Dense Matter Equation of State constraints with Observations of Neutron Stars

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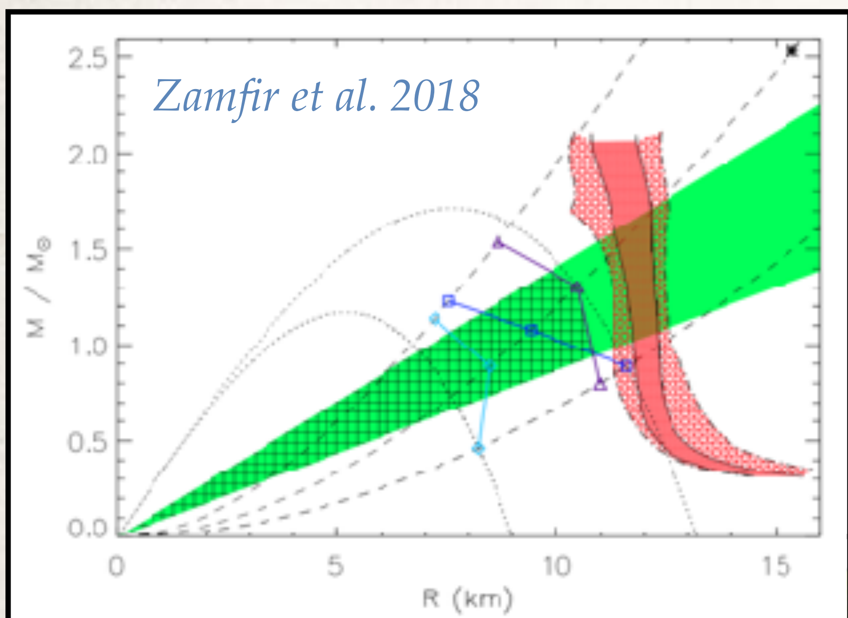
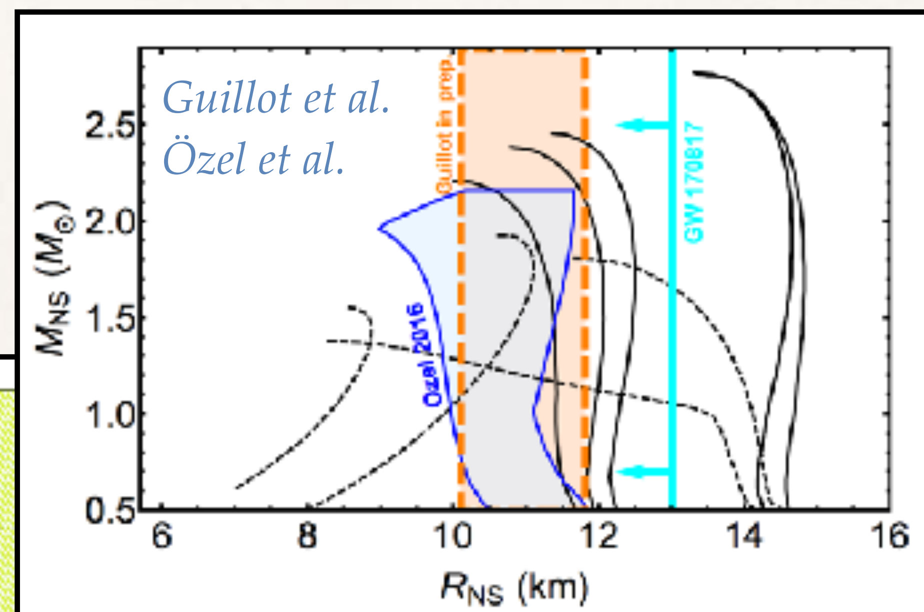
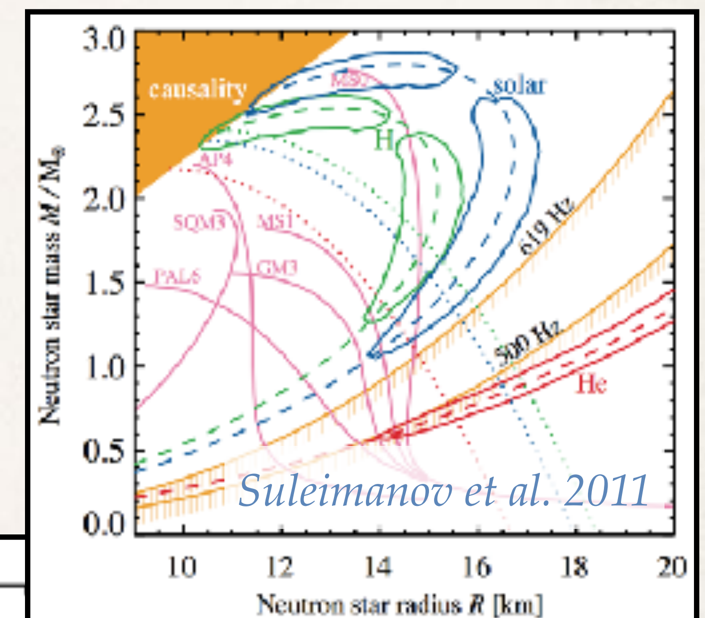
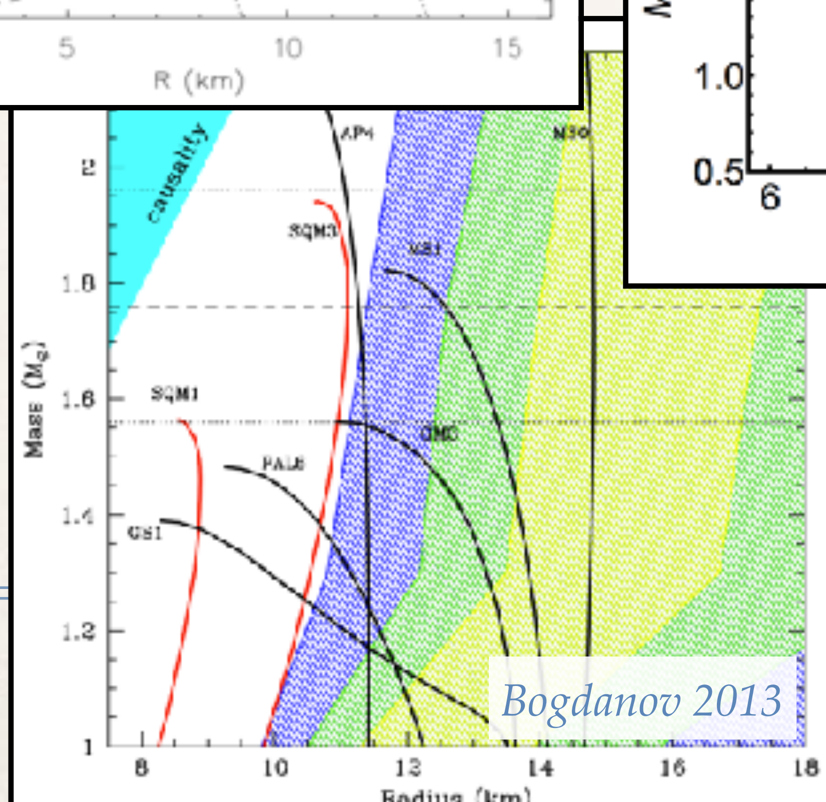
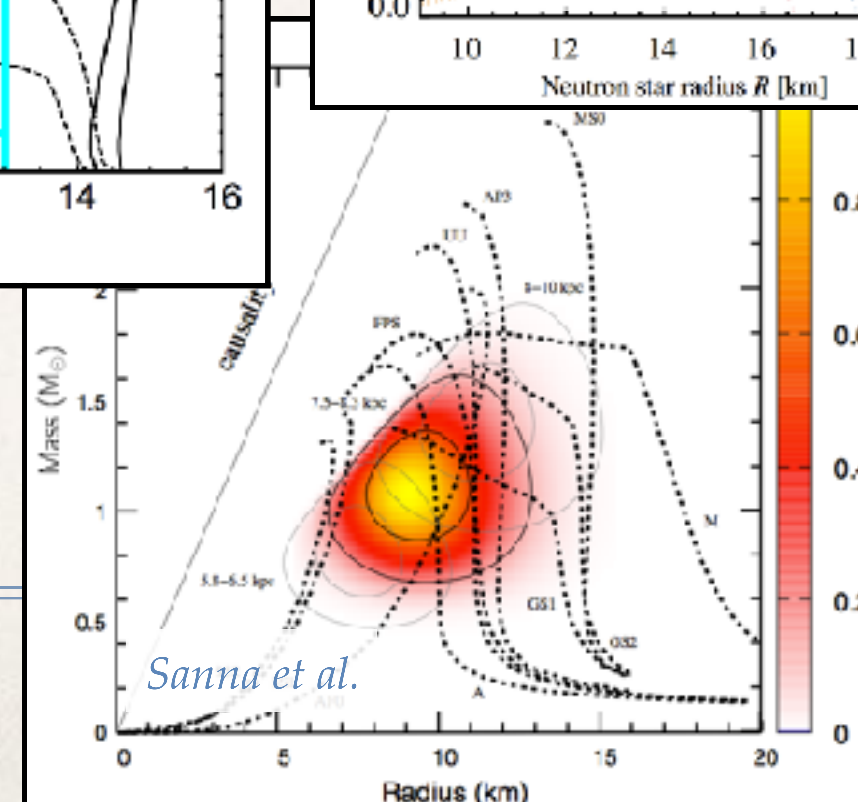


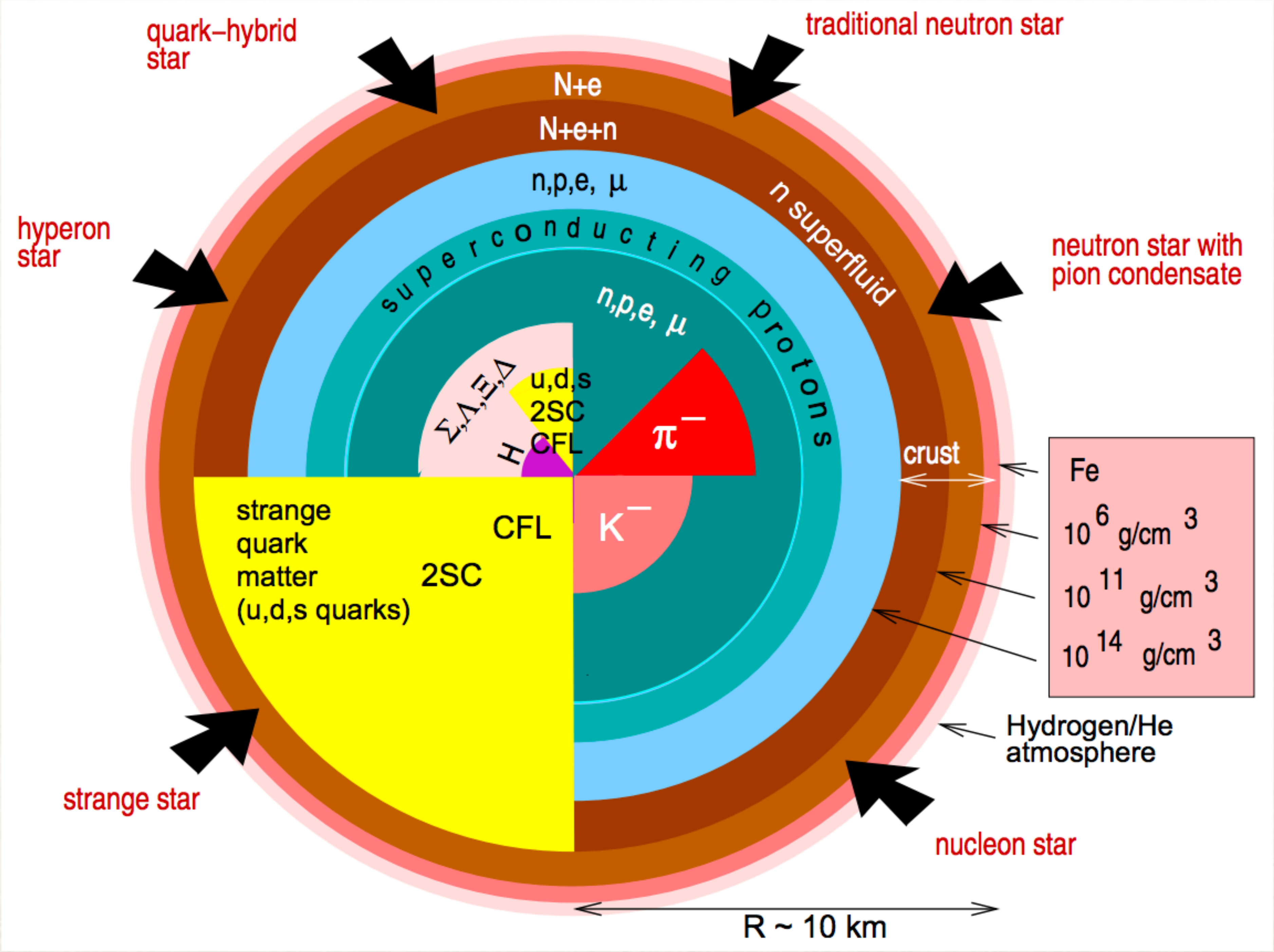






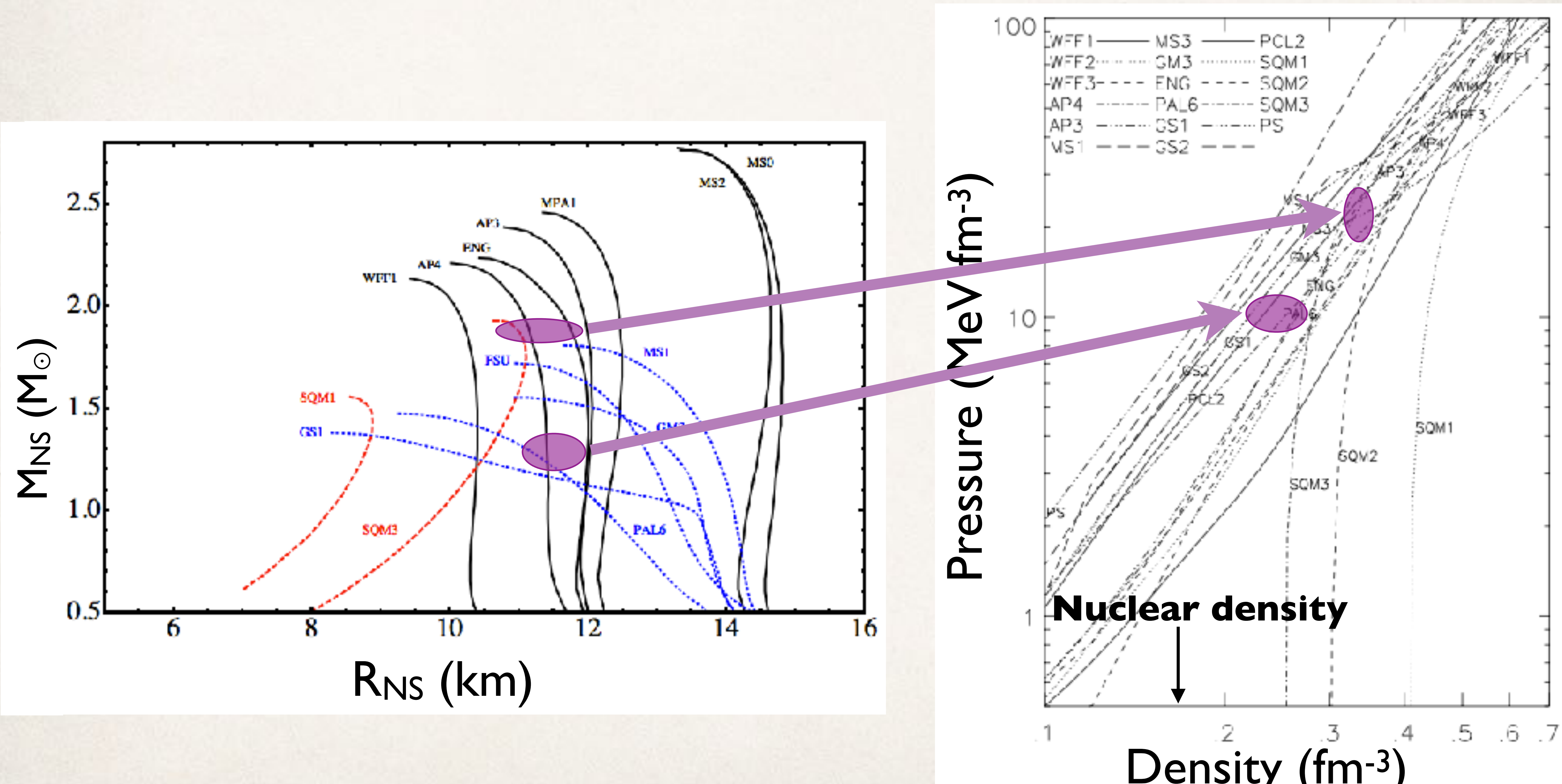


The internal structure of neutron stars is still unknown and many theories are proposed.



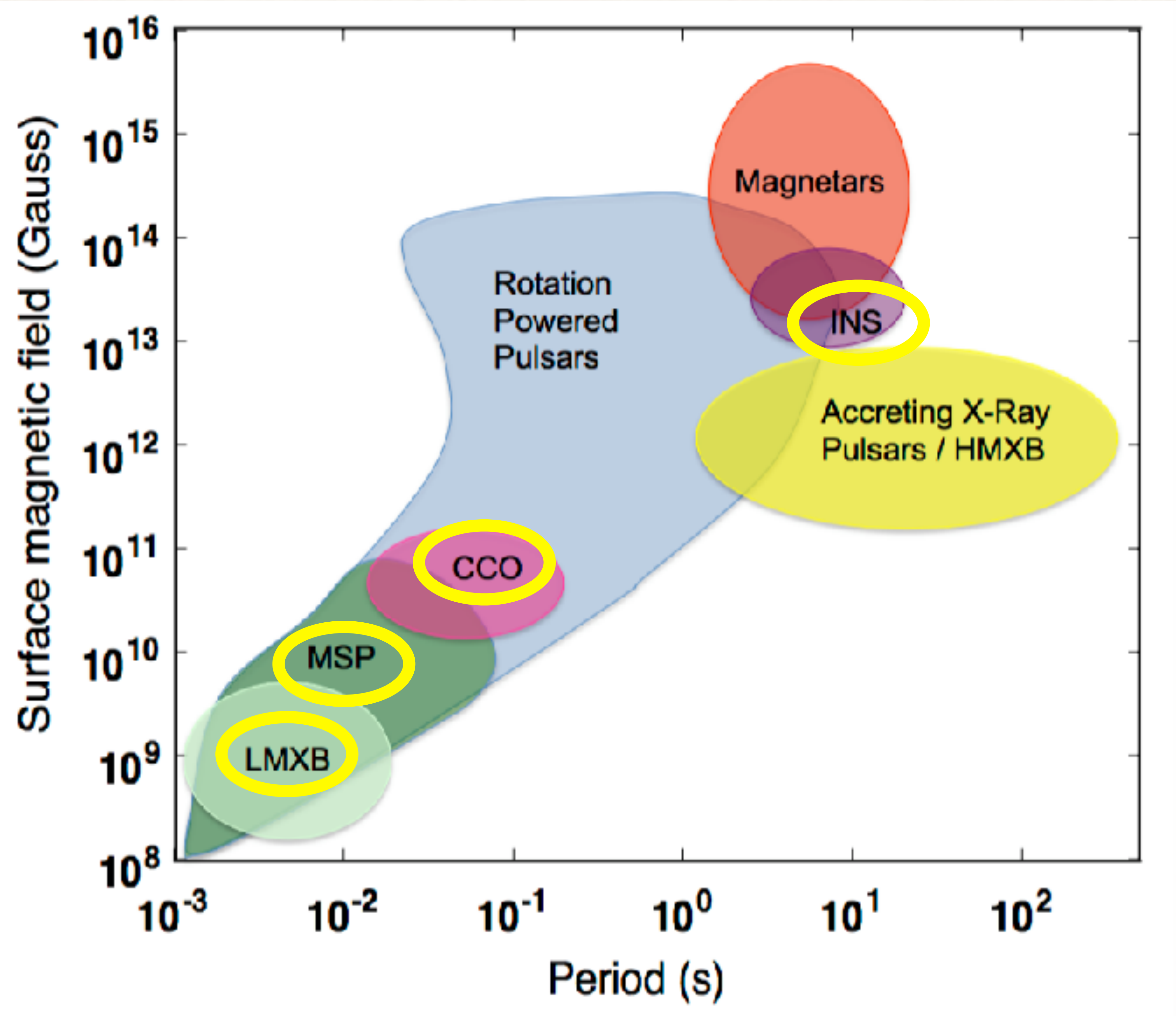
Weber et al. 2007

Dense nuclear matter is described by an equation of state P(ρ). But what is it?



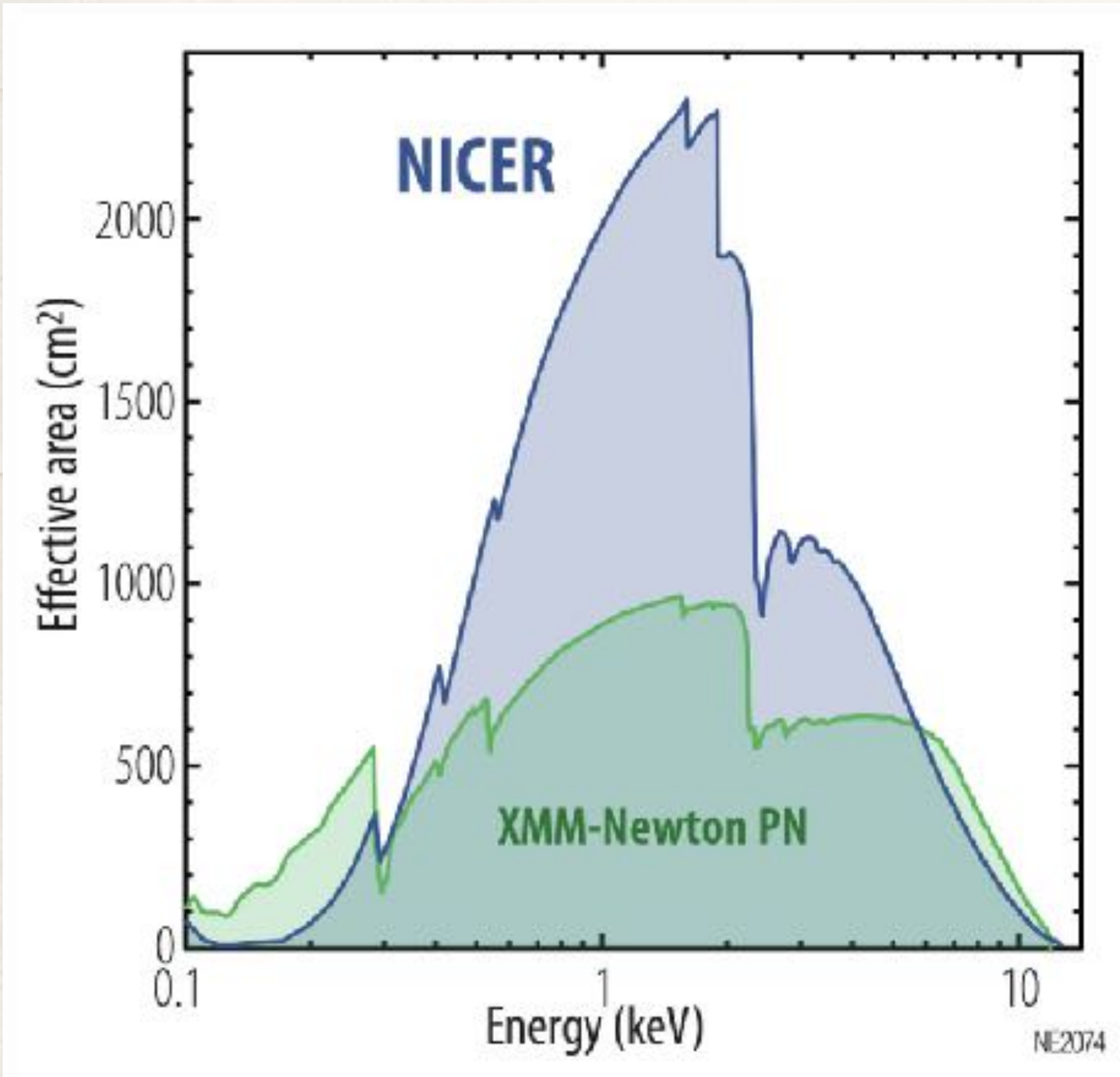
Lattimer and Prakash 2001

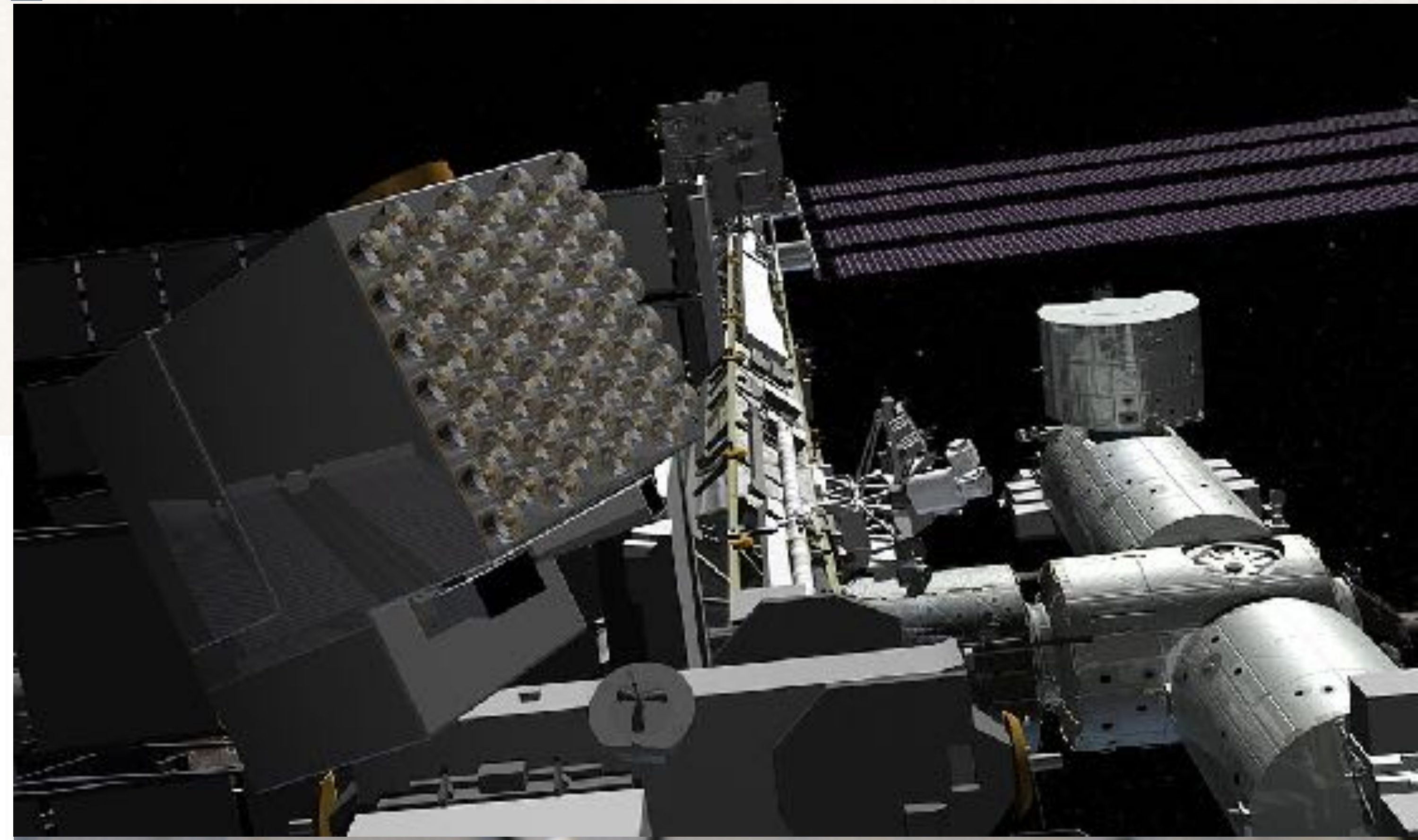
Neutron stars with different properties and observational signatures can be useful for R_{NS} measurements.

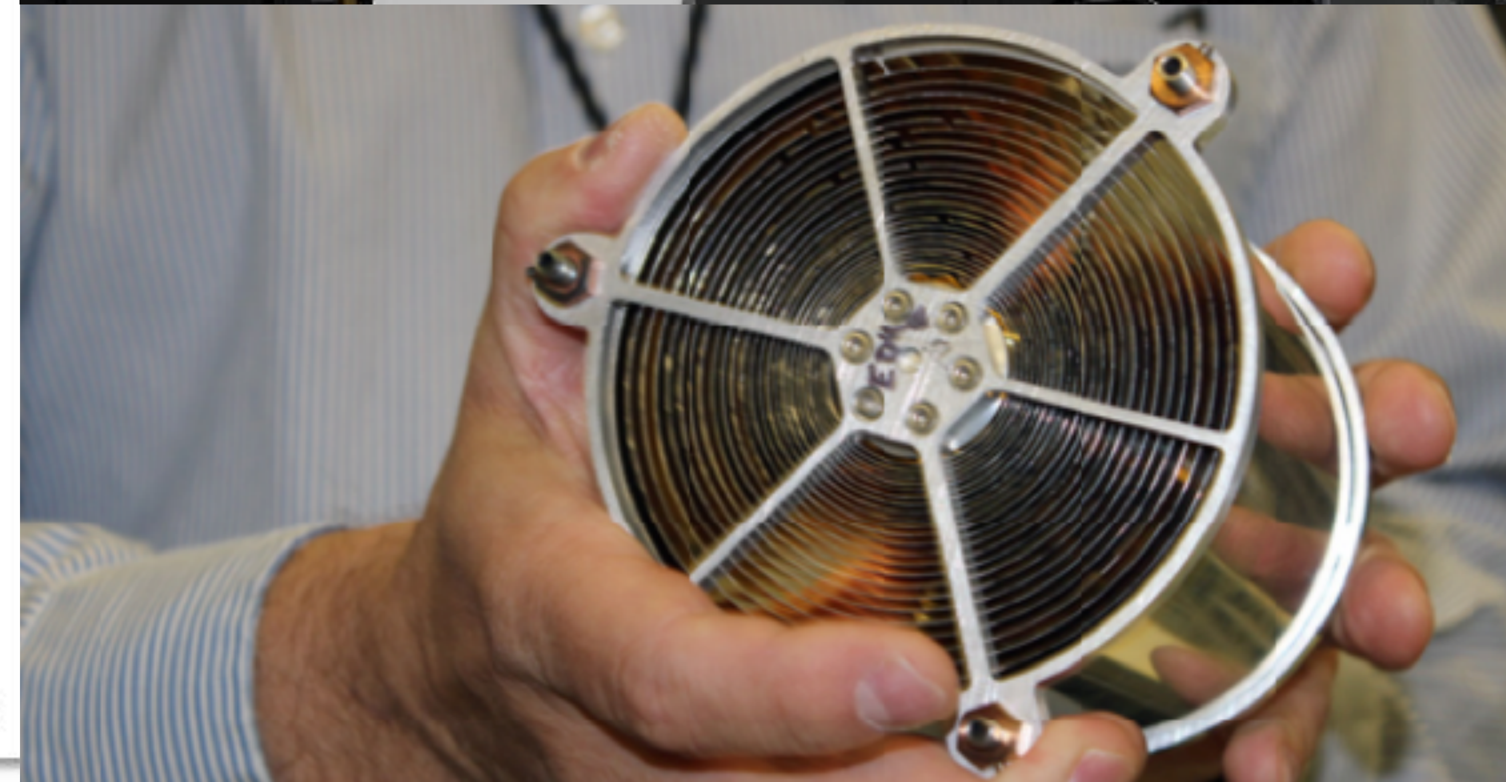


NICER's main science goal is to measure R_{NS} for four millisecond pulsars.

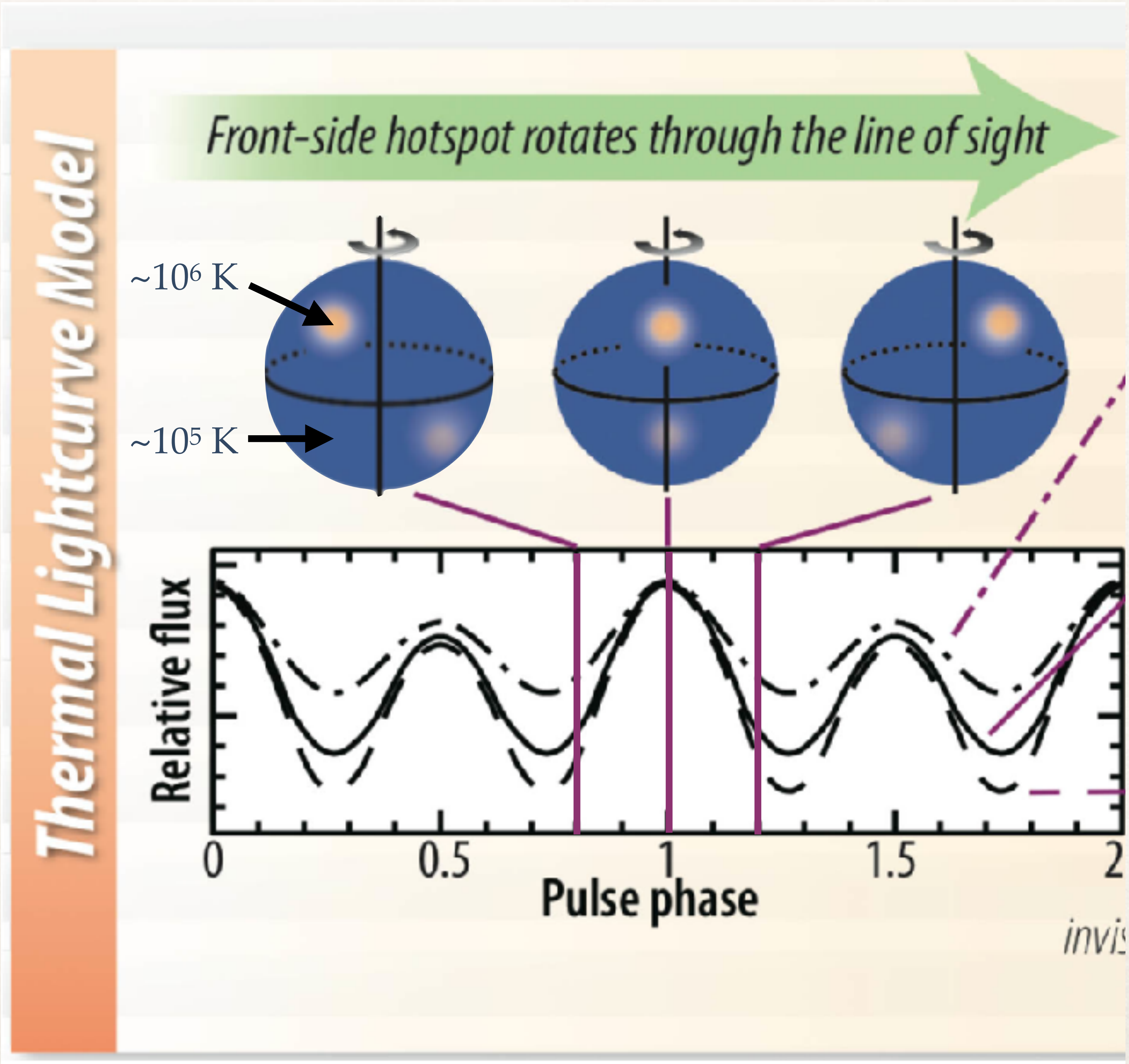
Launched in June 2017



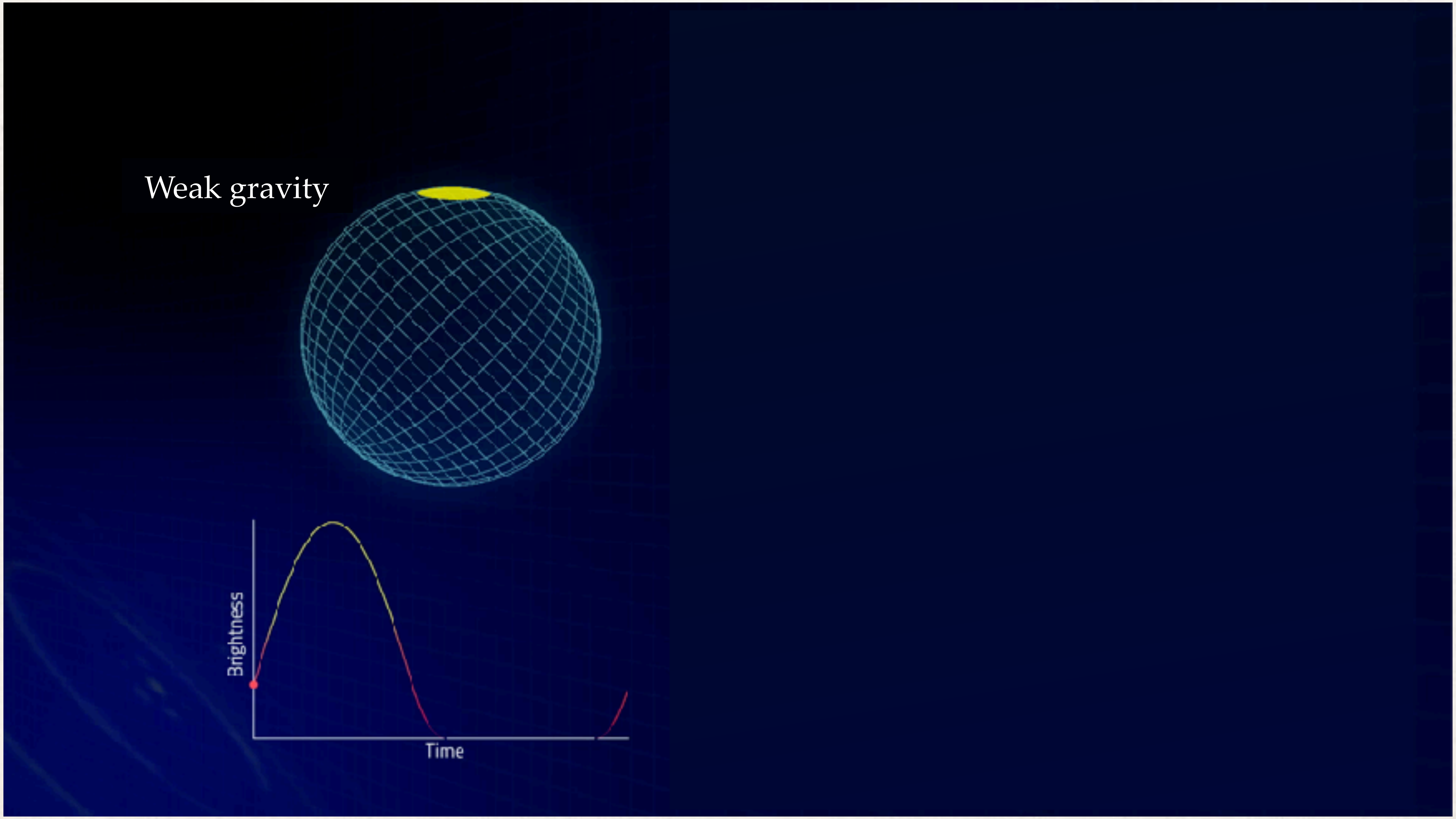




The pulsed emission caused by hot spots on a rotating neutron star can help measure the compactness.



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



Credits: S. Morsink

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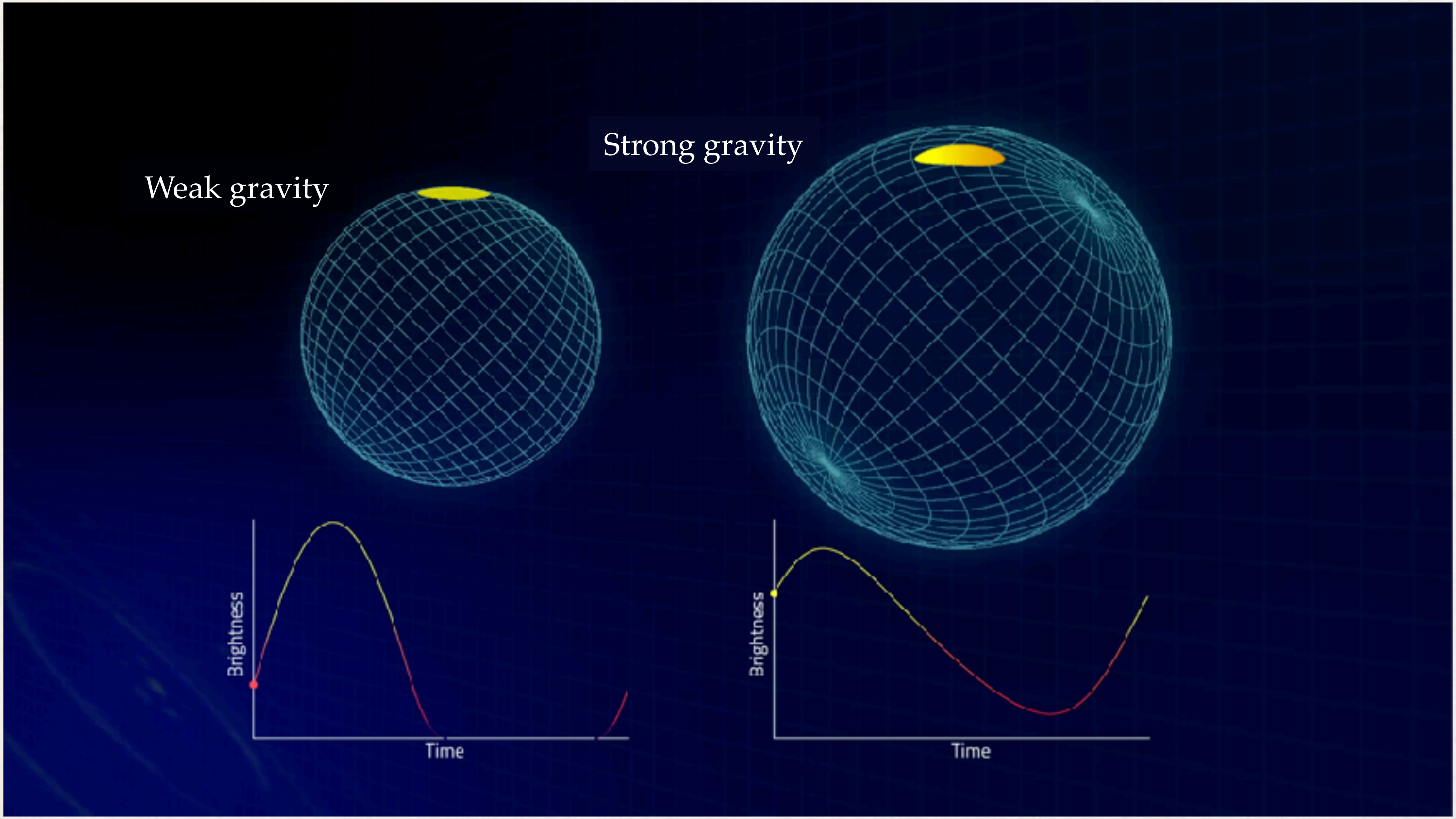

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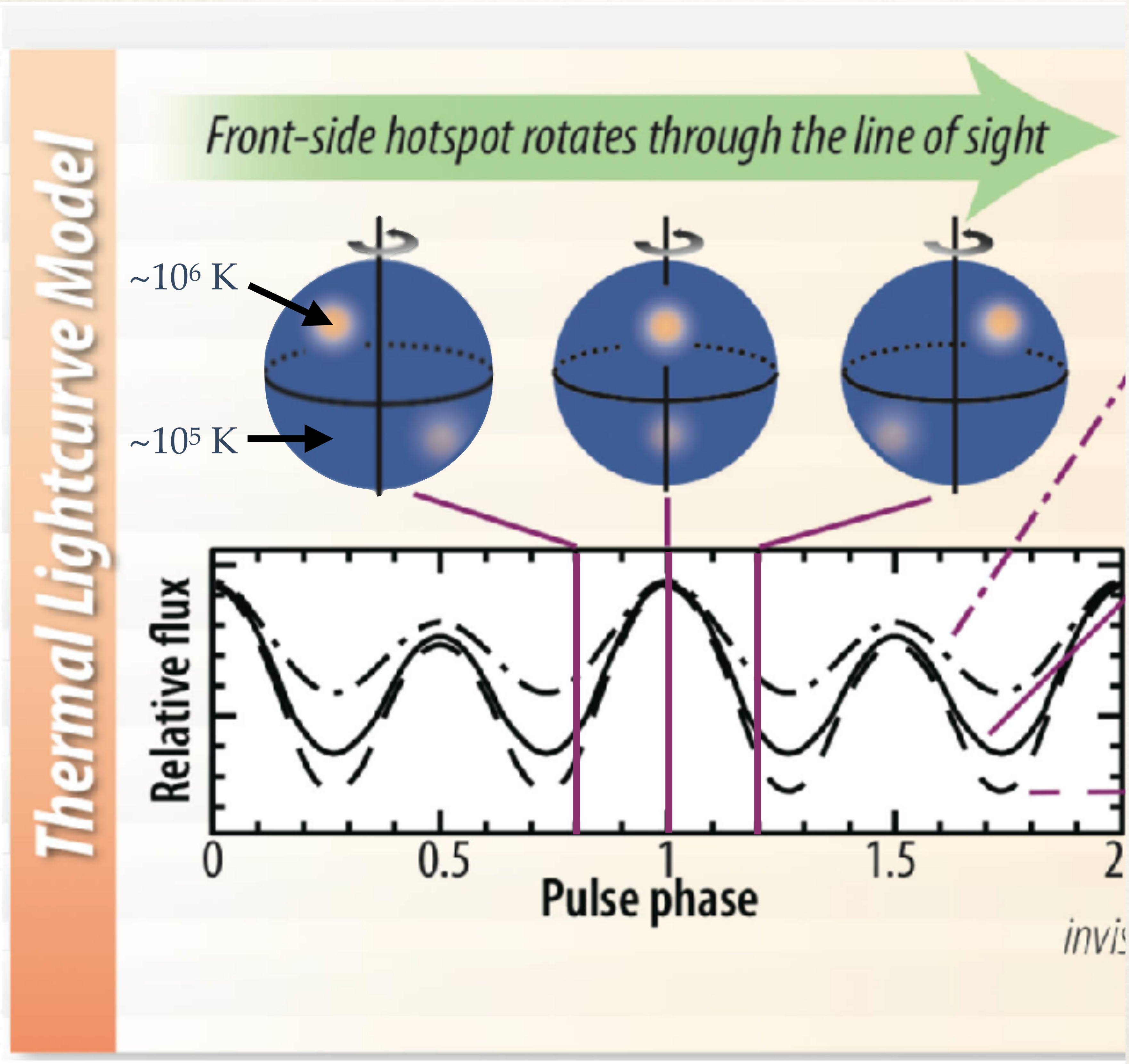
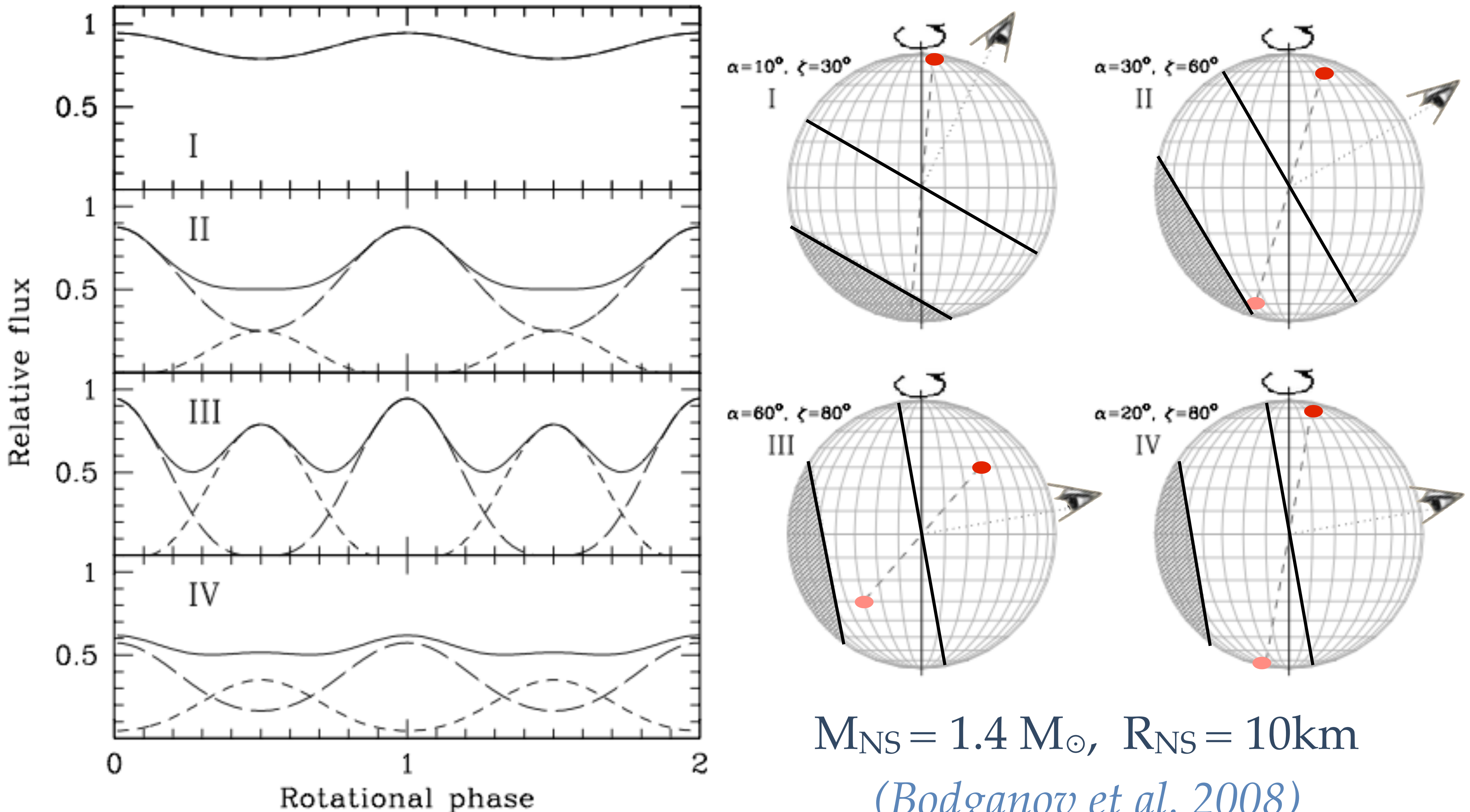


The pulsed emission caused by hot spots on a rotating neutron star can help measure the compactness, but this depends on the system geometry.



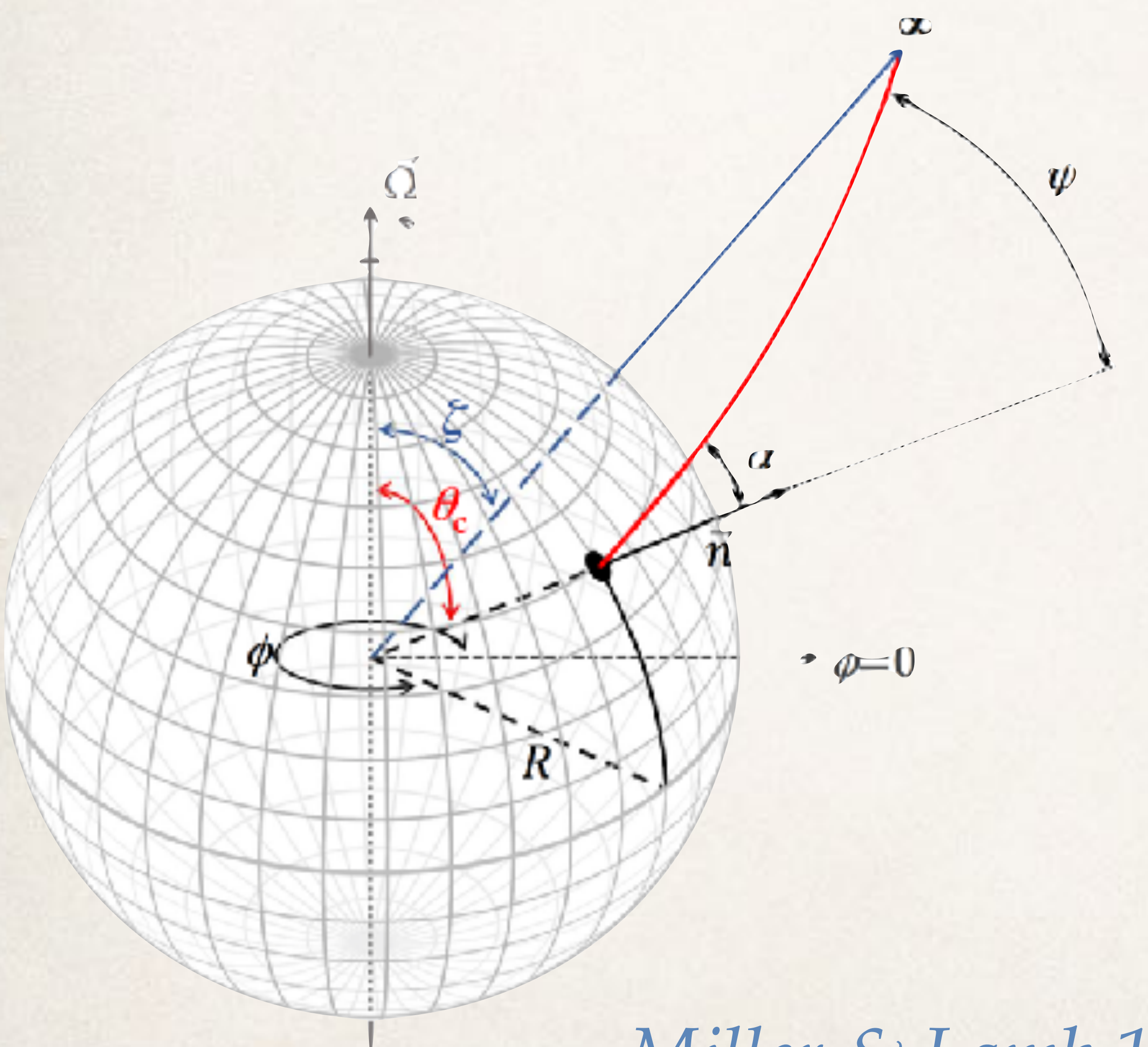
$M_{NS} = 1.4\ M_\odot$, $R_{NS} = 10$km

(Bodganov et al. 2008)

Two main ingredients are necessary to model the lightcurve of millisecond pulsars.

General relativity

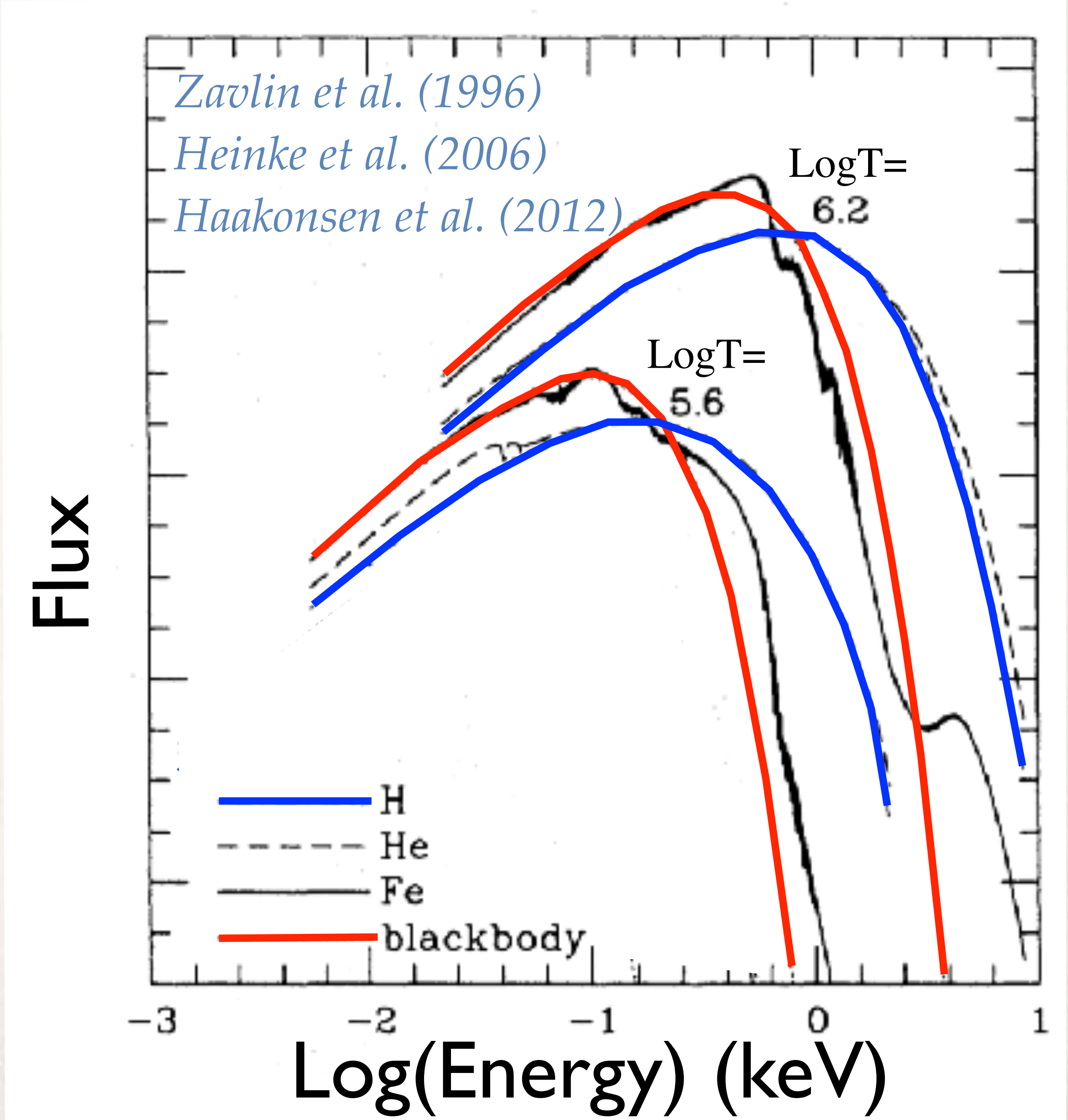
Schwarzschild metric + time delays, doppler boosts / aberration + oblate star



Miller & Lamb 1998
Morsink et al. 2007

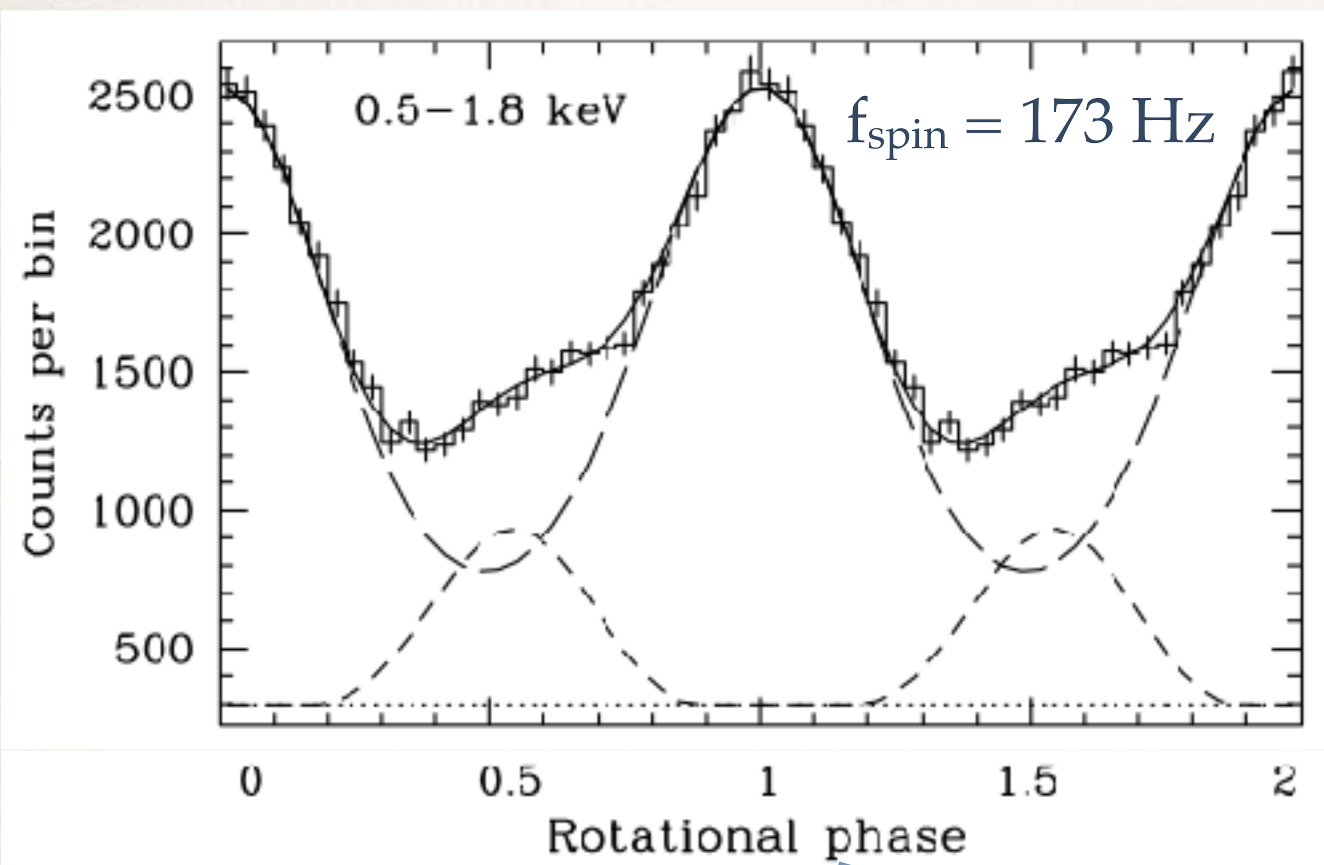
Surface emission model

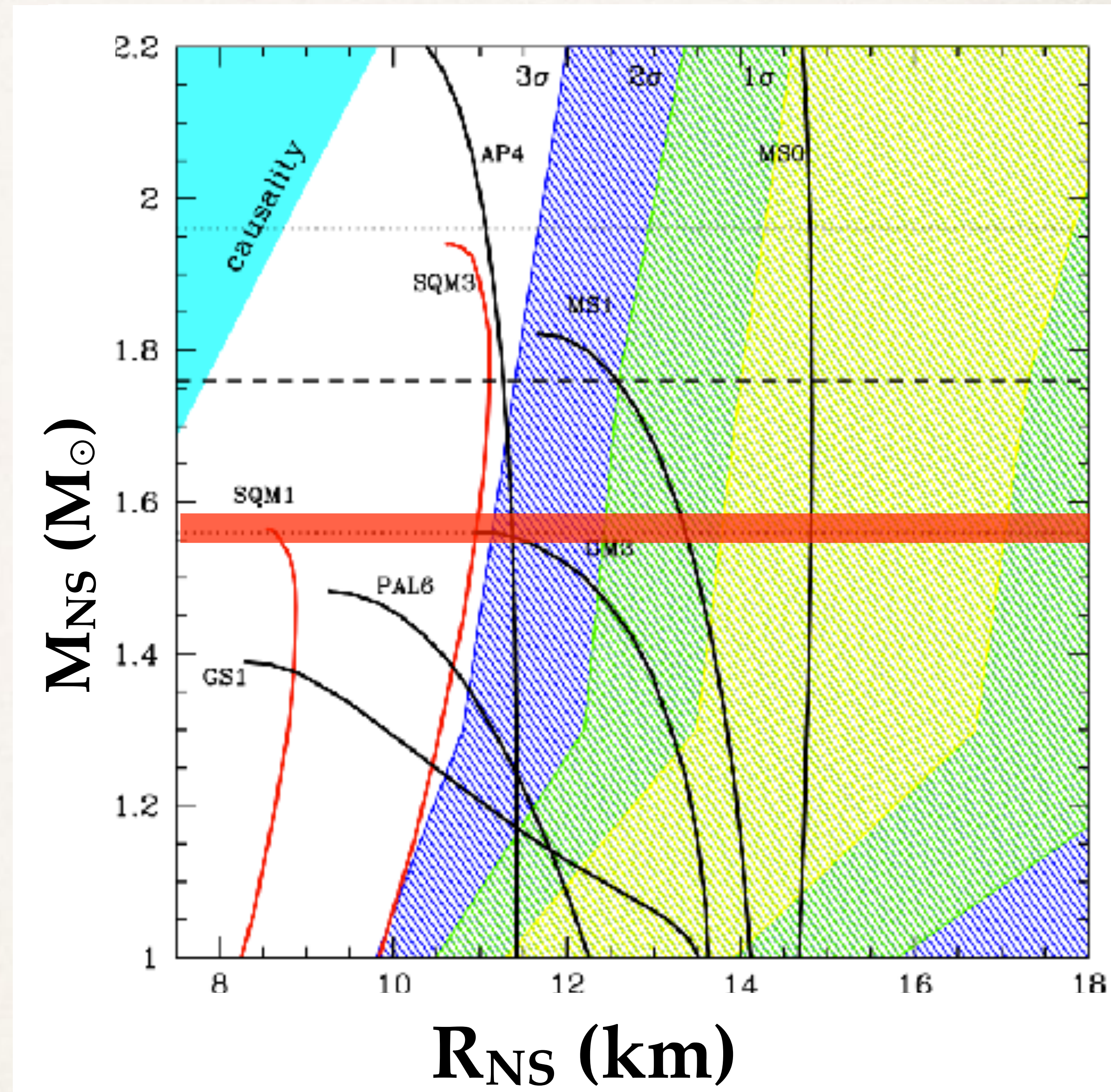
Low-magnetic field, fully-ionized H or He atmosphere



If we can model the lightcurve, it is preferable to know the neutron star mass.

PSR J0437-4715 with XMM-Newton





M/R extracted from lightcurve

Bogdanov (2013)

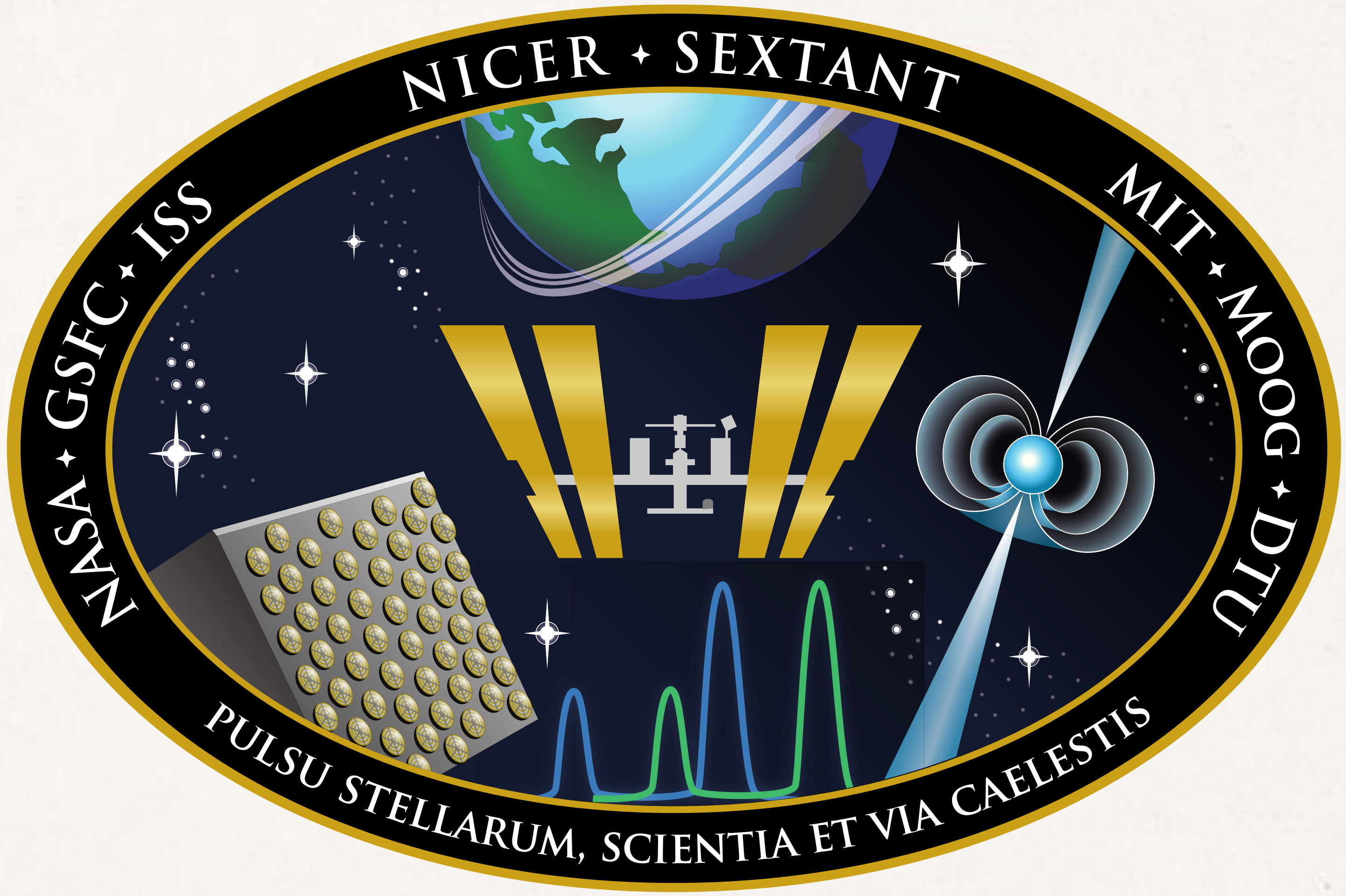
NICER now routinely observes four key target millisecond pulsars.

Analysis is in progress…

There are some difficulties involved with the lightcurve modelling technique used by NICER.

- **Atmospheric composition?**
- **Hot spots properties (these are fitted, but there are some degeneracies)**
- **Difficult to precisely determine the NICER background (non X-ray and X-ray backgrounds)**

What’s new?


NICER ✦ SEXTANT
MIT ✦ MOOG ✦ DTU
NASA ✦ GSFC ✦ ISS
PULSU STELLARUM, SCIENTIA ET VIA CAELESTIS

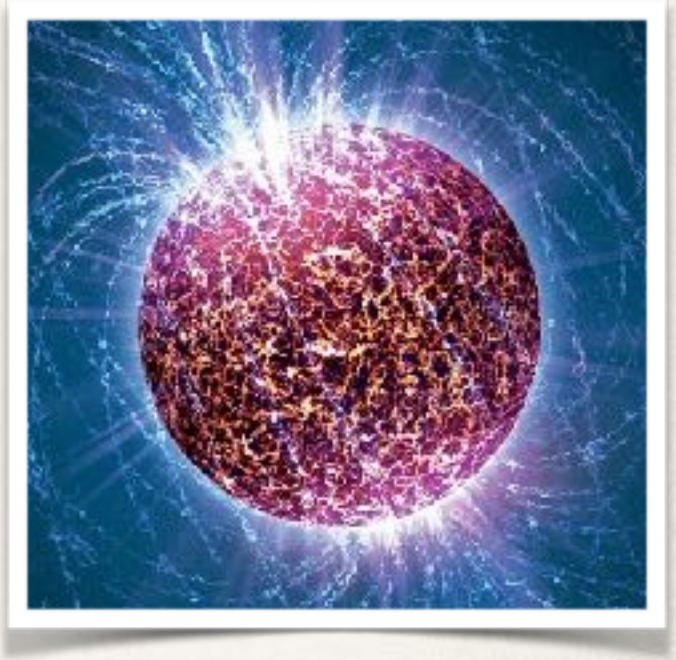
Stay tuned…

X-ray observations of thermally-cooling neutron stars permit obtaining the radius.

To measure the radius, we need to:

- observe/model the surface emission,
- know the distance independently.

$$F_X \propto \left(\frac{R_\infty}{D}\right)^2 \sigma T^4$$



Neutron stars in quiescent low-mass X-ray binaries

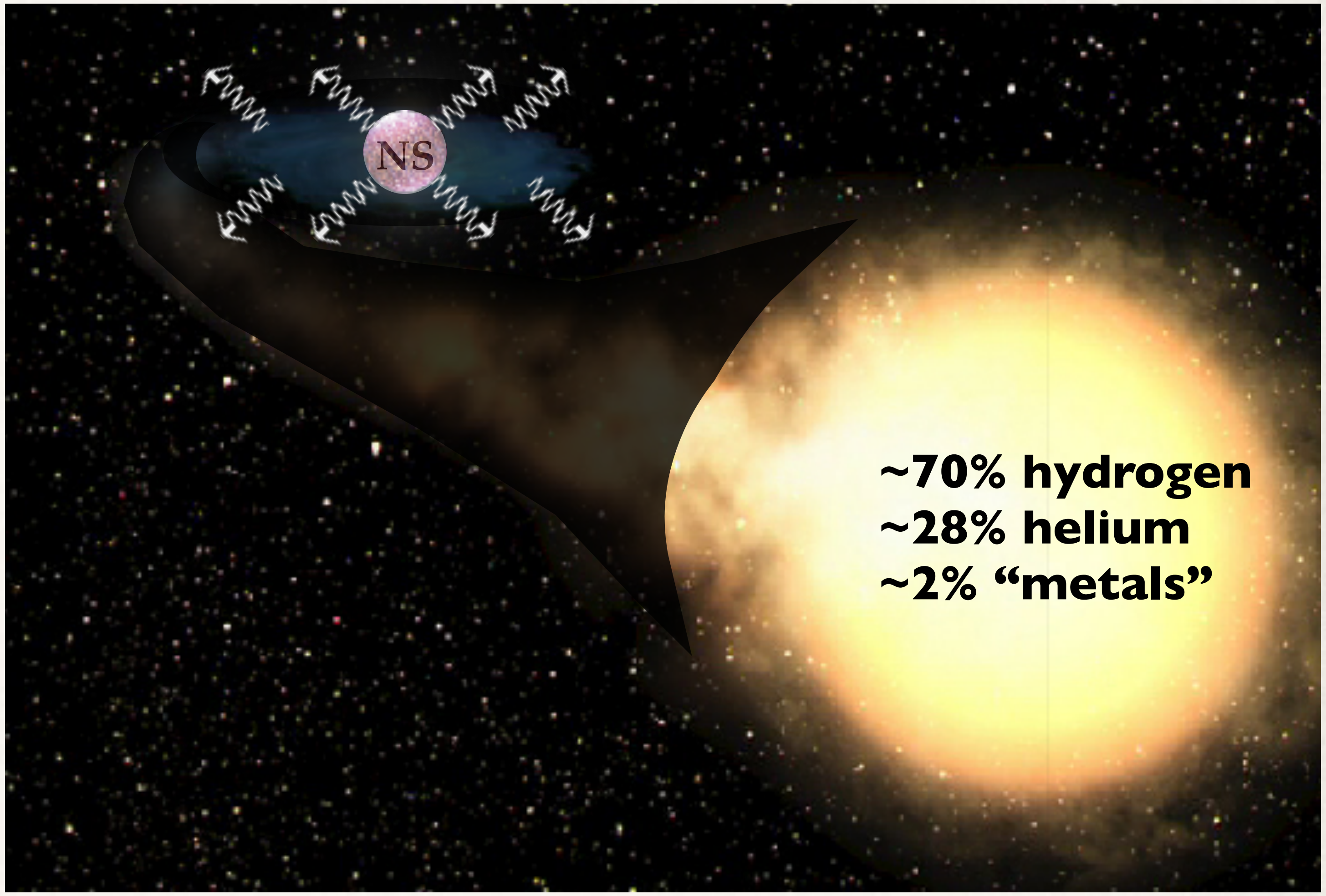
Neutron stars in supernova remnants

Thermally-cooling isolated neutron stars

Neutron stars with thermonuclear bursts

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



$$F_X \propto \left(\frac{R_\infty}{D}\right)^2 \sigma T^4$$

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

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

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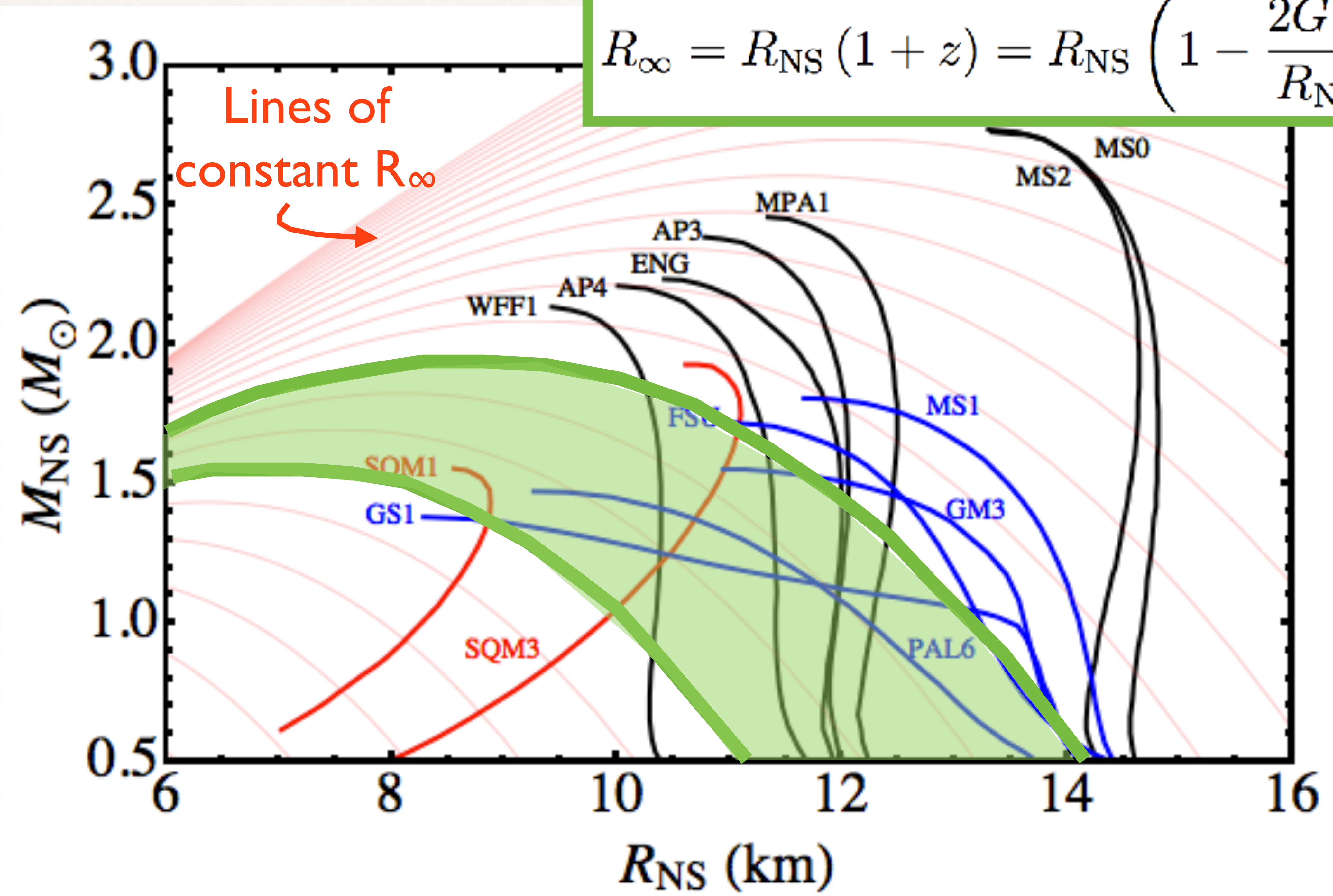
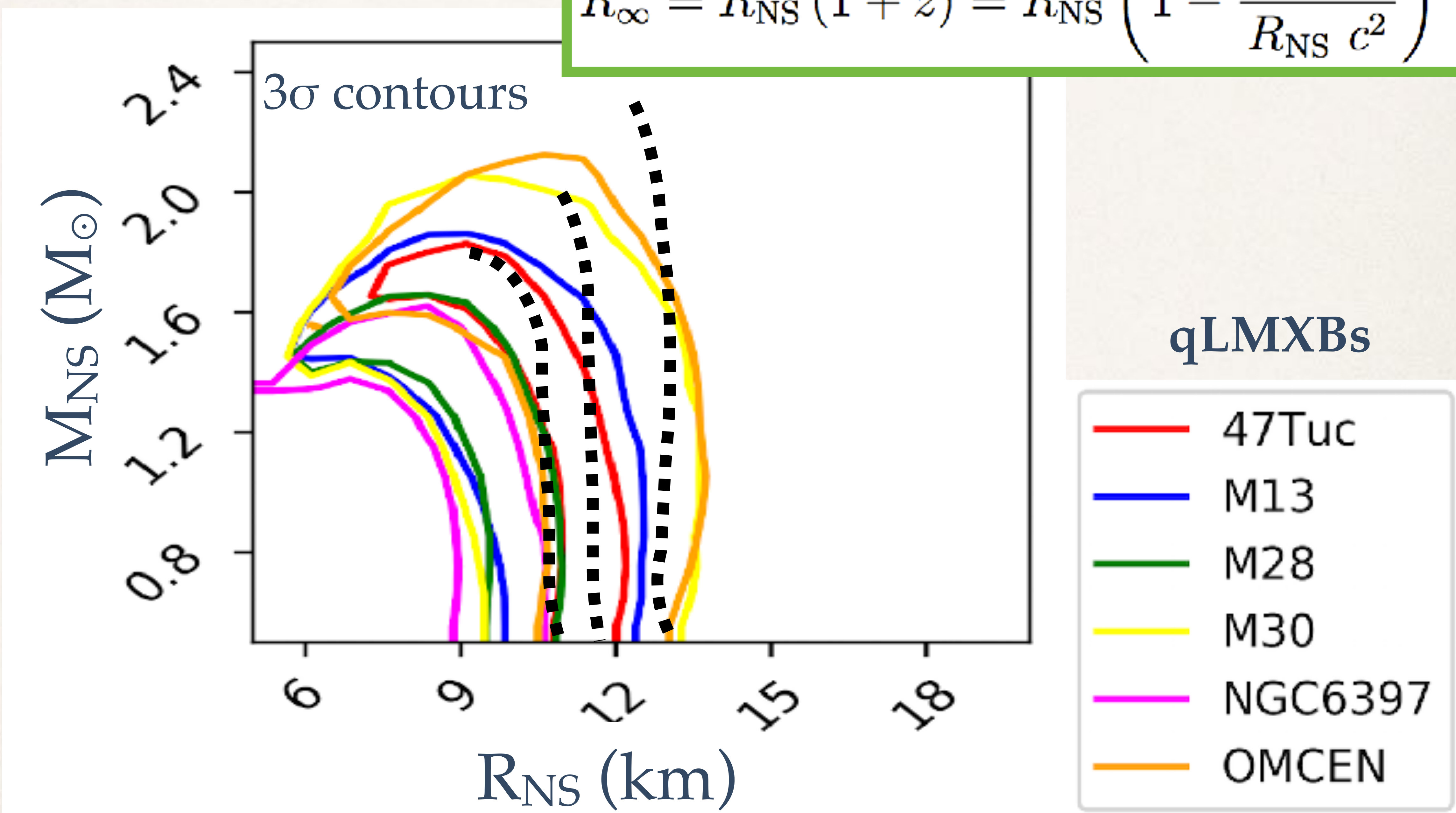
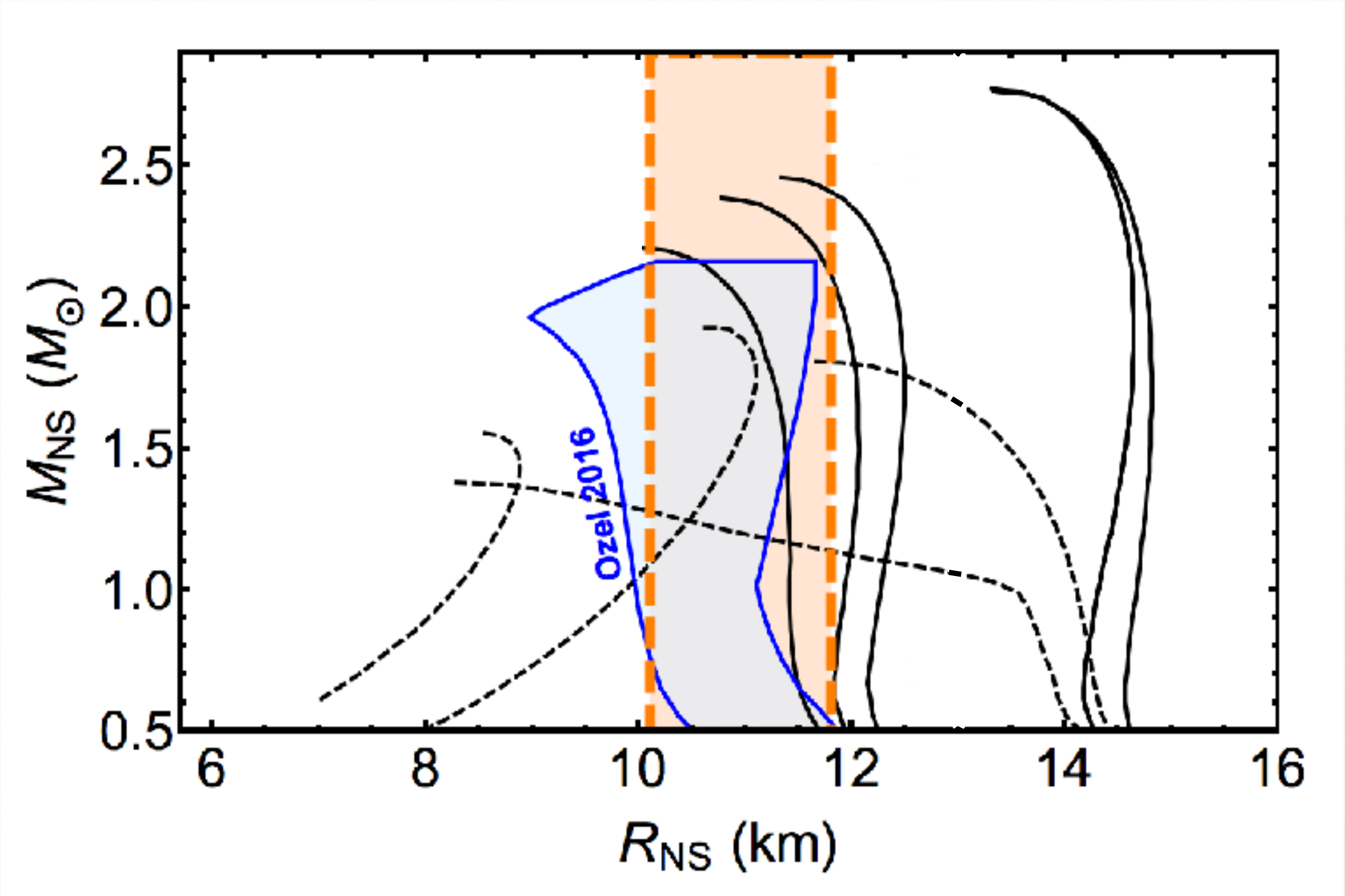


We want to find which equation of state is common to all these M-R measurements.

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



Some constraints have been obtained using these analytical parameterisations of the EoS.



Özel et al. (2016)

Updated results (2017)

There are some difficulties involved with the surface thermal emission technique.

- NS atmospheric composition
- NS surface temperature distribution

Multi-wavelength observations can help!

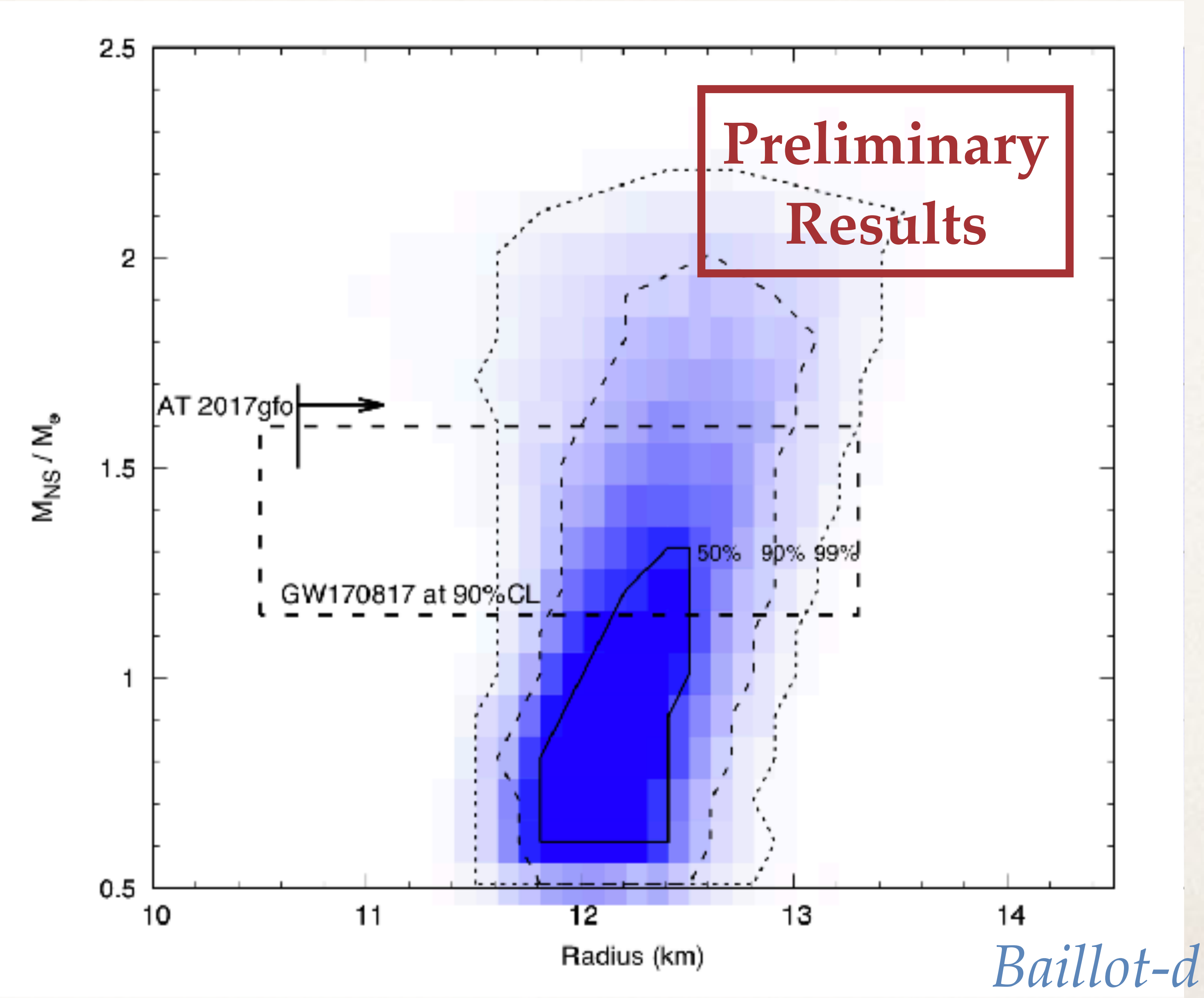
- NS magnetic field and rotation
- Need to parameterise the EoS

What's new?

- **New X-ray data (from Chandra X-ray Observatory)**
- **New distances (expected from Gaia DR3)**
- **New method (realistic parameterisation of the EoS)**

Using a realistic parameterisation of the equation of stat, we improve on previous estimates.

$$P = f\left(\rho, E_{\rm sat}, E_{\rm sym}, L_{\rm sym}, K_{\rm sym}, K_{\rm sat}, Q_{\rm sat}, \ldots\right)$$



Baillot-d'Etivaux, et al.

X-ray observations of thermally-cooling neutron stars permit obtaining the radius.

To measure the radius, we need to:

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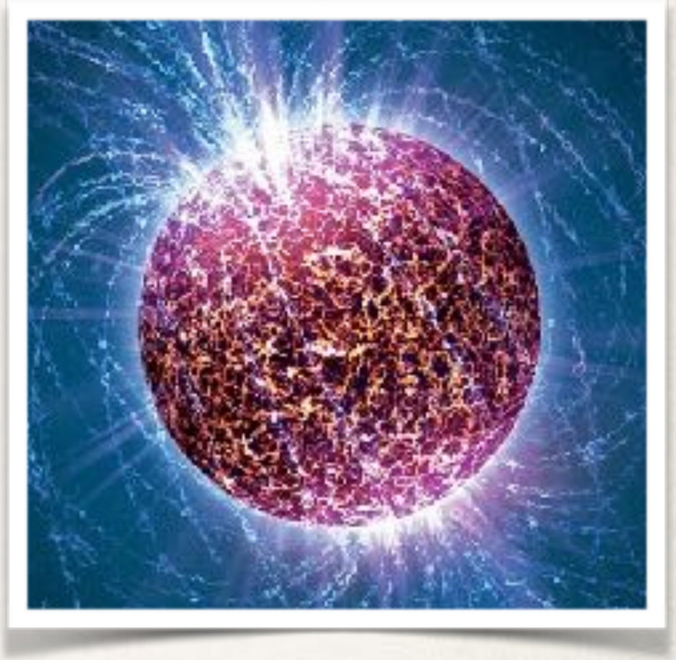

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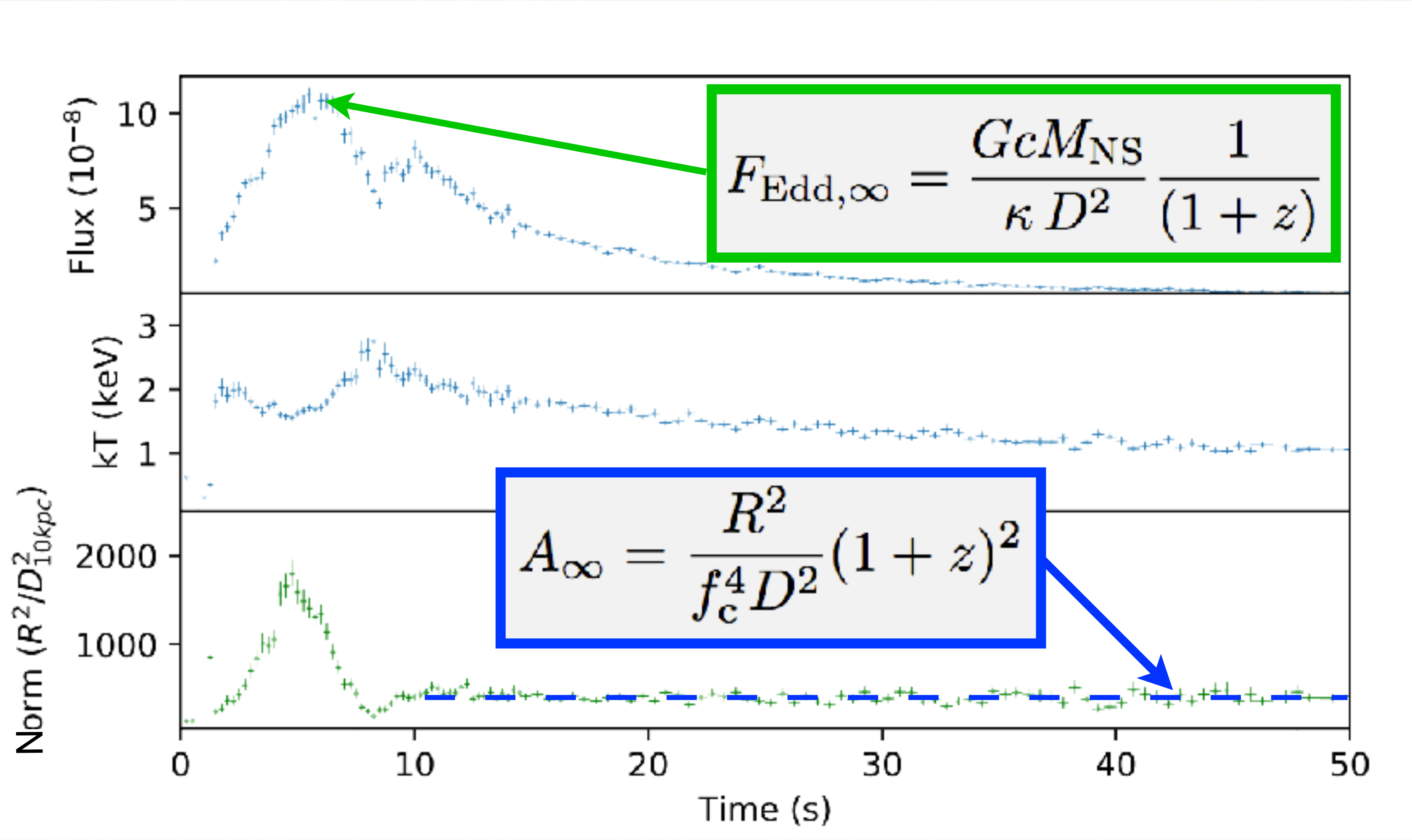
Some LMXBs exhibiting thermonuclear bursts with Photospheric Radius Expansion.

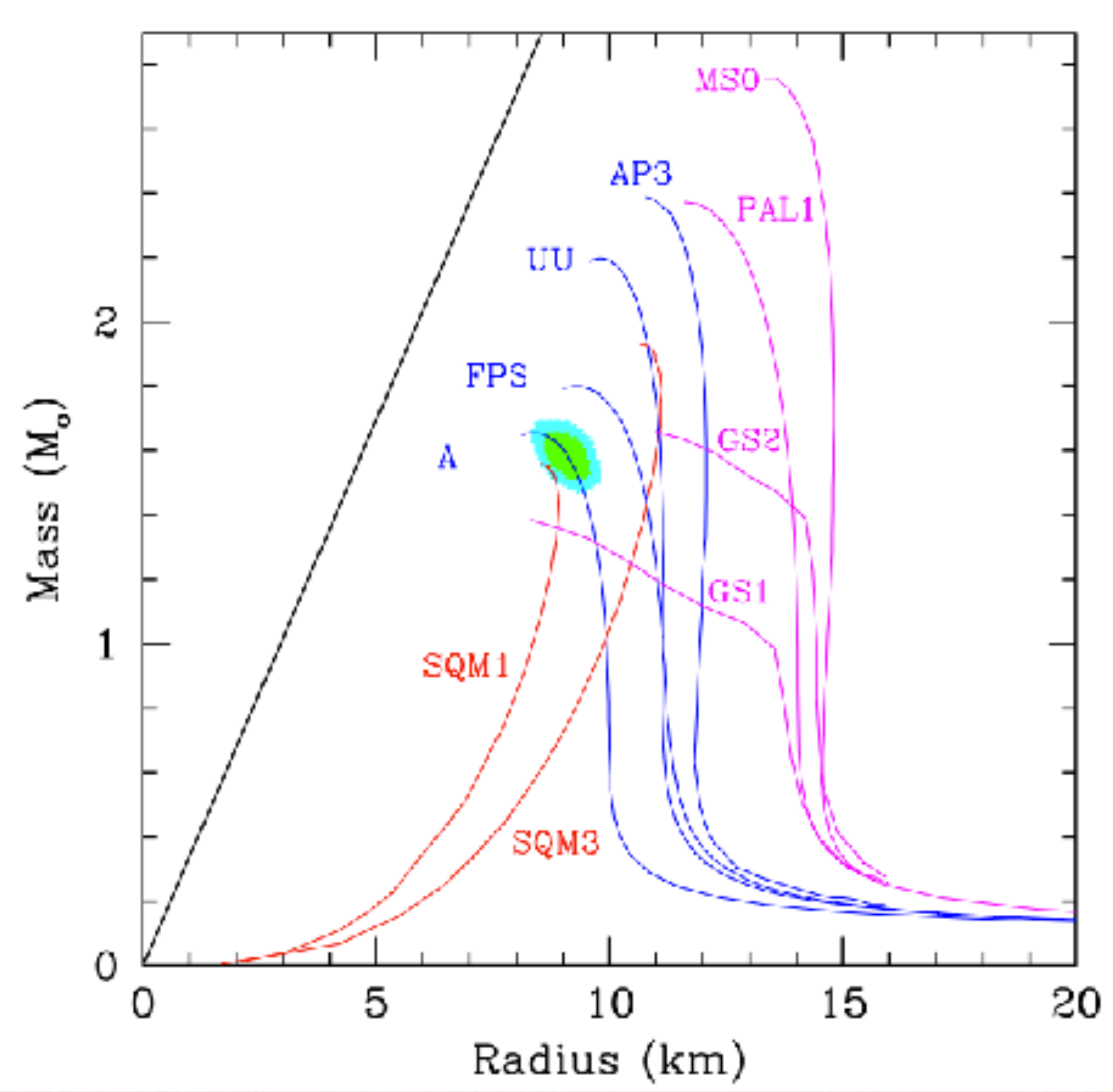
$$L_{\mathrm{Edd}} = \frac{4\pi G c M_{\mathrm{NS}}}{\kappa}$$

The peak flux correspond to the Eddington flux, and the cooling tail gives the size of the emitting area.



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

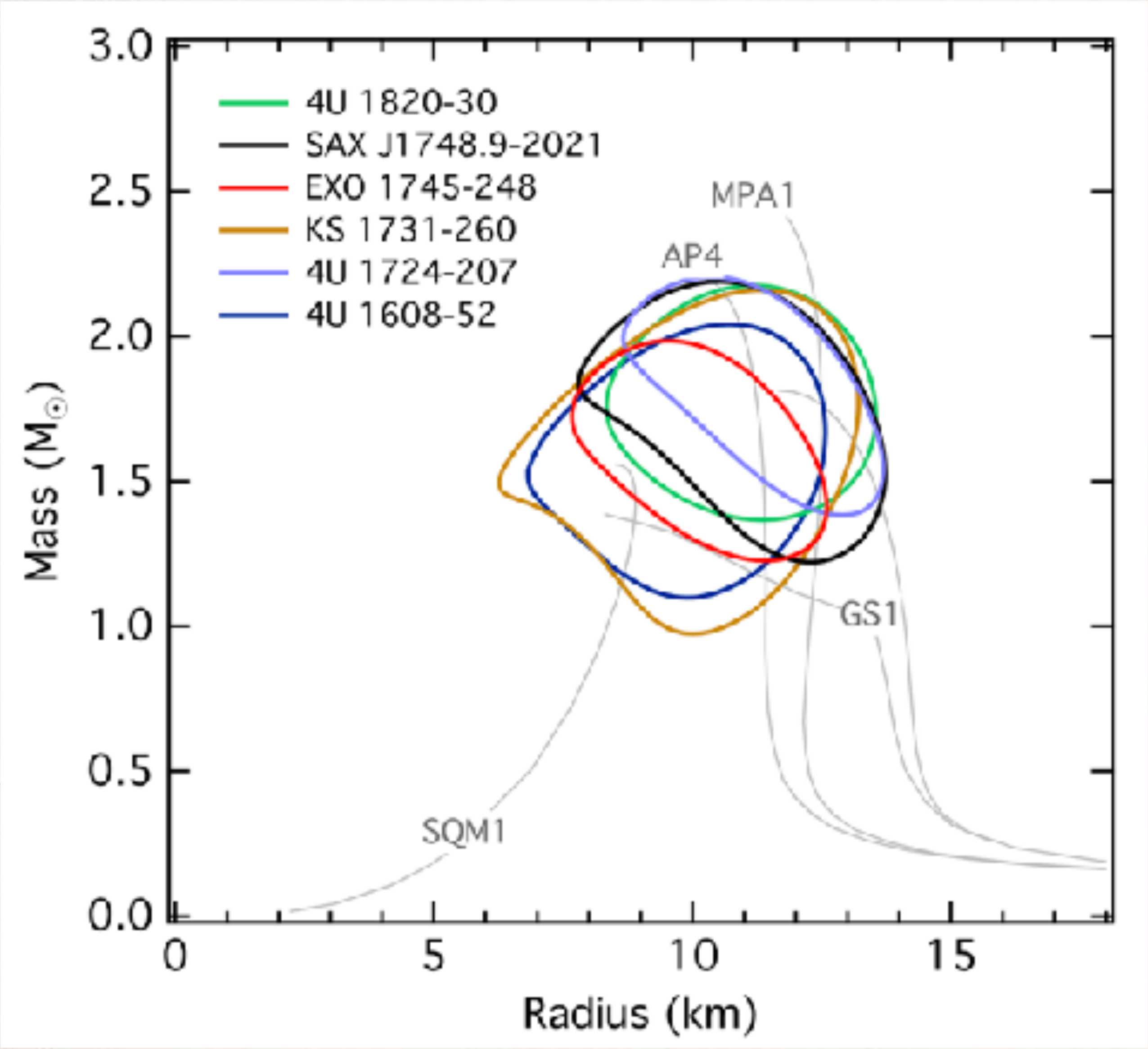
Different analyses and types of sources result in different constraints…



4U 1820–30

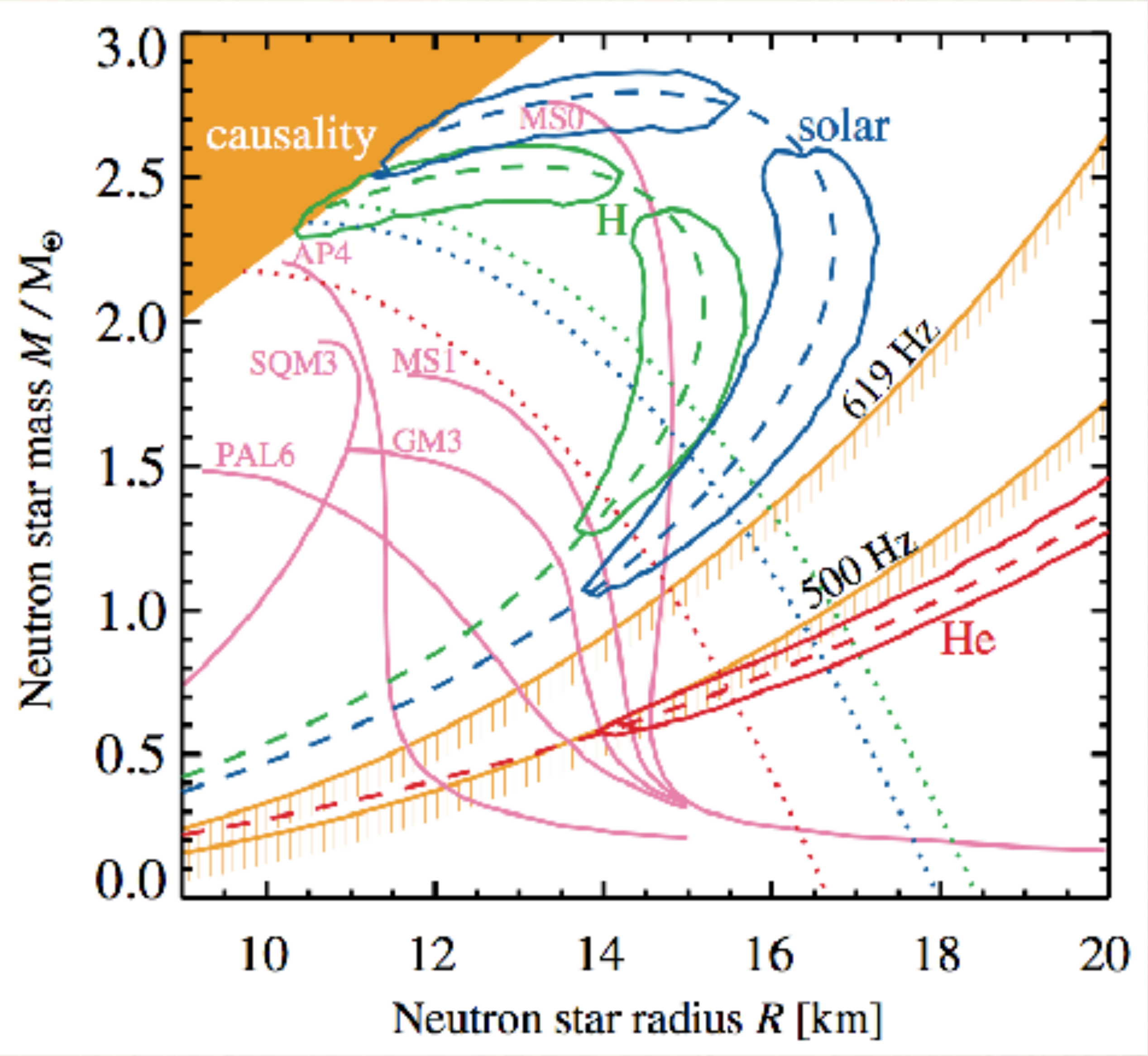
Güver et al. 2010

Different analyses and types of sources result in different constraints…It's a heated debate!



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

Özel et al. 2016



Theory-driven selection of low-hard state bursts

Suleimanov et al. 2011

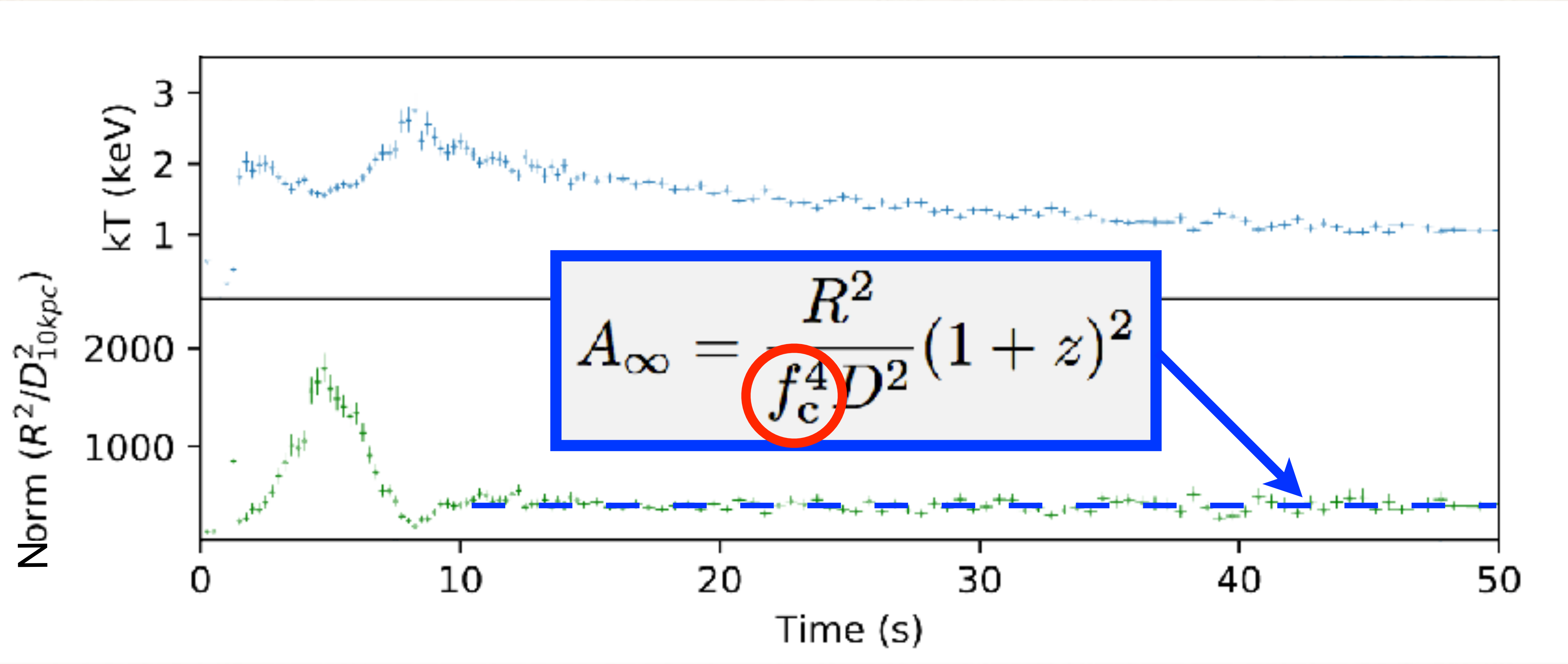
There are some difficulties involved with the Type I X-ray burst technique.

- Atmosphere modelling (i.e., the conversion to/from a blackbody with a colour correction factor f_c)
- Neutron star atmospheric composition
- Distance sometimes unknown

What's new?

- **New method!**
- **New instrument (NICER)**
- **New "problem"**

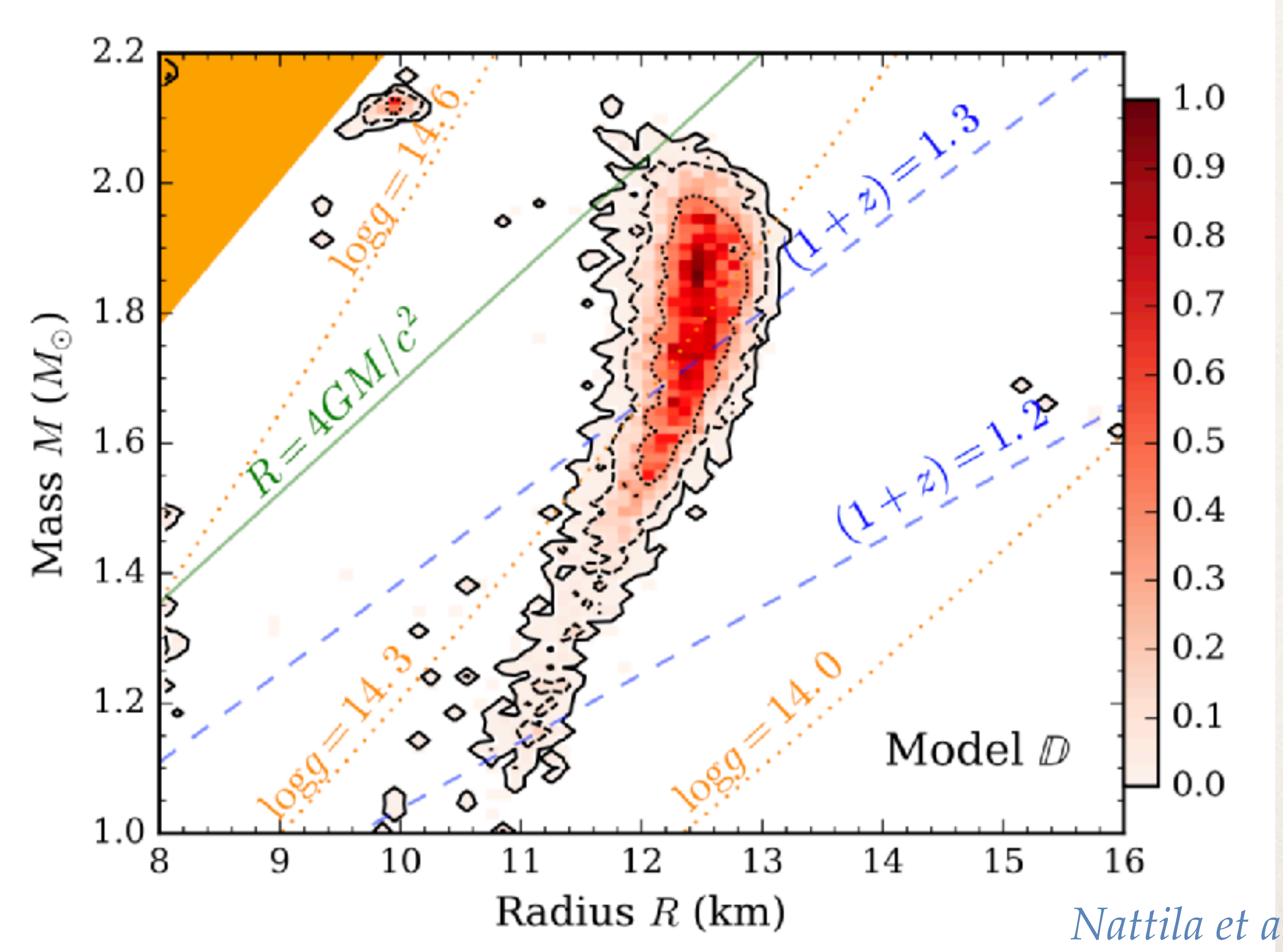
Until recently, the thermal emission was fit with a Planck function, and a colour-correction was used.



f_c is model dependent!

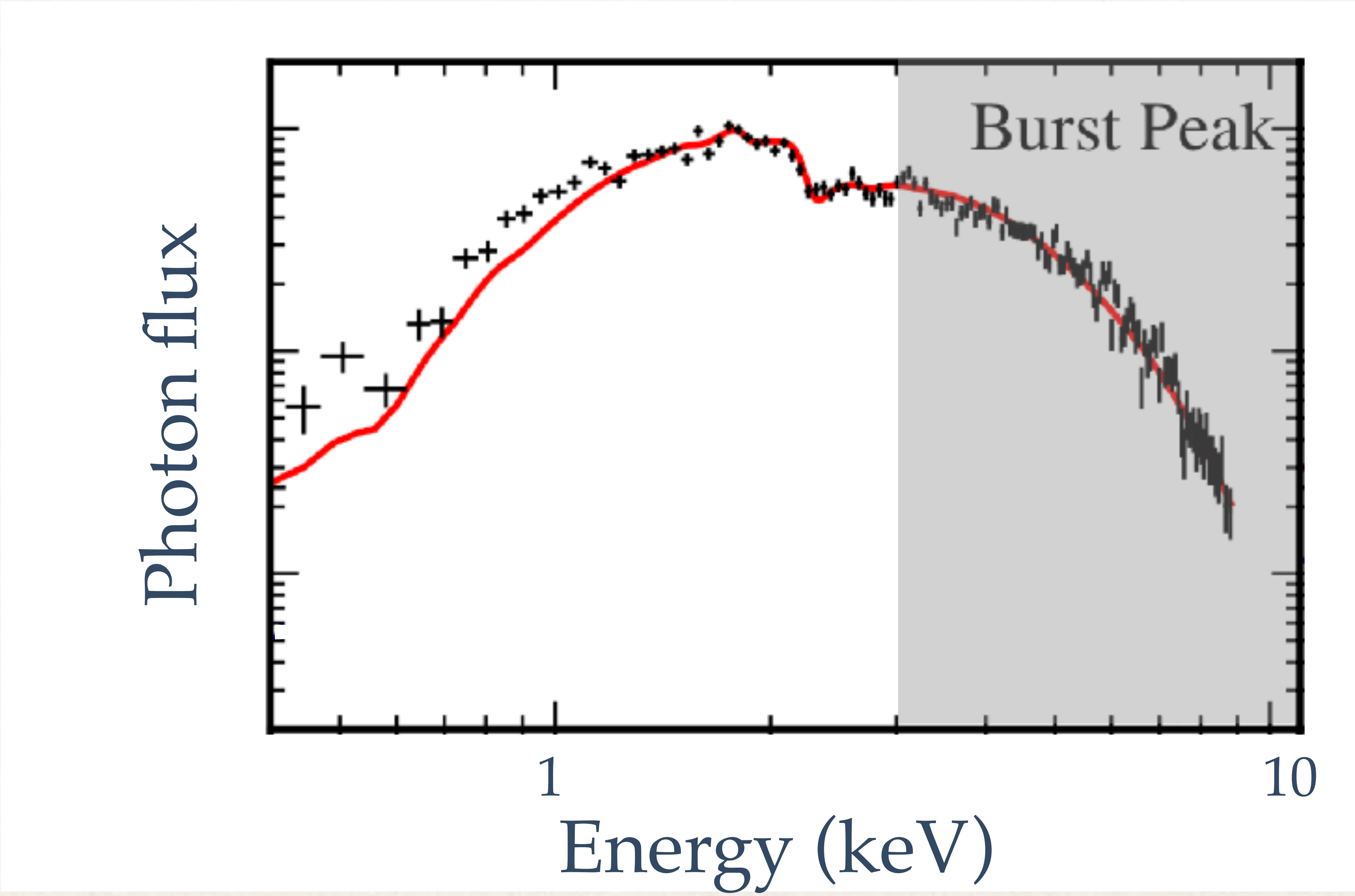
<u>Solution</u>: fit every single spectrum with realistic model

Recent work



Nattila et al. 2017

The observation of type I X-ray burst with NICER showed the presence of a un-modelled soft-E excess.



Keek et al. (2018)

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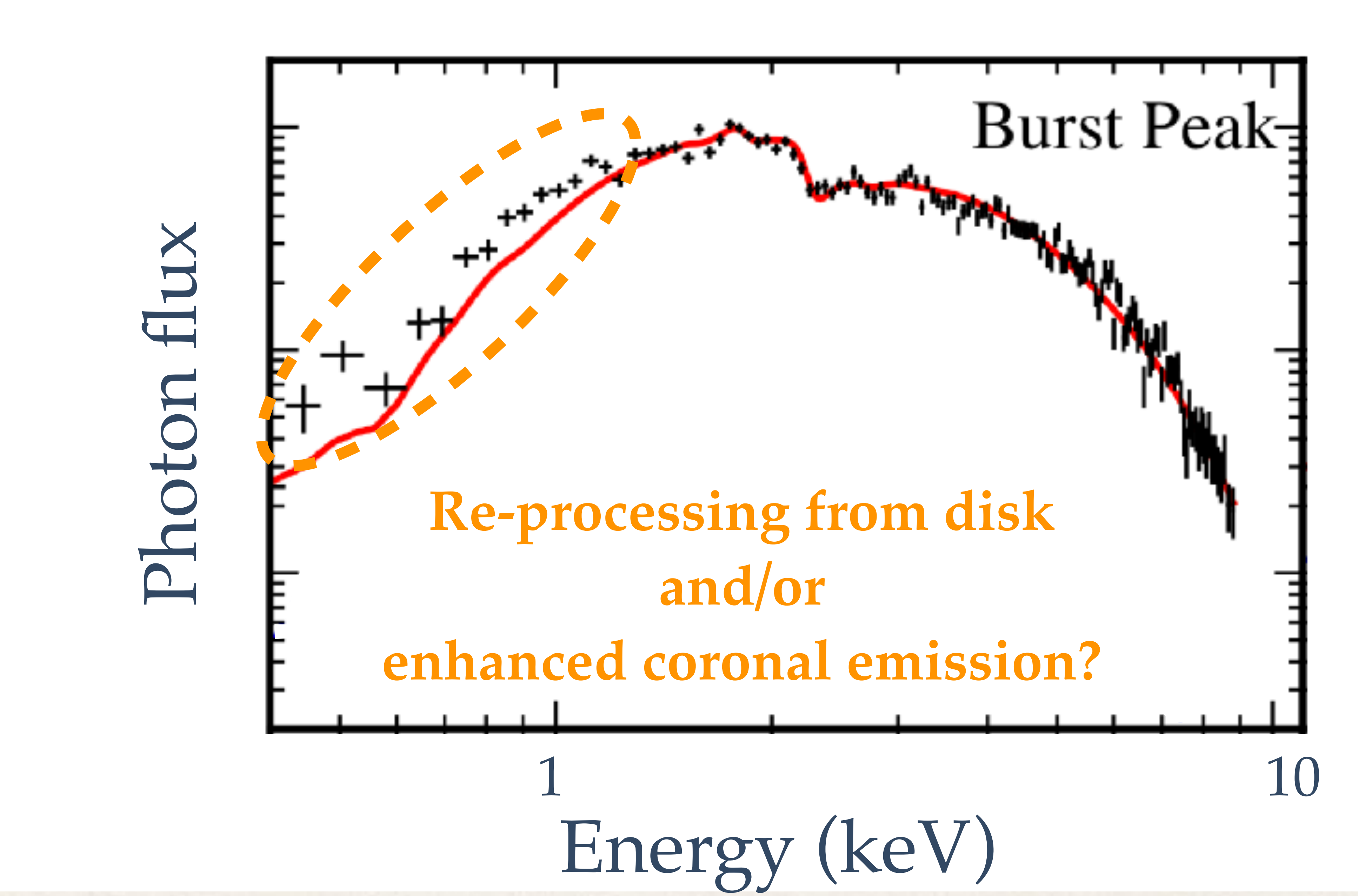
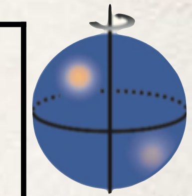
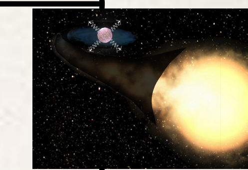


Keek et al. (2018)

Summary – Current status

Pulse-profile of MSP	NICER will produce 4 precise R_{NS} measurements	
Quiescent low-mass X-ray binaries	Some uncertainties related to assumptions. Need parameterisation of EOS (or masses).	
Isolated neutron stars (and CCOs)	Atmosphere modelling difficult (e.g. magnetic field and composition)	
Type-I X-ray bursts	Some modelling uncertainties. Understand the effects of accretion?	
GW from NS-NS merger	Promising technique! But only 1 event so far	
Moment of inertia (radio timing)	Spin-orbit coupling needs decades of data	
Moment of inertia (bow-shock PWN)	Two attempts: See Bejger et al. (2002); Romani et al. (2017)	
Max. rotation of NSs	Look for more pulsars and hope for a faster one	

Summary – Current results

Pulse-profile of MSP	CAN'T TELL YOU!!!
Quiescent low-mass X-ray binaries	R_{NS} ~ 10 – 13 km
Isolated neutron stars (and CCOs)	R_{NS} ~ 10 – 14 km
Type-I X-ray bursts	R_{NS} ~ 11 – 13 km
GW from NS-NS merger	R_{NS} ~ 10.5 – 13.5 km
Moment of inertia (radio timing)	No results yet
Moment of inertia (bow-shock PWN)	$I = 2.4 \times 10^{45}$ g cm^2 – Romani et al. (2017)
Max. rotation of NSs	Limits from fastest pulsar: $R_{NS} < 17$ km