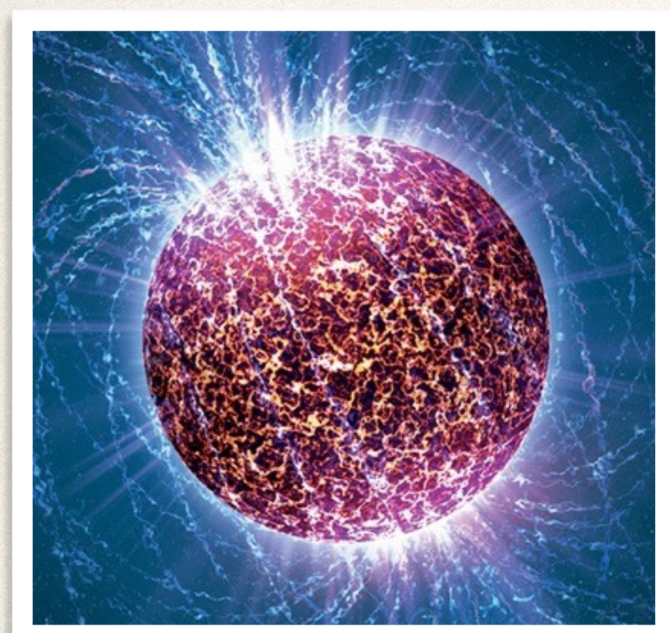
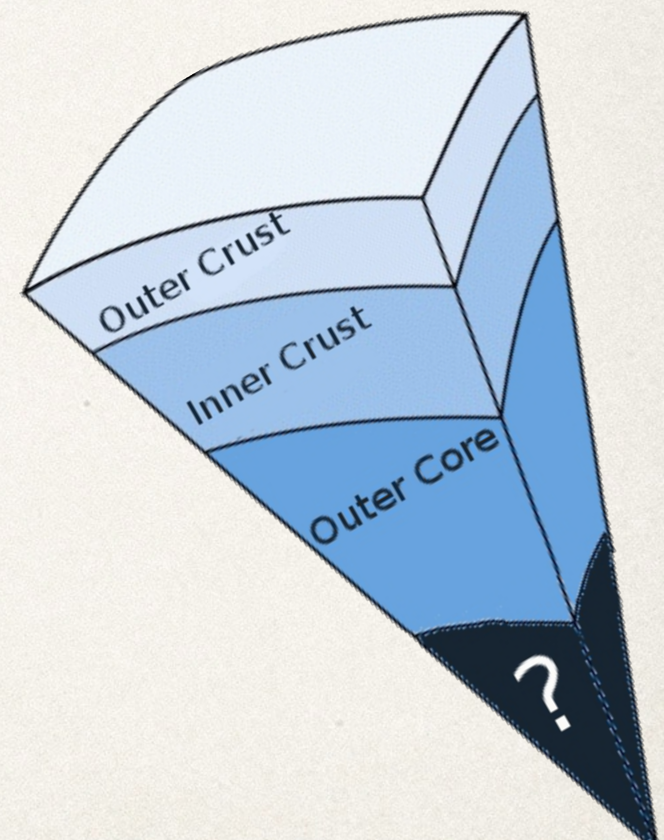
More neutron star radius measurements from NICER to understand dense nuclear matter

Sebastien Guillot





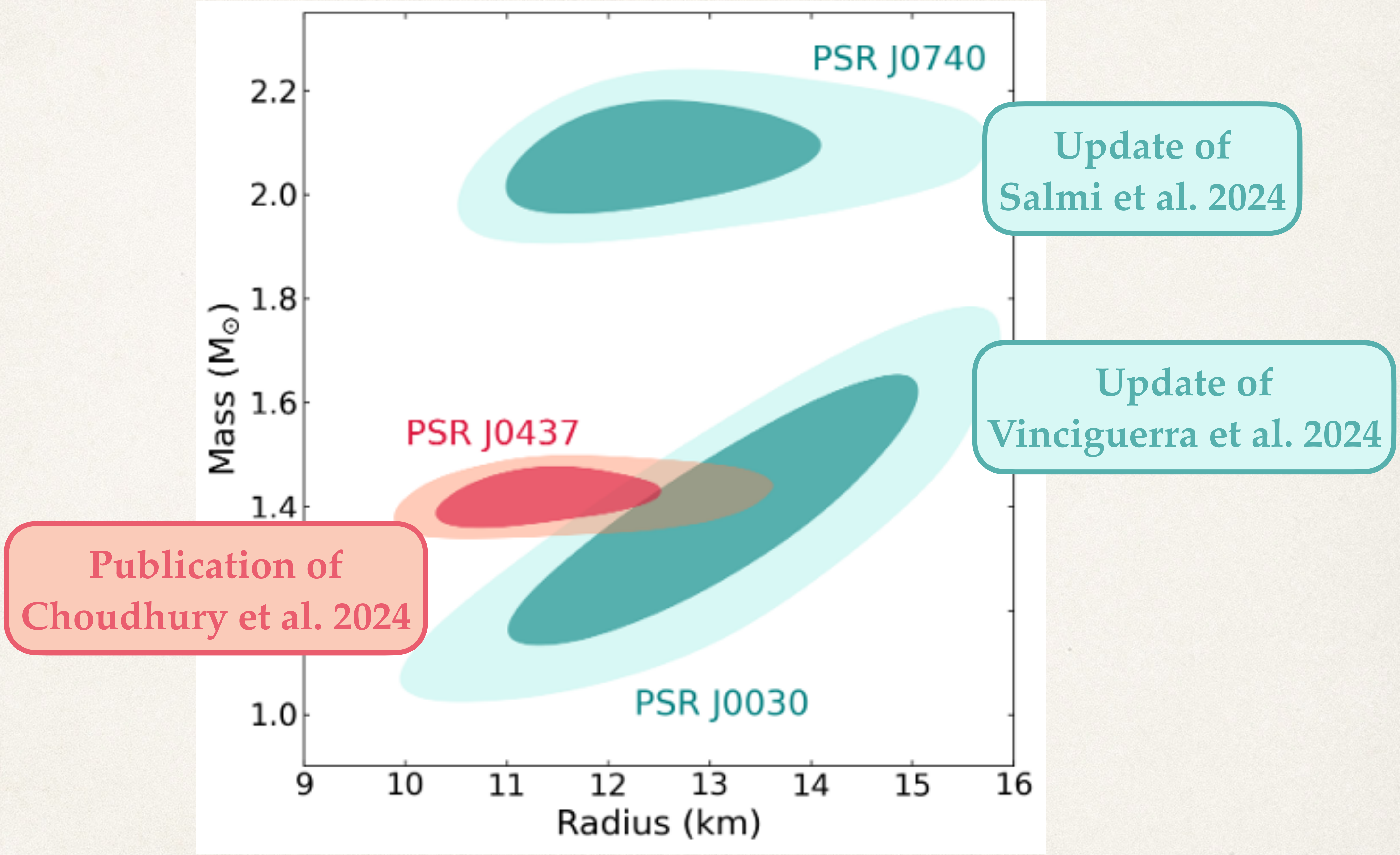
Collaborators

A. Watts, T. Salmi, D. Choudhury, S. Vincinguerra,
And many people in the NICER Science team

at IRAP

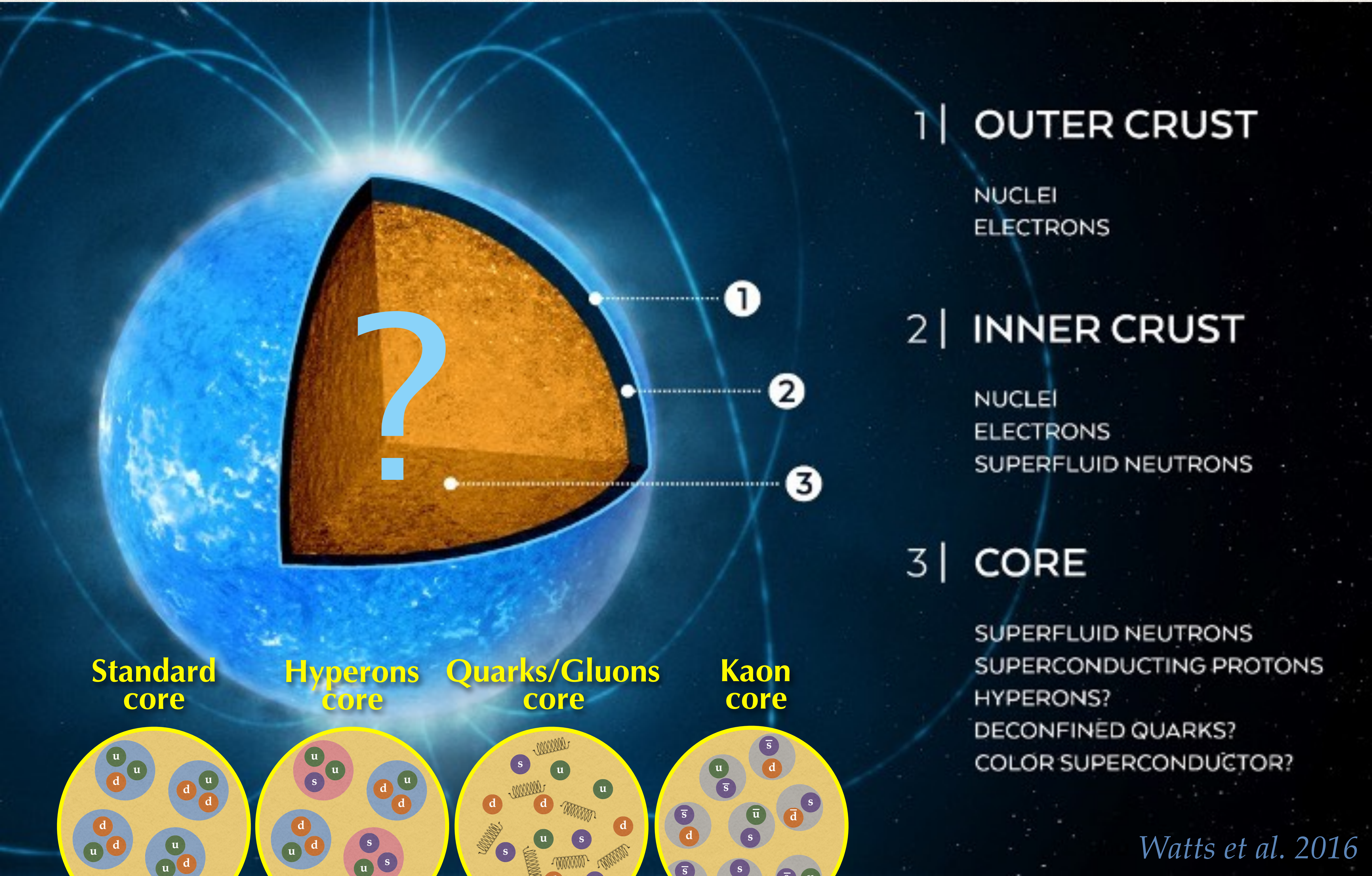
Lucien Mauviard,
Pierre Stammler, Denis Gonzalez

Let's start with the conclusion…



Submitted results for
another pulsar PSR J1231

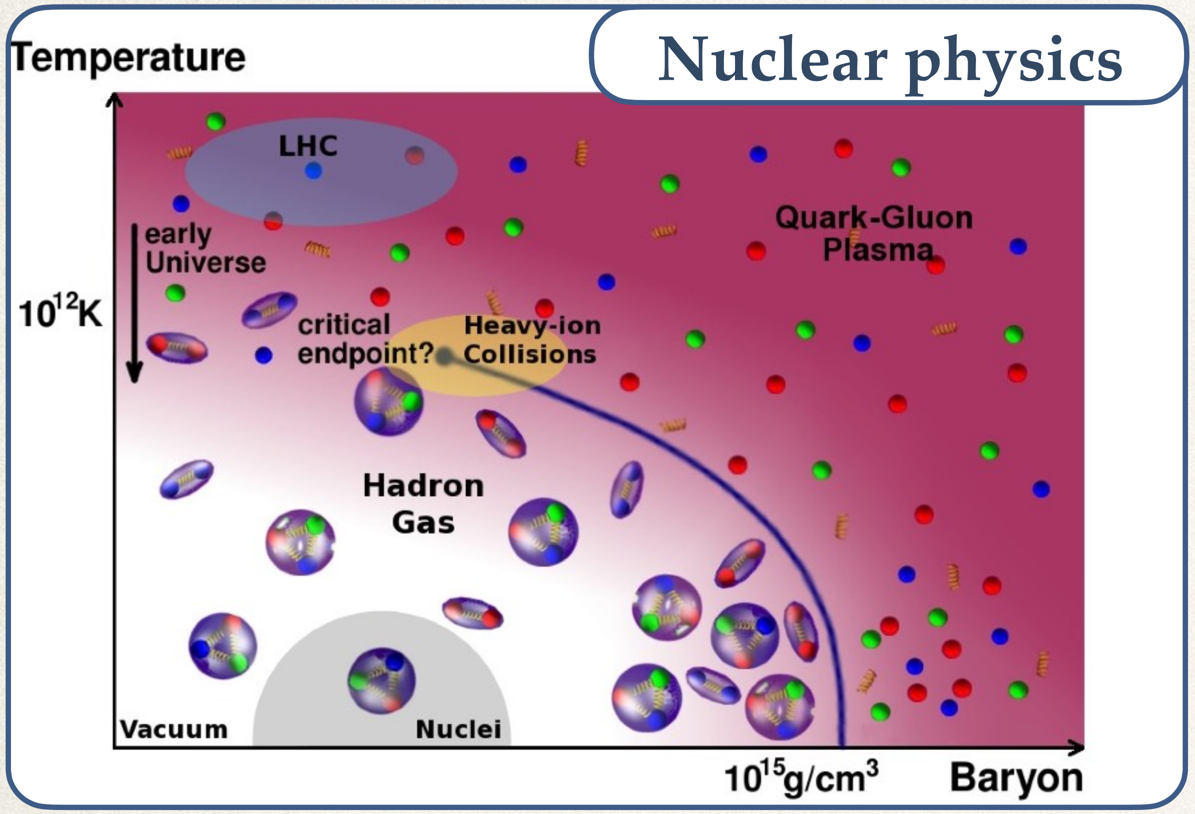
Besides the top ~ 1km, the properties of neutron star interiors are mostly unknown.



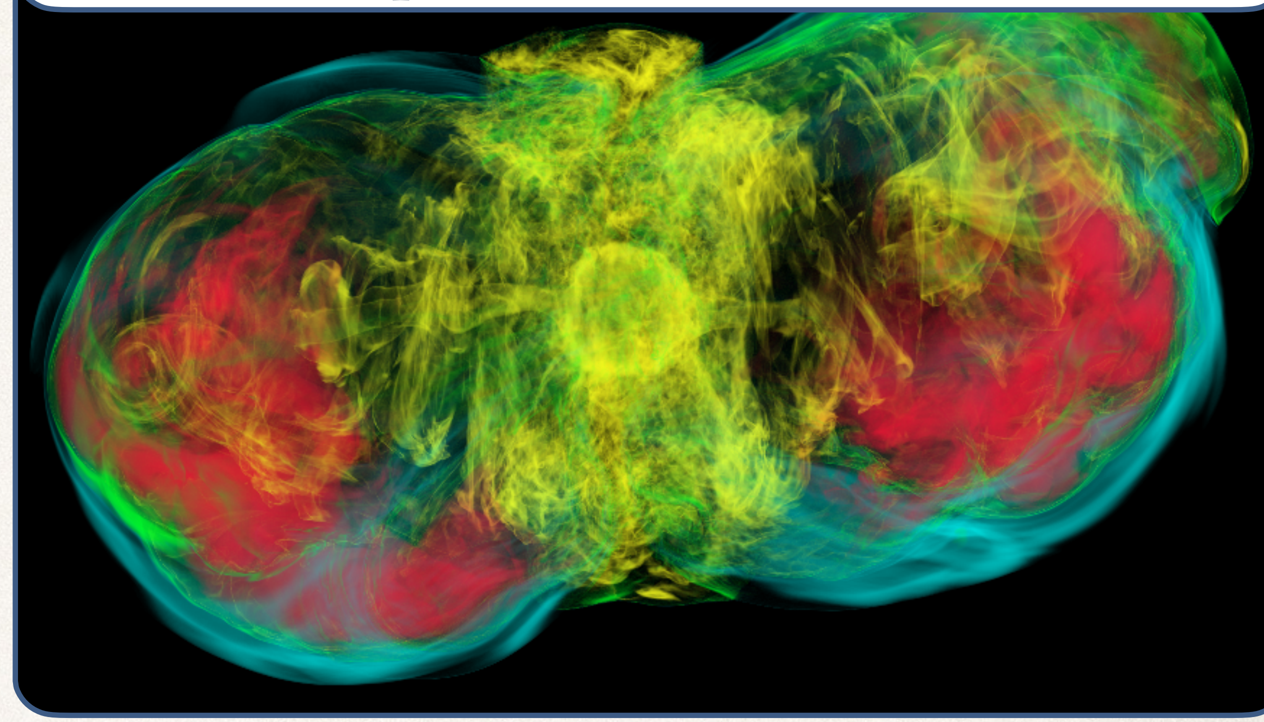
Watts et al. 2016

The dense matter equation of state is a key question of fundamental physics and astrophysics

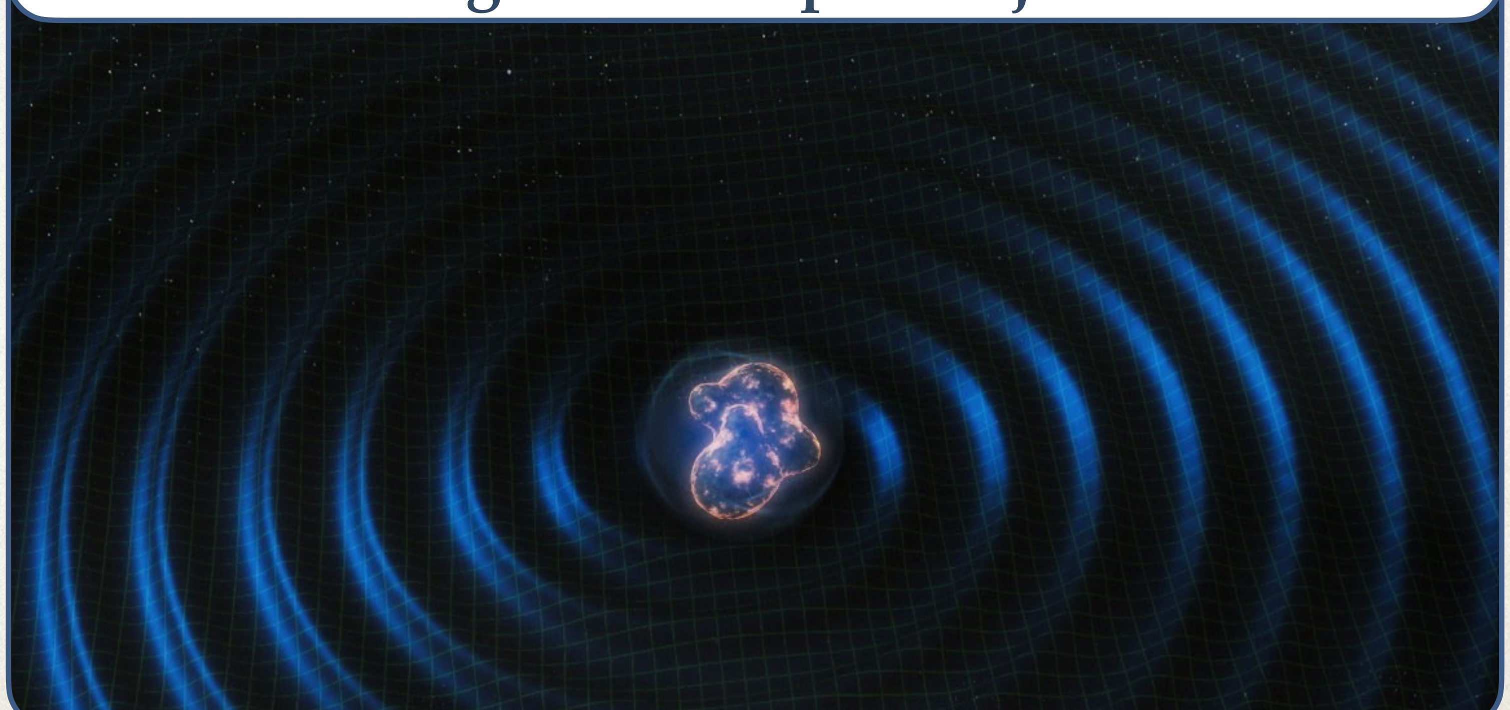
Nuclear physics



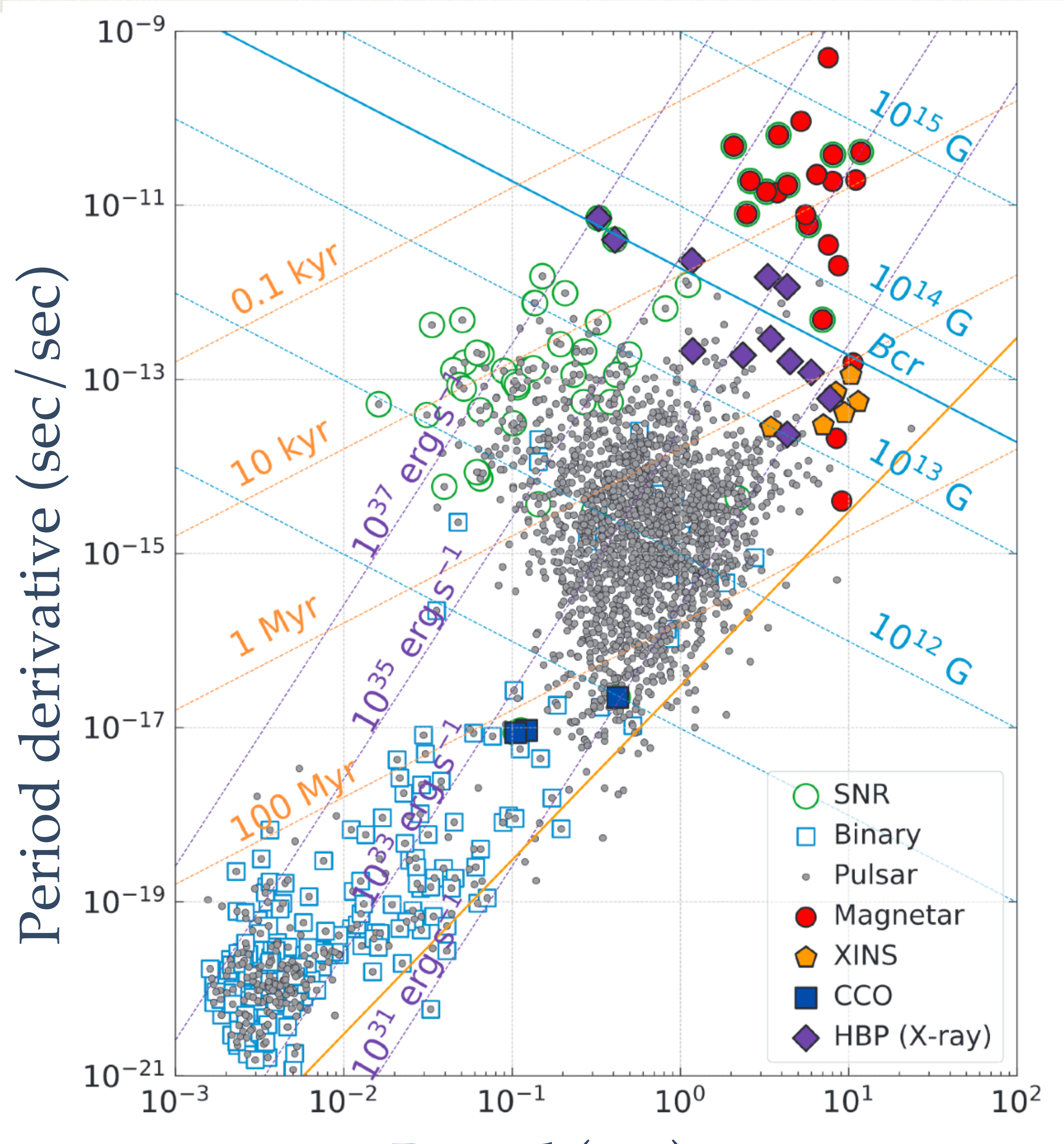
Supernovae mechanisms



Mergers of compact objects



To measure M_{NS} and R_{NS}, choose your players carefully!



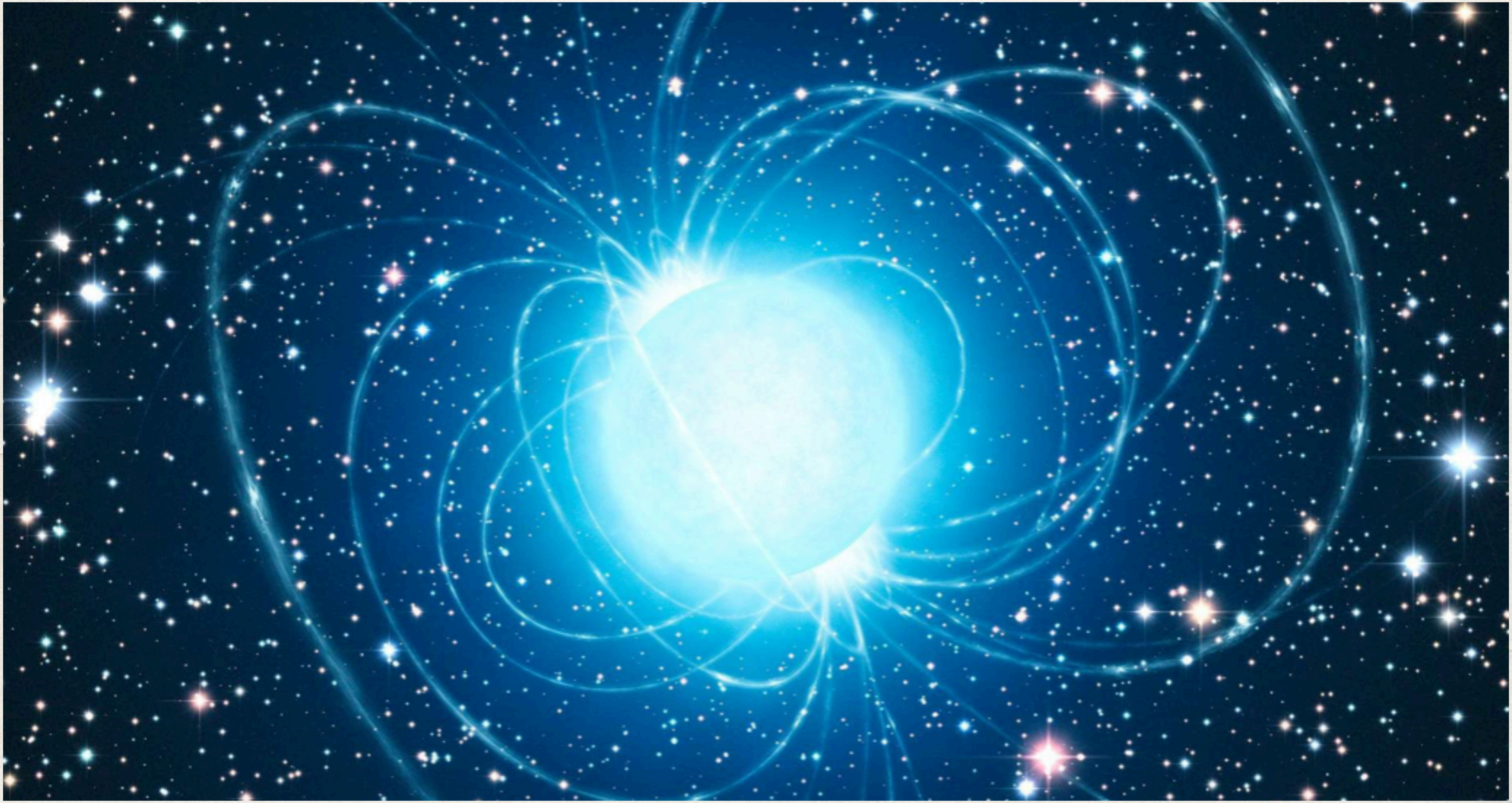
Enoto et al. 2019

Millisecond pulsars are old and fast rotating neutron stars

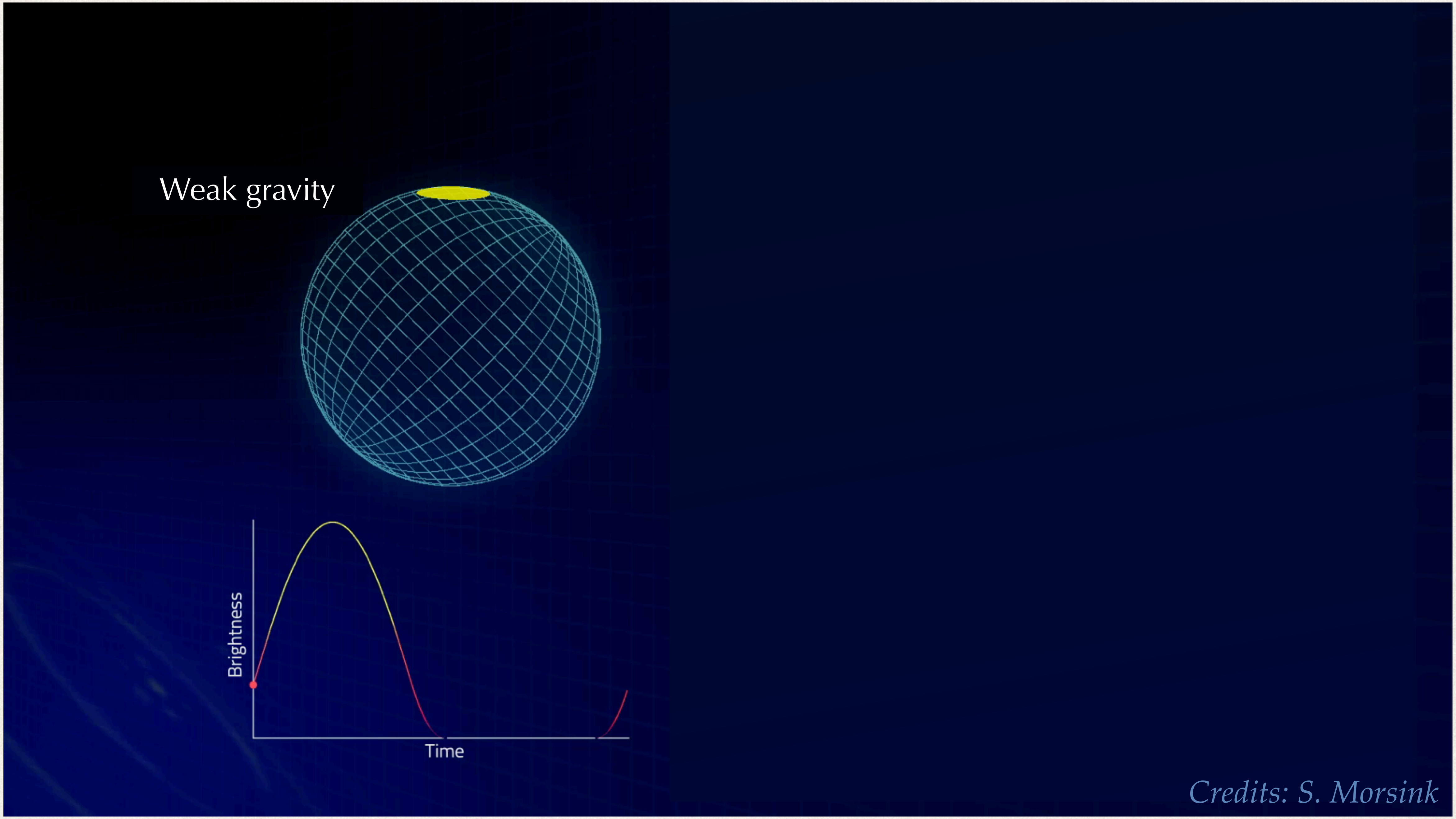
Advantages:

- Very stable on long time scales
- Low B-fields and no accretion
- Purely thermal X-ray emission
- Additional info from radio/gamma

The hot X-ray emission of millisecond pulsar comes from e^-/p^+ bombardment of the surface heating the polar caps.

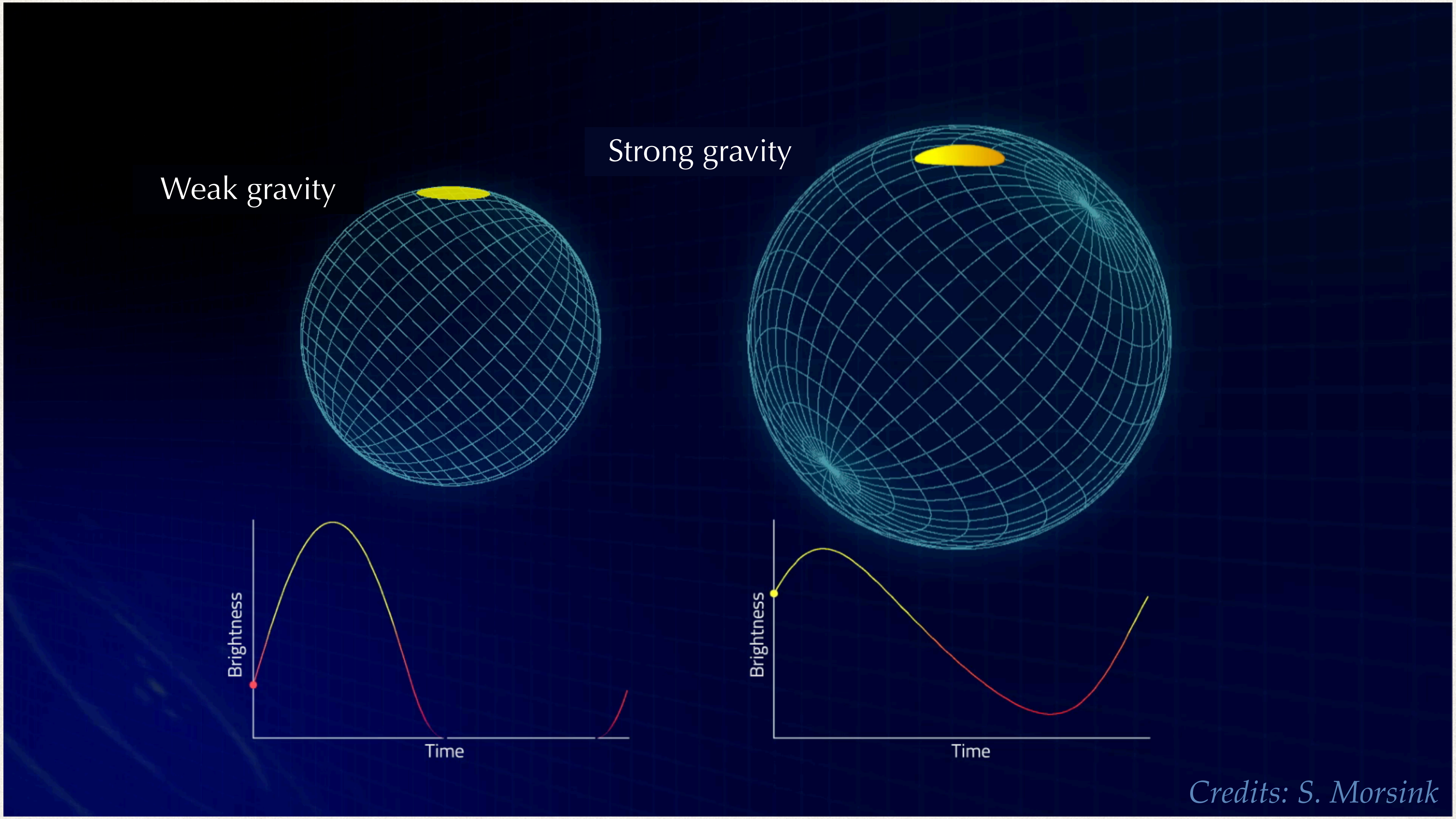


Credits: ESO



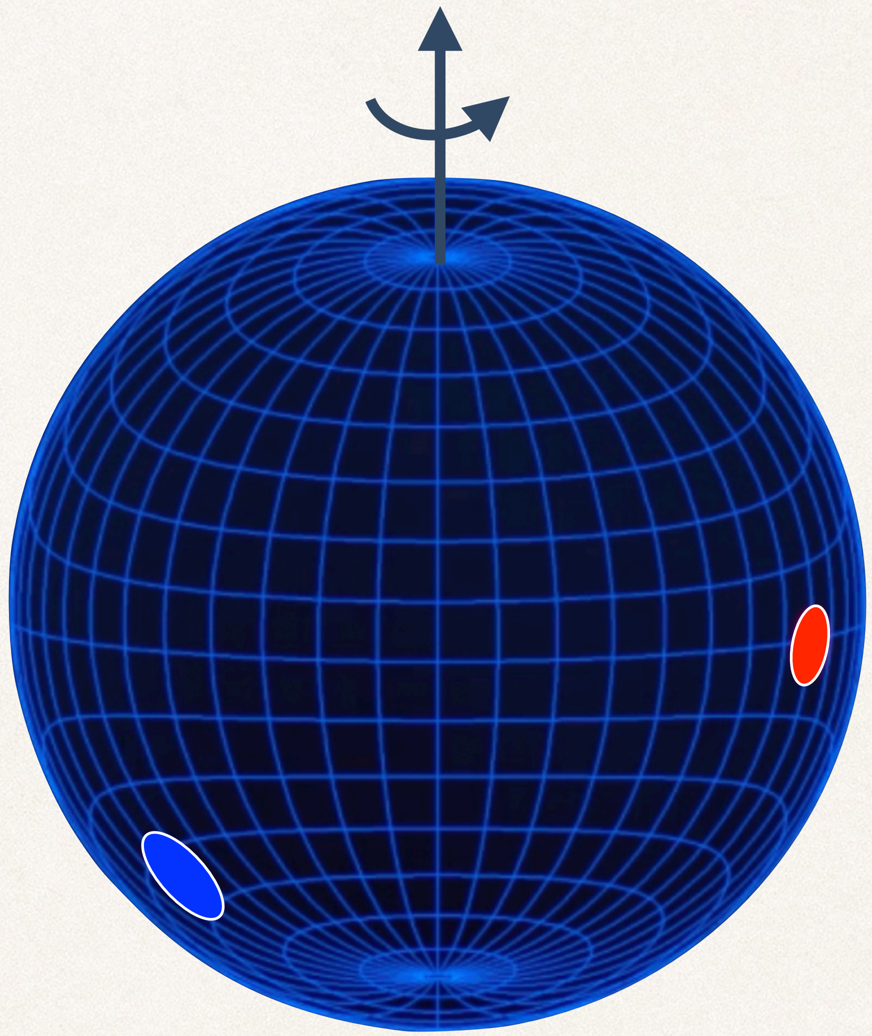
Credits: S. Morsink

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

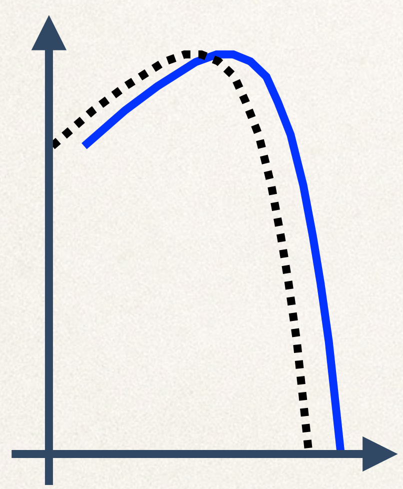


Pulse profile modelling to determine the compactness M_{NS}/R_{NS}

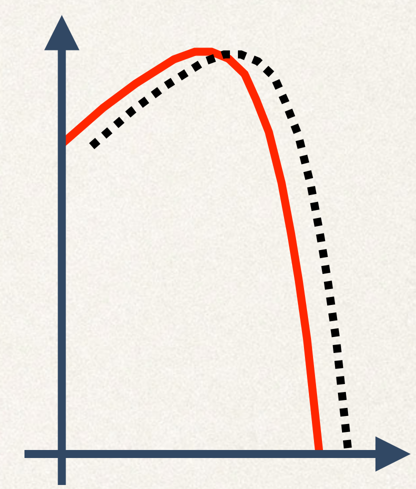
The Doppler effect break the degeneracy between M_{NS} and R_{NS}.



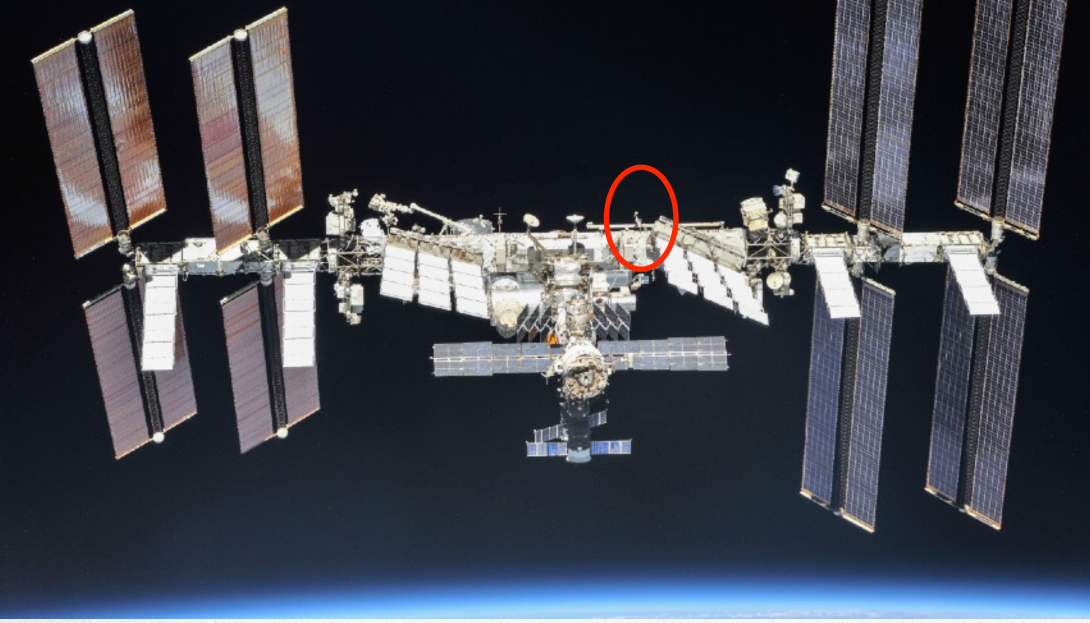
Approaching spot is blue shifted

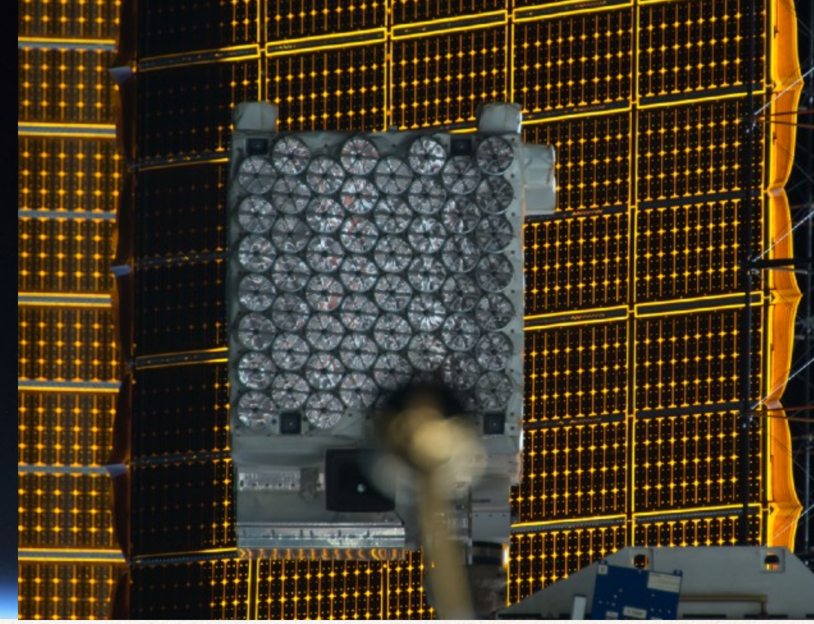


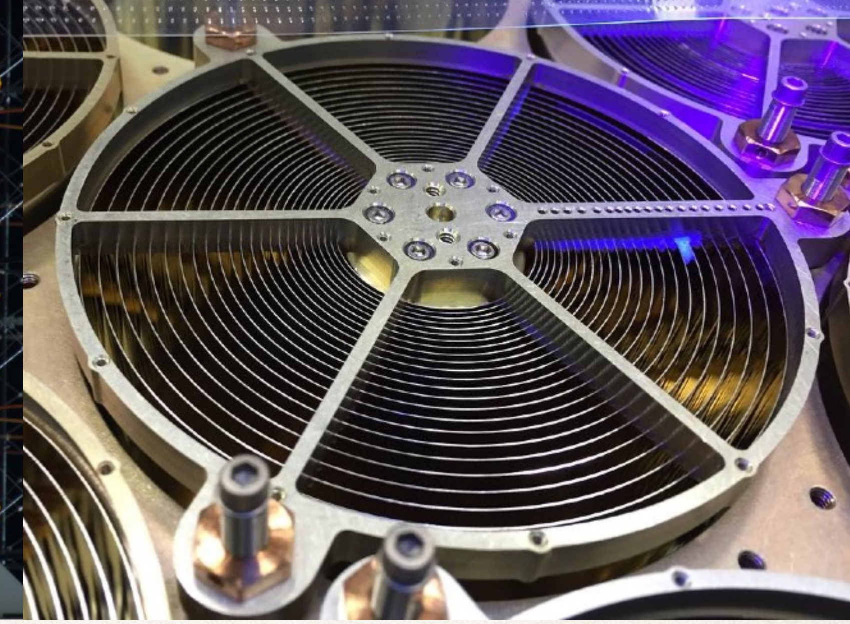
Receding spot is red shifted



The effect depends on the line of sight velocity, i.e., <u>spin frequency</u> and <u>distance from rotation axis</u>

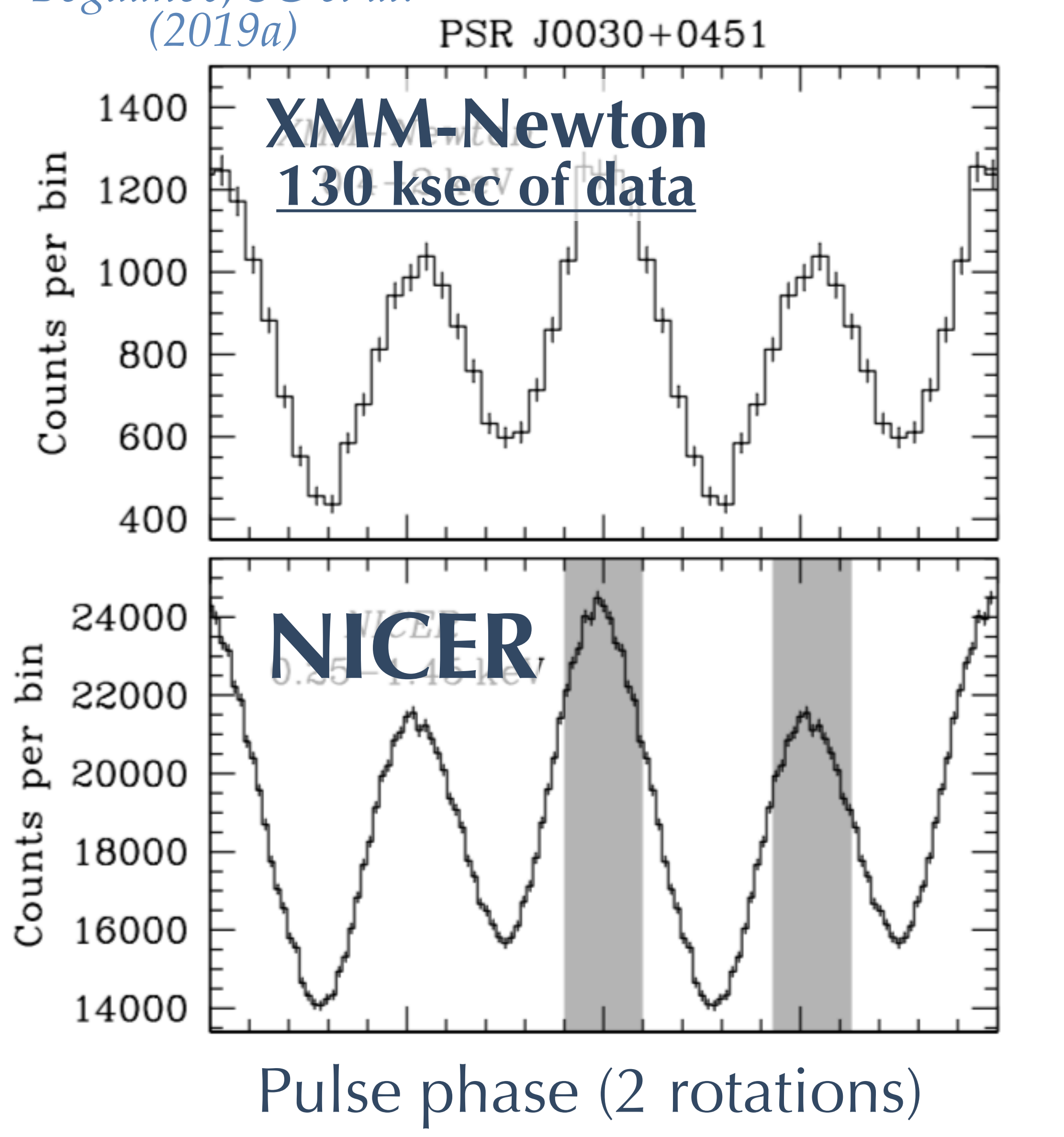


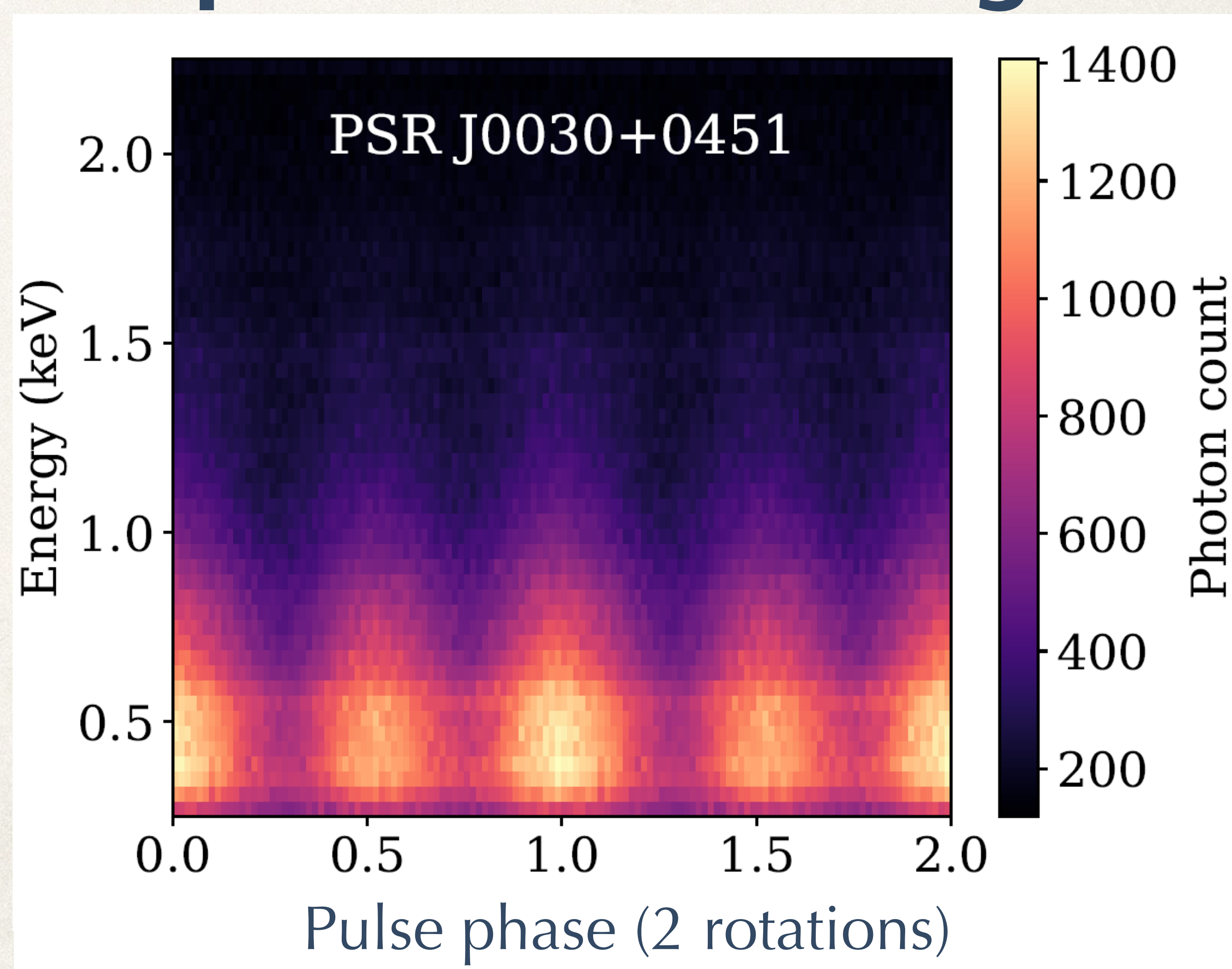




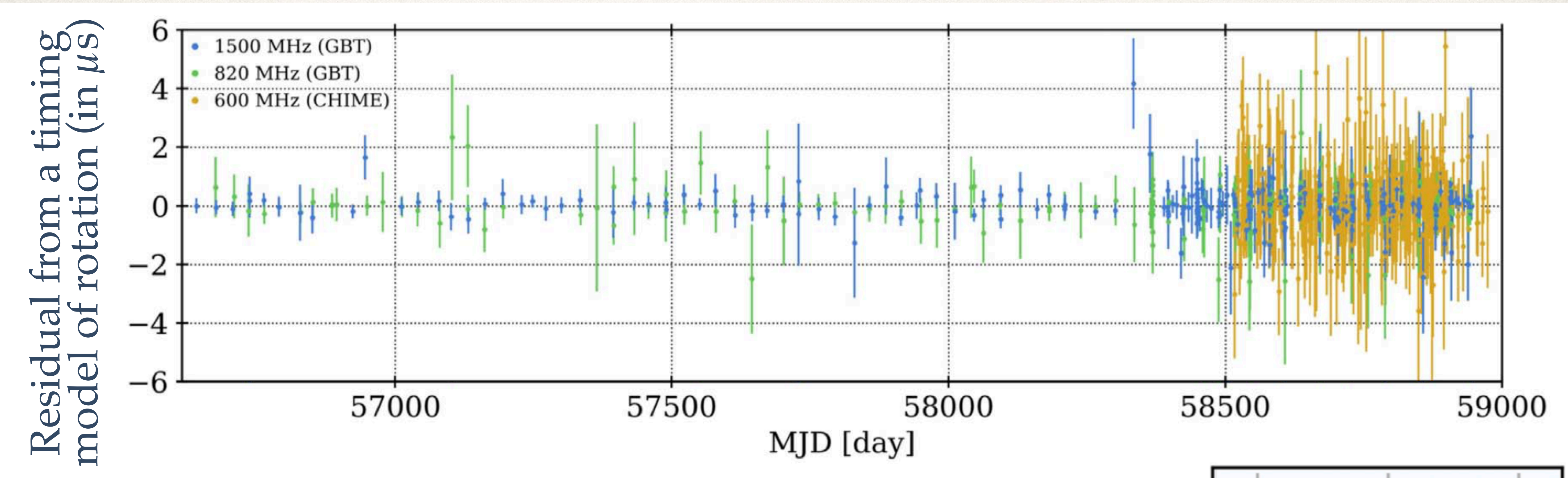
NICER has given us beautiful data sets to perform pulse profile modelling.

Bogdanov, SG et al. (2019a)



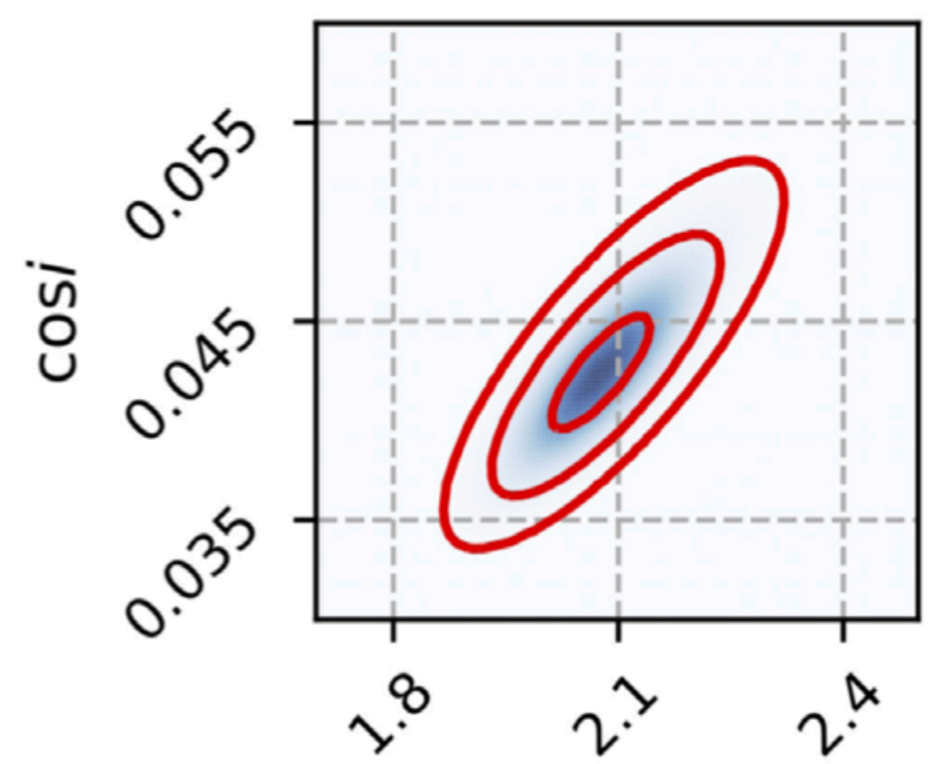


A radio timing solution of the MSP's rotation is critical to the analyses of NICER data.

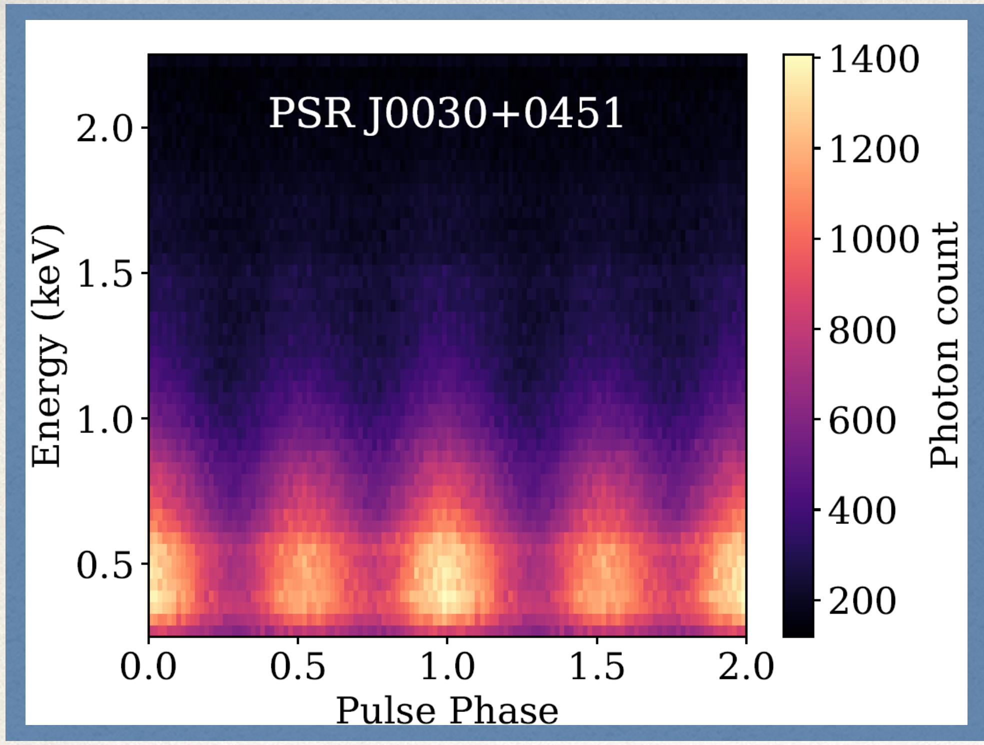


Radio timing provides information on:

- Mass
- Inclination
- Distance

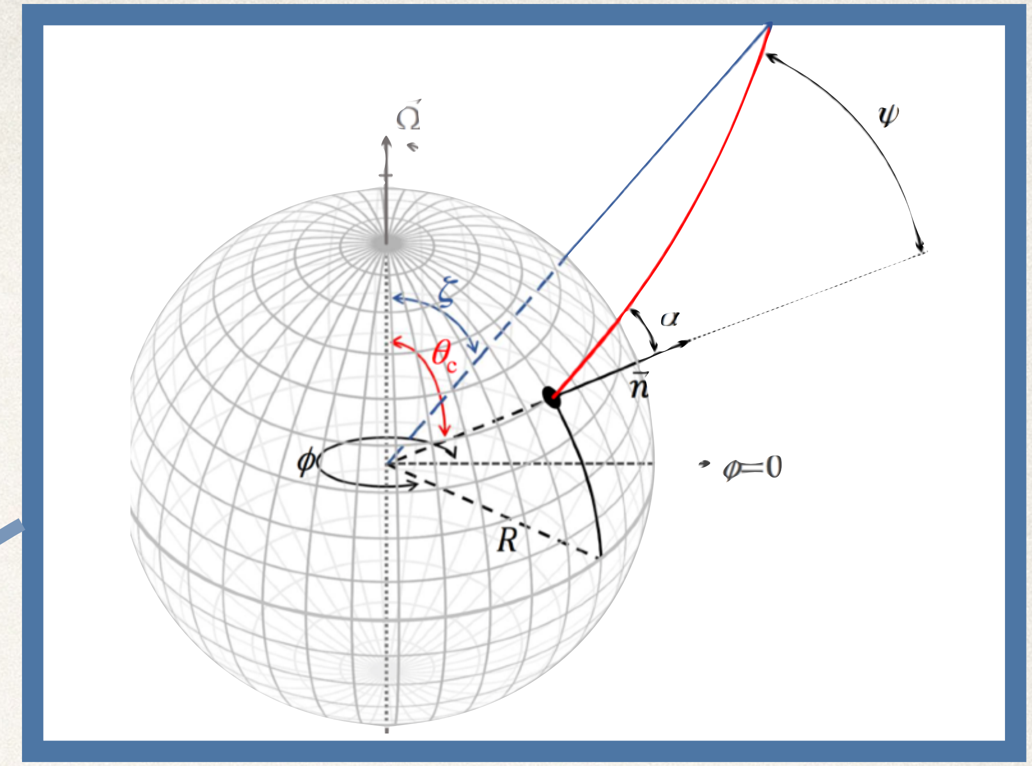


Fonseca et al (2021)

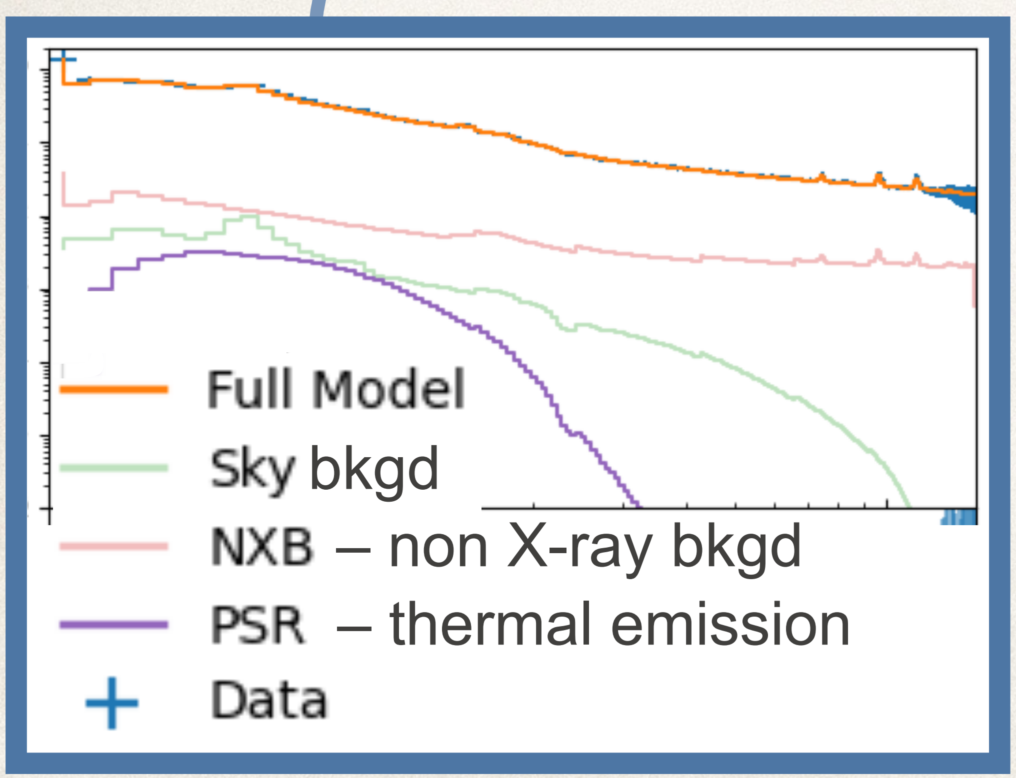


Priors

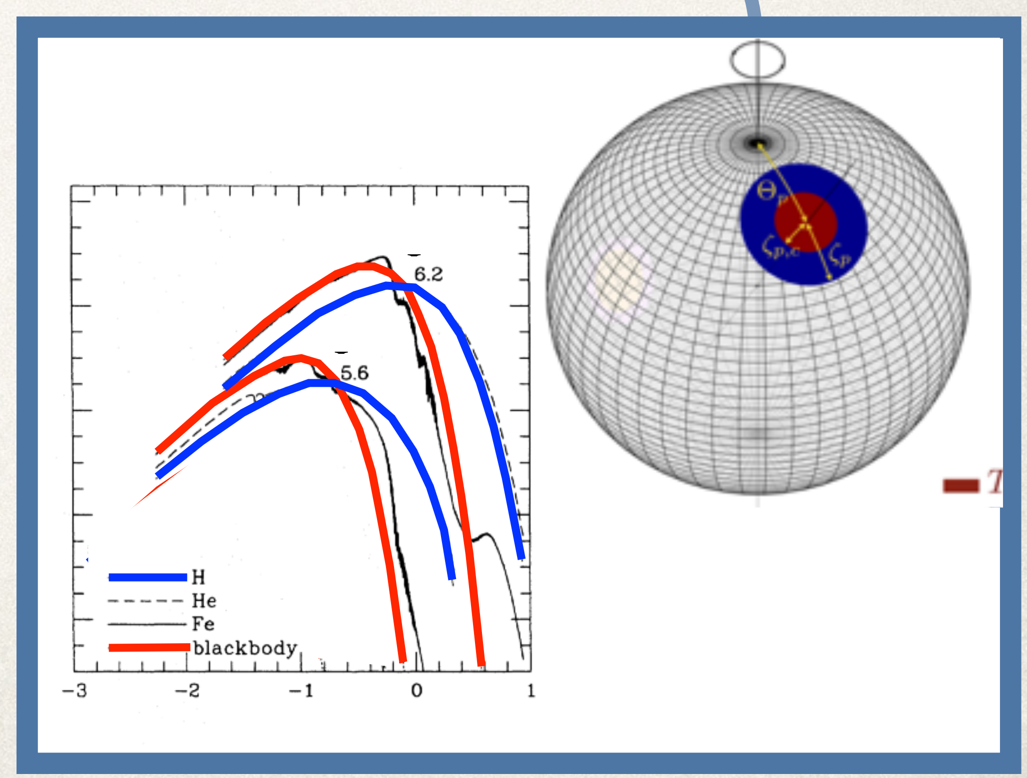
mass
distance
inclination



NS properties inference
(Likelihood statistical sampling)

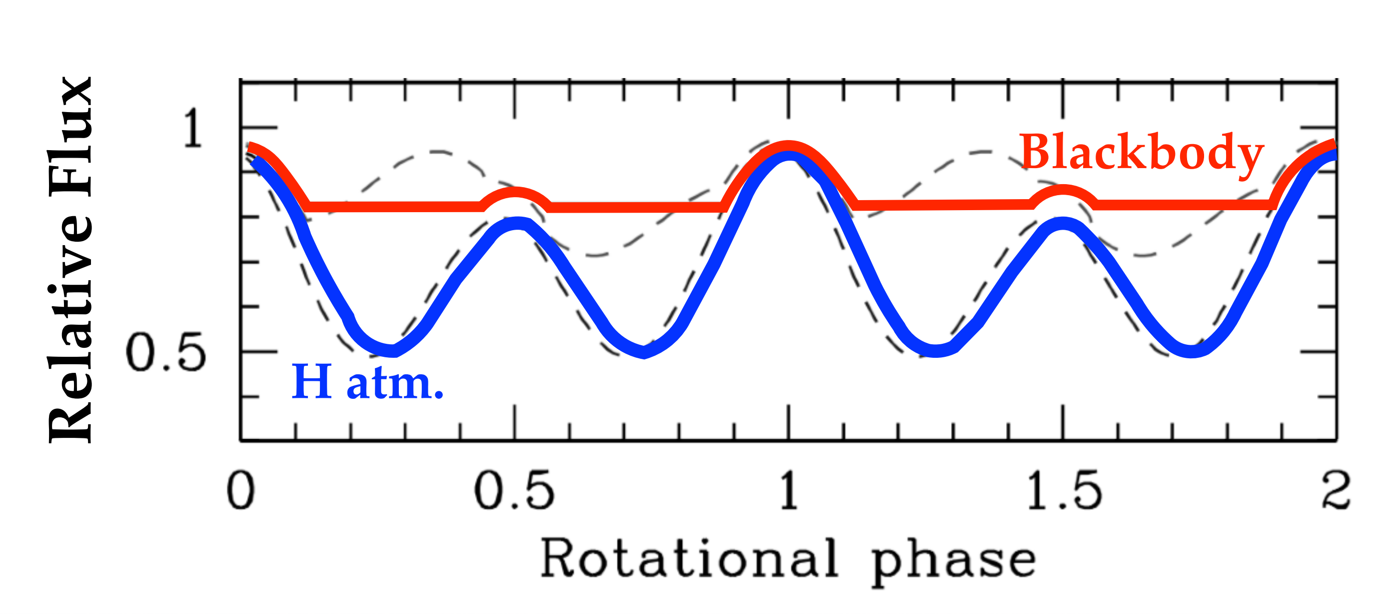


Mass,
Radius,
EOS



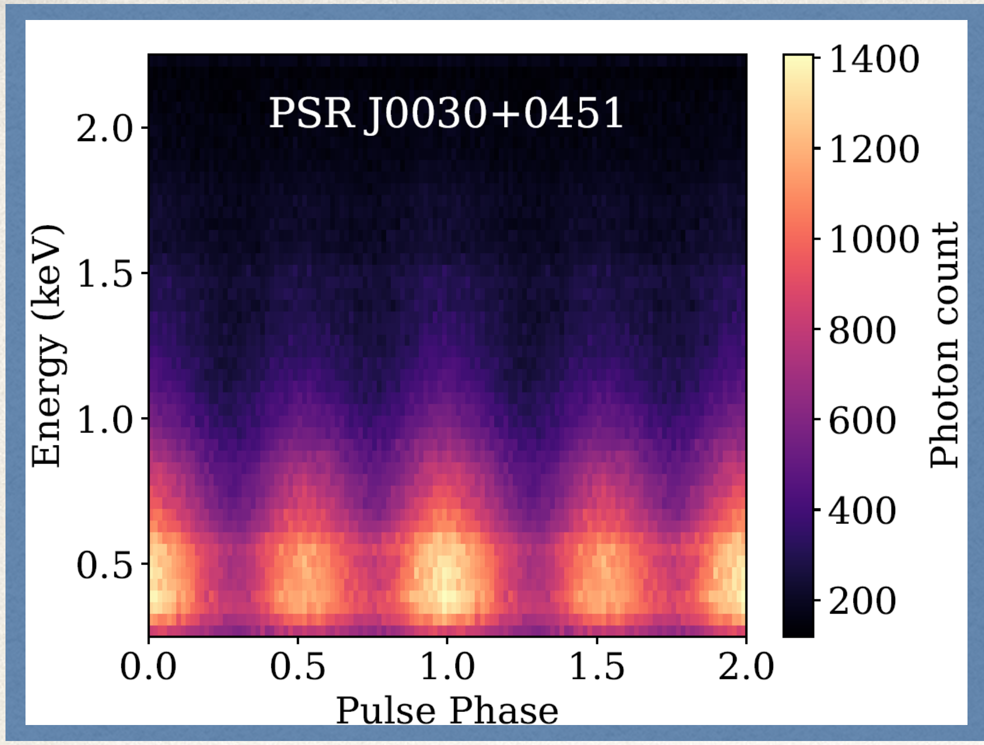
The surface thermal emission is modelled with a NS atmosphere, not a black body.

Blackbody and NS atmosphere generate different pulse profile shapes



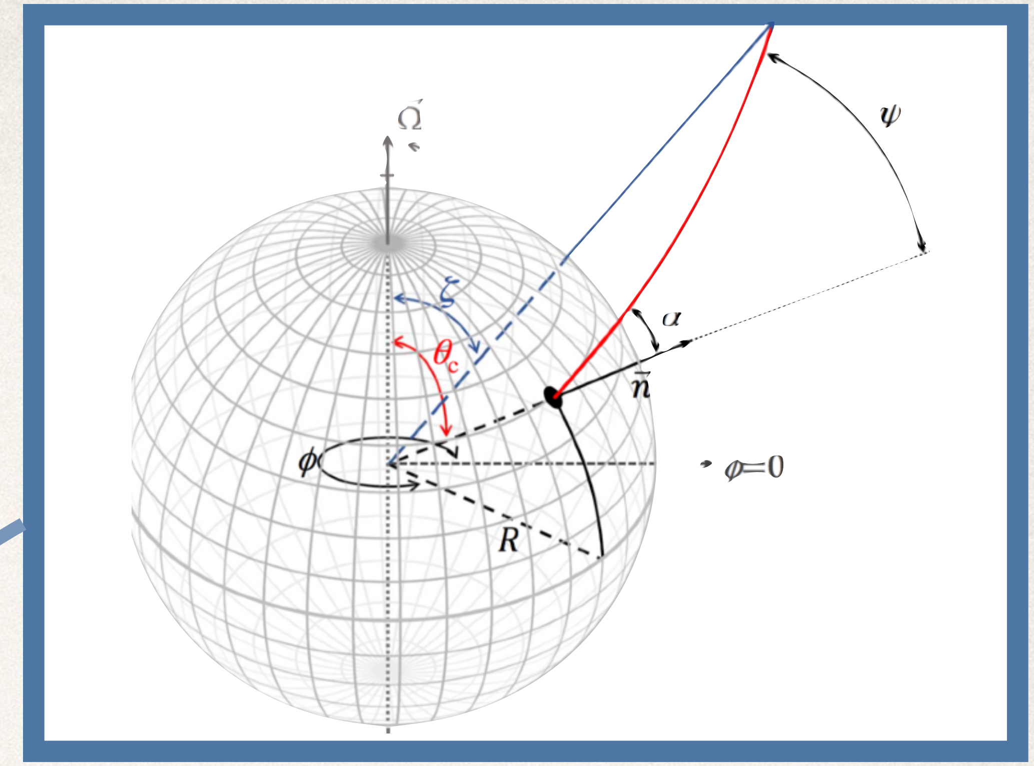
Bogdanov et al. (2007)

In the following, we used Hydrogen atmosphere models



Priors

mass
distance
inclination



NS properties inference
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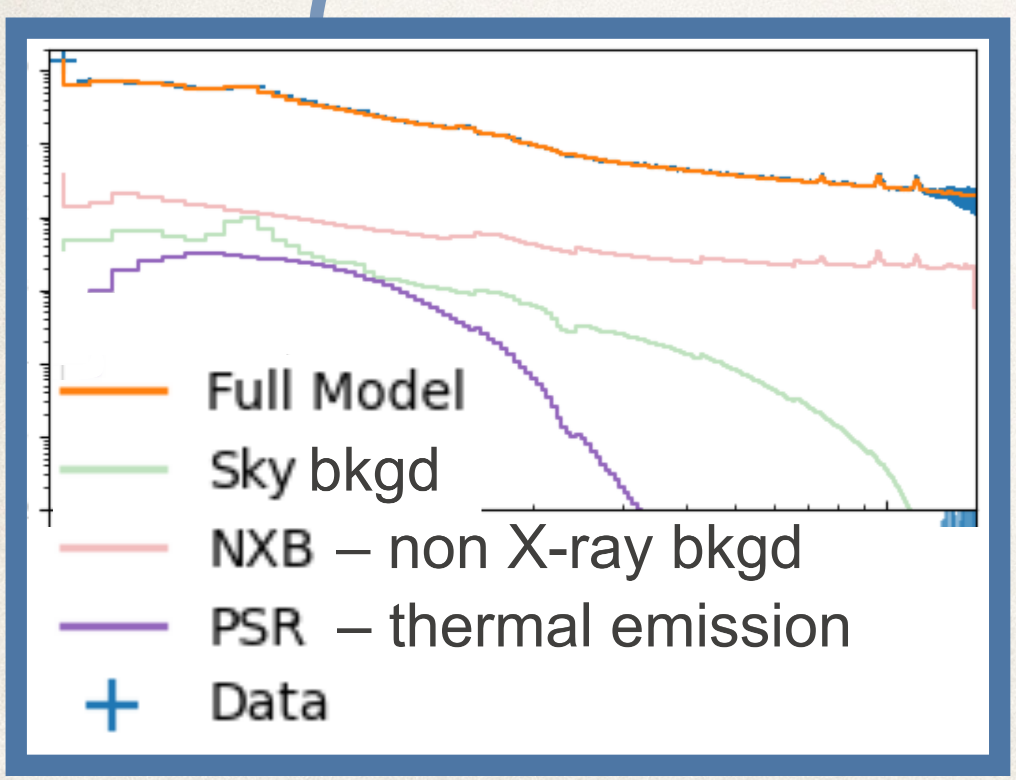
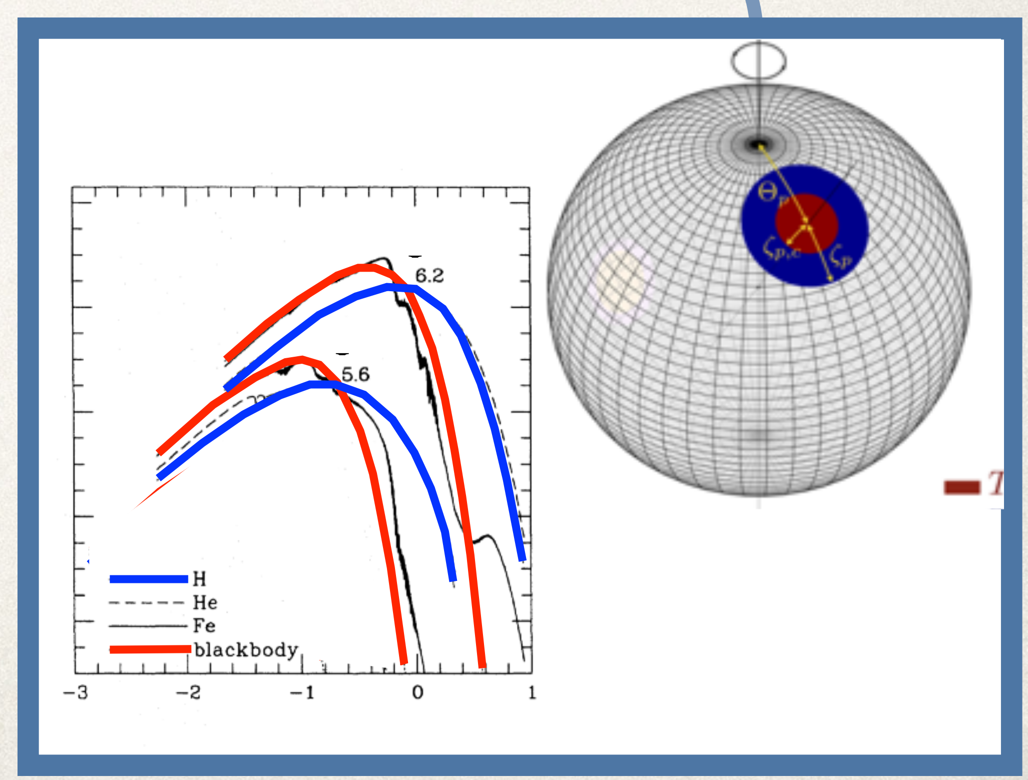
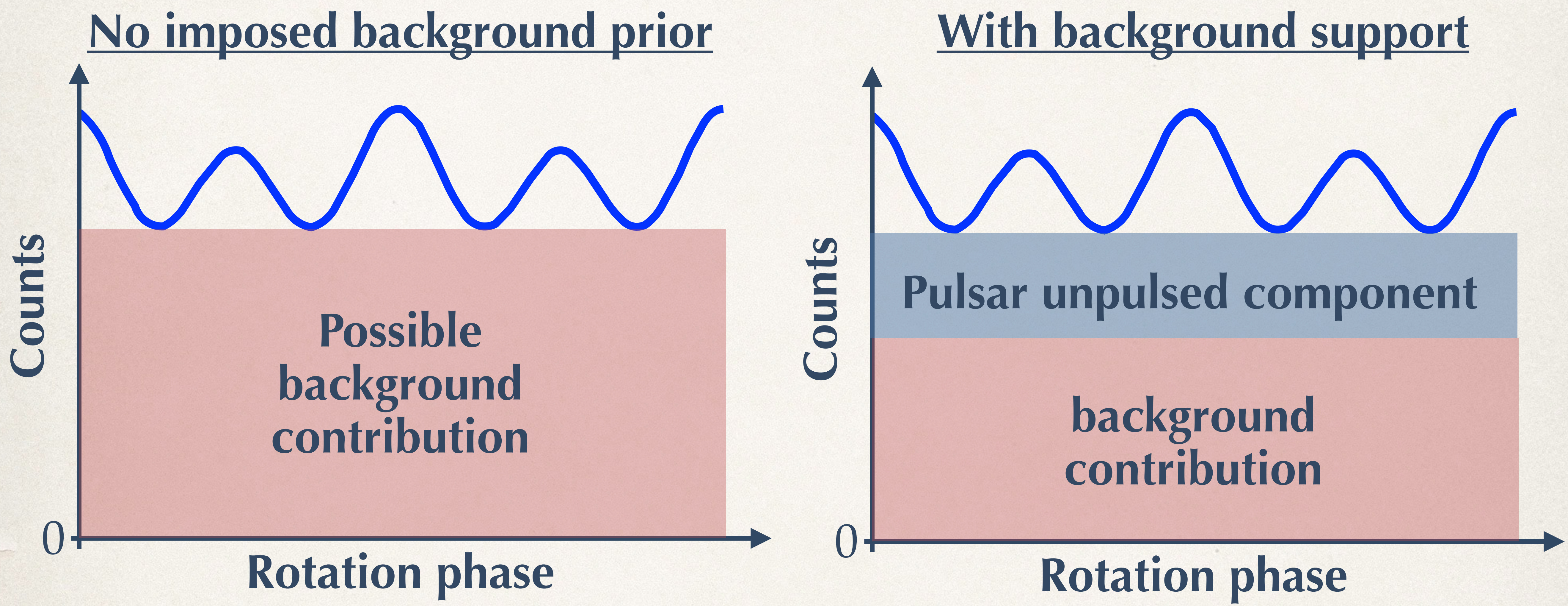


Mass,
Radius,
EOS



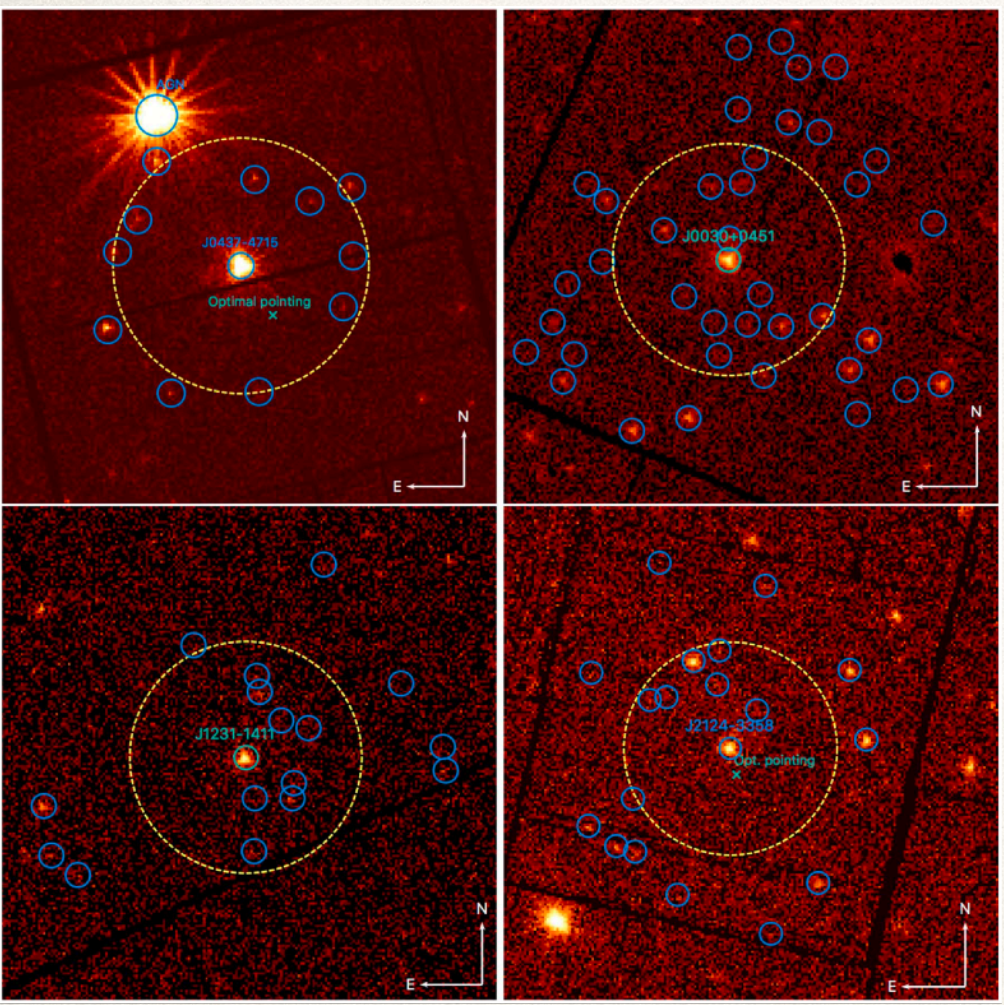
For faint pulsars, the high background in the NICER data needs to be well constrained.



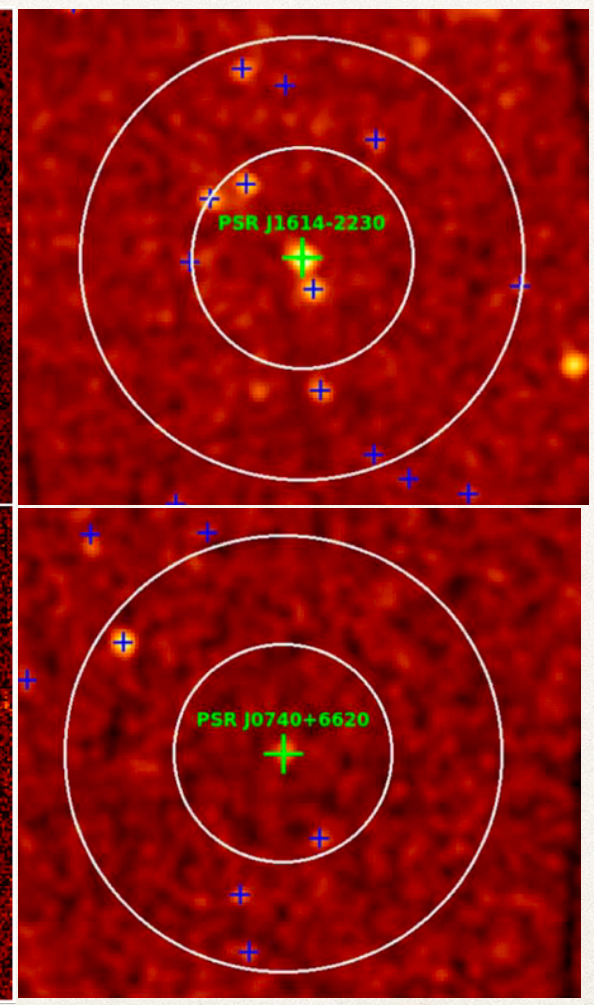
- **3C50**: Empirical background estimates (from blank fields)
- **SCORPEON**: Analytical background
- **External data:** From the XMM-Newton observatory

The background in our NICER datasets can be constrained with XMM-Newton.

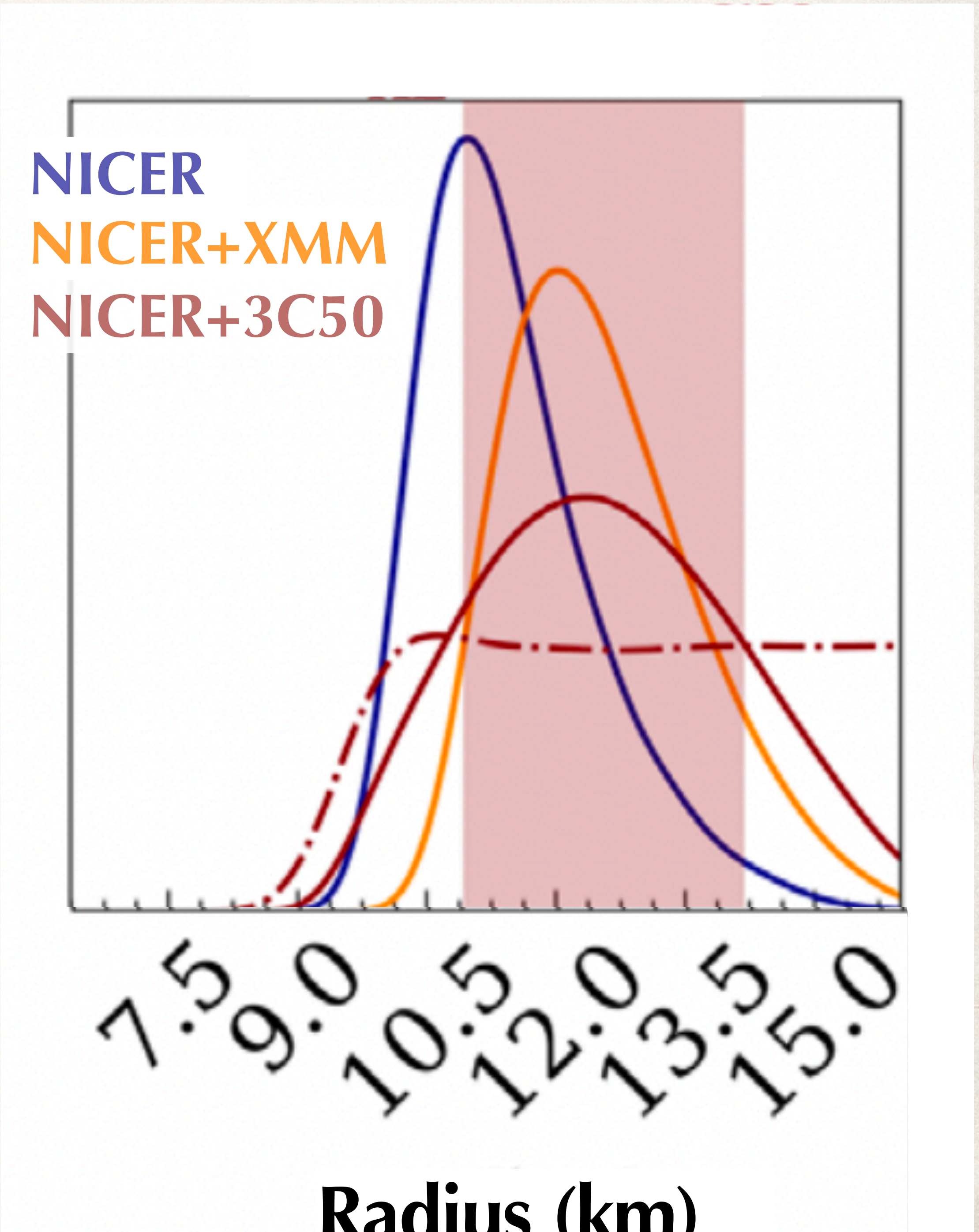
The XMM-Newton data provides a measure of the flux and phase-average spectrum of the MSPs



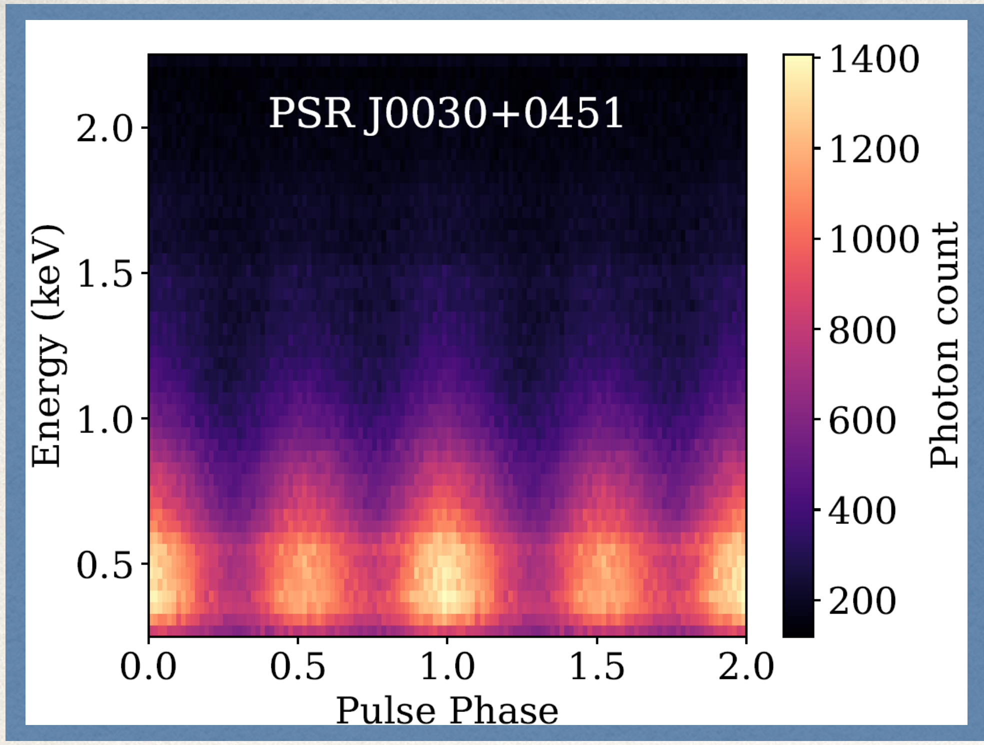
Bogdanov et al. (2019)



Wolff et al. (2021)

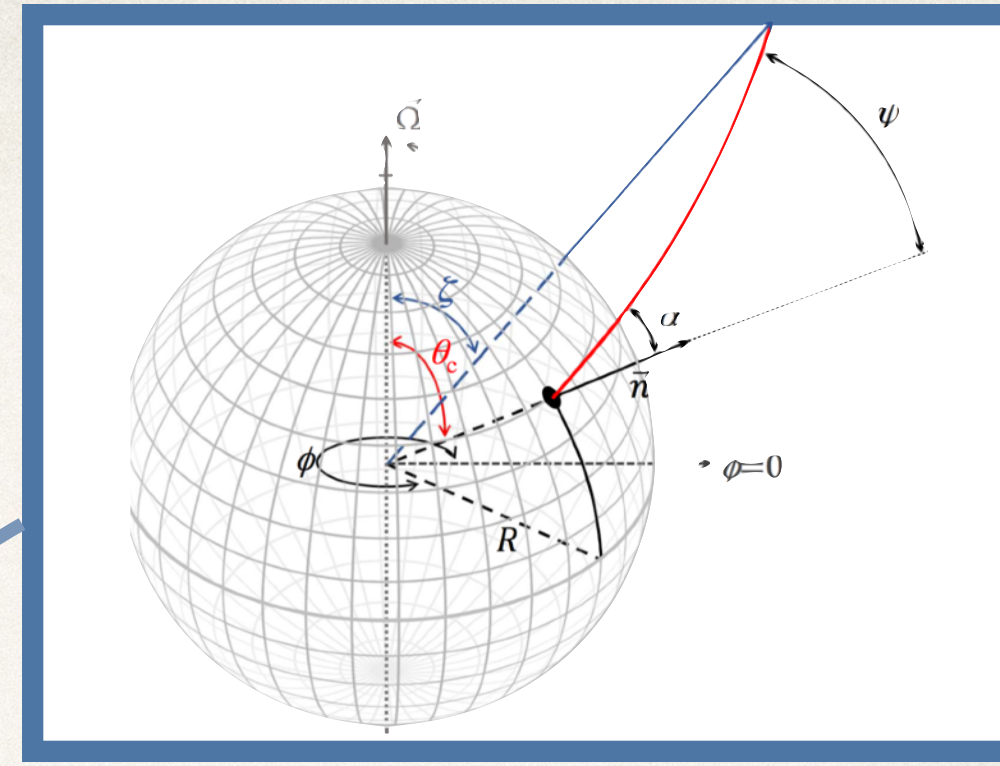


Salmi et al., 2022

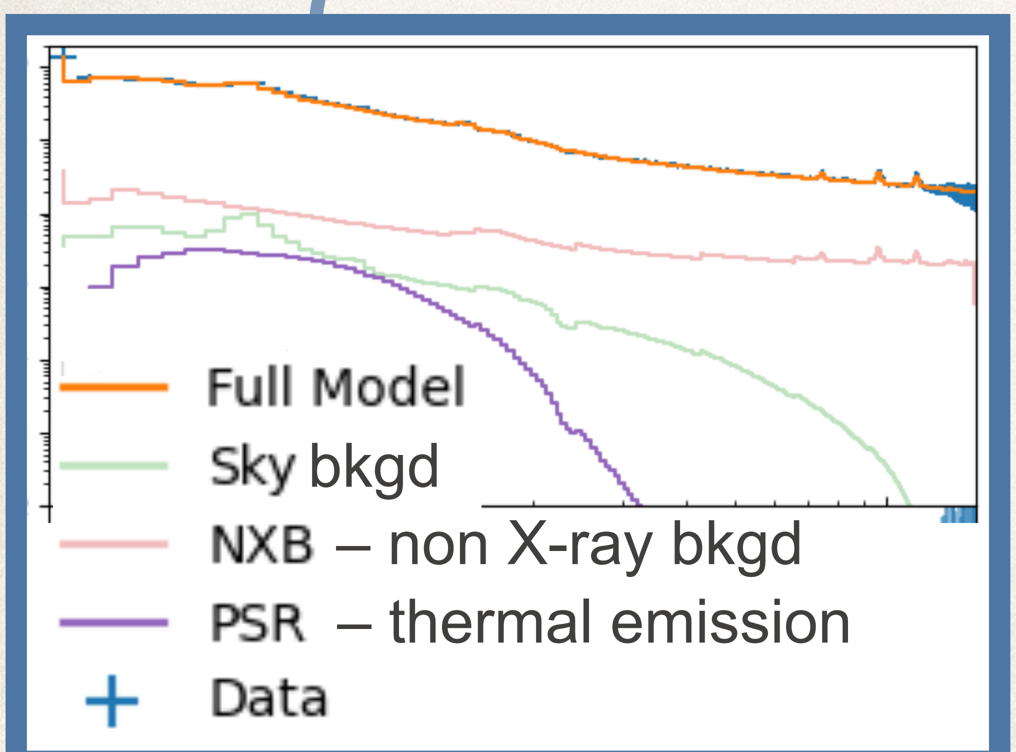


Priors

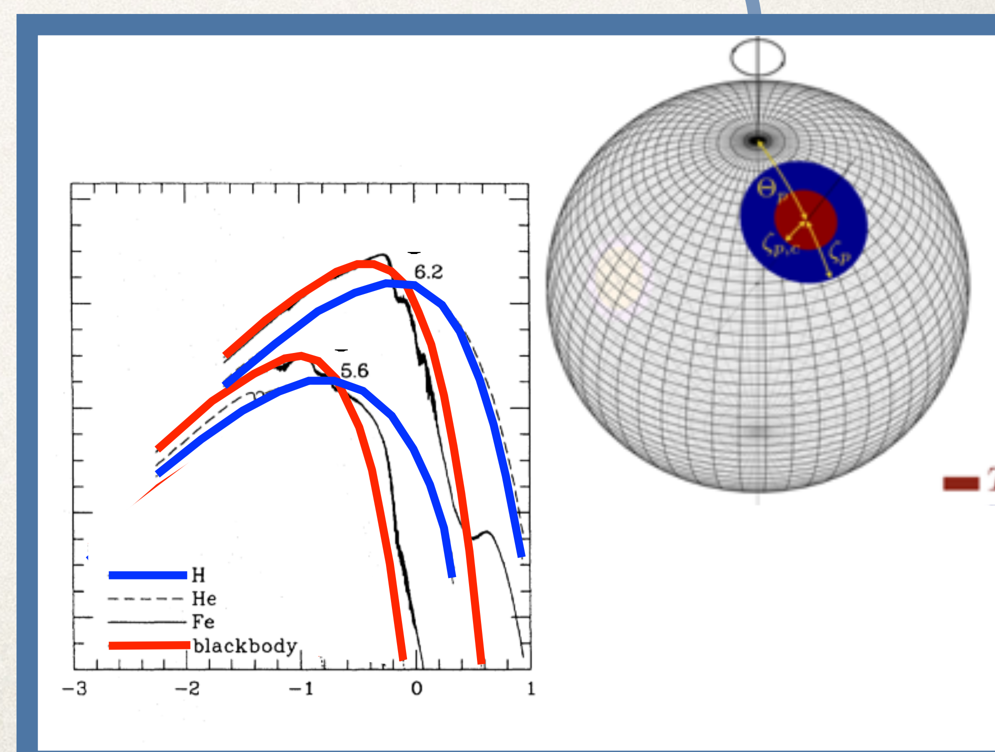
mass
distance
inclination



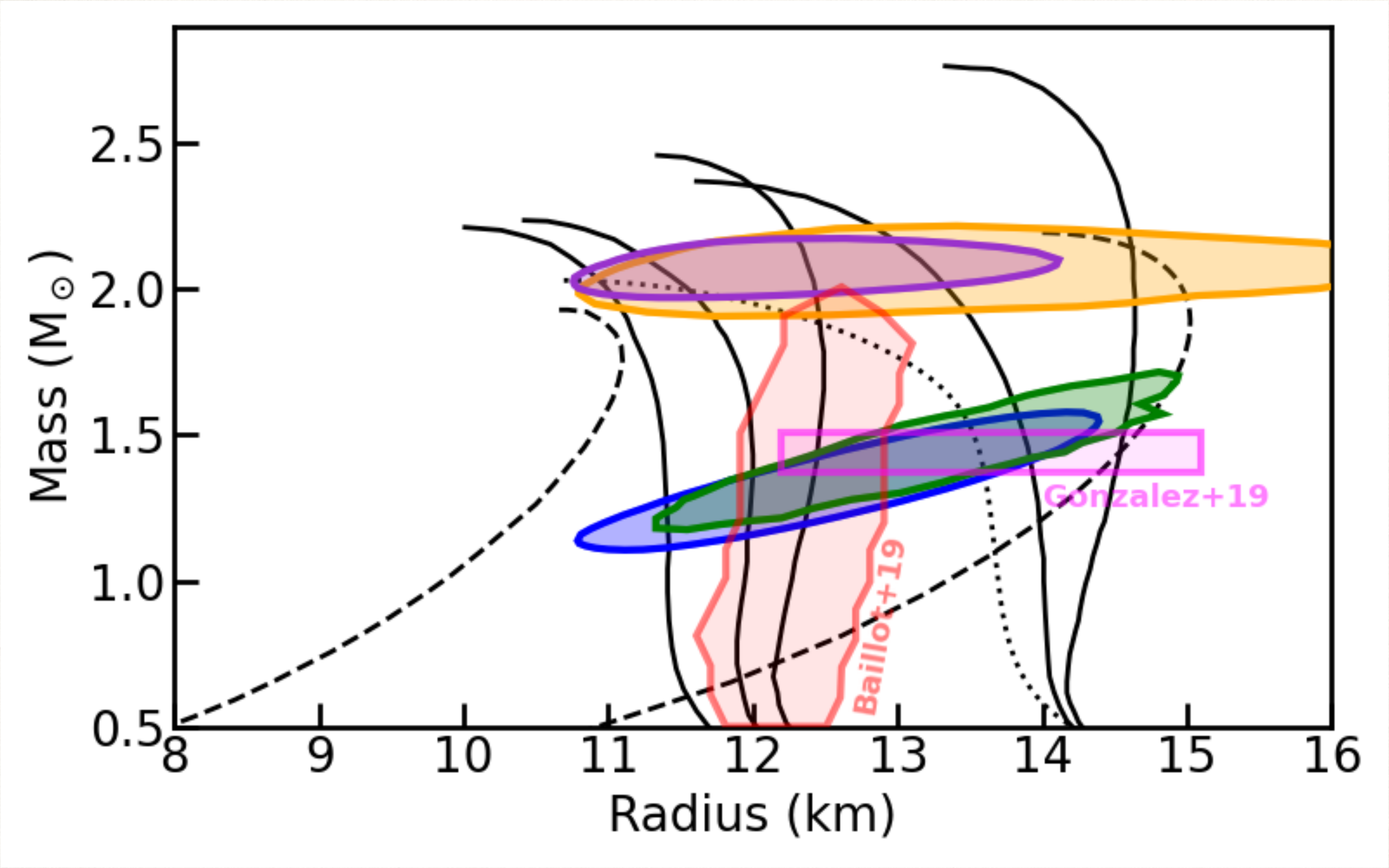
NS properties inference
(Likelihood statistical sampling)



Mass,
Radius,
EOS



The results for the first two pulsars were consistent with other measurements.



- PSR J0030+0451
  - Riley et al. 2019
  - Miller et al. 2019
- PSR J0740+6620
  - Riley et al. 2021
  - Miller et al. 2021

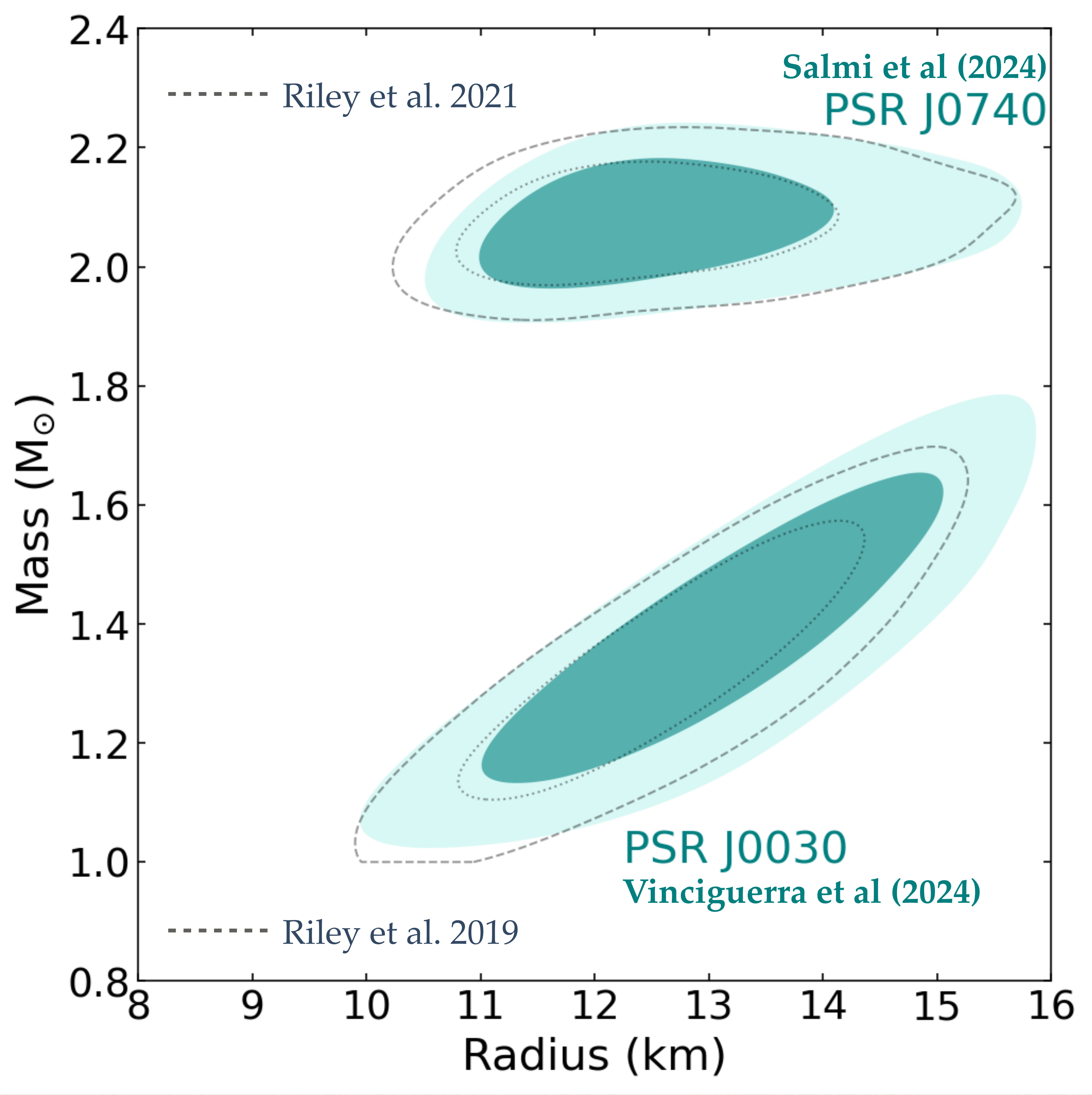
Cold Surface of MSP: Gonzalez-Caniulef et al. 2019

Multiple quiescent LMXB: Baillot-d'Etivaux et al. 2019

Updates to those results were published recently.

PSR J0740+6620
a massive MSP
+1.0 Msec of NICER data
Salmi et al (2024)

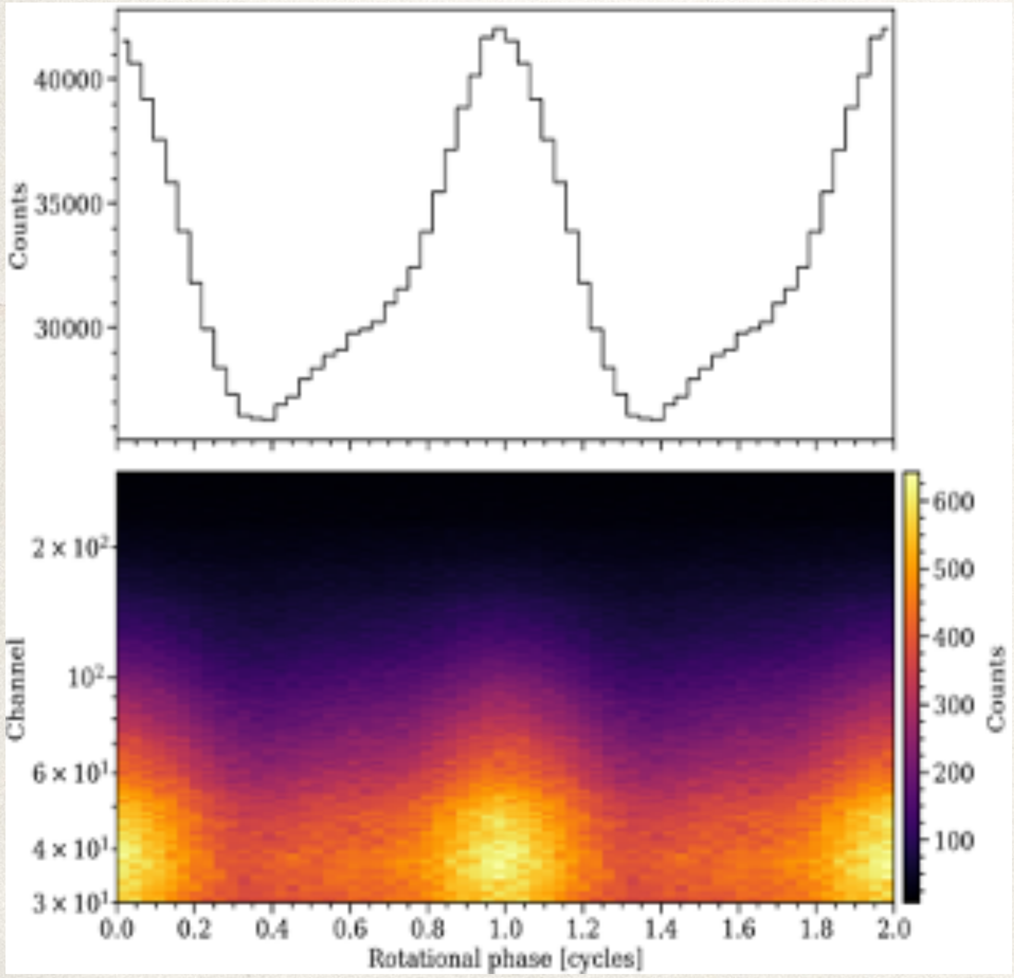
PSR J0030+0451
an isolated MSP
+XMM–Newton data
Vinciguerra et al (2024)



The new results from PSR J0437–4715 were long awaited…Why did it take so long ?

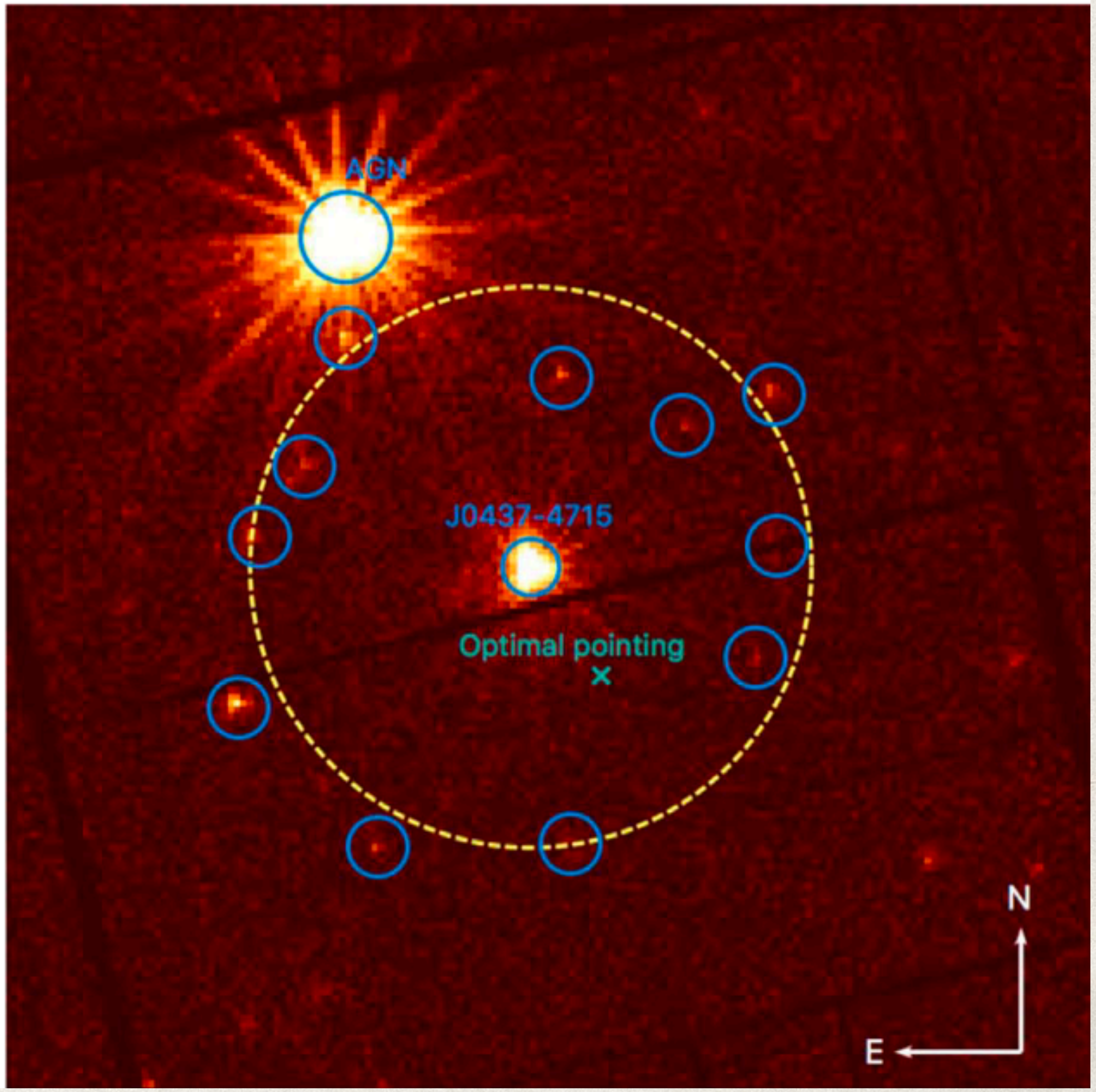
Advantages:

- Precise priors *(Reardon et. al. 2024)* :
  - Mass = 1.418 ± 0.044 Msun
  - Inclination = 137.506 ± 0.016 deg.
  - Distance = 156.98 ± 0.16 pc
- Nearest and brightest: High S/N
- Long observations: Msec of NICER data



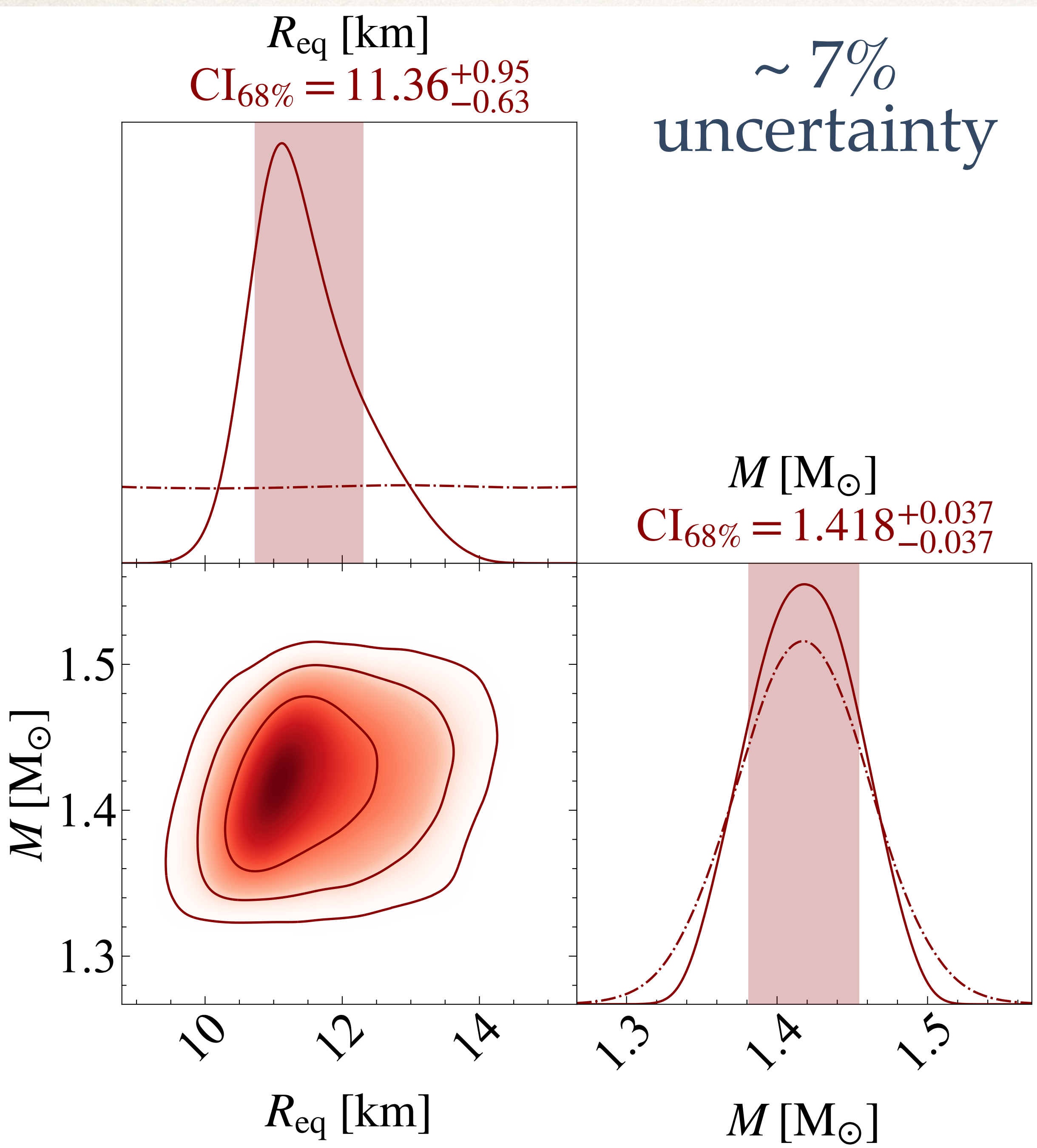
Disadvantages:

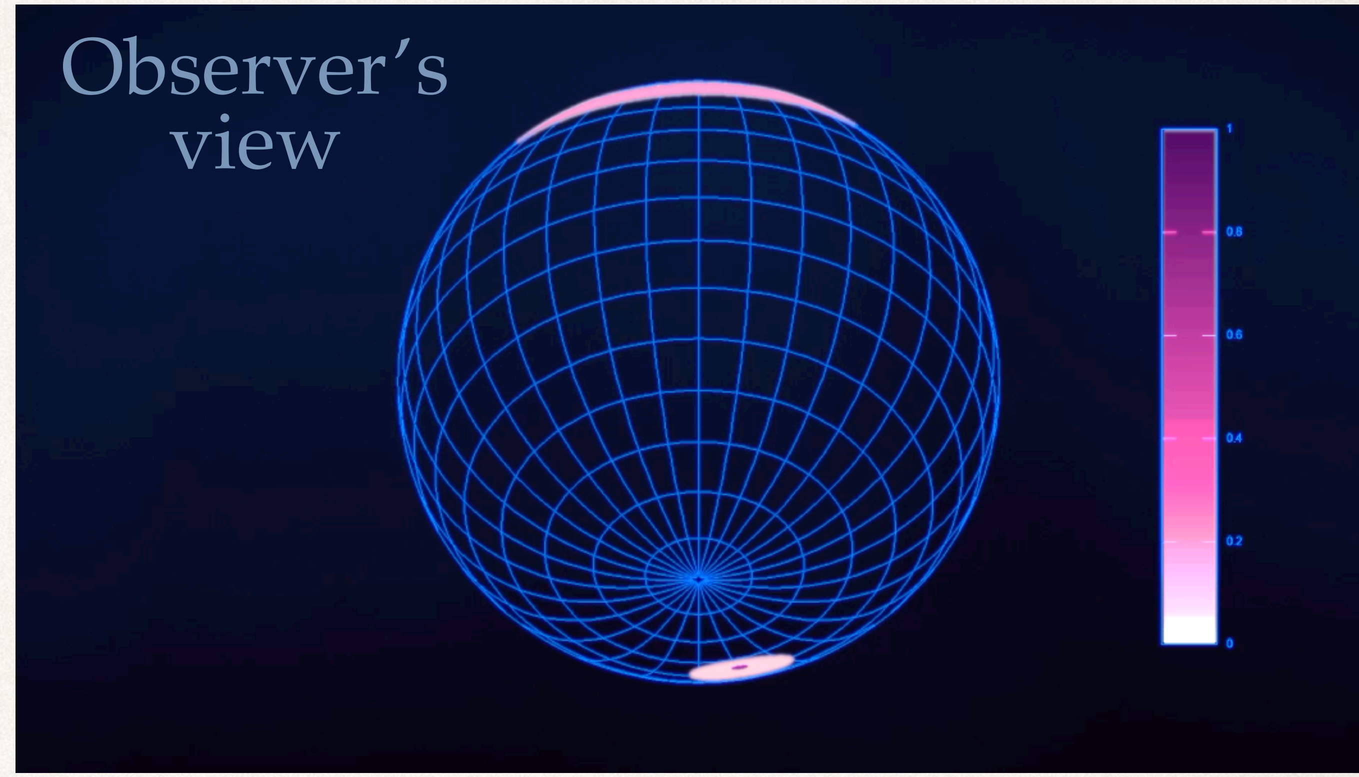
- Neighbour bright source
- Offset pointing :
  - Different instrument response



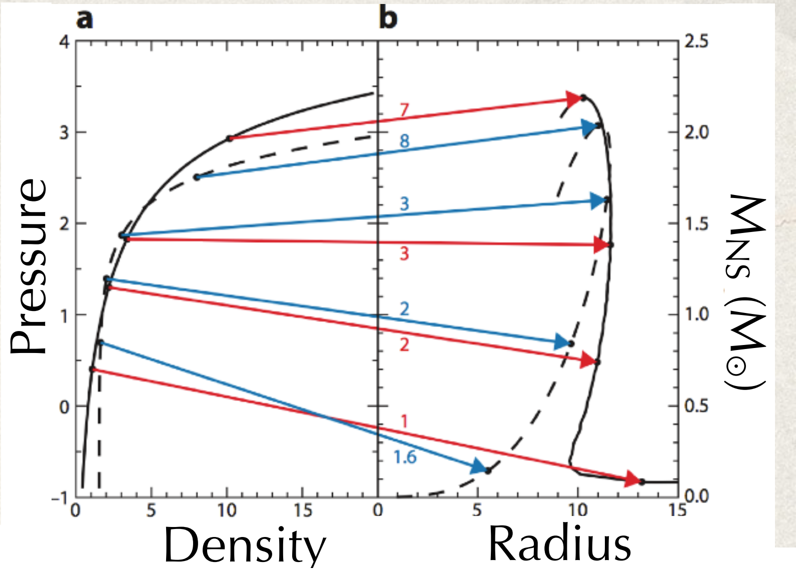
The radius constraints are the best so far…but with a complex geometry.

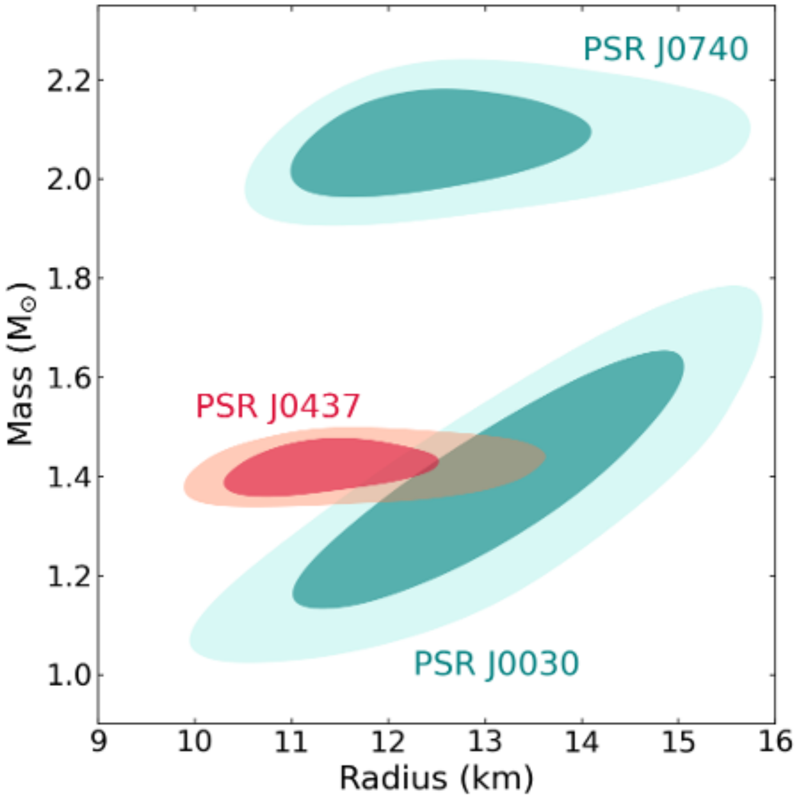
Radius: $11.36^{+0.95}_{-0.63}$ km (68% CI)



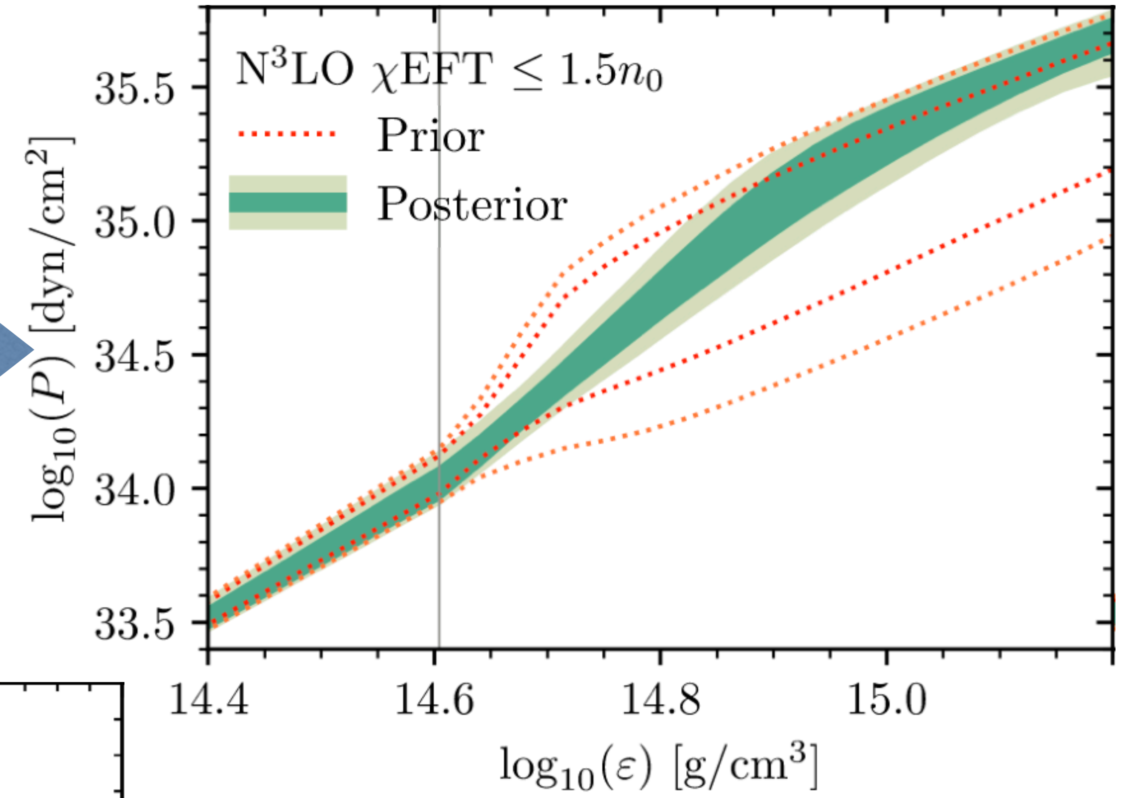


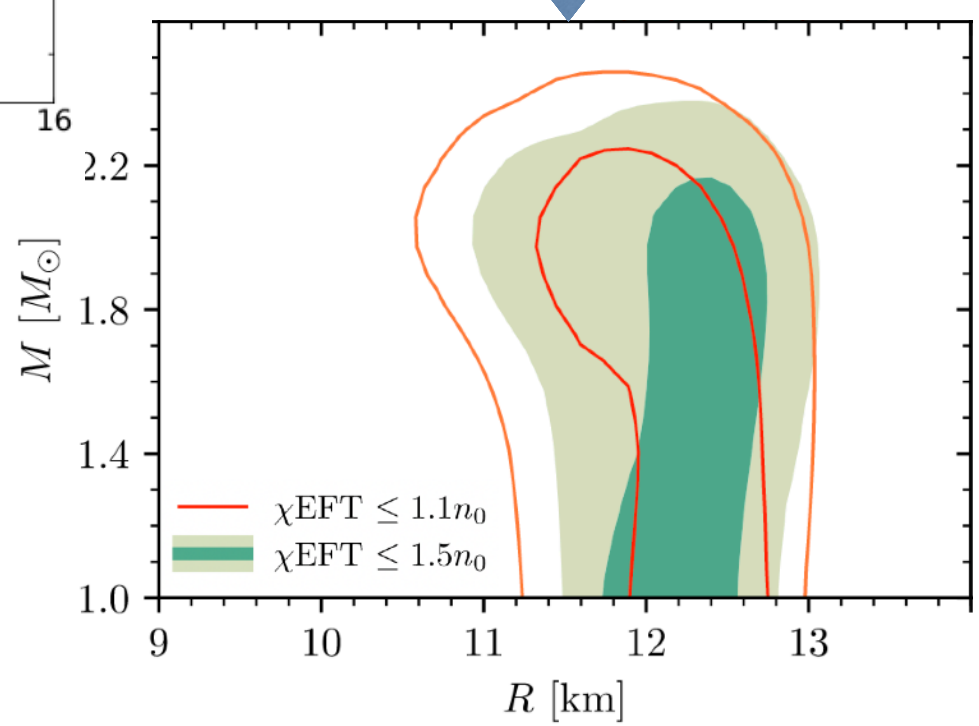
Altogether, these measurements constrain equation of state models.





Rutherford et al (2024)

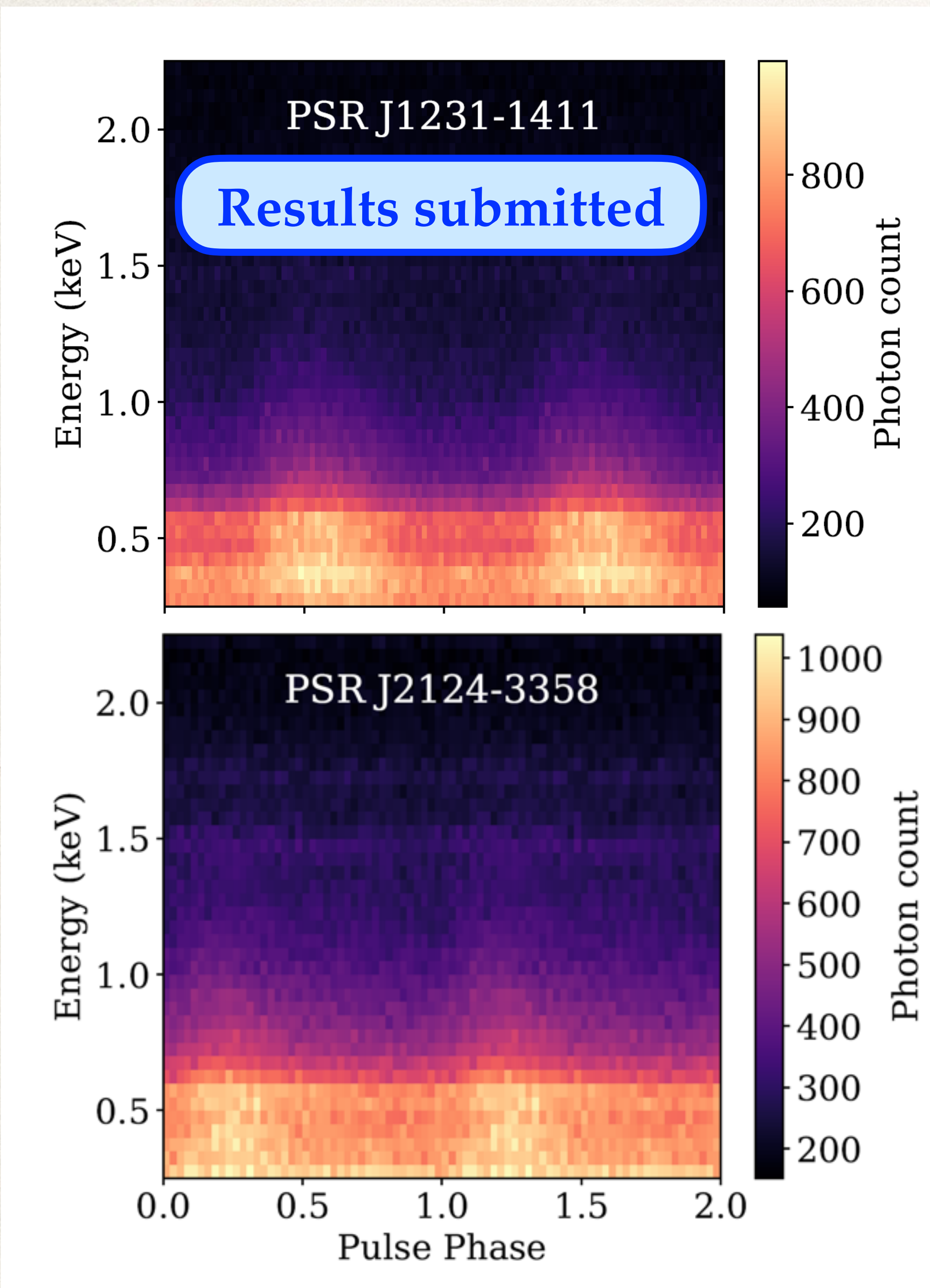




Other models / approaches

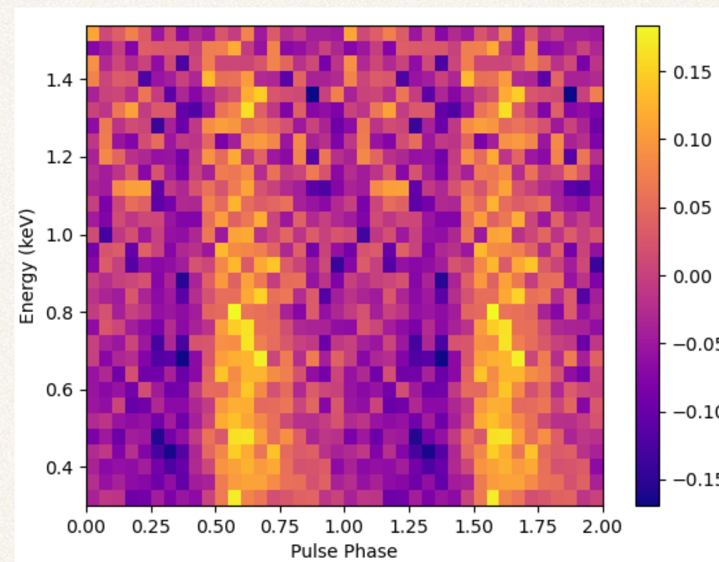
See many of the talks at NuSYM 2024

Several NICER data sets are yet to be analysed to extract M_{NS} and R_{NS}. More results are coming…

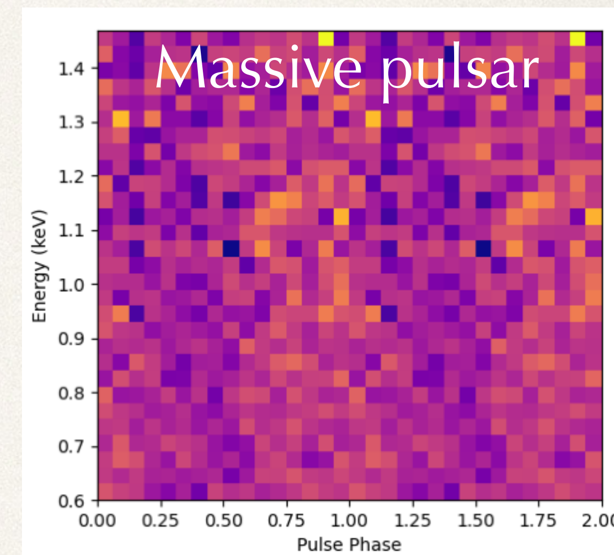


Thesis of Lucien Mauviard at IRAP

PSR J0614–3329



PSR J1614-2230



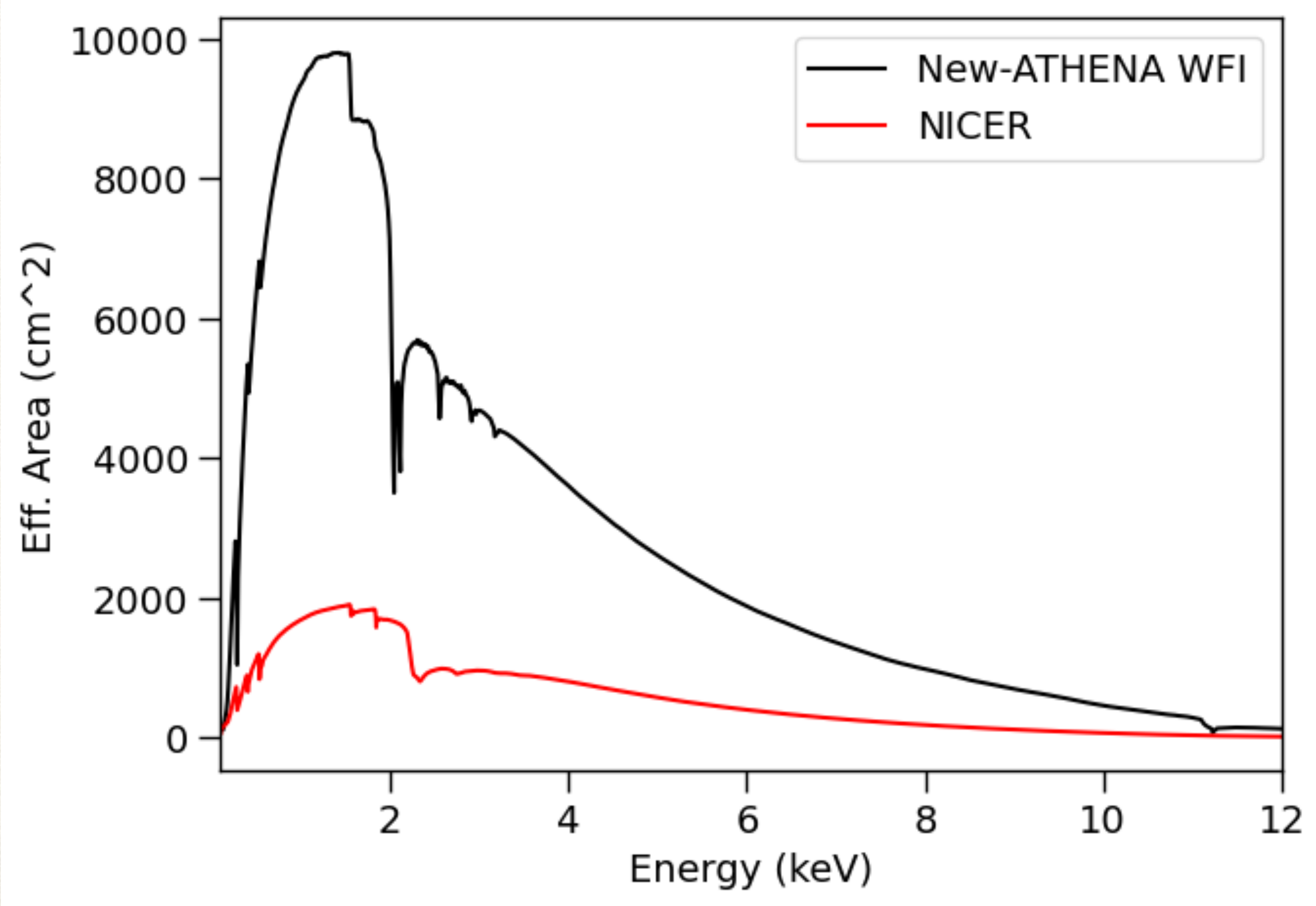
$\Delta R \sim \pm 1$ km

+ a few other pulsars discovered with NICER (*Guillot et al 2019*)

What can we expect in the future with pulse profile modelling ?

New-ATHENA

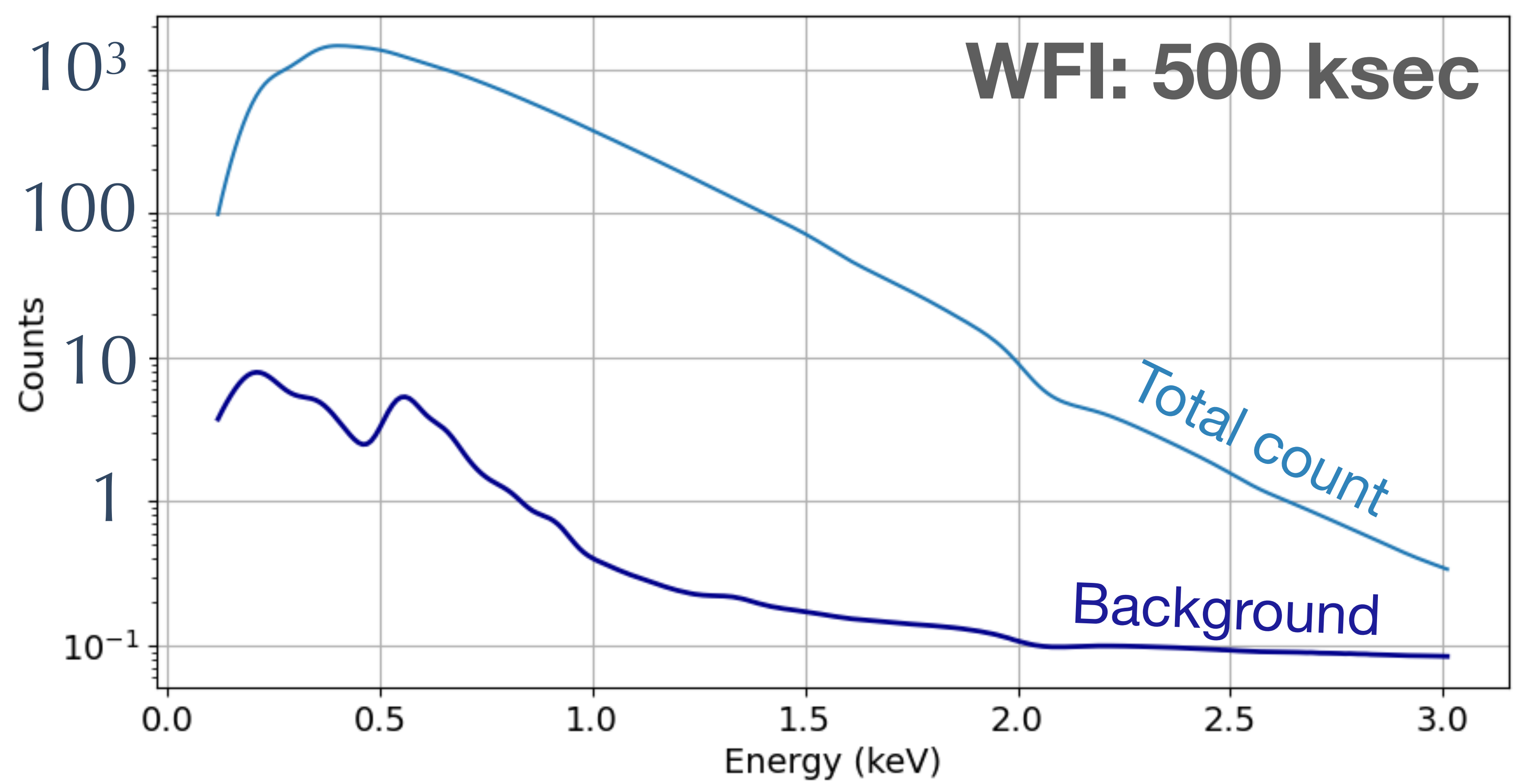
- Sensitivity: about x5 NICER
- Time resolution:
  - 10 µsec (X-IFU)
  - ~100 µsec (WFI)
- Low-background: ~ 0.001 c/s

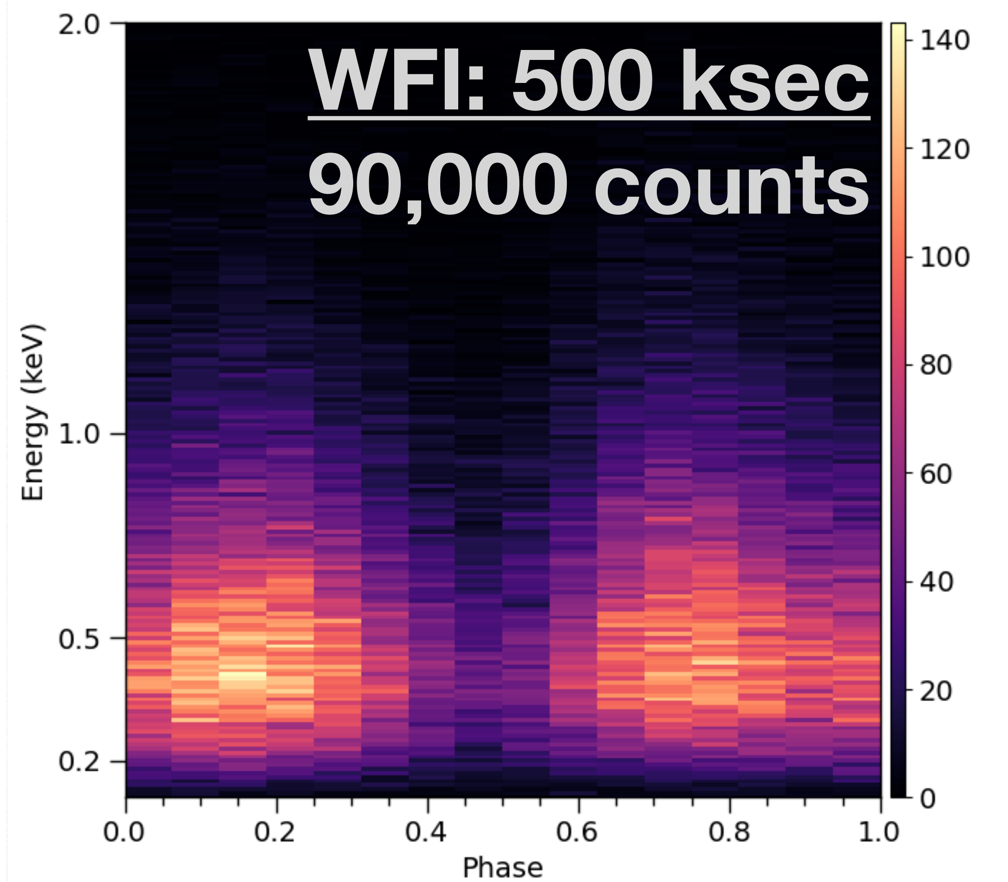


Future prospects for pulse profile modelling with new-Athena are quite promising.

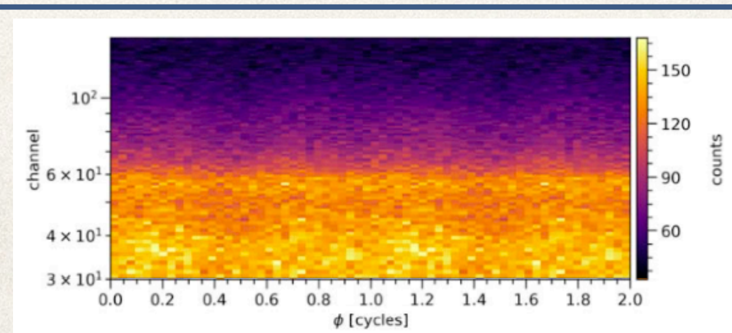
Simulations of PSR J0740+6620 with P_{spin} = 2.88 msec and d=1.2 kpc

R~11.5 km, M=2.08 $M_\odot$ with 2 circular hot spots
Simulation of 500 ksec observations



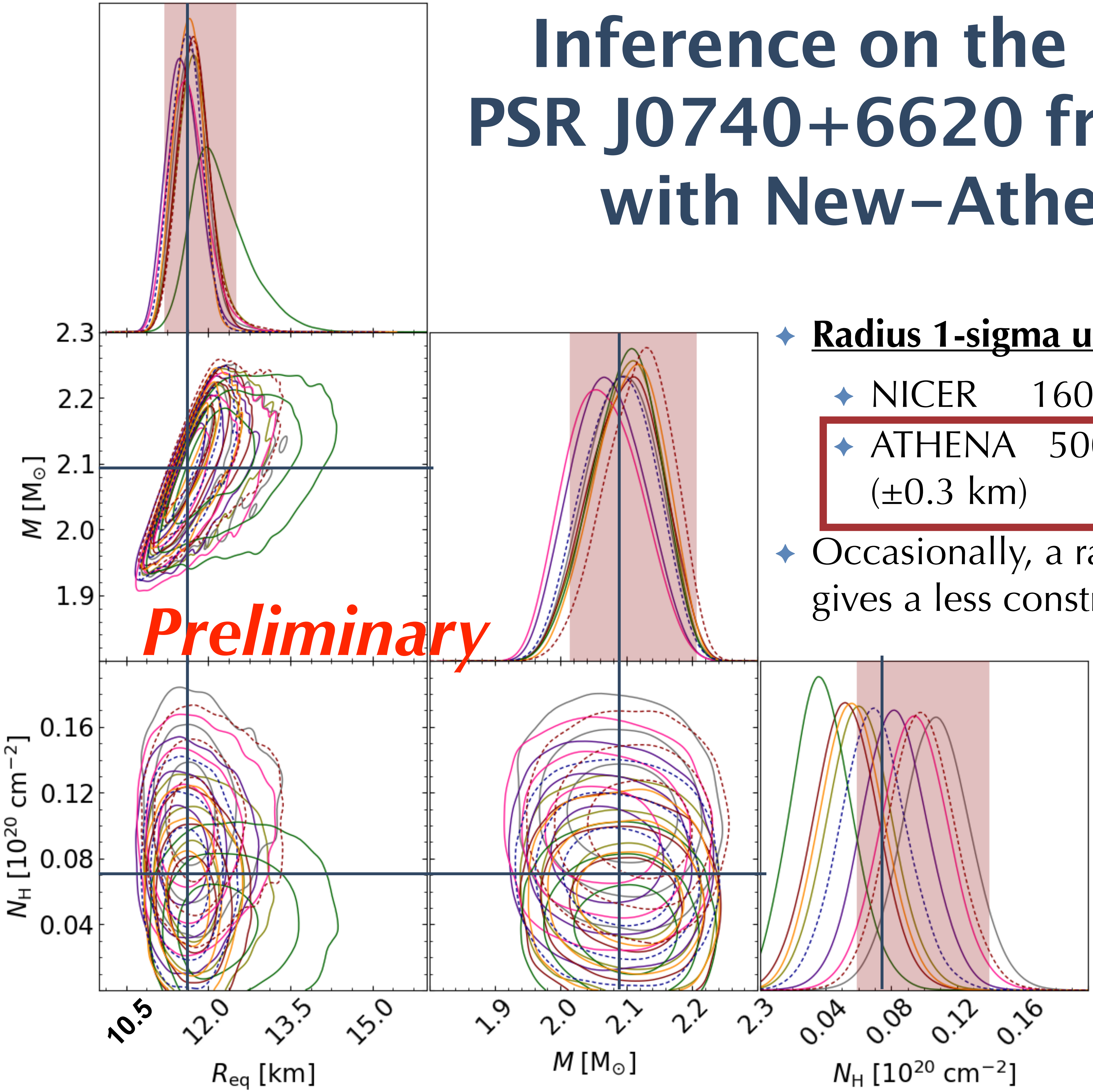


NICER profile for comparison!



X-PSI

Inference on the radius of PSR J0740+6620 from 500 ks with New-Athena WFI



- **Radius 1-sigma uncertainties**
  - NICER 1600 ksec: ~10%
  - ATHENA 500 ksec: ~3% average (±0.3 km)
- Occasionally, a random noise realisation gives a less constrained radius

Statistical uncertainties < 1% for brighter pulsars

For some MSPs, the rest of the surface, although much colder than the hot spots, can be detected in the soft X-ray and the far UV.

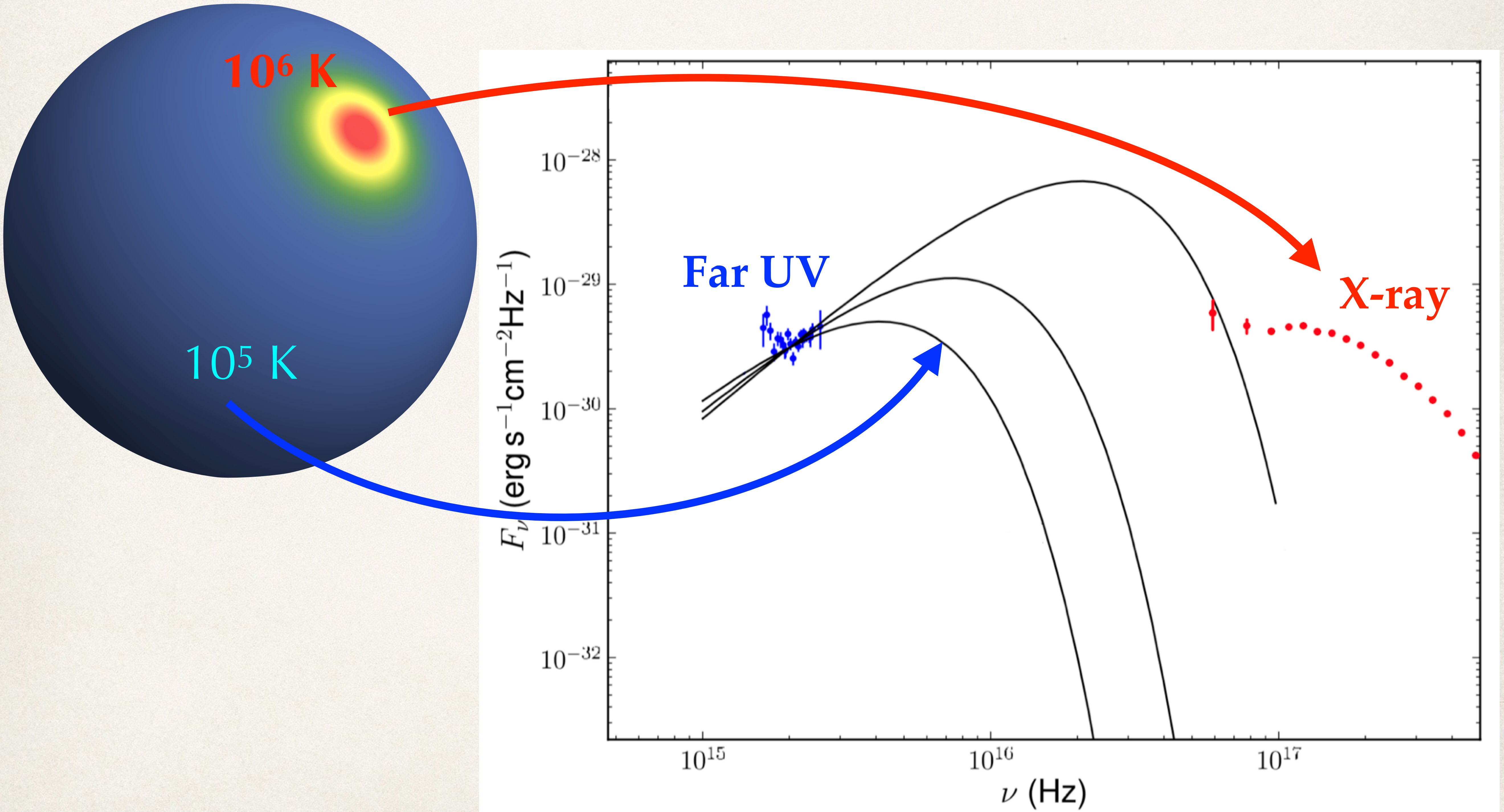
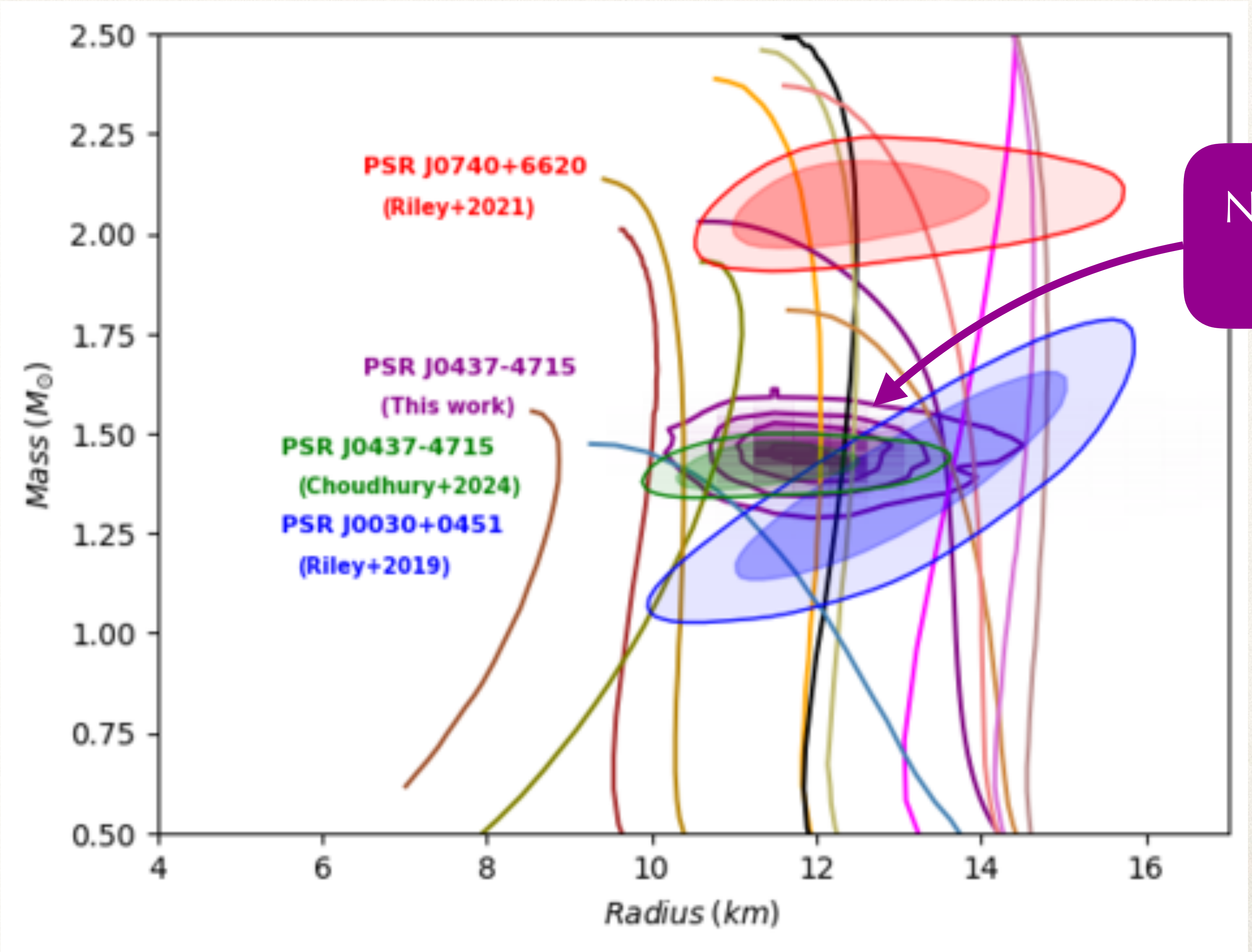


Figure adapted from Durant et al. (2012)

Using Far UV observations for PSR J0437-4715, we obtain independent constraints on the radius.

Stammler et al., in preparation

$R_{NS} = 12.1 \pm 1.0$ km



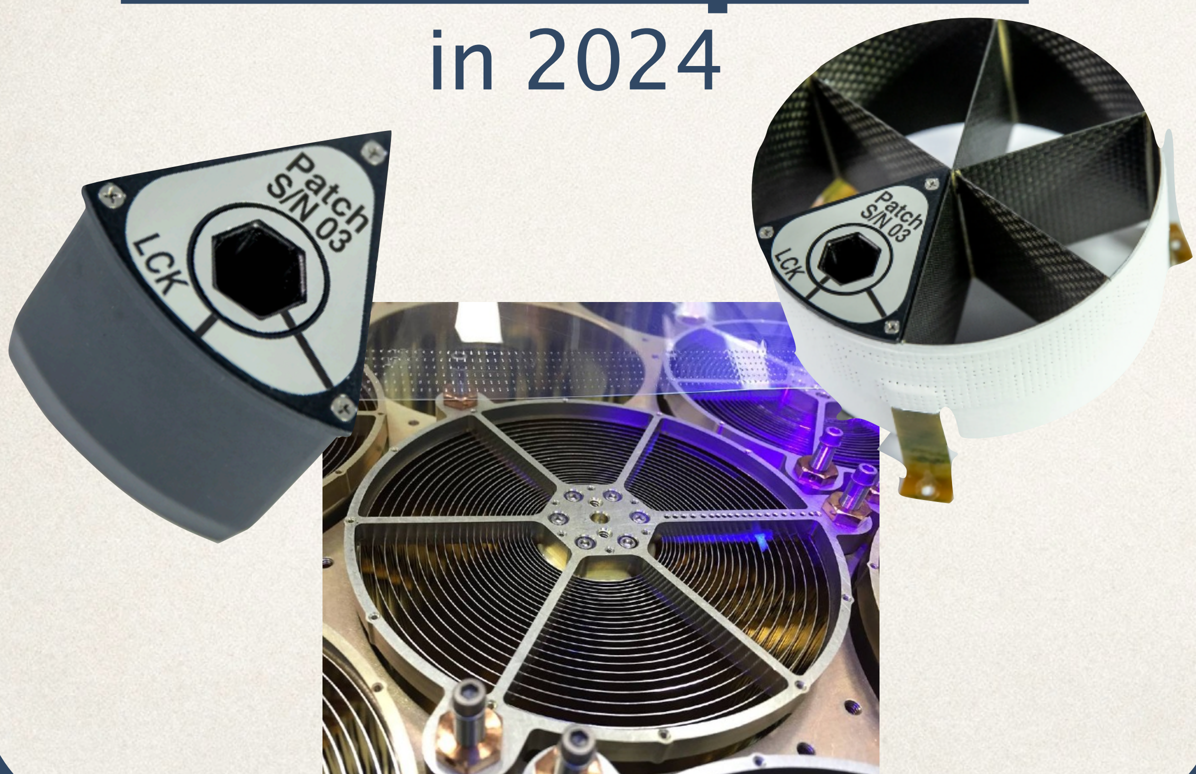
No NICER data involved!

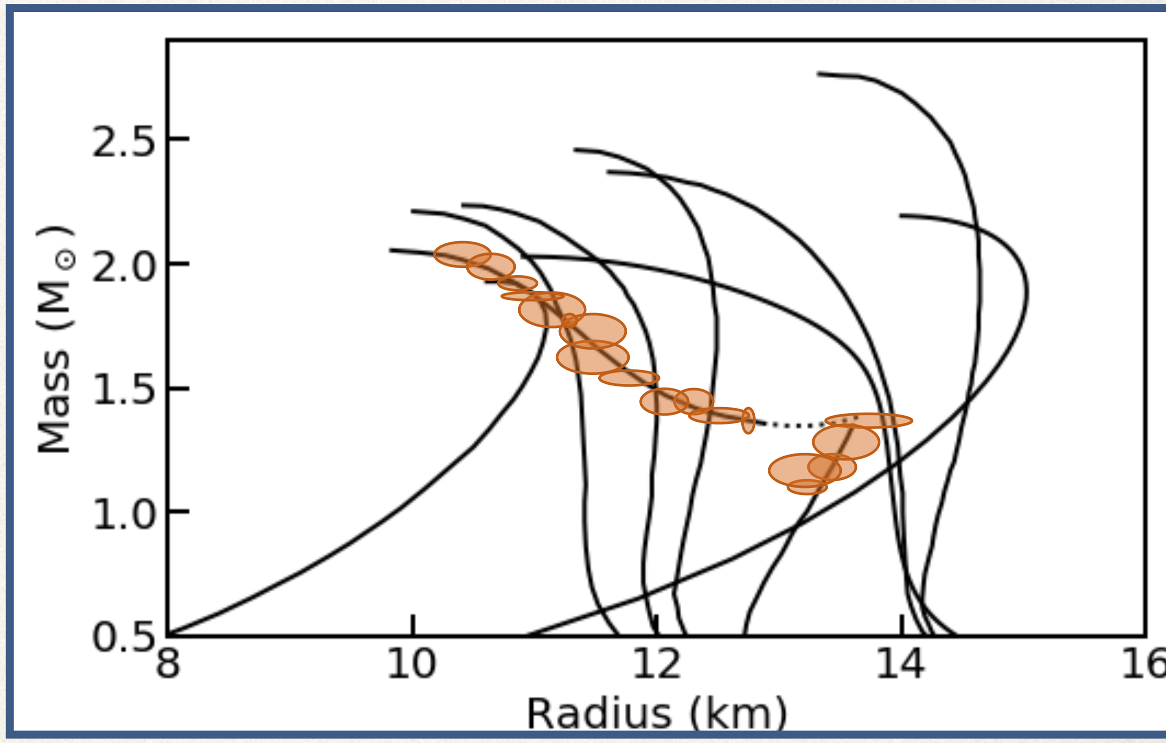
Conclusions

- Pulse profile modelling is a demonstrated technique to measure M and R.
- NICER results for 3 pulsars are published; 1 is submitted; more are coming…
- We now know that characterising the background is key.
- Complementary methods exists to measure M and R.
- NewATHENA measurement will bring constraints on M and R to another level.

NICER repairs

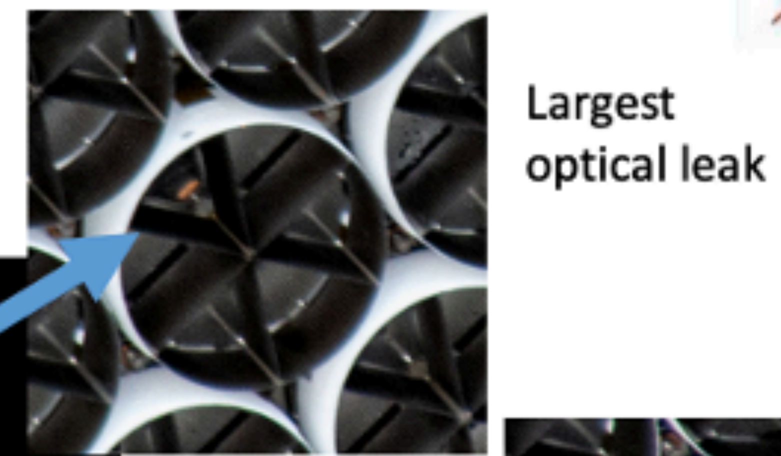
in 2024

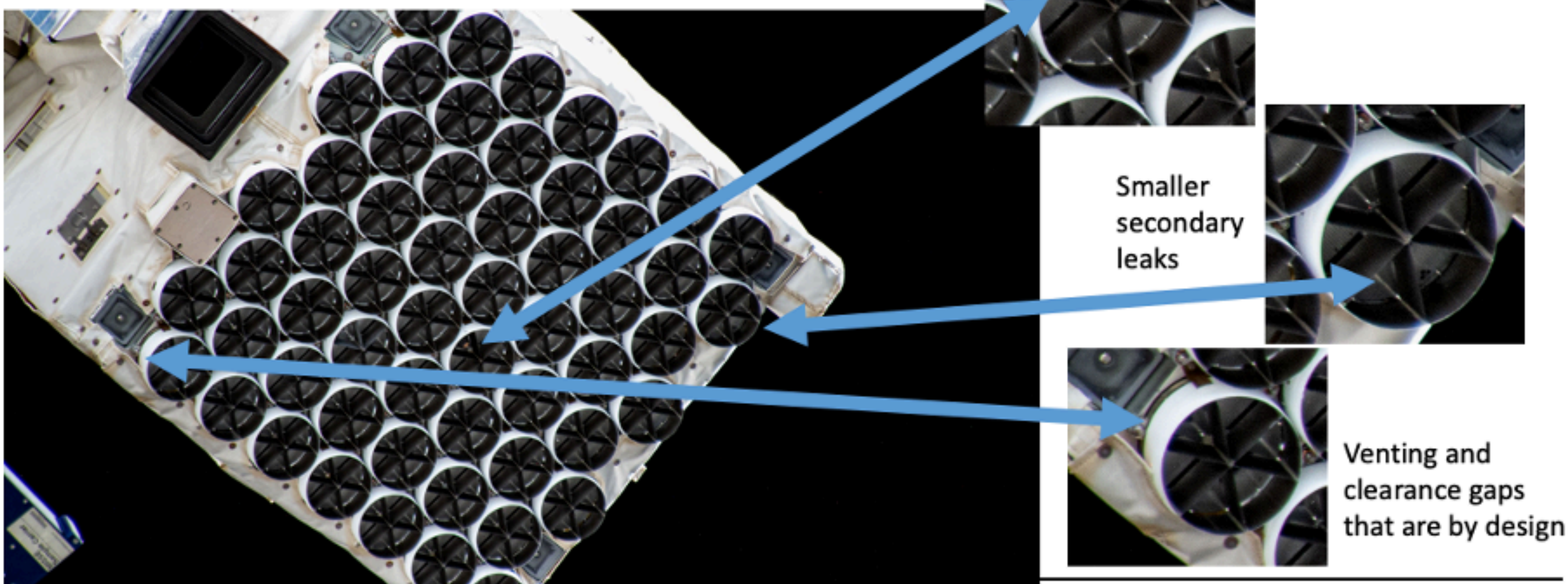




Imagery reveals major contributors to optical leak

- Largest optical leak is nearly in the middle
- There are several smaller pinholes
- But also gaps by design
- Confirmed using Engineering Test Unit (ETU) and celestial data





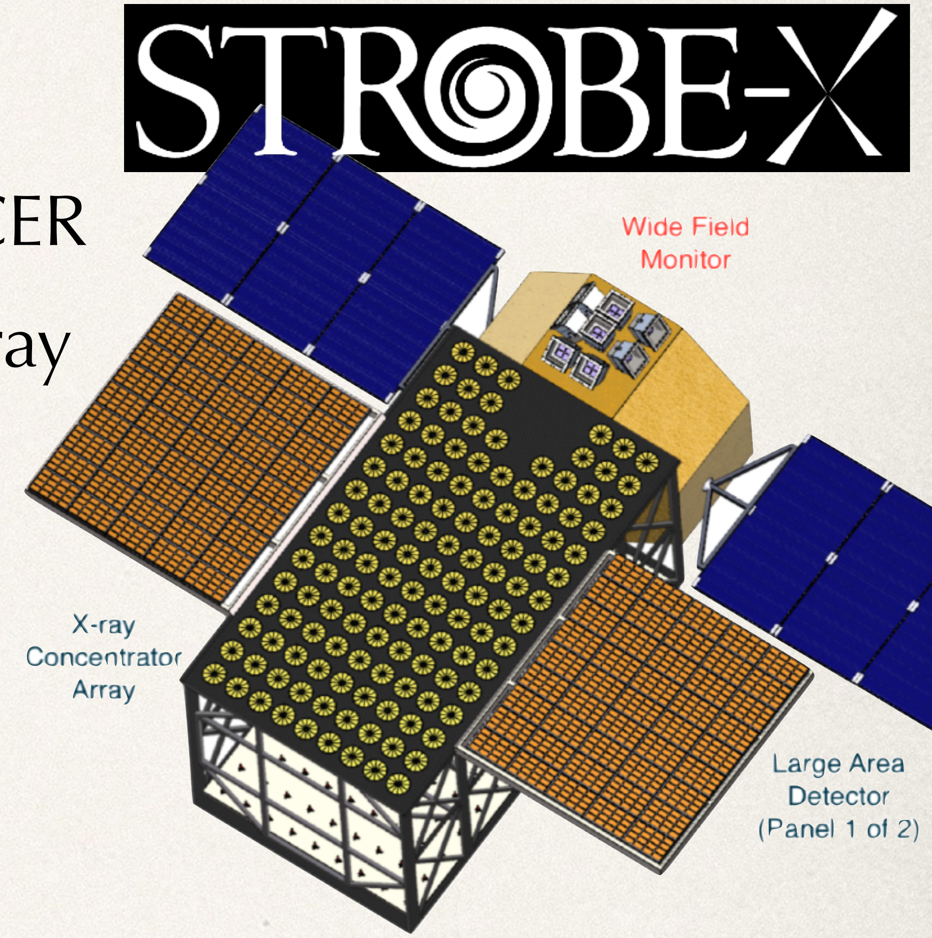
The future for pulse profile modelling looks quite promising, but you'll have to be patient!

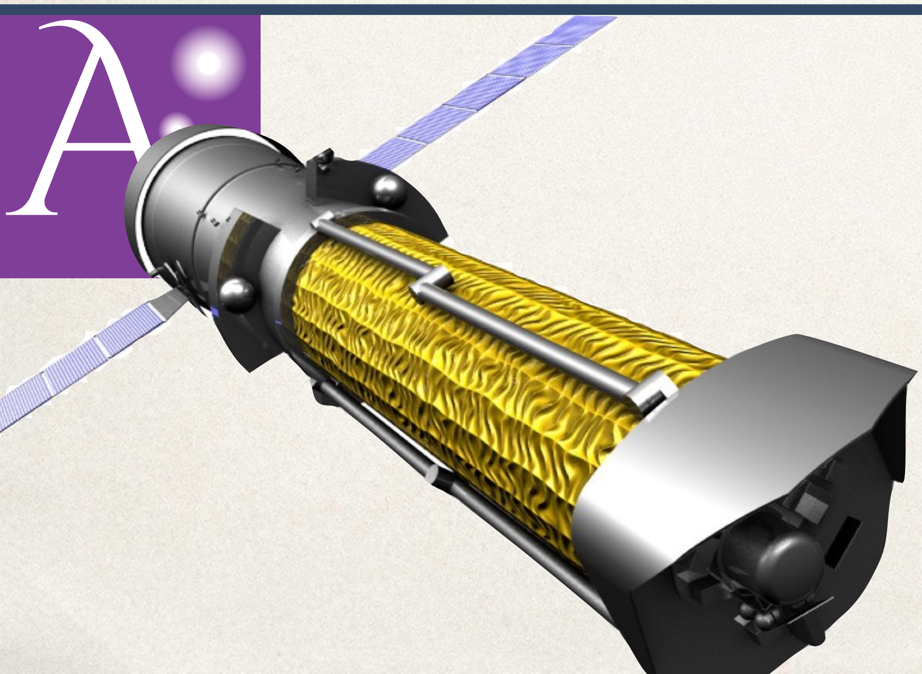
eXTP (~2028)

- Modest imaging capabilities (60″ PSF)
- ~ 4–5 × more sensitive than NICER
- + Hard X-ray instrument

~2030

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



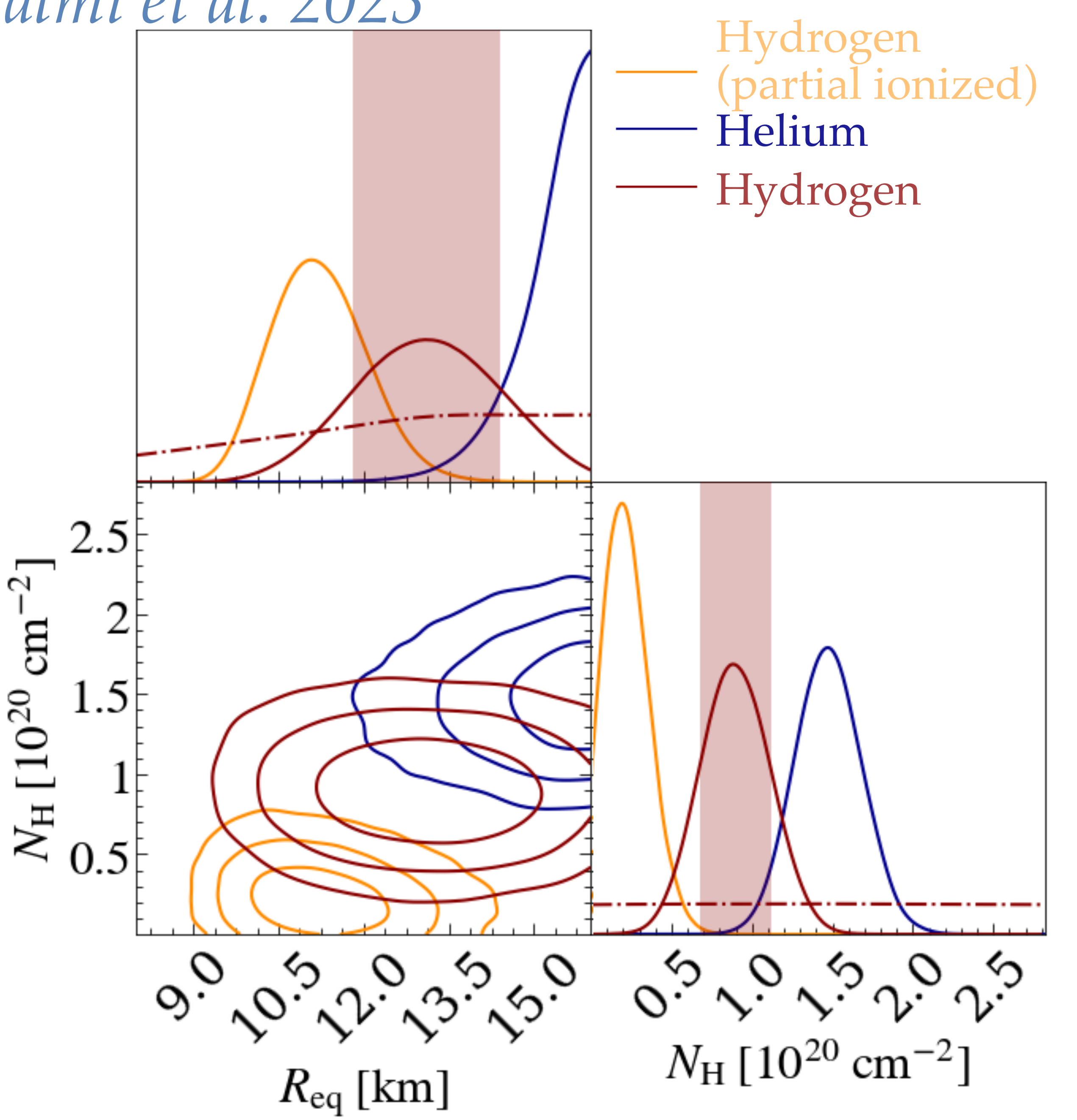


NewAthena (~2037)

New–Athena can discriminate between different atmospheric compositions

NICER data of PSR J0740+6620

Salmi et al. 2023



The choice of atmosphere composition changes the inferred radius.

<u>To solve this degeneracy</u>

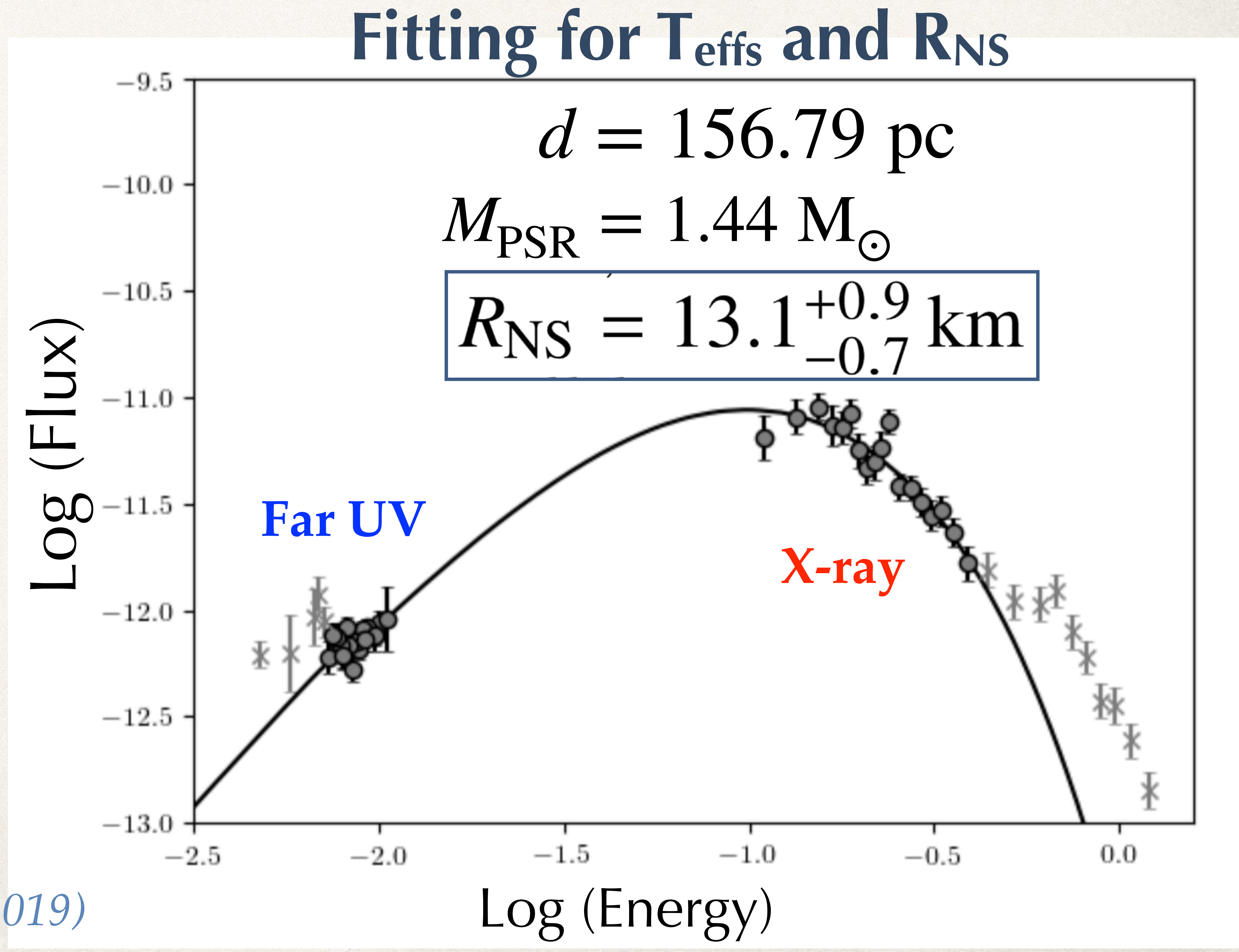
- Measure N_H independently
- Use ATHENA

<u>ATHENA Simulations of H-atmosphere data set, and run the inference with He- atmosphere model</u>

- For 200 ks: ln(Bayes Factor) ~ 30–60
- For 500 ks: ln(Bayes Factor) ~ 100–150

Spectral analysis with realistic atmosphere models can characterise the "cold" thermal component of PSR J0437-4715.

Different atmosphere models adapted to "low" surface temperatures



Gonzalez-Caniulef et al. (2019)