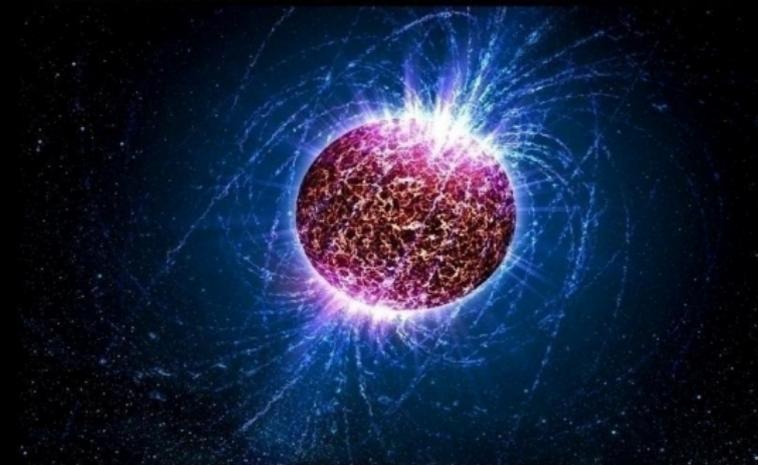# Neutron stars as dark matter probes

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CFisUC

Modern Physics of Compact Stars and Relativistic Gravity 2021
Yerevan, 27-30 Sep 2021

FCT Fundação para a Ciência e a Tecnologia

credits: Symmetry magazine

Effect of DM on NS properties

DM core contributing to 5% of the total NS mass
$$\sqrt{\sigma_{\mathrm{D}}}/m_{\mathrm{D}}^3 = 0.05\,\mathrm{GeV}^{-2}$$
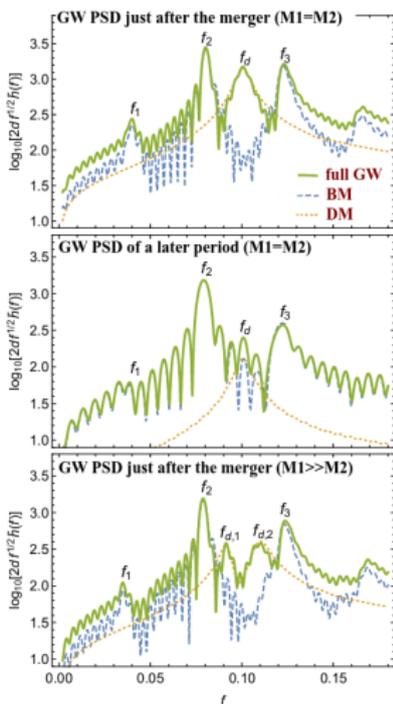
M. Deliyergiyev et al., PRD 99, 063015 (2019)
A. Del Popolo et al., Phys. D. Univ. 28, 100484 (2020)
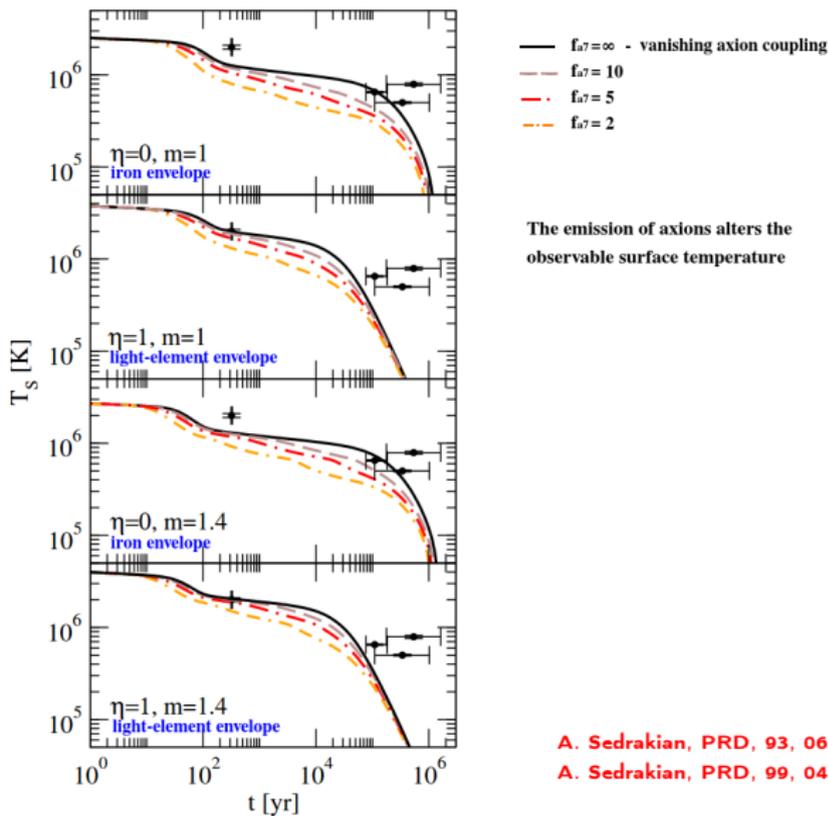J. Ellis et al., PRD 97, 123007 (2018)

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DM admixed NS

Fermionic DM

Accretion onto the NS

Bosonic DM

Conclusions

GW PSD just after the merger (M1=M2)

GW PSD of a later period (M1=M2)

GW PSD just after the merger (M1>>M2)

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)

$f_{a7} = \infty$ - vanishing axion coupling
$f_{a7} = 10$
$f_{a7} = 5$
$f_{a7} = 2$

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, JCAP 07, 012 (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., NPA, 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
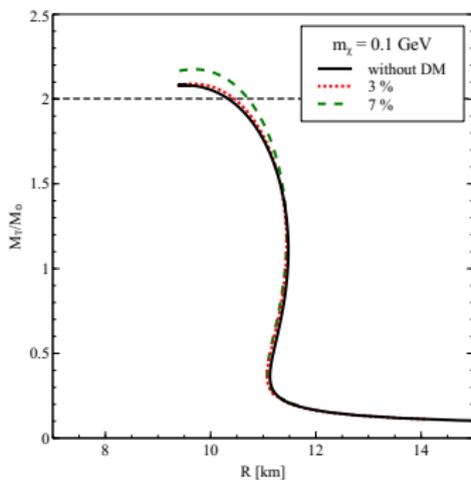
total pressure $p(r) = p_B(r) + p_D(r)$

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)
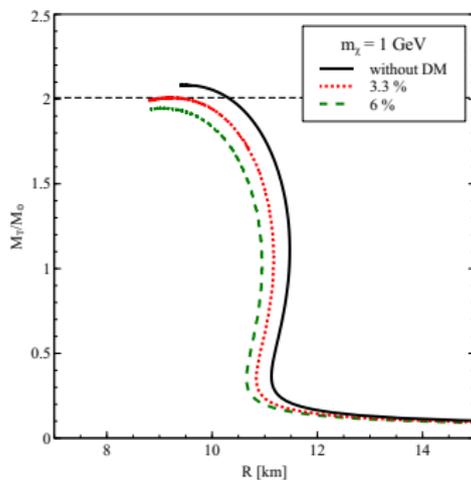
Fraction of DM inside the star:

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

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

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DM admixed
NS

Fermionic DM

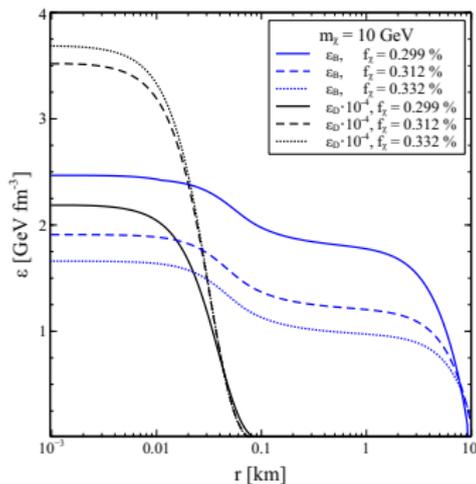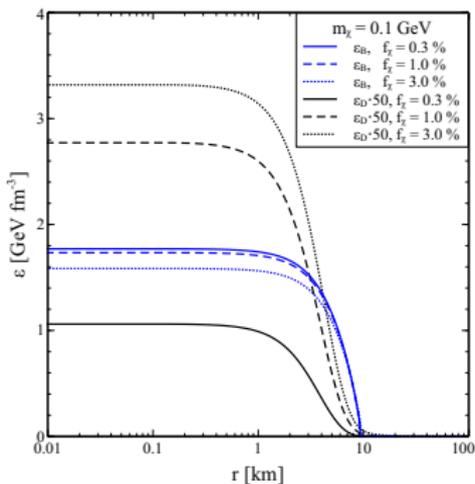Accretion onto
the NS

Bosonic DM

Conclusions

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

for $f_{\chi} = 3.3\ \%$ M_{max} equals to $2\ M_{\odot}$
further increase of the DM fraction
leads to $M_{max} < 2\ M_{\odot}$
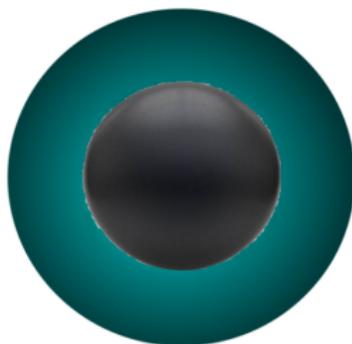
$R_D = 9.4$ km for $f_\chi = 0.3\%$
$R_D = 21.2$ km for $f_\chi = 1.0\ \%$
$R_D = 135.2$ km for $f_\chi = 3.0\ \%$

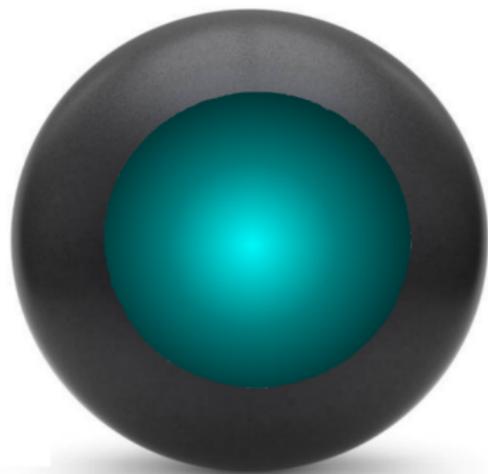Large values of R_D relate to the existence of dilute and extended halos of DM around a baryon core of NS
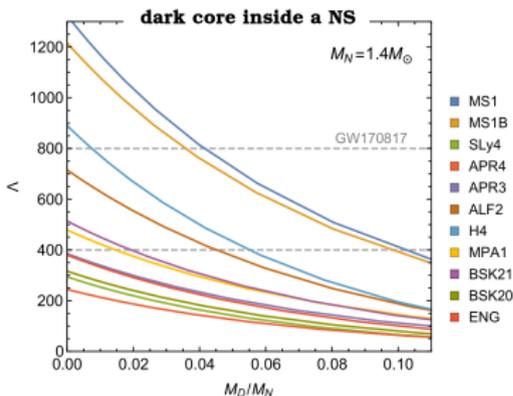
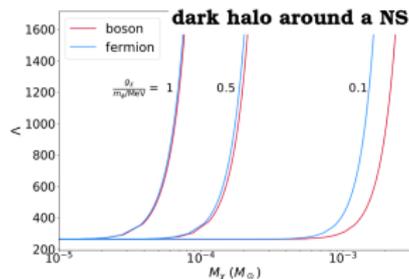**dark matter core**

dark core inside a NS

dark halo around a NS

Tidal deformability can be used as a probe of non standard physics!

- DM modifies tidal interactions between merging NSs in an opposite way: increases due to the presence of DM halo and decreases in the case of a DM core

dark core inside a NS

$M_N = 1.4 M_\odot$

GW170817

MS1
MS1B
SLy4
APR4
APR3
ALF2
H4
MPA1
BSK21
BSK20
ENG

dark halo around a NS

boson
fermion

$\frac{g_\chi}{m_\phi \text{MeV}} = 1$ 0.5   0.1

Λ increases rapidly with increasing total DM mass M_χ. For self-interacting DM with $g_\chi/m_\phi > 1$ MeV^{-1}, $M_\chi > 10^{-4} M_\odot$ will boost Λ above the upper bound ($\simeq 800$) set by GW170817.

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

A. Nelson et al., JCAP 7, 12 (2019)

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
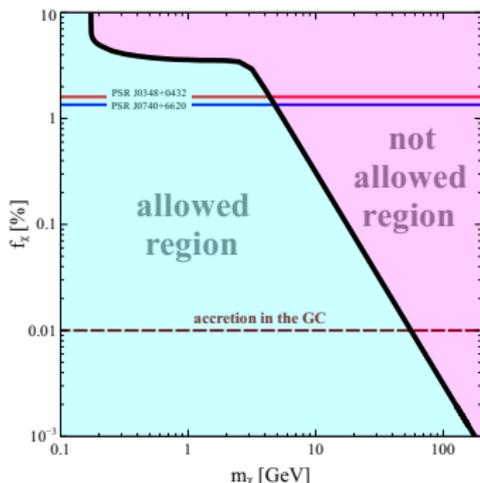
Constraint on the mass of DM particles

Navarro-Frenk-White distribution for DM:

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

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

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

BM distribution in a stellar disc:

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

$\rho_{dc} = 15.0\,M_\odot\,\mathrm{pc}^{-3}$ **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.
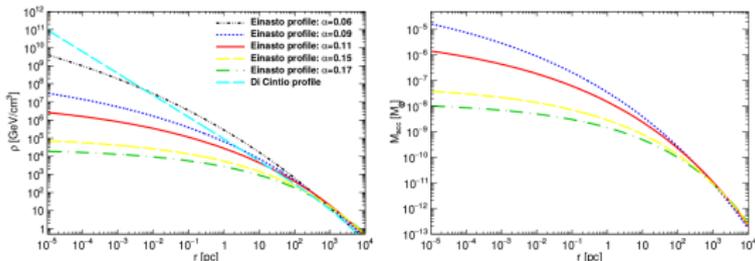
  Kouvaris & Tinyakov (2010)

  In addition, a significant amount of DM can be produced during the supernova explosion and mostly remain trapped inside the star.
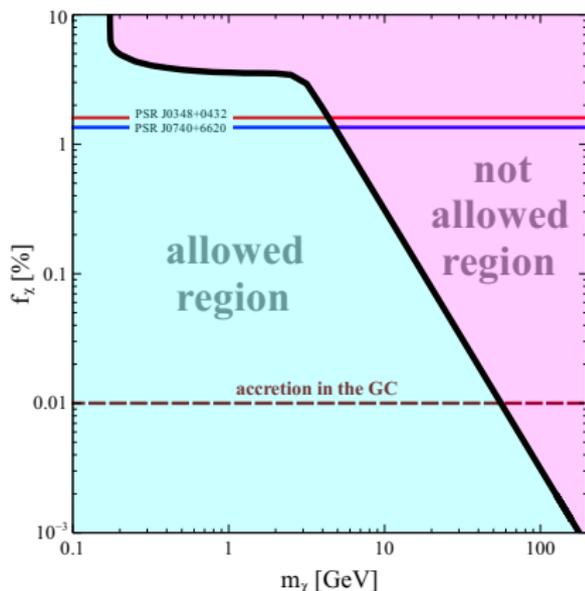
- **Equilibrated NS**

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

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

A. Del Popolo, et al. (2019)

DM admixed NS

Fermionic DM

Accretion onto the NS

Bosonic DM

Conclusions

$2M_\odot$ 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.

Bosonic DM

Bosonic matter EoS

We consider bosonic DM as a complex scalar particles with the self-interaction potential $V(\phi) = \frac{1}{4}|\phi^2|$

Pressure of the system equals to

$$P = \frac{m_\chi^4}{9\lambda} \left(\sqrt{1 + \frac{3\lambda}{m_\chi^4}\rho} - 1 \right)^2,$$

where m_χ is the DM particle mass.

The coupling constant is limited to

$$\lambda \gg 4\pi(m_\chi/M_{Pl})^2 = 8.43 \times 10^{-36} \left(\frac{m_\chi}{100\,\text{MeV}} \right)^2$$

M. Colpi, S. Shapiro, I. Wasserman, PRL 57, 2485 (1986)

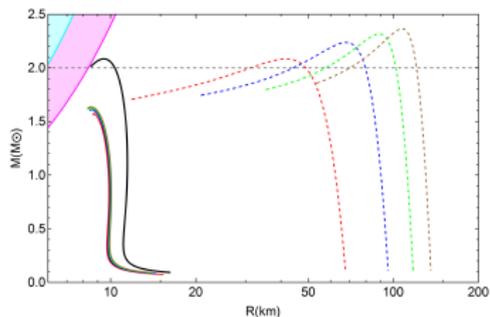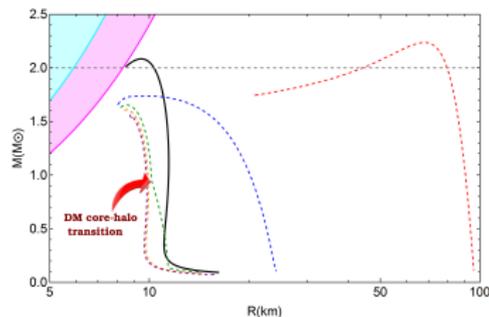# M-R diagrams for DM-admixed NSs
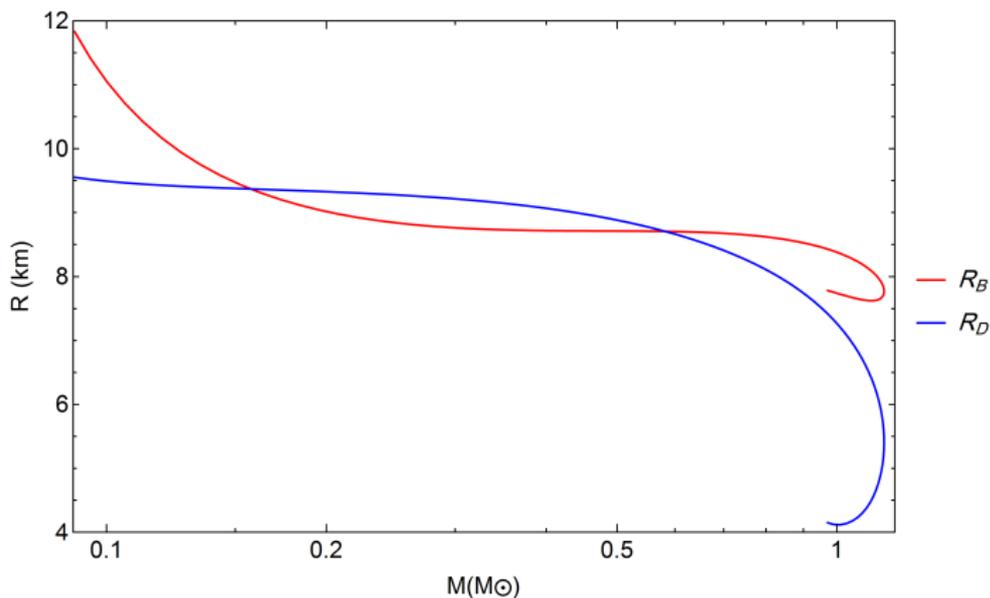
$m_\chi = 400$ MeV (solid curves), 100 MeV (dashed)

coupling constant $\lambda = \pi$, $f_\chi = 20\%$

R corresponds to the outermost radius, R_B or R_D depending on the DM distribution
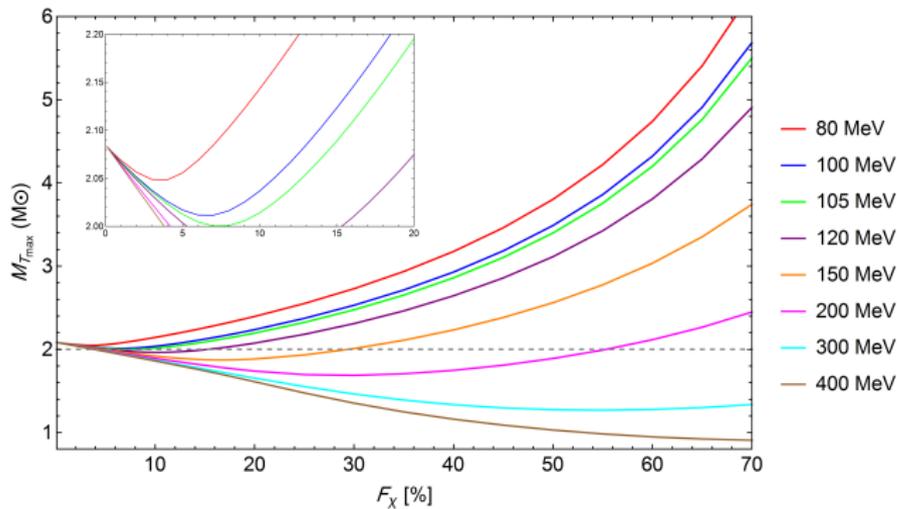
DM admixed NS

Fermionic DM

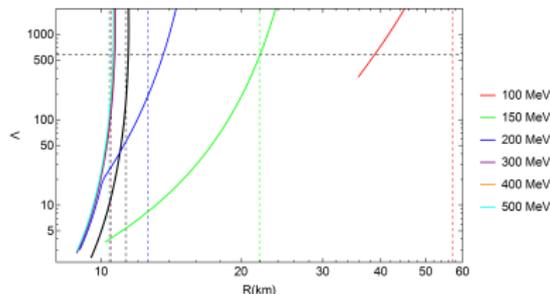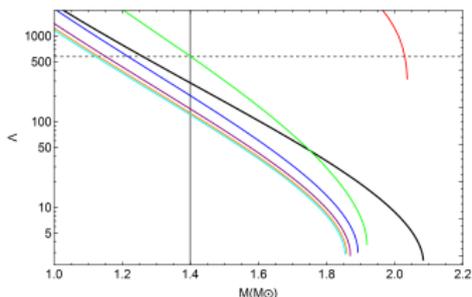Accretion onto the NS

Bosonic DM

Conclusions

Radius of BM (red curves) and DM (blue curves) components as a function of total gravitational mass are depicted for $f_\chi = 40\%$, $m_\chi = 400$ MeV and $\lambda = \pi$

DM particles with $m_\chi \leq 0.105$ GeV are consistent with the $2M_\odot$ constraint for any f_χ (for coupling constant $\lambda = \pi$)

coupling constant $\lambda = \pi$, fraction $f_\chi = 10\%$

Black solid curve → pure BM stars (without DM)
gray solid and dashed lines denote $M = 1.4 M_\odot$ and $\Lambda = 580$
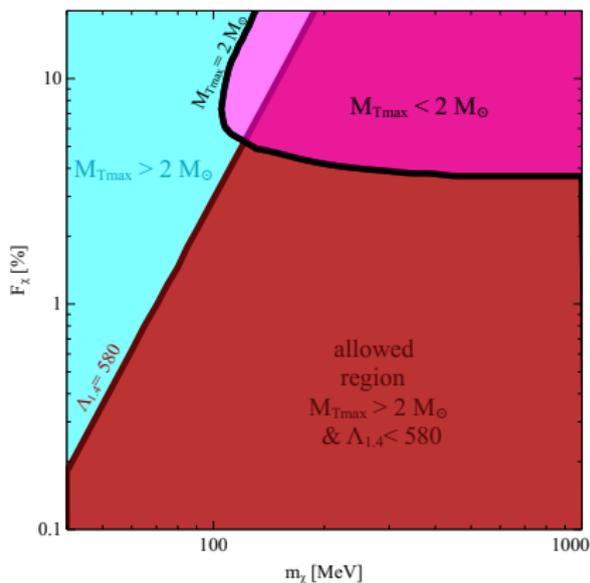We use LIGO/Virgo upper bound $\Lambda_{1.4} \leq 580$

Each vertical line corresponds to $R_{1.4}$ obtained for different values of boson mass

Abbott et al., PRL 121, 161101 (2018)

Love numbers and tidal polarizability are highly sensitive to EoS

$$\Lambda = \frac{2}{3} k_2 \left(\frac{R \ c^2}{G \ M} \right)^5$$

D.R. Karkevandi, S. Shakeri, VS, O. Ivanytskyi, arXiv:2109.03801 (2021)

We conclude that observations of $2M_\odot$ NSs together with $\Lambda_{1.4} \leq 580$ constraint, set by LIGO/Virgo Collaboration, favour sub-GeV DM particles with low fractions below $\sim 5\%$.

D.R. Karkevandi, S. Shakeri, VS, O. Ivanytskyi, arXiv:2109.03801 (2021)

Conclusions

DM admixed
NS

Fermionic DM

Accretion onto
the NS

Bosonic DM

Conclusions

- We demonstrated that DM can create either a dense core or an extended halo around a NS leading not to decrease but to increase of the NS total (gravitational) mass.
- From the combined analysis of the mass-radius relation and tidal deformability of compact stars we set a stringent constraint on fractions and mass of fermionic and bosonic DM.
- Measurements of a $2M_\odot$ NS in the GC will impose an upper constraint on the mass of fermionic DM particles of ~ 60 GeV.
- Tidal deformability constraint together with observations of $2M_\odot$ NSs favour sub-GeV bosonic DM particles with low fractions below $\sim 5\%$.
- 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 Kilometre 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 (eXTP)
  - the Spectroscopic Time-Resolving Observatory for Broadband Energy X-rays (STROBE-X)

  GW telescopes
  -LIGO/Virgo/KAGRA

Thanks for your attention!