Impact of dark matter on compact stars

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1 Accumulation of DM in stars
Outline

1. Accumulation of DM in stars

2. Effect of DM on NS properties
   - Mass and Radius
   - Tidal deformability and waveform
   - NS cooling and heating

3. Fermionic DM

4. Bosonic DM

5. Numerical simulations of DM admixed NS binaries

6. Conclusions
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DM candidates

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credits: Symmetry magazine
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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 loss 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 $M_{acc} \approx 10^{-5}M_\odot - 10^{-9}M_\odot$.

- **Supernova explosion & formation of a proto-NS**
  The newly-born NS should 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.

  - **Equilibrated NS**
    \[
    M_{acc} \approx 10^{-14} \left( \frac{\rho \chi}{0.3 \text{ GeV/cm}^3} \right) \left( \frac{\sigma \chi n}{10^{-45} \text{ cm}^2} \right) \left( \frac{t}{\text{Gyr}} \right) M_\odot, \tag{1}
    \]

    In the most central Galaxy region $M_{acc} \approx 10^{-5}M_\odot - 10^{-8}M_\odot$.

- **Conclusions**

  - **Kouvaris & Tinyakov 2010**
    In addition, a significant amount of DM can be produced during the supernova explosion and mostly remain trapped inside the star.
Dark matter and baryon components do not expel each other but overlap due to absence of non-gravitational interaction.
Effect of DM on Mass and Radius

- **DM core** ⇒ decrease of the maximum mass and observed stellar radius
- **DM halo** ⇒ increase of the maximum mass and the outermost radius

*Ciarcelluti & Sandin 2011; Nelson+ 2019; Deliyergiyev+ 2019; Ivanytskyi+2020; Das+ 2020; Del Popolo+ 2020; Karkevandi+ 2022*

DM core contributing to 5% of the total NS mass

\[ \sqrt{\sigma_D / m_D^3} = 0.05 \text{GeV}^{-2} \]

*Ellis+ 2018*
TOV equations - two fluid system

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 \( M_j(r) = 4\pi \int_0^r \epsilon_j(r') r'^2 dr' \) (j=B,D)

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

**Fraction of DM inside the star:**

\[
f_\chi = \frac{M_D(R_D)}{M_T}
\]
Tidal deformabilities of DM-admixed NS

\[ \Lambda = \frac{2}{3} k_2 \left( \frac{R_{\text{outermost}}}{M_{\text{tot}}} \right)^5 \]

- $k_2$ – Love's number.
- $R_{\text{outermost}} = R_B \geq R_D$ - DM core
- $R_{\text{outermost}} = R_D > R_B$ - DM halo

Speed of sound should be calculated for two-fluid system

Ellis+ 2018; Bezares+ 2019, Sagun+ 2022; Karkevandi+2022; Miao+2022; Leung+2022
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.

Giudice+ 2016; Ellis+ 2018; Bezares+ 2019
Dark matter

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- DM particles are fermions -> the Pauli blocking may prevent them from collapsing into a black hole
- DM particles are bosons -> at zero temperature could form Bose-Einstein condensate leading to gravitational collapse of the bosonic DM leading to the formation of a black hole

Models of asymmetric DM should allow old NSs to exist

Kouvaris 2013

- possibility of its detection via X-ray, γ-ray or neutrino telescopes

Kouvaris 2008

- late-time heating -> higher surface temperature of old NSs

de Lavallaz & Fairbairn 2010

Hamaguchi+ 2019
Equation for thermal balance

The time evolution of the red-shifted temperature is determined by

\[ \frac{d T}{dt} = \frac{-L_\nu - L_\gamma + L_H}{C} \]

- \( C \) - total heat capacity of the NS
- \( L_\nu \) - red-shifted luminosity of the neutrino
- \( L_\gamma \) - red-shifted luminosity of the photon emissions
- \( L_H \) - red-shifted heating power

The photon emission luminosity is given by
\[ L_\gamma = 4\pi R^2 \sigma_B T^4 \]
where \( \sigma_B \) is the Stefan-Boltzmann constant and \( R \) is the NS radius.
Light DM particles, such as axions, could contribute as an additional cooling channel in compact stars and their mergers.

Creation mechanisms:

- nucleon bremsstrahlung
- Cooper pair breaking and formation processes
Cooling of NS with DM

The emission of axions alters the observable surface temperature

Sedrakian 2016; 2019
Heating of NS with DM

DM particles annihilation can cause heating of old NS

For a typical WIMP, its annihilation and capture rates equilibrate in old NSs.

Kouvaris 2008; Kouvaris & Tinyakov 2010; Hamaguchi+ 2019

Evolution of the surface temperatures of a 1.44 $M_\odot$ neutron star situated at various galactic radii. In the present case, $m_\gamma = 10$ GeV, $\sigma_0 = 1.5 \times 10^{-41}$ cm$^2$ and $(r_2, \alpha) = (16 \text{ kpc}, 0.19)$.

Lavallaz & Fairbairn 2010
DM admixed NSs

2 NSs with mass above $2M_\odot$

- PSR J0348-0432: $M = 2.01^{+0.04}_{-0.04} M_\odot$ (Antoniadis+ 2013)
- PSR J0740+6620: $M = 2.14^{+0.20}_{-0.18} M_\odot$ (Cromartie+ 2019)

Dark matter EoS

- Asymmetric dark matter
  relativistic Fermi gas of noninteracting particles with the spin $1/2$
  
  Nelson+ 2019

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)

VS+ 2019; VS+ 2014
Mass-Radius diagram of the DM admixed NSs

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

for \( f_\chi = 3.3 \% \) \( M_{\text{max}} \) equals to \( 2 \ M_{\odot} \)

further increase of the DM fraction leads to \( M_{\text{max}} < 2 \ M_{\odot} \)

Ivanytskyi+ 2020
Internal structure of the stars

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

Large values of $R_D$ relate to the existence of dilute and extended halos of DM around a baryon core of NS.
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**Mass-Radius diagram**

\[
\Lambda = \frac{2}{3} k_2 \left( \frac{R_{\text{outermost}}}{M_{\text{tot}}} \right)^5 \quad \rightarrow \quad \Lambda(1.4M_\odot) < 800; \tag{2}
\]

Abbott+ 2018
Maximal mass of NS as a function of the DM fraction

![Graph showing the maximal mass of a NS as a function of the DM fraction.](image)

- For \( m_\chi = 0.174 \) GeV, \( M_{\text{max}} \) 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
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DM constraint in the Galaxy center

- $2M_\odot$ NS in the GC $\Rightarrow$ $m_\chi < 60$ GeV
- high DM fractions are not supported by GW170817

Measurements of M and R of compact stars at the Galaxy center will put more tight constraints on $m_\chi$ and $f_\chi$. 

Ivanytskyi+ 2020; VS+ 2022
What is the nature of the GW190814 secondary component?

The compact binary merger event GW190814 had primary mass component, a black hole, with $M = 23.2 \, M_\odot$ and the second component with $M = 2.5 - 2.67 \, M_\odot$. The nature of the secondary component raised a lot of questions.

Possible explanations:

- NS with exotic degrees of freedom, e.g. hyperons and/or quarks [Tan+ 2020; Dexheimer+ 2021]
- highly spinning NS [Zhang & Li 2020]
- NS matter with extra stiffening of the EoS at high densities [Fattoyev+ 2020]
- BH from the 'mass gap' [Tews+ 2021; Essick & Landry 2020]

An alternative explanation, the secondary component of GW190814 is a DM-admixed NS [Das+ 2021; Giovanni+ 2022]
GW190814 secondary component as a dark matter admixed neutron star

Secondary component of GW190814 could be explained by the DM extended halo formation around a NS with the DM fraction $f_\chi = 23\%$ for $m_\chi = 100$ MeV.

VS+ 2022 (In prep)
The minimal Lagrangian includes the complex scalar $\chi$ and real vector $\omega^\mu$ fields, which are coupled through the covariant derivative $D^\mu = \partial^\mu - ig\omega^\mu$ with $g$ being the corresponding coupling constant

$$\mathcal{L} = \left( D^\mu \chi \right)^* D^\mu \chi - m^2 \chi^* \chi - \frac{\Omega_{\mu\nu} \Omega^{\mu\nu}}{4} + \frac{m^2_\omega \omega^\mu \omega^\mu}{2}$$

where $\Omega_{\mu\nu} = \partial^\mu \omega^\nu - \partial^\nu \omega^\mu$ and $m_\omega$ is the vector field mass.

Using a mean field approximation for $\omega$, we get

$$p_\chi = \frac{m^2_i}{4} \left( m^2_\chi - \mu_\chi \sqrt{2m^2_\chi - \mu^2_\chi} \right),$$

$$\varepsilon_\chi = \frac{m^2_i}{4} \left( \frac{\mu^3_\chi}{\sqrt{2m^2_\chi - \mu^2_\chi}} - m^2_\chi \right),$$

Chemical potential is limited

$$\mu_\chi \in [m_\chi, \sqrt{2m_\chi}], \quad m_\chi - \text{boson mass}$$

$$m_i = \frac{m_\omega}{g} - \text{interaction scale}$$
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$M = 1$ GeV, $m_I = 1$ GeV

$\epsilon = 1\%$
$\epsilon = 3\%$
$\epsilon = 5\%$

IST EoS
DD2 EoS

Giangrandi+ 2022 (In prep.)
Numerical Simulations of DM Admixed NS Binaries

Two-fluid 3D simulations of coalescencing binary NS systems admixed with DM

**DM component:** Mirror DM (mirrors the BM to a parallel hidden sector, the same particle physics as the observable world and couples to the latter through gravity)

*Berezhiani 2004; Ciancarella+ 2021*

**BM component:** SLy EoS

<table>
<thead>
<tr>
<th></th>
<th>$M_{A,B} (M_\odot)$</th>
<th>Mirror dark matter %</th>
<th>$\rho_c^B$ [$\rho_{nuc}$]</th>
<th>$\rho_c^{\text{in}}$ [$\rho_{nuc}$]</th>
<th>$R_{A,B}$ [km]</th>
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</thead>
<tbody>
<tr>
<td>SLY_M14_0</td>
<td>1.4</td>
<td>0%</td>
<td>3.866</td>
<td>0</td>
<td>11.45</td>
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<td>SLY_M14_5</td>
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<td>10%</td>
<td>4.056</td>
<td>2.499</td>
<td>10.65</td>
</tr>
</tbody>
</table>

- higher DM fraction $\Rightarrow$ a longer inspiral likely due to a lower deformability of dark matter admixed neutron stars.

*Emma+ 2022*
Gravitational waveform and frequency

- decrease of the disk mass $\Rightarrow$ increasing DM fraction
- higher DM fraction $\Rightarrow$ faster formation of the BH after the merger and harder to eject material from the bulk of the stars prior to the BH formation.
- lack of DM ejecta and debris disks $\Rightarrow$ is related to its concentration in the NS core.

<table>
<thead>
<tr>
<th>$M_{ij}$ sphere ($M_\odot$)</th>
<th>$M_{ij}$ integral ($M_\odot$)</th>
<th>$M_{\text{disk}}$ ($M_\odot$)</th>
<th>$f_{\text{merger}}$ [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLy_M14_0</td>
<td>-</td>
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<td>1770</td>
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<tr>
<td>SLy_M14_5</td>
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<td>0.0008</td>
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<tr>
<td>SLy_M14_10</td>
<td>-</td>
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<td>2058</td>
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<td>SLy_M13_0</td>
<td>0.0168</td>
<td>4.8 $\cdot 10^{-3}$</td>
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<td>SLy_M13_5</td>
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<td>0.7 $\cdot 10^{-3}$</td>
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<tr>
<td>SLy_M13_10</td>
<td>0</td>
<td>0.8 $\cdot 10^{-3}$</td>
<td>0.0006</td>
</tr>
<tr>
<td>SLy_M12_0</td>
<td>0</td>
<td>0.3 $\cdot 10^{-3}$</td>
<td>0.19*</td>
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<tr>
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<td>0.16*</td>
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<tr>
<td>SLy_M12_10</td>
<td>0.0027</td>
<td>3.3 $\cdot 10^{-3}$</td>
<td>0.017</td>
</tr>
</tbody>
</table>

Emma+ 2022
Conclusions

- **DM** can be accumulated in the **core** of a NS ⇒ significant decrease of the maximum mass and radius of a star.

- **DM halo** ⇒ increase of the maximum mass and the outermost radius.

- The secondary component of the GW190814 binary merger might be a DM admixed NS.

Changing the position of the NS in the Galaxy the accretion rate of DM varies, which in turn leads to different amount of DM

↓

different modifications of $M$, $R$, $\Lambda$, surface temperature, etc
Smoking gun of the presence of DM in NSs

- by measuring mass, radius, and moment of inertia of NSs with few-%-accuracy.

To see this effect we need high precision measurement of M and R of compact stars as well as NS searches in the central part of the Galaxy with

**radio telescopes**: MeerKAT, SKA, ngVLA plan to increase radio pulsar timing and discover Galactic center pulsars.

**space telescopes**: NICER, ATHENA, eXTP, STROBE-X are expected to measure M and R of NSs with high accuracy.

**DM core** ⇒ mass and radius reduction of NSs toward the Galaxy center  
**DM halo** ⇒ mass increase of NSs toward the Galaxy center  
or variation of mass and radius in different parts of the Galaxy

- by performing binary numerical-relativity simulations and kilonova ejecta for  
  DM-admixed compacts stars for different DM candidates, their particle mass,  
  interaction strength and fractions with the further comparison to GW and  
  electromagnetic signals.

Large statistics on NS-NS, NS-BH mergers by LIGO/Virgo/KAGRA would be very helpful  
The smoking gun of the presence of DM could be:  
**supplementary peak in the characteristic GW spectrum of NS mergers; exotic waveforms;**  
**modification of the kilonova ejection;**  
**post-merger regimes**: the next generation of GW detectors, i.e., the Cosmic Explorer and Einstein Telescope.

- by detecting objects that go in contradiction with our understanding.

As a potential candidate for a DM-admixed NS could be the secondary component of  
GW190814.

- High/low surface temperature of NSs towards the Galaxy center
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(5)

where $\Omega^{\mu\nu} = \partial^\mu \omega^\nu - \partial^\nu \omega^\mu$ and $m_\omega$ is the vector field mass.

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(6)

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$\mu_\chi \in [m_\chi, \sqrt{2}m_\chi]$, $m_\chi$ - boson mass $m_i = \frac{m_\omega}{g}$ - interaction scale