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Universidade de Coimbra

Breaking a degeneracy between the effects of dark matter and strongly interacting matter at high densities with the next-generation GW detectors

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CFisUC

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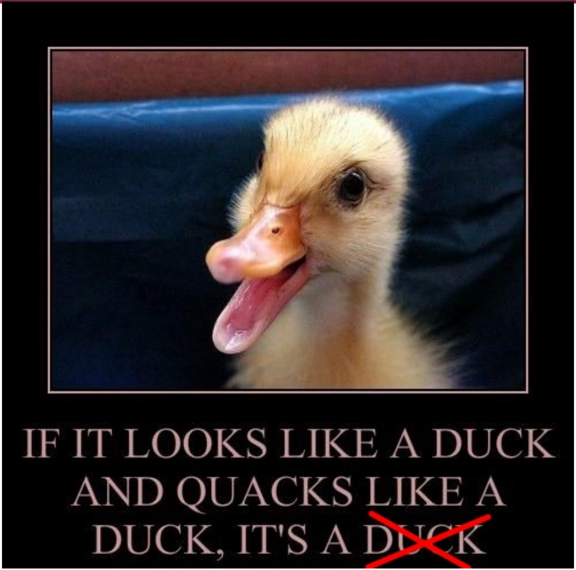
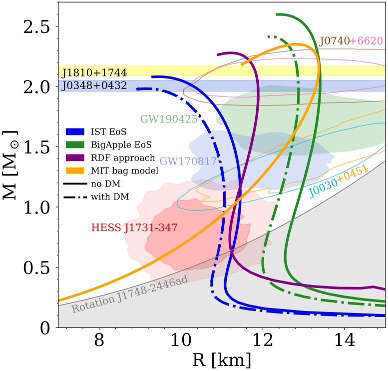
FCT Fundação para a Ciência e a Tecnologia


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

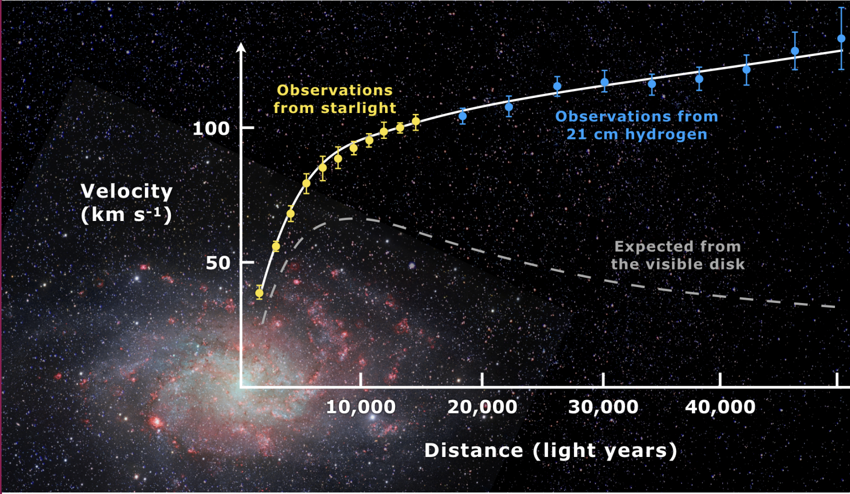
- In NSs and NS mergers we can probe the EoS at densities up to $\sim 5n_0$
- Gravitational-wave inference of GW170817 and HIC suggest soft EoS at $2-3n_0$
- To reach $2M_\odot$ the EoS should be stiff enough at $> 3n_0$
- HESS J1731-347 favours a very soft EoS at $2-2.5n_0$

Oliinychenko et al. (2023)
Danielewicz et al. (2002)
Demorest et al. (2010)
Antoniadis et al. (2013)
Doroshenko et al. (2022)



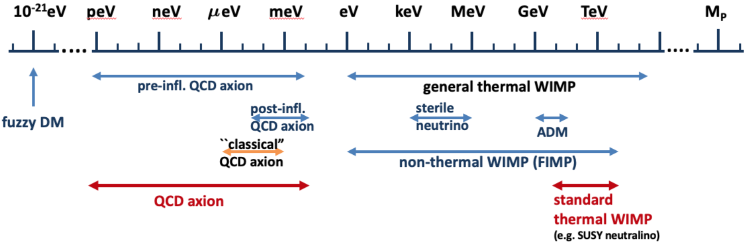
Sagun et al. (2023)

Rotational curves of galaxies



The term **dark matter** was proposed in 1933 by Fritz Zwicky

90 years of ignorance



10^{-21}eV peV neV μeV meV eV keV MeV GeV TeV M_P

fuzzy DM

pre-infl. QCD axion

post-infl. QCD axion

``classical" QCD axion

QCD axion

general thermal WIMP

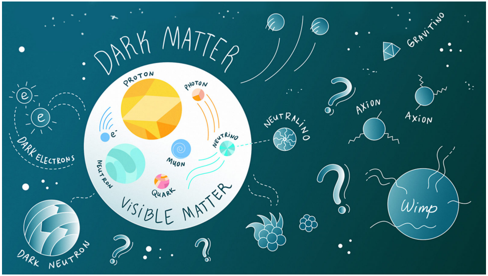
sterile neutrino

ADM

non-thermal WIMP (FIMP)

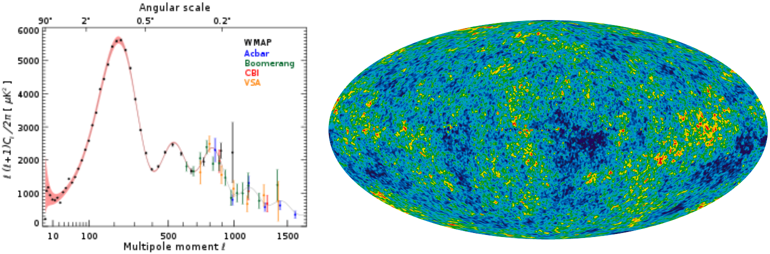
standard thermal WIMP

(e.g. SUSY neutralino)



credits: Symmetry magazine

Cosmic microwave background

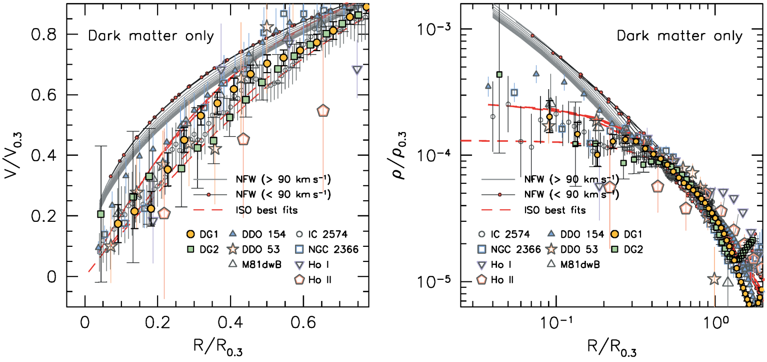


Planck data

Lambda cold (non-relativistic) dark matter model gives a good description of the CMB

LCDM model also agrees with the gravitational weak and strong lensing, large-scale structure formation

Core-cusp problem



Del Popolo & Le Delliou 2021

The cuspy Navarro-Frenk-White profile doesn't agree with the observational data of dwarf galaxies dominated by DM. They present significant departures from the LCDM model predictions.

Possible solution: DM is self-interacting

Merging clusters of galaxies

Combined analyses of several merging clusters of galaxies gives a stringent constraints on DM-DM & DM-BM interactions:

- an upper limit on the DM self-interaction cross-section of $\sigma/m < 1.25\ cm^2 g^{-1}$ (68% CL)

  Clowe+ 2006; Randall+2008

- self-collisional cross-section $\sigma/m < 0.19\ cm^2 g^{-1}$ (95% CL) at collision velocity $v_{DM-DM} \sim 1000$ km/s **Robertson +2021**

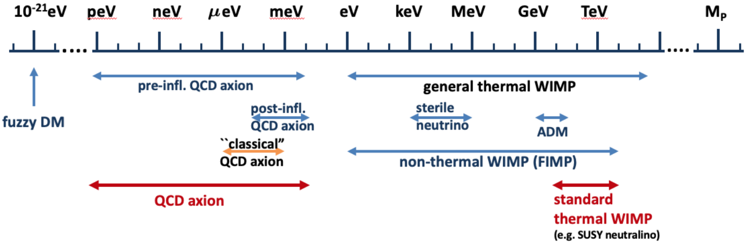
Bullet Cluster (1E 0657-56)

Pandora's Cluster (Abell 2744)

MACS J0025.4-1222

Collisions of galaxy clusters exhibit large separation between hot gas and DM
the total mass concentration (mostly DM), baryonic matter (hot gas). Credits: NASA.

Asymmetric DM



I will focus on heavy DM of $\geq$MeV mass range

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

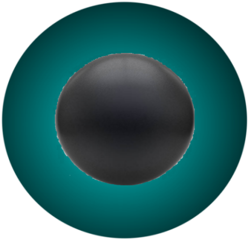
$$M_{acc} \approx 10^{-14} \left(\frac{\rho_{\chi}}{0.3 \ \frac{GeV}{cm^3}} \right) \left(\frac{\sigma_{\chi n}}{10^{-45} cm^2} \right) \left(\frac{t}{Gyr} \right) M_{\odot}, \tag{1}$$

  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

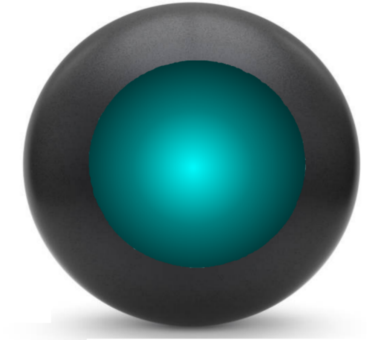
  Bramante et al. (2022)

DM and NS structure

dark matter core



dark core inside a NS



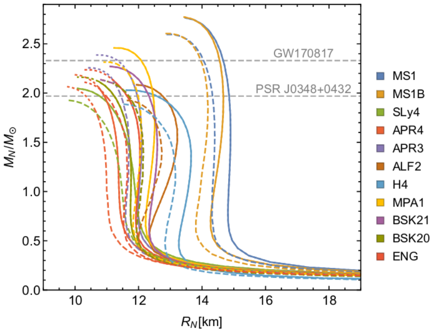
dark halo around a NS

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:

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

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

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

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

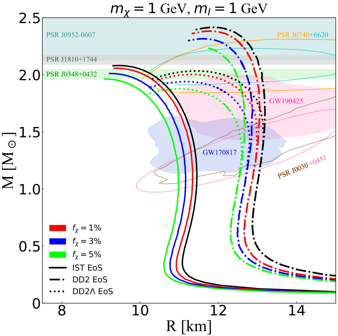
$$p_\chi = \frac{m_I^2}{4}\left(m_\chi^2 - \mu_\chi \sqrt{2m_\chi^2 - \mu_\chi^2}\right) \tag{3}$$

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

Chemical potential is limited

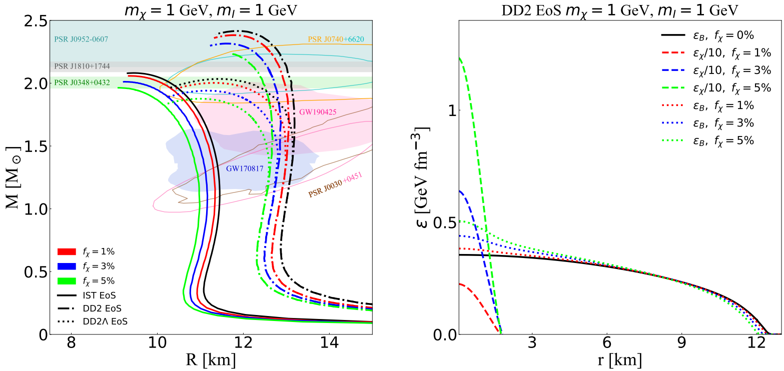
$\mu_\chi \in [m_\chi, \sqrt{2}m_\chi]$, m_χ - boson mass

$m_I = \frac{m_\omega}{g}$ - interaction scale



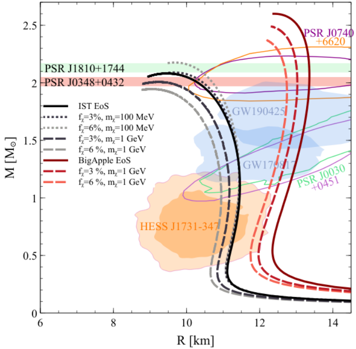
Giangrandi+ 2022

DM admixed NSs



Giangrandi+ 2022

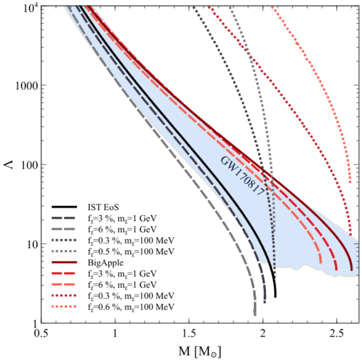
DM admixed NSs



Tidal deformability parameter

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

k_2 – Love's number



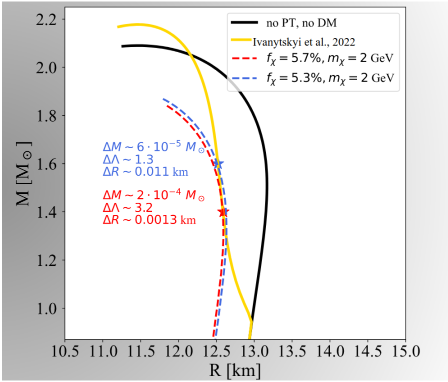
- $R_{outermost} = R_B \geq R_D$ - DM core
- $R_{outermost} = R_D > R_B$ - DM halo

Speed of sound should be calculated for two-fluid system **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?



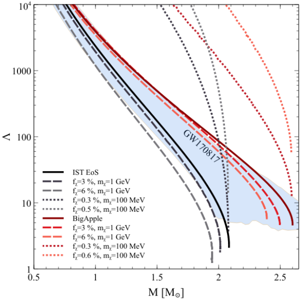
Sagun et al. 2024 In prep.

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

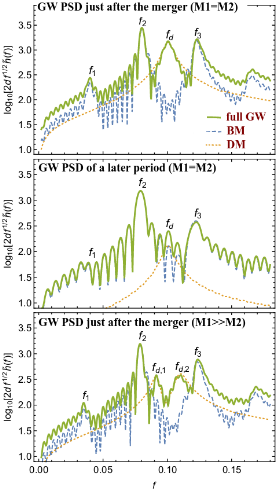
- How does DM bias the inference of the EoS from next-generation GW telescopes data?
- Can we distinguish between populations of NSs with and without DM using tidal deformability measurements from the Einstein Telescope and Cosmic Explorer?

2408.14711 [astro-ph.HE]

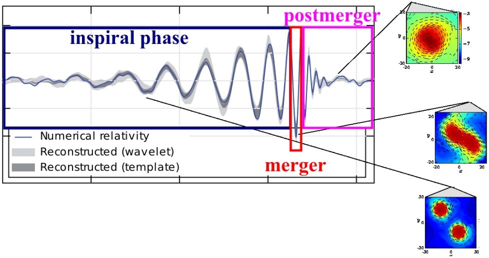


The answers are in the next talk by Hauke Koehn

Effect of DM on GW waveform



Giudice+ 2016; Ellis+ 2018; Bezares+ 2019



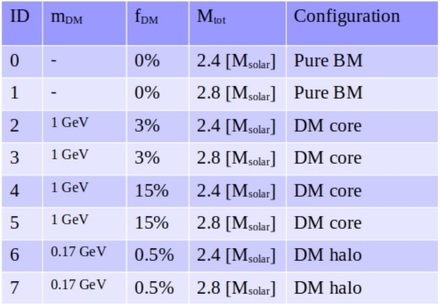
The DM cores may produce a supplementary peak in the characteristic GW spectrum of NS mergers, which can be clearly distinguished from the features induced by the baryon component

Initial setups

- Initial data are obtained solving Einstein's equations using the SGRID code
- Numerical simulations are performed with the BAM code

- DM is treated as a Relativistic Fermi gas of particles with mass m_{DM} and spin one-half

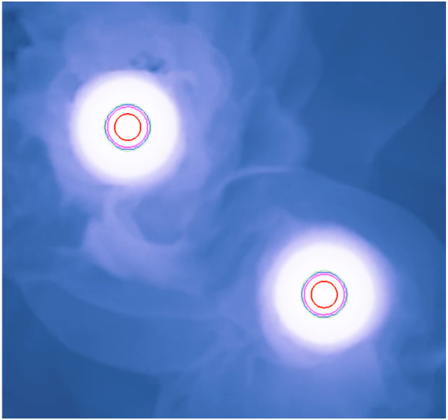
  Ivanytskyi+ 2020
- BM is described by Sly4 EoS
- Both DM core and halo configurations along with pure BM NSs
- Different DM mass fractions
- Different resolutions: 128, 144 and 192 points
- Two different total mass to better study the DM effects on the post-merger phase
- Quasi-equilibrium configuration obtained through the sgrid code.



ID	m_{DM}	f_{DM}	M_{tot}	Configuration
0	-	0%	2.4 [M_{solar}]	Pure BM
1	-	0%	2.8 [M_{solar}]	Pure BM
2	1 GeV	3%	2.4 [M_{solar}]	DM core
3	1 GeV	3%	2.8 [M_{solar}]	DM core
4	1 GeV	15%	2.4 [M_{solar}]	DM core
5	1 GeV	15%	2.8 [M_{solar}]	DM core
6	0.17 GeV	0.5%	2.4 [M_{solar}]	DM halo
7	0.17 GeV	0.5%	2.8 [M_{solar}]	DM halo

Rüter+ 2023; Giangrandi+ 2024 (In prep)

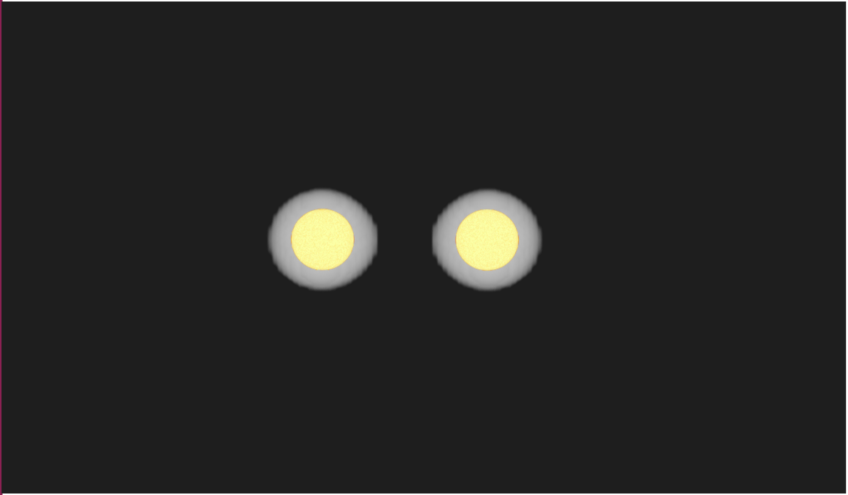
Mergers of Dark Matter Admixed Neutron Stars: core



Rüter+ 2023; Giangrandi+ 2024 (In prep)

- Dark matter core configuration
- Baryonic matter: Sly4 EoS
- Dark matter: fermions with mass 1 GeV, fraction 3%
- $1.2M_\odot + 1.2M_\odot$
- Eccentricity ~ 0
- Non-spinning stars

Mergers of Dark Matter Admixed Neutron Stars: halo



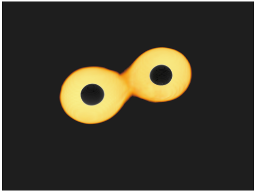
Rüter+ 2023; Giangrandi+ 2024 (In prep)

Dark matter core simulations

- Higher DM fraction leads to a longer inspiral likely due to a lower deformability of DM-admixed NSs;
- Faster formation of the BH after the merger and harder to eject material from the bulk of the stars prior to the BH formation;
- The lack of DM ejecta and debris disks is related to its concentration in the NS core;
- DM component might remain gravitationally bound after the merger of BM and orbit the center of the remnant with an orbital separation of a few km;
- The orbital separations of typically a few km is resulted in a kHz-band GW signal that could be sought in GW searches;

Bauswein+ 2023

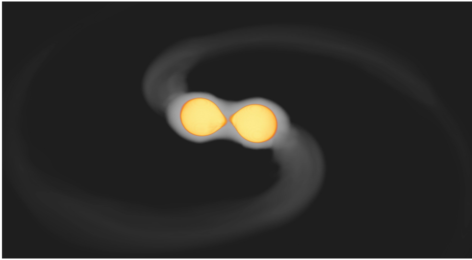
- The DM core and a host star are likely to spin at different rotational frequencies just after the merger due to the absence of non-gravitational interaction. Further on, they may synchronise via the gravitational angular momentum transfer, including tidal effects;
- DM core favours a formation of a one-arm spiral instability.



Rüter+ 2023; Giangrandi+ 2024 (In prep)

Dark matter halo simulations

- At t=0, two DM-admixed stars have still not touched each other;
- Higher DM fractions leads to more extended DM haloes, and, consequently, to higher tidal deformabilities;



Rüter+ 2023; Giangrandi+ 2024 (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.
- 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

↓

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.

- **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 et al. MNRAS 528, 4, 6319 (2024); Giangrandi et al. Particles 7, 179 (2024)