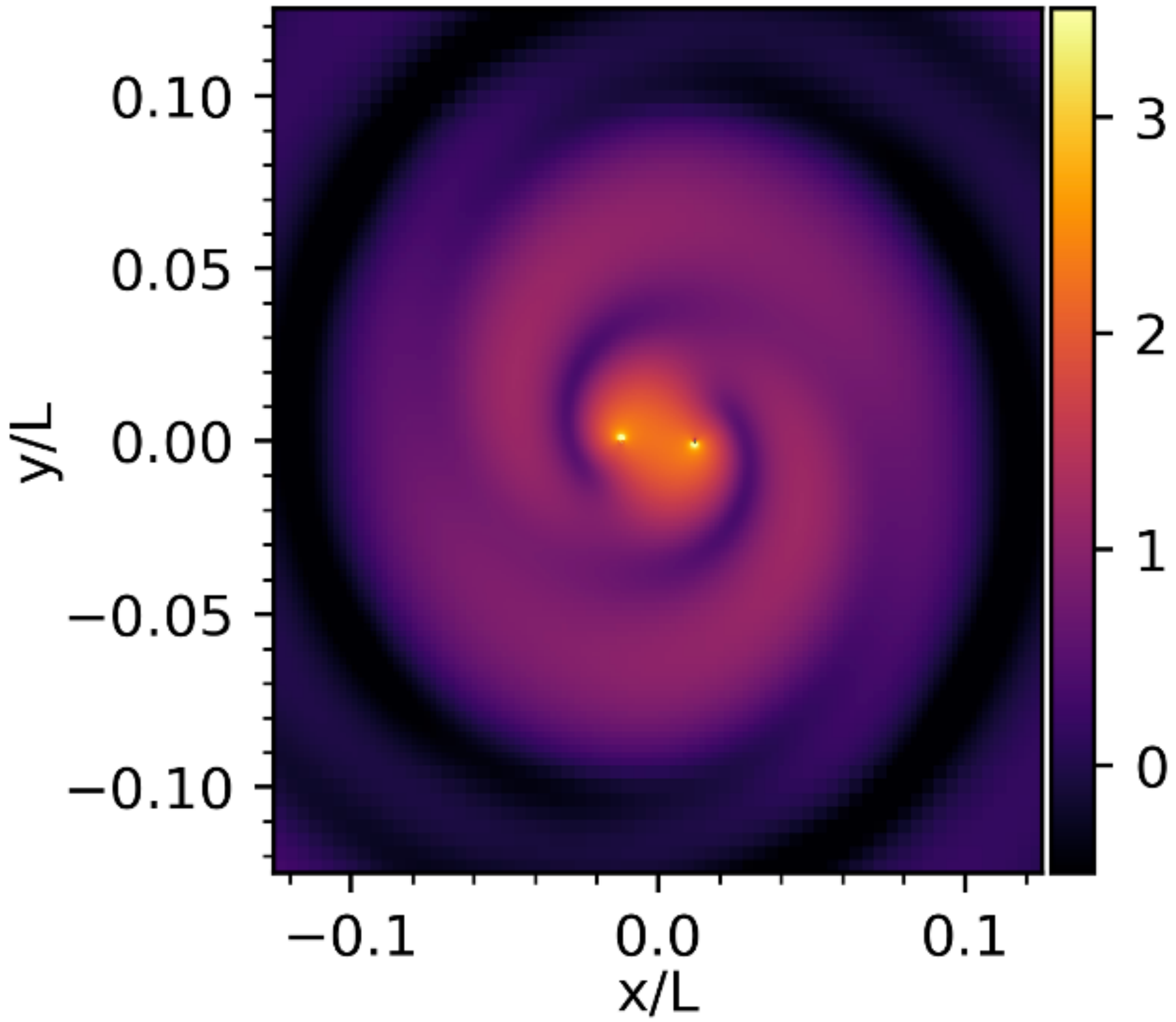
Strong gravity as a probe of physics beyond the Standard Model + GR

Katy Clough, Queen Mary University of London

J Bamber, KC et. al 2023
Phys.Rev.D 107 2, 024035



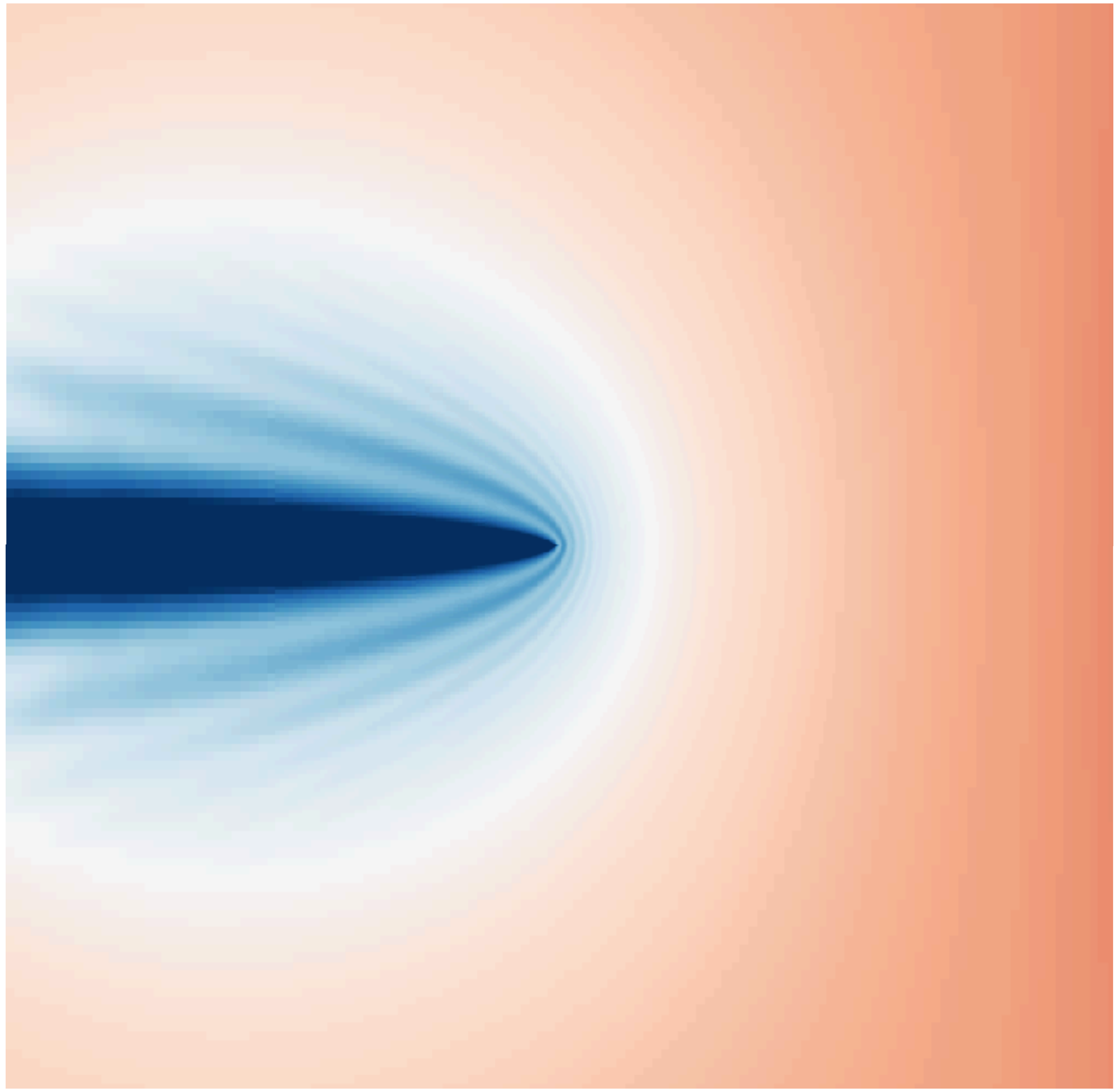
Science & Technology Facilities Council

Queen Mary University of London

Relevant JENAS questions/wishlist:

- Dark Matter Fundamental Nature
- Can we tell deviations from GR from matter/waveform systematics
- Nonlinearities in the black hole ringdown
- What else do we want to search for that LISA or 3G enables but that will not already be ruled out by the late 2030s?
- Tests of gravity vs modelling systematics
- Can we identify the nature of dark matter from its environmental effect on EMRIs?
- What is the fundamental nature of gravity?
- Numerical relativity beyond GR - how far can we go?
- Waveform generation in modified gravity and efficient confrontation against GW data
- Numerical Relativity beyond GR and SM

D Traykova, KC et. al. 2021, 2023
Phys.Rev.D 104 (2021) 10, 103014



Relevant JENAS questions/wishlist:

D Traykova, KC et. al. 2021, 2023
Phys.Rev.D 104 (2021) 10, 103014

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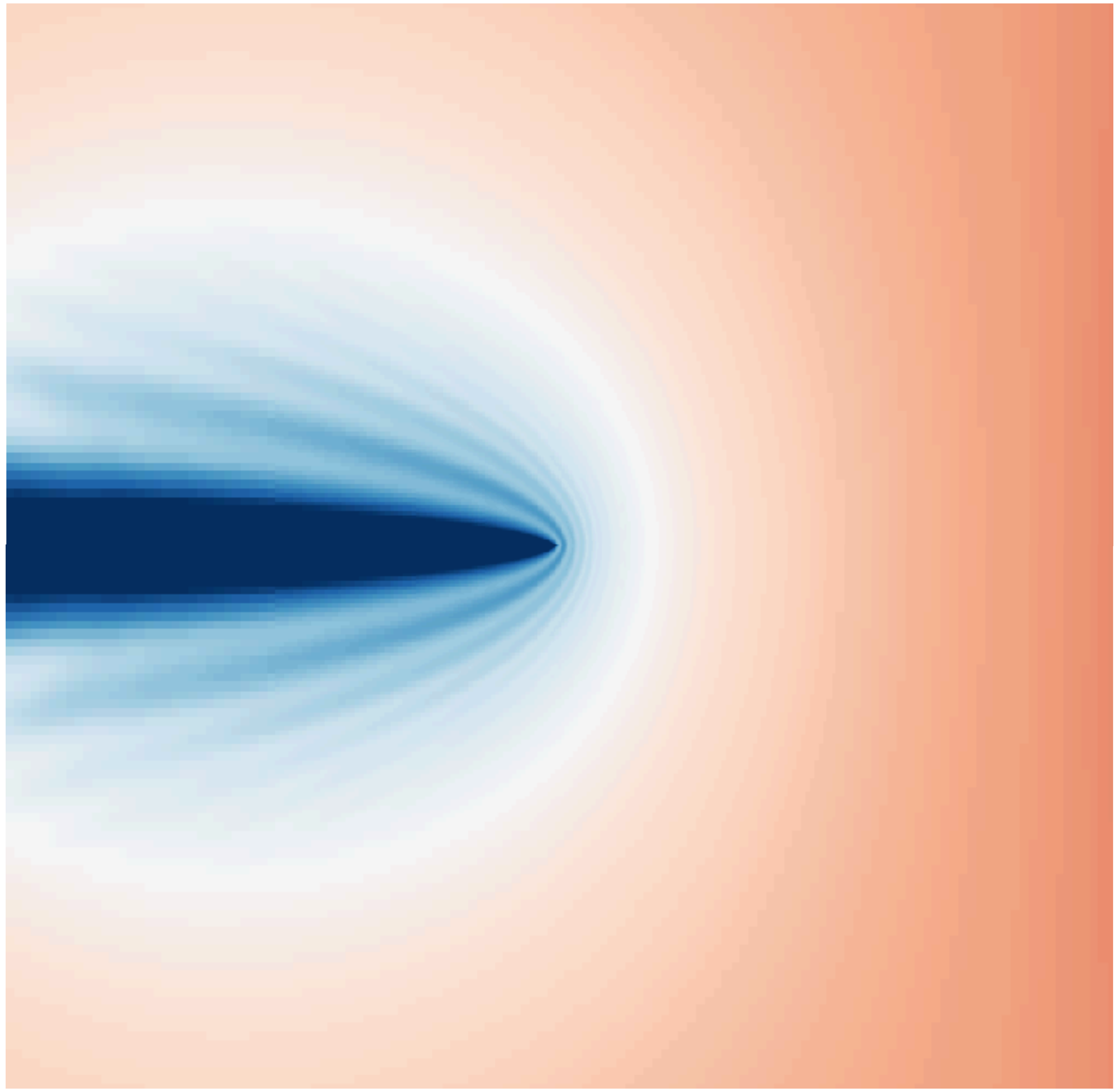


Can we probe the fundamental nature of dark matter?

Can we distinguish matter / modifications to GR / waveform systematics?

Numerical relativity beyond GR + SM
- how far can we go?

Can we probe the fundamental nature of dark matter?

Possible in principle to probe wave or particle nature, some reasons to be optimistic for LISA data

Can we distinguish matter / modifications to GR / waveform systematics?

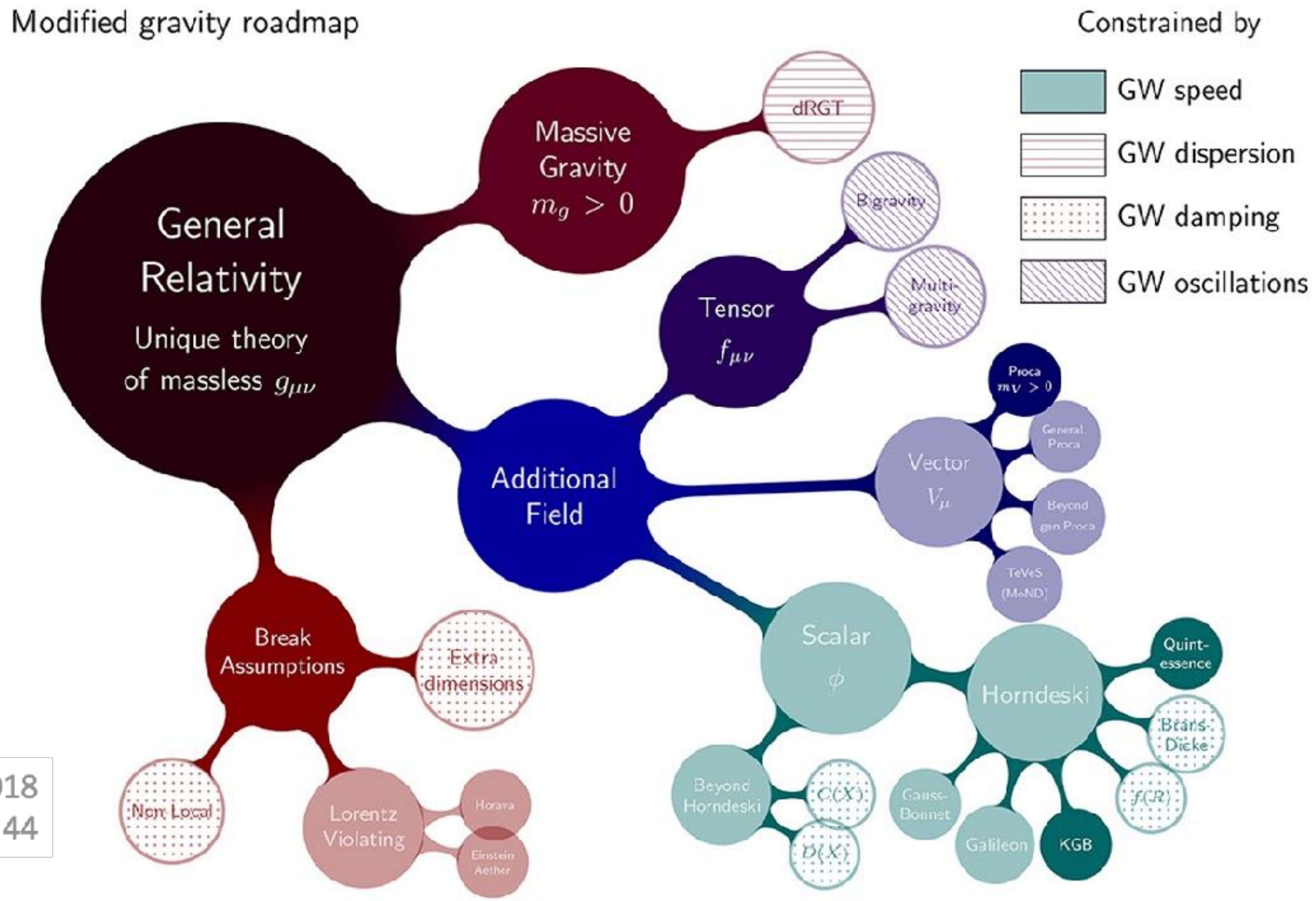
Now in a position to answer this for specific models, which should be informative for LIGO modelling

Numerical relativity beyond GR + SM - how far can we go?

Probably not far enough on our own, but can usefully combine analytic and numerical studies

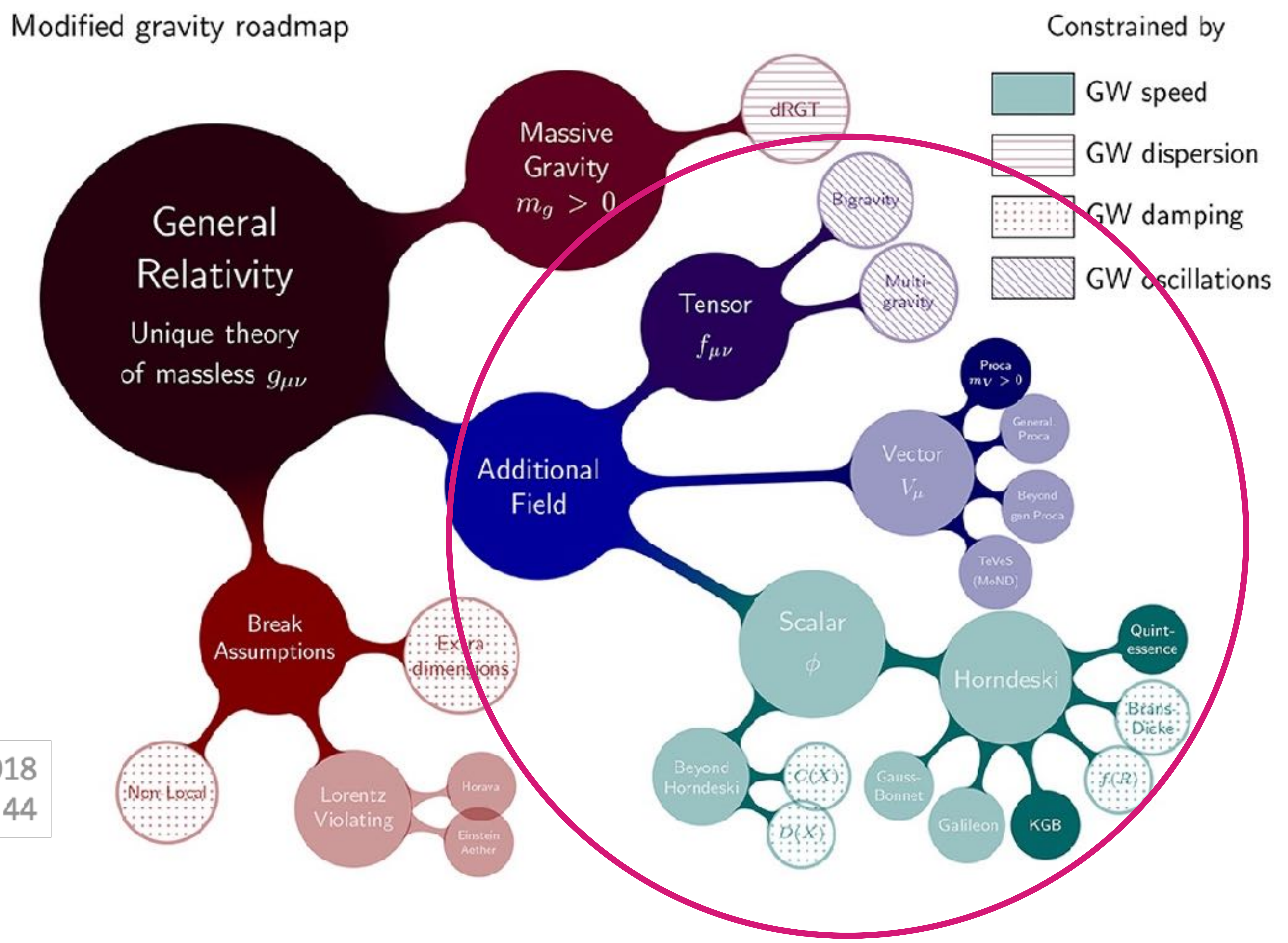
Preliminaries

Fields in modified gravity



JM Ezquiaga et. al 2018
Front.Astron.Space Sci. 5 44

Fields in modified gravity



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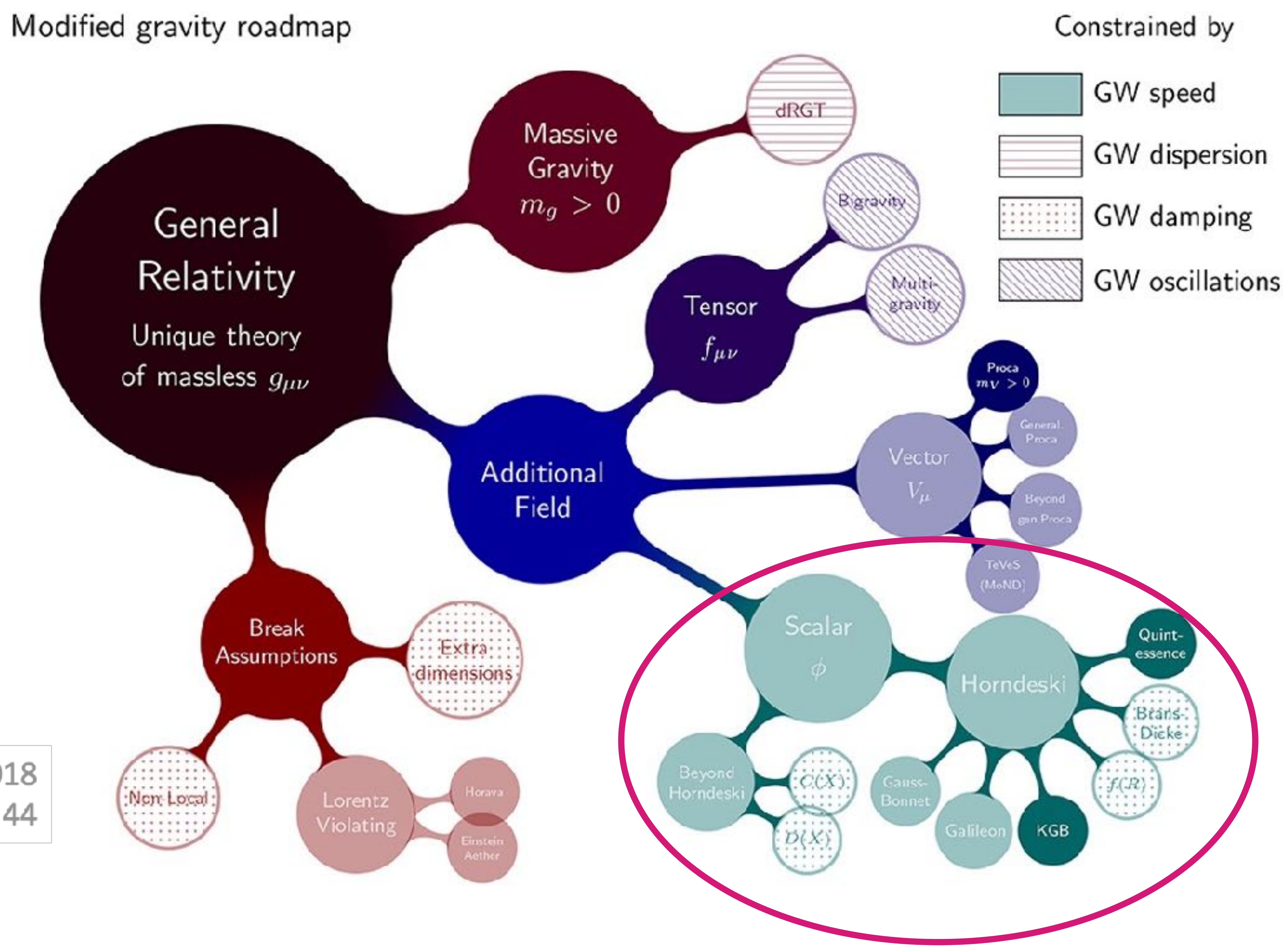
Fields in modified gravity



JM Ezquiaga et. al 2018
Front.Astron.Space Sci. 5 44

The next order action of scalar-tensor theories beyond GR

Most general parity-invariant scalar-tensor theory of gravity up to (derivatives)^4:

$$S = \frac{1}{16\pi} \int d^4x \sqrt{-g} \left(R - X + g_2(\phi) X^2 - V(\phi) + \lambda(\phi) \mathscr{L}_{GB} \right)$$

where
$$X = \nabla^\mu \phi \nabla_\mu \phi$$
$$\mathscr{L}_{GB} = R^2 - 4 R_{\mu\nu} R^{\mu\nu} + R_{\mu\nu\rho\sigma} R^{\mu\nu\rho\sigma}$$

Equation of motion for the scalar field has a two sources

Coupling to curvature $\lambda(\phi)$
Potential $V(\phi)$

$$\Box\phi = \lambda'(\phi)\mathscr{L}_{GB} + V'(\phi)$$

See review:
Scalarisation, D Doneva et. al 2022
arXiv:2211.01766 [gr-qc]

Equation of motion for the scalar field has a two sources

$$\Box\phi = \lambda'(\phi)\mathcal{L}_{GB} + V'(\phi)$$

Matter - mass and self interactions

See review:
Scalarisation, D Doneva et. al 2022
arXiv:2211.01766 [gr-qc]

Equation of motion for the scalar field has a two sources

$$\Box \phi = \lambda'(\phi)\mathscr{L}_{GB} + V'(\phi)$$

Coupling to curvature
(Approximately
Riemann^2)

See review:
Scalarisation, D Doneva et. al 2022
arXiv:2211.01766 [gr-qc]

Fundamental fields can then be:

1. An effective description of dark matter (or dark energy)

$$\Box\phi = \lambda'(\phi)\mathscr{L}_{GB} + V'(\phi)$$

2. An additional gravitational degree of freedom

Fundamental fields can then be:

D Traykova, KC et. al. 2021, 2023
Phys.Rev.D 104 (2021) 10, 103014

1. An effective description of dark matter

2. An additional gravitational degree of freedom

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Fundamental fields can then be:

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HO Silva et al 2021
Phys.Rev.Lett. 127 (2021) 3, 031101
M Elley et al 2022
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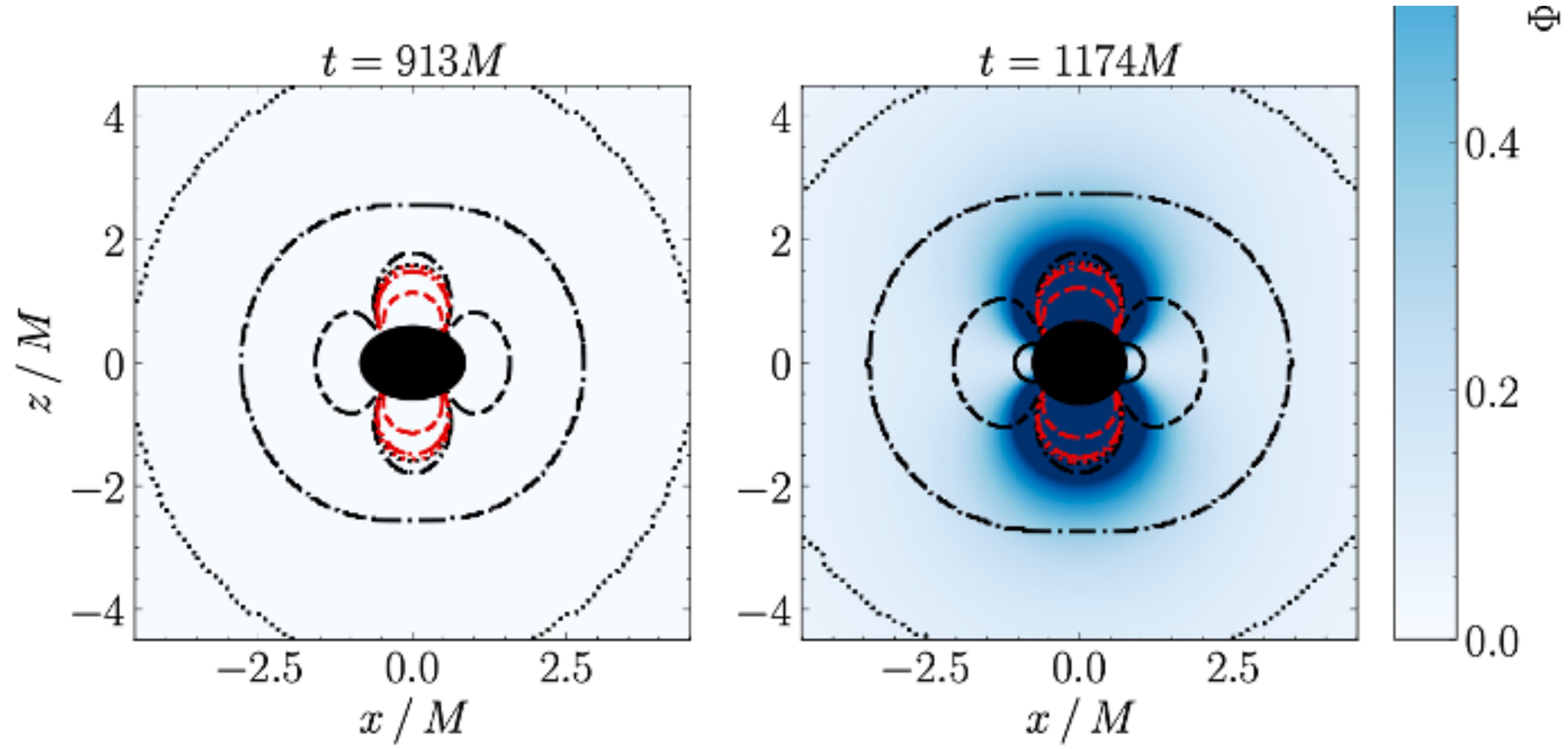


Can we probe the fundamental nature of dark matter?

Can we distinguish matter / modifications to GR / waveform systematics?

Numerical relativity beyond GR + SM - how far can we go?

Does dark matter give signatures in strong gravity environments?

$$\rho \sim 1\ \mathrm{GeV/cm^3}\ \textbf{or}\ 1\ \mathrm{M_\odot/pc^3}$$

(Particle physicist) (Astrophysicist)

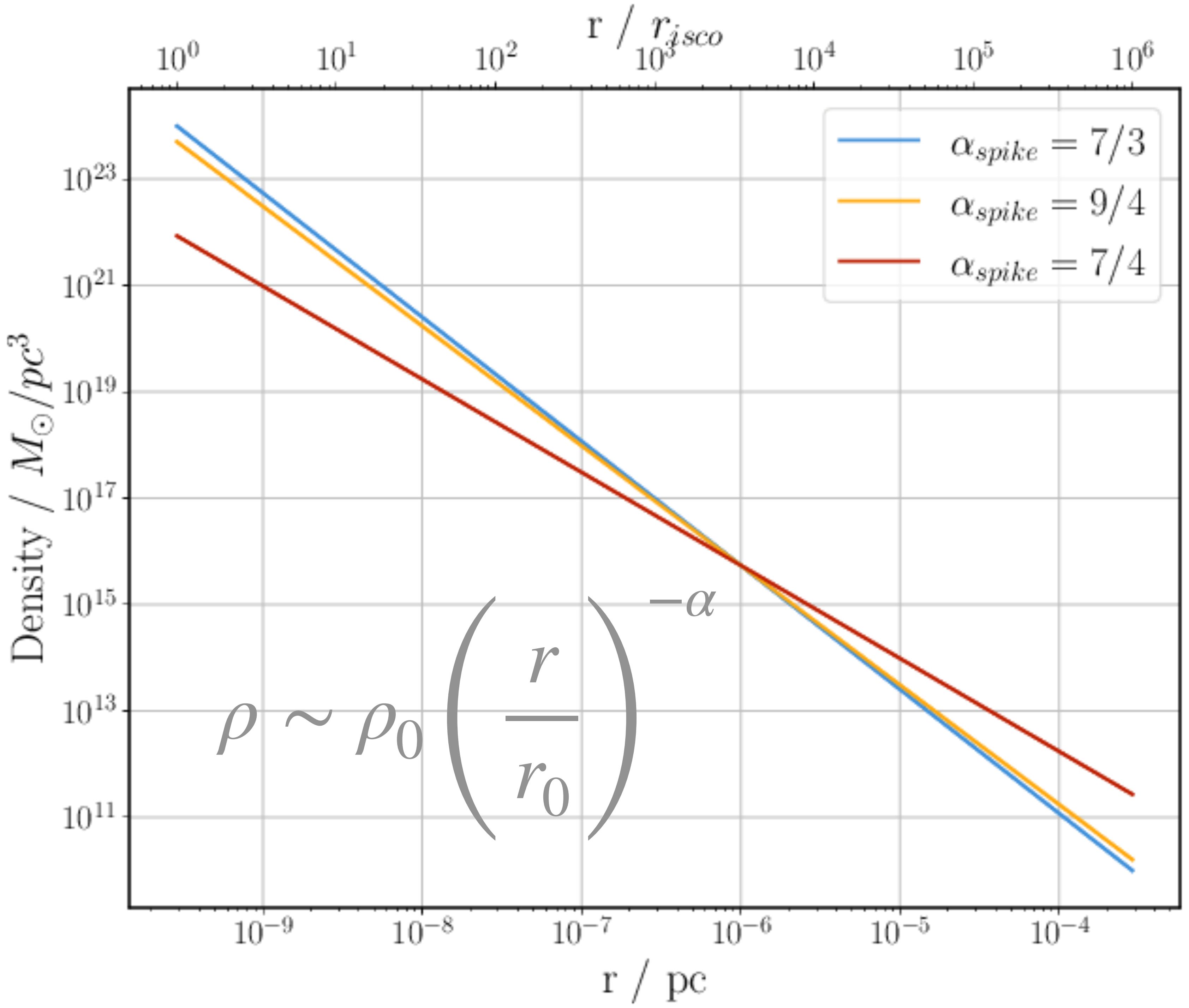
Does dark matter give signatures in strong gravity environments?

Tiny effect at average galactic densities

$$\frac{\rho}{1/R_s^2} \sim 10^{-30} \left(\frac{M_{BH}}{10^6 M_\odot} \right)^2$$

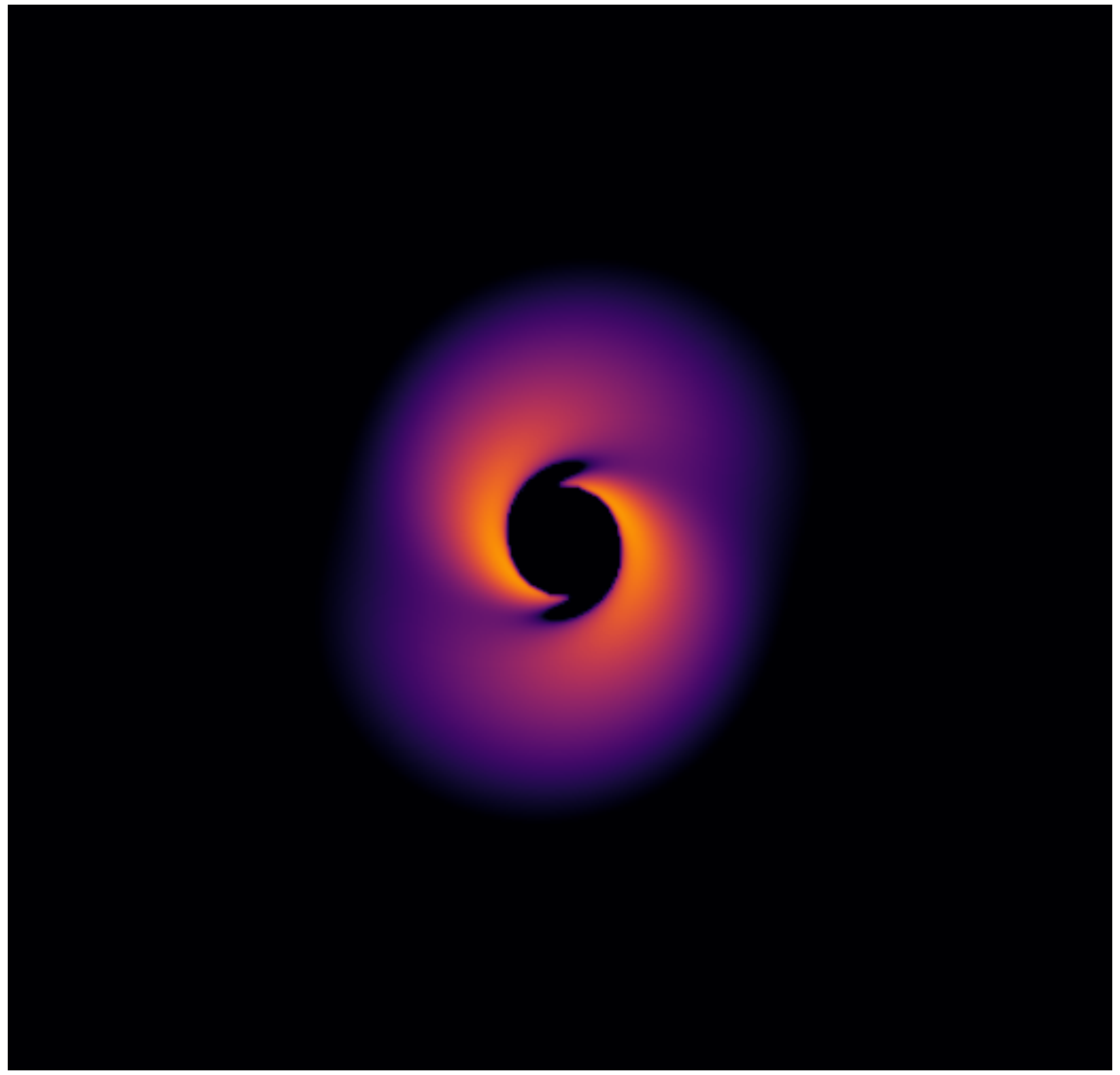
(Numerical relativist)

However, potential for significant enhancements around BHs



Accretion

Becker et.al. 2021
Circularization vs. Eccentrification in Intermediate Mass Ratio Inspirals inside Dark Matter Spikes



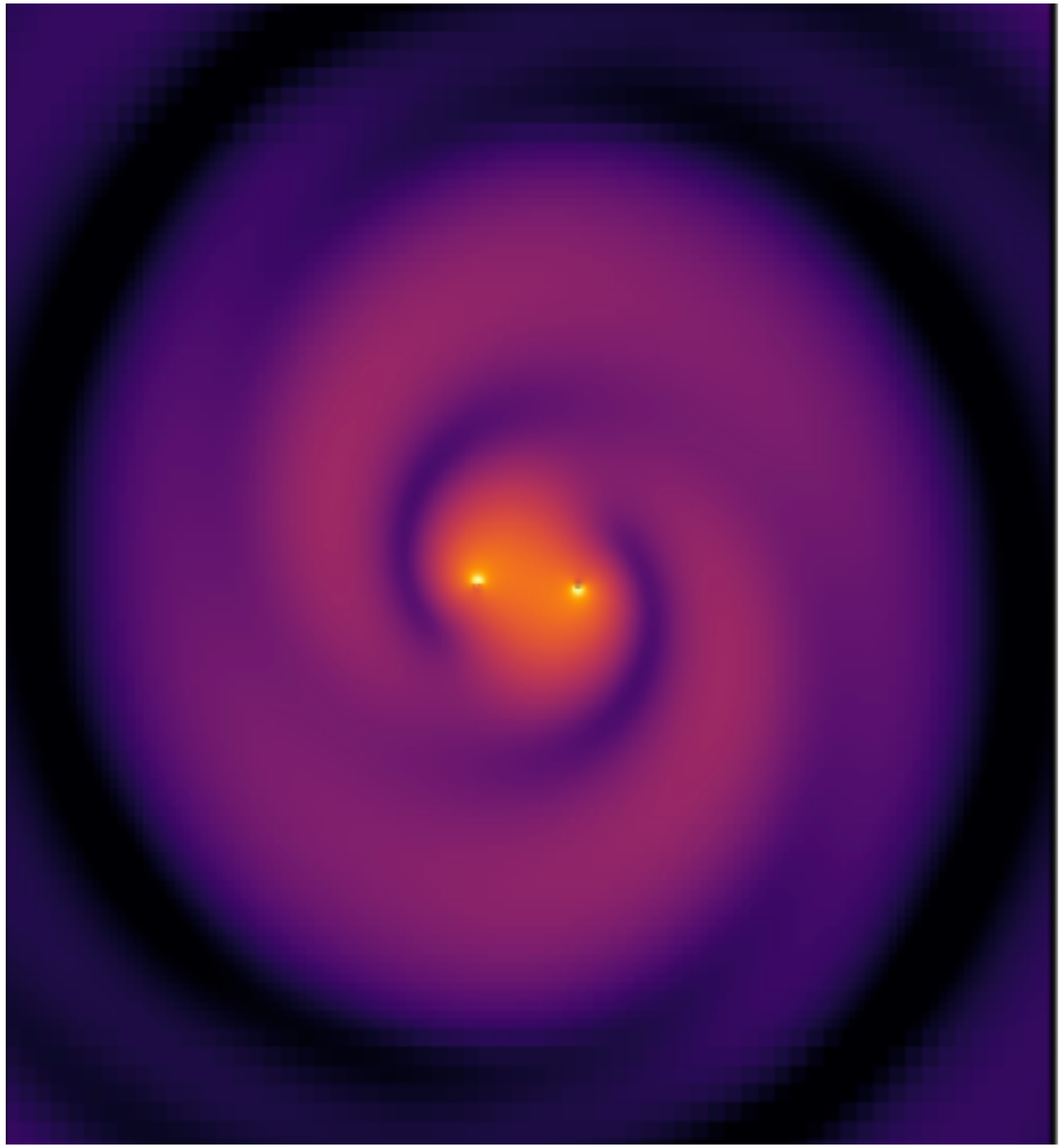
Superradiance

Review by Brito et. al. (updated 2020)
Superradiance: New Frontiers in Black Hole Physics

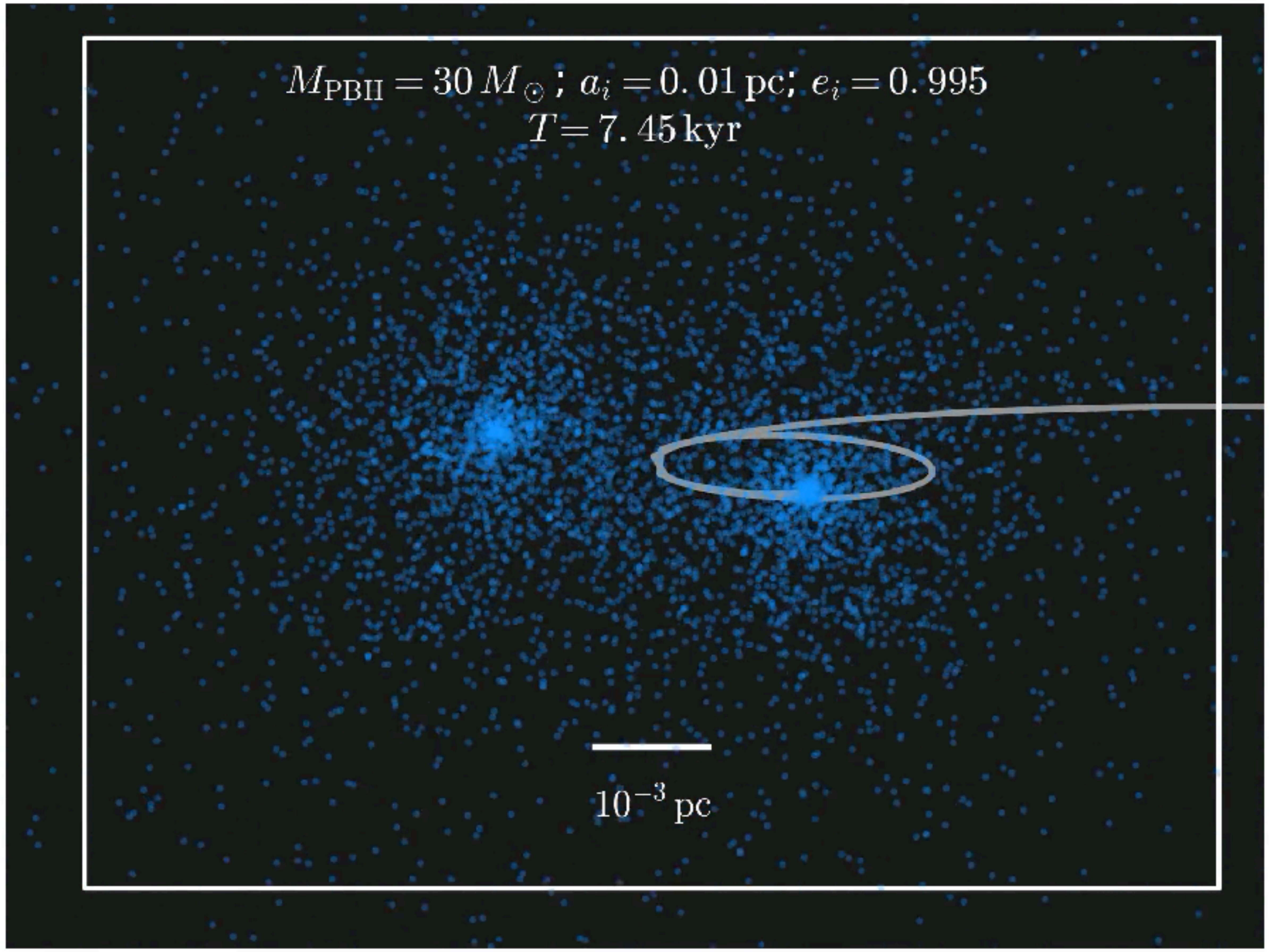
Our ability to characterise DM:

- Depends on how the DM is enhanced around the BHs

- Is strongest for larger mass BHs for a given density



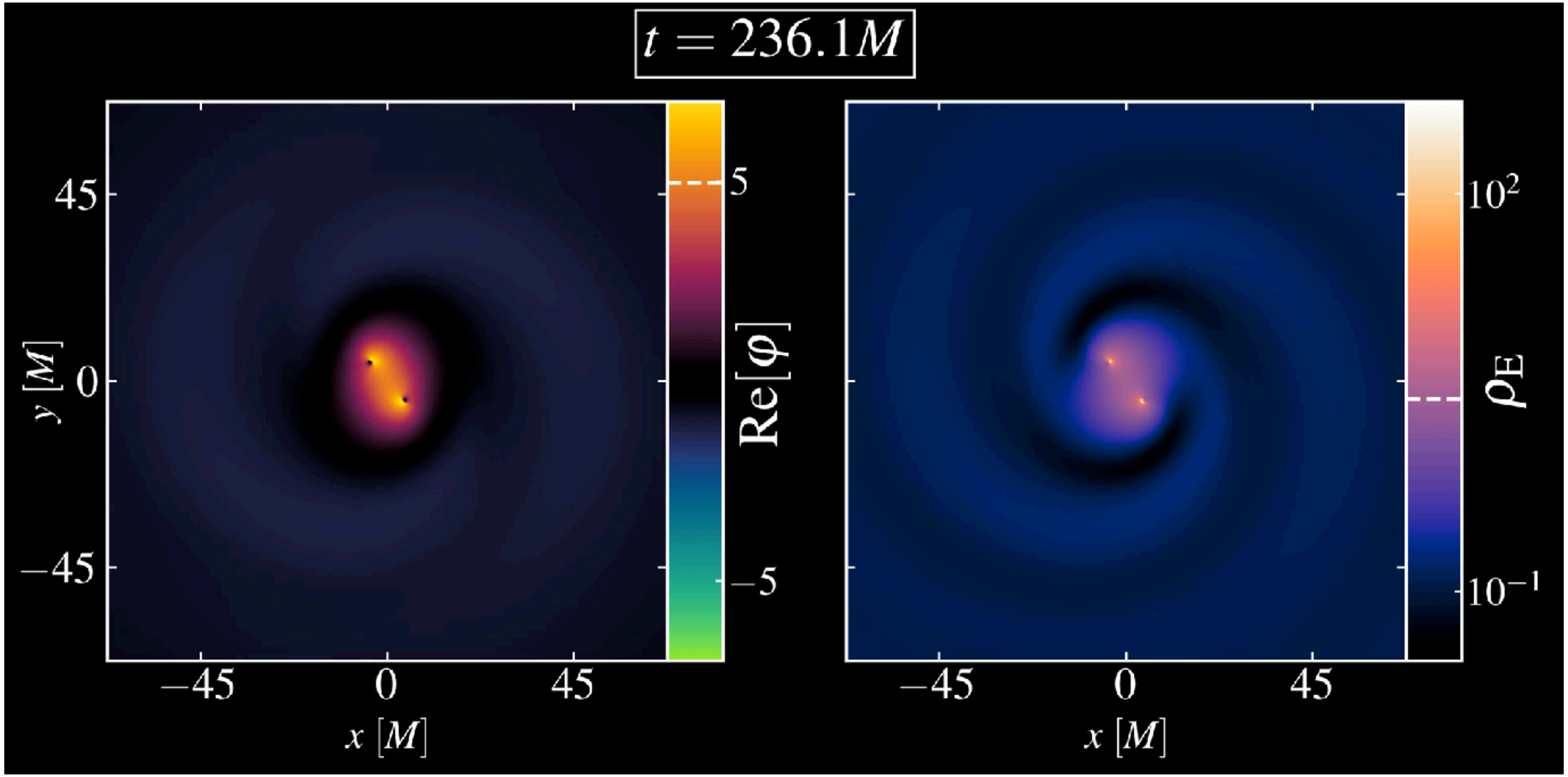
Equal mass binaries have been thought to be an unlikely candidate due to DM dispersal



Bertone et. al. 2020
Gravitational wave probes of dark matter: challenges and opportunities

However, wave like case seems to resist dispersal, and forms a central overdensity

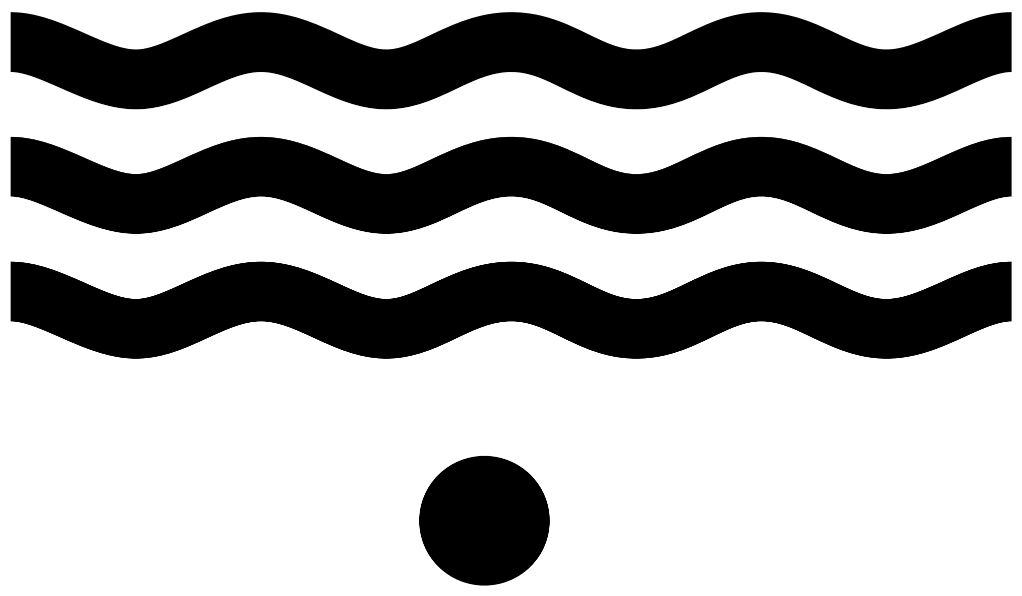
Field



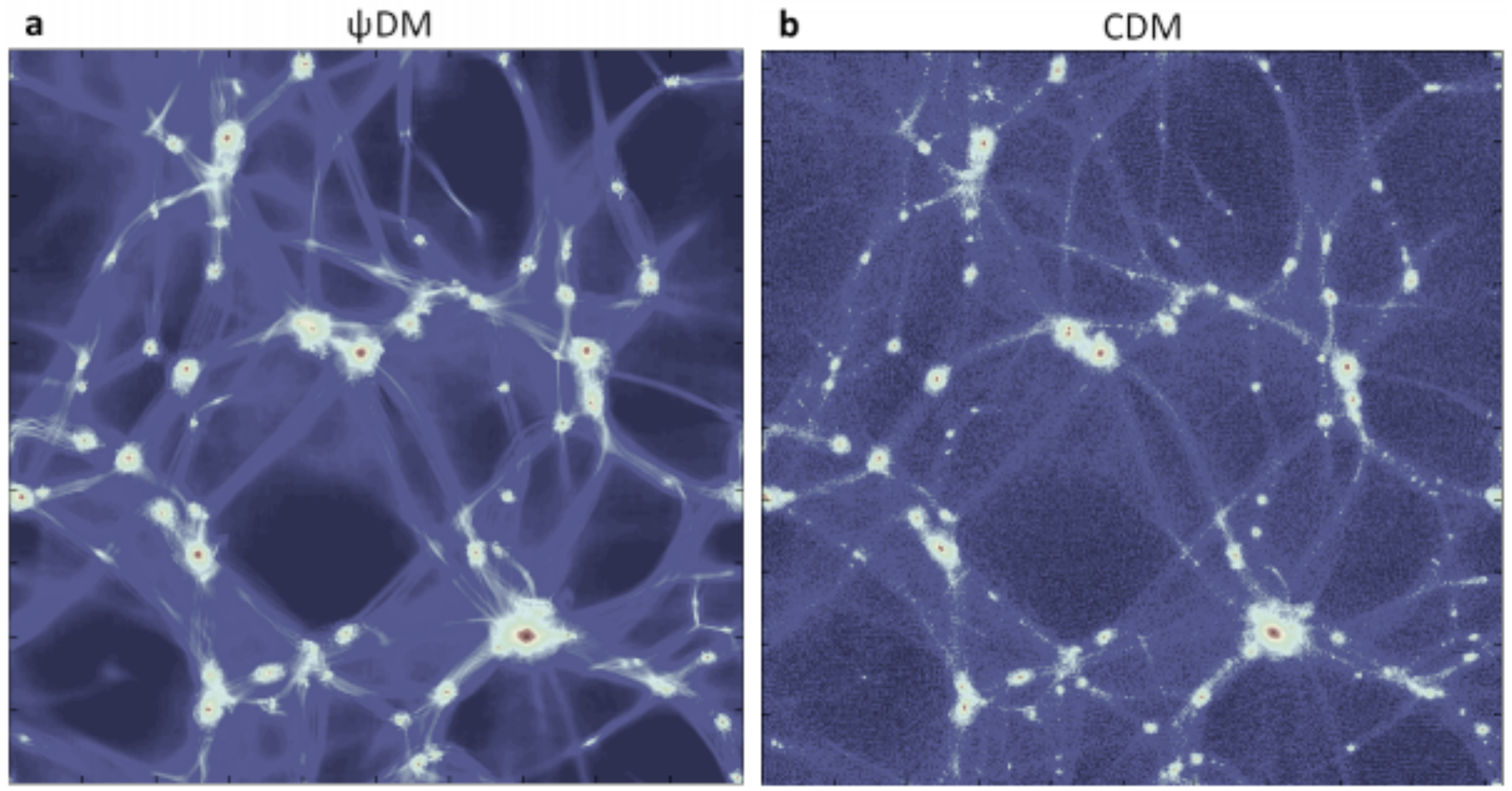
energy density

J. Bamber, J. Aurrekoetxea, KC, P. Ferreira 2023
Phys Rev D 107 2, 024035

Wave versus particle: the strong gravity perspective

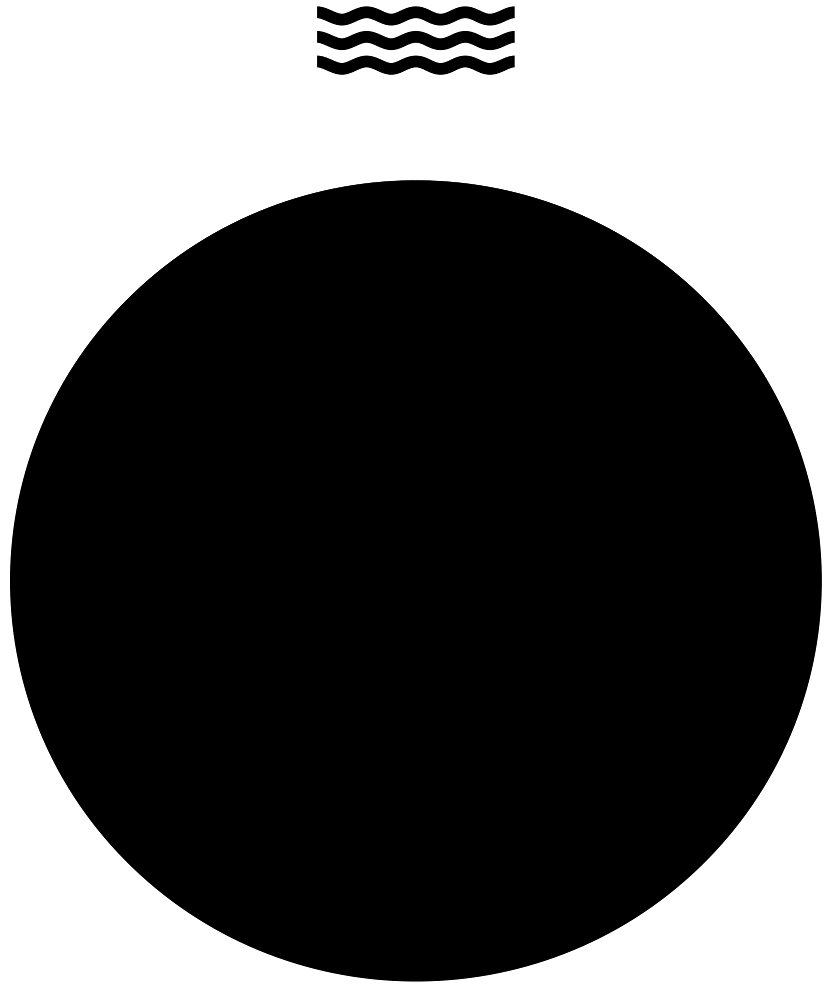


Wave



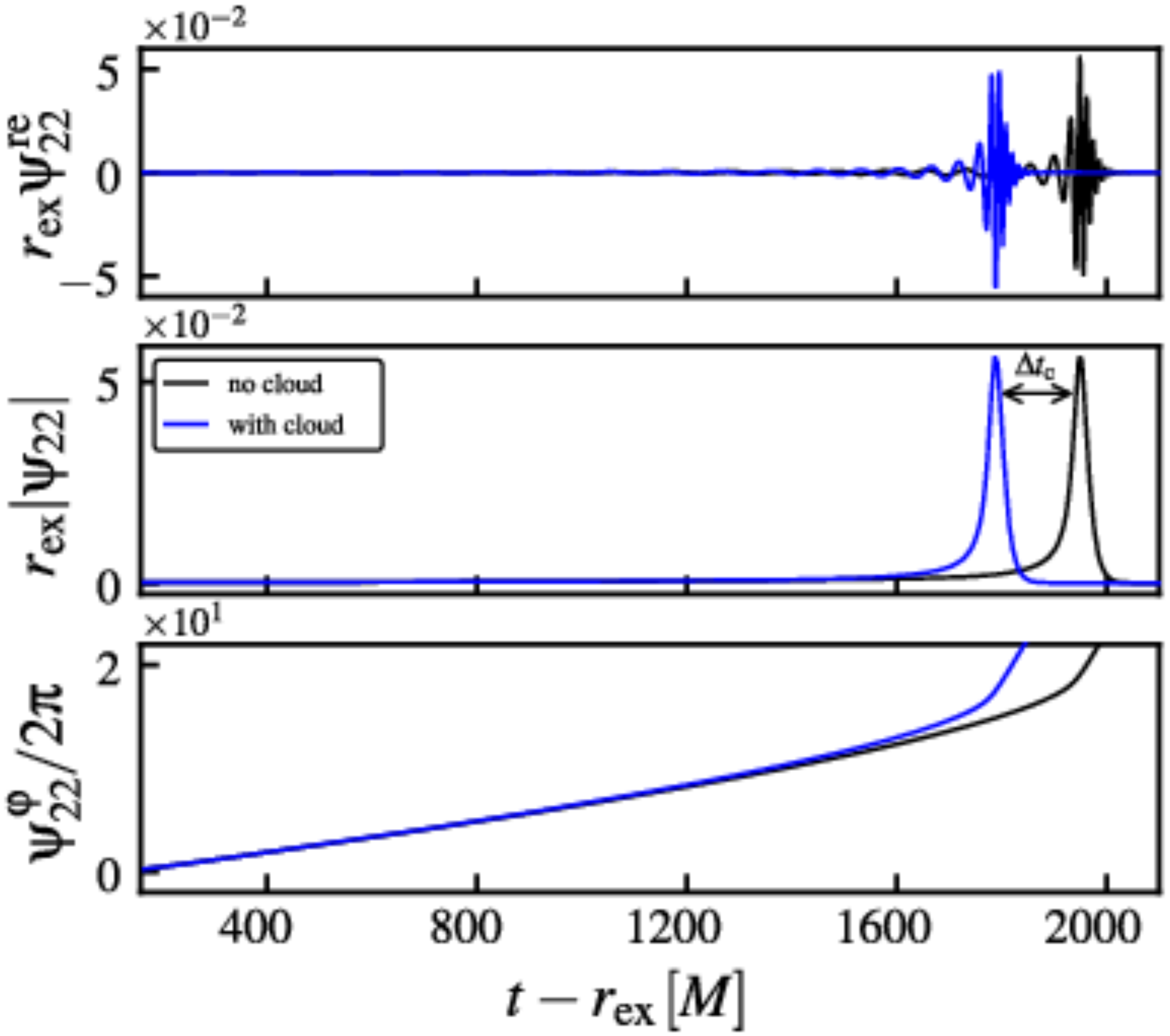
Schive et al. 2014
Cosmic structure as the quantum interference of a coherent dark wave

See also Wave Dark Matter review by Lam Hui
Ann.Rev.Astron.Astrophys. 59 (2021) 247-289



Particle

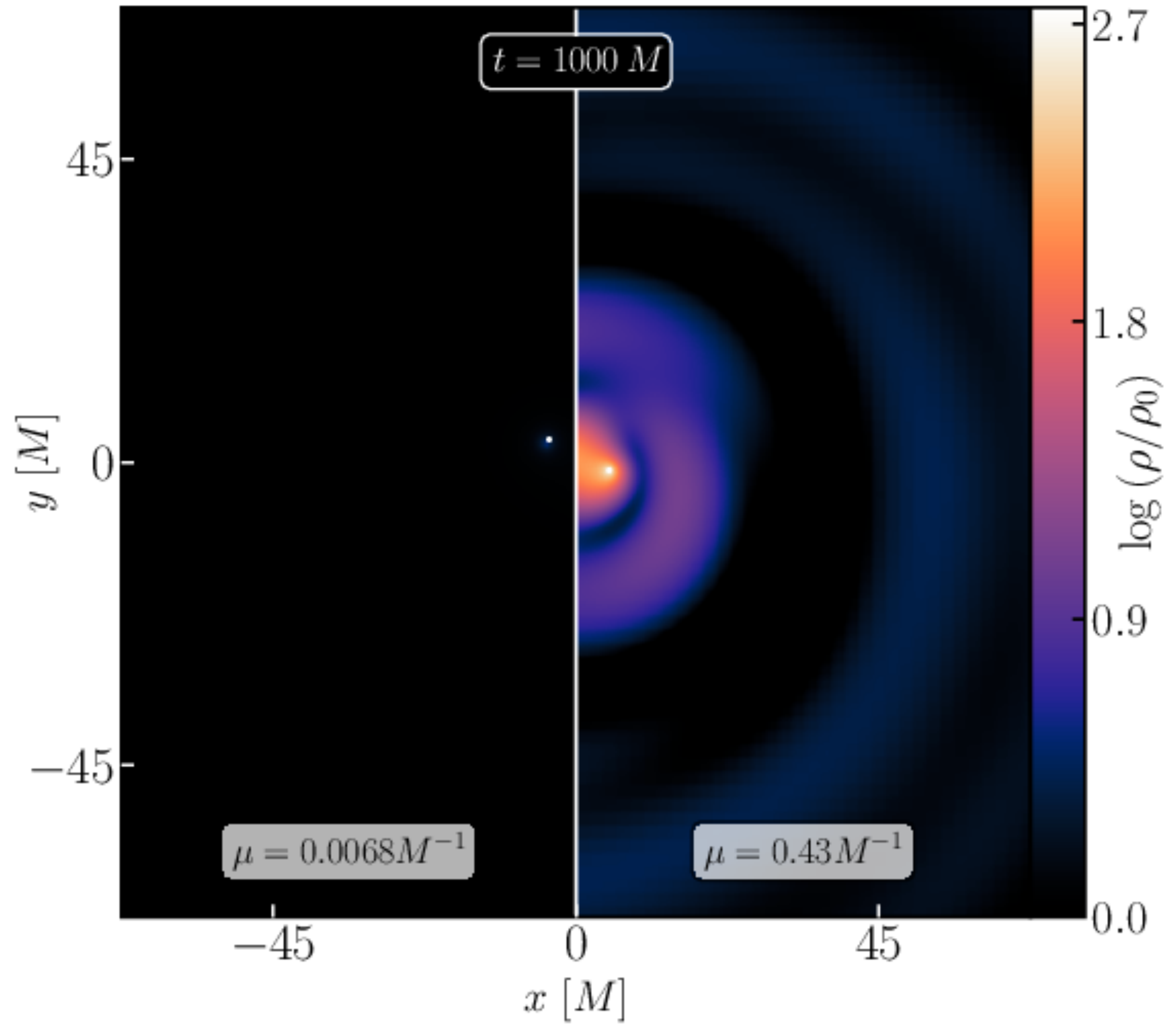
Potentially significant dephasing



Josu Aurrekoetxea

University of Oxford

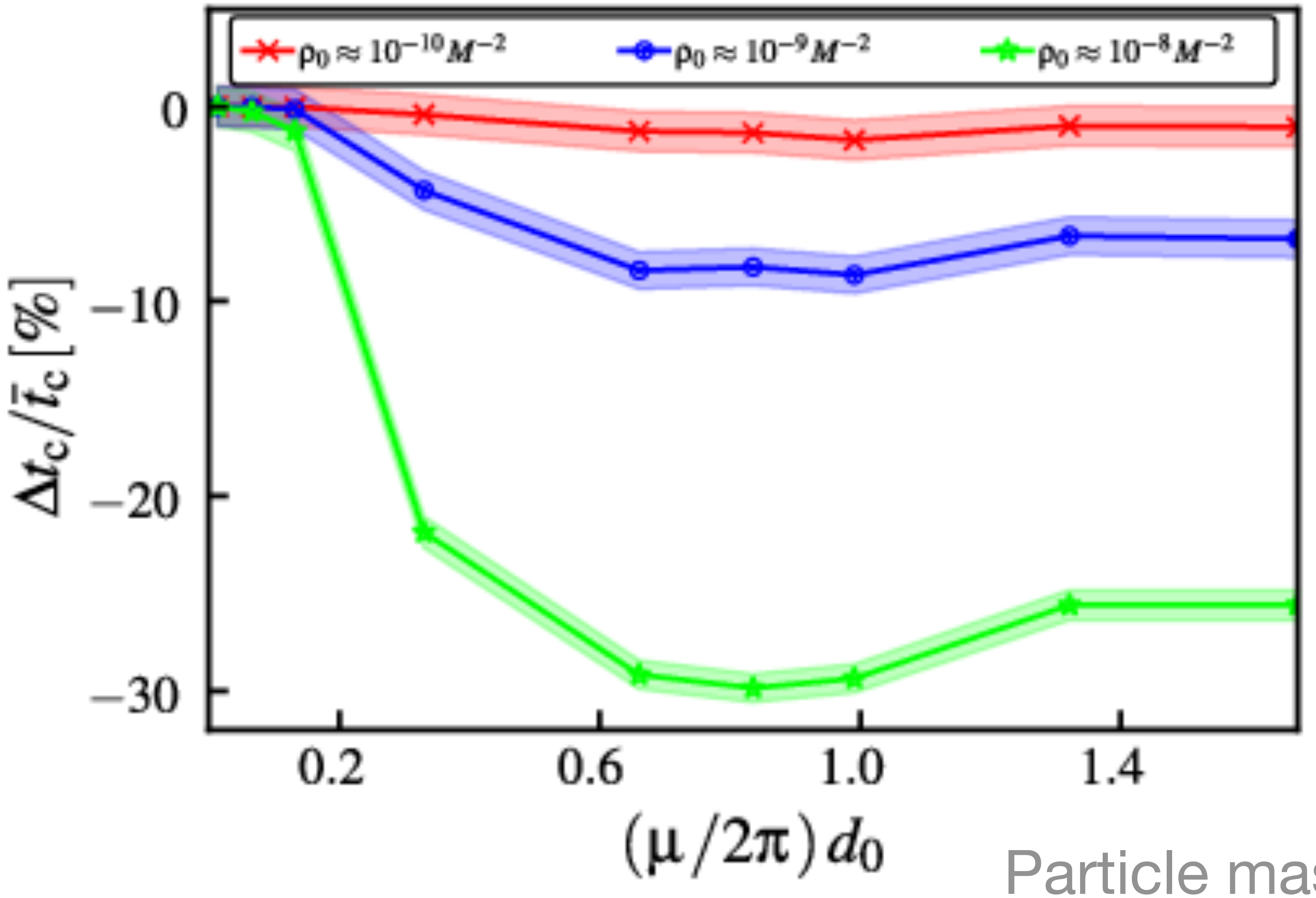
density



J. Aurrekoetxea, KC, J Bamber, P Ferreira 2023
arXiv 2311.18156 [gr-qc]

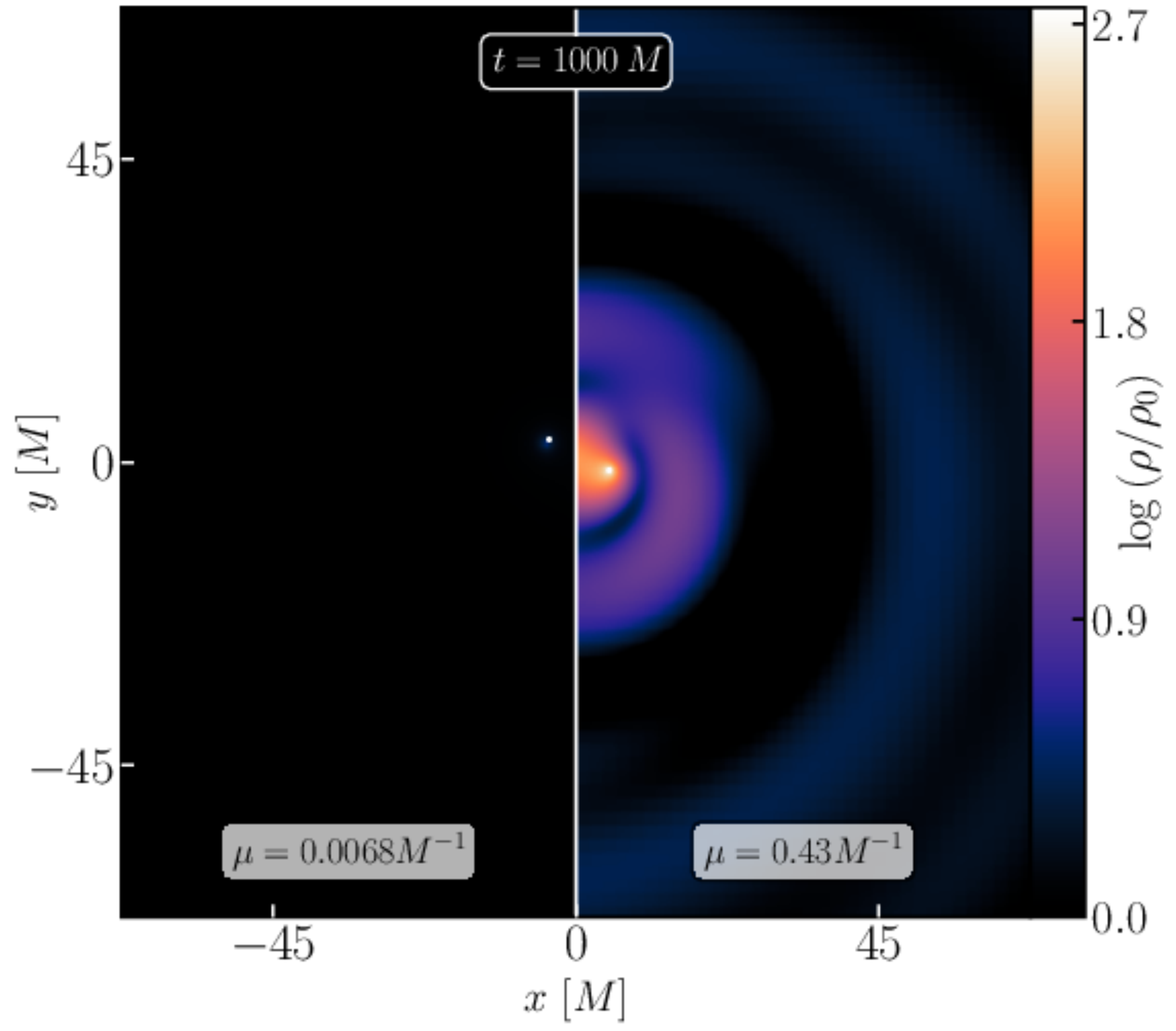
Surprisingly persistent effect at higher masses

dephasing



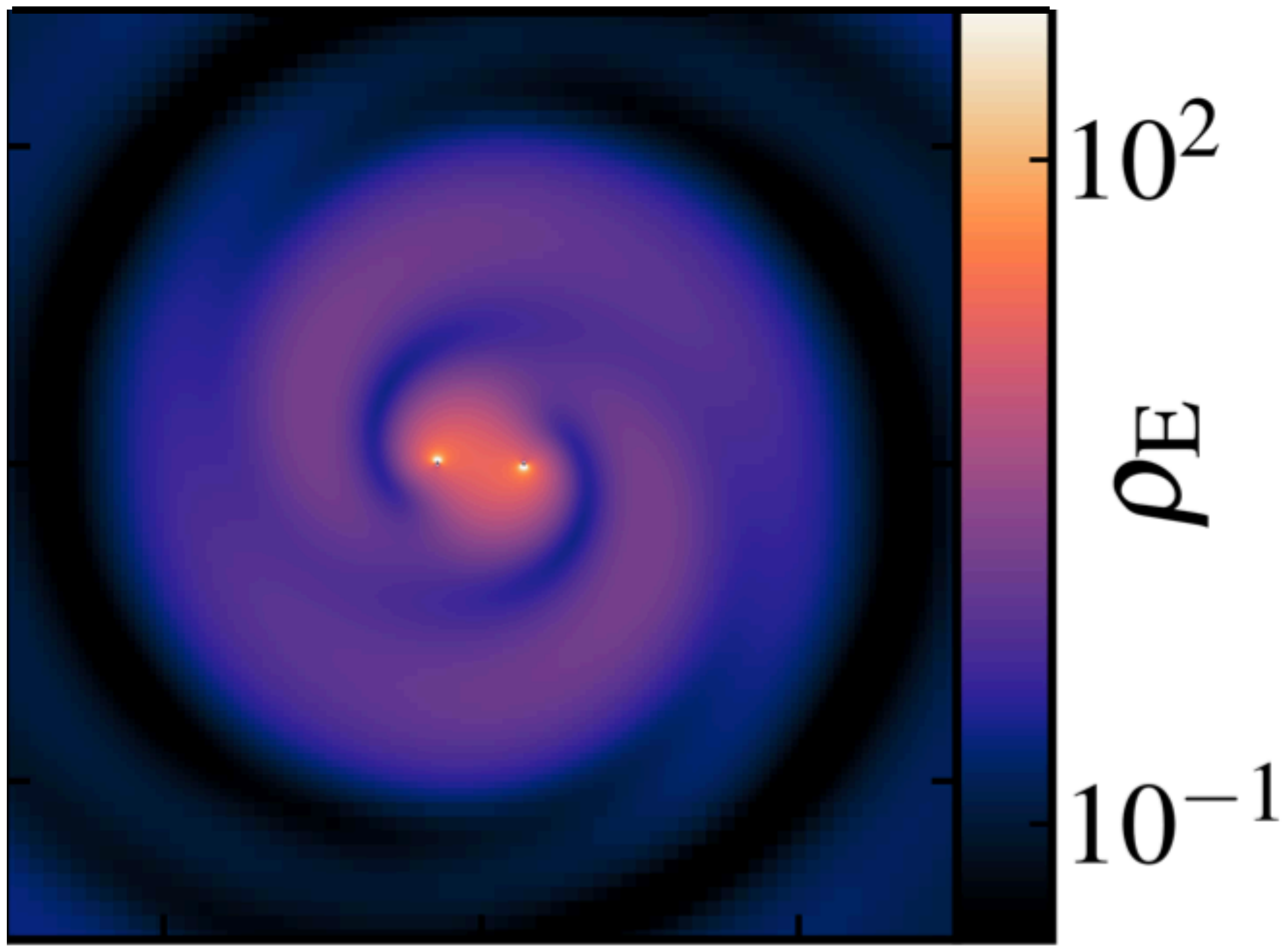
Particle mass

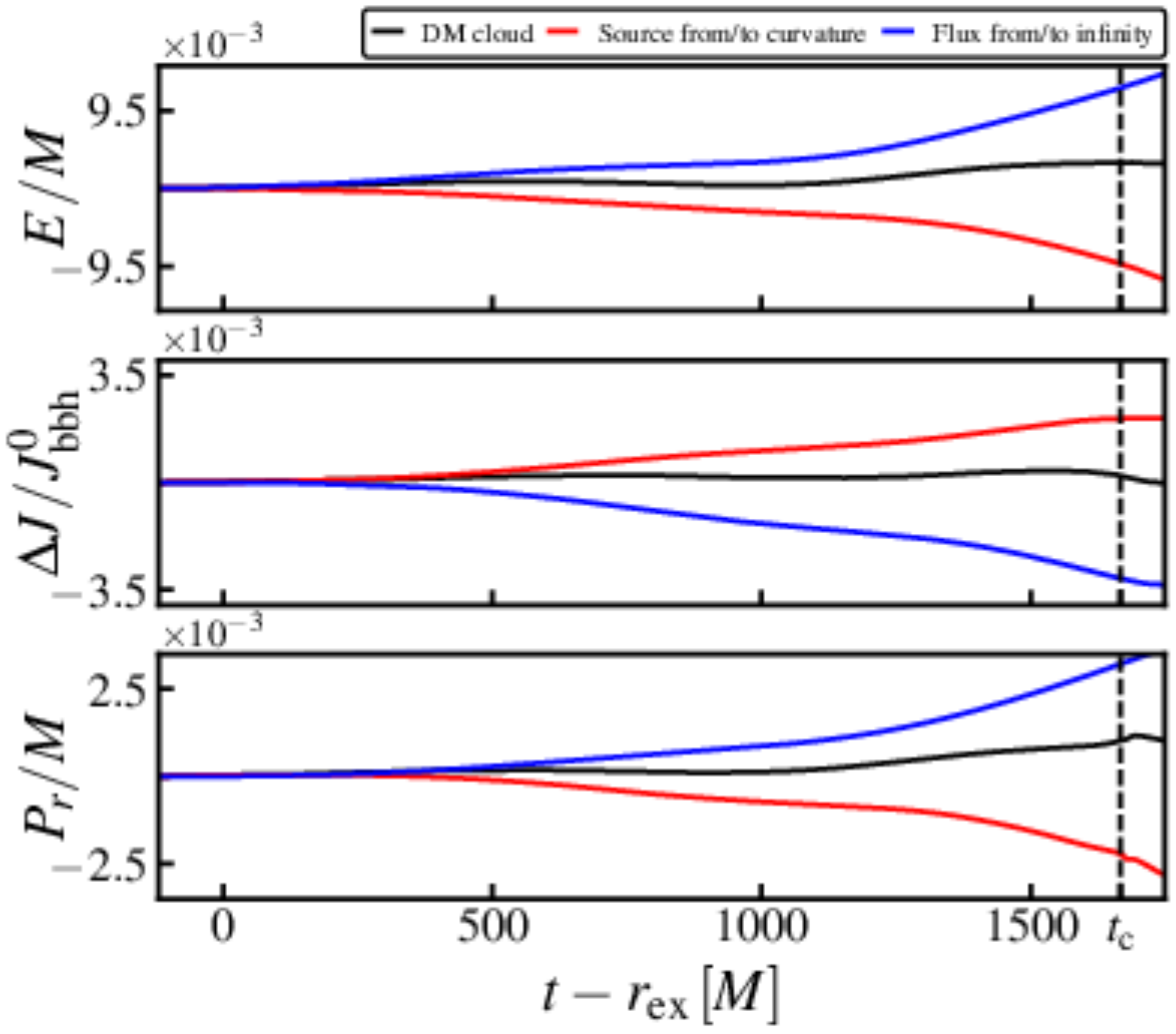
density



J. Aurrekoetxea, KC, J Bamber, P Ferreira 2023
arXiv 2311.18156 [gr-qc]

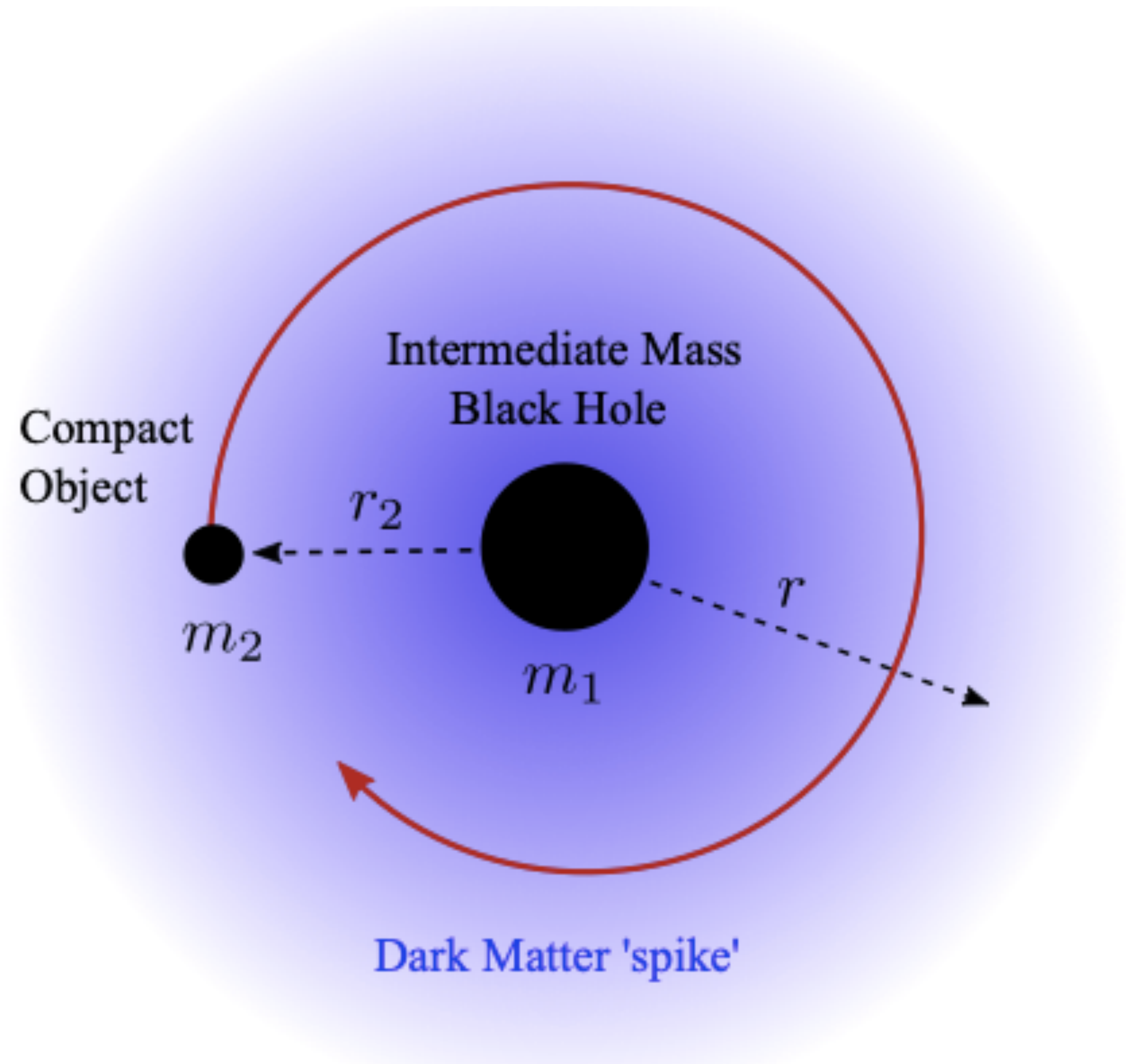
Due to radial force of central overdensity and accretion, rather than drag forces

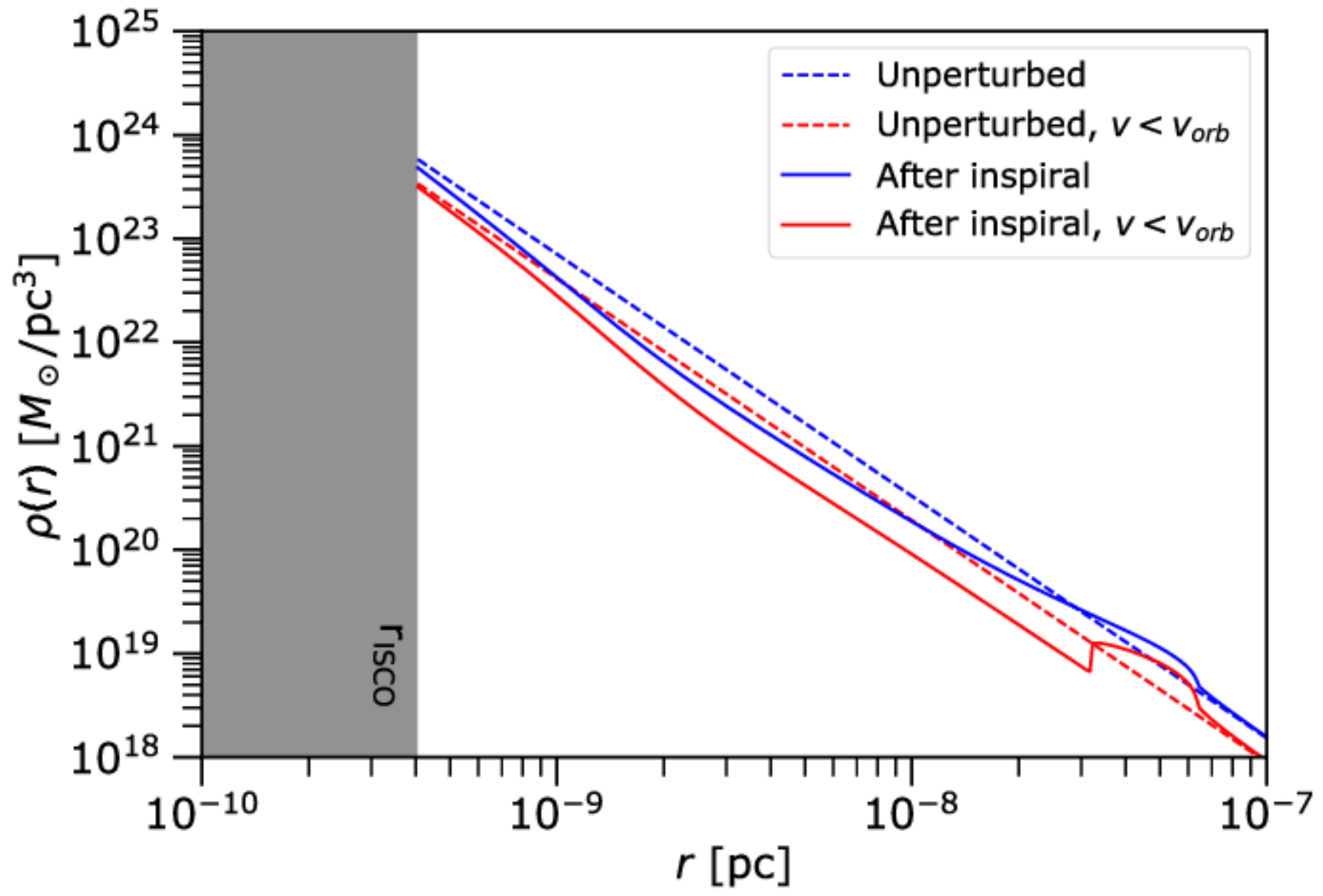




J. Aurrekoetxea, KC, J Bamber, P Ferreira 2023
arXiv 2311.18156 [gr-qc]

Highlights importance of matter dynamics, as already considered in particle / IMRI case

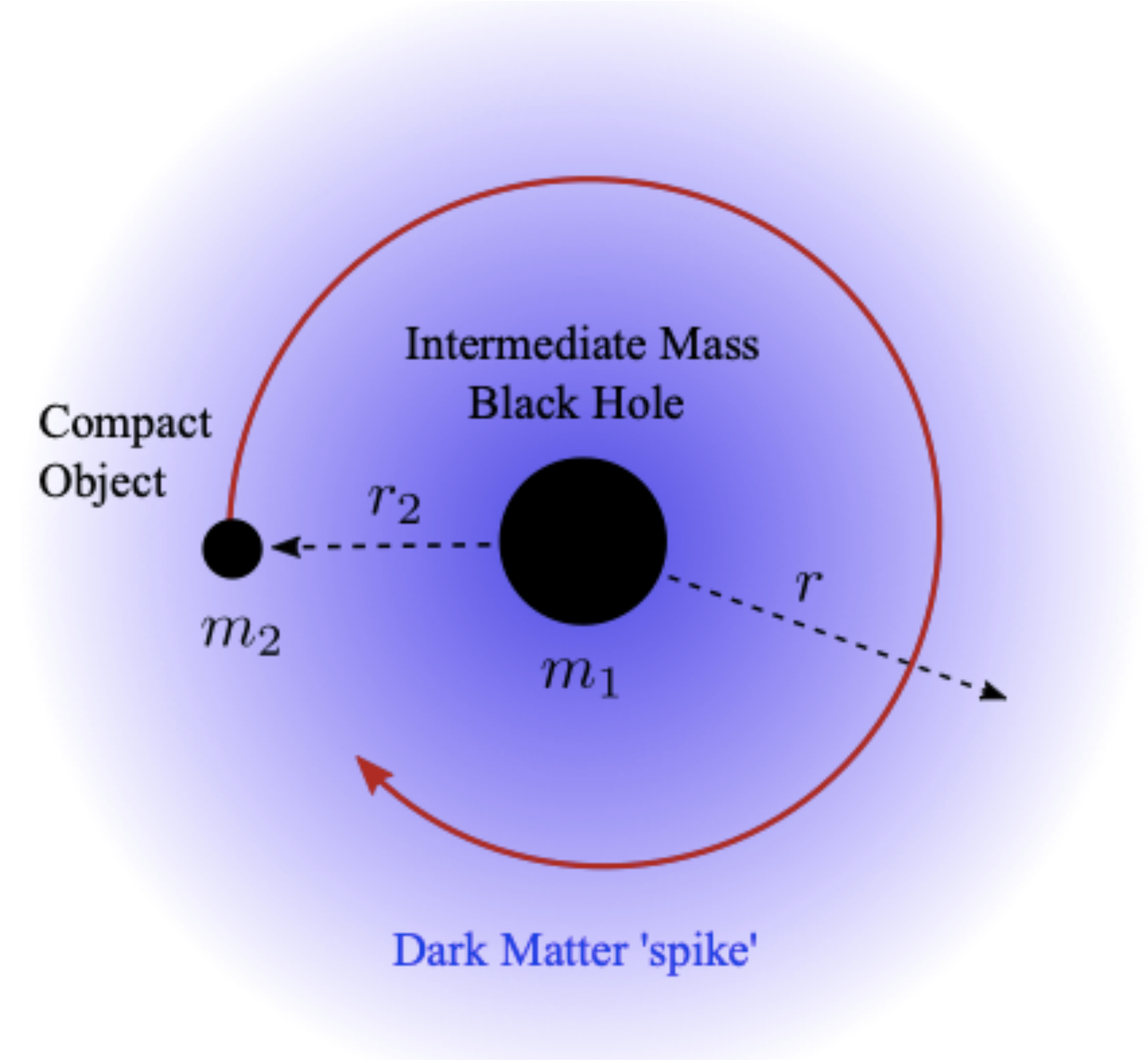




Kavanagh et. al. 2020, Coogan et. al. 2022
Detecting dark matter around black holes with gravitational waves: Effects of dark-matter dynamics on the gravitational waveform

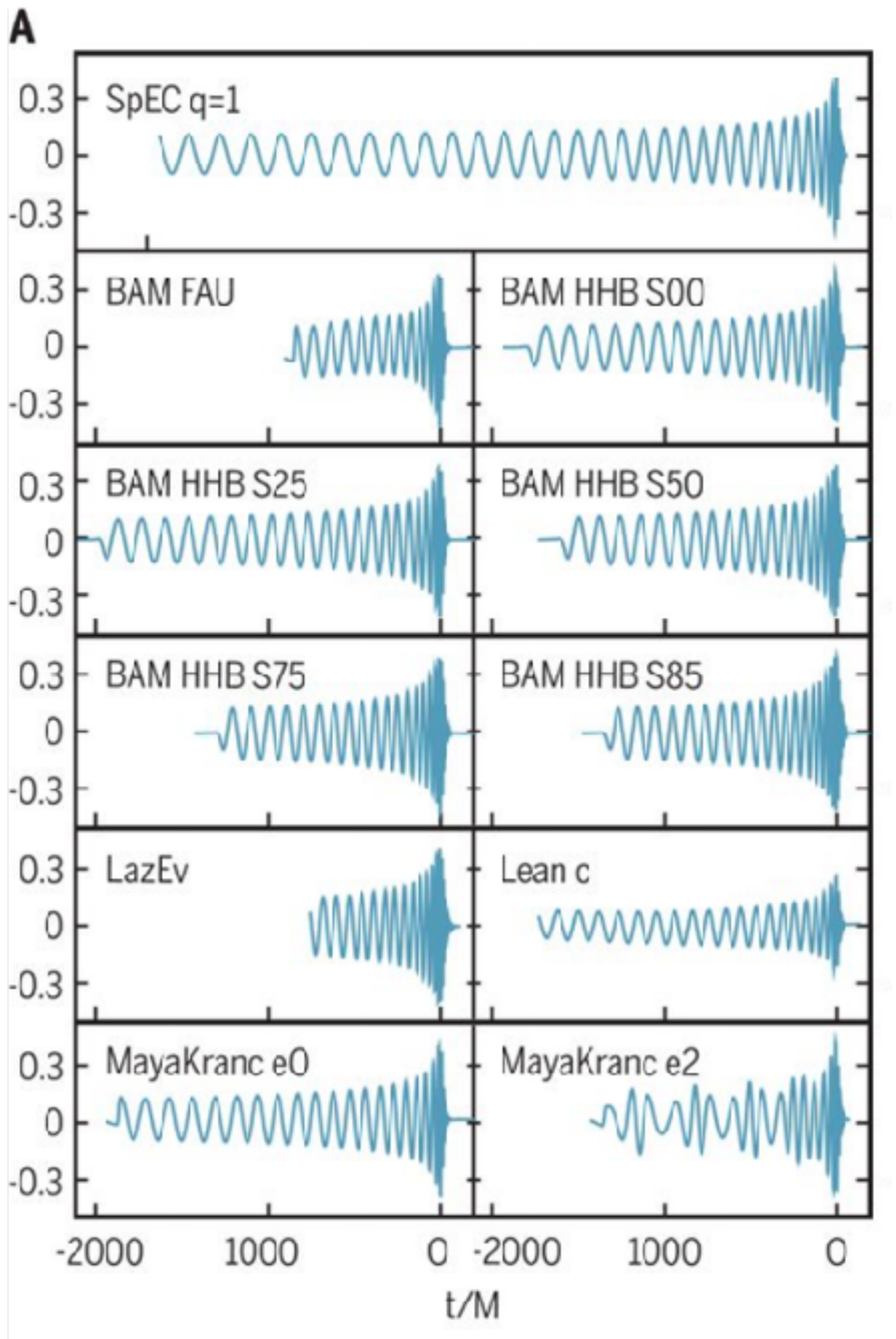
In the wave-like case most studies assume BHs moving through a static density profile

D Traykova, KC et. al. 2021, 2023
Phys.Rev.D 104 (2021) 10, 103014



Next steps

- Understand the differences between the particle and wave cases
- Test the robustness of backward models to this new source of dephasing
- Study the impact of spin / unequal masses / self interactions



Can we probe the fundamental nature of dark matter?

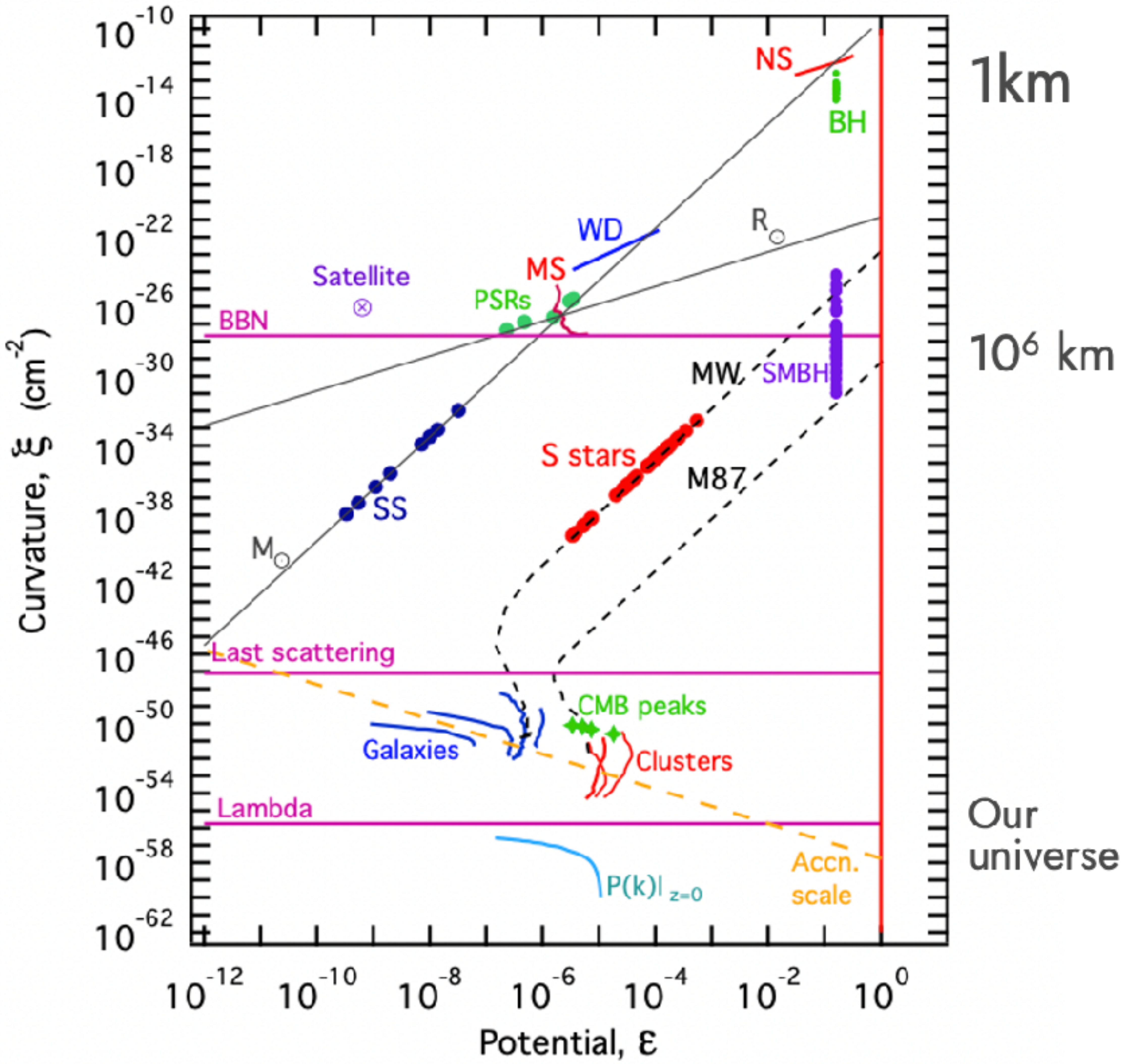
Can we distinguish matter / modifications to GR / waveform systematics?

Numerical relativity beyond GR - how far can we go?

Would we have seen this already?

New curvature ($R^{\mu\nu\rho\sigma}R_{\mu\nu\rho\sigma}$) scales probed with BH and NS measurements

T. Baker et. al 2015
Astrophys.J. 802 (2015) 63



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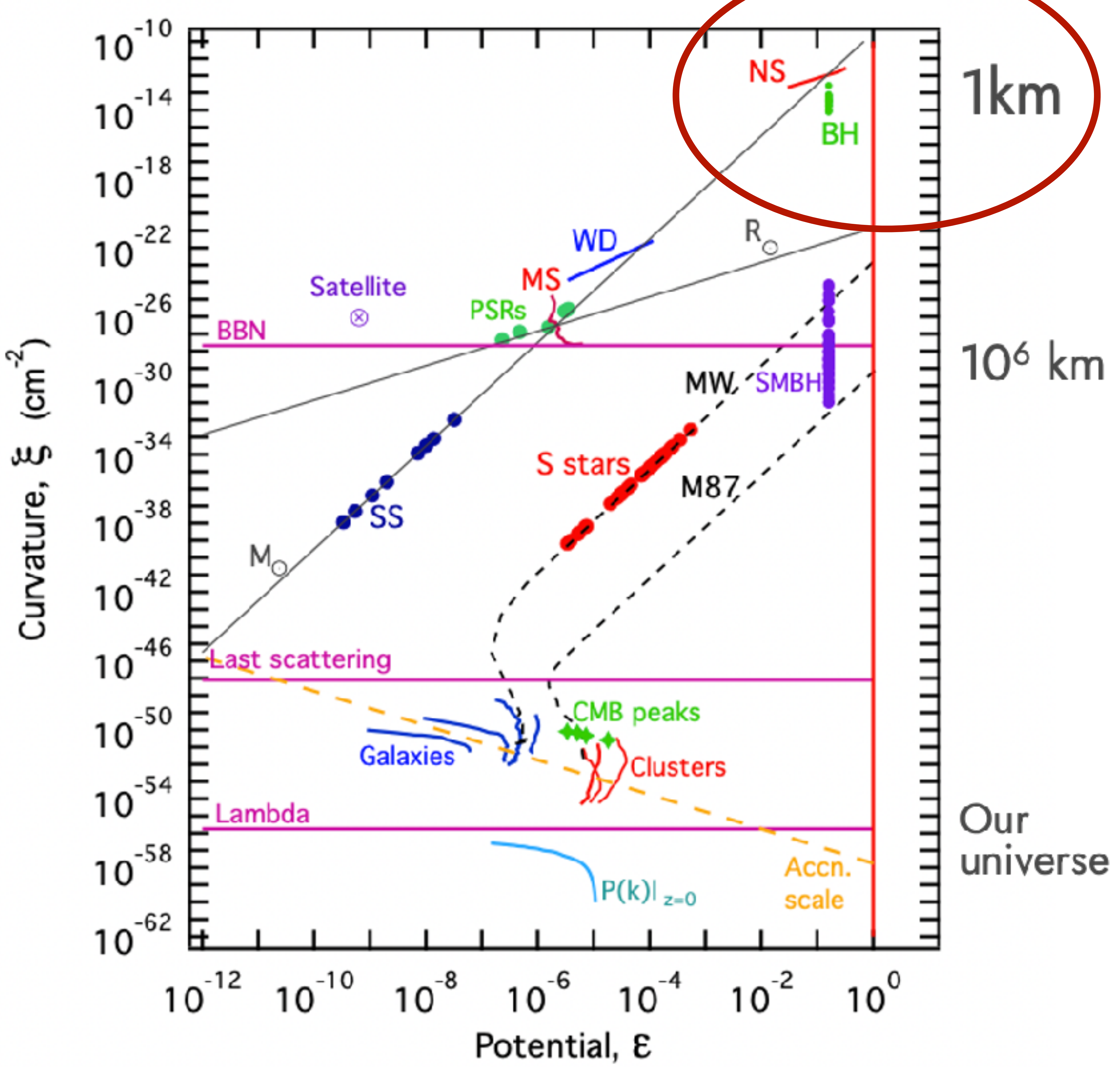
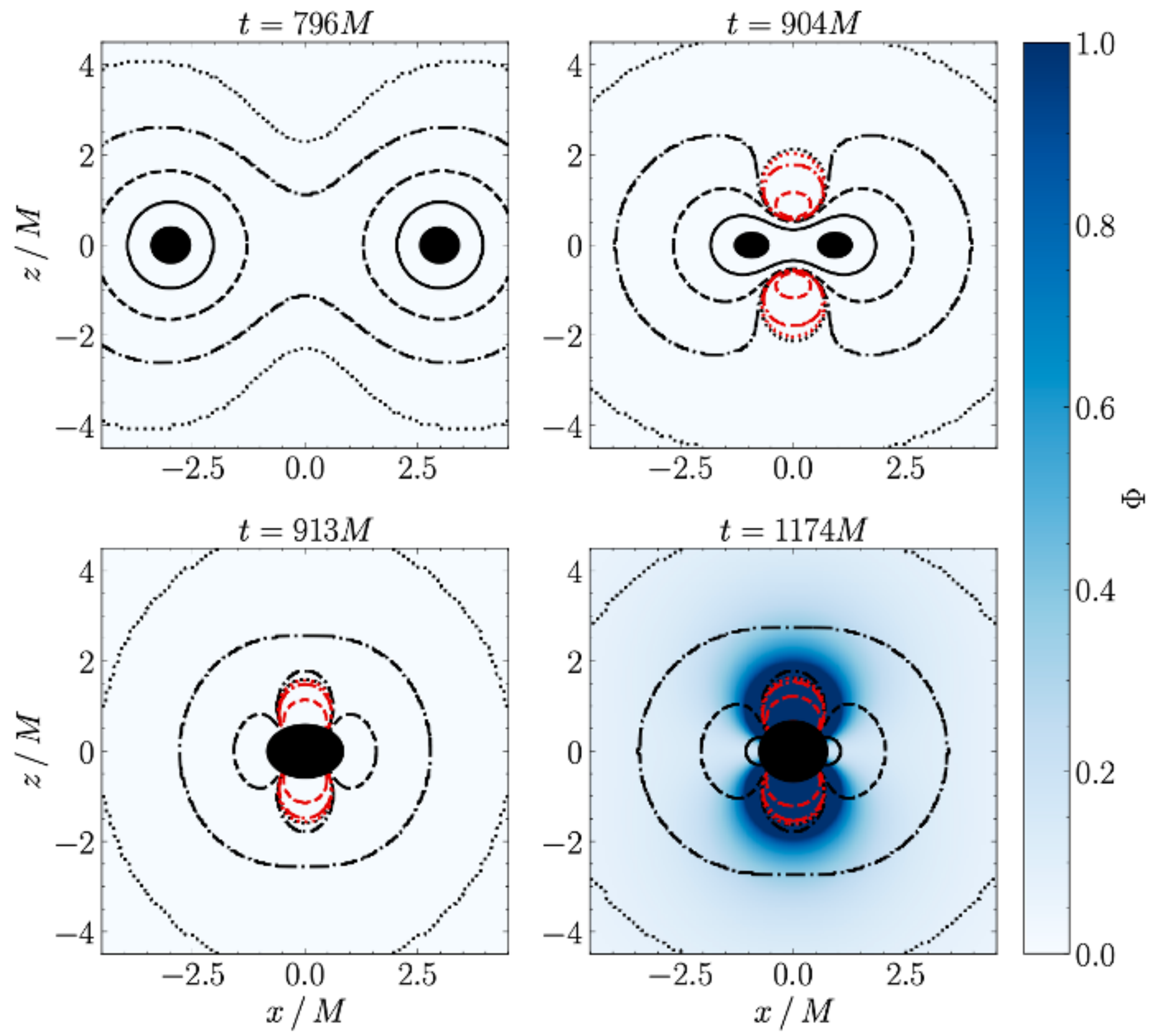


Interesting regimes identified in the decoupling limit

e.g. stealth dynamical scalarization for Type II

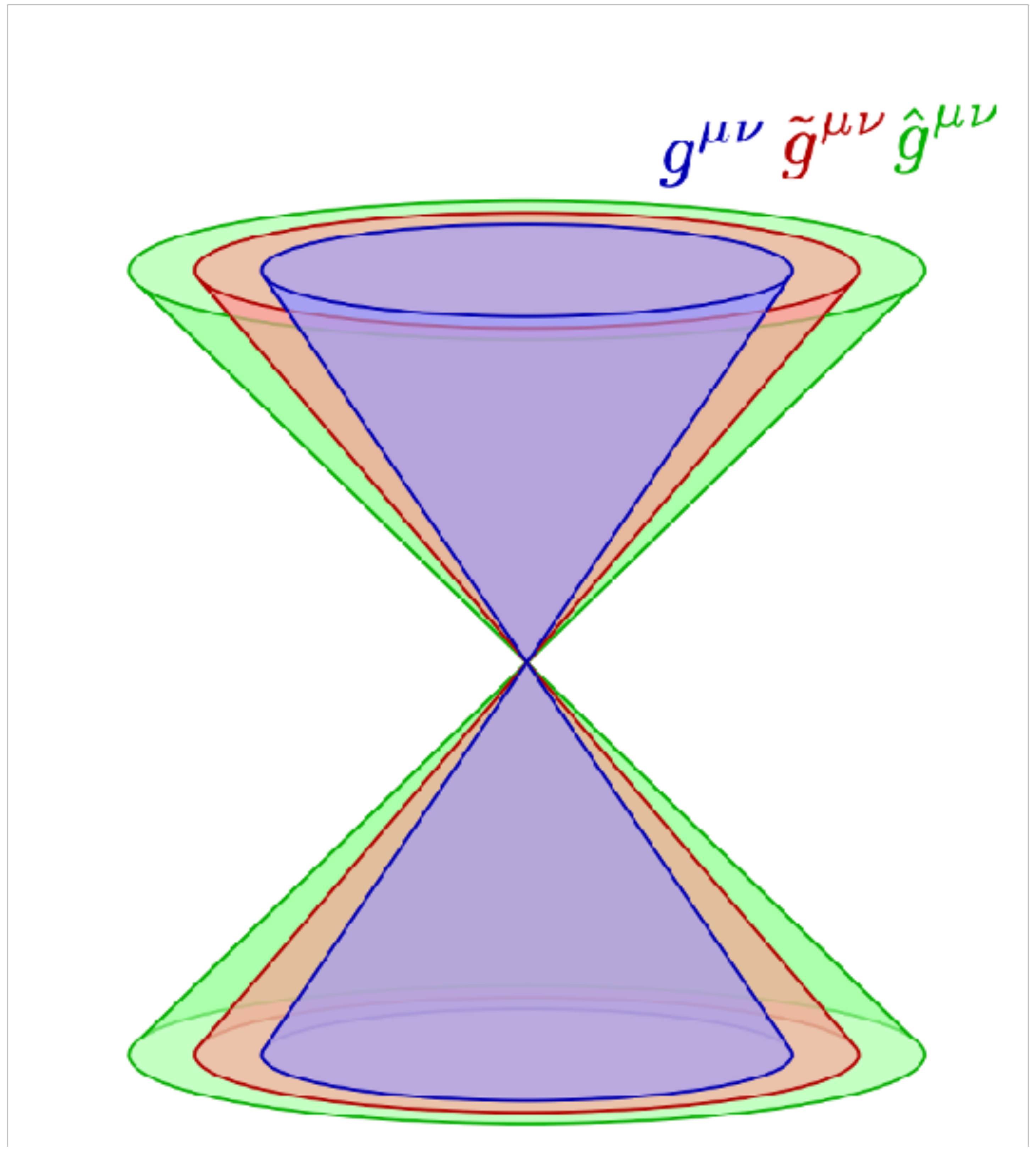
HO Silva et al 2021
Phys.Rev.Lett. 127 (2021) 3, 031101
M Elley et al 2022
Phys.Rev.D 106 (2022) 4, 044018



See also:
M Okounkova 2020
Phys.Rev.D 102 (2020) 8, 084046

Well posed evolutions

ÁD Kovács and H Reall 2020
Phys.Rev.Lett. 124 (2020) 22, 221101



Aron Kovacs
Queen Mary University of London

Well posed formulation of the full theory proposed in Modified Harmonic Gauge

(in weak coupling limit)

Equation of motion for the scalar field as before

$$\Box \phi = \lambda'(\phi)\mathscr{L}_{GB} + V'(\phi)$$

Coupling to curvature
(Approximately
Riemann^2)

See review:
Scalarisation, D Doneva et. al 2022
arXiv:2211.01766 [gr-qc]

Equation of motion for the metric is “a hot mess”

$$\rho^{\rm GB} = \frac{\Omega M}{2} - M_{kl}\Omega^{kl}, \tag{A2a}$$

$$J_i^{\rm GB} = \frac{\Omega_i M}{2} - M_{ij}\Omega^j - 2\left(\Omega^j{}_{[i}N_{j]} - \Omega^{jk}D_{[i}K_{j]k}\right), \tag{A2b}$$

$$\begin{aligned}
S_{ij}^{\rm GB} = {} & 2\gamma^k{}_{(i}\Omega^{{\rm TF},l}_{j)}\left(\mathcal{L}_n A_{kl} + \tfrac{1}{\alpha}(D_kD_l\alpha)^{\rm TF} + A_{km}A^m{}_l\right) \\
& -\Omega^{\rm TF}_{ij}\left(\mathcal{L}_n K + \tfrac{1}{\alpha}D^kD_k\alpha - 3A_{kl}A^{kl} - \tfrac{K^2}{3}\right) \\
& -\tfrac{\Omega}{3}\left(\mathcal{L}_n A_{ij} + \tfrac{1}{\alpha}(D_iD_j\alpha)^{\rm TF} + A_{im}A^m{}_j\right) \\
& -\Omega_{nn}M_{ij} + N_{(i}\Omega_{j)} - 2\epsilon_{(i}{}^{kl}B_{j)k}\Omega_l \\
& +\gamma_{ij}\Big[\rho^{rhs} - N^k\Omega_k + \tfrac{M}{6}\left(\Omega_{nn} + \tfrac{\Omega}{3}\right) - \tfrac{1}{3}\Omega^{{\rm TF},kl}M_{kl} \\
& \quad -\Omega^{{\rm TF},kl}\left(\mathcal{L}_n A_{kl} + \tfrac{1}{\alpha}(D_kD_l\alpha)^{\rm TF} + A_{km}A^m{}_l\right) \\
& \quad +\tfrac{2\Omega}{9}\left(\mathcal{L}_n K + \tfrac{D^kD_k\alpha}{\alpha} - \tfrac{3}{2}A_{kl}A^{kl} - \tfrac{K^2}{3}\right)\Big],
\end{aligned} \tag{A2c}$$

with

$$M_{ij} = R_{ij} + \frac{1}{\chi}\left(\frac{2}{9}\tilde{\gamma}_{ij}K^2 + \frac{1}{3}K\tilde{A}_{ij} - \tilde{A}_{ik}\tilde{A}_j{}^k\right), \tag{A3a}$$

$$N_i = \tilde{D}_j\tilde{A}_i{}^j - \frac{3}{2\chi}\tilde{A}_i{}^j\partial_j\chi - \frac{2}{3}\partial_i K, \tag{A3b}$$

$$B_{ij} = \epsilon_{(i}{}^{kl}D_kA_{j)l}, \tag{A3c}$$

$$\Omega_i = f'\left(\partial_i K_\phi - \tilde{A}^j{}_i\partial_j\phi - \frac{K}{3}\partial_i\phi\right) + f''K_\phi\partial_i\phi, \tag{A3d}$$

$$\Omega_{ij} = f'\left(D_iD_j\phi - K_\phi K_{ij}\right) + f''(\partial_i\phi)\partial_j\phi, \tag{A3e}$$

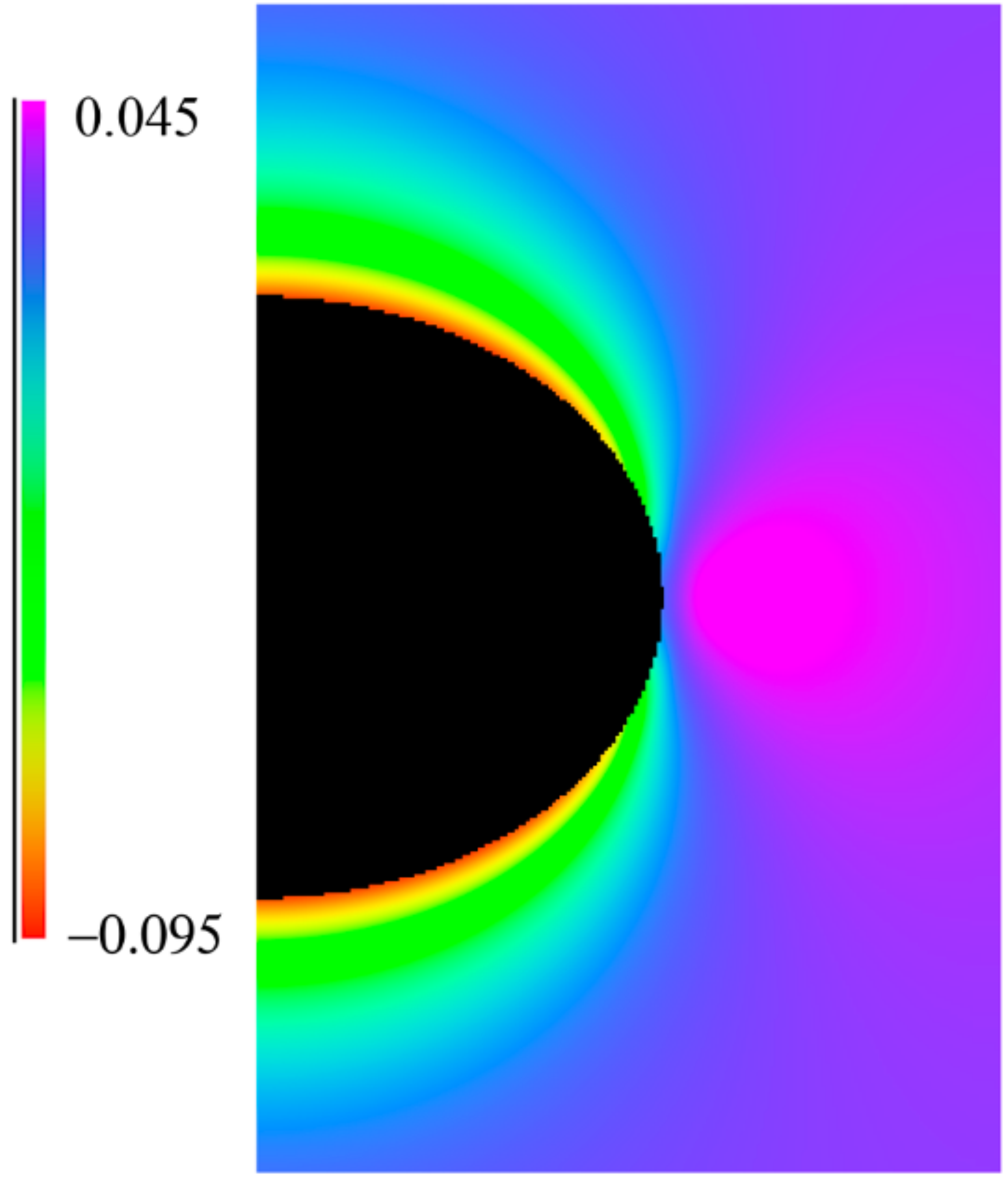
$$\Omega_{nn} = f''K_\phi^2 - \frac{f'}{\alpha}D^k\alpha D_k\phi - f'\mathcal{L}_n K_\phi, \tag{A3f}$$

Well posed evolutions

Fully non linear studies in GHC with excision

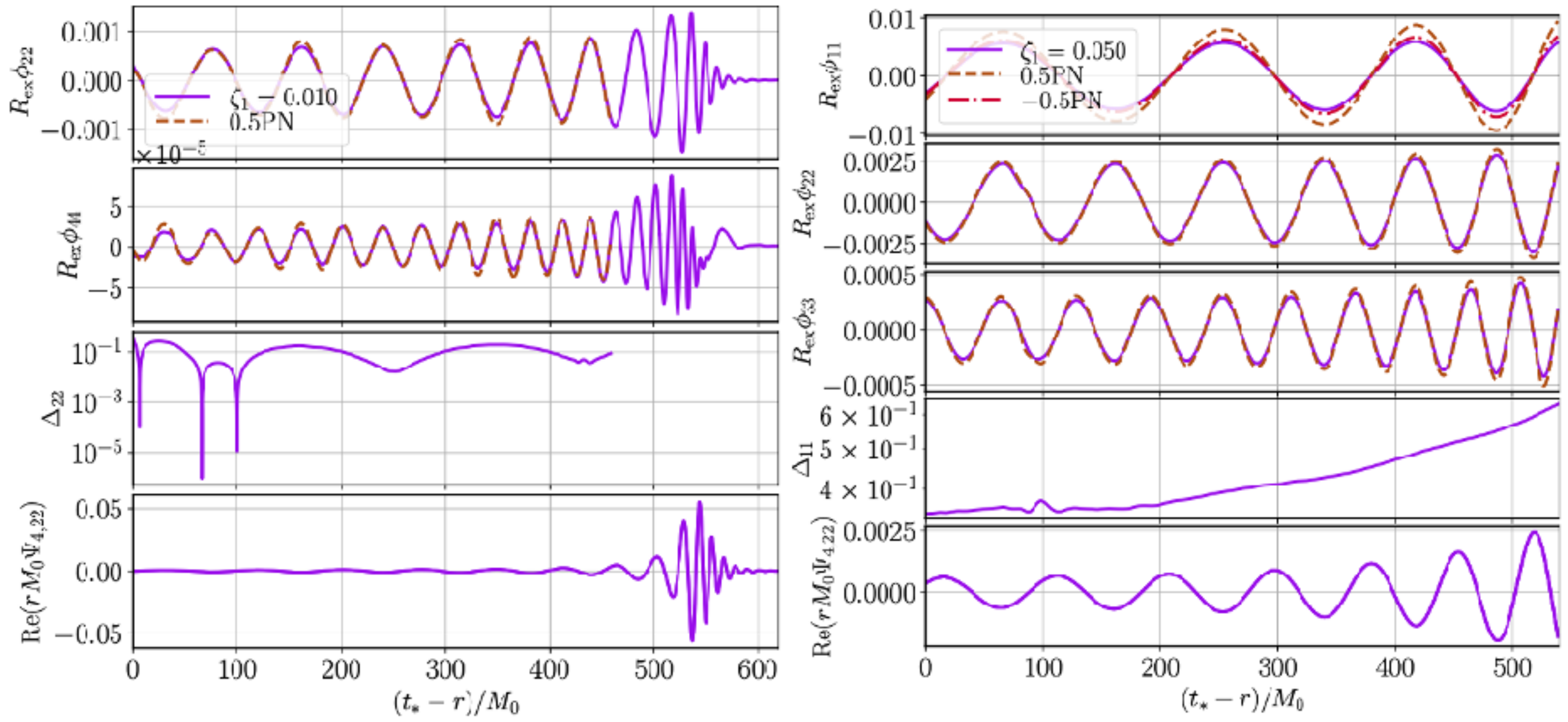
WE East, JL Ripley 2021
Phys.Rev.D 103 (2021) 4, 0440404
Phys.Rev.Lett. 127 (2021) 10, 101102

A Hegade et. al. 2023
Phys.Rev.D 107 (2023) 4, 044044



Well posed evolutions

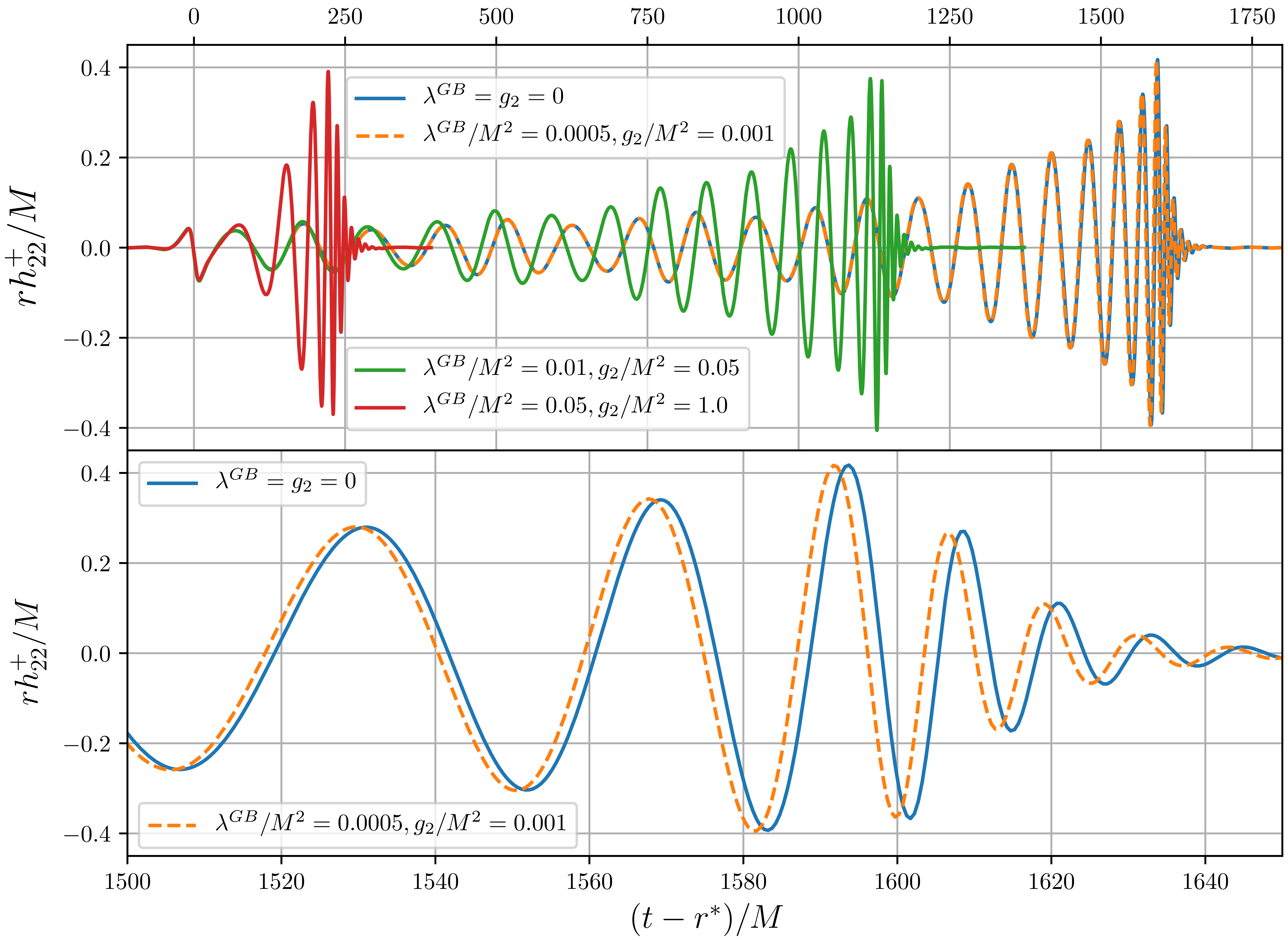
PN approximations insufficient



(a) $q = 1$ (b) $q = 2/3$

M Corman et. al. 2023
Phys.Rev.D 107 (2023) 2, 2

Similar studies without explicit excision



Llibert Areste Salo

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Pau Figueras

Queen Mary University of London

L Areste Salo, KC, P Figueras
PRL 129 (2022) 26, 261104

Revisiting stealth scalarisation with backreaction

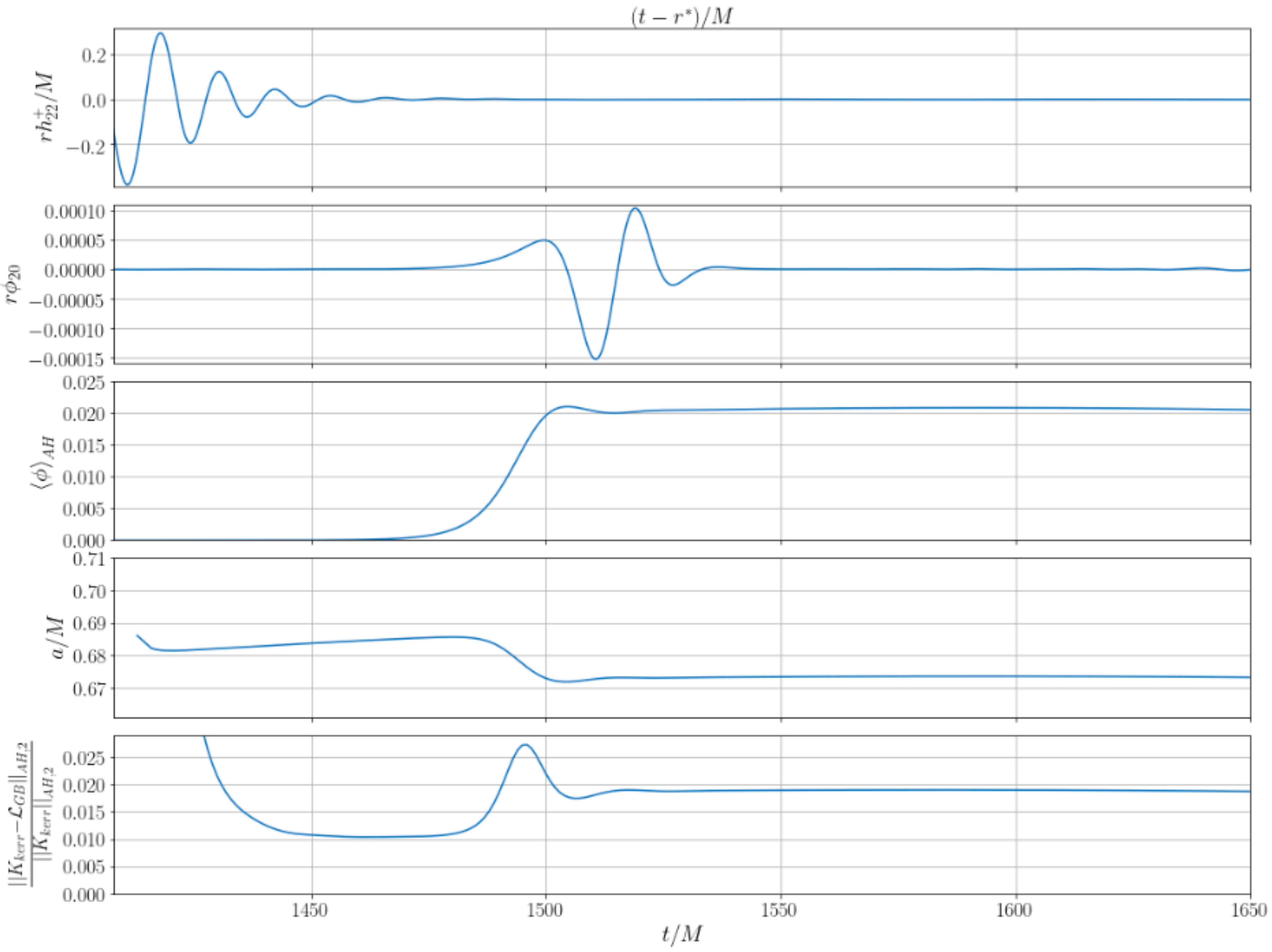
Tensor GW

Scalar GW

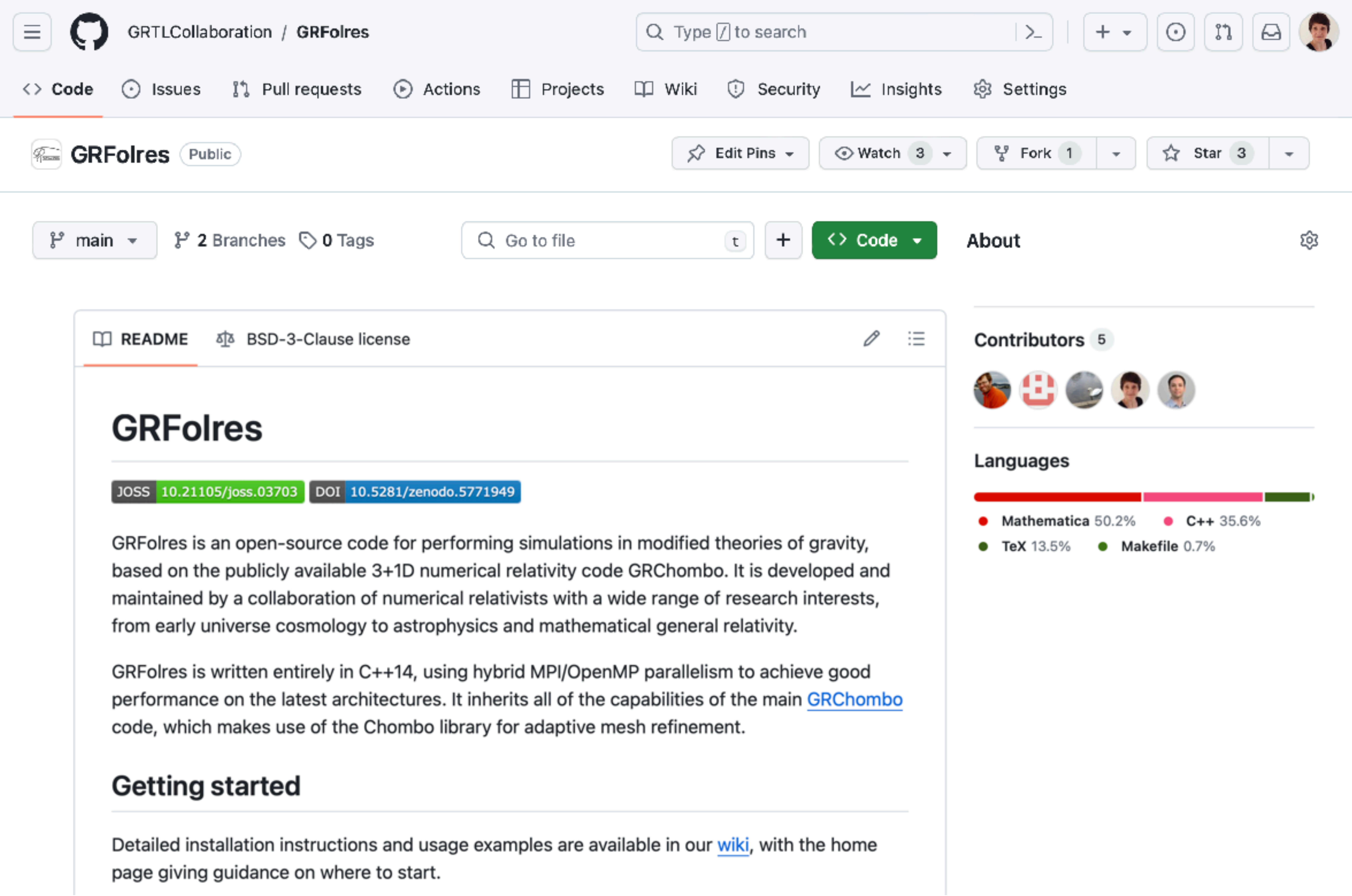
Scalar field at horizon

BH spin

Deviation in Kretschmann scalar



Evolution code publicly available: GRFolres

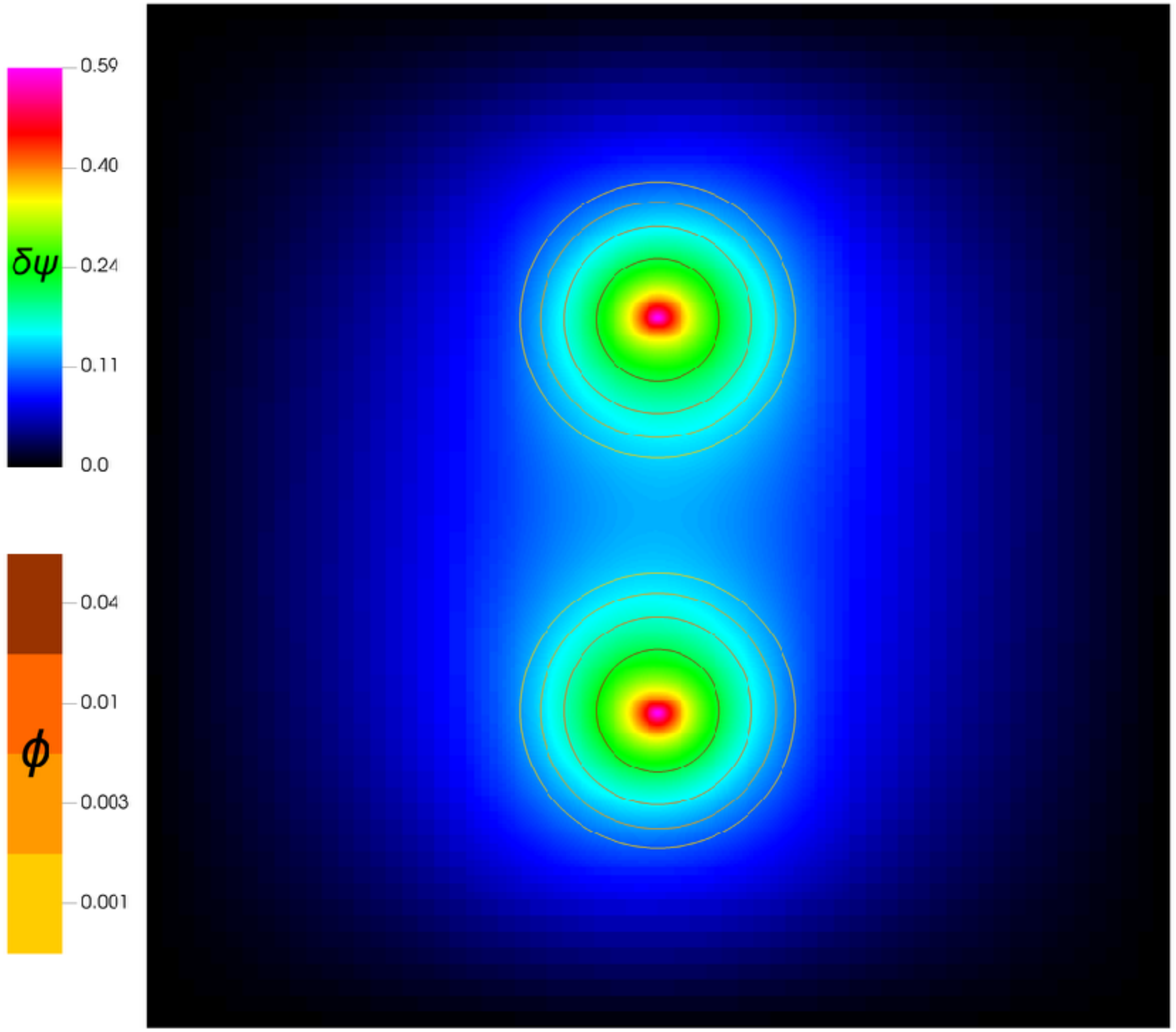


Llibert Areste Salo
Queen Mary University of London

Generic initial conditions : code coming soon

Change in metric solution

Scalar field profile



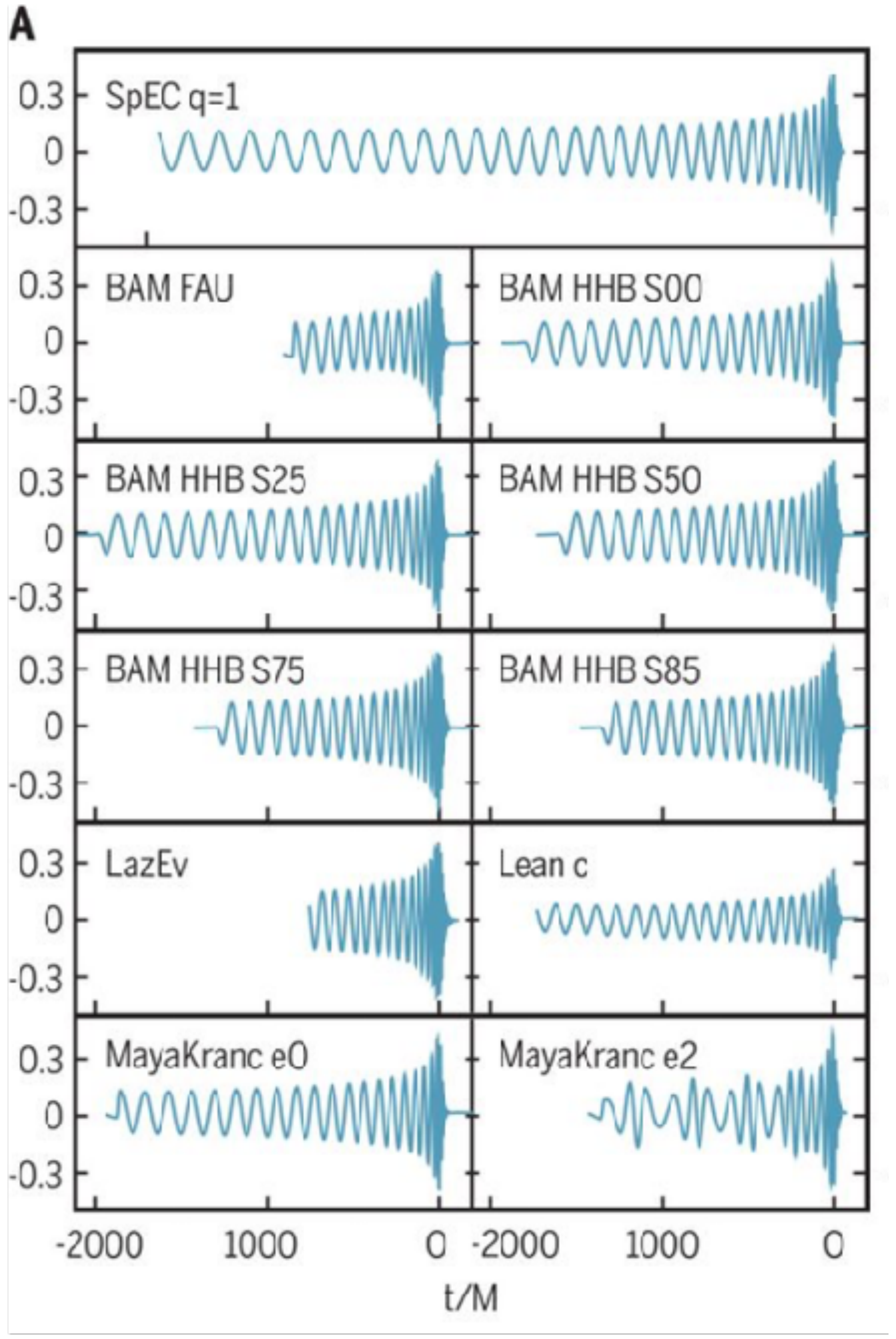
Sam Brady

Queen Mary University of London

S. Brady, L Areste Salo, KC, P Figueras, Annamalai P.S. Phys.Rev.D 108 (2023) 10, 104022

Next steps

- Test the robustness of LIGO “beyond GR” pipelines to several “best case” models
- Compare to DM waveforms
- Study the impact of spin and unequal masses



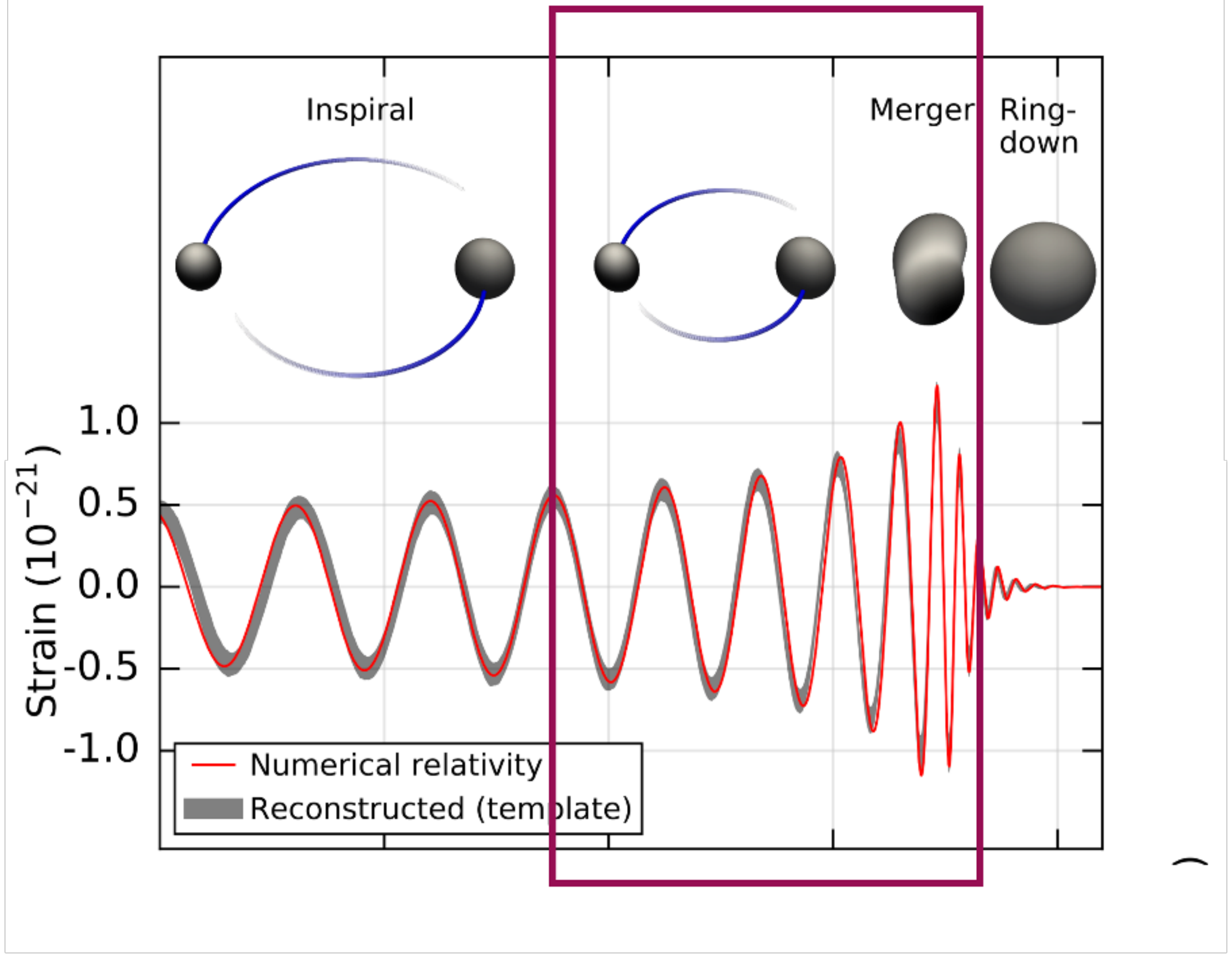
Can we probe the fundamental nature of dark matter?

Can we distinguish matter from modifications to GR?

Numerical relativity beyond GR + SM
- how far can we go?

Numerical relativity

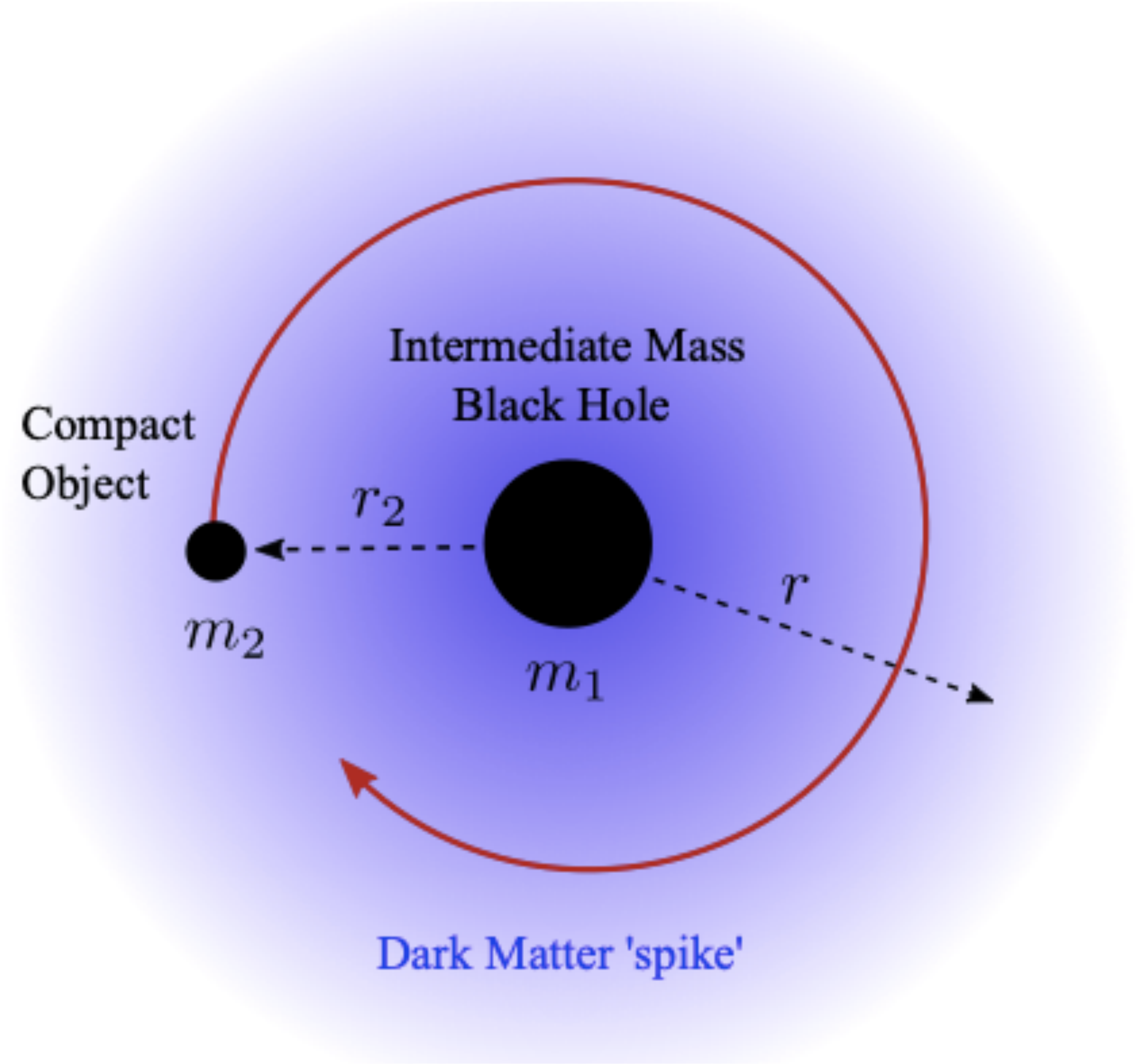
LIGO Collaboration 2016
Phys. Rev. Lett. 116, 061102 (2016)



Works well for the late inspiral / merger of approximately equal mass objects

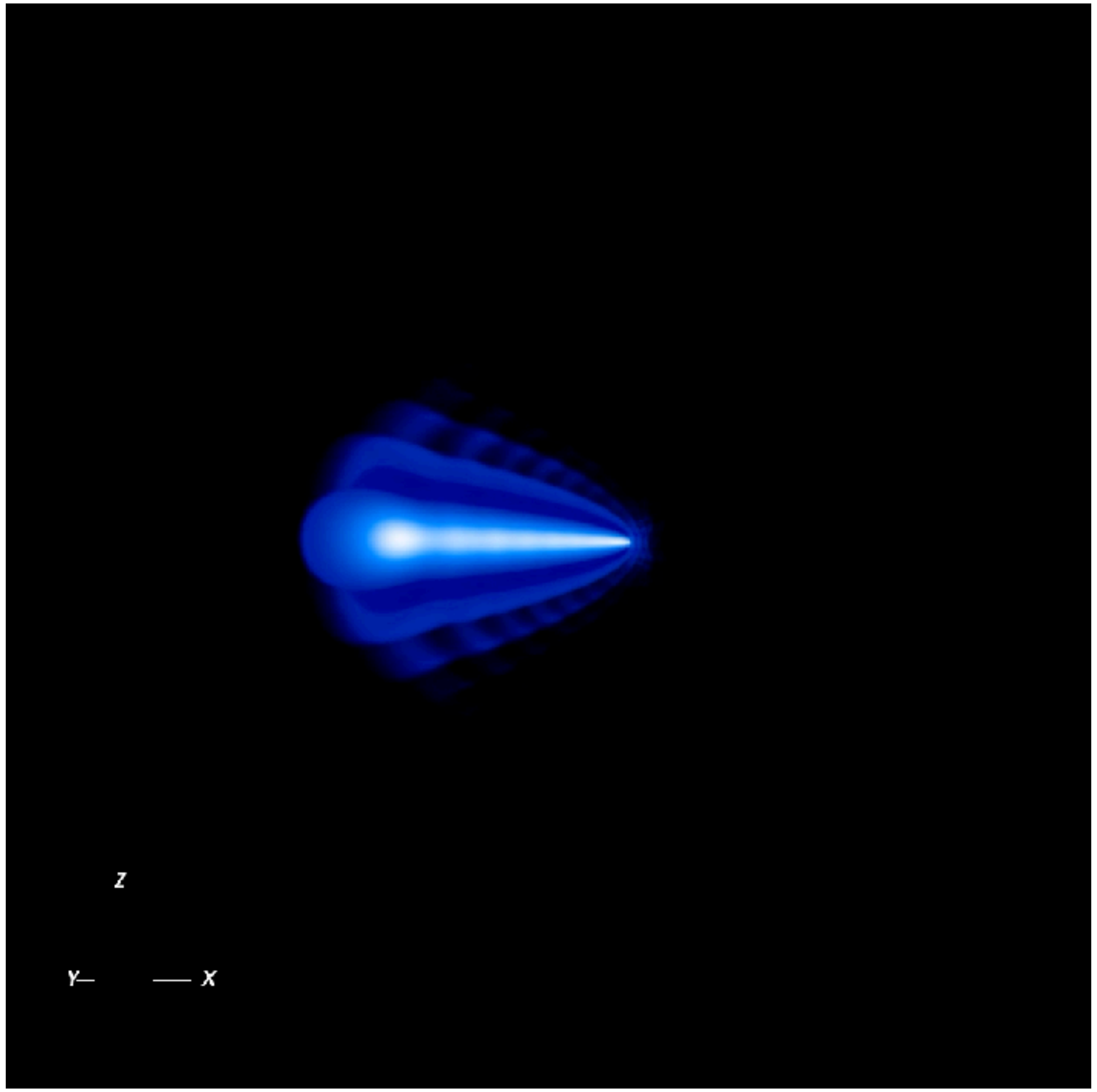
Numerical relativity

Does not work well for long inspirals where length/time scales very different



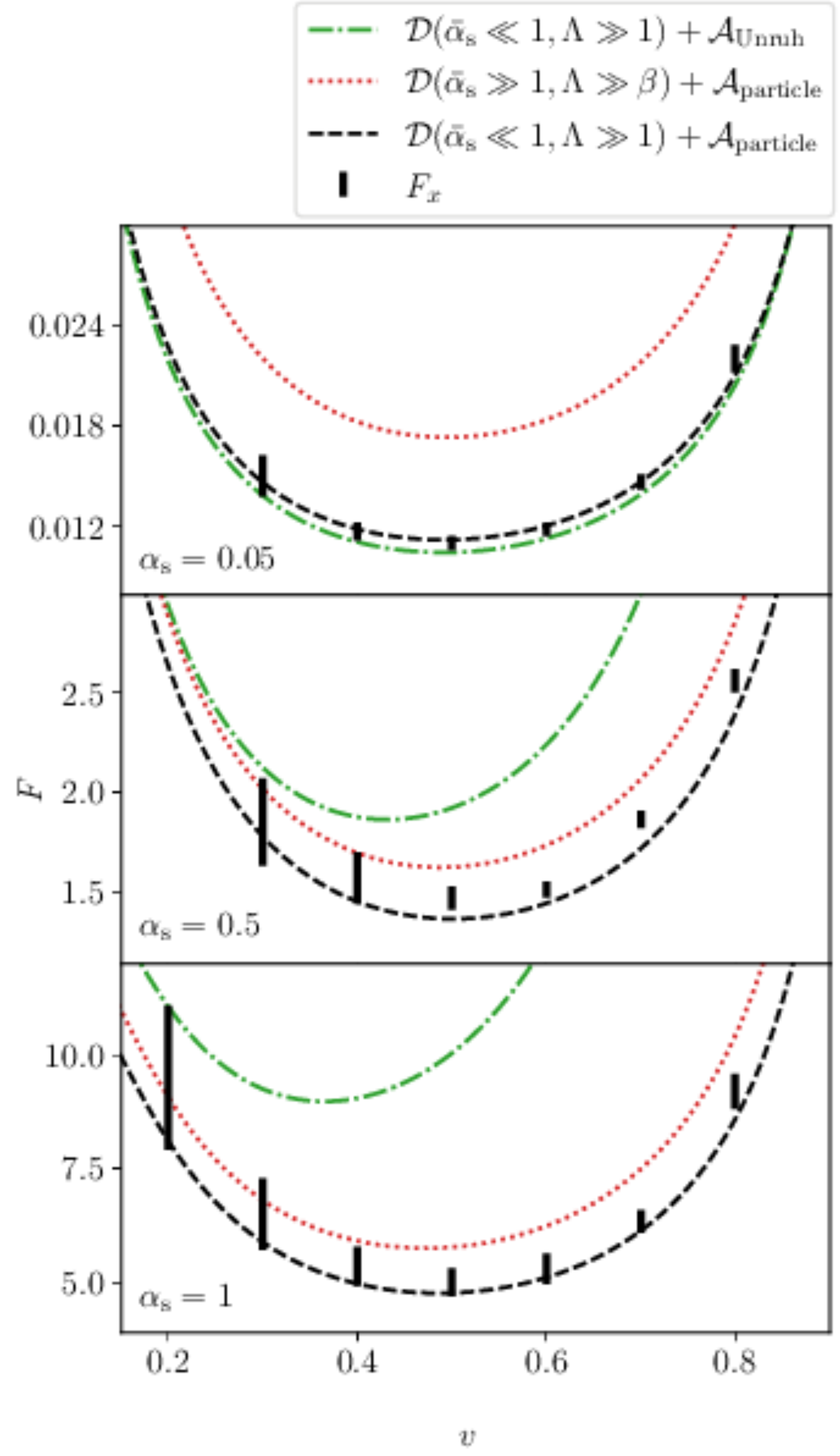
Kavanagh et. al. 2020, Coogan et. al. 2022
Detecting dark matter around black holes with gravitational waves:
Effects of dark-matter dynamics on the gravitational waveform

But relativistic / strong gravity effects may be important here



D Traykova, R Vicente, KC et. al. 2021, 2023
Phys.Rev.D 104 (2021) 10, 103014, arXiv [gr-qc] 2305.10492

Dynamical friction and gravitational Magnus effect - combining numerics and analytics



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D Traykova, R Vicente, KC et. al. 2021, 2023

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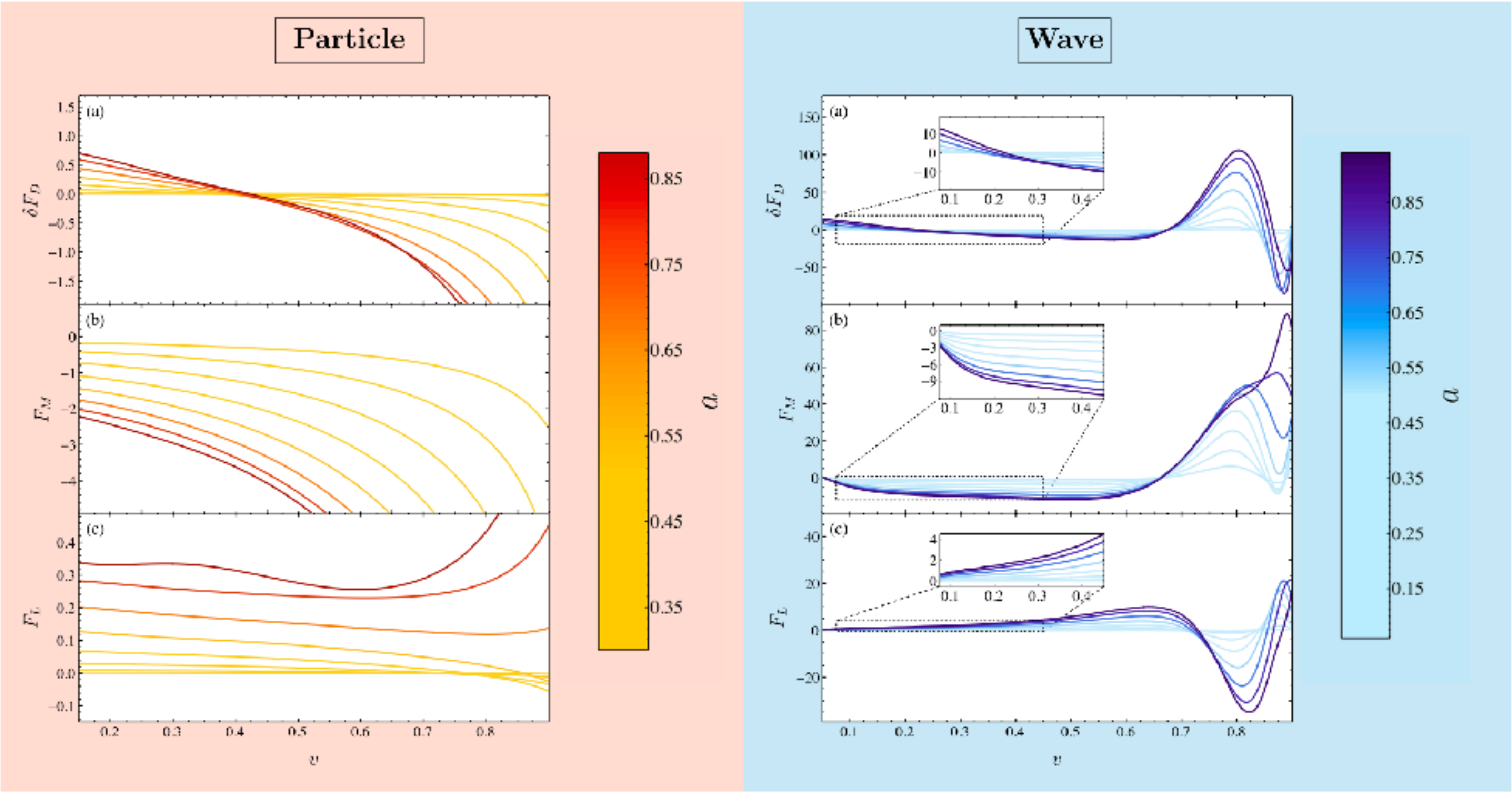
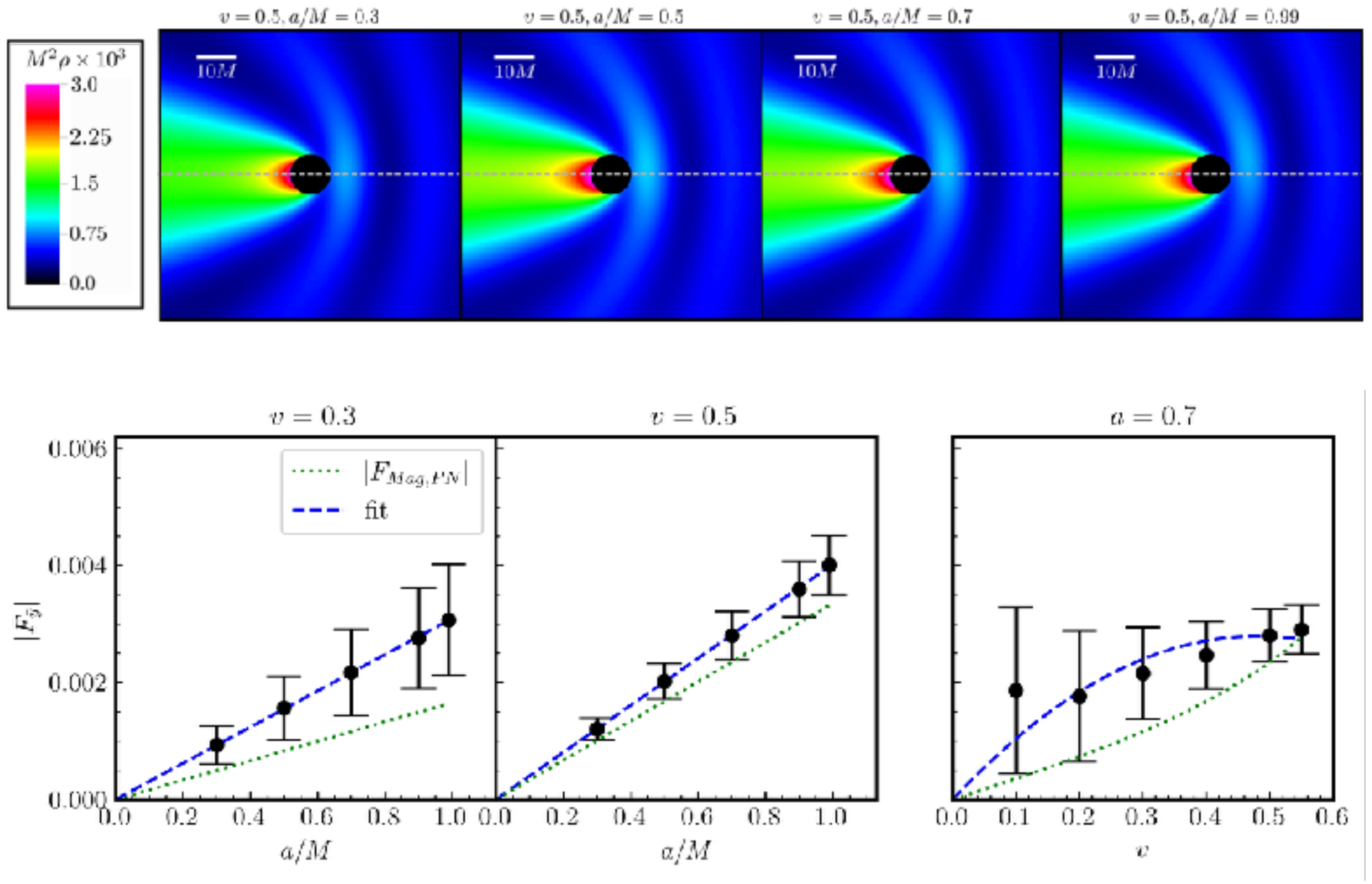


Relativistic aerodynamics of spinning black holes

Conor Dyson,[1,*] Jaime Redondo-Yuste,[1,†] Maarten van de Meent,[1,2] and Vitor Cardoso[1,3,4]

To appear (tomorrow!)



Gravitational Magnus effect from scalar dark matter

Zipeng Wang,[1] Thomas Helfer,[2] Dina Traykova,[3] Katy Clough,[4] and Emanuele Berti[1]

To appear (tomorrow!)

Summary

Can we probe the fundamental nature of dark matter?

Possible in principle to probe wave or particle nature, some reasons to be optimistic for LISA data

Can we distinguish matter / modifications to GR / waveform systematics?

Now in a position to answer this for specific models, which should be informative for LIGO modelling

Numerical relativity beyond GR + SM - how far can we go?

Probably not far enough on our own, but can usefully combine analytic and numerical studies