Constraints on the fraction of cold fermionic dark matter particles inside the neutron stars

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ICPPA, 5-9 October 2020
DM candidates

DM admixed
NS
Accretion onto the NS
Conclusions
Effect of DM on NS properties

DM admixed
NS
Accretion onto
the NS
Conclusions

GW170817
PSR J0348+0432

$\frac{M_{\text{DM}}}{M_{\odot}}$
$R_N [\text{km}]$

DM core contributing to 5% of the total NS mass
$\sqrt{\sigma_D/m_D^3} = 0.05 \text{ GeV}^{-2}$

M. Deliyergiyev et al., PRD 99, 063015 (2019)
J. Ellis et al., PRD 97, 123007 (2018)
Effect of DM on GW waveform

The DM cores may produce a supplementary peak in the characteristic GW spectrum of NS mergers, which can be clearly distinguished from the features induced by the baryon component.

J. Ellis et al., PLB, 781, 607 (2018)
M. Bezares et al., PRD, 100, 044049 (2019)
Cooling of NS with DM

DM admixed NS

Accretion onto the NS

Conclusions

The emission of axions alters the observable surface temperature

A. Sedrakian, PRD, 93, 065044 (2016)
DM admixed NSs

2 NSs with mass above $2M_\odot$

- PSR J0348-0432: $M = 2.01^{+0.04}_{-0.04} M_\odot$ (Antoniadis et al.’13)
- PSR J0740+6620: $M = 2.14^{+0.20}_{-0.18} M_\odot$ (Cromartie et al.’19)

**Dark matter EoS**

- Asymmetric dark matter
  relativistic Fermi gas of noninteracting particles with the spin $\frac{1}{2}$
  

**Baryon matter EoS**

- EoS with induced surface tension (IST EoS)
  *consistent with:*
  nuclear matter ground state properties,
  proton flow data,
  heavy-ion collisions data,
  astrophysical observations,
  tidal deformability constraint from the NS-NS merger (GW170817)

TOV equations

2 TOV equations:

\[
\begin{align*}
\frac{dp_B}{dr} &= -\frac{(\epsilon_B + p_B)(M + 4\pi r^3 p)}{r^2 (1 - 2M/r)} \\
\frac{dp_D}{dr} &= -\frac{(\epsilon_D + p_D)(M + 4\pi r^3 p)}{r^2 (1 - 2M/r)}
\end{align*}
\]

Total pressure \( p(r) = p_B(r) + p_D(r) \)

Gravitational mass \( M(r) = M_B(r) + M_D(r) \), where \( M_j(r) = 4\pi \int_0^r \epsilon_j(r')r'^2 dr' \) (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

BM and DM are coupled only through gravity, and their energy-momentum tensors are conserved separately.
Mass-Radius diagram of the DM admixed NSs

$m_\chi = 0.1 \text{ GeV}$

$m_\chi = 1 \text{ GeV}$

$M_{\text{max}} > 2 M_\odot$ for any $f_\chi$

for $f_\chi = 3.3 \%$ $M_{\text{max}}$ equals to $2 M_\odot$ further increase of the DM fraction leads to $M_{\text{max}} < 2 M_\odot$

Internal structure of the stars

$R_D = 9.4$ km for $f_\chi = 0.3\%$
$R_D = 21.2$ km for $f_\chi = 1.0\%$
$R_D = 135.2$ km for $f_\chi = 3.0\%$

Large values of $R_D$ relate to the existence of dilute and extended halos of DM around a baryon core of NS
Maximal mass of NS as a function of the DM fraction

![Graph showing the relationship between maximal mass of NS and DM fraction]

for $m_\chi = 0.174$ GeV $M_{max}$ is $2 M_\odot$

DM particles with $m_\chi \leq 0.174$ GeV are consistent with the $2 M_\odot$ constraint for any $f_\chi$

For heavier DM particles the NS mass can reach $2 M_\odot$ only if $f_\chi$ is limited from above
Constraint on the mass of DM particles

Navarro-Frenk-White distribution for DM:

\[ \rho_\chi(d) = \rho_c \cdot \frac{d_c}{d} \cdot \left(1 + \frac{d}{d_c}\right)^{-2} \tag{1} \]

\[ \rho_c = 5.22 \pm 0.46 \cdot 10^7 \, M_\odot \, \text{kpc}^{-3} \text{ and } d_c = 8.1 \pm 0.7 \, \text{kpc} \]


BM distribution in a stellar disc:

\[ \rho_B(d) = \rho_{dc} e^{-\frac{d}{d_{dc}}} \tag{2} \]

\[ \rho_{dc} = 15.0 \, M_\odot \, \text{pc}^{-3} \text{ and } d_{dc} = 3.0 \, \text{kpc} \]


<table>
<thead>
<tr>
<th>Pulsar</th>
<th>distance to the GC</th>
<th>( f_\chi^* ) (NFW distr)</th>
<th>( f_\chi^* ) (Einasto distr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSR J0348+0432</td>
<td>9.9 kpc</td>
<td>1.6 \pm 0.4 %</td>
<td>1.35 \pm 0.05 %</td>
</tr>
<tr>
<td>PSR J0740+6620</td>
<td>8.6 kpc</td>
<td>1.35 \pm 0.35 %</td>
<td>1.12 \pm 0.049 %</td>
</tr>
</tbody>
</table>

\( f_\chi^* \) corresponds the DM fraction in the surrounding medium around the NS.

Fraction inside the NS will depend on the accretion rate during all the life stages of a star and the cross-section of DM with BM.
DM accumulation regimes

- **Progenitor**
  During the star formation stage the initial mixture of DM and BM contracting to form the progenitor star. Trapped DM undergoes scattering processes with baryons leading to its kinetic energy lost and thermalisation.

- **Main sequence (MS) star**
  From this stage of star evolution accretion rate increases due to big gravitational potential of the star. In the most central Galaxy region \( M_{\text{acc}} \approx 10^{-5} M_{\odot} - 10^{-9} M_{\odot} \).

- **Supernova explosion & formation of a proto-NS**
  The newly-born NS will be surrounded by the dense cloud of DM particles with the temperature and radius that corresponds to the last stage of MS star evolution, i.e. a star with a silicone core.

  Kouvaris & Tinyakov (2010)
  In addition, a significant amount of DM can be produced during the supernova explosion and mostly remain trapped inside the star.

- **Equilibrated NS**
  \[ M_{\text{acc}} \approx 10^{-14} \left( \frac{\rho \chi}{0.3 \text{ GeV/cm}^3} \right) \left( \frac{\sigma \chi n}{10^{-45} \text{ cm}^2} \right) \left( \frac{t}{\text{Gyr}} \right) M_{\odot}, \]

  In the most central Galaxy region \( M_{\text{acc}} \approx 10^{-5} M_{\odot} - 10^{-8} M_{\odot} \).
DM admixed

NS

Accretion onto the NS

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DM constraint in the GC

2 $M_\odot$ NS in the GC $\Rightarrow$ $m_\chi < 60$ GeV

More precise modeling of DM accumulation inside the NSs will put more tight constraints on $m_\chi$. 
Conclusions

- Using the observational fact of existence of the two heaviest known NSs (i.e., PSR J0348+0432, PSR J0740+6620) with the masses exceeding the two solar ones, we presented an allowable range of masses and fractions of DM particles.

- We demonstrated that DM lighter than 0.2 GeV can create an extended halo around the NS leading not to decrease but to increase of the NS total (gravitational) mass.

- By using recent results on the distribution of DM in Milky Way, we made an estimation of the fraction of DM in NSs in the GC. Measurements of a $2 M_\odot$ NS in the GC will impose an upper constraint on the mass of DM particles of $\sim 60$ GeV.

- We expect to have more NSs observations and measurements of their masses with higher precision from the following telescopes:
  
  **radio telescopes**
  - the Karoo Array Telescope (MeerKAT)
  - the Square Kilometer Array (SKA)
  - the Next Generation Very Large Array (ngVLA)

  **space telescopes**
  - the Neutron Star Interior Composition Explorer Mission (NICER)
  - the Advanced Telescope for High Energy Astrophysics (ATHENA)
  - the enhanced X-ray Timing and Polarimetry mission (eXT)
  - the Spectroscopic Time-Resolving Observatory for Broadband Energy X-rays (STROBE-X)
Thanks for your attention!