Continuous Gravitational Waves and Neutron stars Workshop

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R-modes as probe of Dark matter in neutron stars

(S. Shirke, **S. Ghosh** et al, Journal of Cosmology and Astroparticle Physics(JCAP) 12 (2023), 008)

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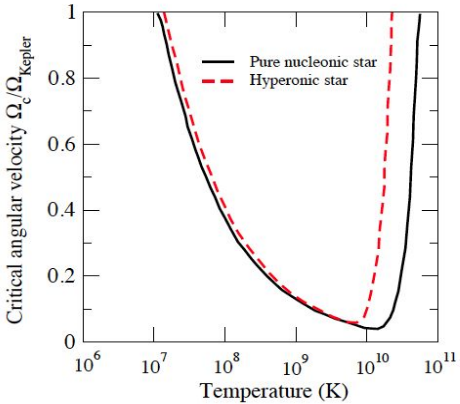
LSC

R-modes as source of CGW

- Toroidal mode of fluid oscillation in neutron stars for which the restoring force is the Coriolis force.
- Unstable in all rotating stars due to the Chandrasekhar- Friedman -Schutz(CFS) mechanism although dissipation mechanisms can damp and saturate the oscillations. Dissipation timescales determine the instability window.
- Spindown of young pulsars, accreting pulsars leading to continuous GW emissions.



R-mode instability window (Chatterjee+ 2006)

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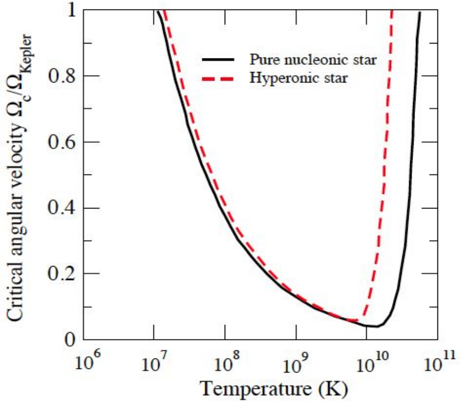
- EOS inference from r-modes - **Ghosh, MNRAS 525, 448-454 (2023)**



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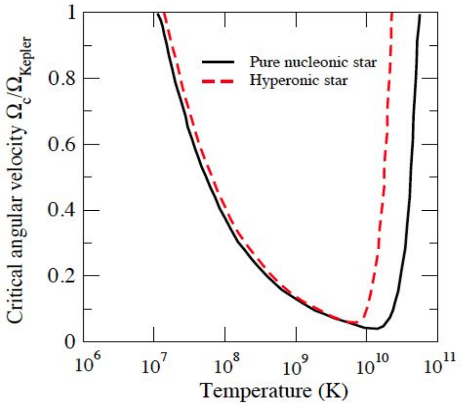

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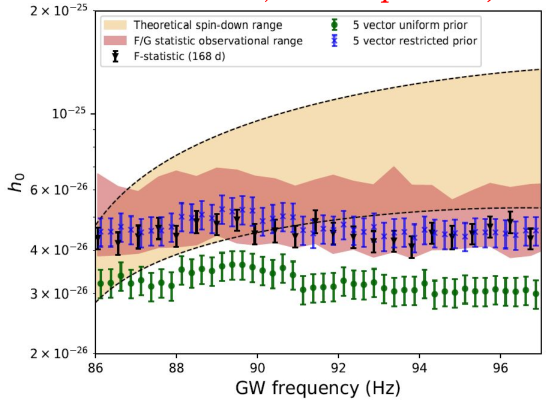
Abbott et al, 2021 *ApJ* **922,** 71

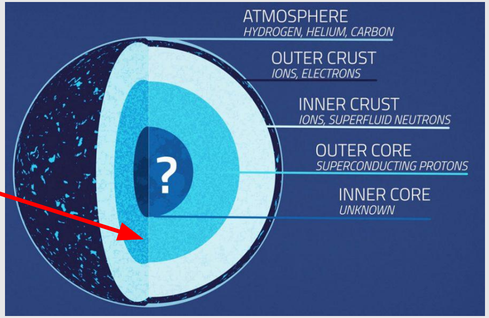


- ➢ GW Searches using LVK data :
  - Crab pulsar (Rajbhandari et al. 2021)
  - PSR J0537-6910 with n ≈ 7 (Fesik & Papa 2020, Abbott et al. 2021)
- ➢ No detection of GW but upper limits on r-mode amplitude were obtained.

Dark matter in Neutron stars

- Dark matter ~ 25% of the Universe.
- Particle nature of dark matter still unknown.

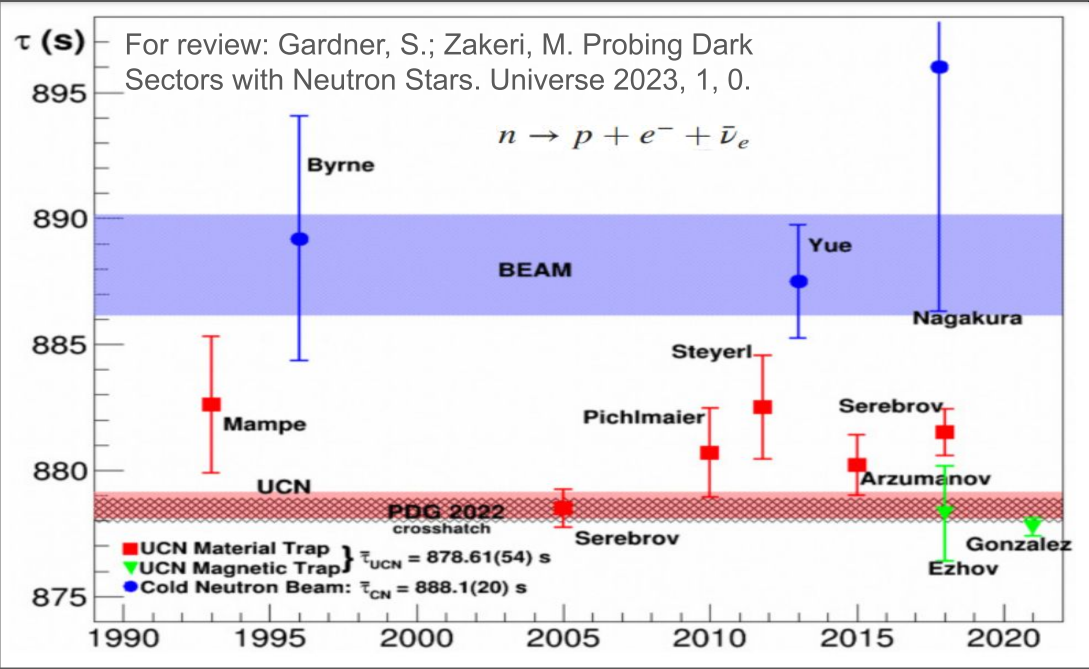
- Possibility of Dark matter-admixed neutron star with a DM core or a DM halo.



- Primary driving mechanisms:
  - Accretion/Capture
  - Particle Decay
  - DM Seed

- Constraints on the dark matter mass and self-interaction from neutron star observations.

Neutron Decay Anomaly

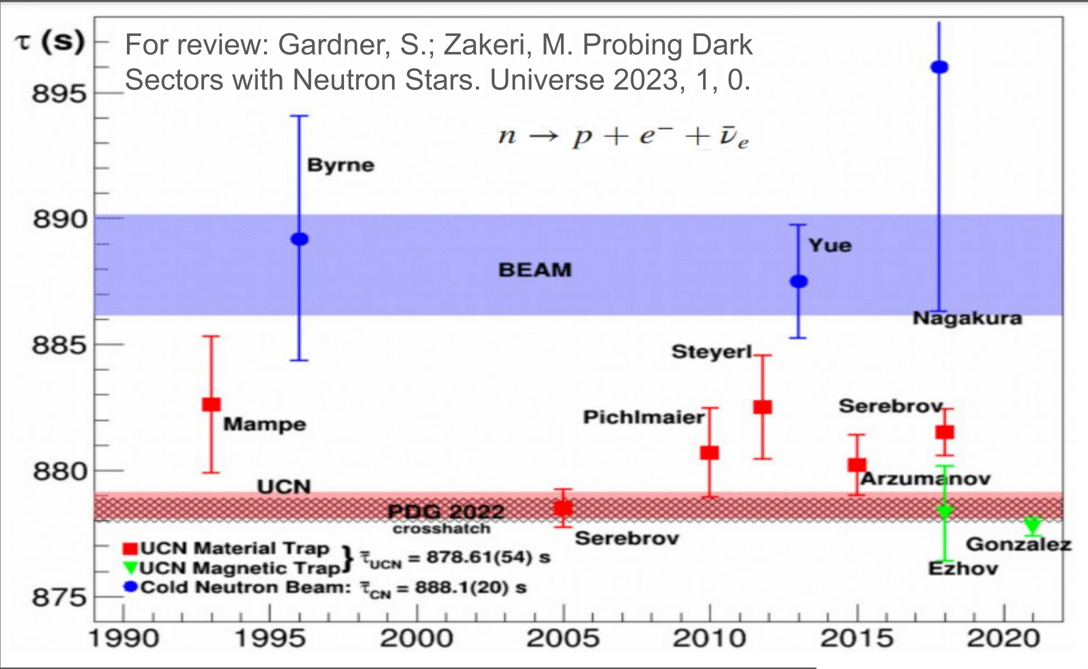


- Neutron lifetime:
  - Bottle/Trap Method
  - Beam Method
- Discrepancy in measured lifetime:

  $\Delta\tau \sim 9.5$ s with 4σ
- Dark decay channel?
- Branching ratio ~ 1%

  i. e. $\Gamma_{dark}/\Gamma_{proton} \approx 1/100$

Neutron Decay Anomaly



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Possibility of a dark decay Channel ?

$$n \to \chi + \phi$$

PHYSICAL REVIEW LETTERS **120,** 191801 (2018)

Editors' Suggestion Featured in Physics

Dark Matter Interpretation of the Neutron Decay Anomaly

Bartosz Fornal and Benjamín Grinstein
Department of Physics, University of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093, USA

EOS model description

- **Hadronic Matter:** Relativistic Mean-Field Model (RMF)

$$\mathcal{L}_{int} = \sum_N \bar{\psi}_N \left[\boxed{g_\sigma}\sigma - \boxed{g_\omega}\gamma^\mu\omega_\mu - \boxed{\frac{g_\rho}{2}}\gamma^\mu \boldsymbol{\tau}\cdot\boldsymbol{\rho}_\mu\right]\psi_N - \frac{1}{3}\boxed{b}m_N(g_\sigma\sigma)^3 - \frac{1}{4}\boxed{c}(g_\sigma\sigma)^4$$

$$+ \boxed{\Lambda_\omega}(g_\rho^2\boldsymbol{\rho}^{\boldsymbol{\mu}}\cdot\boldsymbol{\rho}_{\boldsymbol{\mu}})(g_\omega^2\omega^\nu\omega_\nu) + \frac{\overset{=0}{\zeta}}{4!}(g_\omega^2\omega^\mu\omega_\mu)^2$$

Parameters:

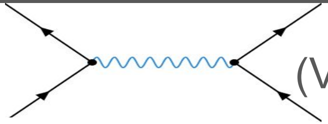
$\{n_{sat}, E_{sat}, K_{sat}, E_{sym}, L_{sym}, m^*/m\}$

Model	n_{sat} (fm^{-3})	E_{sat} (MeV)	K_{sat} (MeV)	E_{sym} (MeV)	L_{sym} (MeV)	m^*/m
HTZCS [86]	0.15	-16.0	240	31	50	0.65
Stiffest [7]	0.145	-15.966	238.074	31.080	56.483	0.550

[86] Hornick et al., PRC 98 (2018) [7] Ghosh, D. C., Schaffner-Bielich, EPJA 58 (2022)

- **Dark Matter:** Self-interacting fermionic DM in chemical equilibrium

$$n \rightarrow \chi + \phi$$



(Vector repulsion)

$$\mu_\chi = \mu_n$$

$$\mathcal{L} \supset -g_V\bar{\chi}\gamma^\mu\chi V_\mu - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu$$

$$\mu_\chi = \sqrt{k_{F_\chi}^2 + m_\chi^2} + Gn_\chi$$

$$\epsilon_{DM} = \frac{1}{\pi^2}\int_0^{k_{F_\chi}} k^2\sqrt{k^2 + \underset{938\ \mathrm{MeV}=}{m_\chi^2}}\,dk + \boxed{\frac{1}{2}Gn_\chi^2}$$

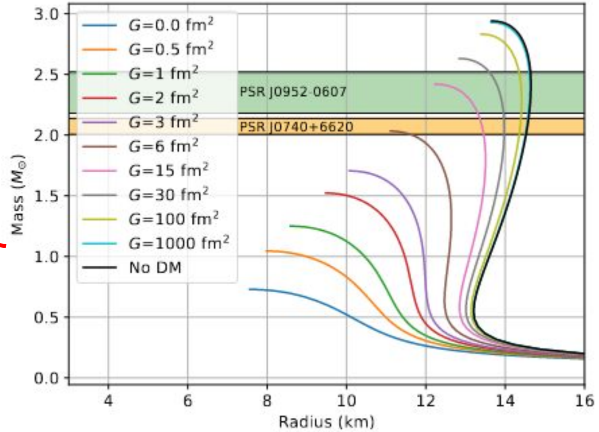
$$\boxed{G = \left(\frac{g_V}{m_V}\right)^2}$$

$$n_\chi = \frac{k_{F_\chi}^3}{3\pi^2}$$

Cross Section and Shear Viscosity

➢ Constraints on the self-interaction strength(G) from multi-messenger observations.

$$G > 5.6\ \mathrm{fm}^2$$



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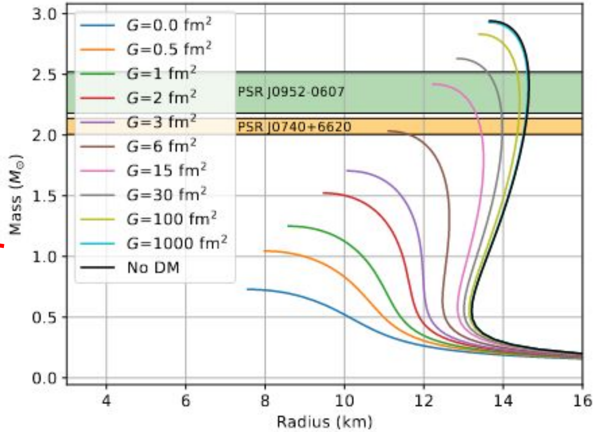
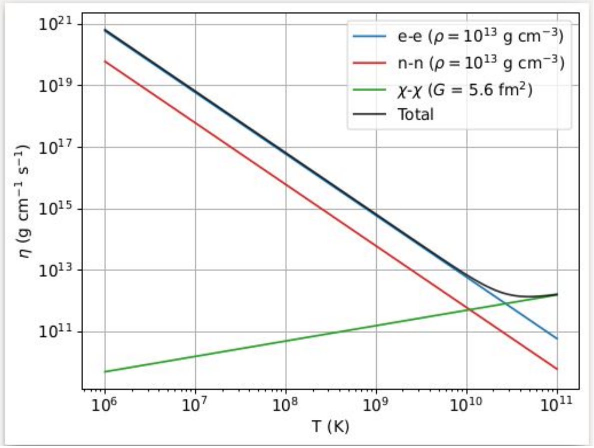


➢ Shear viscosity from the kinetic theory -

$$\eta_\chi \approx \frac{\sqrt{m_\chi kT}}{\sigma_\chi}$$

➢ Negligible compared to the canonical shear viscosity .

➢ Ongoing microscopic calculation for shear viscosity from DM.(Shirke et al., To be published)



Shirke, Ghosh et al, JCAP 12 (2023) 008

Bulk viscosity and the reaction timescale

- Bulk viscosity depends on the relaxation timescale of the reaction.

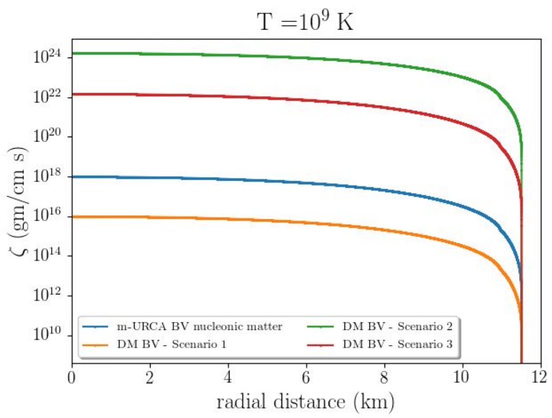
$$\zeta = P(\gamma_\infty - \gamma_0)\frac{\boxed{\tau}}{1+(\omega\tau)^2}$$

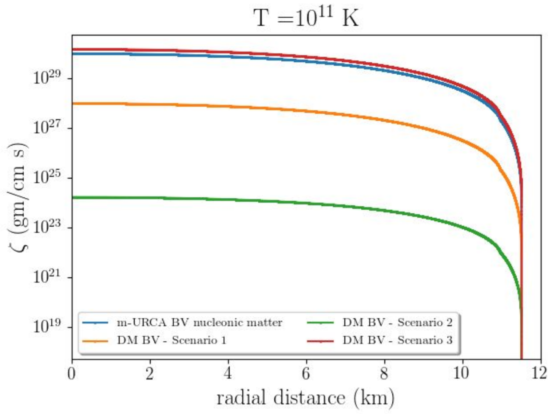
Experimental constraints : $\Gamma_{\text{dark}}/\Gamma_{\text{proton}} \approx 1/100$

Dark sector Process: $n \leftrightarrow \chi + \varphi$

1. Modified URCA Process : $n + N \to p + e^- + \bar{\nu}_e + N$
   $p + e^- + N \to n + \nu_e + N$
2. Constant timescale : **$\tau = 8.88\times10^4$ sec**
3. Direct URCA process: $n \to p + e^- + \bar{\nu}_e$
   $p + e^- \to n + \nu_e$

- Two free parameters: G and τ
- Negligible effect of G





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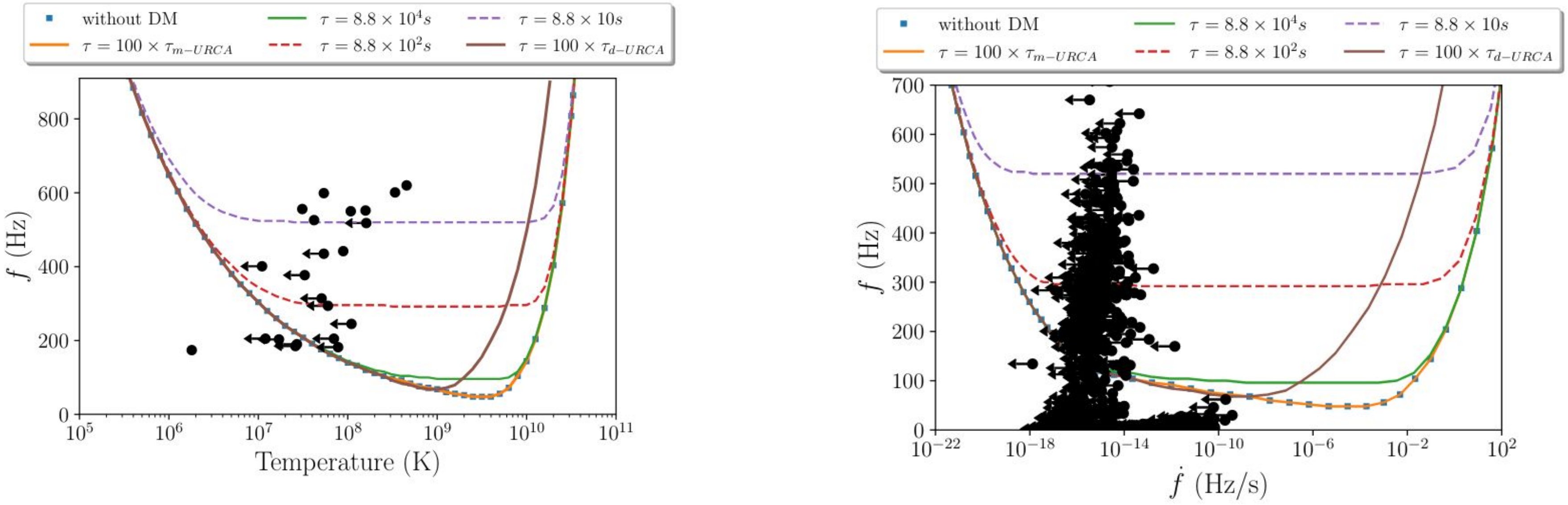
R-mode instability window

- Boundary obtained by matching the dissipation and GW emission timescales.

$$\boxed{\frac{1}{\tau(\Omega_c)} = \frac{1}{\tau_{GW}(\Omega_c, T)} + \frac{1}{\tau_{SV}(\Omega_c, T)} + \frac{1}{\tau_{BV}(\Omega_c, T)} = 0}$$

- $\boxed{f\text{-}T \longrightarrow f\text{ - }\dot{f}\ \textit{boundary}}$ - assuming that the power-loss due to the spin-down driven by r-mode instability is equal to the luminosity (both neutrino and photon luminosity) of the star.



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Summary

- First investigation of the effect of DM on r-modes of NSs and instability window
- Hadronic model: RMF; DM model: Neutron Decay Anomaly
- Constraints: CEFT, Multi-messenger astrophysics
- $G > 5.6\ \mathrm{fm}^2$ & $f_{DM} < 37.9\%$; $f_{DM} < 13.7\%$ for $\sigma/m > 0.1\ \mathrm{cm}^2/\mathrm{g}$

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- DM SV negligible for $T < 10^{10}$ K
- Negligible effect of G on r-mode instability window
- DM BV significant in cases when $\tau_{DM} = 100 \times \tau_{d\text{-}Urca}$ and τ=constant
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- Future: Possible for any other DM model?
Microscopic calculation for SV?