Observational constraints on spinning, general relativistic BEC stars

Arunava Mukherjee

Post-doctoral Visiting Scientist

ICTS-TIFR, Bangalore

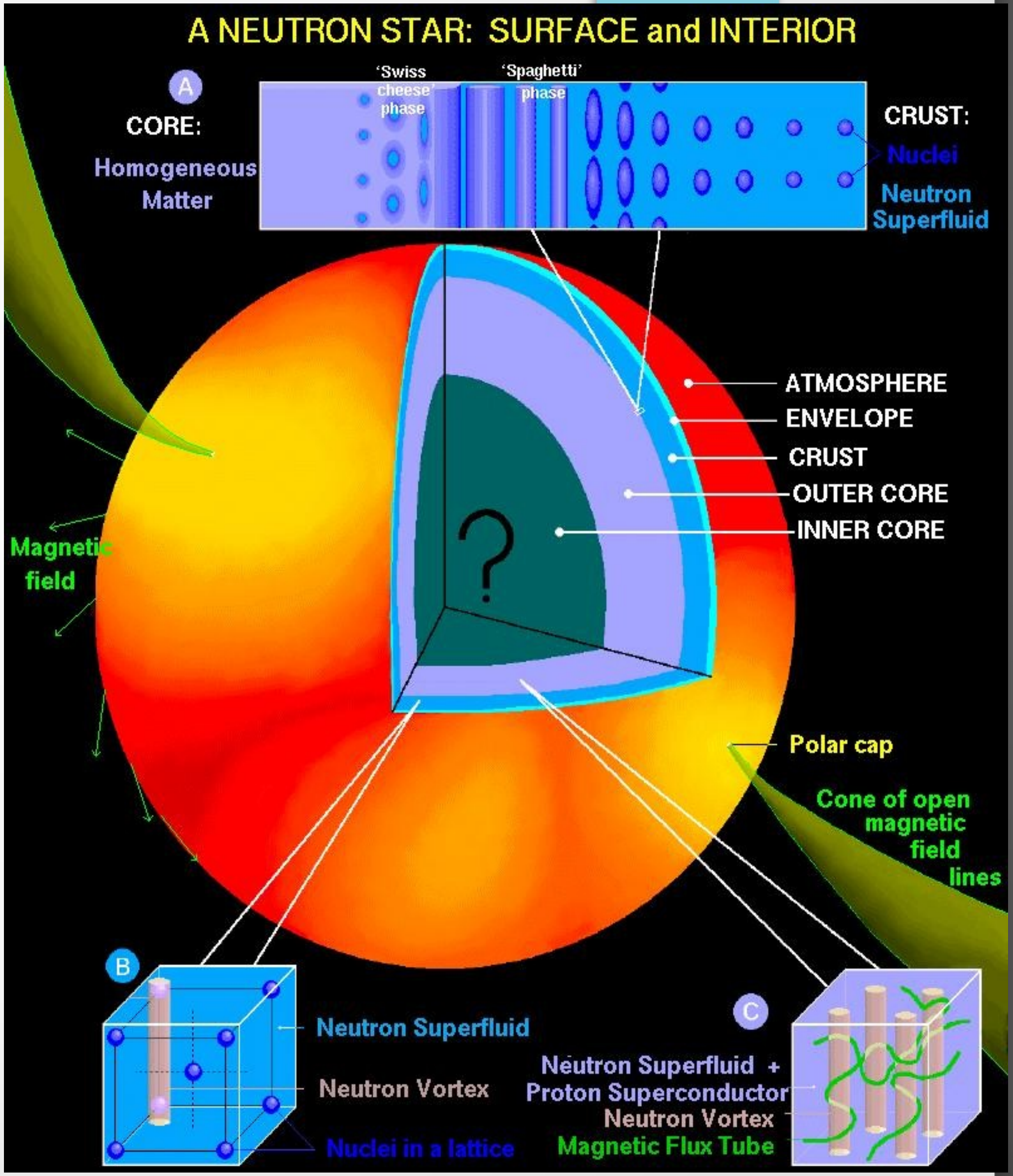
Neutron Star Workshop, NCRA-TIFR, Pune

21 November, 2014

(in collaboration with ***late* Shreya Shah** and **Sukanta Bose**)

An overview of neutron star

- Typical mass ~ 1-2 M_{Sun}
- Radius ~ 10 km
- Density ~ 10^{15} g/cm^3
- Magnetic field ~ 10^8 – 10^{16} G
- Stellar spin frequency ~ 10^{-1} – 10^3 Hz



Thus properties of neutron stars are extreme in several aspects!!!

Superconducting neutron fluid: **a new equation of state (CSW EoS)**

- Chavanis and Harko studied an EoS of neutron star which was originally derived by M. Colpi, S. L. Shapiro, and I. Wasserman [Phys. Rev. Lett. 57, 2485 (1986)].
- It consists of Cooper-pair of superconducting (BCS) neutron fluid.
- The algebric form of this EoS can be written as:

$$P = \frac{c^4}{36K}\left[\left(1 + \frac{12K}{c^2}\rho\right)^{1/2} - 1\right]^2$$

where, $\rho c^2 = \epsilon$, ϵ is the total energy-density of the fluid; P is the pressure of the fluid; c is the speed of light in vacuum; and

$$K = \frac{\lambda\hbar^3}{4m^4c}$$

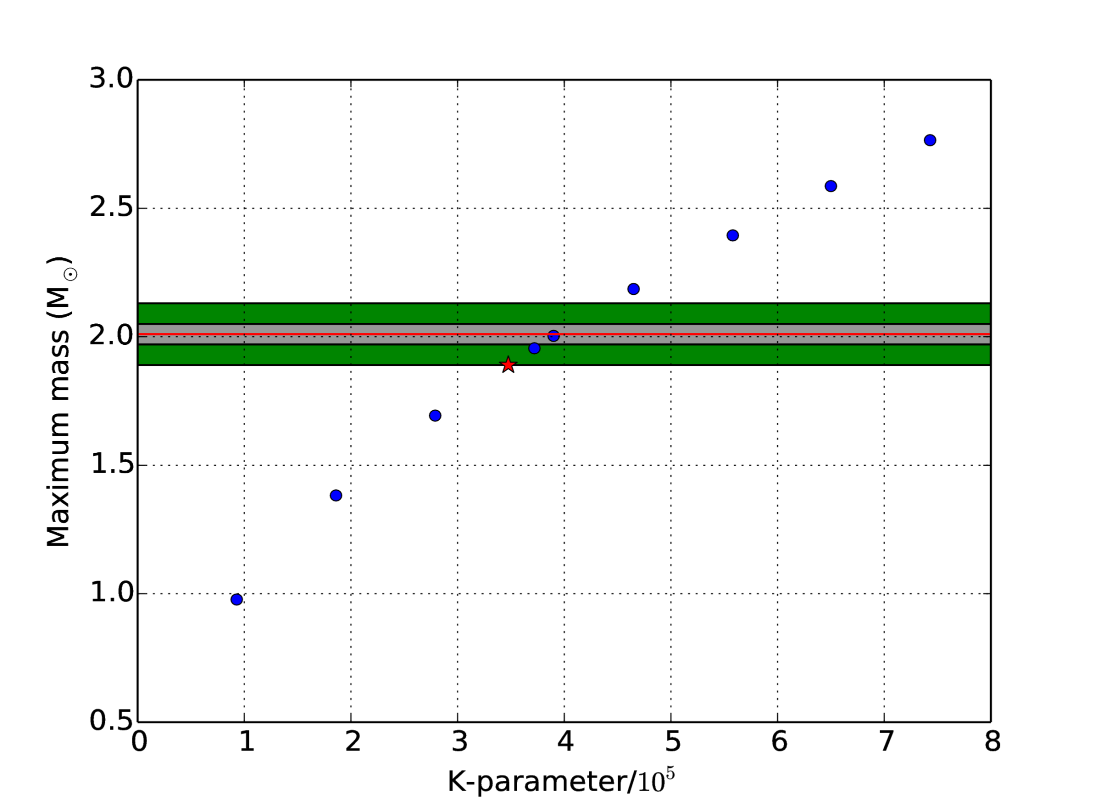
here, m be the mass of the neutron Copper-pair, $m_n = 1.67492716\times10^{-27}$ kg, is the mass of a neutron; h-bar = 1.054571596× 10−34 Js, is Planck's constant, and .....

Scattering-length and Cooper-pair mass are the *two* free parameters of the model

- λ is a dimensionless quantity defined by,

$$\lambda = (9.523 \times 8\pi)\frac{a}{1\,\mathrm{fm}}\frac{m}{2m_n}$$

where, a is the scattering length, and m is the Cooper-pair mass, both of which are not quite well-determined quantity in such a high density and low temperature regime.



- For different values of scattering length and mass of the Cooper-pair the EoS changes
  => so does the maximum stable mass!

- Both this quantities are captured in the free parameter K in the CSW EoS.

Fig: free parameter K Vs maximum mass of the stable star

Different combinations of scattering length and Cooper pair mass

- Even if we allow the Cooper pair mass 'm' and scattering length to vary => EoS is essentially determined by the one and only one free parameter 'K'.

$$\lambda = (9.523 \times 8\pi)\frac{a}{1\,\mathrm{fm}}\frac{m}{2m_n}$$

$$K = \frac{\lambda \hbar^3}{4m^4 c}$$

- <u>Remember:</u> for a fixed value of 'K'-parameter the equation of state remains the same!

$$P = \frac{c^4}{36K}\left[\left(1 + \frac{12K}{c^2}\rho\right)^{1/2} - 1\right]^2$$

- Therefore, we numerically compute the mass (M) and radius (R) for equilibrium star with these CSW-EoSs with different values of K-parameters.

Gravitational mass (M) and radius (R) for different central densities for K = 3.48×10^5 cm^5 g^{-1} s^{-2}

(*minimum K*)

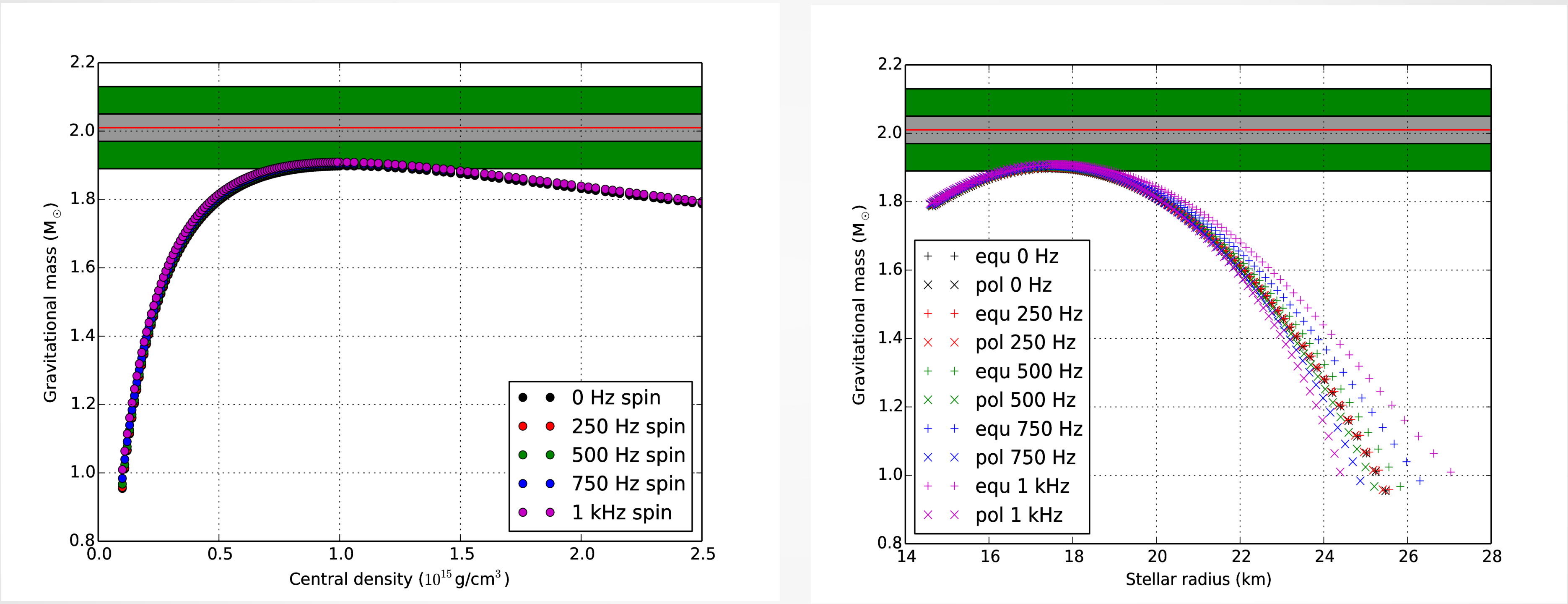


Fig: Relationships between gravitational mass with the central-density (left-panel), and with radius (right-panel) of the neutron star (for different stellar spin-frequencies) computed for this CSW-EoS ***<u>of lower-bound in K-parameter</u>***. Both equatorial ("equ" in figure) and polar ("pol" in figure) radii are shown here.

Gravitational mass (M) and radius (R) for different central densities for K = 3.72 x 10^5 cm^5 g^{-1} s^{-2}

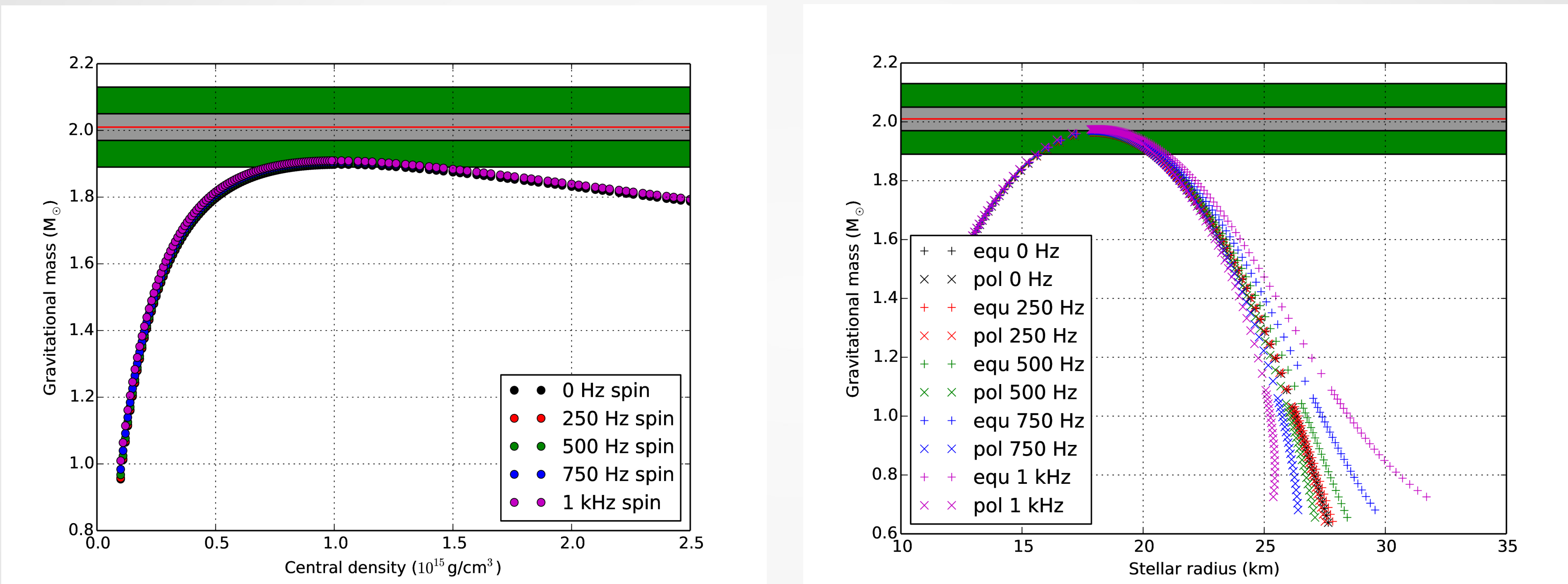


Fig: Relationships between gravitational mass with the central-density (left-panel), and with radius (right-panel) of the neutron star (for different stellar spin-frequencies) computed for this CSW-EoS for the mentioned K-value. Both equatorial (“equ” in figure) and polar (“pol” in figure) radii are shown in the figure.

Gravitational mass (M) and radius (R) for different central densities for K = 4.65×10^{5} cm^{5} g^{-1} s^{-2}

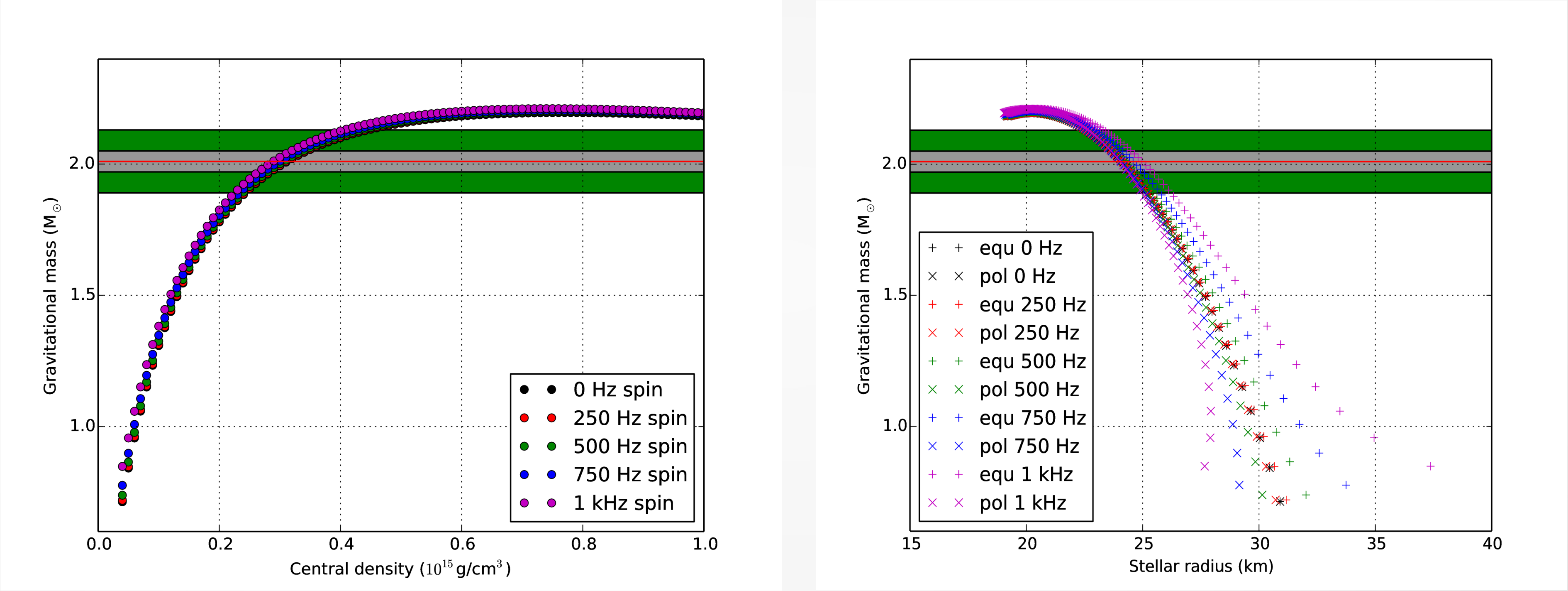


Fig: Relationships between gravitational mass with the central-density (left-panel), and with radius (right-panel) of the neutron star (for different stellar spin-frequencies) computed for this CSW-EoS for the mentioned K-value. Both equatorial ("equ" in figure) and polar ("pol" in figure) radii are shown in the figure.

Gravitational mass (M) and radius (R) for different central densities for K = 5.58×10^5 cm^5 g^{-1} s^{-2}

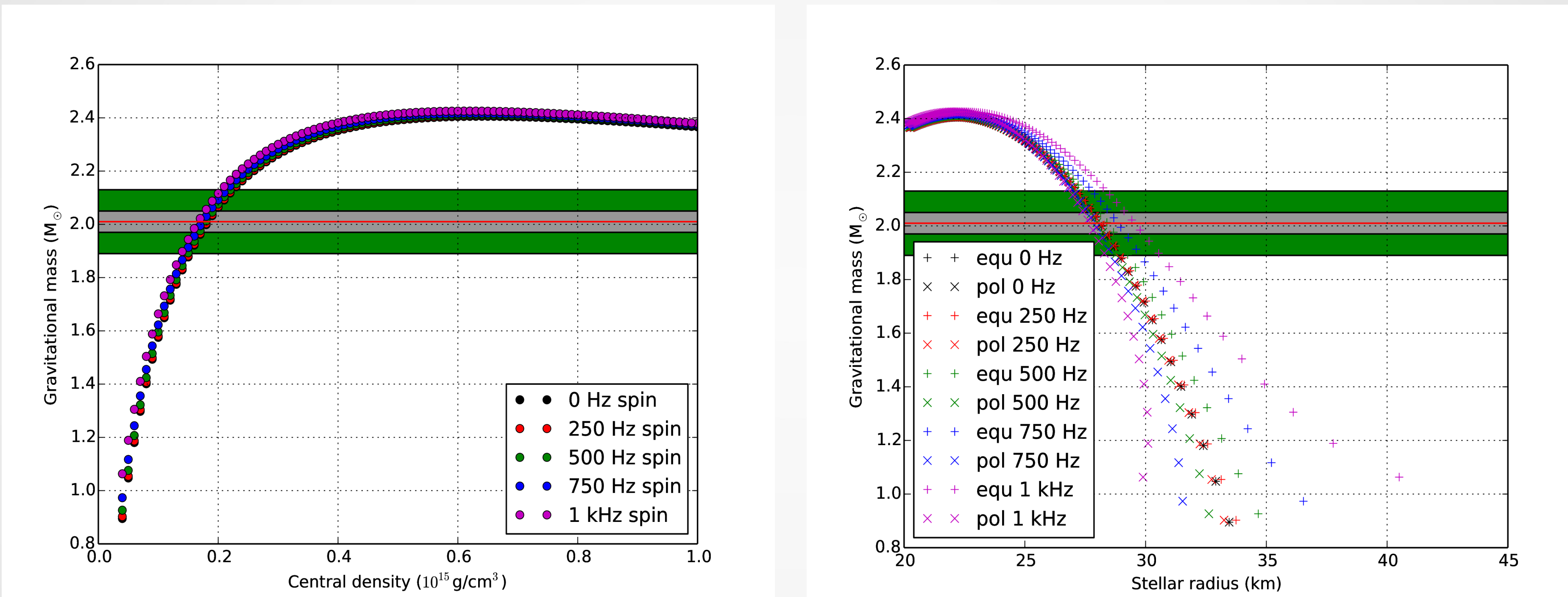
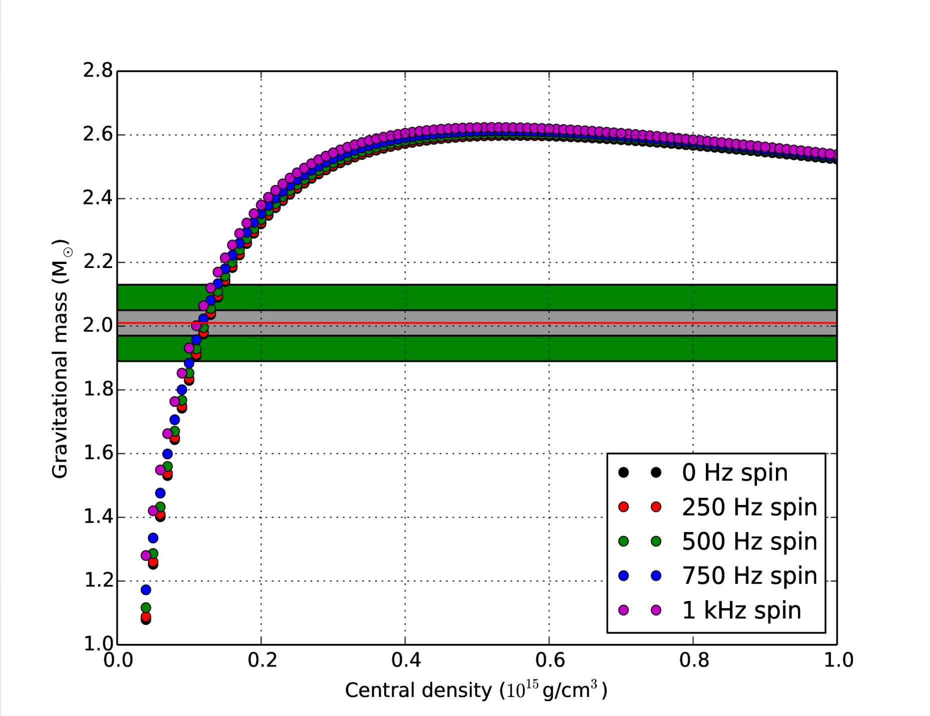


Fig: Relationships between gravitational mass with the central-density (left-panel), and with radius (right-panel) of the neutron star (for different stellar spin-frequencies) computed for this CSW-EoS for the mentioned K-value. Both equatorial ("equ" in figure) and polar ("pol" in figure) radii are shown in the figure.

Gravitational mass (M) and radius (R) for different central densities for K = $6.50 \times 10^5\ cm^5\ g^{-1}\ s^{-2}$



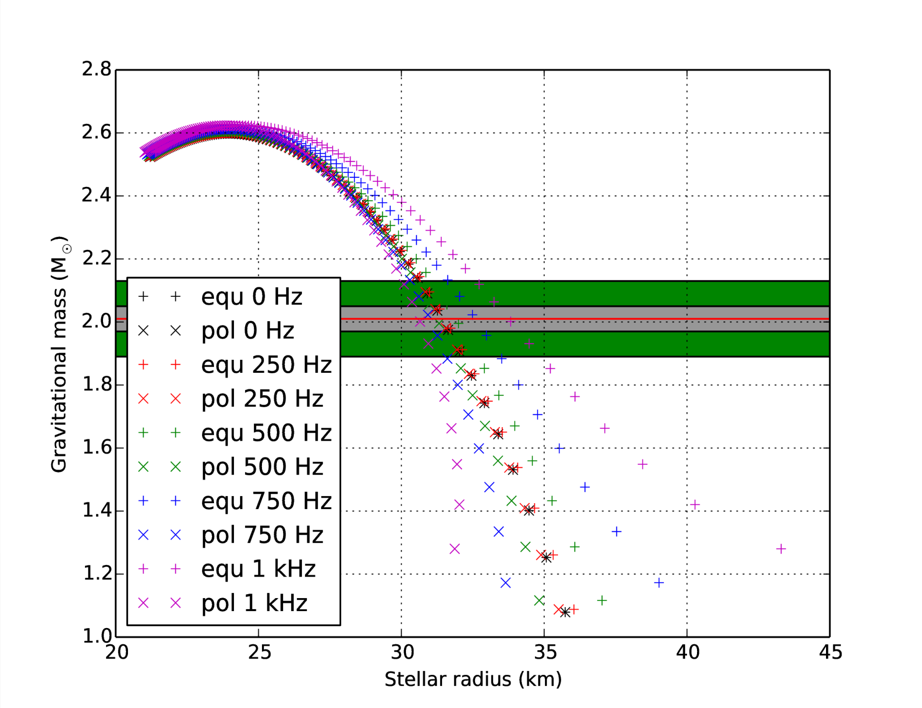
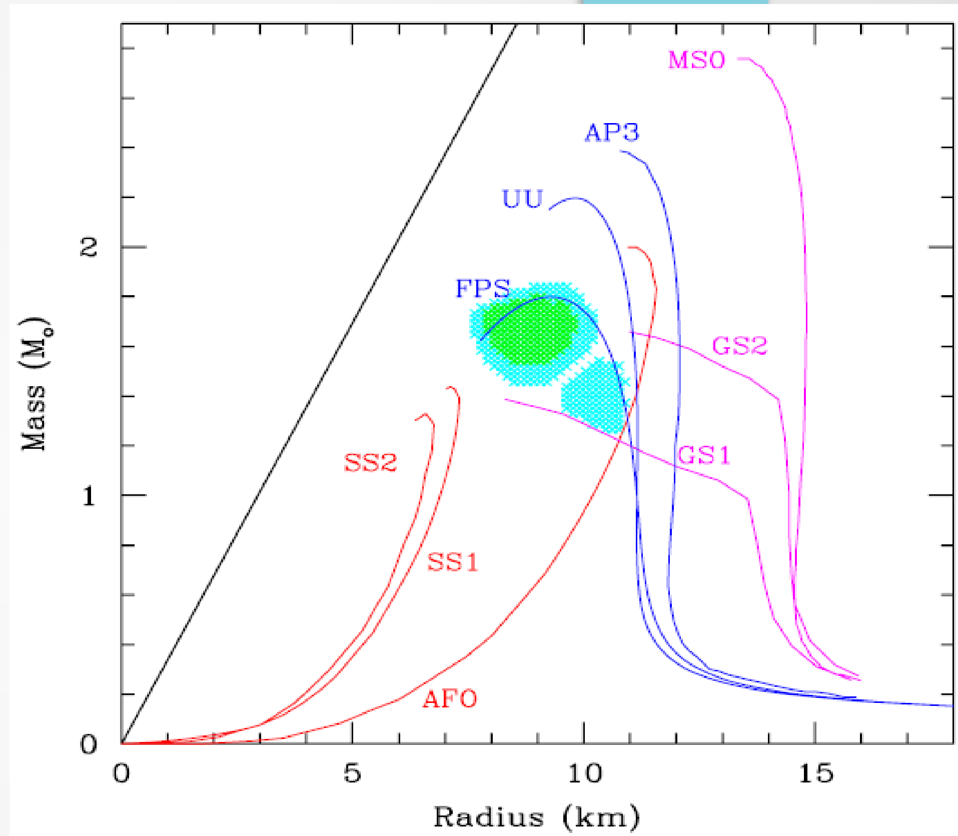


Fig: Relationships between gravitational mass with the central-density (left-panel), and with radius (right-panel) of the neutron star (for different stellar spin-frequencies) computed for this CSW-EoS for the mentioned K-value. Both equatorial ("equ" in figure) and polar ("pol" in figure) radii are shown in the figure.

Constraint from X-ray astronomy

- Neutron stars in the LMXB systems often exhibit thermonuclear X-ray bursts
- From Eddington luminosity of the PRE bursts, neutron star mass M is often estimated
- During these bursts, the burning area is believed to cover the whole surface of the neutron star
- Analyzing the X-ray spectra several authors estimated the emission area of the burning stellar surface
- This provides one of the very rare astronomical measurements of radius of a neutron star!!!



Plot of 1σ and 2σ contours for the mass and radius of the Neutron star in EXO 1745−248, based on the spectroscopic data during thermonuclear bursts combined with a distance measurement to the globular cluster. Neutron star radii larger than ∼ 13 km are not favored for this data (Ref.: Ozel, Guver & Psaltis, 2009, ApJ, 693, 1775).

Observation of mass and radius

- F. Ozel, G. Baym and T. Güver (PhysRevD.82.101301, 2010) reported the analysis of three neutron star LMXBs, 4U 1608–248, EXO 1745–248, and 4U 1820–30.

- These authors analyzed photon energy spectra of a number the thermonuclear X-ray bursts from those three sources and estimated the gravitational mass (M) and radius (R) of the respective neutron stars.

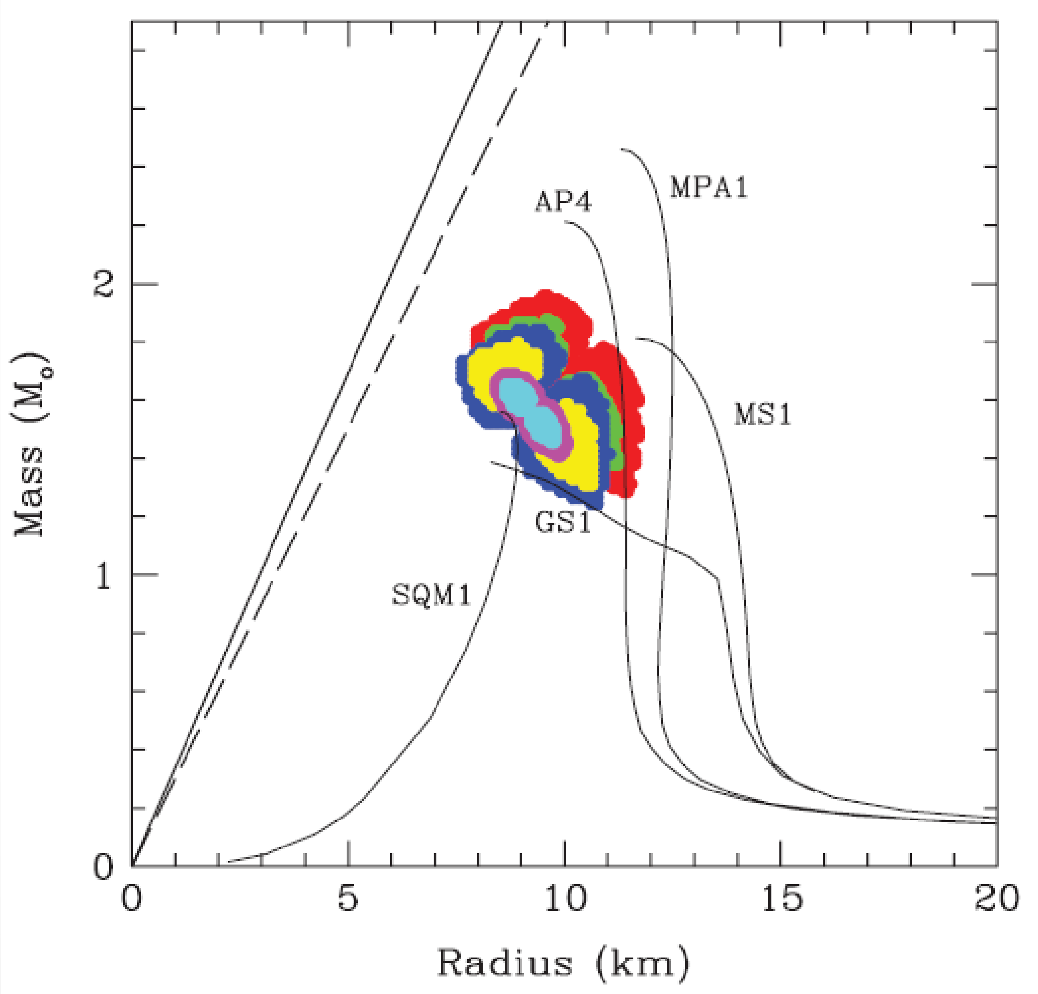


Fig: The 1 & 2-sigma confidence contours for the masses and radii of three neutron stars in the binaries 4U 1608-248 (green/red), EXO 1745-248 (yellow/blue), and 4U 1820 -30 (cyan/magenta), compared with predictions of representative EoS.

Observation of mass and radius (continued ...)

Using astronomical observations F. Ozel, A. Gould and T. Güver (ApJ v748, 5O, 2012) estimated a strong upper bound on the radius of the neutron star, $R < 12.5$ km of another LMXB source KS 1731−260!

T. Güver et al. (ApJ v719, 1807, 2010) reported a precisely measured mass

$M = 1.58 \pm 0.06\, M_{\odot}$ and radius $R = 9.11 \pm 0.4$ km !!!

All these reported observational values of neutron star radius is in severe contradiction with the EoS proposed by M. Colpi, S. L. Shapiro, and I. Wasserman, Phys. Rev. Lett. 57, 2485 (1986) and its application as a realistic NS-EoS by P. H. Chavanis and T. Harko, Phys. Rev. D 86, 064011 (2012)!!!

Computing stellar structure and comparing with observations: summary

- We numerically solve the equilibrium hydro-static stellar structure equations (with help of Nick Stergioulus) to obtain the stellar structures

- We computed it for different central densities and stellar spin frequencies corresponding to EoSs having different scattering lengths.

- Finally, we compare the neutron star radii for different observed masses.

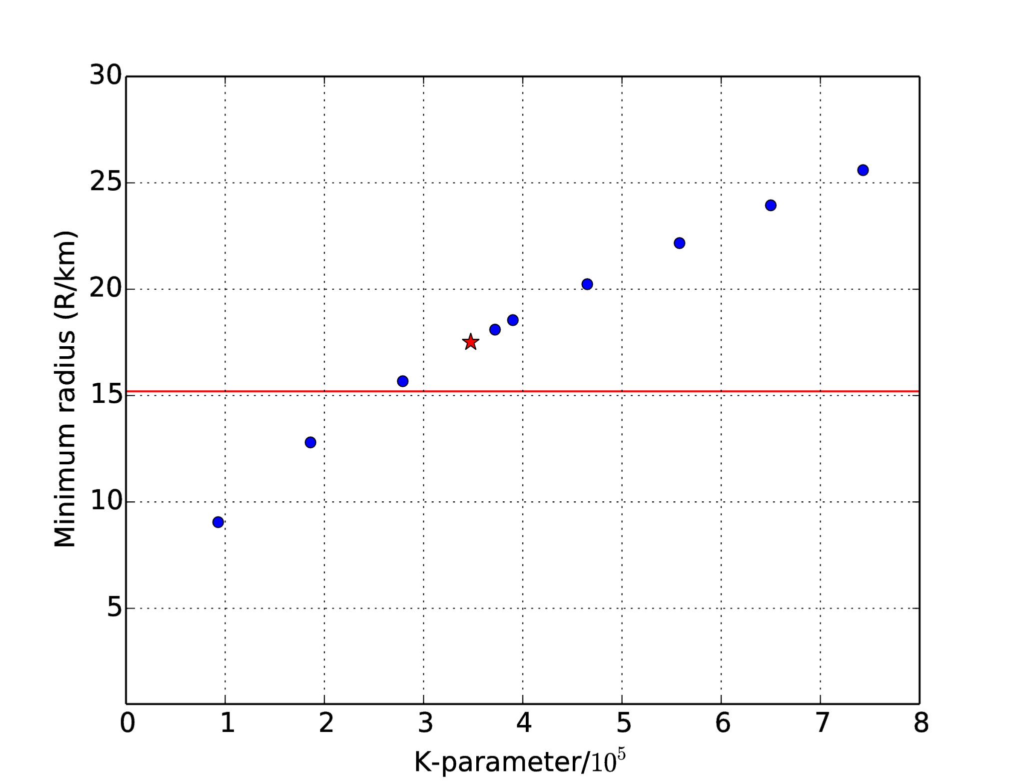


Fig: Free parameter K Vs minimum radii of stable configuration of the non-spinning star.

Acknowledgments

We <u>dedicate this work to ***late Shreya Shah***</u> who left for her heavenly adobe on 14 June, 2014 close to the final stage for this work.

We would like to thank Sharon Morsink and Nick Stergioulas for providing us with useful computational assistance.

We also thank Sanjay Reddy, Michael Forbes, and Nils Anderson for helpful discussions.

AM and SB thank the Institute for Nuclear Theory at the University of Washington, Seattle, for its hospitality, and the Department of Energy for partial support. AM thanks Department of Physics and Astronomy, WSU, Pullman for its hospitality.

Thank you very much for your kind attention.