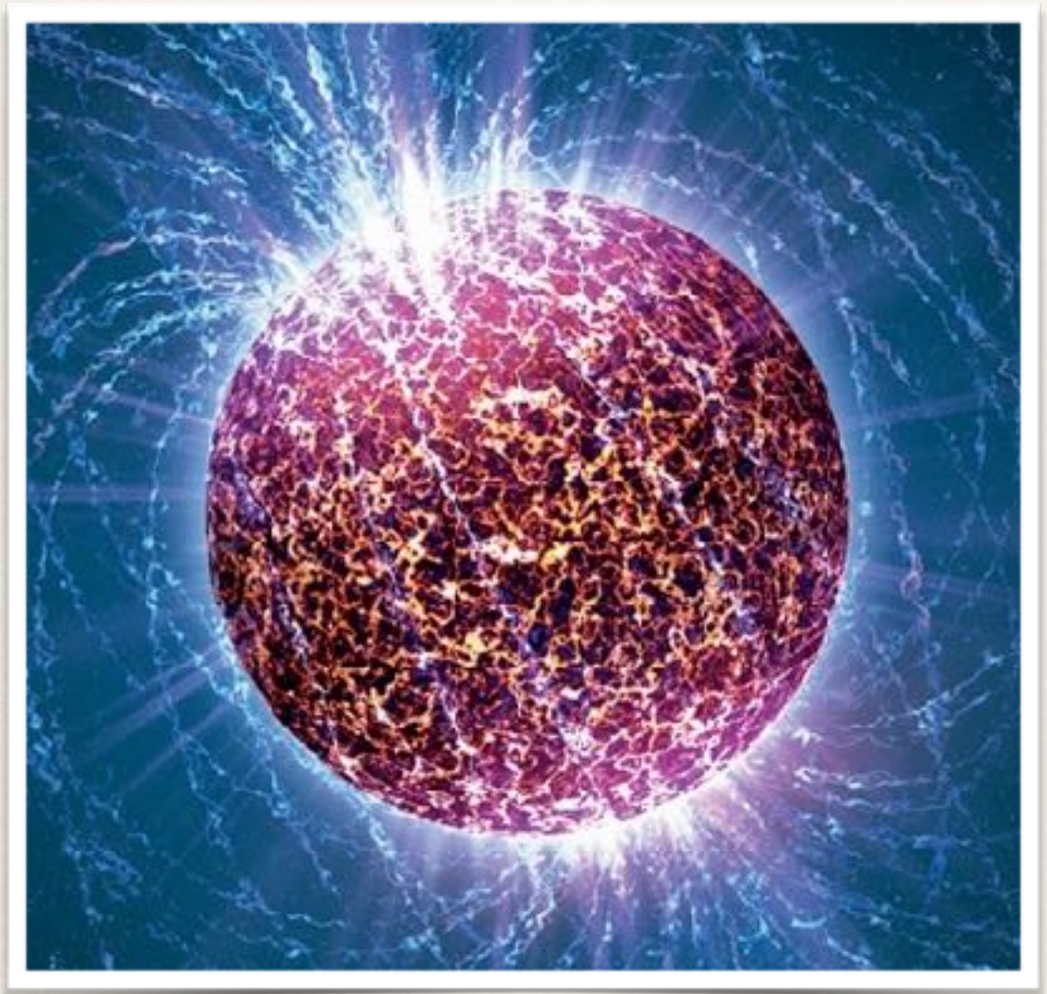
First results on the Equation of state constraints from NICER

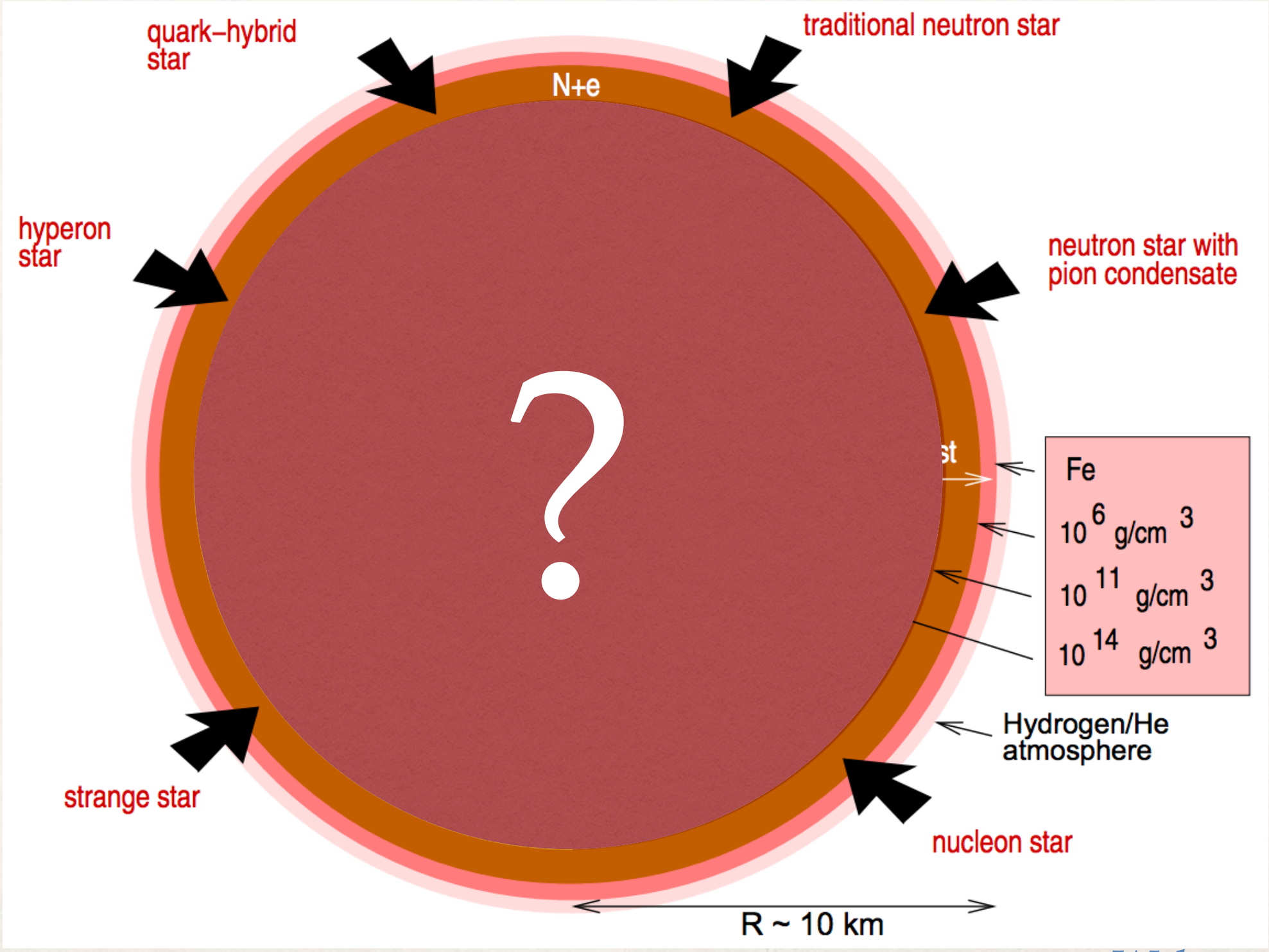


Sebastien Guillot

Institut de Recherche en Astrophysique et Planétologie, Toulouse, France

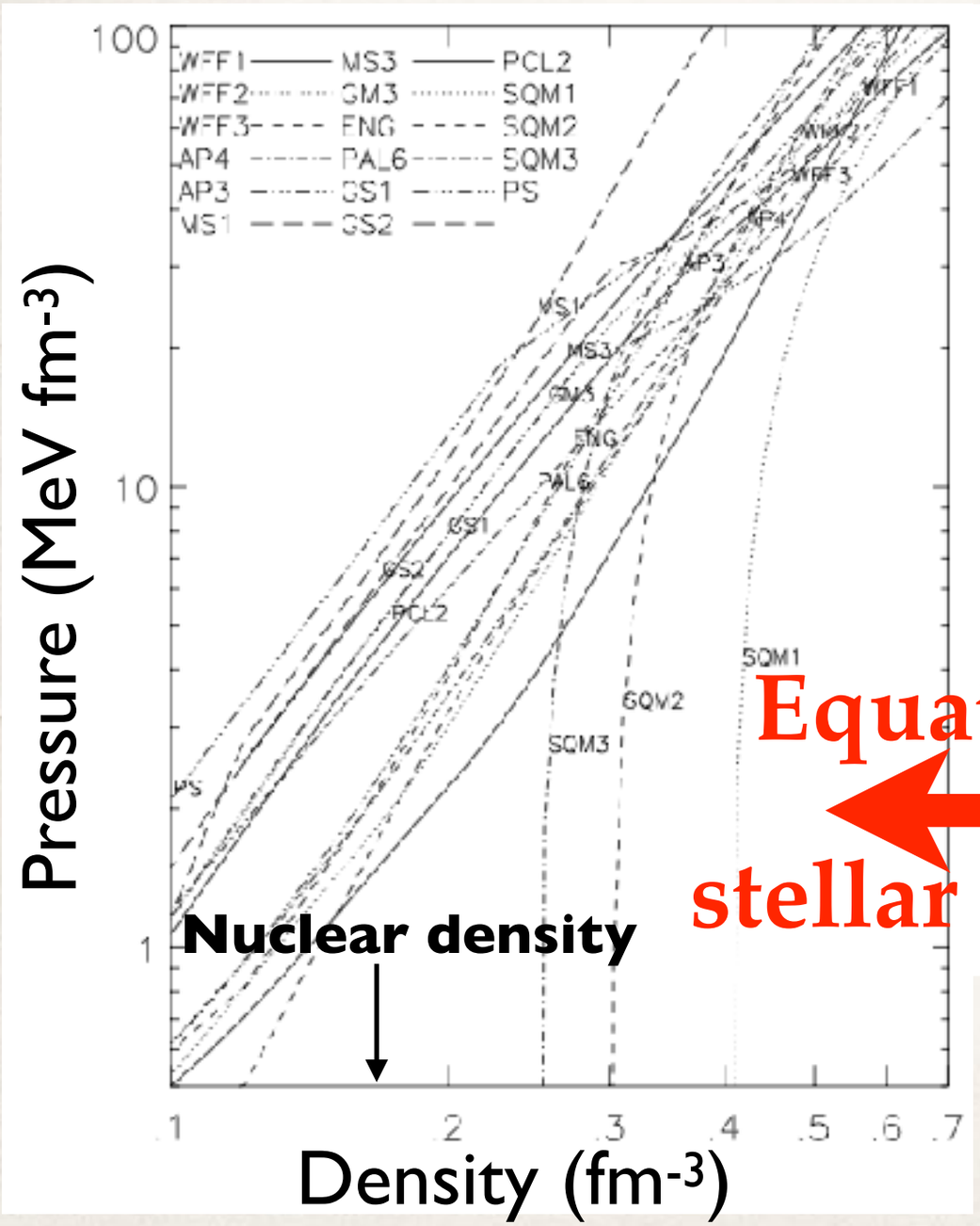
Post-doc CNES

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

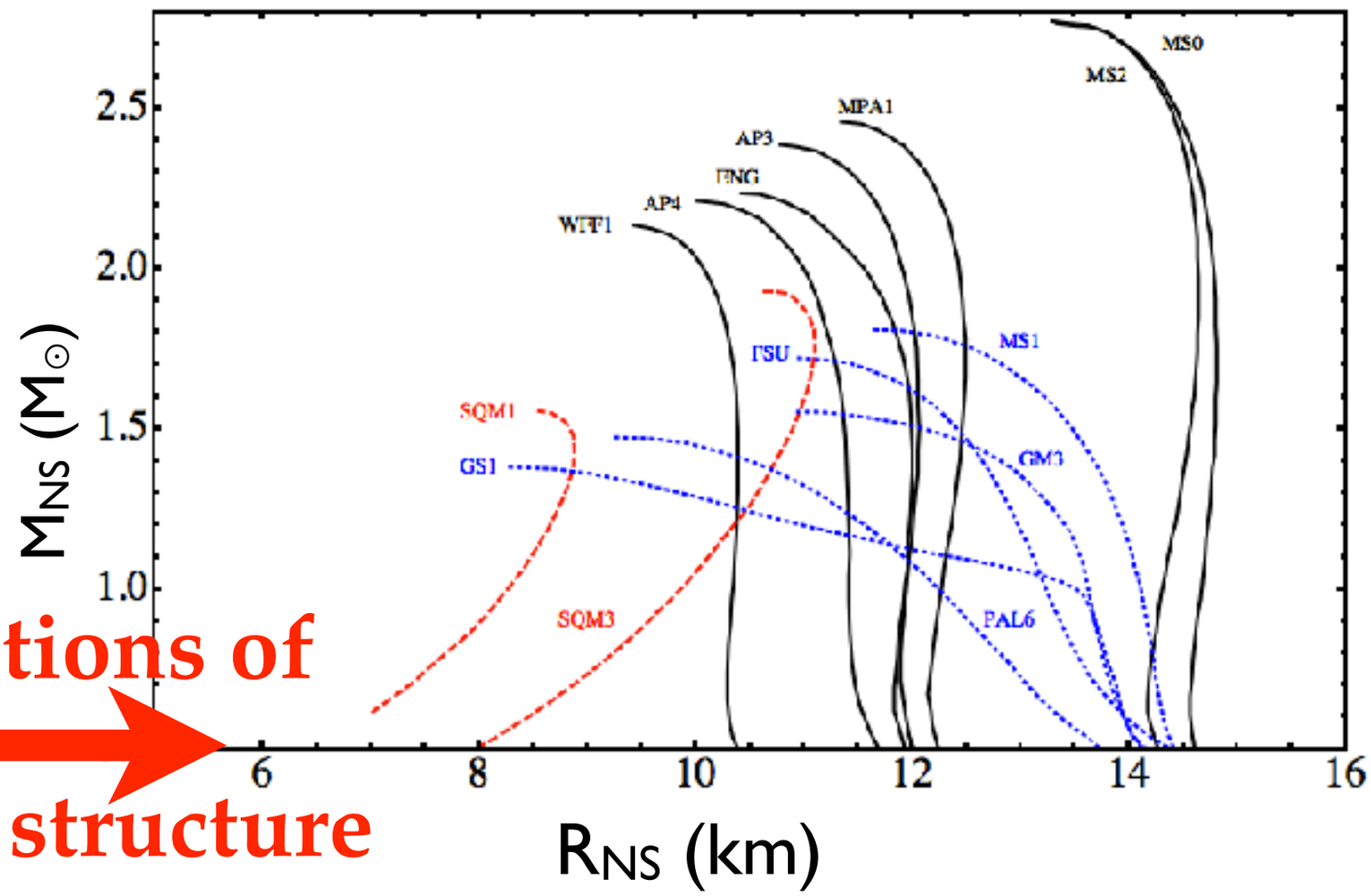


Weber et al. 2007

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

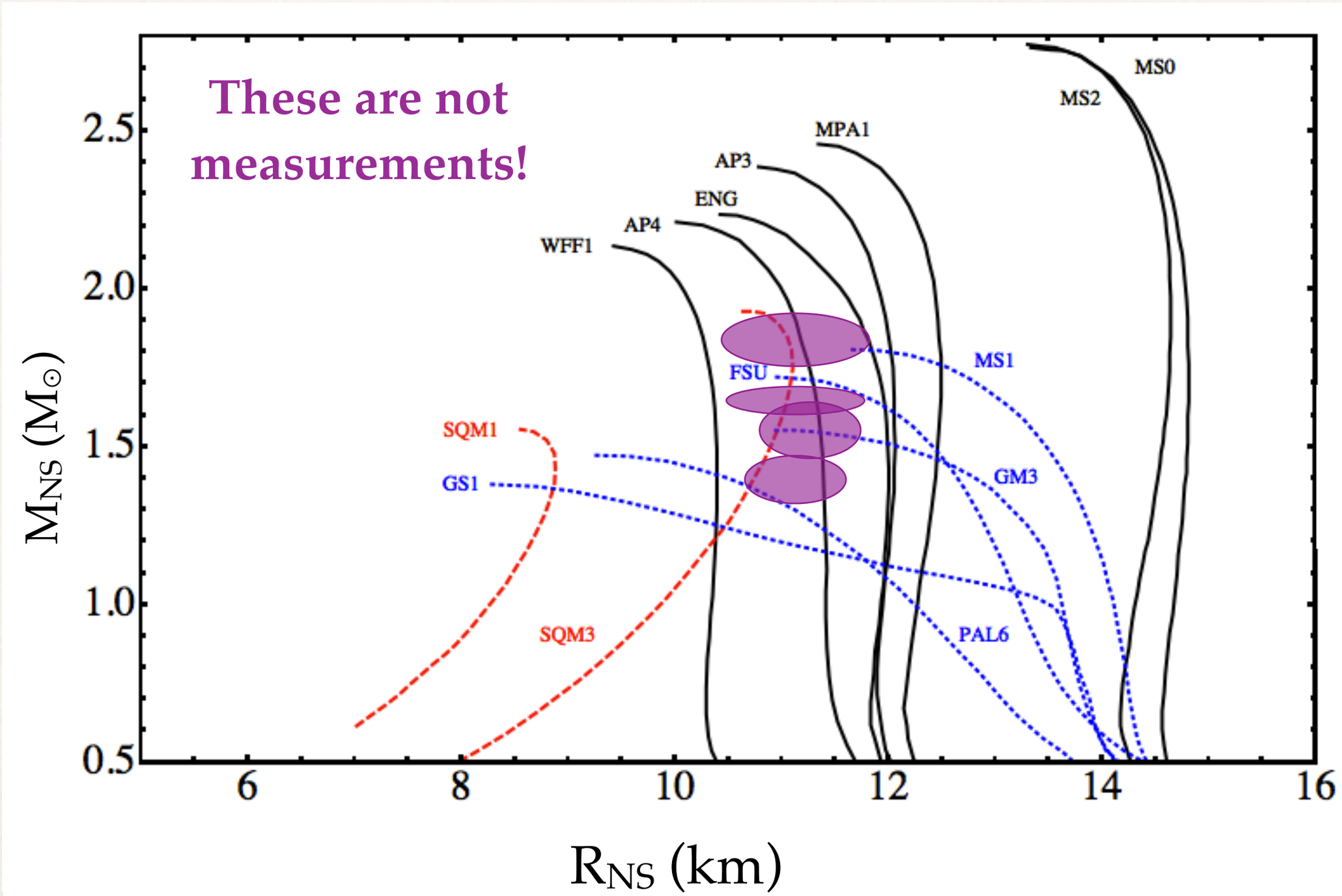


Equations of stellar structure

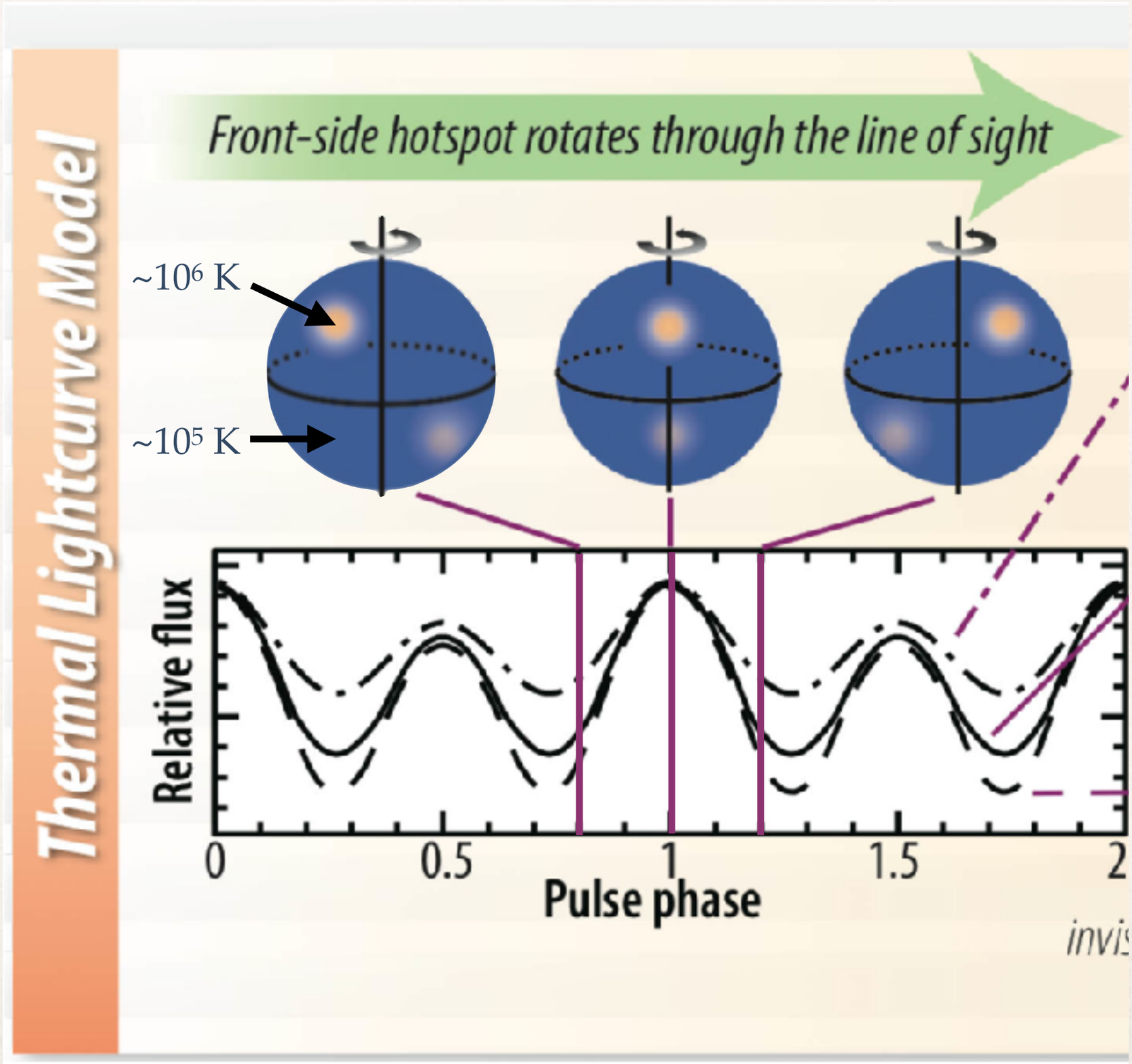


Lattimer and Prakash 2001

Ideally, we want measurements of both the mass M_{NS} and the radius R_{NS}.

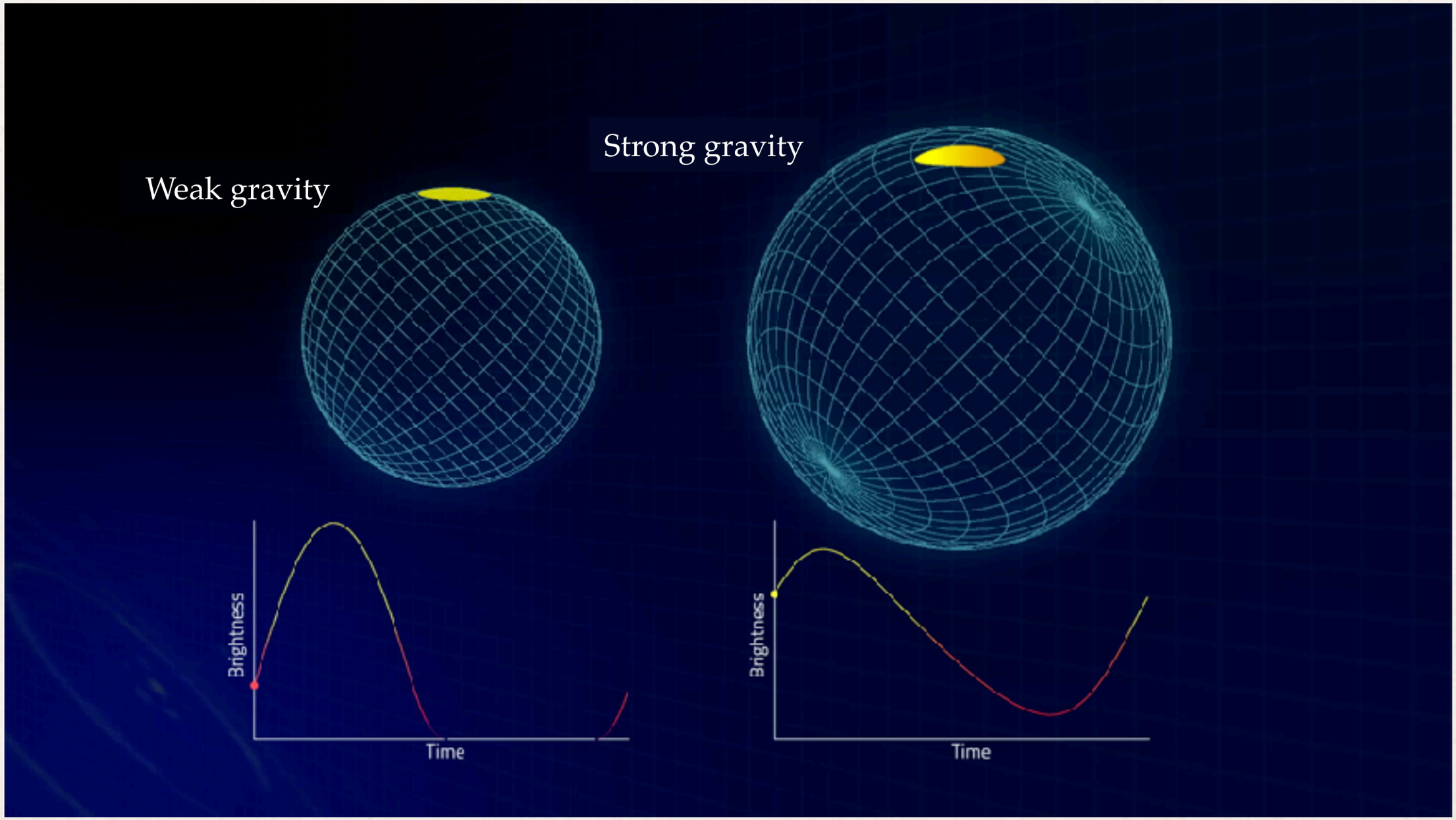


The pulsed emission caused by hot spots on a rotating neutron star can help measure the compactness.



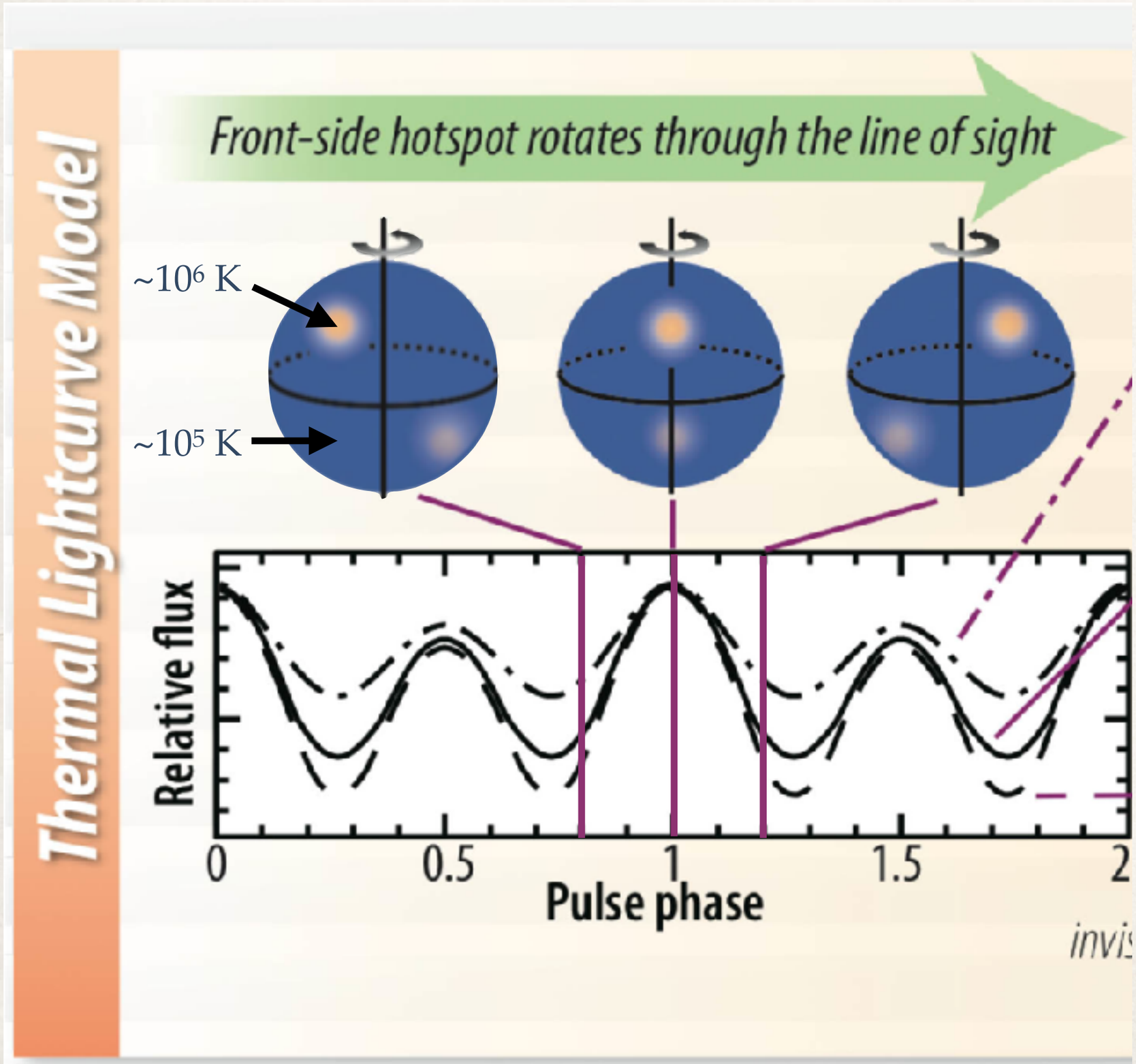
Credits: NASA/NICER

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



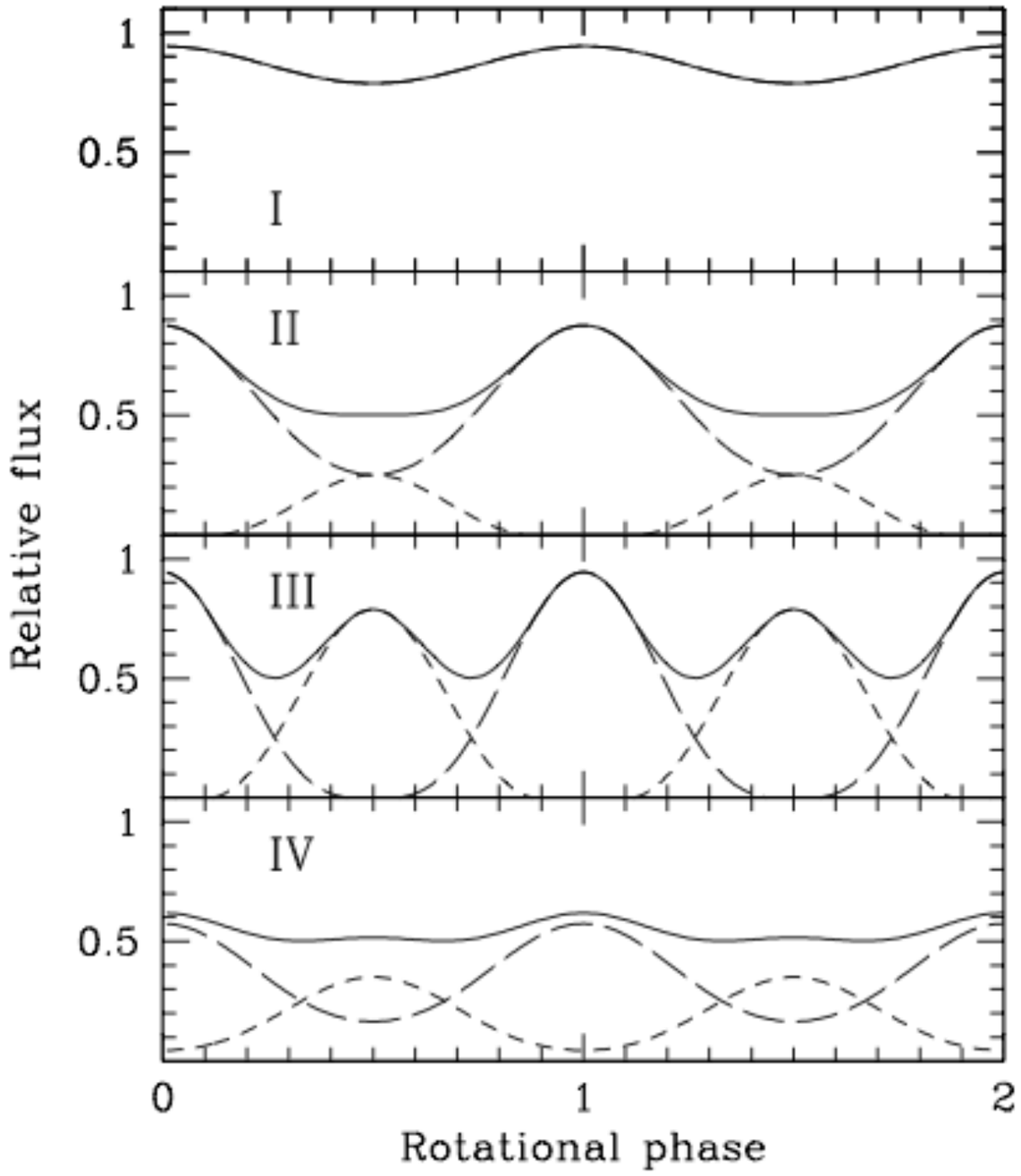
Credits: S. Morsink / NASA

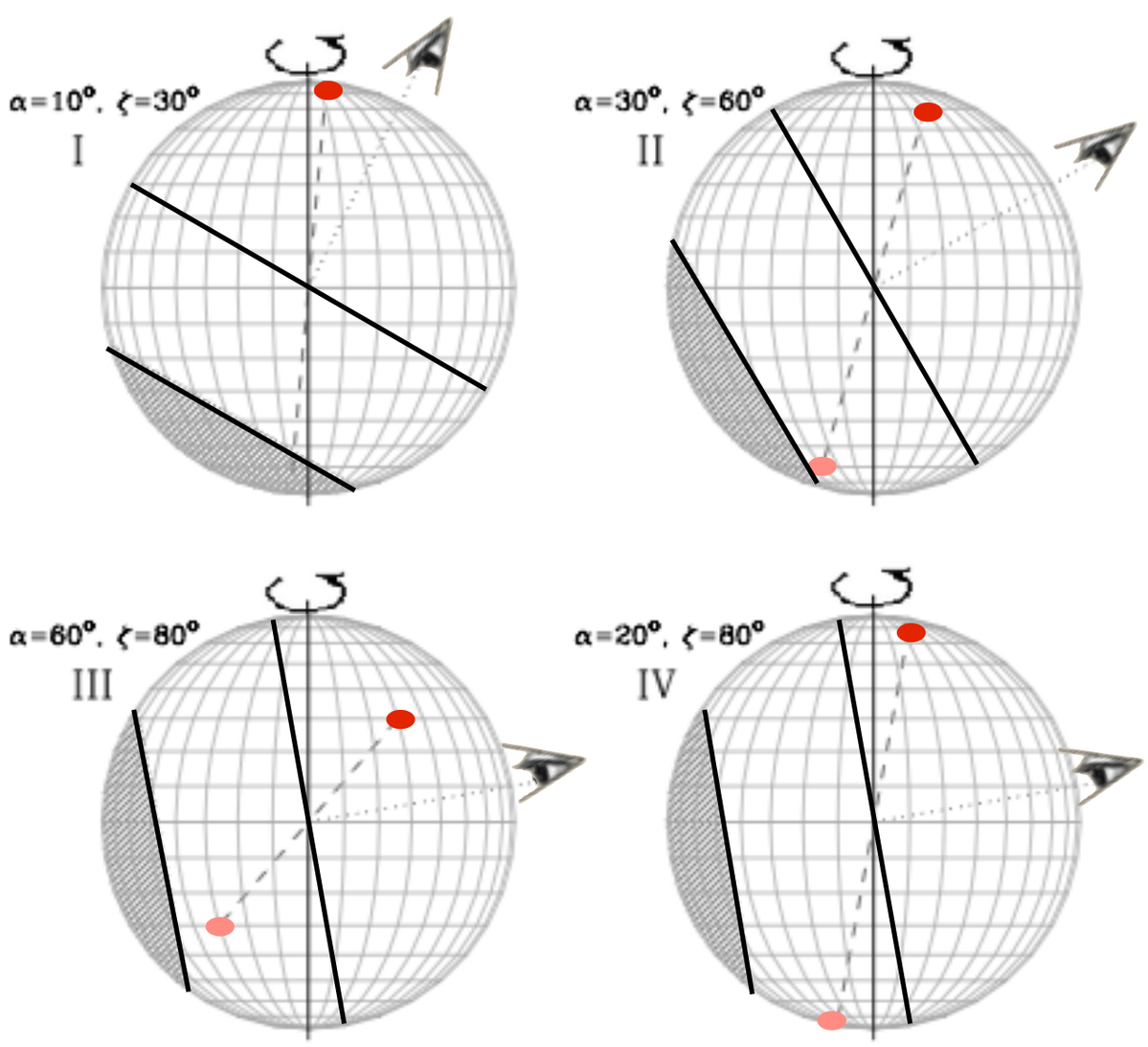
The pulsed emission caused by hot spots on a rotating neutron star can help measure the compactness.



Credits: NASA/NICER

The pulsed emission also depends on the system geometry.



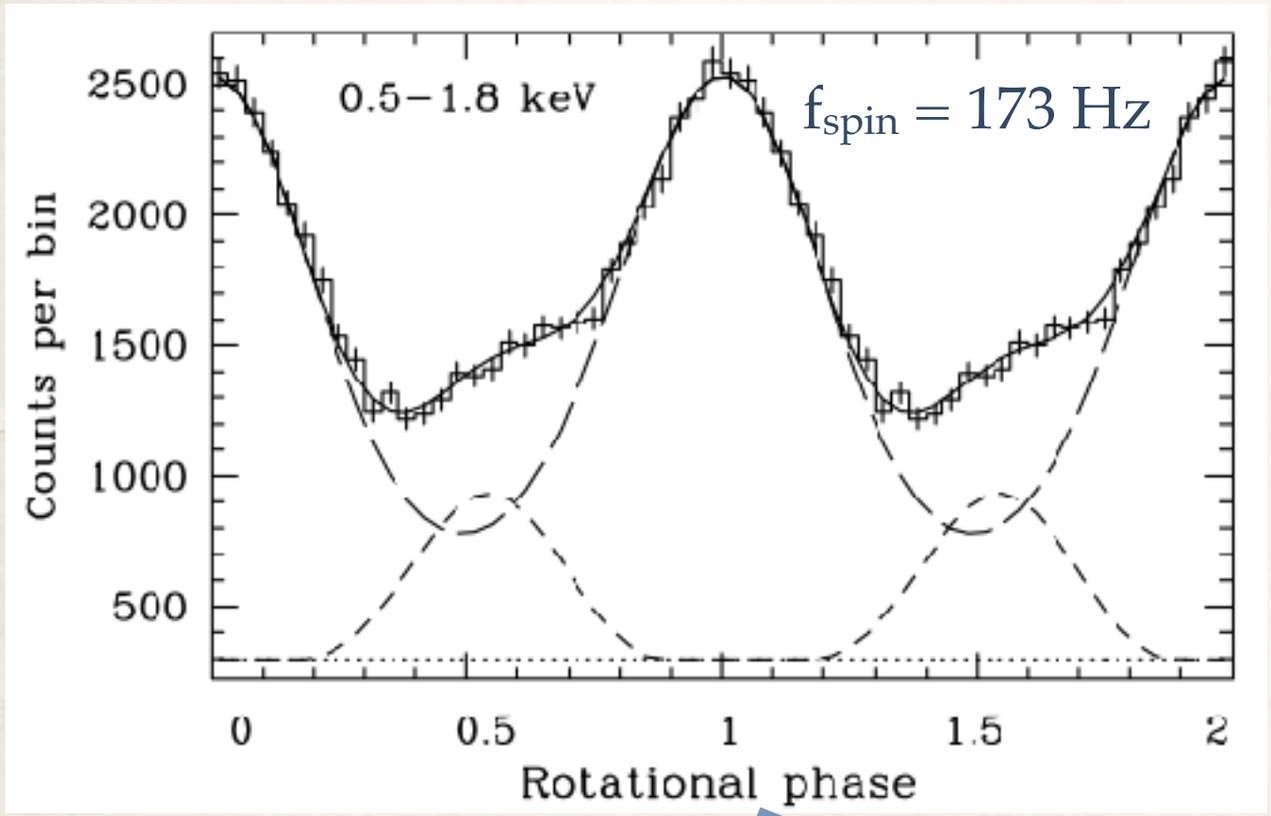


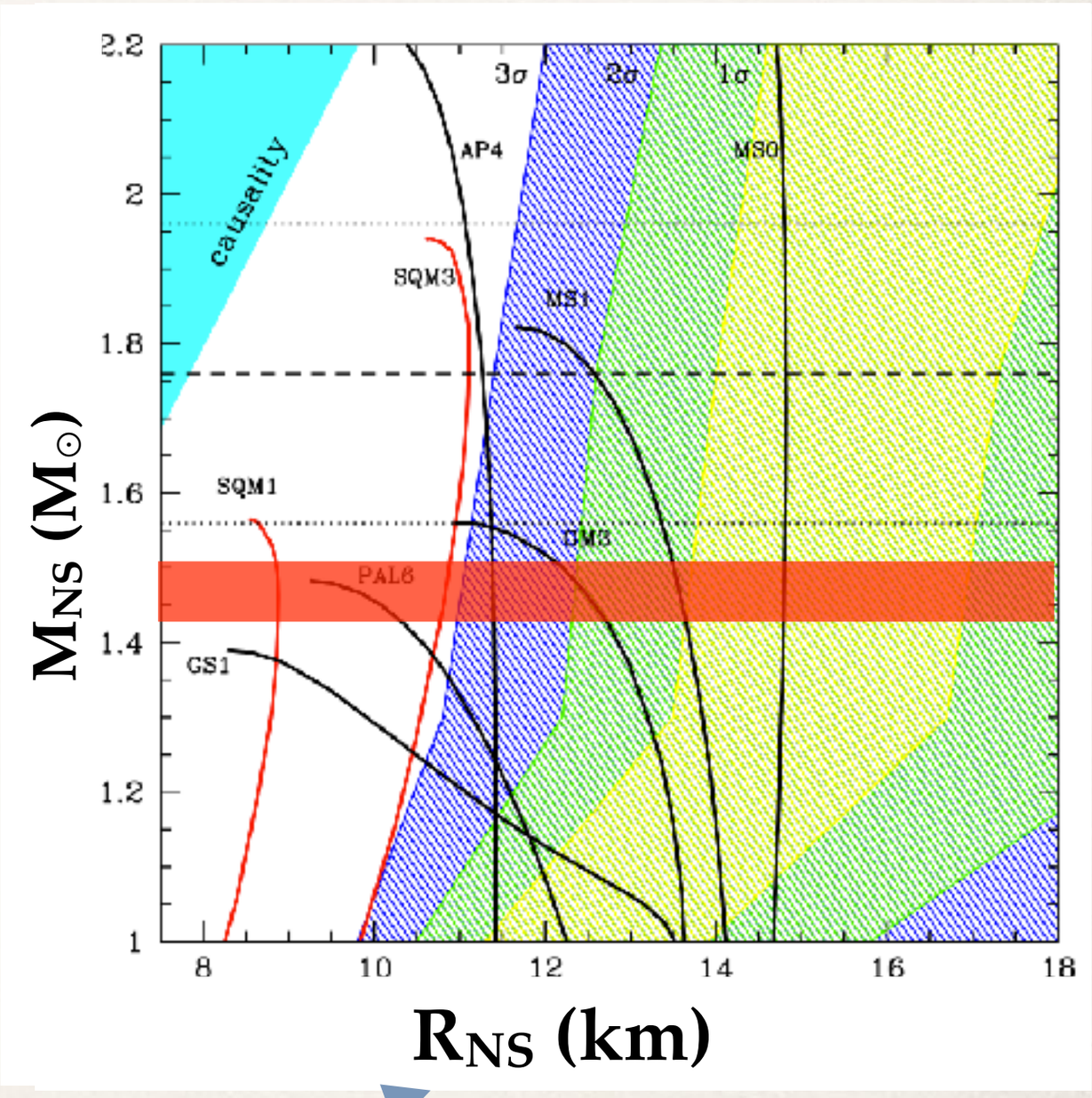
$M_{NS} = 1.4\ M_{\odot}$, $R_{NS} = 10\text{km}$

(Bodganov et al. 2008)

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

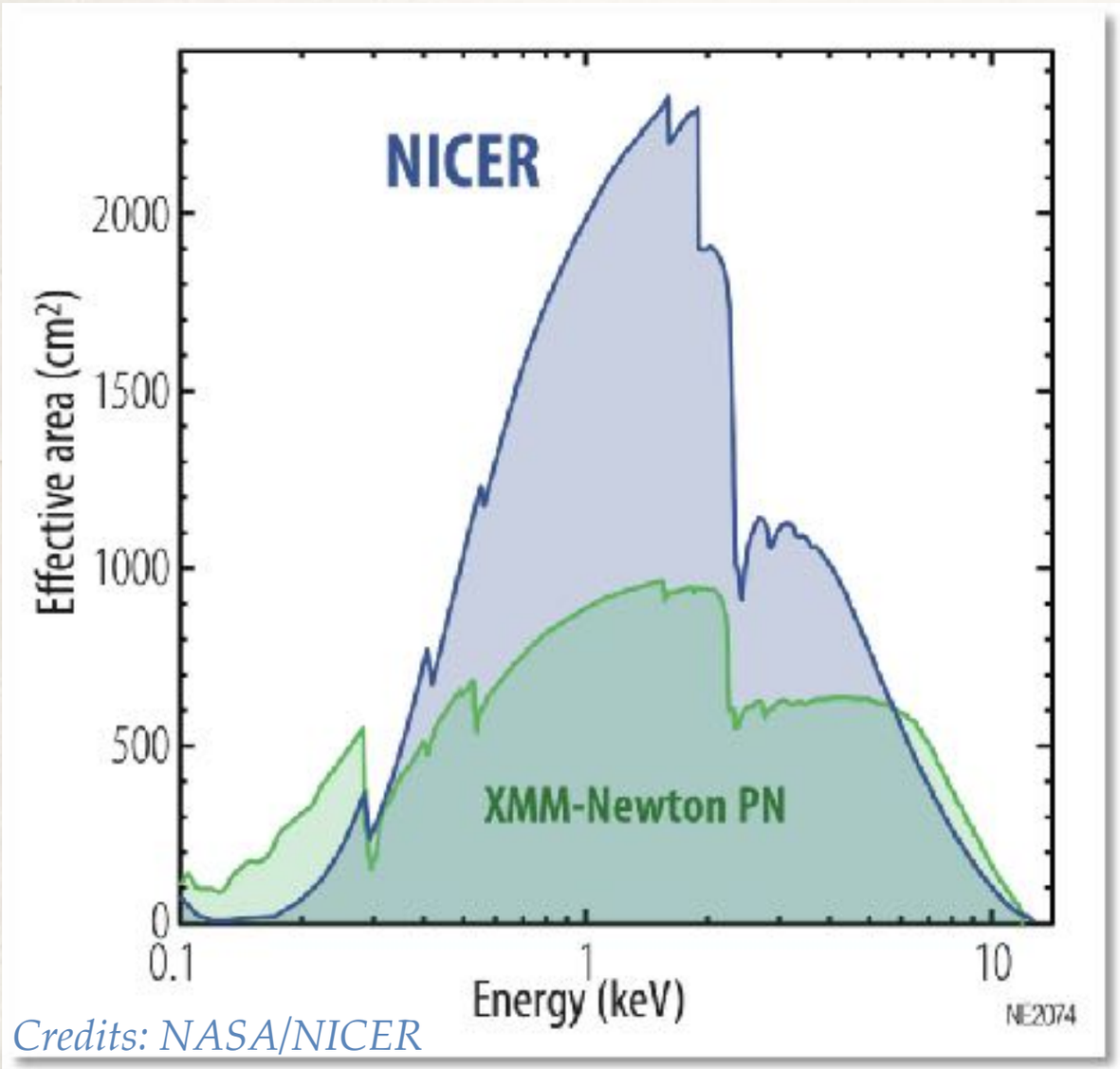
PSR J0437-4715 with XMM-Newton



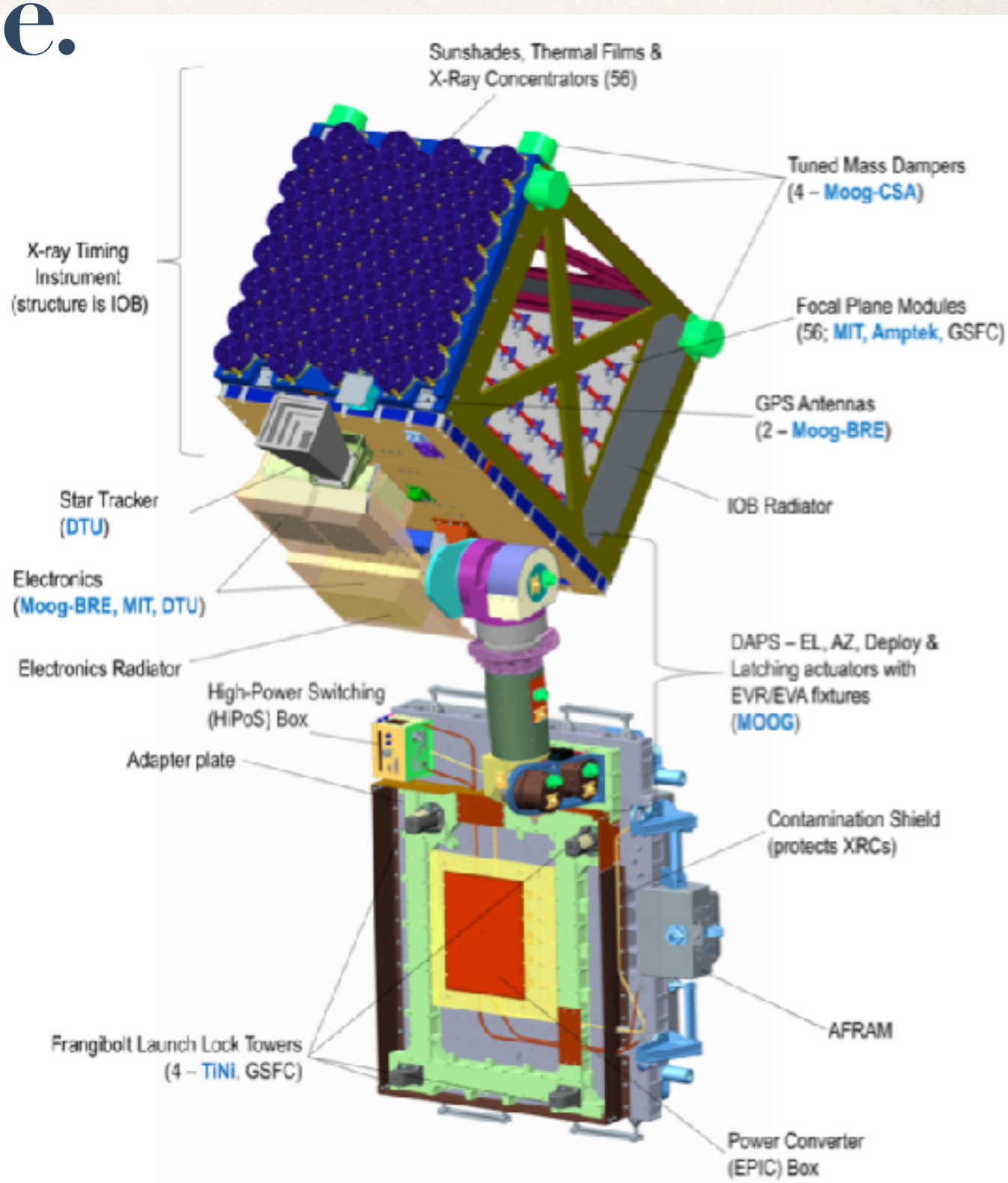


M/R extracted from lightcurve *Bogdanov (2013)*

NICER is NASA's fast X-ray photon counting machine.

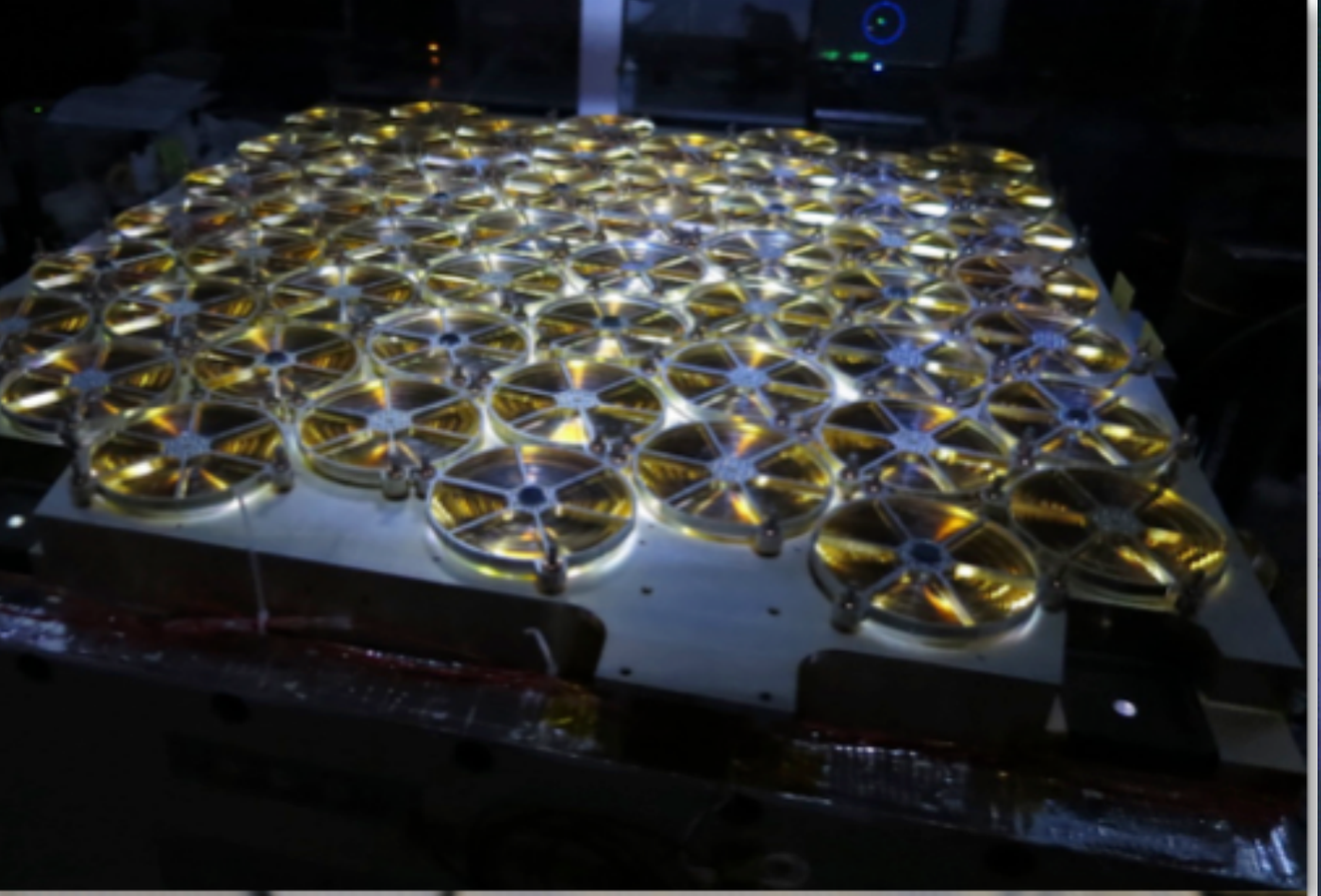


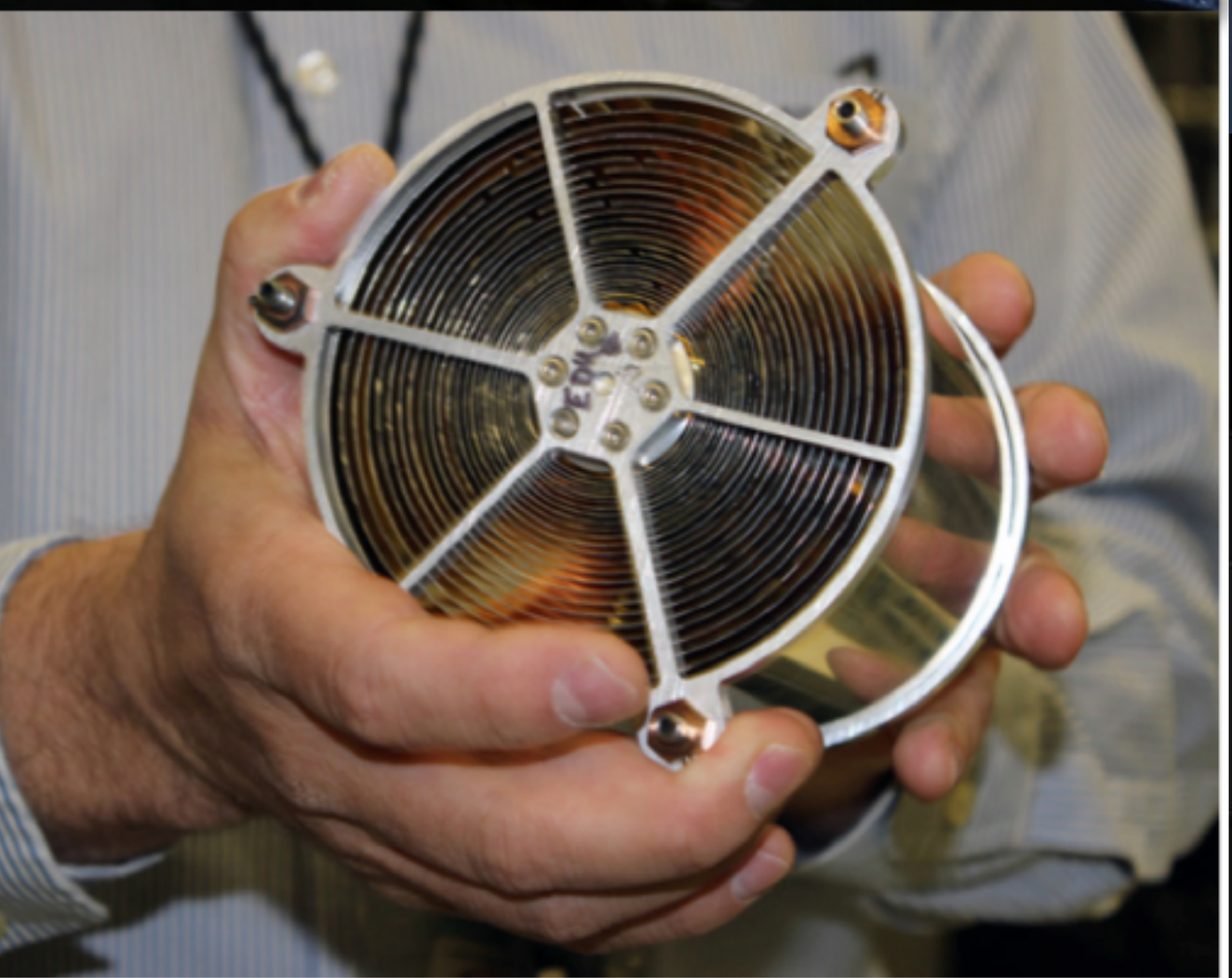
Credits: NASA/NICER

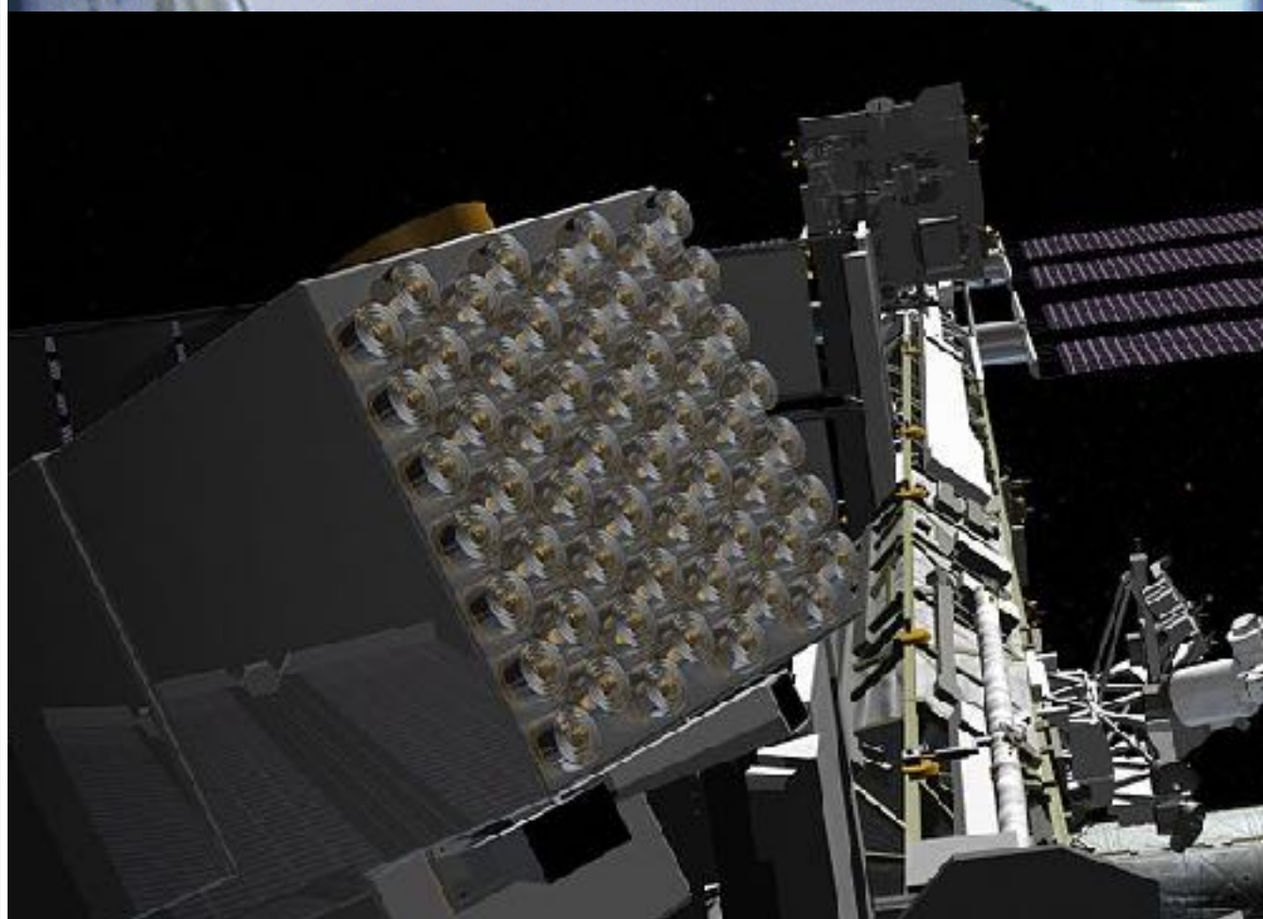


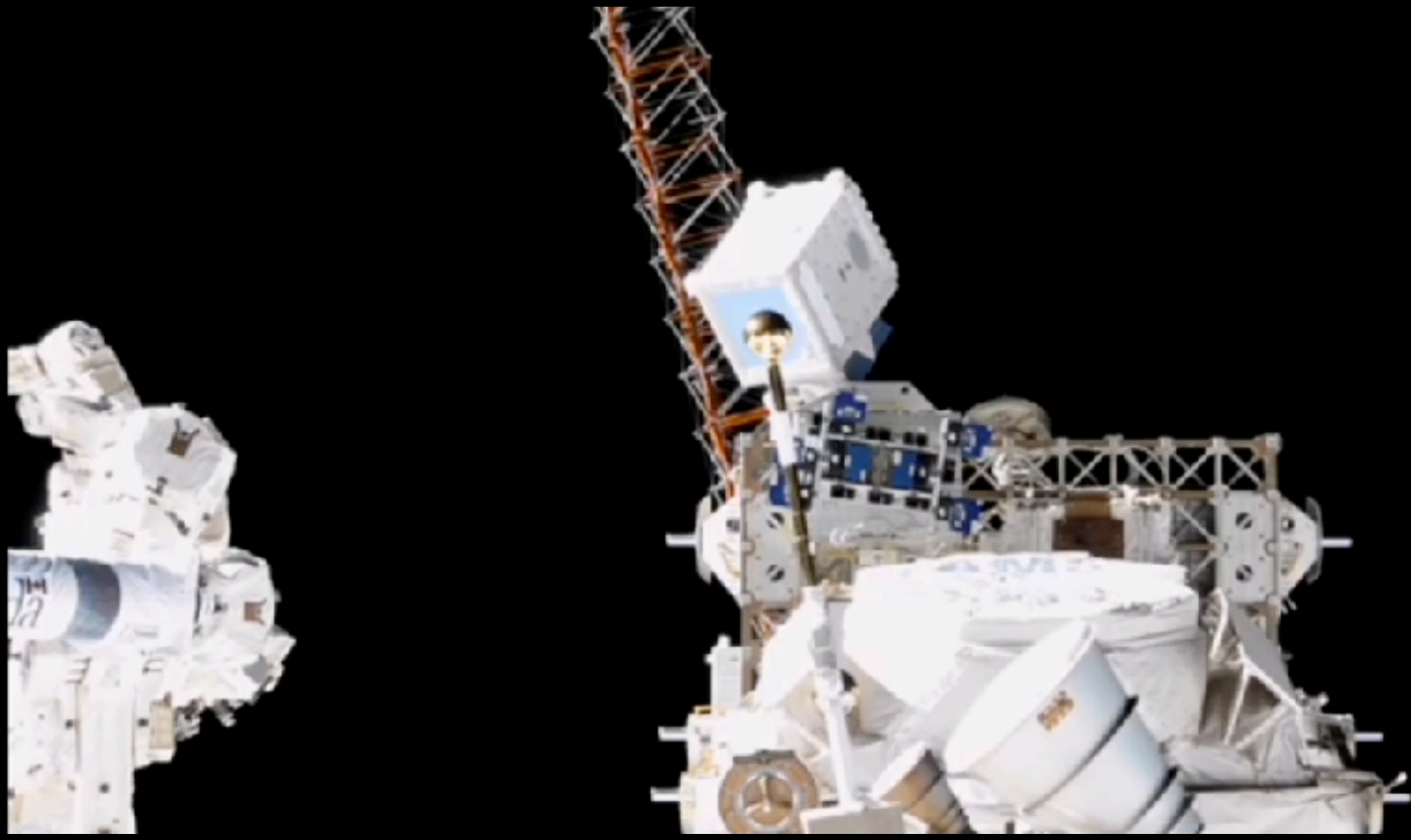
Launched in June 2017

Credits: NASA/NICER









Credits: NASA/NICER

Data

Light curve model I:
Relativistic ray tracing

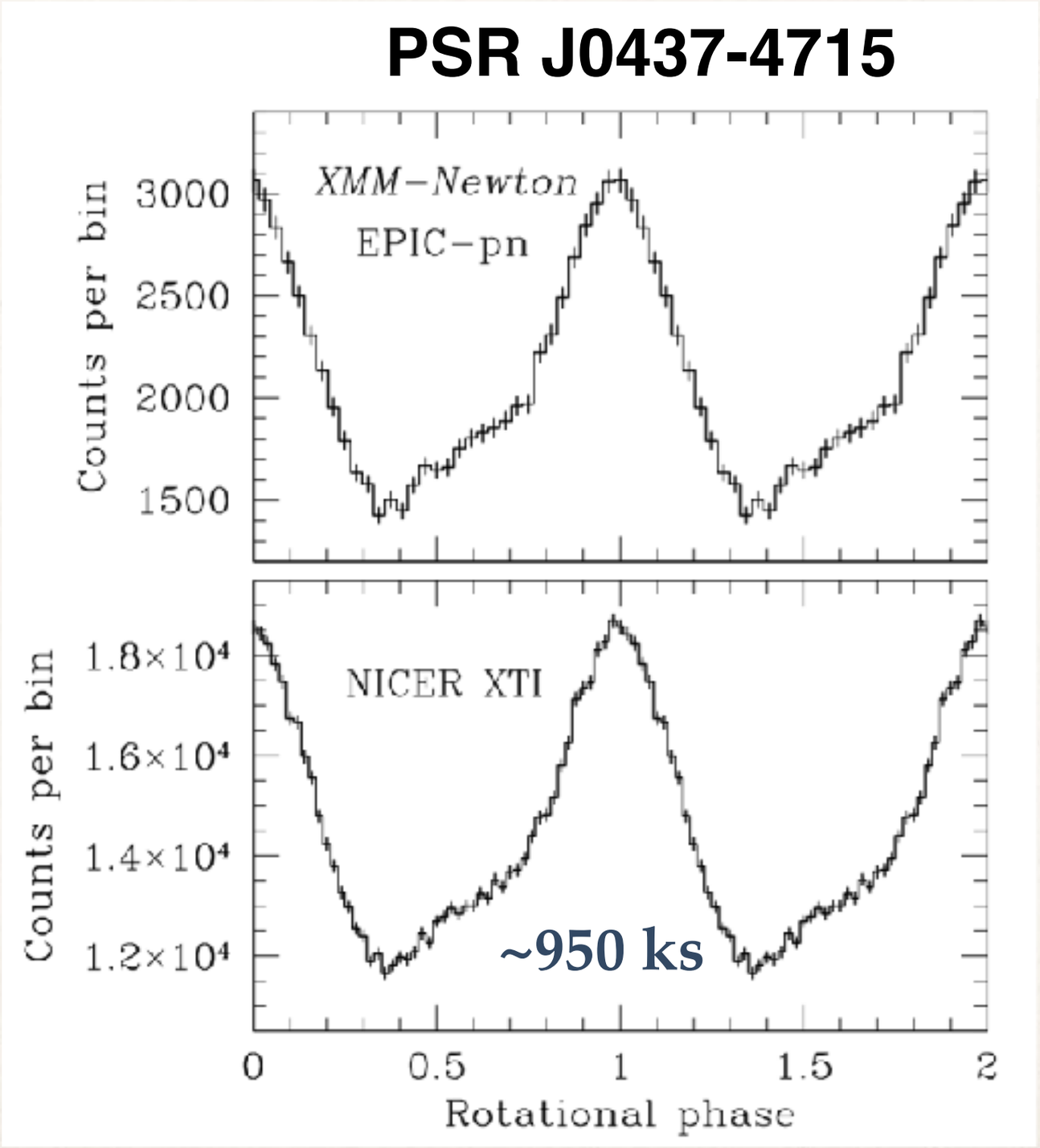
NS properties inference
(Likelihood statistical sampling)

Instrument properties

Mass,
Radius,
EOS

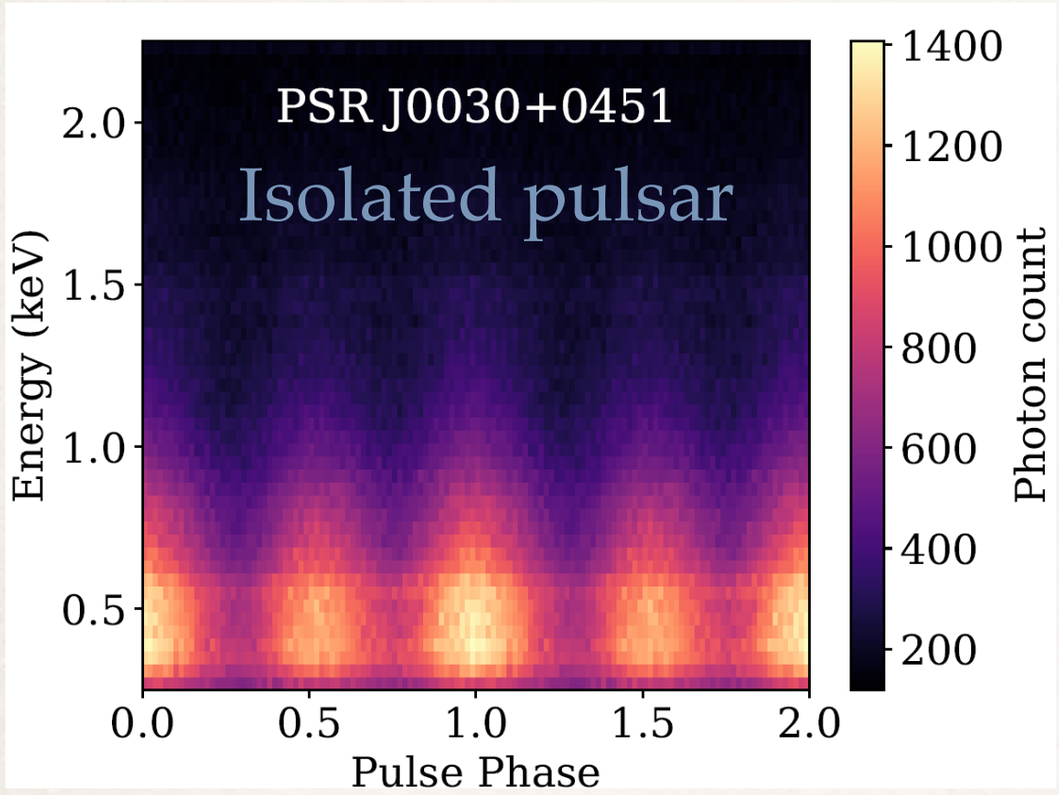
Light curve model II:
Surface emission model
+ emission pattern

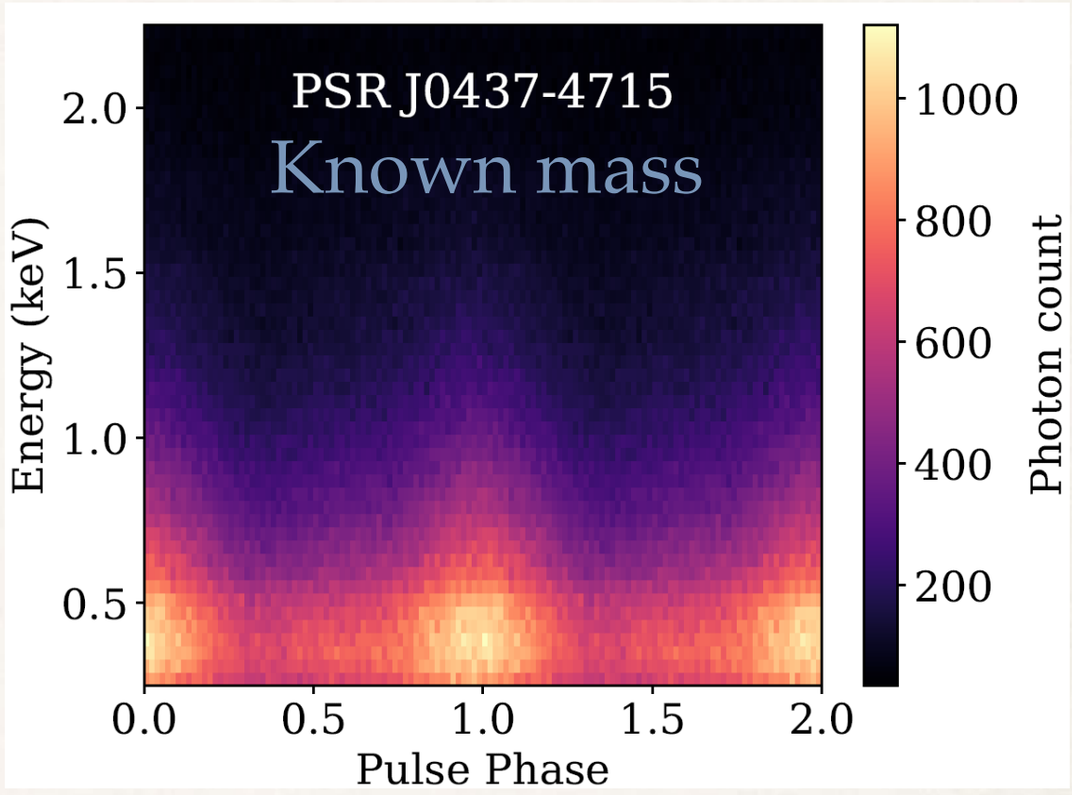
NICER now routinely observes a few key target millisecond pulsars to give us unprecedented signal-to-noise data.

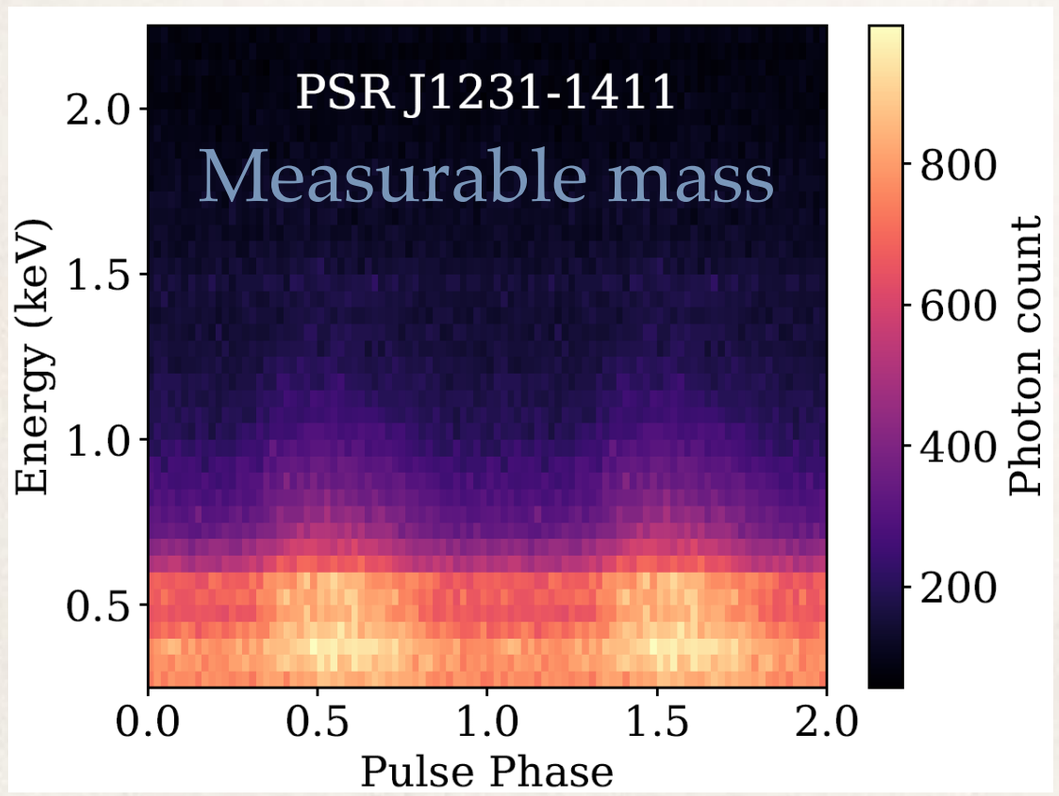


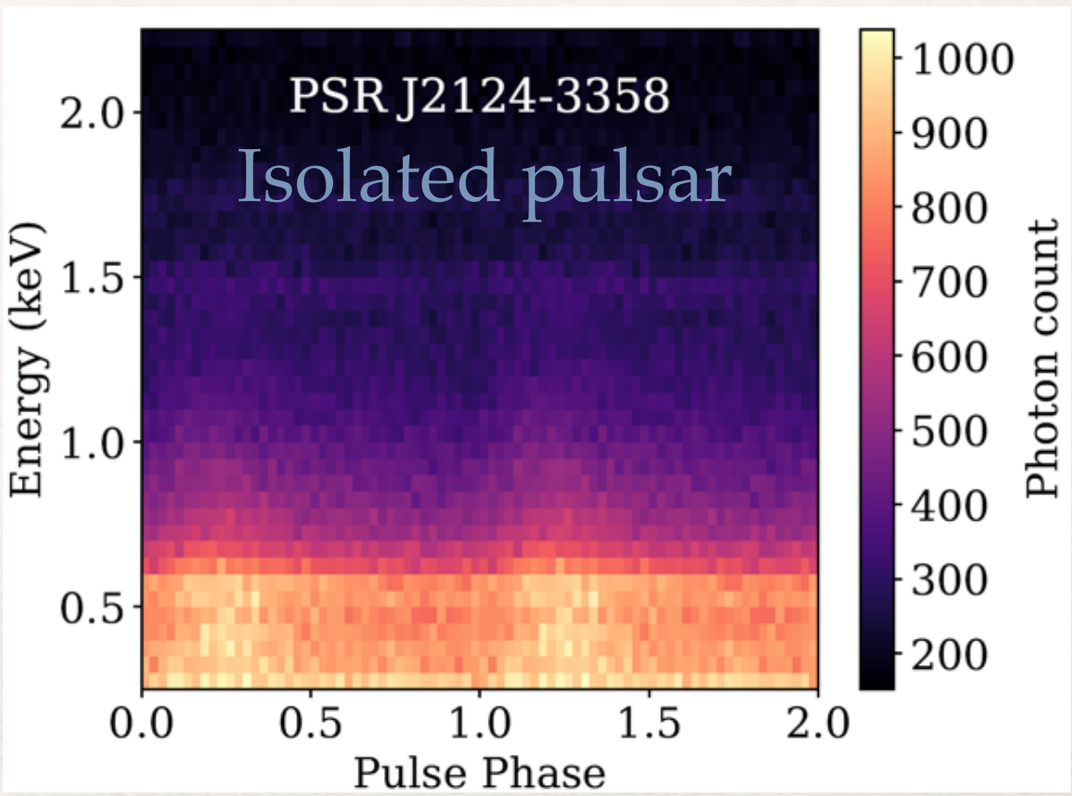
Credits: NICER Science Team

In addition to the pulse profile shape, the energy information is important.



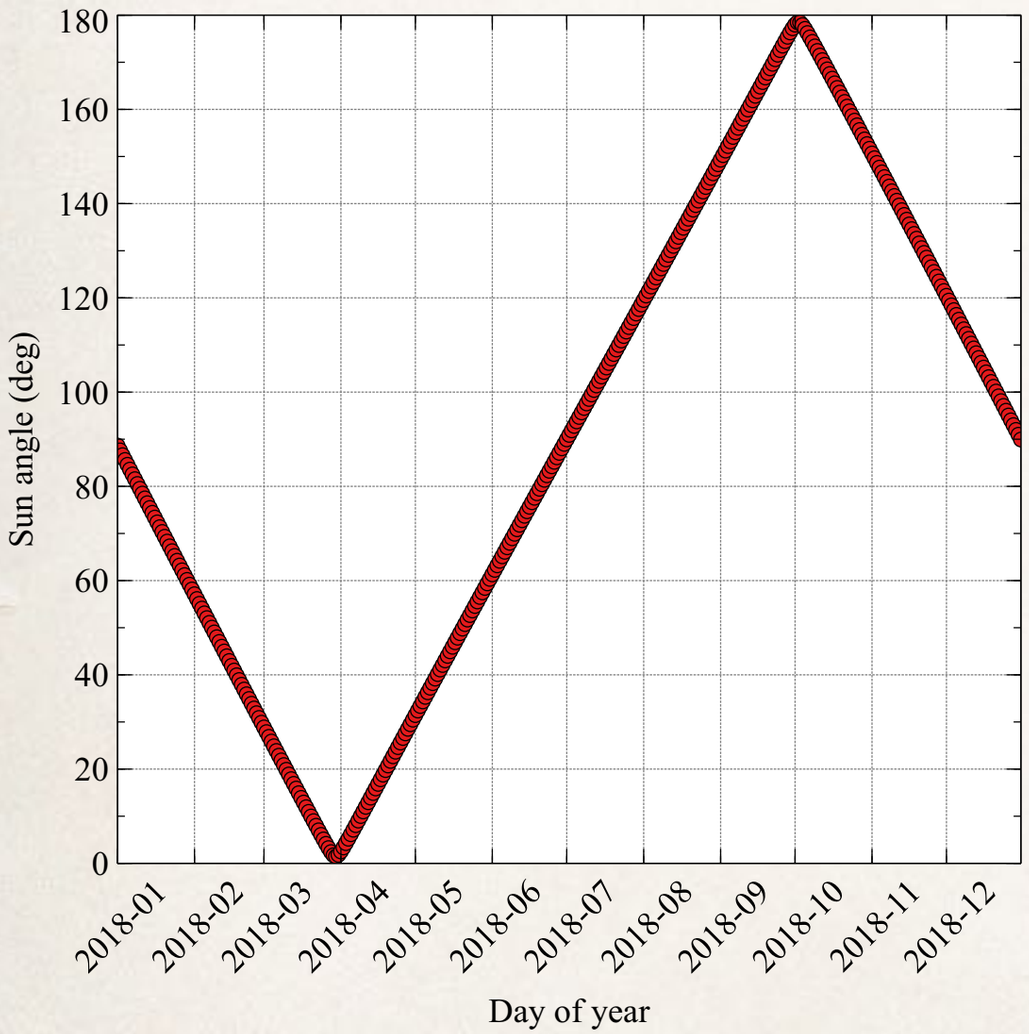


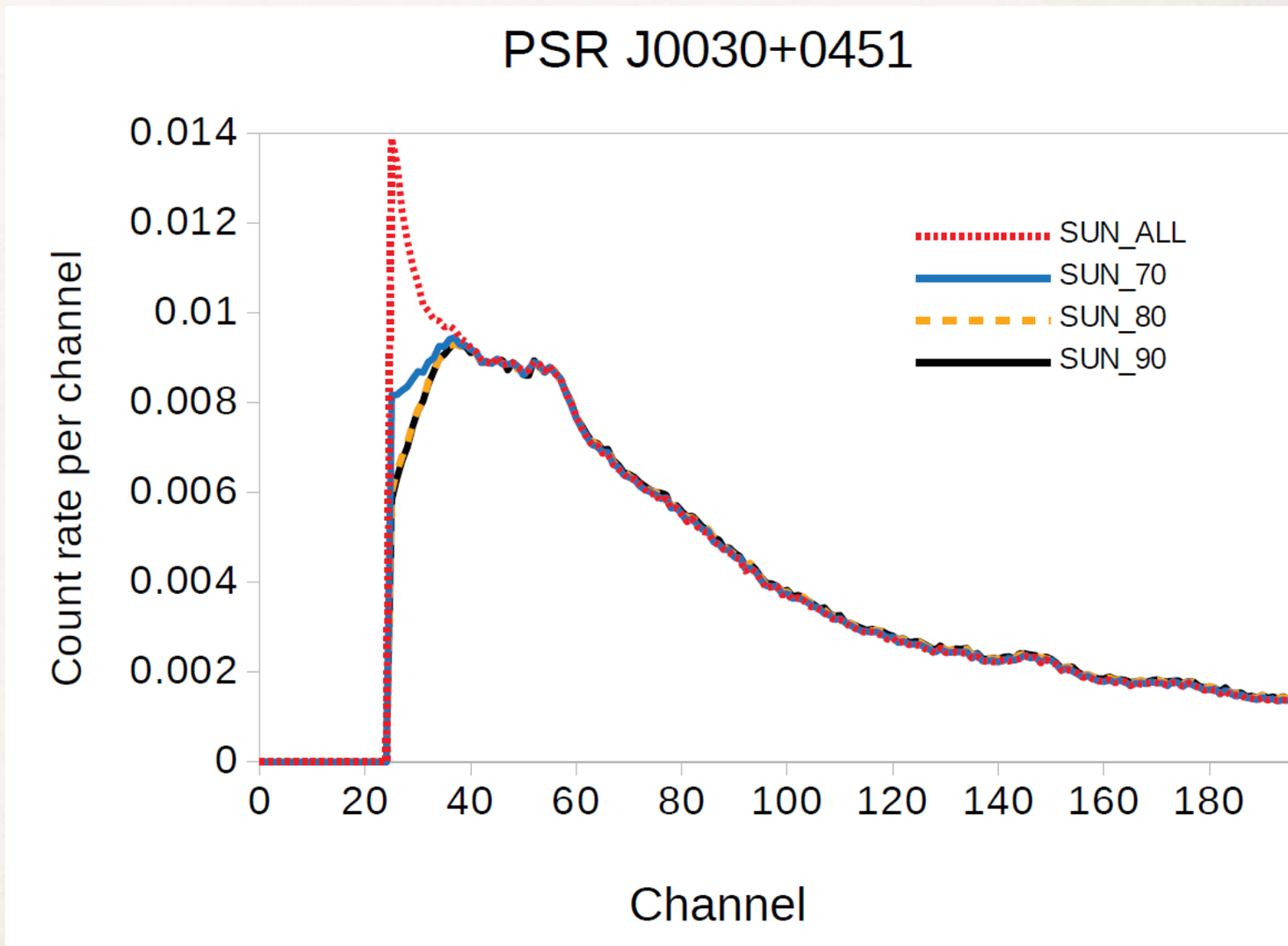




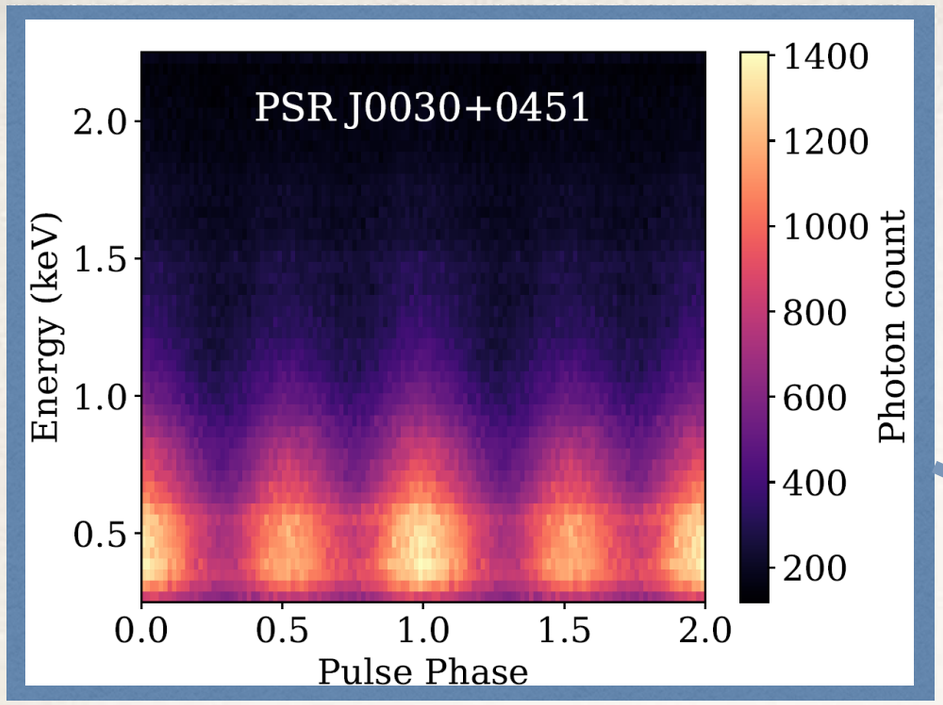
Using a new instrument means that we need to understand its response.

Optical loading at soft-energies





Credits: NICER Science Team



Light curve model I:
Relativistic ray tracing

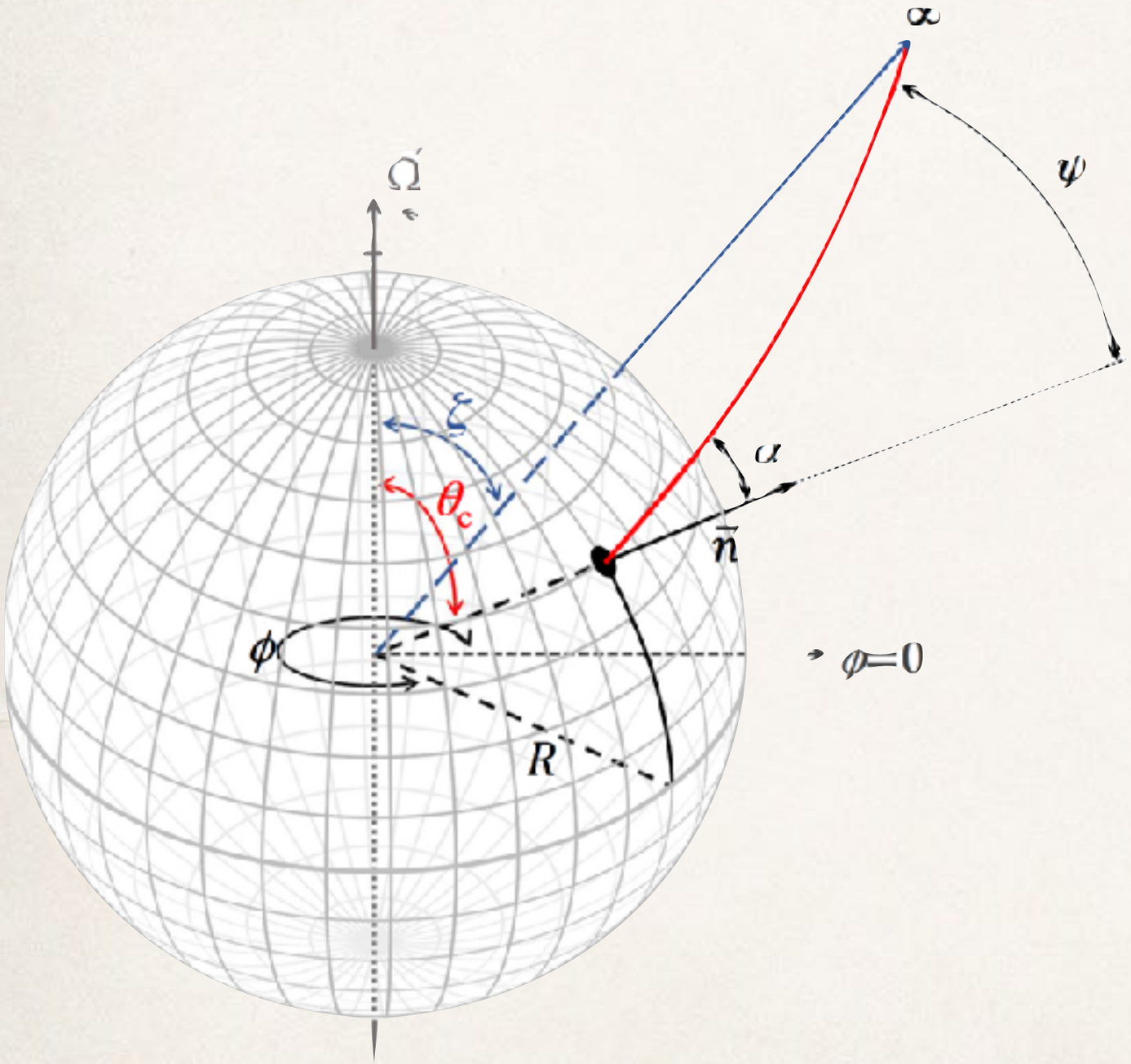
NS properties inference
(Likelihood statistical sampling)

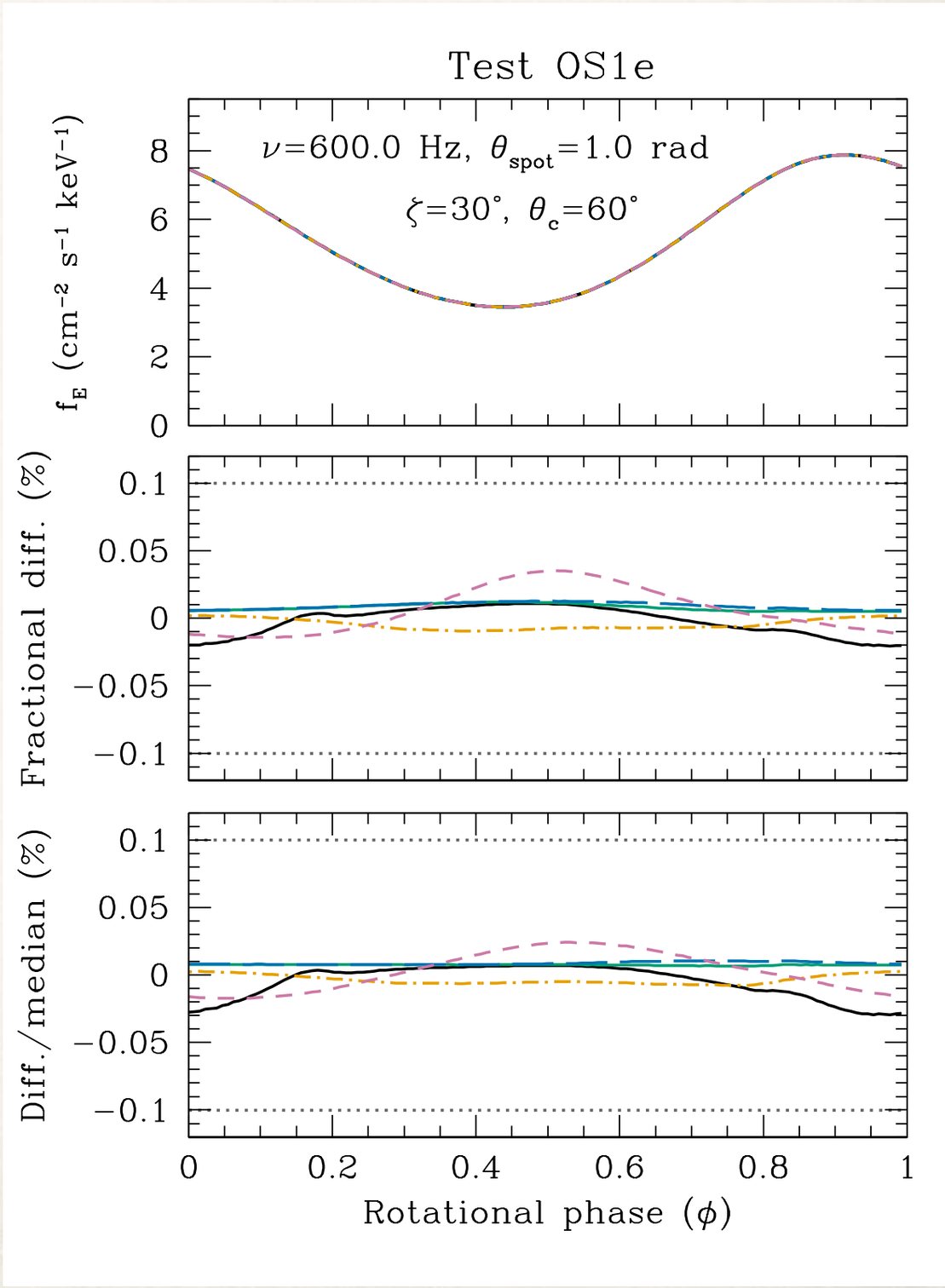
Instrument properties

Mass,
Radius,
EOS

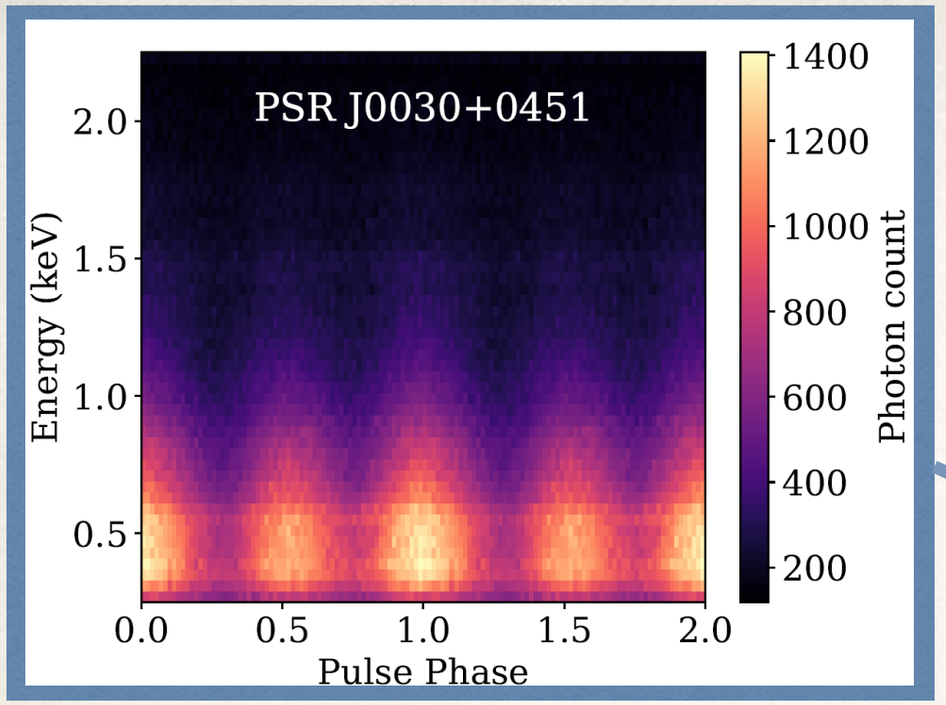
Light curve model II:
Surface emission model
+ emission pattern

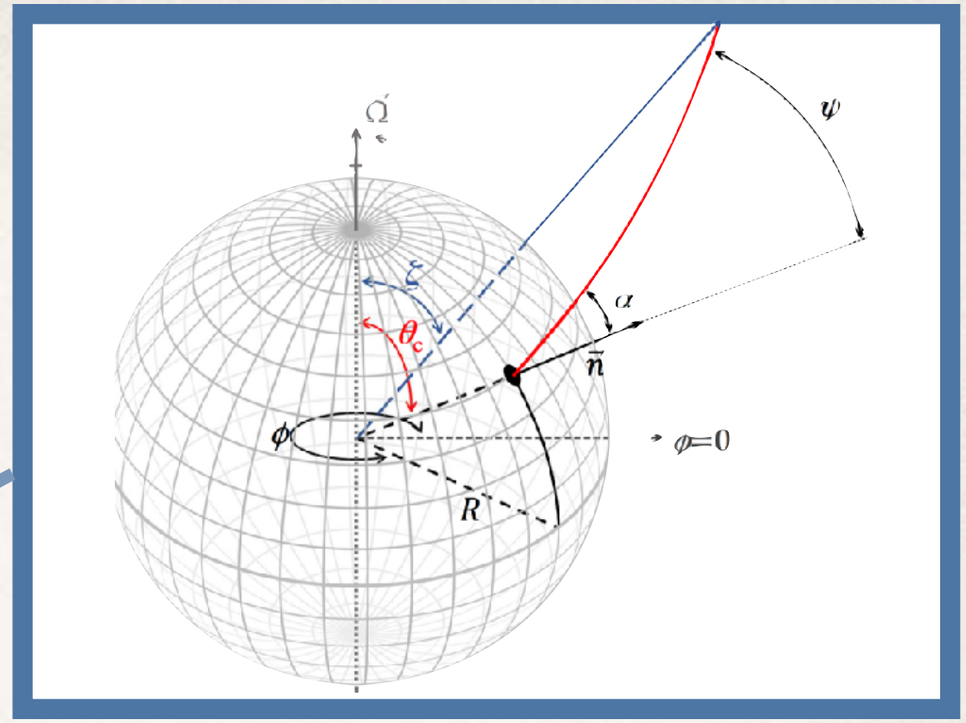
The light curve modelling requires a relativistic ray-tracing model





Figures from NICER Science Team





NS properties inference
(Likelihood statistical sampling)

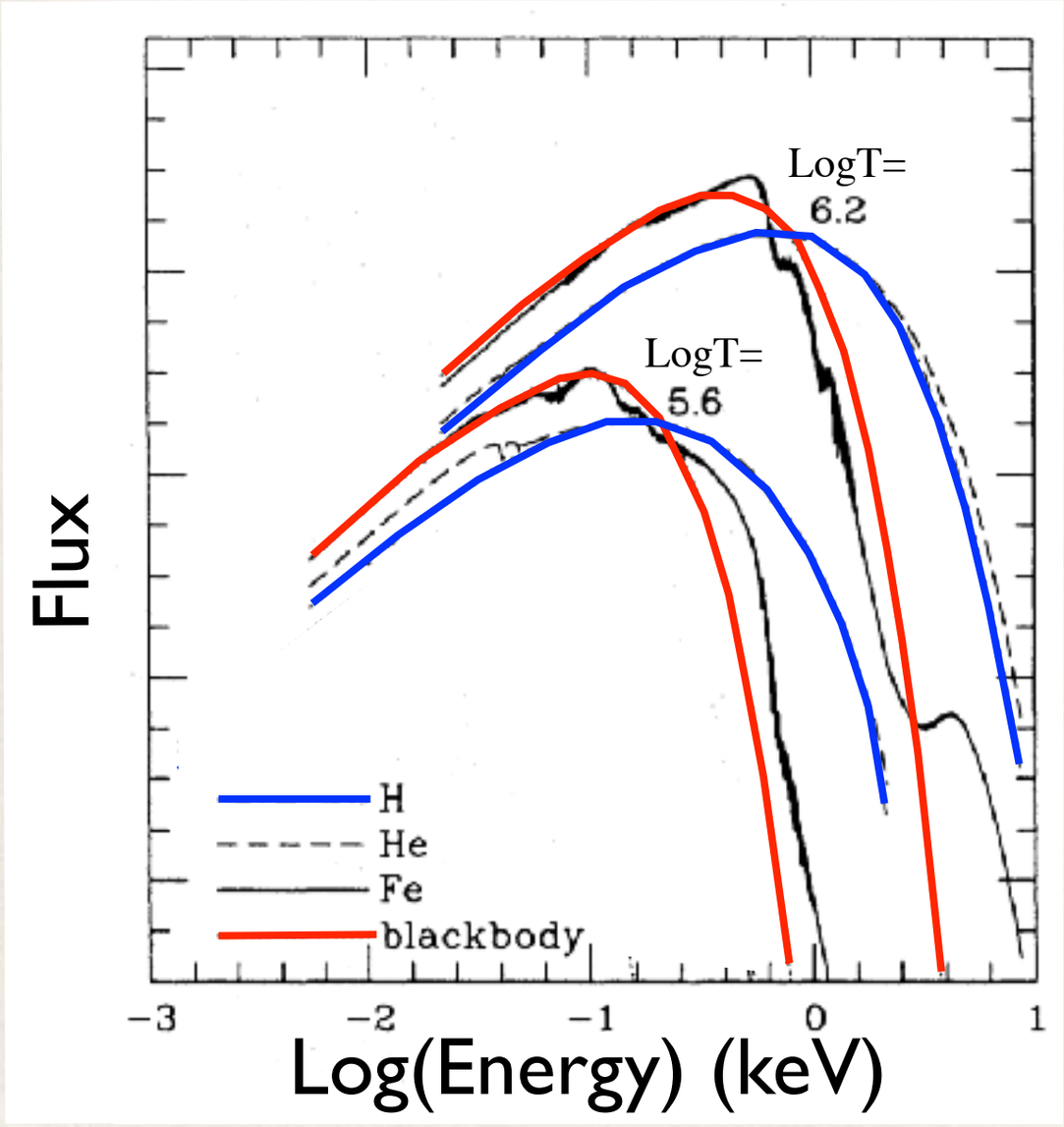
Instrument properties

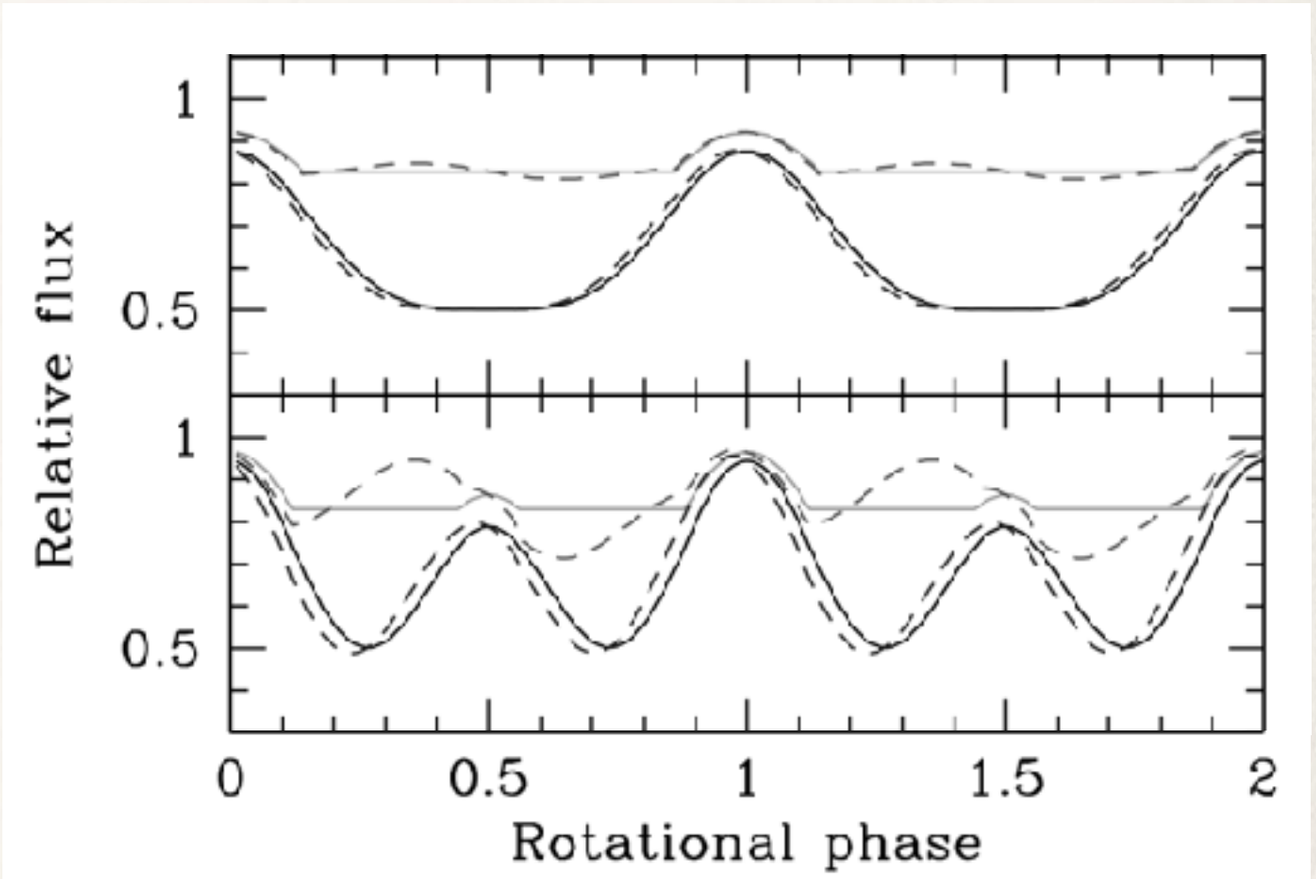
Mass,
Radius,
EOS

Light curve model II:
Surface emission model
+ emission pattern

The thermal emission from a NS surface is modelled with a NS atmosphere.

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

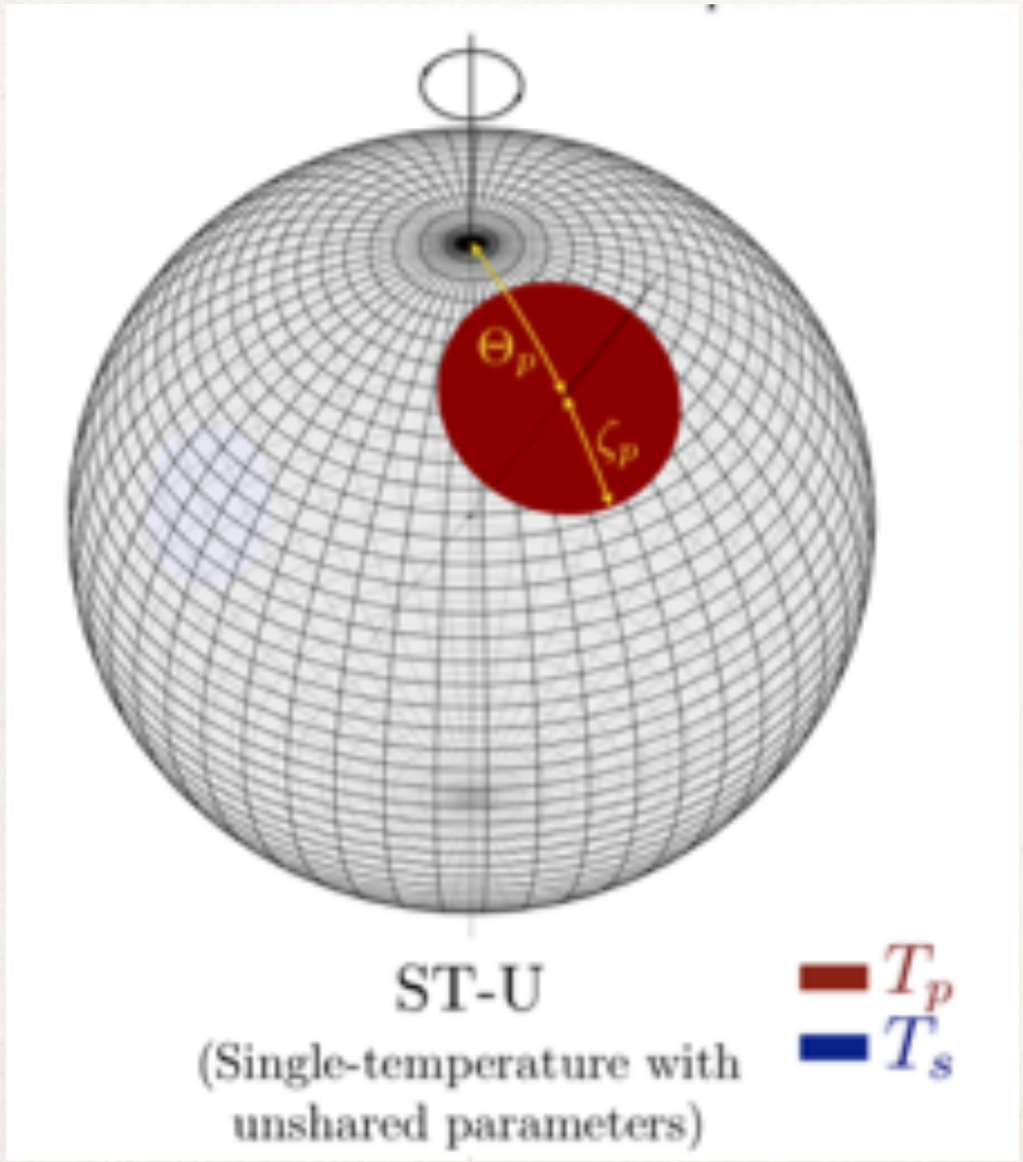




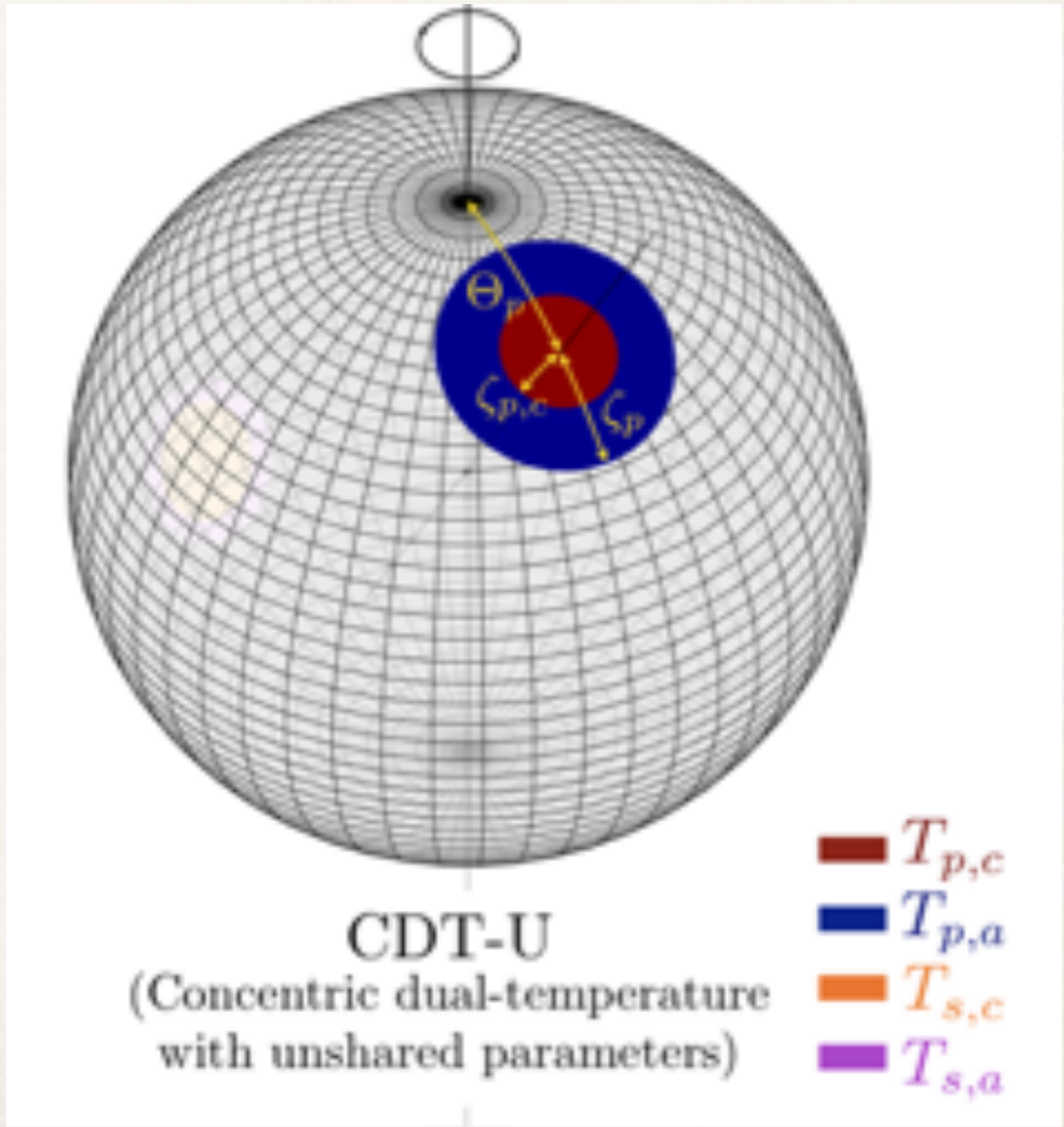
Bogdanov et al. (2007)

The emission pattern of the hotspots are not well predicted by theory.

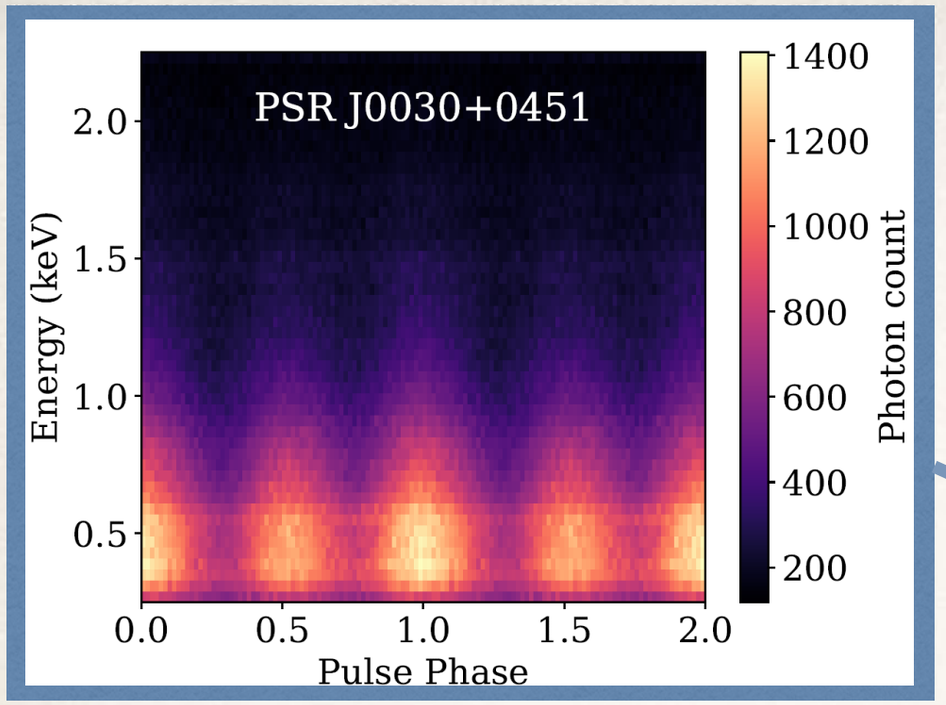
Two polar caps with Uniform Temperature

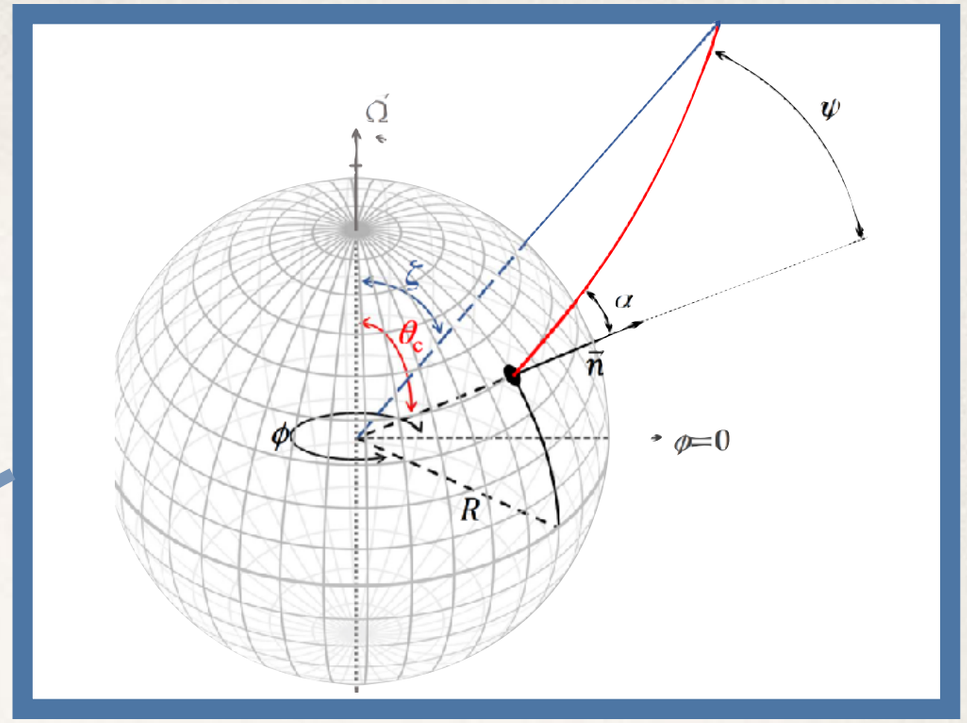


Two polar caps with two temperatures



Courtesy of Anna Watts

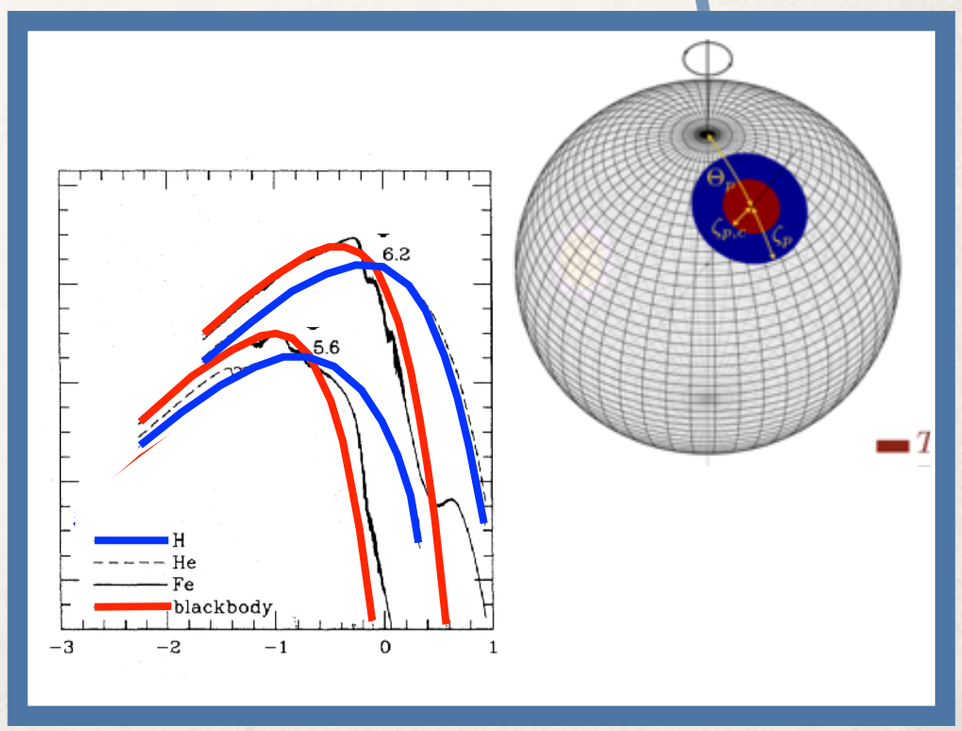




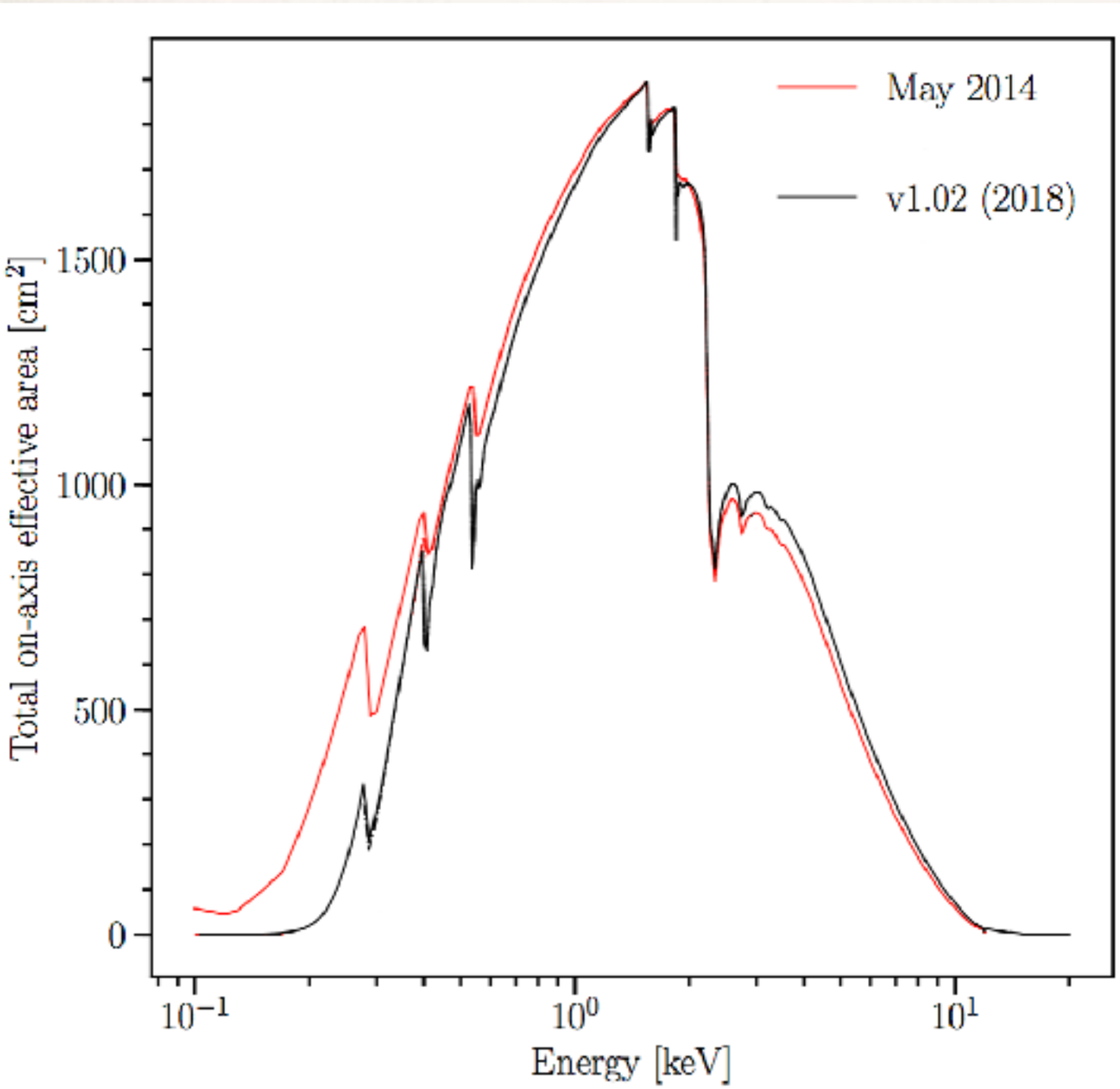
NS properties inference
(Likelihood statistical sampling)

Instrument properties

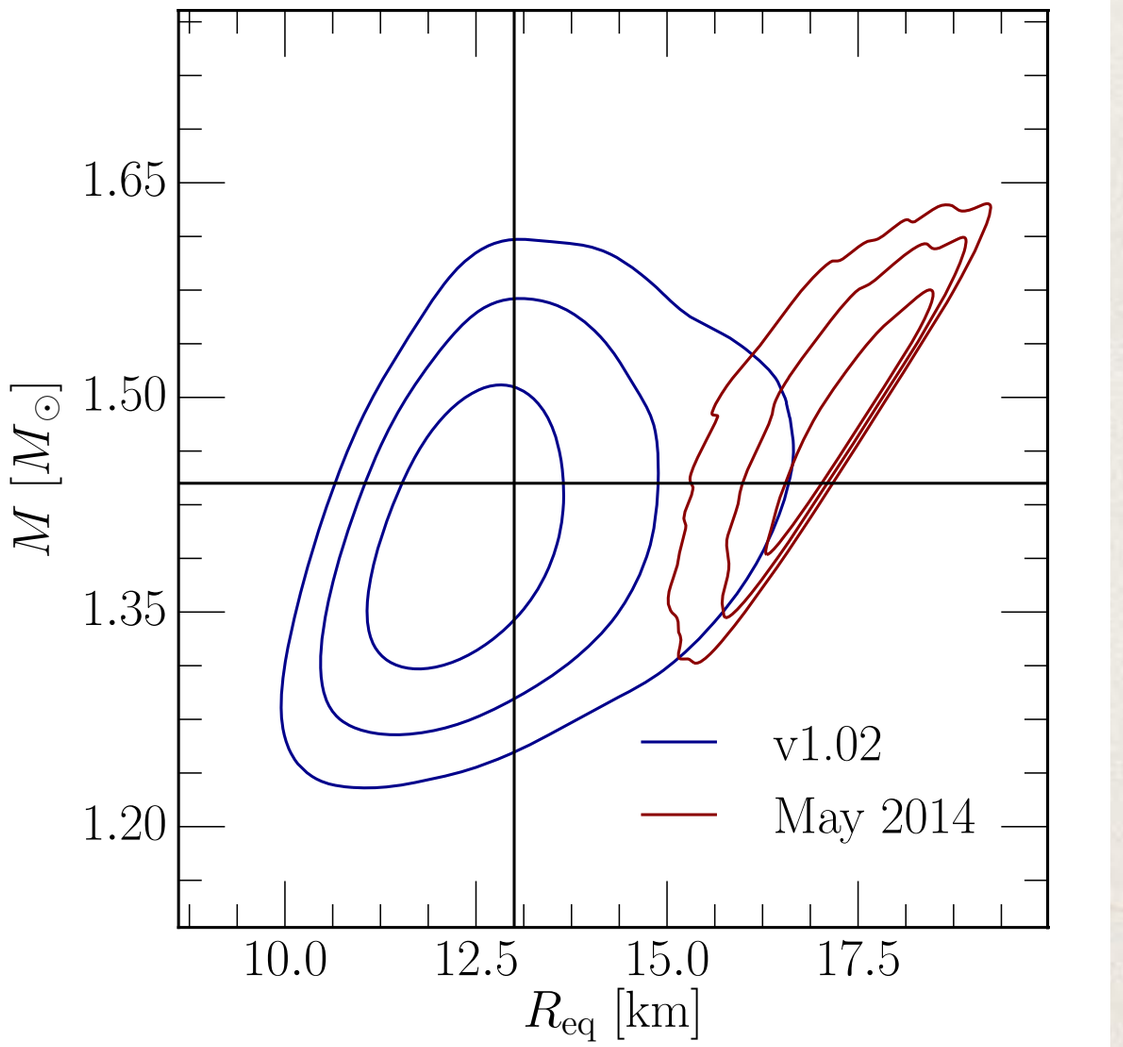
Mass,
Radius,
EOS



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

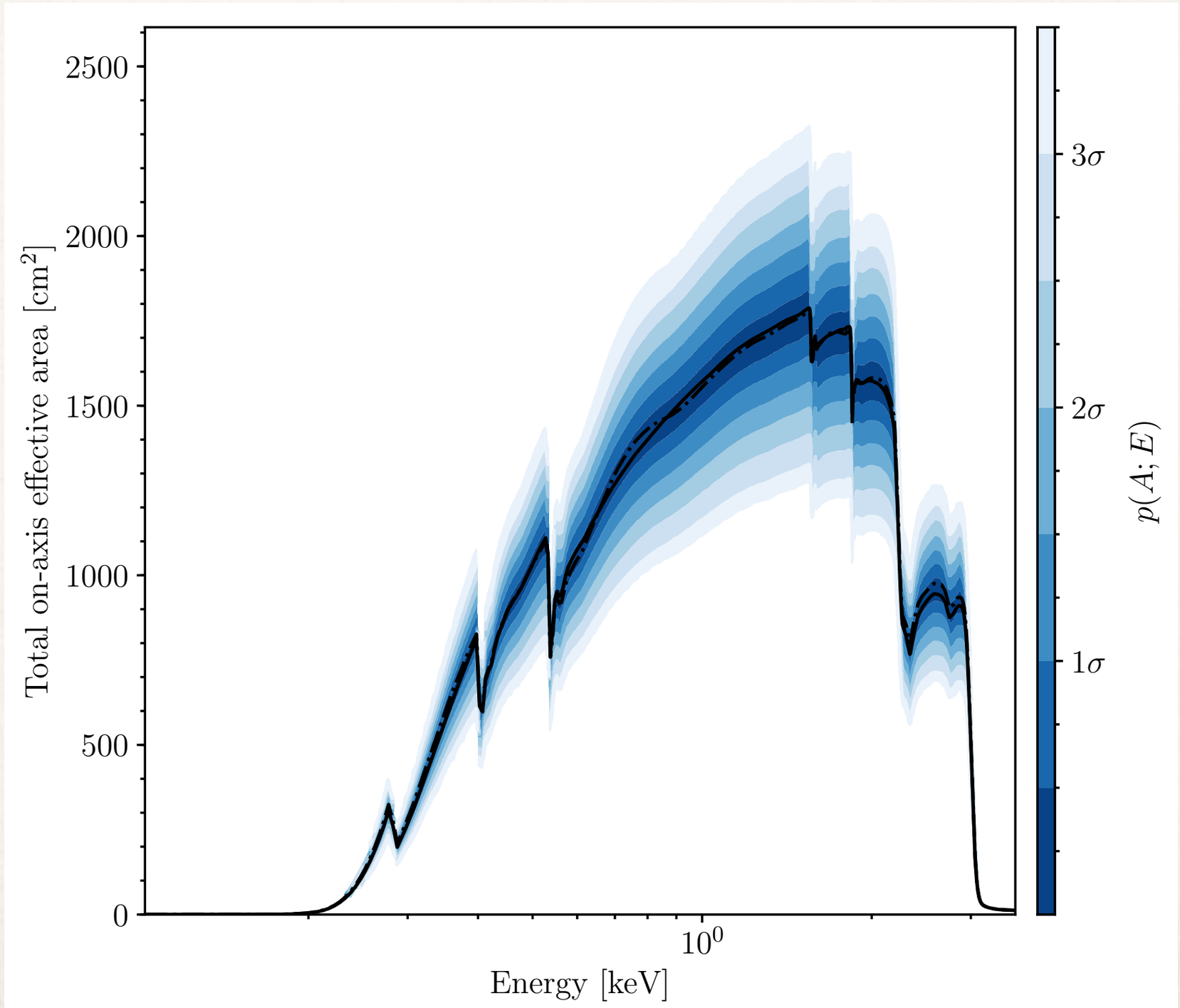


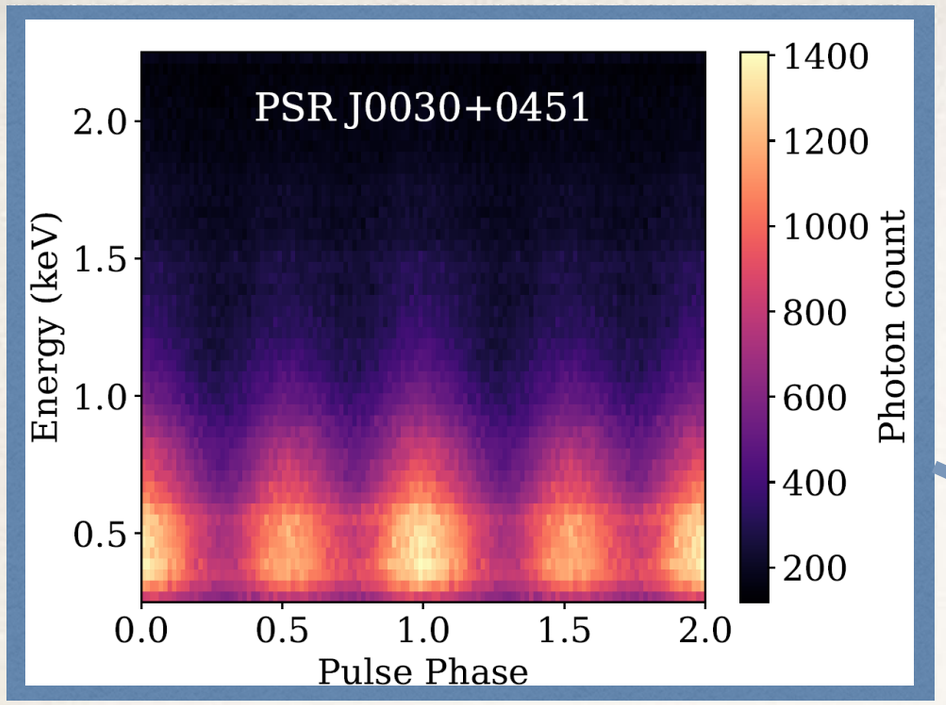
Effects on synthetic data

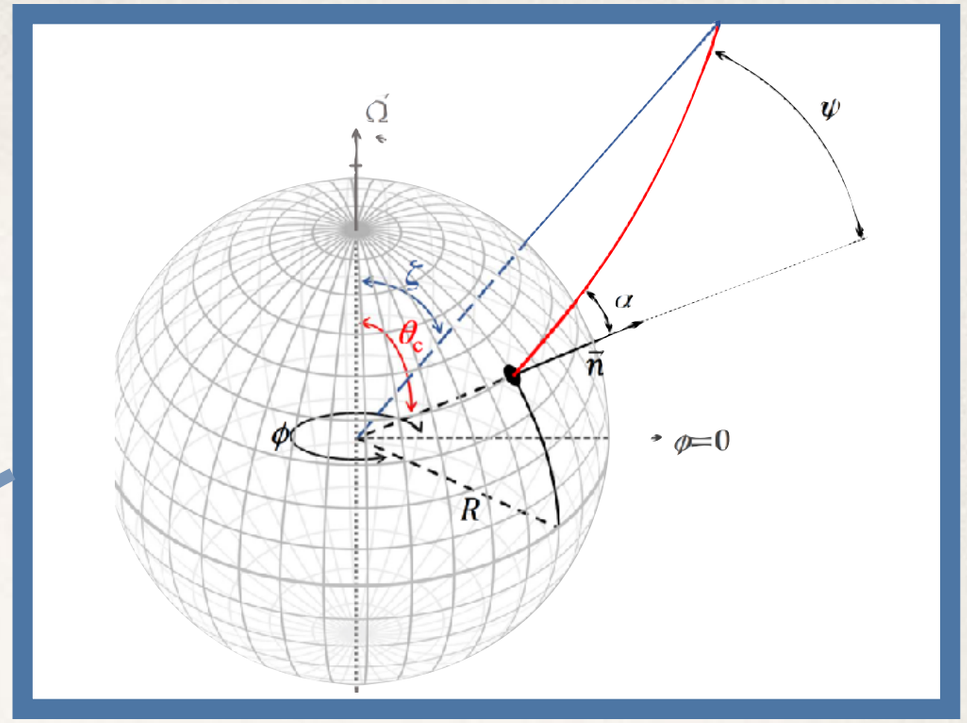


Figures from NICER Science Team

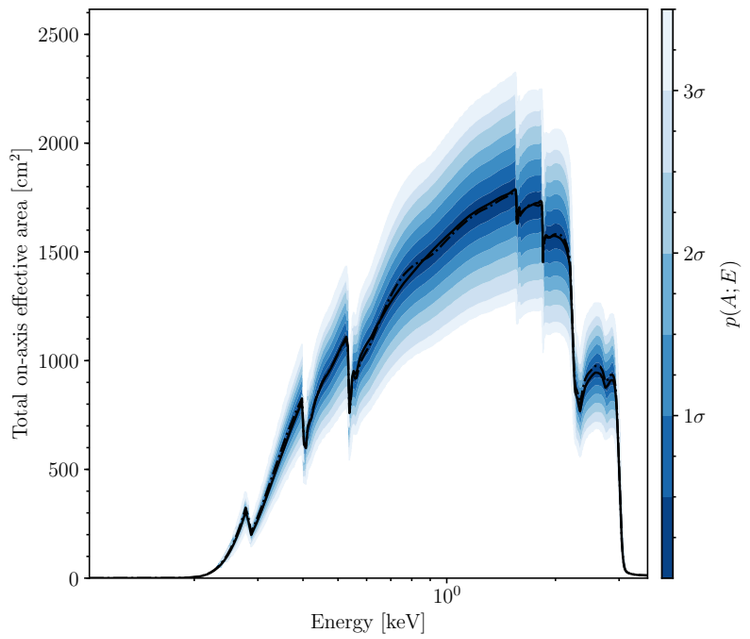
We parameterize the instrument response, with a prior on the effective area.



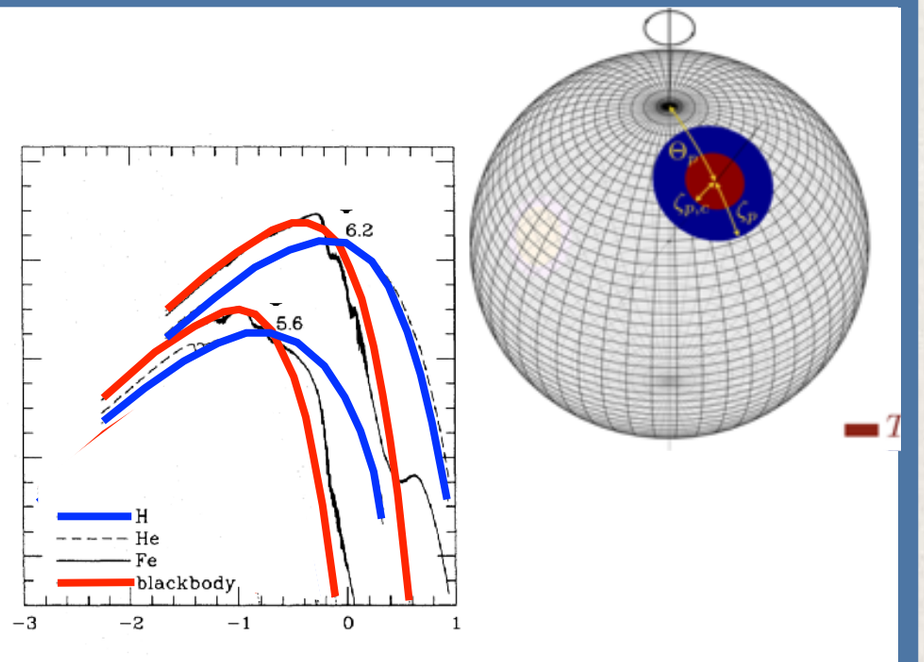




NS properties inference
(Likelihood statistical sampling)



Mass,
Radius,
EOS

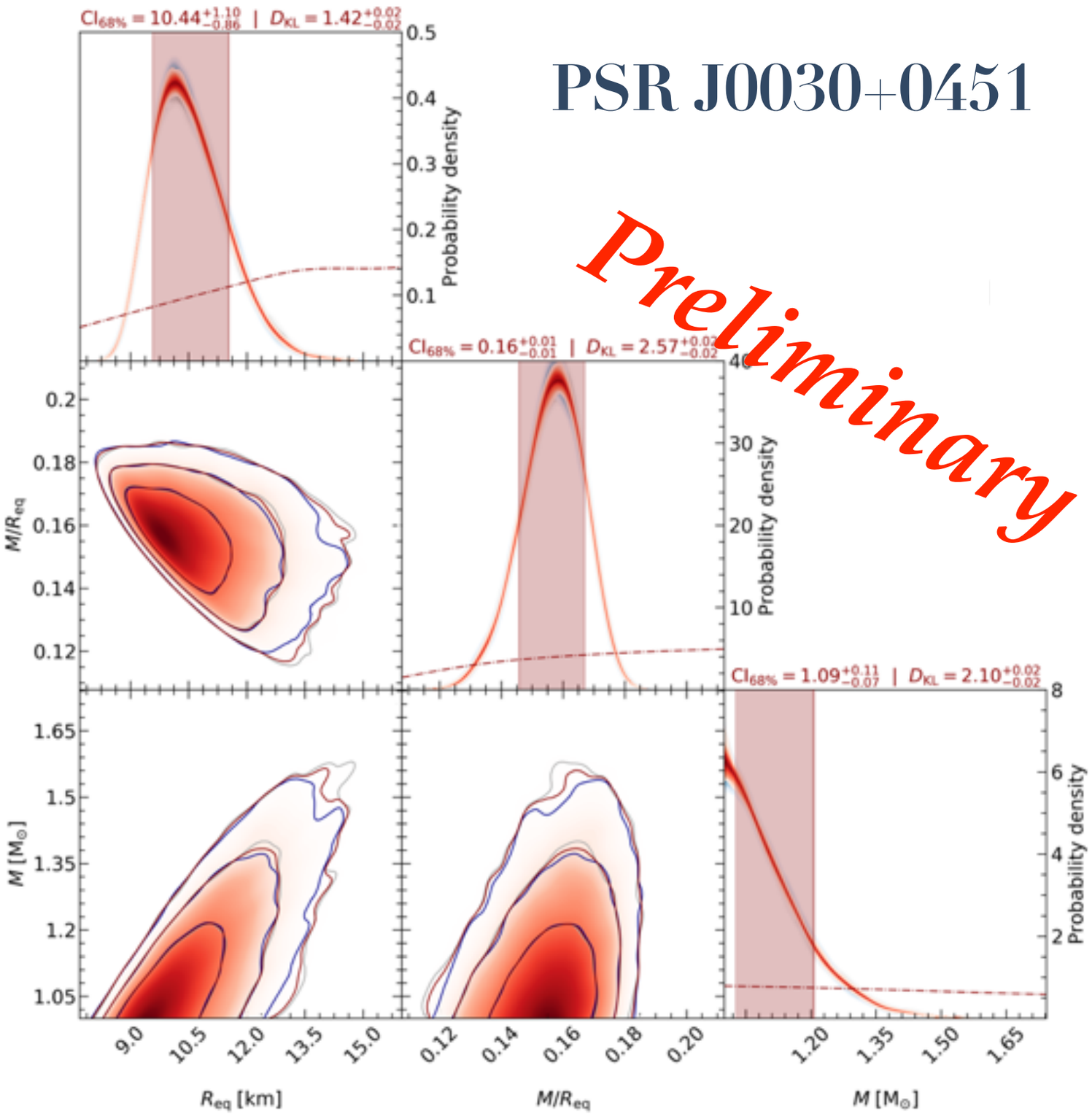


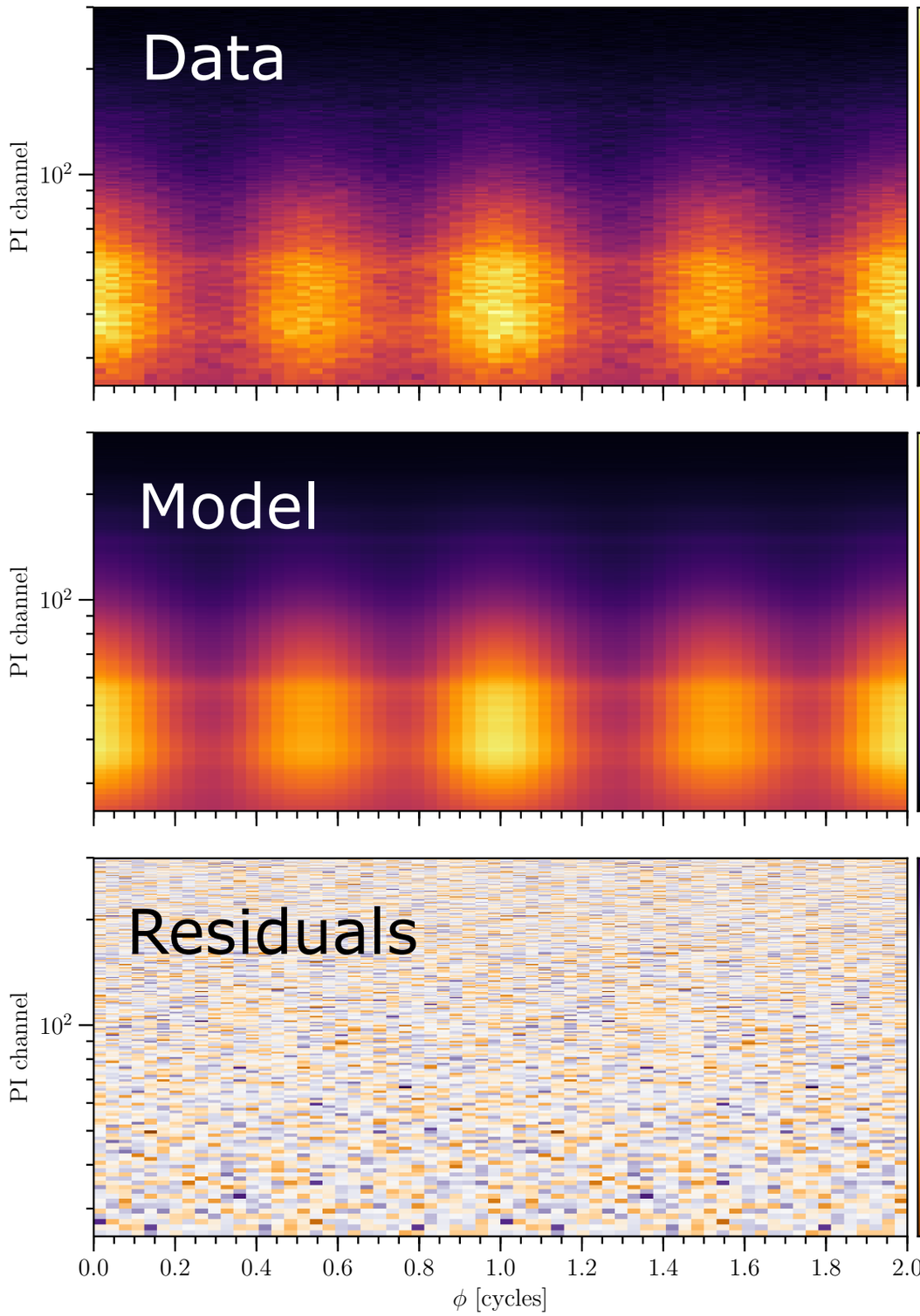
Preliminary results for uniform temperature two-polar caps model

Courtesy of Tom Riley & Anna Watts

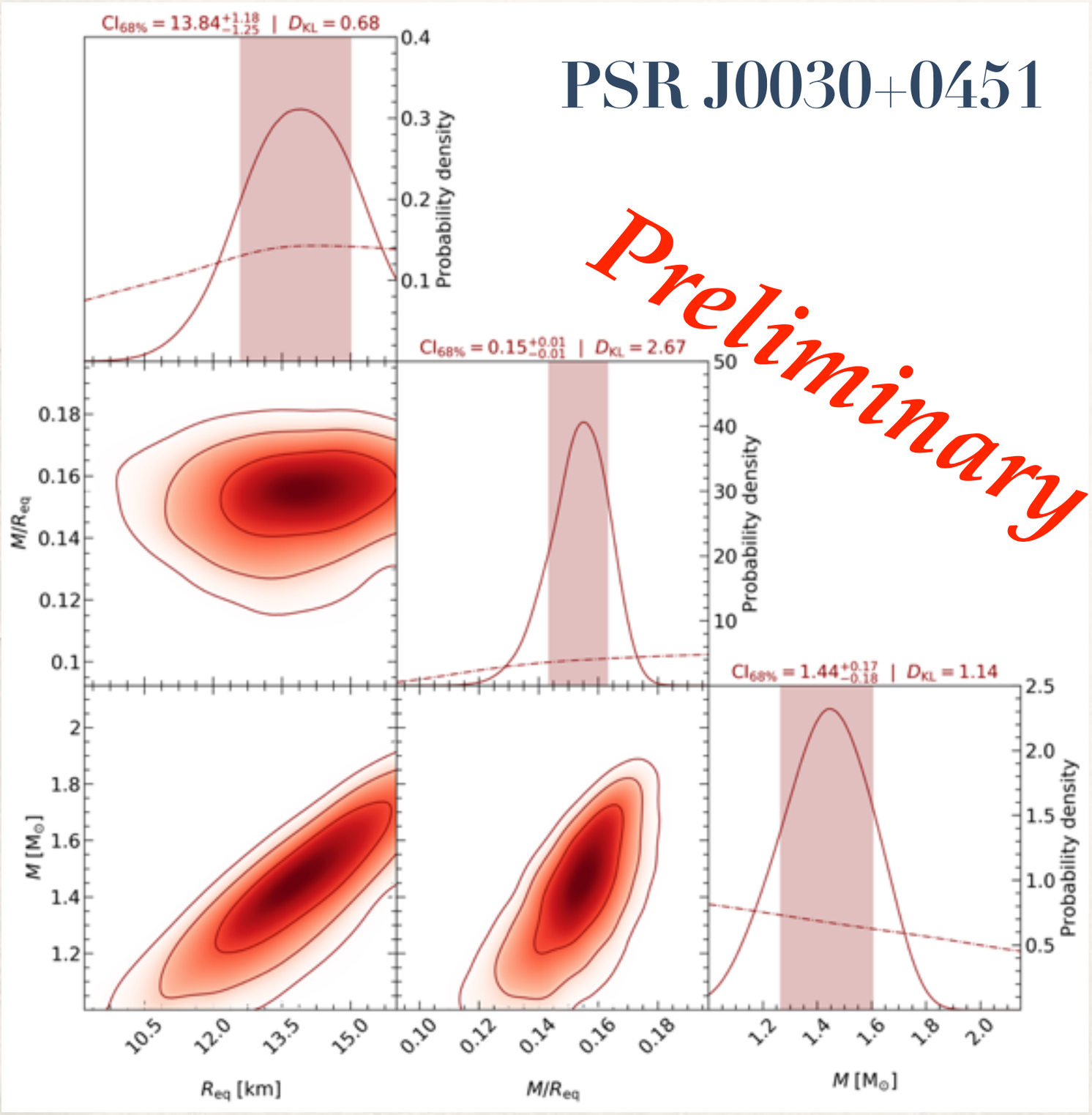
PSR J0030+0451

Preliminary



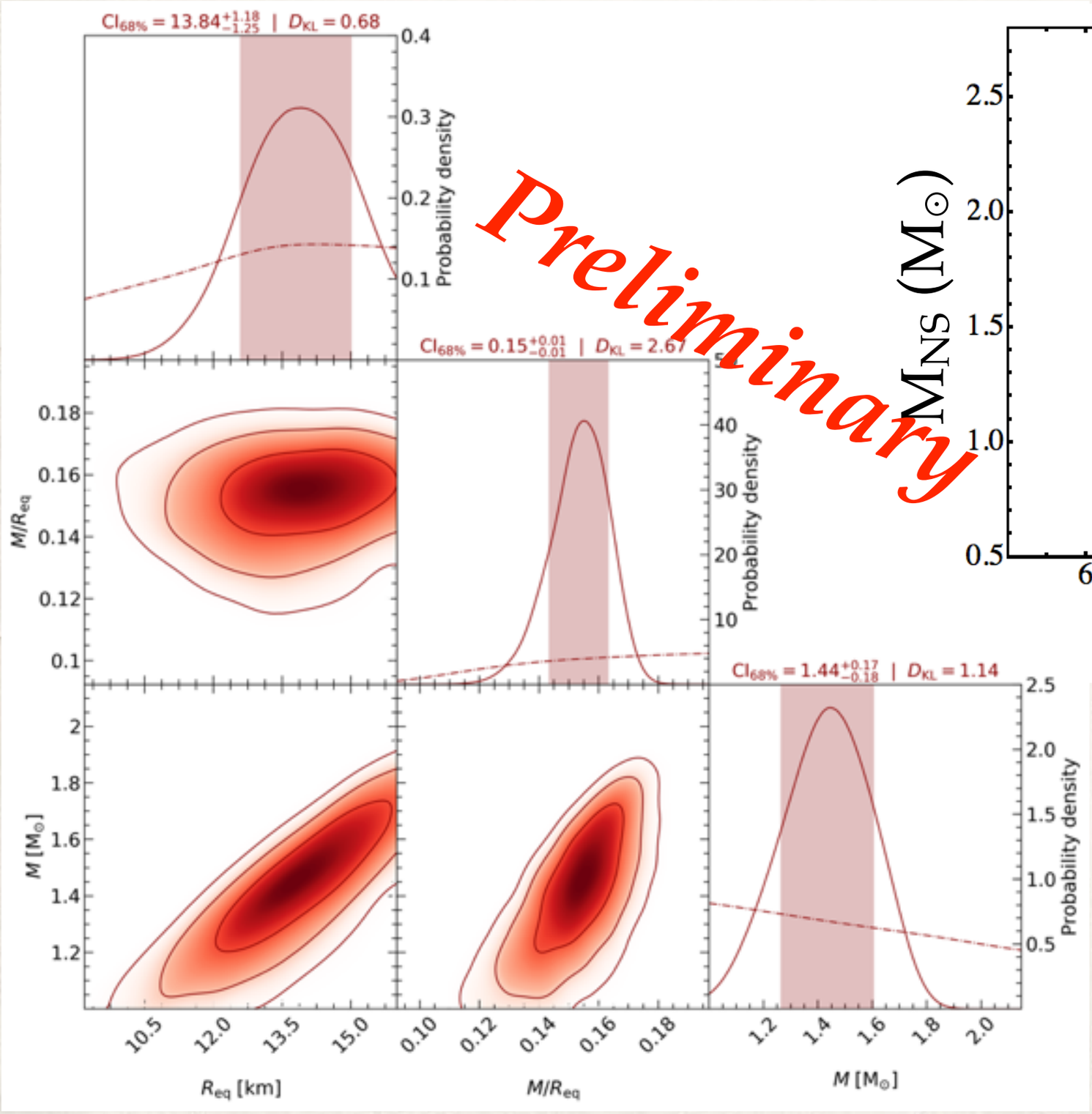


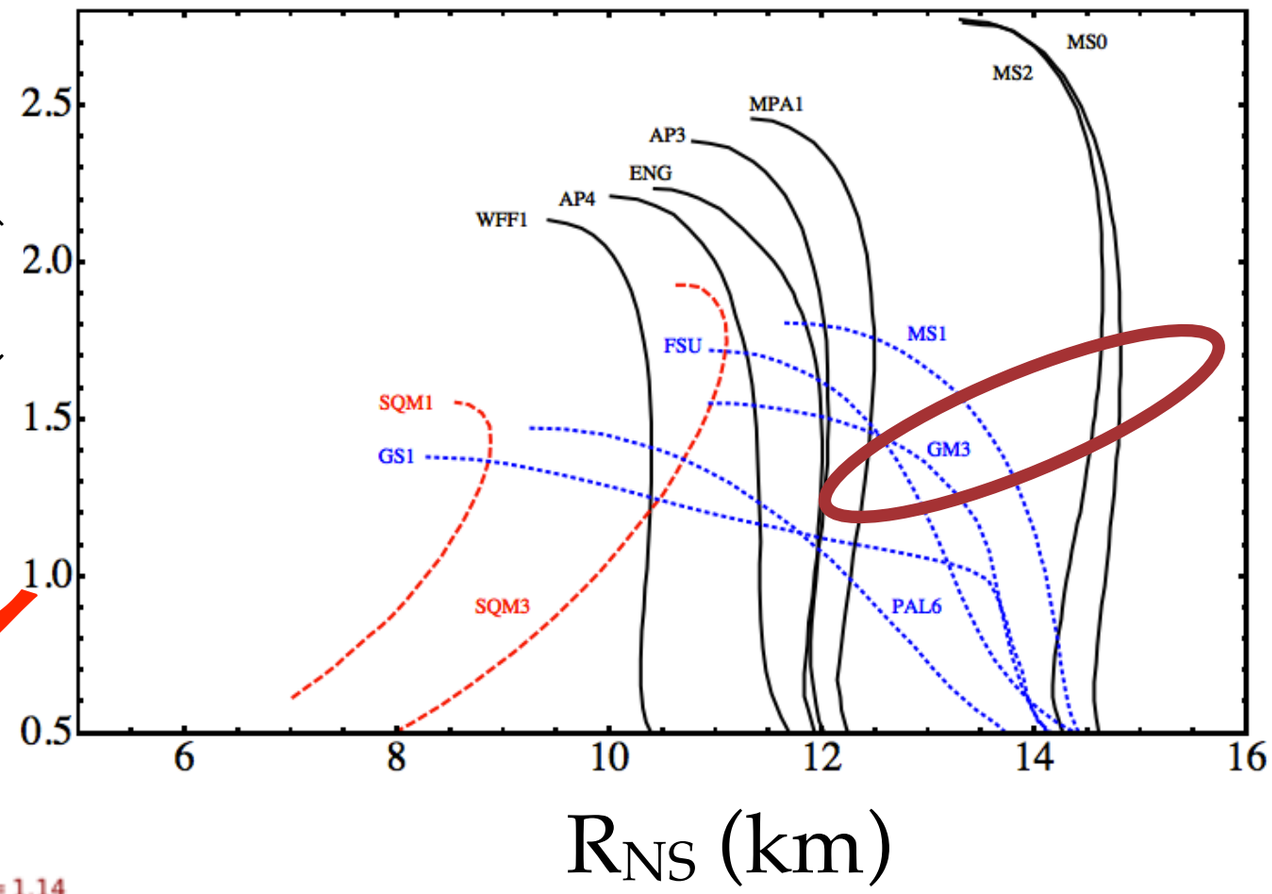
Preliminary results for dual-temperature two polar caps model.



Courtesy of Tom Riley & Anna Watts

Preliminary results for dual-temperature two polar caps model.

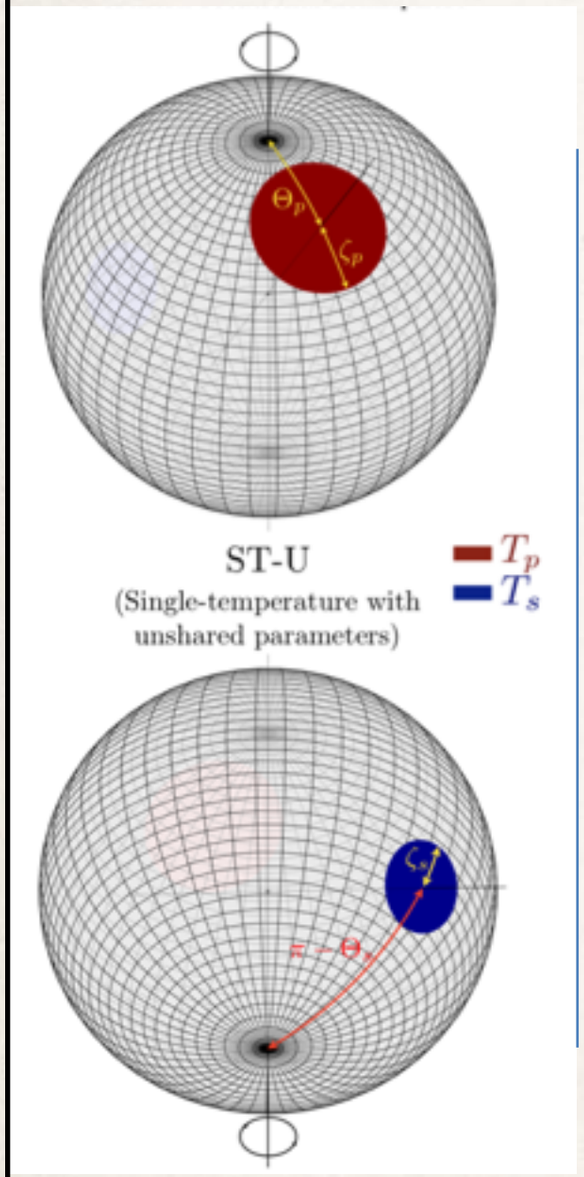


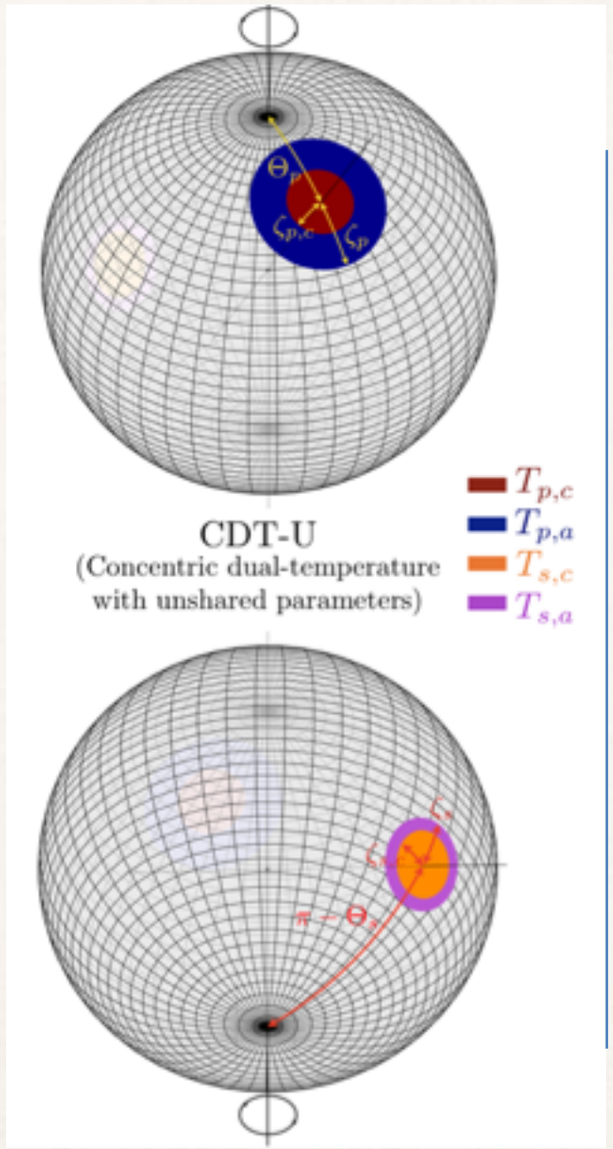


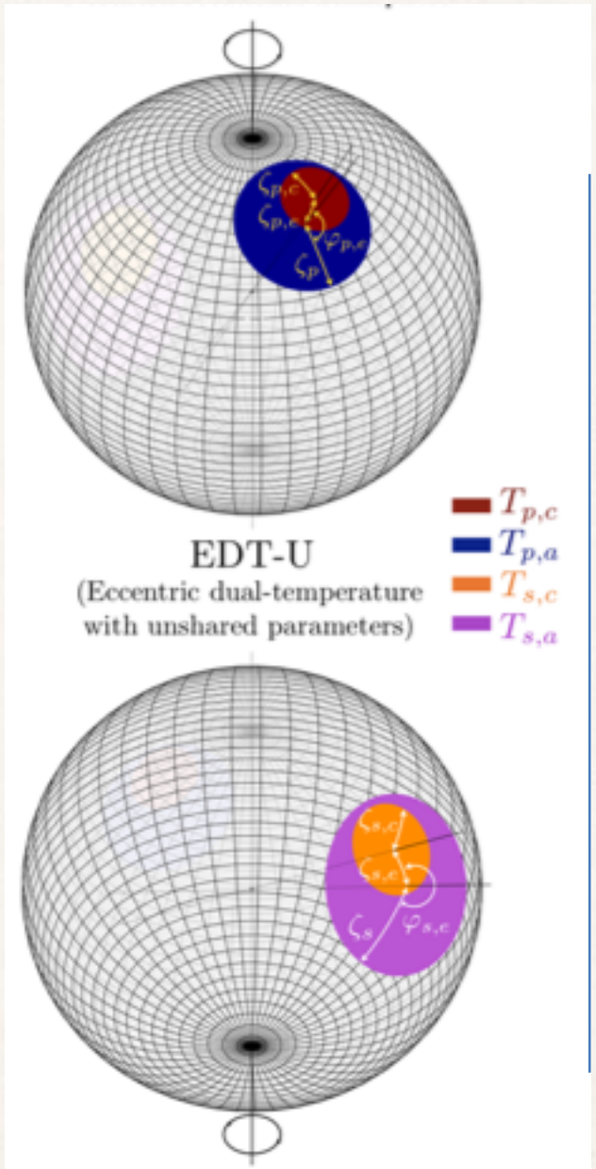
PSR J0030+0451

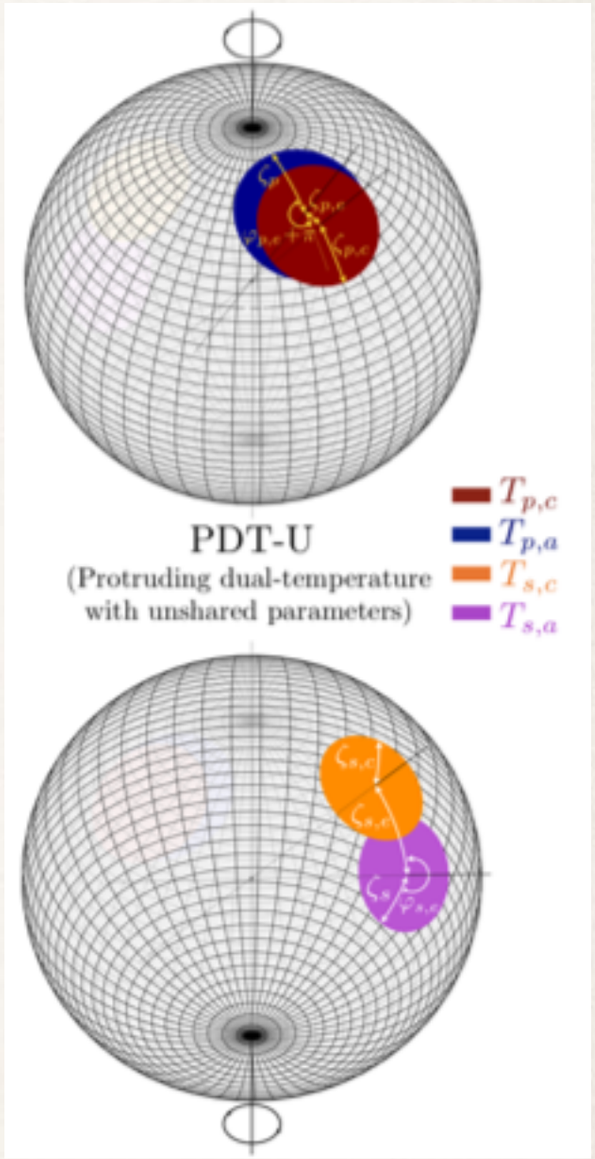
More complicated emission patterns to test

Northern rotational hemisphere









Southern rotational hemisphere

Courtesy of Anna Watts

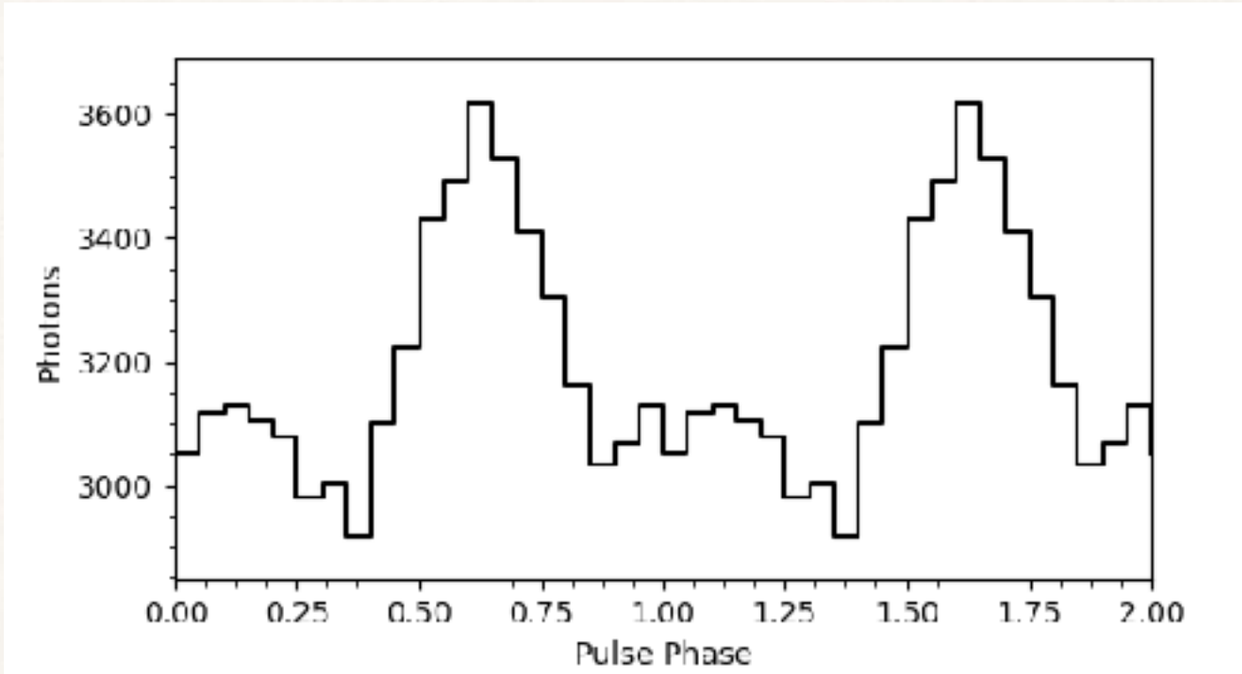
Summary of preliminary results from NICER

- For PSR J0030+0451:
  - Favors two polar caps with non-uniform temperatures
  - A radius in the range 12–15 km, preferring stiff EOS
  - The first mass measurement of an isolated pulsar.
  - More models to test, improved NICER calibration

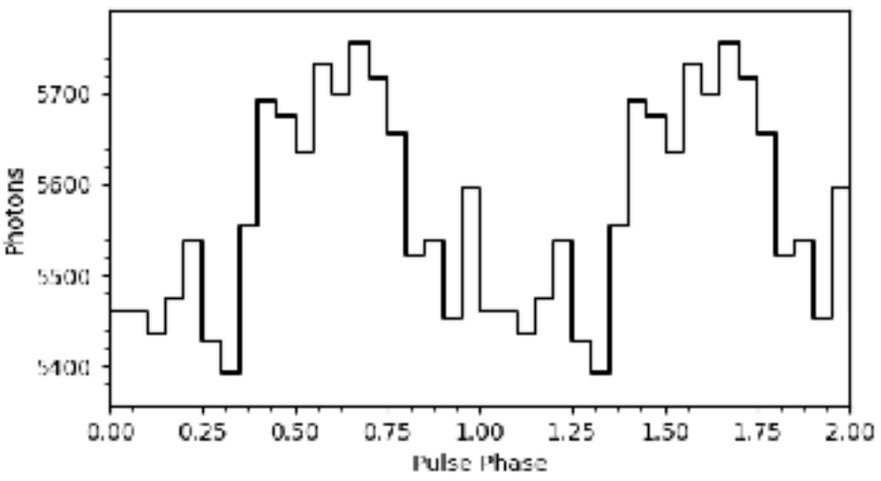
- For other millisecond pulsars:
  - On track to deliver 5% uncertainties with definitive data sets for two other pulsars.
  - Newly discovered pulsars added to the target list.

Newly discovered millisecond pulsars with NICER

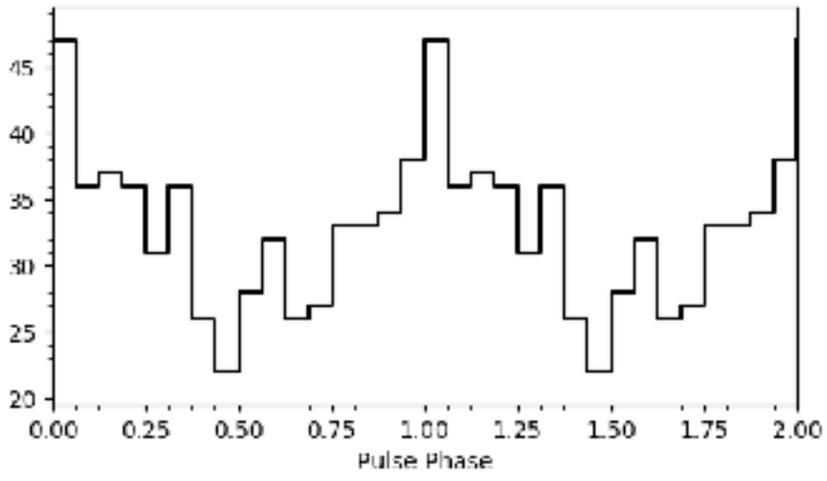
PSR J0614–3329



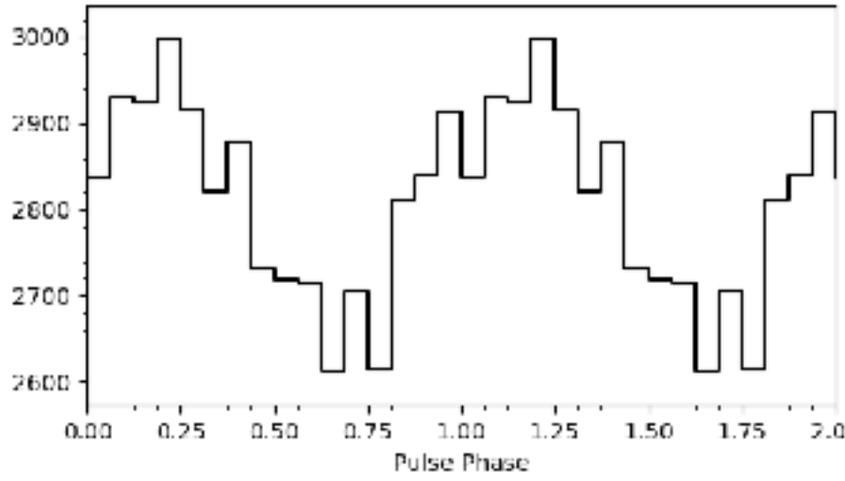
PSR J0636–5129



PSR J1744–1134



PSR J2241–5236

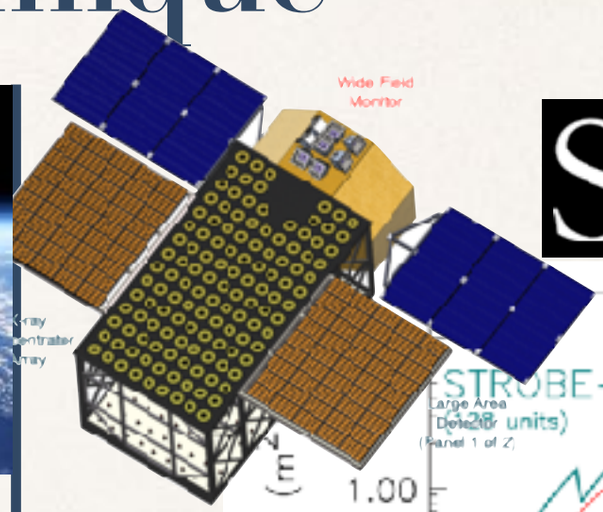


Guillot et al., in prep.

Future missions will fully enable the light curve modelling technique

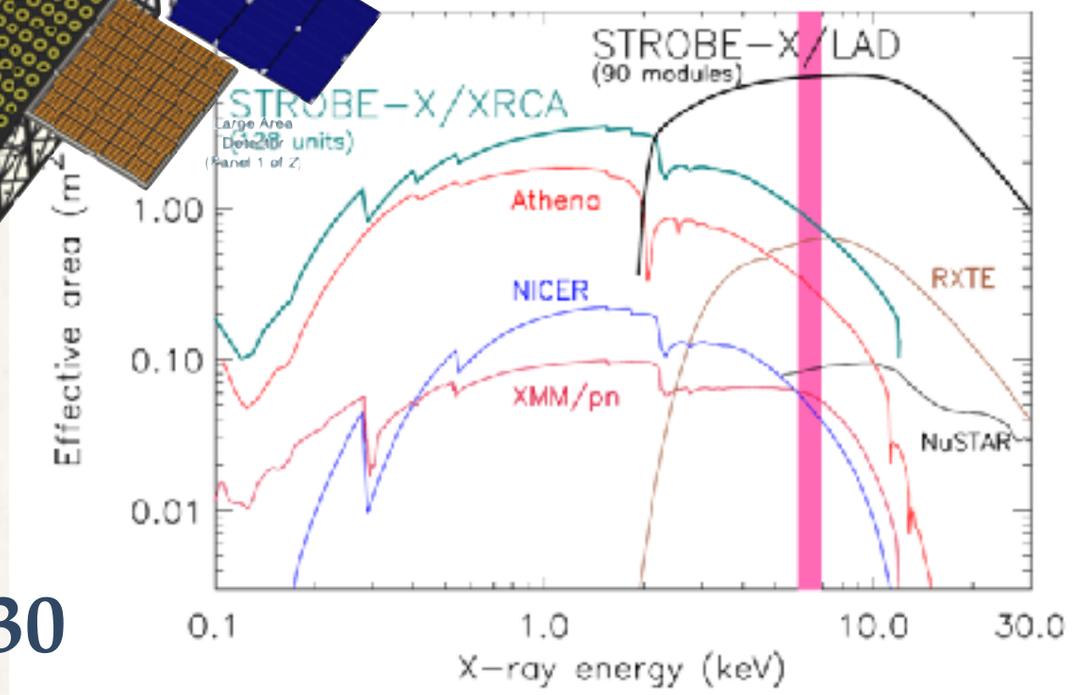
eXTP (~2025)

- Some imaging capabilities (60” PSF)
- ~ 4× more sensitive than NICER
- 10 μs time resolution
- + Hard X-ray instrument

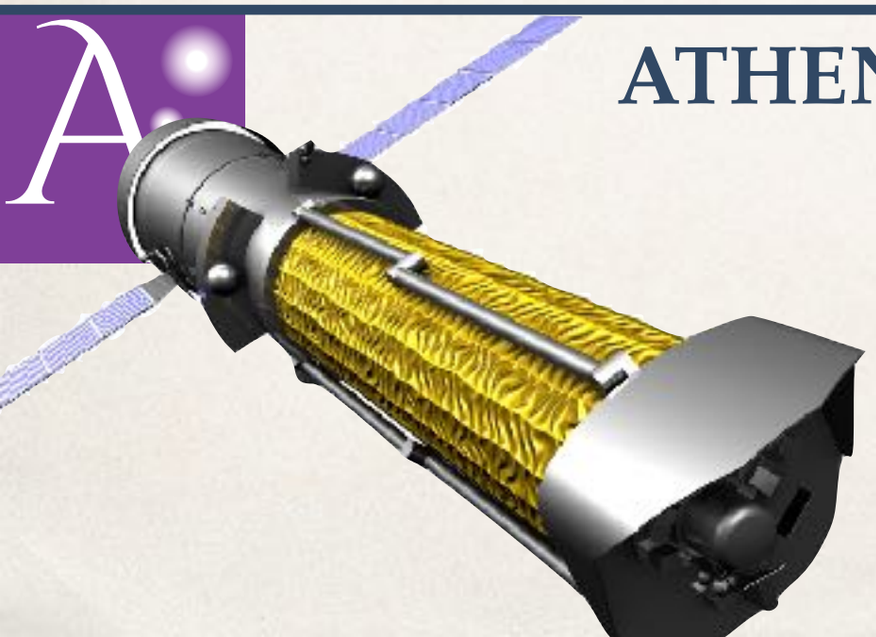


~2030

STROBE-X

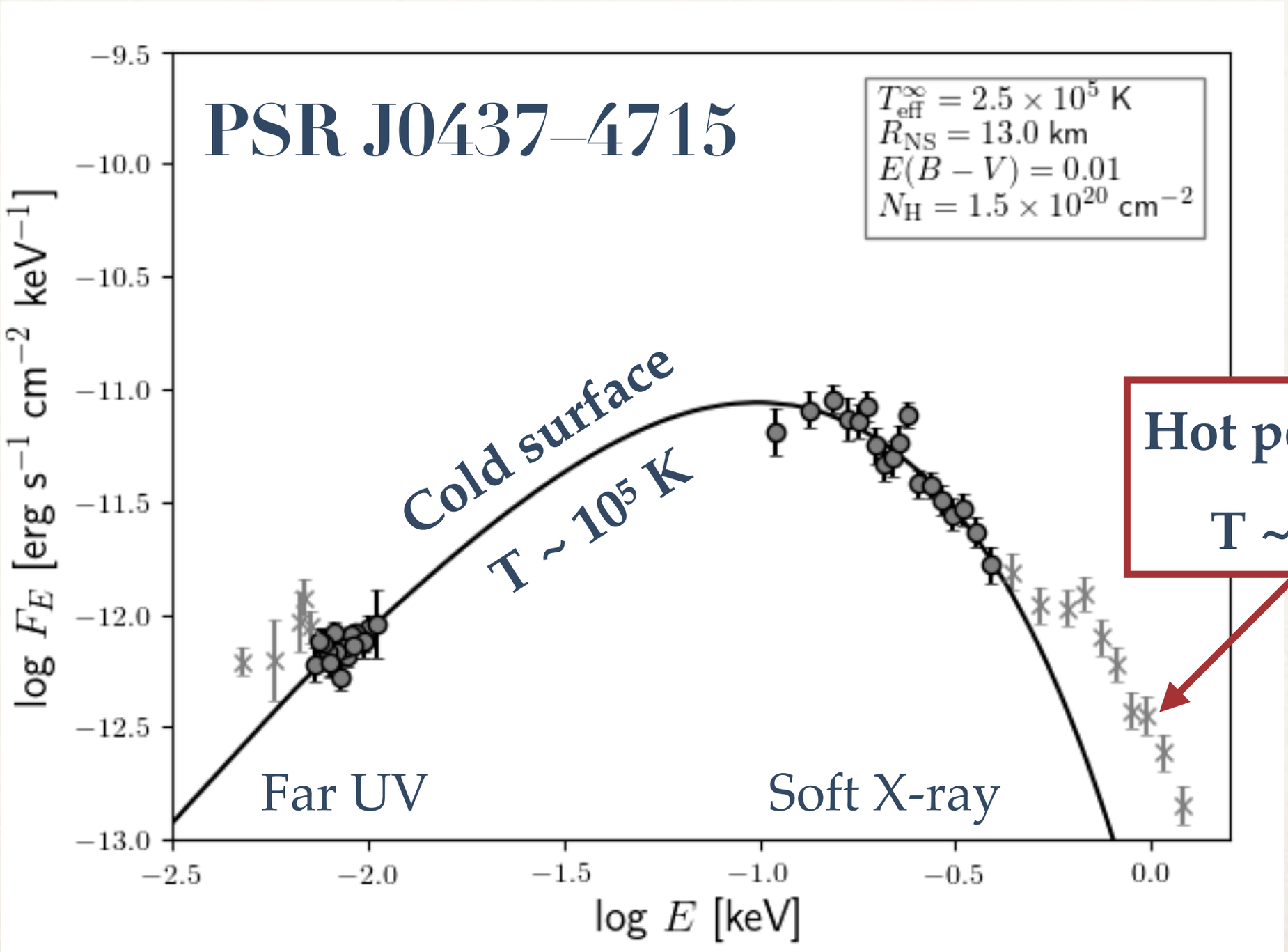


ATHENA (~2030)



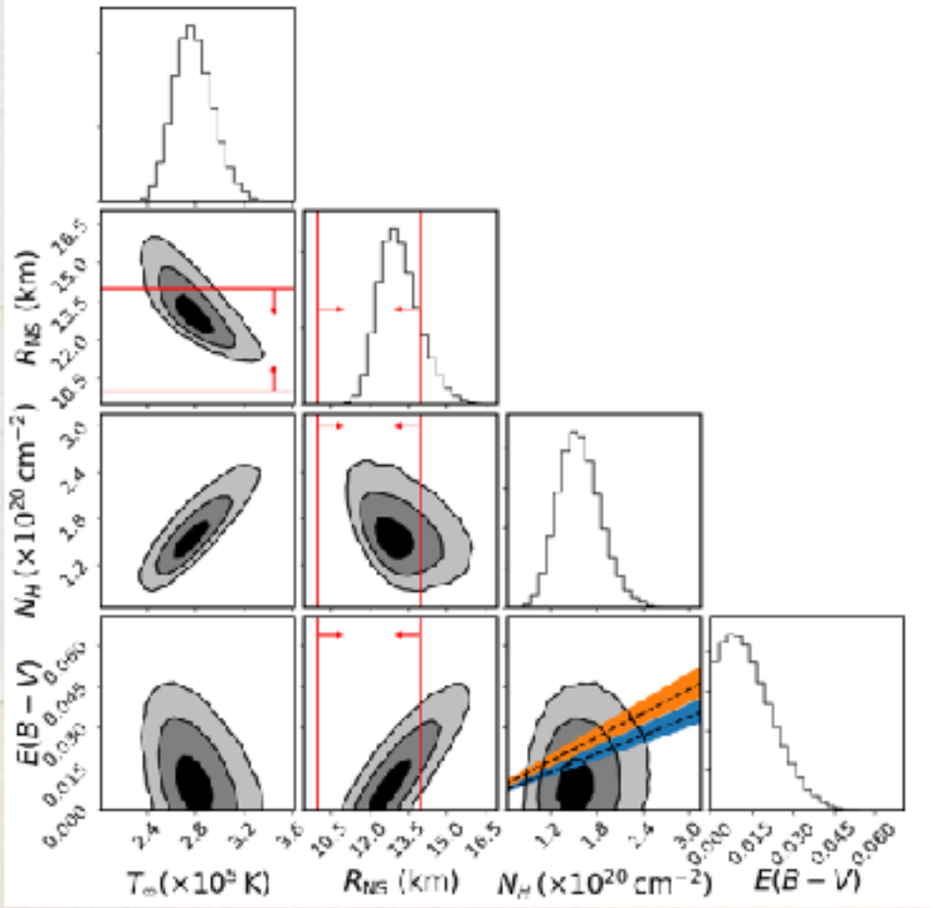
- Good imaging capabilities (5” PSF)
- ~ 10× more sensitive than NICER
- 10 μs time resolution

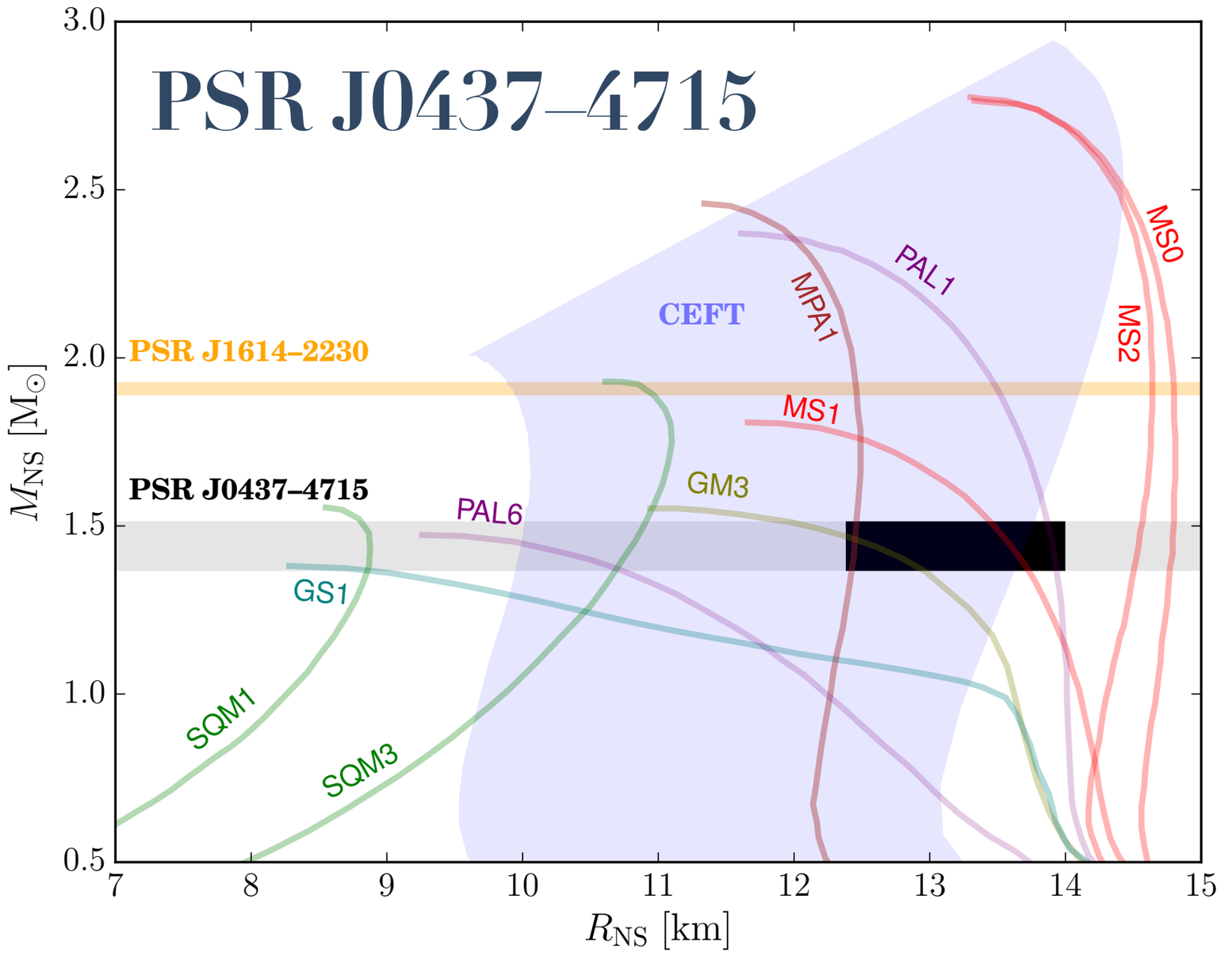
The cold surface of millisecond pulsars can also be used to measure their radius.



Gonzalez-Canuilef, Guillot & Reisenegger, 2019

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





Gonzalez-Canuilef, Guillot & Reisenegger, 2019

Summary

- For PSR J0030+0451:
  - R = 12–15 km, to be confirmed
  - M = 1.2–1.7 $M_\odot$
- Results expected soon for 4 other millisecond pulsars
- Future missions will fully exploit this technique to provide many more M and R measurements.