Learning About Dense Matter Using NICER

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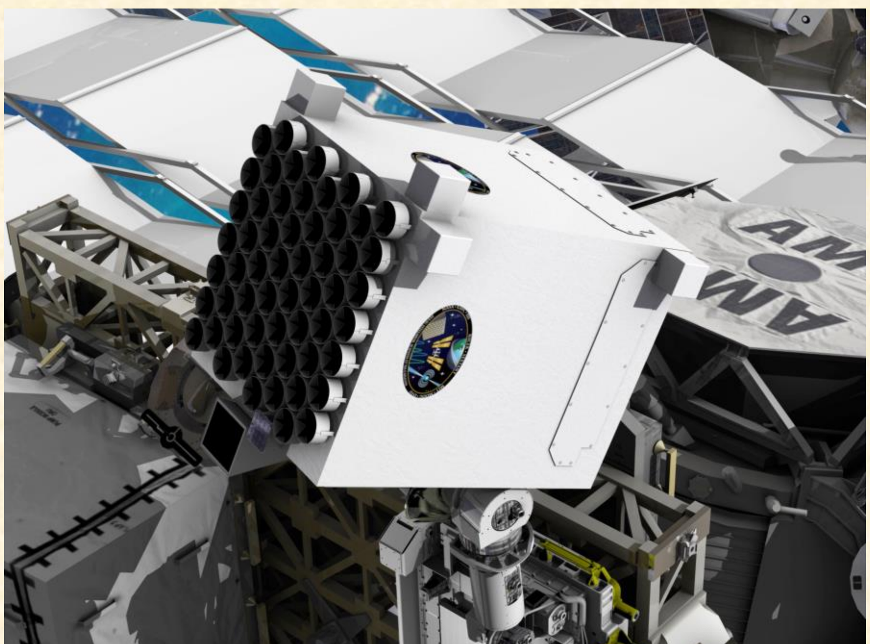
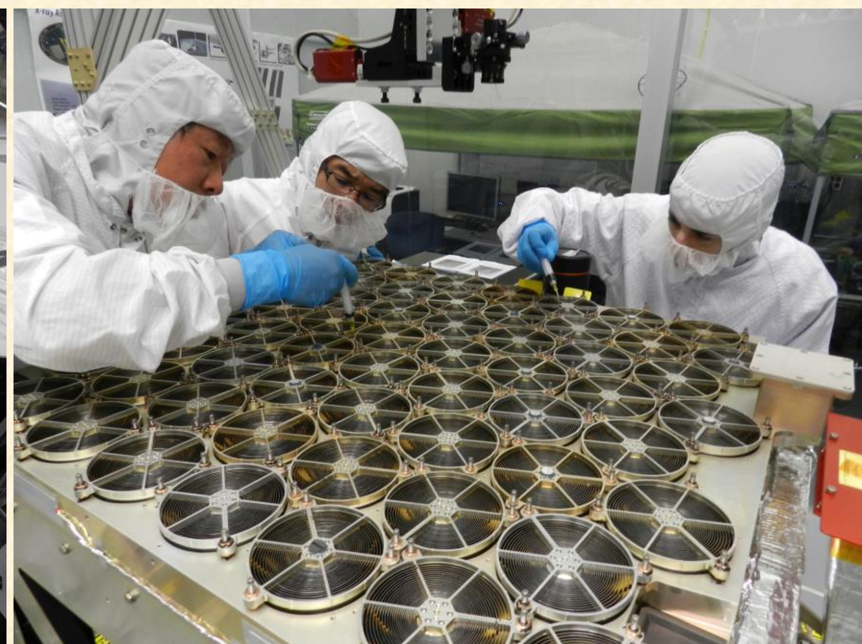




Outline

- The importance of neutron star radii
- NICER measurements of mass and radius of PSR J0030+0451

Will talk only about our work (Miller, Lamb, Dittmann+ 2019)
Please also read other papers in the ApJ Letters focus issue, especially Riley et al. 2019; Raaijmakers et al. 2019; Bilous et al. 2019

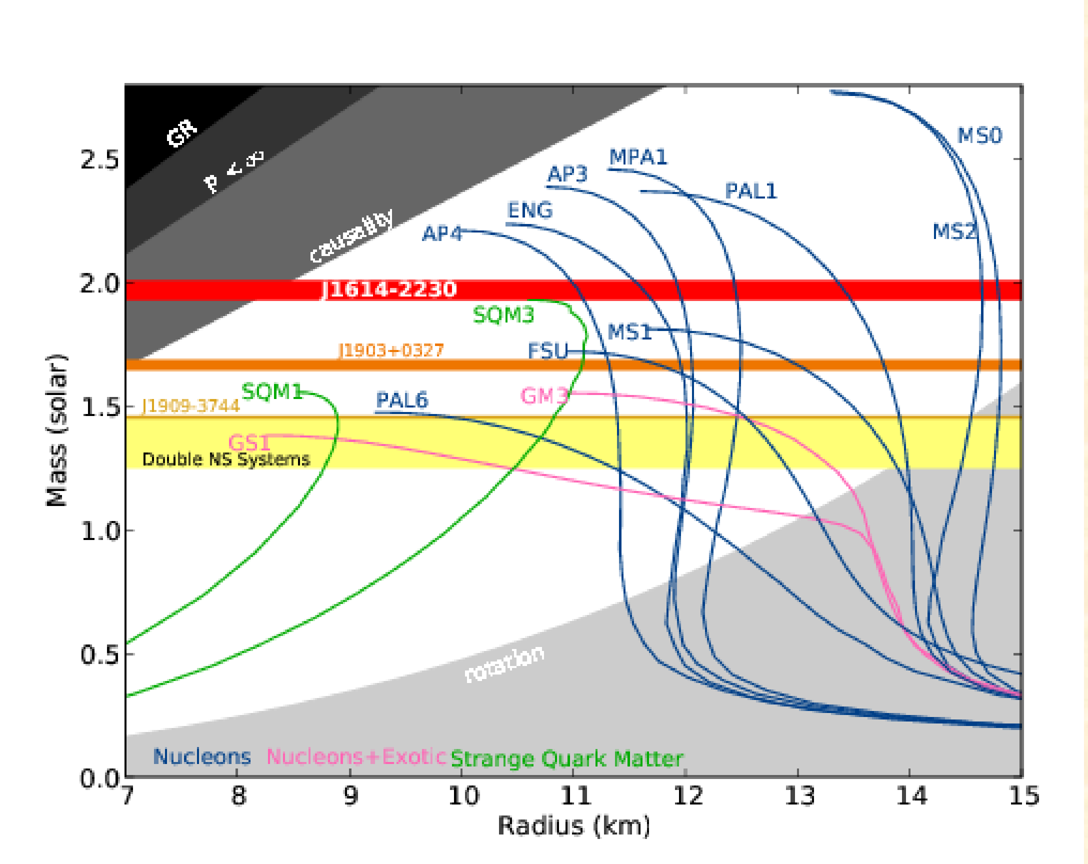
Key point: favored models from the two NICER groups are fully consistent with each other in M, R, and spot patterns

But First: The Main Results

- For the 205.53 Hz pulsar PSR J0030+0451 Isolated pulsar: no indep knowledge of M
- Equatorial radius $R_e = 13.02^{+1.24}_{-1.06}\ \mathrm{km}$
- Gravitational mass $M = 1.44^{+0.15}_{-0.14}\ M_\odot$
- Best configuration has three spots; almost equally good configuration has two spots
- All spots are in the rotational hemisphere opposite observer. At least one spot is highly elongated

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

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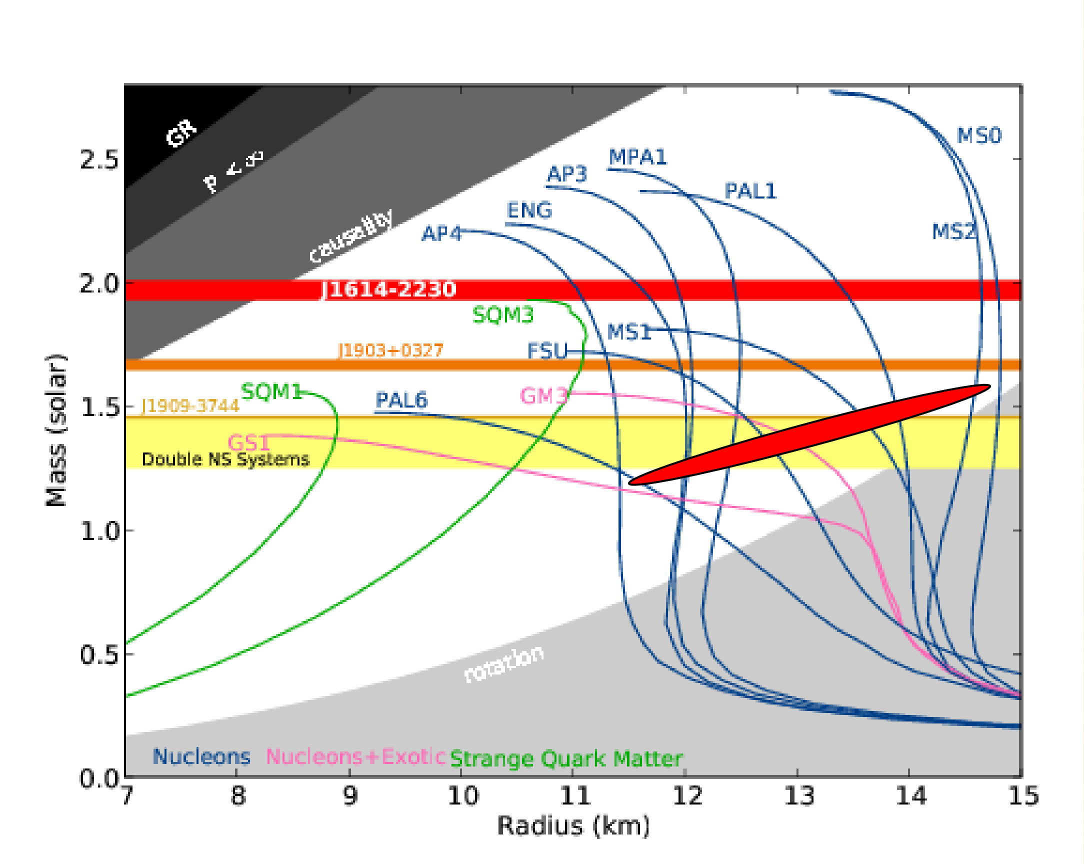
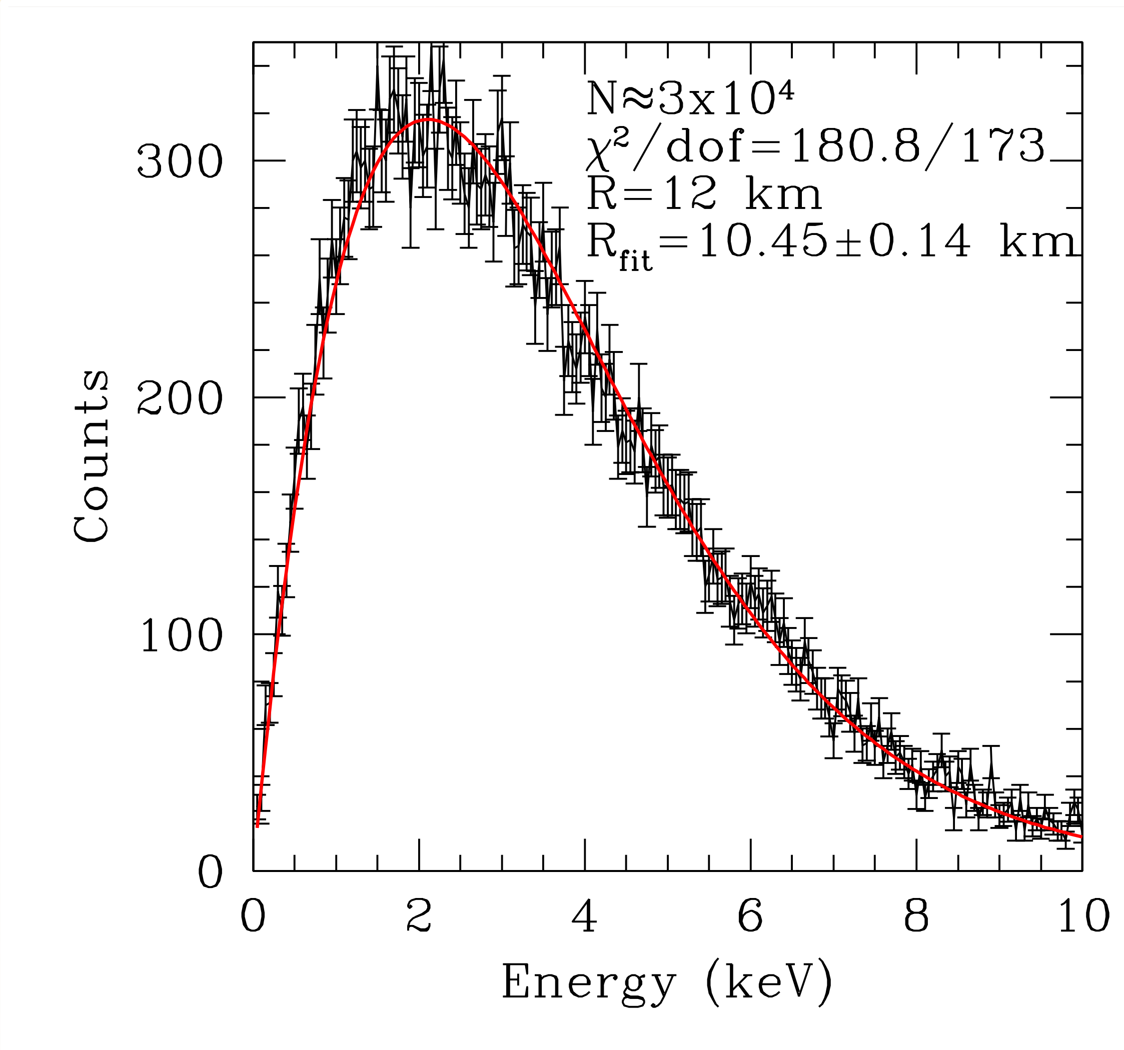


Demorest+ 2010

Radius Bias with T Variation



Example of the bias toward low radii from single-temp fits to surface with varying temperature.

Temperature varies smoothly from 2 keV (equator) to 0.2 keV (pole).

Fit is good, but R is 13% low. With narrower T profile, correction is larger

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

Assume perfect energy response, zero N_H

Key: Minimal Systematic Errors

- Extensive work by Fred Lamb (Illinois) and myself with our collaborators suggests that when we fit *energy-dependent* waveforms, 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 Idea in Brief

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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

Concern about rotation?

- Fundamentally, we are tracing photons from the star to the observer
- If star is not rotating, this is relatively simple: no rotation means spherical symmetry, so a given photon travels in a plane
- ***Not*** true when there is rotation; frame-dragging.
- Also, star becomes oblate

Frame-dragging doesn’t matter

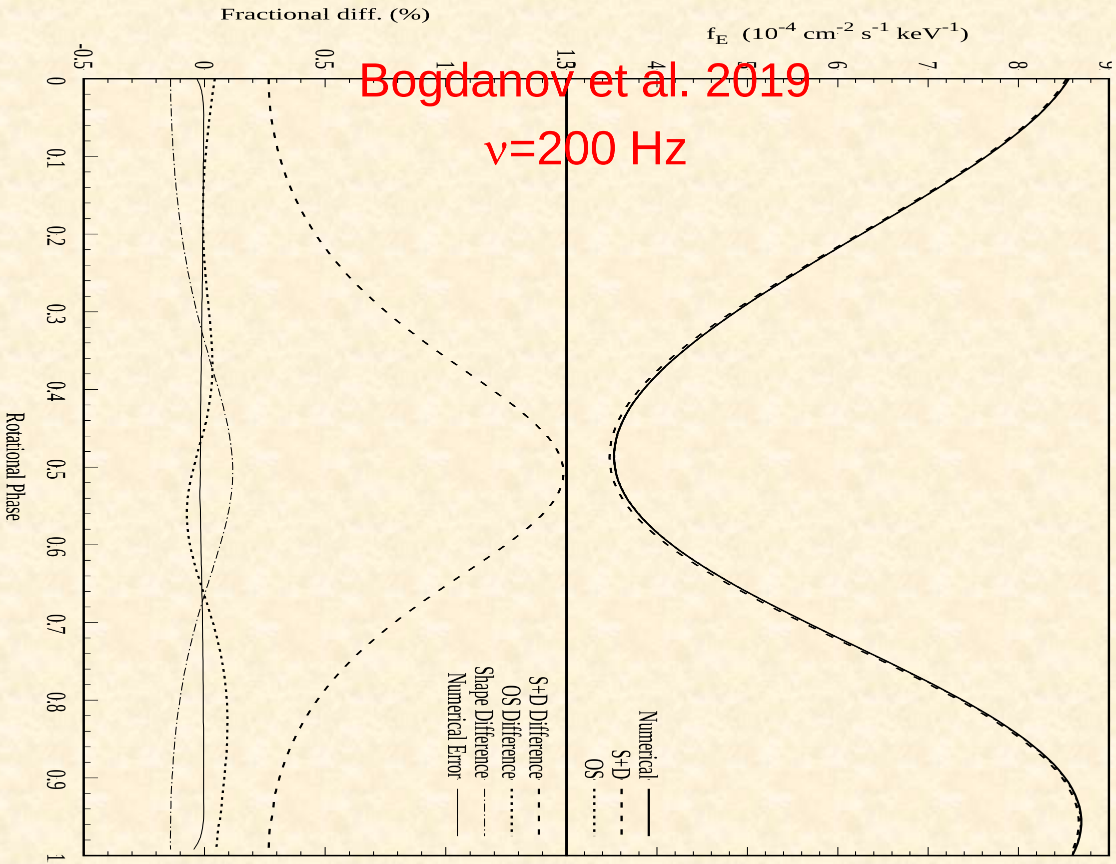
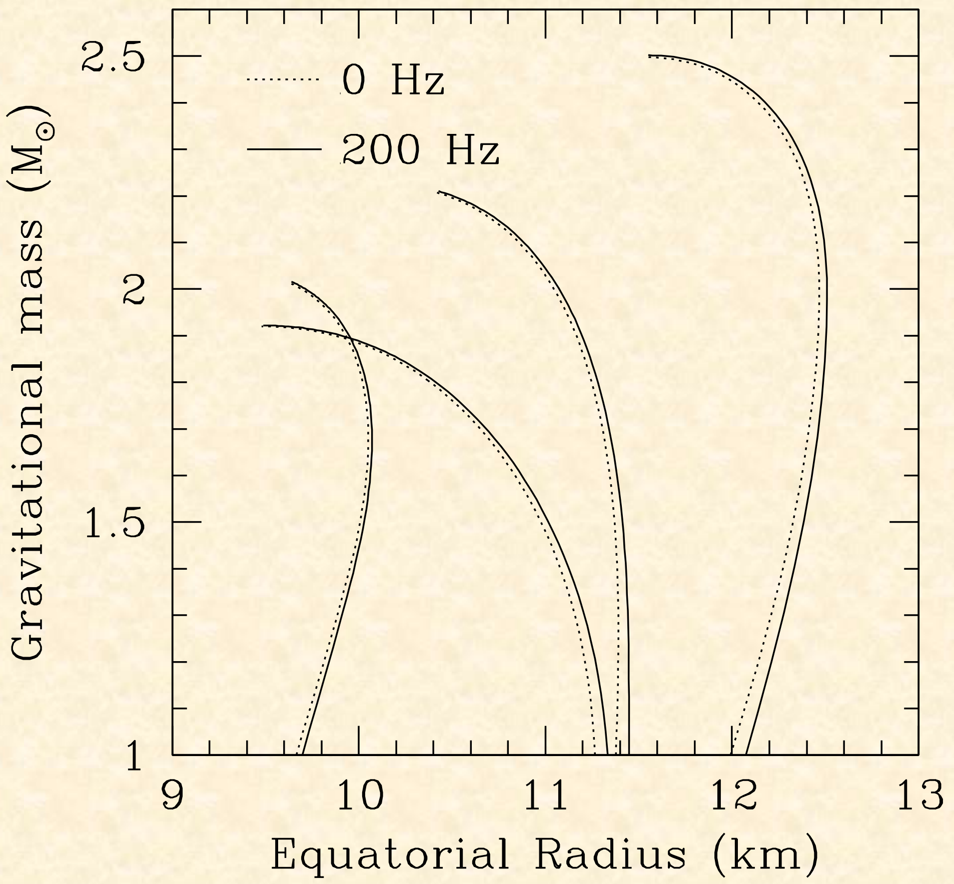


Figure by Sharon Morsink based on original concept by Scott Lawrence (UMd)

Approximations:
S+D: star is spherical, Schwarzschild+SR ray tracing.
OS: star is oblate, Schwarzschild+SR ray tracing.
Compare with full numerical waveform

Conclusion: to the precision we need, we can treat spacetime as if there is no rotation

Effect of Rotation on M-R Curves

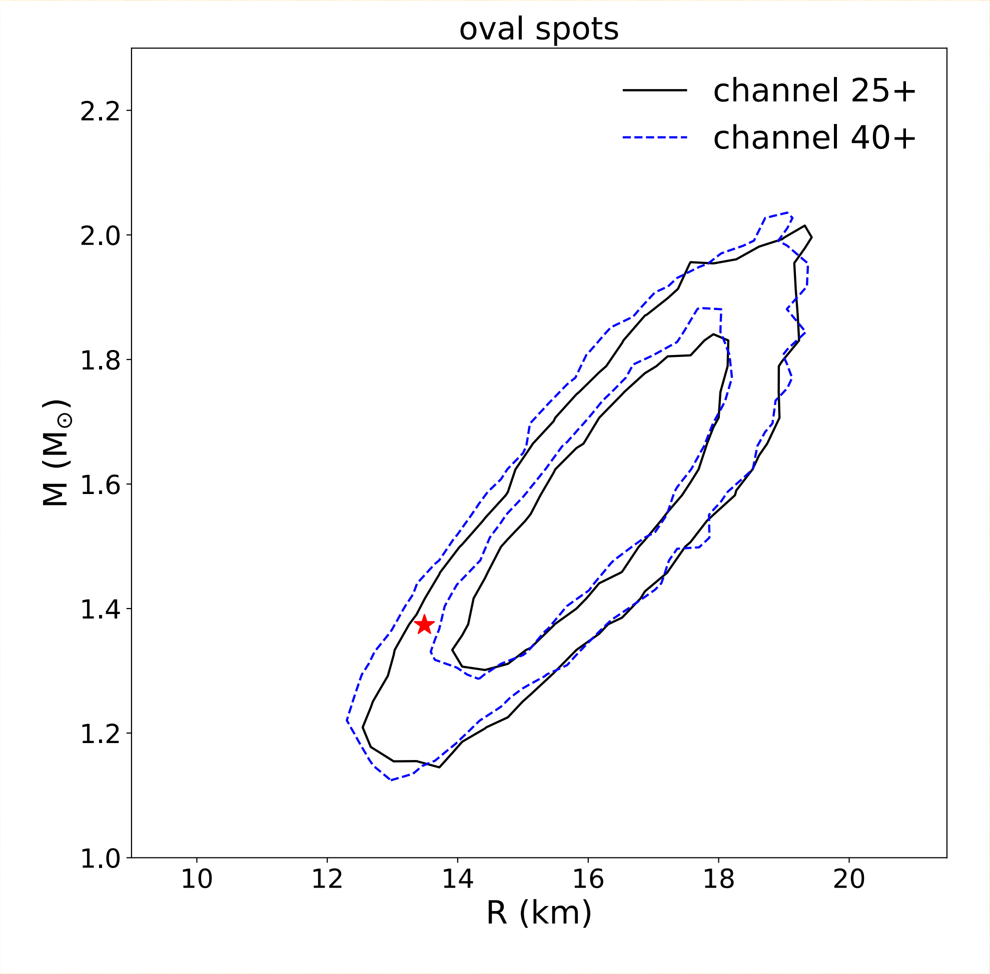


M vs. R for four EOS, at 200 Hz vs. 0 Hz. Difference is negligible compared with measurement precision. Calculations by Sharon Morsink.

Models Used in Fits

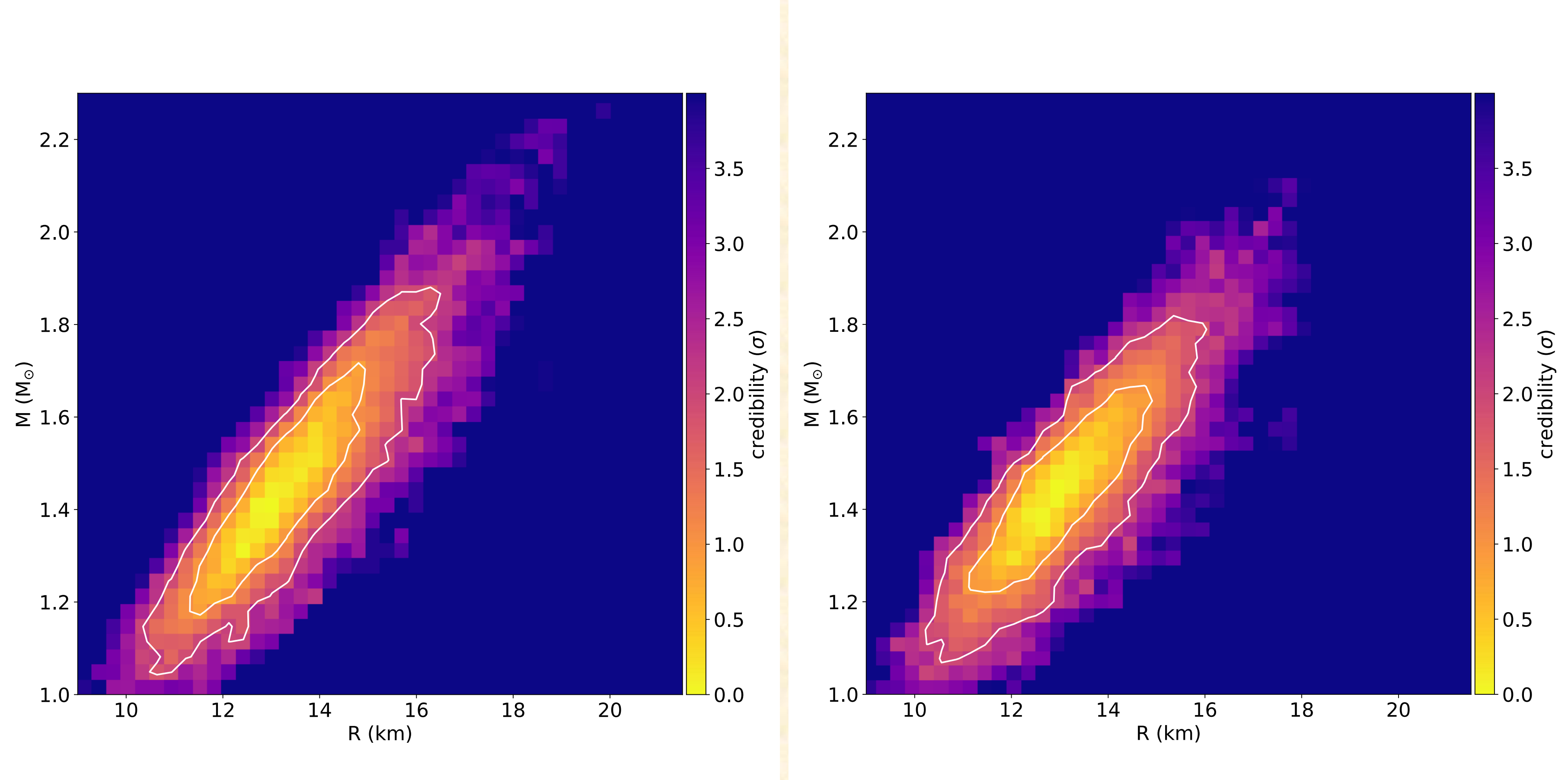
- We consider uniform-temperature spots
  Possibly different T; arbitrary locations
- Each spot can be oval: start with a circular spot and stretch or squash it azimuthally
  Fits include unmodulated background
- Fits use two or three oval spots
  Arbitrary overlap of spots
  Gives great flexibility of modeling (e.g., can have isolated spots, or crescents)

Fit to Synthetic Two-oval Data



Inner contour: 68% of posterior probability
Outer contour: 95% of posterior probability

Mass-Radius Posteriors for J0030

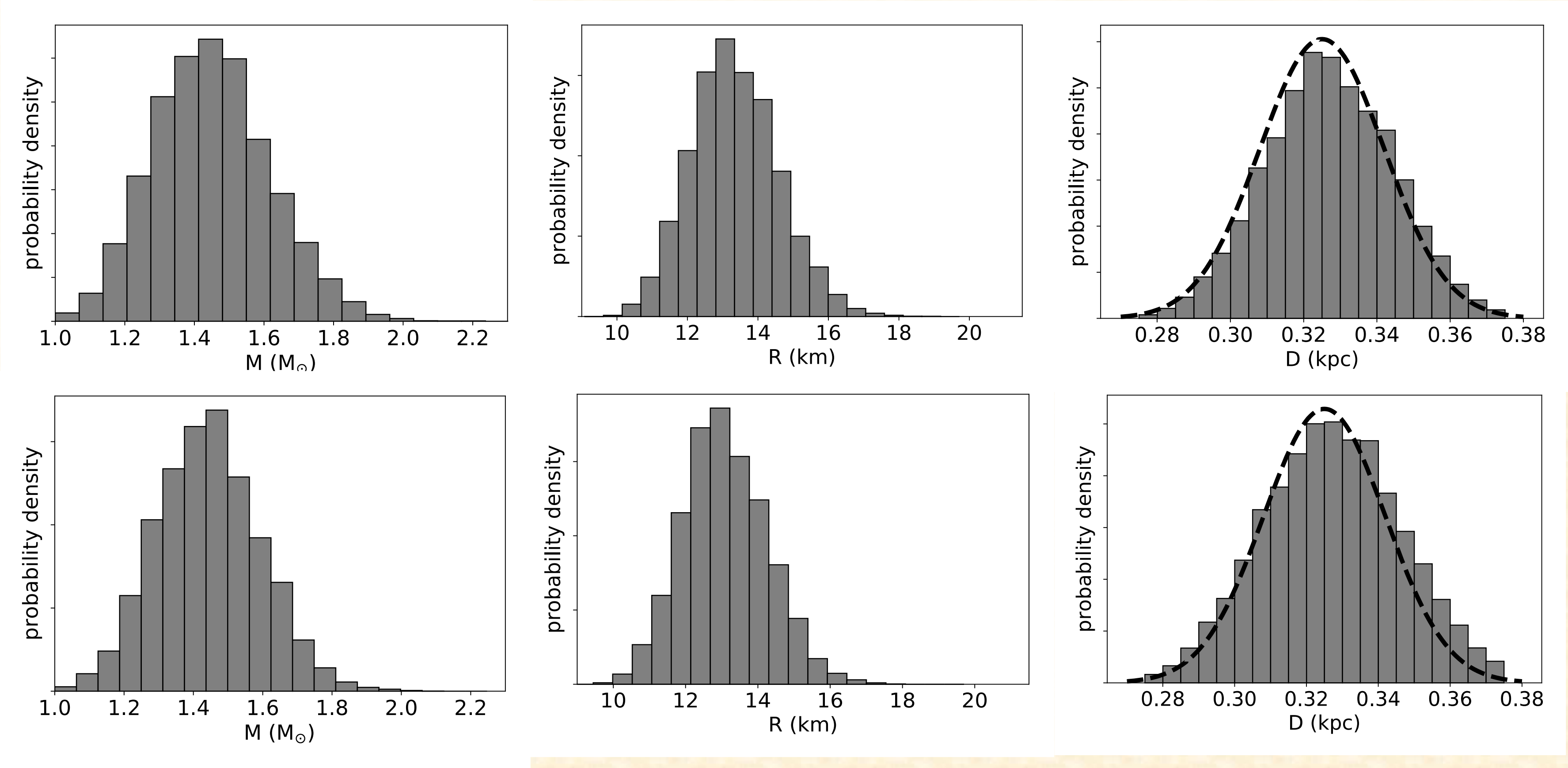


Left: M-R posterior for NICER J0030 data, two ovals

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

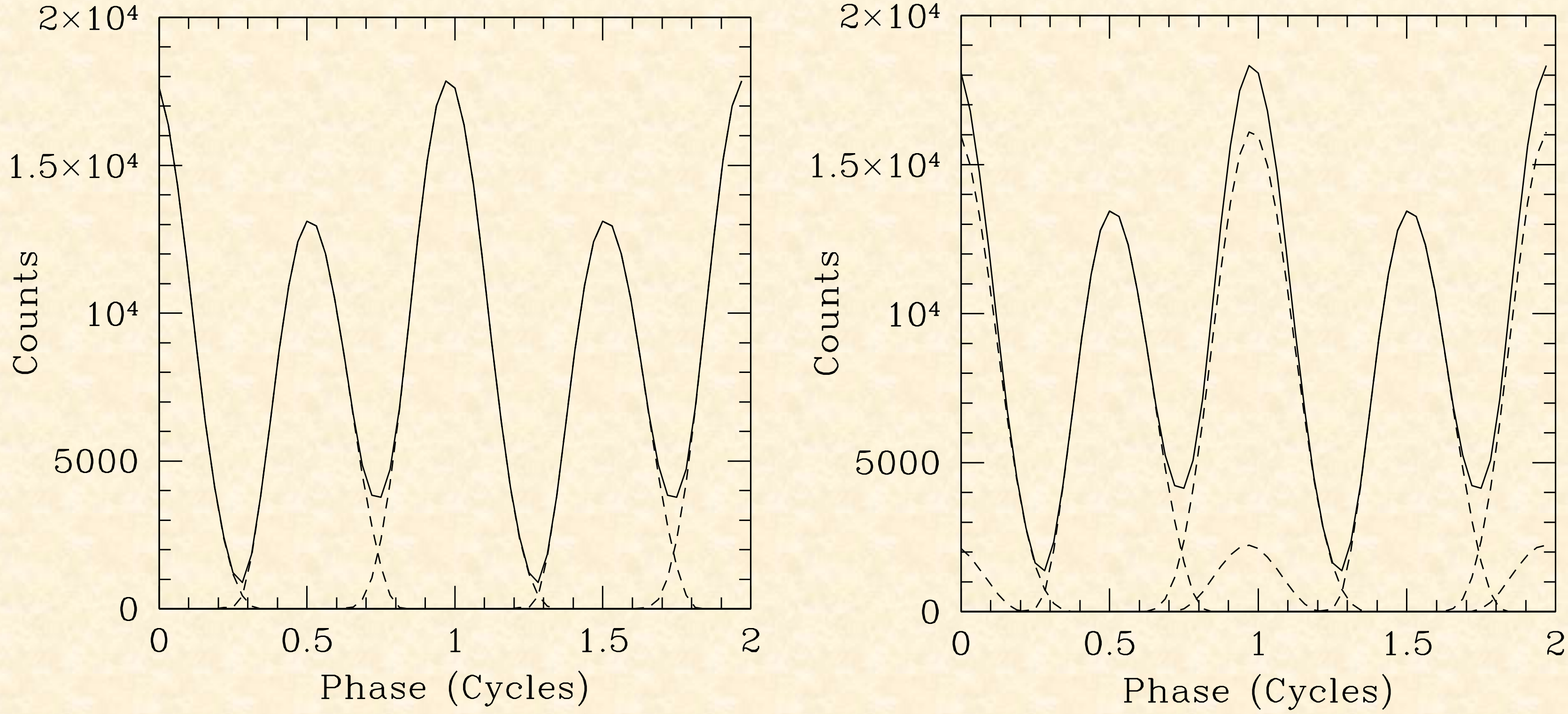
1D Posteriors: NICER 2,3-oval

Gaussian prior on distance: $d = 0.325 \pm 0.017\ \mathrm{kpc}$; chan 40-299



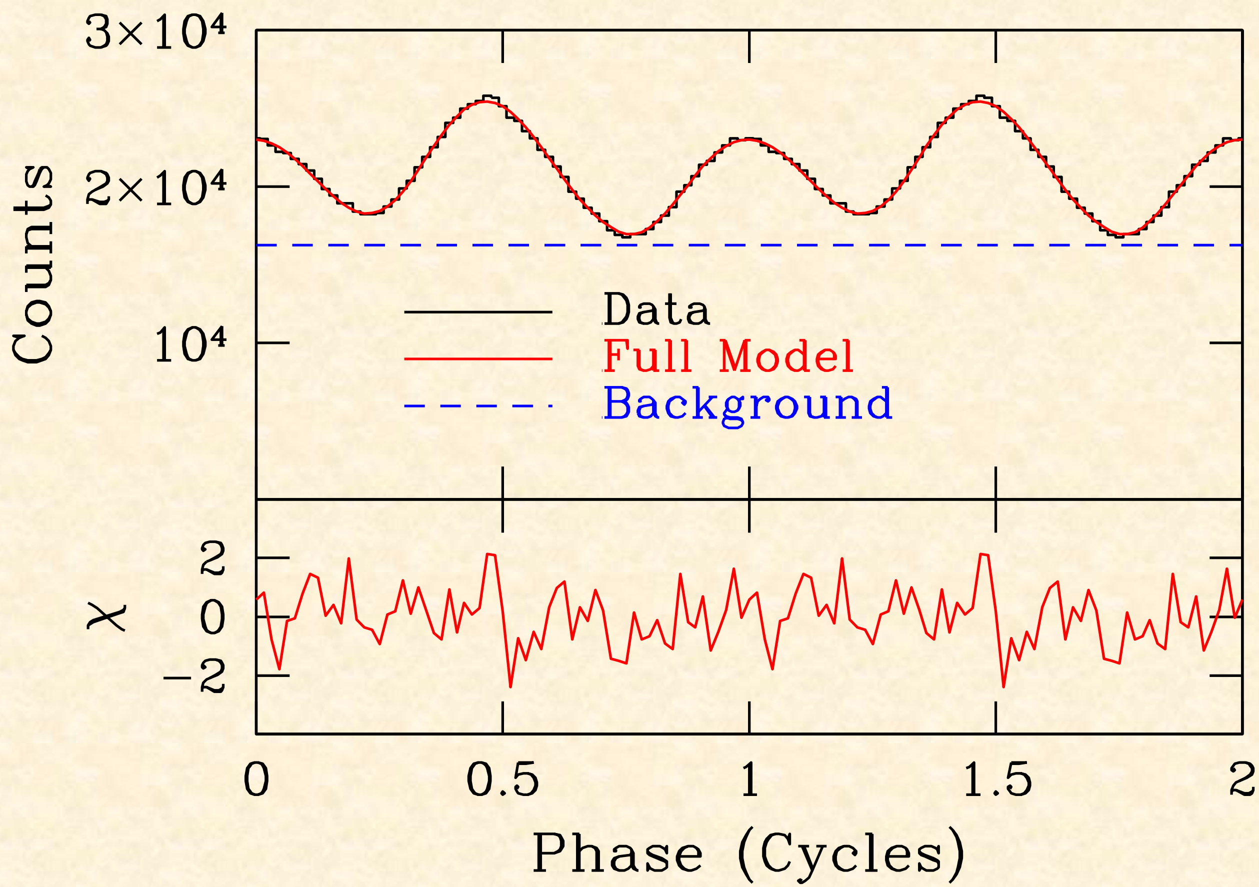
Top: analysis of NICER data, two-oval model
Bottom: analysis of NICER data, three-oval model
Dotted line on right: distance prior

Bolometric Waveforms



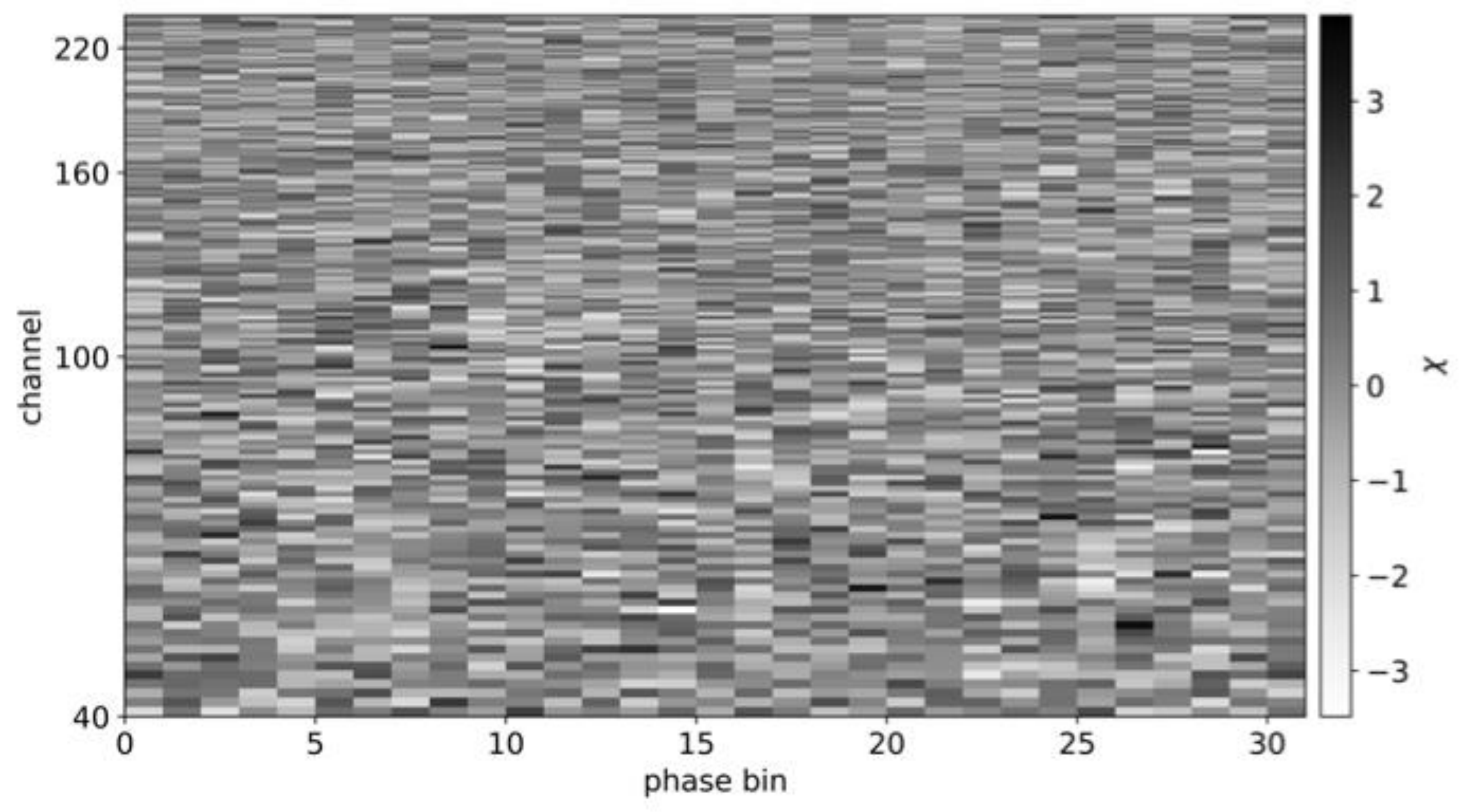
Left: two-oval model fits to NICER J0030 data
Right: three-oval model fits to NICER J0030 data
Dotted lines are individual spots; solid, total

Bolometric Residuals



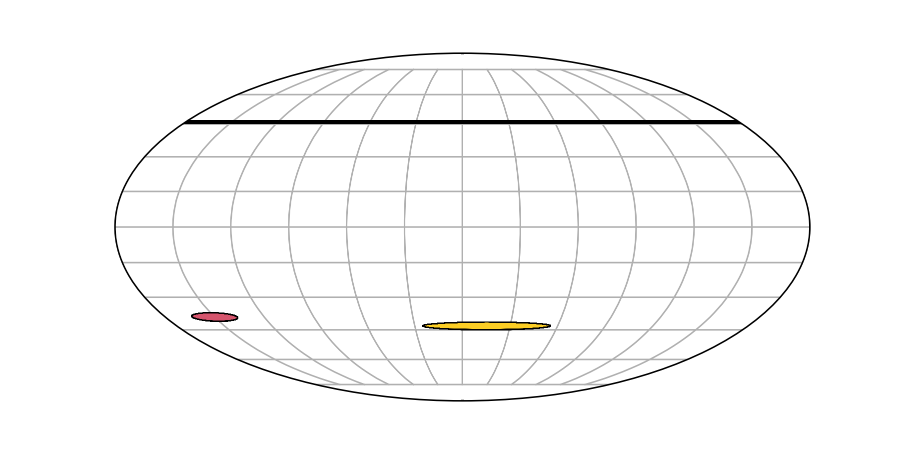
Residuals of best-fit three-oval model compared with J0030 NICER data, for 64 phases. Fit is good

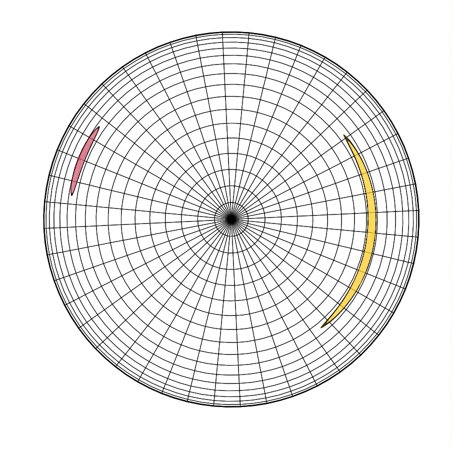
Phase-Channel Residuals

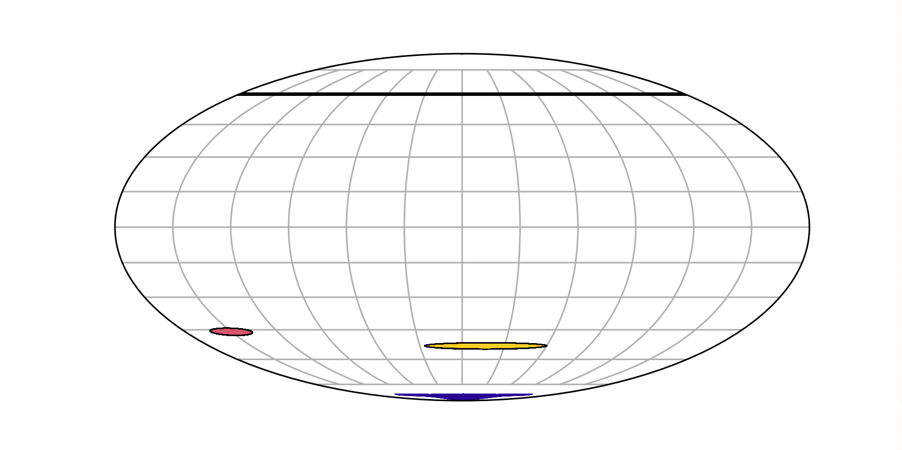


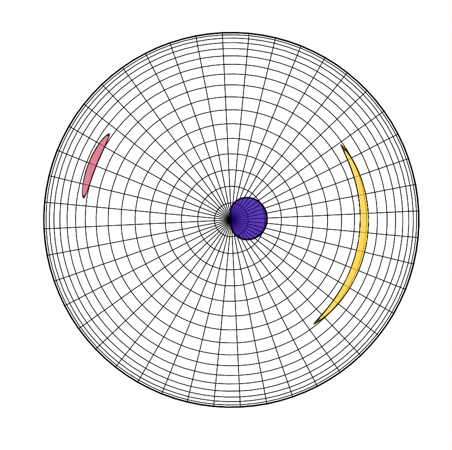
Residuals (in χ) for best three-oval fit to NICER J0030 data. No patterns are evident, as one would expect from a good fit (χ^2/dof=8189/8040, 12%)

Spot Patterns



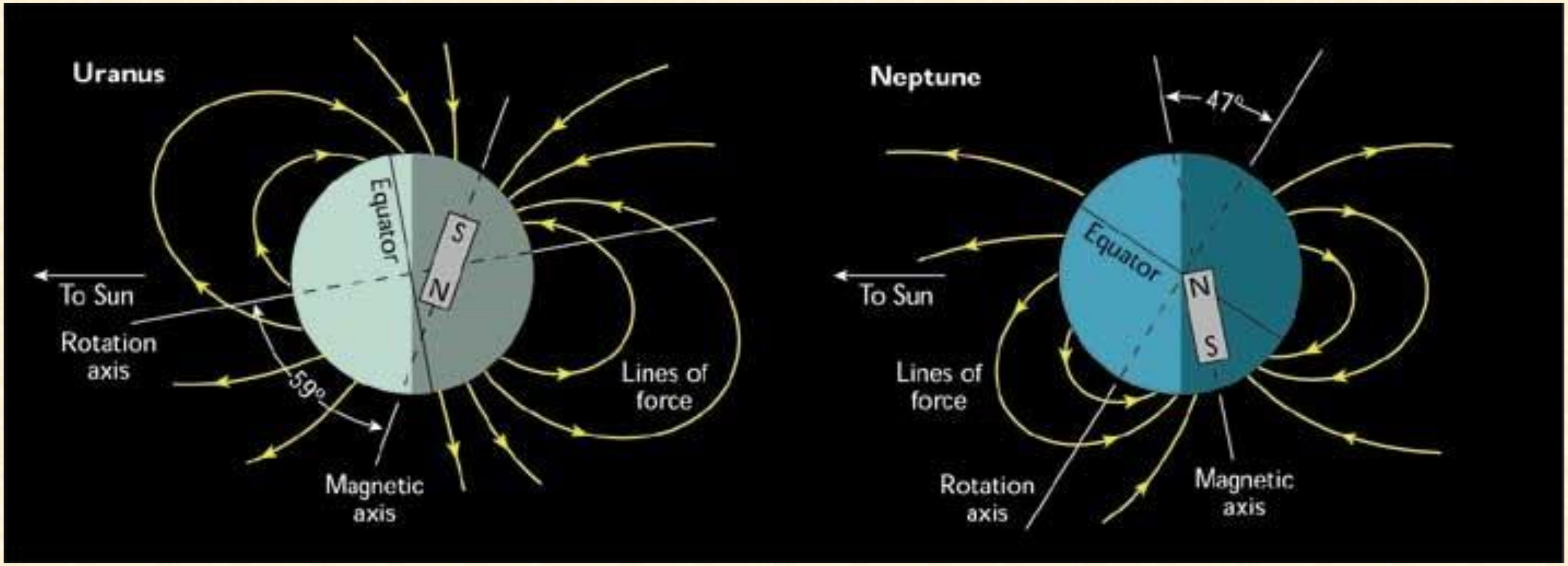






Top: two-oval fit. Bottom: three-oval fit
Horizontal solid line shows observer inclination

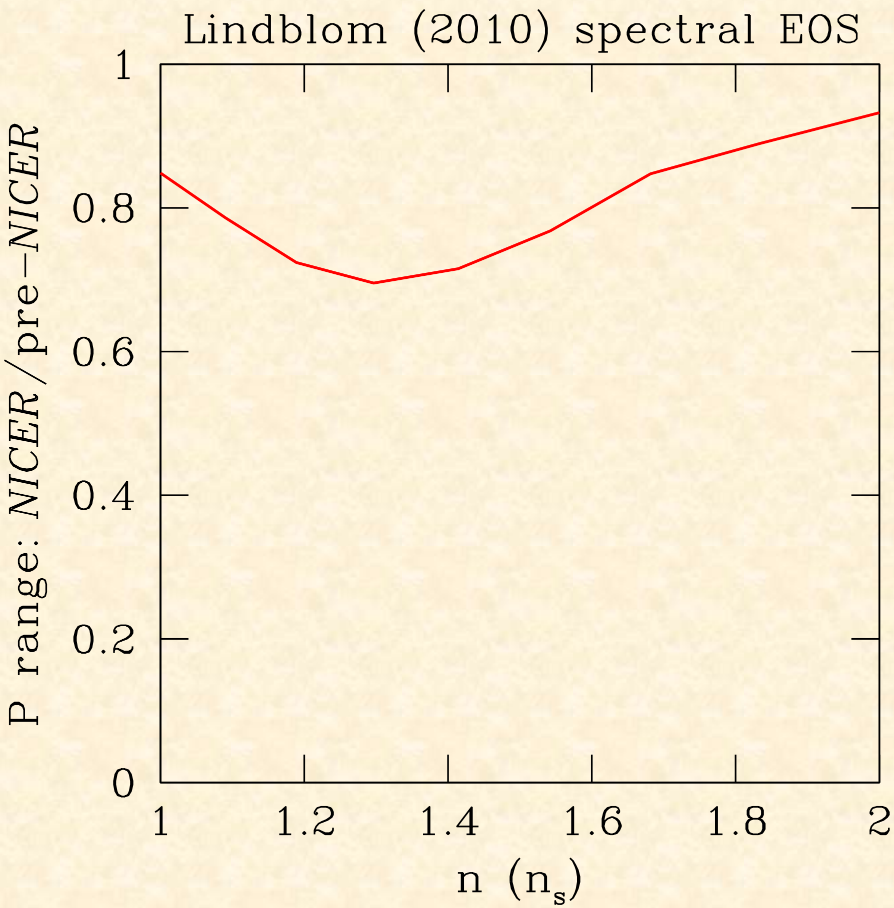
Shouldn't B be a centered dipole?



Credit: NASA

- Uranus' and Neptune's fields aren't!
- Millisecond pulsars go through complex evolution; B, spots need not be simple

NICER Contribution to EOS



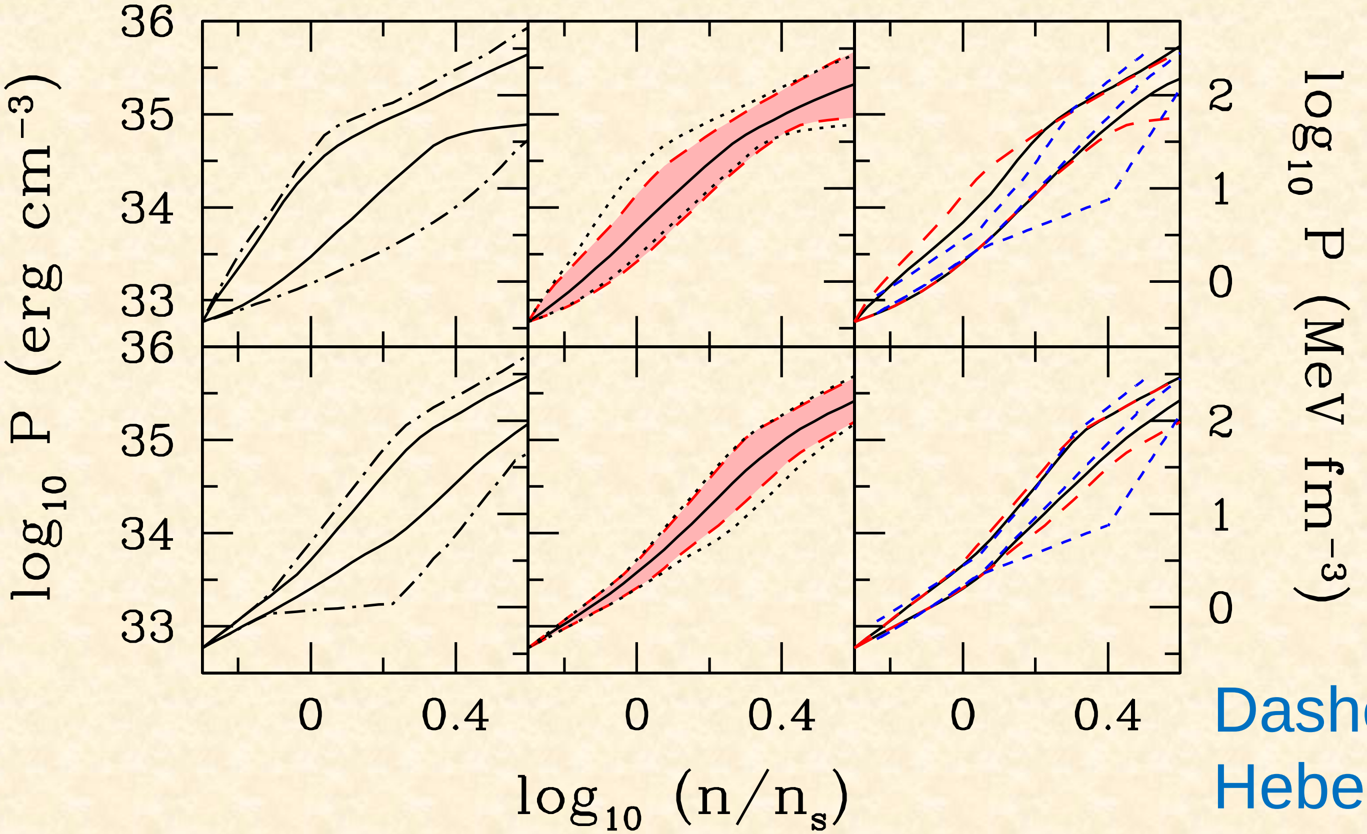
Red line: ratio of the 5%-95% pressure range when NICER (M,R) from J0030 is included, to the range prior to NICER, as a function of density

NICER M and R reduces pressure range by 10-30% from ~ρ_{sat} to 2ρ_{sat}

Exposure time will ~double by end of 2020.

Can incorporate into full EOS constraints: Miller, Chirenti, Lamb 2020, many other papers

Implications for Equation of State



Dashed lines: Hebeler+ EOS

Top: spectral EOS. Bottom: piecewise polytrope

Left: prior (dot-dash 0%-100%; solid 5%-95%)

Middle: result of adding NICER M-R for J0030; 5%-95%

Right: result of also adding high-M and Λ upper limit

Conclusions

- First NICER measurements, for PSR J0030+0451, have already tightened EOS constraints. Full, (M,R) posterior samples: https://zenodo.org/record/3473466
- Key: measurements appear reliable as well as precise
- Doubling+ of data set and contributions from analysis of other pulsars (especially J0437 [best precision] and J0740 [highest mass]) will improve constraints substantially