The effect of dark matter on compact stars and constraints we put on strongly interacting matter at high densities

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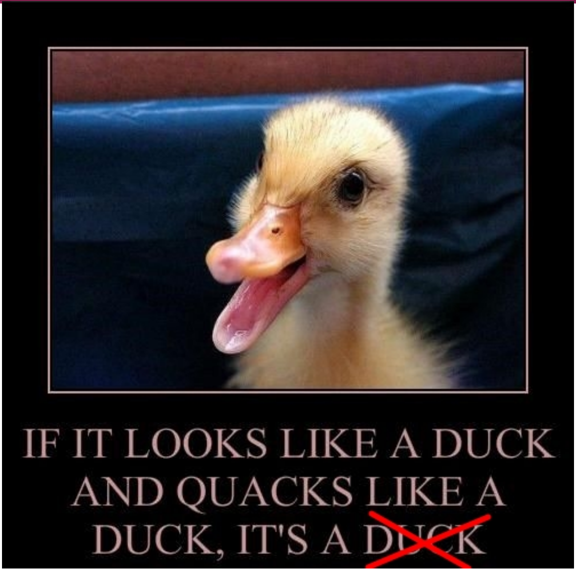
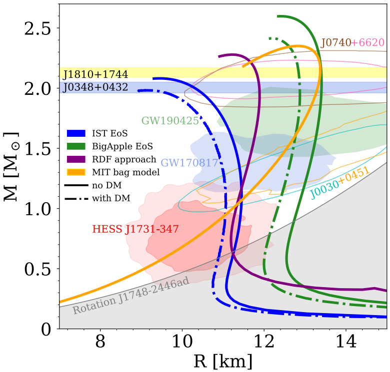

IF IT LOOKS LIKE A DUCK
AND QUACKS LIKE A
DUCK, IT'S A DUCK

Recap of the current constraints on the EoS of the QCD matter

- In NSs and NS mergers we can probe the EoS at densities up to $\sim 5n_0$
- Gravitational-wave inference of GW170817 and HIC suggest soft EoS at $2-3n_0$
- To reach $2M_\odot$ the EoS should be stiff enough at $> 3n_0$
- HESS J1731-347 favours a very soft EoS at $2-2.5n_0$

Oliinychenko+ 2023
Danielewicz+ 2002
Demorest+ 2010
Antoniadis+ 2013
Doroshenko+ 2022



Sagun+ 2023

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

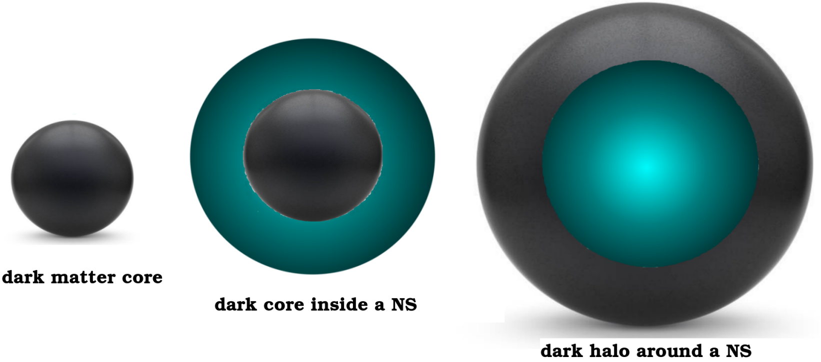
  In addition, a significant amount of DM can be produced during the supernova explosion and mostly remain trapped inside the star.
- **Equilibrated NS**

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

  In the most central Galaxy region $M_{acc} \approx 10^{-5} M_{\odot} - 10^{-8} M_{\odot}$.
- **Rapid DM accumulation**
  A rapid DM accumulation could occur while passing through an extremely dense regions with primordial DM clumps

  Bramante+ 2022

DM and NS structure

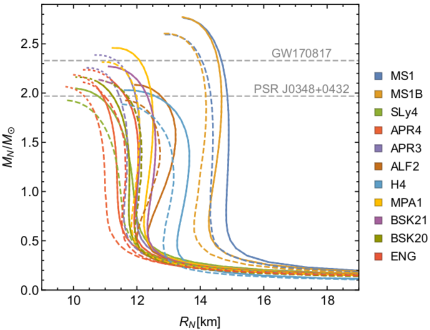


Dark matter and baryon components do not expel each other but overlap due to absence of non-gravitational interaction

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

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

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:

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

Ivanytskyi+ 2020

Asymmetric Bosonic Dark Matter

The minimal Lagrangian includes the complex scalar χ and real vector ω^μ fields, which are coupled through the covariant derivative $D^\mu = \partial^\mu - ig\omega^\mu$ with g being the corresponding coupling constant

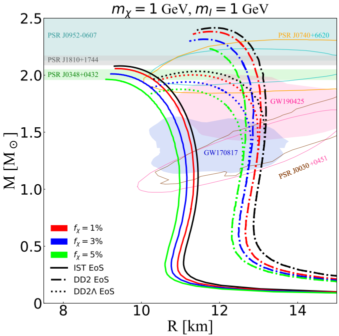
$$\mathcal{L} = (D_\mu \chi)^* D^\mu \chi - m_\chi^2 \chi^* \chi - \frac{\Omega_{\mu\nu}\Omega^{\mu\nu}}{4} + \frac{m_\omega^2 \omega_\mu \omega^\mu}{2} \quad (2)$$

where $\Omega^{\mu\nu} = \partial^\mu \omega^\nu - \partial^\nu \omega^\mu$ and m_ω is the vector field mass.
Using a mean field approximation for ω, we get

$$p_\chi = \frac{m_I^2}{4}\left(m_\chi^2 - \mu_\chi\sqrt{2m_\chi^2 - \mu_\chi^2}\right) \quad (3)$$

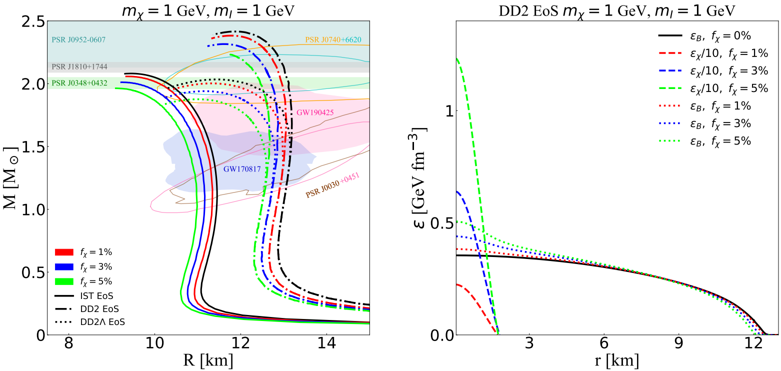
$$\varepsilon_\chi = \frac{m_I^2}{4}\left(\frac{\mu_\chi^3}{\sqrt{2m_\chi^2 - \mu_\chi^2}} - m_\chi^2\right) \quad (4)$$

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



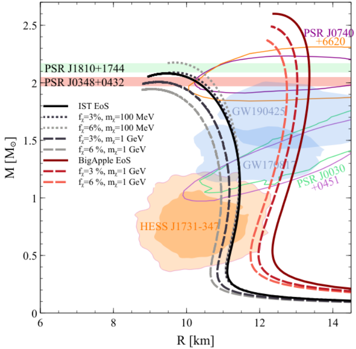
Giangrandi+ 2022

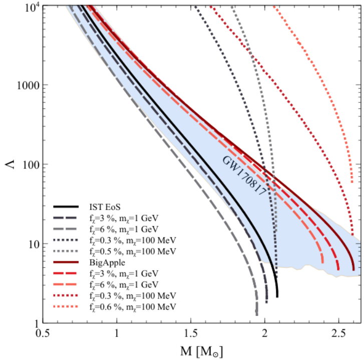
DM admixed NSs



Giangrandi+ 2022

DM admixed NSs





Tidal deformability parameter

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

k_2 – Love's number

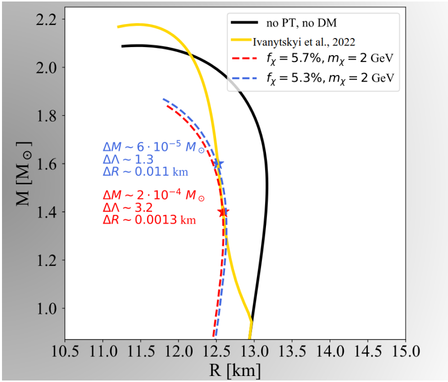
- $R_{outermost} = R_B \geq R_D$ - DM core
- $R_{outermost} = R_D > R_B$ - DM halo

Speed of sound should be calculated for two-fluid system **Giangrandi+ 2022**

Degeneracy between the DM and QGP cores

- DM and QGP cores may present undistinguishable mass, radius and tidal deformability;

How to split this degeneracy?

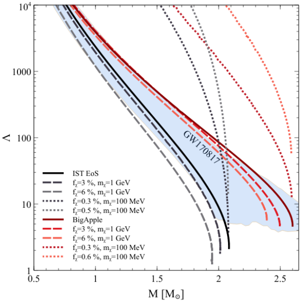


Sagun+ 2024 In prep.

An accumulated DM inside compact stars could mimic an apparent stiffening of strongly interacting matter equation of state and constraints we impose on it at high densities.

Next-generation GW telescopes

- How does DM bias the inference of the EoS from next-generation GW telescopes data?
- Can we distinguish between populations of NSs with and without DM using tidal deformability measurements from the Einstein Telescope and Cosmic Explorer?



EINSTEIN TELESCOPE

COSMIC EXPLORER

Koehn+ 2408.14711 [astro-ph.HE]

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.
- HESS J1731-347 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, 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 ⇒ 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. **Rüter+ 2023; Giangrandi+ 2024 (In prep)**

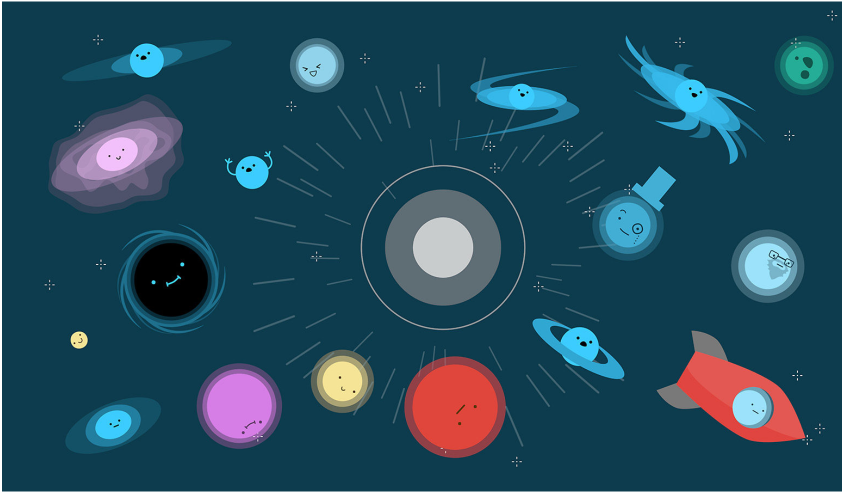
- **by detecting objects that go in contradiction with our understanding.**

HESS J1731-347 could be a candidate for a DM-admixed NS

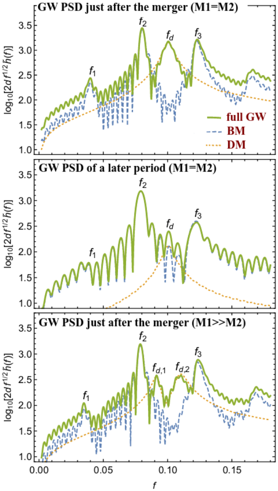
- **High/low surface temperature of NSs towards the Galaxy center**

Ávila+ 2024; Giangrandi+ 2024

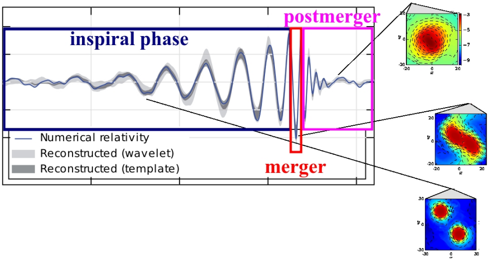
Thanks for your attention!



Effect of DM on GW waveform

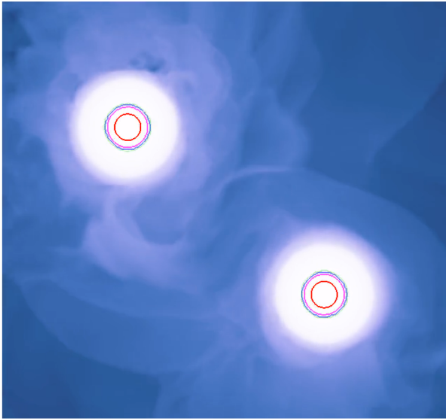


Giudice+ 2016; Ellis+ 2018; Bezares+ 2019



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

Mergers of Dark Matter Admixed Neutron Stars



Rüter+ 2023; Giangrandi+ 2024 (In prep)

- Dark matter core and halo configurations
- Baryonic matter: Sly4 EoS
- Dark matter: fermions with mass 1 GeV and 170 MeV, fractions 0.5%, 3%, 15%
- $1.2M_\odot + 1.2M_\odot$ and $1.4M_\odot + 1.4M_\odot$
- Eccentricity ~ 0
- Non-spinning stars