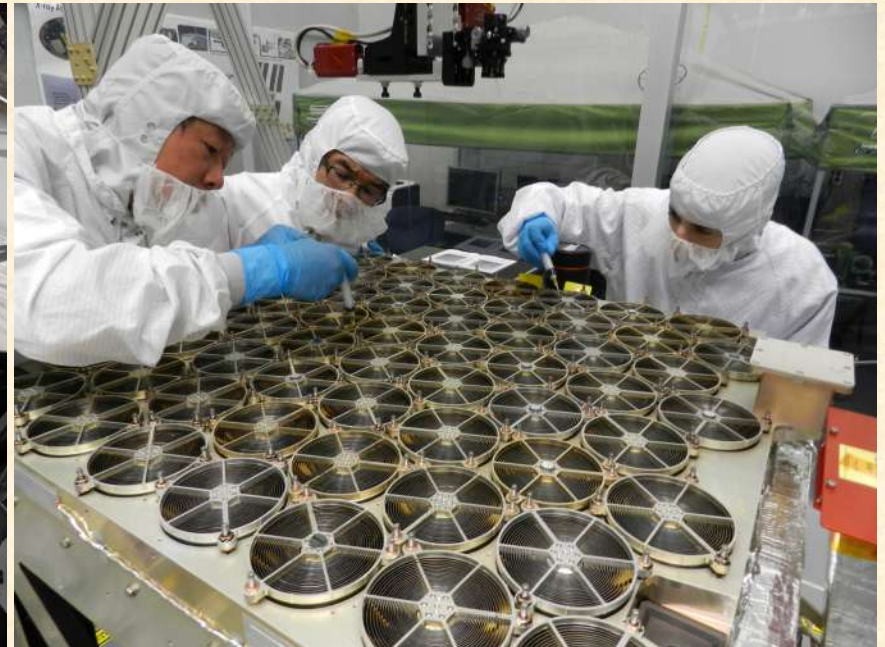
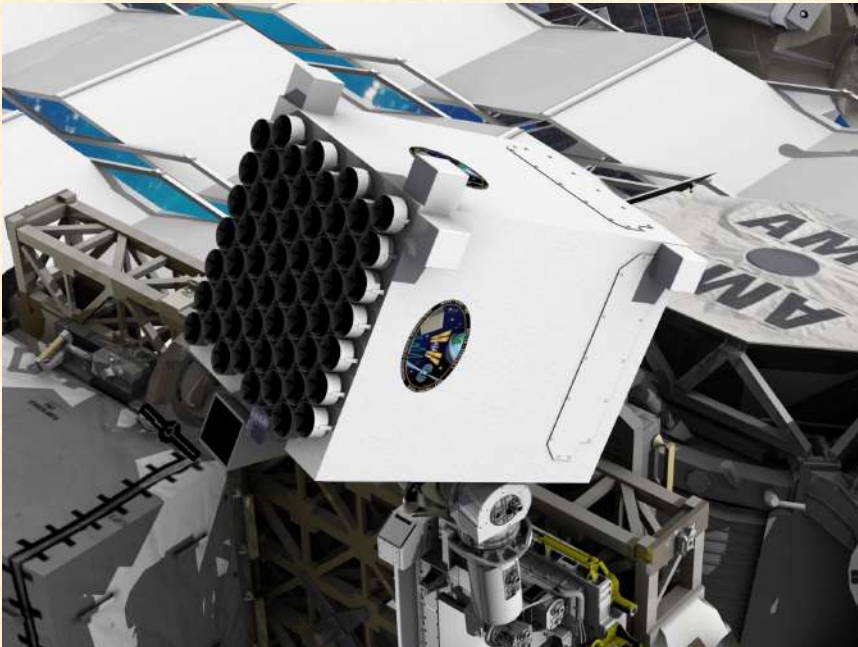


NICER, Gravitational Waves, and Neutron Stars

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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

Questions During Talk

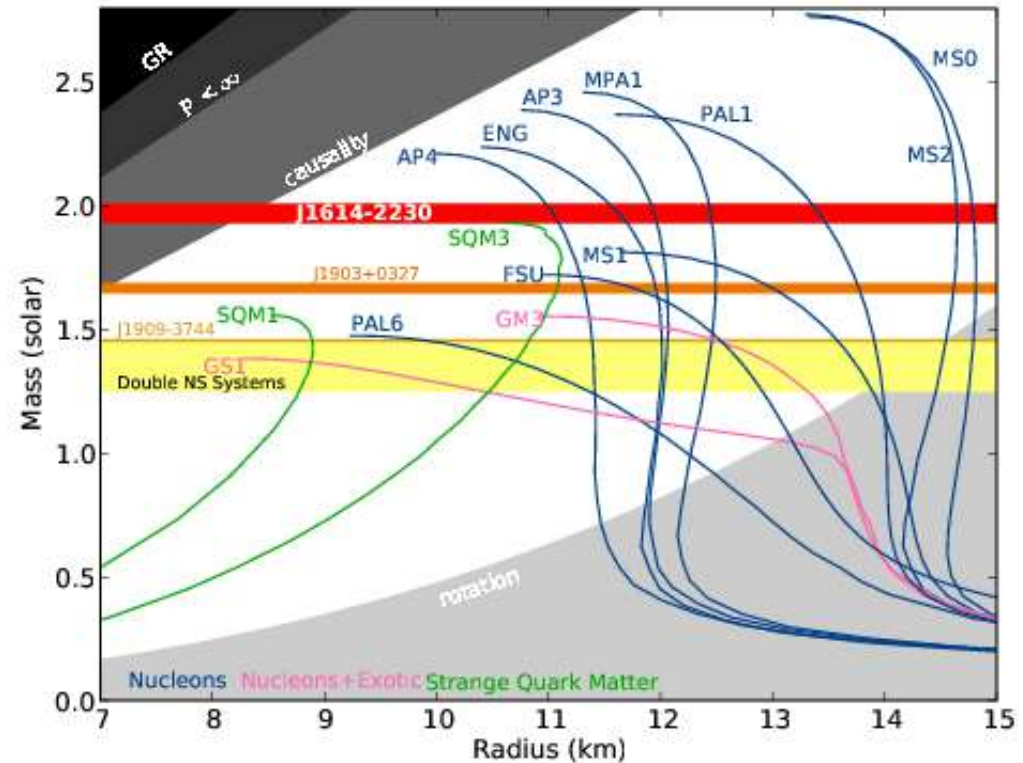
- Please feel free to ask questions at any time
- I will also pause twice during the talk to determine whether anyone would like to pursue discussion points

But First: The Main Results

- For the 205.53 Hz pulsar PSR J0030+0451
Isolated pulsar: no indep knowledge of M
- Equatorial radius $R_e = 13.02_{-1.06}^{+1.24}$ km
- Gravitational mass $M = 1.44_{-0.14}^{+0.15} M_{\odot}$
- 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

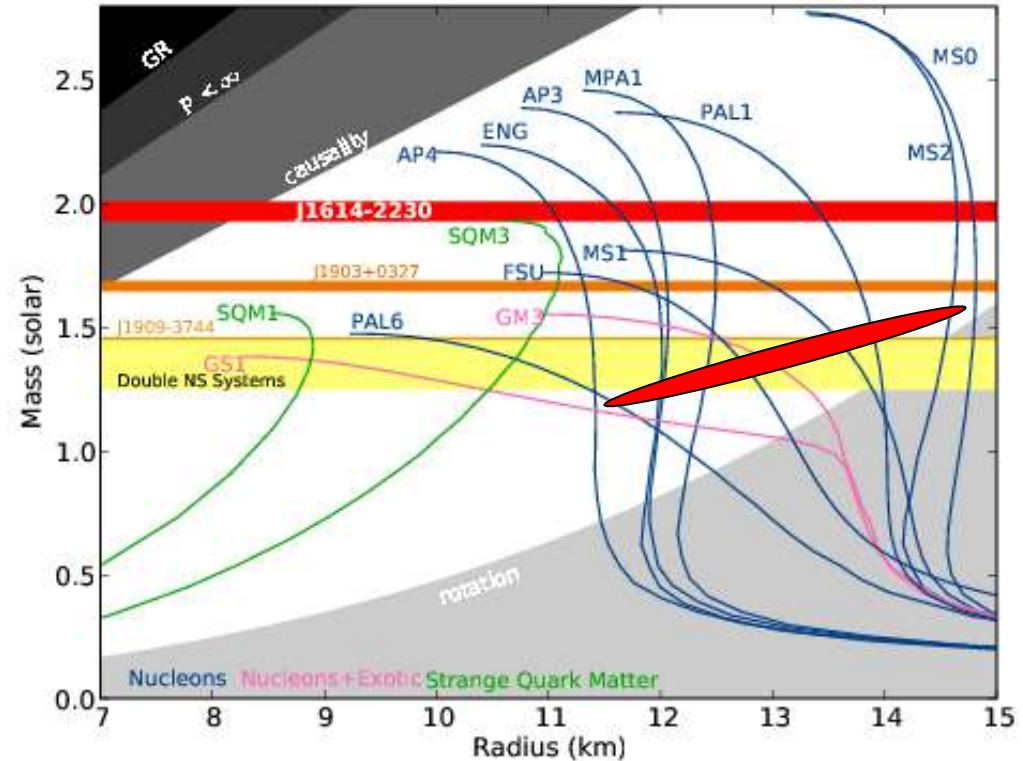
- Radius would provide great EOS leverage
Wide range in models
- But tough to measure
- Previous published measurements are susceptible to huge systematic error
- NICER X-ray pulse modeling can help



Demorest+ 2010

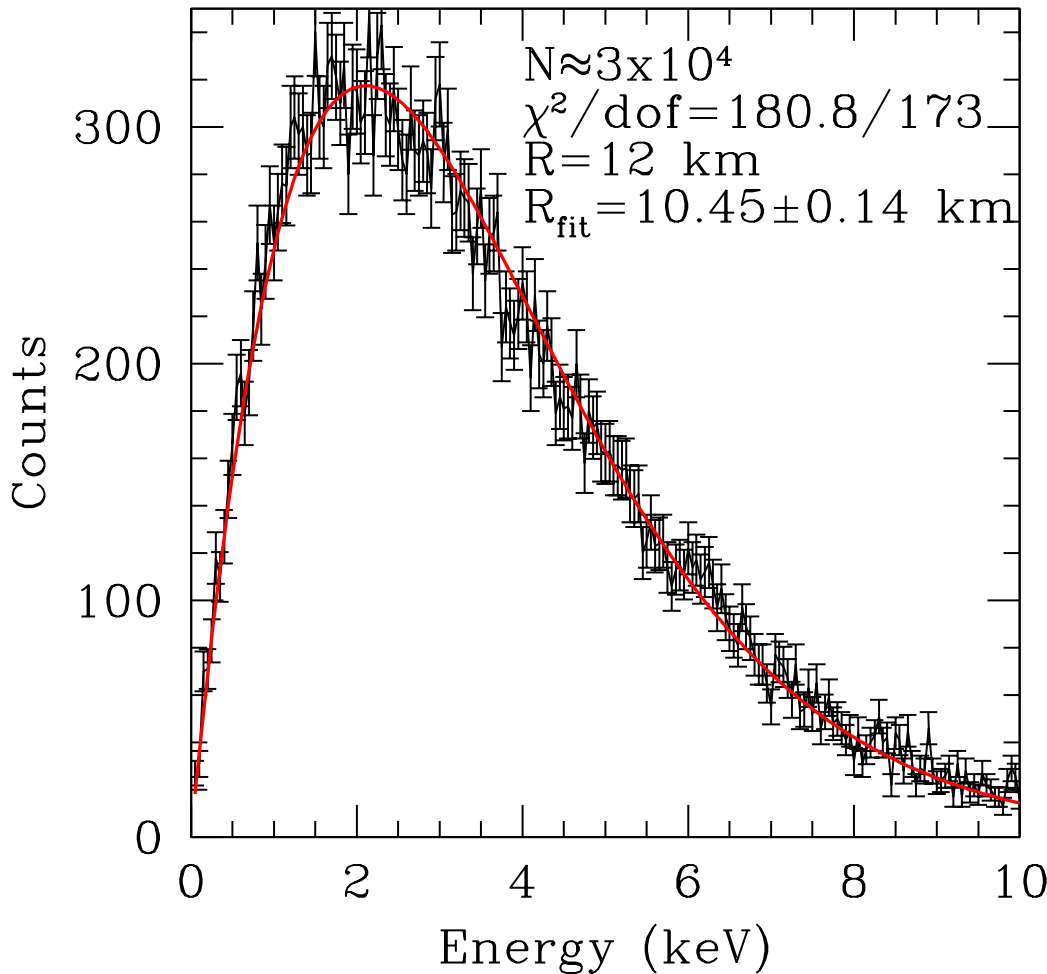
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Demorest+ 2010

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



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

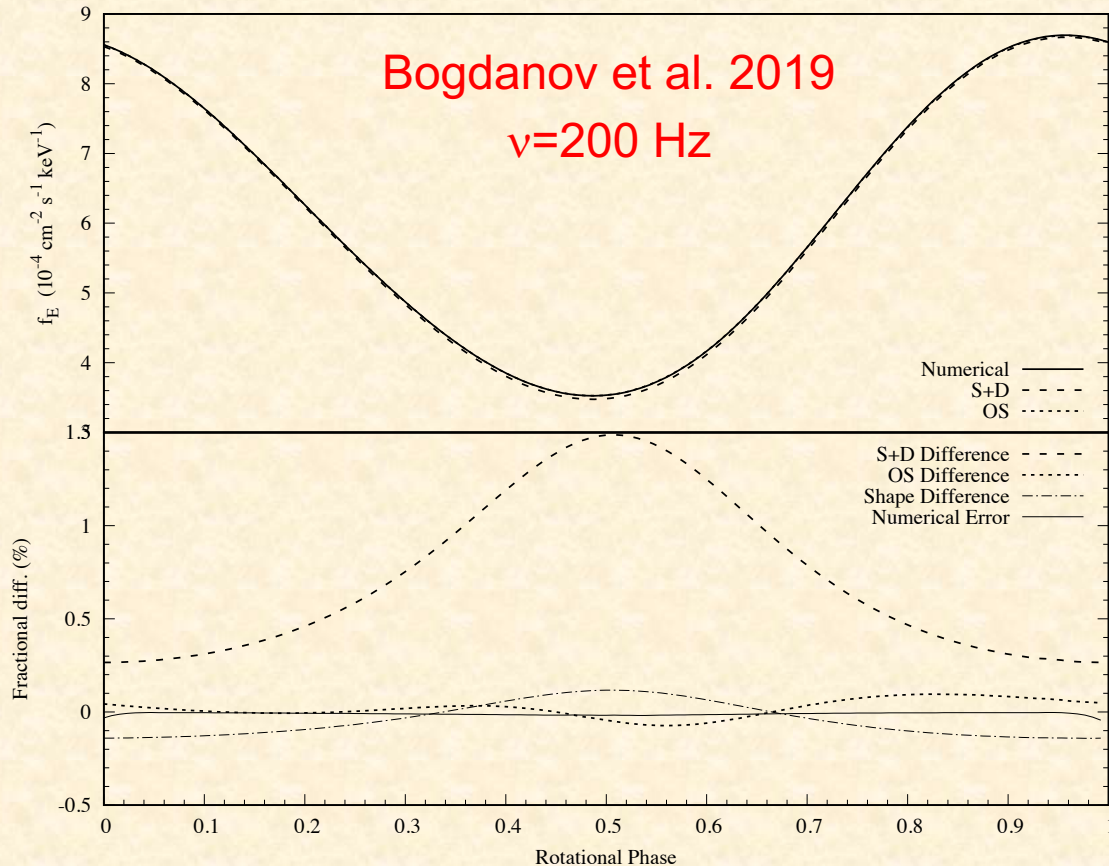


Figure by Sharon Morsink based on original concept by Scott Lawrence (UMd)

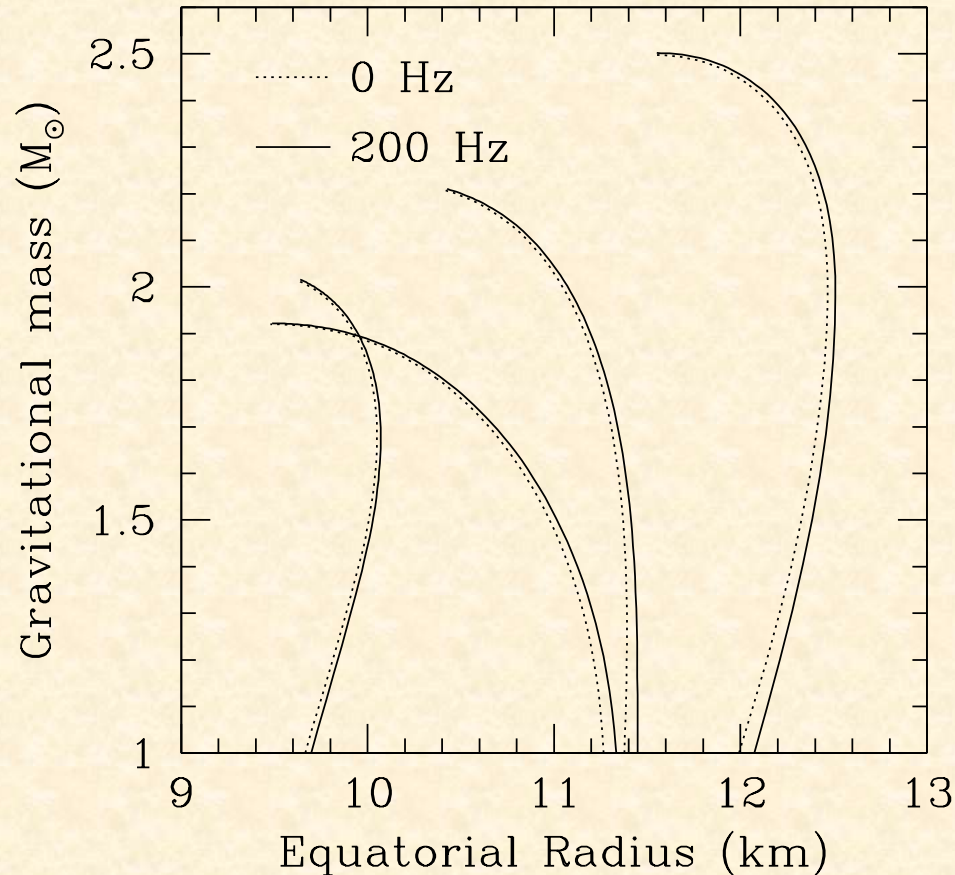
Approximations:
S+D: star is spherical,
Schwarzschild+SR ray
tracing.

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

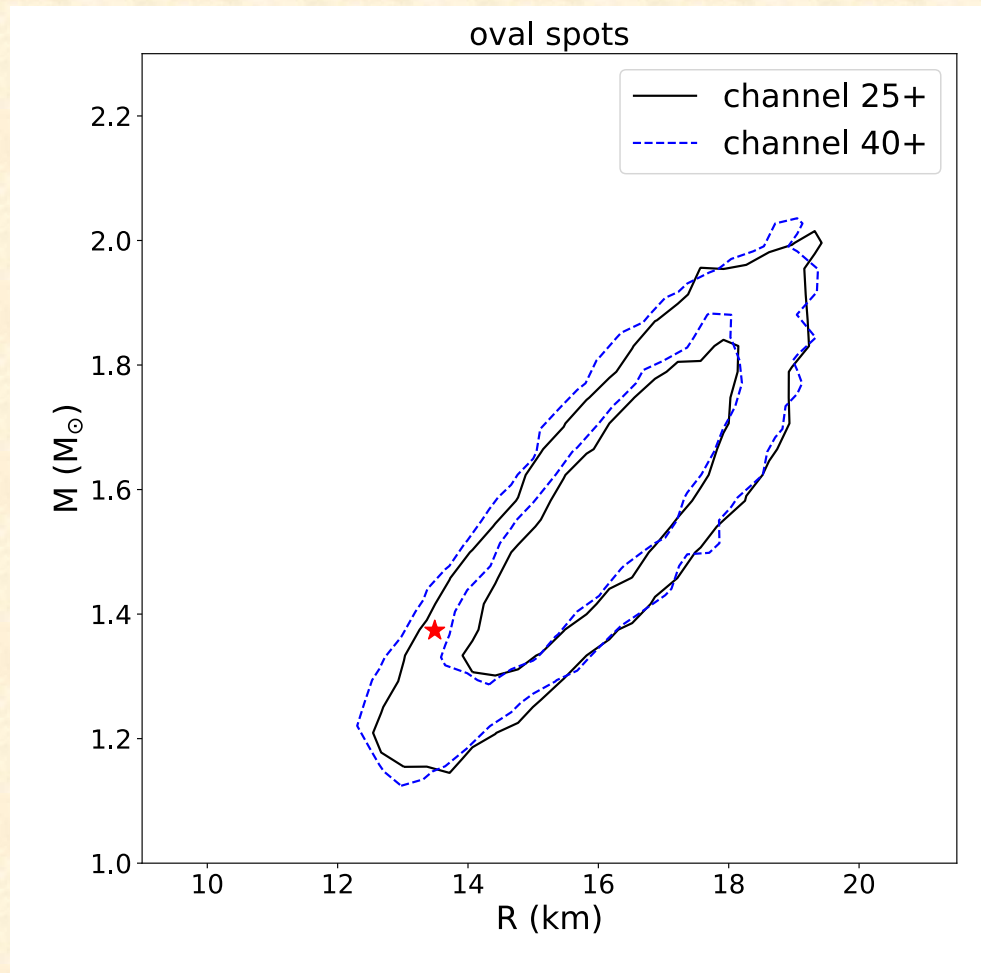


M vs. R for four EOS, at 200 Hz vs. 0 Hz. Difference is negligible compared with measurement precision. Calculations by Sharon Morsink.

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)

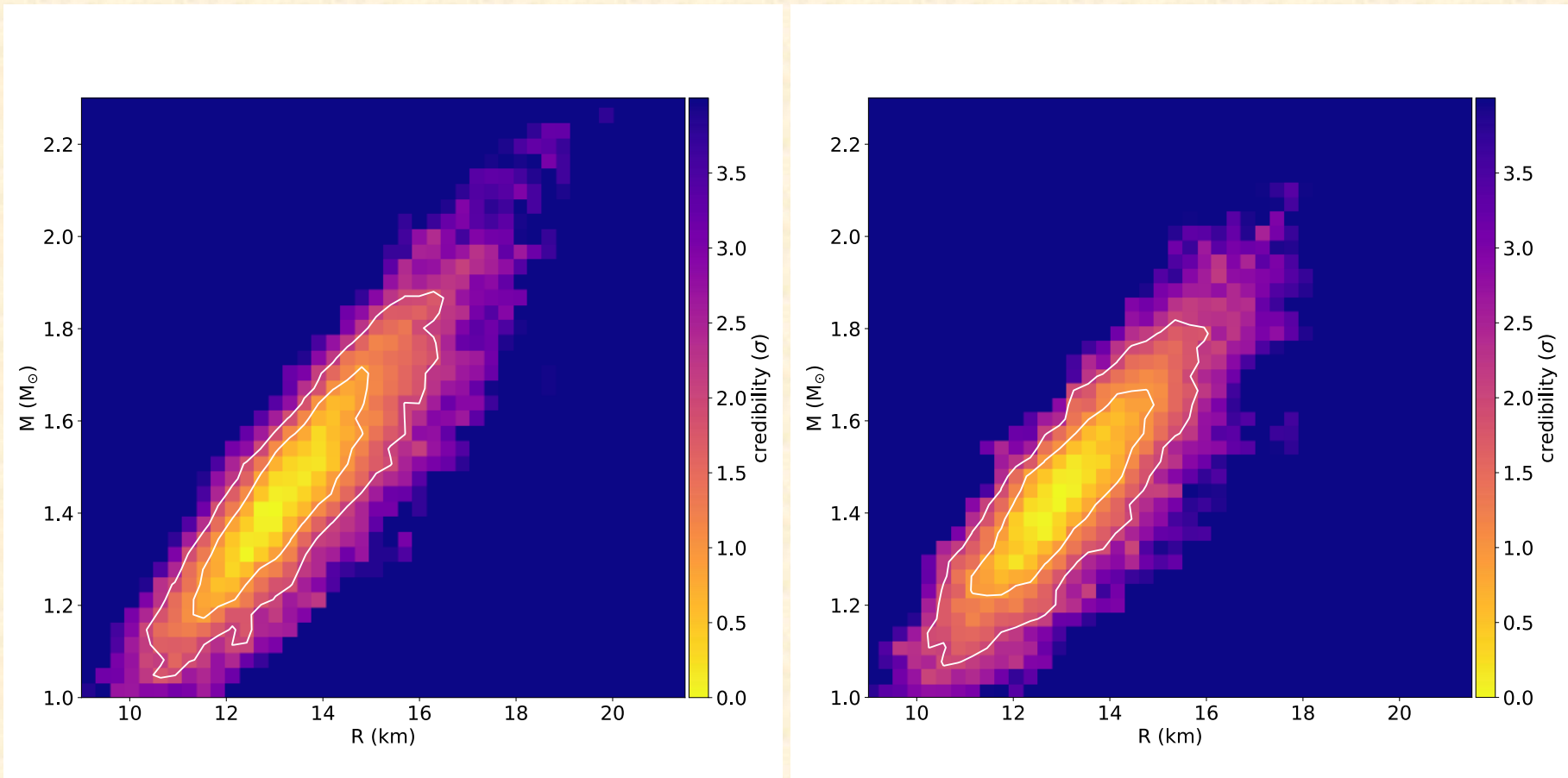
Fit to Synthetic Two-oval Data



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

Any Questions At This Stage?

Mass-Radius Posteriors for J0030

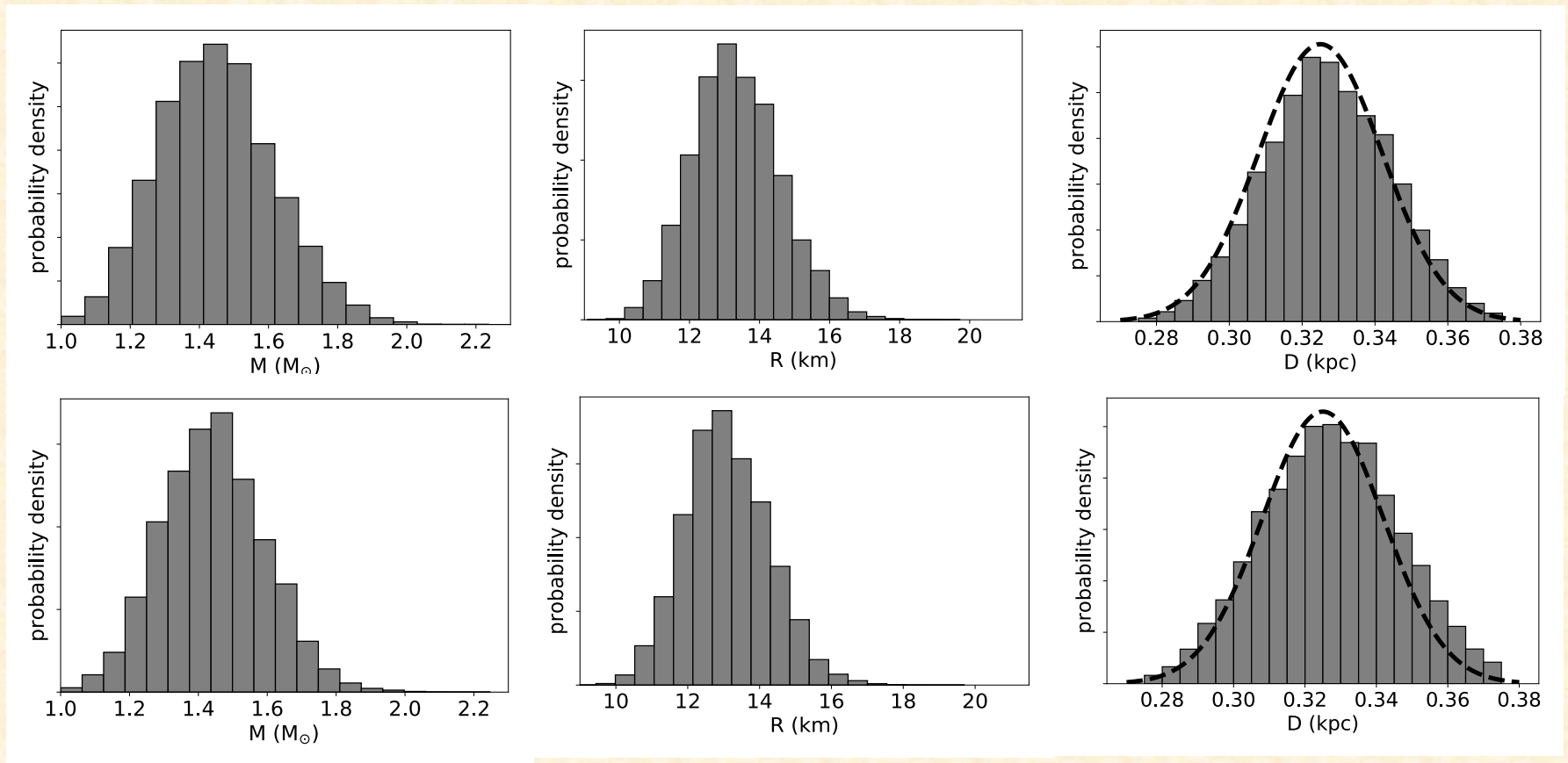


Left: M-R posterior for NICER J0030 data, two ovals

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

1D Posteriors: NICER 2,3-oval

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

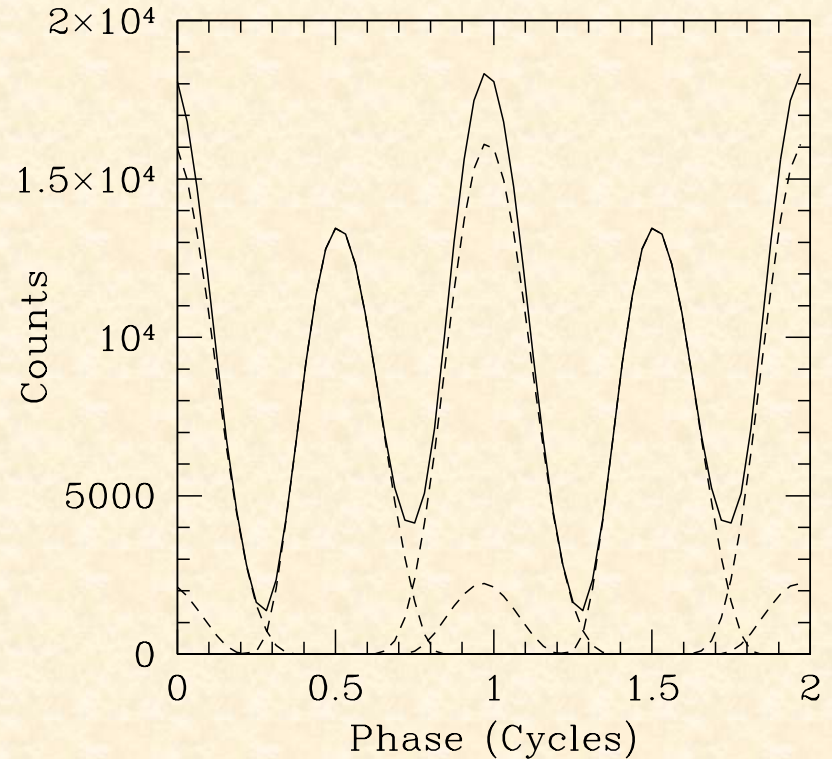
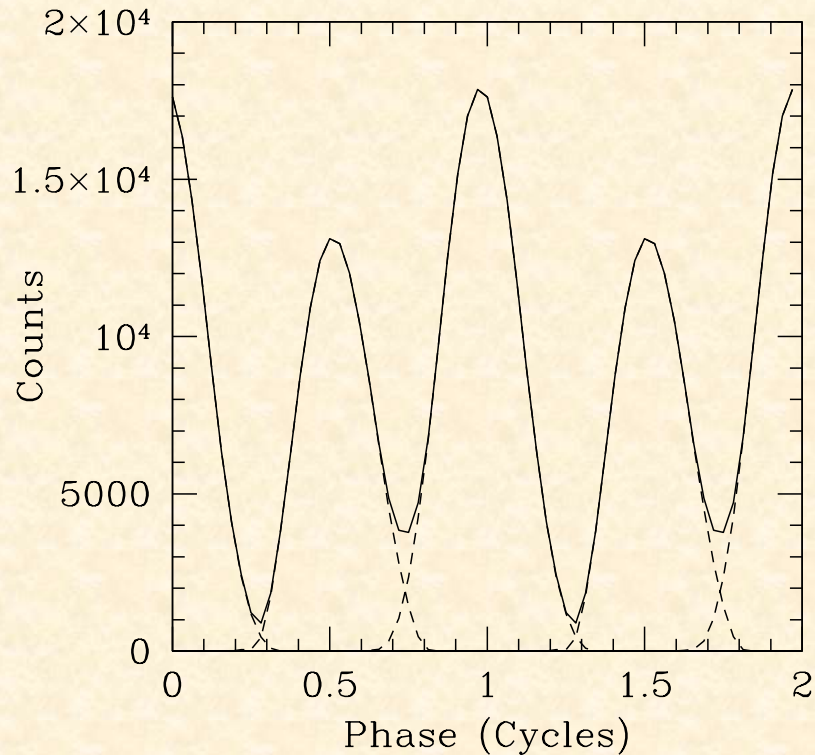


Top: analysis of NICER data, two-oval model

Bottom: analysis of NICER data, three-oval model

Dotted line on right: distance prior

Bolometric Waveforms

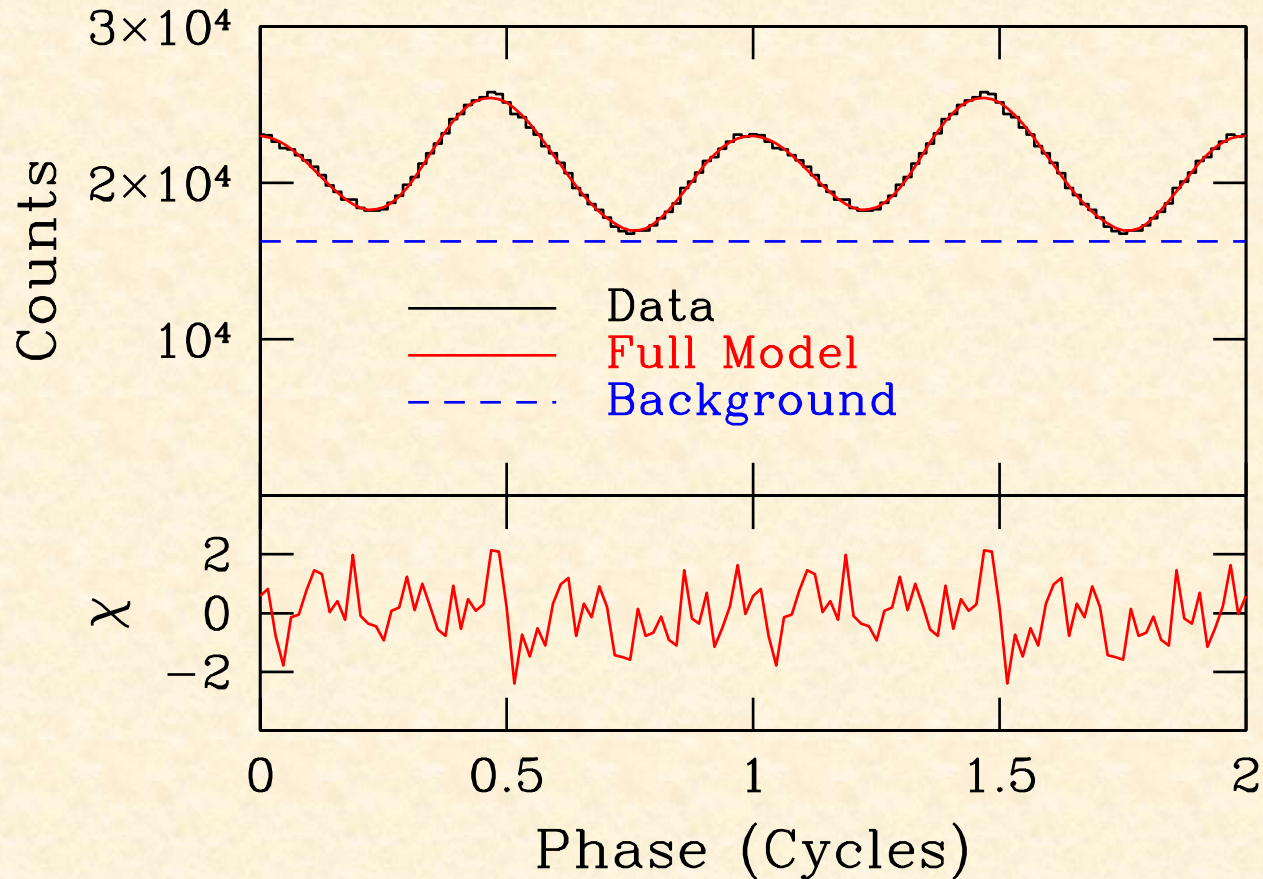


Left: two-oval model fits to NICER J0030 data

Right: three-oval model fits to NICER J0030 data

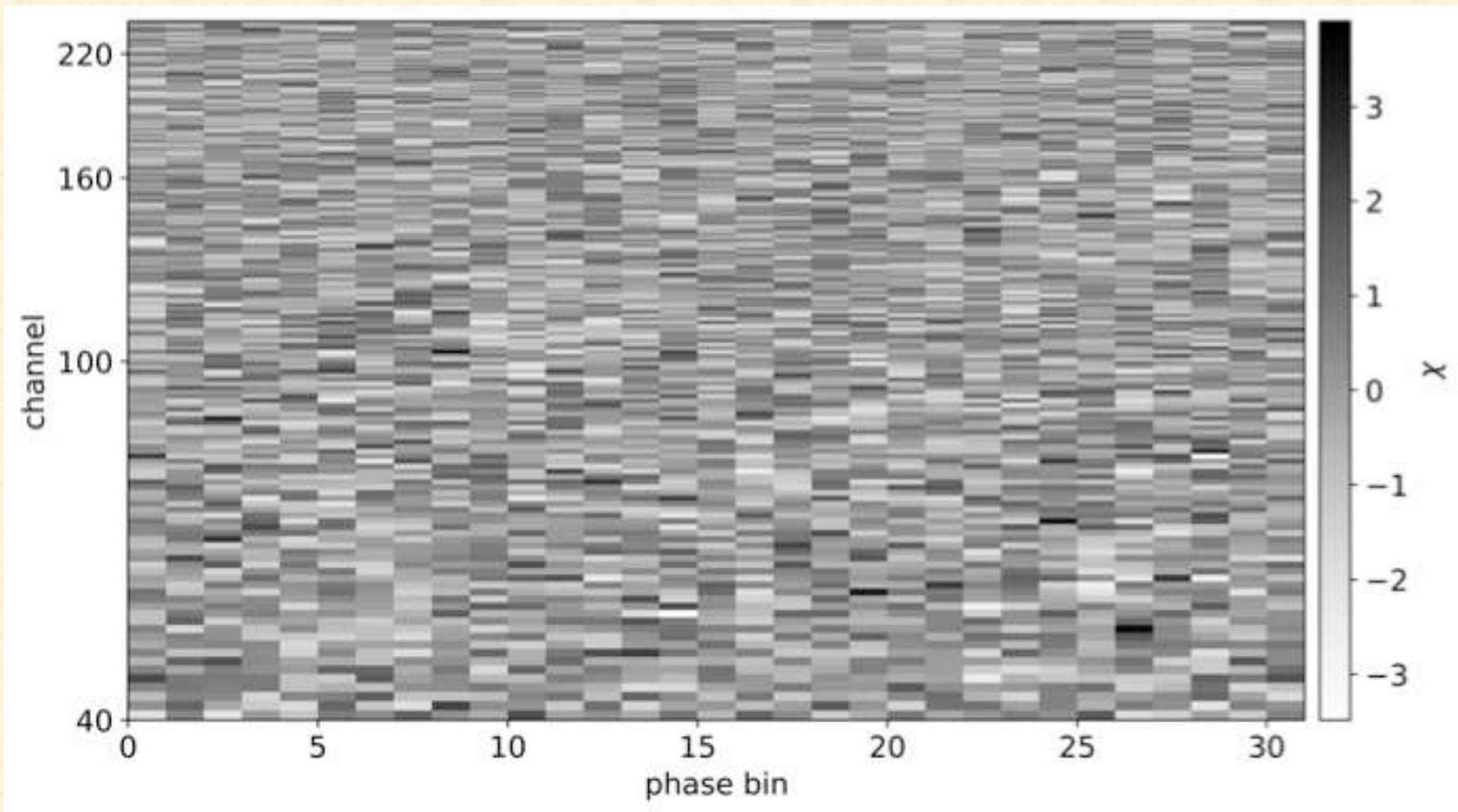
Dotted lines are individual spots; solid, total

Bolometric Residuals



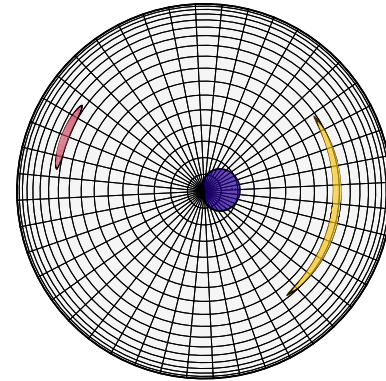
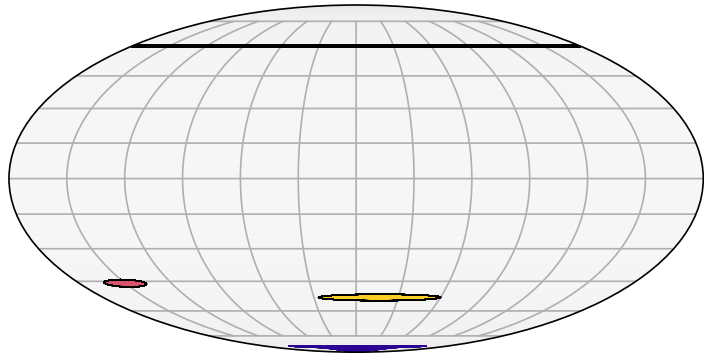
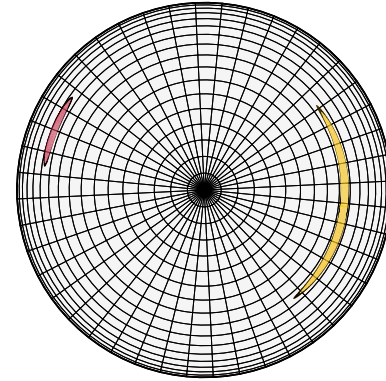
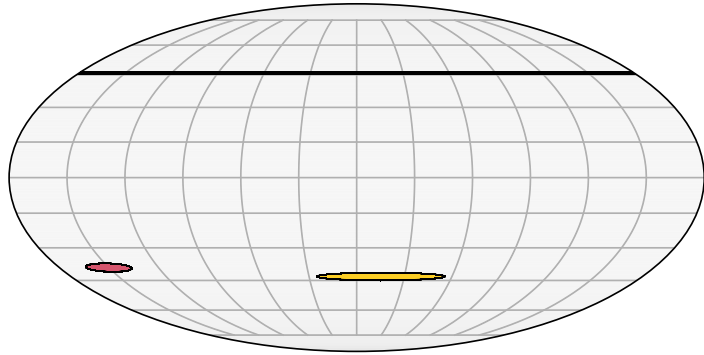
Residuals of best-fit three-oval model compared with J0030 NICER data, for 64 phases. Fit is good

Phase-Channel Residuals



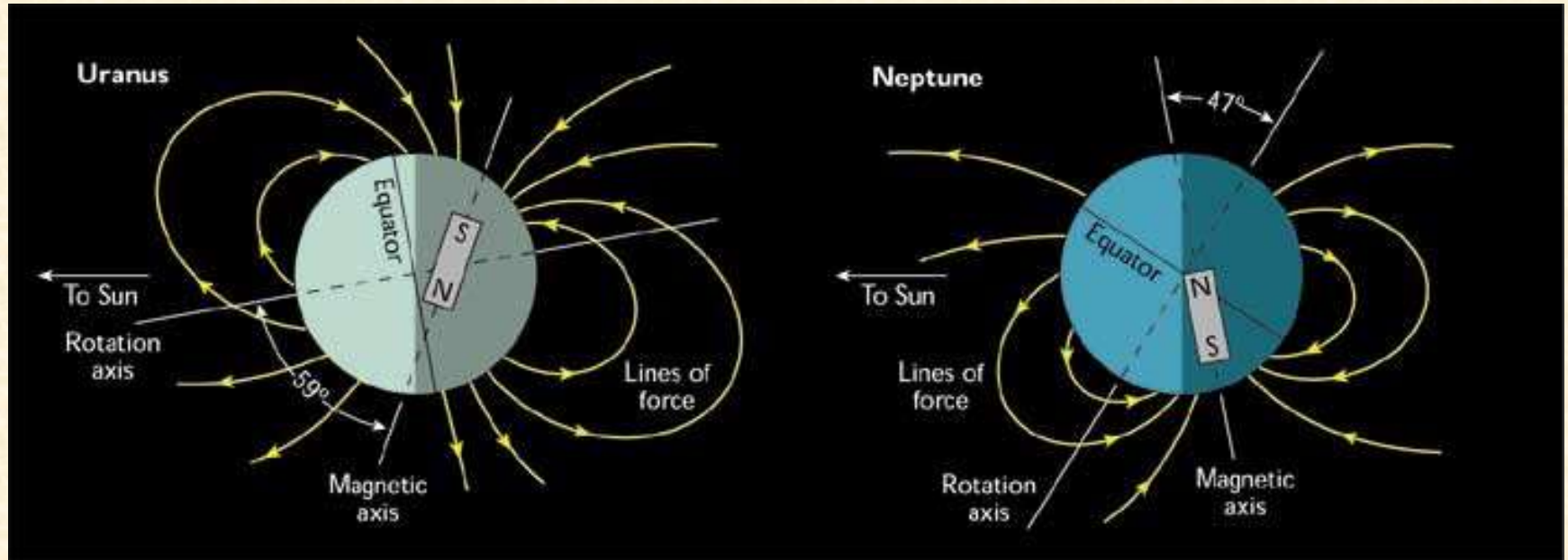
Residuals (in χ) for best three-oval fit to NICER J0030 data. No patterns are evident, as one would expect from a good fit ($\chi^2/\text{dof}=8189/8040$, 12%)

Spot Patterns



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

Shouldn't B be a centered dipole?

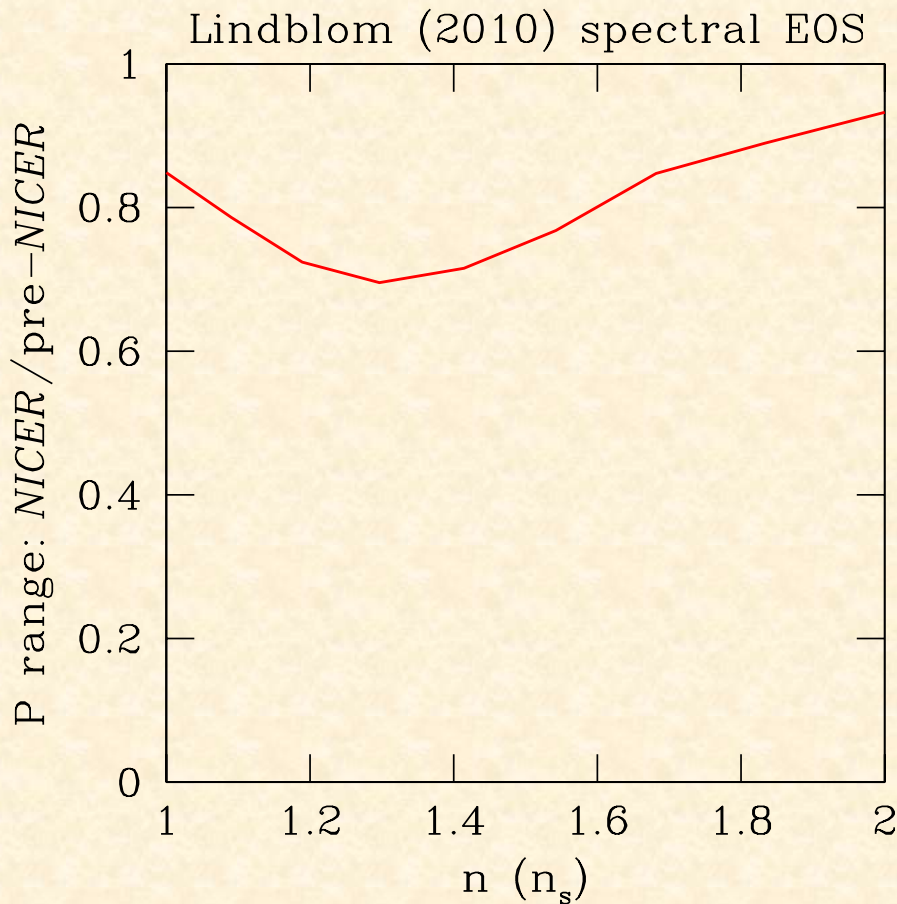


Credit: NASA

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

Any Questions?

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

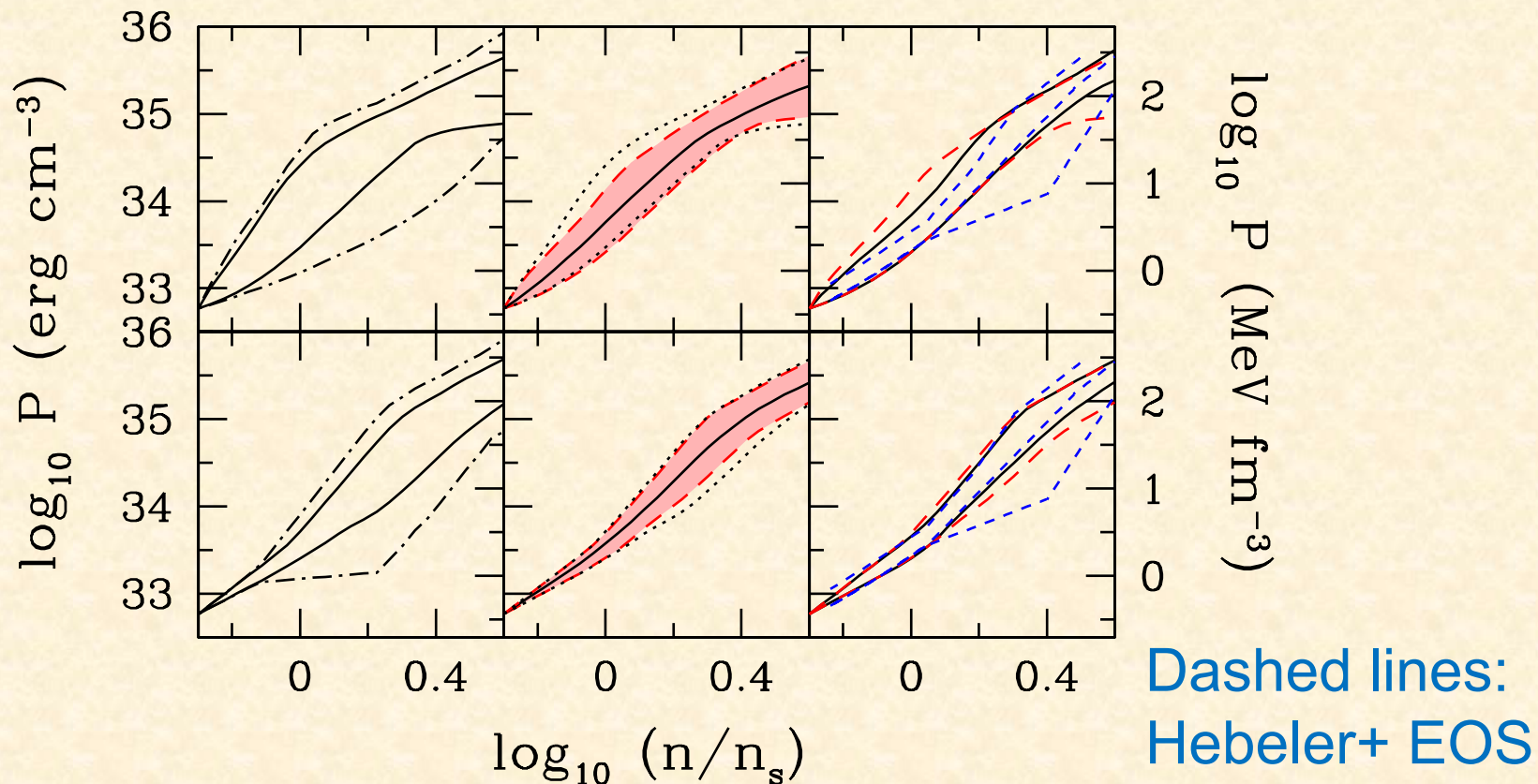
NICER M and R reduces pressure range by 10-30% from $\sim\rho_{\text{sat}}$ to $2\rho_{\text{sat}}$

Exposure time will \sim double by end of 2020.

Can incorporate into full EOS

constraints: Miller, Chirenti, Lamb 2020, many other papers

Implications for Equation of State



Top: spectral EOS. Bottom: piecewise polytropes
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