Impact of Bosonic Dark Matter on Neutron Star Structure and X-ray Pulse Profiles

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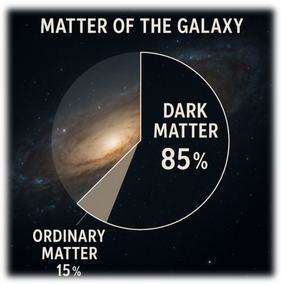
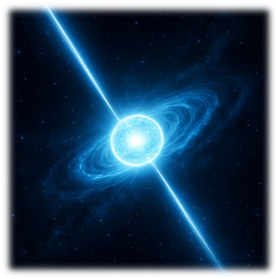
Dark matter effects on neutron stars

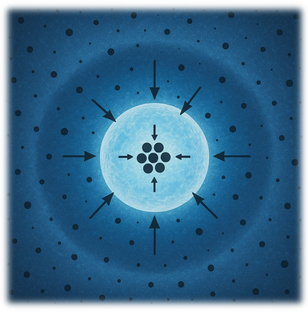
Dark matter (DM)



Neutron star (NS)



Accumulation of DM within NSs



Two Fluid DM admixed NSs

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi(T^{\mu\nu}_{DM} + T^{\mu\nu}_{BM})$$

Energy-momentum tensors are conserved separately for baryonic matter (BM) and DM fluids.

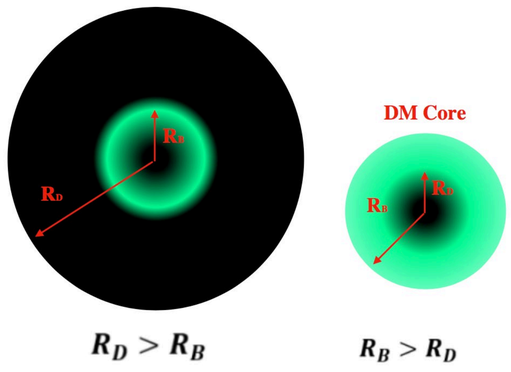
Two-fluid TOV equations

$$\frac{dp_{\rm B}}{dr} = -(p_{\rm B}+\epsilon_{\rm B})\frac{m+4\pi r^3(p_B(r)+p_D(r))}{r(r-2m)},$$

$$\frac{dp_{\rm D}}{dr} = -(p_{\rm D}+\epsilon_{\rm D})\frac{m+4\pi r^3(p_B(r)+p_D(r))}{r(r-2m)},$$

$$\frac{dm}{dr} = 4\pi r^2(\epsilon_B+\epsilon_D), \quad m = m_D(r)+m_B(r)$$

DM distributions in NSs



$R_D > R_B$ $\qquad$ $R_B > R_D$

Total mass $M_T = M_B(R_B) + M_D(R_D)$

DM fraction $F_\chi = M_D(R_D)/M_T$

Bosonic DM

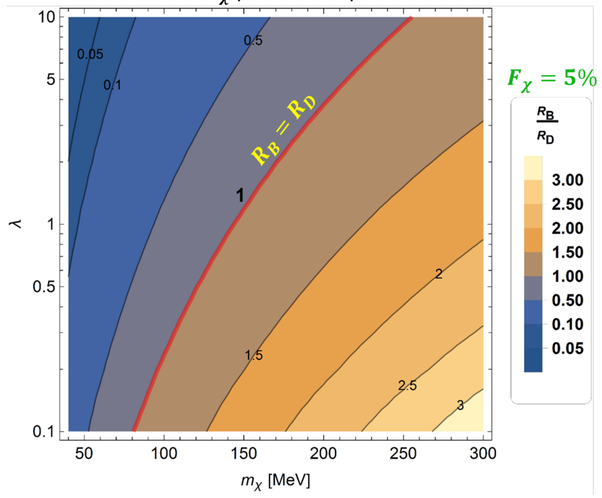
$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi^*\partial^\mu\phi - \frac{m_\chi^2}{2}\phi^*\phi - \frac{\lambda}{4}(\phi^*\phi)^2$$

$$P = \frac{m_\chi^4}{9\lambda}\left(\sqrt{1+\frac{3\lambda}{m_\chi^4}\rho}-1\right)^2$$

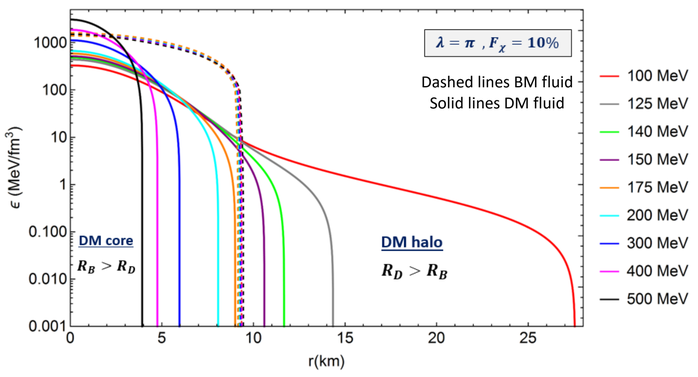
Self-repulsive bosonic DM described by complex scalar field, where λ and m_χ are the coupling constant and mass of bosons, respectively.

For the BM we use DD2 EOS.

DM core to DM halo transition



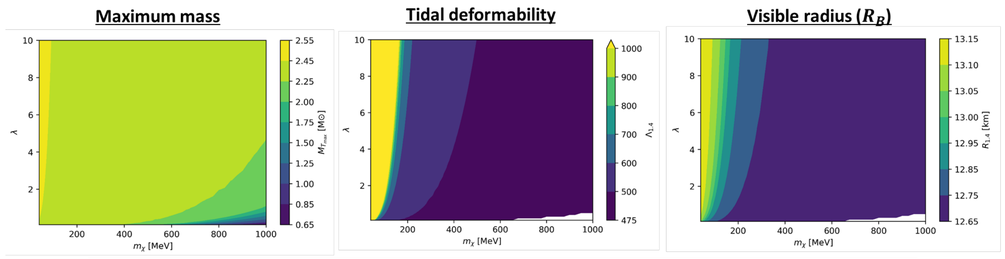
Energy density distribution



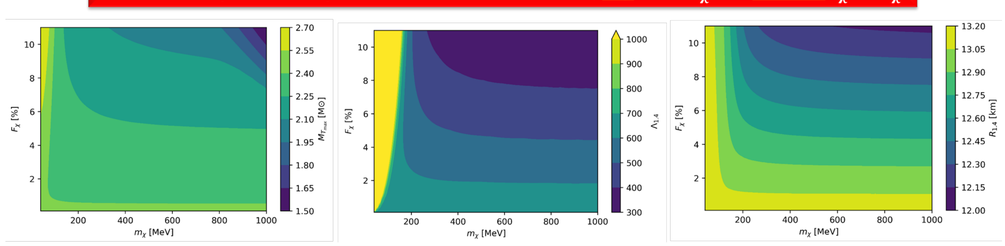
Heavy DM particles mainly reside in the core while light ones form a halo around the NS

Impact of DM on NSs observable features

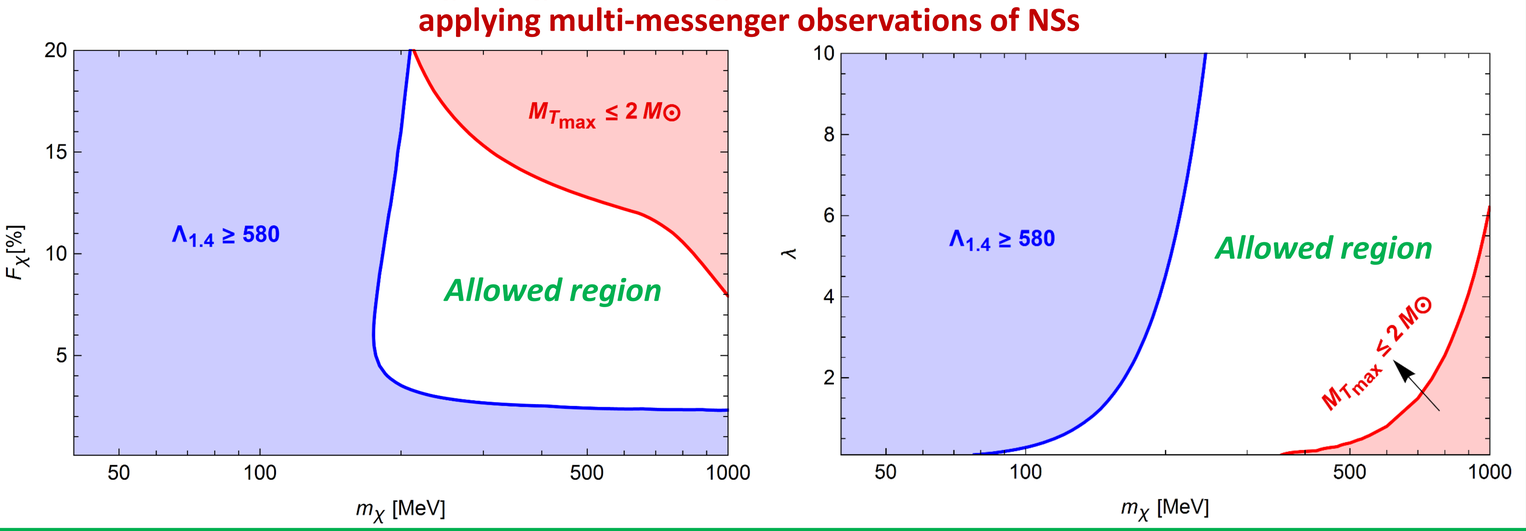
Maximum mass | Tidal deformability | Visible radius (R_B)



Scan over the parameter space of the bosonic DM model, Top: $\lambda - m_\chi$ and Bottom: $F_\chi - m_\chi$

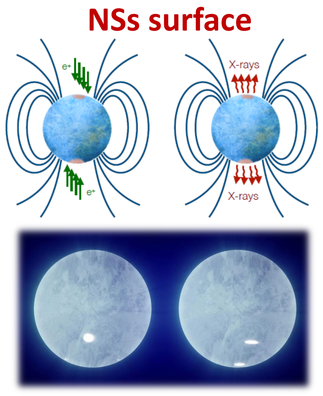


Excluded $F_\chi - m_\chi$ and $\lambda - m_\chi$ parameter spaces of Bosonic DM applying multi-messenger observations of NSs

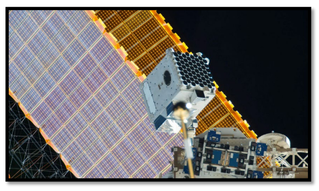


DM effects on X-ray pulse profiles

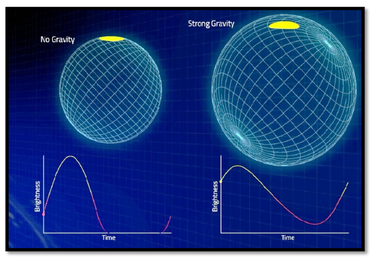
X-ray hot spots on NSs surface



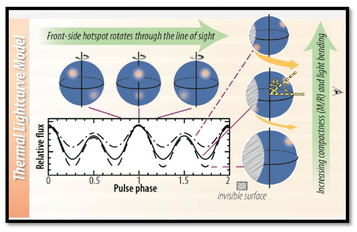
NICER X-ray telescope

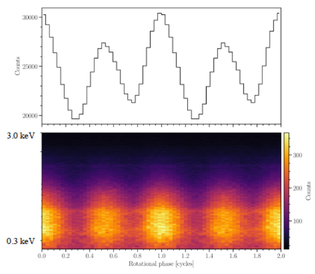


Pulse profile due to the curvature of space-time



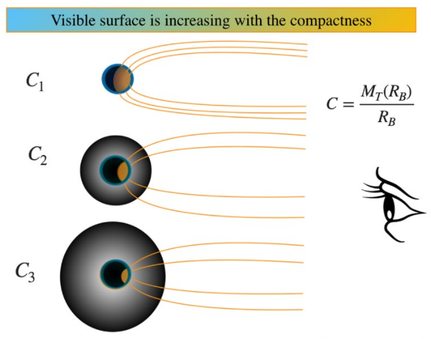
The effect of compactness on the pulse profile





The light propagation will be affected due to the halo of DM

Visible surface is increasing with the compactness



$C = \frac{M_T(R_B)}{R_B}$

$M_T = 1.4M_\odot$ For all cases

$C_1 > C_2 > C3$

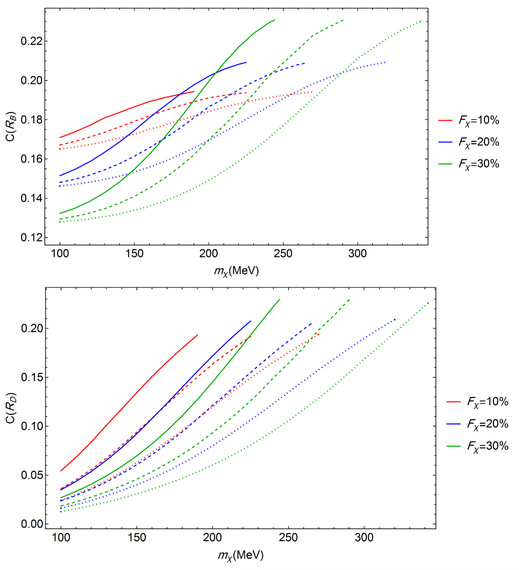
DM halo changes the compactness (C) of the object.

C with respect to DM parameters

$C(R_B) = \frac{M_T(R_B)}{R_B}$

$M_T = 1.4\,M\odot$

$C(R_D) = \frac{M_T(R_D)}{R_D}$

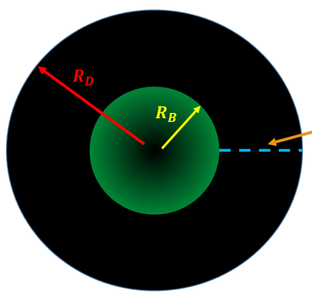


Metric function in the presence of DM halo around neutron stars

We assume a spherically symmetric non-rotating space-time (Schwarzschild metric) outside R_B

$$ds^2 = -g(r)dt^2 + f(r)dr^2 + r^2d\theta^2 + r^2\sin^2\theta d\phi^2$$

The formation of the DM halo around NS can potentially change the geometry outside the surface of NS and also the light propagation characteristics in this region.



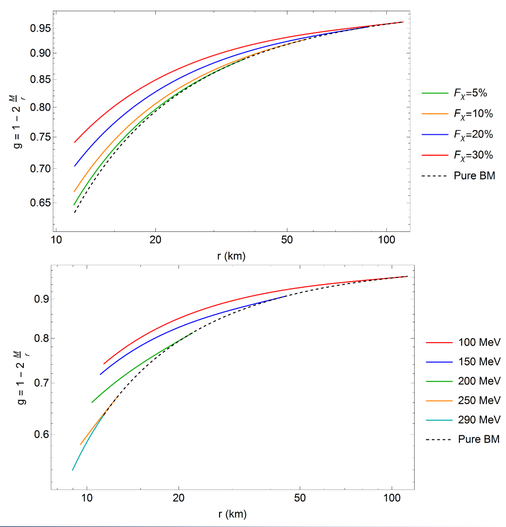
$$g(r) = f(r)^{-1} = 1 - 2M(r)/r$$

The total mass $M(r)$ has two contributions coming from both BM and DM fluids at $r \geq R_B$.

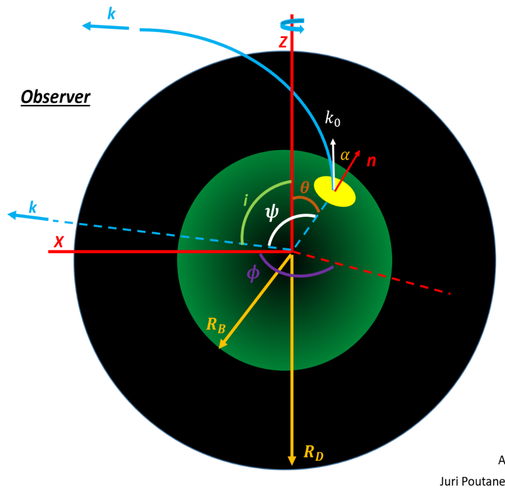
In a NS without DM halo, $M(r \geq R_B)$ is a constant value, the similar situation happens for a DM admixed NS with DM core formation.

We need to determine the metric function $g(r)$ outside the surface of NS taking into account the DM halo contribution

Variation of metric function



Pulse profile modeling and ray tracing in presence of DM halo

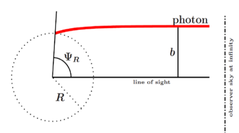


$$\cos\Psi = \cos i\cos\theta + \sin i\sin\theta\cos\phi,$$

$$\mathcal{F} = g(R_B)\delta^5 I'(\alpha')\cos\alpha\frac{d\cos\alpha}{d\cos\Psi}\frac{dS'}{D^2},$$

$$\Psi = \int_{R_B}^{\infty}\frac{dr}{r^2}\left[\frac{1}{b^2} - \frac{g(r)}{r^2}\right]^{-1/2},$$

$$b = R_B\sin\alpha/\sqrt{g(R_B)},$$

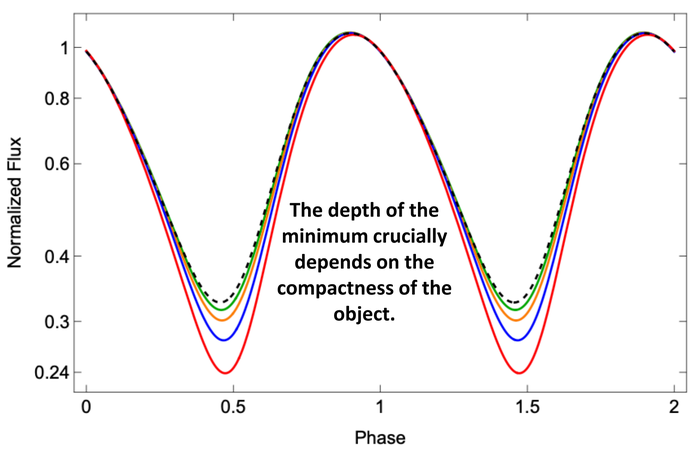


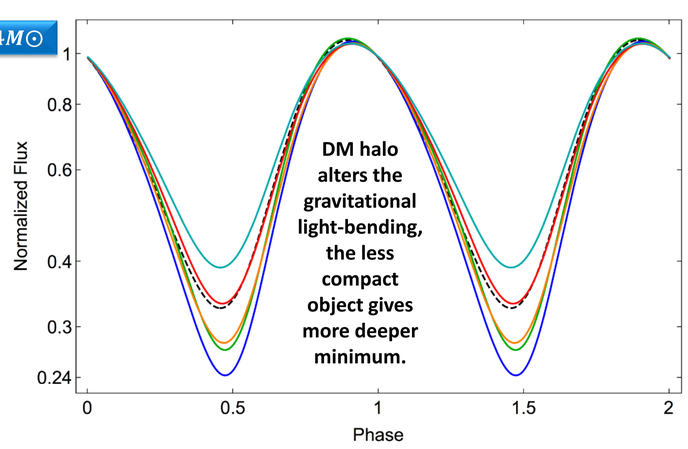
Andrei M. Beloborodov, ***Astrophys.J.Lett. 566 (2002) L85-L88***

Juri Poutanen, Andrei M. Beloborodov, **Mon.Not.Roy.Astron.Soc. 373 (2006) 836-844**

The pulse profile of DM admixed NSs with DM halo

$M_T(R_D) = 1.4M\odot$





Our results show that the DM admixed NSs could be considered as a novel possibility in the Pulse Profile modeling and numerical simulation codes to interpret X-ray observations of compact objects during the (Bayesian) analysis of NICER, STROBE-X and eXTP telescopes.

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