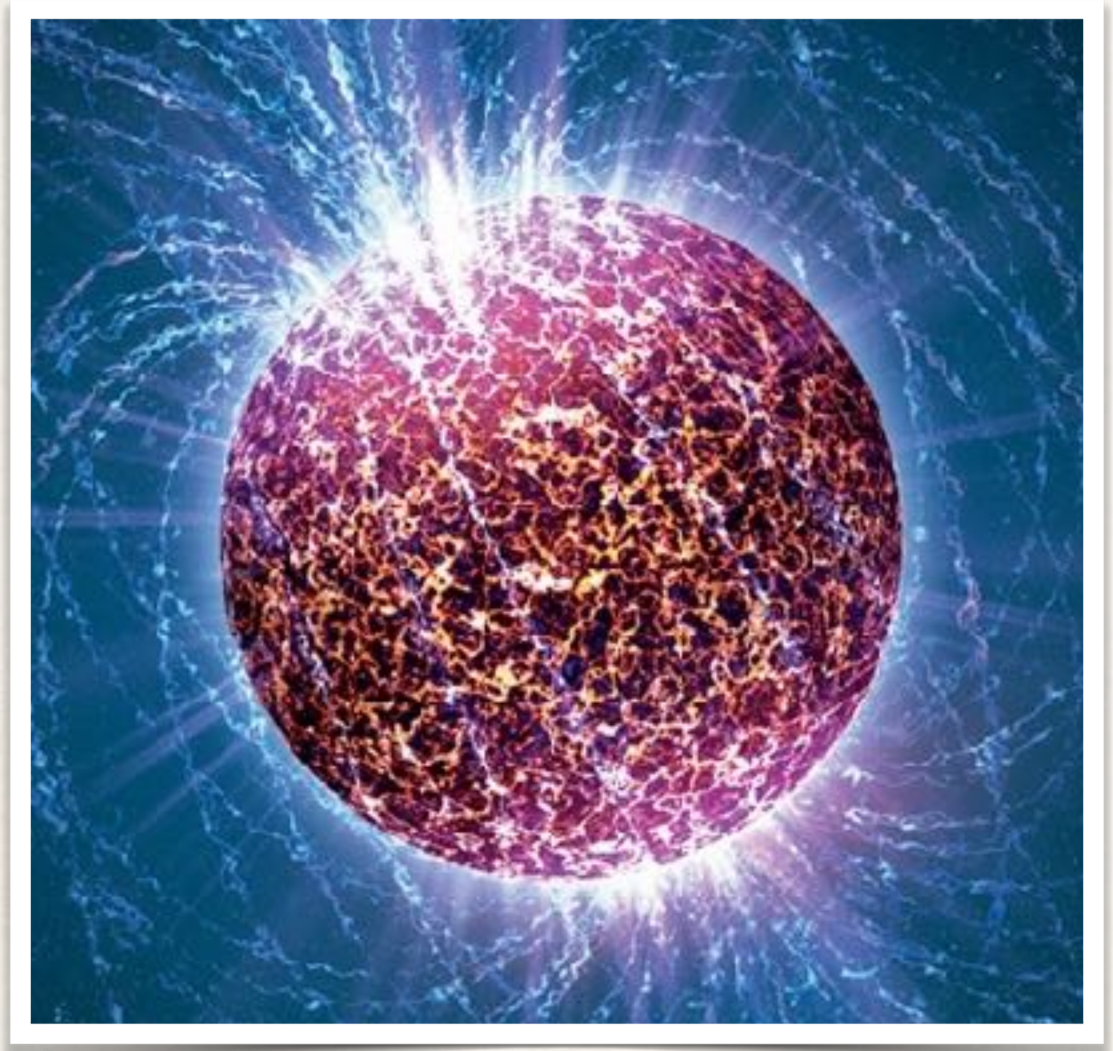
Constraining nuclear physics parameters L_{sym}, K_{sym} and Q_{sat} from astrophysical data

Based on paper: Baillot d'Etivaux, SG, JM et al. 2019



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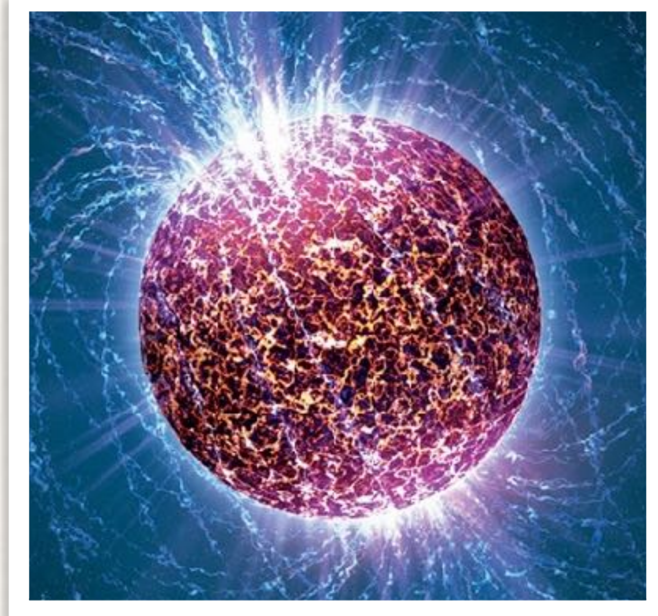
Measuring the radius precisely is rather difficult for neutron stars.



To measure the radius, we need to:

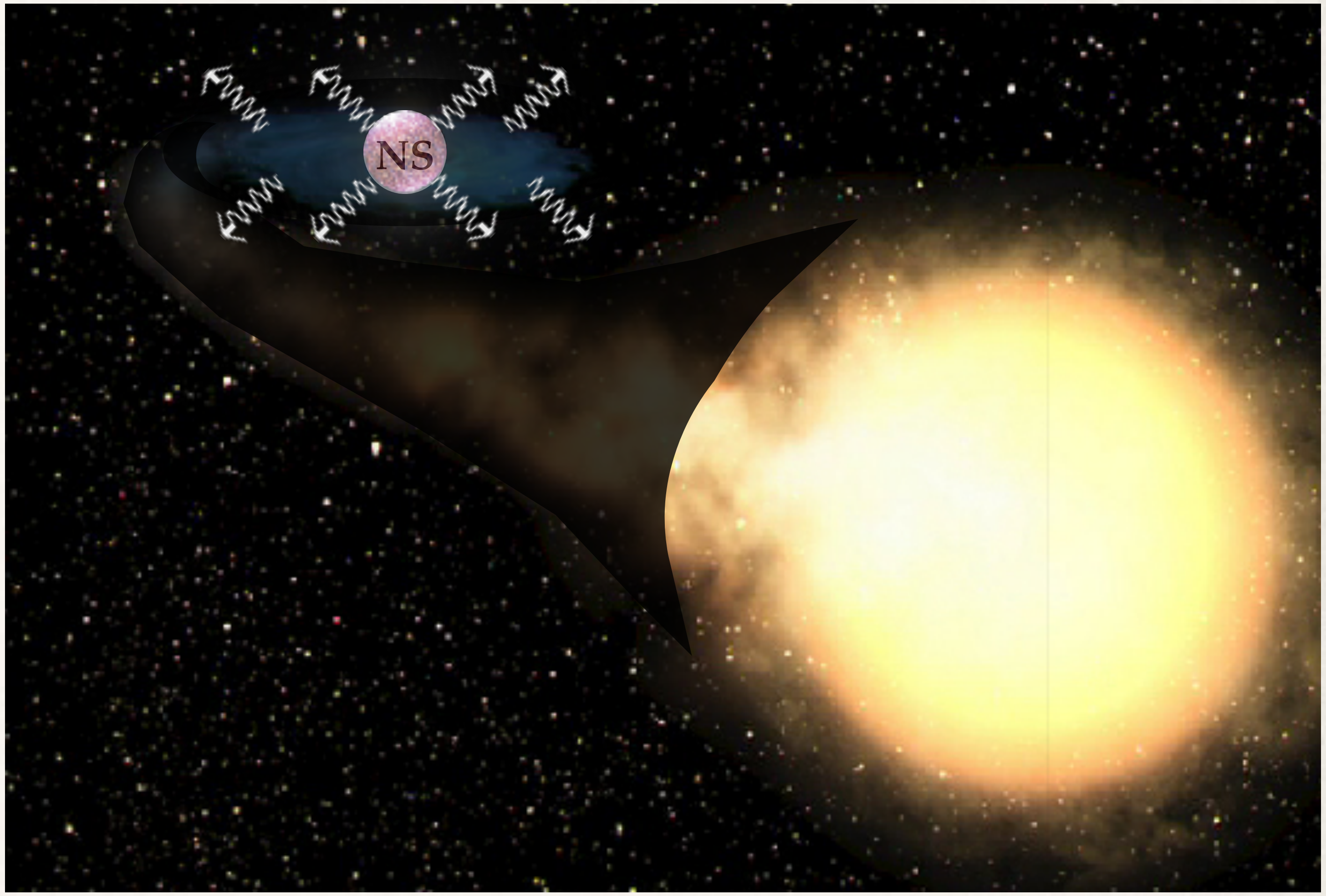
- observe the surface thermal emission,
- correctly model this emission,
- know the distance independently.

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

Neutron stars
in quiescent low-mass X-ray binaries

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

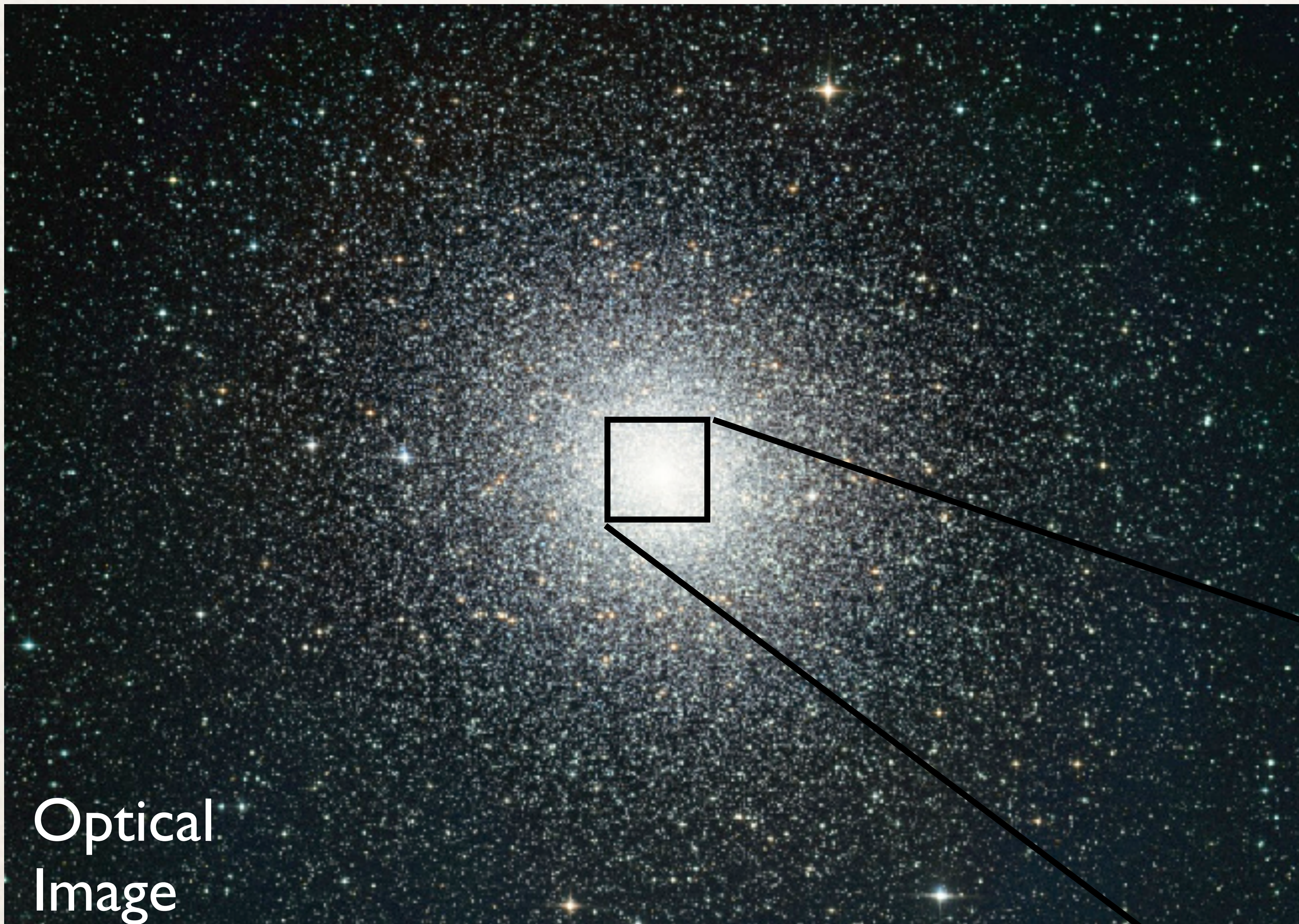
Surface thermal emission at $T_{eff} \sim 10^6$ K, powered by residual heat from the deep crust radiating outwards through the **atmosphere** with $L_X = 10^{32\text{-}33}$ erg/sec

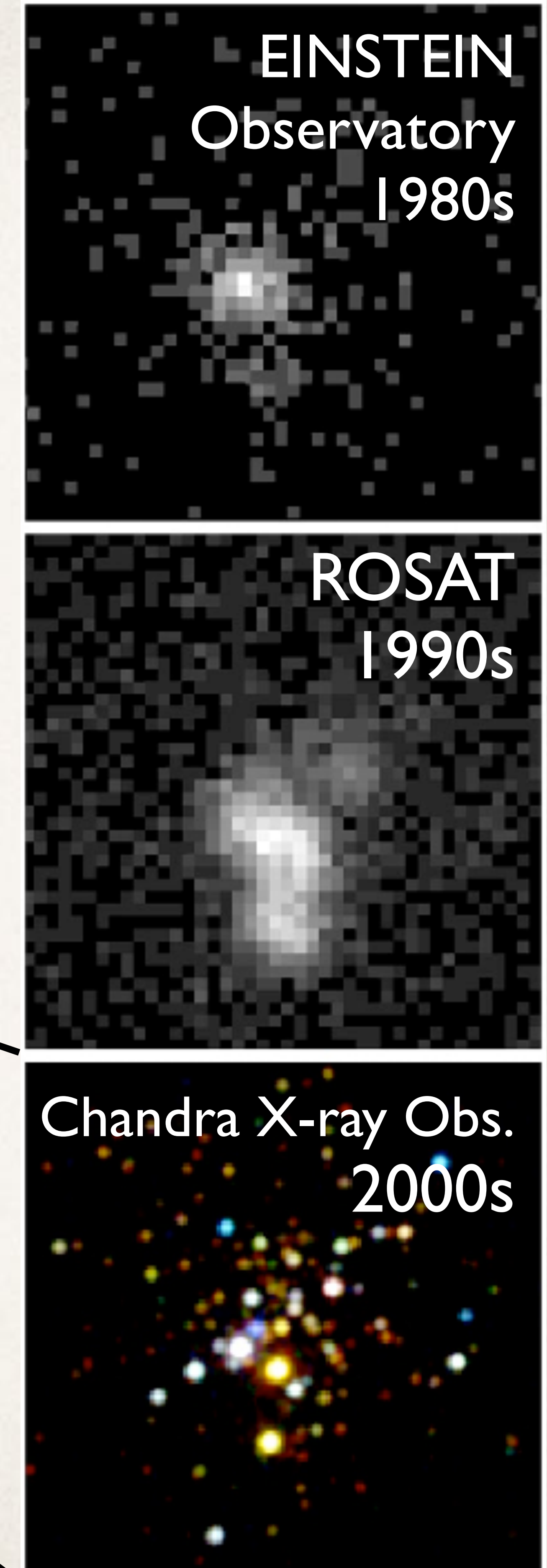


X-ray Spectral fitting of this surface emission gives us T_{eff} and $F_X \propto (R_\infty/D)^2$

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

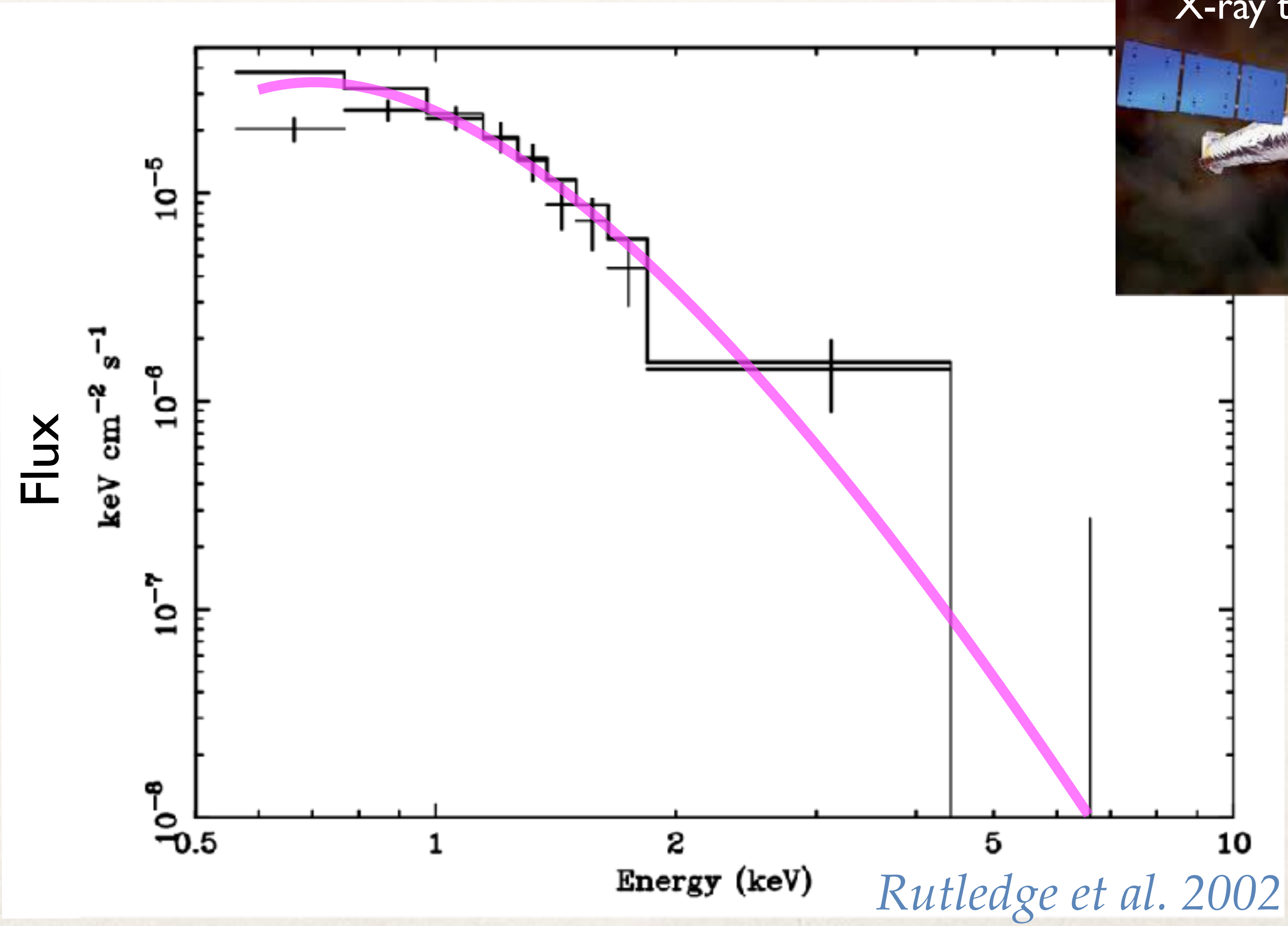
Globular clusters host an over-abundance of LMXB systems...





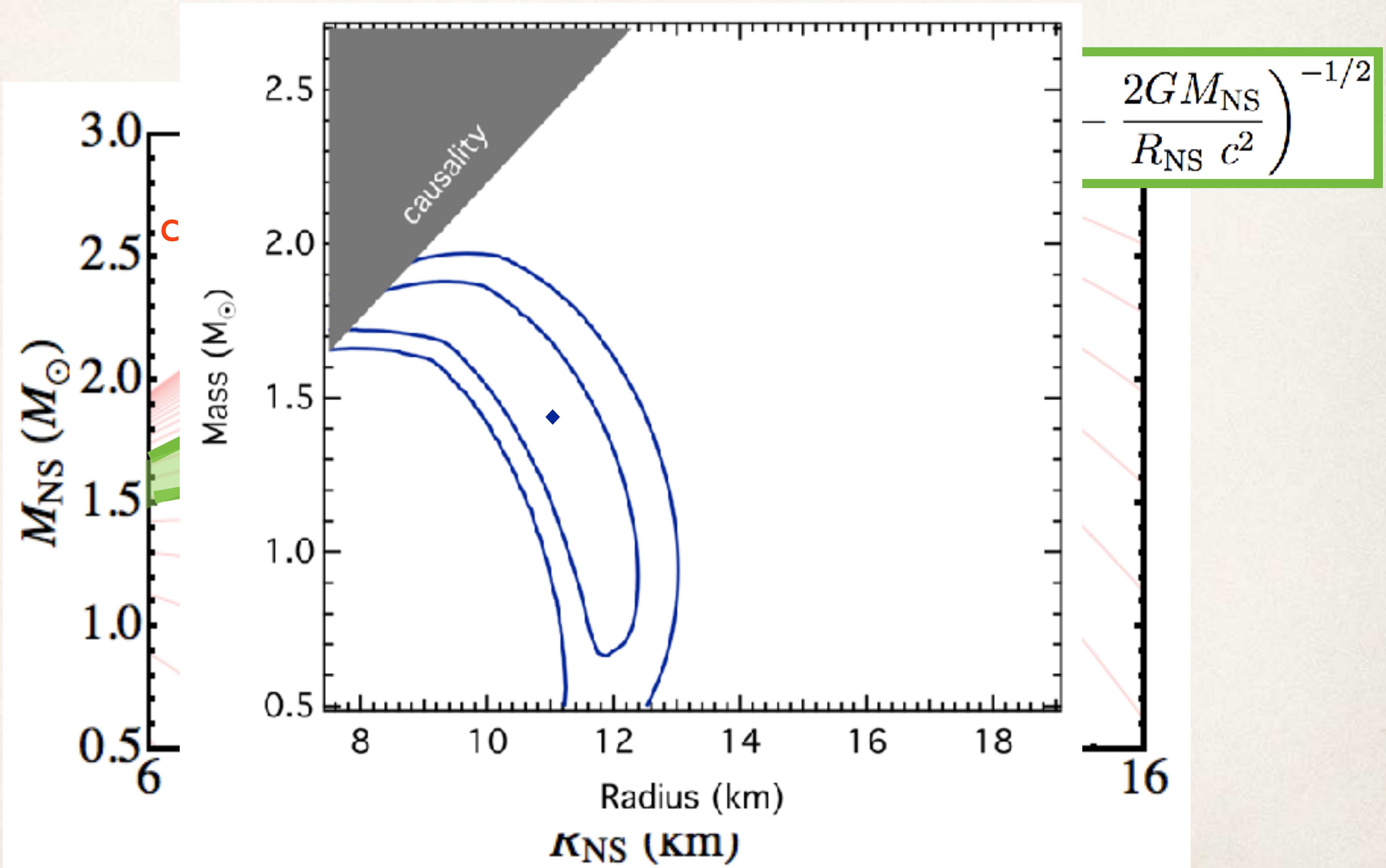
...and they have independently measured distances.

The first globular cluster qLMXB was discovered in Omega Centauri.

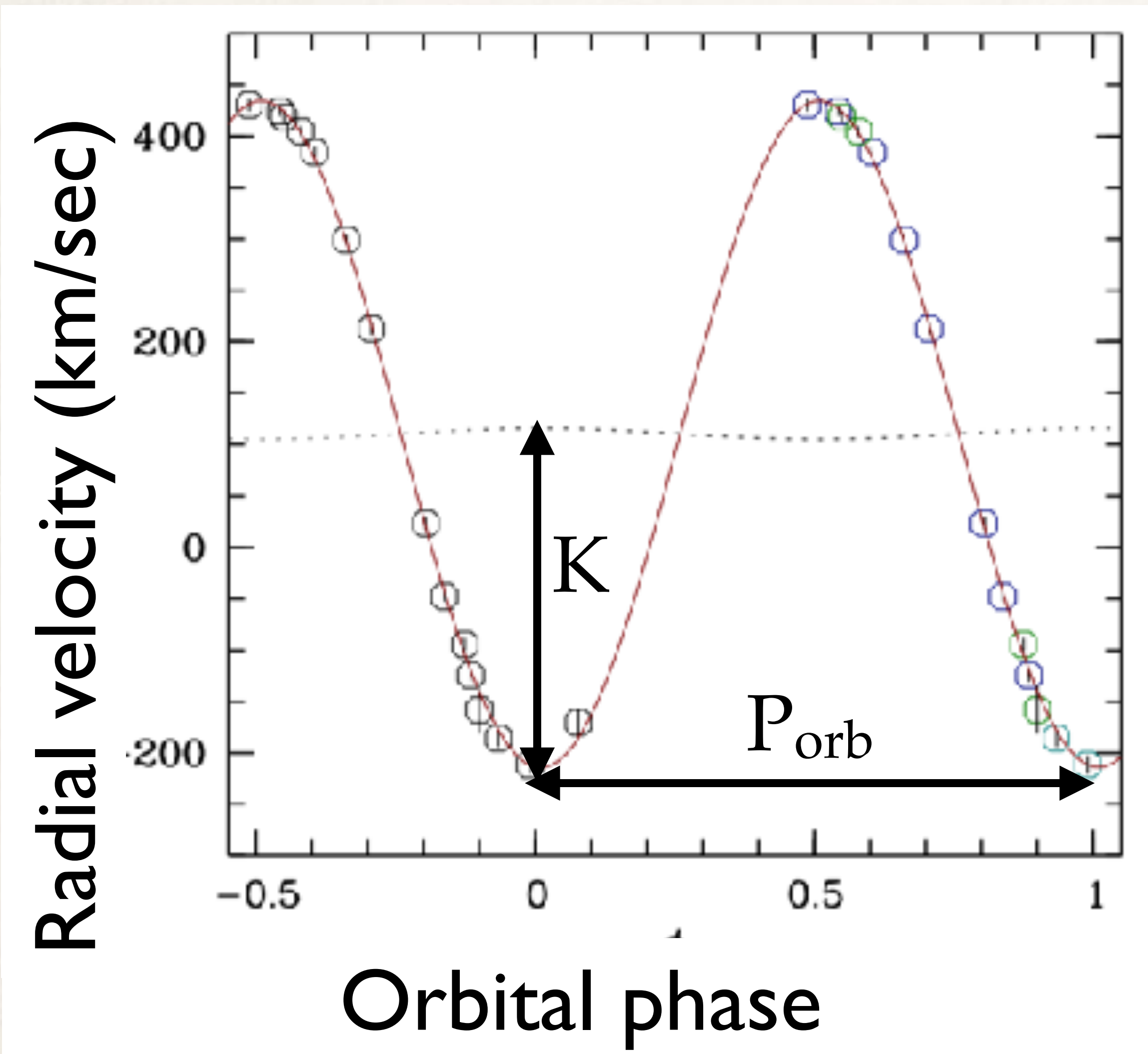


Rutledge et al. 2002

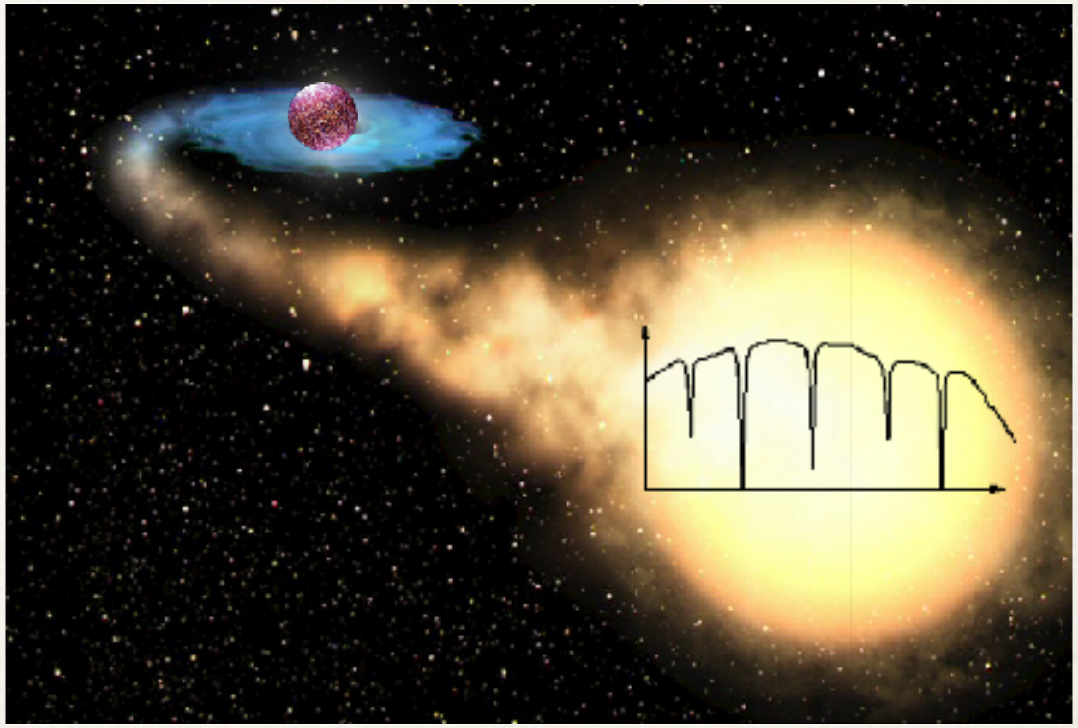
Because of gravitational redshift, the radius is degenerate with the unknown mass.



The degeneracy between M_{NS} and R_{NS} can be broken by measuring M_{NS} independently.

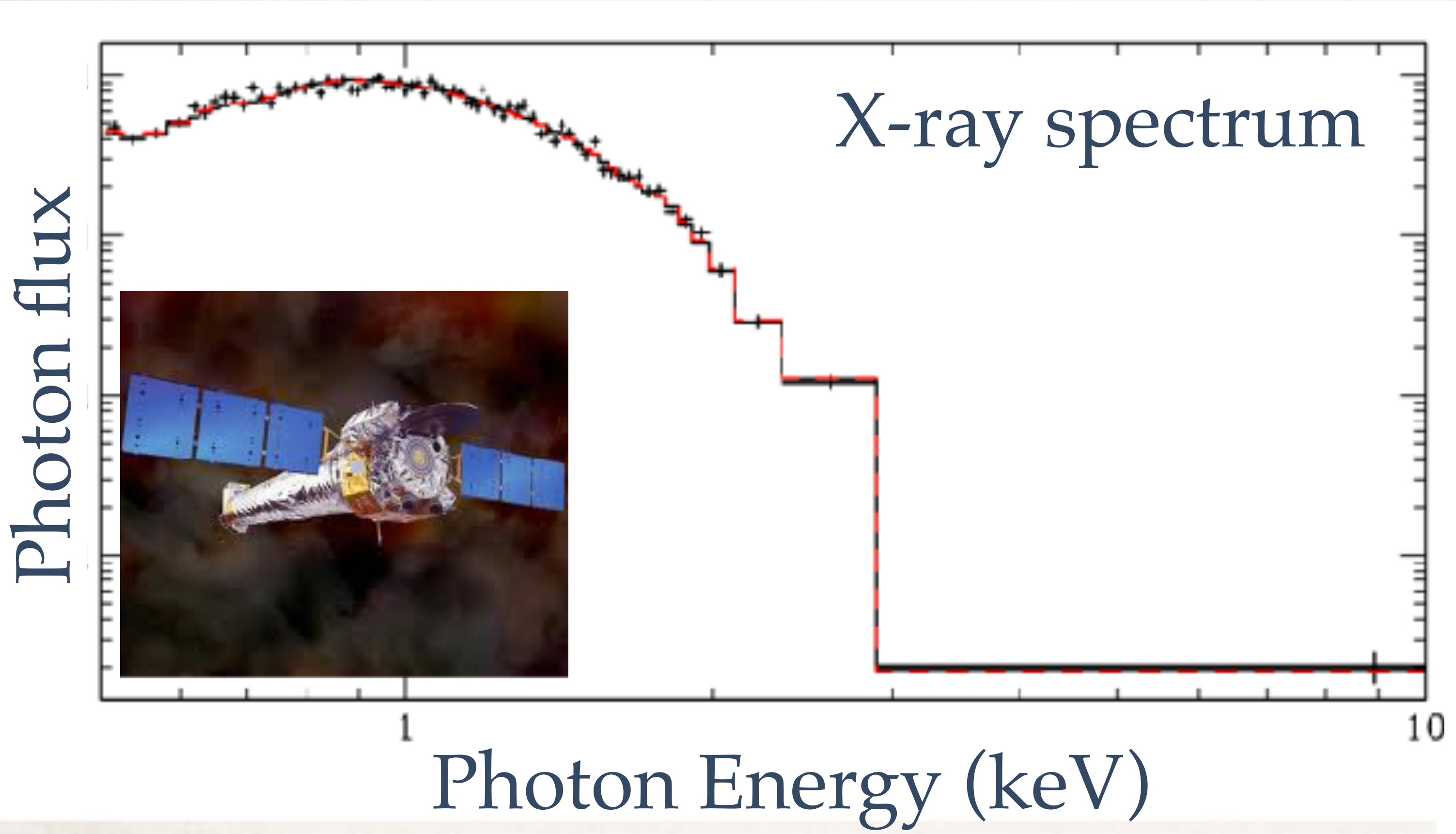


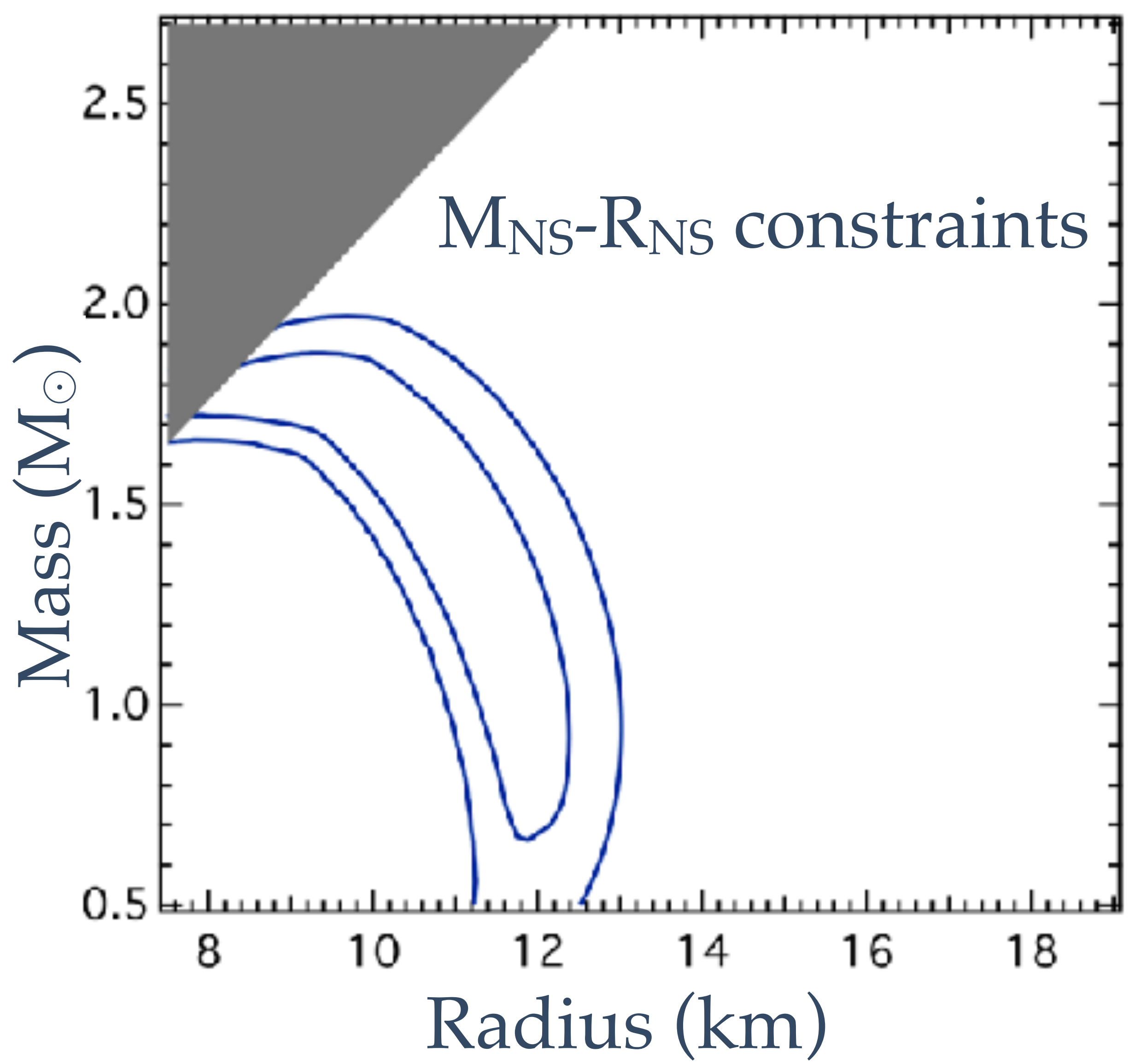
Observing the binary companion to the NS



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

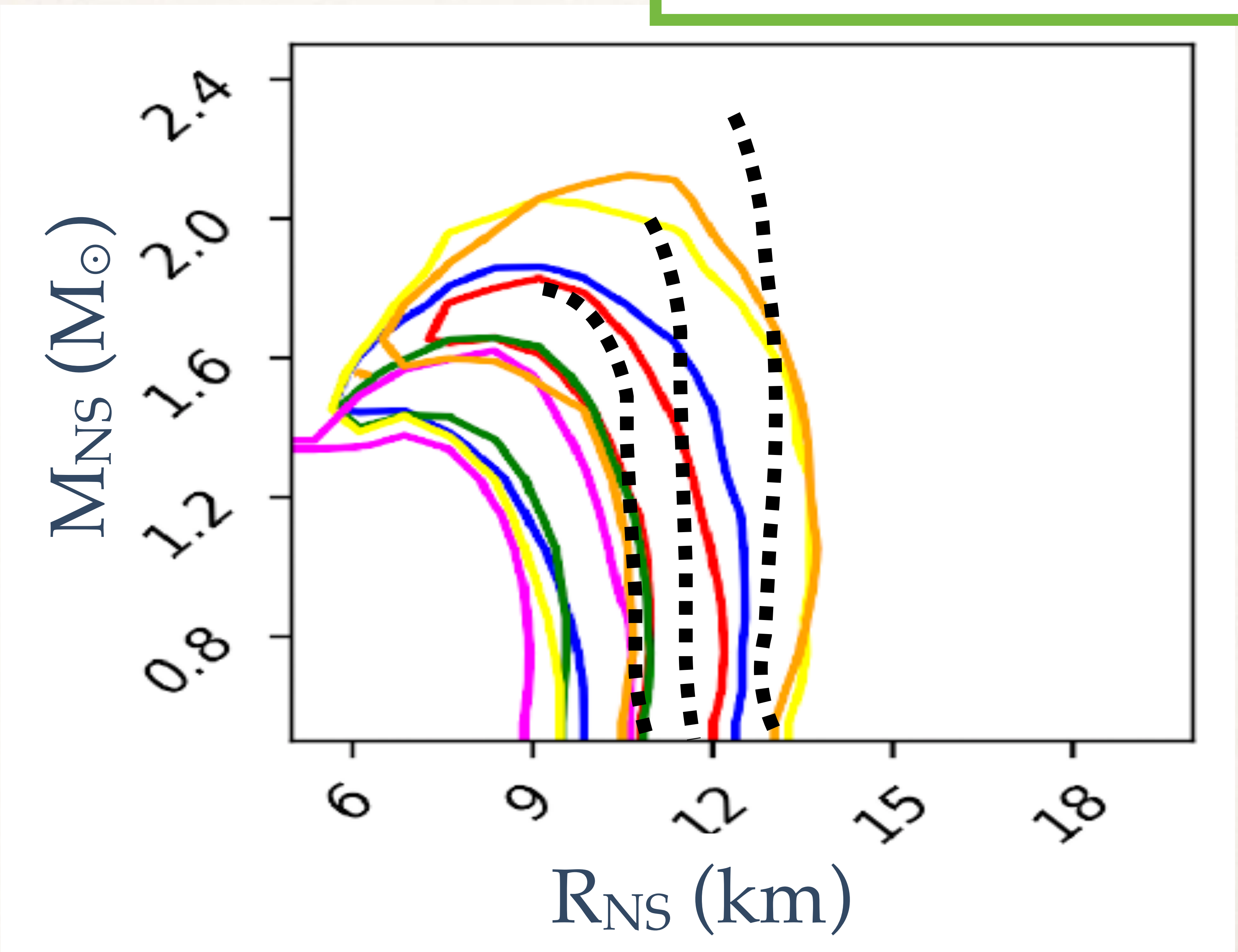
To sum up, the X-ray spectra of thermally emitting neutron stars is used to extract their M_{NS} and R_{NS}.





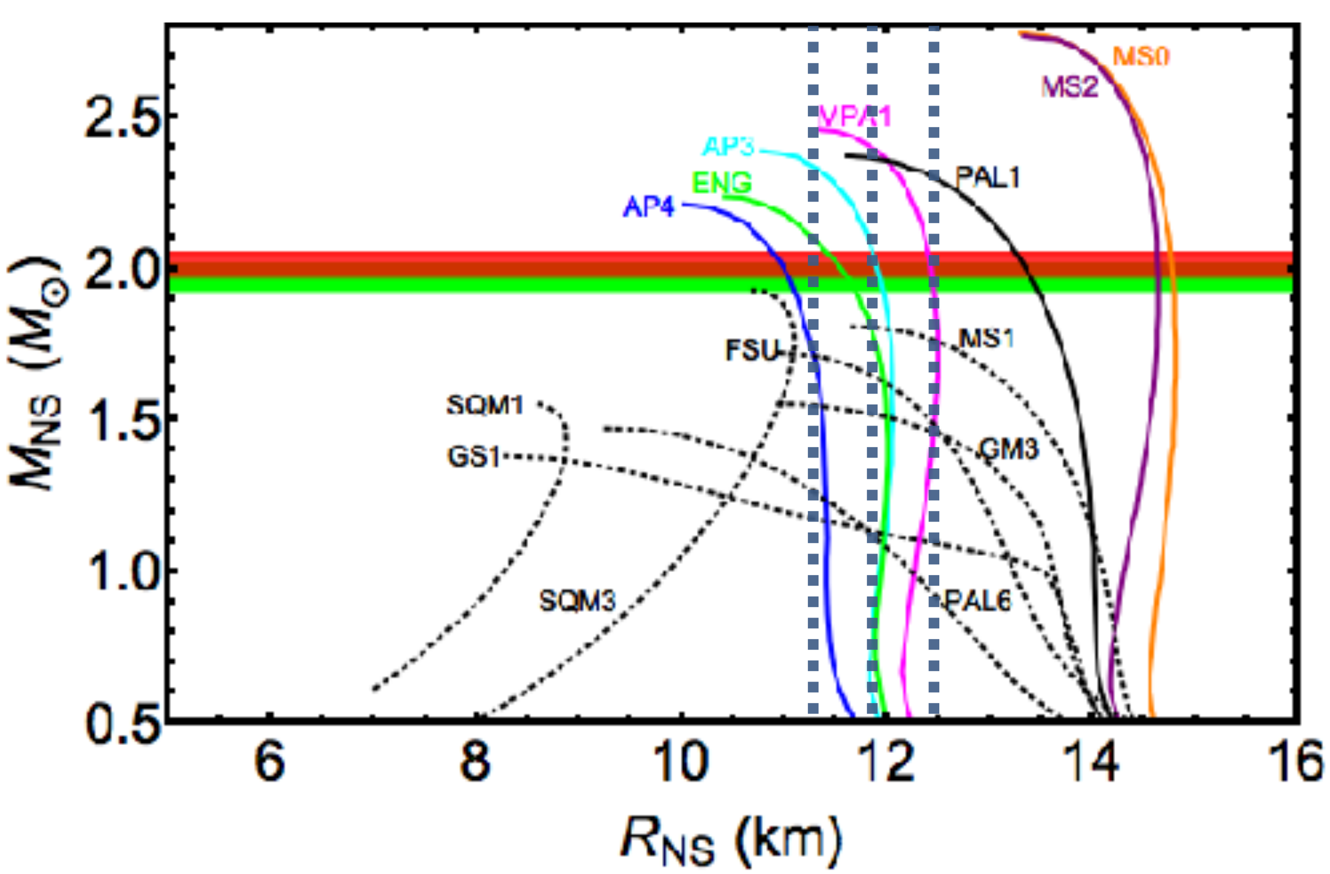
We want to find which equation of state in M-R space is common to all these measurements.

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



Seven sources with known distances.

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

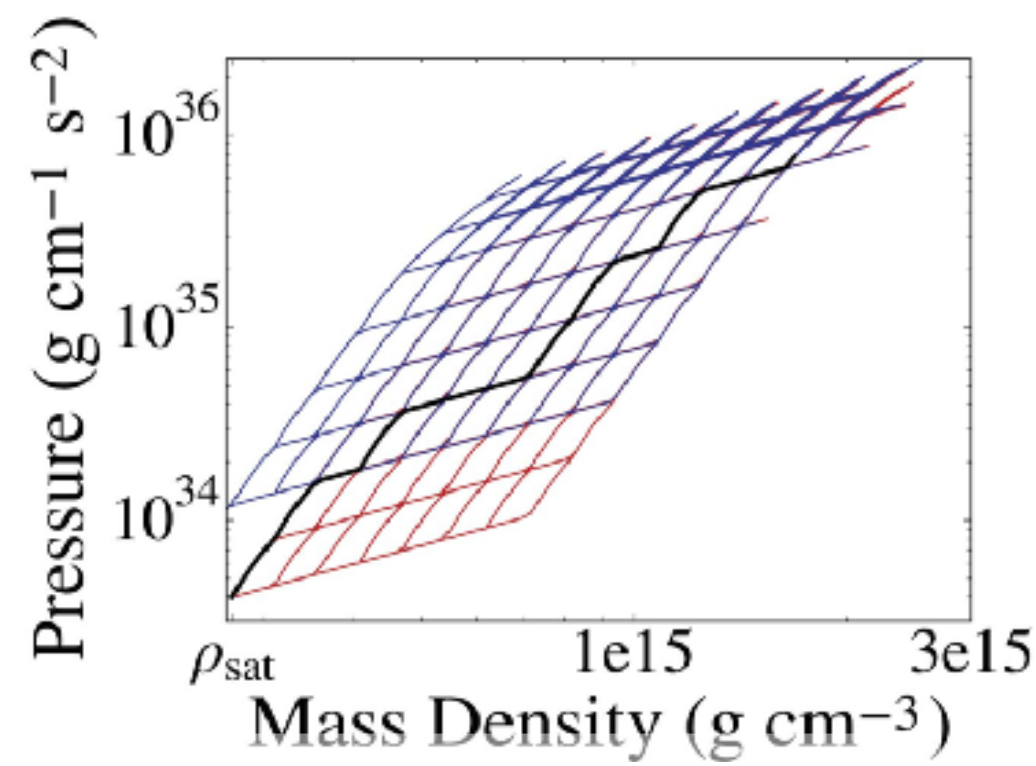


<u>Constant R_{NS}</u>

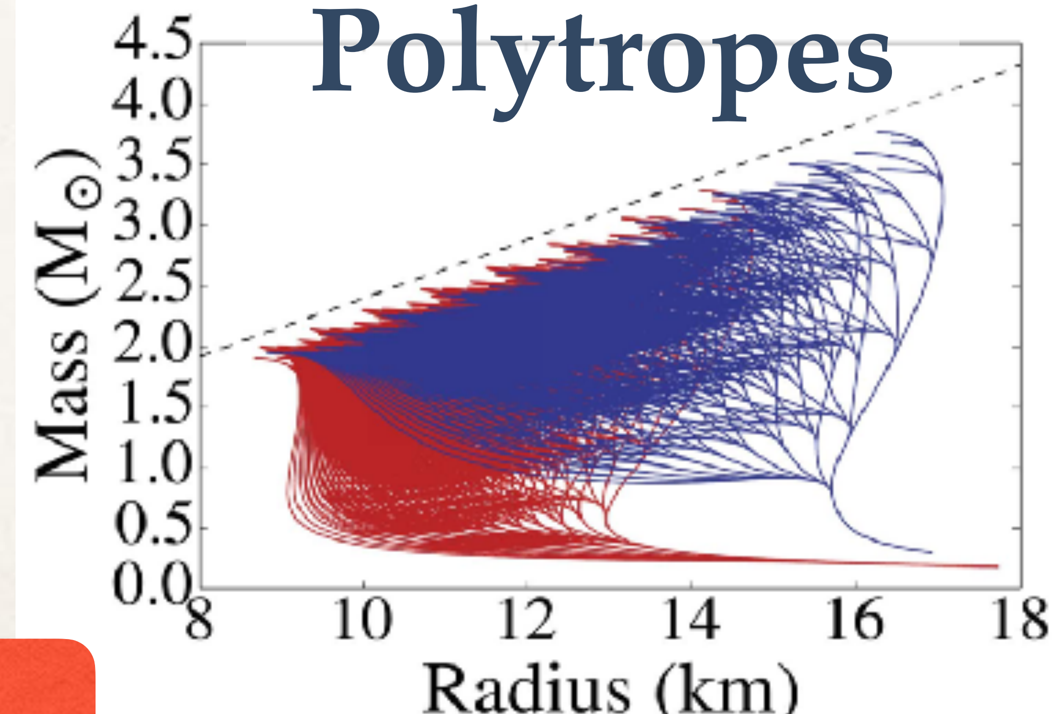
i.e., the radius is the same for all neutron stars

Guillot et al. 2013, 2014, 2016

Analytical parameterizations



Polytropes



Read et al. (2009), Raithel et al. (2016)

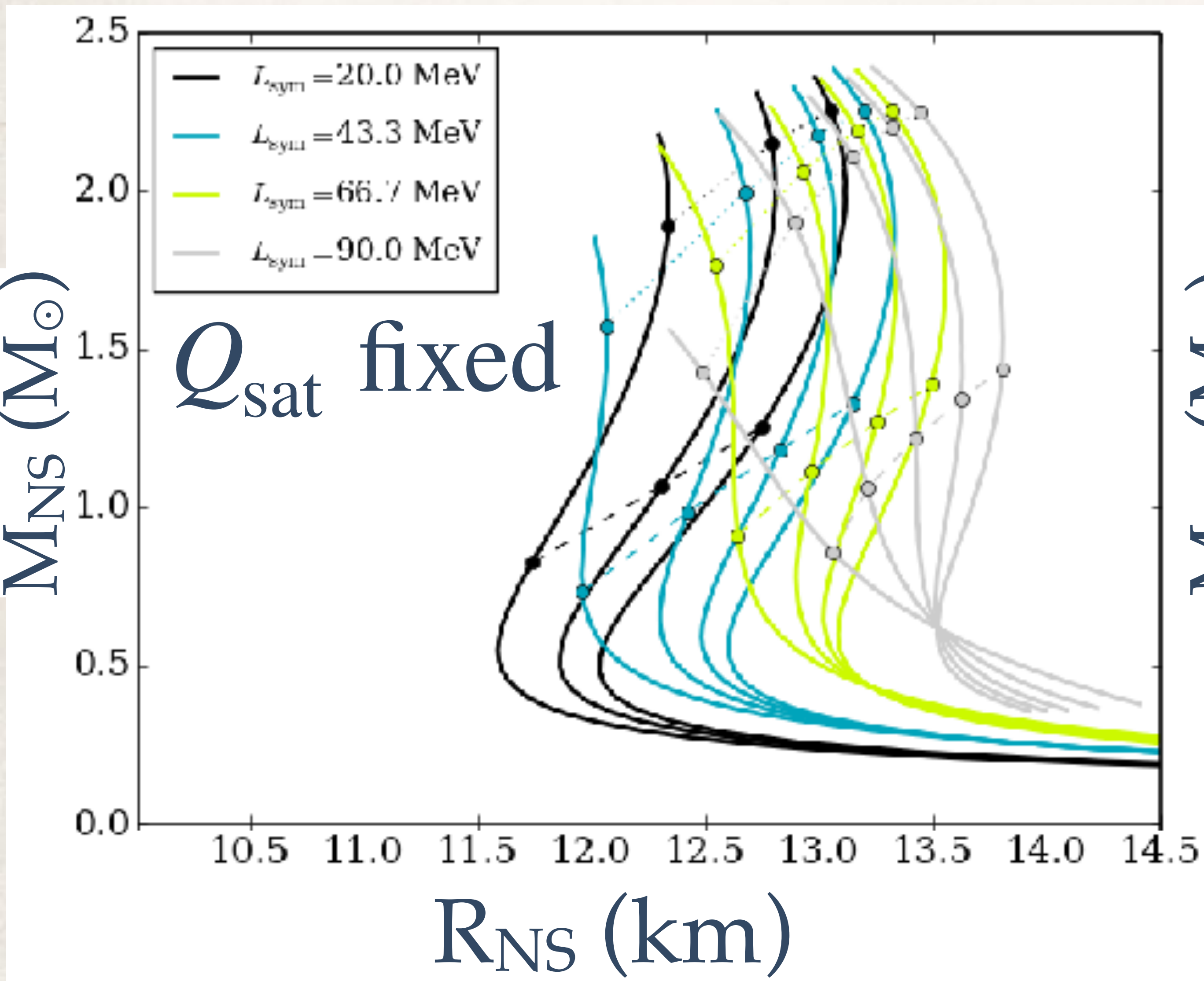
Using a realistic, physically-driven, parameterisation of the equation of state is preferable.

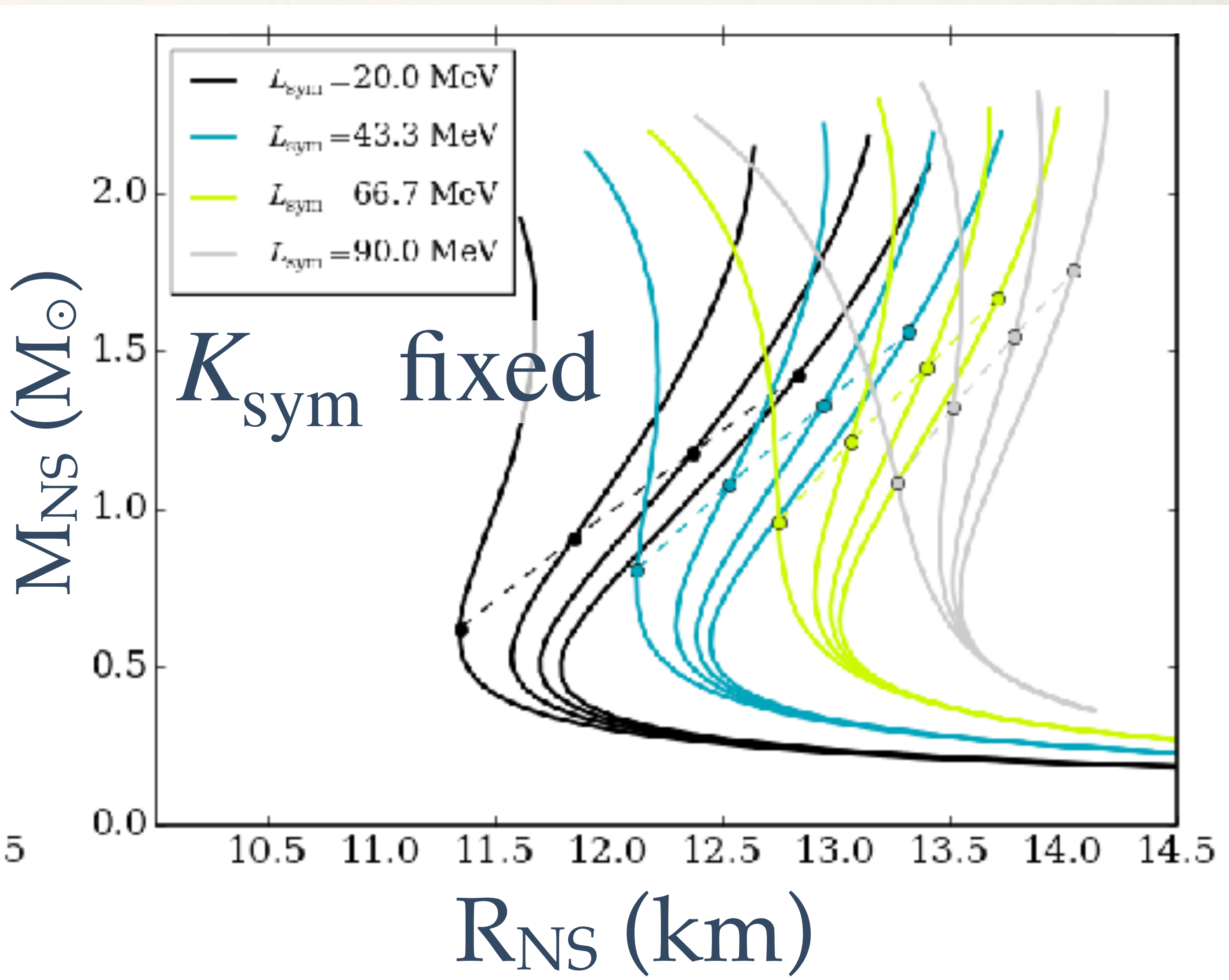
$$e_{sat} = E_{sat} + \frac{1}{2}K_{sat}x^2 + \frac{1}{3!}Q_{sat}x^3 + \frac{1}{4!}Z_{sat}x^4 + \ldots$$

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

With x

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

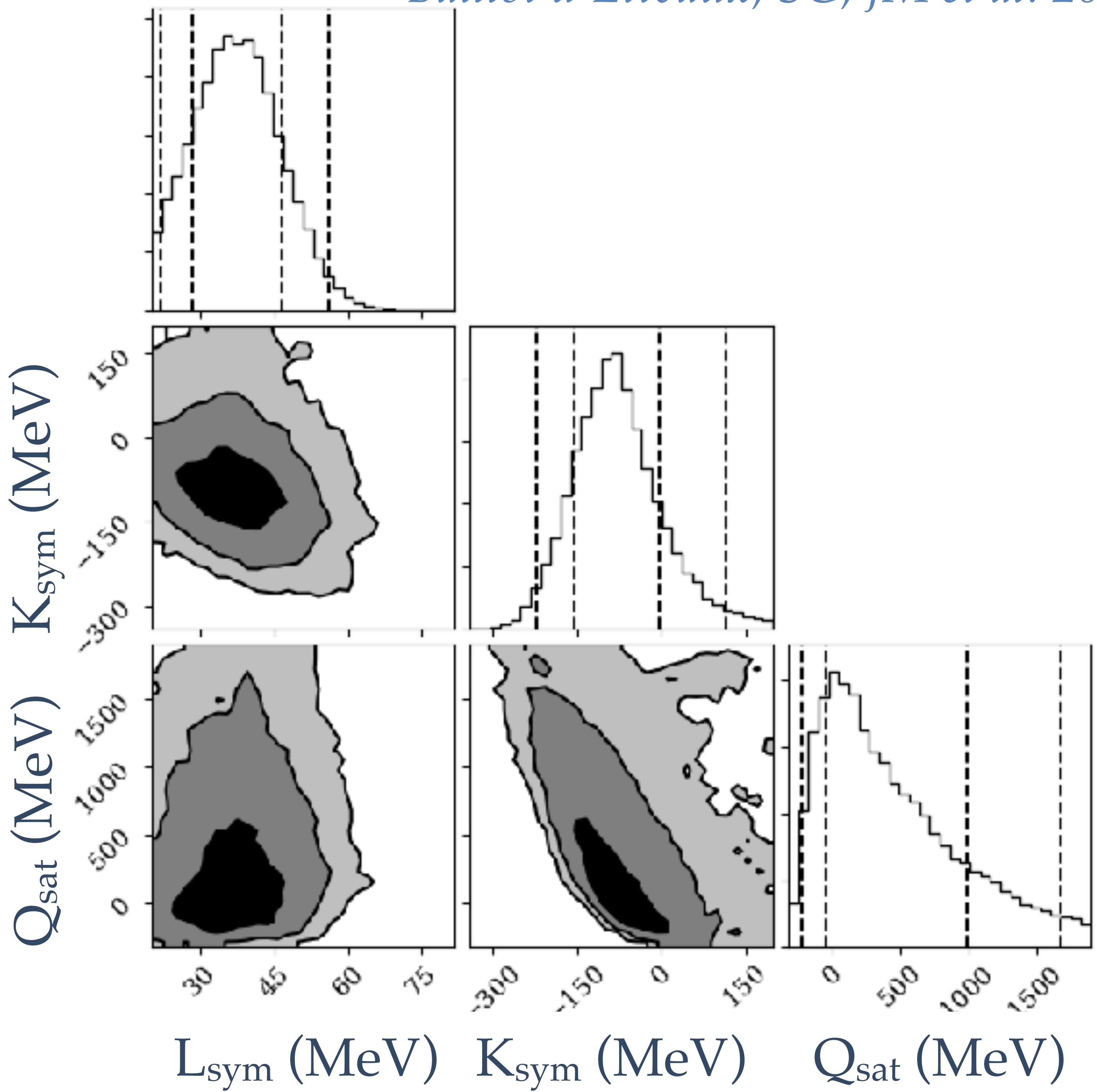




Margueron et al. 2018 *Baillot d'Etivaux, SG, JM et al. 2019*

Our measurements of these three parameters improve on previous estimates.

Baillot d'Etivaux, SG, JM et al. 2019



<u>Our measurements</u> (2σ):

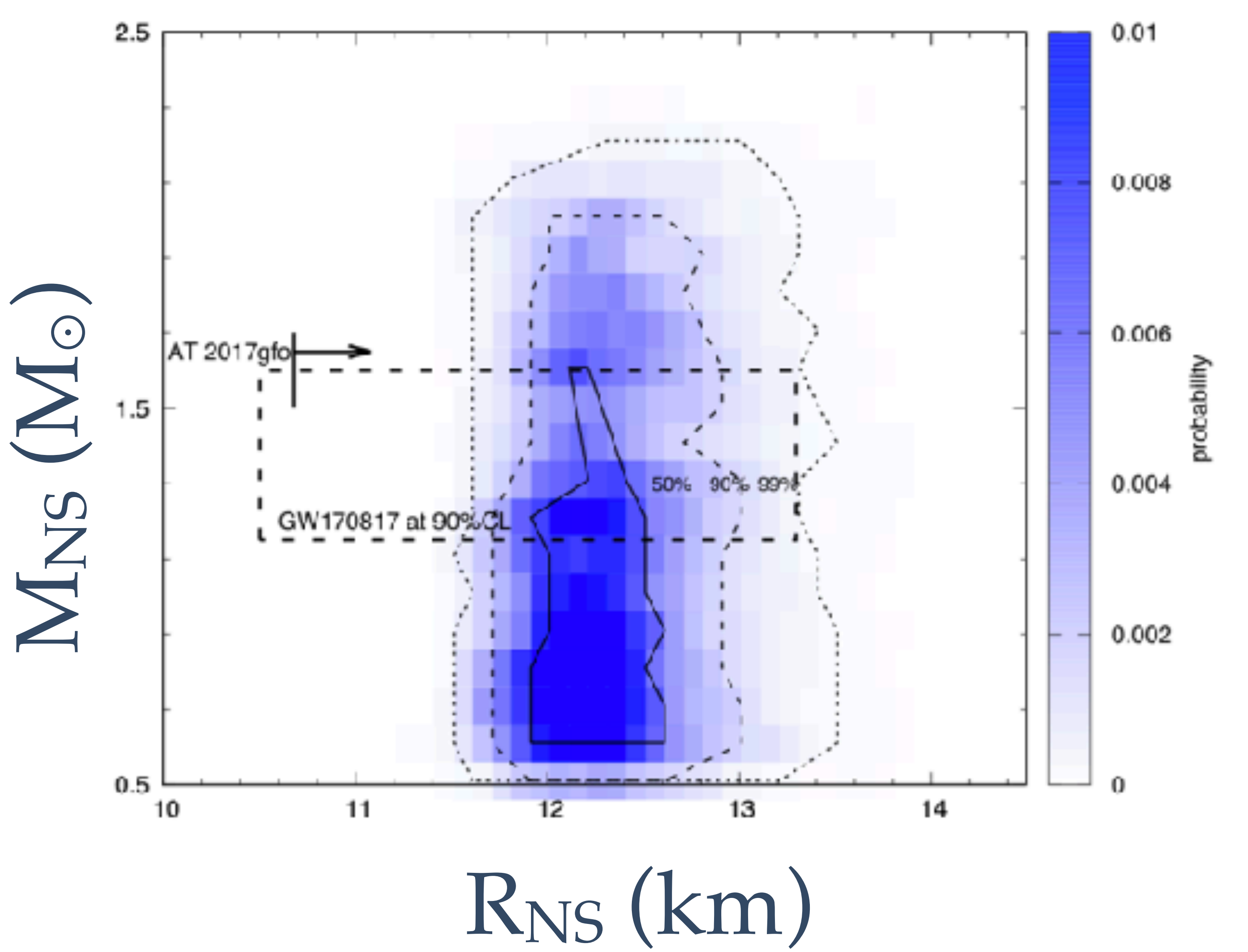
- L_{sym} ~ 25 – 60 MeV
- K_{sym} ~ -250 – 130 MeV
- Q_{sat} ~ -200 – 1900 MeV

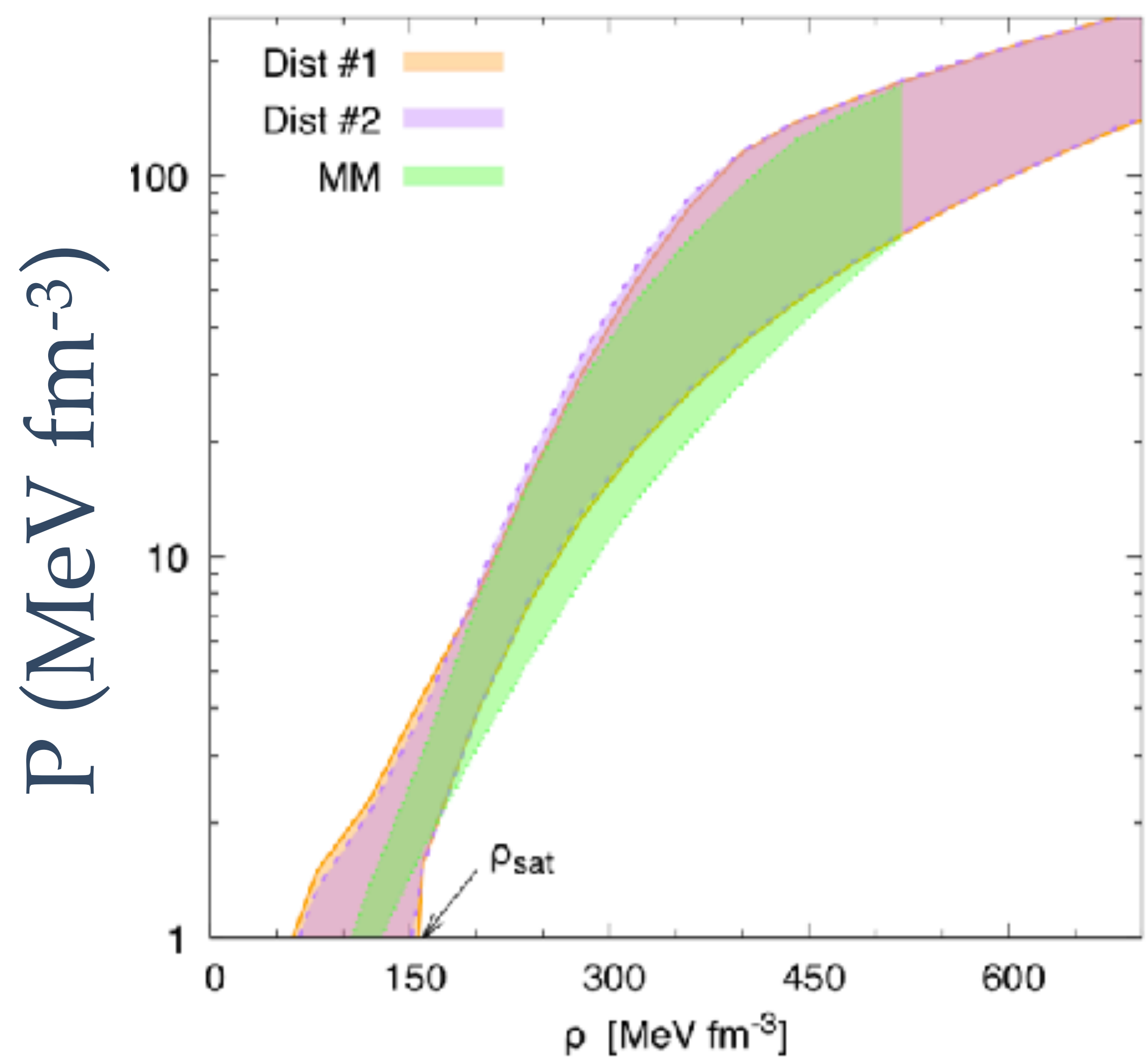
<u>For comparison:</u>

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, JM et al. 2019

Summary

- By applying the meta-model of Margueron et al. (2018) directly to astrophysical data, we extract measurements of the parameters Lsym, Ksym and Qsat:

$$L_{\rm sym} = 37.2^{+9.2}_{-8.9}\,\mathrm{MeV}$$

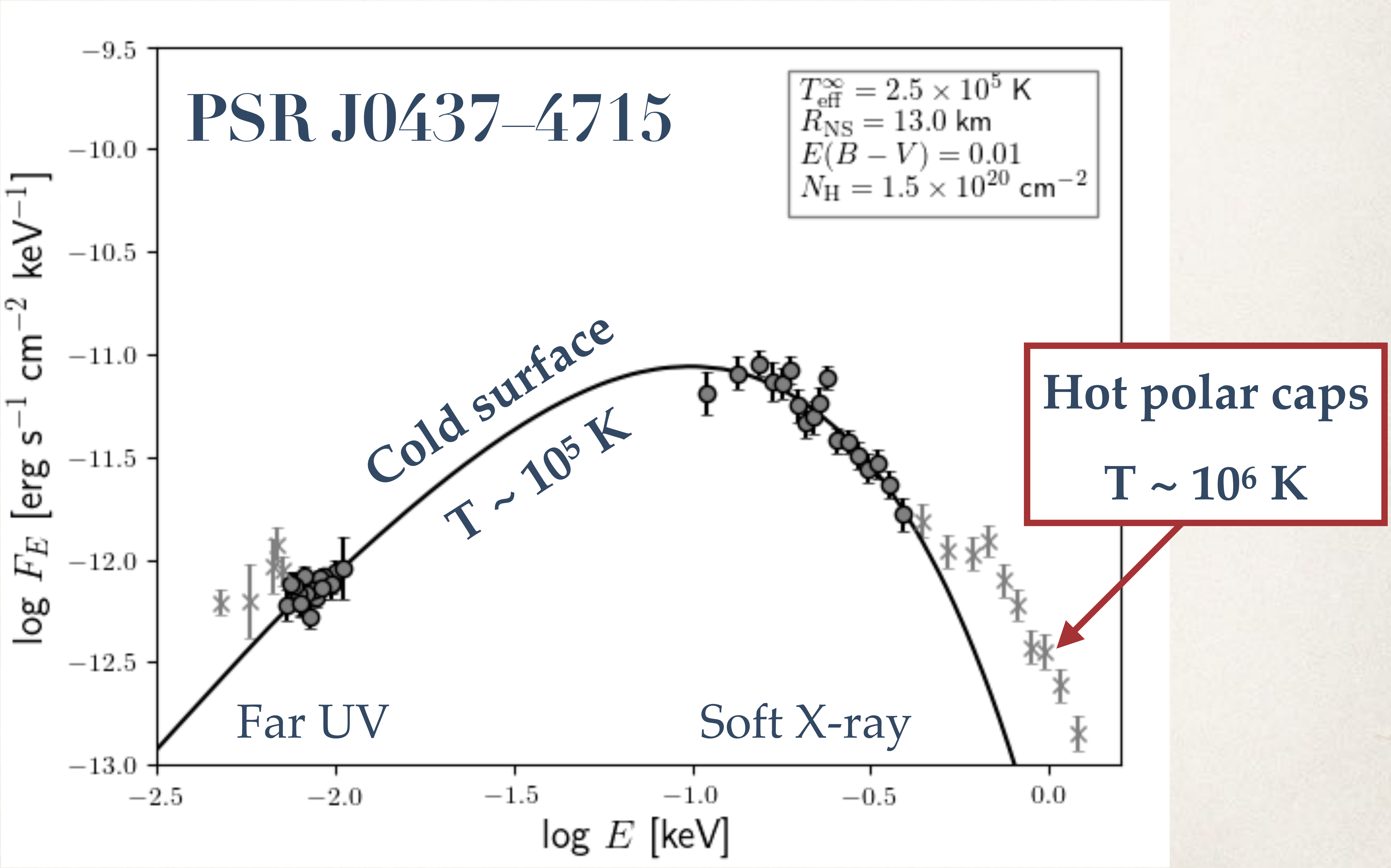
$$K_{\rm sym} = -\,85^{+82}_{-70}\,\mathrm{MeV} \quad \Rightarrow \quad R_{\rm NS} = 12.4 \pm 0.4\,\mathrm{km}$$

$$Q_{\rm sat} = 318^{+673}_{-366}\,\mathrm{MeV}$$

Baillot d'Etivaux, SG, JM et al. 2019

- This requires assuming that **<u>all neutron stars are described by the same equation of state</u>**.

The cold surface of millisecond pulsars can also be used to measure their radius.



Gonzalez-Canuilef, Guillot & Reisenegger, 2019

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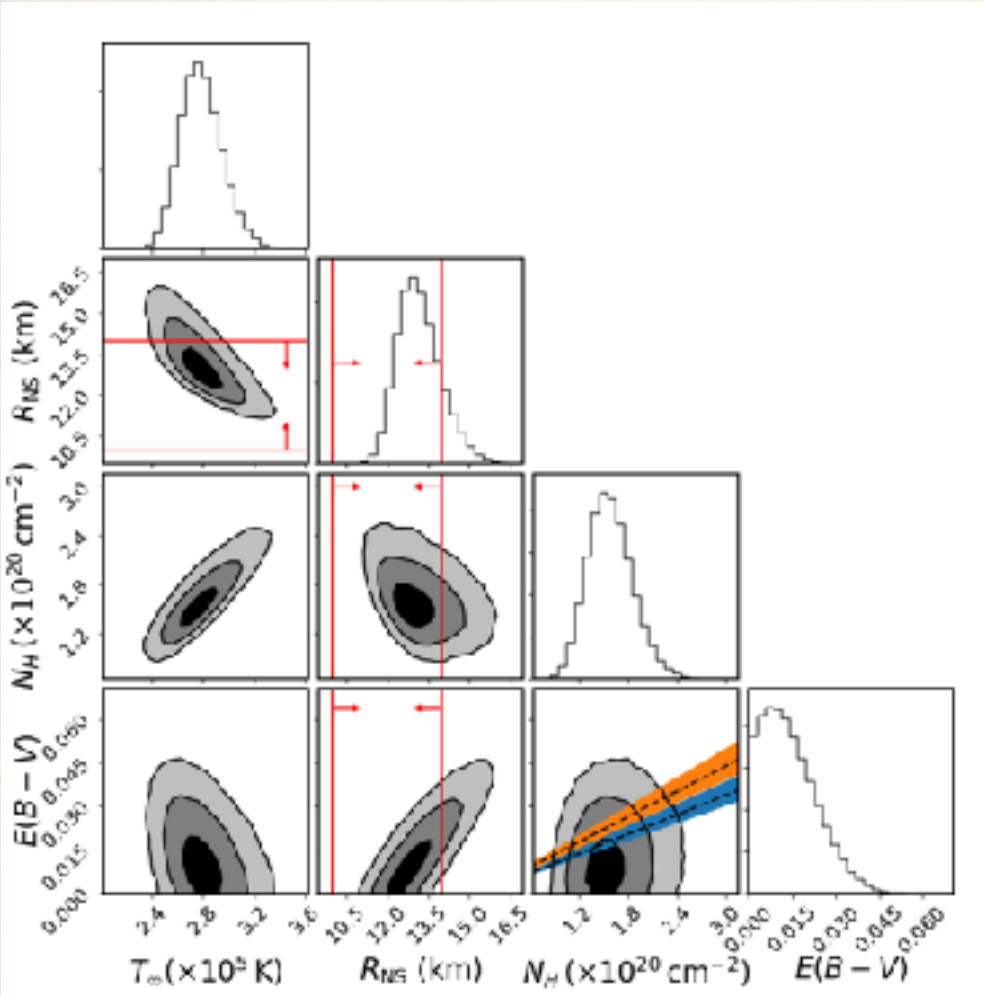
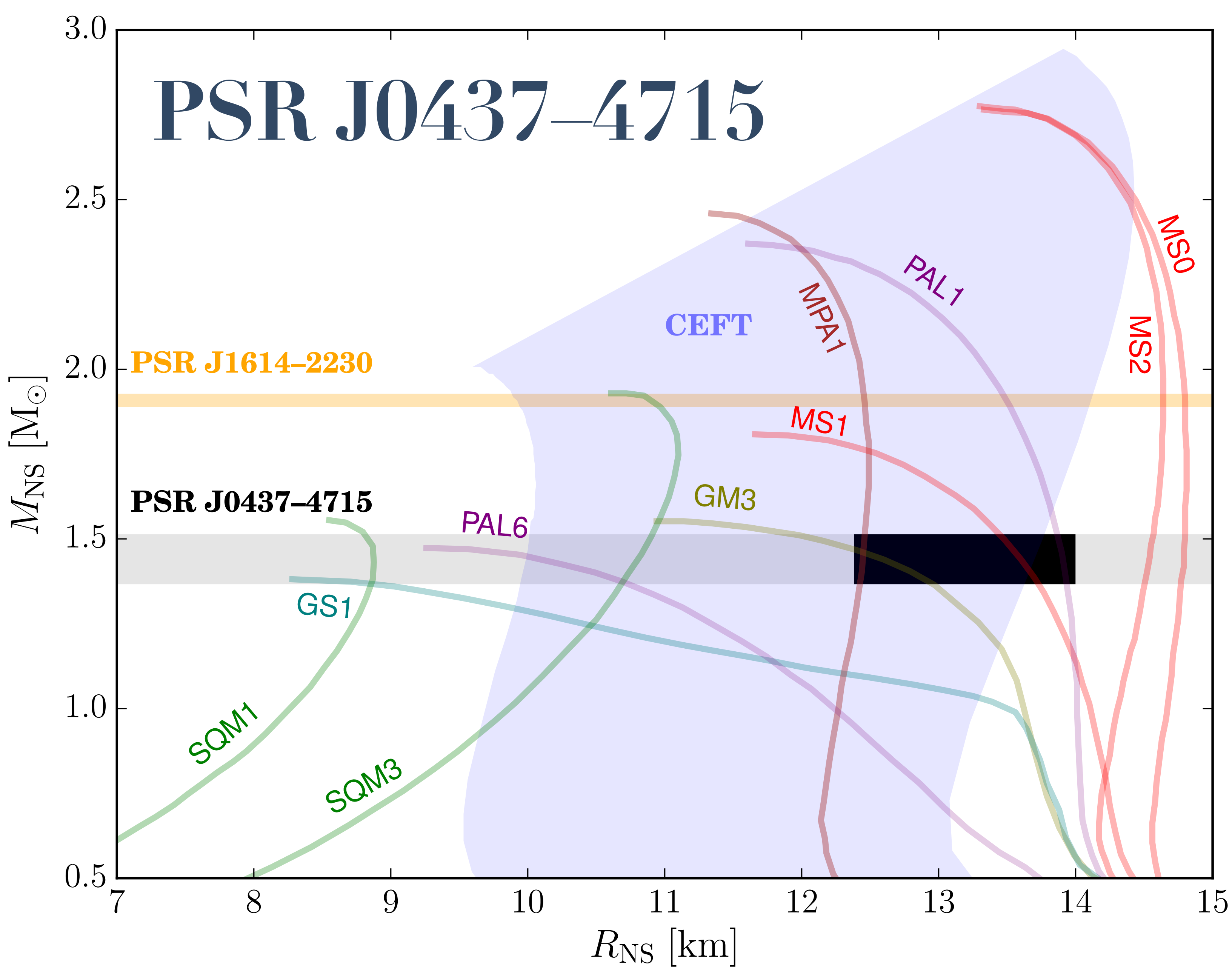
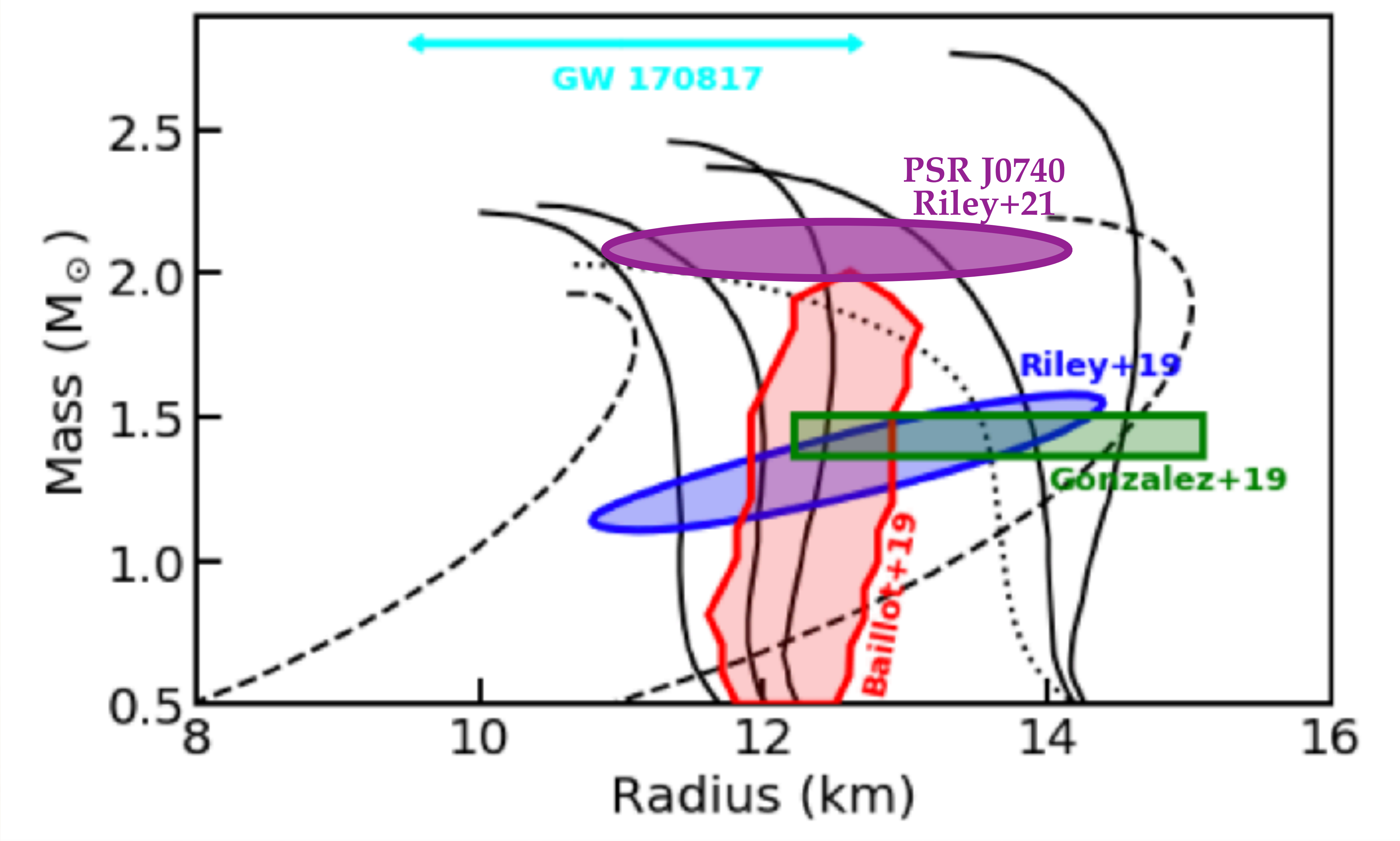




Gonzalez-Canuilef, Guillot & Reisenegger, 2019

Conclusion

So far, results from different approaches are consistent with each other.



Gonzalez-Canuilef, SG et al. 2019
Baillot-d'Etivaux, SG, JM et al. 2019
Riley et al. 2019
Riley et al. 2021
Abbott et al. 2018