Constraining the properties of neutron star matter using X-ray oscillations

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Constraining the properties of neutron star matter using X-ray observations of neutron stars

Using observations of X-ray oscillations

- Why use X-ray oscillations?
- Deriving constraints from X-ray oscillations
- Prospects

Constraining the properties of neutron star matter using X-ray observations of neutron stars

- Measure the fluxes and spectra of cool, non-accreting neutron stars (isolated neutron stars or qLMXBs)

- Measure the fluxes and spectra of thermonuclear X-ray bursts of accreting neutron stars

- Measure the fluxes and spectra of X-ray oscillations produced by rotation of neutron stars

For a recent detailed review and discussion, see
Miller & Lamb, Eur. Phys. J. A. 52, 63–83 (2016)

Measuring fluxes and spectra of cool, non-accreting neutron stars (isolated neutron stars or qLMXBs)

Compana + Stella 2004; Heinke+ 2003, 2006, 2014; Mereghetti 2011; Servillat+ 2012; Catuneanu+ 2013; Guillot+ 2013; Bahramian+ 2015

Possible sources of systematic error —

- Uncertainties in the composition and other properties of the neutron star atmosphere
- Uncertainties in the fraction of the stellar surface that is emitting and the temperature distribution over the emitting region
- Uncertainties in the interstellar absorption along the line of sight
- Possible that the varying power-law spectral component seen in some qLMXBs is produced by non-thermal emission. If so, some or even most of the radiation from these stars might be produced by a process other than thermal emission from the stellar surface.

Measuring the fluxes and spectra of thermonuclear X-ray bursts from accreting neutron stars

van Paradijs 1979; Sztajno+ 1987; Lewin+ 1993; Ozel 2006; Ozel+ 2009, 2012, 2015; Güver+ 2010a, 2010b, 2012a, 2012b, 2013; Steiner+ 2010, 2013, 2015; Suleimanov+ 2011a, 2011b, 2012, 2015; Poutanen +Suleimanov 2013; Poutanen+ 2014; Kajava+ 2014; Nättilä+ 2015, 2016

Possible sources of systematic error —

- Nonuniform emission over the stellar surface
  - Nonuniform fuel deposition and propagation of heating and burning
  - Variation of surface gravity and comoving emission with latitude
- Uncertainties in the orientation of the surface emission and observer
- Obscuration and reprocessing of burst emission by the accretion disk
- Time varying emission by the disk, its corona, and any boundary layer

The simplified models currently being used are inconsistent with data

Nättilä+ 2016: Allow for nonuniform emission, use detailed spectral data

Evidence for nonuniform emission over the stellar surface

Current model atmosphere spectra agree well with burst spectra

This model has $F=0.95F_{Edd}$

Best fit: χ^2/dof=42.3/48

Best B-E fit: χ^2/dof=55.6/50

For full 102-segment data set,

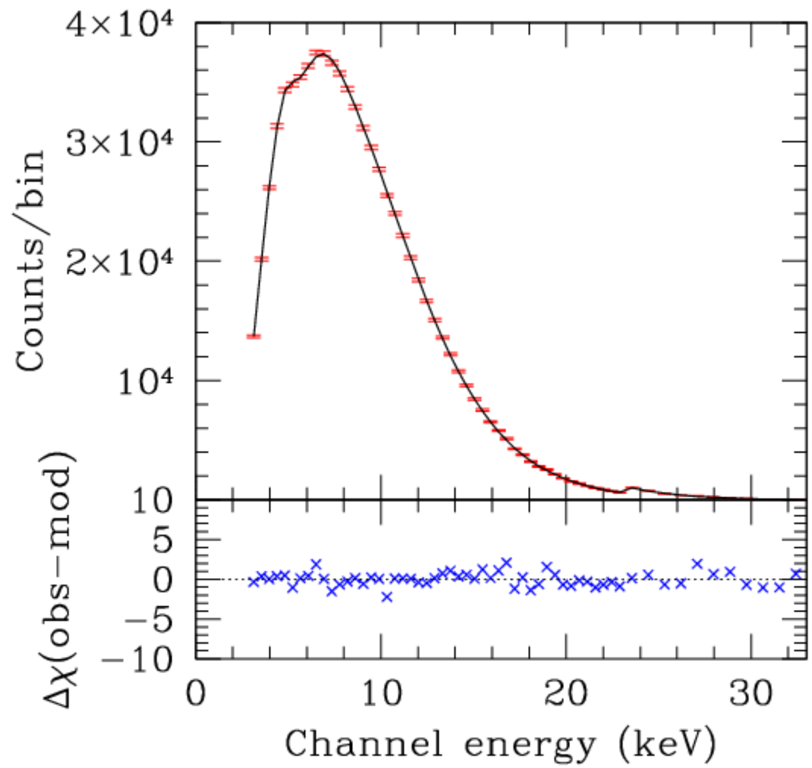
best fit has χ^2/dof=5238/5098

(best B-E: χ^2/dof=5770/4998)

Fits are *spectacularly* good, so

the emitting area can be inferred.

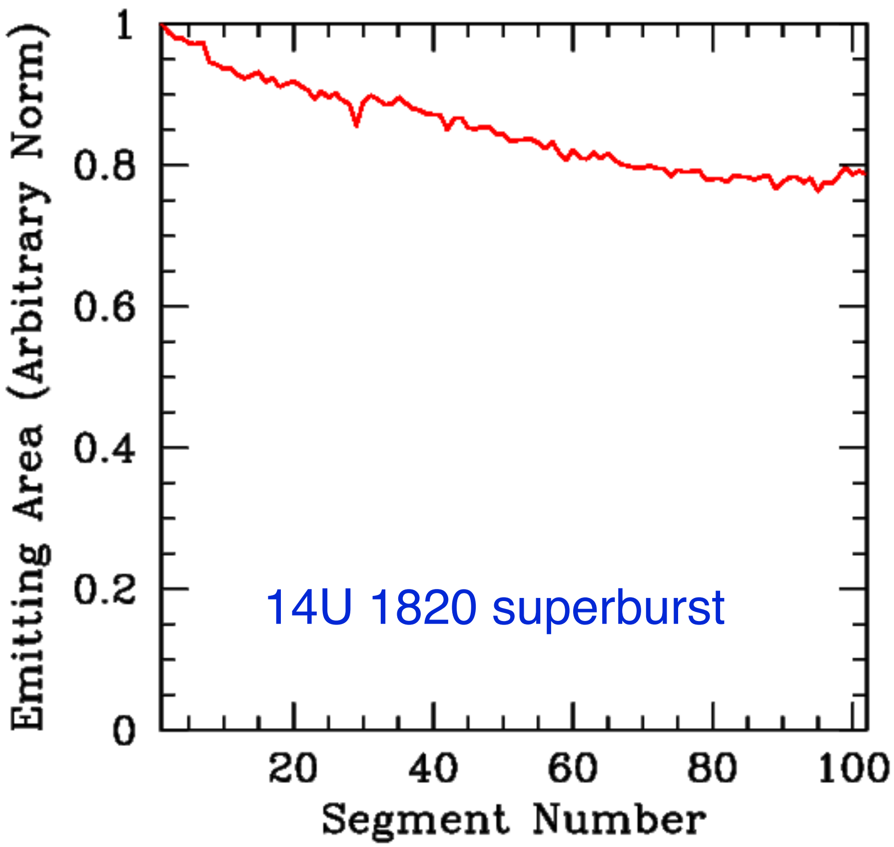
64-second segment at peak temperature; 1820 superburst



Boutloukos, Miller, & Lamb 2010 (pure He, log g = 14.3, $F=0.95F_{Edd}$ Suleimanov et al. 2010 model)

Evidence for nonuniform emission over the stellar surface

Inferred relative emitting areas, assuming a constant photospheric radius



102 16-s segments near the peak (Miller et al., in prep)

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Constraining the properties of neutron star matter using X-ray oscillations

Three relevant types of X-ray oscillations —

- Accretion-powered X-ray oscillations from accretion-powered millisecond X-ray pulsars
- Nuclear-powered X-ray oscillations during thermonuclear X-ray bursts from accreting neutron stars with millisecond spin periods
- X-ray oscillations produced by thermal X-ray emission from the magnetic polar regions of rotation-powered millisecond pulsars

All of these oscillations are generated by the rotation of the star and are nearly periodic

Accretion-powered X-ray oscillations from accretion-powered millisecond X-ray pulsars

Poutanen + Gierlinski 2003; Poutanen + Beloborodov 2006; Leahy+ 2008, 2009, 2010; Lamb+ 2009a, 2009b; Morsink + Leahy 2011; Patruno + Watts 2012

- These oscillations are bright during X-ray outbursts, *but*…
- The duty cycle of X-ray outbursts is small
- The emission geometry is complex
- The waveforms are highly variable
- Uncertainties in the Comptonization of the thermal X-ray emission from near the stellar surface by shock-heated infalling gas may produce significant systematic errors in the inferred constraints on the EOS

Thermonuclear-powered X-ray oscillations produced during X-ray bursts on accreting millisecond pulsars

Strohmayer+ 1997; Miller + Lamb 1998; Weinberg+ 2001; Artigue+ 2013; Lo+ 2013; Psaltis+ 2014; Miller + Lamb 2015; review: Watts 2012

- X-ray oscillations are very bright during X-ray bursts
- The X-ray emission is thermal
- Spectrum and beaming pattern are well understood (the opacity in the hot atmosphere is dominated by electron scattering so the surface composition matters little), *but*…
- Oscillations are observed during only *some* bursts from *some* stars, and the duty cycle is small

Not a problem for a satellite with an all-sky monitor that can maneuver quickly to point its main instrument at burst-active stars, but such oscillations are unsuitable for NICER

X-ray oscillations produced by thermal emission from the poles of rotation-powered millisecond pulsars

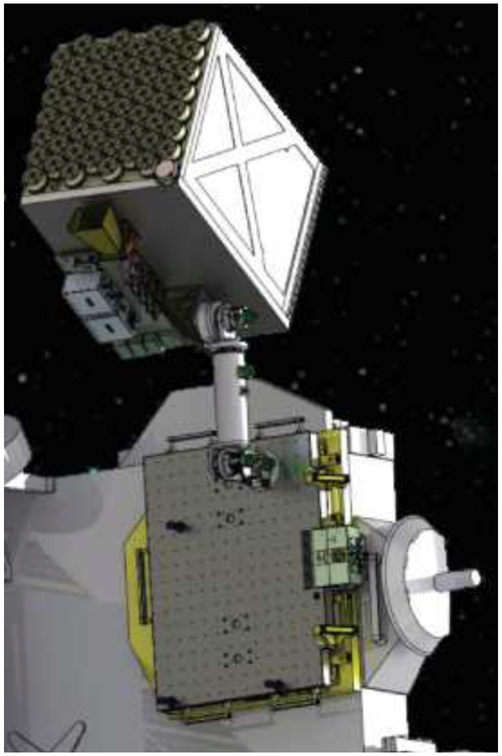
Bogdanov+ 2007, 2008; Bogdanov + Grindlay 2009; Bogdanov+ 2013, 2015; Miller + Lamb 2016

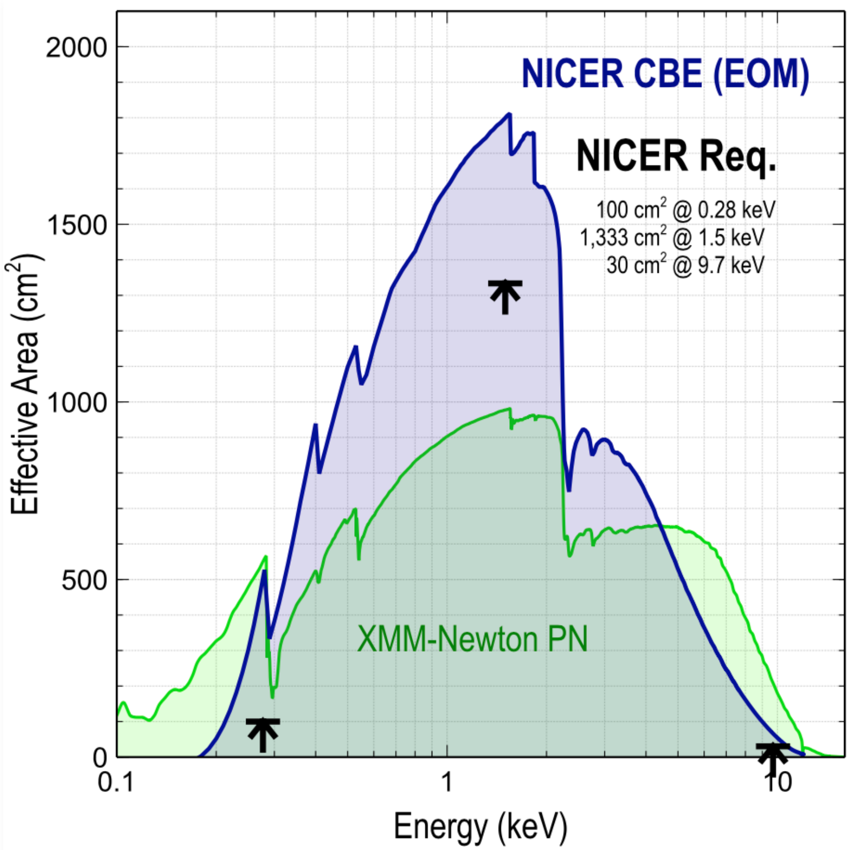
- These X-ray oscillations are *always* present
- The oscillating emission is thermal at low X-ray energies, although oscillating nonthermal emission can be present at higher energies
- We know independently the orientation of the magnetic axis and the observer's sightline for some systems, *but*…
- The oscillating thermal emission is relatively weak
- The emitting atmosphere is cool, so its atomic composition and atomic radiative processes matter (detailed H and He atmosphere models exist)

Prospects for measuring *M* and *R* using X-ray oscillations

NICER

Scheduled for launch 2017 Feb 1





The prime scientific objective is to measure the radii of 4 millisecond pulsars to +/- 5% (1σ), to constrain the properties of cold dense matter

Prospects for measuring X-ray oscillations

eXTP(enhanced X-ray Timing and Polarization) — China

Aiming for launch in 2025

Current baseline eXTP payload is:

- Large Area Detector (3.4 m^2)
- Spectroscopic Focusing Array
- Polarimetry Focusing Array
- Wide Field Monitor (a slightly scaled down version of LOFT/WFM)

LOFT-P (Large Observatory for X-ray Timing – Probe) — USA

NASA probe-class mission concept

- Probe-class X-ray observatory designed to work in the 2–30 keV band
- Would address LOFT science using a > 6 m^2 Large Area Detector

Constraining the properties of neutron star matter using observations of X-ray oscillations

Analyze data using Bayesian methods

- Compute odds of different EOS models
- Estimate parameters in parameterized EOS models
- Use M and R estimates to constrain EOS models

Here I will discuss estimating M and R.

Uncertainties in *M* and *R* measurements

- Most sensitive to hot spot colatitude and observer inclination
- Sensitive, but less so, to *R* and hot spot rotational frequency ν_{rot}
- Depend weakly on the sizes and spectra of the backgrounds
- For fixed spot and observer geometry, *R*, and ν_{rot}, uncertainties in *M* and *R* scale as $1/\mathcal{R}$, where $\mathcal{R} \equiv N_{osc}/\sqrt{N_{tot}} = f_{rms}\sqrt{N_{tot}}$
- For favorable geometries, $\mathcal{R} \sim 400$ yields uncertainties $\sim 10\%$
- For $f_{rms} \sim 10\%$, one needs $\sim 10^7$ total counts to achieve $\mathcal{R} \sim 400$
- For favorable geometries, this mean $\sim 10^6$ counts from the spot

Relevant approximations to neutron star properties and exterior spacetimes

Schwarzschild spacetime + Doppler (S+D) approximation

Miller + Lamb 1998, Poutanen + Gierlinski 2003

- Treats star as spherical and exterior spacetime as Schwarzschild
- Includes all special relativistic effects and treats them exactly

Oblate-star Schwarzschild spacetime (OS) approximation

Morsink+ 2007, Cadeau+ 2007, AlGendy + Morsink 2014

- Treats star as oblate but exterior spacetime as Schwarzschild
- Includes all special relativistic effects and treats them exactly

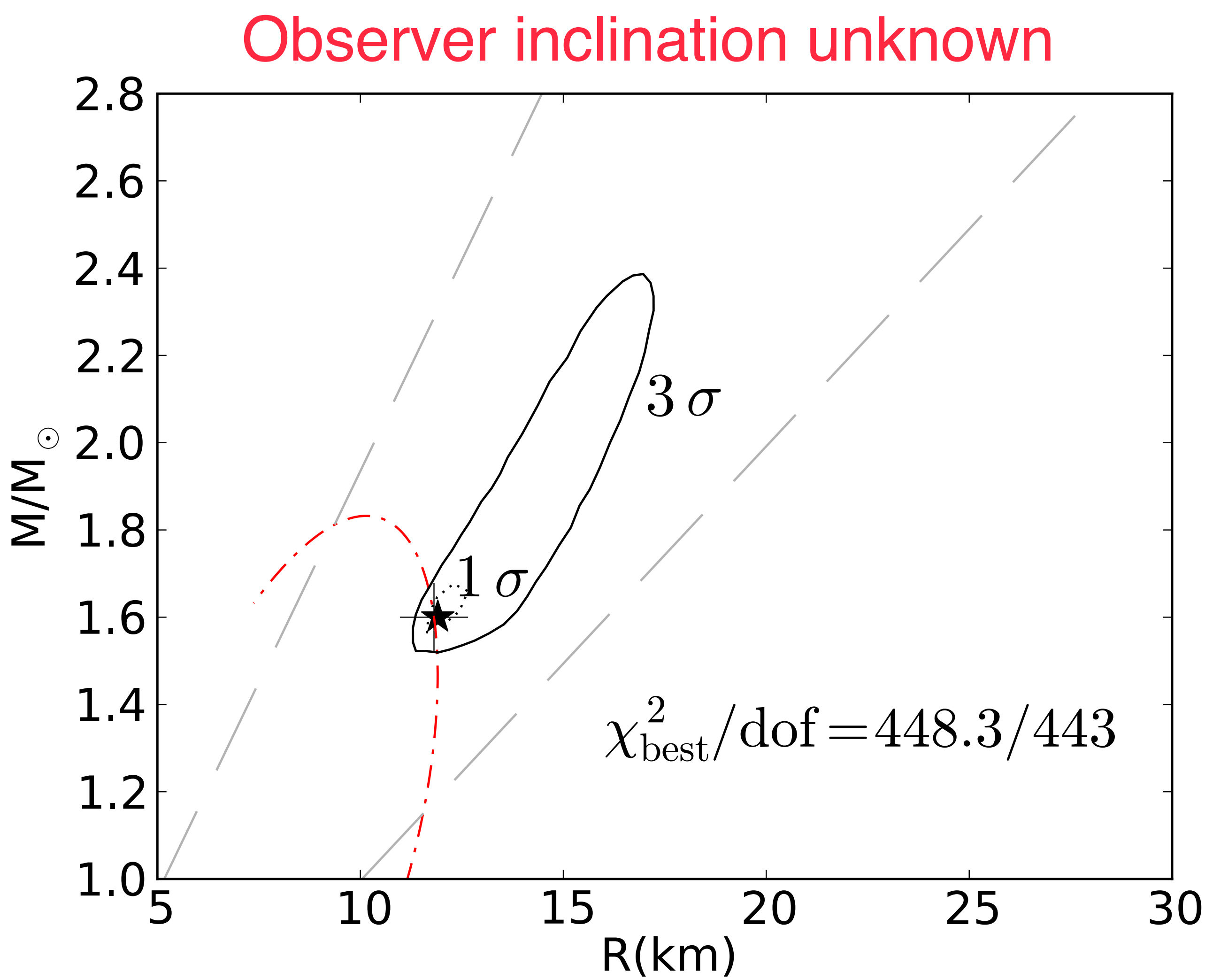
Full numerical stellar structure, spacetime, and ray-tracing

Results from comprehensive Bayesian studies of parameter estimation using X-ray oscillation data

Lo, Miller, Bhattacharyya, Lamb 2013 (S+D); Miller + Lamb 2015, 2016 (OS)

- Multiple data segments can be combined
- Credible regions expand slowly with decreasing spot inclination for inclinations $> 60°$
- Extra, independent information helps
  - Knowing the observer's inclination helps a lot
  - Knowing the distance helps some
  - Knowing M somewhat reduces uncertainty in R
- If the hot spot is small enough to be treated as point-like, the count rate is too small to construct interesting constraints on M and R
- Incorrect spot shape in pulse waveform models increased uncertainties but did not bias M and R by much
- Incorrect temperature profile in the pulse waveform model increased uncertainties but did not bias M and R by much

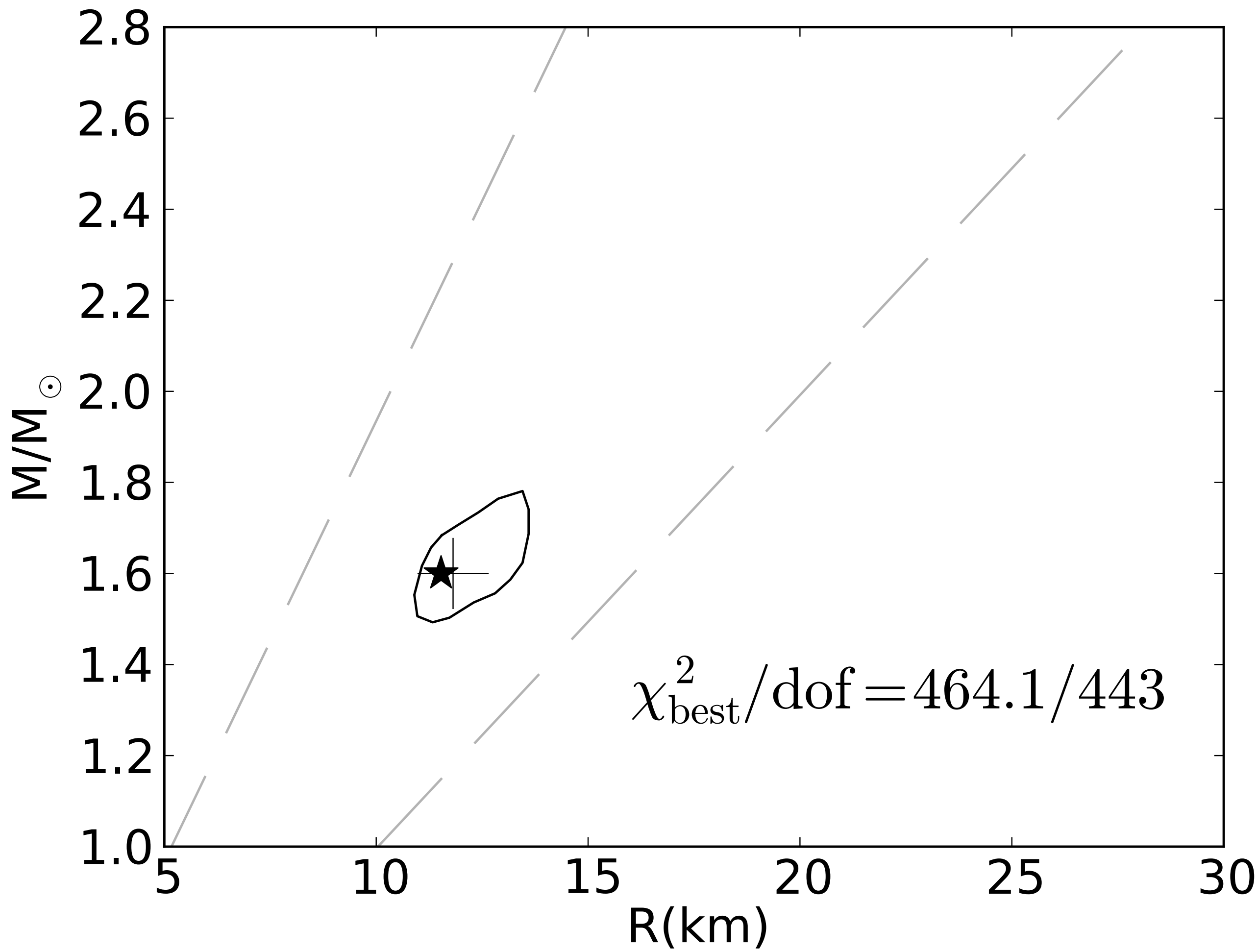
Knowledge of observer's inclination helps a lot



Lo et al. (2013) spot and observer inclinations = 90°, high background, S+D model

Knowledge of observer's inclination helps a lot

Observer inclination known



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Bayesian analyses of synthetic waveforms

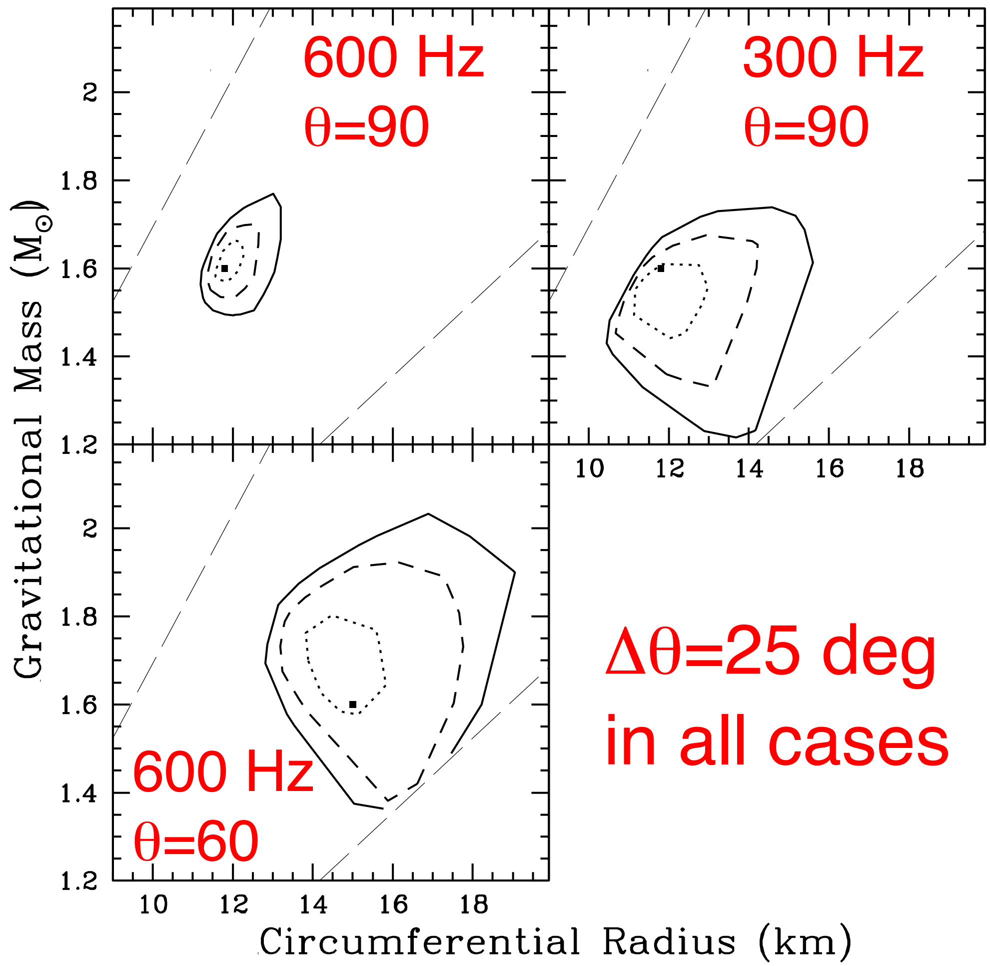
Miller + Lamb 2015 (OS)

$M = 1.6\ M_\odot$

$R_{eq} = 11.8$ km or 15 km

10^6 spot counts

$9\text{x}10^6$ background counts



PSR J0437 Bayesian *R* and *M* Estimation Study

Miller + Lamb 2016 (OS)

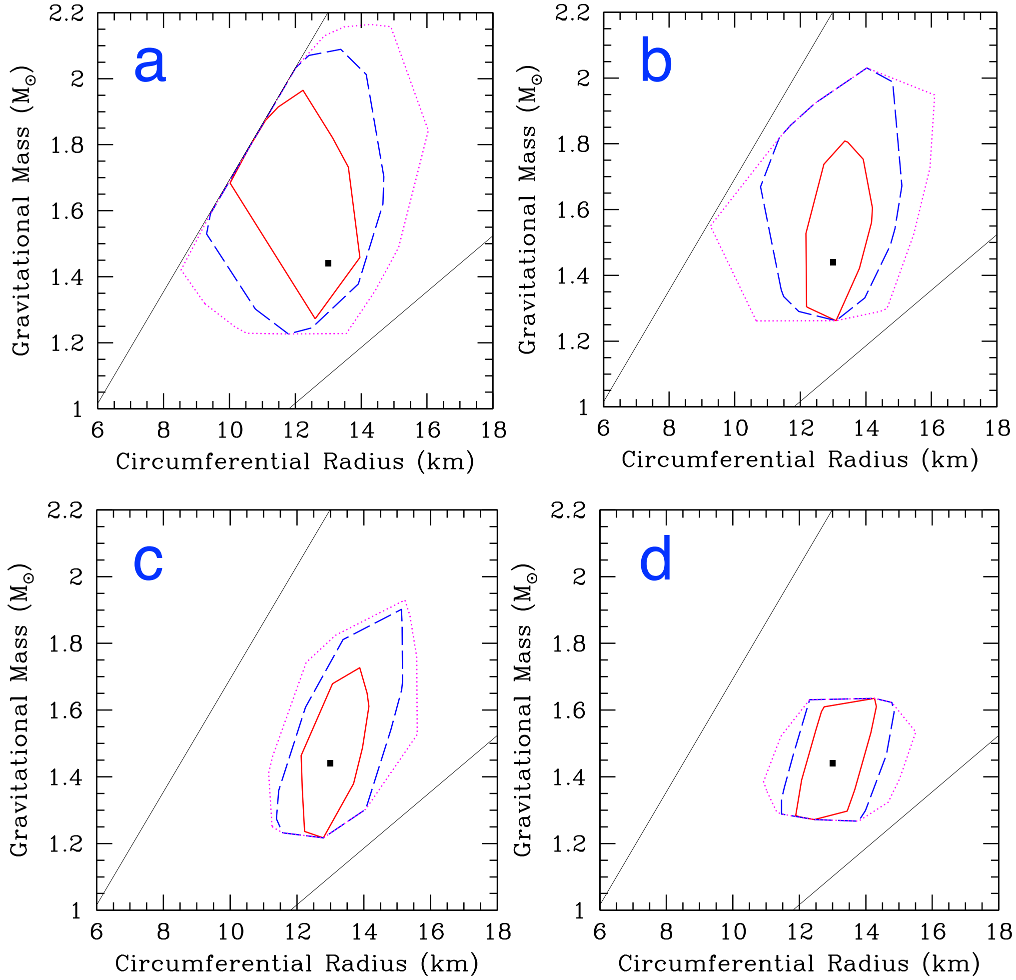
- 174 Hz pulsar PSR J0437–4715
- $M = 1.44\ M_\odot$, $R = 13$ km ($c^2R/GM = 6.1$)
- Observer's inclination = 42°
- Distance = 156.3 pc
- Duration of observation = 1 Msec

- H atmosphere, one tiny spot, inclination = 36°
  (comoving radiation temperature = 0.1896 keV)
  Total counts from the hot spot = 6×10^5

- Unmodulated background from the stellar surface
  (comoving effective temperature = 0.0474 keV)
- Total counts from the stellar surface = 4×10^5

- Unmodulated power-law background
  (dN/dE = const. x E^{-2})
- Total counts from the power-law = 2×10^5

PSR J0437 Bayesian *M* and *R* Estimation Study



a: Only the redshifted effective temperature *T* is known independently

b: *T* and the observer's inclination are known

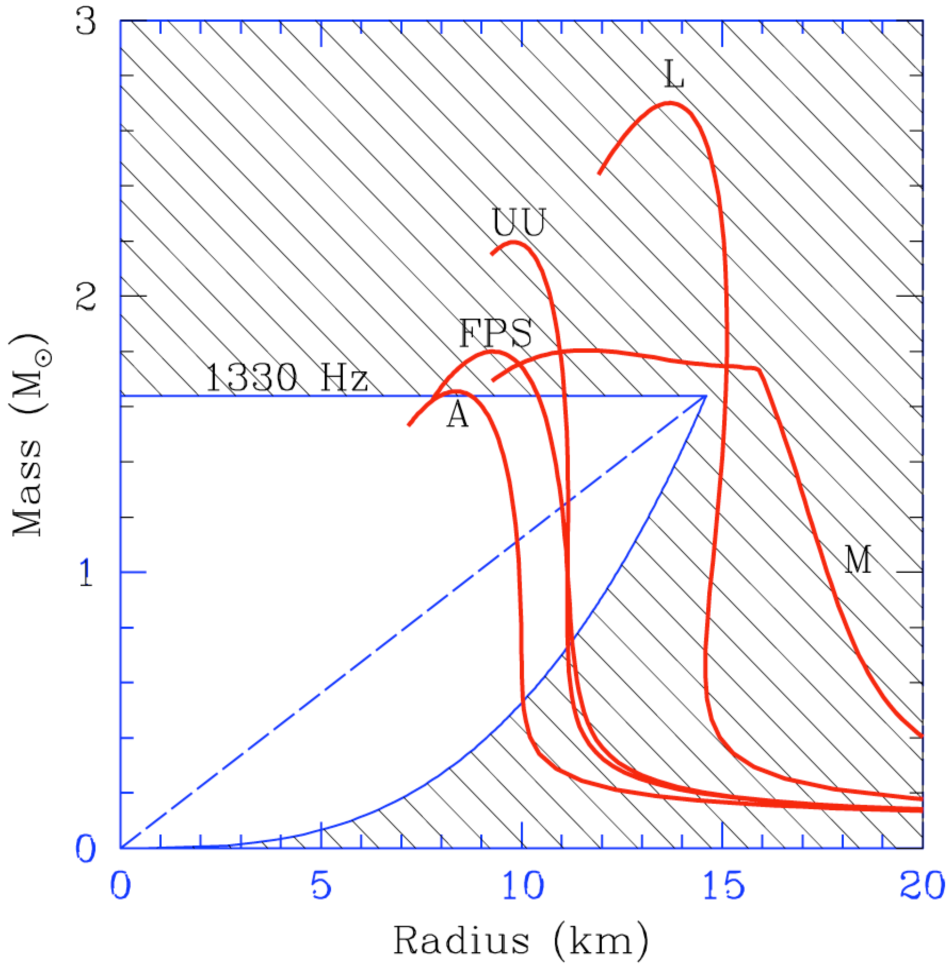
c: *T*, the observer's inclination, and the spot inclination are known

d: *T*, the observer's inclination, the spot inclination, and the mass are known

Accurately measuring *M* and *R* using NICER

- These results show that if $\mathcal{R} \sim 400$, *M* and *R* can be measured with 5%–10% uncertainties
- If $f_{\rm rms} \sim 0.25$, as in J0437, accumulating ~ few x10^6 total counts from the thermal X-ray oscillations of a single pulsar will yield $\mathcal{R} \sim 400$
- Preliminary estimates indicate that this will require combining weeks or months of NICER observations of each pulsar
- More time may be required when there are two hot spots, due to the additional degeneracies involved
- The pulse waveform analysis subgroup of the NICER Waveform Science Working Group is working hard to improve these estimates

Future possibility
Measuring *M* and *R* using kilohertz QPOs



NS EOS models vs. 4U 0614 kilohertz QPO frequency data (from Miller+ 1998)

see Barret+ 2005a, 2005b, 2006, 2007, 2011, 2013