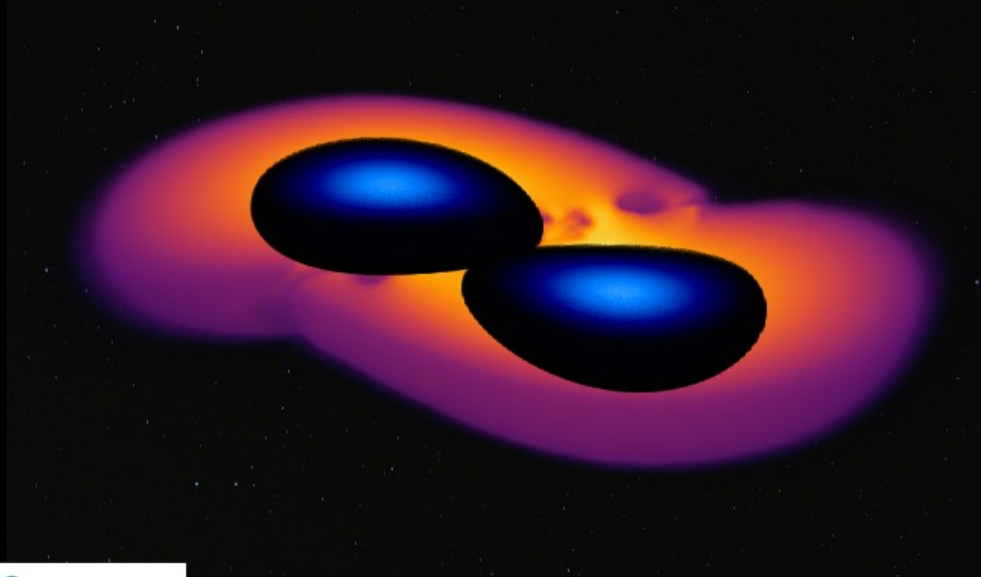


# Dark Matter in Neutron Stars: Imprints on Stellar Structure and Gravitational Waves

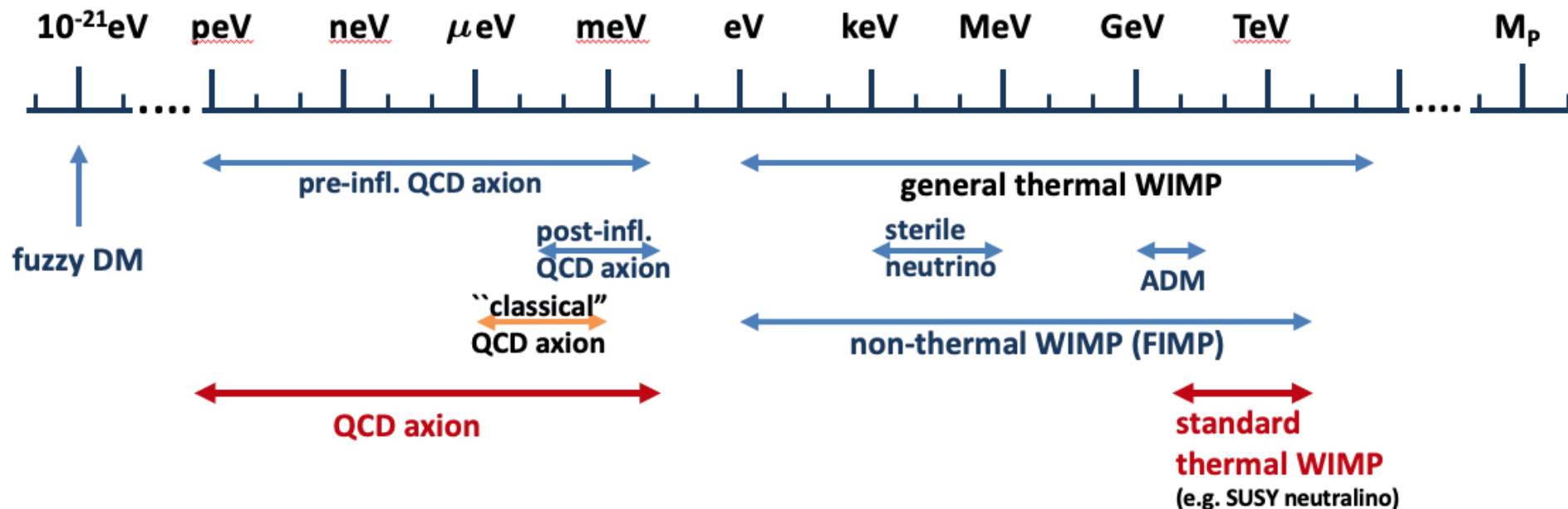
**Violetta Sagun**  
**University of Southampton**

In collaboration with A. Abac, A. Adhikari, T. Dietrich, M. Emma, E. Giangrandi, O. Ivanytskyi, H. Koehn, N. Kunert, C. Providência, H. R. Rüter, R. Somasundaram, W. Tichy



Arxiv: 2504.20825 [astro-ph.HE]

# 92 years of ignorance



I will focus on heavy DM of  $\geq \text{MeV}$  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 baryon 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  $M_{\text{acc}} \approx 10^{-5} M_{\odot} - 10^{-9} M_{\odot}$ .

- **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.

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

- **Equilibrated NS**

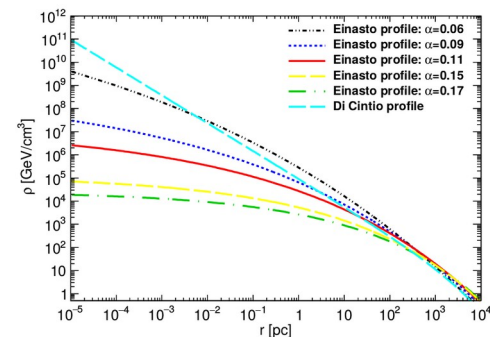
$$M_{\text{acc}} \approx 10^{-14} \left( \frac{\rho_{\chi}}{0.3 \frac{\text{GeV}}{\text{cm}^3}} \right) \left( \frac{\sigma_{\chi n}}{10^{-45} \text{cm}^2} \right) \left( \frac{t}{\text{Gyr}} \right) M_{\odot}$$

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

- **Rapid DM accumulation**

A rapid DM accumulation could occur while passing through an extremely dense regions with DM clumps

Kouvaris & Tinyakov (2010)  
Del Popolo et al. (2024)



Bramante et al. (2022)

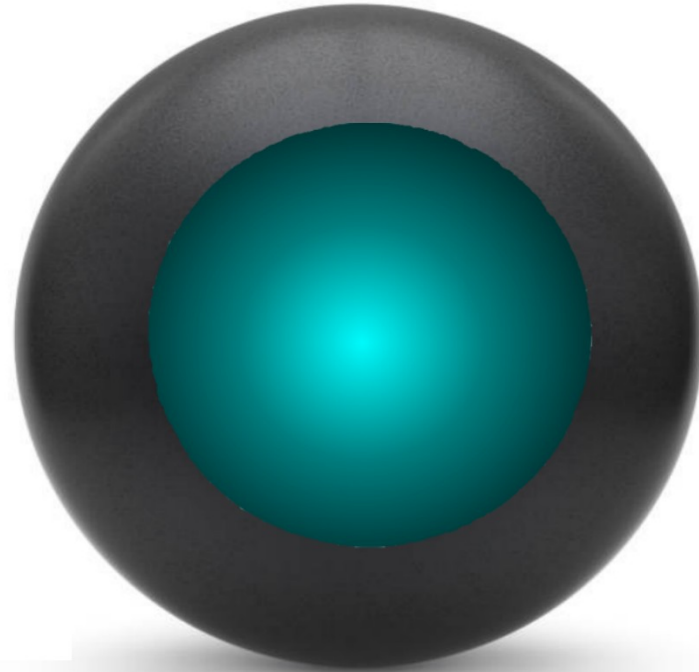
# Evidences of DM



**dark matter core**



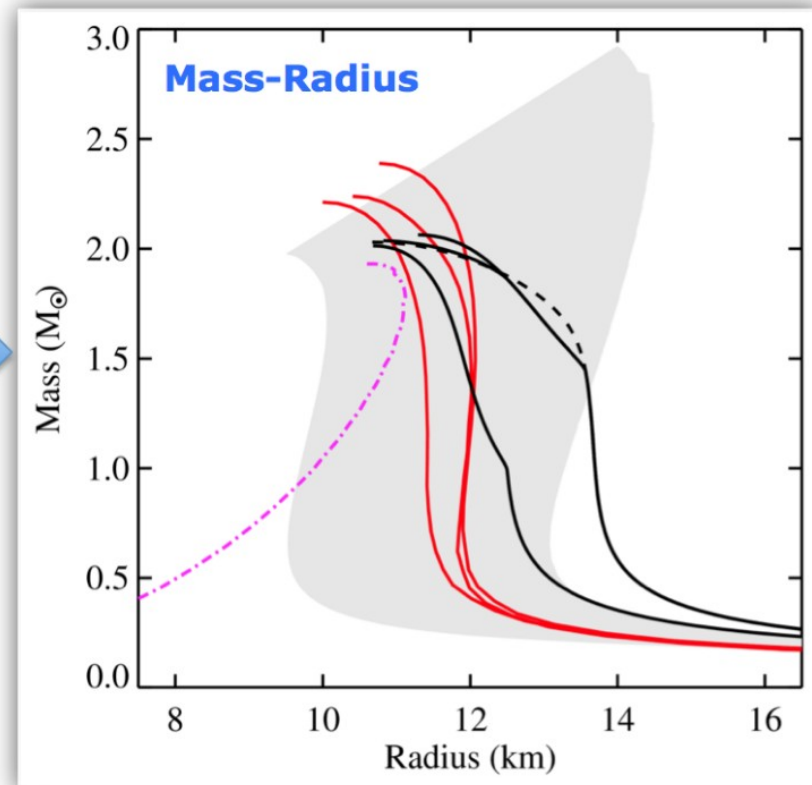
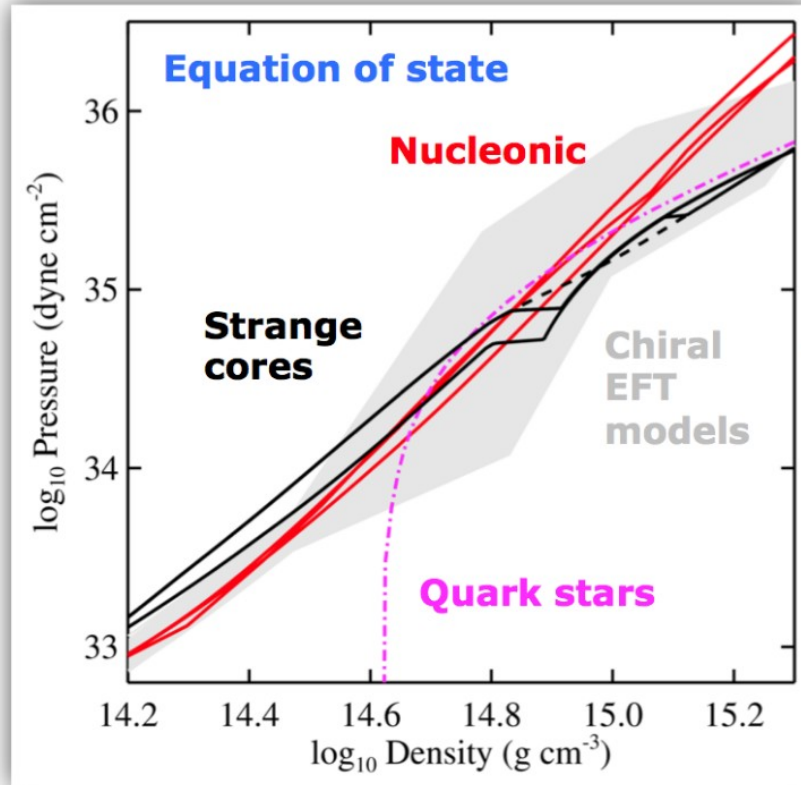
**dark core inside a NS**



**dark halo around a NS**

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

# Internal composition of compact stars



Equation of state is an input to the Tolman-Oppenheimer-Volkoff (TOV) equation



# Two-fluid approach

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)

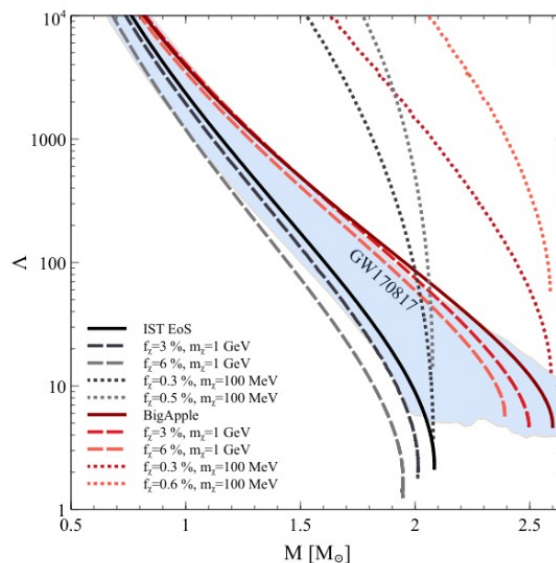
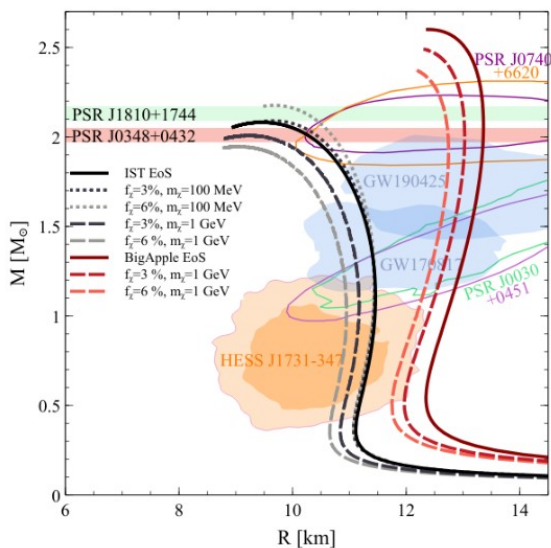
$M_T = M_B(R_B) + M_D(R_D)$  - total gravitational mass

Fraction of DM inside the star:

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



# DM admixed NSs



Tidal deformability parameter

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

$k_2$  – Love's number

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

**The speed of sound is calculated considering the total energy density and pressure**

Giangrandi+ 2022

$$c_{s,\text{tot}}^2 = \frac{dp_{\text{tot}}}{d\varepsilon_{\text{tot}}}$$



# Next-generation GW telescopes

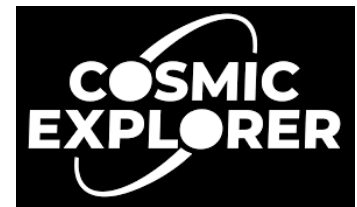
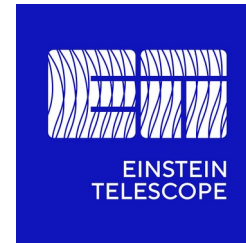


- How does DM bias the inference of the EoS from next-generation GW telescopes data?
  - Can we distinguish between populations of NSs with and without DM using tidal deformability measurements from the Einstein Telescope and Cosmic Explorer?
- we created a catalog of 500 high-SNR BNS events and used the Fisher matrix approach to obtain estimates of the posterior uncertainties.
- In different instances of the catalog the injected baryonic EOS, DM particle mass, and the chosen distribution for the DM fraction were varied.

**We find that DM could bias the EoS in future detections; however, due to degeneracy, it is challenging to detect**

**More on this in Afonso Ávila's next talk**

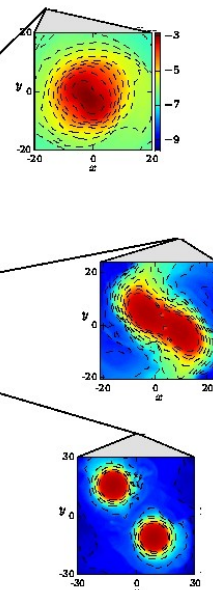
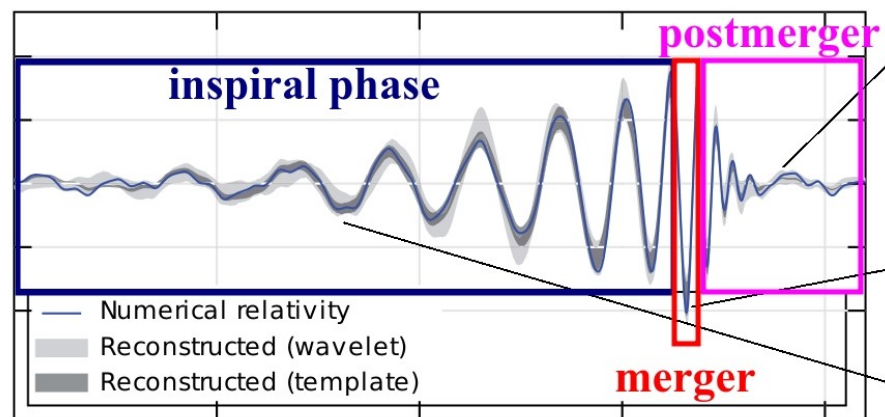
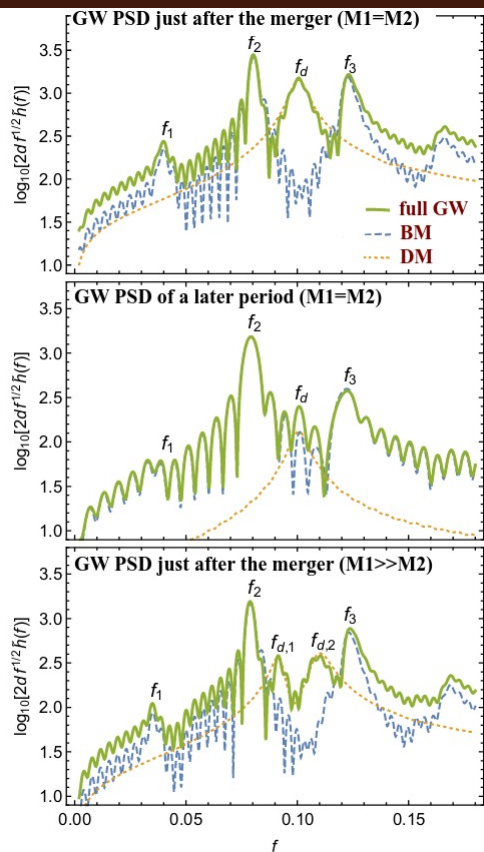
Koehn+ 2024







# Probing DM with BNS mergers



## What is the impact of DM on

- GW waveform
- post-merger phase
- kilonova ejects
- remnant

Giudice+ 2016; Ellis+ 2018; Bezares+ 2019



# Initial setups



- Initial data are obtained solving Einstein's equations using the SGRID code
- Numerical simulations are performed with the BAM code
- DM is modeled as a Relativistic Fermi gas of particles with mass  $m_{\text{DM}}$  and spin one-half
- BM is described by Sly4 EoS

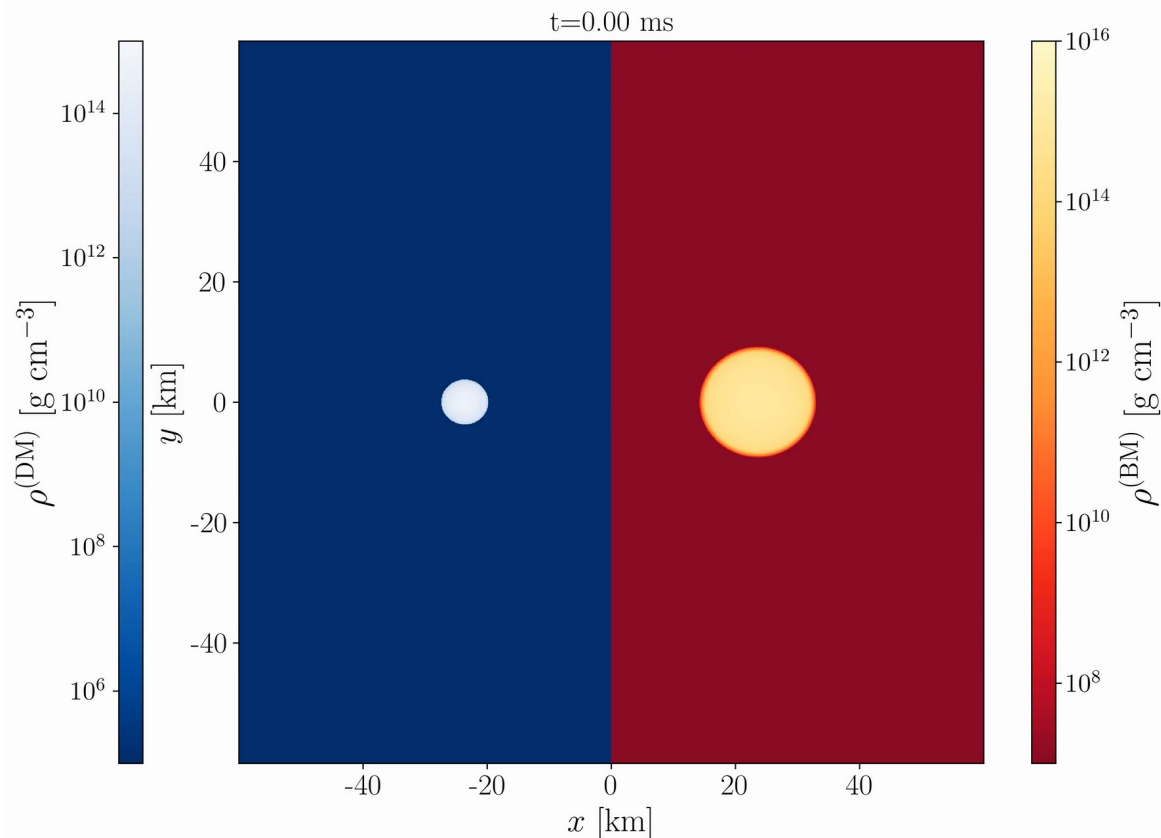
Ivanytskyi+ 2020

Rüter+ 2023

| identifier         | $m_{\text{DM}}$ [GeV] | $f_{\text{DM}}$ [%] | $2 \cdot M_{\text{TOV}}$ [ $M_{\odot}$ ] | $M_{\text{ADM}}$ [ $M_{\odot}$ ] | $J_{\text{ADM}}$ [ $M_{\odot}^2$ ] | $R^{(\text{BM})}$ [km] | $R^{(\text{DM})}$ [km] | $d_{\text{in}}$ [km] | $\Lambda^{\text{out}}$ | DM Morphology |
|--------------------|-----------------------|---------------------|------------------------------------------|----------------------------------|------------------------------------|------------------------|------------------------|----------------------|------------------------|---------------|
| M24 <sub>00</sub>  | -                     | 0                   | 2.40                                     | 2.382                            | 6.39                               | 11.400                 | -                      | 53.05                | 818                    | None          |
| M24 <sub>3C</sub>  | 1                     | 3                   | 2.40                                     | 2.381                            | 6.08                               | 11.154                 | 5.329                  | 47.02                | 730                    | Core          |
| M24 <sub>05H</sub> | 0.17                  | 0.5                 | 2.40                                     | 2.381                            | 6.09                               | 11.377                 | 18.645                 | 46.91                | 2908                   | Halo          |
| M28 <sub>00</sub>  | -                     | 0                   | 2.80                                     | 2.778                            | 8.38                               | 11.407                 | -                      | 56.02                | 310                    | None          |
| M28 <sub>3C</sub>  | 1                     | 3                   | 2.80                                     | 2.774                            | 7.91                               | 11.143                 | 5.122                  | 47.07                | 234                    | Core          |
| M28 <sub>05H</sub> | 0.17                  | 0.5                 | 2.80                                     | 2.774                            | 7.86                               | 11.379                 | 16.575                 | 46.98                | 901                    | Halo          |



# Dark matter core configuration

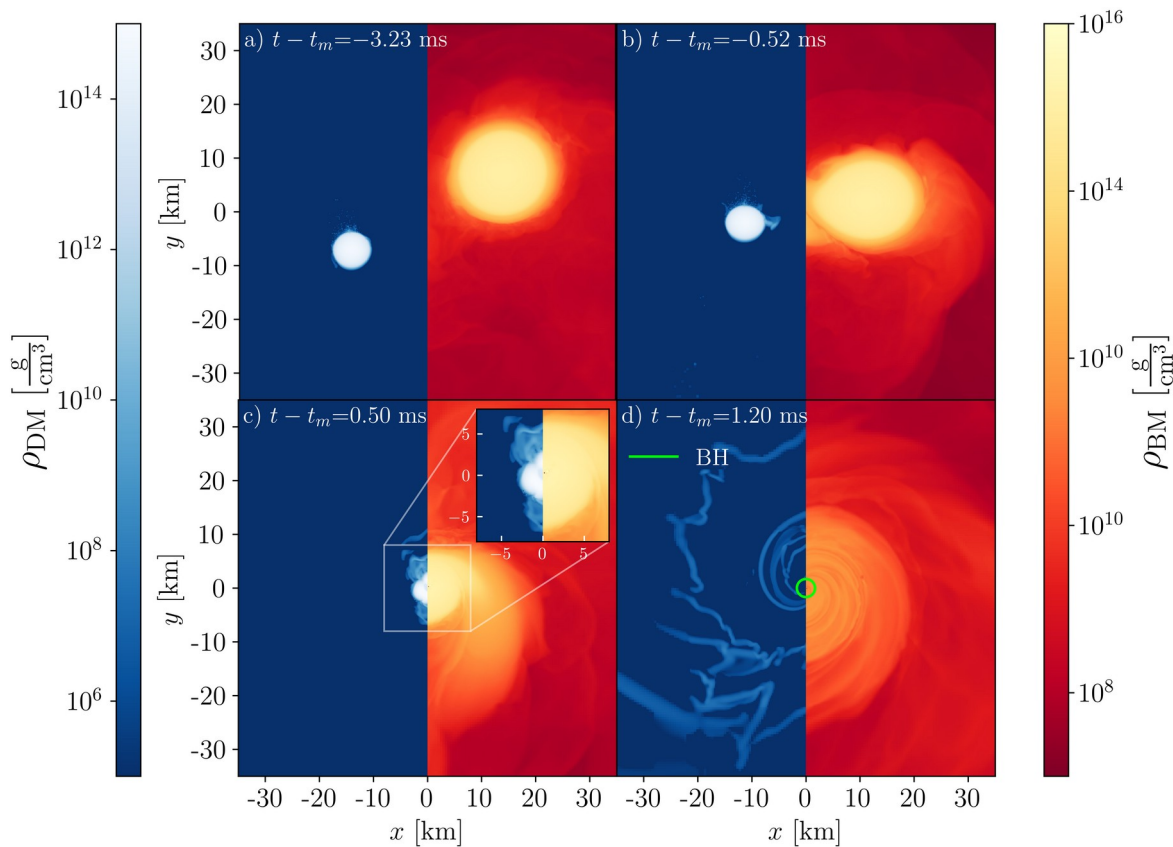


- Baryonic matter: Sly4 EoS
- Dark matter: fermions with mass 1 GeV, fraction 3%
- $1.2M_{\odot} + 1.2M_{\odot}$
- Eccentricity  $\sim 0$
- Non-spinning stars

Giangrandi+ 2025



# Dark matter core configuration

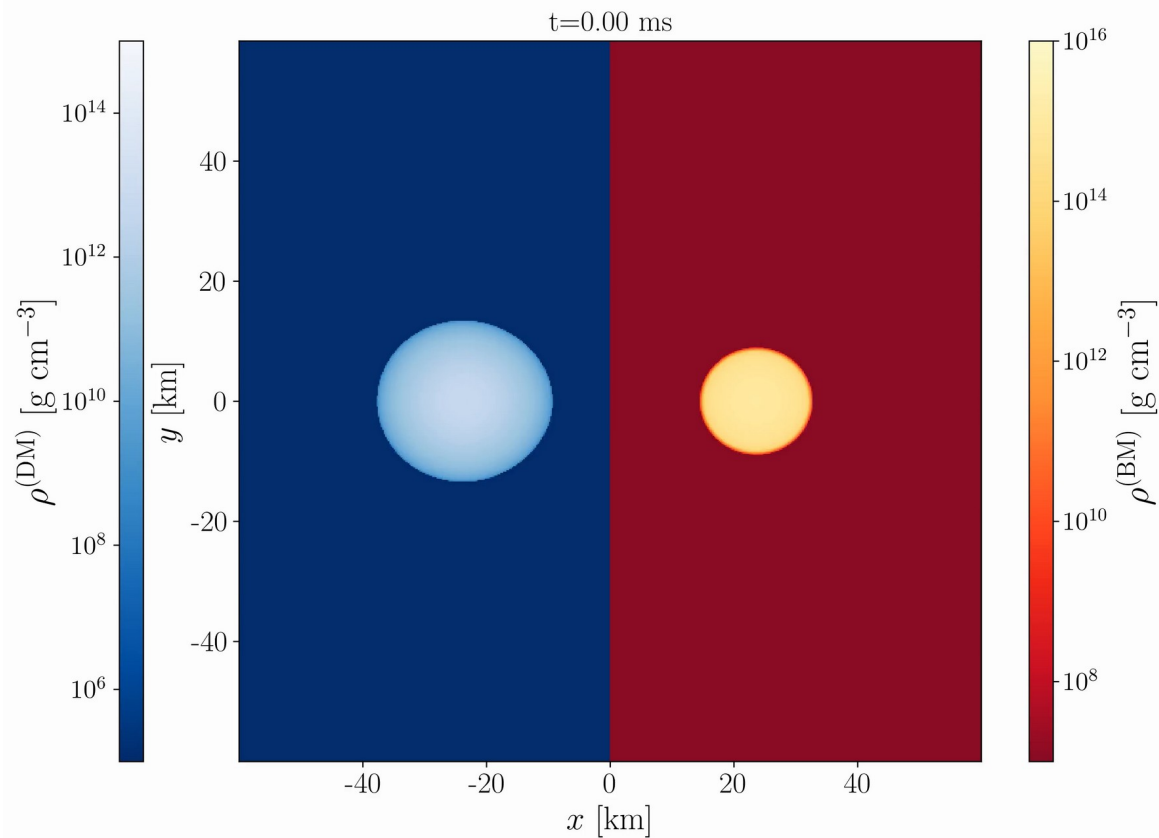


- DM core configurations exhibit a delayed merger in comparison to the BM configurations. A longer inspiral is due to a lower deformability of DM-admixed NSs;
- Faster formation of the BH after the merger and harder to eject material from the bulk of the stars prior to the BH formation;

Giangrandi+ 2025



# Dark matter halo configuration



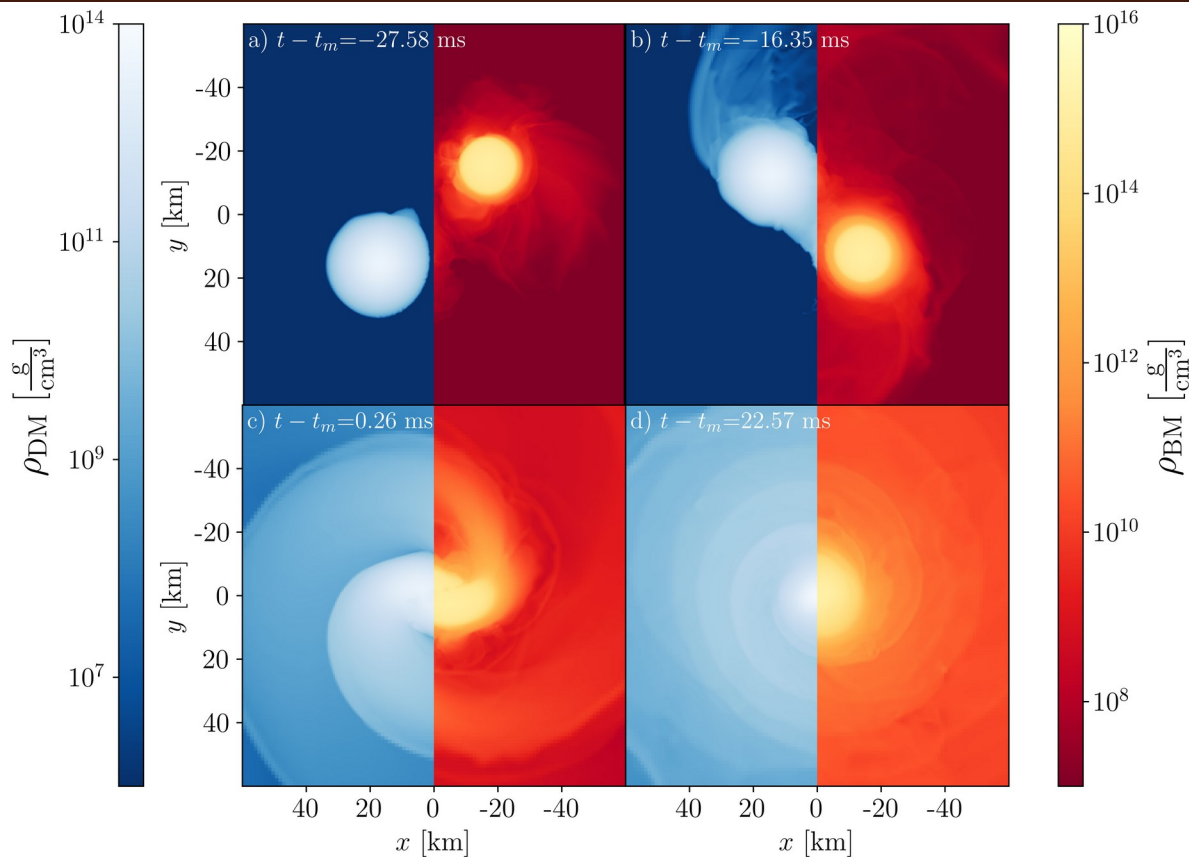
At  $t=0$ , two DM-admixed stars have still not touched each other

Extended DM halos come into contact earlier, forming a common envelope around the inspiraling BM stars

Giangrandi+ 2025



# Dark matter halo configuration

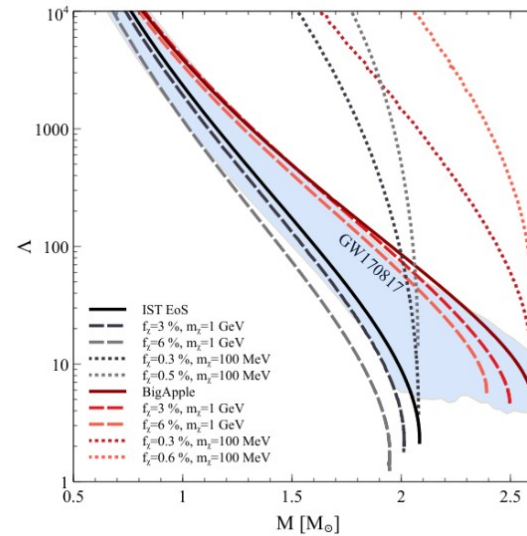
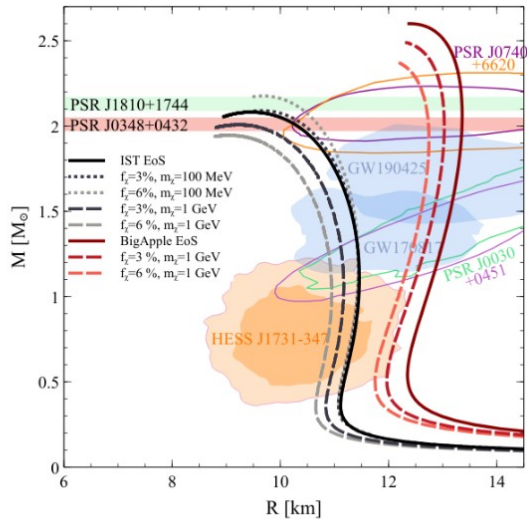


- DM-halo configurations evolve into a more diffuse and spatially extended cloud-like DM distribution surrounding the HMNS.
- During the merger, DM-halo simulations show a higher peak of the BM density compared to the DM-core or purely baryonic runs, suggesting that a diffuse halo may have an impact on the densities reached during the merger.
- For the 2.4 Msun system the DM halo exhibits a significantly lower post-merger rotational velocity, ~twice smaller the ones seen in DM core configurations. BM angular velocity is less affected.

Giangrandi+ 2025



# DM admixed NSs



Tidal deformability parameter

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

$k_2$  – Love's number

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

The speed of sound is calculated considering the total energy density and pressure

Giangrandi+ 2022

$$c_{s,\text{tot}}^2 = \frac{dp_{\text{tot}}}{d\varepsilon_{\text{tot}}}$$

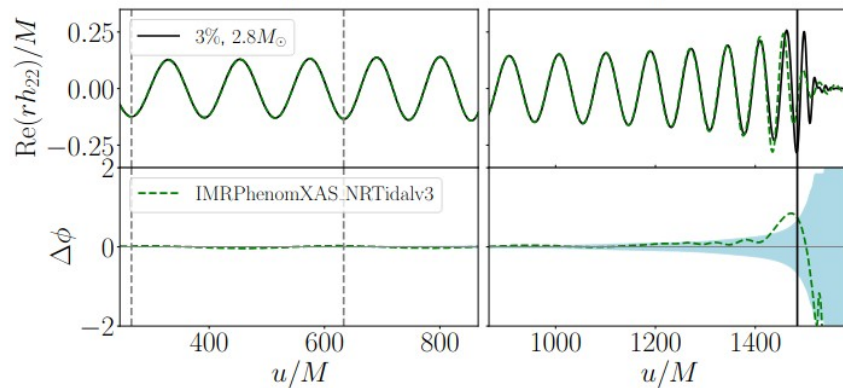
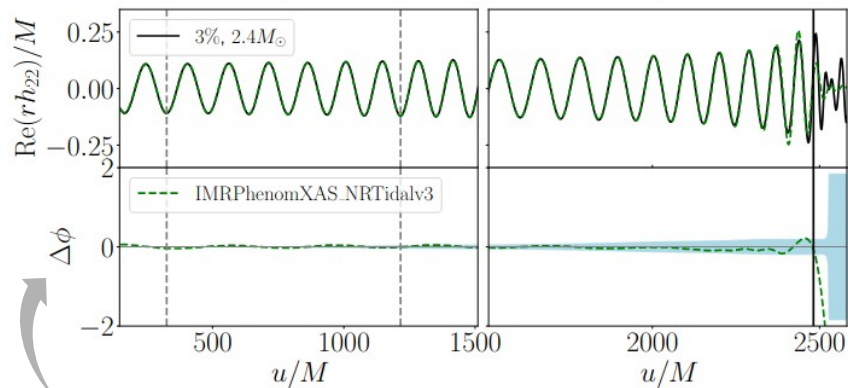
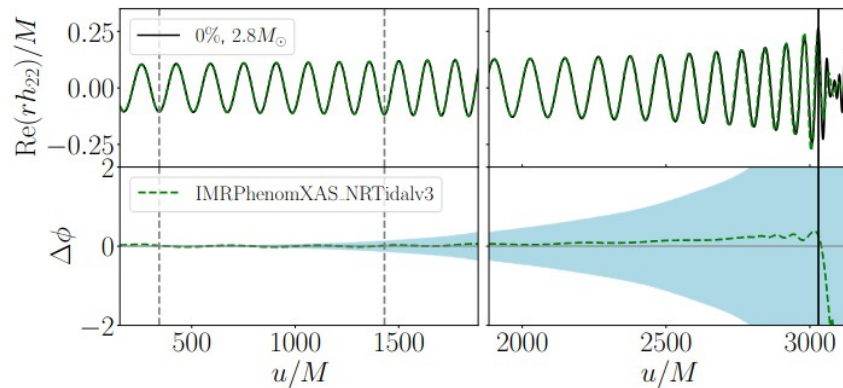
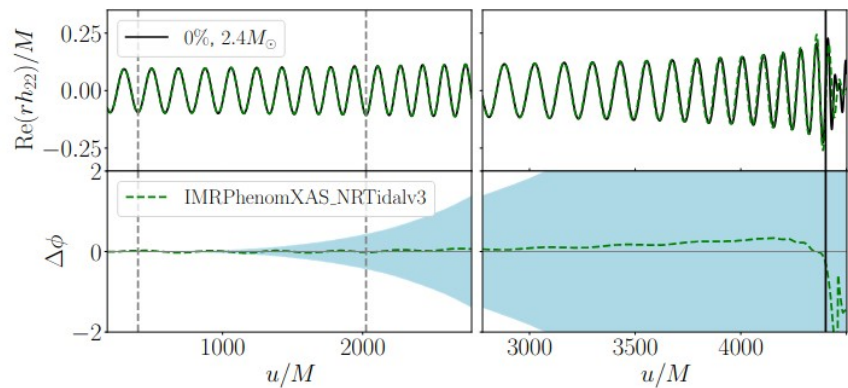




# Time-domain dephasing comparisons



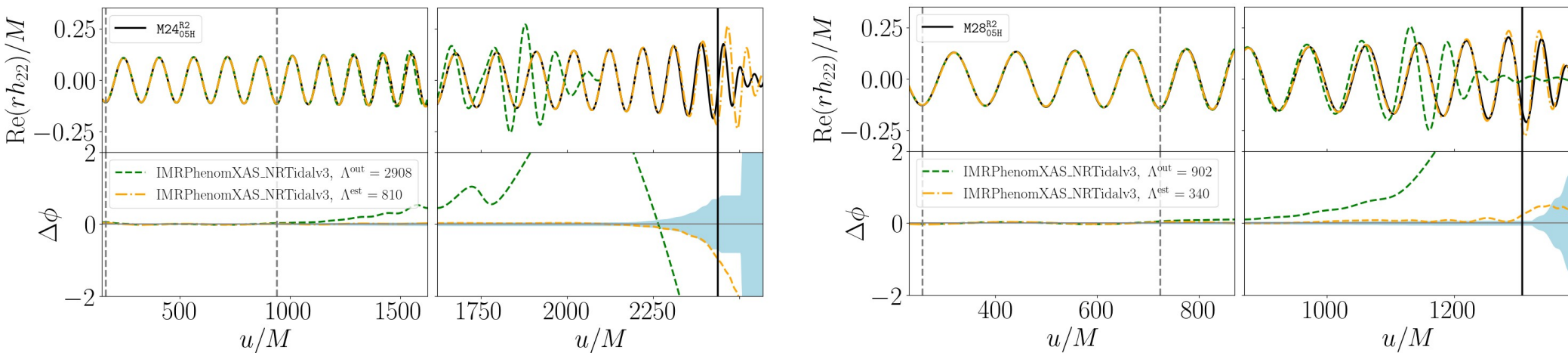
The real part of the GW strain as a function of the retarded time



the phase difference between the waveform model and the NR waveform



# Time-domain dephasing comparison: halo

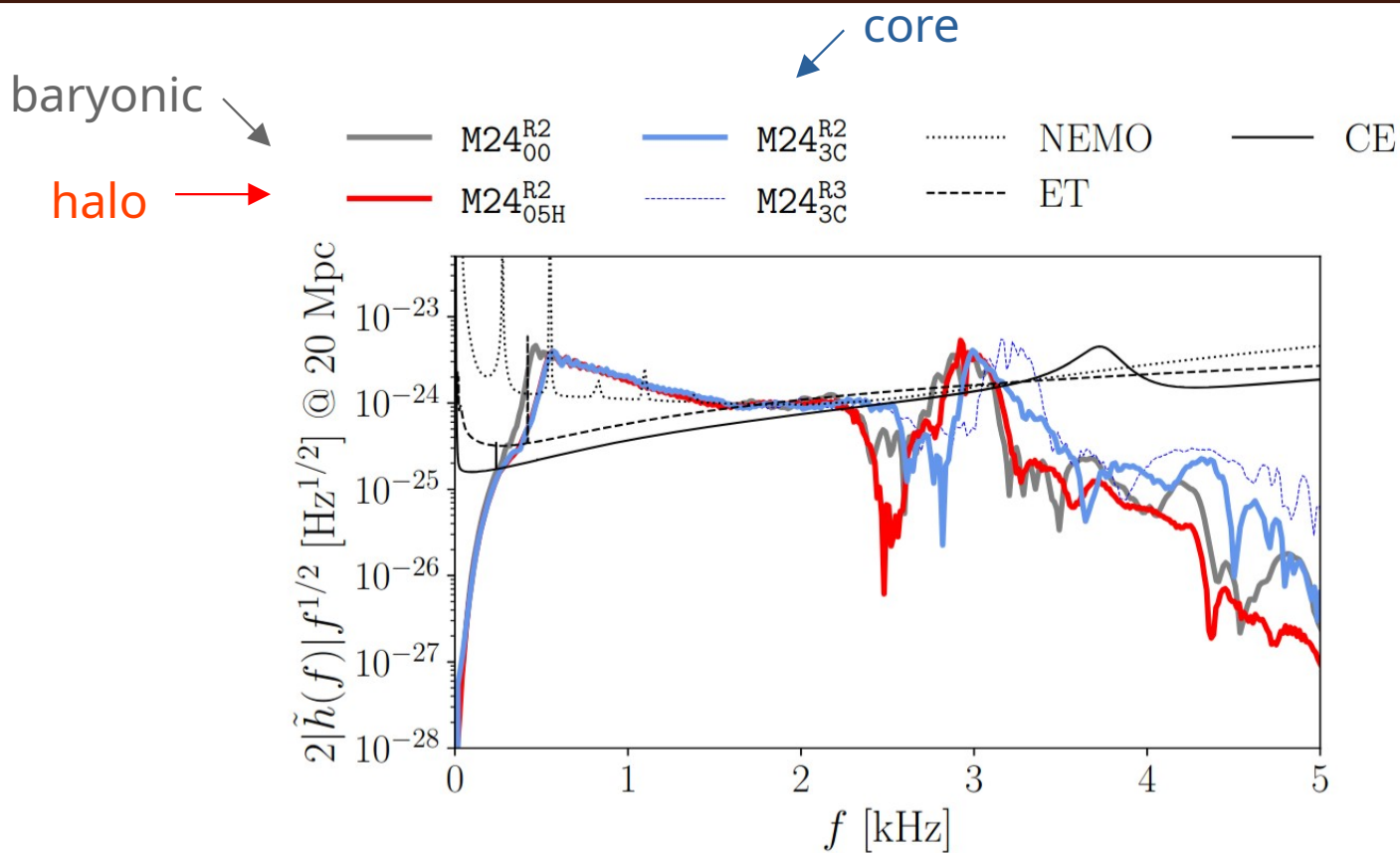


Giangrandi+ 2025

The extracted GW signal for DM halo configurations showed significant deviations from the IMRPhenomXAS\_NRTidalv3 model, suggesting a tension between the two-fluid speed of sound calculations and the existing waveforms.



# Post-merger phase



| identifier       | $f_2^{\text{NR}} [\text{kHz}]$ | $f_2^{\text{fit}}(\Lambda^{\text{out}}) [\text{kHz}]$ |
|------------------|--------------------------------|-------------------------------------------------------|
| $M24_{00}^{R2}$  | 2.983                          | 2.677                                                 |
| $M24_{3C}^{R2}$  | 2.990                          | 2.733                                                 |
| $M24_{3C}^{R3}$  | 3.156                          | 2.733                                                 |
| $M24_{05H}^{R2}$ | 2.923                          | 1.931                                                 |

$M24_{3C}^{R3}$  shows a noticeable shift towards higher frequencies with  $f_2 = 3.156 \text{ kHz}$



# Conclusions

- We performed the first simulations of DM-admixed BNS systems within a full GR framework, using constraint-solved initial data;
- The extracted GW signal for DM halo configurations showed significant deviations from the IMRPhenomXASNRtidalv3 model, suggesting a tension between the numerical simulations and two-fluid calculations. In contrast, the DM core and baryonic configurations agree well with the model;

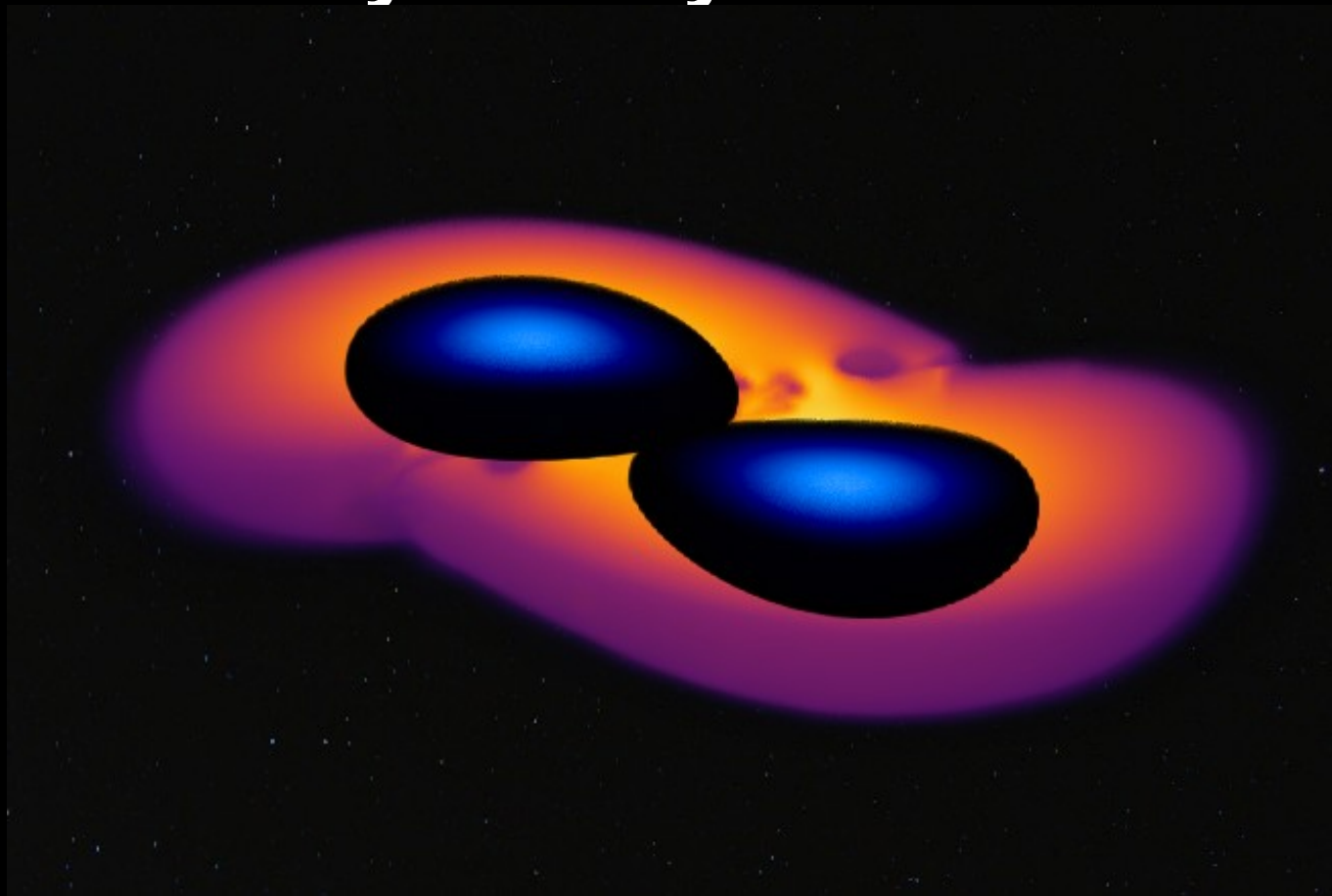
**→ There is a need to develop new waveform models that consistently account for the effects of DM**

- Heavy DM: leads to a longer inspiral due to the lower deformability of DM-admixed Nss  
favours BH formation after the merger  
decreases ejecting material from the bulk of the stars
- We observe modifications in the BM ejecta that could have important implications for kilonova emission and r-process nucleosynthesis. In addition, we find a DM ejecta component with a mass in the range  $[10^{-6}, 10^{-4}] M_{\odot}$
- In the post-merger phase we do not observe additional peaks, instead a frequency shift of 200 Hz in core configurations.

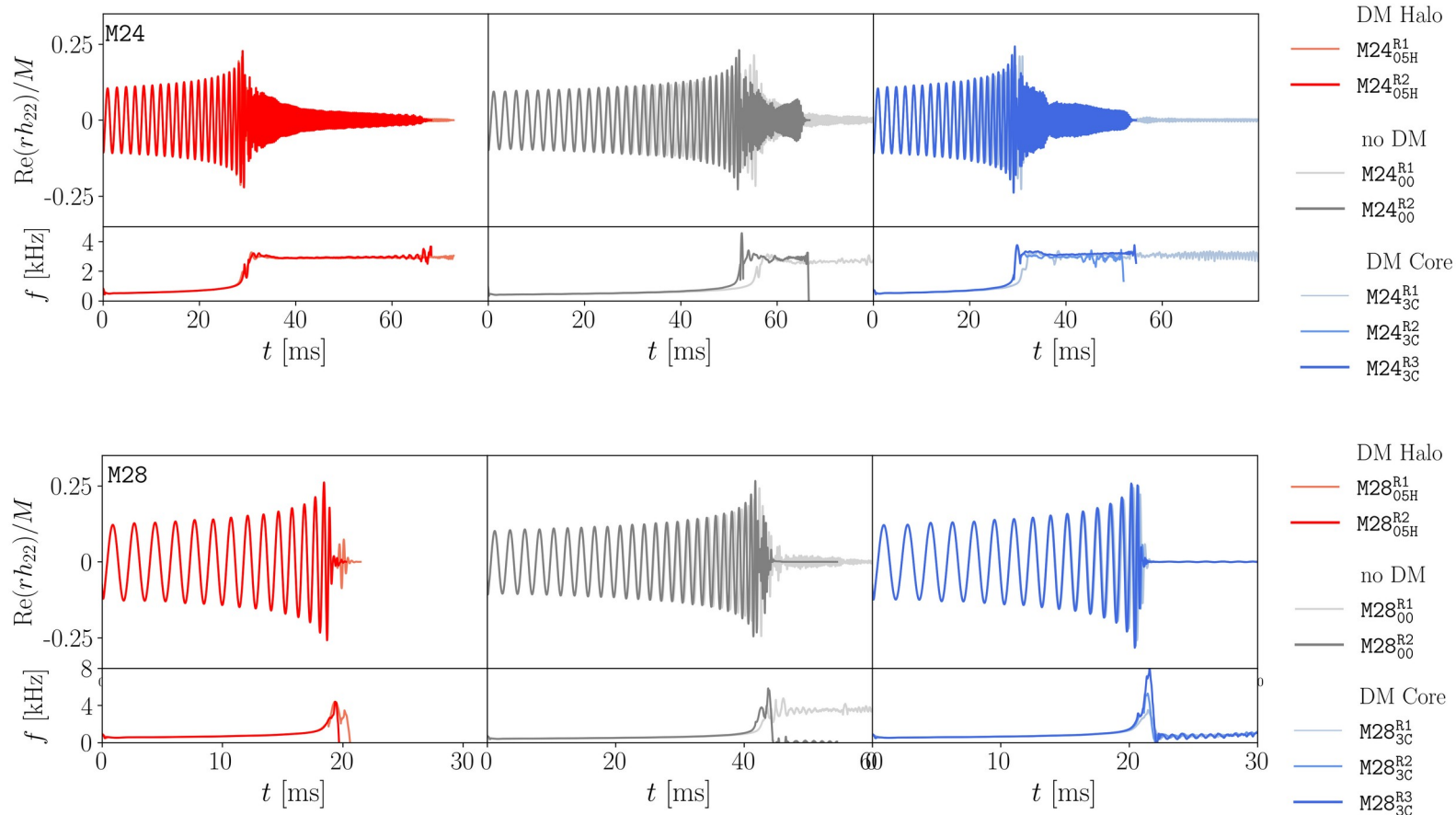
**More details in Giangrandi et al. 2504.20825**

**Here's a joke about dark matter but you can't see it**

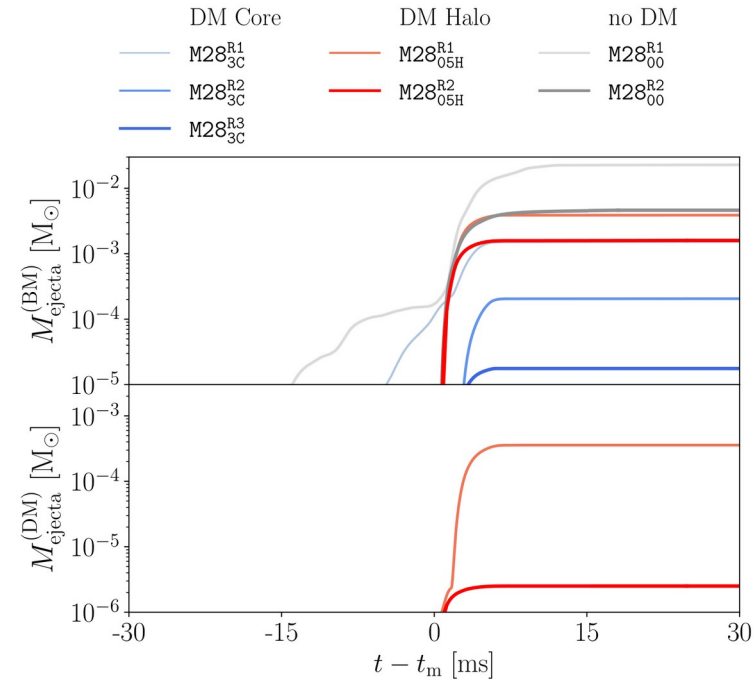
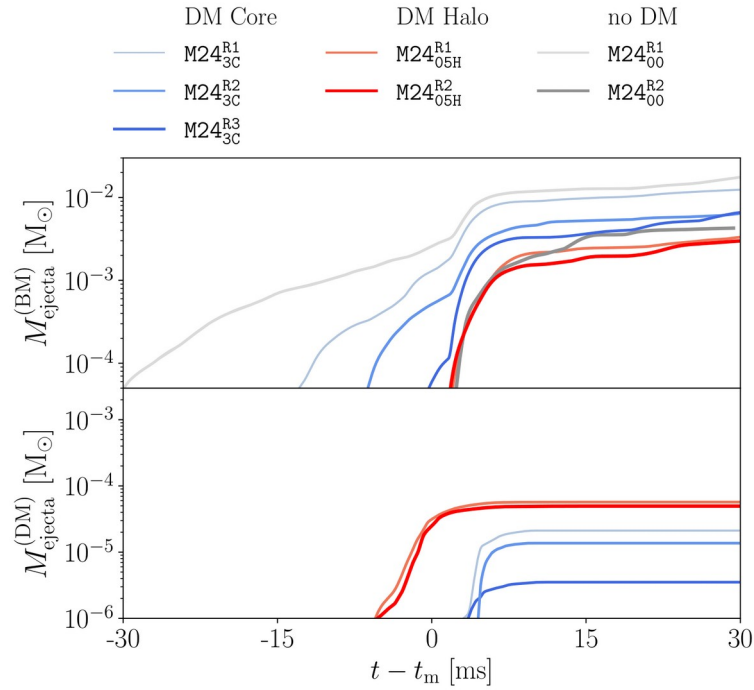
**Thank you for your attention!**



# Waveform strain and frequency

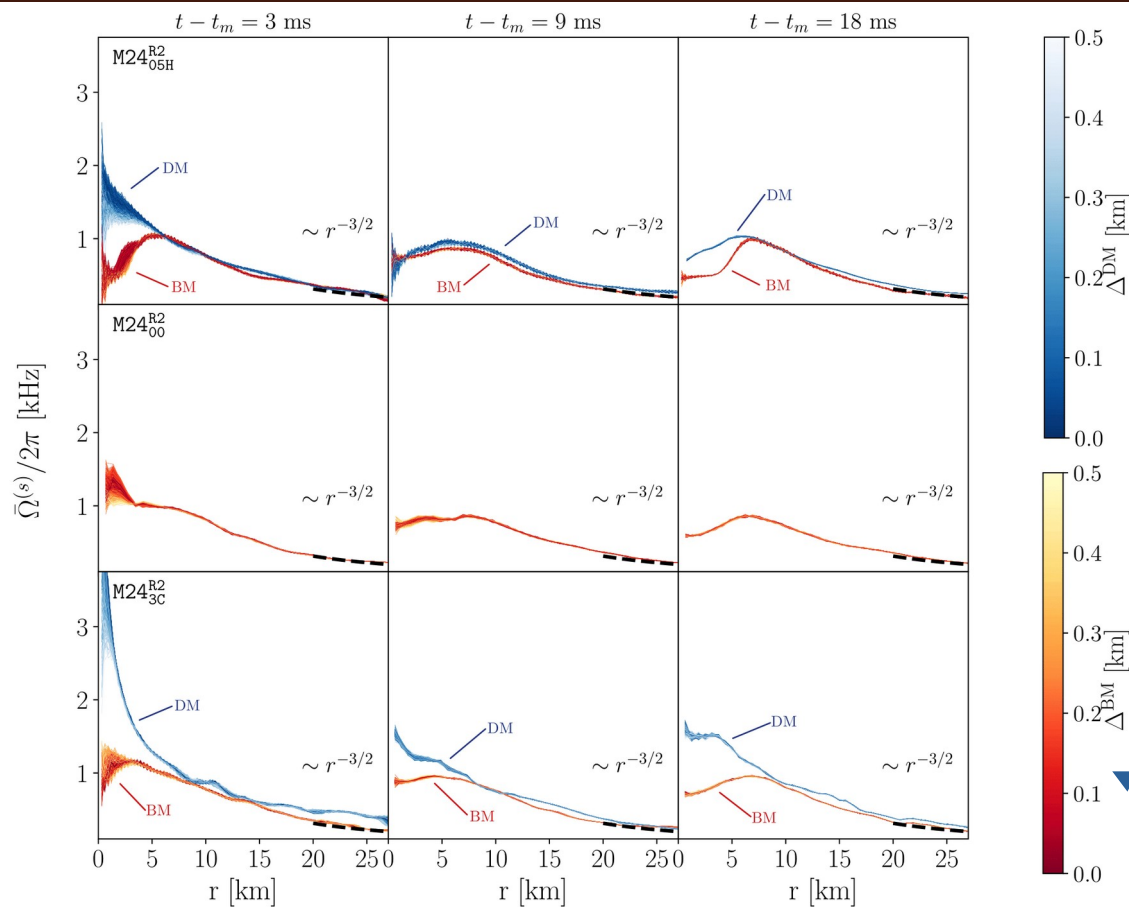






- **BM ejecta:** DM-core configurations can suppress BM ejecta in higher mass systems.  
less massive systems → DM-cores enhance shock-driven BM ejecta via more violent mergers.  
DM halos generally lead to similar BM ejecta compared to the DM-free scenario.
- **DM ejecta:** We observe DM ejecta in the range  $[10^{-6}, 10^{-4}] M_{\odot}$

# Rotational dynamics



- DM cores exhibit higher rotational velocities compared to DM halo configurations.
- BM angular velocity shows less pronounced changes
- Halo configurations show the presence of a central region with lower BM angular velocities, suggesting a more complex rotational profile.

the distance between the chosen center and the location of the lapse minimum