Impact of asymmetric fermionic and bosonic dark matter on neutron star properties

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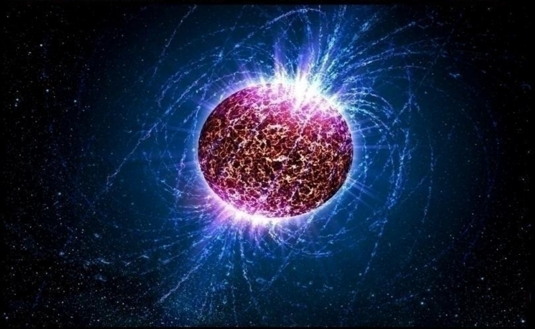

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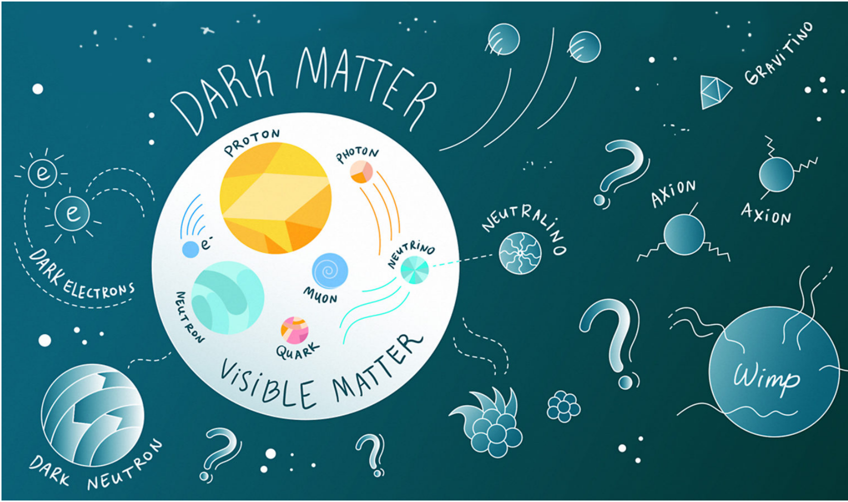
Fundação para a Ciência e a Tecnologia

DM candidates

DM admixed NS
Fermionic DM
Bosonic DM
Conclusions



credits: Symmetry magazine

DM accumulation regimes

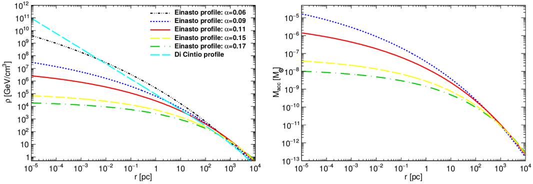
- Progenitor
  During the star formation stage the initial mixture of DM and BM contracting to form the progenitor star. Trapped DM undergoes scattering processes with baryons leading to its kinetic energy lost and thermalisation.
- Main sequence (MS) star
  From this stage of star evolution accretion rate increases due to big gravitational potential of the star. In the most central Galaxy region $M_{acc} \approx 10^{-5} M_\odot - 10^{-9} M_\odot$.
- 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

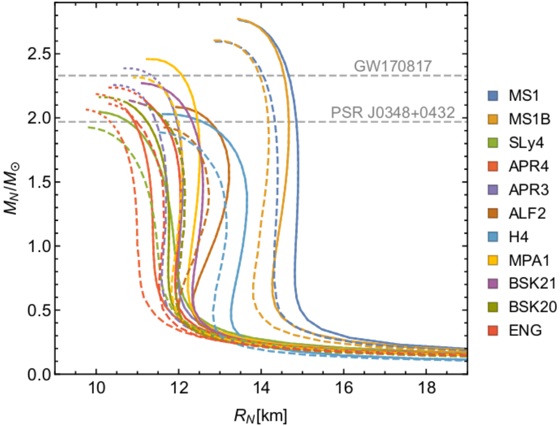
$$M_{acc} \approx 10^{-14} \left(\frac{\rho_\chi}{0.3 \, \frac{GeV}{cm^3}} \right) \left(\frac{\sigma_{\chi n}}{10^{-45} \, cm^2} \right) \left(\frac{t}{Gyr} \right) M_\odot , \qquad \textbf{(1)}$$

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



Del Popolo+ 2019

Effect of DM on NS properties

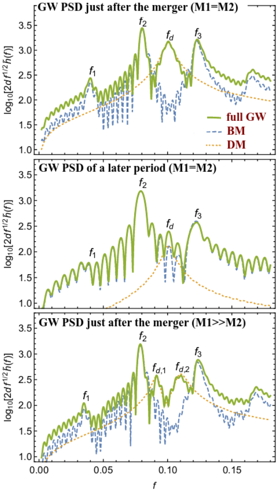


DM core contributing to 5% of the total NS mass

$$\sqrt{\sigma_D}/m_D^3 = 0.05\,\mathrm{GeV}^{-2}$$

Deliyergiyev+ 2019; Del Popolo+ 2020; Ellis+ 2018

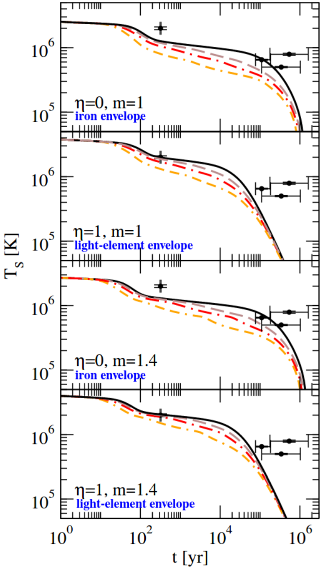
Effect of DM on GW waveform



Ellis+ 2018; Bezares+ 2019

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

Cooling of NS with DM



The emission of axions alters the observable surface temperature

Sedrakian 2016; Sedrakian 2019

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

TOV equations

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 $p(r) = p_B(r) + p_D(r)$

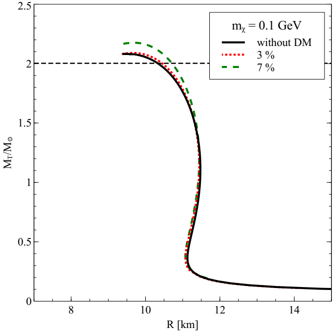
gravitational mass $M(r) = M_B(r) + M_D(r)$, where $M_j(r) = 4\pi \int_0^r \epsilon_j(r')r'^2 dr'$ (j=B,D)

Fraction of DM inside the star:

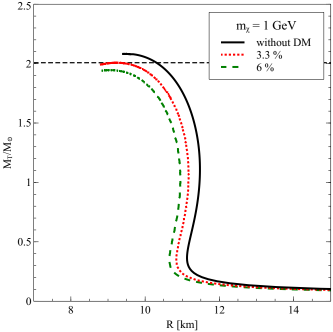
$$f_\chi = \frac{M_D(R_D)}{M_T}$$

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

Mass-Radius diagram of the DM admixed NSs



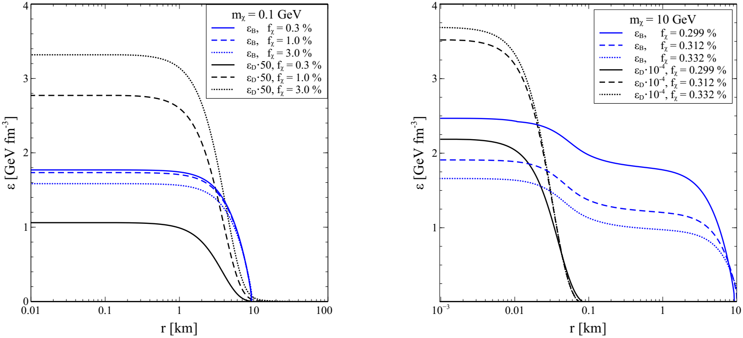
$M_{max} > 2\ M_\odot$ for any f_χ



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

Ivanytskyi+ 2020

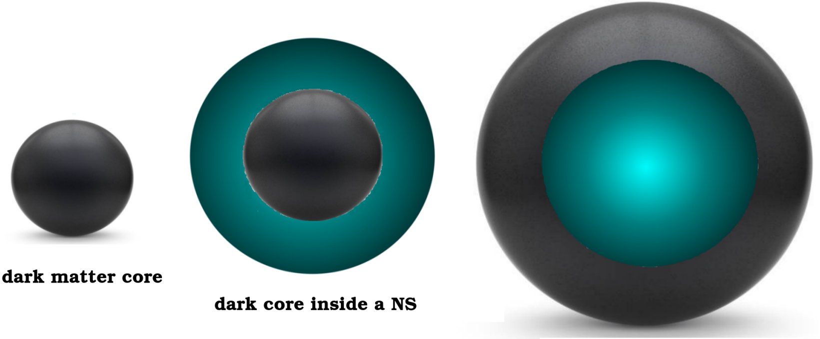
Internal structure of the stars



$R_D = 9.4$ 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

Dark matter and neutron star structure



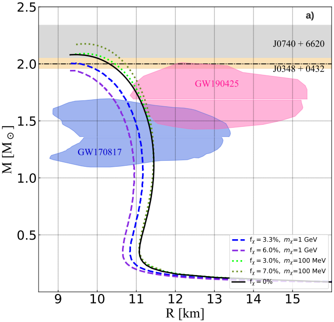
dark matter core

dark core inside a NS

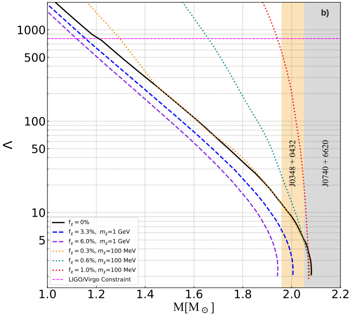
dark halo around a NS

DM admixed NSs

Mass-Radius diagram



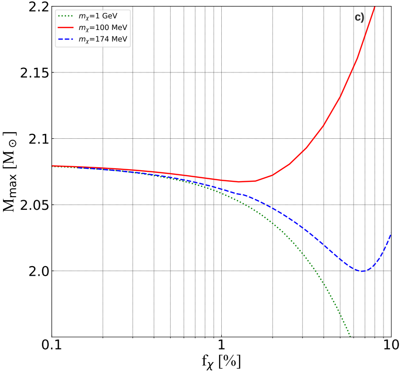
Tidal deformabilities



$$\Lambda = \frac{2}{3} k_2 \left(\frac{c^2 R_{\rm outermost}}{G M_{\rm tot}} \right)^5 \longrightarrow \Lambda(1.4 \mathrm{M}_\odot) < 800; \qquad (2)$$

Ivanytskyi+ 2020; VS+ 2022

Maximal mass of NS as a function of the 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_χ

For heavier DM particles the NS mass can reach 2 $M_\odot$ only if f_χ is limited from above

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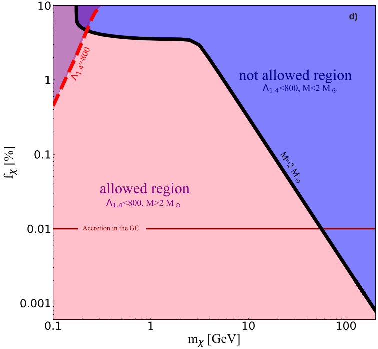
DM constraint in the Galaxy center



- $2M_\odot$ 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_χ and f_χ.

Ivanytskyi+ 2020; VS+ 2022

Asymmetric Bosonic Dark Matter

The Lagrangian used includes **self-interacting** DM particles as:

$$\mathcal{L} = \frac{1}{2}(D_\mu\varphi)^* D^\mu\varphi - \frac{1}{2}m_\chi^2\varphi^*\varphi - \tag{3}$$

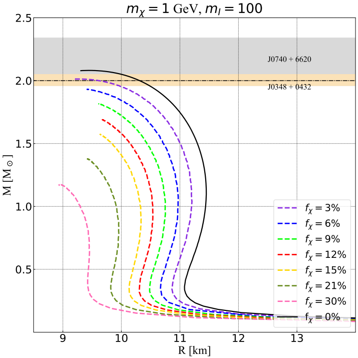
$$\frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} - \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu \tag{4}$$

with $D_\mu\varphi = (\partial_\mu - ig\omega_\mu)\varphi$.
Using a mean field approximation for ω, we recollect after calculations an EoS of self-interacting Bose-Einstein condensate:

$$n = \frac{m_I^2}{2}\frac{\mu_\chi^2 - m_\chi^2}{\sqrt{2m_\chi^2 - \mu_\chi^2}}$$

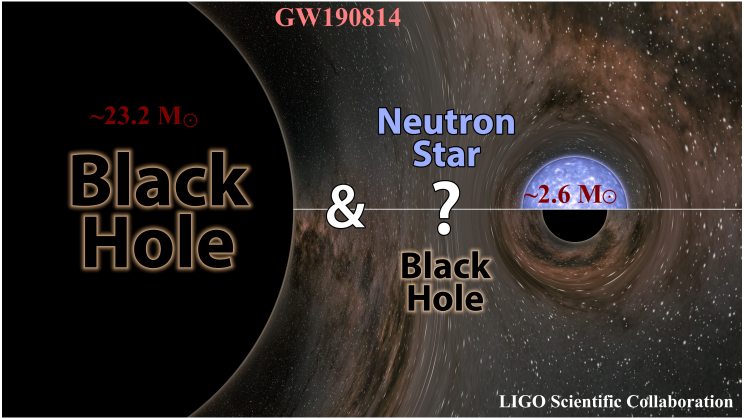
$$p = \left(\frac{m_I}{2}\right)^2\left[m_\chi^2 - \mu_\chi^2\sqrt{2m_\chi^2 - \mu_\chi^2}\right]$$

Chemical potential is limited
$\mu_\chi \in [m_\chi, \sqrt{2}m_\chi]$, m_χ - boson mass
$m_I = \frac{m_\omega}{g}$ - self-interaction scale



Giangrandi+ 2022 (In prep.)

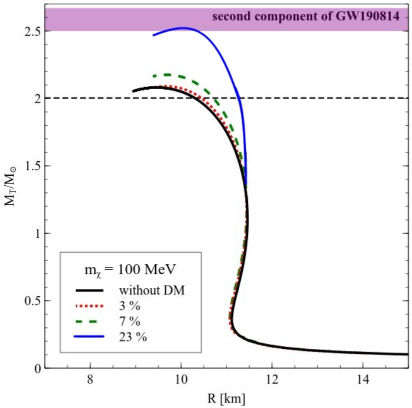
What is the nature of the GW190814 secondary component?



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. The proposed candidates as a compact star span from highly spinning NS to exotic degrees of freedom

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)

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.

NSs in different parts of the Galaxy could contain different amount of DM

↓

different modifications of M, R, Λ, etc

- 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

  space telescopes: NICER, ATHENA, eXTP, STROBE-X

- Large statistics on NS-NS, NS-BH mergers by LIGO/Virgo/KAGRA would be very helpful

Thanks for your attention!