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

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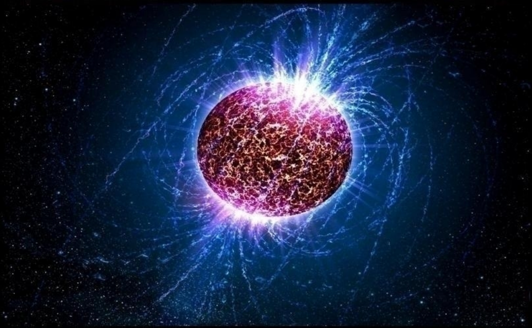
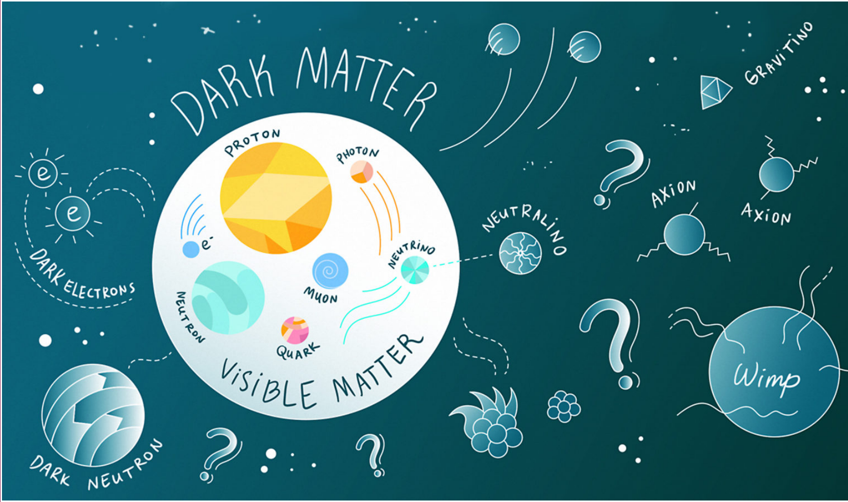


ICPPA, 5-9 October 2020

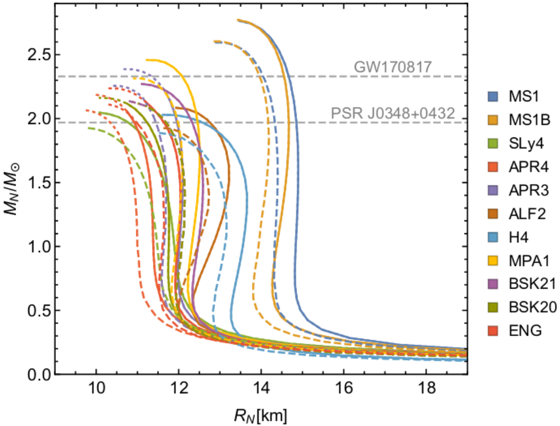
Fundação para a Ciência e a Tecnologia

DM candidates



credits: Symmetry magazine

Effect of DM on NS properties

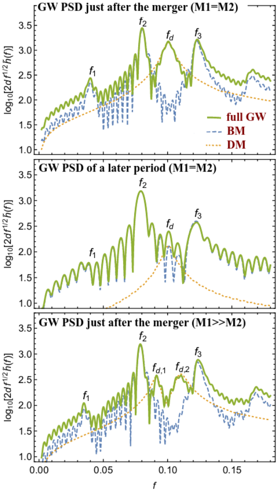


DM core contributing to 5% of the total NS mass

$$\sqrt{\sigma_\mathrm{D}}/m_\mathrm{D}^3 = 0.05\,\mathrm{GeV}^{-2}$$

M. Deliyergiyev et al., PRD 99, 063015 (2019)
A. Del Popolo et al., Phys. D. Univ. 28, 100484 (2020)
J. Ellis et al., PRD 97, 123007 (2018)

Effect of DM on GW waveform

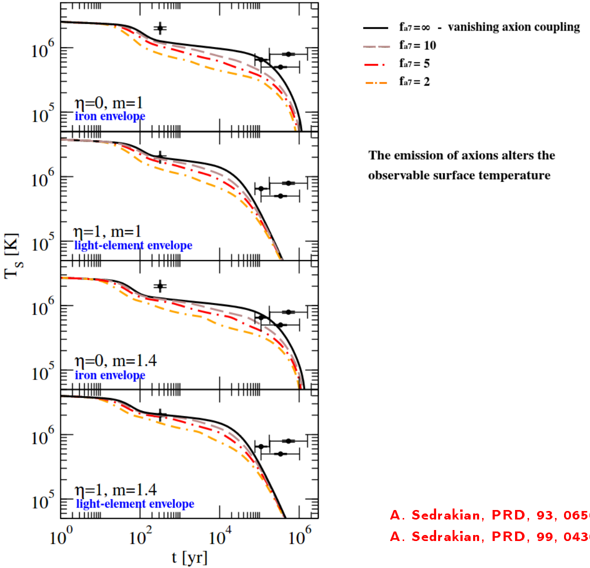


J. Ellis et al., PLB, 781, 607 (2018)

M. Bezares et al., PRD, 100, 044049 (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

A. Sedrakian, PRD, 93, 065044 (2016)
A. Sedrakian, PRD, 99, 043011 (2019)

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 1/2

A. Nelson, S. Reddy, D. Zhou, arXiv:1803.032668(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, I. Lopes, A. Ivanytskyi, ApJ, 871, 157 (2019)
VS, A. Ivanytskyi, K. Bugaev, et al., Nucl. Phys. A, 924, 24 (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 $p(r) = p_B(r) + p_D(r)$

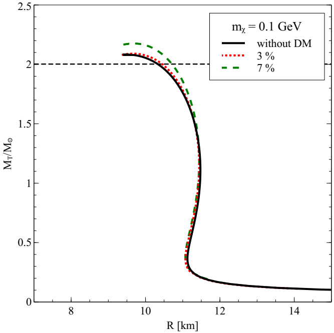
gravitational mass $M(r) = M_B(r) + M_D(r)$, where $M_j(r) = 4\pi \int_0^r \epsilon_j(r')r'^2 dr'$ (j=B,D)

Fraction of DM inside the star:

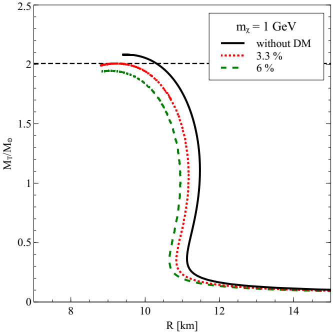
$$f_\chi = \frac{M_D(R_D)}{M_T}$$

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

Mass-Radius diagram of the DM admixed NSs



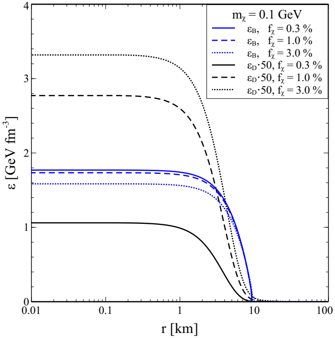
$M_{max} > 2\ M_\odot$ for any f_χ

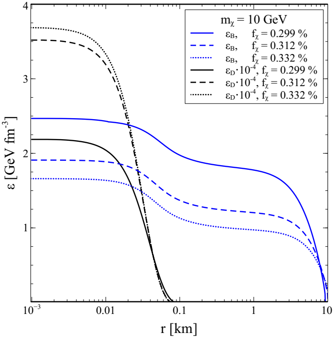


for $f_\chi = 3.3$ % M_{max} equals to 2 $M_\odot$
further increase of the DM fraction
leads to $M_{max} < 2\ M_\odot$

O. Ivanytskyi, VS, I. Lopes, Phys. Rev. D, 102, 063028 (2020)

Internal structure of the stars

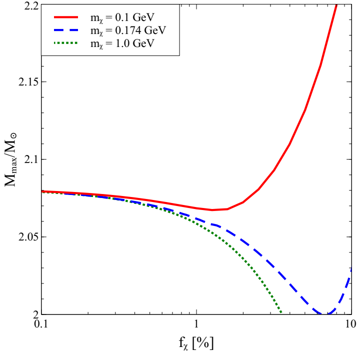




$R_D = 9.4$ km for $f_\chi = 0.3\%$
$R_D = 21.2$ km for $f_\chi = 1.0$ %
$R_D = 135.2$ km for $f_\chi = 3.0$ %

Large values of R_D relate to the existence of dilute and extended halos of DM around a baryon core of NS

Maximal mass of NS as a function of the DM fraction

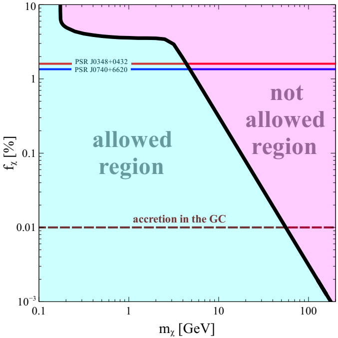


for $m_\chi = 0.174$ GeV M_{max} is 2 $M_\odot$

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

Constraint on the mass of DM particles



Navarro-Frenk-White distribution for DM:

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

$\rho_c = 5.22 \pm 0.46\, 10^7\, M_\odot \mathrm{kpc}^{-3}$ **and** $d_c = 8.1 \pm 0.7$ kpc

H.-N. Lin, X. Li, arXiv:1906.08419 (2019)

BM distribution in a stellar disc:

$$\rho_B(d) = \rho_{dc} e^{-\frac{d}{d_{dc}}} \quad (2)$$

$\rho_{dc} = 15.0\, M_\odot \mathrm{pc}^{-3}$ **and** $d_{dc} = 3.0$ **kpc**

Y. Sofue, Publ. Astr. Soc. Jap., 65, 118 (2013)

Pulsar	distance to the GC	f_χ^* (NFW distr)	f_χ^* (Einasto distr)
PSR J0348+0432	9.9 kpc	1.6 ± 0.4 %	1.35 ± 0.05 %
PSR J0740+6620	8.6 kpc	1.35 ± 0.35 %	1.12 ± 0.049 %

f_χ^* 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

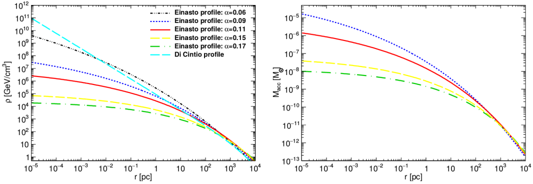
- Progenitor
  During the star formation stage the initial mixture of DM and BM contracting to form the progenitor star. Trapped DM undergoes scattering processes with baryons leading to its kinetic energy lost and thermalisation.
- Main sequence (MS) star
  From this stage of star evolution accretion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

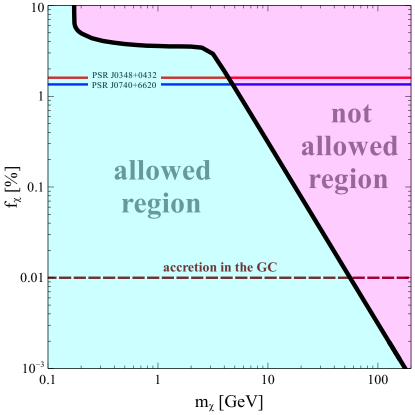
$$M_{acc} \approx 10^{-14} \left(\frac{\rho_\chi}{0.3 \ \frac{GeV}{cm^3}} \right) \left(\frac{\sigma_{\chi n}}{10^{-45} cm^2} \right) \left(\frac{t}{Gyr} \right) M_\odot , \quad (3)$$

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



A. Del Popolo, et al. (2019)

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_χ.

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!