Symmetry Energy & Maximum Rotation of Neutron Stars

Isaac Vidaña
CFC, University of Coimbra

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Motivation

Ω_{Kepler} : absolute upper limit on the rotational frequency of neutron stars

(matter ejected from equator for $\Omega > \Omega_{Kepler}$)

$$\Omega_{Kepler} \approx 7800 \sqrt{\left(\frac{M}{M_{sun}}\right)\left(\frac{10km}{R}\right)^3}\, s^{-1}$$

But instabilities can prevent neutron stars from reaching Ω_{Kepler} ➔ more stringent limit in rotation

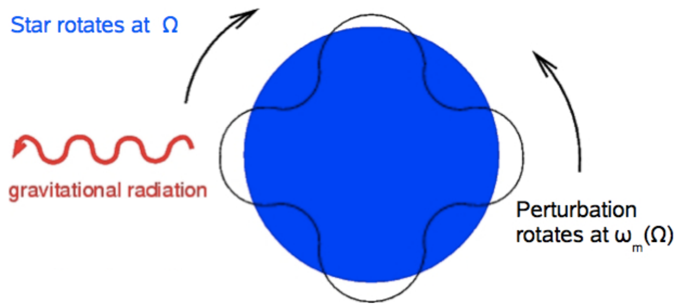
R-mode instability : toroidal mode of oscillation

✓ restoring force: Coriolis

✓ emission of GW in hot & rapidly rotating NS (CFS mechanism)

- GW makes the mode unstable
- Dissipation (viscosity) stabilizes the mode

τ_{GW}, τ_{diss} ➔ Critical angular velocity Ω_c



$$A \propto A_0\, e^{-i\omega_m(\Omega)t + im\phi - t/\tau(\Omega)}$$

In this talk …

Study the role of the symmetry energy slope parameter L on the maximum rotational frequency of neutron stars by using both microscopic (BHF, APR & AFDMC) and phenomenological (Skyrme & RMF) approaches of the nuclear matter EoS

based on: Phys. Rev. C 85, 045808 (2012)

Microscopic approaches

BHF with Av18 + UIX

- $$\frac{E}{A}(\rho,\beta) = \frac{1}{A}\sum_{\tau}\sum_{k\le k_{F_\tau}}\left(\frac{\hbar^2k^2}{2m_\tau} + \frac{1}{2}\mathrm{Re}\left[U_\tau(\vec{k})\right]\right)$$

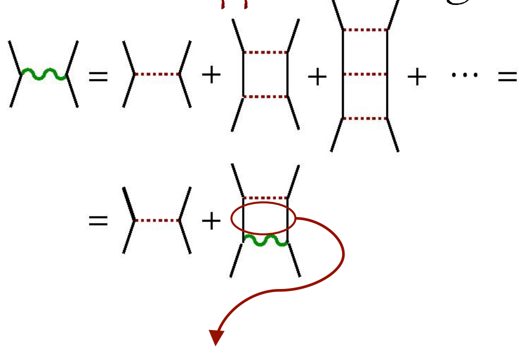
Infinite sumation of two-hole line diagrams

✓ $$G(\omega) = V + V\frac{Q}{\omega - E - E' + i\eta}G(\omega)$$

✓ $$E_\tau(k) = \frac{\hbar^2k^2}{2m_\tau} + \mathrm{Re}\left[U_\tau(k)\right]$$

✓ $$U_\tau(k) = \sum_{\tau'}\sum_{k'\le k_{F_{\tau'}}}\left\langle \vec{k}\vec{k}'\middle|G(\omega = E_\tau(k) + E_{\tau'}(k'))\middle|\vec{k}\vec{k}'\right\rangle_{\mathcal{A}}$$

Partial sumation of pp ladder diagrams



✓ Pauli blocking

✓ Nucleon dressing

APR & AFDMC parametrized

- $$\frac{E}{A}(\rho,\beta) = E_0 u\frac{u-2-s}{1+us} + S_0u^\gamma\beta^2, \qquad u = \rho/\rho_0$$

Heiselberg & Hjorth-Jensen Phys. Rep. 328, 237 (2000)

- $$\frac{E}{A}(\rho,\beta) = E_0 + a(\rho-\rho_0)^2 + b(\rho-\rho_0)^3e^{\gamma(\rho-\rho_0)} + C_s\left(\frac{\rho}{\rho_0}\right)^{\gamma_s}\beta^2$$

Gandolfi et al., MNRAS 404, L35 (2010)

Phenomenological approaches

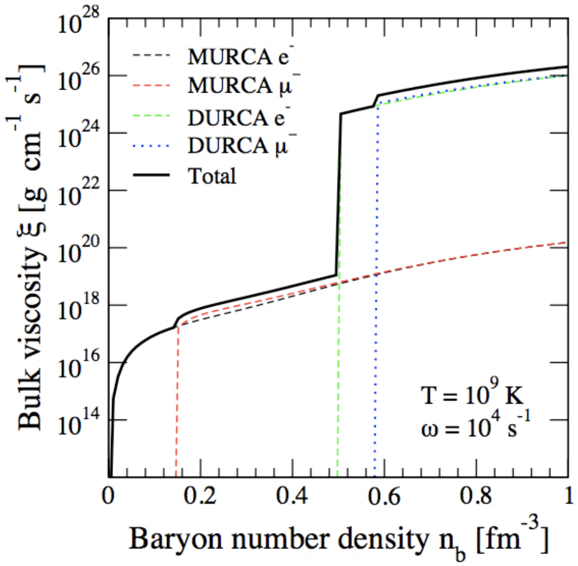
Skyrme

- Lyon group SLy: SLy0-SLy10, Sly230a
- SkI family: SkI1-SkI6
- Rs, Gs, SGI, SkMP, SkO, SkO', SkT4-5, SV

Relativistic mean field models

- Non-linear Walecka models (NLWM) with constant coupling constants: GM1, GM3, TM1, NL3, NL3-II, NL-SH
- Density dependent hadronic models (DDH) with density dependent coupling constants: DDME1, DDME2, TW99, PK1, PK1R, PKDD

Bulk & shear viscosities



$$\xi = \xi_{MURCA} + \xi_{DURCA} = \sum_{Nl} \frac{|\lambda_{Nl}|}{\omega^2} \left|\frac{\partial P}{\partial X_l}\right| \frac{\partial \varsigma_l}{\partial n_b} + \sum_{l} \frac{|\lambda_l|}{\omega^2} \left|\frac{\partial P}{\partial X_l}\right| \frac{\partial \varsigma_l}{\partial n_b}$$

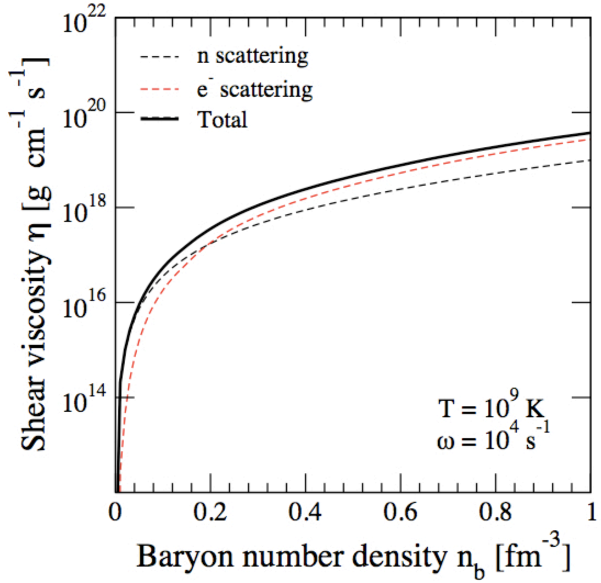
✓ Modified URCA

$$N + n \rightarrow N + p + l + \bar{\nu}_l, \quad N + p + l \rightarrow N + n + \nu_l$$

✓ Direct URCA

$$n \rightarrow p + l + \bar{\nu}_l, \quad p + l \rightarrow n + \nu_l$$

Haensel et al., AA 357, 1157 (2000); AA 372, 130 (2001)



$$\eta = \eta_n + \eta_e$$

✓ n scattering [1]

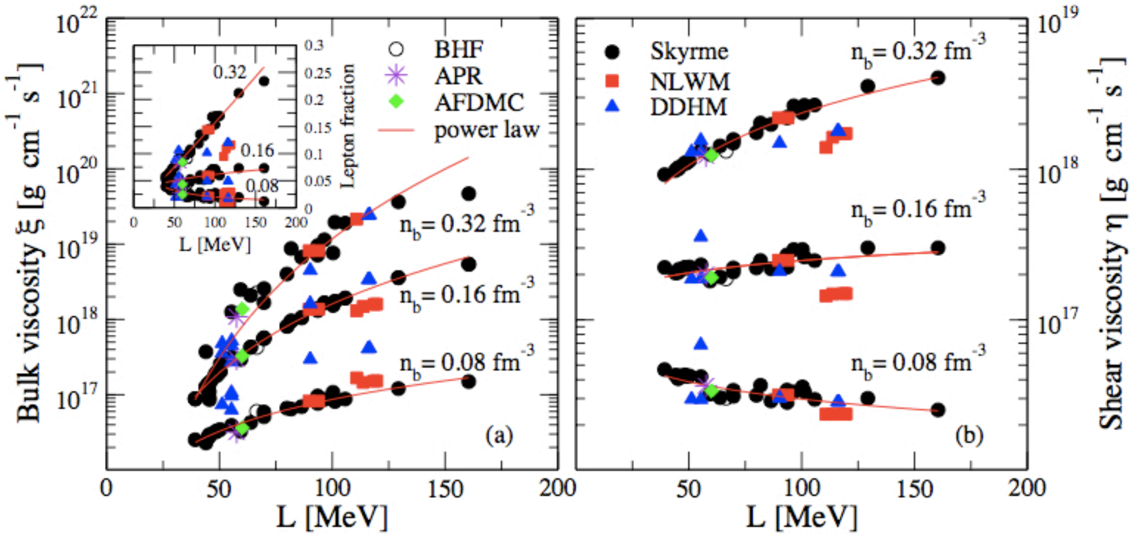
$$\eta_n = 2 \times 10^{18} \left(\frac{\rho}{10^{15}\, gcm^{-3}}\right)^{9/4} \left(\frac{T}{10^9 K}\right)^{-2}$$

✓ e^- scattering [2]

$$\eta_e = 4.26 \times 10^{-26} \left(x_p n_b\right)^{14/9} T^{-5/3}$$

[1] Cutler & Lindblom., ApJ 314, 234 (1987).
[2] Shternin & Yakovlev, PRD 78, 063006 (2008)

L dependence of ξ and η

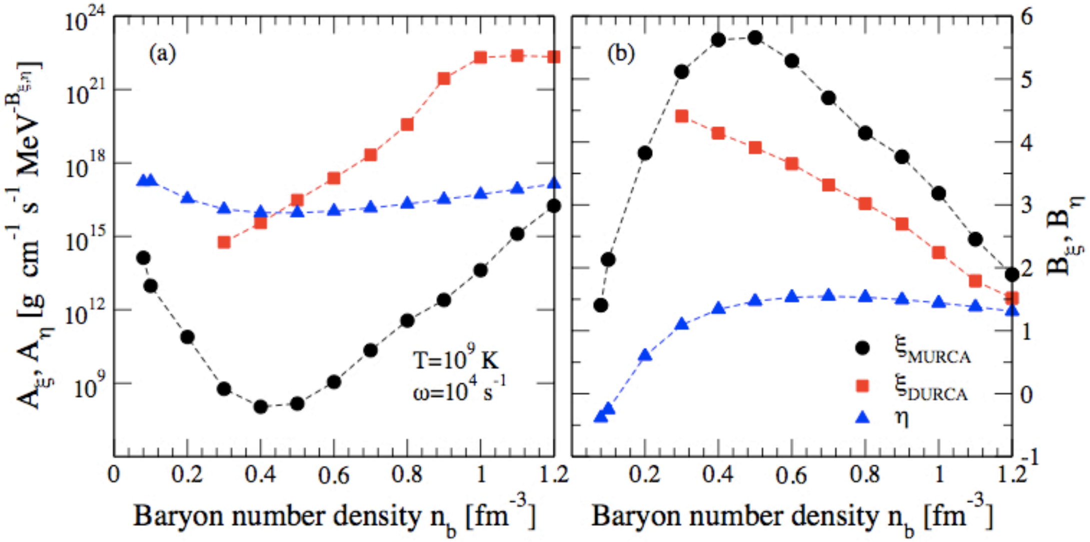


- ✓ ξ increases with L for all densities
- ✓ η increases with L for $n_b > n_0$ & decreases with L for $n_b < n_0$

consequence of lepton fraction dependence

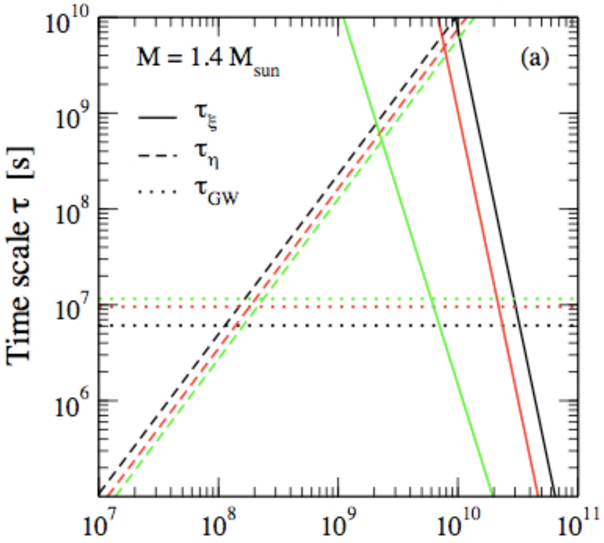
L dependence described by simple power laws

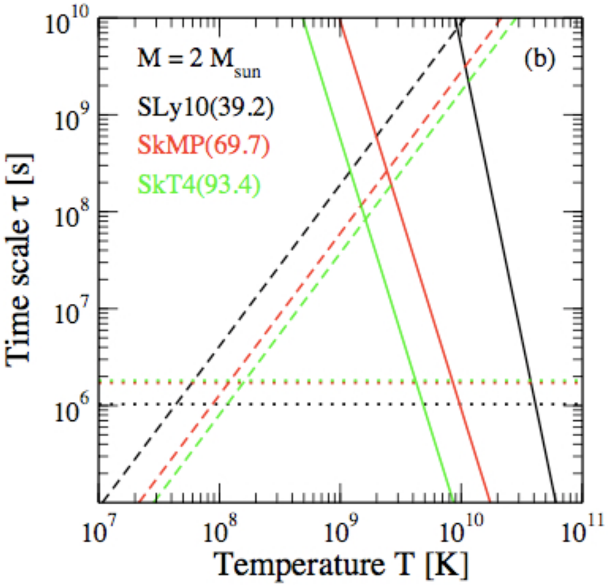
$$\xi = A_\xi L^{B_\xi}, \eta = A_\eta L^{B_\eta}$$



Dissipative time scales of r-modes

$$\frac{1}{\tau_i} = -\frac{1}{2E}\left(\frac{dE}{dt}\right)_i$$





- $$\frac{1}{\tau_\xi} = \frac{4\pi}{690}\left(\frac{\Omega^2}{\pi G\bar{\rho}}\right)^2 R^{2l-2}\left[\int_0^R \rho r^{2l+2} dr\right]^{-1} \int_0^R \xi\left(\frac{r}{R}\right)^2\left[1+0.86\left(\frac{r}{R}\right)^2\right] r^2 dr$$
- $$\frac{1}{\tau_\eta} = (l-1)(2l+1)\left[\int_0^R \rho r^{2l+2} dr\right]^{-1} \int_0^R \eta r^{2l} dr$$
- $$\frac{1}{\tau_{GW}} = \frac{32\pi G\Omega^{2l+2}}{c^{2l+3}} \frac{(l-1)^{2l}}{[(2l+1)!!]^2}\left(\frac{l+2}{l+1}\right)^{2l+1} \int_0^R \rho r^{2l+2} dr$$

✓ τ_{GW} larger for models with larger L

Larger L ➔ stiffer EoS ➔ less compact star ➔ τ_{GW} larger

✓ τ_ξ & τ_η smaller for models with larger L

τ_ξ (τ_η) decrease with ξ (η) but ξ (η) increase with L

✓ τ_{GW}, τ_ξ & τ_η decrease when increasing M

Given an EoS: the more massive the star the denser it is

➔ $\tau_{GW}, \tau_\xi \sim (\rho/\xi)R^2$ & $\tau_\eta \sim (\rho/\eta)R^2$ decrease

Critical angular velocity

- time dependence of an r-mode $\sim e^{-i\omega t - t/\tau}$

$$\frac{1}{\tau(\Omega,T)} = -\frac{1}{\tau_{GW}(\Omega)} + \frac{1}{\tau_{\xi}(\Omega,T)} + \frac{1}{\tau_{\eta}(T)}$$

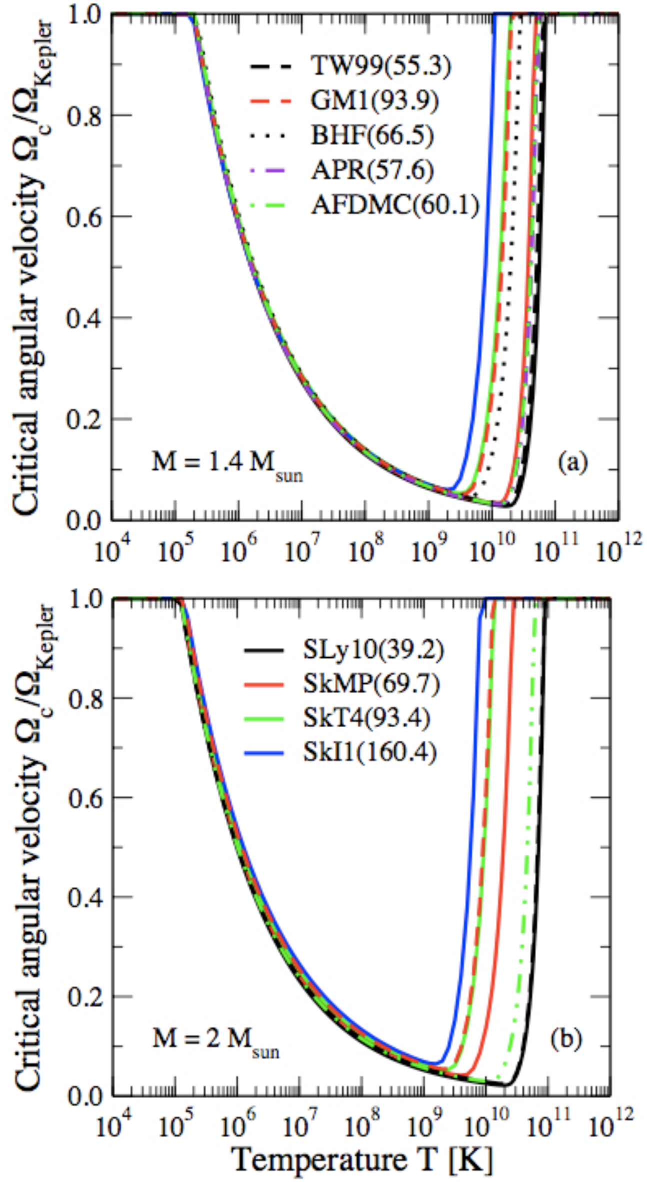
➔ $\frac{1}{\tau(\Omega_c,T)} = 0$ r-mode instability region

$\Omega < \Omega_c$ stable

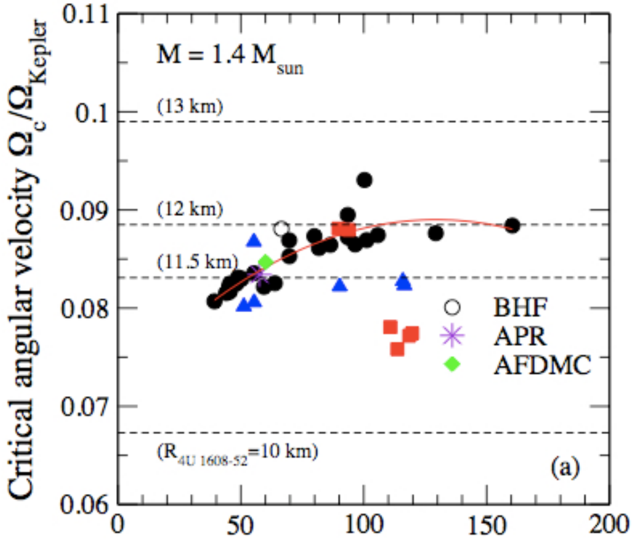
$\Omega > \Omega_c$ unstable

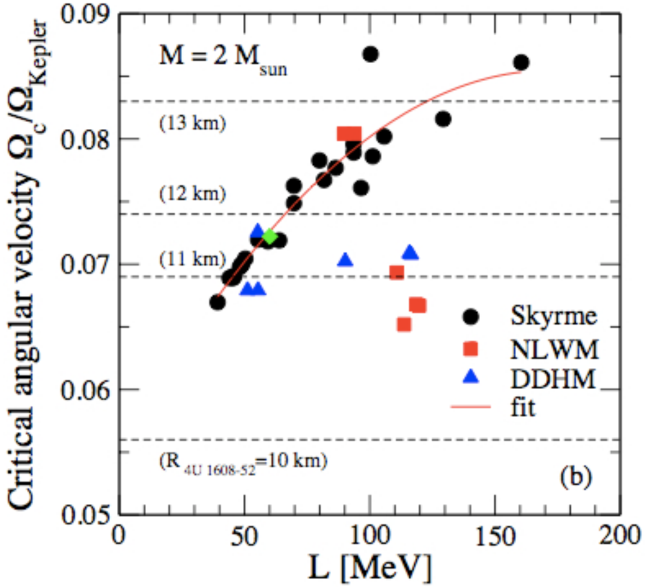
✓ instability region smaller for models with larger L (increase of ξ & η with L)

✓ instability region larger for more massive star (time scales decrease when M increases)



Constraining L from LMXBs





- observational constraints from pulsar in LMXB 4U 1608-52

  ✓ estimated core temperature $T \sim 4.55 \times 10^8$ K

  ✓ measured spin frequency 620 Hz

  radius: 10, 11.5, 12 or 13 km
  mass: 1.4 or 2 $M_\odot$

$$\Omega_{Kepler} \approx 7800\sqrt{\left(\frac{M}{M_{sun}}\right)\left(\frac{10\,km}{R}\right)^3}\; s^{-1}$$

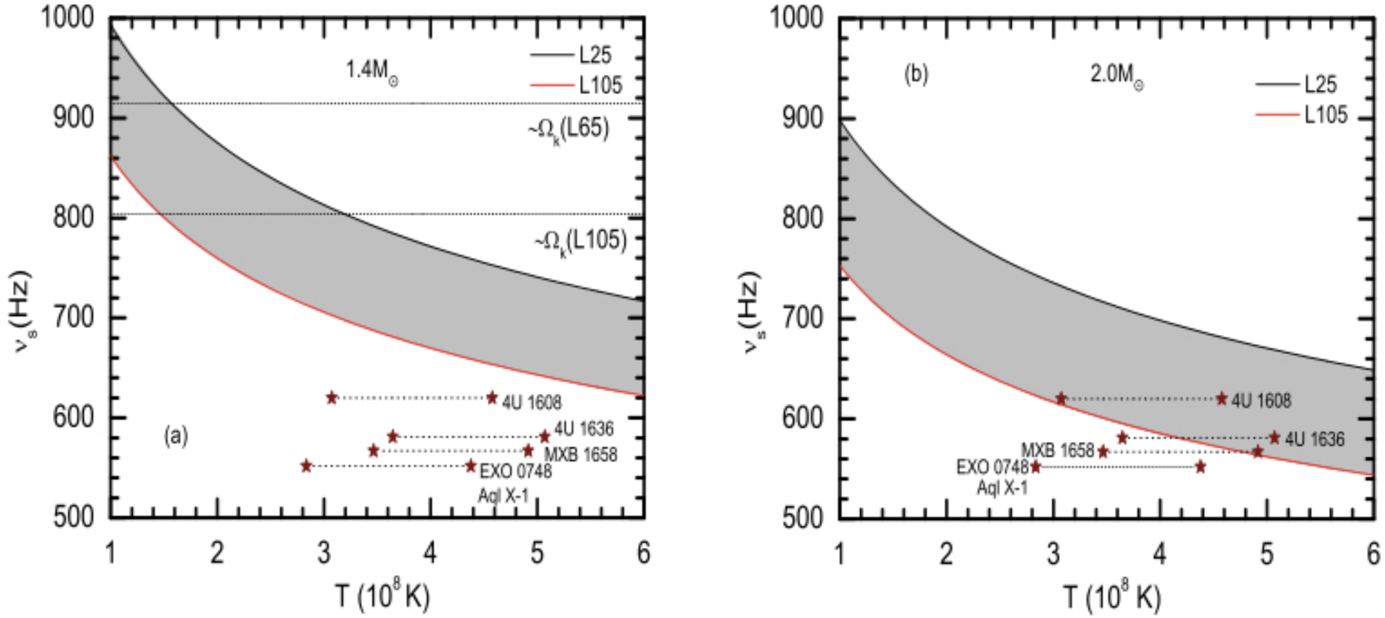
✓ No constraint on L if

- $R_{4U\,1608\text{-}52} < 11$ km ($\Omega_c > \Omega$)
- $R_{4U\,1608\text{-}52} > 12(13)$ km & M=1.4(2)$M_\odot$ ($\Omega_c < \Omega$)

✓ L > 50 MeV if (assuming 4U 1608-52 stable)

- $R_{4U\,1608\text{-}52}$ is 11.5-12(11.5-13) km & M=1.4(2)$M_\odot$

This is in contrast with the recent work of Wen, Newton & Li where they obtain L< 60 MeV (PRC 85, 025801 (2012))



However, they consider electron-electron scattering at the crust-core ($\rho<\rho_0$) boundary as the main dissipation mechanism. Therefore, their calculation of is done in a region wher η decreases with L

Summary & Conclusions

Study the role of the symmetry energy slope parameter L on the maximum rotational frequency of neutron stars by using both microscopic and phenomenological approaches of the nuclear matter EoS

- r-mode instability region smaller for models with larger L (increase of ξ & η with L).

- L dependence of ξ & η can be described by simple power laws $\xi=A_\xi L^{B_\xi}$ & $\eta=A_\eta L^{B_\eta}$.

- Constraints on L from LMXB 4U 1608-52: L > 50 if 4U 1608-52 assumed stable with 11.5-12 (11.5-13) km and M=1.4(2) $M_\odot$. Otherwise no constraints.


MERCI!
THANK YOU!
FRAPAR.