Measuring the radius of neutron stars with and other results from the NICER mission

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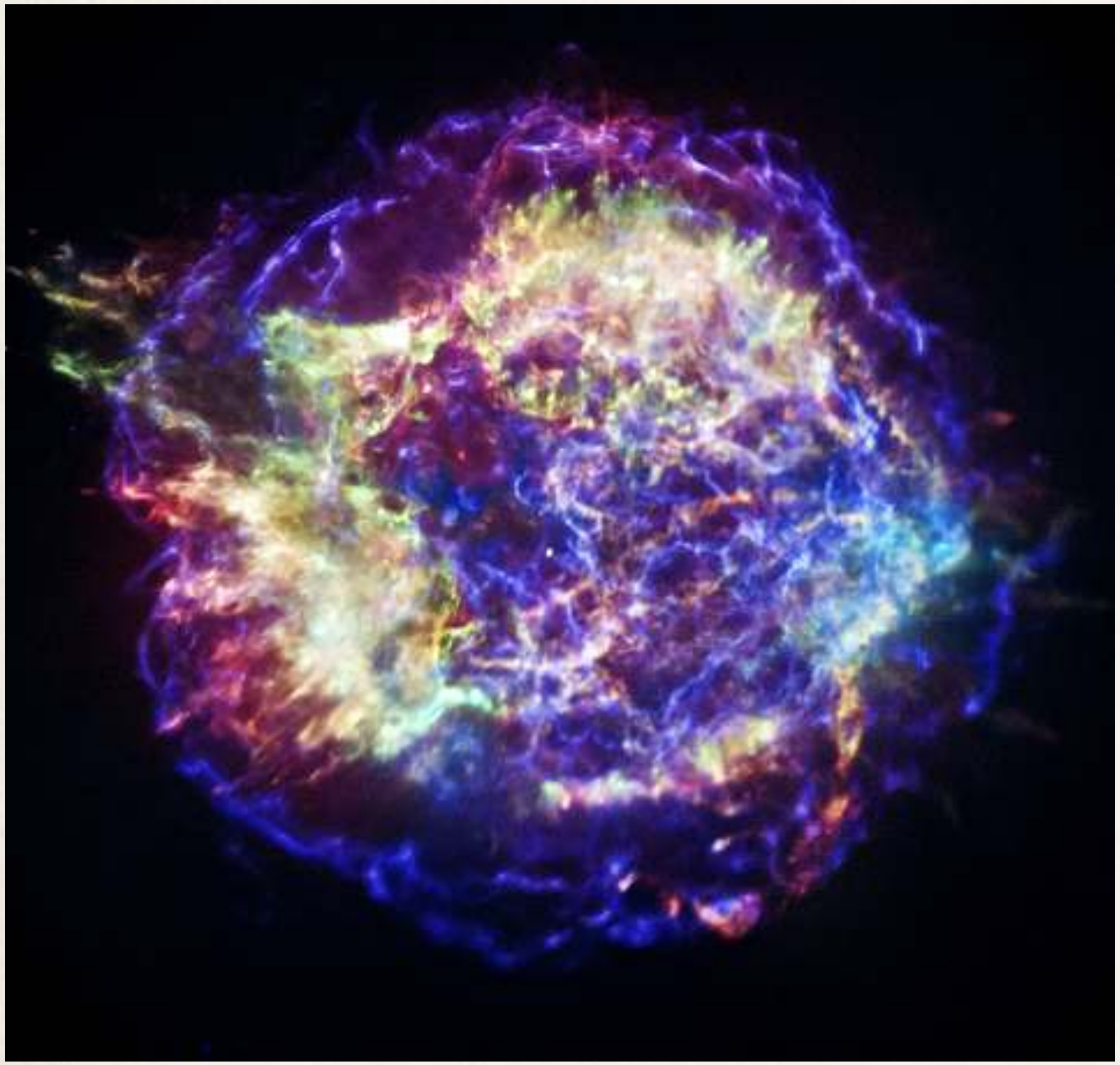
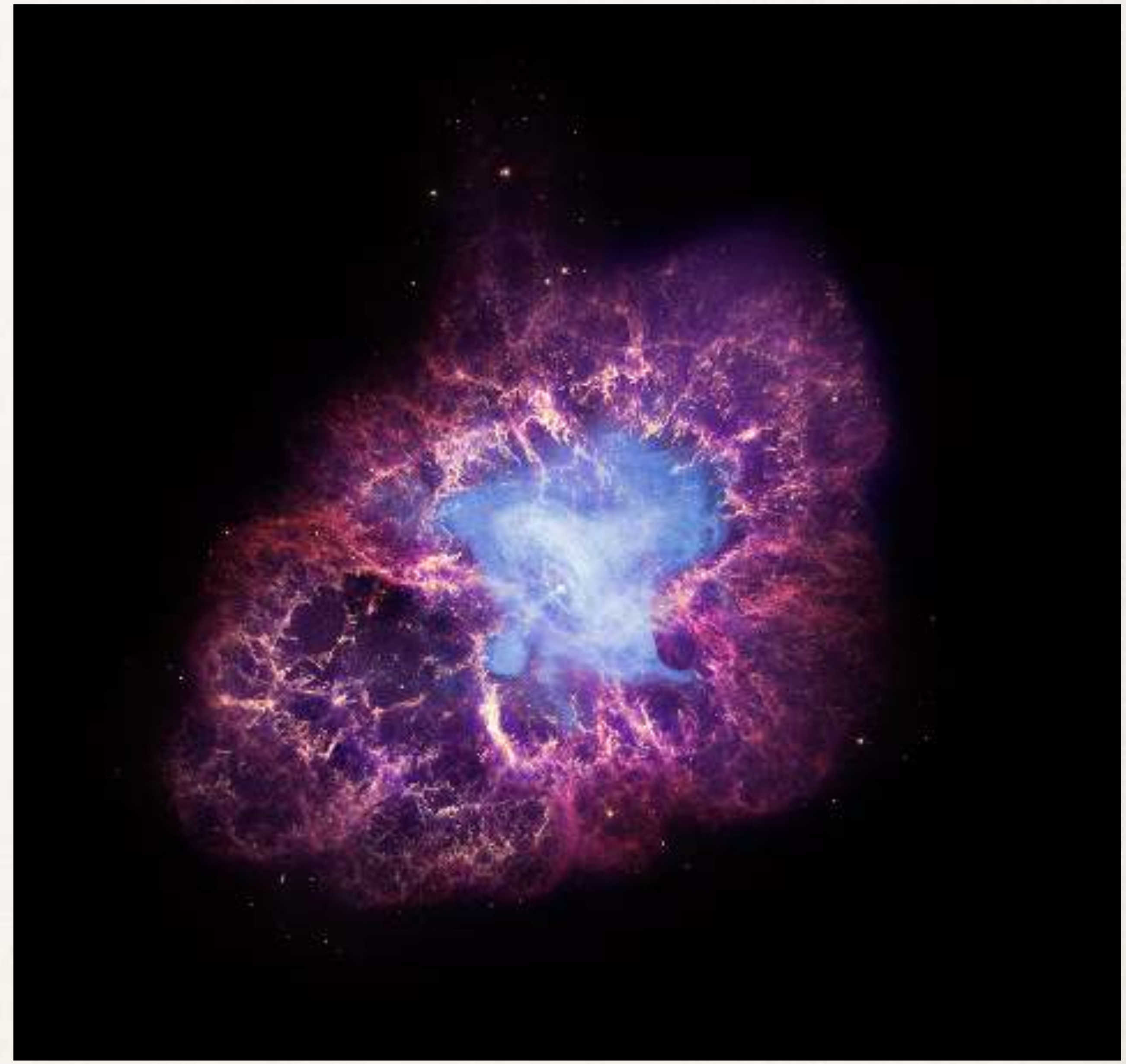
Collaboration with the NICER Science Team

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

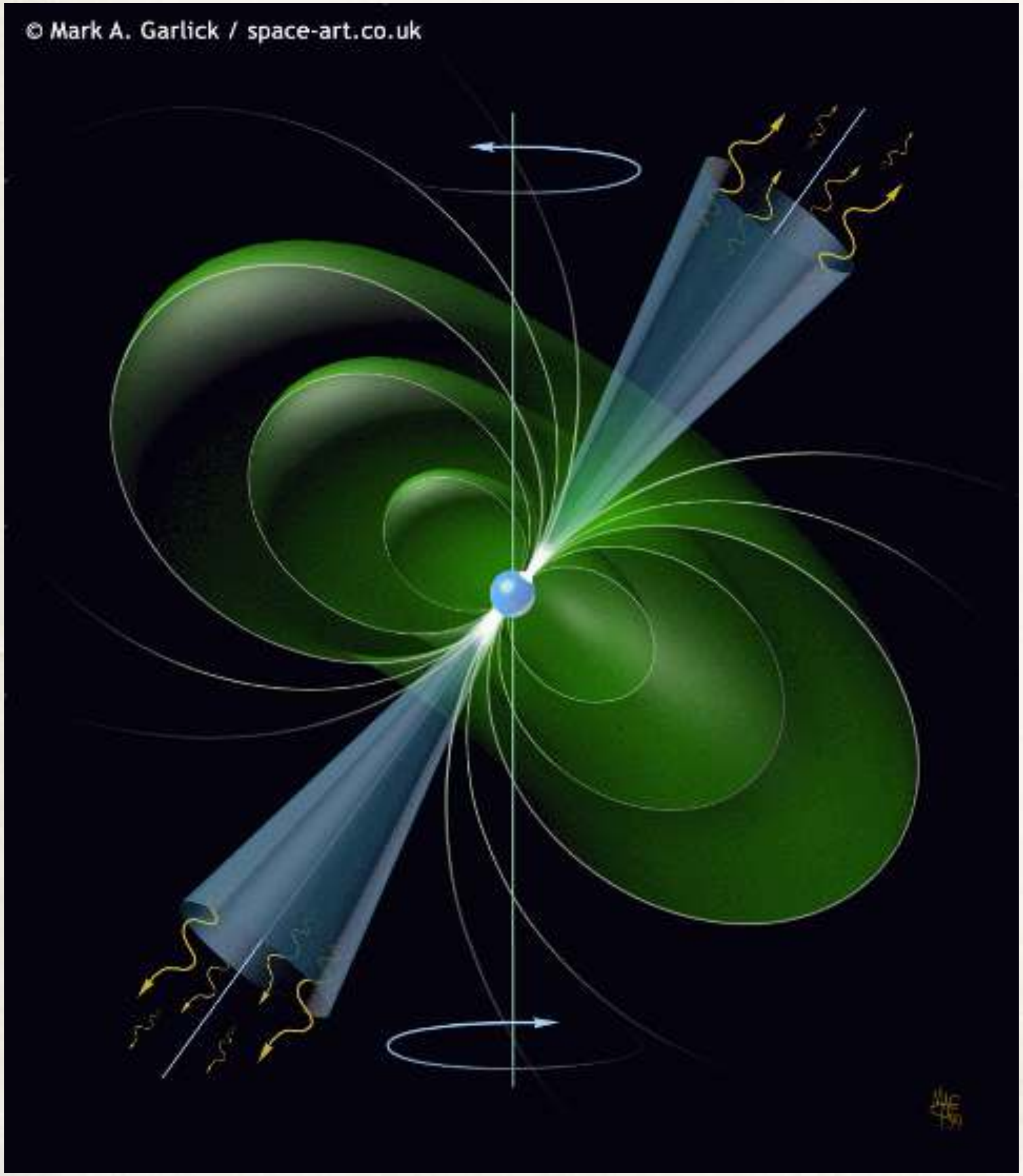


Cassiopeia A
X-ray image
Credits: NASA CXO



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

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

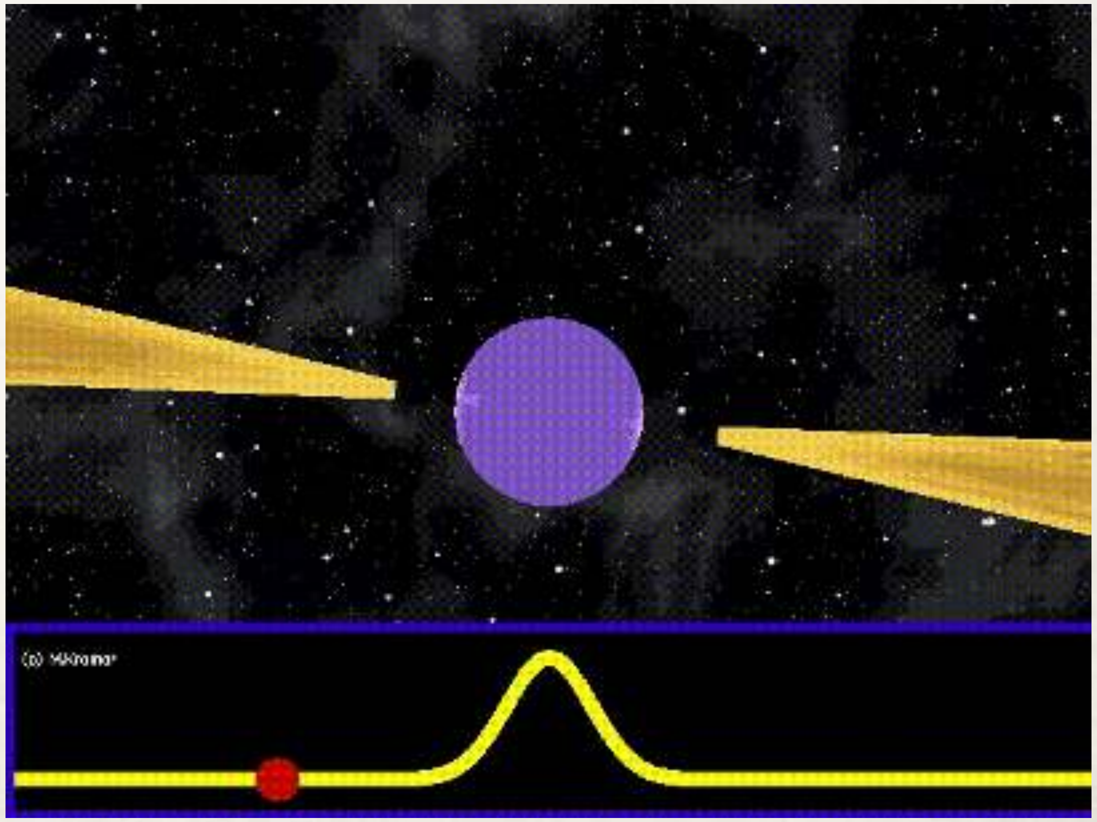


$R_{NS} \sim 11 - 14$ km

$M_{NS} \sim 1.0 - 2.0\ M_{\odot}$

$B \sim 10^{8} - 10^{15}$ G

$P_{spin} \sim 0.001 - 10$ sec



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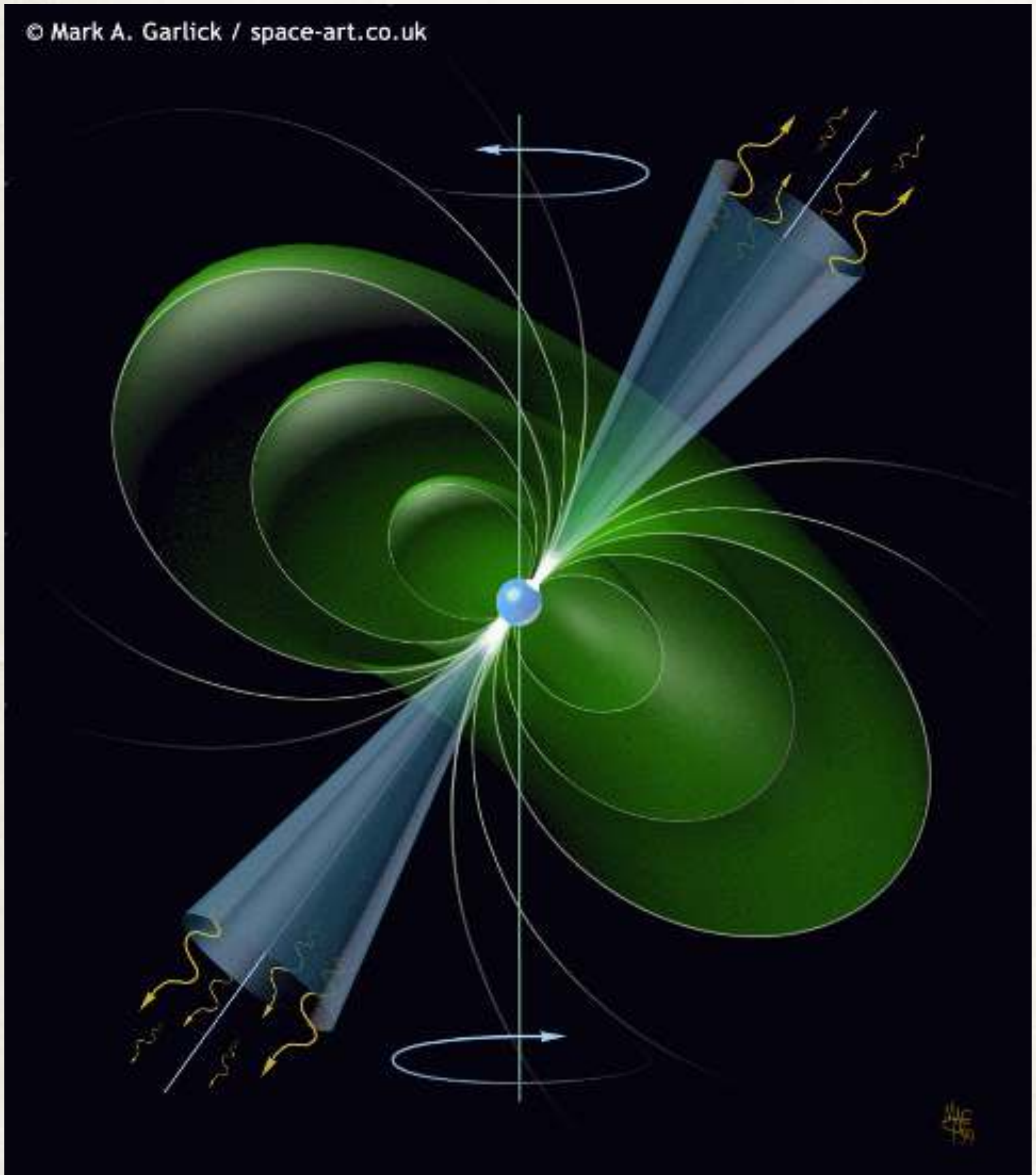

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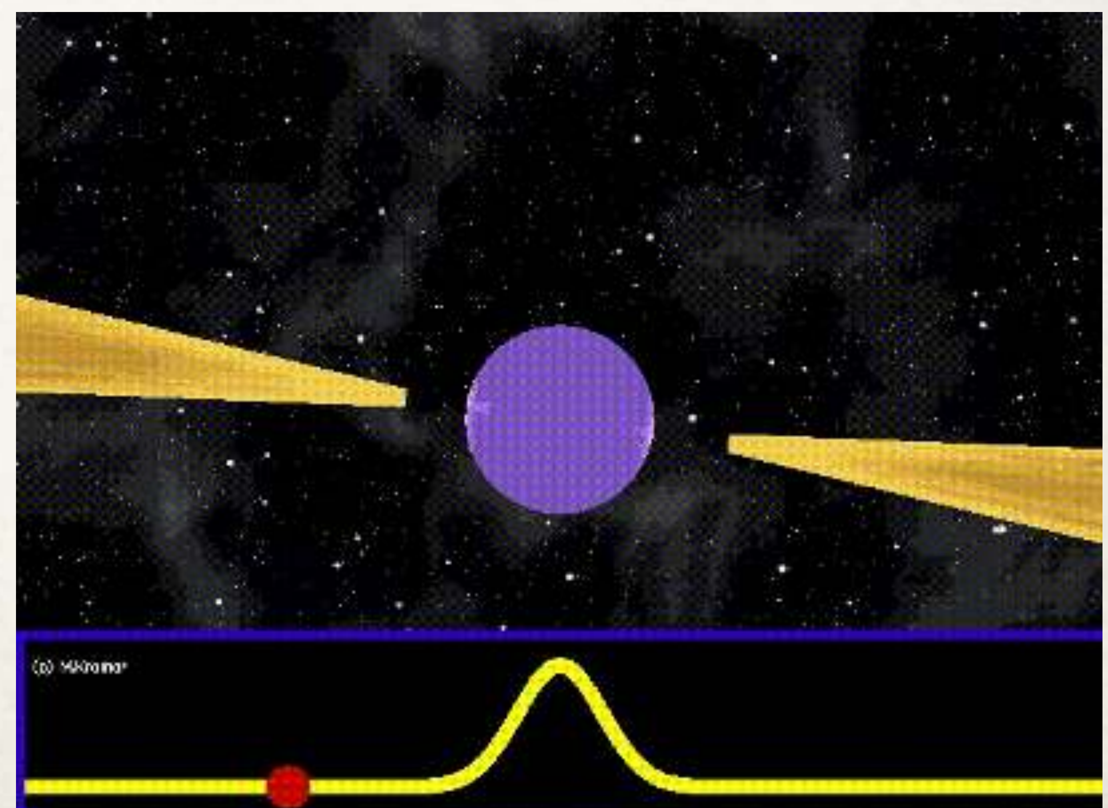
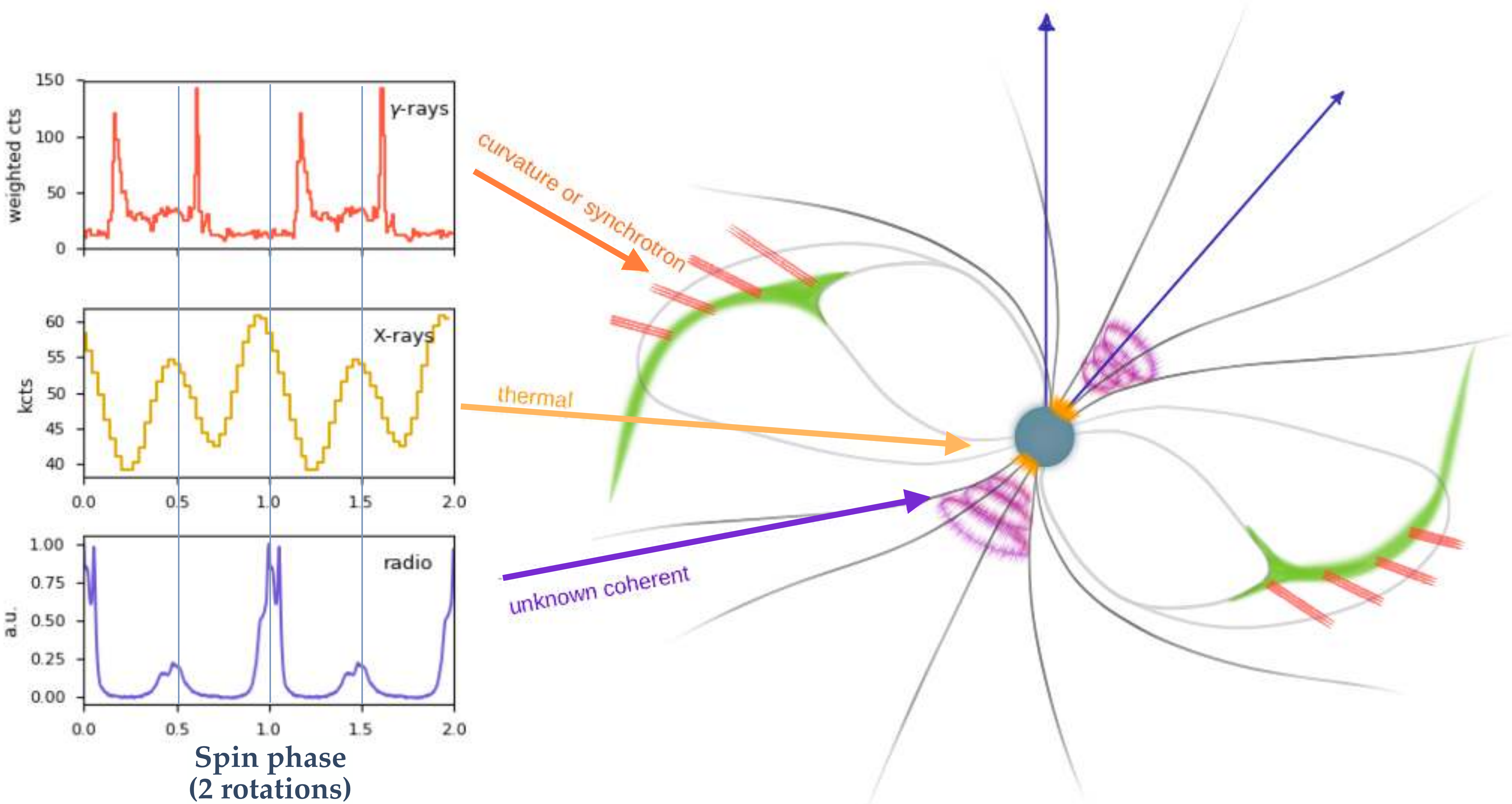


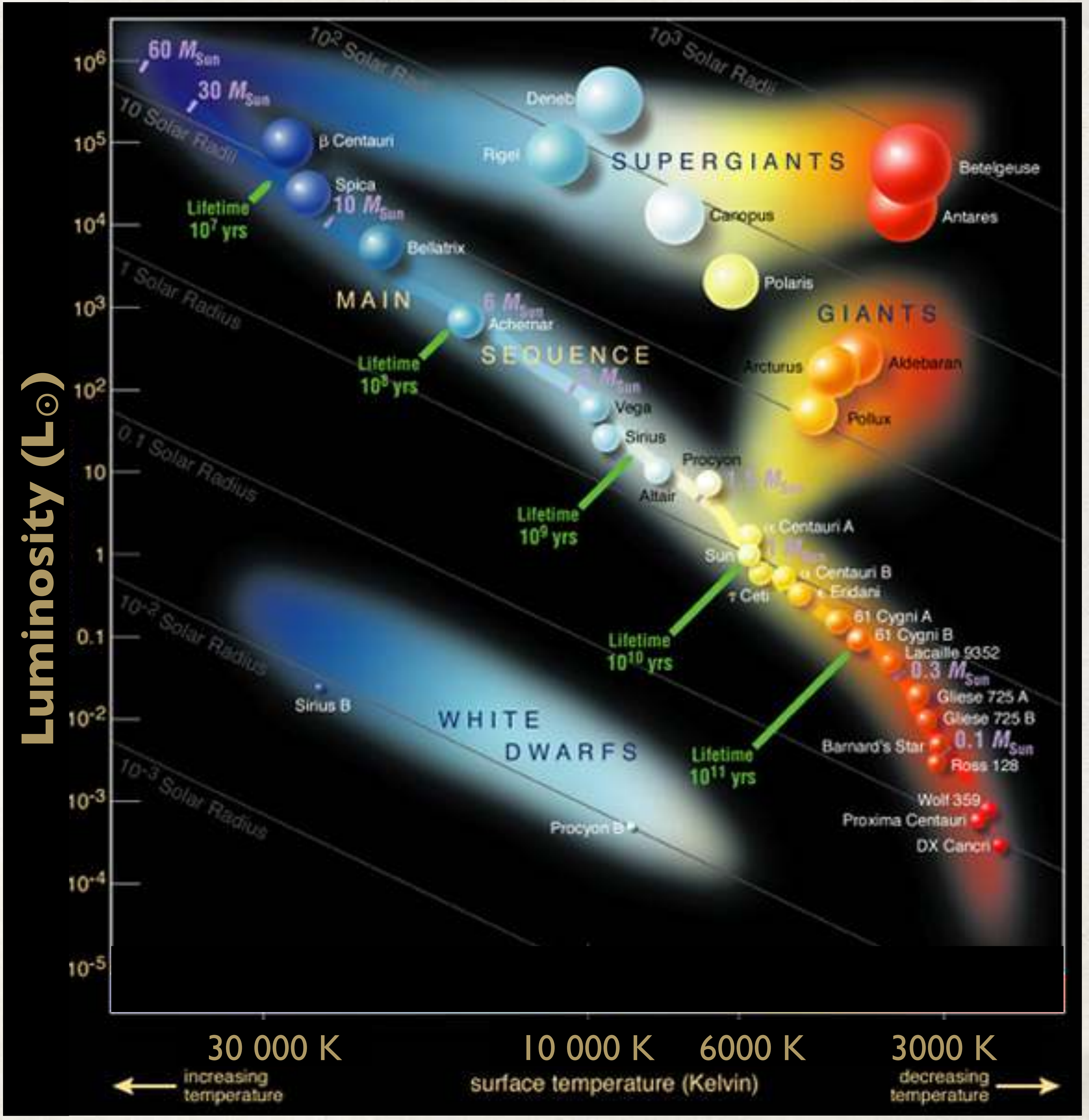
Some pulsars show pulsations at different wavelengths.



Spin phase
(2 rotations)

Credits: A. Bilous

Where would neutron stars be on the HR diagram?



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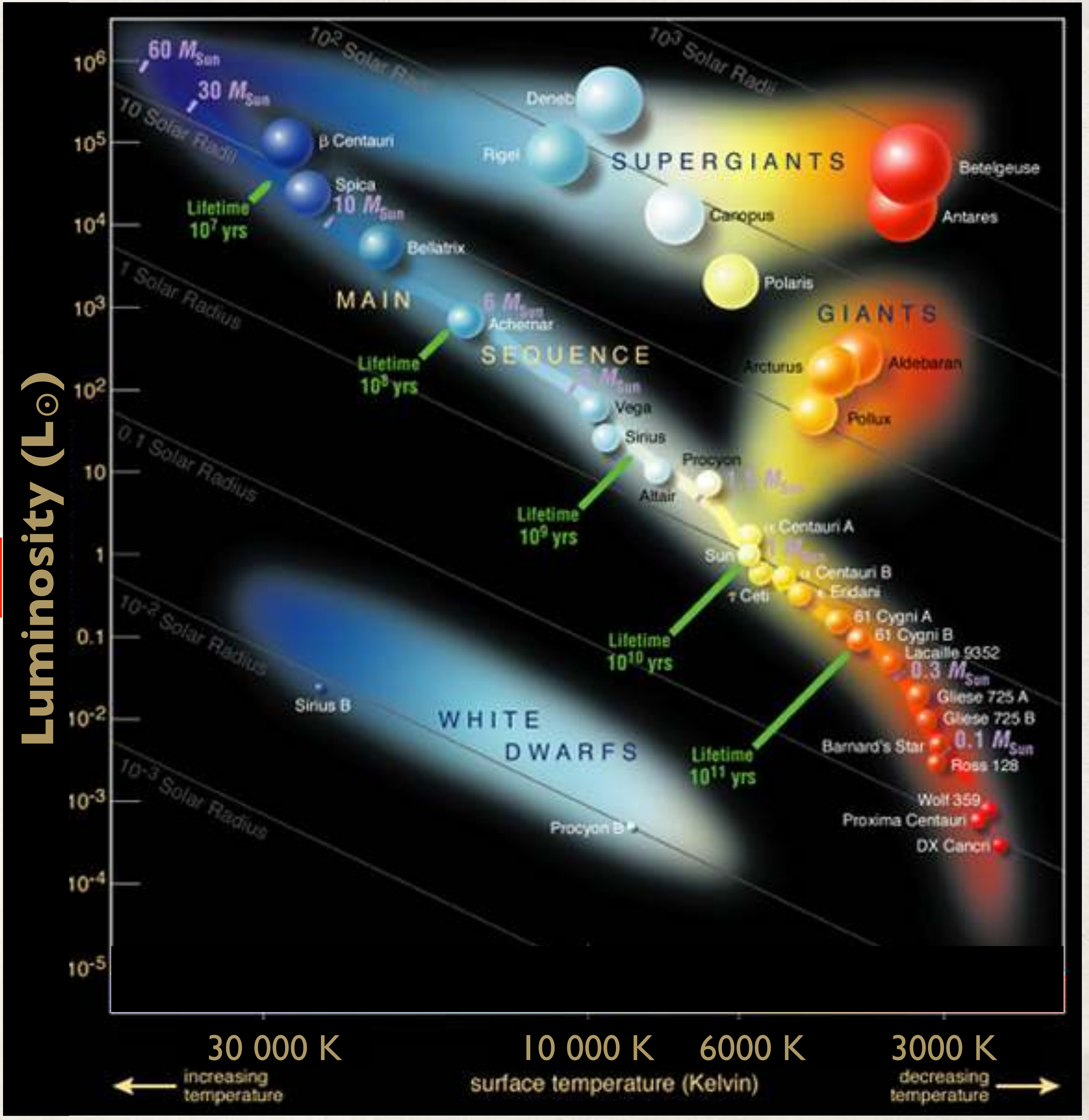
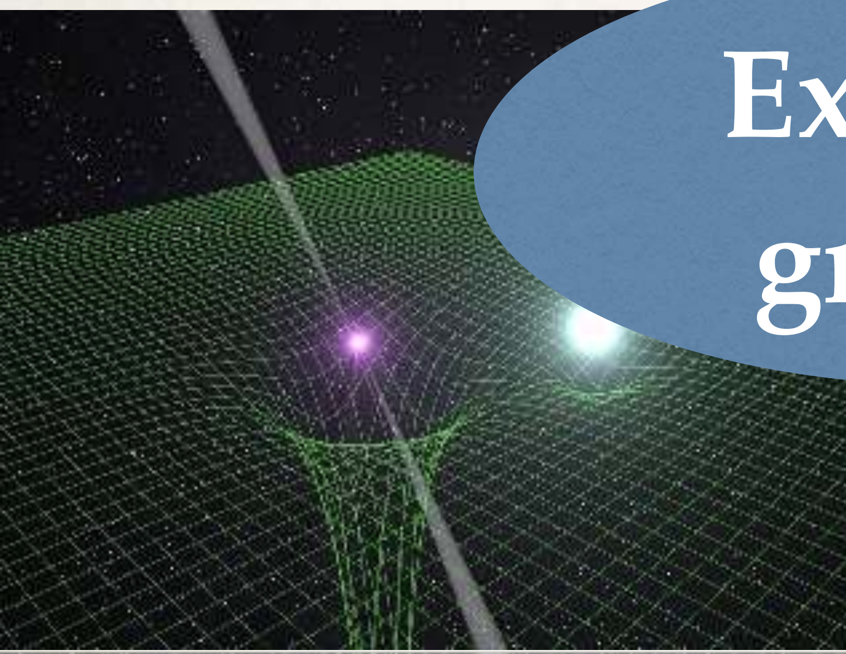
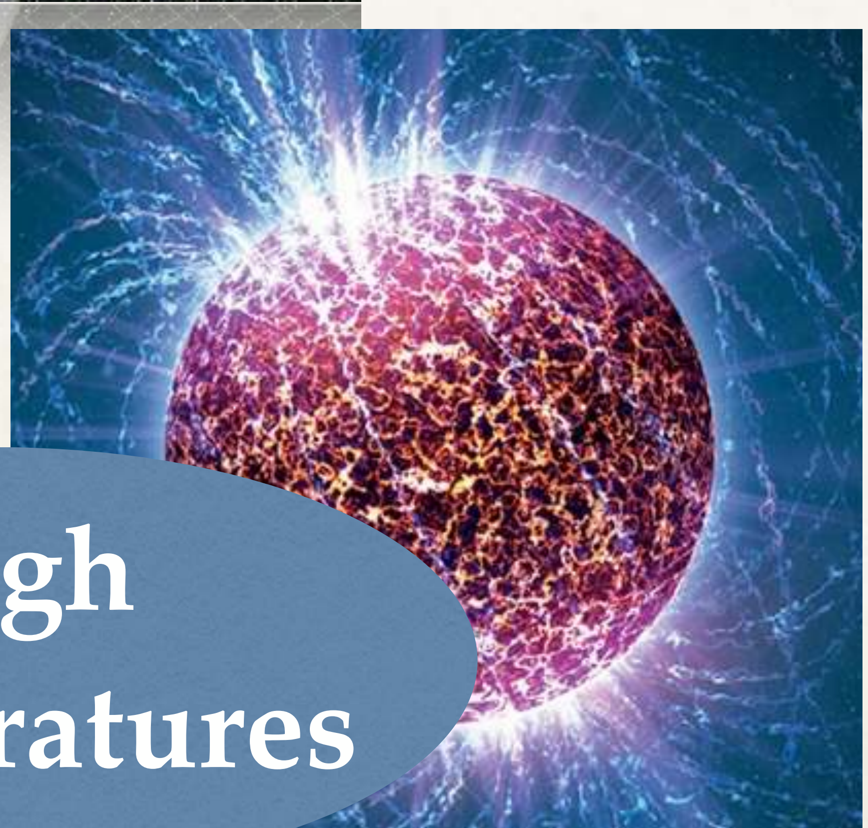


Neutron stars are amazing laboratories for extreme physics.

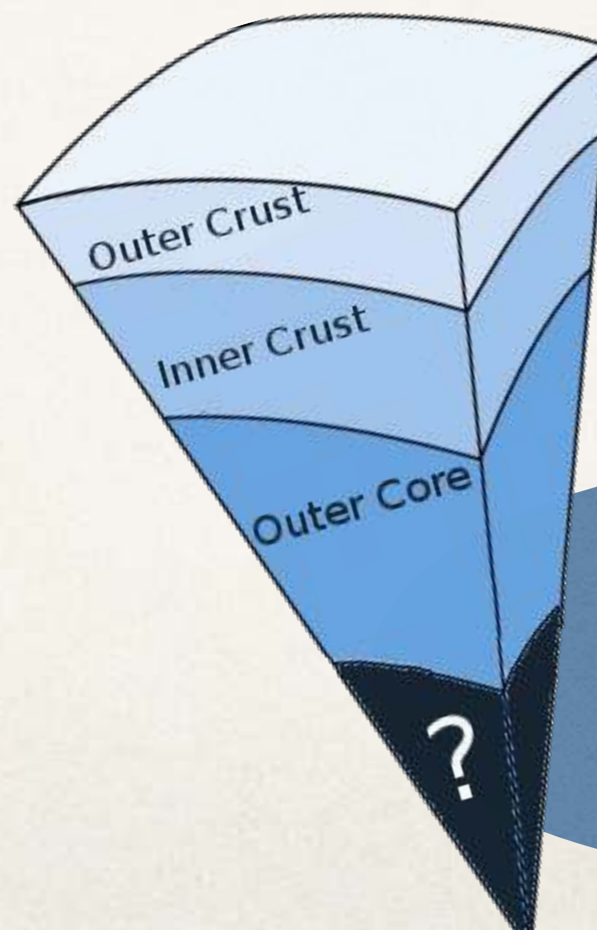


Extreme gravity

Extreme B-fields

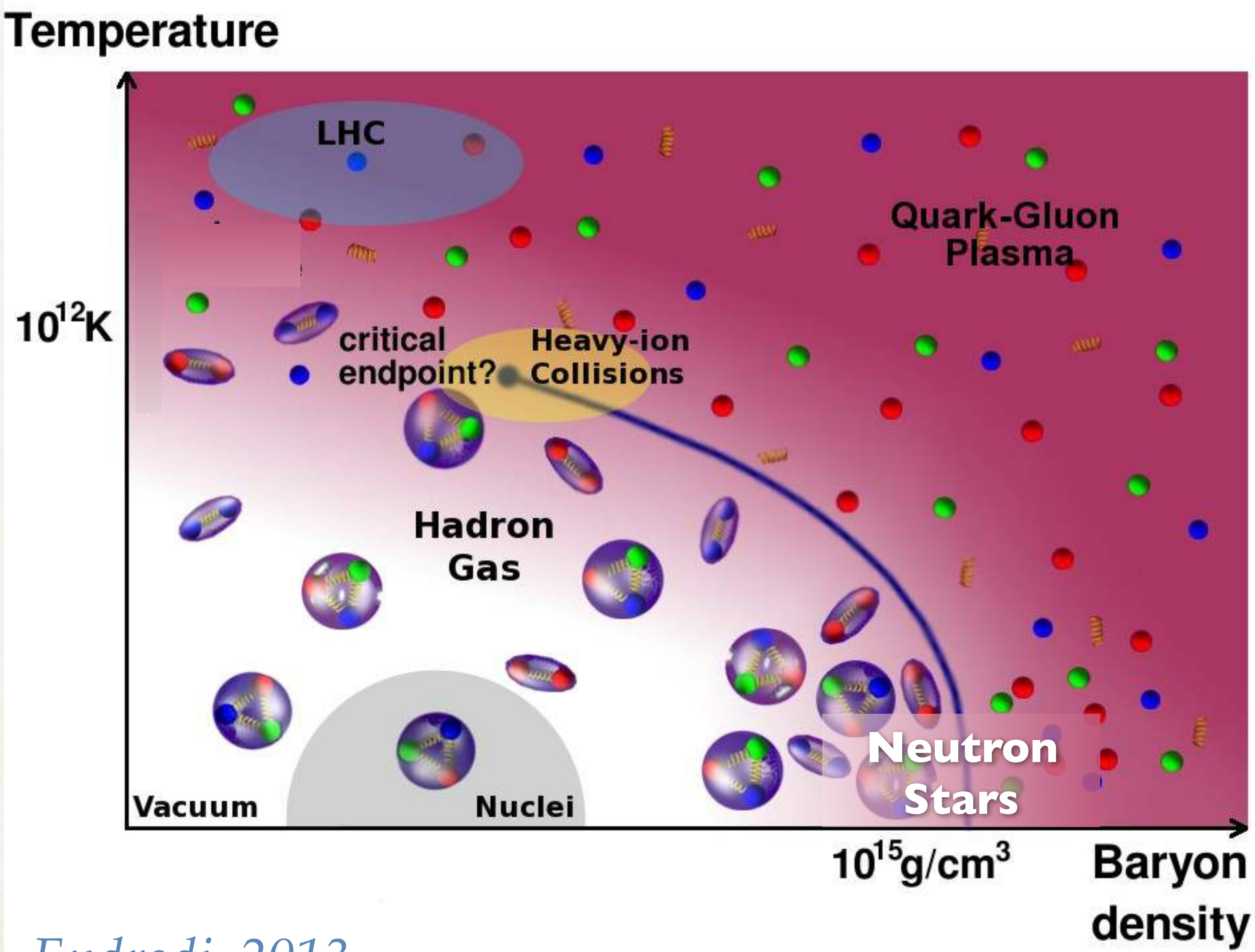


High temperatures



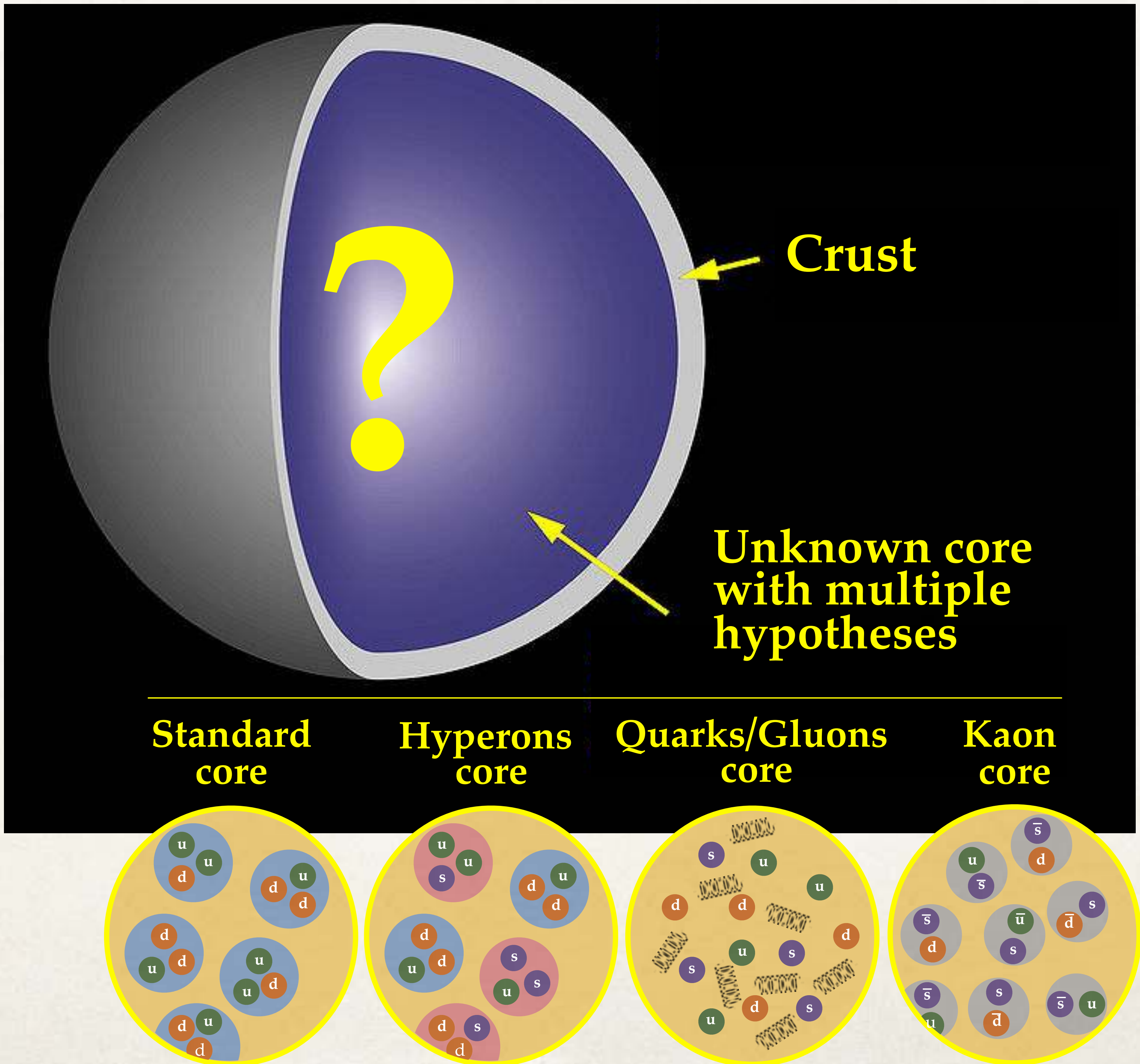
Extreme densities

Neutron stars provide tests of nuclear physics that are out of reach from experiments and calculations.

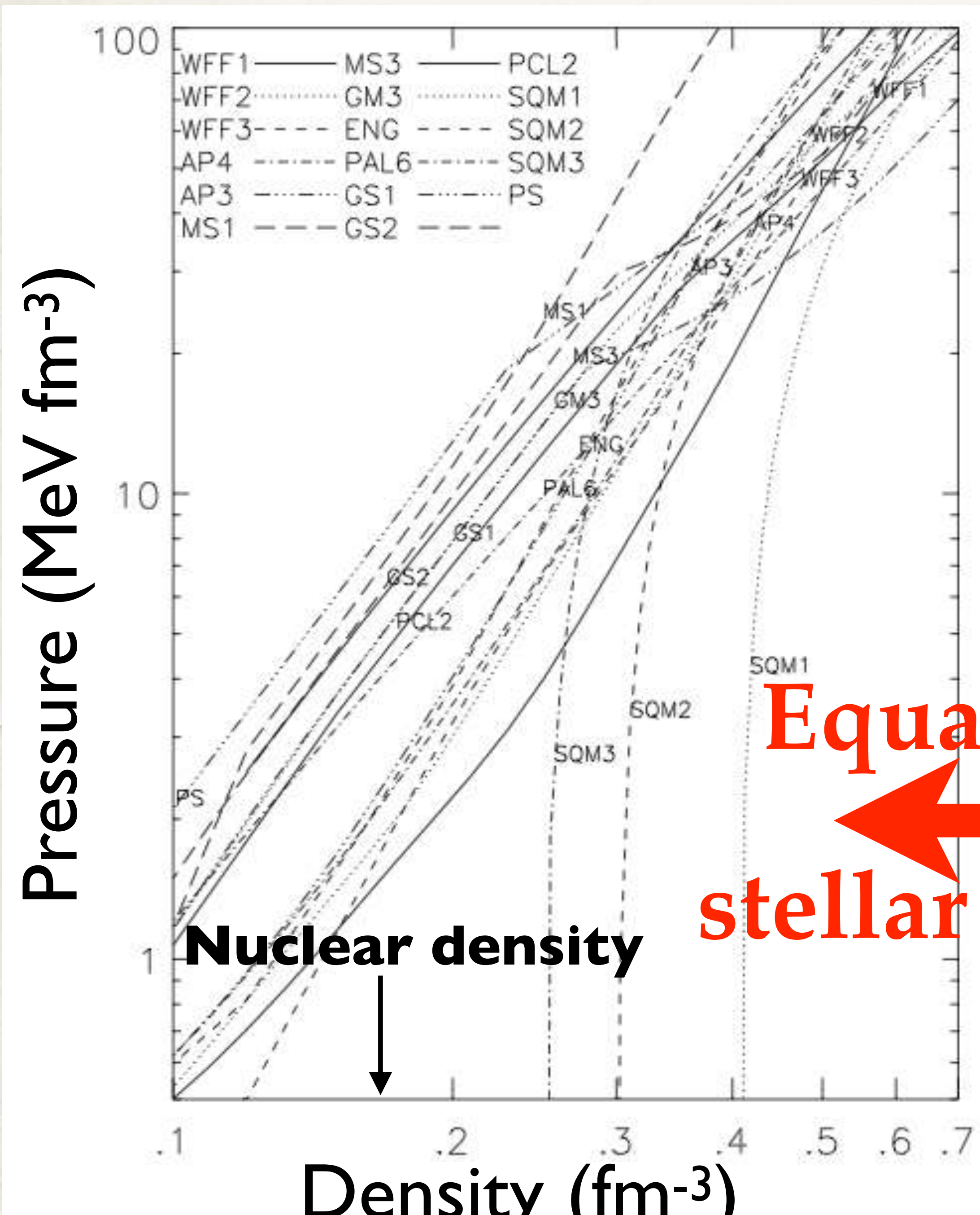


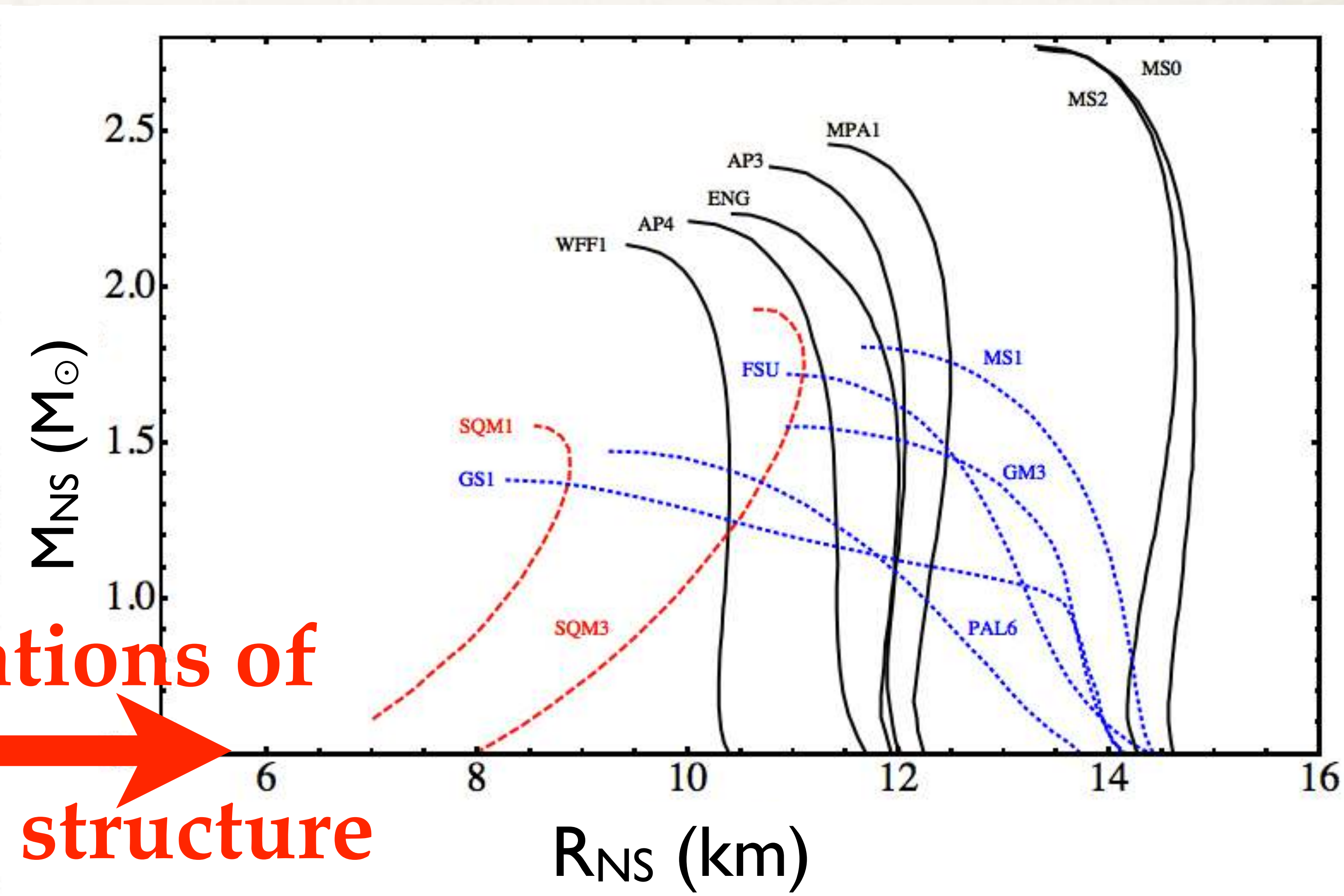
Endrodi, 2013

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



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





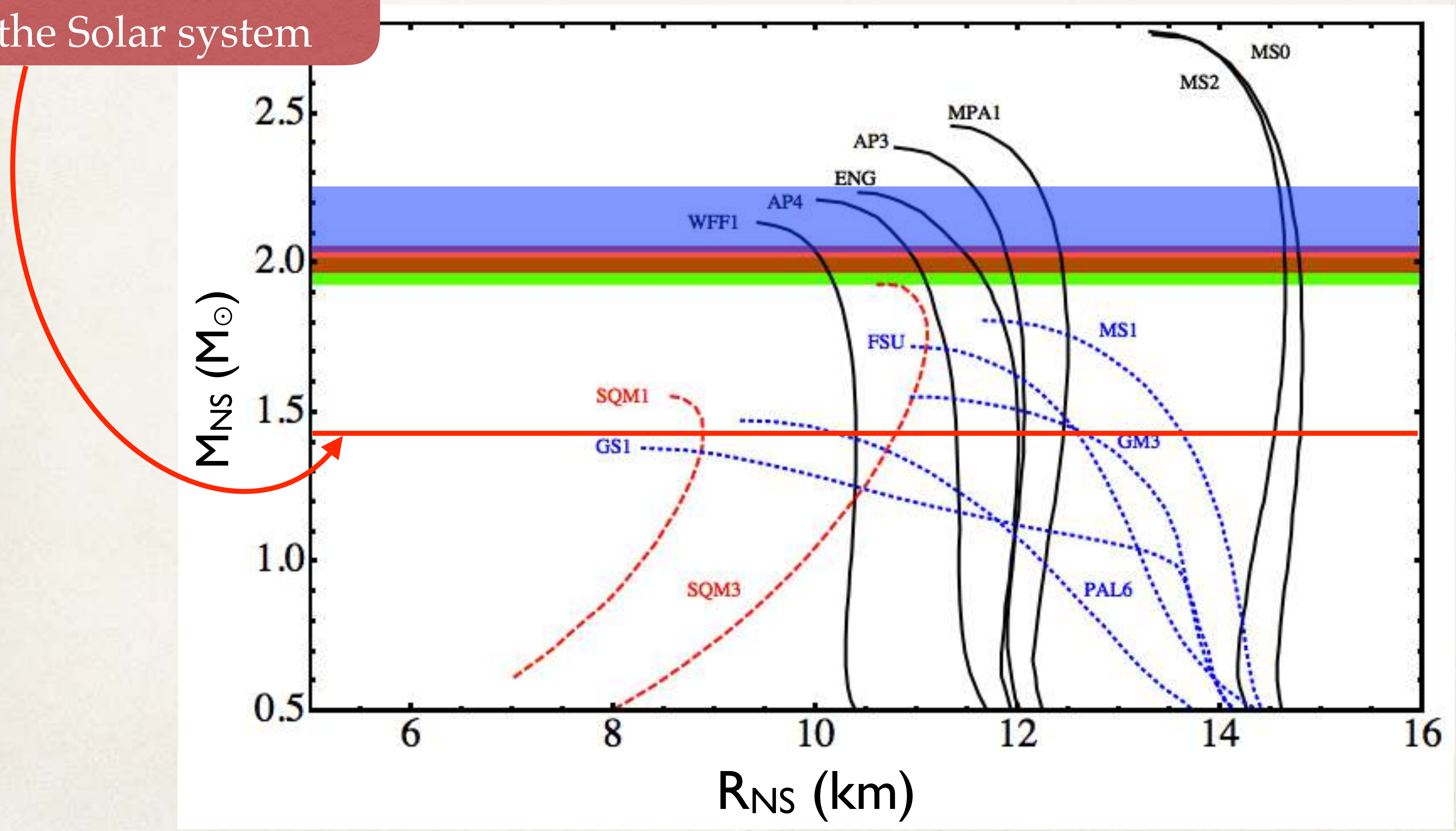
Lattimer and Prakash 2001

Many theoretical EoS exist,
see a catalog at CompOSE.obspm.fr

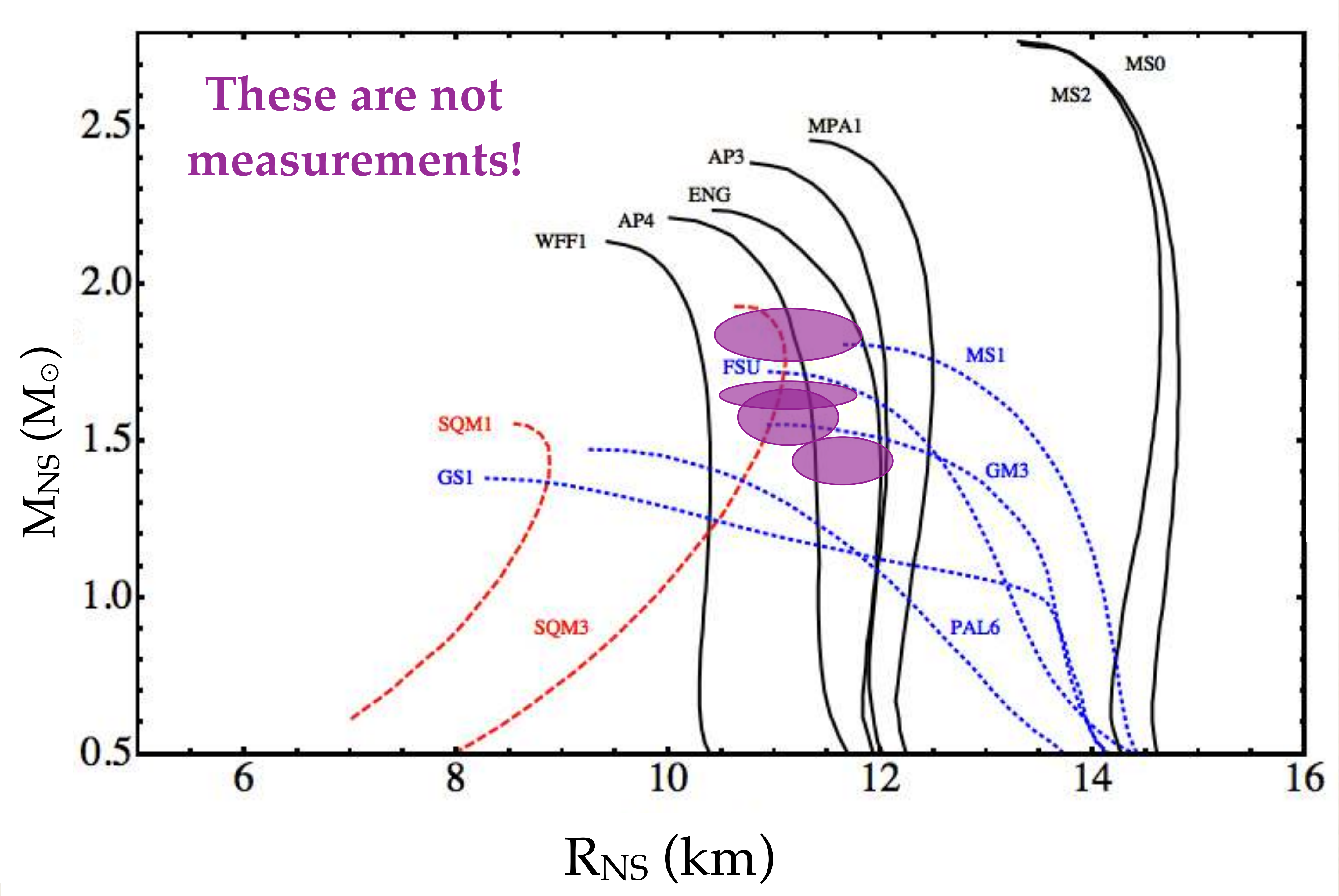
Measurements of the mass M_{NS} exist, but only high-M_{NS} are useful.

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

Most precise mass measurement outside the Solar system

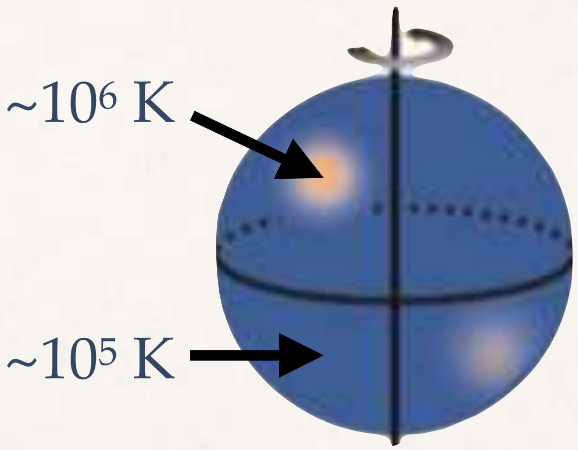


Measuring R_{NS} is difficult and measuring both R_{NS} and M_{NS} is even more difficult.



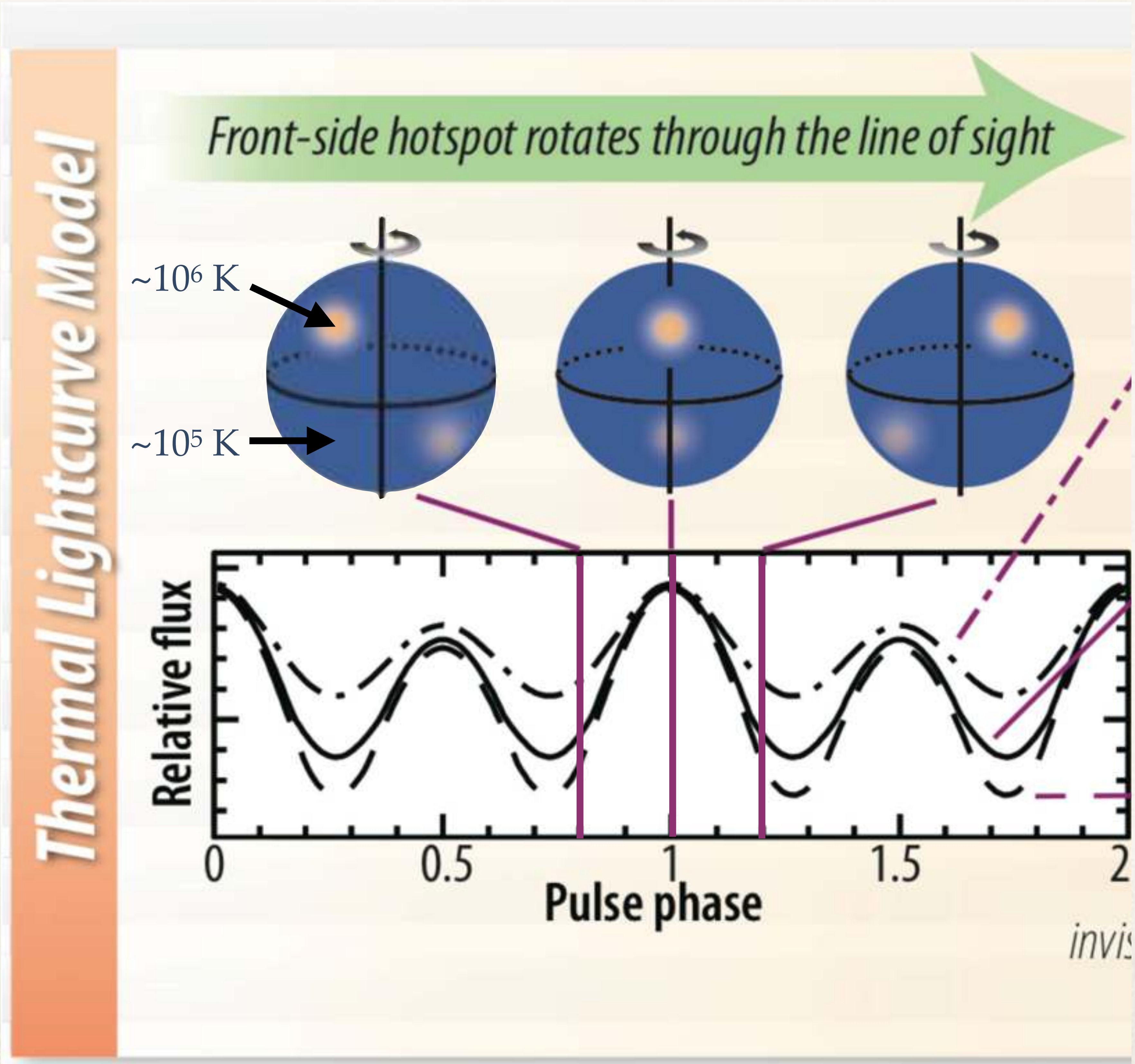
Here is the NICER way.

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



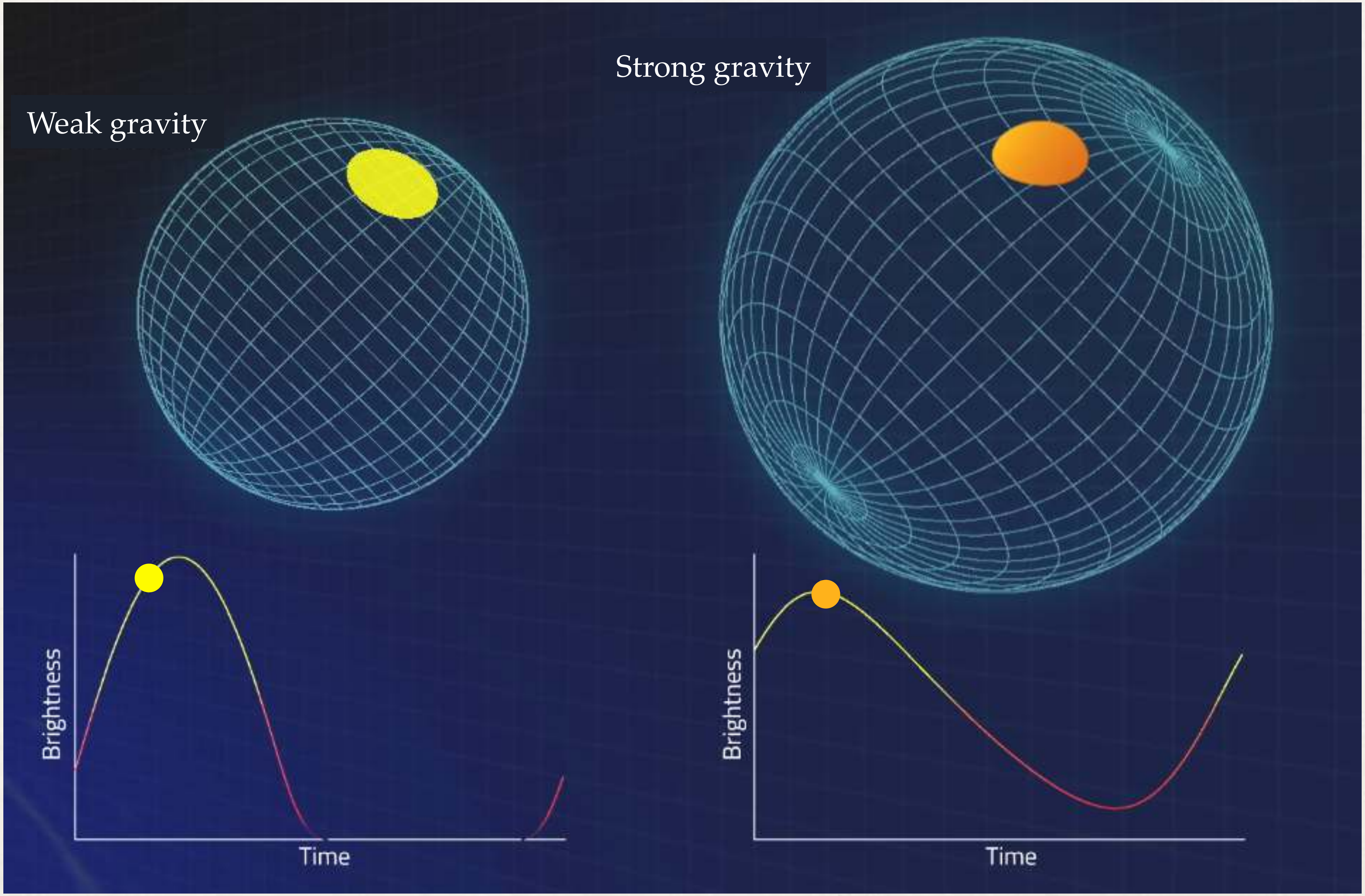
Credits: NASA/NICER

The pulsed 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

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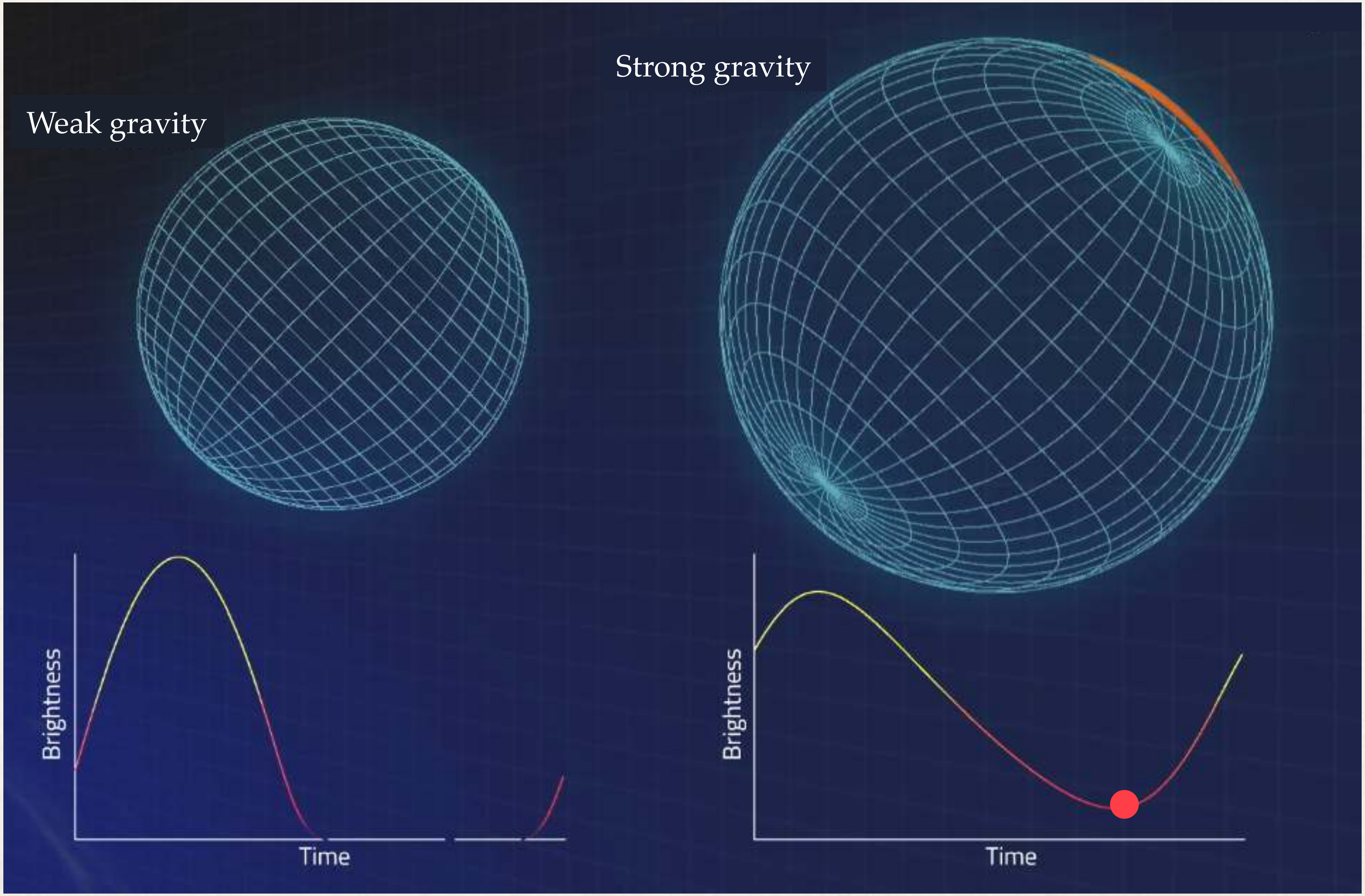

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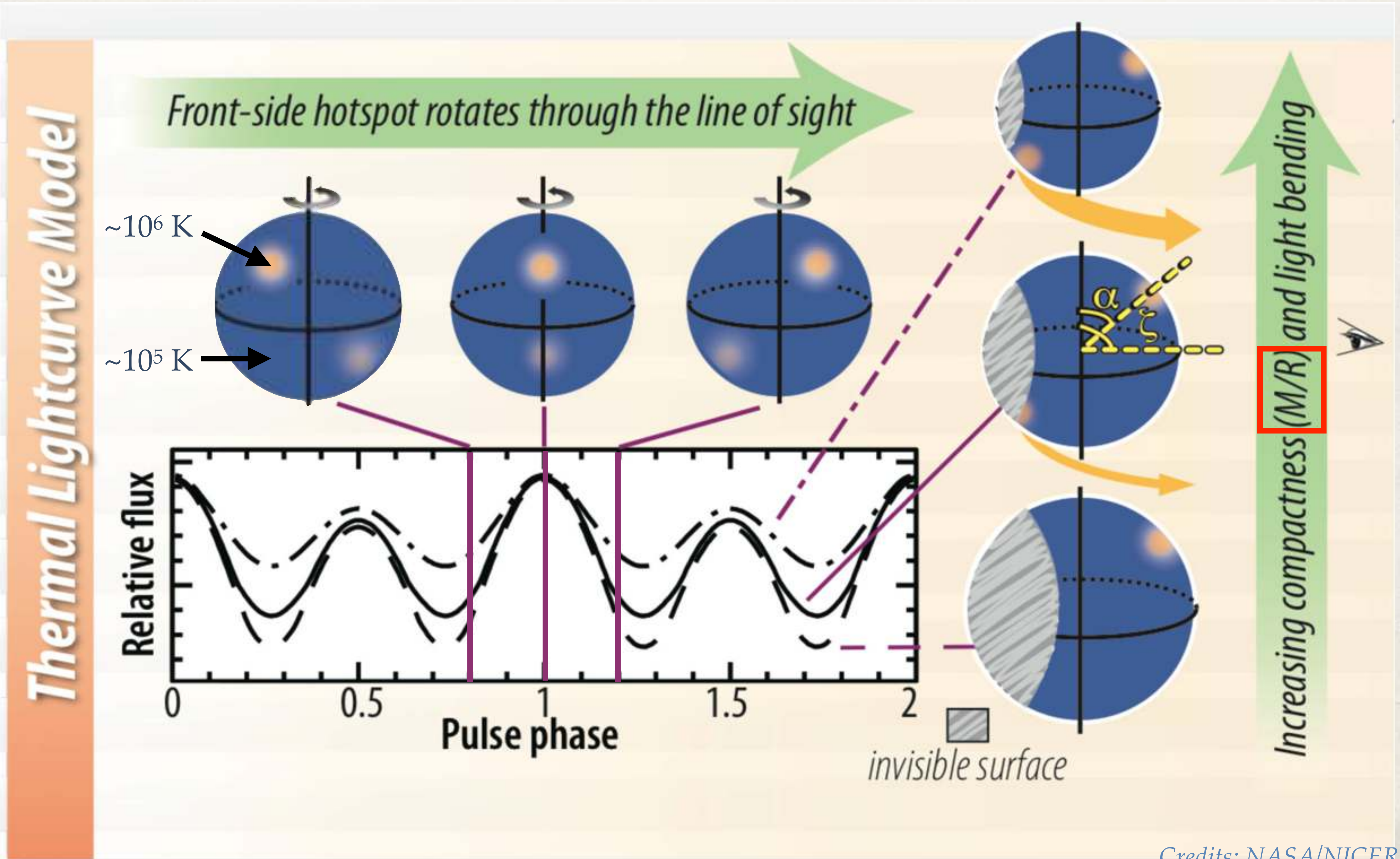
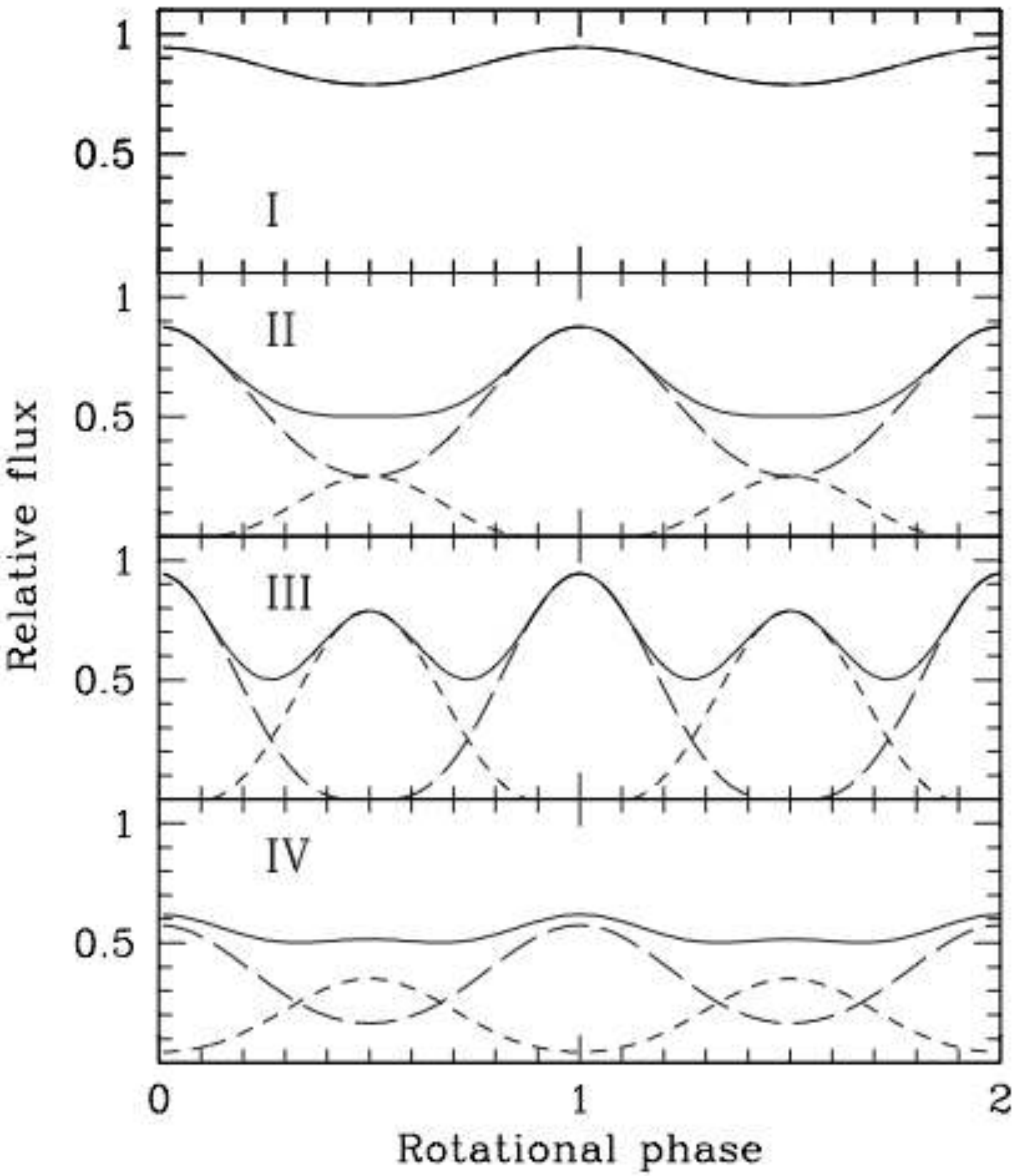
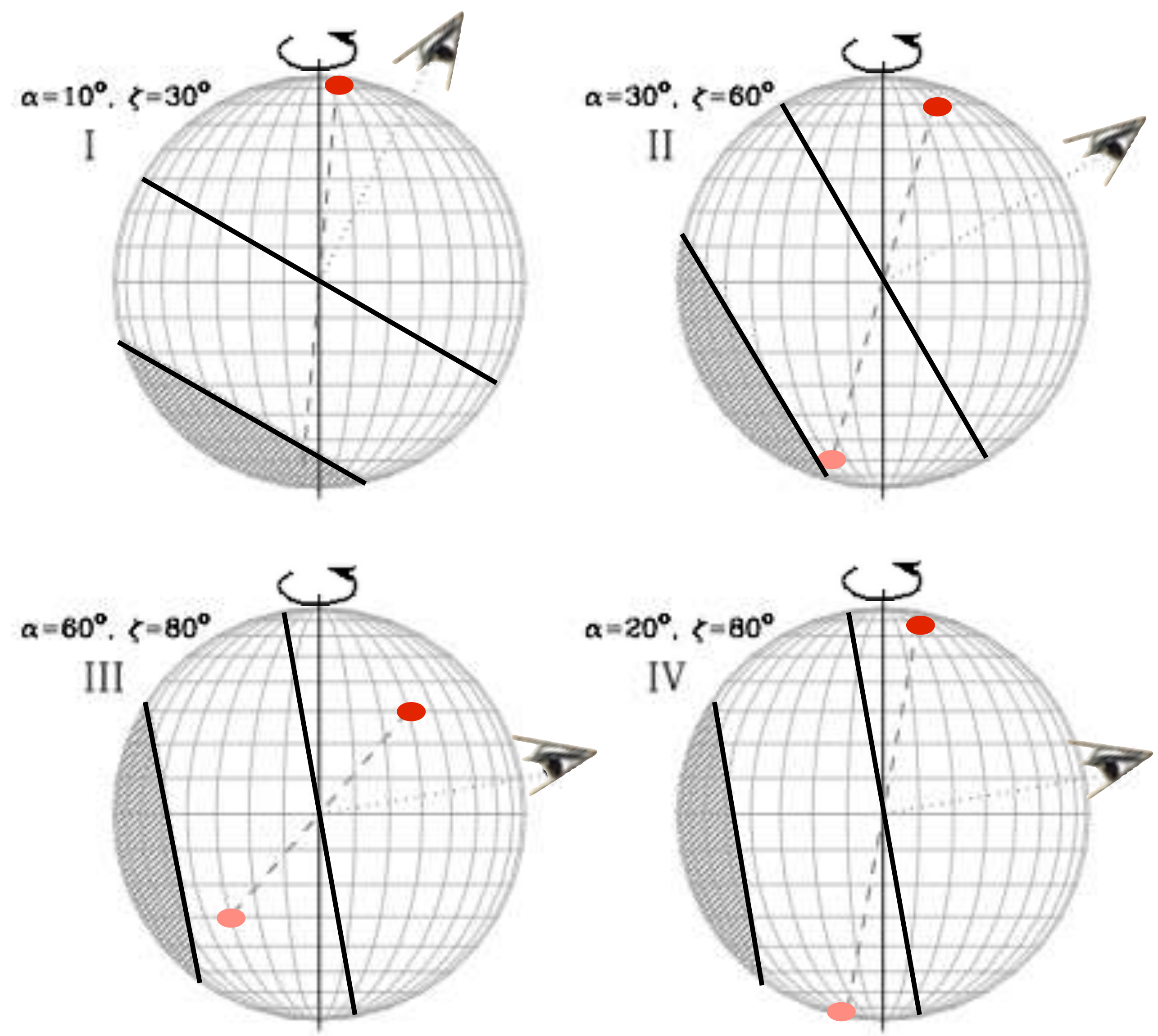
The pulsed emission caused by hot spots on a rotating neutron star can help measure the compactness.



Credits: NASA/NICER

The pulsed emission also depends on the system geometry.



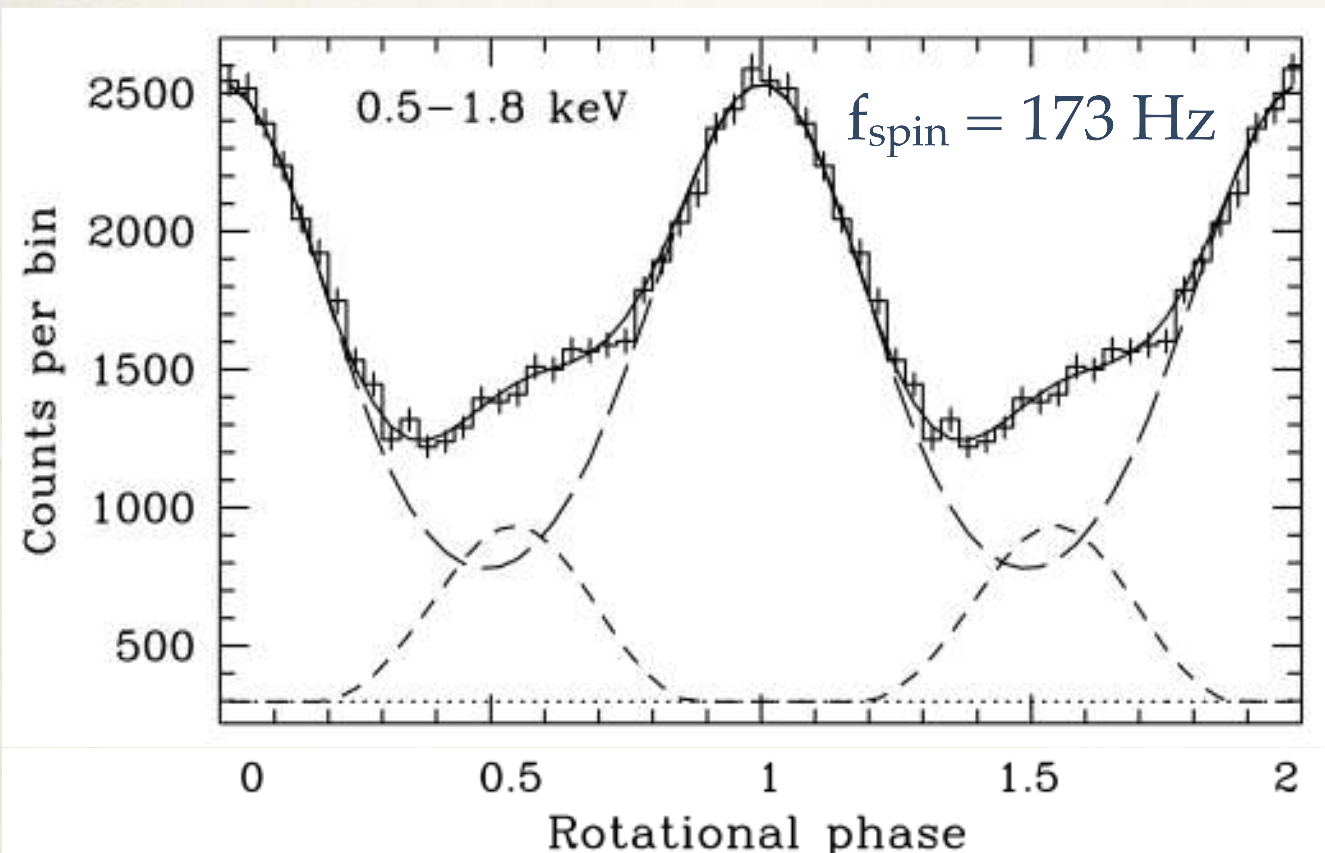


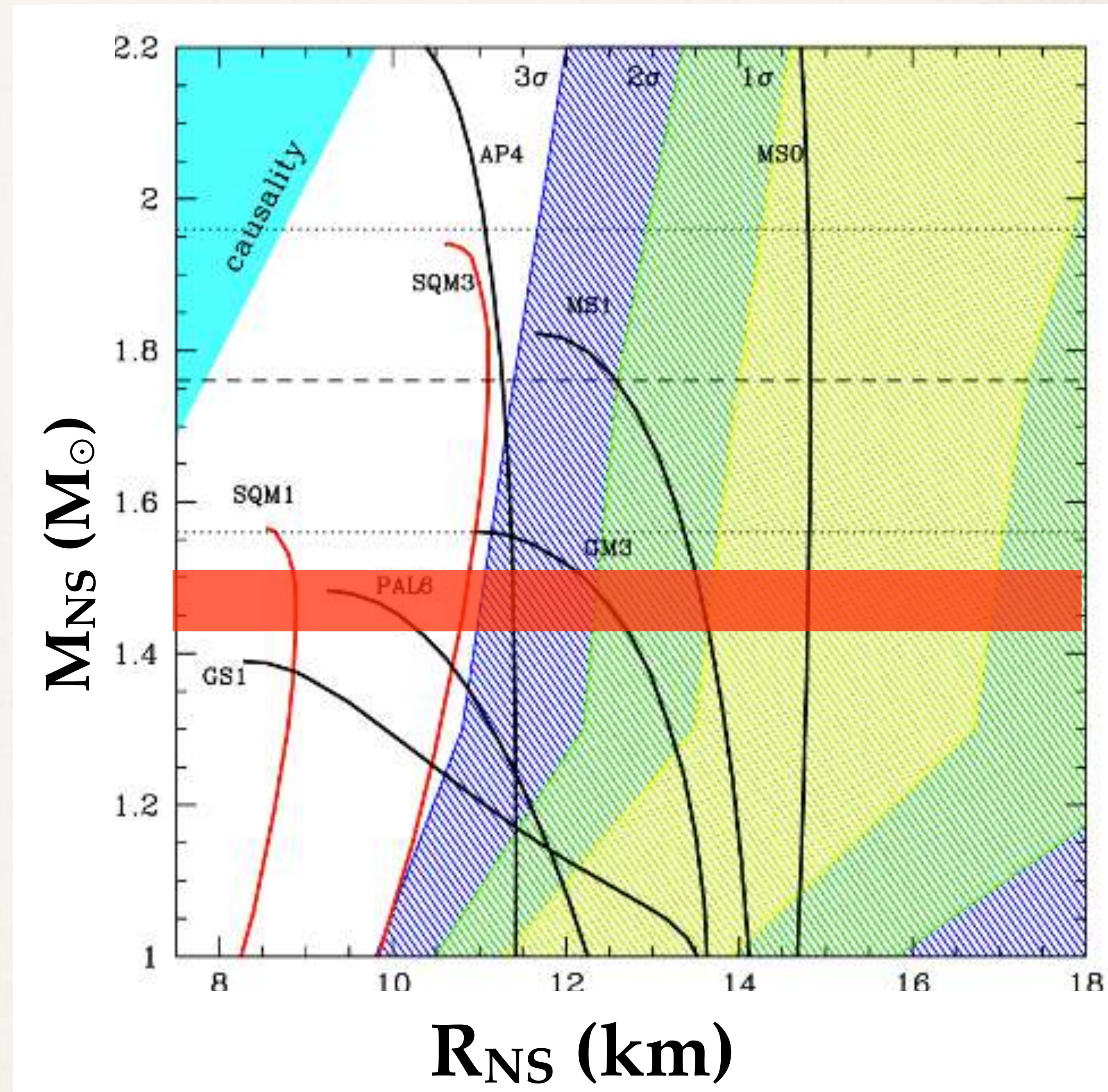
$M_{NS} = 1.4\ M_{\odot}$, $R_{NS} = 10km$

(Bodganov et al. 2008)

To model the light curve, it is preferable to know the neutron star mass…and to collect a large number of photons from the pulsar.

PSR J0437-4715 with XMM-Newton

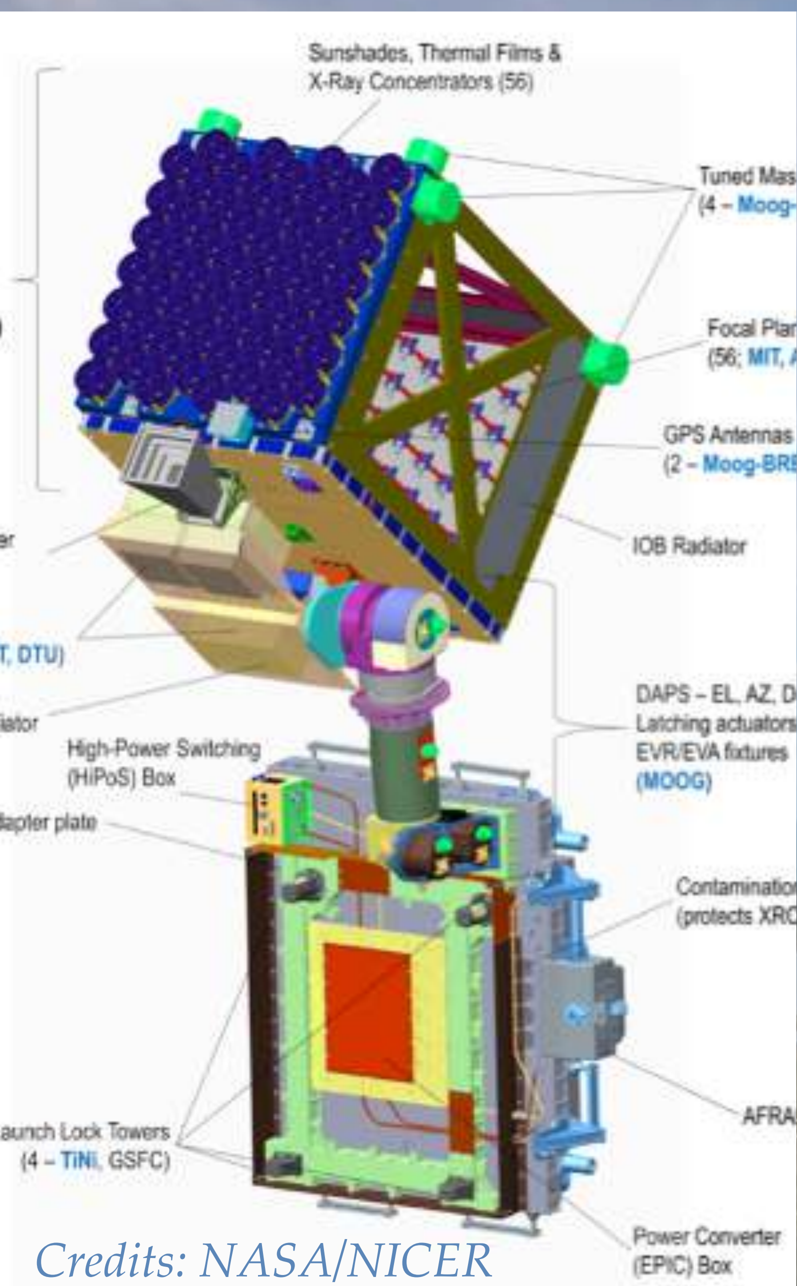




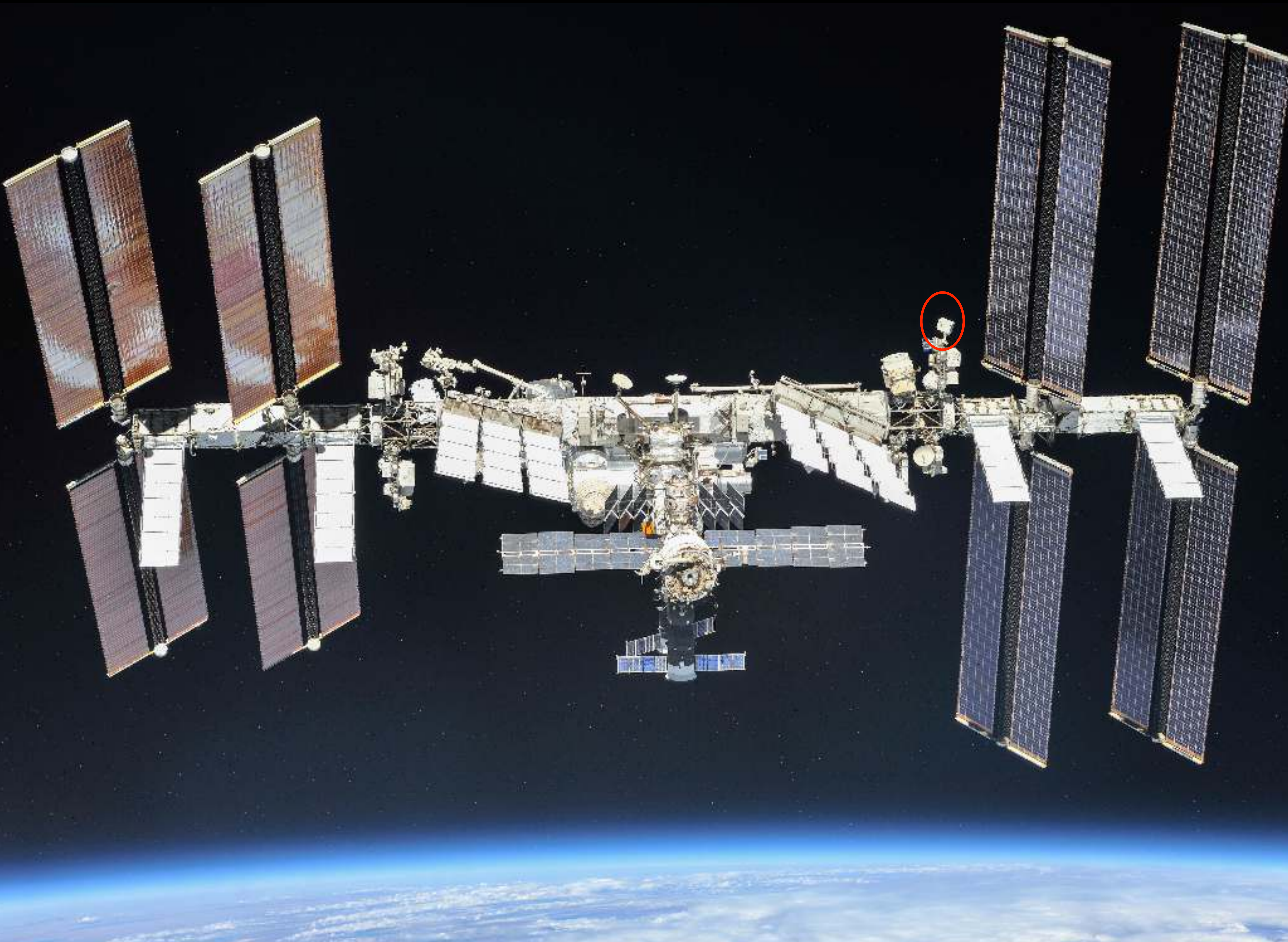
M/R extracted from lightcurve

Bogdanov (2013)

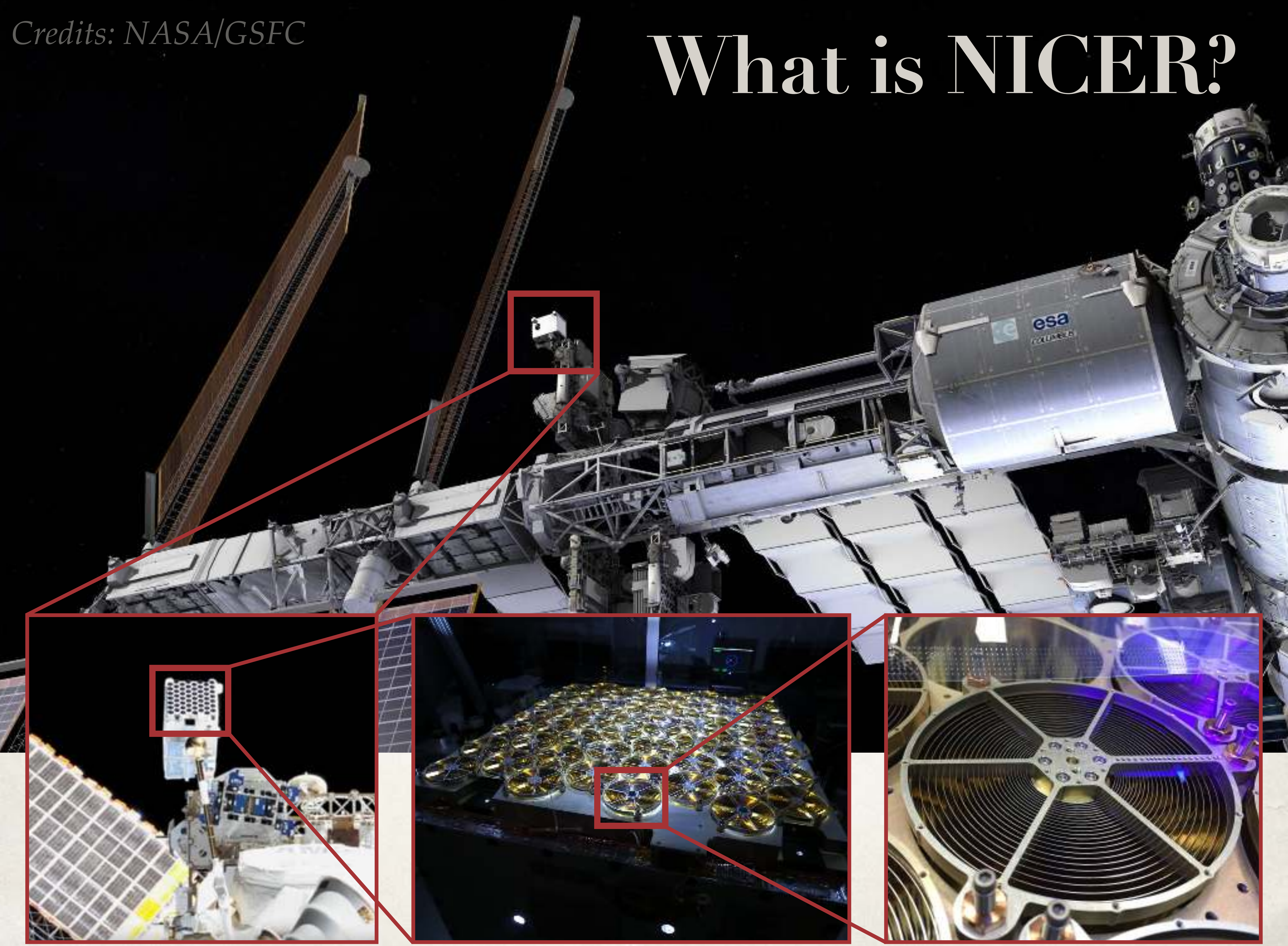
Since June 2017, the Neutron Star Interior Composition Explorer observes millisecond pulsars to measure their M_{NS} and R_{NS}.



Credits: NASA/NICER



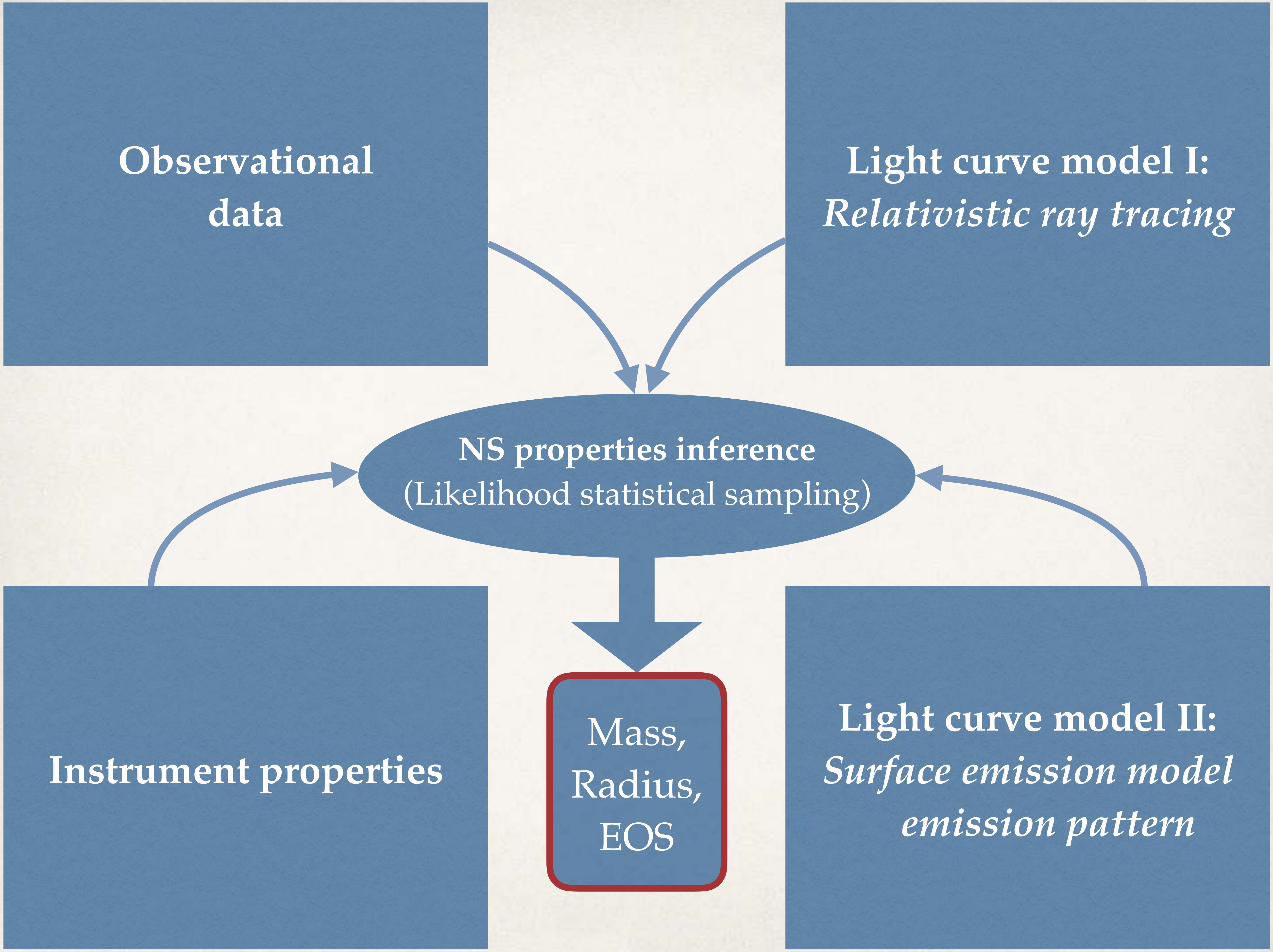
What is NICER?



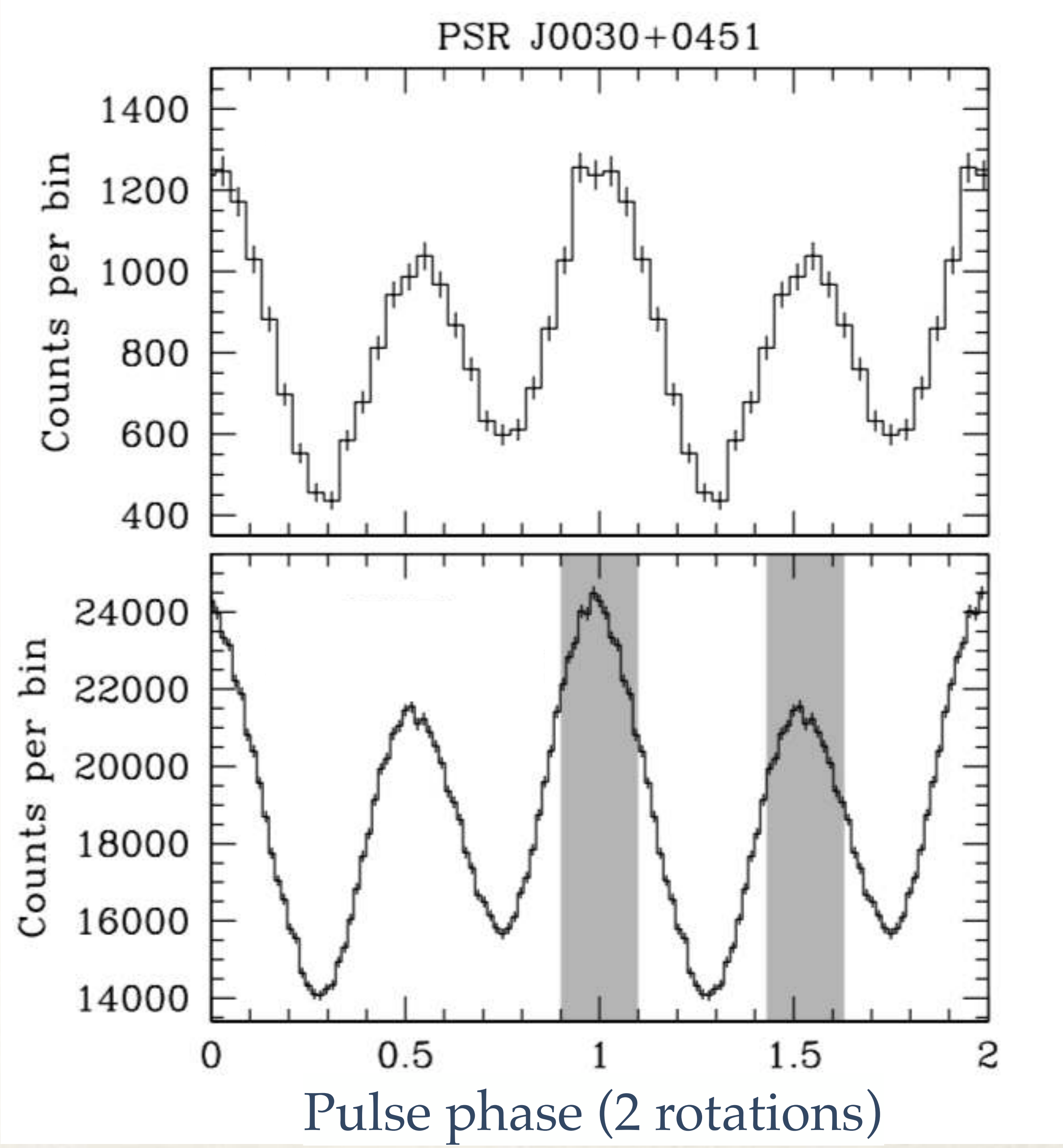
Credits: NASA/GSFC

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

An example with PSR J0030+0451


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

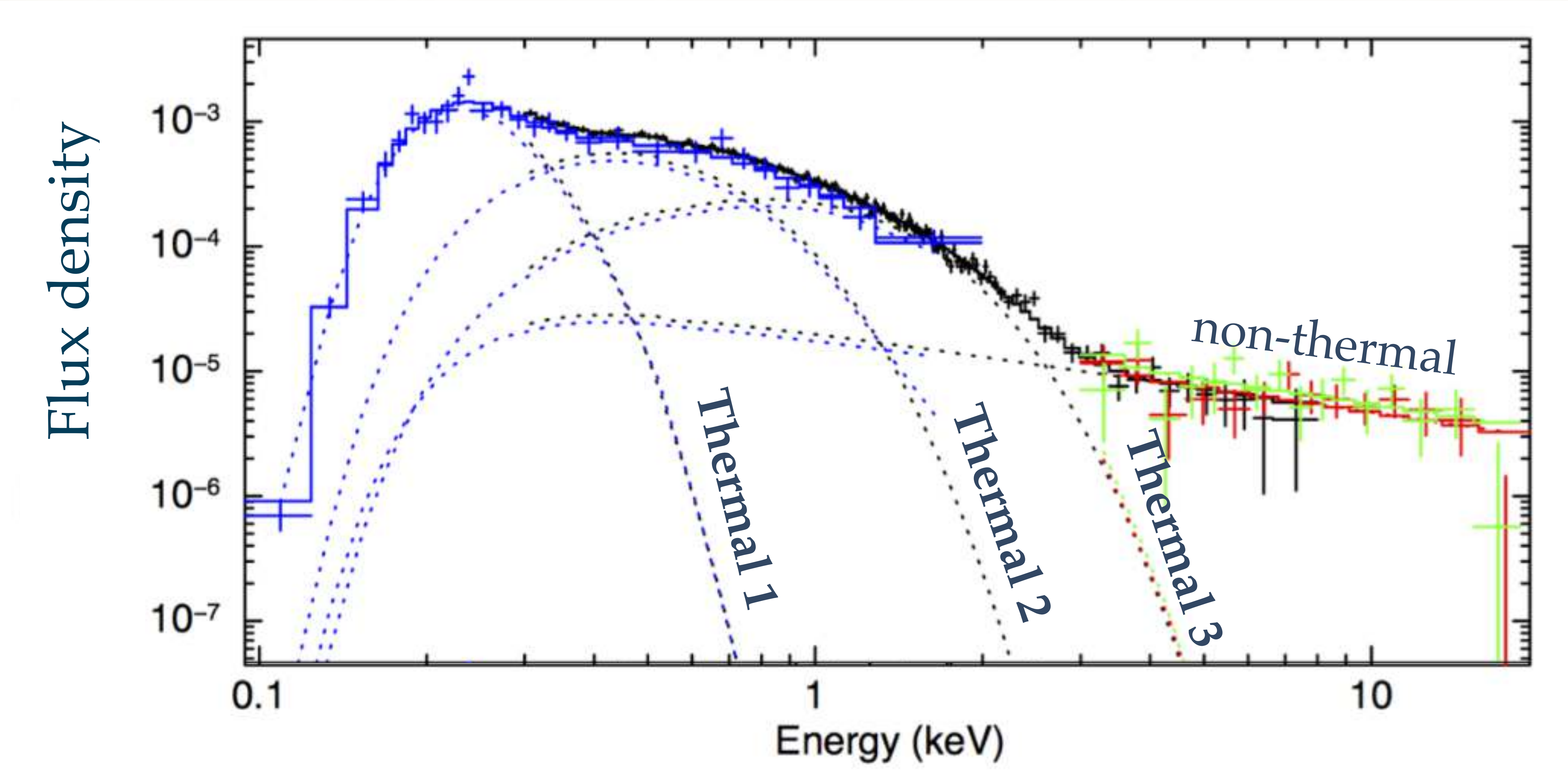
NICER

1.3 Msec of data

Bogdanov, Guillot et al. (2019a)

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

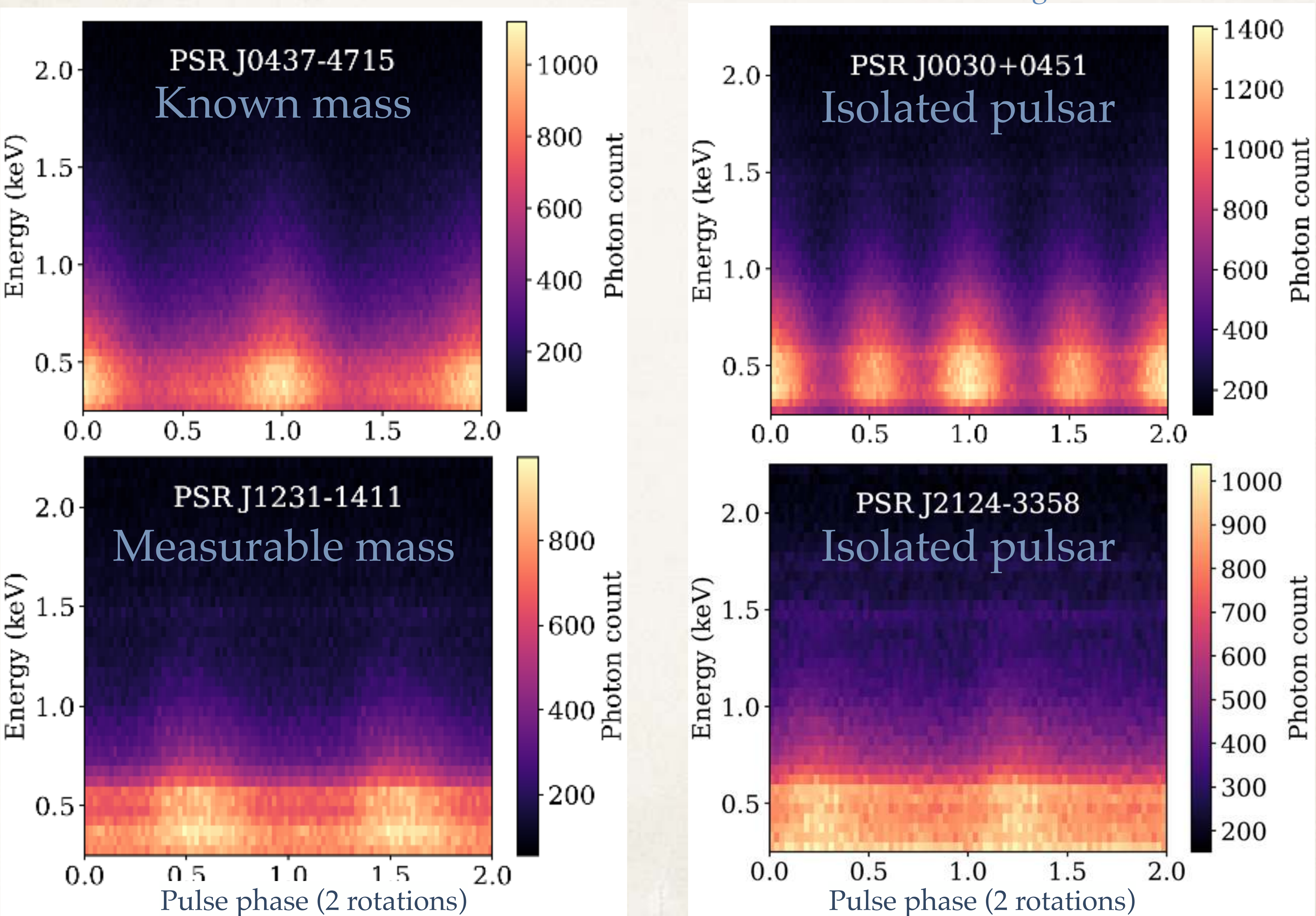
Example X-ray spectrum of a millisecond pulsar



Guillot et al. (2016)

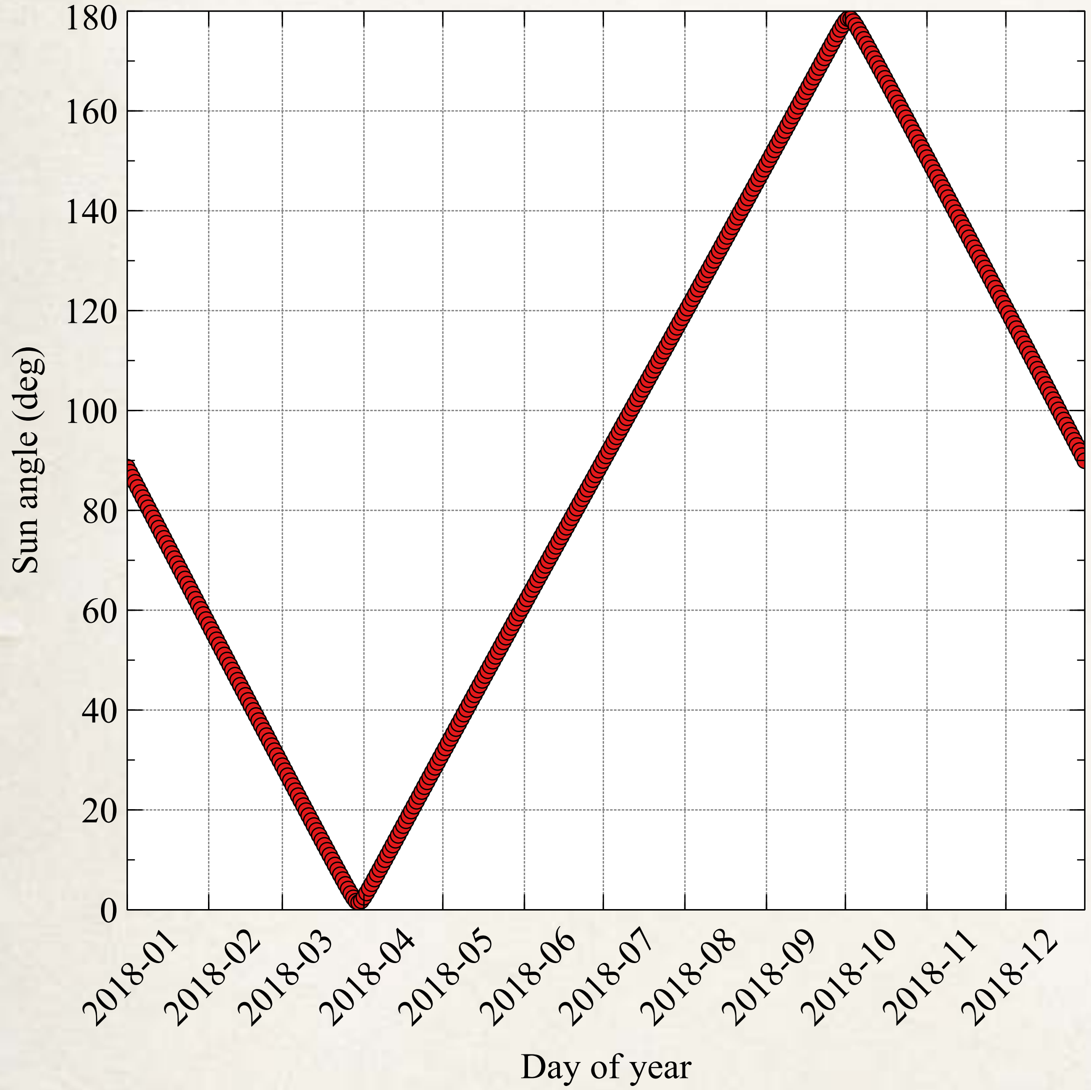
NICER observations of MSPs provide the pulsed information in phase-energy space.

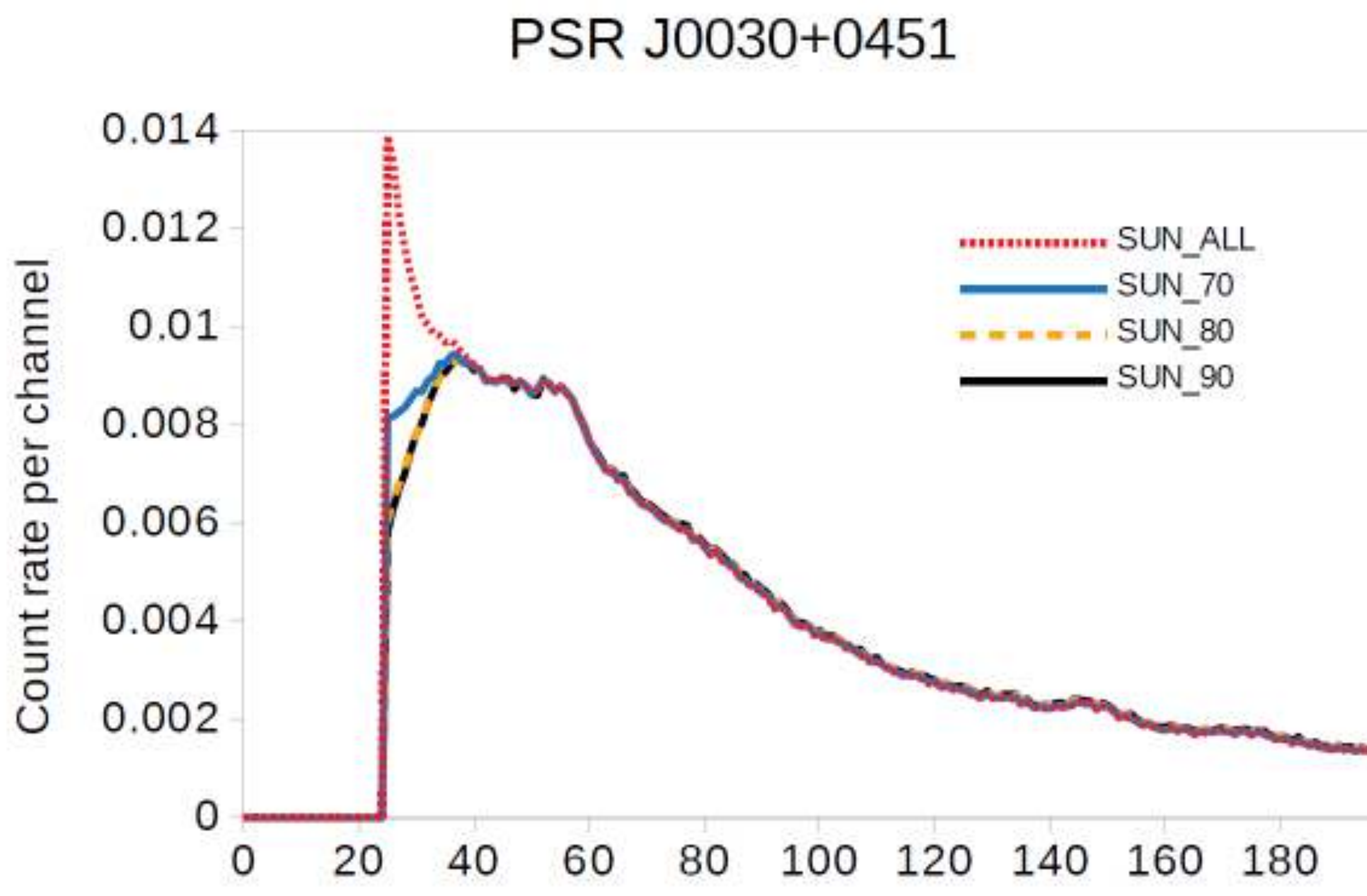
Bogdanov, Guillot et al. (2019a)



We also needed to understand all the components in the data…

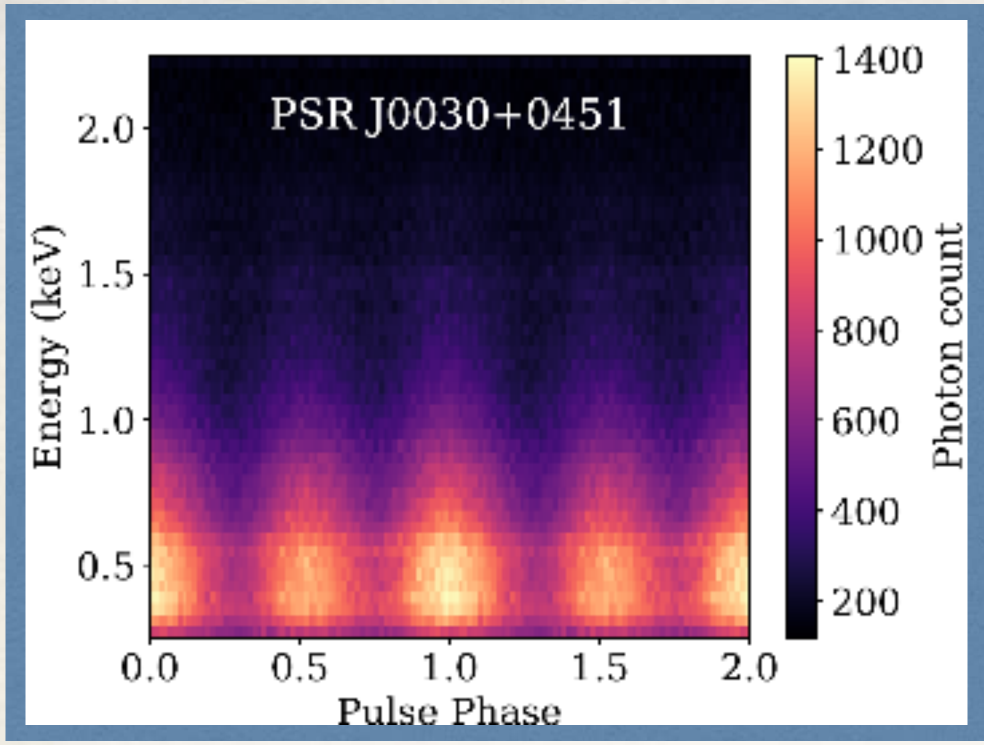
Contamination at soft-energies





NICER Instrument Channel
≈ detected photon energy

Credits: NICER Science Team



Light curve model I:
Relativistic ray tracing

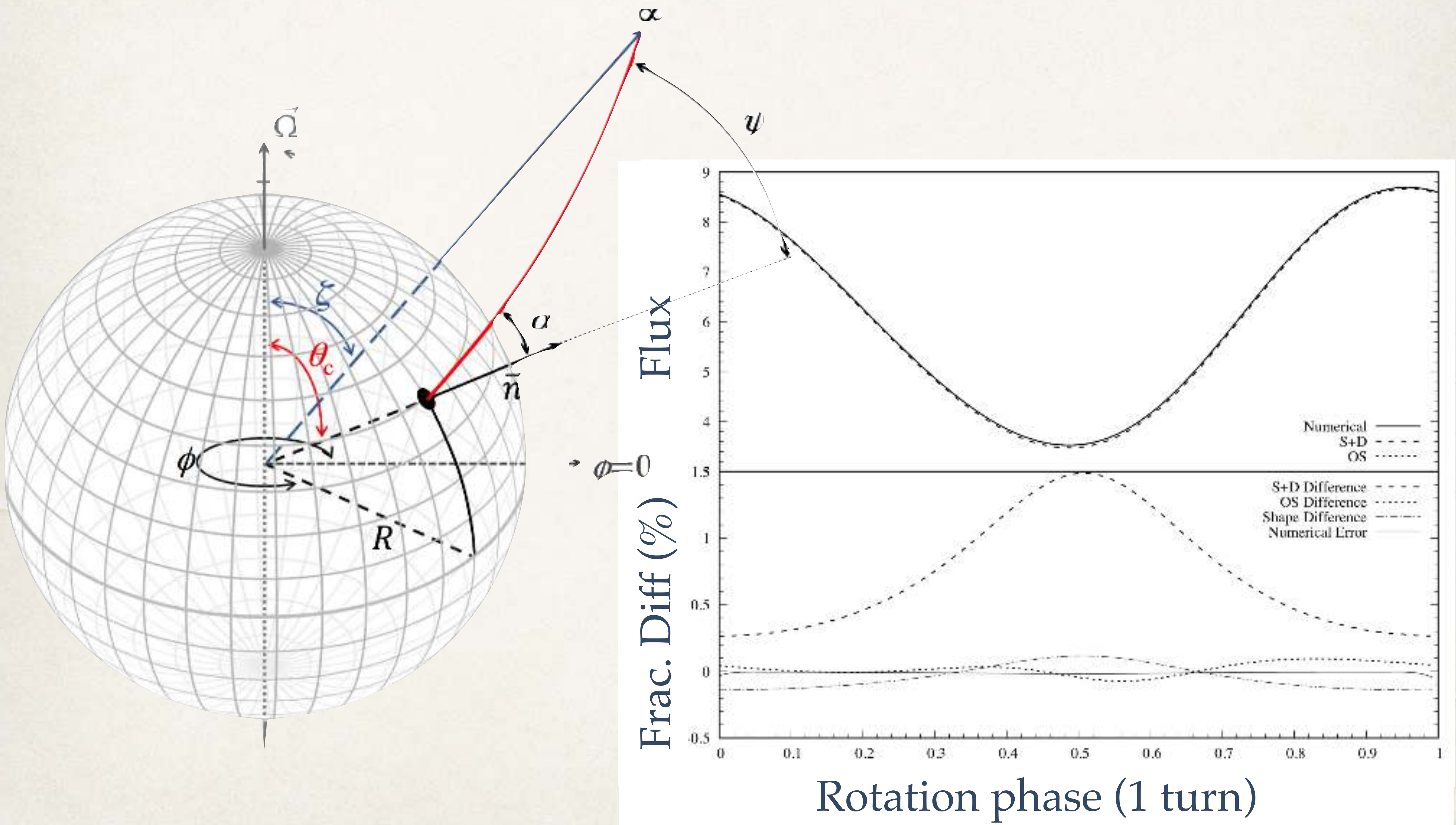
NS properties inference
(Likelihood statistical sampling)

Instrument properties

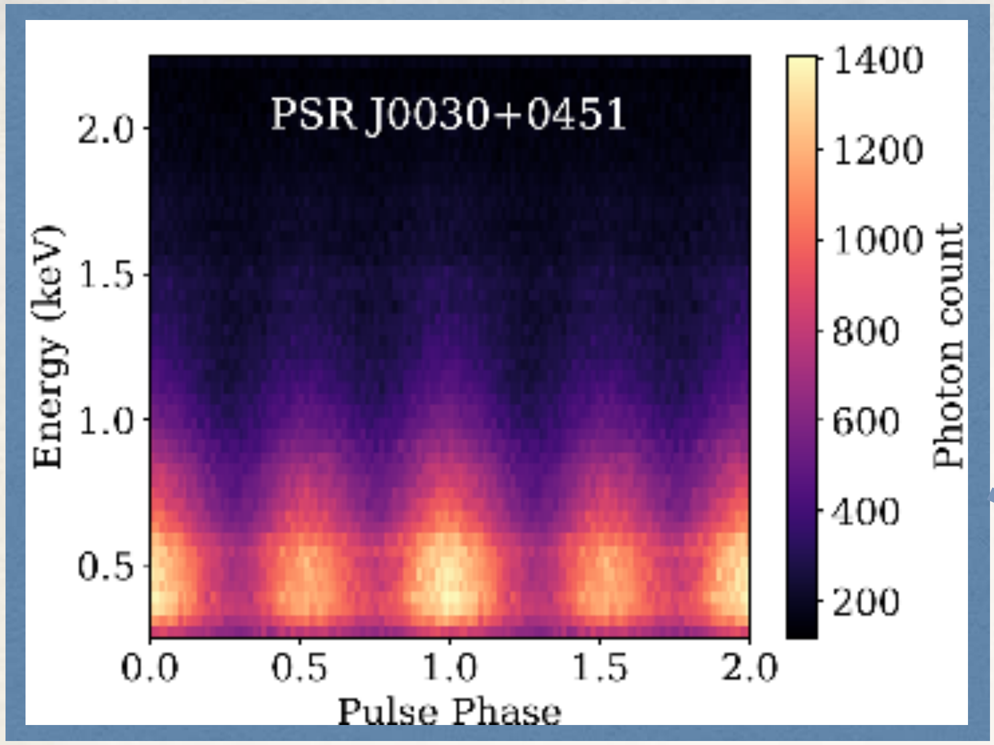
Mass,
Radius,
EOS

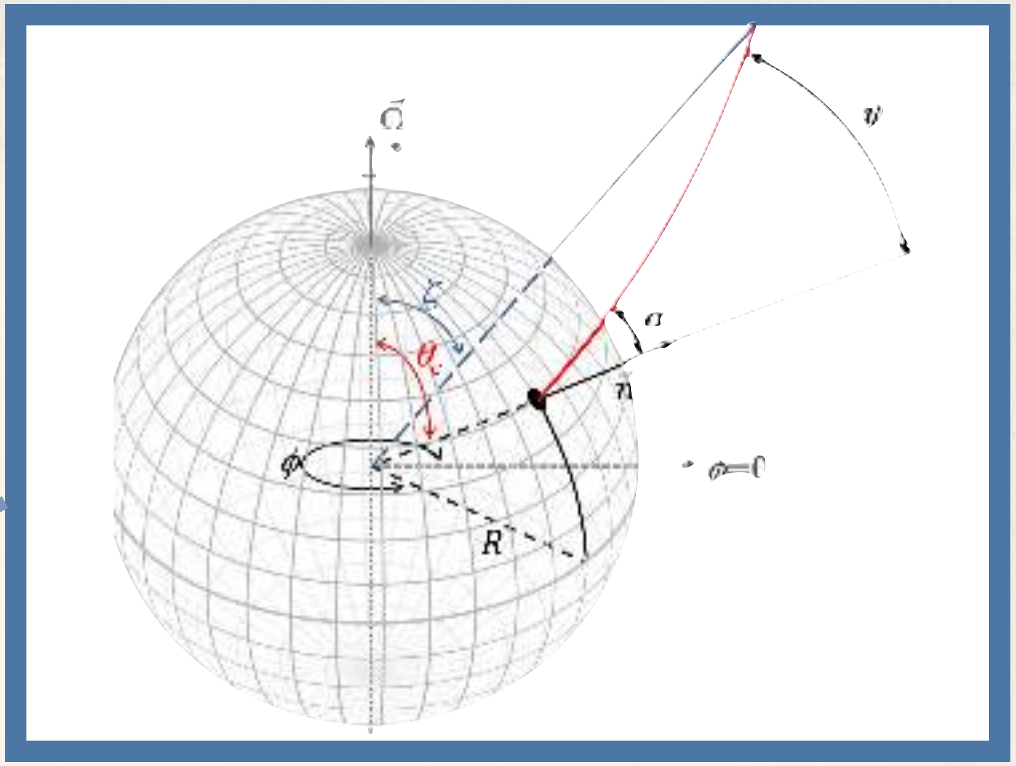
Light curve model II:
Surface emission model
+ emission pattern

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



Bogdanov, …, Guillot et al. (2019b)





NS properties inference
(Likelihood statistical sampling)

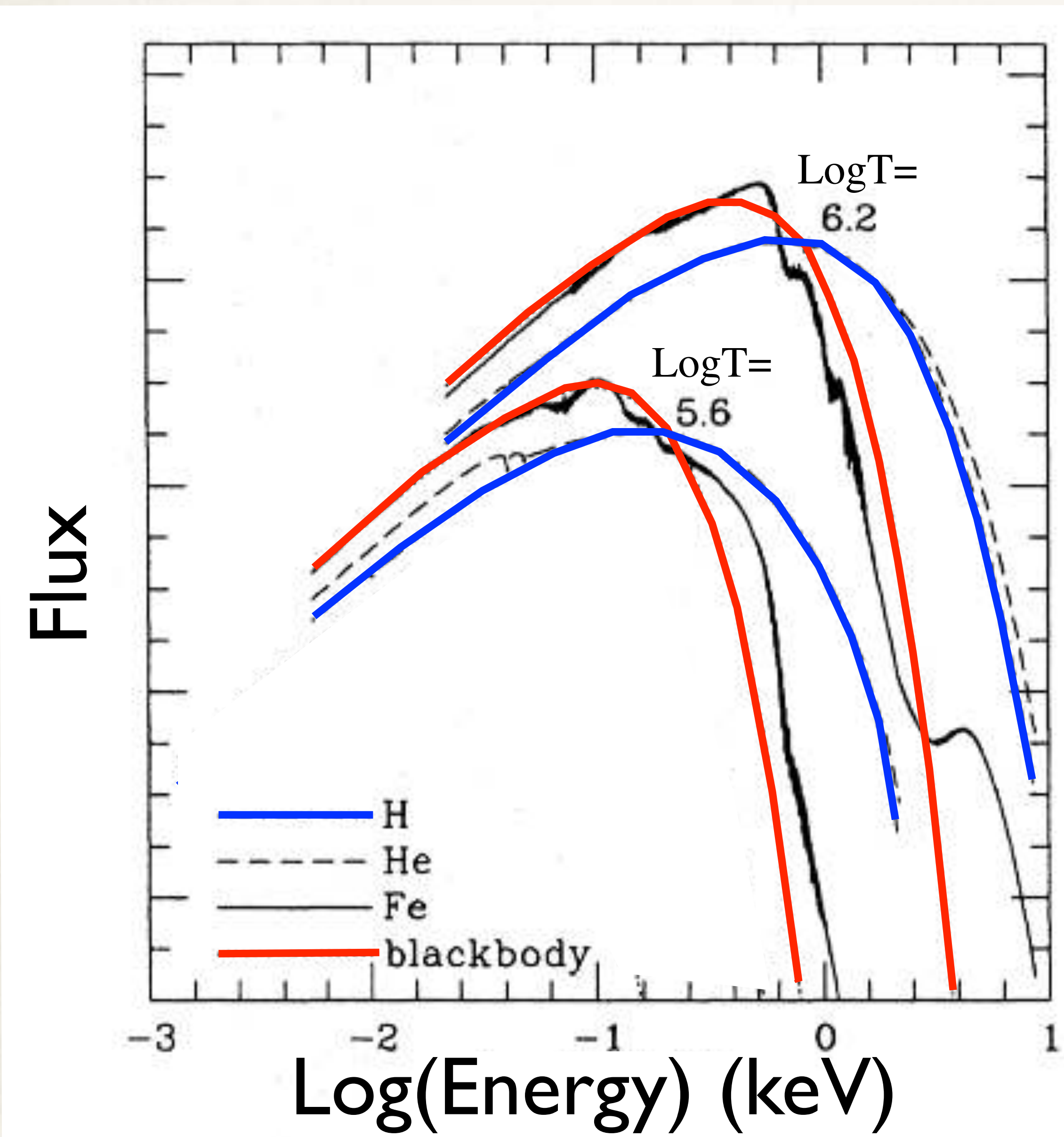
Instrument properties

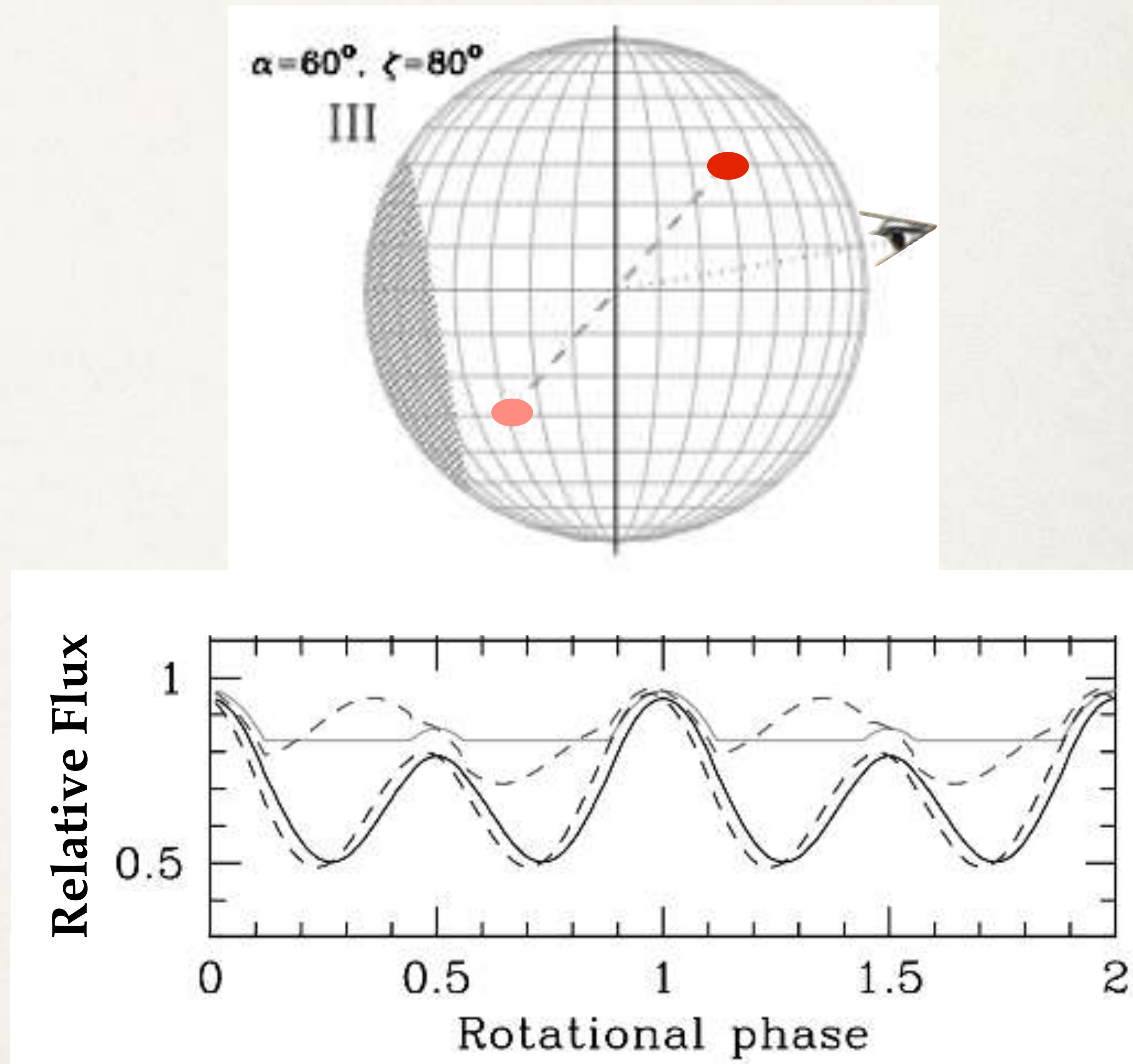
Mass,
Radius,
EOS

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.

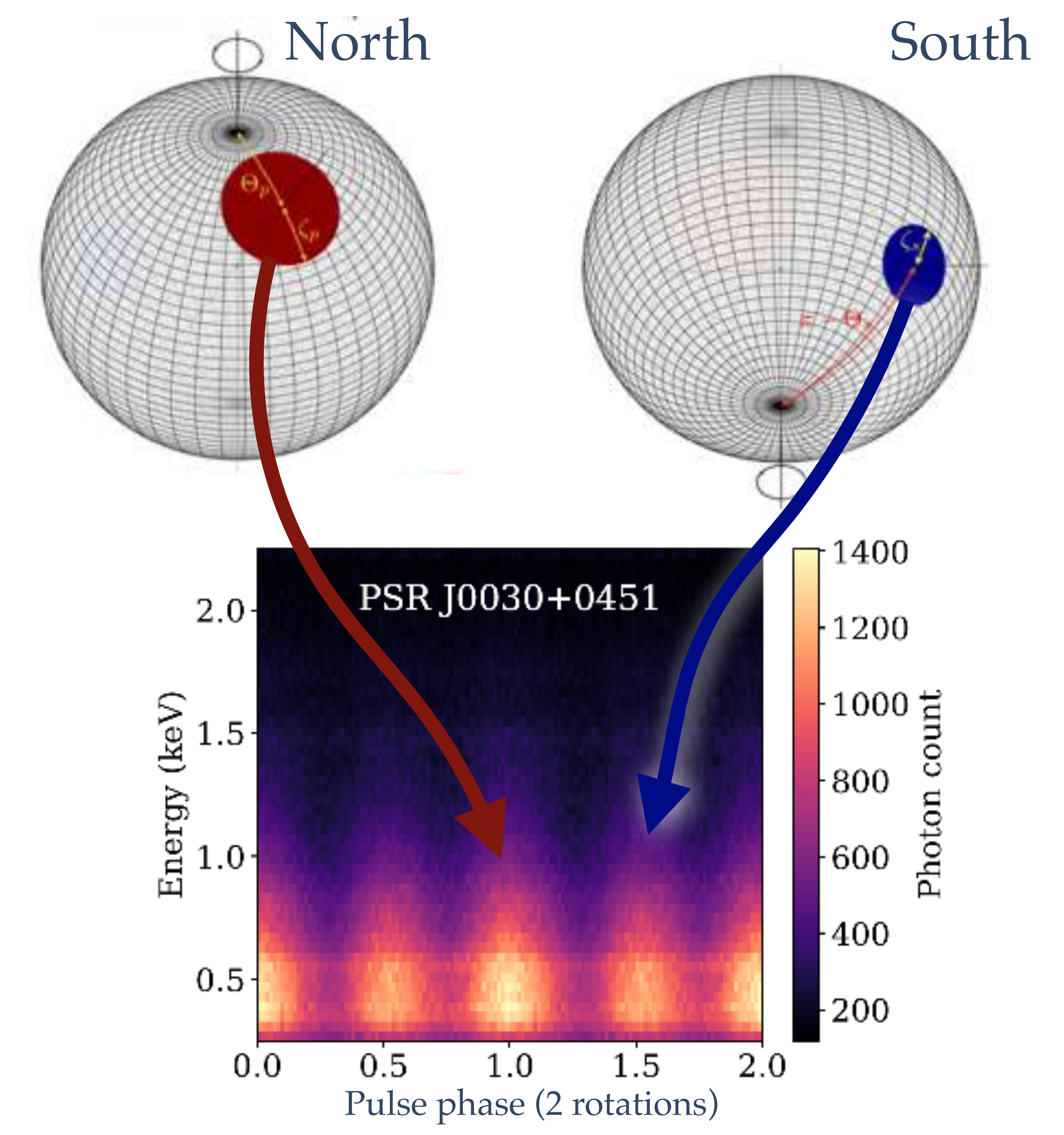
Models by Zavlin et al. (1996),
Heinke et al. (2006),
Haakonsen et al. (2012)





Bogdanov et al. (2007)

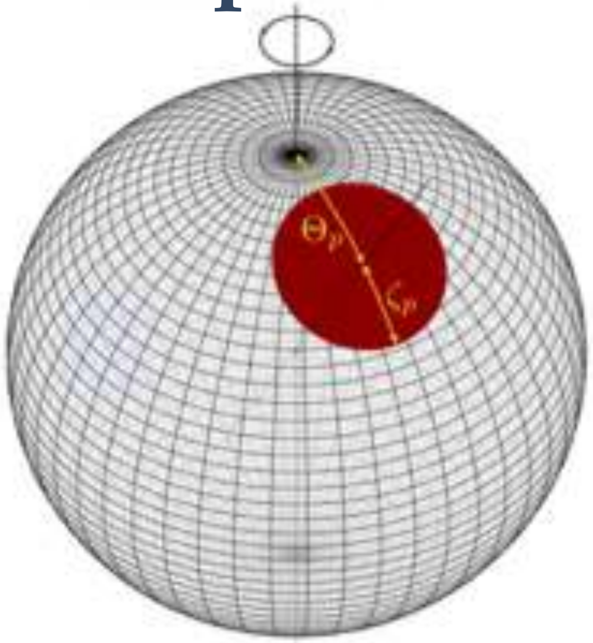
The surface patterns (shape, size, etc.) of the hot spots must also be modelled.



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

Riley, …, SG et al. (2019)

Single Temperature

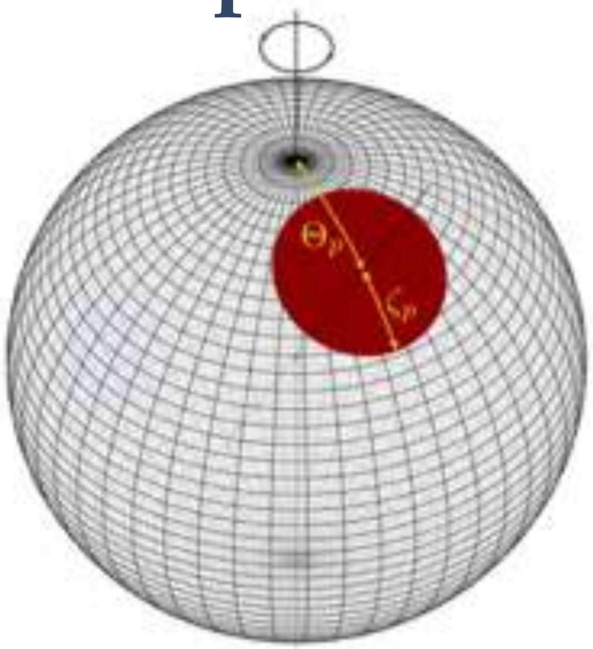


Circular

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

Riley, …, SG et al. (2019)

Single Temperature



Circular

Single Temperature

Concentric

Dual Temperature

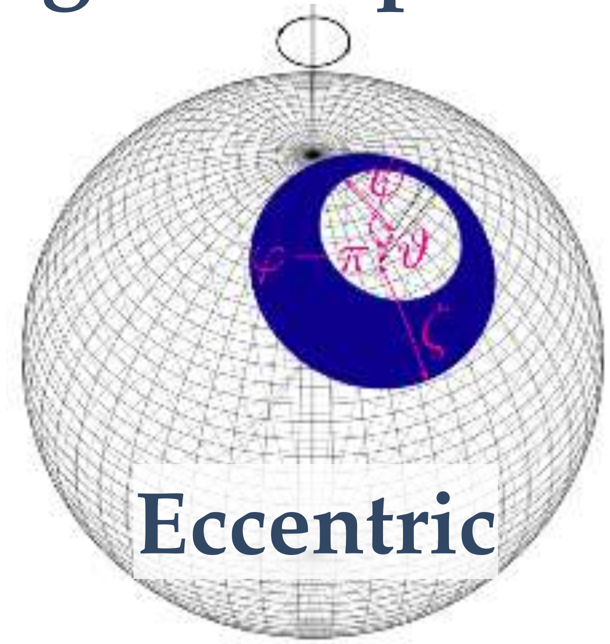
Concentric

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

Riley, …, SG et al. (2019)

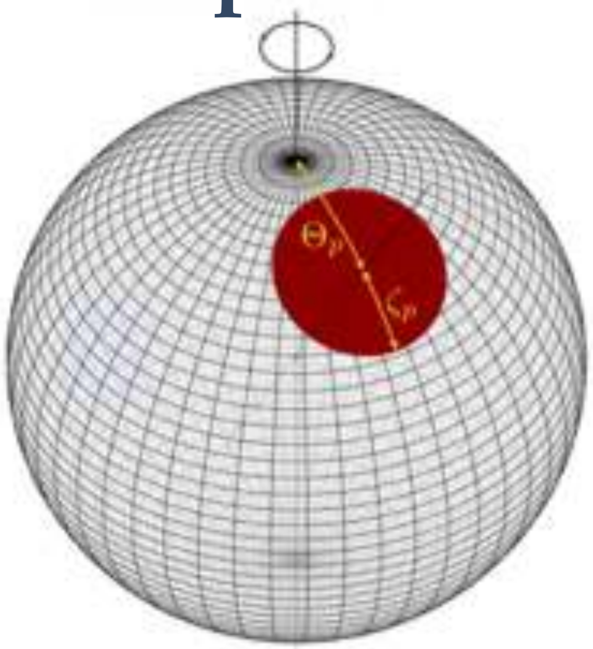
Single Temperature

Concentric



Eccentric

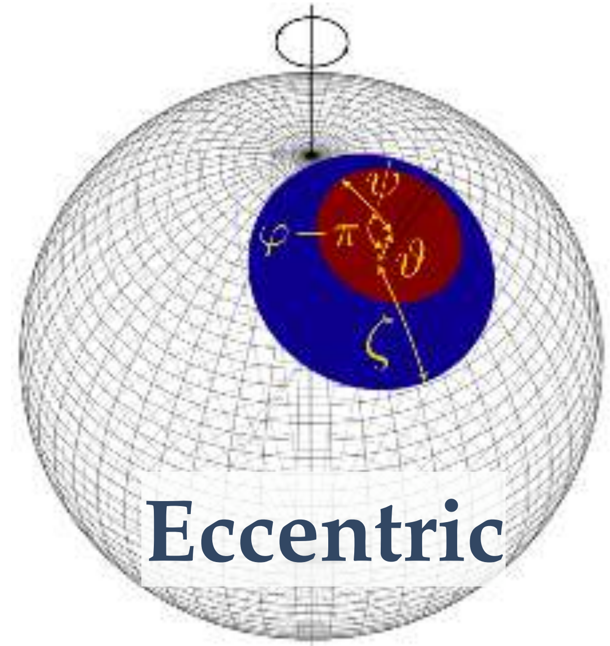
Single Temperature



Circular

Dual Temperature

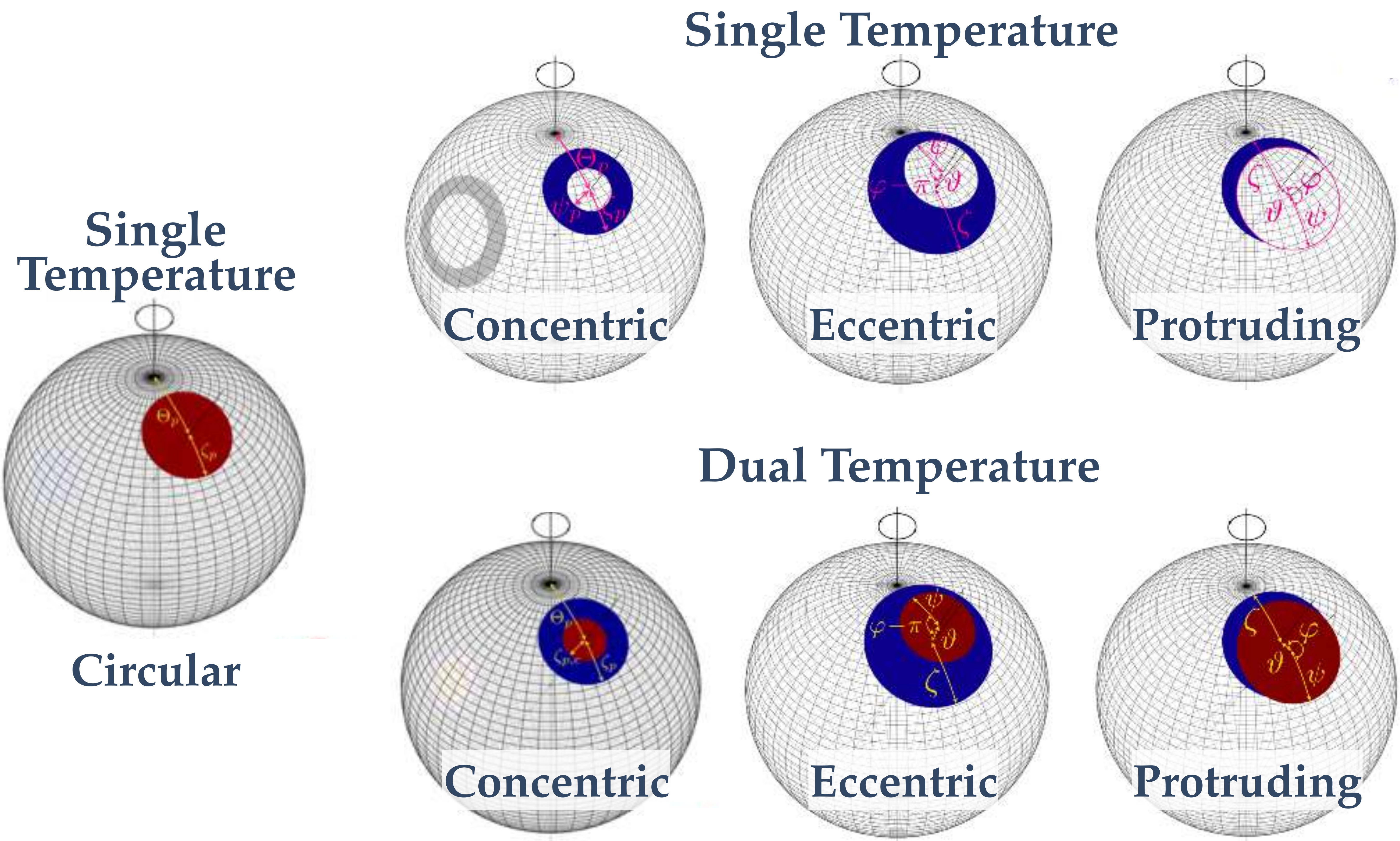
Concentric



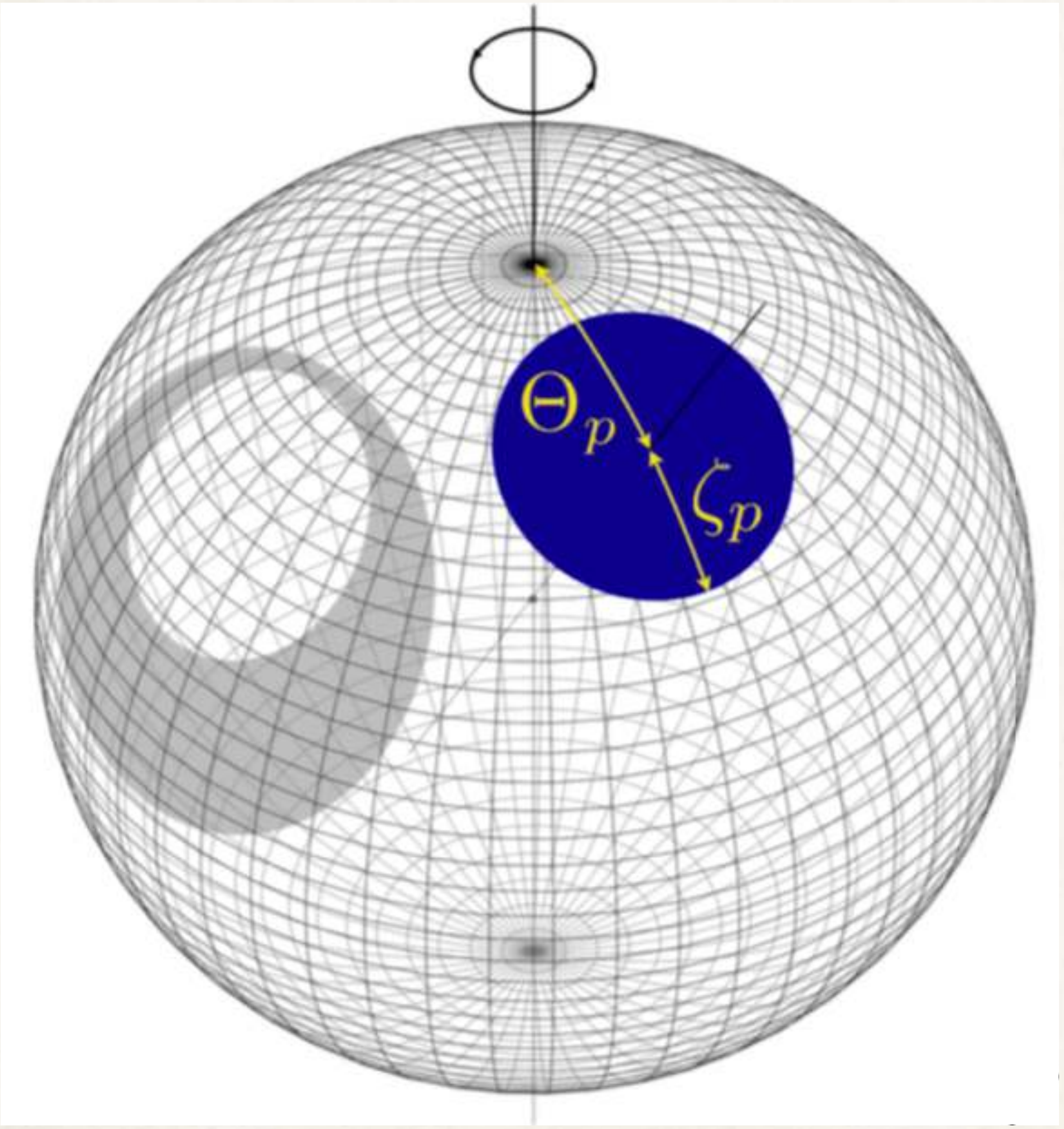
Eccentric

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

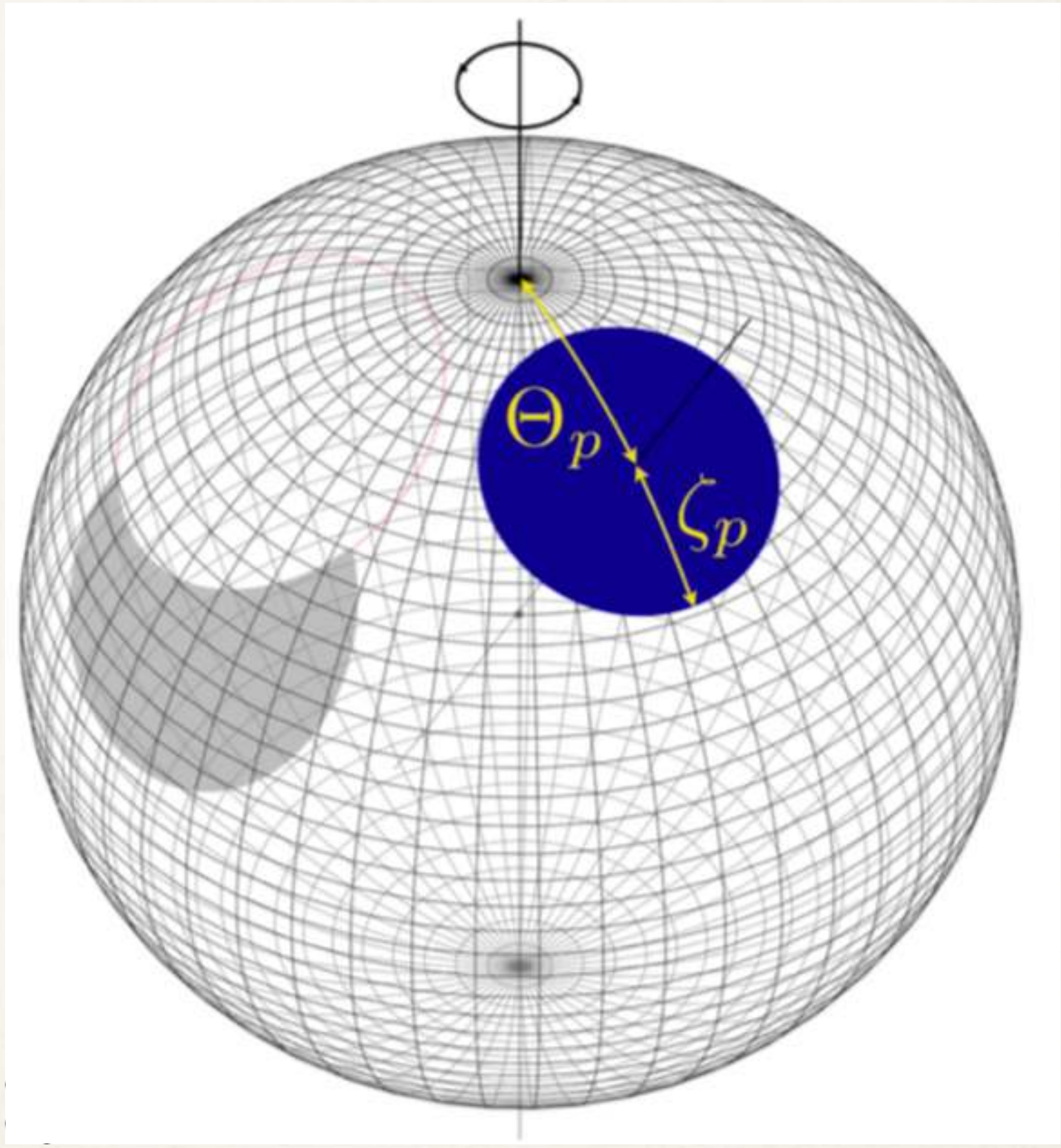
Riley, …, SG et al. (2019)



…and we tested combinations of hot spot patterns.

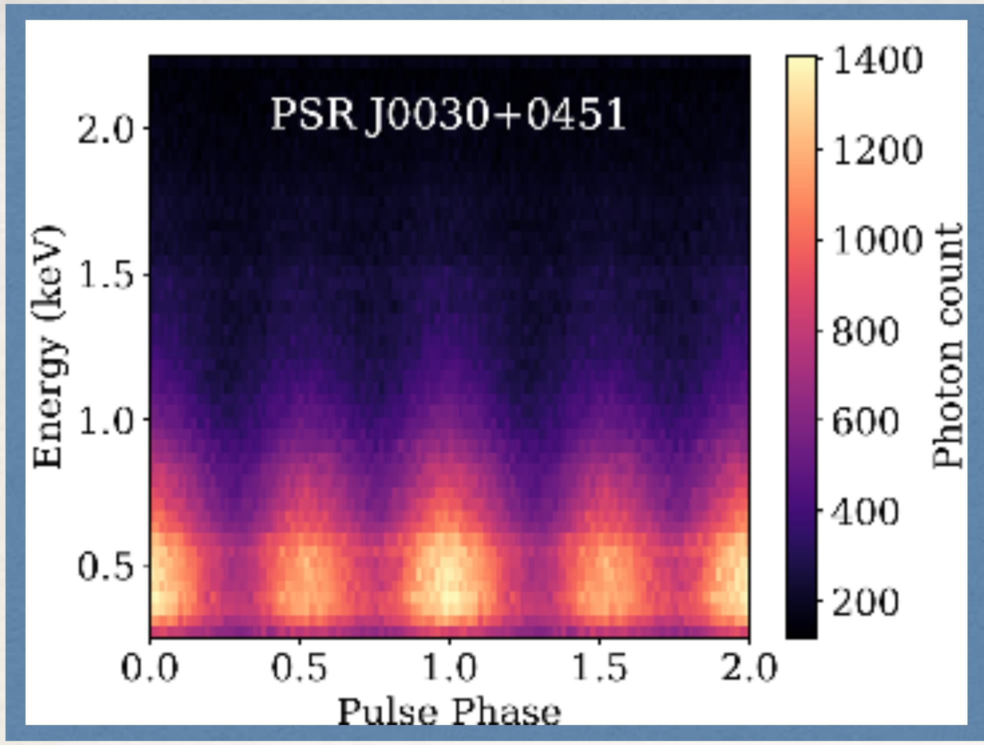


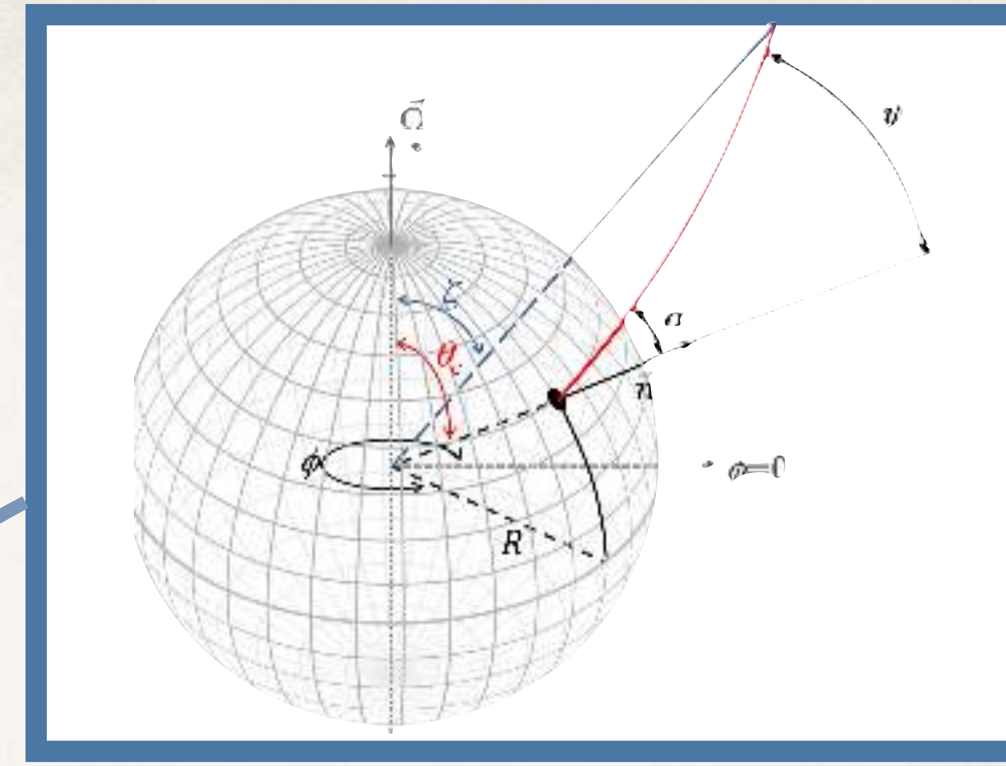
Single Temperature +
Eccentric Single Temperature



Single Temperature +
Protruding Single Temperature

Riley, …, SG et al. (2019)

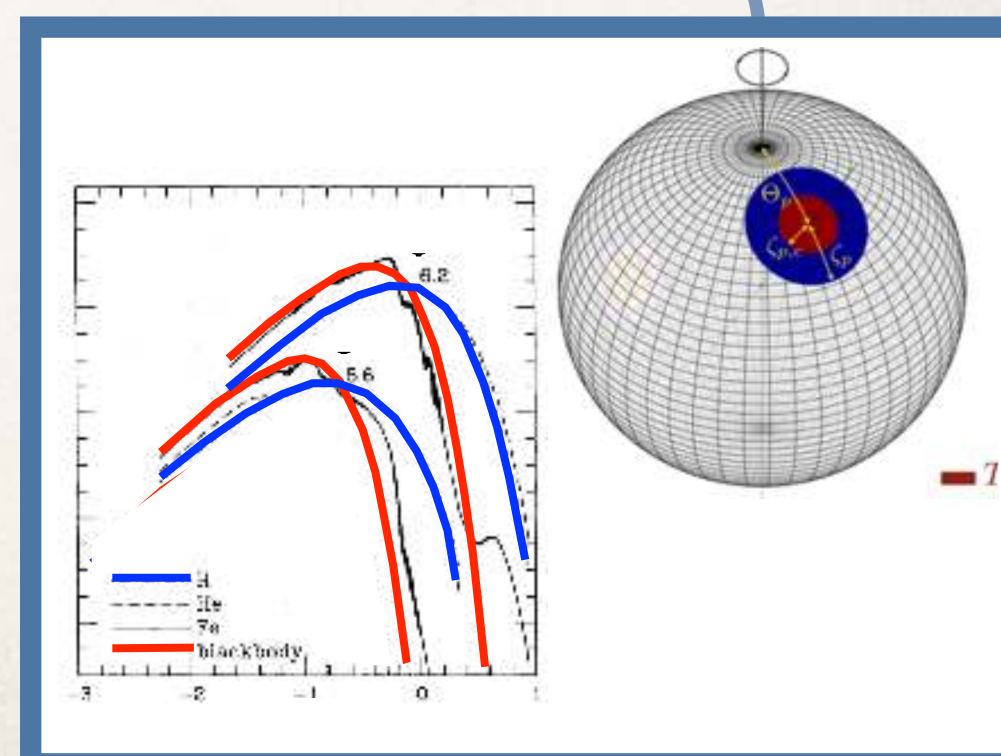




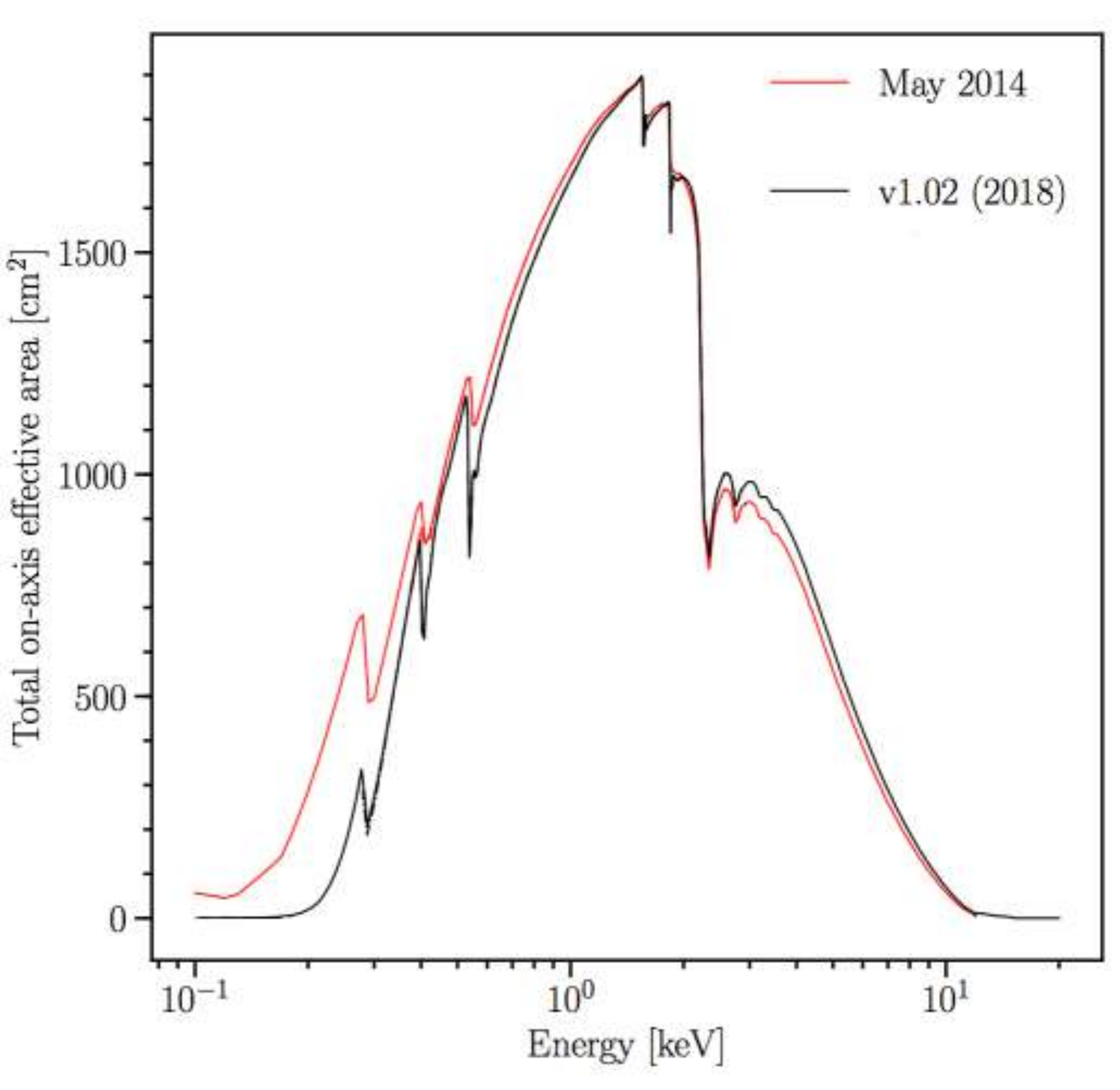
NS properties inference
(Likelihood statistical sampling)

Instrument properties

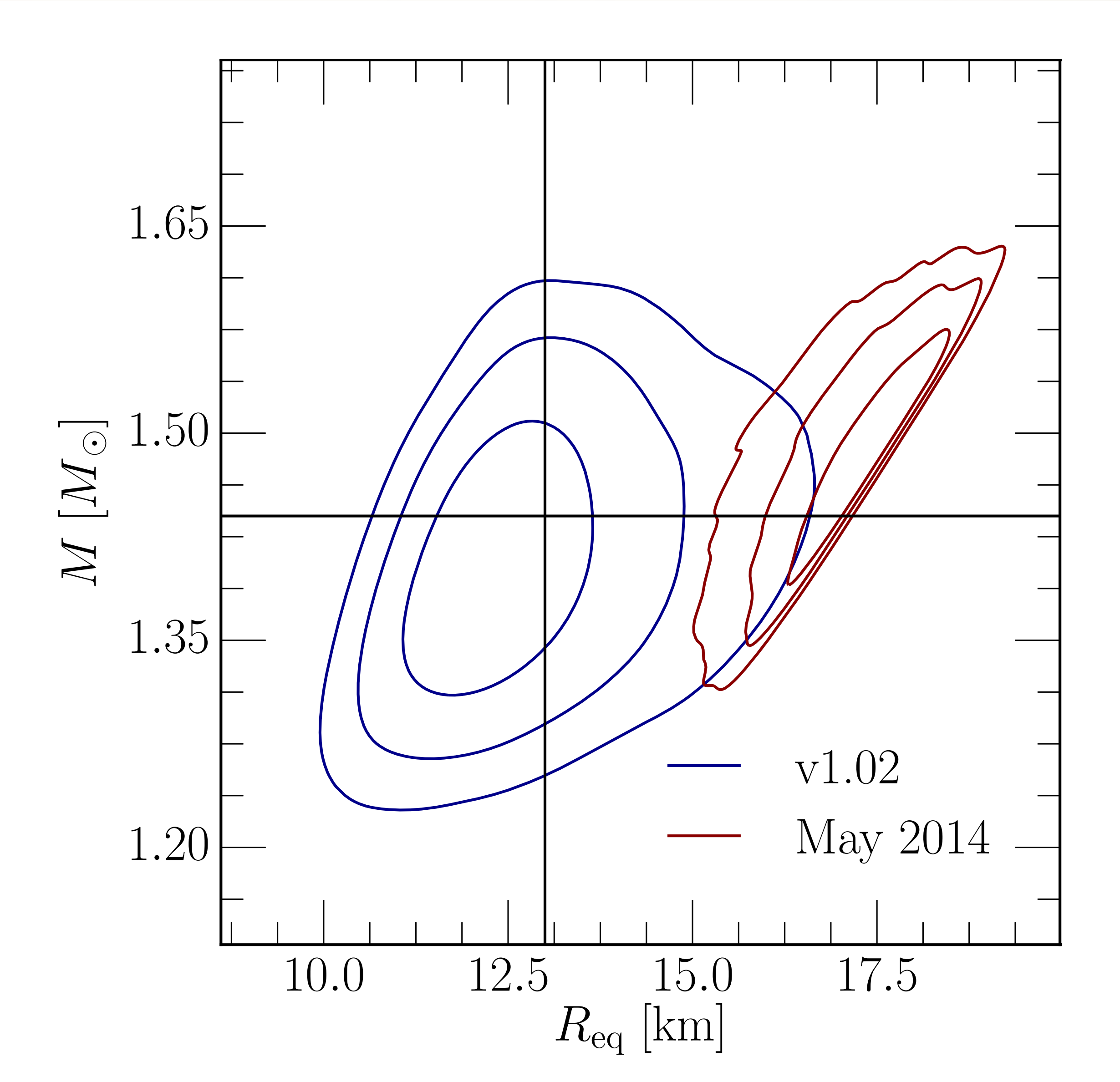
Mass,
Radius,
EOS



The instrument properties also play a crucial role in the lightcurve modeling.

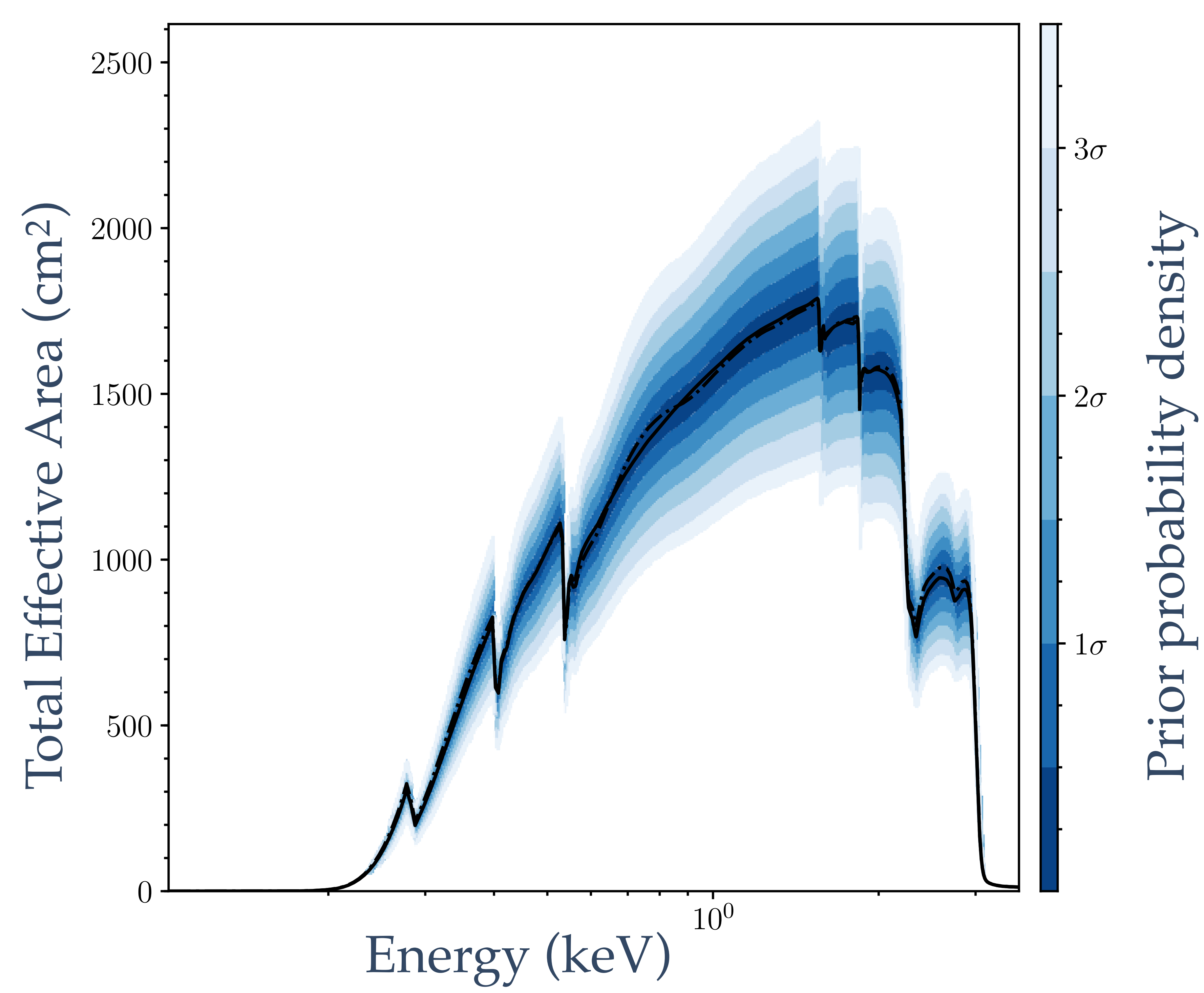


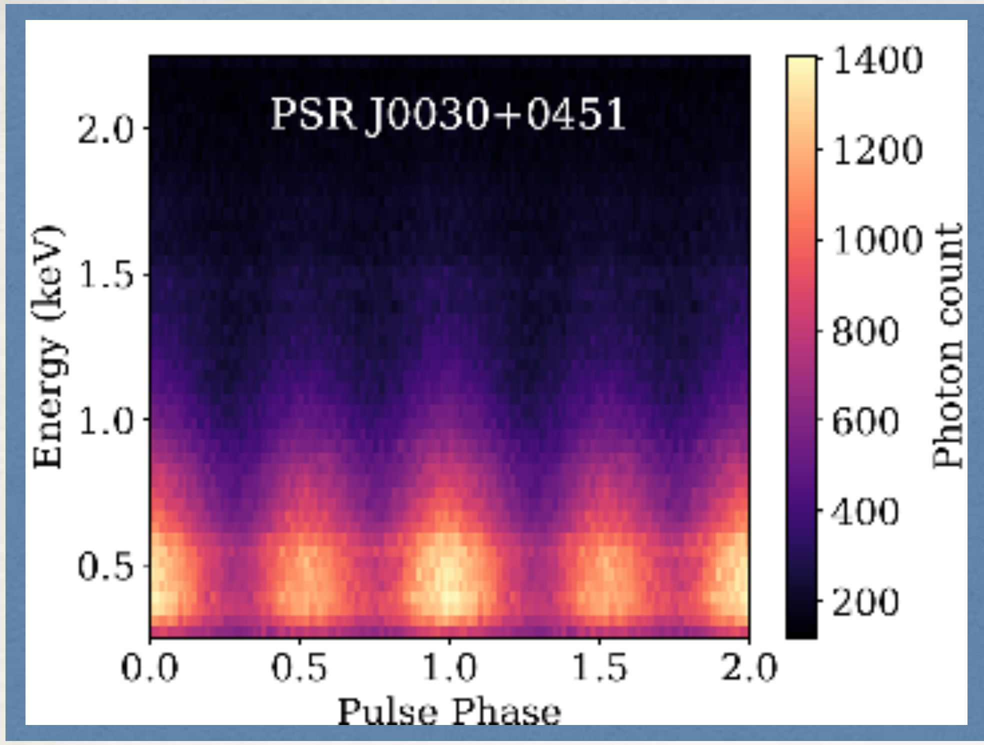
Effects on synthetic data

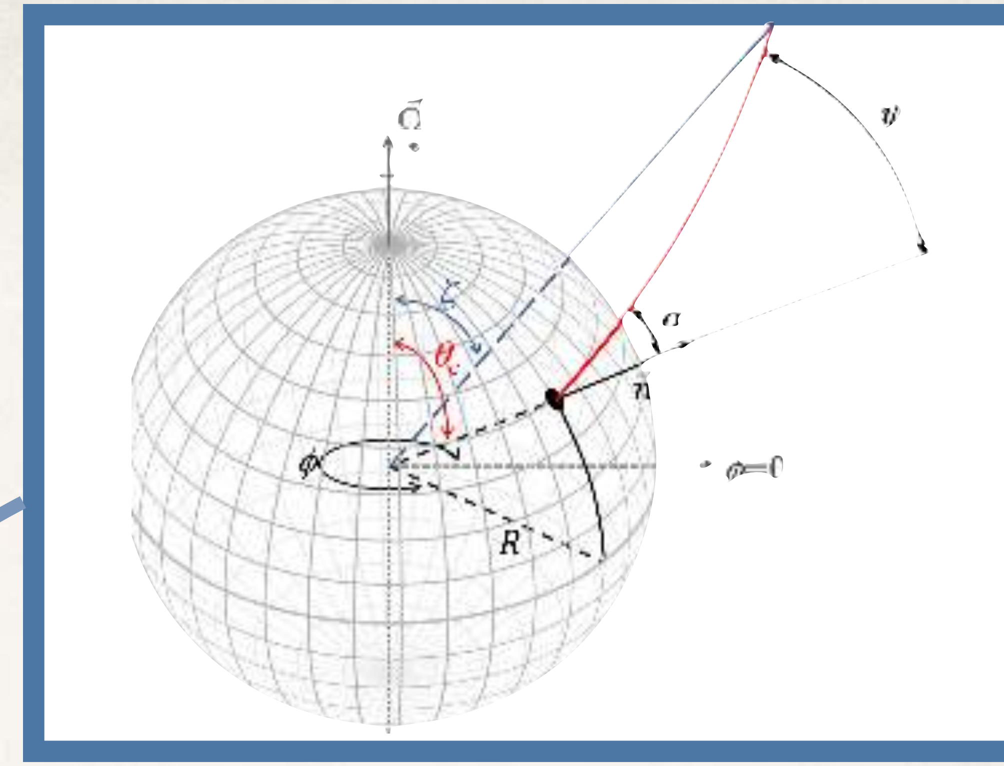


Figures from NICER Science Team

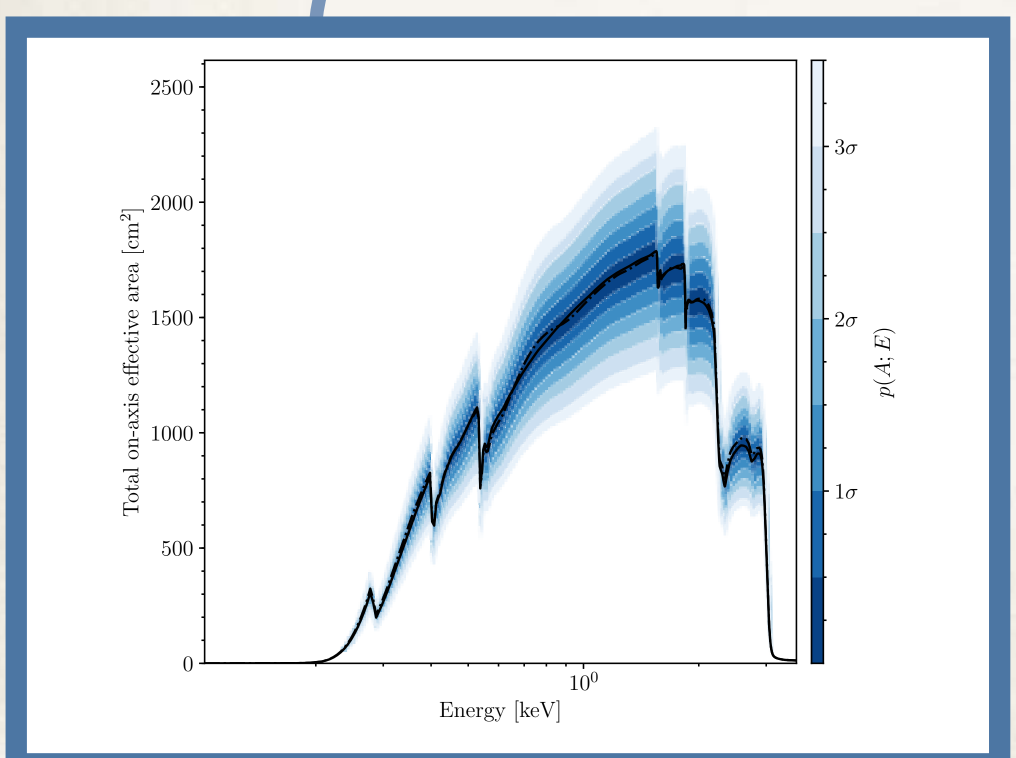
We parametrize the instrument response, and include its uncertainties in the model.



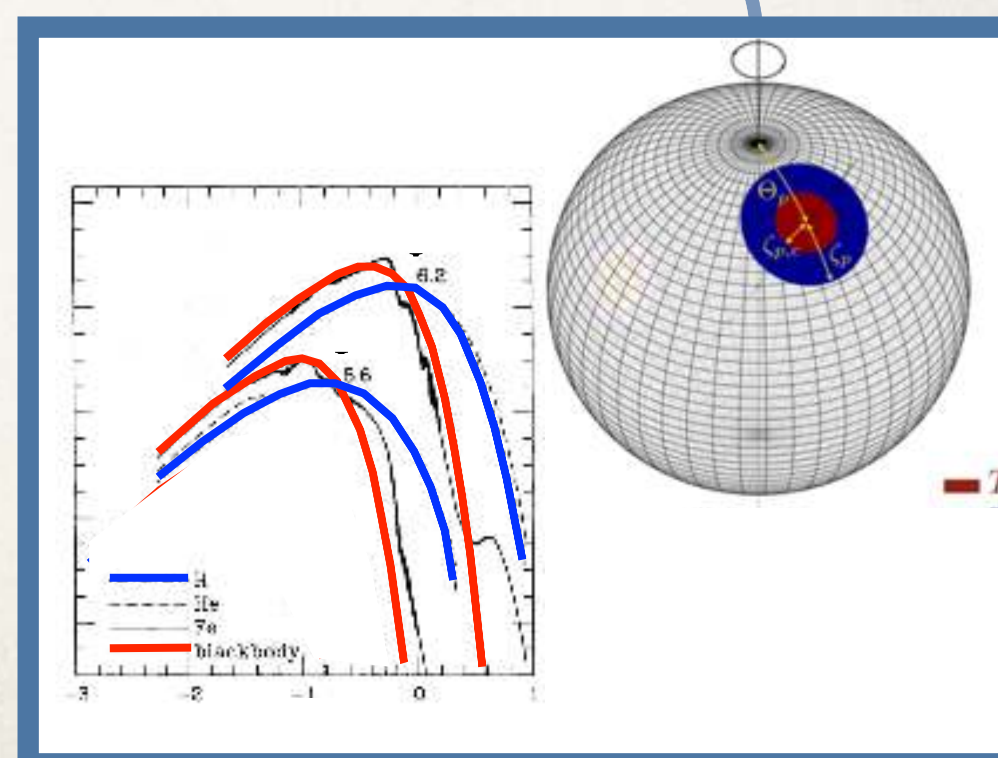




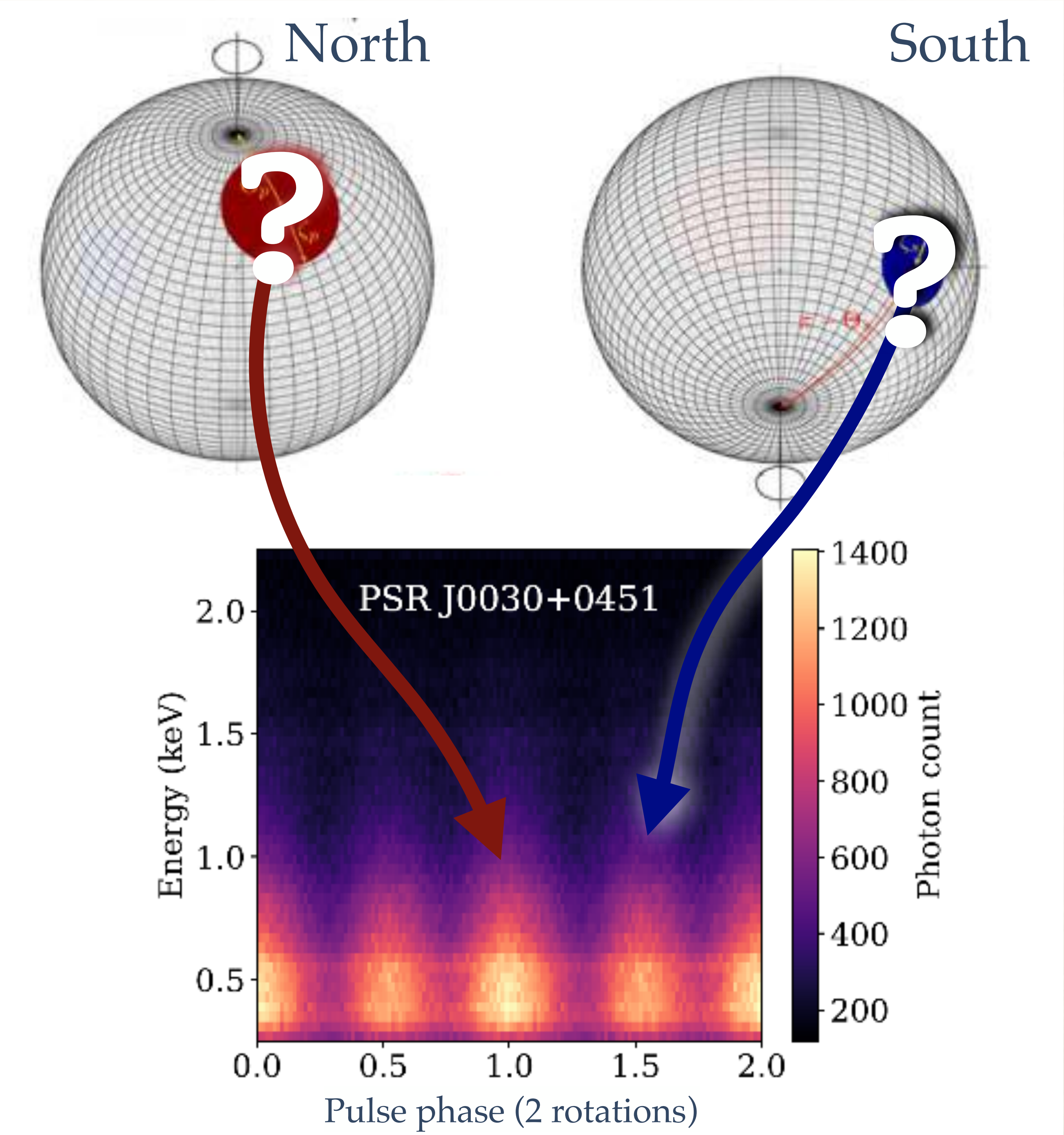
NS properties inference
(Likelihood statistical sampling)



Mass,
Radius,
EOS

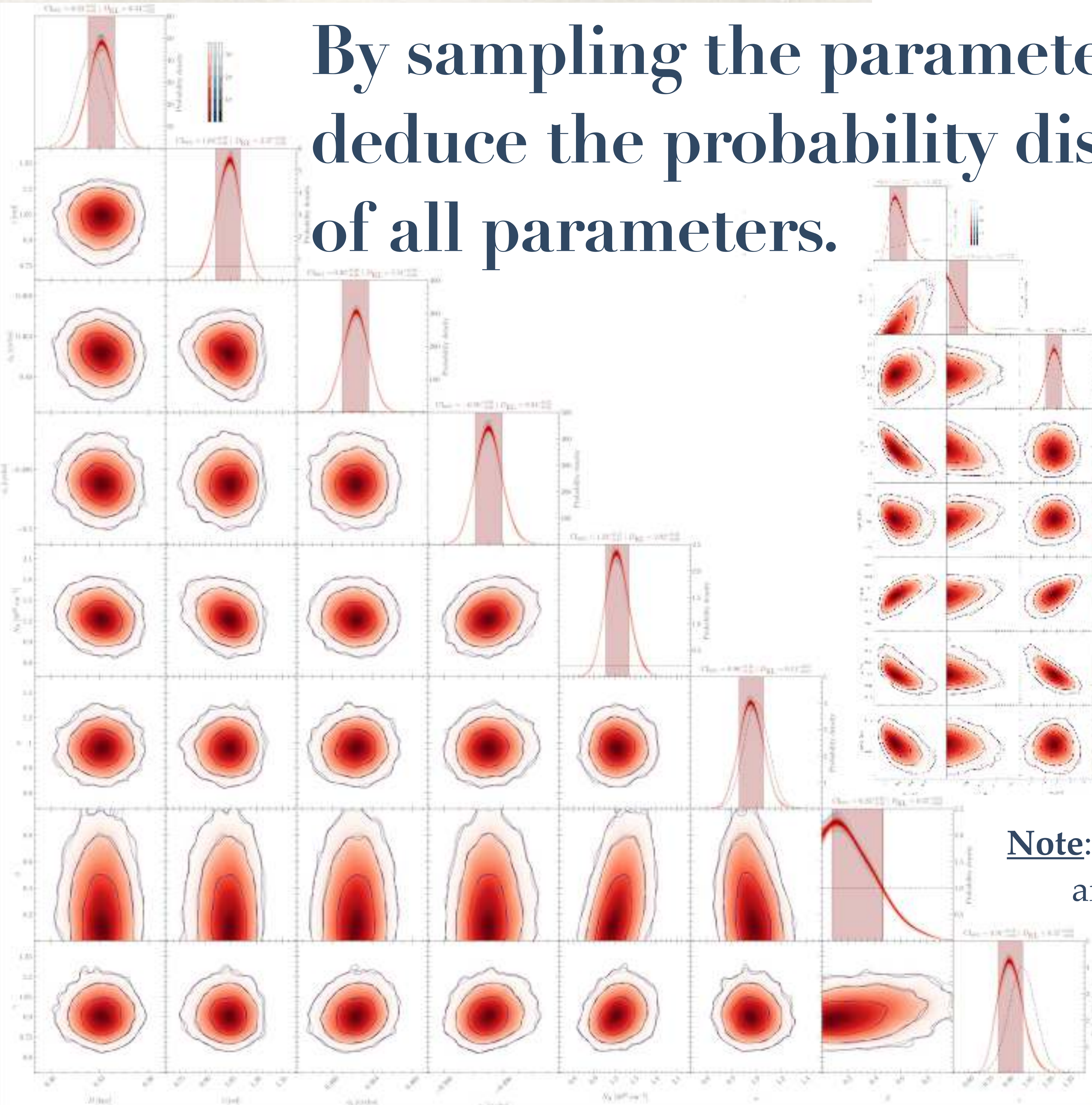


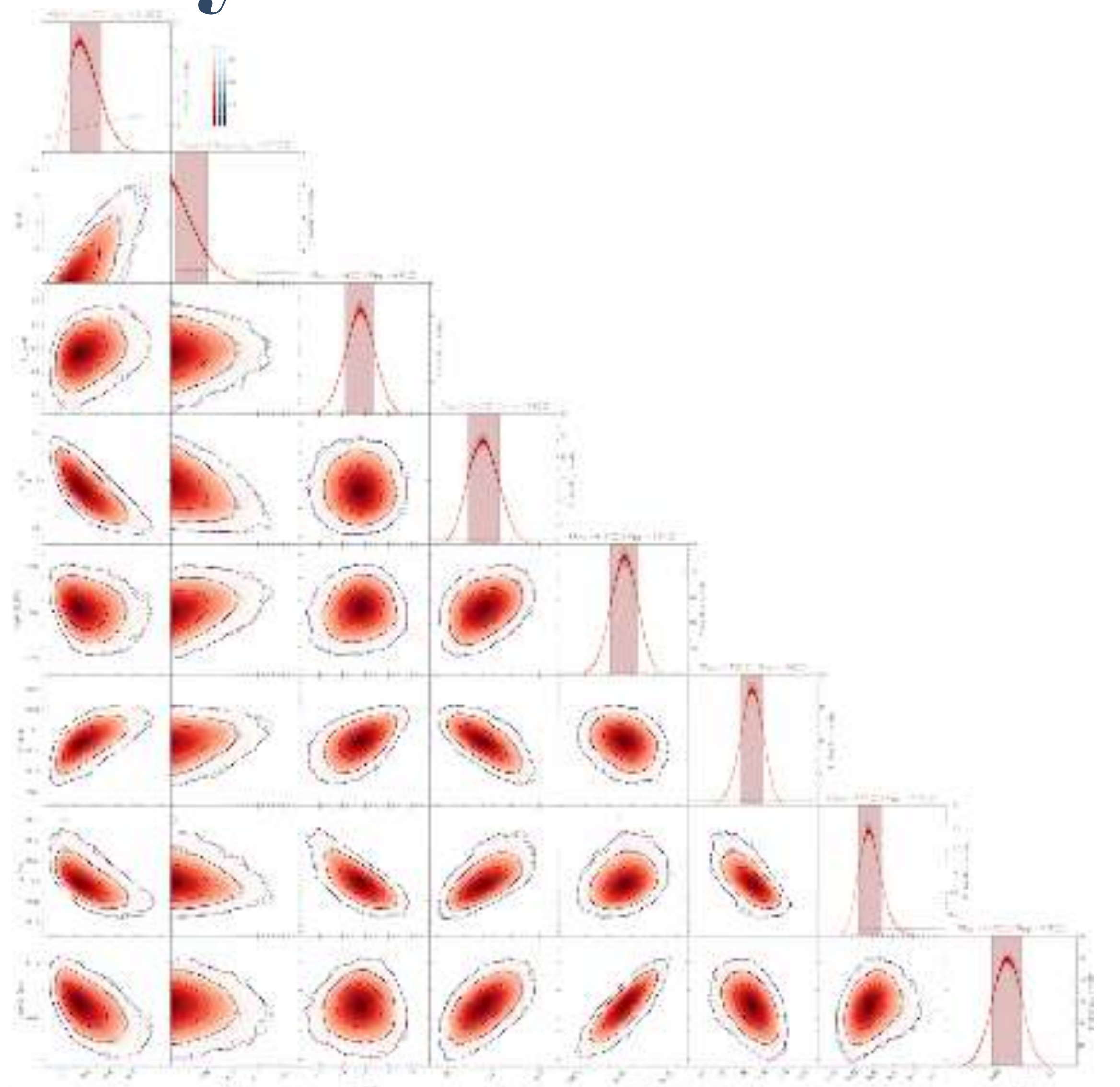
The parameter spaces of the models have between 44 and 52 dimensions that we explore with a Bayesian sampler.



Results from the analysis of NICER data for PSR J0030+0451

By sampling the parameter space, we deduce the probability distributions of all parameters.





<u>Note</u>: all posterior likelihoods are publicly available.

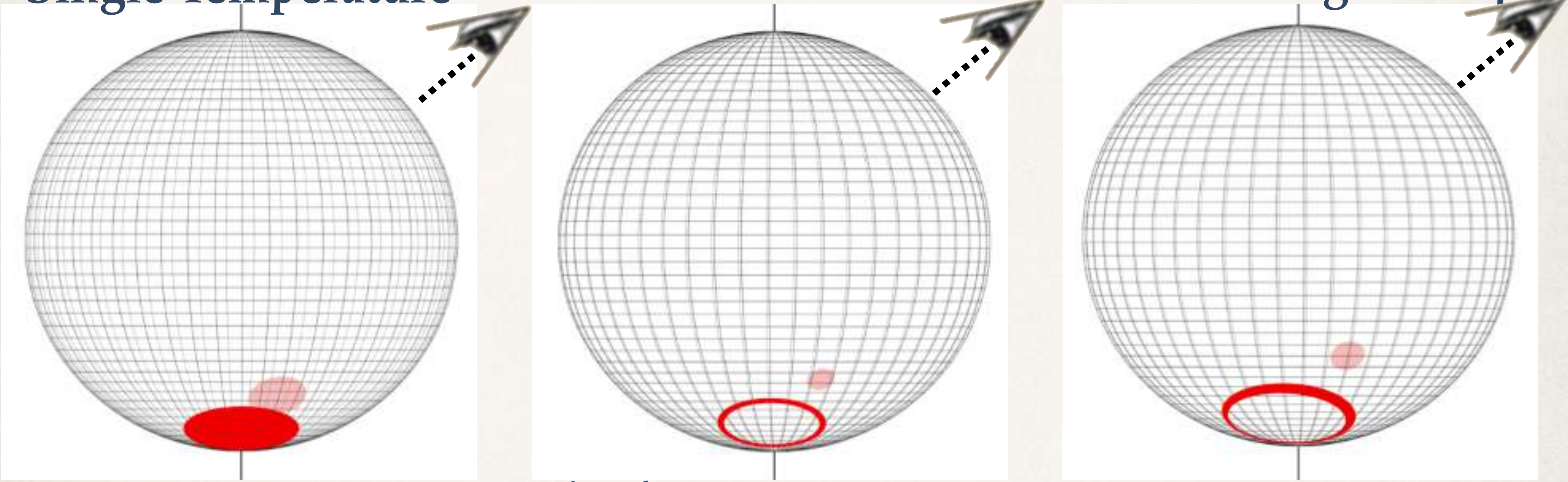
Riley, …, SG et al. (2019)

First surprise: Both hot spots are on the far hemisphere visible from the Earth.

First surprise: Both hot spots are on the far hemisphere visible from the Earth.

Single Temperature +
Single Temperature

Single Temperature +
Eccentric Single Temp.

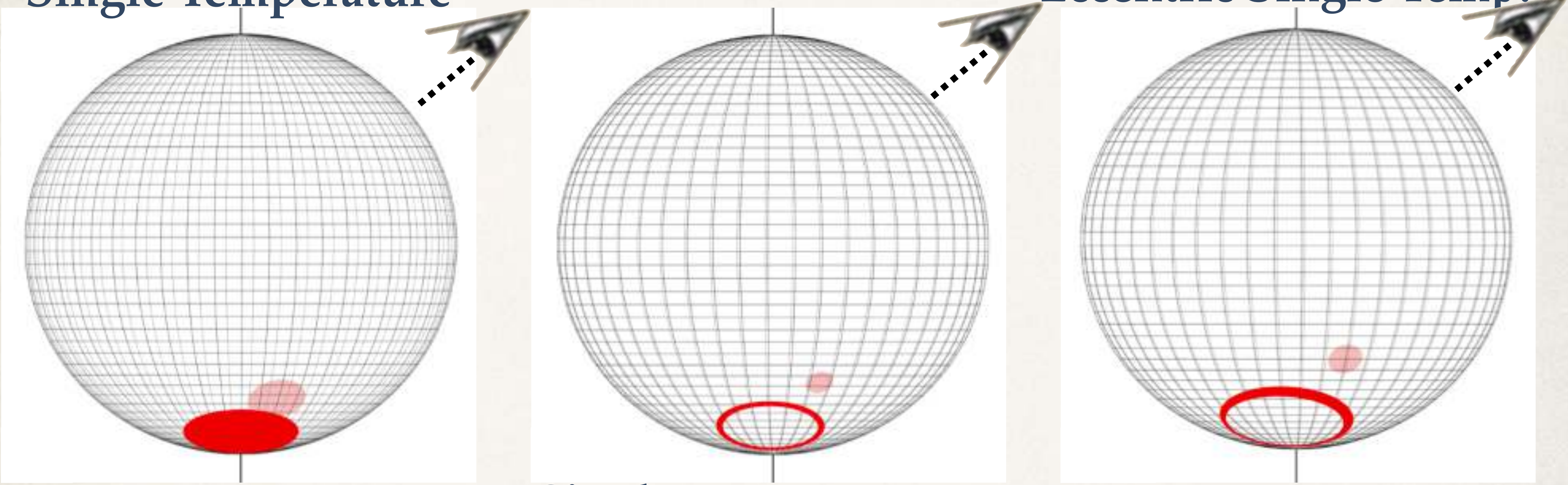


Single Temperature +
Concentric Single Temperature

First surprise: Both hot spots are on the far hemisphere visible from the Earth.

Single Temperature + Single Temperature

Single Temperature + Eccentric Single Temp.

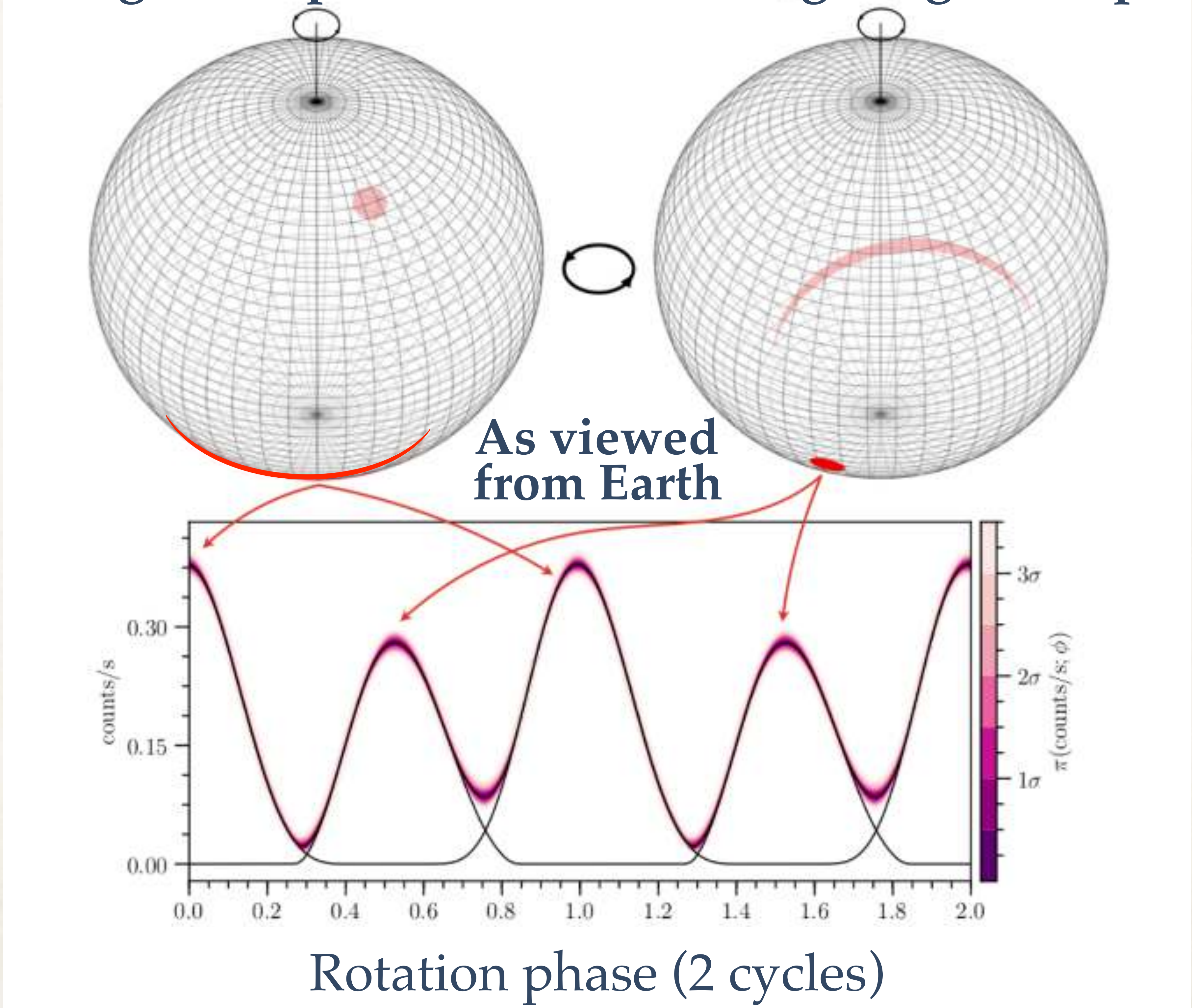


Single Temperature + Concentric Single Temperature

Second surprise: The hot spots are separated close to each other (not antipodal).

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

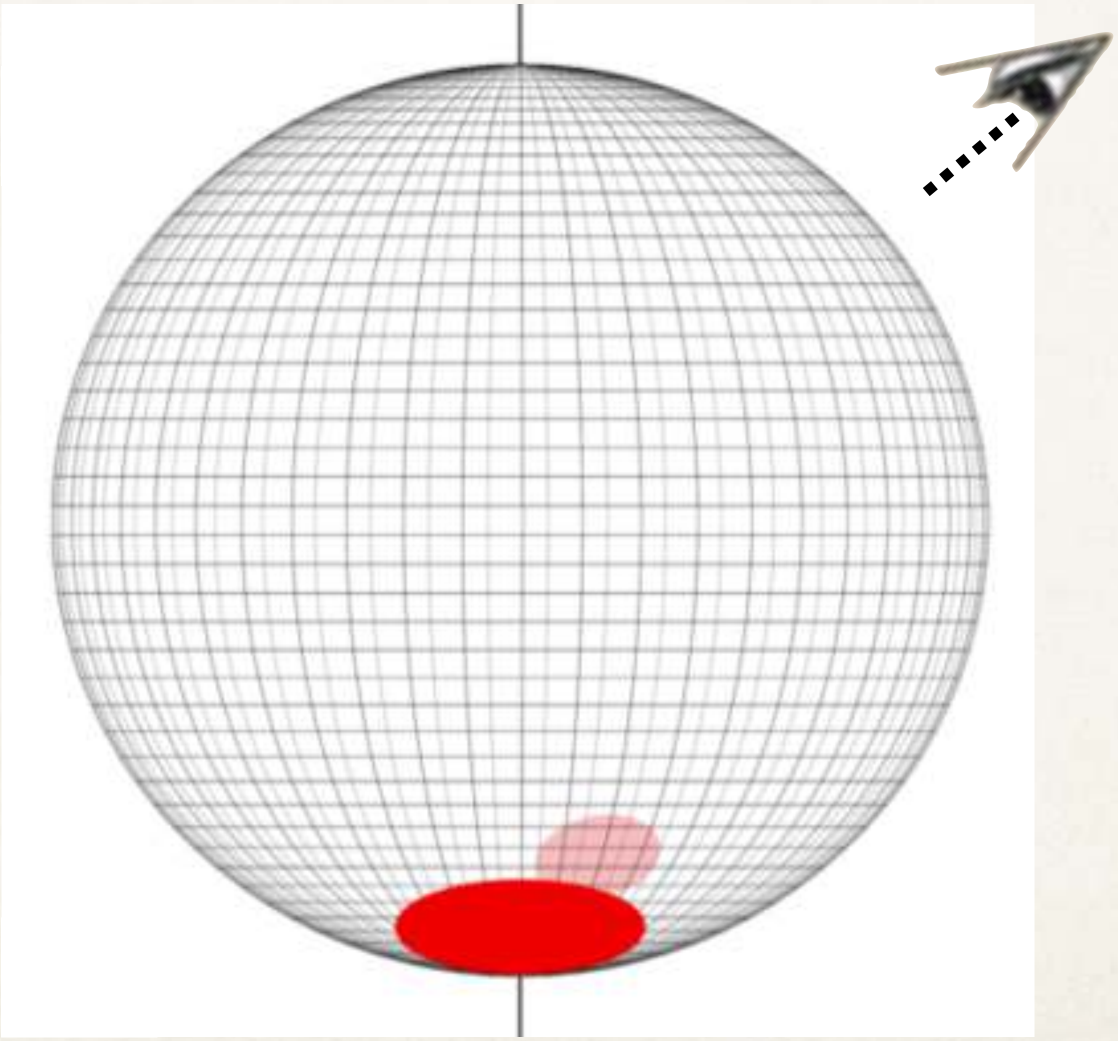
Single Temperature + Protruding Single Temp.

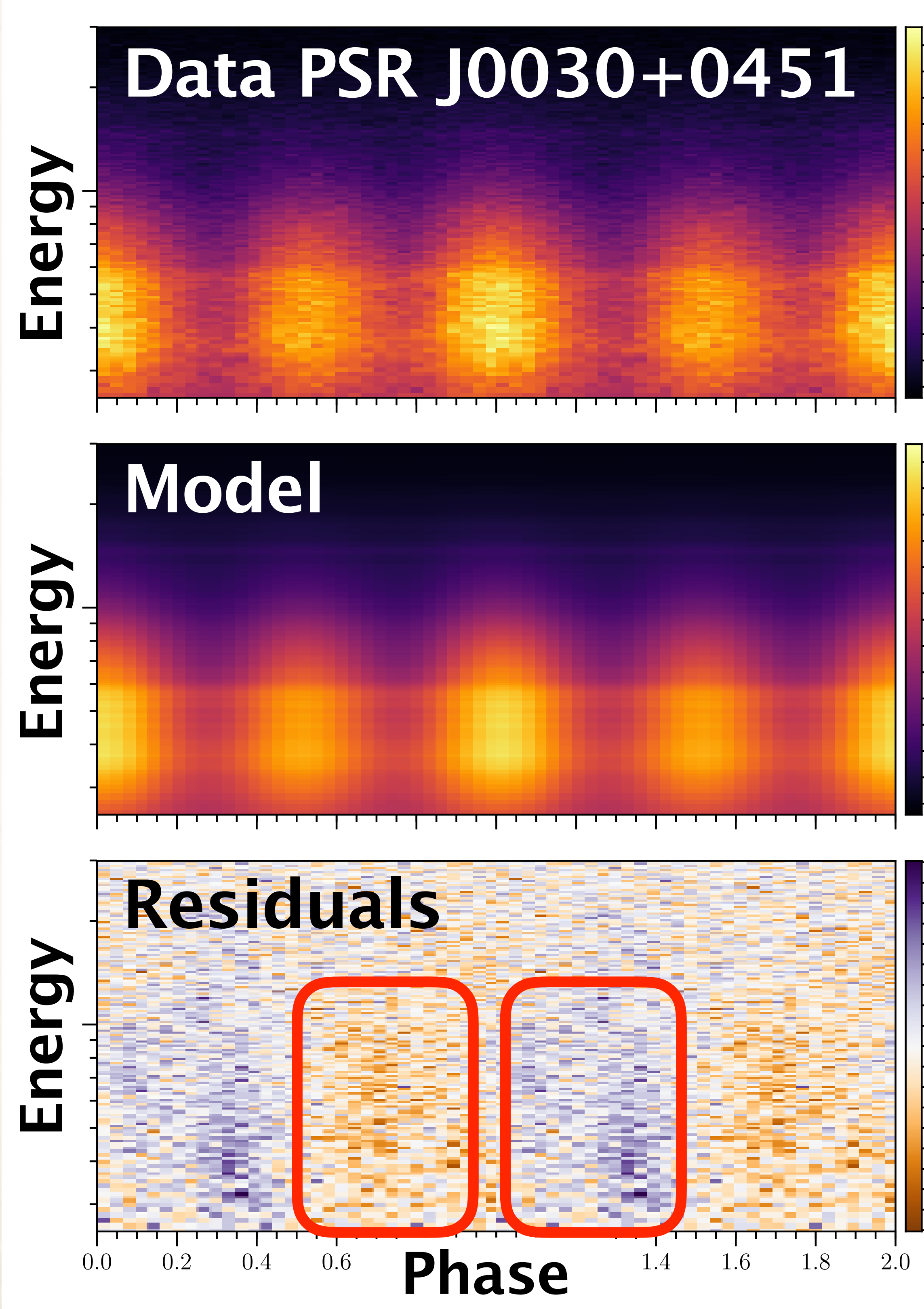


The simplest model shows clear residuals between the model and the data.

ST+PST

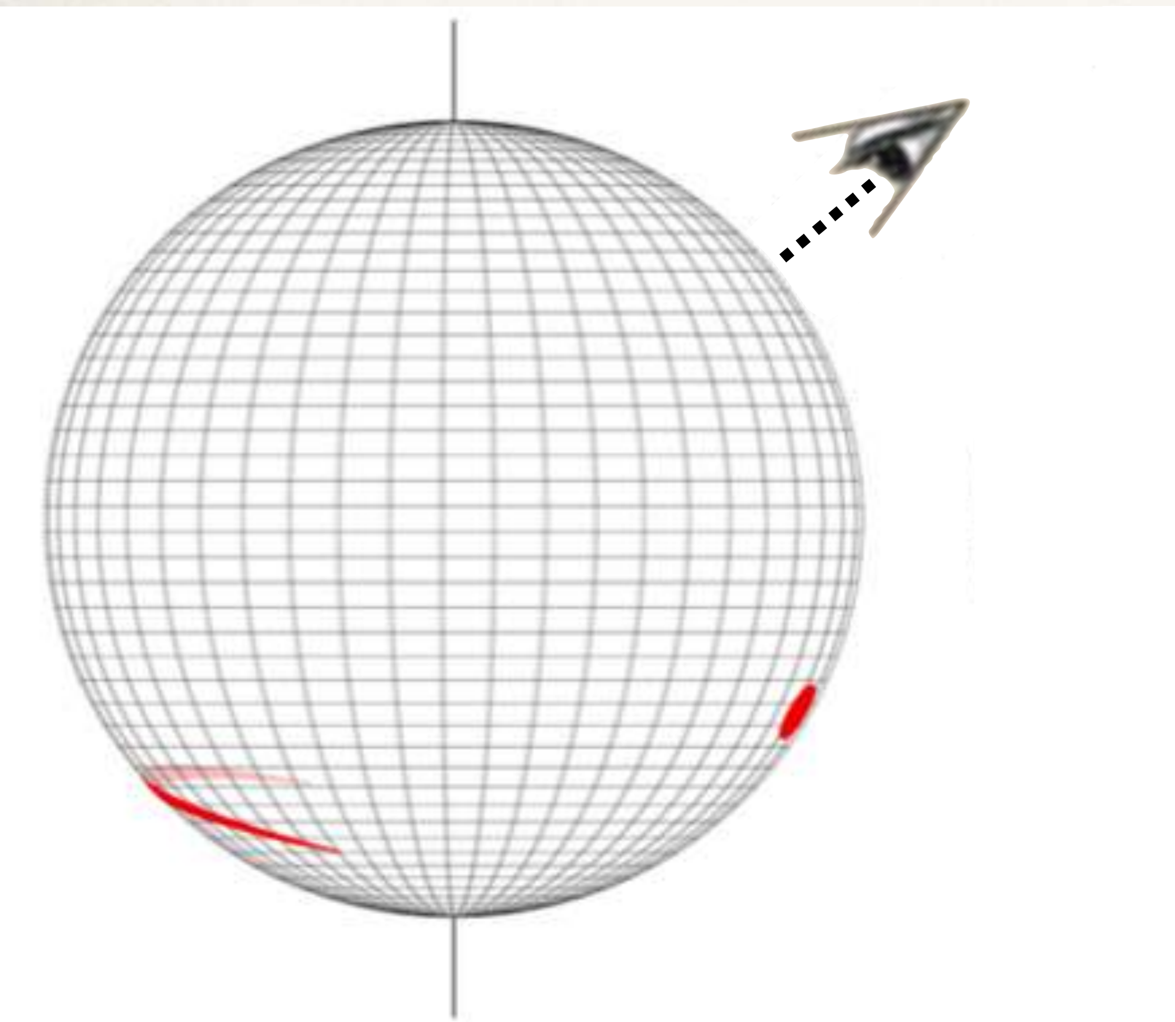
Single Temperature +
Protruding Single Temp.



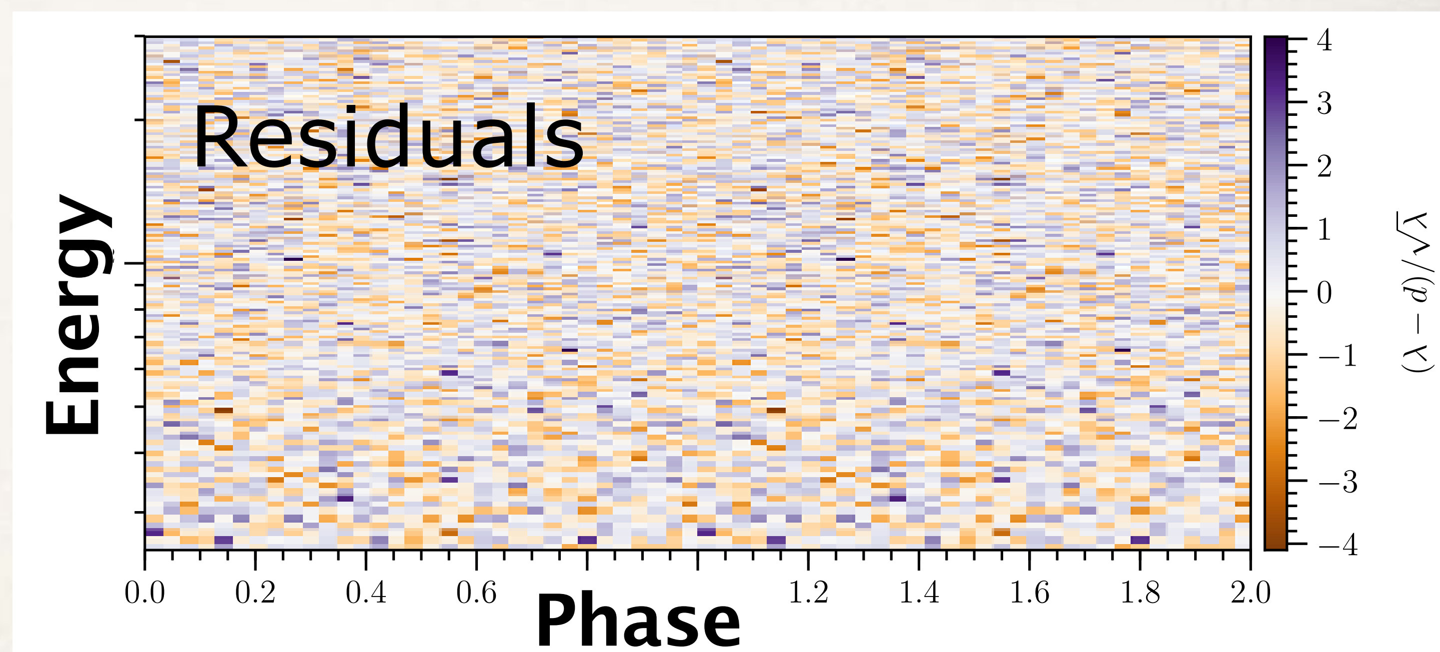


Riley, …, SG et al. (2019)

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

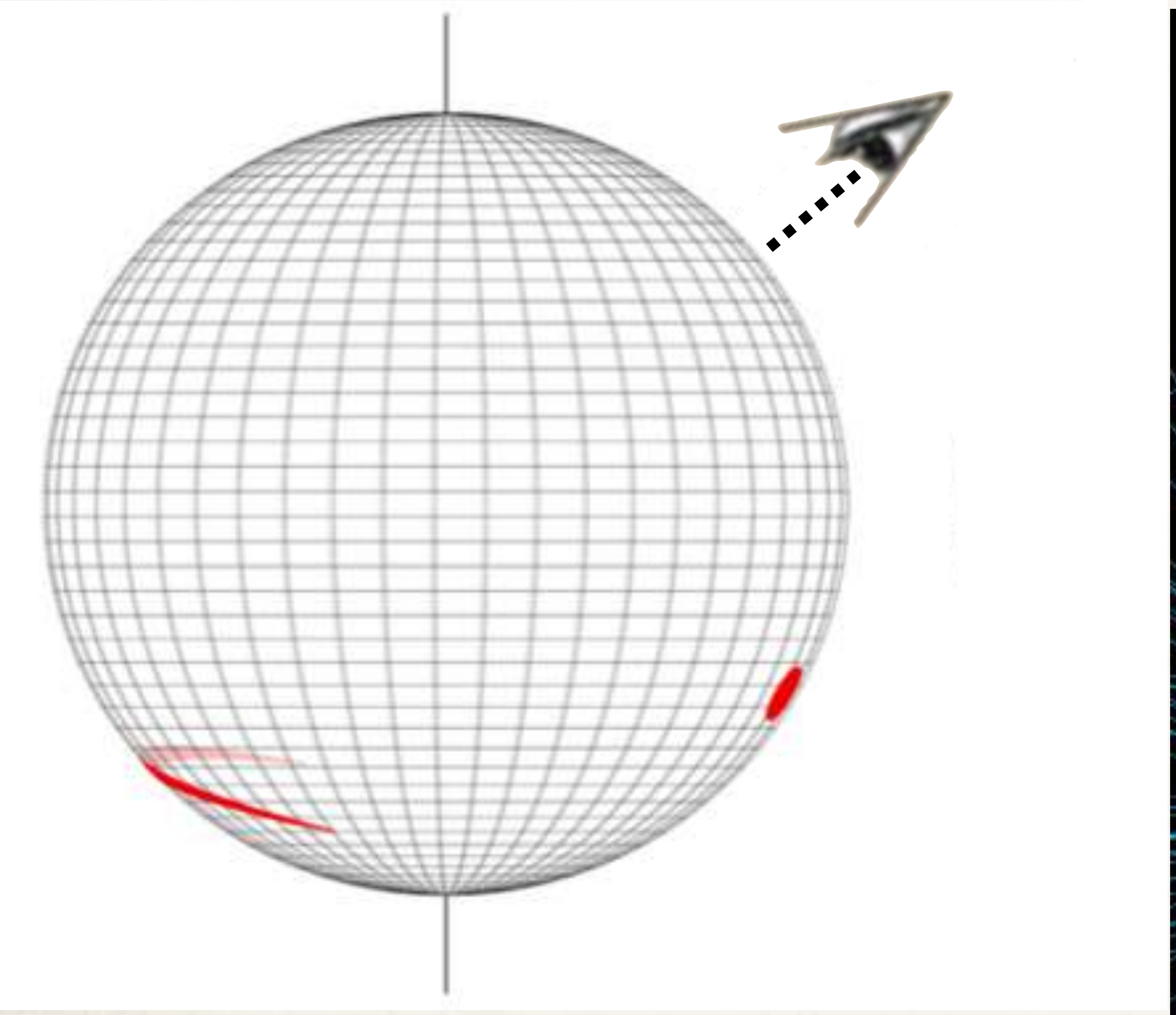


Single Temperature + Protruding Single Temp.

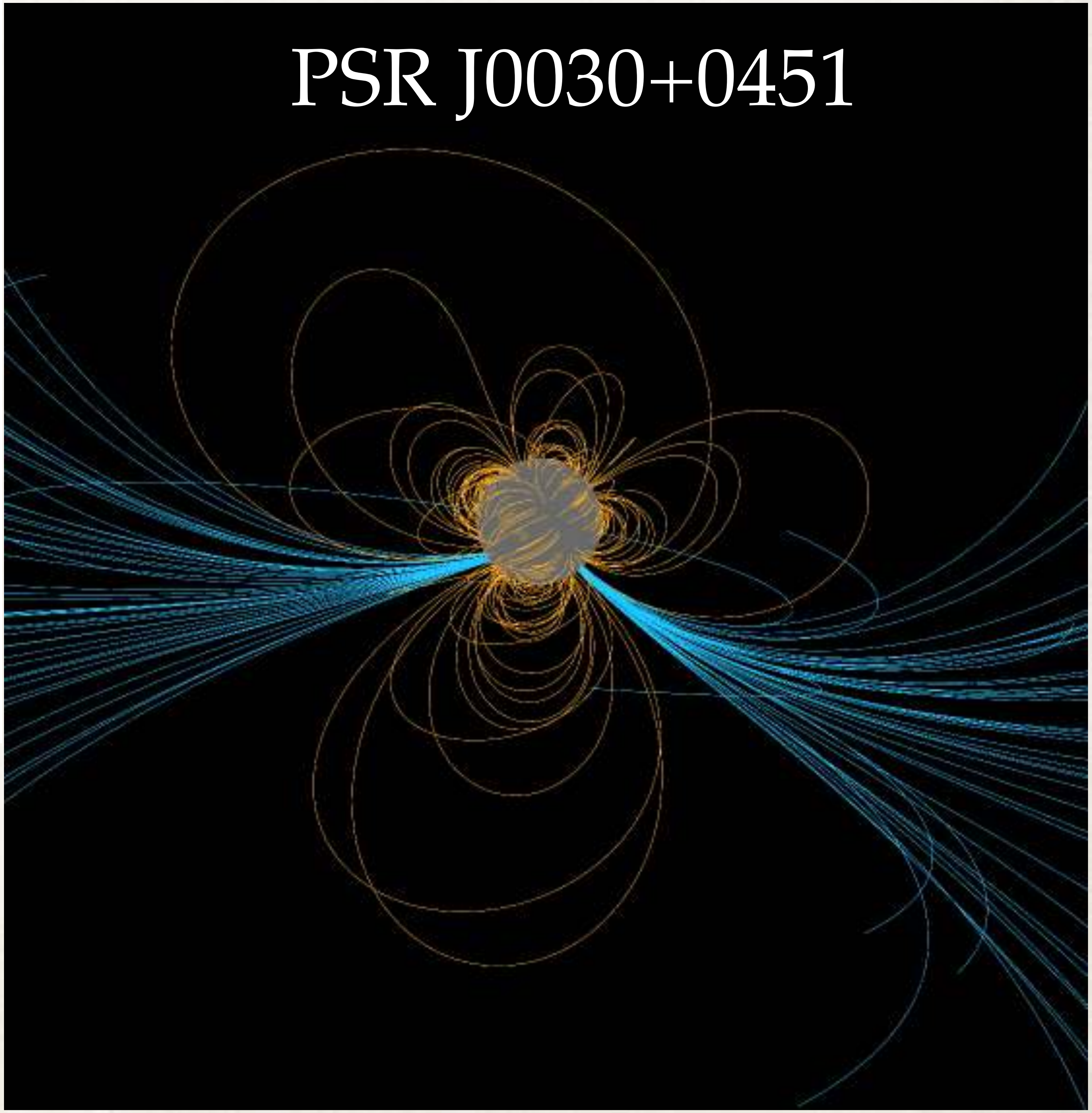


Riley, …, SG et al. (2019)

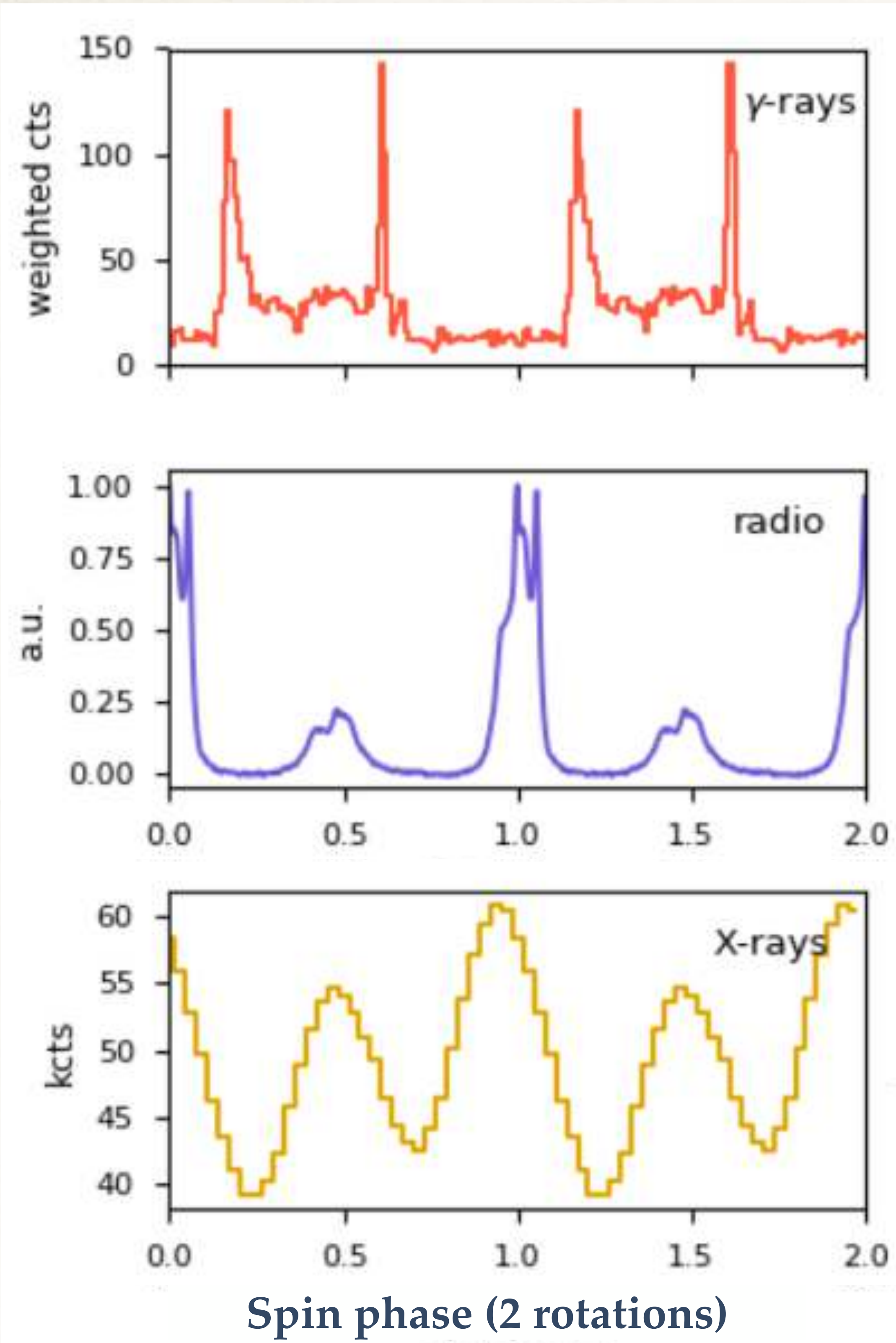
But overall, the spot shapes and locations raise many questions about the magnetosphere.



Bilous, …, SG et al. (2019)

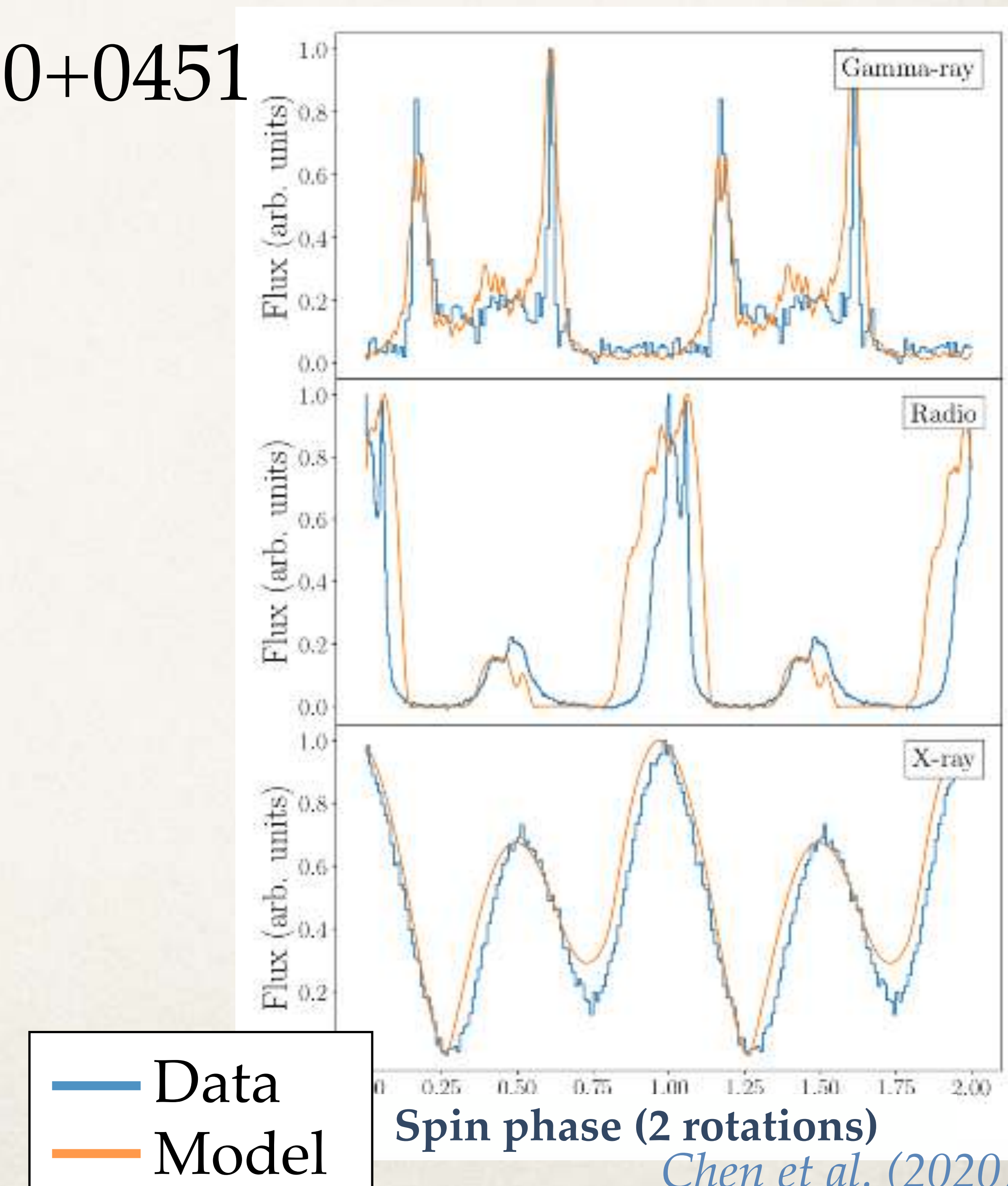


A multipolar magnetic field must be present around (at least some) pulsars.



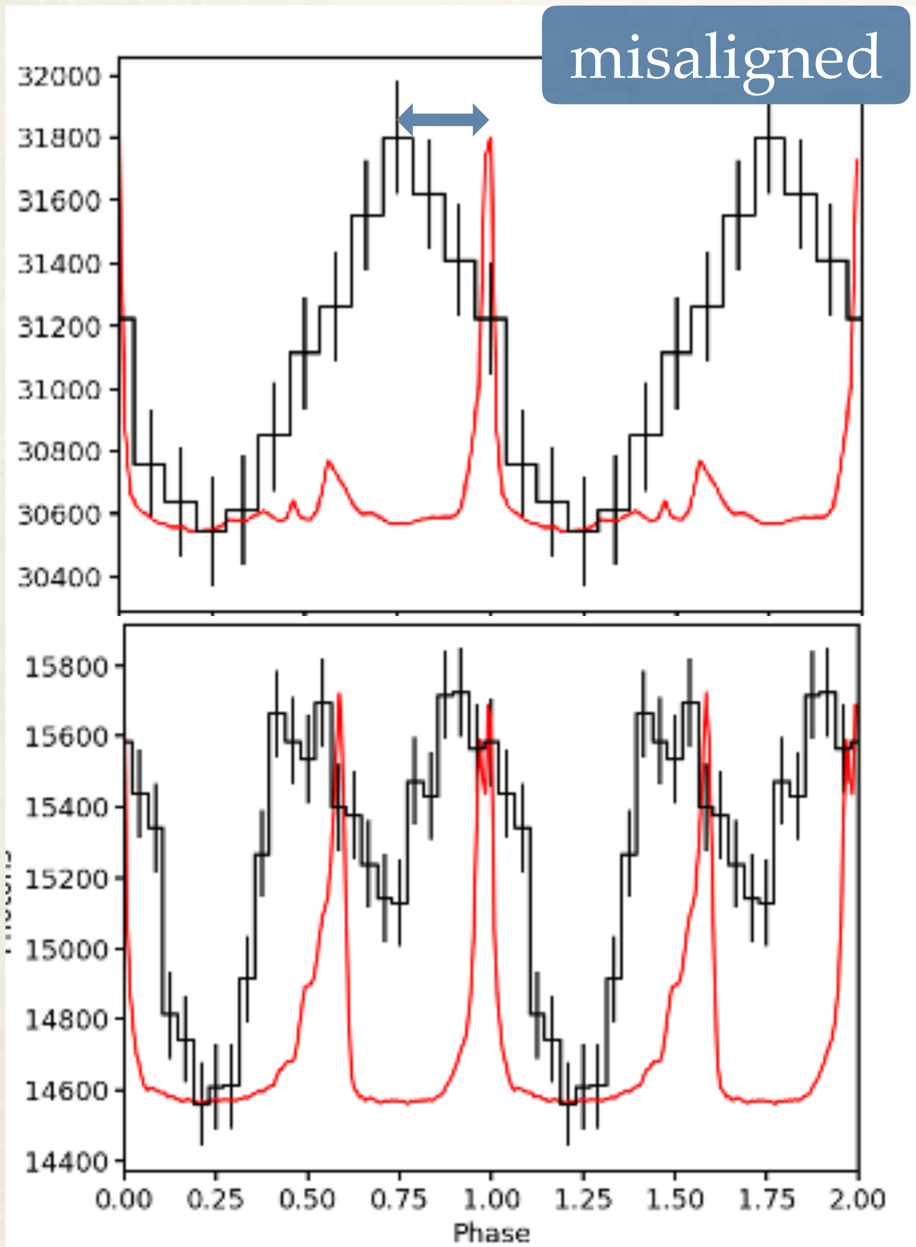
Semi-qualitative model of multiwavelength emission with dipole+quadrupole

PSR J0030+0451

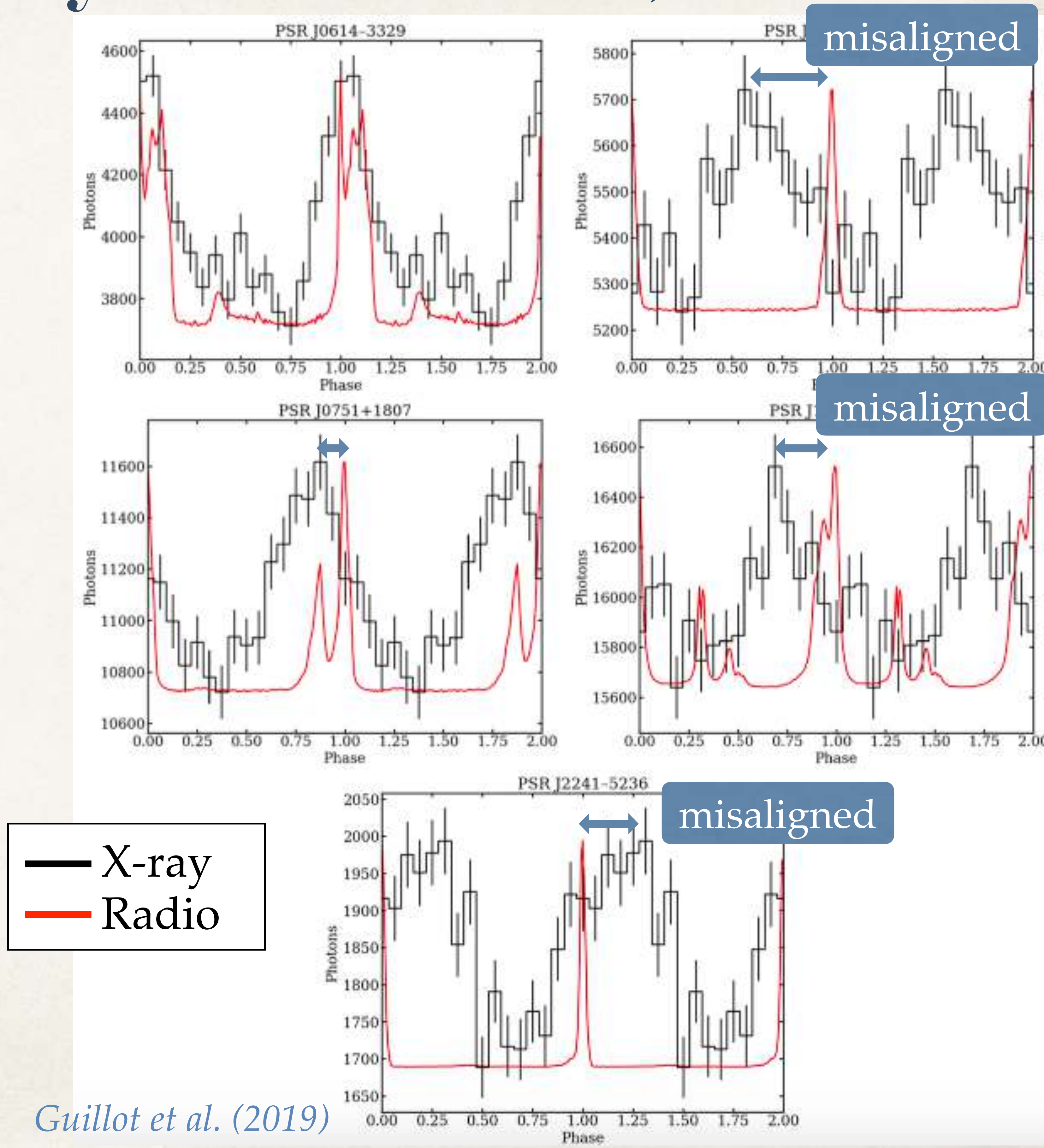


Chen et al. (2020)

With the discovery of new MSPs, we had other surprises.

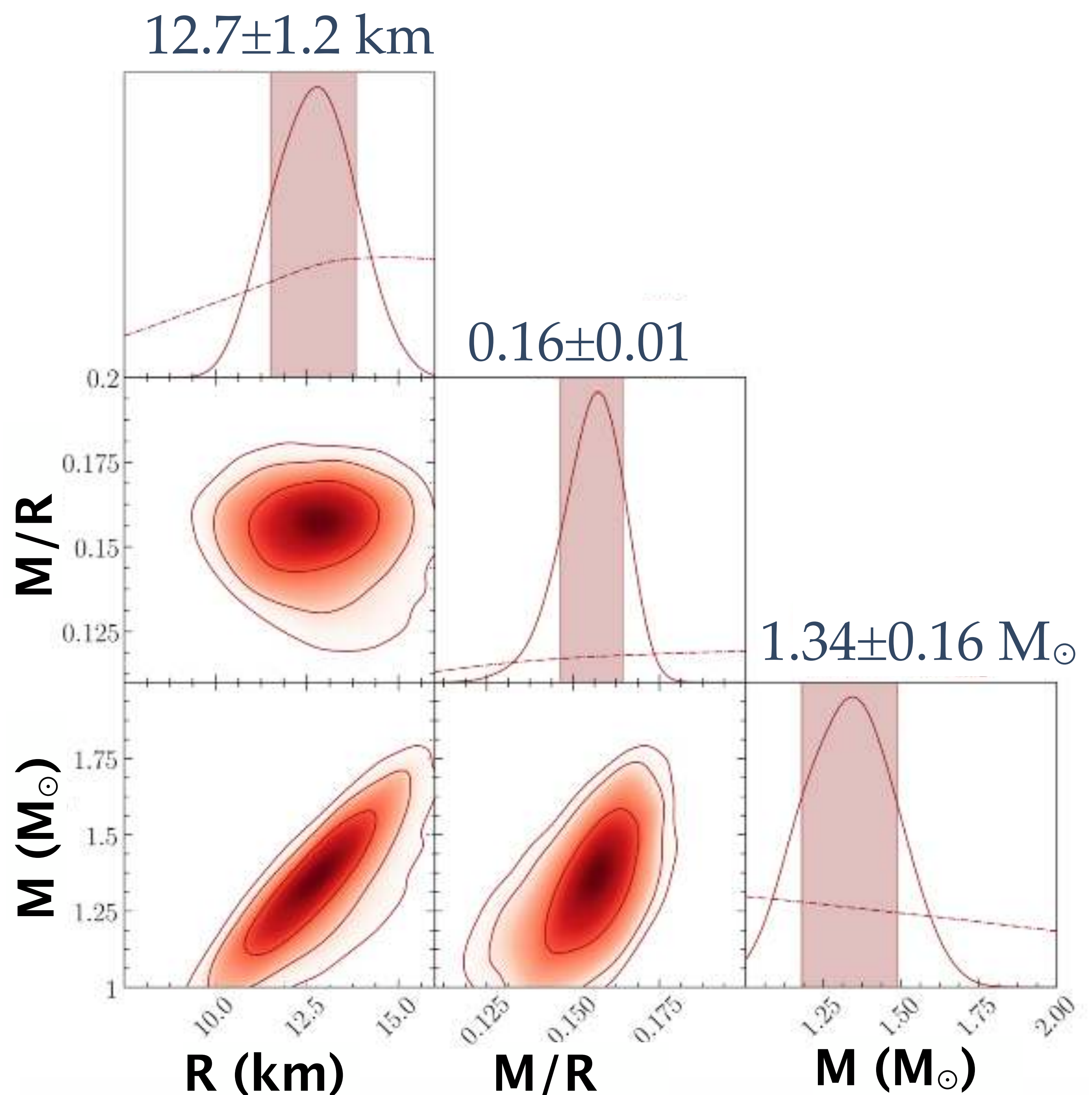


Guillot et al. (in prep.)



Guillot et al. (2019)

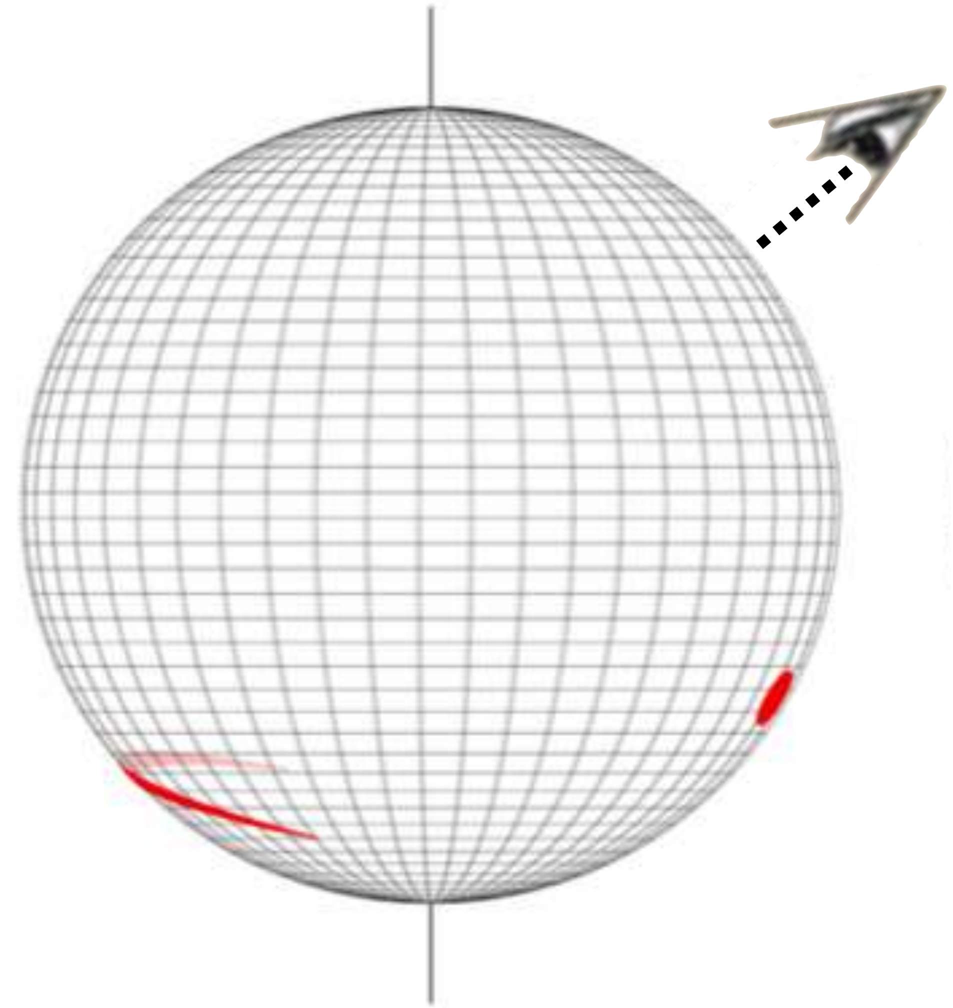
From the light curve modelling, we also constrain M and R. With the ST+PST model, we obtain:



ST+PST

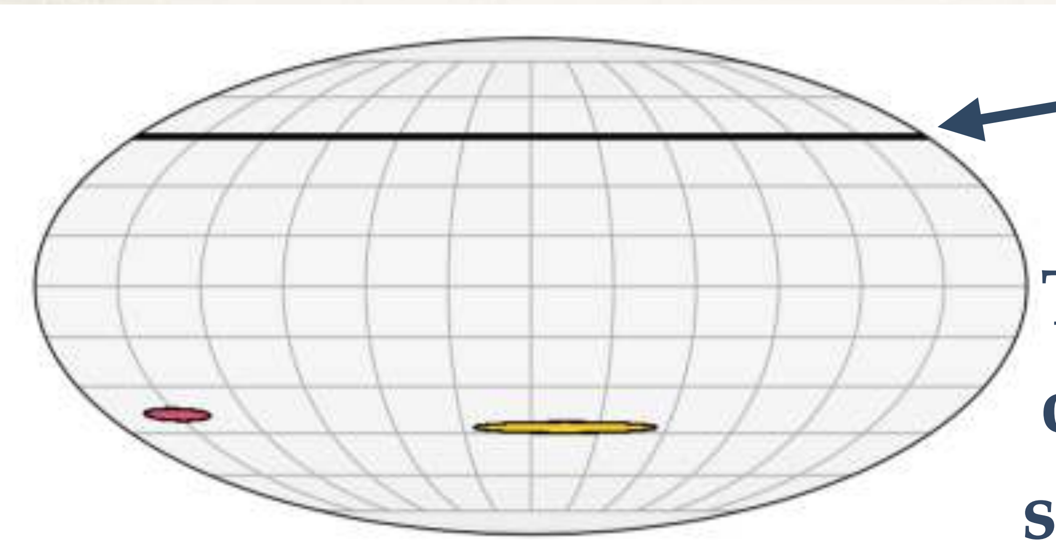
Single Temperature +

Protruding Single Temp.



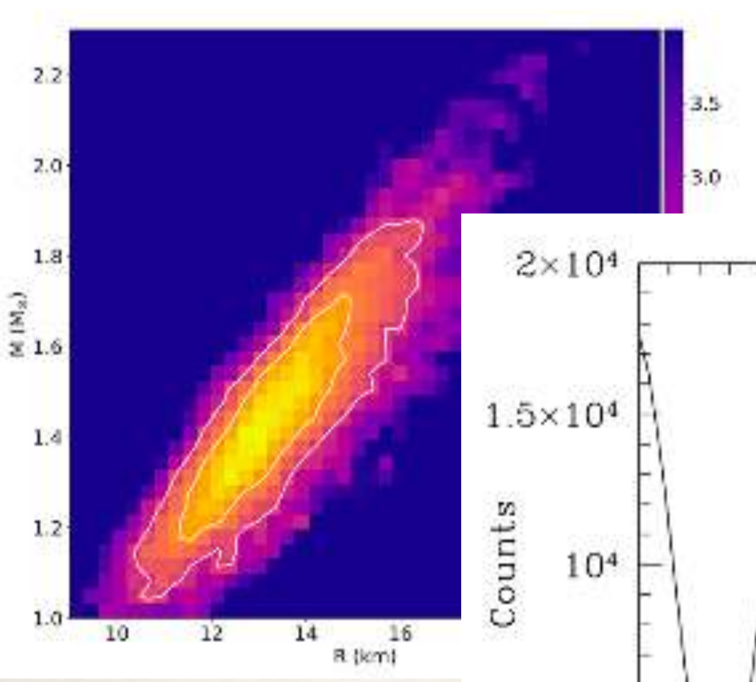
Riley, …, SG et al. (2019)

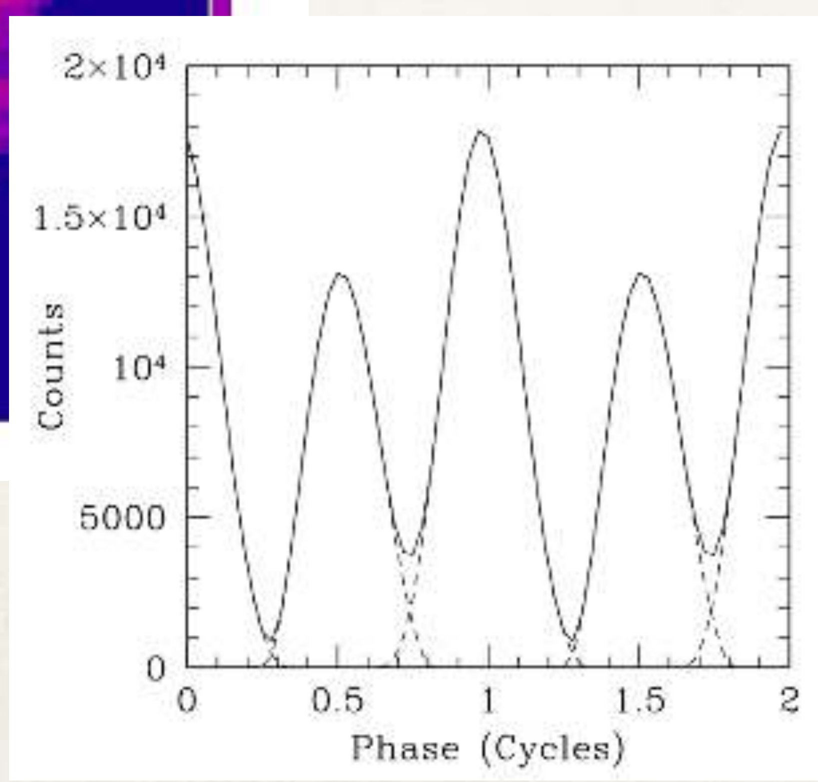
An independent analysis in the NICER Science Team finds similar constraints on the neutron stars parameters (with a different approach).



Observer

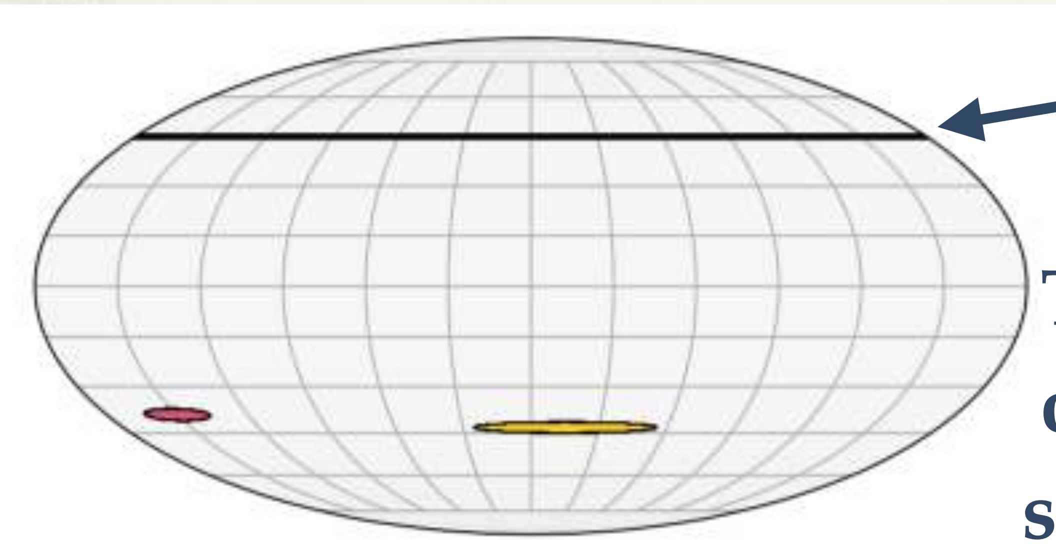
Two oval spots





Miller, …, SG et al. 2019

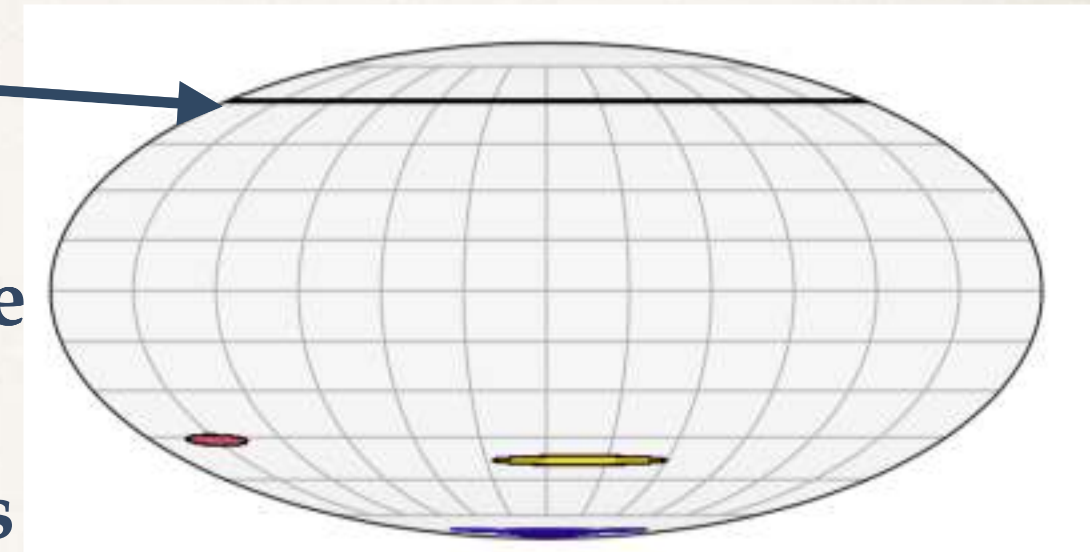
An independent analysis in the NICER Science Team finds similar constraints on the neutron stars parameters (with a different approach).

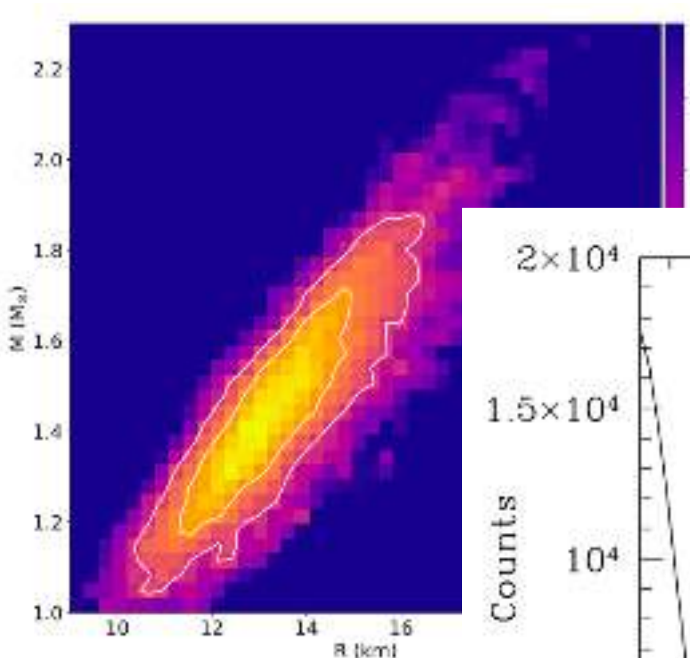


Observer

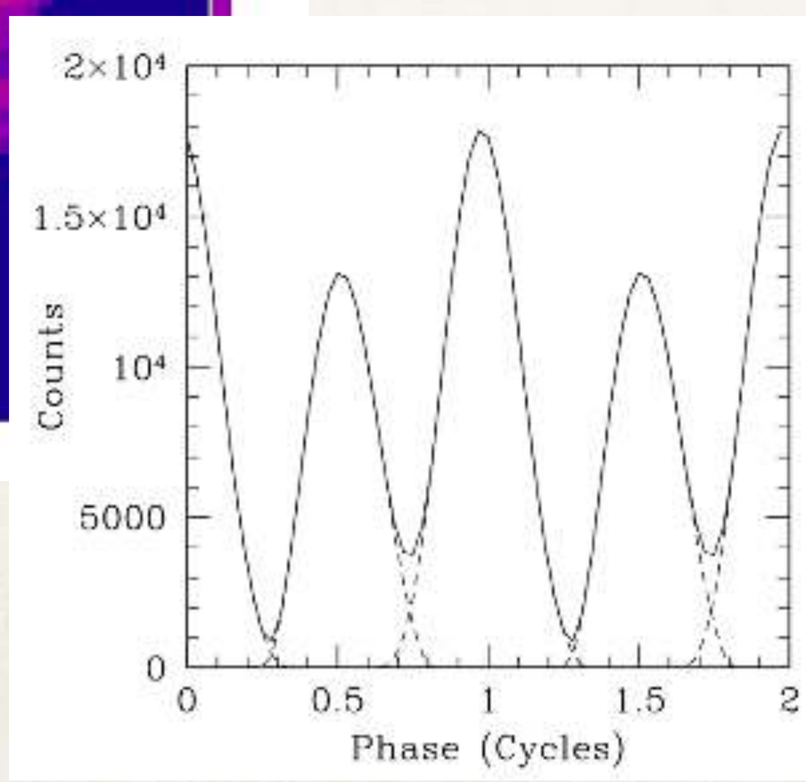
Two oval spots

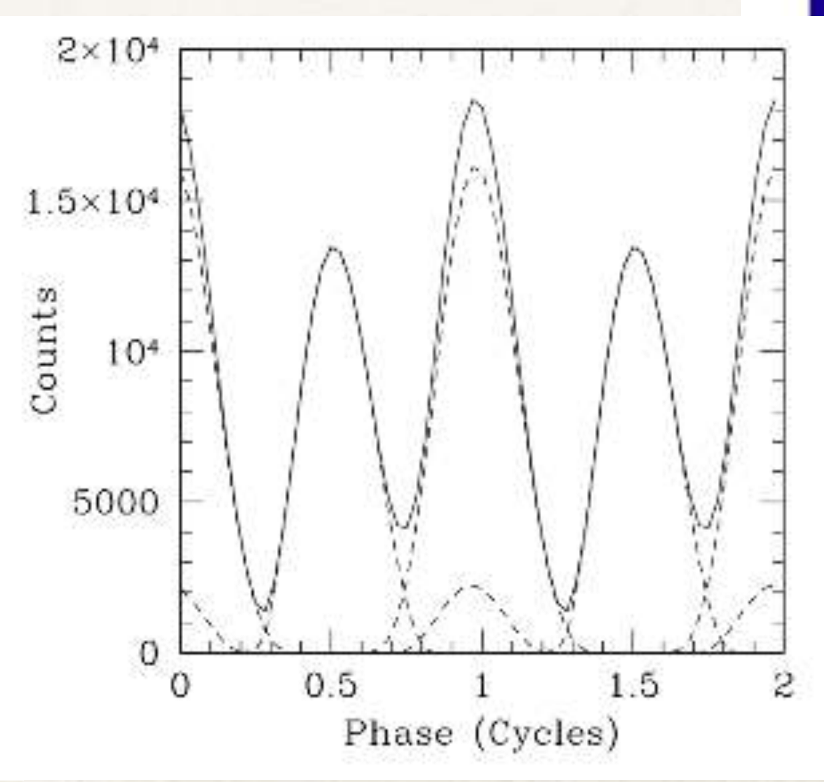
Three oval spots

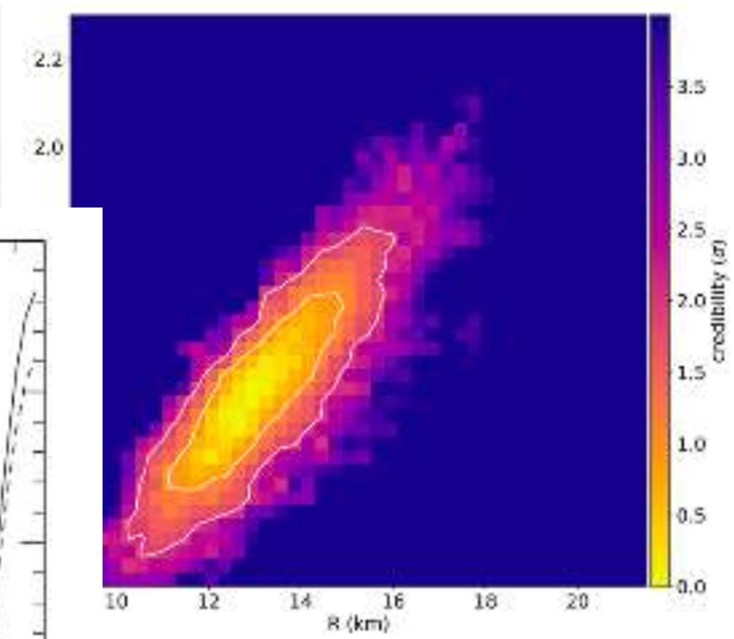




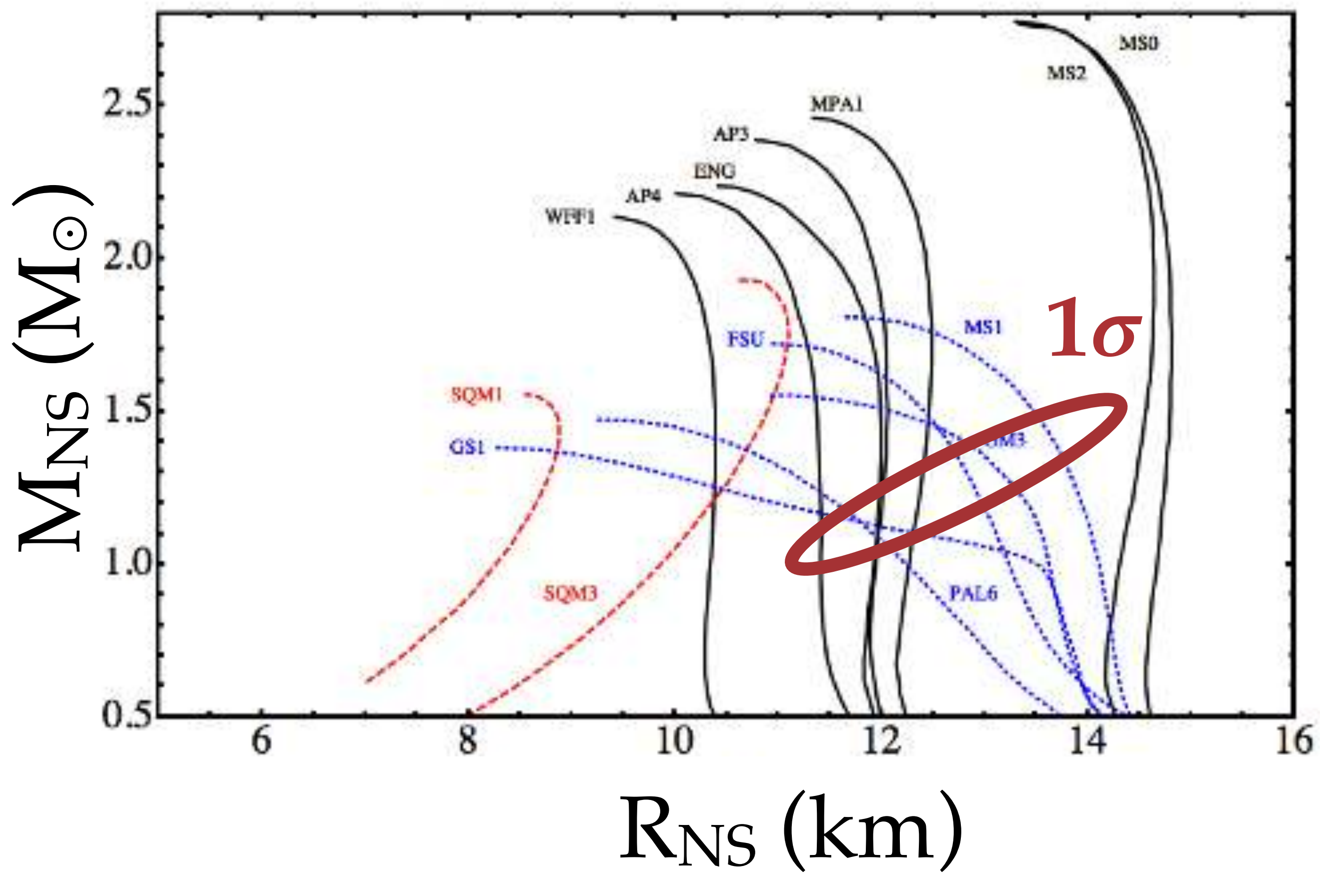
Miller, …, SG et al. 2019

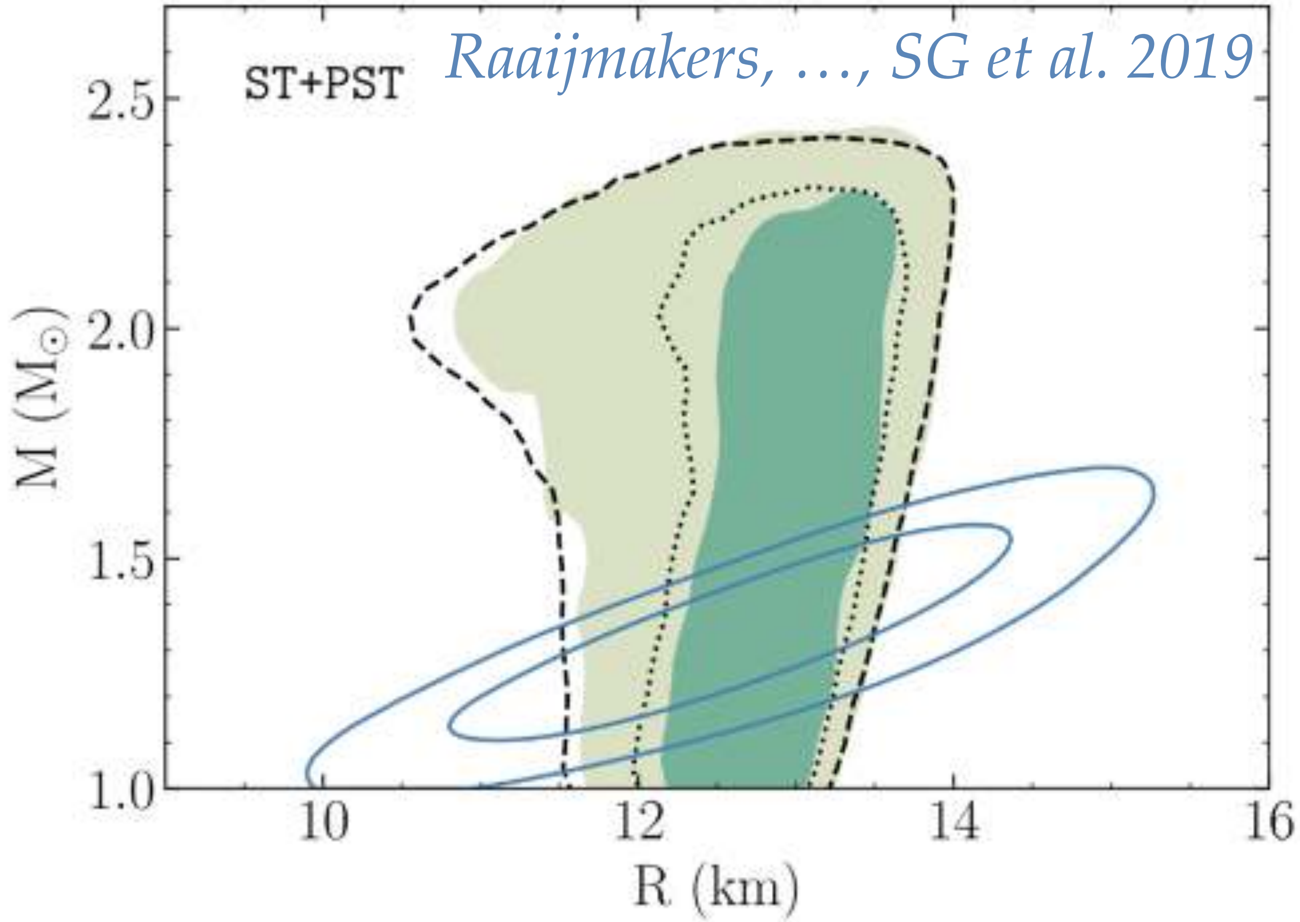






However, equation of state models are "modestly" constrained by the M-R measurements.





PSR J0030+0451 has a small preference for EoSs consistent with ~12 km

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

Full NICER results for PSR J0030+0451 were presented in an ApJL Special Focus Issue.

Summary for PSR J0030+0451:

- The first mass measurement of an isolated pulsar.
- Statistical evidence favours more complex polar cap models
- A radius in the range 11–14 km, preferring stiff equation of state

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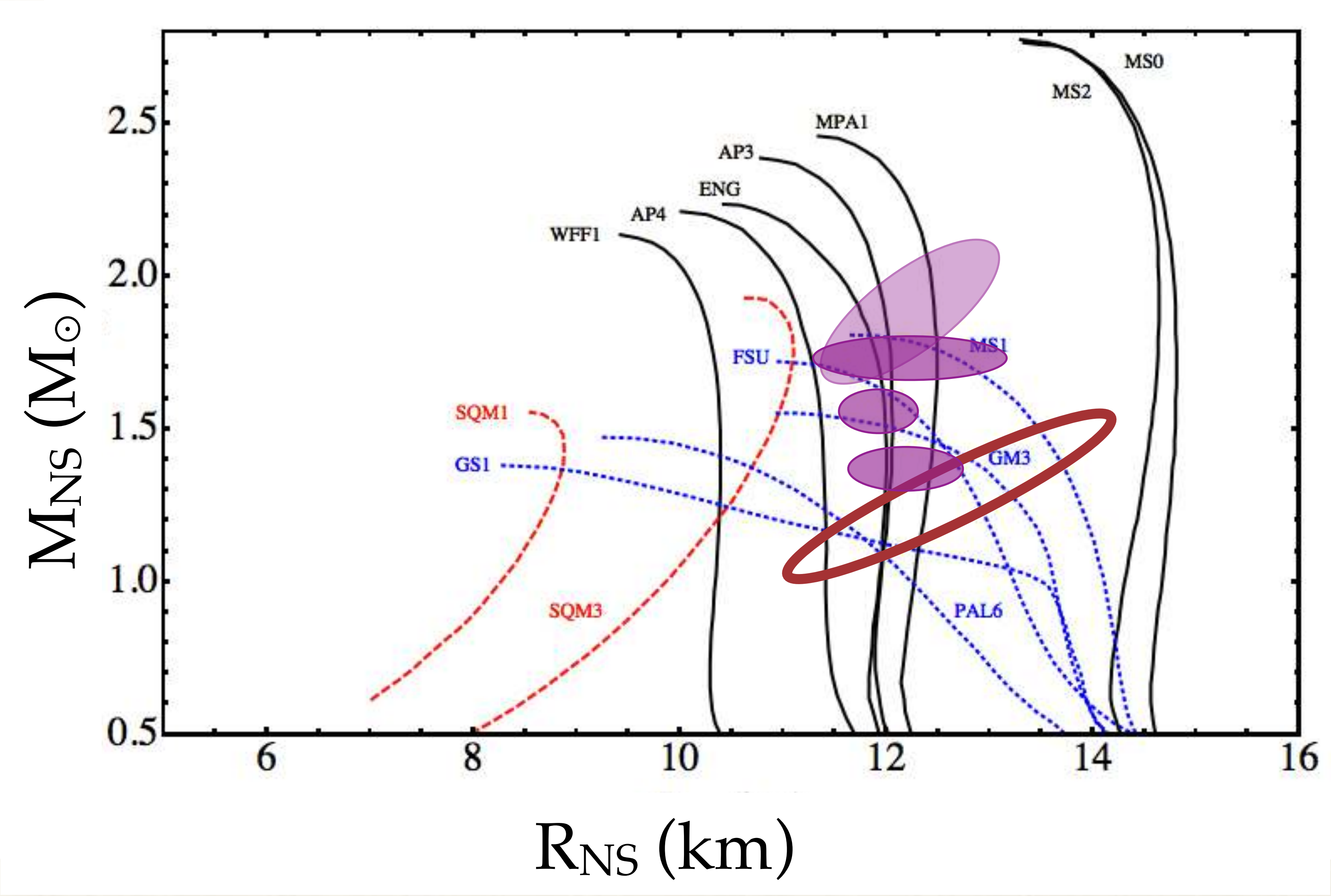
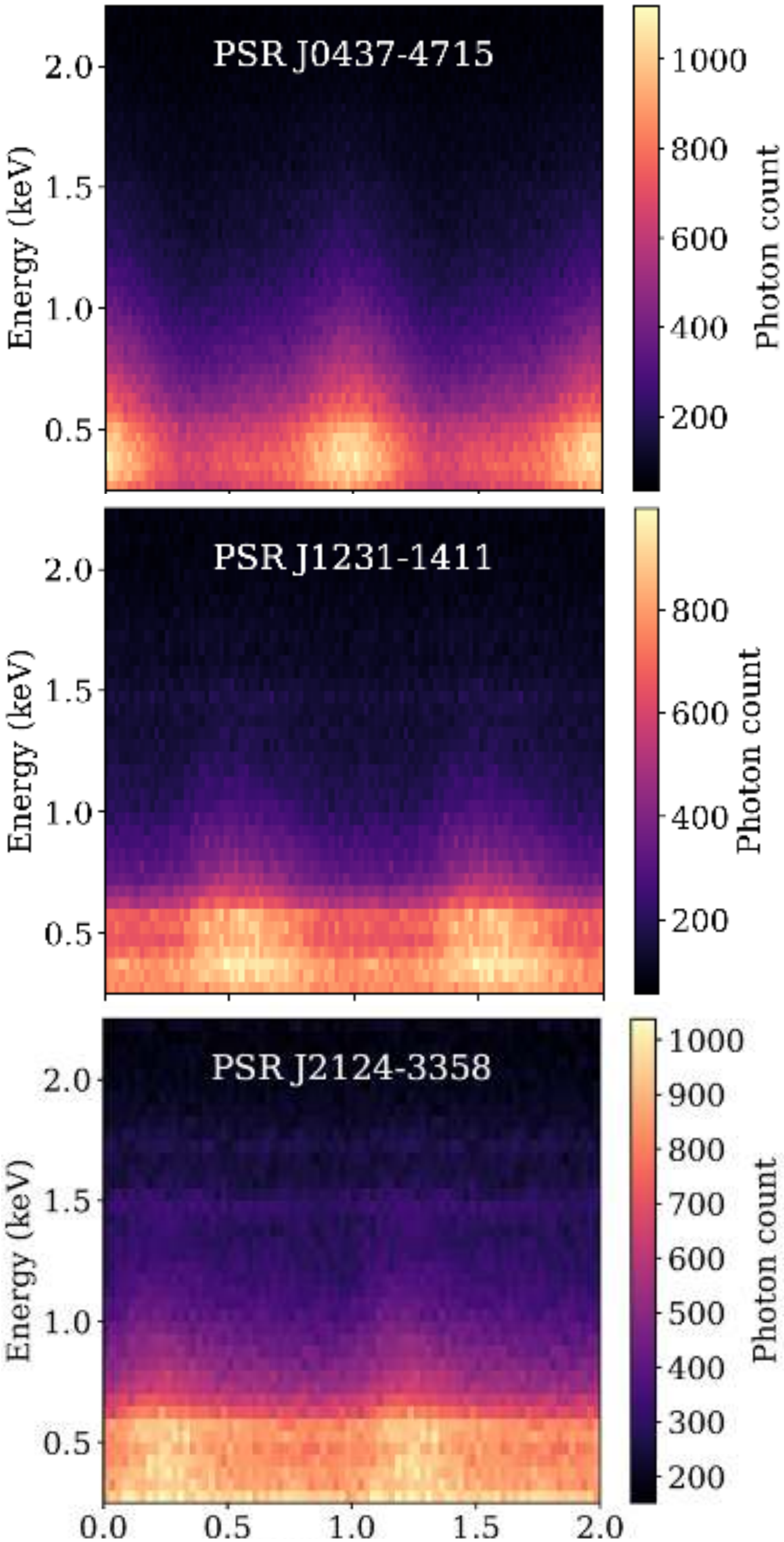
Seven papers:

- M_{NS}–R_{NS} results from Riley et al. 2019 (Amsterdam group)
- M_{NS}–R_{NS} results from Miller et al. 2019 (Illinois-Maryland group)
- Implication for the equation of state
- Implication for structure of the magnetic field
- Presentation of the NICER data of four millisecond pulsars
- Presentation of the ray-tracing model
- NICER discovery of five new millisecond pulsars suitable for radius measurements

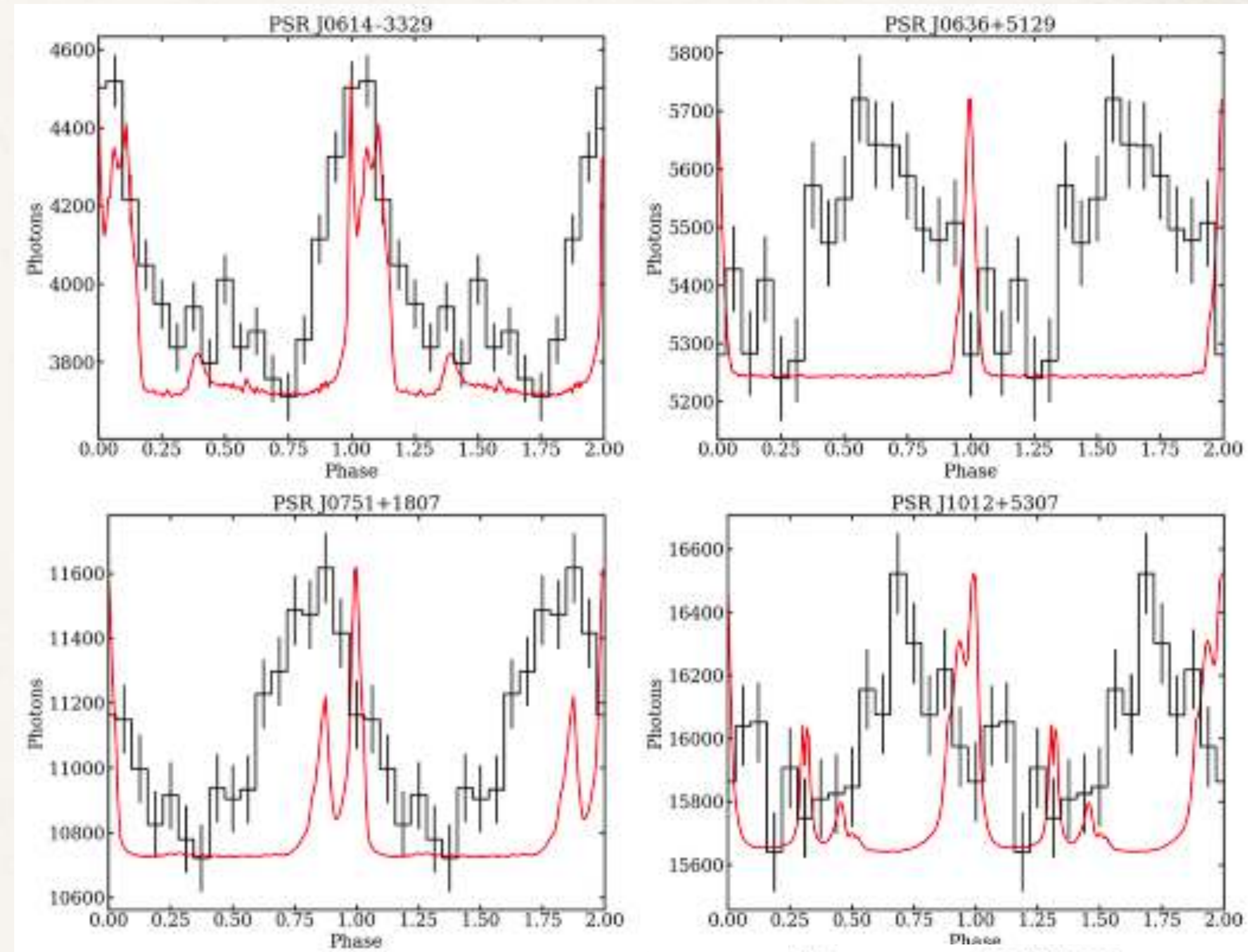
More than one M_{NS}-R_{NS} measurement will be necessary to constrain the equation of state.

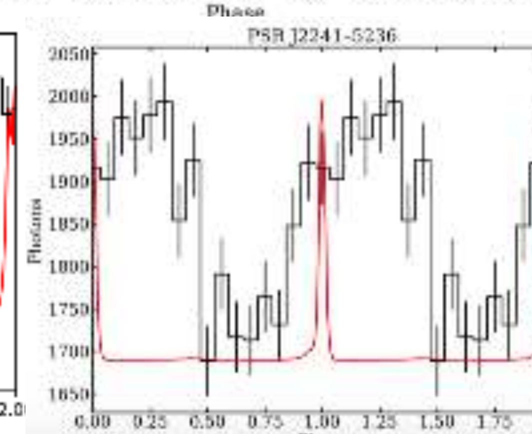


There are still many data sets to analyse to extract M_{NS} and R_{NS}, including newly discovered millisecond pulsars.

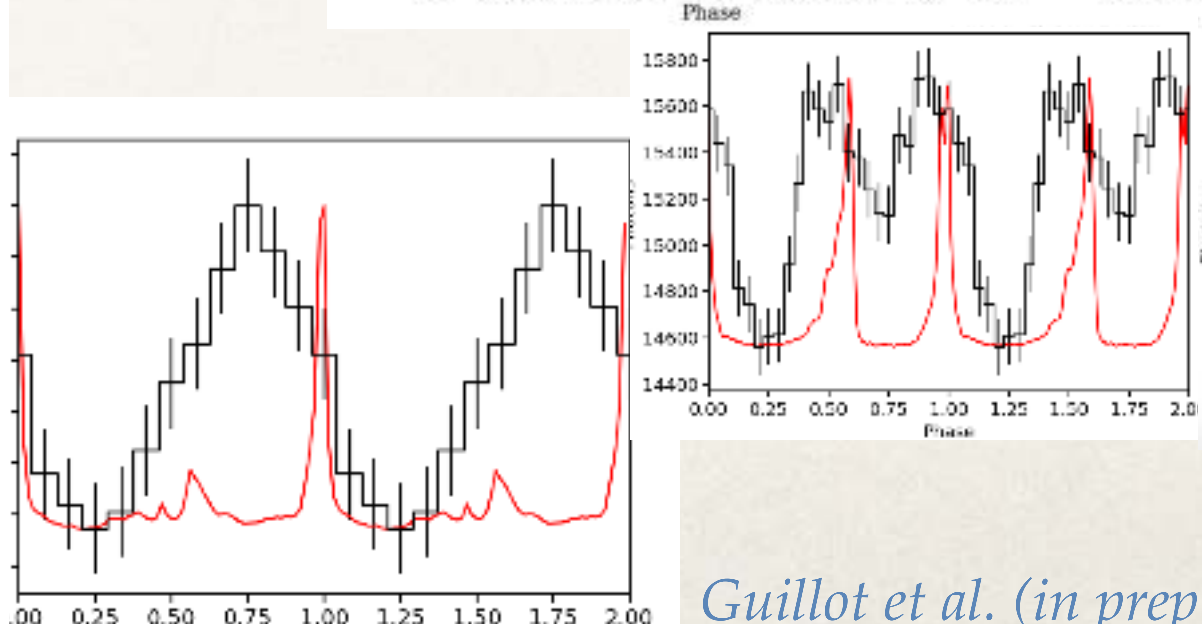


Bogdanov, SG et al. (2019)





Guillot et al. (2019)



Guillot et al. (in prep.)

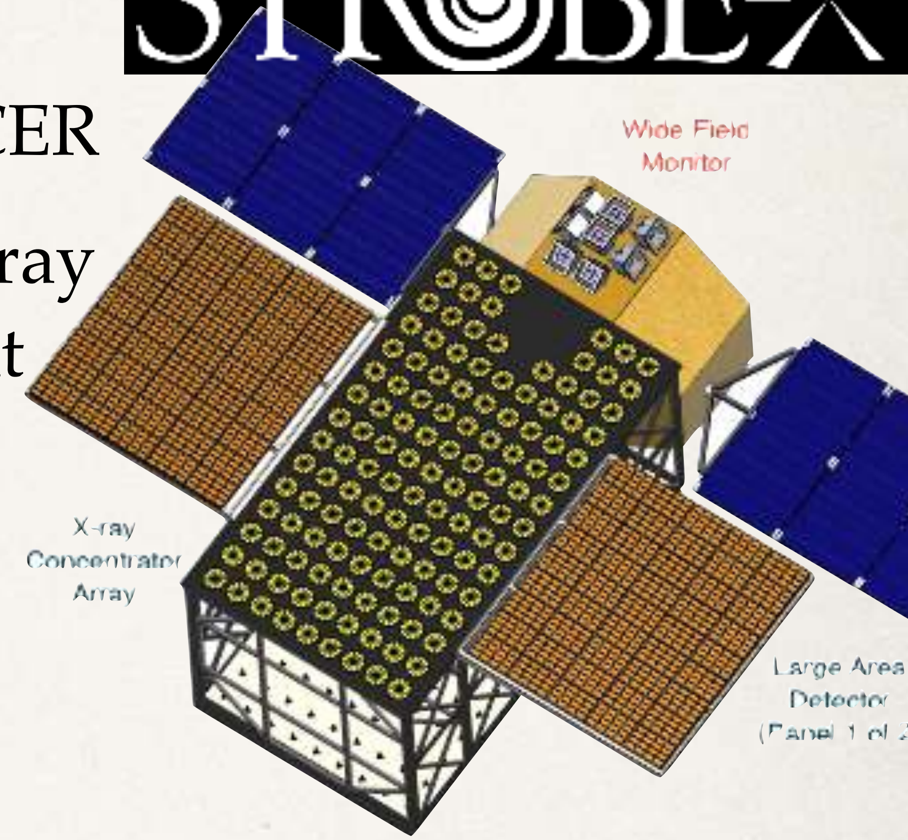
Future missions will fully enable the light curve modelling technique to measure M_{NS} and R_{NS}.

eXTP (~2025)

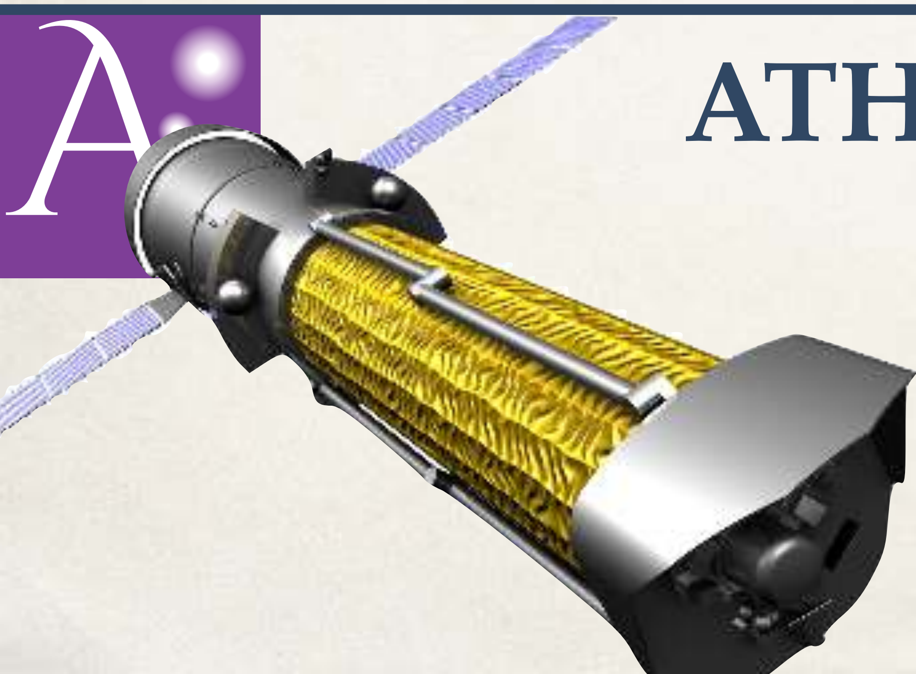
- Modest imaging capabilities (60″ PSF)
- ~ 4× more sensitive than NICER
- + Hard X-ray instrument

STROBE-X ~2030

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

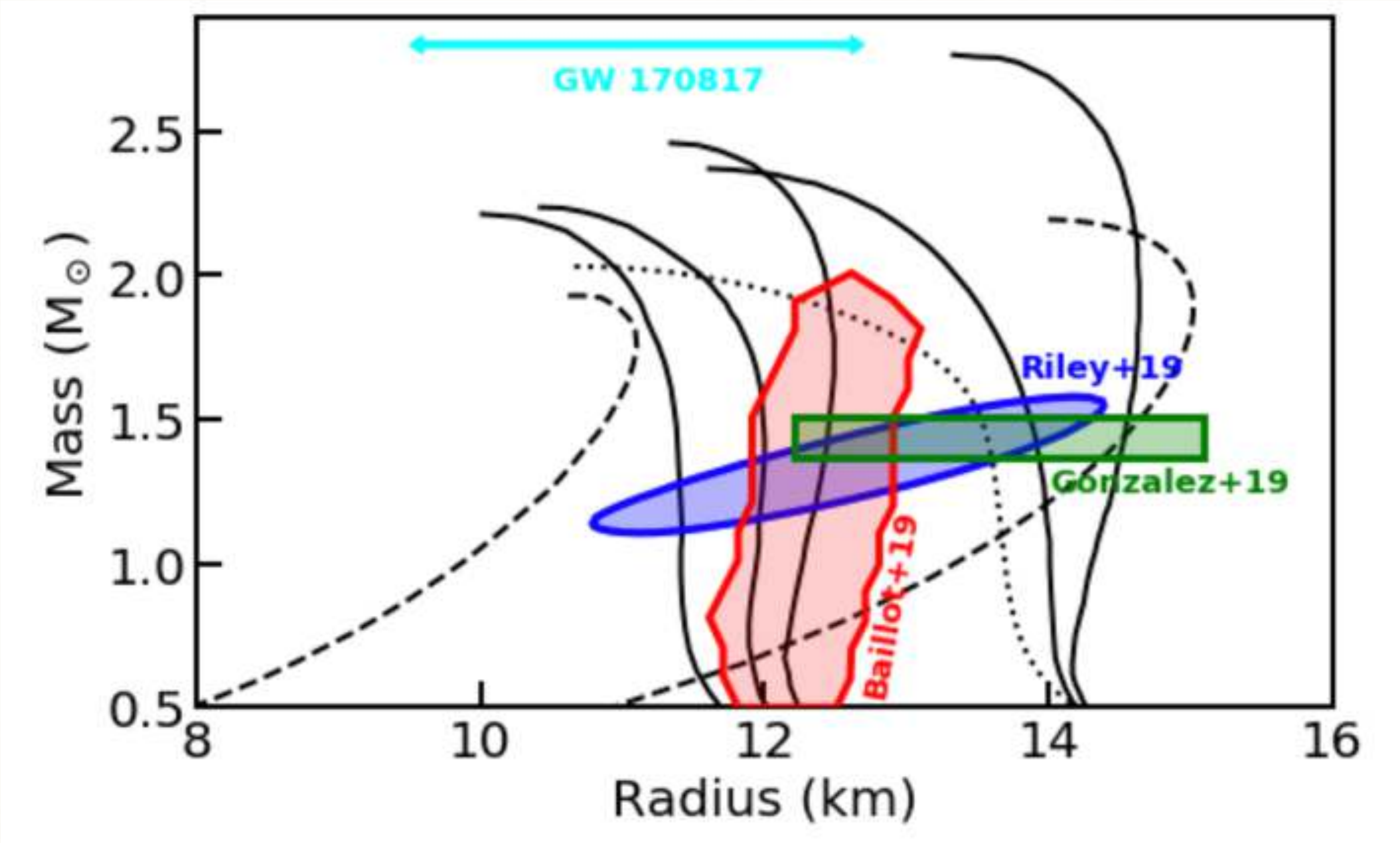


ATHENA (~2032)



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

For the moment, the NICER results are quite promising and consistent with other recents measurements.



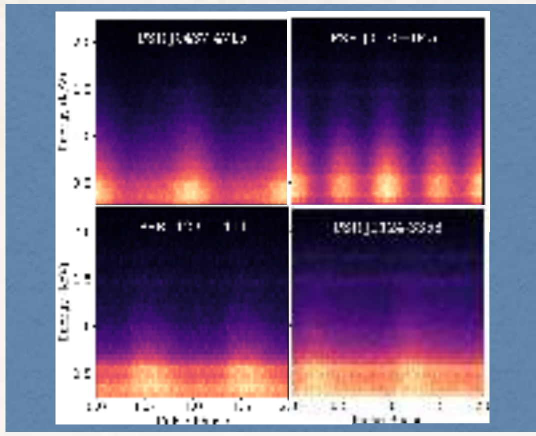
Gonzalez-Canuilef, SG et al. 2019

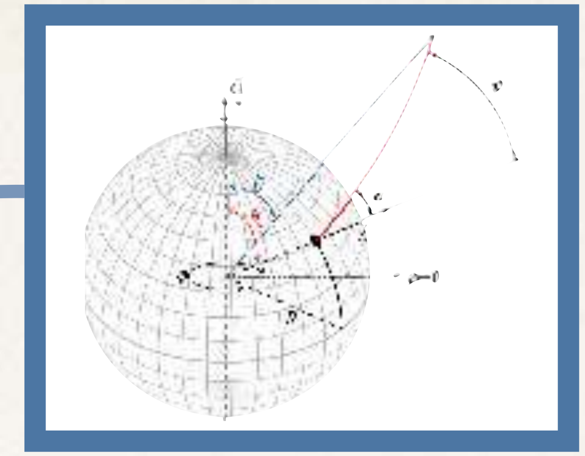
Baillot-d'Etivaux, SG et al. 2019

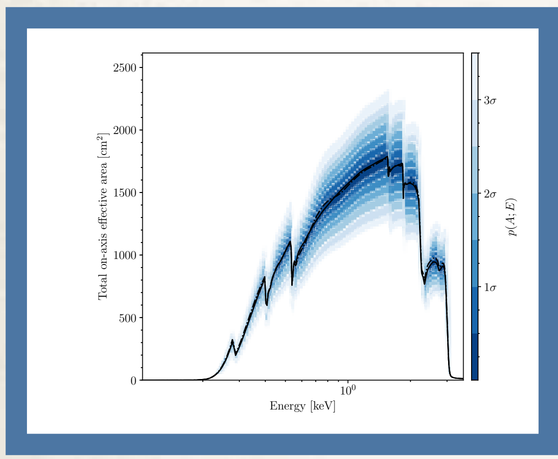
Riley et al. 2019

Abbott et al. 2018

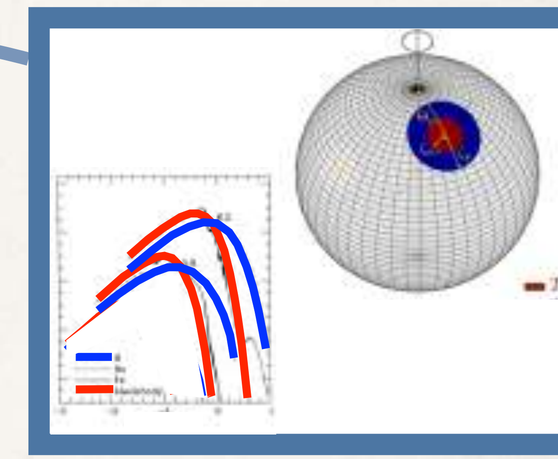
Summary

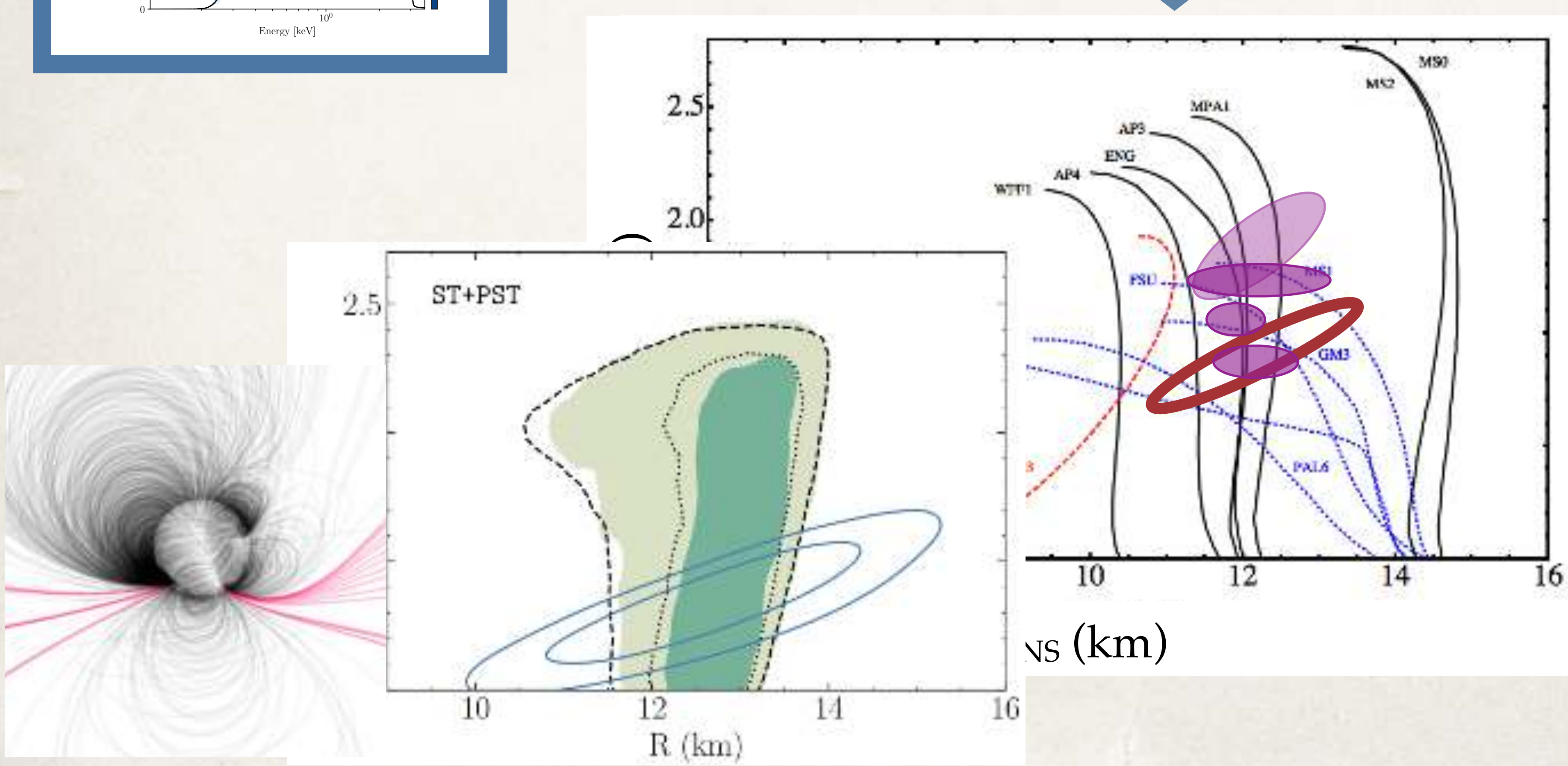




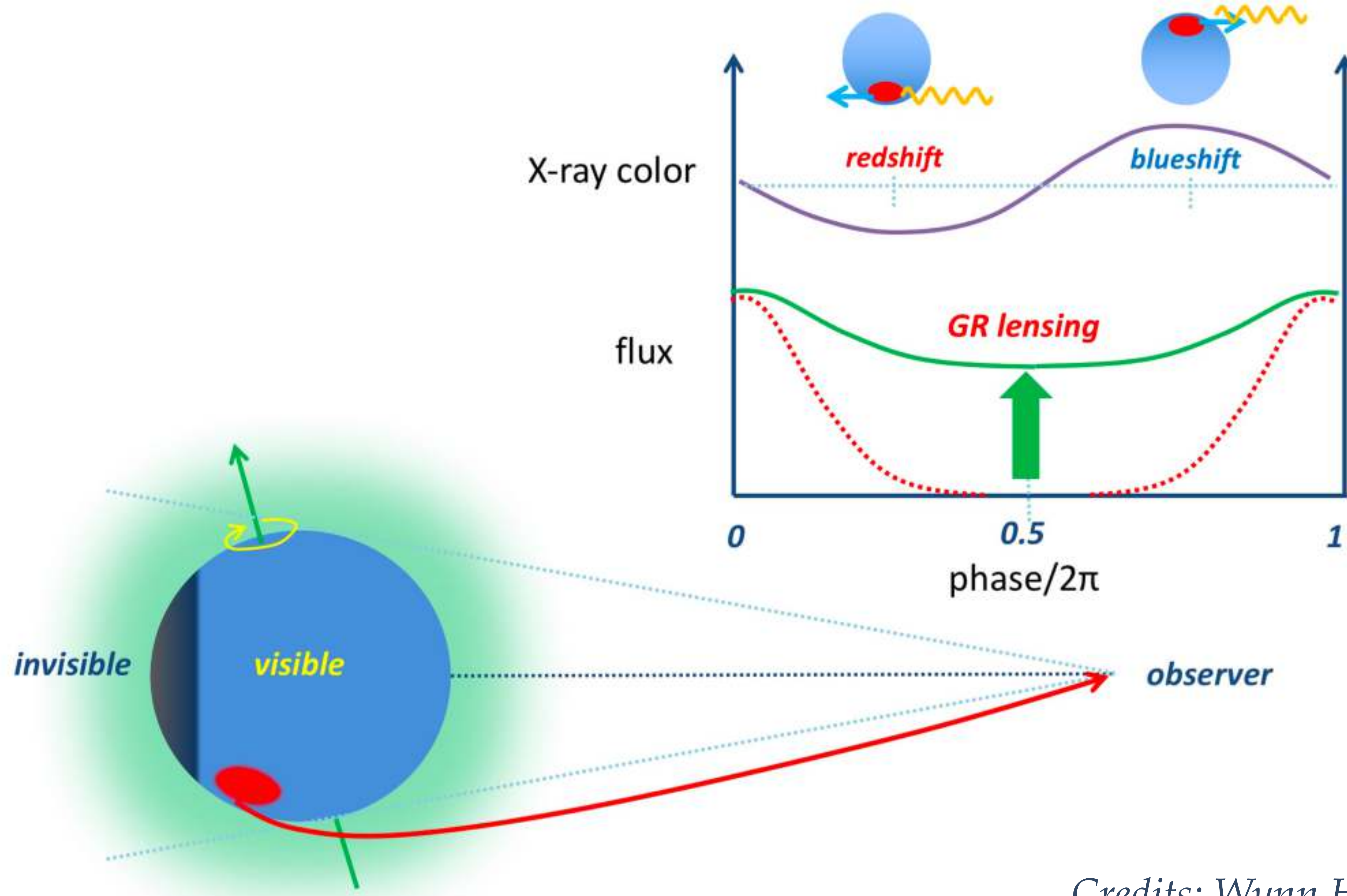


NS properties inference
(Likelihood statistical sampling)



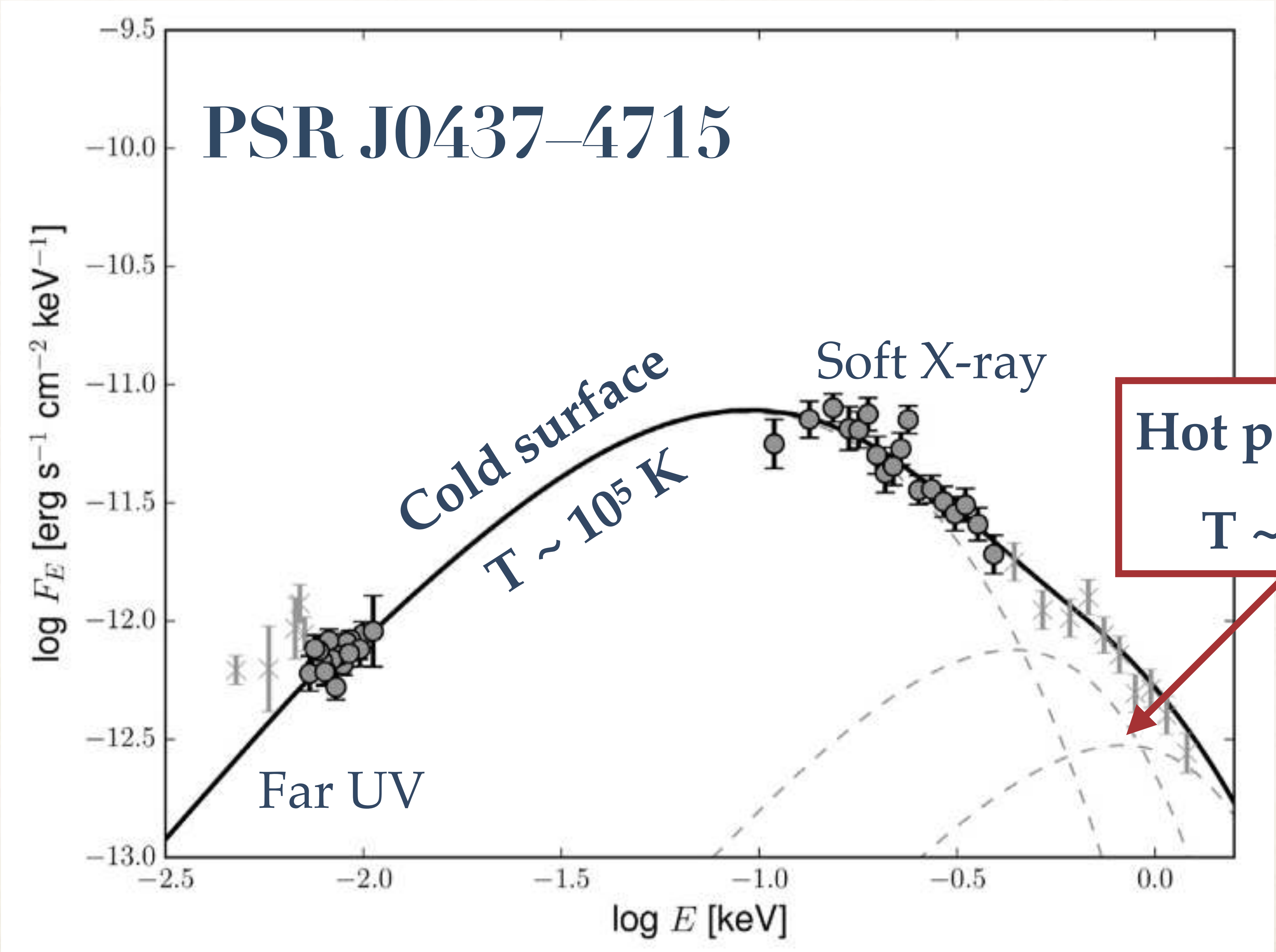


NICER produced one measurement of M_{NS} and R_{NS} and is on track to deliver 5% uncertainties for two other pulsars.



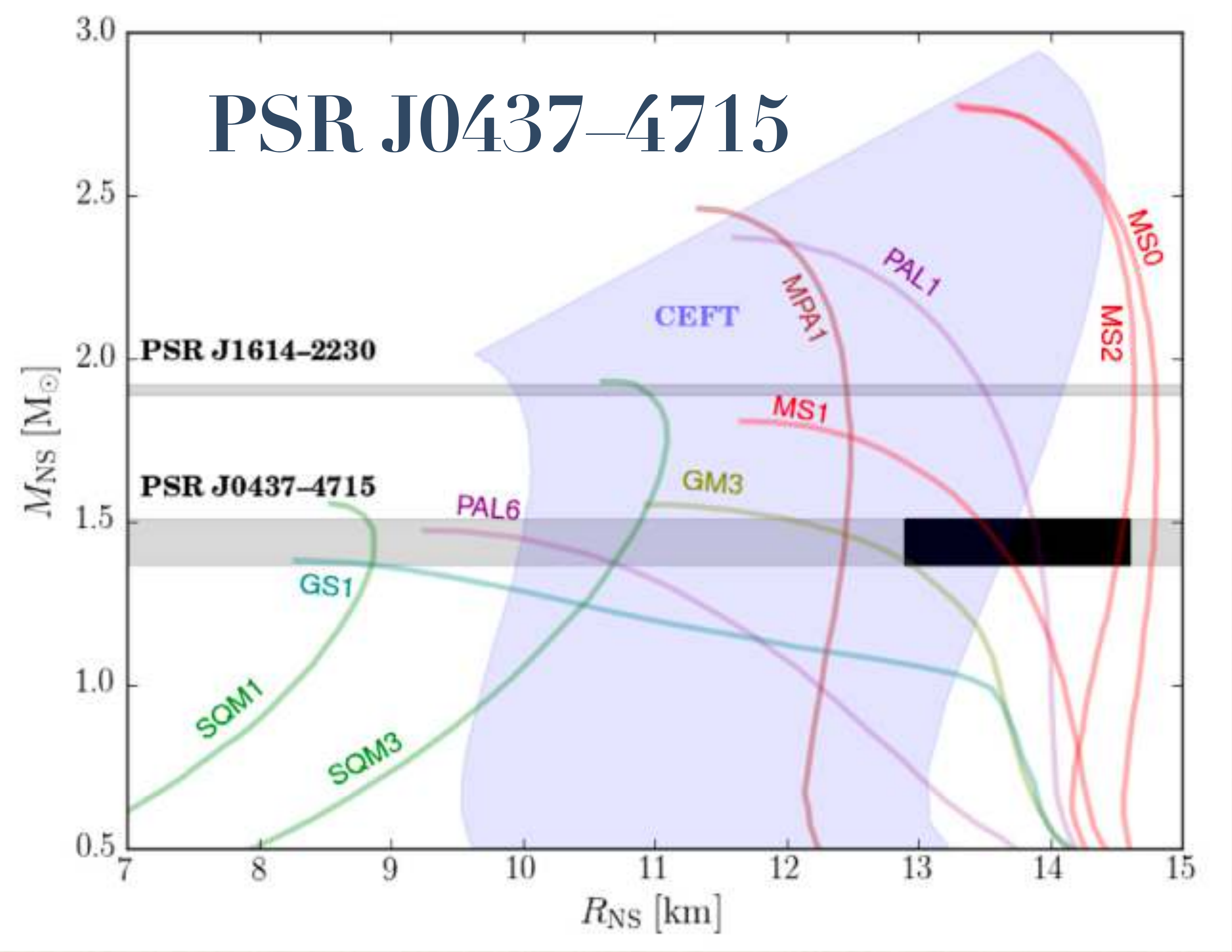
Credits: Wynn Ho

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

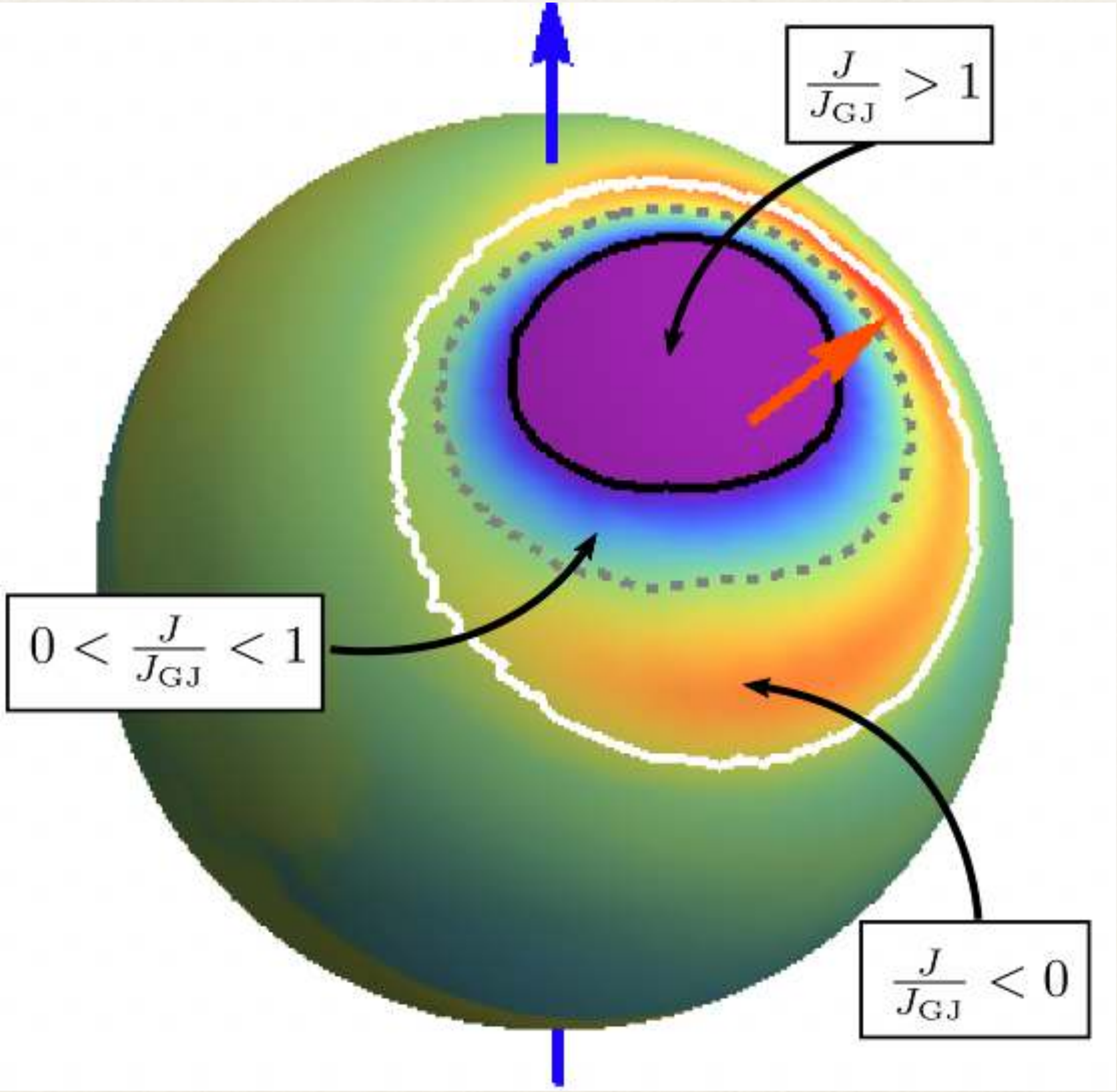


Gonzalez-Canuilef, Guillot & Reisenegger, 2019

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



Gonzalez-Canuilef, Guillot & Reisenegger 2019


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

To get $M_{NS}(R_{NS})$ from $P(\rho)$, one must solve the equations of stellar structure.

relativistic corrections

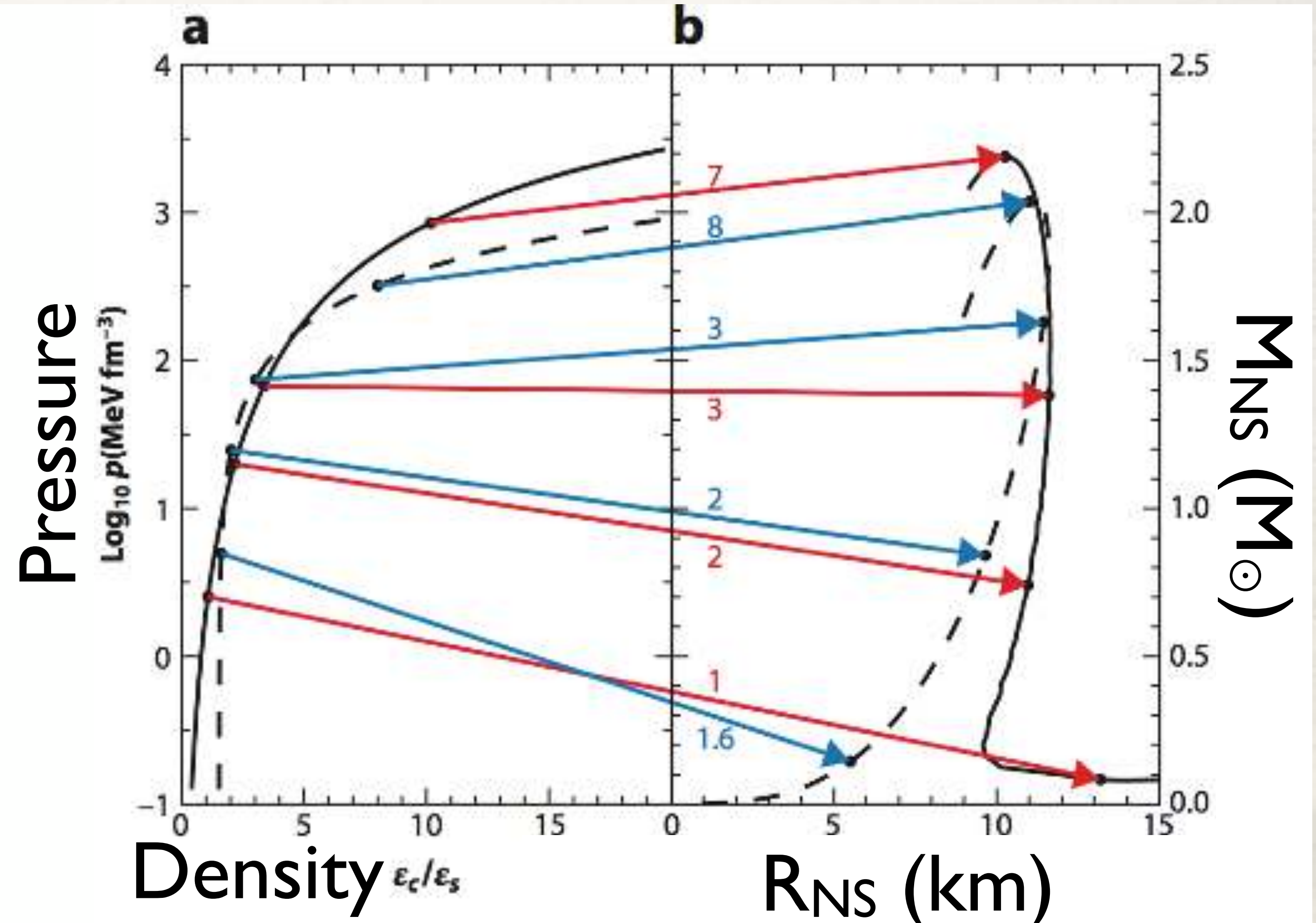
Hydrostatic equilibrium

$$\frac{dP}{dr} = -G\frac{\rho(r)M(r)}{r^2}\left(1+\frac{P(r)}{\rho(r)}\right)\left(1+\frac{4\pi r^3 P(r)}{M(r)}\right)\left(1-\frac{2GM(r)}{r}\right)^{-1}$$

Mass continuity

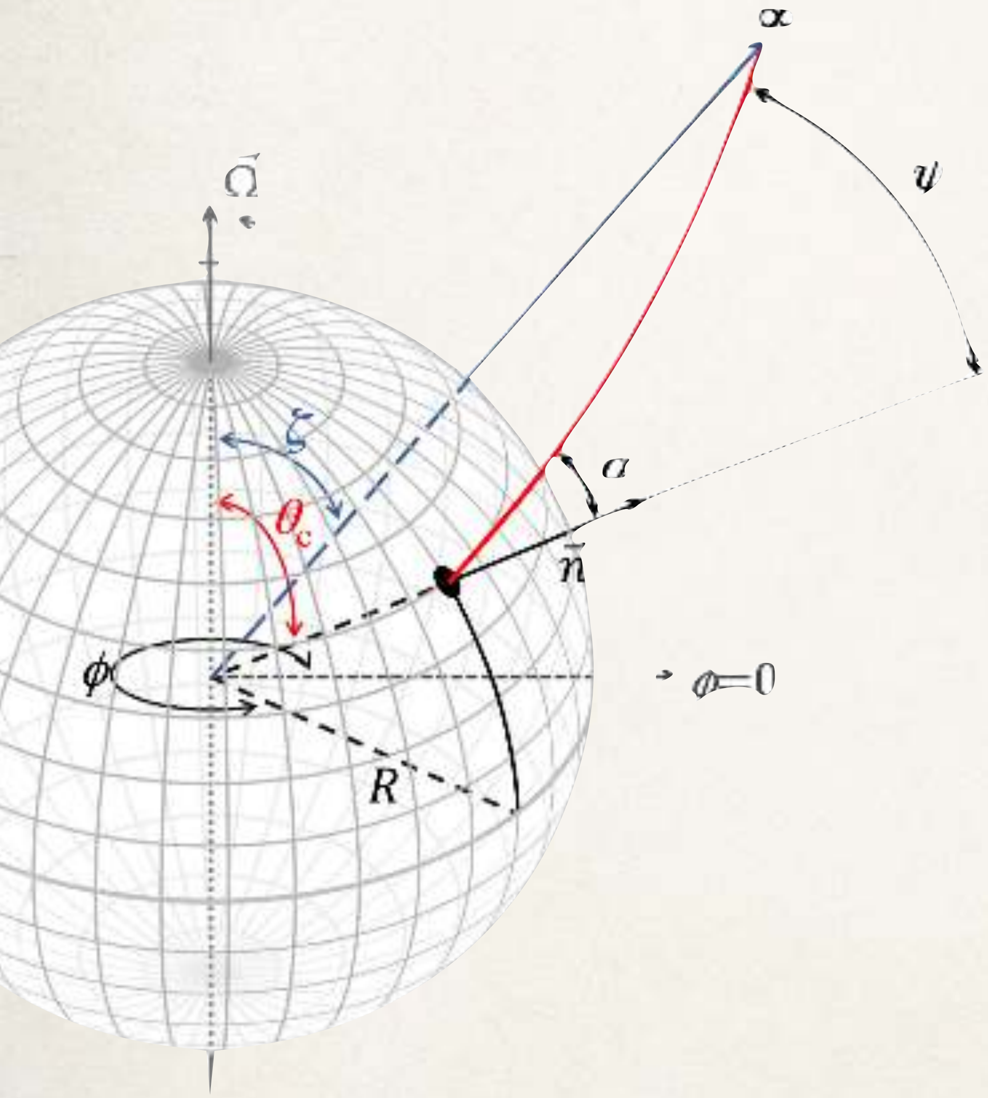
$$\frac{dM}{dr} = 4\pi r^2 \rho(r)$$

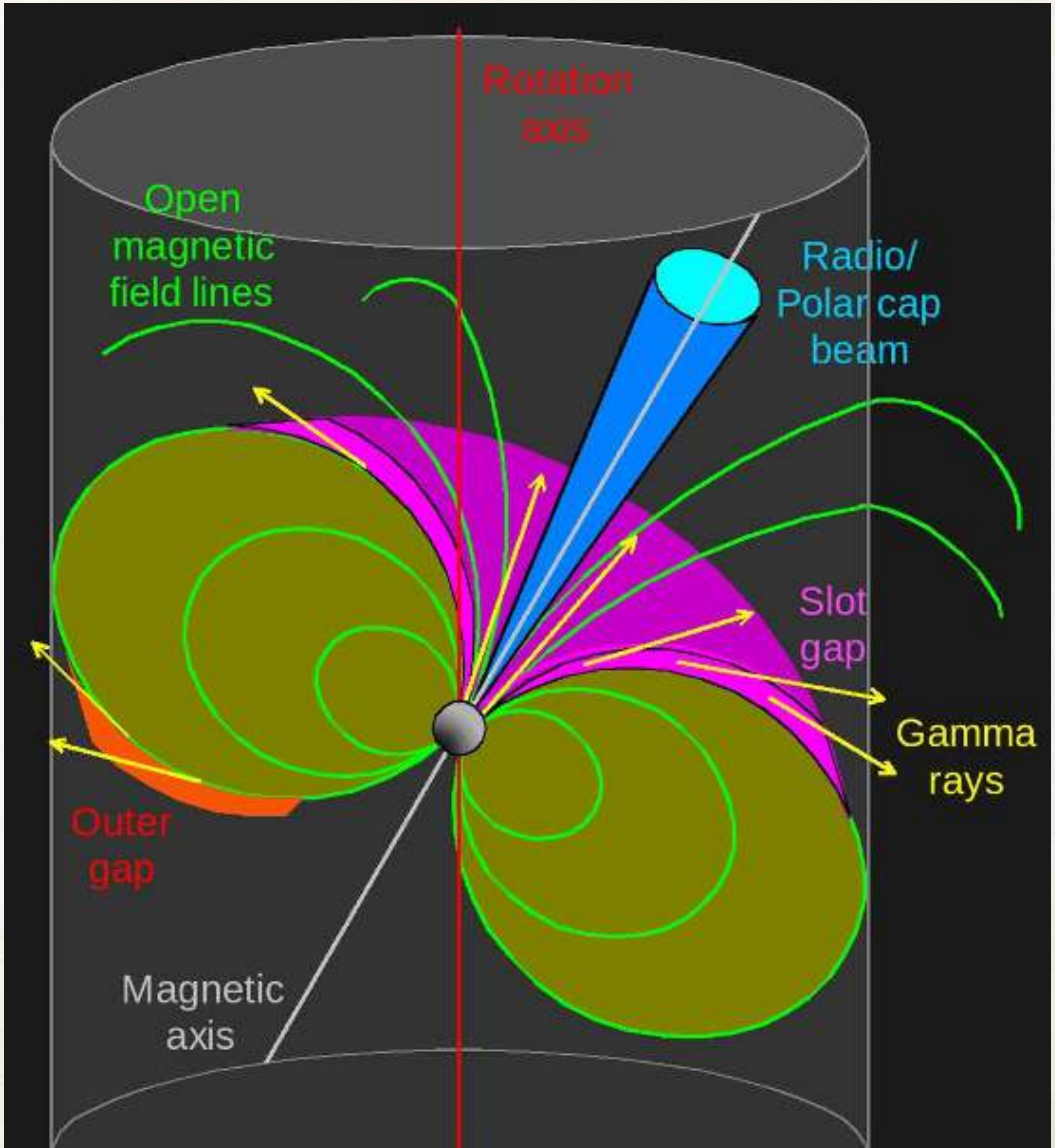
Tolman-Oppenheimer-Volkoff equations



J. Lattimer, 2012

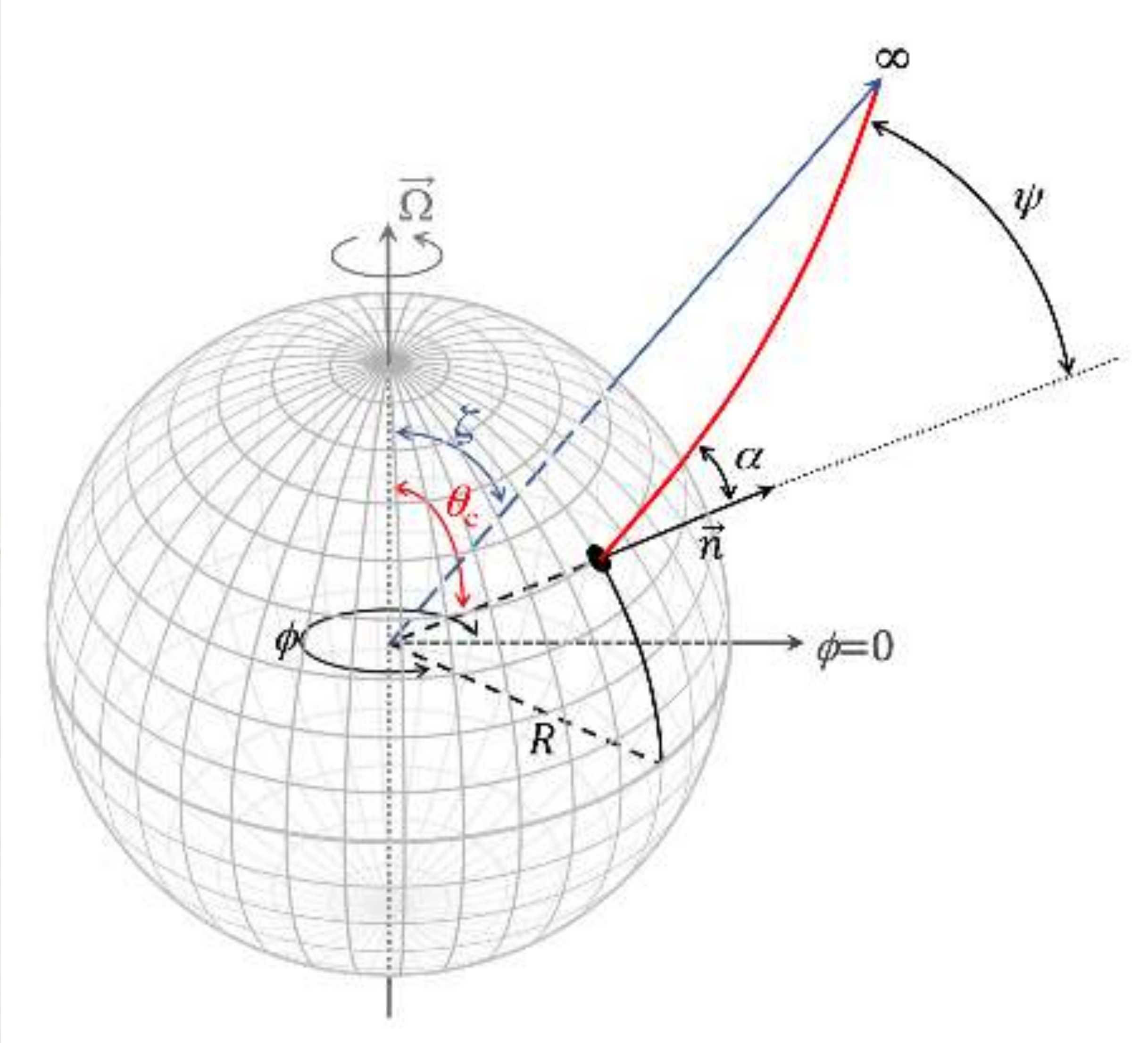
An independent measurement of the geometry (two angles) helps the light curve modelling.





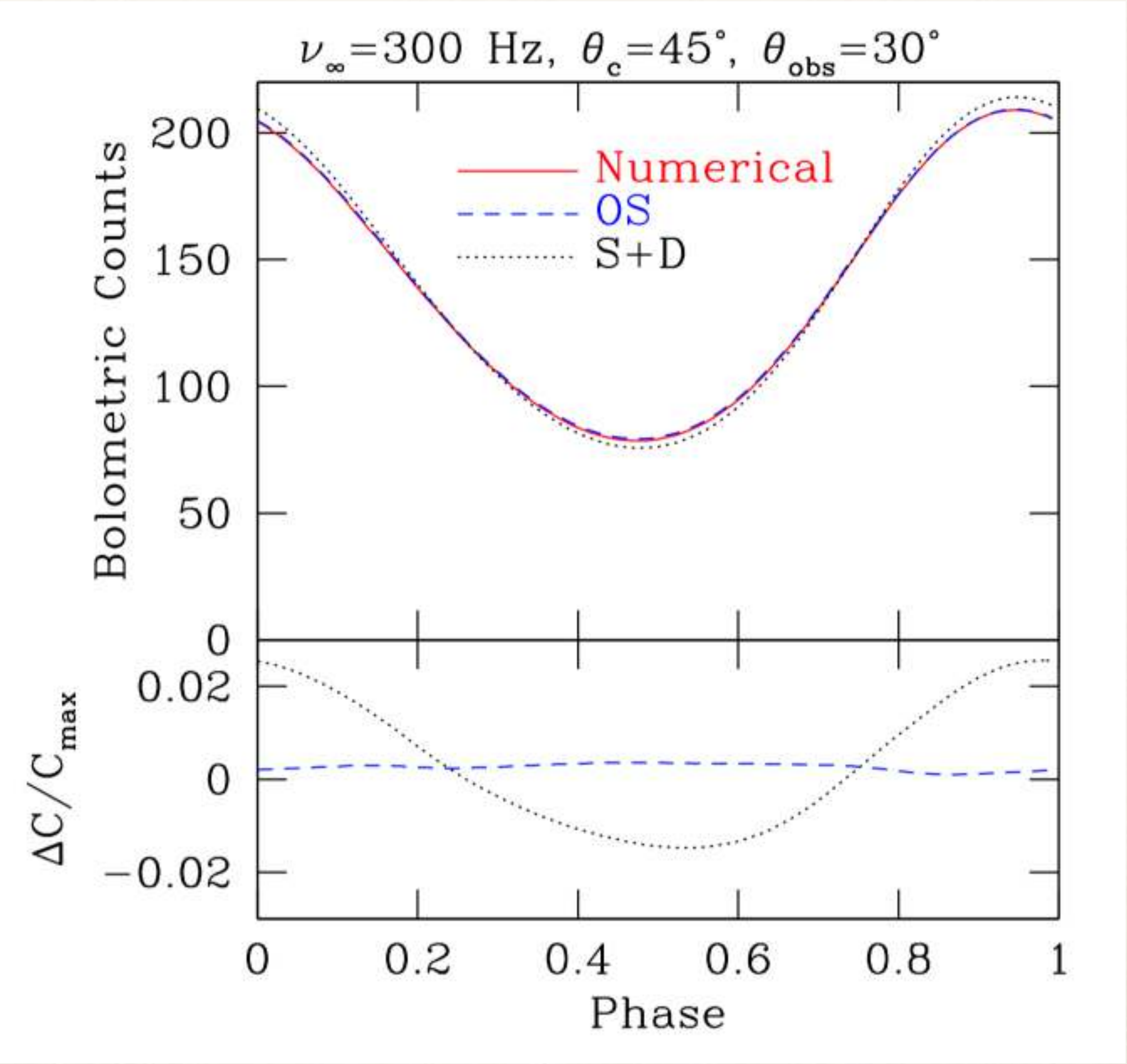
The curved spacetime around the neutron stars bends photon trajectories, but not only!

$$f_0 = \sqrt{\frac{GM}{R^3}}$$



- $f_{spin} \lll f_0$: Schwarzschild approx.
  Pechenick et al. 1983
- $f_{spin} \ll f_0$: Schwarzschild+Doppler approx. (includes time delays, Doppler boost/aberration, Frame dragging)
  Miller & Lamb 1998
- $f_{spin} \lesssim f_0$: Oblate star.
  Morsink et al. 2007

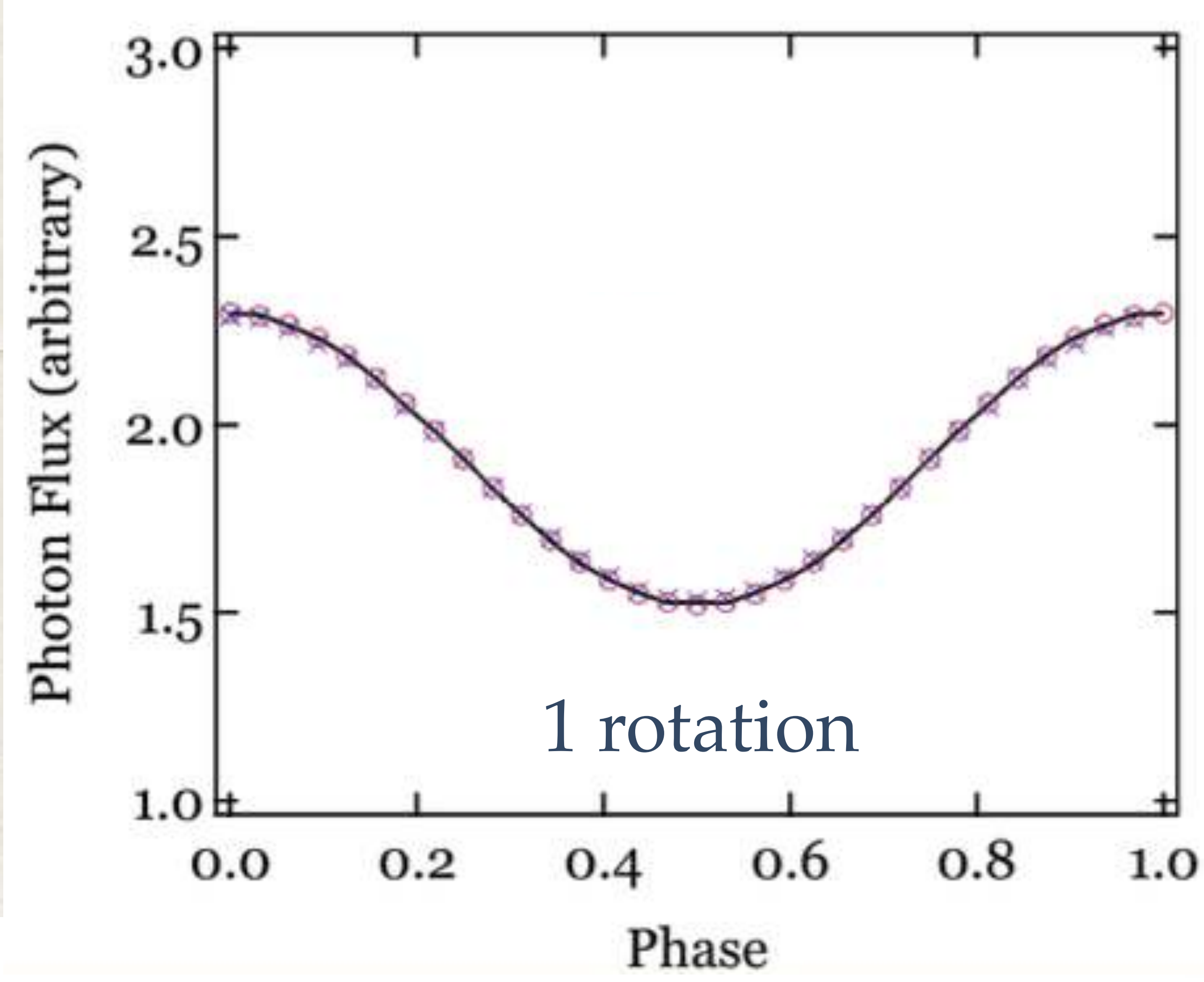
For fast and reliable modelling of the light curve of MSPs, we have to use approximations.



Also, very fast rotating neutron stars can help resolve degeneracies.

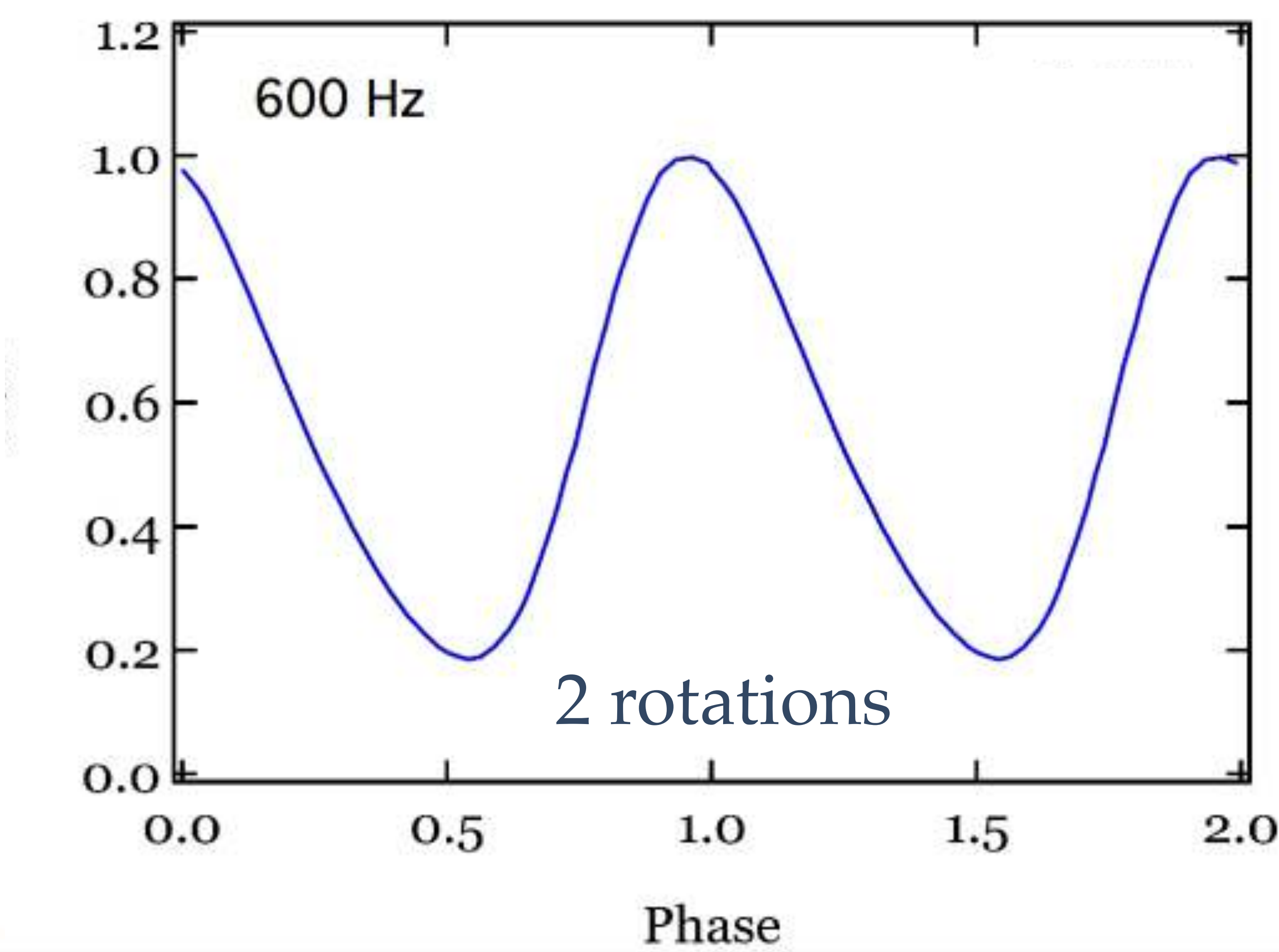
f_{spin} < 300 Hz

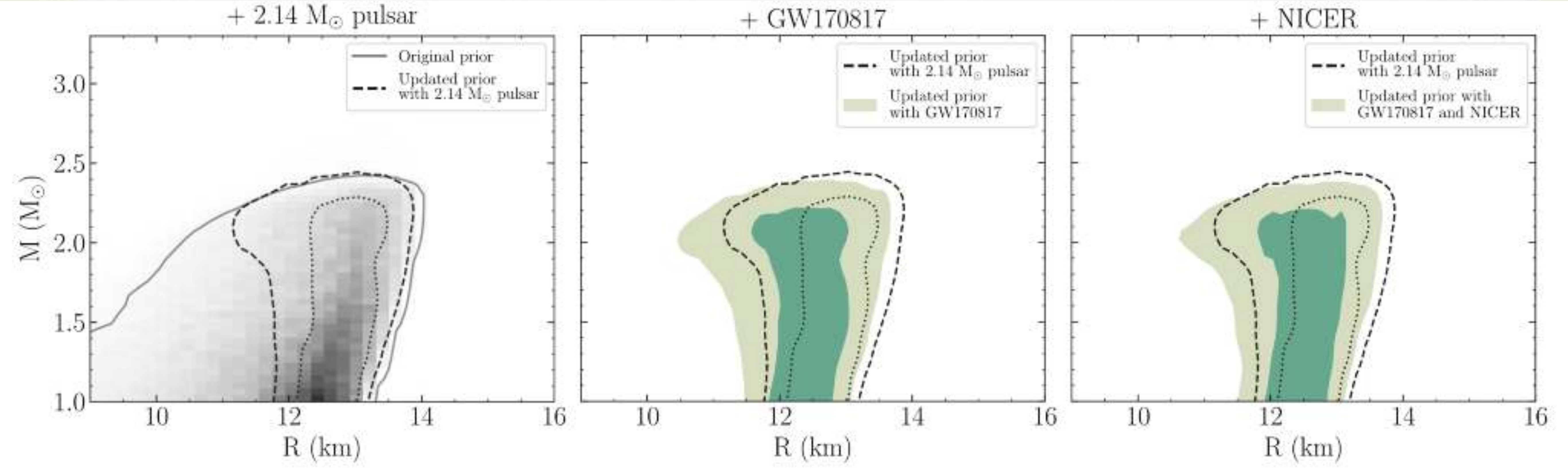
the pulse profile is sinusoidal. M_{NS}/R_{NS} is highly correlated with the geometry.



f_{spin} > 300 Hz

relativistic effects make the pulse profile asymmetric, which break degeneracies.





Raaijmakers, …, SG et al. 2020