Impact of asymmetric bosonic dark matter on neutron star properties

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GW170817: the first NS-NS merger

- Typical inspiral pattern

$$\begin{cases} M_{\rm tot} = 2.84^{+0.47}_{-0.09}\mathrm{M}_\odot \\ \mathcal{M} = 1.188^{+0.04}_{-0.02}\mathrm{M}_\odot \end{cases} \tag{1}$$

- Kilonova-associated
- Tidal deformability parameter extraction;

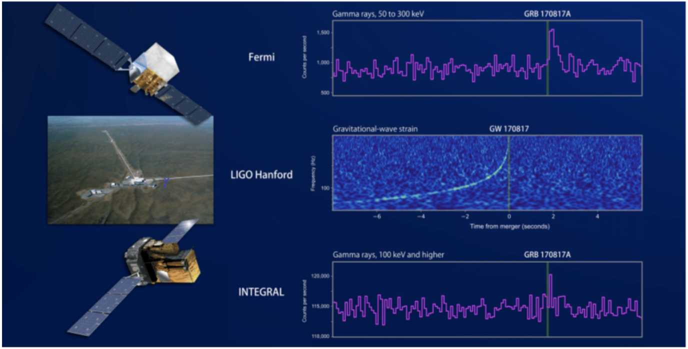


Figure 1: GW170817 and its γ counterpart signals. [LIGO/Virgo Collab 2017]]

Tidal disruption: a new constraints

- Tidal deformability parameter can be written as:

$$\Lambda = \frac{2}{3} k_2 \left(\frac{R_{\mathrm{out}}}{GM} \right)^5 \tag{2}$$

being $k_2 = k_2(\beta, R)$ the Love's number, R_{out} the outer-most radius and M the total mass.

- Masses extracted by the GW signal;
- Constraints on Λ, R as:

$$\begin{cases} \Lambda(1.4\mathrm{M}_\odot) \leq 800 \\ R(1.4\mathrm{M}_\odot) = 11.89^{+2.7}_{-3.3}\mathrm{km} \end{cases} \tag{3}$$

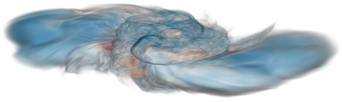


Figure 2: Last time-steps before the merger phase.

[Radice et al., ApJ 869:130 (2018)]

An insight on the NS interior

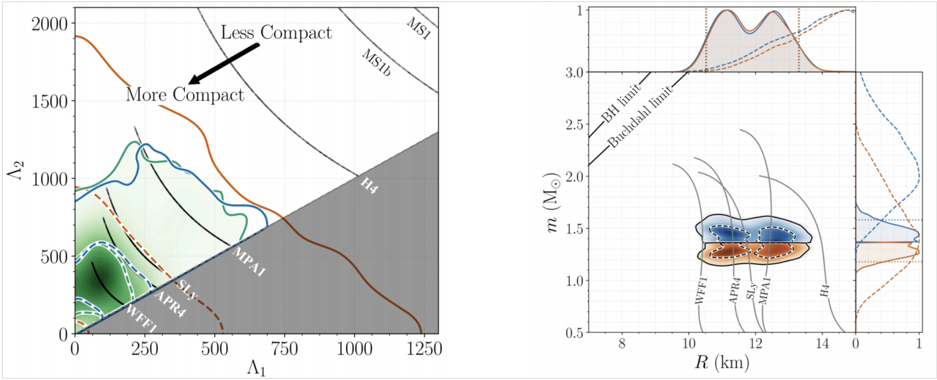


Figure 3: *(Left)* Λ-Constraints on the two NSs of GW170817, *(Right)* Constraints derived from the same event on the Equation of State.

LIGO-Virgo Collaboration Phys. Rev. X 9, 011001 (2019)

Dark matter distribution

- Light dark matter (DM) particles ($m_\chi \simeq 100$ MeV) tend to create diluted halo structures inside the Neutron Star (NS);
- Heavier DM particles ($m_\chi \gtrsim 1$ GeV) form compact cores.

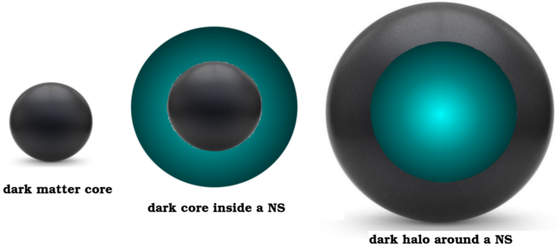


Figure 4: Different configurations of DM structures in compact objects.

V. Sagun et al. arXiv:2111.13289 [astro-ph.HE]

TOV equations

2 TOV equations:

$$\frac{dp_B}{dr} = -\frac{(\epsilon_B + p_B)(M + 4\pi r^3 p)}{r^2\,(1 - 2M/r)}$$

$$\frac{dp_D}{dr} = -\frac{(\epsilon_D + p_D)(M + 4\pi r^3 p)}{r^2\,(1 - 2M/r)}$$

BM and DM are coupled only through gravity, and their energy-momentum tensors are conserved separately

total pressure $p(r) = p_B(r) + p_D(r)$

gravitational mass $M(r) = M_B(r) + M_D(r)$, where $M_j(r) = 4\pi \int\limits_0^r \epsilon_j(r')r'^2 dr'$ (j=B,D)

Fraction of DM inside the star:

$$f_\chi = \frac{M_D(R_D)}{M_T}$$

$M_T = M_B(R_B) + M_D(R_D)$ - total gravitational mass

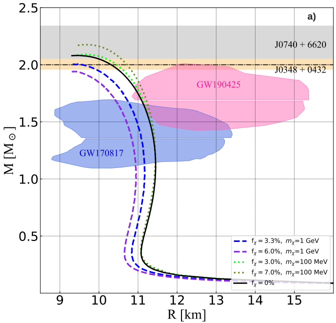
O. Ivanytskyi, et al. PRD 102, 063028 (2020)

Effect of dark matter

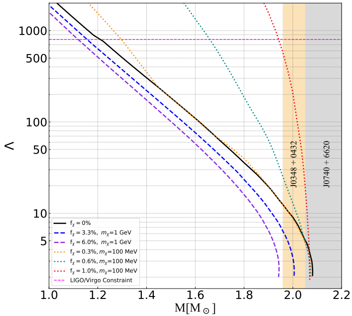
- DM effects mass, radius and, therefore, tidal deformability of NSs

Tidal deformability parameter: $$\Lambda = \frac{2}{3}k_2\left(\frac{R_{out}}{GM}\right)^5 \qquad (4)$$

Mass-Radius diagram



Tidal deformabilities



An example of an impact of fermionic DM on M-R relation and tidal deformability of NSs

V. Sagun, et al. arXiv:2111.13289 [astro-ph.HE]

Bosonic stars

- Considering bosonic DM particles, there's no Fermi pressure and the uncertainty principle is the only one preventing the collapse;
- Once captured, DM particles slow down and tend to thermalize in the core

$$r_{\text{th}} = \left(\frac{9kT_c}{8\pi\rho_c m} \right)^{\frac{1}{2}} \tag{5}$$

$$t_{\text{th}} = 0.2\text{yr} \left(\frac{m}{\text{TeV}} \right)^2 \left(\frac{\sigma}{10^{-43}\text{cm}^2} \right)^{-1} \left(\frac{T}{10^5\text{K}} \right)^{-1} \tag{6}$$

- The bosonic component can become self-gravitating

$$M_{\text{sg}} > \frac{4\pi}{3} \rho_c r_{\text{th}}^3 \tag{7}$$

or form a Bose-Einstein Condensate (BEC).

- When $r_{\text{BEC}} \lesssim r_{\text{sch}}$, a black hole is formed in the inner core.

C. Kouvaris, Adv.High Energy Phys. 2013, 856196 (2013)

Asymmetric Bosonic Dark Matter

The Lagrangian used includes **self-interacting** DM particles as:

$$\mathcal{L} = \frac{1}{2}(D_\mu\varphi)^* D^\mu\varphi - \frac{1}{2}m_\varphi^2\varphi^*\varphi - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} - \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu \tag{8}$$

with $D_\mu\varphi = (\partial_\mu - ig\omega_\mu)\varphi$.
Using a mean field approximation for ω, we recollect after (not so short) calculations an EoS of self-interacting Bose-Einstein condensate:

$$n = \frac{m_I^2}{2}\frac{\mu_\varphi^2 - m_\varphi^2}{\sqrt{2m_\varphi^2 - \mu_\varphi^2}} \tag{9}$$

$$p = \left(\frac{m_I}{2}\right)^2\left[m_\varphi^2 - \mu_\varphi^2\sqrt{2m_\varphi^2 - \mu_\varphi^2}\right] \tag{10}$$

Chemical potential is limited $\mu_\varphi \in [m_\varphi, \sqrt{2}m_\varphi]$, m_φ - boson mass
$m_I = \frac{m_\omega}{g}$ - self-interaction scale

Induced Surface Tension (IST) EoS

$$\begin{cases} p = \sum_i^{all\ particles} [p_{id}(T, \mu_i - pV_i - \Sigma S_i + U_{at} \pm U_{sym}) + p_{id}(\mu_e) - p_{at} + p_{sym}] \\ \Sigma = \sum_i^{all\ particles} p_{id}(T, \mu_i - pV_i - \alpha \Sigma S_i + U_0) R_i \end{cases}$$

p_{id} – pressure of the ideal gas for quantum statistics
V – excluded volume, Σ – induced surface tension
U_0, α – model parameters

- Thermodynamic consistency of the model:

$$\frac{\partial p_{int}}{\partial n_{id}} = n_{id} \tag{11}$$

- Parametrization of the mean field potential:

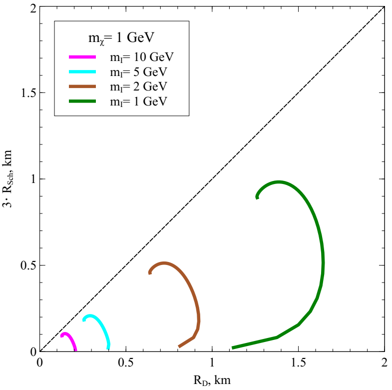
$$U_{at} = -C_d^2 n_{id}^{\kappa} \tag{12}$$

- Symmetry energy pressure:

$$P_{sym}(n) = \frac{A_{sym} n^2}{[1 + (B_{sym} n)^2]^2} \tag{13}$$

VVS, et al., Nucl. Phys. A, 924, 24 (2014)
A. Ivanytskyi et al., PRC 97, 064905 (2018)

Gravitational instability of DM-admixed NS



- consider fixed central densities n_D^c and n_B^c
- solve TOV $\Rightarrow R_D$ and R_B
- vary n_D^c to get new R_D and R_B
- along the curves central density of DM component is varying

Schwarzschild radius is defined as:

$$R_{\mathrm{Sch}} = 2GM \tag{14}$$

To avoid an instability against complete gravitational collapse the star's radius should be of the order of the last stable Kepler orbit $R_{SO} = 3R_{Sch}$ around a BH of Schwarzschild radius.

The radius of the BEC equals to R_D

E. Giangrandi et al., in Prep., (2022)

Summary

- We considered a novel model of self-interacting bosonic DM and tested an effect of particle's mass, coupling constant and DM fraction of compact star properties
- We analyzed conditions of gravitational instability in the core of a star that appears at R_D equal to the last stable Kepler orbit
- We admit a possibility of a DM condensate driven BH formation inside a compact star.

Thank you for attention!