Compact Object Mergers Beyond Einstein

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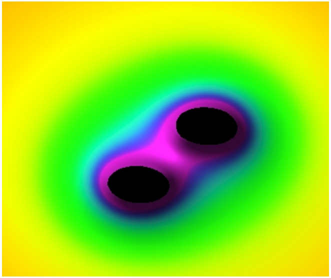


Exciting time where we're using gravitational wave astronomy to place constraint on new physics in entirely new way ...

Tests of General Relativity with Binary Black Holes from the second LIGO–Virgo Gravitational-Wave Transient Catalog

The LIGO Scientific Collaboration and the Virgo Collaboration
(compiled 29 October 2020)

Gravitational waves enable tests of general relativity in the highly dynamical and strong-field regime. Using events detected by LIGO–Virgo up to 1 October 2019, we evaluate the consistency of the data with predictions from the theory. We first establish that residuals from the best-fit waveform are consistent with detector noise, and that the low- and high-frequency parts of the signals are in agreement. We then consider parametrized modifications to the waveform by varying post-Newtonian and phenomenological coefficients, improving past constraints by factors of ~2; we also find consistency with Kerr black holes when we specifically target signatures of the spin-induced quadrupole moment. Looking for gravitational-wave dispersion, we tighten constraints on Lorentz-violating coefficients by a factor of ~2.6 and bound the mass of the graviton to $m_g \leq 1.76 \times 10^{-23}$ eV$/c^2$ with 90% credibility. We also analyze the properties of the merger remnants by measuring ringdown frequencies and damping times, constraining fractional deviations away from the Kerr frequency to $\delta\hat{f}_{220} = 0.03^{+0.38}_{-0.35}$ for the fundamental quadrupolar mode, and $\delta\hat{f}_{221} = 0.04^{+0.27}_{-0.32}$ for the first overtone; additionally, we find no evidence for postmerger echoes. Finally, we determine that our data are consistent with tensorial polarizations through a template-independent method. When possible, we assess the validity of general relativity based on collections of events analyzed jointly. We find no evidence for new physics beyond general relativity, for black hole mimickers, or for any unaccounted systematics.

Modified gravity theories

However, it's unclear whether most of these modifications are on the same theoretical footing as general relativity.

Modified gravity theories

Focus here on theories that give full (non-linear) alternative predictions to what happens when compact objects merge.

Well-posedness

The Einstein equations can be treated as a well-posed initial problem (Choquet-Bruhat 1952) e.g. in a harmonic formulation where we fix:

$$H^a := \Box x^a = 0 \ .$$

Major obstacle: Finding well-posed initial value problem in theories that modify the principal part of Einstein equations.

- Without weak hyperbolicity, arbitrarily high frequency perturbations blow up $\sim e^{\alpha\omega t}$
- Without strong hyperbolicity, arbitrarily high frequency perturbations blow up $\sim (\omega t)^n$
- Not just a numerical problem, but something you're forced to confront in simulations.

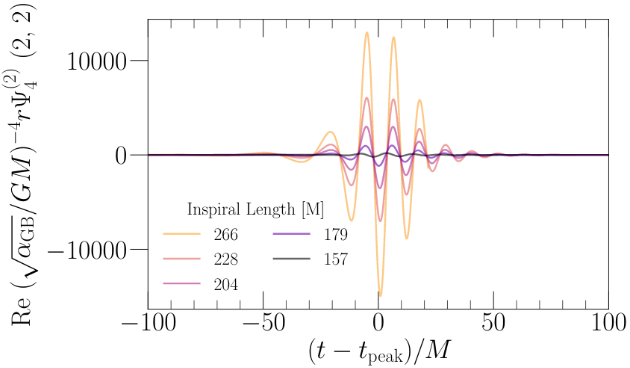
Modifying general relativity

$$S = \int d^4x\sqrt{-g}\Big(\frac{1}{2}R - \frac{1}{2}(\nabla\phi)^2 - V(\phi) + \alpha(\phi)(\nabla\phi)^4 + \beta(\phi)\mathcal{G} + \ldots$$
$$+ \gamma(\phi)\,{}^*R^{abcd}R_{abcd} + (R^{abcd}R_{abcd})^2/\Lambda^6 + \ldots\Big)$$

- Some modifications no longer have 2nd order equations of motion (E.g. Chern-Simons)
- Then have no choice but to use an approximate approach: e.g. order-reduction (Okounkova+ 2020, Galvez Ghersi+ 2021) or modify short wavelength behavior (Cayuso & Lehner 2020)
- **Potential problems:** Fail to capture non-perturbative or secular effects.

“Nope!"

Secular growth in order reduction



Okounkova (2020)

Modifying general relativity

$$S = \int d^4x\sqrt{-g}\left(\frac{1}{2}R - \frac{1}{2}(\nabla\phi)^2 - V(\phi) + \alpha(\phi)(\nabla\phi)^4 + \beta(\phi)\mathcal{G} + \ldots\right)$$

- For those with 2nd order equations (Horndeski theories) **may** be well-posed, but in general aren't in commonly used formulations.
- General Horndeski theories, no generalized harmonic gauge where the equations of motion are strongly hyperbolic in a generic weak-field background (Papallo & Reall 2017).

"Maybe. . . "

Modification to generalized harmonic — Kovacs & Reall (2020)

Introduce auxiliary metrics that determine gauge and constraint propagation.
Define

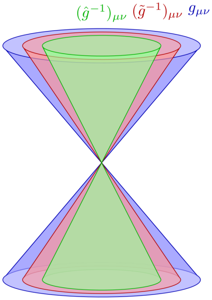
$$C^c := H^c - \tilde{g}^{ab}\nabla_a\nabla_b x^c = 0 \ .$$

Modify equations of motion as

$$E^{ab} - \frac{1}{2}\left(\delta^a_d\hat{g}^{bc} + \delta^b_d\hat{g}^{ac} - \delta^c_d\hat{g}^{ab}\right)\nabla_c C^d = 0$$

so constraint propagates as

$$\hat{g}^{ac}\nabla_a\nabla_c C^b = \ldots \ .$$



Modification to generalized harmonic — Kovacs & Reall (2020)

For $\{g_{ab}, \tilde{g}_{ab}, \hat{g}_{ab}\}$ distinct, equations of motion in modified harmonic formulation are strongly hyperbolic for Horndeski theories at sufficiently weak coupling, i.e. with $\lambda \ll L^2$.

Doesn't tell you about non-negligible coupling. (But don't expect to be able to make a general statement.)

Non-perturbative dynamics of Horndeski

Question: Can we get this to work with strong-field/dynamical systems (e.g. black hole mergers) and non-negligible coupling?

WE & Justin Ripley PRD 103, 044040 (2021) arXiv:2011.03547

Einstein scalar Gauss Bonnet gravity

- Focus on Einstein scalar Gauss Bonnet

$$S = \frac{1}{8\pi} \int d^4x \sqrt{-g} \left(\frac{1}{2} R - \frac{1}{2} (\nabla\phi)^2 + \beta(\phi)\mathcal{G} \right)$$

with $\mathcal{G} = R^2 - 4R^{ab}R_{ab} + R^{abcd}R_{abcd}$.

- Representative example of Horndeski, violates null convergence condition
- Has attracted much attention lately, due to black hole solutions with scalar hair
- Can leverage experience regarding hyperbolicity in spherically symmetric case

ESGB equations in modified harmonic

Evolution variables $\{g_{ab}, \partial_t g_{ab}, \phi, \partial_t \phi\}$

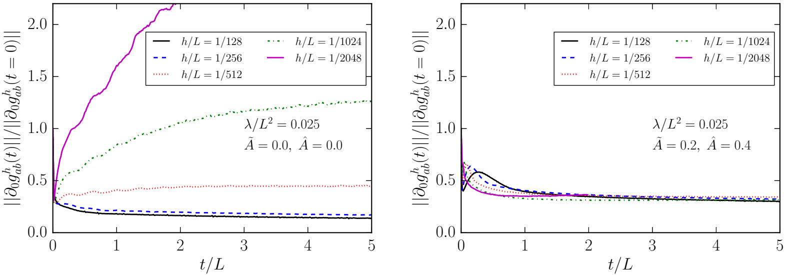
$$\begin{pmatrix} A_{ab}{}^{ef} & B_{ab} \\ C^{ef} & D \end{pmatrix} \partial_t^2 \begin{pmatrix} g_{ef} \\ \phi \end{pmatrix} + \begin{pmatrix} F_{ab}^{(g)} \\ F^{(\phi)} \end{pmatrix} = 0$$

with gauge choices $\{H^a, \tilde{g}_{ab}, \hat{g}_{ab}\}$.

- Equations now fully nonlinear, but linear with respect to repeated derivatives: e.g., no terms like $(\partial_c^2 g_{ab})^2$.
- Additional gauge degrees of freedom. (However, simple choices for $\tilde{g}_{ab}$ and $\hat{g}_{ab}$ seem to work.)
- Breakdown of equations inside black holes much more severe. **Excision essential.**

Improved hyperbolicity

Harmonic vs. auxiliary metric harmonic



Use of auxiliary metrics removes frequency dependent growth associated with weak (and not strong) hyperbolicity.

Shift-symmetric Einstein Scalar Gauss Bonnet

$$\Box\phi + \lambda\mathcal{G} = 0 \; ,$$

$$R_{ab} - \frac{1}{2}g_{ab}R + 2\lambda\delta^{efcd}_{ijg(a}g_{b)d}R^{ij}{}_{ef}\nabla^g\nabla_c\phi =$$

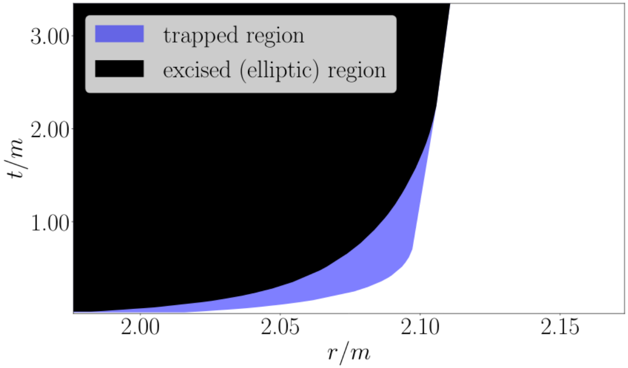
$$\nabla_a\phi\nabla_b\phi - \frac{1}{2}\left(\nabla\phi\right)^2 g_{ab} \; ,$$

- Vacuum black holes are not stationary solutions.
- Static solutions of black holes with scalar hair for $\lambda/M^2 \lesssim 0.2$ (Sotiriou & Zhou 2014)

See Witek+ (2019); Okounkova (2020) for mergers in test-field/order-reduced framework

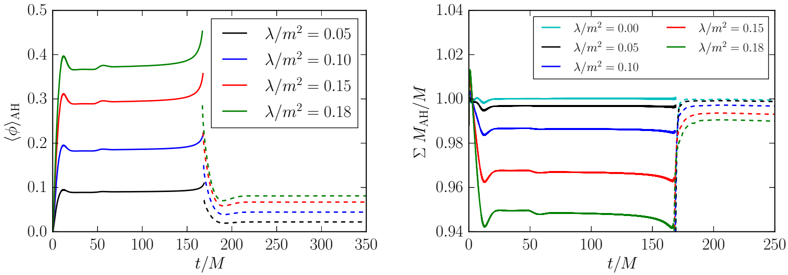
Breakdown of hyperbolicity in spherical symmetry

In spherical symmetry, when λ exceeds this limit, elliptic region develops outside black hole horizon (Ripley & Pretorius 2020).

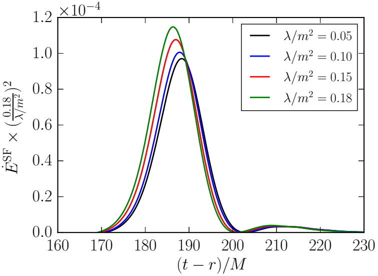


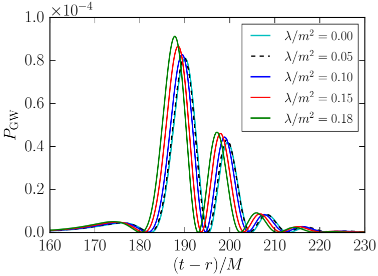
Roughly, PDEs are Tricomi type.

Black hole collisions in shift-symmetric ESGB



Black holes develop scalar hair while shrinking, and then collide.





Scalar and gravitational wave radiation in full shift-symmetric ESGB.

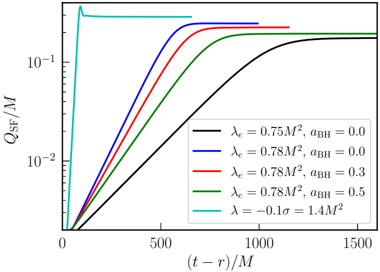
$\mathbb{Z}_2$ Symmetric Einstein Scalar Gauss Bonnet

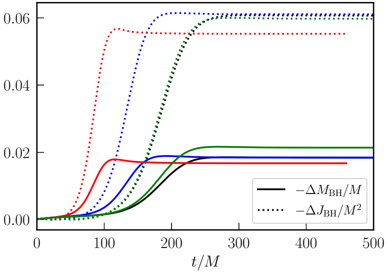
$$\beta(\phi) = \frac{\lambda}{2}\phi^2 + \frac{\sigma}{4}\phi^4 + \dots$$

- Vacuum black holes are stationary solutions, but can be unstable: $\Box\phi \approx -\lambda\phi\mathcal{G}$.
- Instability affects non-spinning BHs for $\lambda > 0$, only sets in at higher spin for $\lambda < 0$ (Doneva+ 2018, Silva+ 2018, Dima+ 2020).
- Stationary solutions of black holes with scalar hair for band of masses/spins at fixed coupling (Silva+ 2018, Berti+ 2021, Herdeiro+ 2021)

WE & Justin Ripley PRL 127, 101102 (2021) arXiv:2105.08571

Range of parameters where black holes with scalar hair are the stable endpoint of evolving a vacuum black hole.



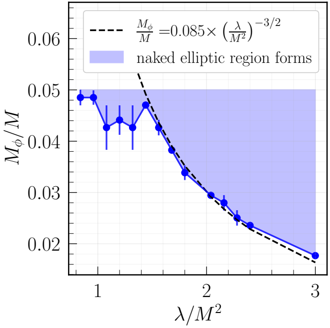


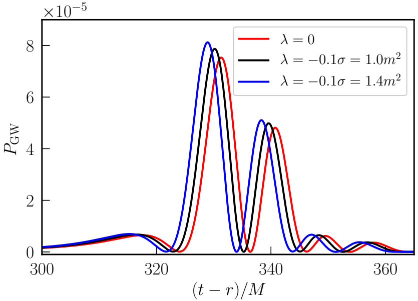
$\lambda > 0$: non-zero spin reduces instability

$\lambda < 0$: spin-induced scalarization

But cf. Maximum stable stationary BH has $\lambda_e \approx 8.6M^2$

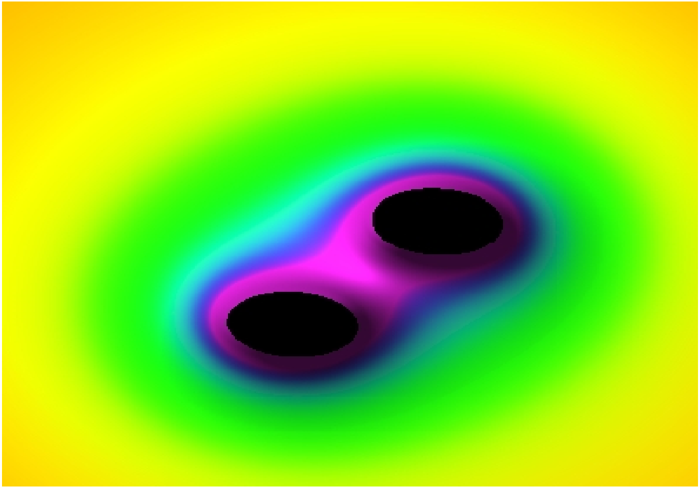
Hyperbolicity of dynamical formation more severely restricts parameters (compared to constructing stationary solutions)





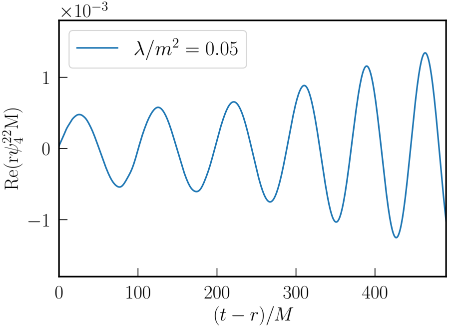
But still have interesting range (e.g. where effect on merger gravitational waves is significant)

Binary black hole inspiral in shift-symmetric ESGB



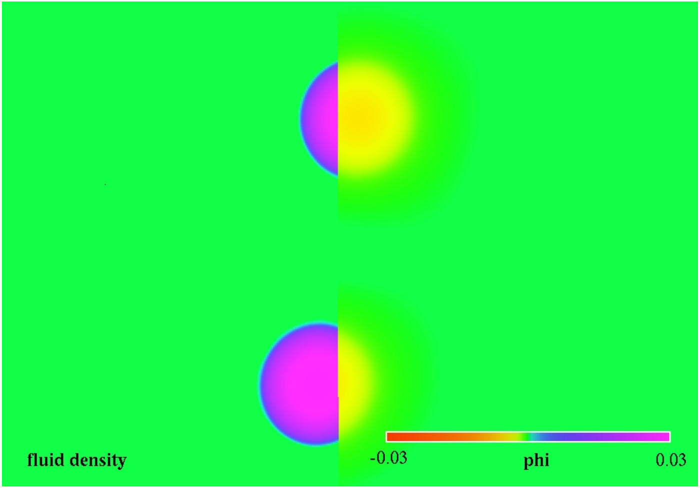
Binary black hole inspiral in shift-symmetric ESGB

Methods work well for quasi-circular inspiral at similarly large coupling, though merger may lead to earlier breakdown of theory (or methods).



Work in progress with J. Ripley and M. Corman

Binary neutron star merger



Neutron star mergers can create small black holes (relative to other known astrophysical channels), probe the smallest coupling.

Conclusions/Future work

We have now the tools to give complete answer to questions like: *What is the gravitational wave signal from a black hole merger in a Horndeski theory of gravity?*

Future work:

- Formulate/solve modified initial value problem (side-stepped here by using vacuum ID; see Kovacs 2021)
- Determine domain where theories are well-posed, and can give predictions for GW observations of compact object mergers.
- Compare to order-reduction, other approximations that may not capture secular/non-perturbative effects.