Nuclear physics at hundreds of parsecs* with neutron stars

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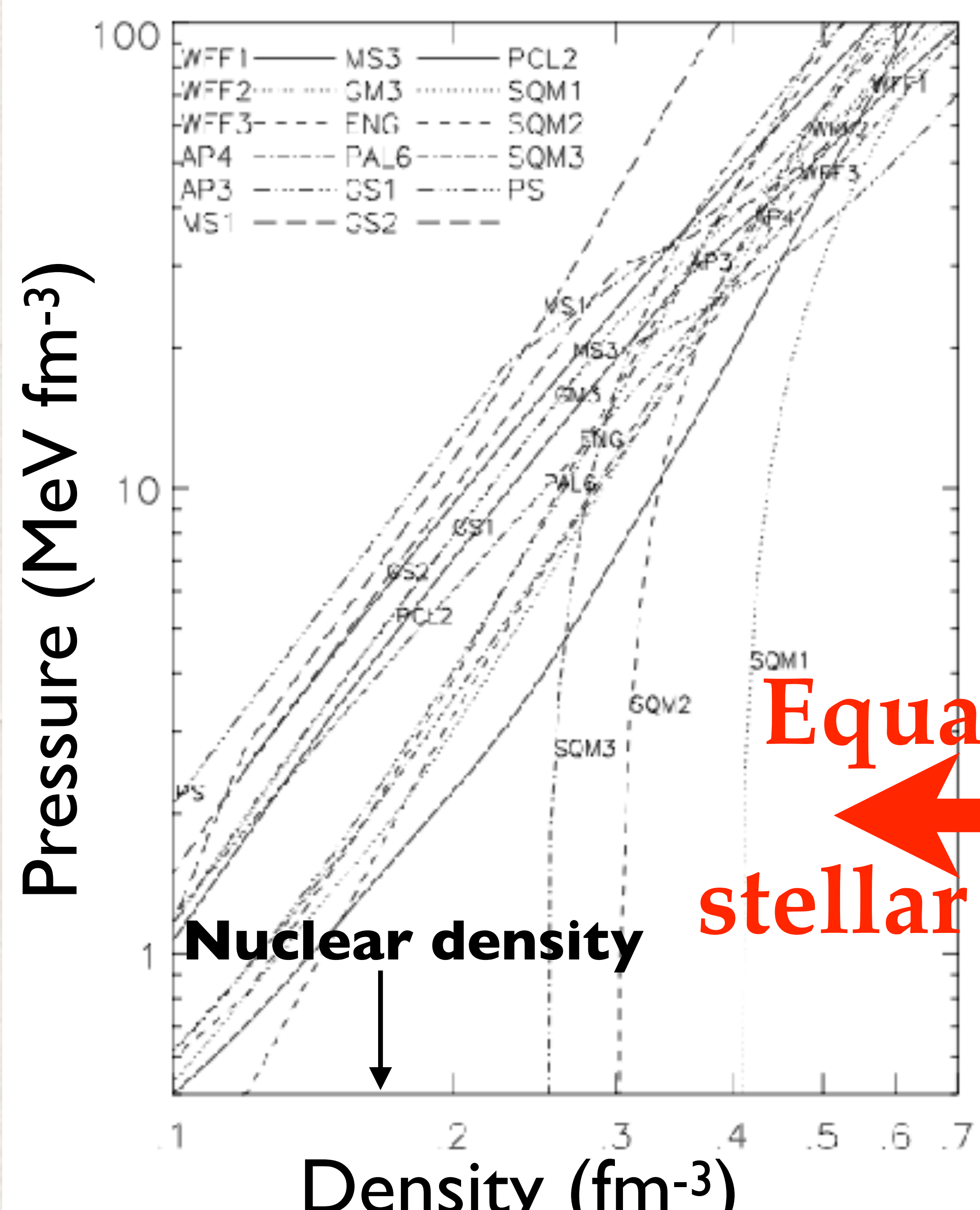
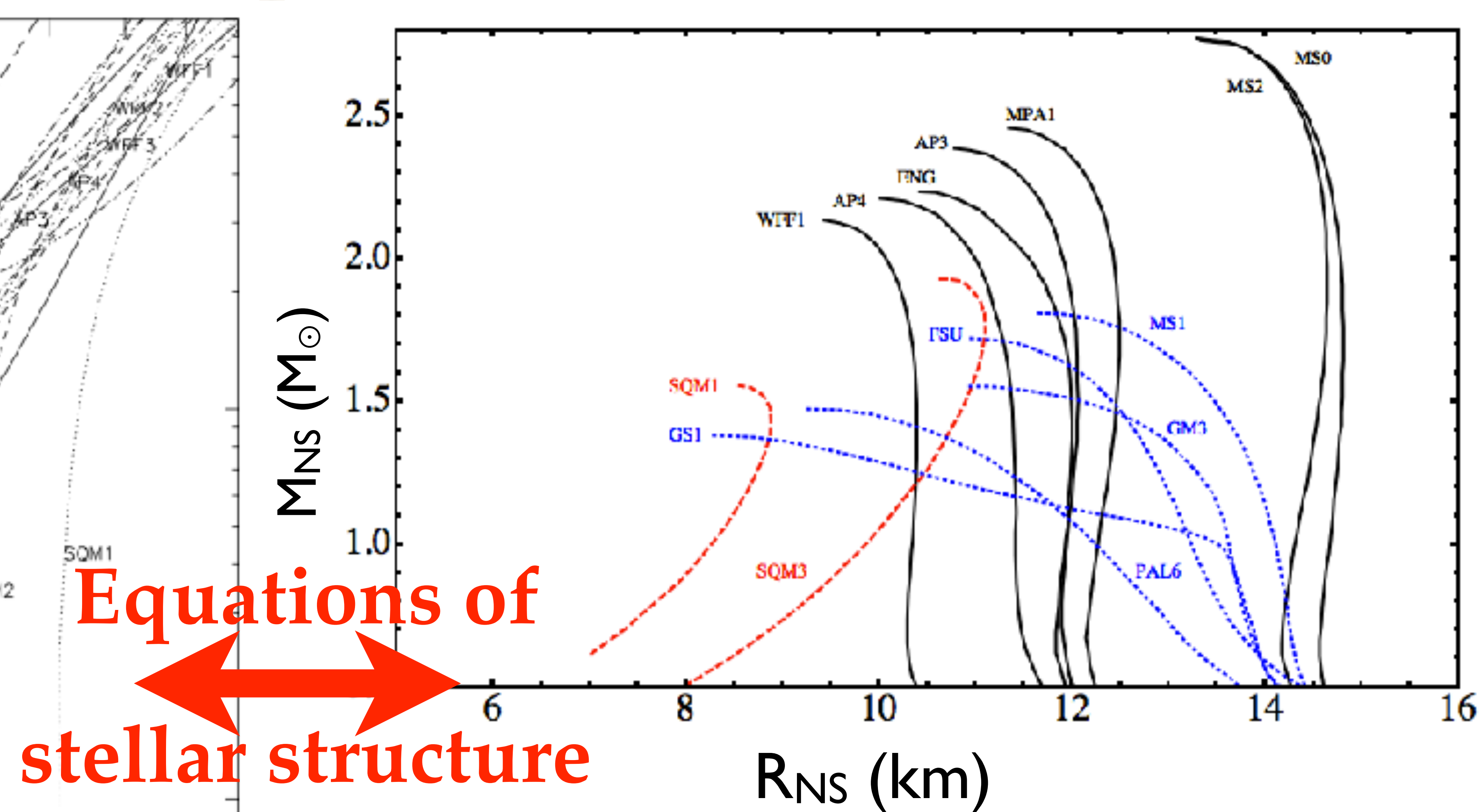
*** 1 parsec = 3.26 light years**

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

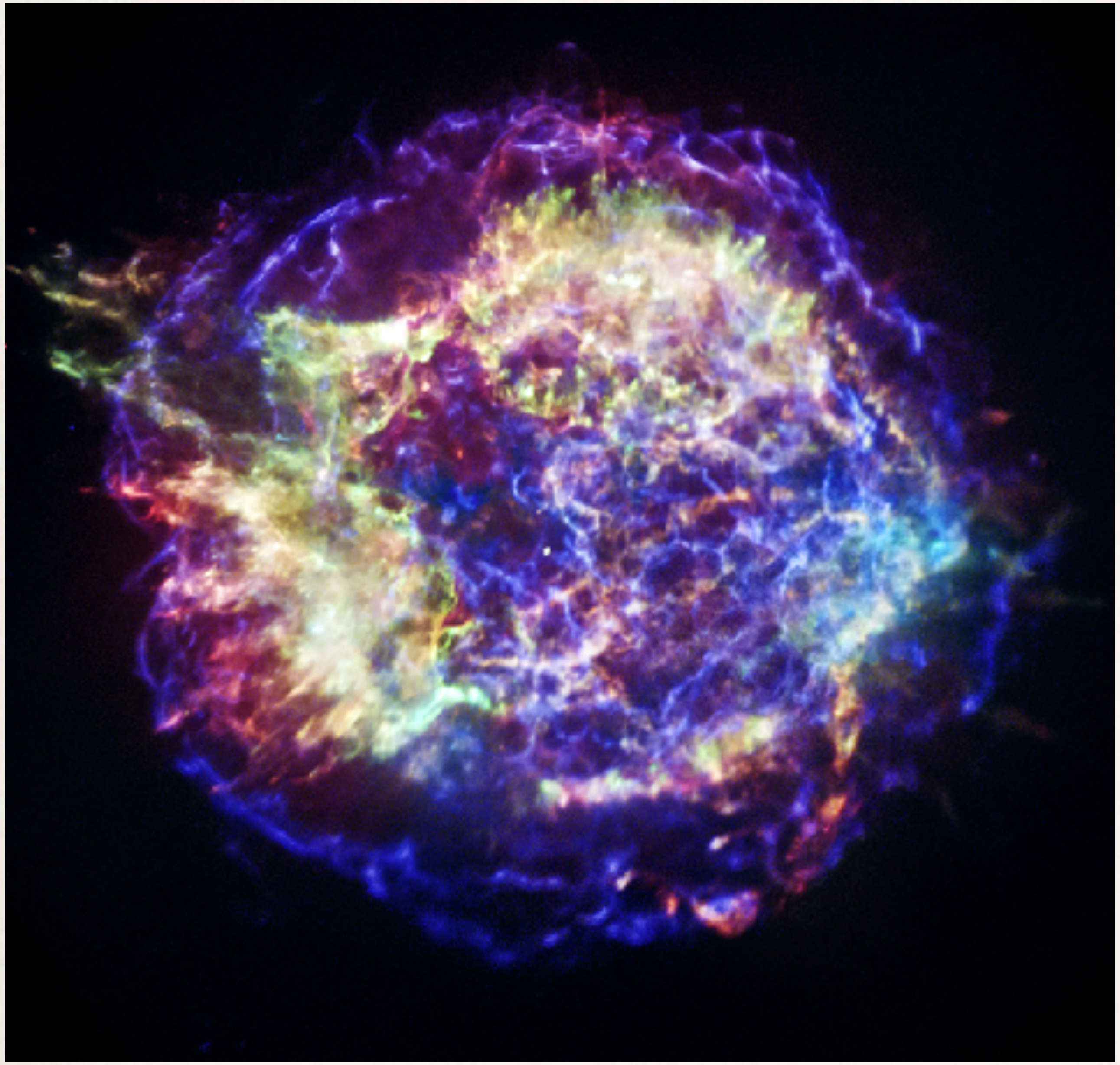




See catalog of theoretical EoS at
CompOSE.obspm.fr

Lattimer and Prakash 2001

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



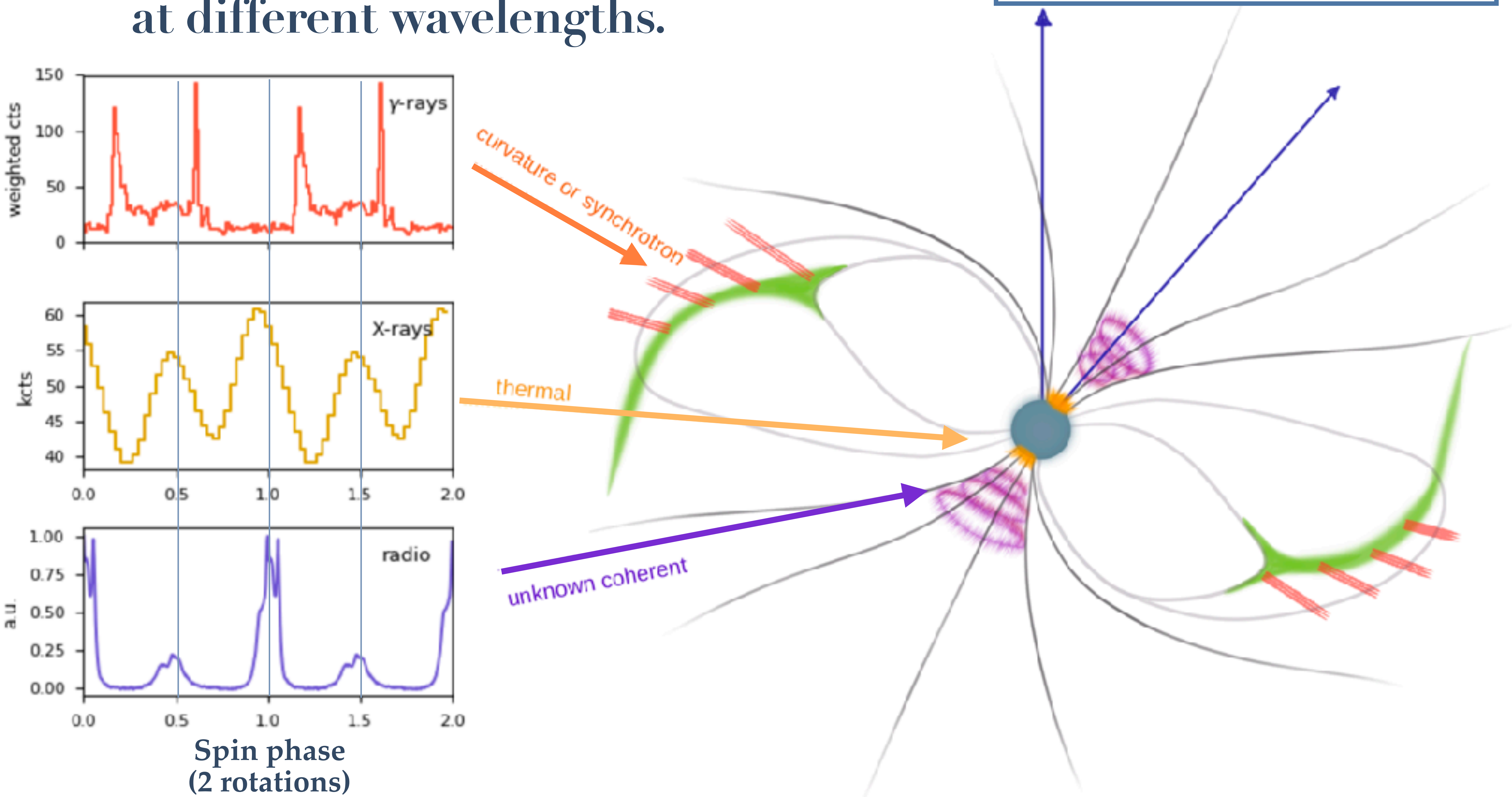
Cassiopeia A
X-ray image
Credits: NASA CXO

Crab Nebula
Composite X-ray+IR+Opt
Credits: NASA CXC / ESA / JPL

All pulsars are neutron stars, but not all neutron stars are pulsars!

$R_{NS} \sim 10 - 15$ km
$M_{NS} \sim 1.0 - 2.0\ M_{\odot}$
$B \sim 10^{8} - 10^{15}$ G
$P_{spin} \sim 0.001 - 10$ sec

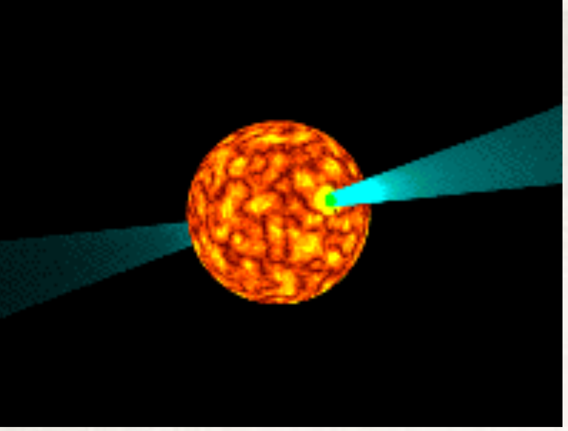
Some pulsars show pulsations at different wavelengths.



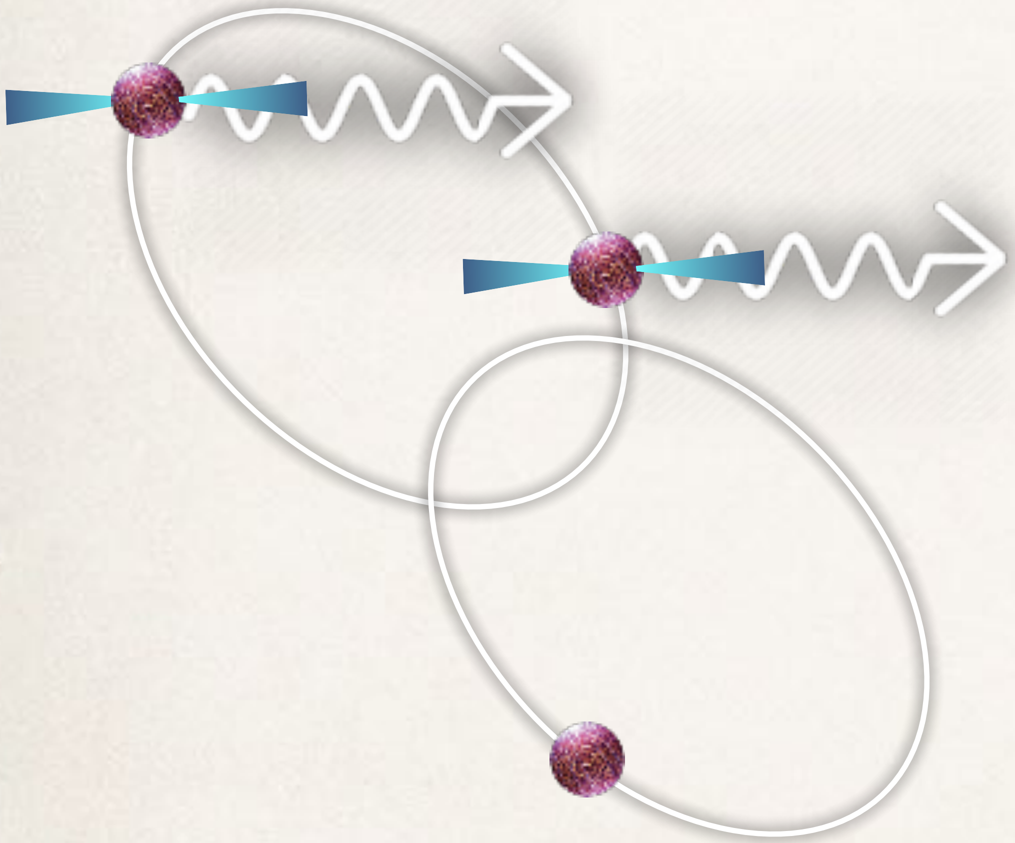
Spin phase
(2 rotations)

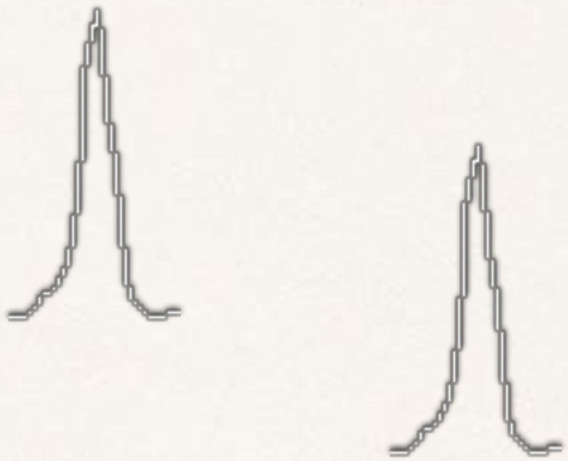
Credits: A. Bilous

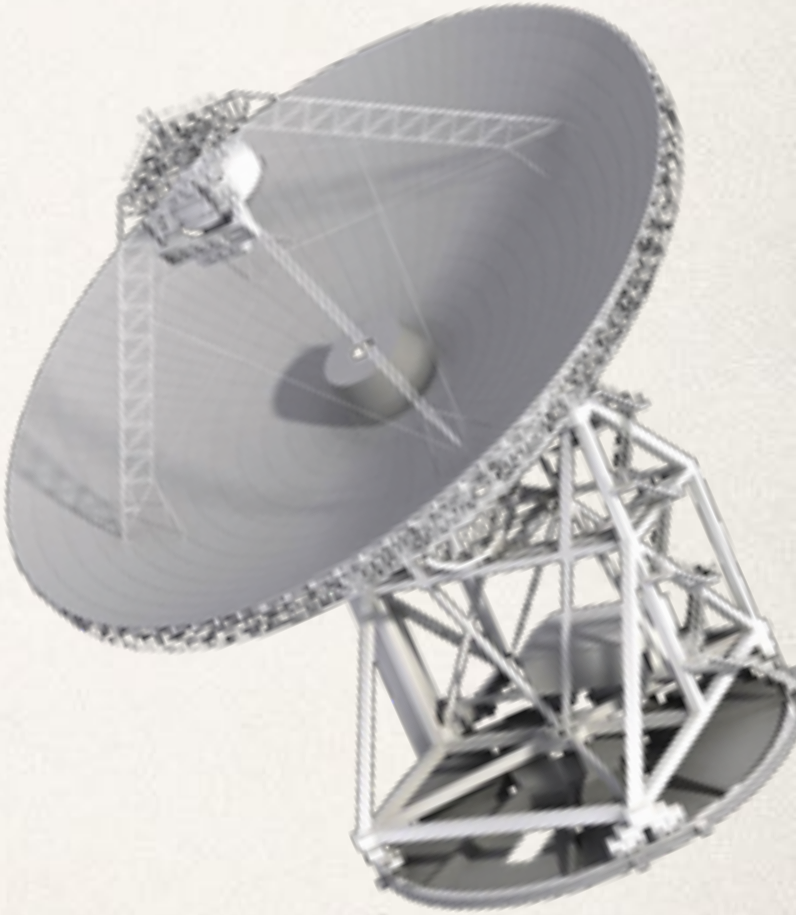
Part 1
Measuring neutron star masses



Radio timing of pulsars in binary systems permits measurements of orbital parameters.







Long term monitoring of binary pulsars results in precise determination of "post-Keplerian" parameters

Measured Orbital Parameters for PSR B1913+16

Fitted Parameter	Value
$a_p \sin i$ (s)	2.3417725 (8)
e	0.6171338 (4)
T_0 (MJD)	52144.90097844 (5)
P_b (d)	0.322997448930 (4)
ω_0 (deg)	292.54487 (8)

Keplerian parameters

Double-NS system PSR B1913+16

Best M_{NS} measurement

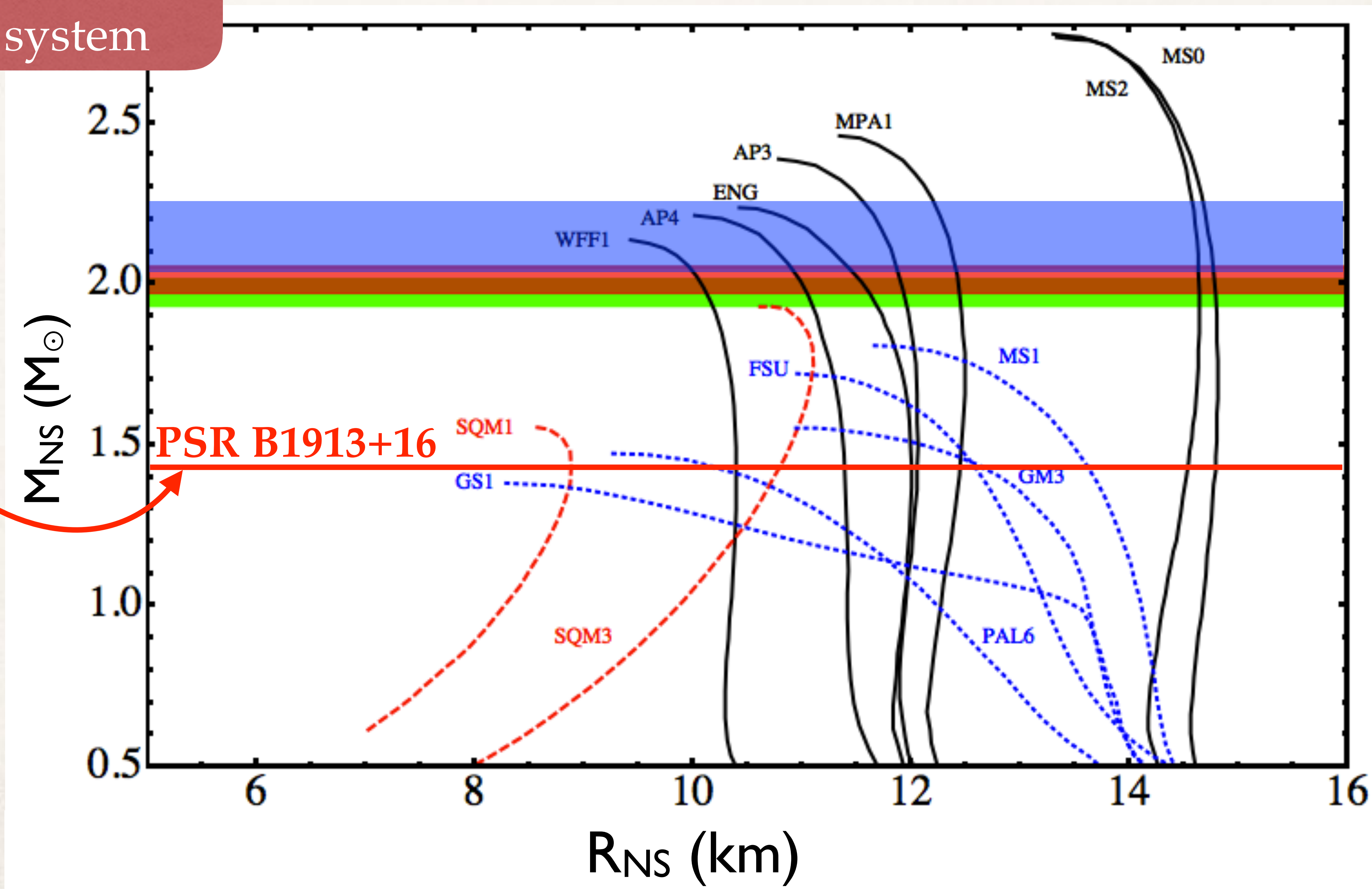
$M_{PSR} = 1.4414 \pm 0.0002\ M_{\odot}$

Weisberg et al. 2005

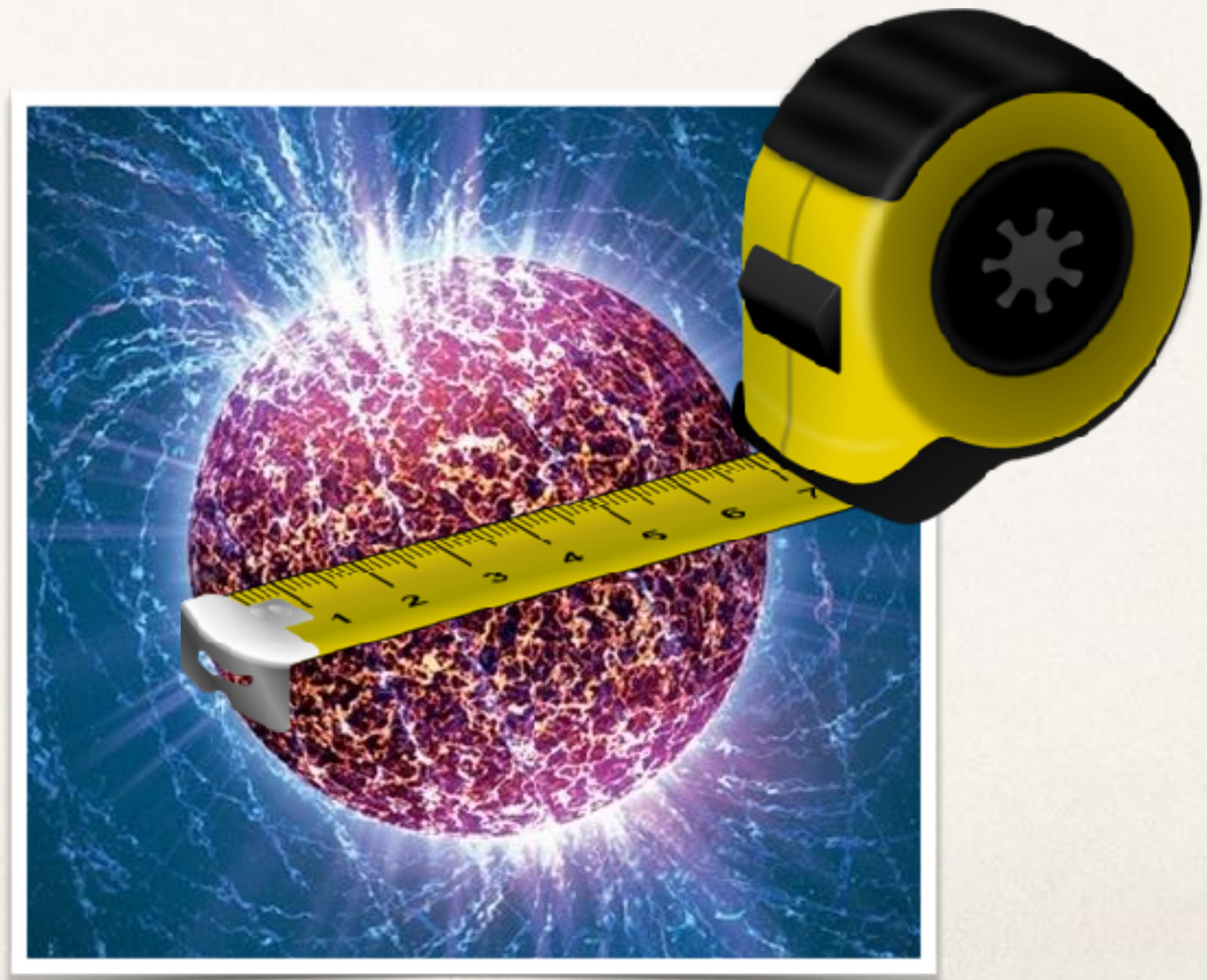
Measurements of the mass M_{NS} exist, but only high-M_{NS} are useful.

Demorest et al. 2010
Antoniadis et al. 2013
Cromartie et al. 2019

Most precise mass measurement outside the Solar system



Part 2
Measuring neutron star radii



Direct measurements of neutron star sizes are currently impossible.

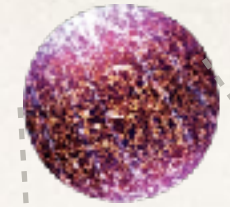
Interferometry measurements of stellar surfaces for 23 stars

List of stars with resolved images

From Wikipedia, the free encyclopedia

List of stars with resolved images

Star	Image	Diameter: Angular (mas)	Diameter: Geometric (Sun = 1)	Distance (ly)	Imager
Almaaz B (Epsilon Aurigae B)			5.9 ± 0.1	ca. 2000	
Theta^1 Orionis C		0.2	10.6 ± 1.5	1400	Very Large Telescope - AMBER[18], GRAVITY[20]
Sheliak A (Beta Lyrae A)		0.46	6	960 ± 50	CHARA array - MIRC[18]
Algol Ab (Beta Persei Ab)		0.56 ± 0.10	0.9	93 ± 2	
Proxima Centauri		1.02 ± 0.08	0.141 ± 0.007	4.246 ± 0.006	Very Large Telescope
Algol Aa1 (Beta Persei Aa1) (stationary object)		0.88 ± 0.05	4.13	93 ± 2	CHARA array - MIRC[6]
Algol Aa2 (Beta Persei Aa2) (orbiting object)		1.12 ± 0.07	3	93 ± 2	CHARA array - MIRC[6]
Regulus (Alpha Leonis A)		1.24 ± 0.02	3.2 ± 0.1 (polar) 4.2 ± 0.1 (equator)	79.3 ± 0.7	CHARA array - MIRC[5]
Rasalhague (Alpha Ophiuchi A)		1.62 ± 0.03	2.39 ± 0.01 (polar) 2.87 ± 0.02 (equator)	48.6 ± 0.8	CHARA array - MIRC[4]
Caph (Beta Cassiopeiae)		1.70 ± 0.04	3.1 ± 0.1 (polar) 3.8 ± 0.1 (equator)	54.7 ± 0.3	CHARA array - MIRC[5]
Alderamin (Alpha Cephei)		1.35 ± 0.02 (polar) 1.75 ± 0.03 (equatorial)	2.20 ± 0.04 (polar) 2.74 ± 0.04 (equator)	48.8 ± 0.36	CHARA array - MIRC[4]
Almaaz A (Epsilon Aurigae A)		2.27	3.7 ± 0.7	ca. 2000	CHARA array - MIRC[21]
Zeta Andromedae Aa		2.502 ± 0.008	15.0 ± 0.8 (polar)	189 ± 3	CHARA array - MIRC[7][8]



The nearest neutron star would have an angular size 150000 smaller than the best measurement to date.

It would require an interferometer with the Earth-moon distance as baseline

Even indirectly, measuring the radius of neutron stars precisely is rather difficult.

To measure the radius, we need to:

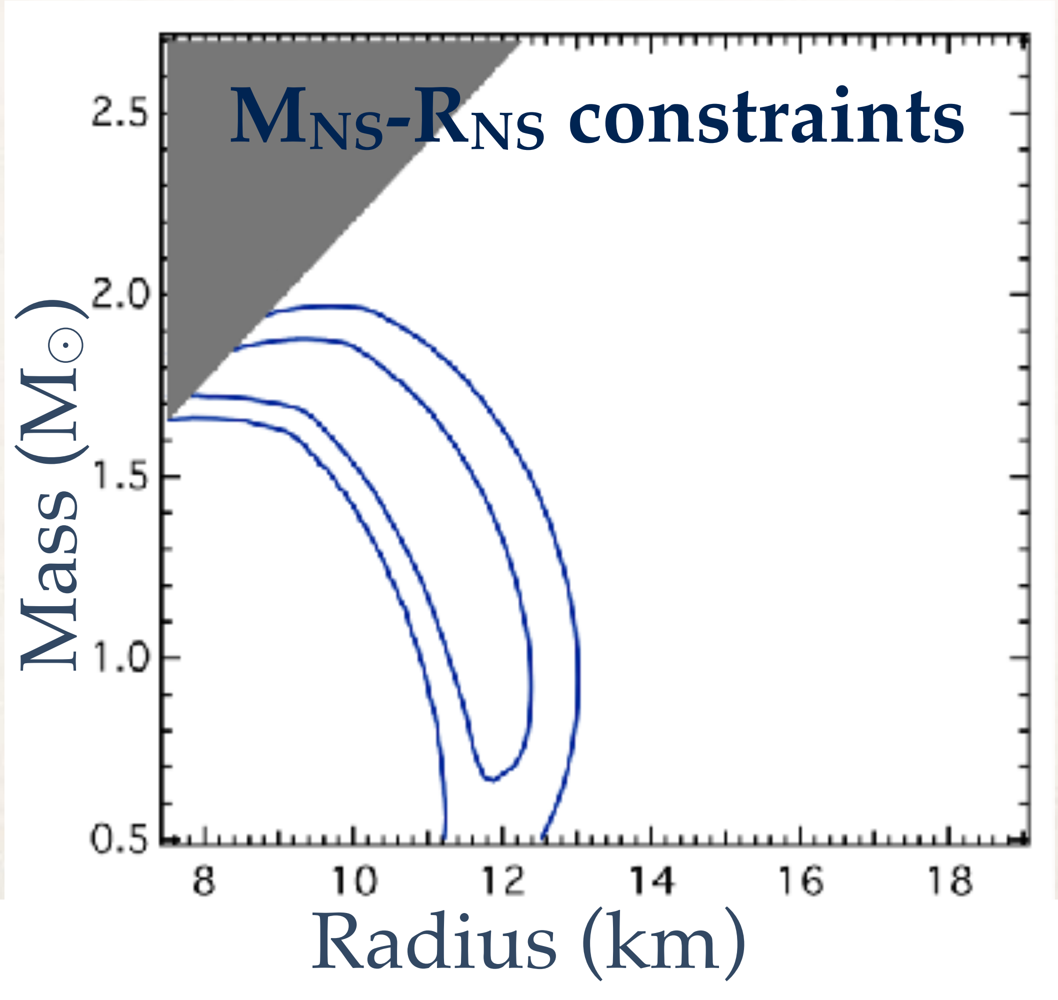
- observe the surface thermal emission,
- correctly model this emission,
- know the distance independently.

Luminosity

$$L = 4\pi R_{\infty}^{2}\, \sigma T_{\rm eff}^{4}$$

Flux

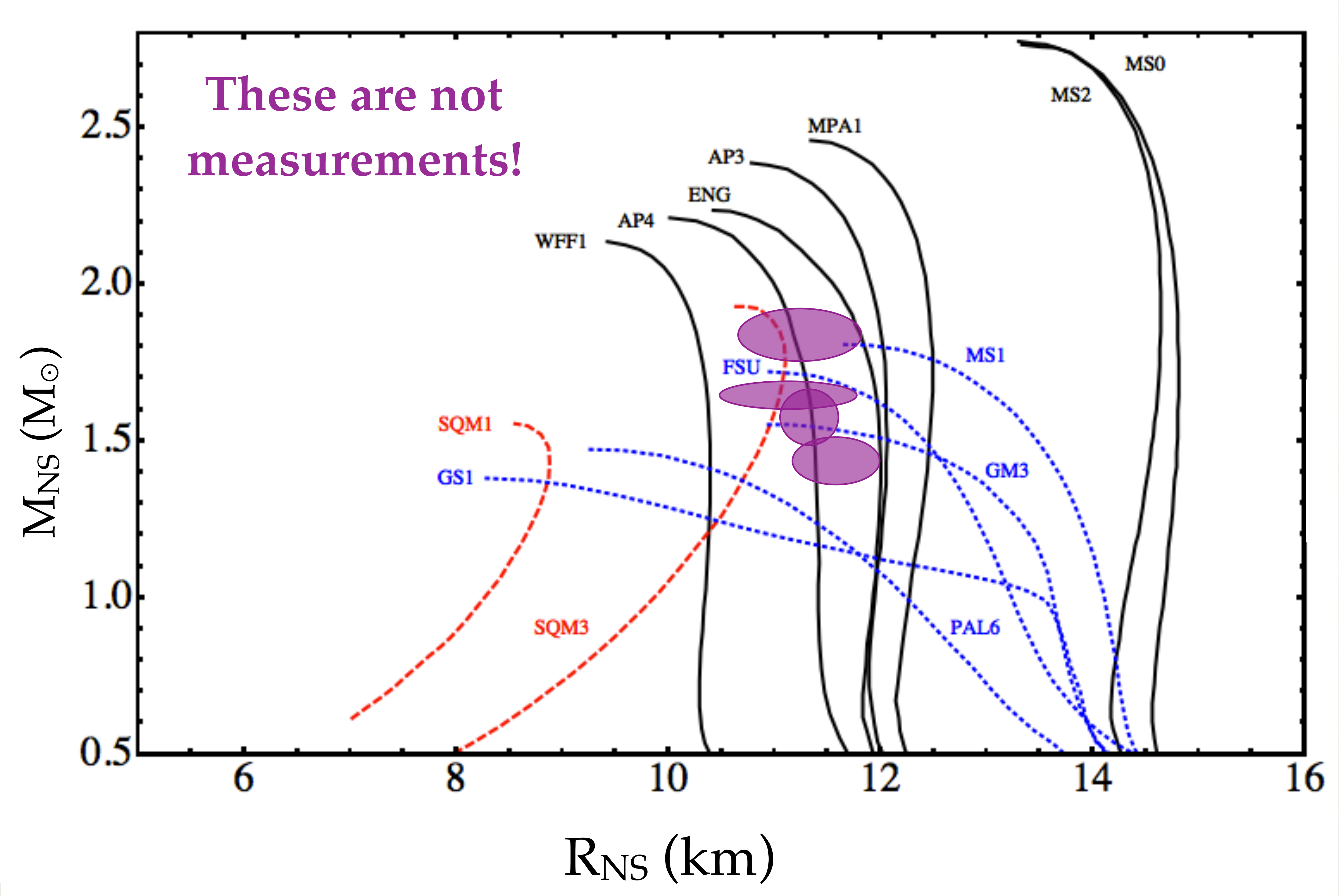
$$F = \left(\frac{R_{\infty}}{D}\right)^{2} \sigma T_{\rm eff}^{4}$$



With a M_{NS}-R_{NS} degeneracy because

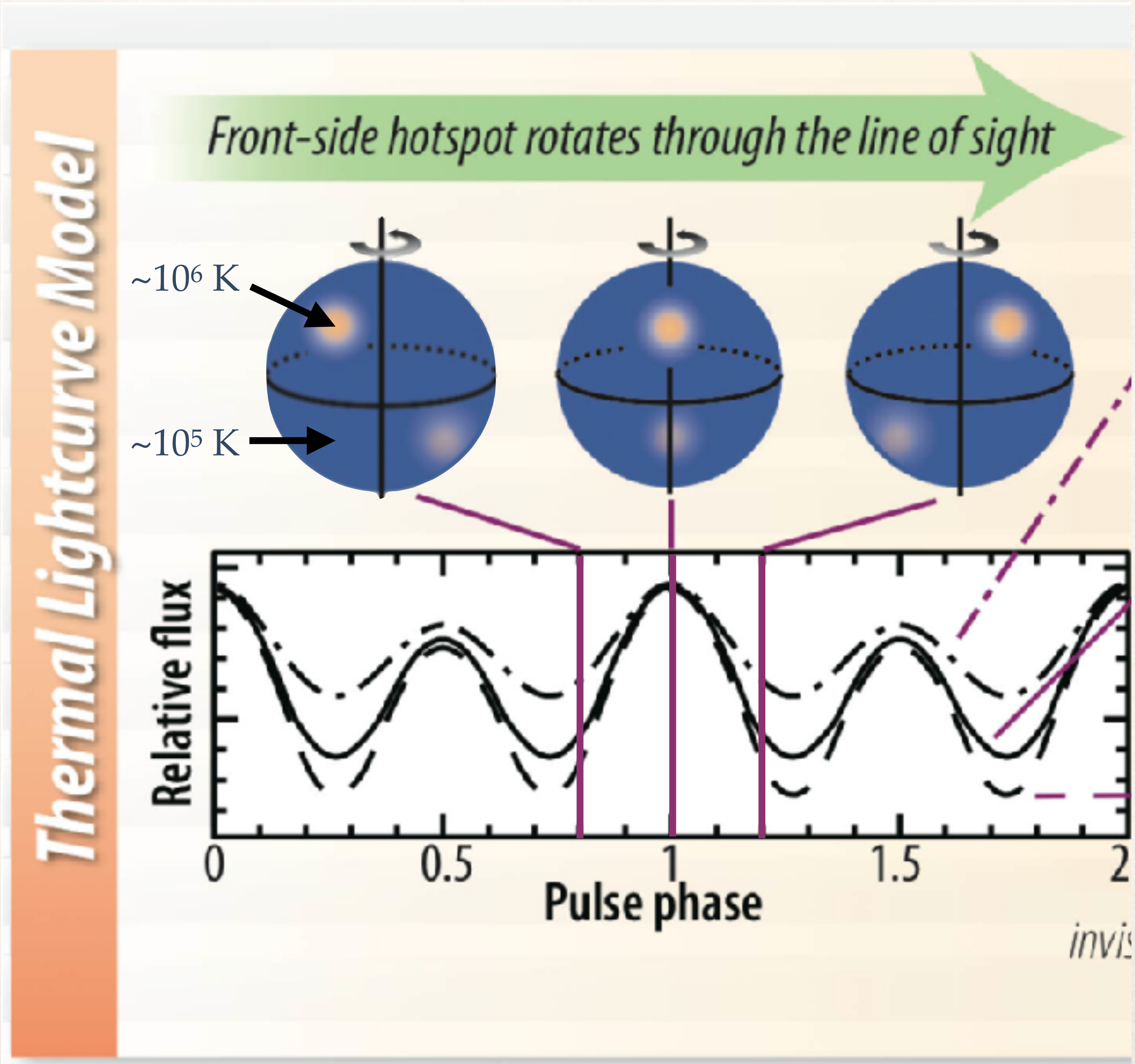
$$R_{\infty} = f\left(R_{NS}, M_{NS}\right)$$

Measuring R_{NS} is difficult, but measuring R_{NS} and M_{NS} for the same neutron star is even more difficult.



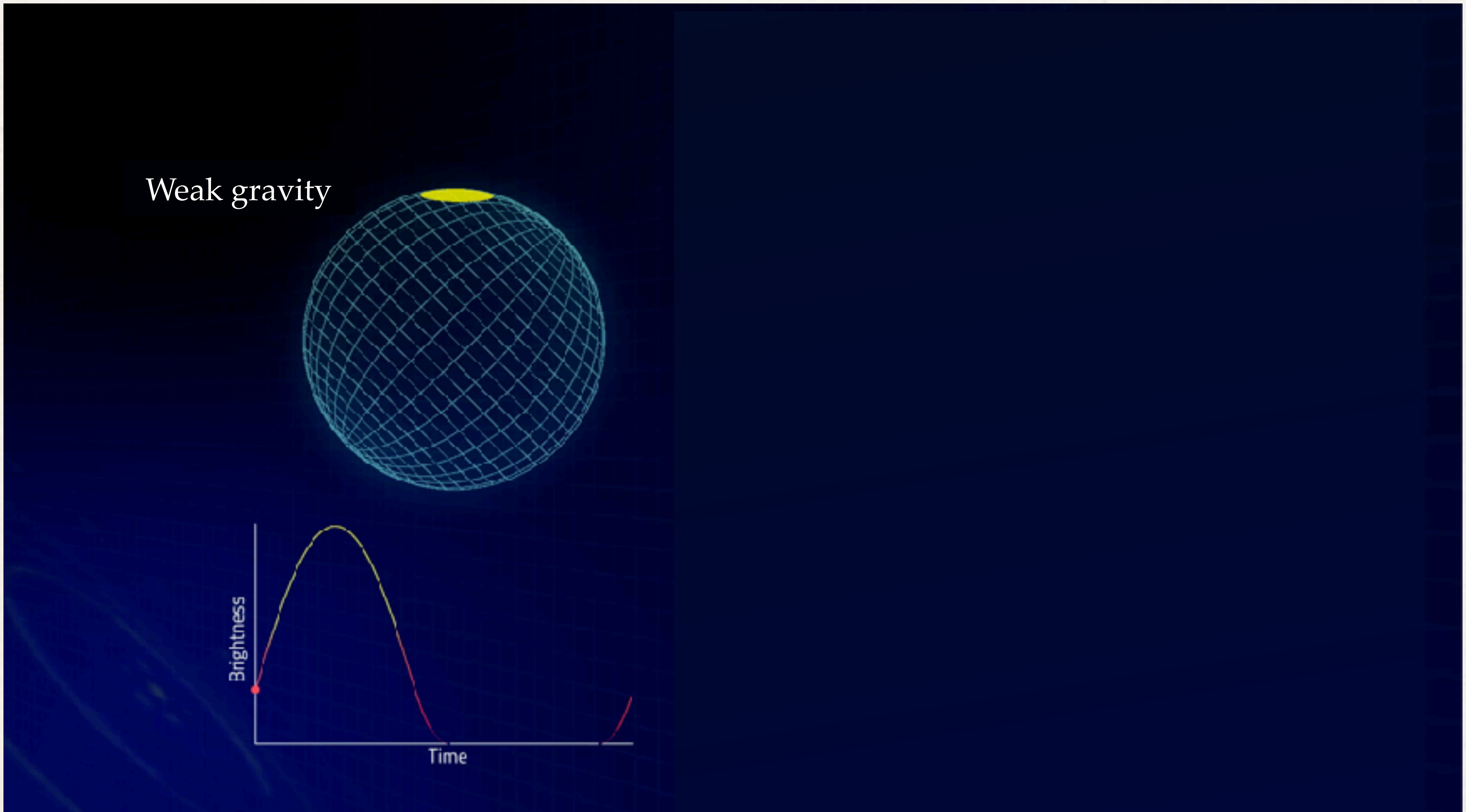
But there is a NICER way…

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



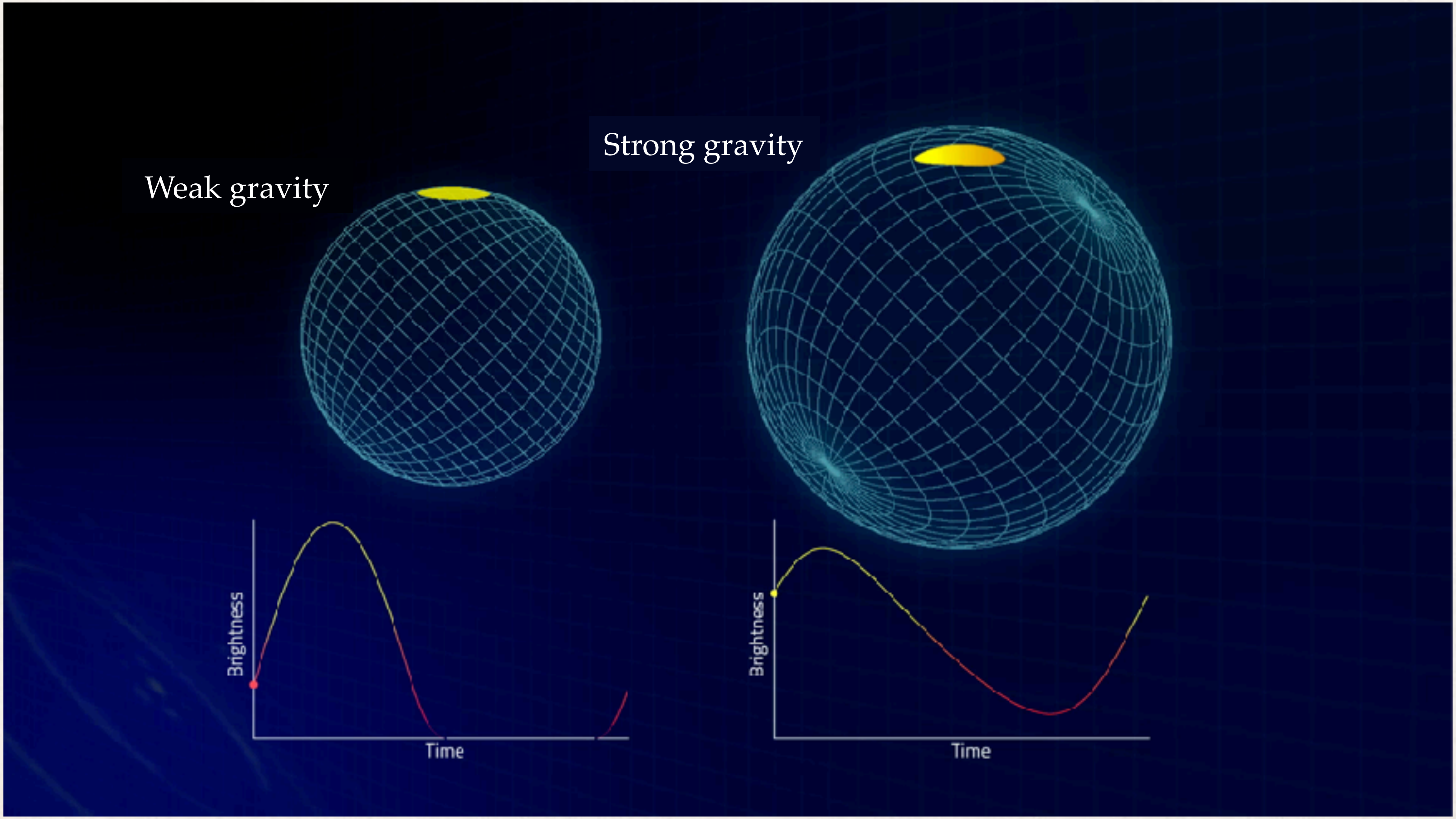
Credits: NASA/NICER

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



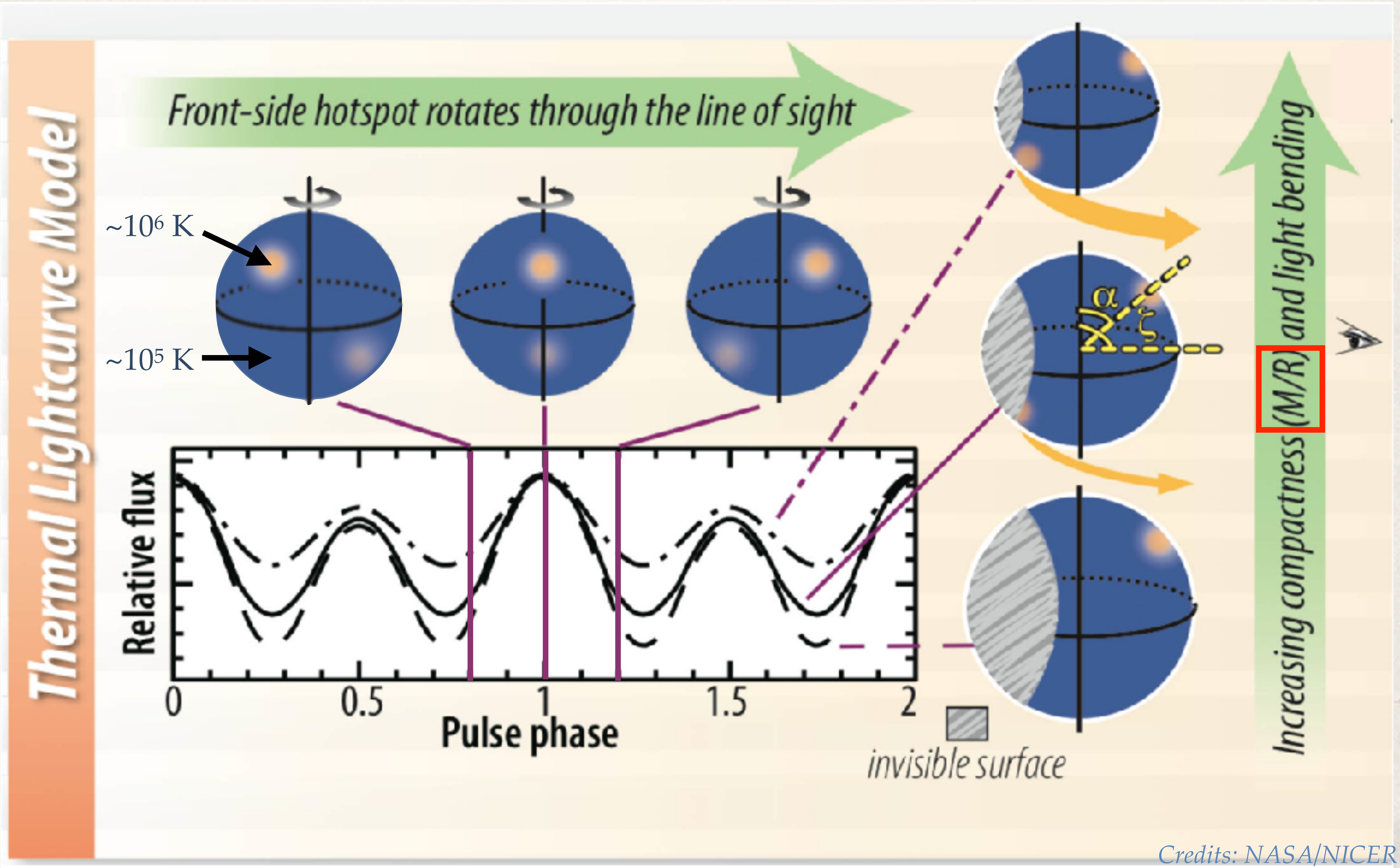
Credits: S. Morsink / NASA

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



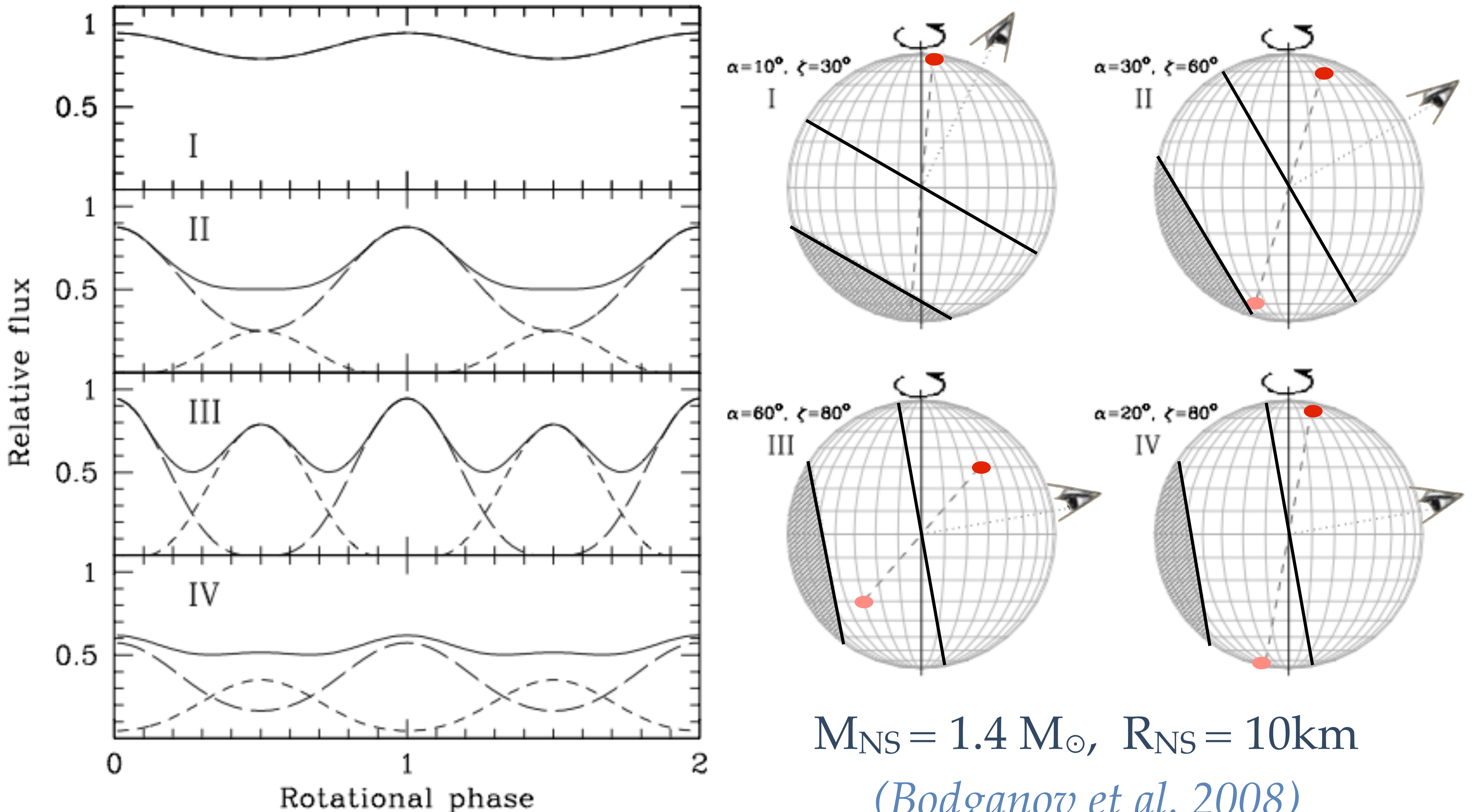
Credits: S. Morsink / NASA

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



Credits: NASA/NICER

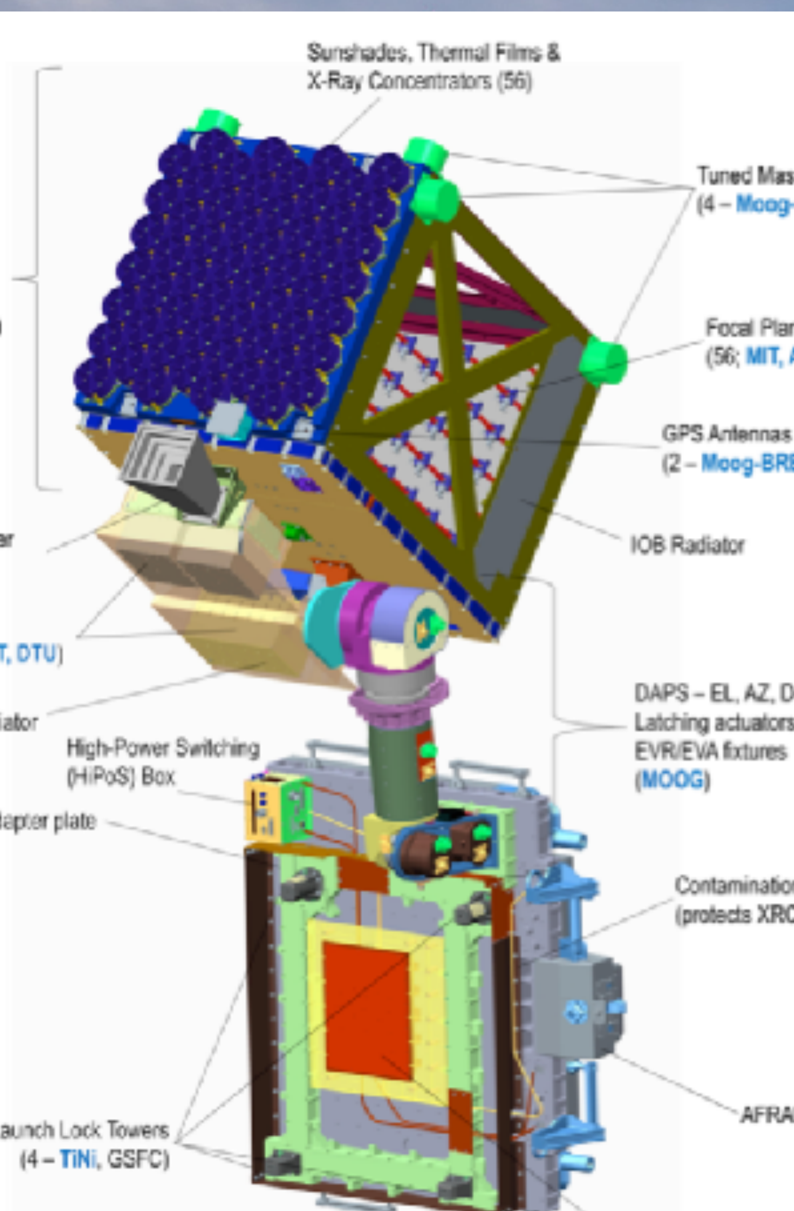
The pulsed emission also depends on the system geometry.



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

(Bodganov et al. 2008)

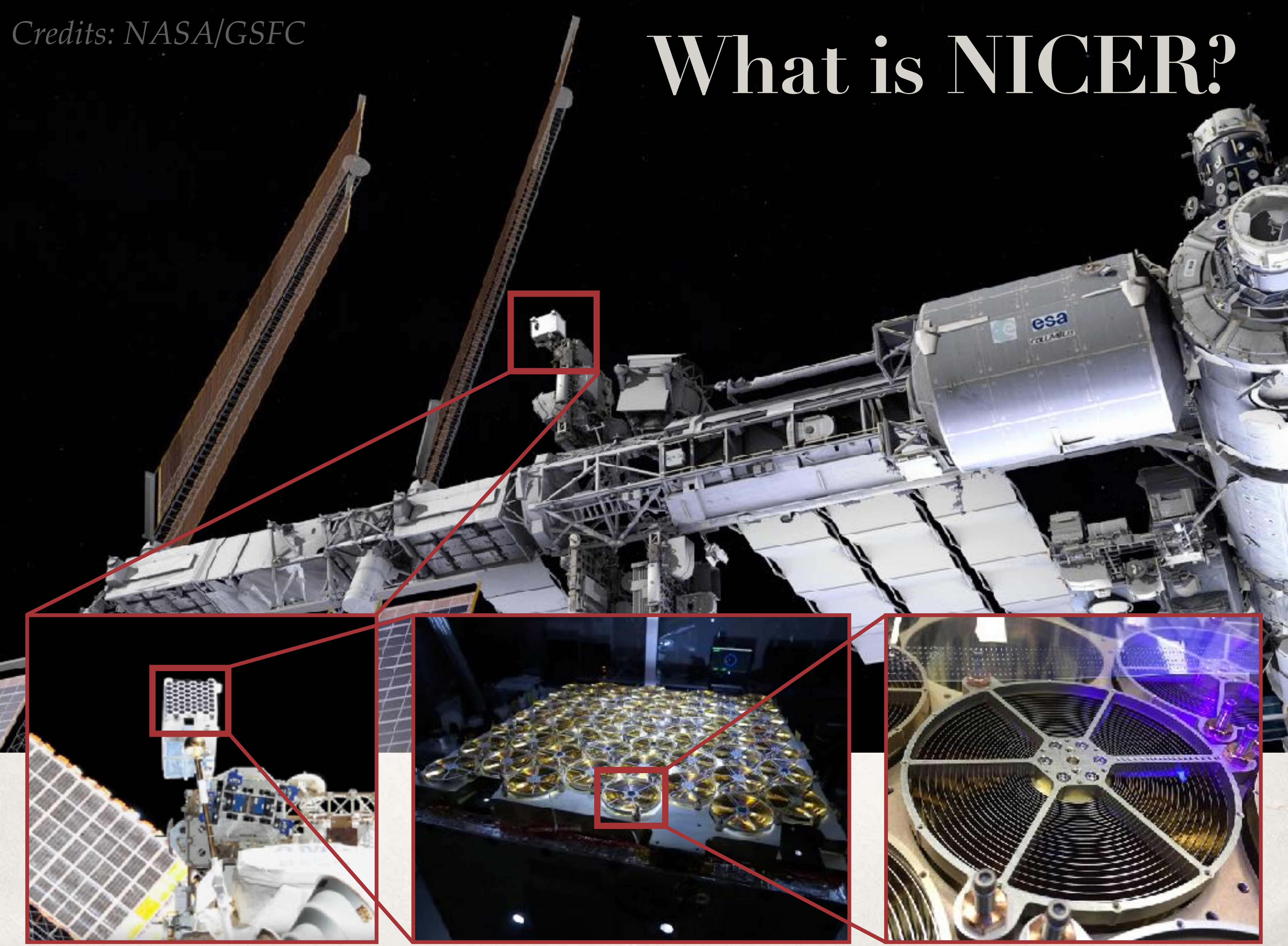
Since June 2017, the Neutron Star Interior Composition Explorer observes millisecond pulsars to measure their M_{NS} and R_{NS}.



Credits: NASA/NICER

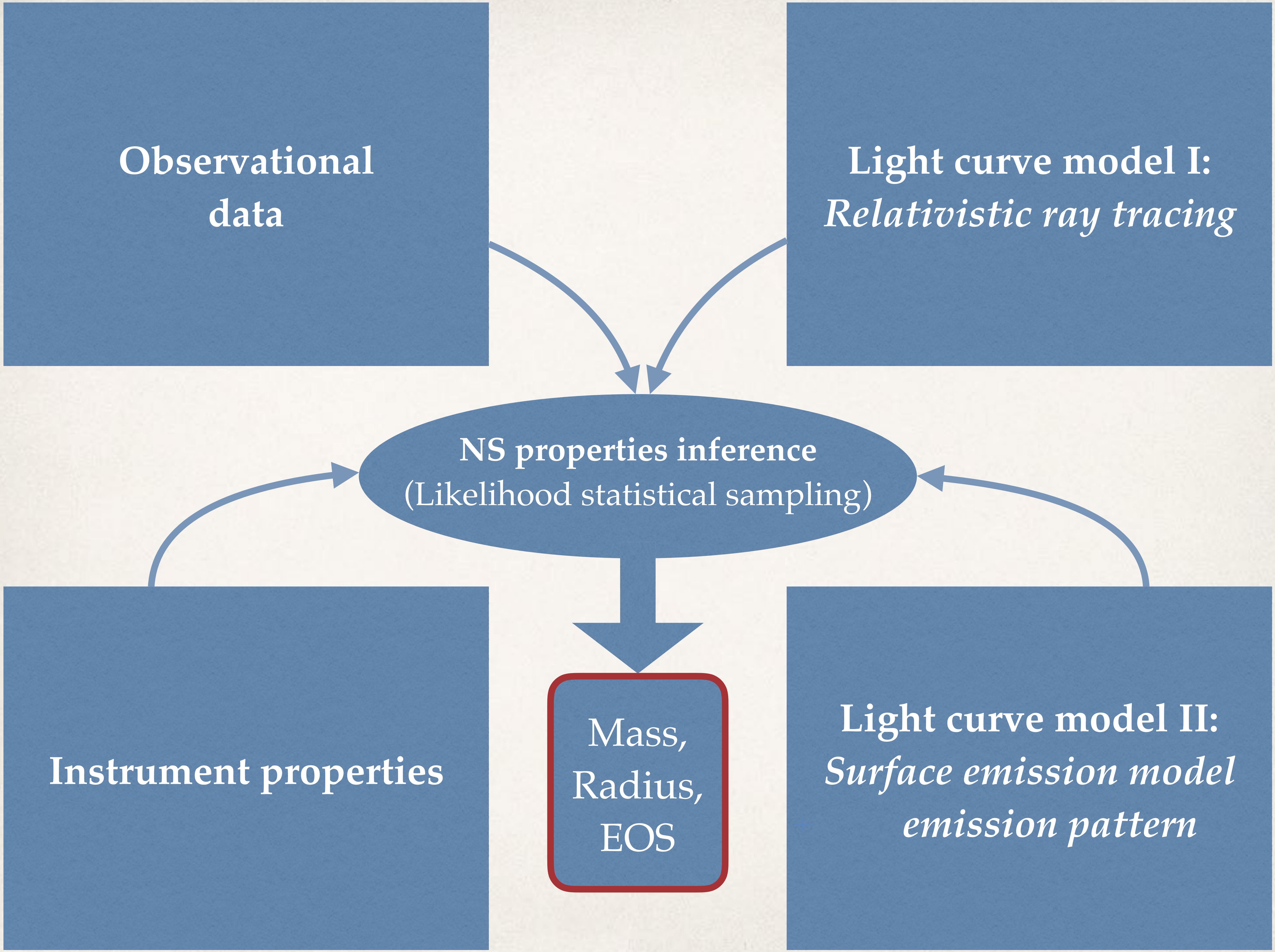
What is NICER?

Credits: NASA/GSFC

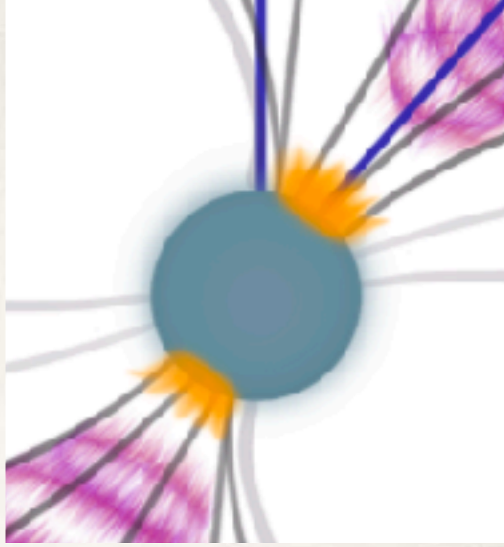


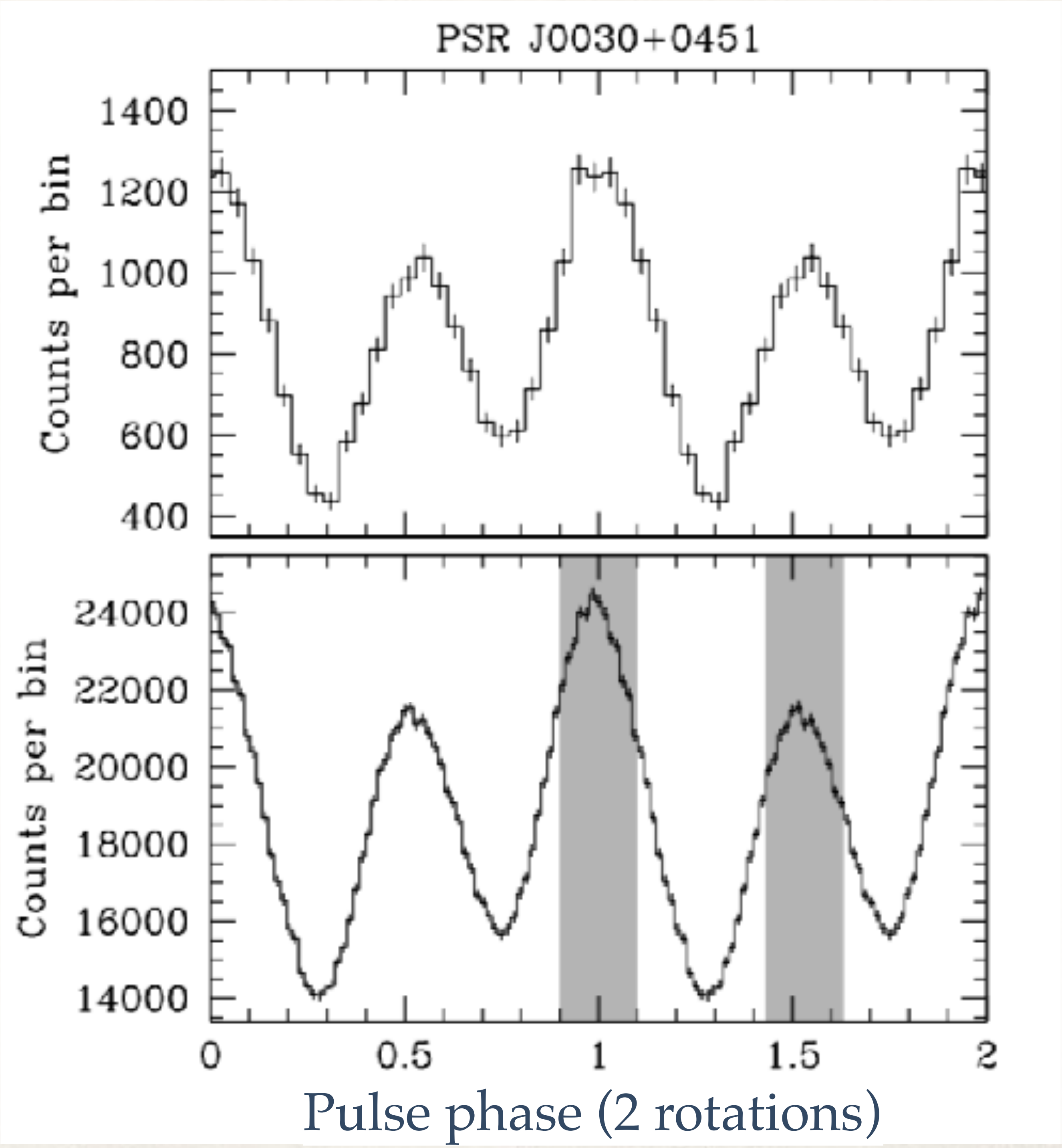
The ingredients to infer M_{NS} and R_{NS} with NICER:

An example with
PSR J0030+0451
and
PSR J0740+6620


Observational data
Light curve model I:
Relativistic ray tracing
NS properties inference
(Likelihood statistical sampling)
Instrument properties
Mass,
Radius,
EOS
Light curve model II:
Surface emission model
emission pattern

NICER now routinely observes a few key target millisecond pulsars to give us unprecedented signal-to-noise data.





XMM-Newton

130 ksec of data

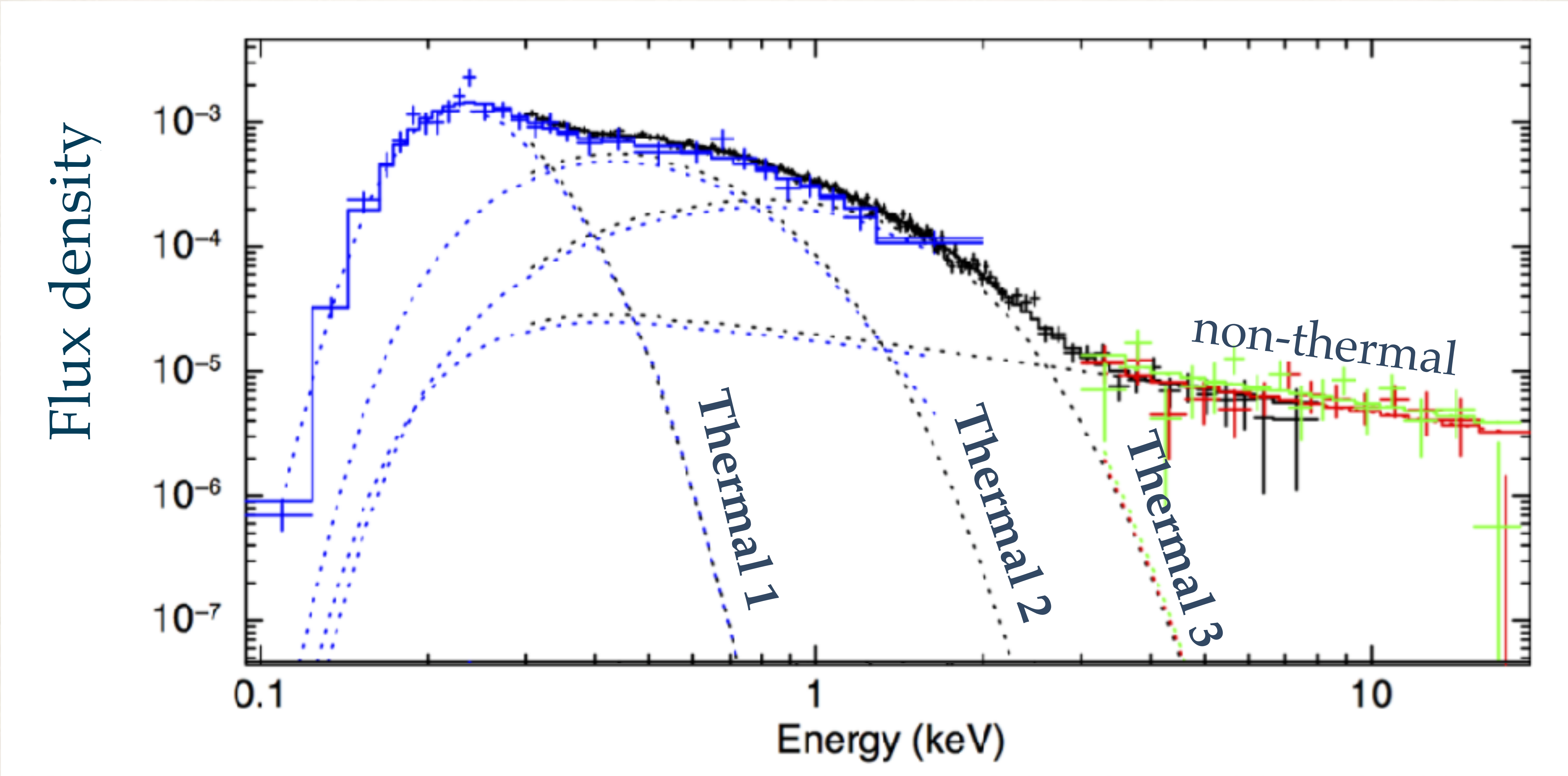
NICER

1.3 Msec of data

Bogdanov, Guillot et al. (2019a)

In addition to their pulse profiles, the spectra of these pulsars carry information.

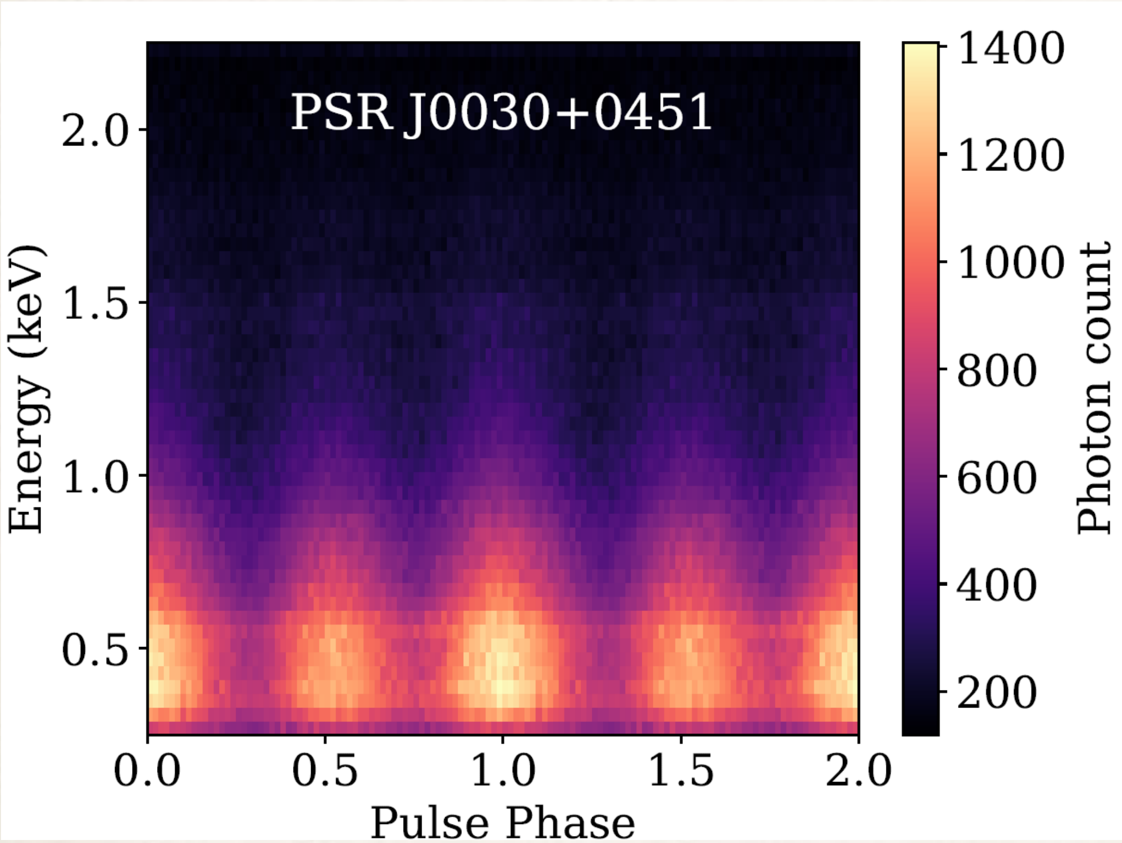
Example X-ray spectrum of a millisecond pulsar



Guillot et al. (2016)

NICER observations provide the pulsed information in phase-energy space.

PSR J0030+0451

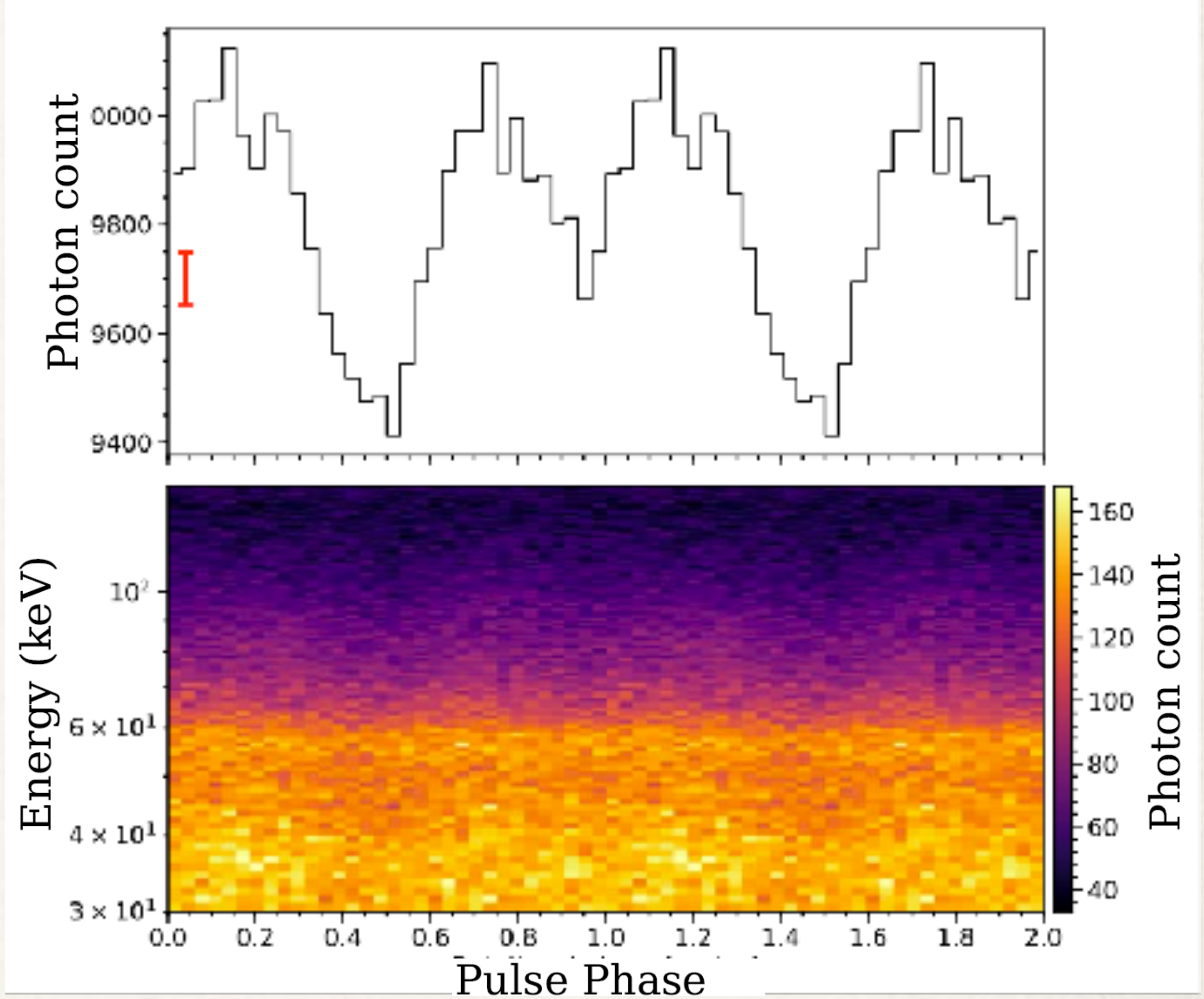


Bogdanov, Guillot et al. (2019a)

Isolated pulsar

No known mass!

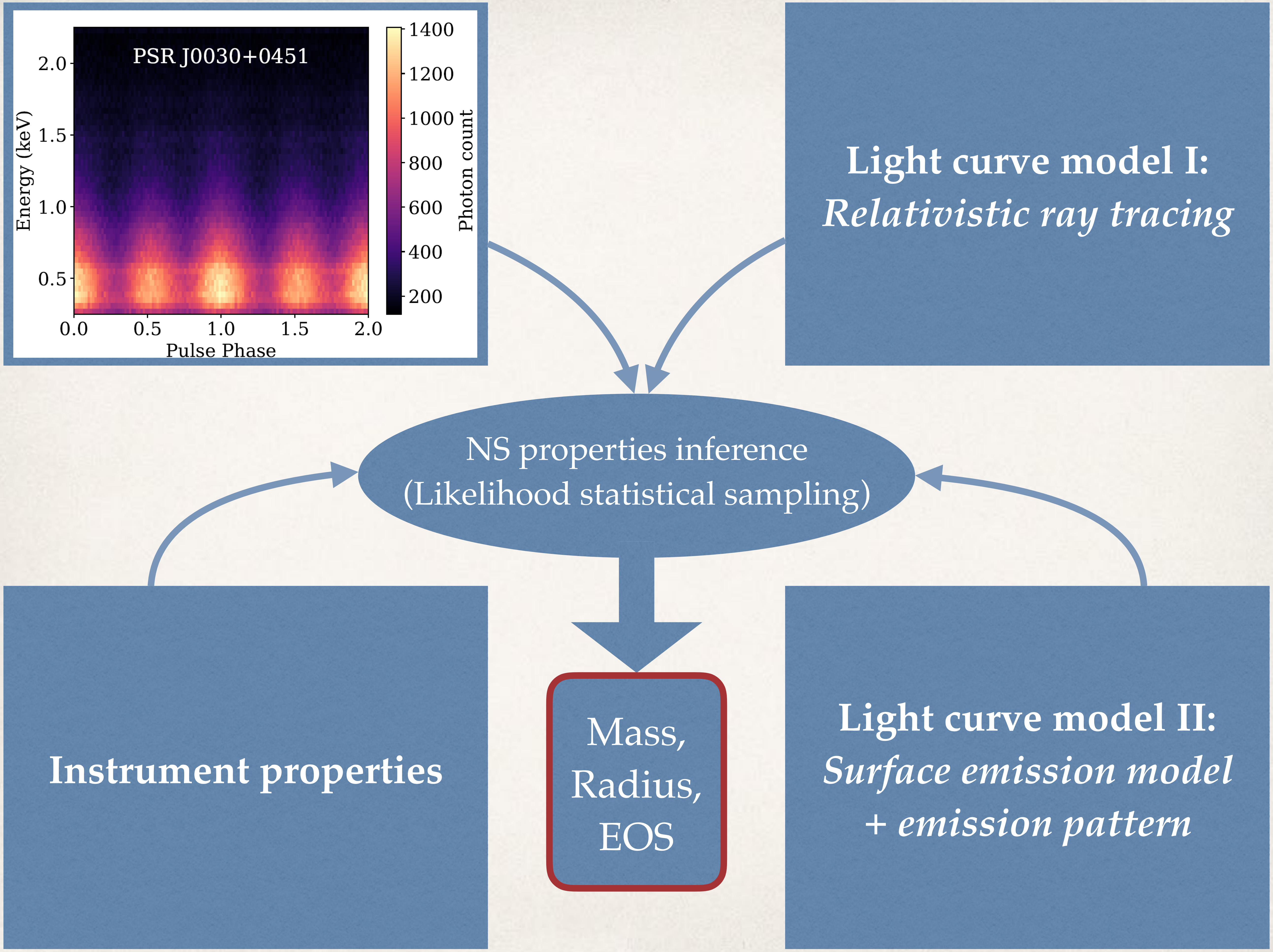
PSR J0740+6620



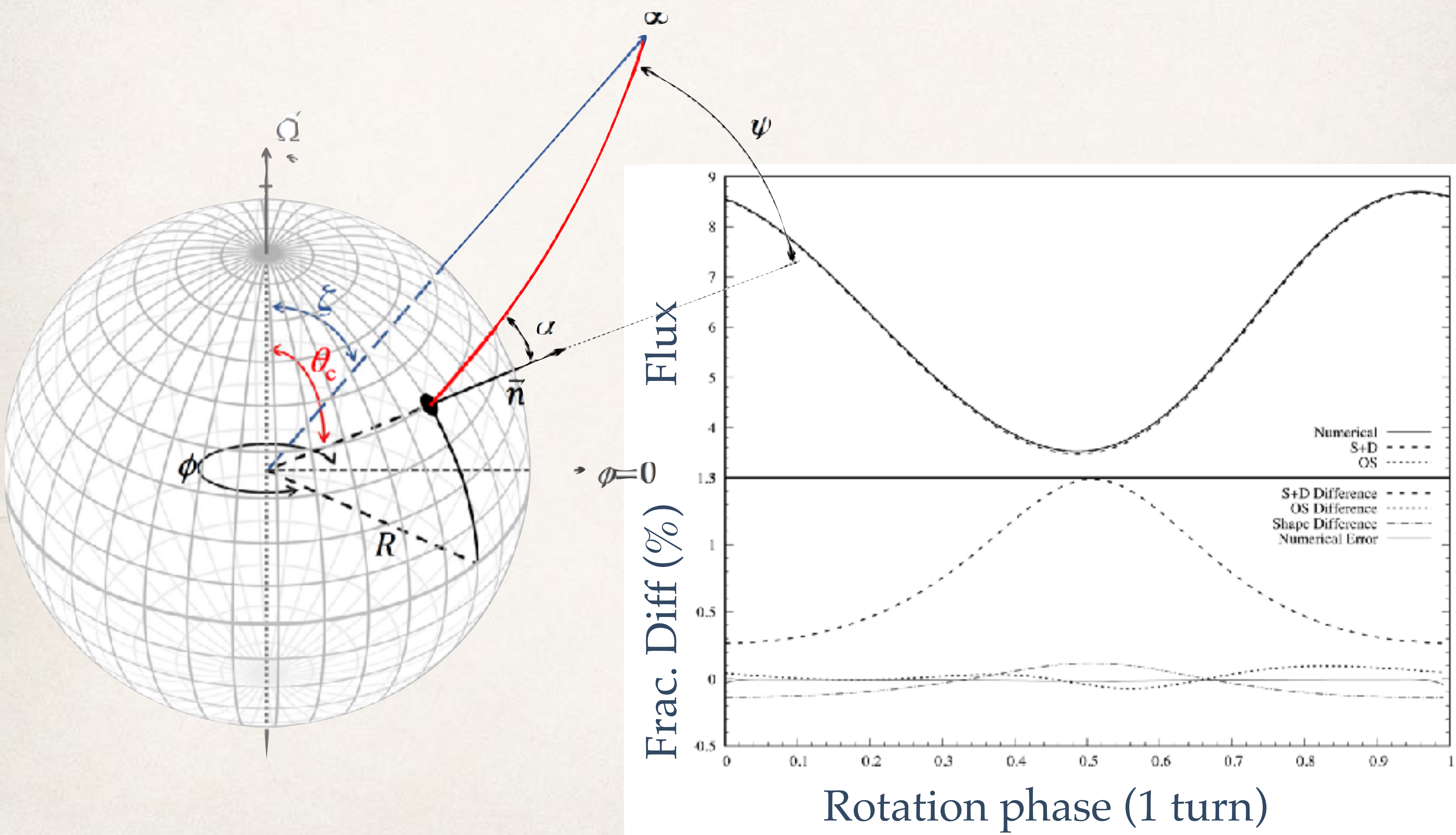
Riley et al. (2021)
Wolff, Guillot et al. (2021)

Binary system

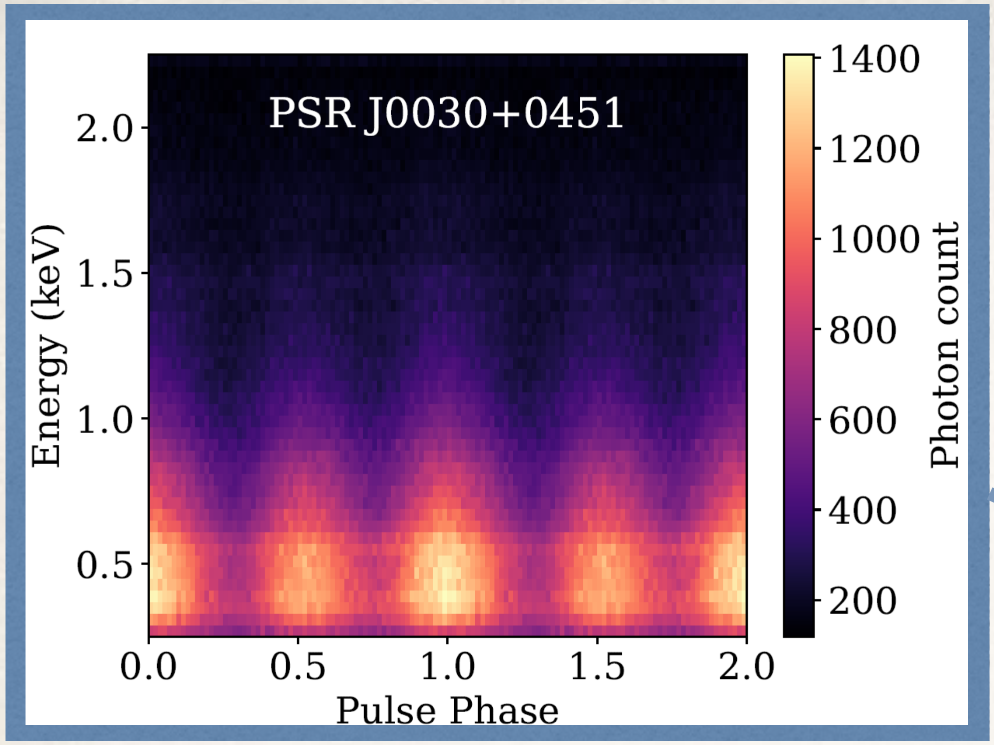
M = 2.07±0.07 Msun

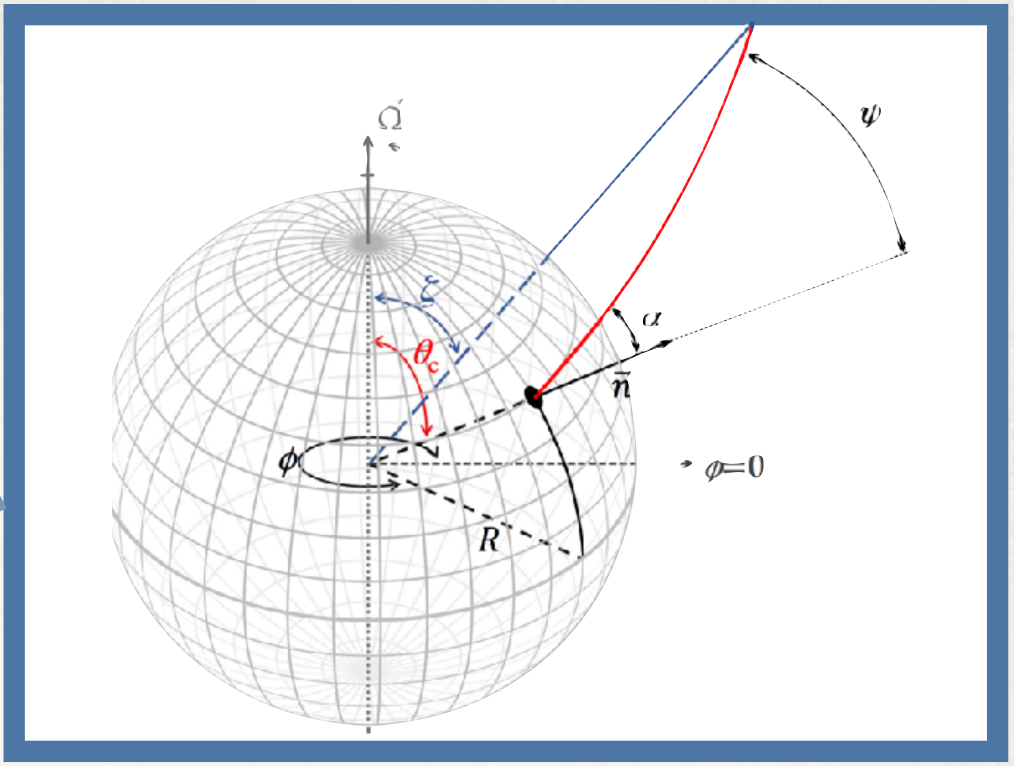

PSR J0030+0451
Energy (keV)
2.0
1.5
1.0
0.5
0.0
0.5
1.0
1.5
2.0
Pulse Phase
1400
1200
1000
800
600
400
200
Photon count
Light curve model I:
Relativistic ray tracing
NS properties inference
(Likelihood statistical sampling)
Instrument properties
Mass,
Radius,
EOS
Light curve model II:
Surface emission model
+ emission pattern

The light curve modelling requires a relativistic ray-tracing model.



Bogdanov, …, Guillot et al. (2019b)





NS properties inference
(Likelihood statistical sampling)

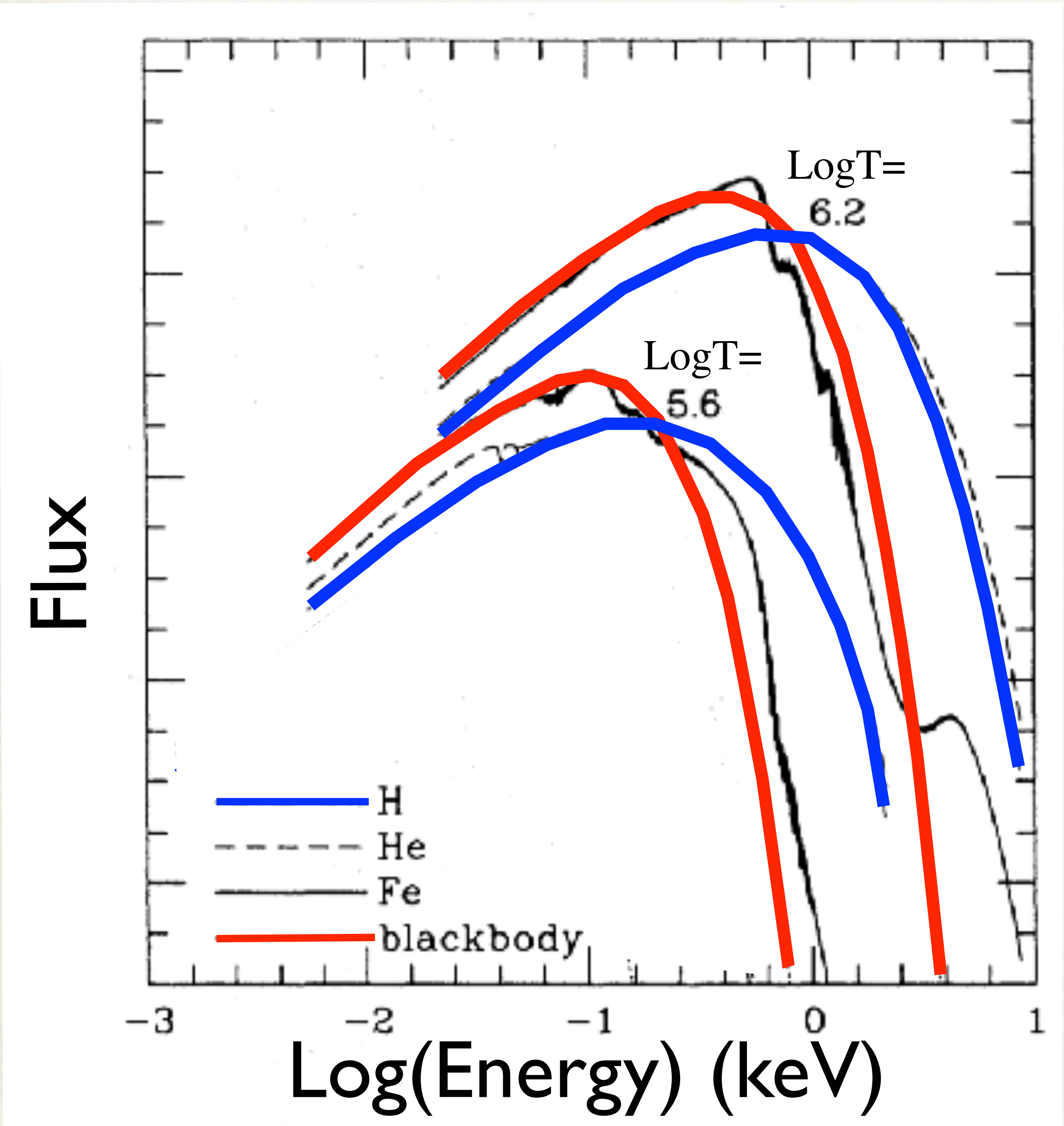
Instrument properties

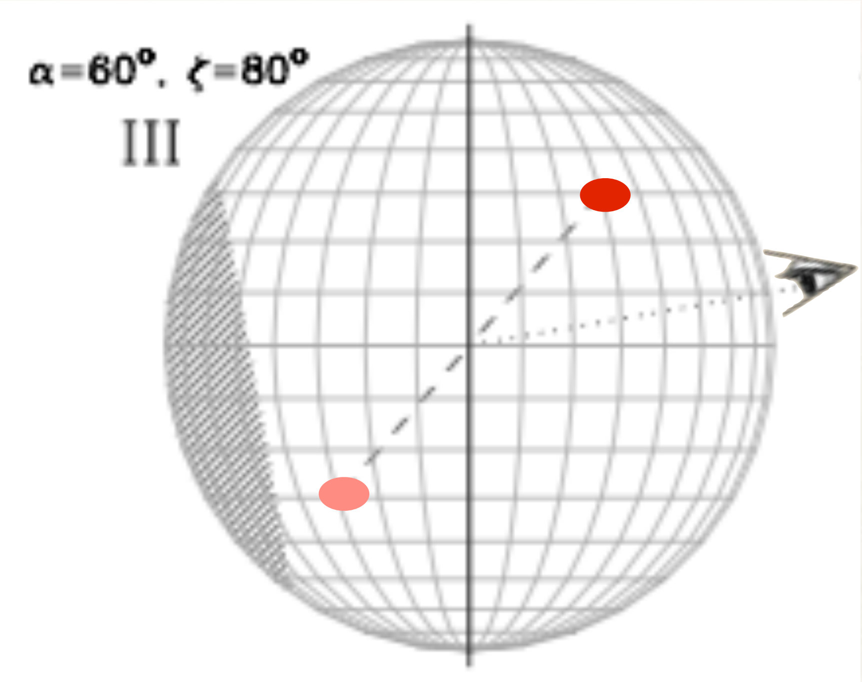
Mass,
Radius,
EOS

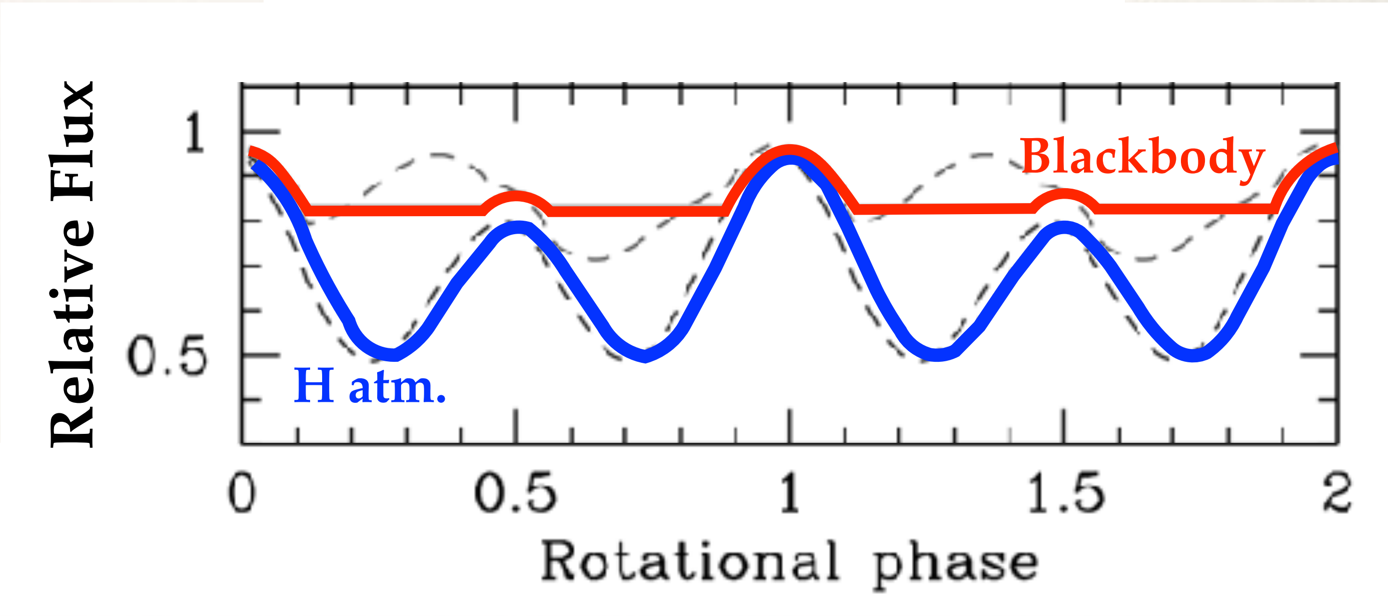
Light curve model II:
Surface emission model
+ emission pattern

The thermal emission from a NS surface is modelled with a NS atmosphere, not a black body.

Models by Zavlin et al. (1996), Heinke et al. (2006), Haakonsen et al. (2012)

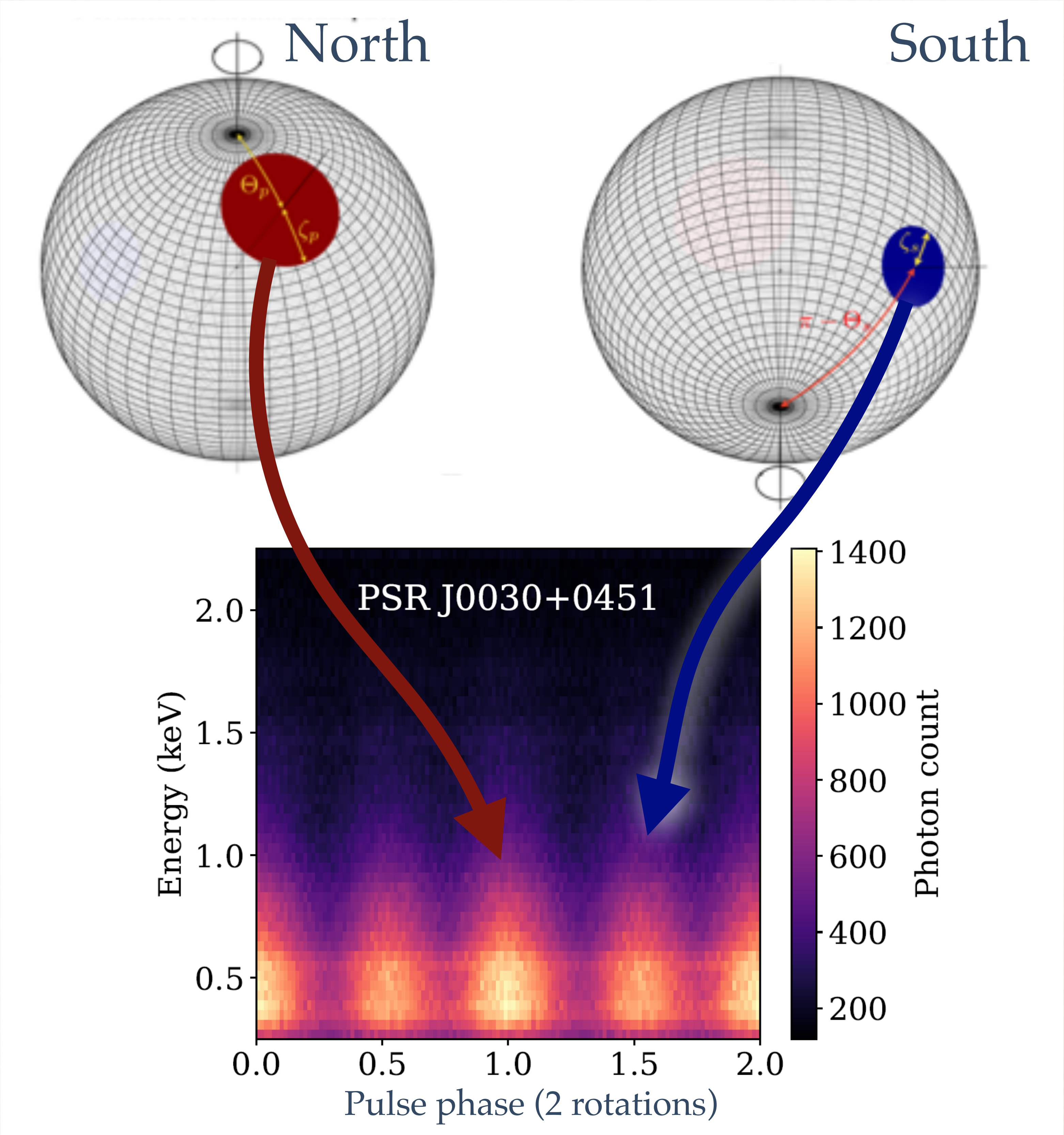






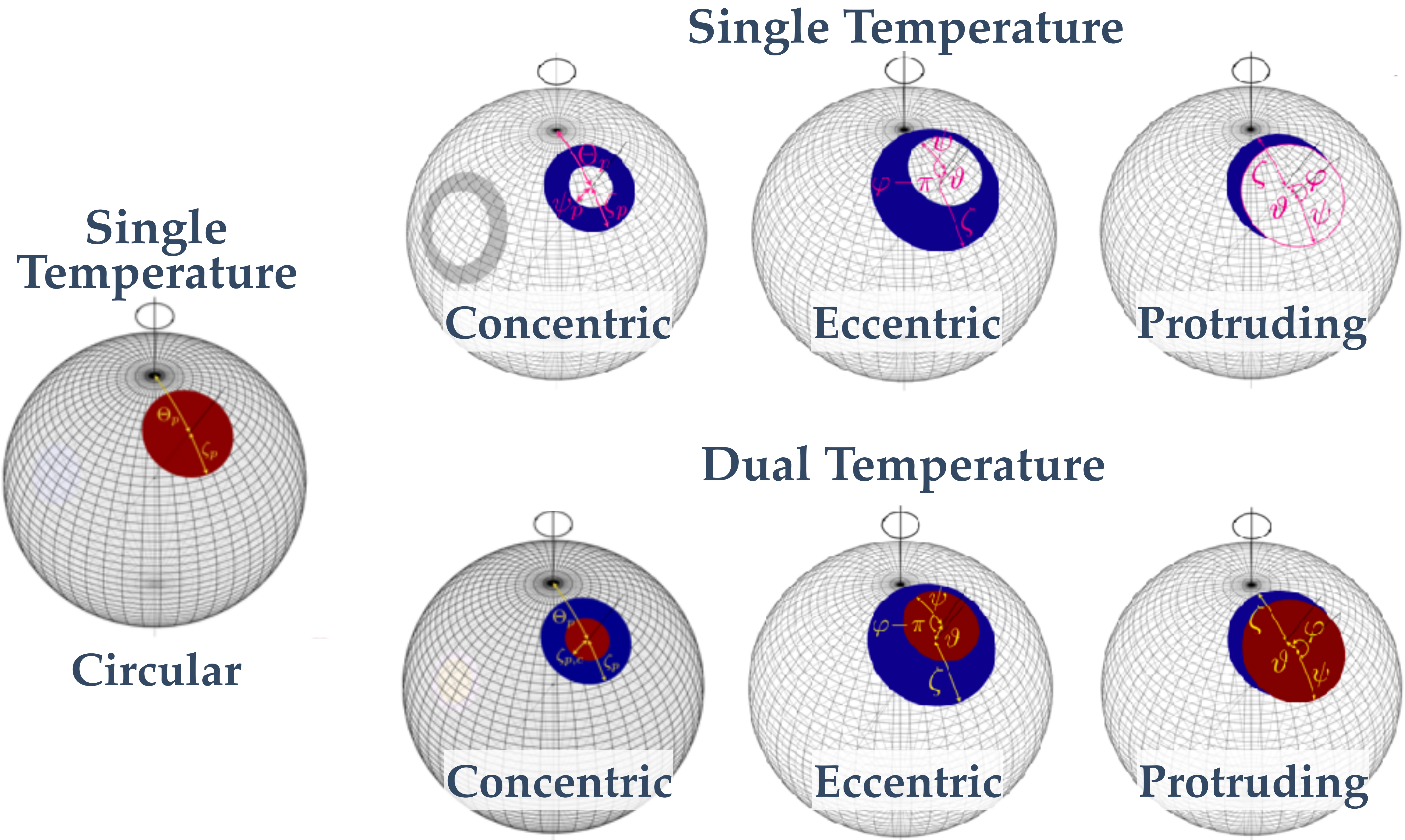
Bogdanov et al. (2007)

The surface patterns (shape, size, etc.) of the hot spots must also be modelled.

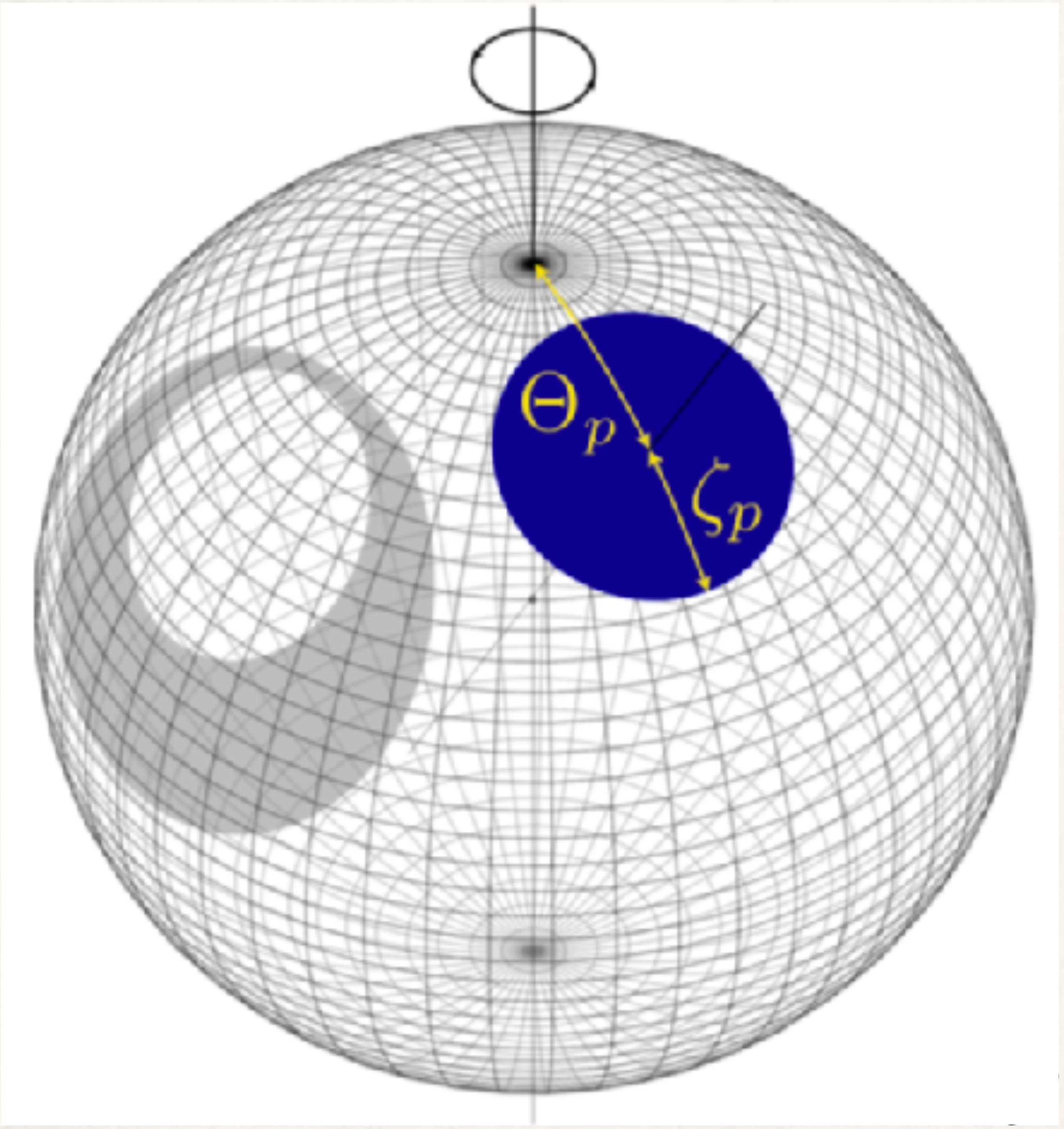


We considered progressively more complicated surface patterns for a hot spot…

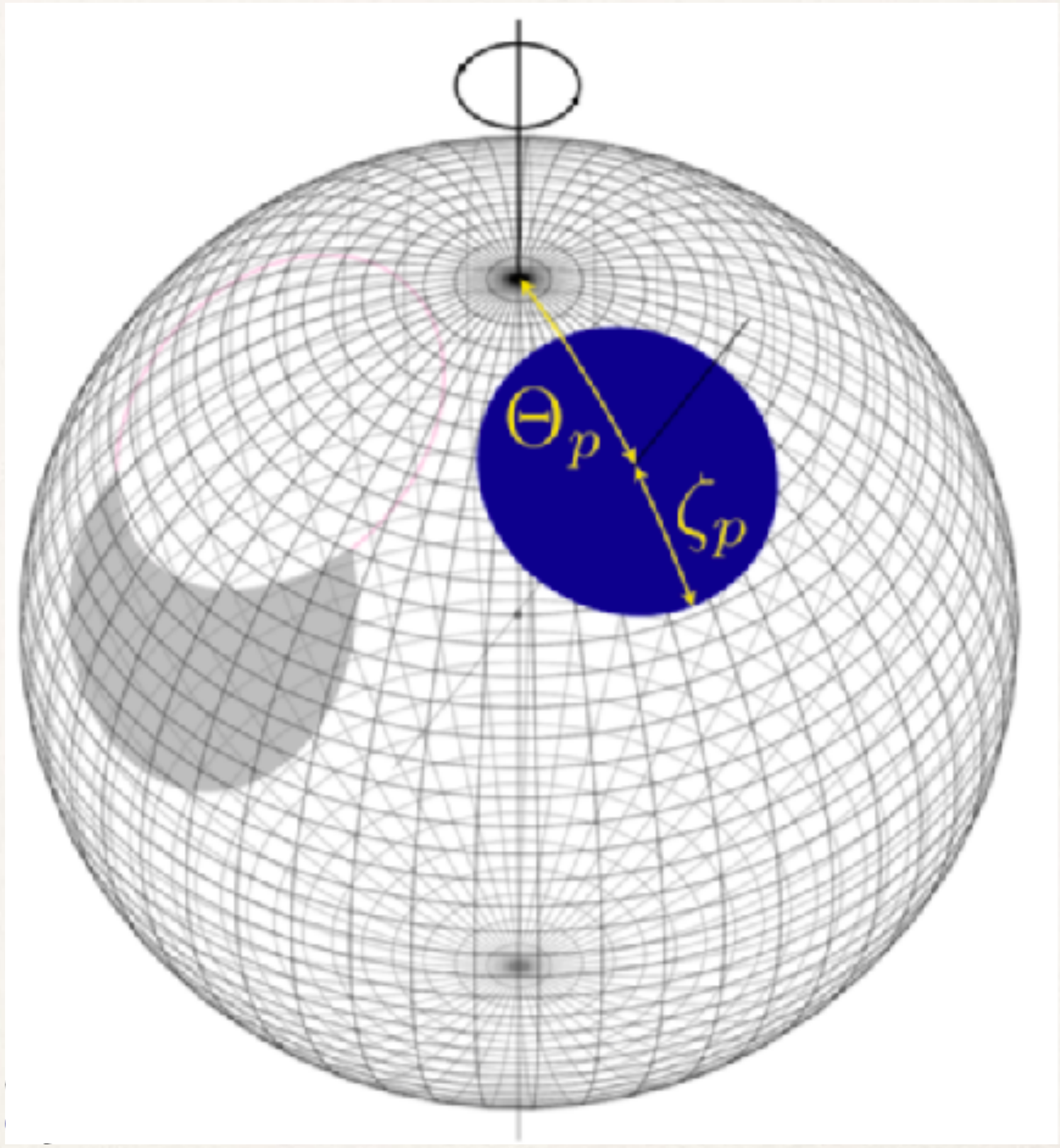
Riley, …, SG et al. (2019)



…and we tested combinations of hot spot patterns.

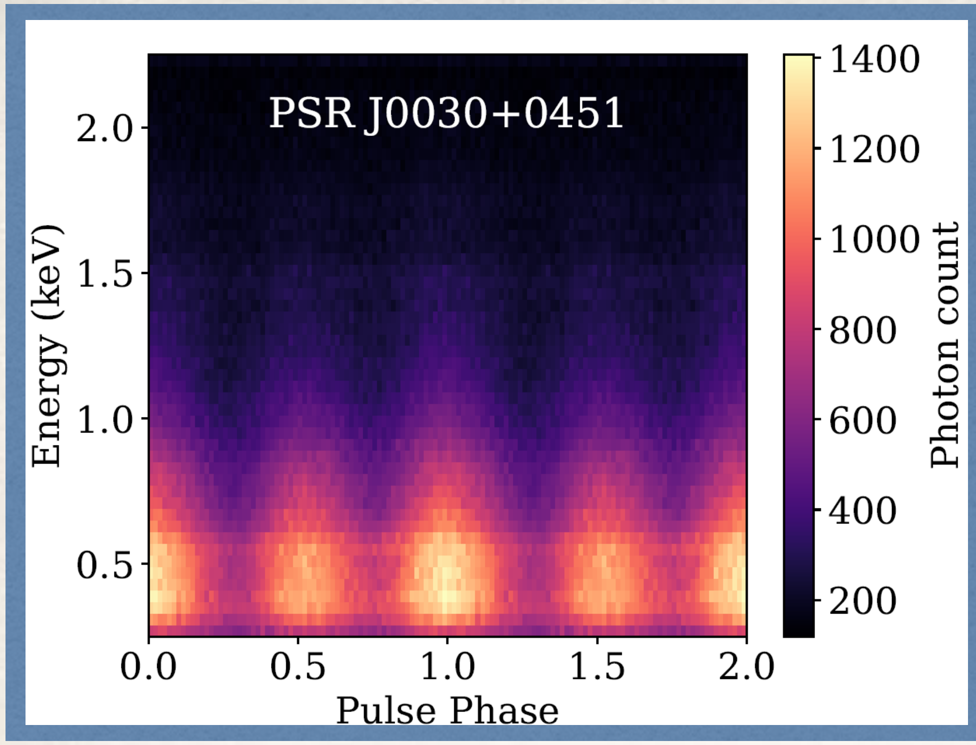


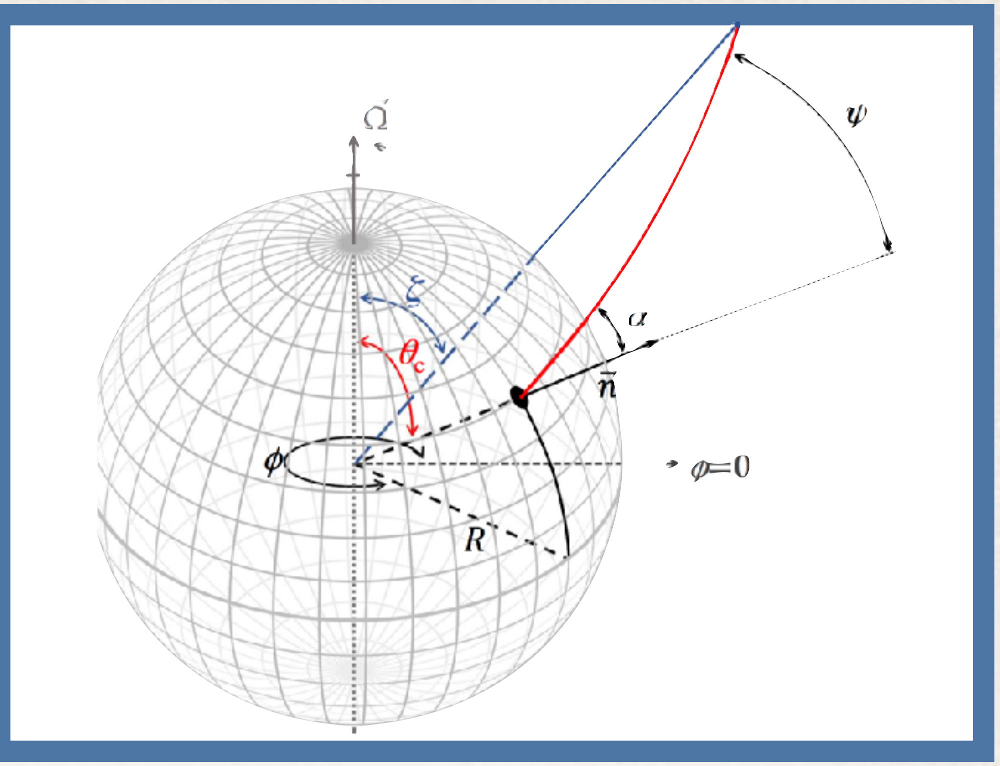
Single Temperature +
Eccentric Single Temperature



Single Temperature +
Protruding Single Temperature

Riley, …, SG et al. (2019)

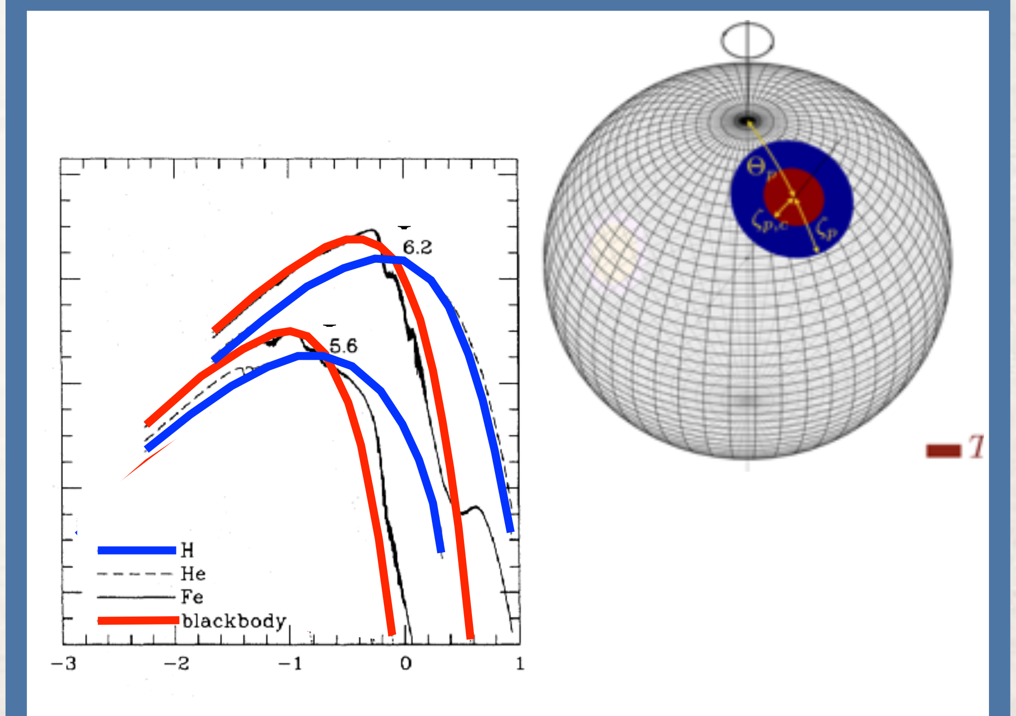




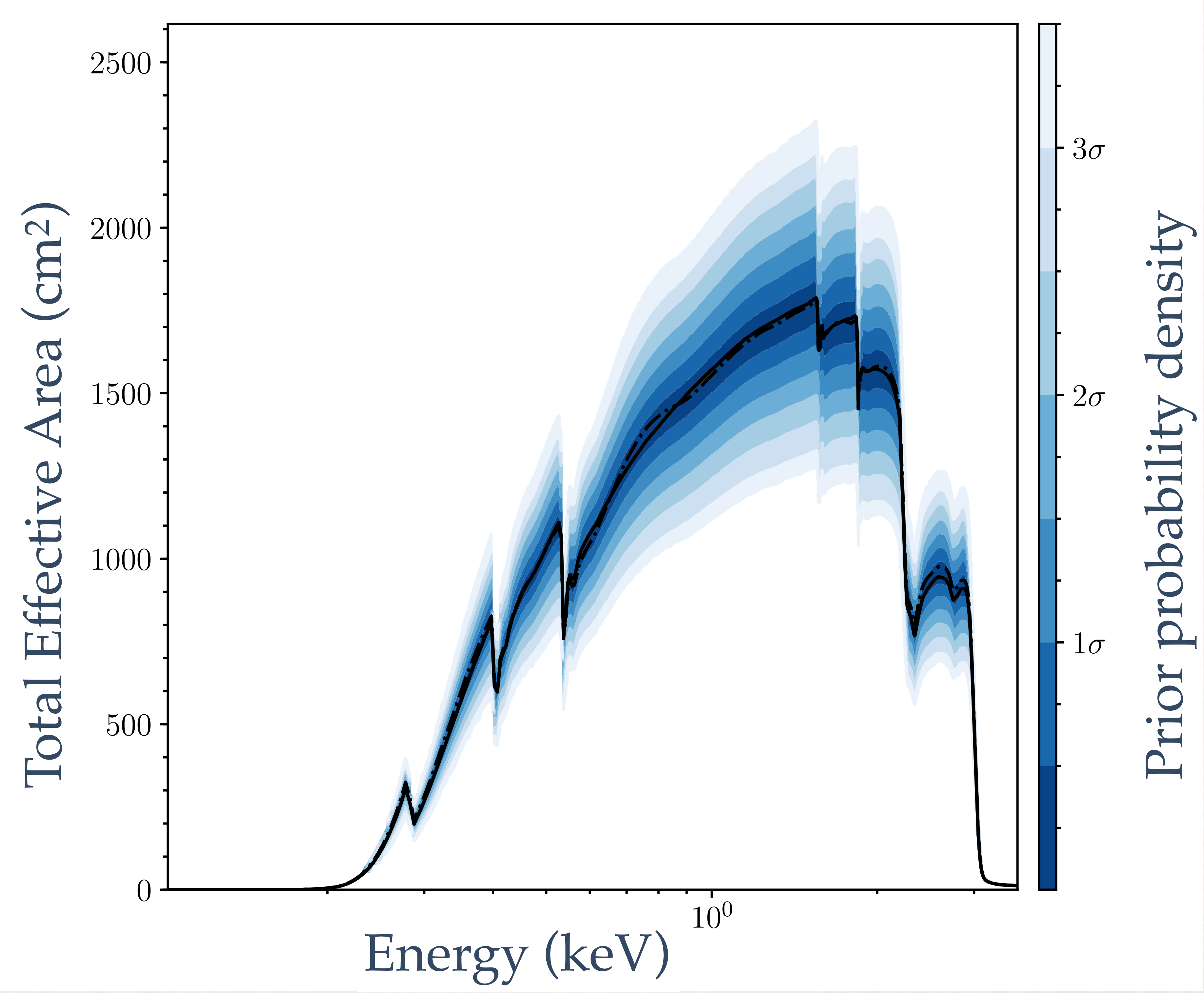
NS properties inference
(Likelihood statistical sampling)

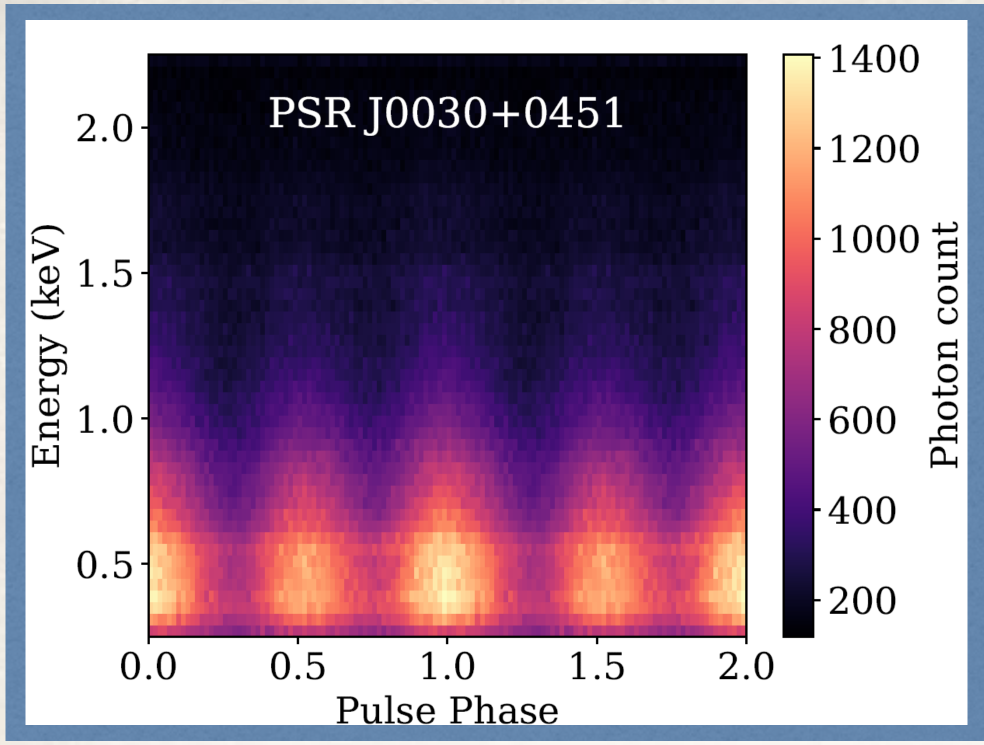
Instrument properties

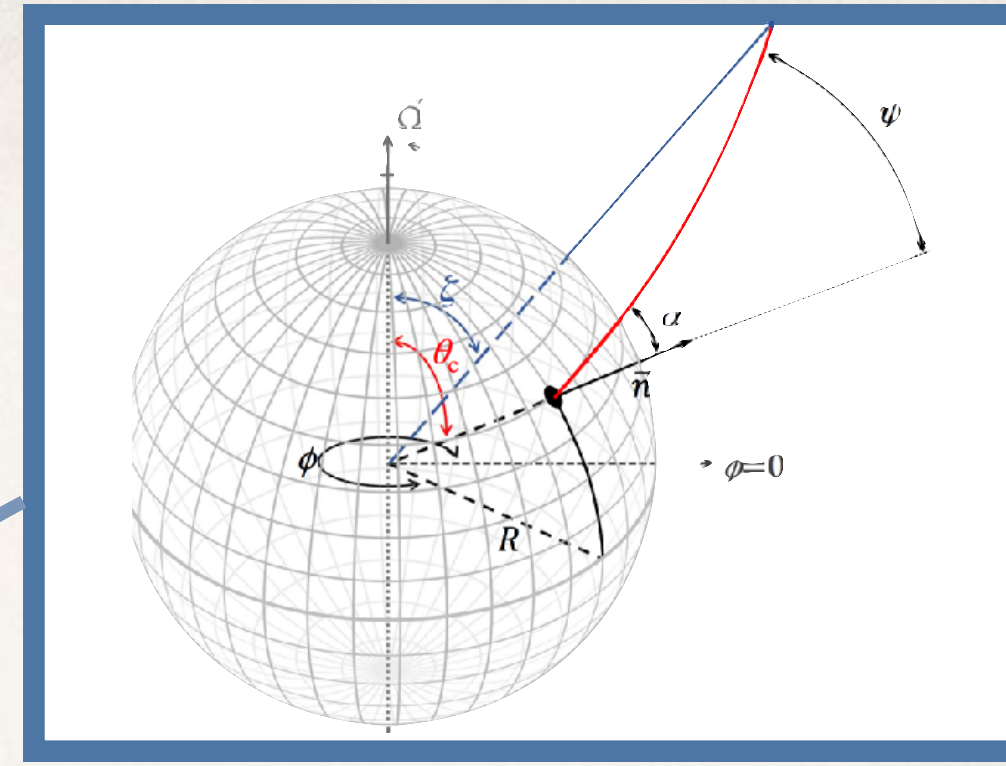
Mass,
Radius,
EOS



We parametrize the instrument response, and include its uncertainties in the model.

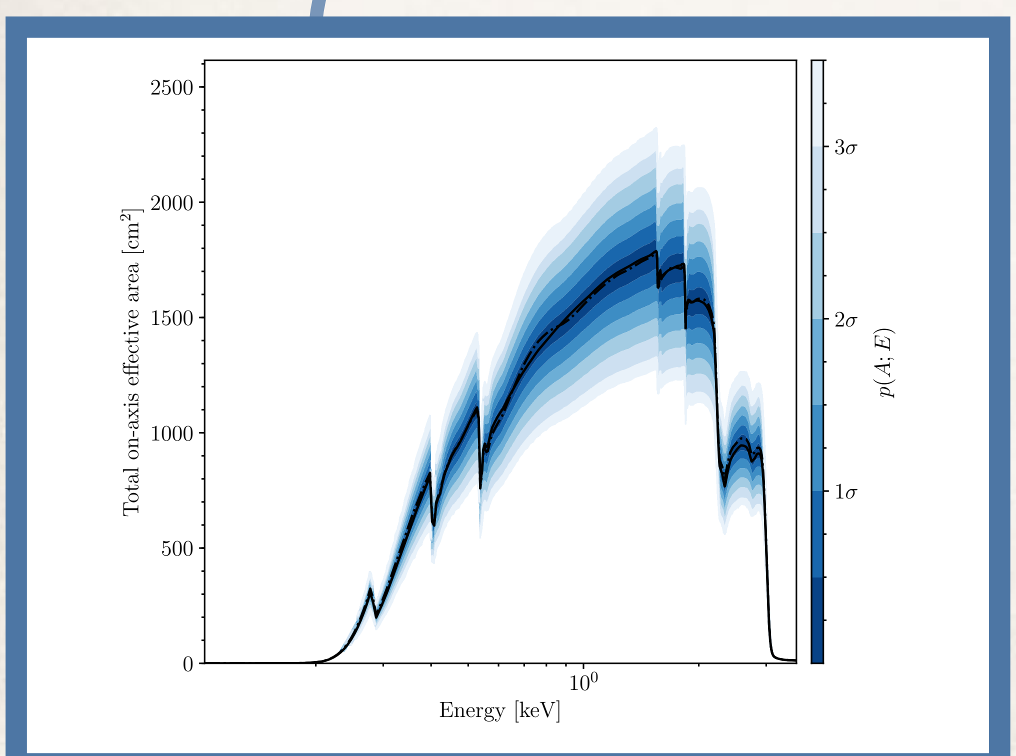


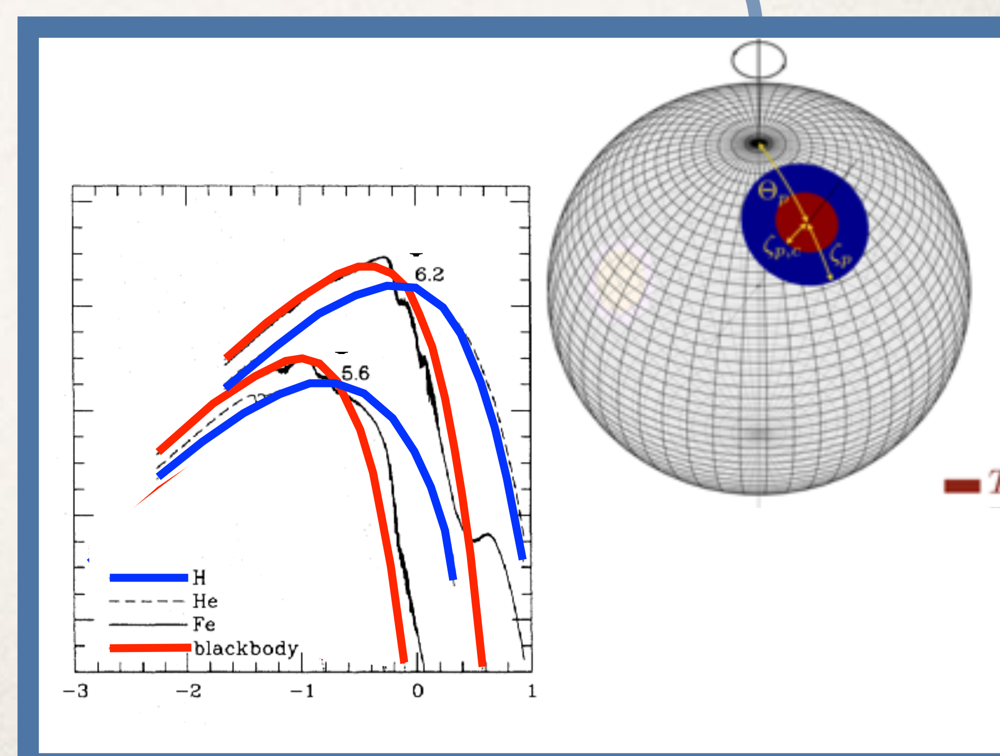




NS properties inference
(Likelihood statistical sampling)

Mass,
Radius,
EOS



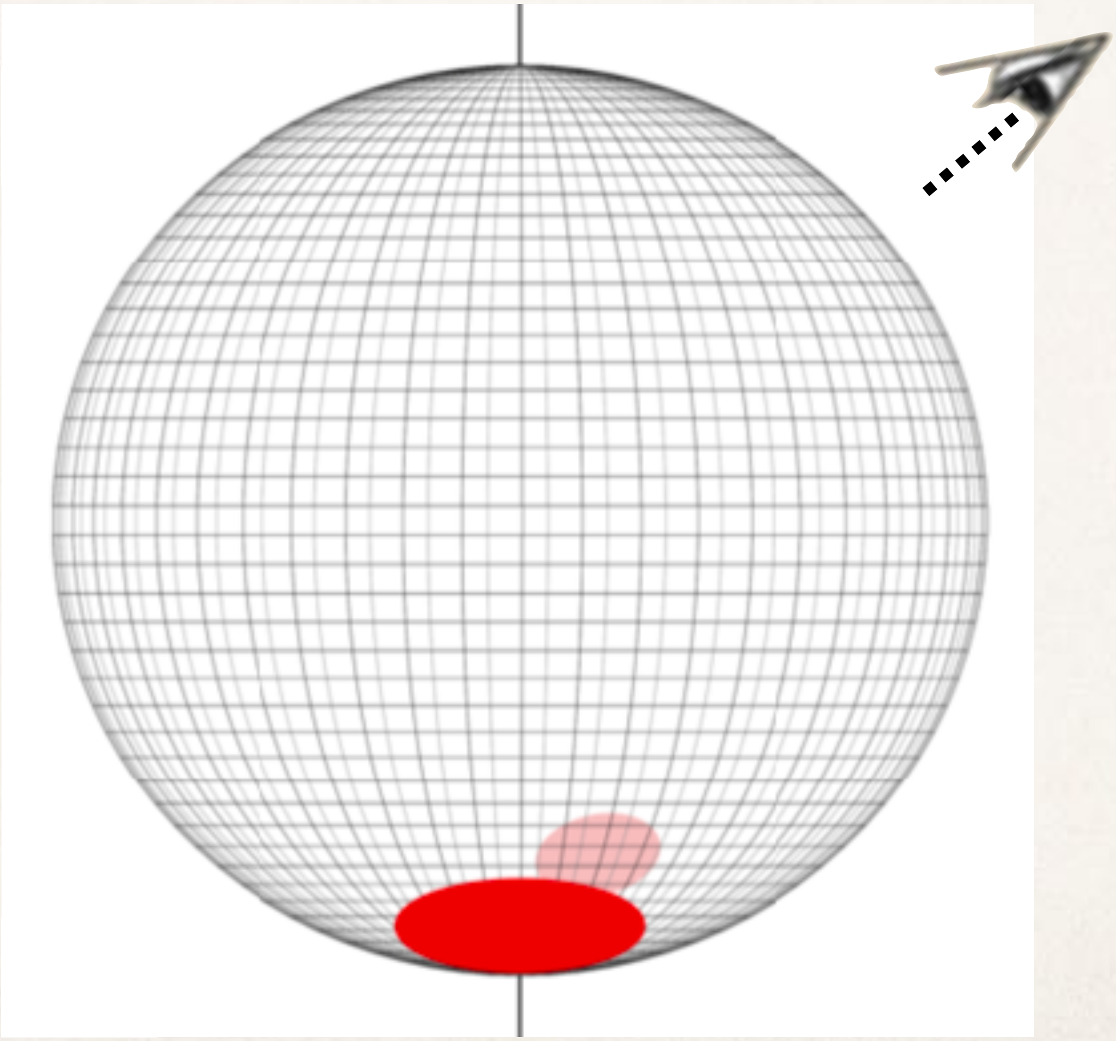


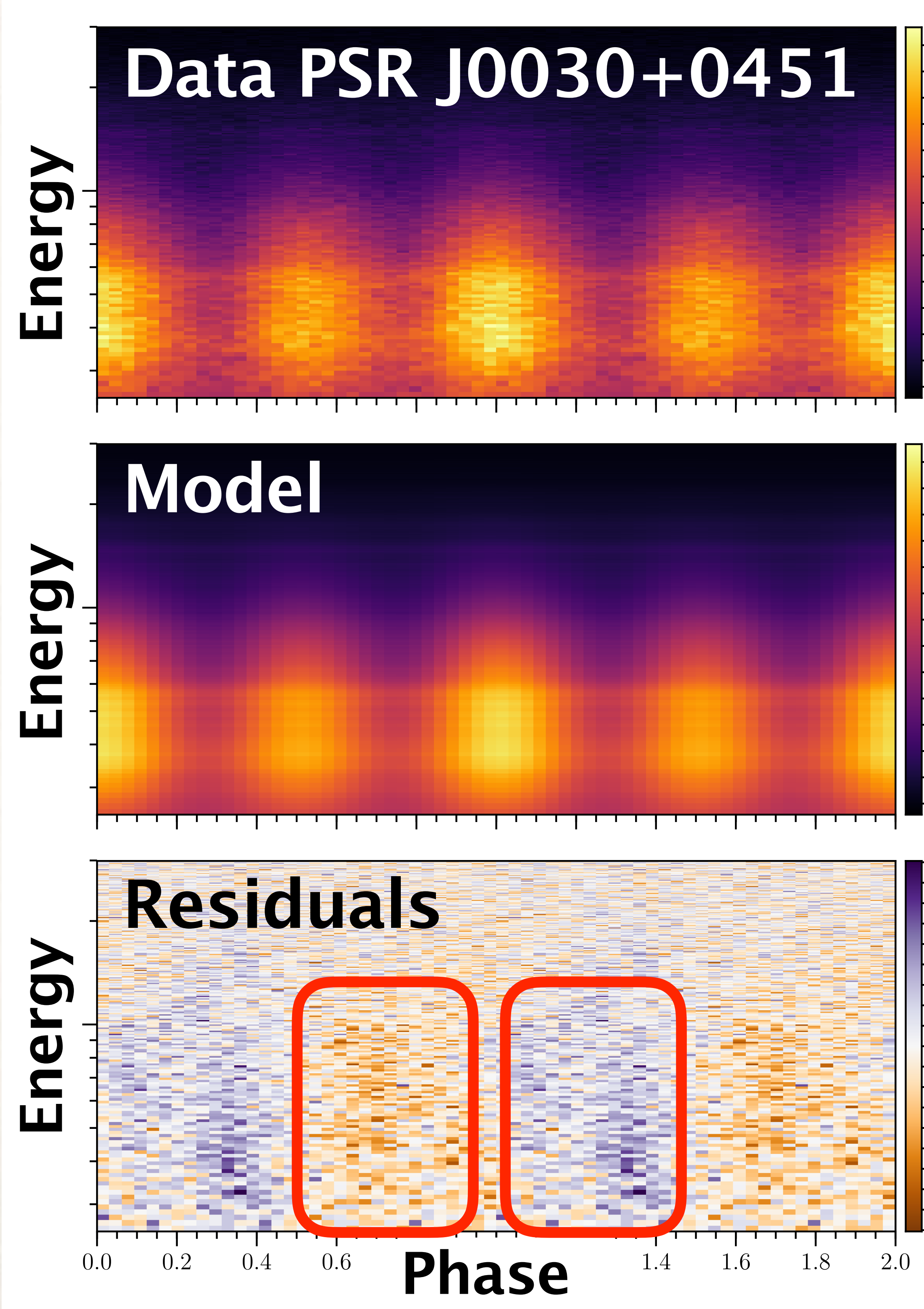
Results from the analyses of NICER of Pulsar 1: PSR J0030+0451

The simplest model shows clear residuals between the model and the data.

ST+ST

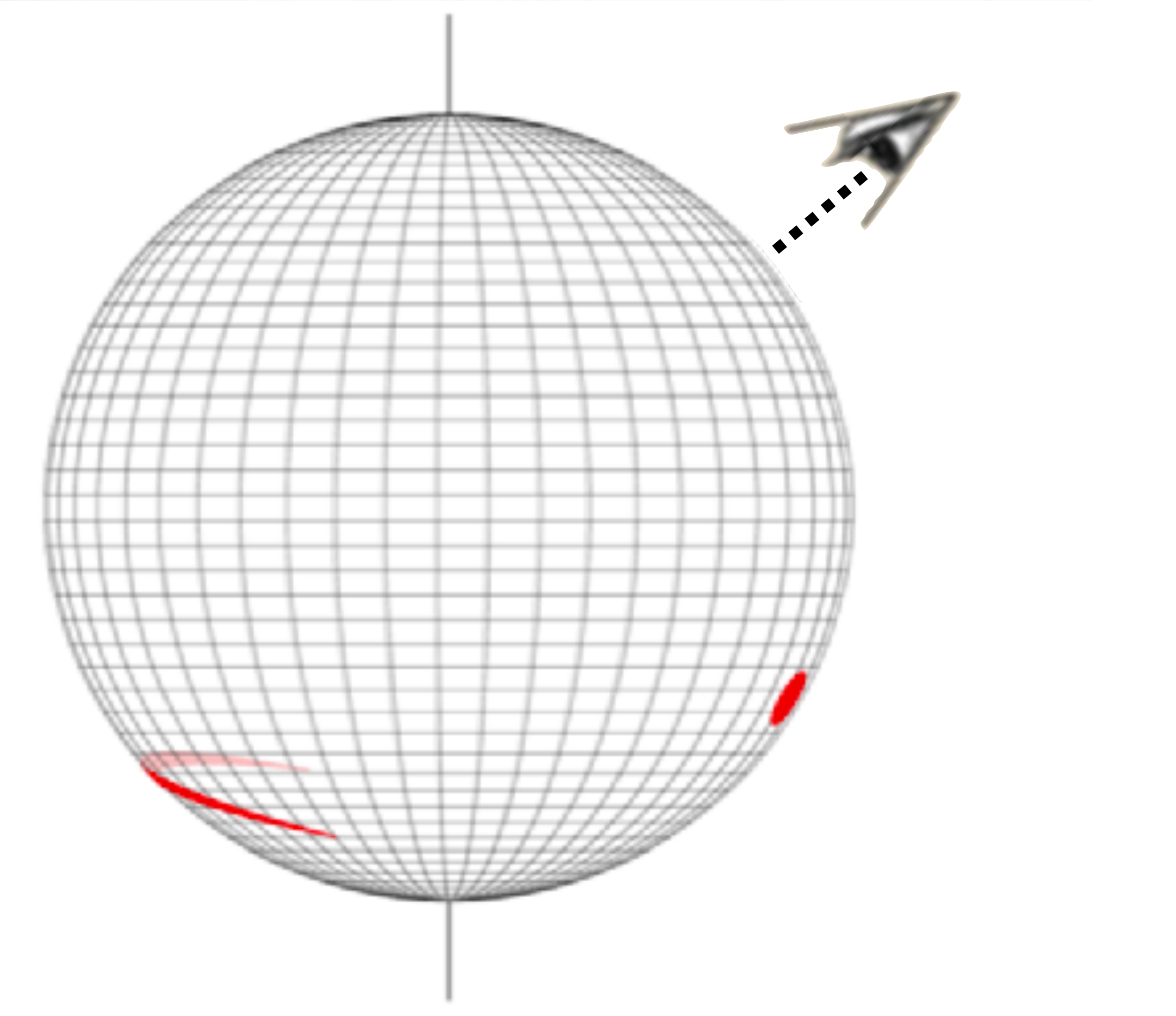
Single Temperature +
Single Temperature



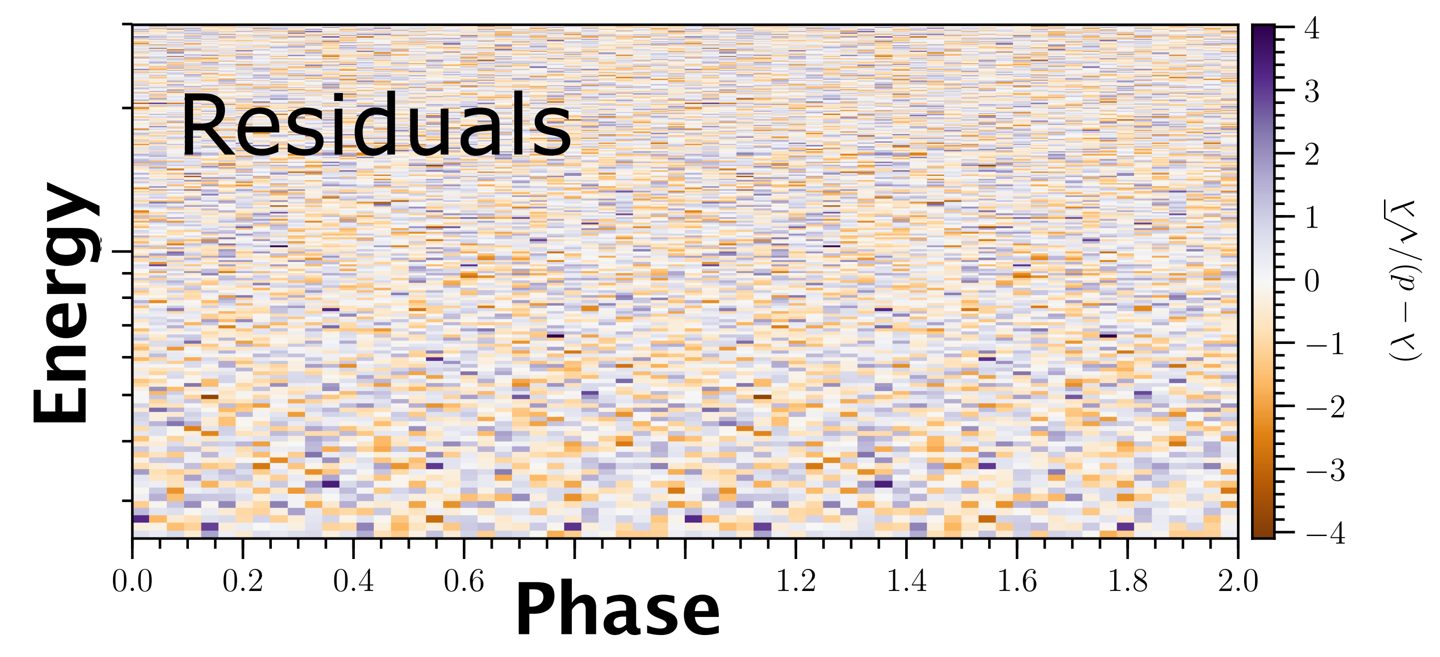


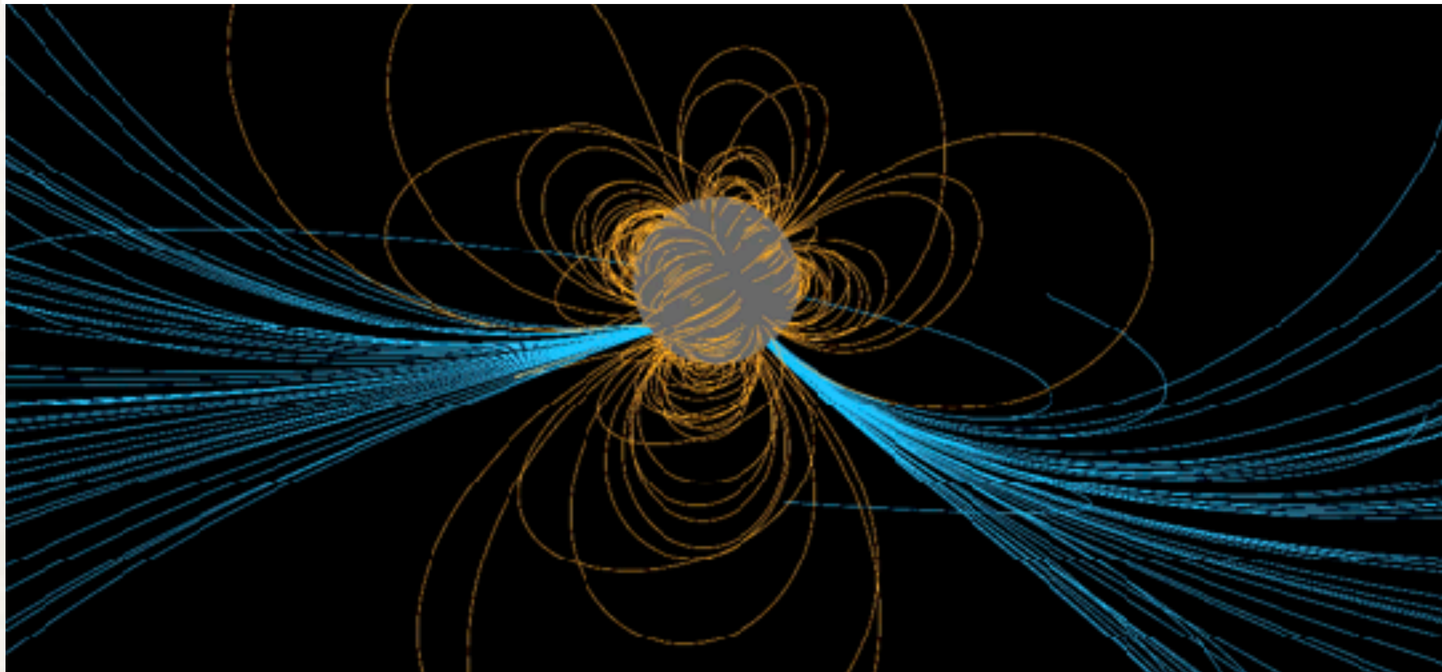
Riley, …, SG et al. (2019)

The statistically preferred model shows no residuals, and a higher likelihood.



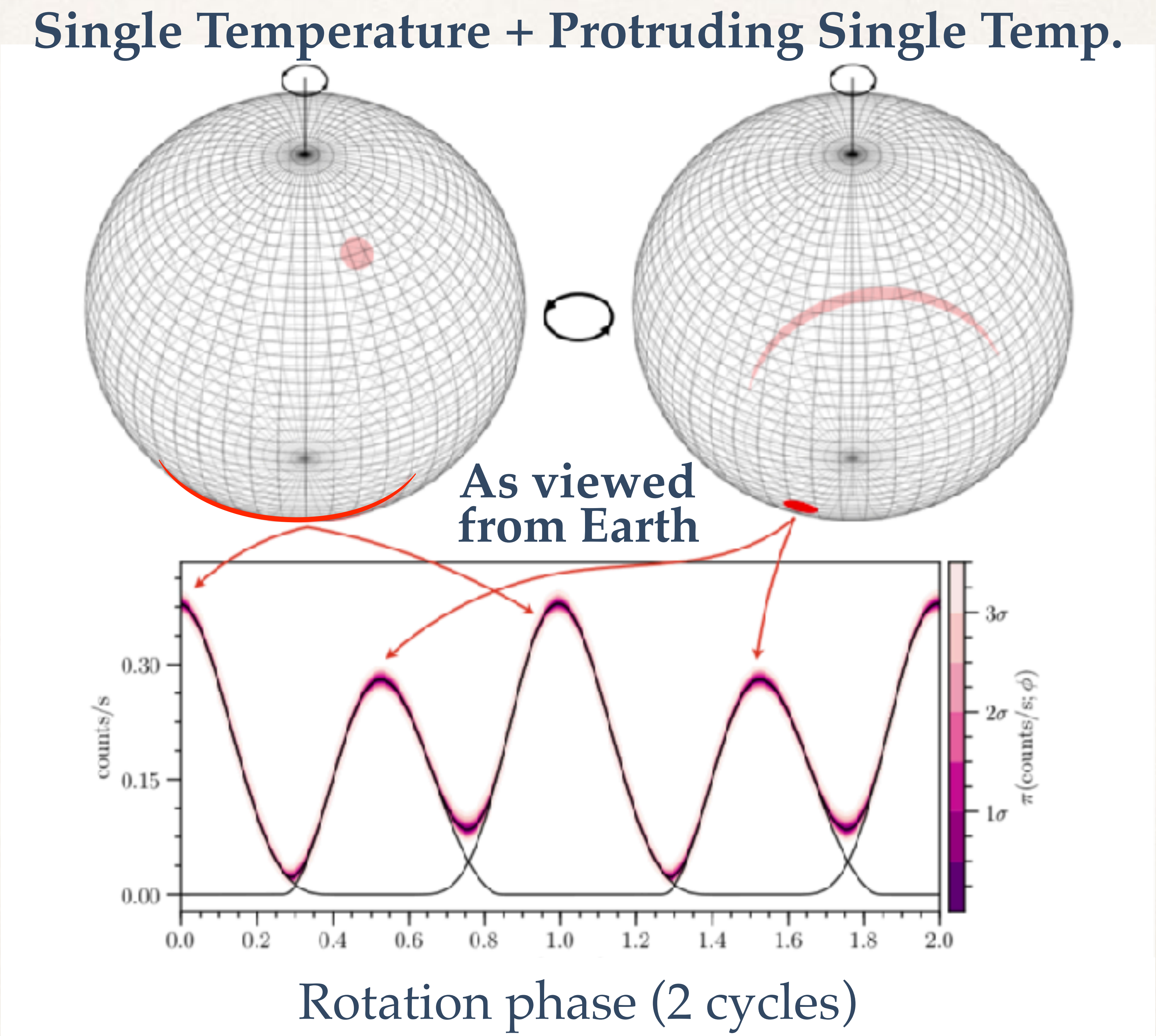
Single Temperature +
Protruding Single Temp.



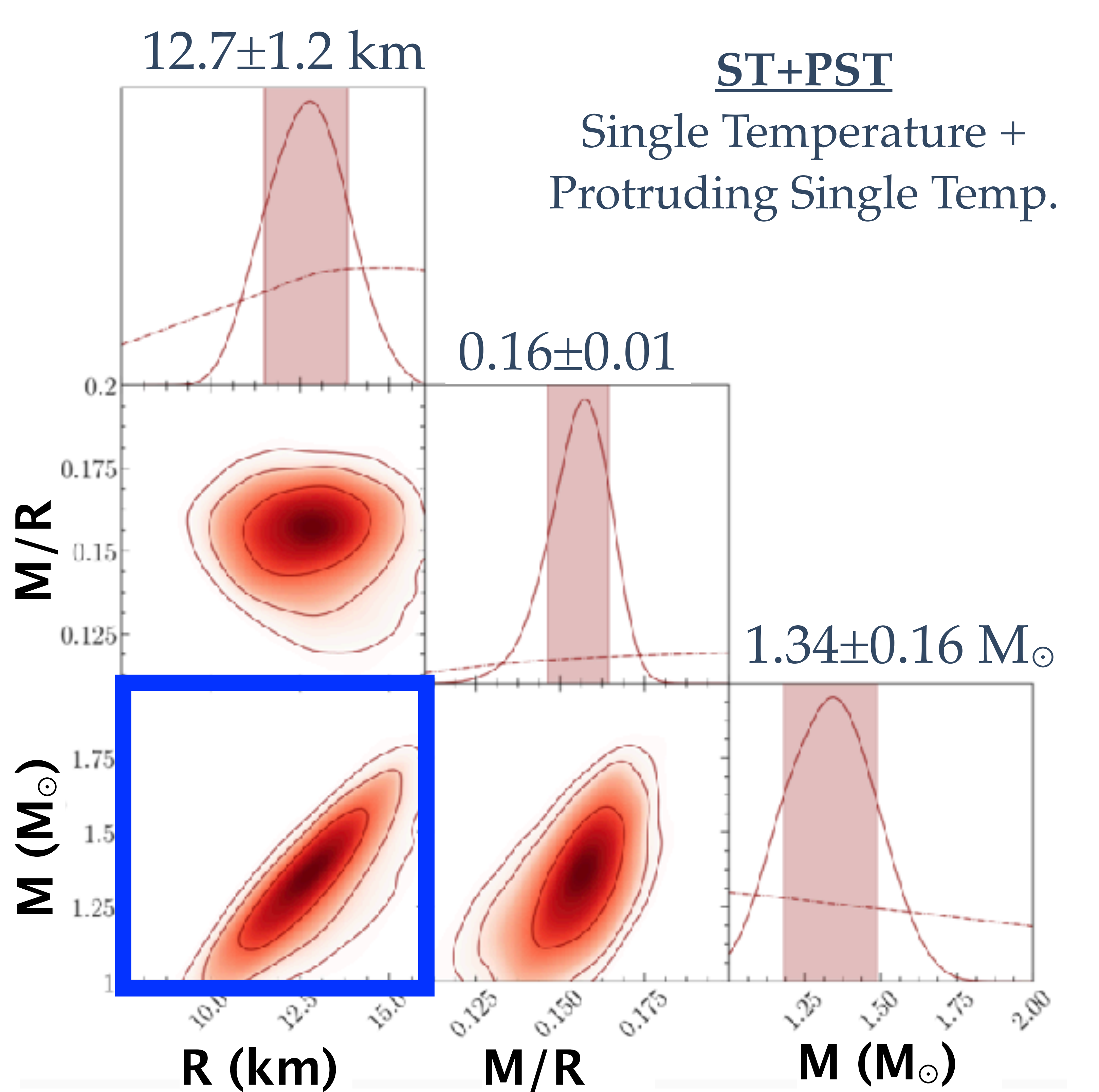


Riley, …, SG et al. (2019)

The preferred model consist is a small circular spot and an elongated crescent.



In addition to the unexpected geometry, we also constrain M and R.



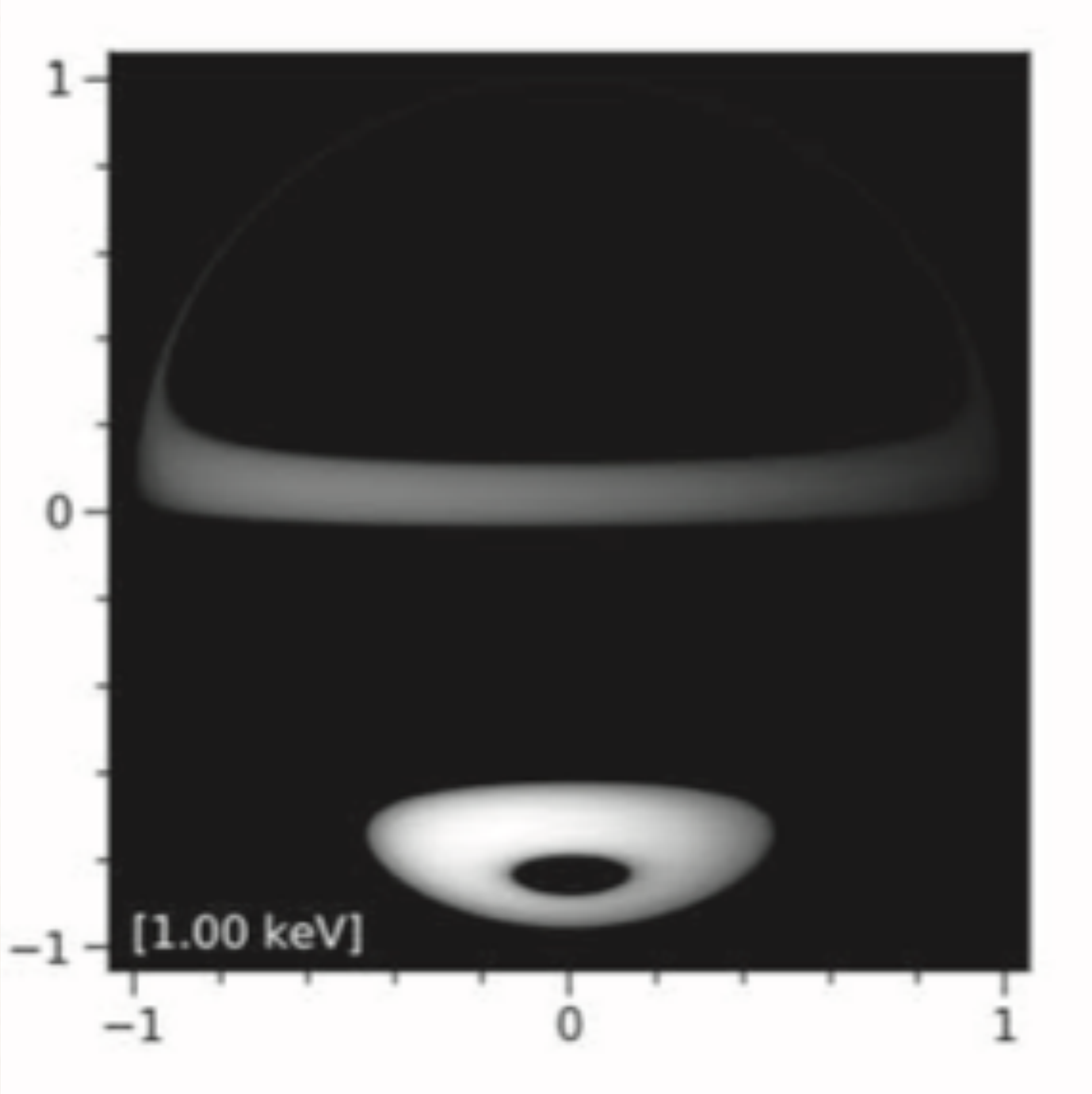
Riley, …, SG et al. (2019)

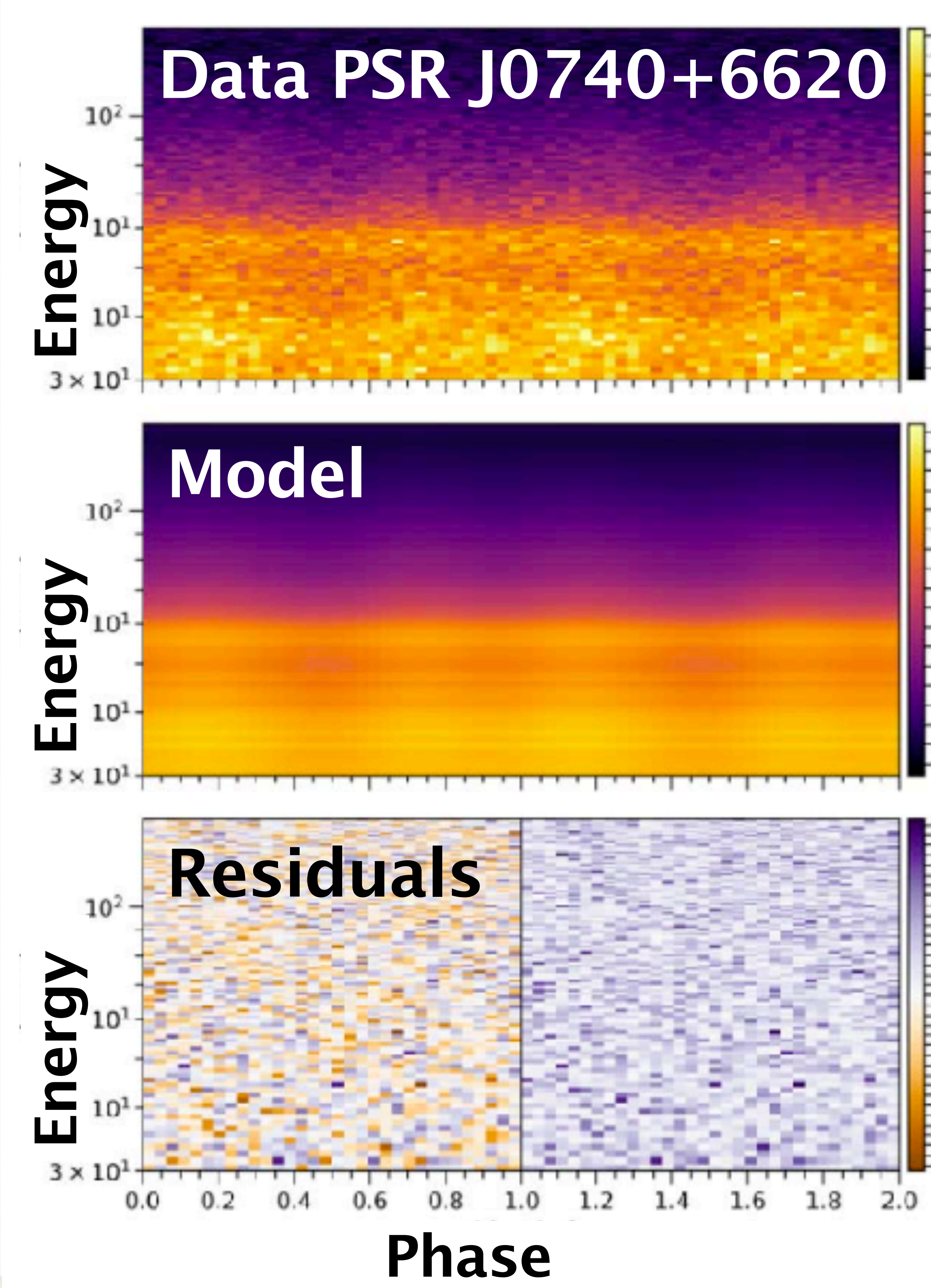
Results from the analyses of NICER of Pulsar 2: PSR J0740+6620

The simplest model is a good description of the data.

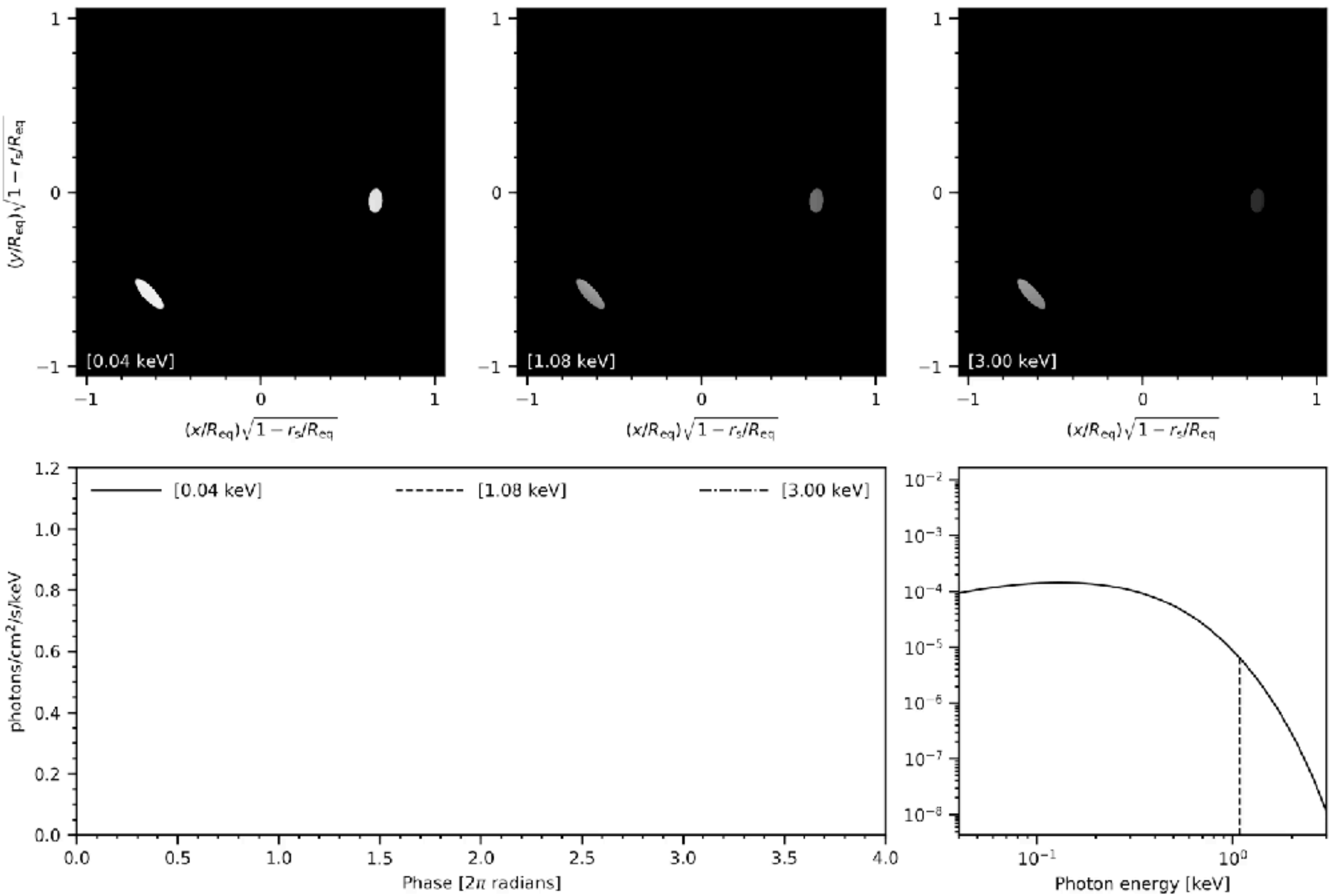
<u>**ST+ST**</u>

Single Temperature +
Single Temperature



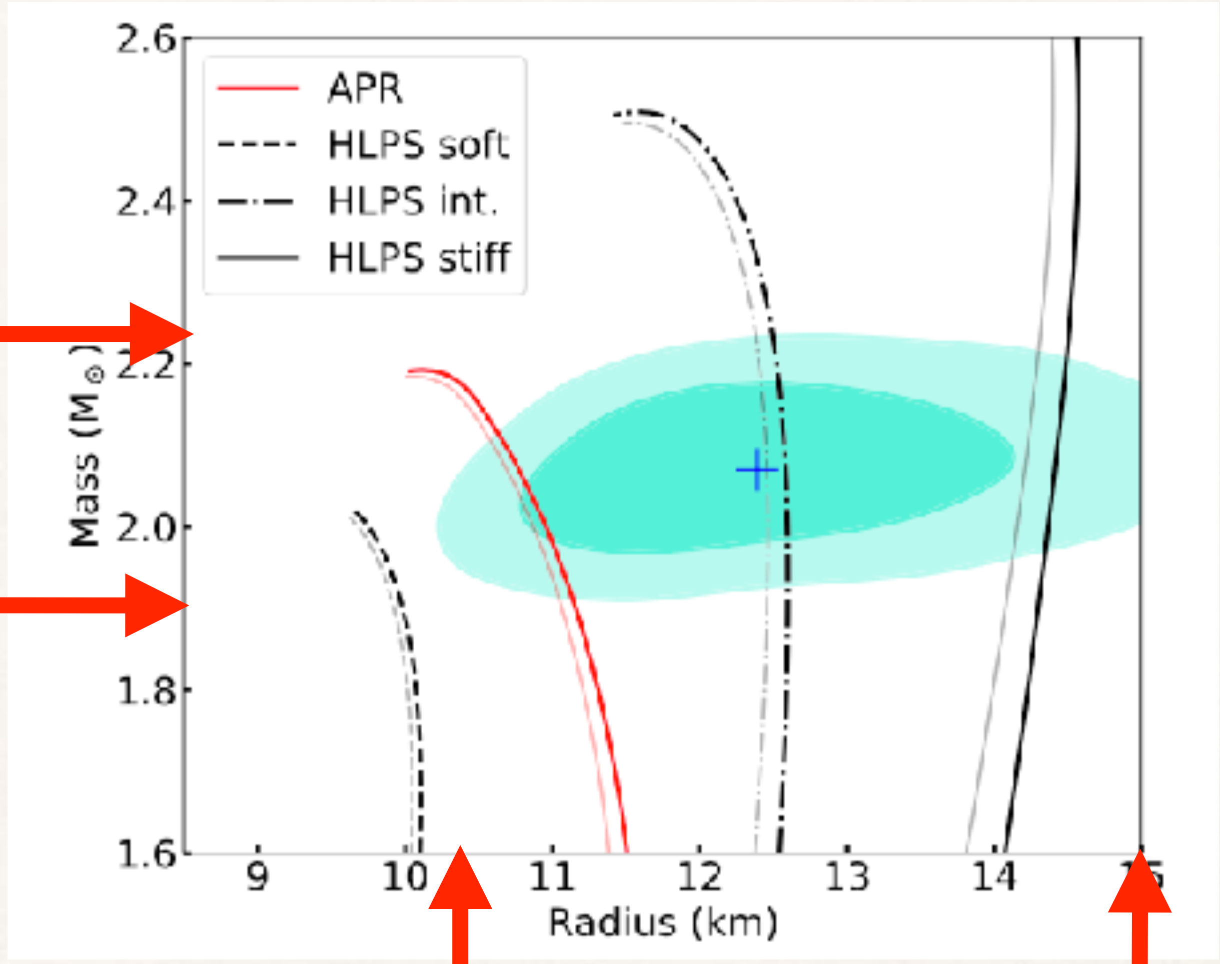


Riley, …, SG et al. (2021)


[0.04 keV]
[1.08 keV]
[3.00 keV]
$(y/R_{eq})\sqrt{1 - r_s/R_{eq}}$
$(x/R_{eq})\sqrt{1 - r_s/R_{eq}}$
photons/cm^2/s/keV
Phase [2π radians]
Photon energy [keV]

The M-R constraints from PSR J0740+6620 are useful thanks to its independently measured high mass.

Using mass prior from radio timing observations:
M = 2.07±0.07 Msun

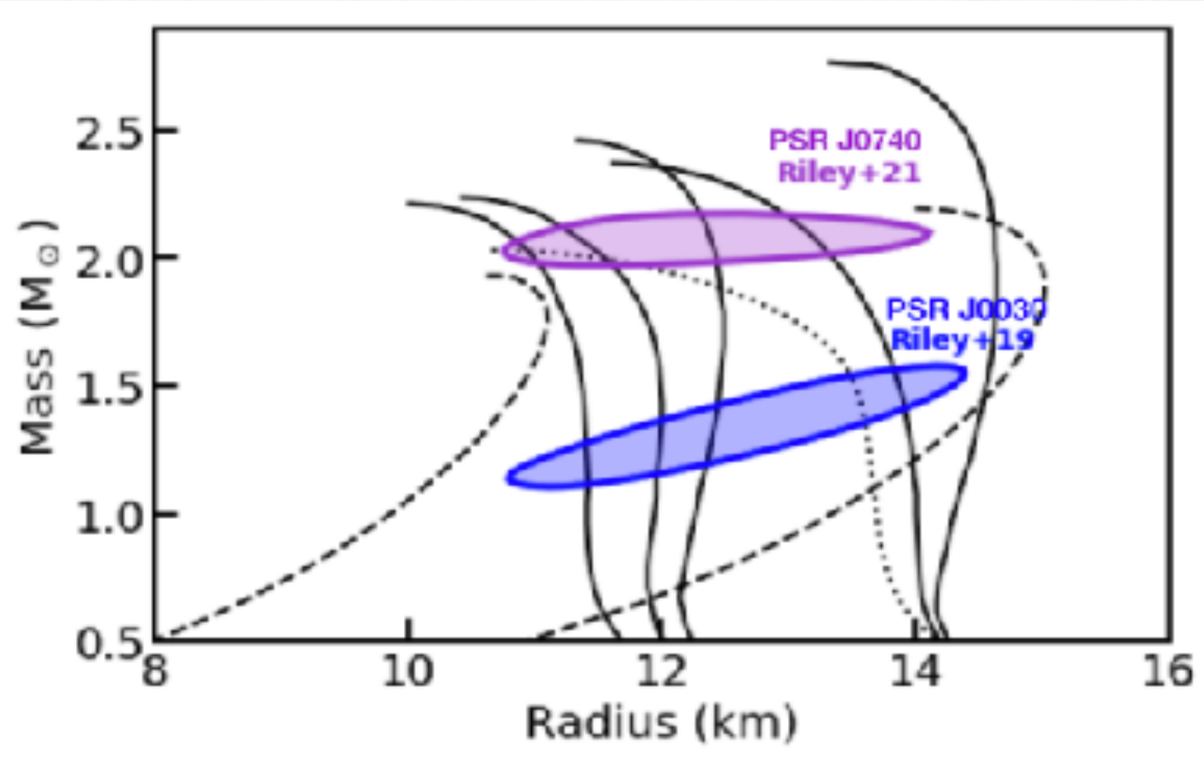


Constraints on radius from NICER+XMM data
R = 12.39±1.30 km

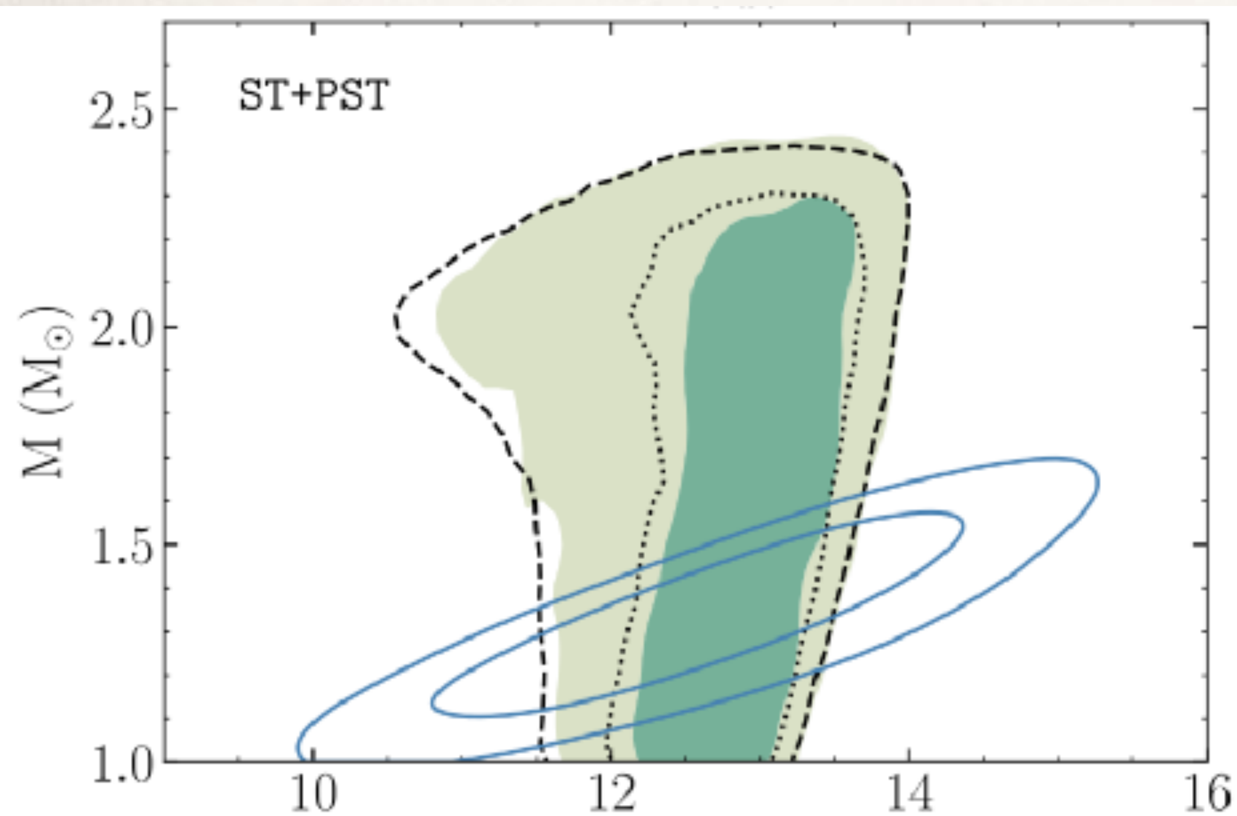
Riley, …, SG et al. (2021)

See also Miller, …, SG et al. (2021)

The NICER results for these two pulsars bring some additional constraints on equation of state models.

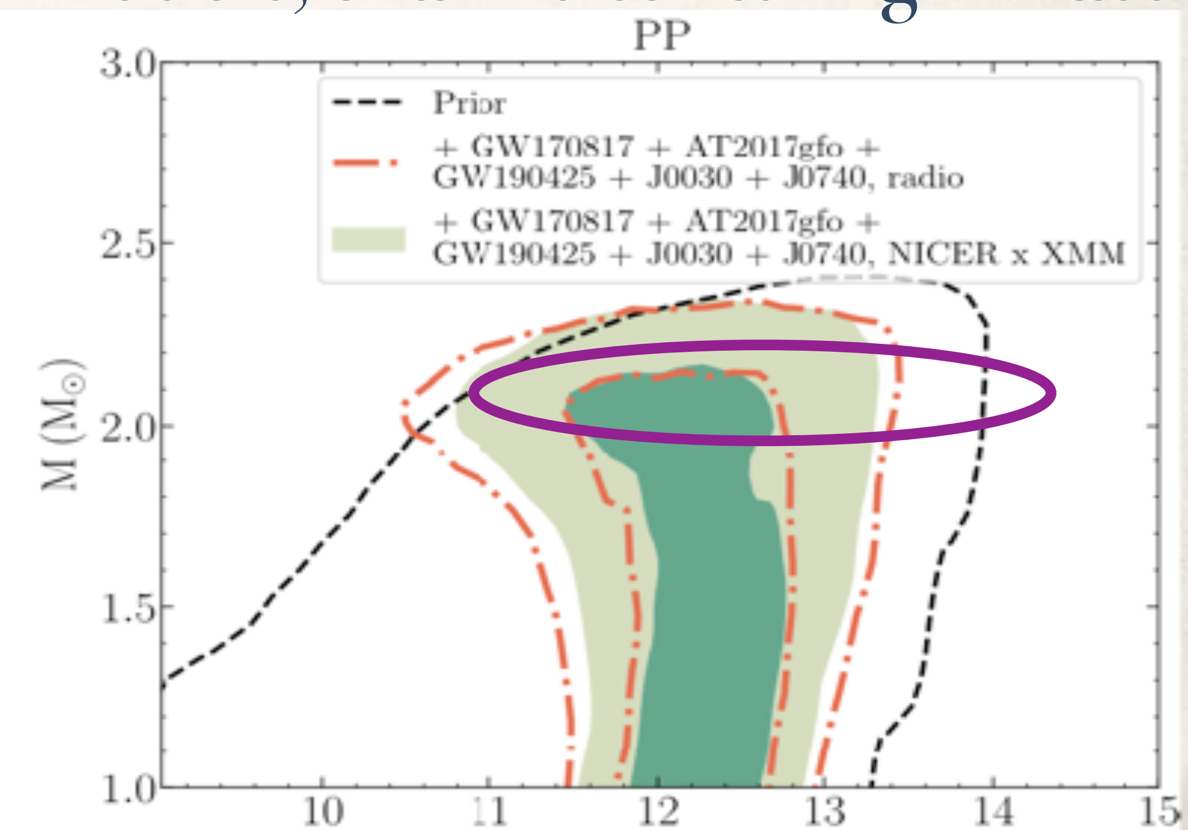


PSR J0030+0451 brings little additional information on EoSs parametrization (polytropes)



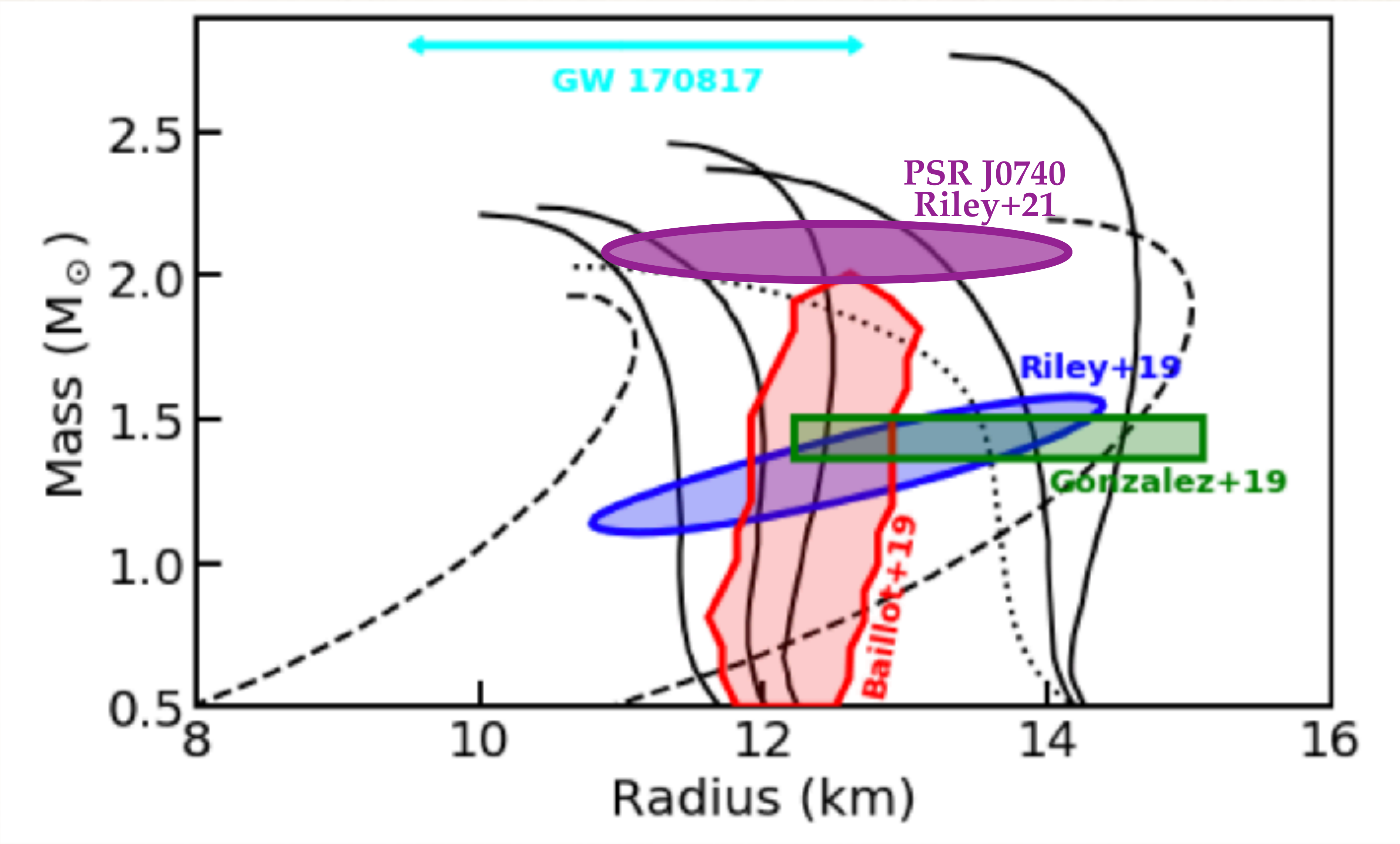
Raaijmakers et al. (2019)

PSR J0740+6620 adds some improvement on the EoSs models, thanks to its high mass.



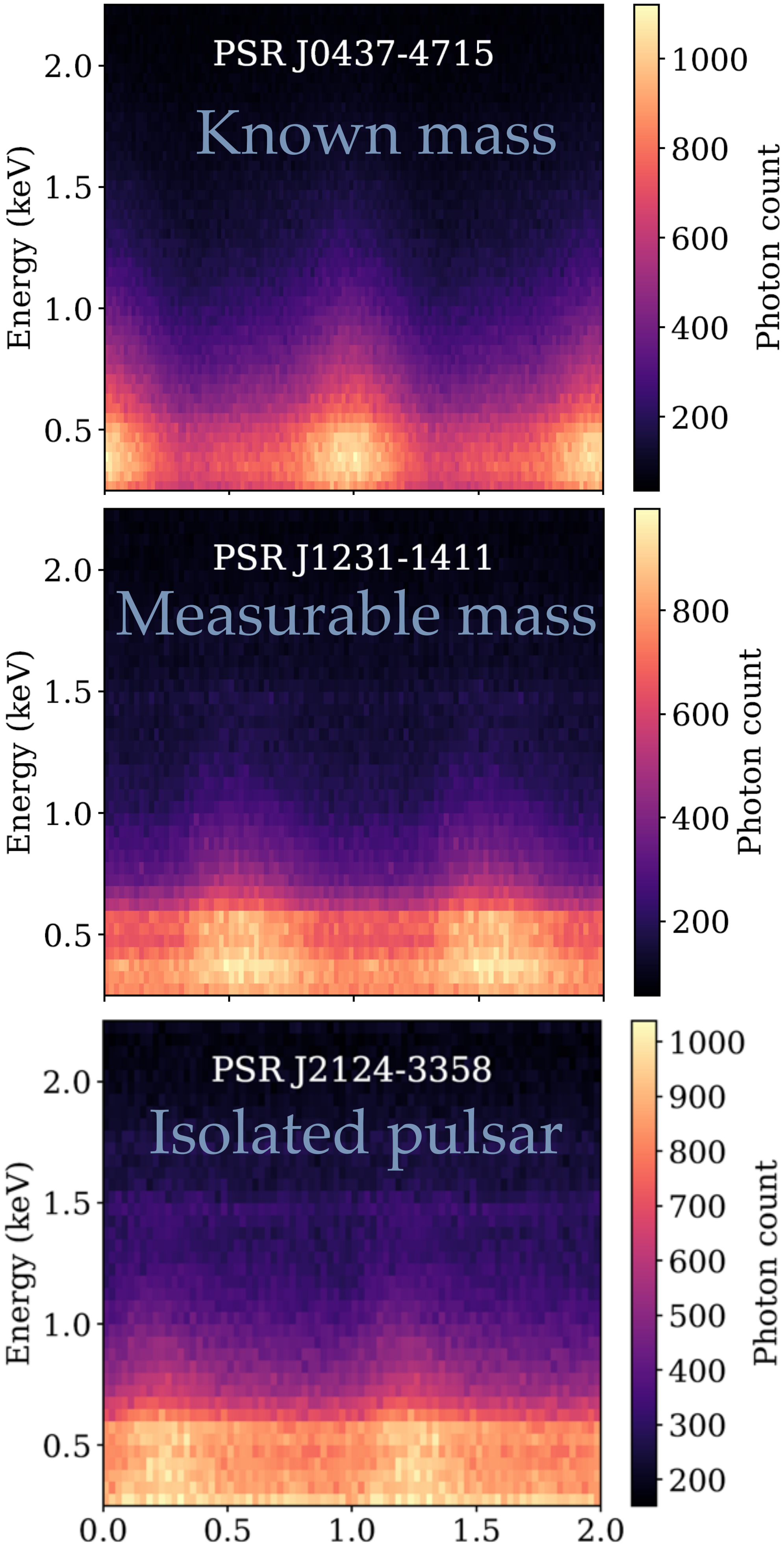
Raaijmakers et al. (2021)

NICER's results are quite promising and consistent with other recents measurements.



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

There are still many data sets to analyse to extract M_{NS} and R_{NS}, including newly discovered millisecond pulsars.

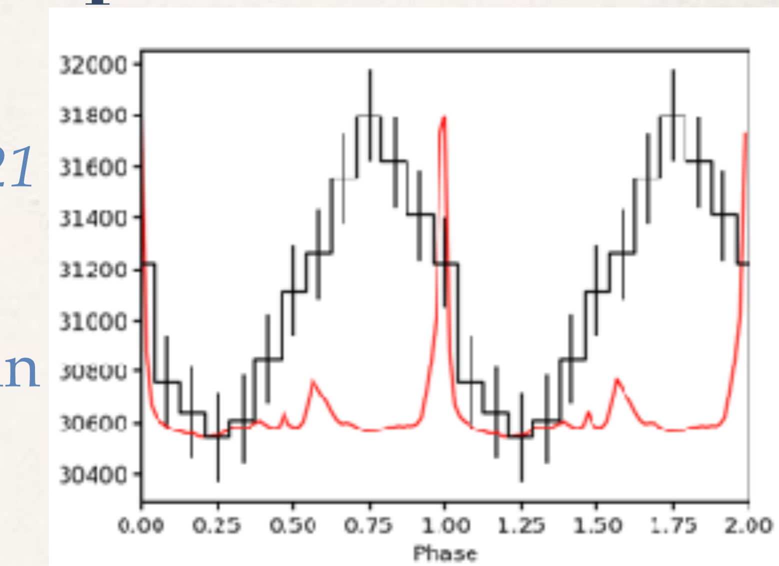


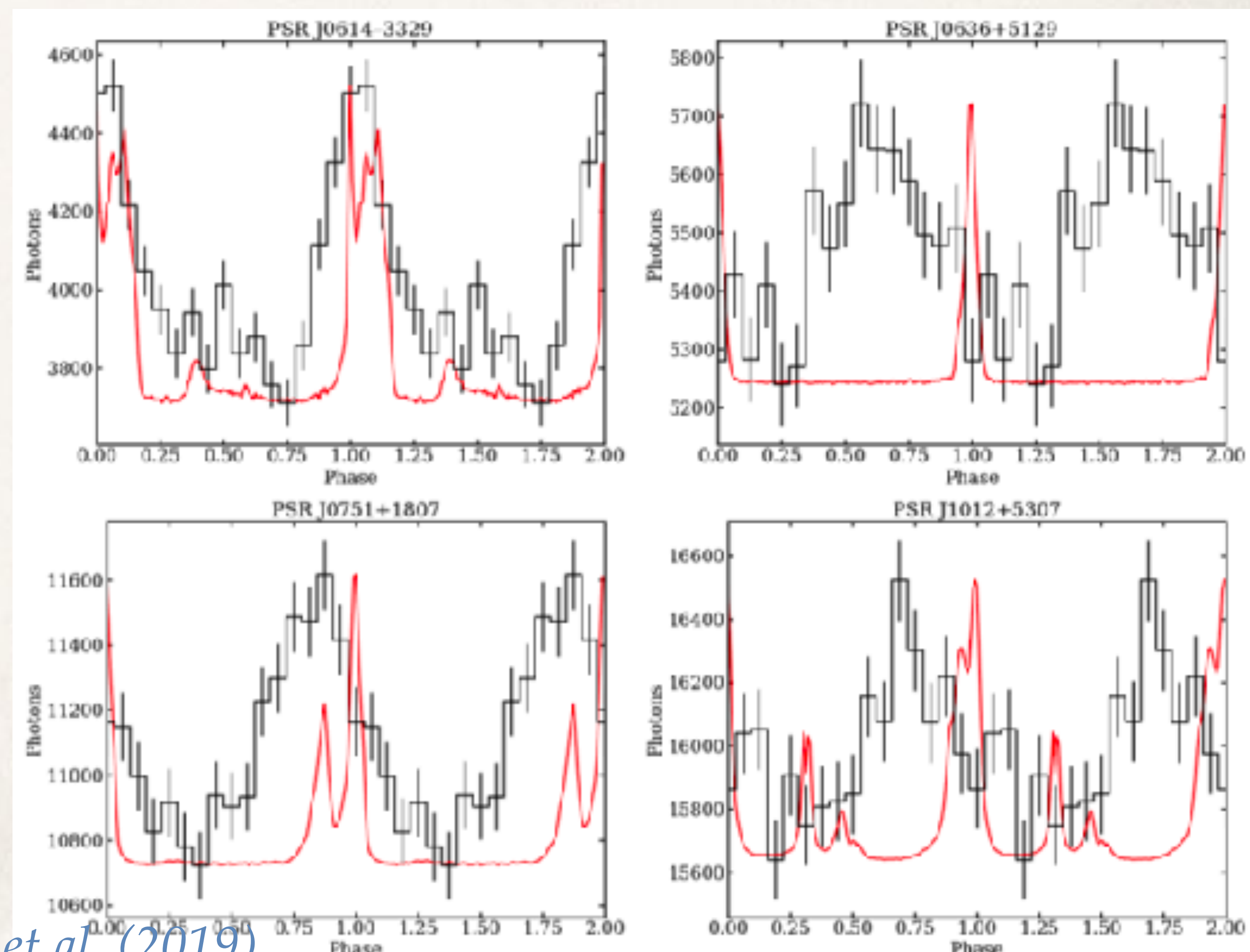
Bogdanov, SG et al. (2019)

PSR J1614-2230

Wolff, Guillot et al. 2021

Known high mass:
M = 1.908±0.016 Msun





Guillot et al. (2019)

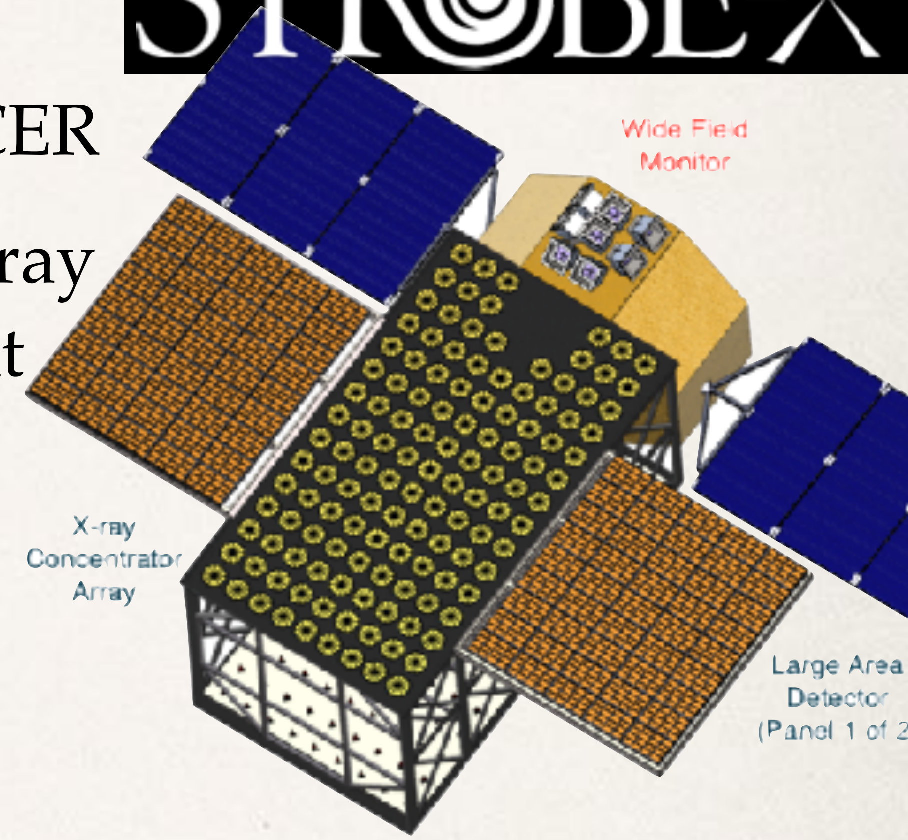
Future missions will fully enable the light curve modelling technique to measure M_{NS} and R_{NS}.

eXTP (~2025)

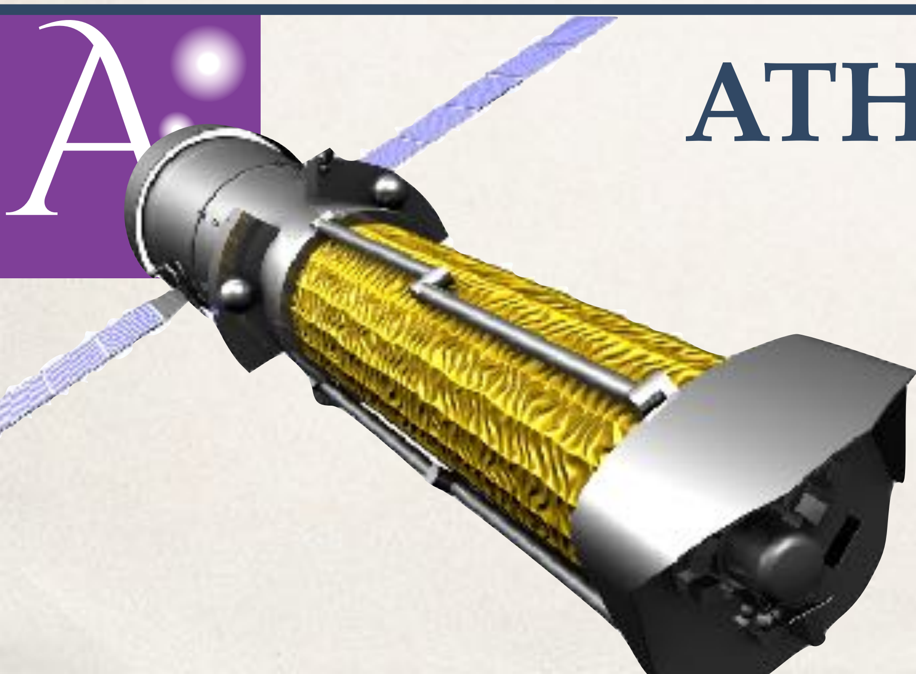
- Modest imaging capabilities (60″ PSF)
- ~ 4× more sensitive than NICER
- + Hard X-ray instrument

~2030 STROBE-X

- ~ 10× NICER
- + Hard X-ray instrument

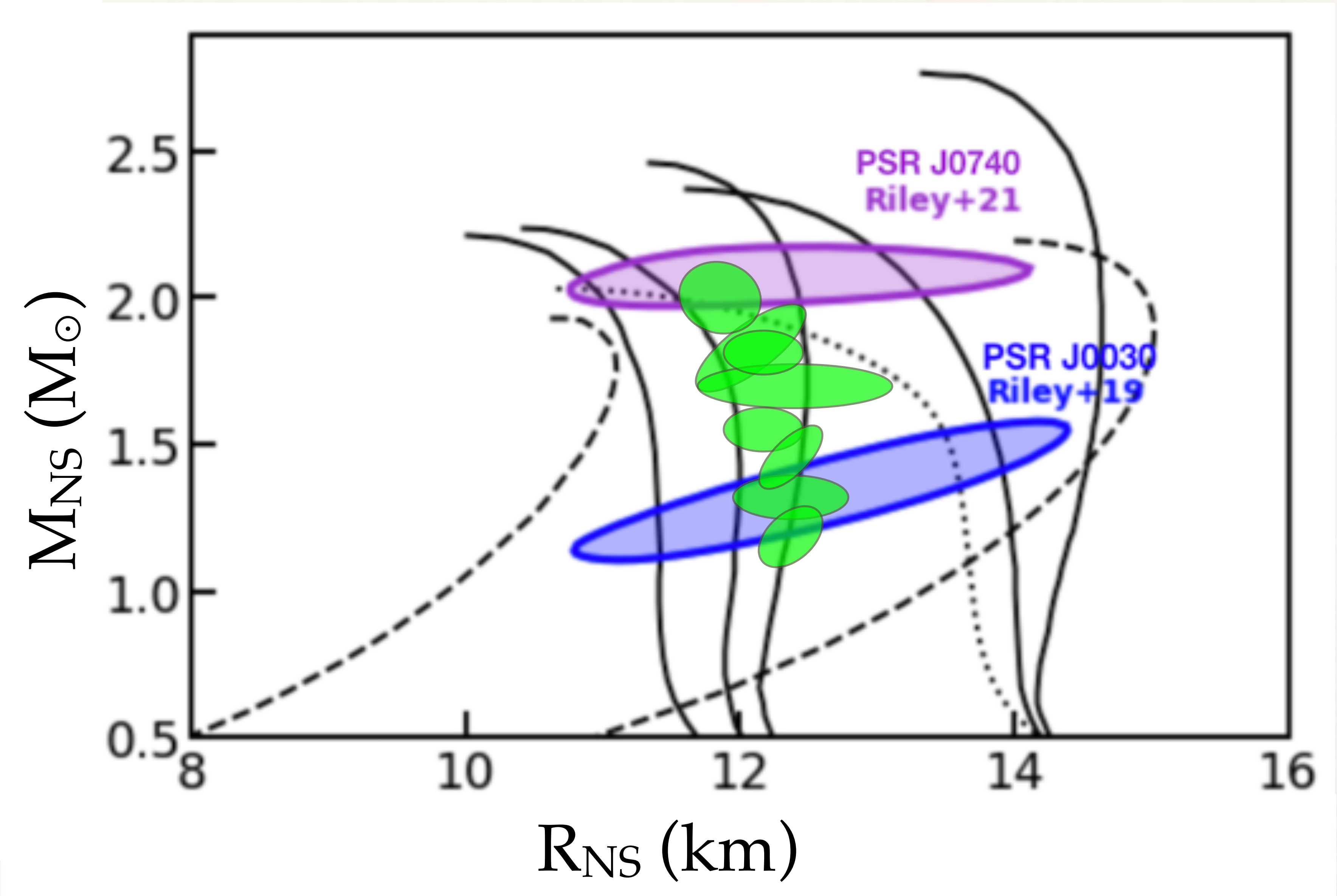


ATHENA (~2032)

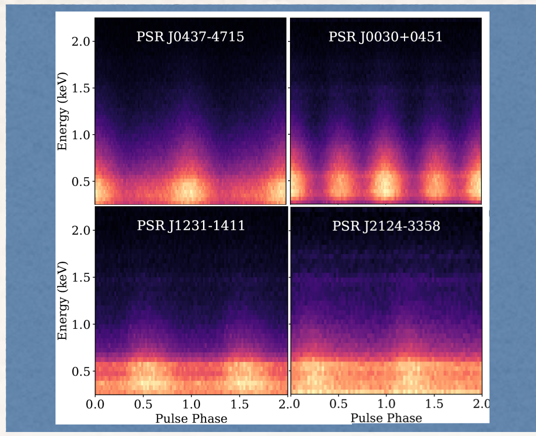


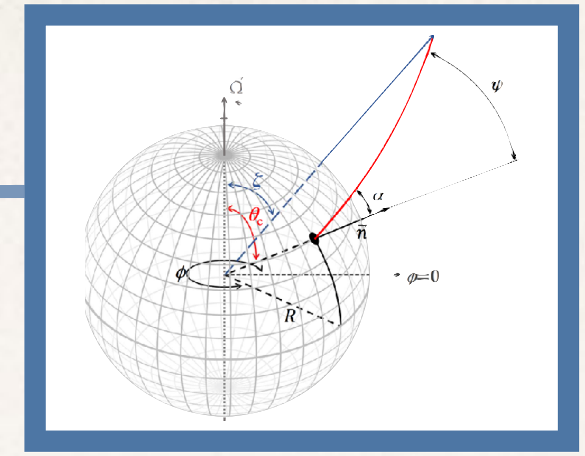
- Good imaging capabilities (5″ PSF)
- ~ 5–10 × more sensitive than NICER
- 10 μs time resolution

Overall, more M_{NS}-R_{NS} measurements are necessary to constrain the equation of state.

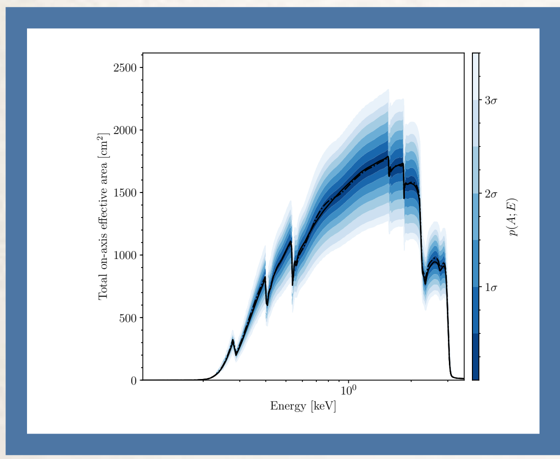


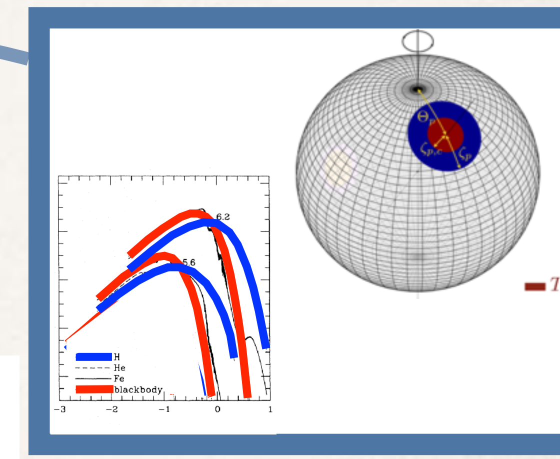
Summary

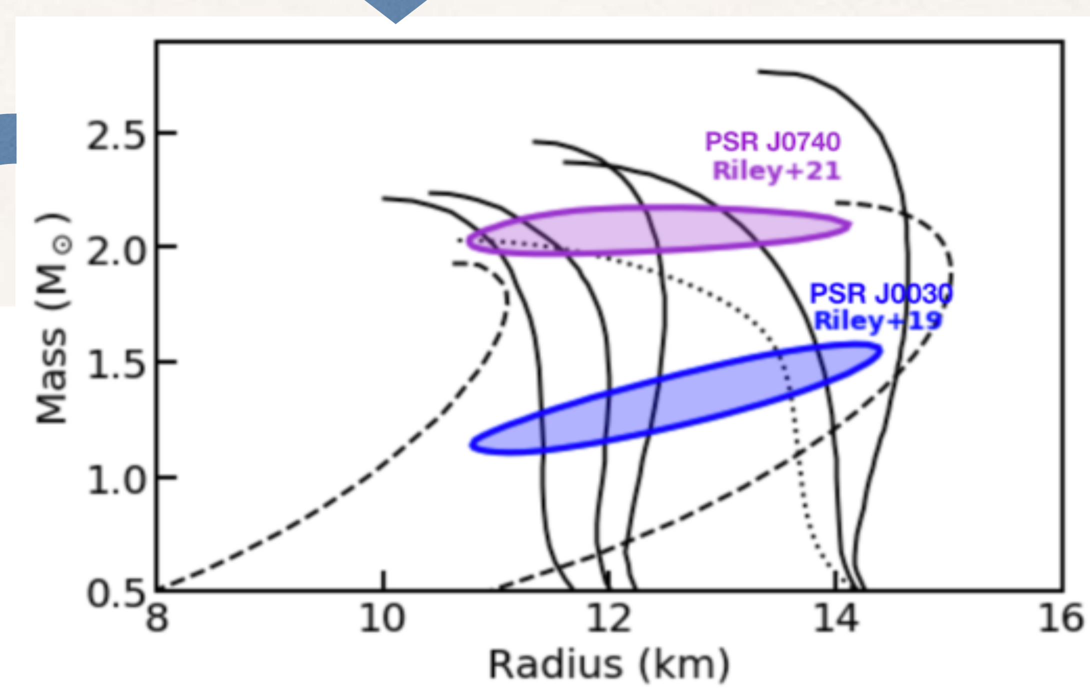


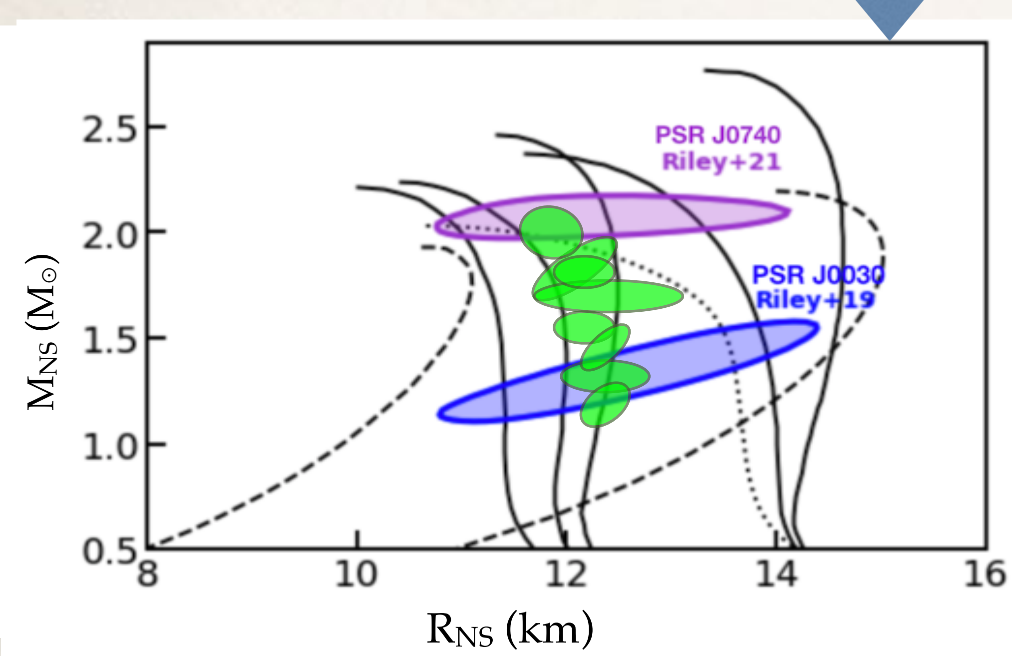


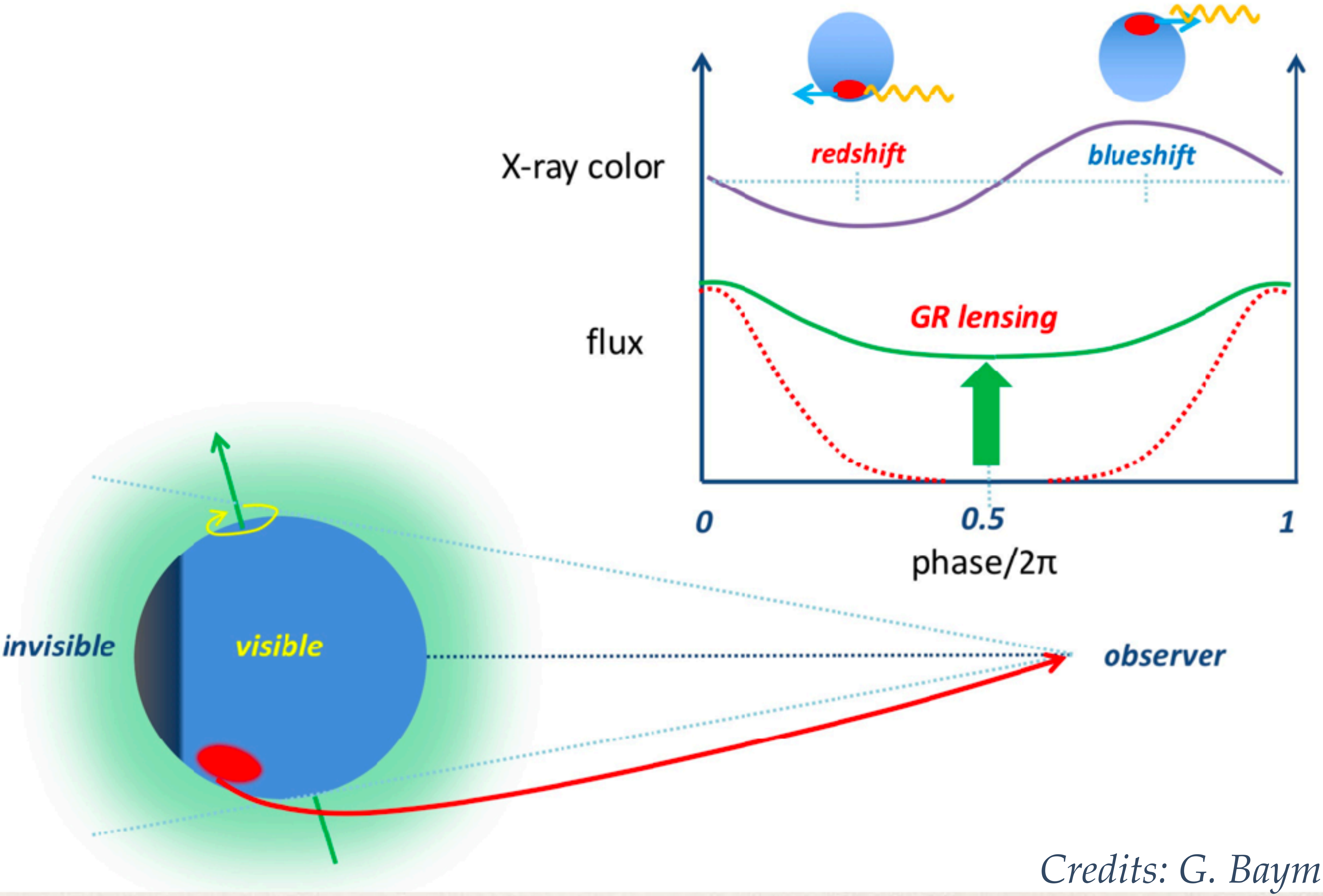
NS properties inference
(Likelihood statistical sampling)



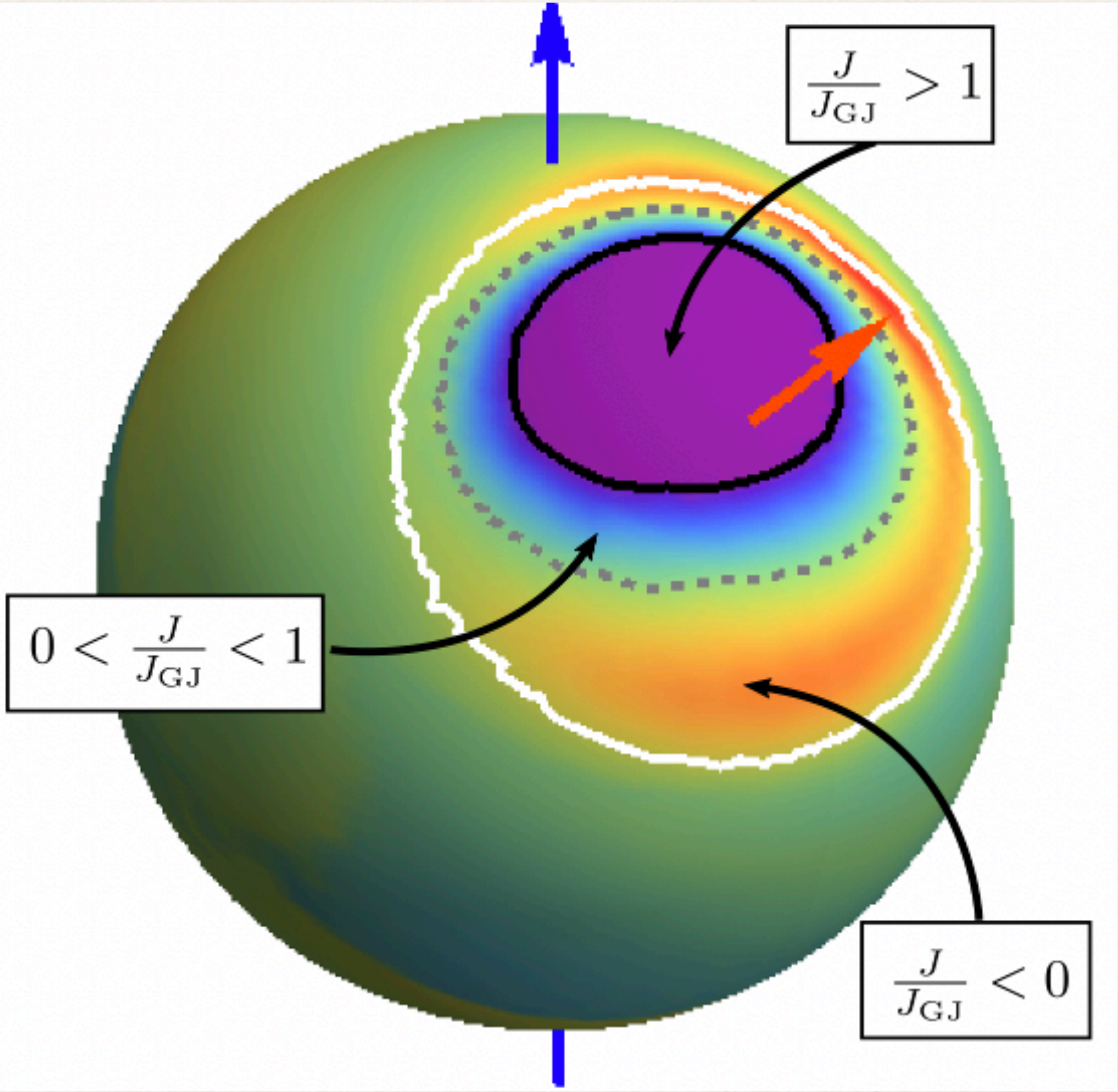




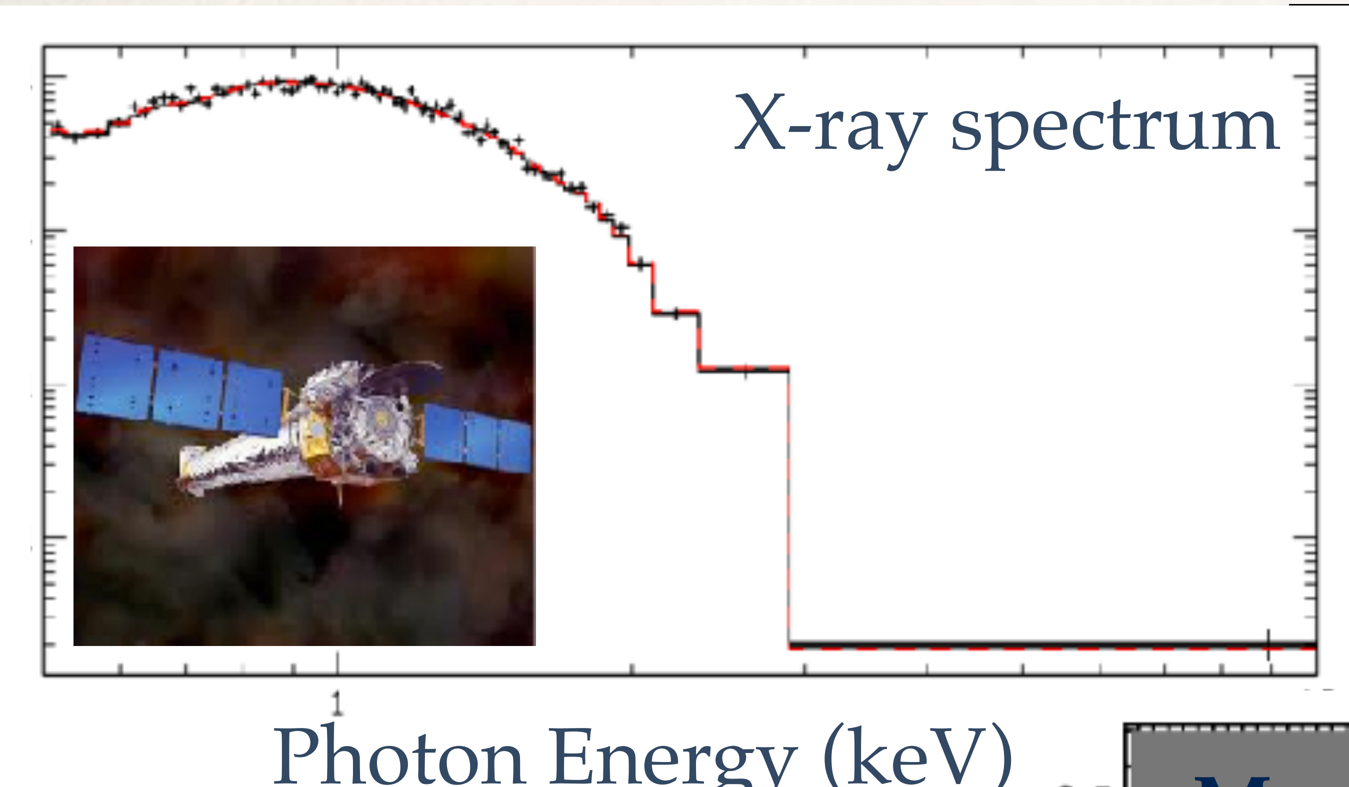


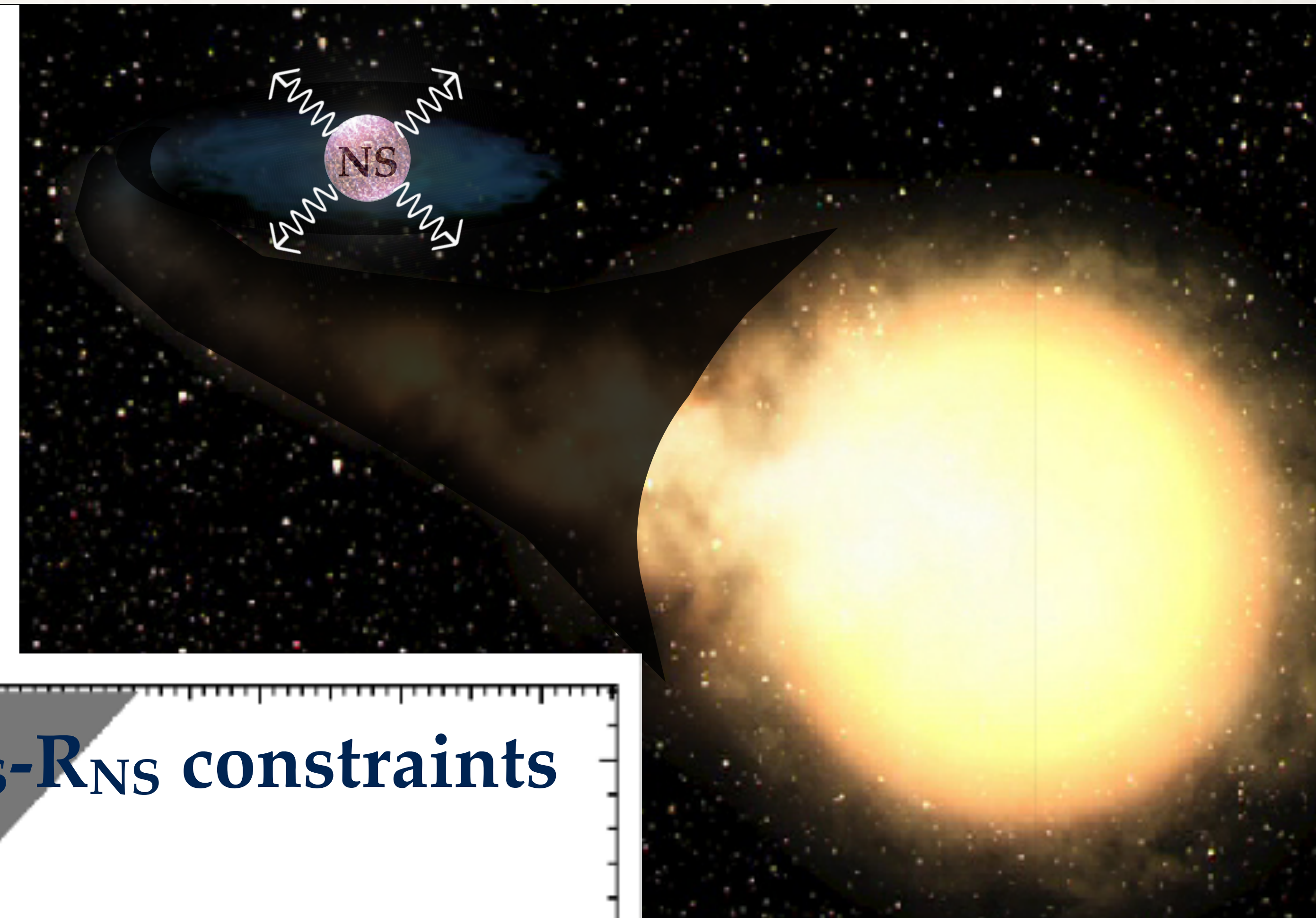


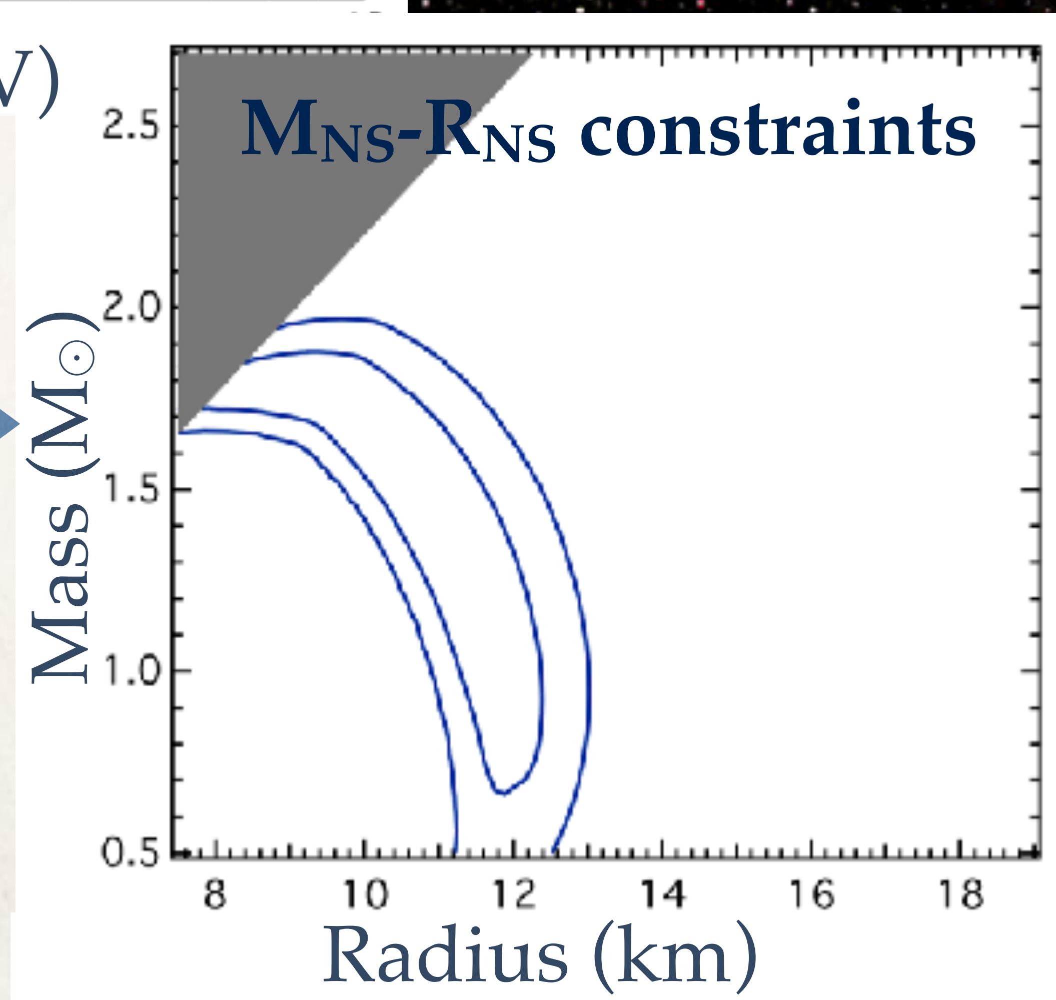
Credits: G. Baym


$\frac{J}{J_{\mathrm{GJ}}} > 1$
$0 < \frac{J}{J_{\mathrm{GJ}}} < 1$
$\frac{J}{J_{\mathrm{GJ}}} < 0$

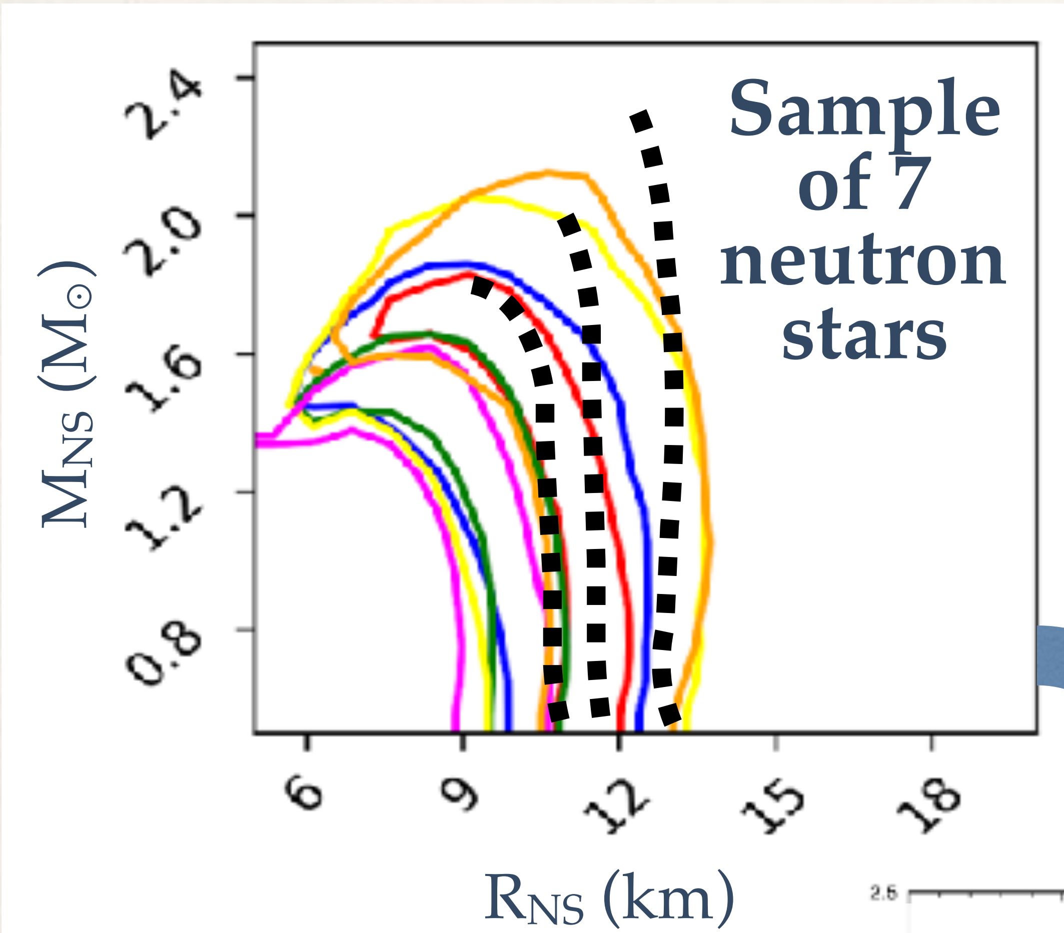
Only a small selection of neutron stars permit radius measurement that (we think) are reliable.

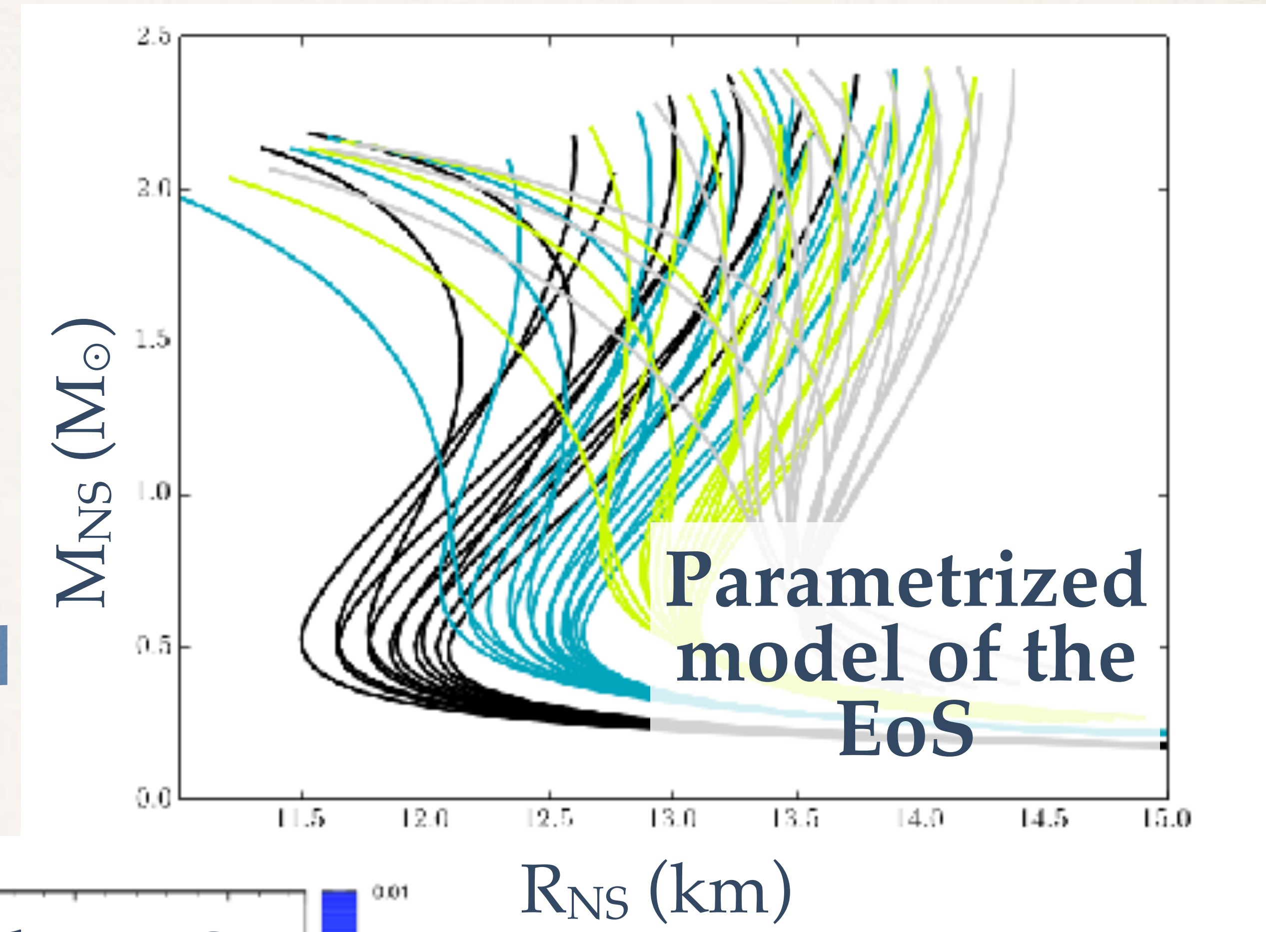


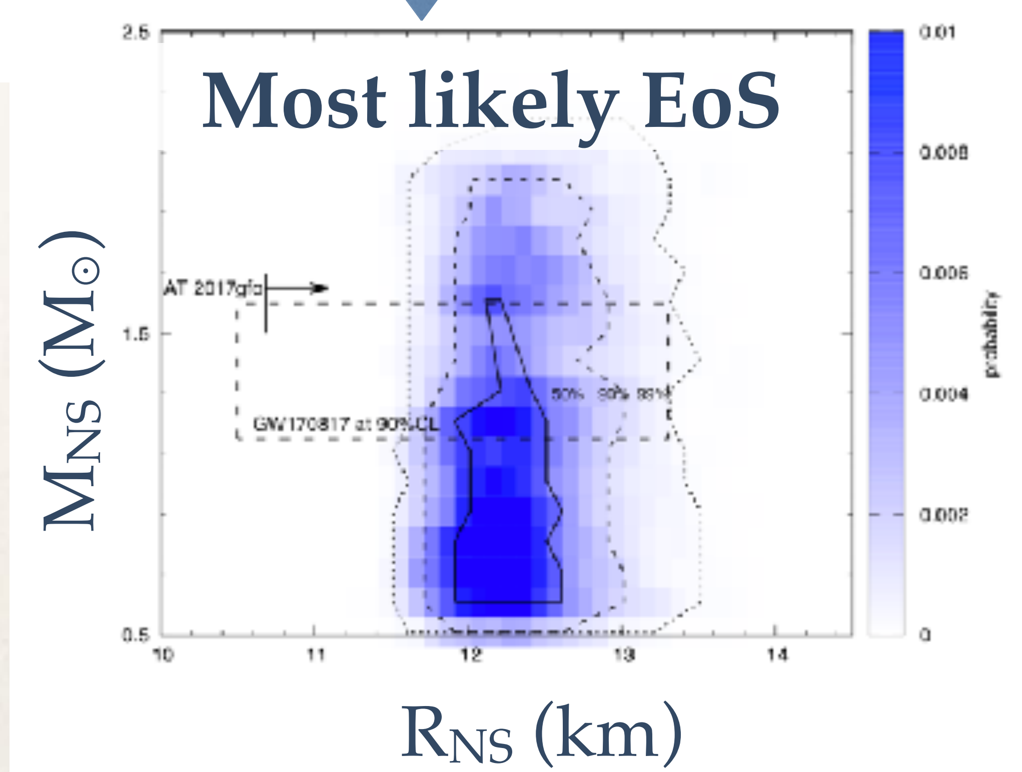




Statistical analysis of multiple neutron stars with a parametrised model of the equation of state.







$$f\left(L_{sym}, K_{sym}\right)$$

Baillot d'Etivaux, Guillot, Margueron, Webb et al. 2019