Multi-Messenger Probes of Dark Matter With Neutron Stars and Binary Neutron Star Mergers

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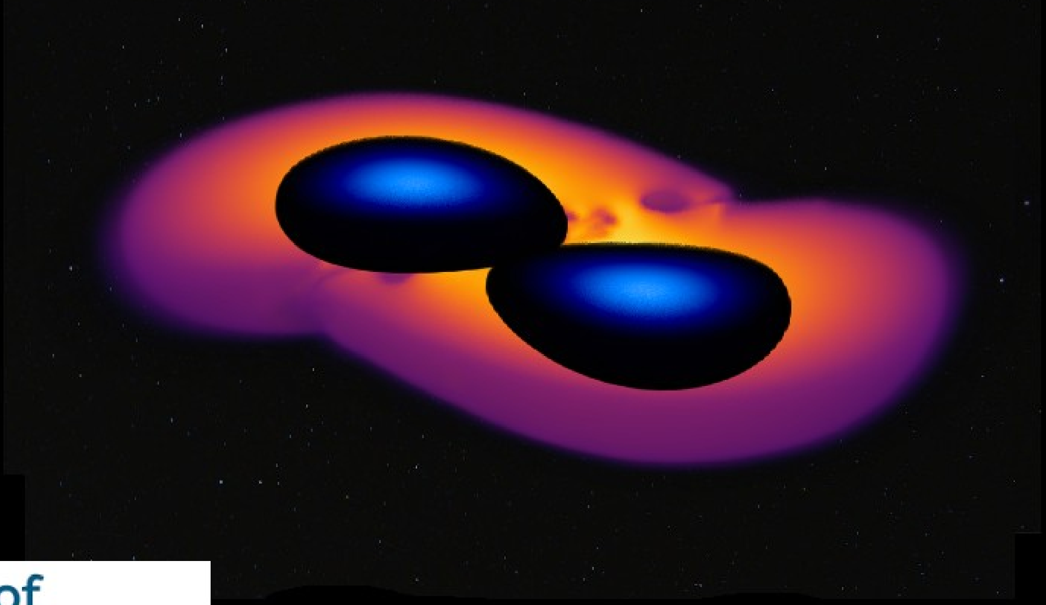

Arxiv: 2504.20825 [astro-ph.HE]

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STAG RESEARCH CENTRE

11 Sep 2025

How many STRONG evidences support dark matter existence?

It's quiz time!

a) Zero, I don't believe in DM no matter what

b) One

c) Five

d) Many

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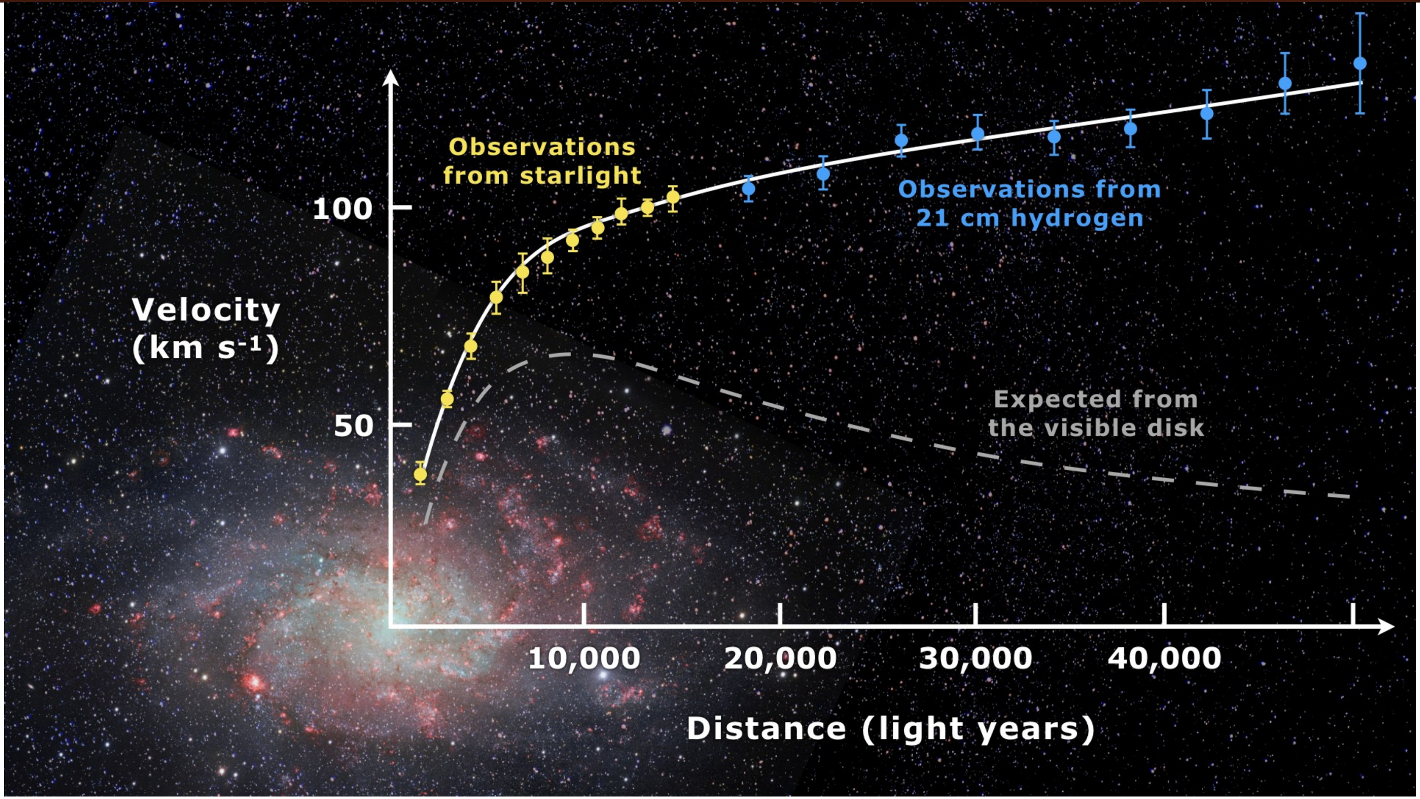
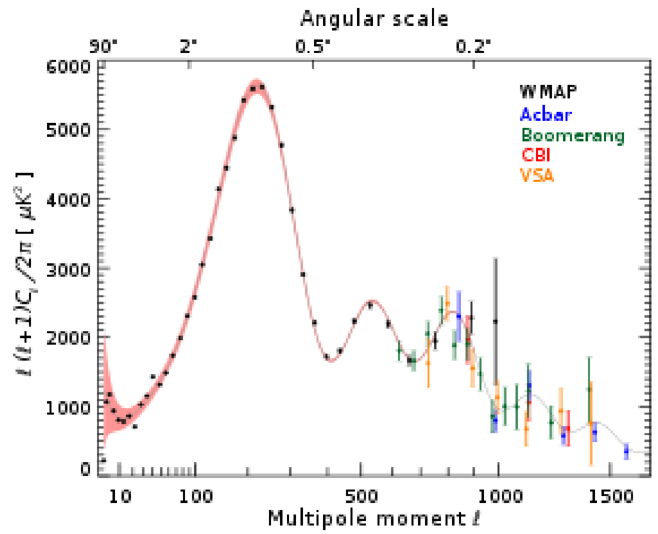
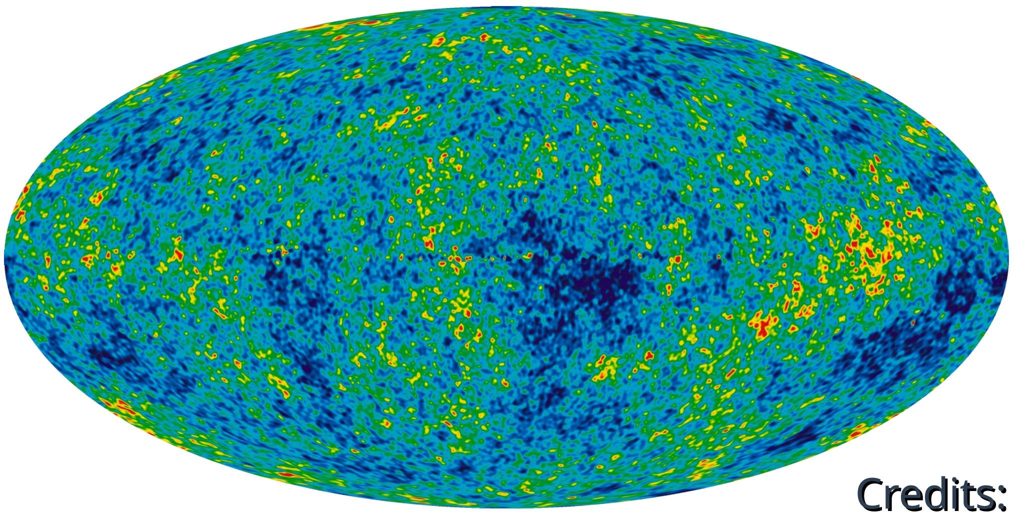
Rotational curves of galaxies



The term dark matter was proposed in 1933 by Fritz Zwicky

Cosmic microwave background





Credits: Planck

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

Merging clusters of galaxies

Bullet Cluster (1E 0657-56)

Pandora's Cluster (Abell 2744)

MACS J0025.4-1222

The strongest evidence for the particle nature of dark matter and not the modification of gravity!

Credits: NASA

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

Bullet Cluster computer simulation

Credit: Andrew Robertson
Durham University

the total mass concentration (mostly DM), baryonic matter (hot gas)

Constraints on DM-DM & DM-BM interactions

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 $\sigma/m < 1.25\ \mathrm{cm}^2\ \mathrm{g}^{-1}$ (68% CL)

Clowe+ 2006; Randall+2008

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

Robertson +2021

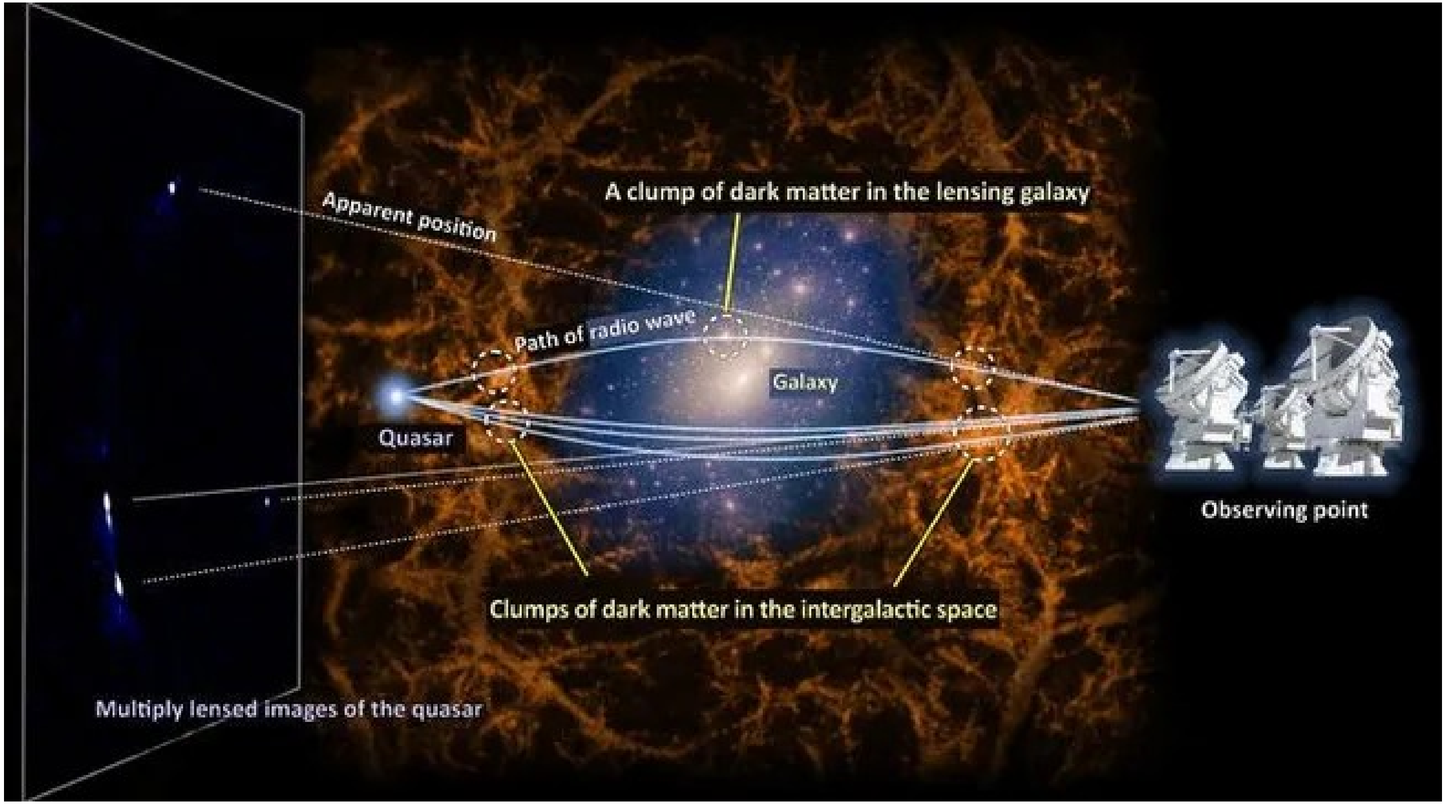
Bullet Cluster (1E 0657-56)

Pandora's Cluster (Abell 2744)

MACS J0025.4-1222

Gravitational lensing

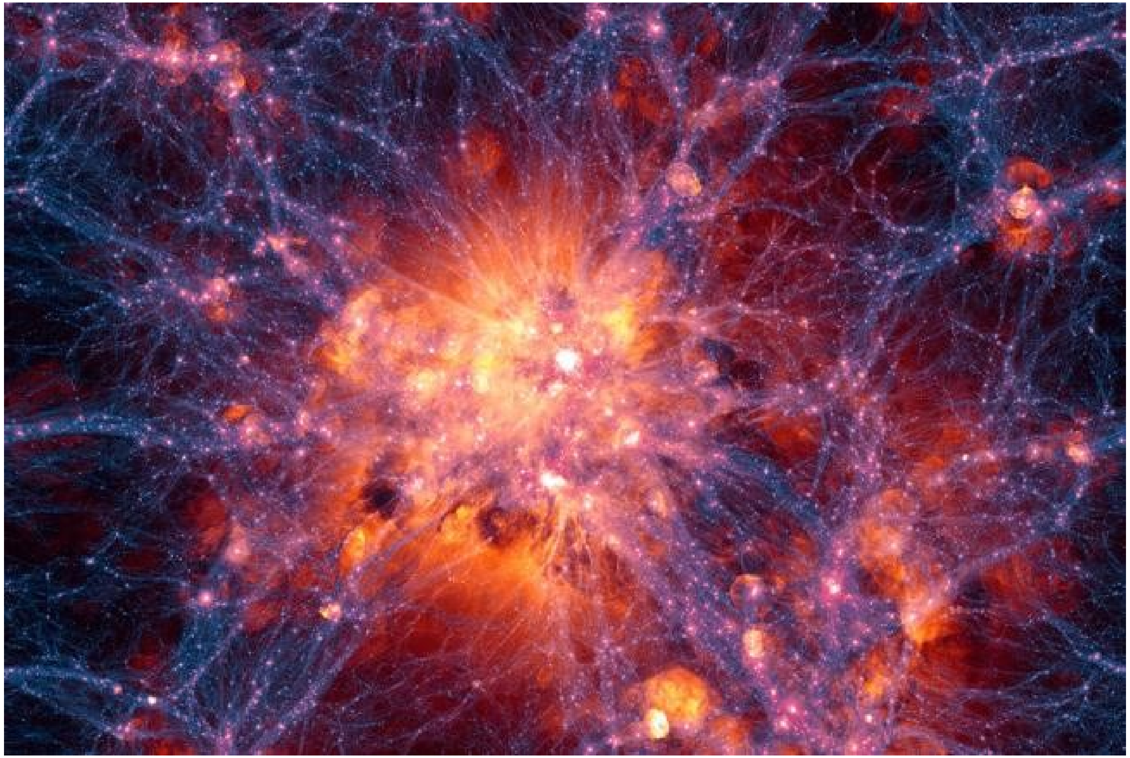
Light bending by galaxy clusters (e.g., the Bullet Cluster) shows much more mass than what is visible in stars and gas



credit: NAOJ, K. T. Inoue

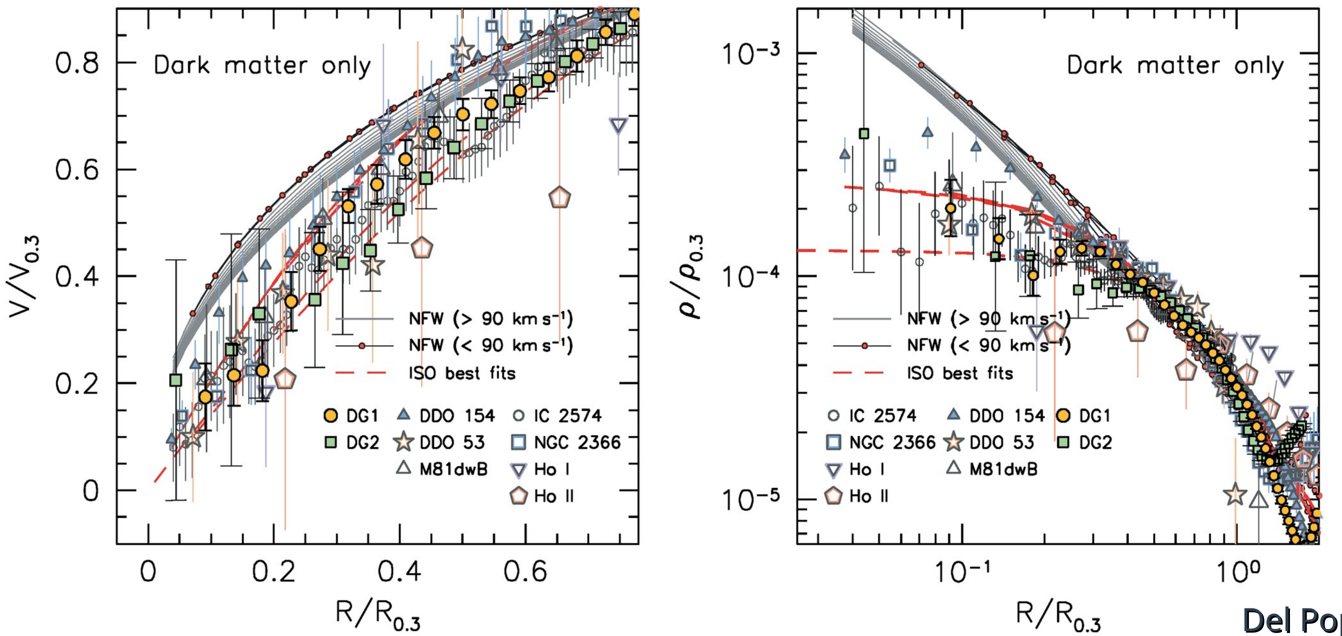
Large-Scale Structure formation, galaxy formation and stability

- **Large-Scale Structure formation** – The distribution of galaxies and cosmic web cannot be explained without non-baryonic BM
- **Galaxy formation and stability** – Numerical simulations show galaxies would not form or survive long enough without DM halos



Credit: Illustris

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

What is the mass range for DM candidates?

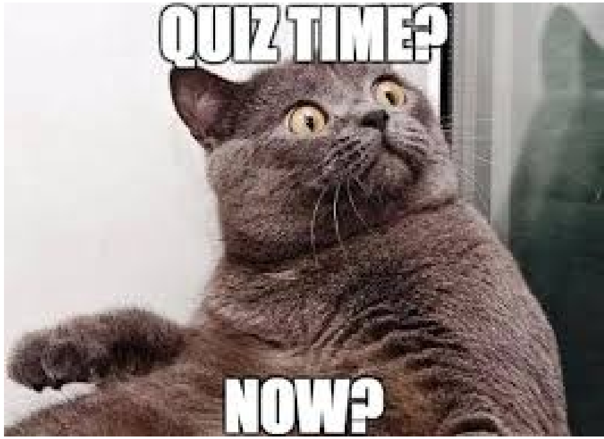
It's quiz time!

a) Zero, I still don't believe in DM

b) 30 orders of magnitude

c) 50 orders of magnitude

d) 90 orders of magnitude



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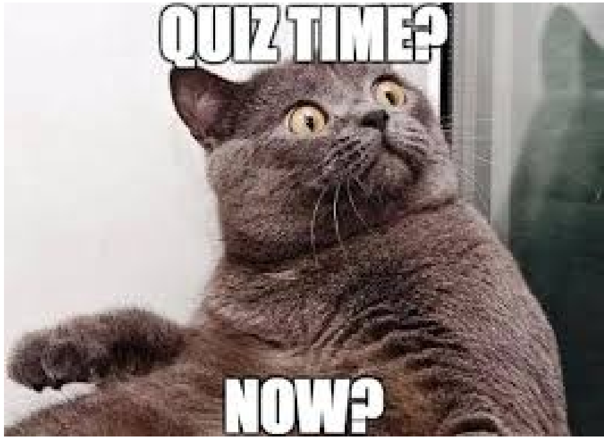
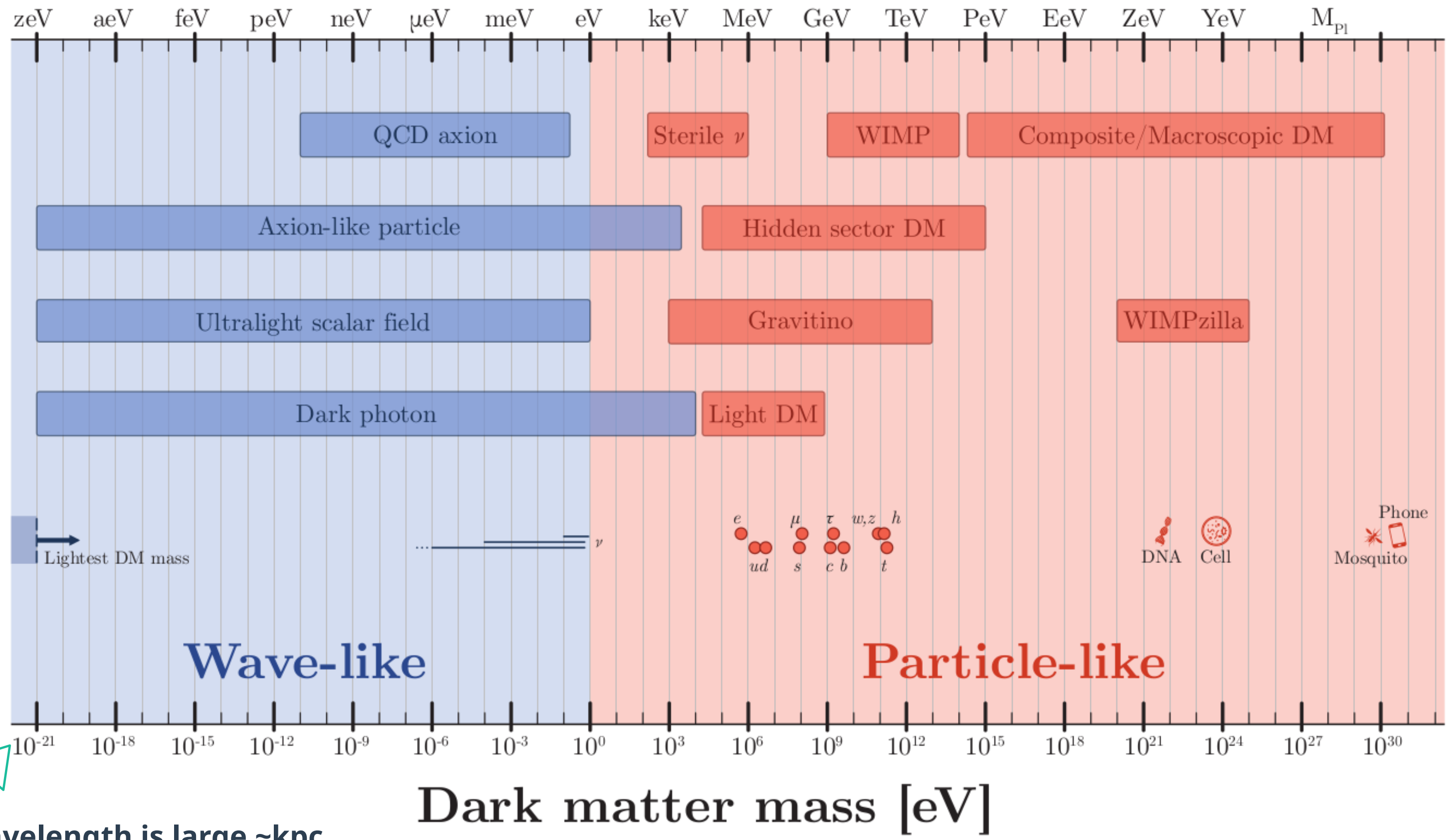


Mass range of DM candidates



de Broglie wavelength is large ~kpc
DM cannot be treated as a collection of point particles;
instead, it behaves as a coherent classical field

Credits: E. Giangrandi

The most 'popular' DM candidates

- <u>Ultralight (wave-like) DM</u>

  Axion(-like) particles / fuzzy DM: $m \sim 10^{-22}$ eV – 10^{-5} eV

- <u>Heavy DM</u>

  Weakly Interacting Massive Particles (WIMPs), asymmetric DM: $m \sim 1$ GeV – 10 TeV

- <u>Macroscopic objects (non-particle candidate)</u>

  Primordial black holes: $m \sim 10^{10}$ GeV – 10^{19} GeV

- <u>Standard Model DM</u>

  Sexaquarks: $m \sim 2$ GeV
  neutral, flavor and isospin singlet, spin-0 bound state composed of 6 quarks, uuddss

- <u>Mirror DM</u>

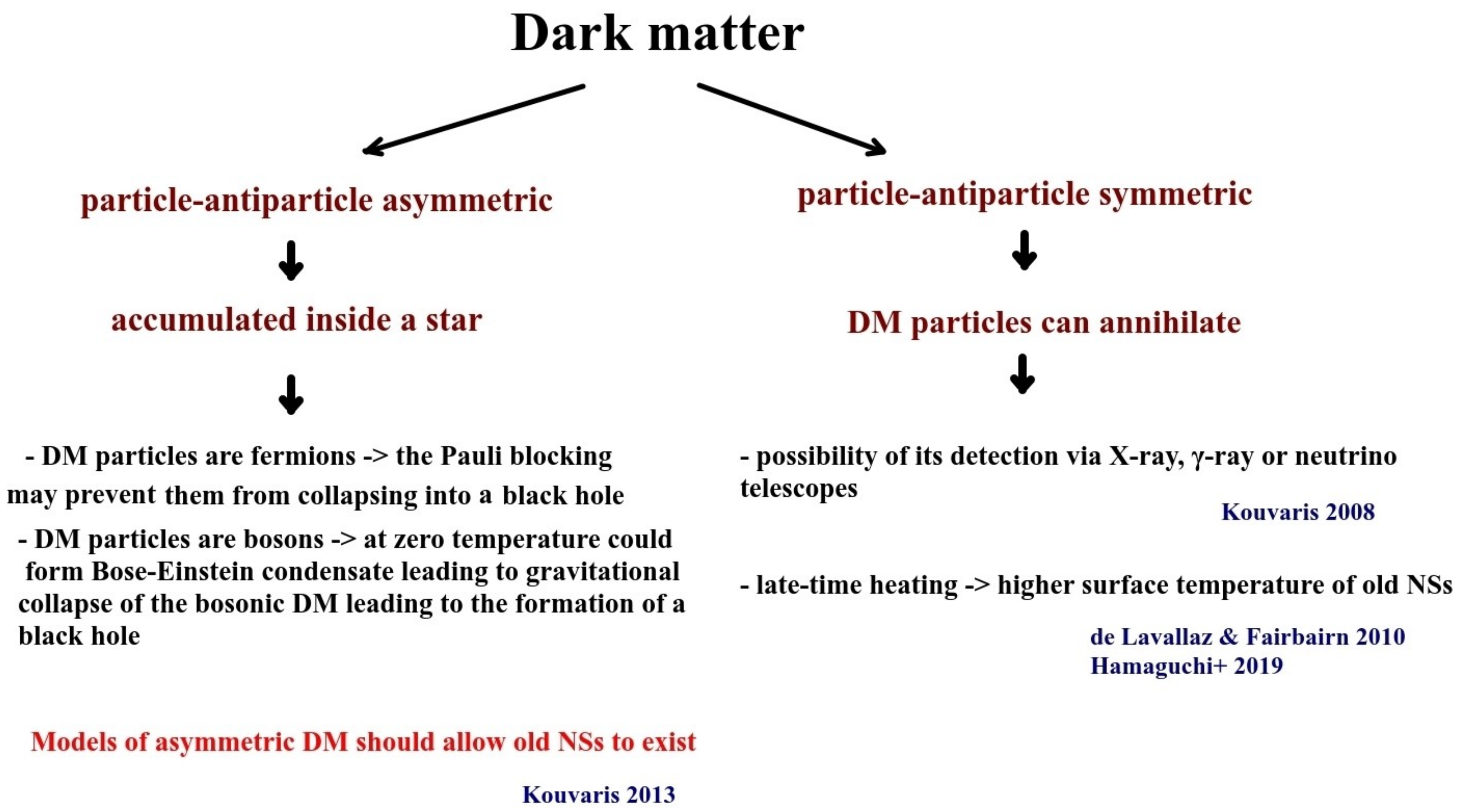
  Dark Standard Model particles

Works of Masha Baryakhtar, Mia Kumamoto, Antonio Gómez-Bañón, Steven Harris

Works of Glennys Farrar & VS

Works of Jaki Noronha-Hostler, Steven Harris

Symmetric vs. asymmetric DM



Equation for thermal balance

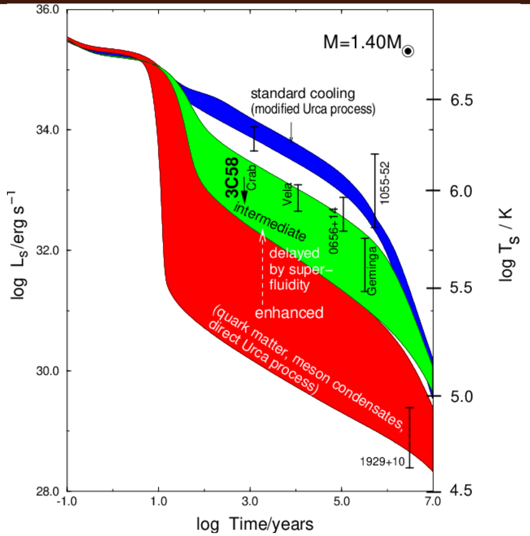
The time evolution of the red-shifted temperature is determined by

$$C\frac{dT^\infty}{dt} = -L_\nu^\infty - L_\gamma^\infty \pm L_H^\infty$$

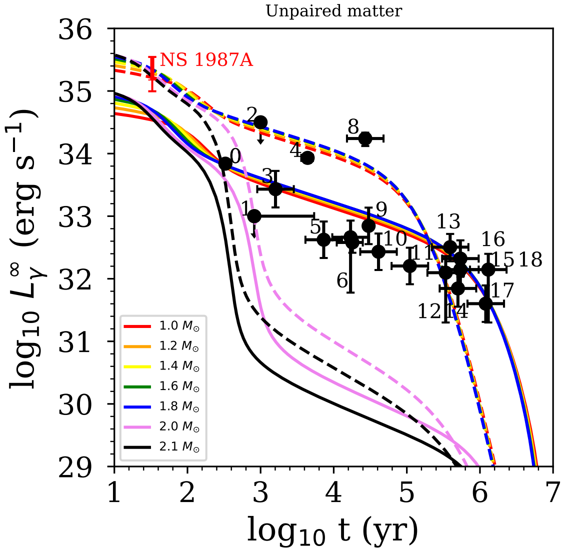
C - total heat capacity of the NS
L_ν^∞ - red-shifted luminosity of the neutrino
L_γ^∞ - red-shifted luminosity of the photon emissions
L_H^∞ - source of heating/cooling

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: F. Weber



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

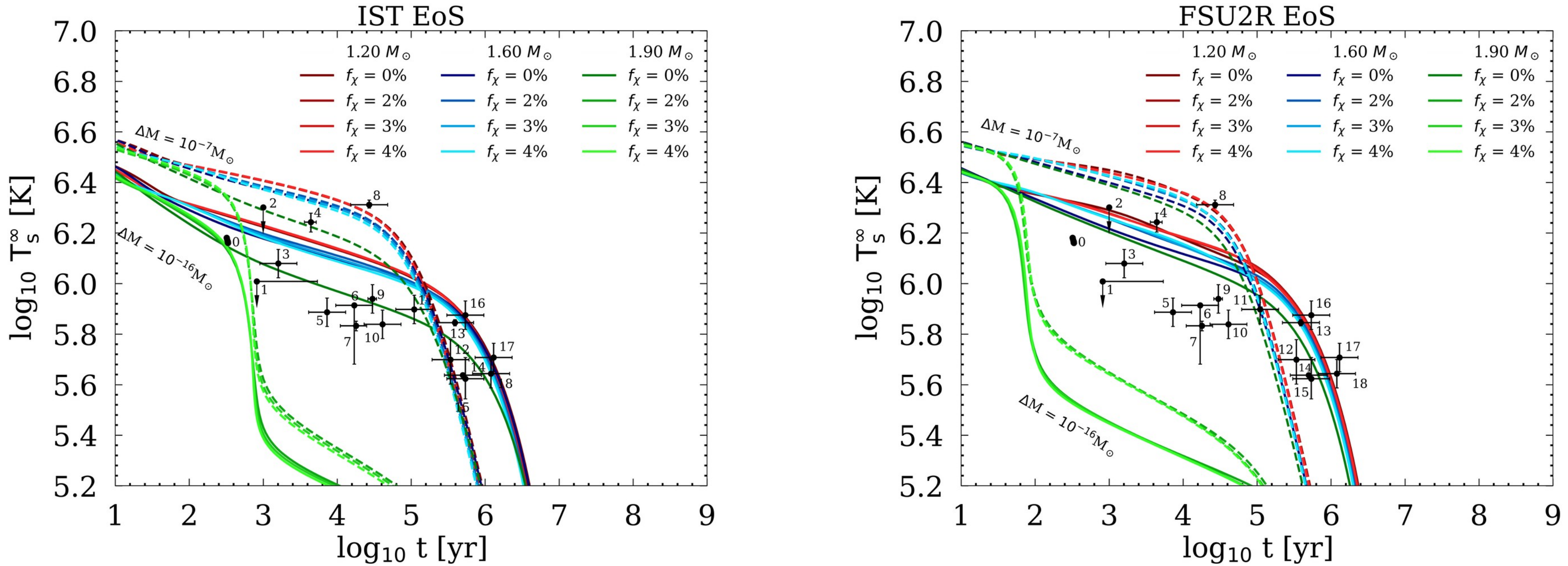
↓

Creation mechanisms:

- nucleon bremsstrahlung
- Cooper pair breaking and formation processes

Buschmann+ 2022; Dietrich & Clough 2019

Rapid neutron star cooling triggered by asymmetric DM



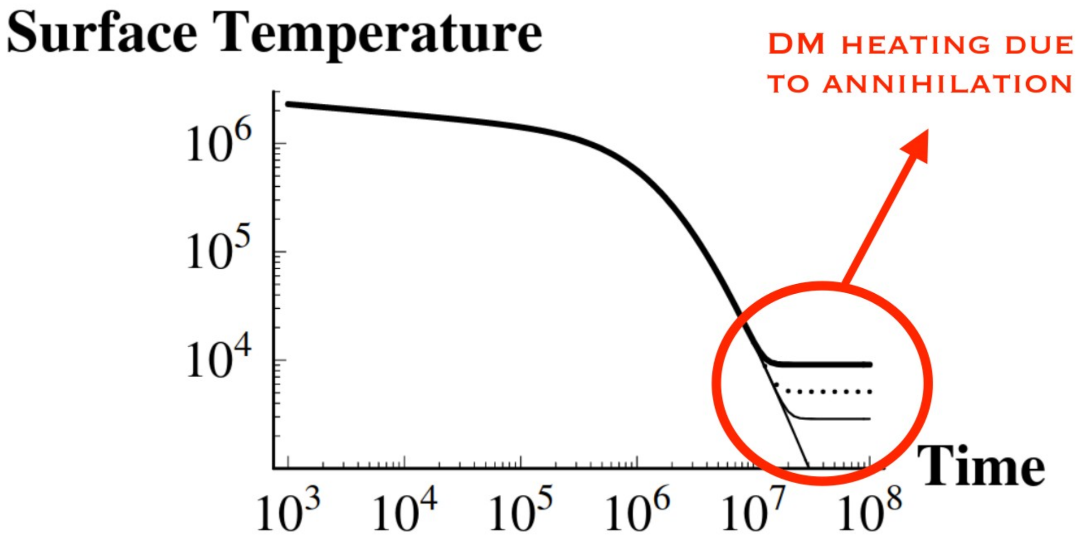
Ávila+ 2024; Giangrandi+ 2024

accumulated DM pulls inwards the outer baryonic layers of the star -> increase the baryonic density in the NS core-> trigger an early onset of the direct Urca process + modification of the photon emission from the surface caused by the decrease of the radius

Heating of NS with DM

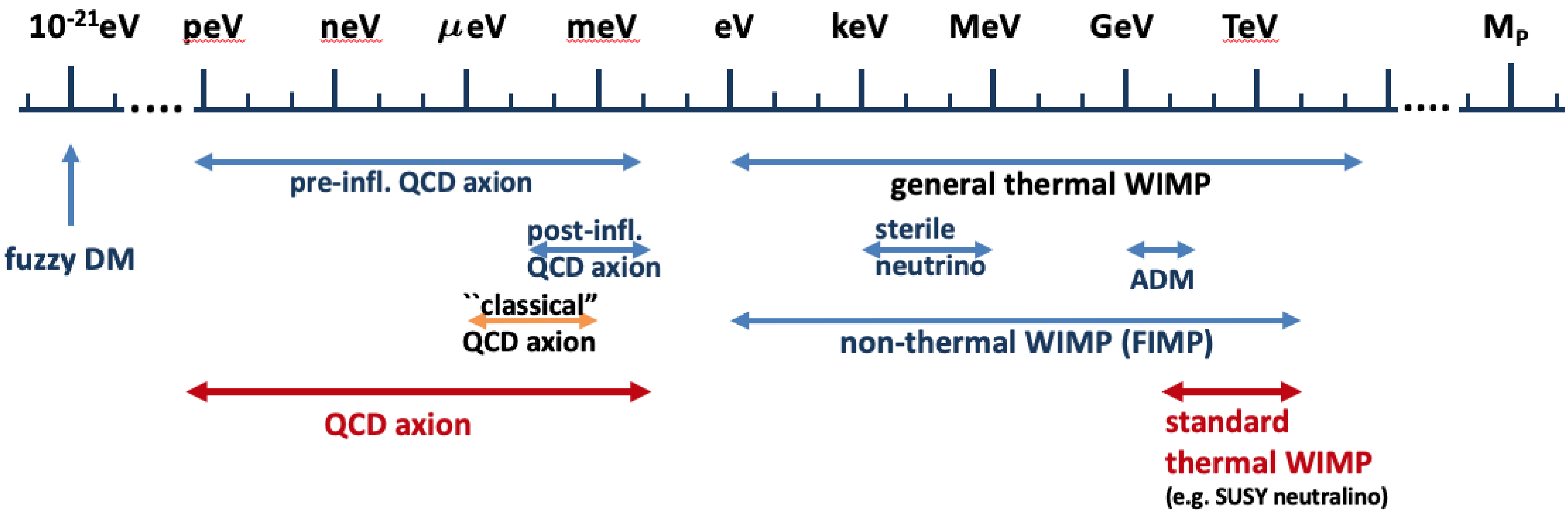
DM particles annihilation can cause heating of old NS

For a typical WIMP, its annihilation and capture rates equilibrate in old NSs.



Kouvaris 2008; Kouvaris & Tinyakov 2010;
Lavallaz & Fairbairn 2010; Hamaguchi+ 2019

DM mass range



I will focus on heavy DM of ≥MeV mass range

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 $p(r) = p_B(r) + p_D(r)$

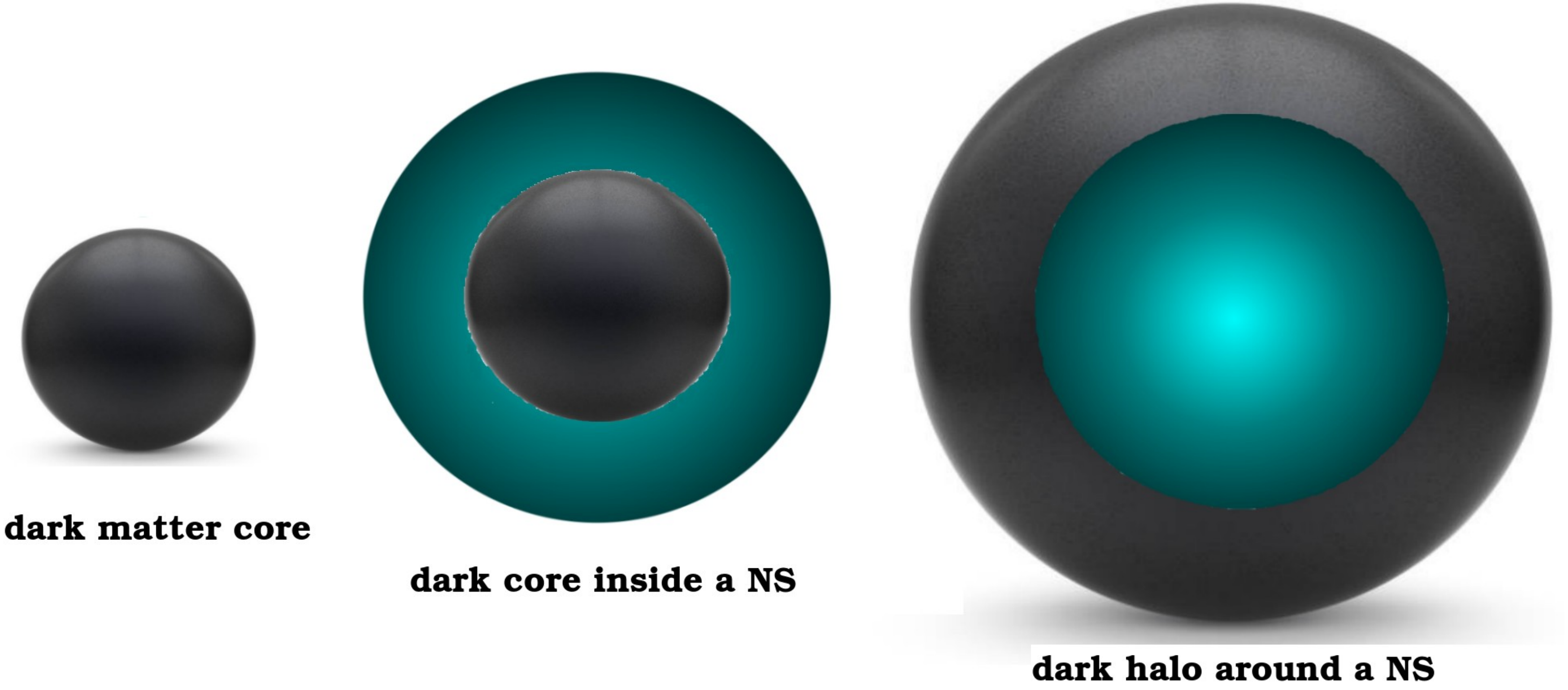
gravitational mass $M(r) = M_B(r) + M_D(r)$, where $M_j(r) = 4\pi \int_0^r \epsilon_j(r')r'^2 dr'$ (j=B,D)

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

Fraction of DM inside the star:

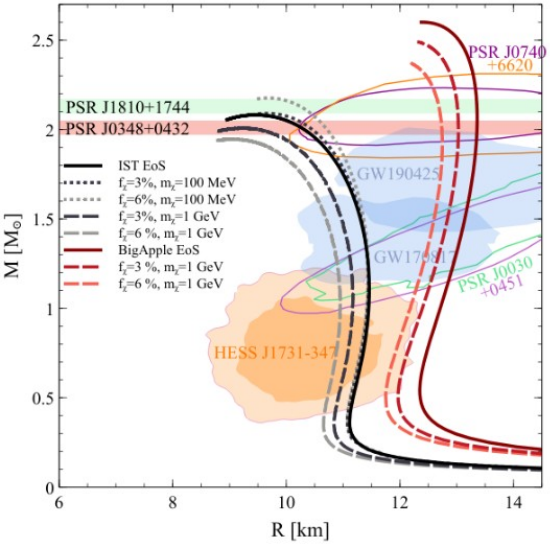
$$f_\chi = \frac{M_D(R_D)}{M_T}$$

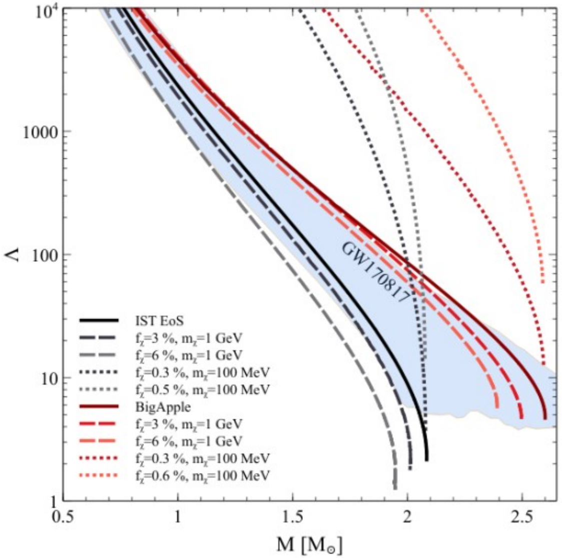
Evidences of DM



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

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

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

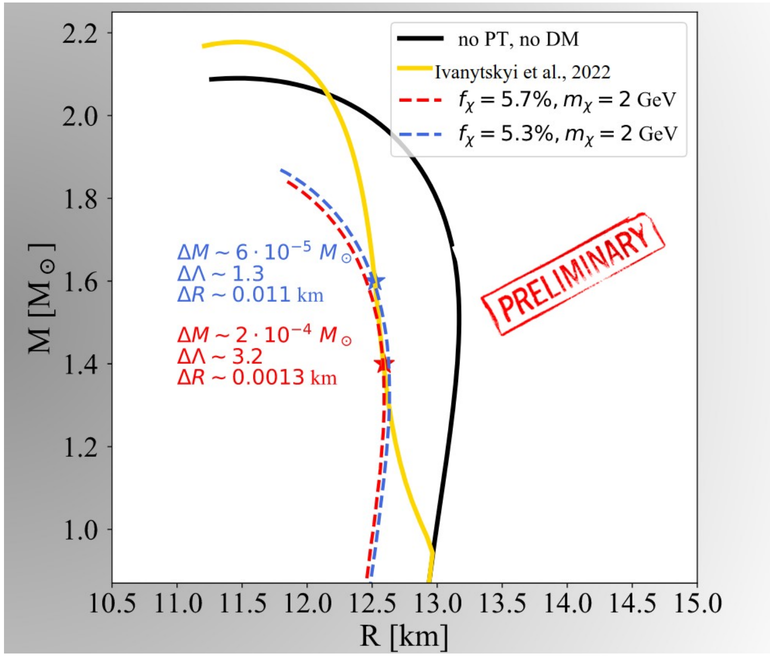
Giangrandi+ 2022

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

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+ 2025 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?

→ 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

Koehn+ 2024

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

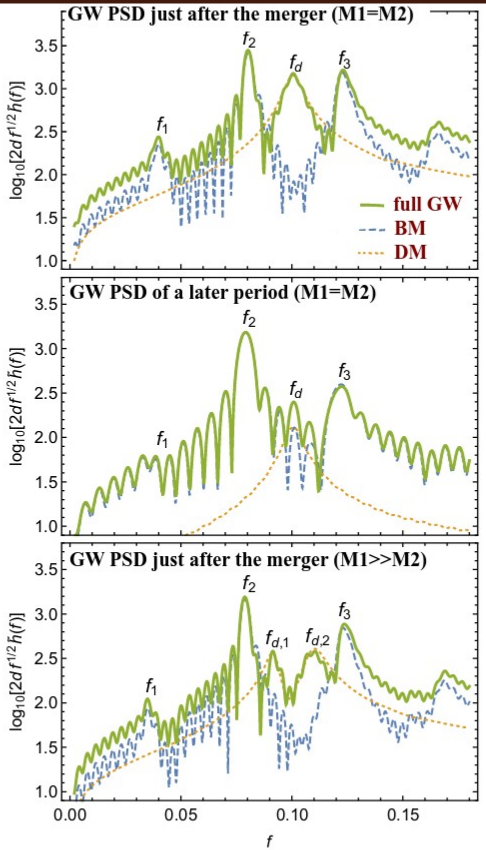
- by performing binary numerical-relativity simulations and kilonova ejecta for DM-admixed compacts stars for different DM candidates, their particle mass, interaction strength and fractions with the further comparison to GW and electromagnetic signals.
  Large statistics on NS-NS, NS-BH mergers
  The 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

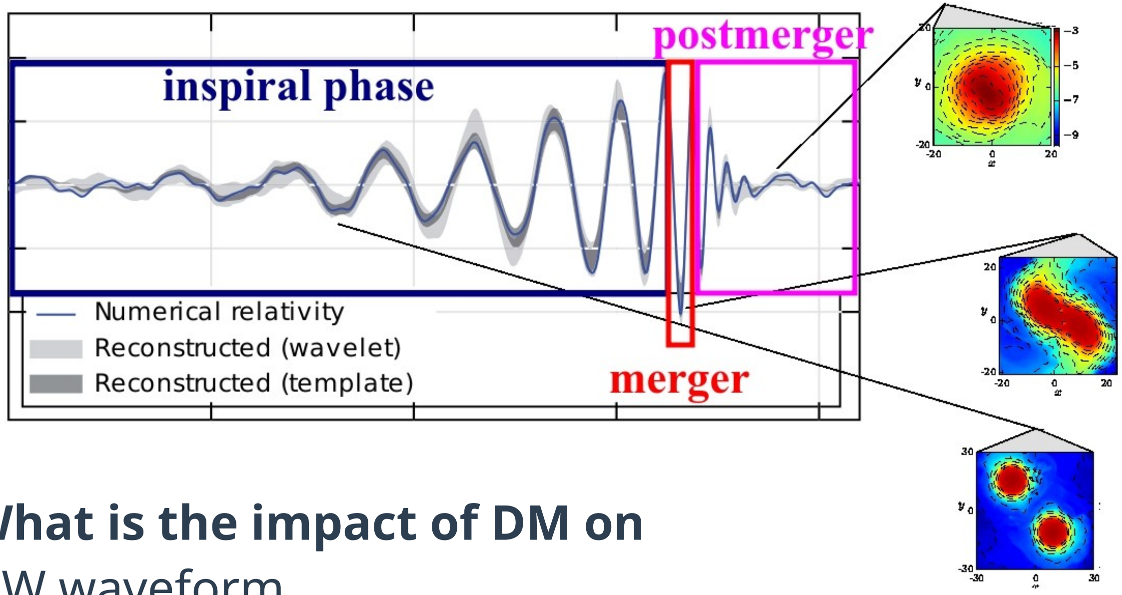
- by detecting objects that go in contradiction with our understanding
  HESS J1731-347 or the secondary component of GW190814 could be candidates for a DM-admixed NS

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

Speculative!

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

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.

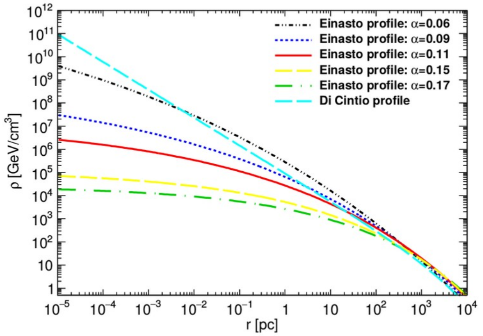
  Kouvaris & Tinyakov (2010)

  Del Popolo et al. (2024)

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

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

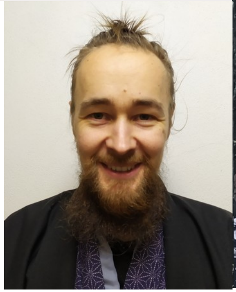
  In the most central Galaxy region $M_{acc} \approx 10^{-5}\, M_\odot - 10^{-8}\, M_\odot$.



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

Bramante et al. (2022)

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_{DM} and spin one-half

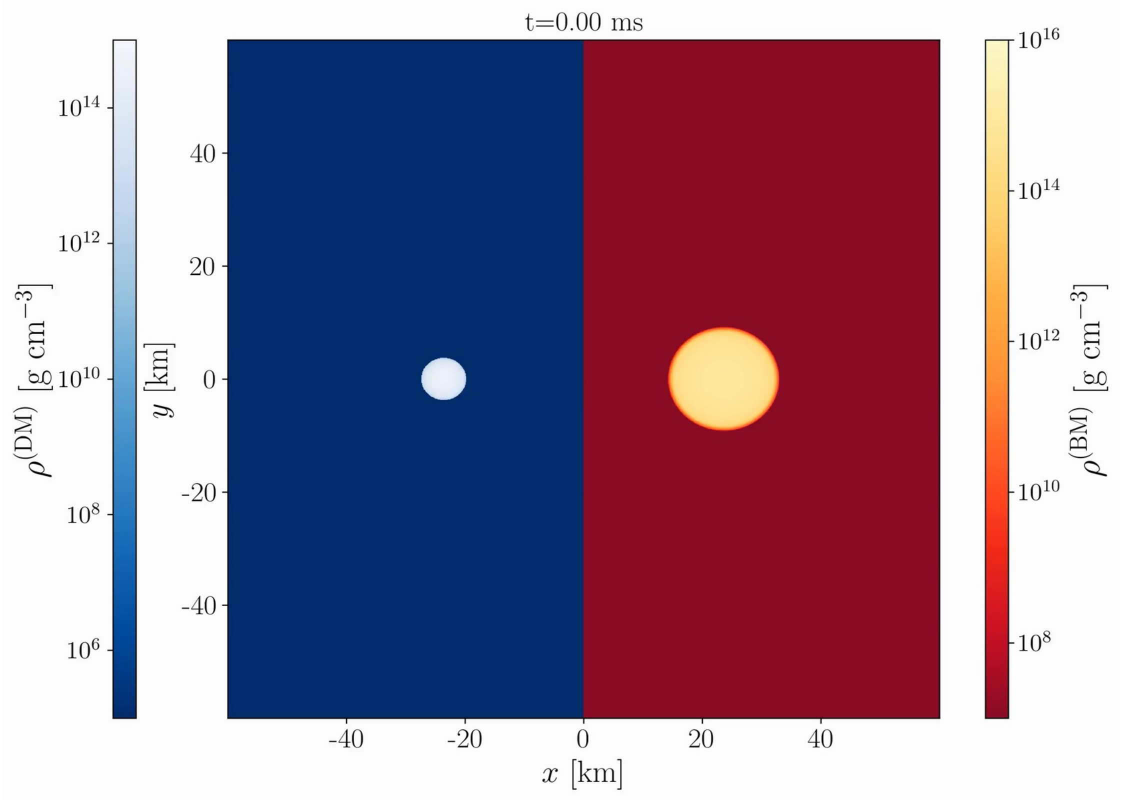
Ivanytskyi+ 2020

- BM is described by Sly4 EoS

Rüter+ 2023

identifier	m_{DM} [GeV]	f_{DM} [%]	$2 \cdot M_{TOV}$ [$M_\odot$]	M_{ADM} [$M_\odot$]	J_{ADM} [$M_\odot^2$]	$R^{(BM)}$ [km]	$R^{(DM)}$ [km]	d_{in} [km]	Λ^{out}	DM Morphology
$M24_{00}$	-	0	2.40	2.382	6.39	11.400	-	53.05	818	None
$M24_{3C}$	1	3	2.40	2.381	6.08	11.154	5.329	47.02	730	Core
$M24_{05H}$	0.17	0.5	2.40	2.381	6.09	11.377	18.645	46.91	2908	Halo
$M28_{00}$	-	0	2.80	2.778	8.38	11.407	-	56.02	310	None
$M28_{3C}$	1	3	2.80	2.774	7.91	11.143	5.122	47.07	234	Core
$M28_{05H}$	0.17	0.5	2.80	2.774	7.86	11.379	16.575	46.98	901	Halo

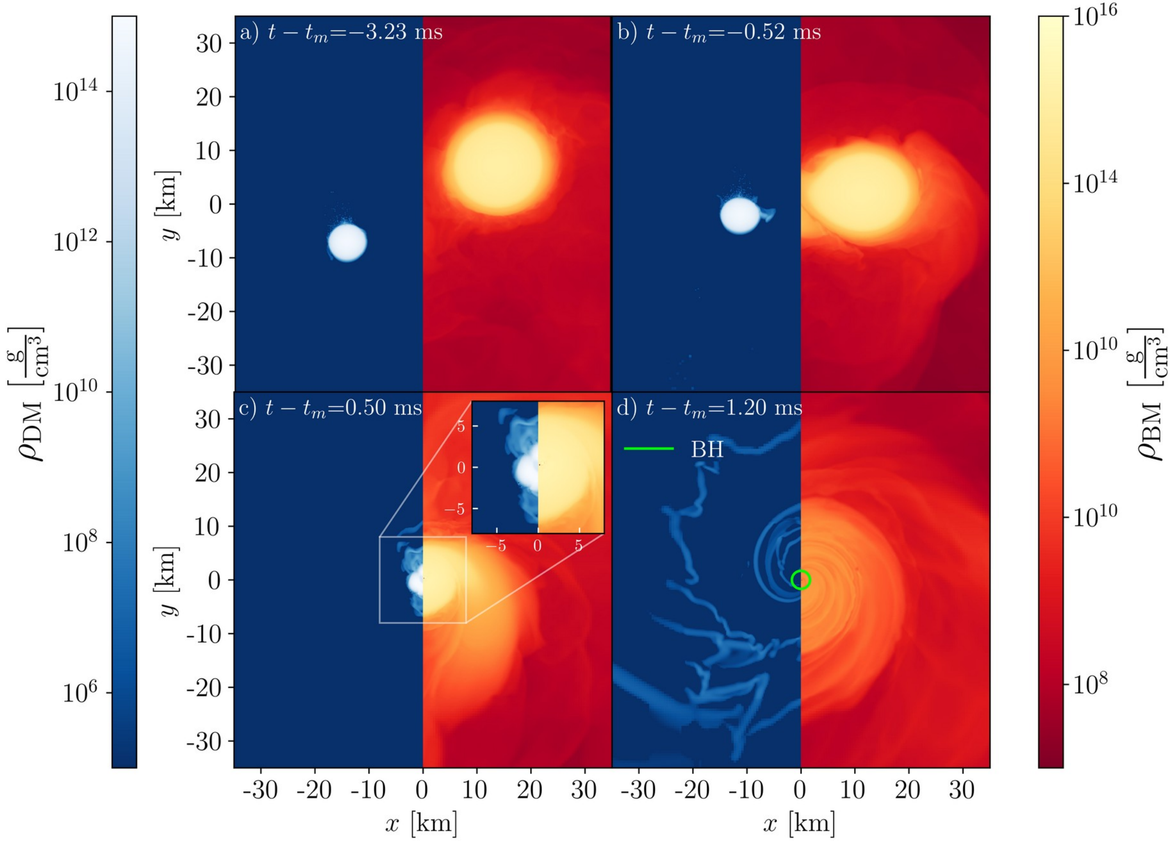
Dark matter core configuration



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

Giangrandi+ 2025

Dark matter core configuration



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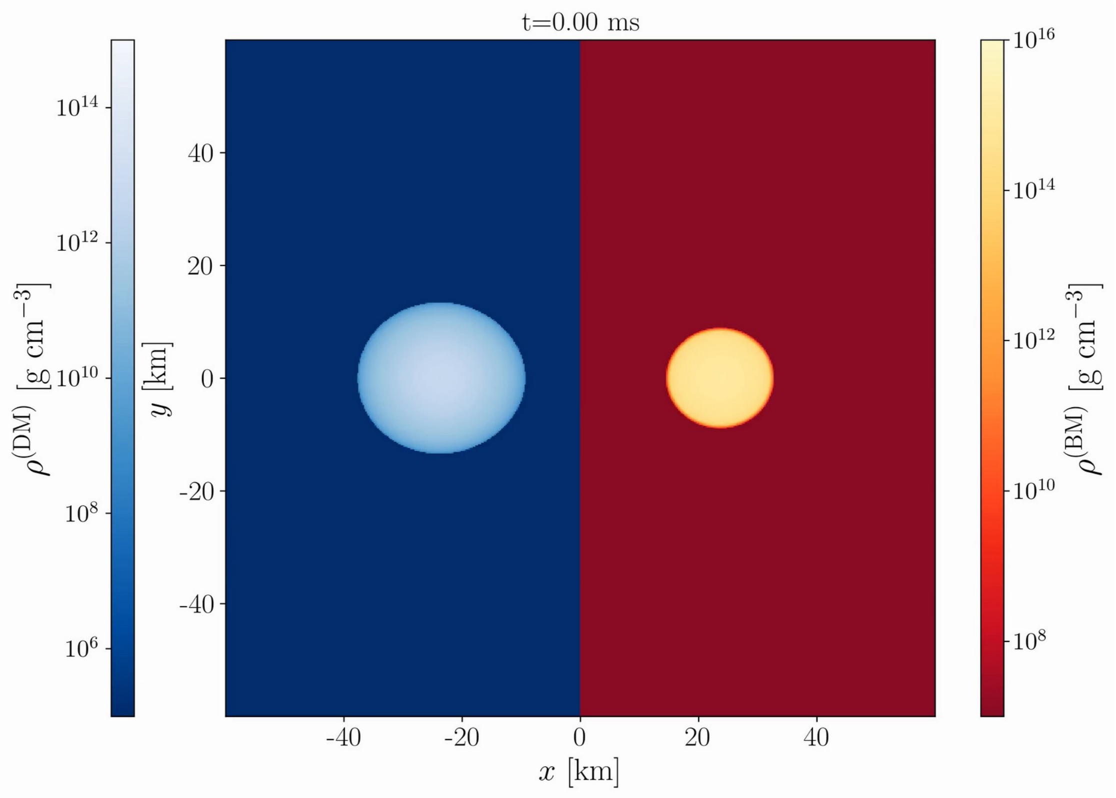
- DM core configurations exhibit a delayed merger in comparison to the BM configurations. A longer inspiral is due to a lower deformability of DM-admixed NSs;
- Faster formation of the BH after the merger and harder to eject material from the bulk of the stars prior to the BH formation;

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

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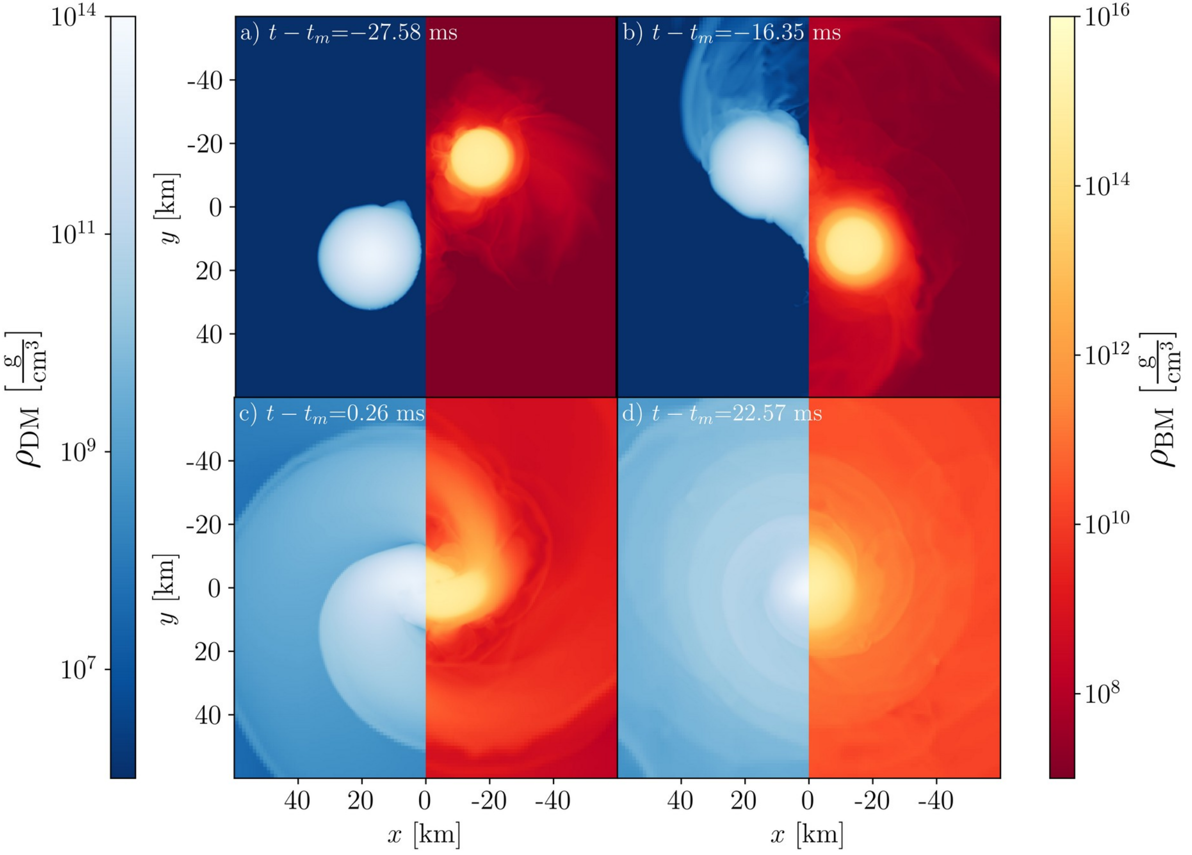
Dark matter halo configuration



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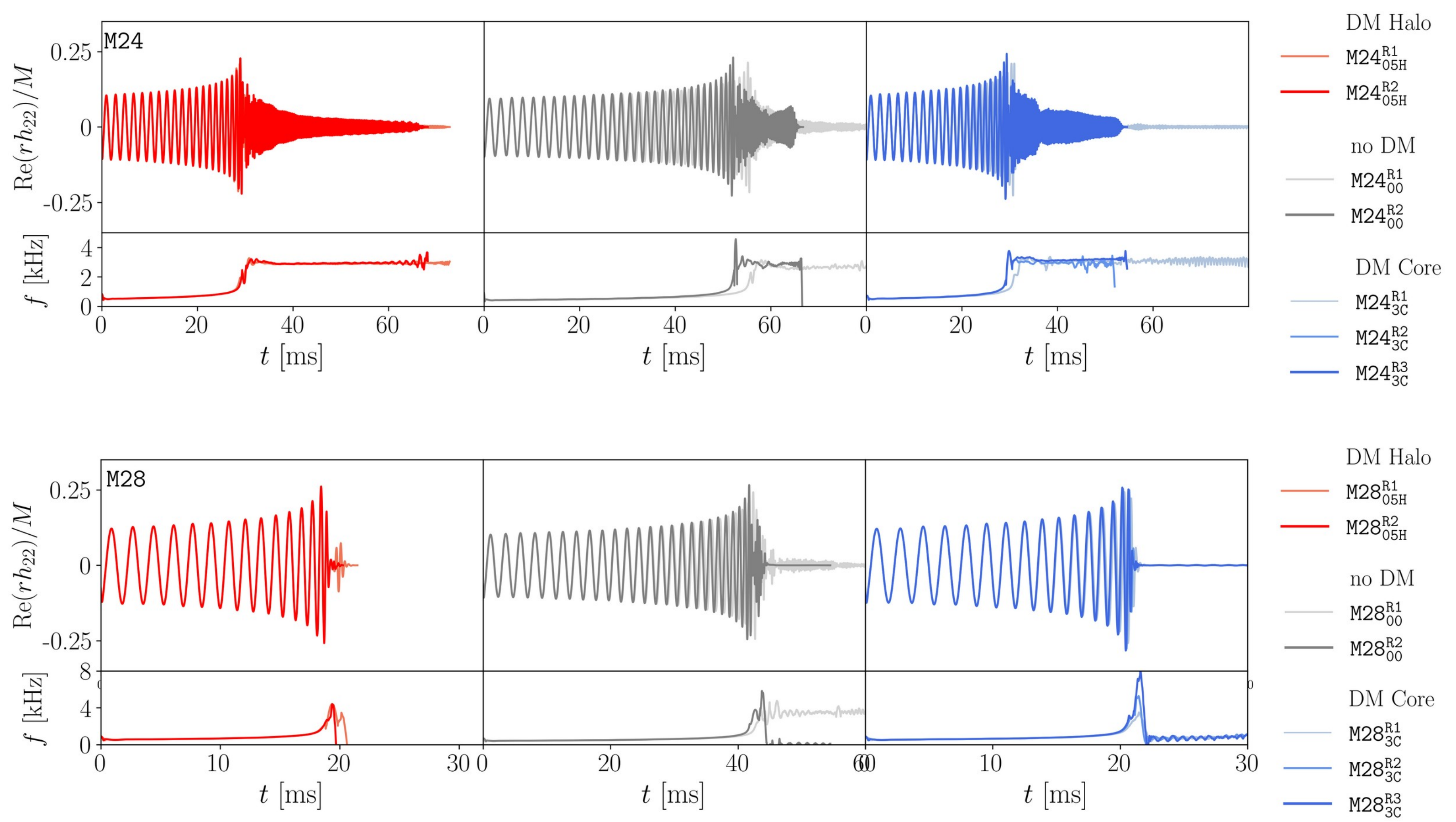
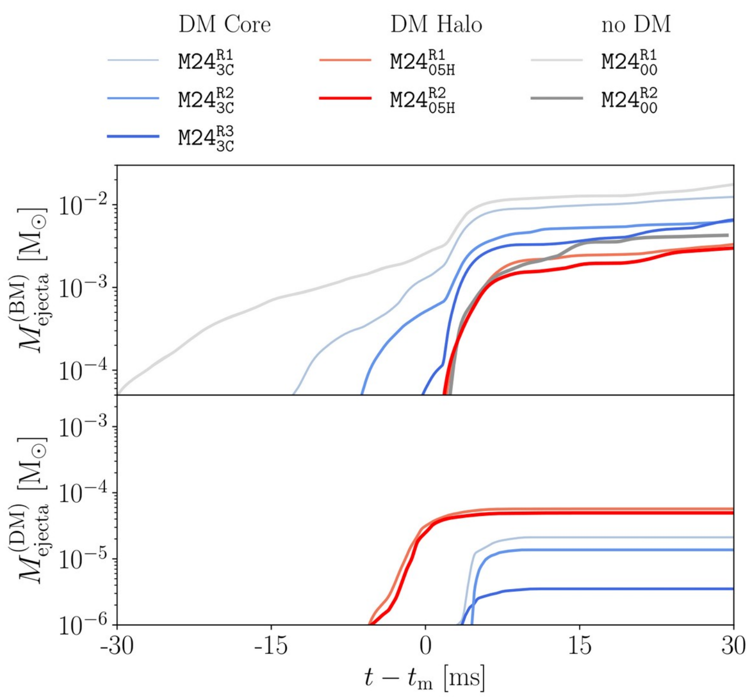
- DM-halo configurations evolve into a more diffuse and spatially extended cloud-like DM distribution surrounding the HMNS.
- During the merger, DM-halo simulations show a higher peak of the BM density compared to the DM-core or purely baryonic runs, suggesting that a diffuse halo may have an impact 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.

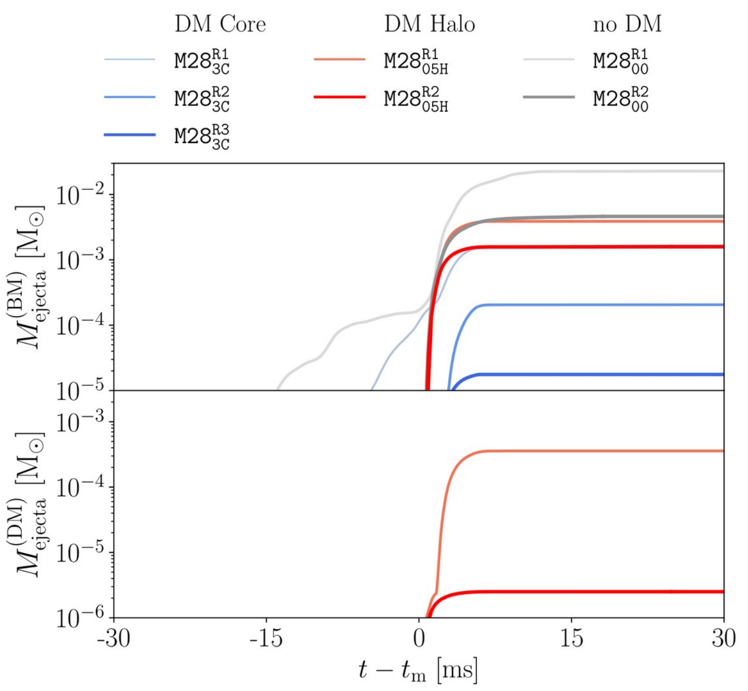
Waveform strain and frequency



Violetta Sagun University of Southampton

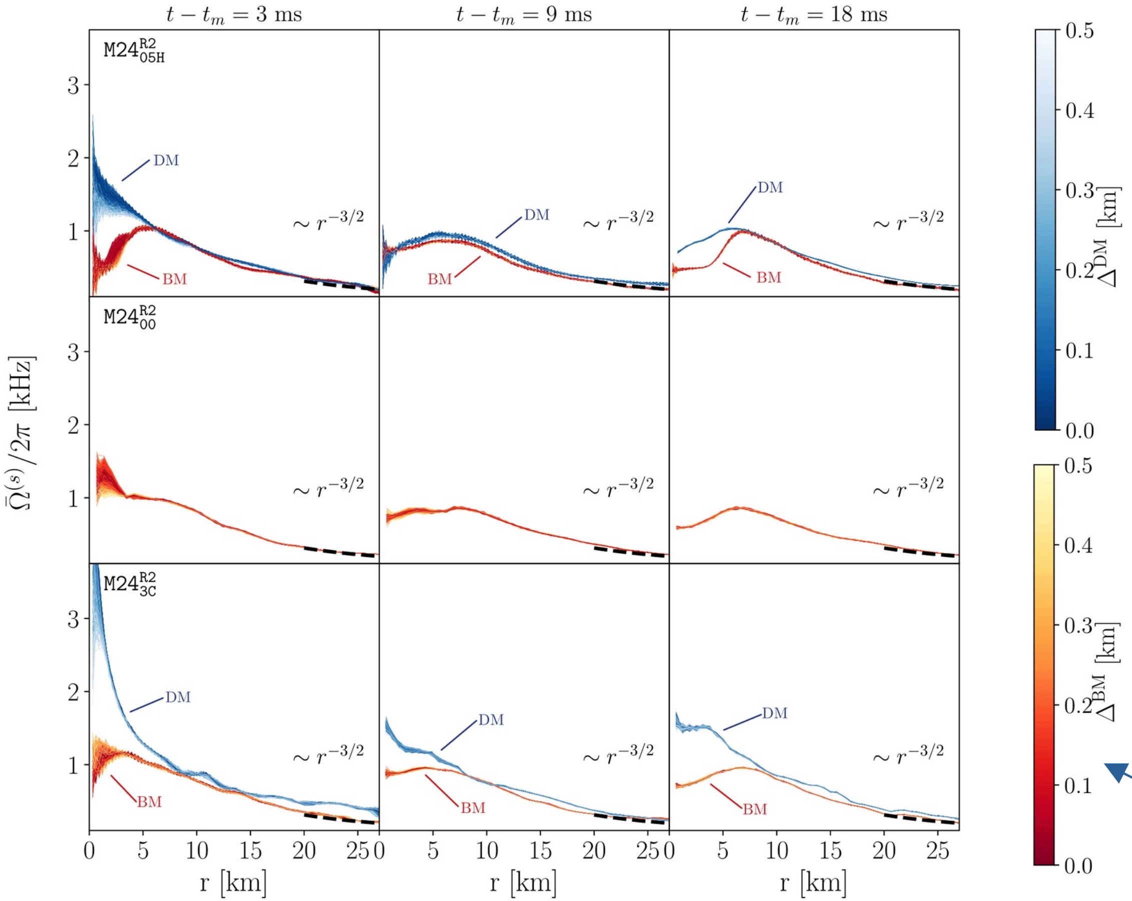
Ejecta





- **BM ejecta:** DM-core configurations can suppress BM ejection 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 $[10^{-6}, 10^{-4}]$ $M_\odot$

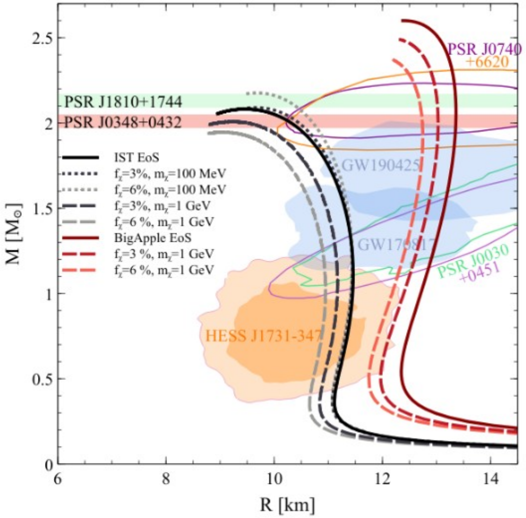
Rotational dynamics

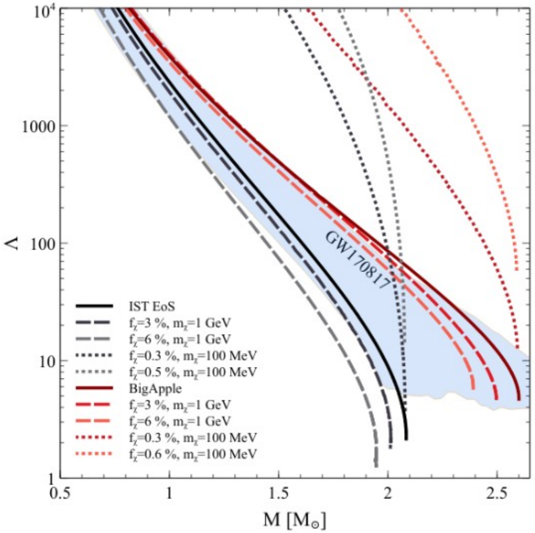


- DM cores exhibit higher rotational velocities compared to DM halo configurations.
- BM angular velocity shows less pronounced changes
- Halo configurations show the presence of a central region with lower BM angular velocities, suggesting a more complex rotational profile.

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

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

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

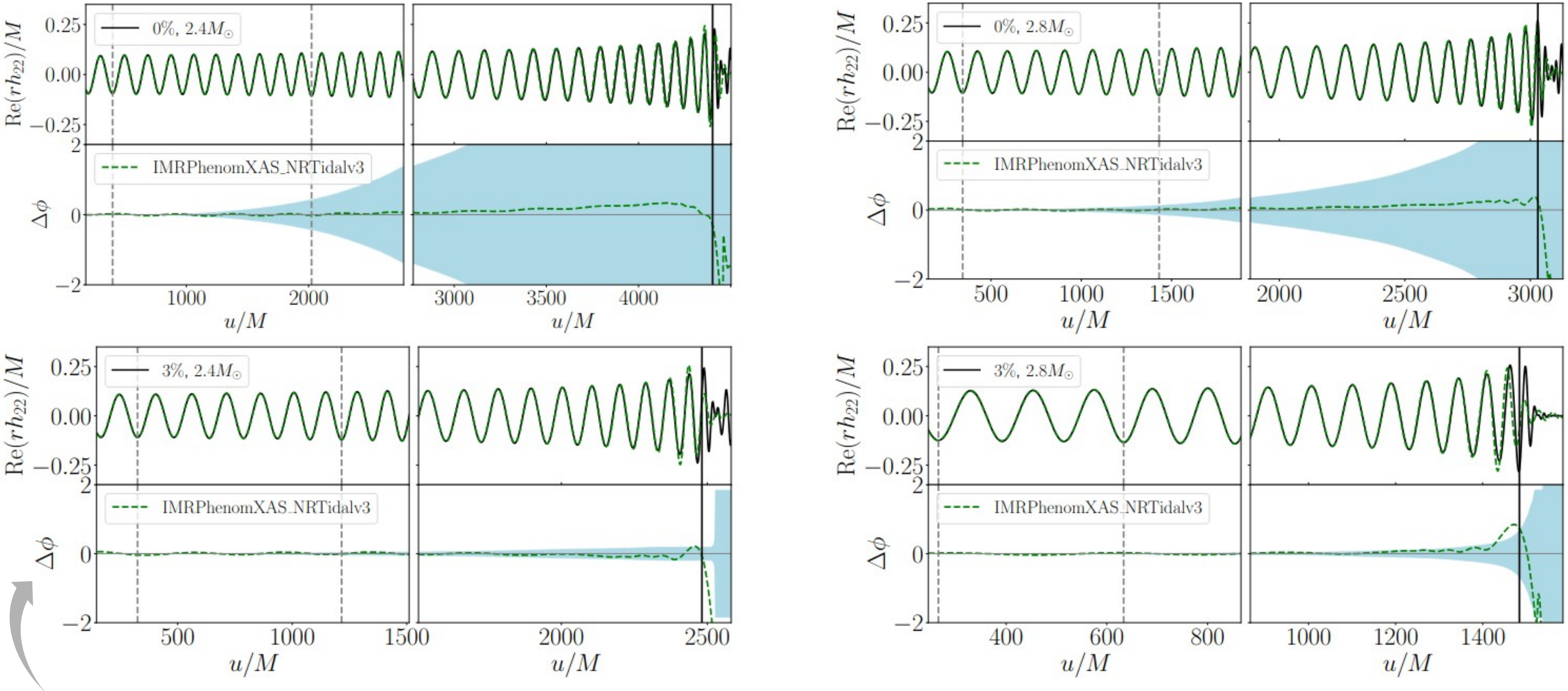
The speed of sound is calculated considering the total energy density and pressure

Giangrandi+ 2022

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

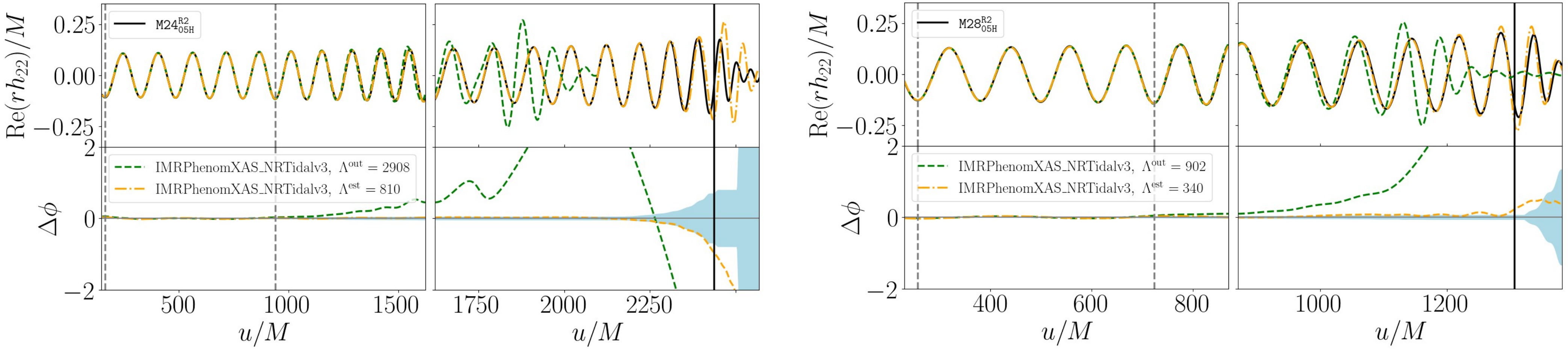
Time-domain dephasing comparisons

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

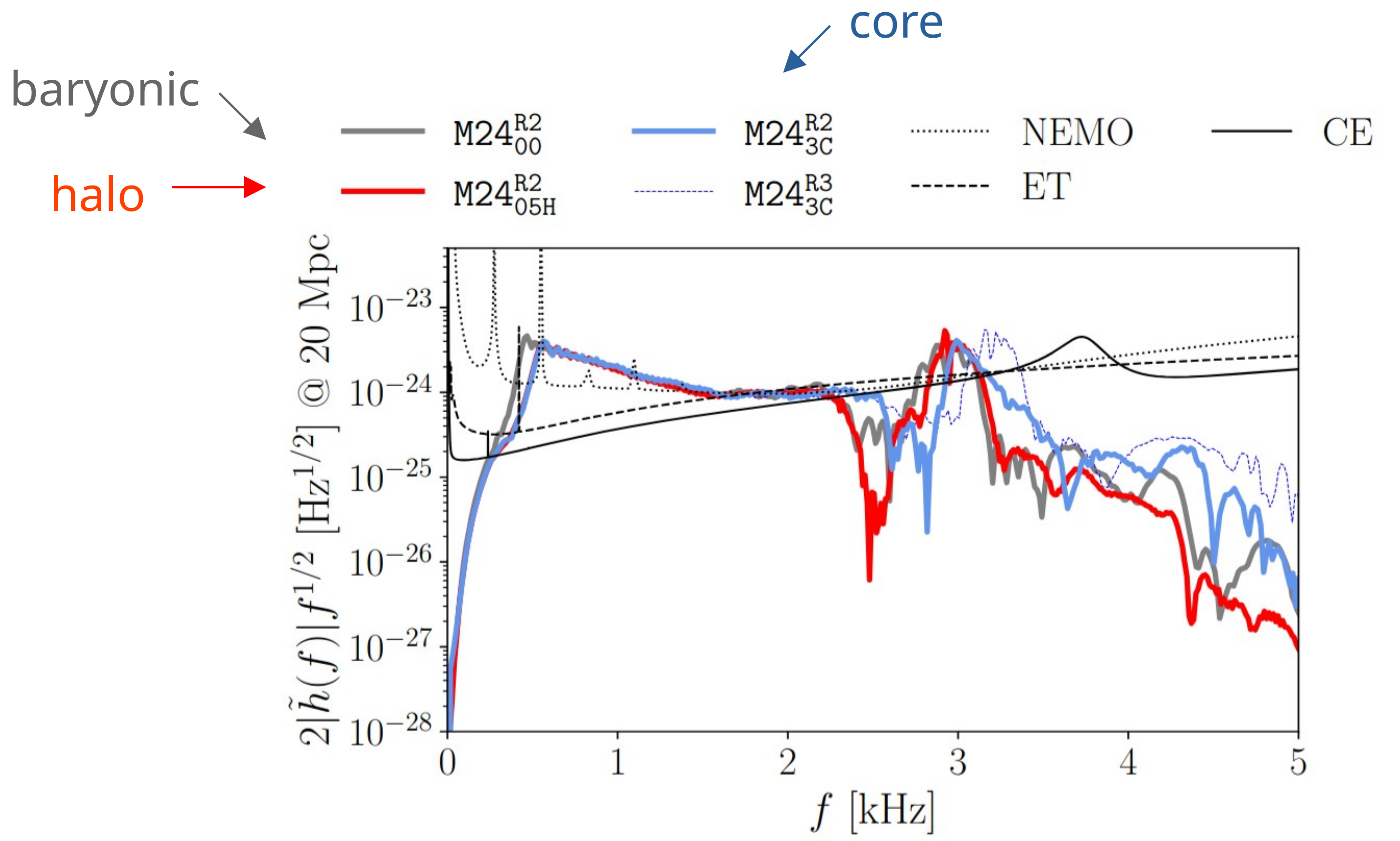
Time-domain dephasing comparison: halo



Giangrandi+ 2025

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

Post-merger phase



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

M24$^{R3}_{3C}$ shows a noticeable shift towards higher frequencies with f_2 = 3.156 kHz

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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!