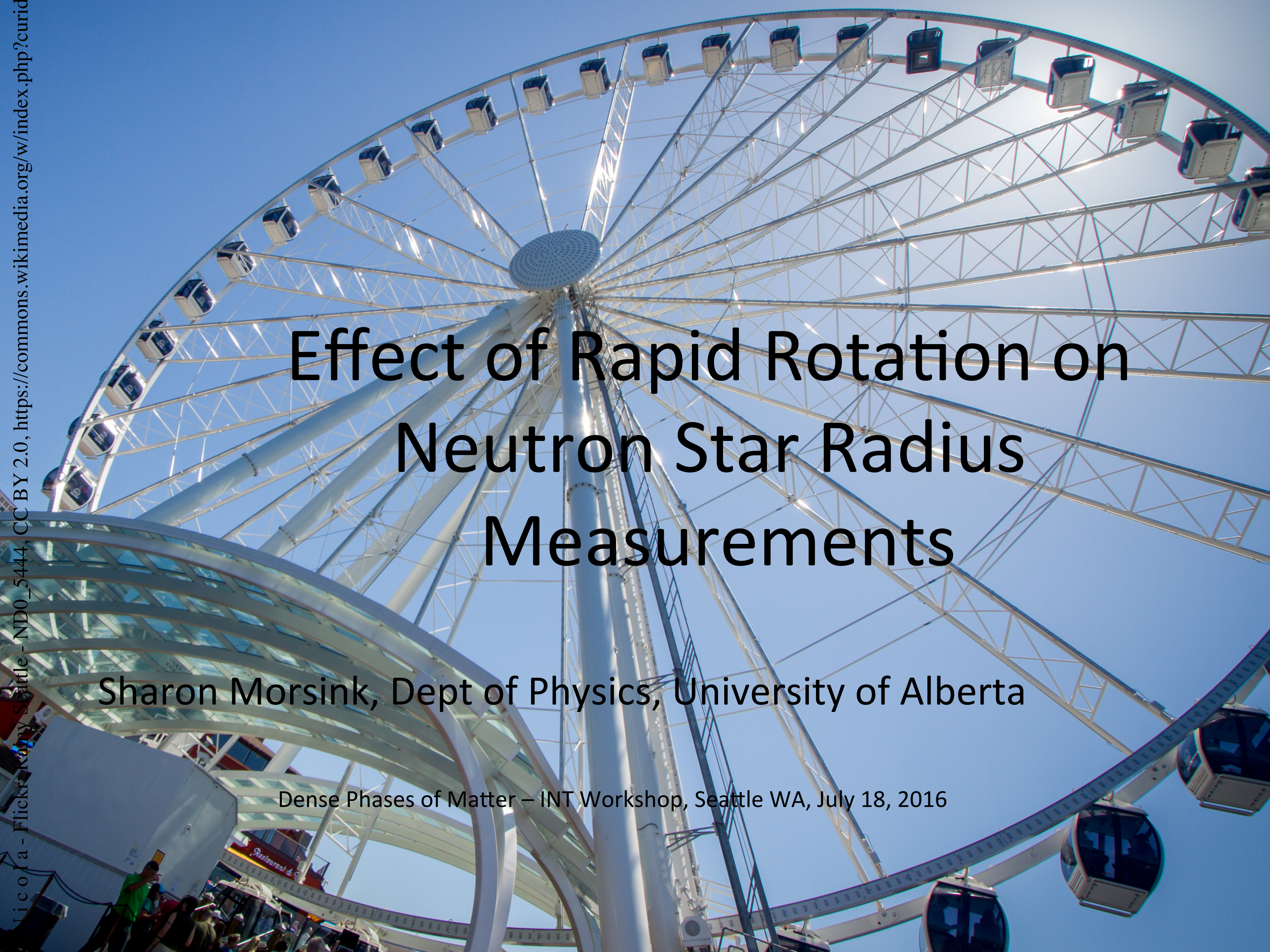

Effect of Rapid Rotation on Neutron Star Radius Measurements

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Dense Phases of Matter – INT Workshop, Seattle WA, July 18, 2016

Outline

- Quasi-universality for rotating neutron stars
- Effect of Rapid Rotation on
  - Mass – Radius constraints
  - Luminosity Radius determination
  - Eddington Luminosity
  - Radius determinations with undetected hot spots

Mass-Radius Constraints

- Pulse-profiles (cf Fred Lamb's talk for rotating ms pulsars (~200 Hz) and accreting ms pulsars (200 – 600 Hz)
- Some Eddington-Limited X-ray burst stars spin at ~600 Hz
- Quiescent LMXB neutron stars don't have detected pulsations, but they *might* spin fast.

Digression on Black Hole “No Hair”

- Black holes are very simple!
- Describe a rotating BH with 2 parameters: M, a
- Event Horizon radius given by:

  $R_{EH} = 2M + M[(1-(a/M)^2)^{1/2} - 1]$

- Gravitational field outside of BH:

  $\Phi(r,\theta) = - M/r + \Phi_2/r^3 P_2(\cos\theta) + \ldots$

  $\Phi_2 = M a^2$

- Properties of a BH are independent of the properties of the stuff that formed it.

Neutron Stars Have "Hair"

- Given a mass and spin (M and Ω) different EOS predict different Radii (R)
- However, given M, R, Ω dimensionless quantities: $x = GM/Rc^2$ $y = \Omega^2 R^3/GM$
- Many secondary NS properties depend only on x, y.
- I Love Q (Moment of Inertia, Love number, Quadrupole moment) relationships
- "Neutron Star Universality" (Yagi & Yunes 2013)

Example: Moment of Inertia

- Expect Moment of Inertia of the form:

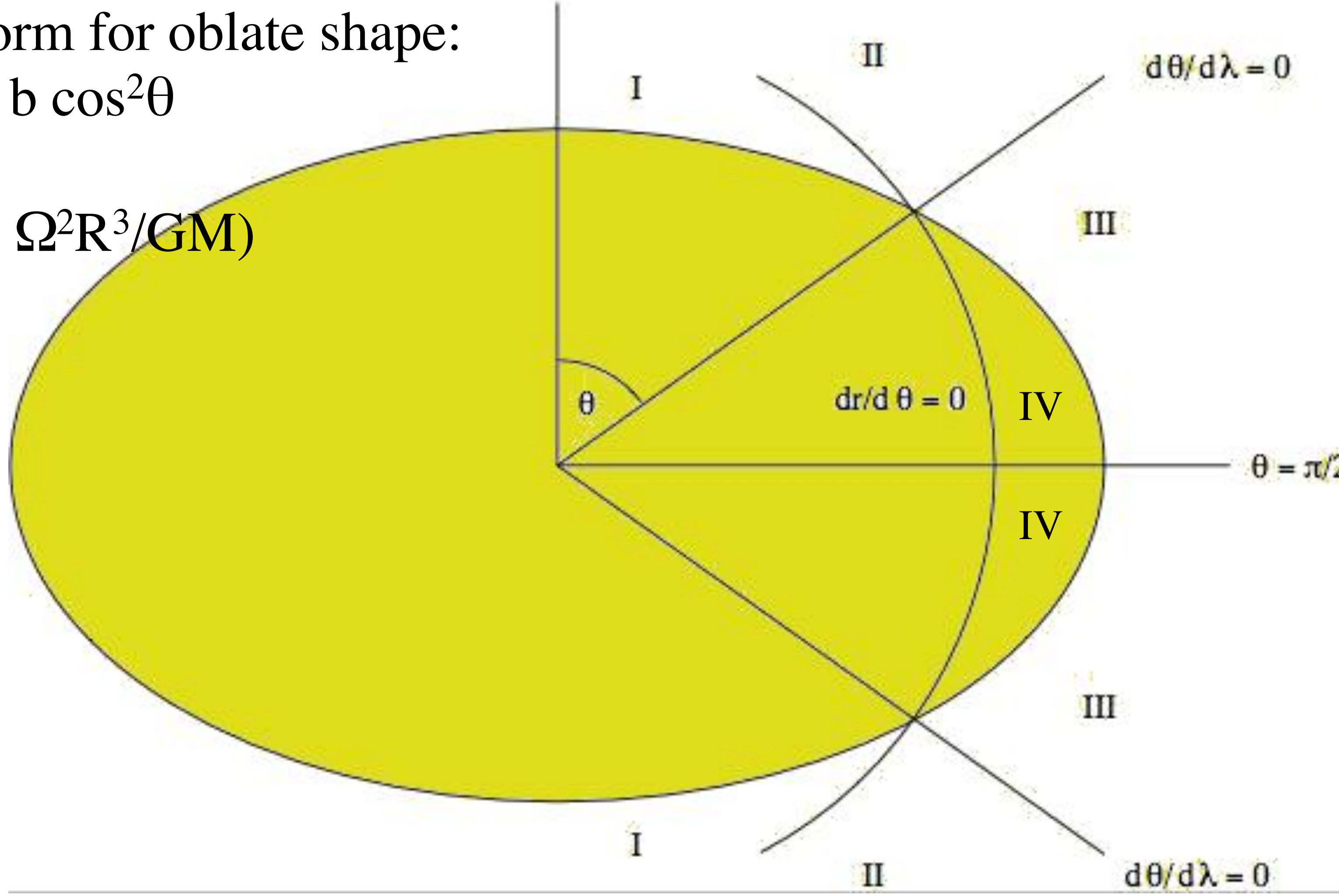
  $I = \beta M R^2$

  Where β depends on how density varies inside the star. (Ravenhall & Pethick, 1994; Lattimer & Prakash, 2001)
- For Neutron Stars $\beta = \beta(M/R, \Omega^2 R^3/GM)$ with β a known function
- Similar functions for quadrupole moment, ellipticity, acceleration due to gravity, oscillation mode frequencies, etc…

Stellar Oblateness

Universal form for oblate shape:
$R(\theta) = R_e - b\cos^2\theta$

$b = b(M/R,\ \Omega^2 R^3/GM)$

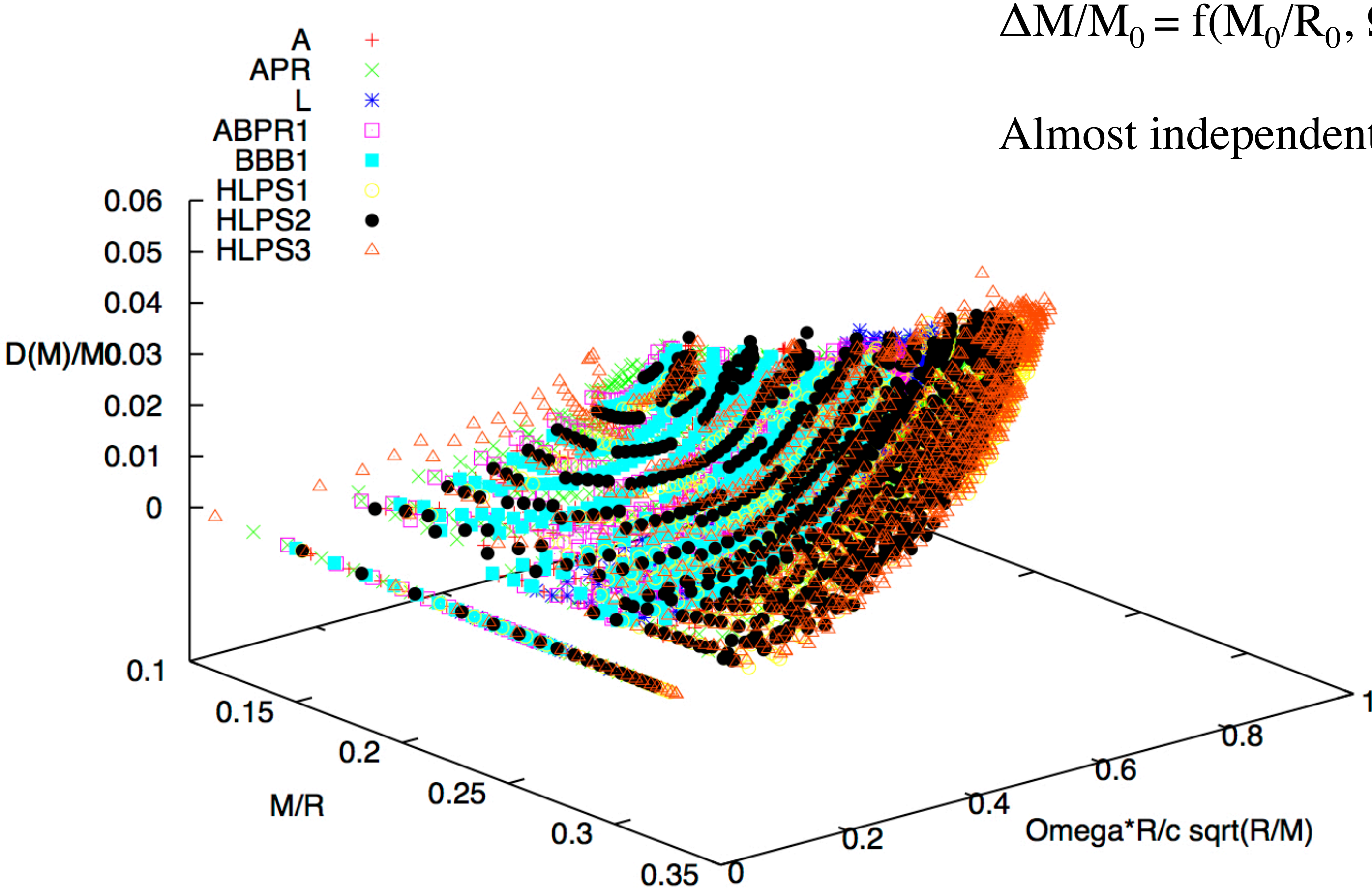


Morsink, Leahy, Cadeau & Braga 2007 ApJ

Fractional Increase In Mass

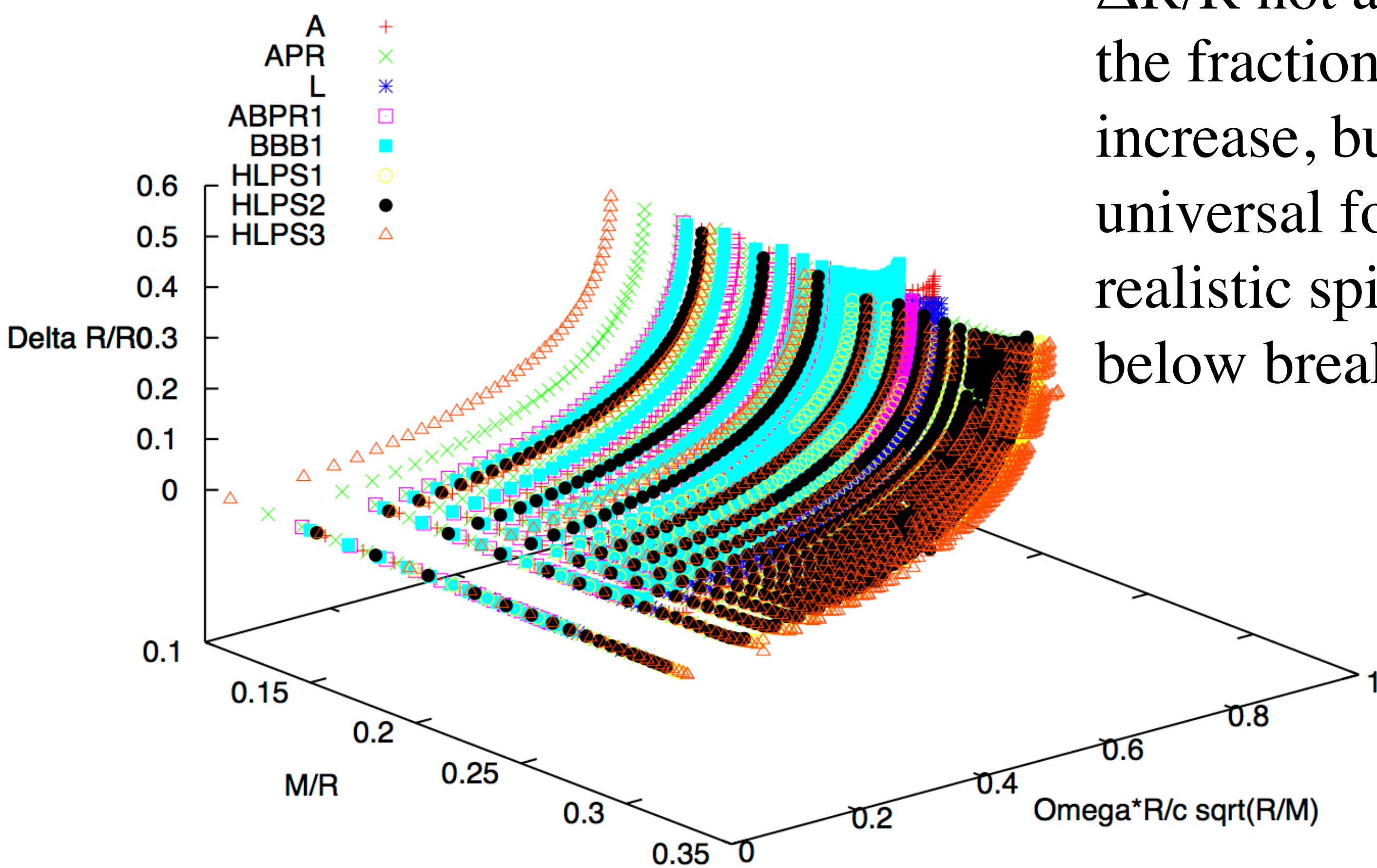
$\Delta M/M_0 = f(M_0/R_0, \Omega^2 R_0^3/GM_0)$

Almost independent of EOS



$\Delta M/M \sim - M/\Delta R + \Omega^2 R^2$

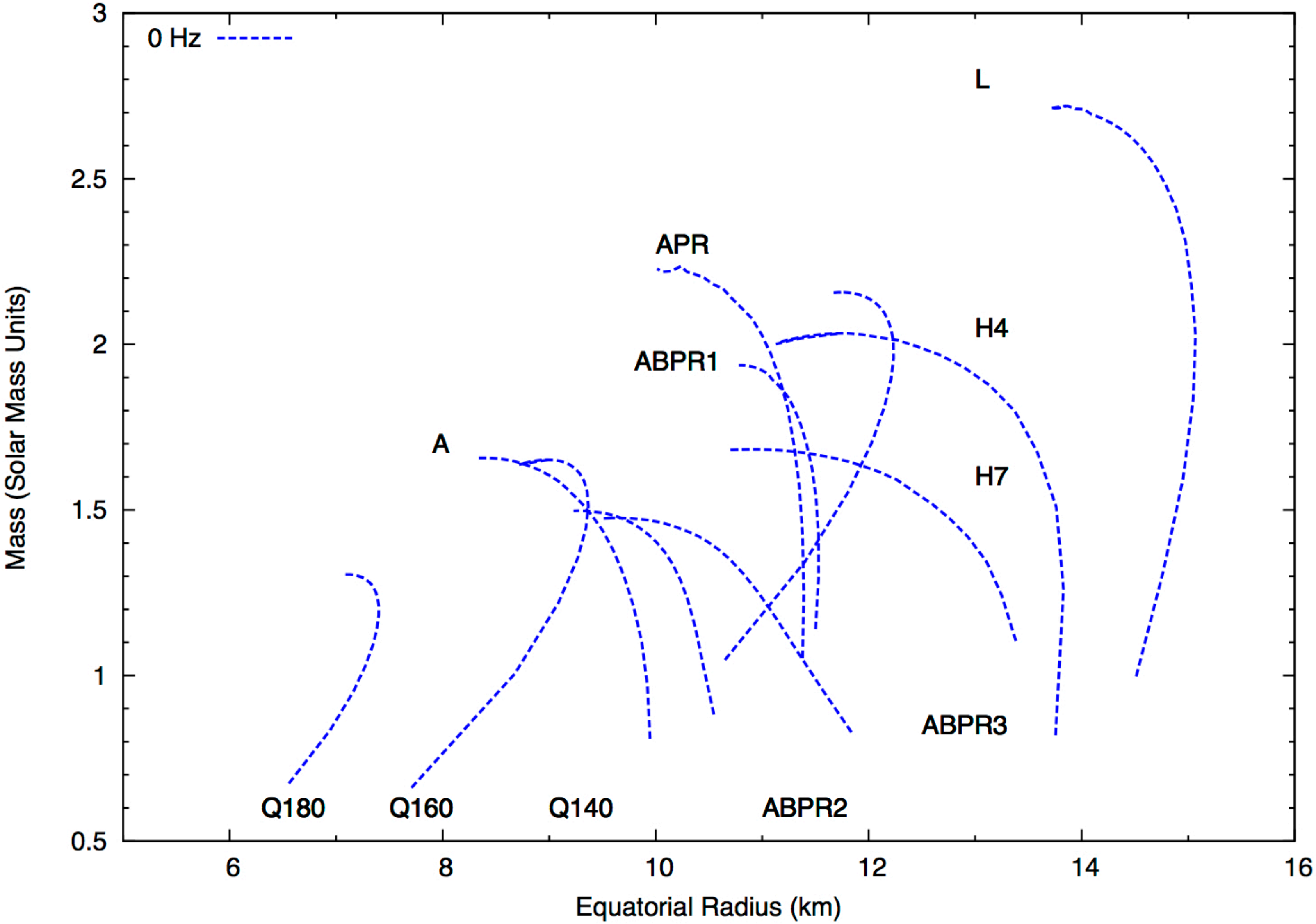
Fractional Increase in Radius



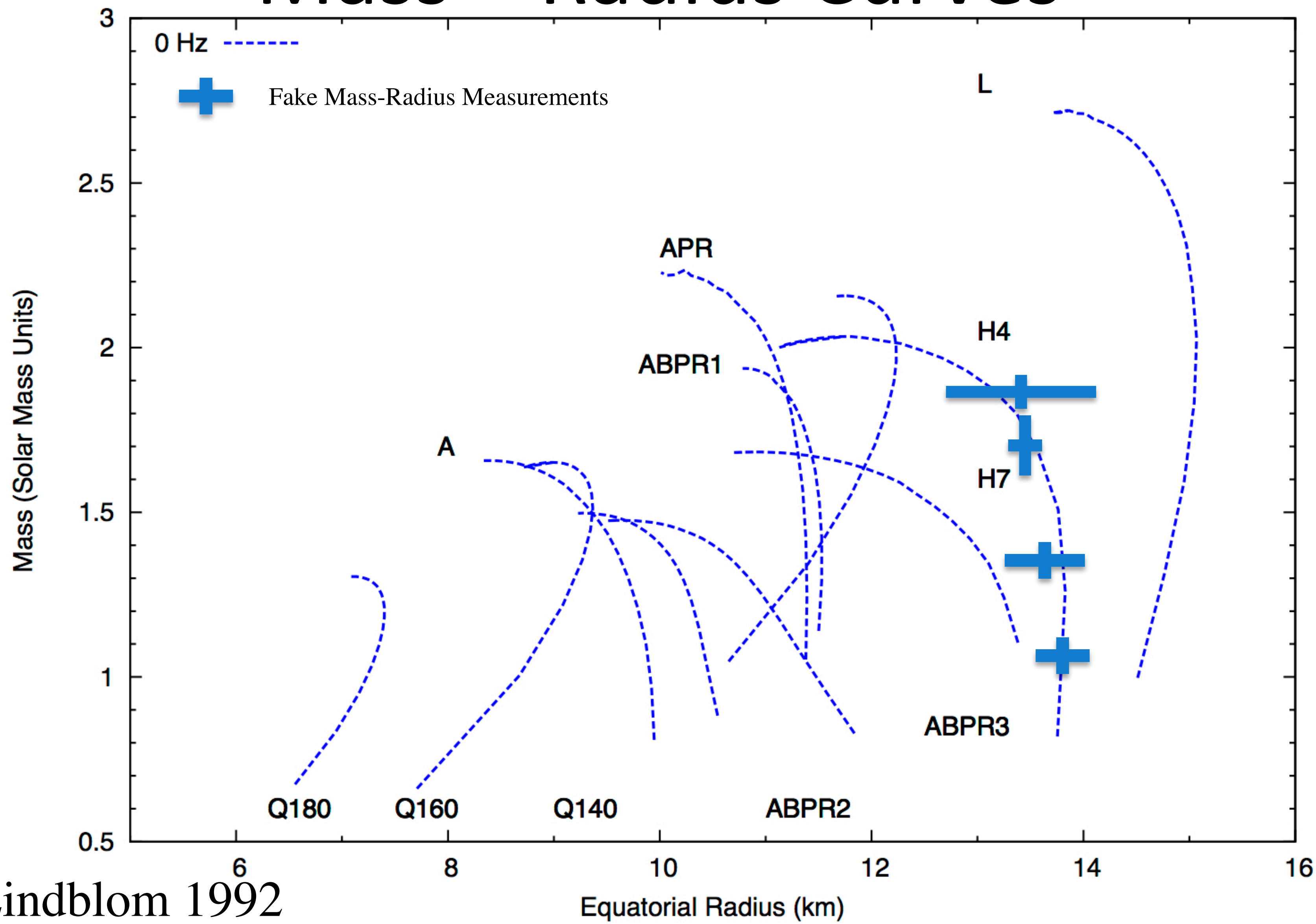
ΔR/R not as tight as the fractional mass increase, but almost universal form for realistic spins well below break-up

Morsink & Fedorowich, in prep…

Mass – Radius Curves

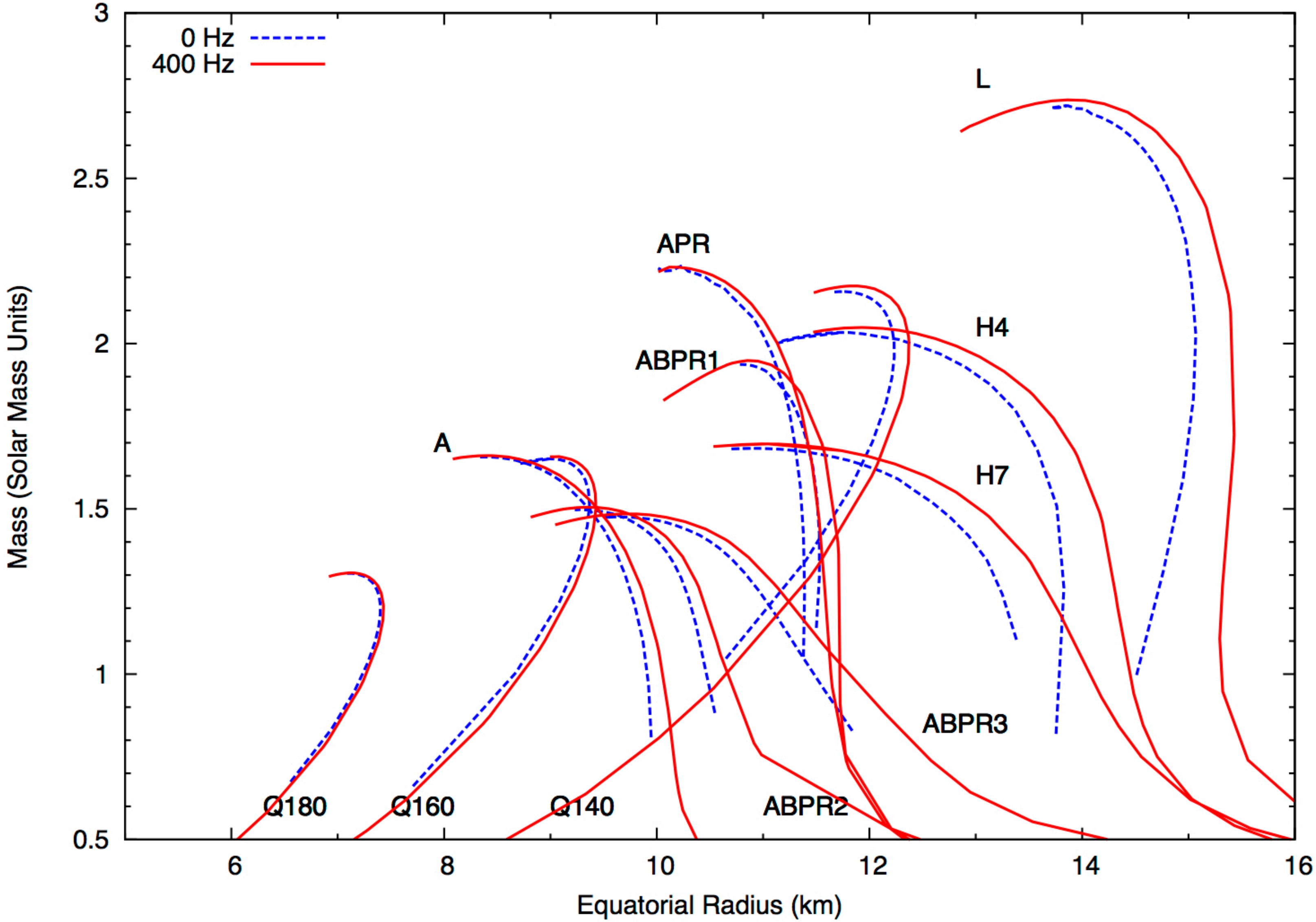


Mass – Radius Curves

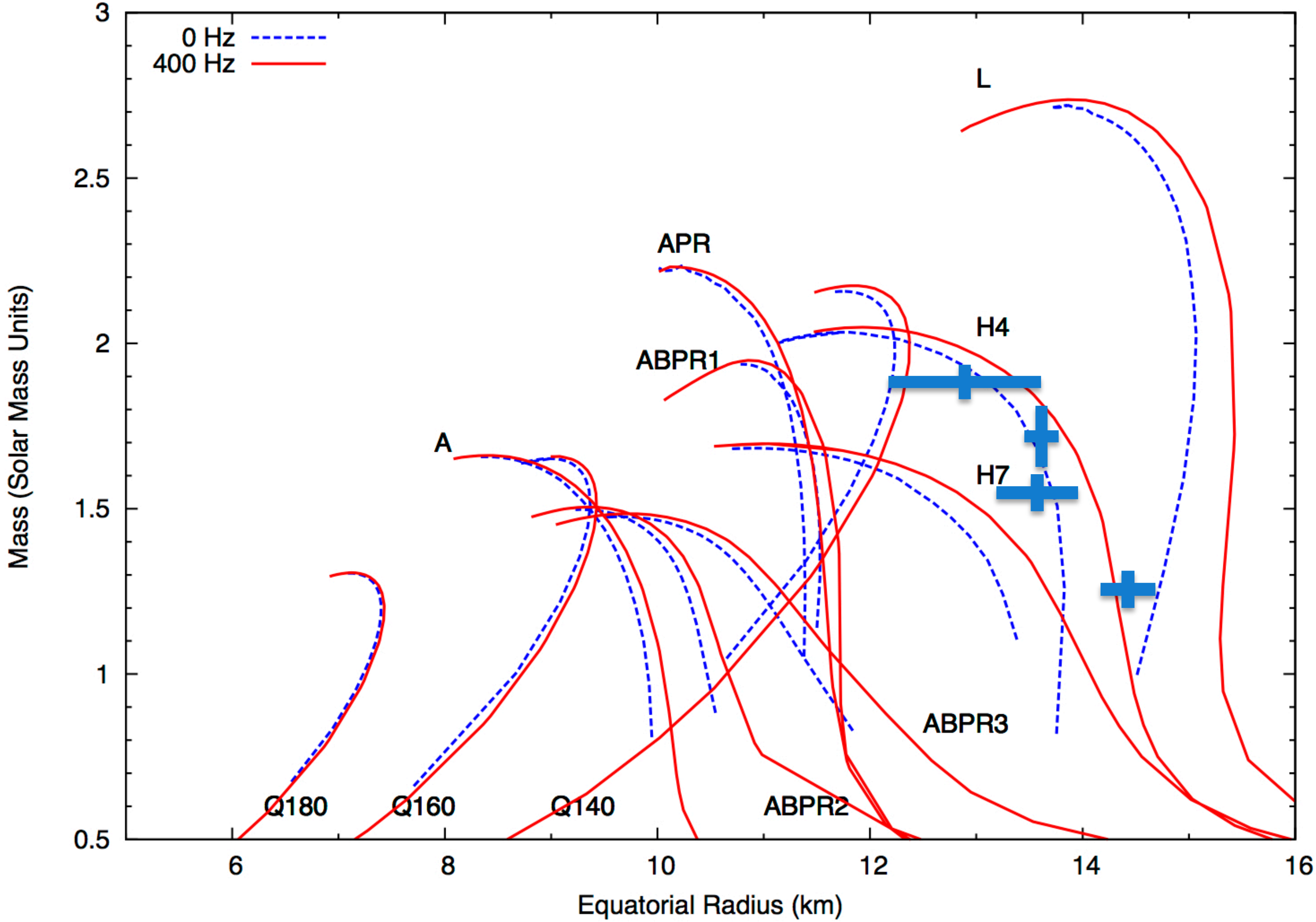


Lindblom 1992

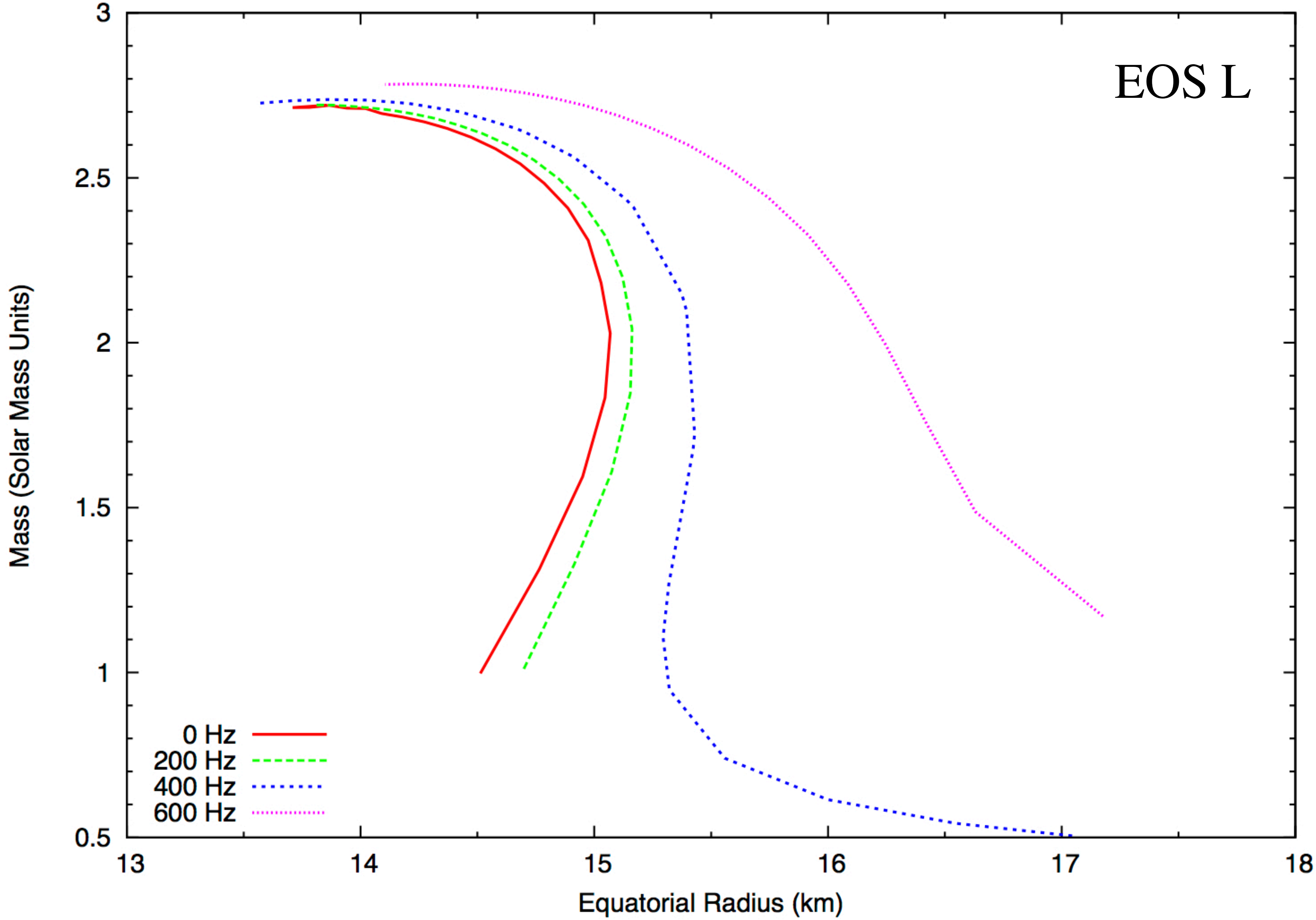
Mass – Radius Curves



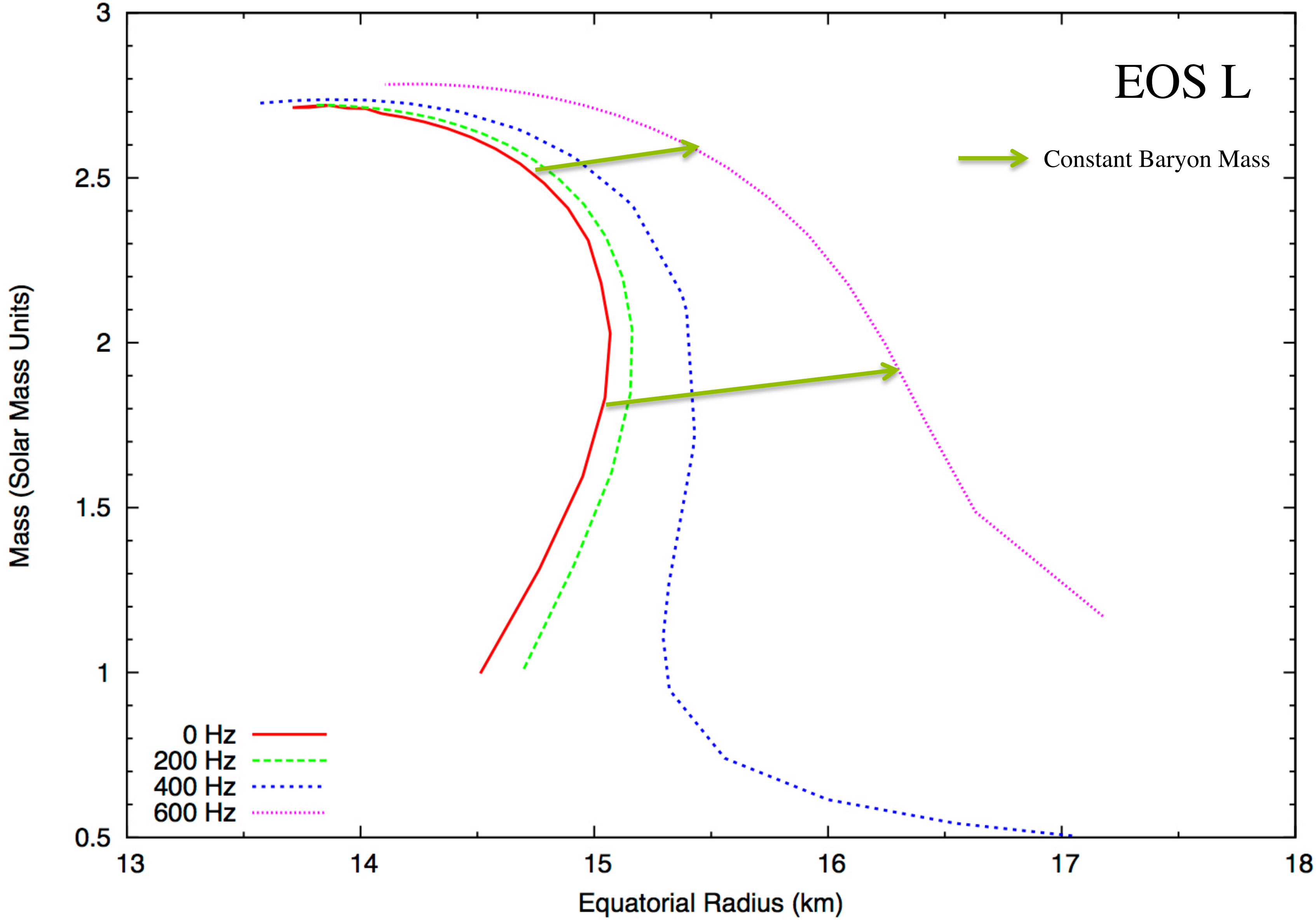
Mass – Radius Curves



Effect of Spin on a stiff EOS

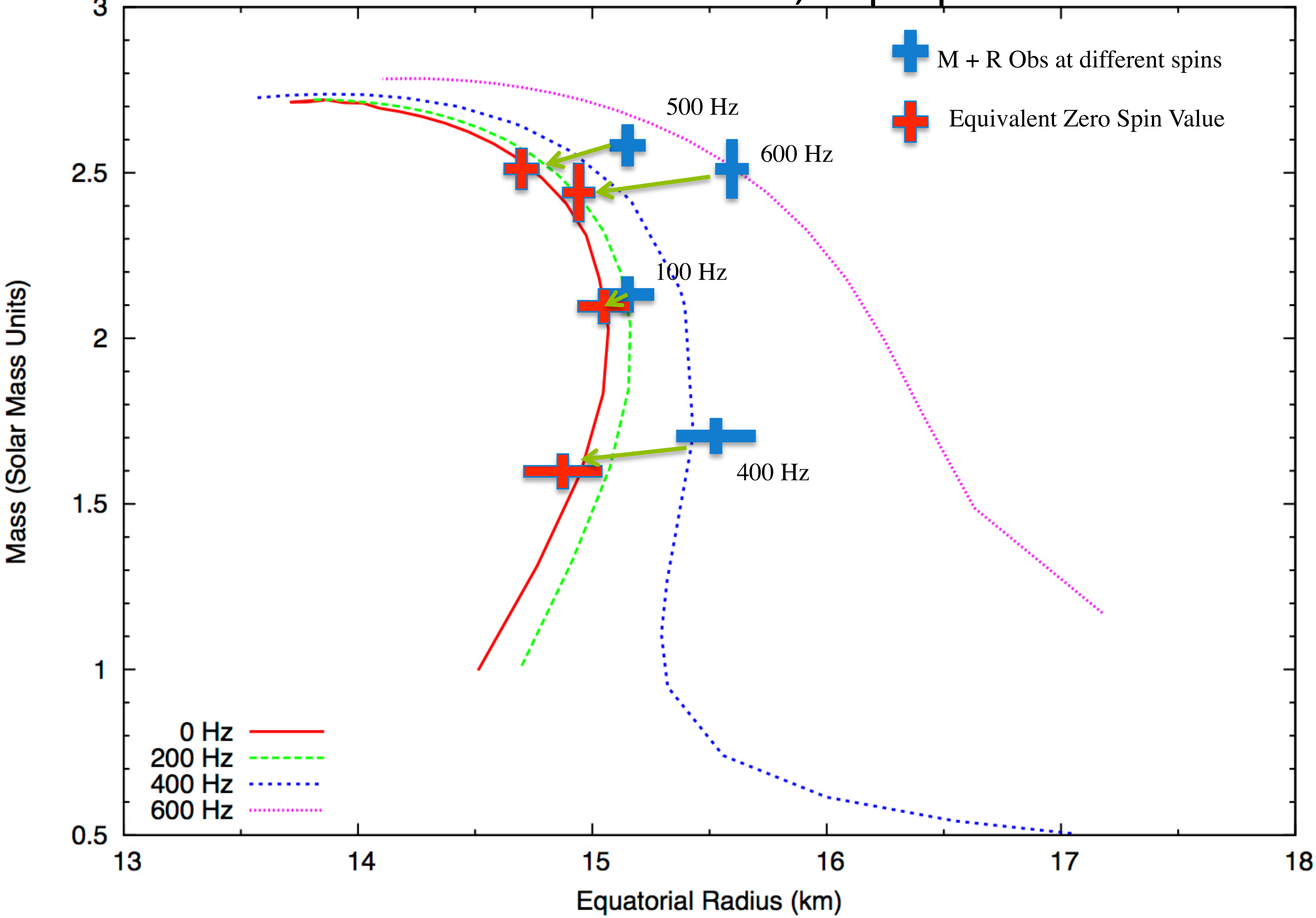


Effect of Spin

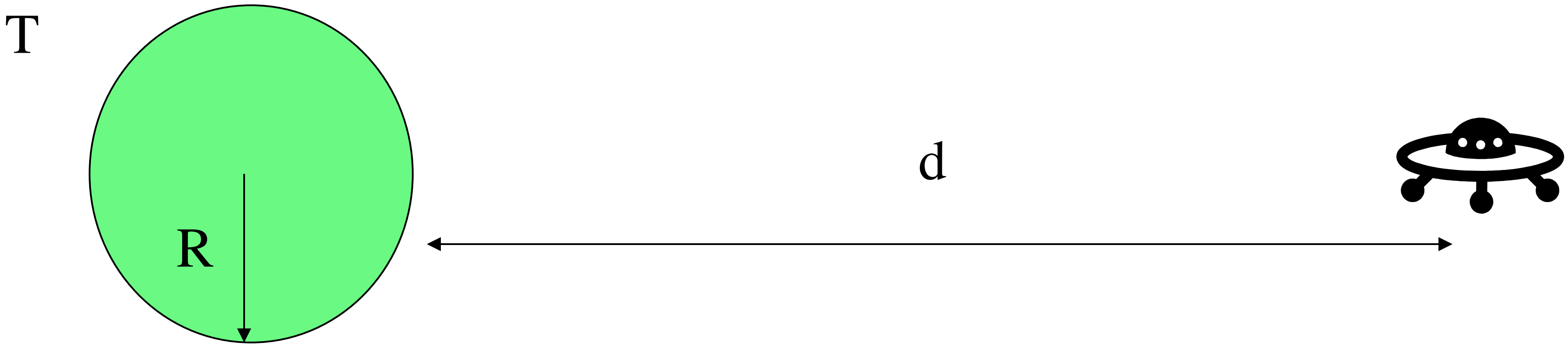


Mapping Spin to Zero Spin Curve

Morsink & Fedorowich, in prep



A Uniformly Emitting Blackbody Sphere



In Newtonian physics, if d, temperature (T) and flux (F) are measured then the "Luminosity Radius" is given by:

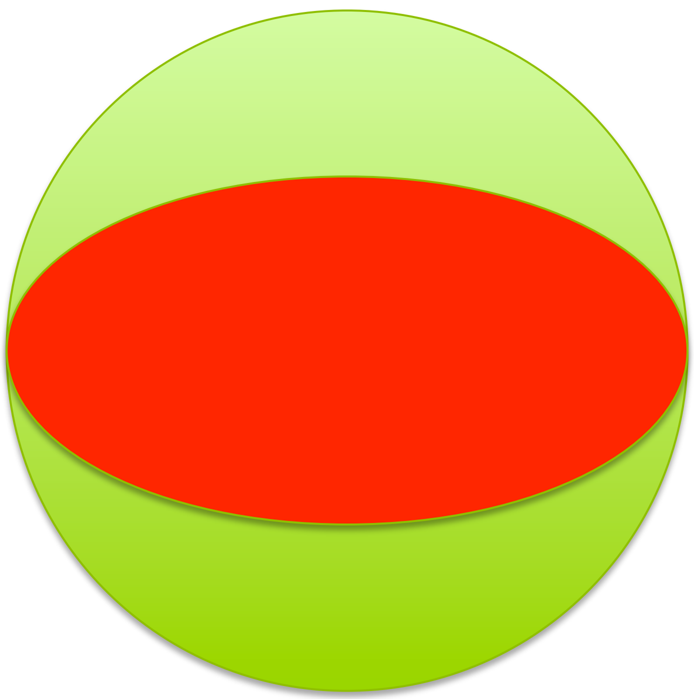
$$R_L = \frac{d}{T^2}\sqrt{\frac{F}{\sigma}}$$

In General Relativity, the gravitational redshift Effect must be corrected for, so the actual radius is:

$$R = R_L\sqrt{1-\frac{2M}{R}}$$

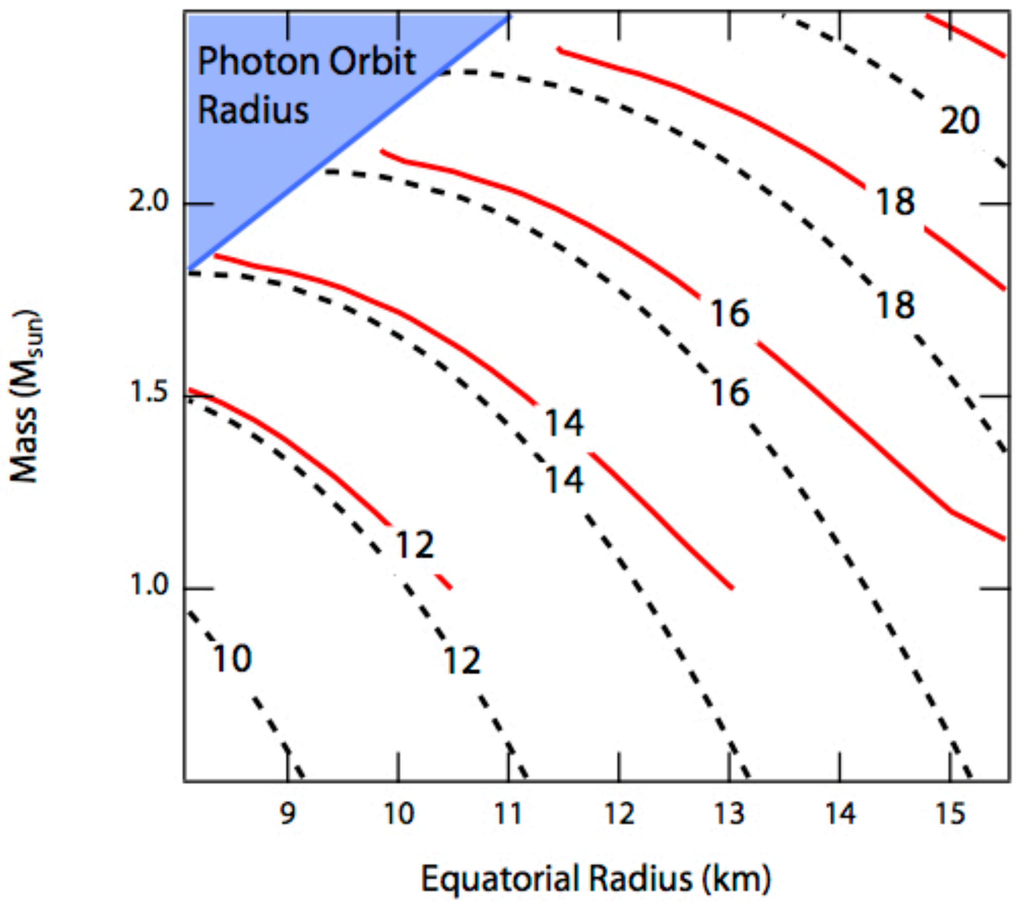
Unfortunately, real neutron stars aren't uniformly emitting blackbodies, so use more realistic spectra…

Rotational Effect on Luminosity Radius



- An oblate star with the same equatorial radius as a spherical star has a smaller cross-sectional area A
- Flux ~ A so assuming a sphere underestimates the equatorial radius of the star

Luminosity Radius vs "Real" Radius



Baubock, Ozel, Psaltis, Morsink, ApJ 2015

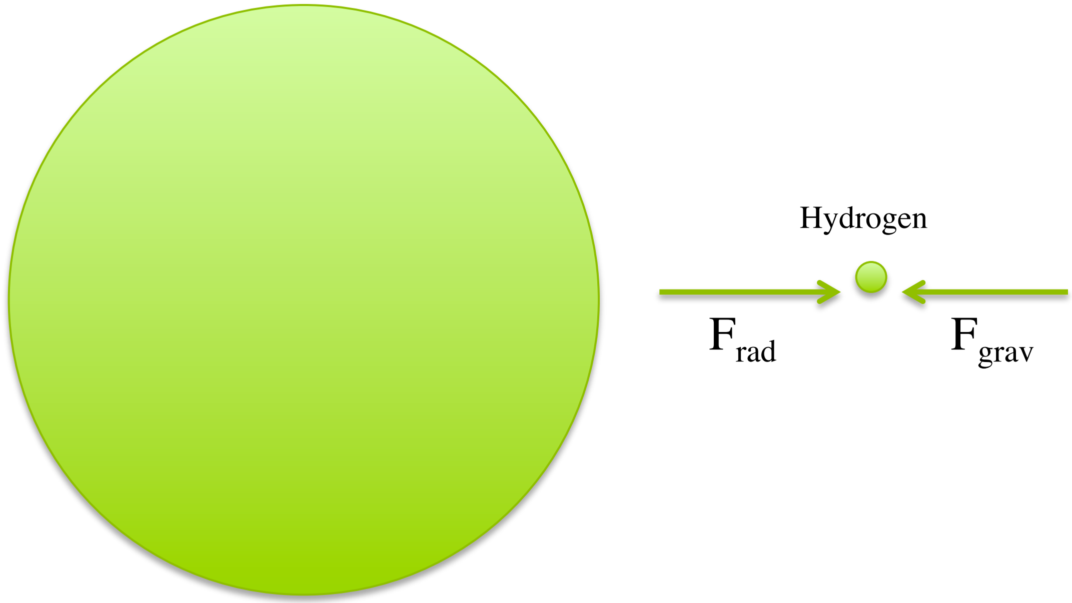
(Calculation is for pure blackbody, also includes Doppler boosting effects)

Assuming a spherical star could lead to underestimating the radius by 3-5%

----------- Luminosity Radius for zero spin $R_L = R(1\text{-}2M/R)^{-1/2}$

——— Luminosity Radius for spinning star (600 Hz)

Eddington Limit – Spherical Star Maximum Allowed Flux

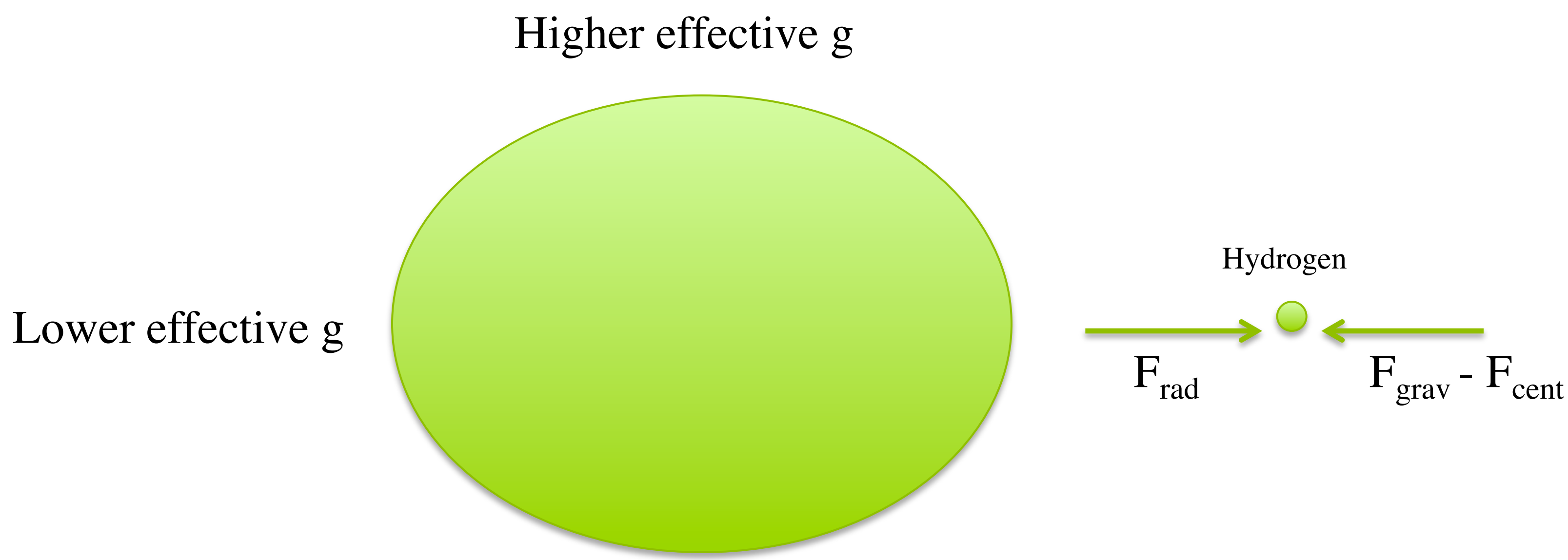


Newtonian Gravity: $F_0 = 2GMm_pc/d^2(1+X)\sigma_T$

General Relativity: $F_{Edd} = F_0\,(1\text{-}2M/R)^{1/2}$

(1) Acceleration due to gravity is stronger at the surface
(2) Gravitational Redshift makes light appear dimmer

Eddington Limit – Rotating Star

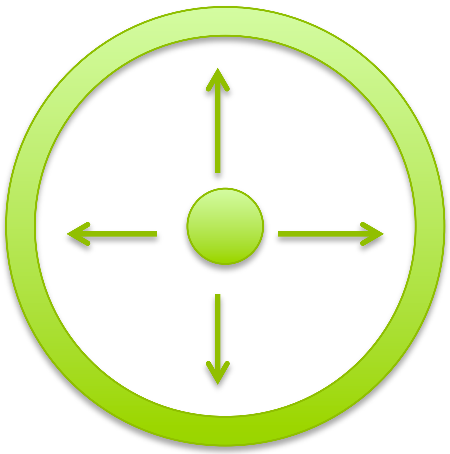


At Equator: $F_{Edd} = F_0\,(1\text{-}2M/R_e)^{1/2}\,(1 - a\,\Omega^2\,R^3/GM)\,f_L$

(1) $a > 0$ centrifugal reduction in effective surface gravity
(2) $f_L < 1$ Luminosity radius reduction factor (due to rotation)

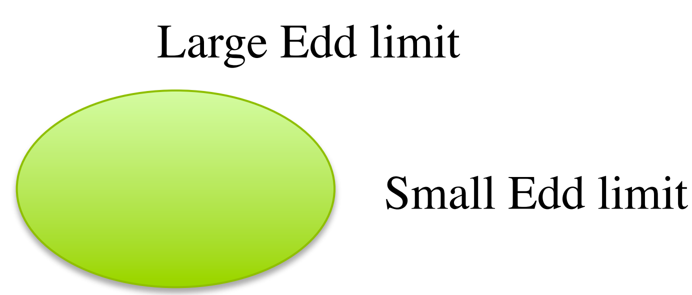
For 600 Hz, both corrections reduce Eddington by up to 15%
(AlGendy & Morsink, ApJ 2014)

Eddington-Limited X-ray Bursts



- During Type I X-ray burst radiation flux can exceed Eddington
- Atmosphere can be pushed off of star
- Away from star, Newtonian Eddington limit applies
- When atmosphere cools off it falls back onto star and "touches down"

- Rotating Relativistic Eddington limit only applies when atmosphere is in hydrostatic equilibrium with star
- Since Edd limit is largest at pole, touch-down takes place first at pole, and then moves down to equator.



Effect of an undetected hot spot on luminosity radius

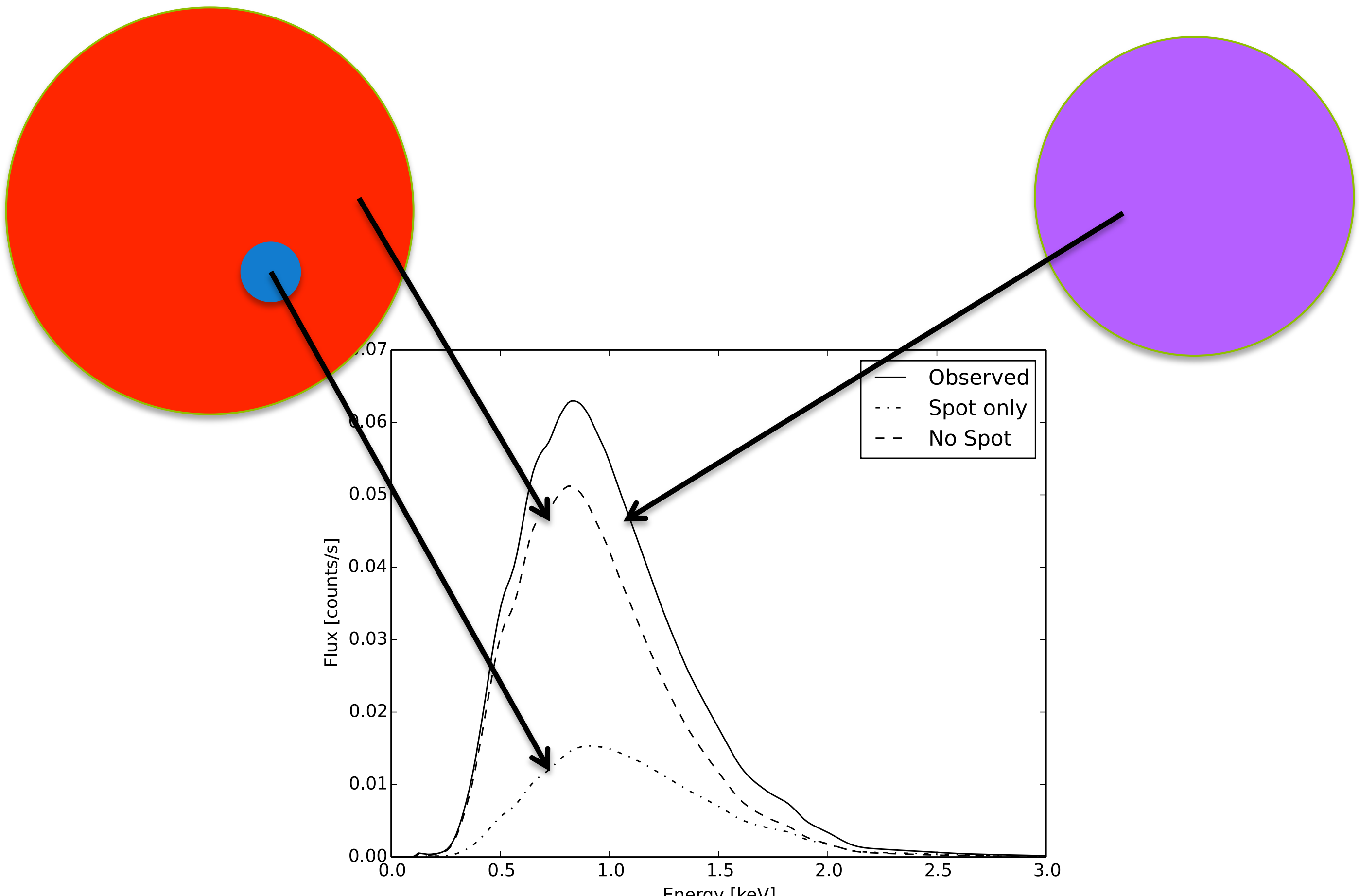
- Radius determined through luminosity radius method for many stars without pulsations – we normally assume that they are not rotating and they have a homogeneous temperature
- Example – Quiescent LMXBs
- BUT, what if they are rotating and have a hot spot that our telescope can't detect????

Elshamouty, Heinke, Morsink, Bogdanov, & Stevens, ApJ to appear in 2016

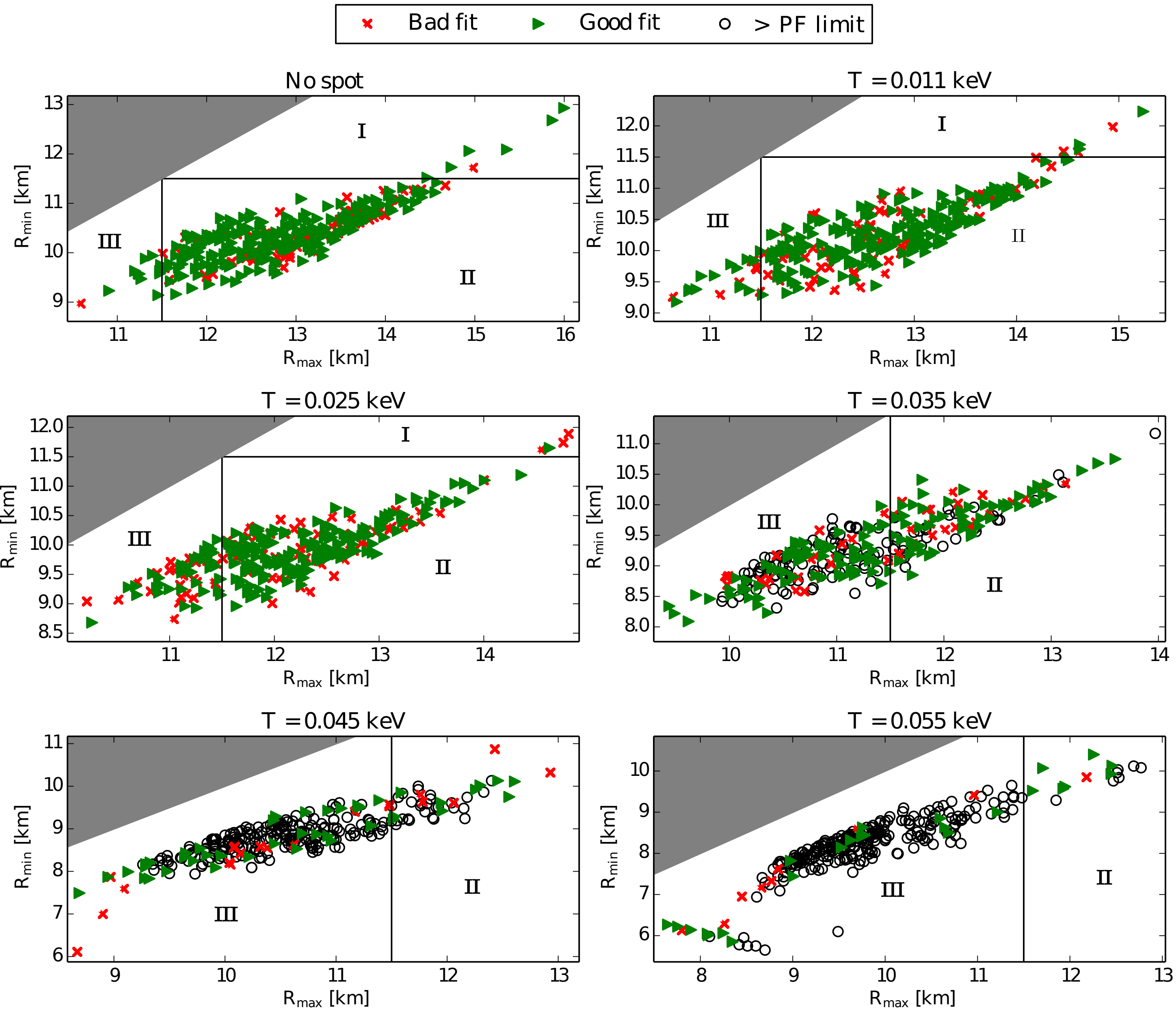
What happens if we can’t tell that the star has a hot spot?

Reality

What we infer: hotter T and smaller R



Elshamouty et al 2016



True R = 11.5 km

I: Fit R > 11.5 km

II: Fit allows true R

III: Fit R < 11.5 km

XSPEC fits assuming homogeneous surface – leads to bias towards smaller radius – Also true if star is not rotating

Conclusions

- Spinning stars are more fun!
- If we know the spin of a star, we can factor in effect of rotation and find the equatorial radius of the star.
- If it is unknown if the star is spinning, then luminosity radius method tends to lead to underestimating the star's radius, if it is actually spinning.