Investigating the effect of dark matter component on neutron star equation of state using GW170817 observation

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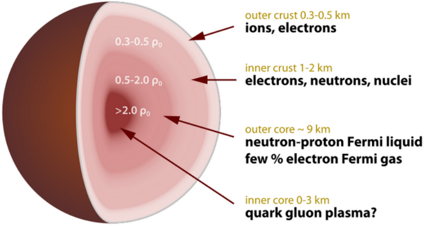
Motivation

- Neutron stars (NS) are nature's laboratory that can shed light on the different branches of physics [1].



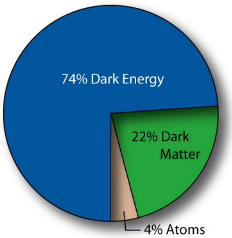
1. The outward pressure of the matter inside.
2. The inward gravitational collapse.
3. Tolman-Oppenheimer-Volkoff (TOV) equation → Neutron star mass-radius relationship → Neutron star EoS.

- GW observation from a merging binary NS, GW170817 data opens up a new way to understand the neutron star structure and the underlying EoS of dense matter.
- For neutron star binary merger the tidal field of the companion induces a quadrupole moment to the other neutron star → tidal deformability (EoS sensitive).

[1] https://www.universetoday.com/140036/inside-the-crust-of-neutron-stars-theres-nuclear-pasta-the-hardest-known-substance-in-the-universe/

Dark matter inside neutron star

- Energy budget of the Universe [2]:



1. Dark matter accretion inside neutron stars. I. Goldman and S. Nussinov, Phys. Rev. D 40, 3221 (1989).
2. DM capture inside stars due to energy loss by scattering- C. Kouvaris, P. Tinyakov, Phys.Rev. D82, 063531 (2010).
3. Dark matter can be present during the formation processes of astrophysical objects.

- Dark-matter admixed neutron stars (DANSs) have been investigated extensively.
- Effects of bosonic as well as fermionic dark matter have been considered.
- C. Kouvaris, P. Tinyakov, Phys.Rev. D82, 063531 (2010), P. Ciarcellut, F. Sandin, Phys. Lett. B 695, 19 (2011), G. Panotopoulos, I. Lopes, Phys.Rev. D96, 083004 (2017), J. Ellis, G. Hutsi,K. Kannike,L. Marzola,M. Raidal, V. Vaskonen, Phys.Rev. D97, 123007 (2018), D. R. Karkevandi, S. Shakeri, V. Sagun, O. Ivanytskyi, Phys.Rev.D 105 (2022) 2, 023001 .....

[2] https://map.gsfc.nasa.gov/media/060916/index.html

Dark Matter-normal matter interaction

- Interaction between the normal matter and dark matter: (a) Only gravitational interaction (b) non-gravitational interaction.
- Only gravitational interaction: two-fluid picture $\rightarrow$ different EoS of dark matter and normal matter [3].

$$\frac{dP_{DM}}{dr} = -(P_{DM} + \varepsilon_{DM})\frac{4\pi r^3(P_{DM} + P_{NM}) + m(r)}{r(r - 2m(r))}, \tag{1}$$

$$\frac{dP_{NM}}{dr} = -(P_{NM} + \varepsilon_{NM})\frac{4\pi r^3(P_{DM} + P_{NM}) + m(r)}{r(r - 2m(r))}, \tag{2}$$

$$\frac{dm(r)}{dr} = 4\pi(\varepsilon_{DM}(r) + \varepsilon_{NM}(r))r^2. \tag{3}$$

- Non-gravitational interaction: single fluid picture with an EoS including the effect of dark matter component.

[3] for details see A. Das, T. Malik, A. C. Nayak, arXiv:2011.01318; Qian-Fei Xiang, Wei-Zhou Jiang,Dong-Rui Zhang, and Rong-Yao Yang, Phys.Rev. C89, 025803 (2014), etc.

Single fluid picture: Dark matter with uniform density

- Nuclear matter (Walecka Model with NL3 parametrization)[4]:

$$\mathcal{L} = \bar{\psi}\Big[\gamma^{\mu}\left(i\partial_{\mu} - g_v V_{\mu} - g_{\rho}\vec{\tau}.\vec{b_{\mu}}\right) - (M_n + g_s\phi)\Big]\psi + \frac{1}{2}\partial_{\mu}\phi\partial^{\mu}\phi$$
$$- \frac{1}{2}m_s^2\phi^2 - \frac{1}{3}g_2\phi^3 - \frac{1}{4}g_3\phi^4 - \frac{1}{4}V^{\mu\nu}V_{\mu\nu} + \frac{1}{2}m_V^2V^{\mu}V_{\mu}$$
$$- \frac{1}{4}\vec{b^{\mu\nu}}.\vec{b_{\mu\nu}} + \frac{1}{2}m_{\rho}^2\vec{b^{\mu}}\vec{b_{\mu}}. \tag{4}$$

- Dark matter (Higgs portal interaction)[5]:

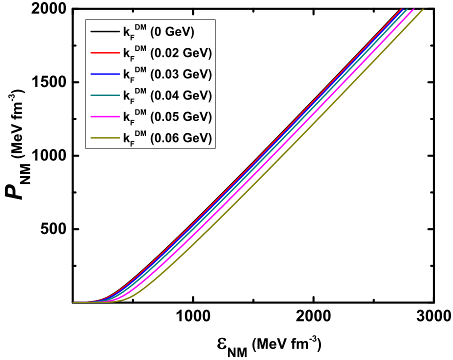
$$\mathcal{L}_{DM} = \bar{\chi}\Big[i\gamma^{\mu}\partial_{\mu} - M_{\chi} + yh\Big]\chi + \frac{1}{2}\partial_{\mu}h\partial^{\mu}h - \frac{1}{2}M_h^2h^2 + f\frac{M_n}{v}\bar{\psi}h\psi. \tag{5}$$

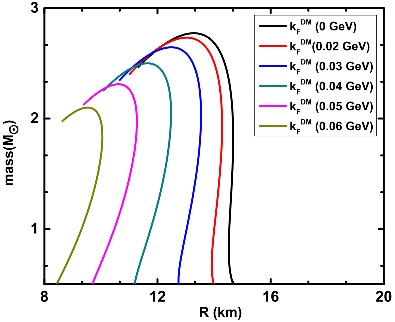
- We consider dark matter mass $M_{\chi} = 200GeV$.
- We consider the the value of $y = 0.07$.[6]

[4] G. A. Lalazissis, J. Konig and P. Ring, Phys. Rev. **C55**, 540 (1997)
[5] G. Panotopoulos, I. Lopes, Phys.Rev. D96, 083004 (2017)
[6] G. Panotopoulos and I. Lopes, Phys. Rev. D 96, 083004 (2017); S. P. Martin, Adv. Ser. Dir. High Energy Phys. 21, 1 (2010).

EoS and M-R plot

- We consider: $n_B = 10^3 n_{DM}$; $n_B = 0.16\ \text{fm}^{-3}$.
- $n_{DM} = (k_F^{DM})^3/(3\pi^2) \implies k_F^{DM} \sim 0.033$ GeV.
- We consider: $0.02\ \text{GeV} \leq k_F^{DM} \leq 0.06\ \text{GeV}$[7].





- Conclusion 1: With an increase in dark matter component EoS becomes softer.
- Conclusion 2: Dark matter component decreases maximum mass.

[7] A. Das, T. Malik, A. C. Nayak, Phys.Rev.D 99 (2019) 4, 043016

Tidal Deformability

- The tidal deformability describes the degree of deformation of NS due to the tidal field: $\lambda = \frac{2}{3}k_2R^5$, $\Lambda = \frac{2}{3}k_2C^{-5}$.

$$k_2 = \frac{8C^5}{5}(1-2C)^2\left[2+2C(y_R-1)-y_R\right] \times \Big\{2C\left(6-3y_R+3C(5y_R-8)\right) + 4C^3\left[13-11y_R+C(3y_R-2)+2C^2(1+y_R)\right] + 3(1-2C)^2\left[2-y_R+2C(y_R-1)\right]\log(1-2C)\Big\}^{-1};\ \ C = M/R;\ \ y_R = y(R) \tag{6}$$

- The quantity y can be obtained by solving the following differential equation,

$$r\frac{dy(r)}{dr} + y(r)^2 + y(r)F(r) + r^2Q(r) = 0. \tag{7}$$

- The dimensionless variable $y \equiv \frac{rH'}{H}$. $H(r)$ encodes tidal perturbation [8, 9].

[8] T. Hinderer, Astrophys. J. 677, 1216 (2008);

[9] T. Hinderer, B. D. Lackey, R. N. Lang, and J. S. Read, Phys. Rev. D 81, 123016 (2010).

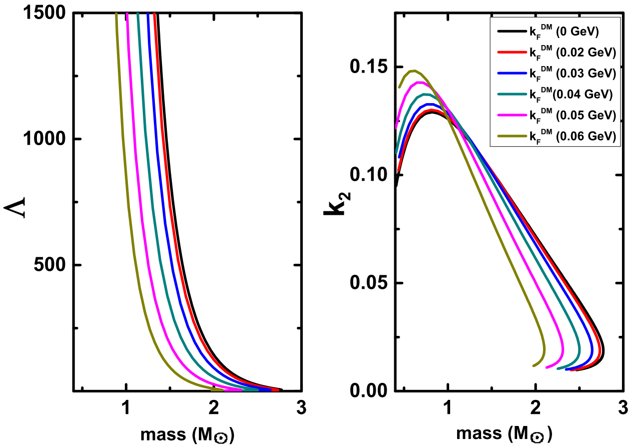
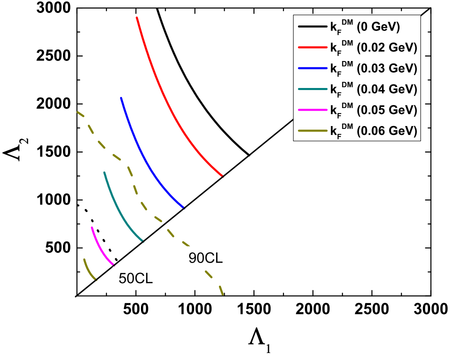


Figure: Dimensionless tidal deformability (Λ) of NS and Love number(k_2) as a function of neutron star mass for different dark matter Fermi momentum is shown.



- Effective dimensionless tidal deformability of the binary merger [10]:

$$\tilde{\Lambda} = \frac{16}{13} \frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5}; \tag{8}$$

- Chirp mass: $\mathcal{M}_c = (m_1 m_2)^{3/5}(m_1 + m_2)^{-1/5}$.
- Conclusion 3: In the presence of dark matter components stiff EoS can evade GW constraints.

[10] B. P. Abbott et al., Phys. Rev. Lett. 121, 161101 (2018)

Conclusion and future work

- We have confronted the neutron star EoS in the presence of a dark matter component using the gravitational wave constraint from the binary star merger.
- For a uniformly distributed dark matter inside a neutron star, the EoS becomes softer which eventually produces lower NS mass with increasing dark matter density.
- In the presence of dark matter, some EoS can satisfy gravitational wave bound which are otherwise excluded.
- These results can be model-dependent so one needs a model-independent way to describe the effect of dark matter.
- A possible degeneracy in results: (a) EoS, (b) theory of gravity.
- We should look for observable which may break such degeneracy.

Thank You!

- Energy-density including DM:

$$\varepsilon = g_v V_0(\rho_p + \rho_n) + g_\rho b_0(\rho_p - \rho_n) + \frac{1}{\pi^2}\int_0^{k_p} dk k^2\sqrt{k^2 + (M_n^\star)^2}$$
$$+\frac{1}{\pi^2}\int_0^{k_n} dk k^2\sqrt{k^2 + (M_n^\star)^2} + \frac{1}{\pi^2}\int_0^{k_F^{DM}} dk k^2\sqrt{k^2 + (M_\chi^\star)^2}$$
$$+\frac{1}{2}m_s^2\phi_0^2 + \frac{1}{3}g_2\phi_0^3 + \frac{1}{4}g_3\phi_0^4 - \frac{1}{2}m_V^2 V_0^2 - \frac{1}{2}m_\rho^2 b_0^2 + \frac{1}{2}M_h h_0^2. \tag{9}$$

- Pressure including DM:

$$P = \frac{1}{3\pi^2}\int_0^{k_p}\frac{k^4 dk}{\sqrt{k^2 + (M_n^\star)^2}} + \frac{1}{3\pi^2}\int_0^{k_n}\frac{k^4 dk}{\sqrt{k^2 + (M_n^\star)^2}}$$
$$+\frac{1}{3\pi^2}\int_0^{k_F^{DM}}\frac{k^4 dk}{\sqrt{k^2 + (M_\chi^\star)^2}}$$
$$-\frac{1}{2}m_s^2\phi_0^2 - \frac{1}{3}g_2\phi_0^3 - \frac{1}{4}g_3\phi_0^4 + \frac{1}{2}m_V^2 V_0^2 + \frac{1}{2}m_\rho^2 b_0^2 - \frac{1}{2}M_h h_0^2, \tag{10}$$

Effective mass:

$$M_n^\star = M_n + g_s\phi_0 - \frac{fM_n}{v} h_0, \tag{11}$$
$$M_\chi^\star = M_\chi - yh_0. \tag{12}$$

The baryon density (ρ), scalar density (ρ_s) and dark matter scalar density (ρ_s^{DM}) are

$$\begin{aligned} \rho &= \langle\psi^\dagger\psi\rangle = \tfrac{\gamma}{(2\pi)^3} \int_0^{k_F} d^3k, \\ \rho_s &= \langle\bar{\psi}\psi\rangle = \tfrac{\gamma}{(2\pi)^3} \int_0^{k_F} \tfrac{M_n^\star}{\sqrt{M_n^{\star\,2}+k^2}} d^3k, \\ \rho_s^{\mathrm{DM}} &= \langle\bar{\chi}\chi\rangle = \tfrac{\gamma}{(2\pi)^3} \int_0^{k_F^{\mathrm{DM}}} \tfrac{M_\chi^\star}{\sqrt{M_\chi^{\star\,2}+k^2}} d^3k, \end{aligned} \tag{13}$$

$$r\frac{dy(r)}{dr}+y(r)^2+y(r)F(r)+r^2Q(r)=0, \tag{14}$$

with,

$$F(r)=\frac{r-4\pi r^3\left((\varepsilon(r))-(P(r)\right)}{r-2m(r)},$$

and

$$Q(r)=\frac{4\pi r\left(5\varepsilon(r)+9P(r)+\frac{\varepsilon(r)+P(r)}{\partial P(r)/\partial\varepsilon(r)}-\frac{6}{4\pi r^2}\right)}{r-2m(r)}-4\left[\frac{m(r)+4\pi r^3P(r)}{r^2\left(1-2m(r)/r\right)}\right]^2,$$

NL3 parameter set

- $M_n = 939$ MeV, $m_s = 782.501$ MeV, $m_\rho = 763$ MeV, $g_s = 10.217$, $g_v = 12.868$, $g_\rho = 4.474$, $g_2 = -10.431$ fm^{-1}, $g_3 = -28.885$.
- Charge radii, binding energies, neutron radii of spherical nuclei.
- Nuclear matter properties: binding energy per nucleon, nuclear saturation density, asymmetry energy, incompressibility.

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TABLE I. The total binding energies charge radii, and neutron radii used in the fit (values in parentheses) together with the NL3 predictions.

Nucleus	BE (MeV)	r_{ch} (fm)	r_n (fm)
^{16}O	−128.83 (−127.62)	2.730 (2.730)	2.580
^{40}Ca	−342.02 (−342.06)	3.469 (3.450)	3.328 (3.370)
^{48}Ca	−415.15 (−416.00)	3.47 0 (3.451)	3.603 (3.625)
^{58}Ni	−503.15 (−506.50)	3.740 (3.769)	3.740 (3.700)
^{90}Zr	−782.63 (−783.90)	4.287 (4.258)	4.306 (4.289)
^{116}Sn	−987.67 (−988.69)	4.611 (4.627)	4.735 (4.692)
^{124}Sn	−1050.18 (−1049.97)	4.661 (4.677)	4.900 (4.851)
^{132}Sn	−1105.44 (−1102.90)	4.709	4.985
^{208}Pb	−1639.54 (−1636.47)	5.520 (5.503)	5.741 (5.593)
^{214}Pb	−1661.62 (−1663.30)	5.581 (5.558)	5.855

nuclei, used for NL1 the doubly closed shell nucleus ^{132}Sn as well as the heavier lead isotope ^{214}Pb were also included in the fit. The experimental values for the total binding energies were taken from the experimental mass tables [16], the charge radii from Ref. [17]. The available neutron radii are

TABLE II. Parameters of the Lagrangian NL3, NL3-II, NL1, and NL-SH together with the nuclear matter properties obtained with these effective forces.

	NL3	NL3-II	NL1	NL-SH
M (MeV)	939	939	938	939
m_σ (MeV)	508.194	507.680	492.250	526.059
m_ω (MeV)	782.501	781.869	783.000	783.000
m_ρ (MeV)	763.000	763.000	763.000	763.000
g_σ	10.217	10.202	10.138	10.4444
g_ω	12.868	12.854	13.285	12.945
g_ρ	4.474	4.480	4.976	4.383
g_2 (fm^{-1})	−10.431	−10.391	−12.172	−6.9099
g_3	−28.885	−28.939	−36.265	−15.8337
Nuclear matter properties				
ρ_0 (fm^{-3})	0.148	0.149	0.153	0.146
$(E/A)_\infty$ (MeV)	16.299	16.280	16.488	16.346
K (MeV)	271.76	272.15	211.29	355.36
J (MeV)	37.4	37.7	43.7	36.1
m^*/m	0.60	0.59	0.57	0.60

- To study the tidal deformability one studies evolution on metric perturbations [11, 12].

$$g_{\mu\nu} = g^{(0)}_{\mu\nu} + h_{\mu\nu}, \tag{15}$$

$$g^{(0)}_{\mu\nu} = \mathrm{diag}\left(-e^{\alpha(r)}, e^{\beta(r)}, r^2, r^2\sin^2\theta\right), \tag{16}$$

- In general relativity gauge choices or coordinate transformation in very crucial for the proper representation of perturbation.
- In the Regge-Wheeler gauge,

$$h_{\mu\nu} = \mathrm{diag}\Big(- e^{\alpha(r)} H(r) \mathrm{Y}_{20}(\theta,\phi), -e^{\beta(r)} H(r)\mathrm{Y}_{20}(\theta,\phi), r^2 K(r)\mathrm{Y}_{20}(\theta,\phi), r^2\sin^2\theta K(r)\mathrm{Y}_{20}(\theta,\phi)\Big), \tag{17}$$

- Using the Einstein equation we can obtain the evolution equation for $H(r)$ and $K(r)$. However evolution of $H(r)$ and $K(r)$ are not independent.
- The dimensionless variable $y \equiv \frac{rH'}{H}$.

[11] T. Hinderer, Astrophys. J. 677, 1216 (2008);

[12] T. Hinderer, B. D. Lackey, R. N. Lang, and J. S. Read, Phys. Rev. D 81, 123016 (2010).