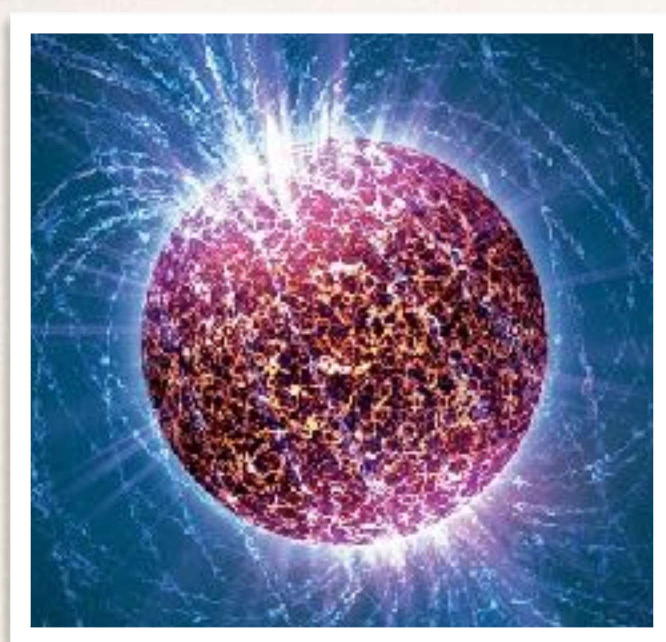
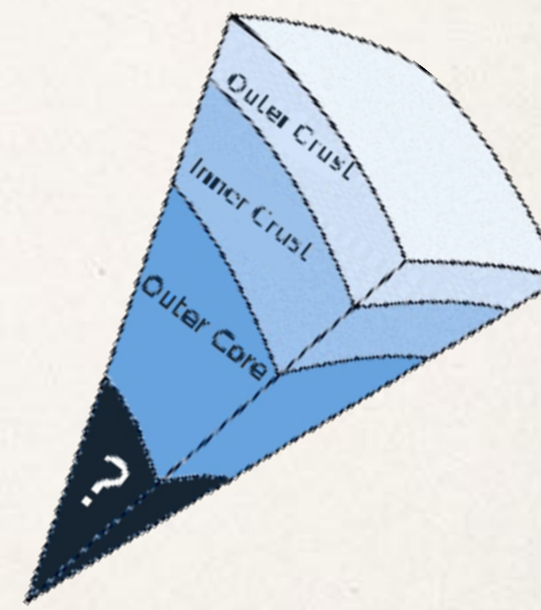
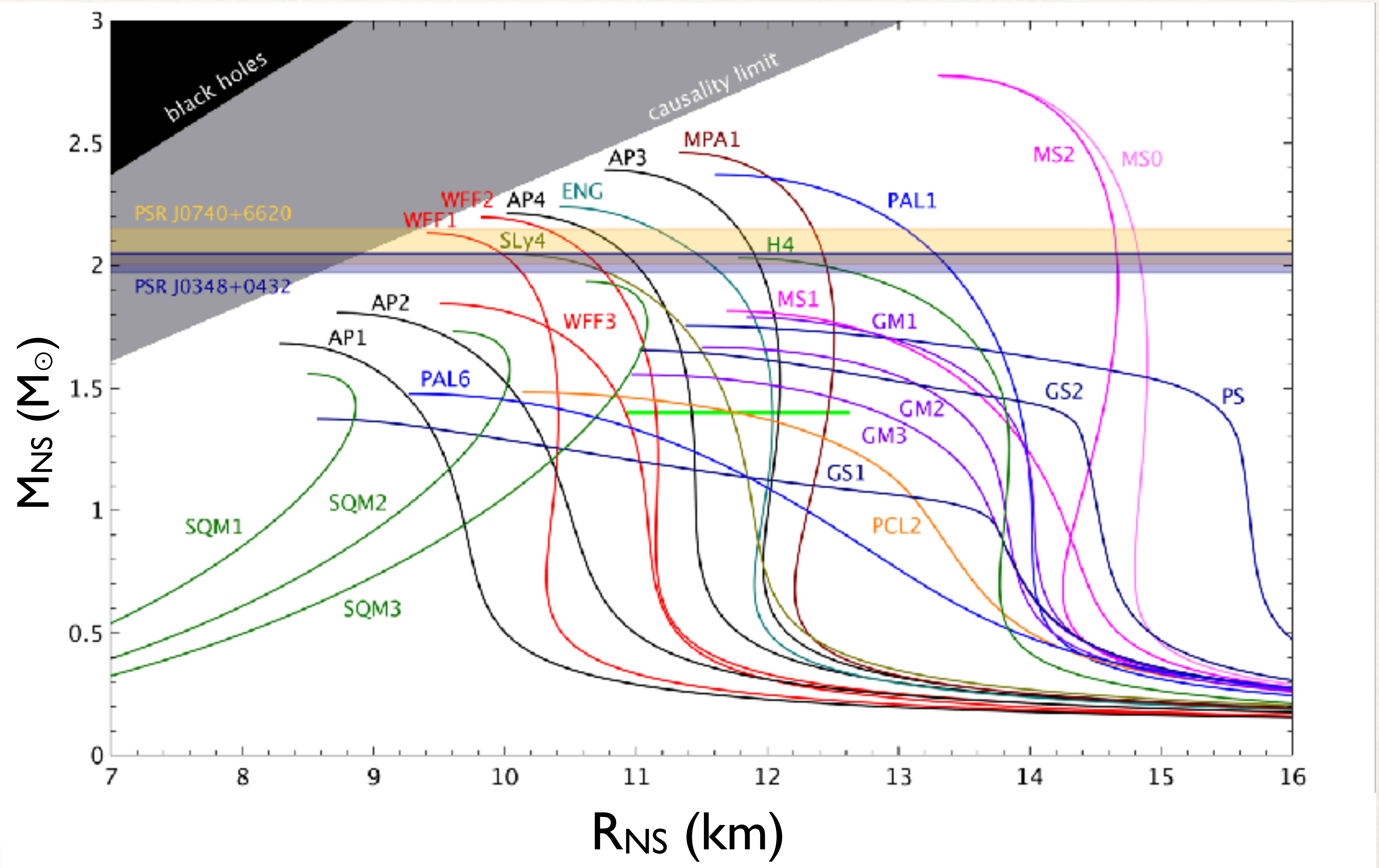
Mass-Radius constraints on the equation of state with phase-averaged X-ray observations

Sebastien Guillot



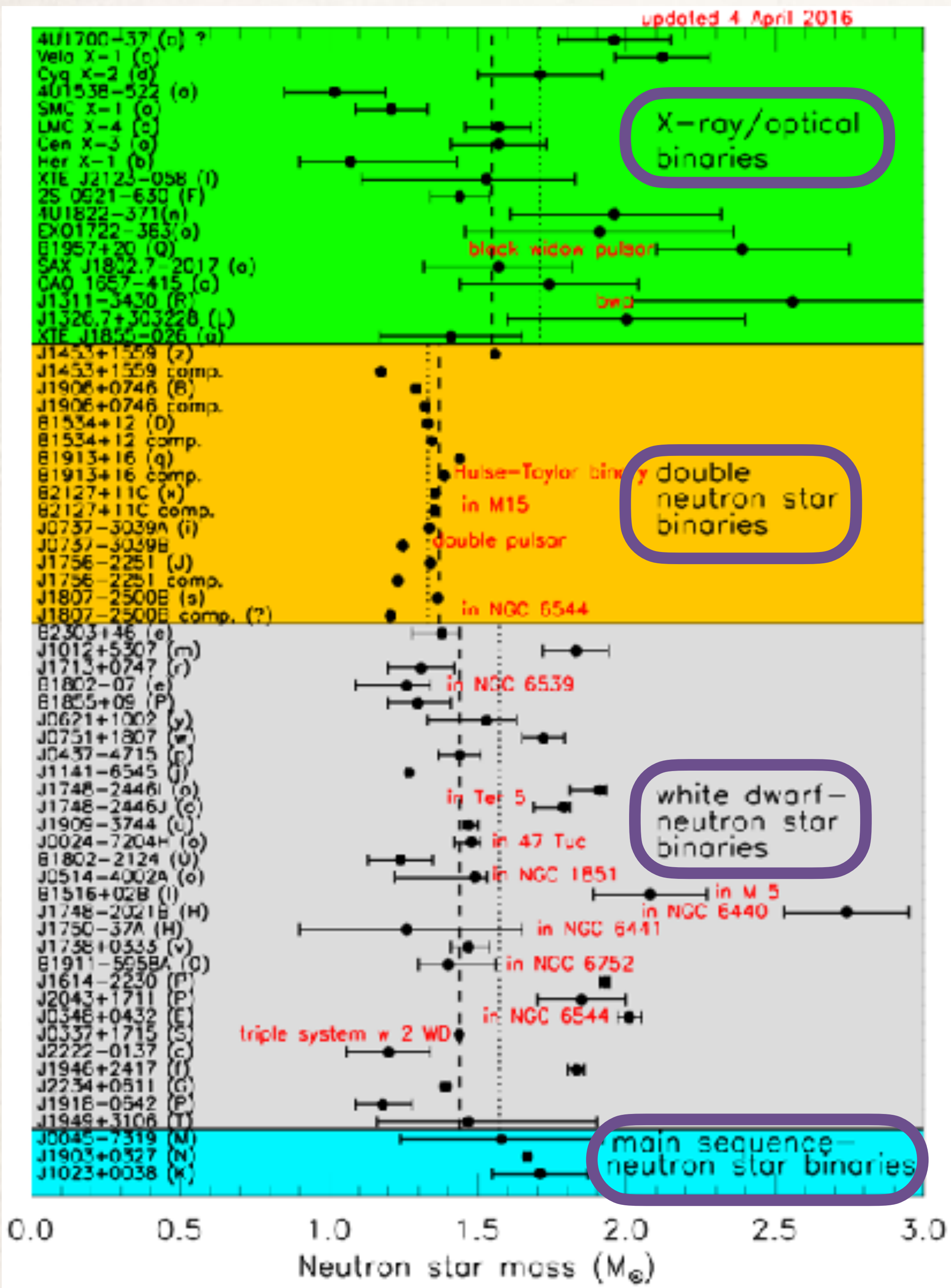


To determine the equation of state P(ρ), one needs to measure M_{NS} and/or R_{NS}.

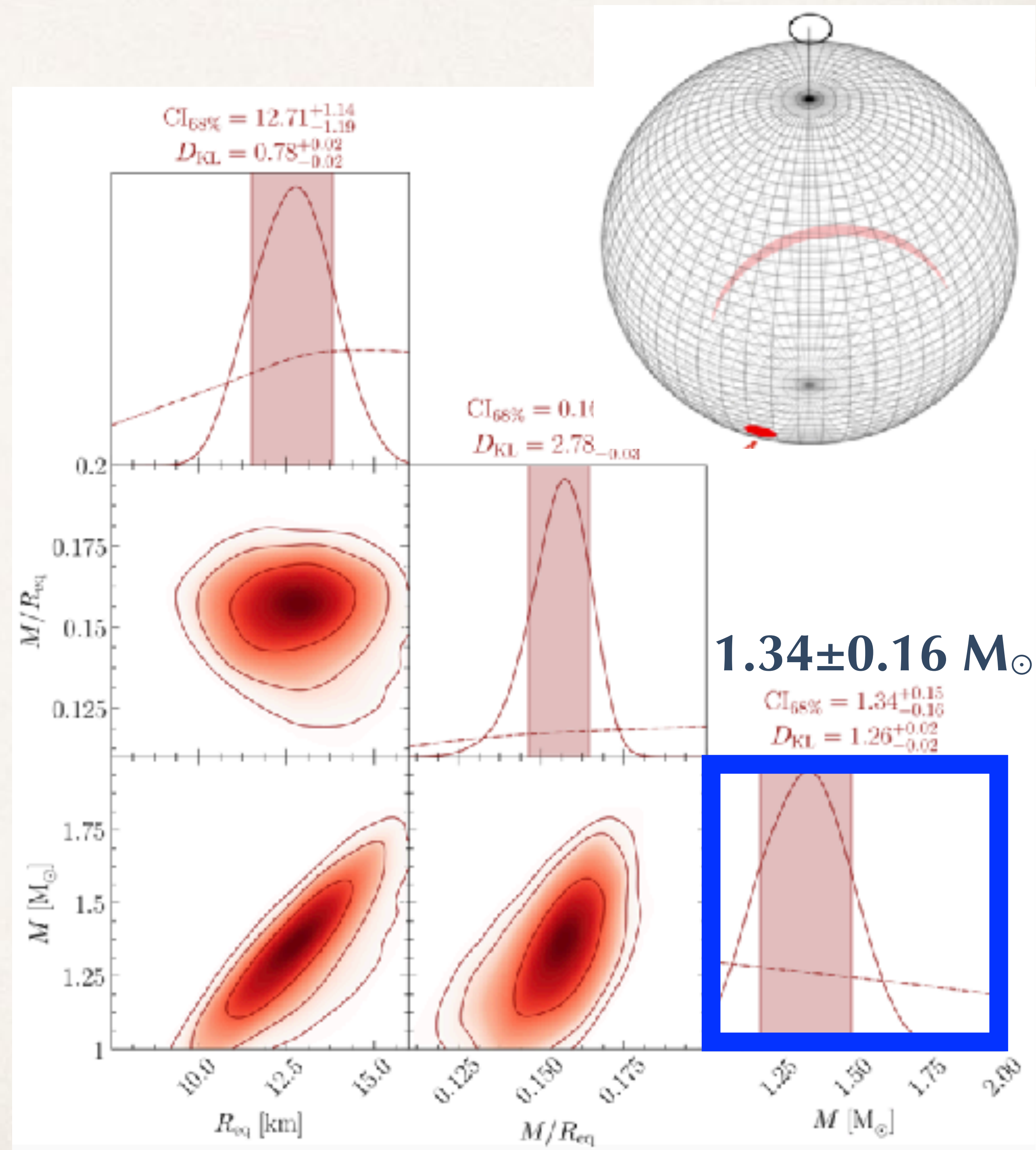


Credits: N. Wex

Measuring the masses requires neutron stars in binary systems or pulse profile modelling.



https://stellarcollapse.org

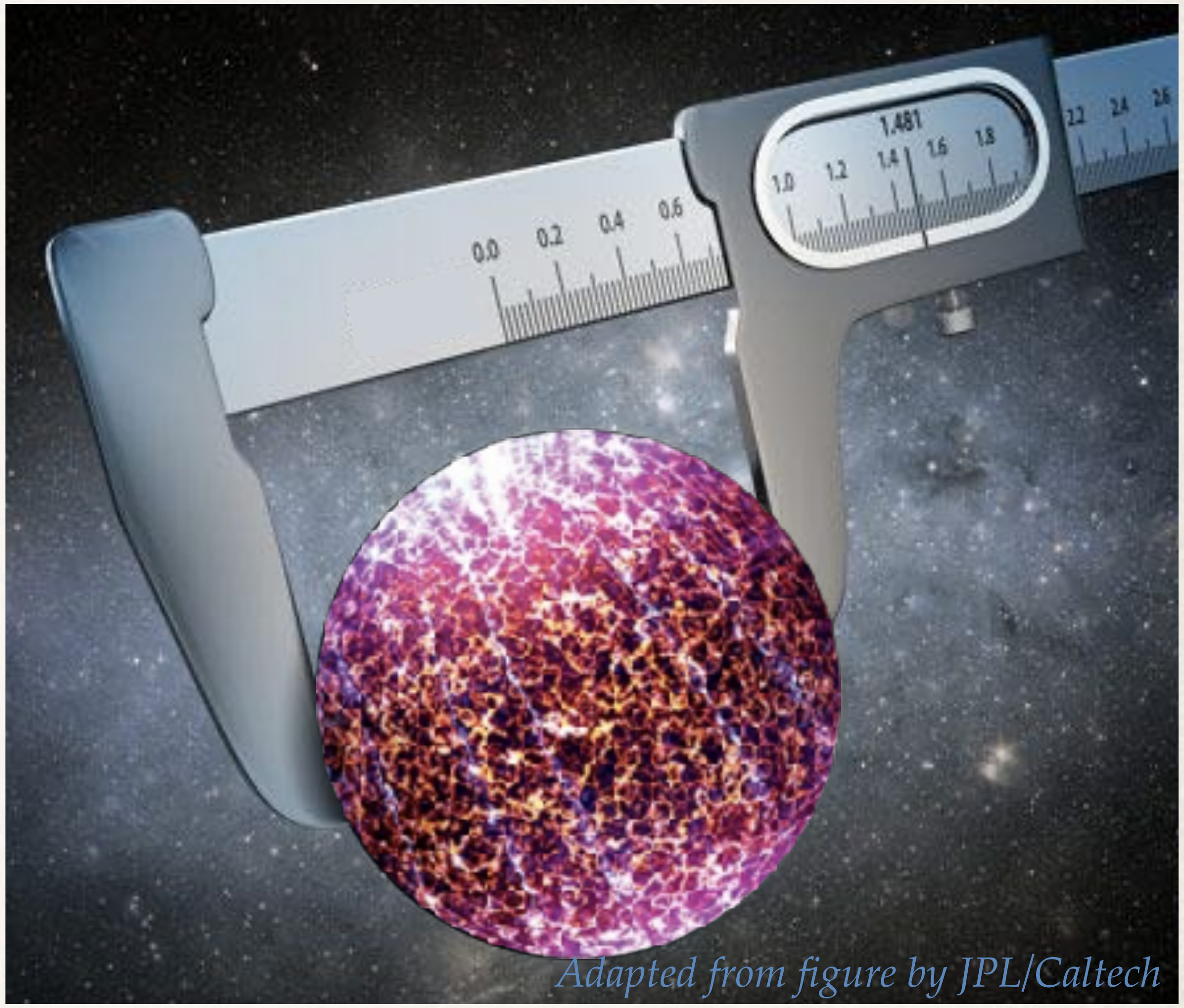


Riley et al. 2019

Measuring the radius precisely is rather difficult for neutron stars.

To measure the radius of a star, we need to:

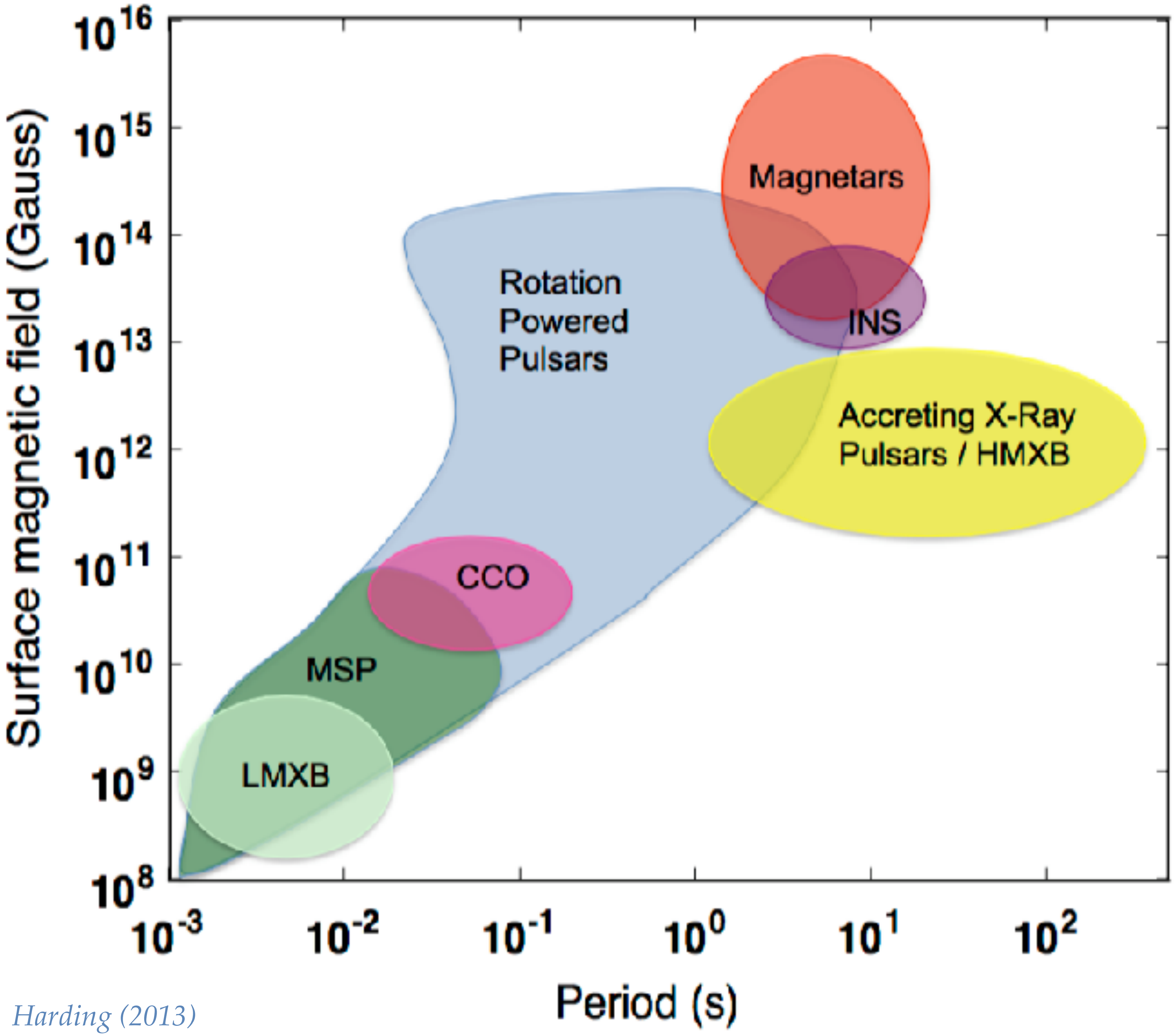
1. observe the surface thermal emission
2. correctly model this emission
3. know the distance



Adapted from figure by JPL/Caltech

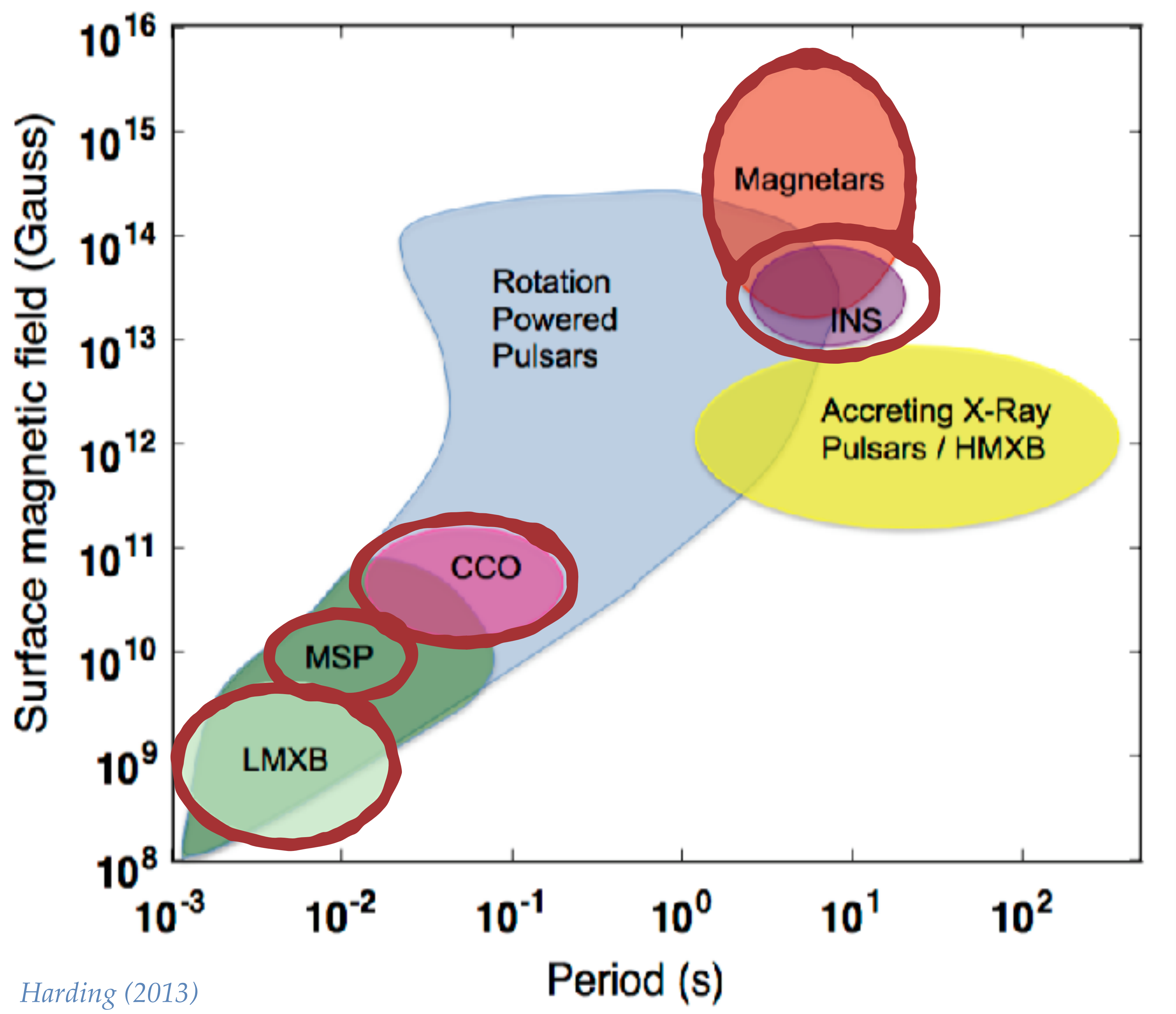
$$L = 4\pi R^2 \sigma T_{\rm eff}^4 \longrightarrow F = \left(\frac{R}{D}\right)^2 \sigma T_{\rm eff}^4$$

Neutron stars come in many flavours, with different properties and observational signatures.



Harding (2013)

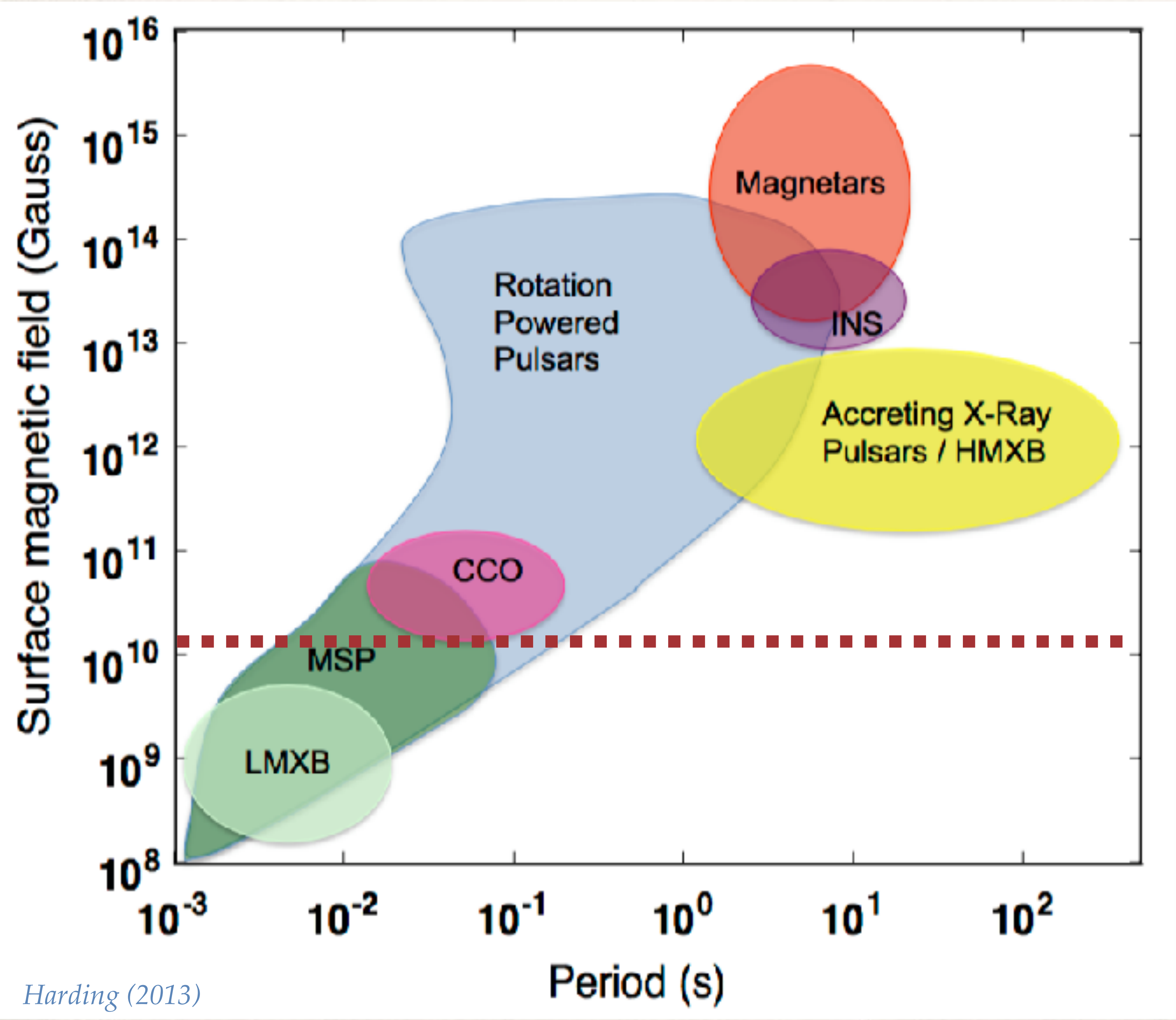
Neutron stars come in many flavours, with different properties and observational signatures.



Harding (2013)

The emission from the entire surface needs to be visible

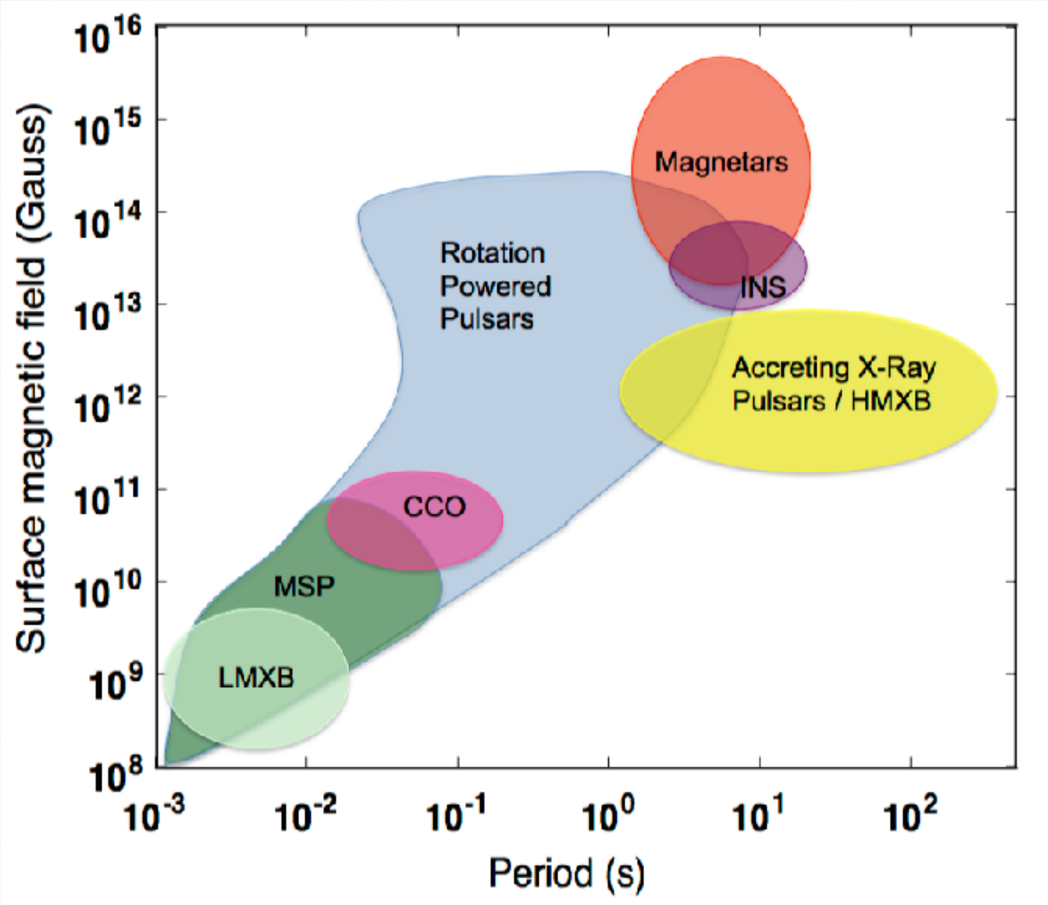
Neutron stars come in many flavours, with different properties and observational signatures.



Highly magnetised atmospheres are difficult to model

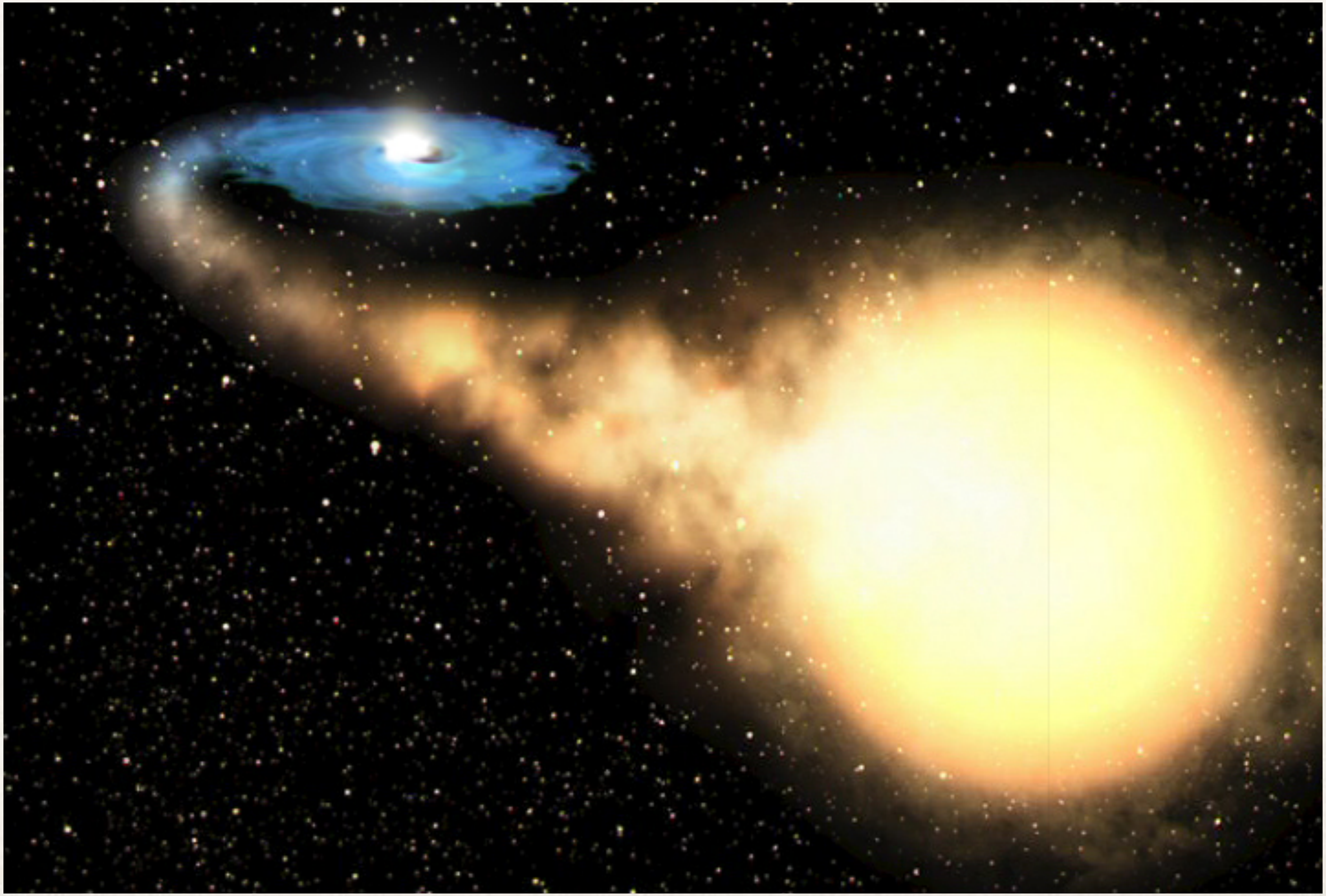
For $B \lesssim 10^{10}$ G, opacities of free-free processes in 10^6 K atmosphere are unaffected

OUTLINE

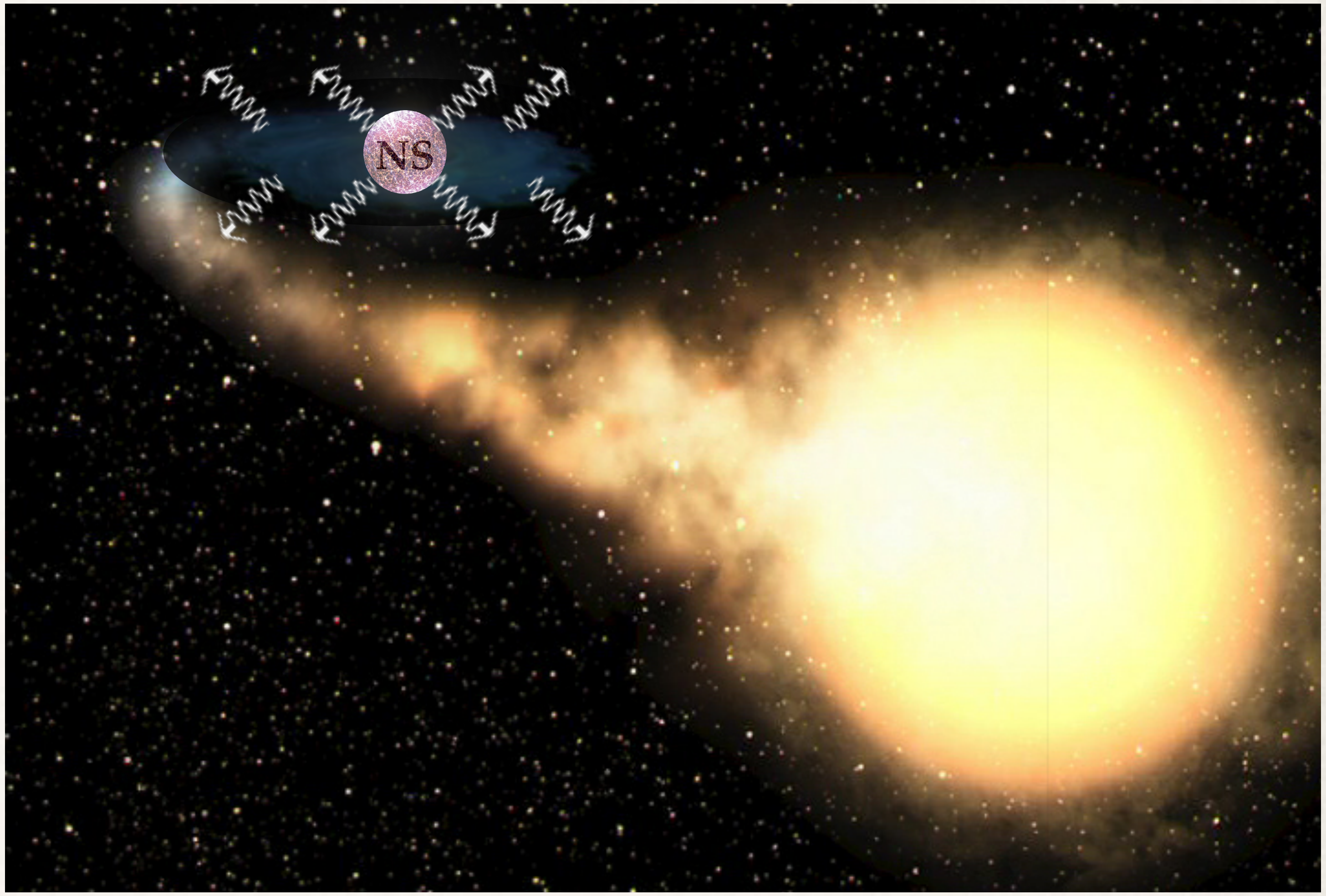


1. Low mass X-ray binaries in quiescence
2. Millisecond pulsars
3. Thermonuclear bursts in X-ray binaries

1. We will start with low-mass X-ray binaries.



Quiescent low-mass X-ray binaries are ideal systems for radius measurements.

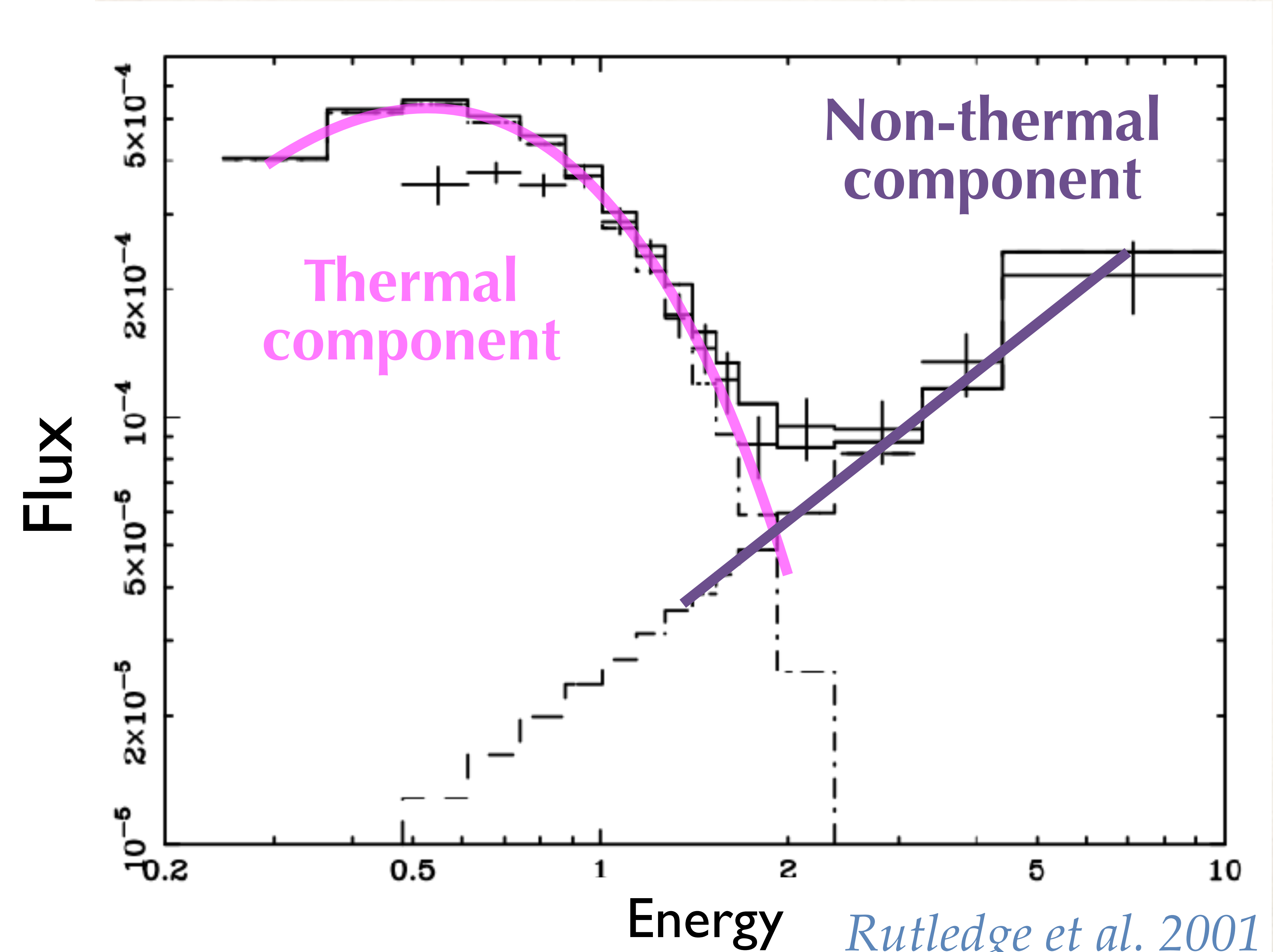


Surface thermal emission at $T_{eff} \sim 10^6$ K, powered by residual heat from the deep crust radiating outwards through the **atmosphere** with $L_X = 10^{32-33}$ erg/sec

Spectral fitting of this surface emission gives us T_{eff} and $F_X \propto (R_\infty/D)^2$

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

A radius measurement was obtained from Cen X-4 (a known field LMXB) observed during quiescence.



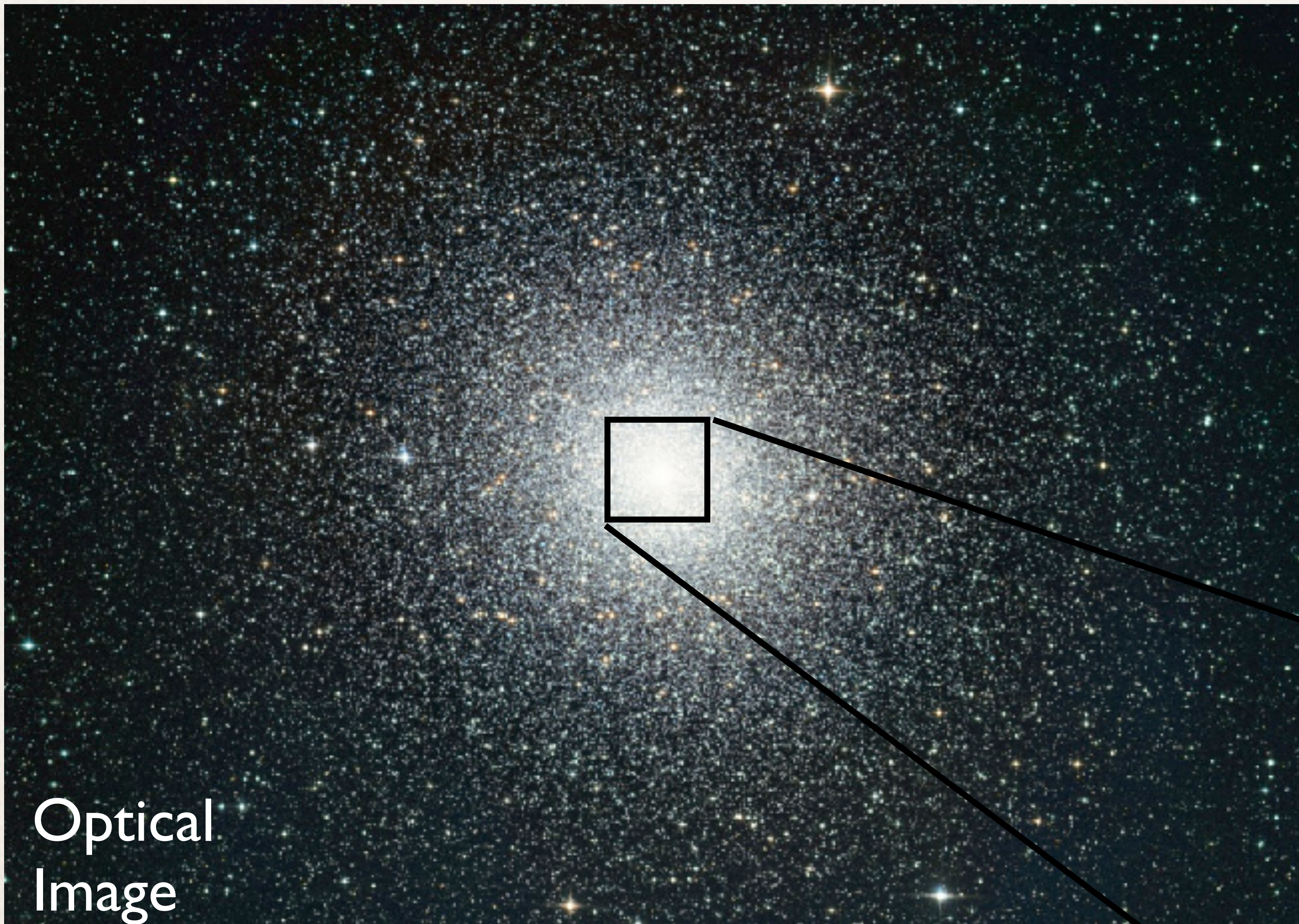
Rutledge et al. 2001

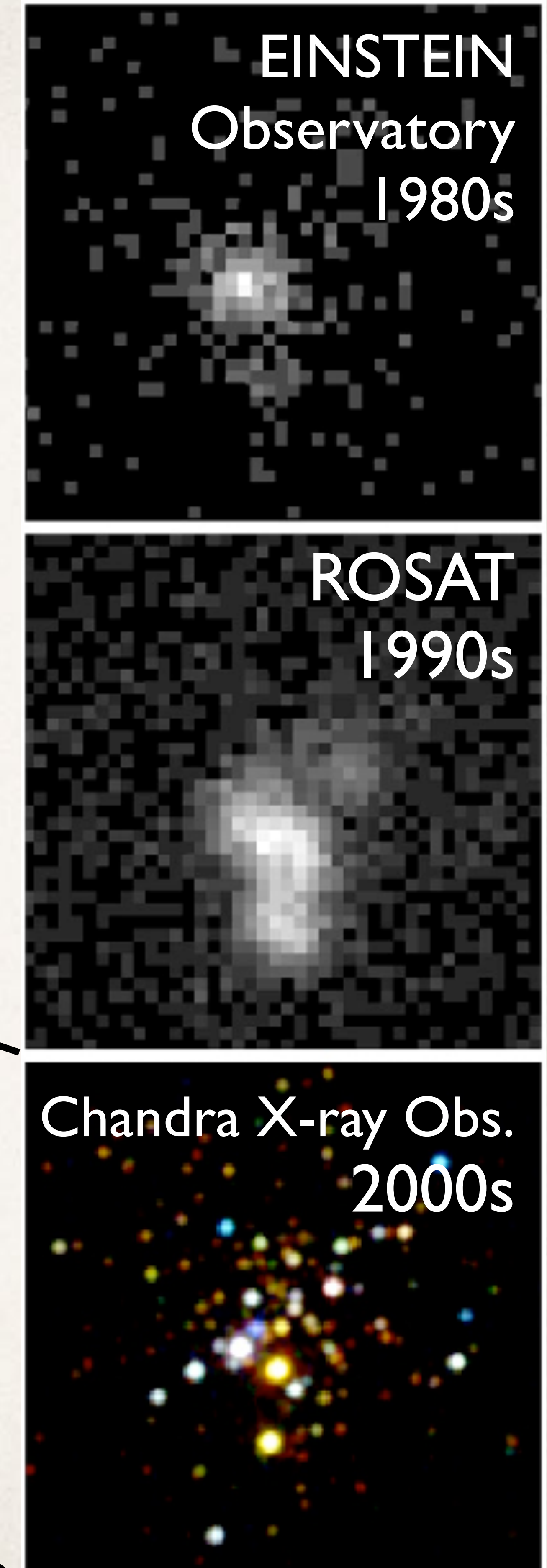
BUT

Possible evidence of residual accretion

Distance poorly constrained

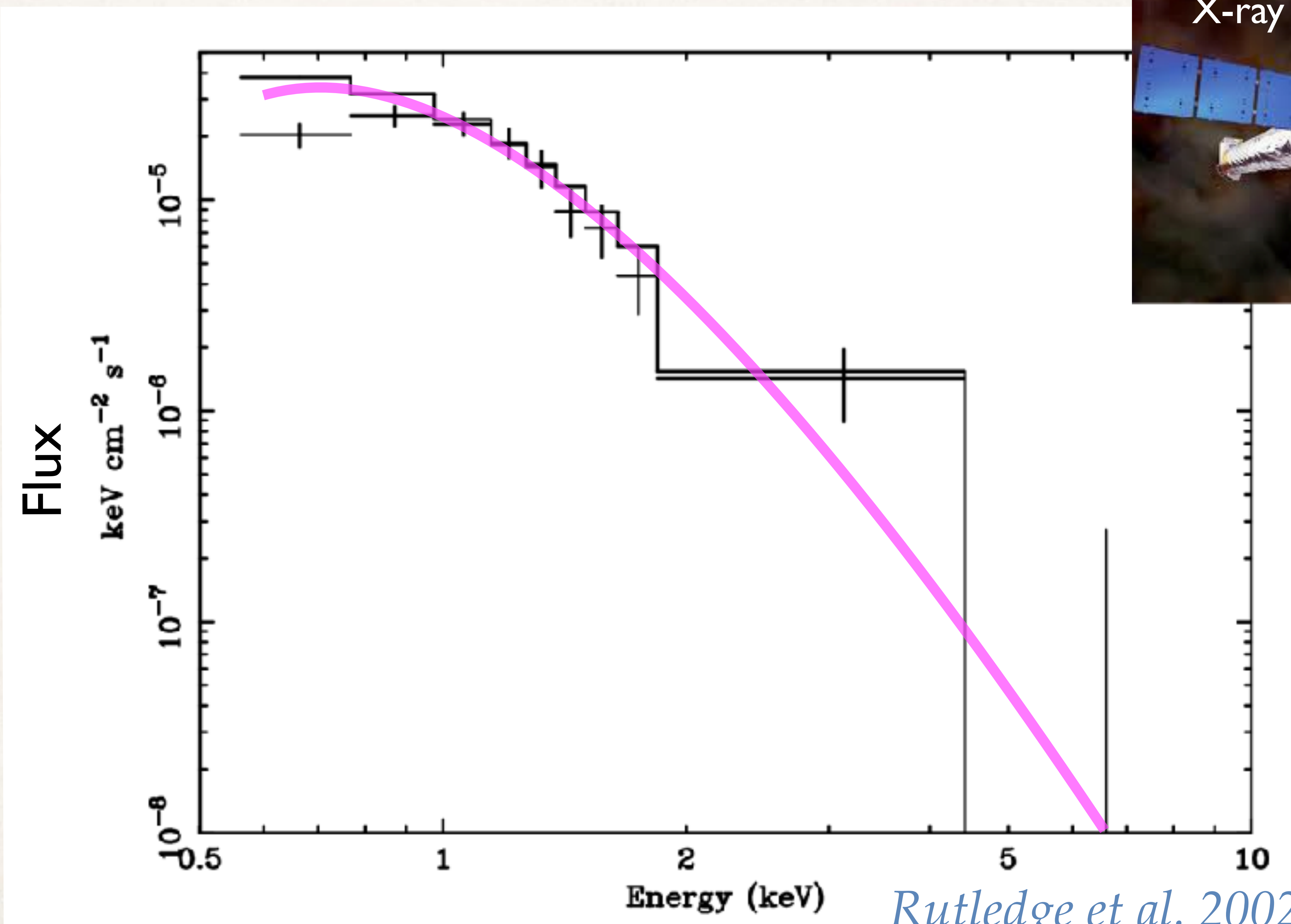
Globular clusters host an over-abundance of LMXB systems...





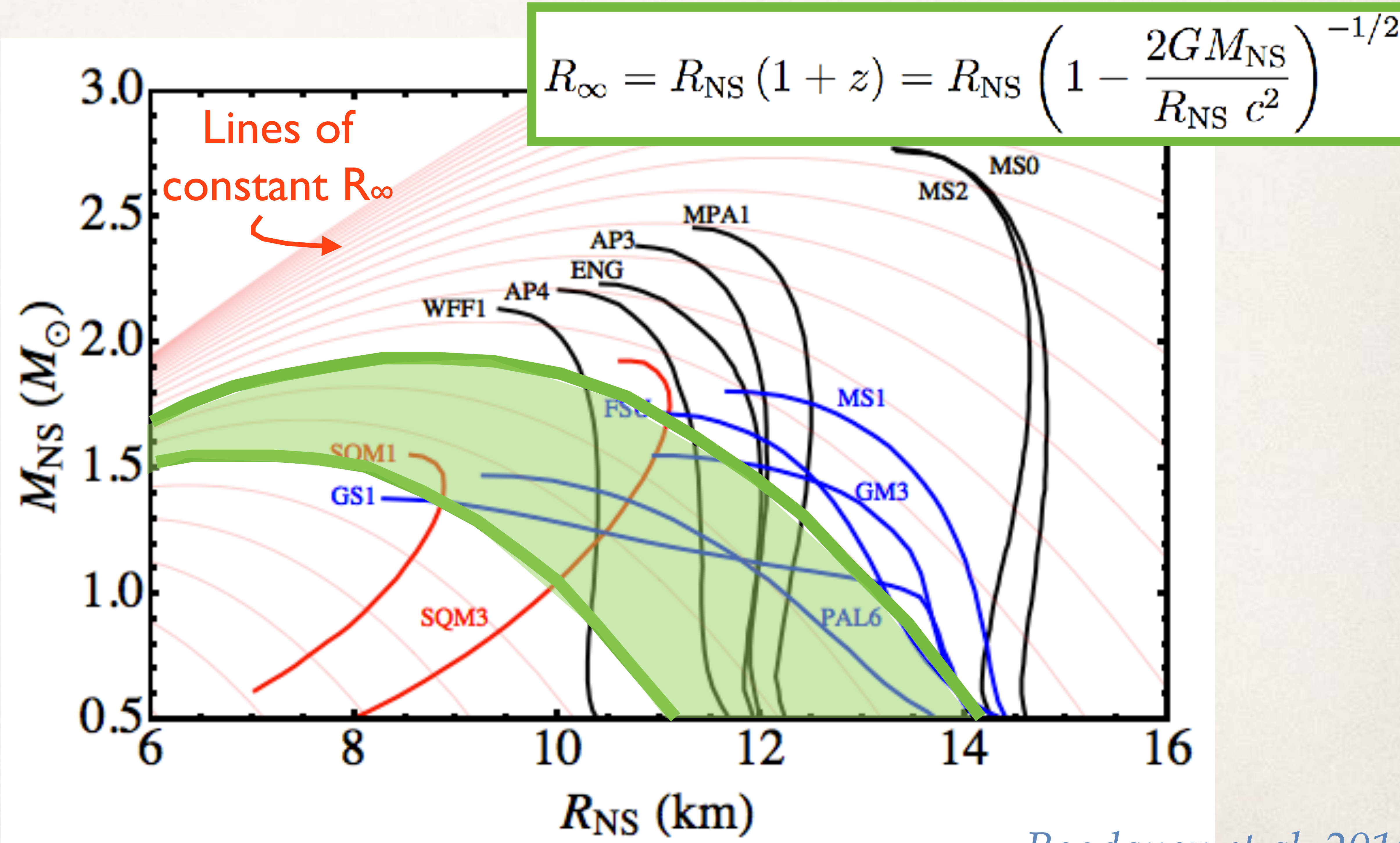
...and they have independently measured distances.

The first globular cluster qLMXB was discovered in Omega Centauri.



Rutledge et al. 2002

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



Bogdanov et al. 2016

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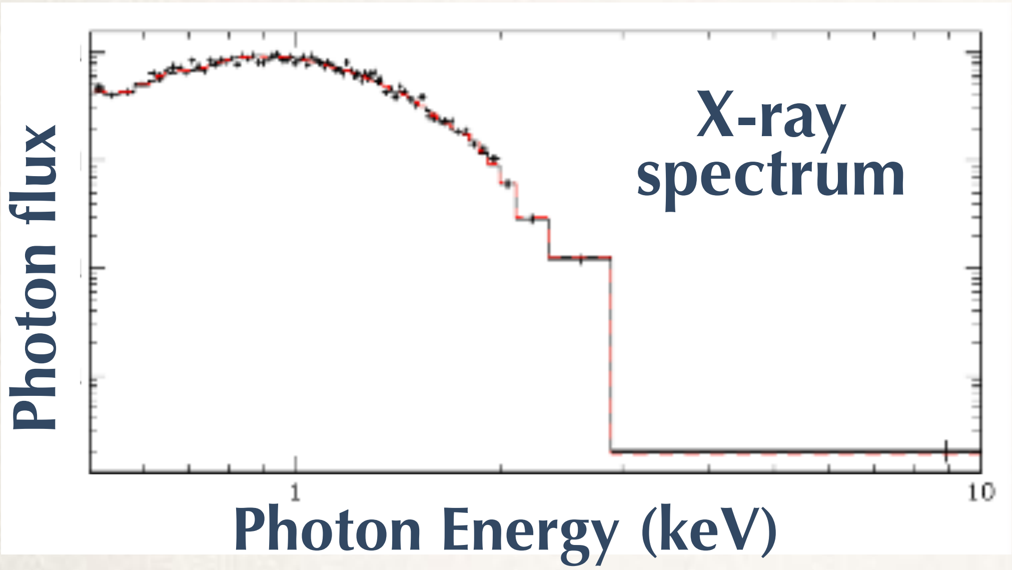
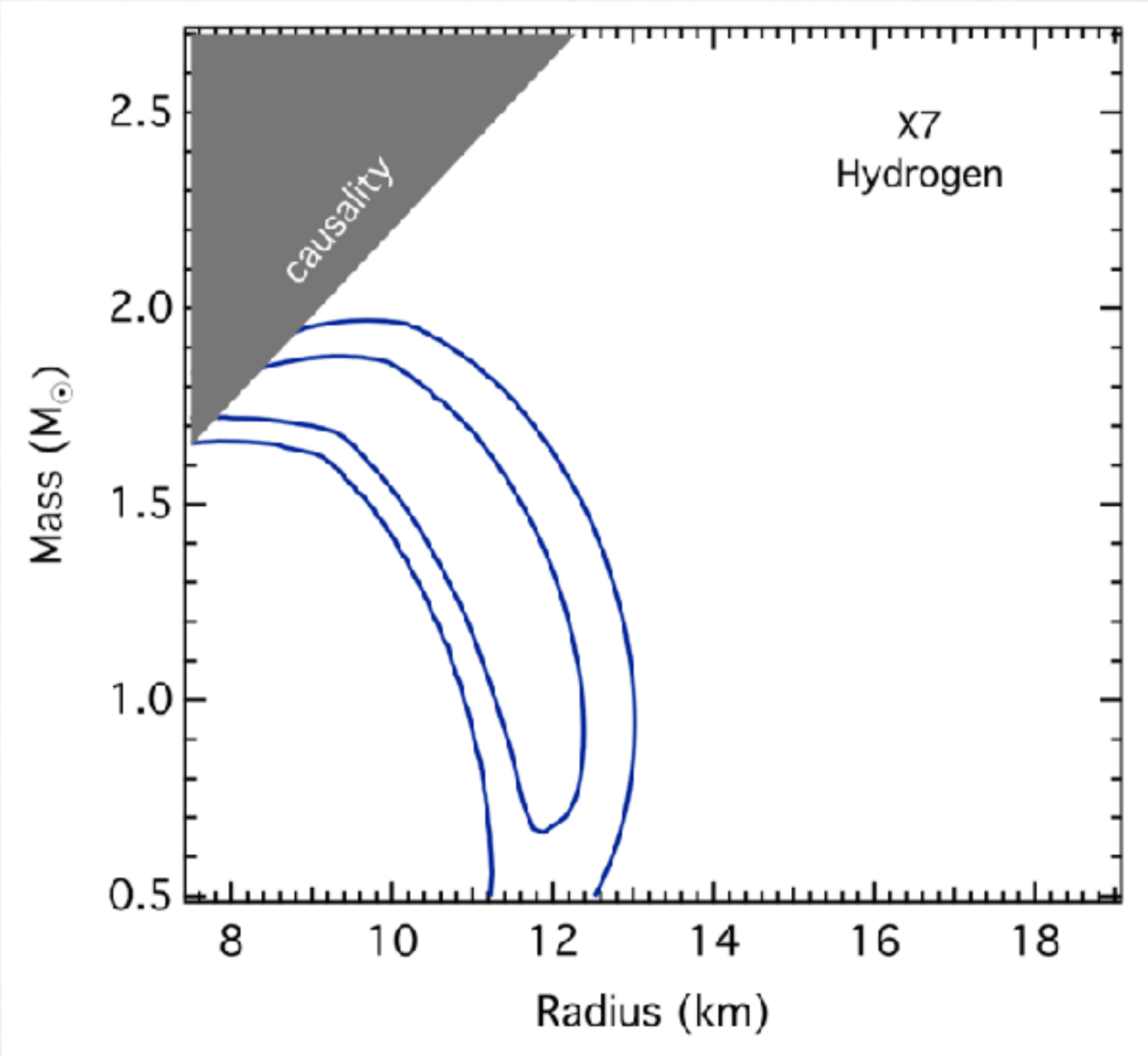
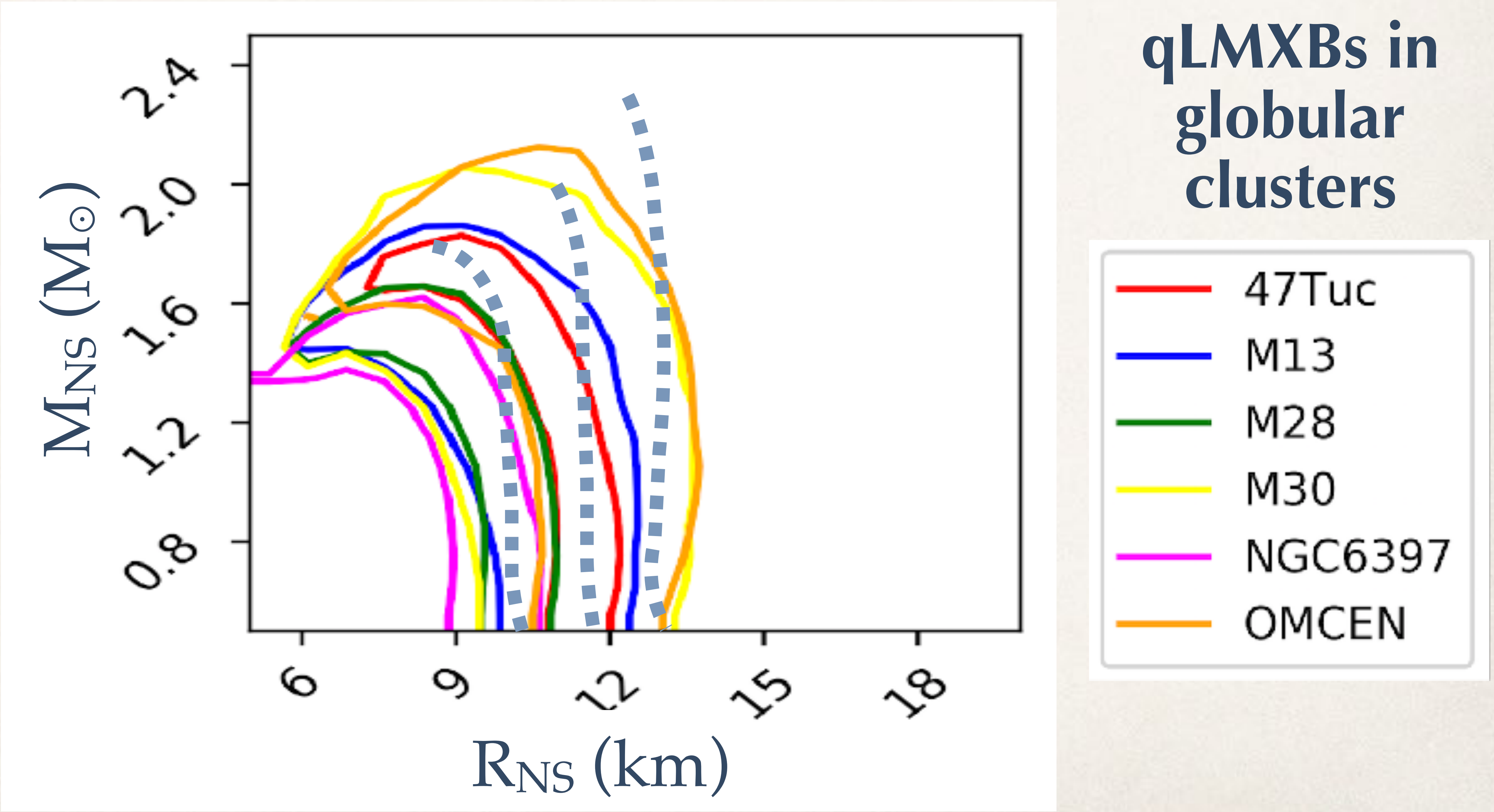




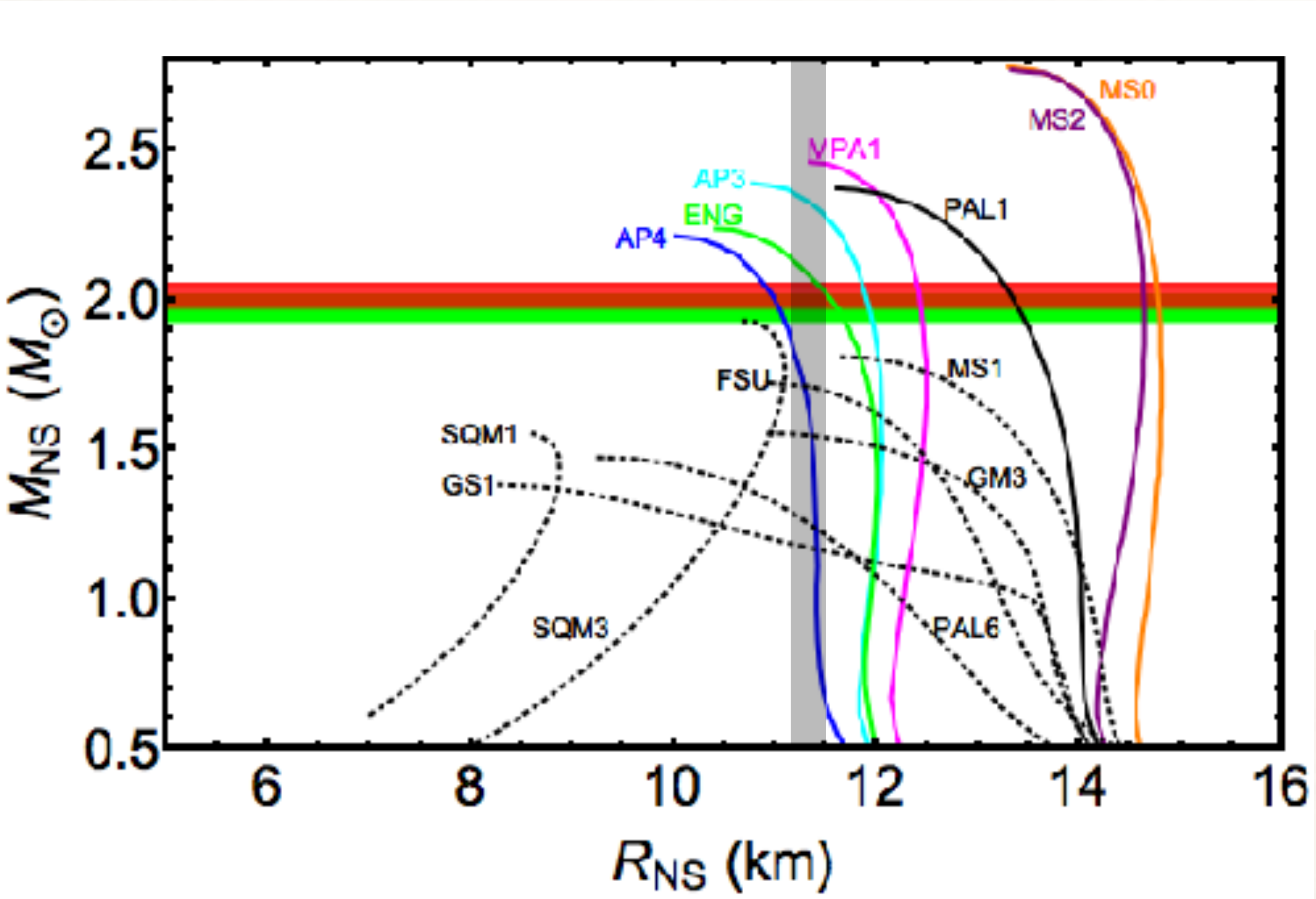
$$L \sim 4\pi \left(\frac{R_\infty}{d}\right)^2 \sigma\, T_{\mathrm{eff},\infty}^4$$

Bogdanov et al. 2016

We want to find which <u>equation of state</u> is common to all these M–R measurements.



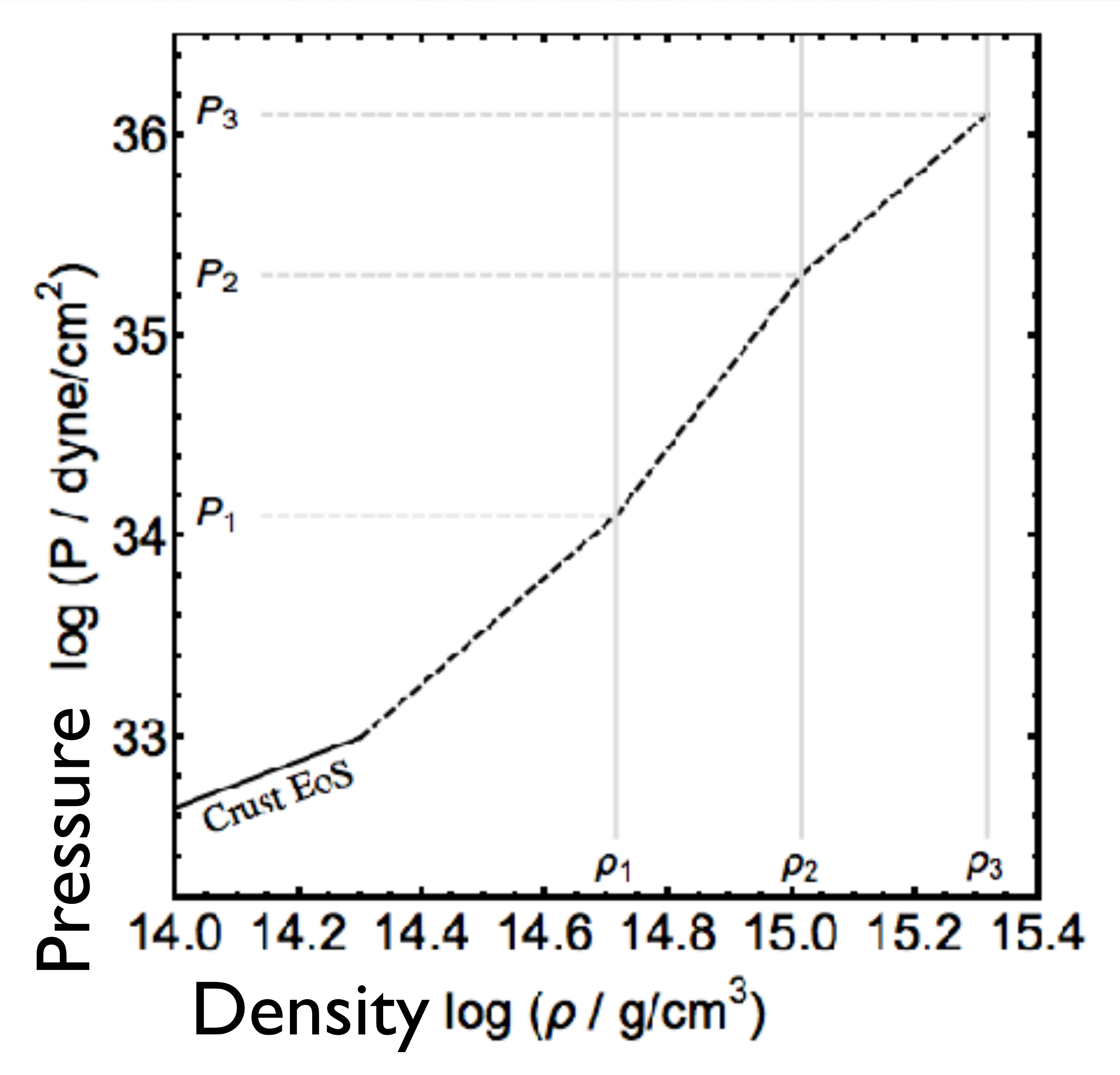
A solution consists in combining these observations in a statistical analysis.



Constant R_{NS}

i.e., the radius is the same for all neutron stars

Guillot et al. 2013
Guillot & Rutledge 2014
Guillot 2016



Piecewise polytropes

Analytical parameterizations

Read et al. 2009
Özel et al. 2016

We used a physically-driven, parameterisation of the equation of state is preferable.

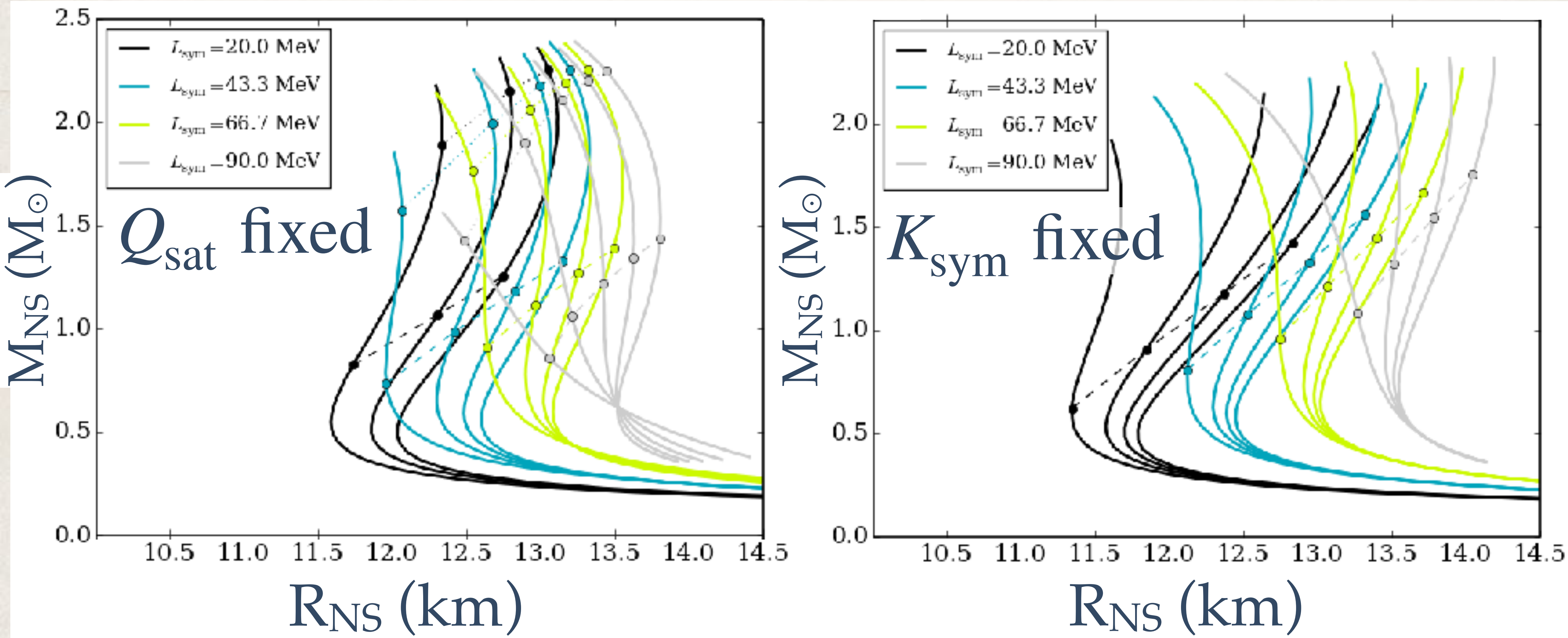
Meta-model of J. Margueron et al.

$$e_{sat} = E_{sat} + \frac{1}{2}K_{sat}x^2 + \frac{1}{3!}Q_{sat}x^3 + \frac{1}{4!}Z_{sat}x^4 + \ldots$$

$$e_{sym} = E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2 + \frac{1}{3!}Q_{sym}x^3 + \frac{1}{4!}Z_{sym}x^4 + \ldots,$$

with

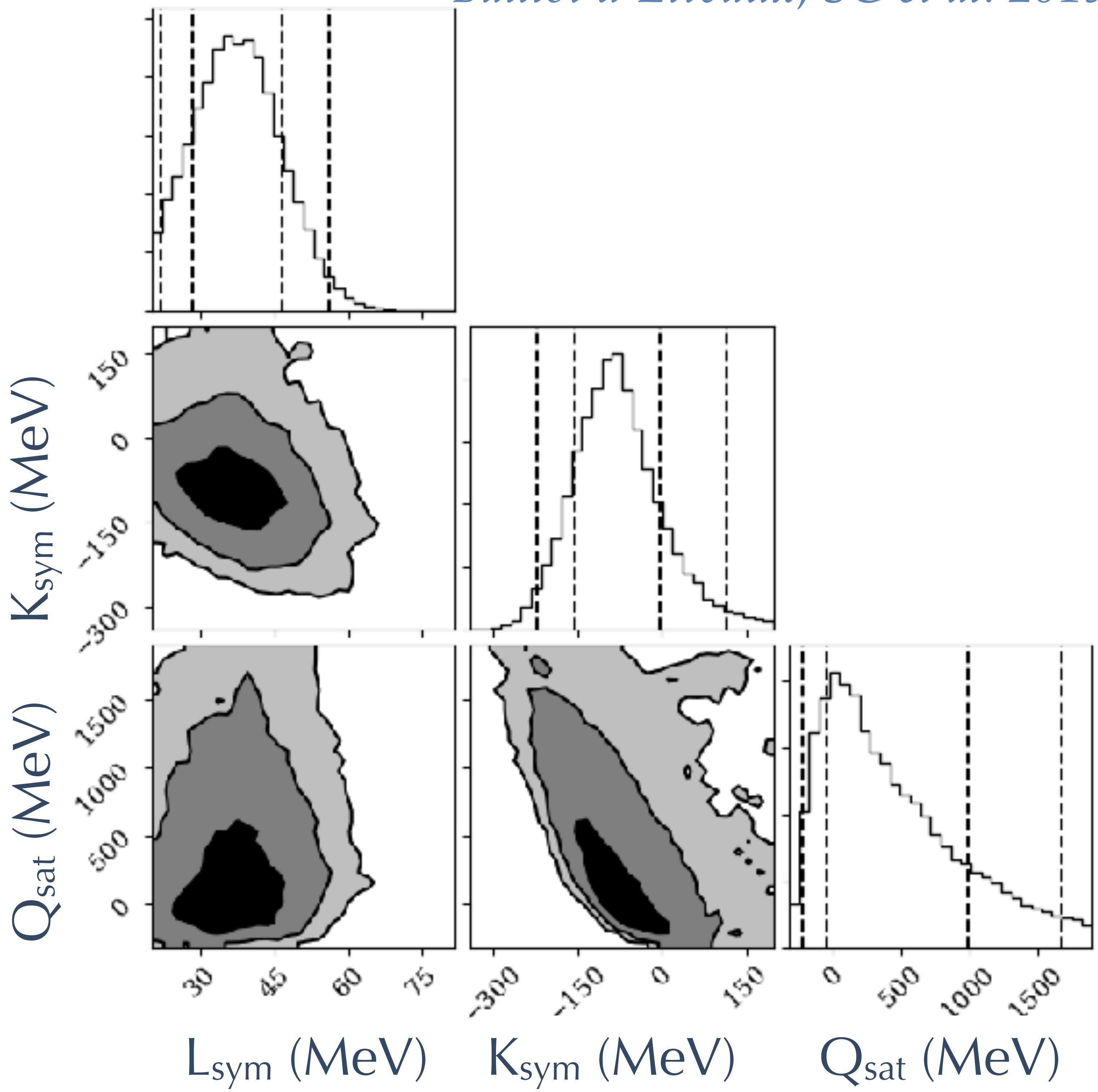
$$x = \frac{n - n_{sat}}{3n_{sat}}$$



Margueron et al. 2018
Baillot d'Etivaux, SG et al. 2019

The measurements of these three parameters improve over previous estimates.

Baillot d'Etivaux, SG et al. 2019



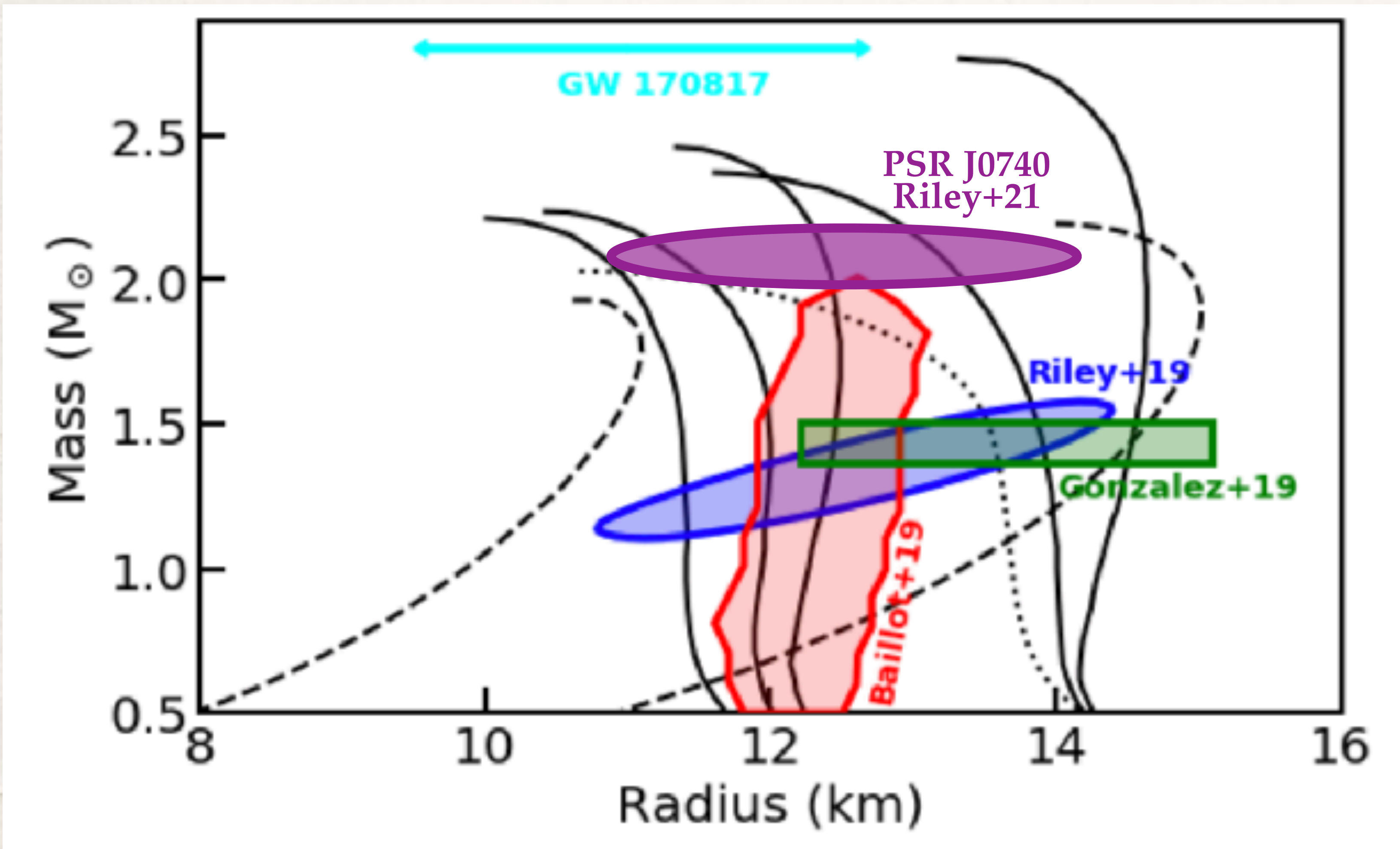
<u>Our 2σ measurements</u>:

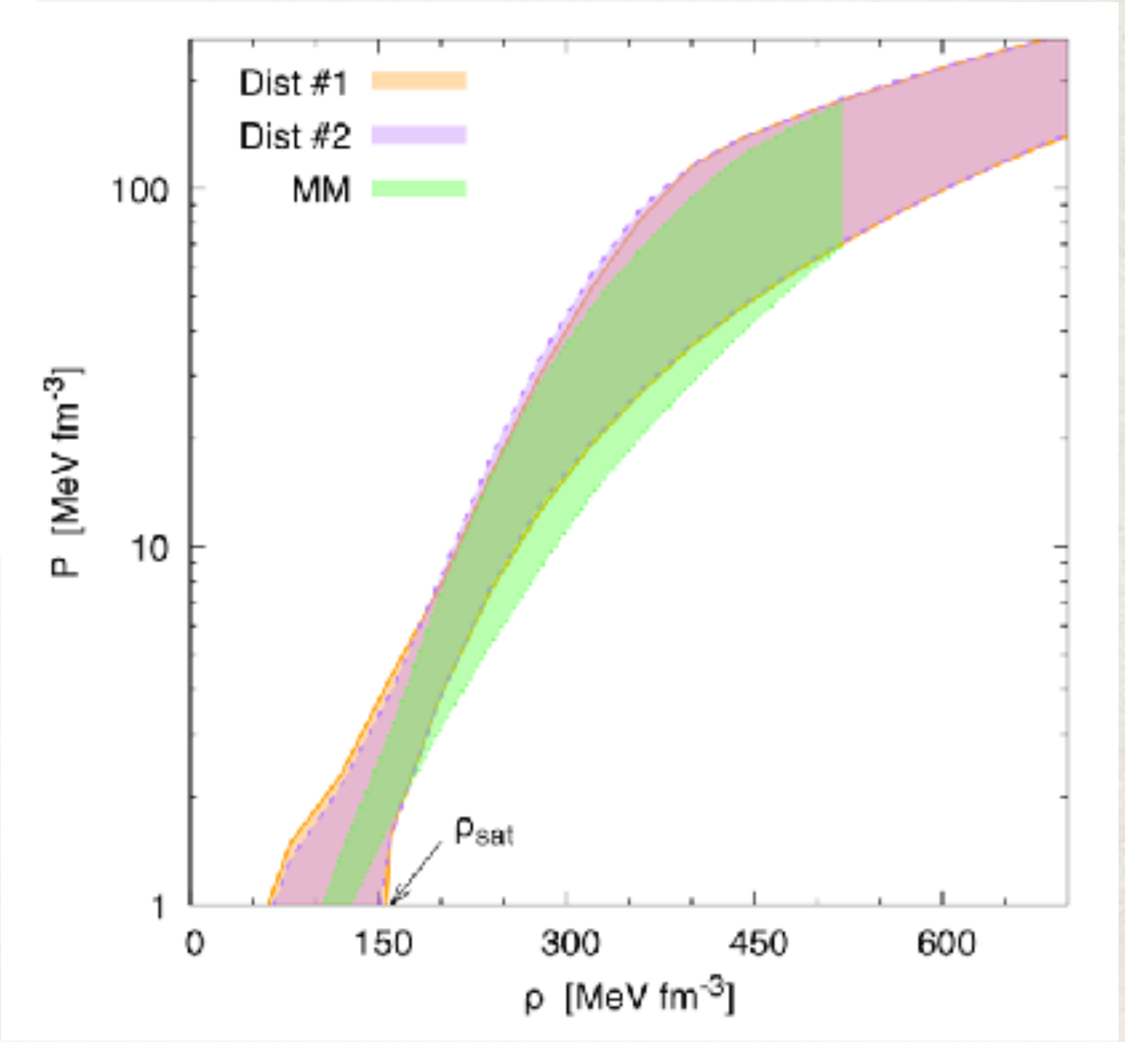
- L_{sym} ~ 25 – 60 MeV
- K_{sym} ~ -250 – 130 MeV
- Q_{sat} ~ -200 – 1900 MeV

Ranges of value from experimental and theoretical estimates:

- L_{sym} ~ 20 – 90 MeV
- K_{sym} ~ -400 – 200 MeV
- Q_{sat} ~ -1300 – 1900 MeV

Our analysis results in M_{NS}–R_{NS} or in P–ρ space are consistent with other measurements.



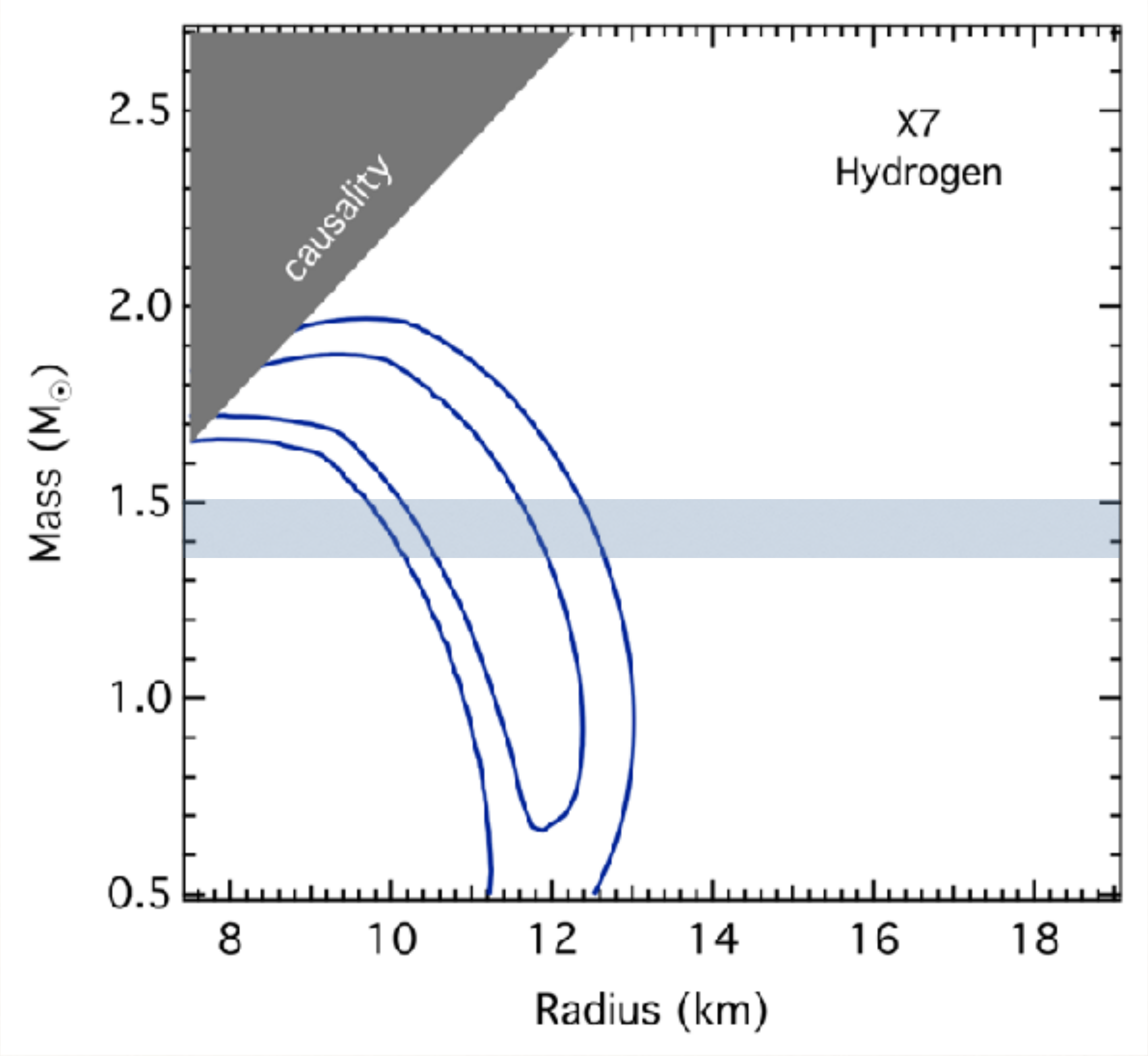


Baillot d'Etivaux, SG et al. 2019

There remains some discussion points and possible caveats!

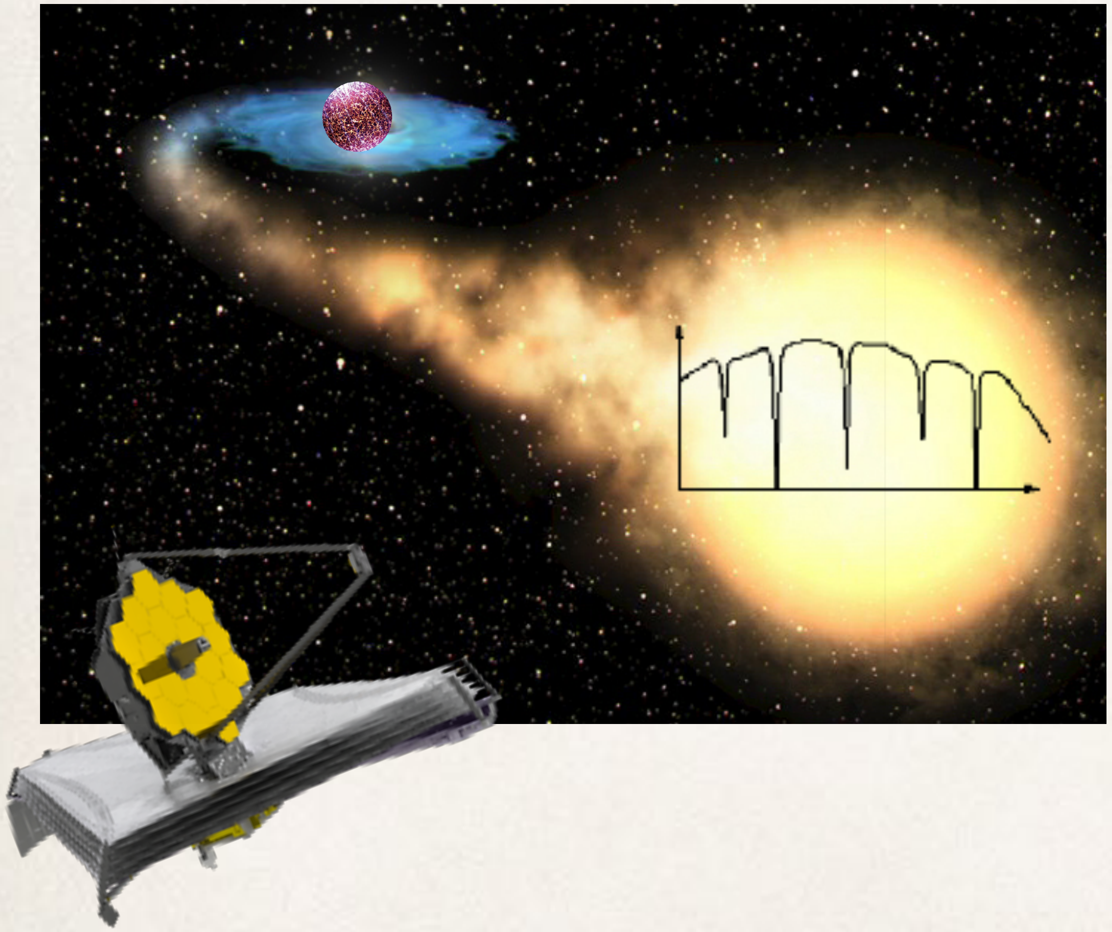
- Why only use qLMXBs in globular clusters ? → Field LMXB may not return to full quiescence
- What is the **<u>composition</u>** of the neutron star atmosphere ? → Hydrogen, Helium or something else
- Is the **<u>surface magnetic</u>** field really negligible ? → No measurement, but expected for LXMBs
- Is the emission really from the **<u>entire surface</u>** ? → No constraints exist, but …
- What are the effects of assuming **<u>slowly rotating</u>** neutron stars? → Fast rotation may bias the R measurement

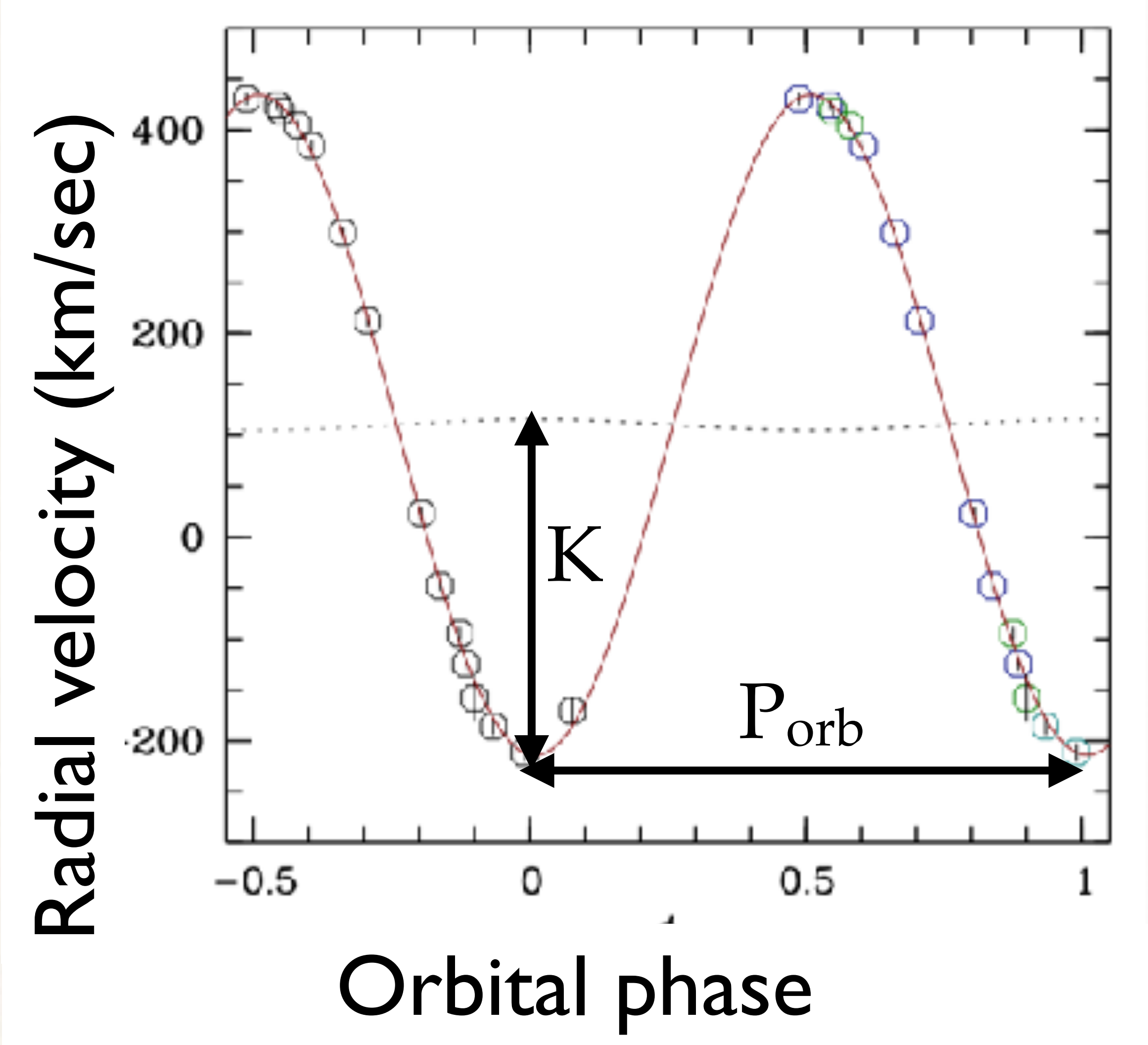
Another question: Could we measure the mass to break the M–R degeneracy?



This requires identifying the companion star and determining the orbital parameters

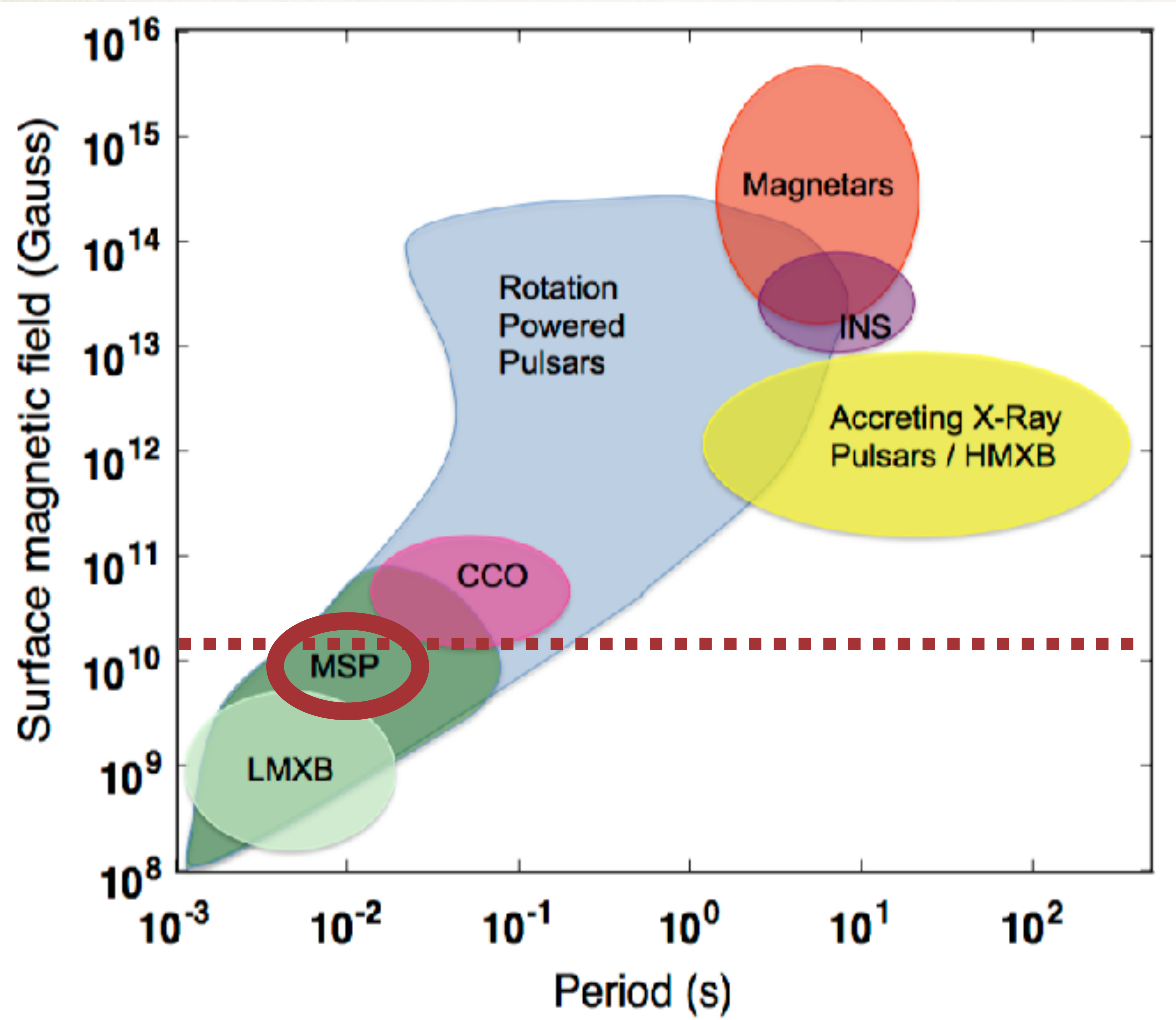
Observing the binary companion to the NS





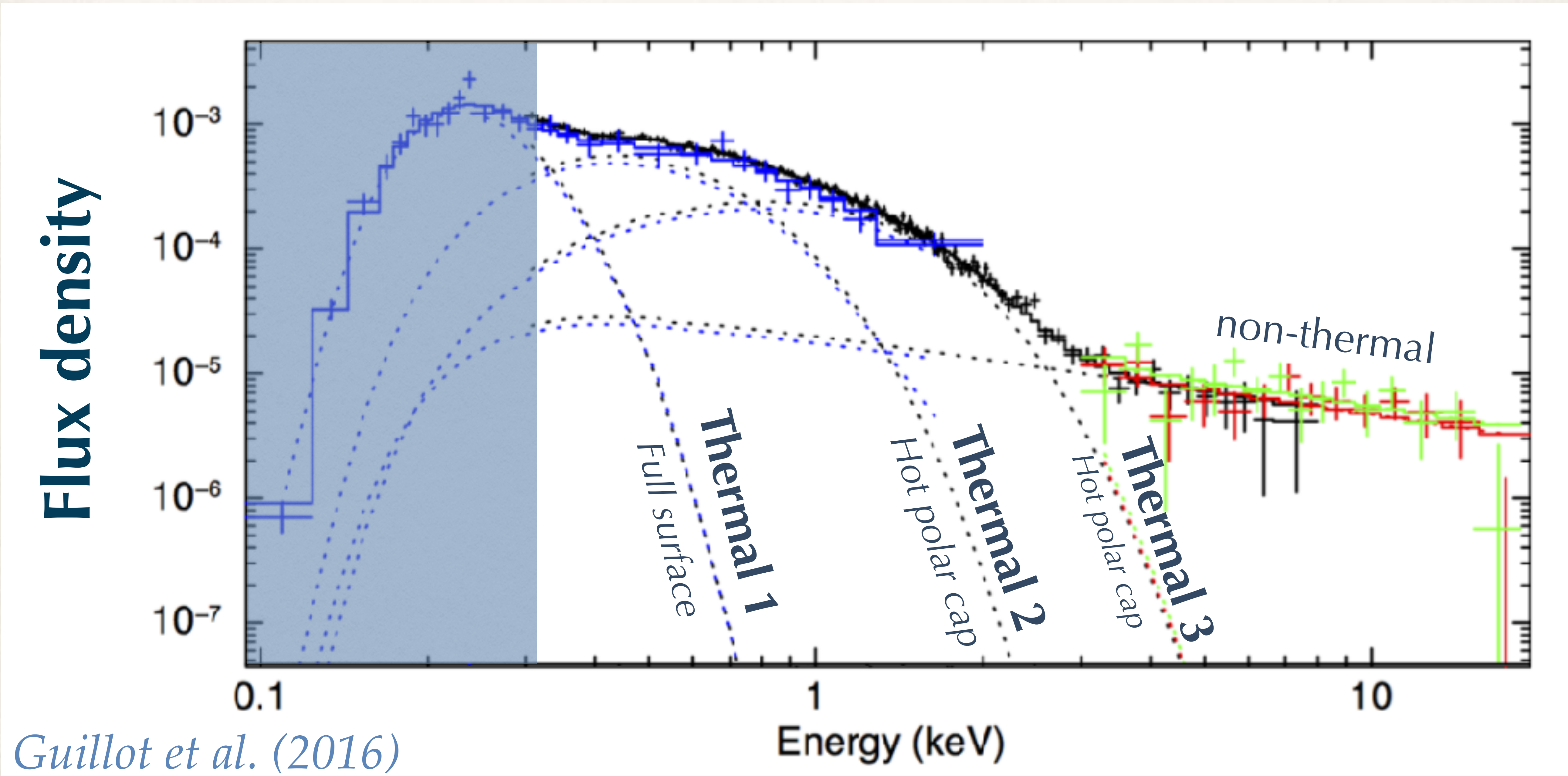
$$\frac{M_{\rm NS}^3 \sin^3 i}{(M_{\rm NS} + M_{\rm comp})^2} = \frac{P_{\rm orb} K^3}{2\pi G}$$

2. Rotation powered millisecond pulsars also have thermal surface emission.



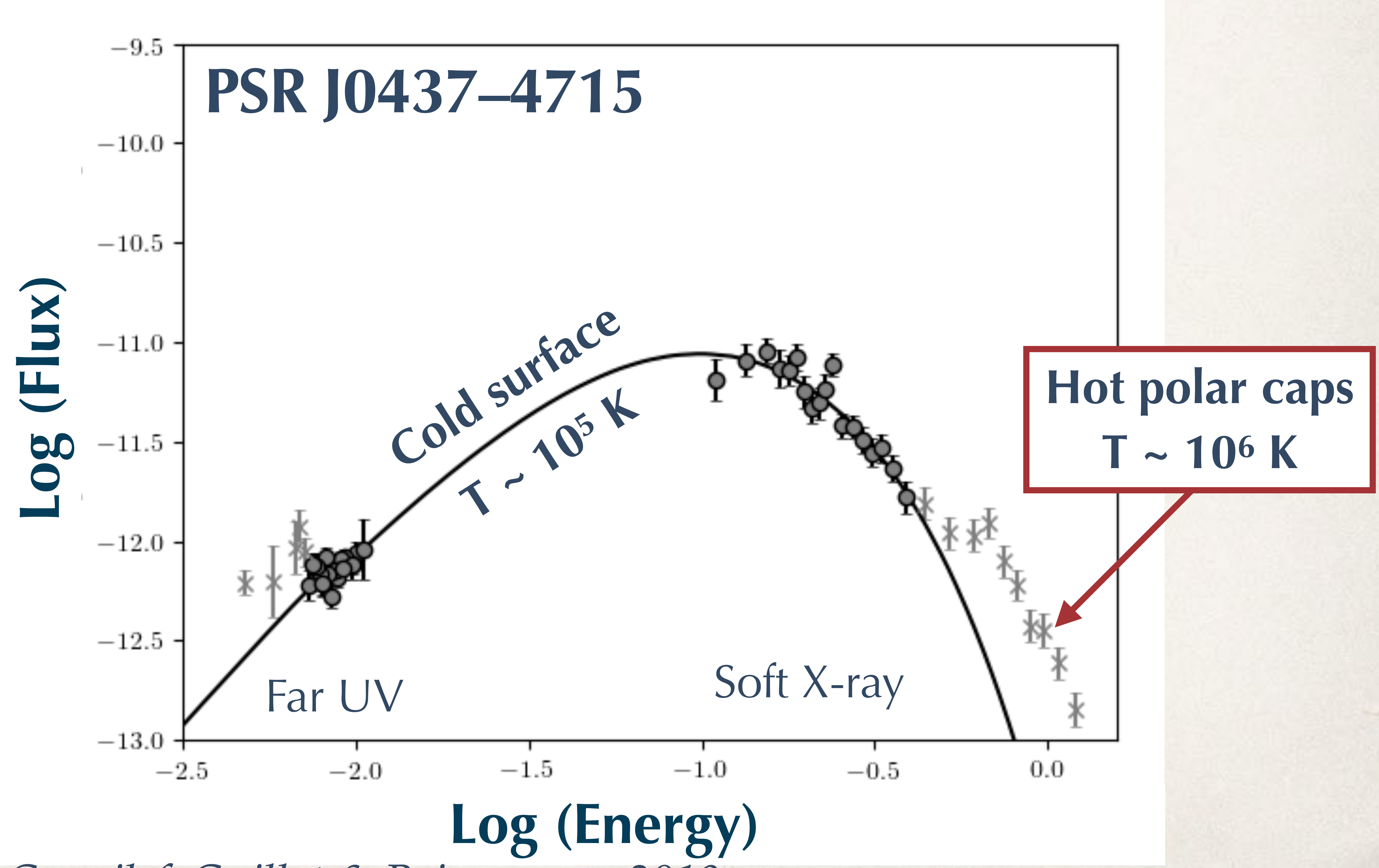
The surface emission from rotation-powered MSPs with known masses can also be used to extract the radius with phase-average spectroscopy.

The nearest MSP
PSR J0437–4715



Guillot et al. (2016)

In the far UV, the Rayleigh–Jeans tail of the surface thermal emission gives the handle to constrain the neutron star size.



Gonzalez-Canuilef, Guillot & Reisenegger, 2019

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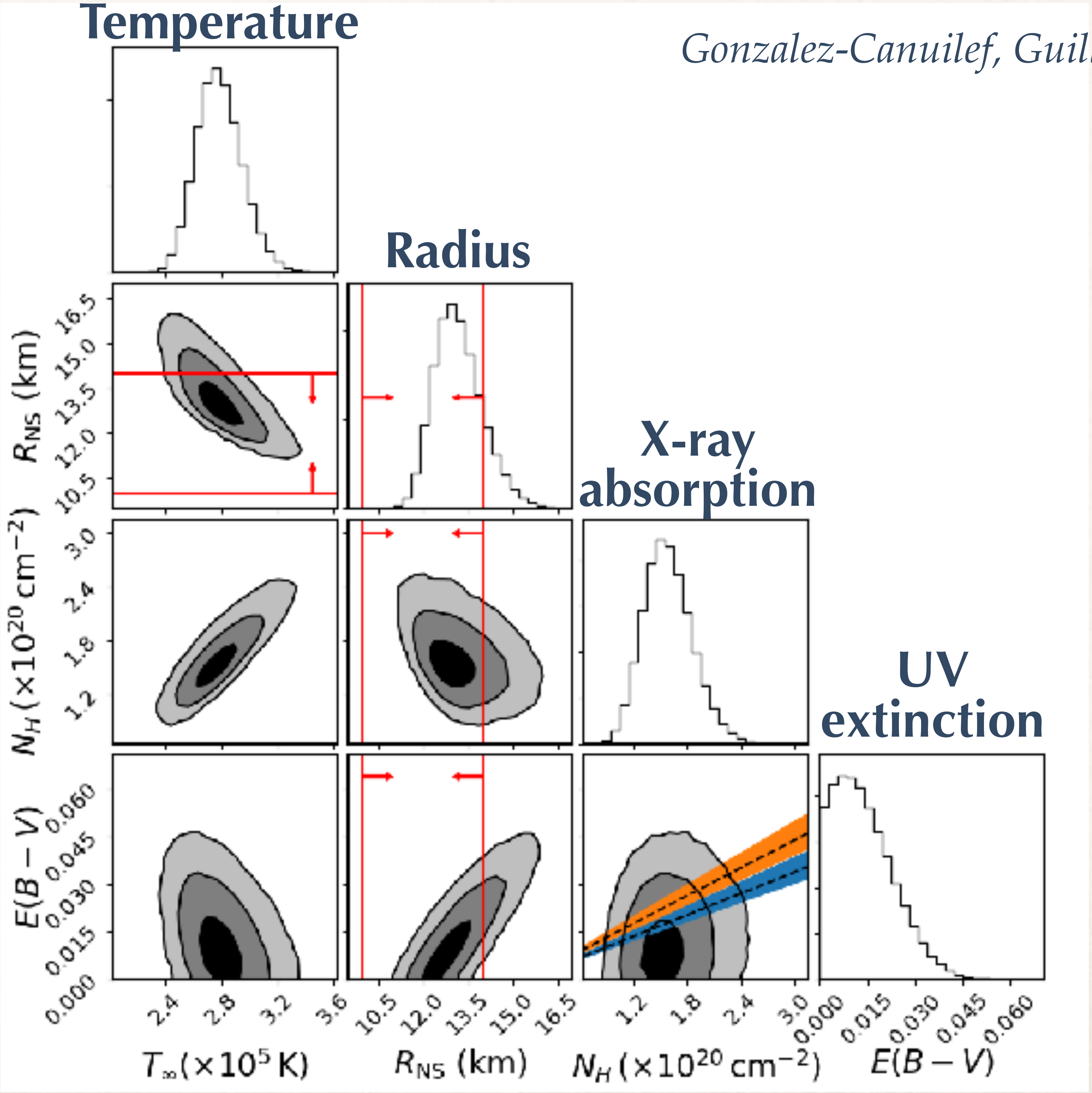
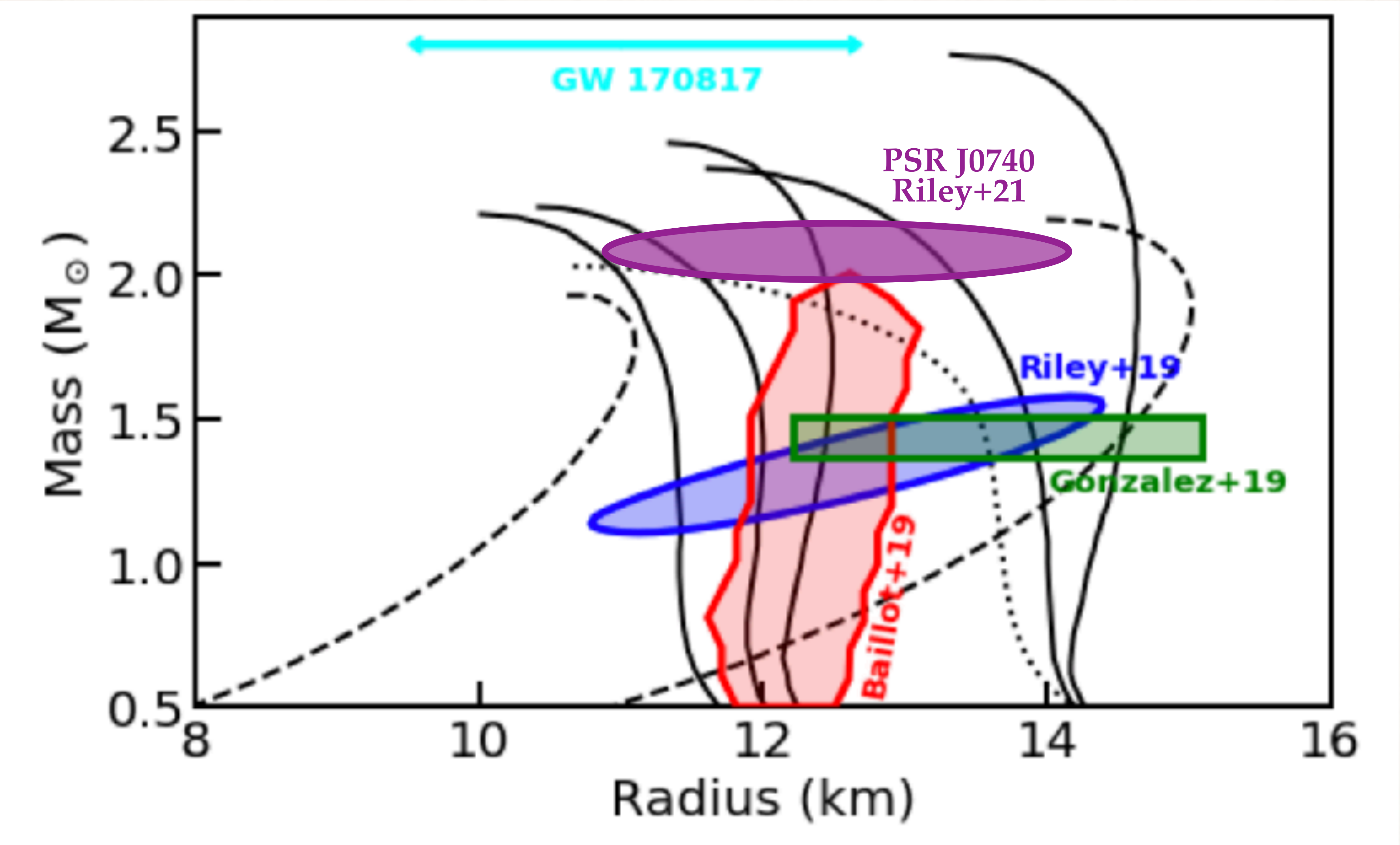


Gonzalez-Canuilef, Guillot & Reisenegger, 2019

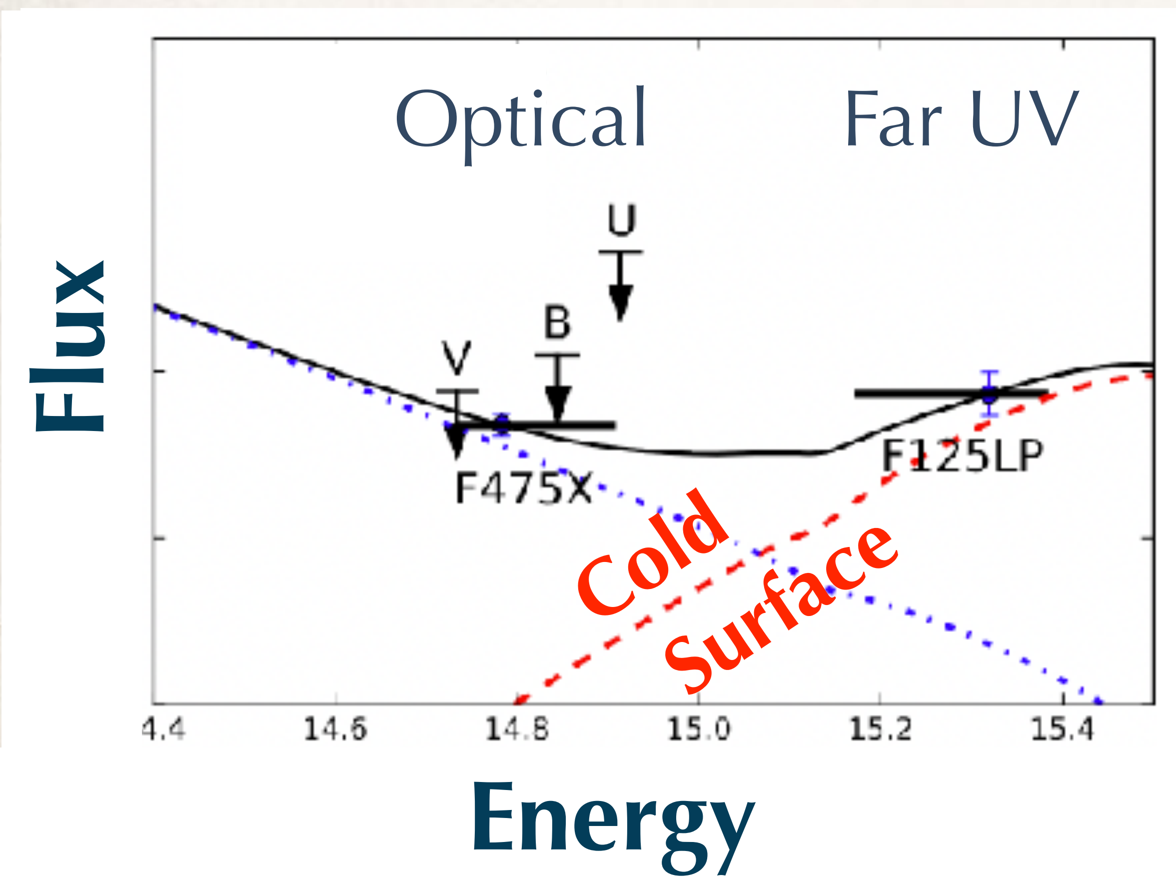
We find a radius for PSR J0437–4715 consistent with other measurements.



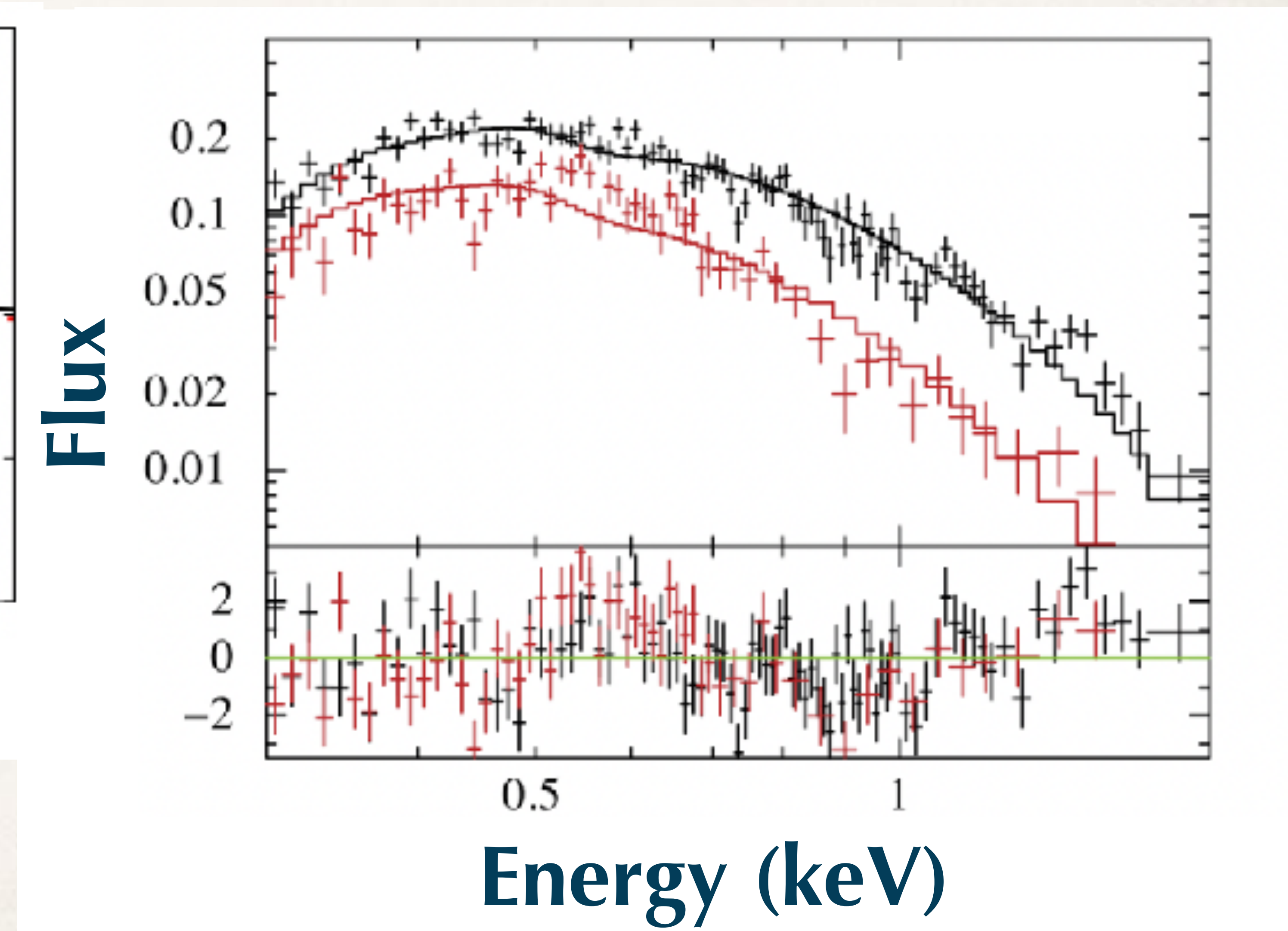
Gonzalez-Canuilef, Guillot & Reisenegger, 2019

This method may be applicable to another MSP with observed far UV emission.

PSR J2124–3358

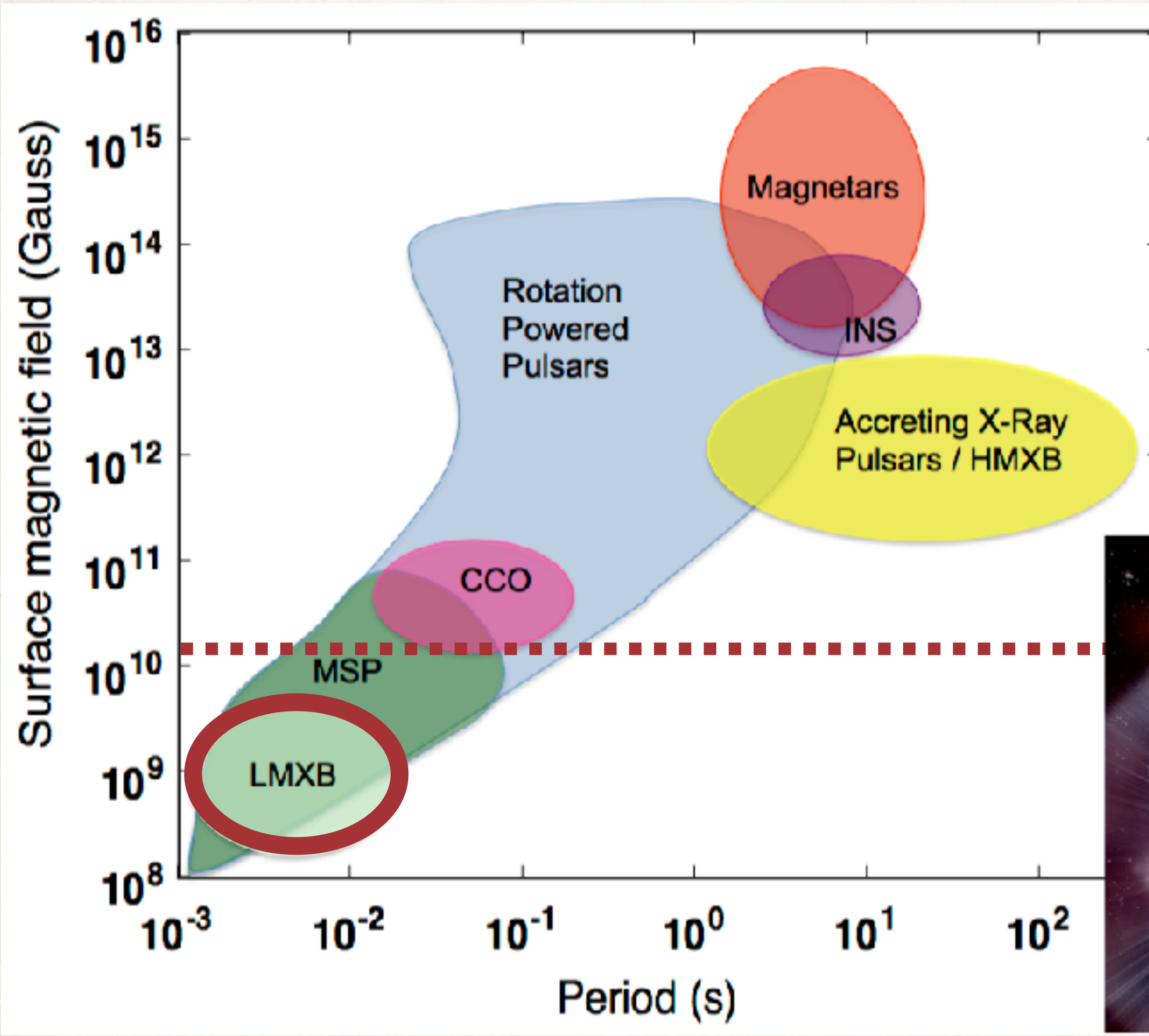


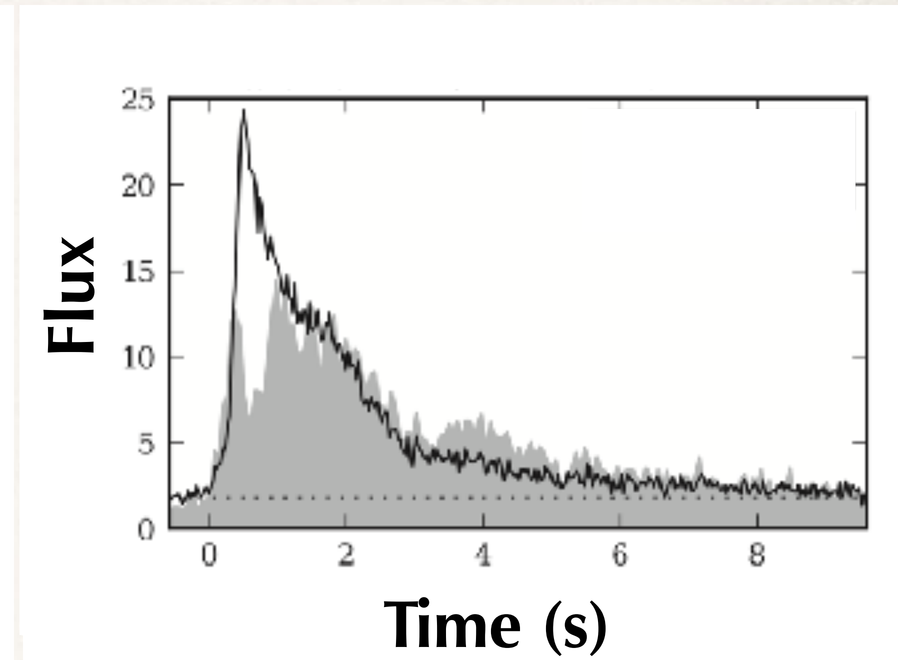
Rangelov et al. 2017



Bogdanov, SG et al. 2019

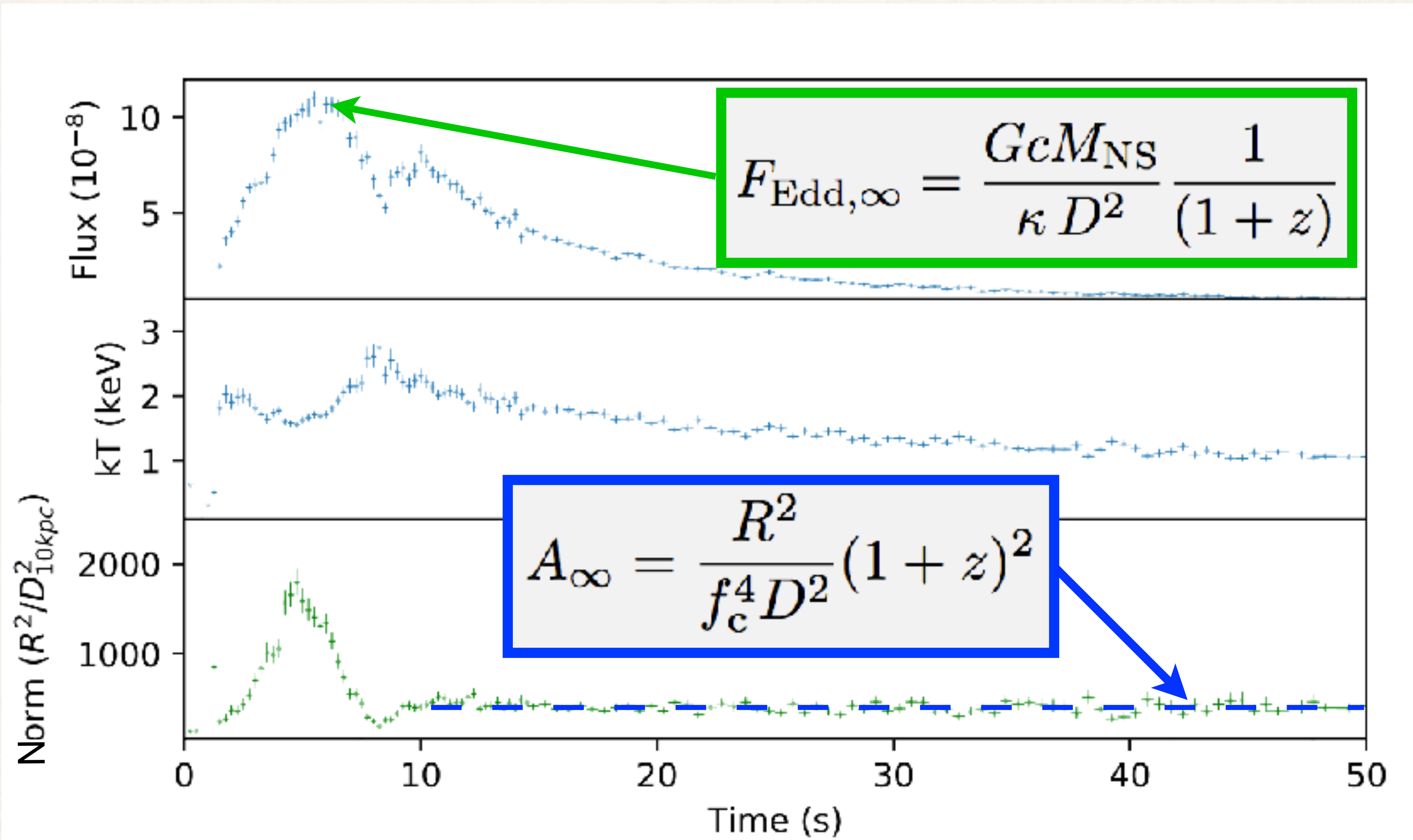
3. During accretion outbursts, LMXBs experience thermonuclear explosion from the neutron star surface.





Some of these thermonuclear bursts reach a critical luminosity and push out the photosphere.

$$L_{\mathrm{Edd}} = \frac{4\pi G c M_{\mathrm{NS}}}{\kappa}$$

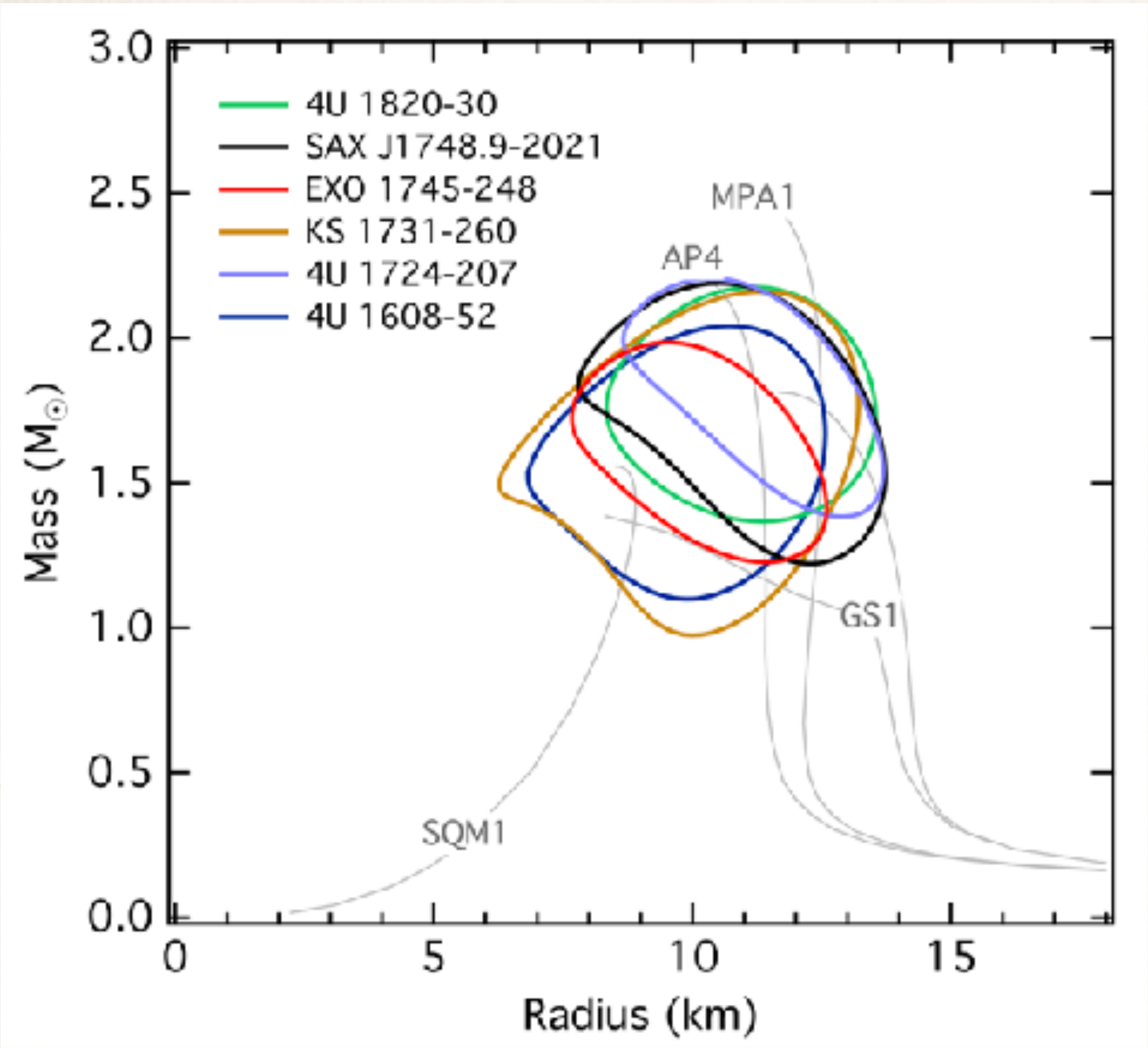


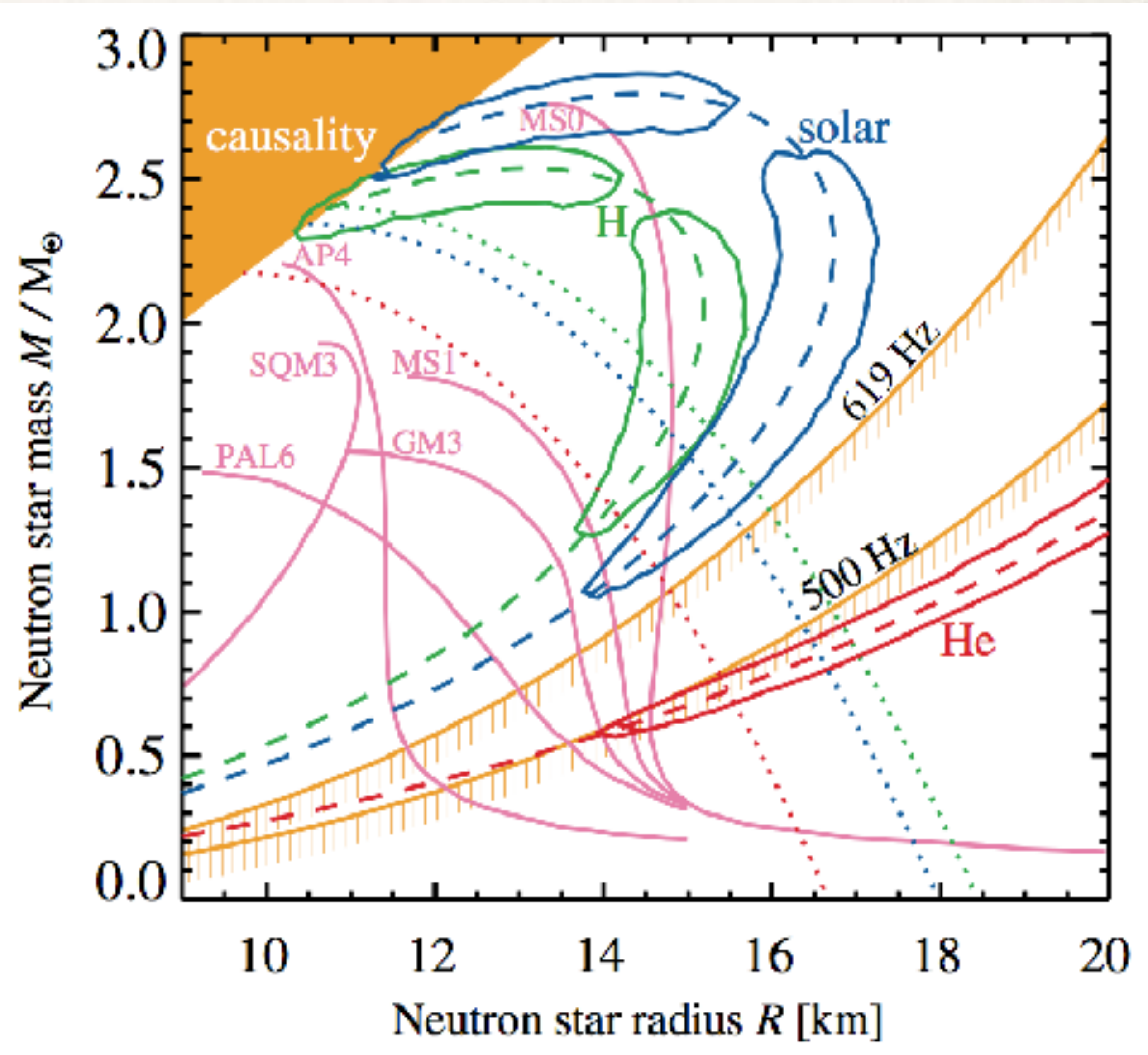
$$F_{\mathrm{Edd},\infty} = \frac{G c M_{\mathrm{NS}}}{\kappa D^2} \frac{1}{(1+z)}$$

$$A_{\infty} = \frac{R^2}{f_c^4 D^2}(1+z)^2$$

with $$(1+z) = \left(1 + \frac{2GM_{\mathrm{NS}}}{c^2 R_{\mathrm{NS}}}\right)^{-1/2}$$

Different analysis method and LMXB spectral states result in different constraints.





Data-driven selection of (high-soft state) bursts

Theory-driven selection of low-hard state bursts

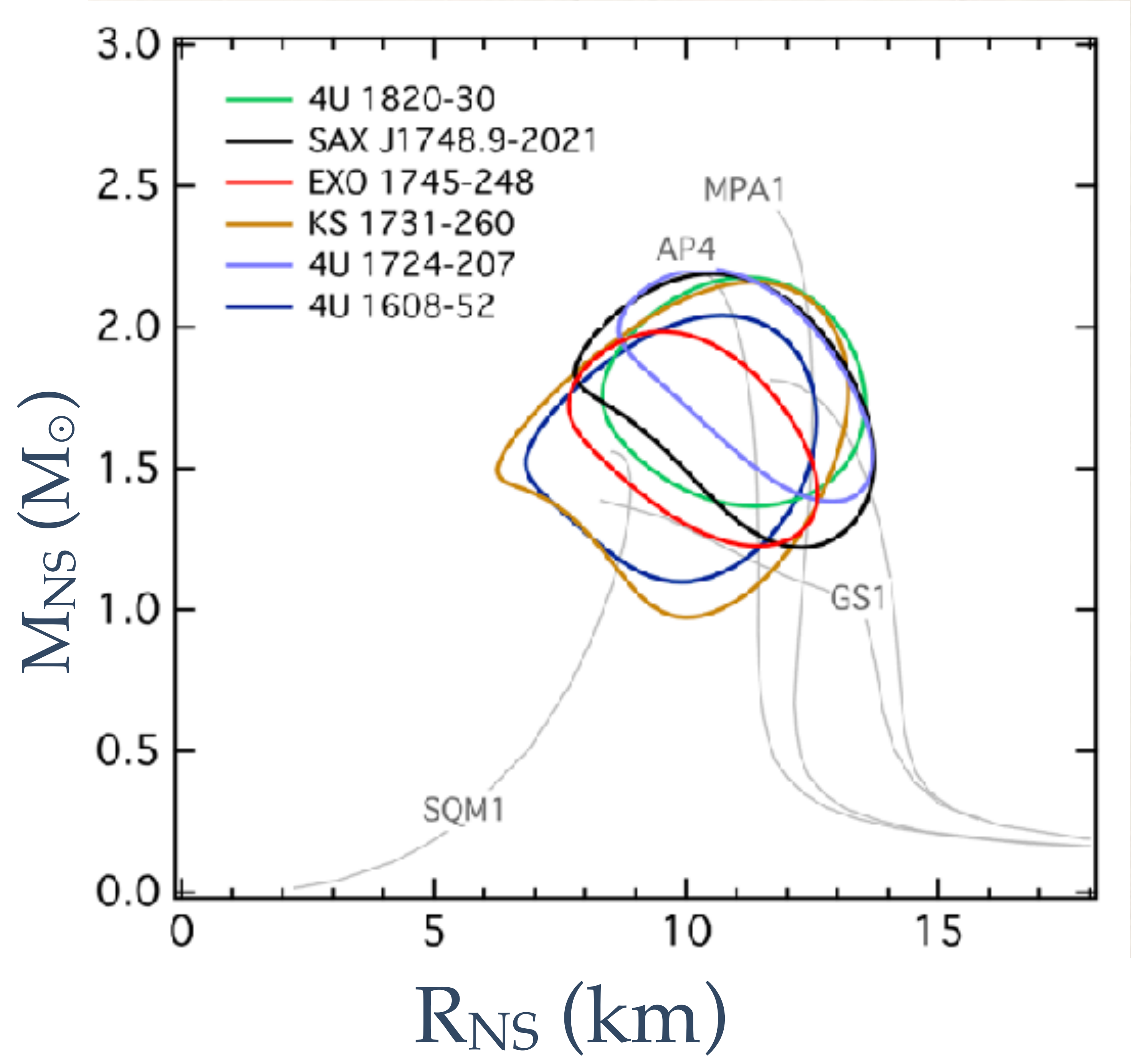
Özel et al. 2016

Suleimanov et al. 2011

A lot of uncertainties remain and make the measurements poorly constrained.

$$F_{\mathrm{Edd},\infty} = \frac{G c M_{\mathrm{NS}}}{\kappa\, D^2} \frac{1}{(1+z)}$$

$$A_\infty = \frac{R^2}{f_c^4 D^2}(1+z)^2$$



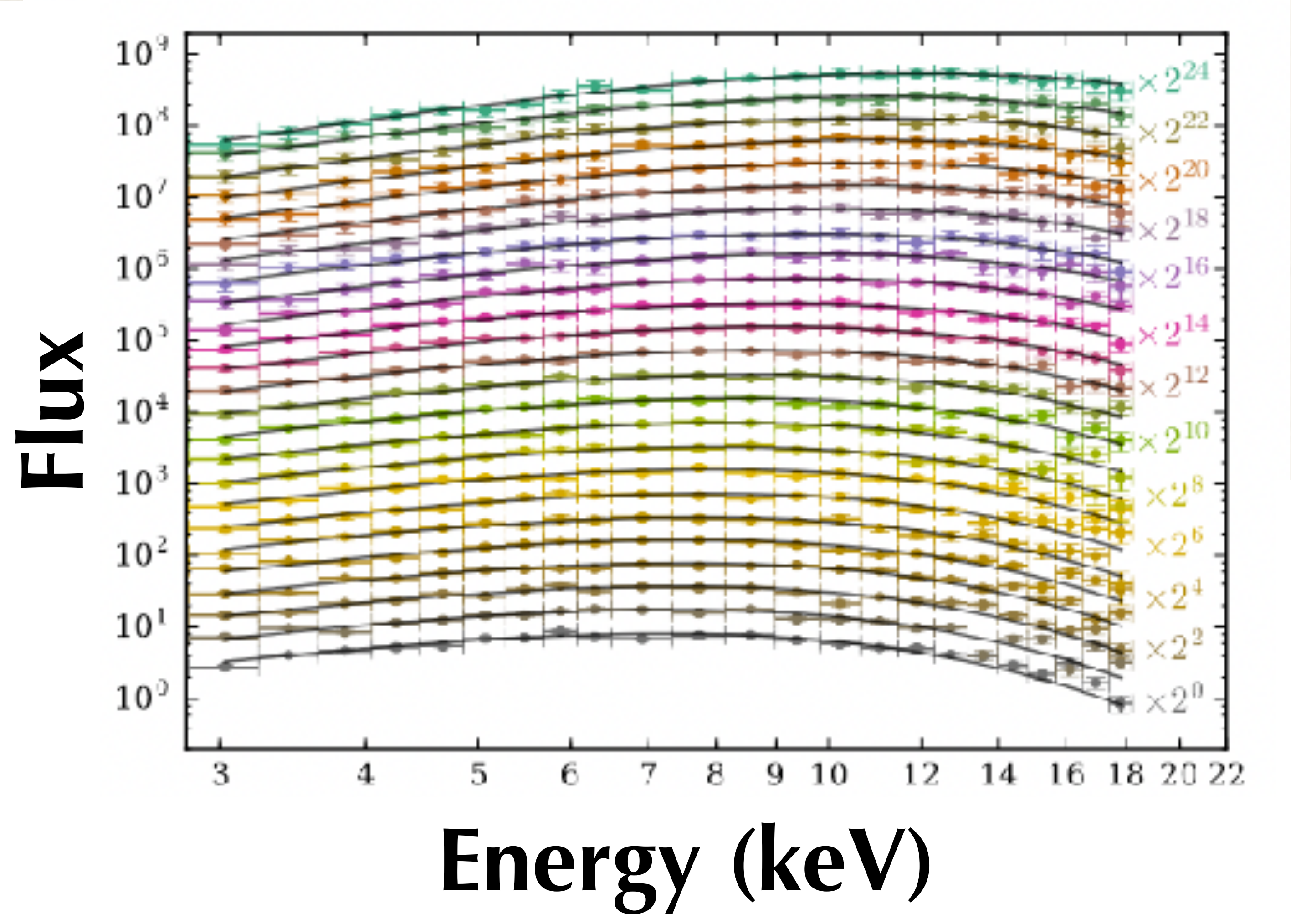
Sources of uncertainty include:

- Distance
- Atmospheric composition (via κ)
- Atmospheric modelling (via f_c)

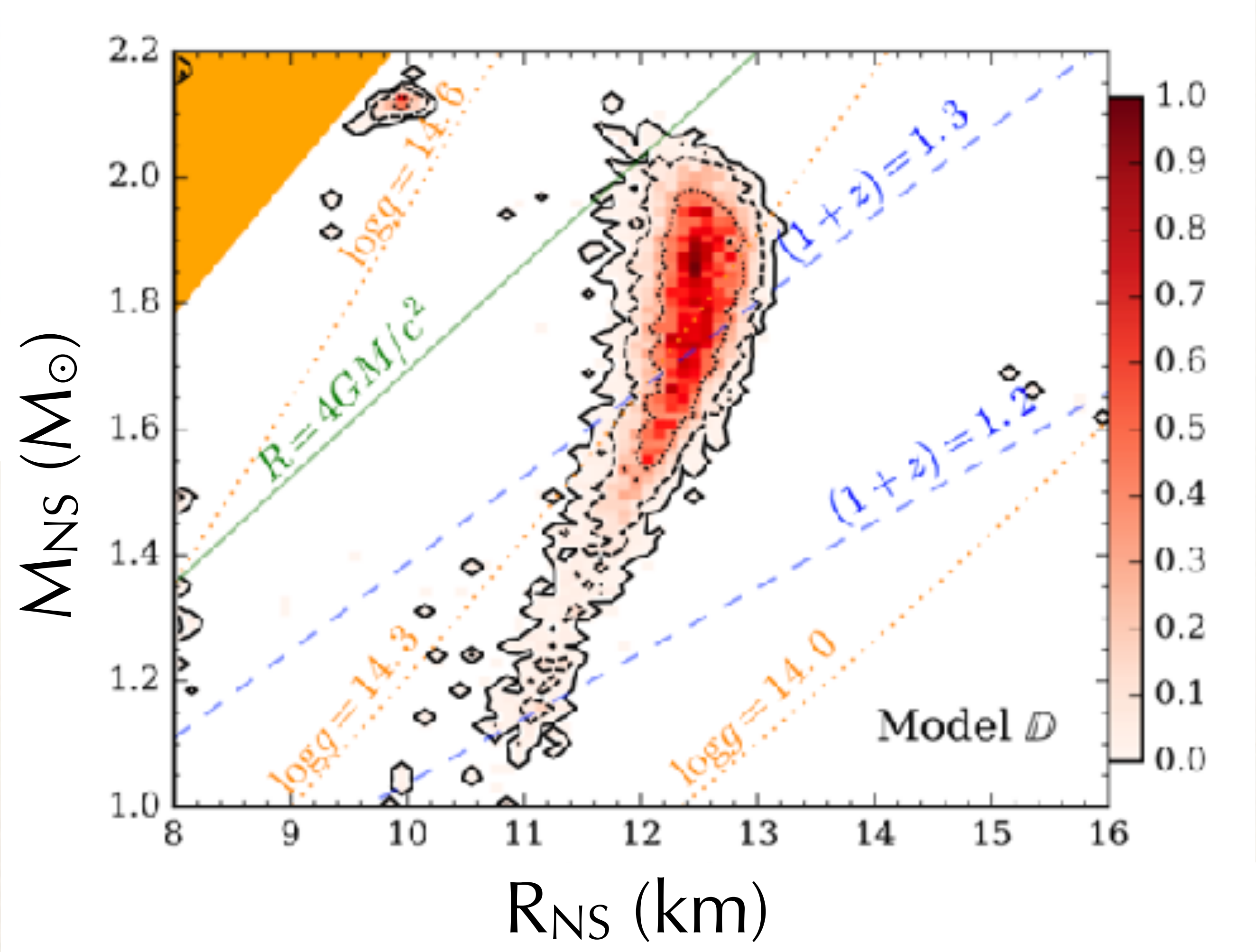
Recent developments in the field of Type I X-ray bursts ?

1. **A new method**

The direct spectral fits with realistic models during the burst evolution avoids using color-correction factors.



Burst from 4U 1702–429



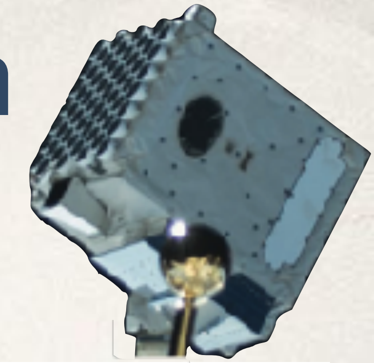
Nattila et al. 2017

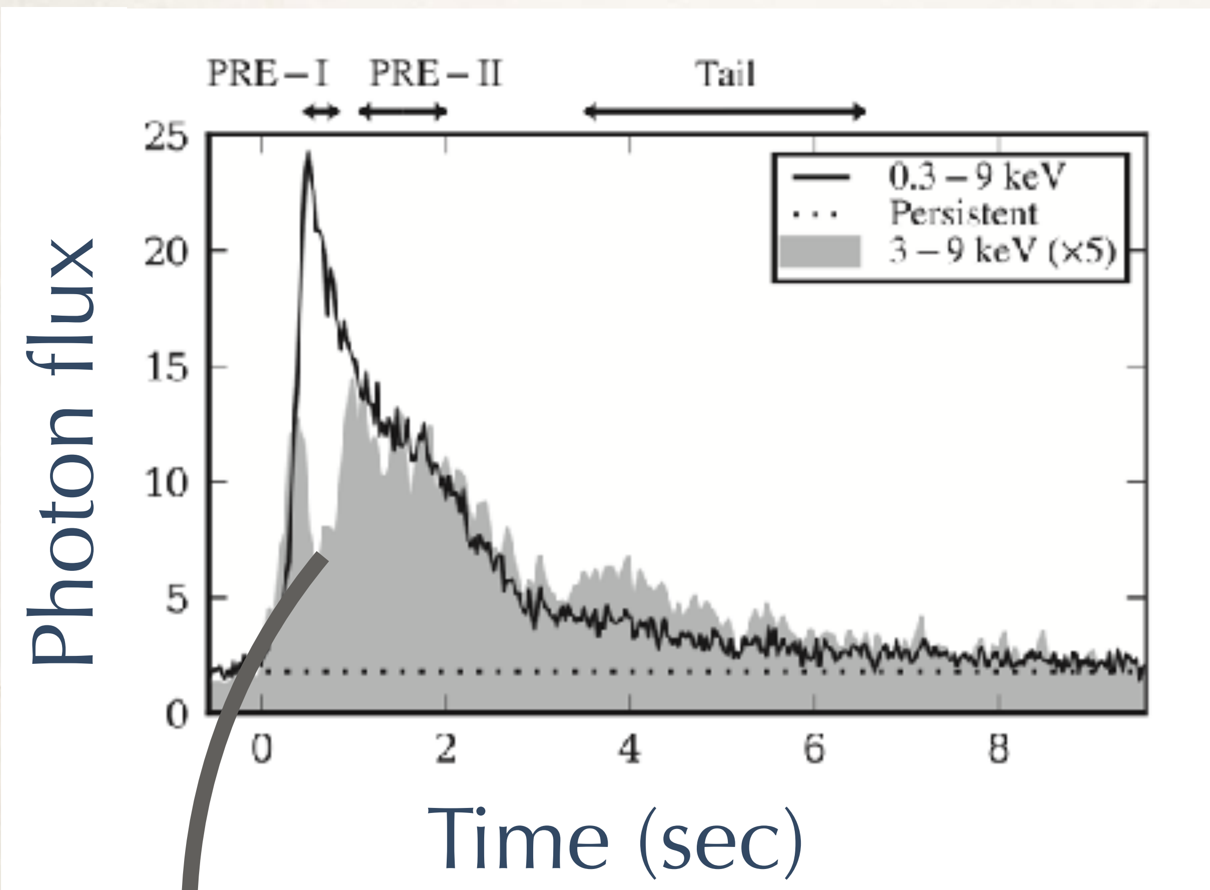
Recent developments in the field of Type I X-ray bursts ?

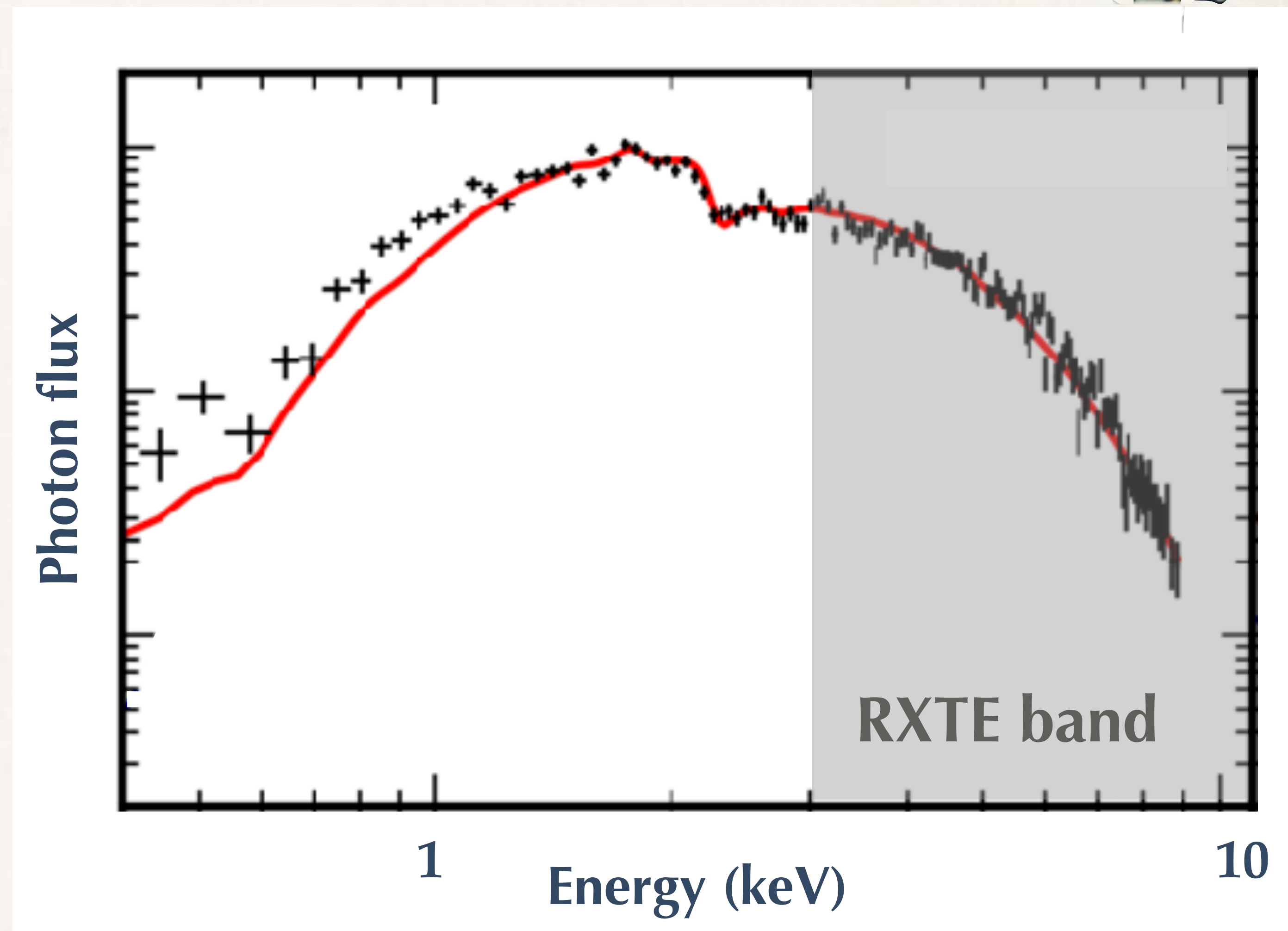
1. **A new method**

2. **A new instrument**

The observation of type I X-ray bursts with NICER shows the whole burst evolution in the soft X-ray band.







Keek et al. (2018)

In the RXTE band, the drop in flux comes from the temperature drop as the photosphere expands. With its 0.3–10 keV range, NICER sees the full evolution

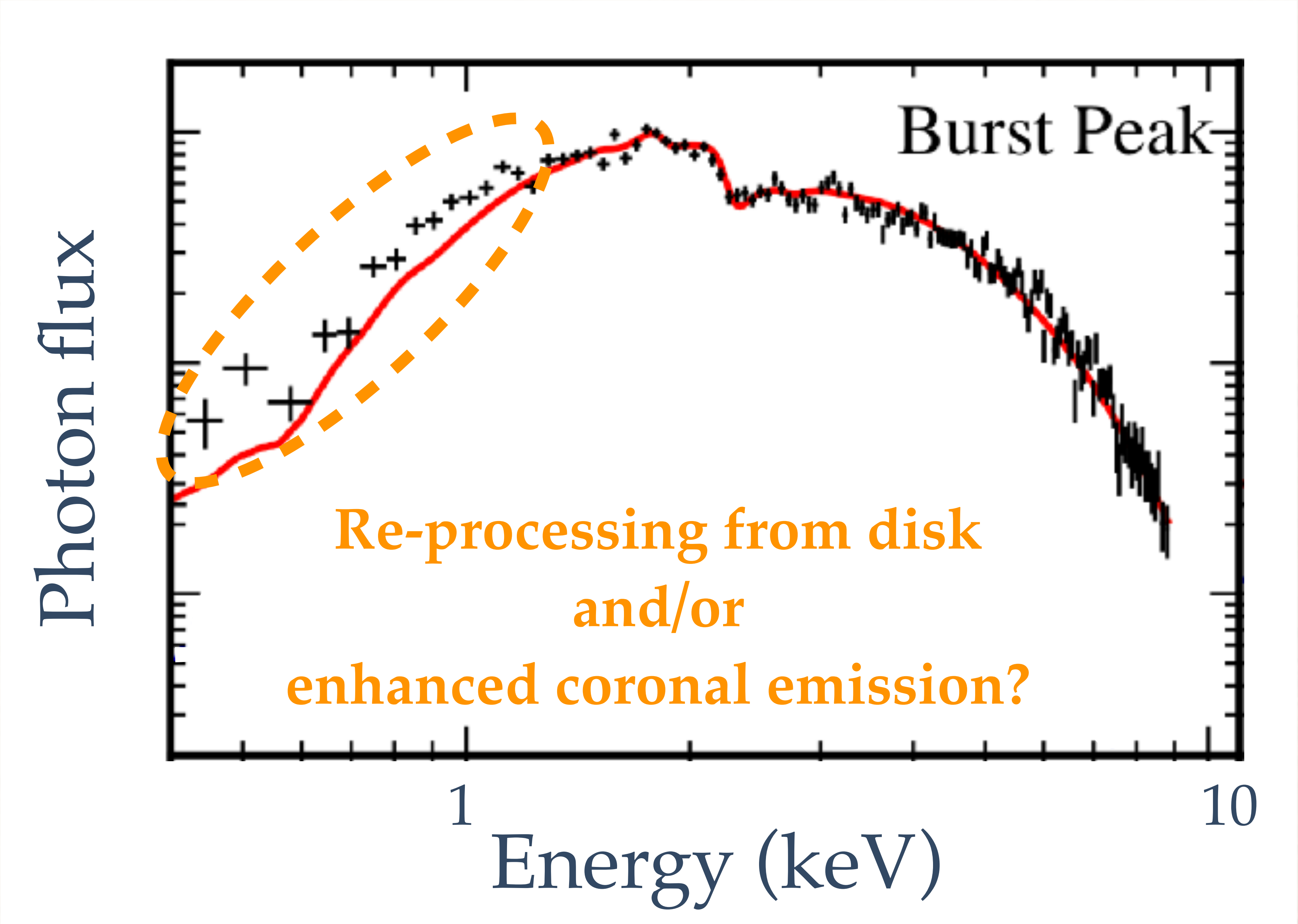
Recent developments in the field of Type I X-ray bursts ?

1. **A new method**

2. **A new instrument**

3. **A new problem**

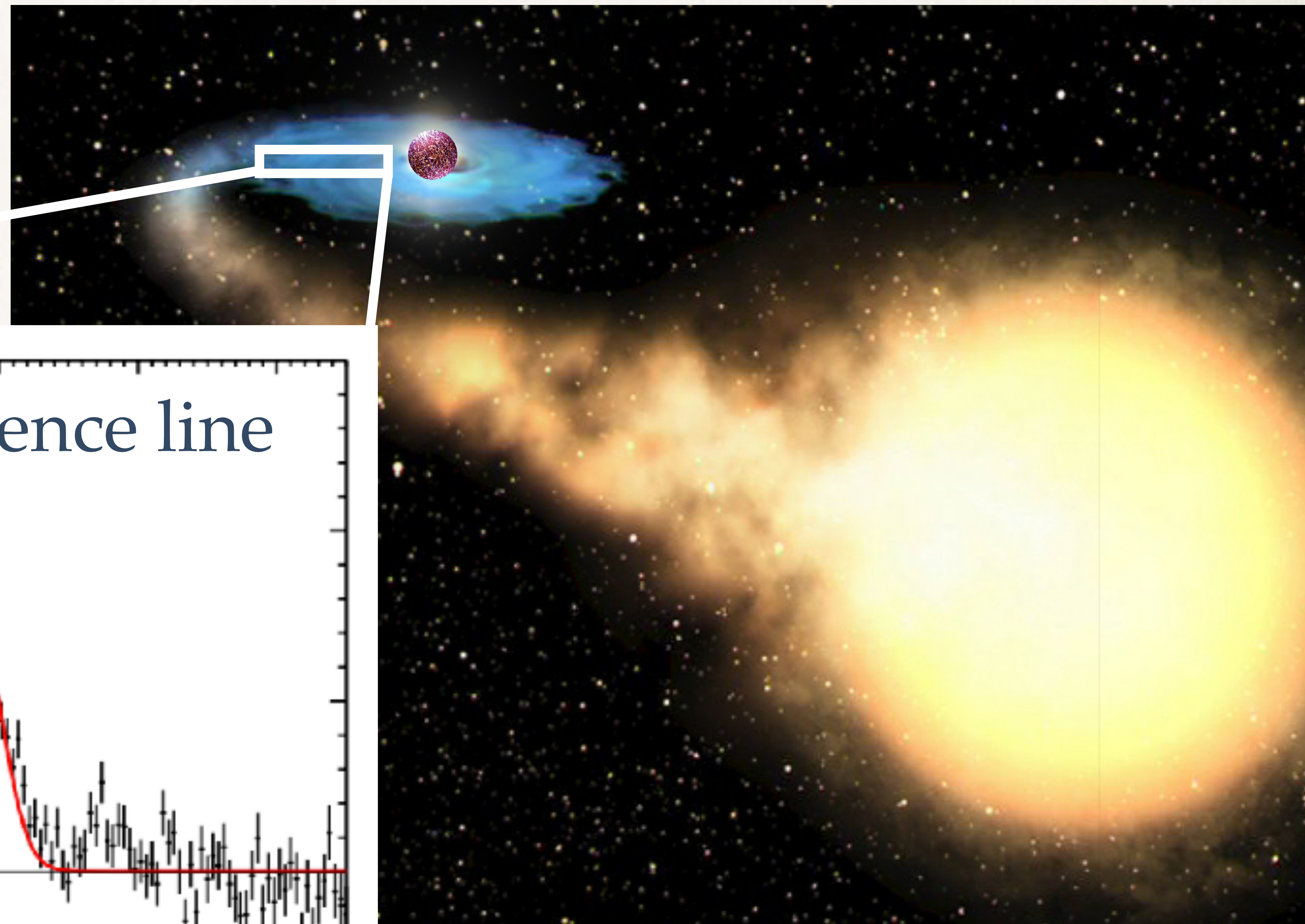
But NICER observations of type I X-ray burst also showed the presence of a un-modelled excess at low energies.

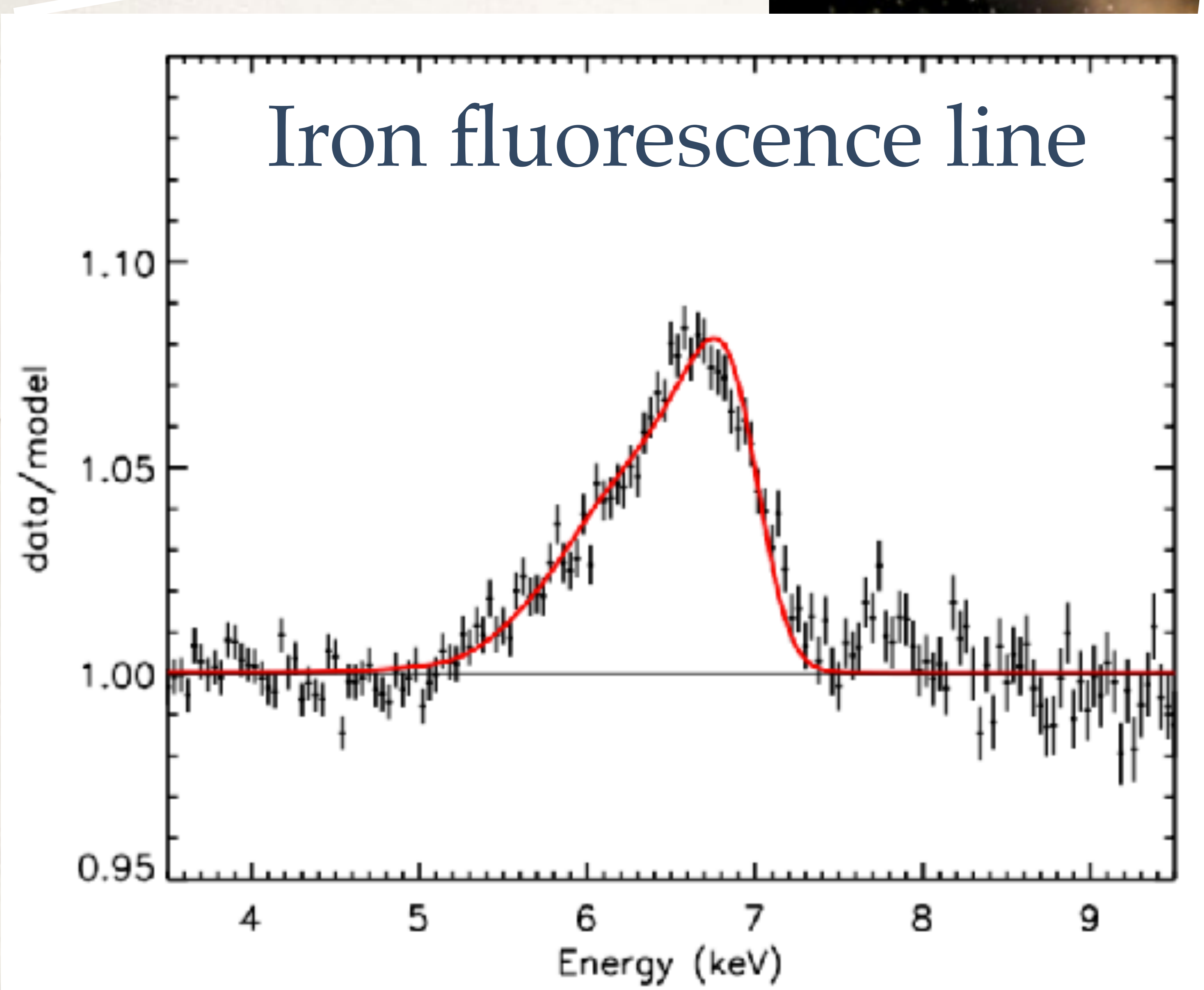


Keek et al. 2018

Güver et al. 2021, 2022

<u>Bonus slide</u>: The inner extent of an accretion disk gives an upper limit on the neutron star size



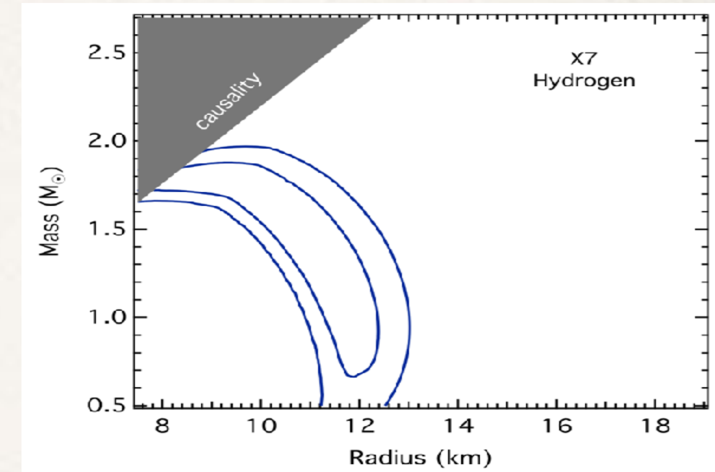


e.g., Ludlam et al. 2018, 2020

CONCLUSIONS

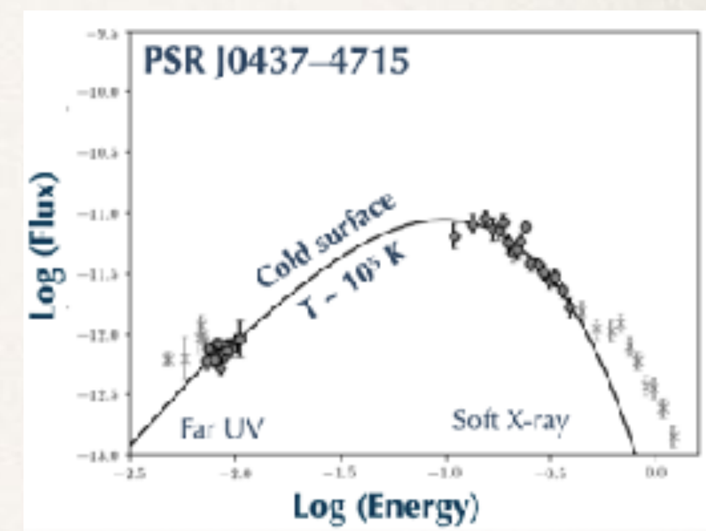
1. Quiescent Low mass X-ray binaries

   Several qLMXBs can be combined, but assumptions may bias the results



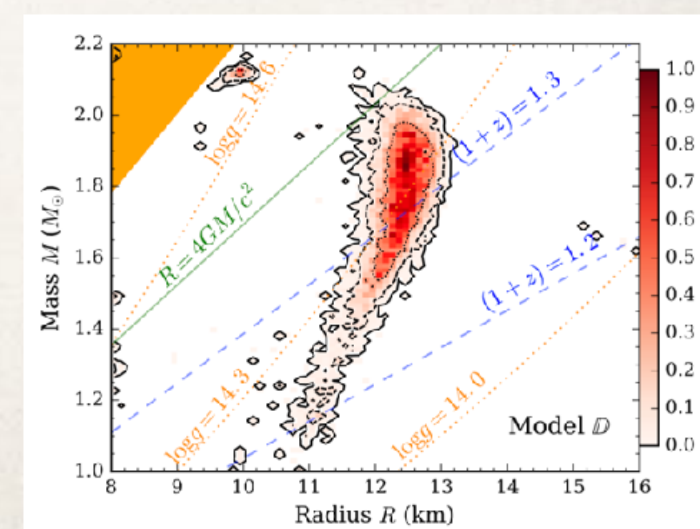
2. Cold surface of millisecond pulsars

   Only 1 MSP so far, but great potential if combined with pulse profile modelling



3. Thermonuclear bursts in X-ray binaries

   Very promising “direct spectral fit” method, but still some physical processes to clarify



There remains some discussion points and possible caveats!

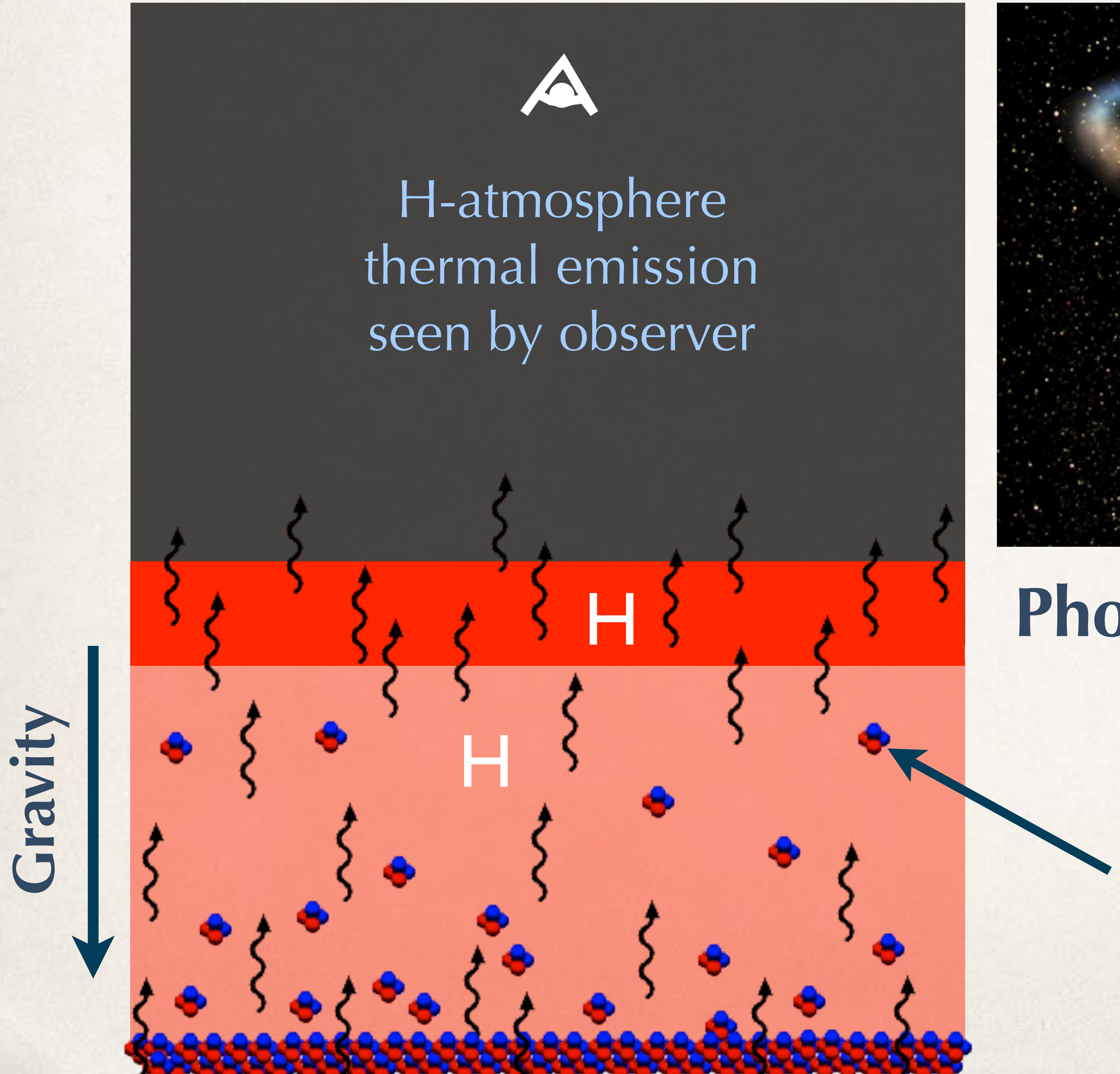
- Why only use qLMXBs in globular clusters ?

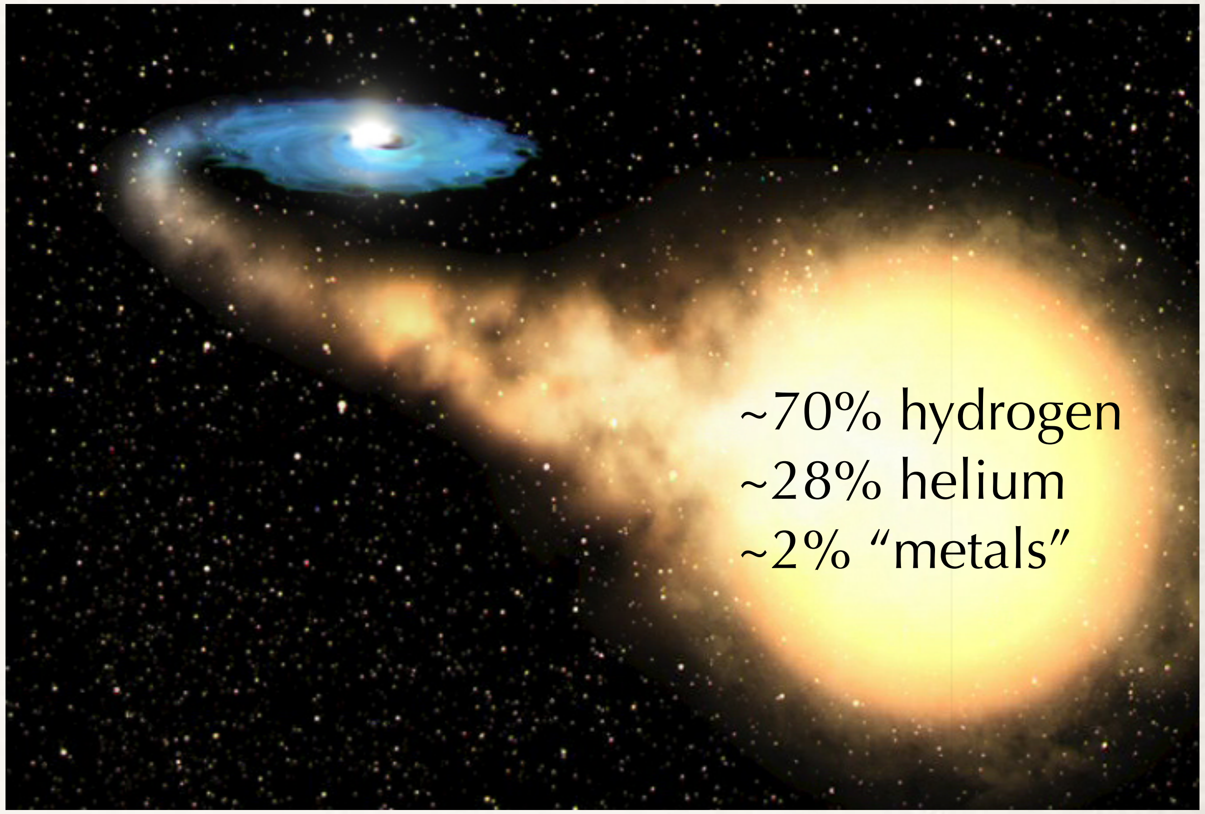
→ Field LMXB may not return to full quiescence

There remains some discussion points and possible caveats!

- Why only use qLMXBs in globular clusters ? → Field LMXB may not return to full quiescence
- What is the composition of the neutron star atmosphere ? → Hydrogen, Helium or something else

The atmospheric composition of an accreting neutron star depends on the donor star.

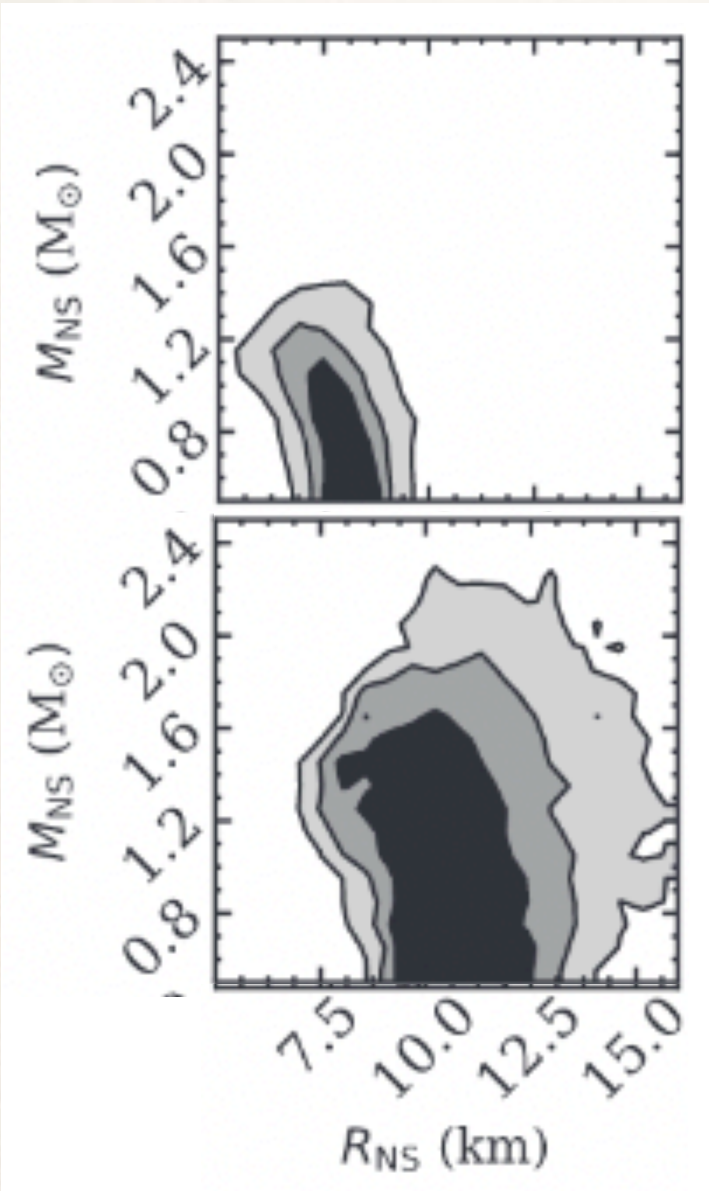




Photosphere $\lesssim$ 1 cm

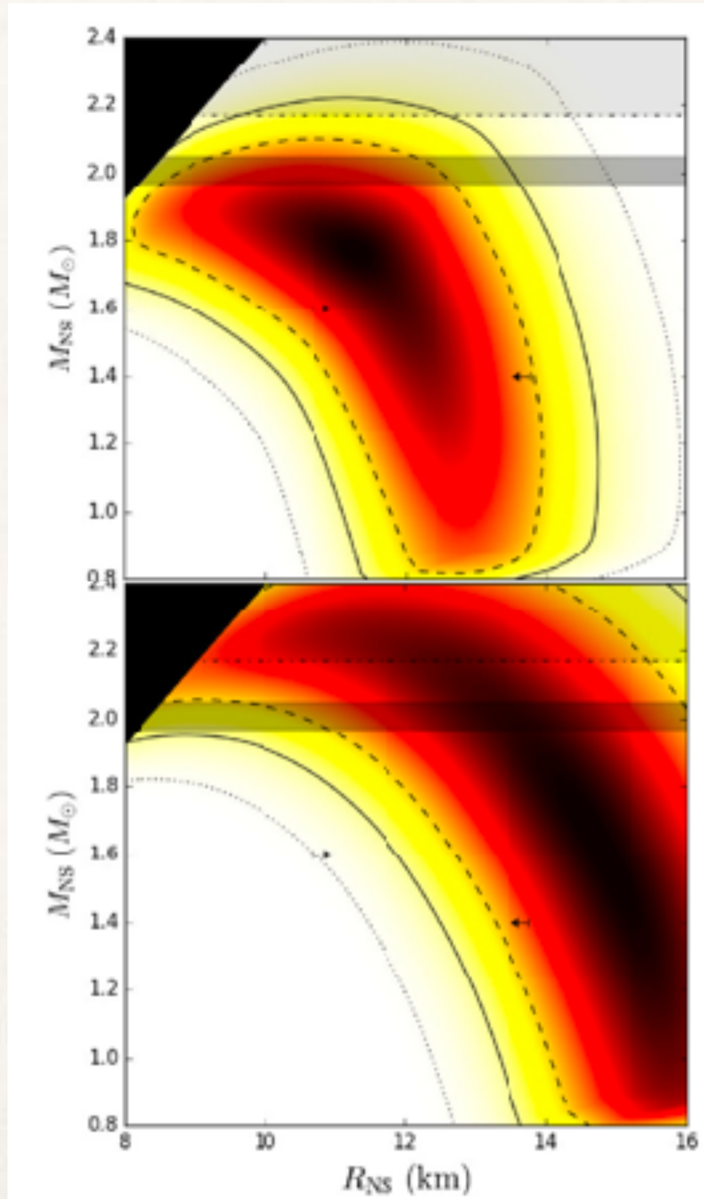
Assuming the wrong composition may severely bias the result.

qLMXB in M30



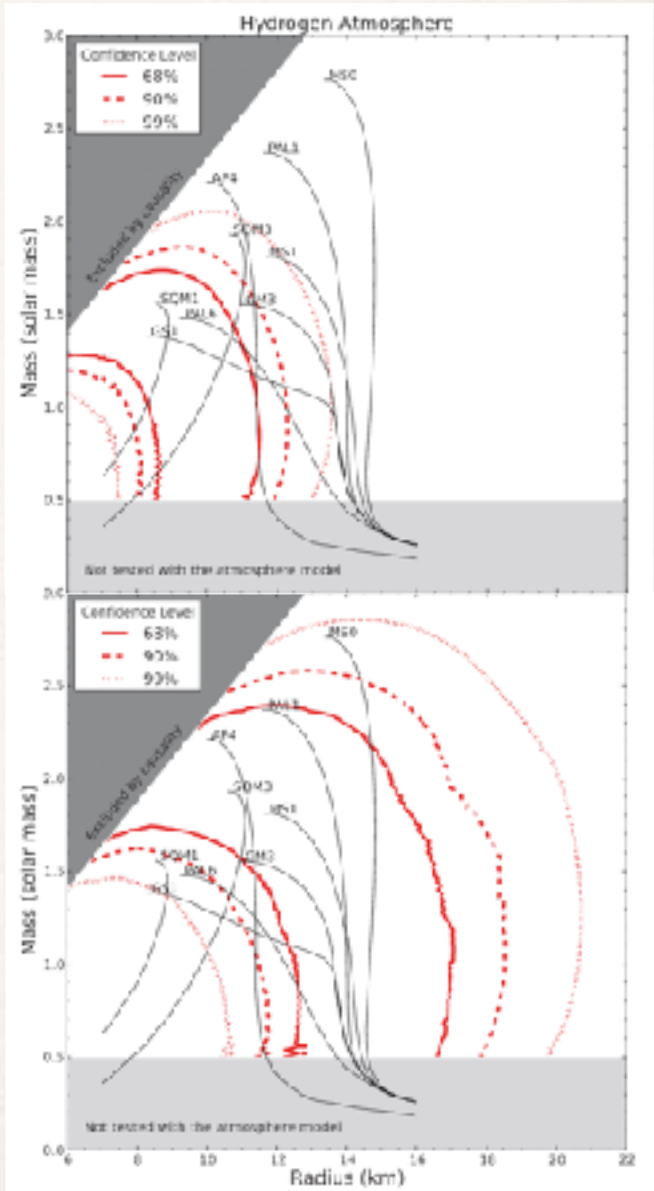
Echiburú, SG et al. 2020

qLMXB in M13



Shaw et al. 2018

qLMXB in M28



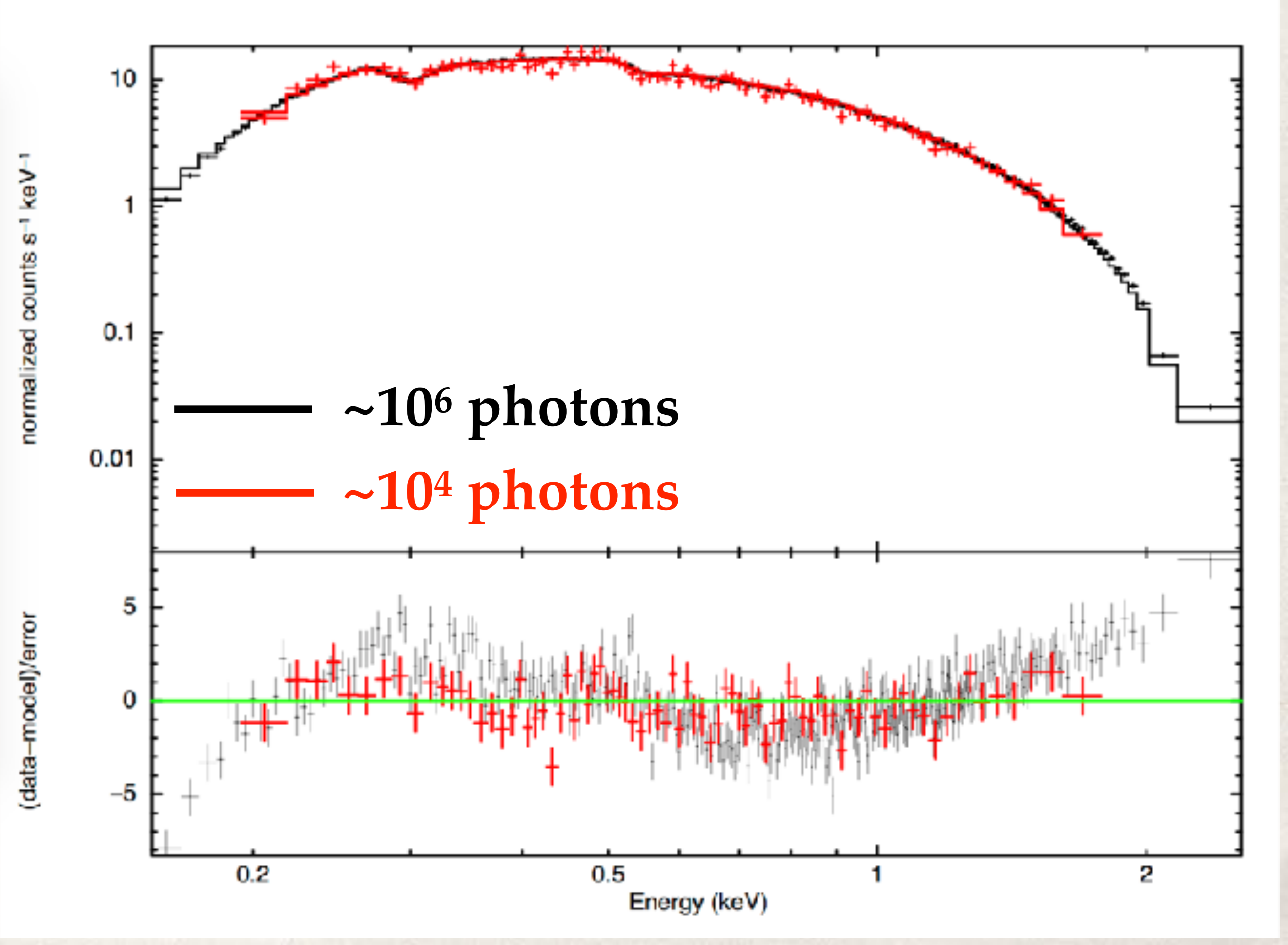
Shaw et al. 2012

Can we tell if a neutron star atmosphere is composed of H or He?

Extremely high S/N spectra permit detection of the subtle variations between H and He atmospheres

NS simulated with He-atmosphere, and fitted with H-atmosphere

Simulations for proposed mission ***Lynx***



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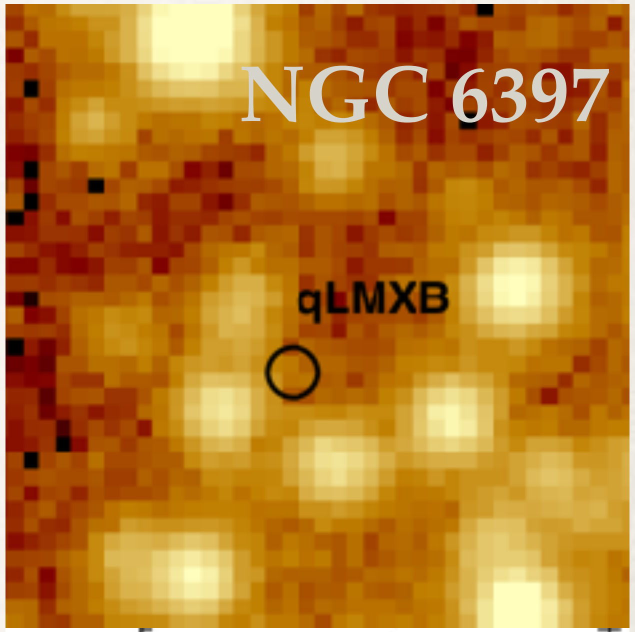
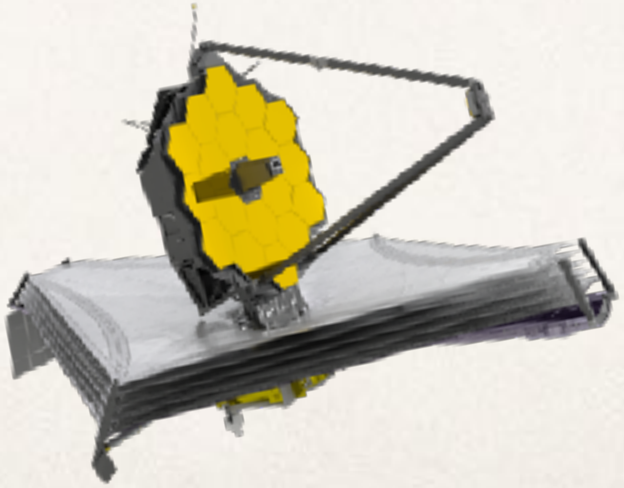
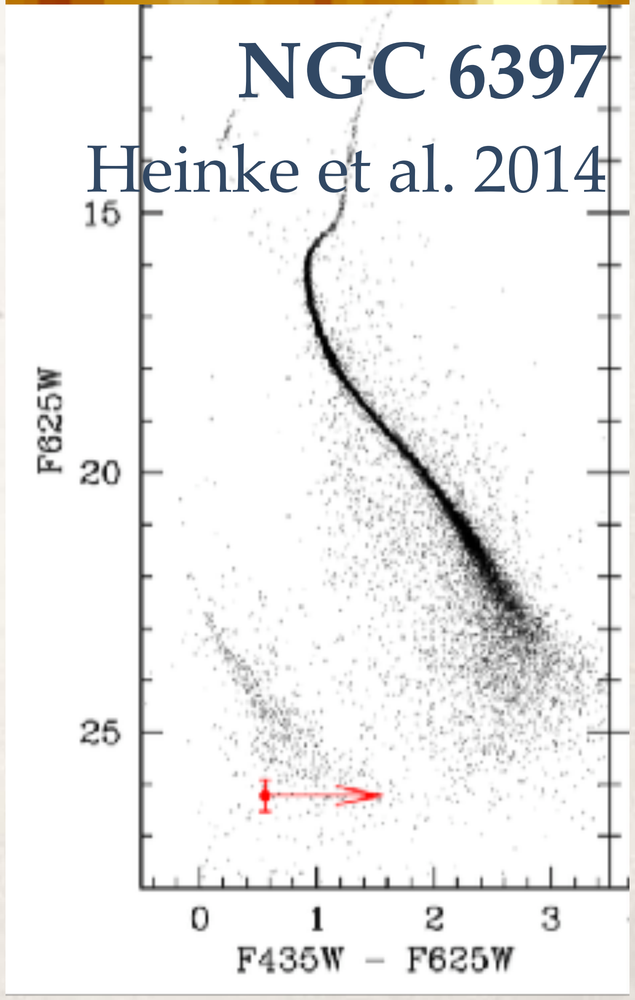


<u>Identifying the donor star in the crowded environments of globular clusters</u>

- Very difficult with ground based (e.g., VLT), even with AO
- Difficult with Hubble Space Telescope
- Easier with JWST





There remains some discussion points and possible caveats!

- Why only use qLMXBs in globular clusters ? → Field LMXB may not return to full quiescence
- What is the composition of the neutron star atmosphere ? → Hydrogen, Helium or something else
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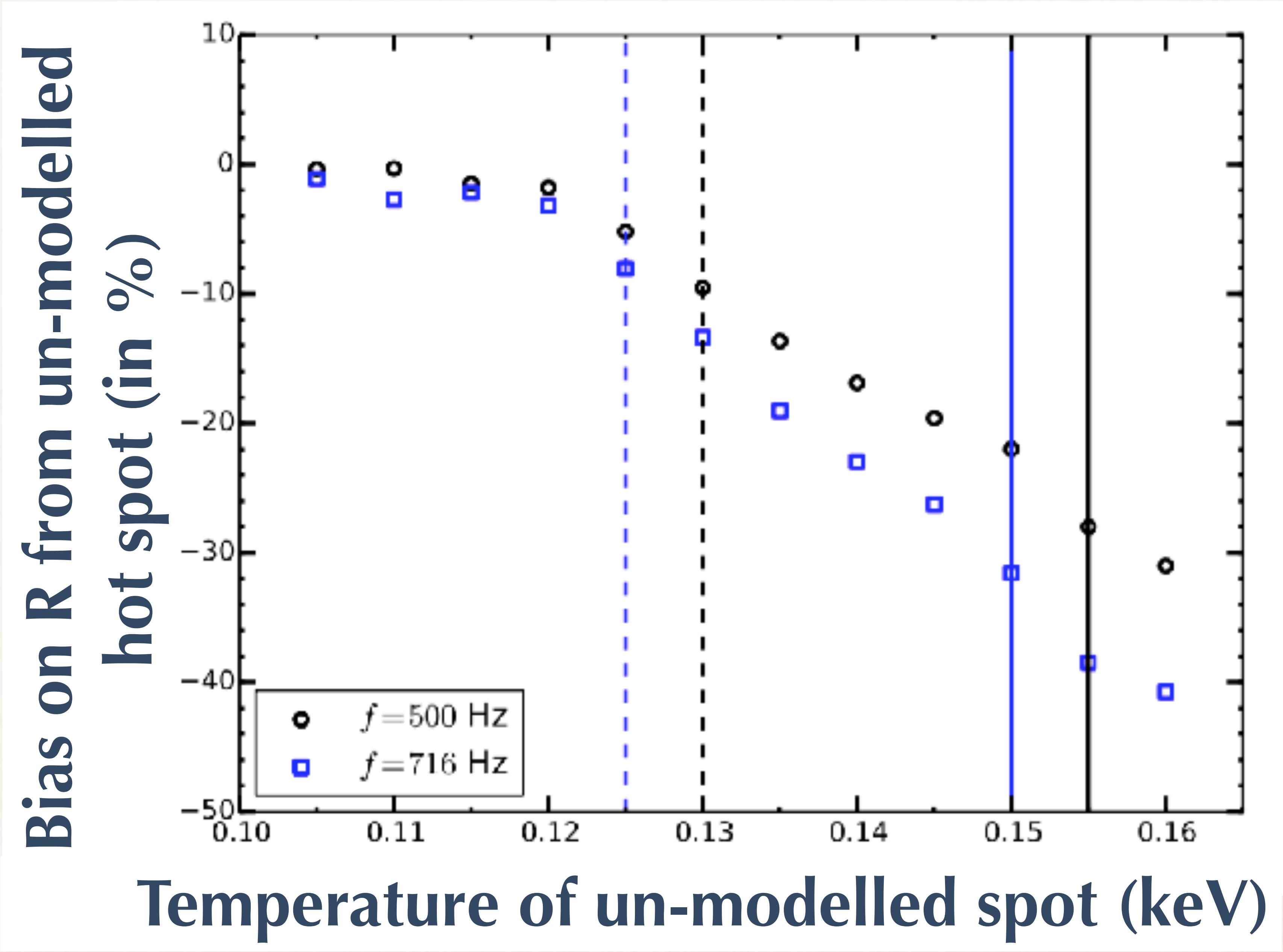
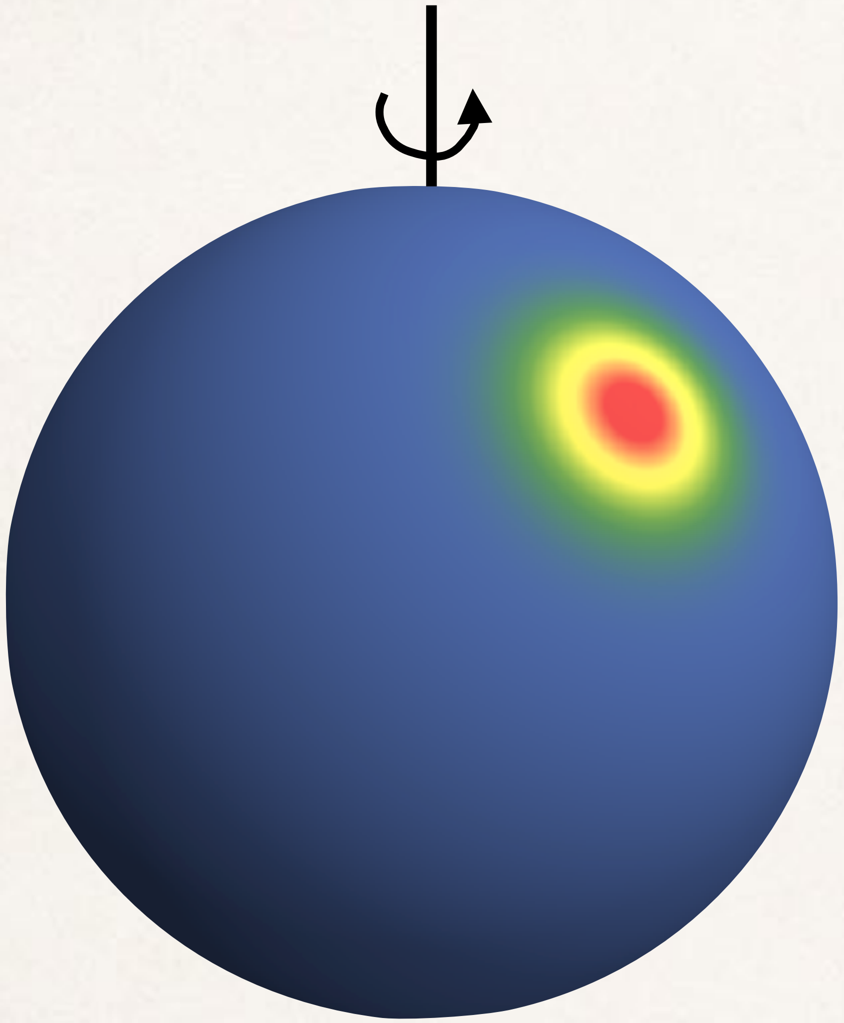
- Is the emission really from the entire surface ? → No constraints exist, but …

Assuming a uniform surface temperature may bias the radius measurement.

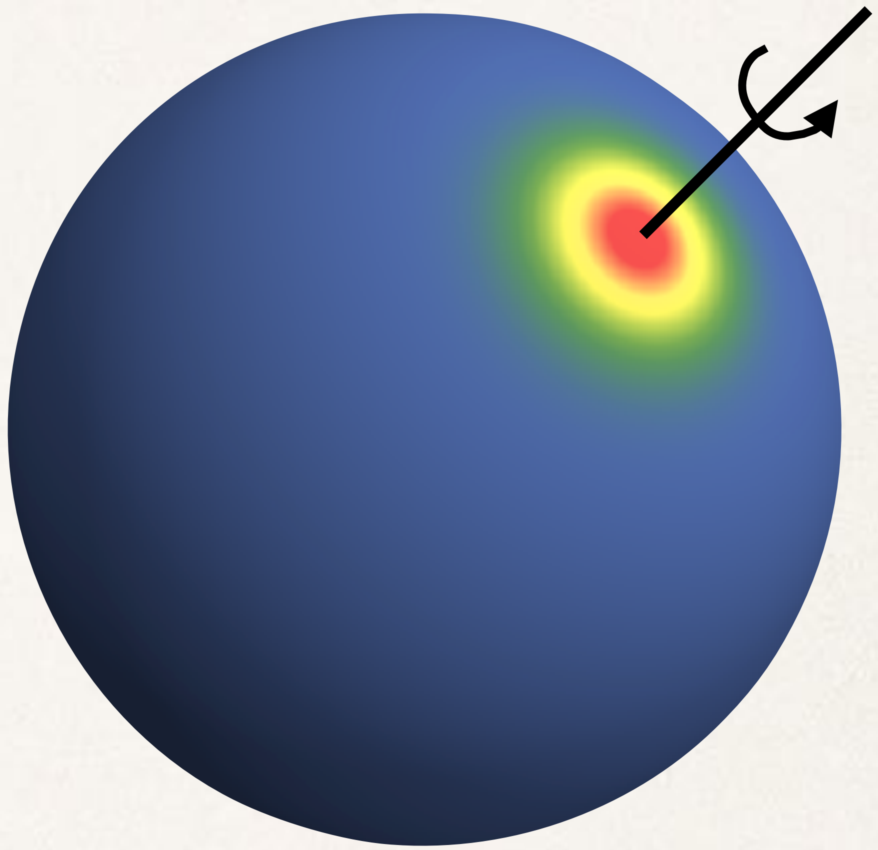


Elshamouty et al. 2016

Can we tell whether the surface temperature is uniform or not?



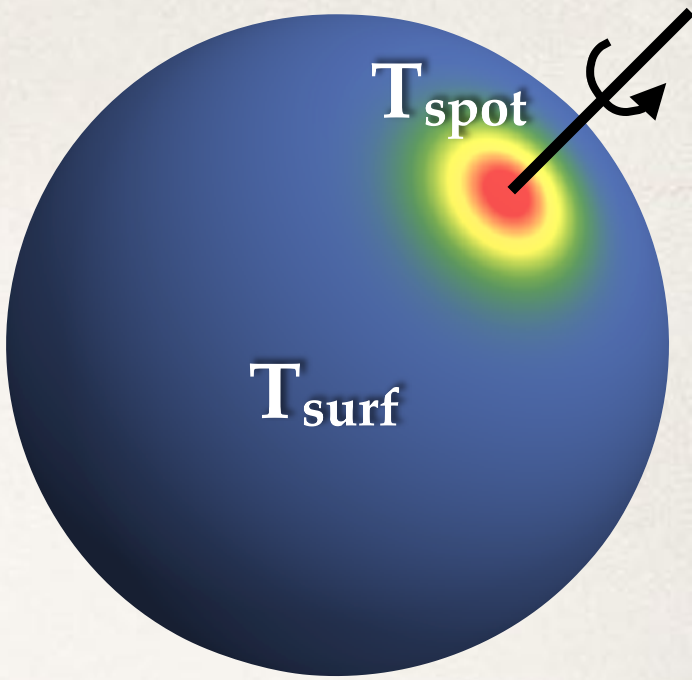
Non-uniform surface manifests as X-ray pulsations

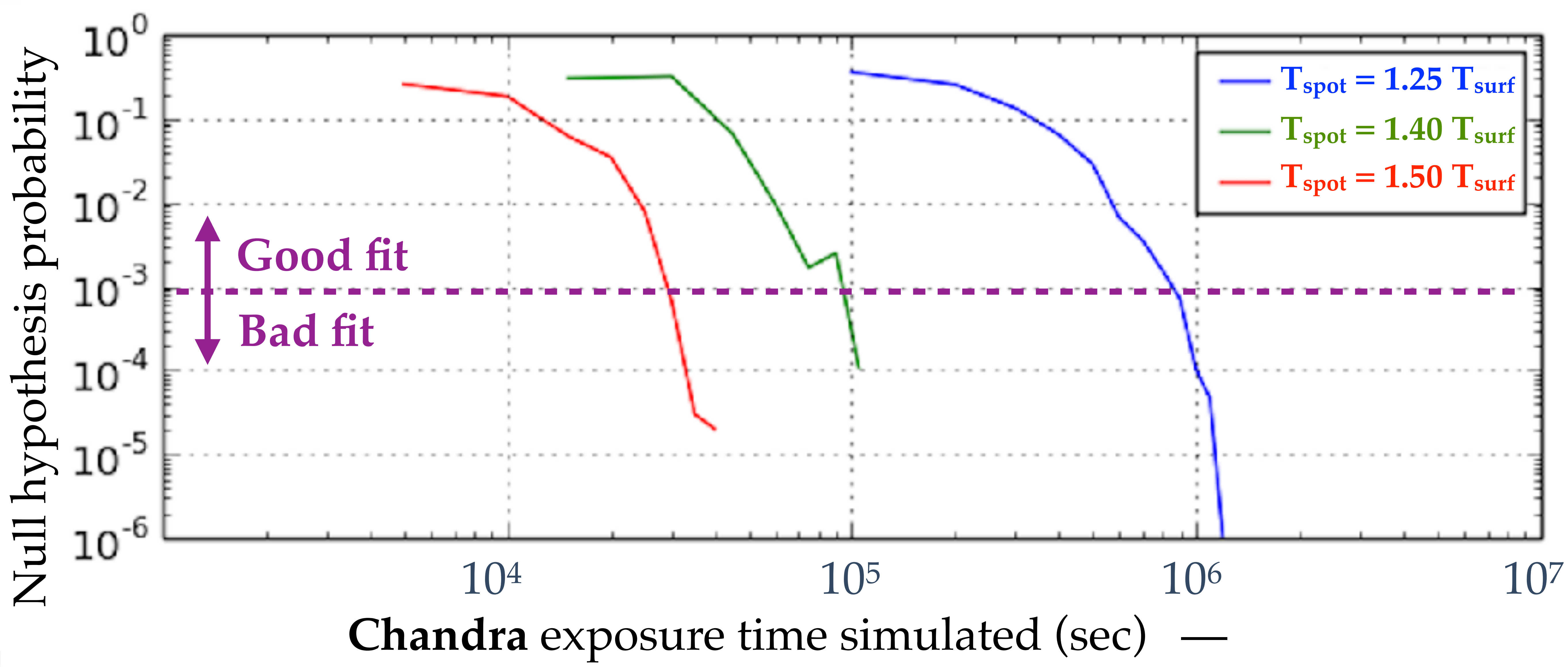


No X-ray pulsations for some specific geometries

Can we tell from the X-ray spectra?

A hot spot that does not generate X-ray pulsations may be detected spectrally.





Simulations by Goran Doll Carriel

There remains some discussion points and possible caveats!

- Why only use qLMXBs in globular clusters ? → Field LMXB may not return to full quiescence
- What is the composition of the neutron star atmosphere ? → Hydrogen, Helium or something else
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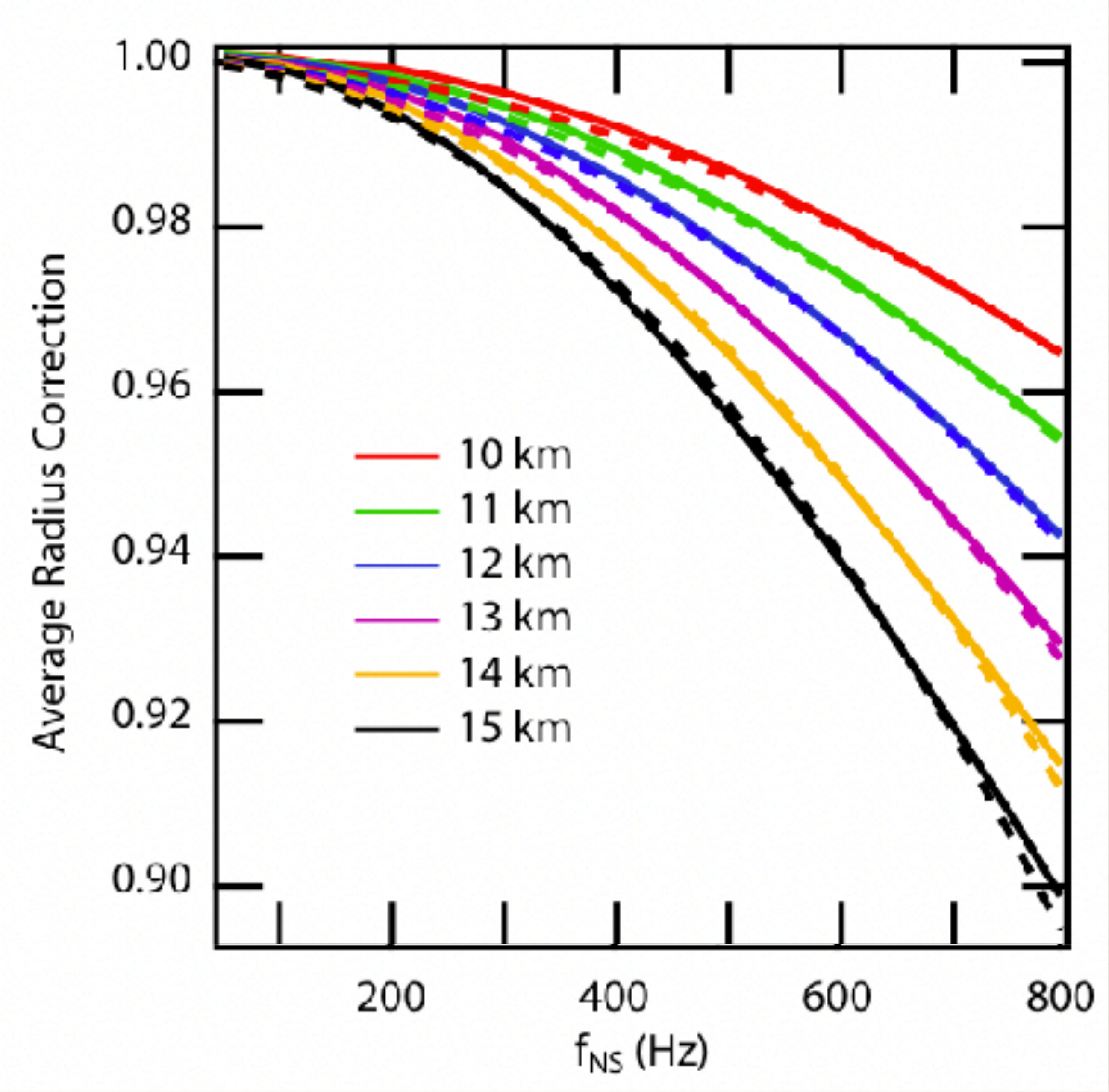
- Is the emission really from the entire surface ? → No constraints exist, but …
- What are the effects of assuming slowly rotating neutron stars? → Fast rotation may bias the R measurement

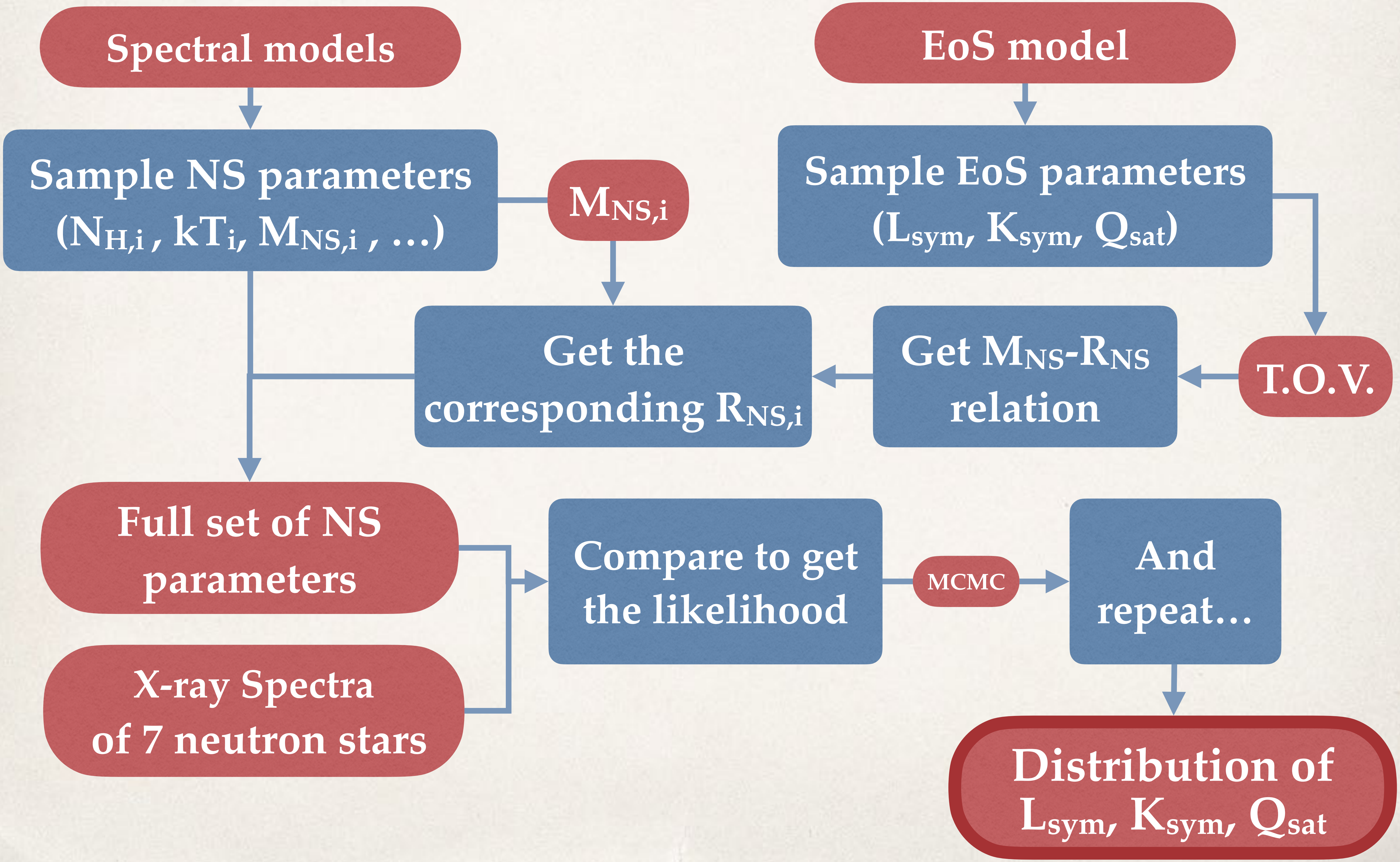
Rotation broadens the spectrum and neglecting it may bias the radius.

- No measurement of spin in qLMXB since no X-ray or radio pulsations.
- Other LMXBs have spin frequencies in the range ~200–600 Hz
- Ignoring rotation will bias the radius by a few % at most for a 12 km NS



Bauböck et al. 2015

The MCMC samples the parameters space to fits the observed X-ray spectra.



The ATHENA X-ray Observatory will drastically improve constraints!

$$\left.\frac{\Delta R_{\rm NS}}{R_{\rm NS}}\right|_{1.4\,M_\odot} = \pm 1.7\%$$

R-SCIOBJ-331

*"Athena shall constrain the equation of state of neutron stars by obtaining X-ray spectra of **seven quiescent low mass X-ray binaries** with a good distance estimate."*