Neutron Star Measurements with NICER

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Plan of Talk

- Our results, and how we obtained them, for PSR J0030+0451 and PSR J0740+6620
- Implications for the equation of state of the matter in neutron star cores

Based on Miller et al. 2019 and Miller et al. 2021; see also Riley et al. 2019, 2021 and Raaijmakers et al. 2019, 2021

The Main Results

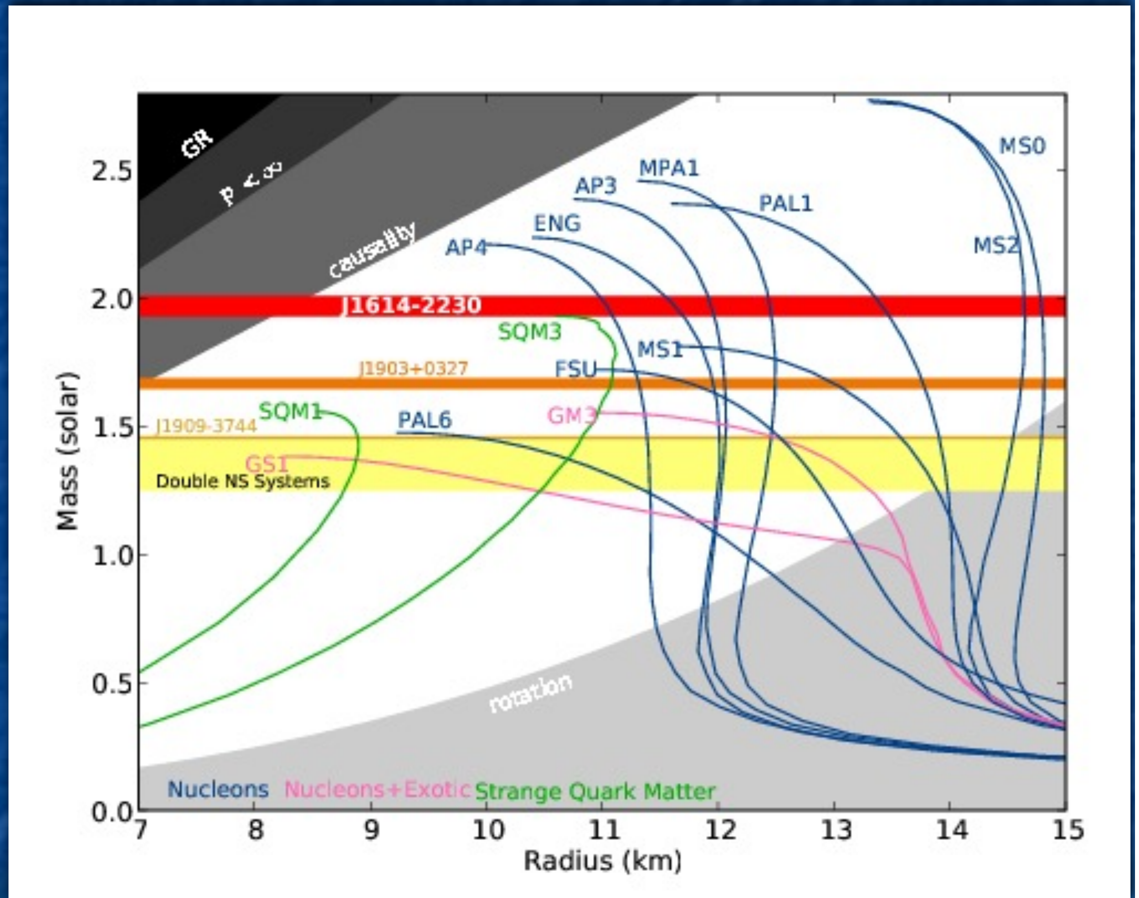
- Recall: for the 205.53 Hz pulsar PSR J0030+0451
  Isolated pulsar: no indep knowledge of M
  We get R_e=13.02(+1.24,−1.06) km and
  M=1.44(+0.15, −0.14) M_{sun} (all 1σ)

- For the 346.53 Hz pulsar PSR J0740+6620
  Mass (from radio) = 2.08+−0.07 M_{sun}
  Radius (our analysis) = 12.2 − 16.3 km

Philosophy: when we fit the X-ray data we allow the radius to be whatever value fits the data. Only when we consider EOS implications do we impose constraints on radius.

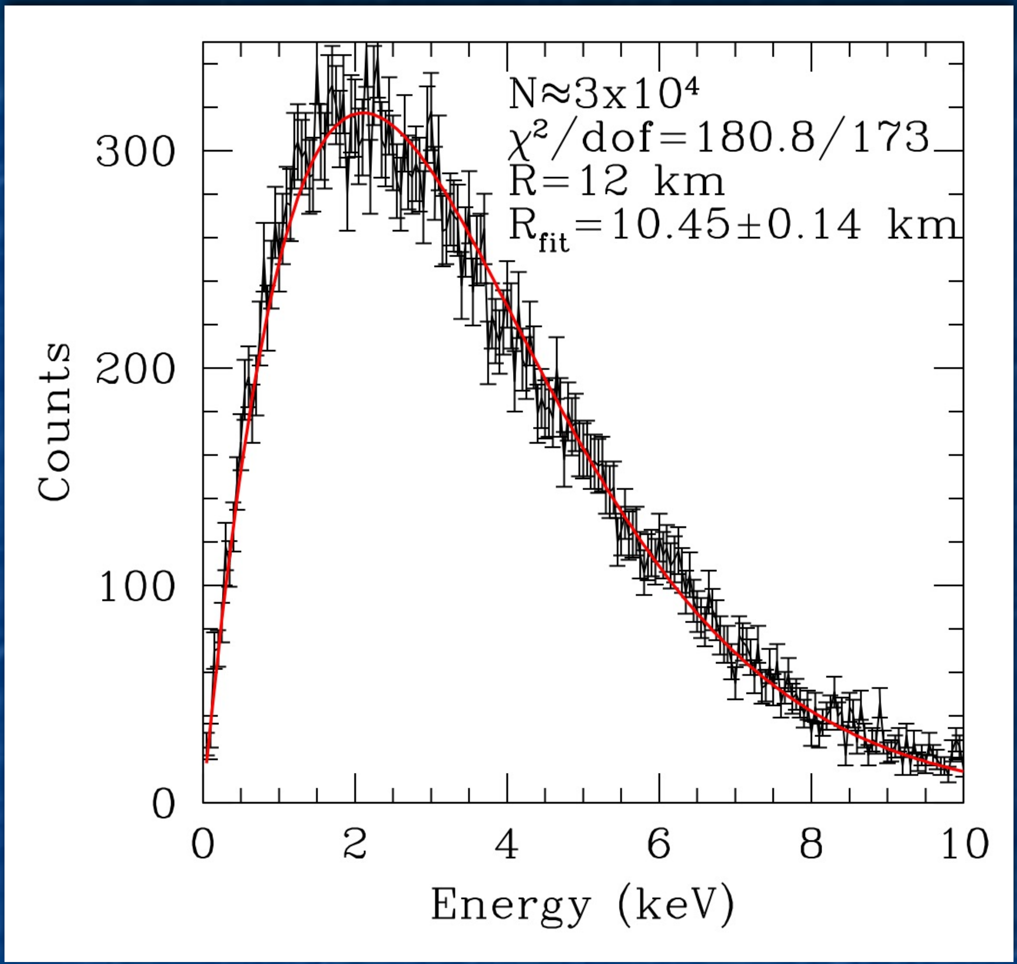
The Importance of Radii

- Radius would provide great EOS leverage
  Wide range in models
- But tough to measure
- Previous published measurements based on X-ray observations are susceptible to huge systematic error
- NICER X-ray pulse modeling can help



Demorest+ 2010

Radius Bias with T Variation



Perfect energy response, zero N_H

T varies smoothly from 2 keV (equat) to 0.2 keV (pole).

Fit is good, but R is 13%, and 10σ, low.

For this type of data, a good fit does *not* guarantee a reliable result

NICER Reduces Systematic Errors

- Extensive work by Fred Lamb (Illinois) and myself with our collaborators suggests that when we fit *rotational-phase dependent* spectra, such as with NICER, systematic errors are minimized
- We have generated synthetic data using models with different beaming, spectra, spot shapes, temperature distributions etc. than used in fitting the data
- Conclusion: if good fit, no significant bias

The NICER Idea in Brief

2019 December 18

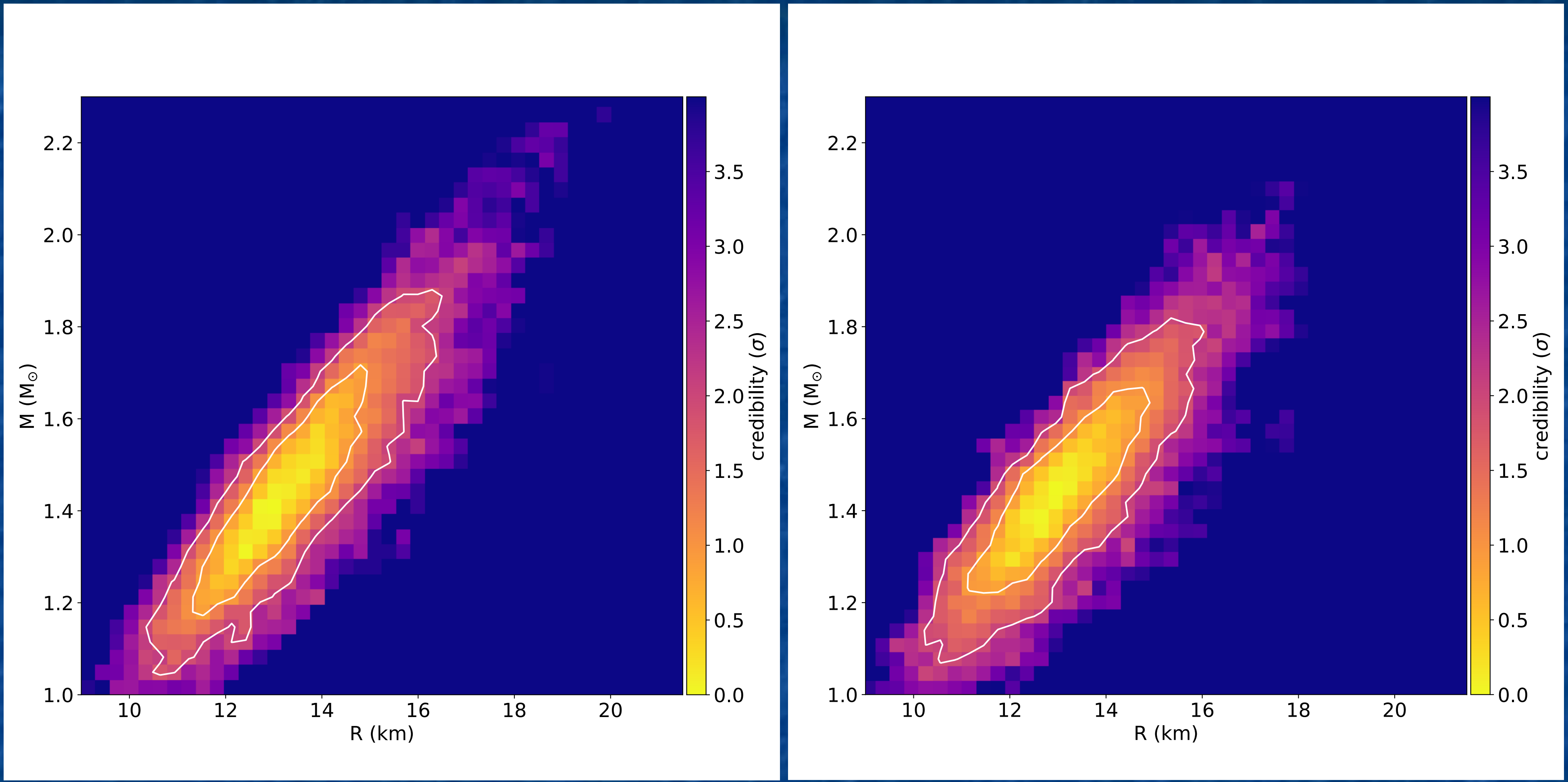
A Hotspot Map of Neutron Star J0030's Surface
Image Credit: NASA, NICER, GSFC's CI Lab

Bayesian fits: trace rays from hot spots on NS surface, compare with energy-dep waveform

Our Modeling of Hot Spots

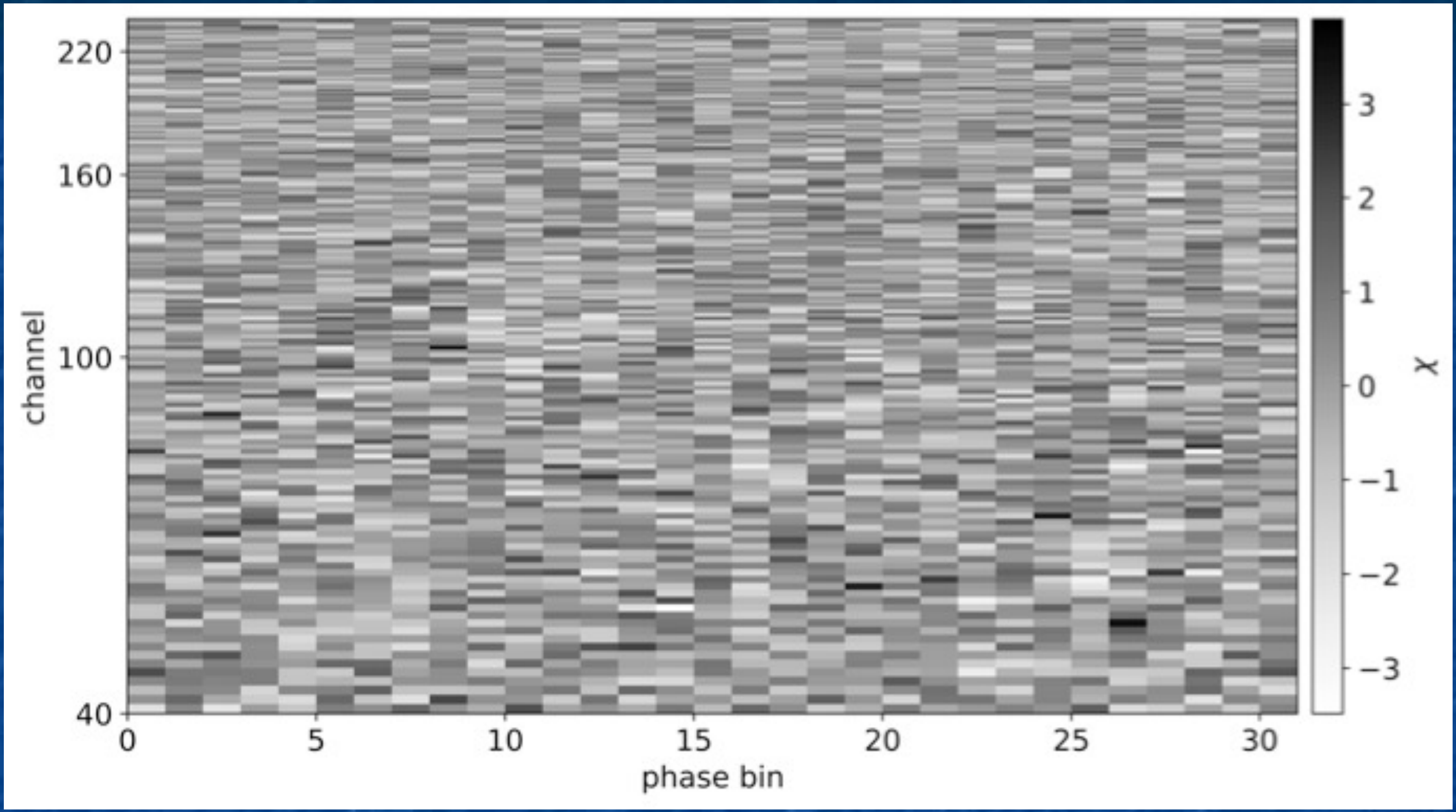
- Can have multiple spots (have used up to 4), circular or oval, arbitrary size, location, temperature, overlap
  Let the algorithm find the best fit!
- We then fold the pulse profile through the responses and compare directly with data
- We use NICER data for both pulsars, and also XMM-Newton data for J0740 (weaker source)

Mass-Radius Posteriors for J0030



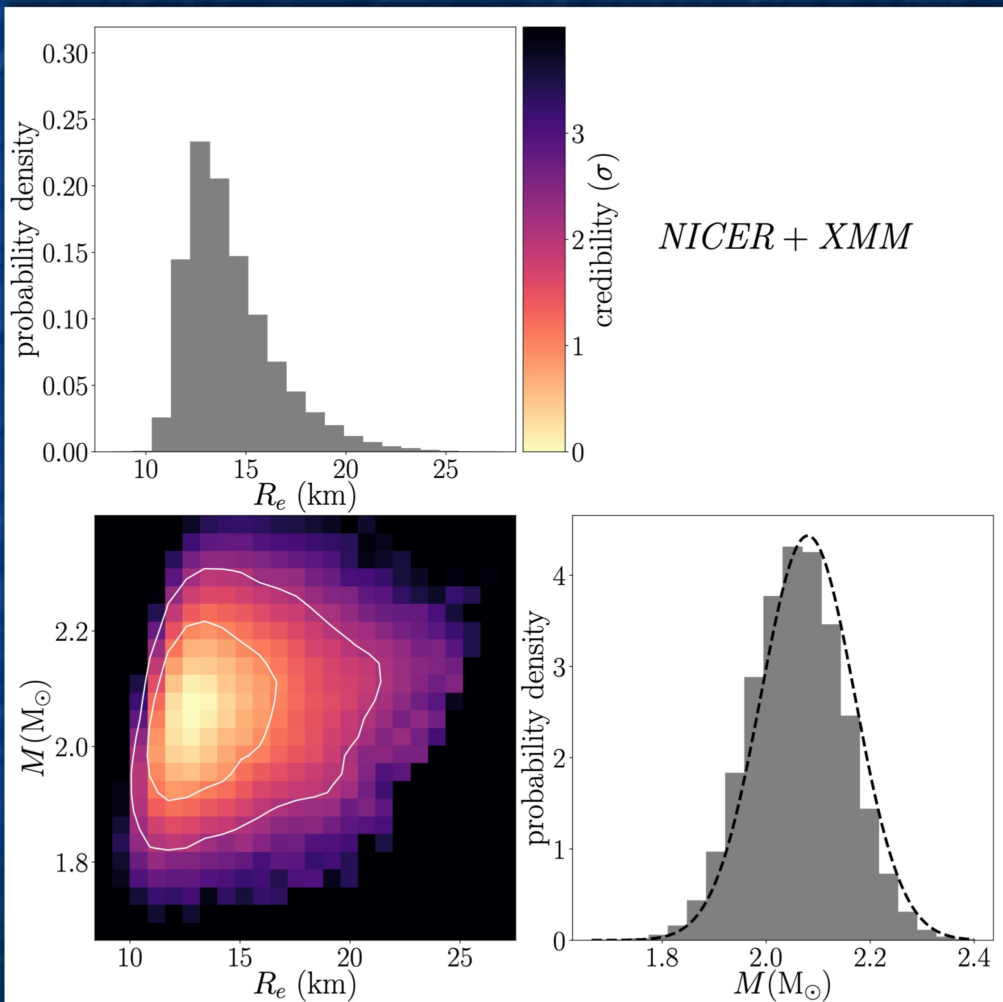
Left: M-R posterior for NICER J0030 data, two ovals
Right: M-R posterior for NICER J0030 data, three ovals

J0030 Model Fits Data Well



Residuals (in χ) for our best fit to NICER J0030 data. No patterns are evident, as one would expect from a good fit (χ^2/dof=8189/8040, 12%)

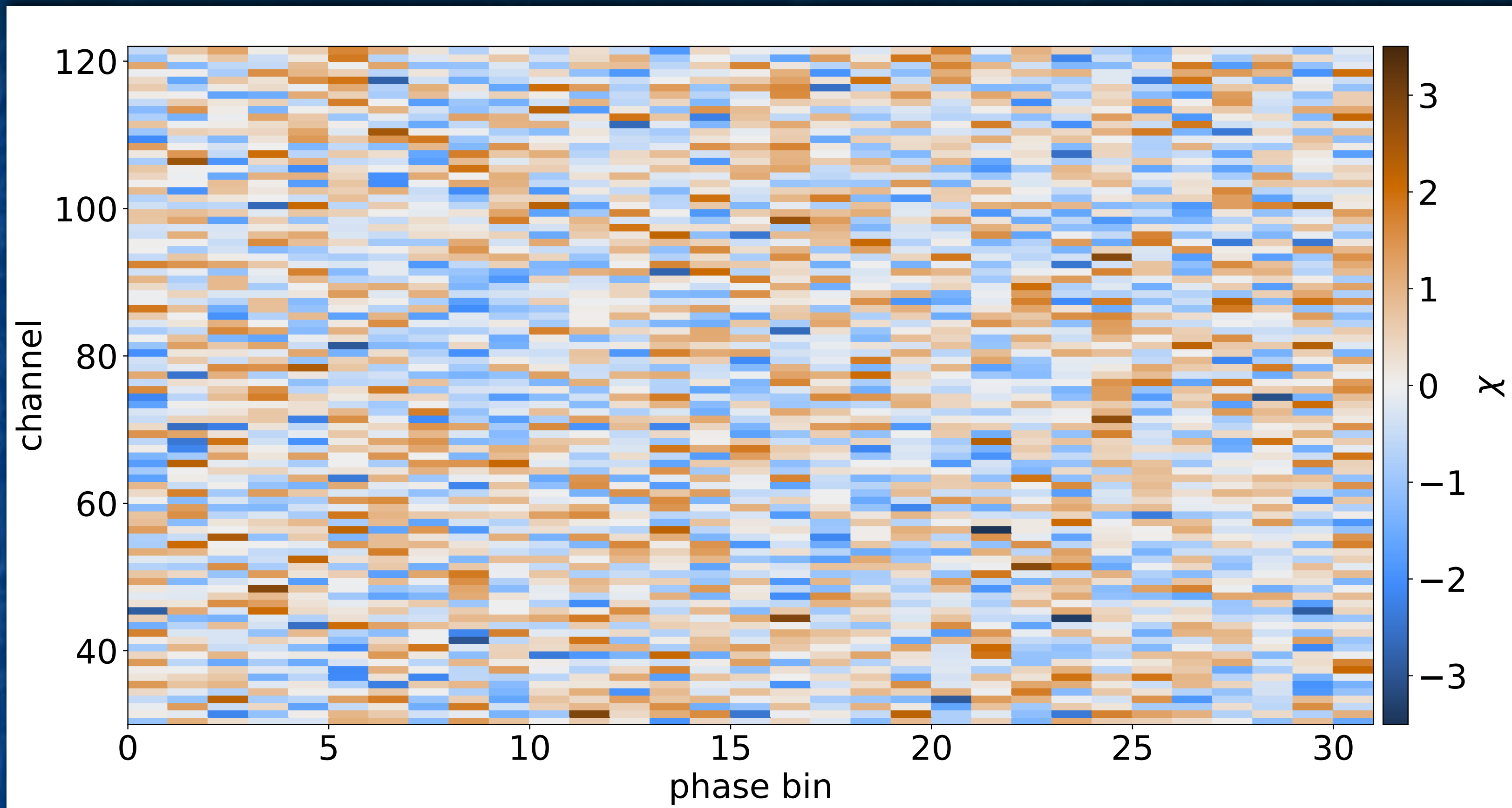
J0740 NICER+XMM: M and R



Radius of PSR J0740+6620: $13.7^{+2.6}_{-1.5}$ km (1σ)

Dashed line: prior on mass from NANOGrav and CHIME/Pulsar data

Model Fits Data Well

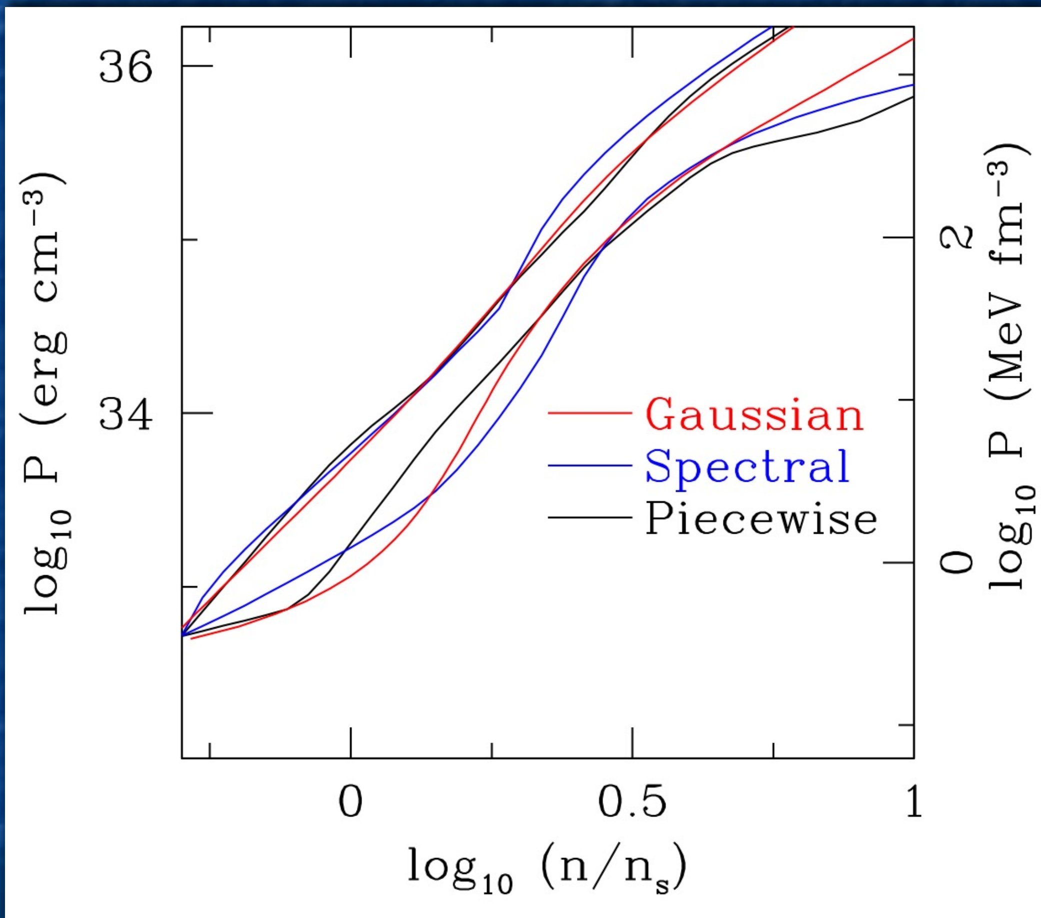


Phase-channel residuals of model to NICER data

For best fit, χ^2/dof = 2912.4/2901 (p-value 0.437)

Model also fits bolometric NICER data and XMM data well

J0030, J0740, Other Measurements Provide Tight EOS Constraints

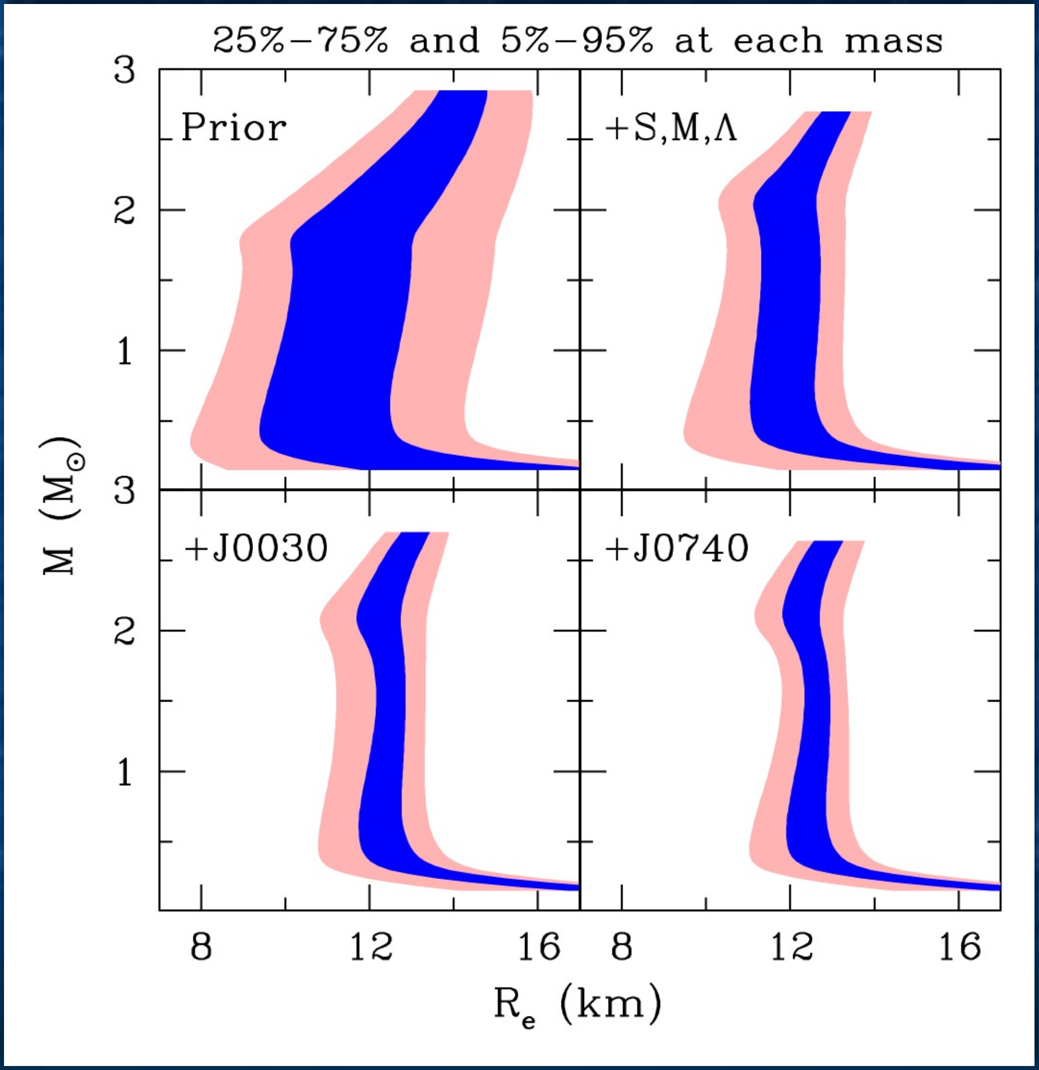


3 EOS models:

- Gaussian process
- Spectral parameterization
- Piecewise polytrope

Good EOS convergence in ~ 1.5 – 5 ρ_{sat} range

Tight Mass-Radius Constraints



Sequence:

- Priors
- Pre-NICER observations
- +PSR J0030+0451
- +PSR J0740+6620

1σ radius: 11.8 – 13.1 km for 1.4 M_{sun} spanning all three EOS models.

+− 5%   Pretty impressive!


Width ranges for a
1.4-solar mass
Neutron Star
Theoretical
495 Beltway
Washington, D.C.
2 miles (3.2 km)
NASA's Goddard Space Flight Center/S. Wiessinger

Conclusions and Future Work

- PSR J0740 radius is 12.2 – 16.3 km (1σ)
  PSR J0030 radius is 12.0 − 14.3 km (1σ)
- EOS at ~ 1.5 – 5 ρ_{sat} is converging between different models

> We now know the radius of a slowly rotating 1.4 M_{sun} neutron star to +− 5%: 11.8 – 13.1 km

- Future for J0740: more NICER counts means better harmonics; should be better upper limits
- For NICER: additional pulsars, improvements to our first pulsar J0030

Prospects are bright!