Using Millisecond Pulsars to constrain dense matter with NICER

A NICER view of the 1.4 solar-mass edge-on pulsar PSR J0614-3329, *Mauviard al. 2025*

In collaboration with:
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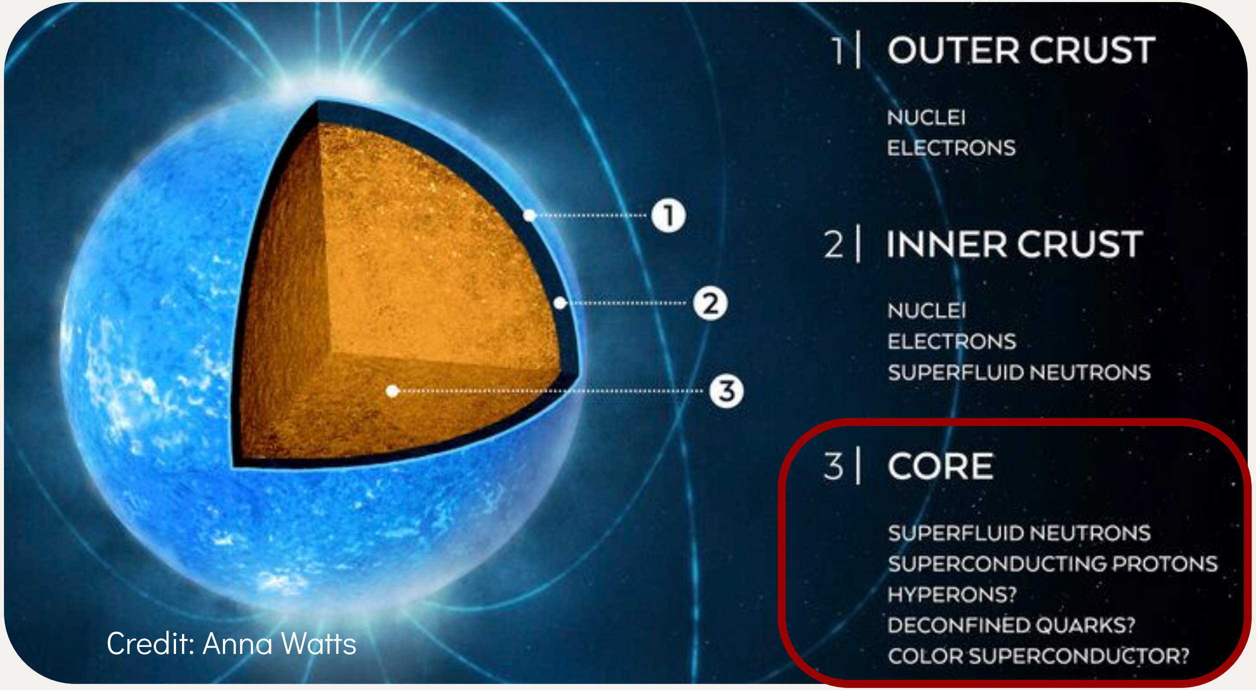
P. Stammler, M. Mendes, N.Rutherford, A. Schwenk, I. Svensson, and *many others*

Lucien Mauviard, PhD Student
IRAP CNRS, Toulouse, France

Journées ATPEM 2025
1st of October 2025

What's inside a Neutron Star ?



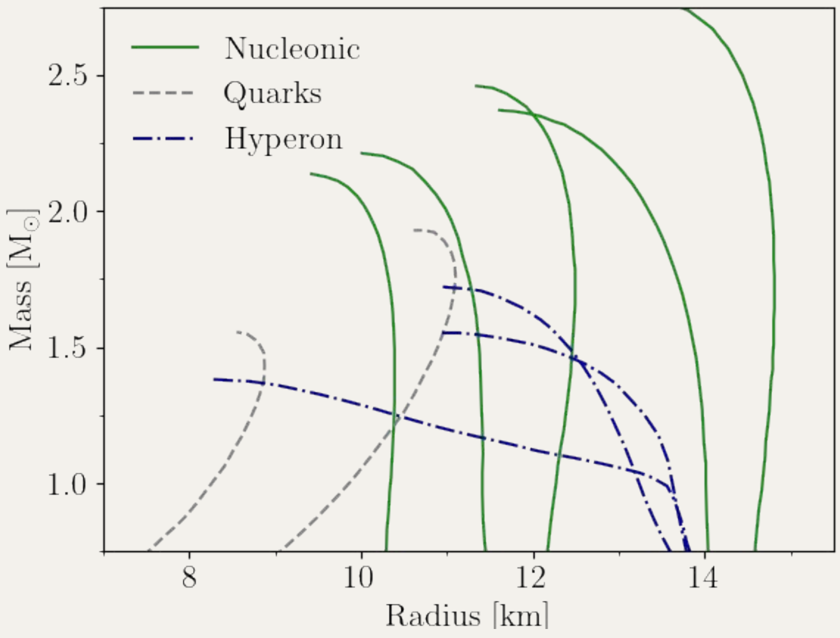
What is the composition of dense matter ?

- Stable only inside neutron star
- Experiments on Earth can not probe such densities
- Millisecond pulsar are very stable and hence good probes to study dense matter

Neutron Star Equation of State (EoS)

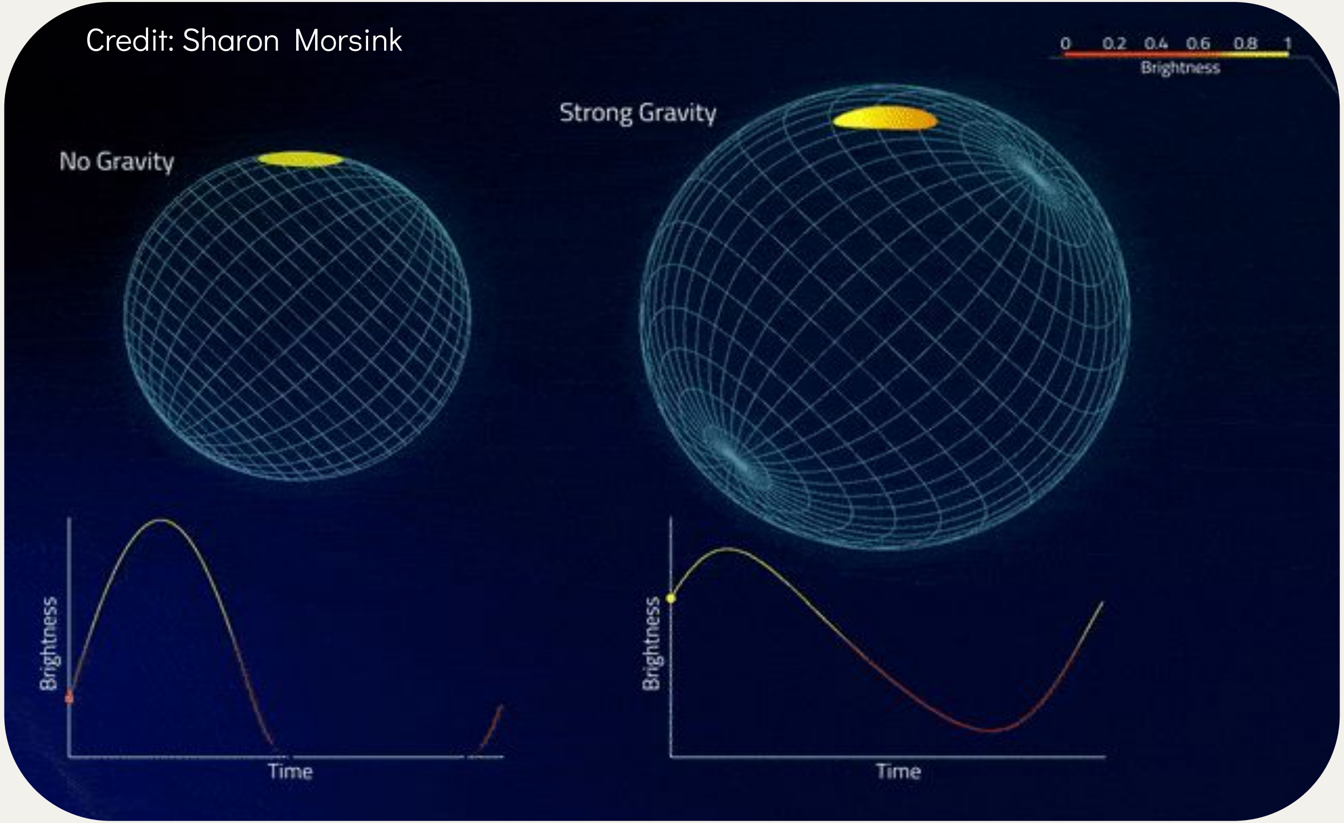
- In practice, we can probe the composition of dense matter via the Equation of State (EoS) of the neutron stars core

- The EoS of dense matter can be constrained by “simple” macroscopic observables of neutron stars: mass, radius, tidal deformability, moment of inertia…



Tight and reliable measurements of mass and radius of neutron stars are needed to better constrain the EoS

Pulse profile modeling (PPM)



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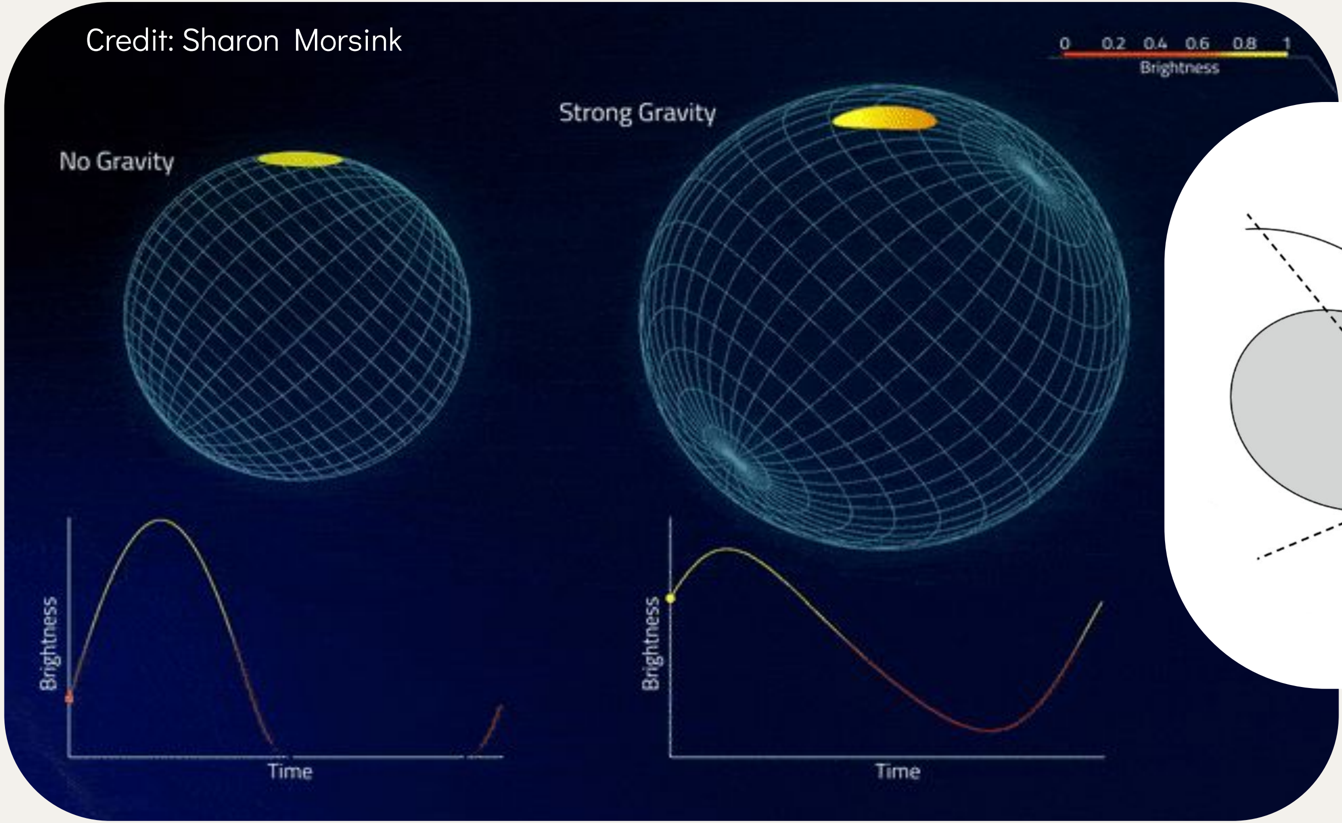
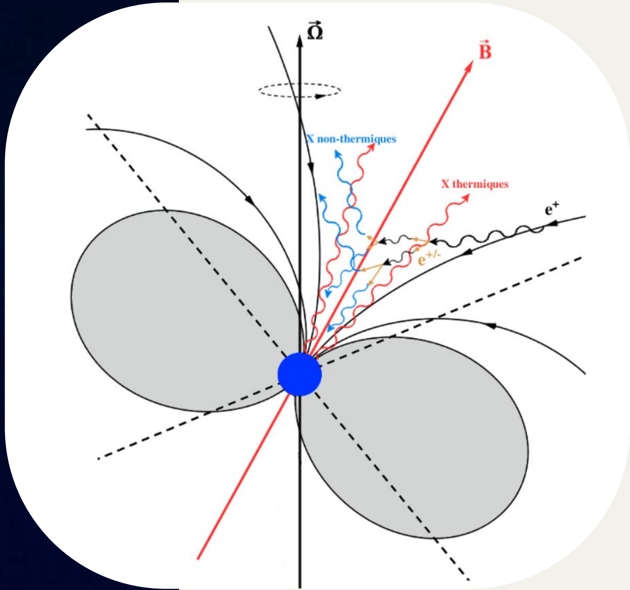
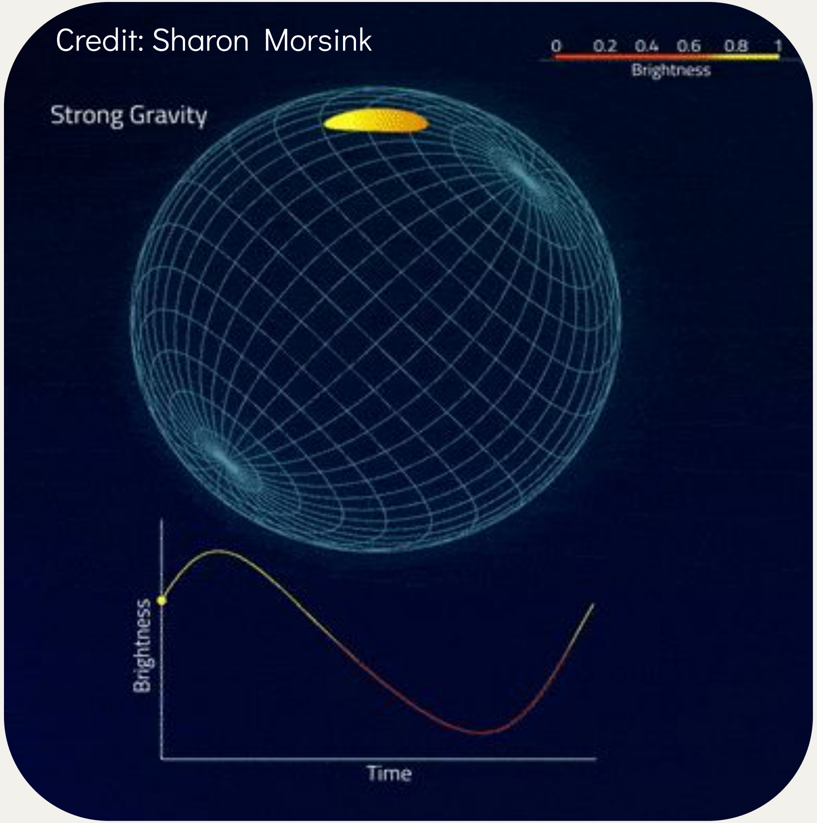


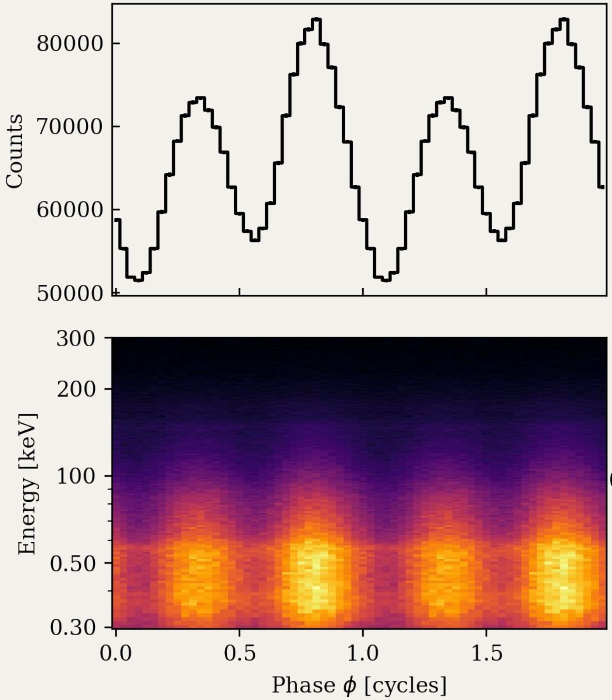
Pair creation in the magnetosphere



Particles shower at the magnetic poles heat the surface

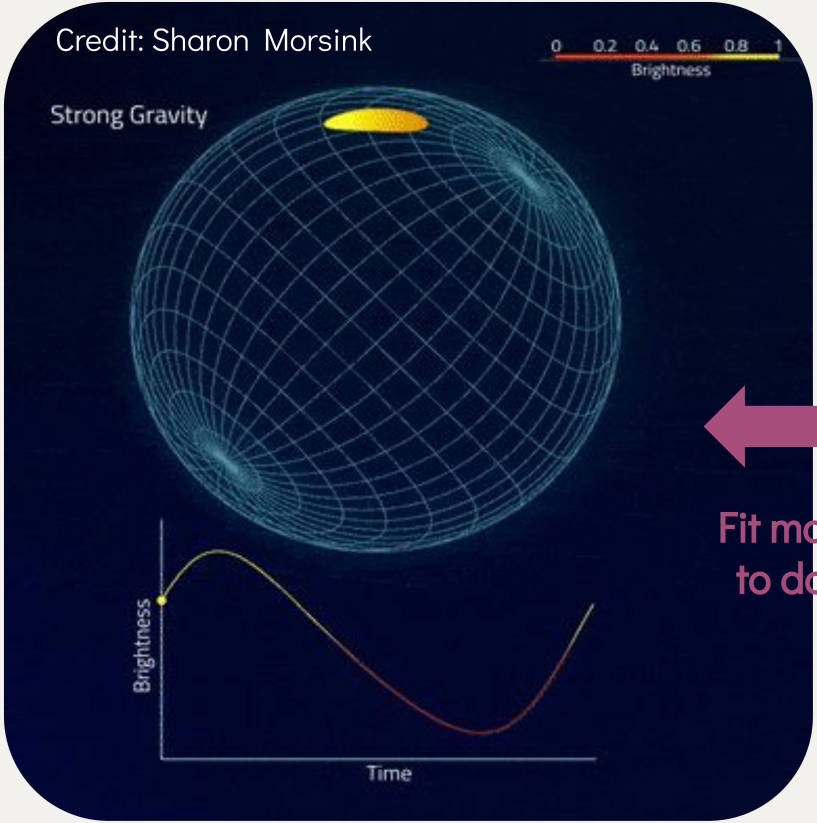
Pulse profile modeling (PPM)



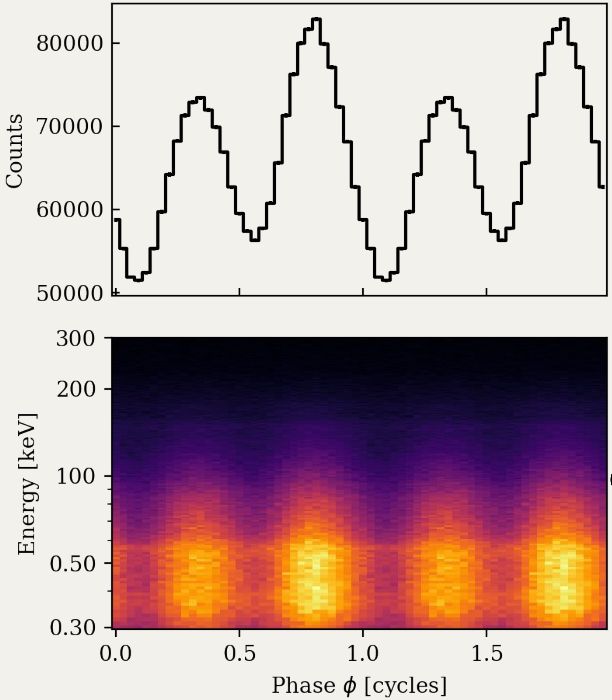


Neutron Star Interior Composition ExploreR (NICER)

Pulse profile modeling (PPM)



Fit model to data



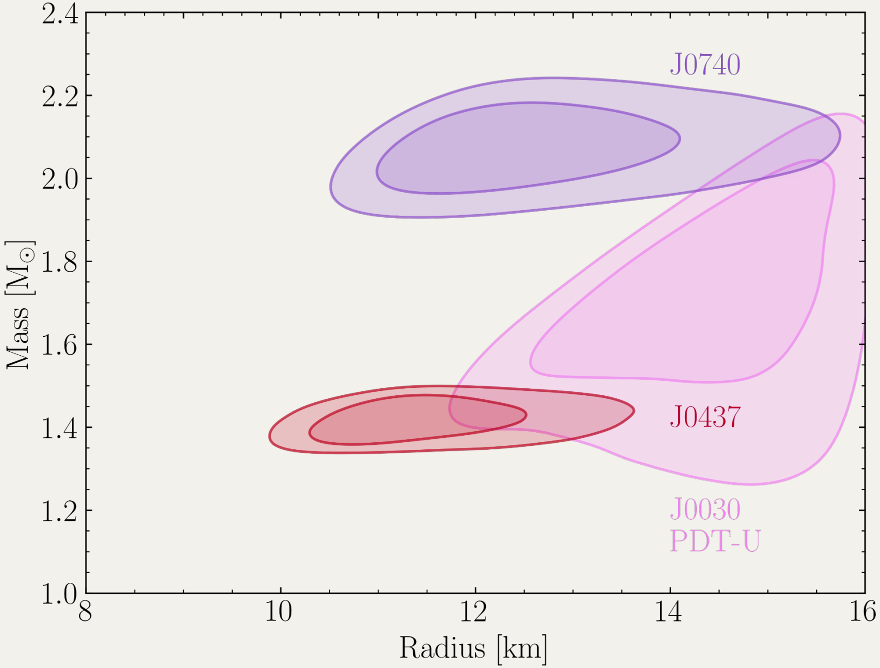
Neutron Star Interior Composition ExploreR (NICER)

Constraints from PPM

- PPM can be performed with X-ray Pulse Simulation and Inference (X-PSI, **Riley et al. 2023**) software on NICER data

- X-PSI has been successfully used on 4 millisecond pulsars (MSPs)
  Riley+2019,2021; Salmi+2022,2023,2024; Vinciguerra+2023; Choudhury+2024

- 2 of them have tight radius constraints thanks to mass and inclination prior



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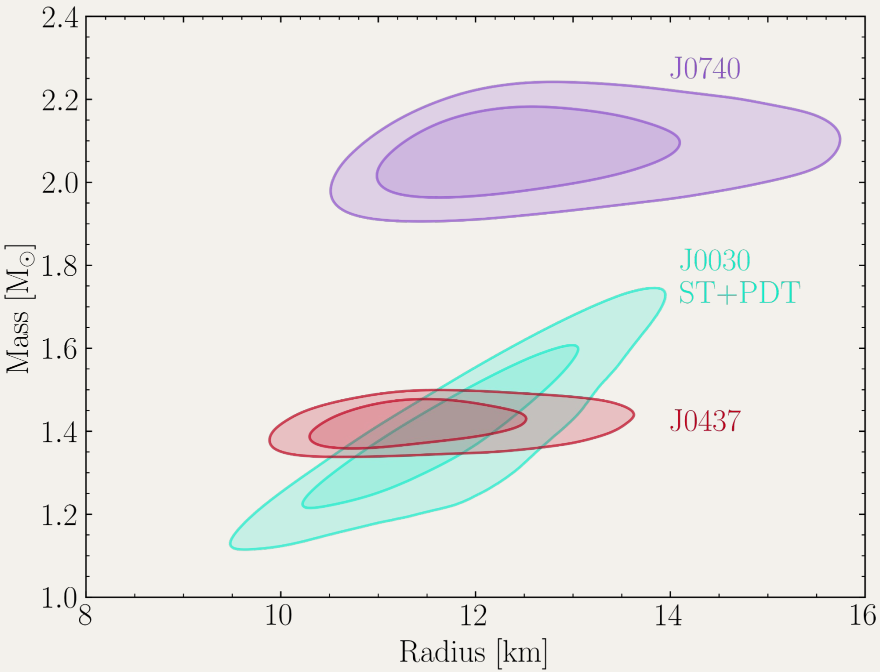

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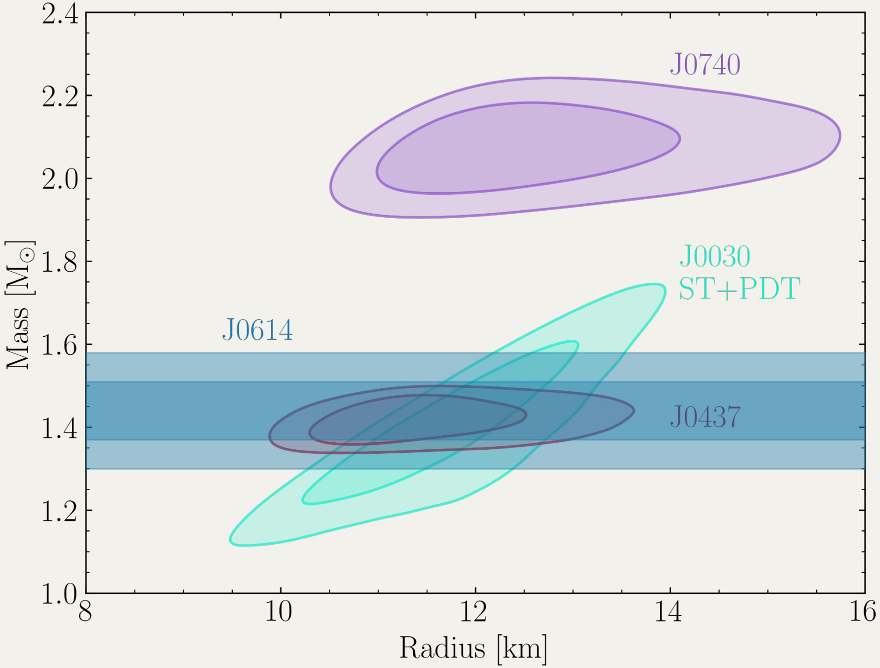
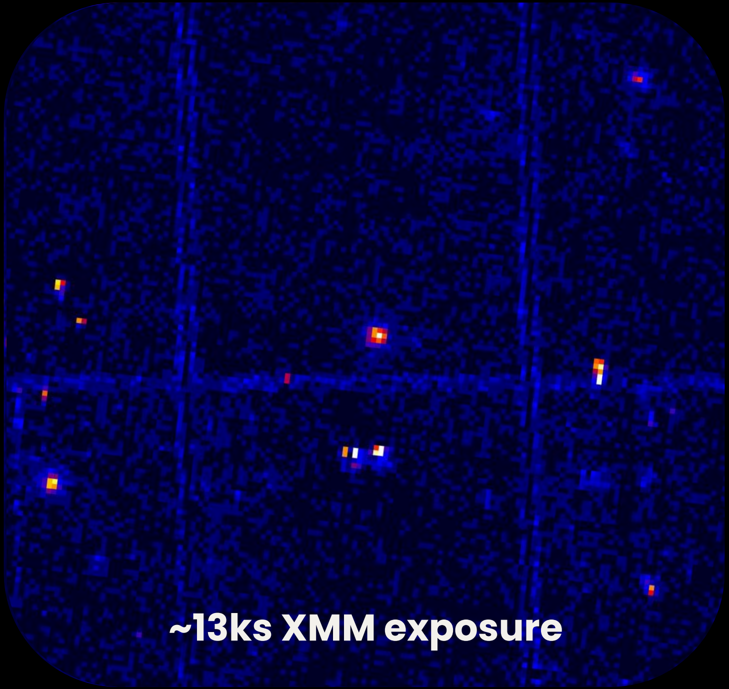
The MSP PSR J0614−3329 has constrained mass and long accumulated NICER exposure



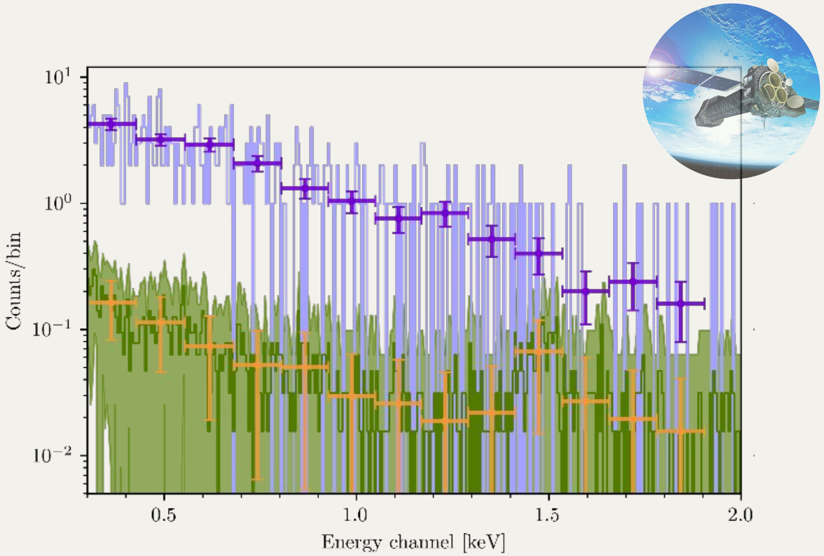
Characteristics of PSR J0614-3329



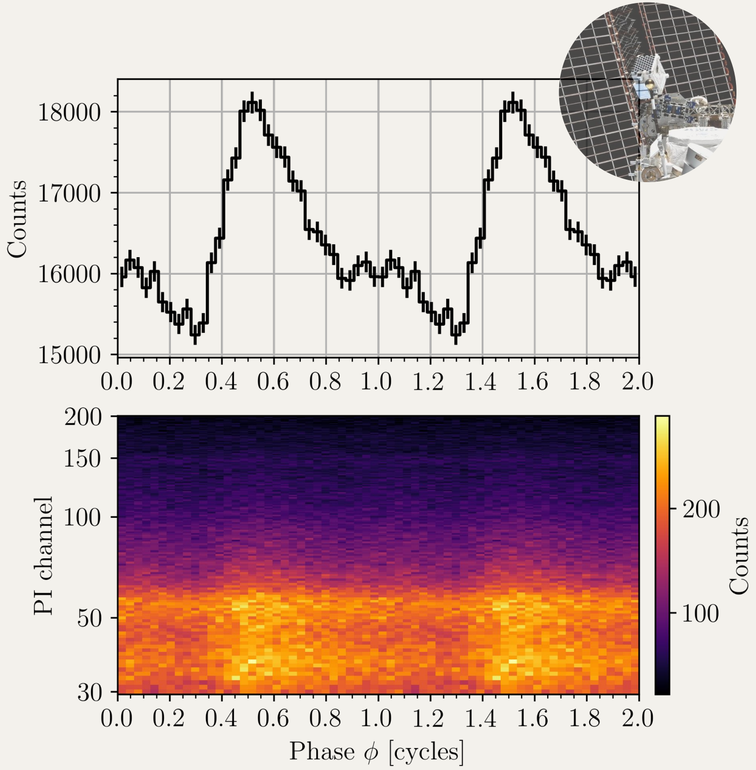
- Millisecond pulsar : P~3ms
- White Dwarf Compagnon with a Hydrogen atmosphere
  - The MSP likely has a similar atmosphere
- Mass and inclination from radio timing:
  - $M = 1.44 \pm 0.07\ M_\odot$
  - $sin(i) = 0.99954 \pm 0.00008$
- Distance ~ 540-630pc
- Observations
  - ~13ks XMM Imaging observations
  - **~1.1 Ms NICER** observations with high timing but no imaging

X-ray data of PSR J0614−2230

The phase-averaged XMM spectra inform the NICER source and background spectra



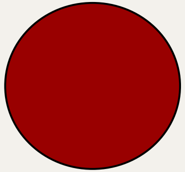
XMM/PN phase-averaged spectrum

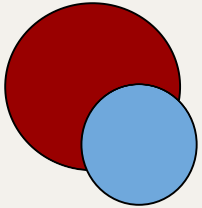


NICER phase-resolved spectrum

Different surface geometries – Best Fits

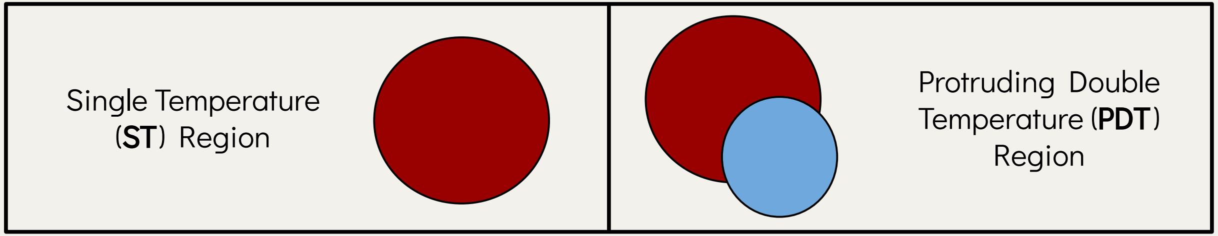
Single Temperature (**ST**) Region





Protruding Double Temperature (**PDT**) Region

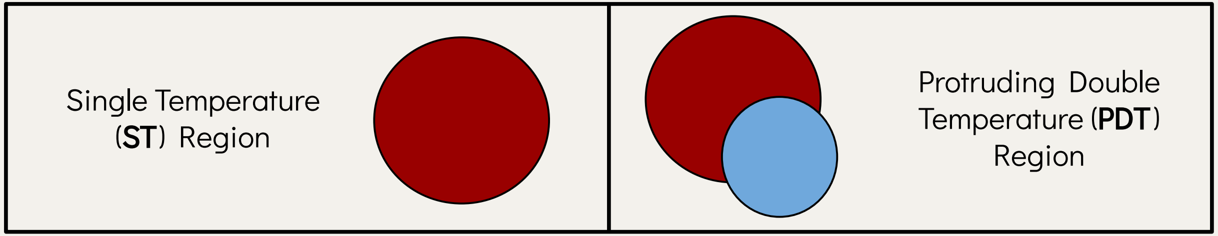
Different surface geometries – Best Fits

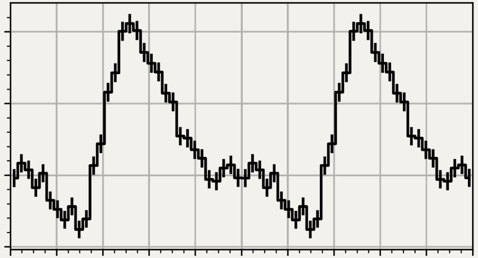


Increased surface geometry complexity →

ST+ST | ST+PDT | PDT+PDT

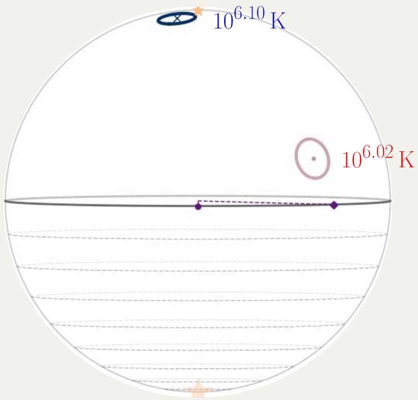
Different surface geometries – Best Fits



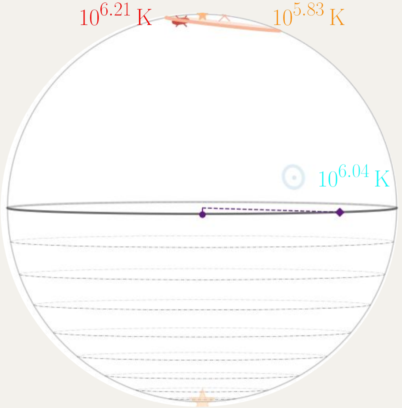


Increased surface geometry complexity

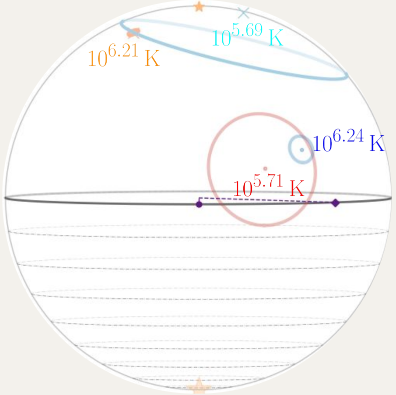
ST+ST



ST+PDT



PDT+PDT



Different surface geometries – Best Fits

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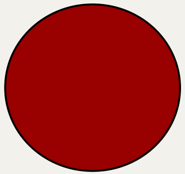
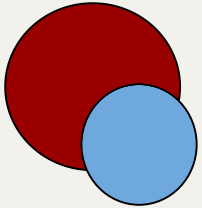
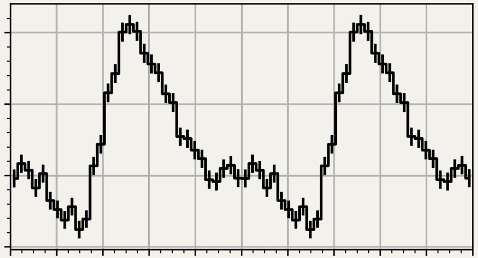


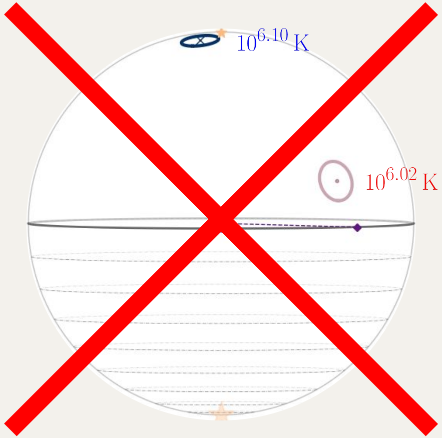


Protruding Double Temperature (**PDT**) Region

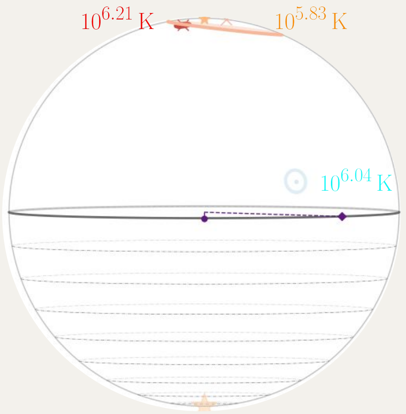


Increased surface geometry complexity

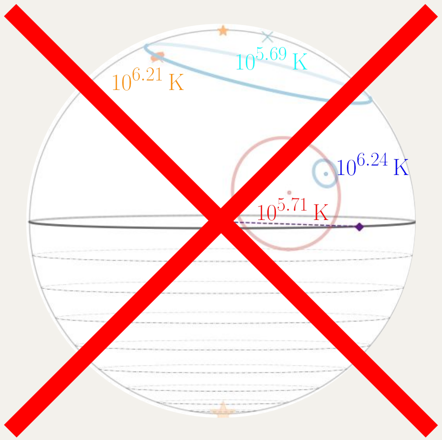
ST+ST



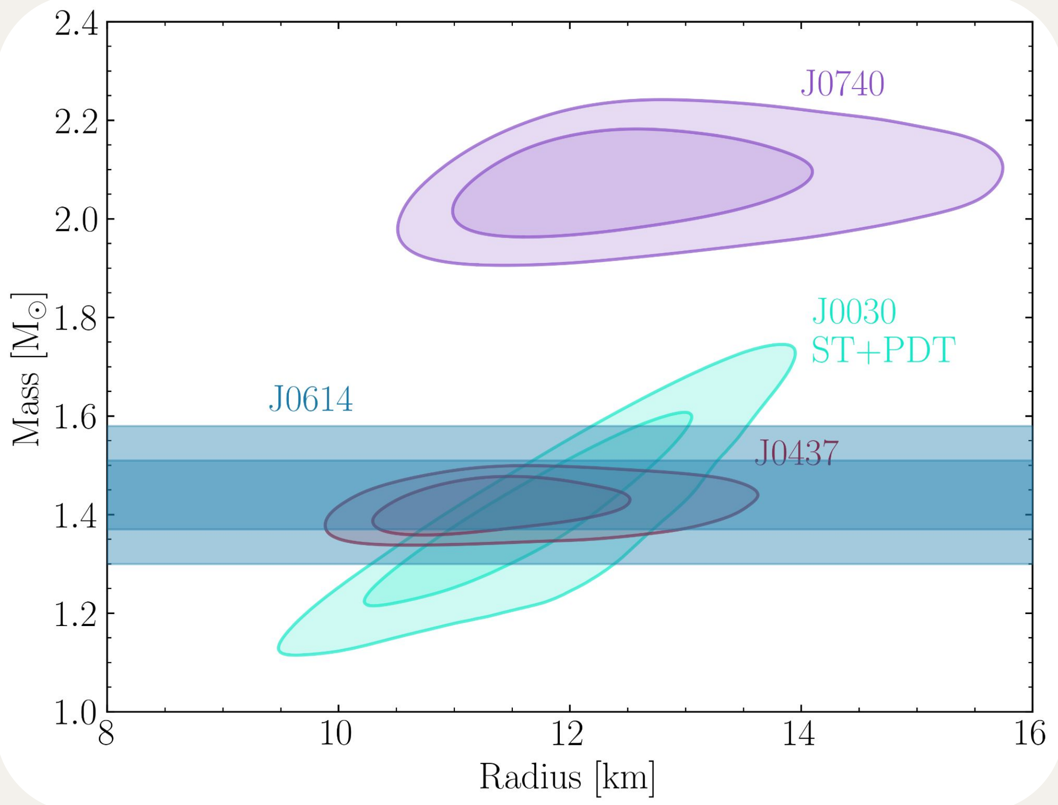
ST+PDT



PDT+PDT



Mass-Radius constraints from PSR J0614−3326



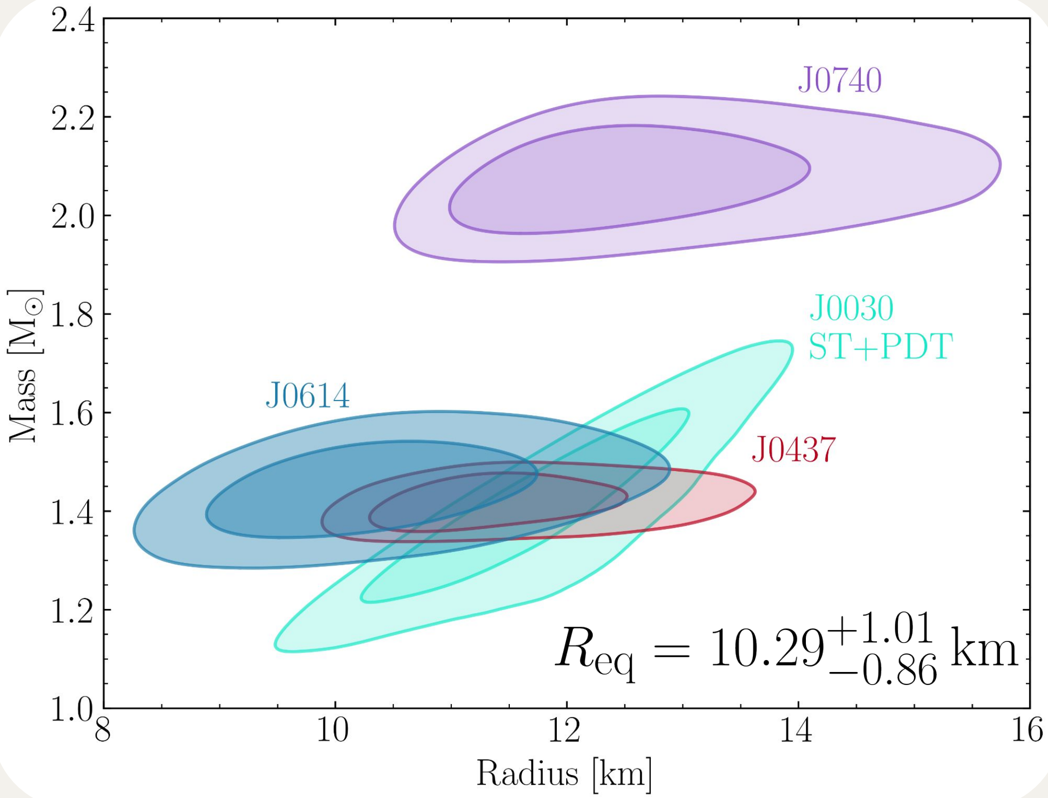
Mass–Radius constraints from PSR J0614–3326

Mass is essentially informed by radio prior

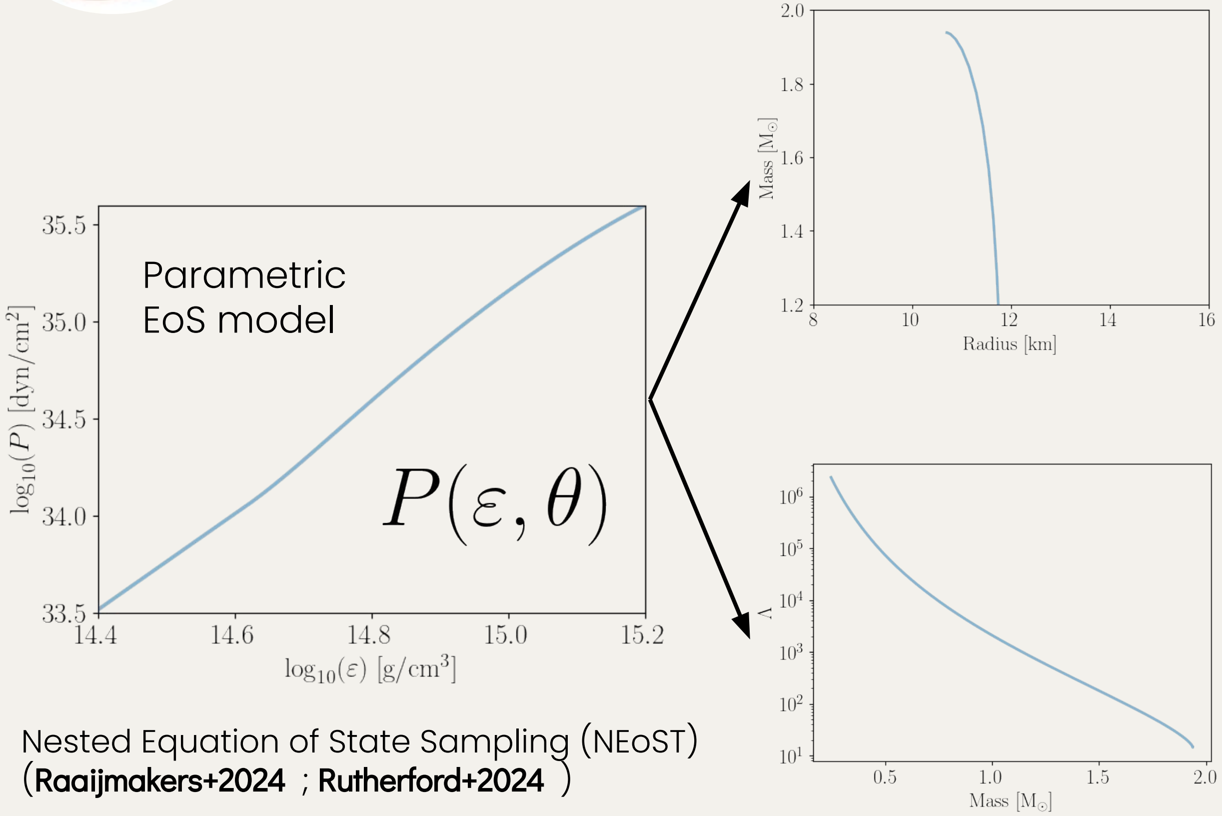
Radius and geometry are:

- consistent across models
- resilient to different assumptions

Mass-radius posterior distributions and contours are already available

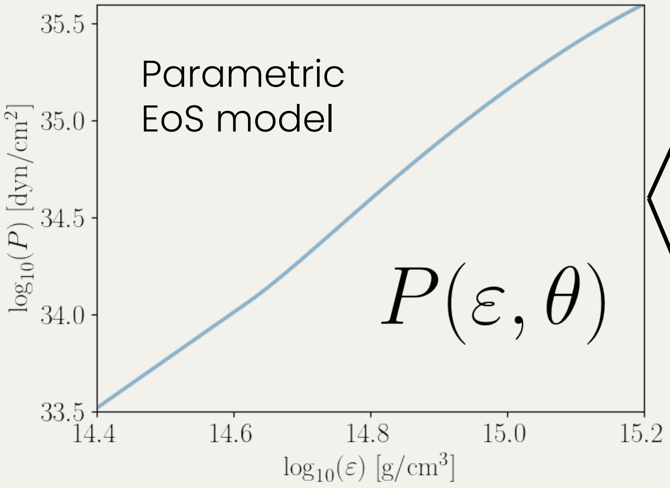


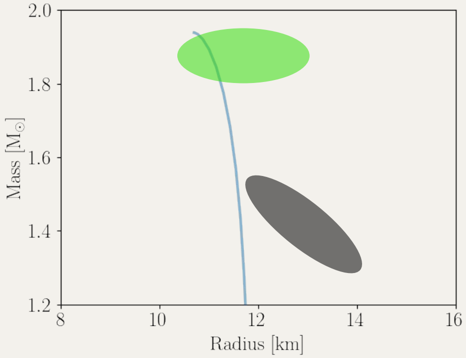
EoS Inference



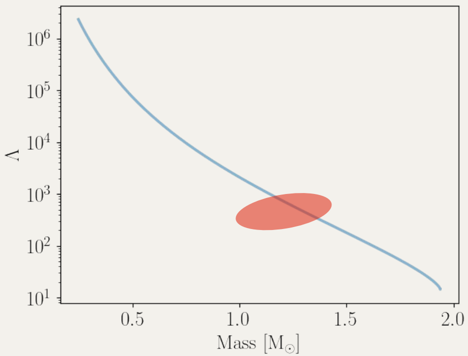
Nested Equation of State Sampling (NEoST)
(**Raaijmakers+2024** ; **Rutherford+2024**)

EoS Inference





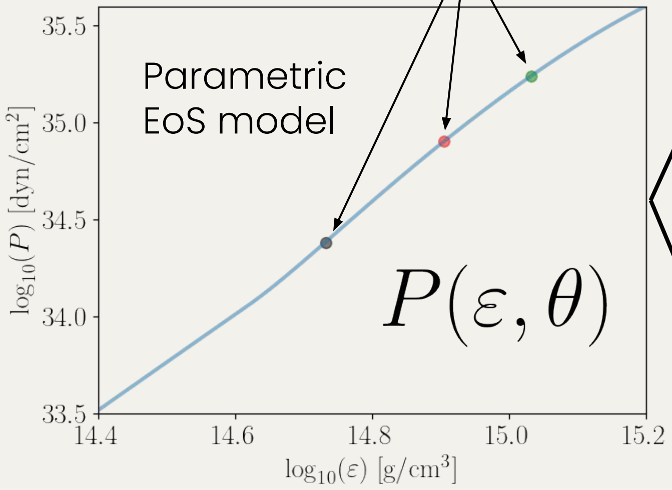
Compare observables to data

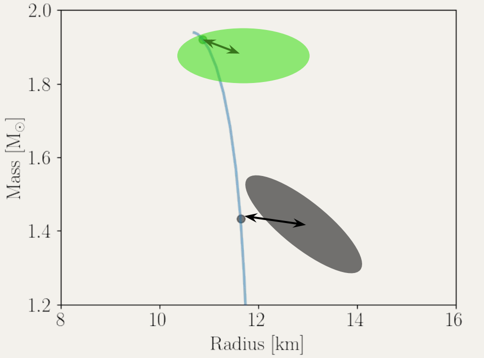


Nested Equation of State Sampling (NEoST)
(**Raaijmakers+2024** ; **Rutherford+2024**)

EoS Inference

One central density parameter per data constraint





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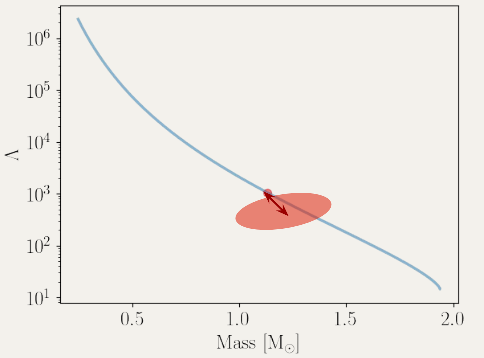

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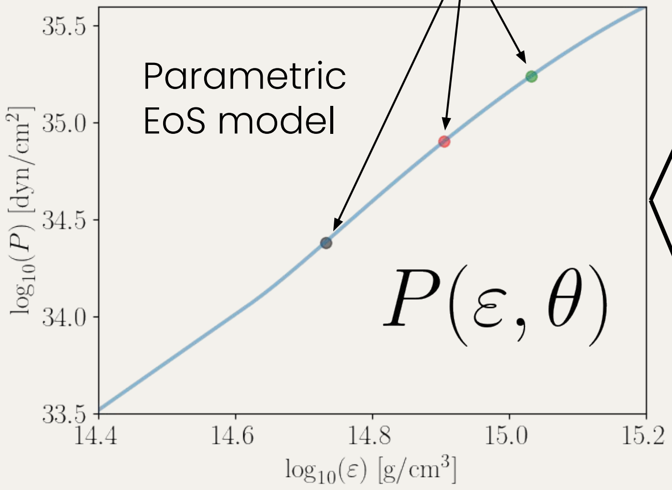

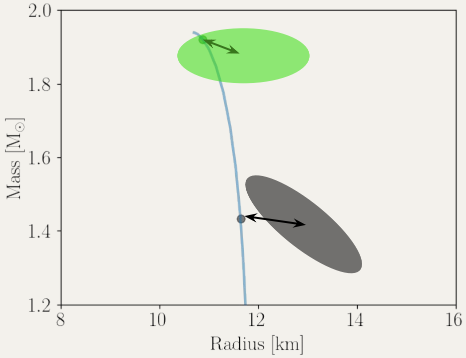

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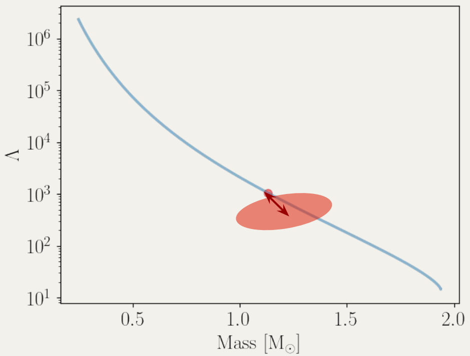


$$\mathcal{L}(\theta|\text{data})$$

Likelihood

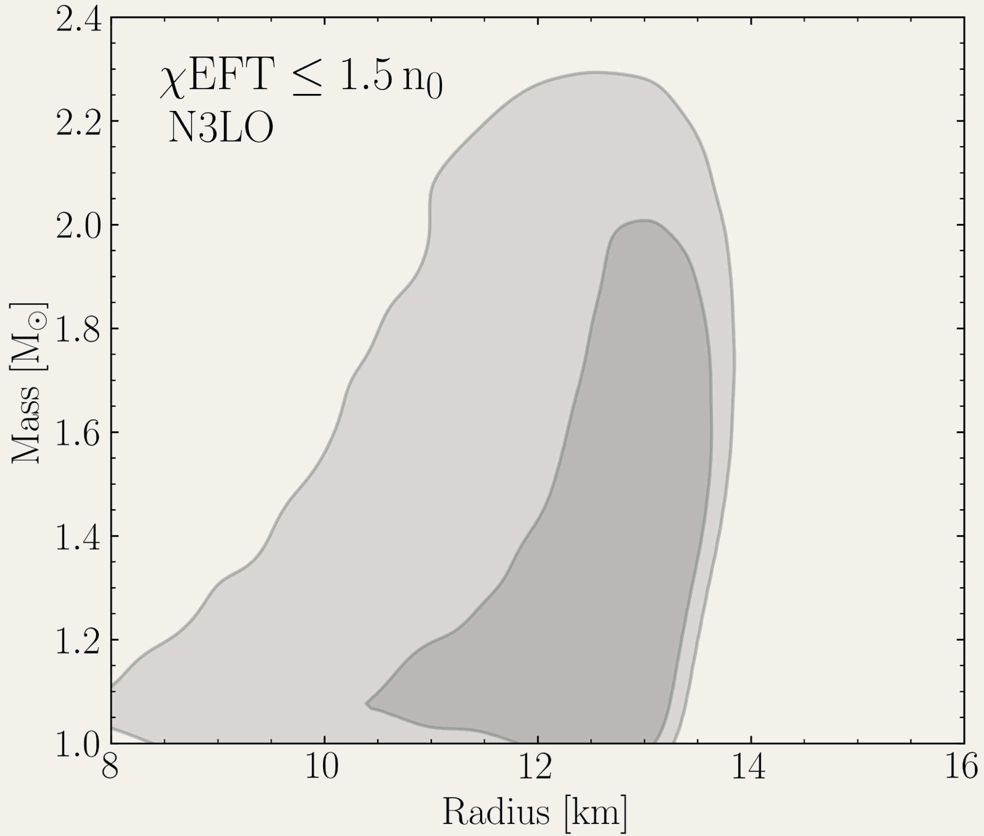
Bayesian inference is used to get the posterior distributions of the parameters and observables

Nested Equation of State Sampling (NEoST)
(**Raaijmakers+2024** ; **Rutherford+2024**)

Implications for dense matter

Piecewise polytrope EoS model constraints from joint fit of PPM and GW measurements

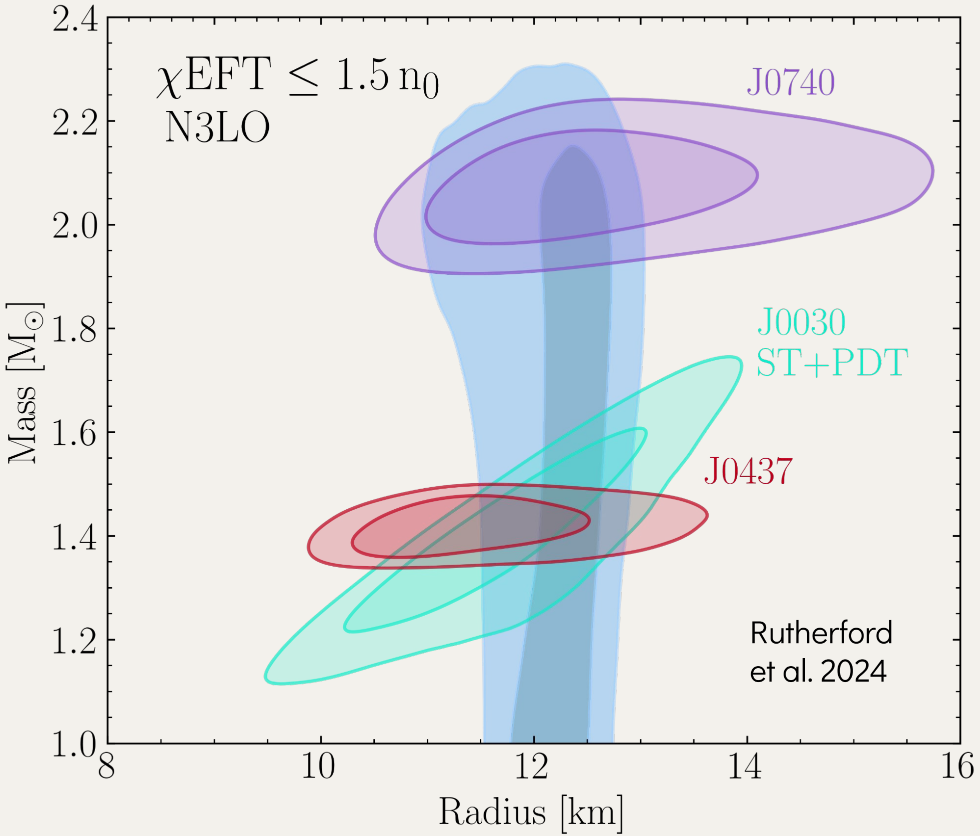
Nuclear physics prior : Causality, Continuity with the crust, …



Implications for dense matter

Piecewise polytrope EoS model constraints from joint fit of PPM and GW measurements

Without J0614



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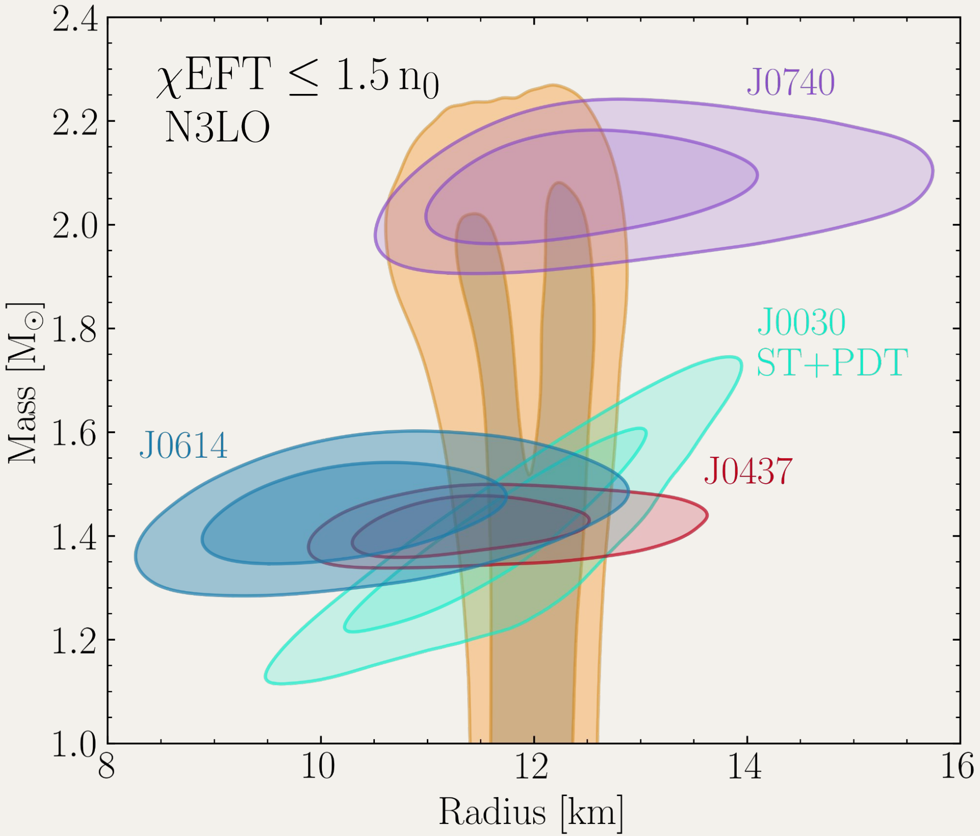
With J0614



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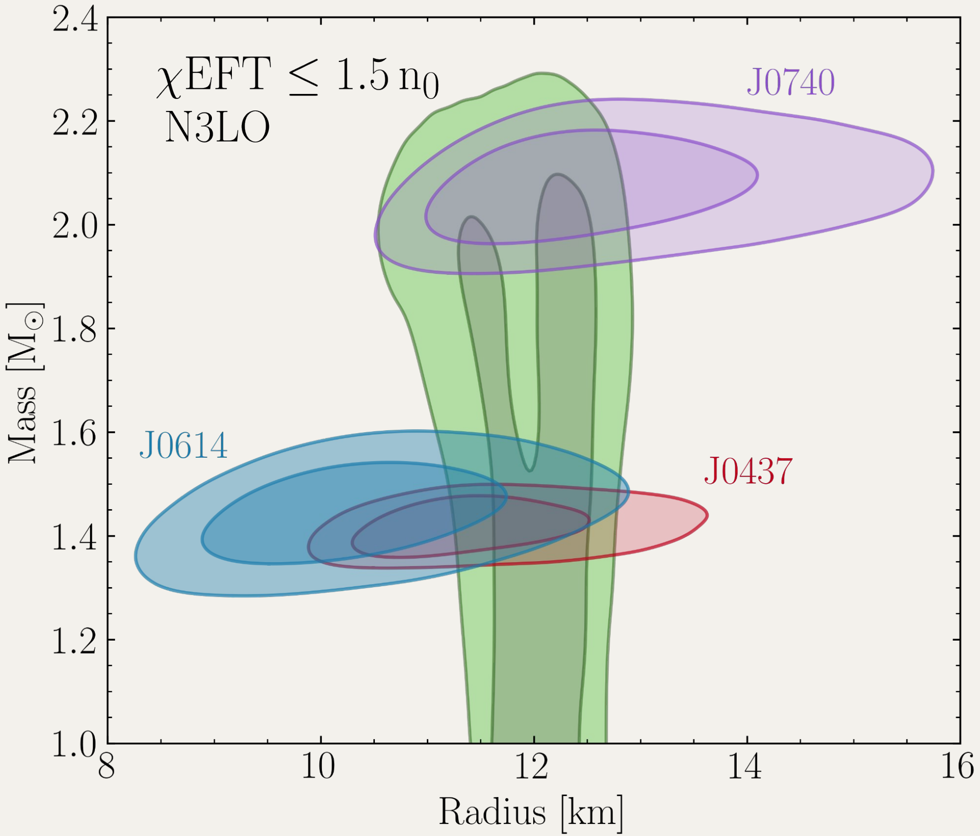

With J0614 and without J0030

Implications for dense matter

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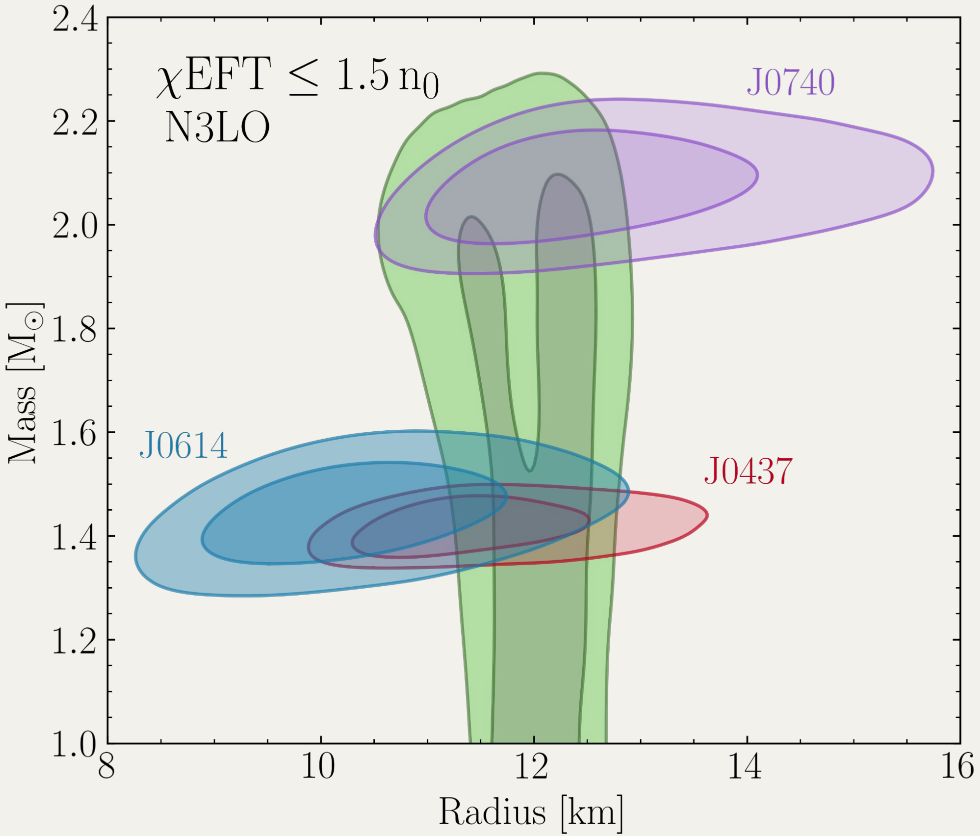


With J0614 and without J0030

Mauviard et al. 2025
arxiv:2506.14883

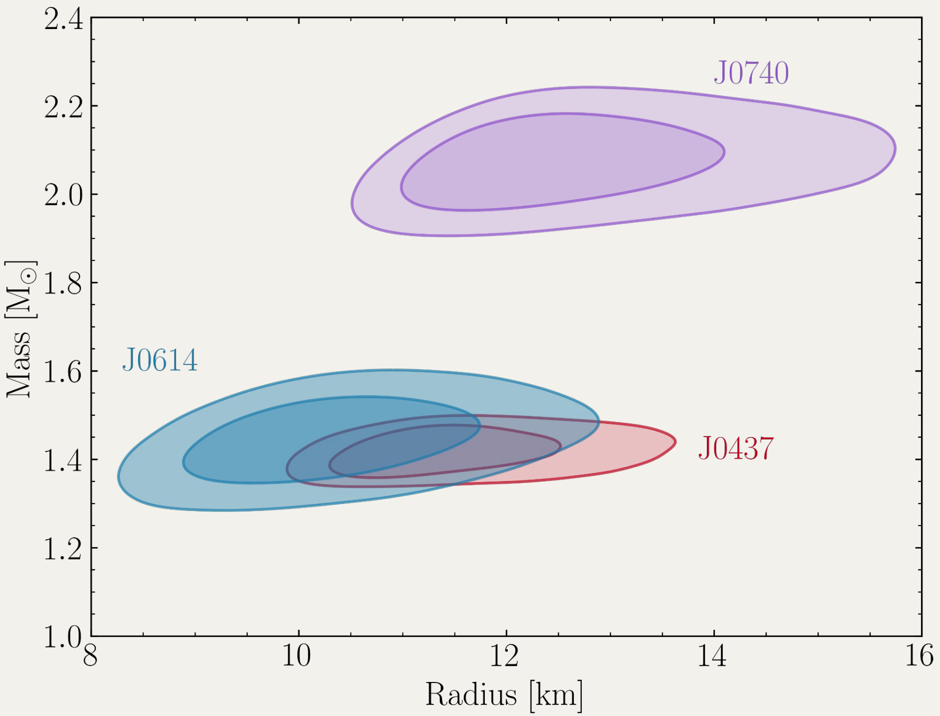
Improving constraints on EoS

Tighter mass from radio timing helps constrain better the radius

NewAthena and eXTP will tighten radius constraint with a fraction of the exposure time of NICER

Adding new sources:

- Mass and inclination prior
- Long NICER exposure
- Exposure with other X-ray telescopes
- Ideally with high mass to confront the PSR J0740+6620 measurement



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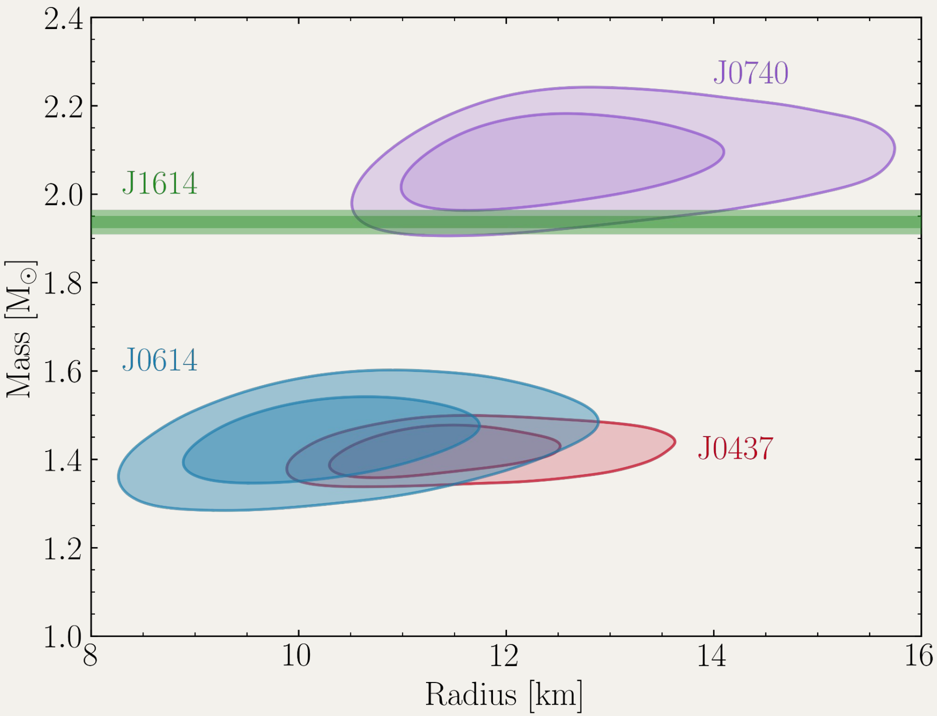
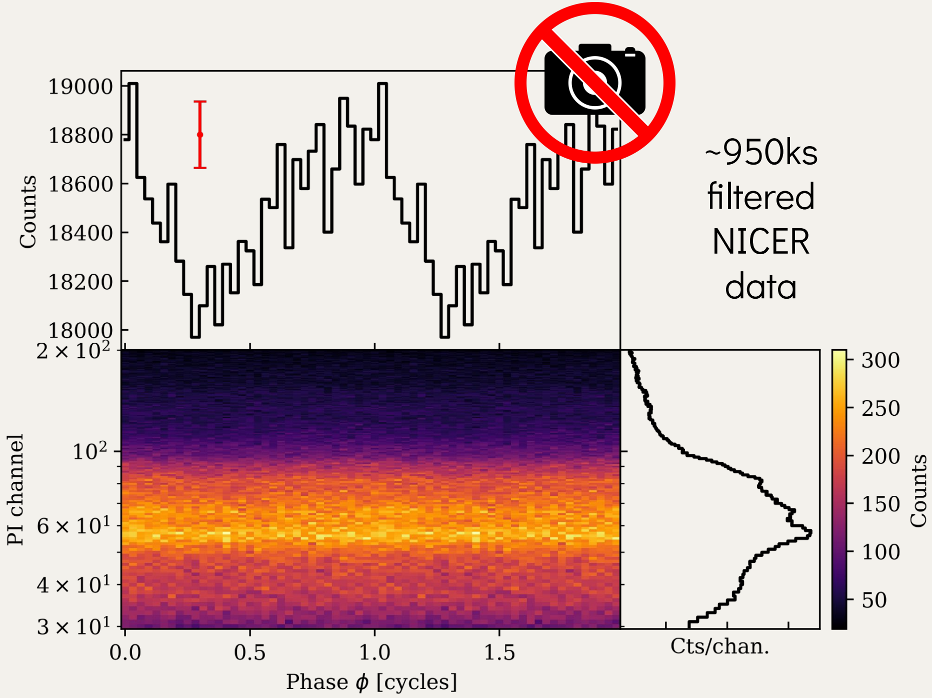
PSR J1614–2230 fits the bill !



Preliminary

Preliminary work on PSR J1614−2230

- Source data has been extracted
  - Noisy pulse profile because the source is faint
- Preliminary analyses have been performed:
  - 1 single ST hotspot fits well the data
  - 2 ST hotspots fit the data slightly better
  - Models more complicated than 2 ST have been tested and bring no improvement



~950ks filtered NICER data

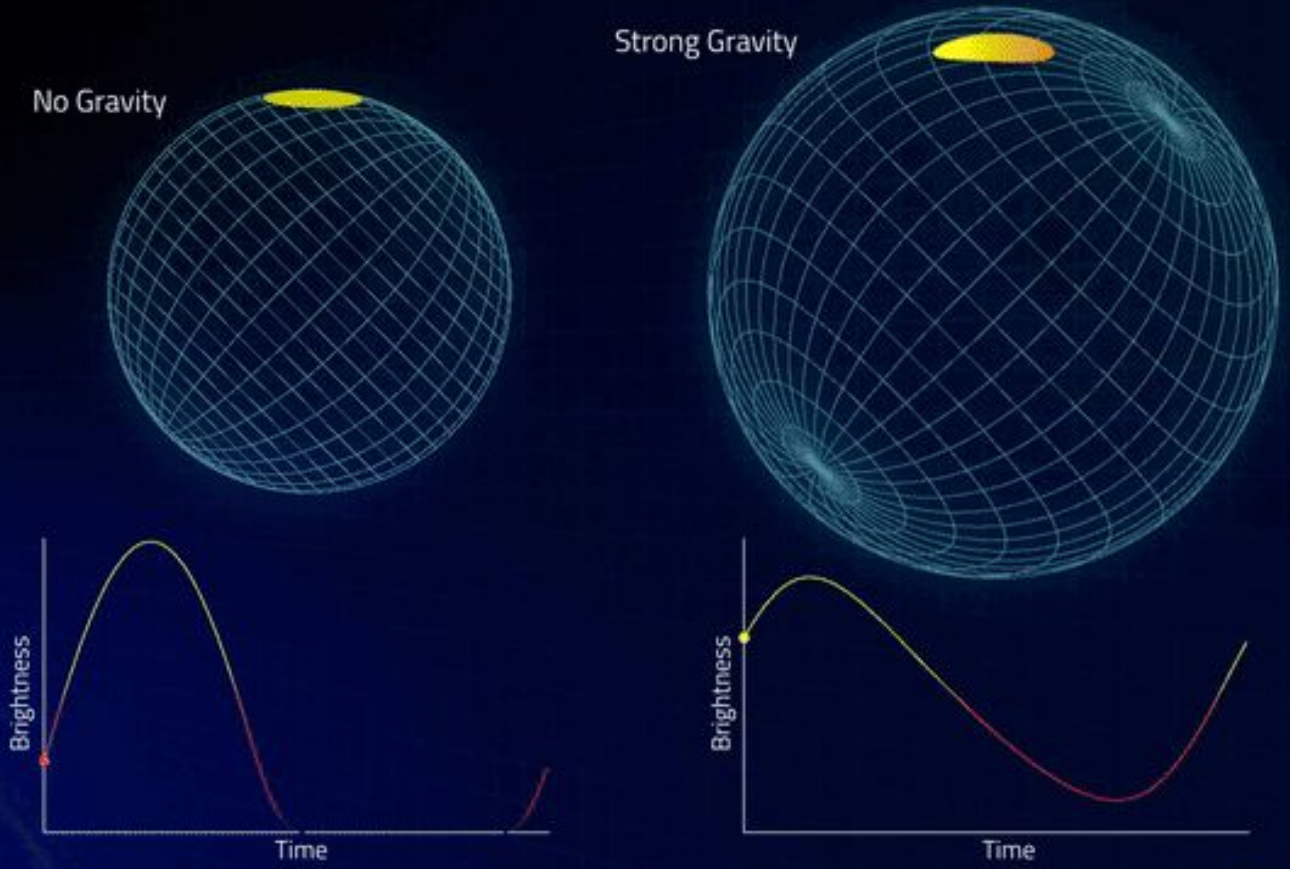
Conclusion

- The analysis of PSR J0614-3329 with PPM results in a radius constraint of $R = 10.3 \pm 1.0$ km with a mass of $M = 1.44 \pm 0.06\ M_{\odot}$
- We retrieve similar radii and non-antipodal hot regions geometries, one at the pole and the other at the equator, over all tested models.
- This new robust measurement is consistent with previous results and allows to further constrain dense matter by pushing it toward softer EoS.
- Better radio mass constraints and observations with NewAthena or eXTP can help narrow down this measurement.
- Analyses of a new MSP is ongoing

Mauviard et al. 2025 - arxiv:2506.14883

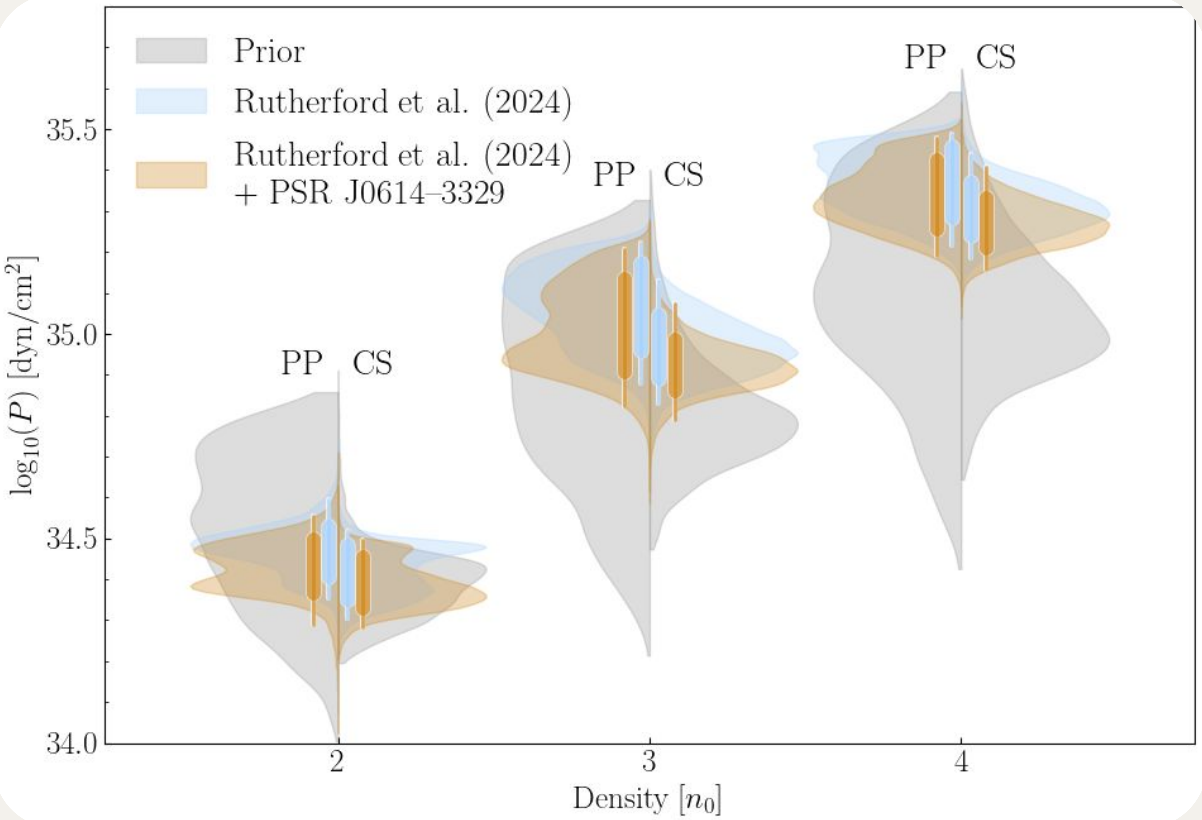
Appendix

Pulse Profile Modeling

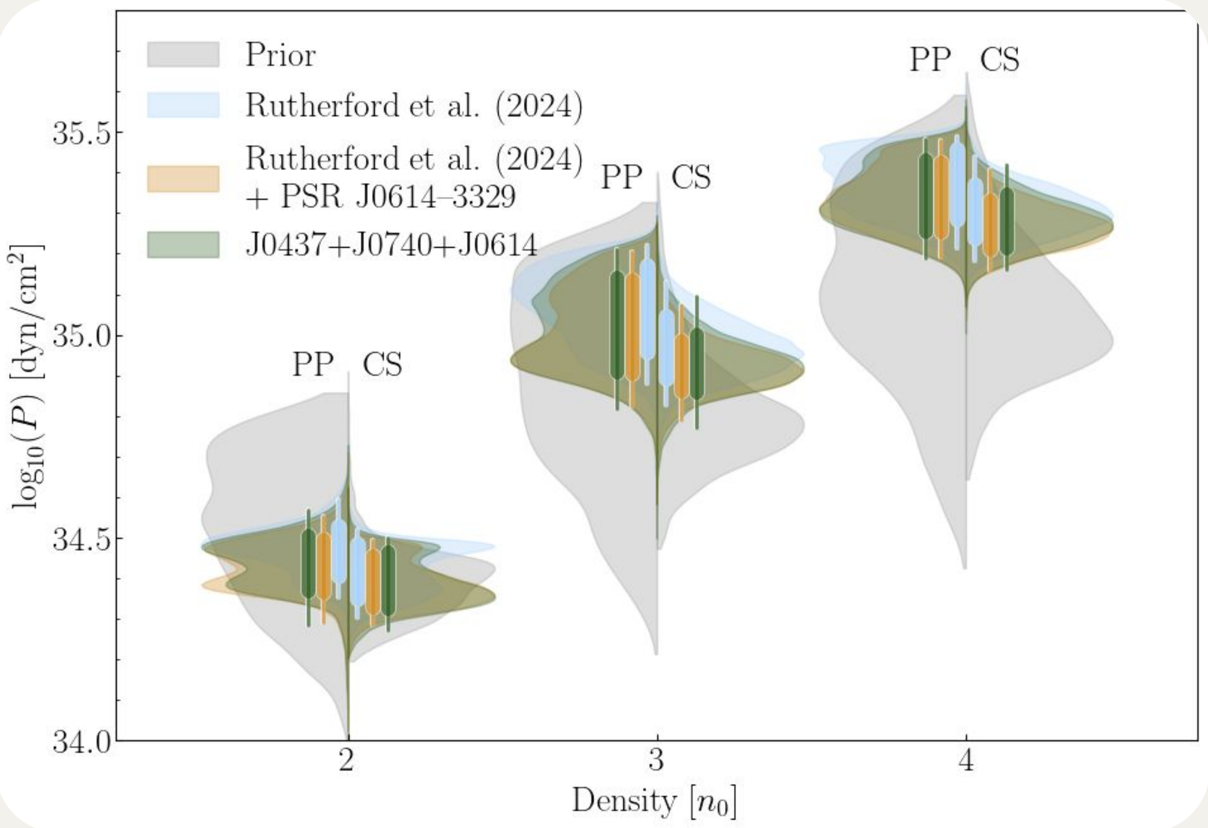


Credit: Sharon Morsink

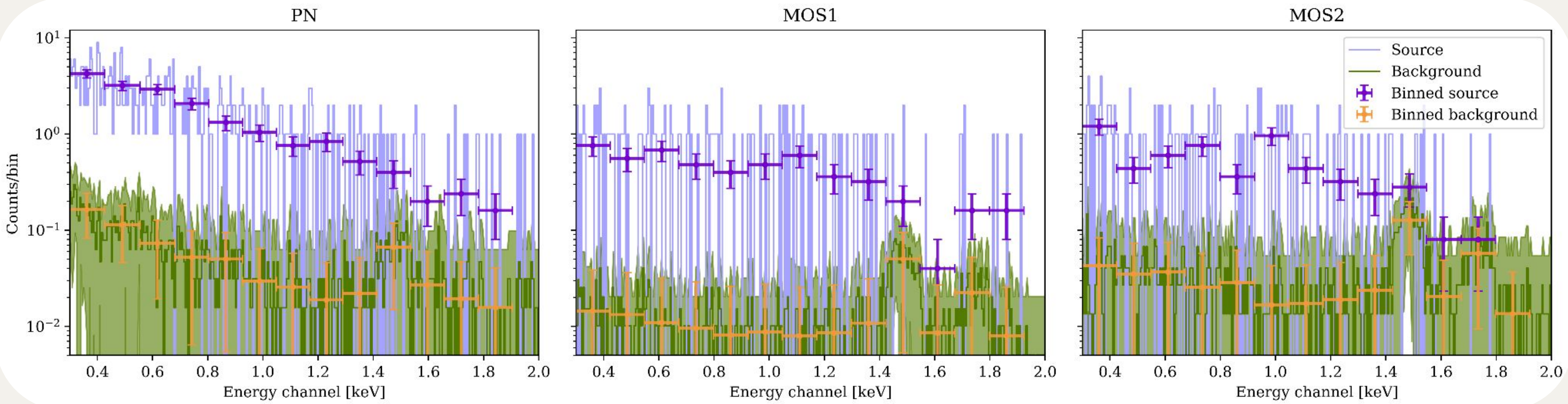
EoS Pressure-Density constraints



EoS Pressure-Density constraints



XMM data of PSR J0614−2230



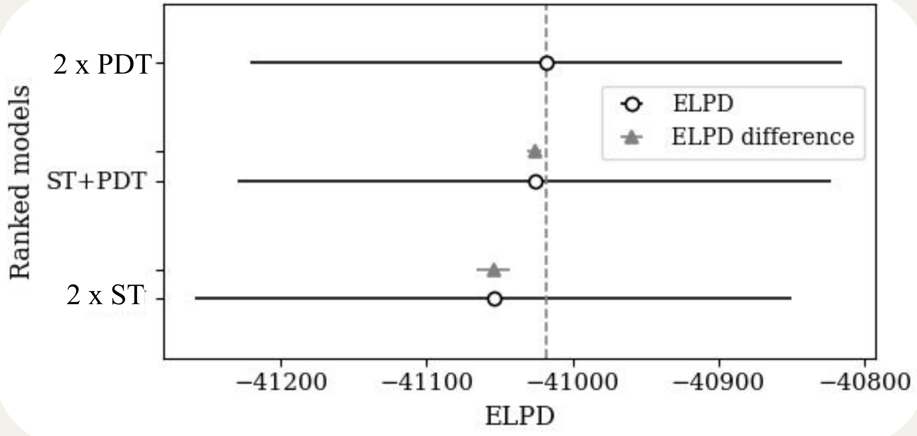
- Source and background spectra are measured and well constrained, which in turn informs the NICER source phase-averaged spectrum
- Background is “fitted” with an uniform prior spanning the green shaded region
- Cross-calibration uncertainty with NICER and within EPIC instruments is taken into account

→ 4 parameters

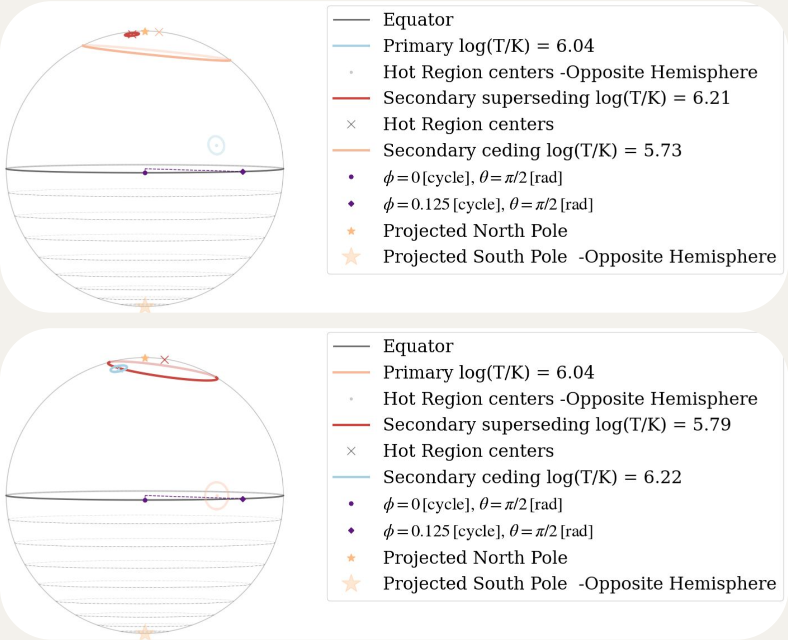
Which model performs the best ?

- Model comparison was undertaken to find the best fitting one, using Evidence and Expected Log Pointwise Predictive Density (ELPD) for comparison
- ST performs significantly worse than the other models
- 2 x PDT performs slightly better than ST+PDT, but not significantly, with a similar radius constraint
- **ST+PDT** being the most simple model, with lower computation time, we picked it as our preferred model

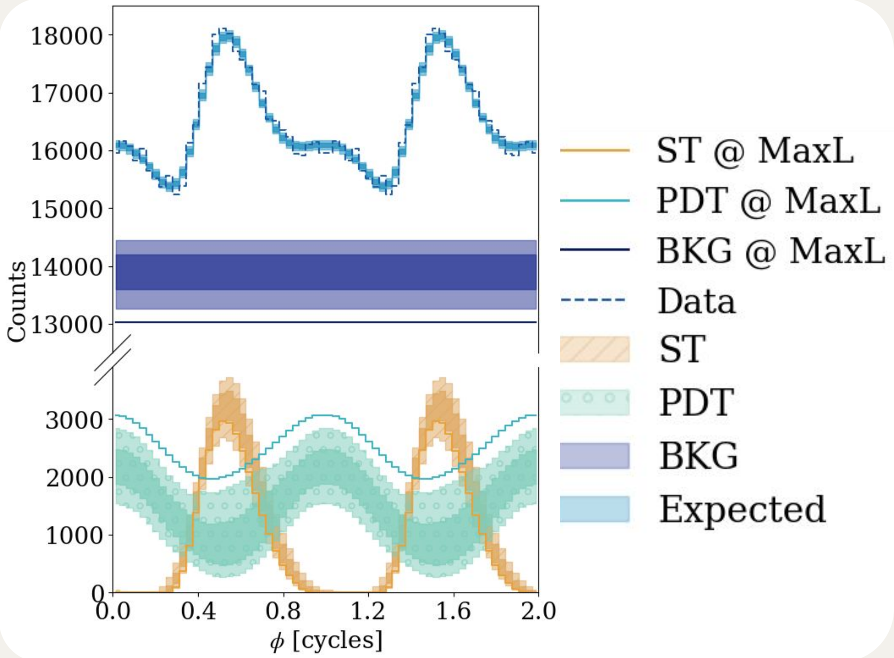
Model	Log-Evidence	Bayes Factor	Parameters
2 x ST	-34597.536	N/A	17
ST+PDT	-34584.879	~313953	21
2 x PDT	-34582.226	~14	25



The best fit geometry for both main modes.



Posterior predictive



High resolution : ST+PDT

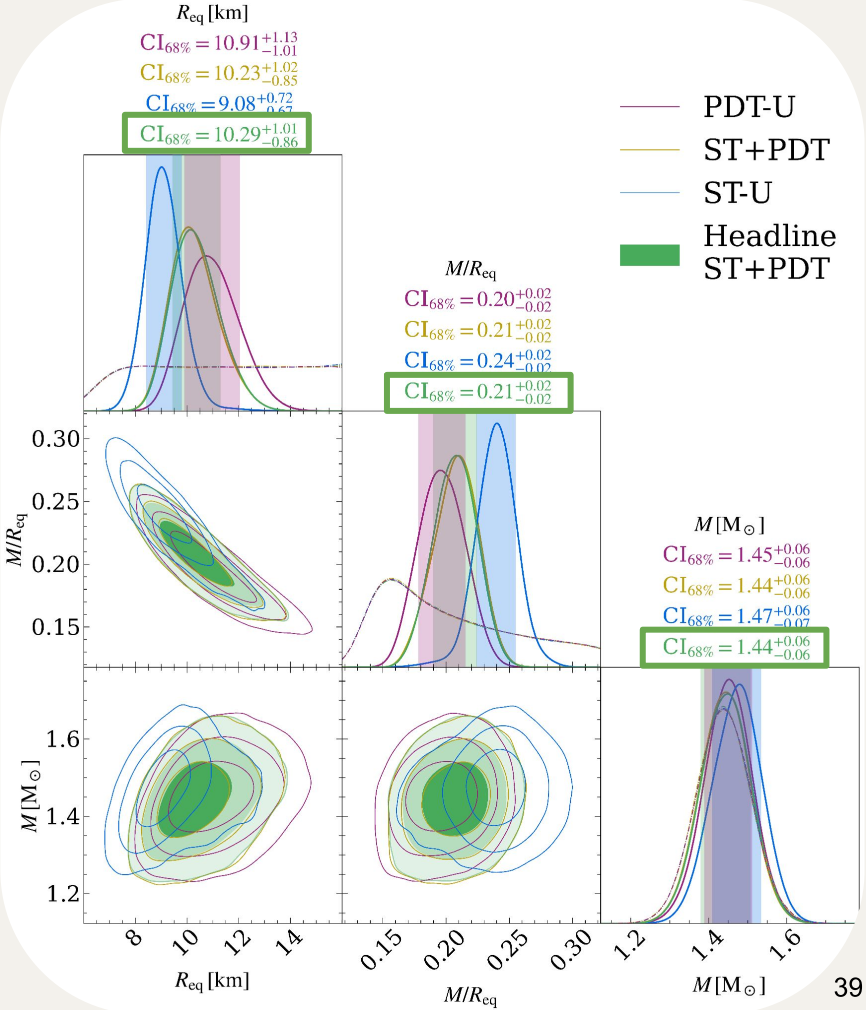
Mass-Radius constraints

Mass is essentially informed by radio prior

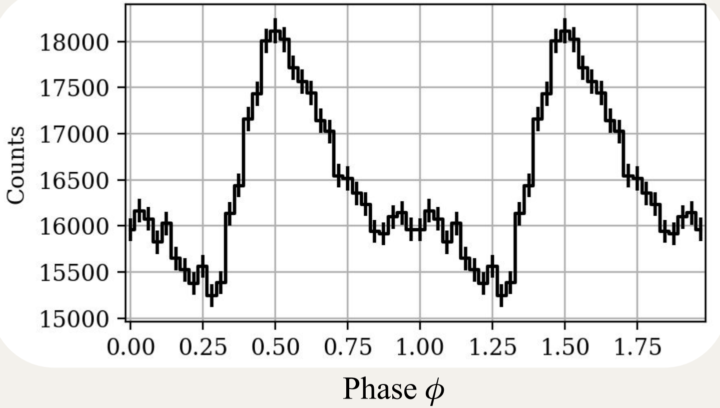
Radius (and geometry) is consistent across models

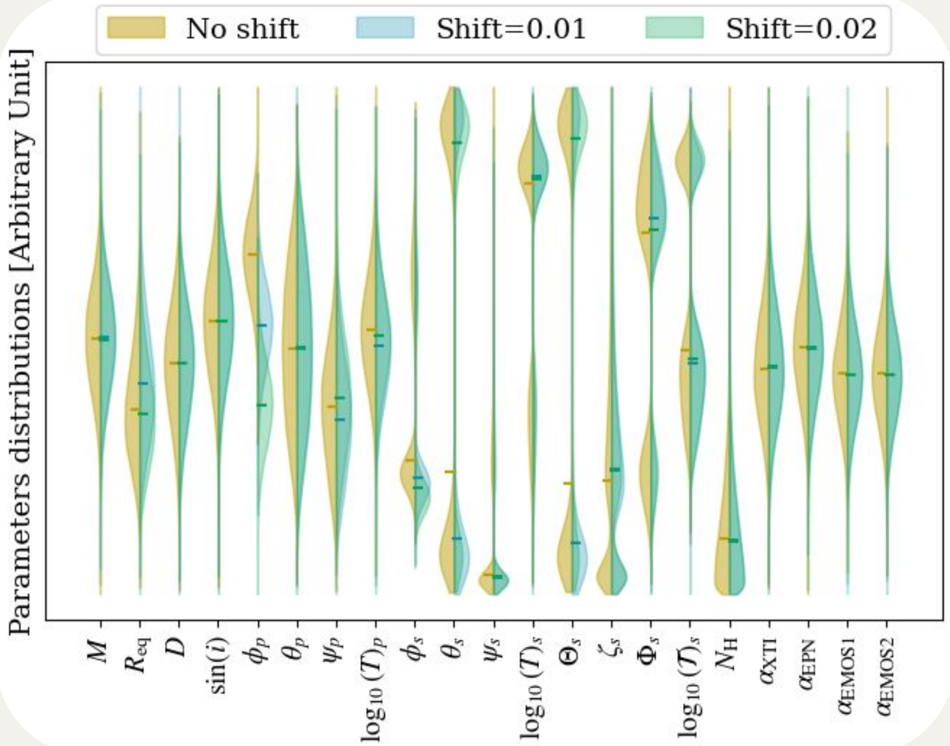
High resolution run constraints matches low resolution one

Radius (and geometry) a resilient to different assumptions



Are ST+PDT analyses resilient to noise ?





- Precision on photon timing ~1μs
- Phase bin size : 1/32 x P ~ 100μs

- Fit data with photons shifted by 0.01 and 0.02 rotational phases (~30μs and ~60μs)

⇒ Same posterior distribution

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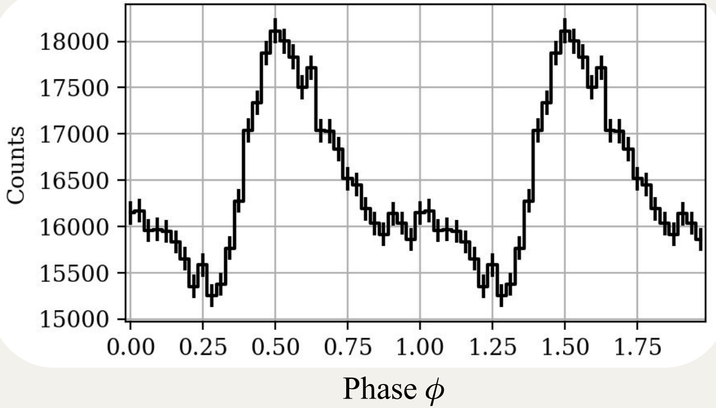

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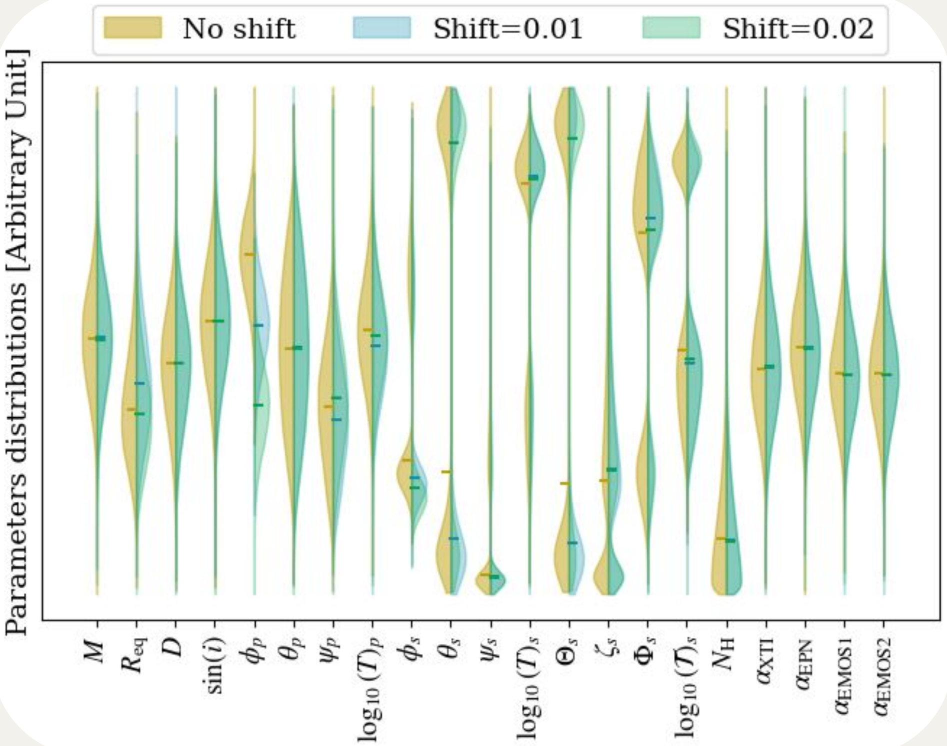
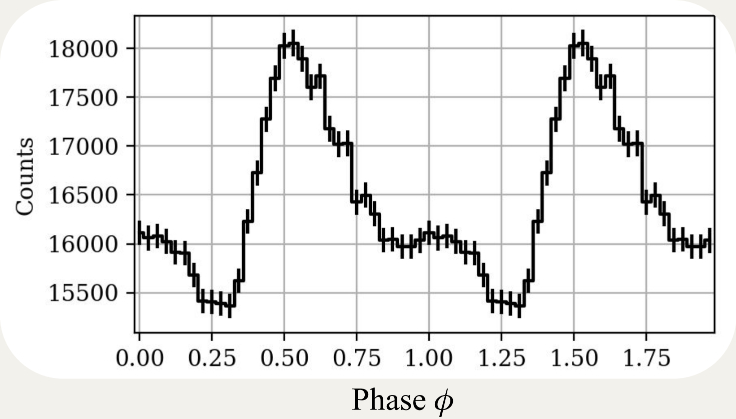
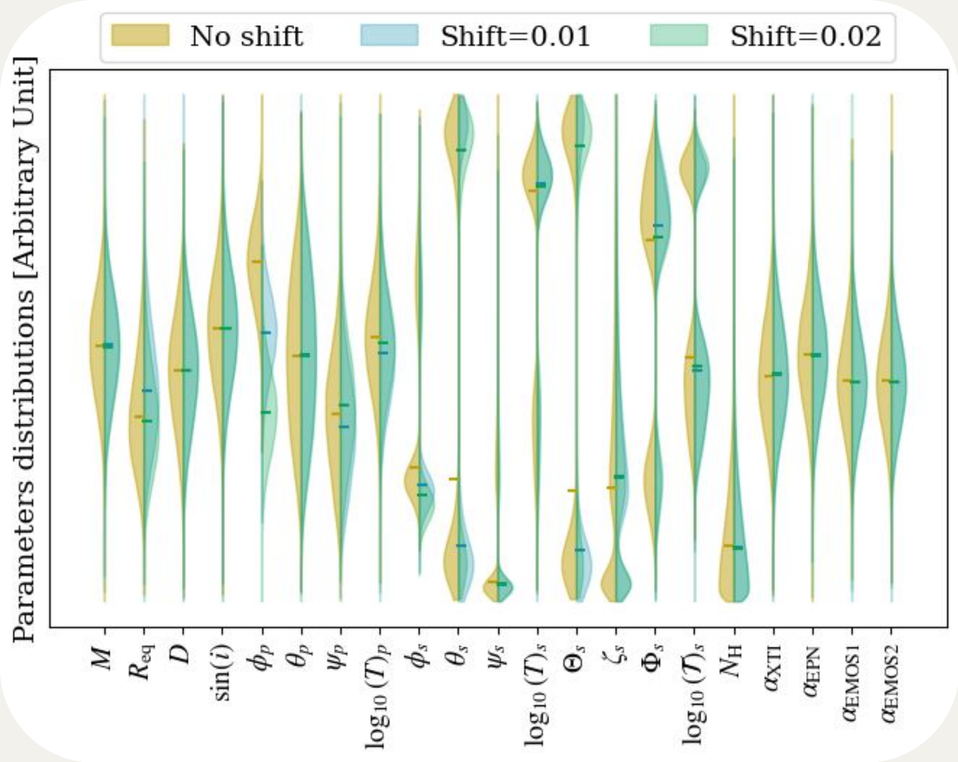


Are ST+PDT analyses resilient to noise ?





- Precision on photon timing ~1μs
- Phase bin size : 1/32 x P ~ 100μs

- Fit data with photons shifted by 0.01 and 0.02 rotational phases (~30μs and ~60μs)

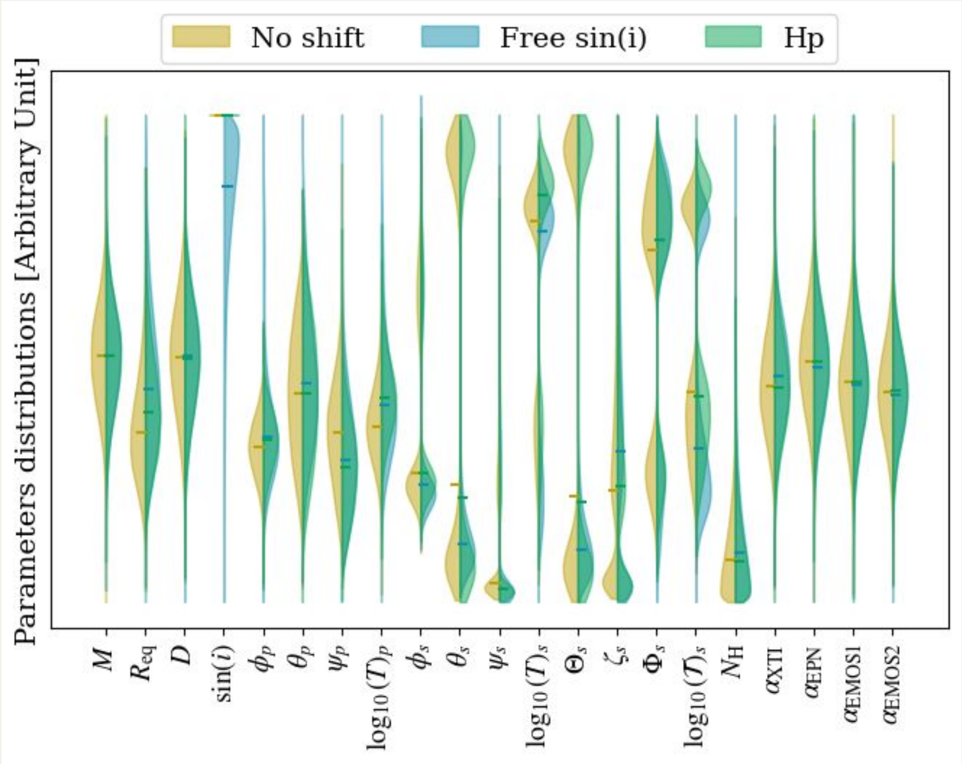
⇒ Same posterior distribution

Relaxing different assumptions with ST+PDT

We did test run relaxing the 2 main assumptions that were made during analysis:

- Alignment of the MSP spin axis with its orbital momentum
  - We let the inclination unconstrained a priori
- Atmosphere made of fully ionized Hydrogen
  - We tested a partially ionized atmosphere model

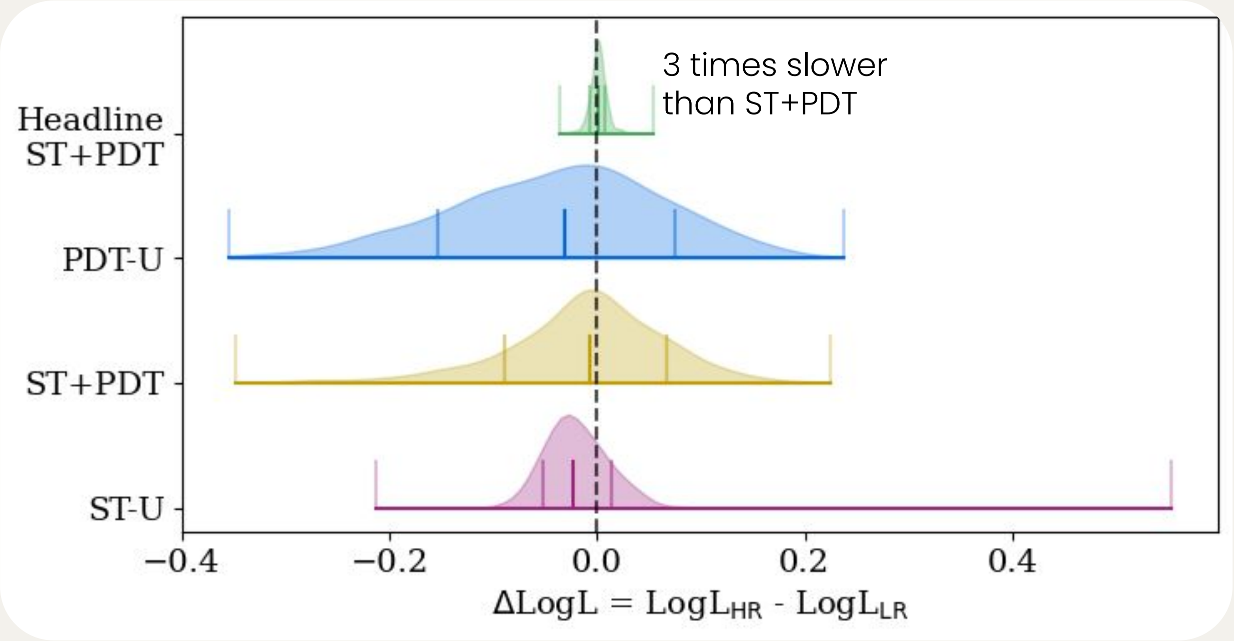
Results proved very similar with the reference ST+PDT run



Test of resolution settings

Extensive tests of the simulation parameters

Goal : Fast and accurate likelihood computation

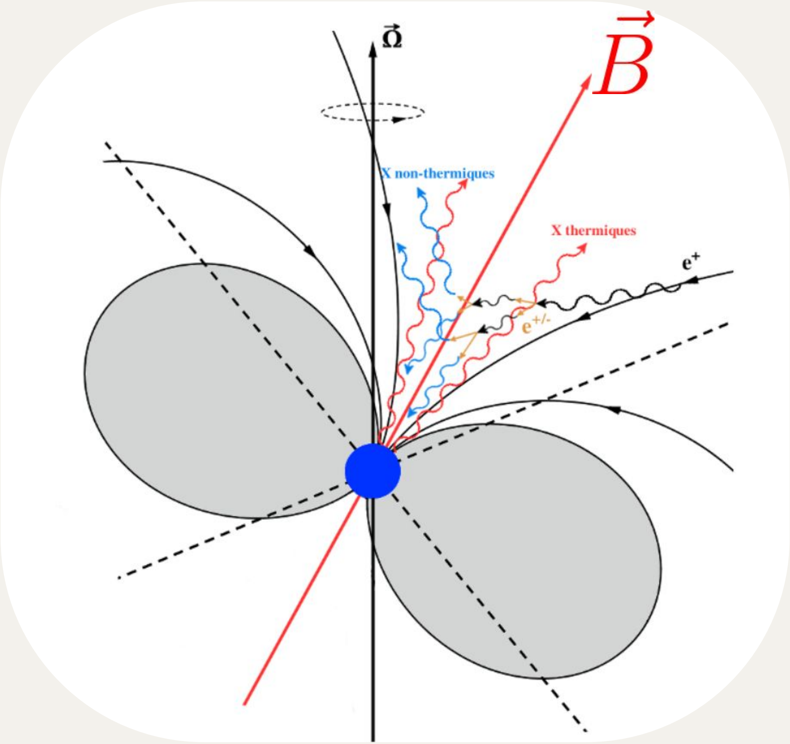


Emission mechanisms

- Non-thermal magnetospheric emissions
  - Radiative processes : SR, CR, ICS
  - *Radio, hard X-rays, ɣ-rays*

- Surface thermal emissions
  - Particle shower heats the atmosphere at ~10^6K
    ⇒ Hotspot on the surface
  - *Soft X-rays*

Simplified representation of a MSP with its magnetosphere and different emission mechanisms.
Adapted from *Benoît Pancrazi* PhD thesis.



X-ray Pulse Simulation and Inference : X-PSI

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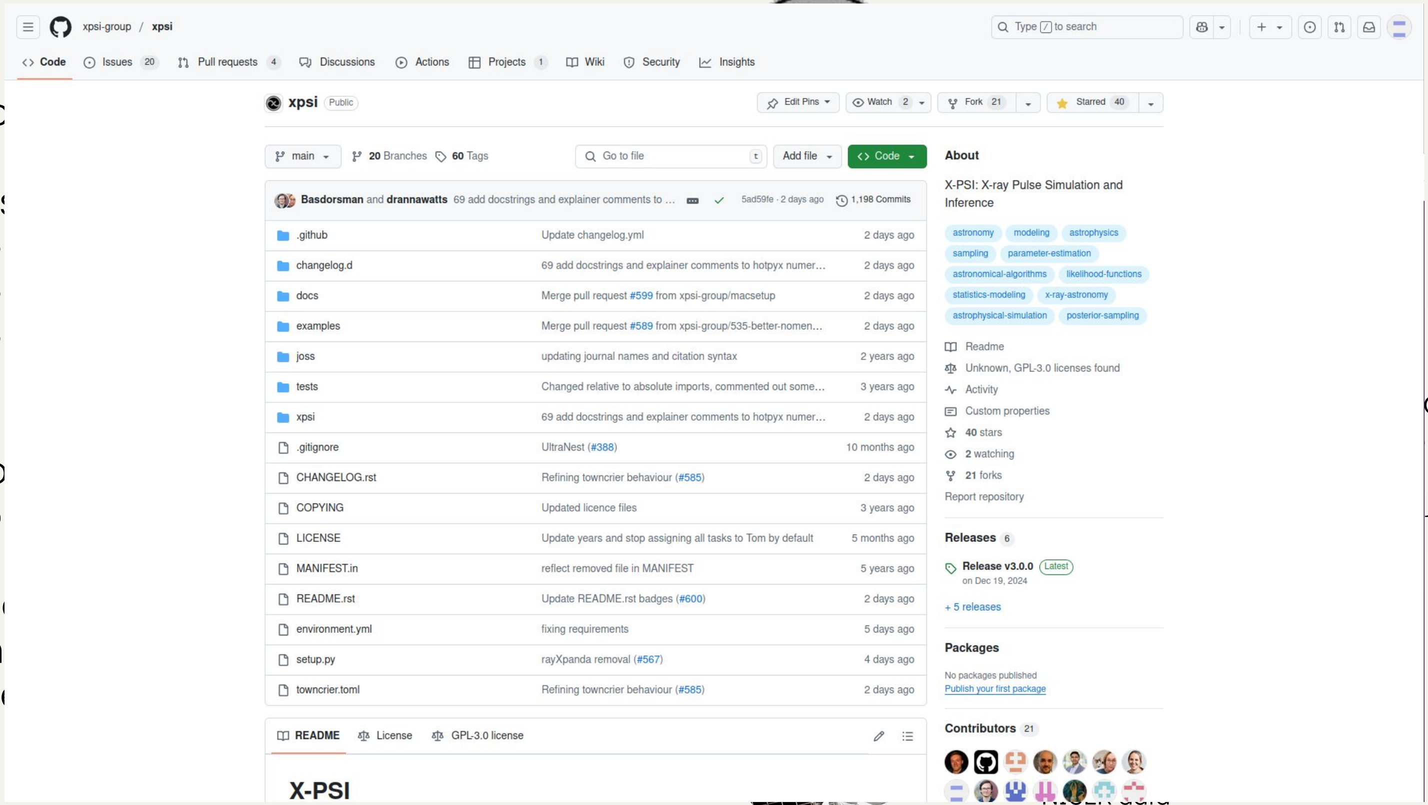

or distribution
parameters

$$p(\ \theta \mid \mathrm{data}\ )$$

Mass and
radius
included

Neutron Star Interior Composition ExploreR (NICER)

Instrument	Timing Resolution	Effective Area	Imaging
XMM PN	Imaging : 0.03 ms	~1200cm² @ 1.5 keV	Yes
	Timing : 30 μs		No
NICER	<300ns	~1900cm² @ 1.5 keV	No