Probing dark matter with neutron stars

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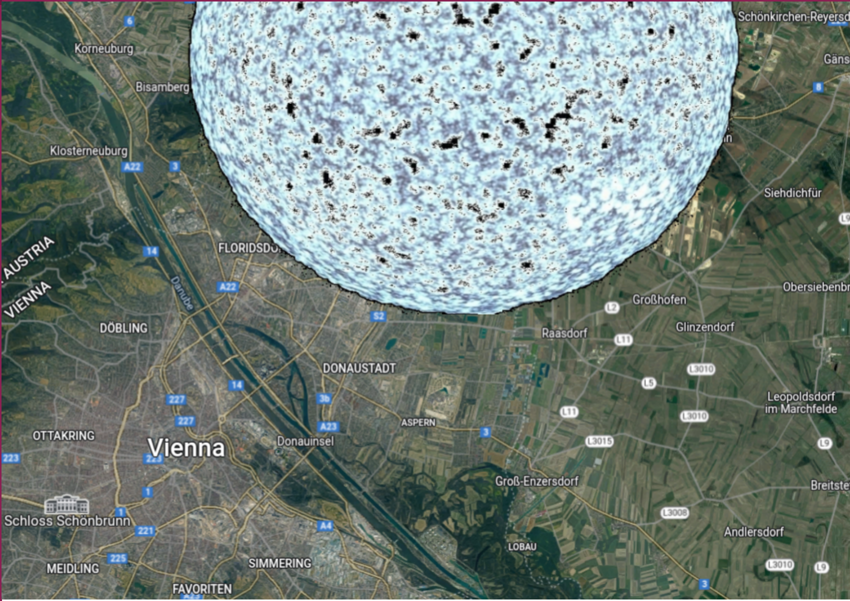
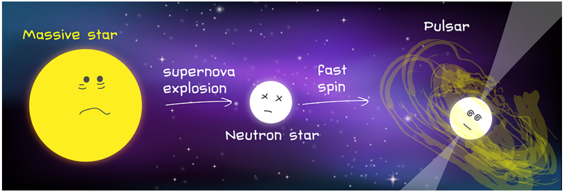
Neutron star has a size of Vienna



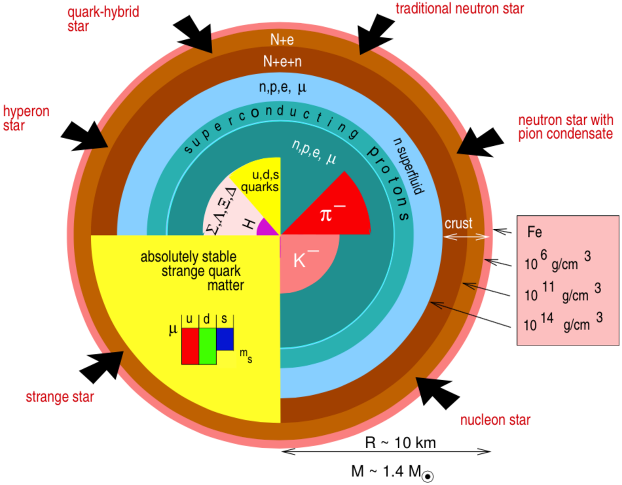
Neutron star

- the last stage of massive star evolution, produced in core collapse supernova explosion. Usually detected as a pulsar
- the most compact and exotic astrophysical objects in the universe that are accessible by direct observations
- the most extreme objects in terms of the rotation speed, density, radius, magnetic field, etc.



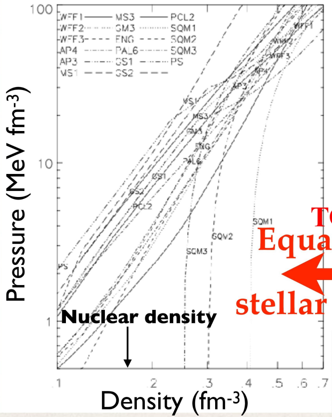
	Neutron star	White dwarf	Sun
$M_{max}(M_\odot)$	2	1.44	1
R (km)	11-12	10^4	$7 \cdot 10^5$
n_c (g/cm^3)	$10^{14} - 10^{15}$	10^7	10^2
rotation speed (s)	$10^{-3} - 1$	100	$2 \cdot 10^6$
B (G)	$10^8 - 10^{16}$	100	1
T (K)	$10^6 - 10^{11}$	10^3	10^5

Different Possible Structures

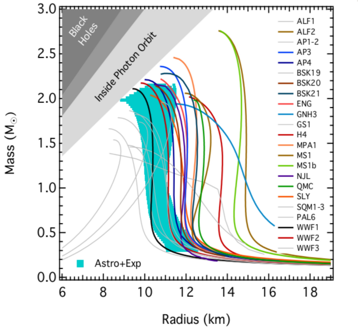


[Weber, J. Phys. G **27**, 465 (2001)]

EoS ⇔ M-R diagram



TOV
Equations of
stellar structure



Lattimer and Prakash 2001

DM candidates

credits: Symmetry magazine

DM accumulation regimes

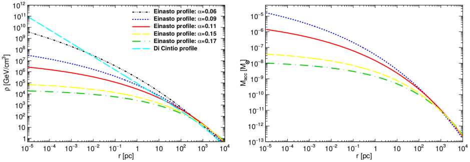
- Progenitor
  During the star formation stage the initial mixture of DM and BM contracting to form the progenitor star. Trapped DM undergoes scattering processes with baryons leading to its kinetic energy loss and thermalisation.
- Main sequence (MS) star
  From this stage of star evolution accretion 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.

  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

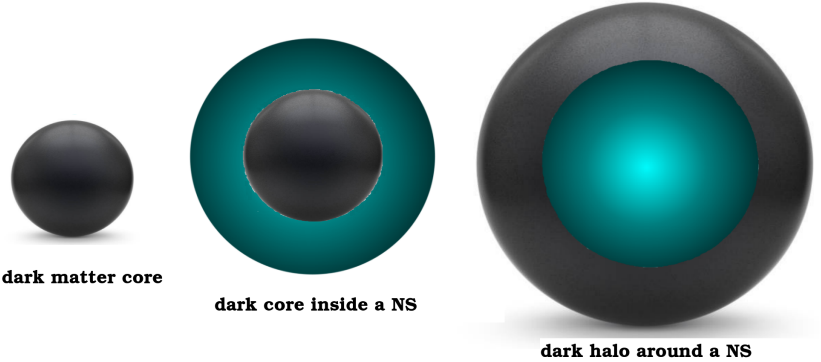
$$M_{acc} \approx 10^{-14} \left(\frac{\rho_{\chi}}{0.3 \ \frac{GeV}{cm^3}} \right) \left(\frac{\sigma_{\chi n}}{10^{-45} cm^2} \right) \left(\frac{t}{Gyr} \right) M_{\odot} , \quad (1)$$

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



Del Popolo+ 2019

DM and NS structure



Dark matter and baryon components do not expel each other but overlap due to absence of non-gravitational interaction

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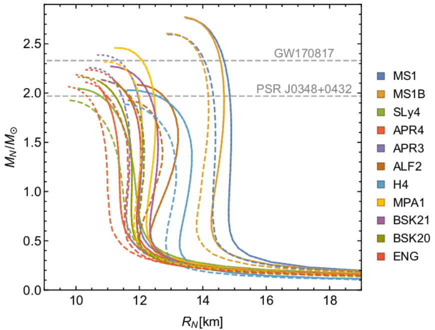
Effect of DM on Mass and Radius

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

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:

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

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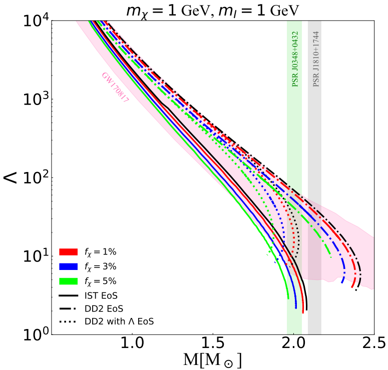
Tidal deformabilities of DM-admixed NS



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

Tidal deformability parameter

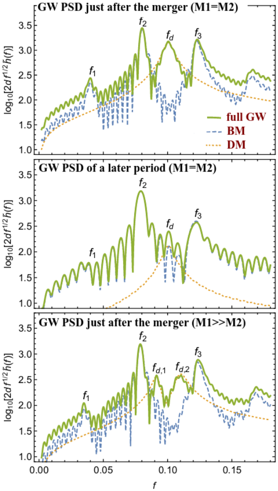
$$\Lambda = \frac{2}{3} k_2 \left(\frac{R_{\text{outermost}}}{M_{\text{tot}}} \right)^5$$

k_2 – Love's number.

- $R_{outermost} = R_B \geq R_D$ - DM core
- $R_{outermost} = R_D > R_B$ - DM halo

Speed of sound should be calculated for two-fluid system **Das+ 2020**

Effect of DM on GW waveform



Giudice+ 2016; 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

Numerical Simulations of DM Admixed NS Binaries

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

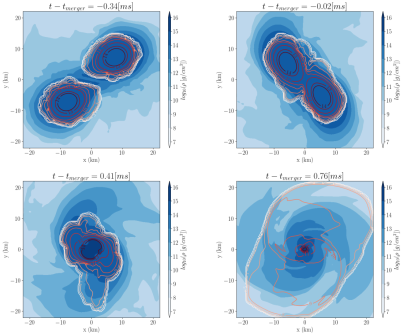
DM component: Mirror DM (mirrors the BM to a parallel hidden sector, the same particle physics as the observable world and couples to the latter through gravity)

Berezhiani 2004; **Ciancarella+ 2021**

BM component: SLy EoS

Initial configurations

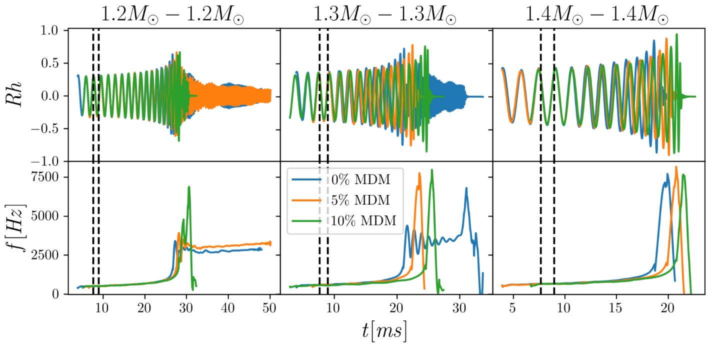
	$M_{A,B}$ ($M_\odot$)	Mirror dark matter %	ρ_c^b [ρ_{nuc}]	ρ_c^{dm} [ρ_{nuc}]	$R_{A,B}$ [km]
SLy_M14_0	1.4	0%	3.866	0	11.45
SLy_M14_5	1.4	5%	4.360	2.234	11.00
SLy_M14_10	1.4	10%	4.713	2.854	10.60
SLy_M13_0	1.3	0%	3.624	0	11.46
SLy_M13_5	1.3	5%	4.058	2.087	11.04
SLy_M13_10	1.3	10%	4.366	2.679	10.63
SLy_M12_0	1.2	0%	3.398	0	11.46
SLy_M12_5	1.2	5%	3.791	1.960	11.04
SLy_M12_10	1.2	10%	4.056	2.499	10.65



Emma+ 2022

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

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

	M_{ej} sphere ($M_\odot$)	M_{ej} integral ($M_\odot$)	M_{disk} ($M_\odot$)	$f_{merger}[Hz]$
SLy_M14_0	-	-	0.001	1770
SLy_M14_5	-	-	0.0008	2030
SLy_M14_10	-	-	0.0014	2058
SLy_M13_0	0.0168	$4.8 \cdot 10^{-3}$	0.062	1817
SLy_M13_5	0	$0.7 \cdot 10^{-3}$	0.001	1910
SLy_M13_10	0	$0.8 \cdot 10^{-3}$	0.0006	2221
SLy_M12_0	0	$0.3 \cdot 10^{-3}$	0.19*	1746
SLy_M12_5	0.0016	$2.6 \cdot 10^{-3}$	0.16*	1818
SLy_M12_10	0.0027	$3.3 \cdot 10^{-3}$	0.017	2198

Emma+ 2022

Dark matter

particle-antiparticle asymmetric

↓

accumulated inside a star

↓

- 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

particle-antiparticle symmetric

↓

DM particles can annihilate

↓

- 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

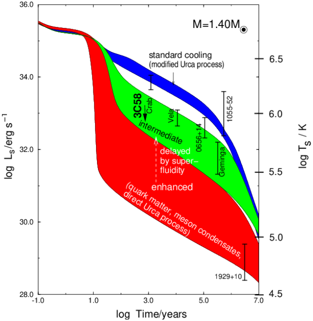
The time evolution of the red-shifted temperature is determined by

$$C\frac{dT^{\infty}}{dt} = -L_{\nu}^{\infty} - L_{\gamma}^{\infty} + L_{H}^{\infty}$$

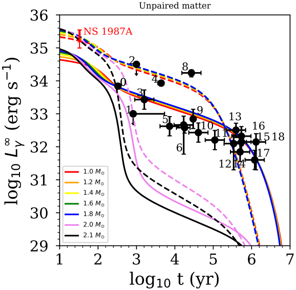
C - total heat capacity of the NS
L_{ν}^{∞} - red-shifted luminosity of the neutrino
L_{γ}^{∞} - red-shifted luminosity of the photon emissions
L_{H}^{∞} - red-shifted heating power

The photon emission luminosity is given by $L_{\gamma} = 4\pi R^2 \sigma_B T_S^4$, where σ_B is the Stefan-Boltzmann constant and R is the NS radius.

NS cooling



Credits: Fridolin Weber



Light DM particles, such as axions, could contribute as an additional cooling channel in compact stars and their mergers

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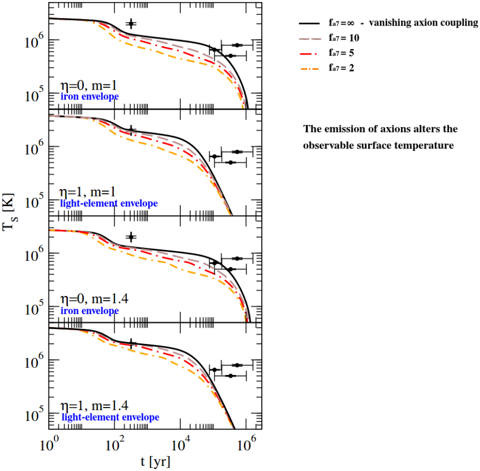
Creation mechanisms:

- nucleon bremsstrahlung
- Cooper pair breaking and formation processes

Buschmann+ 2022; Dietrich & Clough 2019

Cooling of NS with DM



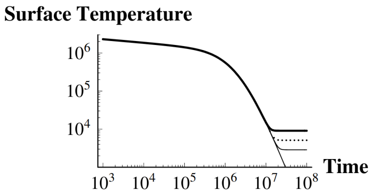
The emission of axions alters the observable surface temperature

Sedrakian 2016; 2019

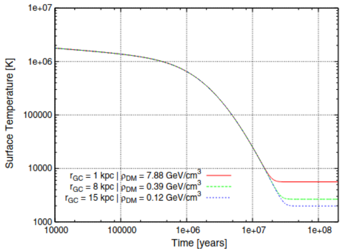
Heating of NS with DM

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, $m_\chi = 10$ GeV, $\sigma_0 = 1.5 \times 10^{-41}$ cm^2 and $(r_{-2}, \alpha) = (16$ kpc$, 0.19)$.

Lavallaz & Fairbairn 2010

DM admixed NSs

4 NSs with mass above $2M_\odot$

- PSR J0348+0432: $M = 2.01^{+0.04}_{-0.04} M_\odot$ (Antoniadis+ 2013)
- PSR J0740+6620: $M = 2.08^{+0.07}_{-0.07} M_\odot$ (Fonseca+ 2021)
- PSR J1810+1744: $M = 2.13^{+0.04}_{-0.04} M_\odot$ (Romani+ 2021)
- PSR J0952-0607: $M = 2.35^{+0.17}_{-0.17} M_\odot$ (Romani+ 2022)

Dark matter EoS

- **Asymmetric dark matter**
  relativistic Fermi gas of noninteracting particles with the spin 1/2

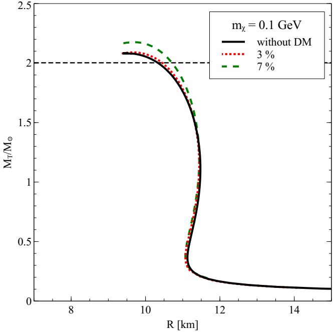
  Nelson+ 2019

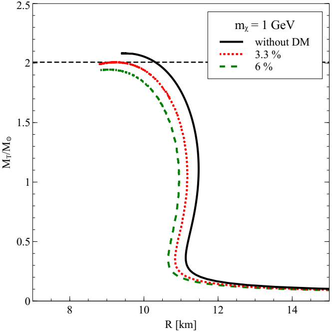
Baryon matter EoS

- **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



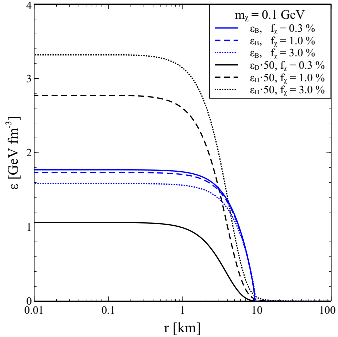


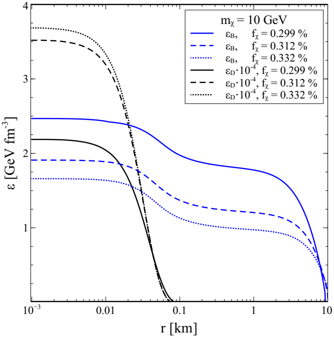
$M_{max} > 2\ M_\odot$ for any f_χ

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



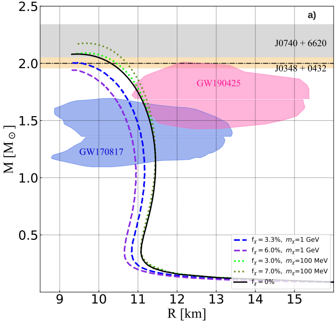


$R_D = 9.4$ km for $f_\chi = 0.3\%$
$R_D = 21.2$ km for $f_\chi = 1.0$ %
$R_D = 135.2$ km for $f_\chi = 3.0$ %

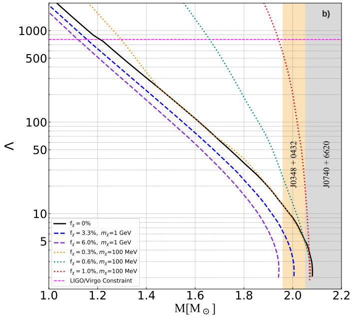
Large values of R_D relate to the existence of dilute and extended halos of DM around a baryon core of NS

DM admixed NSs

Mass-Radius diagram



Tidal deformabilities

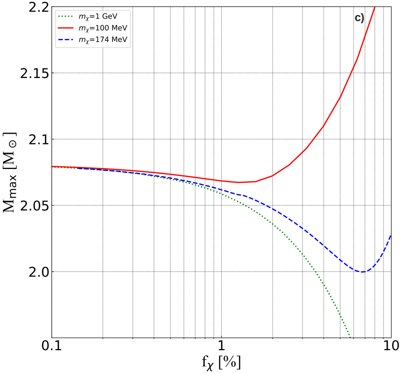


$$\Lambda = \frac{2}{3} k_2 \left(\frac{R_{\mathrm{outermost}}}{M_{\mathrm{tot}}} \right)^5 \longrightarrow \Lambda(1.4\mathrm{M}_\odot) < 800; \qquad (2)$$

Abbott+ 2018

Ivanytskyi+ 2020; VS+ 2022

Maximal mass of NS as a function of the DM fraction

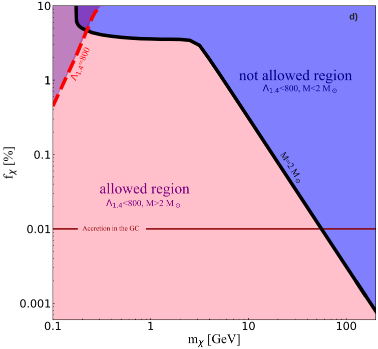


for $m_\chi = 0.174$ GeV M_{max} is 2 $M_\odot$

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

DM constraint in the Galaxy center

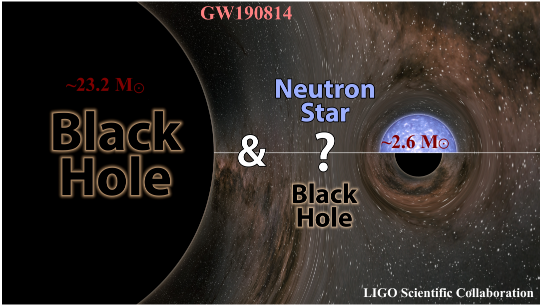


- $2M_\odot$ NS in the GC $\Rightarrow$ $m_\chi < 60$ GeV
- high DM fractions are not supported by GW170817

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

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.

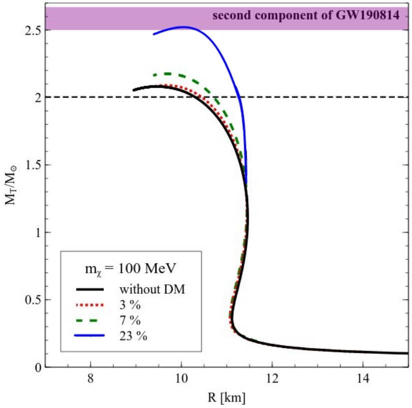
Possible explanations:

- NS with exotic degrees of freedom, e.g. hyperons and/or quarks **[Tan+ 2020; Dexheimer+ 2021, Ivanytskyi+ 2022]**
- 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)

Conclusions

- DM can be accumulated in the core of a NS $\Rightarrow$ significant decrease of the maximum mass and radius of a star.
- DM halo $\Rightarrow$ 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

$\downarrow$

different modifications of M, R, Λ, surface temperature, etc

The effect of DM could mimic the properties of strongly interacting matter

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 $\Rightarrow$ mass and radius reduction of NSs toward the Galaxy center
DM halo $\Rightarrow$ 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**

Thanks for your attention!