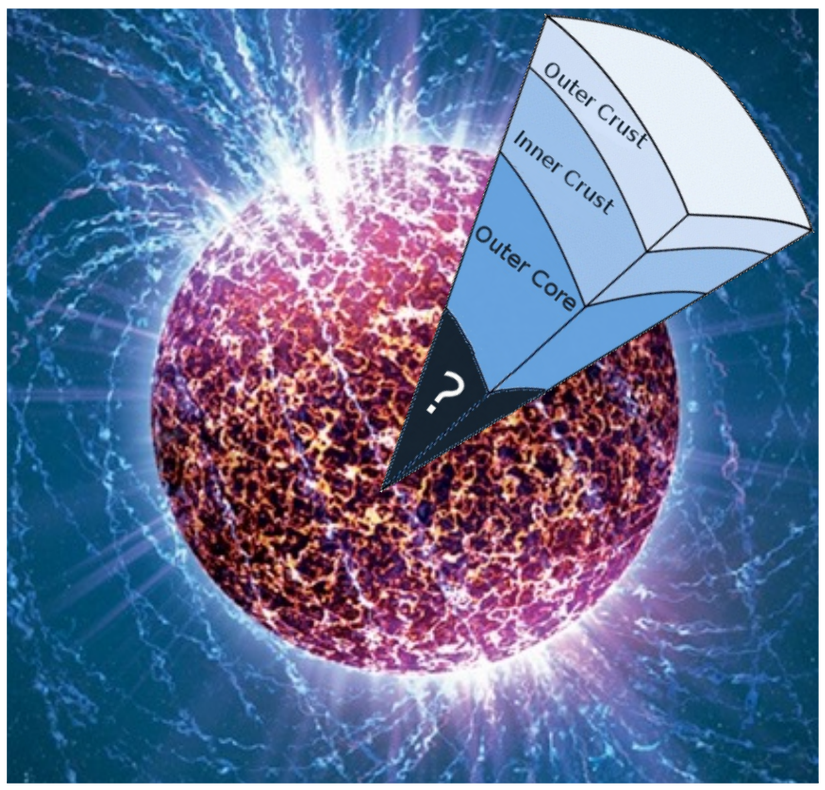
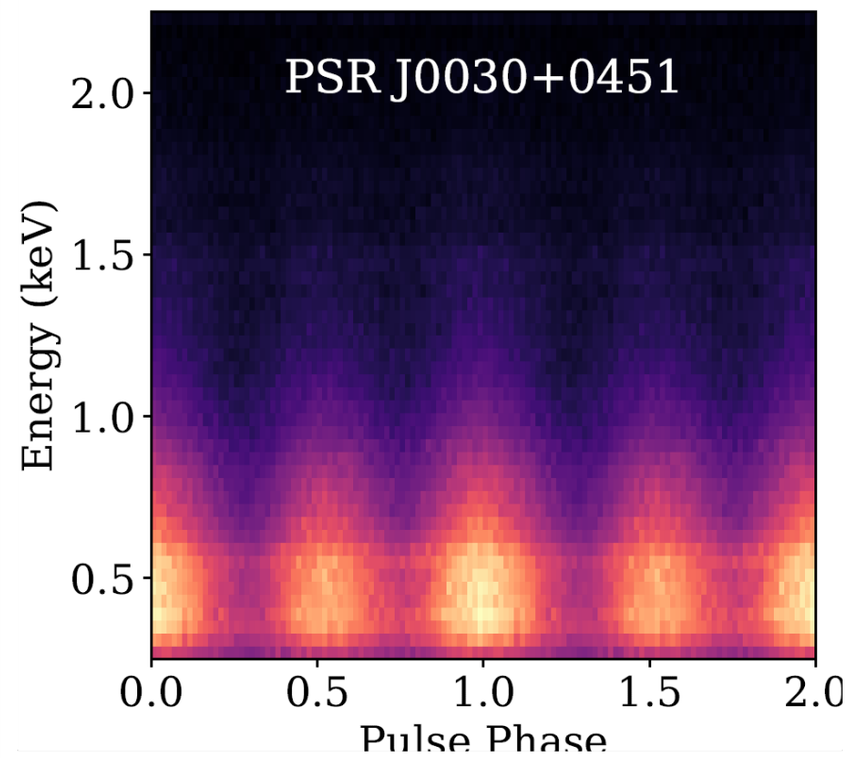
Probing the dense matter inside neutron stars

From NICER to (New)ATHENA



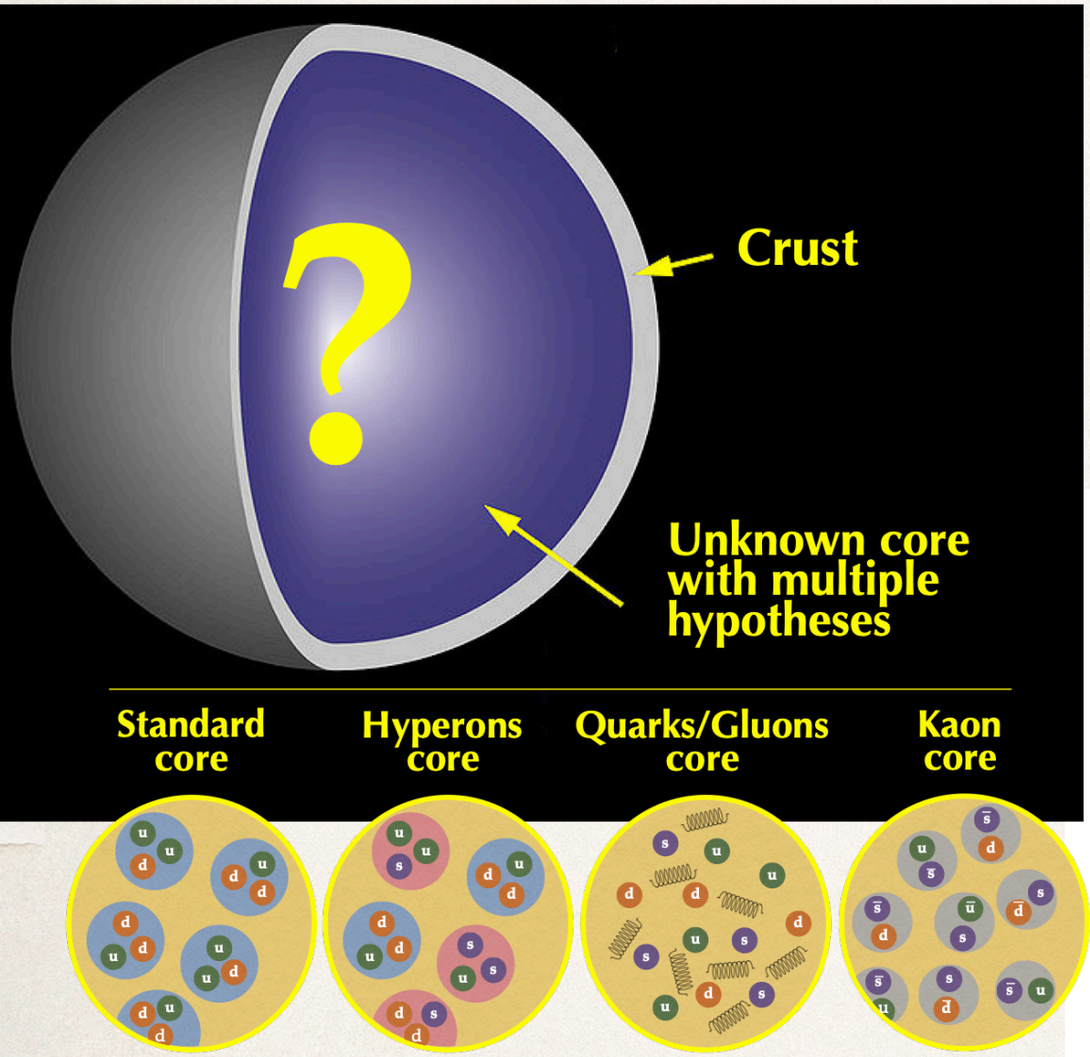
Sebastien Guillot

irap
astrophysique & planétologie



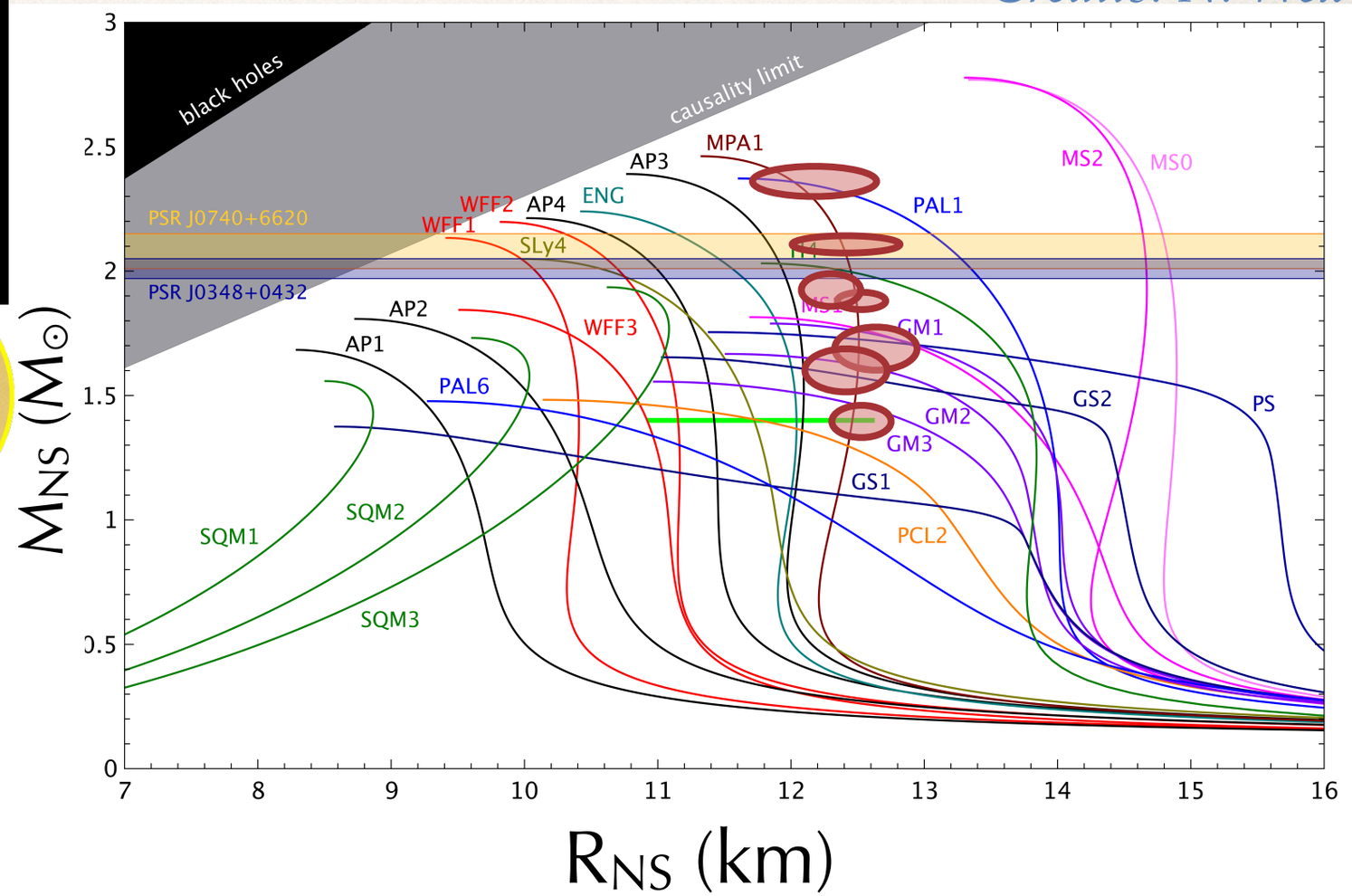
Collaboration with the NICER Science Team

The equation of state P(ρ) of the unknown interior of neutron stars can be determined with measurements of M_{NS} – R_{NS} with a few % precision.

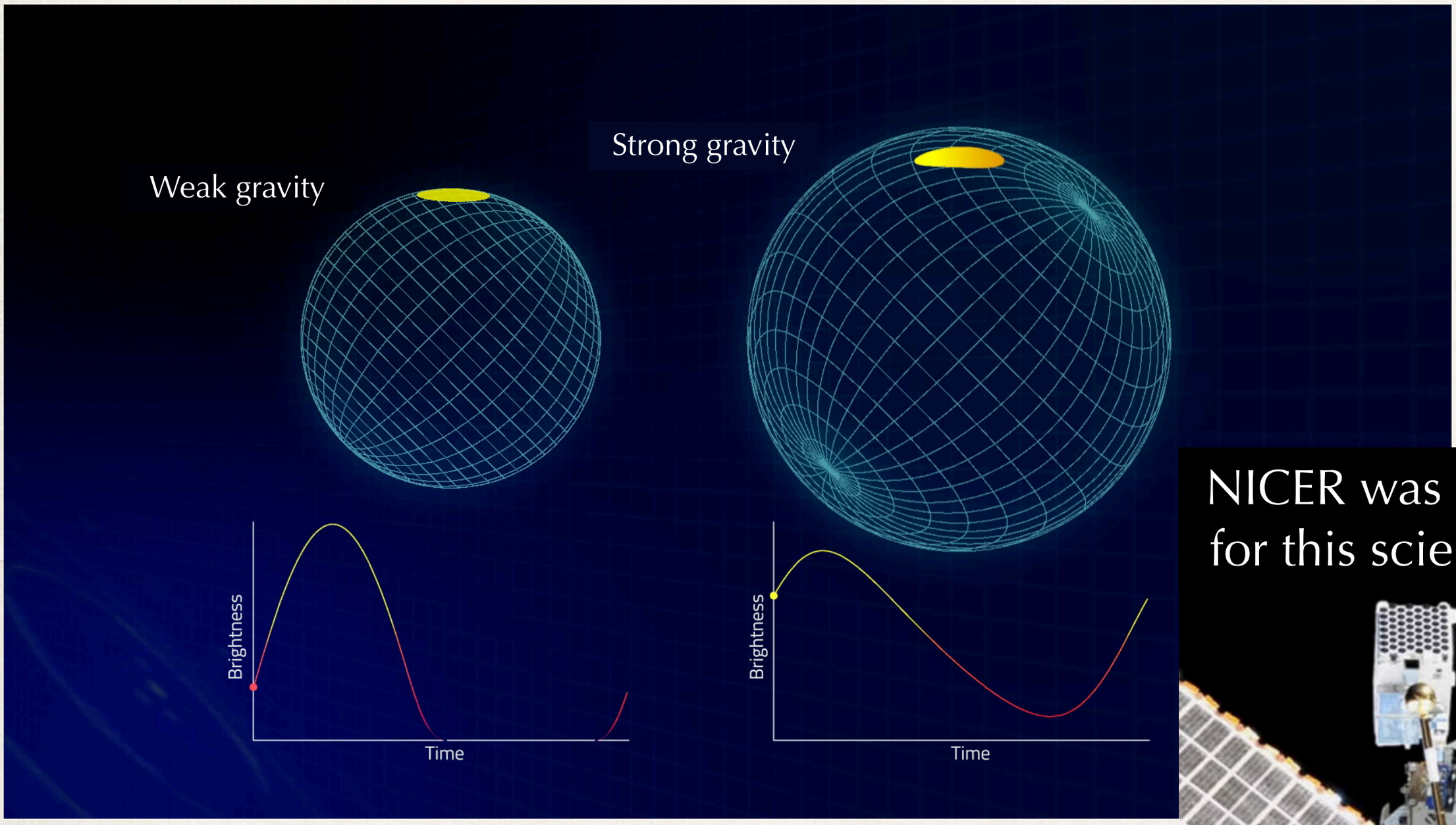


$$P(\rho) \rightleftarrows M(R)$$

Credits: N. Wex

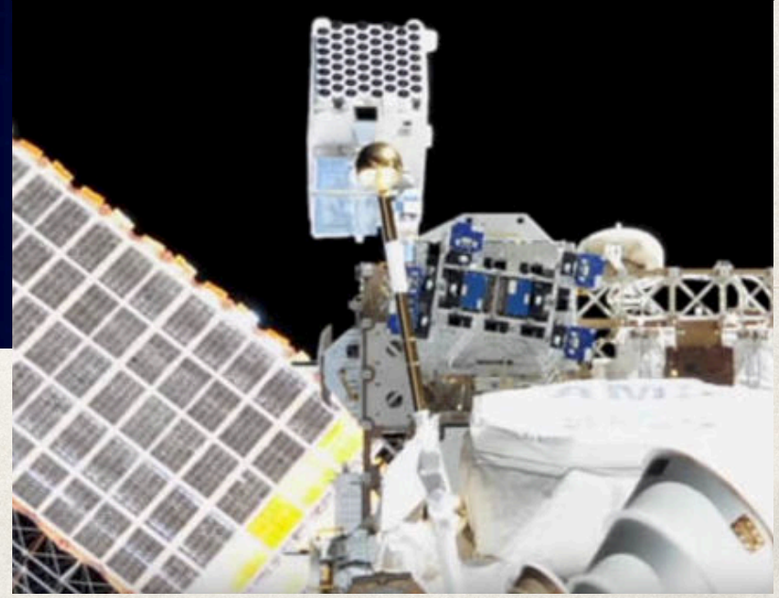


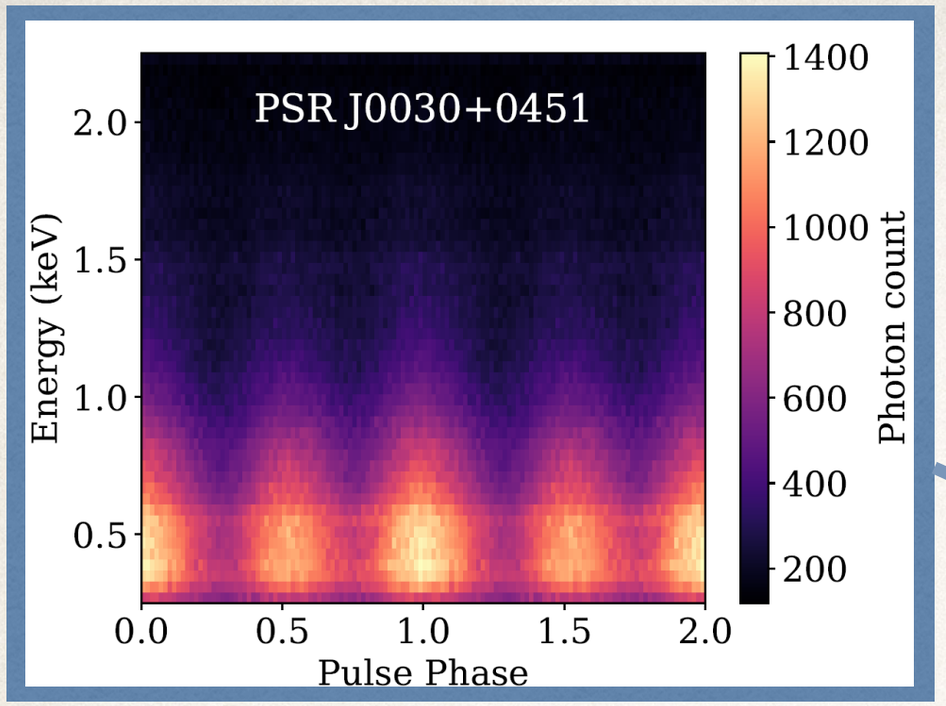
Strong gravity permits seeing beyond the hemisphere of the neutron star, leaving imprints on the lightcurves of millisecond pulsars.

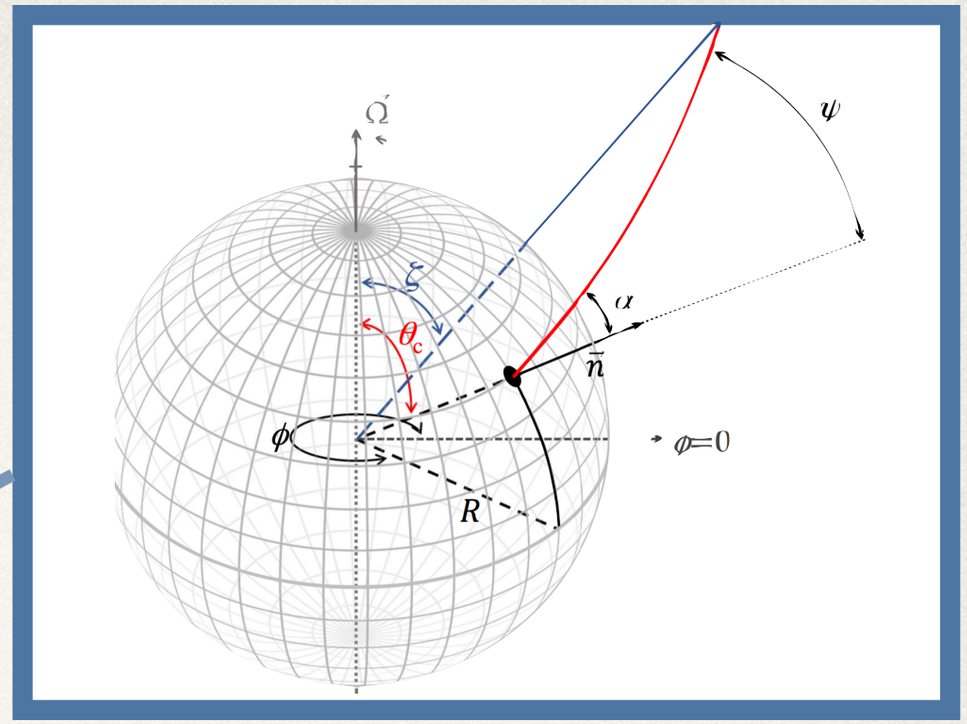


Credits: S. Morsink

NICER was launched for this science goal.

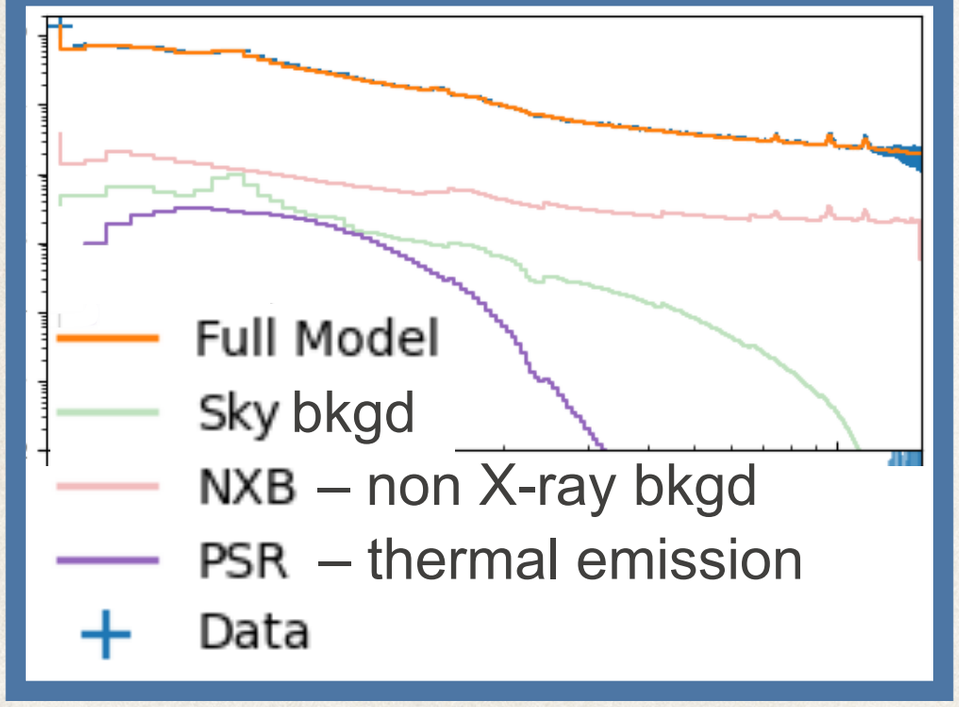


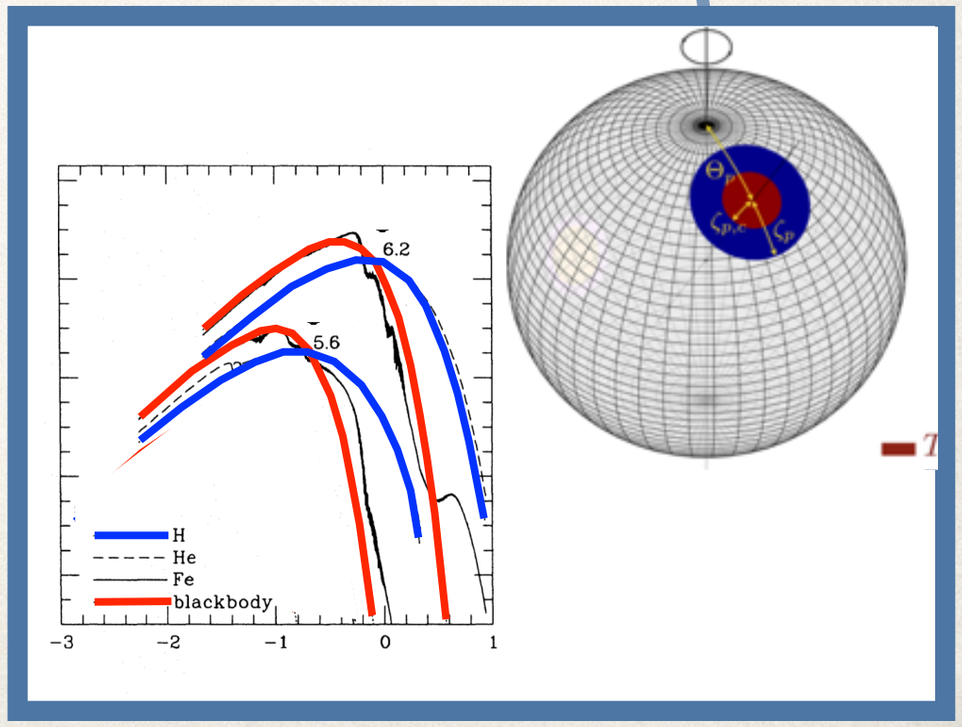




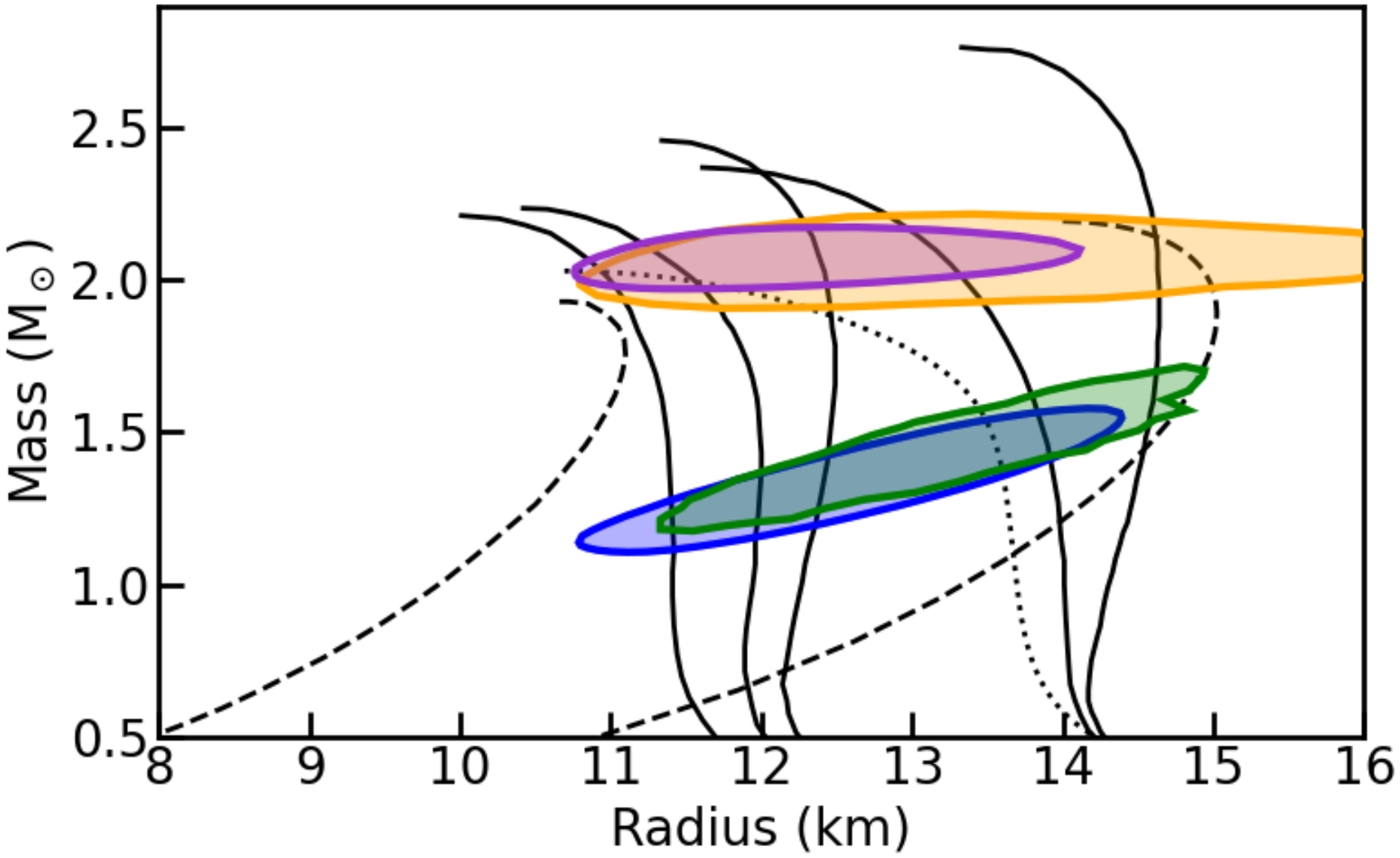
NS properties inference
(sampling of parameter space)

Mass,
Radius,
EOS





The NICER Science Team published the results for two pulsars.



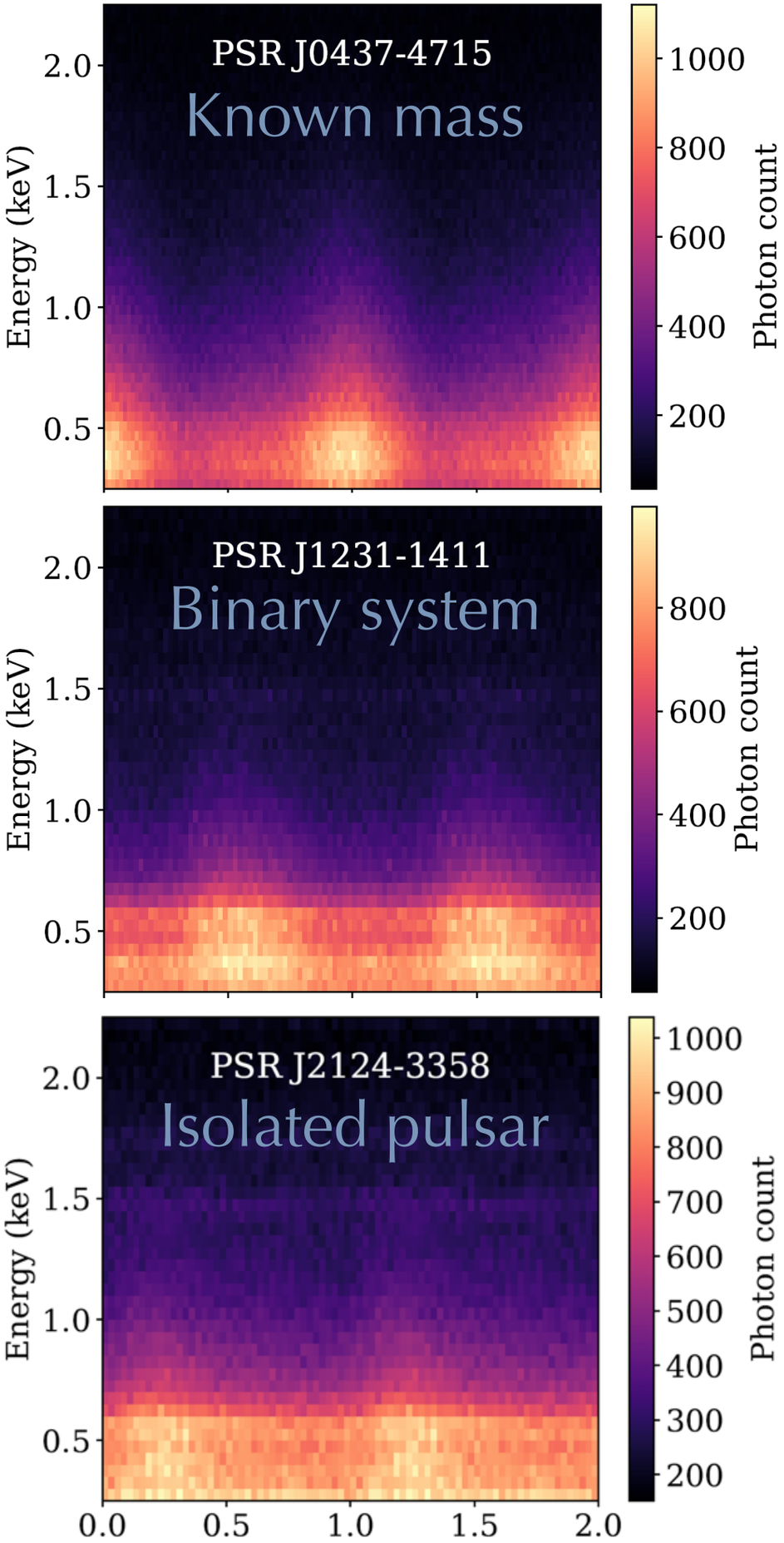
The two independent analyses for each target are consistent

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

See also additional analyses in Salmi et al. 2022, 2023 Vinciguerra et al. 2023a, 2023b

See also a third independent re-analysis of PSR J0030+0451 by Afle et al. 2023 finding consistent results

There are still many data sets to analyse, including newly discovered millisecond pulsars.



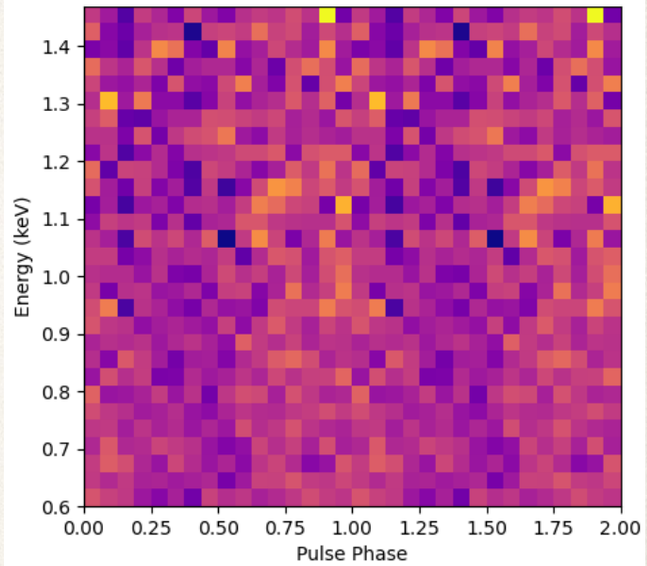
Bogdanov et al. (2019)

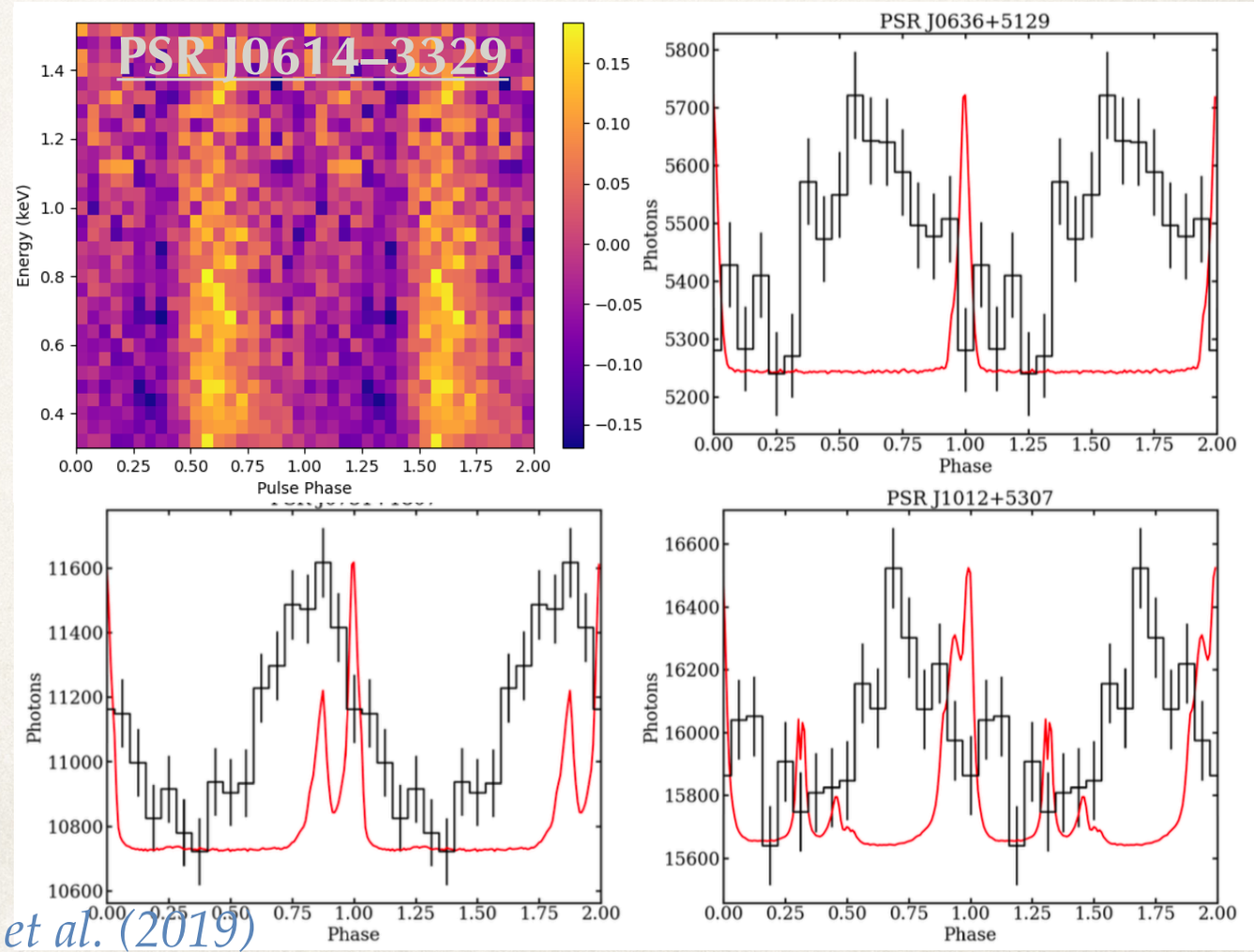
PSR J1614-2230

Wolff et al. 2021

Known high mass:

$M = 1.908 \pm 0.016\ M_\odot$

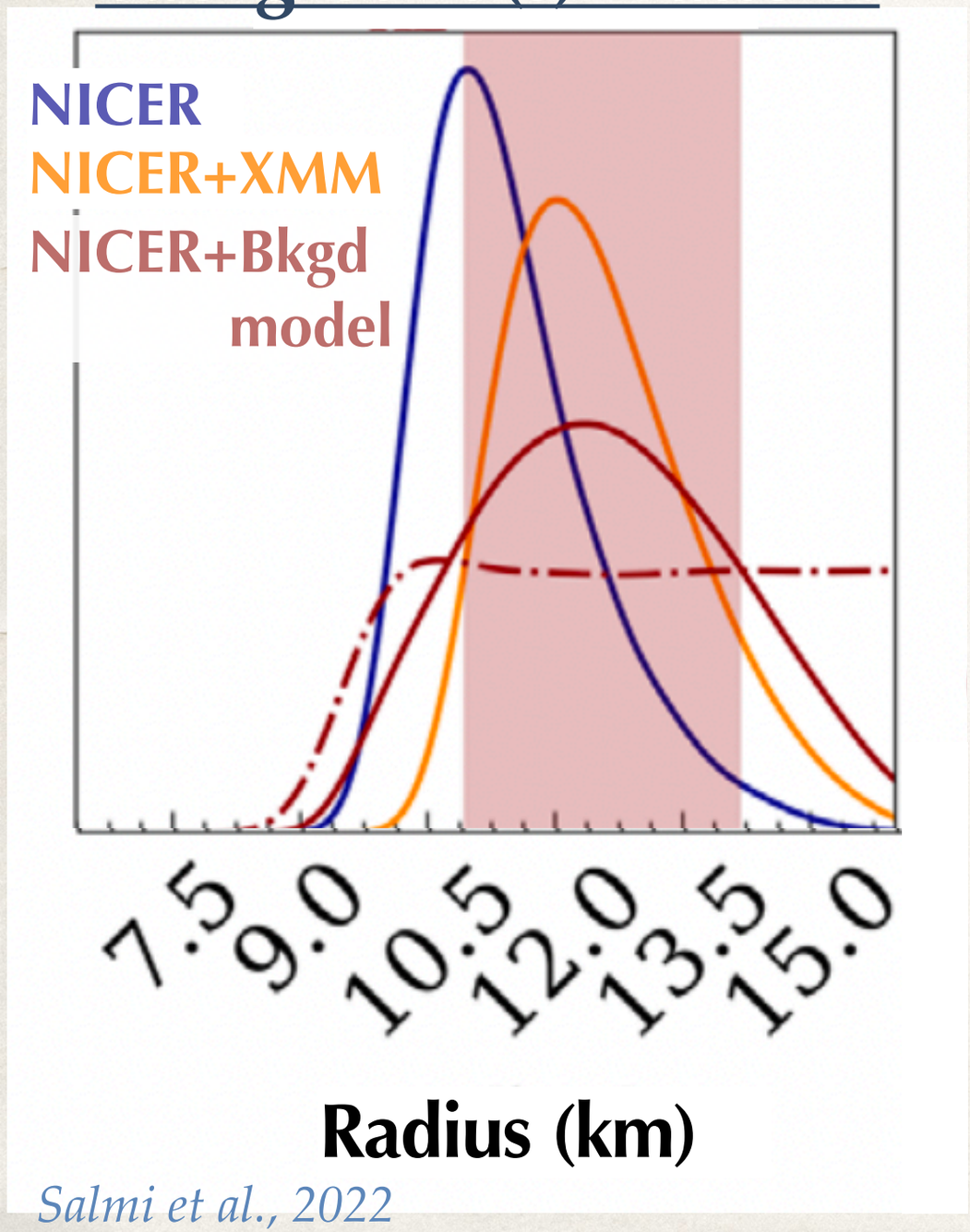




Guillot et al. (2019)

What did we learn from the analysis of NICER observations of millisecond pulsars?

Modelling of the background(s) matters!



Salmi et al., 2022

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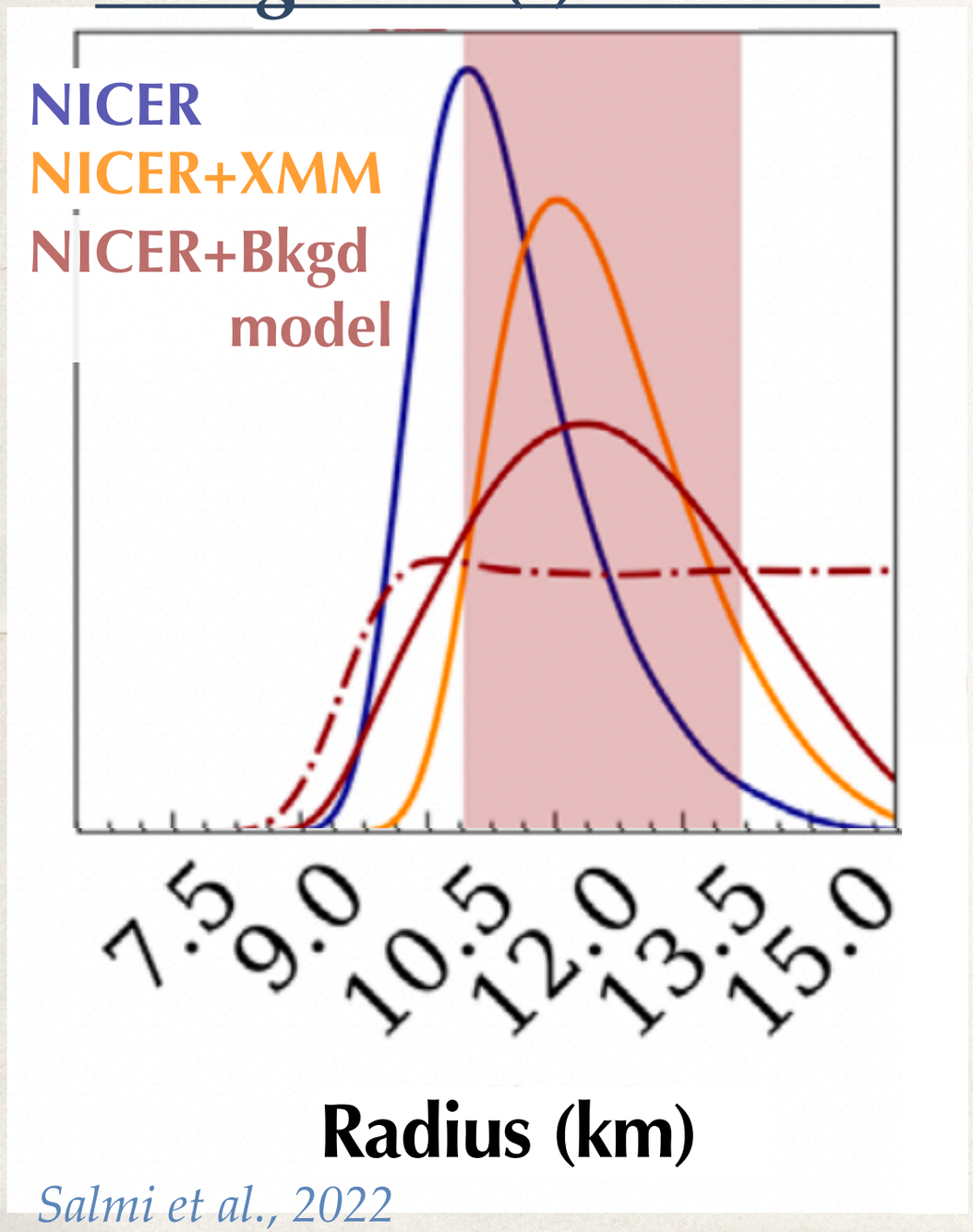
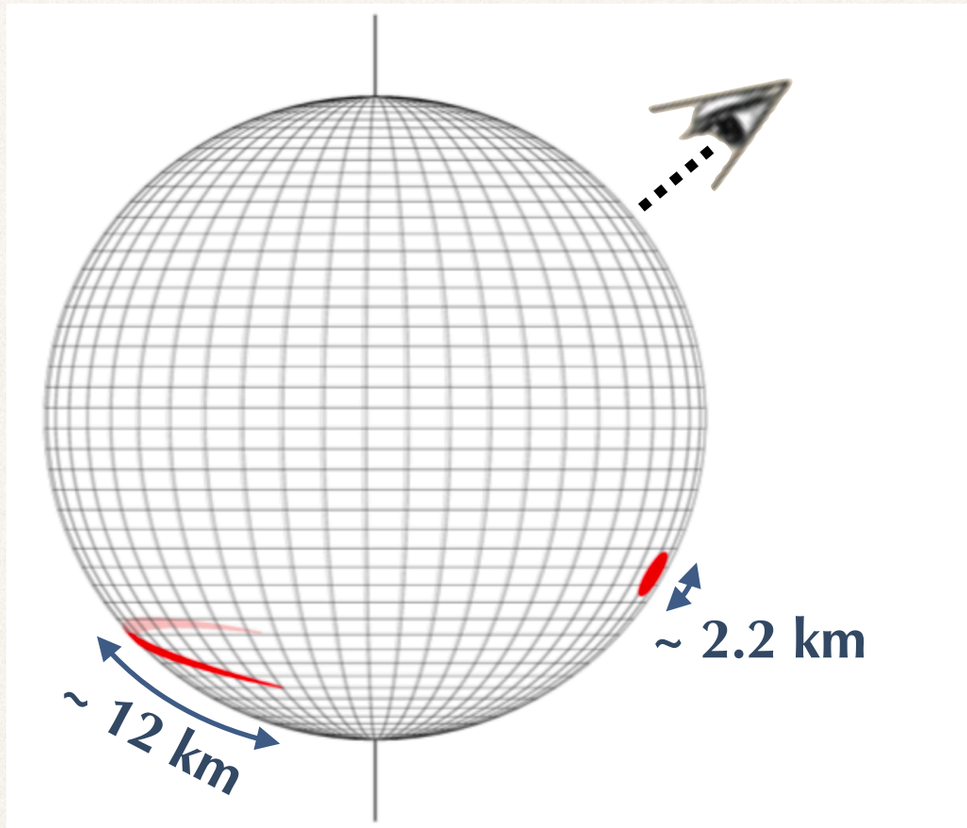
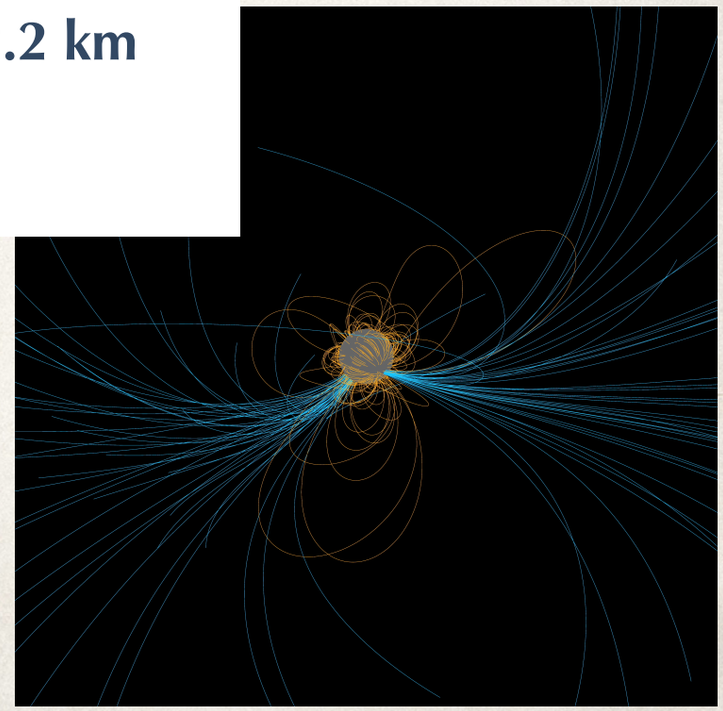


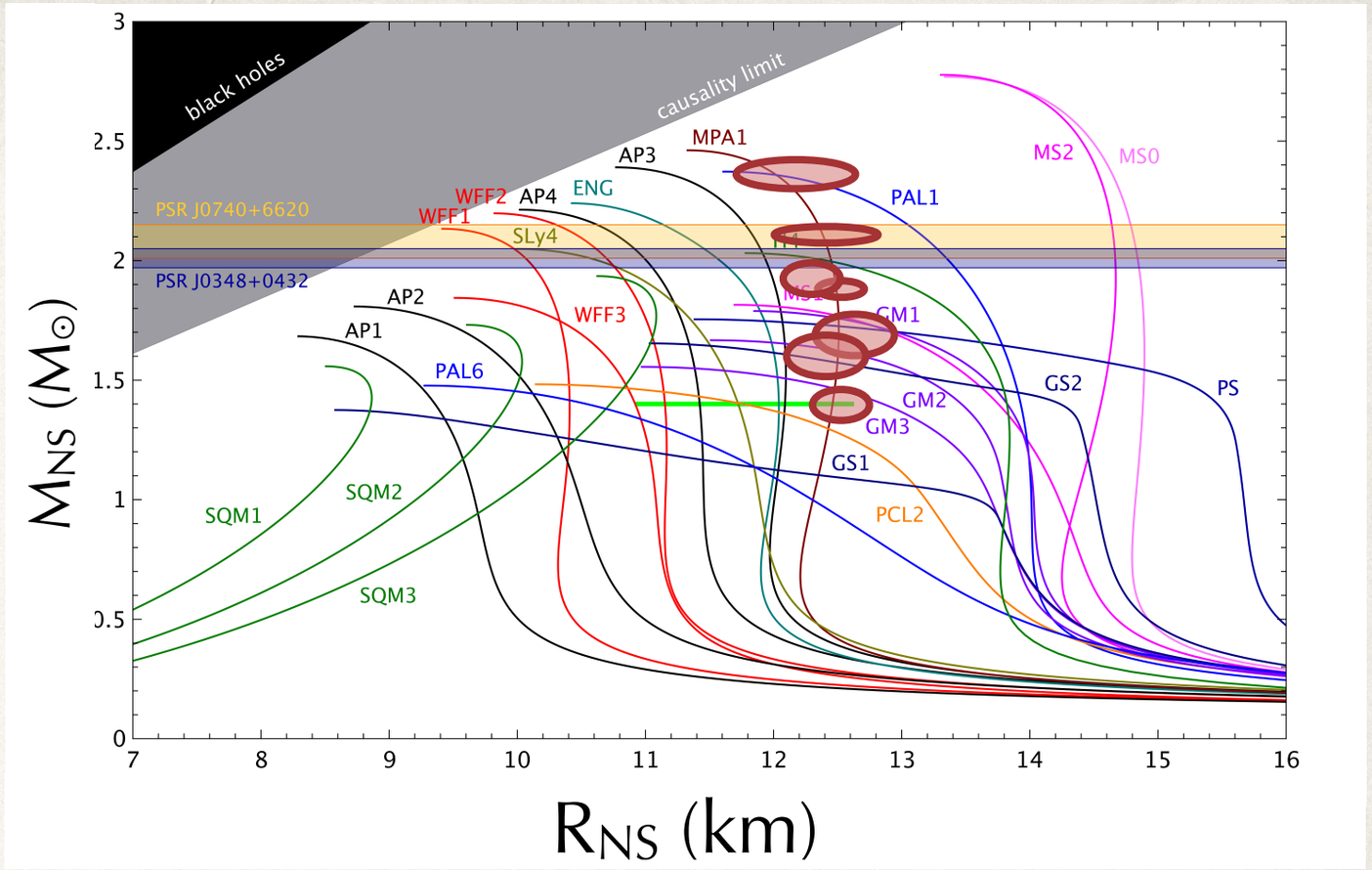
Salmi et al., 2022

The geometry was not as simple as initially anticipated!





Determining the equation of state of dense matter will require the next generation of observatories!



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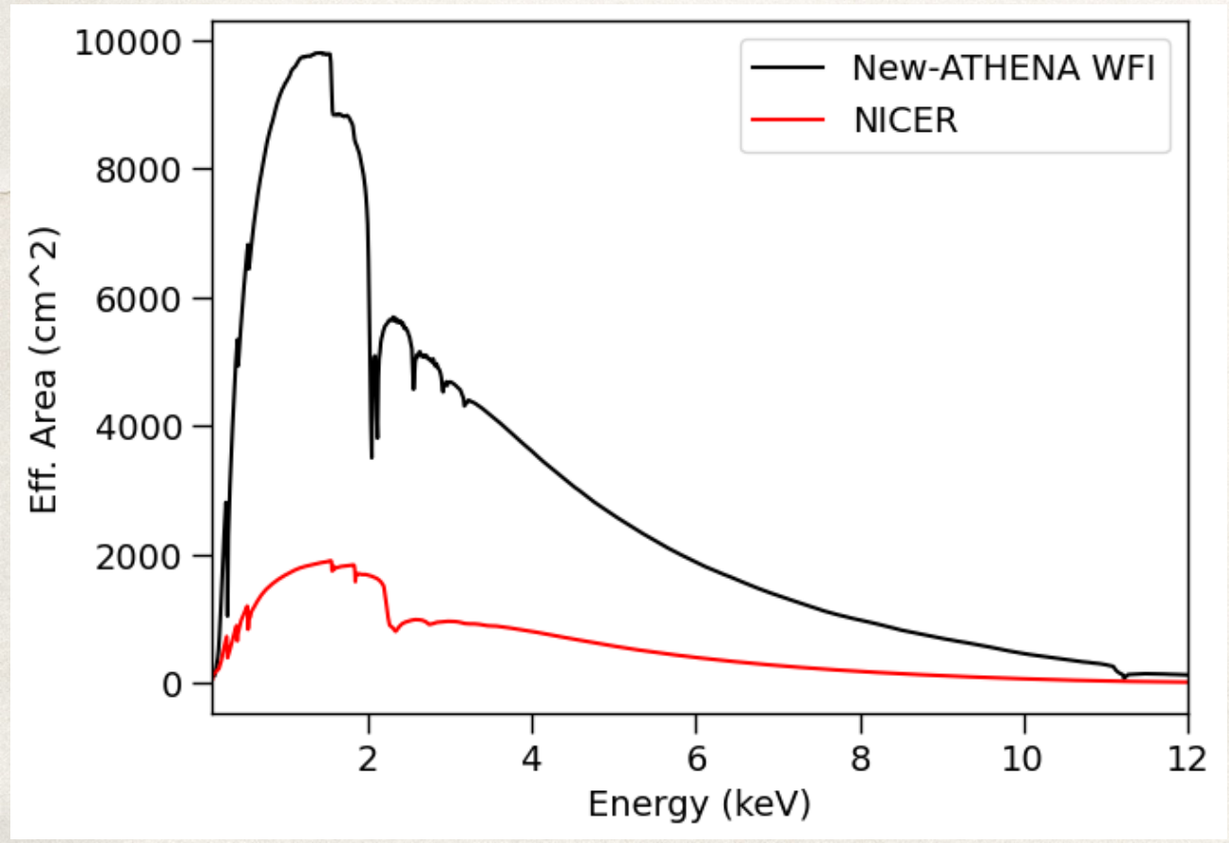
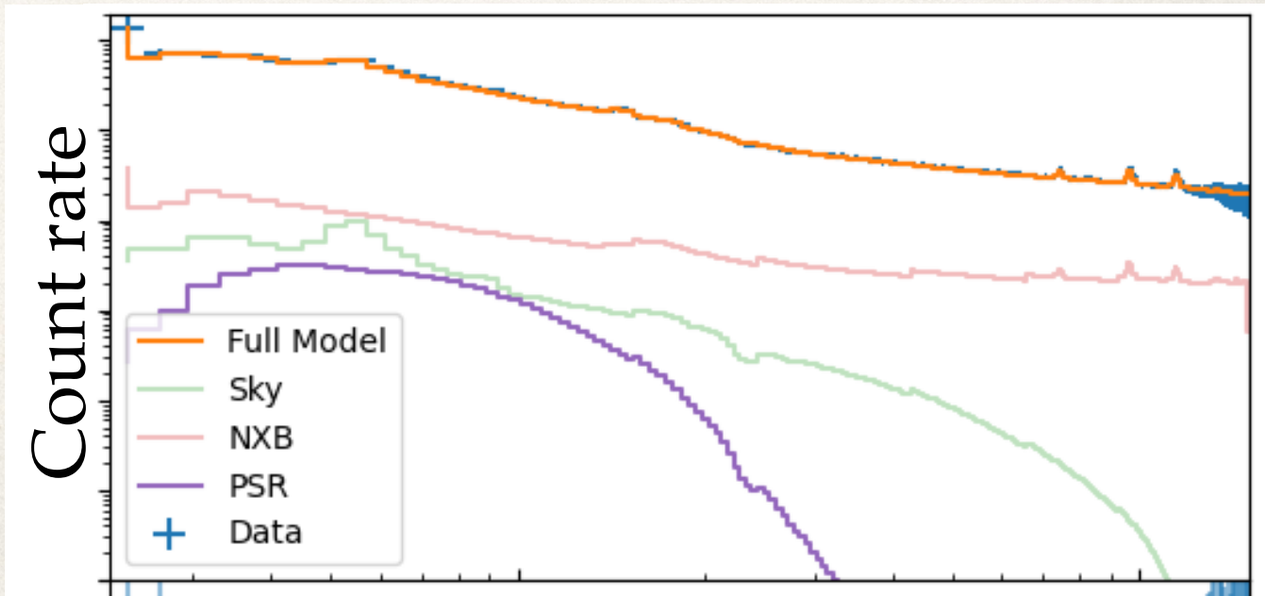
Effective area



Background

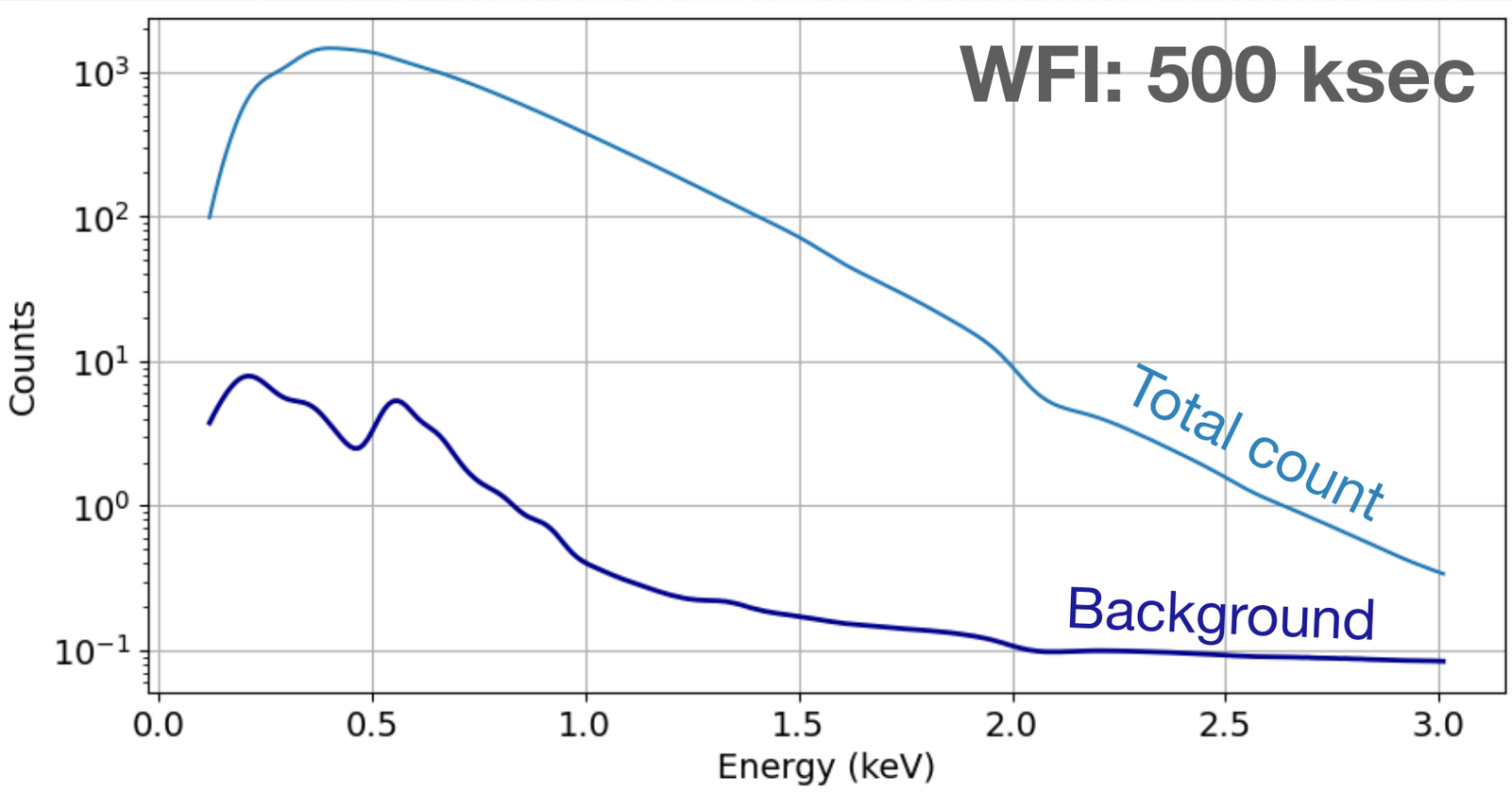
- **New-ATHENA WFI: < 0.001 c/s**
- **NICER: ~ 1 c/s**

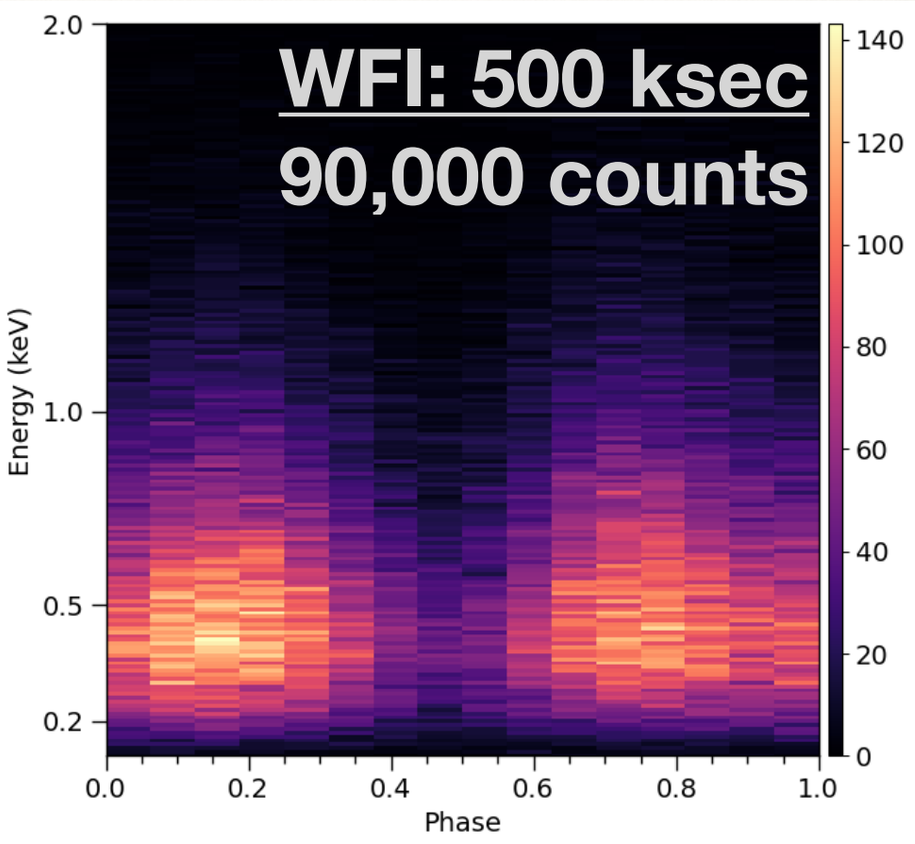


Future prospects for pulse profile modelling with new-Athena are quite promising.

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

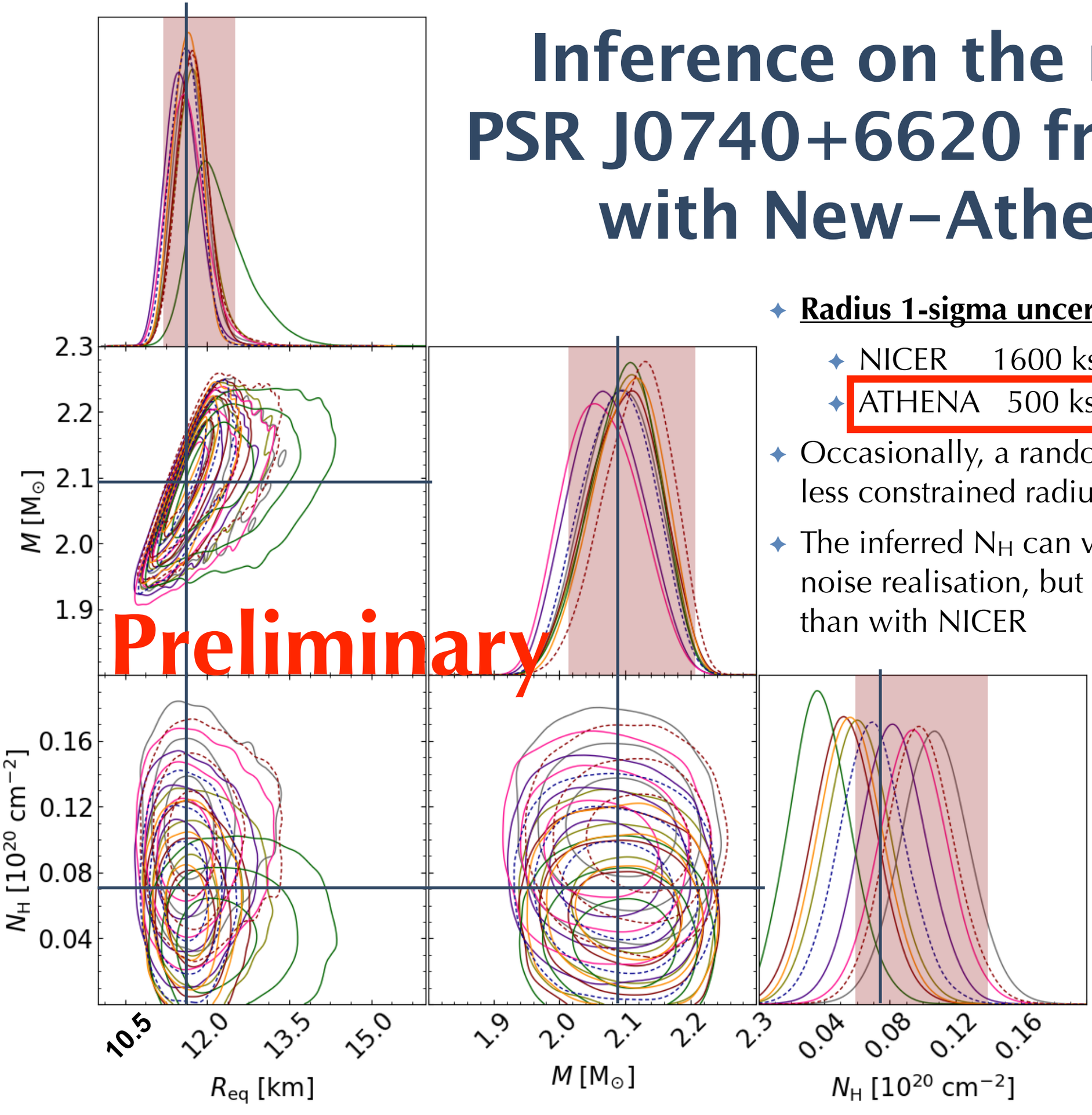
R~11.5 km, M=2.08 $M_\odot$ with 2 circular hot spots
Simulation of 500 ksec observations





X-PSI

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



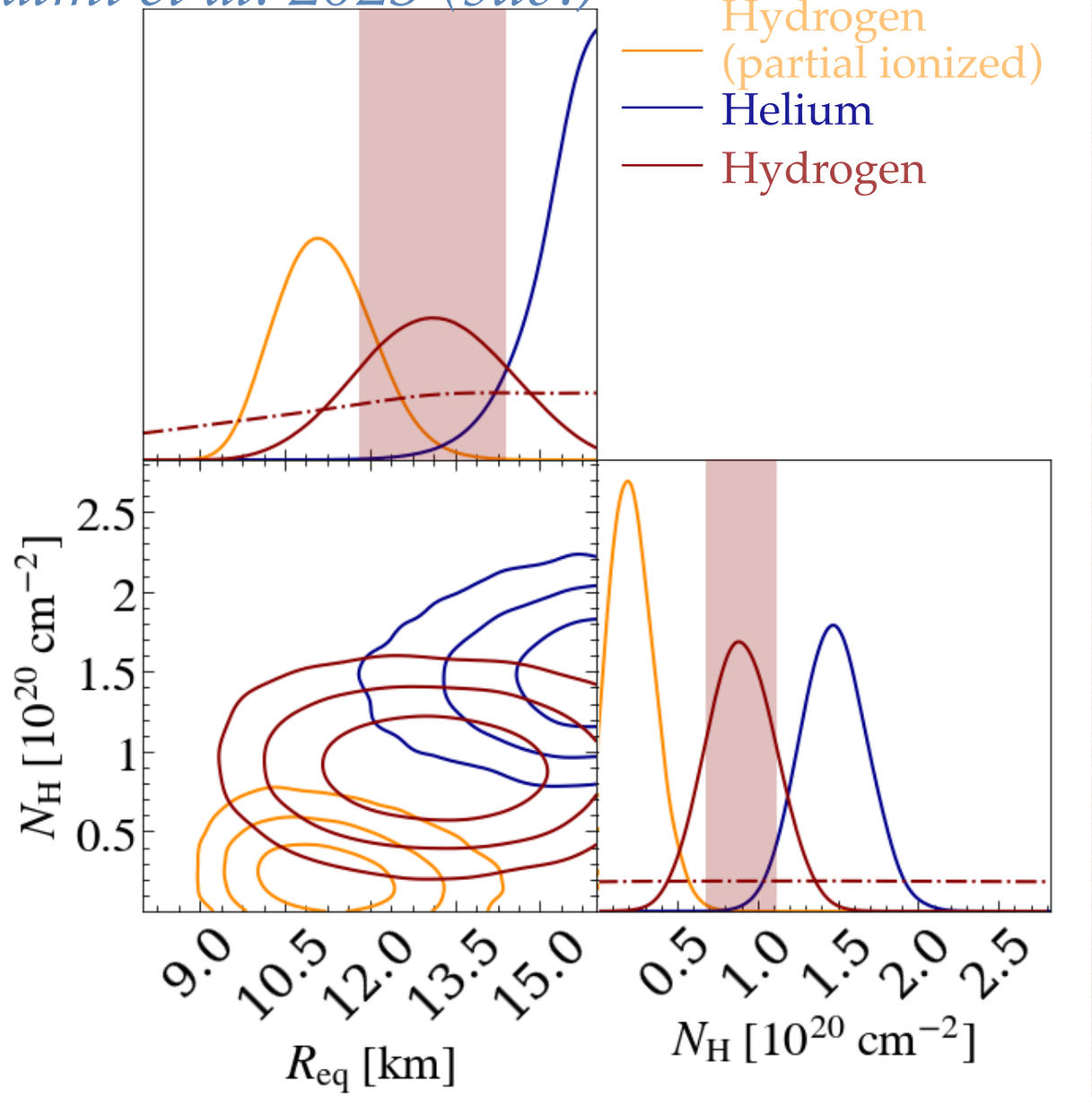
- **<u>Radius 1-sigma uncertainties</u>**
  - NICER 1600 ksec: ~10%
  - ATHENA 500 ksec: ~3% average (±0.3 km)
- Occasionally, a random noise realisation gives a less constrained radius
- The inferred N_H can vary between each random noise realisation, but overall better constrained than with NICER

To be investigated in more details

For faint MSPs, the choice of atmosphere may affect the radius measured.

NICER data of PSR J0740+6620

Salmi et al. 2023 (sub.)



Solutions to solve this degeneracy

- Measure N_H independently
- Use New-ATHENA

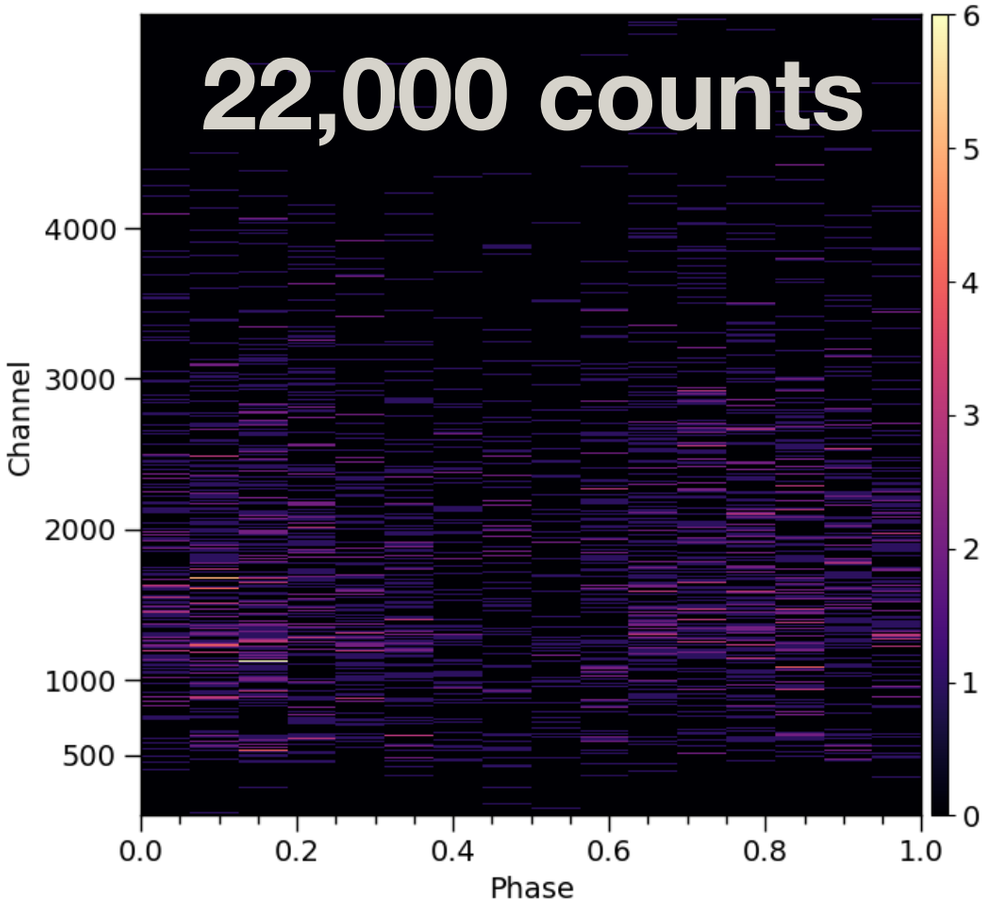
ATHENA Simulations of Hydrogen atmosphere data set, and run the inference with Helium atmosphere model

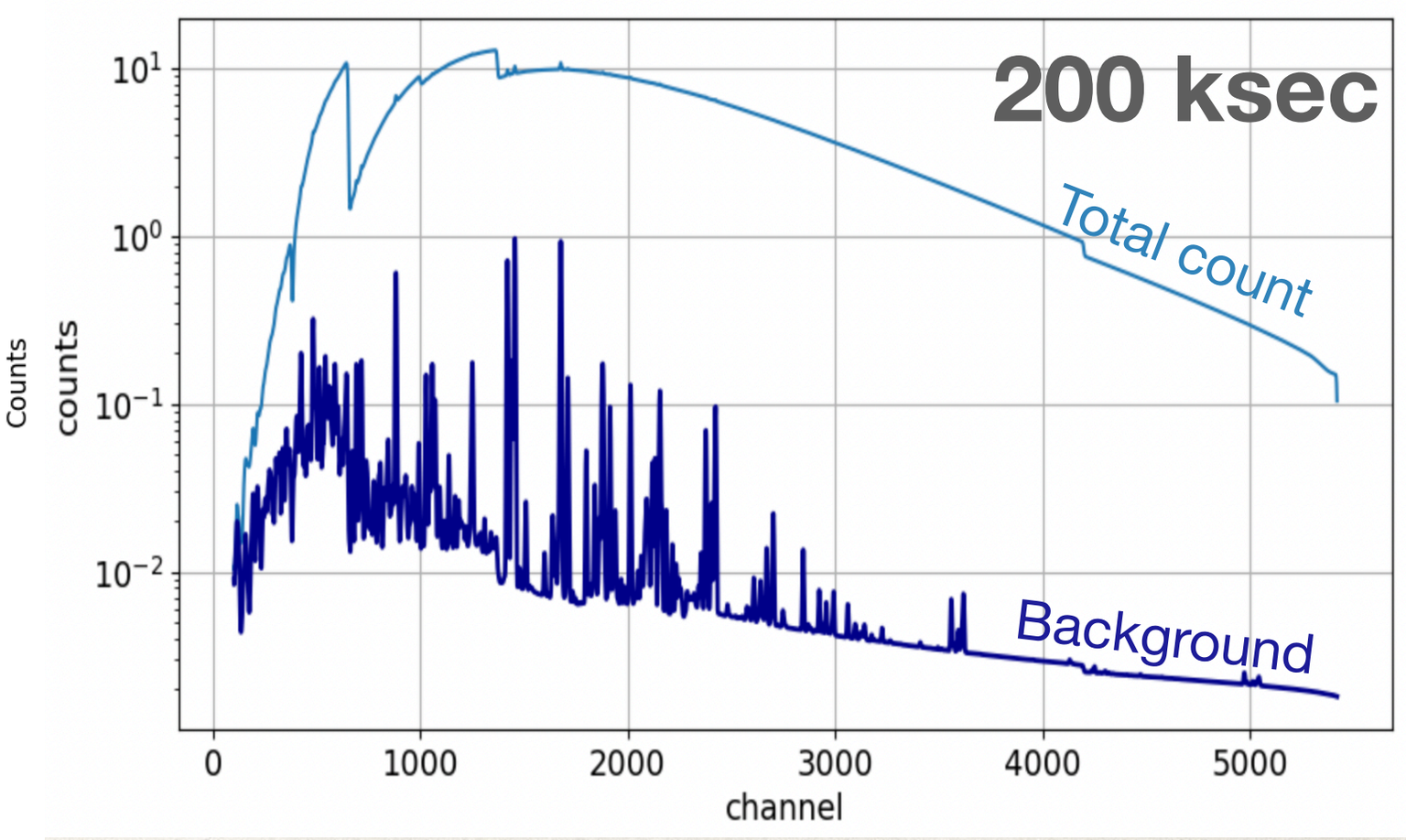
- For 500 ks: ln(Bayes Factor) ~ 100–150

The time resolution of WFI might be limiting, so let's look at X-IFU

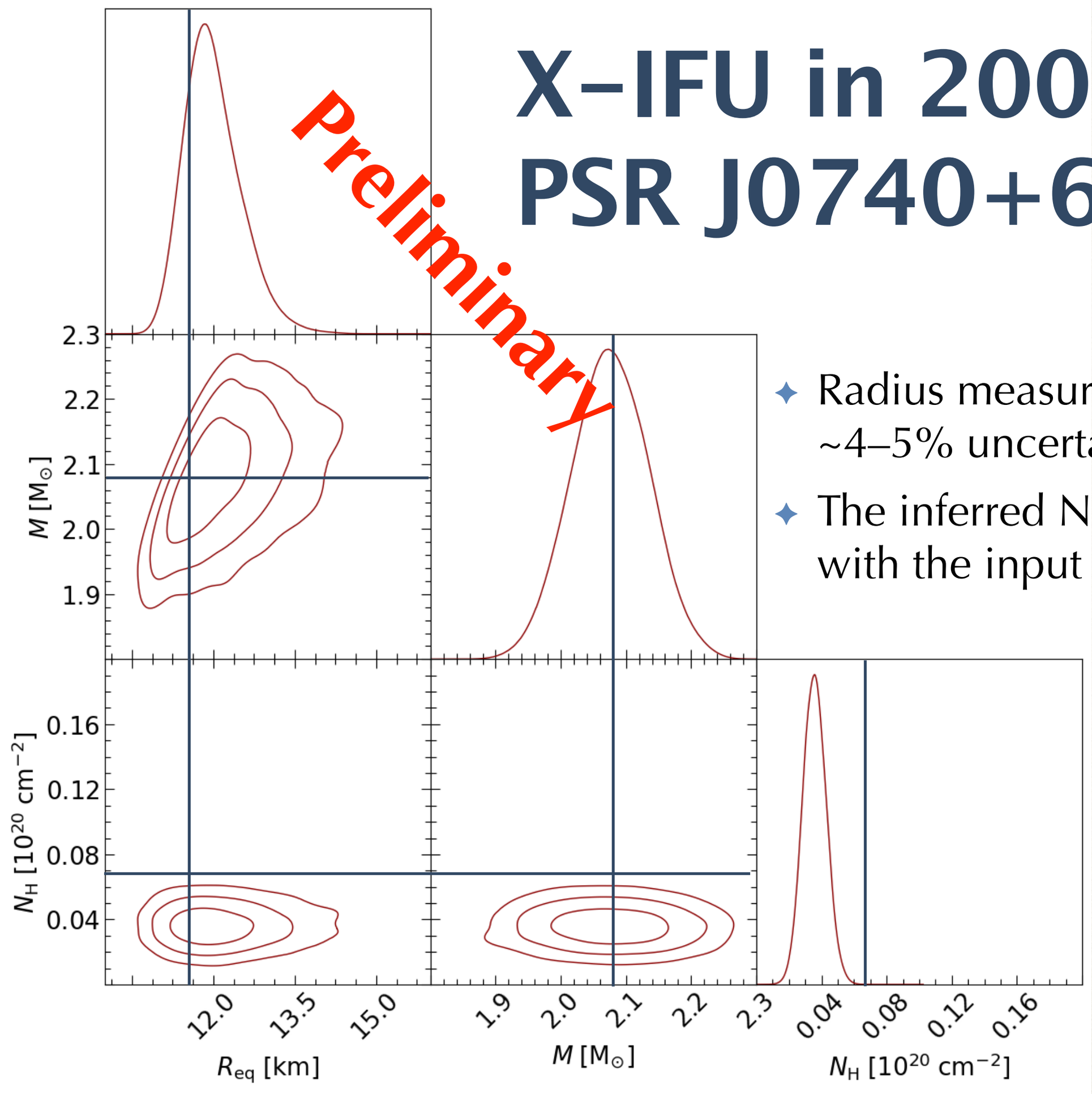
- Time resolution is an important requirement for Spectro-temporal analyses of millisecond pulsars, especially with P_{spin} ~ 2 msec.
- Time resolution: 10 μsec (X-IFU) versus ~100 μsec (WFI)

Simulations of PSR J0740+6620 in 200 ksec with (old) X-IFU





X-IFU in 200 ks for PSR J0740+6620

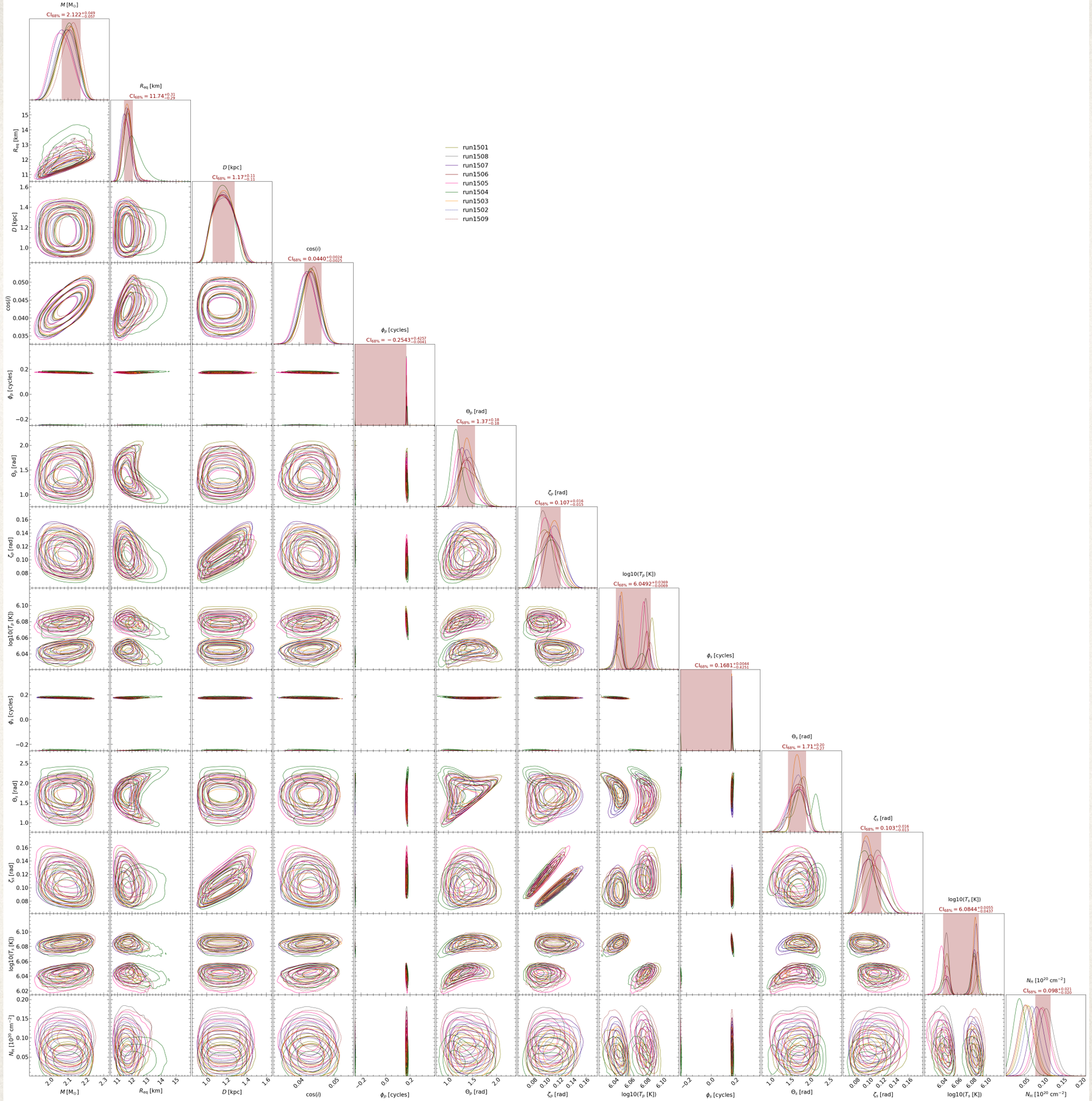


- Radius measurements with ~4–5% uncertainties
- The inferred N_H is inconsistent with the input value

To be investigated in more details and to re-do with newer response matrices

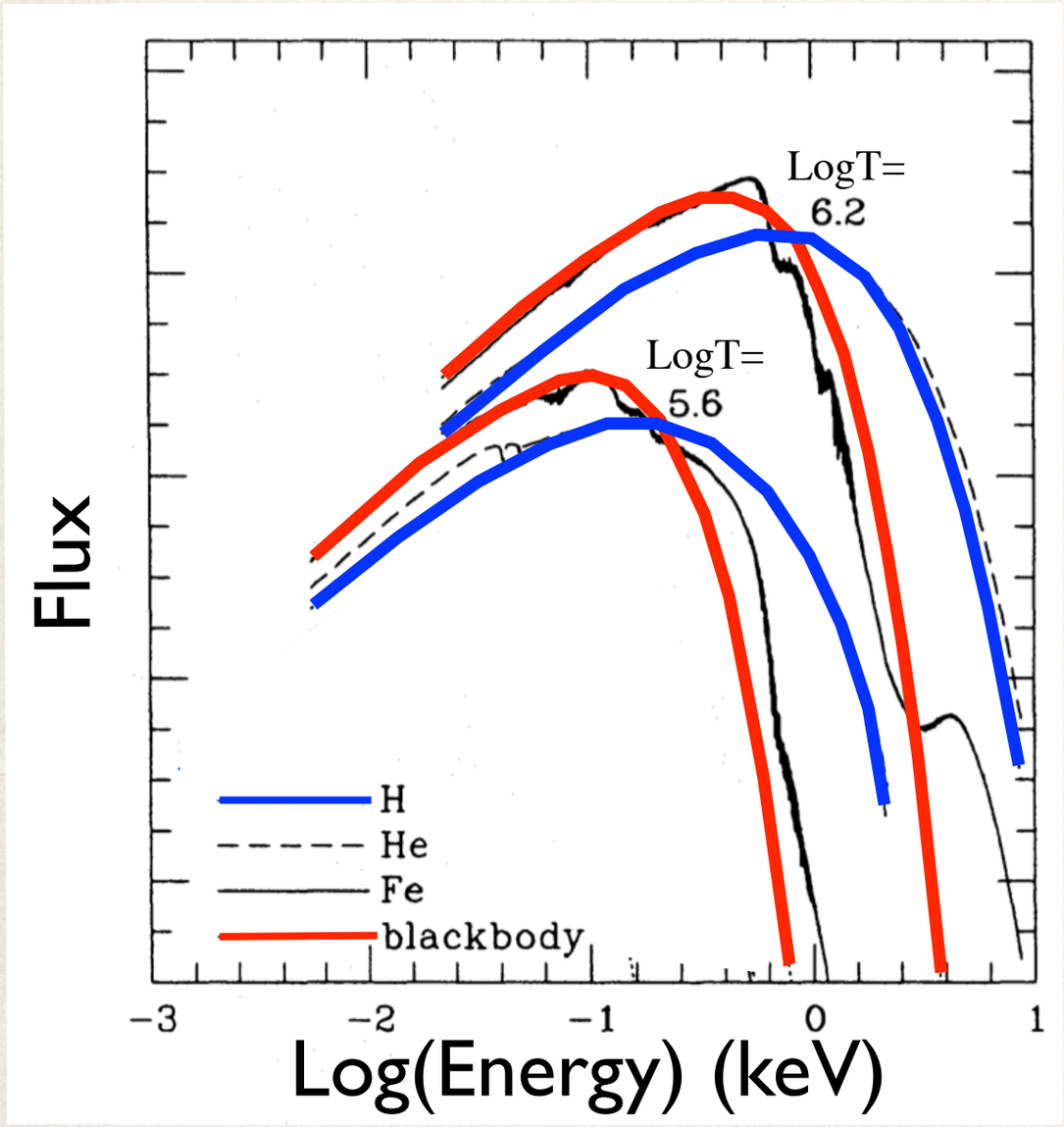
Conclusions

- NICER has **<u>demonstrated of the feasibility</u>** of measuring the radii of millisecond pulsars, but revealed new observational and modelling challenges
- NewAthena has the potential to bring us much closer to **<u>understanding the interior of neutron stars</u>**, with its numerous advantages:
  - High effective area
  - Very low (and known!) background
  - Good timing resolution
- **<u>Unmatched capabilities</u>** compared to current observatories:
  - XMM-Newton in timing mode will not achieve the same quality of measurements, even in several Msec of observations)
- **<u>Open questions</u>**:
  - How does New-Athena compare to other proposed X-ray missions ?
  - Can we harness the high spectral resolution of XIFU?
  - Can New-Athena distinguish between different surface spot patterns ?

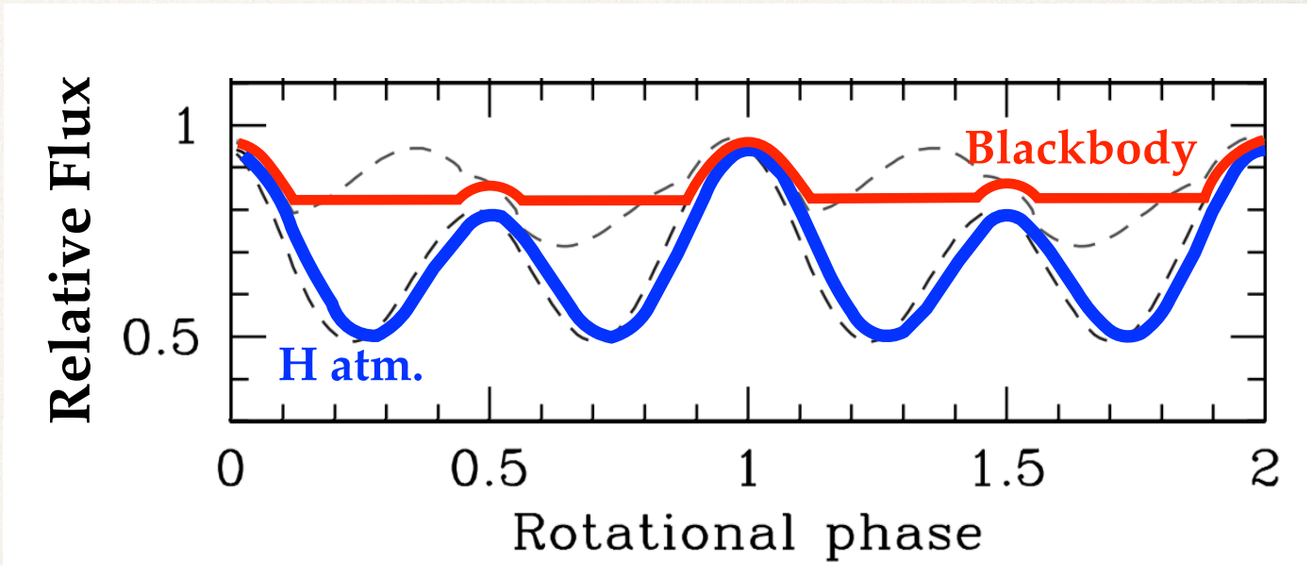

M [$M_\odot$]
$CI_{68\%} = 2.122^{+0.049}_{-0.057}$
R_{eq} [km]
$CI_{68\%} = 11.74^{+0.31}_{-0.29}$
D [kpc]
$CI_{68\%} = 1.17^{+0.11}_{-0.11}$
cos(i)
$CI_{68\%} = 0.0440^{+0.0024}_{-0.0025}$
ϕ_p [cycles]
$CI_{68\%} = -0.2543^{+0.4257}_{-0.0041}$
Θ_p [rad]
$CI_{68\%} = 1.37^{+0.18}_{-0.18}$
ζ_p [rad]
$CI_{68\%} = 0.107^{+0.016}_{-0.015}$
log10(T_p [K])
$CI_{68\%} = 6.0492^{+0.0369}_{-0.0069}$
ϕ_s [cycles]
$CI_{68\%} = 0.1681^{+0.0044}_{-0.4251}$
Θ_s [rad]
$CI_{68\%} = 1.71^{+0.20}_{-0.27}$
ζ_s [rad]
$CI_{68\%} = 0.103^{+0.016}_{-0.013}$
log10(T_s [K])
$CI_{68\%} = 6.0844^{+0.0055}_{-0.0437}$
N_H [10^{20} cm^{-2}]
$CI_{68\%} = 0.098^{+0.021}_{-0.020}$
run1501
run1508
run1507
run1506
run1505
run1504
run1503
run1502
run1509

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

Zavlin et al. (1996)



Blackbody and NS atmosphere generate different pulse profile shapes

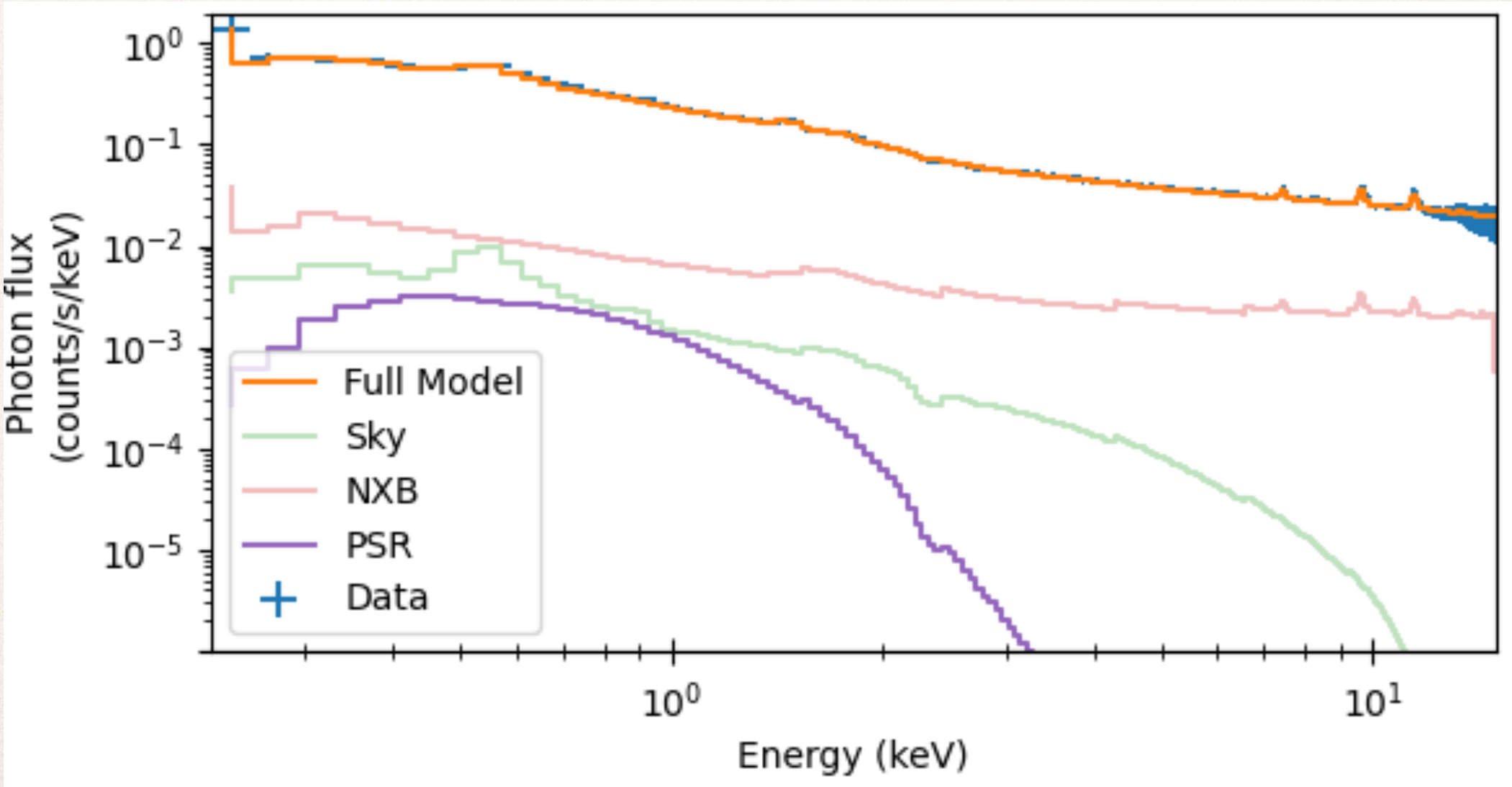


Bogdanov et al. (2007)

In the following, we used Hydrogen atmosphere models

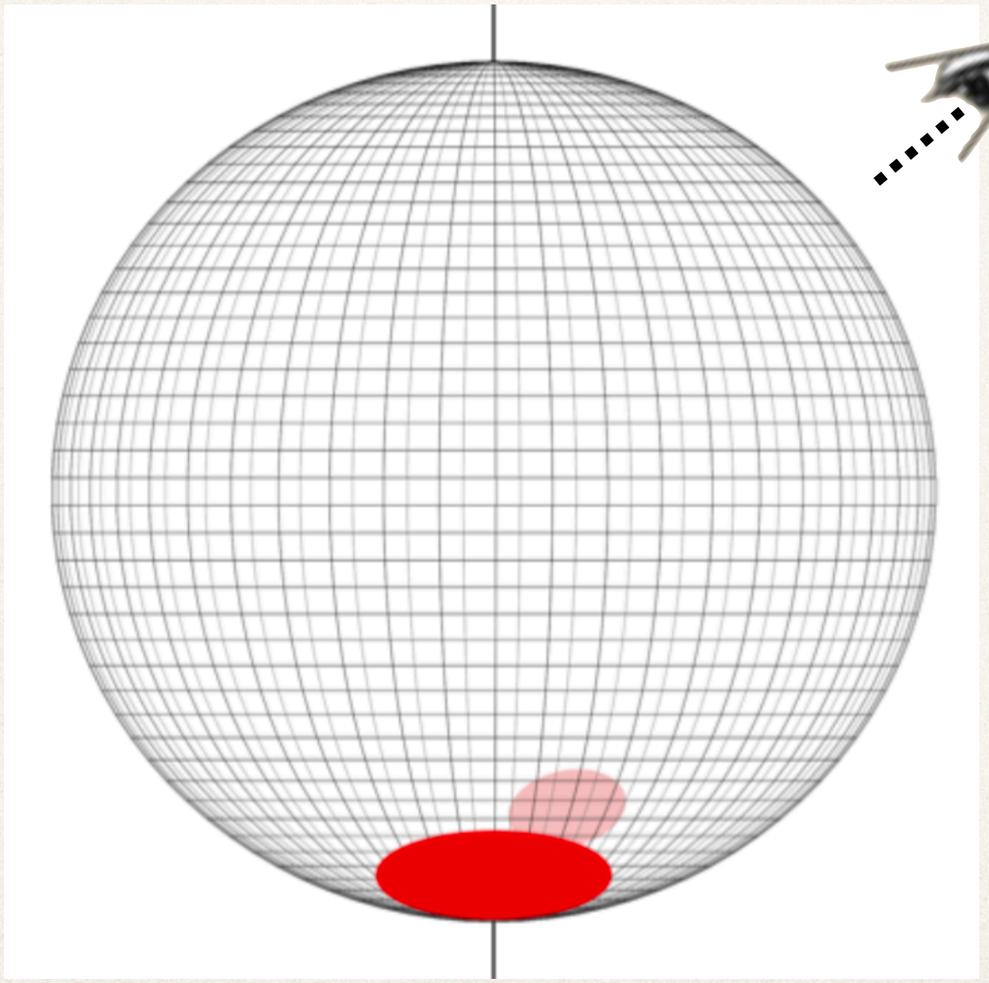
The high background in the NICER data needs to be modelled.

- **3C50**: Empirical background estimates (from blank fields)
- **SCORPEON**: Analytical background

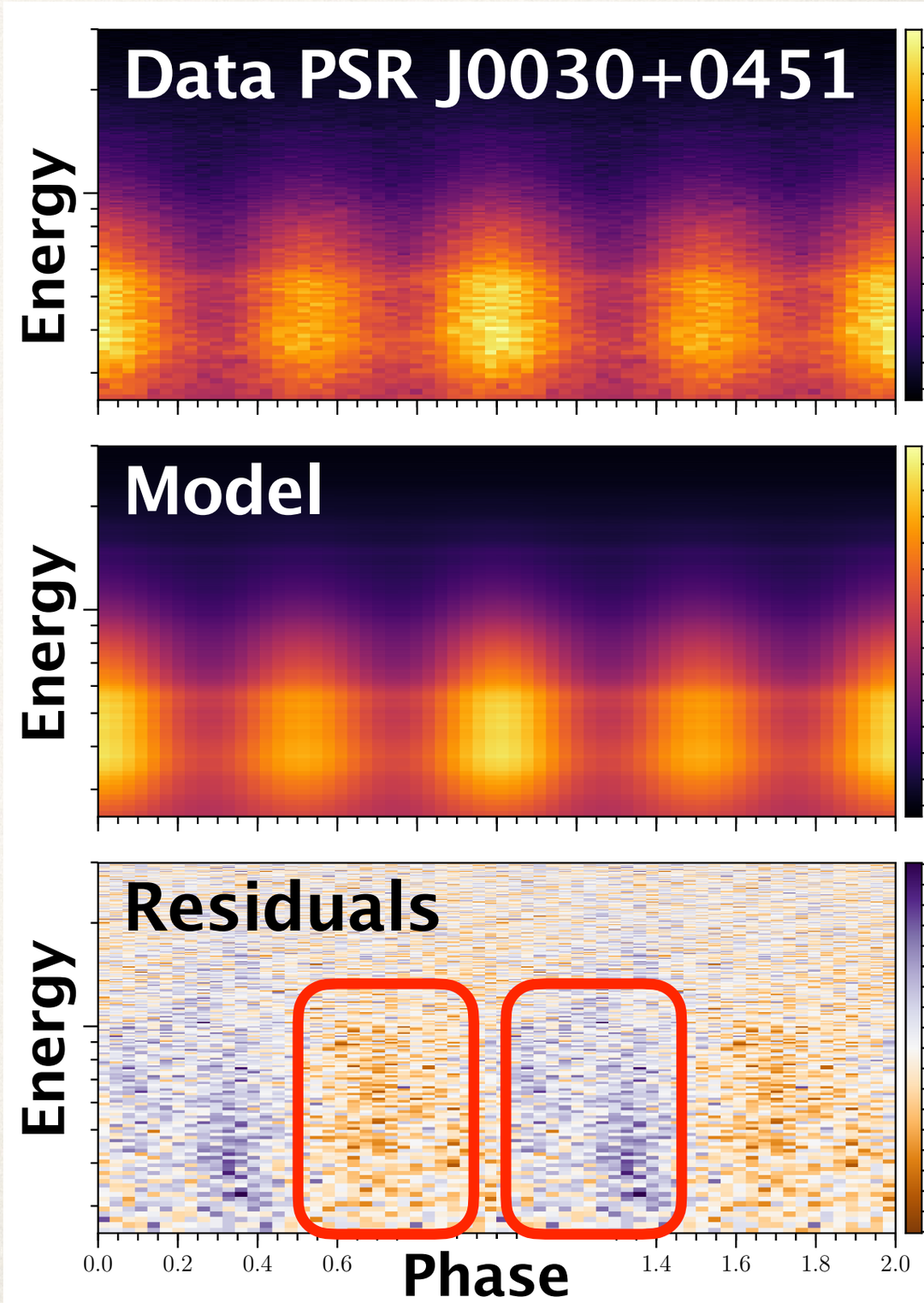


For the pulsar PSR J0030+0451, the simplest model shows clear residuals between the model and the data.

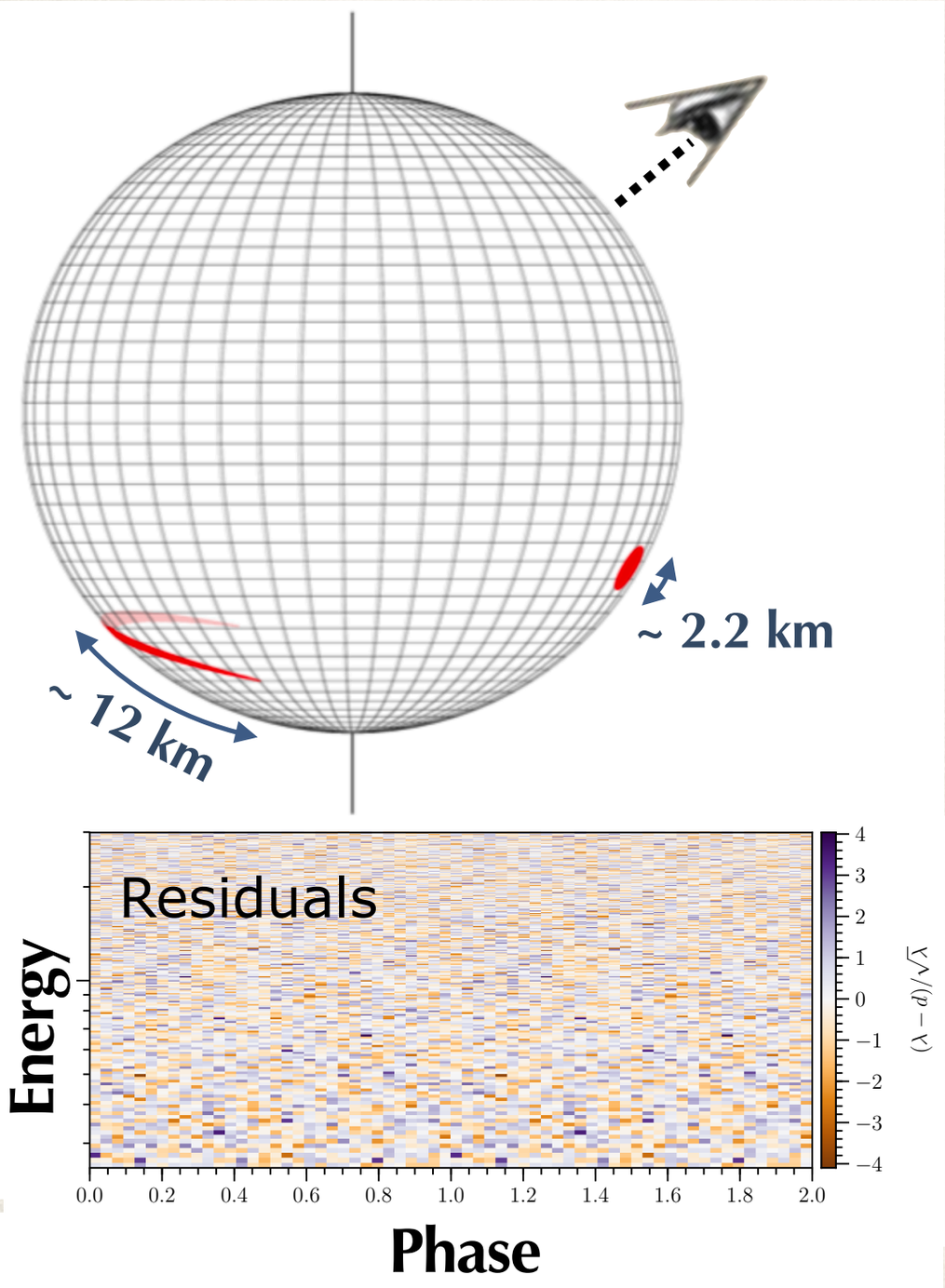
2 circular spots

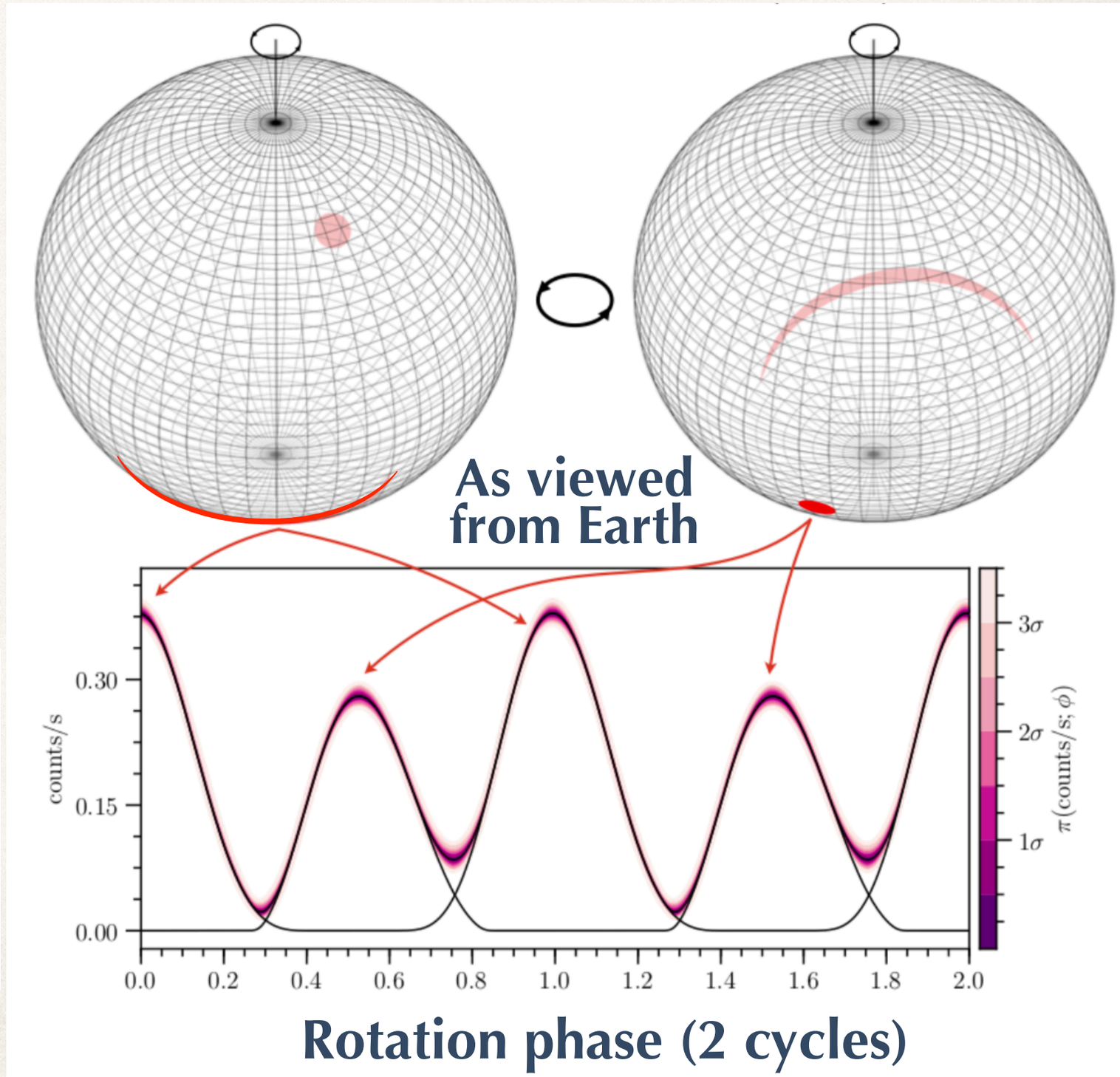


Riley et al. (2019)



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





Riley et al. (2019)