Bosonic Dark Matter Dynamics in Neutron Star

Deep Ghosh

Saha Institute of Nuclear Physics, India

Dark Matter and Black Holes Workshop 2025
Kavli IPMU, Japan

December 1, 2025

based on JCAP 12 (2024) 053, K. Dutta, DG, B. Mukhopadhyaya

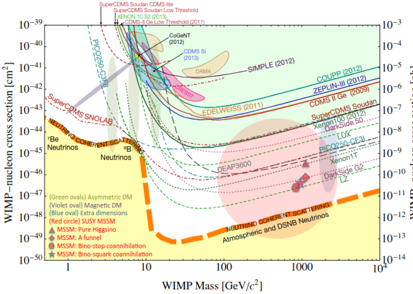
Neutron star as DM laboratory

- The micro-physics of dark matter other than its gravitational signature is an active field of research.
- The DM parameters, $\sigma_{\chi n}$ (DM-nucleon cross-section), $\langle \sigma v \rangle$ (thermally averaged annihilation cross-section) and m_χ (DM mass) are being probed to decipher its non-gravitational interactions.
- Neutron star mostly full of neutrons can capture DM particles in presence of non-gravitational interaction.

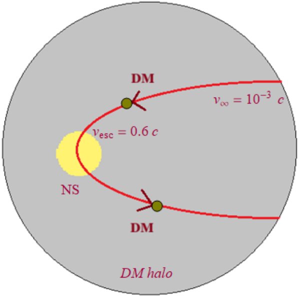
Quick summary

- Constraining $\sigma_{\chi n}$ for both non-annihilating and annihilating DM.
- For non-annihilating DM, existence of old NSs is enough.
- For the latter, the observation of NS surface temperature can be instrumental.

Snowmass, arXiv:1310.8327



DM capture in neutron star



- Neutron star : full of degenerate neutrons
- $M_{NS} \approx (1-2)\ M_\odot,\ R_{NS} \approx 10\ km$
- For DM capture, DM must lose *sufficient* kinetic energy via DM-neutron scattering.
- With a single scattering, DM particles get captured for $m_\chi \leq \mathcal{O}(PeV)$.

DM Capture rate

$$C_c \approx 10^{33}\ year^{-1} \left(\frac{M_{NS}}{M_\odot}\right)\left(\frac{R_{NS}}{10\ km}\right)\left(\frac{10^{-3}c}{v_\chi}\right)\left(\frac{\rho_\chi}{GeVcm^{-3}}\right)\left(\frac{GeV}{m_\chi}\right) min[1, \frac{\sigma_{\chi n}}{\sigma_g}]$$

$\sigma_g = \frac{\pi R_{NS}^2}{\xi N_n} \approx 10^{-45}\ \mathrm{cm}^2,\ \xi = \mathrm{Min}\left[\frac{m_\chi}{0.2\ \mathrm{GeV}}, 1\right]$ Gould (1987), Kouvaris (2008)

$\rho_\chi = 10^{15}\ \mathrm{GeVcm}^{-3}$ with particles $m_\chi = 1$ GeV. $\rho_N = 5 \times 10^{38}\ GeV\ cm^{-3}$

The free-fall time for captured DM particles dispersed over the entire volume of the NS is given by, $t_{ff} = \sqrt{\frac{3\pi}{32 G\rho_\chi}} \sim 2$ years.

Thermalization of DM particles

- The same DM-neutron interaction brings about the thermalization of DM particles with the NS core temperature.
- The thermalization time is smaller than the free-fall time, eventually preventing the collapse within few years.

McDermott et.al (2012)

$$t_{th} \approx \frac{p_F\,(m_\chi + m_n)^3}{T_{NS}\sigma_{\chi n}\rho_N m_\chi m_n} = \begin{cases} 5 \text{ days} \left(\frac{m_\chi}{10^2 \text{ GeV}}\right)^2 \left(\frac{keV}{T_{NS}}\right)\left(\frac{\sigma_g}{\sigma_{\chi n}}\right), \text{for } m_\chi \gtrsim 1\text{GeV}, \\ 24\ s \left(\frac{0.1 \text{ GeV}}{m_\chi}\right)\left(\frac{keV}{T_{NS}}\right)\left(\frac{\sigma_g}{\sigma_{\chi n}}\right), \text{for } m_\chi \lesssim 1\text{GeV}. \end{cases}$$

For thermalization : $\sigma_{\chi n} \gtrsim 10^{-57} cm^2$ for a NS around 10^{10} years of age.

- DM particles form a dark core inside the star after thermalization with thermal radius given by

$$r_{th} = \sqrt{\frac{3T_{NS}}{2\pi G\rho_N m_\chi}} = 26\ m \left(\frac{T_{NS}}{keV}\frac{GeV}{m_\chi}\right)^{1/2}$$

Goldmann & Nussinov (1989)

Dark core collapse

- The average DM density increases for same number of particles, reducing the free-fall time, $t_{ff} \sim 6$ s for $\rho_\chi = 10^{28}\ GeV\ cm^{-3}$, $\rho_\chi = m_\chi N_\chi / V_{th}$, $V_{th} = \frac{4}{3}\pi r_{th}^3$
- Due to thermalization, the pressure prevents the free-fall. Hence, there is another time scale, i.e. the sound crossing time, $t_c = r_{th}/v_{th} \sim 10^{-8} s$.
- Dark core collapse happens when $t_{ff} < t_c \implies \rho_\chi \gtrsim \rho_N$.
- The DM core collapses to a tiny black hole inside the star. Such a BH eventually can devour the entire NS, transforming it into a solar mass BH.
- The formation of tiny BH and its evolution to a large BH depend on the thermal state of DM particles inside the NS, specially if these are bosonic.

Bosonic DM and Black hole formation

- If DM particles are bosonic, Bose-Einstein condensate can form, for which the critical DM number needed for collapse is smaller than any non-BEC state.
- Black holes from the BEC state : $T_{NS} < T_c \;\&\; N_\chi > N_{ch}$

$$N_{ch} = 10^{38}\left(\frac{GeV}{m_\chi}\right)^2, \; T_c = \frac{2\pi}{m_\chi}\left(\frac{3N_\chi}{4\pi r_{th}^3\zeta(3/2)}\right)^{2/3}, \; r_{th} \sim 26m\left(\frac{T_{NS}}{keV}\frac{GeV}{m_\chi}\right)^{1/2}$$

- Black holes from the non-BEC state : $T_{NS} > T_c \;\&\; N_\chi > N_{sg}$,

$$N_{sg} = 3\times 10^{49}\left(\frac{GeV}{m_\chi}\right)^{5/2}\left(\frac{T_{NS}}{keV}\right)^{3/2}$$

- It is apparent that the ambient NS temperature and the DM abundance inside the star decide the BH formation.

In previous studies, the analysis is performed with constant NS temperature while the thermal state of DM is taken as an input.

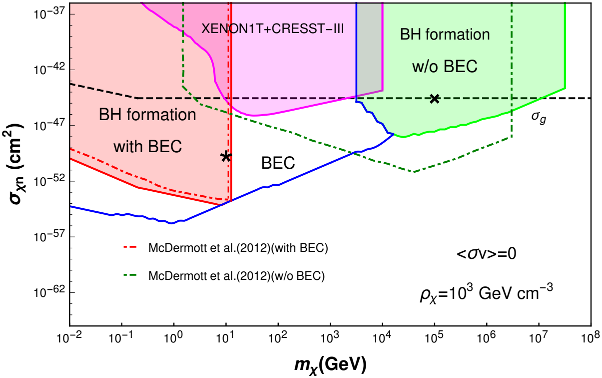
We dynamically determine the thermal state of DM and subsequent BH formation, taking the NS temperature evolution into account, for given values of $\sigma_{\chi n}$, $\langle\sigma v\rangle$ and m_χ.

Constraints on DM-neutron interaction

$$\frac{dT_{NS}}{dt} = -\frac{\epsilon_\nu + \epsilon_\gamma - \epsilon_\chi}{c_V}$$

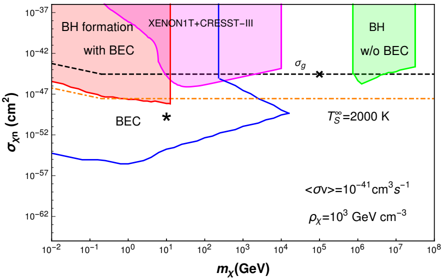
$$\frac{dN_\chi}{dt} = C_c - C_a N_\chi^2$$

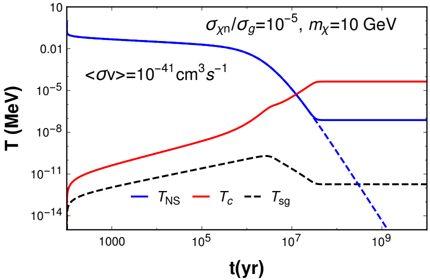
- $\epsilon_\nu, \epsilon_\gamma, \epsilon_\chi$ are emissivities related to neutrino, photon and DM.
- c_V : specific heat of the NS



- We have dynamically derived the DM parameter space for BEC formation (region surrounded by the blue line), ensuring the thermalization of DM particles.
- Constraints on DM parameter space are given from the observation of 10^{10} years old NSs (e.g. PSR B1620-26) which are not transmuted to BHs till now.

Constraints on DM-neutron interaction

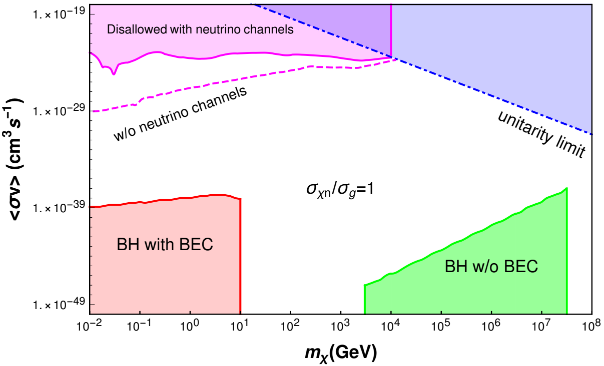




- In presence of DM annihilation, the constraints become weaker from the existence of old pulsar.
- However it modifies the cooling history of the NS, that reflected in the NS surface temperature, which can be observed in the JWST.
- In capture-annihilation equilibrium, the surface temperature is determined by the capture rate, in turn by $\sigma_{\chi n}$.

$$T^f_{NS} \approx 1.8 \times 10^{-5}\ \text{MeV} \left(\frac{m_\chi}{10\ \text{GeV}}\ \frac{C_c}{8\times10^{35}\ \text{year}^{-1}}\right)^{0.45}$$

Complementarity between DD and ID



- The existence of an old NS can put a lower bound to the thermally averaged DM annihilation rate, if the DM-neutron scattering rate becomes known from direct detection experiments.

End note

- The search of solar mass black holes is exciting, because there is no known astrophysical mechanism for generating such a black hole.
- If we find such a black hole, then it might point towards new physics paradigms, including DM interpretations.
- The LVK collaboration is actively searching for solar mass compact objects in binary merger systems.

Recent arXiv arrivals regarding this : S. Khadkikar, D. Singh, arXiv: 2507.07895, S. Bhattacharya et al., arXiv : 2507.15951