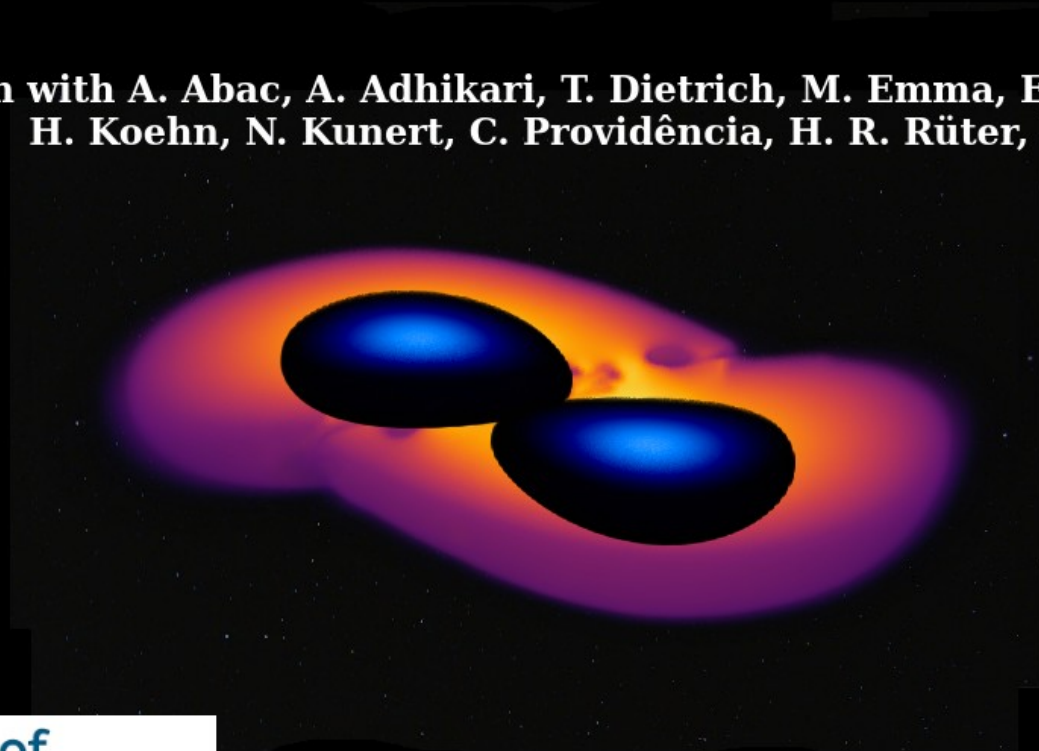


# Dark Matter Inside Neutron Stars: A Hidden Ingredient

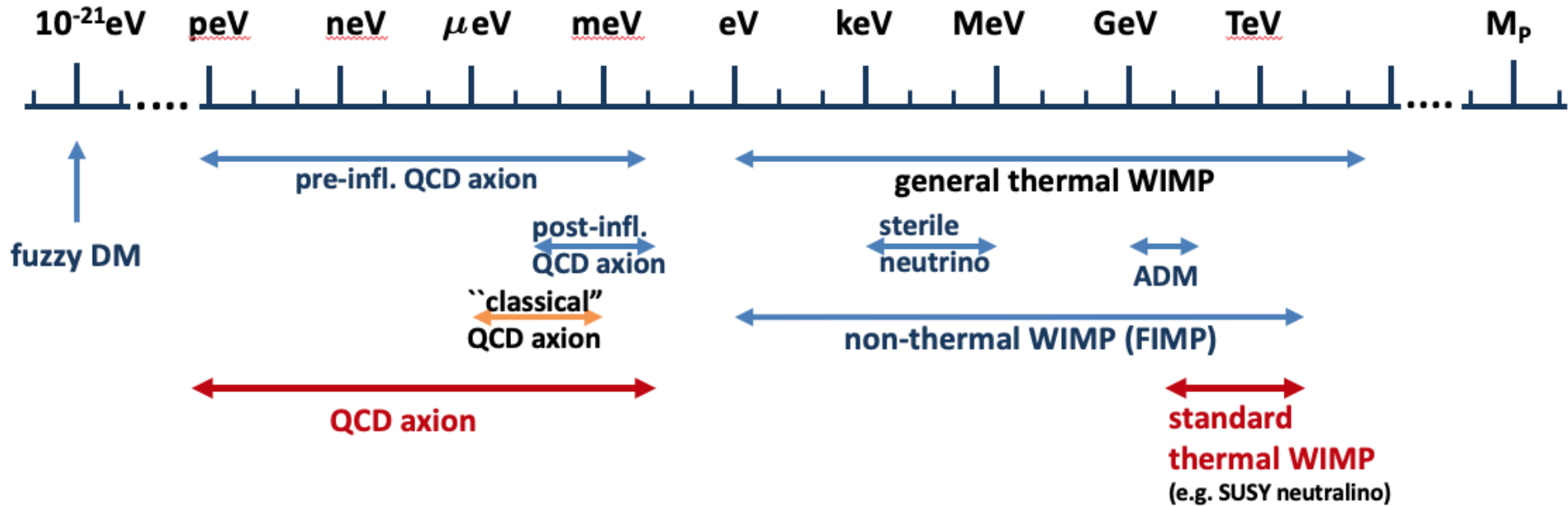
**Violetta Sagun**  
**University of Southampton**

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  $\geq$ 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  $M_{acc} \approx 10^{-5} M_{\odot} - 10^{-9} M_{\odot}$ .

- 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**

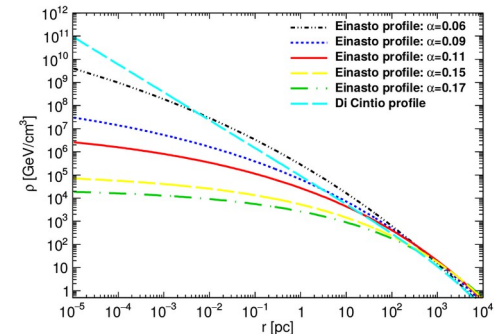
$$M_{acc} \approx 10^{-14} \left( \frac{\rho_{\chi}}{0.3 \frac{\text{GeV}}{\text{cm}^3}} \right) \left( \frac{\sigma_{\chi n}}{10^{-45} \text{cm}^2} \right) \left( \frac{t}{\text{Gyr}} \right) M_{\odot}$$

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

- 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)

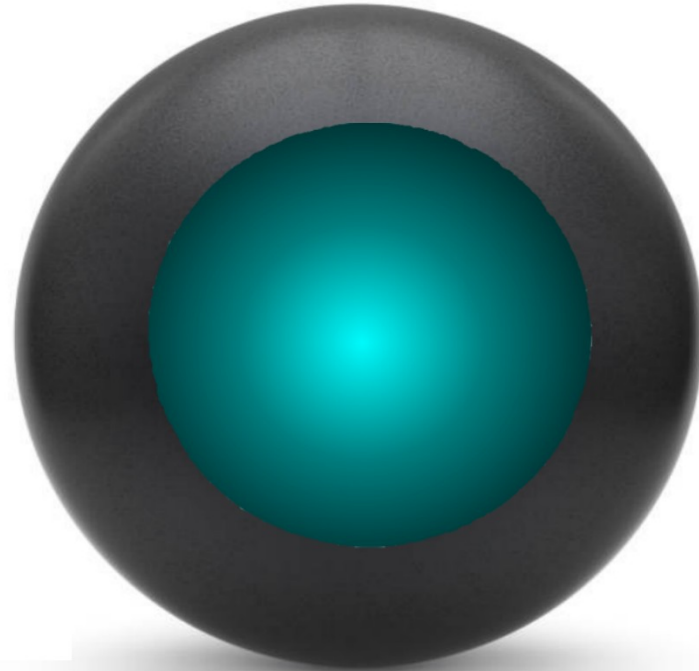
# Evidences of DM



**dark matter core**



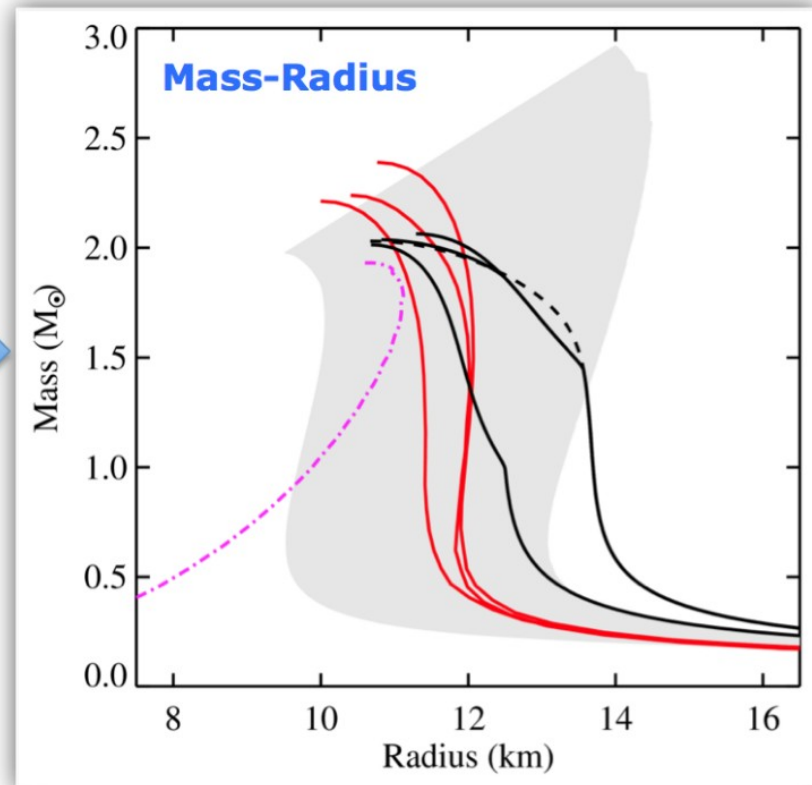
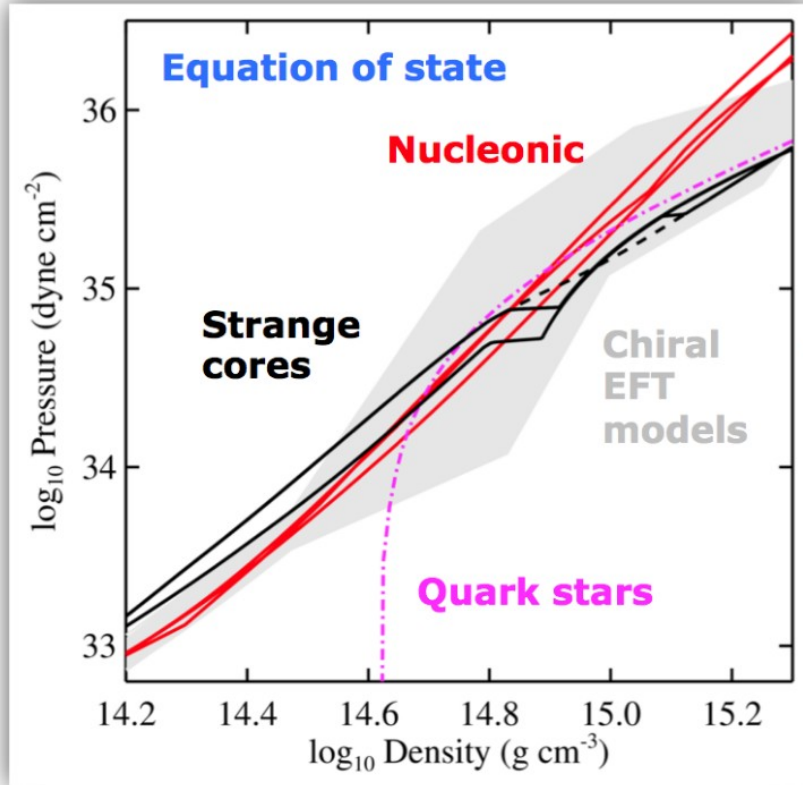
**dark core inside a NS**



**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)

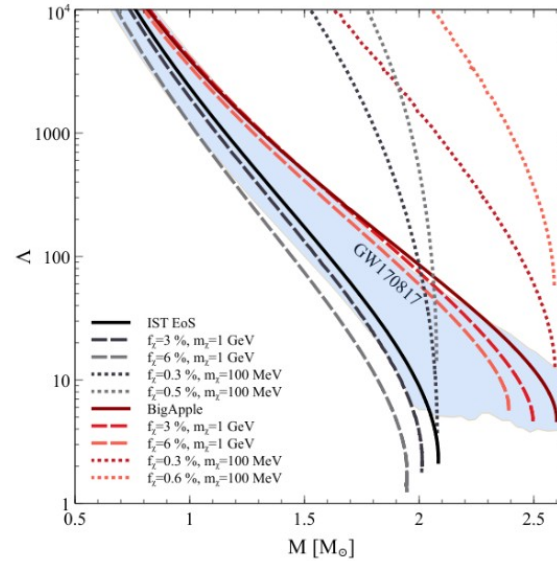
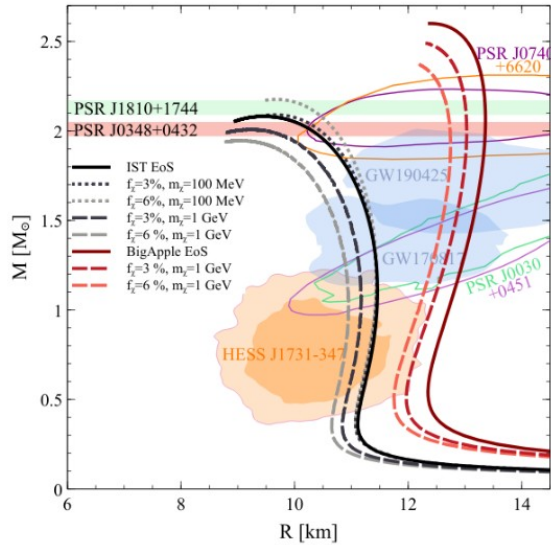
$M_T = M_B(R_B) + M_D(R_D)$  - total gravitational mass

Fraction of DM inside the star:

$$f_x = \frac{M_D(R_D)}{M_T}$$



# 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

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

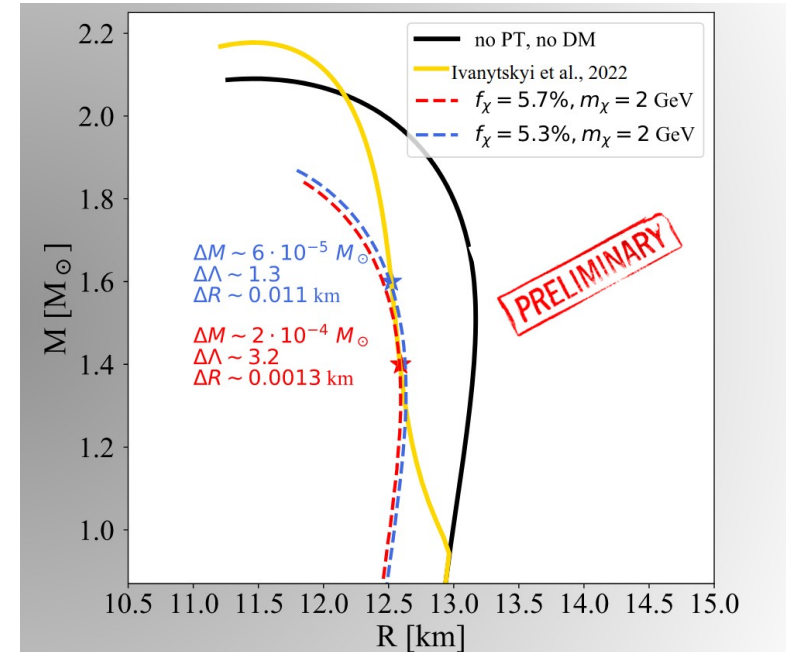




# Degeneracy between the DM-admixed, baryonic and hybrid stars

DM-admixed and hybrid stars may present undistinguishable mass, radius and tidal deformability

**How to split this degeneracy?**



Cipriani+ 2026 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.

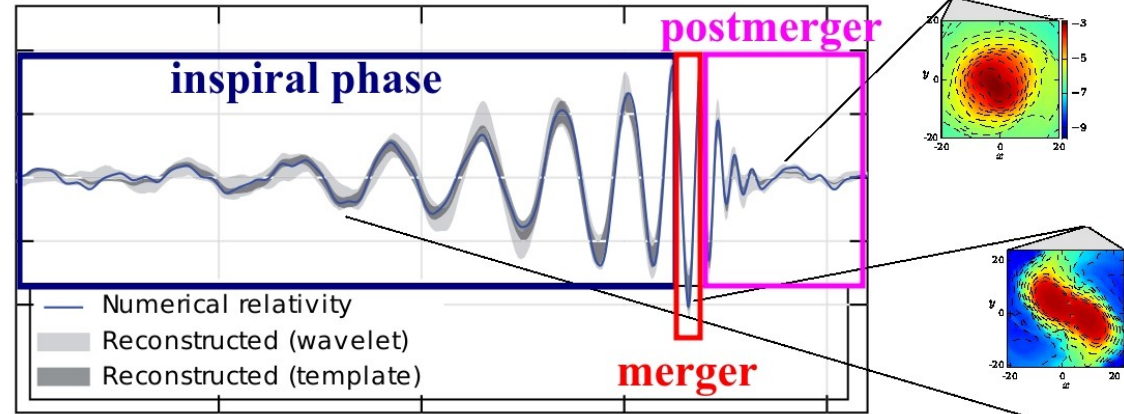
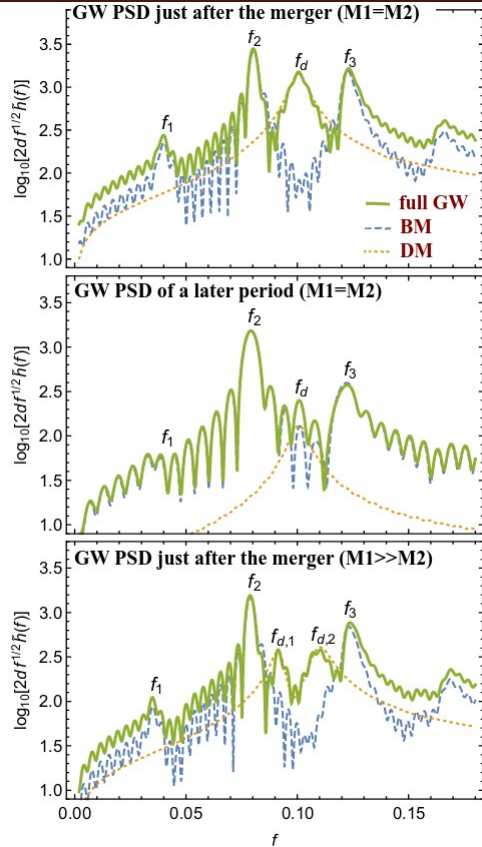
# Smoking gun signature of DM in NSs



- **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  
**X-ray telescopes:** NICER, ATHENA, eXTP, STROBE-X are expected to measure  $M$  and  $R$  of NSs with high accuracy  
**radio telescopes:** MeerKAT, SKA, ngVLA plan to increase radio pulsar timing and discover Galactic center pulsars  
**missing pulsar problem?**  
  
**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 compact 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  
The smoking gun of the presence of DM would 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
- **High/low surface temperature of NSs towards the Galaxy center**



# 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

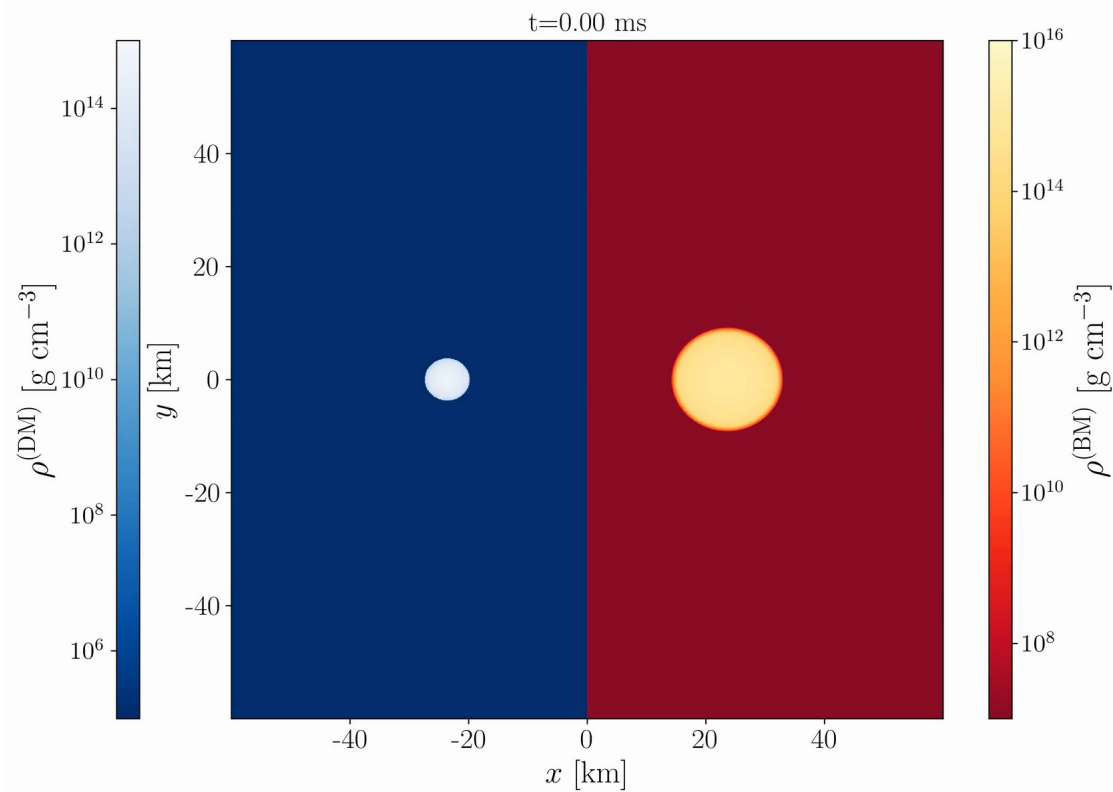
Ivanytskyi+ 2020

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

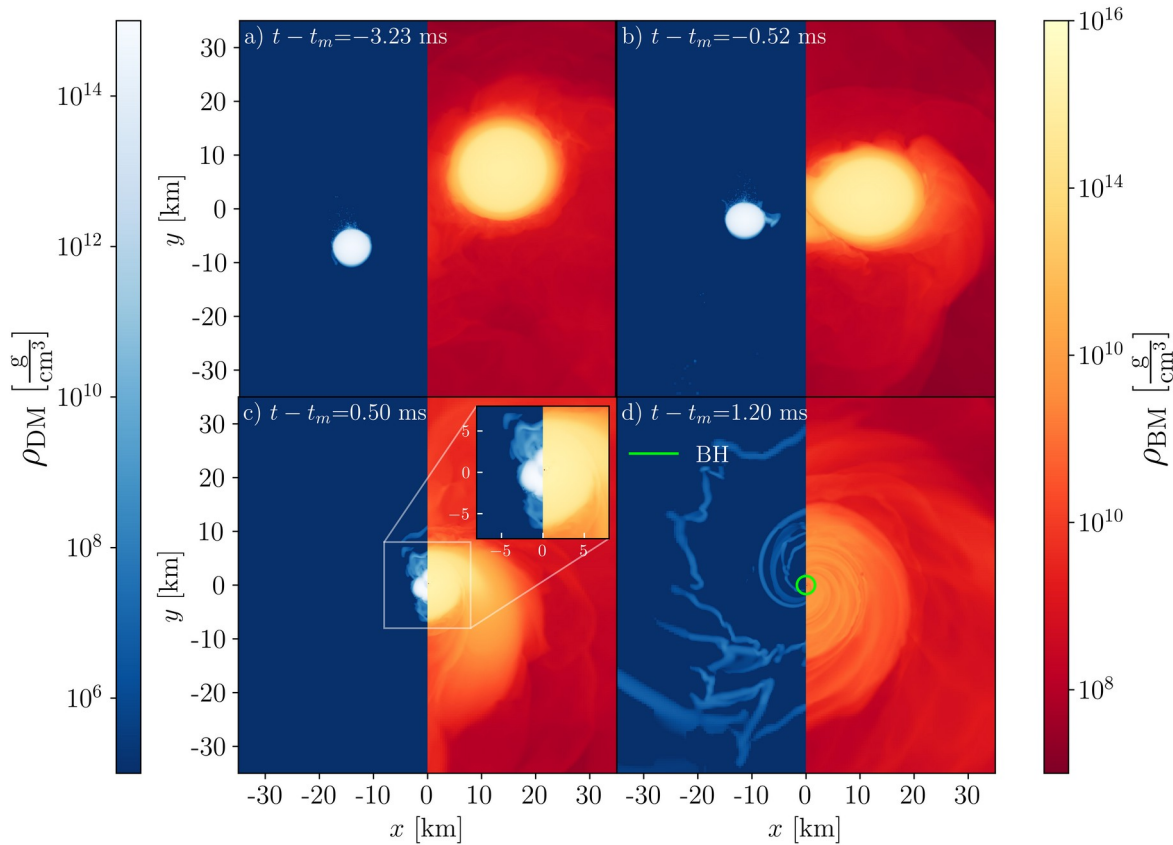


- Baryonic matter: Sly4 EoS
- Dark matter: fermions with mass 1 GeV, fraction 3%
- $1.2M_{\odot} + 1.2M_{\odot}$
- Eccentricity  $\sim 0$
- Non-spinning stars

Giangrandi+ 2025



# Dark matter core configuration

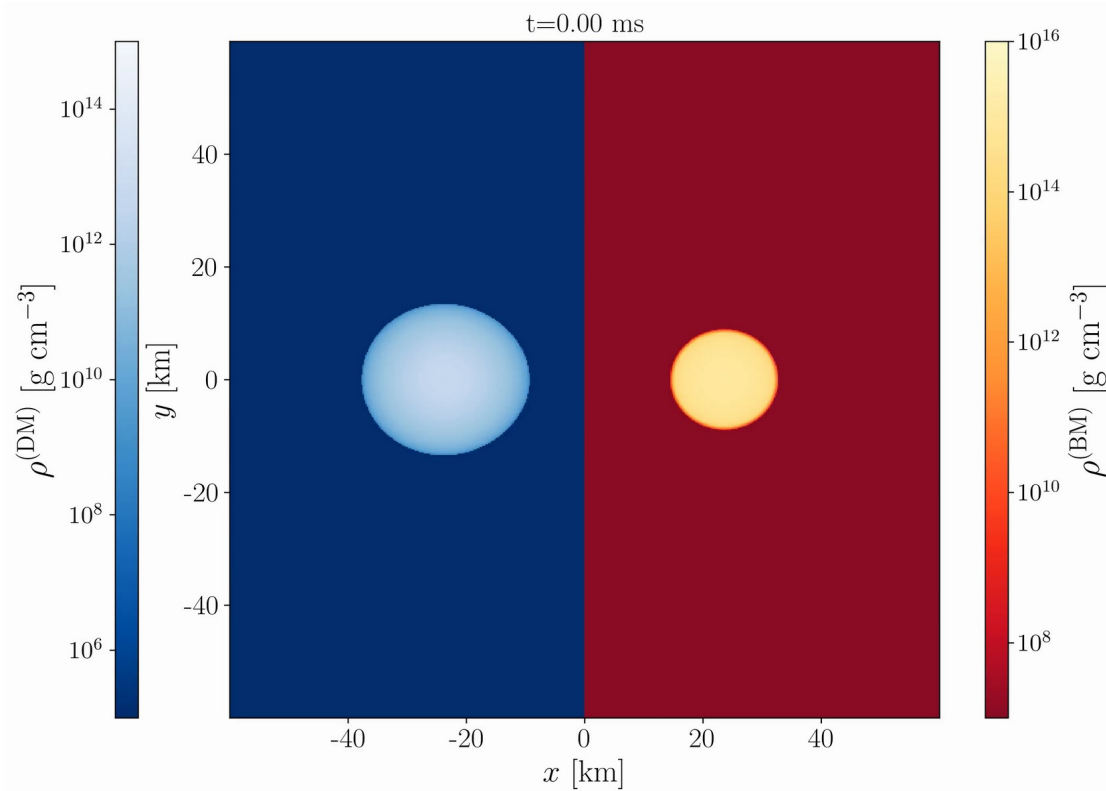


- DM core configurations exhibit a delayed merger in comparison to the BM configurations. A longer inspiral is due to a lower deformability of DM-admixed NSs;
- Faster formation of the BH after the merger and harder to eject material from the bulk of the stars prior to the BH formation;

Giangrandi+ 2025



# Dark matter halo configuration



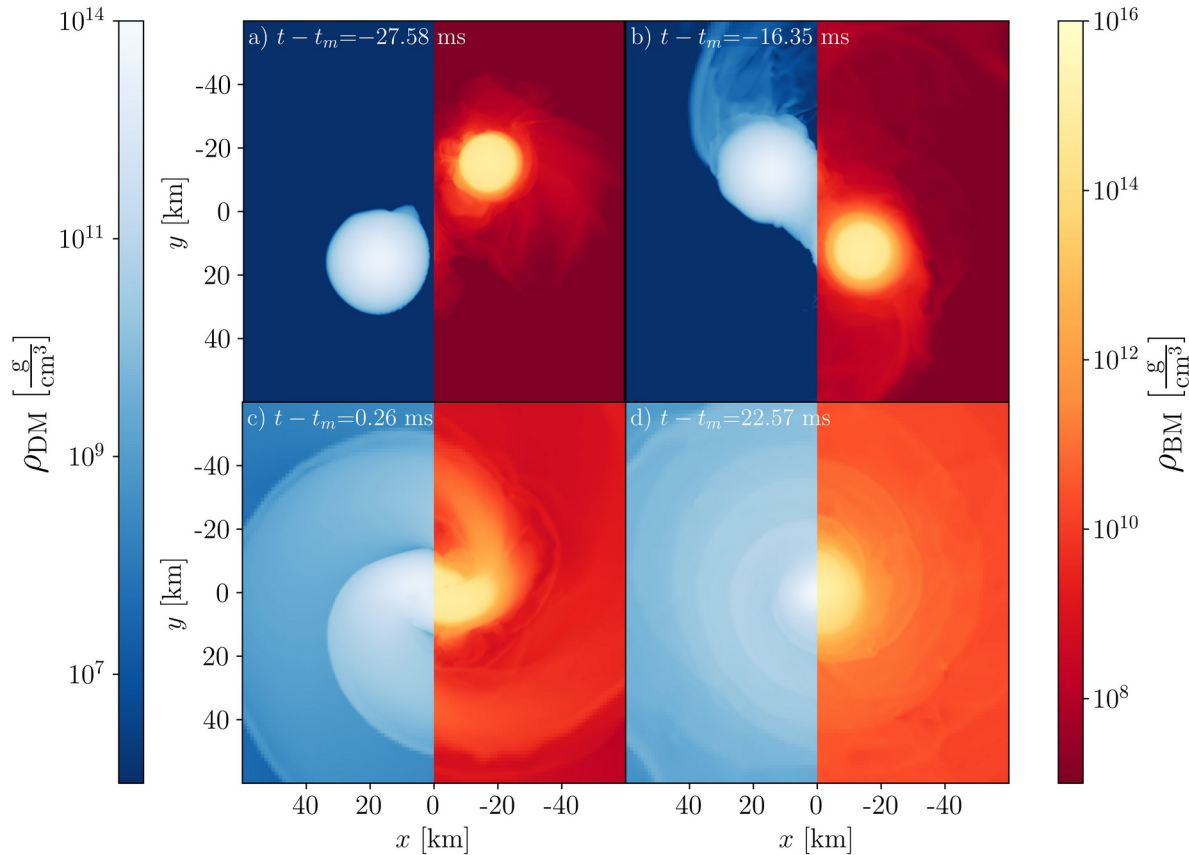
At  $t=0$ , two DM-admixed stars have still not touched each other

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

Giangrandi+ 2025



# Dark matter halo configuration

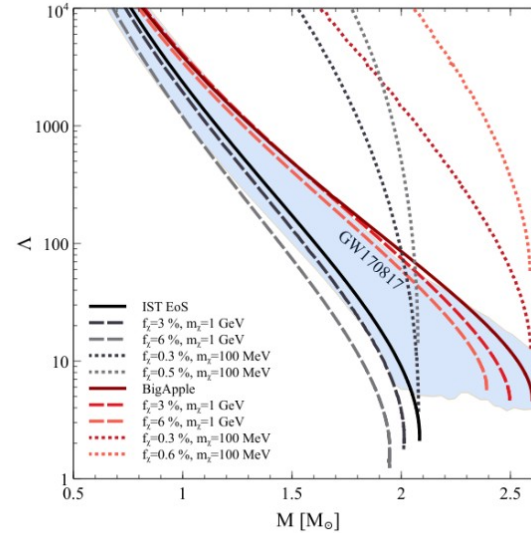
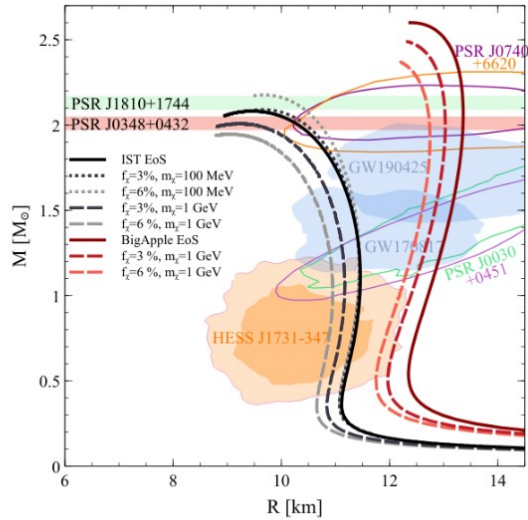


- DM-halo configurations evolve into a more diffuse and spatially extended cloud-like DM distribution surrounding the HMNS.
- During the merger, DM-halo simulations show a higher peak of the BM density compared to the DM-core or purely baryonic runs, suggesting that a diffuse halo may have an impact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

Giannandi+ 2022

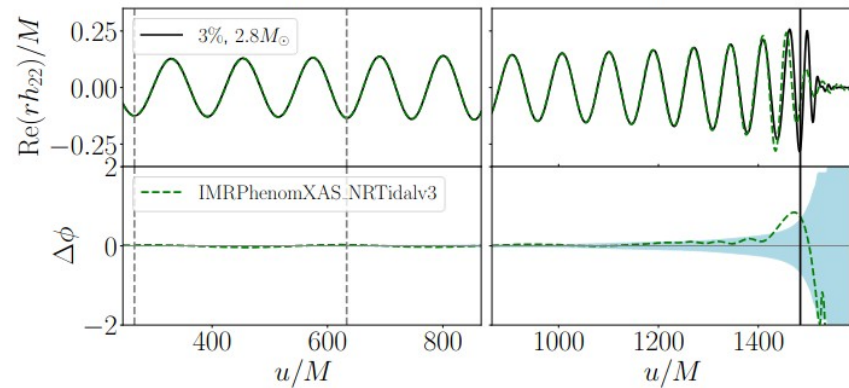
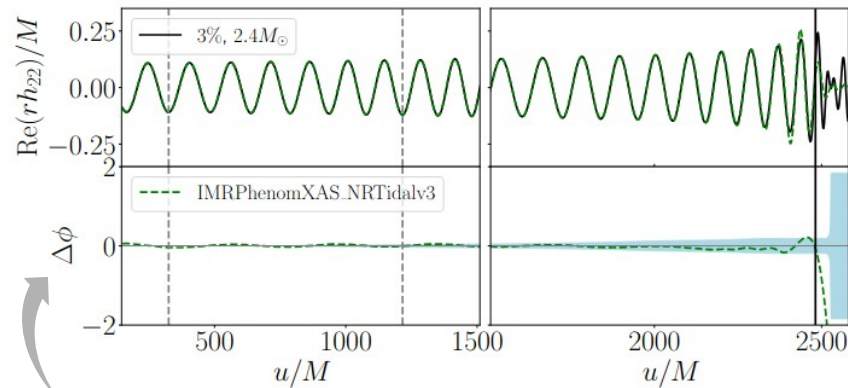
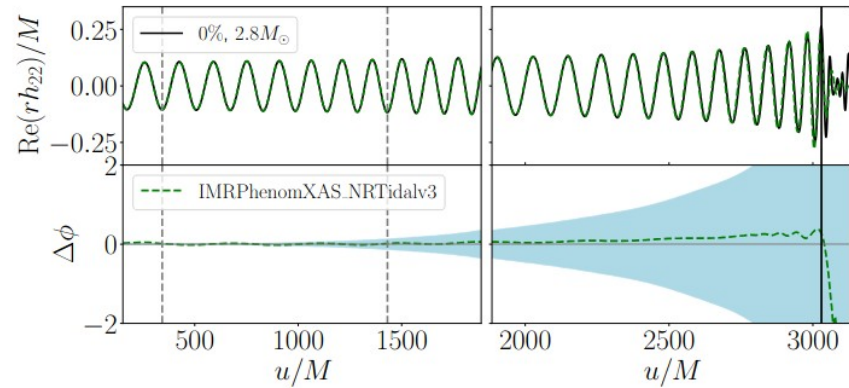
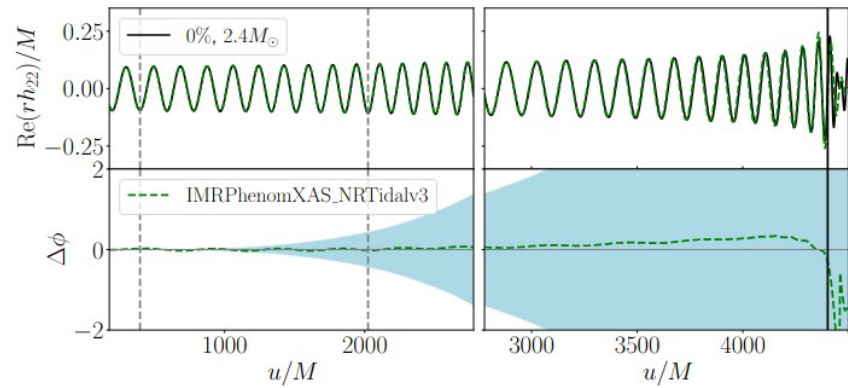
$$c_{s,\text{tot}}^2 = \frac{dp_{\text{tot}}}{d\varepsilon_{\text{tot}}}$$



# Time-domain dephasing comparisons



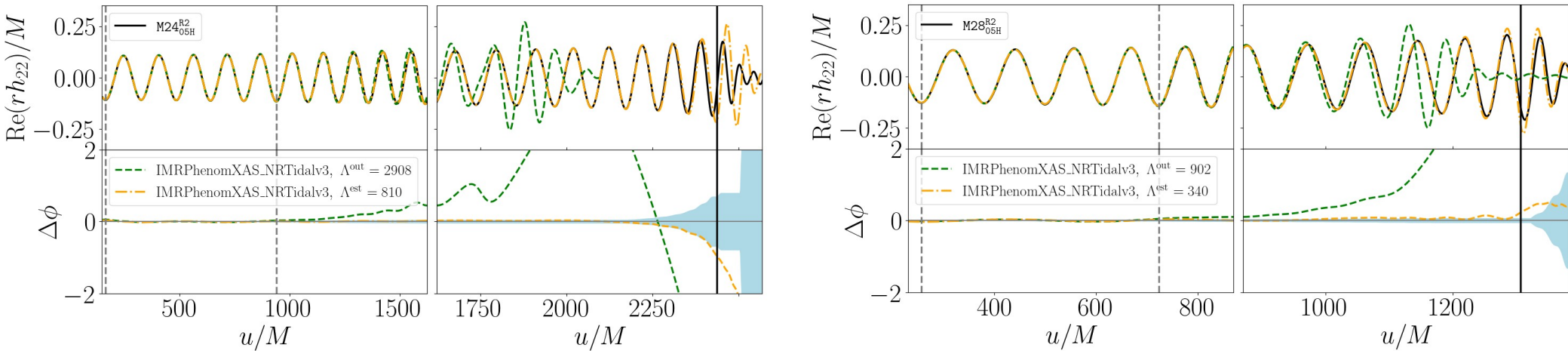
The real part of the GW strain as a function of the retarded time



the phase difference between the waveform model and the NR waveform



# Time-domain dephasing comparison: halo

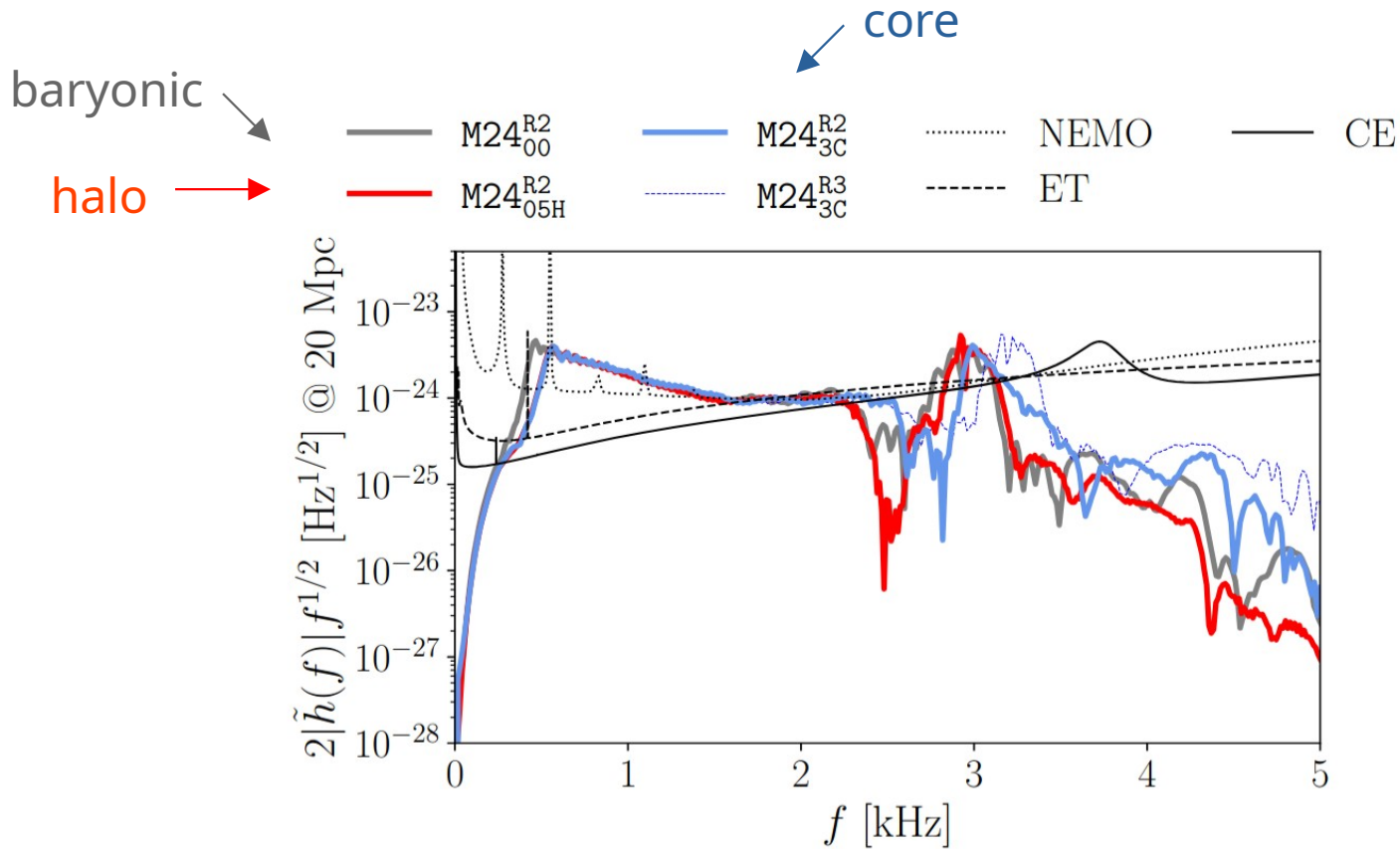


Giangrandi+ 2025

The extracted GW signal for DM halo configurations showed significant deviations from the IMRPhenomXASNRTidalv3 model, suggesting a tension between the two-fluid speed of sound calculations and the existing waveforms.



# Post-merger phase



identifier	$f_2^{\text{NR}}$ [kHz]	$f_2^{\text{fit}}(\Lambda^{\text{out}})$ [kHz]
M24 <sub>00</sub> <sup>R2</sup>	2.983	2.677
M24 <sub>3C</sub> <sup>R2</sup>	2.990	2.733
M24 <sub>3C</sub> <sup>R3</sup>	3.156	2.733
M24 <sub>05H</sub> <sup>R2</sup>	2.923	1.931

M24<sub>3C</sub><sup>R3</sup> shows a noticeable shift towards higher frequencies with  $f_2 = 3.156$  kHz



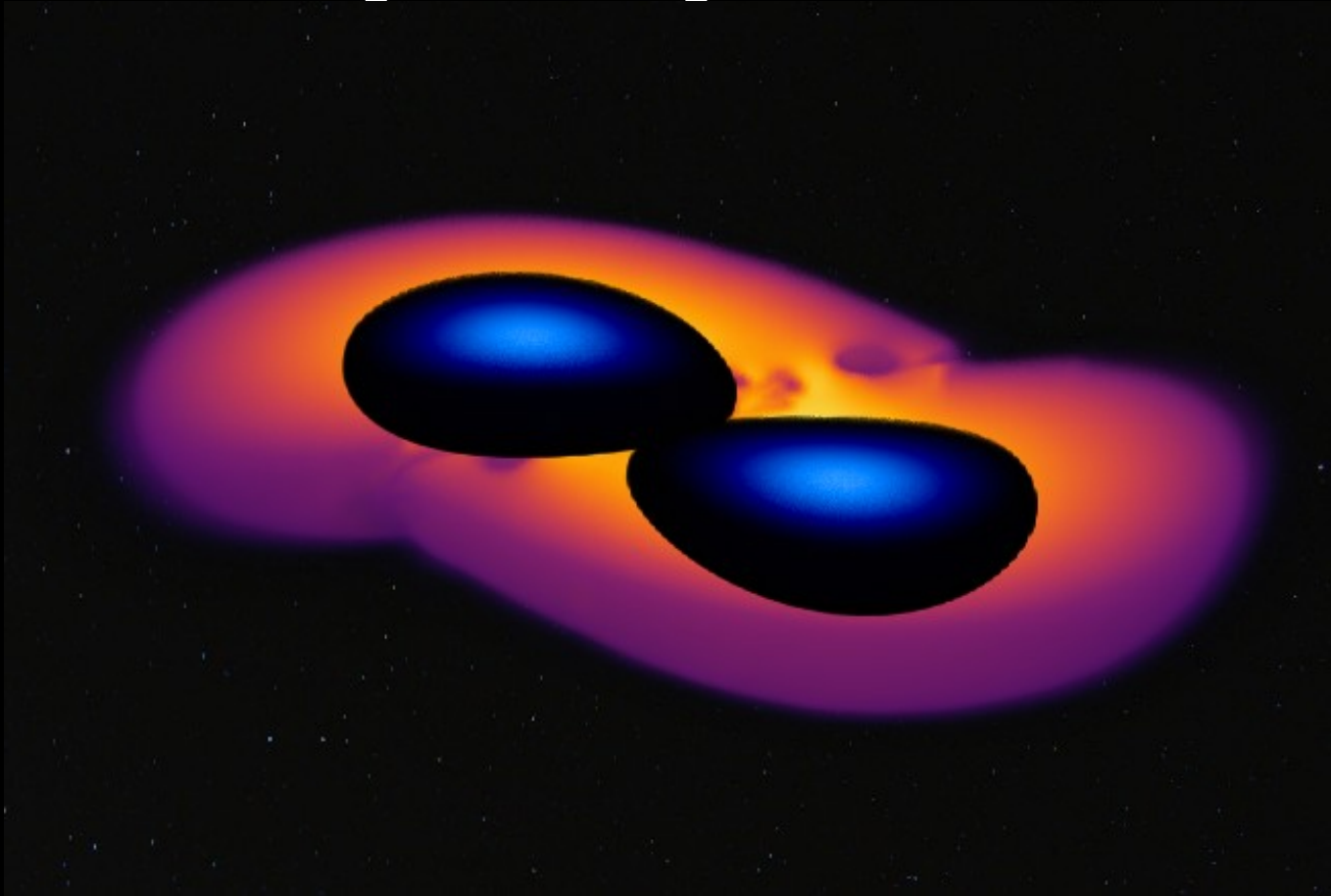
# Conclusions

- 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;
- A higher DM fraction leads to a longer inspiral due to the lower deformability of DM-admixed Nss;
- We observe faster BH formation after the merger and increased difficulty in ejecting material from the bulk of the stars before BH formation
- In the post-merger phase we do not observe additional peaks, instead a frequency shift of 200 Hz in core configurations.
- We observe the BM ejecta modifications that could have implications for the kilonovae and r-process nucleosynthesis. Additionally there is a DM ejecta in the range  $[10^{-6}, 10^{-4}] M_{\odot}$

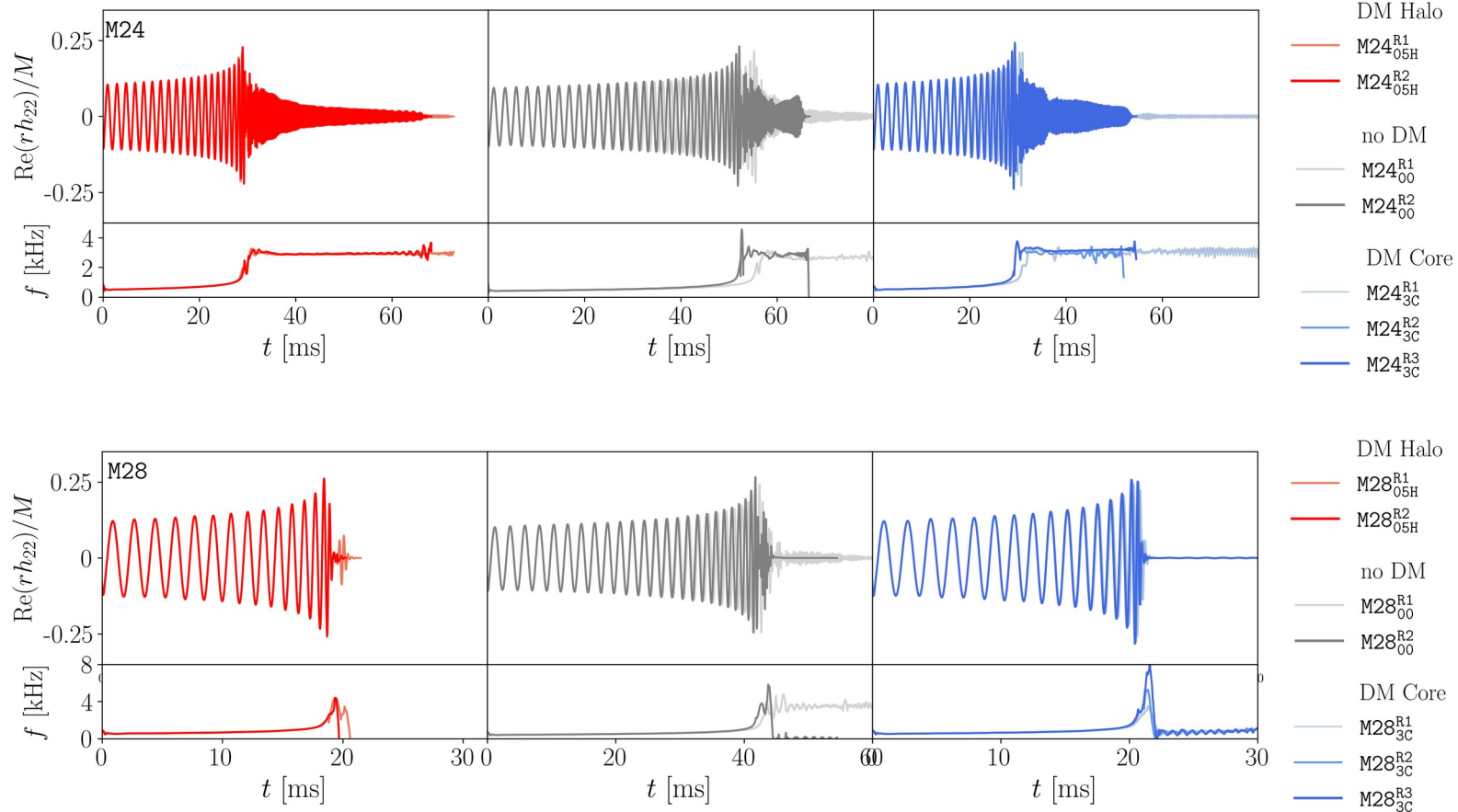
**More details in Giangrandi et al. 2504.20825**

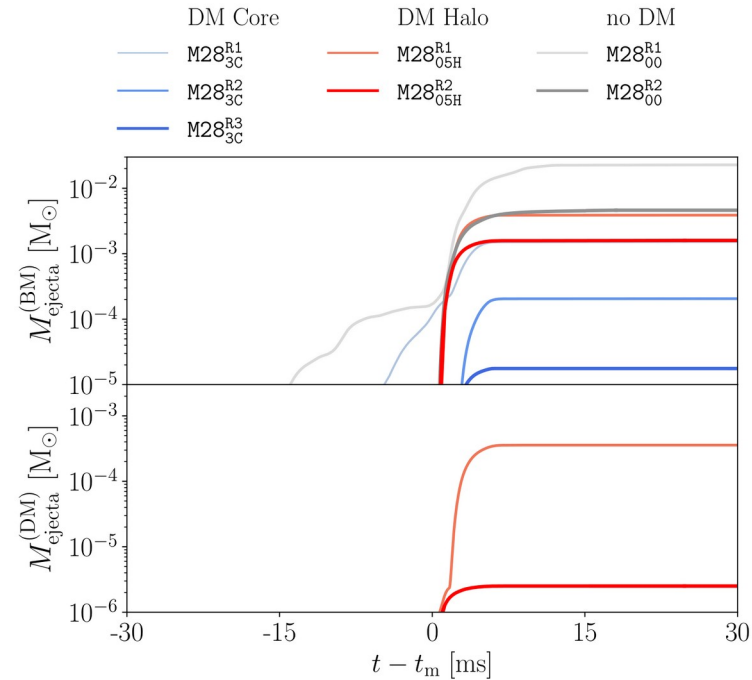
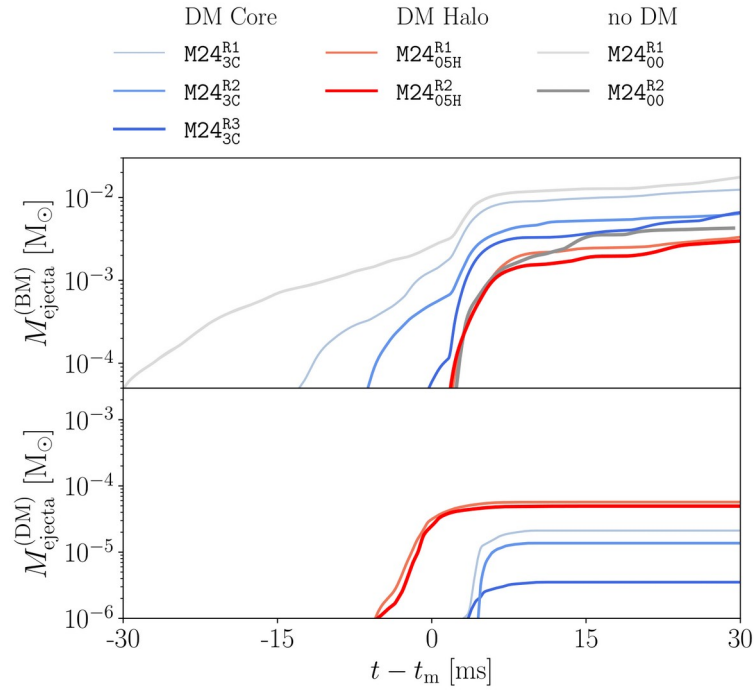
**Here's a joke about dark matter but you can't see it**

**Thank you for your attention!**



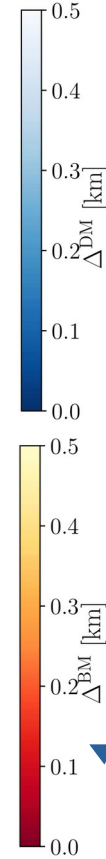
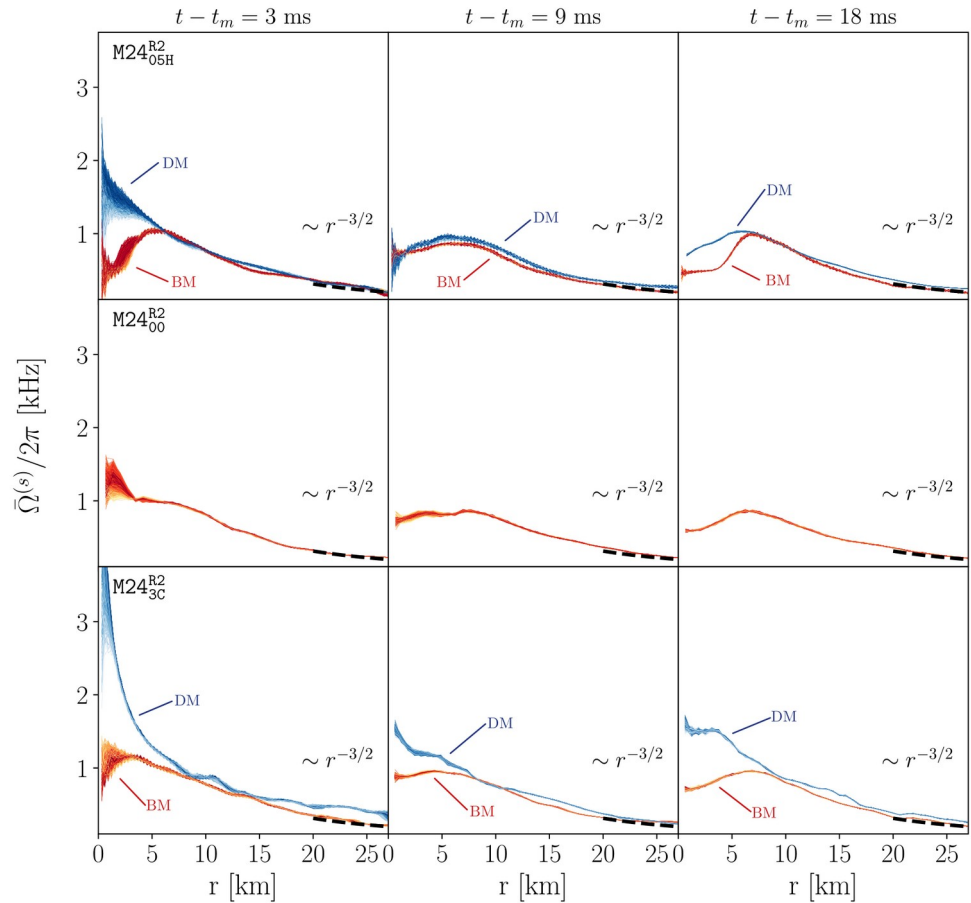
# Waveform strain and frequency





- **BM ejecta:** DM-core configurations can suppress BM ejecta in higher mass systems. less massive systems  $\rightarrow$  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