Future dense matter constraints from millisecond pulsars with NewAthena

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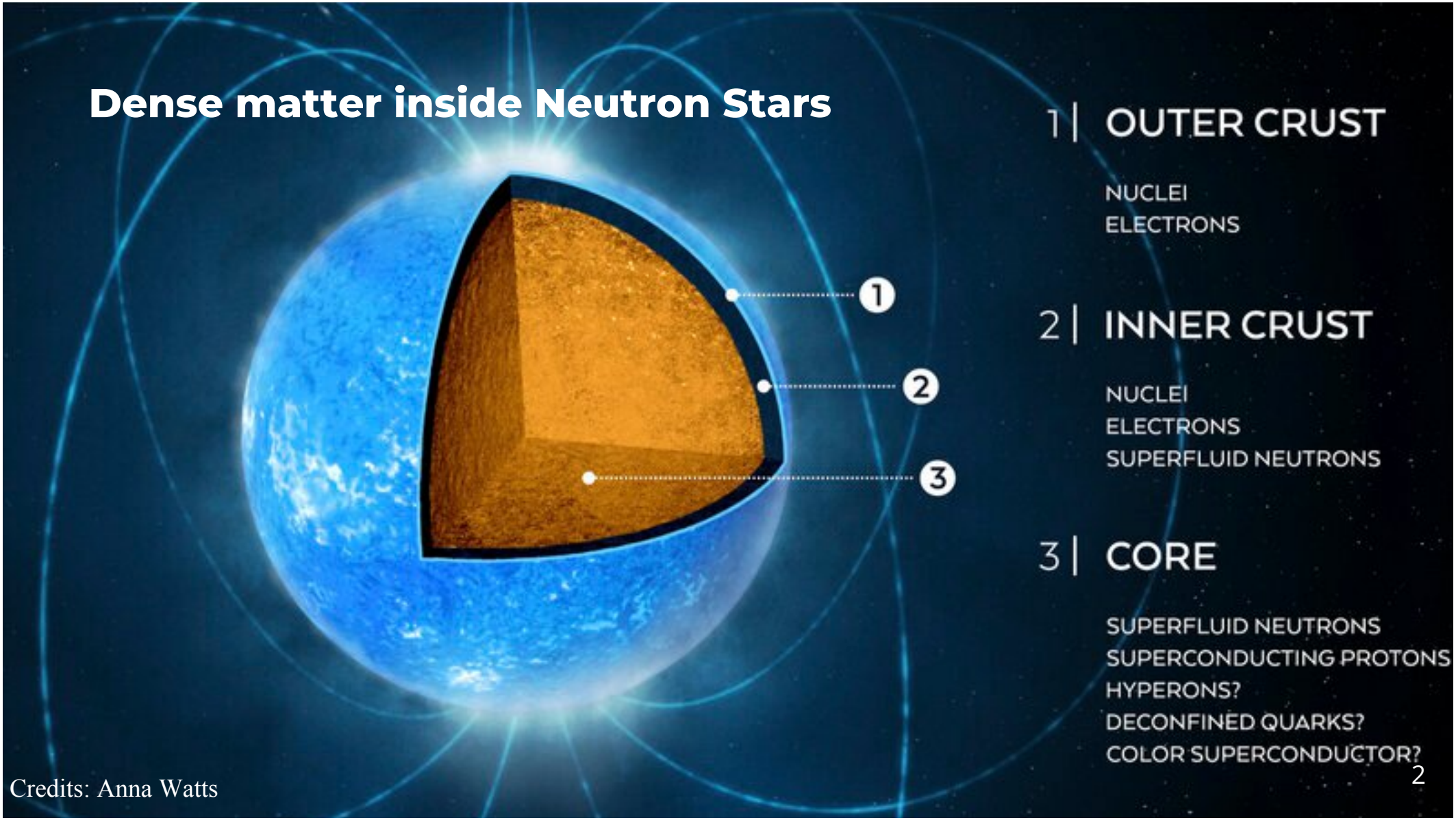
NewAathena Rising: SWG4

Currently looking for a PostDoc in Europe, starting early 2027

Dense matter inside Neutron Stars



Credits: Anna Watts

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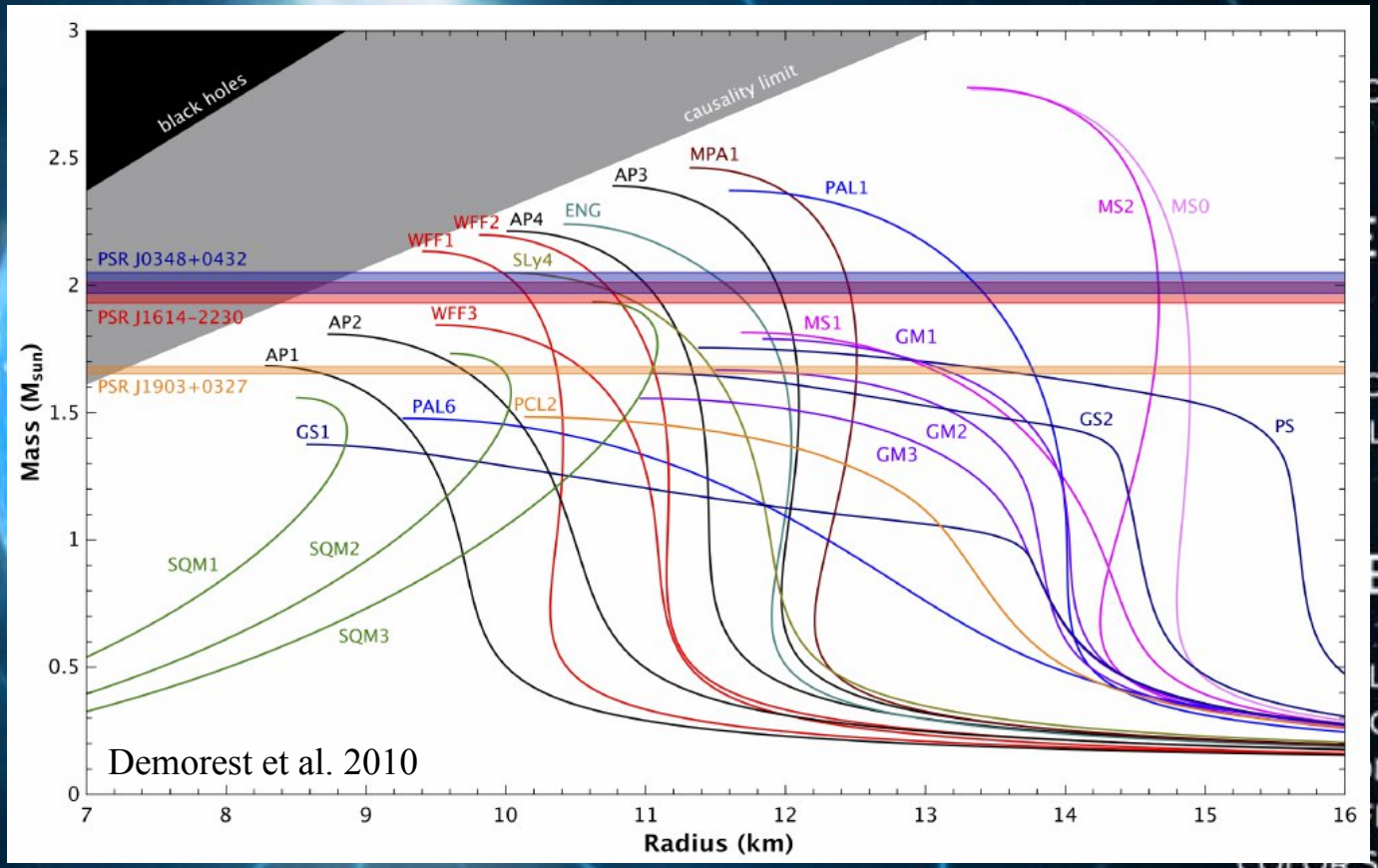

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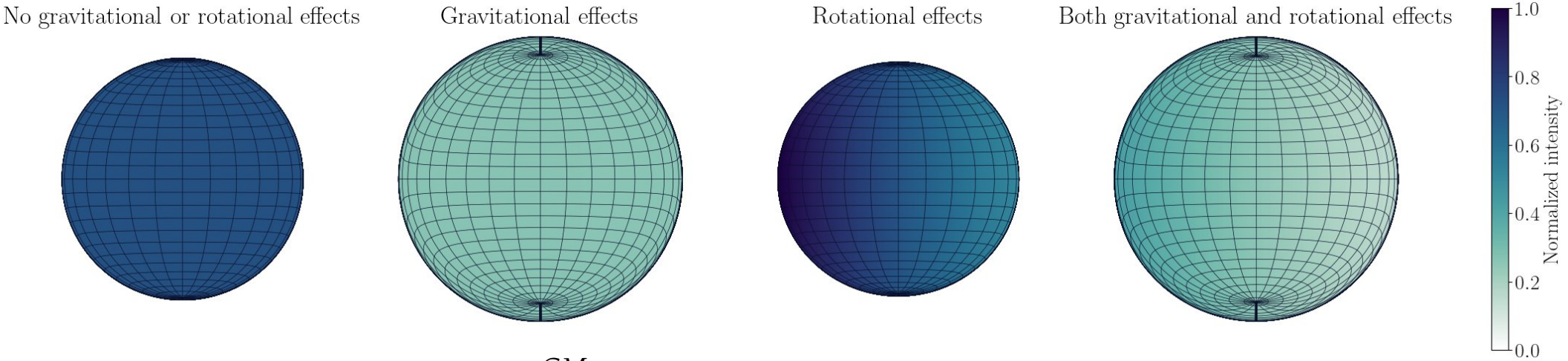
Pulse Profile Modeling to measure mass and radius of MSPs

- Pulse Profile Modeling (PPM) models the phase-resolved spectra from surface emission of neutron stars.
- Millisecond pulsars (MSPs), in particular, have high spin frequency and hot spot on their surface.
- The X-Ray Pulse Simulation and Inference (X-PSI) is a PPM software that incorporate instrument response and can be used to simulate and fit X-ray pulsed emissions of MSPs



Observable quantities: $C = \frac{GM}{Rc^2}$ $v = Rf$

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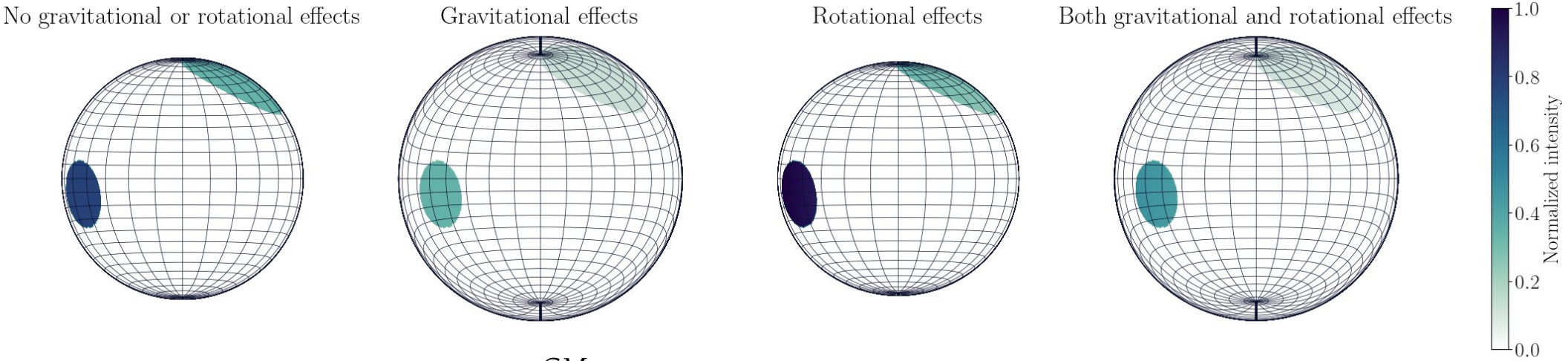

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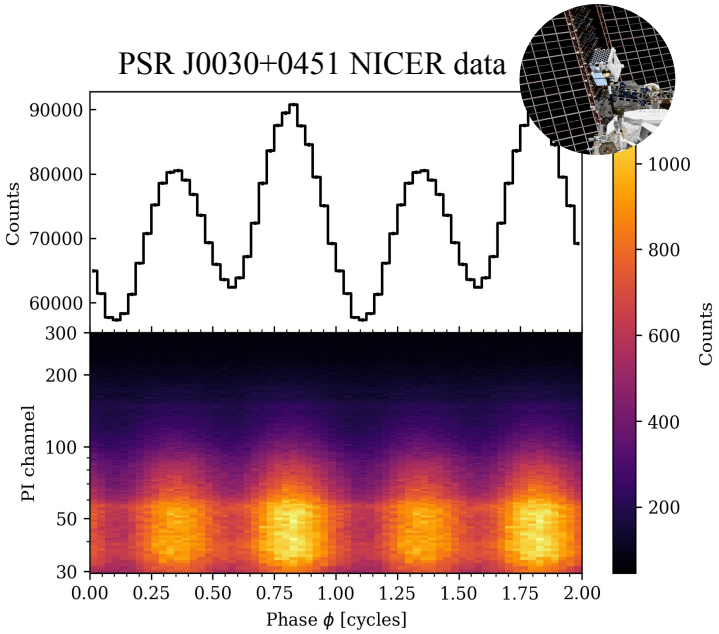
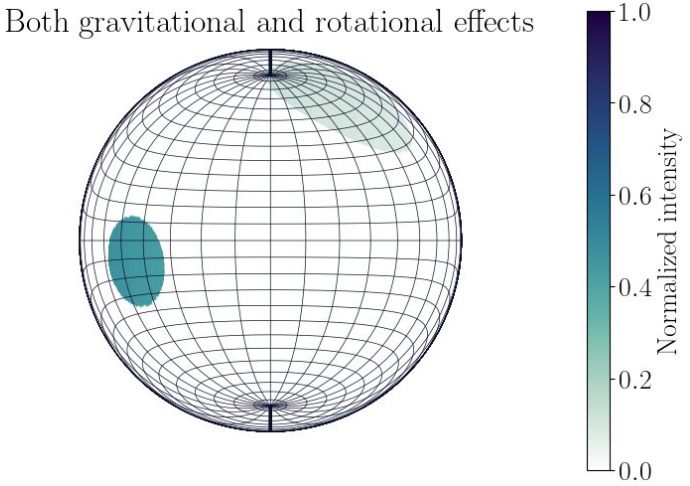
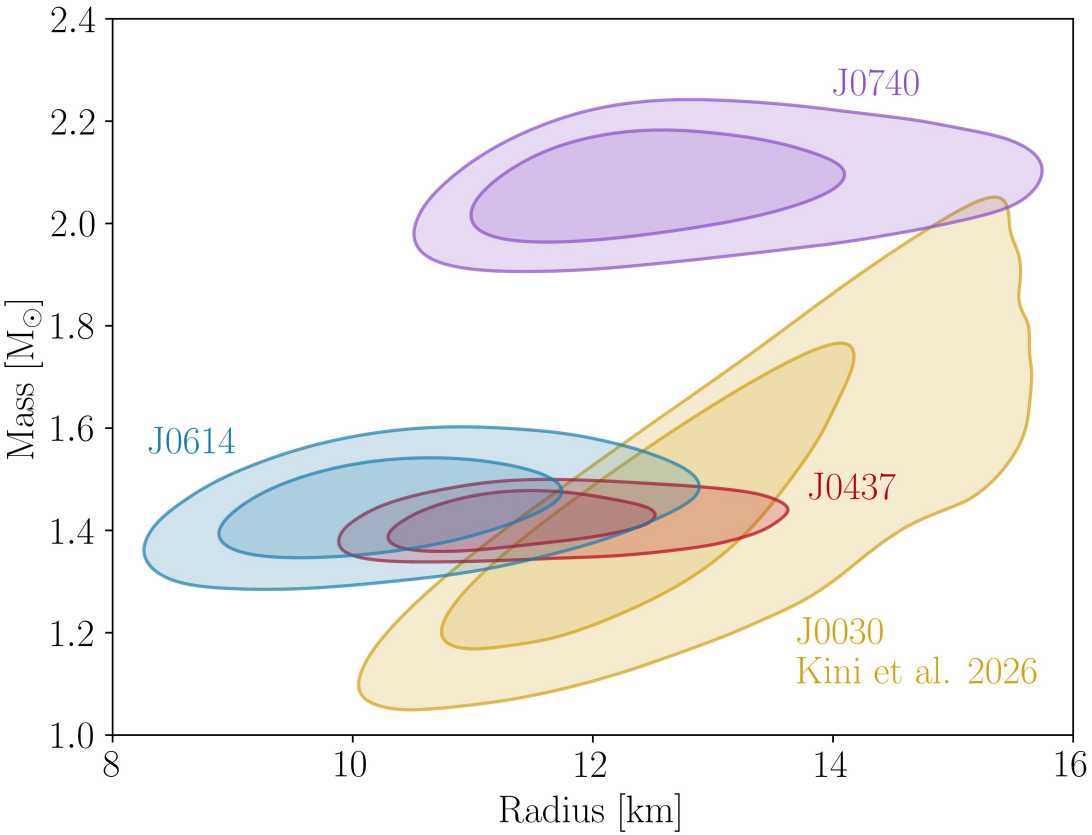


Fit the model to the data to get geometry and M-R

X-PSI



Application with NICER and XMM-Newton data with X-PSI



PSR J0740+6620 - Salmi et al. 2024

- Also Riley et al. 2021, Miller et al. 2021, Salmi et al. 2022, Dittmann et al. 2024
- Massive source with faint emissions
- Simple hot spot geometry

PSR J0437-4715 - Choudhury et al. 2024

- Very bright source with the best radius constraint
- Complex hot spot geometry

PSR J0030-0451 - Kini, Mauviard, et al. 2026 - New result !

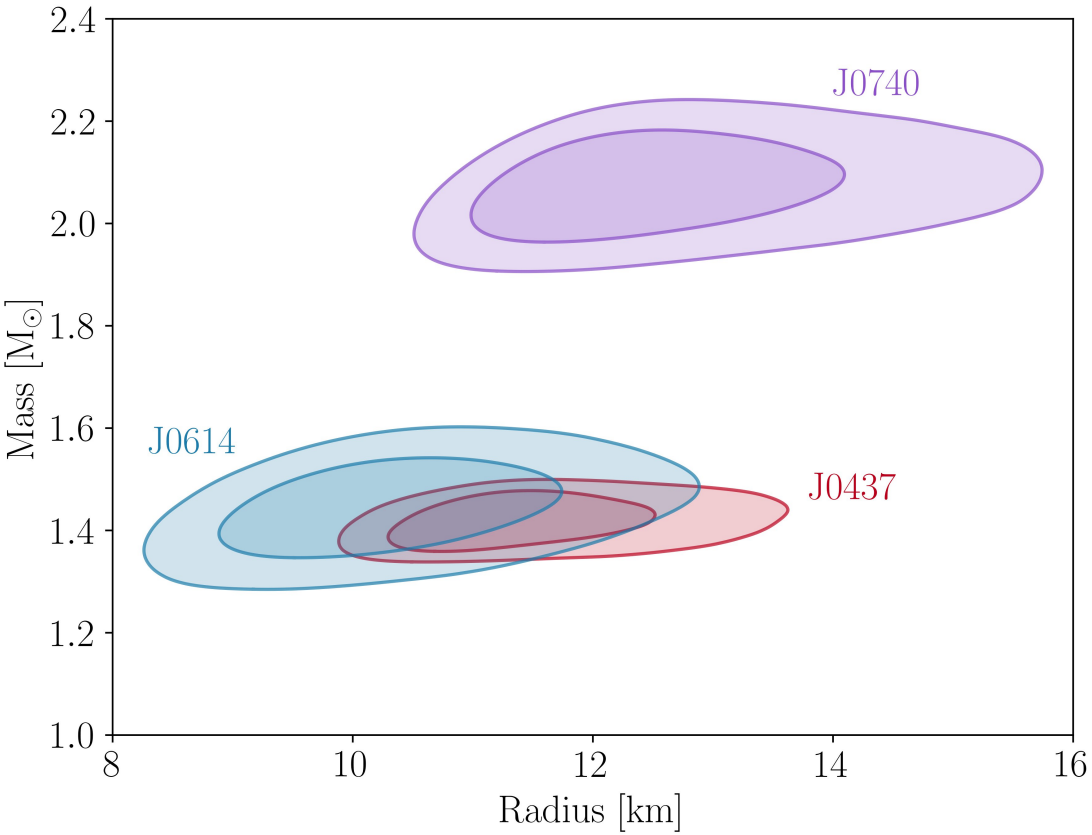
- Also Riley et al. 2019, Miller et al. 2021, Vinciguerra et al. 2024
- Bright source without mass prior
- Complex hot spot geometry

PSR J0614-3329 - Mauviard et al. 2025

- Rather faint source with well constrained geometry prior
- Intermediate complexity hot spot geometry

For other sources (qLMXBs) see Christine's talk right after !

PPM on MSPs using NewAthena



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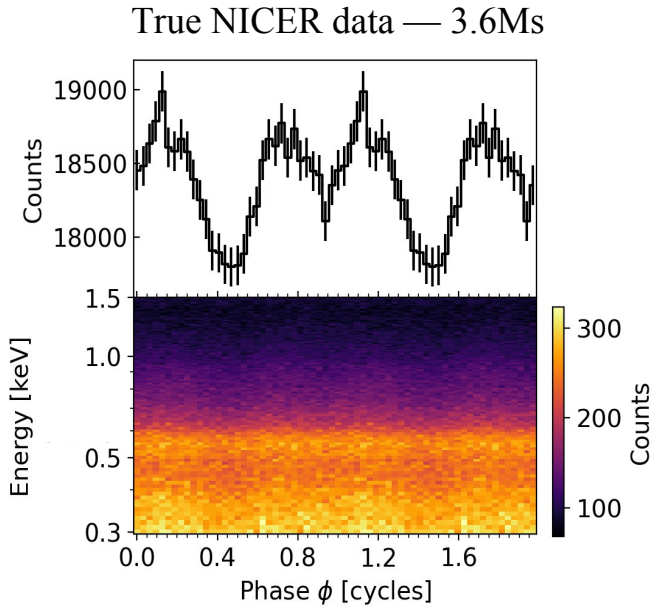
Why NewAthena ?

- MSPs are dim sources, which currently require long exposure time to get constraints from PPM
- NICER has high and poorly constrained background



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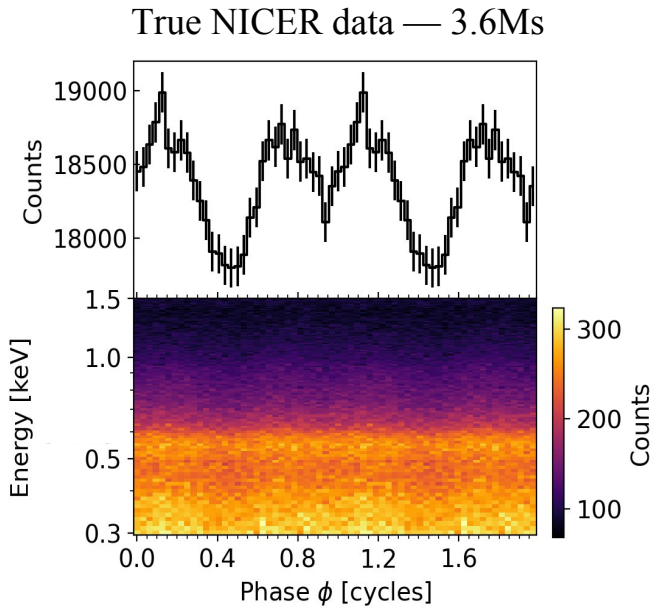
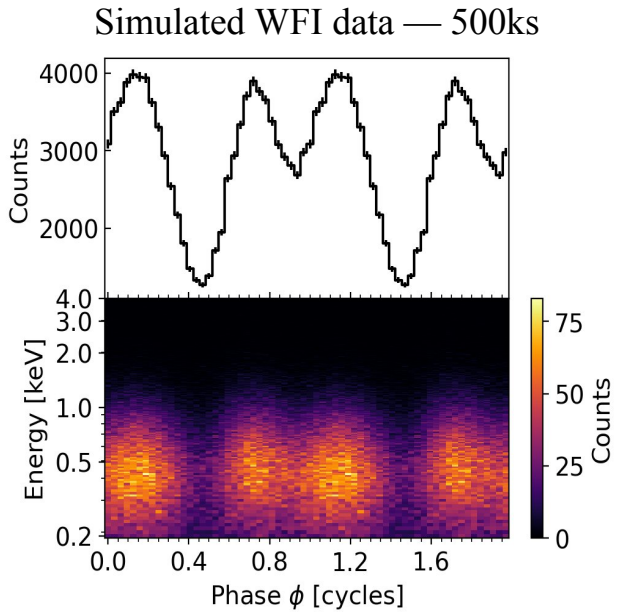
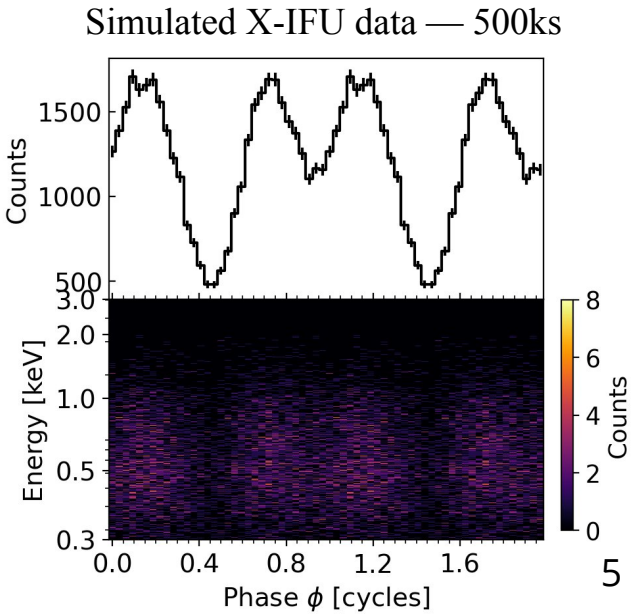
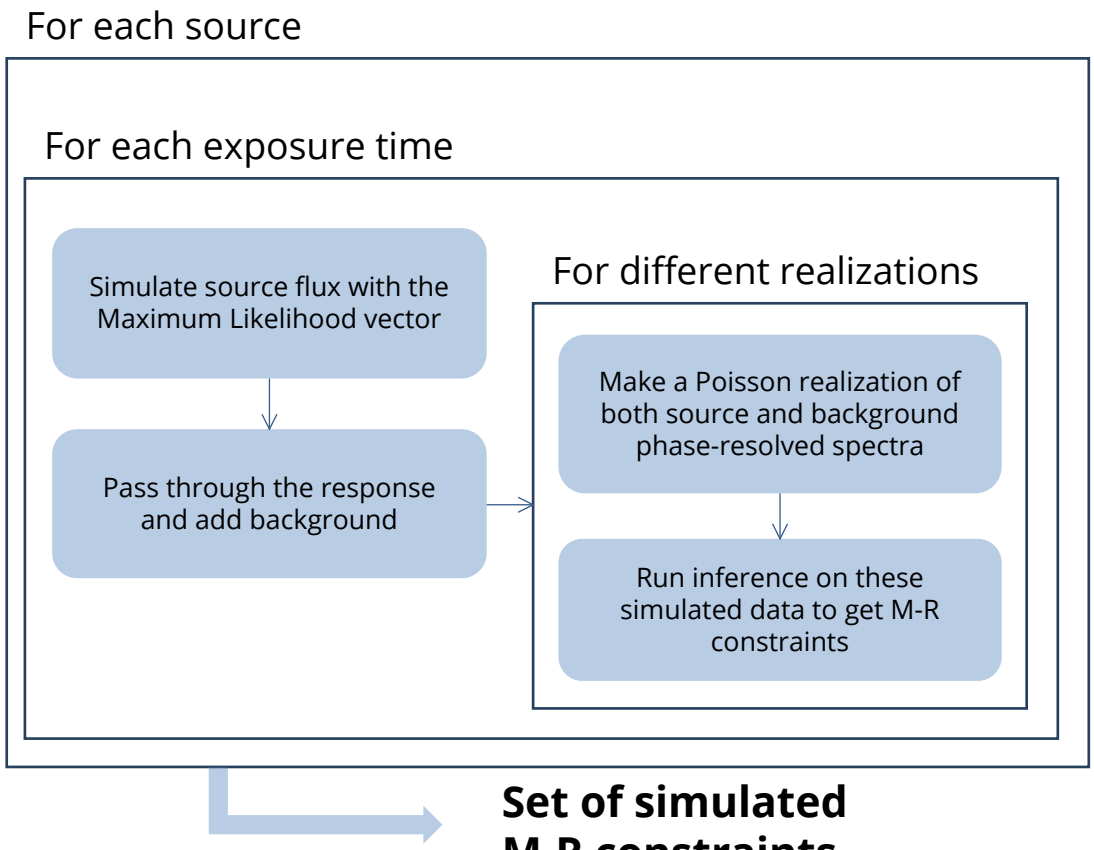
- With NewAathena we will get usable constraints with ~100ks of exposure time
- The background will be much lower and better constrained







PPM on MSPs with NewAthena data



Assumptions:

- We use only Fast Detector (FD, 80μs) WFI data for PPM
  Also with X-IFU (10μs) later
- No NICER or XMM data are used, only WFI data
- The source is extracted from a 9" radius region
- The background is extracted from a region 5 times larger than the source (45" radius)
- Latest on axis response and background without filter
- Same priors as in previous analyses
- Maximum Likelihood solution of past analyses as the ground truth

Characteristics of the difference sources

PSR J0740+6620

- Exposures: 100ks, 200ks, 300ks, 400ks, 500ks
- 7 realizations

PSR J0437-4715

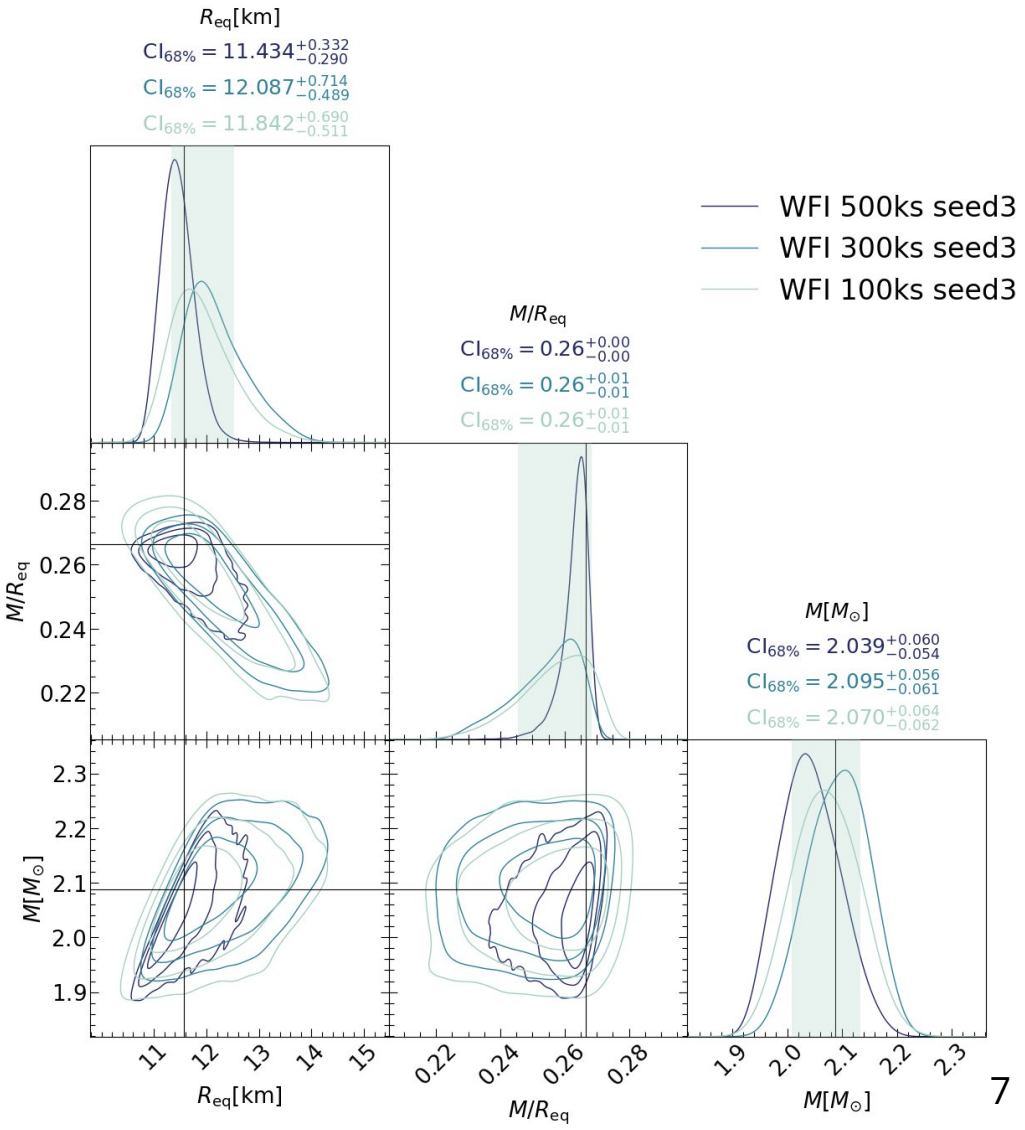
- Not tested yet but will use 100ks and 200ks

PSR J0614-3329

- Exposures: 100ks, 200ks, 300ks
- 7 realizations

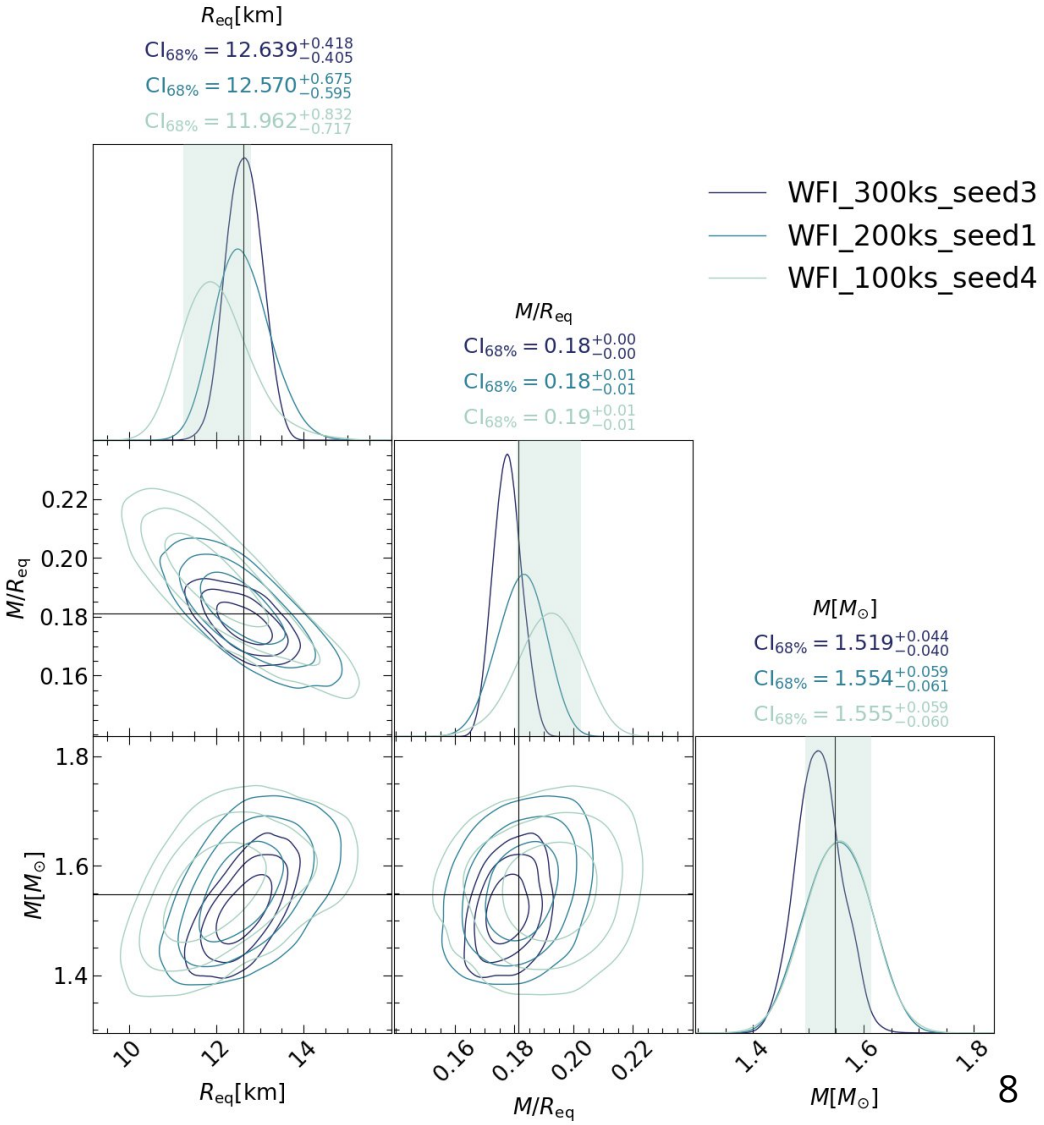
Results for PSR J0740+6620

- Input values are always retrieved in the 68% credible interval region
- Uncertainties on the radius decrease with exposure time
- Using 100ks of FD already divide the uncertainties on the radius by ~2 compared to current 3.6Ms NICER + XMM
- Using the target 500ks narrows it down to ±300m (~3.5 times decrease of the 68% CI)
- But beware the realization: same exposures can get different results



Results for PSR J0614-3329

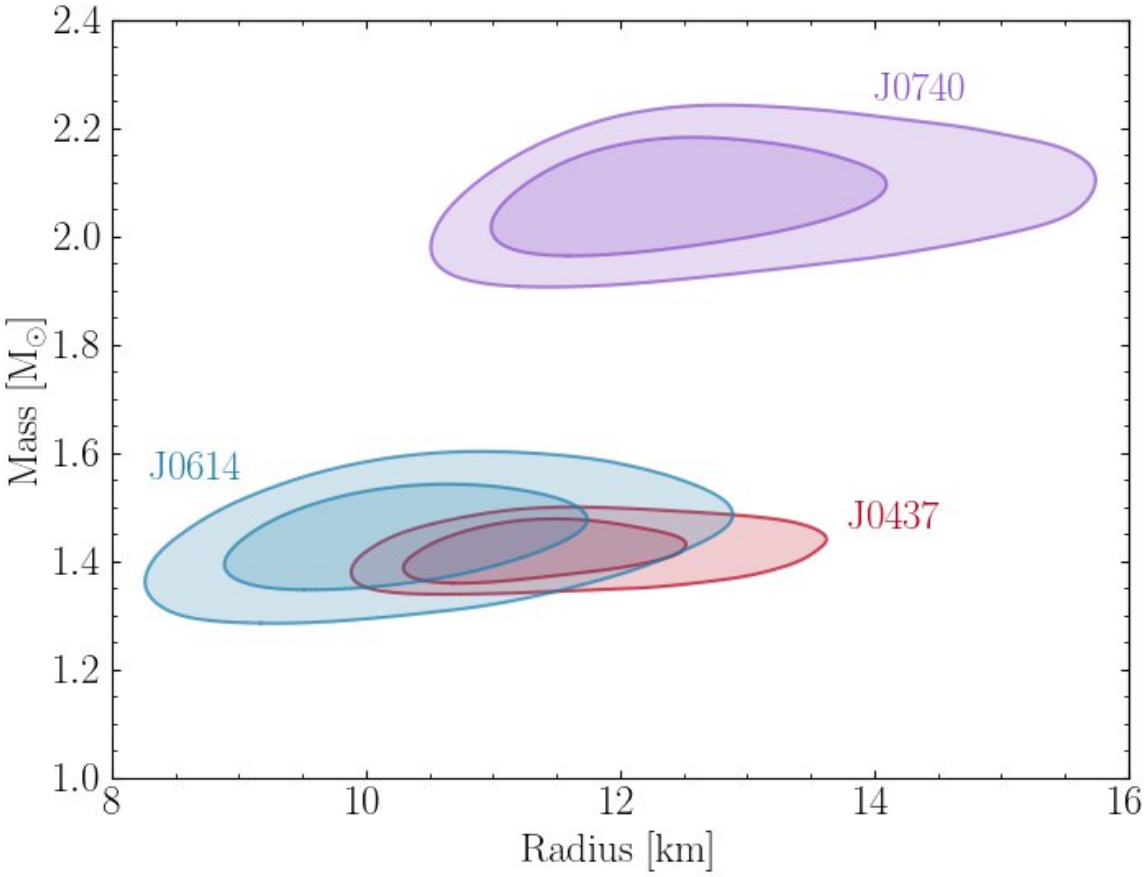
- Using 100ks of FD already decrease the uncertainties on the radius by ~15% compared to current 1.6Ms NICER + XMM
- Using the target 300ks narrows it down to ±400m (~2.5 times decrease of the 68% CI)
- More difficult than PSR J0740+6620 because of a more complex model
  ➡ Results are still preliminary



Effect on the inferred Equation of State

Using WFI - FD

- J0740 constraint improves significantly with 500ks
- J0614 also improves with 300ks but the shifts due to the input radius being ~12km
- J0437 will be done in the near future
- We narrow uncertainties of both to ±400m



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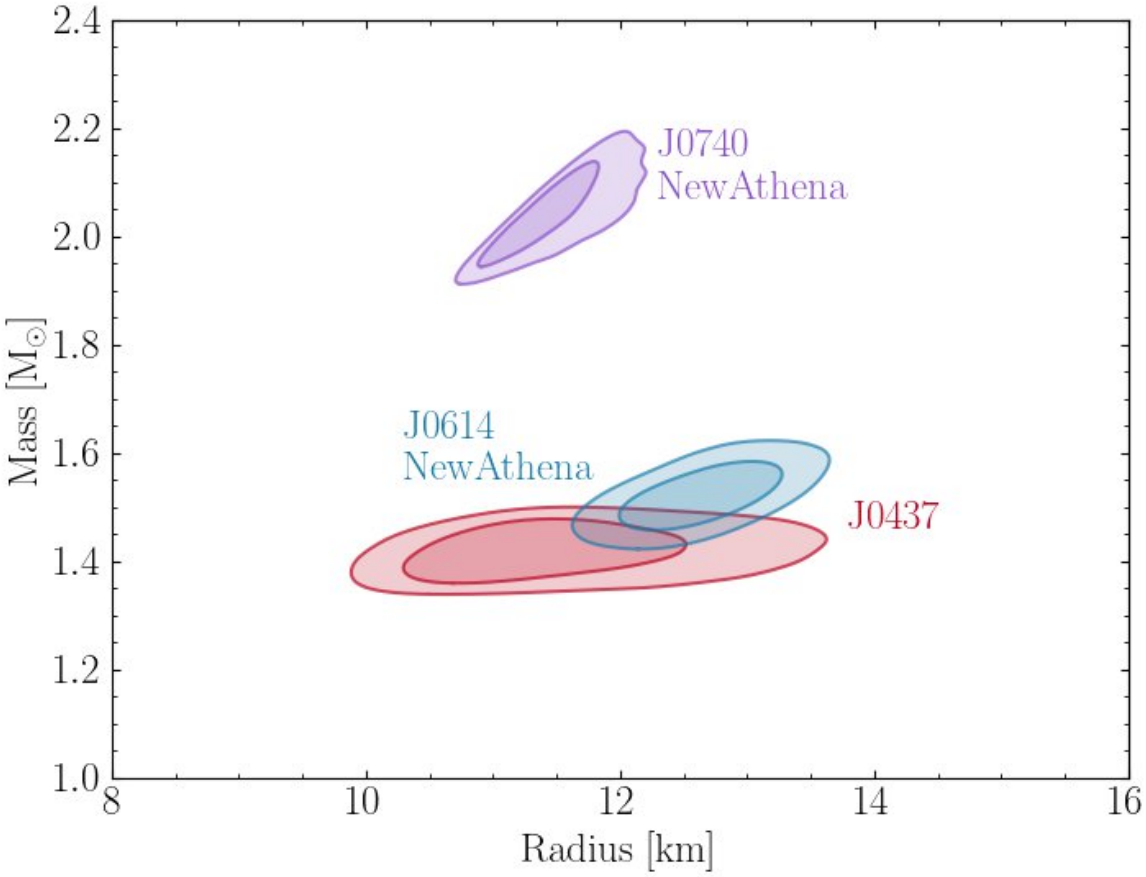

Future improvements

NewAathena Special Issue

- Can we get a reliable background estimate using WFI/FD ?
- We will run the pipeline testing the expected constraints with X-IFU
- Perform the analysis for other sources
- Investigate the expected mass-radius in light of the expected improved radio mass priors from SKA
- Run Equation of State inference using NEoST once proper M-R constraints will be available

Conclusion

- We are not done with NICER yet: new mass-radius measurements coming soon !
- NewAthena will be an important asset to constrain the Equation of State of dense matter
- With simulations, we estimate the increase in accuracy obtained using NewAthena for mass and radius measurements of millisecond pulsars.
- Using only NewAthena WFI/FD, we can reach ±400 m uncertainties on the radius of multiple MSPs within the 1Ms of allocated time on the mock observing plan (3 times better than current analyses using NICER+XMM)