Numerical Relativity beyond General Relativity

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Workshop “Connecting the dots”

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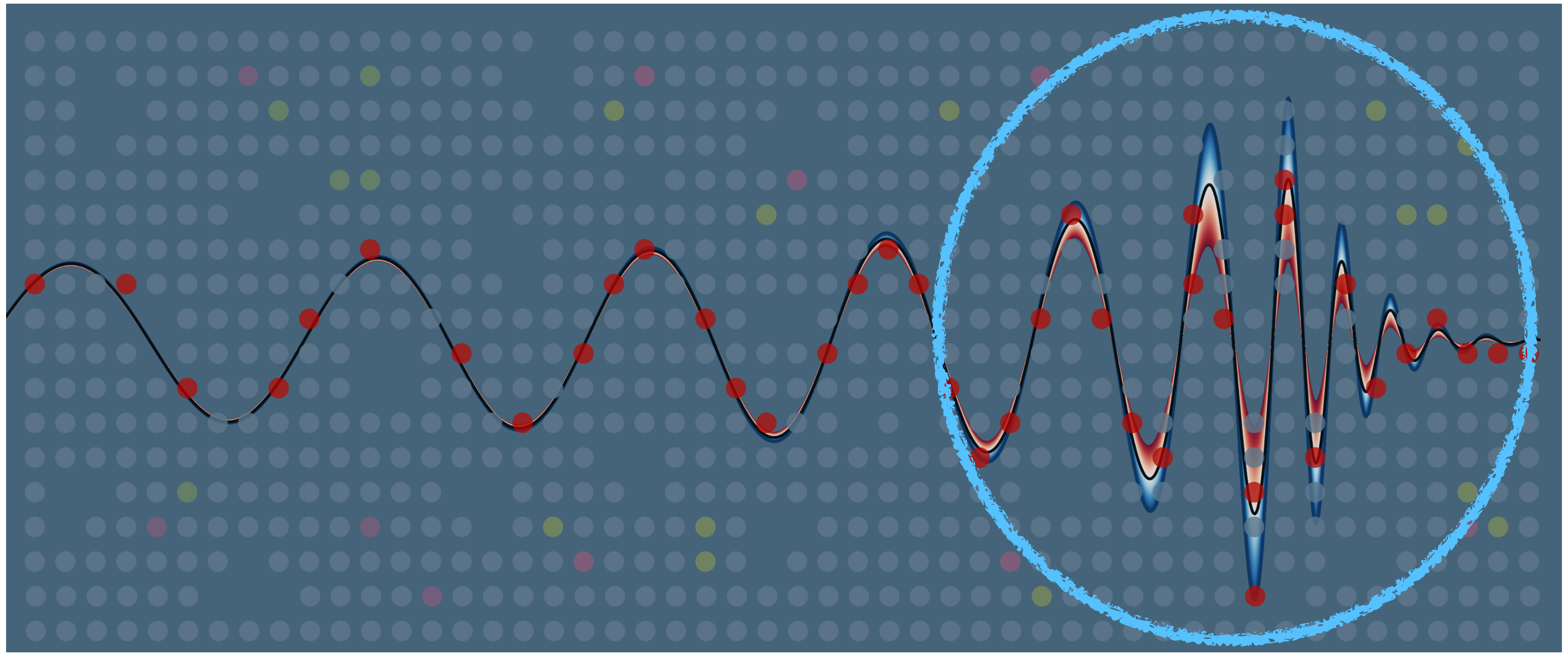
Connecting theory and observations



Credit: H. O. Silva

- Waveform templates crucial for signal characterisation
- Formation and (stability) properties of black holes and compact objects
- Construct consistent inspiral-merger-ringdown waveform models in and beyond General Relativity
- Combine theory-agnostic waveforms (e.g. Maggio, Silva, Buonanno, Ghosh ‘22) and theory-specific waveforms

See Laura and Mohammed’s talks for PN calculation; Geraint’s and Nathan’s talks on parameter estimation.

Landscape of Numerical Relativity beyond GR

In four spacetime dimensions the only divergence-free symmetric rank-2 tensor constructed solely from the metric and its derivatives up to second order, and preserving diffeomorphism invariance, is the Einstein tensor plus a cosmological constant. [Lovelock ’69-‘72]

Extra fields

- Scalar-tensor theory (Healy+’11, Barausse+ ’12, Shibata+ ’13, Berti et al ’13, Palenzuela+ ’15, Gerosa+ ’16, Sperhake+ ’17, Sagunski+’17, Rosca-Mead+ ’19, ’20, Mendes+ ’21)
- Einstein-Maxwell-Dilaton (Hirschmann+ ’17, Liebling ’19)
- *Horndeski gravity* (Ripley+ ’19, Bernard+ ’19, Kovacs+ 20, Figueras+ ’20, ’21, Dima+ '21, Bezares+ ’20, ’21, Lara+ 22; Review: Ripley ’22)
- Boson stars (Liebling & Palenzuela ’12, Palenzuela+ ’17, Helfer+ ’18, ’19, ’21, Clough+ ’18, Bezares+ ’18-’22, Alcubierre+ ’19, Di Giovanni+’21, Jaramillo+ ’22, …)
- Ultralight scalars (Bamber+ ’22, Ficarra+ in prep.)

Higher curvature

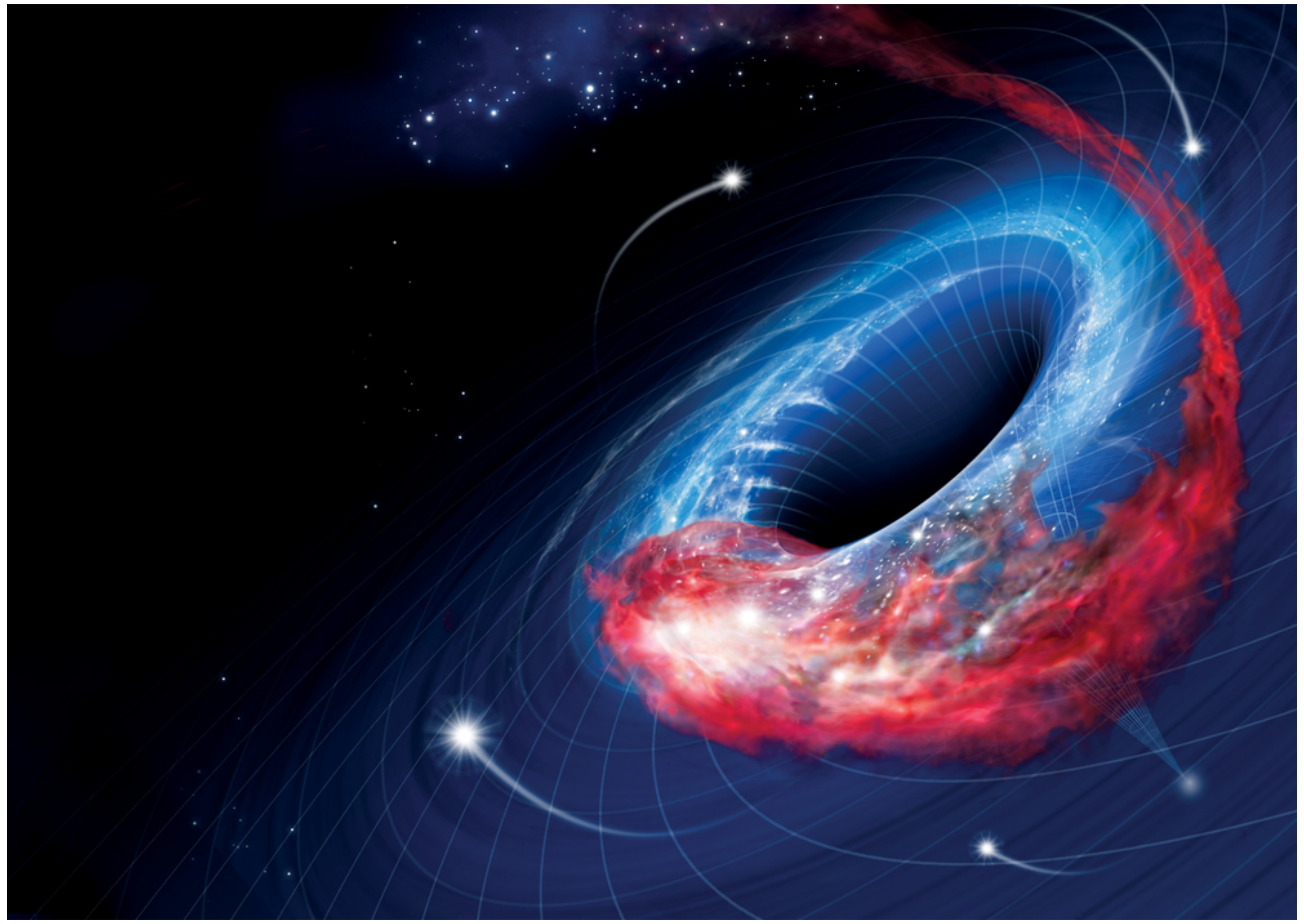
- Effective field theory of gravity (Held+ ’21, Held+ ’23, Cayuso+ ‘23)
- Semi-classical gravity (Benitez+ ’20)
- Black holes with near-horizon fluctuations (Liebling+ ’17)
- Scalar Gauss–Bonnet gravity (Benkel+ ’16; Ripley+ ’19, ‘20, Ramazanoglu ’19, Dima+ ’20, Hegade+ ’22; HW+ ’18, Okounkova ’20, East+ ‘21, Silva+’21; Elley+ ’22, Franchini+ 22, Salo+ ’22, Corman+ ’22, Thaalba+ ’23)
- Dynamical Chern-Simons gravity (Okounkova+ ’17 - ’19, Doneva+ ’20, ’21, Richards+ ’23)

Lorentz violations

- Einstein-æther theory (Garfinkle+ ’07; Barausse, Sarbach et al’19)
- Bimetric gravity (Torsello+ ’19, Kocic+ ’20)

Focus today: higher derivative gravity

- Higher curvature corrections relevant in strong-curvature regime
- Bottom-up: series expansion in curvature
- Top-down: inspired by low-energy limit of quantum gravity candidates, e.g., string theories
  (Gross & Sloan '87, Kanti et al '95, Moura & Schiappa 06, Cano et al ’21)



$$\mathscr{L} = R - \frac{1}{2}(\nabla\Phi)^2 + \frac{\alpha_{GB}}{4} f(\Phi)\mathscr{G} - \frac{1}{2}(\nabla\theta)^2 + \frac{\alpha_{CS}}{4}\theta\, R^*R + F_2(\mathscr{R}^2) + F_3(\mathscr{R}^3) + \dots$$

Scalar Gauss-Bonnet | Dynamical Chern-Simons | Effective field theory of gravity

$$\mathscr{G} = R_{abcd}R^{abcd} - 4R_{ab}R^{ab} + R^2$$

How to formulate higher derivative gravity theories?

- Field equations may have (i) mixed hyperbolic-elliptic character, (ii) higher time derivatives,…
- Causal and well-posed initial value formulation necessary for numerical stability

Order-by-order expansion

- Expand metric and scalars in coupling parameter

$$G^{(0)}_{\mu\nu}[g^{(n)}] \sim T^{eff}_{\mu\nu}(g^{(n-1)}, \ldots, \Phi^{(n-1)}, \ldots)$$

$$\Box^{(0)} \Phi^{(n)} \sim F(\mathscr{R}^{(n-1)}, \ldots, \Phi^{(n-1)}, \ldots)$$

- Easy to implement
- BUT: secular effects
- Consider RG flow [Ghersi & Stein '21]

Fixing a la Israel-Stewart

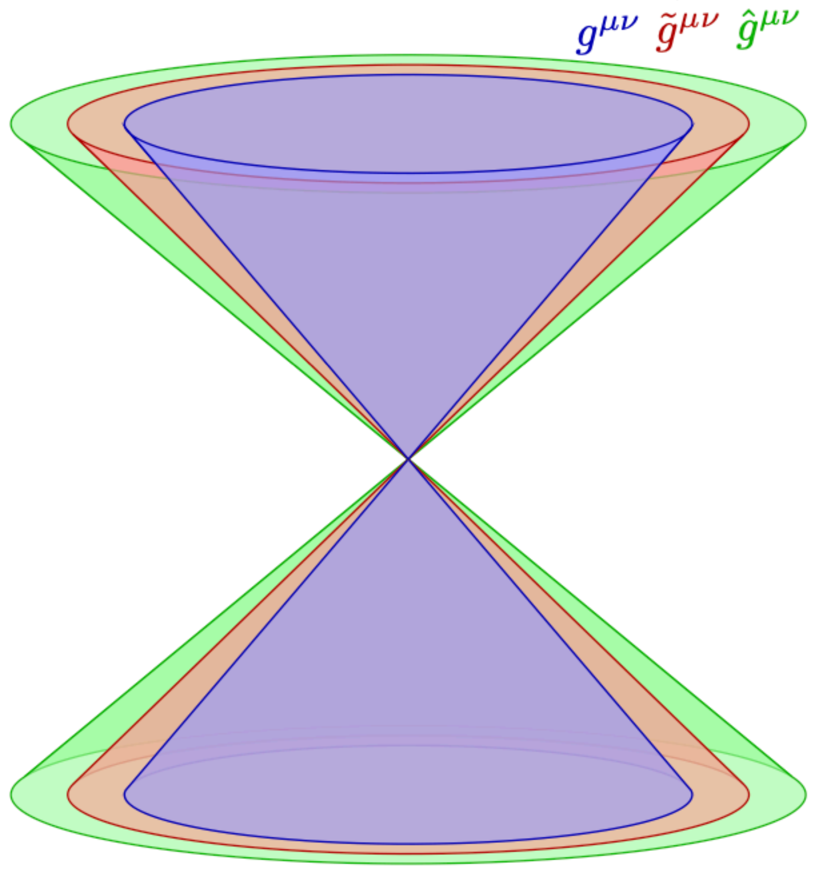
- Inspired by relativistic hydrodynamics (Cayuso, Ortiz, Lehner '17; Allwright, Lehner '18,…)
- Toy model: $\Box\, \Phi \sim \lambda \partial_x^4 \Phi$
- Superluminal modes
- Fix:

$$\Pi = \partial_x^2 \Phi \rightarrow \Box\, \Phi \sim \lambda \partial_x^2 \Pi$$

$$\sigma \Box\, \Pi \sim \partial_x^2 \Phi - \tau \partial_t \Pi - \Pi$$

Modified gauge conditions

- Modified generalized harmonic gauge (Kovacs, Reall '20)
- Gauge dofs propagate along light cone of auxiliary metric



See Aron's and Miguel's talks

Building
a (hairy) black hole

Ultralight scalars:
Black holes anchor long-lived scalar clouds

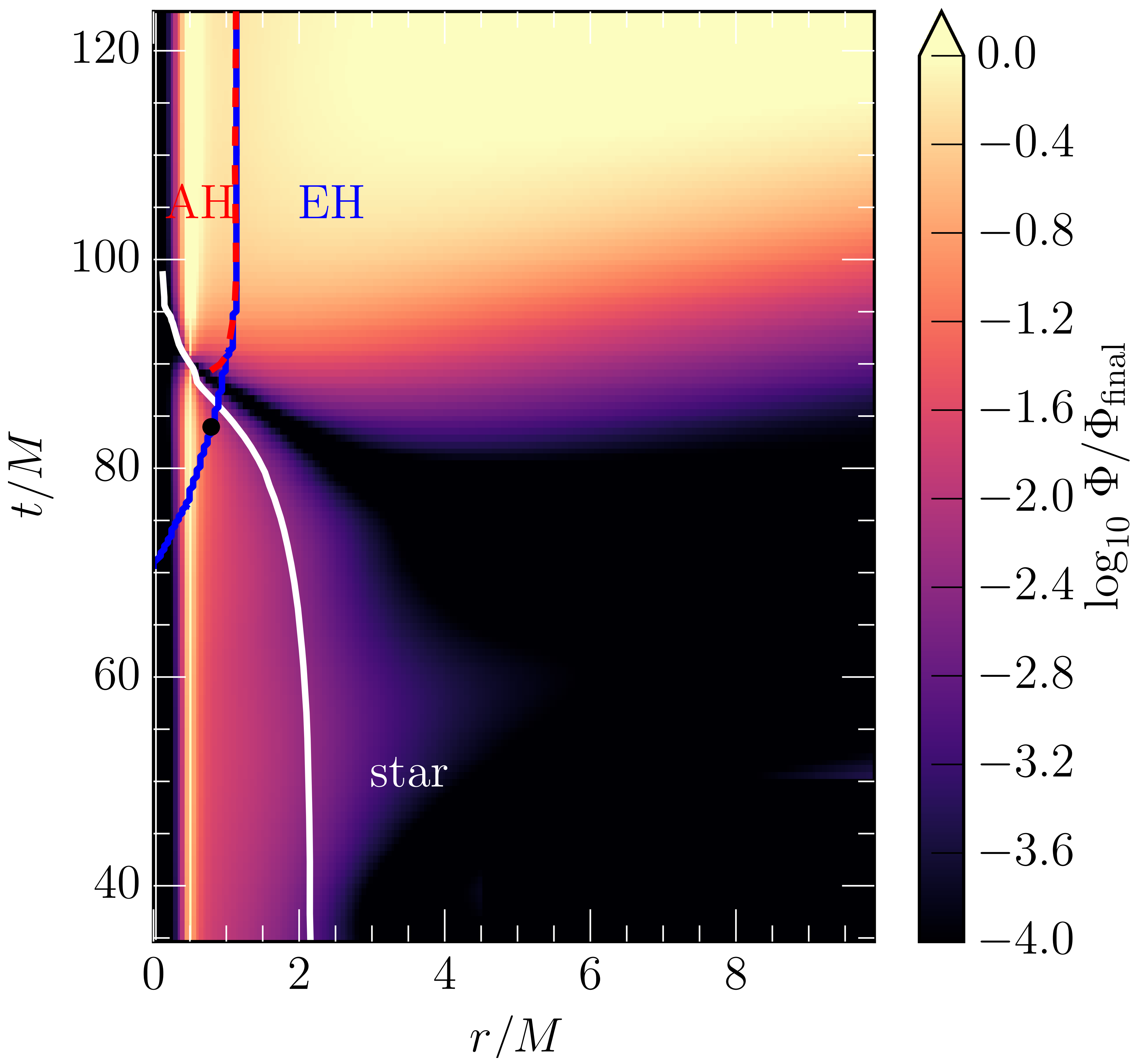
$$\Box\theta - \mu^2\theta = 0$$

E.g.: in quadratic gravity:
Black holes have scalar charge, but neutron stars do not!

$$\Box\Phi + \frac{\alpha_{GB}}{4}\mathcal{G} = 0 \qquad \Box\theta + \frac{\alpha_{CS}}{4}R^*R = 0$$

See Thomas' talk for solution space, Nico' talk for QNMs + mode stability

Growing monopole and dipole hair in quadratic gravity
(A. Hegade, E.R. Most, J. Noronha, HW, N. Yunes ’21, ’22)



How does the black hole hair form?

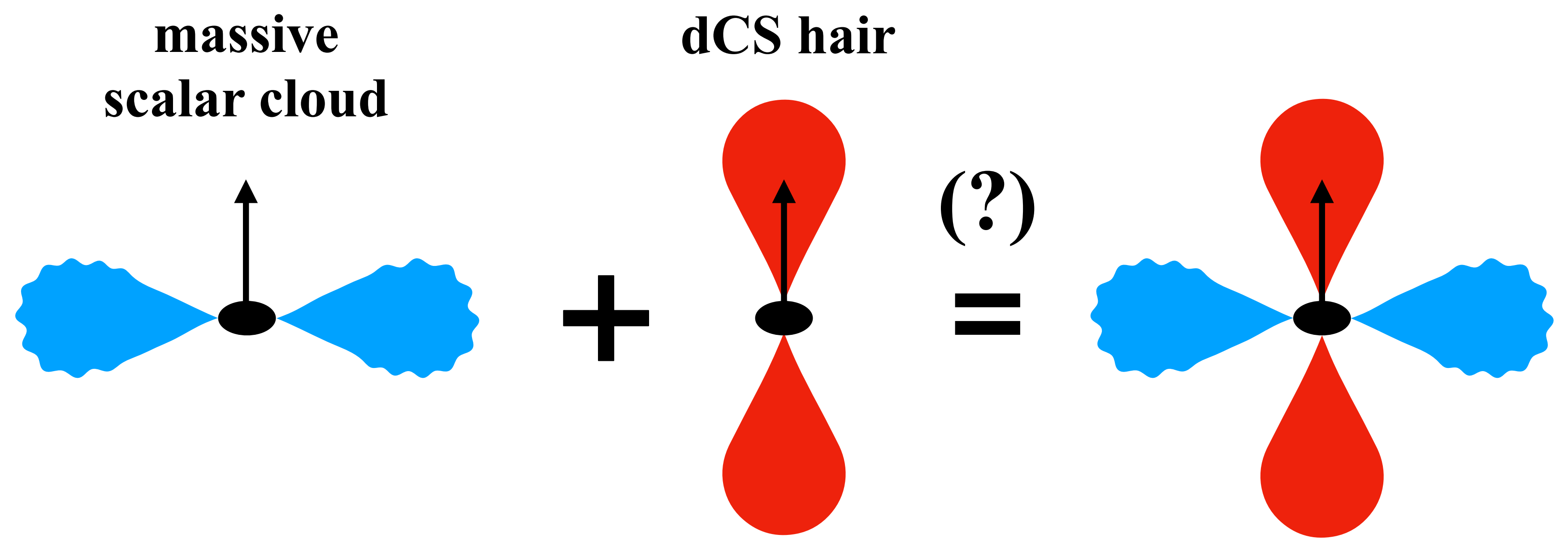
- simulated stellar collapse
- scalar field growth triggered by formation of event horizon

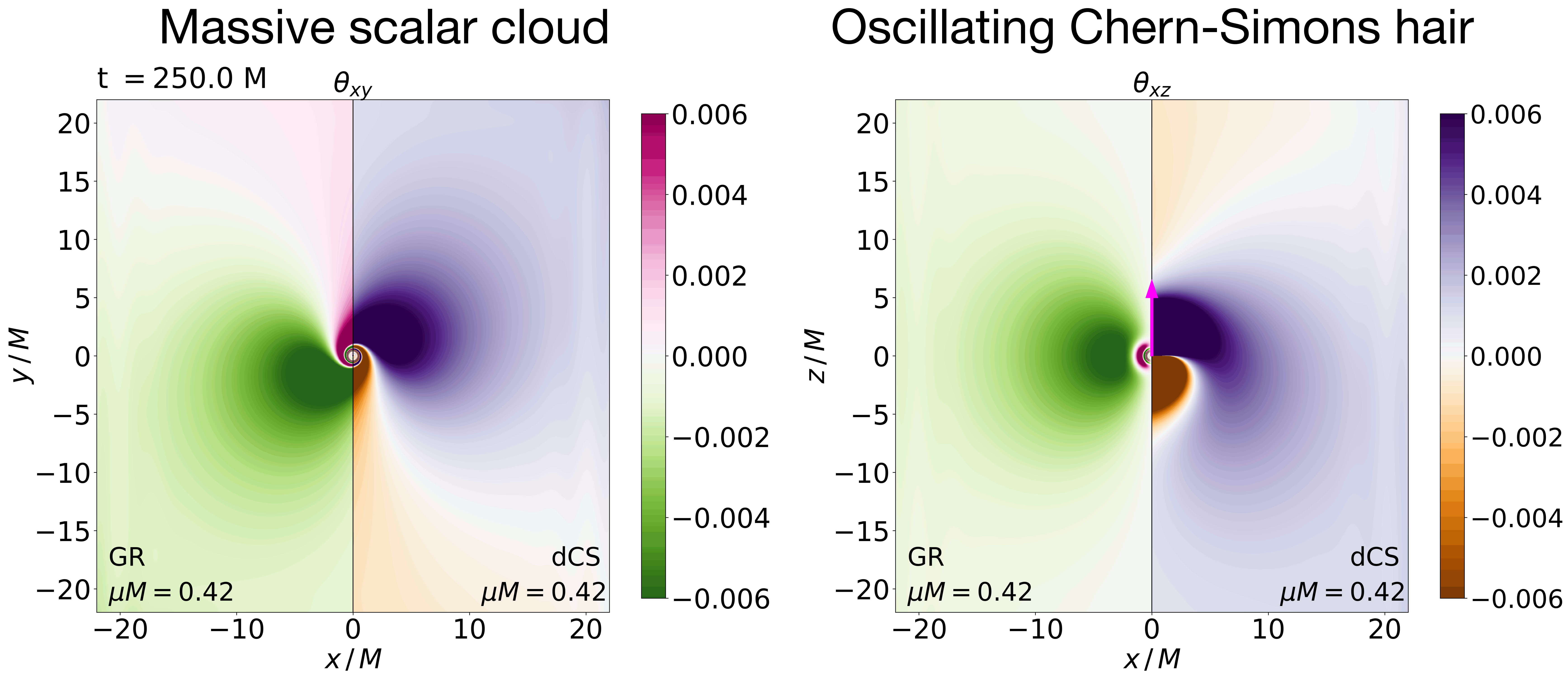
(BH formation: Benkel, Sotiriou, **HW** '16, **HW** et al '19, Ripley & Pretorius '19, Doneva et al ’21;
BHs: Kanti et al '95, Torii et al '96, Pani et al '09, '11, Yunes & Stein ’11, Sotiriou & Zhou ’14, Ayzenberg et al '14, Maselli et al ’15, Kunz et al '11, ’14
Scalarization: Silva et al '17, Doneva et al '17, Antoniou et al '17, Macedo et al '19, Ripley & Pretorius ’20, Silva et al '19, Blazquez-Salcedo et al '18, ’20, Dima et al '20, Hod '20, Doneva et al '20, Herdeiro et al '20, Berti et al ’20; see review by Doneva, Silva, Sotiriou et al ’22, …)

Scalar clouds non minimally coupled to gravity
(C. Richards, A. Dima, HW '23)

- Evolving massive scalar cloud around single black hole
- Non minimally coupled to gravity via Pontryagin density

$$\Box\theta + \frac{\alpha_{CS}}{4} R^*R - \mu^2\theta = 0$$





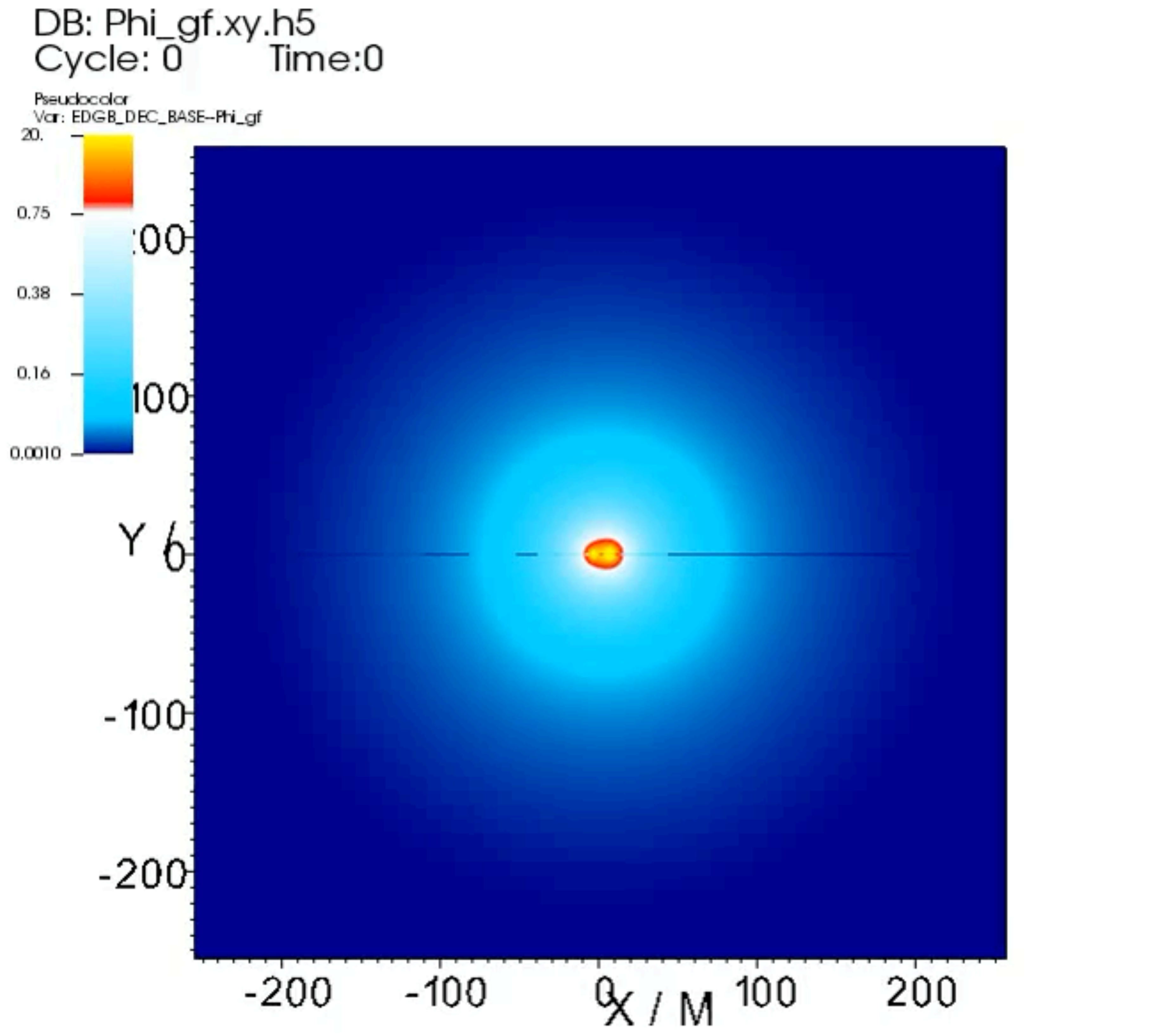
BH Spin: a/M = 0.99
Particle mass
$M\mu = 0.42$

See: massive dCS scalar around Schwarzschild (Macedo '18), Superadiance of massive scalar around dCS black hole (Alexander et al '22)

Merging
black holes beyond GR

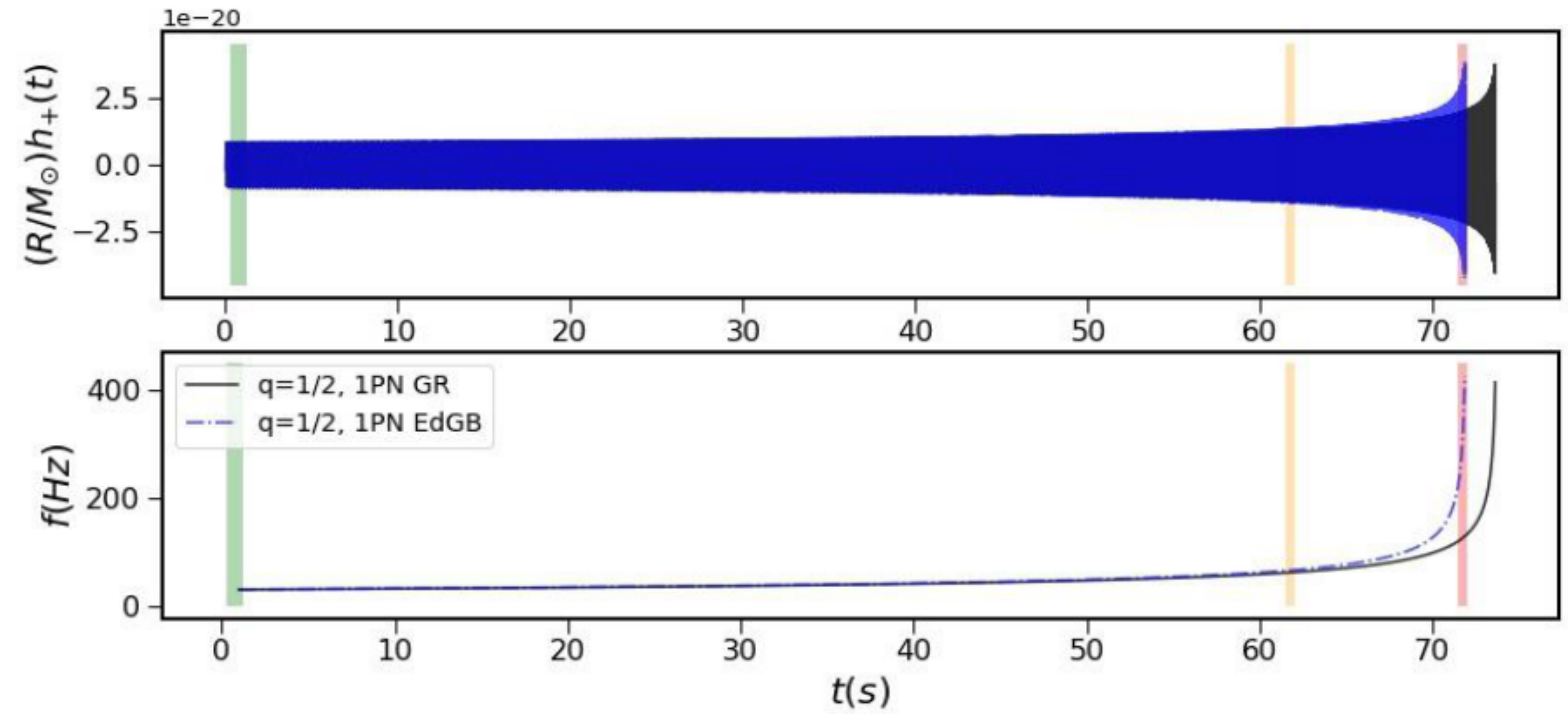
Scalar Gauss-Bonnet gravity I

(HW, Gualtieri, Pani, Sotiriou ’19; Shiralilou, Hinderer, Nissanke, Ortiz, HW ’20, ’21)



(HW, Gualtieri, Pani, Sotiriou ’19)

- Coalescence of black holes with scalar hair (``charge”)
  - scalar dipole radiation
  - Gravitational wave phase shift



PN Waveform (Shiralilou, Hinderer, Nissanke, Ortiz, HW ’20, ’21)

[See also: Yagi+ ’11, Julie+ ’18, ’19, Lyu+ ’22]

Canuda

Open-source numerical relativity code for fundamental physics

DOI 10.5281/zenodo.7791842

Witek, Helvi; Zilhao, Miguel; Bozzola, Gabriele; Cheng, Cheng-Hsin; Dima, Alexandru; Elley, Matthew; Ficarra, Giuseppe; Ikeda, Taishi; Luna, Raimon; Richards, Chloe; Sanchis-Gual, Nicolas; Silva, Hector

https://bitbucket.org/canuda/

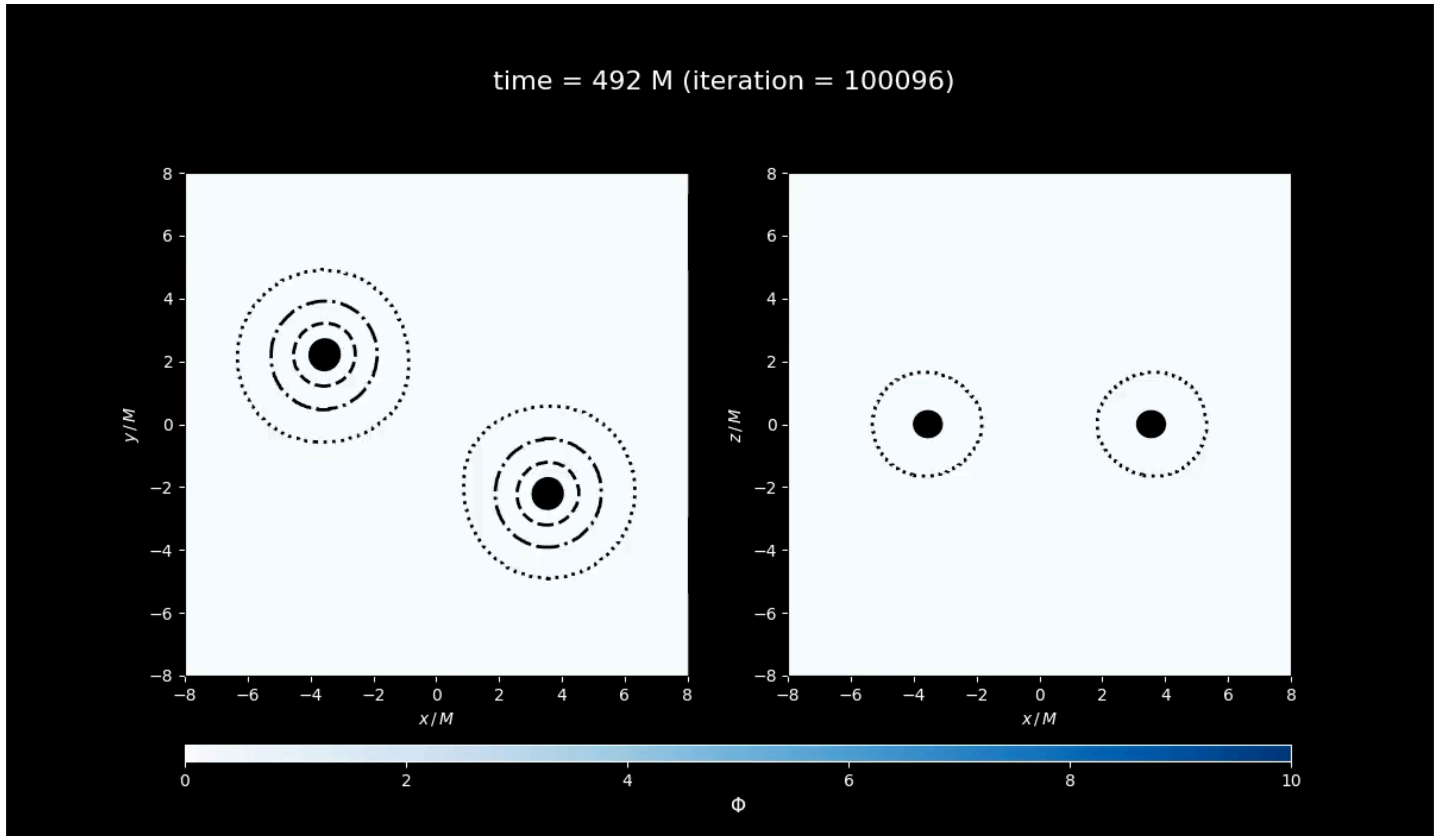
Canuda Numerical Relativity

[Equivalent numerical approach in dCS: Okounkova et al ’17-’19]

Scalar Gauss-Bonnet gravity II: dynamical (de-)scalarization
(Silva, Elley, HW, Yunes '21, '22)

$$(\Box - \mu_{eff}^2)\Phi = 0 \quad \mu_{eff}^2 \sim -\lambda\,\mathcal{G}$$

- Consider quadratic coupling of scalar field
- Scalarization of single black holes if $\mu_{eff}^2 < 0$
- Coalescence → dynamical scalarization or desclarization
- Nonlinear phenomenon may affect only merger and postmerger!



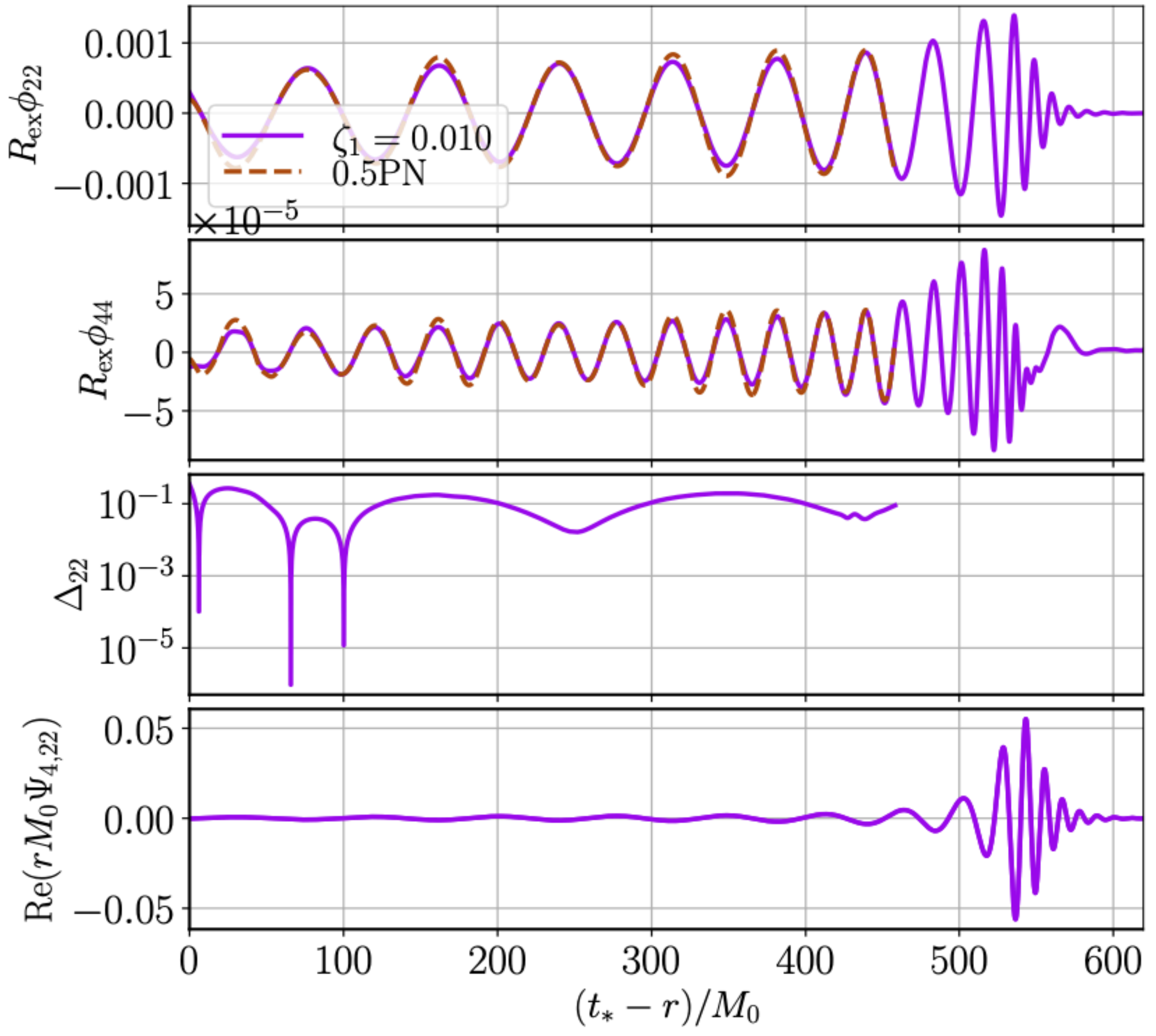
[Single BHs: Silva et al '17, Doneva et al '17, Antoniou et al '17, Blazquez-Salcedo '18, Macedo et al '19, Ripley & Pretorius '20,
Spin-induced scalarization: Dima et al '20, Hod '20, Doneva et al '20, Herdeiro et al '20, Berti et al '20,
Binaries: Silva, HW, Elley, Yunes '21; East, Ripley '21; Review: Doneva et al '22]

Scalar Gauss-Bonnet gravity w/ modified generalized harmonic gauge

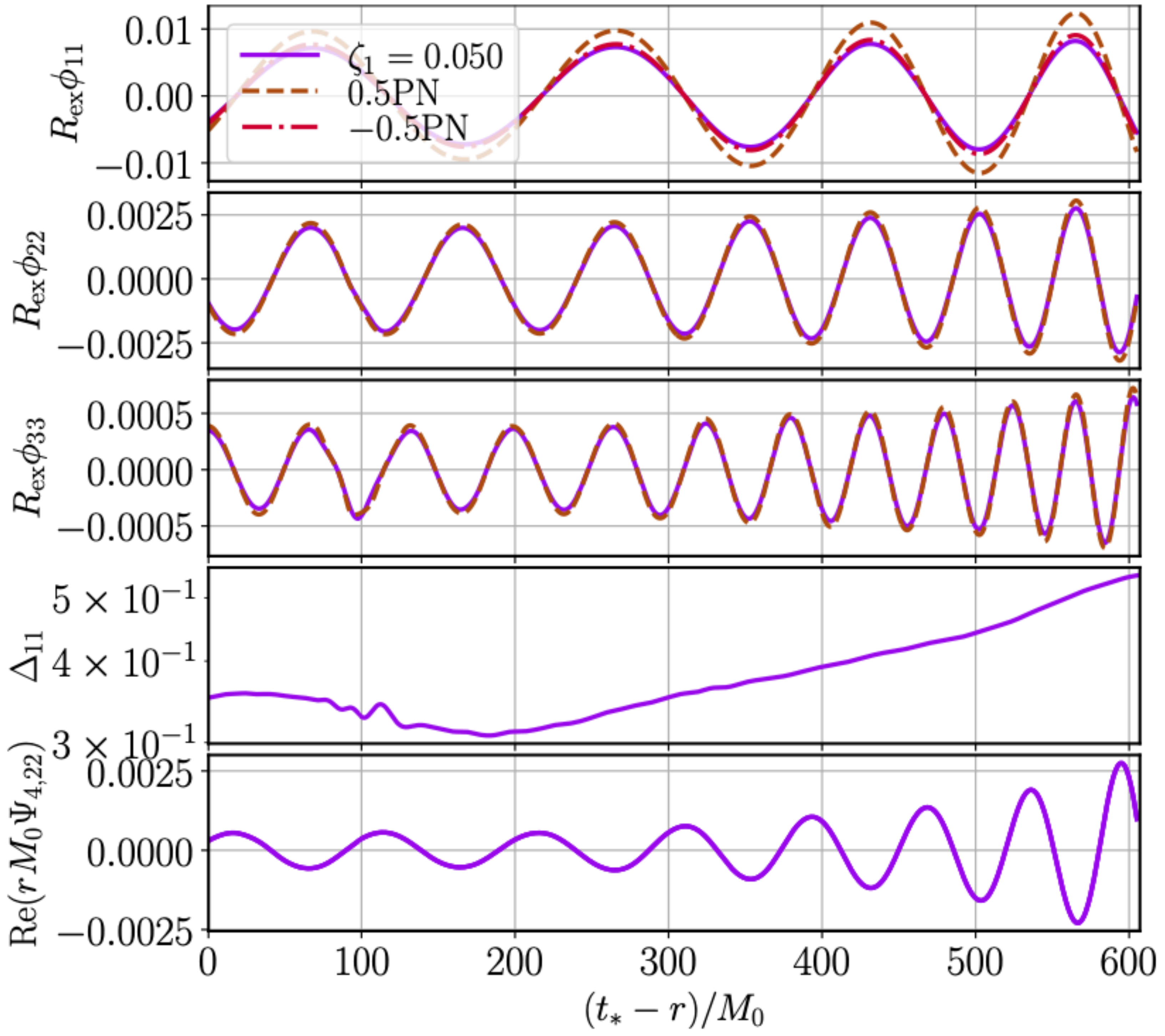
(Corman, Ripley, East ’22)

- Scalar Gauss-Bonnet gravity $\mathscr{L} = R - \frac{1}{2}(\nabla\Phi)^2 + \frac{\alpha_{GB}}{4}\Phi\mathscr{G}$
- Modified generalized harmonic gauge
- Breakdown near merger for some parameters

Mass ratio q = 1



Mass ratio q = 1/2



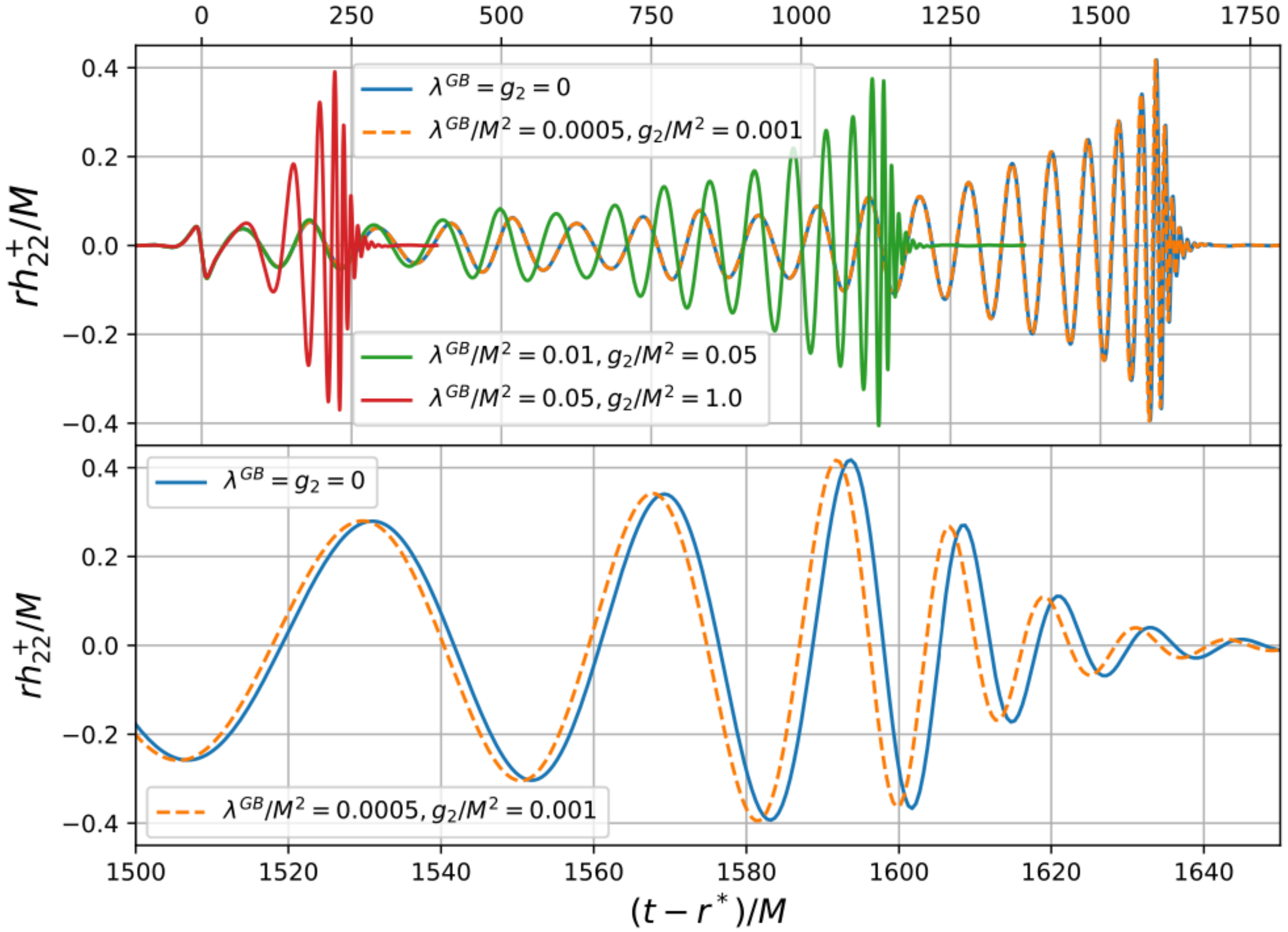
[See also Kovacs & Reall ’20, East & Ripley ’21, ’22]

Four derivative scalar-tensor theory
(Sole, Clough, Figueras ’22)

- General scalar-tensor theory w/ up to four derivatives

$$\mathscr{L} = R - \frac{1}{2}(\nabla\Phi)^2 + \frac{\lambda_{GB}}{4}\Phi\mathscr{G} + g_2(\Phi)(\nabla\Phi)^4$$

- Using ccZ4 w/ modified puncture gauge (inspired by modified generalized harmonic gauge)
- Binary black holes w/ q=1, d=11M

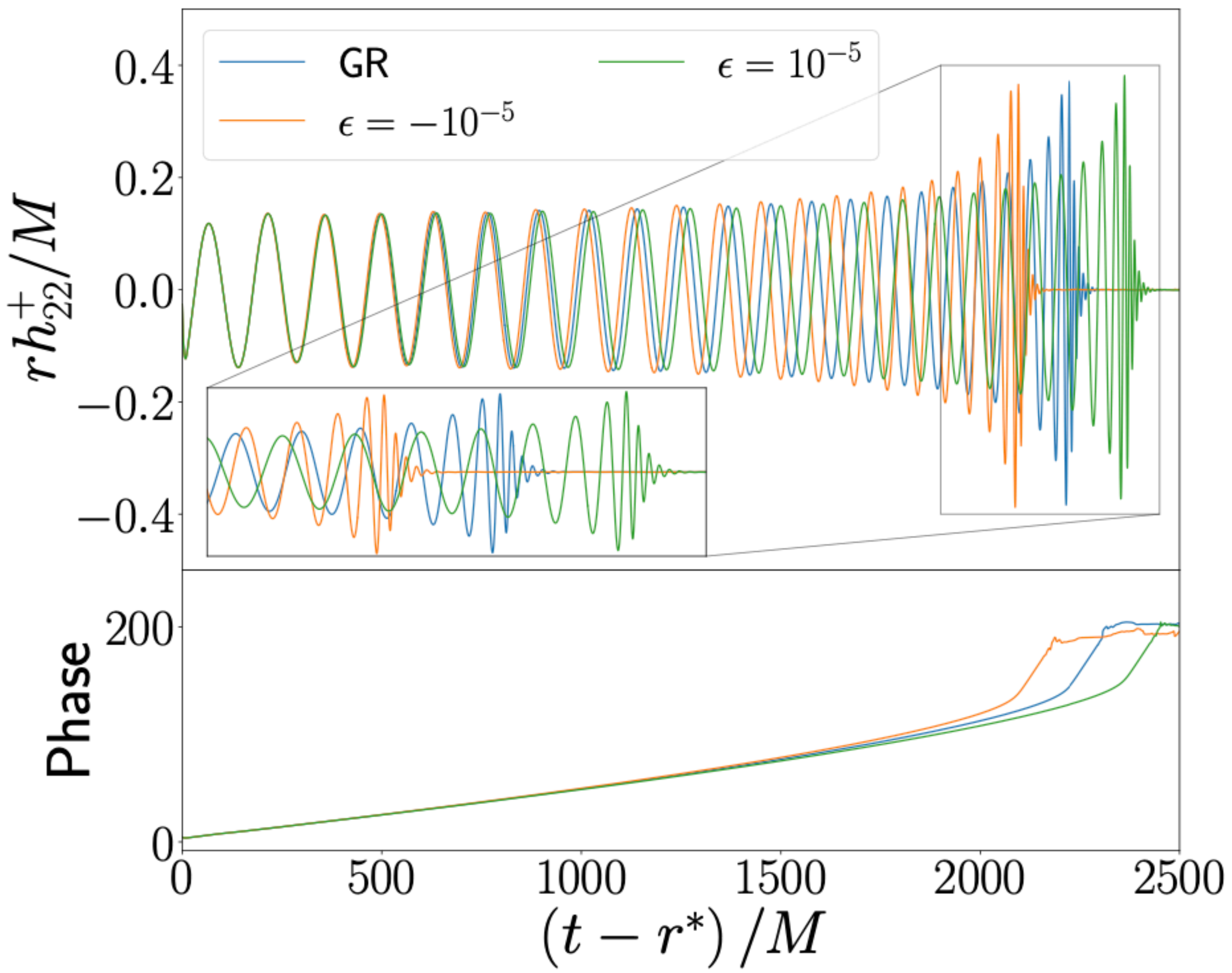


Fourth order effective field theory of gravity
(Cayuso, Figueras, Franca, Lehner '23)

- Effective field theory of gravity (parity even and in vacuum)

$$\mathscr{L} = R - \frac{1}{\Lambda_6}(R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma})^2 + \ldots$$

- Using
  i. order reduction
  ii. fixing equations a la Israel-Stewart
- Binary black holes w/ q=1, d = 12M



[J. Cayuso, Ortiz, Lehner '17, Allwright & Lehner '18, Franchini et al '22, Lara et al '22, Gerhardinger et al '22]

Note: order reduction refers to inserting the eoms for the Ricci tensor, thus shifting its contribution to higher-order.
Sometimes this terminology is used for the order-by-order expansion, but not here

A note of caution

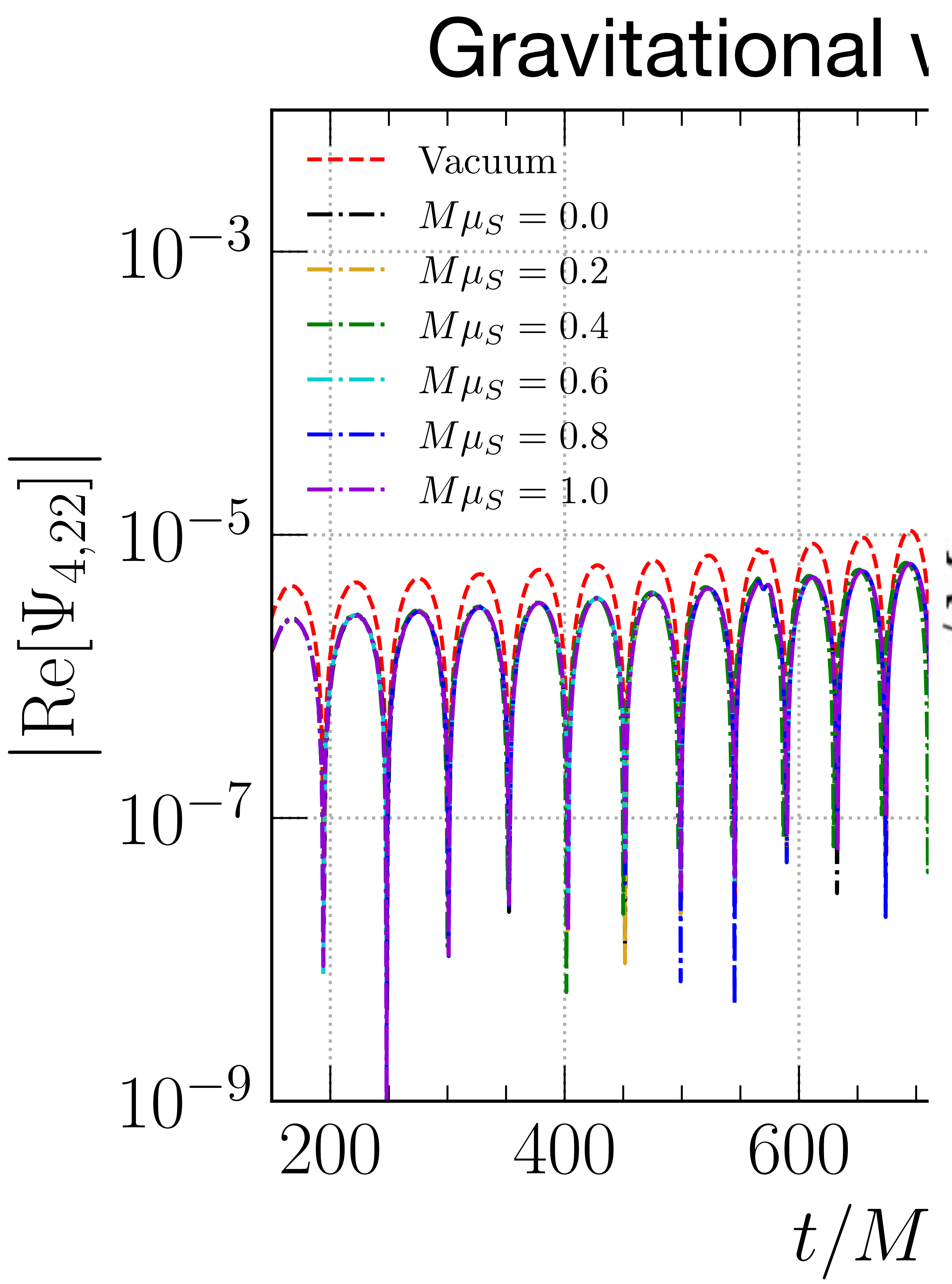
What about degeneracies with

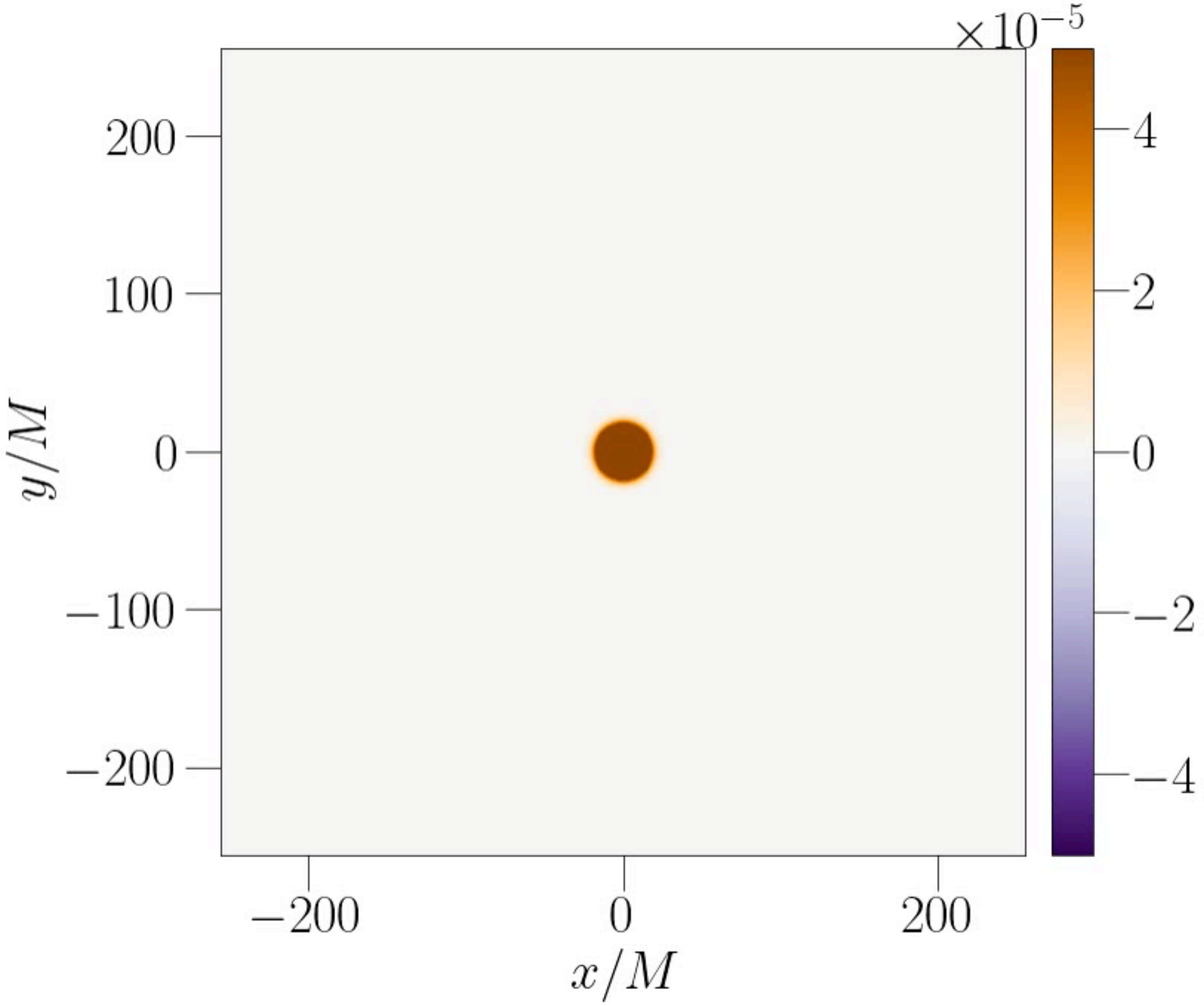
- **Unmodeled GR effects?**
- **Environment?**
- **…**

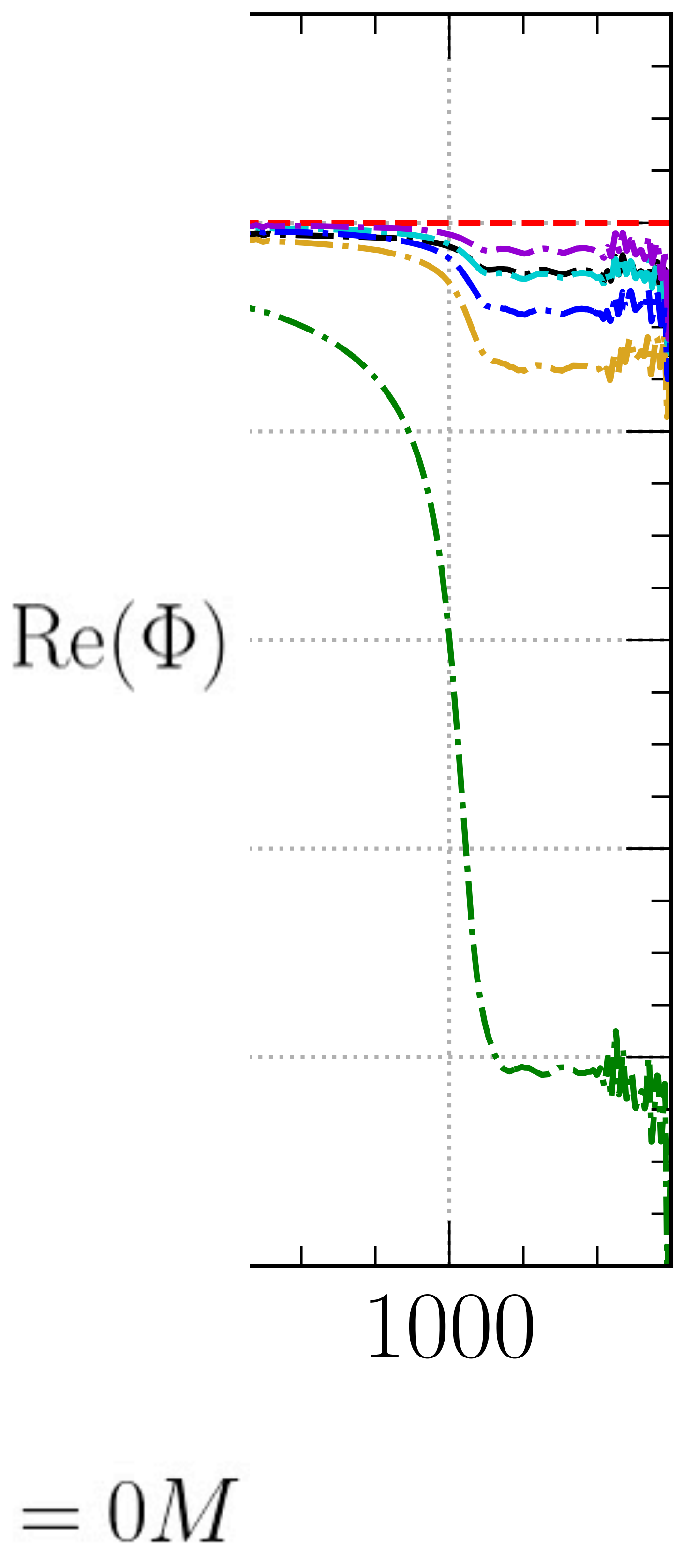
Black holes binaries in dark matter environments
(C.-H. Cheng, Ficarra, HW in prep.)

- Consistent evolution of massive scalar cloud around binary black hole
  - Goal 1: new gravitational wave probe for new particles
  - Goal 2: toy model for environmental effects during merger
- Constraint satisfying initial data and eccentricity reduction

$$\Box \Phi - \mu^2 \Phi = 0$$







[See also Bamber et al ’22]

Summary

Status update in Numerical Relativity beyond GR (focus: higher derivative gravity)

- Proof-of-principle simulations of compact binary coalescence in classes of beyond GR model
- Scalar charges typical yields scalar (dipole/quadrupole) radiation
- Dephasing of gravitational wave signal
- Surprisingly simply merger signal — not as nonlinear as may have been expected

Where do we go from here?

- Synergy w/ PN and constructing full IMR models -> Waveform catalogs?
- Dictionary with theory-agnostic models for the plunge+merger (e.g. EoB)
- Concerns?
    - Robustness: waveform comparison and benchmark from different approaches and codes
    - Eccentricity reduction of initial data
    - Degeneracies with unmodelled GR or environmental effects

Thank you!

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Some advertisement:

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“New Frontiers in Strong Gravity III”
Science Center Benasque / Spain
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https://www.benasque.org/general/cgi-bin/years.pl?ano=2024