Learning about dense matter from NICER observations

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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, 2021 (ApJL); see also Riley et al. 2019, 2021 (ApJL)
Other relevant talks on neutron star observations:
Vinciguerra, Read (yesterday)
Cromartie, Bogdanov, Nättilä (today)

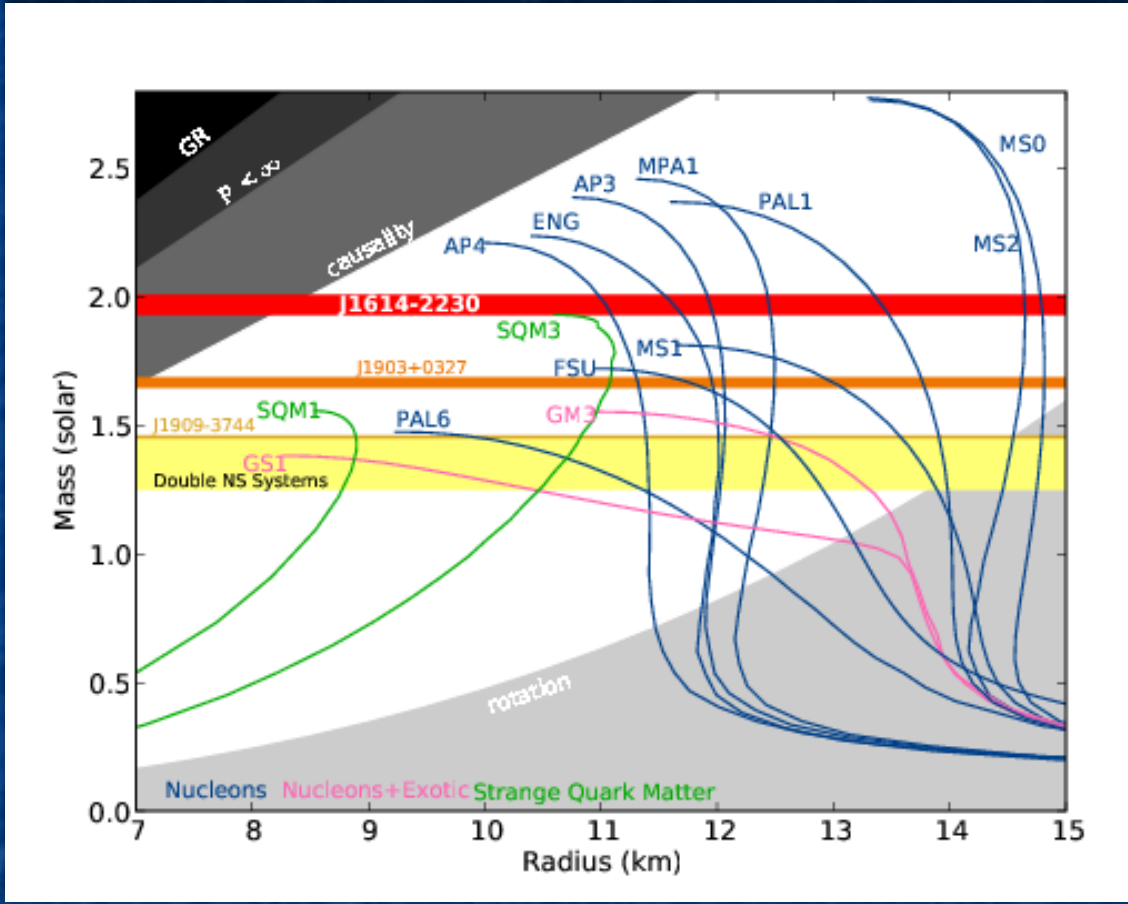
But First: The Main Results

- 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.

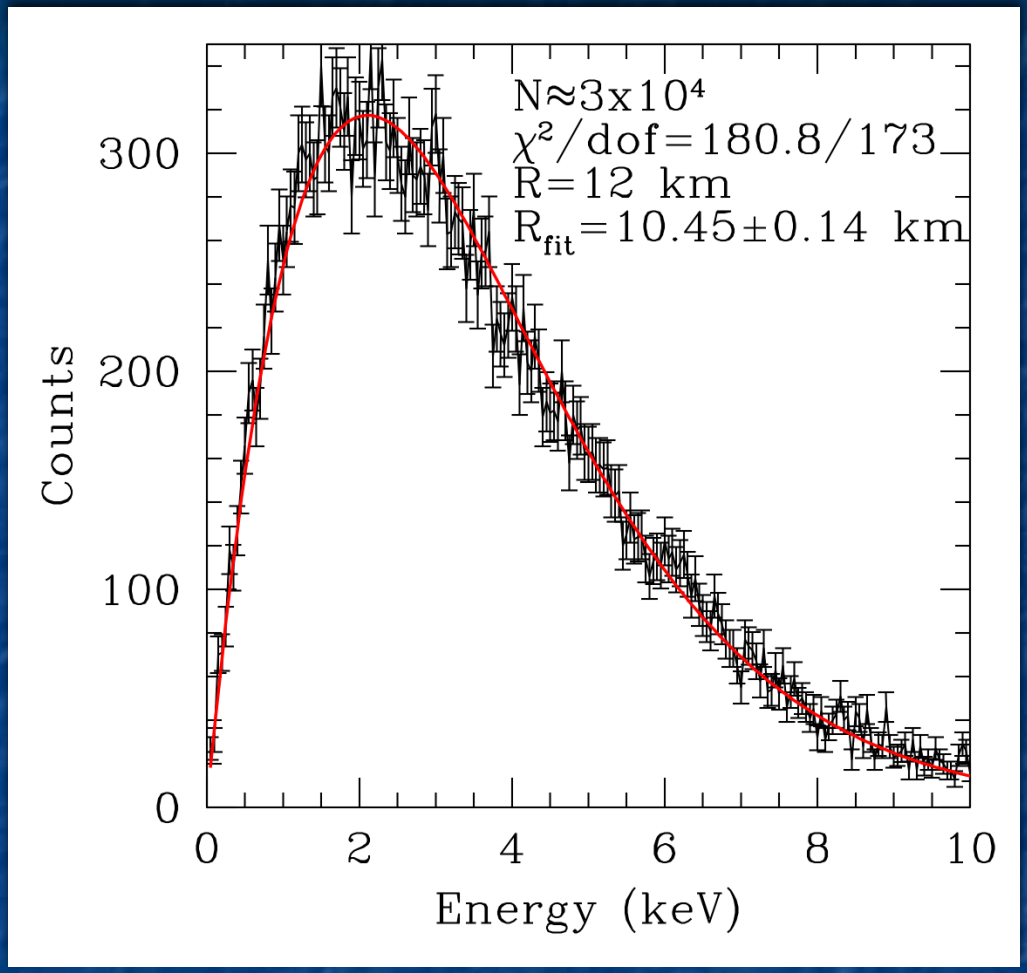
The Importance of Radii

- Radius would provide great EOS leverage
  Wide range in models
- But tough to measure
- Previous published measurements 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 (equator) to 0.2 keV (pole).

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

Good fit and lack of pulsations does ***not*** guarantee uniformity!

But allowing emitting area to vary is promising; see Nättilä talk

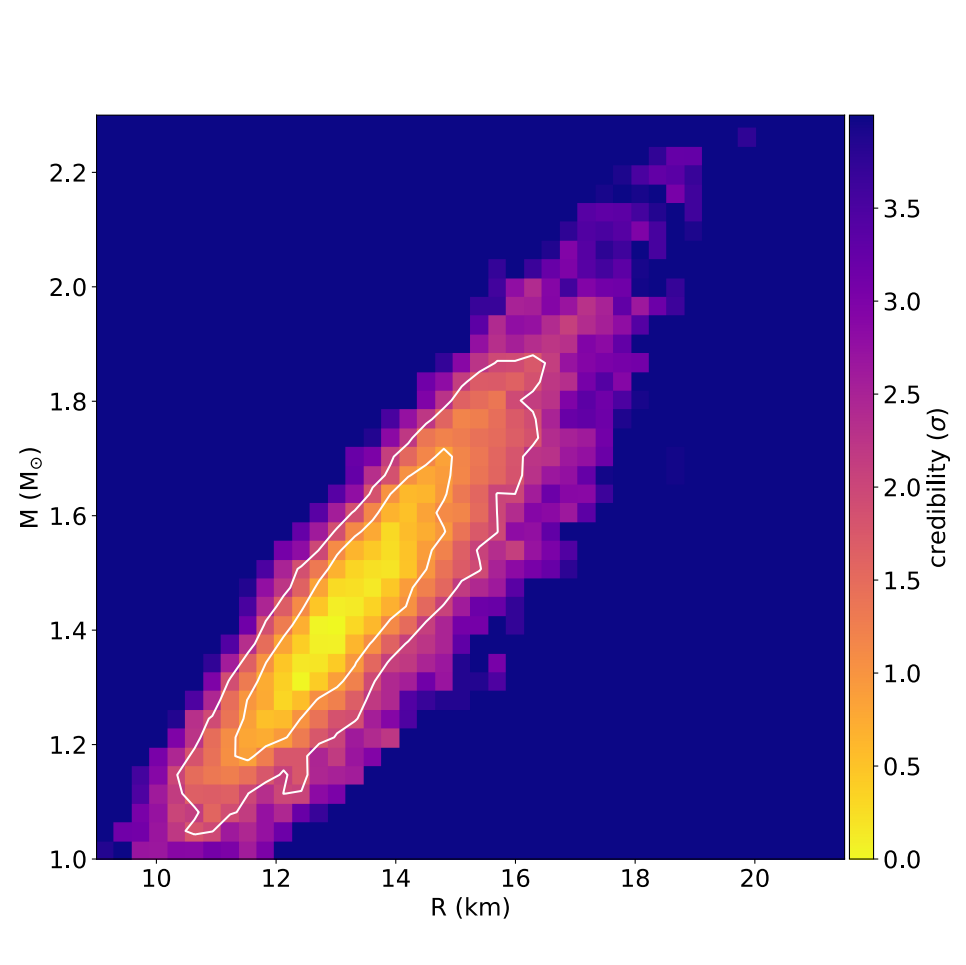
NICER Reduces Systematic Errors

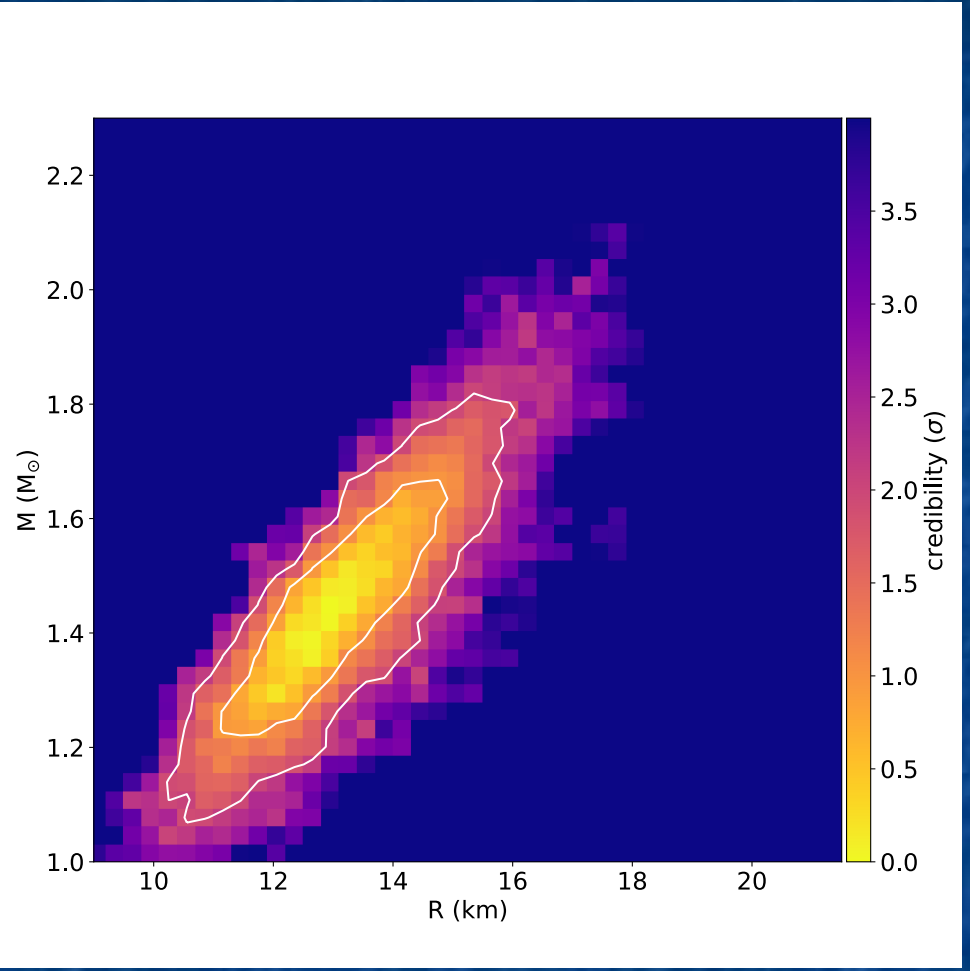
- Extensive work by Fred Lamb (Illinois) and myself with our collaborators suggests that when we fit *rotational-phase dependent* spectra, such as with NICER, systematic errors are minimized
- We have generated synthetic data using models with different beaming, spectra, spot shapes, temperature distributions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

Spot Models

- Some number of spots (we have tried 2-4), which are oval or circular, radiate with a uniform effective temperature, and have arbitrary overlap
- We marginalize over an arbitrary phase-independent background, independent from channel to channel
  Intent is to be as flexible as possible
- If we have background information, we use that to set the prior
  Key is to include reliable information

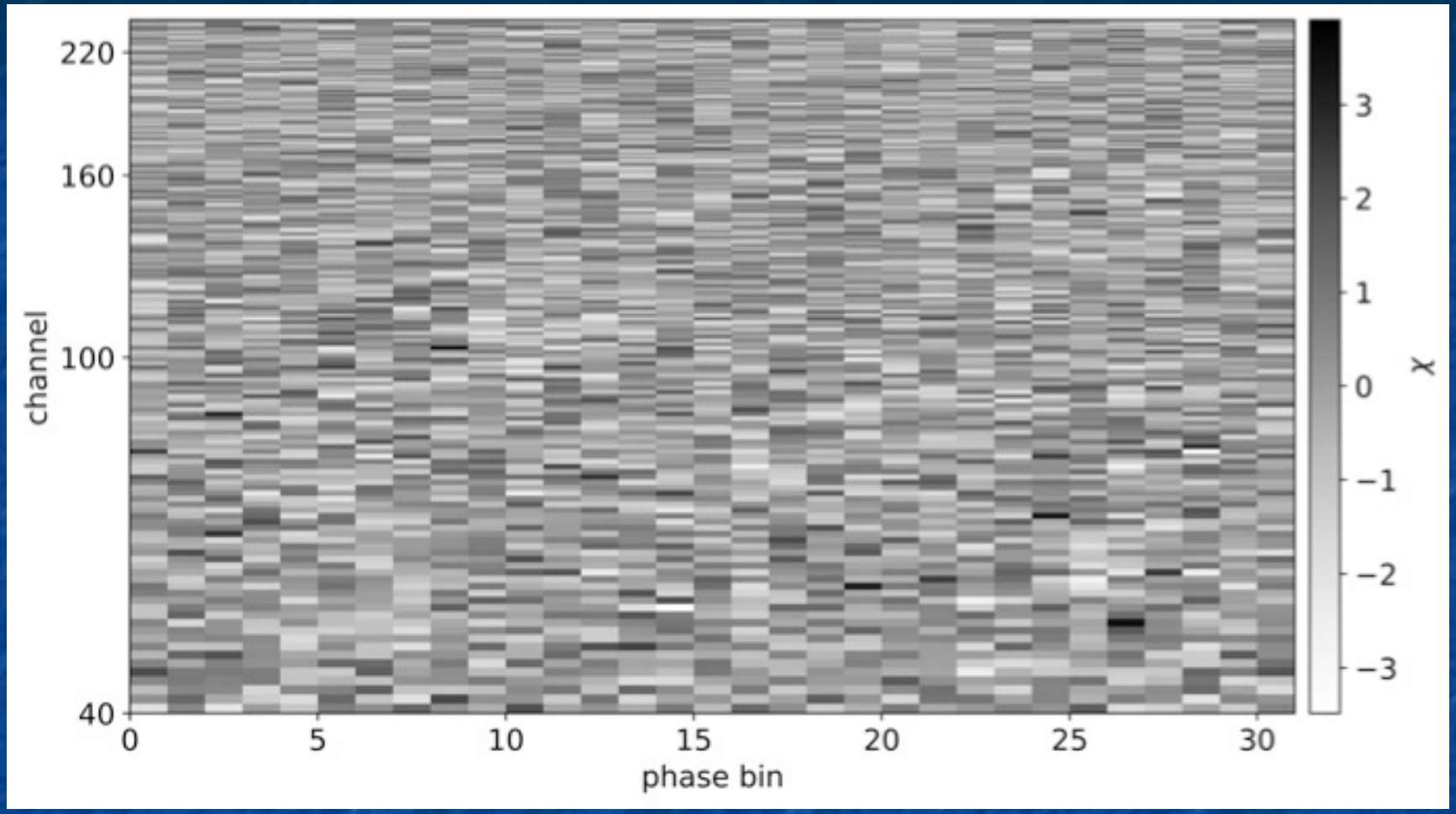
Mass-Radius Posteriors for J0030





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

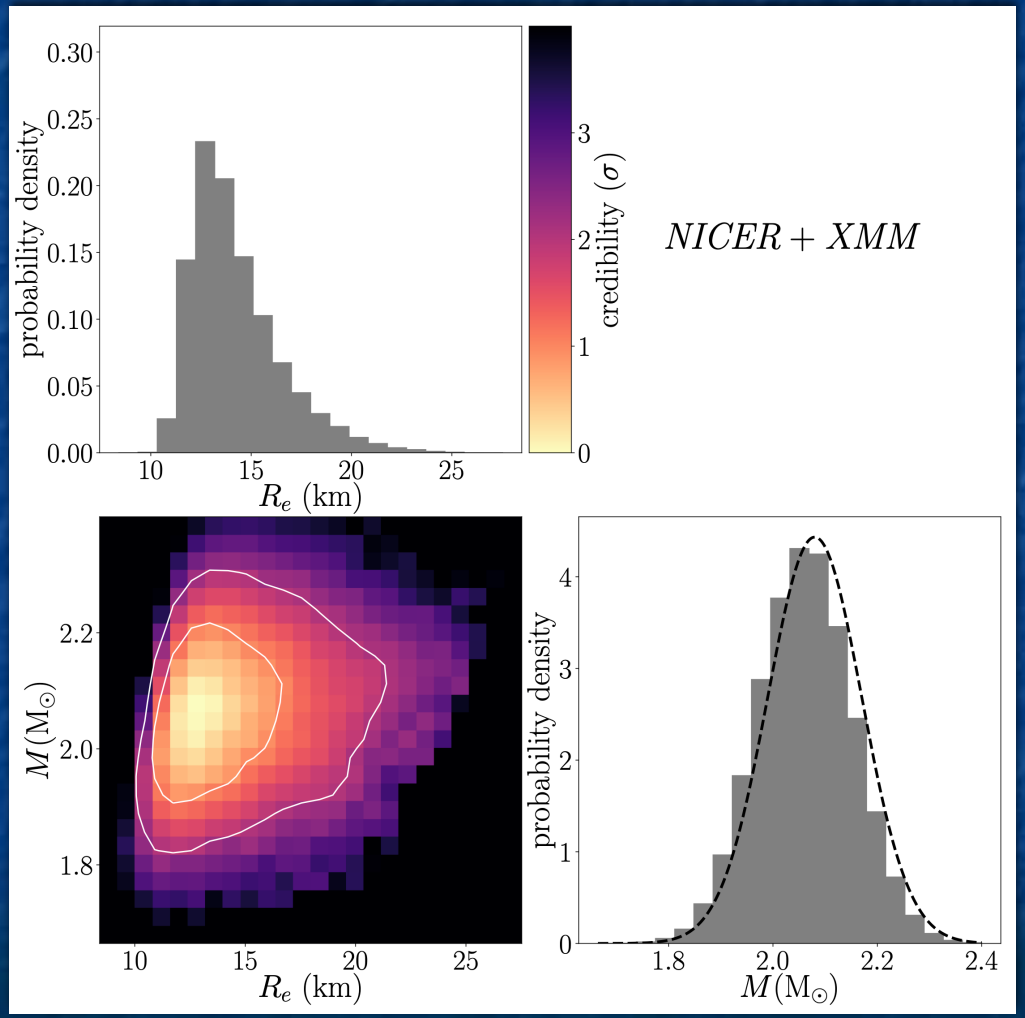
J0030 Model Fits Data Well



Residuals (in χ) for best three-oval 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

Extra information needed; J0740 is very faint in X-rays!



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

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

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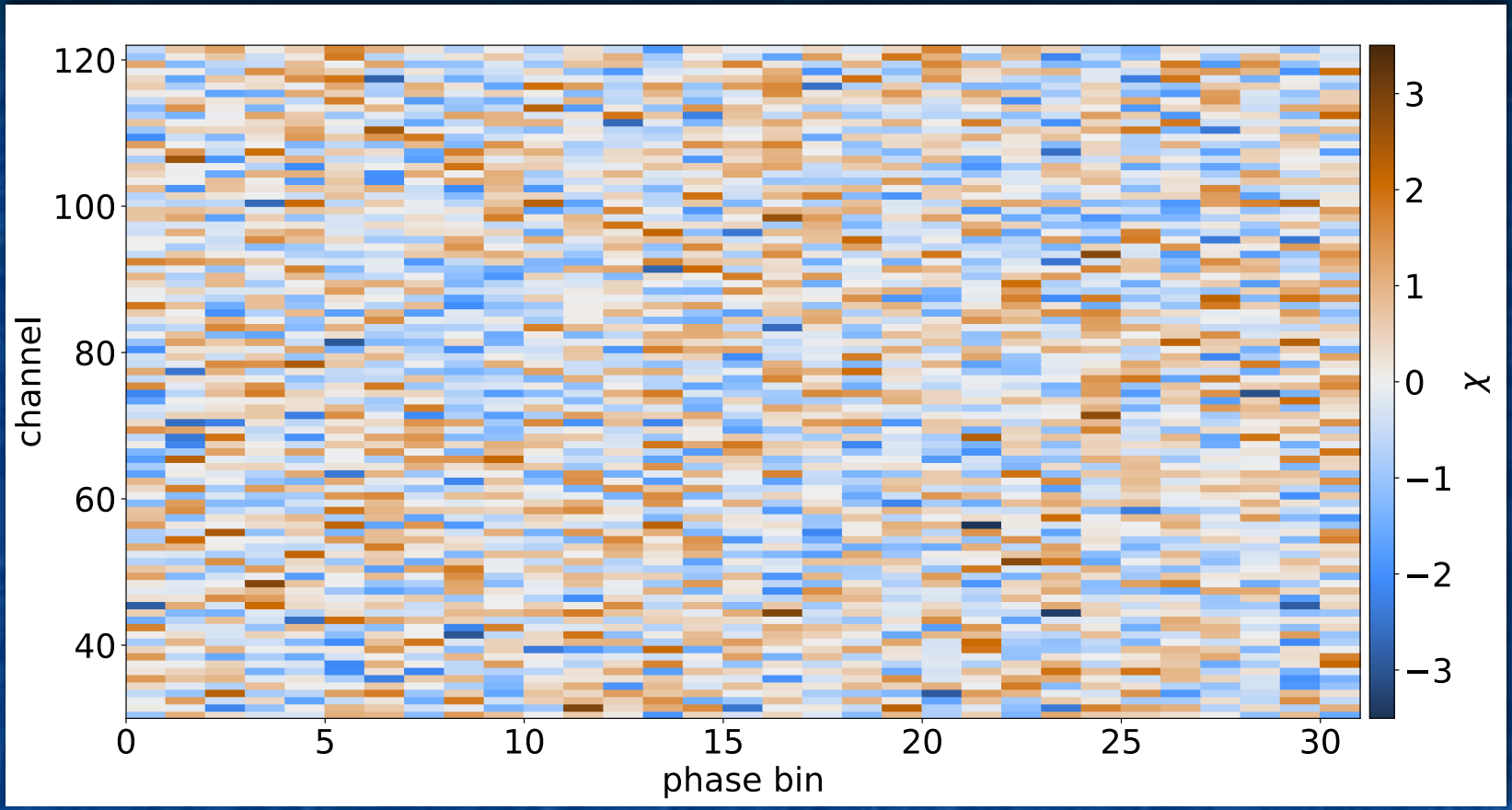
Model Fits Data Well



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

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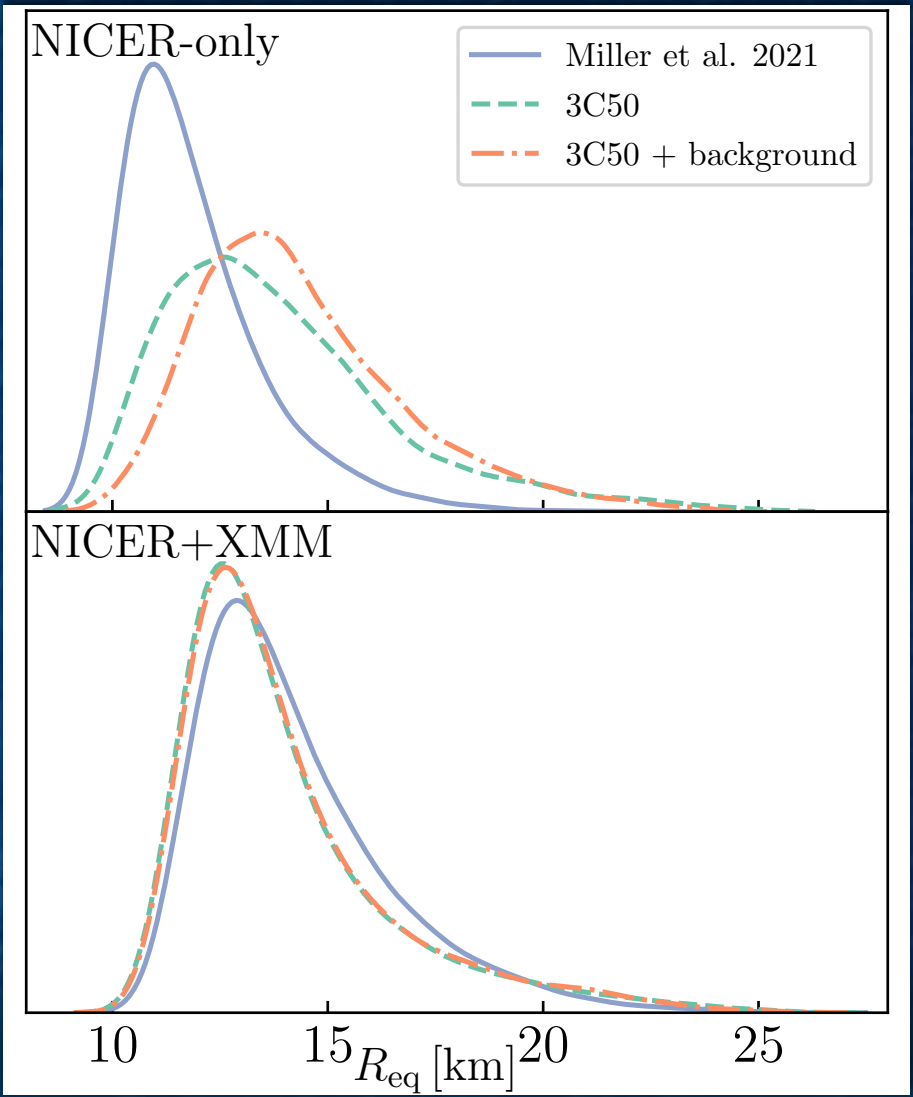
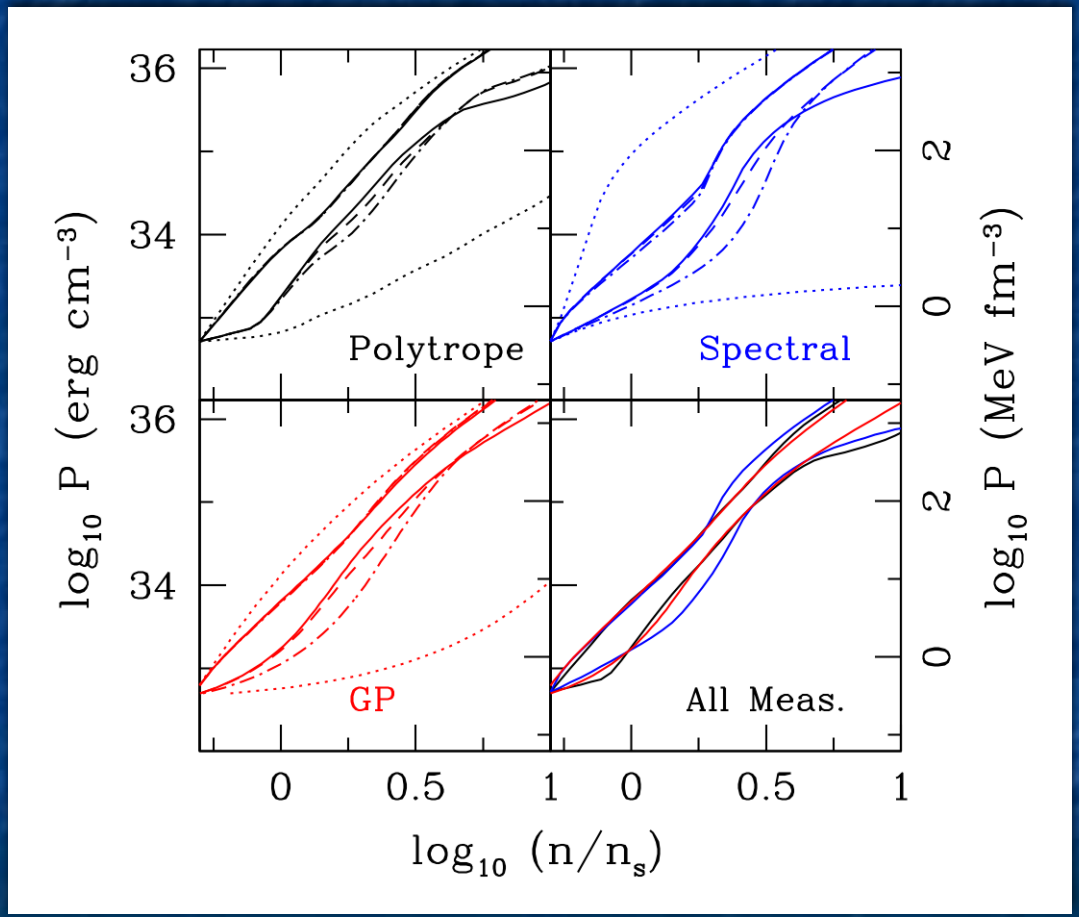
J0740, with and w/o background

- Yesterday Serena mentioned inclusion of background, with the “3C50” data set (to late 2021, but with much stricter cuts, so similar total exposure)
- Some updates, but no major EOS implications with these data



EOS With Different Constraints

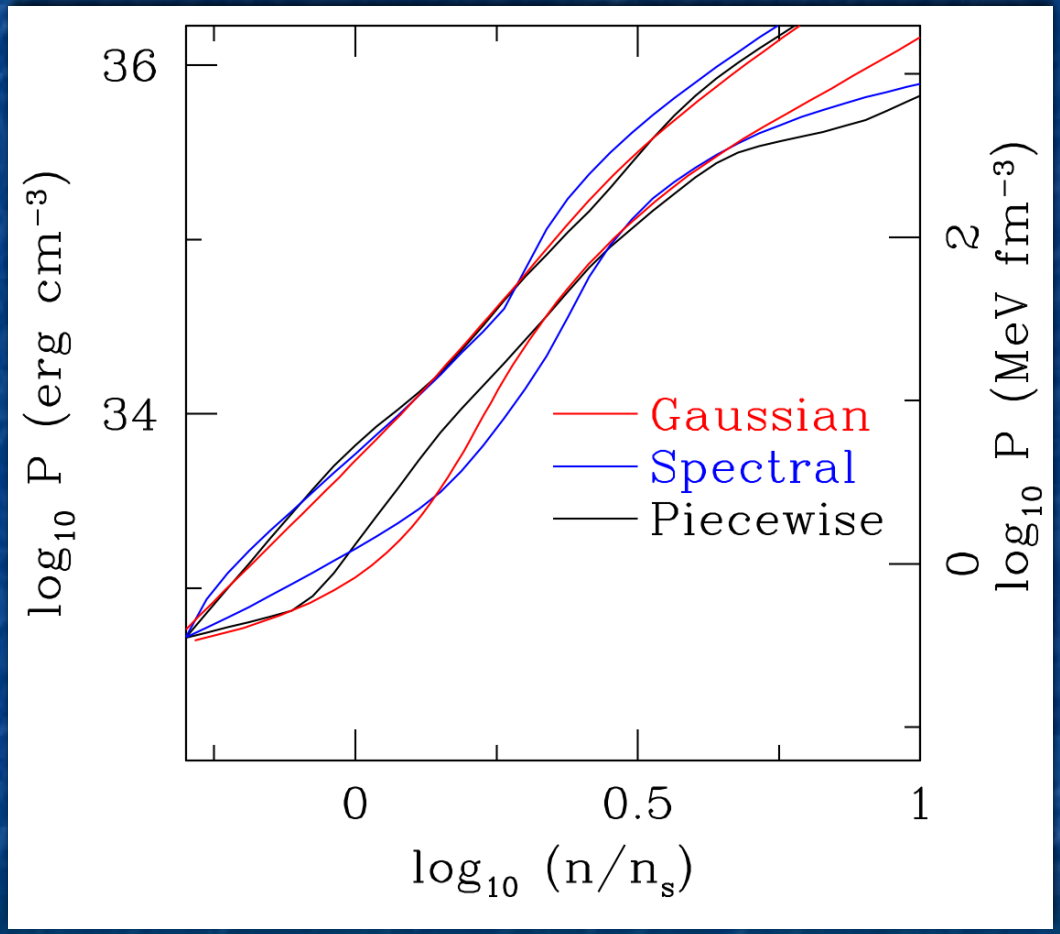


Plot shows 5th to 95th percentile at each density

Assume the QHC19 (Baym et al. 2019) EOS up to $\rho_{sat}/2$ (~ crust/core boundary)

Dotted: Priors
Dot-dash: +pre-NICER
Dashed: +J0030
Solid: +J0740

J0030, J0740, Other Measurements Provide Tight EOS Constraints



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

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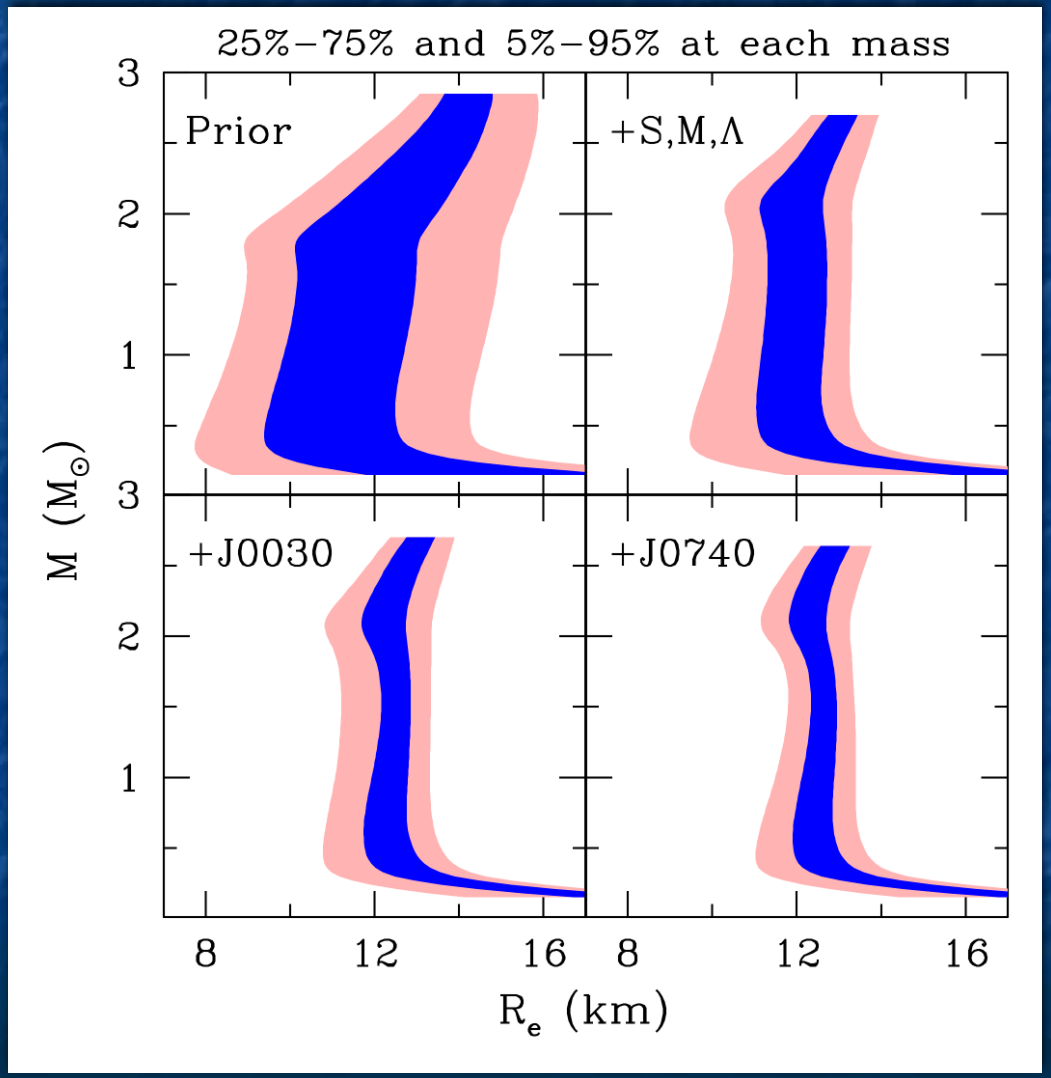
3 EOS models:

- Gaussian process
- Spectral parameterization
- Piecewise polytrope

See also Raaijmakers talk on Thursday

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!

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What comes next?

- Both groups are working on an update to the J0740 analysis, with ~60% more NICER data
  Expect ~20-30% reduction in R uncertainty
- Beyond that: additional pulsars (J0437!), which will help cross-check our published results
- NASA has granted NICER a three-year extension, so within that time the data will improve significantly
- Also, three different groups within NICER are working on background models

Conclusions

- 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