Mergers of Dark Matter Admixed Neutron Stars

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Wolfgang Tichy, Mattia Emma

Dark Matter and Stars
Multi-Messenger Probes of Dark Matter and Modified Gravity

Lisbon
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Hannes Rüter *et al.*
arXiv: 2301.03568

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Scenario

- Two orbiting neutron stars
- Neutron stars are made of baryonic matter and dark matter
- Baryonic and dark matter are modelled as two ideal fluids without direct interaction

Matter

- Energy-momentum tensor

$$T_{\mu\nu} = T^{(BM)}_{\mu\nu} + T^{(DM)}_{\mu\nu}$$

$$T^{(s)}_{\mu\nu} = (e^{(s)} + p^{(s)}) u^{(s)}_{\mu} u^{(s)}_{\nu} + p^{(s)} g_{\mu\nu}$$

$e^{(s)}$ - proper energy density

$p^{(s)}$ - pressure

$u^{(s)\mu}$ - fluid four velocity

3 Configurations

- *Single fluid:*
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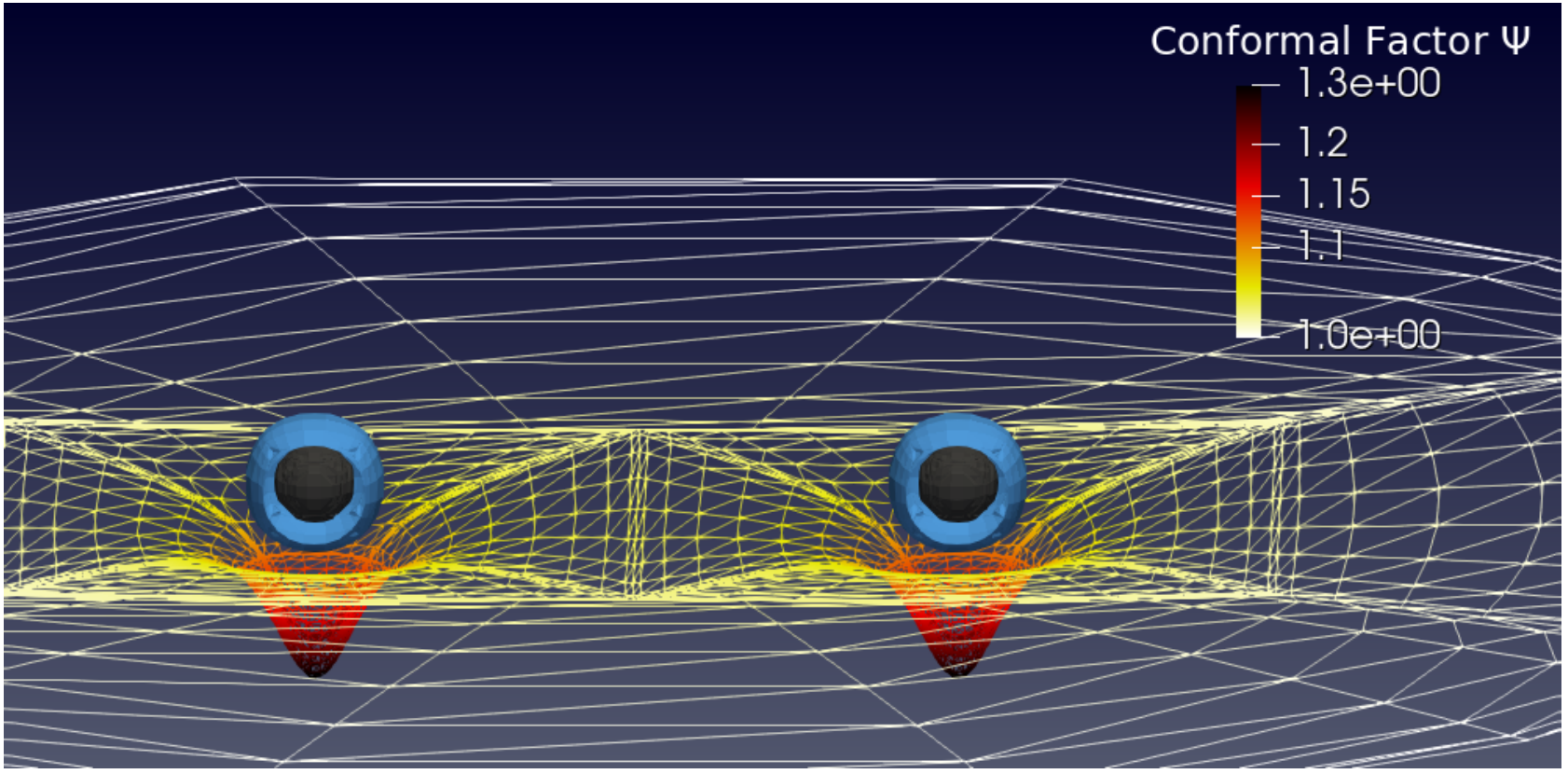
  - 1 GeV fermions, 5 % of mass

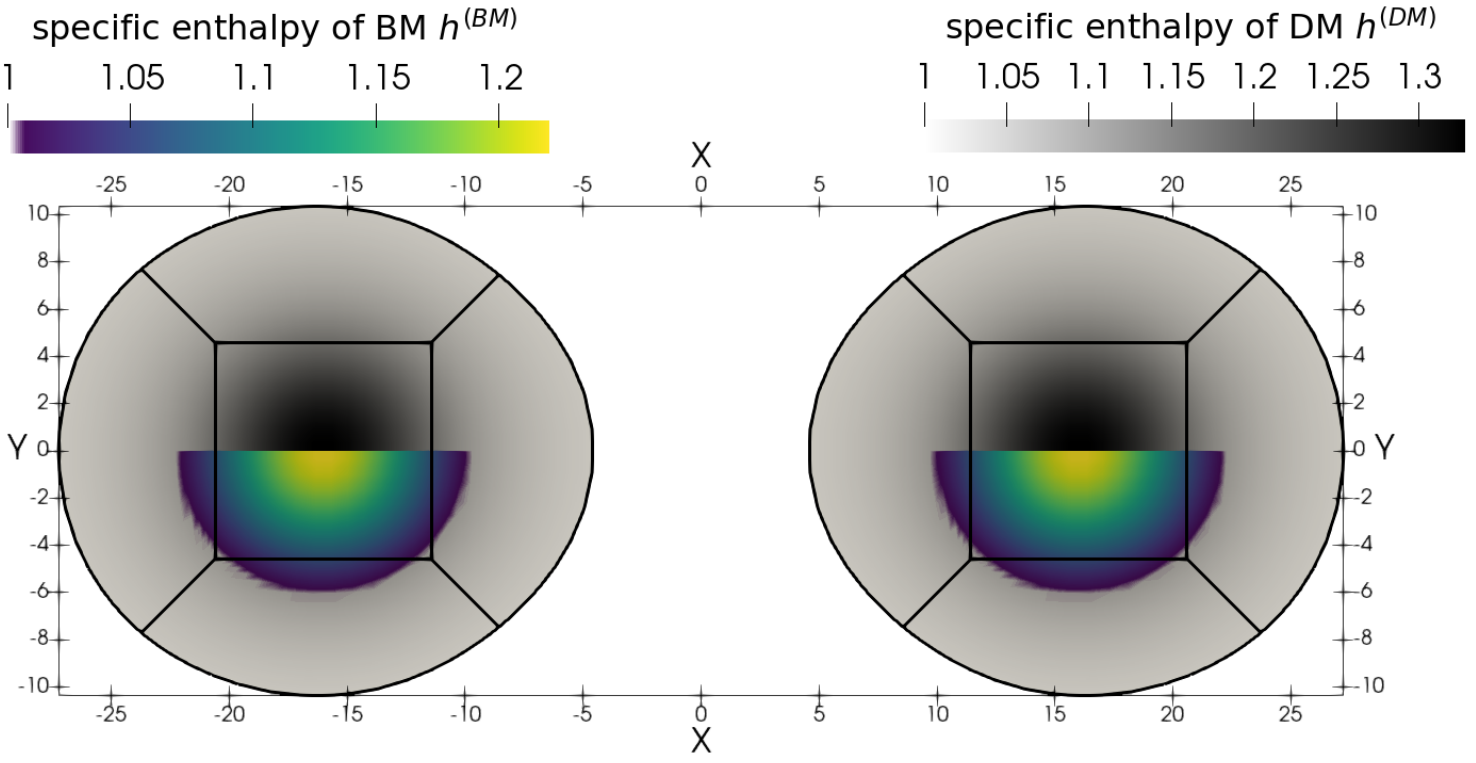
Dark Core



3 Configurations

- *Single fluid:*
  - Purely baryonic neutron star (no dark matter)
- *Dark core:*
  - Dark matter in only in the center
  - 1 GeV fermions, 5 % of mass
- *Dark halo:*
  - Dark matter cloud extends beyond baryonic core
  - 170 MeV fermions, 0.5 % of mass

Dark Halo


specific enthalpy of BM $h^{(BM)}$
1 1.05 1.1 1.15 1.2
specific enthalpy of DM $h^{(DM)}$
1 1.05 1.1 1.15 1.2 1.25 1.3
X
Y
-25 -20 -15 -10 -5 0 5 10 15 20 25
10 8 6 4 2 0 -2 -4 -6 -8 -10

Dark Matter in Neutron Stars

- Capture of dark matter particles

  Scattering cross section: $\sigma_{DM-BM} \approx 10^{-45}\mathrm{cm}^2$

  $\Rightarrow \sim 10^{-10}\ \mathrm{M}_\odot$ dark matter core
- Dark matter from primordial over densities

Motivation

- Dark matter core causes one-arm instability in the post-merger phase
  [Bezares *et al.* – PRD 100 (2019) 044049]
- 0.1 $M_\odot$ core detectable by aLIGO

  0.01 $M_\odot$ core detectable by ET

  [Bauswein *et al.* – arXiv:2012.11908 (2020)]

Initial Data

a.k.a.

Quasi-Equilibrium Configurations

H. R. Rüter, V. Sagun, W. Tichy,
T. Dietrich
arXiv: 2301.03568

Solving the System of PDEs

- 5 PDEs from extended conformal sandwich equations: lapse α, shift β^i, conformal factor ψ
- 2 elliptic PDEs: $\phi^{(BM)}$, $\phi^{(DM)}$
- Solved using SGRID code
  - Spectral discretisation
  - Surface-fitted coordinates
  - Iterative solution of PDE system

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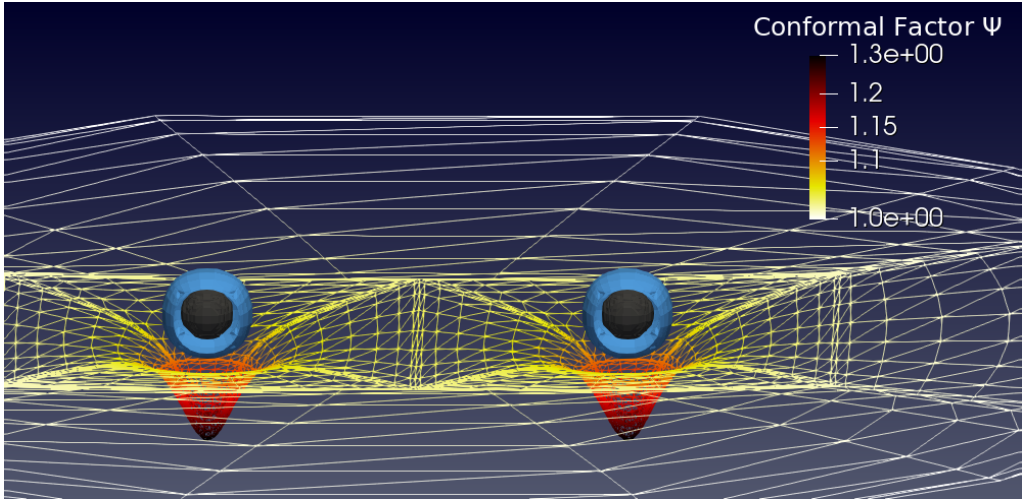


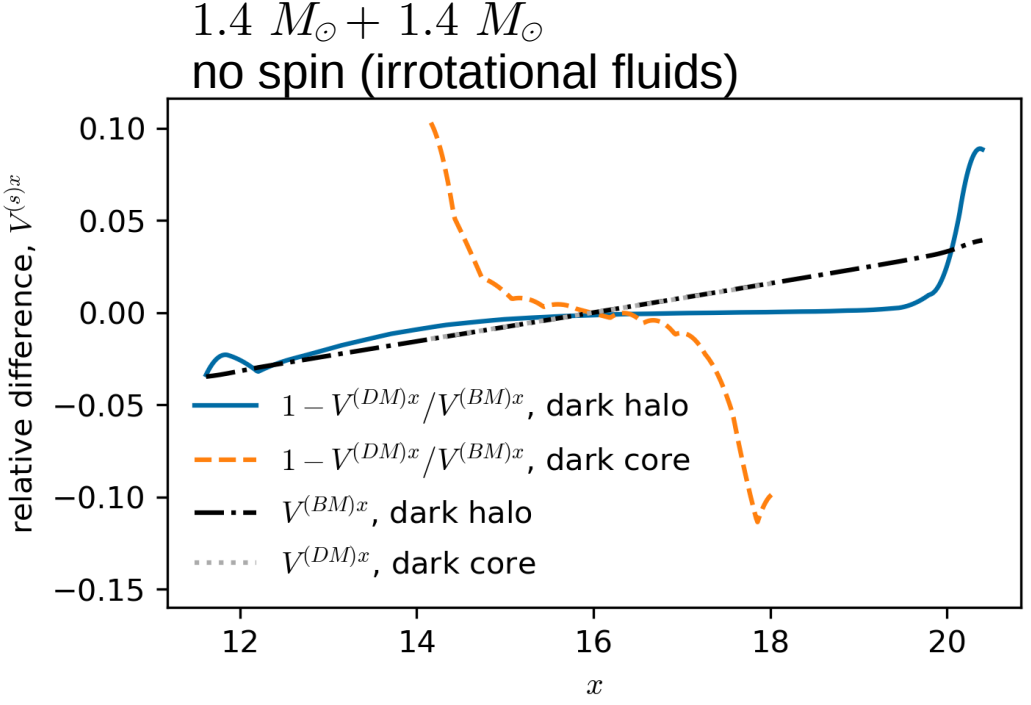
Velocities

- residual three-velocity

$$V^{(s)i} = u^{(s)i}/u^{(s)0} - k^i$$

$$k^i = \Omega(-y, x - x_{CM}, 0)$$

In quasi-equilibrium configurations baryons and dark matter particles move with different velocities.

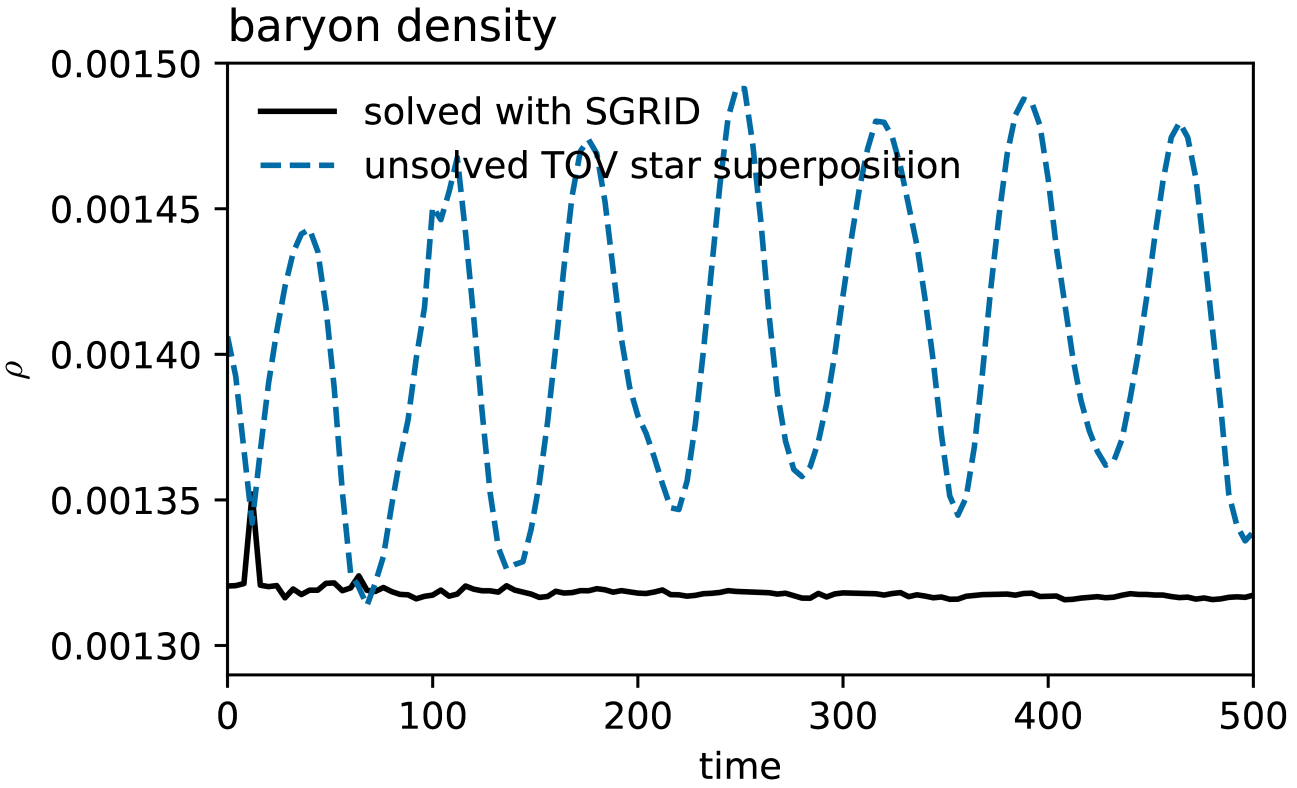


Evolutions

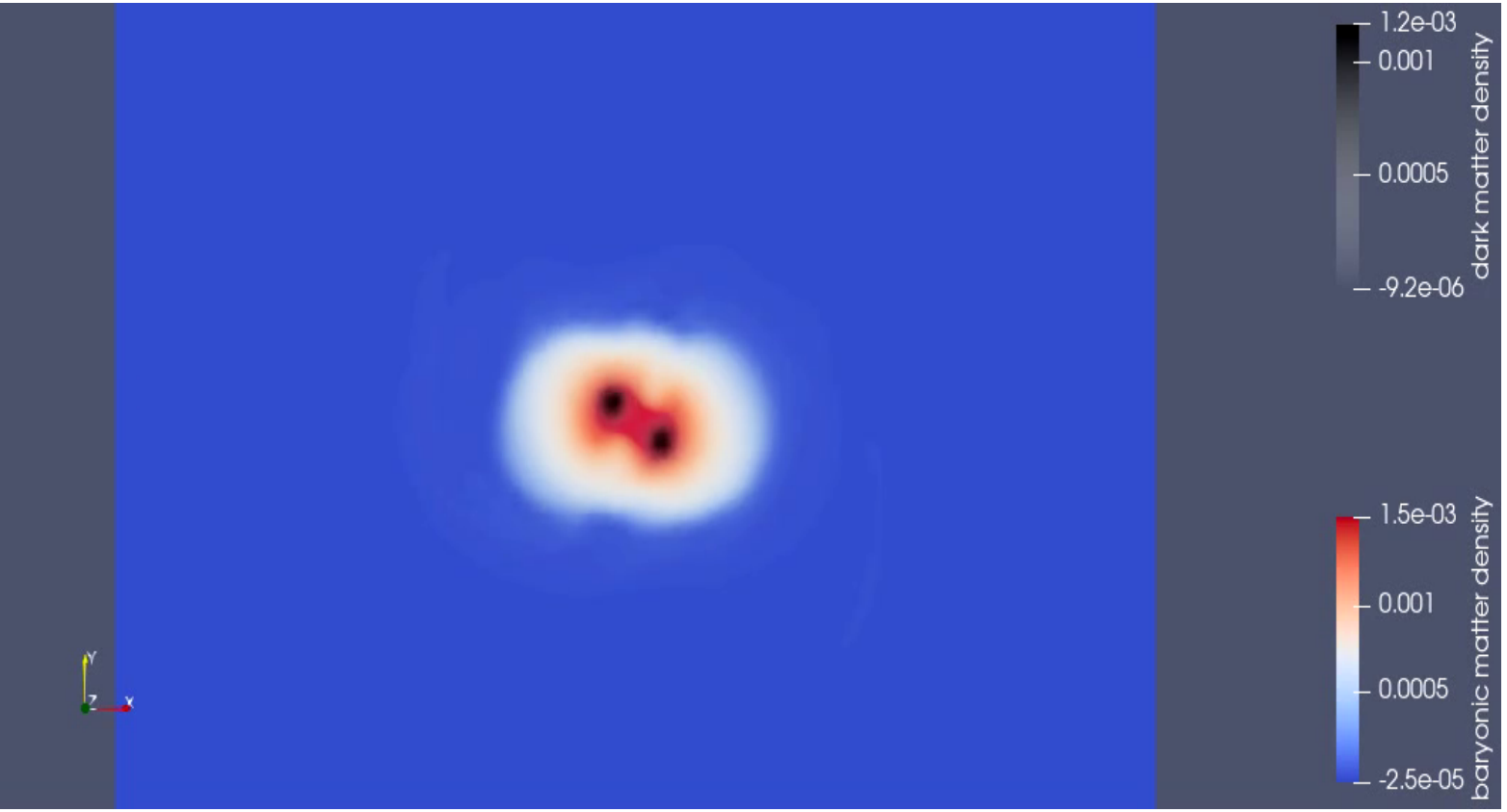
Two Fluid Evolutions

- Using BAM code
  - Z4 for metric evolution
  - two-fluid hydrodynamics
- Evolution of mirror dark-matter admixed binaries by Mattia Emma *et al.* [Particles **5(3)** 273 (2022)]
- Now extended to arbitrary equation of state for the dark matter

Impact of Initial Data

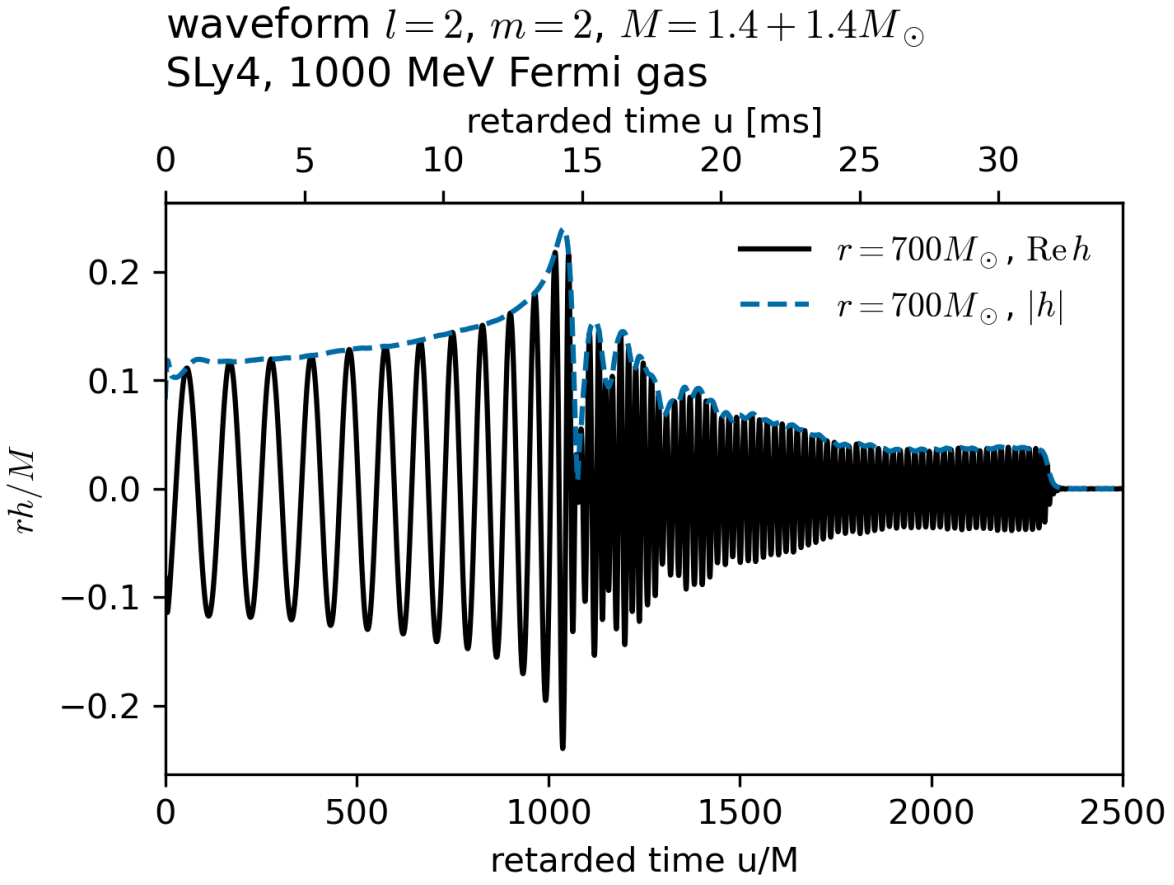


Video



- Dark Core configuration
- Baryonic matter: SLy4 EoS
- Dark matter: 1 GeV fermions, 5 % of mass
- 1.4 $M_\odot$ + 1.4 $M_\odot$
- Eccentricity ≈ 0
- Non-spinning Stars

Waveforms



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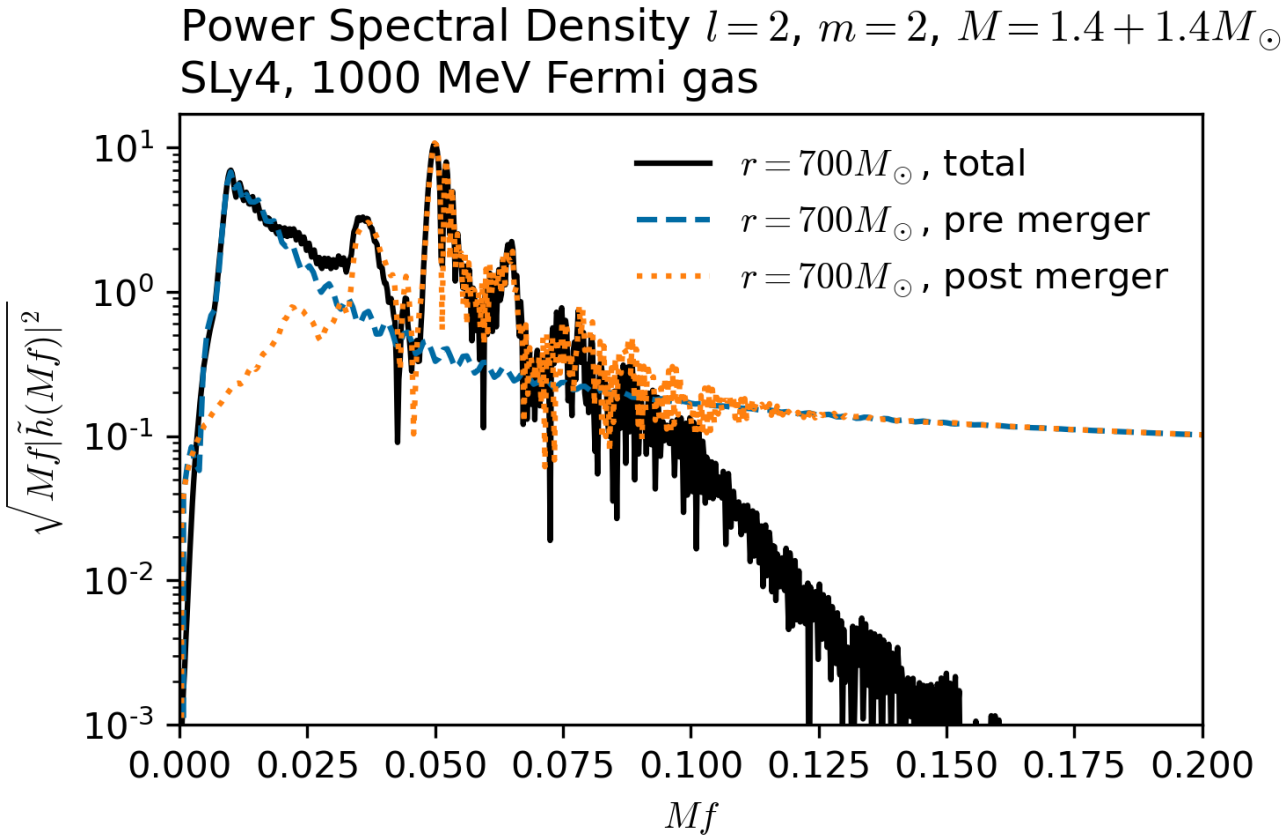

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Bonus

Quasi-Equilibrium Configurations

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Quasi-Equilibrium

- Assume approximate „*helical*“ Killing vector

$$\mathcal{L}_k g_{\mu\nu} = 0$$

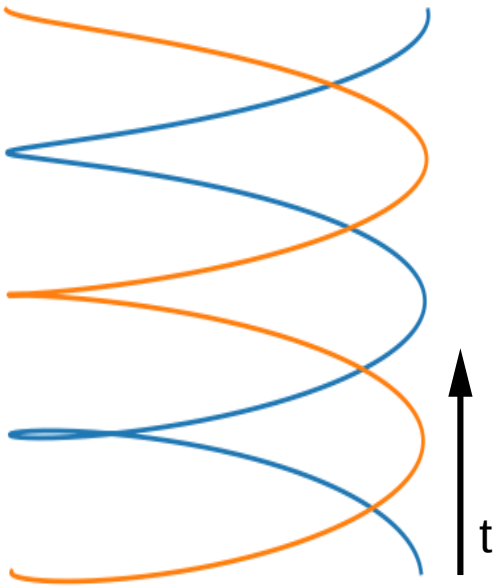
$$k^i = \Omega(-y, x - x_{CM}, 0) + \frac{v_r}{D}(r^i - r^i_{CM})$$

Ω - orbital frequency

r^i_{CM} - center of mass

v_r - radial velocity

D - distance



Quasi-Equilibrium

- Equations of motion
  - Energy-momentum conservation $\nabla^\mu T^{(s)}_{\mu\nu} = 0$
  - Particle number conservation $\nabla^\mu (n_b u^\mu) = 0$
- Fix time derivatives:

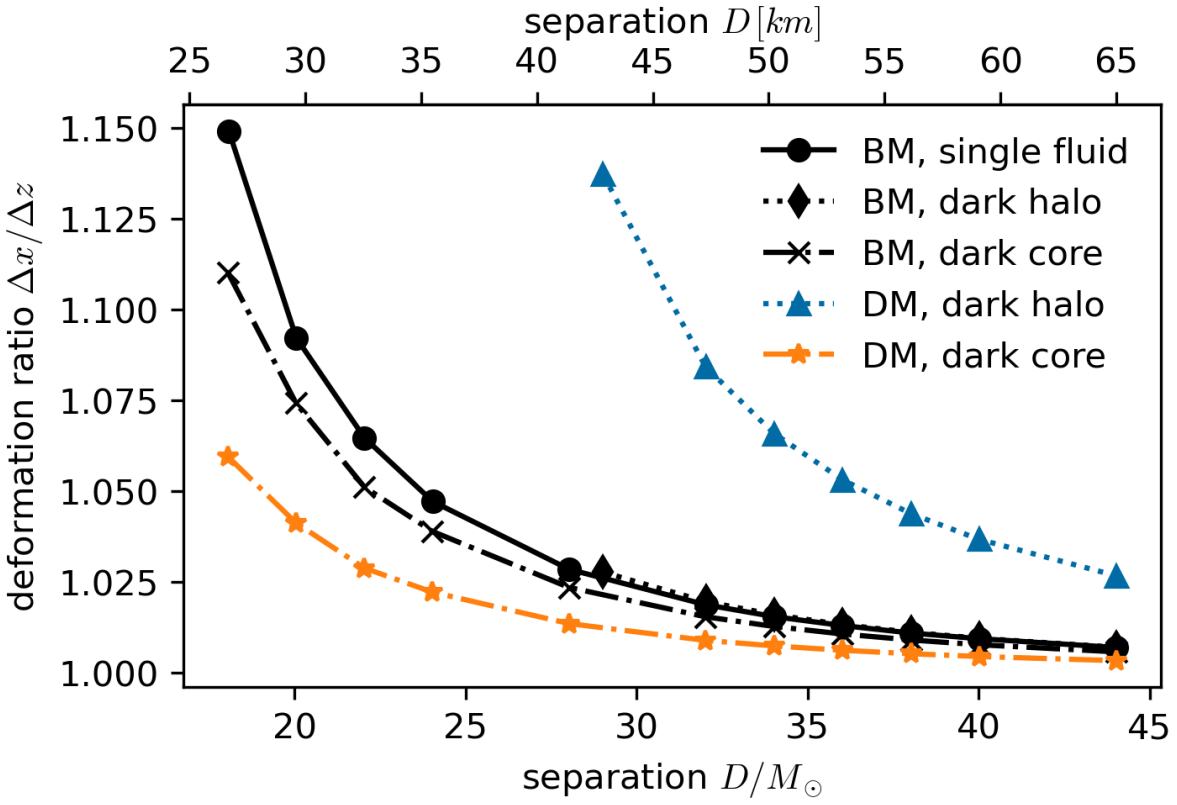
$$\mathcal{L}_k e^{(s)} \approx 0$$

$$\mathcal{L}_k p^{(s)} \approx 0$$

$$\gamma^i_\mu u^{(s)\mu} = \frac{1}{h^{(s)}}(D^i \phi^{(s)} + w^{(s)i})$$

$$\gamma^\mu_i \mathcal{L}_k (\nabla_\mu \phi^{(s)}) \approx 0$$

Deformation



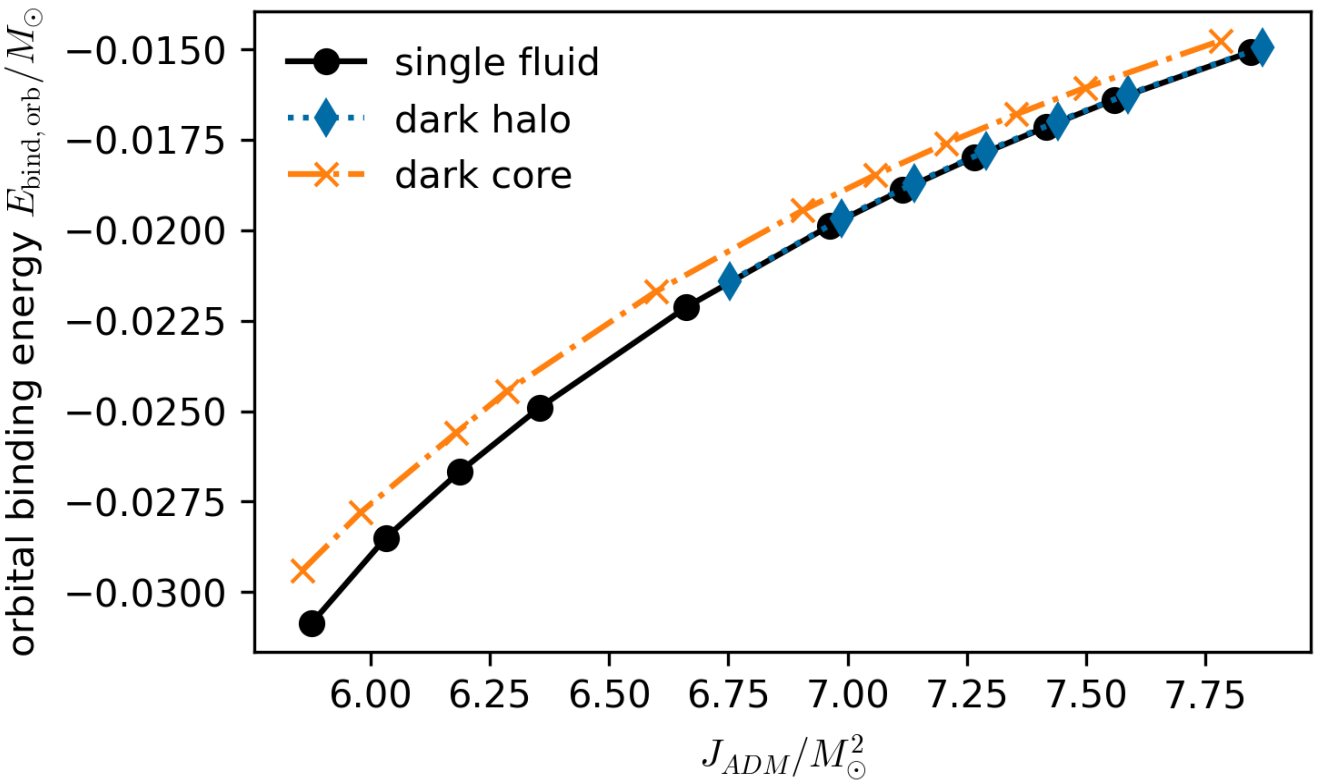
$1.4 + 1.4\ M_\odot$

Baryonic matter:
SLy4 EoS

Dark halo:
0.5% dark matter
Ideal Fermi gas
m_p = 170 MeV

Dark core:
5% dark matter
Ideal Fermi gas
m_p = 1000 MeV

Binding Energy



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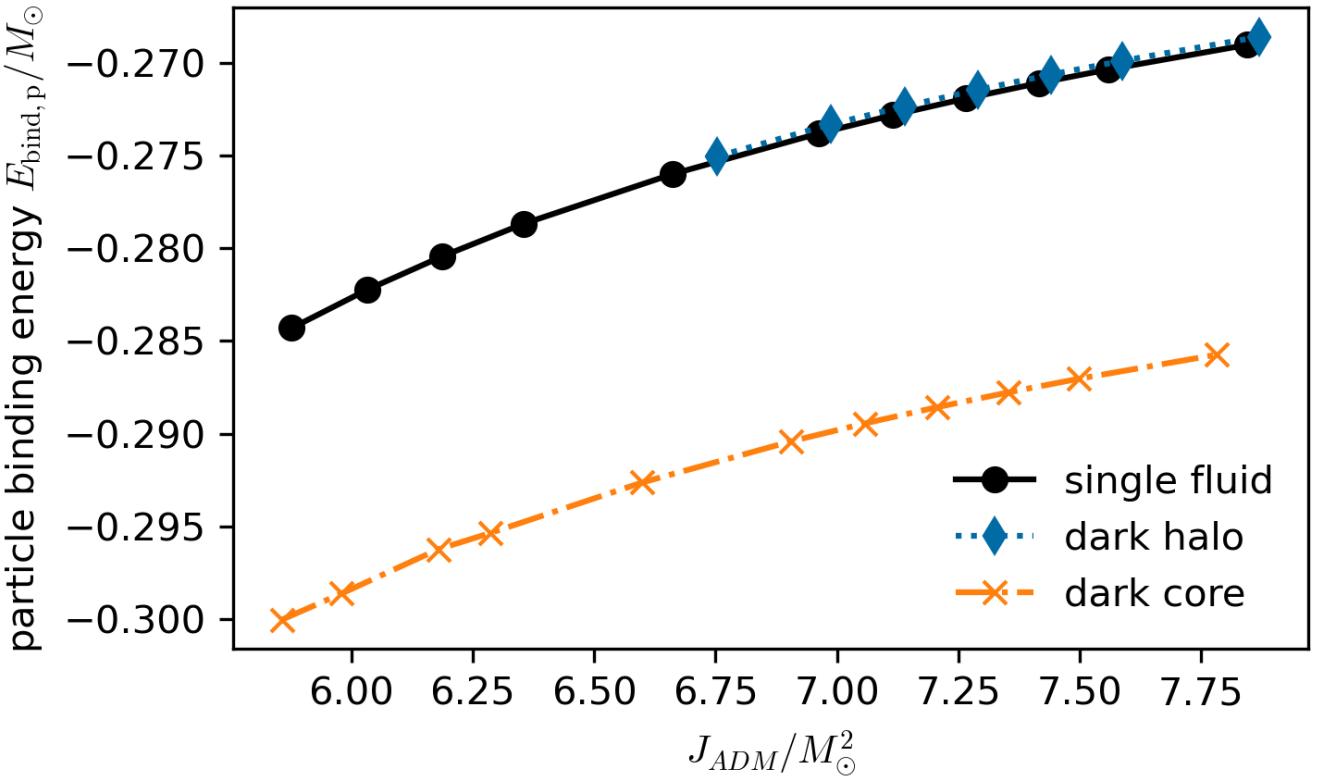

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Mirror dark matter

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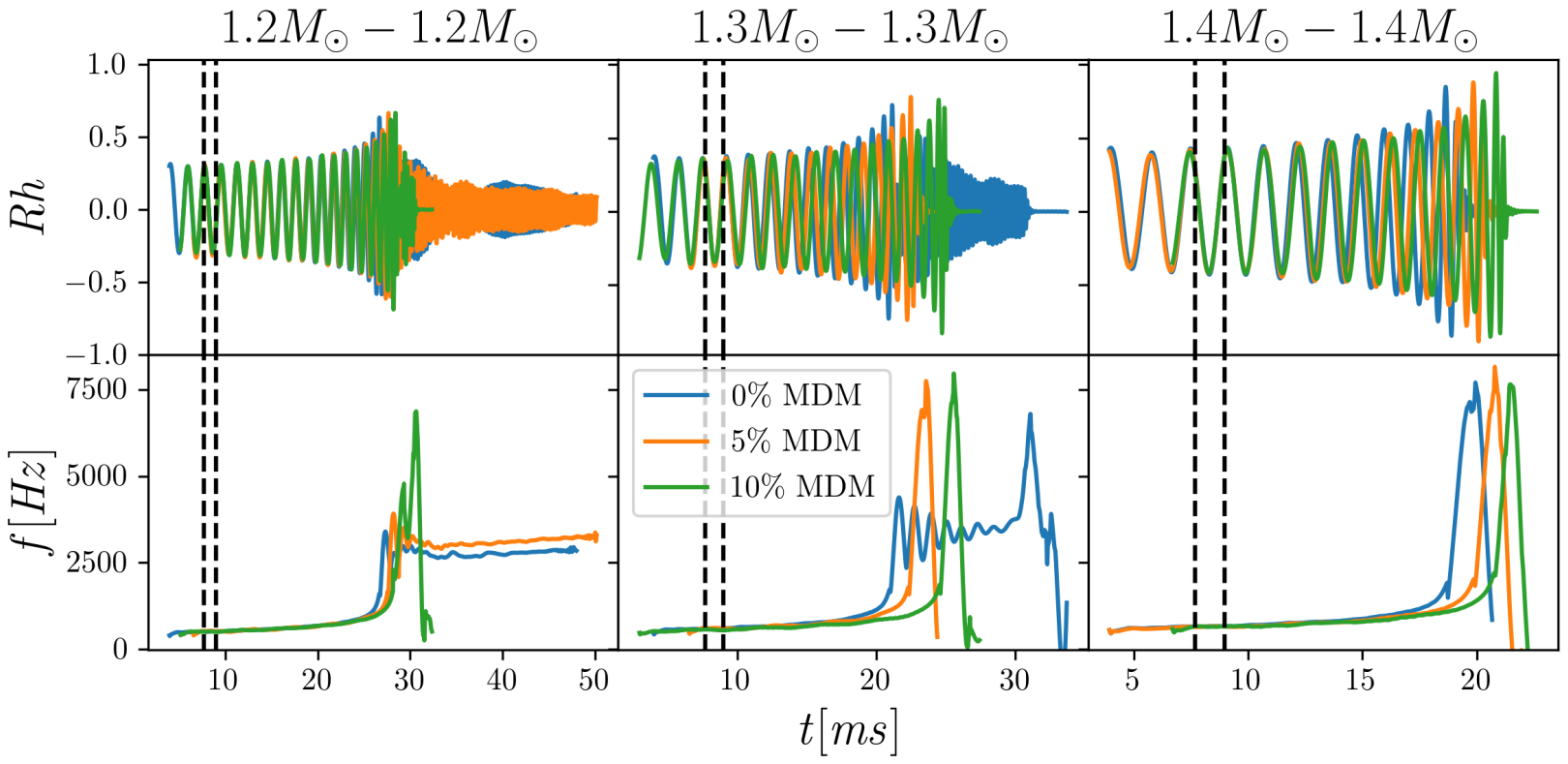
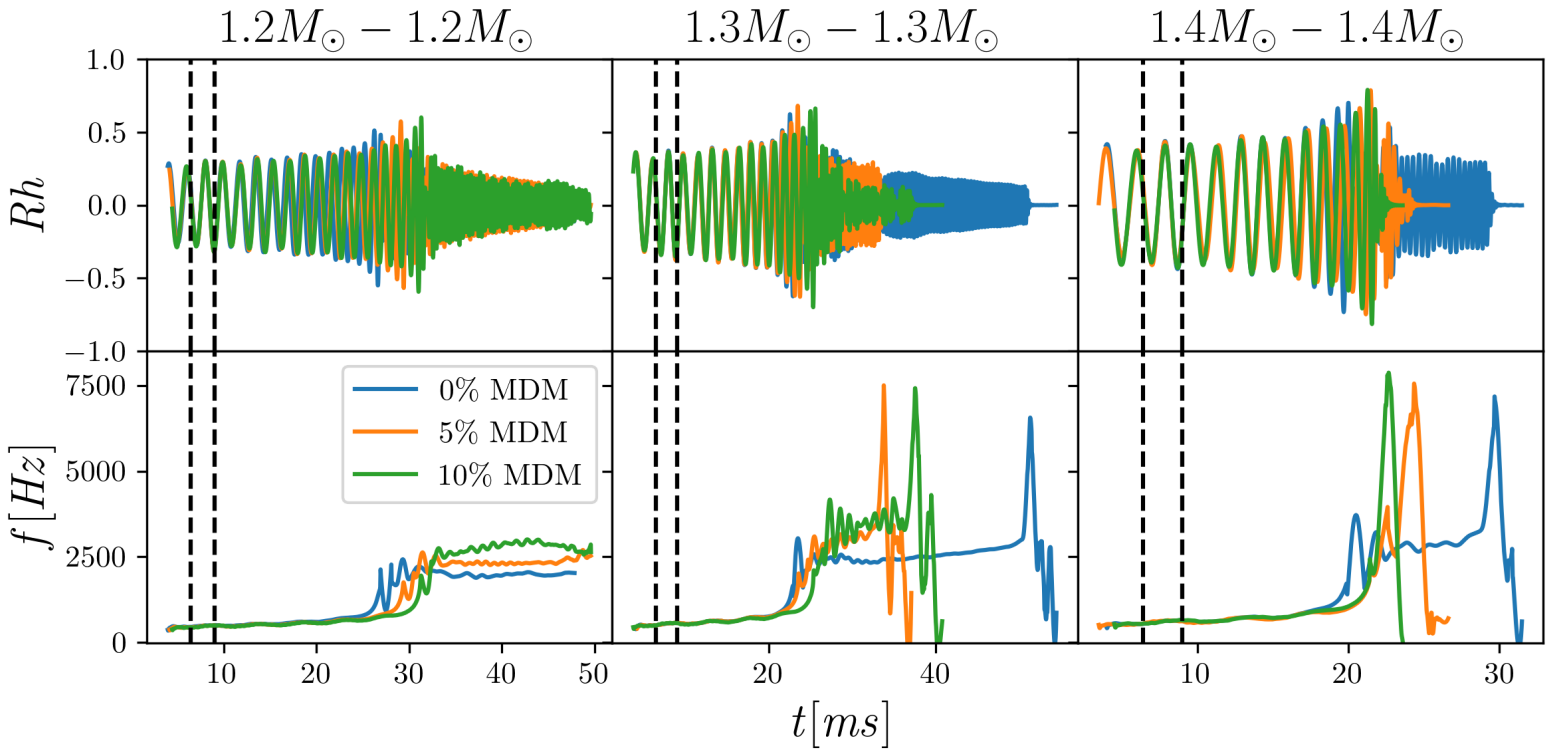


Mirror dark matter
SLy4 EoS for both components

M. Emma *et al.*
Particles **5(3)** 273 (2022)

Waveforms



Mirror dark matter
H4 EoS for both components

M. Emma *et al.*
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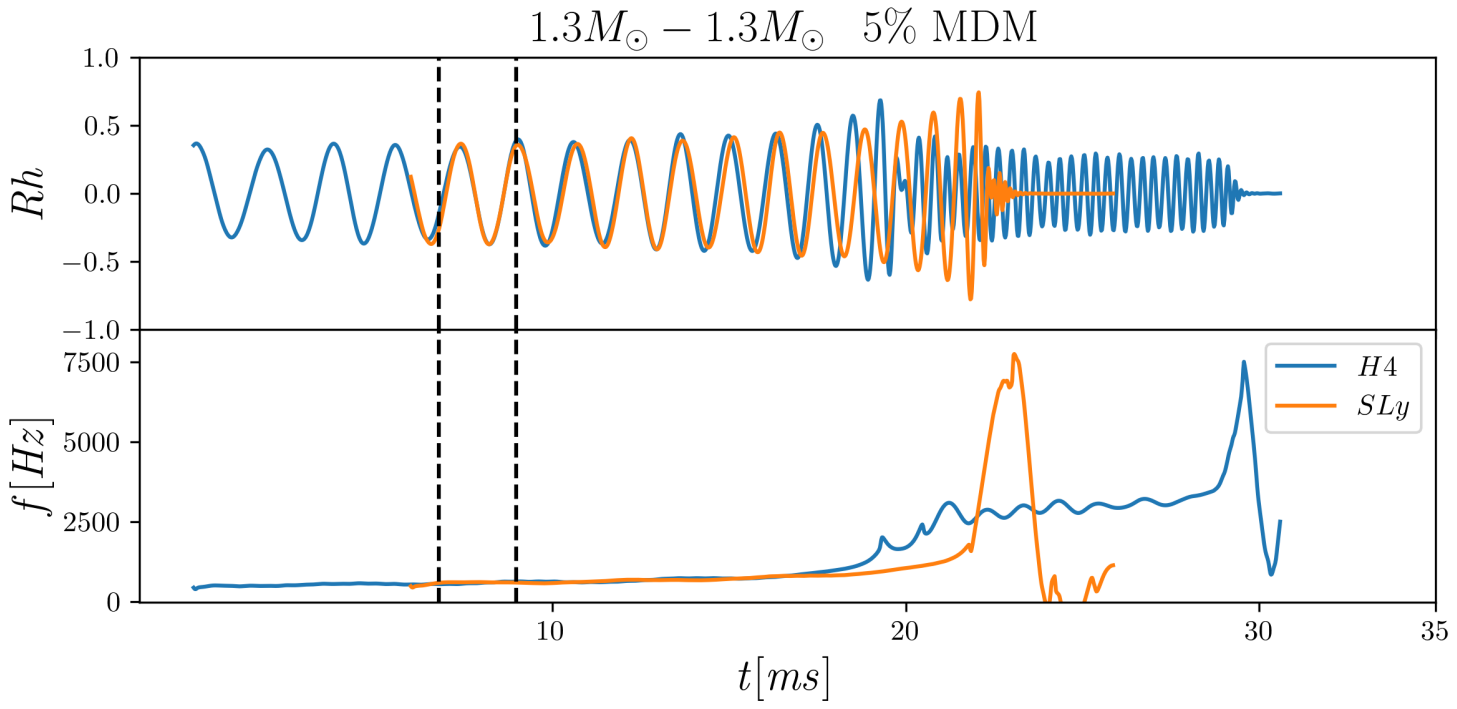
Impact of Equation of State



Mirror dark matter
same EoS for both components

M. Emma *et al.*
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