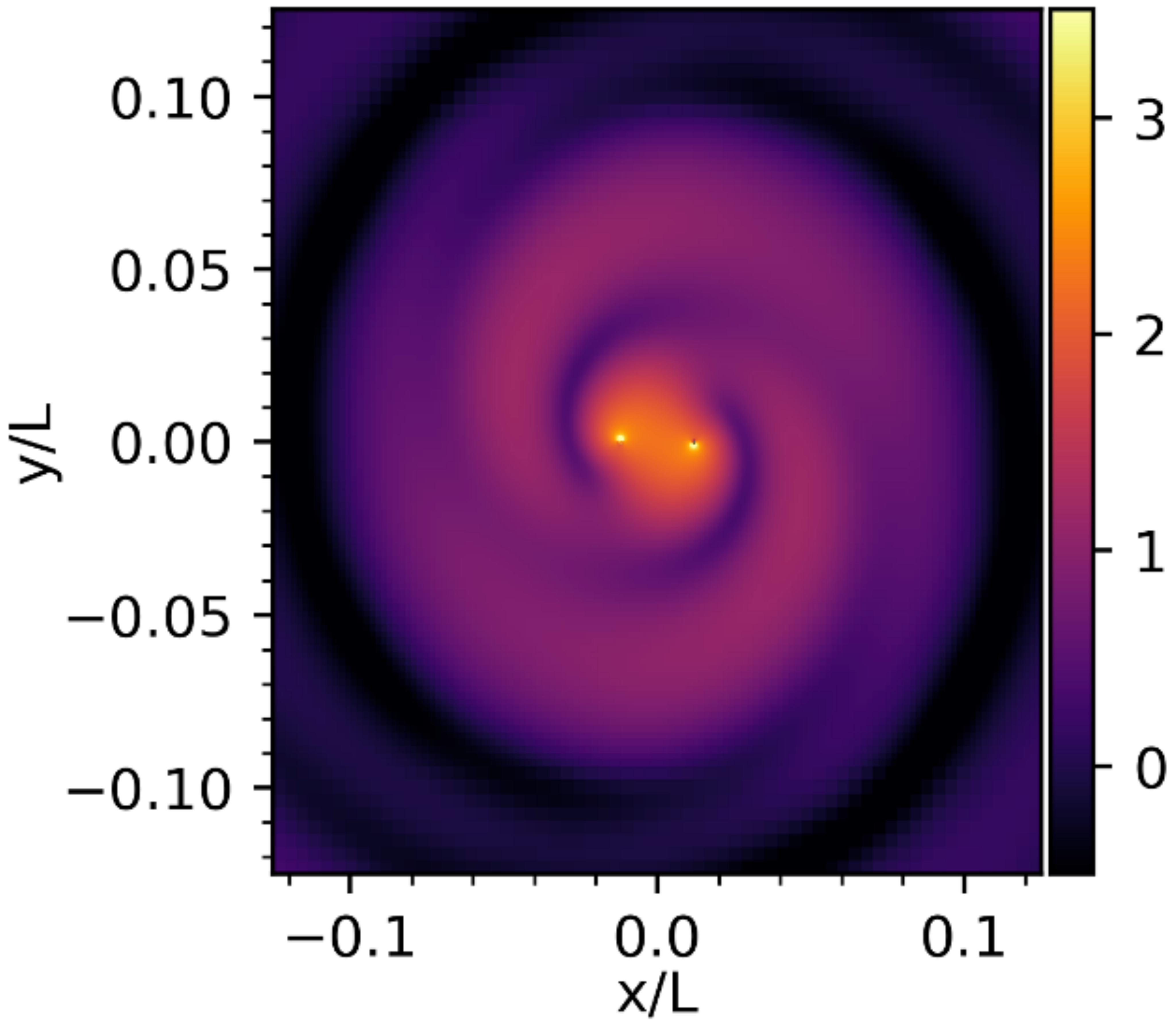
New fundamental fields in strong gravity

Katy Clough, Queen Mary University of London

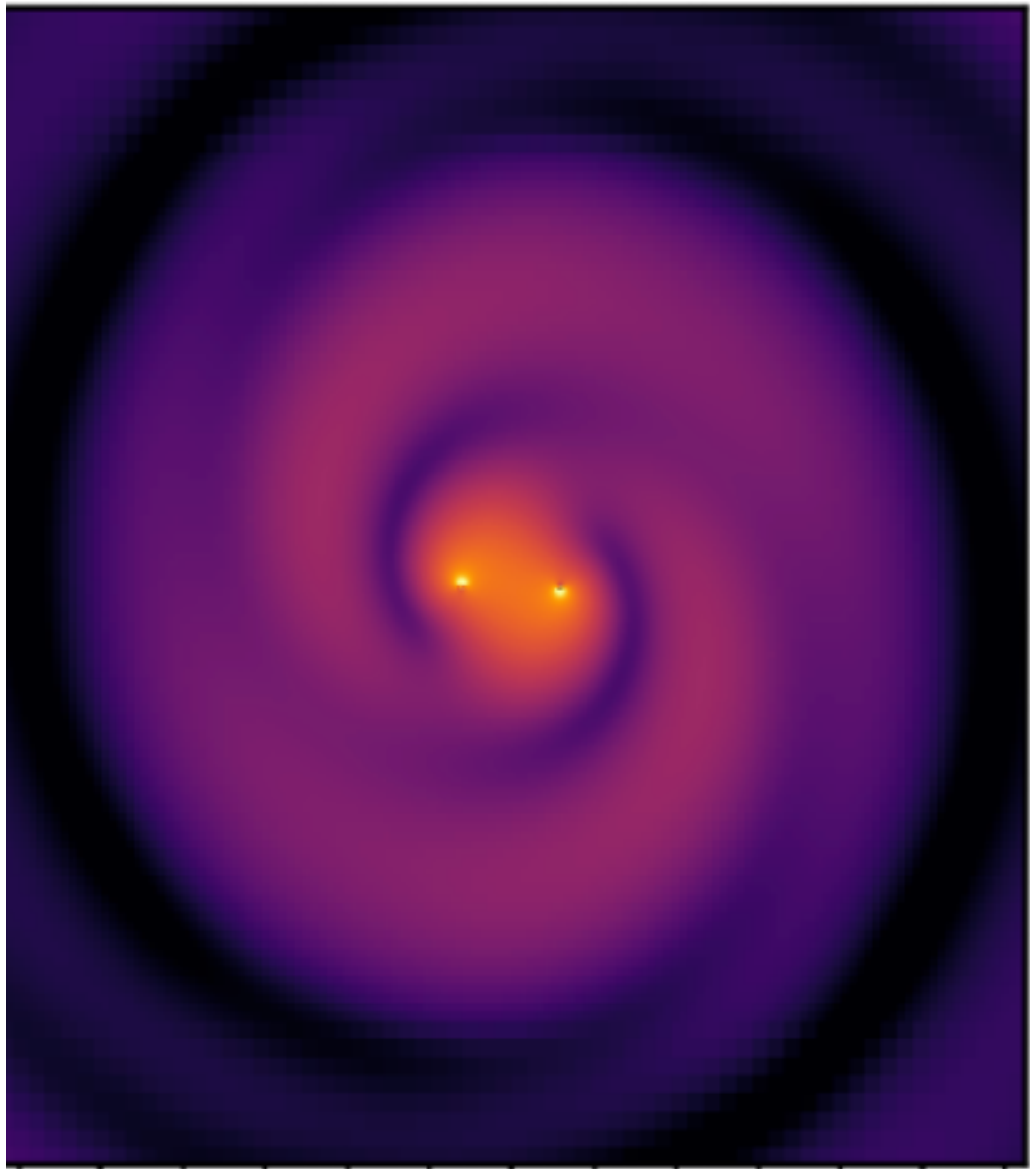


Fields can be:

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

2. An additional gravitational degree of freedom (in an EFT of modified gravity)

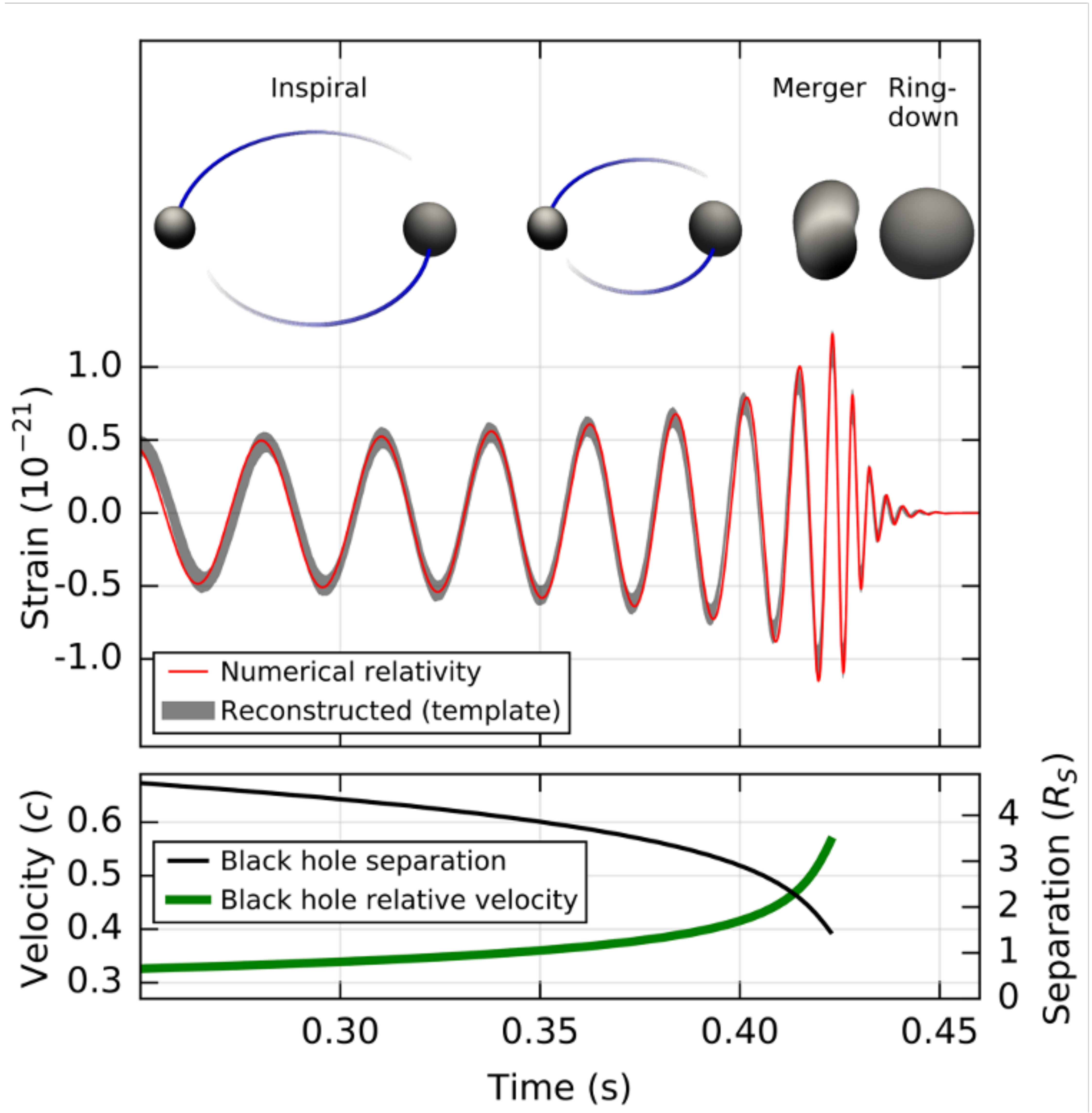
J Bamber, KC et. al 2023
Phys.Rev.D 107 2, 024035



Questions:

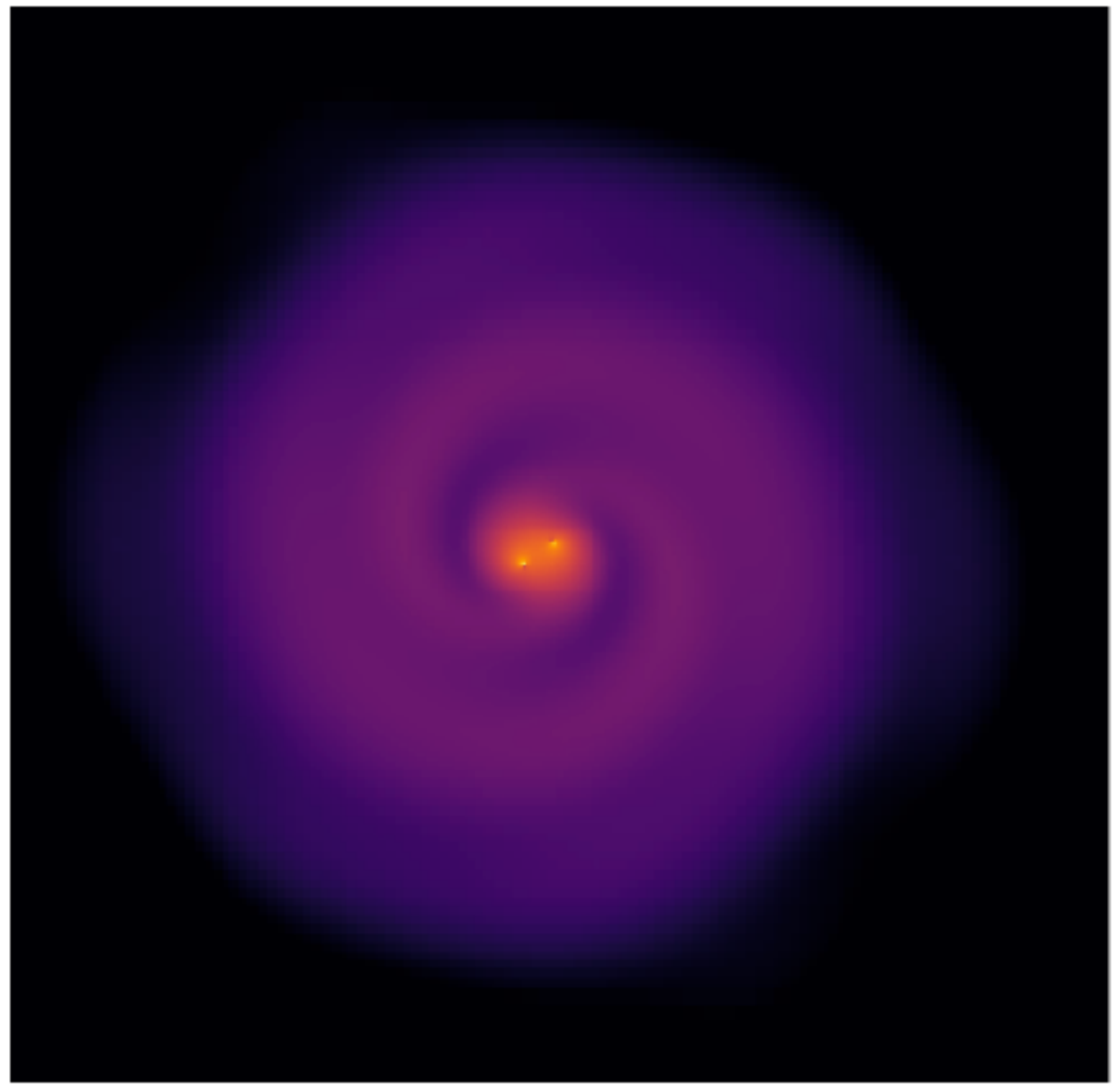
How might these fields affect the merger part of the waveform?

What are the research challenges in each case?



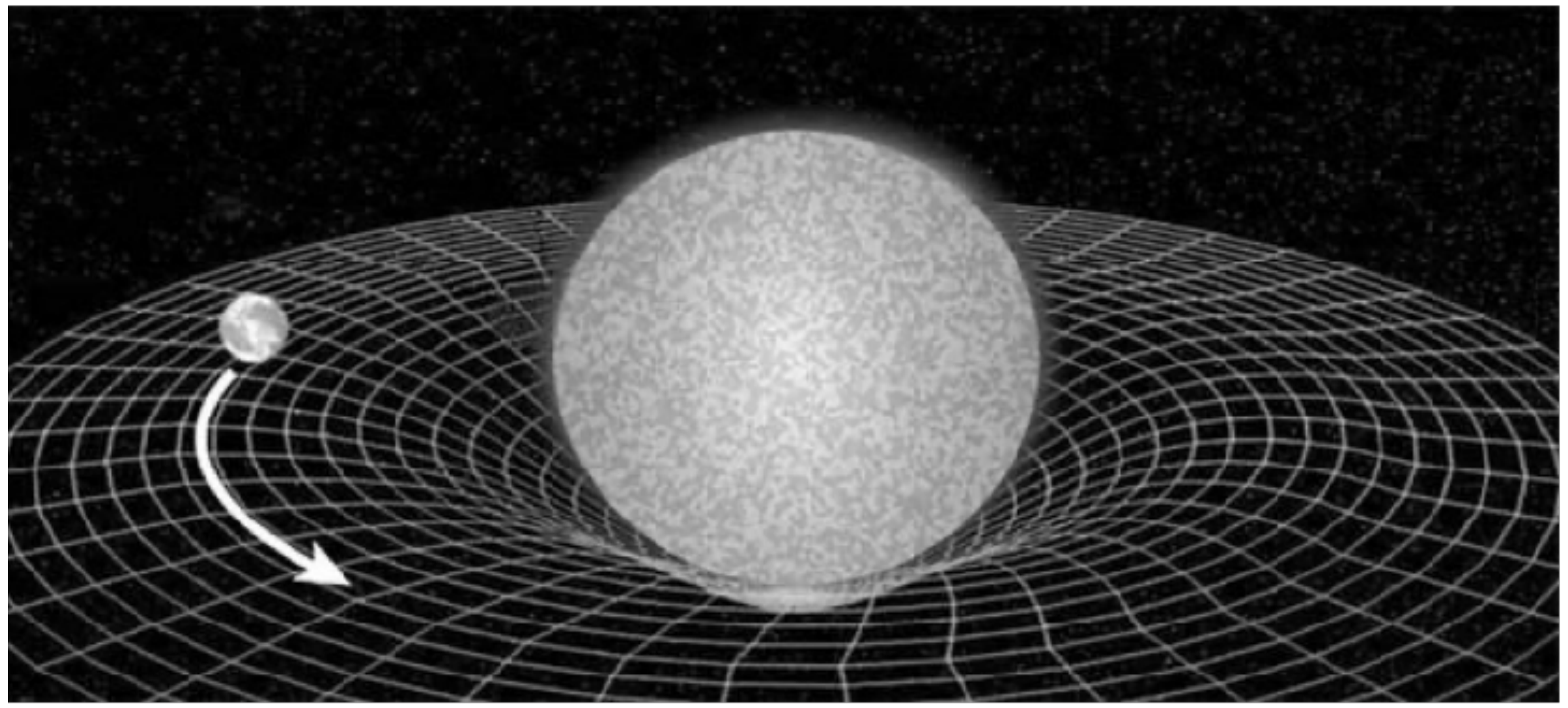
Background

Why would the waveform change due to new field content?



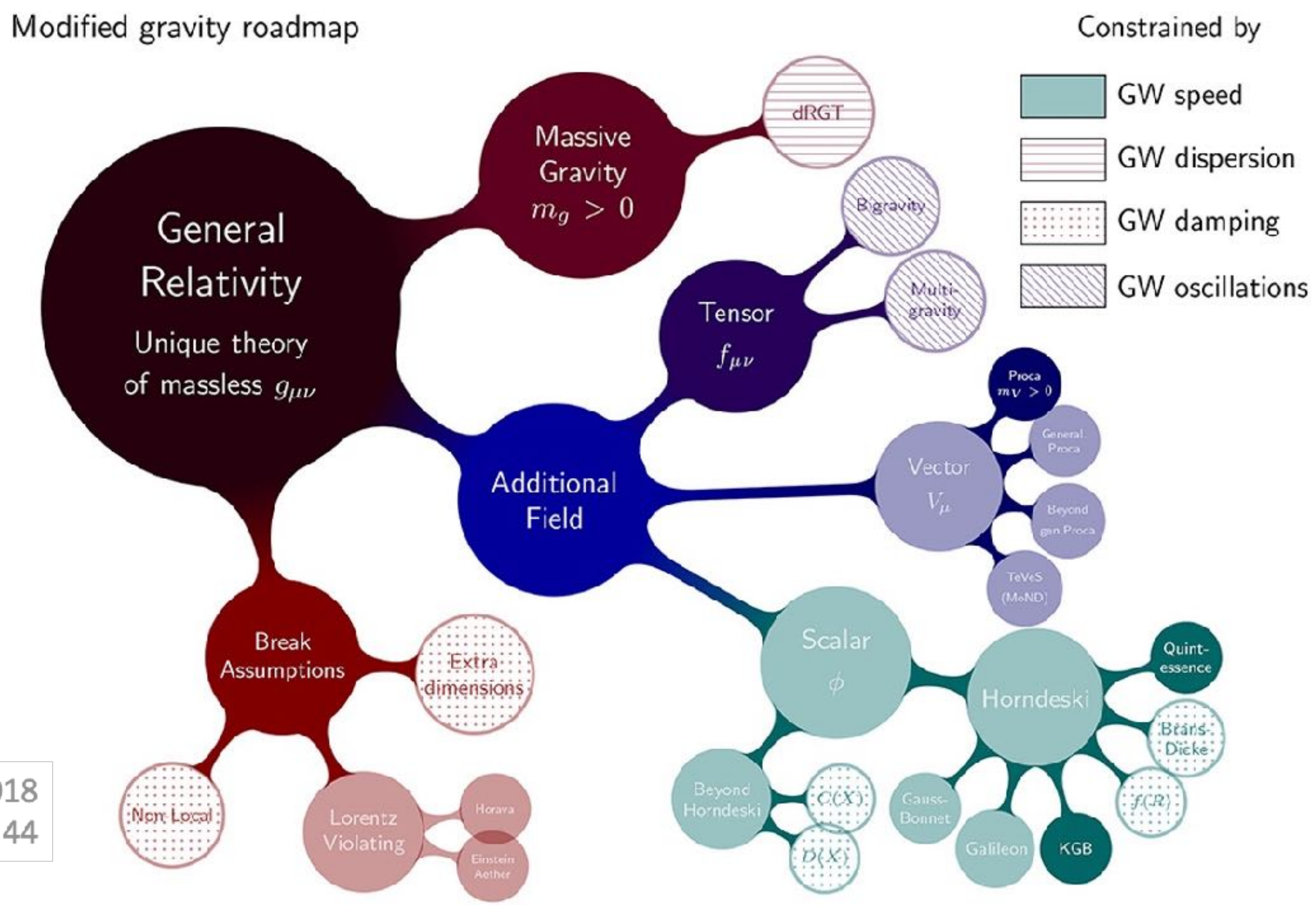
- Radiation/dynamical friction/accretion of the field

- Change in background curvature



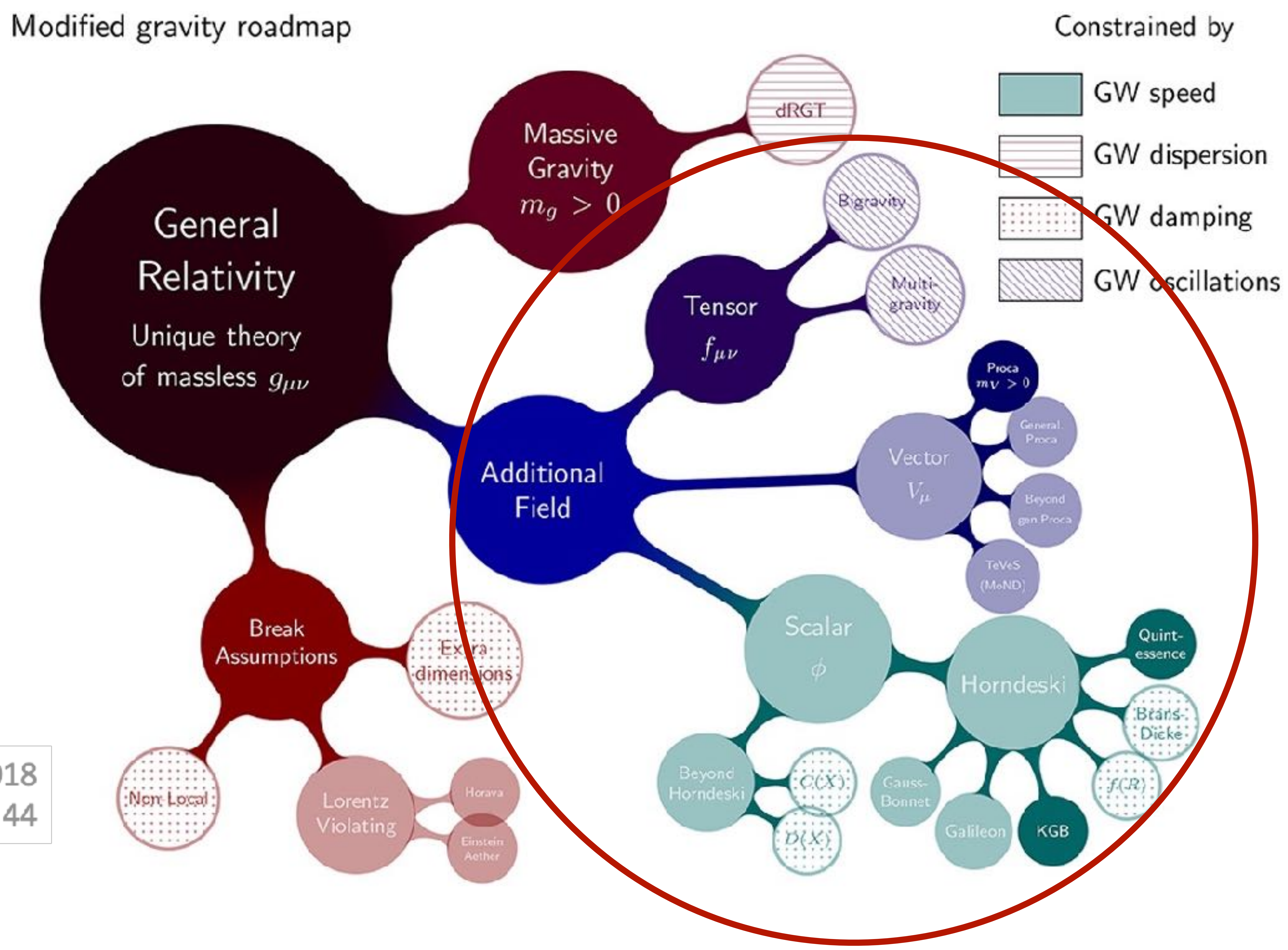
- Higher order curvature effects (in MG)

Fields in modified gravity



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

Fields in modified gravity

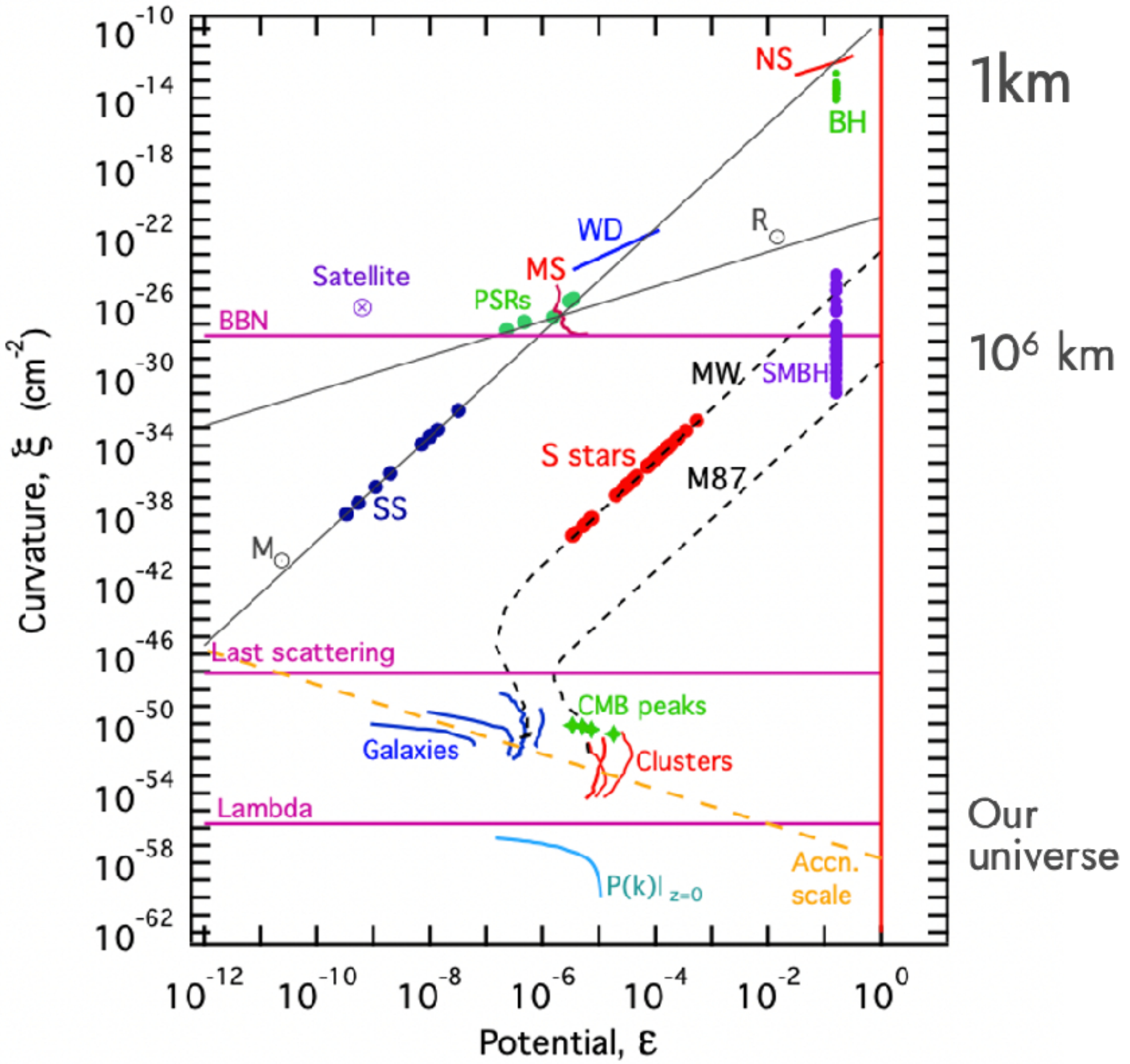


JM Ezquiaga et. al 2018
Front.Astron.Space Sci. 5 44

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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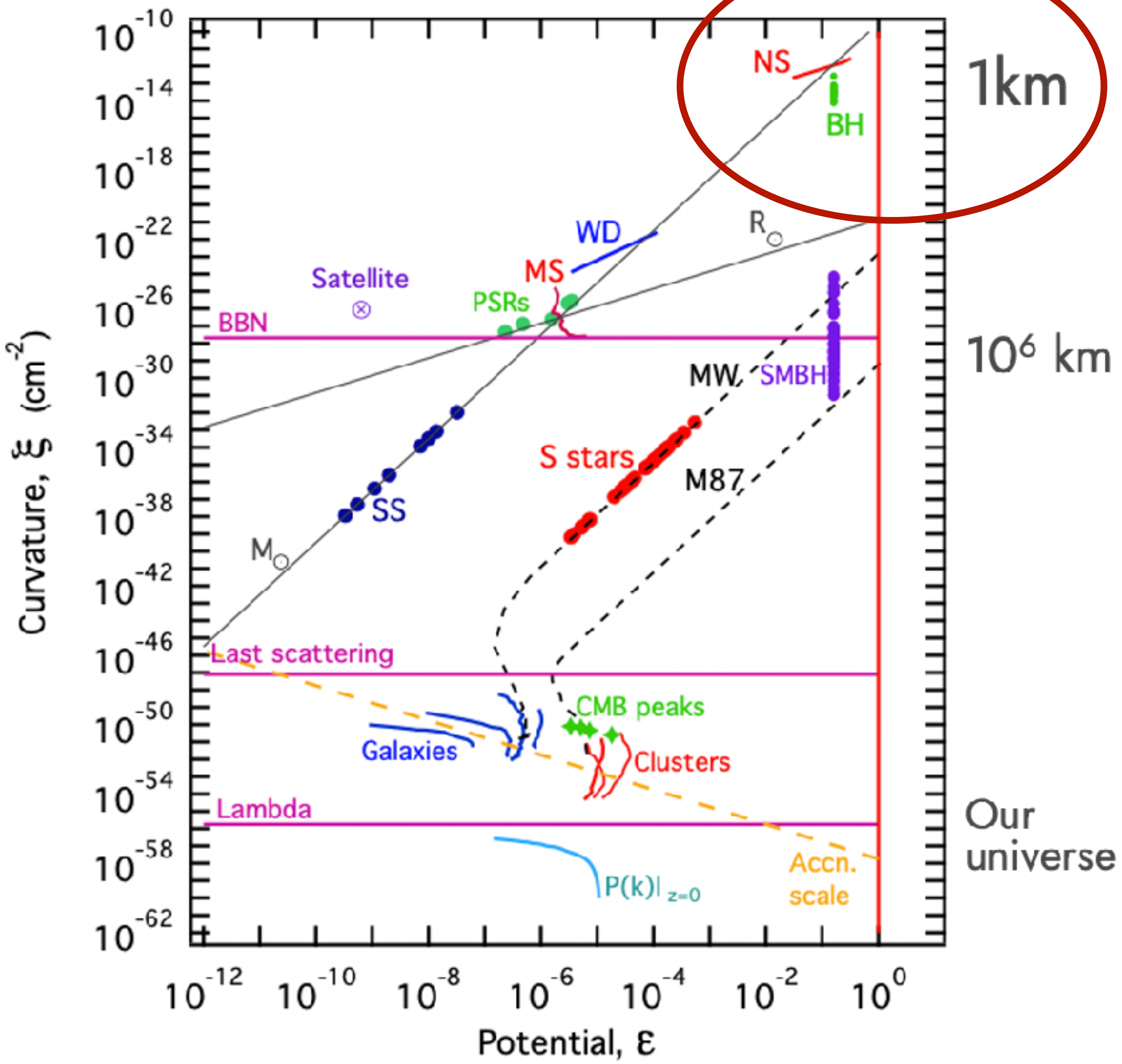
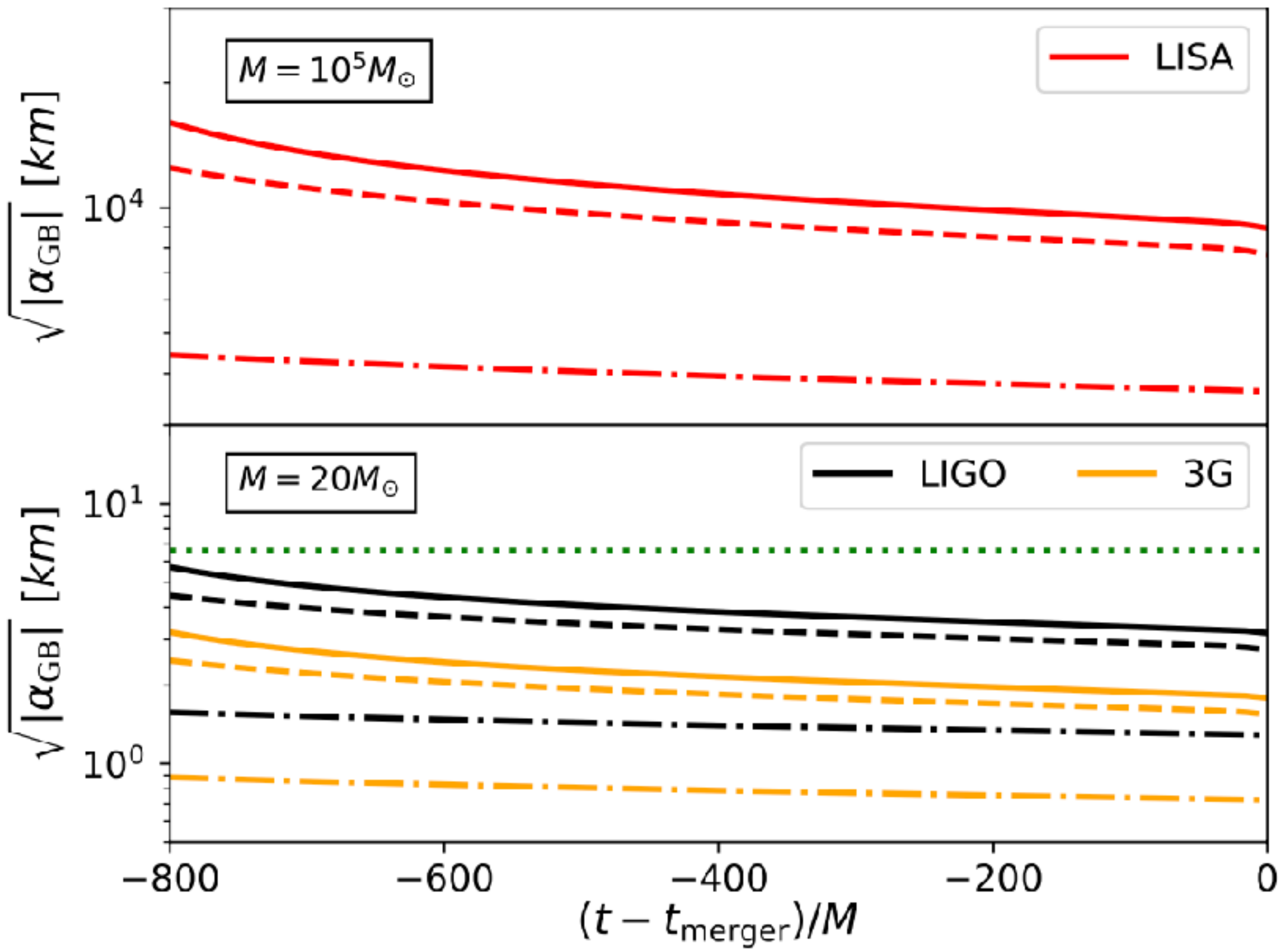


e.g. shift symmetric Einstein scalar Gauss Bonnet

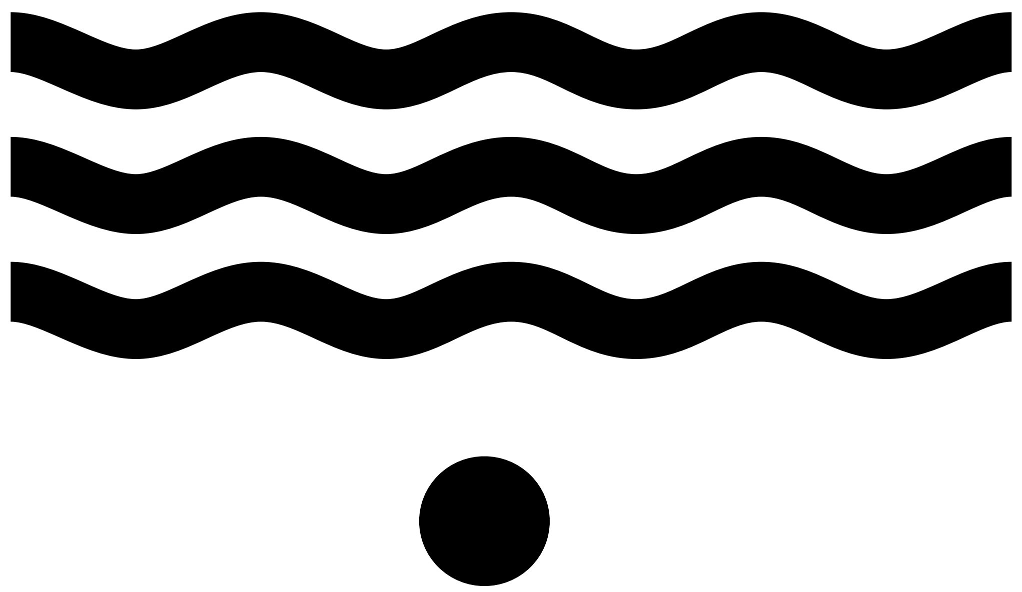
Constraints

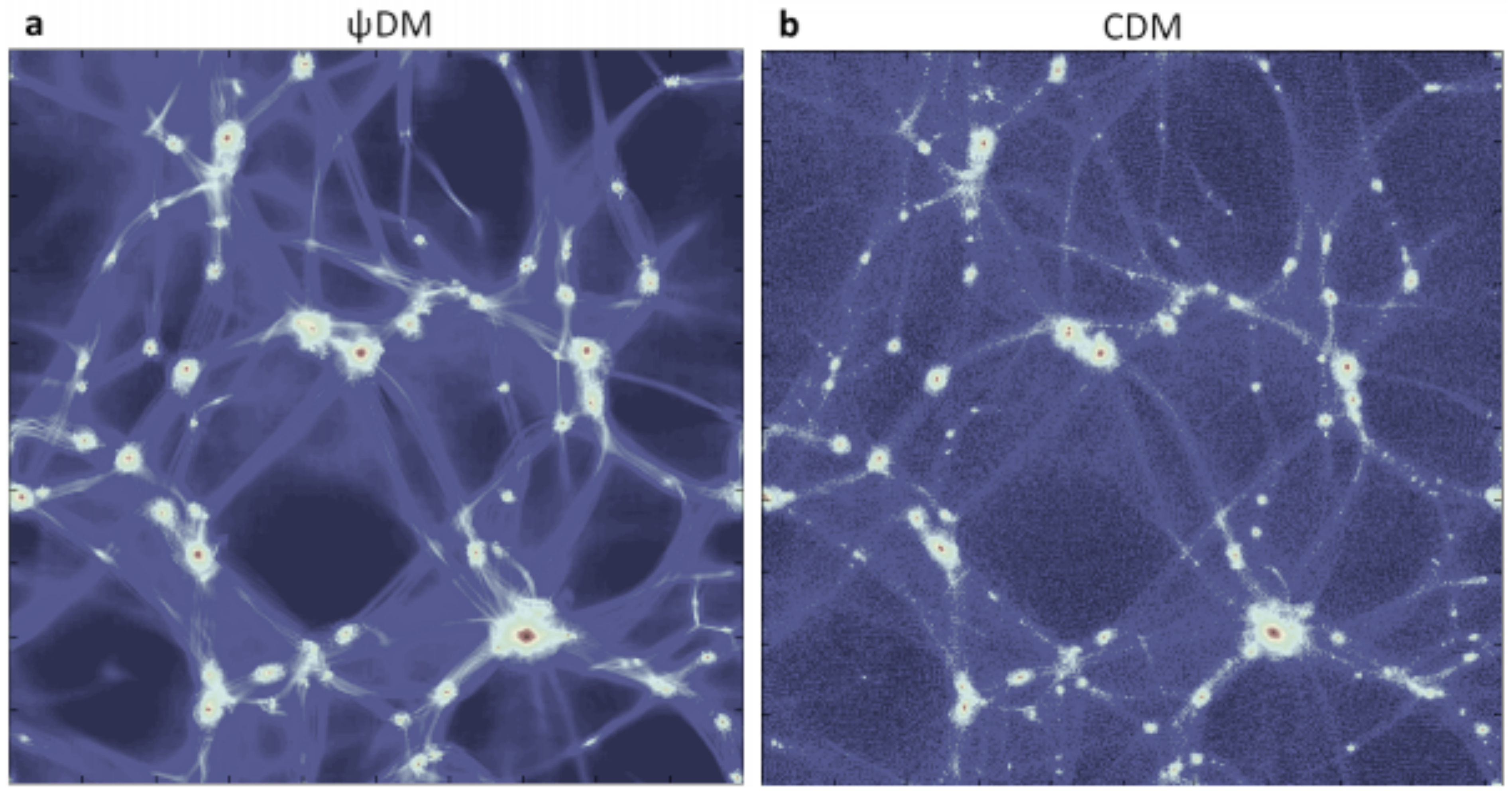
- Depend on coupling with strongest effects for $\sqrt{\alpha_{GB}} \sim R_s$
- Stronger effect for smaller mass BHs

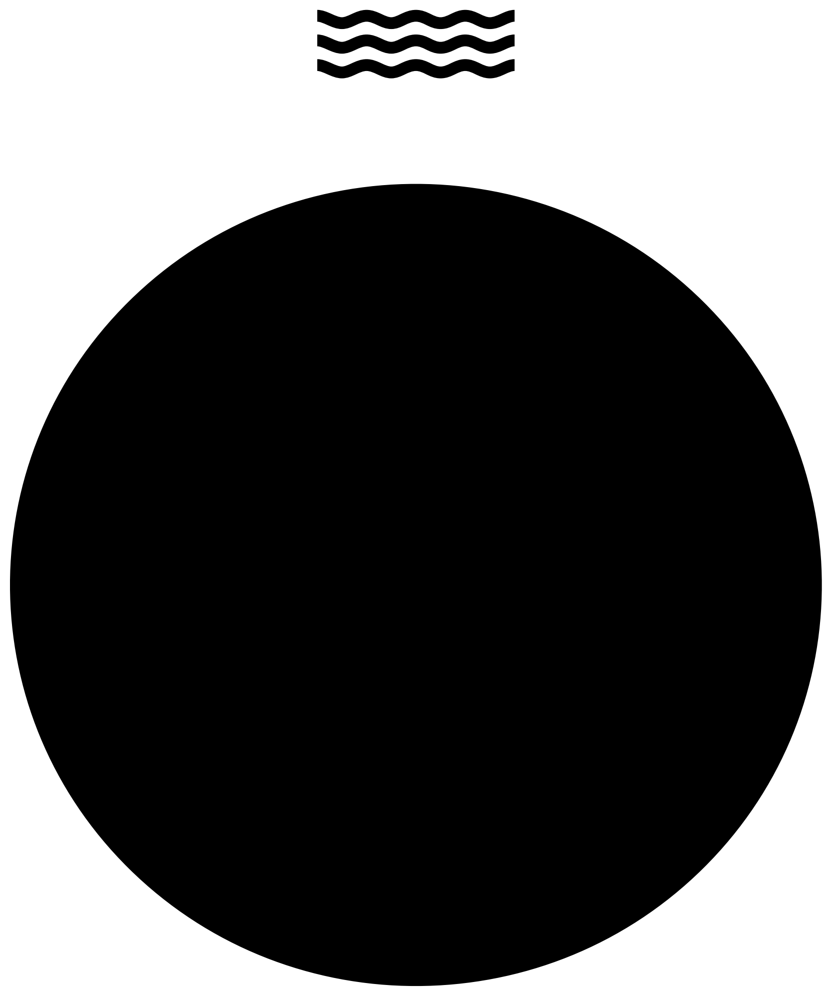
H Witek et al 2019
Phys.Rev.D 99 (2019) 6, 064035



Fields as wave dark matter







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

Would we have seen this already?

Not in standard DM scenarios due to low densities

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

(Particle physicist) (Astrophysicist)

Would we have seen this already?

Not in standard DM scenarios due to low densities

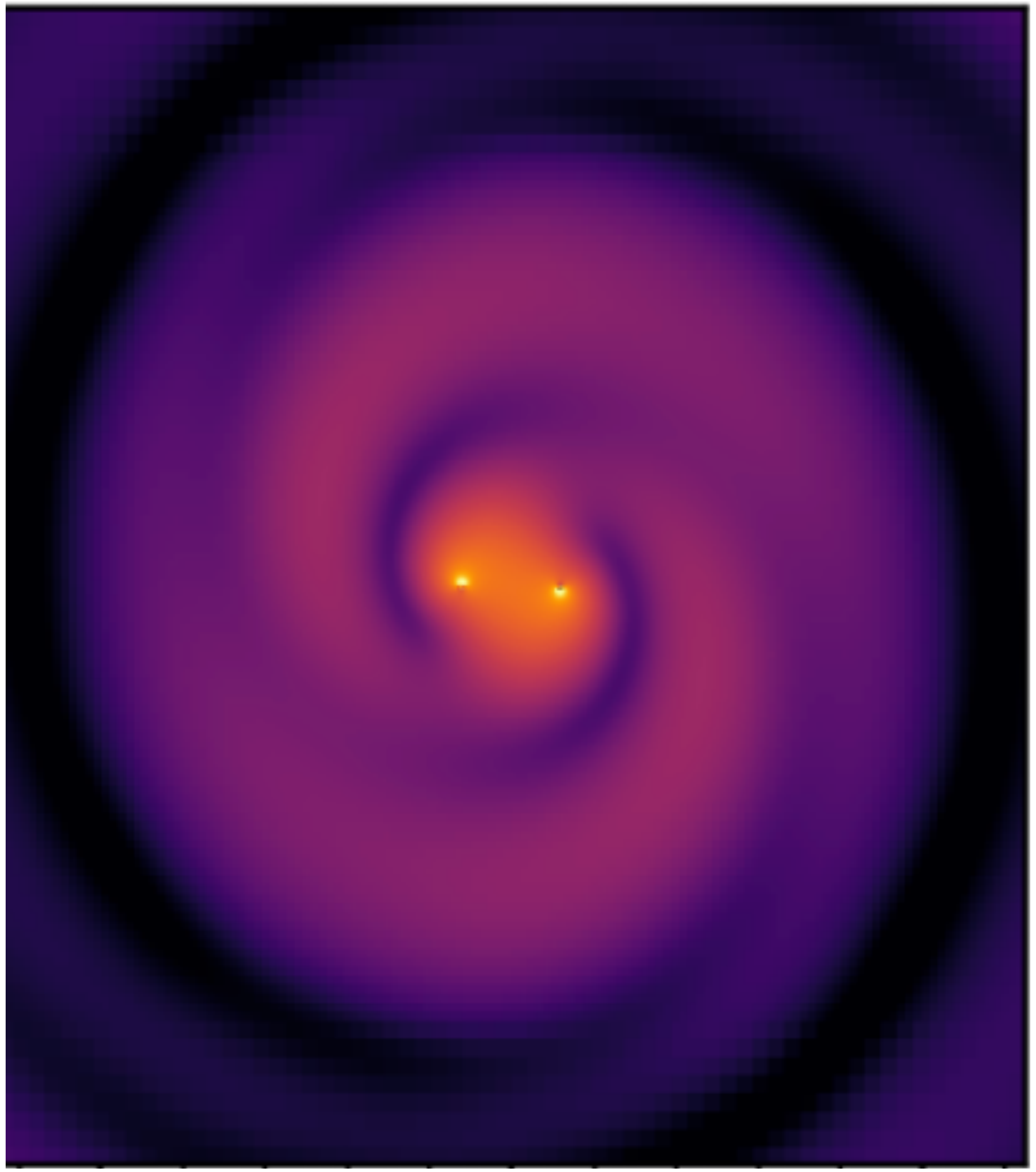
$$\frac{\rho}{1/R_s^2} \sim 10^{-30} \left(\frac{M_{BH}}{10^6 M_\odot} \right)^2$$

(Numerical relativist)

e.g. Wave dark matter accretion onto binaries

Constraints:

- Depend on local dark matter density
- Most strong effect on larger mass BHs

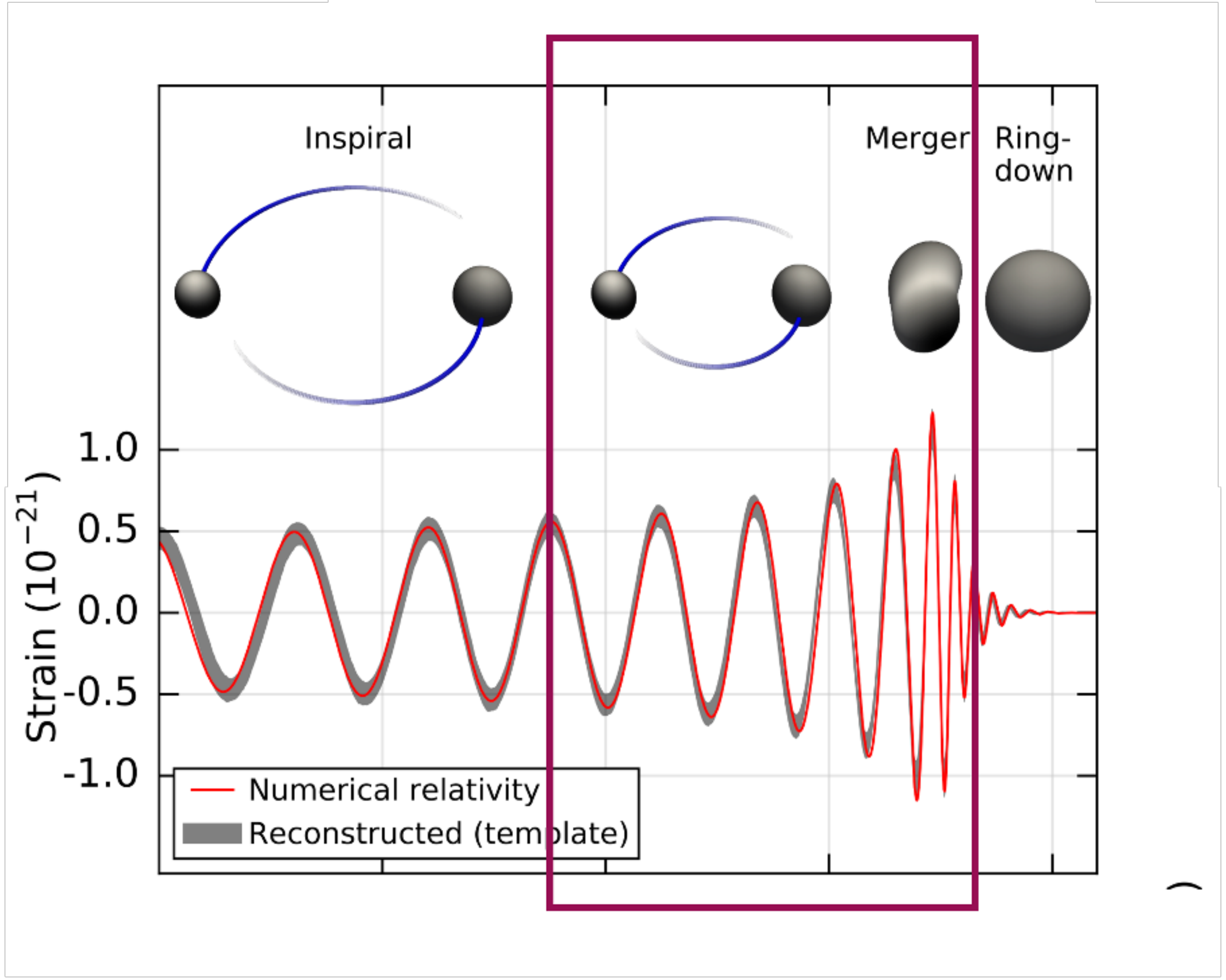


How do we work out how much things change?

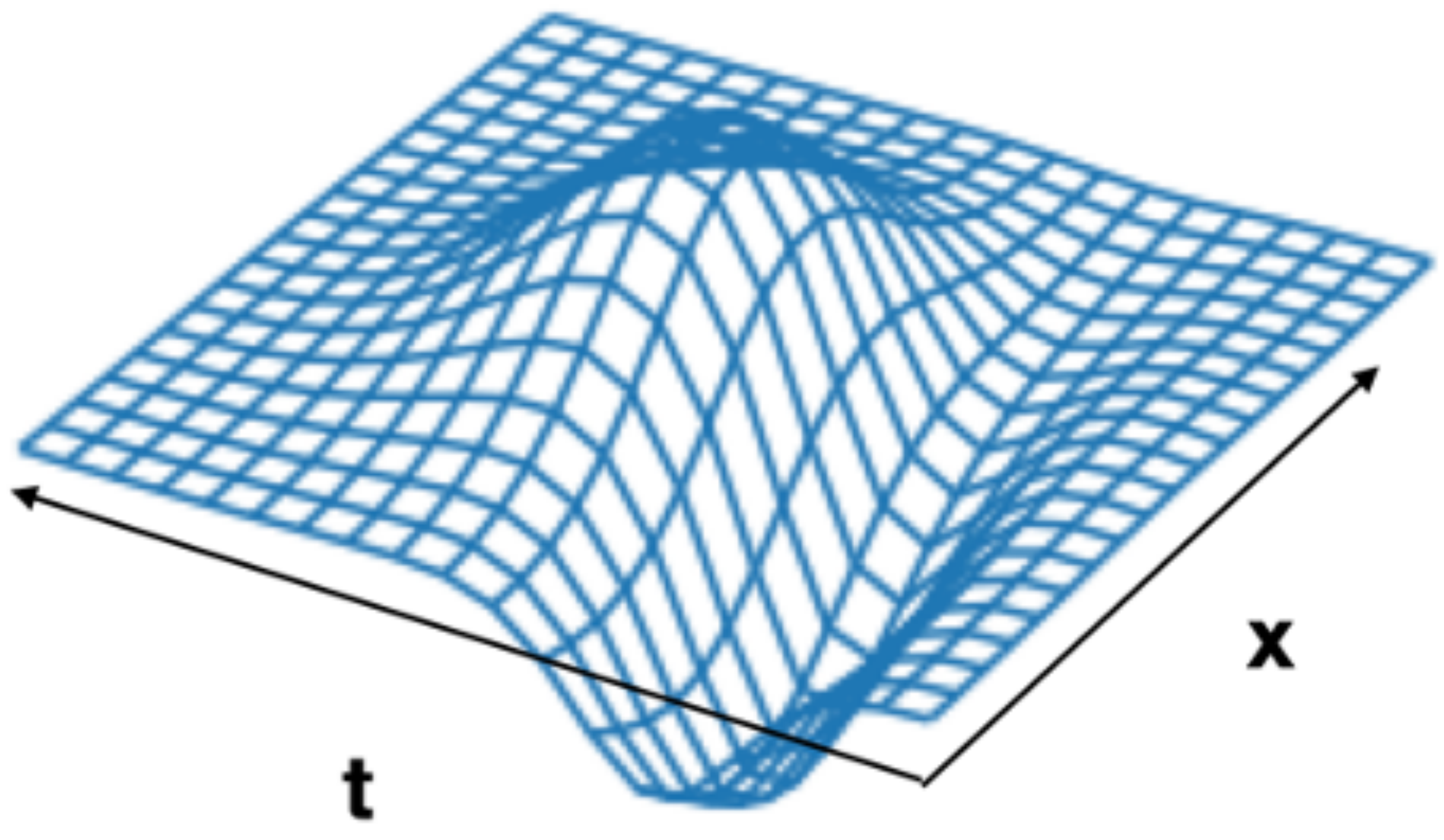
Numerical relativity

(for the late inspiral / merger of approximately equal mass objects)

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



Numerical relativity

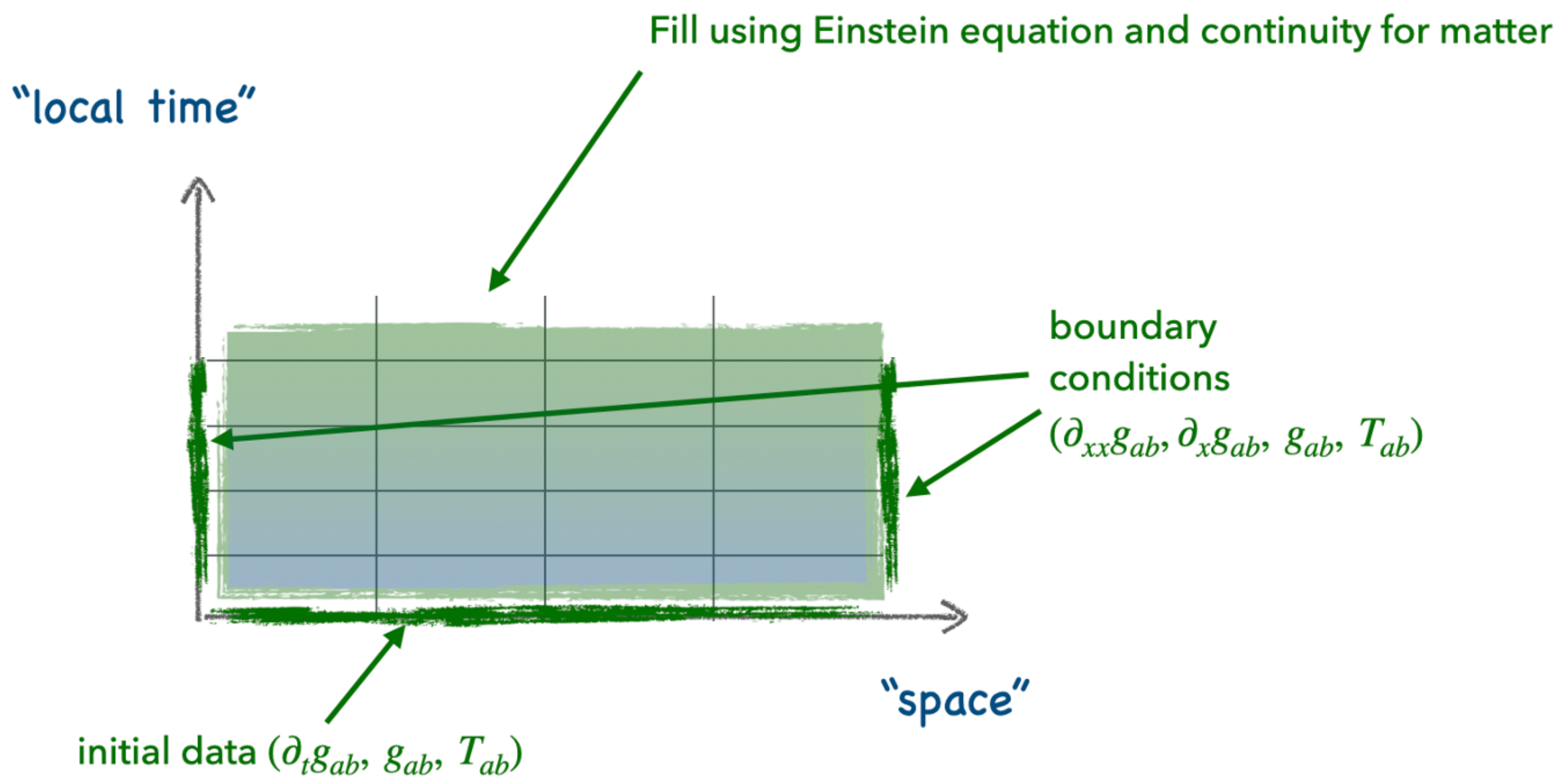


$$ds^2 = \begin{pmatrix} dt & dx & dy & dz \end{pmatrix} \begin{pmatrix} g_{00} & g_{01} & g_{02} & g_{03} \\ g_{10} & g_{11} & g_{12} & g_{13} \\ g_{20} & g_{21} & g_{22} & g_{23} \\ g_{30} & g_{31} & g_{32} & g_{33} \end{pmatrix} \begin{pmatrix} dt \\ dx \\ dy \\ dz \end{pmatrix}$$

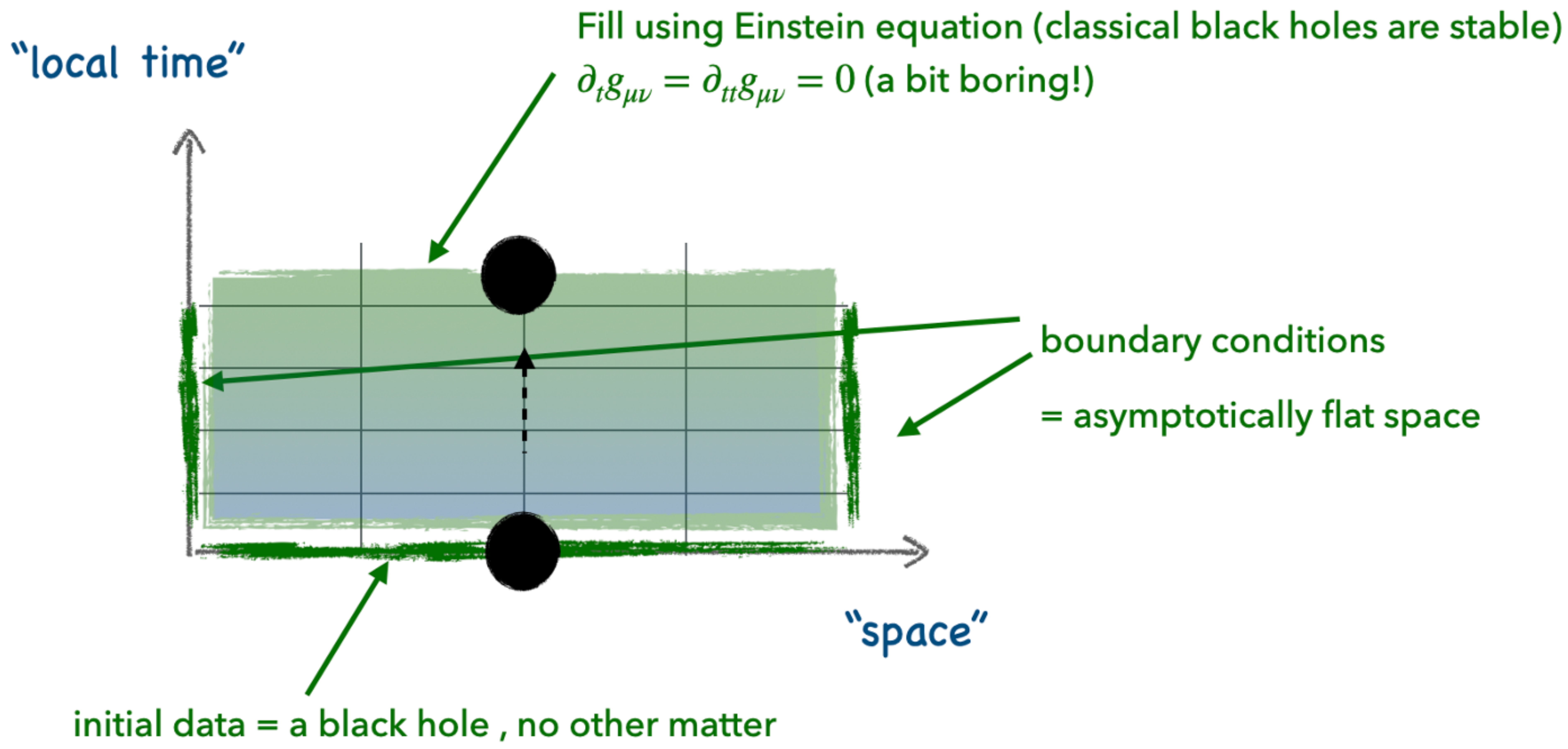
"The spacetime metric"

$$g_{ab}(t, \vec{x})$$

Numerical relativity



Numerical relativity

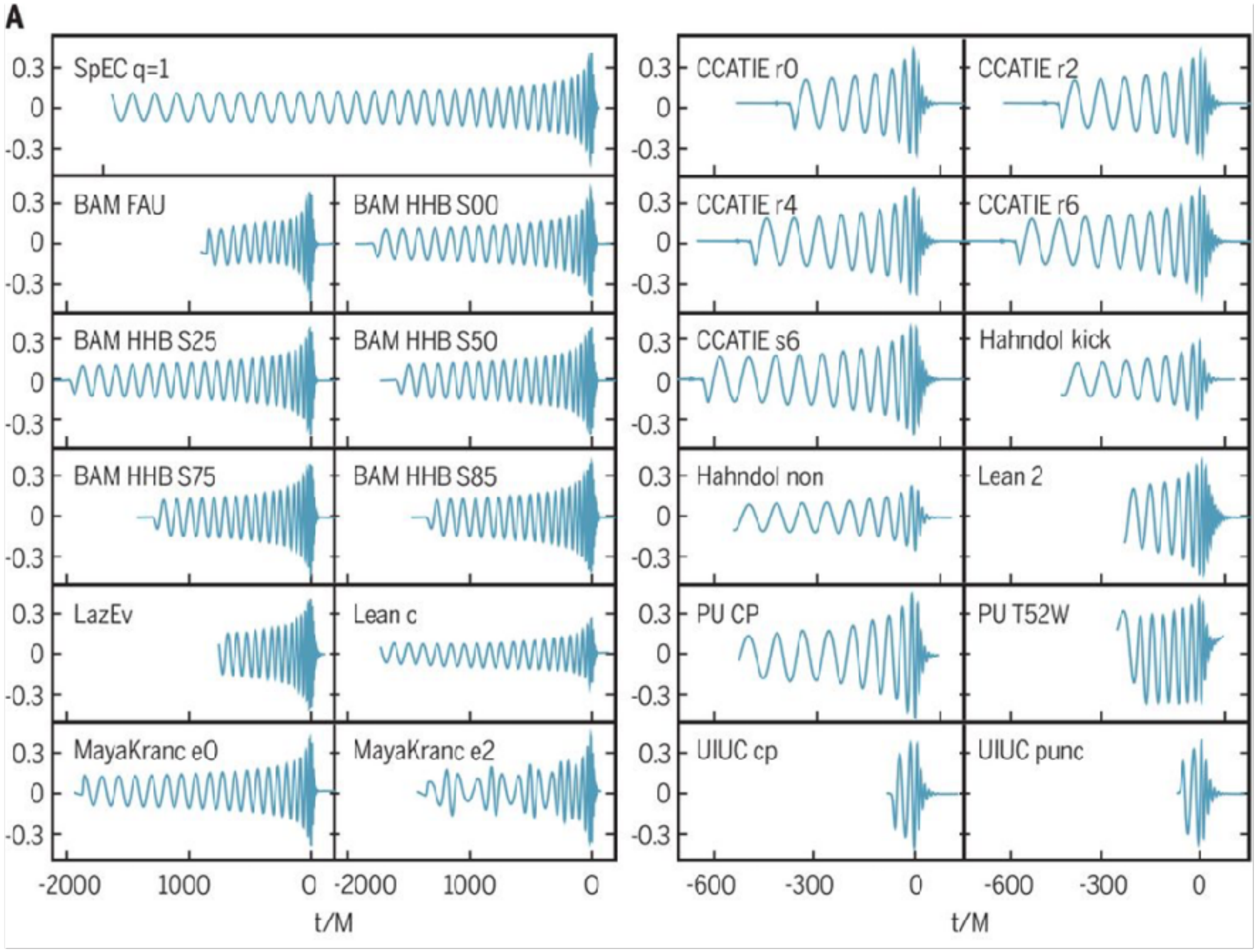


Numerical relativity

- Non trivial to find initial data
- Well posed formulation of evolution equations (includes choice of coordinates)

Waveforms for data analysis

- Data analysis…
- Degeneracies…
- …



Research challenges for numerical simulations of MG and DM

- Initial conditions

- Evolutions

Initial conditions

Modified gravity

- Initial conditions *theory dependent*
- Superposition of isolated solutions (usually) ok
- Solving constraints for general configuration in binary case is unsolved

Dark matter/energy

- Initial conditions *scenario dependent*
- Superposition of isolated solutions problematic
- Solving constraints for general configuration in binary case is solved

Initial conditions

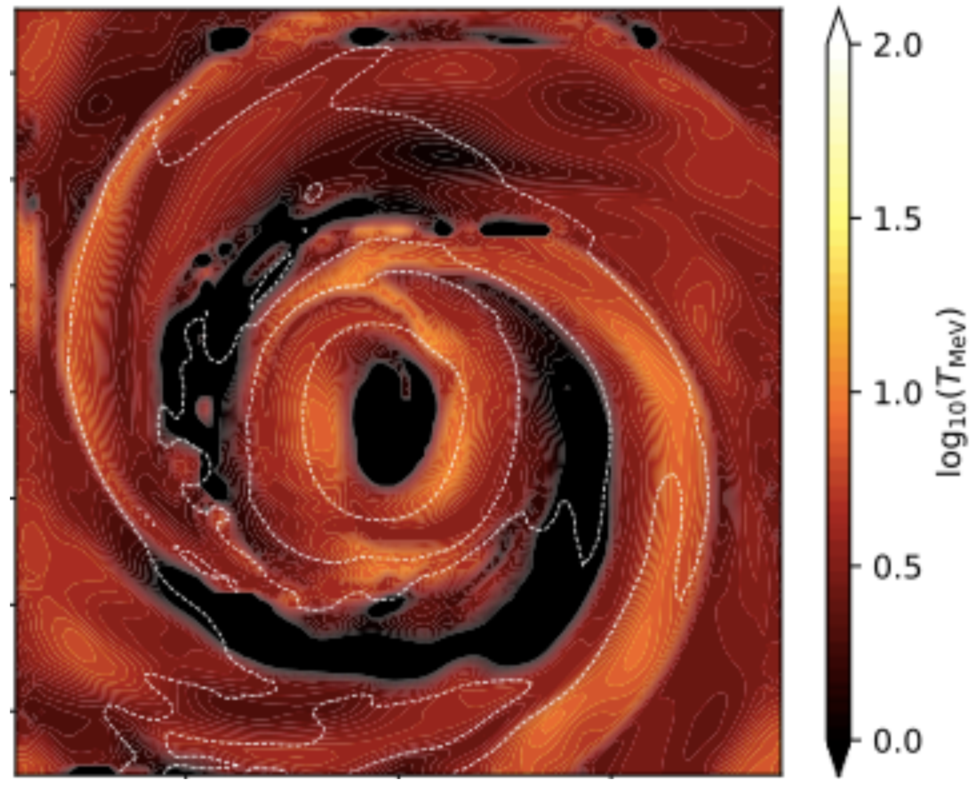
Modified gravity

- Initial conditions *theory dependent*
- Superposition of isolated solutions (usually) **ok**
- Solving constraints for general configuration in binary case is **unsolved**

Dark matter/energy

- Initial conditions *scenario dependent*
- Superposition of isolated solutions **problematic**
- Solving constraints for general configuration in binary case is **solved**

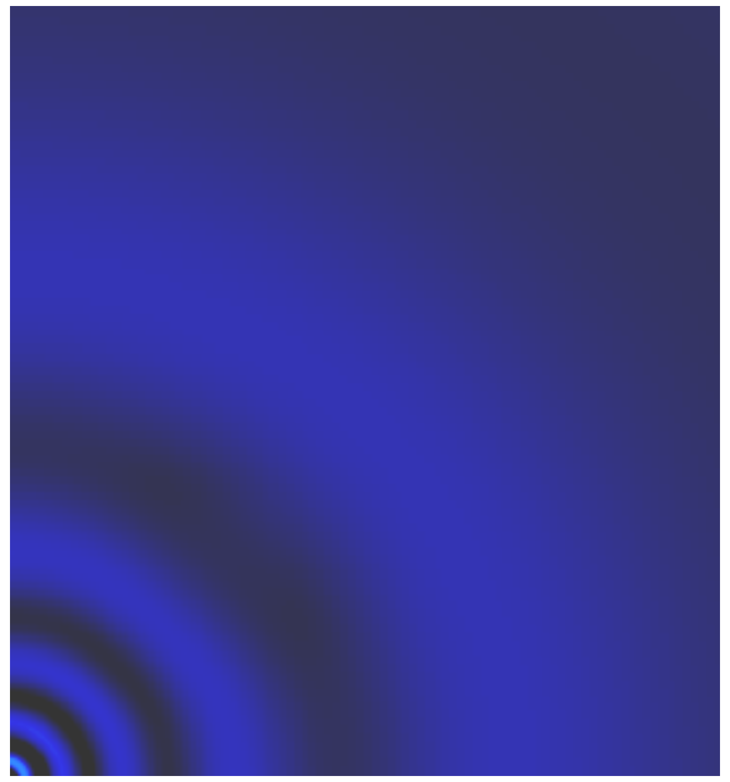
CTTK - A new method to solve the ADM constraints in numerical relativity
J. Aurrekoexea, KC, E.A. Lim, *Class.Quant.Grav.* 40 (2023) 7, 075003



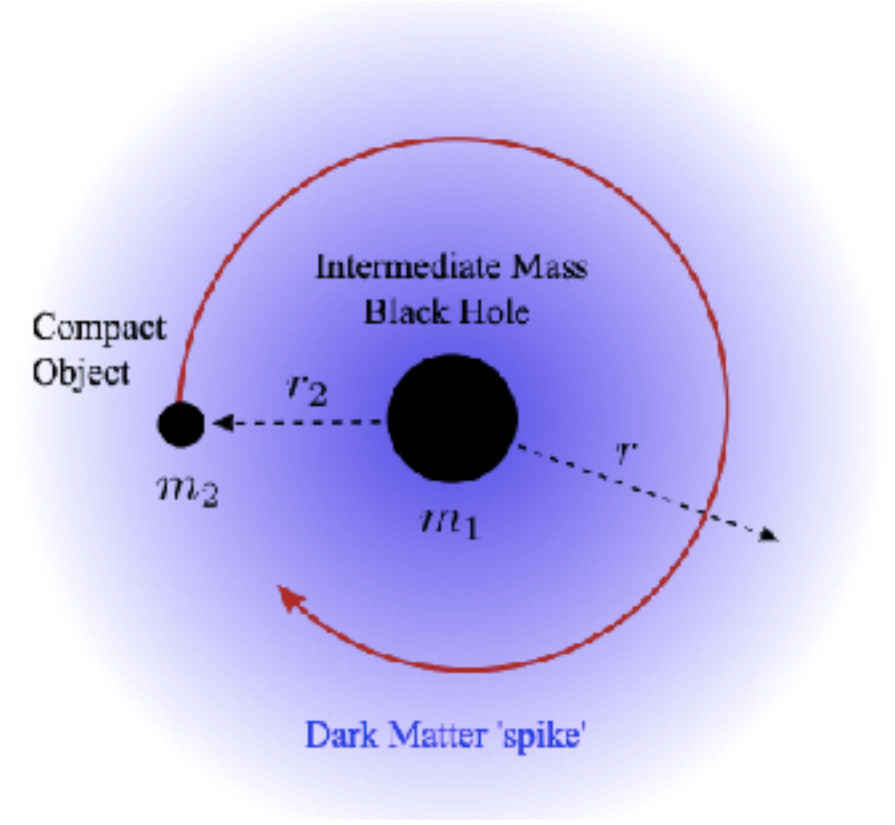
Dietrich et. al. 2019
Cooling binary neutron star remnants via nucleon-nucleon-axion bremsstrahlung

Interactions e.g. bremsstrahlung, or attractive self interactions

Bamber et. al. 2021
Growth of accretion driven scalar hair around Kerr black holes



Kavanagh et. al. 2020, Coogan et. al. 2022
Measuring the dark matter environments of black hole binaries with gravitational waves



Superradiance

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

Dark matter overdensity scenarios

Dark matter minispikes (adiabatic growth, accretion)

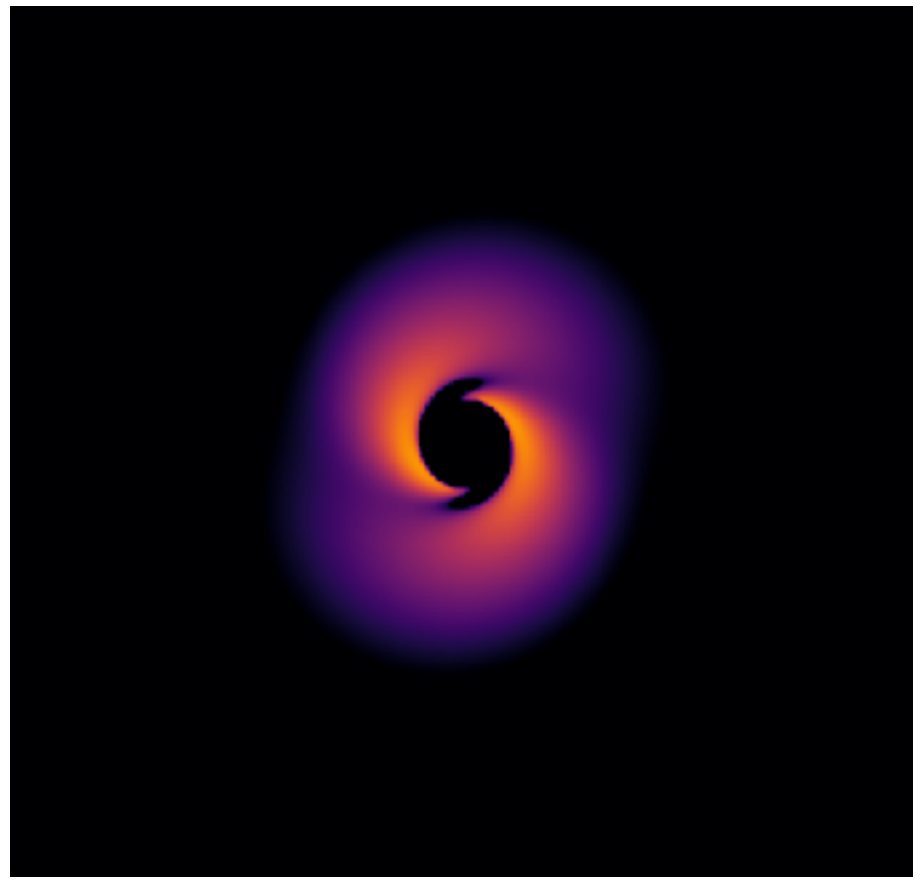


Image credit: Helfer / Clough

Exotic compact objects e.g. boson stars

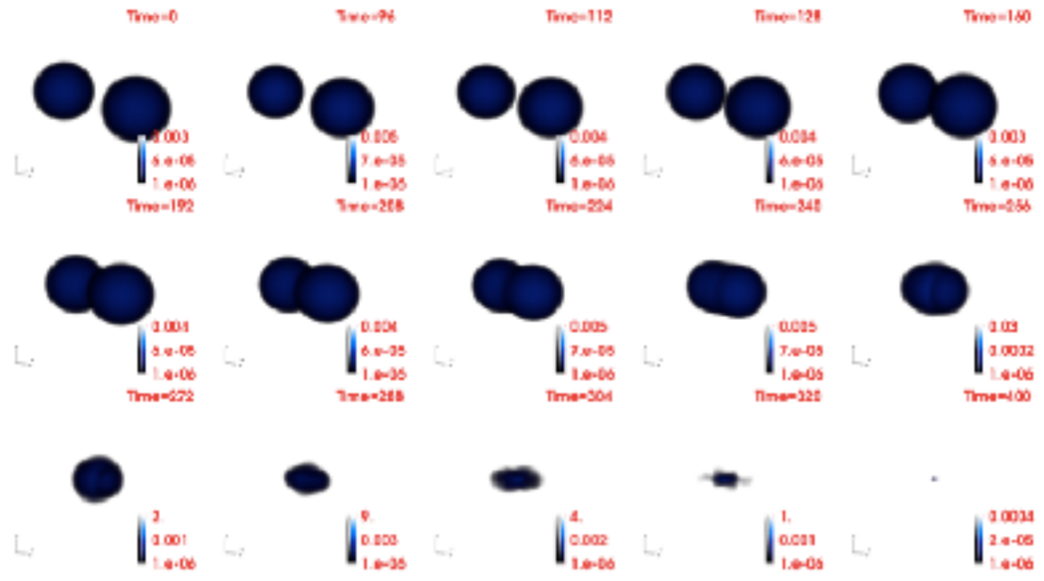


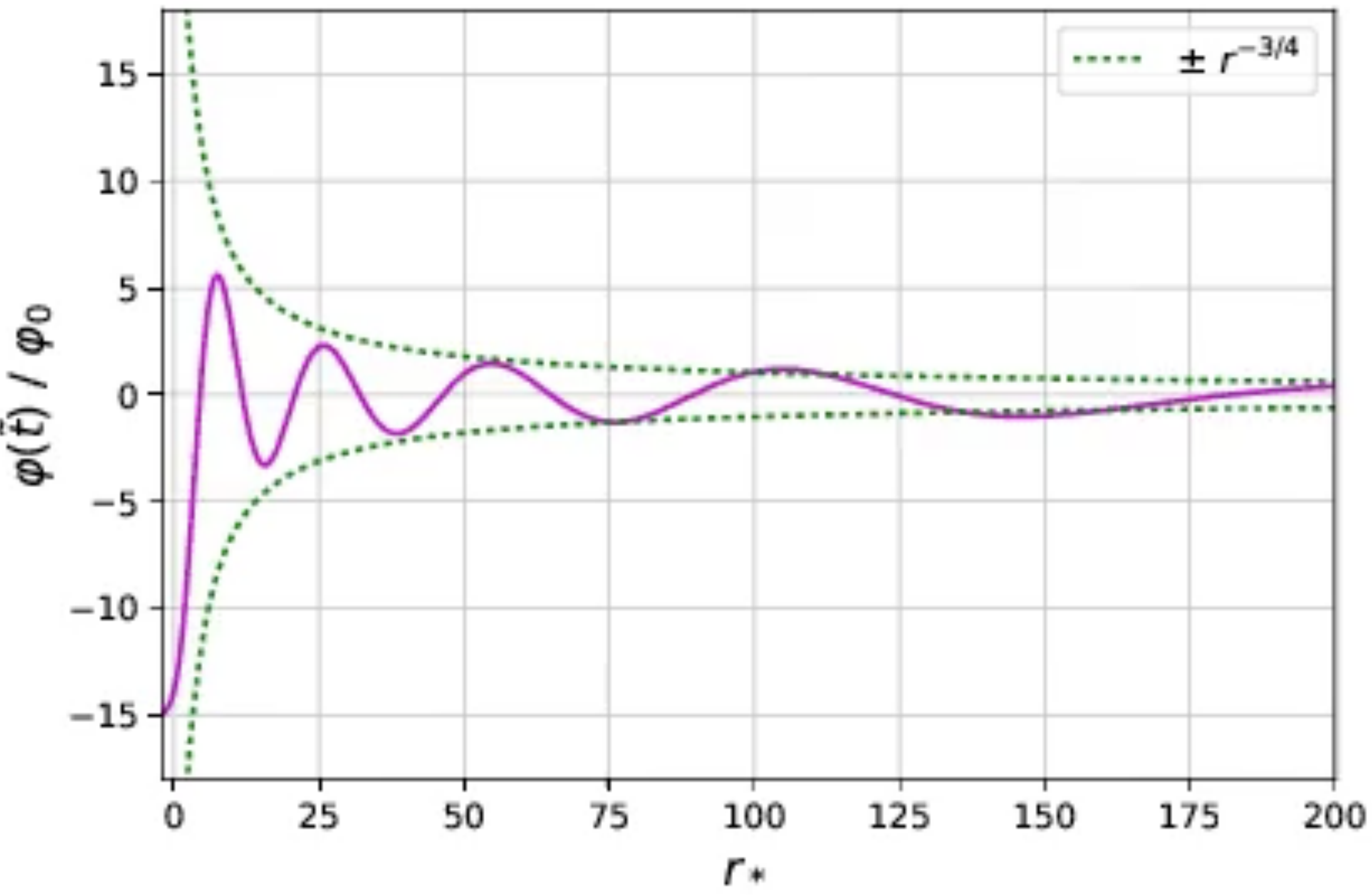
FIG. 5. **Snapshots of the time evolution of the energy density during the head-on collision of two PSs with** $\omega/\mu_V = 0.8925$. **Time is given in code units.**

Bustillo et. al. 2021
GW190521 as a merger of Proca stars: a potential new vector boson of 8.7 × 10−13 eV

Initial conditions

e.g. accretion of wave DM

Field profile

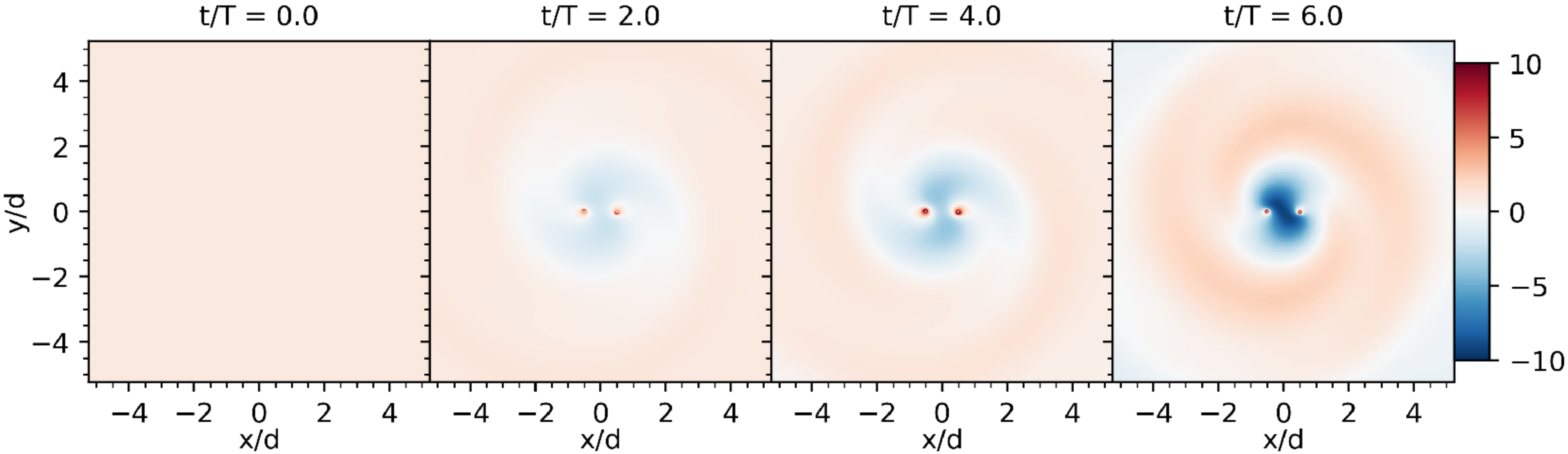


Clough et. al. 2019,
Bamber et. al. 2021
Growth of accretion driven scalar hair around Kerr black holes

Initial conditions

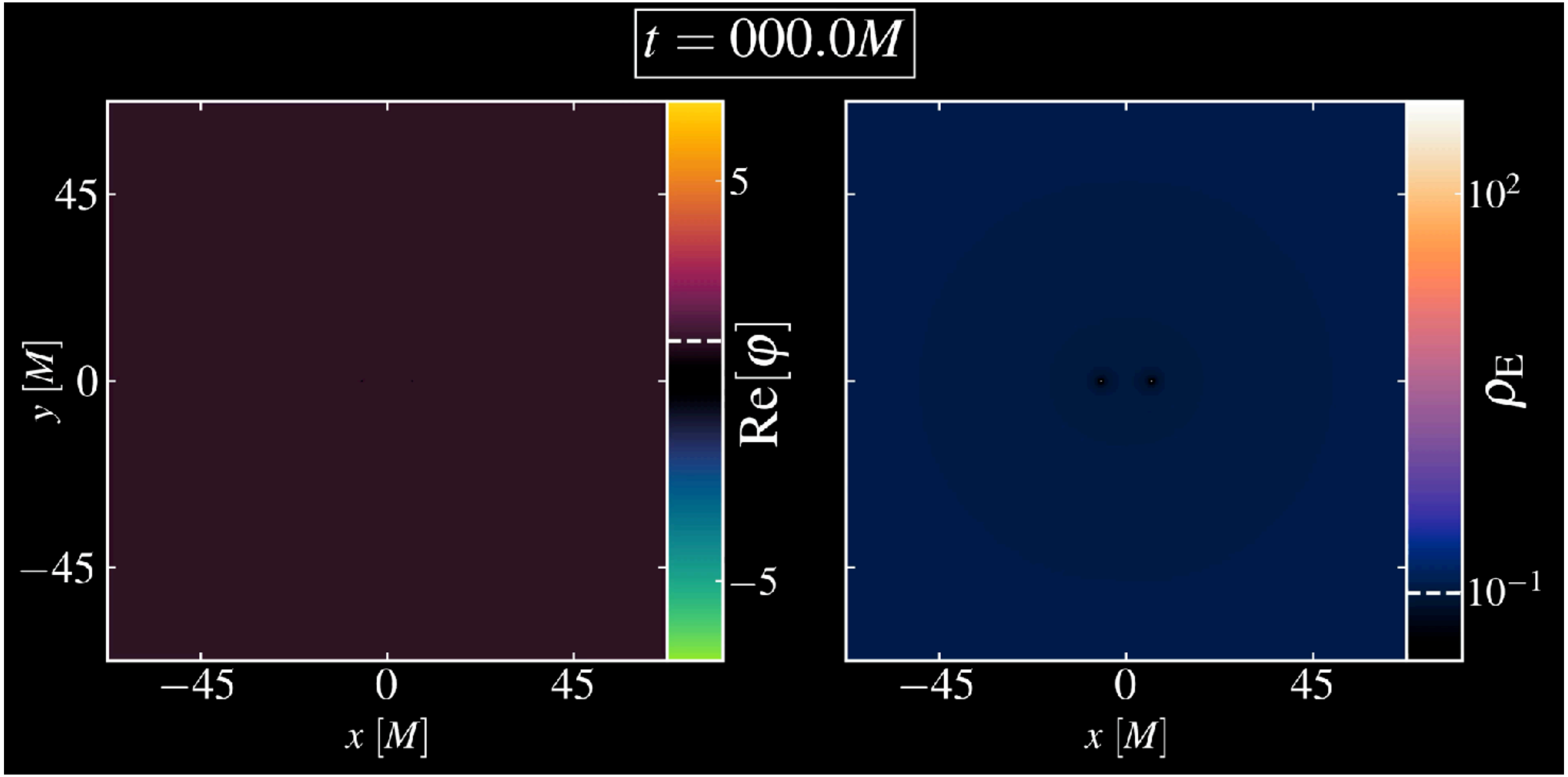
e.g. accretion of wave DM

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



Initial conditions

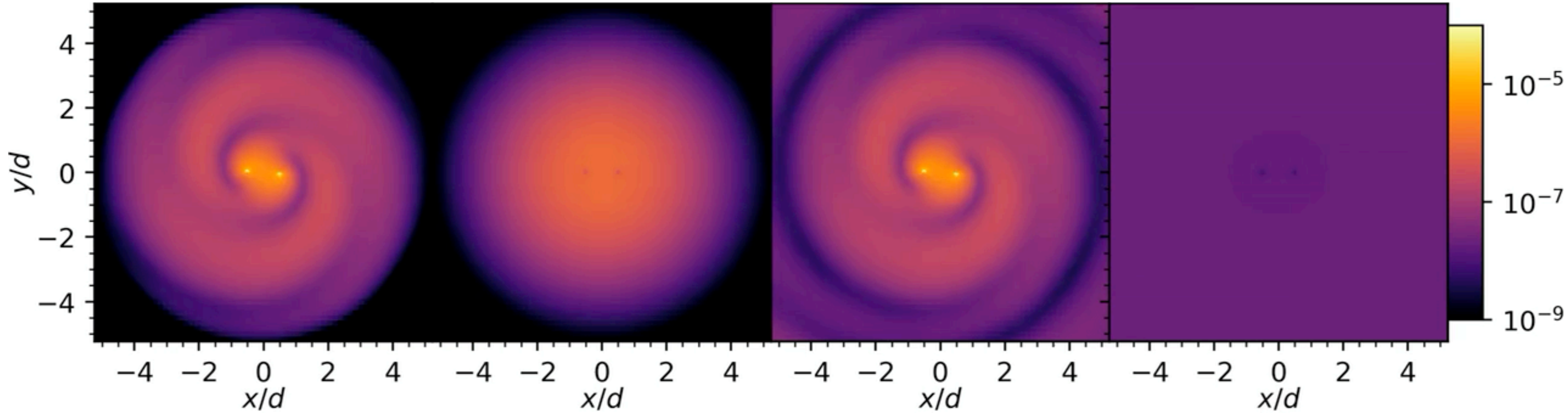
Field



energy density

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

Initial conditions



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

Evolution of fields in strong gravity

Modified gravity

- Well posed formulations only known in some cases
- Range of scales to be simulated ok

Dark matter/energy

- Well posed formulations ok
- Range of scales to be simulated difficult for very small or very large field masses

Evolution of fields in strong gravity

Modified gravity

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Dark matter/energy

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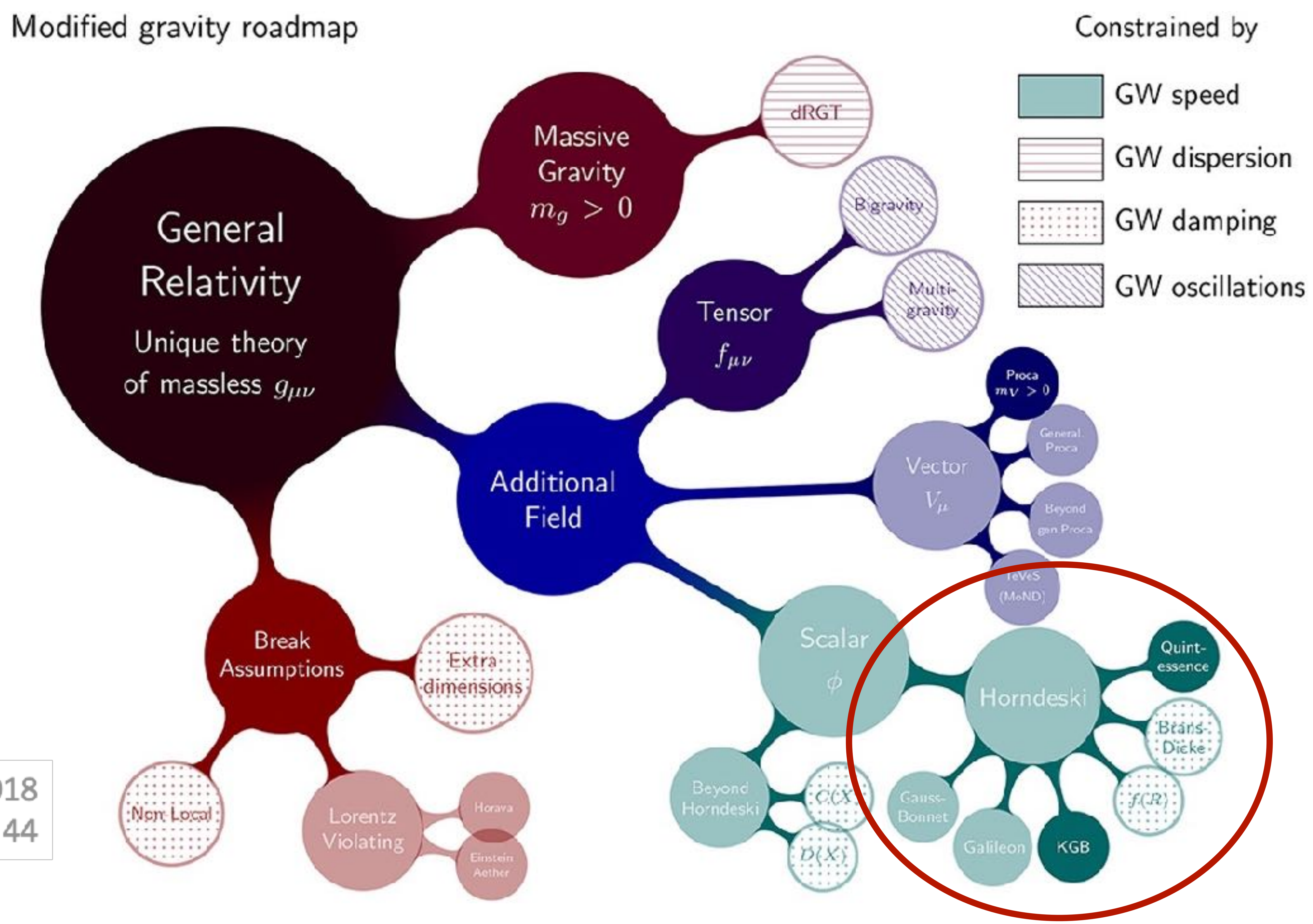
Fundamental fields in modified gravity



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

Well posed evolutions

e.g. Einstein scalar Gauss Bonnet

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

where $X = \nabla^{\mu}\phi\,\nabla_{\mu}\phi$

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

Well posed evolutions

e.g. Einstein scalar Gauss Bonnet

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

where X ~ normal minimally coupled scalar field contribution

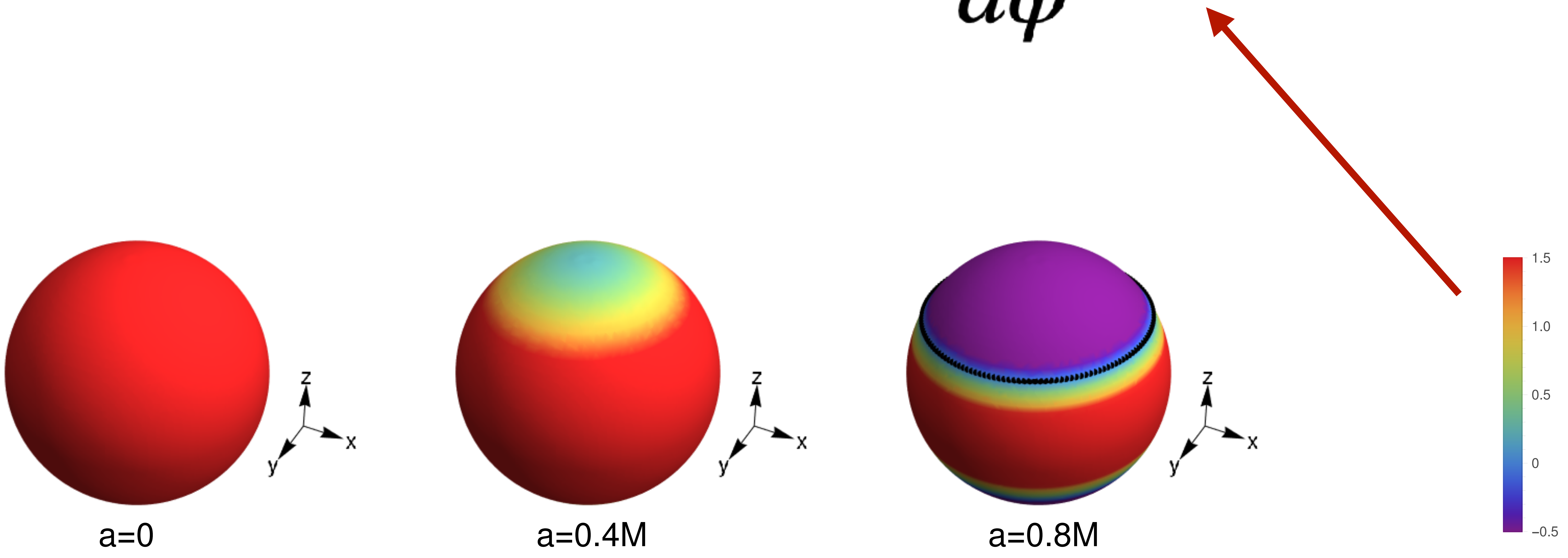
$\mathcal{L}_{GB}$ ~ Kretchmann

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

Well posed evolutions

Eom for the field

$$\Box \phi + \frac{d\lambda}{d\phi} \mathscr{L}_{GB} = 0$$



Well posed evolutions

Eom for the metric

(i.e., ugly)

$$
\begin{aligned}
\rho^{\rm GB} &= \frac{\Omega M}{2} - M_{kl}\Omega^{kl}, && \text{(A2a)}\\
J_i^{\rm GB} &= \frac{\Omega_i M}{2} - M_{ij}\Omega^j - 2\big(\Omega^j{}_{[i}N_{j]} - \Omega^{jk}D_{[i}K_{j]k}\big), && \text{(A2b)}\\
S_{ij}^{\rm GB} &= 2\gamma^k{}_{(i}\Omega^{{\rm TF},l}_{j)}\big(\mathcal{L}_n A_{kl} + \tfrac{1}{\alpha}(D_kD_l\alpha)^{\rm TF} + A_{km}A^m_l\big)\\
&\quad -\Omega^{\rm TF}_{ij}\big(\mathcal{L}_n K + \tfrac{1}{\alpha}D^kD_k\alpha - 3A_{kl}A^{kl} - \tfrac{K^2}{3}\big)\\
&\quad -\tfrac{\Omega}{3}\big(\mathcal{L}_n A_{ij} + \tfrac{1}{\alpha}(D_iD_j\alpha)^{\rm TF} + A_{im}A^m_j\big)\\
&\quad -\Omega_{nn}M_{ij} + N_{(i}\Omega_{j)} - 2\epsilon_{(i}{}^{kl}B_{j)k}\Omega_l\\
&\quad +\gamma_{ij}\Big[\rho^{rhs} - N^k\Omega_k + \tfrac{M}{6}\big(\Omega_{nn} + \tfrac{\Omega}{3}\big) - \tfrac{1}{3}\Omega^{{\rm TF},kl}M_{kl}\\
&\qquad -\Omega^{{\rm TF},kl}\big(\mathcal{L}_n A_{kl} + \tfrac{1}{\alpha}(D_kD_l\alpha)^{\rm TF} + A_{km}A^m_l\big)\\
&\qquad +\tfrac{2\Omega}{9}\big(\mathcal{L}_n K + \tfrac{D^kD_k\alpha}{\alpha} - \tfrac{3}{2}A_{kl}A^{kl} - \tfrac{K^2}{3}\big)\Big], && \text{(A2c)}
\end{aligned}
$$

with

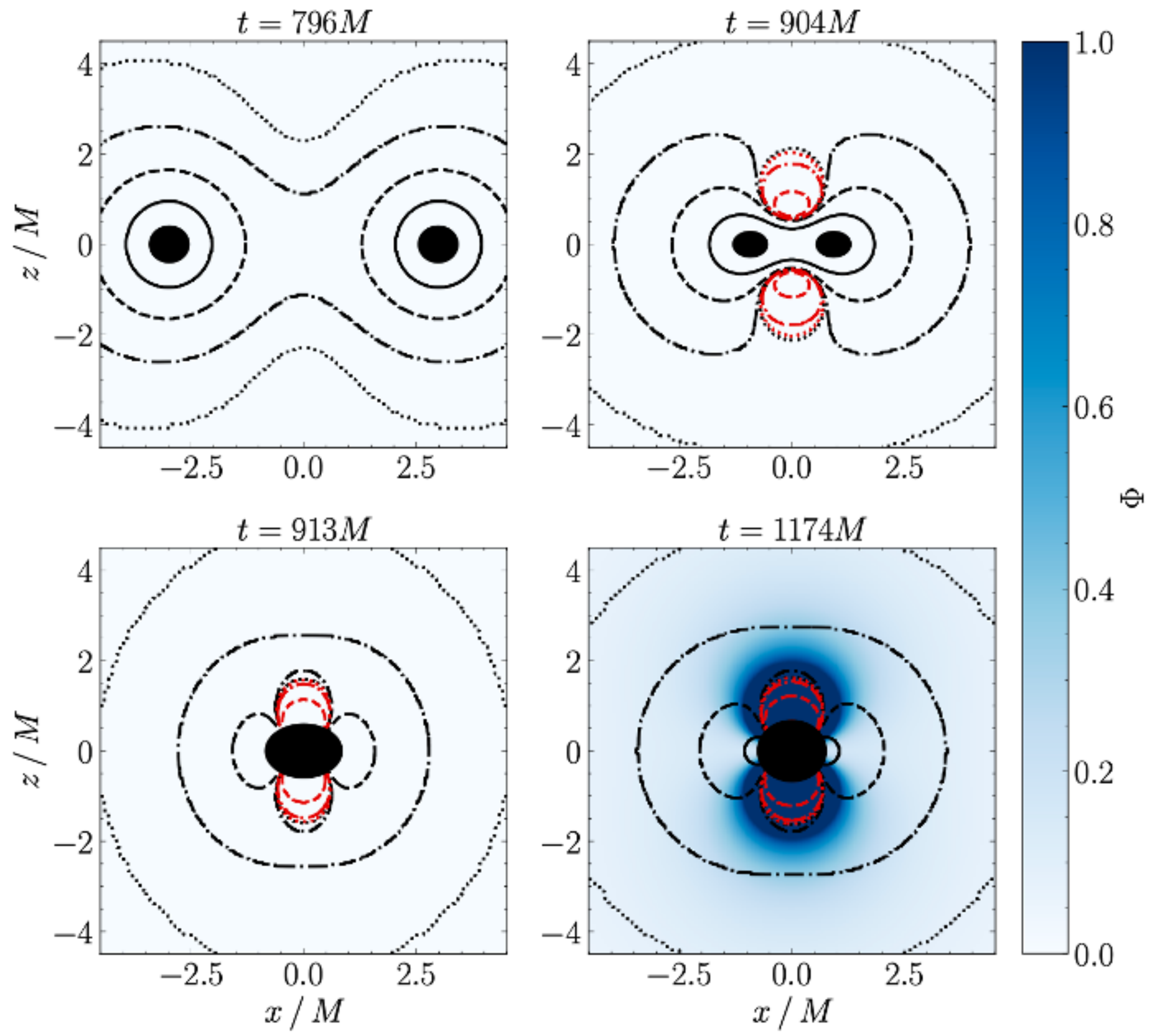
$$
\begin{aligned}
M_{ij} &= R_{ij} + \frac{1}{\chi}\left(\tfrac{2}{9}\tilde\gamma_{ij}K^2 + \tfrac{1}{3}K\tilde A_{ij} - \tilde A_{ik}\tilde A_j{}^k\right), && \text{(A3a)}\\
N_i &= \tilde D_j\tilde A_i{}^j - \frac{3}{2\chi}\tilde A_i{}^j\partial_j\chi - \tfrac{2}{3}\partial_i K, && \text{(A3b)}\\
B_{ij} &= \epsilon_{(i}{}^{kl}D_kA_{j)l}, && \text{(A3c)}\\
\Omega_i &= f'\big(\partial_i K_\phi - \tilde A^j{}_i\partial_j\phi - \tfrac{K}{3}\partial_i\phi\big) + f''K_\phi\partial_i\phi, && \text{(A3d)}\\
\Omega_{ij} &= f'\left(D_iD_j\phi - K_\phi K_{ij}\right) + f''(\partial_i\phi)\partial_j\phi, && \text{(A3e)}\\
\Omega_{nn} &= f''K_\phi^2 - \frac{f'}{\alpha}D^k\alpha D_k\phi - f'\mathcal{L}_n K_\phi, && \text{(A3f)}
\end{aligned}
$$

Well posed evolutions

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

Interesting regimes identified in the decoupling limit

e.g. stealth dynamical scalarization



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

Well posed evolutions - MG

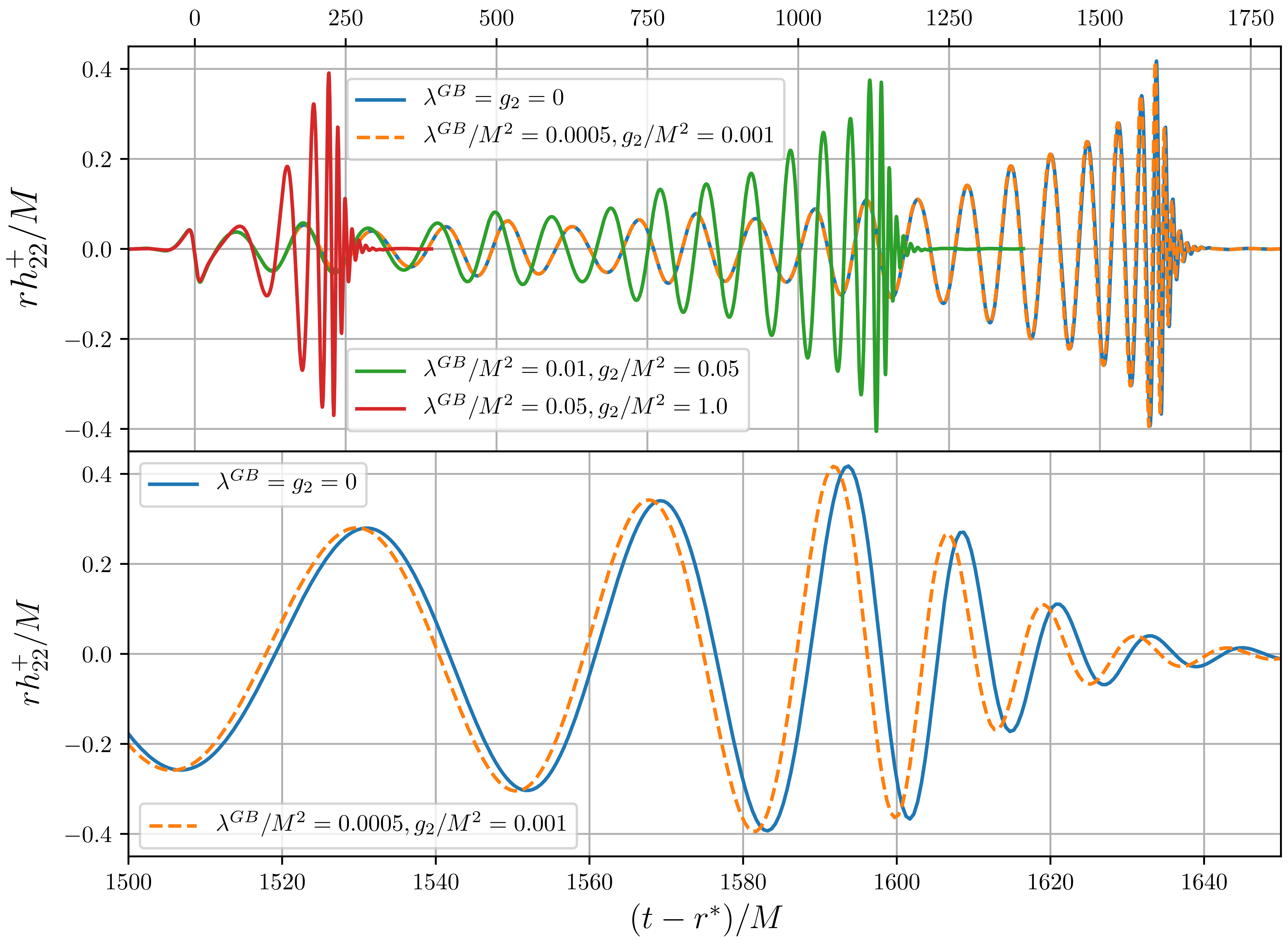
See also:

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

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

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

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



L Aresté Saló, KC, P Figueras
PRL 129 (2022) 26, 261104
And work to appear

Well posed evolutions - MG

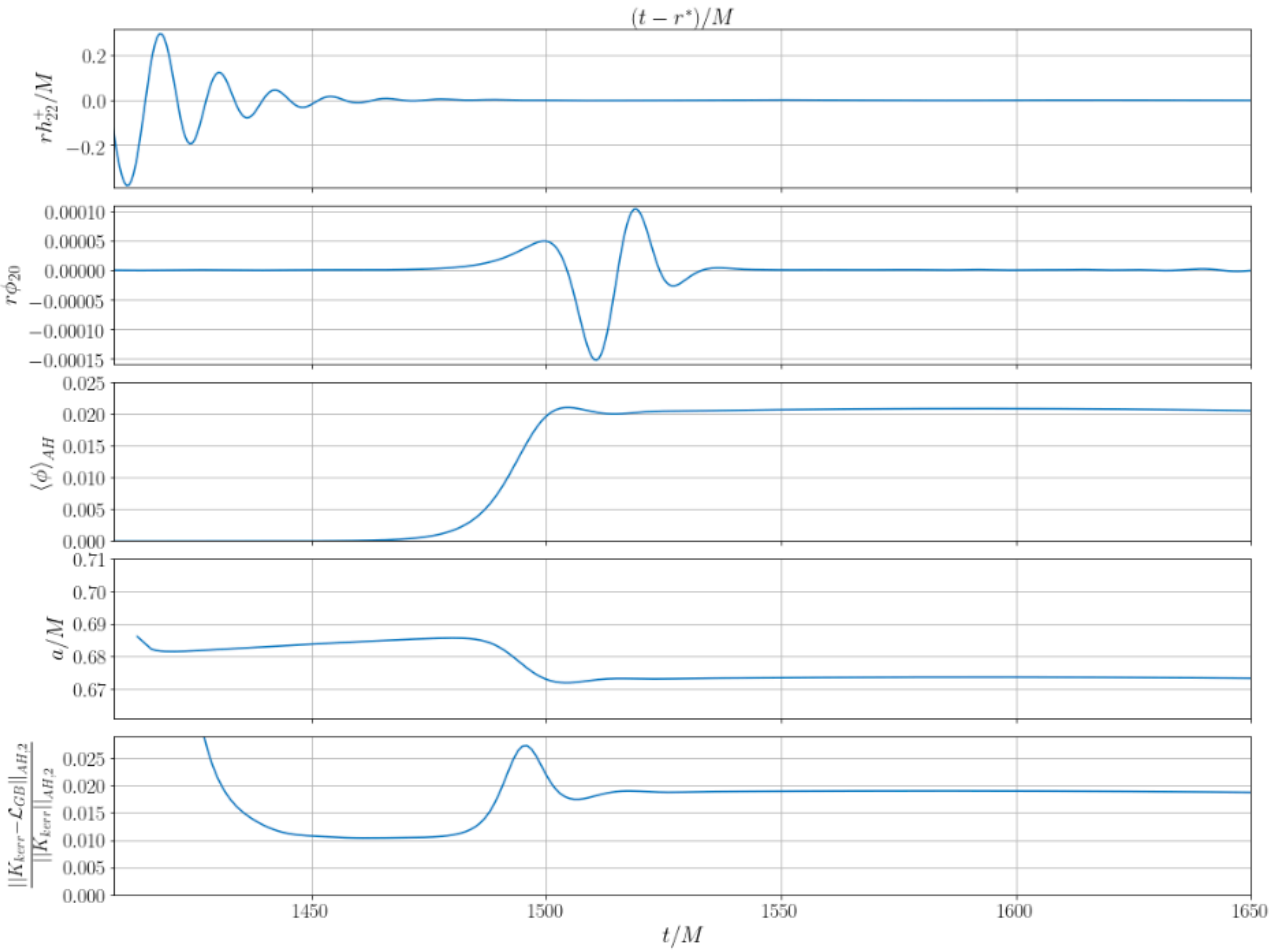
Tensor GW

Scalar GW

Scalar field at horizon

BH spin

Deviation in Kretschmann sca



L Aresté Saló, KC, P Figueras
PRL 129 (2022) 26, 261104
And work to appear

Summary

Summary

- Beyond GR effects now potentially detectable from DM or modified gravity

- Developments in initial data and well posed formulations mean NR tools are now ready to tackle (some of) these effects

- A whole zoo of possible scenarios - major challenge is where to focus efforts