An overview of equation of state constraints from EM observations of neutron stars.

Sebastien Guillot

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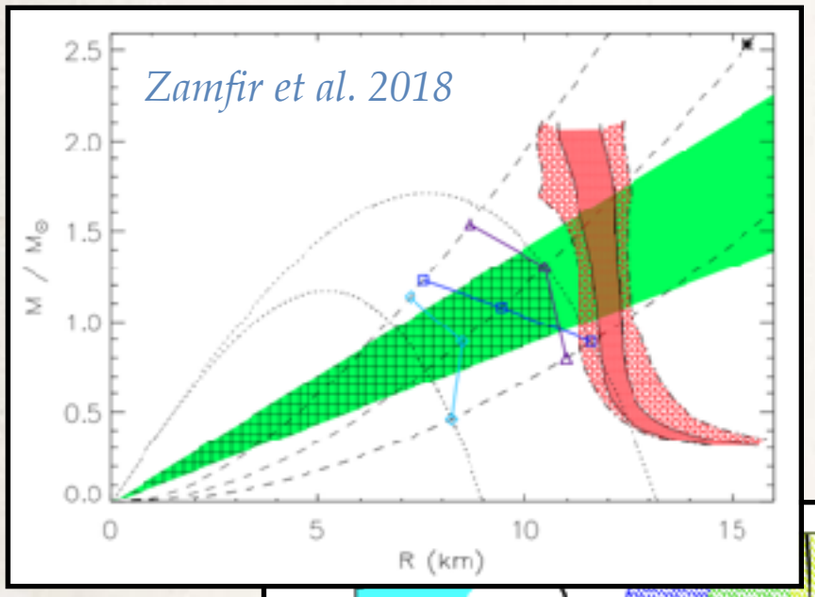
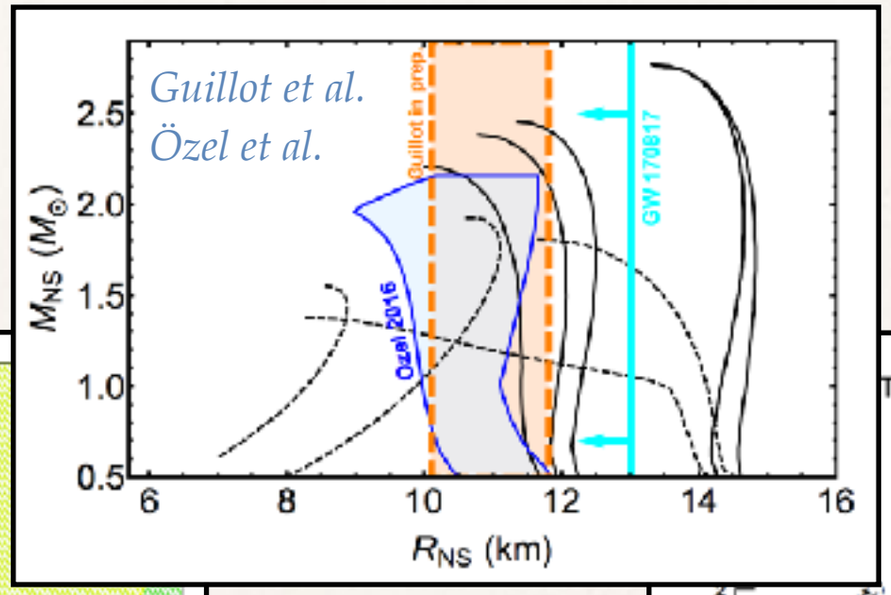
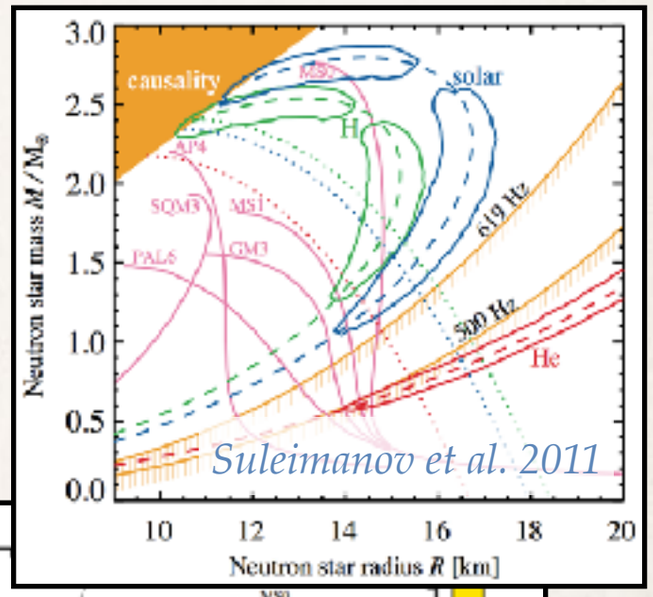
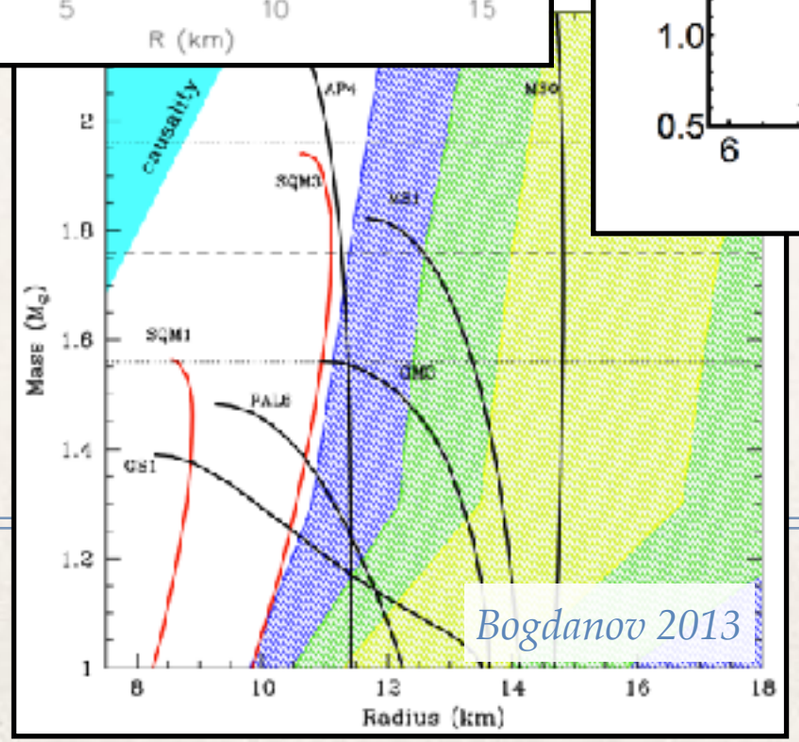
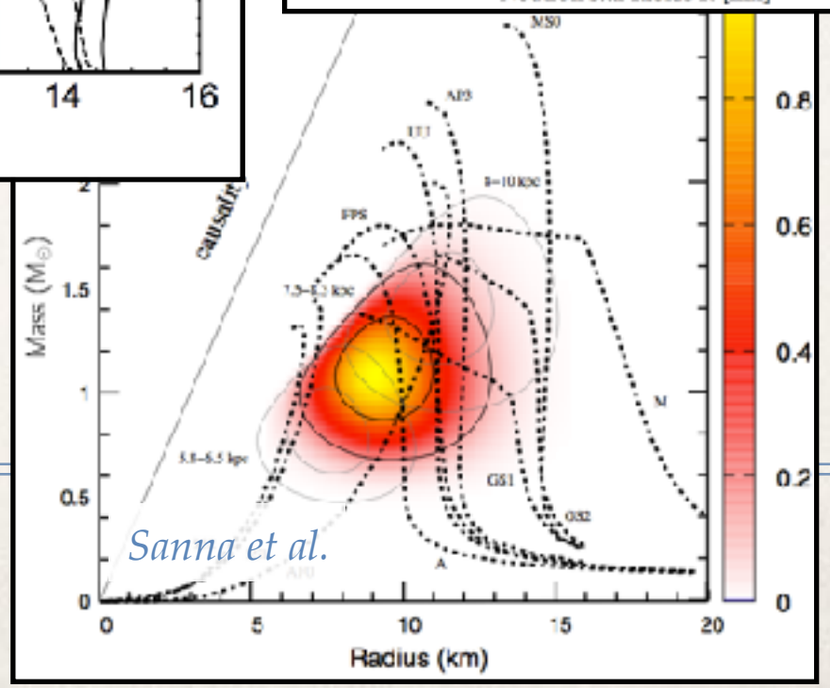
Post-doc CNES







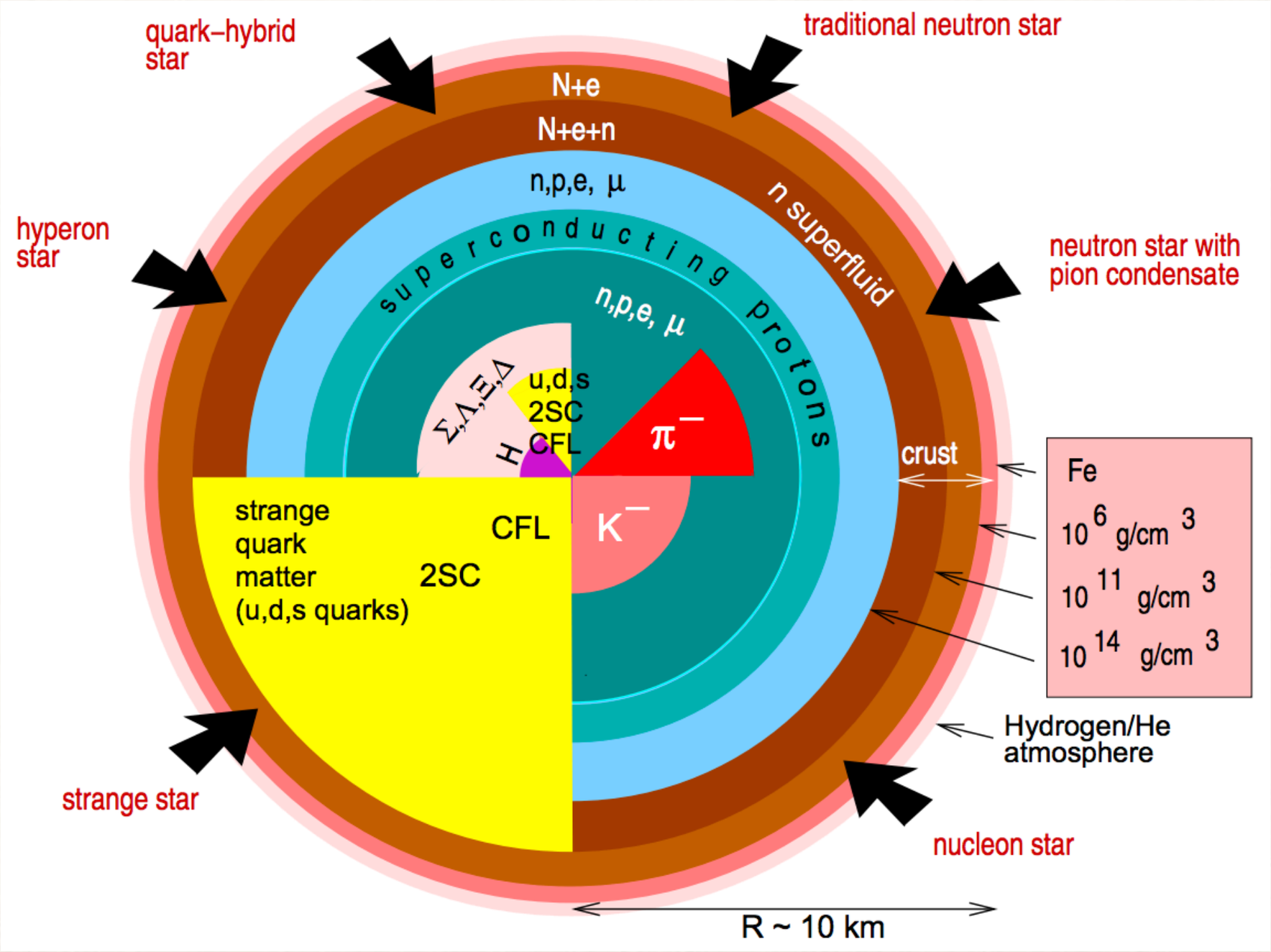




An open question

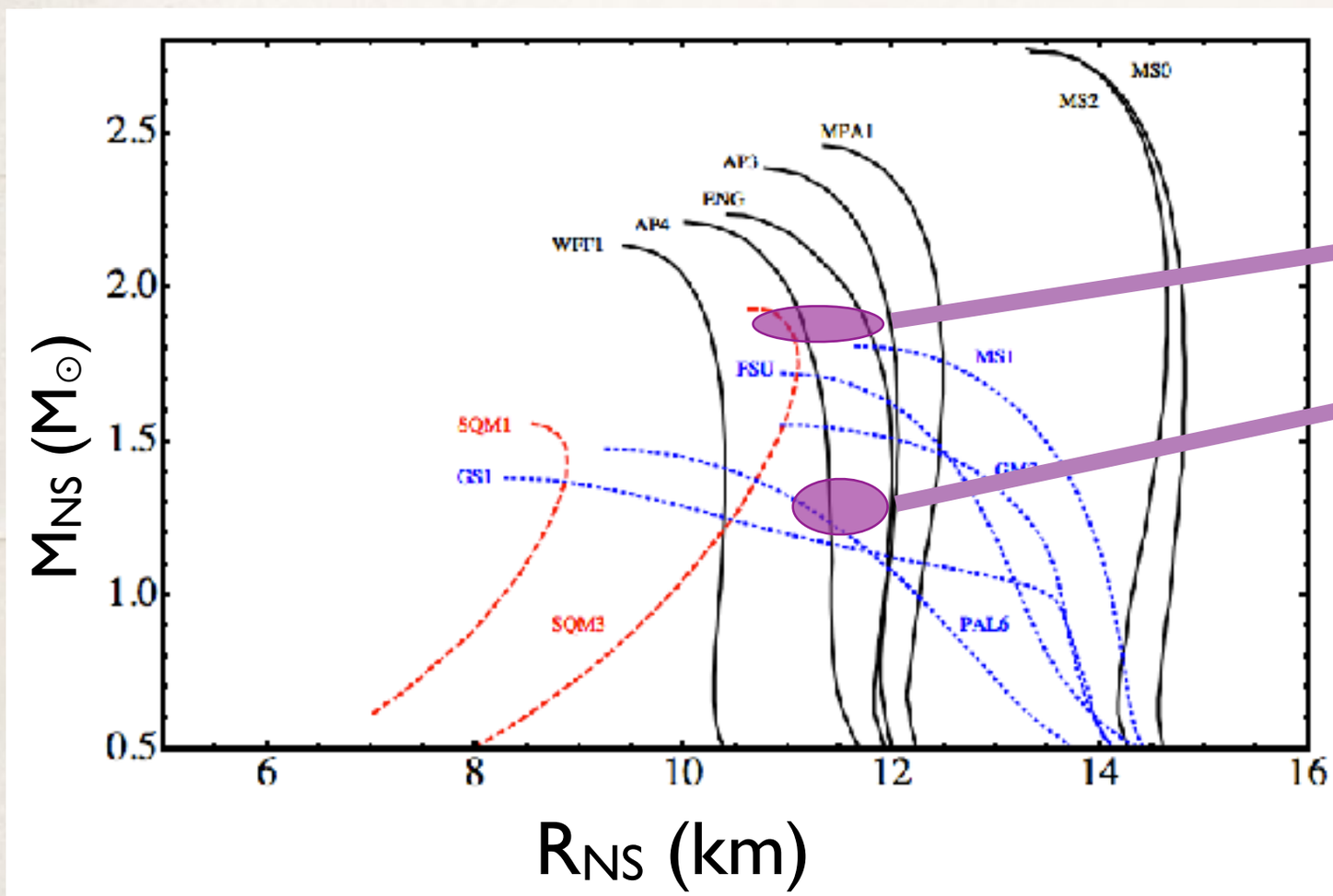
Which observational methods **<u>can</u>** result in reliable and precise measurements of neutron stars radii and masses?

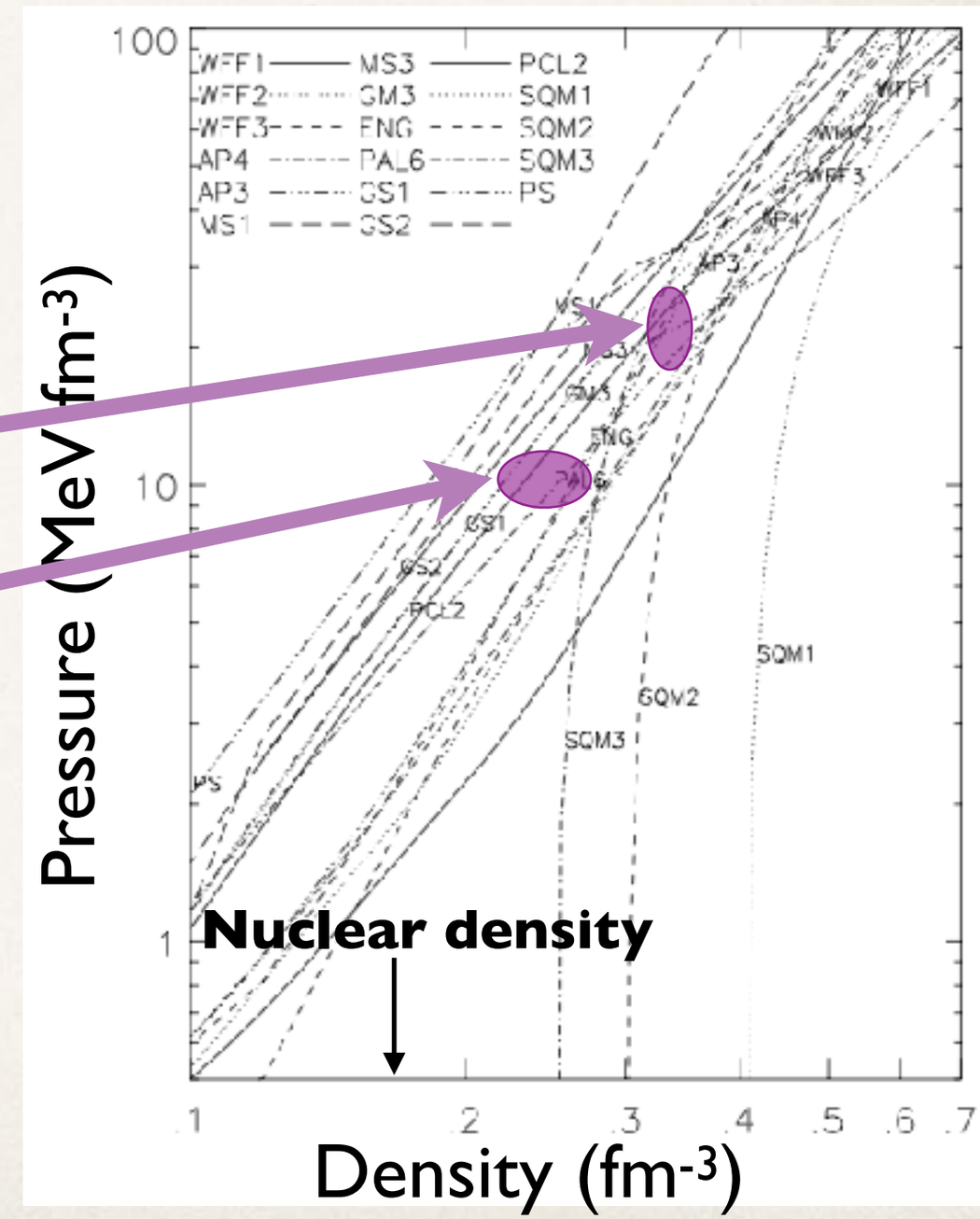
The internal structure of neutron stars is still unknown and many theories are proposed.



Weber et al. 2007

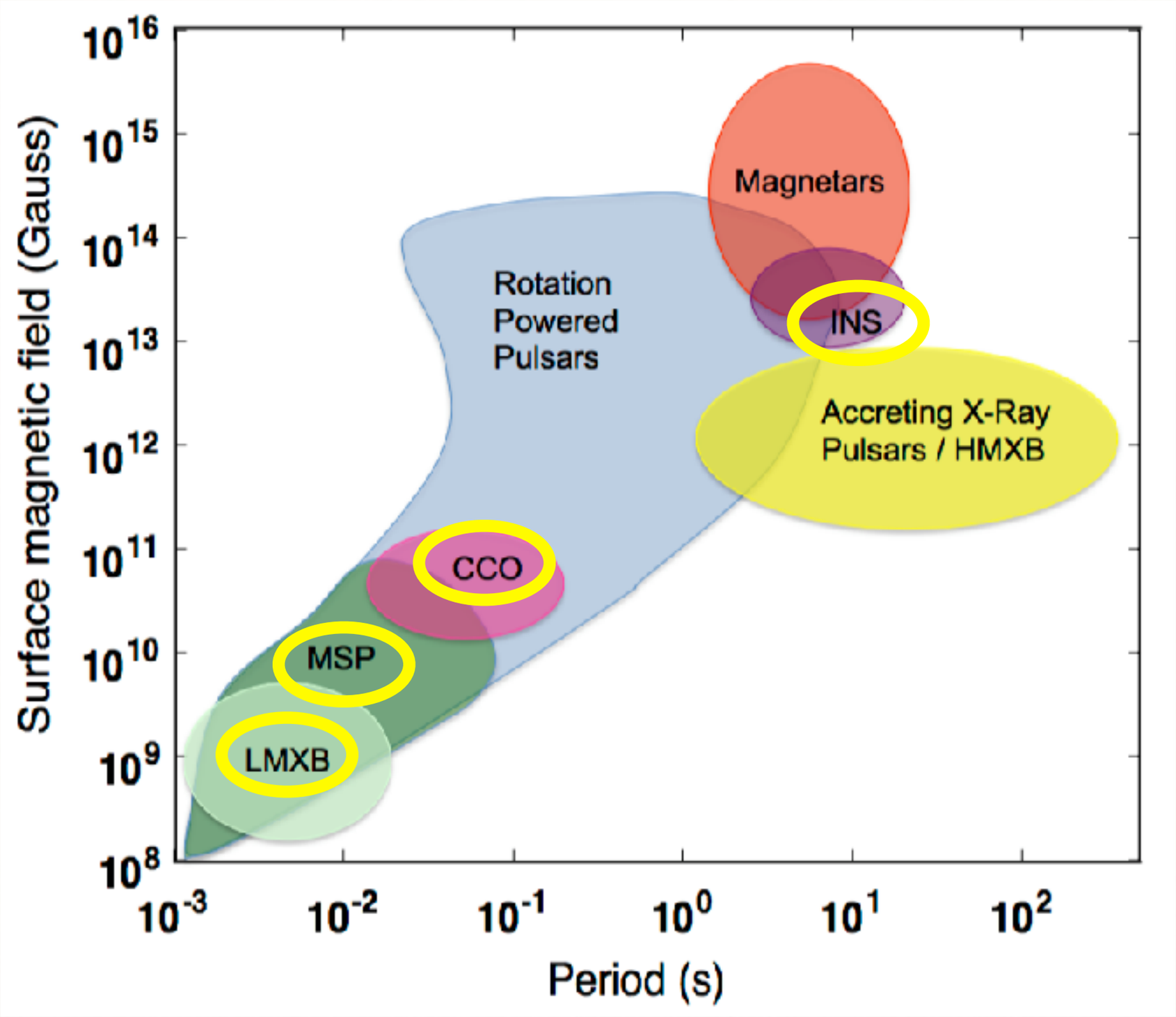
Dense nuclear matter is described by an equation of state P(ρ). But what is it?



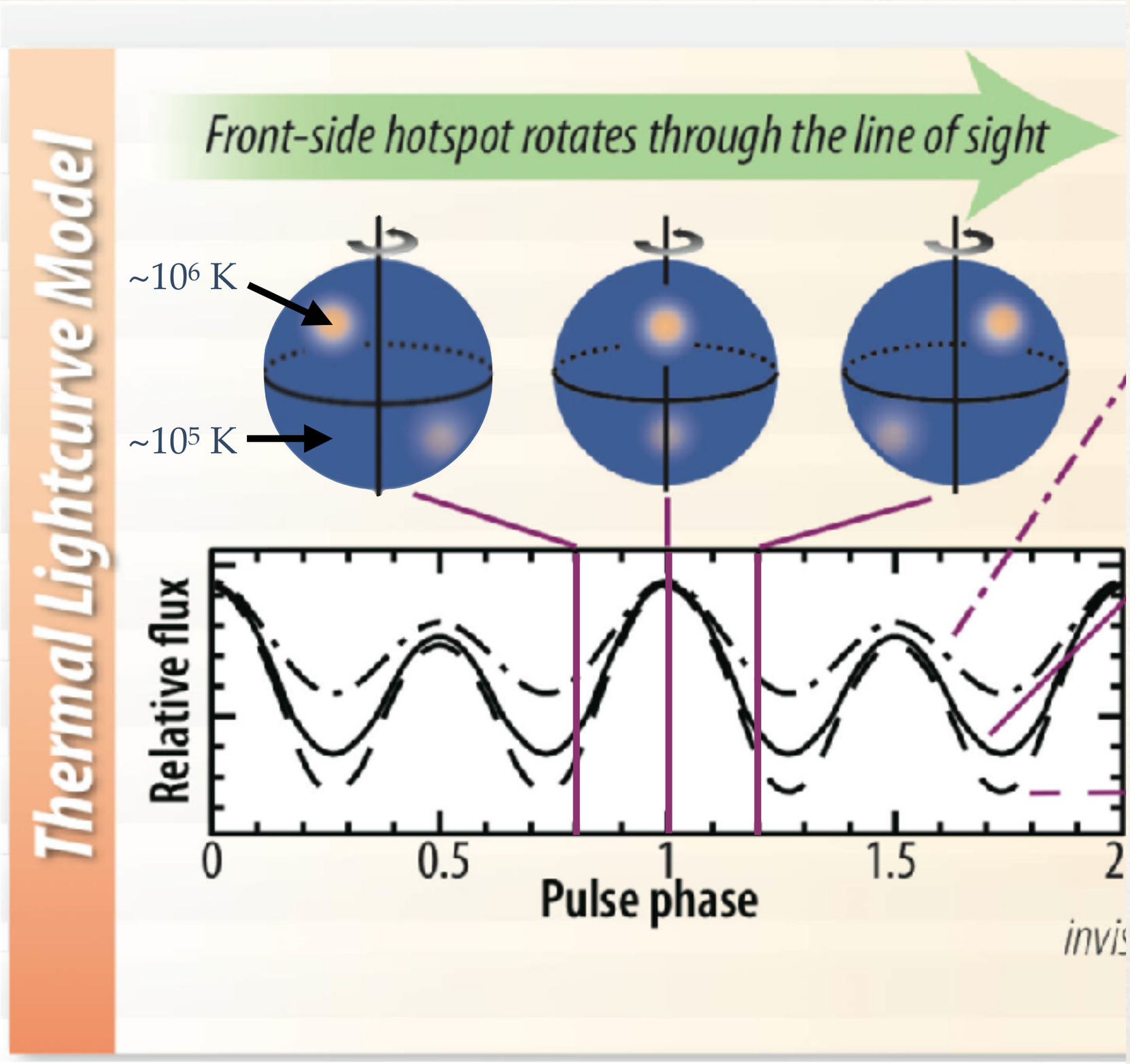


Lattimer and Prakash 2001

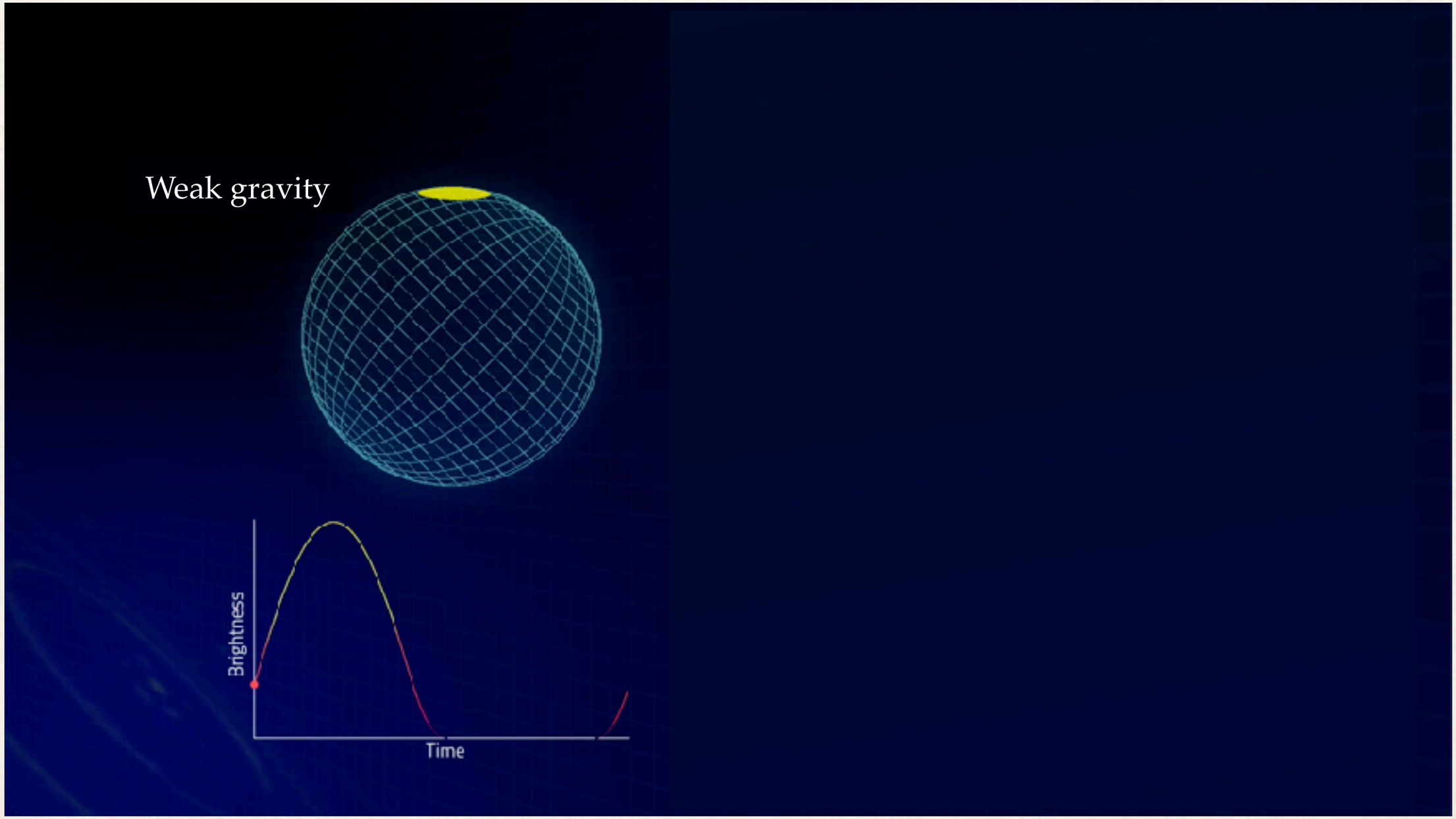
Neutron stars with different properties and observational signatures can be useful for R_{NS} measurements.



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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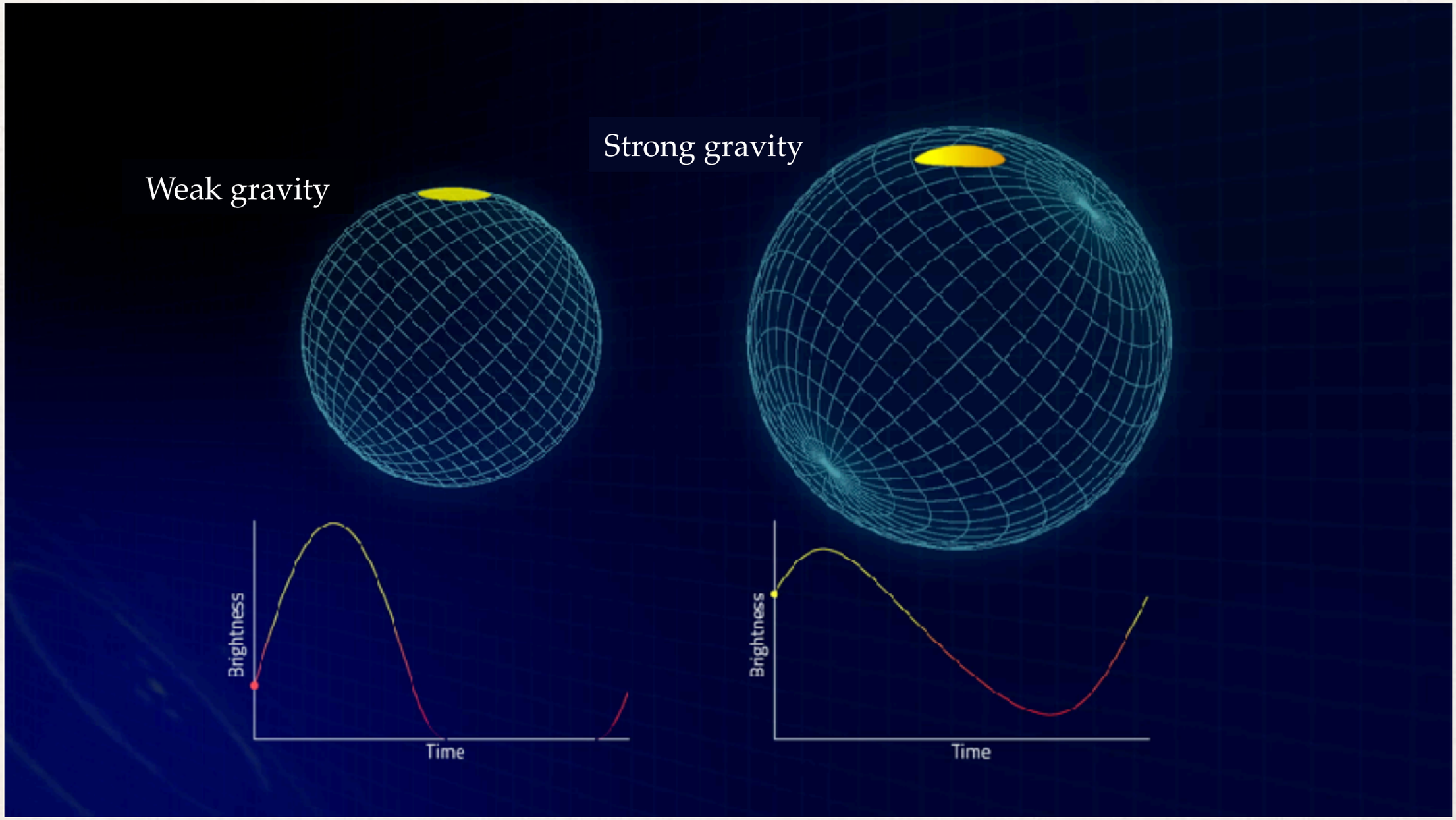
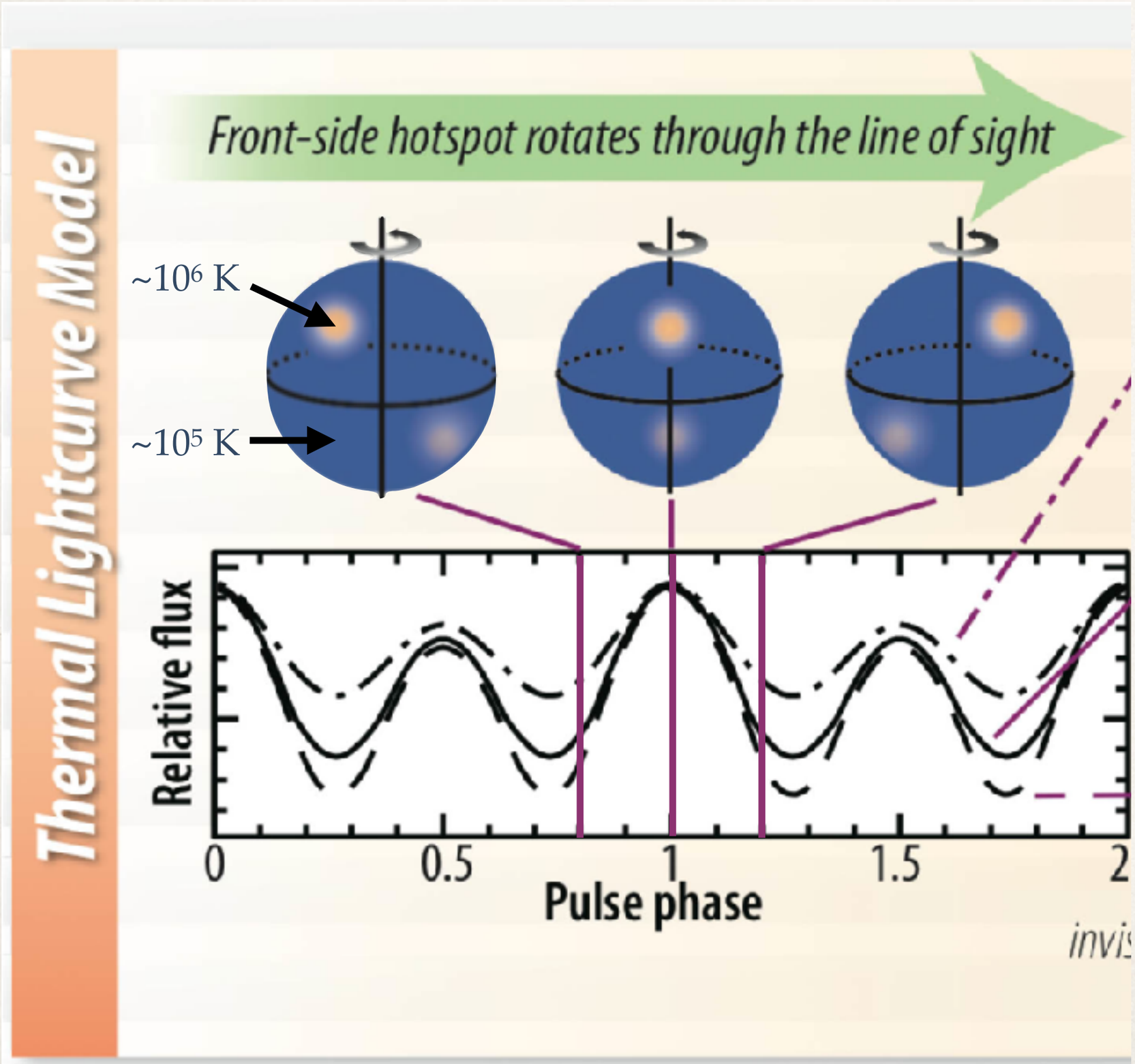
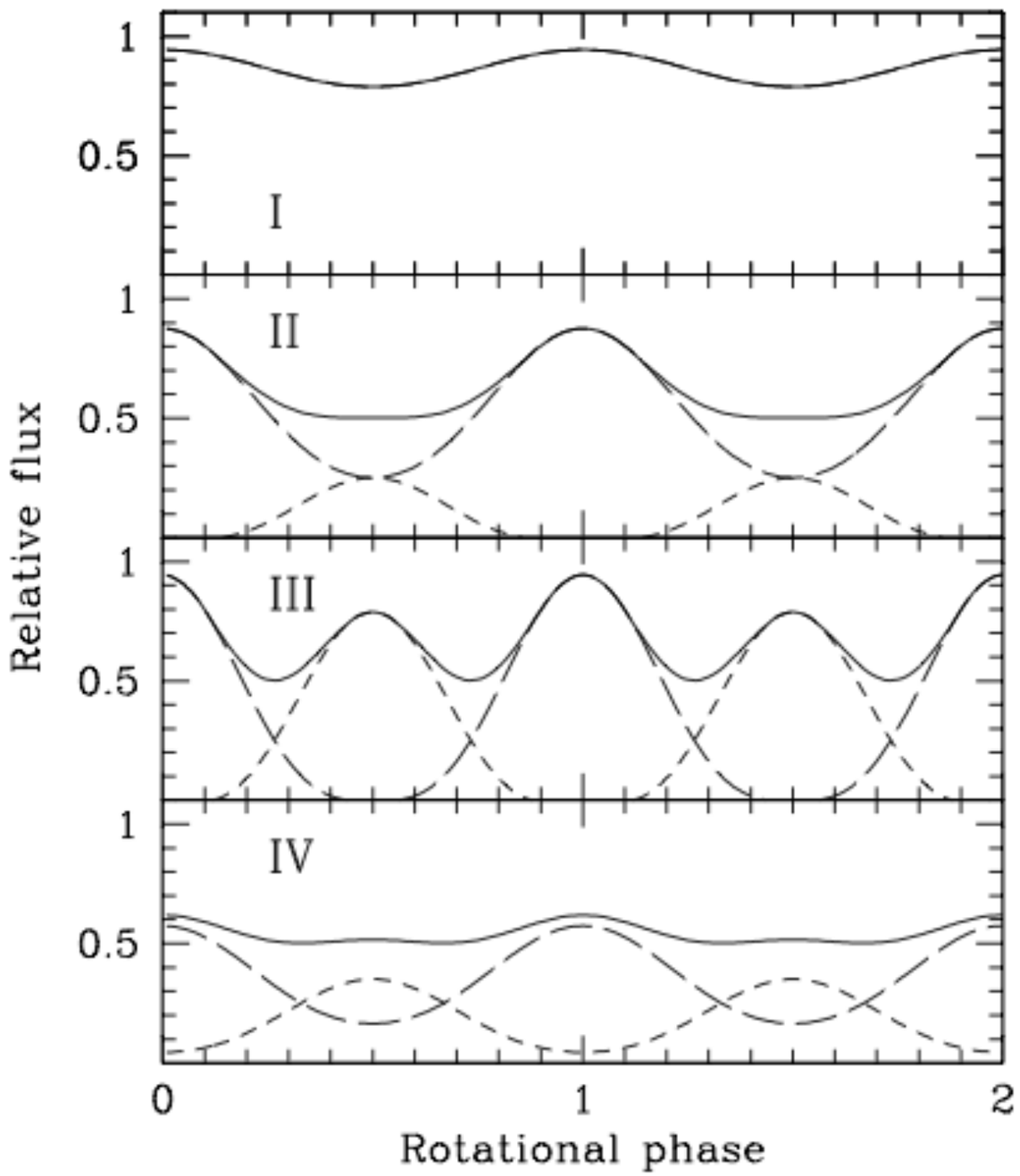


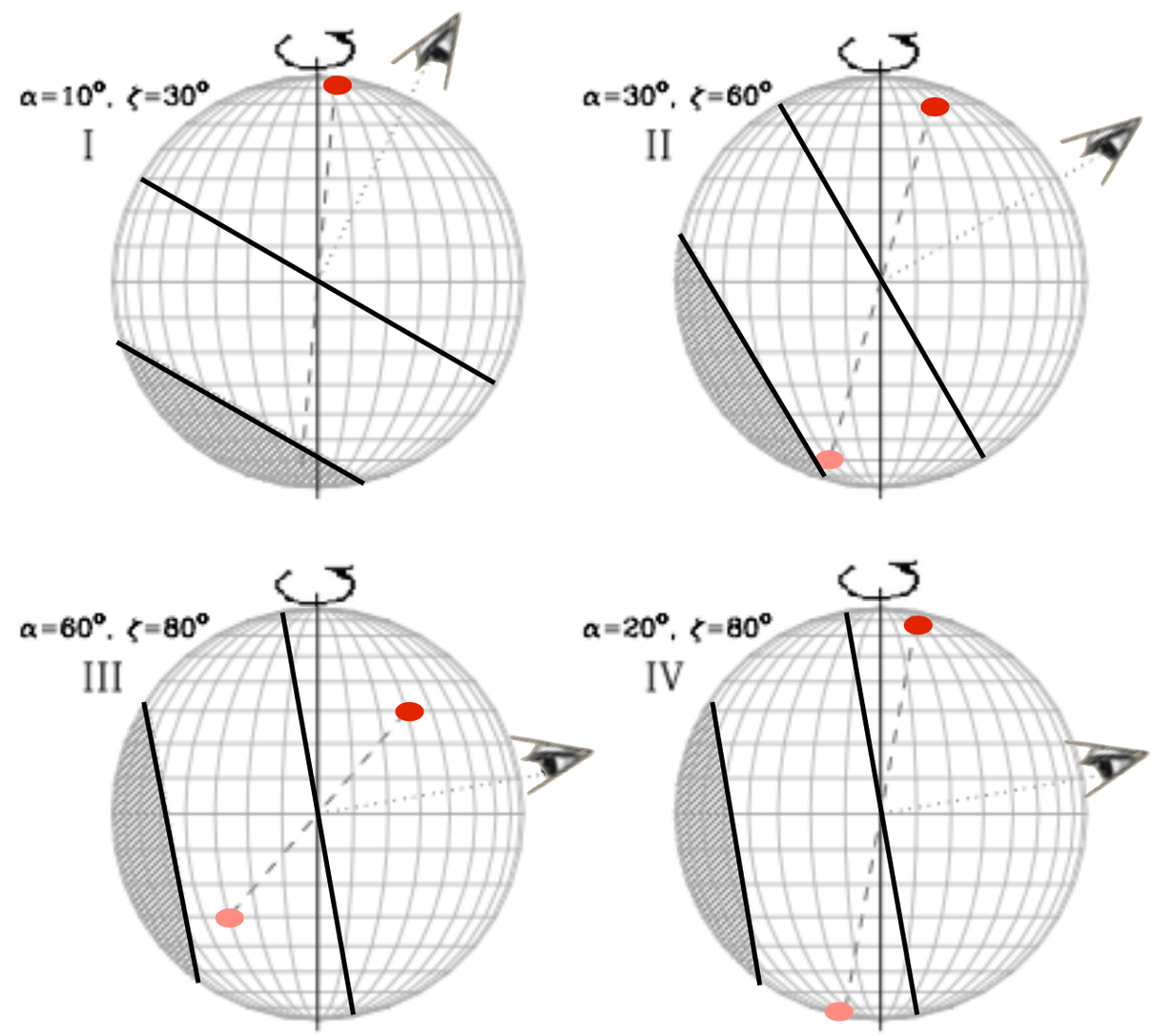
Credits: S. Morsink

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



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





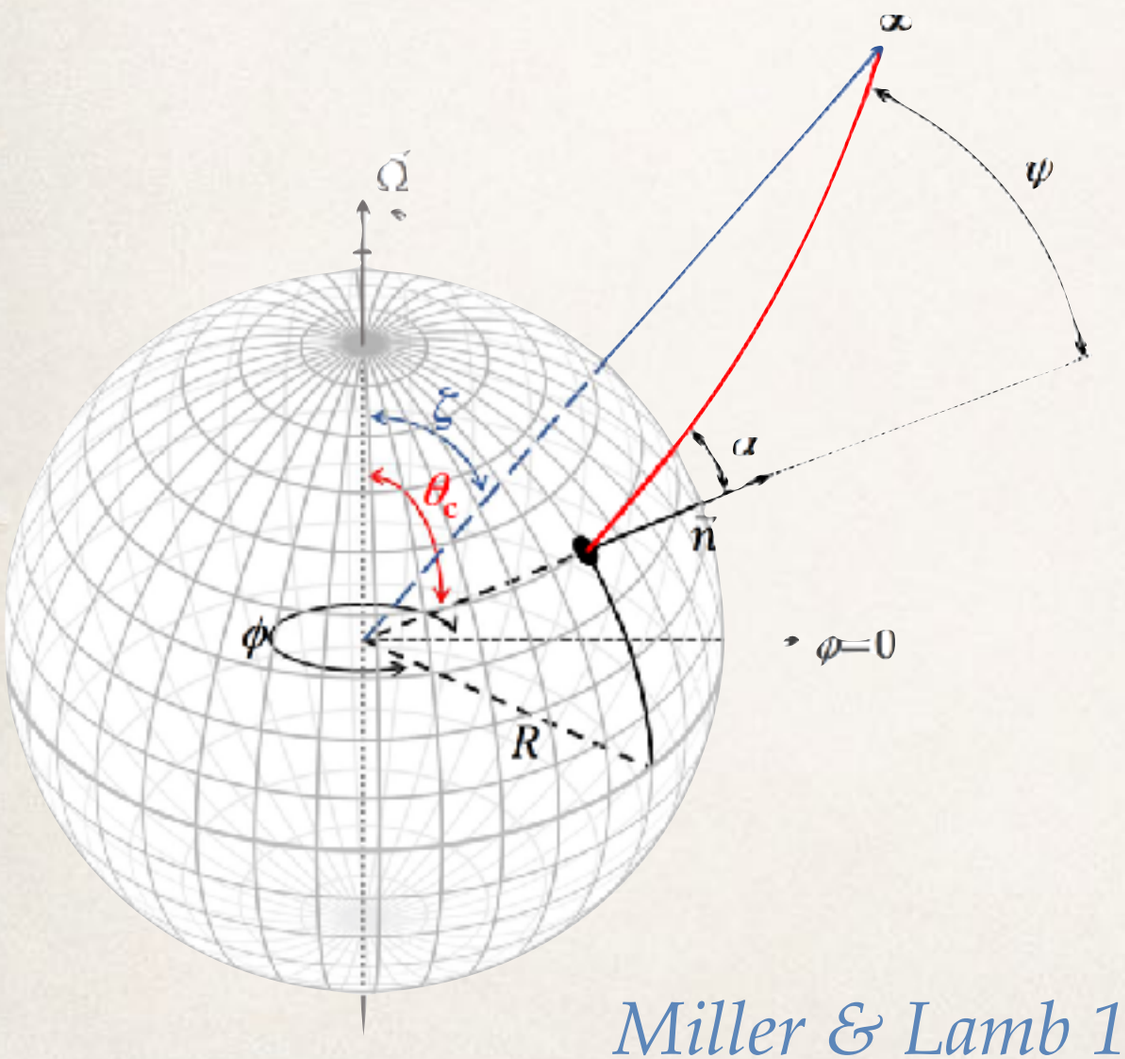
$M_{NS} = 1.4\ M_{\odot}$, $R_{NS} = 10$km

(Bodganov et al. 2008)

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

General relativity

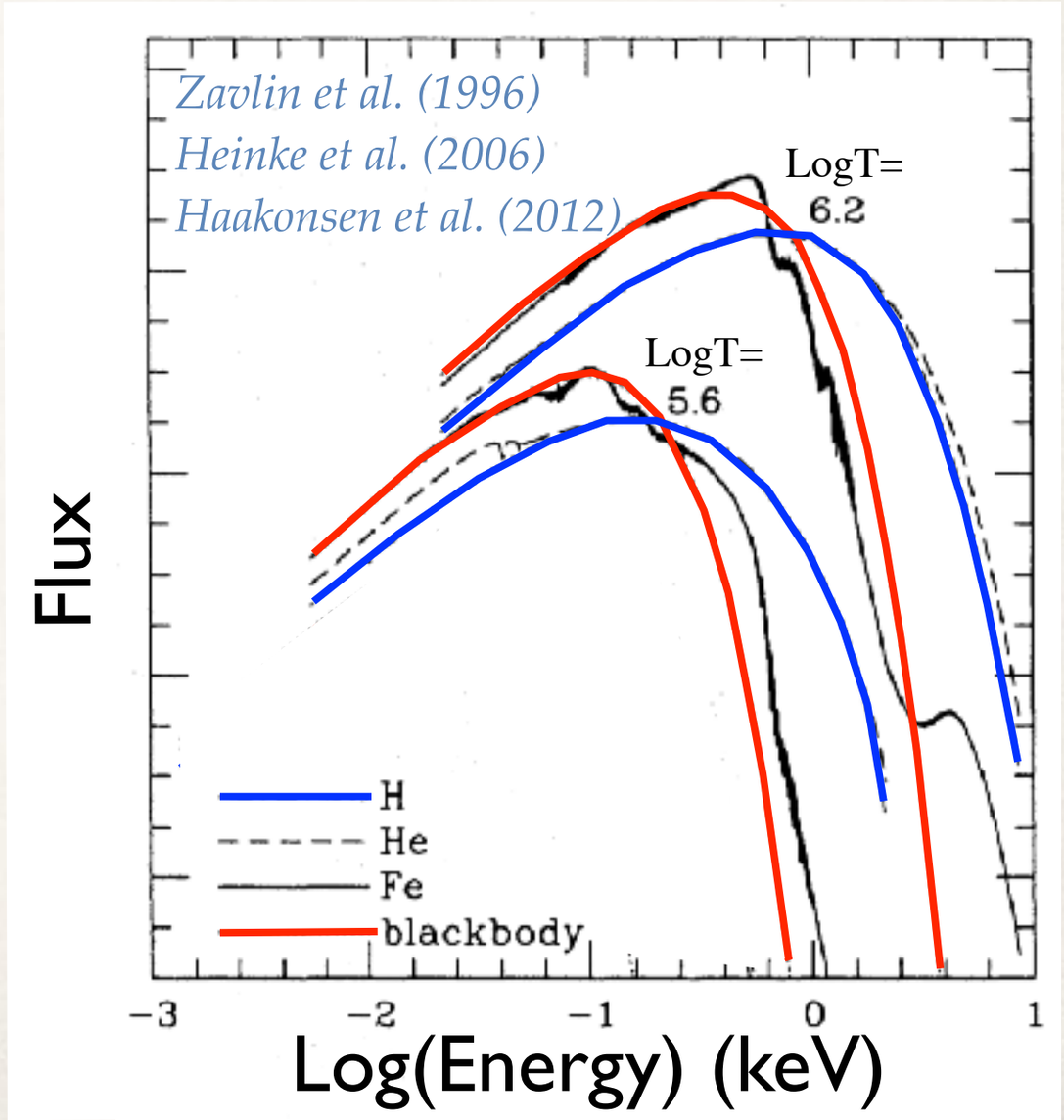
Schwarzschild metric + time delays, doppler boosts/aberration + oblate star



Miller & Lamb 1998
Morsink et al. 2007

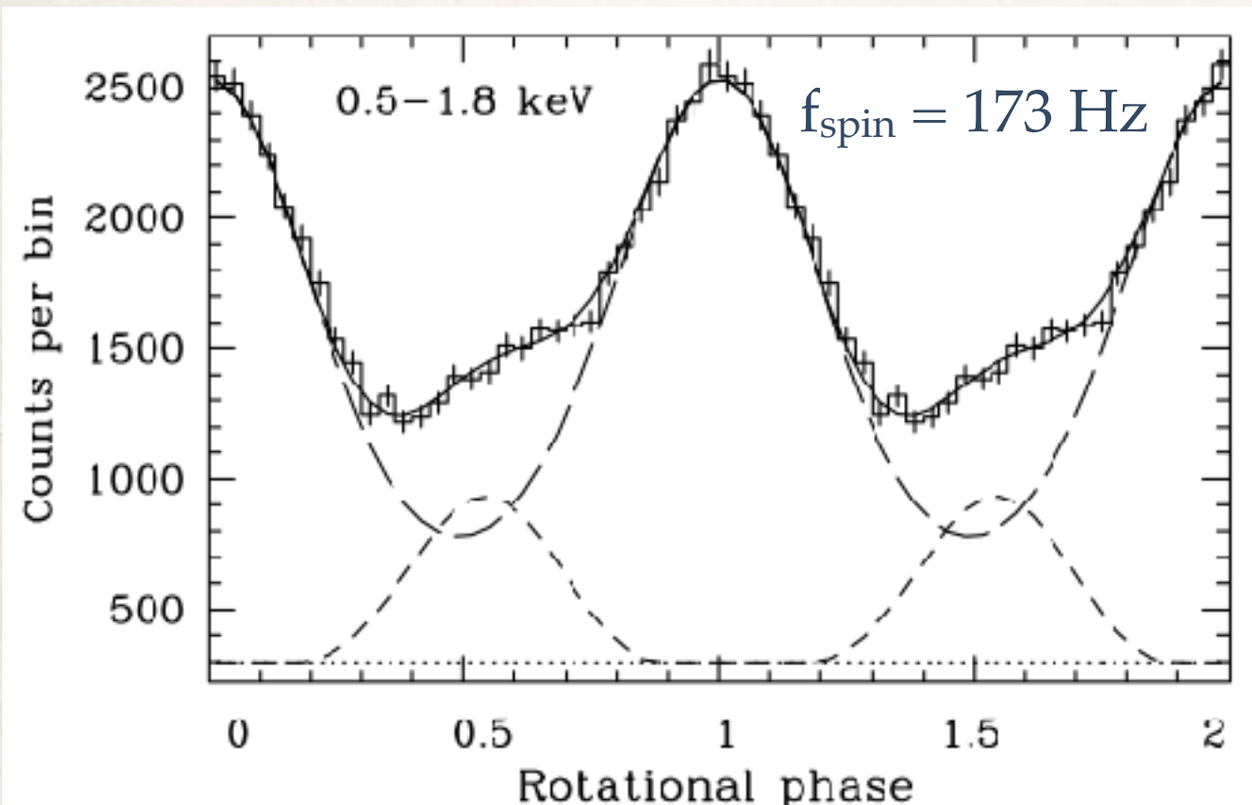
Surface emission model

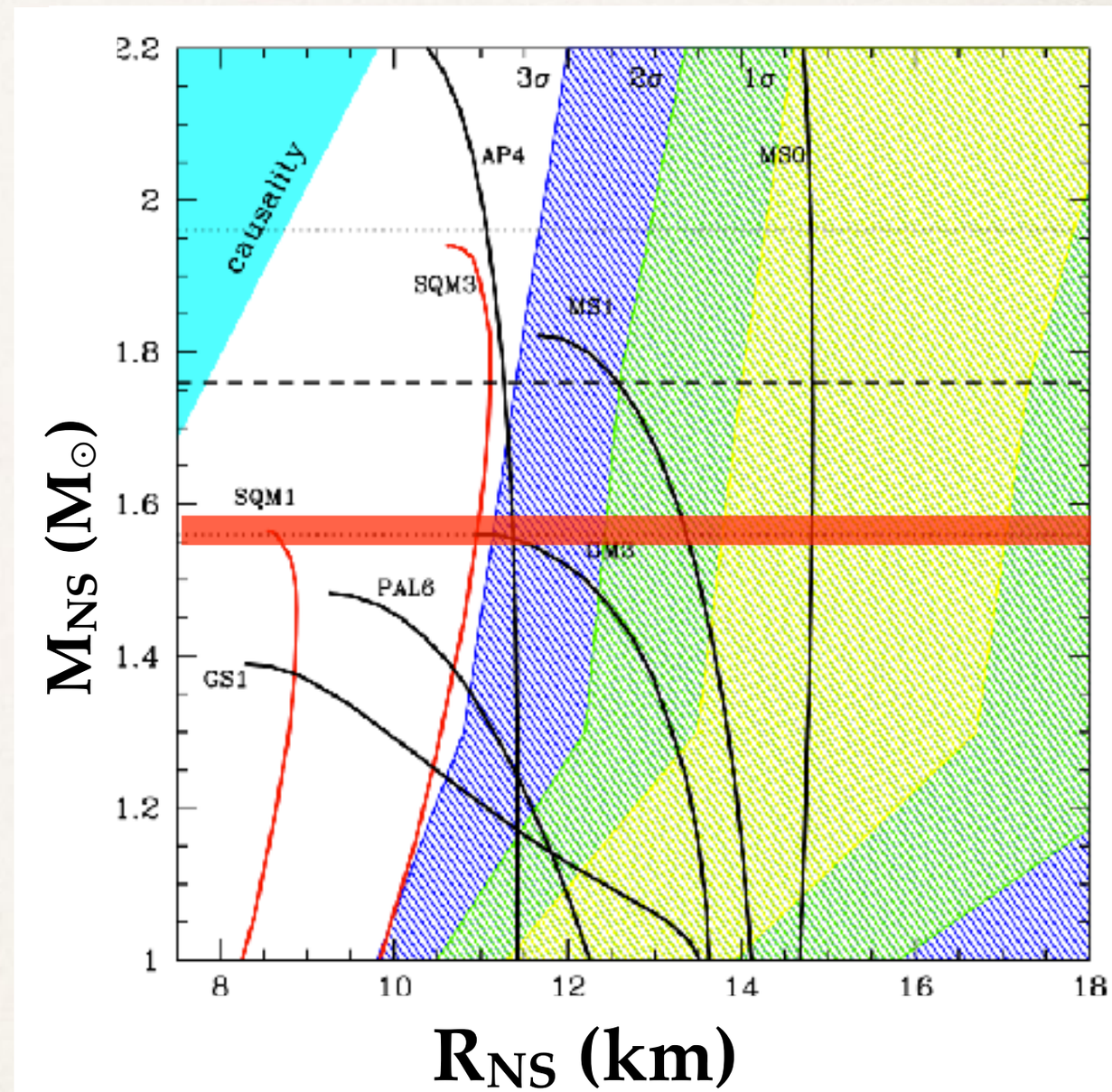
Low-magnetic field, fully-ionized H or He atmosphere



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

PSR J0437-4715 with XMM-Newton



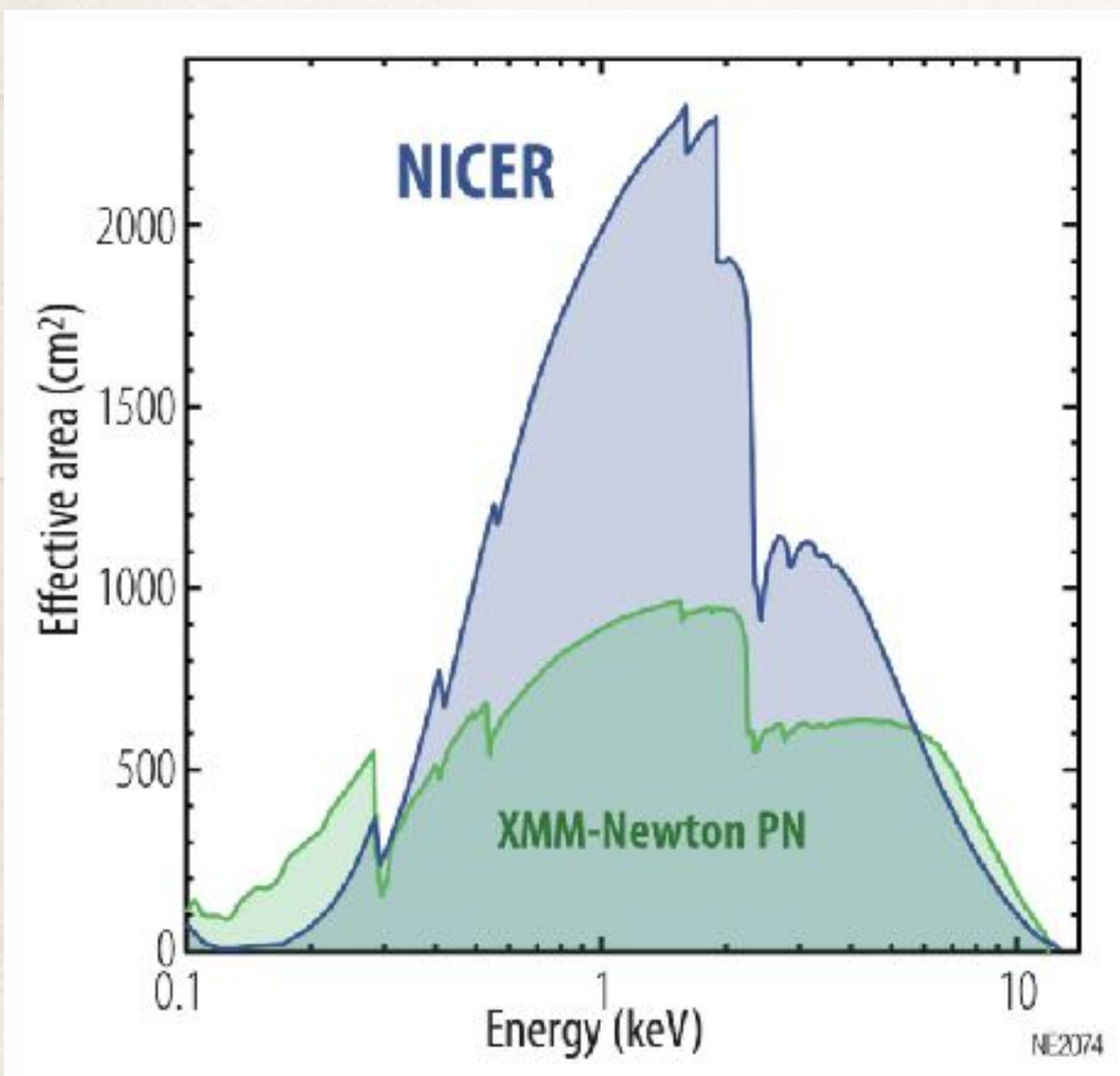


M/R extracted from lightcurve

Bogdanov (2013)

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

Launched in June 2017



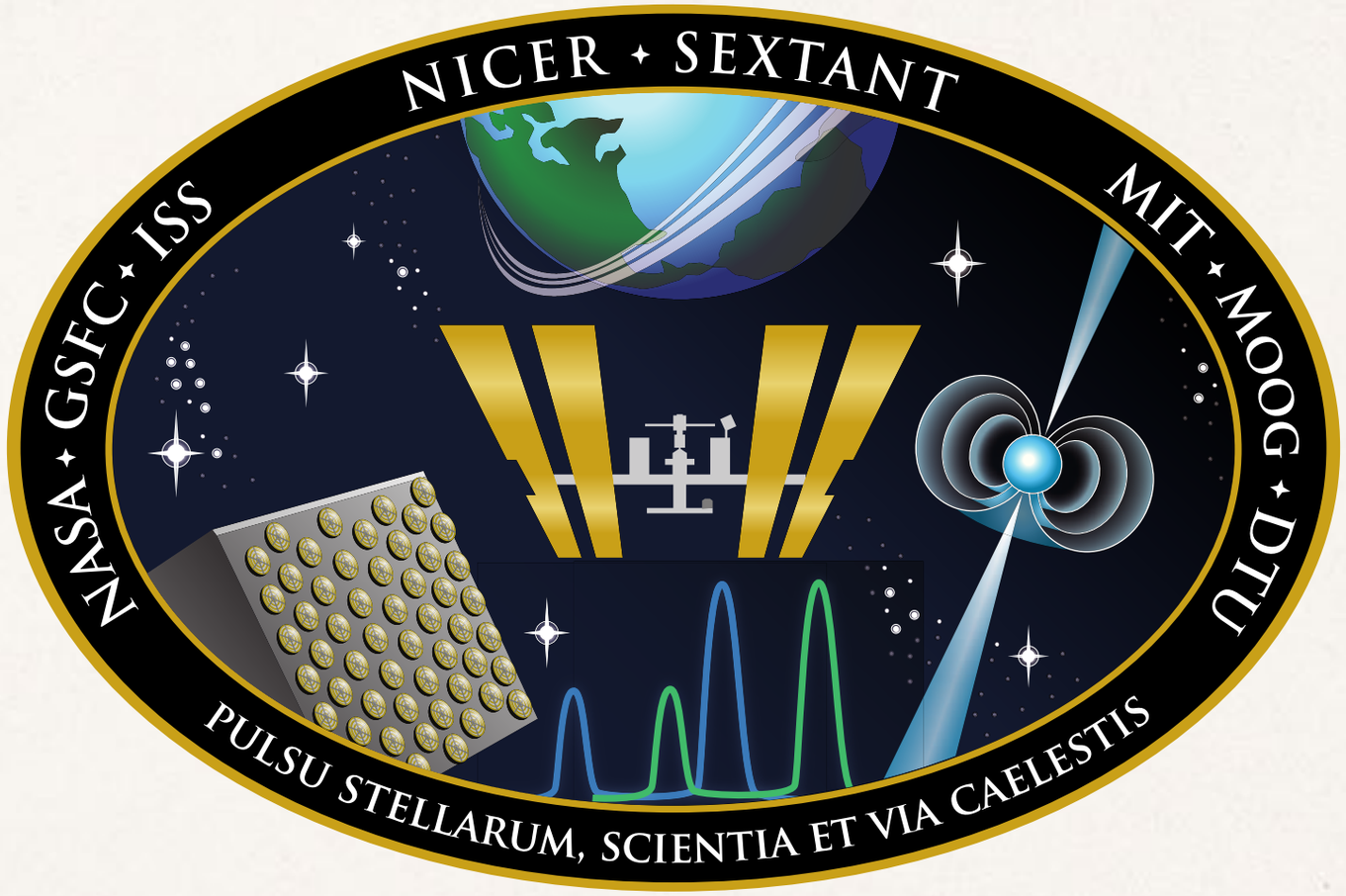
NICER now routinely observes four key target millisecond pulsars.

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?

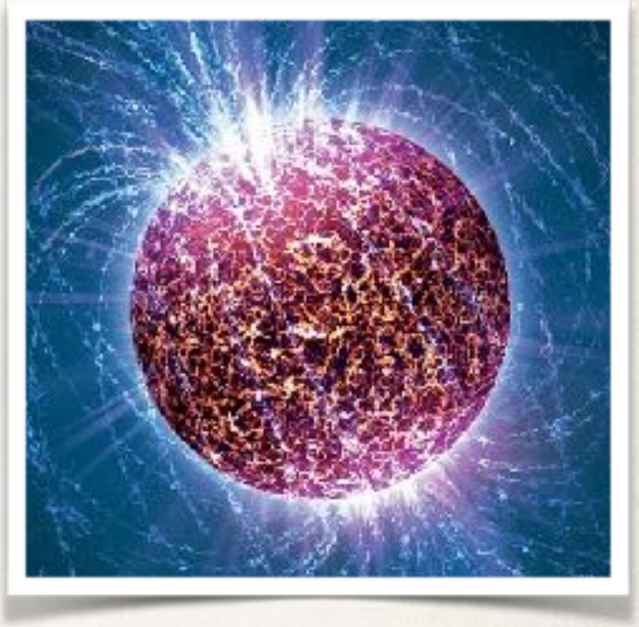

NICER ✦ SEXTANT
MIT ✦ MOOG ✦ DTU
PULSU STELLARUM, SCIENTIA ET VIA CAELESTIS
NASA ✦ GSFC ✦ ISS

Be patient…

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

<u>To measure the radius, we need to</u>:

- 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 <u>quiescent low-mass X-ray binaries</u>

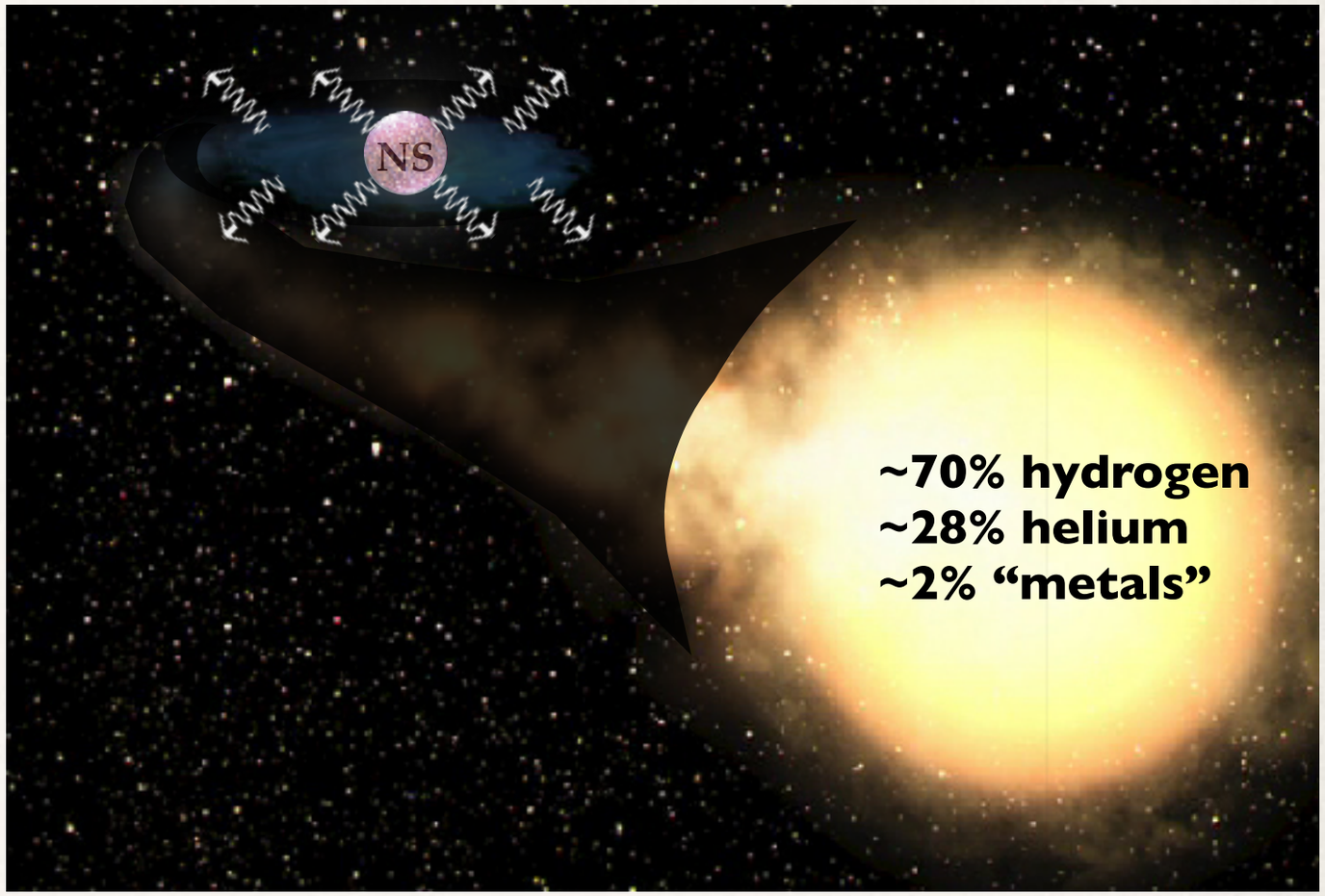
Neutron stars in <u>supernova remnants</u>

Thermally-cooling <u>isolated neutron stars</u>

Neutron stars with <u>thermonuclear bursts</u>

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

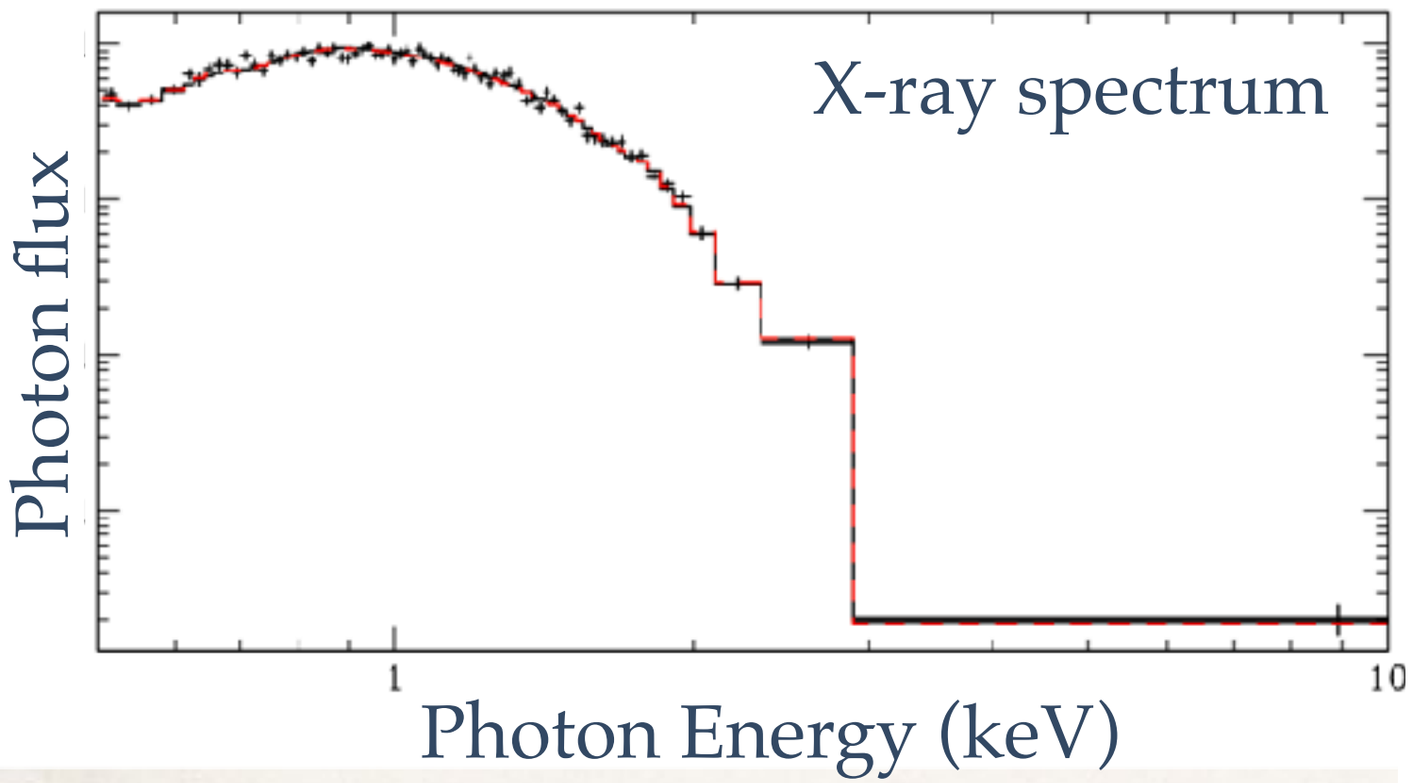
Surface thermal emission at $T_{eff} \sim 10^6$ K, powered by residual heat from the interior radiating outwards through the atmosphere with $L_X = 10^{32\text{-}33}$ erg/sec

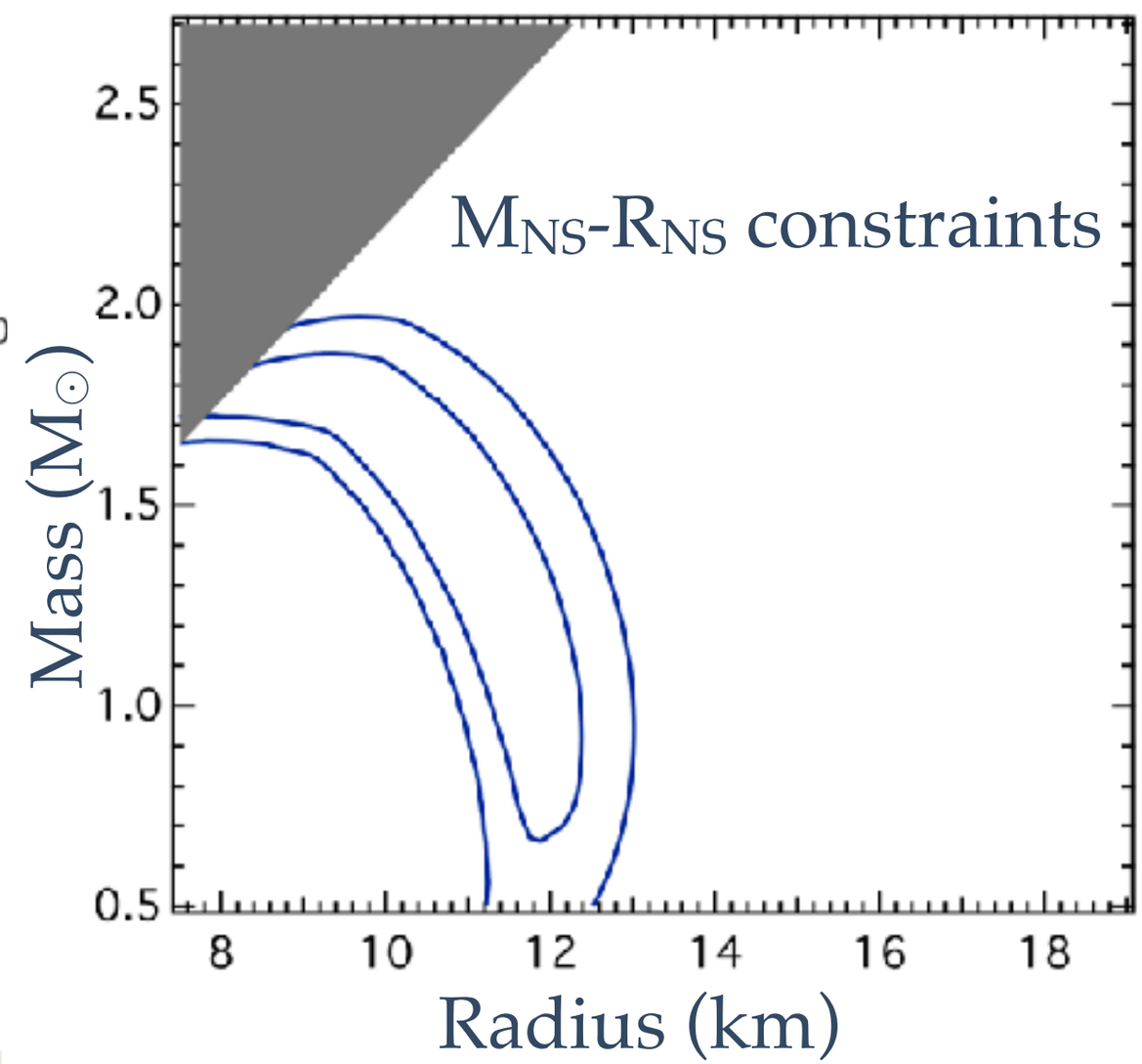


$$F_X \propto \left(\frac{R_\infty}{D}\right)^2 \sigma T^4$$

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

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

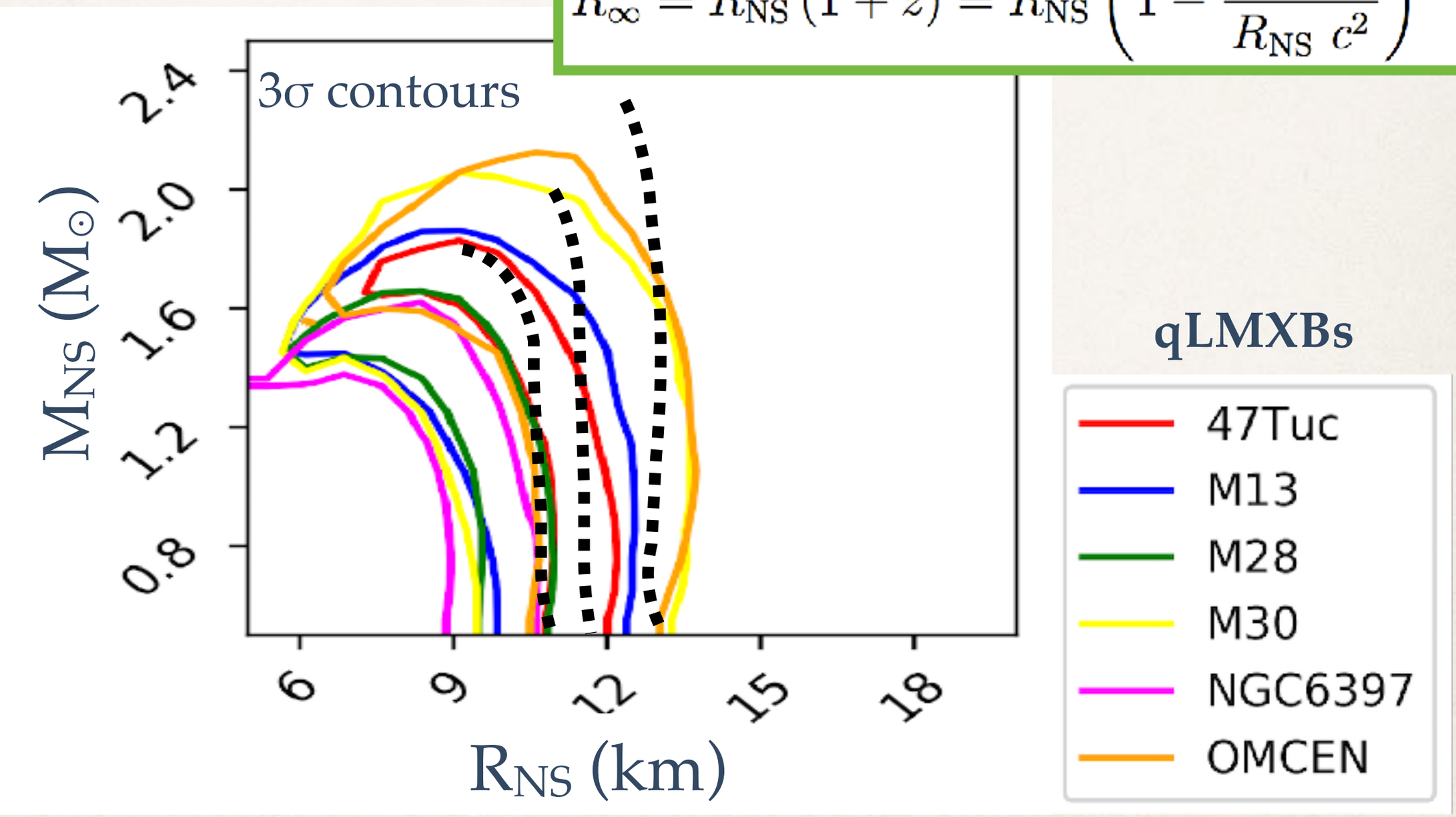




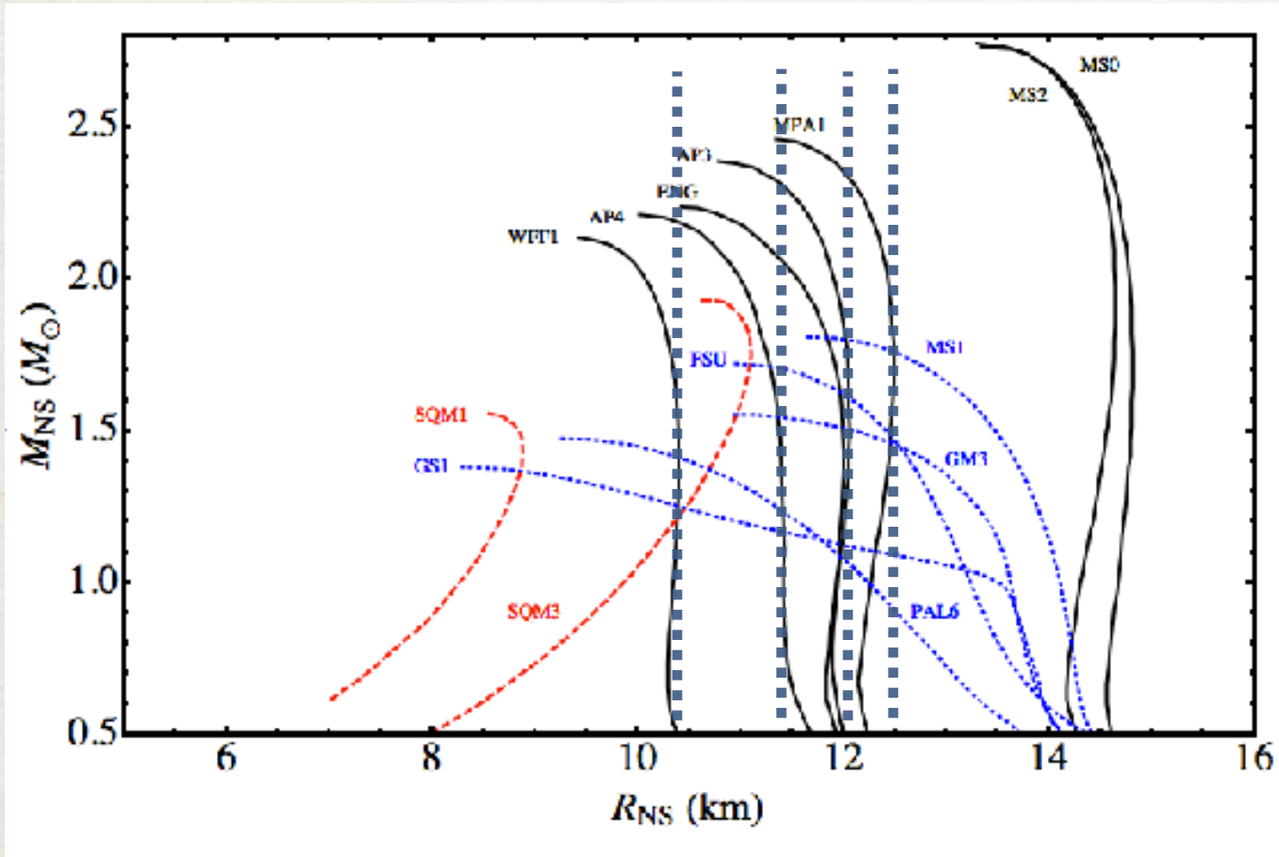
Bogdanov et al. 2016

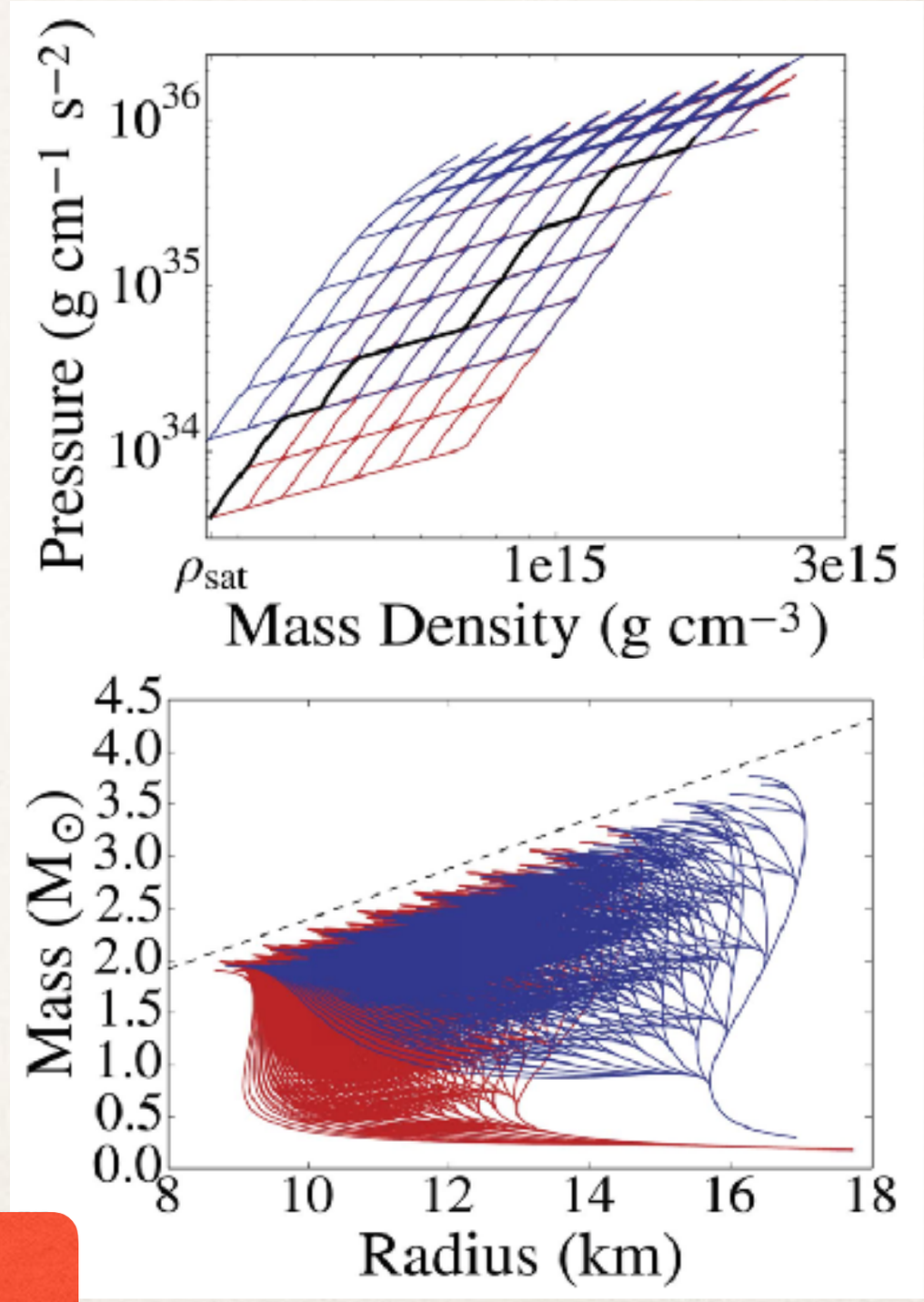
We want to find which <u>equation of state</u> is common to all these M-R measurements.

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



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





Constant R_{NS}

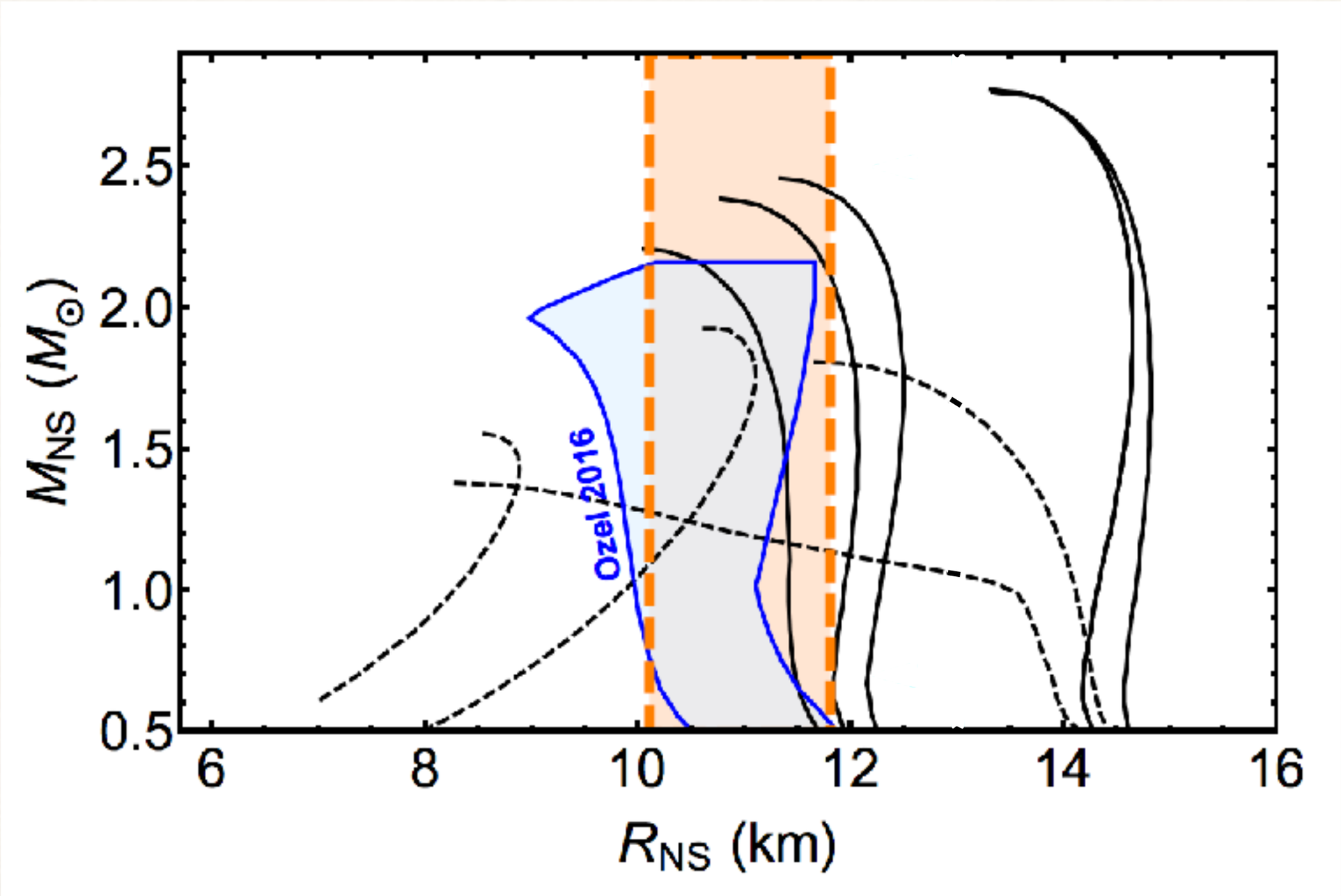
i.e., the radius is the same for all neutron stars

Guillot et al. 2013, 2014, 2016

Analytical parameterizations

Raithel et al. (2016)

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**

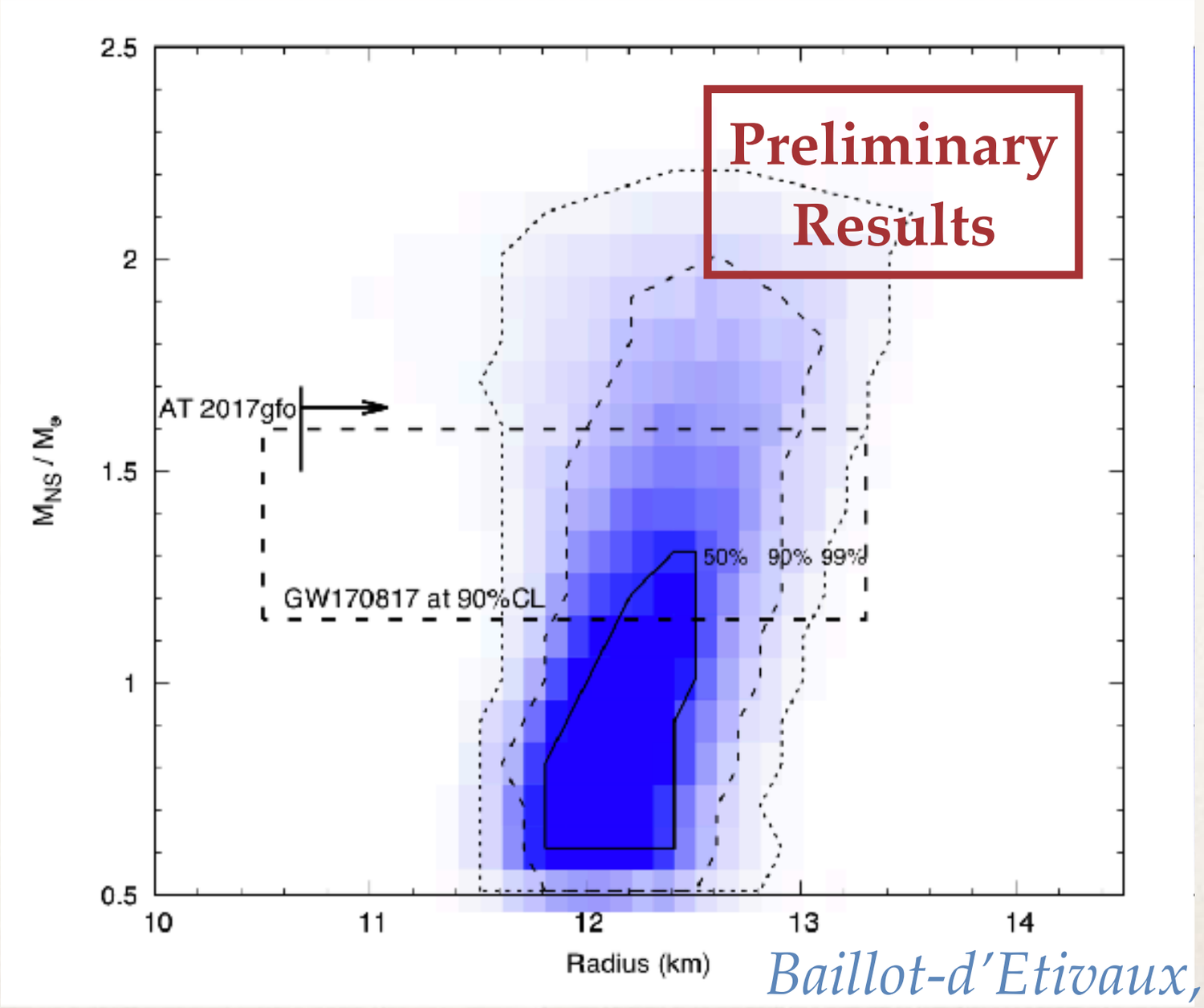
What's new?

- **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 state, we improve on previous estimates.

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

Model of Margueron et al. (2018)



Baillot-d'Etivaux, et al. (in prep.)

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

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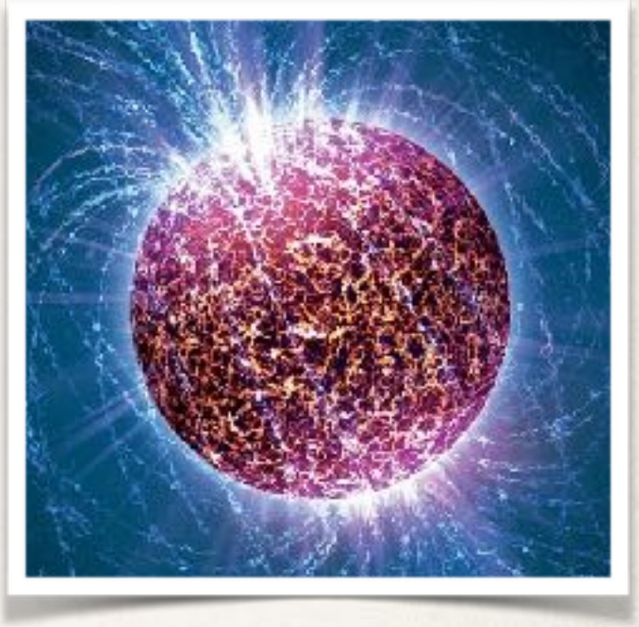

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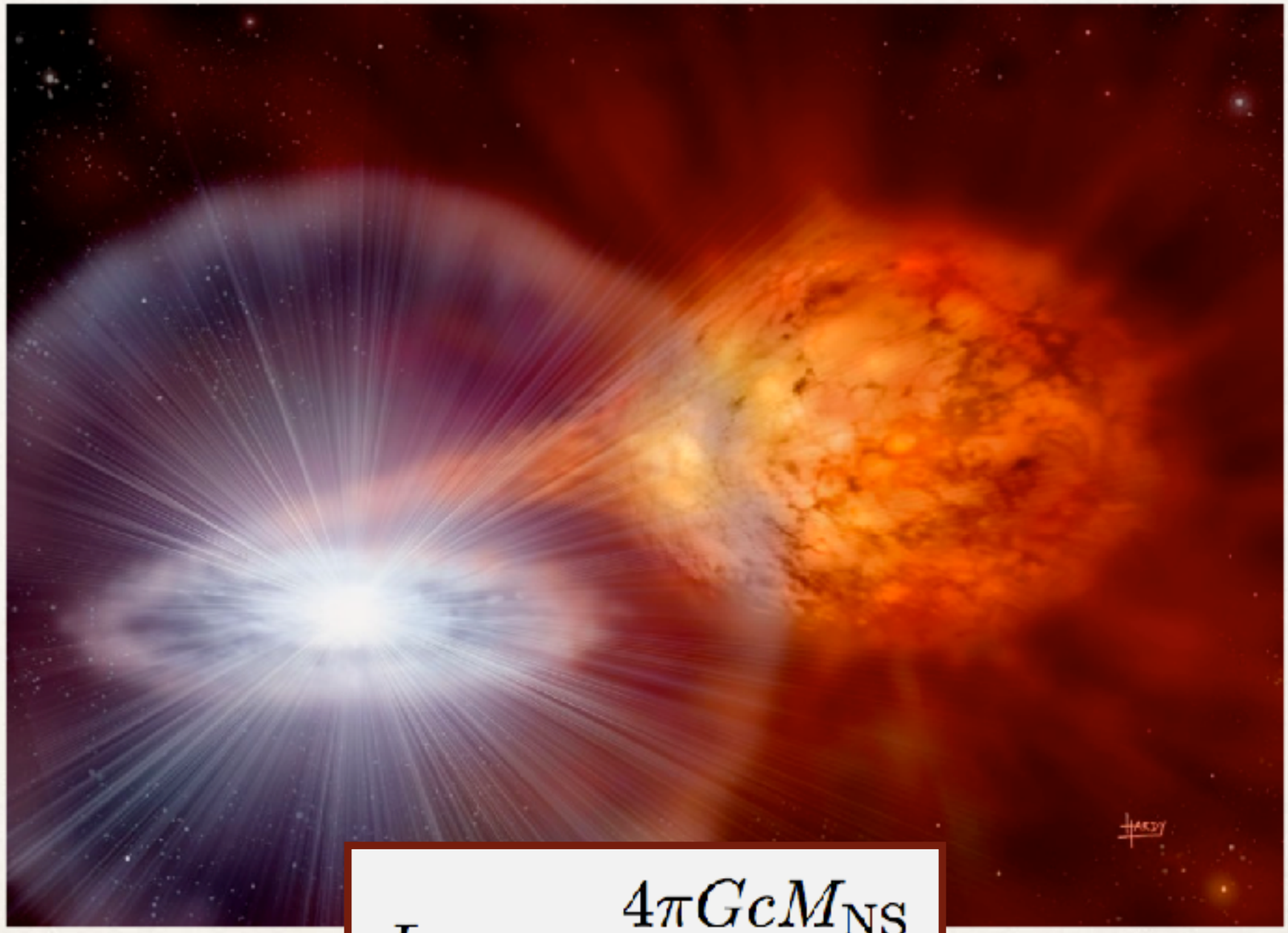
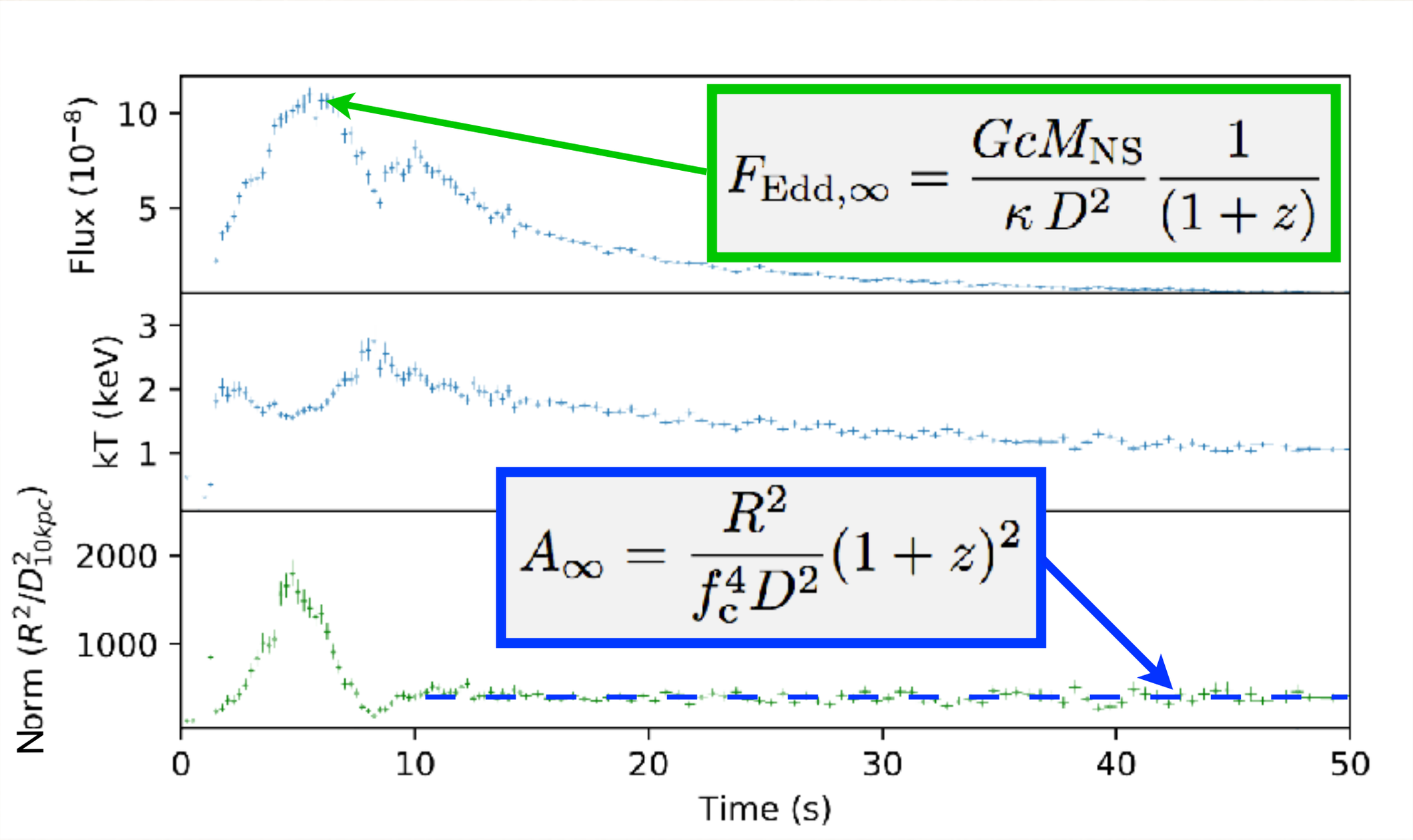
Some LMXBs exhibiting thermonuclear bursts with Photospheric Radius Expansion.



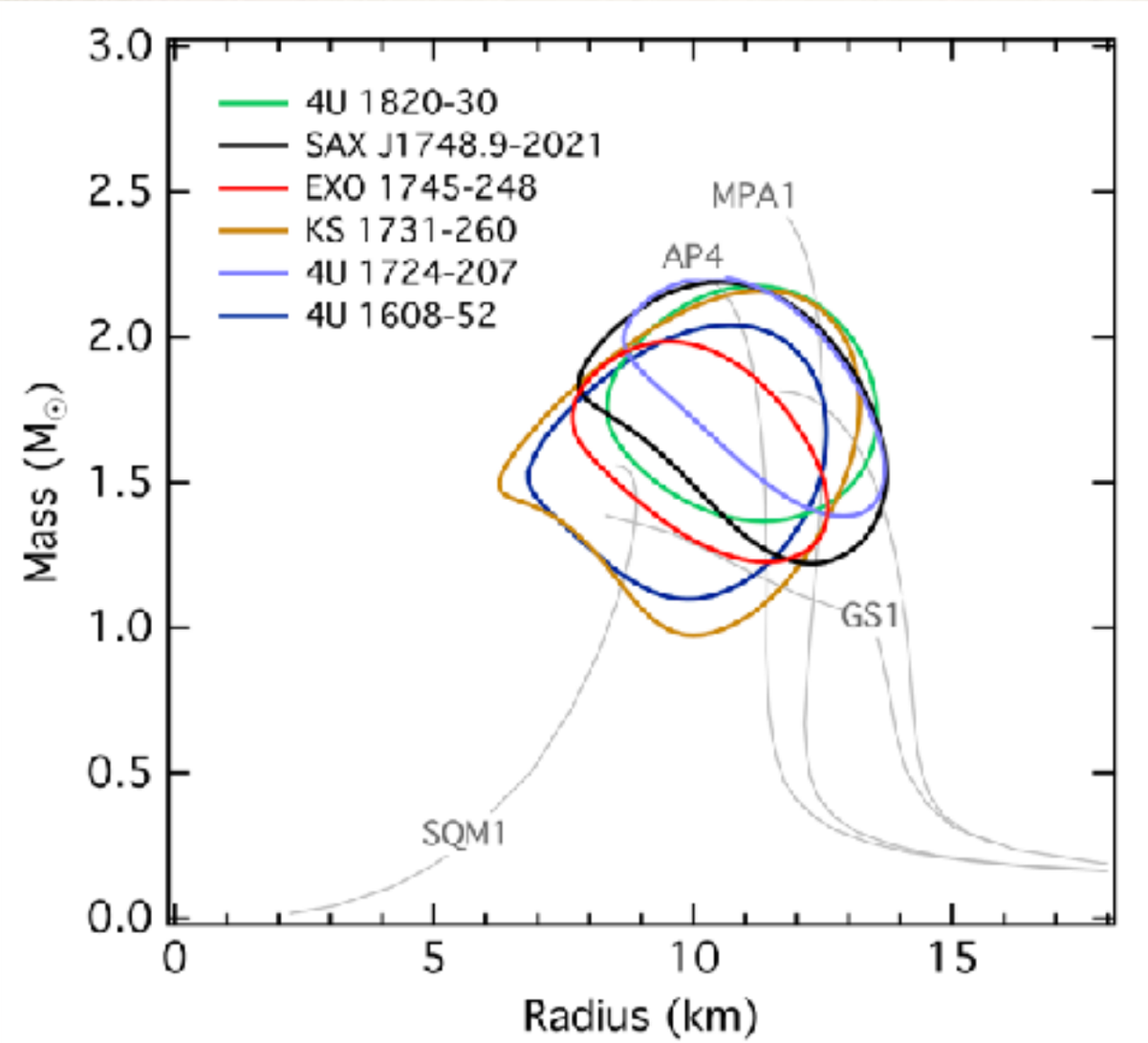
$$L_{\mathrm{Edd}} = \frac{4\pi G c M_{\mathrm{NS}}}{\kappa}$$

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



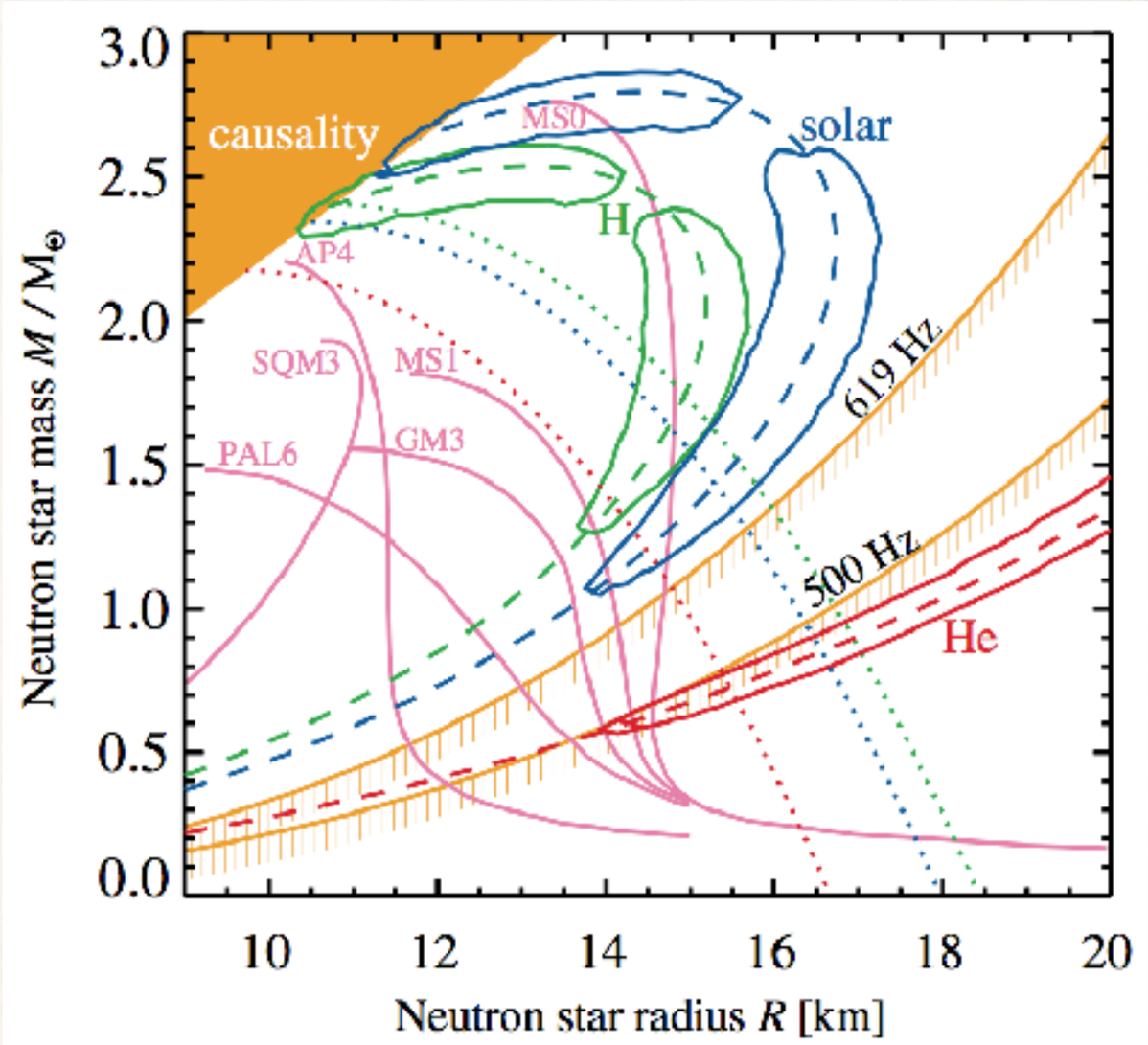
with $(1+z) = \left(1 + \frac{2GM_{\mathrm{NS}}}{c^2 R_{\mathrm{NS}}}\right)^{-1/2}$

Different analyses and types of sources result in different constraints…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

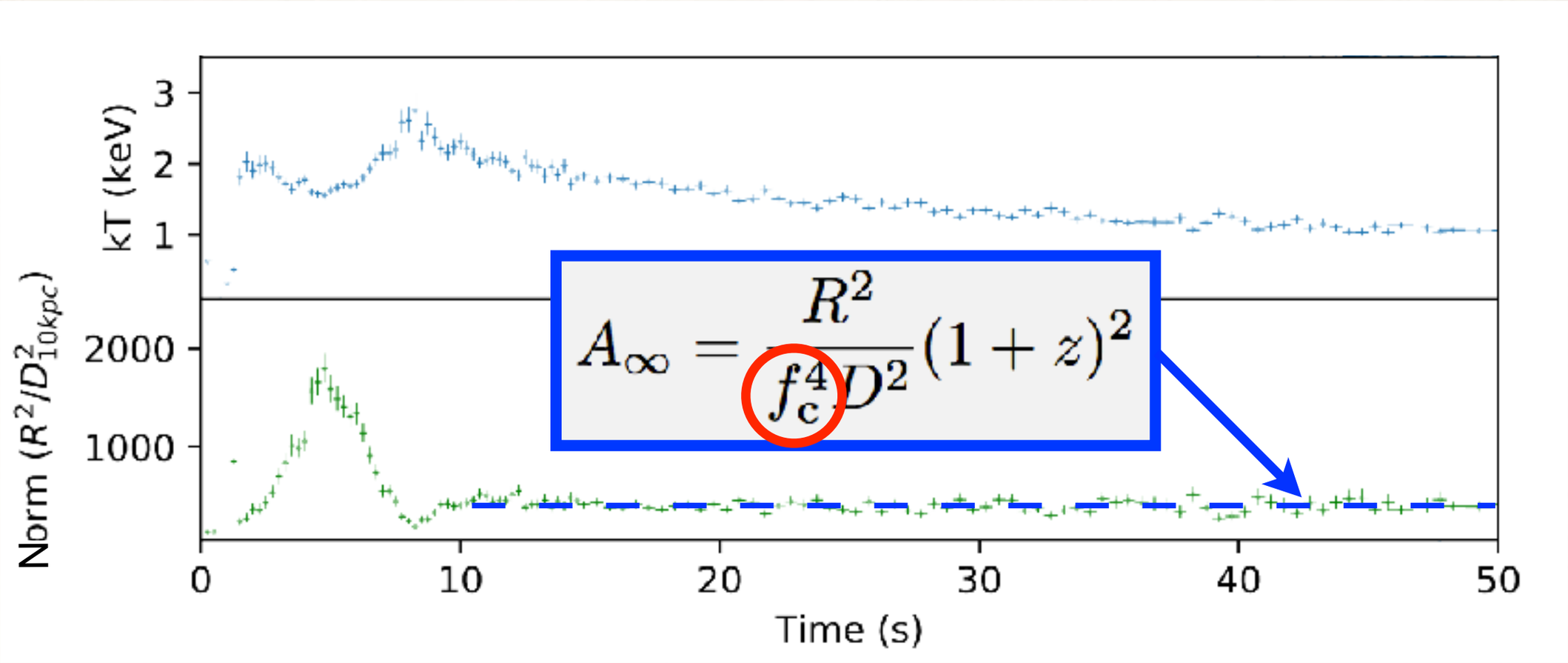
There are some <u>difficulties</u> involved with the Type I X-ray burst technique.

- **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"**

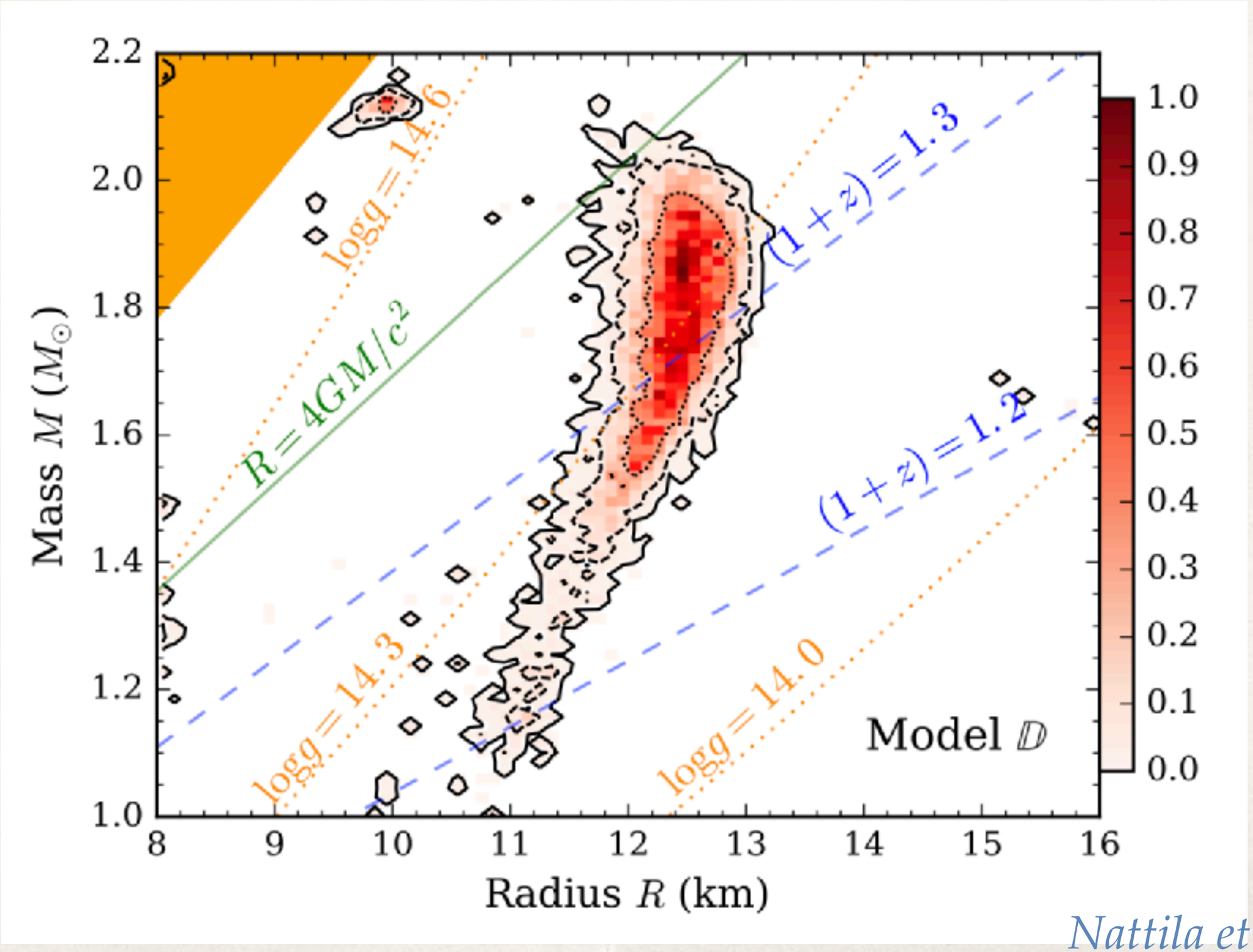
Until recently, the thermal emission was fit with a Planck function, and a colour-correction was used.



f_c is model dependent!

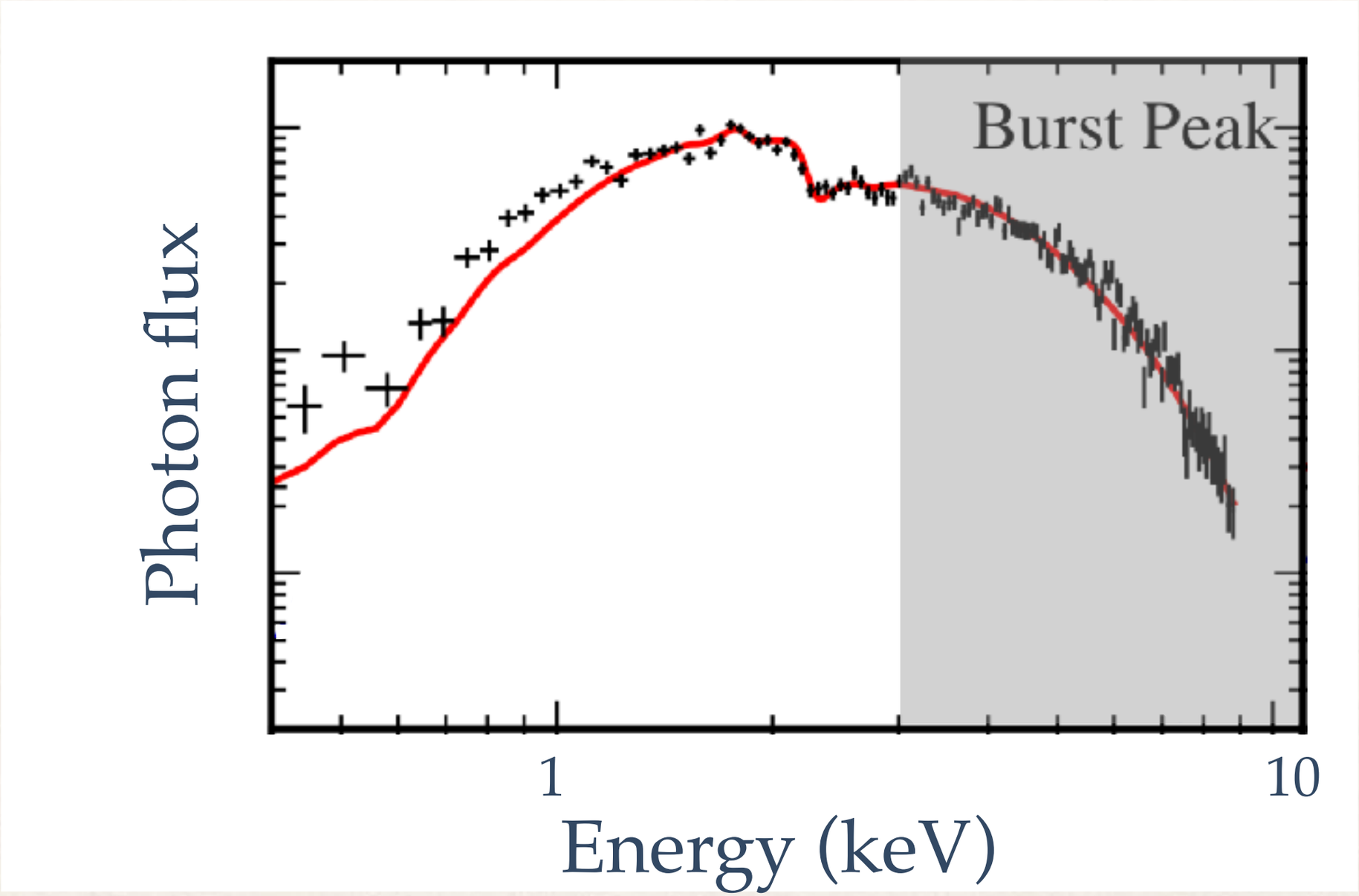
<u>Solution</u>: fit every single spectrum with realistic model

A robust modeling of the cooling tail avoids using color-correction factors.



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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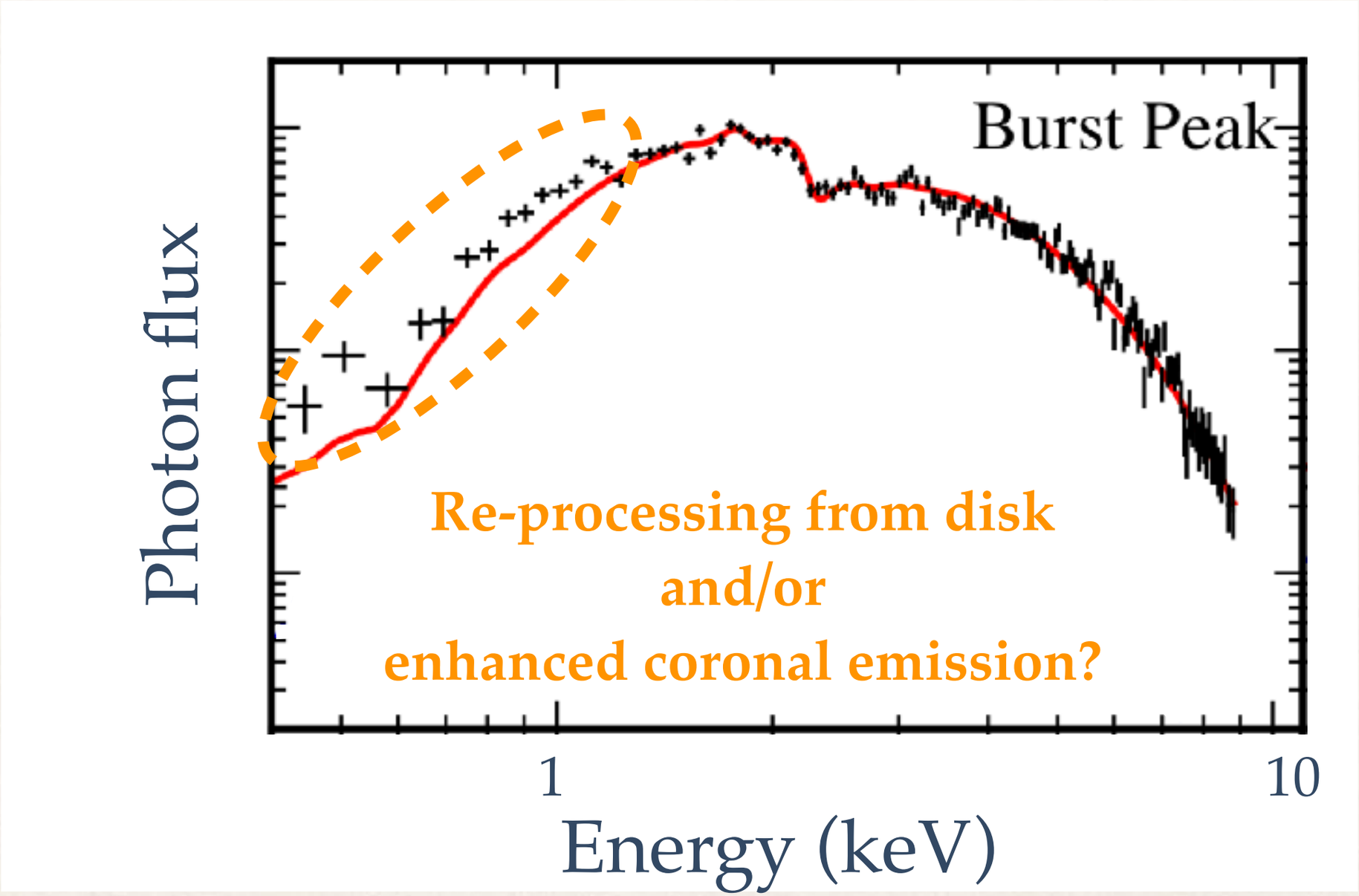
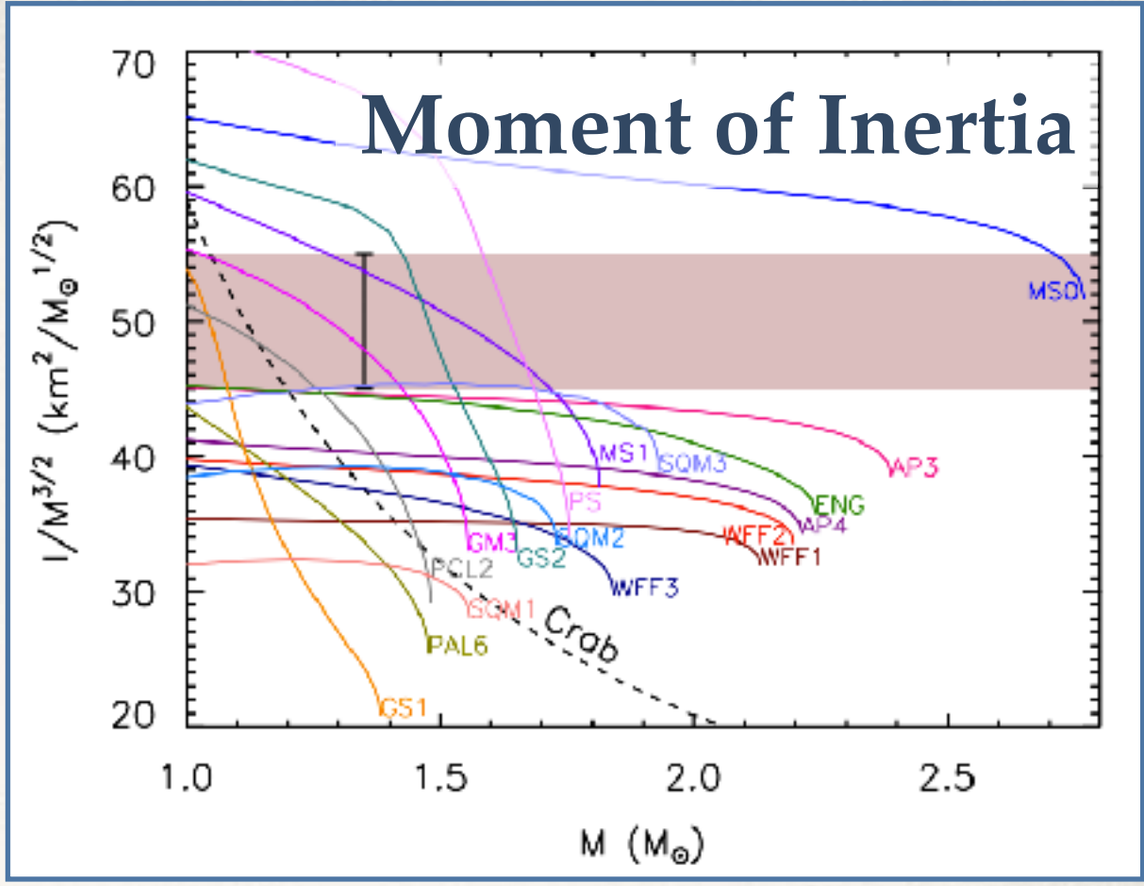
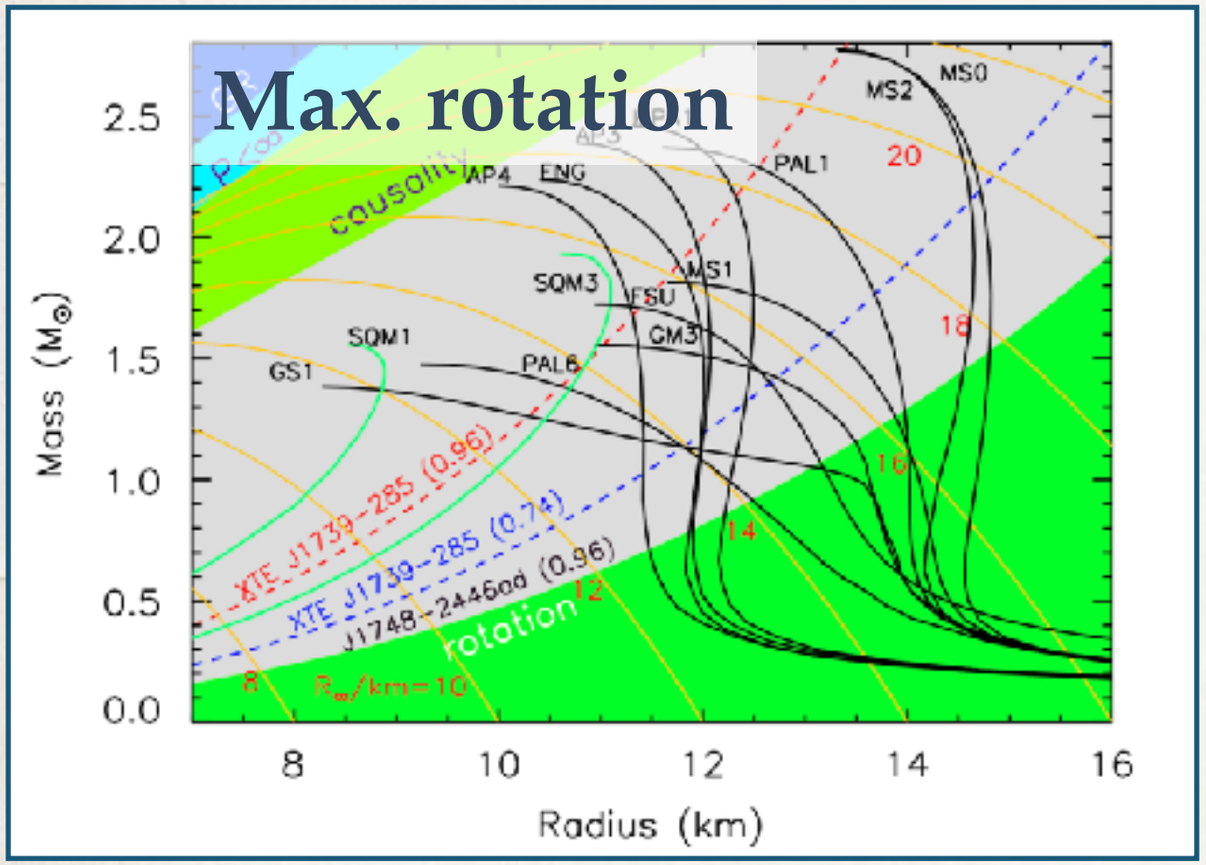


Keek et al. (2018)

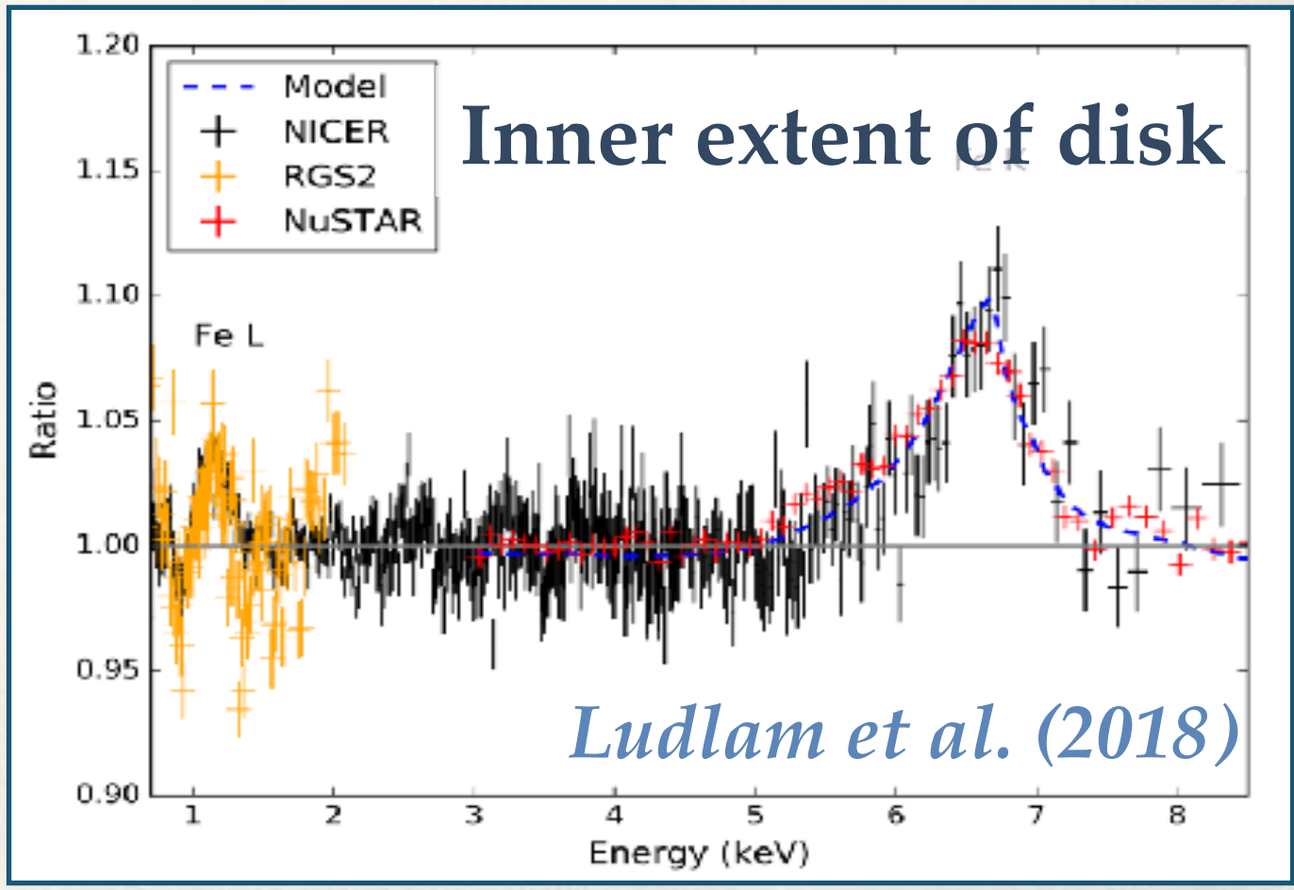
Other methods exist to constrain R_{NS}, or to place limits on it.



Lattimer & Schutz (2005)



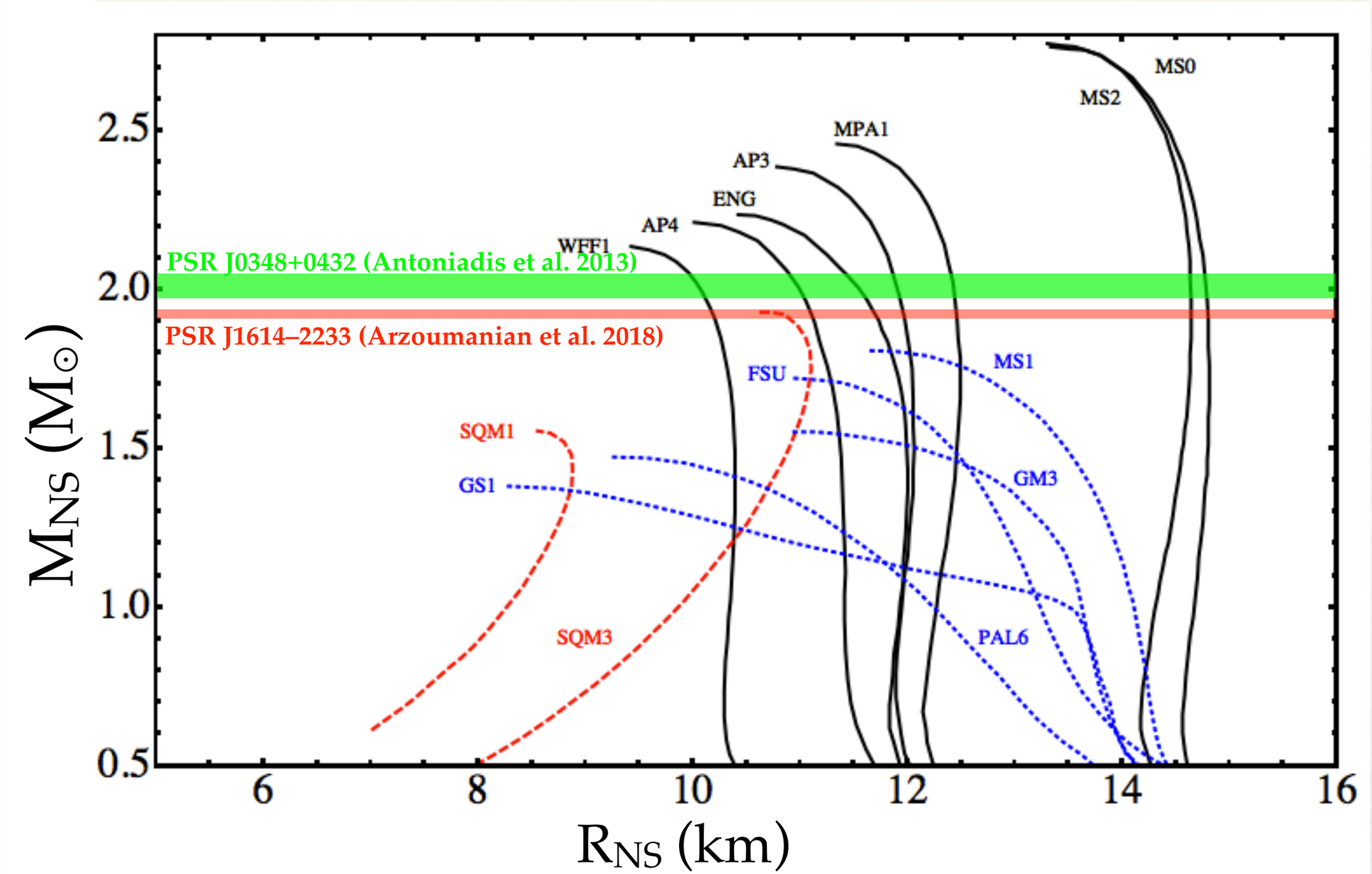
Lattimer & Prakash (2007)



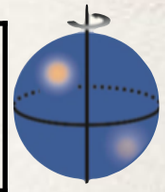
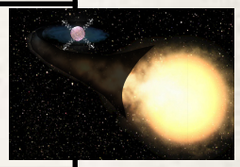
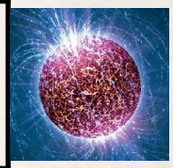
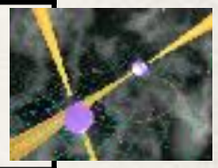
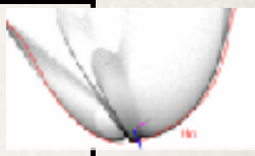
Ludlam et al. (2018)

Limits on the maximum M_{NS} also constrain the equation of state

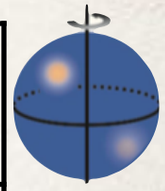
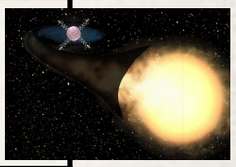
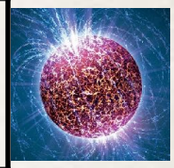
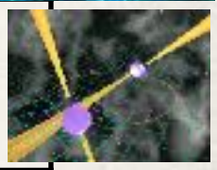
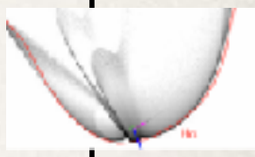
$M_{\mathrm{J1614}} = 1.908 \pm 0.016 M_\odot$ → $M_{\mathrm{max}} \gtrsim 1.9 M_\odot$



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
Inner extent of accretion disks	FeK emission line from accretion disk
Max. mass of NS	Look for more NS and hope for a more massive 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	
Inner extent of accretion disks	Limit from accreting NS: $R_{NS} < 12.6$ km	
Max. mass of NS	$M_{\max} \gtrsim 1.9 M_\odot$	

Summary – Prospects

Pulse-profile of MSP	More measurements in post-*NICER* era.
Quiescent low-mass X-ray binaries	Control uncertainties while waiting for *ATHENA*
Isolated neutron stars (and CCOs)	…
Type-I X-ray bursts	Understand effects of accretion / higher collecting area (e.g. eXTP)
GW from NS-NS merger	More events from LIGO / Virgo / Karga / LIGO Indi
Moment of inertia (radio timing)	More data from current observatories / SKA
Moment of inertia (bow-shock PWN)	3D modelling of the shock
Max. rotation of NSs	SKA searches for faster pulsars
Inner extent of accretion disks	Requires high S/N, broad-band X-ray coverage
Max. mass of NS	SKA searches for more massive NS