Probing the Neutron-Star Equation of State Through X-ray Timing

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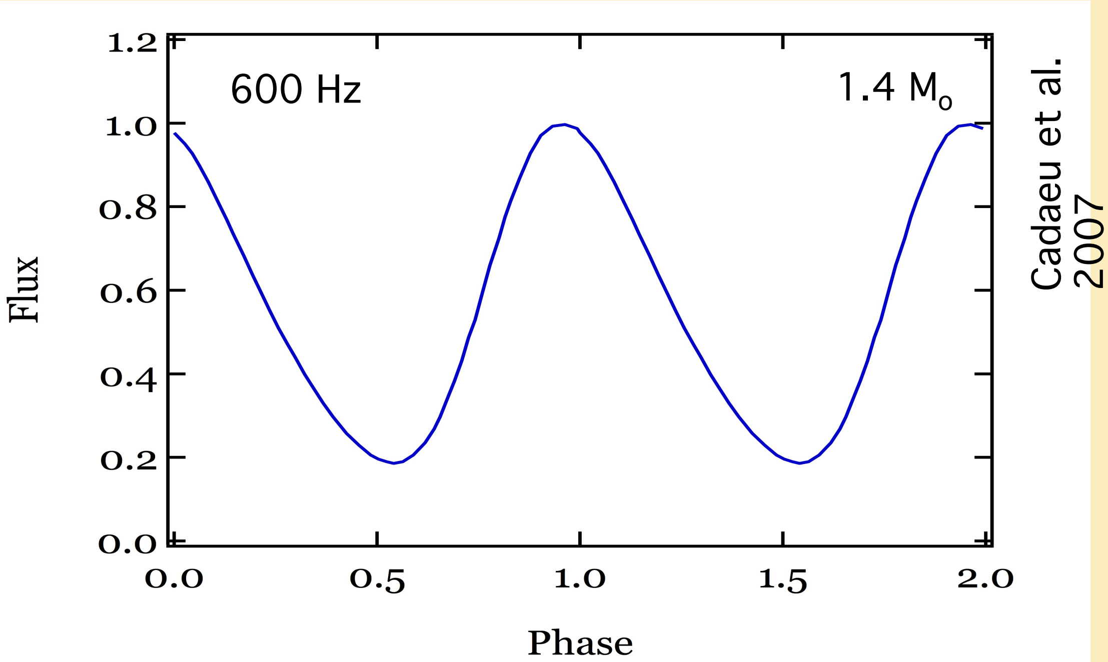
<u>Reference:</u>

Psaltis, Ozel, & Chakrabarty (2014), ApJ, in press
arXiv:1311.1571

The Structure and Signals of Neutron Stars from Birth to Death
Florence, Italy
March 27, 2014

Objective: Use X-ray light curve of rotating hot spot from neutron star surface to measure mass and radius



Issues:

- How many unique observables can be measured from light curve?
- How many parameters are required to describe the system?
- Is there enough information available to solve the problem?

Many important contributions to this problem...

- Pechenick et al. 1983, ApJ, 274, 846
- Riffert and Meszaros 1988, ApJ, 325, 207
- Strohmayer 1992, ApJ, 388, 138
- Pavlov and Zavlin 1997, ApJ, 490, L91
- Zavlin and Pavlov 1998, A&A, 329, 583
- Miller and Lamb 1998, ApJ, 499, L37
- Braje et al. 2000, ApJ, 531, 447
- Psaltis et al. 2000, ApJ, 544, 390
- Weinberg et al. 2001, ApJ, 546, 1098
- Nath et al. 2002, ApJ, 564, 353
- Beloborodov 2002, ApJ, 566, L85
- Poutanen and Beloborodov 2006, MNRAS, 373, 836
- Cadeau et al. 2007, ApJ, 654, 458
- Morsink et al. 2007, ApJ, 663, 1244
- Bogdanov et al. 2007, ApJ, 670, 668
- Baubock et al. 2012, ApJ, 753, 175
- Baubock et al. 2013, ApJ, 766, 87
- Lo et al. 2013, ApJ, 776, 19

The first paper on this topic:

THE ASTROPHYSICAL JOURNAL, **274**:846–857, 1983 November 15

HOT SPOTS ON NEUTRON STARS: THE NEAR-FIELD GRAVITATIONAL LENS

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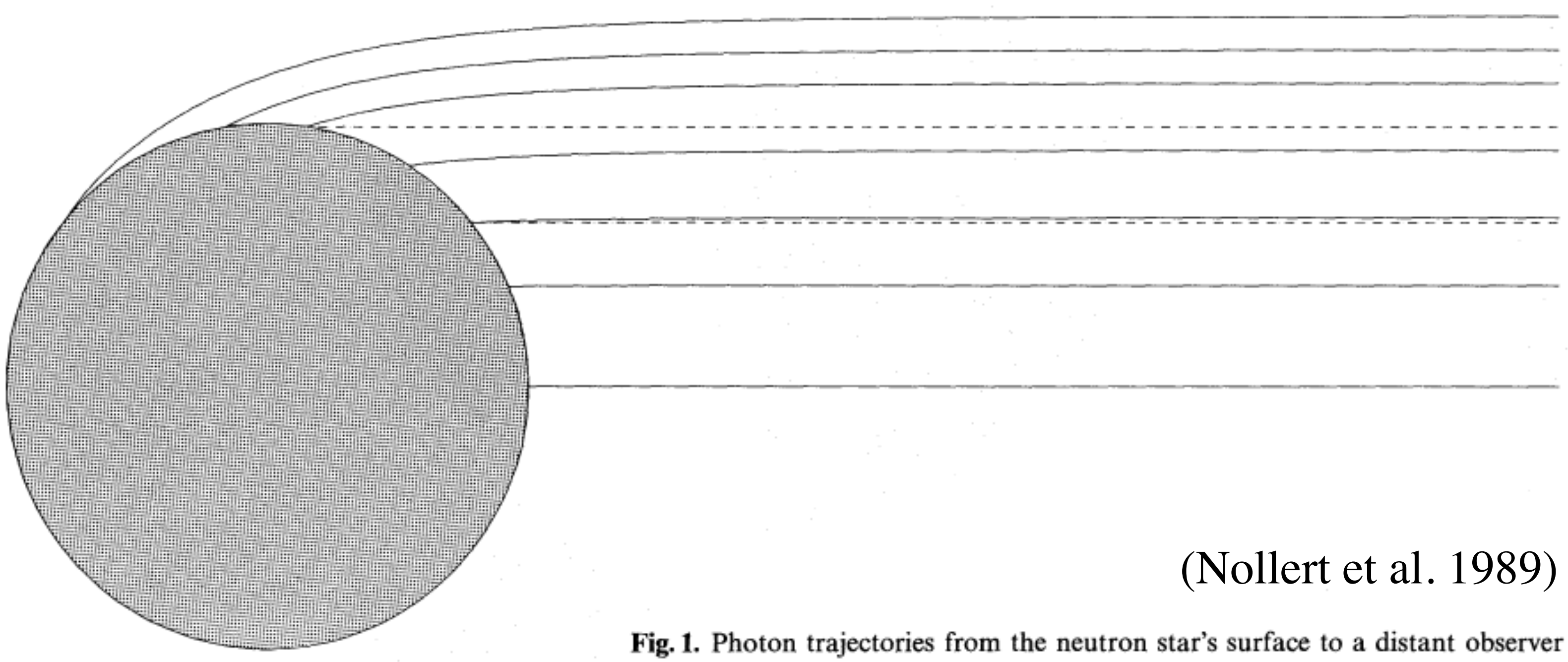
ABSTRACT

We present a simple model for including gravity in the light curves of slowly rotating neutron stars whose emission is confined to circular antipodal polar caps. Both thermal and near thermal cases are considered. We find that for hot polar caps and typical neutron star parameters the light curves are essentially flat as a result of gravitational effects. If, however, photon emission is beamed, structure is, in general, restored to the light curve, depending on the nature of the beaming. For the most relativistic neutron stars we find that there can be sharp peaks in the light curve induced solely by the gravitational lensing effect of the star. We also present results for a single hot spot. In an appendix we derive the tidal deformation of an initially circular cone of light rays.

Subject headings: gravitation — relativity — stars: neutron

Strong gravity near neutron star surface affects photon paths

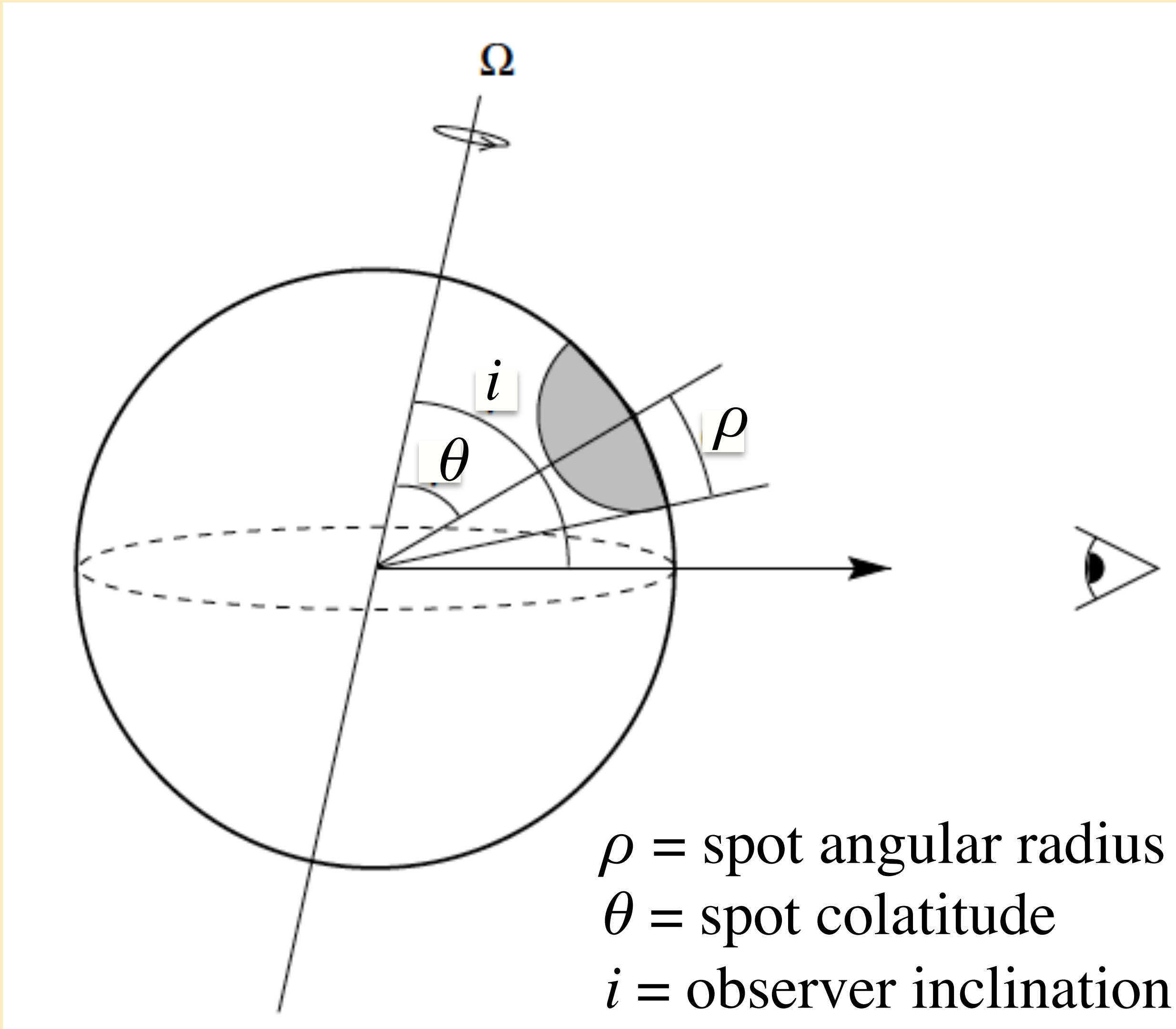


(Nollert et al. 1989)

Fig. 1. Photon trajectories from the neutron star's surface to a distant observer

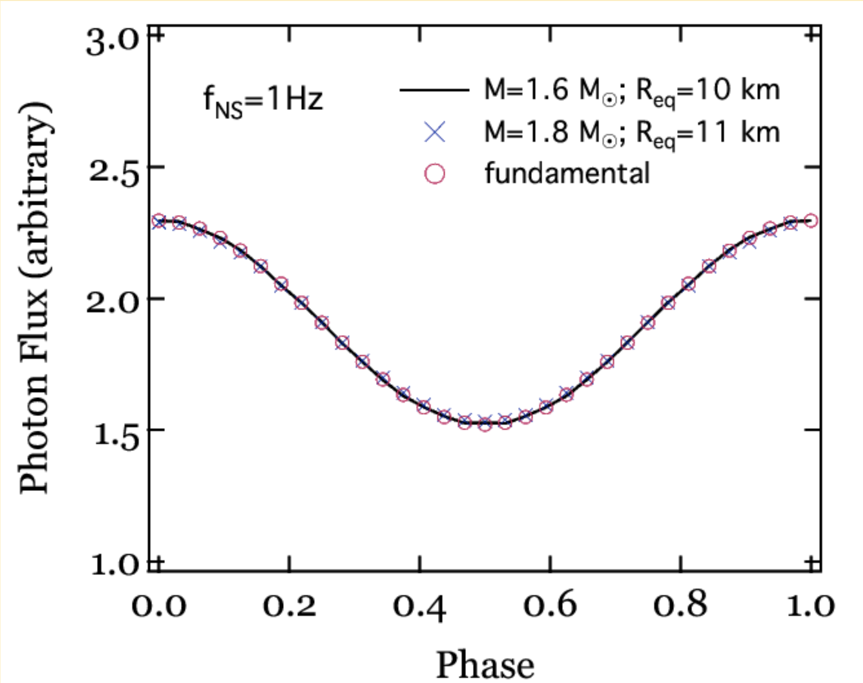
- For a slowly rotating star, effect depends only on "compactness" *M*/*R*
- Light curve from hot spot on rotating star will encode information on stellar parameter(s) and spot/observer geometry

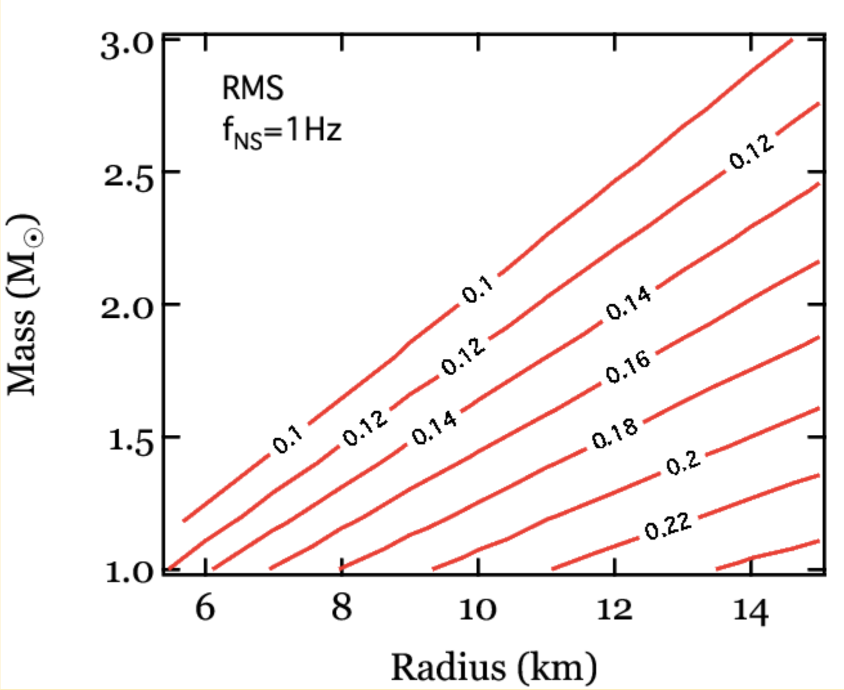
Geometry of circular hot spot and observer



For sufficiently small hot spots, the light curve is independent of the radius (see, e.g., Bogdanov et al. 2007, Lo et al. 2013).

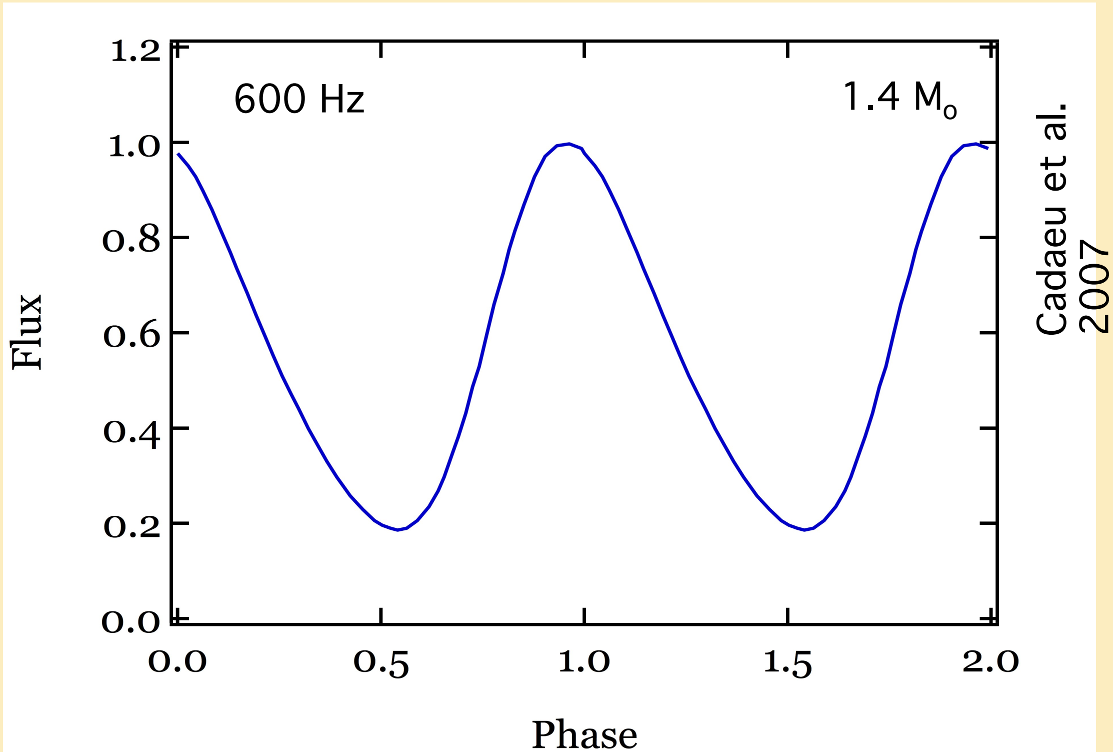
Slow rotation: highly correlated parameters





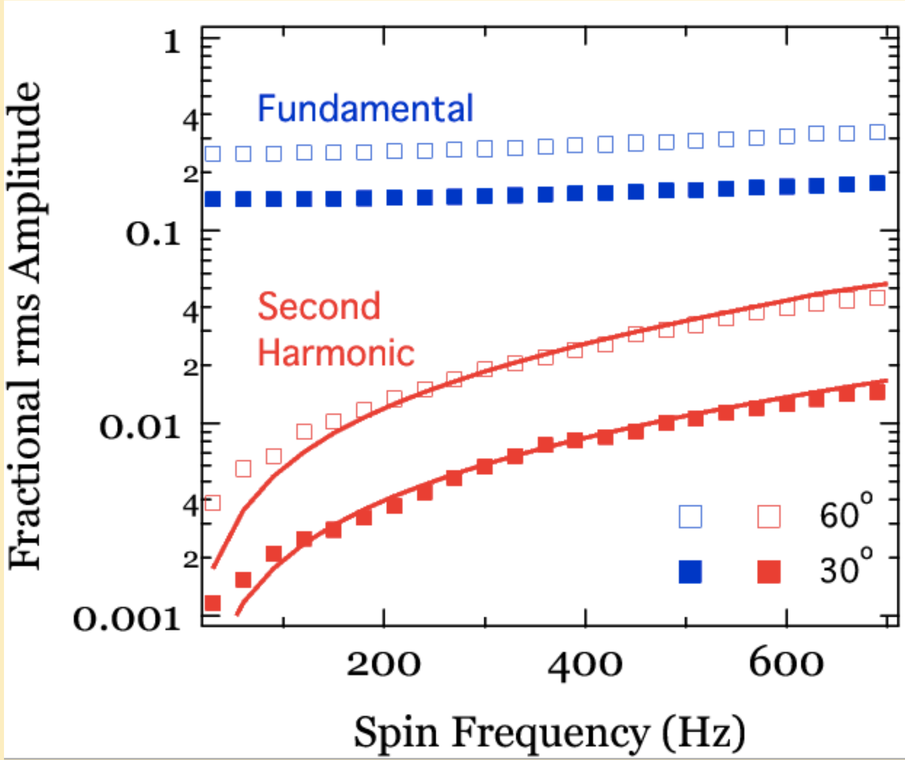
- Three parameters required to describe system: M/R, θ, i (for small spots).
- Light curve from small spot is highly sinusoidal → one measurable (fractional amplitude). (More if spot is occulted.)
- Only M/R ratio can be constrained, and results are highly correlated with angle parameters.

Moderate rotation (>300 Hz): asymmetric light curves



- Relativistic velocity affects pulse shape through several effects:
  - Doppler shifts
  - Aberration (Doppler boosts)
  - Time delays between photons emitted at different spin phases
- Resulting light curve is asymmetric. Peak arrives at earlier phase and minimum arrives at later phase, relative to sinusoid.
- Can parametrize degree of asymmetry through strength of second harmonic

Pulse asymmetry increases with increasing spin



$$\frac{C_2}{C_1} \simeq 2\left(\frac{2\pi f R_{\rm eq}}{c}\right) \sin i \sin \theta_{\rm s}$$
$$= 0.126 \left(\frac{f}{300\ \rm Hz}\right)\left(\frac{R_{\rm eq}}{10\ \rm km}\right) \sin i \sin \theta_{\rm s}\ .$$

However, higher harmonics will be extremely weak.

(see, e.g., Poutanen & Beloborodov 2006)

What is the spacetime for a rotating neutron star?

	Star	Spacetime	Parameters	Maximum Spin[1]
Non-Spinning	Spherical	Schwarzschild	GM/Rc^2	≤100 Hz
Slowly Spinning	Spherical	Kerr	M, R, I	≤500 Hz
Moderately Spinning	Oblate	Hartle-Thorne	M, R, I, Q, R_p/R_{eq}	≤800 Hz
Fast Spinning	Oblate	Numerical	Details of EOS	

(1) For spacetime elements to be accurate to within ~5%, for a neutron star with M=1.4 M_{sun}, R=10 km, I=10^{45} g cm^2.

How many parameters for a moderately rotating neutron star?

Geometric parameters:

- Spot size
- Spot colatitude (*)
- Observer inclination (*)

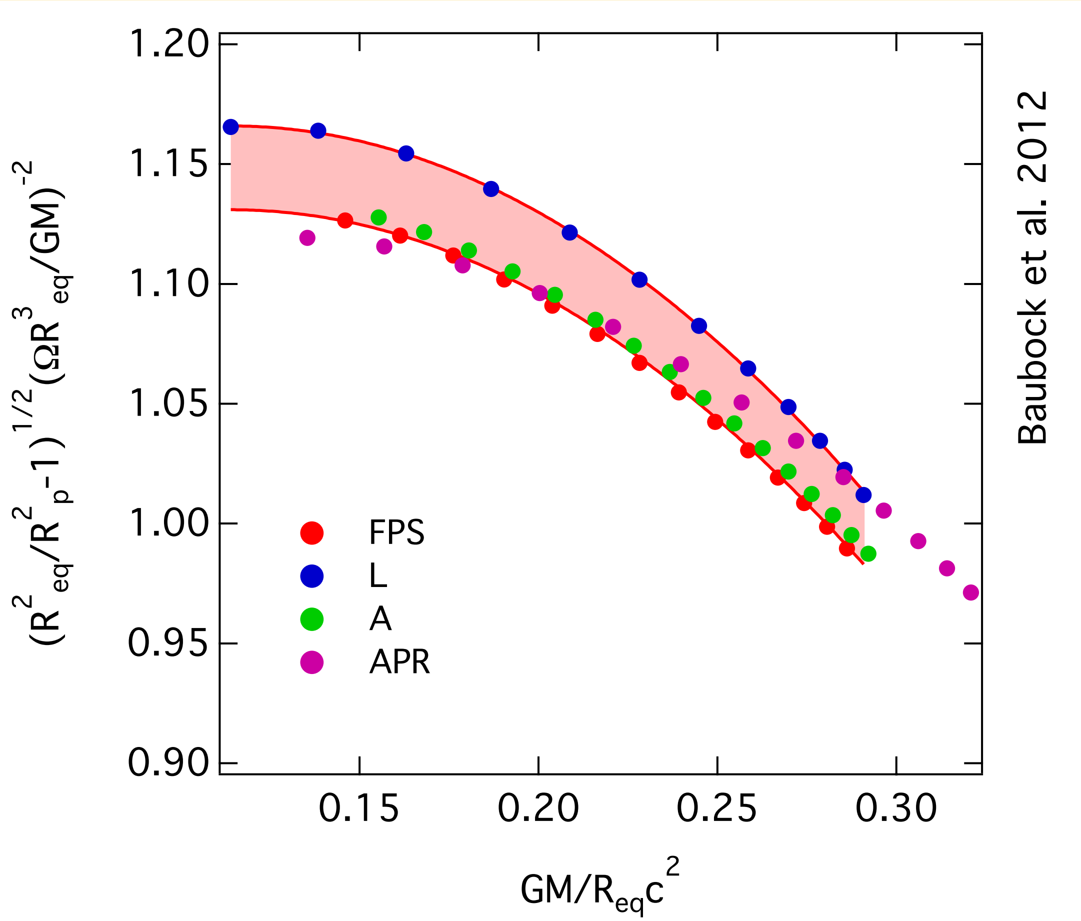
Spacetime parameters:

- Mass (*)
- Equatorial radius (*)
- Moment of inertia
- Ellipticity
- Quadrupole moment

We have already seen that spot size can be neglected for small spots.

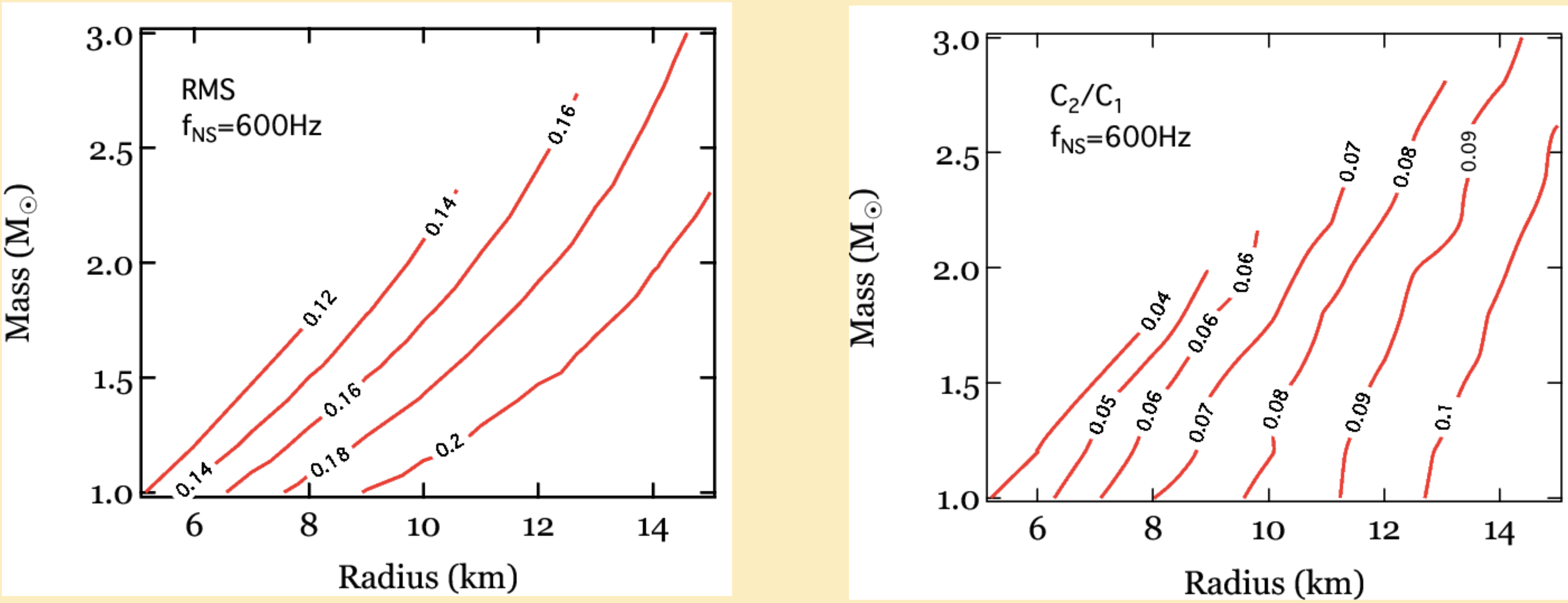
There are tight relations connecting I, ε, and Q to M and R that depend only very weakly on the equation of state (Ravenhall & Pethick 1994, Lattimer & Prakash 2001 Baubock et al. 2013). These are accurate to better than a few percent.

We can thus reduce the problem to the four starred parameters above.



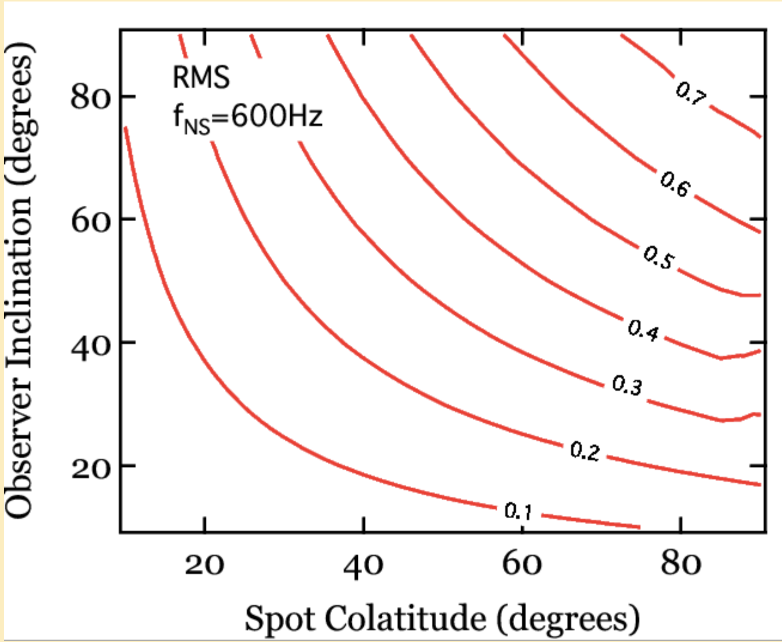
$$\frac{R_p}{R_{eq}} = 1 - 2\left(\frac{\Omega R_{eq}^3}{GM}\right)^4 \left(1.10 + 1.11\left(\frac{GM}{R_{eq}c^2}\right) - 4.88\left(\frac{GM}{R_{eq}c^2}\right)^2\right)^2 \pm 2\%$$

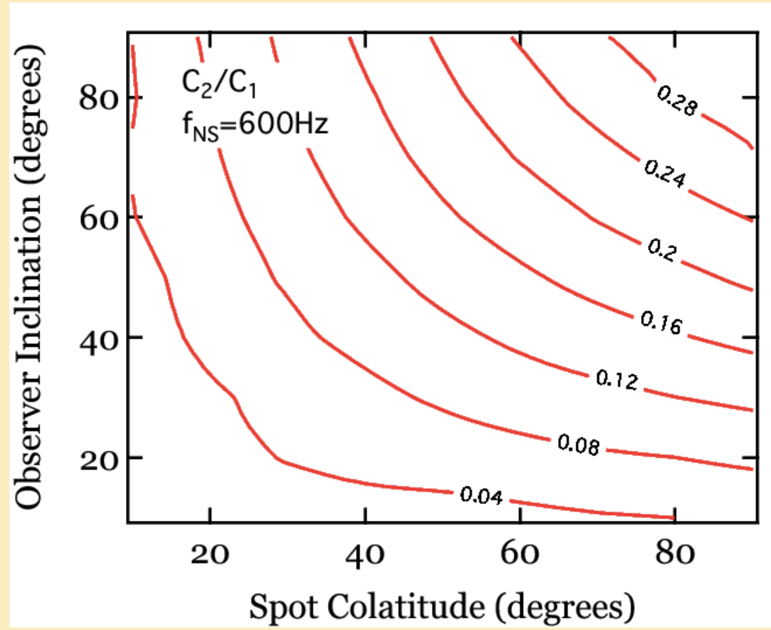
Harmonic content of flux oscillations: mass-radius constraints



- The harmonic content provides (at least) a second measurable. However, the amplitudes are small, and must be measured to <10% accuracy in order to obtain ~1 km resolution in radius. This turns out to be a severe requirement.
- It is unlikely that additional harmonics will be measurable, in practice.
- We still do not have enough measurables to fully solve the problem, resulting in correlations with the geometric angles.

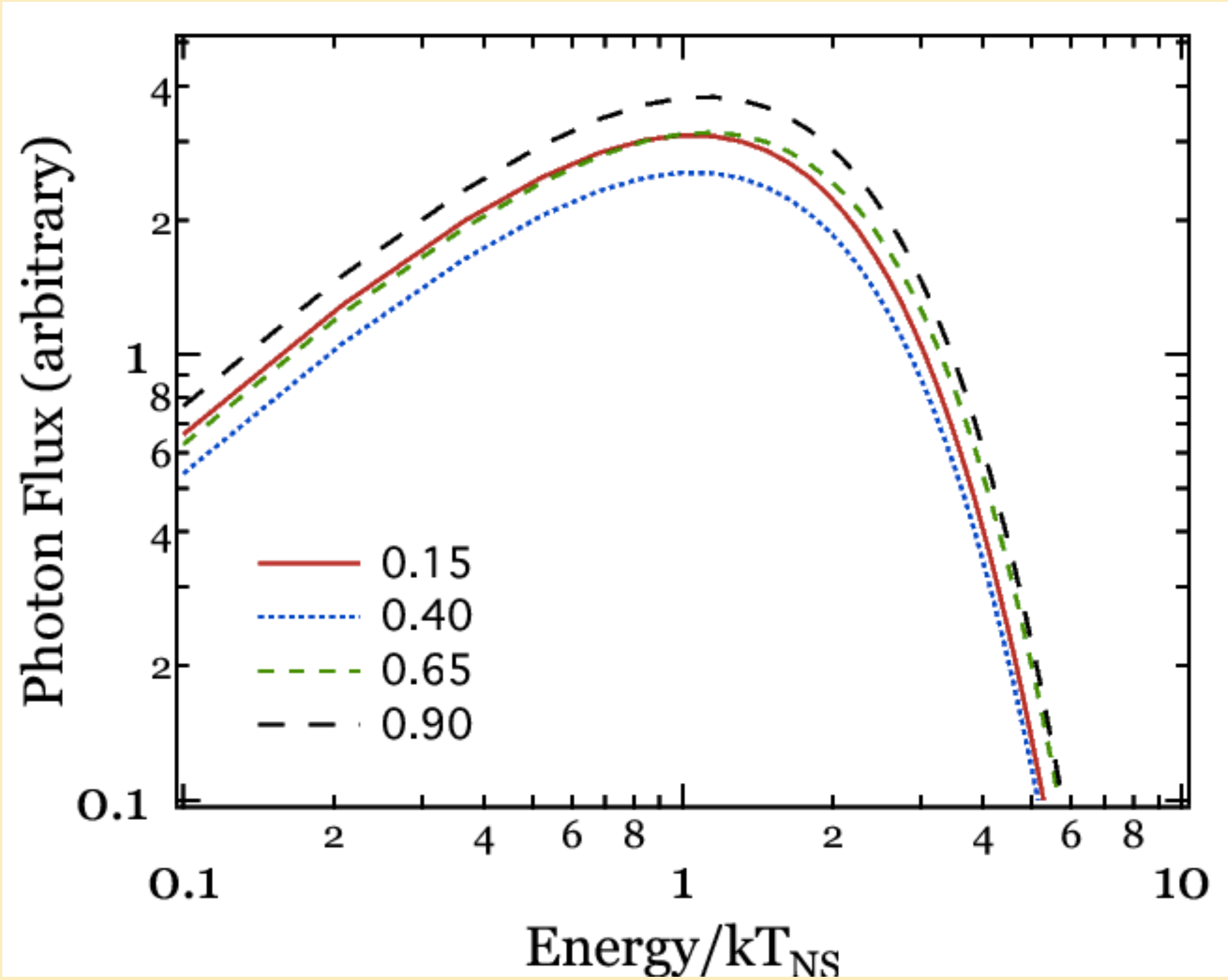
Harmonic content of flux oscillations: geometry constraints





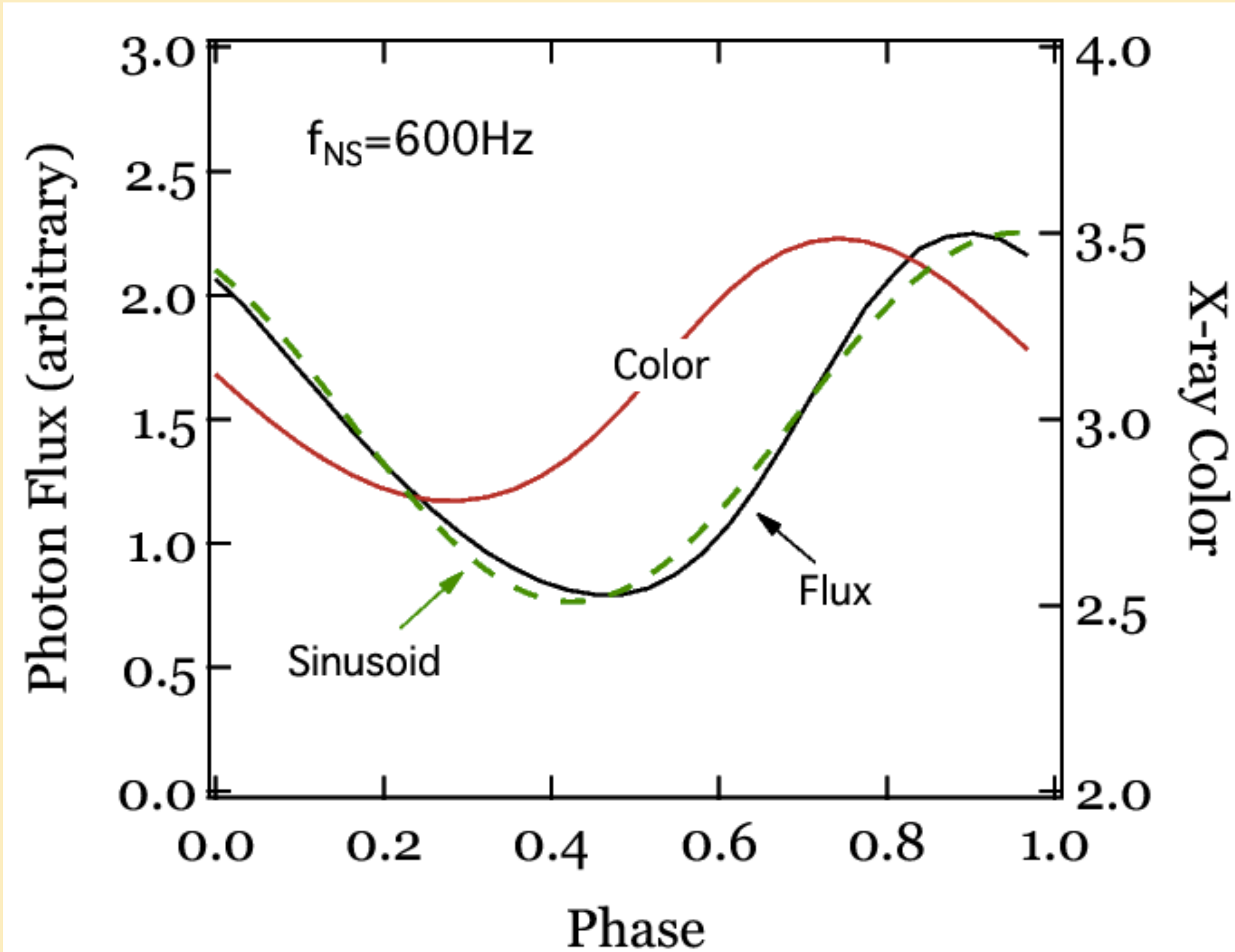
The contours lie primarily along curves with consant values of (sin θ sin i). If one is only interested in M and R, one could use this product as a single nuisance parameter. However, we are still short at least one measurable.

Solution: Exploit energy-dependence of flux oscillation



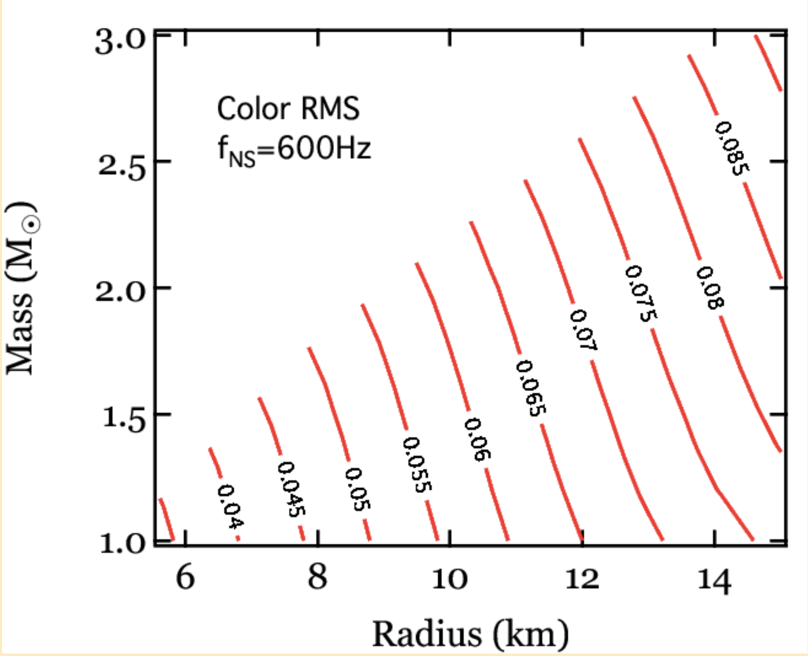
Examine behavior of the “color”: ratio of flux in two different energy bands.

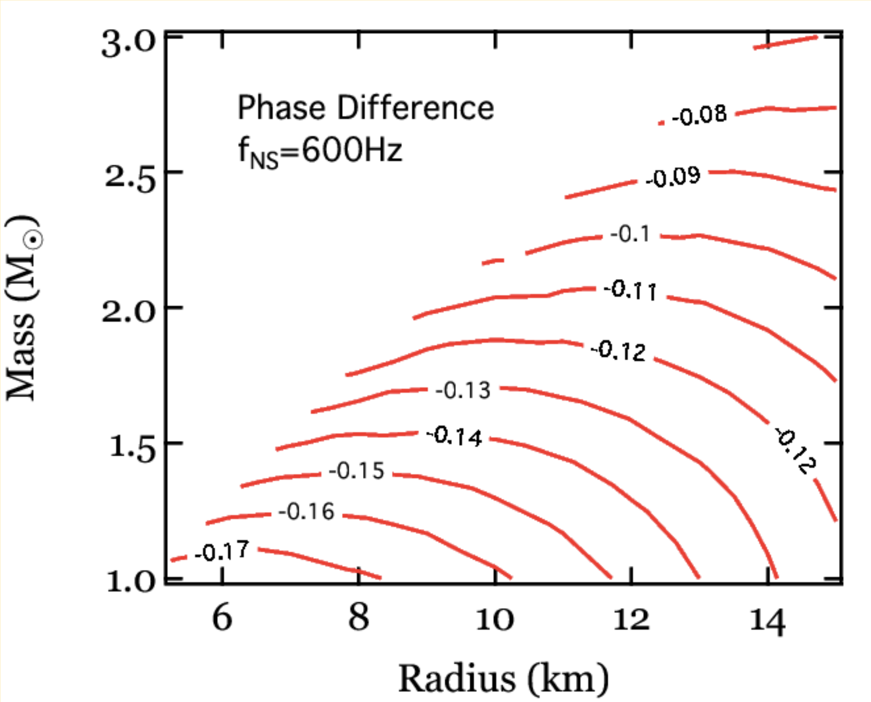
Color oscillation is shifted in phase with respect to flux



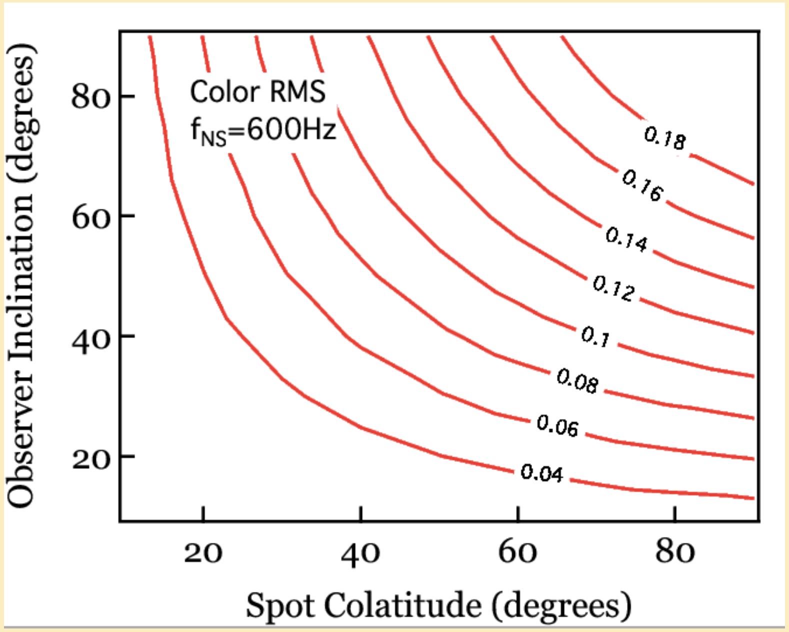
Amplitude and phase of color oscillation provide two additional measurables.

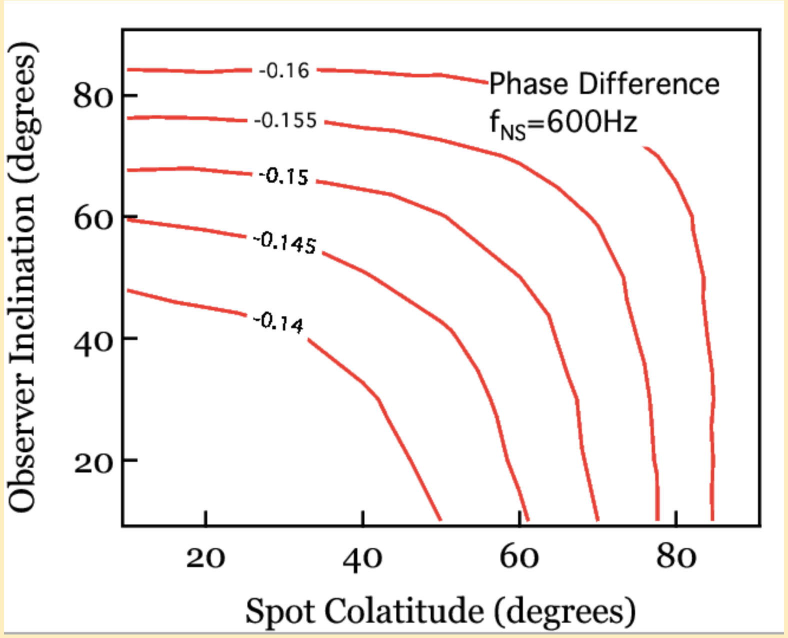
Color oscillations provide nearly orthogonal constraints



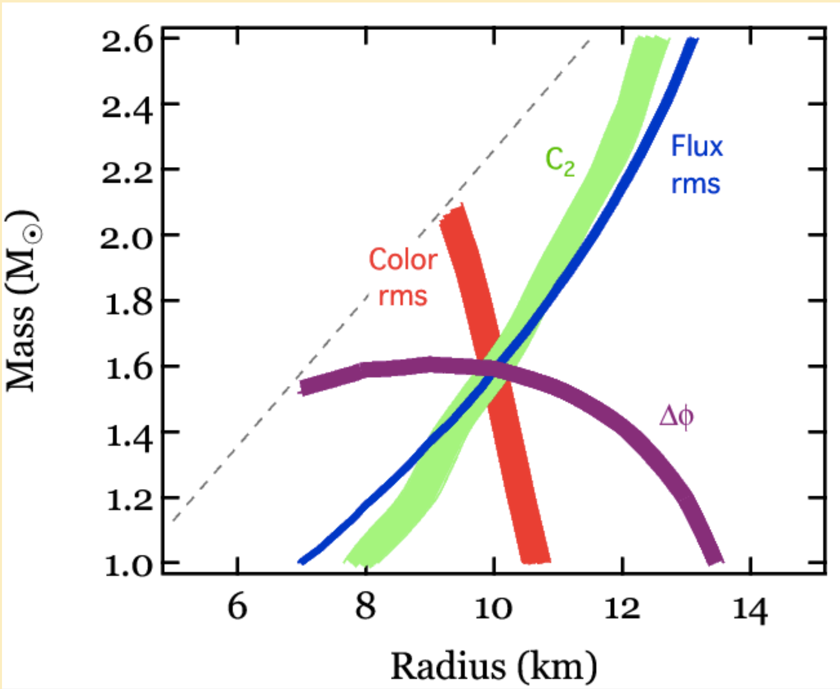


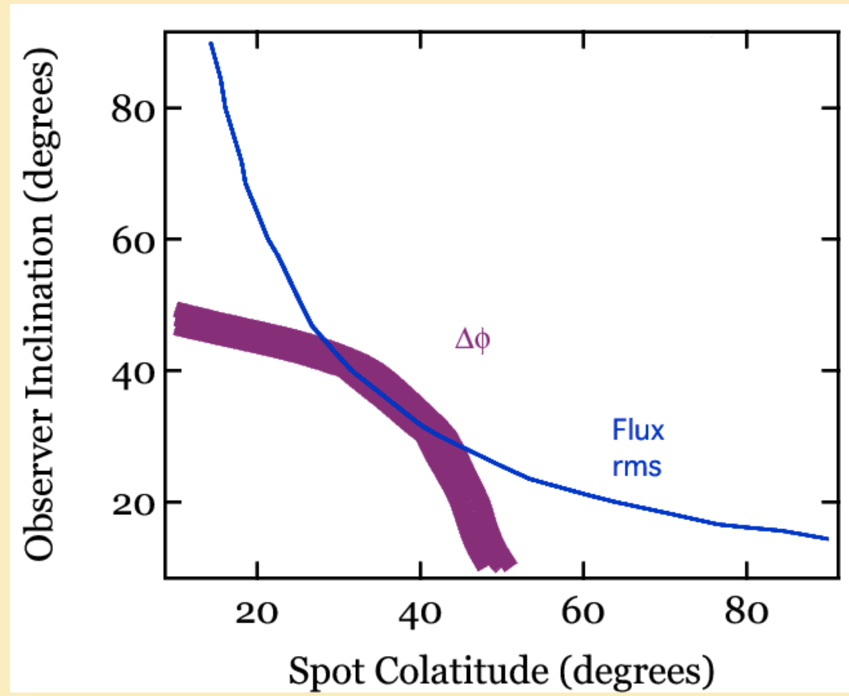
Color oscillations also allow geometric angles to be separated





Combination of flux and color oscillations allow full solution





"True" values:

- $M = 1.6\ M_{sun}$
- $R = 10$ km
- $\theta = 40$ degrees
- $i = 30$ degrees

What is needed for a precise radius measurement?

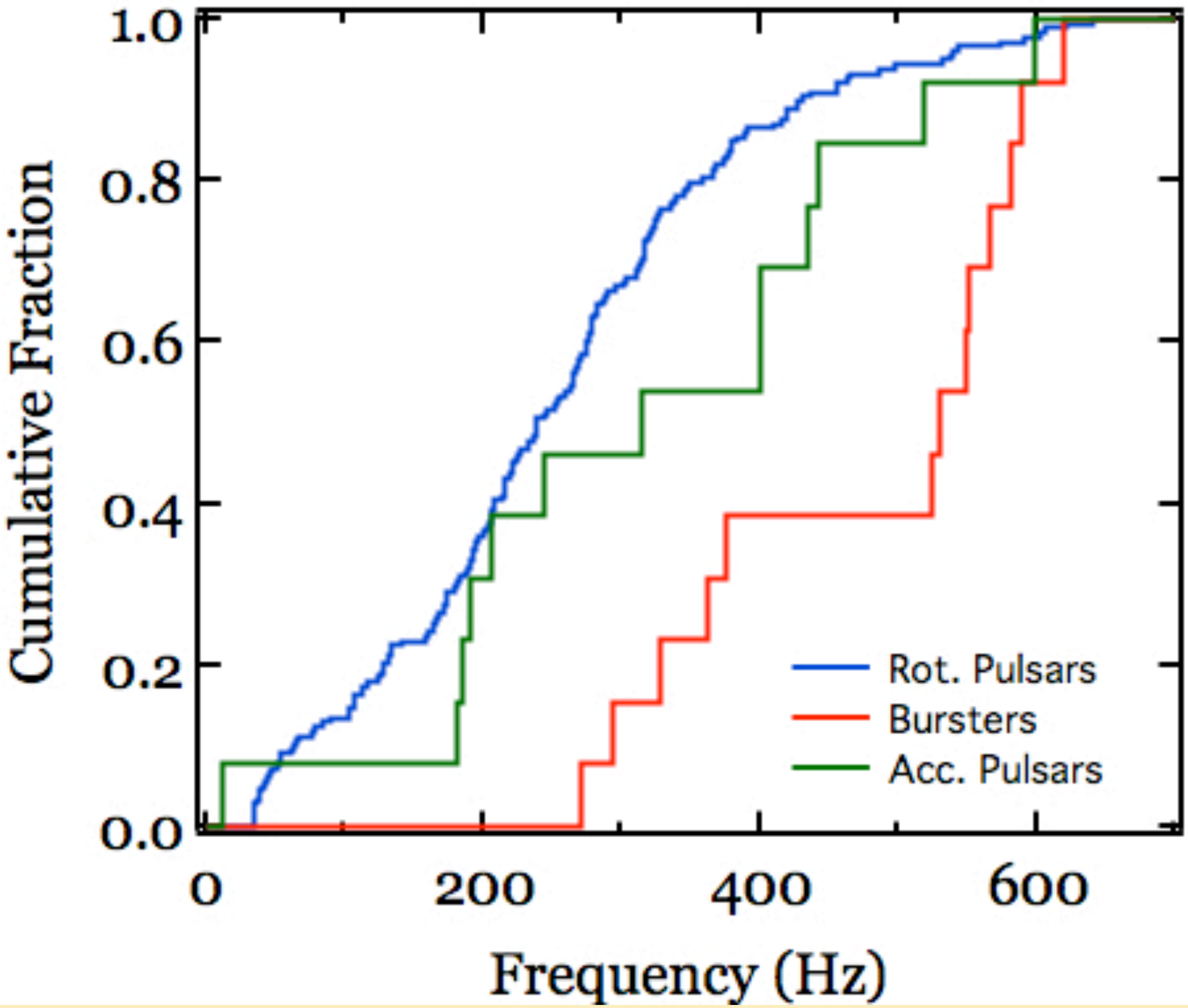
$$\frac{\Delta R_{\rm eq}}{R_{\rm eq}} \simeq 0.055 \left(\frac{C_1}{0.3}\right)^{-1} \left(\frac{f}{600\ \rm Hz}\right)^{-1} \left(\frac{R_{\rm eq}}{10\ \rm km}\right)^{-1} \left(\frac{\sin i}{0.5}\right)^{-1} \left(\frac{\sin\theta_{\rm s}}{0.5}\right)^{-1} \left(\frac{S}{10^6\ \rm cts}\right)^{-1/2}$$

- Fast rotation
- At least 10^6 counts.

How to put this in practice observationally?

Need to use objects where emission is primarily from hot spots on the surface.

- Thermally-emitting rotation-powered millisecond pulsars
  - Pros:
    - Very stable spin rates
    - Accurately known masses (in some cases)
  - Cons:
    - Possible magnetospheric contamination
    - Uncertainties in radiation pattern (beaming)
    - Faint → long integrations with optics
- Thermonuclear X-ray burst oscillations
  - Pros:
    - Very bright
    - Better-understood radiation pattern
  - Cons:
    - Drifting frequencies
    - Short duration → need to stack many bursts



1.0
0.8
0.6
0.4
0.2
0.0
Cumulative Fraction
0
200
400
600
Frequency (Hz)
Rot. Pulsars
Bursters
Acc. Pulsars

Observational prospects

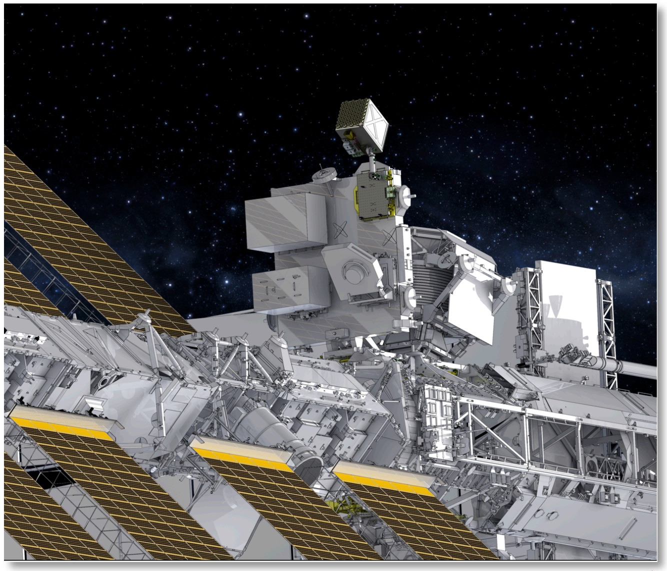
- The NICER mission has been selected by NASA for launch to International Space Station in late 2016. Its primary objective is pulse profile modeling of thermally-emitting millisecond pulsars.

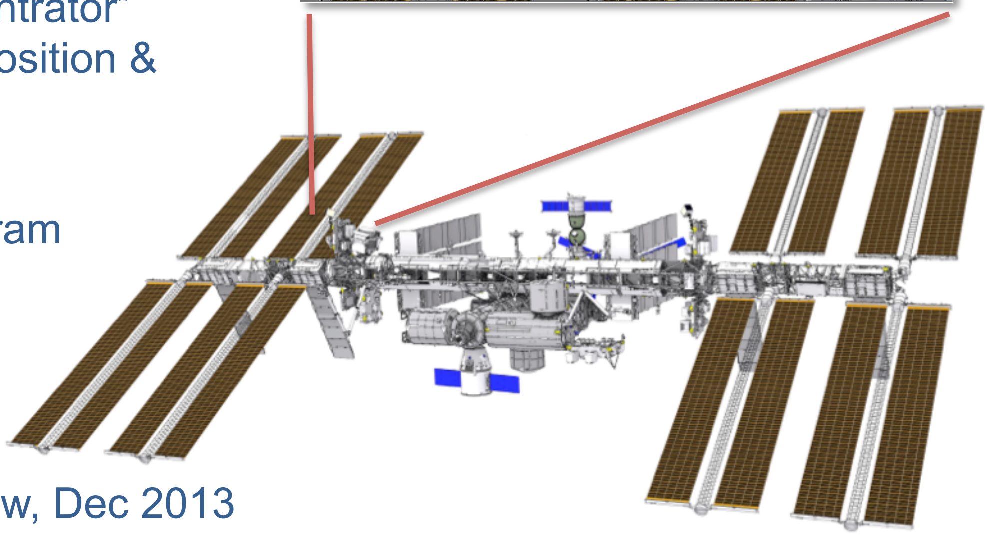
- The LOFT mission was recently proposed to ESA. It was not selected in the M3 round, but will likely be reproposed for M4. If selected it would launch in the mid to late 2020s. It will do pulse profile modeling of X-ray burst oscillations.

An Astrophysics Mission of Opportunity on the International Space Station

NICER

- ***PI:*** *Keith Gendreau, NASA GSFC*
- ***Science:*** Understanding ultra-dense matter through observations of neutron stars in the soft X-ray band
- ***Launch:*** August 2016, SpaceX-12 resupply
- ***Platform:*** ISS ExPRESS Logistics Carrier (ELC), with active pointing over nearly a full hemisphere
- ***Duration:*** 18 months + proposed Guest Observer program (min. 6-month extension)
- ***Instrument:*** X-ray (0.2–12 keV) “concentrator” optics and silicon-drift detectors. GPS position & absolute time reference
- ***Enhancements:***
  - Guest Investigator/Observer program
  - Demonstration of pulsar-based spacecraft navigation
- ***Status:***
  - Passed PDR, Dec 2013
  - Passed ISS Phase 1 Safety Review, Dec 2013
  - CDR scheduled Sept 2014

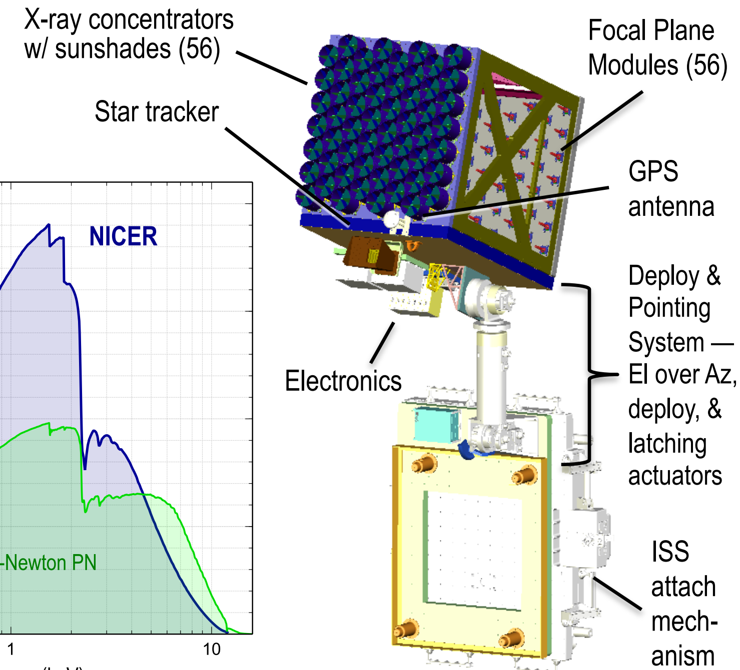


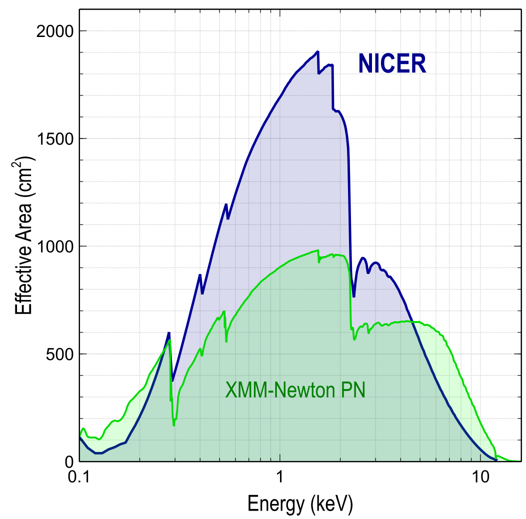


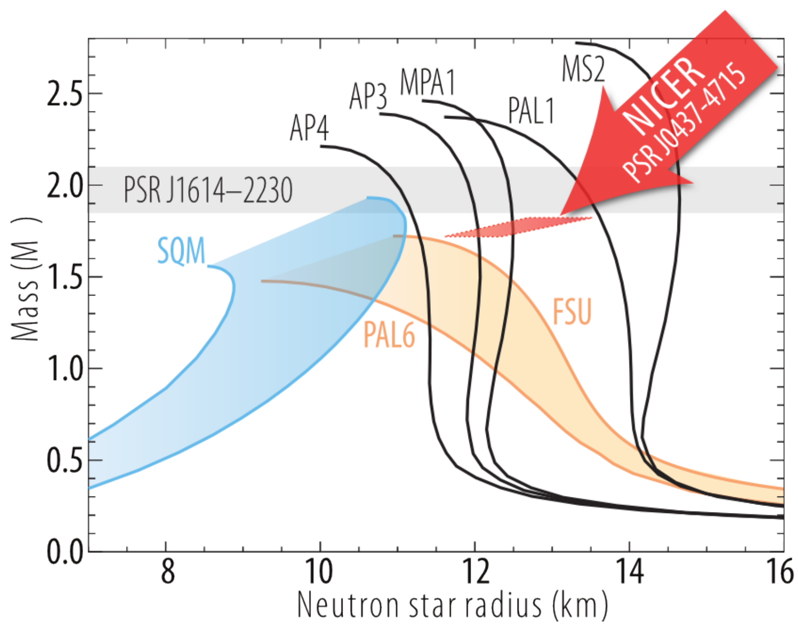
Science objectives and enabling capabilities

An unprecedented combination of time resolution, energy resolution, and sensitivity

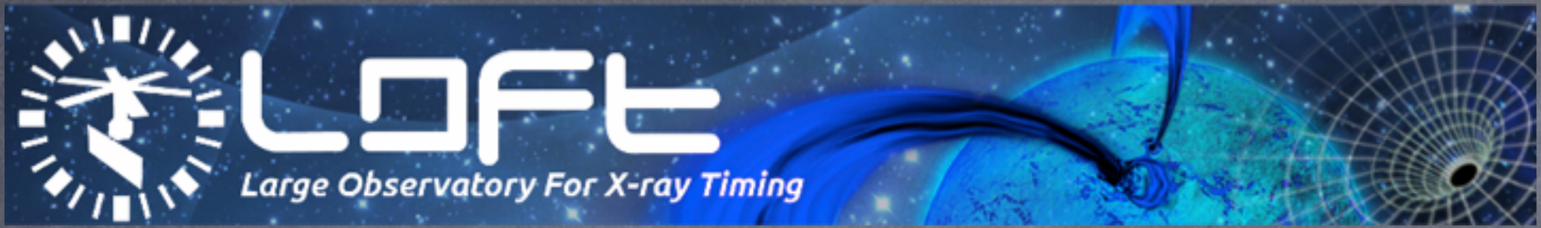
- Tuned for NS thermal emissions, with absolute time resolution enabling phase resolved spectroscopy and coherent lightcurve integration over years
  - ✓ Spectral band: 0.2–12 keV
  - ✓ Timing resolution: 100 nsec RMS absolute
  - ✓ Energy resolution: 125 eV @ 6 keV
  - ✓ Angular resolution: 6 arcmin (non-imaging)
  - ✓ Sensitivity: 5.3×10^{-14} erg/s/cm^2 (5σ)
    - ▪ 0.5–10 keV in 10 ksec, Crab-like





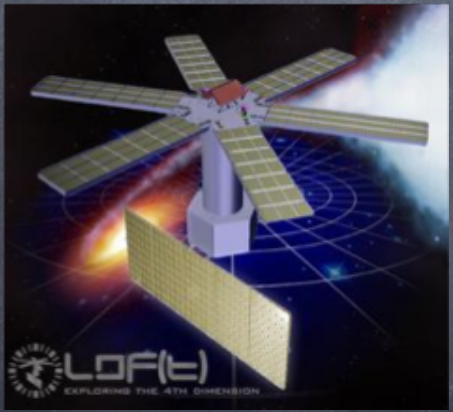


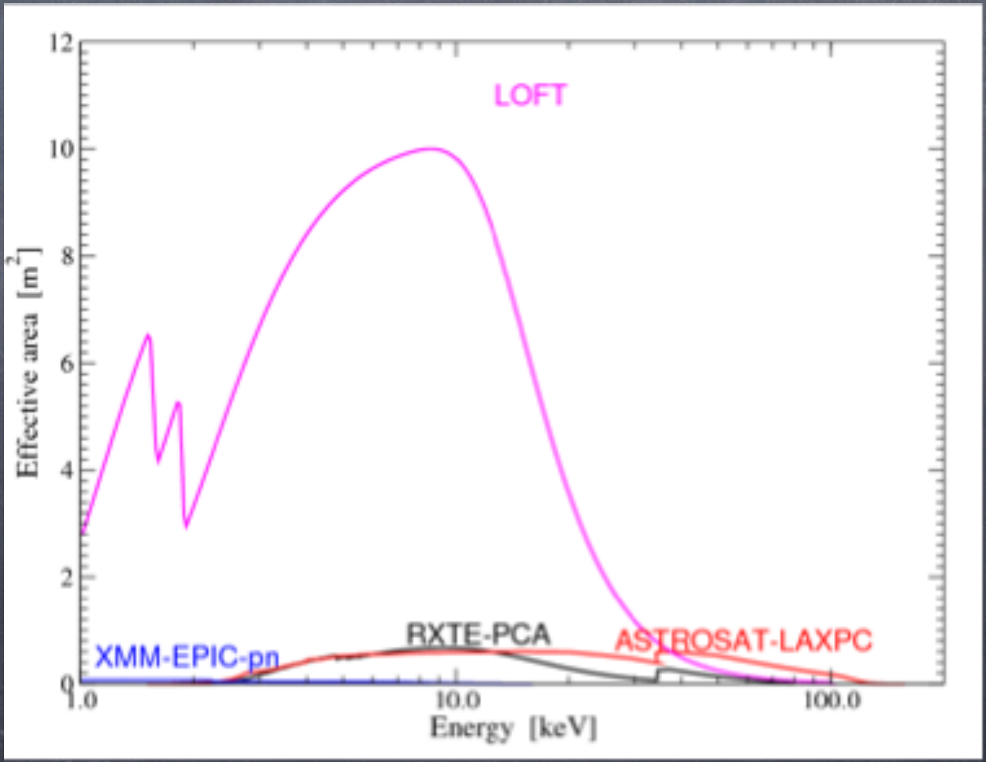
Objective	Measurements
Structure — Reveal the nature of matter in the interiors of neutron stars	Neutron star radii to ±5%; cooling timescales
Dynamics — Uncover the physics iof dynamic phenomena associated with neutron stars	Stability of pulsars as clocks; properties of outbursts, oscillations, and precession
Energetics — Determine how energy is extracted from neutron stars.	Intrinsic radiation patterns, spectra, and luminosities

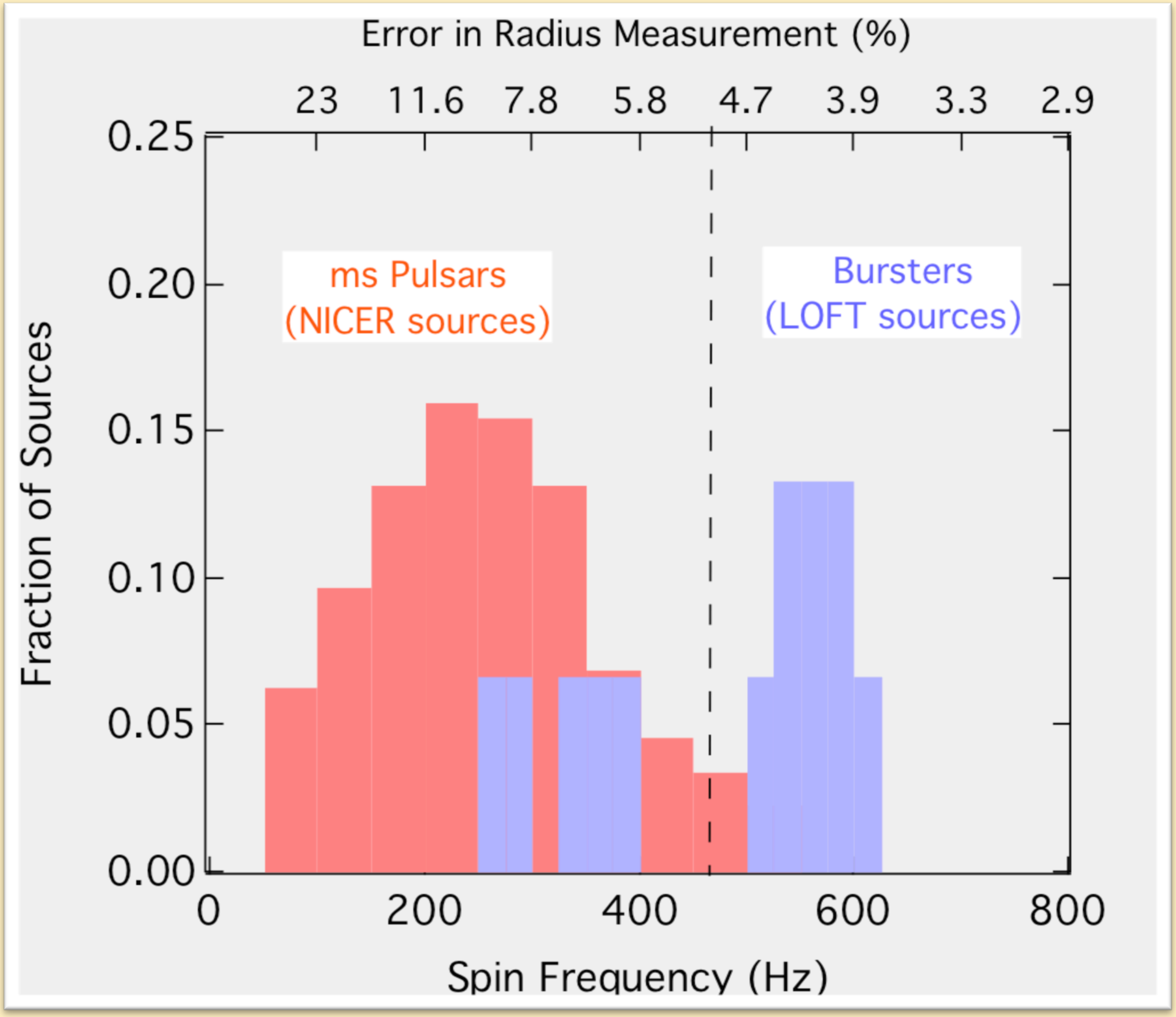


an ESA M3 mission with a possible launch date around 2022

many X-ray silicon drift detectors at 2-30 keV,
with a 10 m^2 area






Error in Radius Measurement (%)
23
11.6
7.8
5.8
4.7
3.9
3.3
2.9
0.25
0.20
0.15
0.10
0.05
0.00
Fraction of Sources
ms Pulsars
(NICER sources)
Bursters
(LOFT sources)
0
200
400
600
800
Spin Frequency (Hz)

Summary

- It is possible to use X-ray pulse profile modeling of surface hot spots on rotating neutron stars to determine the stellar mass and radius separately, but only for moderately rotating (>300 Hz) stars and only by exploiting the energy dependence of the pulse profiles.

- Faster rotators provide more precise radius measurements.

- The NICER mission has been selected by NASA for launch to International Space Station in late 2016. Its primary objective is pulse profile modeling of thermally-emitting millisecond pulsars.

- The LOFT mission was recently proposed to ESA. It was not selected in the M3 round, but will likely be reproposed for M4. If selected it would launch in the mid to late 2020s. It will do pulse profile modeling of X-ray burst oscillations.