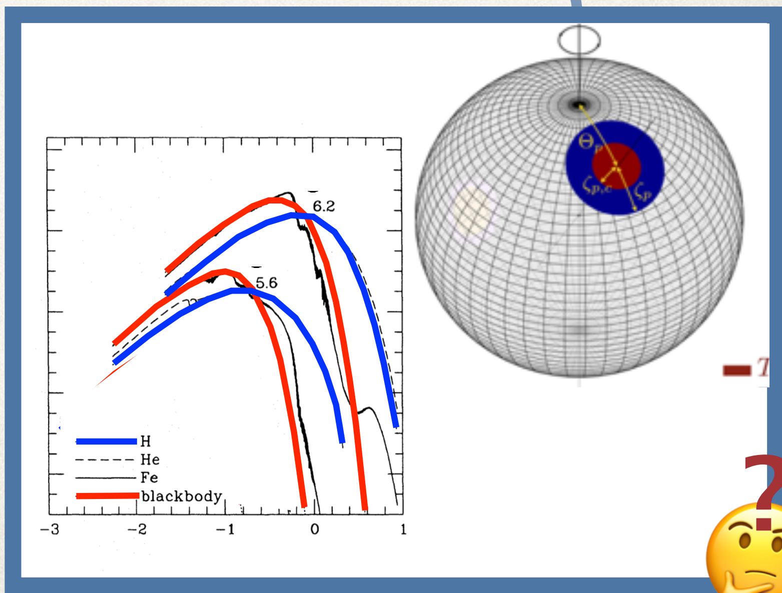


Backup slides

NS properties inference
(Likelihood statistical sampling)

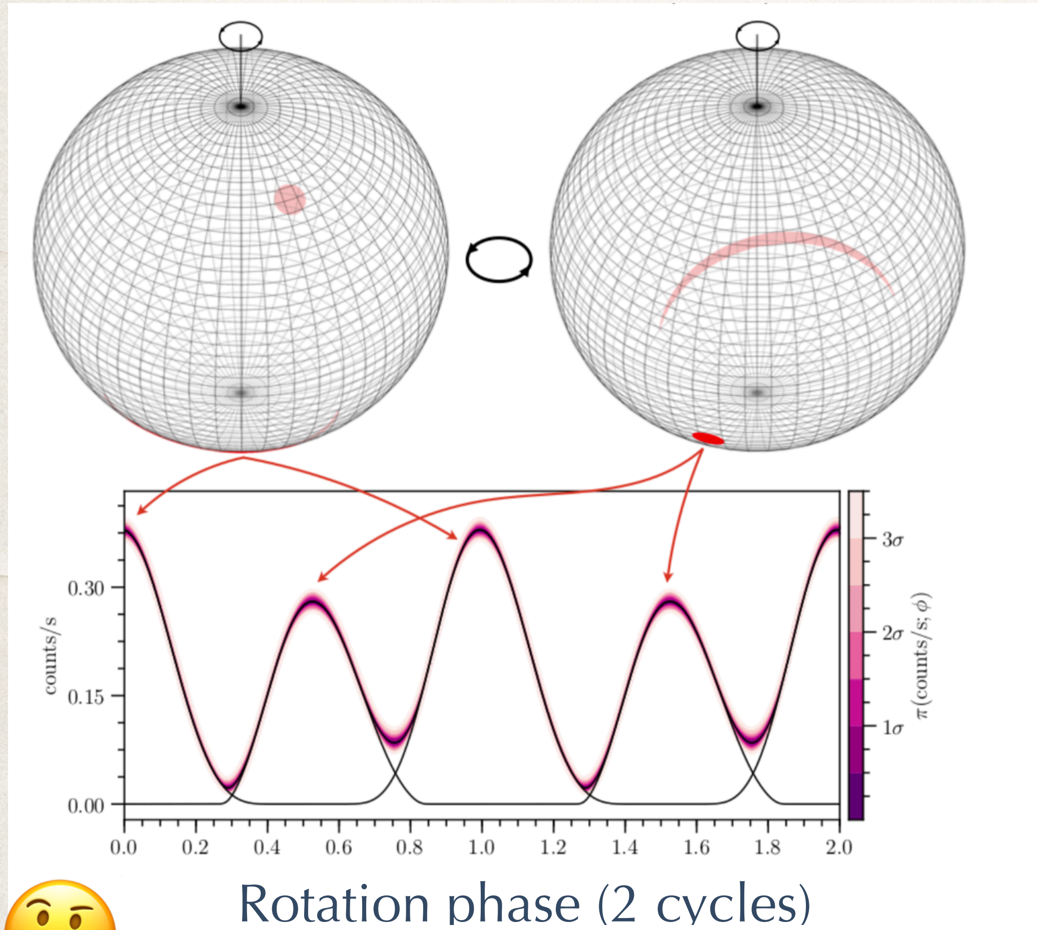


Mass,
Radius,
EOS



In addition to inferring the radii, we also map the surface emission.

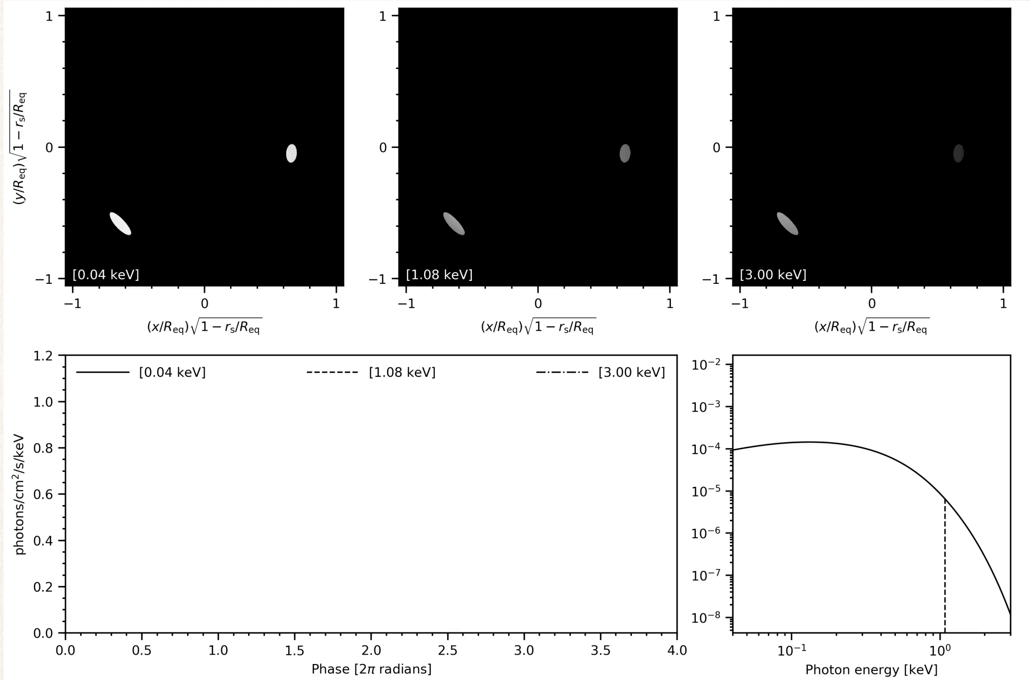
PSR J0030+0451



$R_{J0030} = 12.7 \pm 1.2$ km

Riley et al. (2019)
Miller et al. (2019)

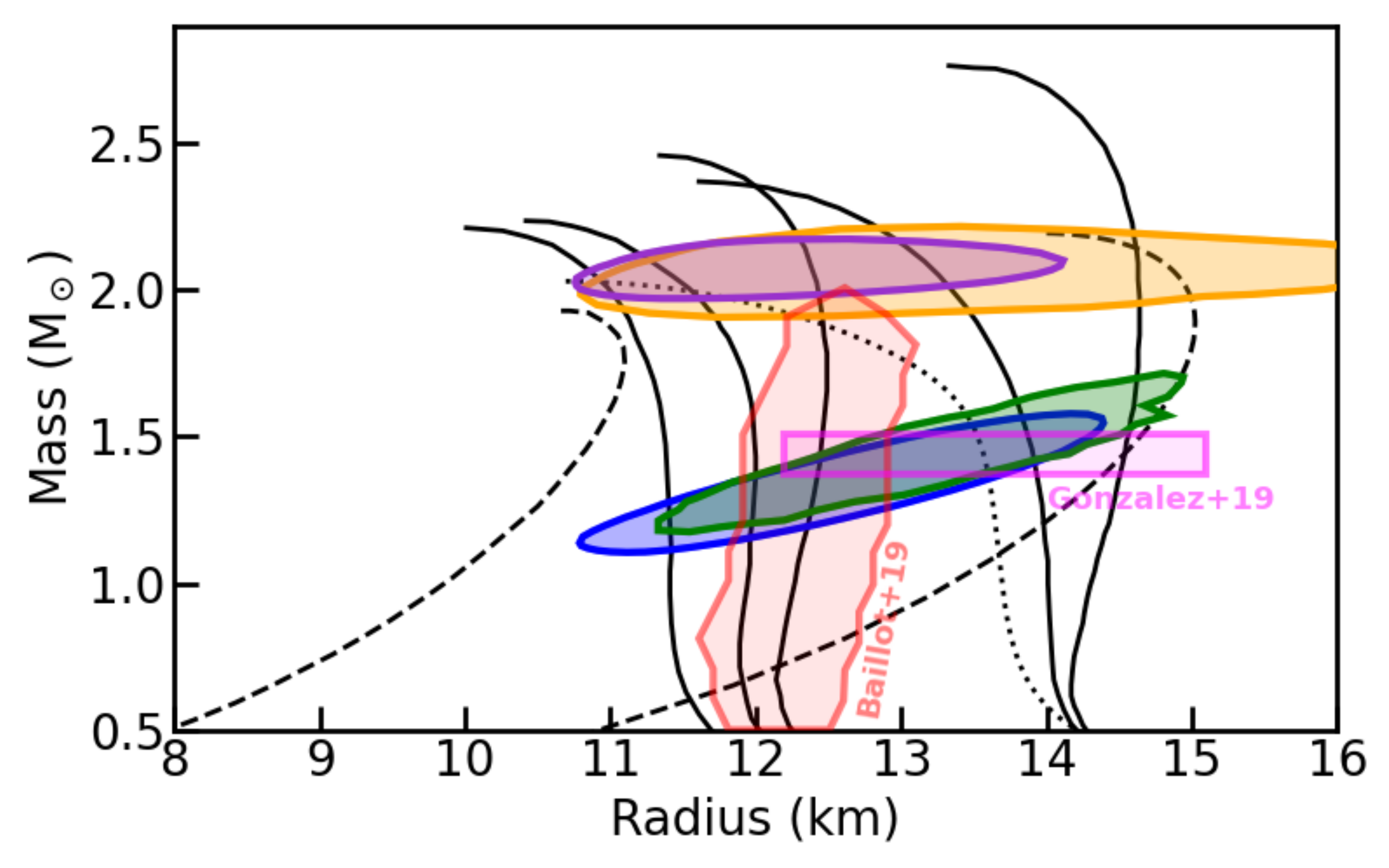
PSR J0740+6620



$R_{J0740} = 12.5 \pm 1.1$ km

Riley et al. (2021)
Miller et al. (2021)
Salmi et al. (2024)
Dittmann et al. (2024)

The results for the first two pulsars were consistent with other measurements.



- **PSR J0030+0451**
  - Riley et al. 2019
  - Miller et al. 2019
- **PSR J0740+6620**
  - Riley et al. 2021
  - Miller et al. 2021

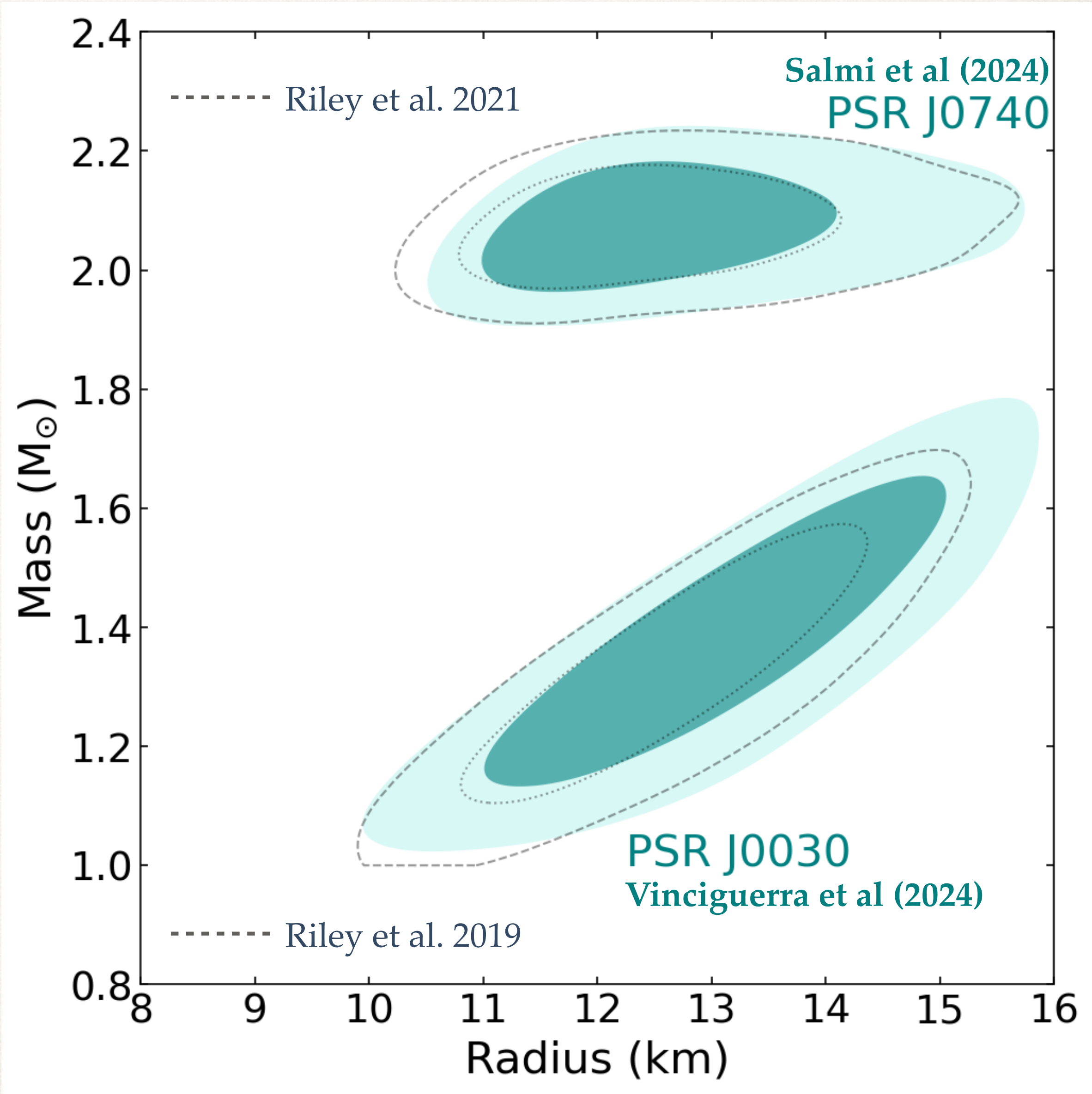
Cold Surface of MSP: Gonzalez-Caniulef et al. 2019

Multiple quiescent LMXB: Baillot-d'Etivaux et al. 2019

Updates to those results were published recently.

PSR J0740+6620
a massive MSP
+1.0 Msec of NICER data
Salmi et al (2024)

PSR J0030+0451
an isolated MSP
+XMM–Newton data
Vinciguerra et al (2024)

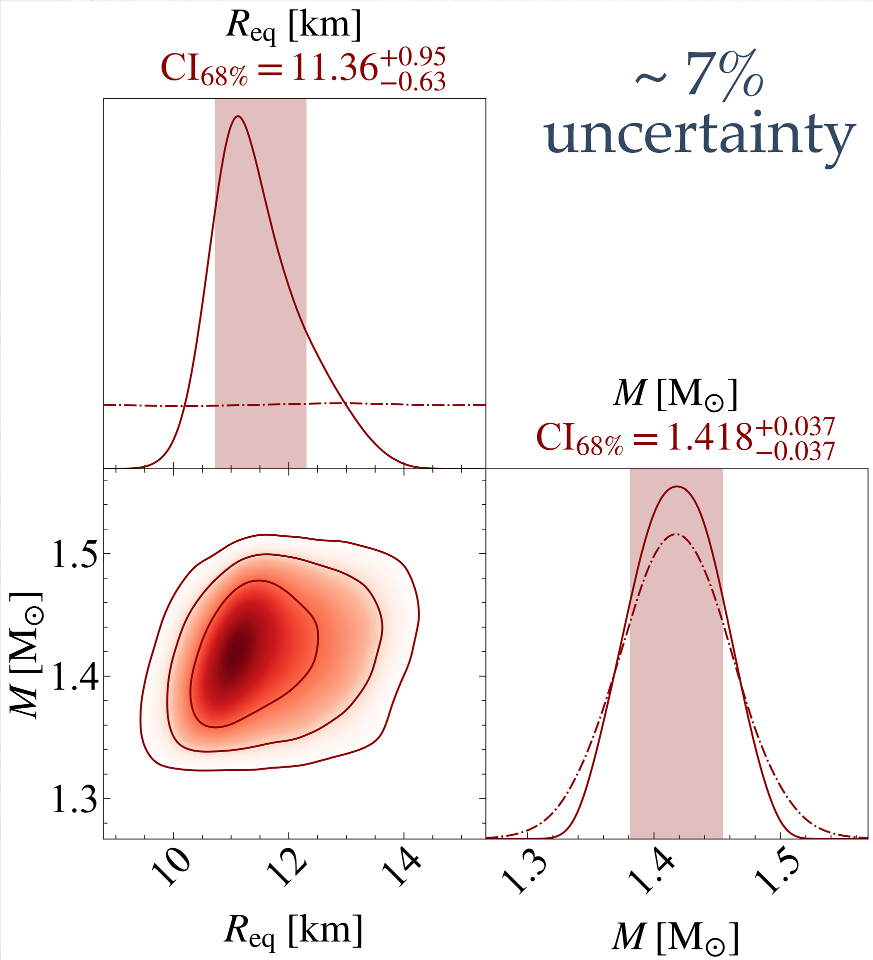


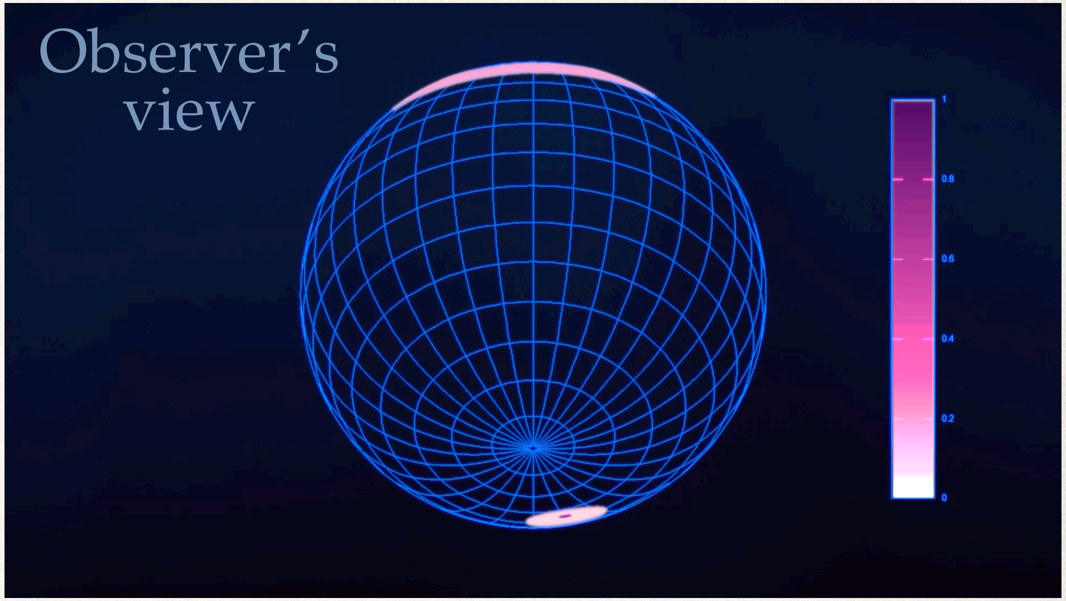
The newest radius constraints are the best so far…Again with a complex geometry.

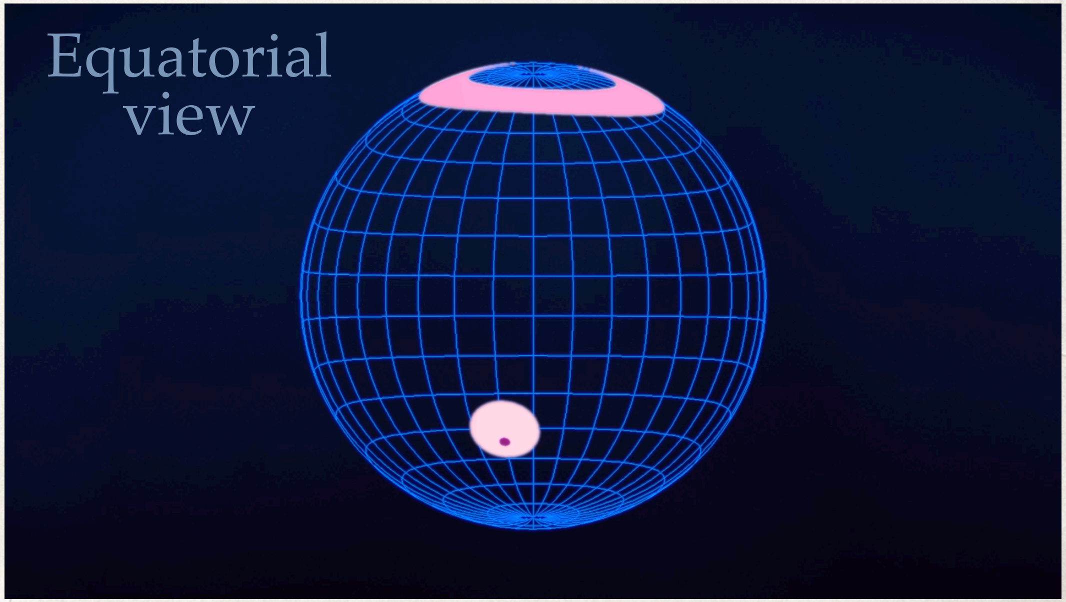
PSR J0437–4715

Radius: $11.36^{+0.95}_{-0.63}$ km

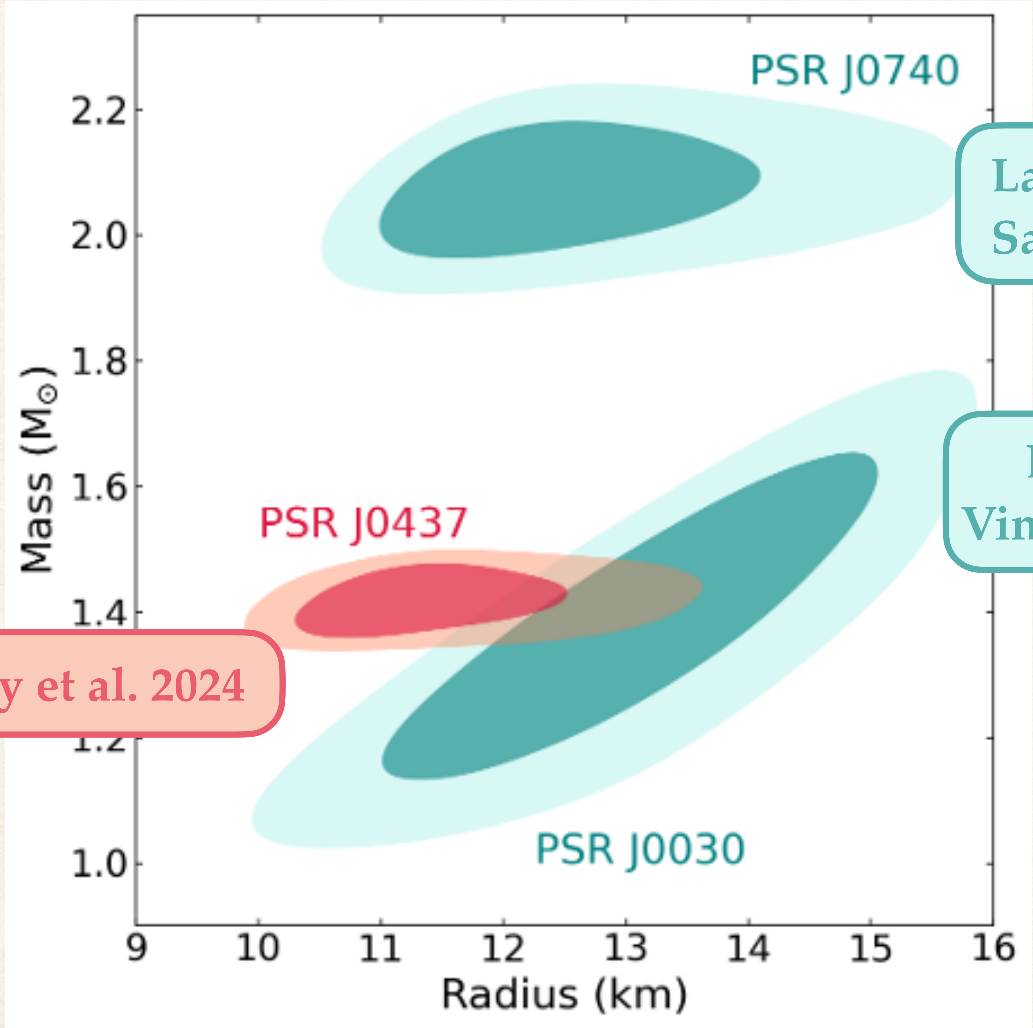
Choudhury et al. (2024)







These three measurements together. Why do they have different shapes ?



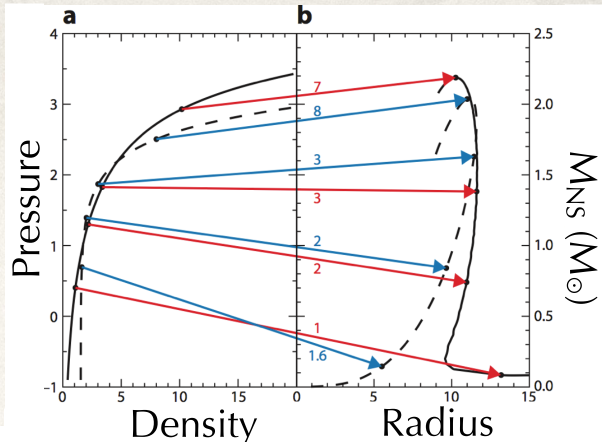
Latest update in Salmi et al. 2024

Latest update in Vinciguerra et al. 2024

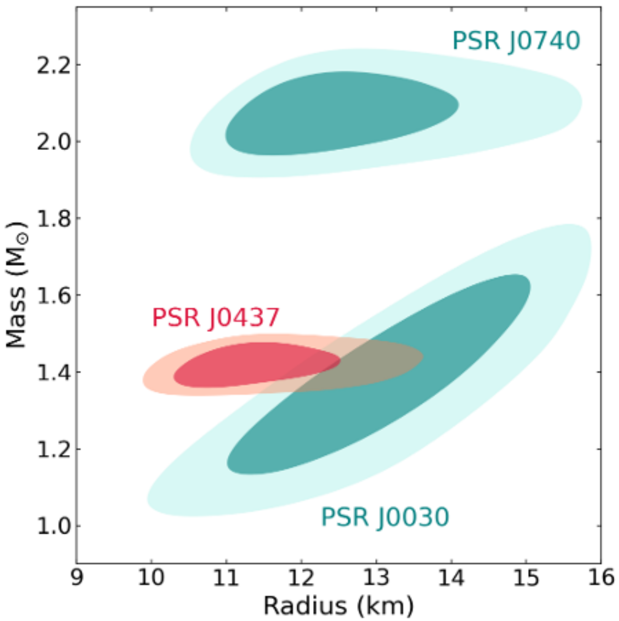
Choudhury et al. 2024

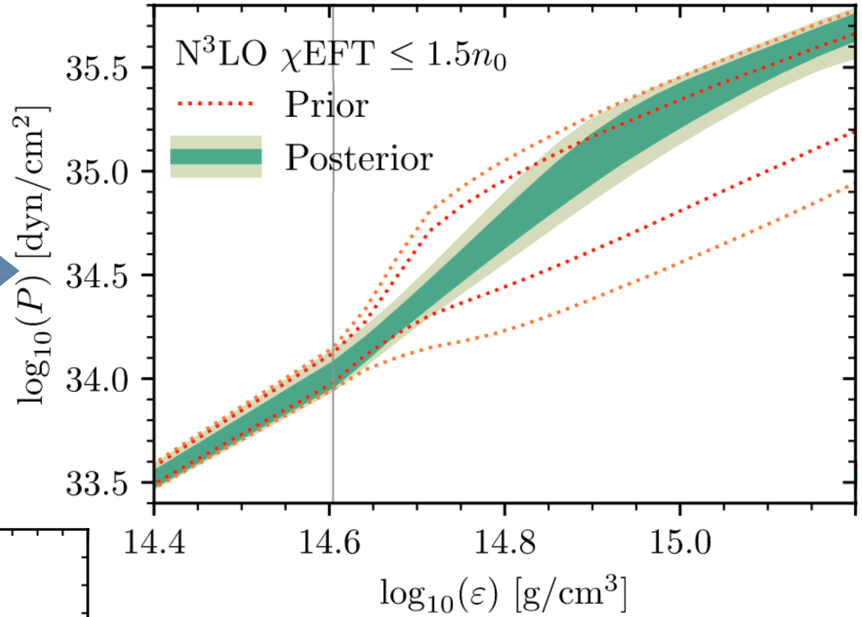
New results for another pulsar PSR J1231–1411

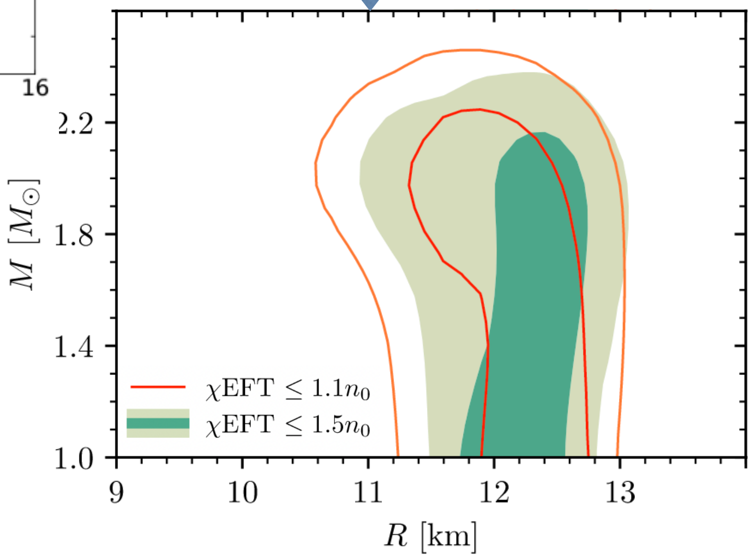
We can now constrain (parametrised) model of the equation of state models.



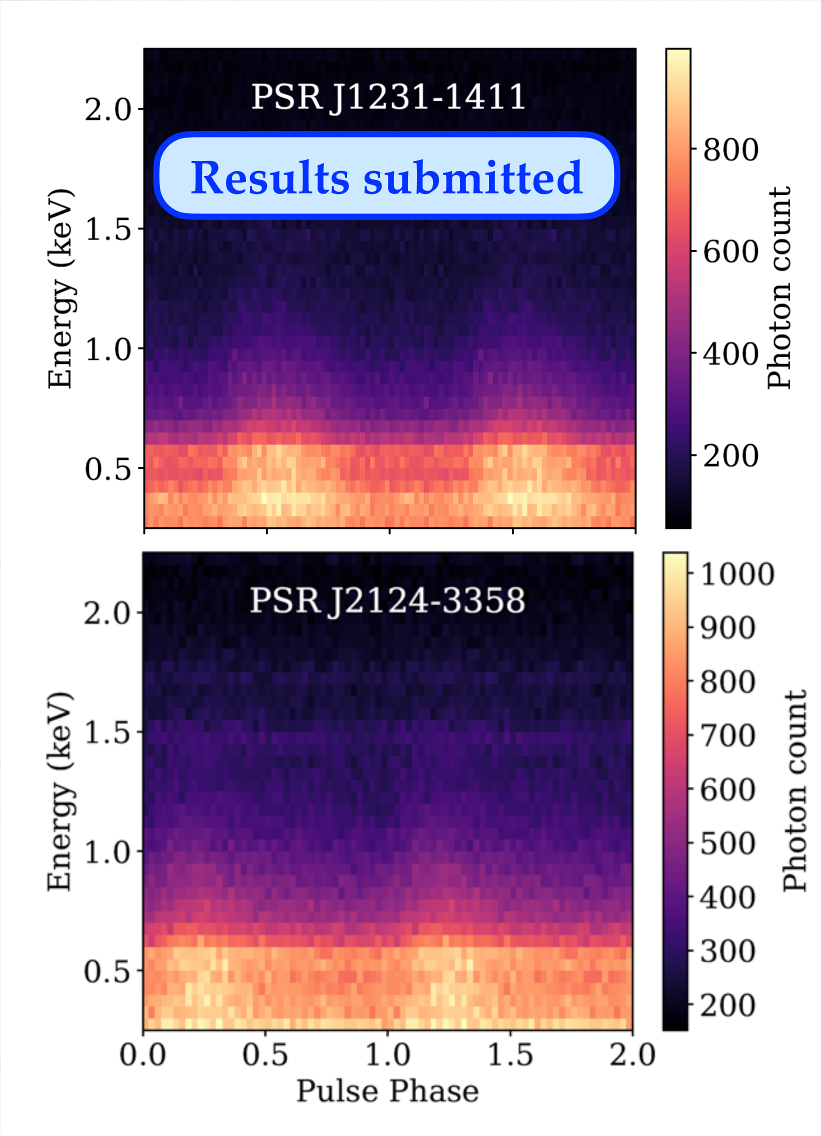
Rutherford et al (2024)





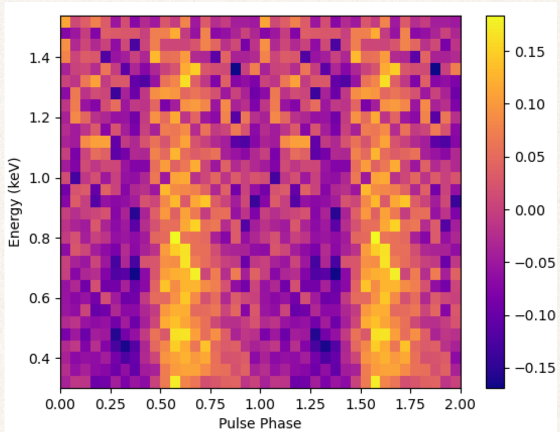


Several NICER data sets are yet to be analysed to extract M_{NS} and R_{NS}. More results are coming…

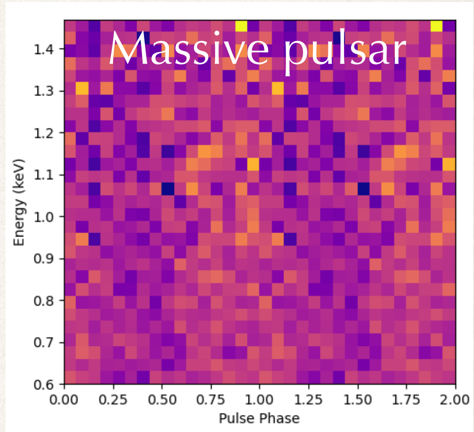


Thesis of Lucien Mauviard at IRAP

PSR J0614–3329



PSR J1614-2230

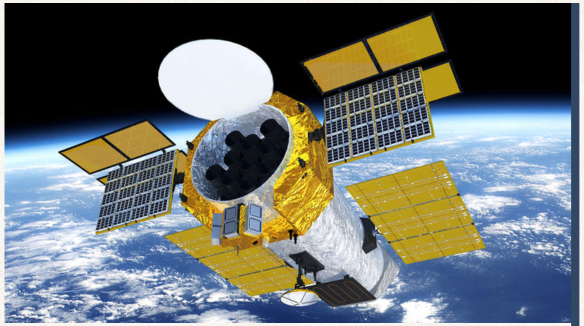


$$\Delta R \sim \pm 1\,\mathrm{km}$$

+ other (faint) pulsars discovered with NICER (*Guillot et al 2019*)

What can we expect in the future with pulse profile modelling ?

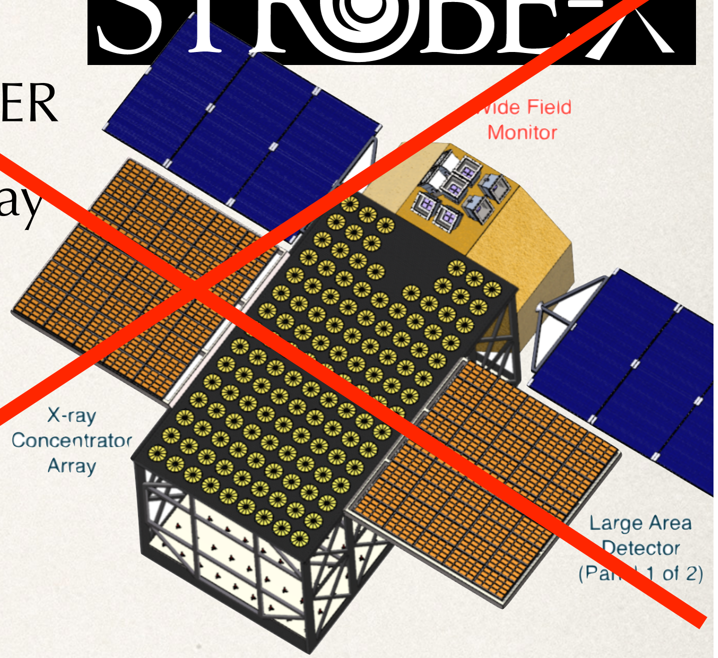
eXTP

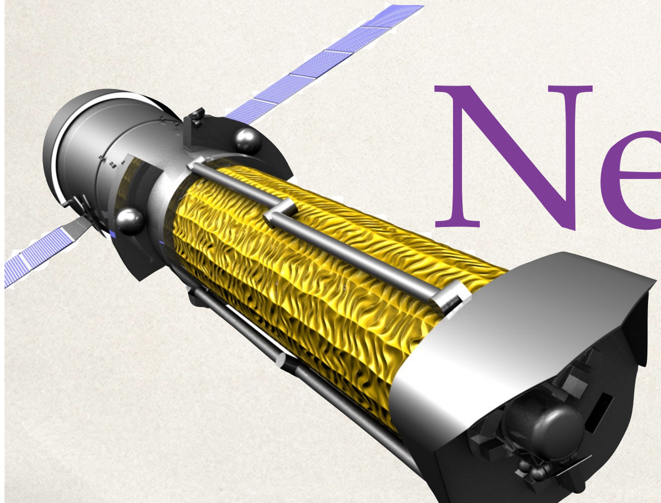


- Modest imaging capabilities (60″ PSF)
- ~ 4–5 × more sensitive than NICER
- + Hard X-ray instrument

~~STROBE-X~~

- ~~~ 10× NICER~~
- ~~+ Hard X-ray instrument~~



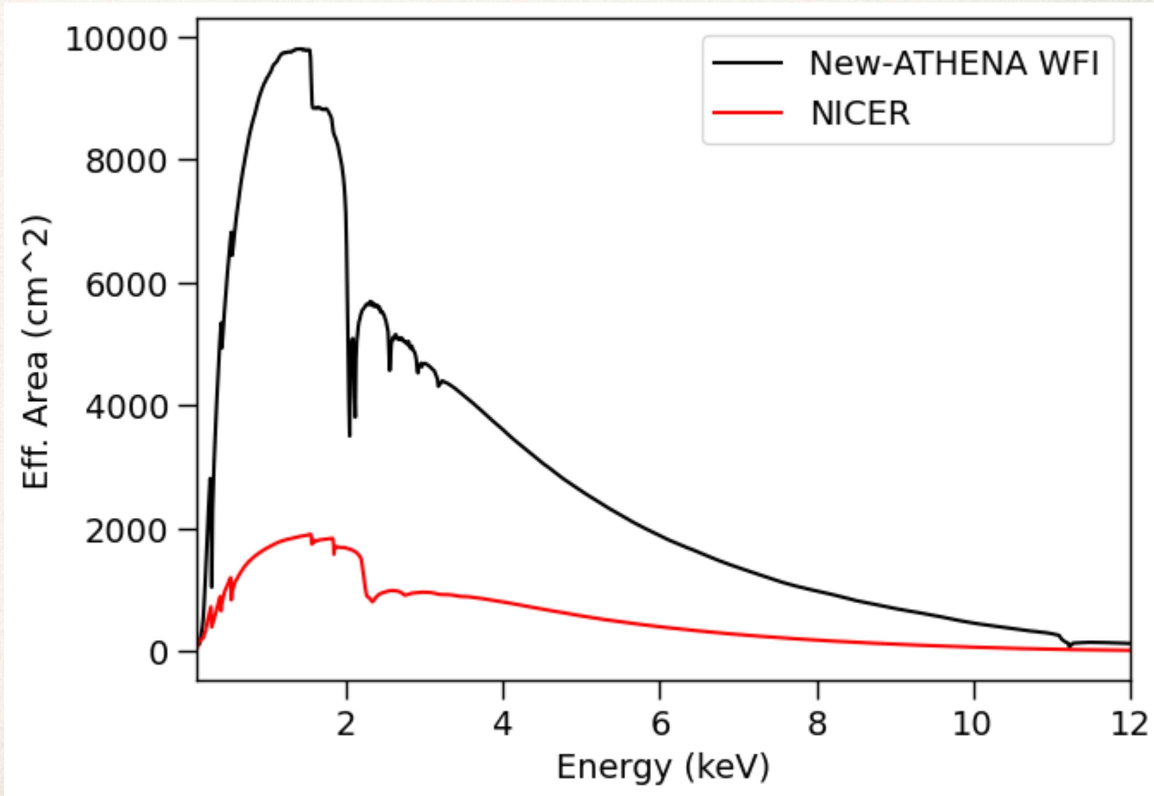


New-ATHENA

What can we expect in the future with pulse profile modelling ?

New-ATHENA

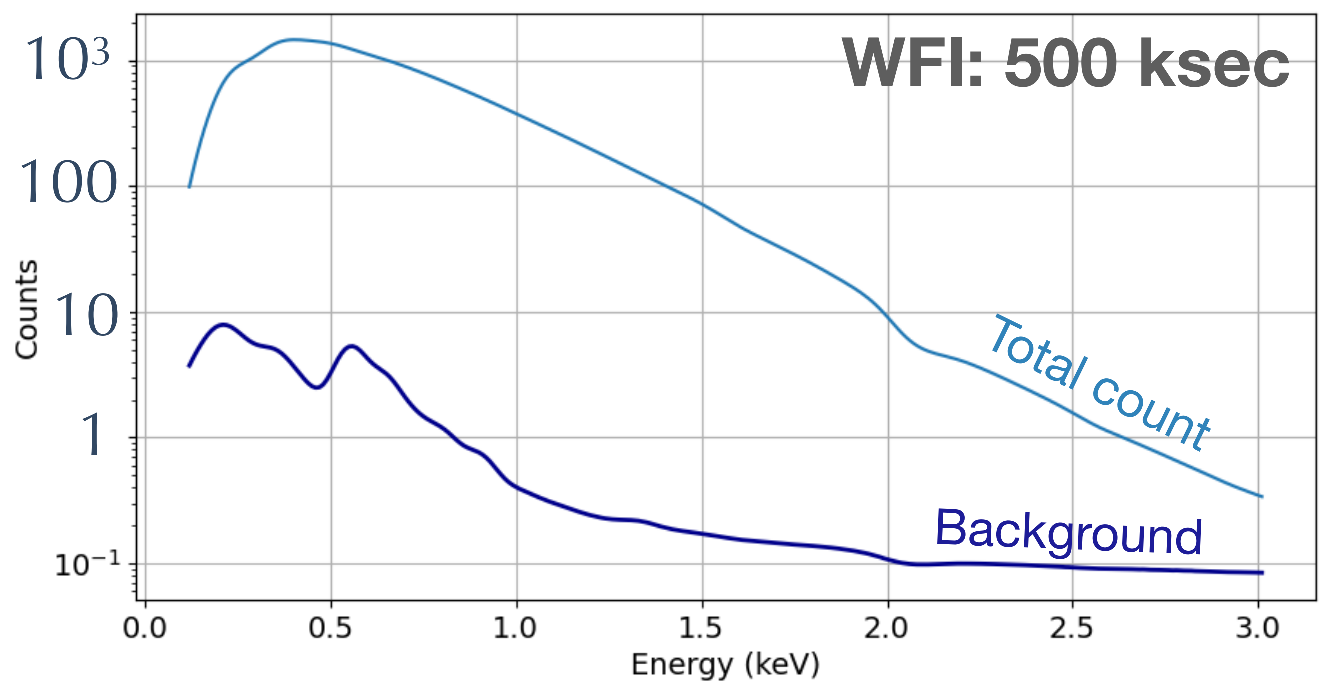
- Sensitivity: about x5 NICER
- Time resolution:
  - 10 µsec (X-IFU)
  - ~100 µsec (WFI)
- Low-background: ~ 0.001 c/s

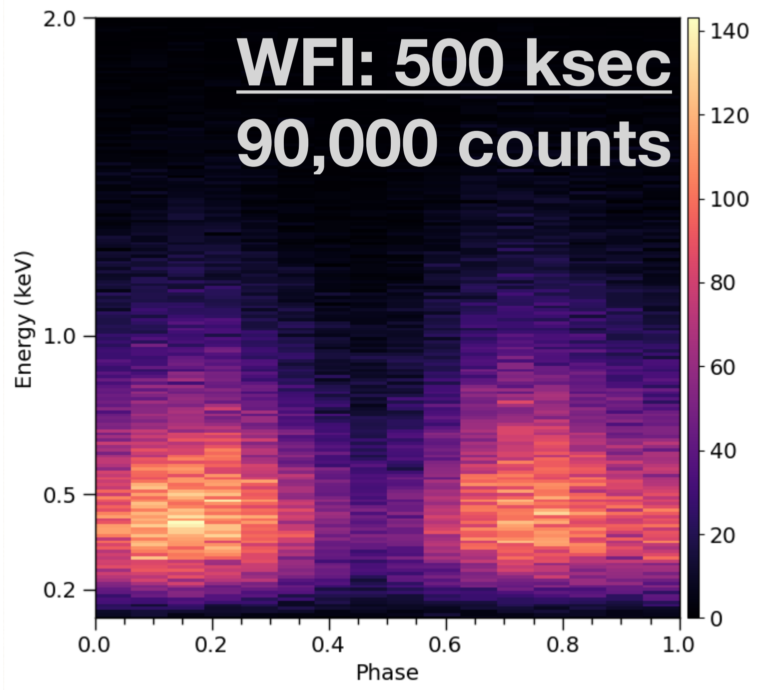


Future prospects for pulse profile modelling with new-Athena are quite promising.

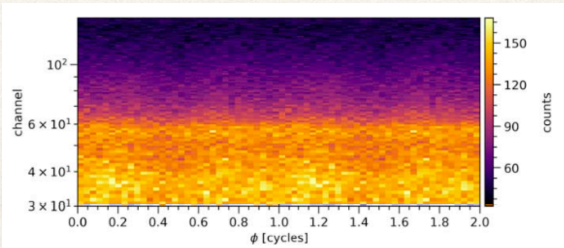
Simulations of PSR J0740+6620 with P_{spin} = 2.88 msec and d=1.2 kpc

R~11.5 km, M=2.08 $M_{\odot}$ with 2 circular hot spots
Simulation of 500 ksec observations



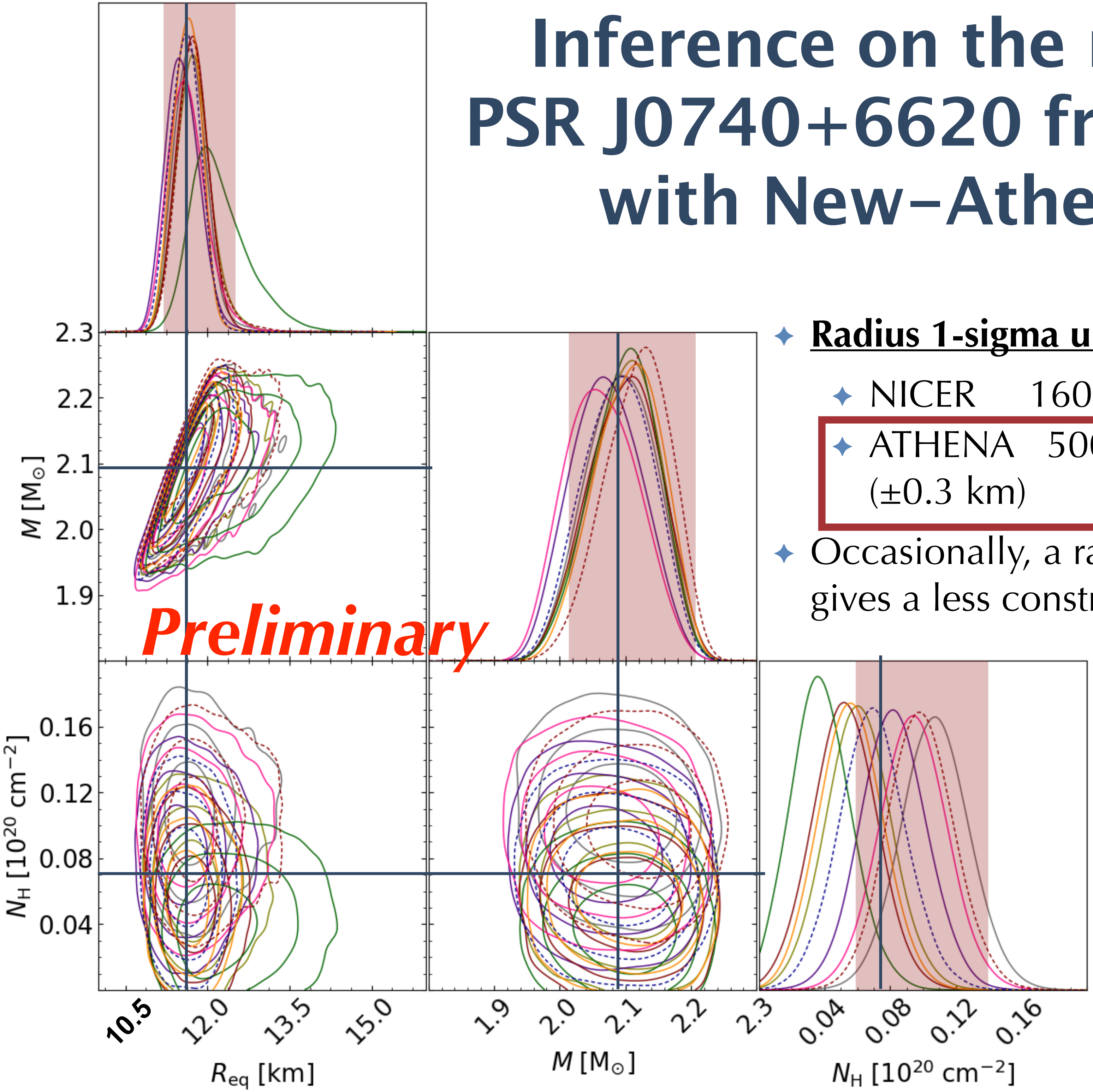


NICER profile for comparison!



X-PSI

Inference on the radius of PSR J0740+6620 from 500 ks with New-Athena WFI



- **Radius 1-sigma uncertainties**
  - NICER 1600 ksec: ~10%
  - ATHENA 500 ksec: ~3% average (±0.3 km)
- Occasionally, a random noise realisation gives a less constrained radius

Statistical uncertainties < 1% for brighter pulsars

For some MSPs, the rest of the surface, although much colder than the hot spots, can be detected in the soft X-ray and the far UV.

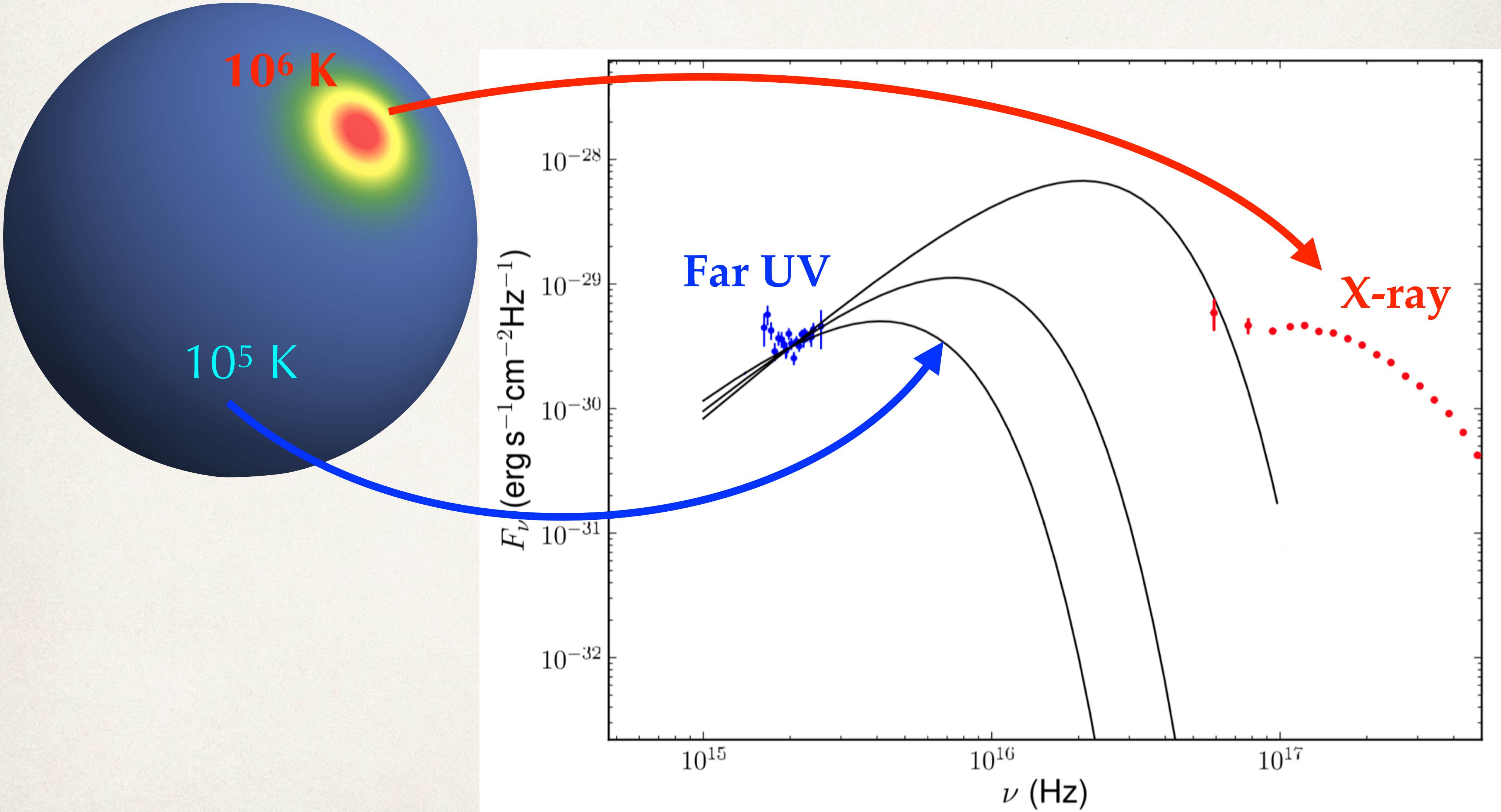
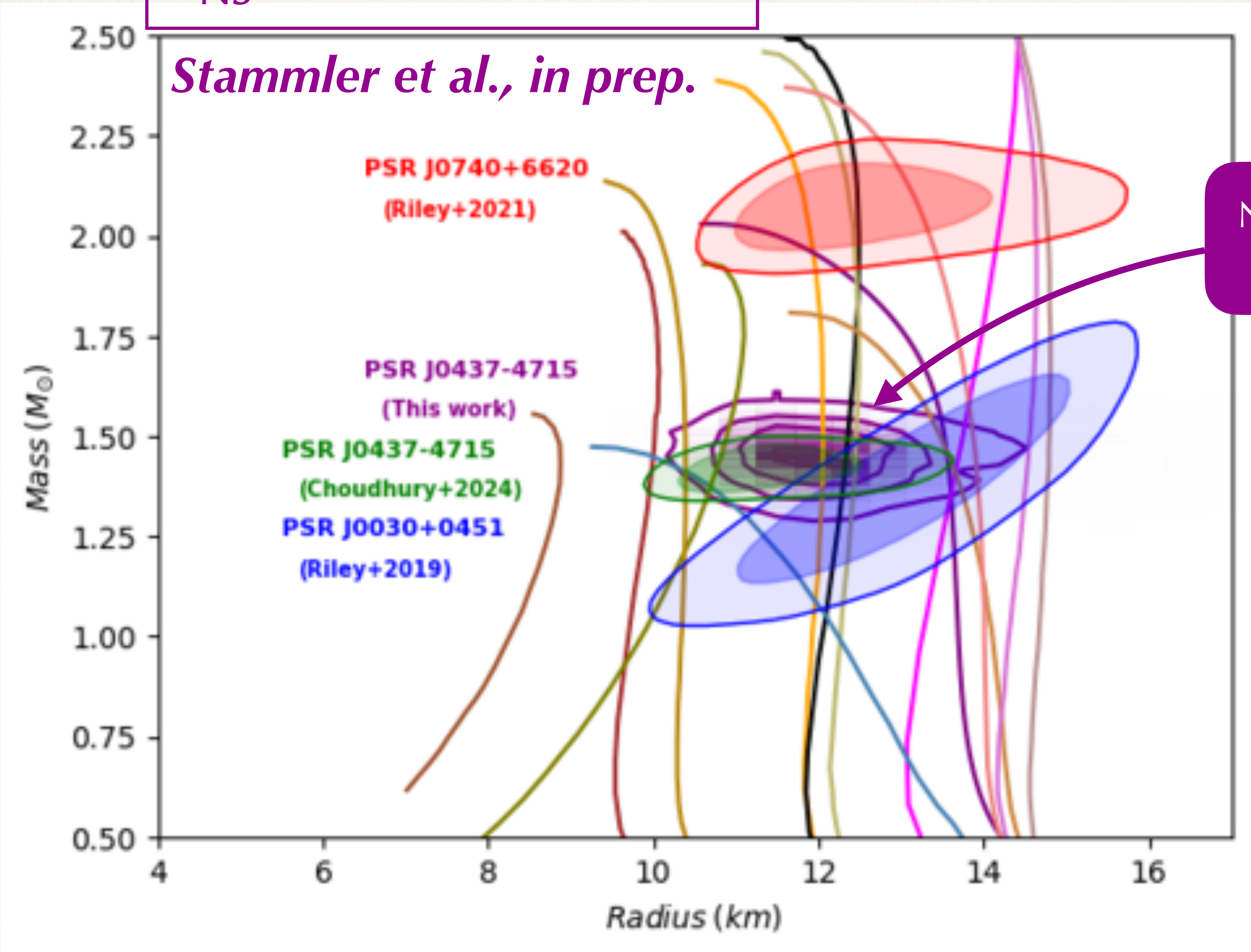


Figure adapted from Durant et al. (2012)

Using Far UV observations for PSR J0437-4715, we obtain independent constraints on the radius.

$\boxed{R_{NS} = 12.1 \pm 1.0 \text{ km}}$

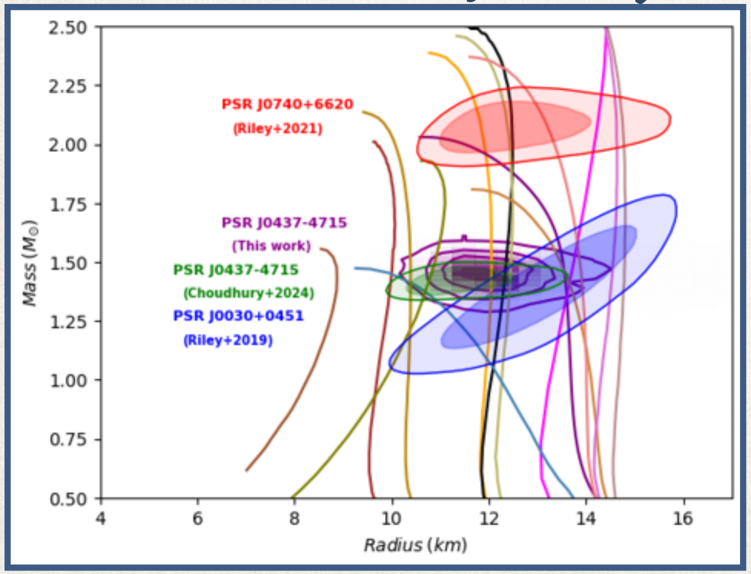


No NICER data involved!

Conclusions

- Pulse profile modelling is a demonstrated technique to measure M and R.
- NICER results for 3 pulsars are published; 1 is submitted; more are coming…
- We now know that characterising the background is key.
- Complementary methods exists to measure M and R.
- NewATHENA measurement will bring constraints on M and R to another level.

Currently



In the future