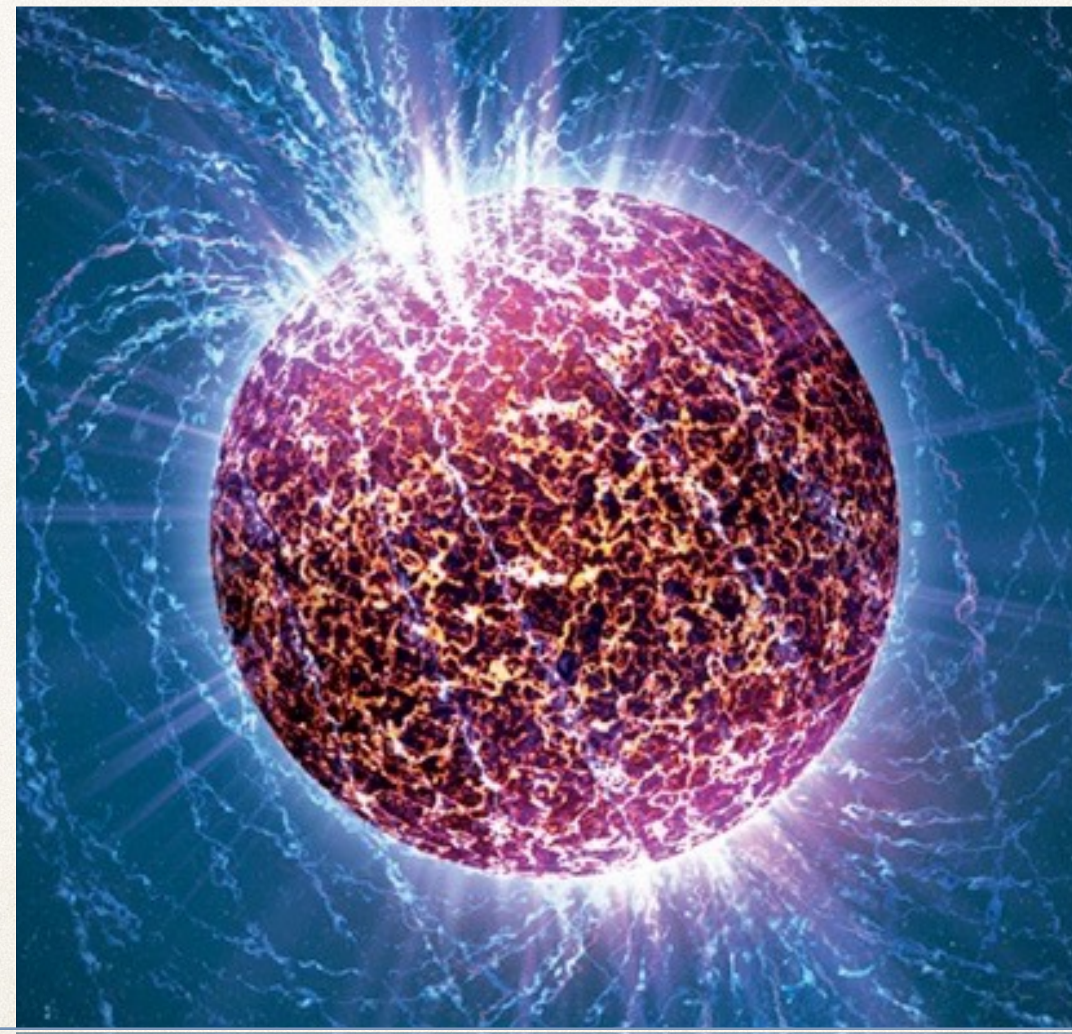
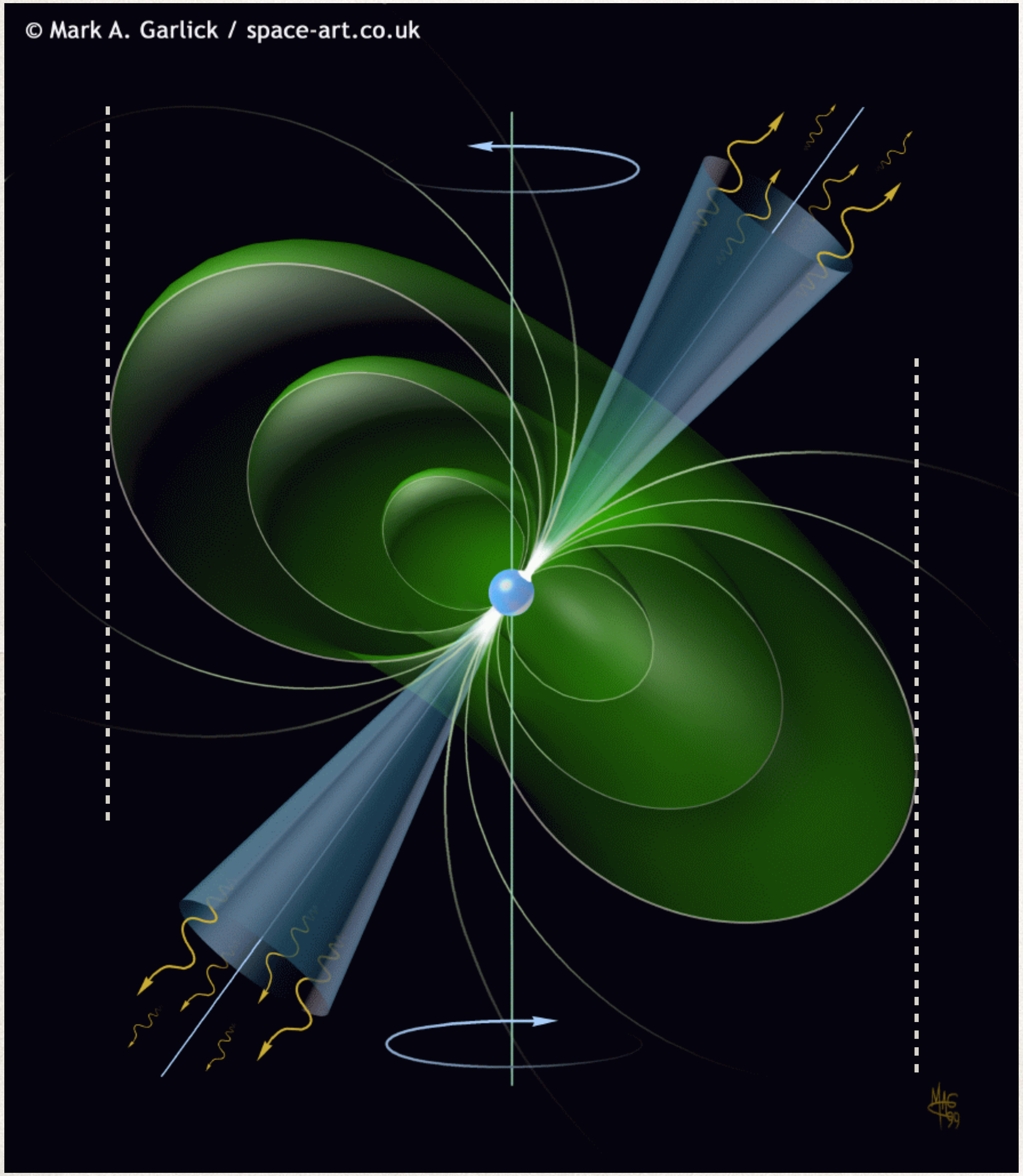
The extreme physics of neutron stars: My observer's viewpoint

Sebastien Guillot

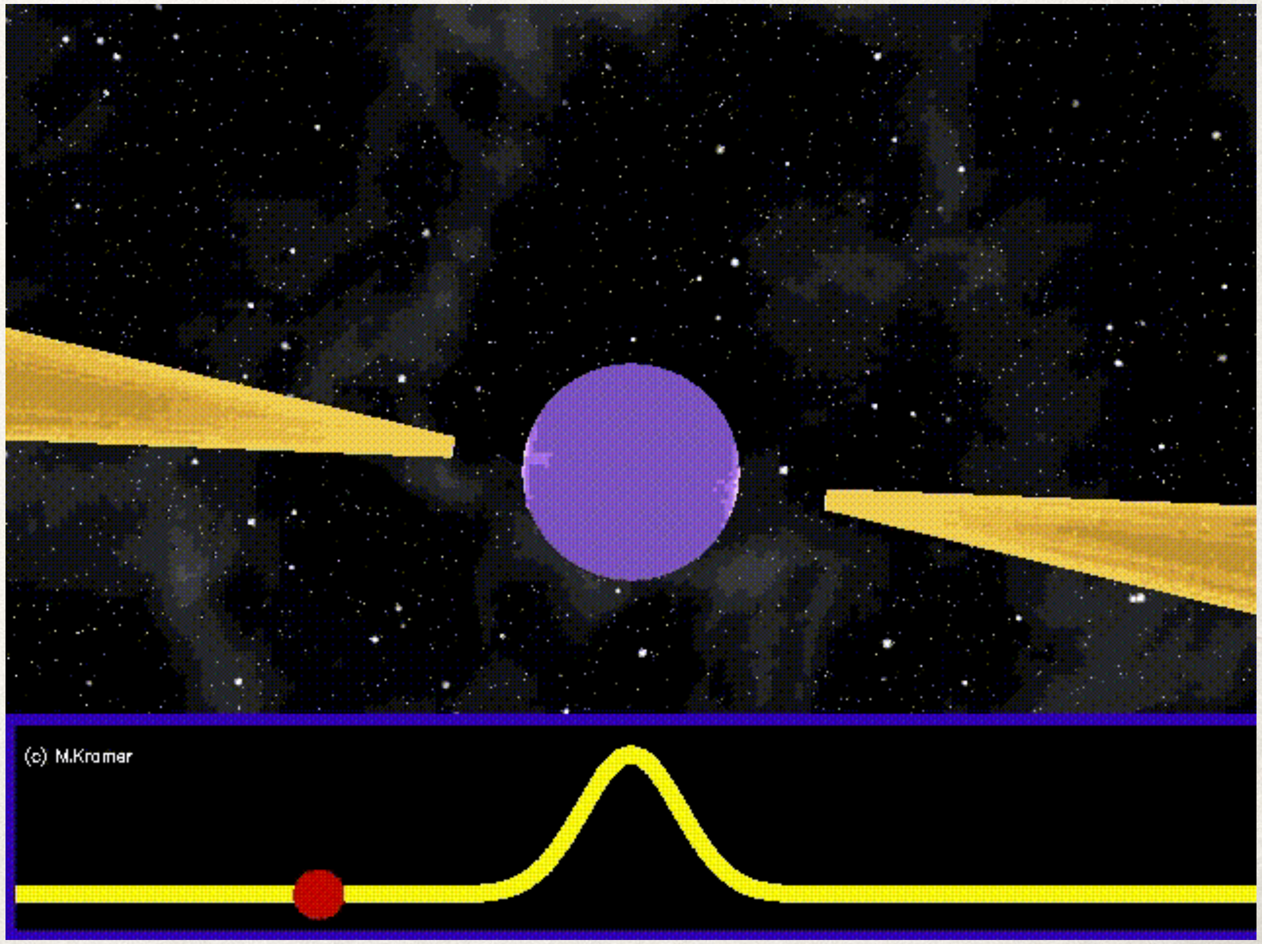


irap
astrophysique & planétologie

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



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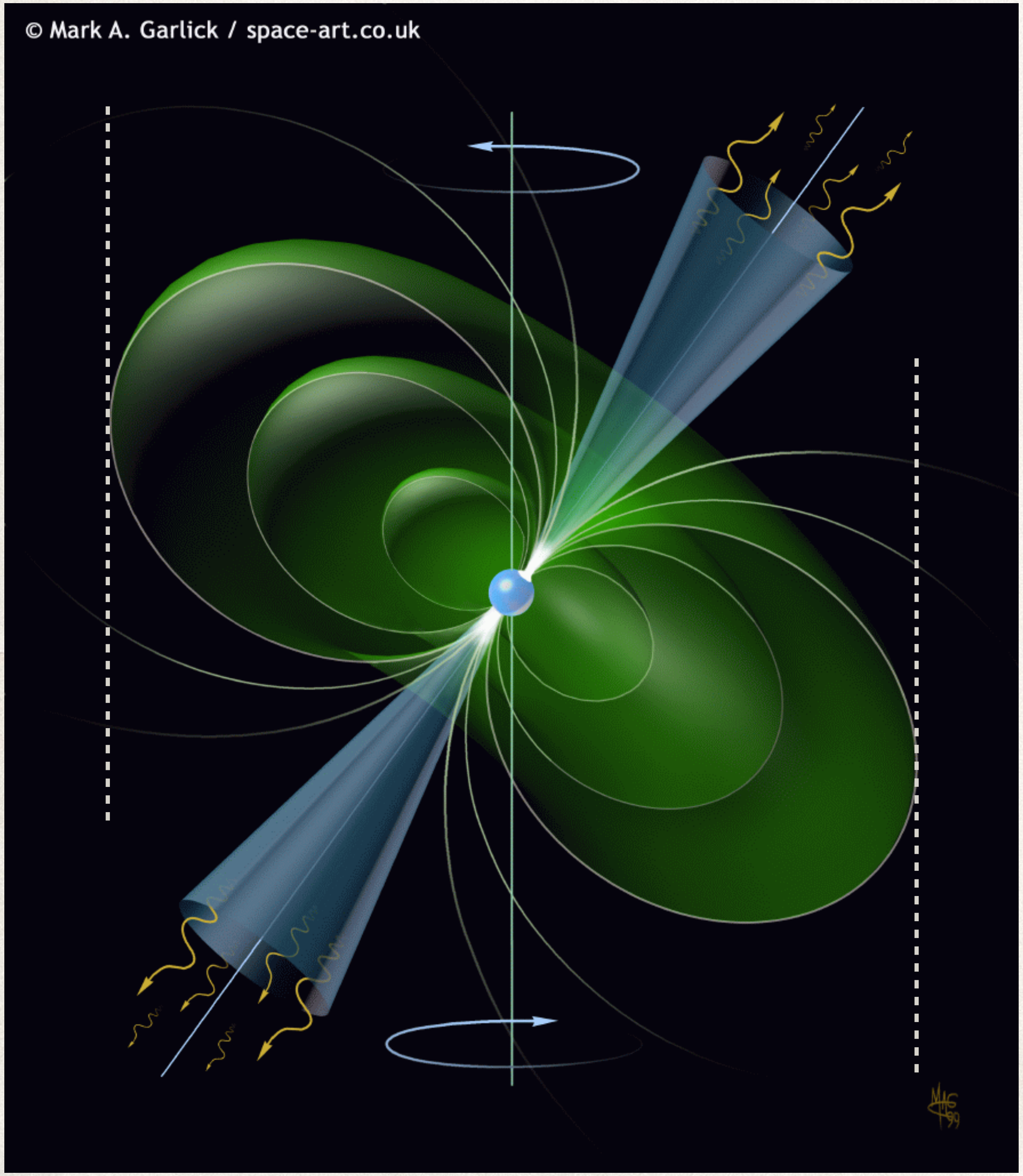

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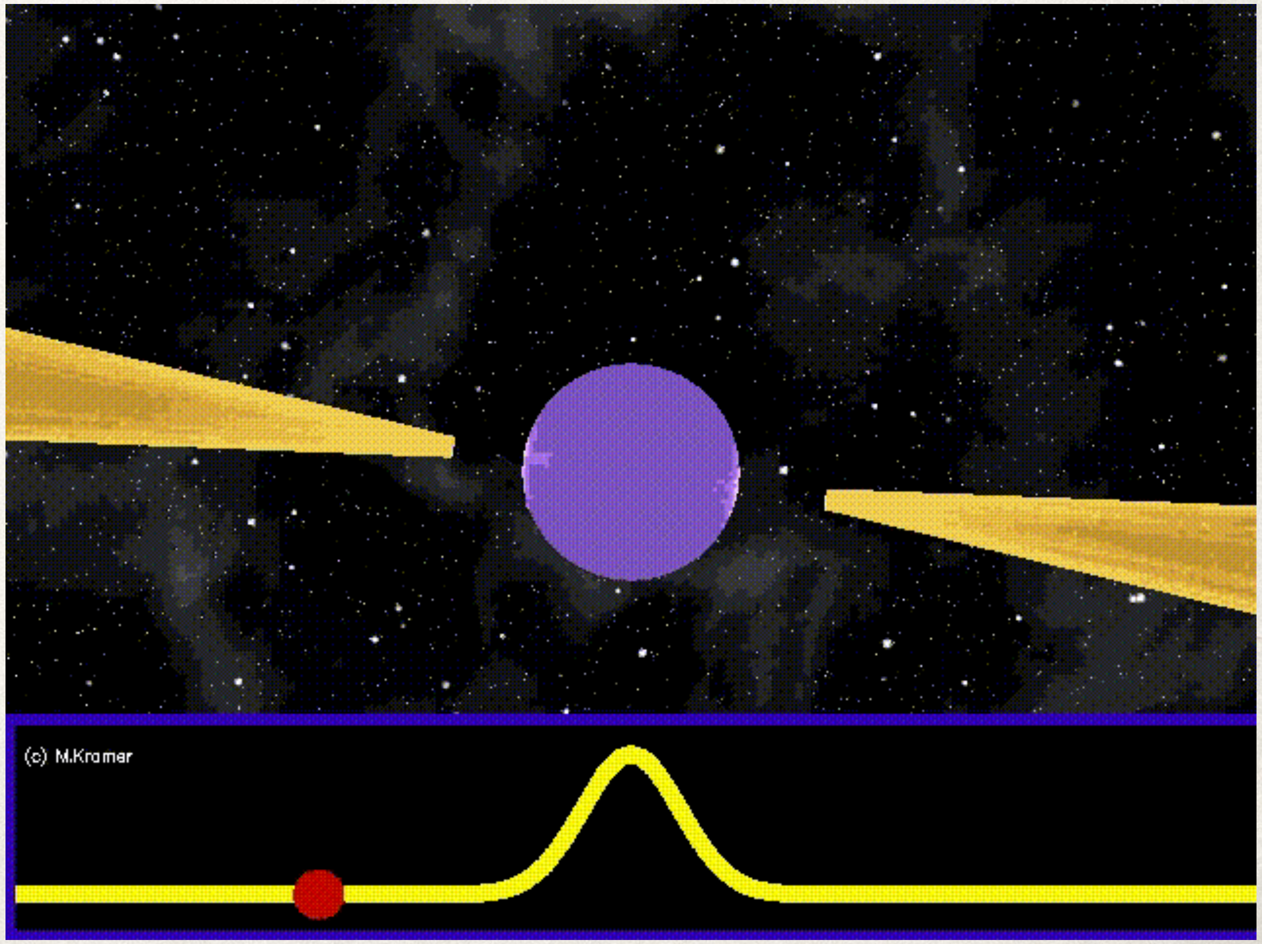
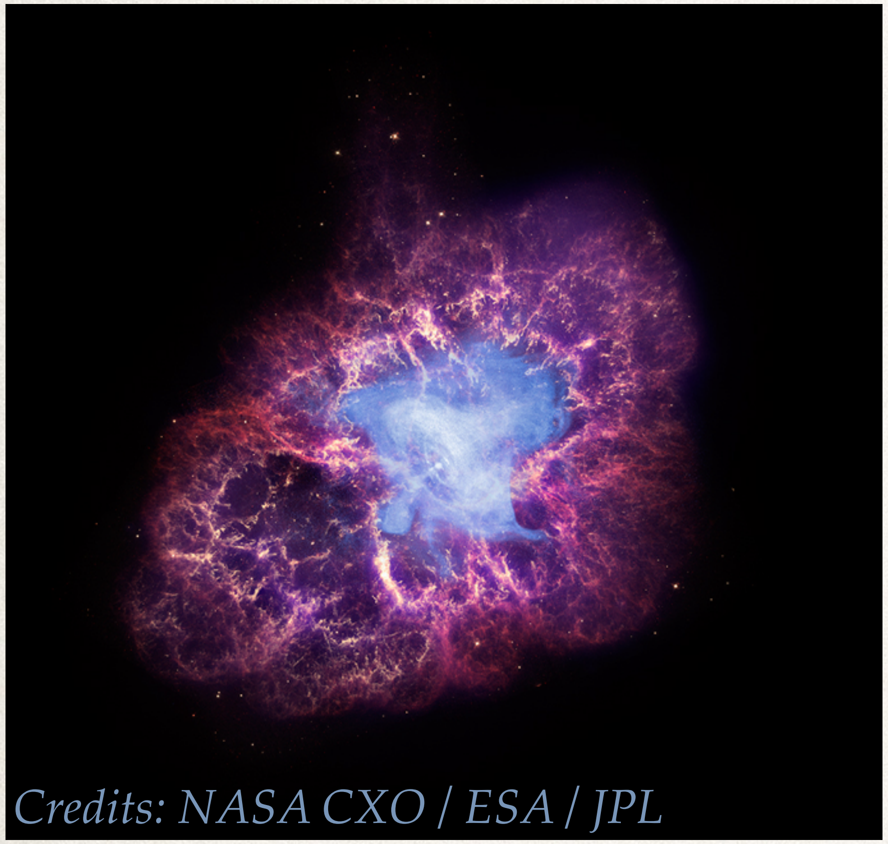


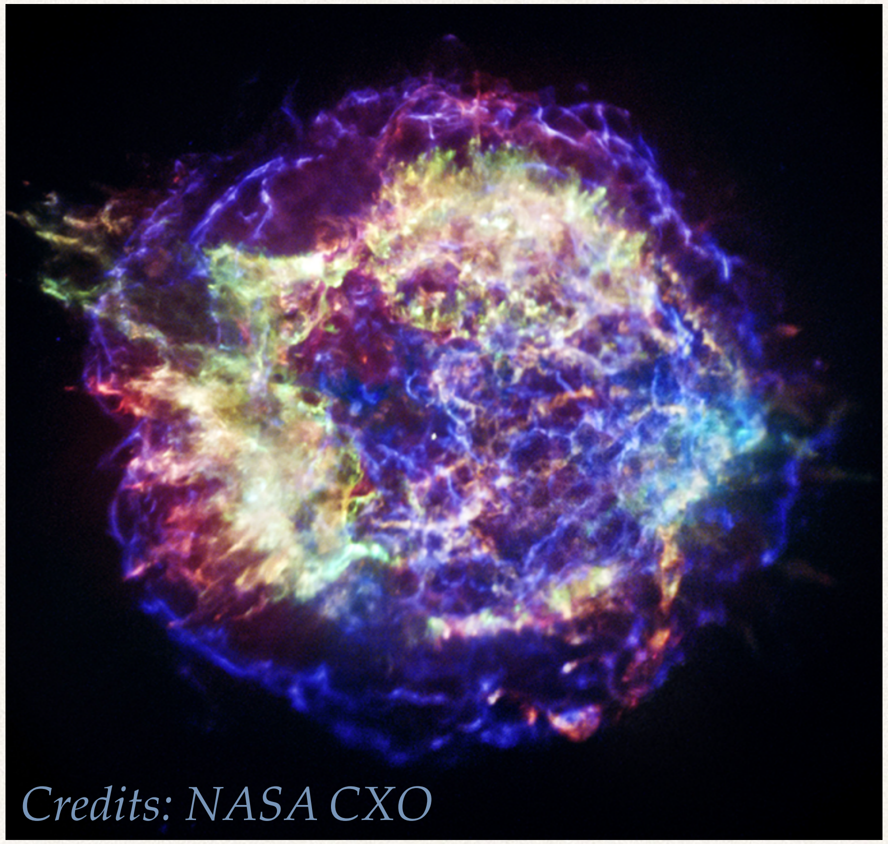
Neutron stars are the remnants of the core-collapse of massive stars.



Crab Nebula

X-ray+IR+Opt

A pulsar, at most wavelengths



Cassiopeia A

X-ray

A neutron star without pulsations

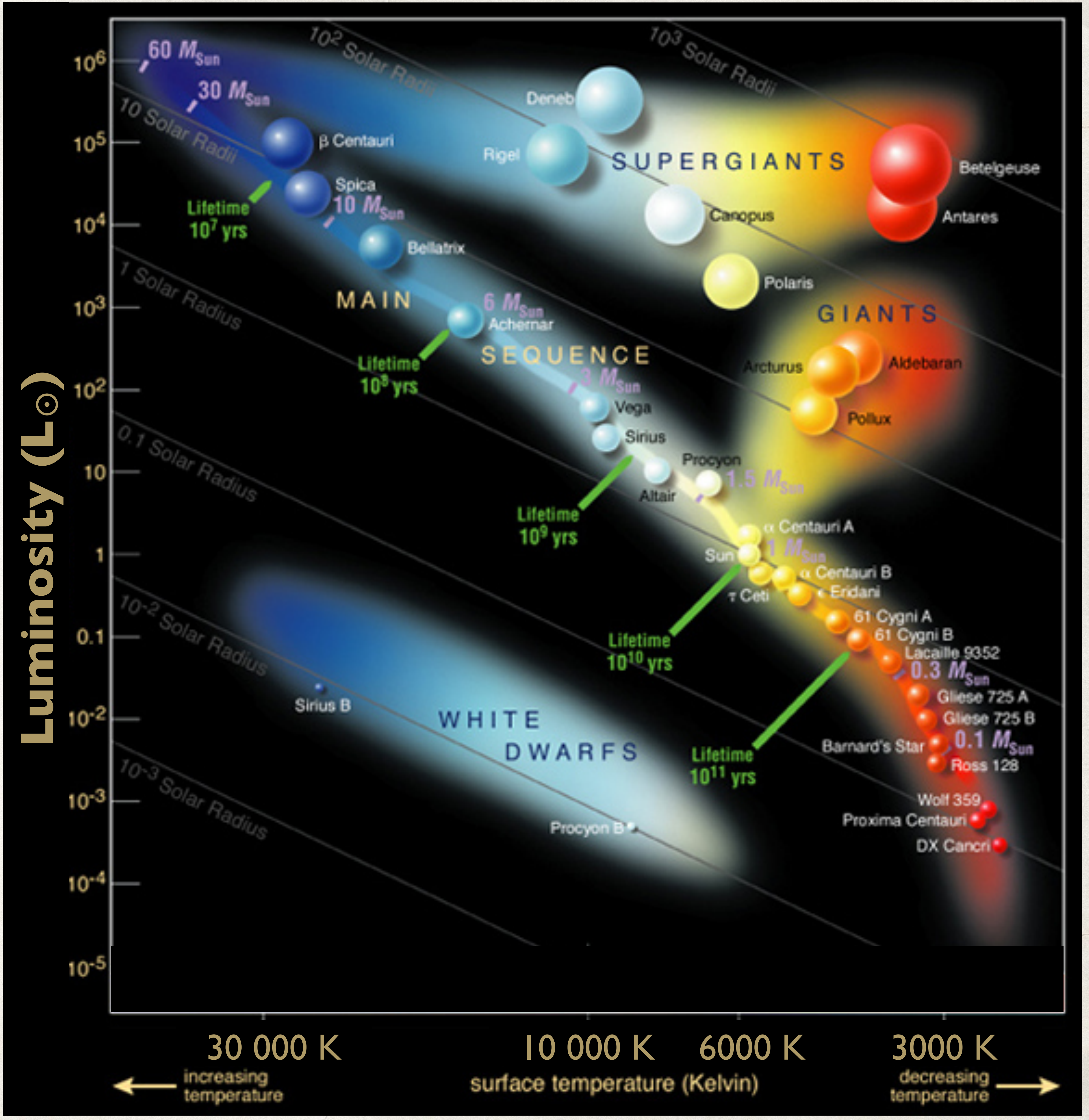
SN 1987 A

X-ray+Optical

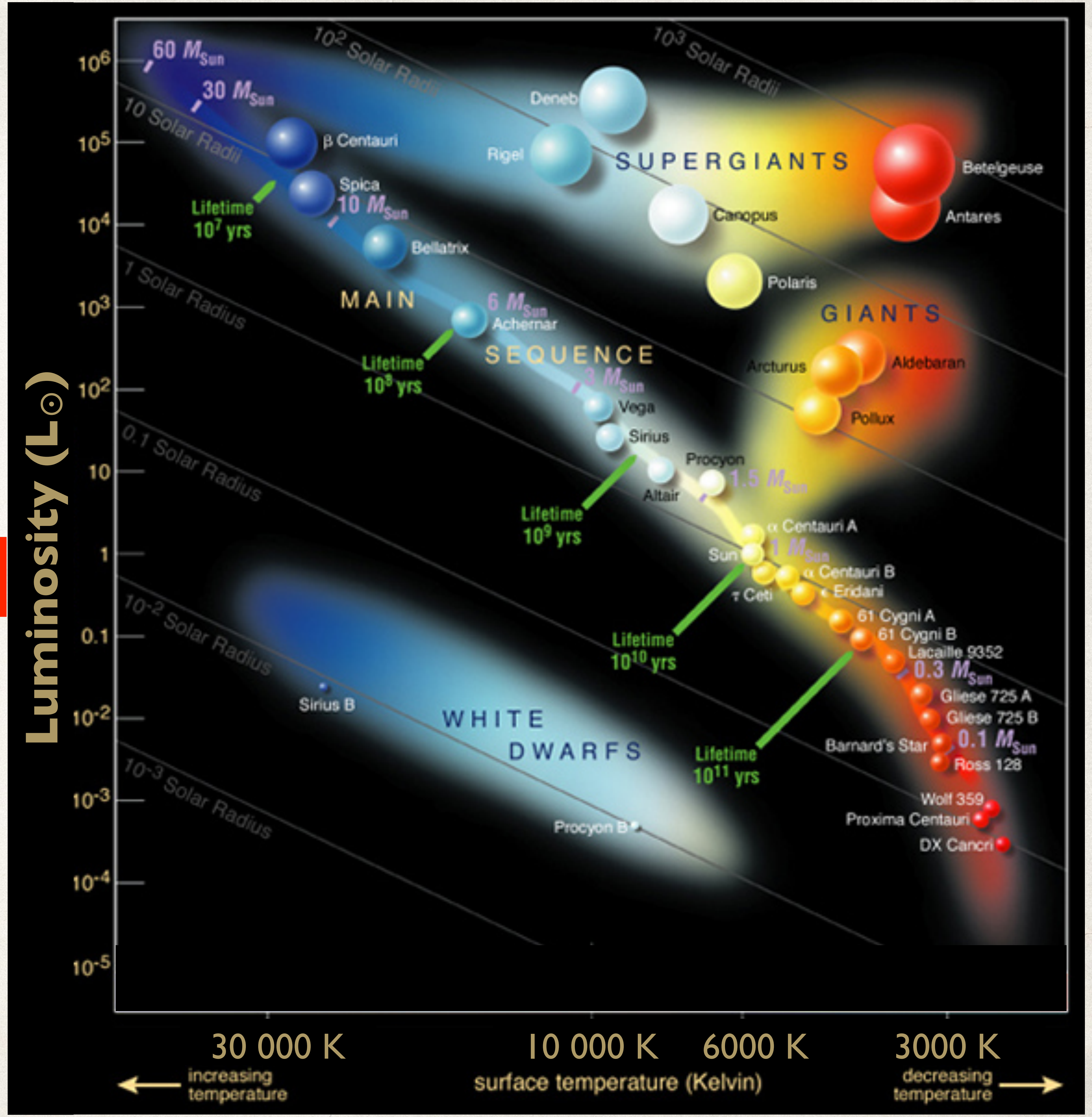
A neutron star, maybe ?

Fransson et al. 2024

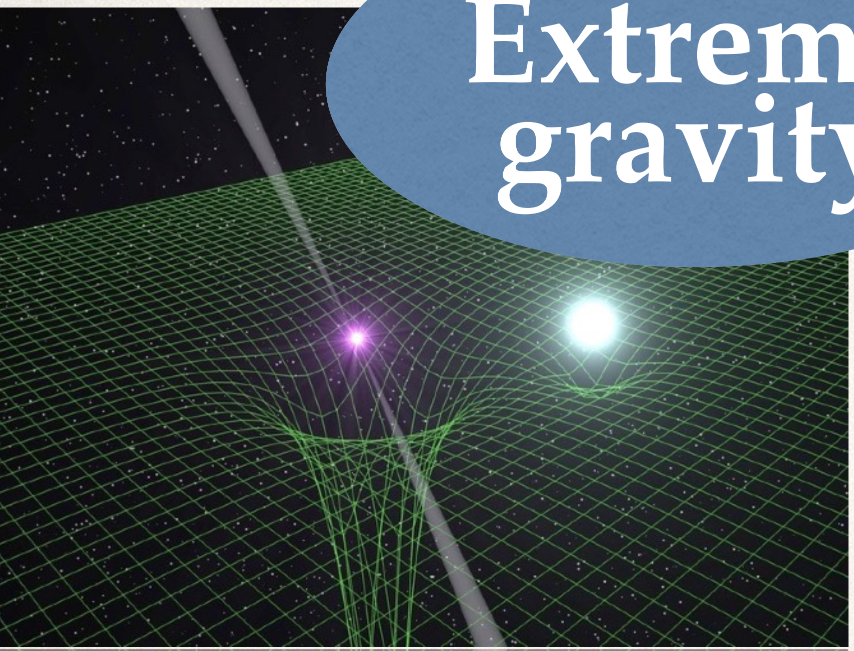
Where would neutron stars be on the HR diagram?



Where would neutron stars be on the HR diagram?

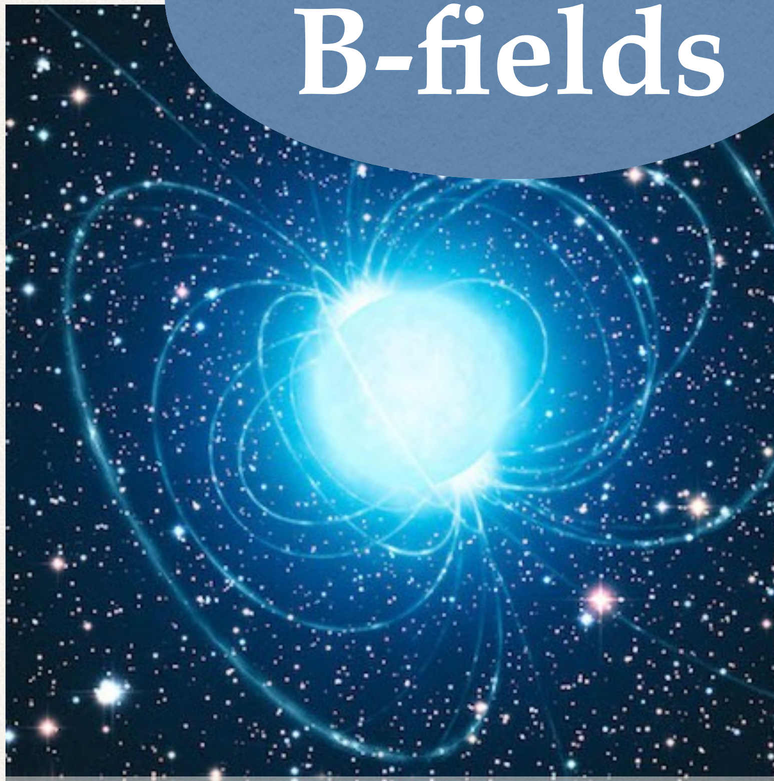


Neutron stars are amazing laboratories for extreme physics.

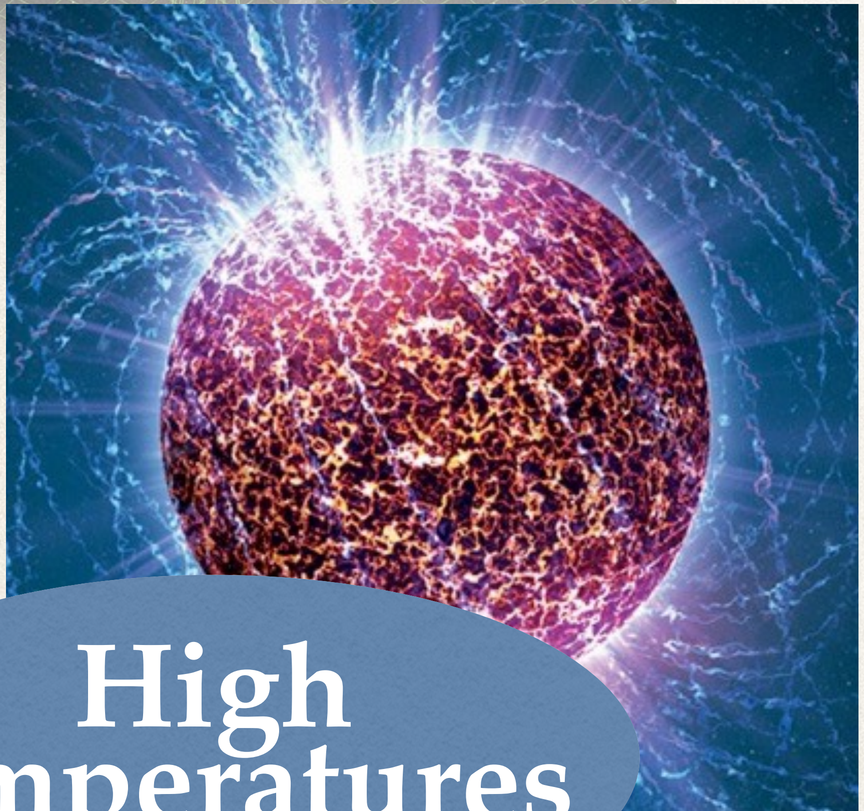


Extreme gravity

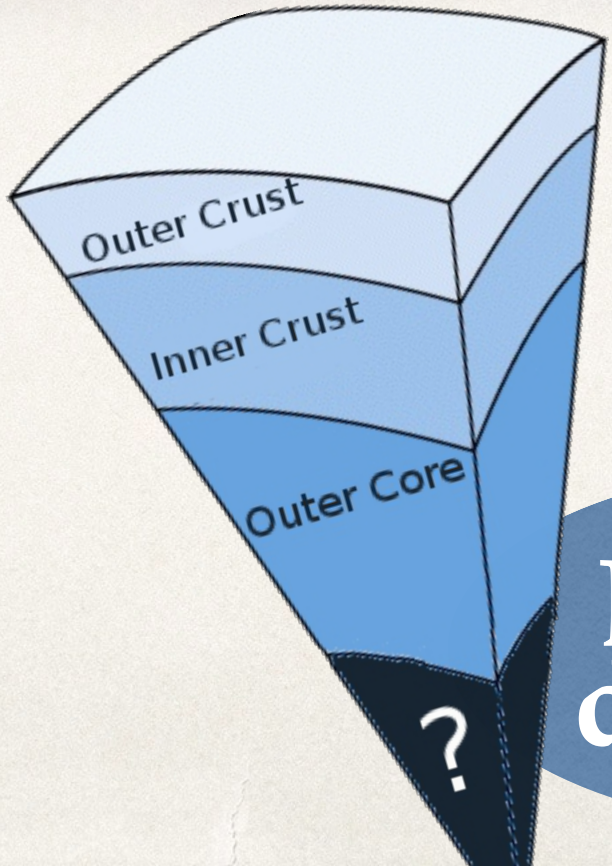
Particle accelerators



Extreme B-fields

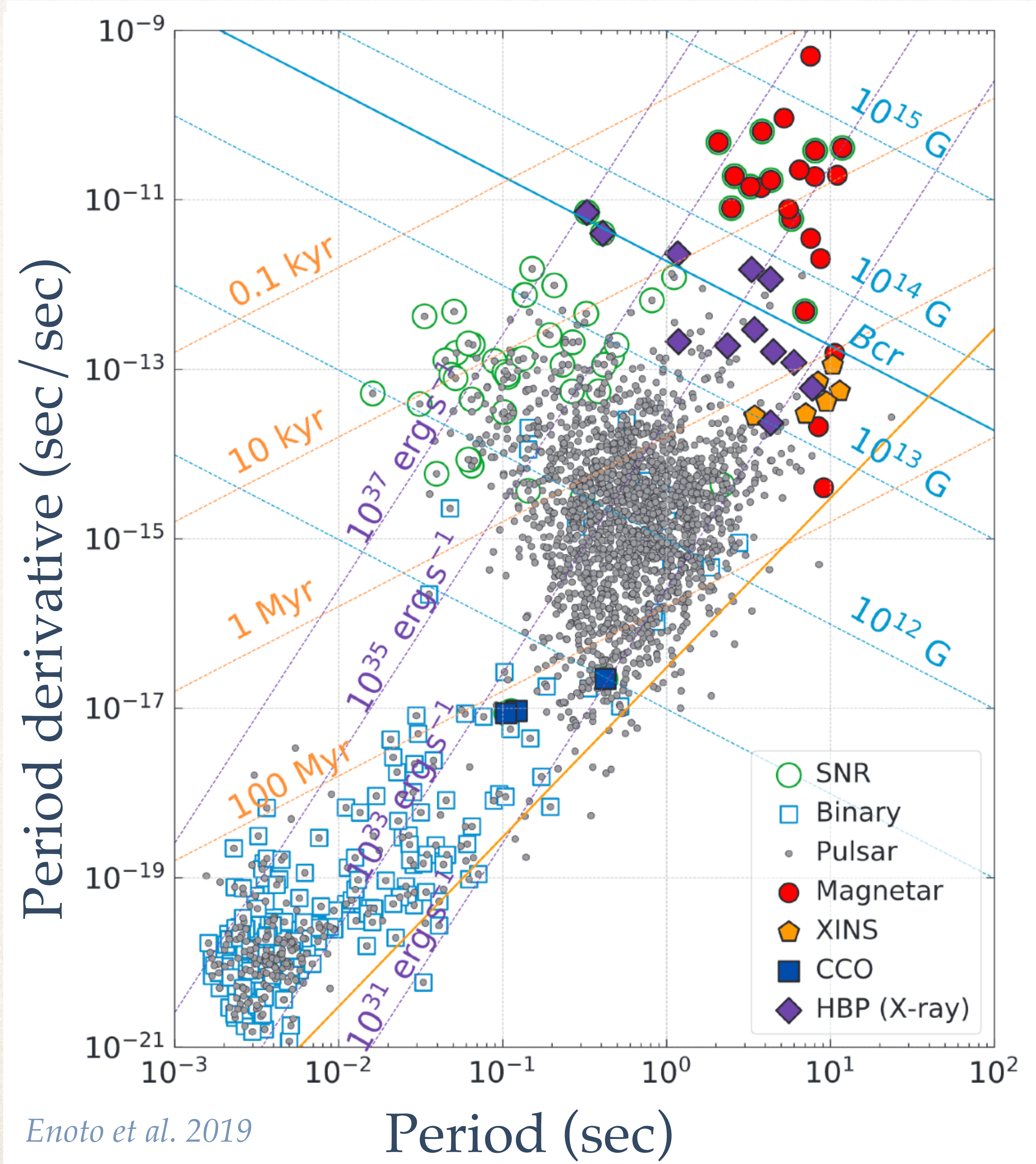


High temperatures



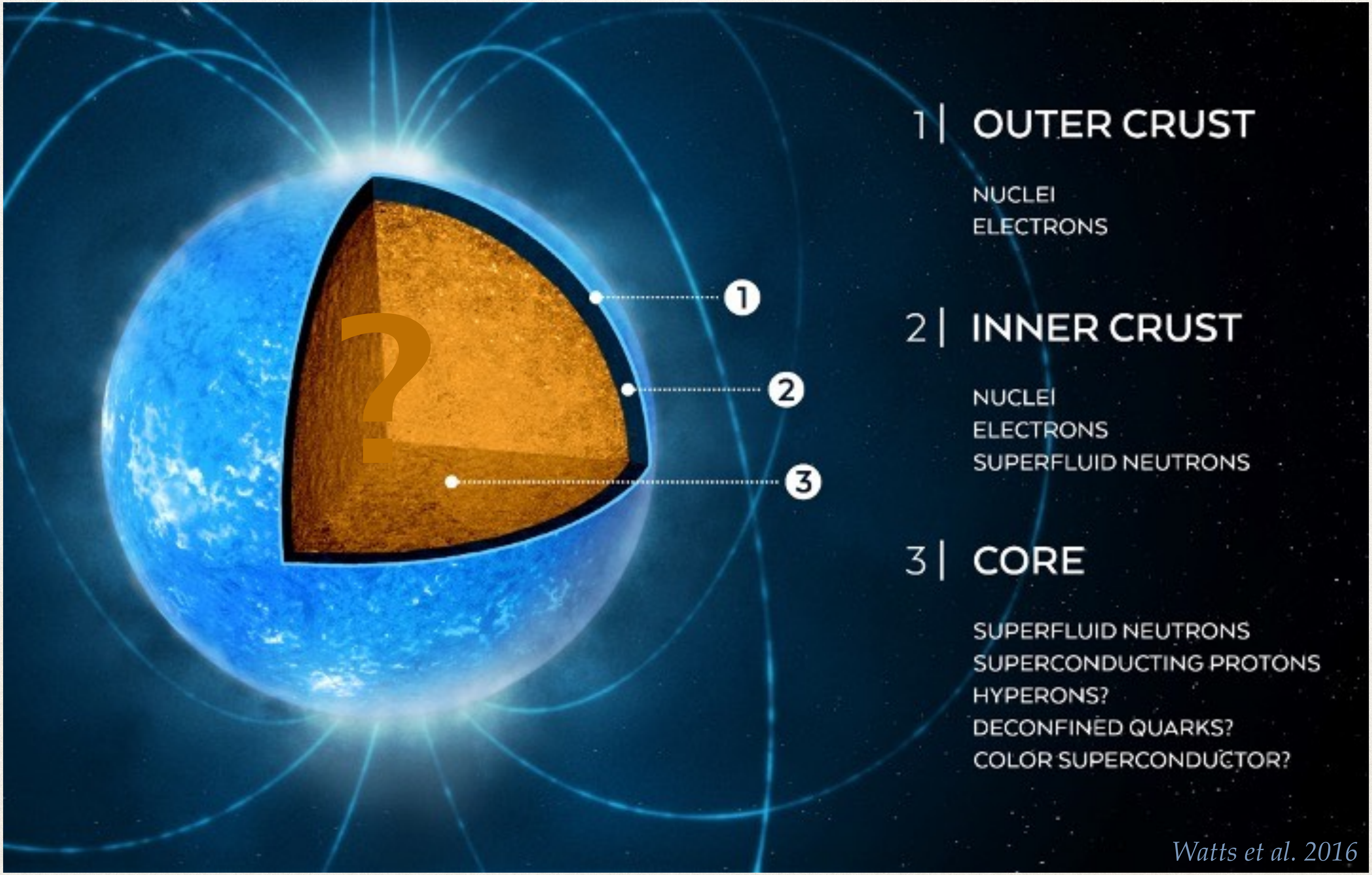
Extreme densities

The extended family of neutron stars is quite broad. Each class exhibit its own phenomenology.

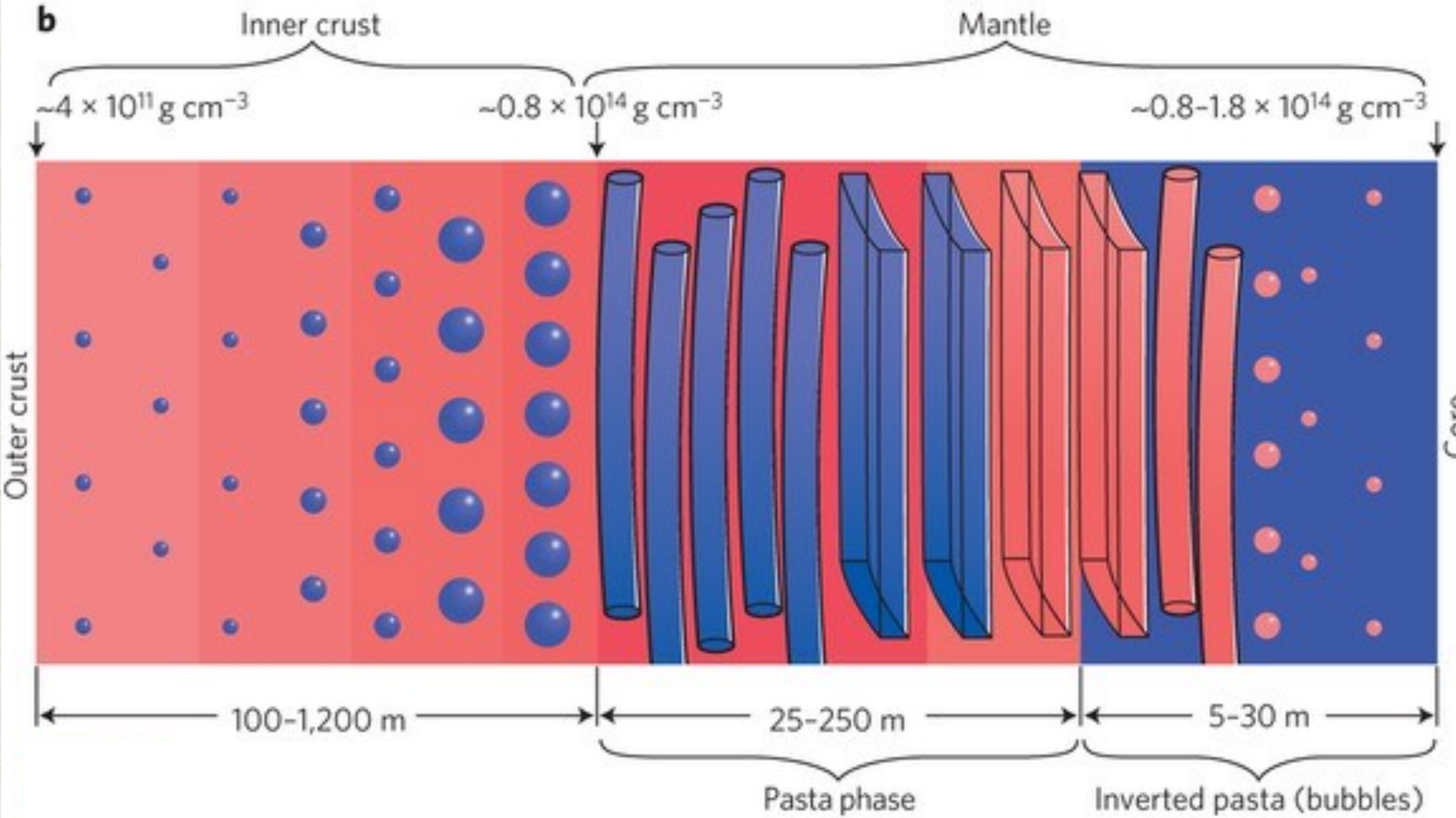


Enoto et al. 2019

The structure of neutron stars is not well known beyond the first top kilometre.

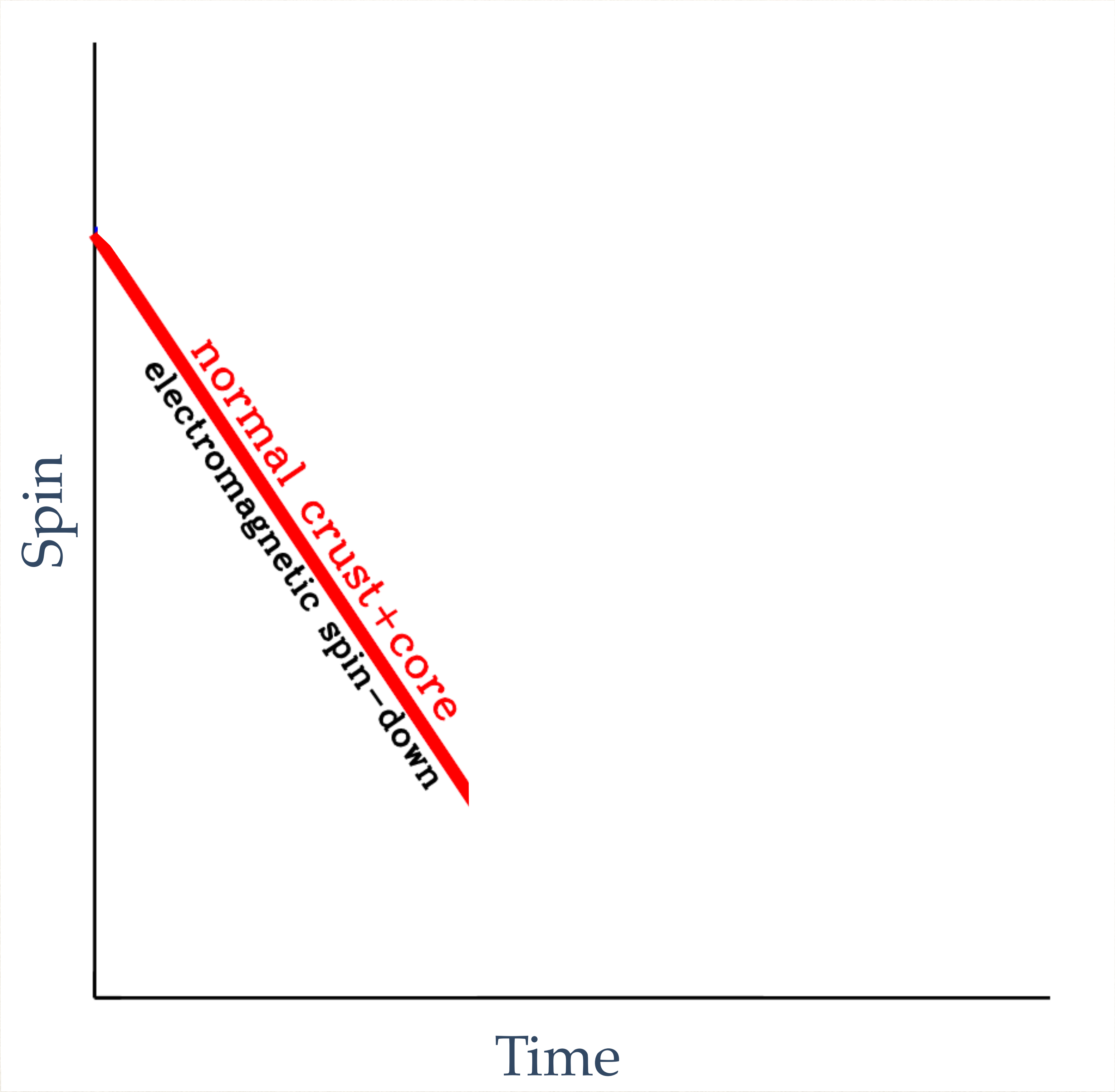


The interesting (and complex) physics starts in the deep crust.



Credits: W. Newton

The superfluid crust can be probed with pulsars.



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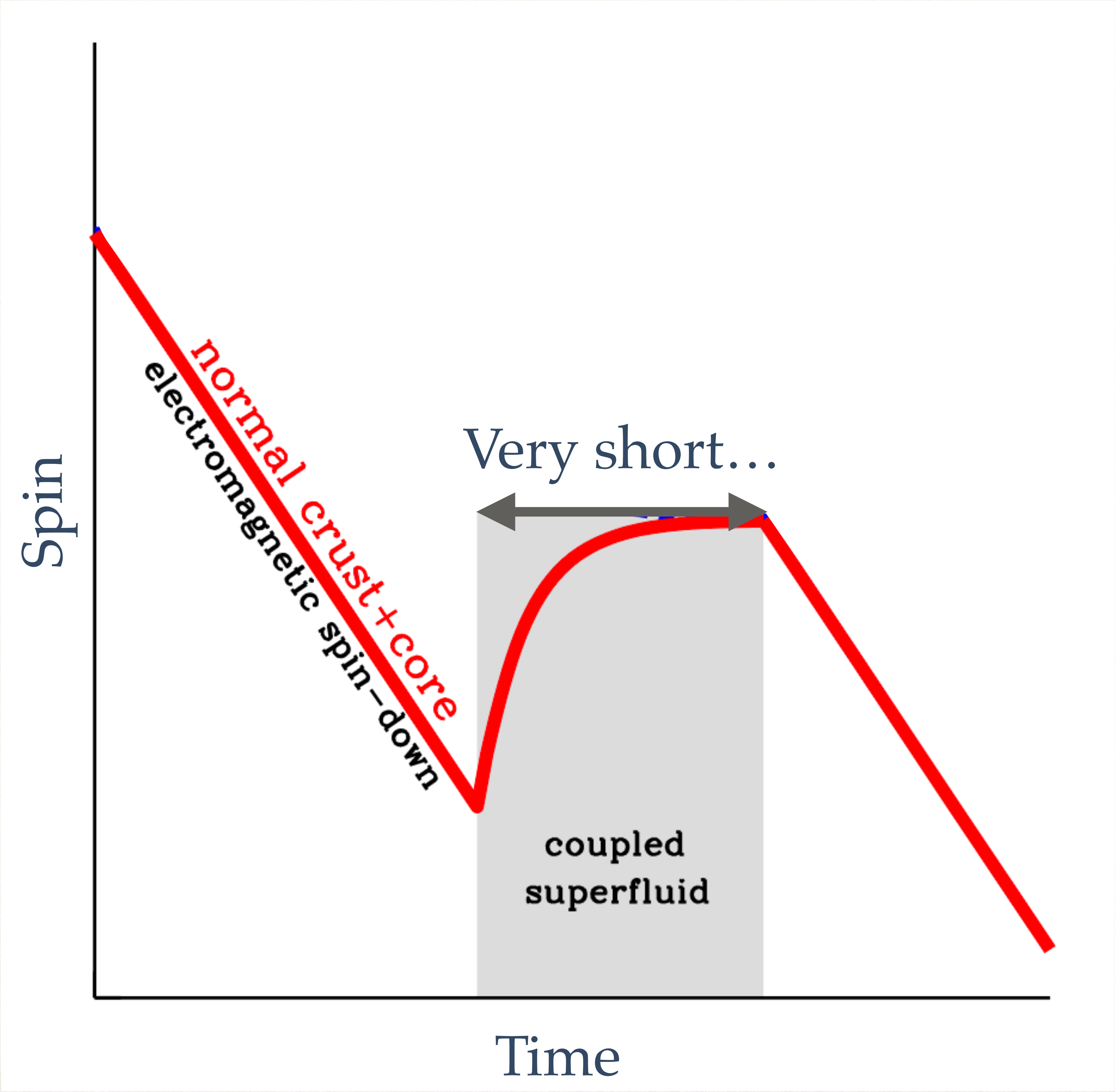

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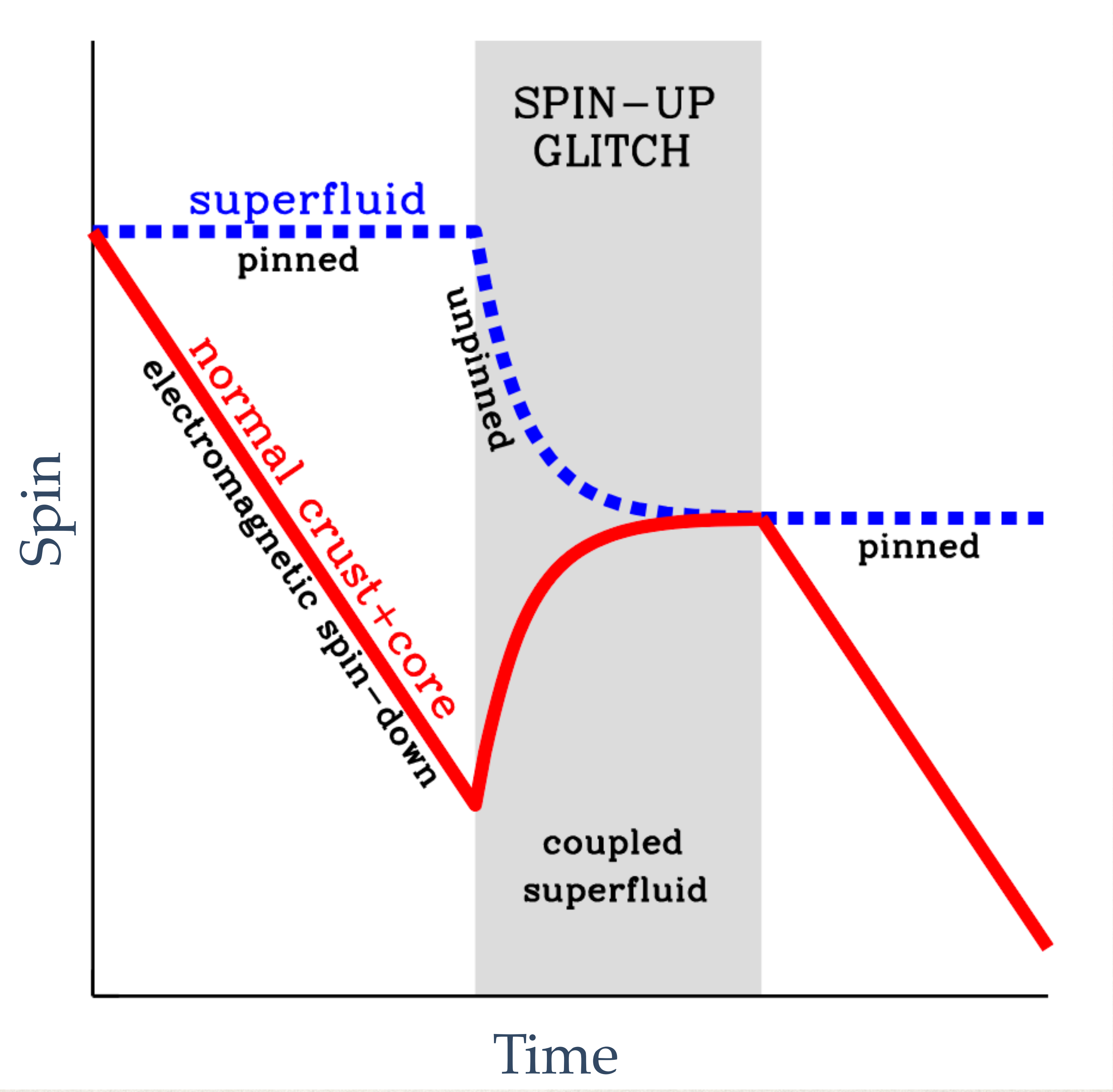

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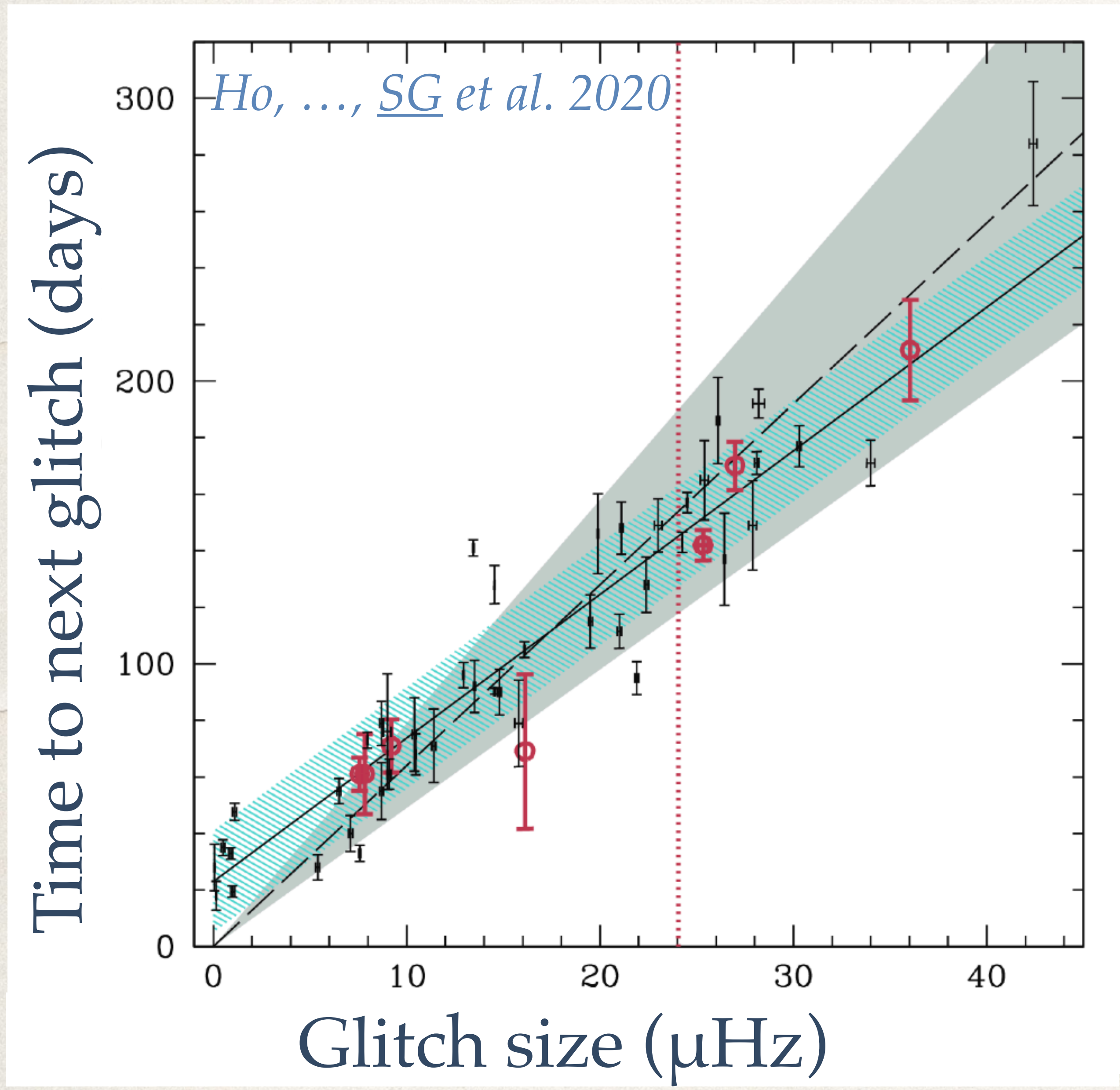
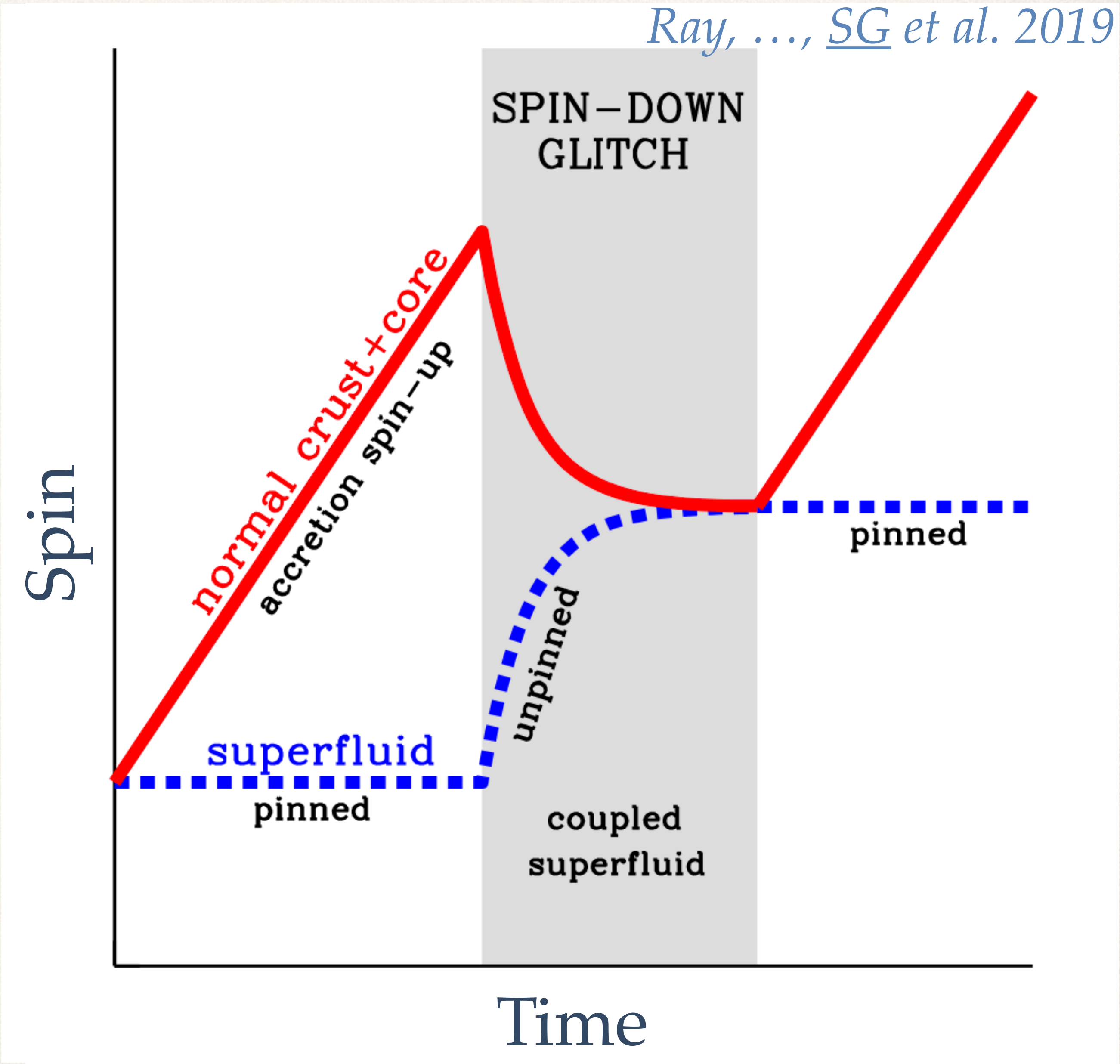


PSR J0537–6910

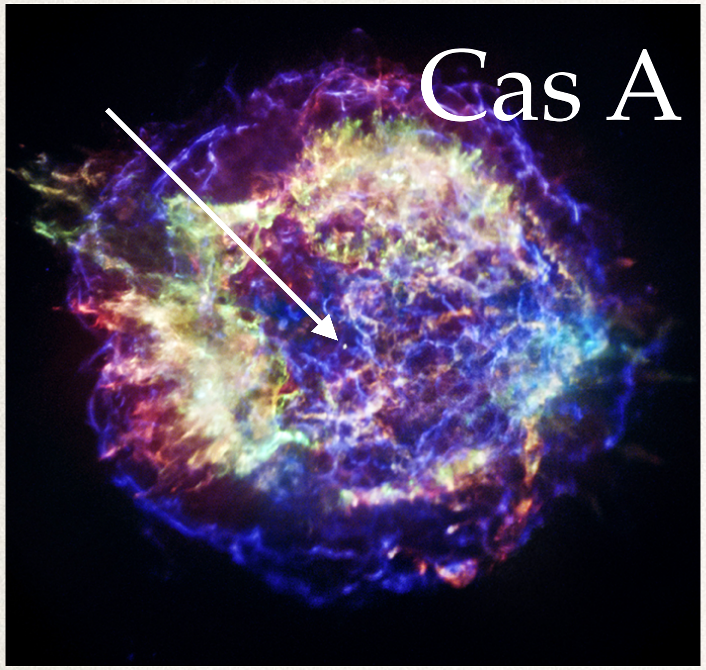
An X-ray (only) young pulsar



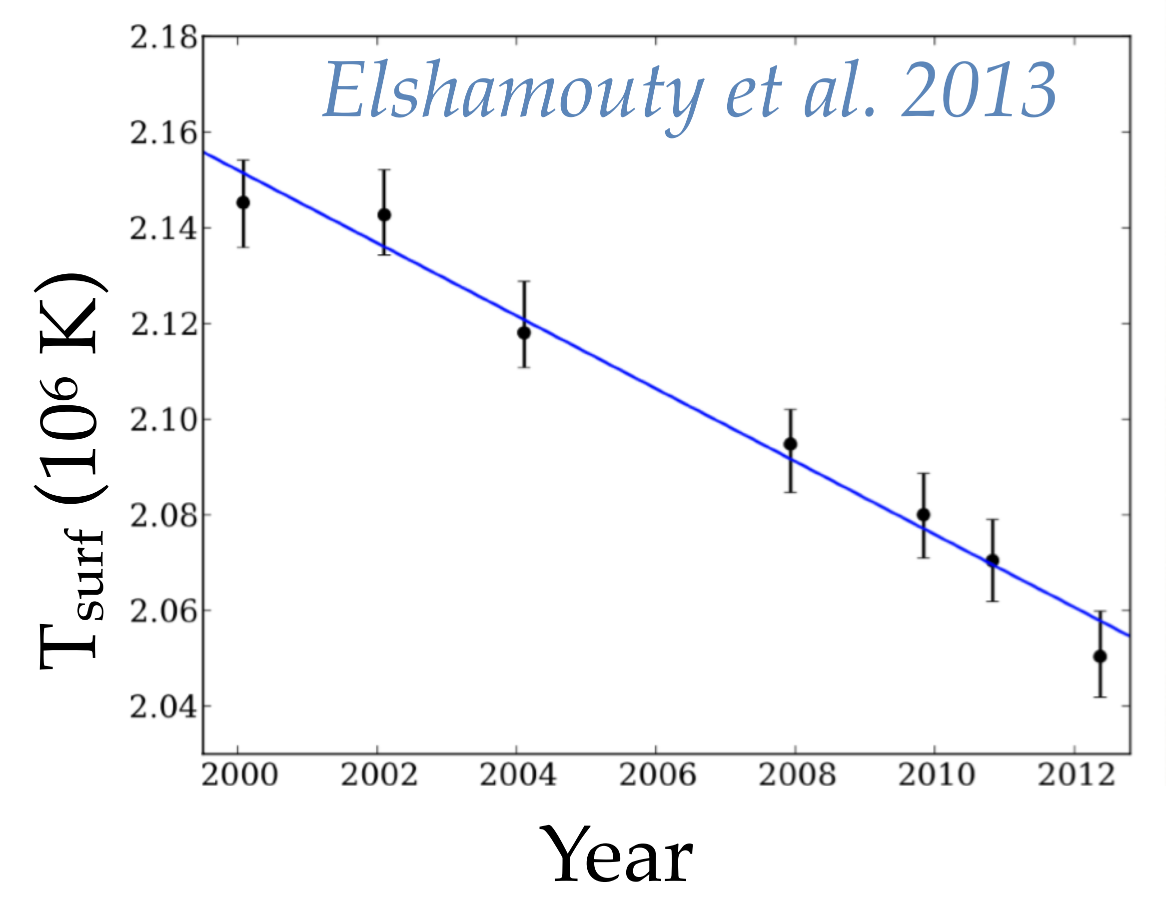
NGC 300 ULX-1

An glitching accreting neutron star

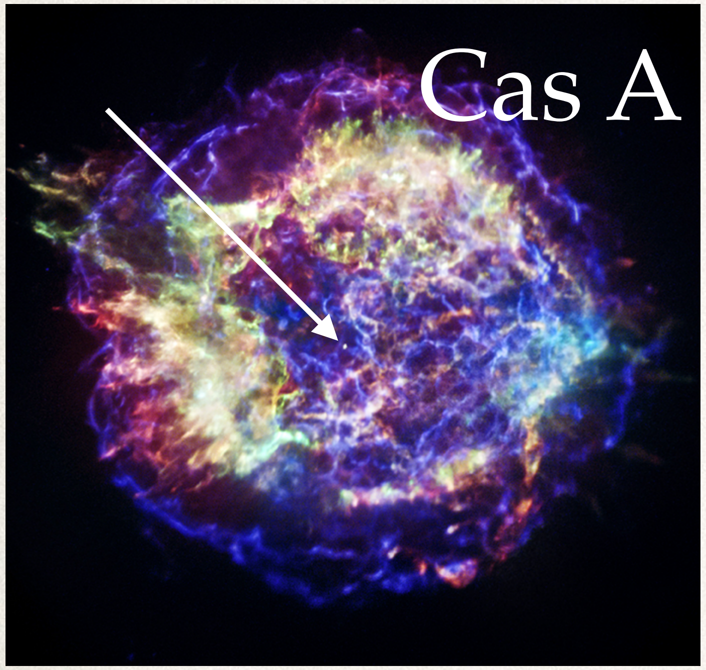
The cooling of neutron stars can also help probe the crust.



Early cooling of the neutron star in Cassiopeia A



The cooling of neutron stars can also help probe the crust.



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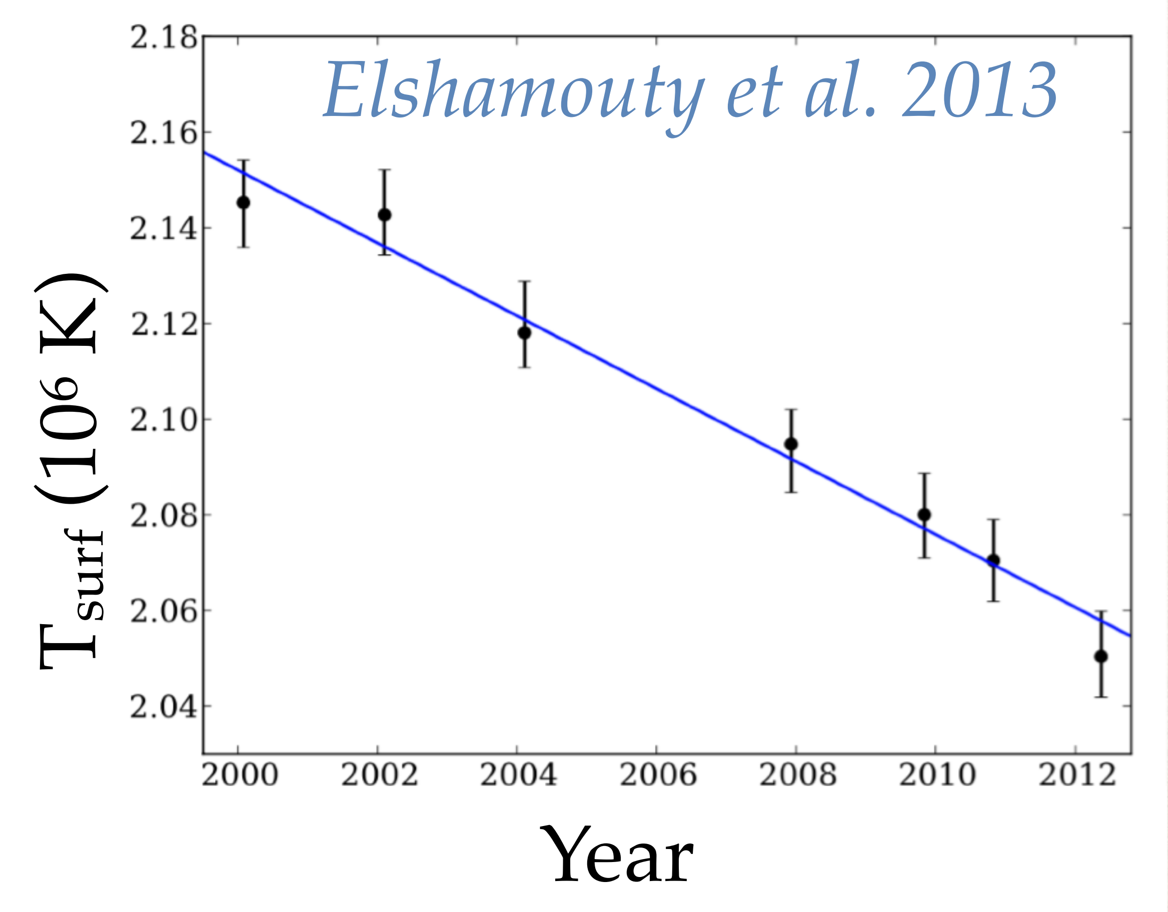

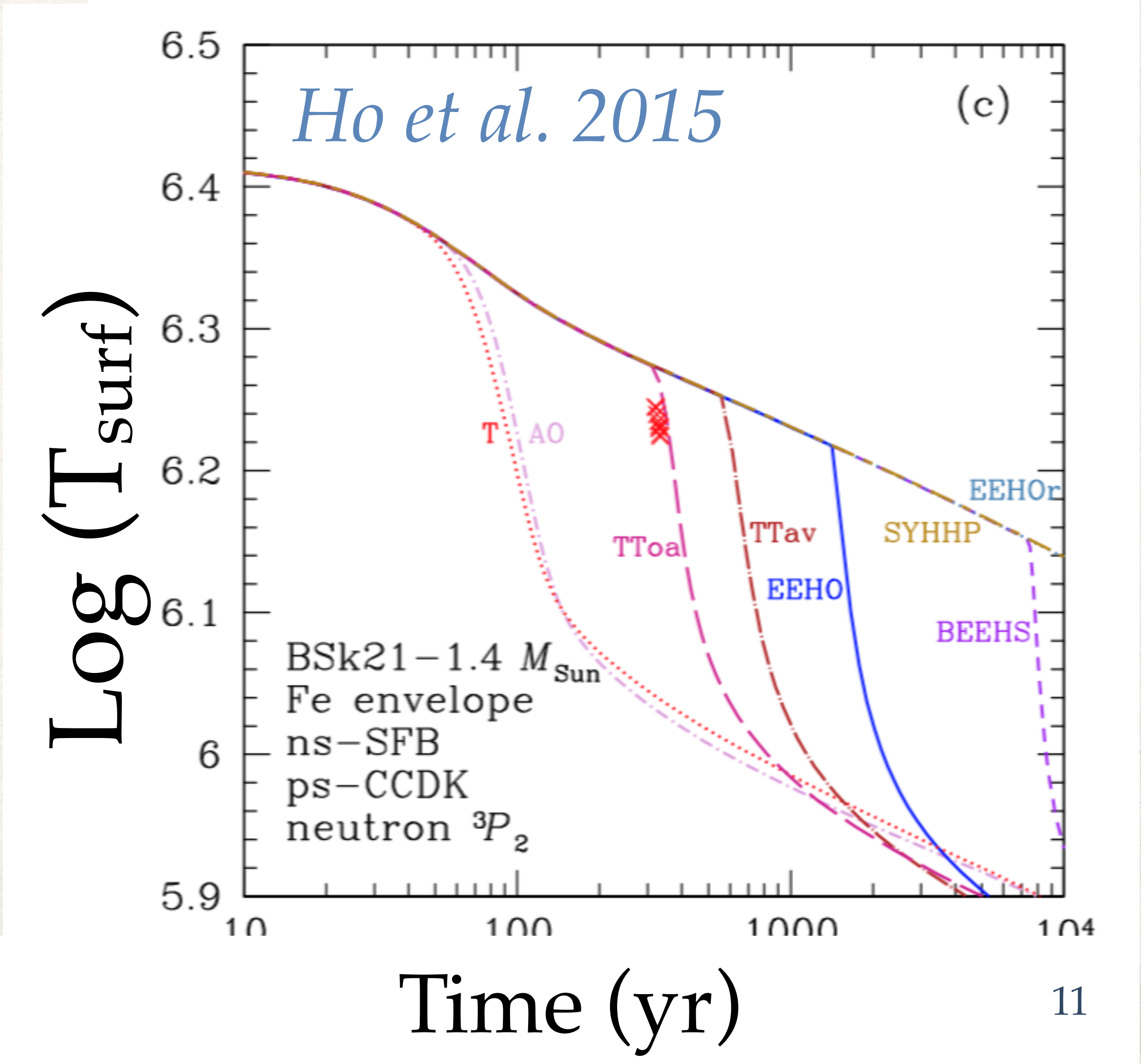

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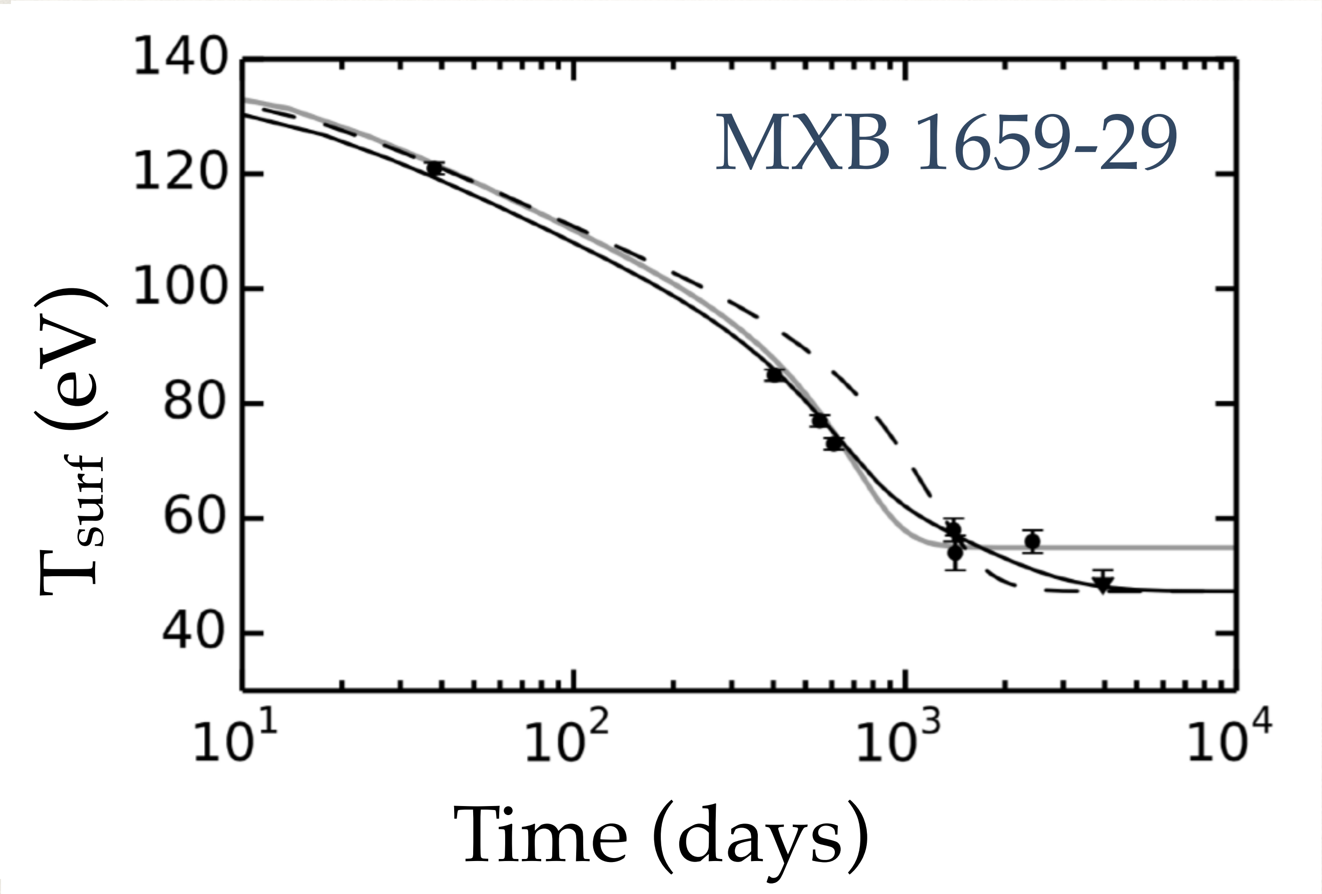
Cooling after accretion bursts



Deibel et al. 2016

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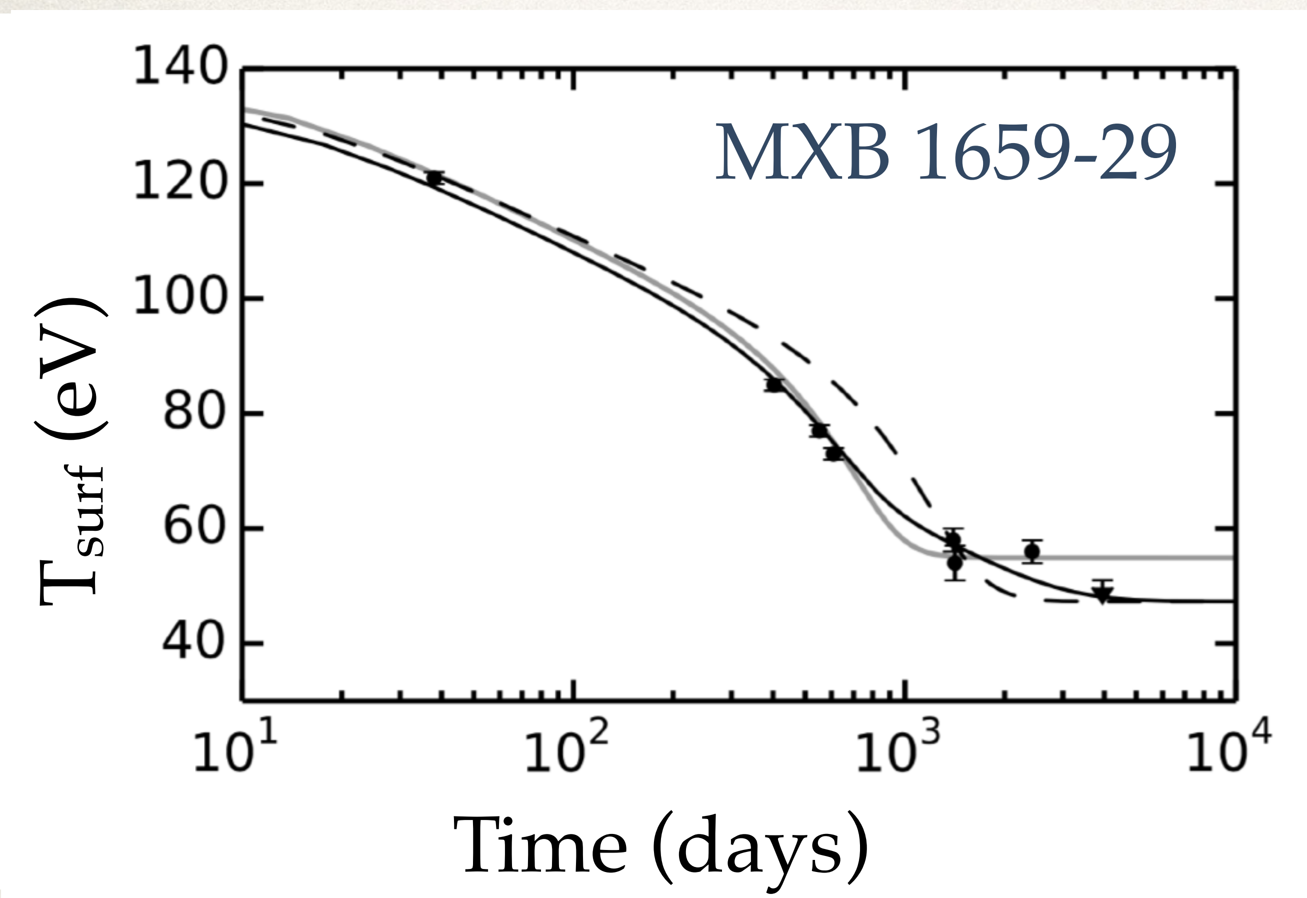
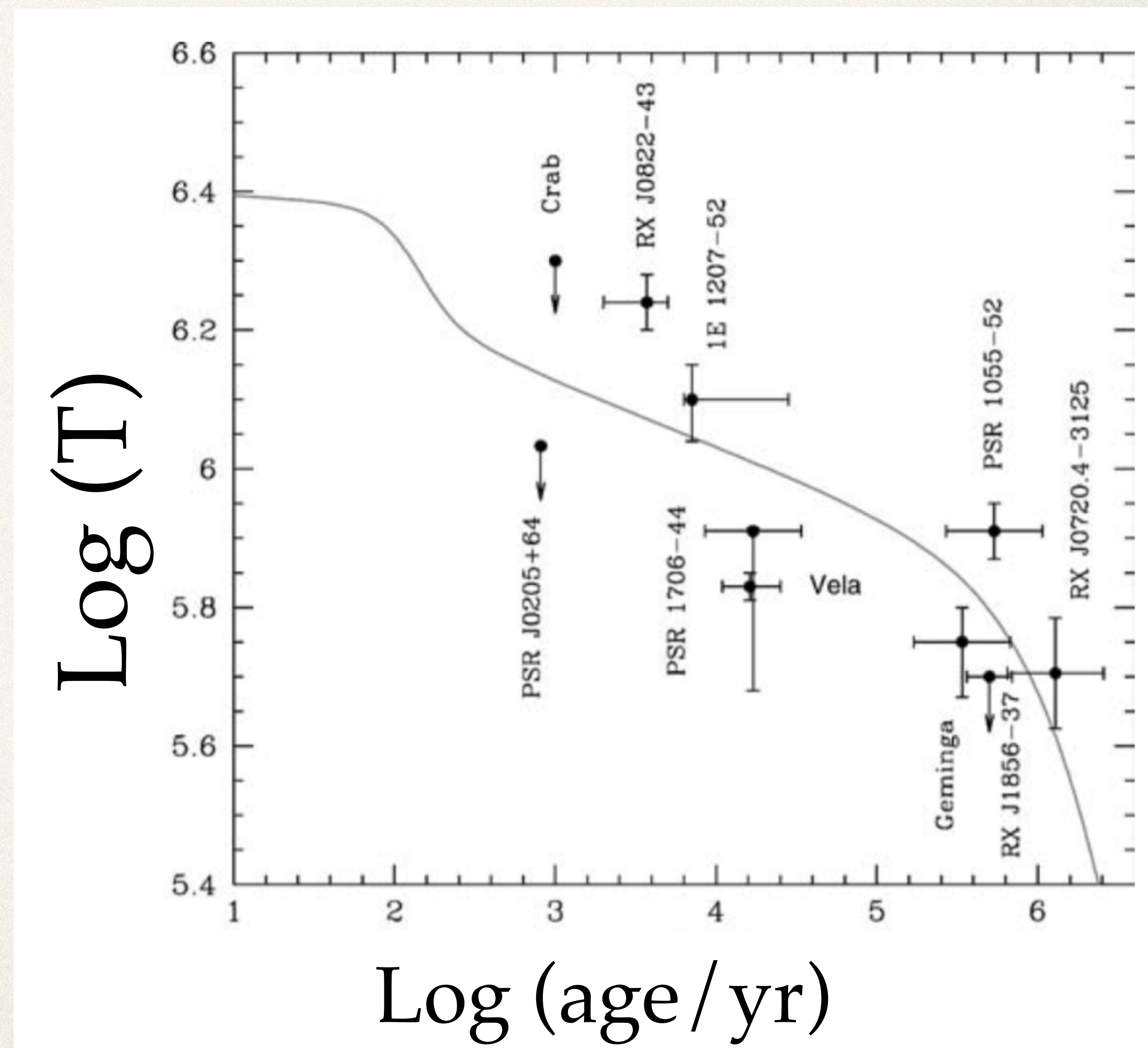


Deibel et al. 2016

Large sample of neutron stars



Yakovlev & Pethick 2004

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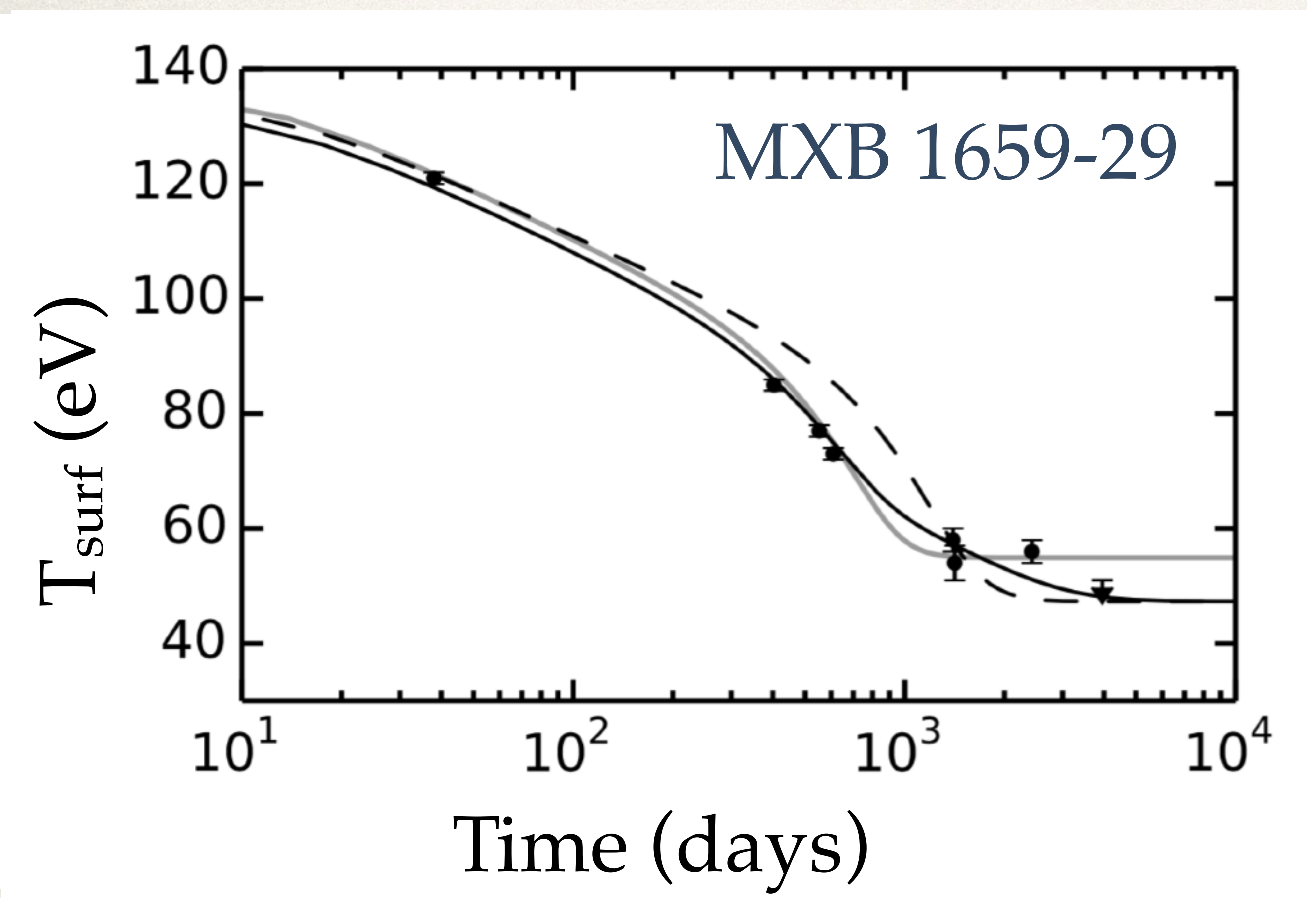
Cooling after accretion bursts



Deibel et al. 2016

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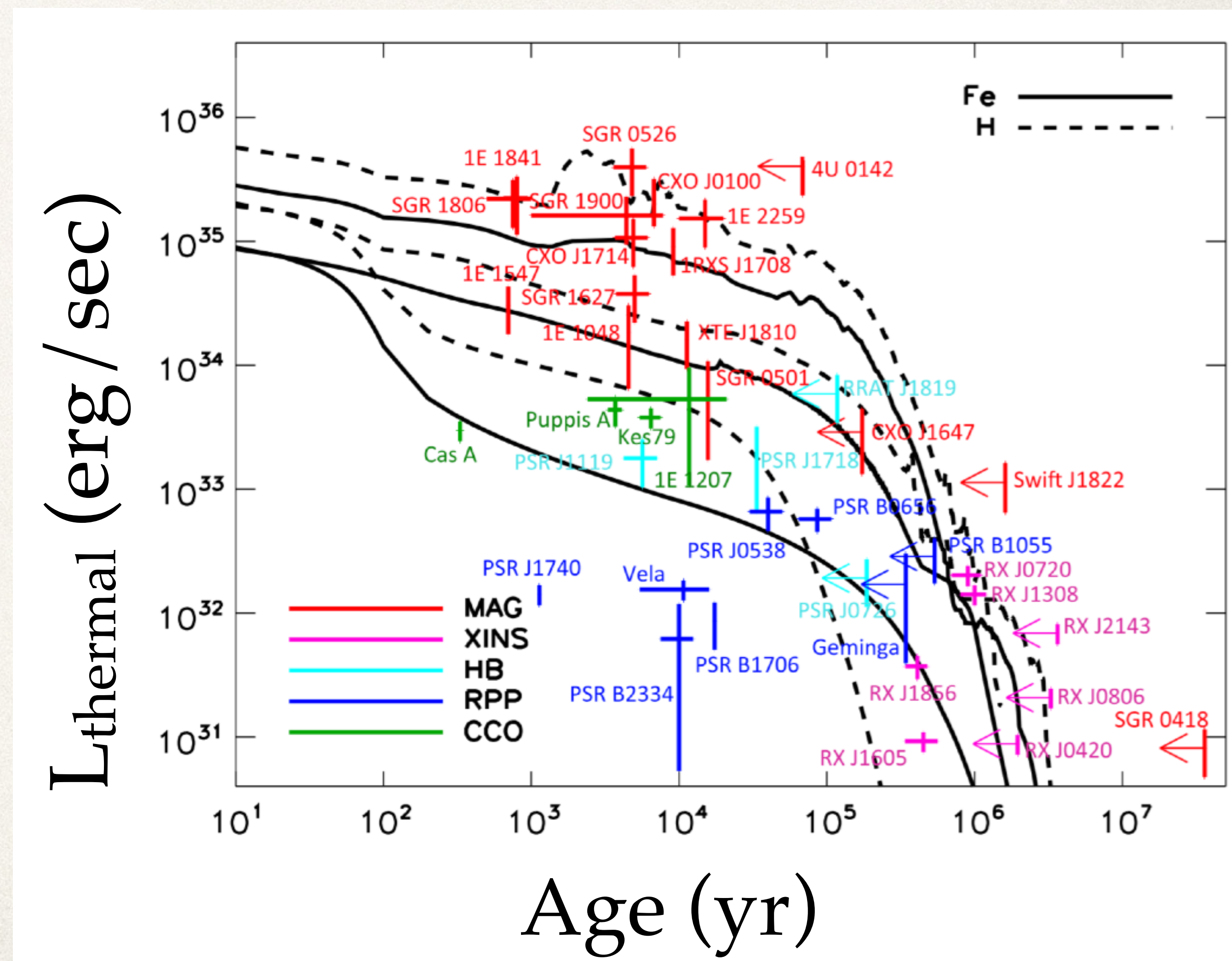
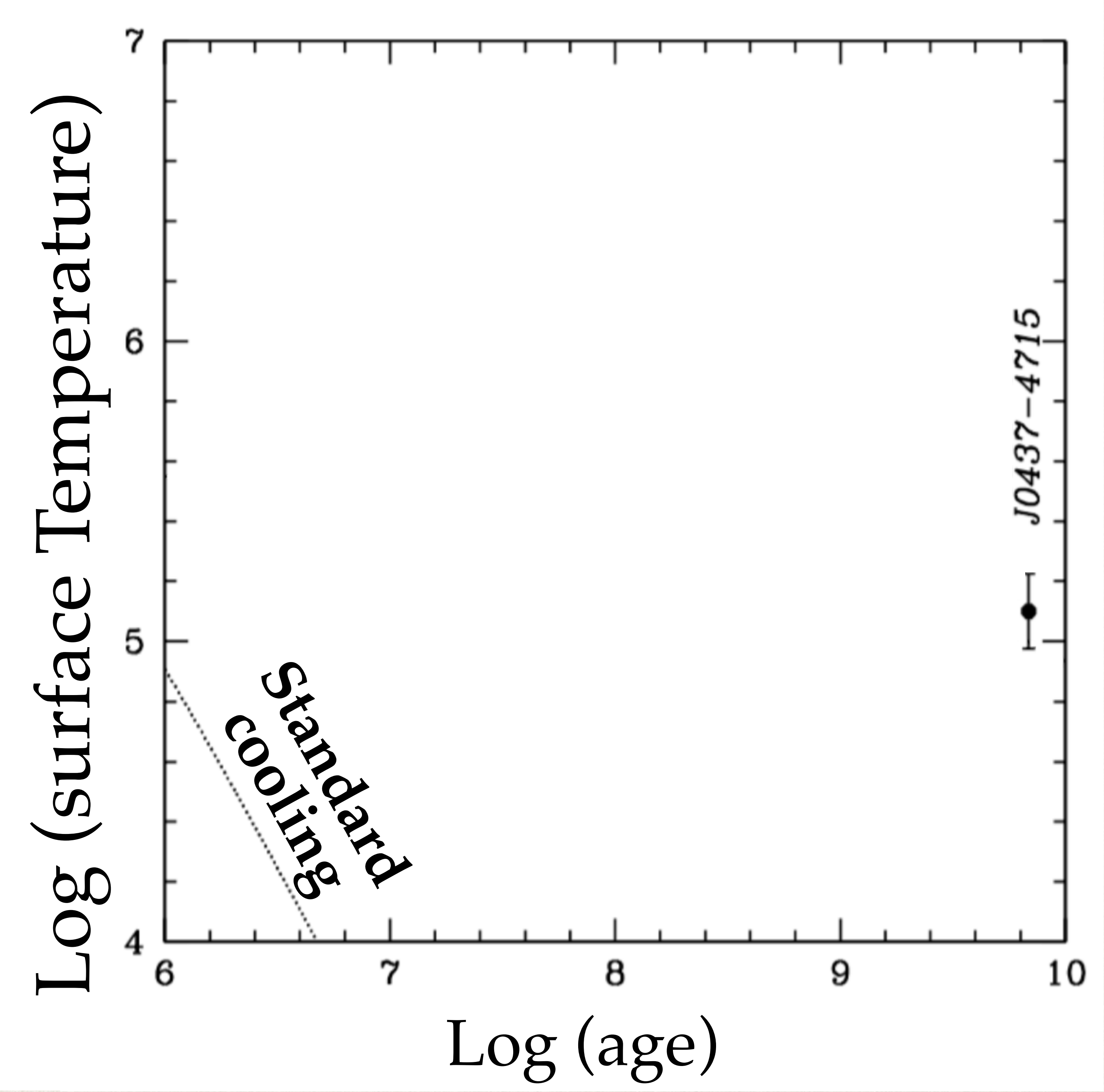


Potekhin, Pons & Page, 2015
with data from Viganò et al. 2013

Some neutron stars are much hotter than predicted by standard cooling.

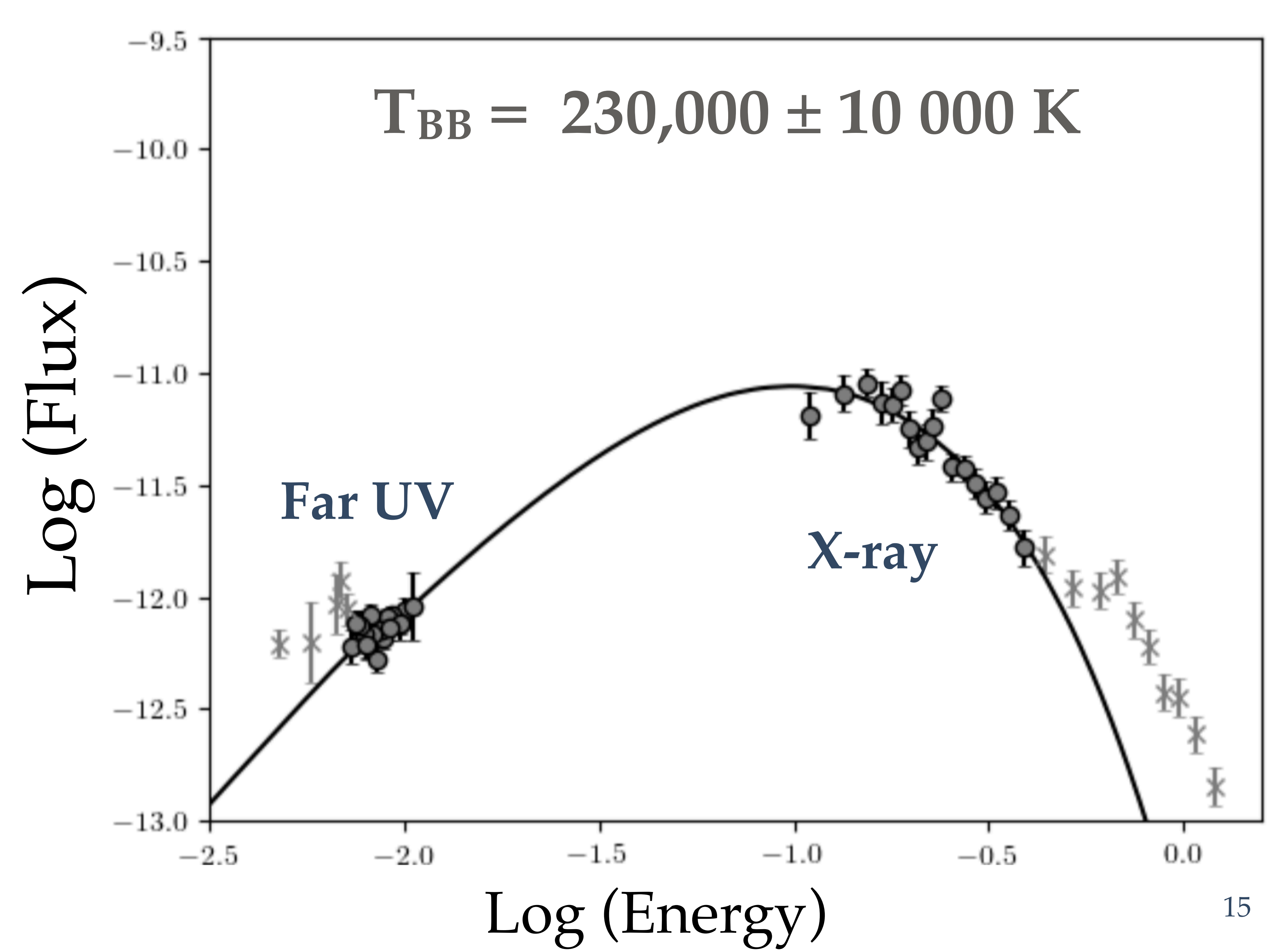


At those temperatures, the neutron star emission peaks between Far-UV and X-rays.

Gonzalez-Caniulef, SG et al (2019)

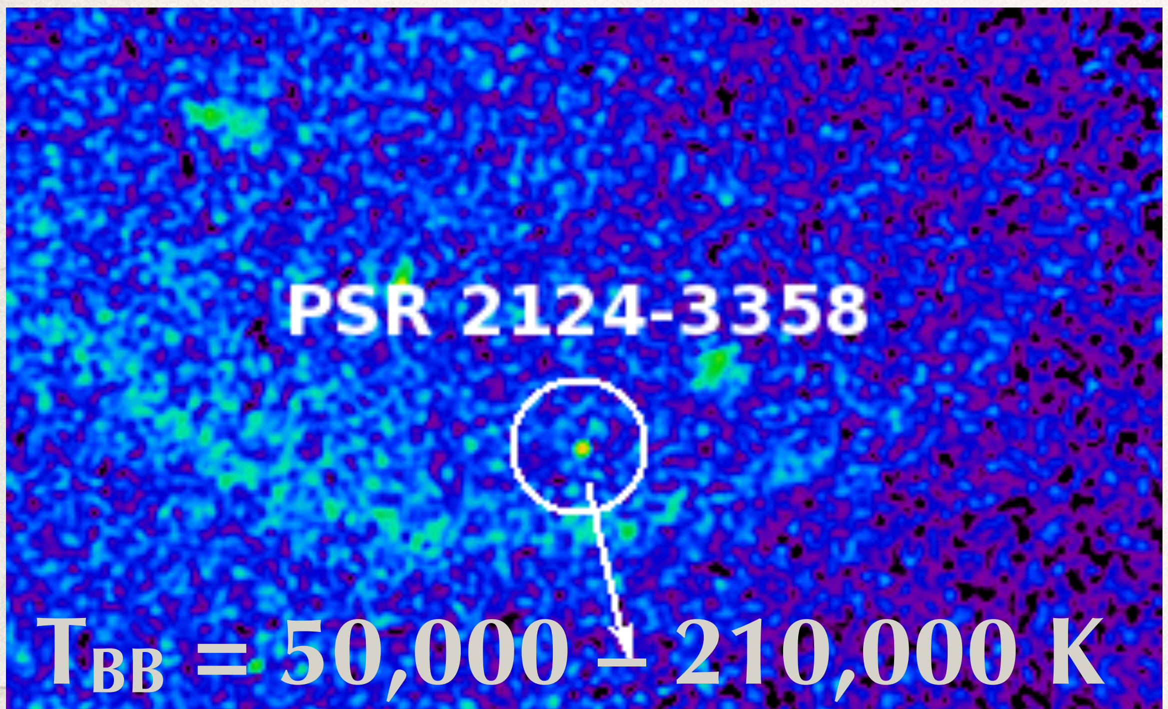
Update in Stammler et al., in preparation

Using neutron star atmosphere models adapted to "low" surface temperatures

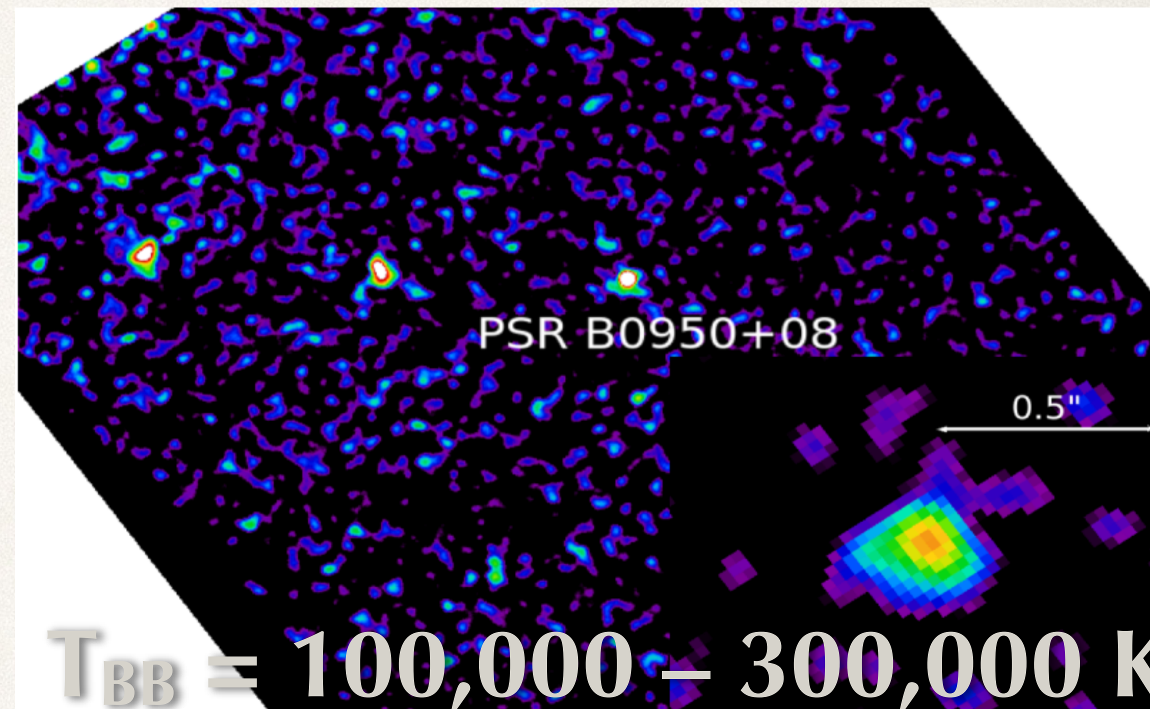


We have determined the temperatures of a handful of old isolated neutron stars.

Programme of HST observations (Opt. and far-UV) of three old isolated neutron stars



Rangelov, …, SG et al. 2017

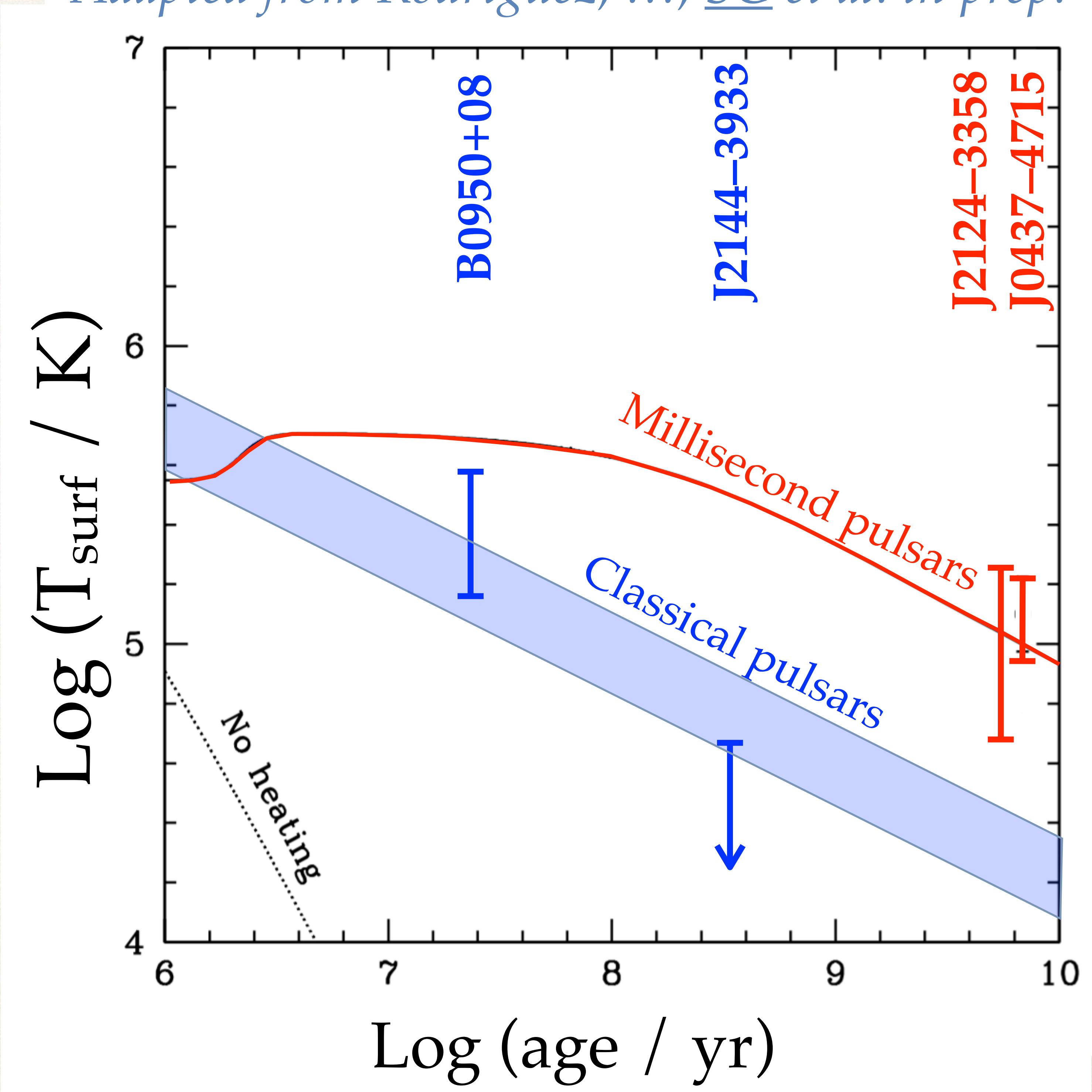


Pavlov …, SG et al. 2017

Guillot et al. 2019

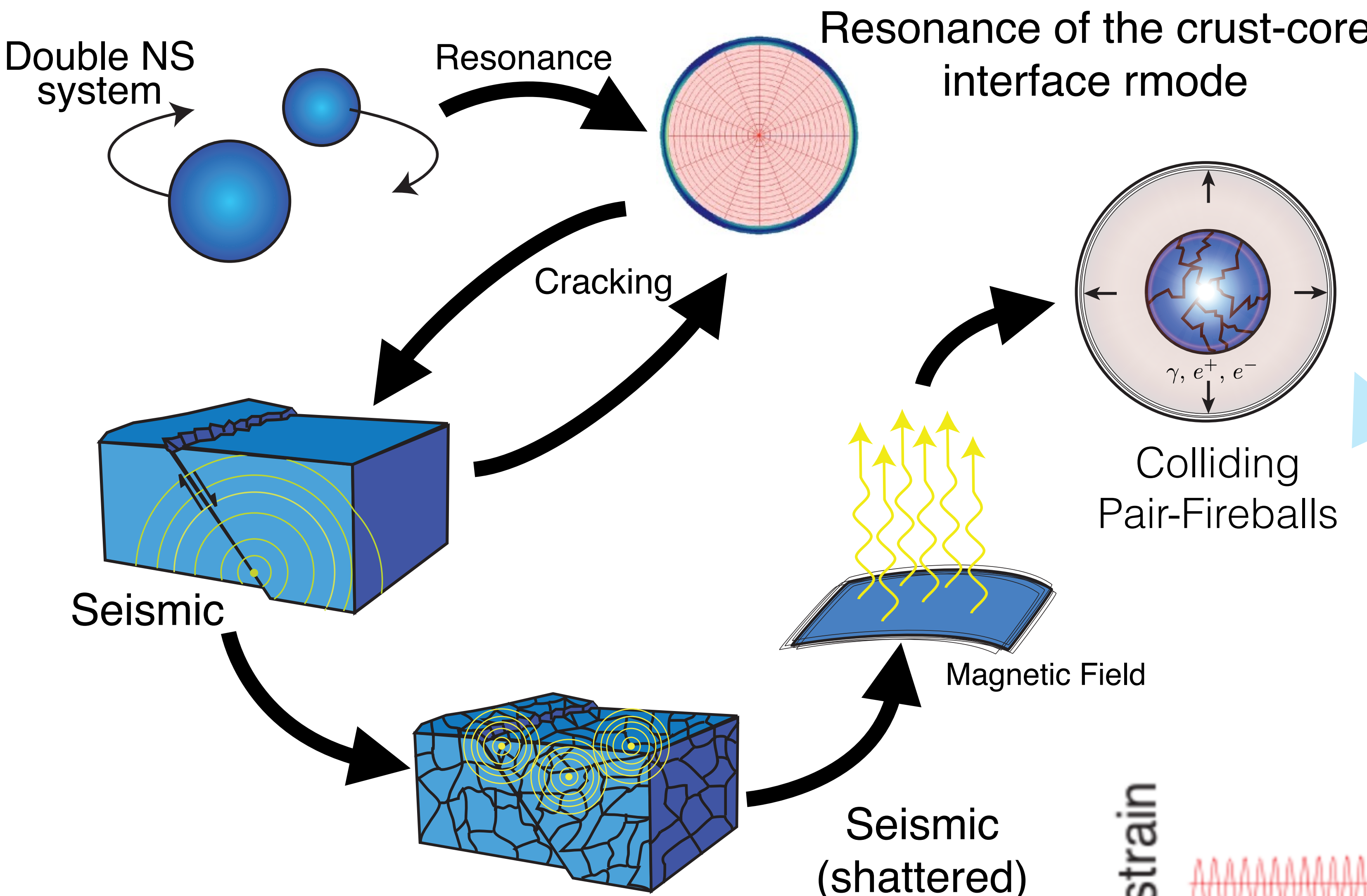
These measurements help constrain physical models of the crust

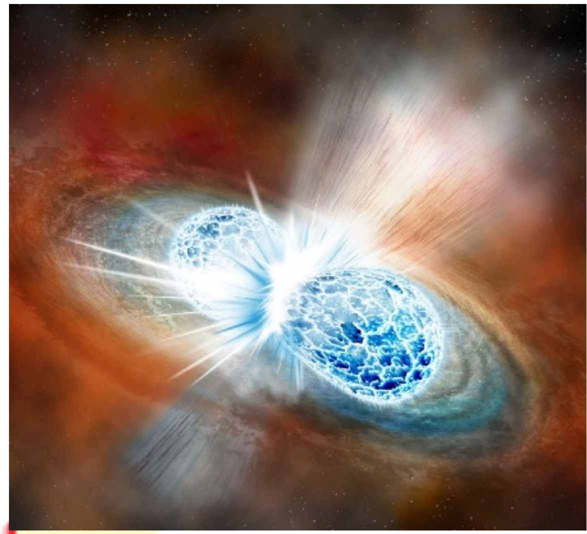
Adapted from Rodriguez, …, SG et al. in prep.

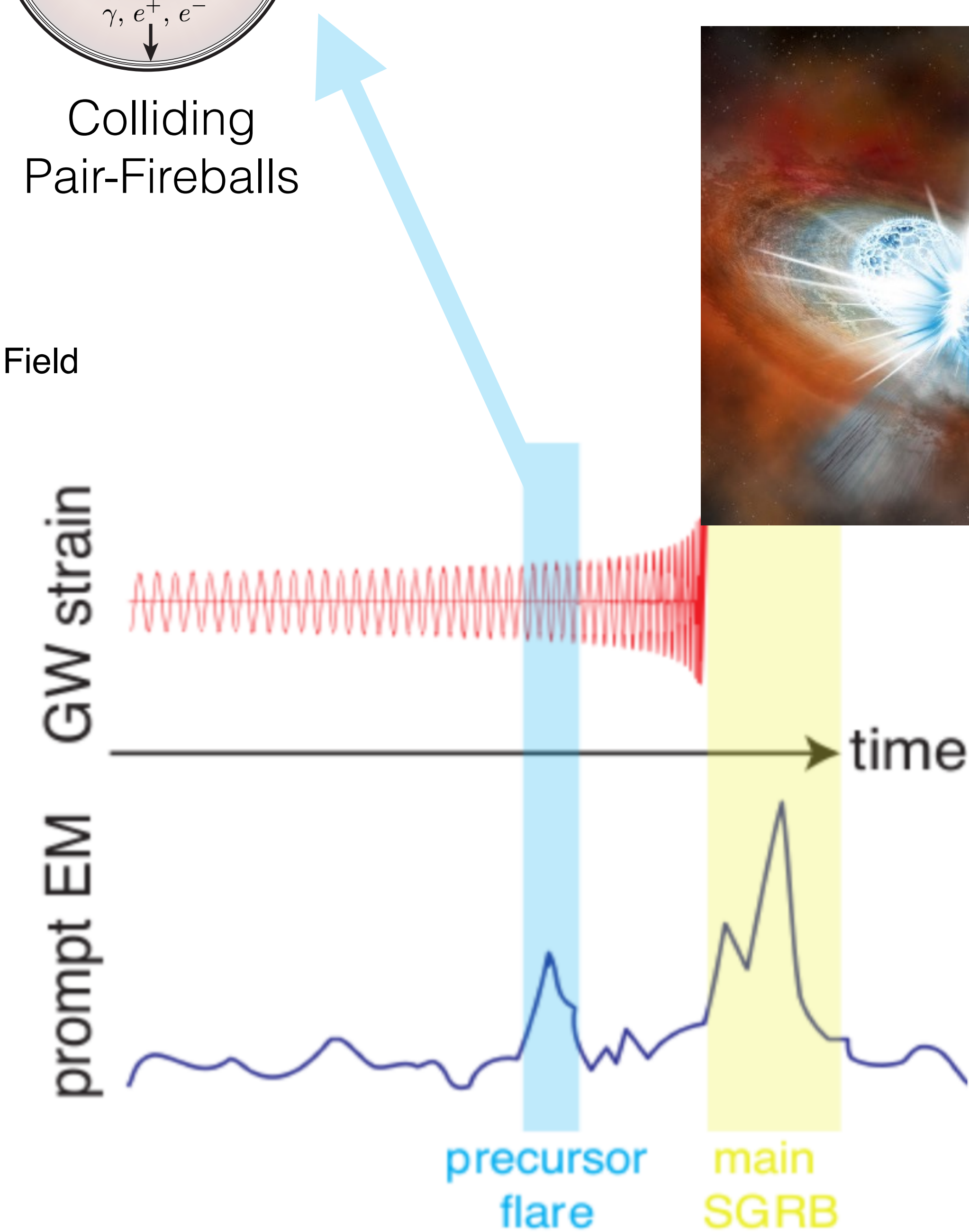


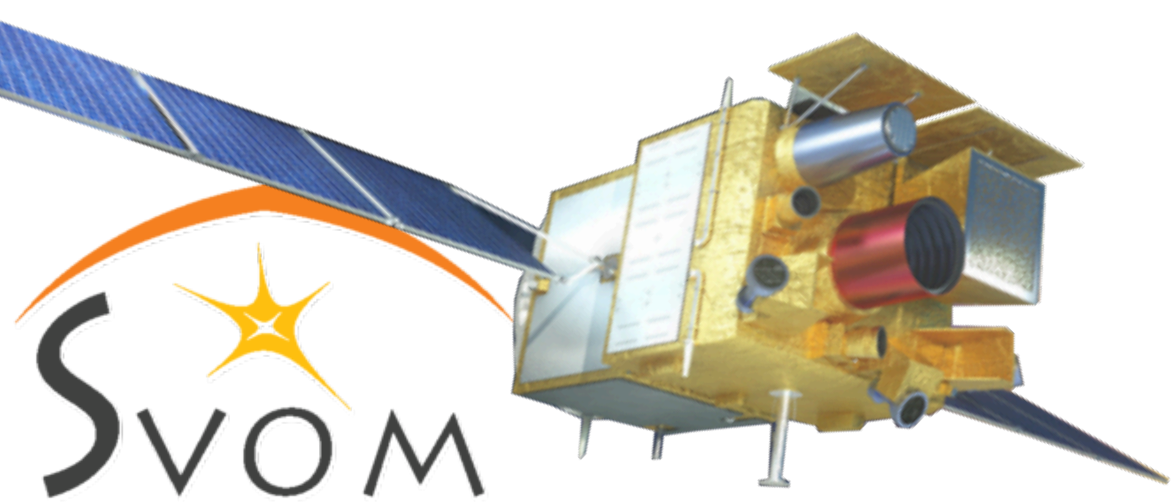
A new multi-messenger method to probe the crust

Tsang et al. 2012
Tsang 2013
Neill et al. 2022, 2023



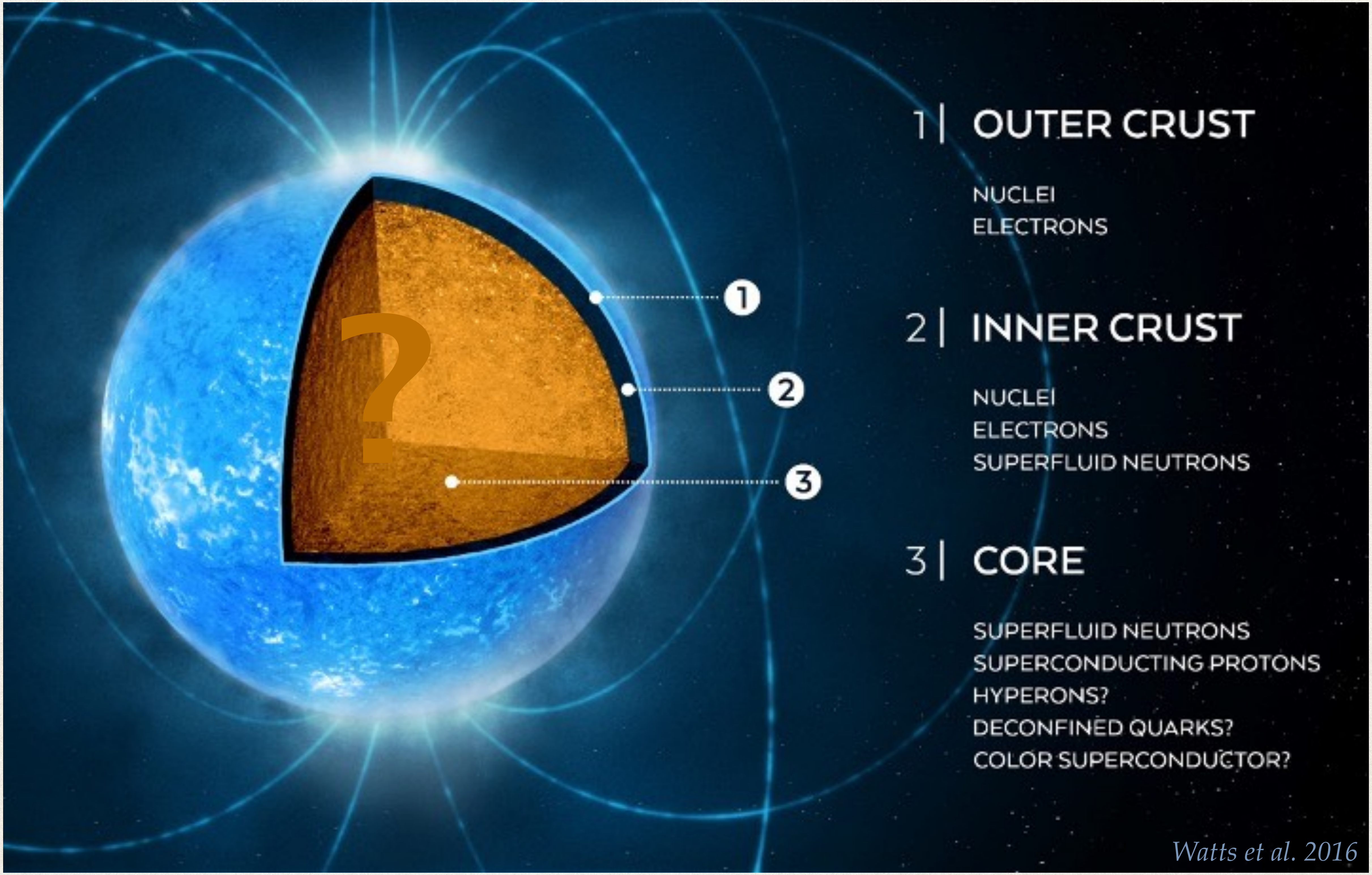






18

Let’s dive in the deep core…



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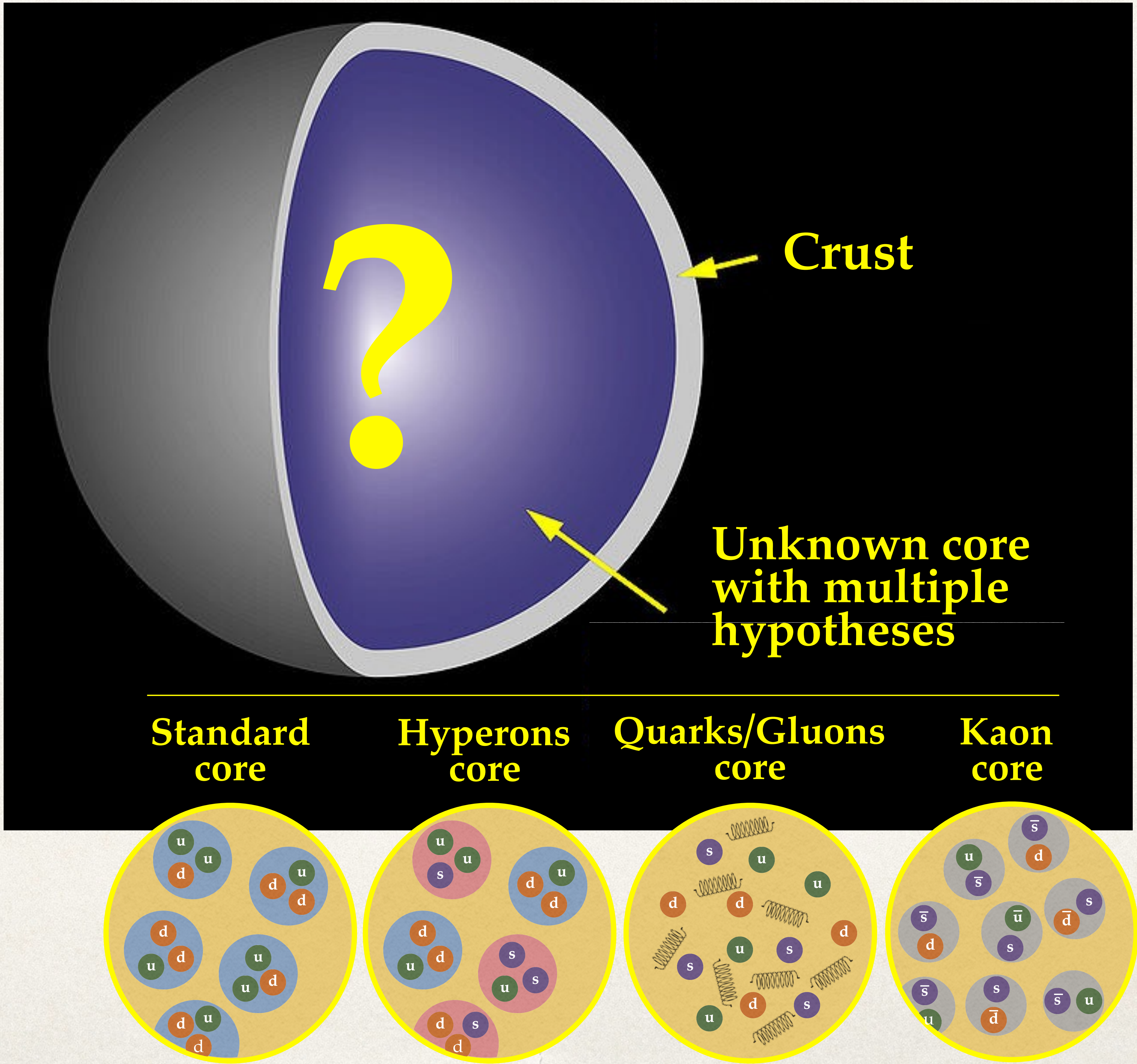
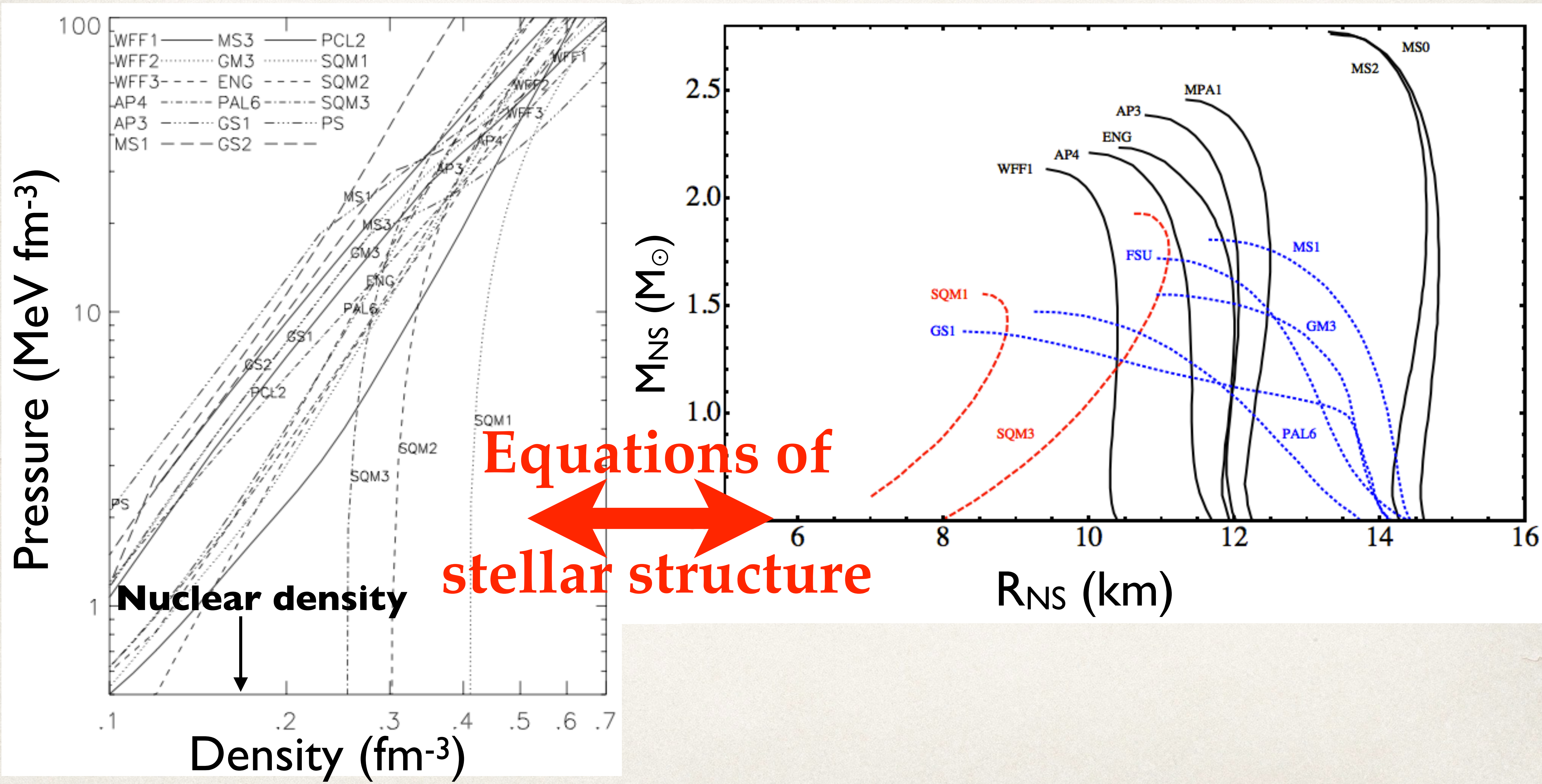
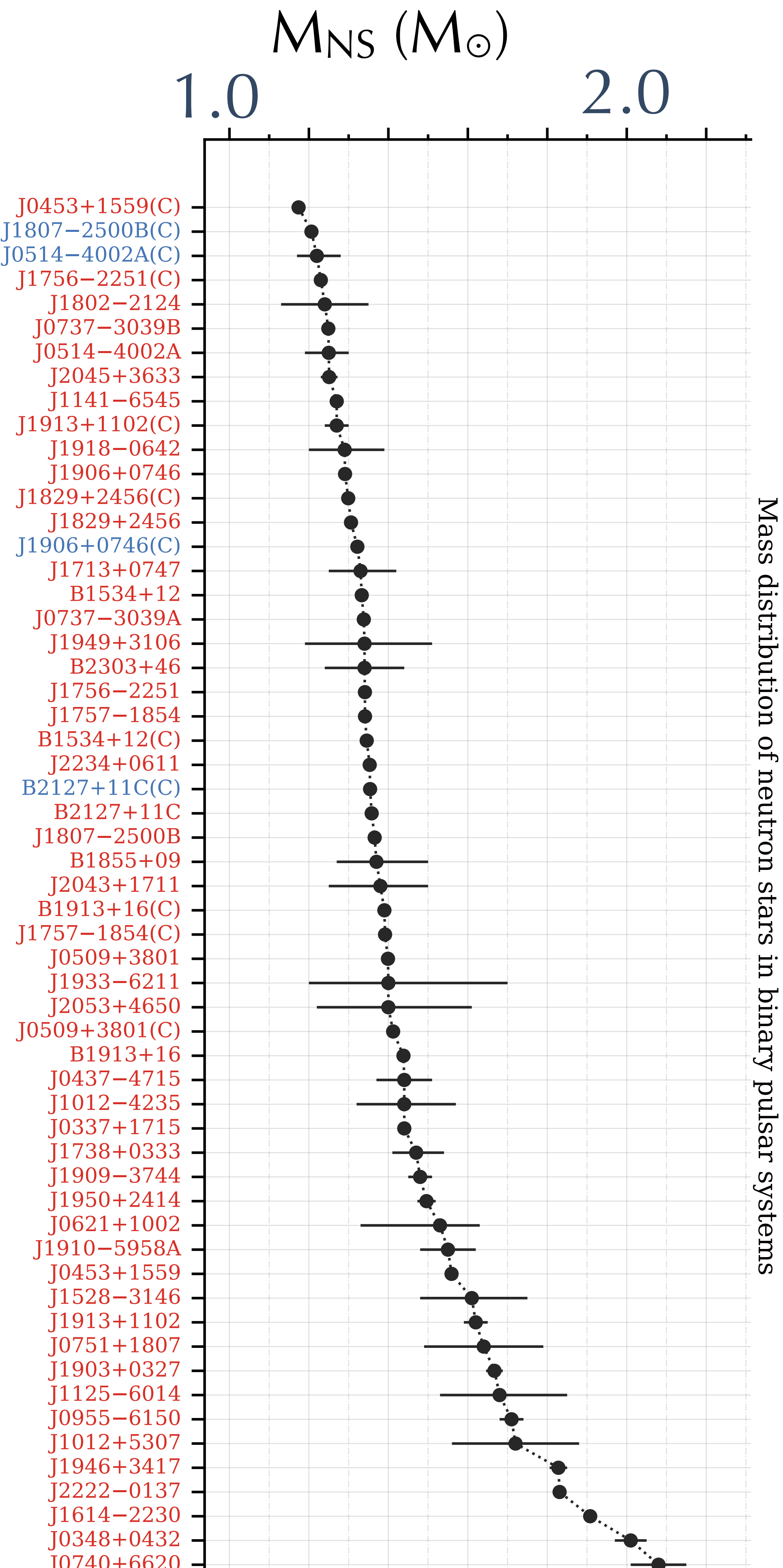


Dense nuclear matter is described by an equation of state P(ρ).



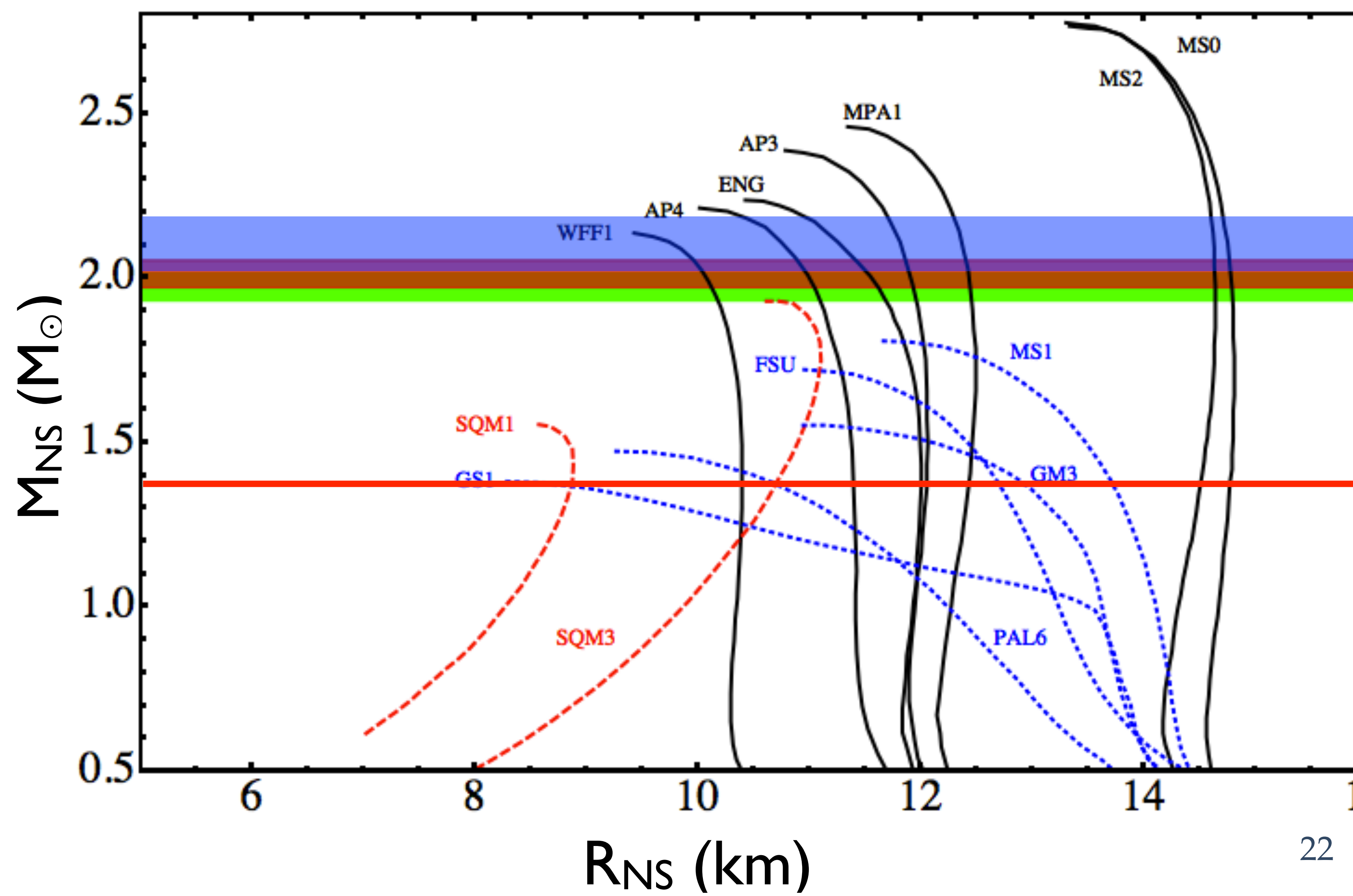
Lattimer and Prakash 2001

Measurements of the mass M_{NS} exist, but only high-M_{NS} are useful.

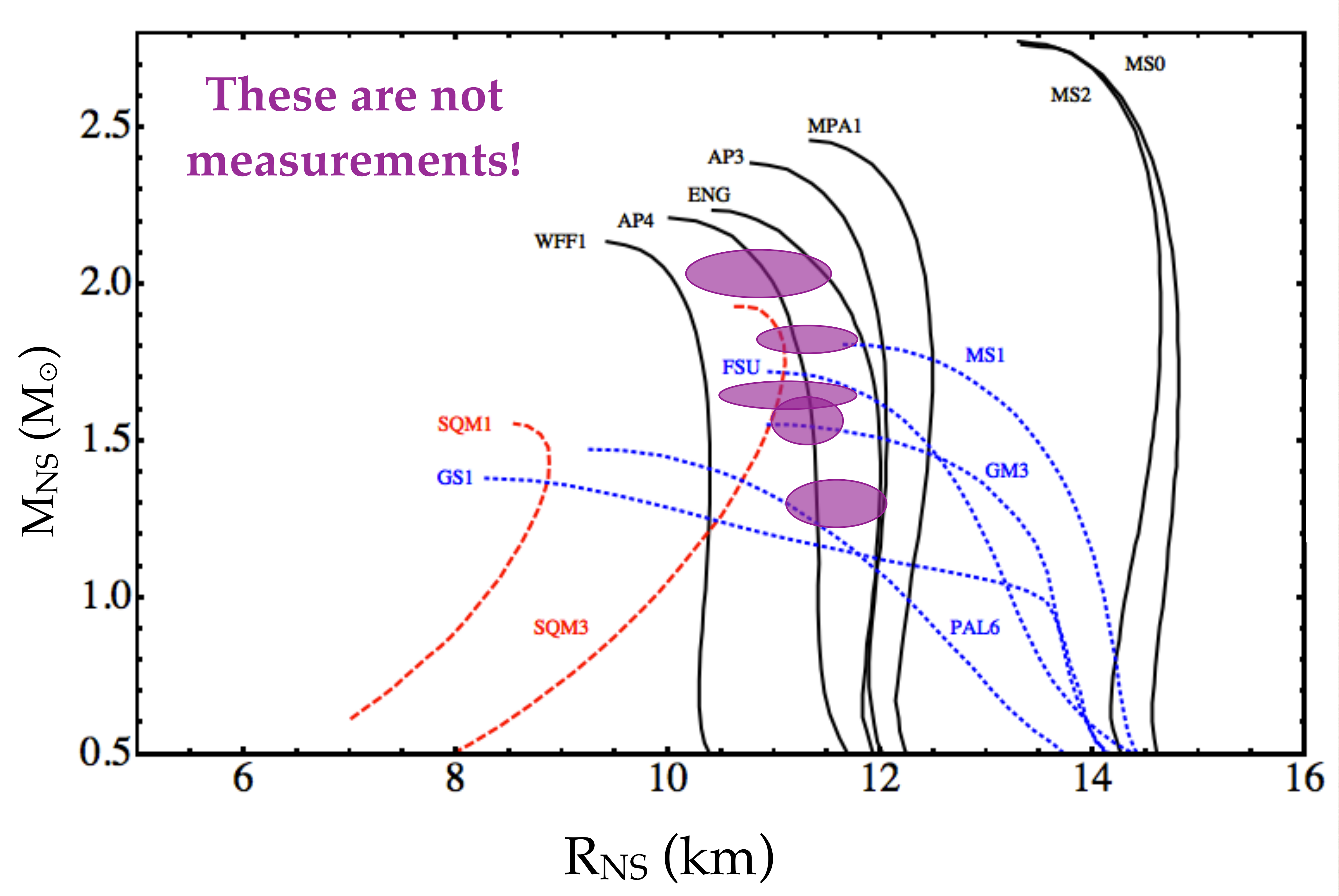


Credits: P. Freire

Demorest et al. 2010
Antoniadis et al. 2013
Fonseca et al. 2021



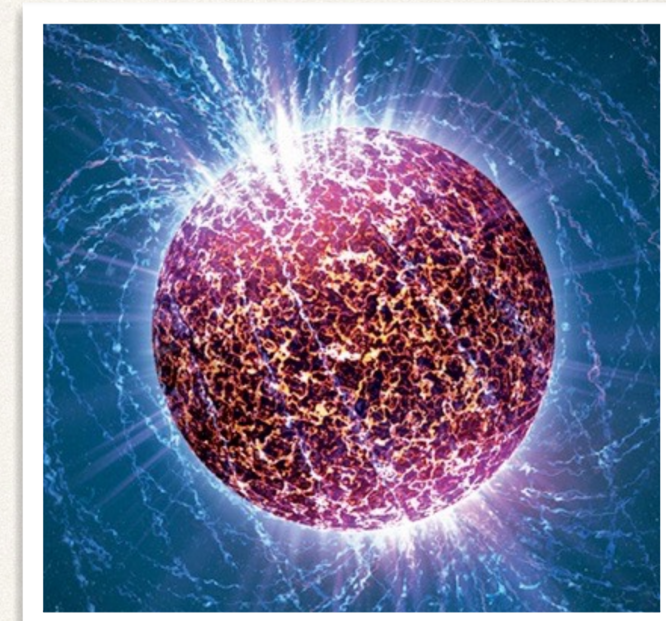
Measuring R_{NS} is difficult and measuring both R_{NS} and M_{NS} is even more difficult.



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.

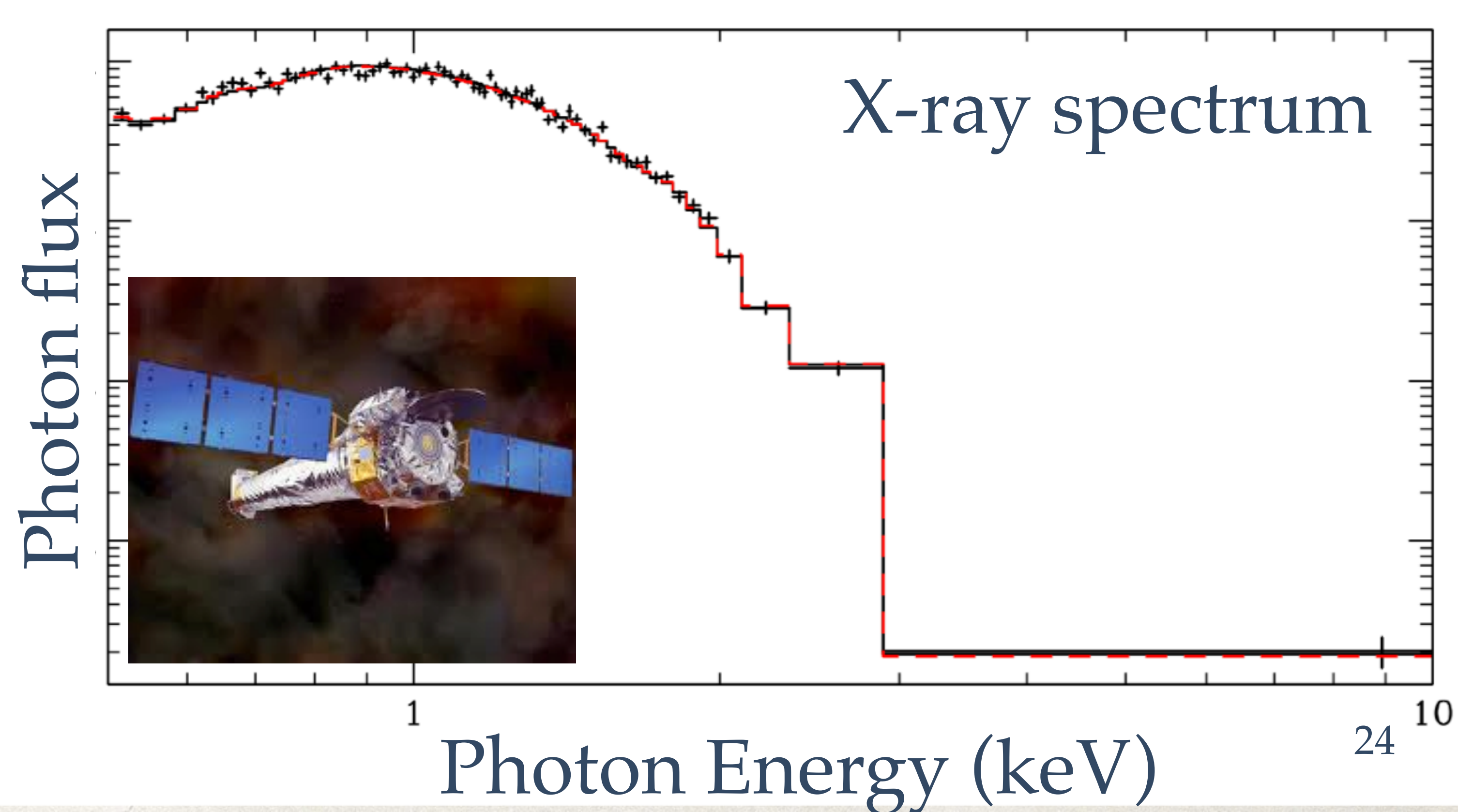


Luminosity

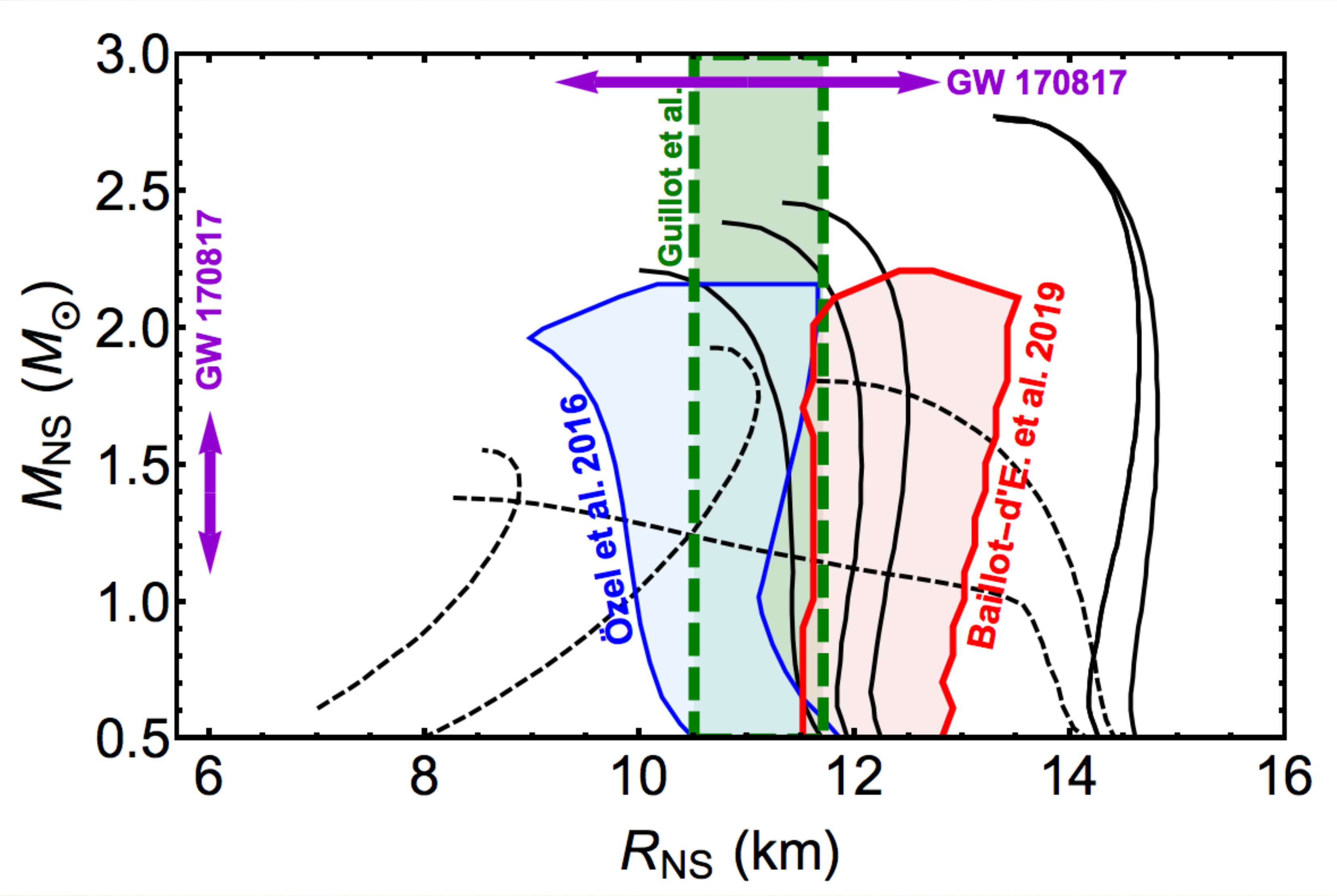
$$L \propto 4\pi R^2 \sigma T_{\rm eff}^4$$

Flux

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



By combining the measurements from a handful of neutron stars, we can constrain the equation of state of dense matter.



Simplistic EoS model

Guillot et al. 2013, 2014

Updated in Guillot 2016

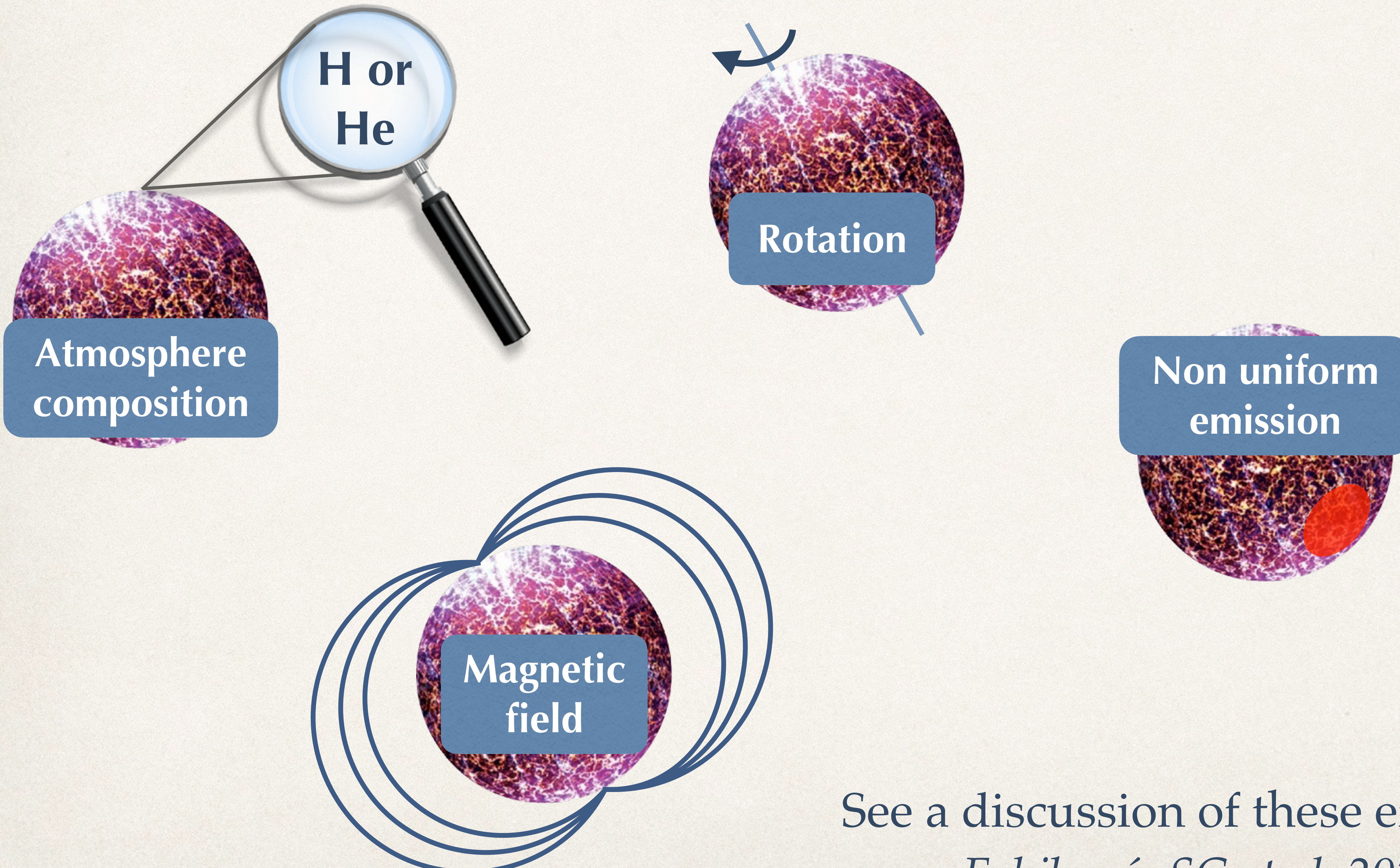
Analytical EoS Model

Ozel, …SG et al. (2016)

Physical (empirical) EoS Model

Baillot d'Etivaux, SG et al. (2019)

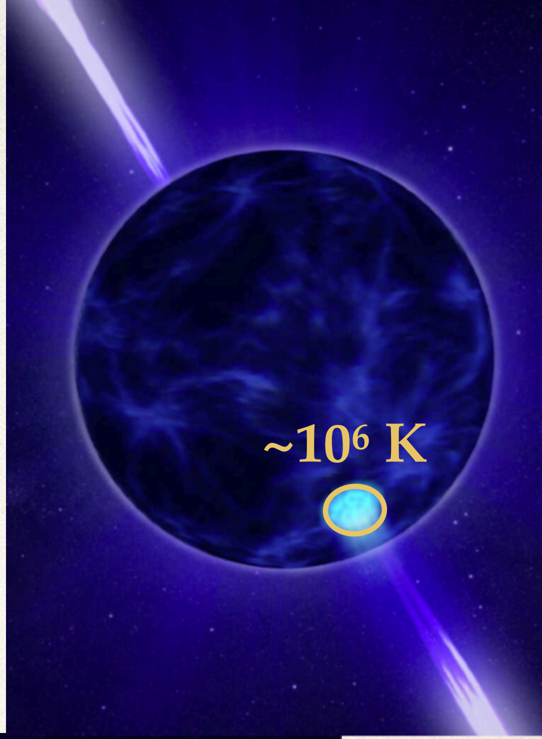
These measurements suffer from systematic uncertainties that can be hard to quantify.

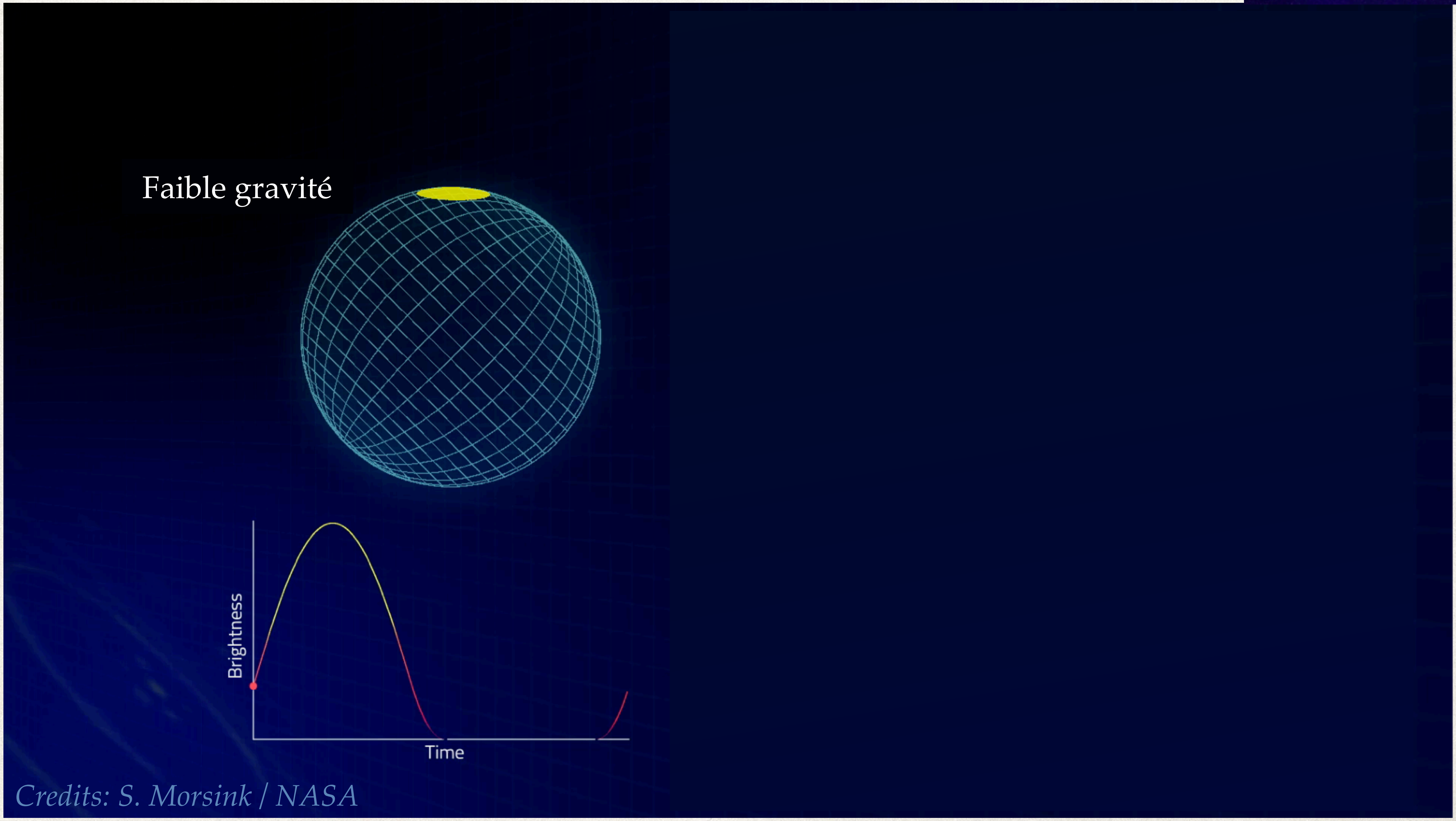


See a discussion of these effects in
Echiburú, SG et al. 2020

But there is a new method, a better method.

Let’s consider a neutron star with localised hot regions are the surface.





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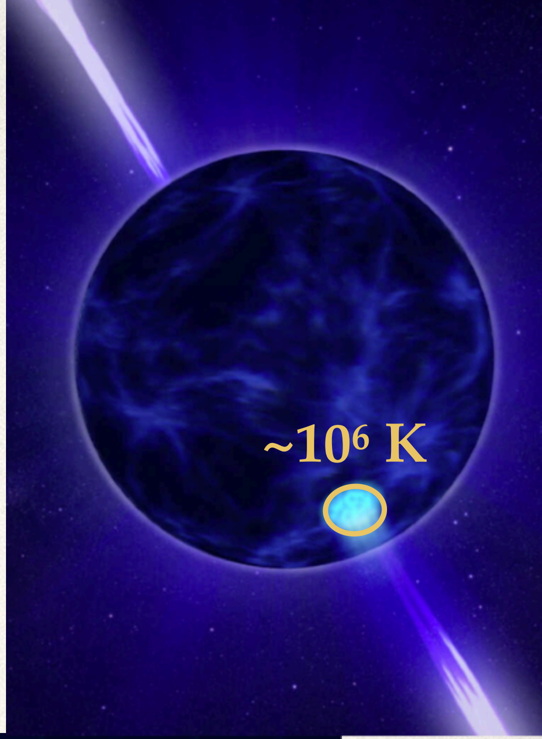
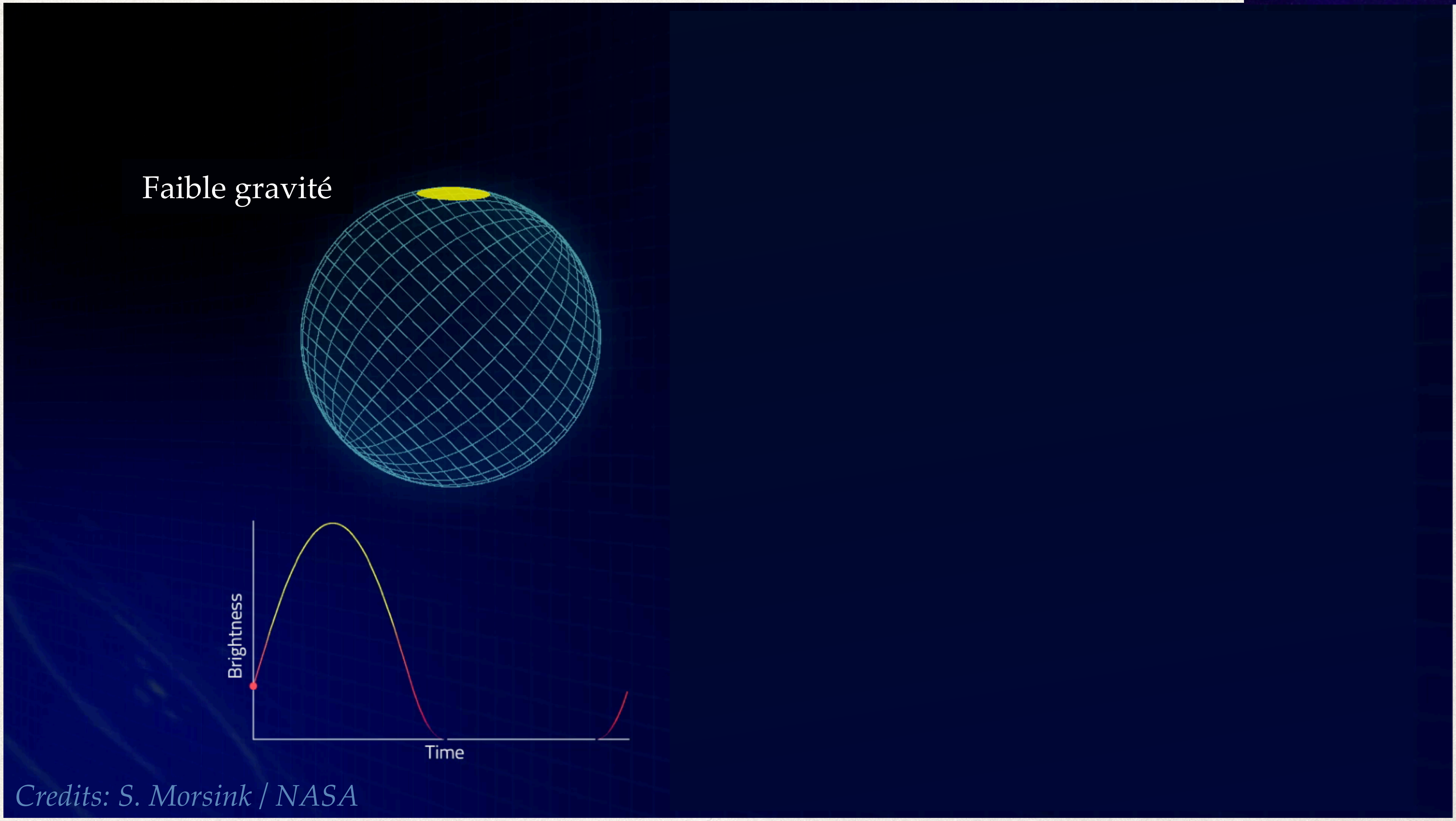
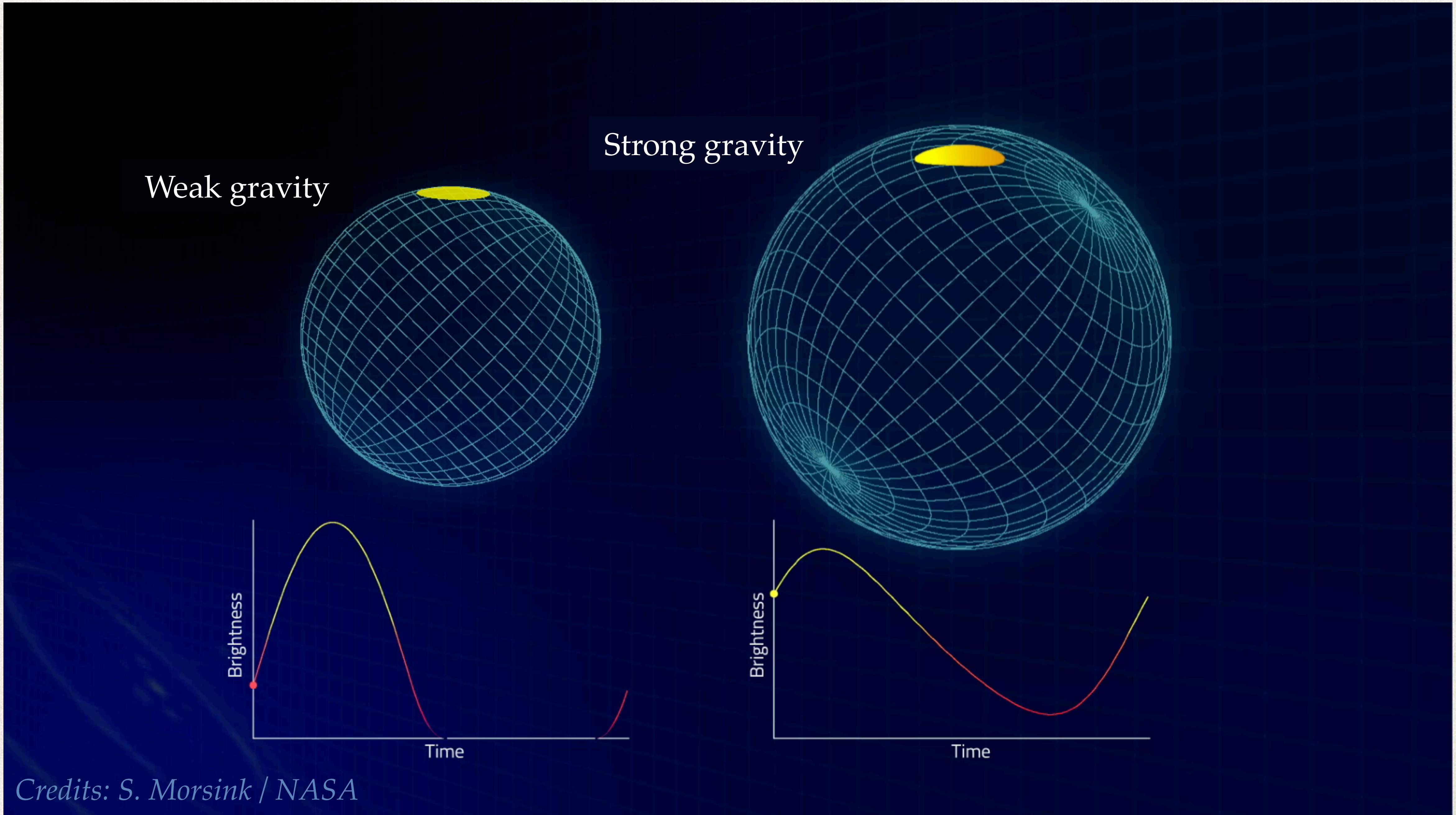




Strong gravity permits seeing beyond the hemisphere of the neutron star.



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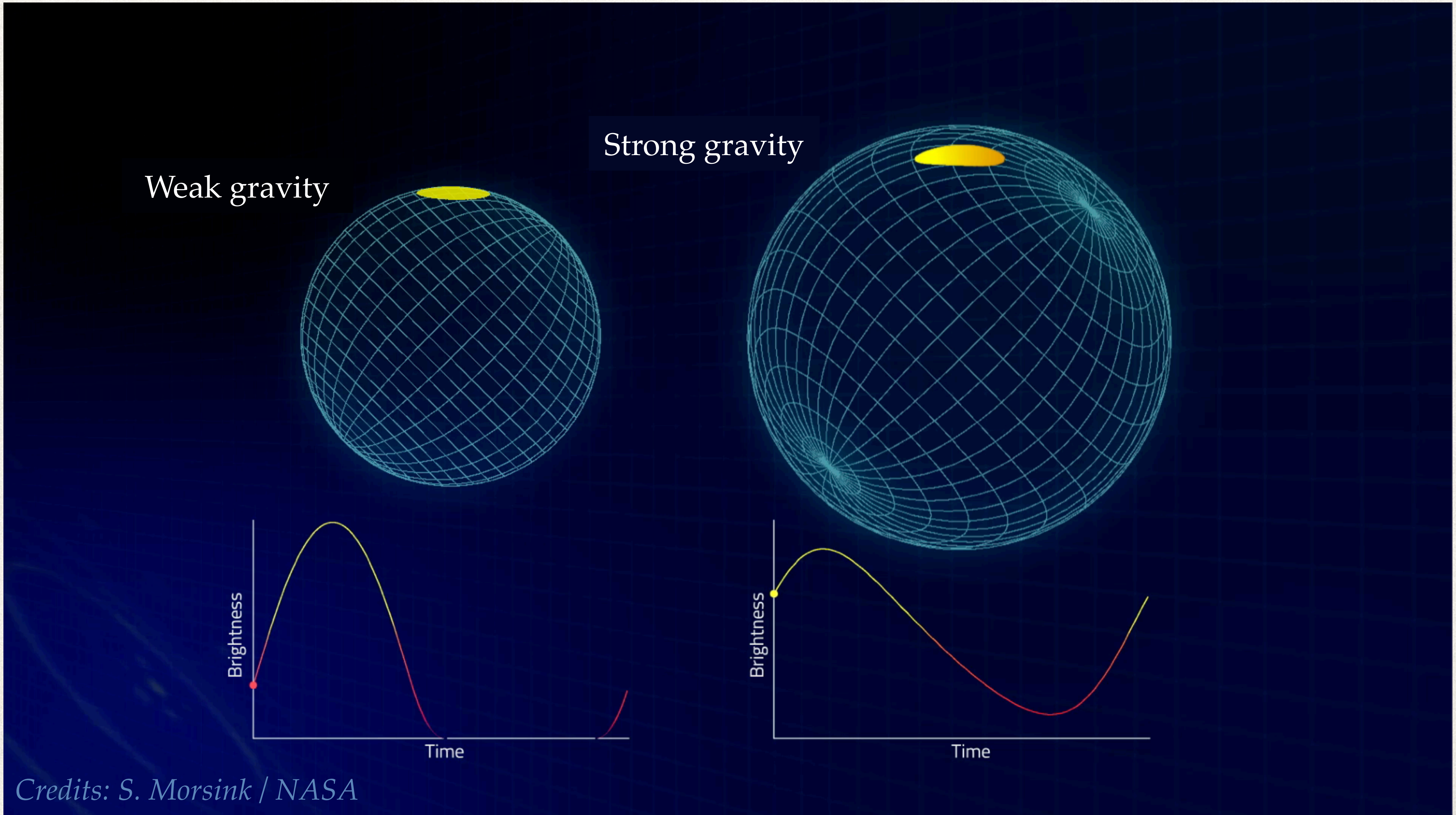
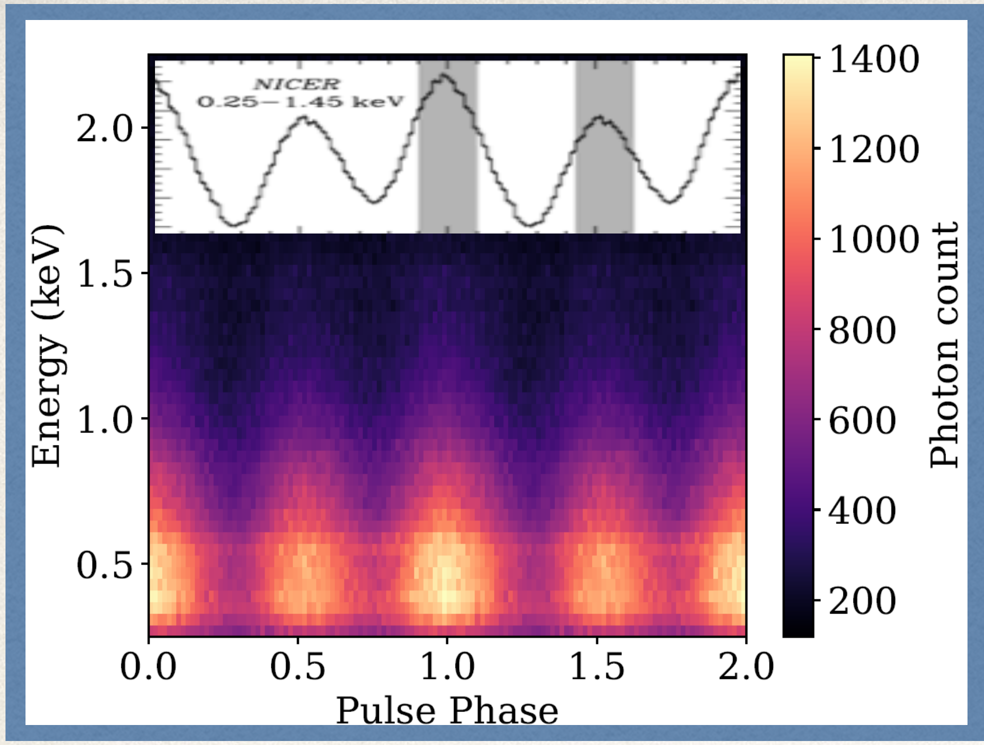
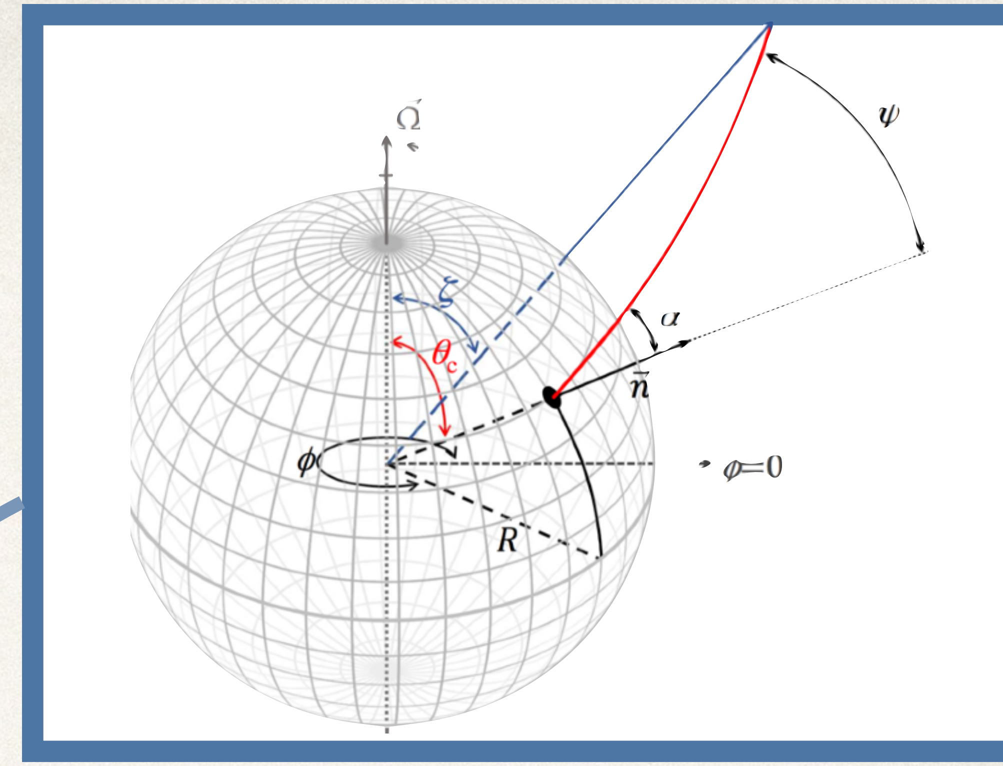
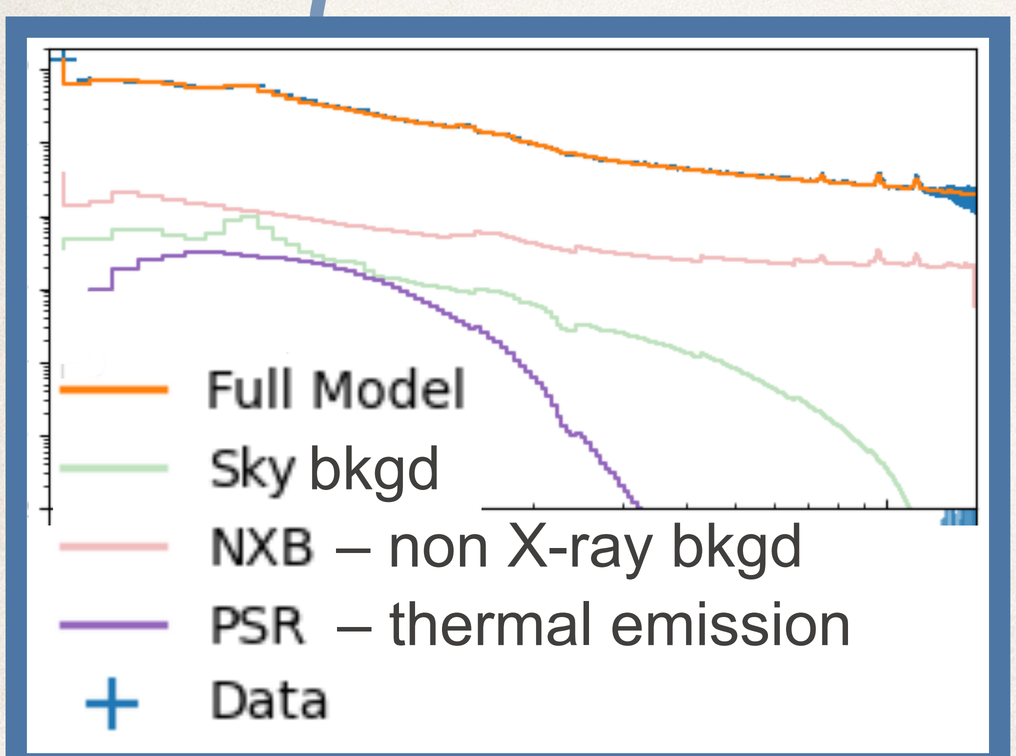


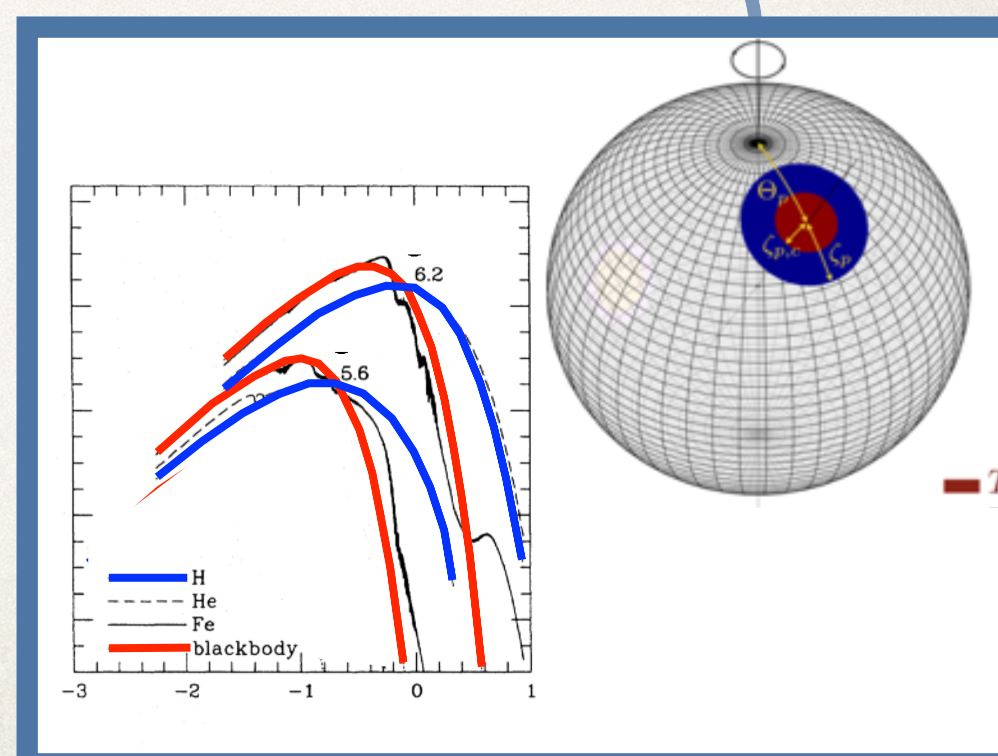


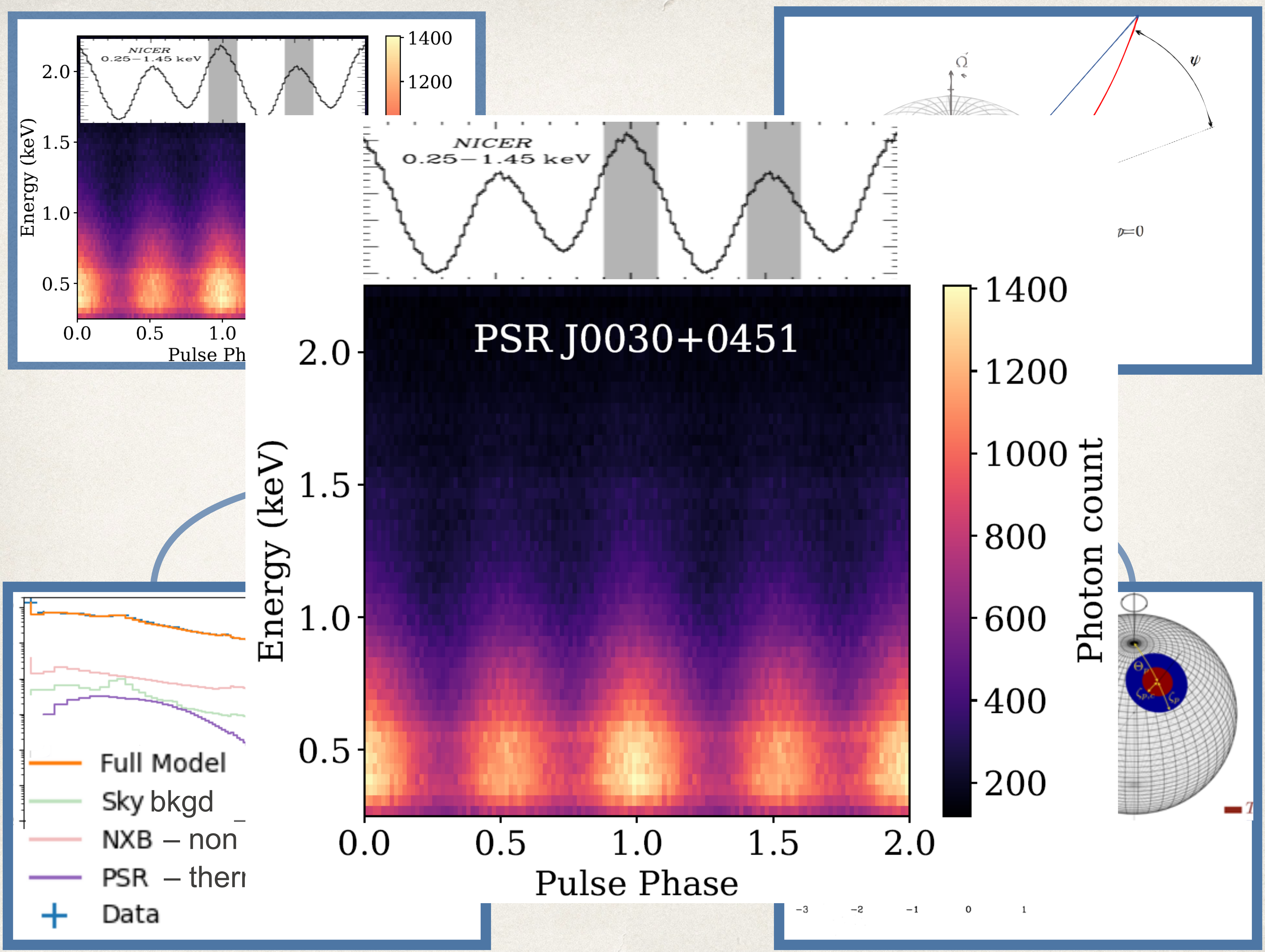


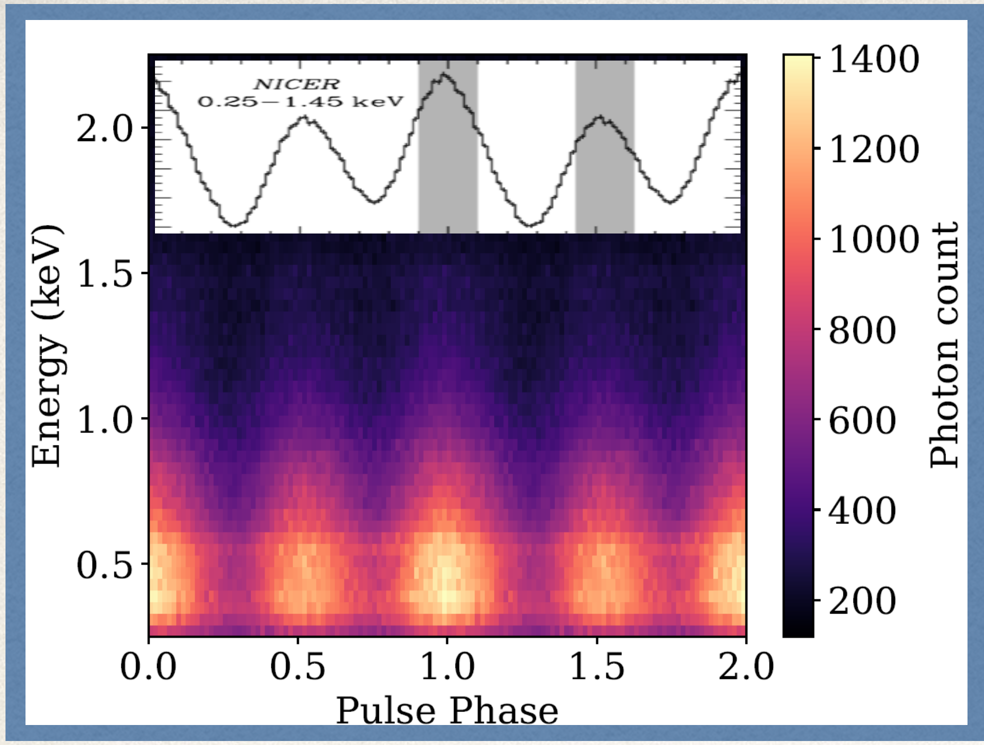
NS properties inference
(Likelihood statistical sampling)

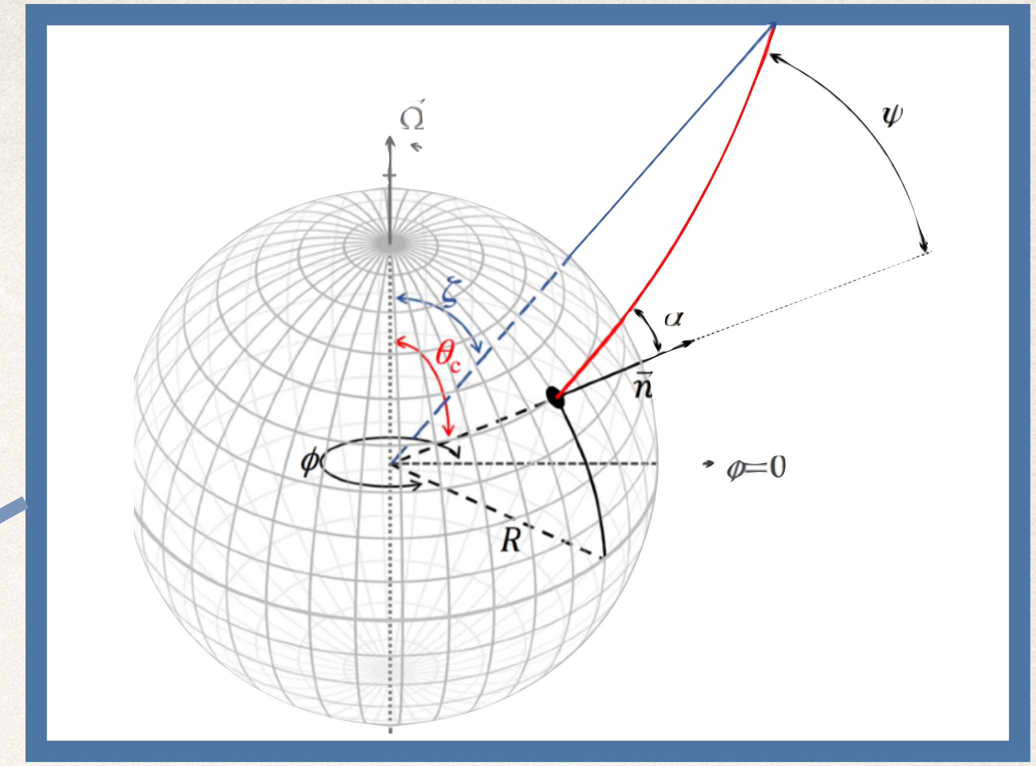
Mass,
Radius,
EOS






PSR J0030+0451
NICER
0.25−1.45 keV
Energy (keV)
Pulse Phase
Photon count
1400
1200
1000
800
600
400
200
Full Model
Sky bkgd
NXB – non
PSR – therı
Data





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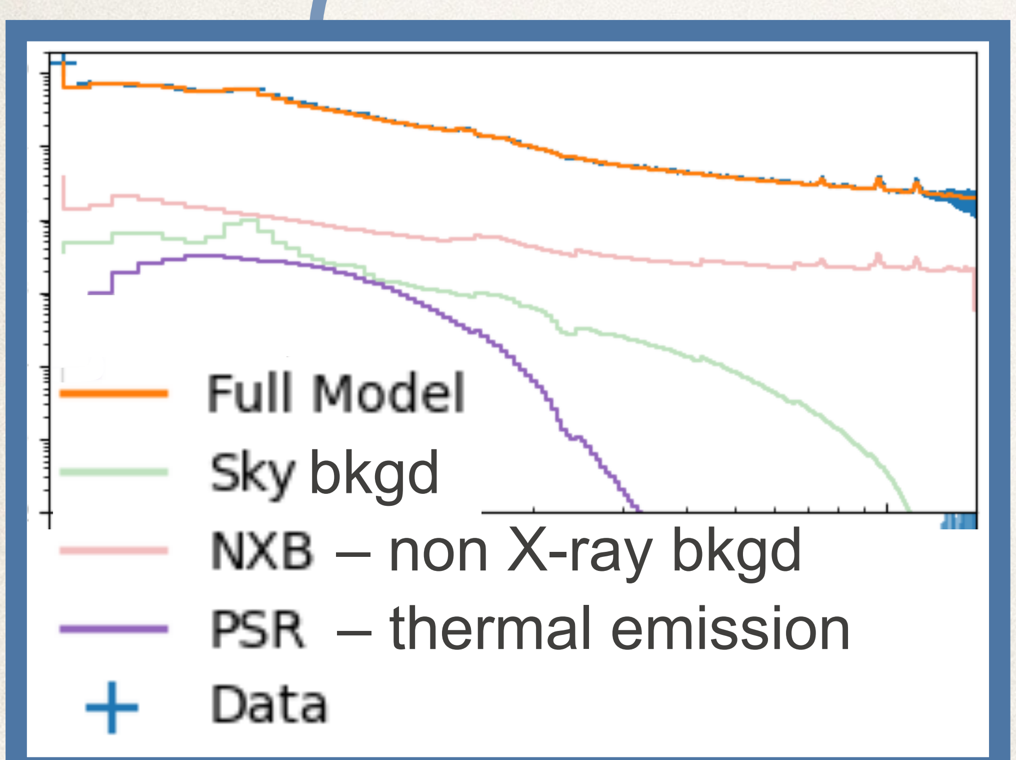
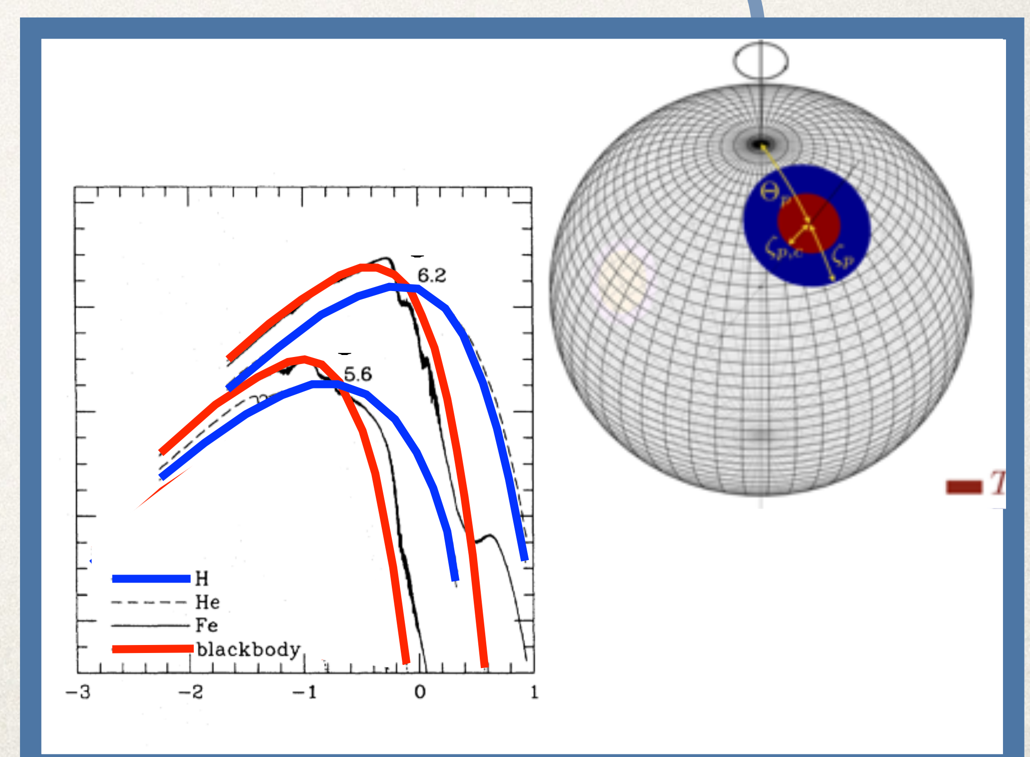
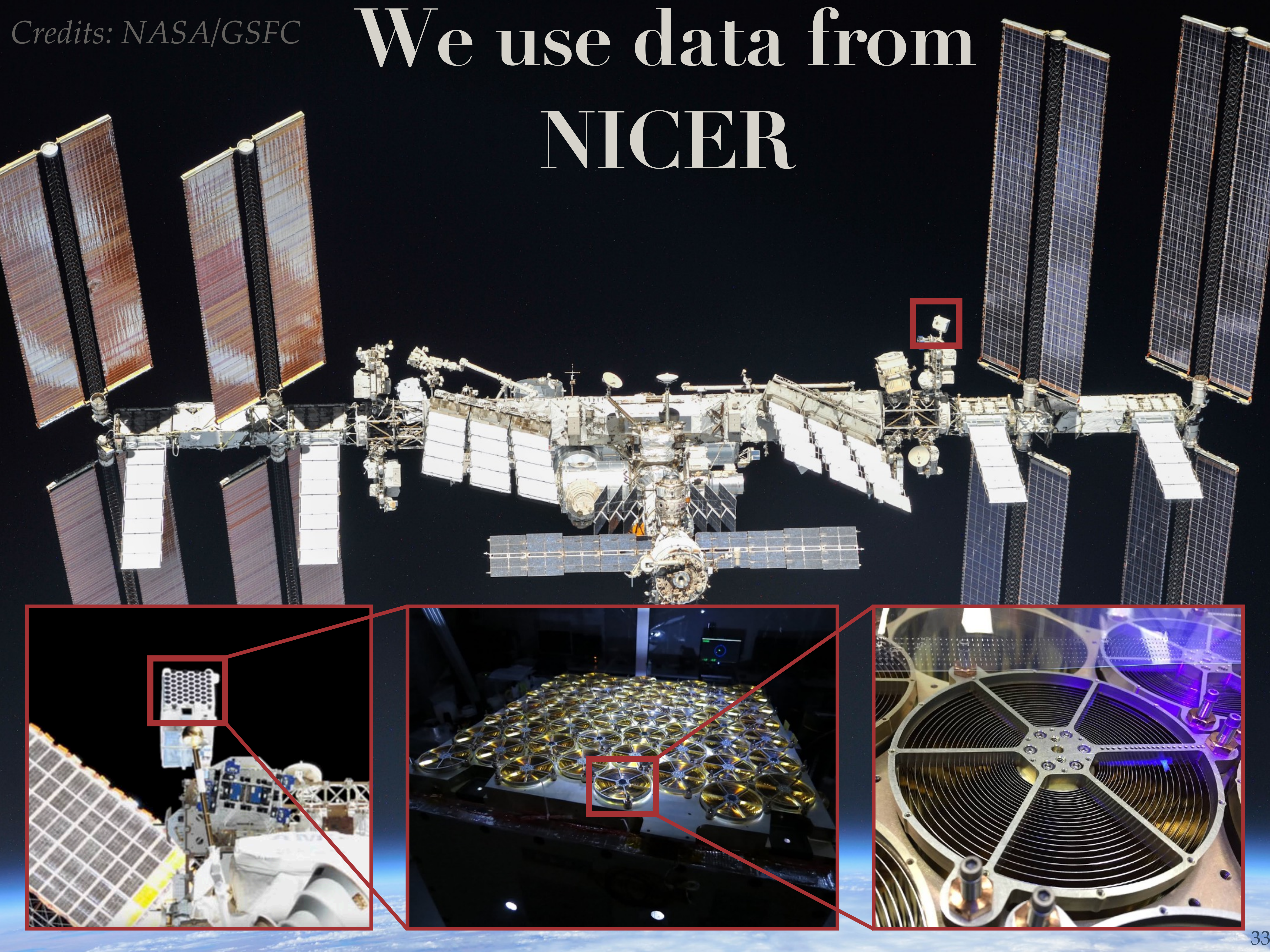
EOS





We use data from NICER

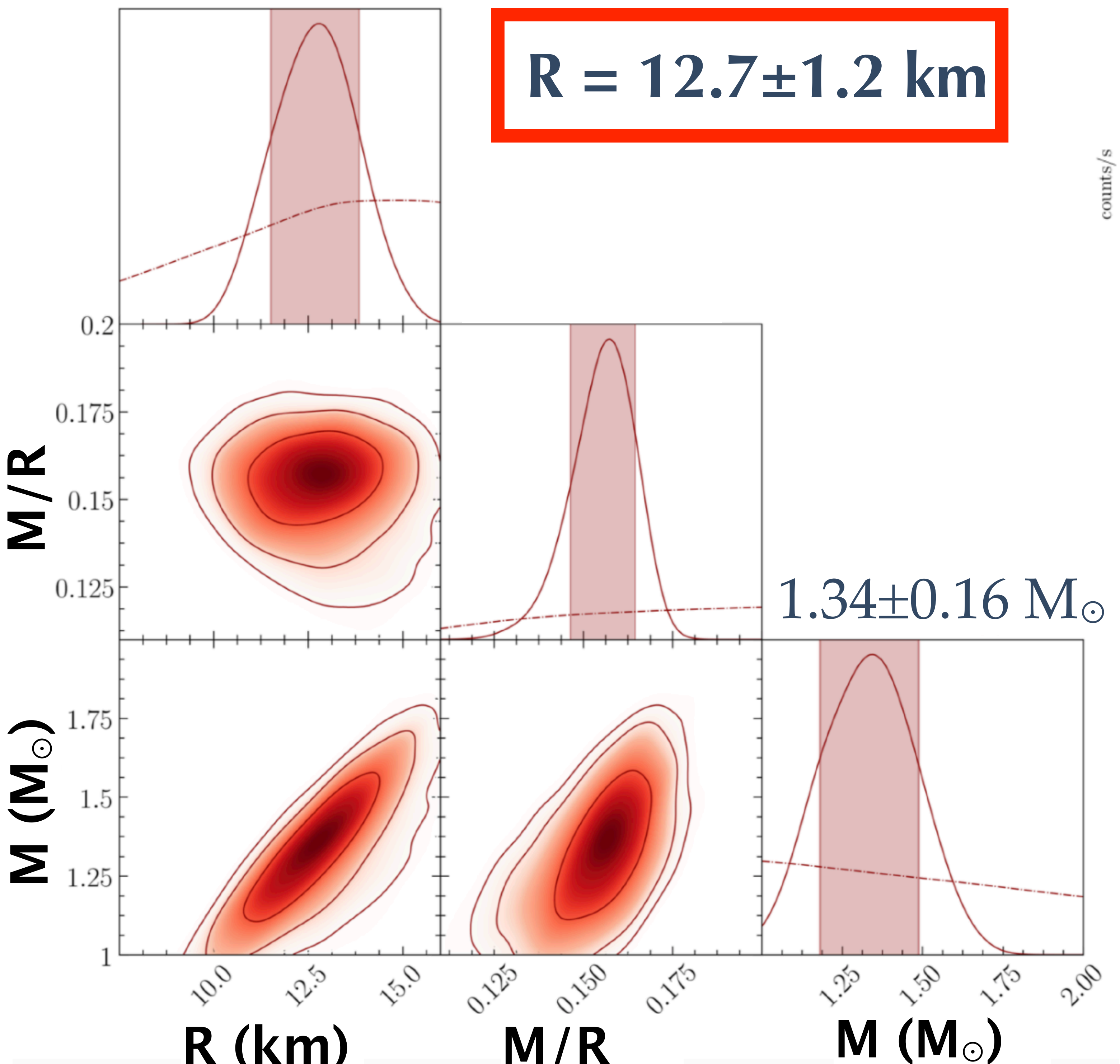


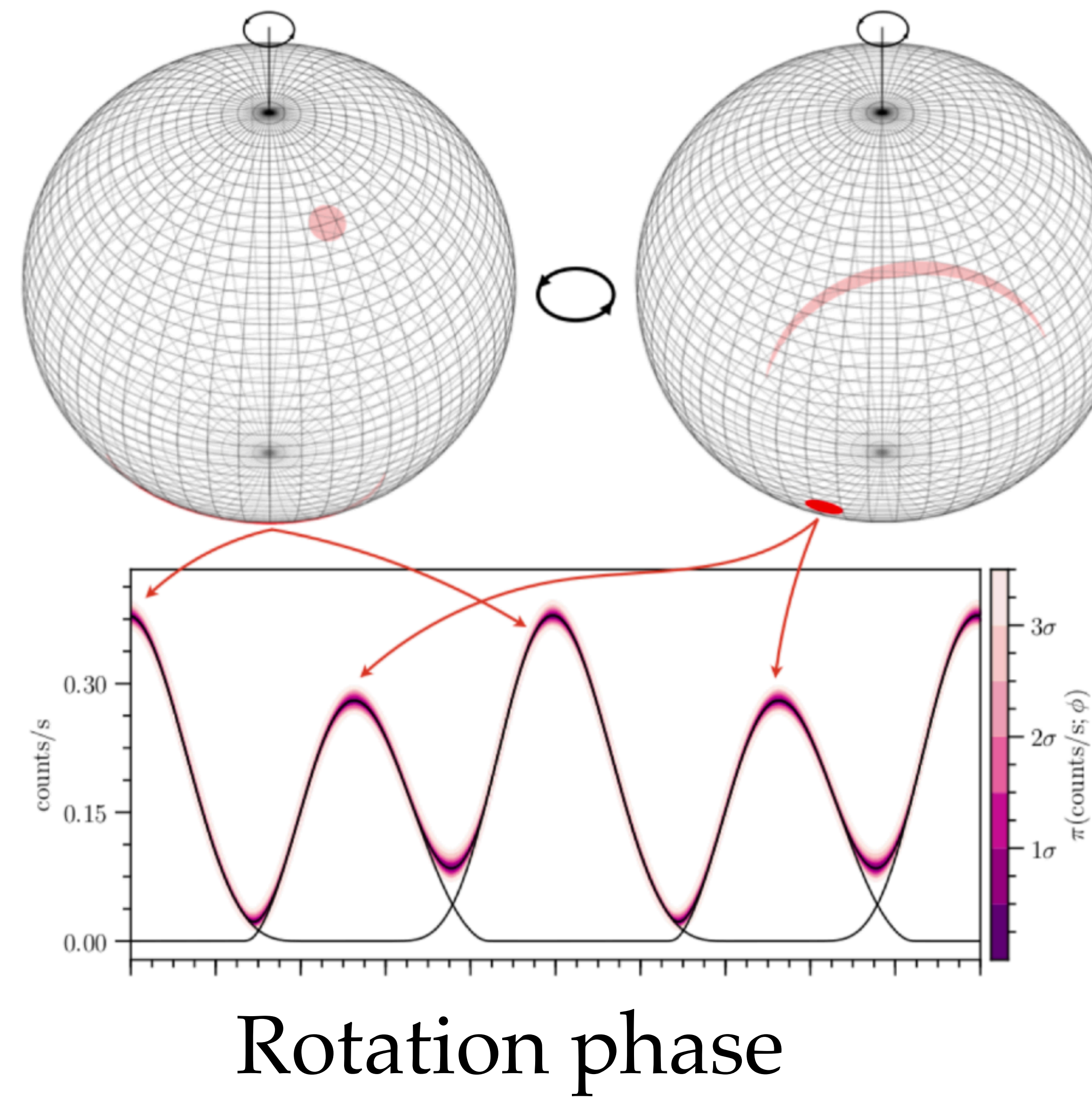
Credits: NASA/GSFC

Here is an example our the first results.

Riley, …, SG et al. (2019)

R = 12.7±1.2 km

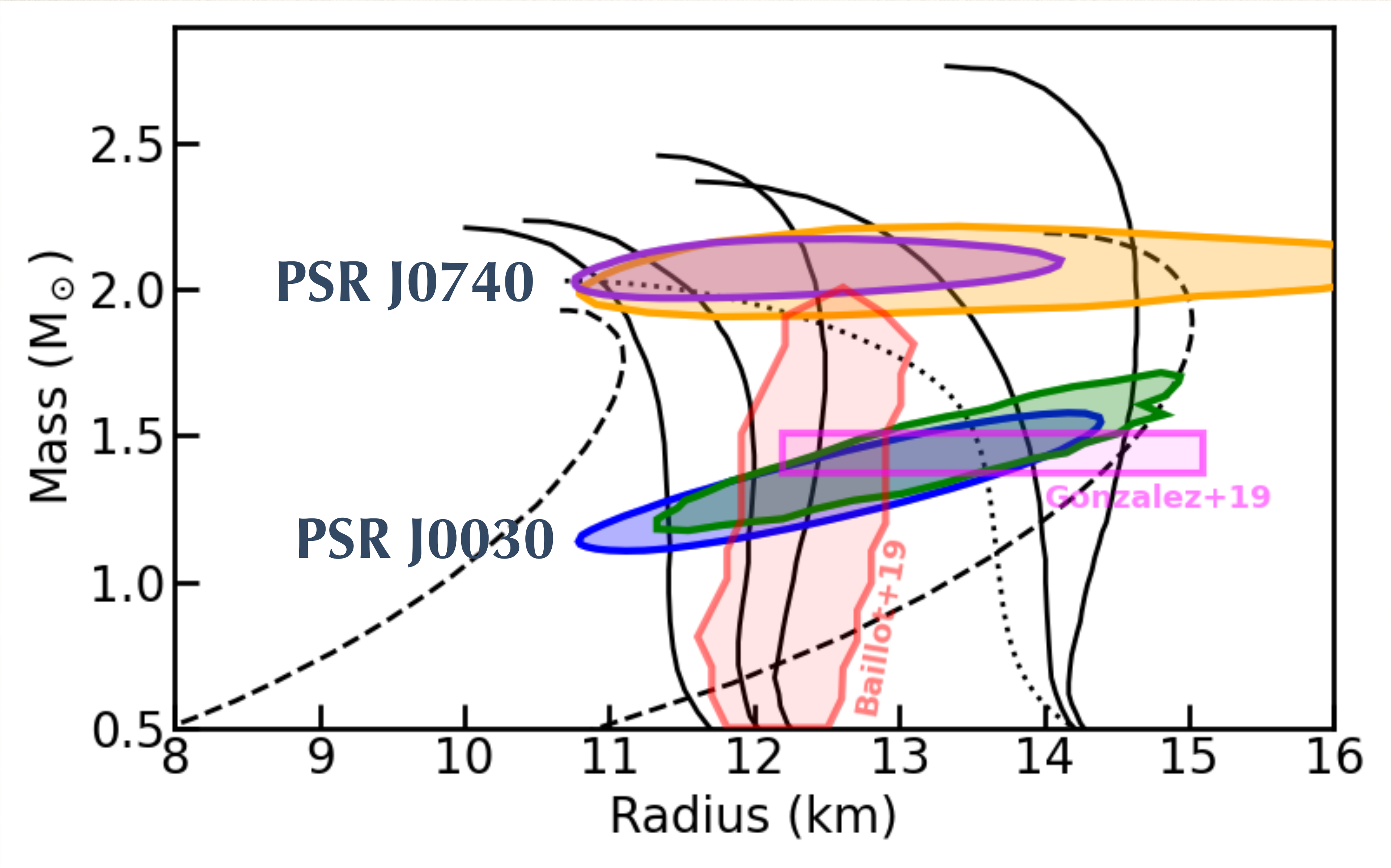




An unexpected geometry that can be explained by an offset dipole thanks to multi-wavelength self-consistent modelling

Pétri, SG et al. (2023)

The NICER Science Team published the results for two pulsars, which are also consistent with previous measurements.



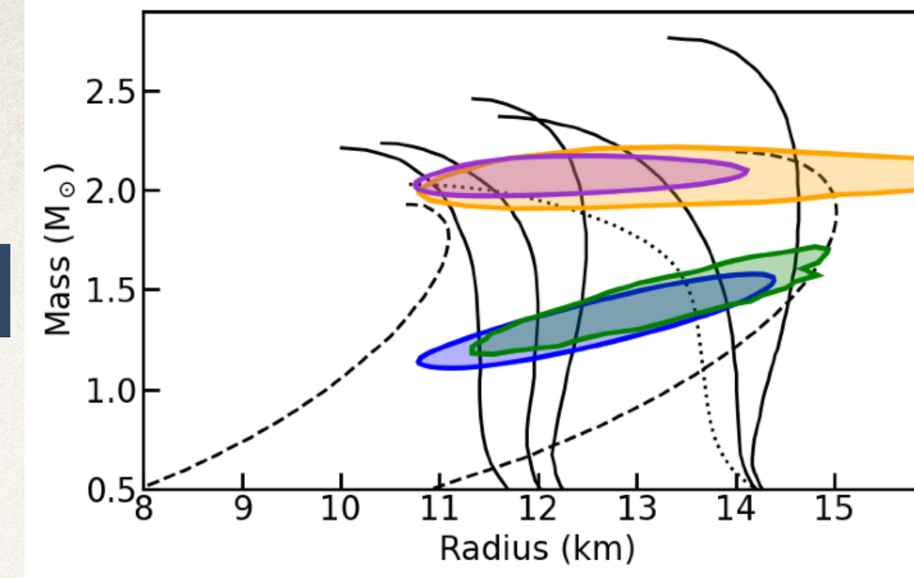
The two independent analyses for each target are consistent

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

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

Multiple thermally-emitting NS: Baillot-d'Etivaux, SG et al. 2019

How can we exploit these measurements to understand dense nuclear matter ?



PSR J0030+0451 brings little additional information on the EoS.

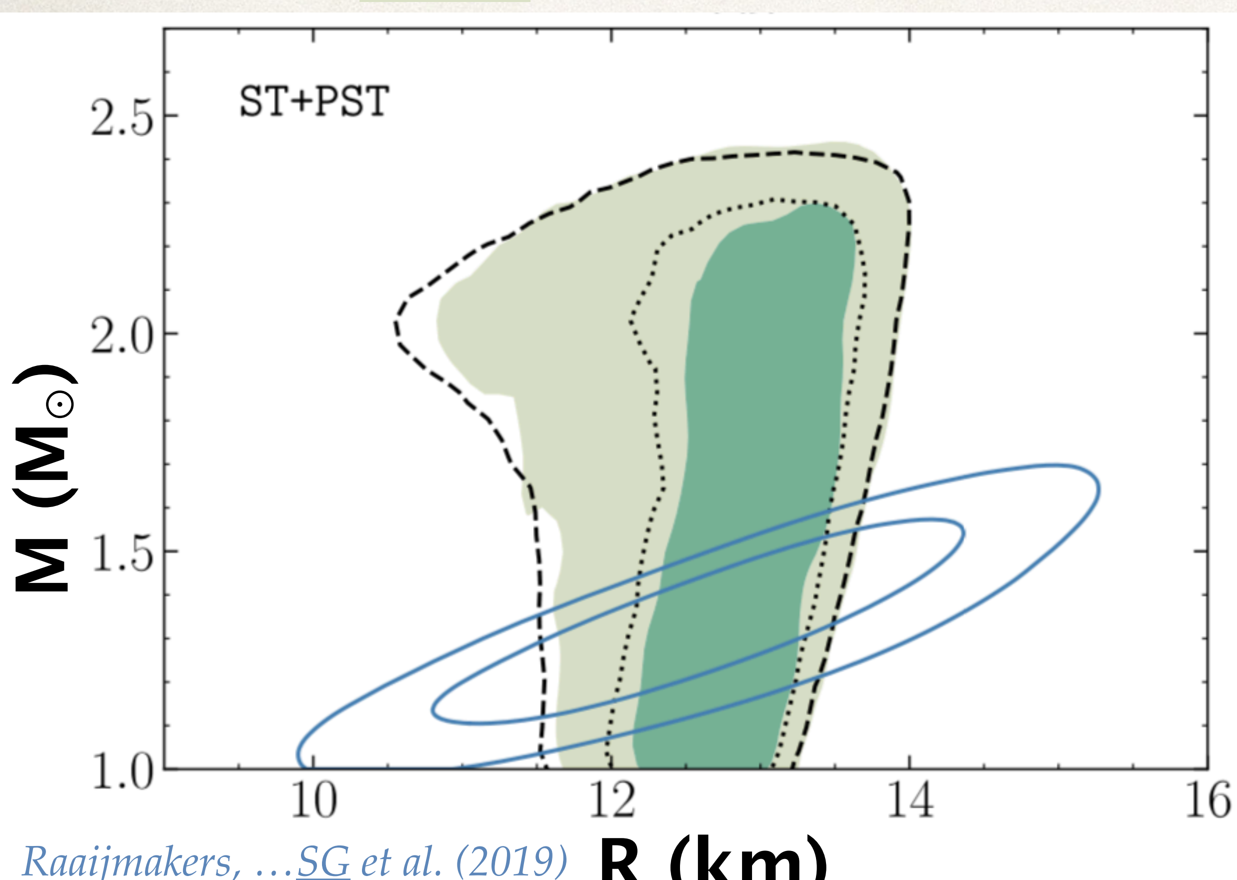
PSR J0740+6620 further constrains the EoS, thanks to its high mass.

Nucl. Phys. + GW170817

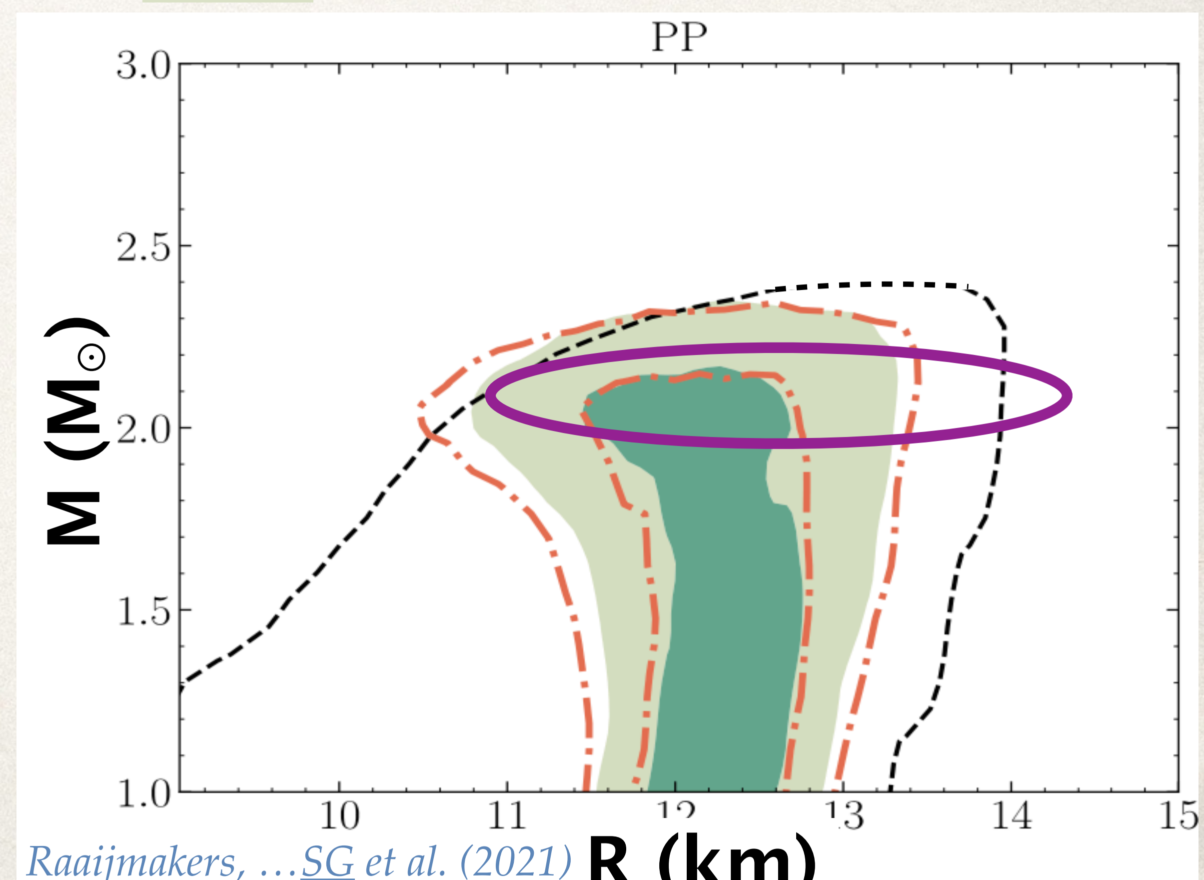
+ PSR J0030

+ mass of PSR J0740

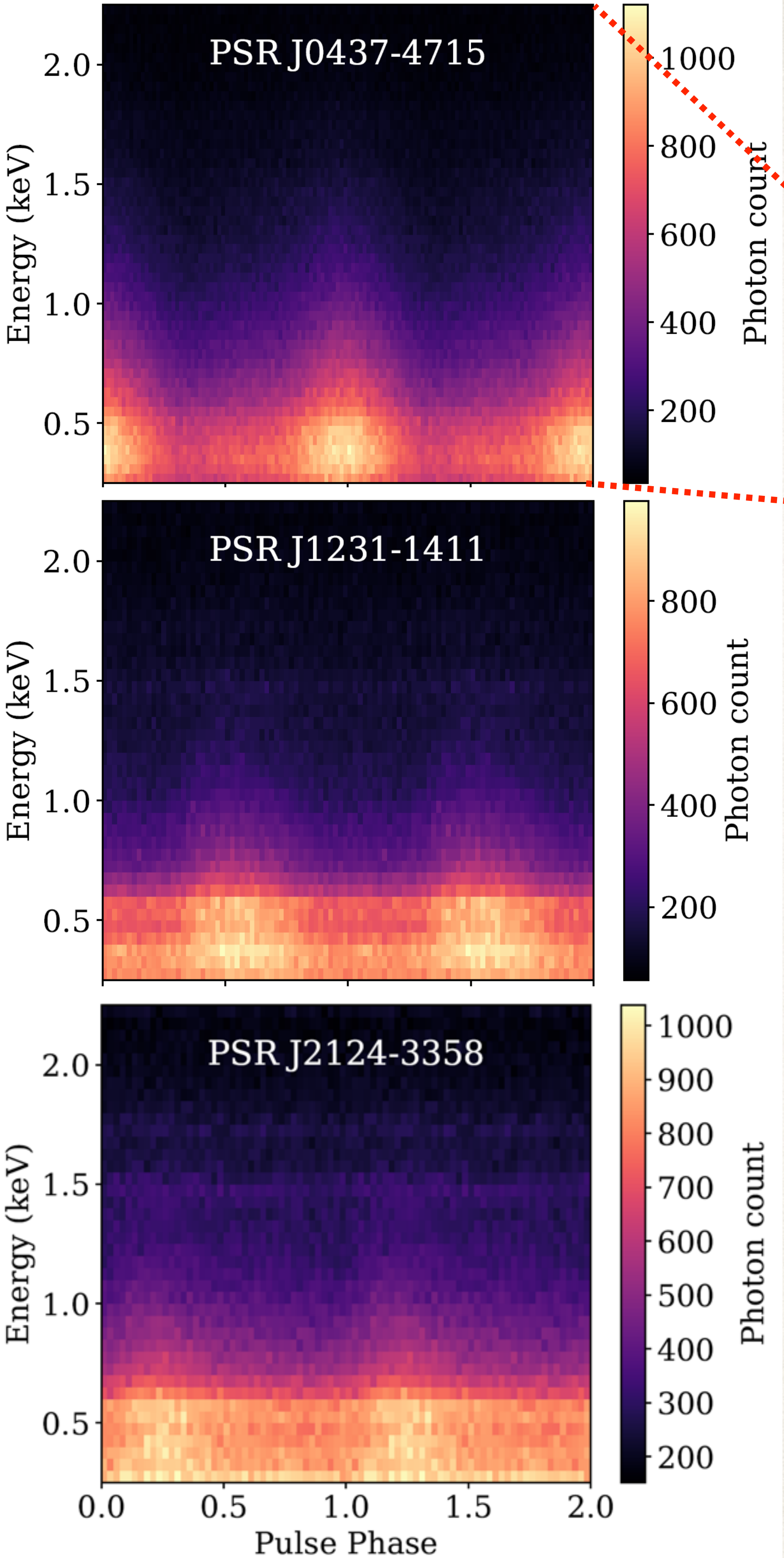
+ PSR J0740



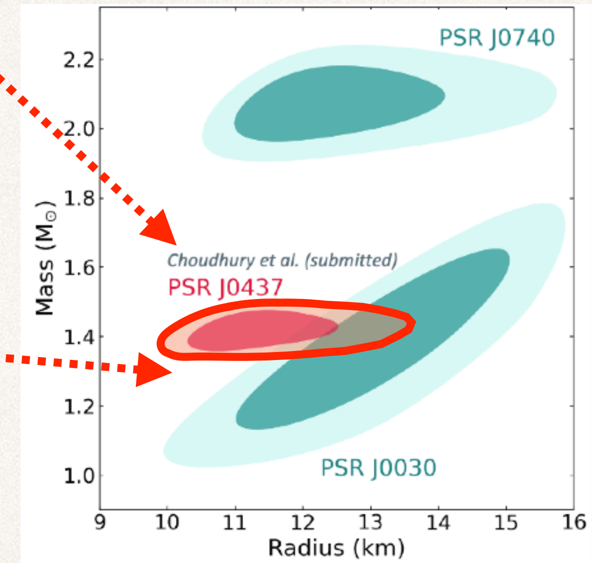
Raaijmakers, …SG et al. (2019)



Raaijmakers, …SG et al. (2021)



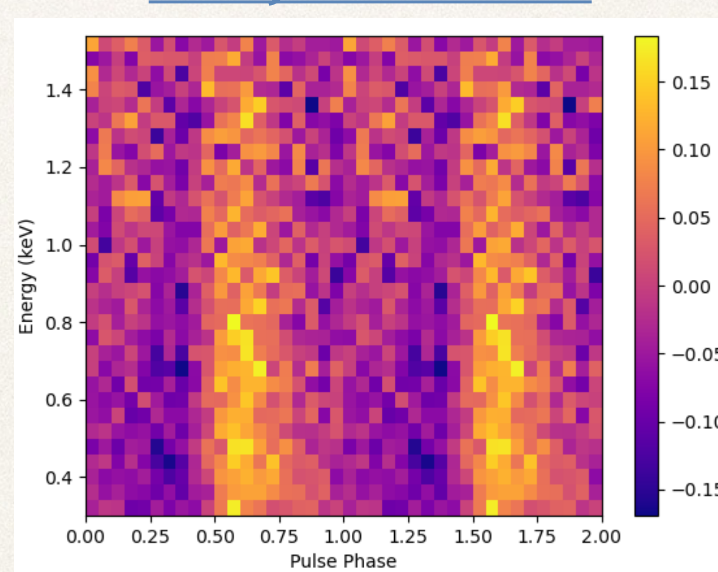
There are still many data sets to analyse to extract M_{NS} and R_{NS}



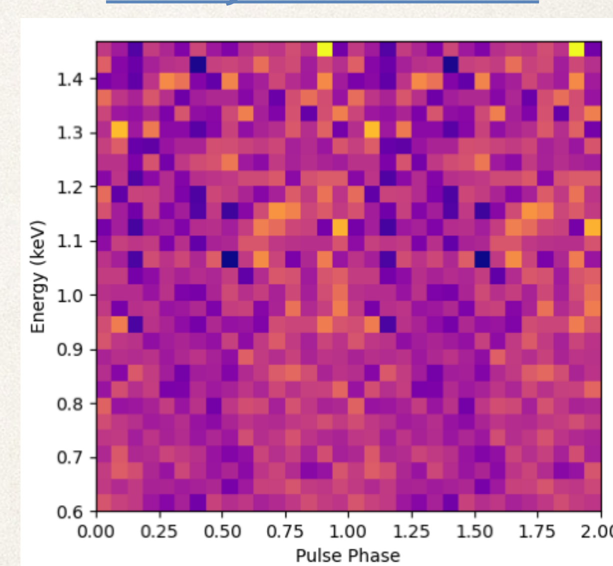
New results for PSR J0437–4715 submitted

Thesis of Lucien Mauviard at IRAP

PSR J0614–3329

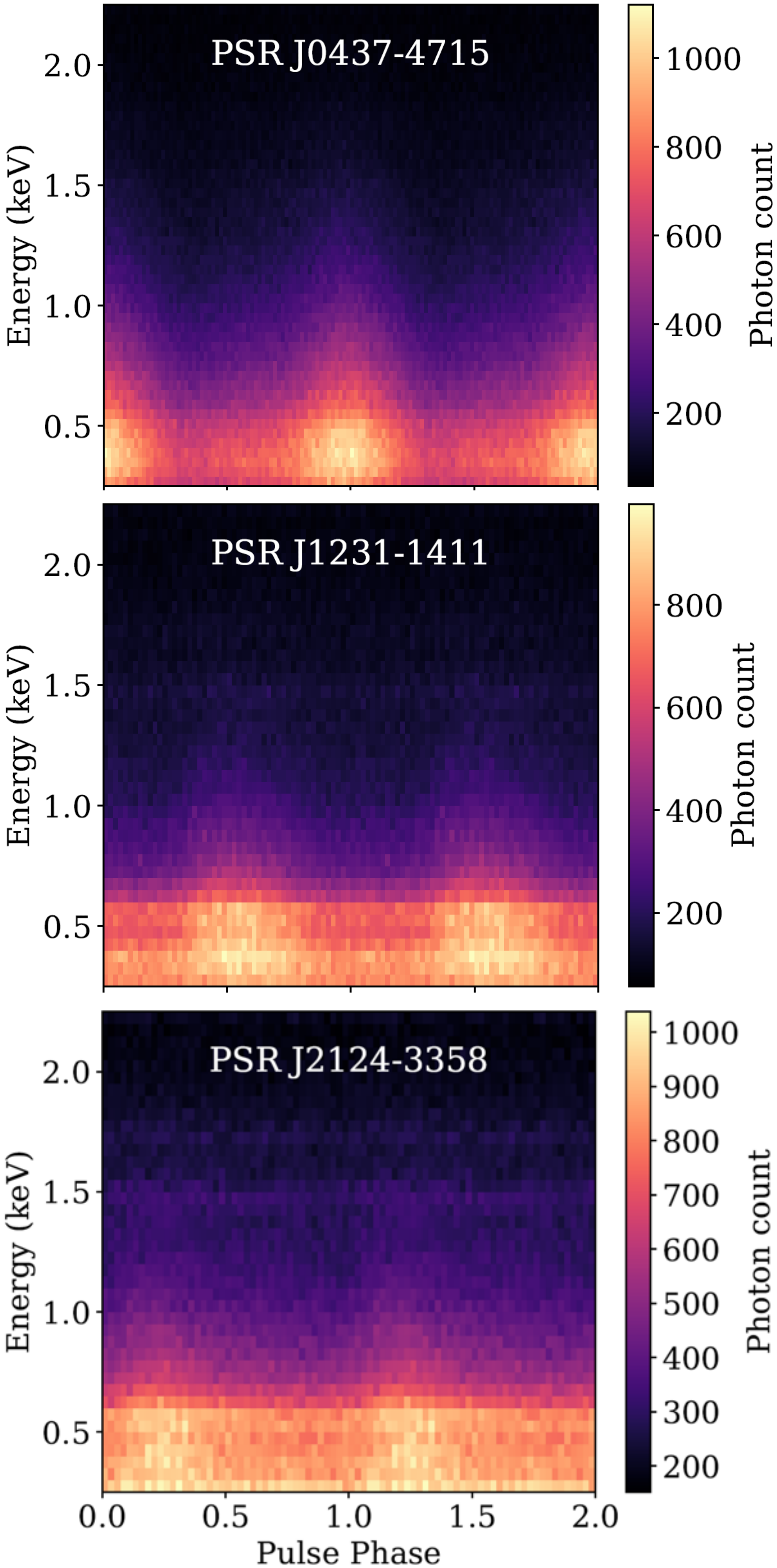


PSR J1614-2230



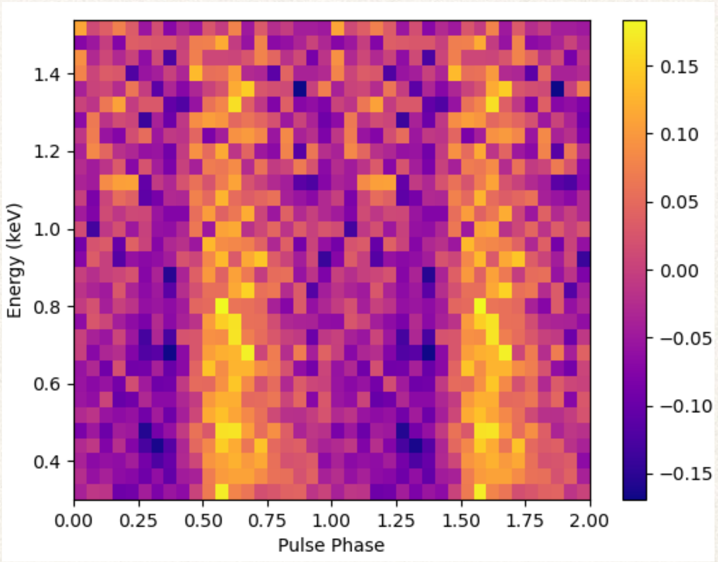
+ a handful of pulsars discovered in *Guillot et al 2019*

There are still many data sets to analyse to extract M_{NS} and R_{NS}

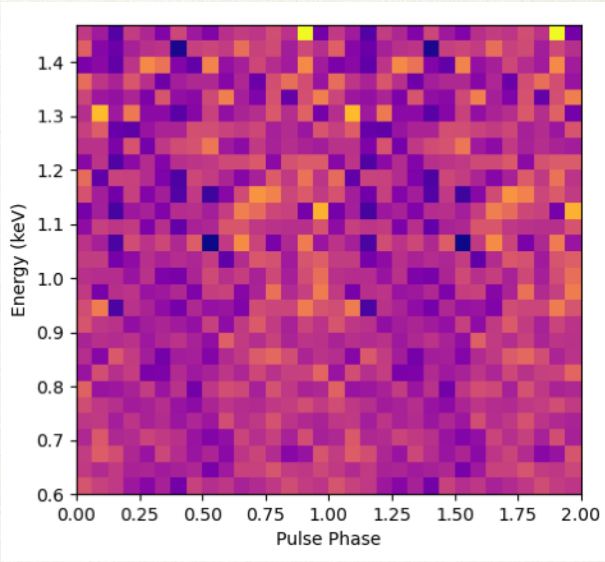


Thesis of Lucien Mauviard at IRAP

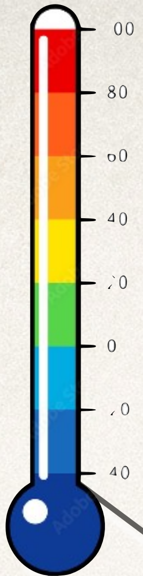
PSR J0614–3329



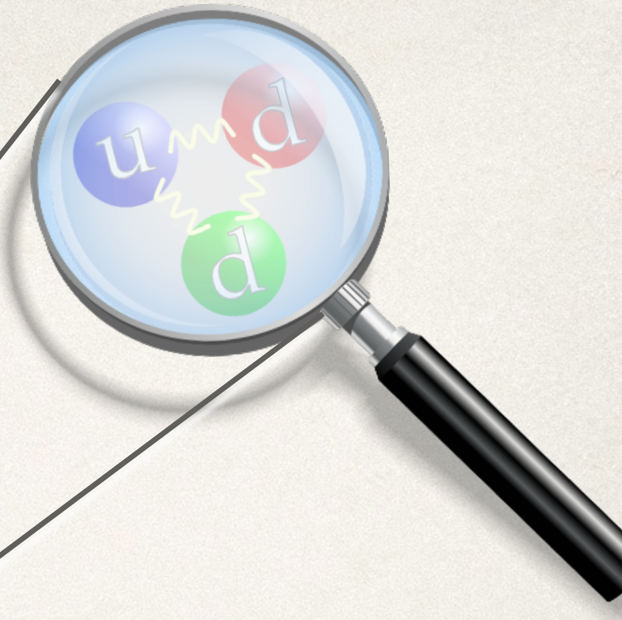
PSR J1614-2230



+ a handful of pulsars discovered in *Guillot et al 2019*



Summary



Thermal evolution studies to understand the crust

The thermal relaxation of the crust directly depends on its.

Surface temperature measurements can therefore help understand the crust.

Probing the core with M_{NS} and R_{NS} measurements

Different methods exist but the results obtained with NICER are the most reliable.

Uncertainties of 5–10% on R_{NS}