Numerical relativity simulations of dark matter admixed neutron star mergers: unveiling effects on gravitational waves and ejecta

E. Giangrandi, H. Rueter, M. Emma, N. Kunert, A. Adhikari, V. Sagun, W. Tichy, C. Providencia, T. Dietrich

University of Coimbra 🇵🇹, University of Potsdam 🇩🇪

dark matter in neutron stars

Neutron stars (NSs) may accumulate a significant amount of dark matter (DM) due to their extreme compactness.

DM significantly influences NS properties, including structure, mass, radius, tidal deformability, moment of inertia and cooling.

as mentioned by Oleksii in his talk yesterday

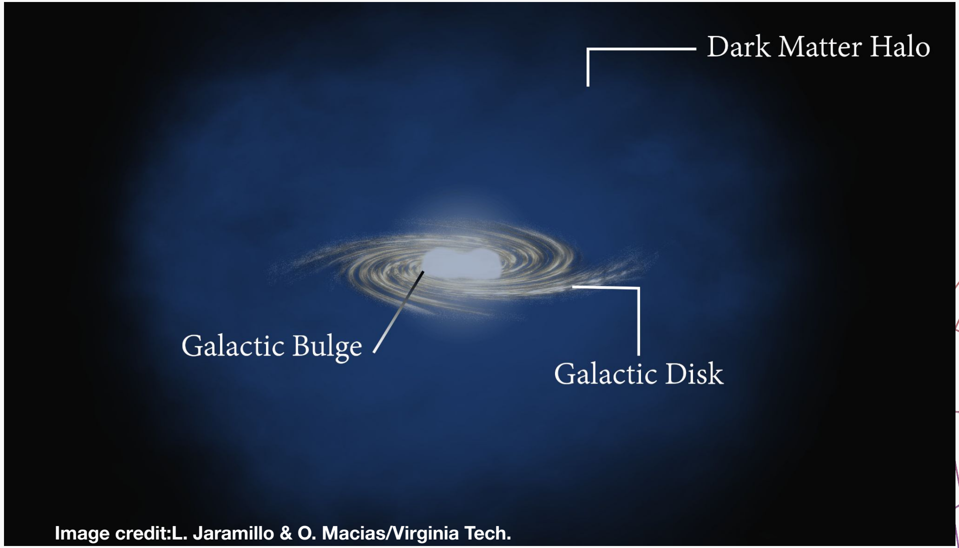


Image credit:L. Jaramillo & O. Macias/Virginia Tech.

two fluid formalism

Violetta Sagun

$$\frac{dp_i}{dr} = -\frac{(\varepsilon_i + p_i)(M_{\text{tot}} + 4\pi r^3 p_{\text{tot}})}{r^2\,(1 - 2M_{\text{tot}}/r)}$$

total pressure $P_{\text{tot}}(r) = P_{\text{BM}}(r) + P_{\text{DM}}(r)$

gravitational mass $m_{\text{tot}}(r) = m_{\text{BM}}(r) + m_{\text{DM}}(r)$

$$m_i(r) = 4\pi \int_0^r \rho(r') r'^{,2} dr'$$

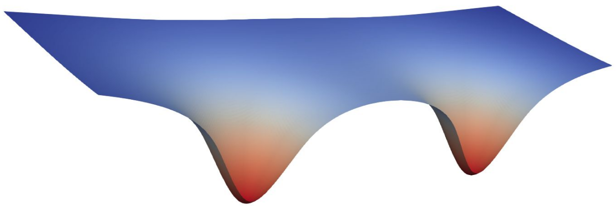
DM mass fraction $f_{\text{DM}} = \frac{M_{\text{DM}}}{M_{\text{tot}}}$

the Bullet Cluster provides constraints on the cross section $\sigma_{\text{DM-n}}$

Cooley et al., 2014

BM and DM coupled only through gravity

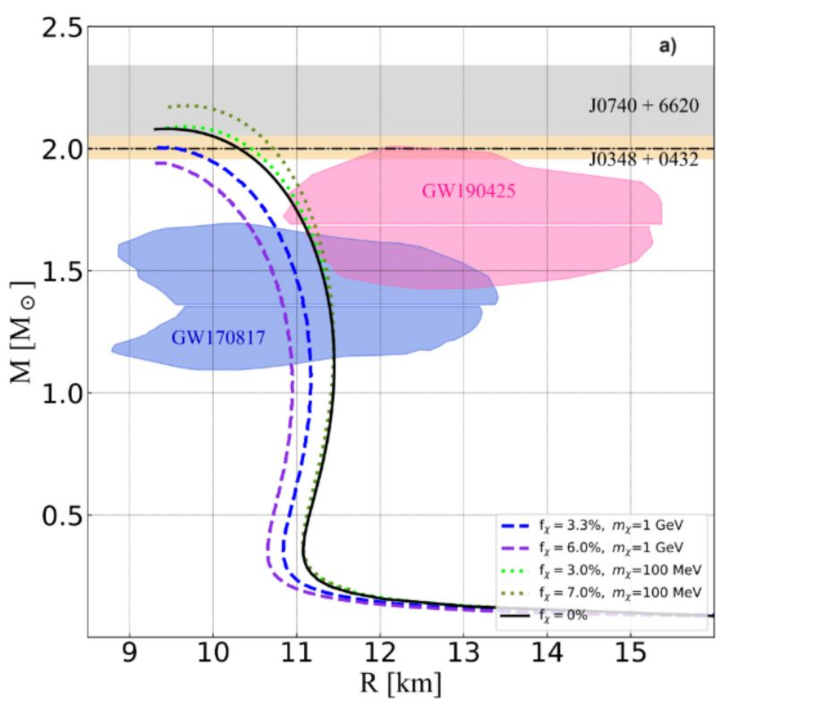
Stress-Energy tensors are conserved separately

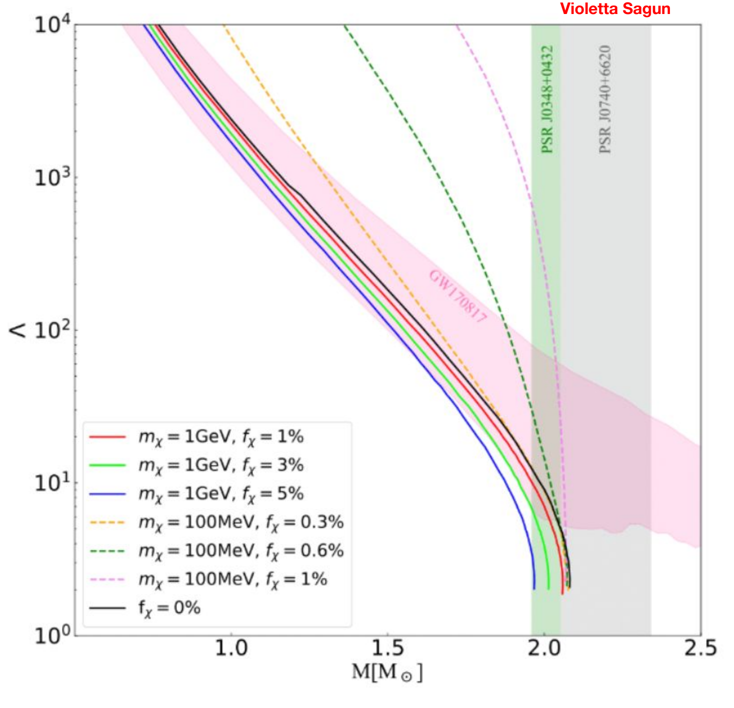


Example of an equatorial slice, showing the gtt component of the metric in a simulation.

two fluid formalism

Violetta Sagun





Sagun, Giangrandi et al., 2021

does dark matter give signatures in strong gravity environments?

$$\rho_{\rm DM} \sim 1\ \frac{\rm GeV}{\rm cm^3}$$

or

$$\sim 1\ \frac{\rm M_\odot}{\rm pc^3}$$

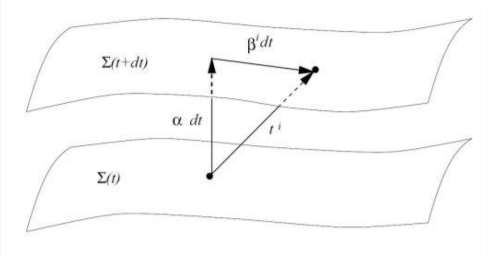
particle physicists

astrophysicists ;)

numerical relativity framework

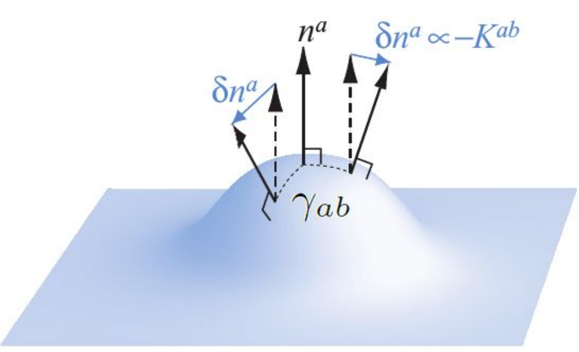

Hannes Rueter

the spacetime metric is decomposed into a temporal and spatial part:



$$ds^2 = -\alpha dt^2 + \gamma_{ij}(\beta^i dt + dx^i)(\beta^j dt + dx^j)$$

lapse shift



we can define the extrinsic curvature as:

$$K_{ij} = -\frac{1}{2\alpha}(\partial_t \gamma_{ij} - \mathcal{L}_\beta \gamma_{ij})$$

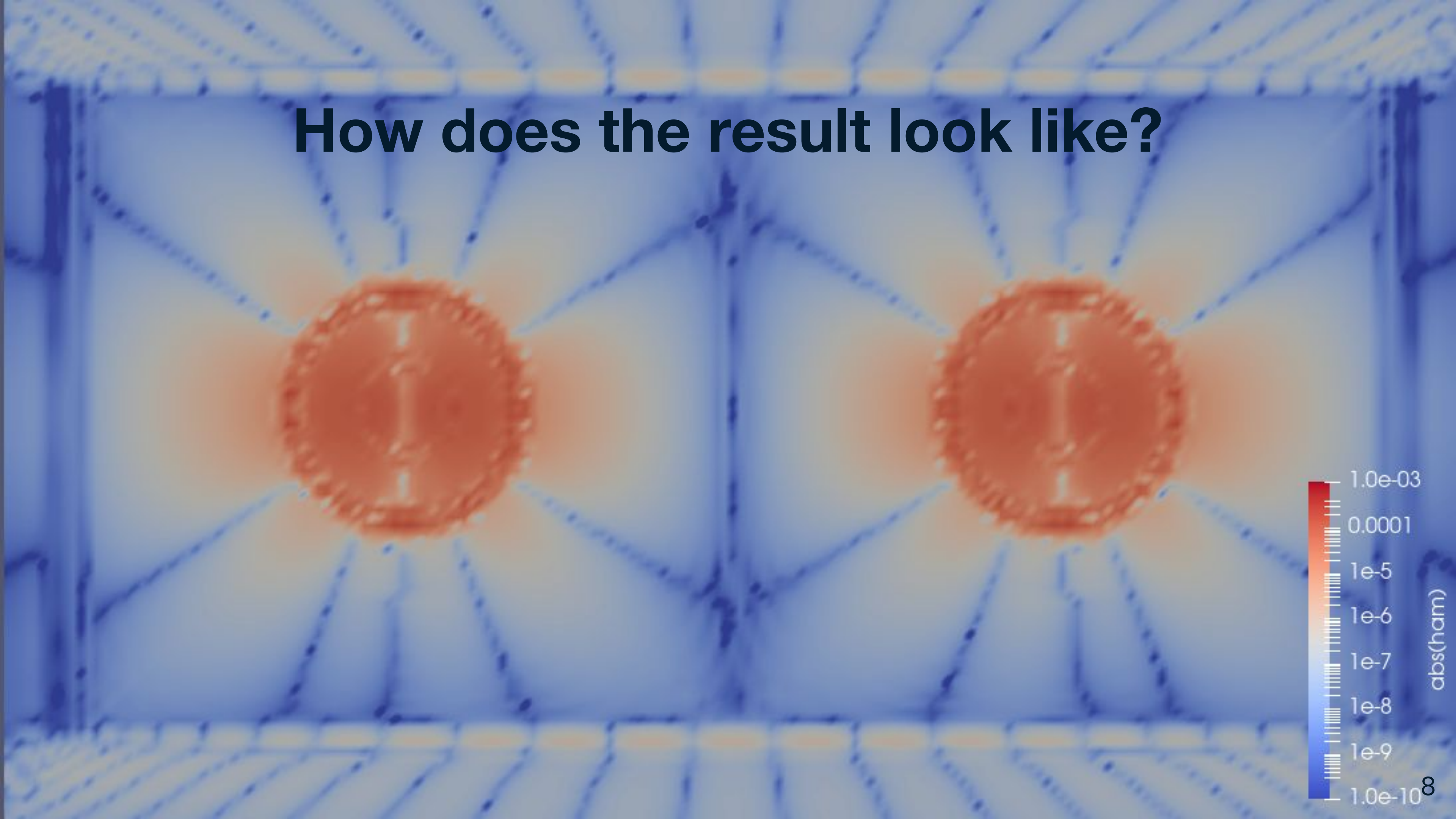
Hamiltonian and momentum constraints

$$R - K_{ij}K^{ij} + K^2 = 16\pi\rho$$

$$D_j(K^{ij} - \gamma^{ij}K) = 8\pi j^i$$

initial data are obtained solving Einstein's equations for the first time using the `sgrid` code

How does the result look like?



numerical simulations

initial setup

numerical simulations: initial setup

DM was treated as a relativistic fermi gas of massive particles with spin one-half

[Sagun, Giangrandi et al. 2021]

BM is described by Sly4 EoS [Gulminelli&Raduta 2015]

different DM mass fractions

different resolutions:

128, 144 and 192 points

two different total masses to better study the DM effects on the r

quasi-equilibrium configurations

ID	m_{DM} [GeV]	f_χ [%]	M_{tot} [$M_\odot$]	BAM res	Time required
01	1	0	2.4	128	138k
02L	1	0	2.8	128	138k
02M	1	0	2.8	144	192k
02H	1	0	2.8	192	402k
03	1	3	2.4	128	138k
04L	1	3	2.8	128	138k
04M	1	3	2.8	144	192k
04H	1	3	2.8	192	402k
05	1	15	2.4	128	138k
06	1	15	2.8	128	138k
07	0.17	0.5	2.4	128	138k
08L	0.17	0.5	2.8	128	138k
08M	0.17	0.5	2.8	144	192k
08H	0.17	0.5	2.8	192	402k

DM cores

longer inspiral likely due to a lower tidal deformability

‘prompter’ collapse to a black hole

harder to eject material from the bulk of the stars

lack of DM ejecta and debris disk due to the concentration in the core

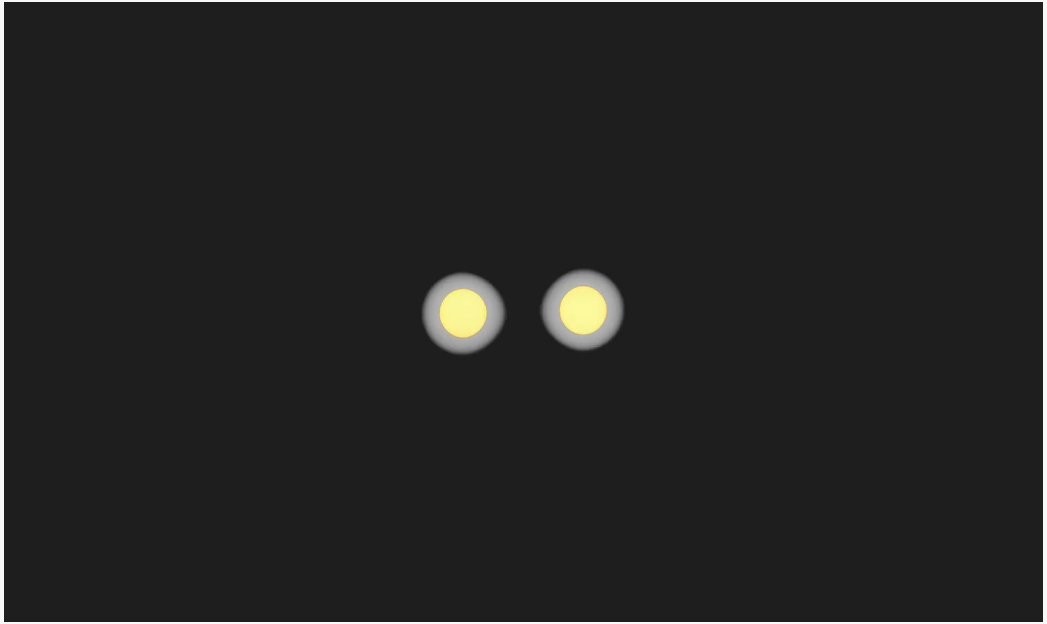
DM haloes

haloes are yet to merge at t=0

highly deformed DM structure

haloes size is comparable to the NS radius

DM and BM are not synchronised due to the lack of interactions right after merger



conclusions

going towards the Galactic center, higher DM concentrations are expected, hence bigger effects

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

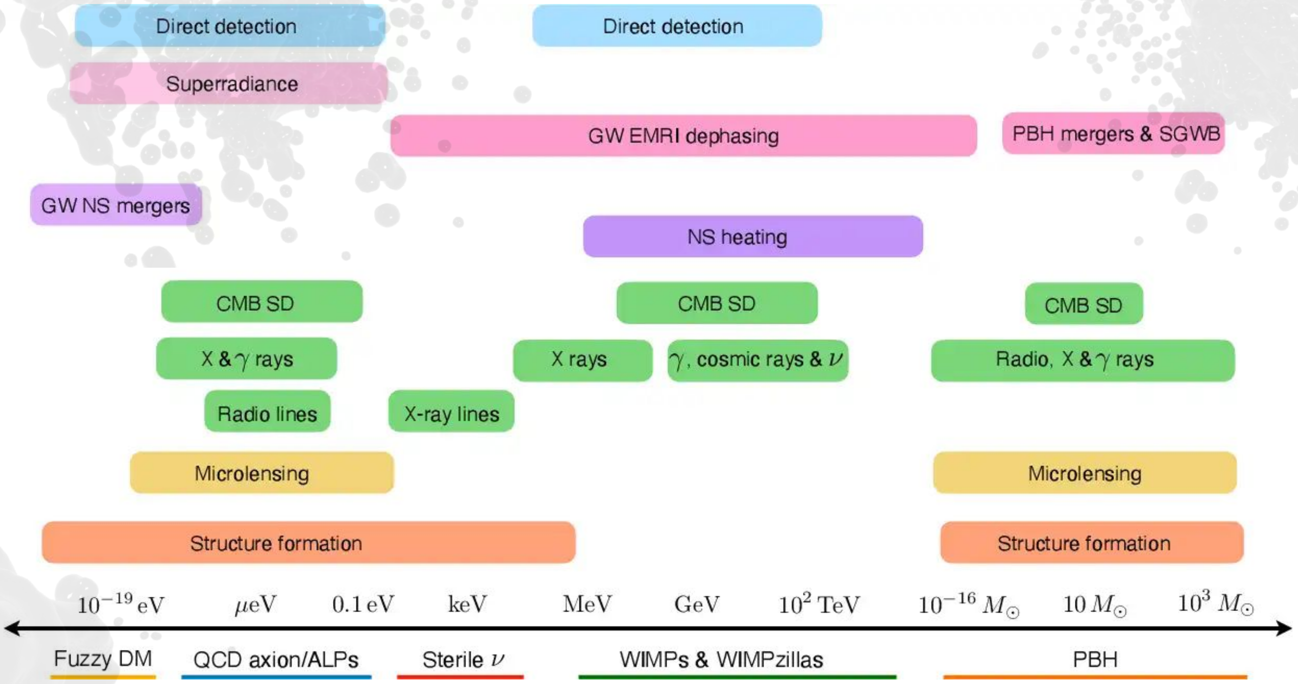
the orbital separations of typically a few km is resulted in a kHz-band GW signal that could be sought in GW searches

the DM core and the 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 synchronize via the gravitational angular momentum transfer, including tidal effects

Giangrandi et al, *in prep*, 2024

Thanks for the attention :)

Dark Matter



EuCAPT white paper, 2022

accumulation of DM in NSs

proto-cloud: mixture of baryonic matter (BM) and DM

accretion throughout the stellar life up to the supernova explosion from the galactic halo

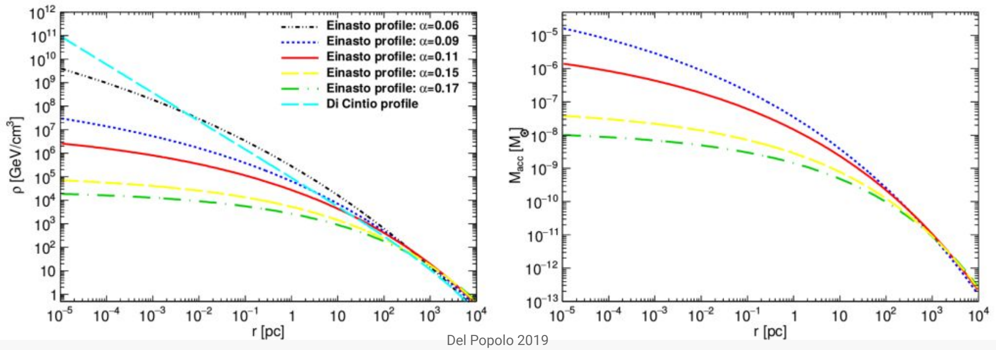
core-collapse: creation of DM due to the extreme transient

NS lifetime

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

Kouvaris 2008
Kouvaris&Tinyakov 2010

DM clumps



Del Popolo 2019

How to obtain initial data

educated initial guess for each fluid, which is a two-dimensional root finding problem

solving two different PDE for the matter velocity potential $^{(3)}u^i = D^i\phi + w^i$

$$D_i[\rho\alpha h^{-1}(D^i\phi + w^i) - \rho_0\alpha u^0(\beta^i + \xi^i)] = 0$$

solving the metric equations, averaging the old and new solution

updating the matter fields and velocity potential

IF residuals are lower than a user-chosen threshold ⟶ END!

updating the center of mass and orbital frequency

updating the matter velocity potential

Grid setup

computational grid made of a hierarchy of cell-centered nested cartesian grid

moving boxes track NSs orbit to follow the binary dynamics

every level has buffer zones populated by interpolation

ensure correct resolution near the stars and far away from the source