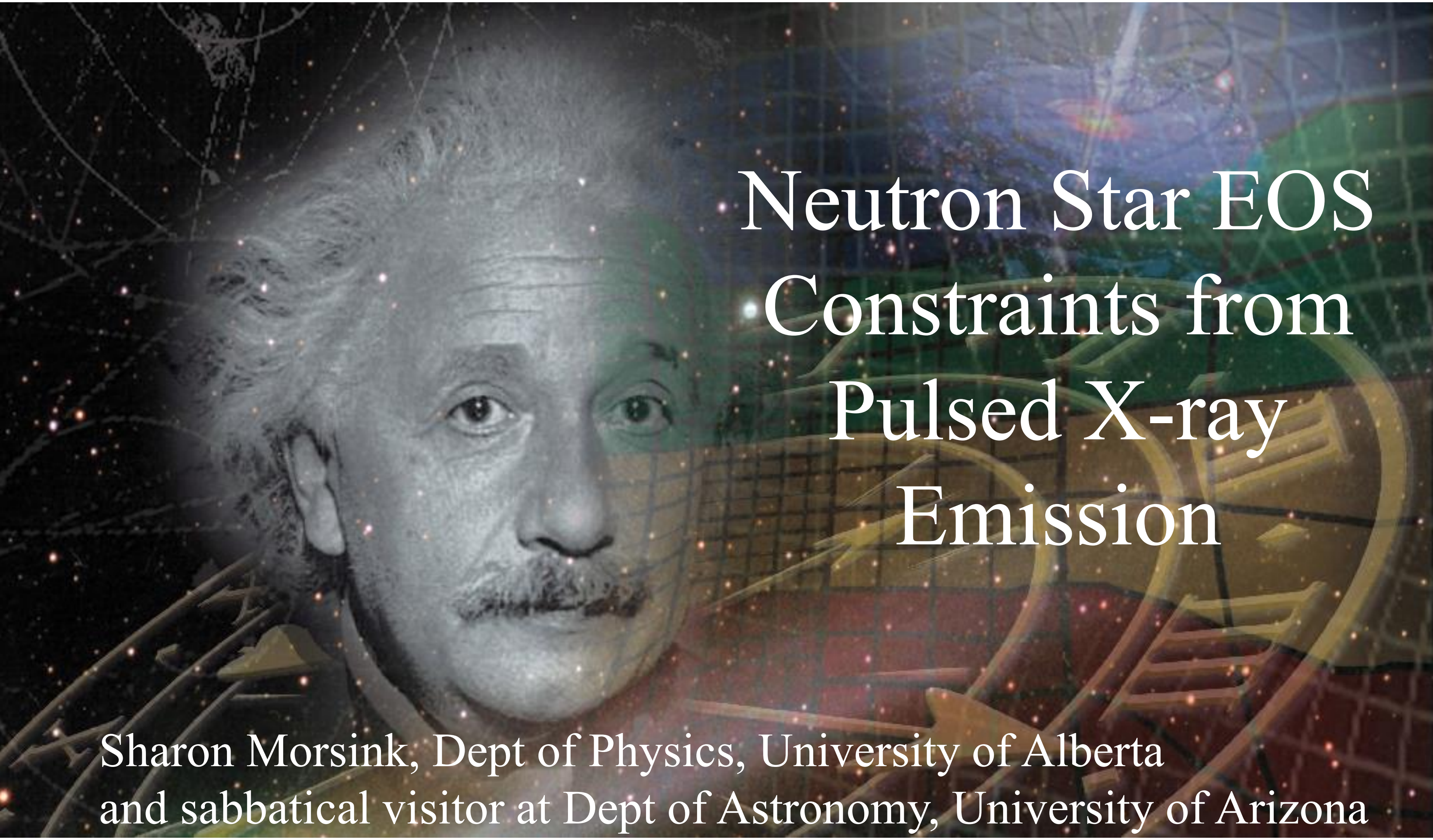

Neutron Star EOS Constraints from Pulsed X-ray Emission

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50th Anniversary Texas Symposium, Dallas TX, Dec. 10, 2013

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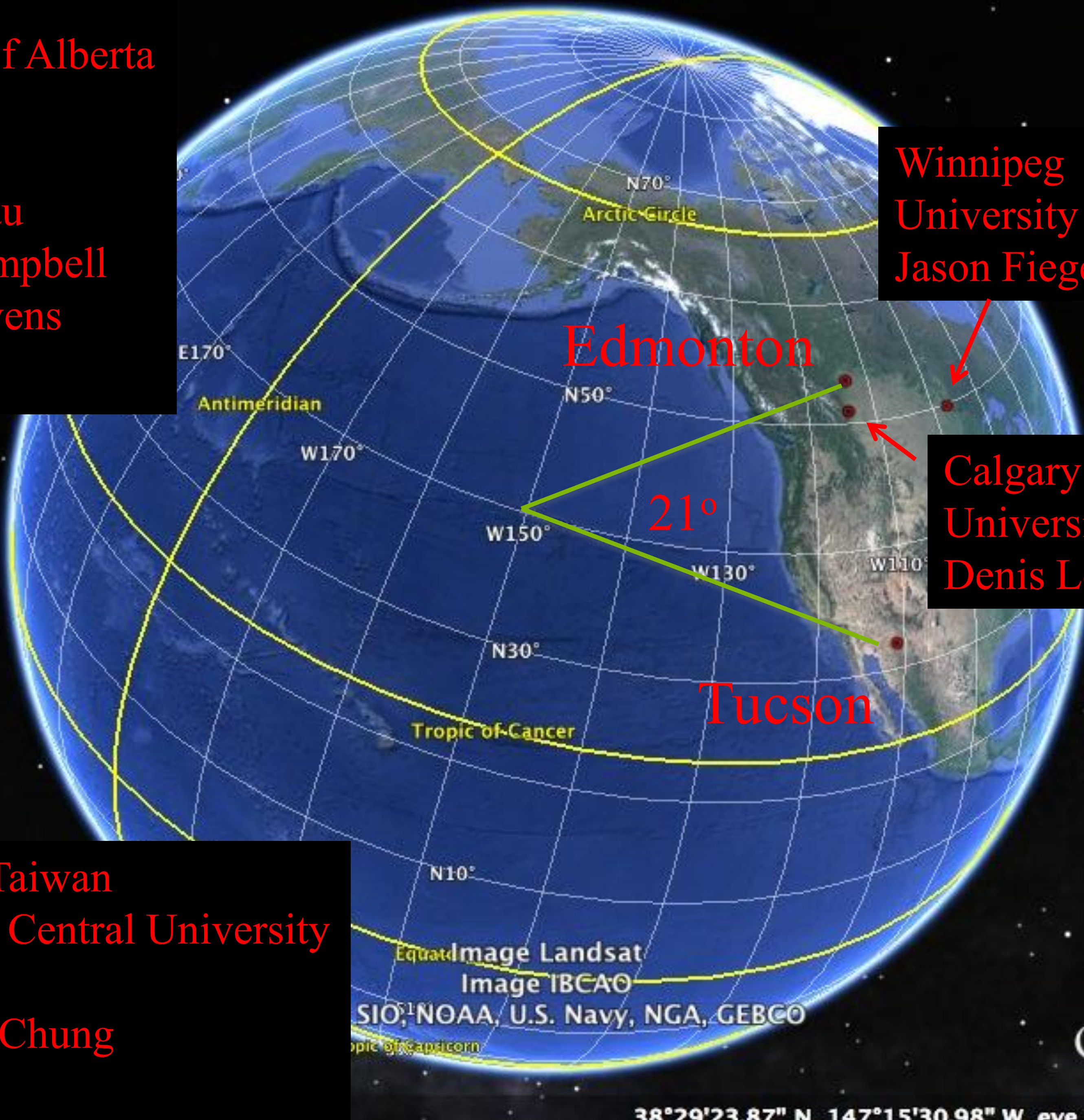


Neutron Stars -- More than just neutrons …

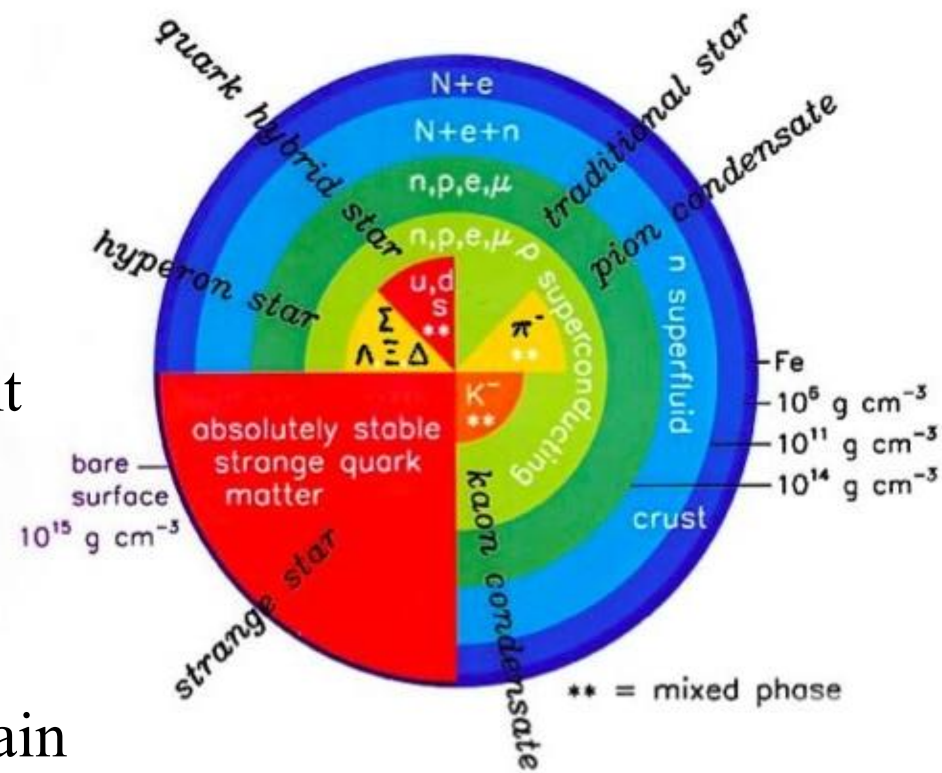
- The behaviour of matter at densities above nuclear density but at low temperature is not well understood.

- Earth-based experiments like the Relativistic Heavy Ion Collider (RHIC) provide information only about the very high T phase

- Different hypotheses include different particle species and phases of matter in the core

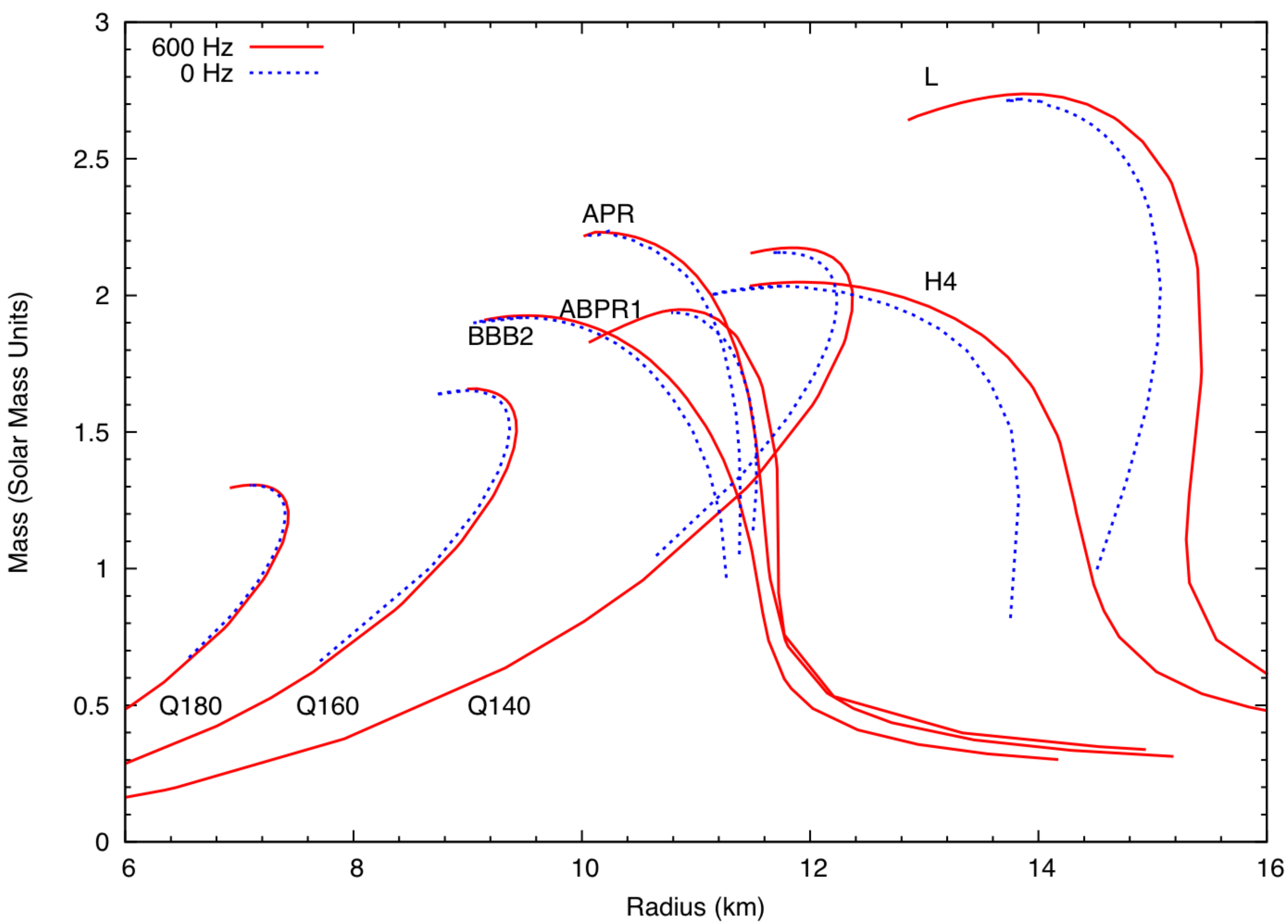
- Each of the possible equations of state (EOS) provides different predictions about the possible masses and radii of NS.

- Major goal of studying NS is to make measurements that constrain the EOS of dense matter.

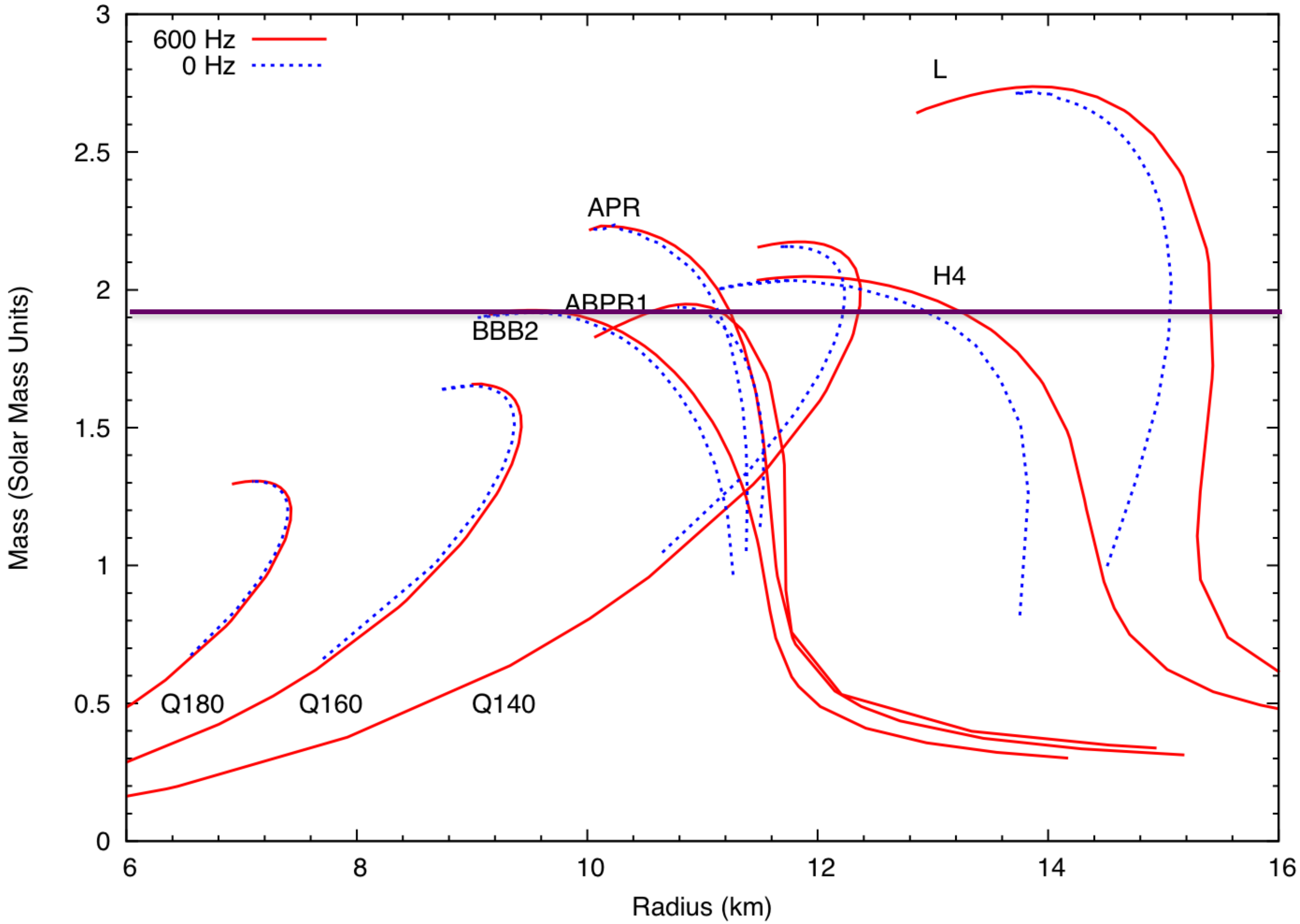


Drawing by James Lattimer

Mass - Radius Curves

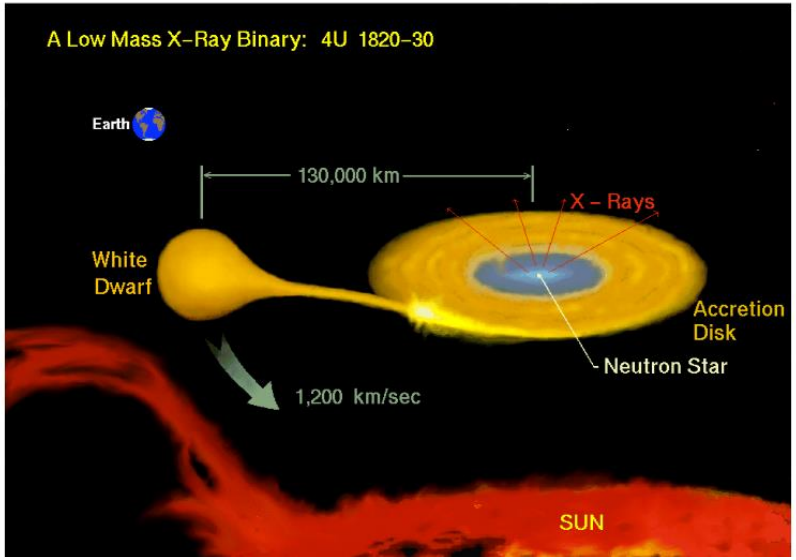


Mass - Radius Curves



Measurement of Shapiro Delay gives M=1.93 $M_{\odot}$ Demorest et al. Nature 2010

Neutron Stars in LMXB

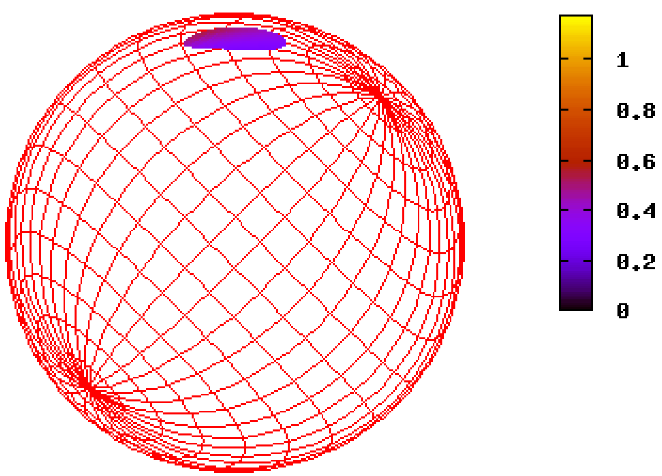


- An accreting NS has different luminosity states: quiescence or outburst
- Quiescence – Little or no accretion, flux mainly from NS surface

- Outburst – heavy accretion
- Accretion powered pulsations sometimes seen
- X-ray Bursts sometimes seen
- Pulsations and X-ray Bursts are flux originating from the NS surface

Rotating Hot Spots

- Rotation Powered X-ray pulsars - no accretion, x-ray emission dominated by emission from the surface (not light cylinder). Eg: Bogdanov ApJ 2013
- Accretion Powered Pulsars – pulsations from hot spot
- X-ray Bursts – oscillations at the spin frequency observed
- A “hot spot” on the NS surface is most likely the source for the periodic flux from these sources



NS Constraints from Rotating Hot Spots

- Find neutron stars whose light is emitted from the star's surface
- Model the local microphysics of the emitting area
  (spot size, shape, emission spectrum and beaming)
- Combine with relativistic raytracing to find which photons
  reach the telescope to construct light curve
- Light-deflection depends on the ratio GM/Rc^2
- Rotational "Doppler" effects depend on $R\Omega/c$

Forward Problem: Make assumptions about properties of star and emission and compute light curve.

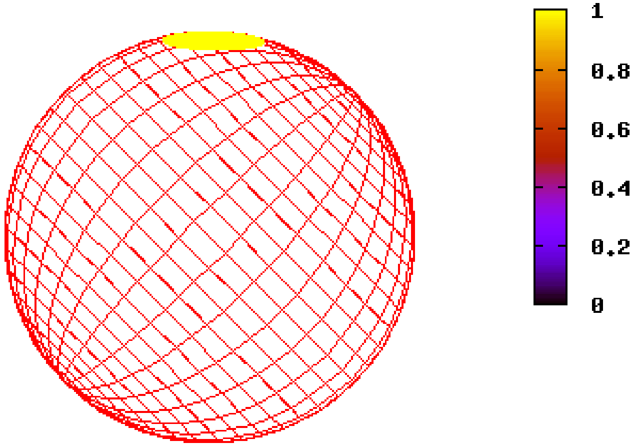
Inverse Problem: Measure light curve and find best fit set of parameters characterizing star and emission properties.

Dependence of Pulse Profiles on M/R

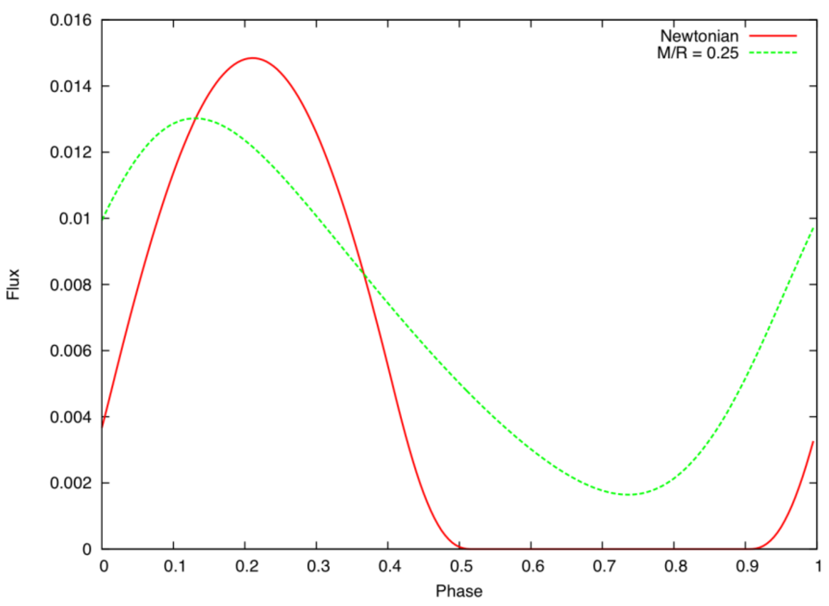
M/R = "compactness" affects how much of the star is visible due to light-bending

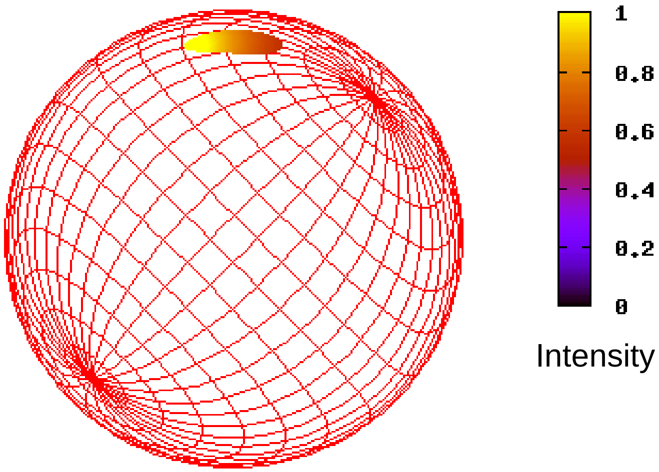
- larger M/R -> less modulation

These effects are independent of the photon's energy.



Newtonian Gravity





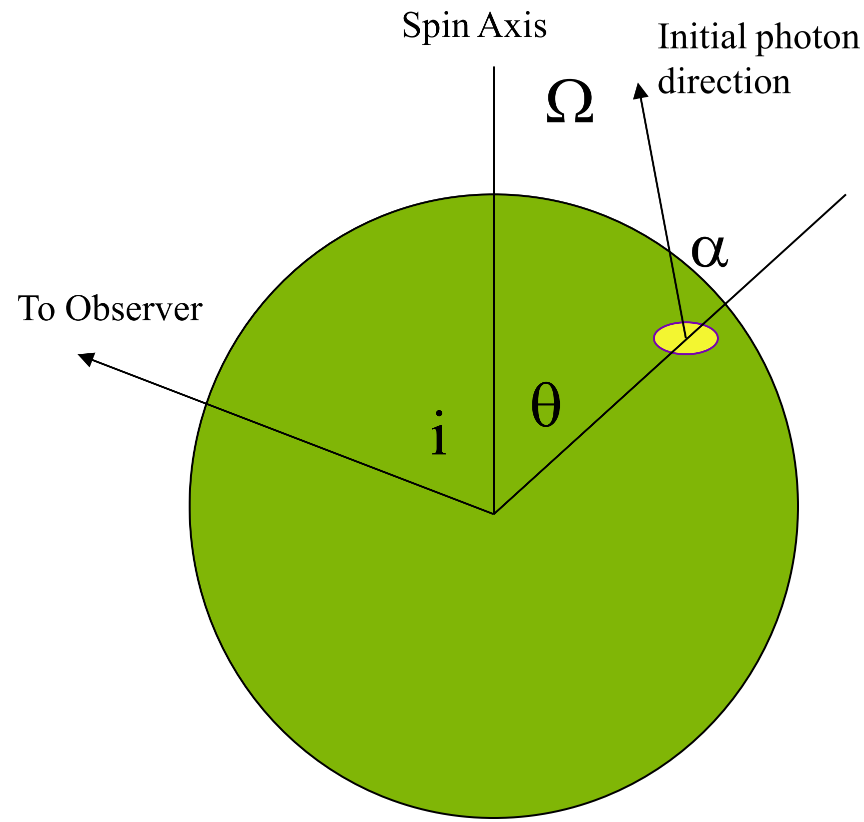
General Relativity M/R = 0.25

Graphics by Brock Moir, U of Alberta undergrad.

Inclination and emission angle

- θ = angle between the hotspot's centre and the spin axis
- i = angle between the observer and the spin axis (orbital and spin angular momenta aligned)
- α = angle between the photon's initial direction and the normal to the surface.

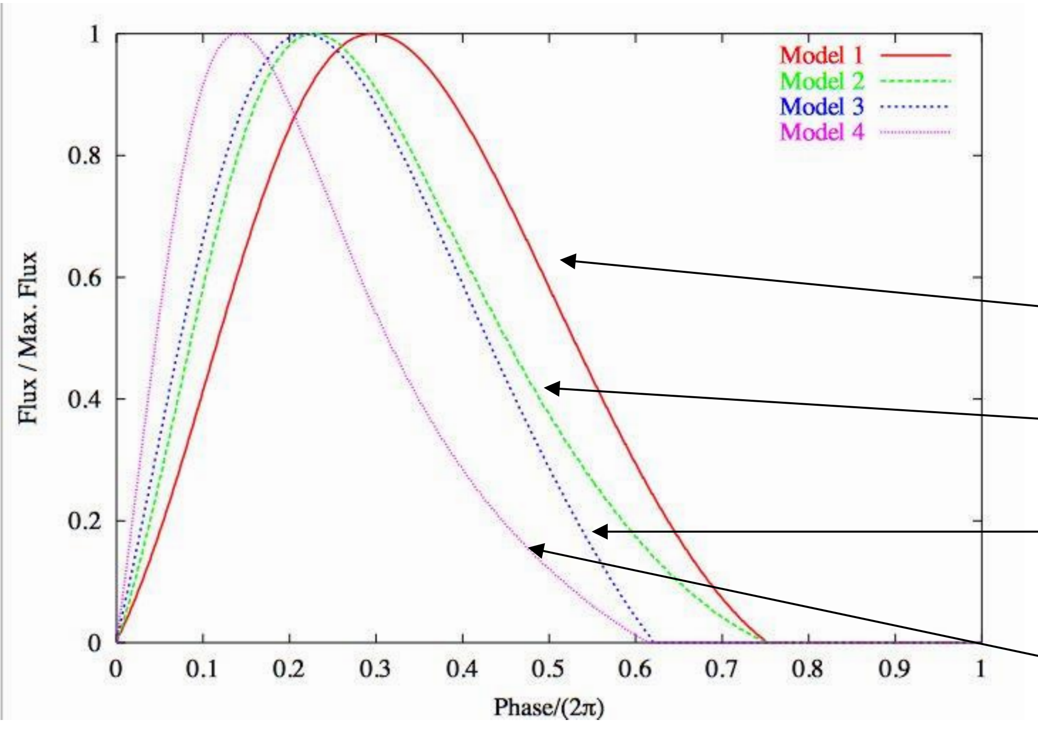
- Small sin(i)sin(θ) low modulation – degeneracy with M/R



Dependence of Pulse Profiles on Speed

$R\,\Omega\,\sin\theta\,\sin i\,(1-2M/R)^{-1/2}$ = speed affects asymmetries between rise and fall times

- larger speed -> larger time asymmetries
- Degeneracy between R and sinθ sini



Pulse Shapes for 1.4 $M_\odot$ Stars
Isotropic + Equatorial Emission

R=9.6 km Spin=300 Hz v=0.08 c

R=9.8 km Spin=600 Hz v=0.16 c

R=15.1 km Spin=300 Hz v=0.11c

R=16.4 km Spin=600 Hz v=0.24 c

C. Cadeau, D. Leahy and S. Morsink, 2005 ApJ

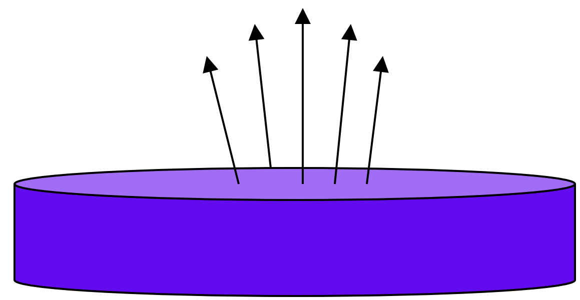
Anisotropic Emission

Beaming affects:

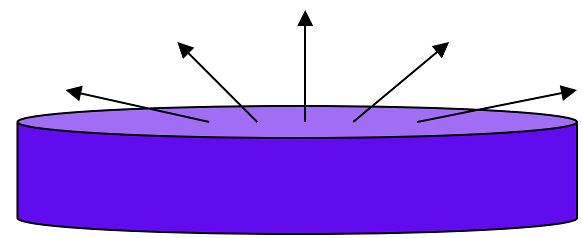
- modulation: anti-beaming, (case C) allows the spot to be seen more easily than normal beaming (case A)
- timing asymmetries: peak emission occurs earlier for C than for A
- Pulse shape: double-peaks or flattened peaks possible with C

Accretion Powered Pulsations – Case C with an unconstrained amount

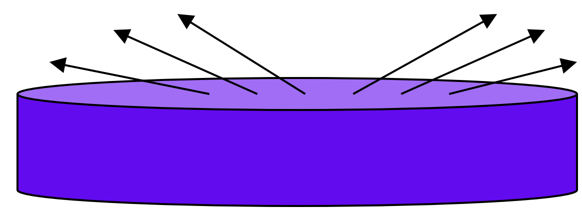
X-ray Burst Oscillations – Case A, fairly well known limb-darkening



A = Beamed towards the normal



B = Isotropic emission

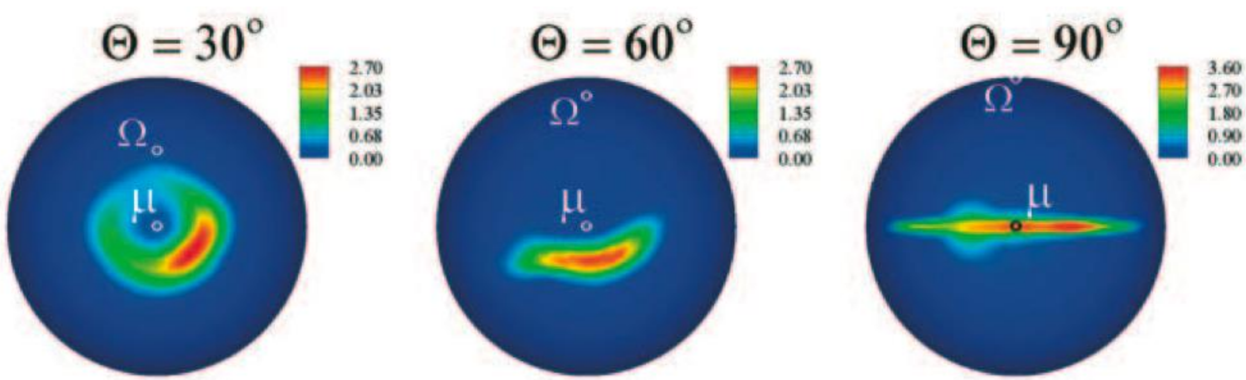


C = Beamed towards the surface

Other complications

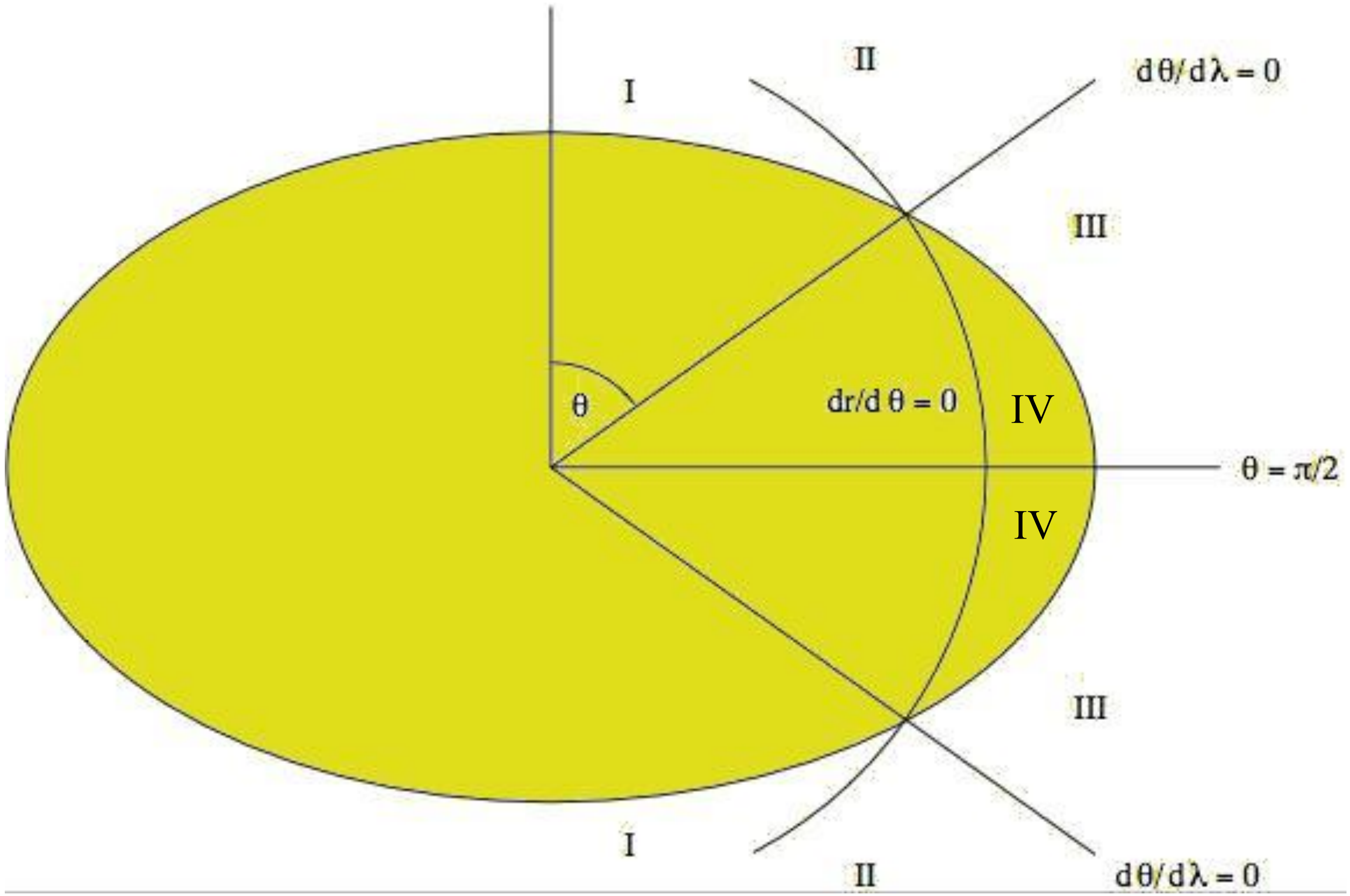
- Oblate shape of star
- Scattering by optically thin plasma near star
- Multiple spots may be visible (Ibragimov and Poutanen 2009)
- Spots are not necessarily circles (Kajava et al 2011)

- MHD simulations by Kulkarni, Romanova & Lovelace
- Accretion onto a rapidly rotating magnetic NS
- Complicated spot shapes result



Kulkarni & Romanova 2005

Stellar Oblateness



Cadeau, Morsink, Leahy & Campbell 2007 ApJ
Morsink, Leahy, Cadeau & Braga 2007 ApJ

X-ray Telescopes

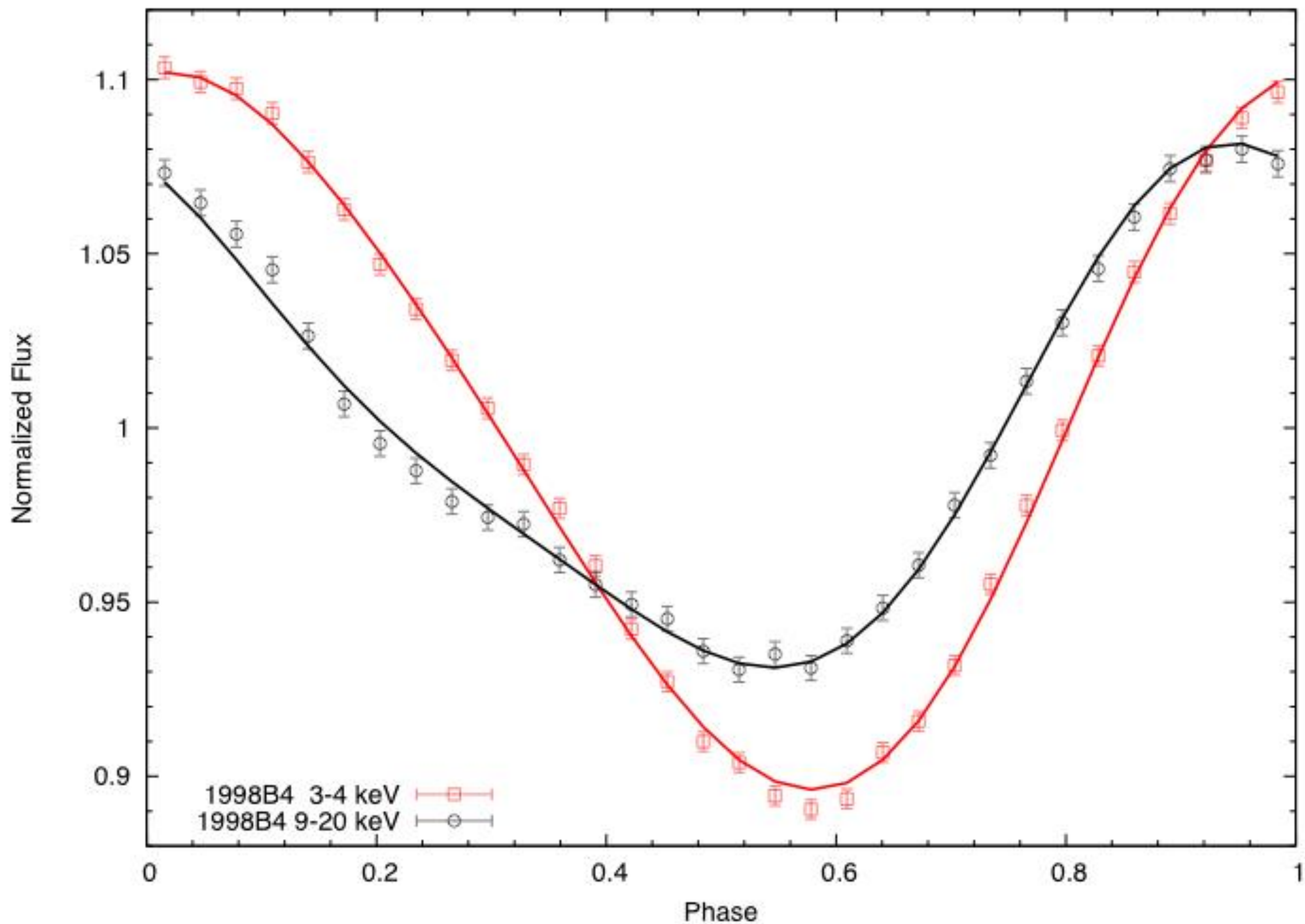
- RXTE (1996 – 2012) X-ray timing
- Chandra and XMM – mainly spectroscopy and imaging, some timing capabilities
- NICER = Neutron Star Interior Composition ExploreR, new instrument on ISS, approved for launch in 2016
- ATHENA: spectroscopy, imaging and timing; if approved launch 2028 (ESA)
- Proposed Missions (ESA)
  - LOFT: Large Observatory For X-ray Timing; if approved launch 2024

Constraints from Accreting ms-Period Pulsars

- Models include oblate shape, time delays
- Unknown inclination angle, mass, radius
- Different pulse shapes in different time periods: allow for changes in spot location and spectrum, keep i, M, R fixed
- Free parameter describing anisotropy and freedom in choosing spectral model dominate precision

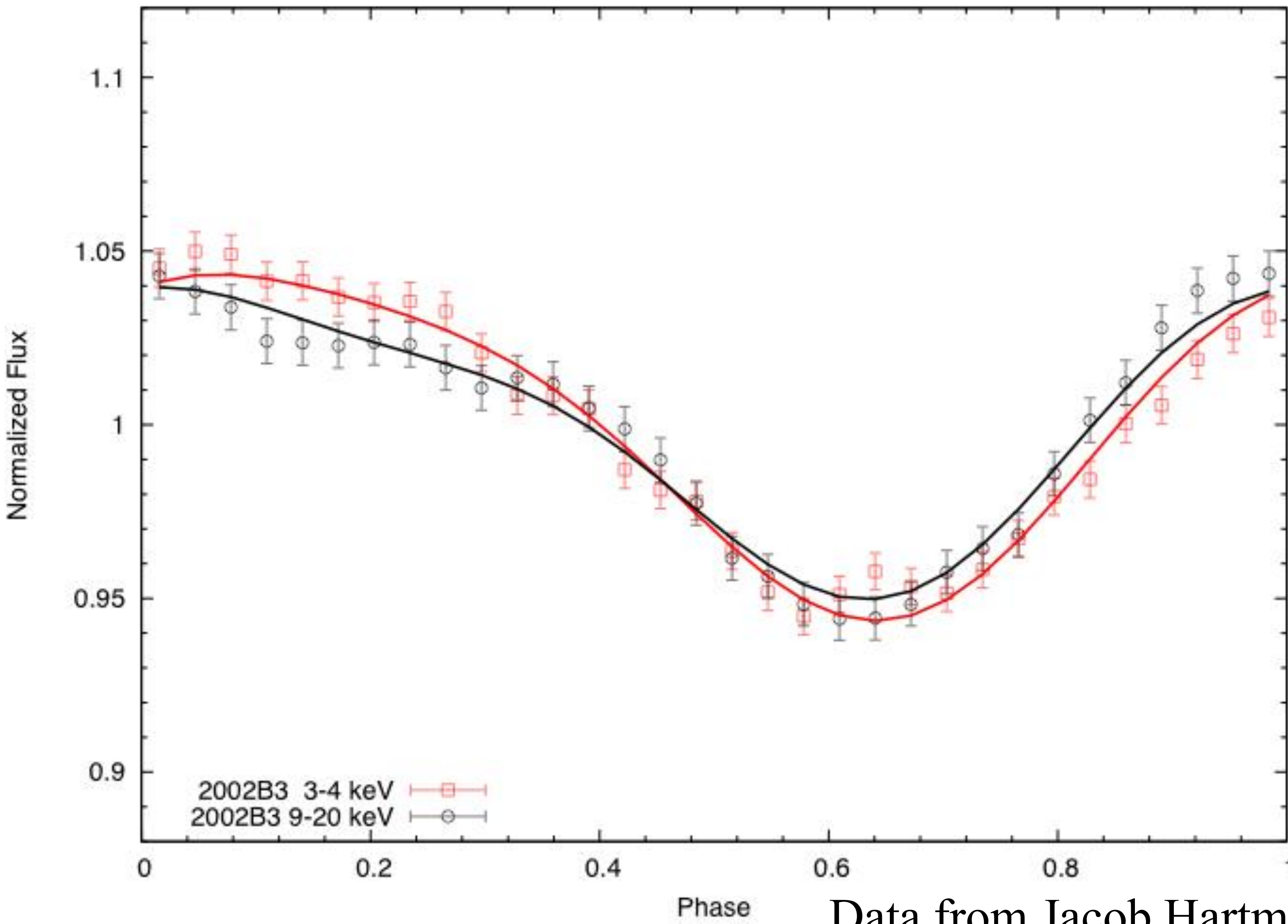
- Leahy, Morsink & Chou, ApJ 2011
- Morsink & Leahy, ApJ 2011
- Leahy, Morsink, Chung, & Chou, ApJ 2009

SAX J1808 1998 Outburst (Box 4)



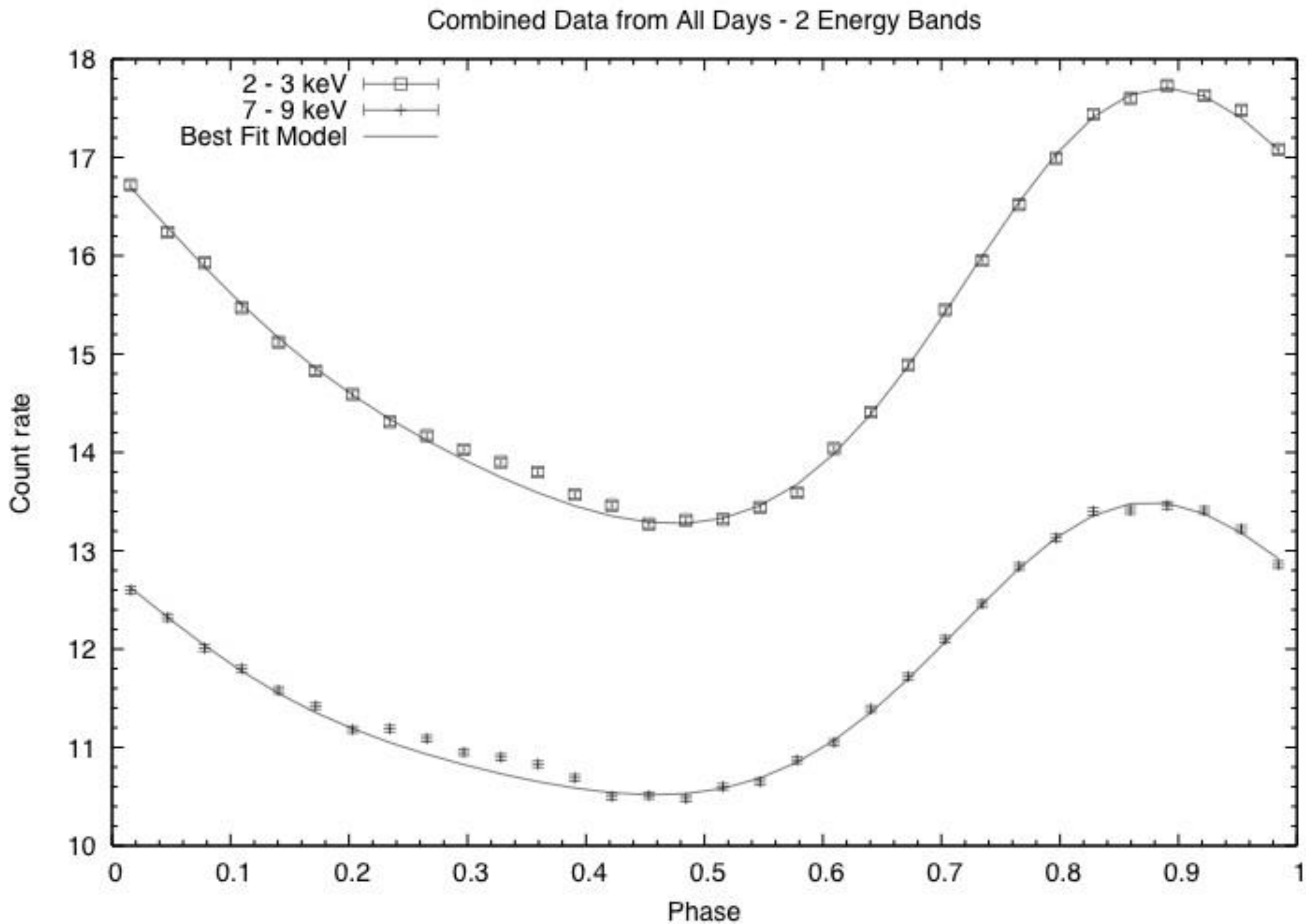
RXTE Data from Jacob Hartman

SAX J1808 2002 Outburst (Box 3)



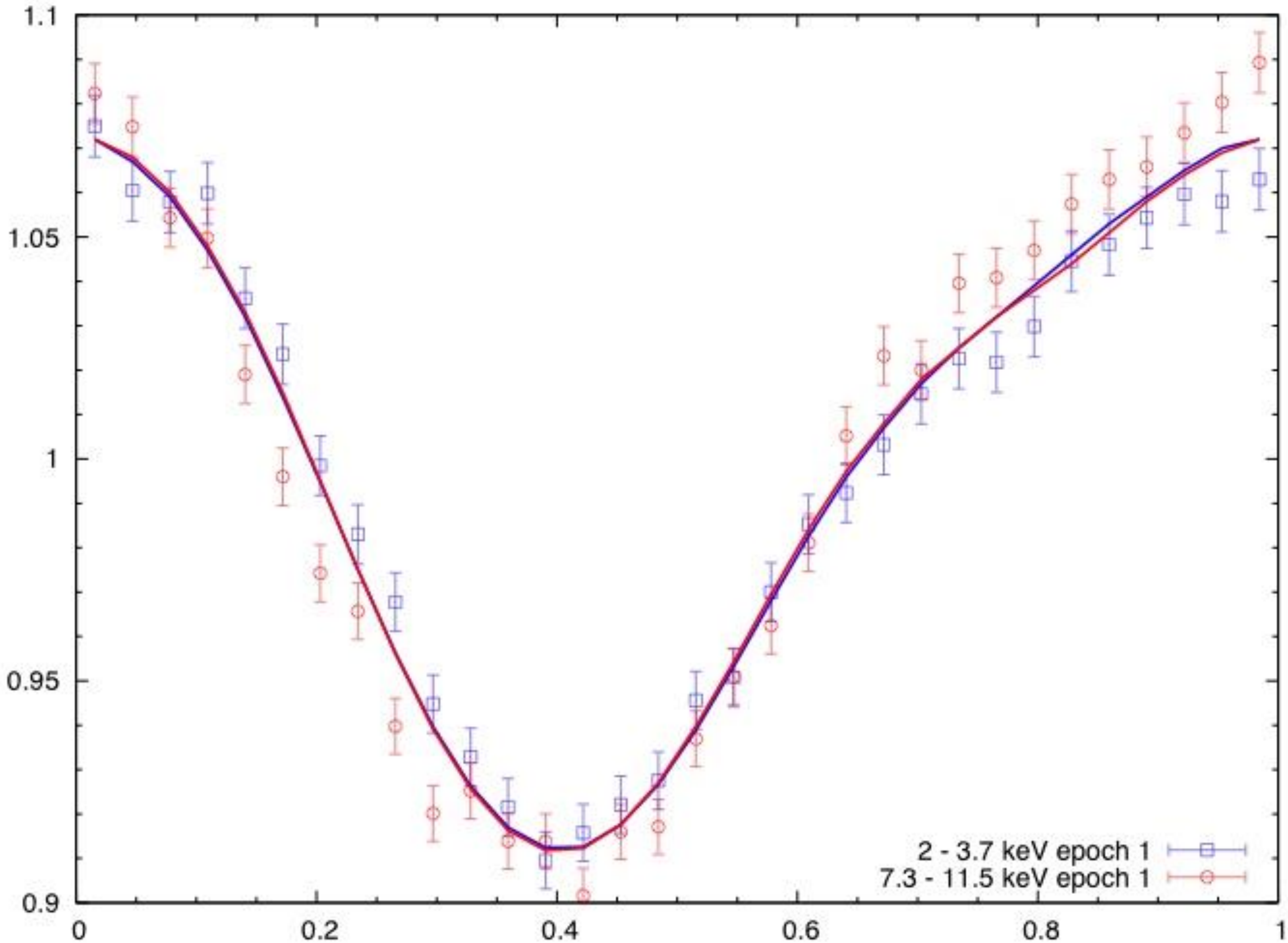
Data from Jacob Hartman

XTE J1814

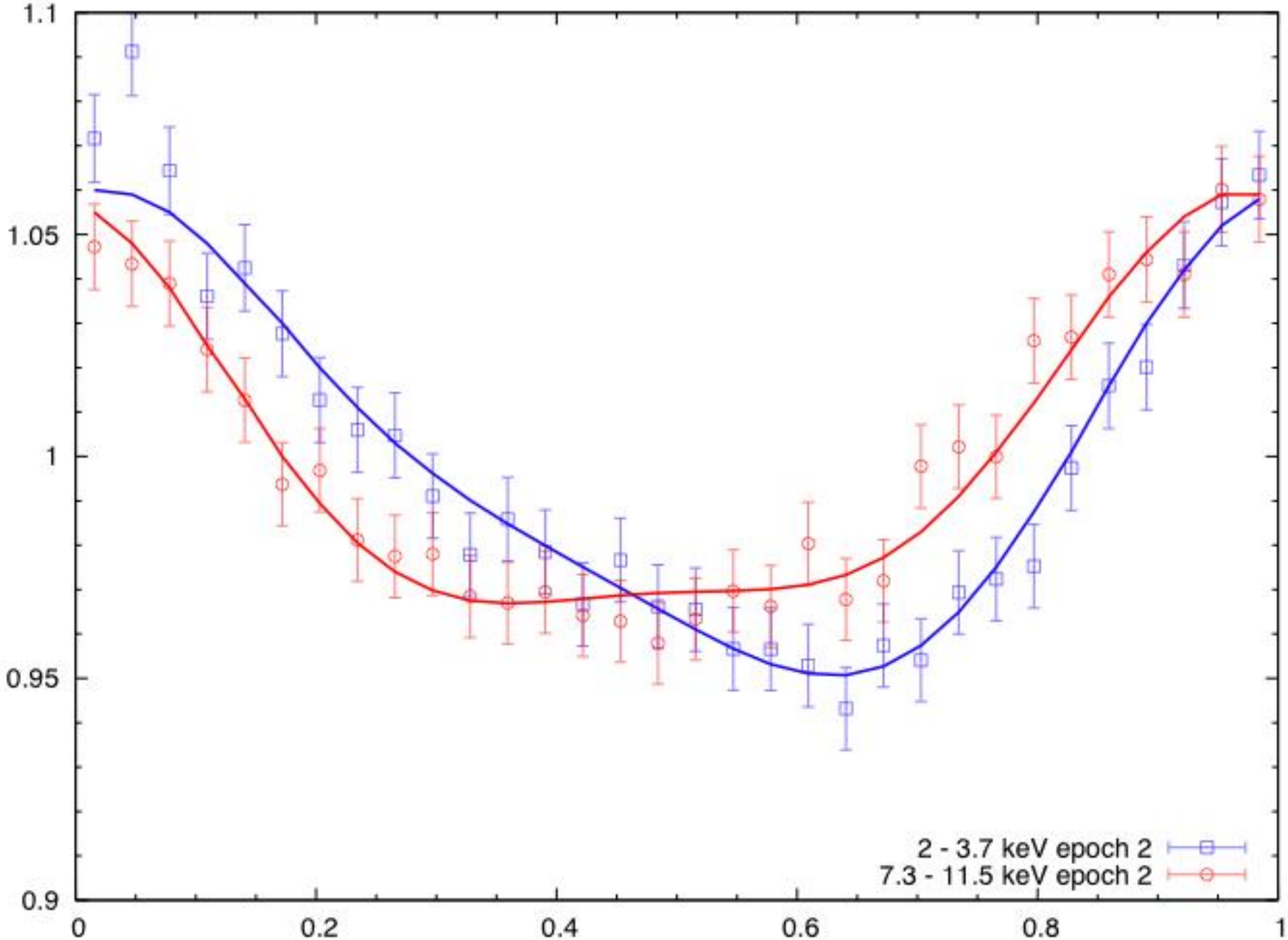


Evidence for an antipodal spot visible part of the time.

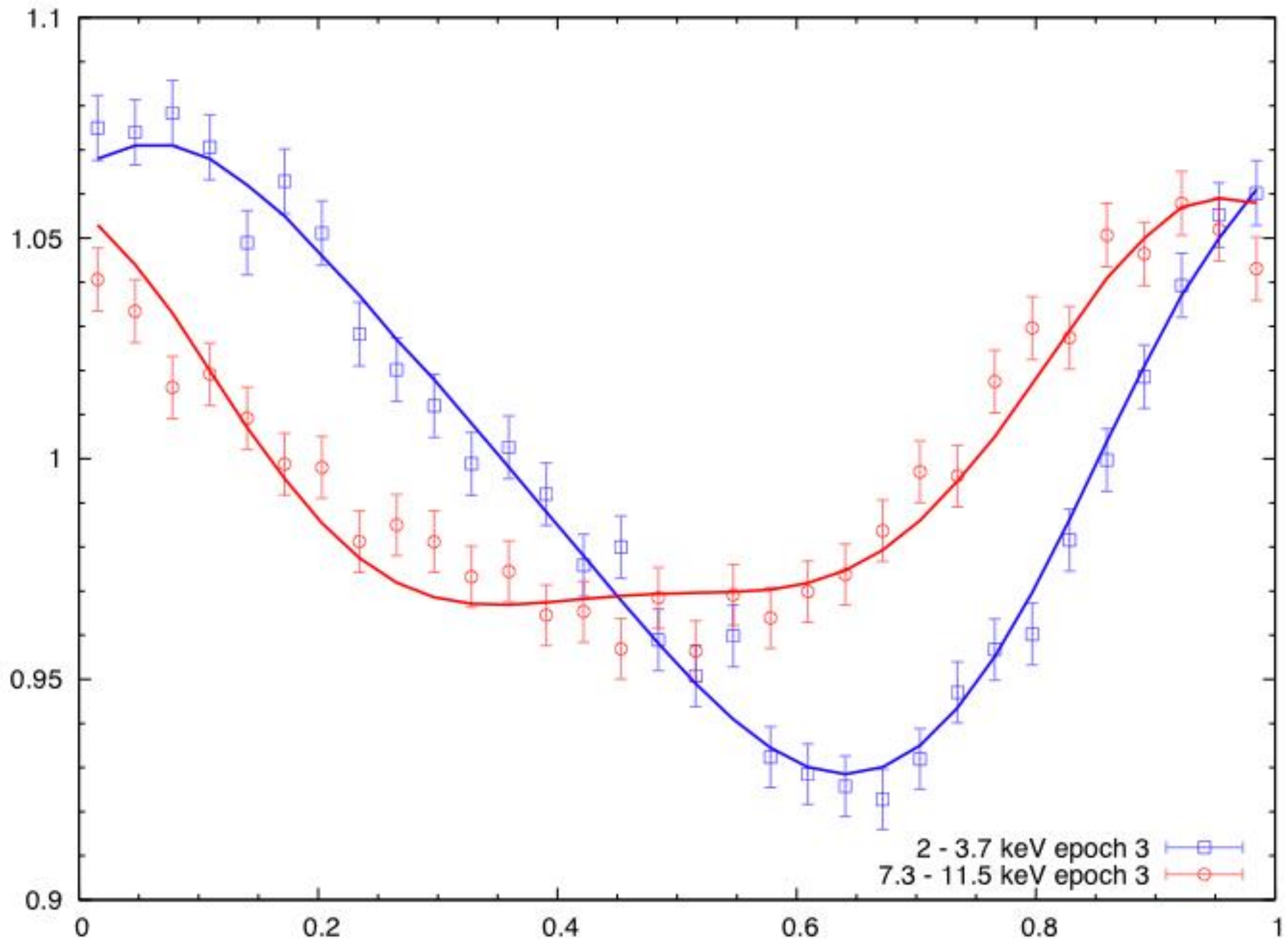
XTE J1807 Epoch 1



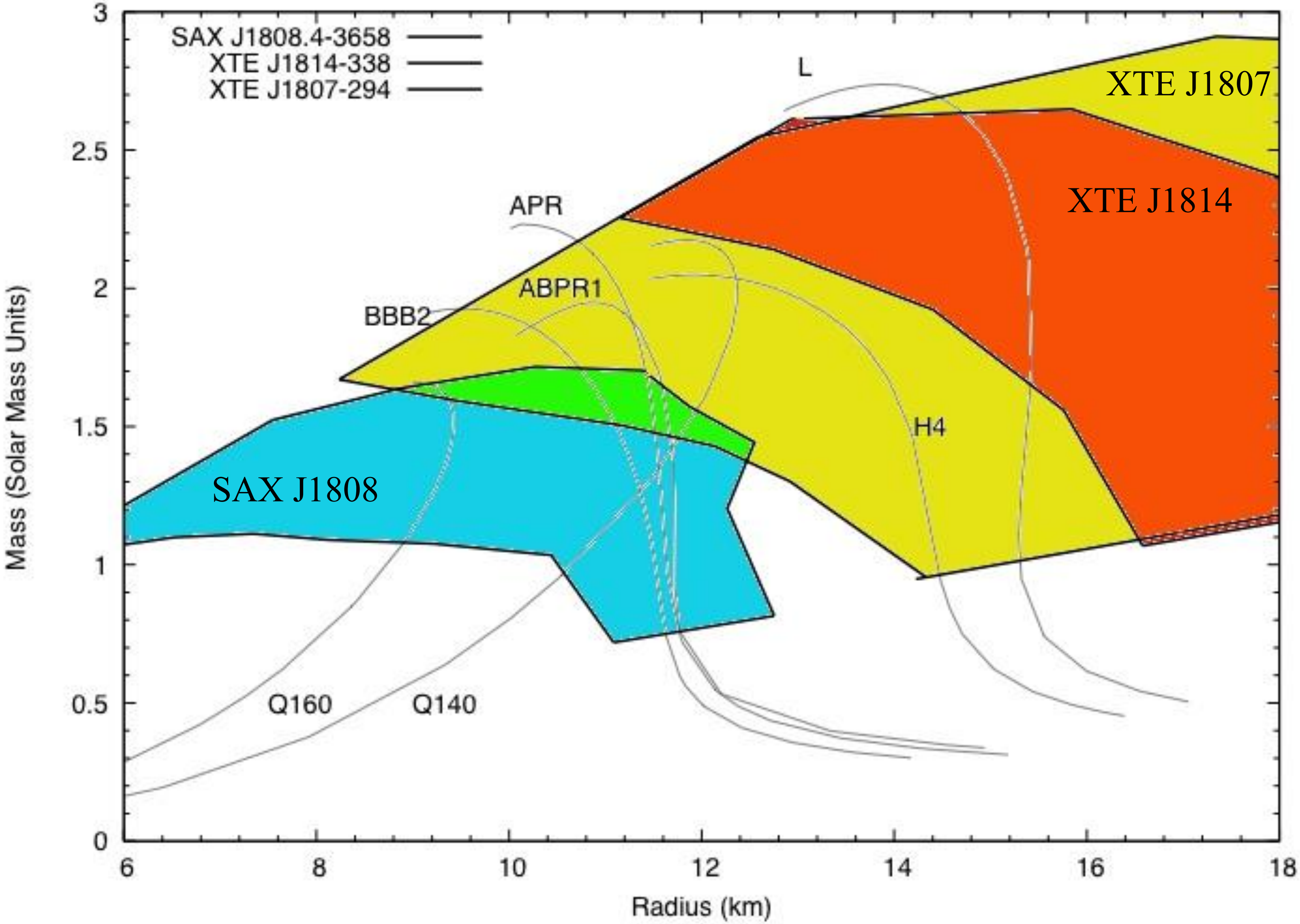
XTE J1807 Epoch 2



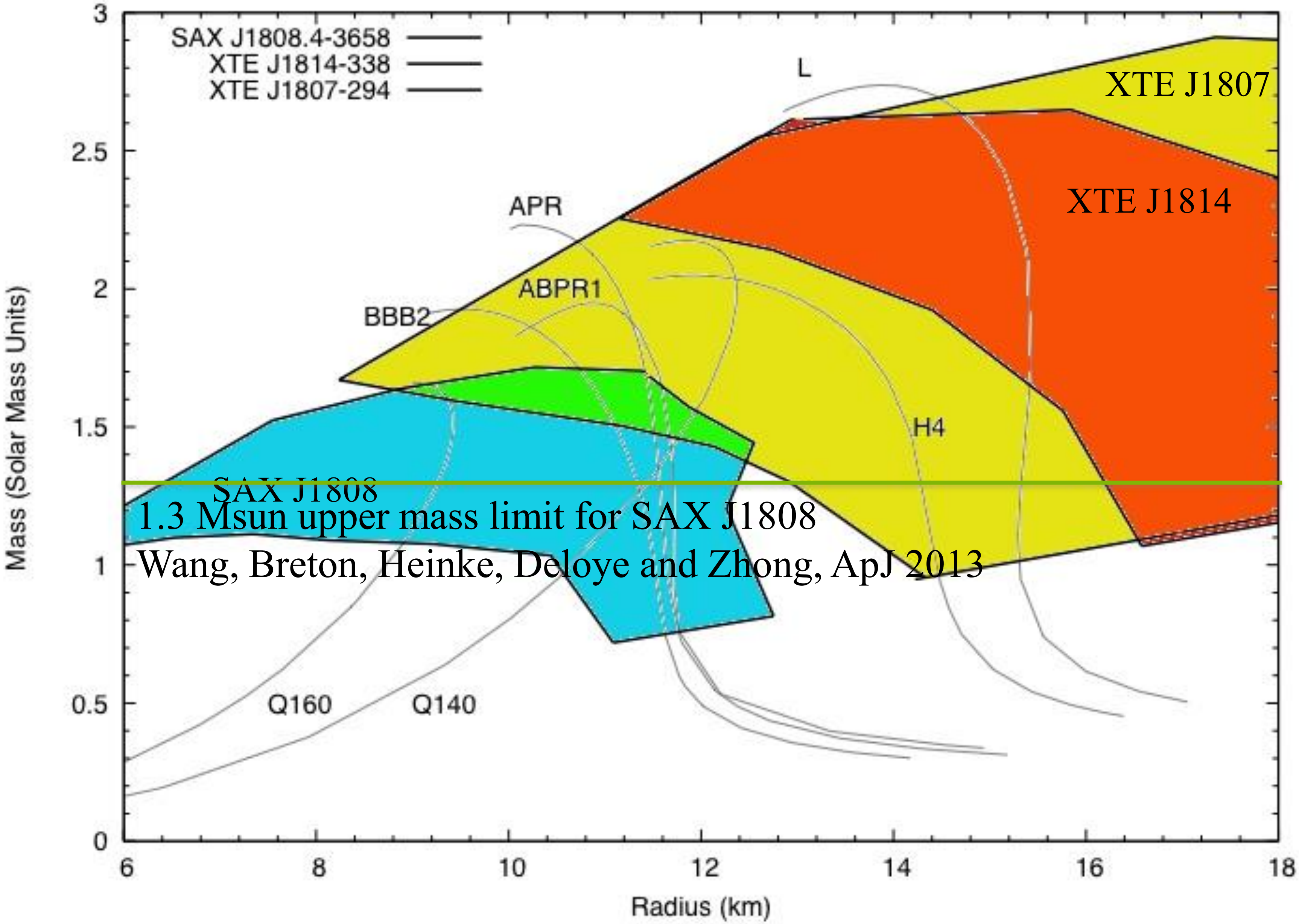
XTE J1807 Epoch 3



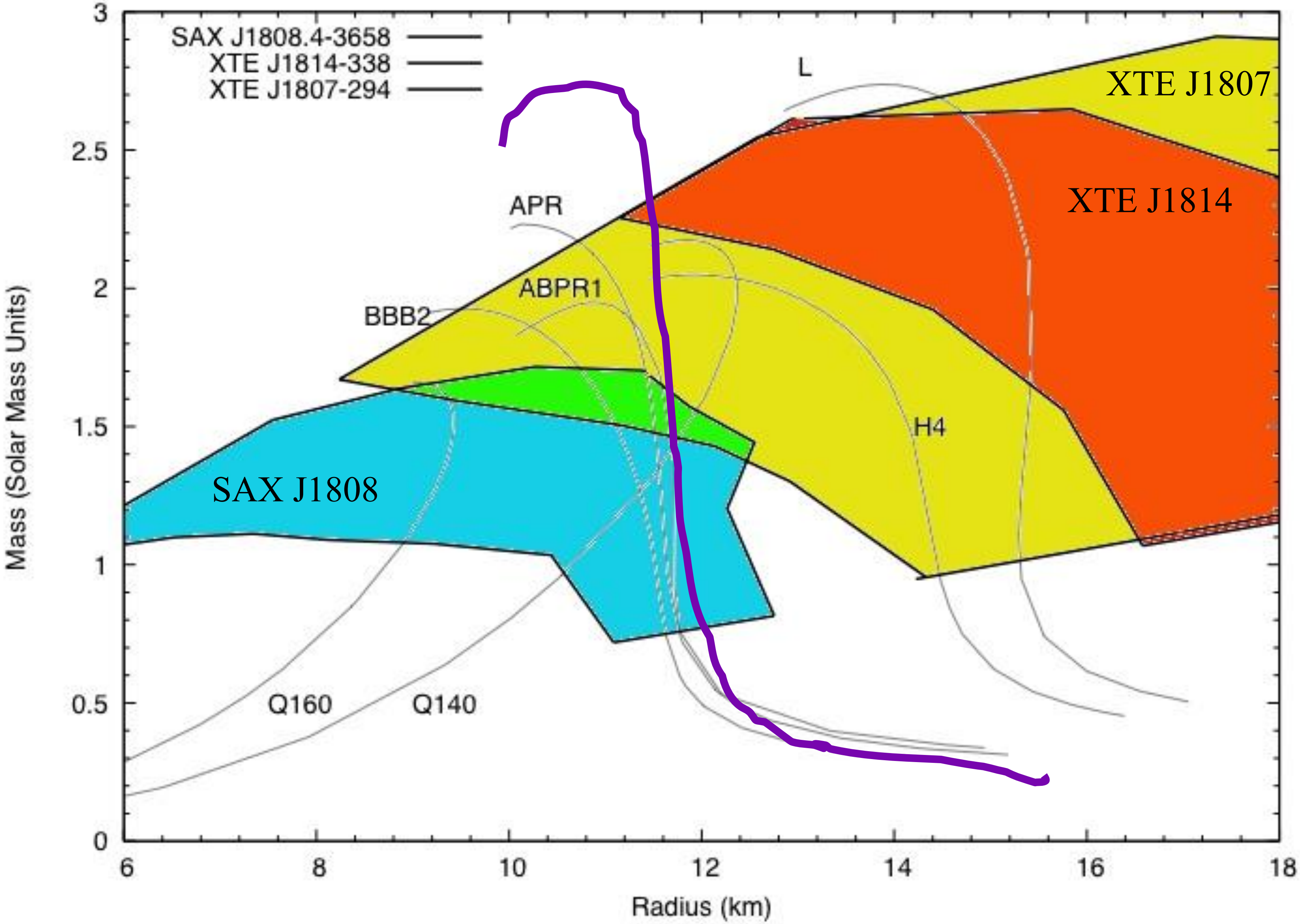
Constraints from 3 stars (3 sigma)



Constraints from 3 stars (3 sigma)



An Allowed EOS?

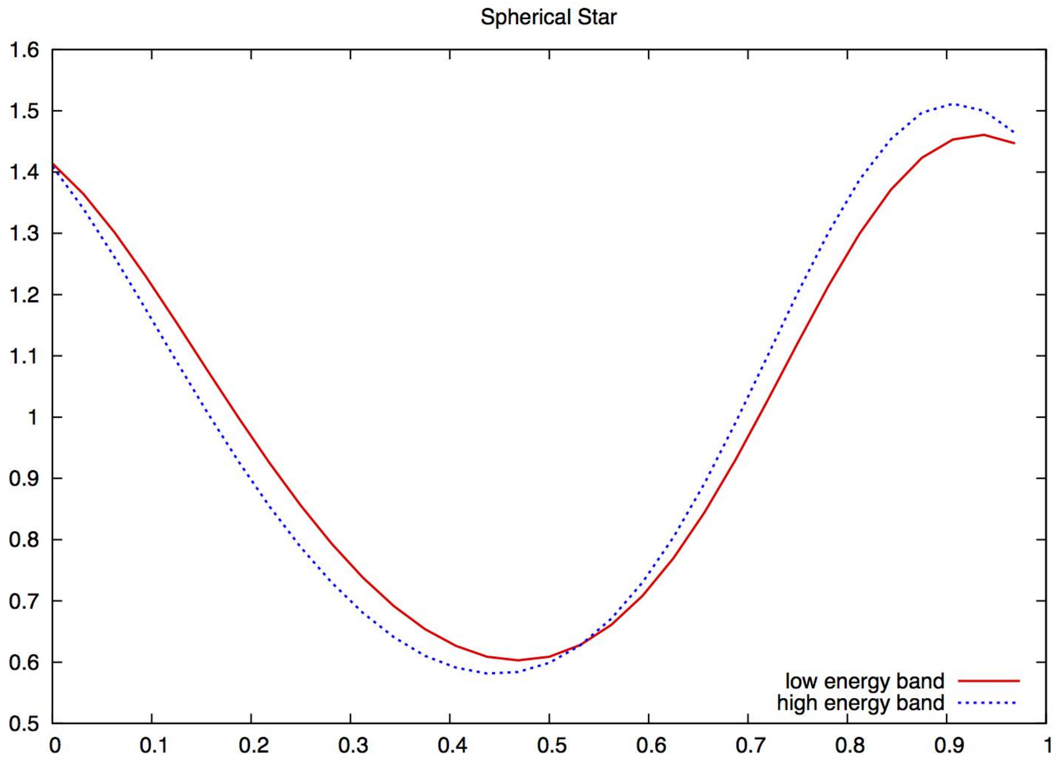


X-ray Bursts

- X-ray burst spectrum is well modeled by a limb-darkened blackbody
- Fewer free parameters may allow for better constraints
- Small subset of LMXB NS have both accretion powered pulsations, and pulsations during X-ray bursts!
- Current collaboration with Jason Fiege (U of Manitoba) making use of genetic algorithms for fitting, Abigail Stevens (MSc U of A) and Denis Leahy (U of Calgary). (See also Lo, Miller, Bhattacharrya & Lamb 2013, Psaltis, Ozel & Chakrabarty 2013)

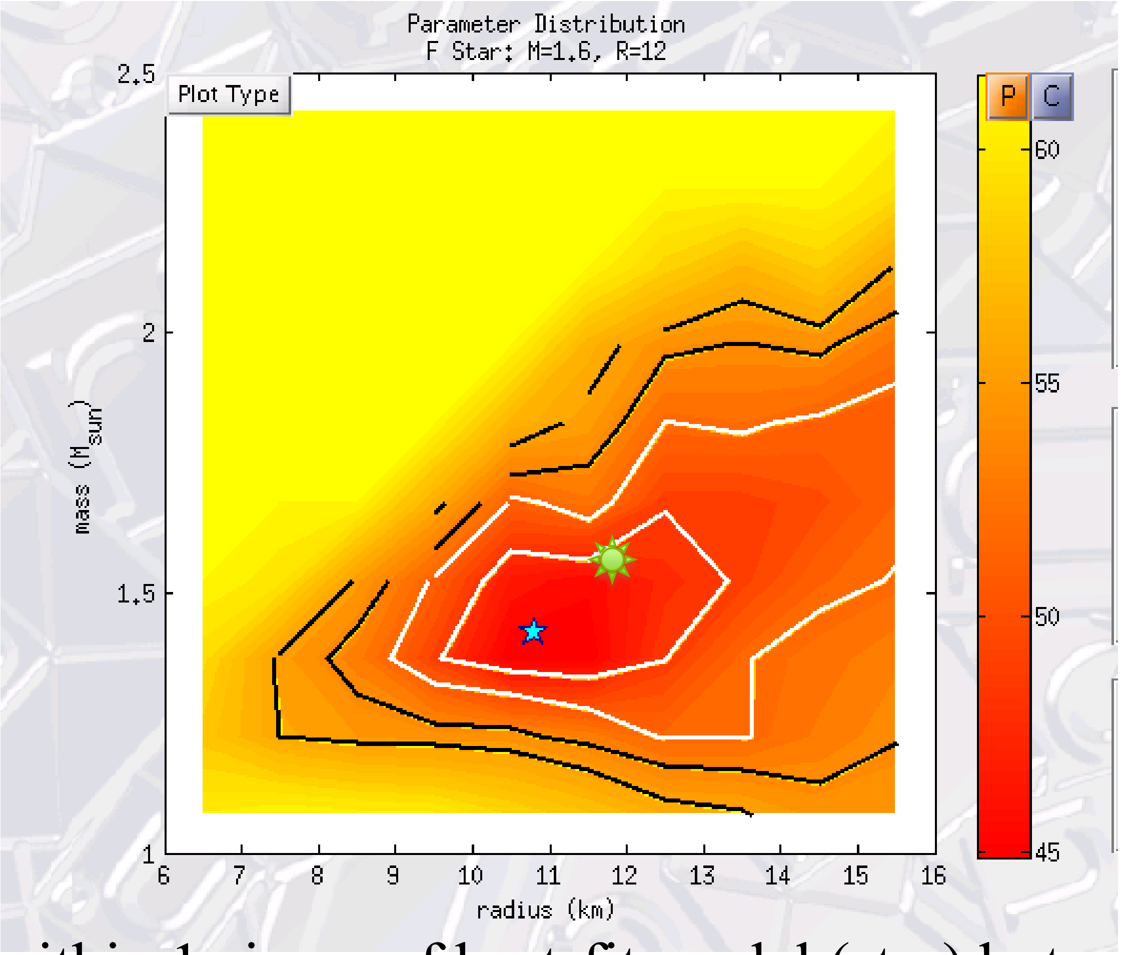
- How precise and accurate can we determine M and R?

Theoretical curves for M=1.6, R=12km, spin=600 Hz, i=60, theta=20
v ~ 0.05 c



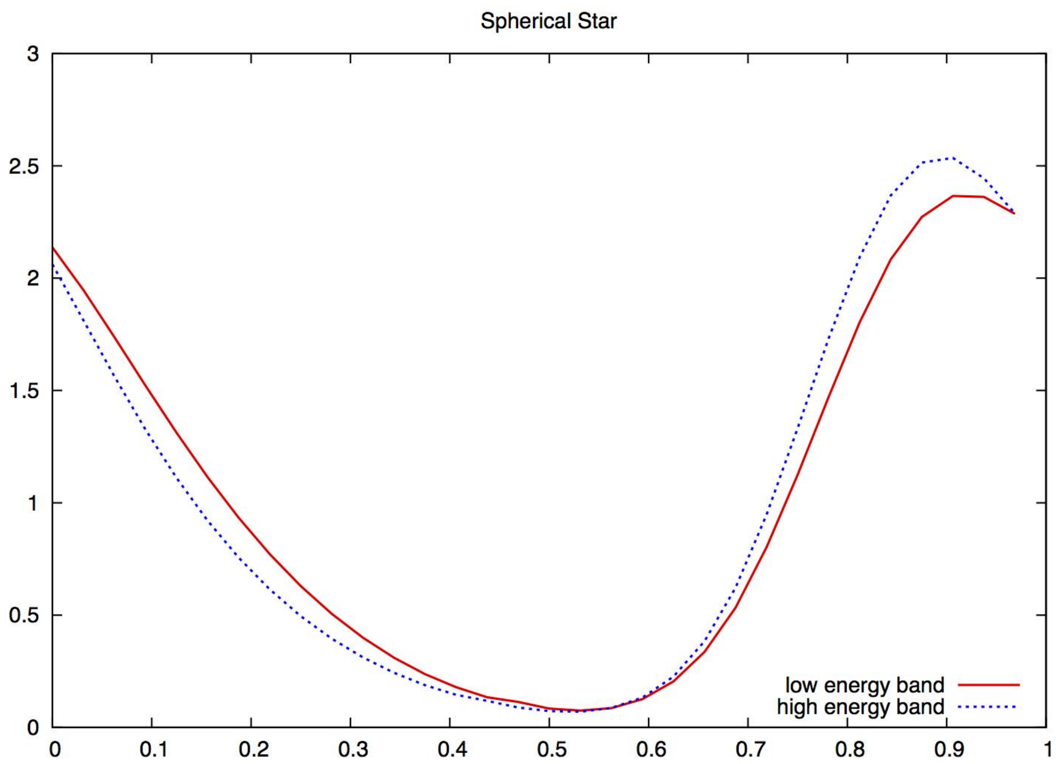
Curves are almost sinusoidal – almost anything will fit!

Genetic Algorithm Best fit contours (after adding Poisson Noise)



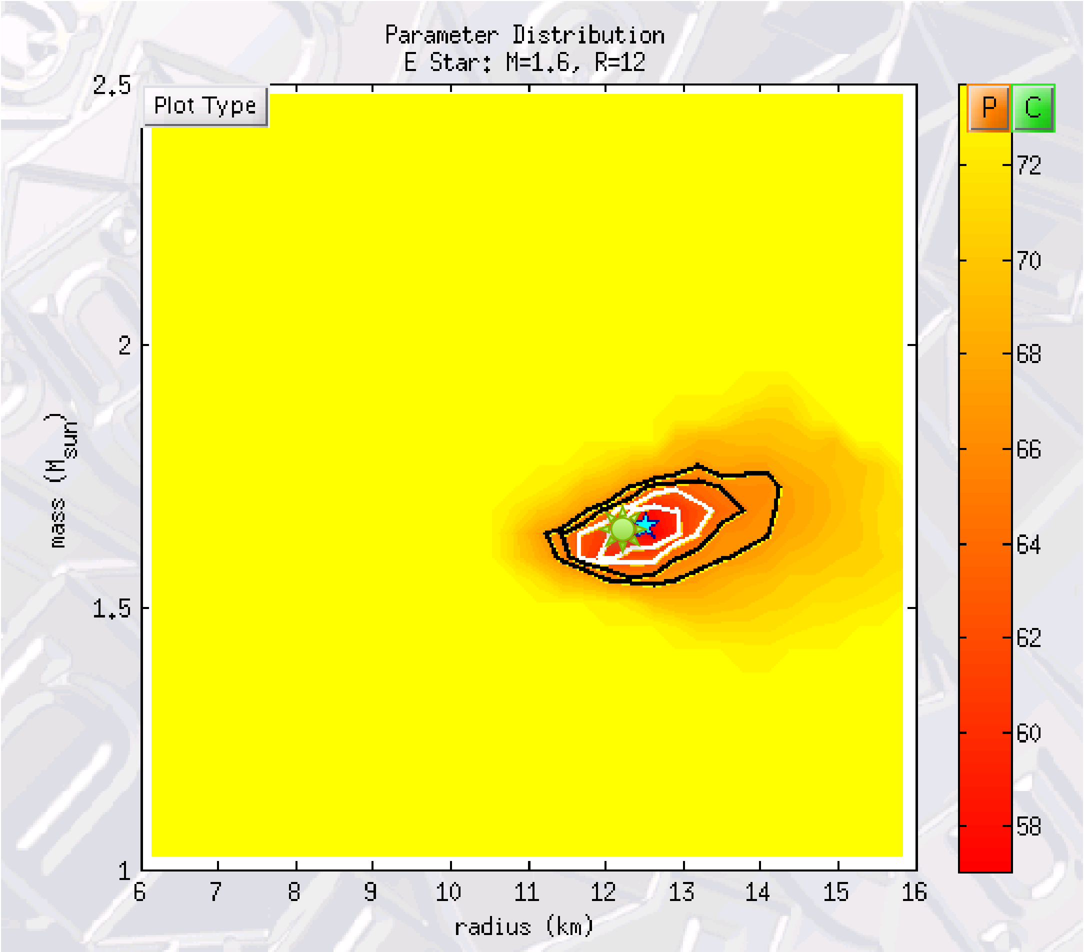
True value within 1 sigma of best-fit model (star) but poor accuracy and precision

Theoretical curves for M=1.6, R=12km, spin=600 Hz, i=60, theta=60
v ~ 0.15 c



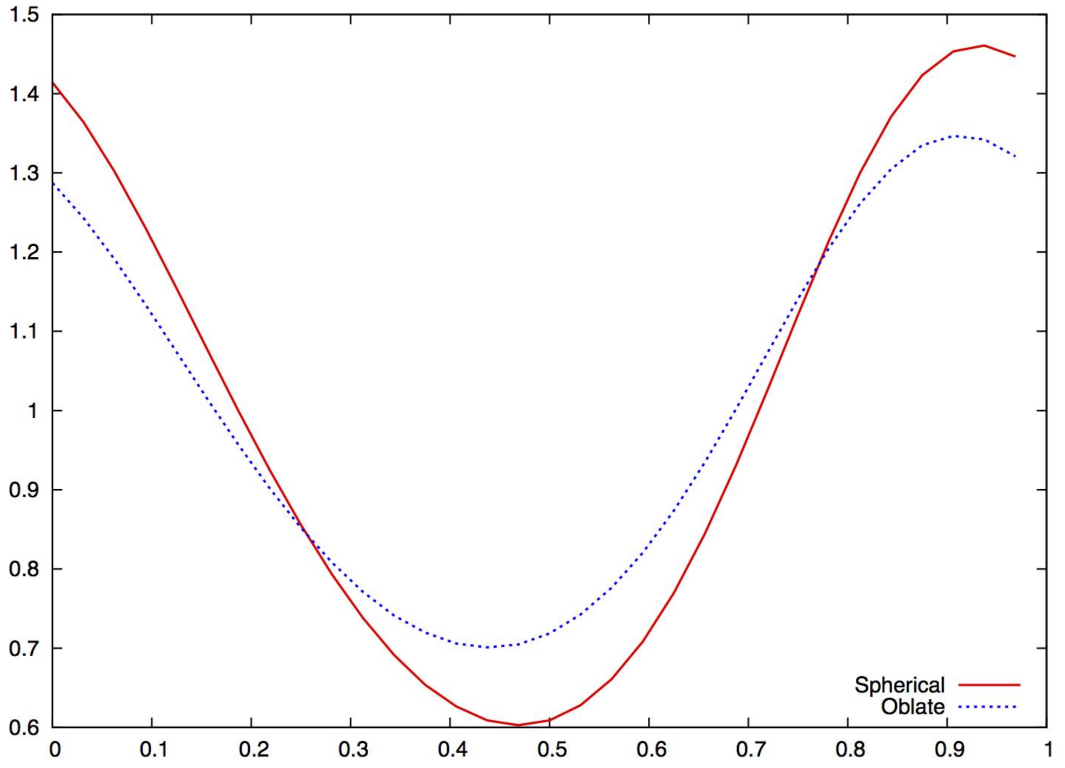
Curves are asymmetric – “features” help fitting

Genetic Algorithm Best fit contours (after adding Poisson Noise)



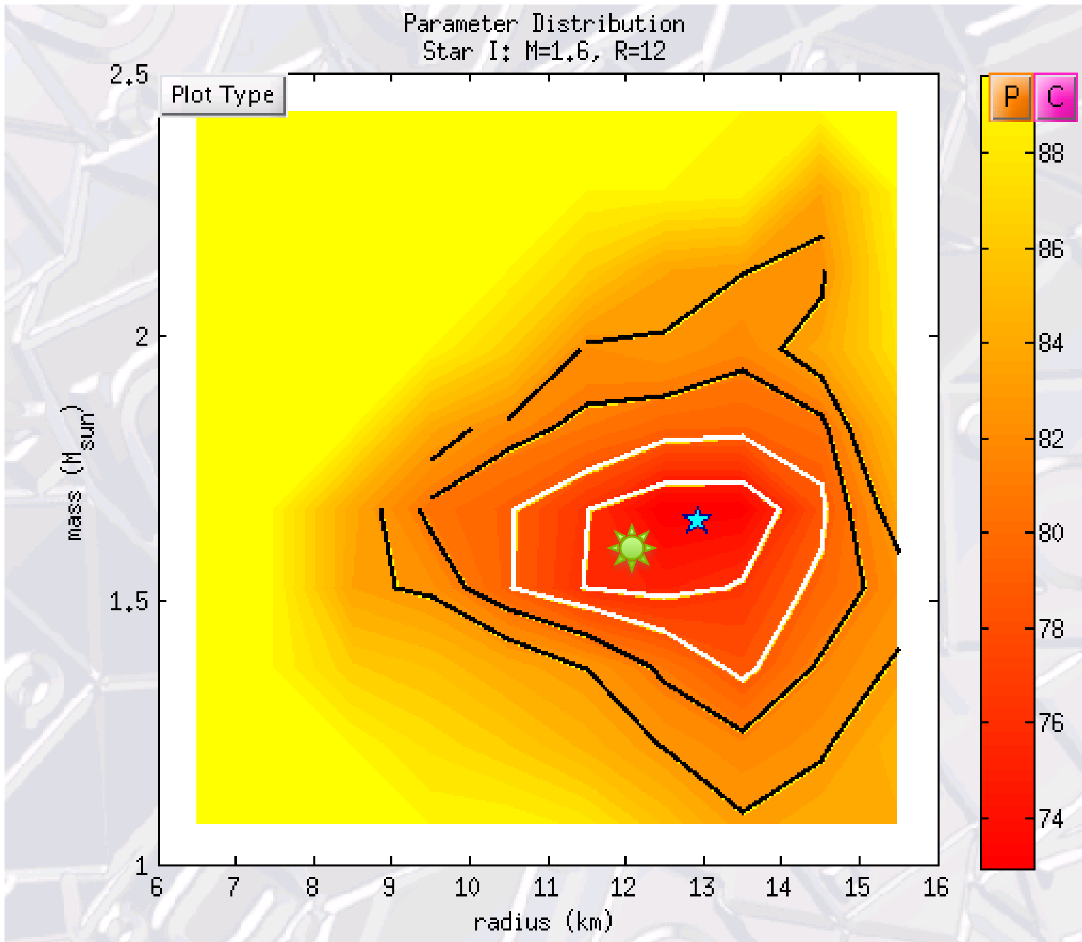
Good accuracy and precision

Theoretical curves for M=1.6, R=12km, spin=600 Hz, i=60, theta=20 and oblate v ~ 0.05 c



Curves are less modulated than those produced by spherical star

Genetic Algorithm Best fit contours (after adding Poisson Noise)



Better accuracy and precision compared to spherical star; oblate shape "breaks" degeneracy between angles and radius

Conclusions

- All methods for constraining Mass and Radius for neutron stars are model dependent and may suffer from unknown systematics
- Important to explore many independent methods to determine EOS!
- X-ray burst observations have potential to provide better constraints, with LOFT's better statistics