Bosonic Dark matter dynamics in neutron stars

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

Preview : 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, thereby can probe DM parameter space. This talk : $\langle \sigma v \rangle = 0$

Quick summary

Excessive DM capture implodes the neutron star into a black hole.
Thermal state of bosonic DM is important in deciding the BH formation.
This can be probed in gravitational wave signals, particularly coming from binary systems.

DM capture in neutron star

- Neutron star : a compact stellar object with mostly degenerate neutrons $\implies M_{NS} \approx (1-2)\, M_{\odot}, \;\; R_{NS} \approx 10\; km$
- In DM-rich regions, DM particles can fall into gravitational potential of neutron star and get captured if there is tiny interaction with neutrons.

DM Capture rate

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

Kouvaris (2008)

$$\sigma_g = \frac{\pi R_{NS}^2}{\xi N_n} \approx 10^{-45}\; \mathrm{cm}^2 \quad [\sigma_h \approx 10^{-35}\; \mathrm{cm}^2]$$

- Within 10^6 years, the DM density inside the star becomes, $\rho_{\chi} \sim 10^{21}\; \mathrm{GeVcm}^{-3}$, assuming 1 GeV DM particles are dispersed over the entire star.

$$\rho_N = 5 \times 10^{38}\; GeV\; cm^{-3}$$

Thermalization of DM particles

- Thermalization of DM particles keeps DM particles into smaller region of the neutron star, thereby the density of DM particles increases.
  For example, if the DM particles are confined within $\mathcal{O}(cm)$, then after 10^6 years, $\rho_{DM} \sim 10^{39}$ GeV cm^{-3}

- Thermalization is facilitated by the same DM-neutron interaction, responsible for the capture.

$$t_{th} \approx \frac{p_F\,(m_\chi + m_n)^3}{T_{NS}\sigma_{\chi n}\rho_N m_\chi m_n} = \begin{cases} 5.4\times10^{-4}\ \text{years}\left(\frac{m_\chi}{10^2\ \text{GeV}}\right)^2\left(\frac{keV}{T_{NS}}\right)\frac{\sigma_g}{\sigma_{\chi n}}, \text{for } m_\chi \gtrsim 1\text{GeV}, \\ 7.7\times10^{-7}\ \text{years}\left(\frac{0.1\ \text{GeV}}{m_\chi}\right)\left(\frac{keV}{T_{NS}}\right)\frac{\sigma_g}{\sigma_{\chi n}}, \text{for } m_\chi \lesssim 1\text{GeV}. \end{cases}$$

McDermott et.al (2012)

- The thermal radius of DM particles are decided by the gravitational potential of DM particles due to neutrons, i.e.

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

Collapse of DM core

- Captured dark matter particles being confined in a smaller region, eventually reach at a density equal to the neutron density. Hence, the self-gravity of DM particles becomes important.
- Thermalized dark core collapses when the DM particle number reaches a critical value, $N_{sg} = 3 \times 10^{49} \left(\frac{GeV}{m_\chi}\right)^{5/2} \left(\frac{T_{NS}}{keV}\right)^{3/2}$
- Bose-Einstein condensate can form, for which the DM core collapse happens with smaller number of particles, i.e.
  $N_{ch} = 10^{38} \left(\frac{GeV}{m_\chi}\right)^2$, when $T_{NS} < T_c,\ T_c = \frac{2\pi}{m_\chi} \left(\frac{3N_\chi}{4\pi r_{th}^3 \zeta(3/2)}\right)^{2/3}$

Given the DM parameters $(m_\chi, \sigma_{\chi n})$ and the temperature evolution of neutron star, BEC and non-BEC states can be determined dynamically.

DM-induced black holes

Conditions for black hole formation

- Fast thermalization of capture DM particles
- Black holes from the BEC state : $T_{NS} < T_c$ & $N_\chi > N_{ch}$
- Black holes from the non-BEC state : $T_{NS} > T_c$ & $N_\chi > N_{sg}$
- Negligible black hole evaporation via Hawking radiation.

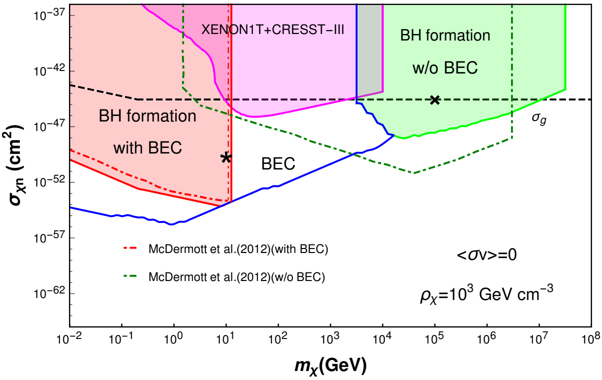
Consequently..

- Mini black holes produced from DM collapse can grow acquiring baryonic matter, eventually devour the entire star.
- Black holes of $(1-2)\ M_\odot$ form from different thermal states.

DM parameter constraint from observation

- Observation of old neutron star, e.g. PSR B1620-26, age of 10^{10} years.
- Gravitational waves from binary systems of solar mass BHs.

Constraints on DM parameters



- In low DM mass regime, BEC and BEC-induced BHs form. In high mass regime, BH forms out of non-BEC state.
- The electroweak mass window is unconstrained by the NS observation, due to BH evaporation.

Distinguishing BEC BH and non-BEC BH

- Implosion time : The time taken to devour the entire star depends on the initial black hole mass.
- The initial black hole mass is different for BEC ($\sim m_\chi N_{ch}$) and non-BEC case ($\sim m_\chi N_{sg}$), thus the implosion times are different.

$$t_I = \begin{cases} 4.6 \times 10^5 \text{ years } \left(\frac{m_\chi}{\text{GeV}}\right) & \text{for BEC BH,} \\ 3.6 \times 10^2 \text{ years } \left(\frac{m_\chi}{10^4 \text{ GeV}}\right)^{3/2} \left(\frac{10^{-5} \text{ MeV}}{T_{NS}}\right)^{3/2} & \text{for non-BEC BH.} \end{cases}$$

Collapse time : $t_c = t_{cap} + t_I$

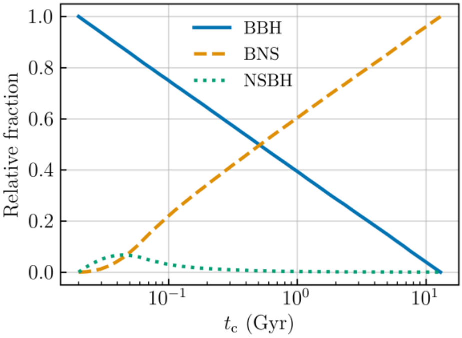
The population study of the binary neutron stars (BNS) and solar mass binary black holes (BBH) can be instrumental in distinguishing between these two types of BHs.

In particular, the relative fraction of BBH and BNS is sensitive to the collapse time. D. Singh et al. (2022)

Takeaways

- Excessive acquisition of DM inside the neutron star can lead to the destruction of the star.
- For bosonic DM, thermal states are important in deciding the Black formation.
- Finding old neutron stars is useful to constrain the DM parameter space.
- Gravitational signals from binary systems with sufficient statistics, one can infer about the thermal state of DM responsible for the BH formation.

Backup Slide : Collapse time and relative fraction



Ref : D. Singh et al. (2022)