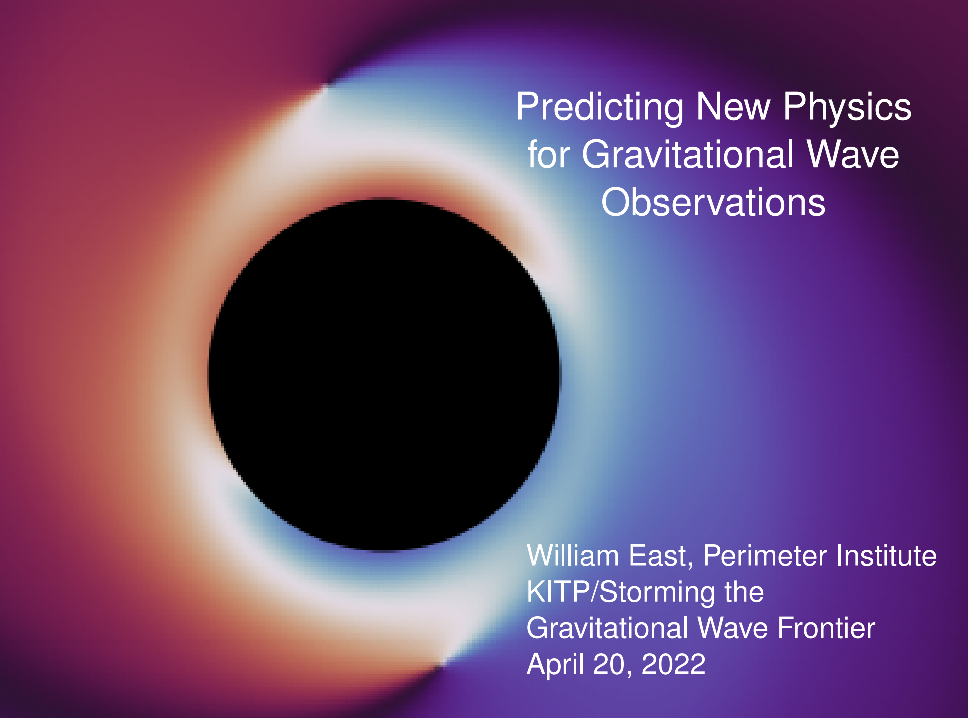


Predicting New Physics for Gravitational Wave Observations

William East, Perimeter Institute

KITP/Storming the
Gravitational Wave Frontier
April 20, 2022

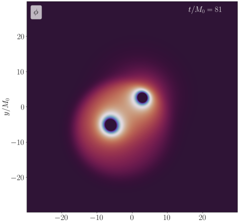
Introduction

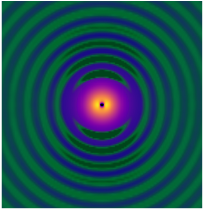
Theme: Making detailed predictions to provide best chance to find (constrain) new physics.

Two examples:

- Modifications to general relativity: Full (non-perturbative) calculations of compact object mergers in Horndeski class.
- Searching for ultralight bosons with black hole superradiance: accurate waveform models and including interactions

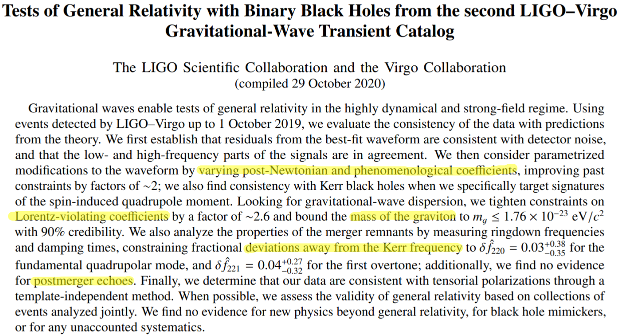
Gravitational wave observations are already constraining these, but theory is lagging behind.





Testing deviations from General Relativity

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.

Updated Tests of GR with GWTC-3 arXiv:2112.06861

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.

“Benchmark" modified theories important to sharpen both theoretical and data analyses.

Modifying general relativity (with a scalar)

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

- Some modifications no longer have 2nd order equations of motion (E.g. Chern-Simons) and seem unlikely to be well-posed.
- For those with 2nd order equations (Horndeski theories) **may** be well-posed for some parameters, but in general aren't in commonly used formulations even at weak coupling (Papallo & Reall 2017).

“Nope!"

Possible Approaches for Evolving Modified Gravity Theories

Order-reduction approximation (Okounkova+ 2019,2020; Galvez Ghersi+ 2021, others)
Advantage: At each order have same principle structure as Einstein-Klein-Gordon *Challenge*: Beyond test field, get secular error effects
Modify short wavelength behavior of theory (Cayuso, Lehner+ 2017,2020; Bezares+ 2021)
Advantage: Have well-posed system with same long-wavelength behavior *Challenge*: Have to introduce new short length/timescales ad-hoc
Solve full equations (WE & Ripley 2020,2021; Figueras & Franca 2021)
Advantage: No approximations to justify *Challenge*: Restricted to theories/parameters where system is well-posed.

We're taking the last mentioned approach.

Modification to generalized harmonic — Kovacs & Reall (2020)

Introduce auxiliary metrics that determine gauge and constraint propagation.
Define

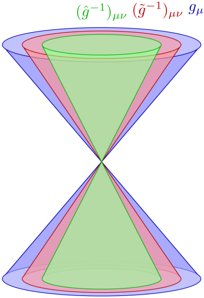
$$C^c := H^c - \tilde{g}^{ab}\nabla_a\nabla_b x^c = 0\ .$$

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

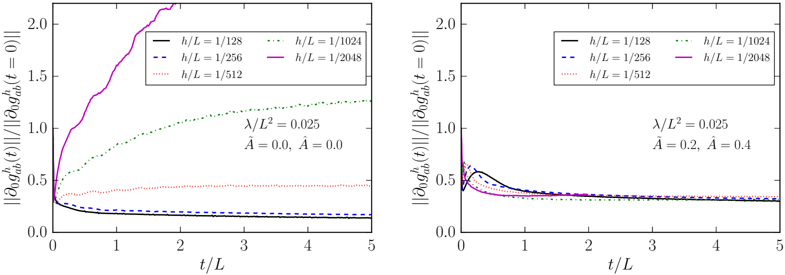
$$\hat{g}^{ac}\nabla_a\nabla_c C^b = \ldots\ .$$



For $\{g_{ab}, \tilde{g}_{ab}, \hat{g}_{ab}\}$ distinct, EOMs are strongly hyperbolic for Horndeski theories at weak coupling, ($\lambda \ll L^2$).

Improved hyperbolicity

Harmonic vs. auxiliary metric harmonic



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

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

WE & Justin Ripley (2021)

Einstein scalar Gauss Bonnet gravity

Focus on this as initial benchmark theory:

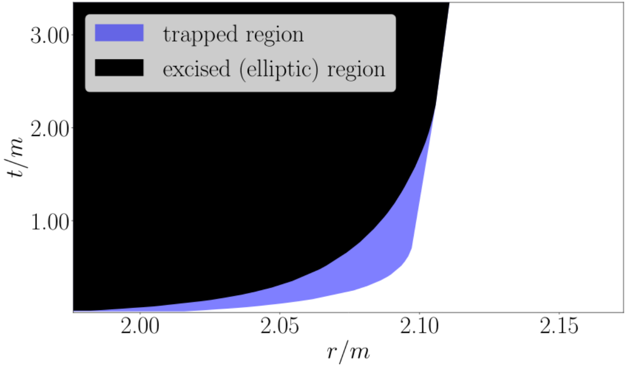
$$S = \frac{1}{8\pi} \int d^4x \sqrt{-g} \left(\frac{1}{2} R - \frac{1}{2} (\nabla\phi)^2 + \beta(\phi)\mathcal{G} \right)$$

with $\mathcal{G} = R^2 - 4R^{ab}R_{ab} + R^{abcd}R_{abcd}$, $\beta(\phi) = \lambda\phi$.

- Representative example of Horndeski, violates null convergence condition. Equations now fully nonlinear.
- Has attracted much attention lately, due to black hole solutions with scalar hair, results on PN expansion, stationary black hole solutions, mergers in test-field/order-reduced framework (Sotiriou+ 2013,2014; Witek+ 2019; Okounkova 2020; Delgado+ 2020, Sullivan+ 2020, Shiralilou+ 2021, others).
- Can leverage experience regarding hyperbolicity in spherically symmetric case

Breakdown of hyperbolicity in spherical symmetry

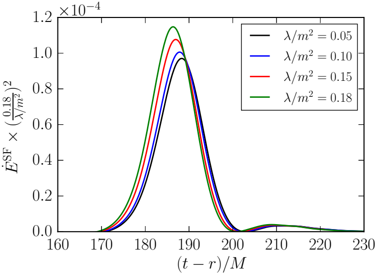
In spherical symmetry, when λ exceeds the limit for a given black hole mass, elliptic region develops outside black hole horizon (Ripley & Pretorius 2020).

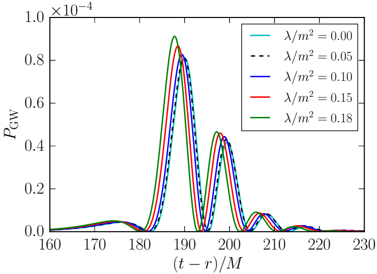


Roughly, PDEs are Tricomi type. **Excision essential.**

Black hole collisions: radiation

Dynamical solutions approaching isolated black hole limit ($\lambda/m^2 \lesssim 0.2$)

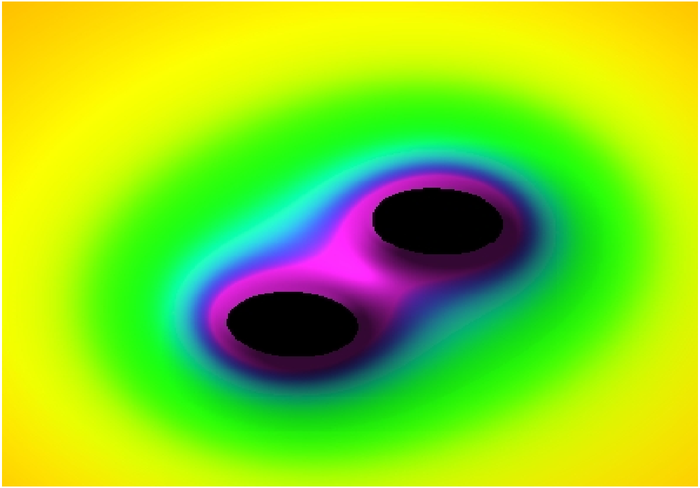




WE & Justin Ripley (2021)

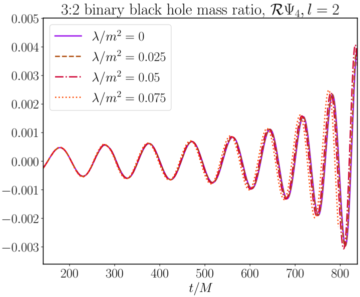
Scalar and gravitational wave radiation in full shift-symmetric ESGB.

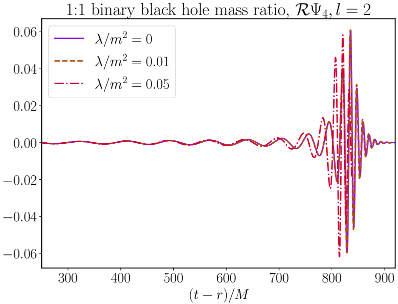
Binary black hole inspirals in shift-symmetric ESGB



Binary black hole inspiral in shift-symmetric ESGB

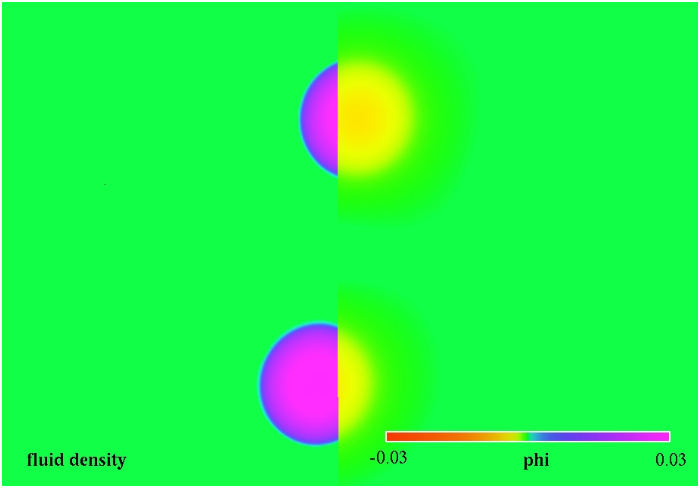
Methods work well for quasi-circular inspiral at similarly large coupling, though merger may lead to earlier breakdown of theory (or methods).





Work in progress: Maxence Corman, Justin Ripley, WE

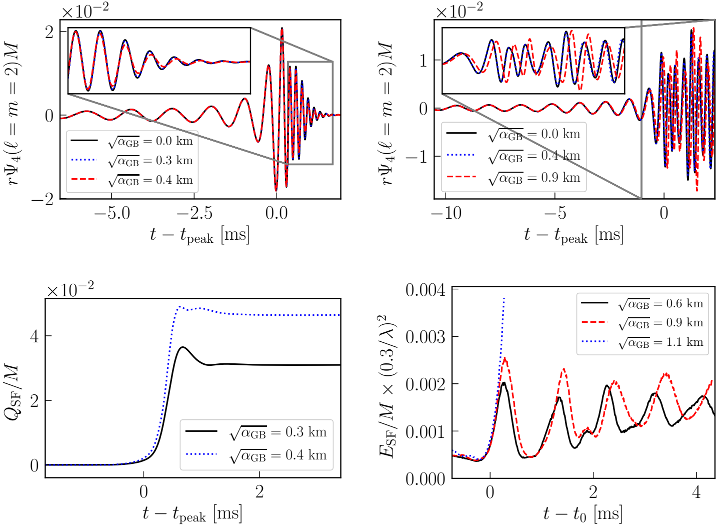
Binary neutron star merger



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

Binary neutron star merger

Prompt collapse vs. Long-lived remnant



WE+, in prep.

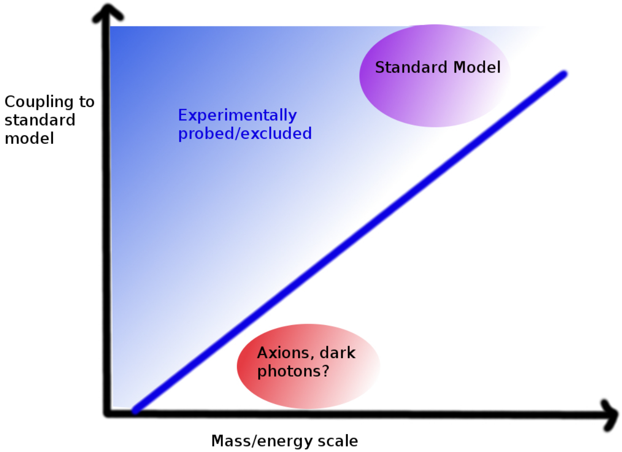
Conclusions/Future work

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

Future work:

- Determine domain where theories are well-posed (Reall 2021), and can give predictions for GW observations of compact object mergers.
- Compare to post-Newtonian, order-reduction, short-wavelength fixing, other approximations.
- Potentially use for benchmarking data analysis methods
- Formulate/solve modified initial value problem (side-stepped here by using vacuum ID; see Kovacs 2021)
- Other phenomenologically interesting theories (see WE & Ripley 2022)

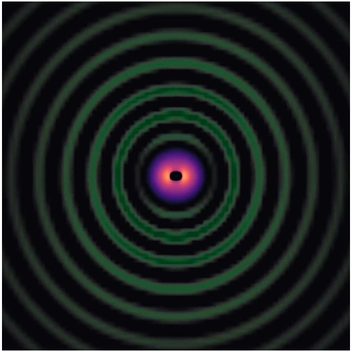
Gravitational wave probe of new particles



Search new part of parameter space: ultralight particles weakly coupled to standard model

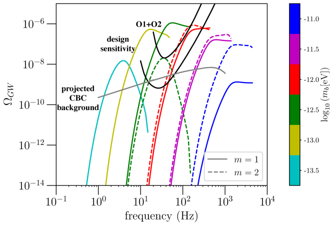
Superradiant instability: realizing the black hole bomb

- **Massive** bosons (scalar and vector) can form bound states, when frequency $\omega < m\Omega_H$ grow exponentially in time.
- Search for new ultralight bosonic particles (axions, dark massive "photons," etc.) with Compton wavelength comparable to black hole radius (Arvanitaki et al.)



WE (2018)

Observational signatures of ultralight boson superradiance



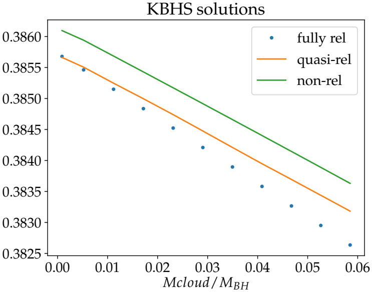
Tsukada, Brito, WE, Siemonsen (2020)

- Measure black hole spin from merger GWs, or EM observations of accreting BHs. (Baryakhtar+ 2017; Ng+ 2021)
- Blind GW searches for either resolved or stochastic sources with LIGO (Brito+ 2017; Tsukada+ 2019; Zhu+ 2020; LVK 2021)
- Targeted GW searches–e.g. follow-up black hole merger events. Obviates need to make assumptions on black hole population. (Isi+ 2019)

GW frequency evolution

Frequency of cloud oscillation/GW has small correction due to self gravity which changes over time. Not taking this into account limits time GW can be coherently integrated (typically assume $|\dot{f}_{\rm GW}| \lesssim 10^{-11}$ Hz/s).

- As cloud dissipates, leads to chirp (increase in $f_{\rm GW}$)
- Nonlinear effect: previously only Newtonian estimates
- Here we use exact solutions under an oscillation-averaged approximation (following Herdeiro & Radu, 2014)



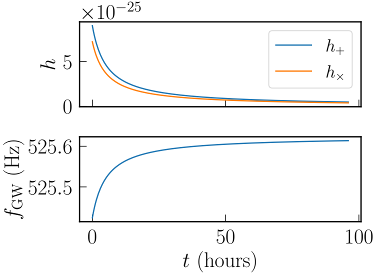
Scalar boson with $\mu M = 0.4$

Work in progress: Taillte May, Nils Siemonsen, WE

Waveform model for black hole superradiance

Introducing `superrad` waveform model:

- Scalar and vector bosons [Siemonsen & WE (2020)]
- Frequency drift as cloud mass evolves
- Fully relativistic (black hole perturbation): valid for loudest signals
- Plan to release publicly available software



$\mu_{\rm Vec.} = 10^{-12}$ eV; $M_{\rm BH} = 20\ M_\odot$;
$a_{\rm BH} = 0.8$; $d_{\rm Obs} = 100$ Mpc

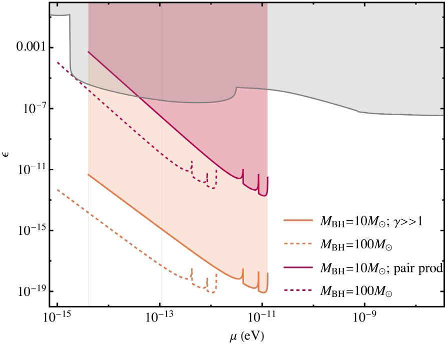
Coming soon: Nils Siemonsen, Taillte May, WE

Kinetic mixing of dark photon

Consider a small kinetic mixing between a (massive) dark photon and the standard model photon

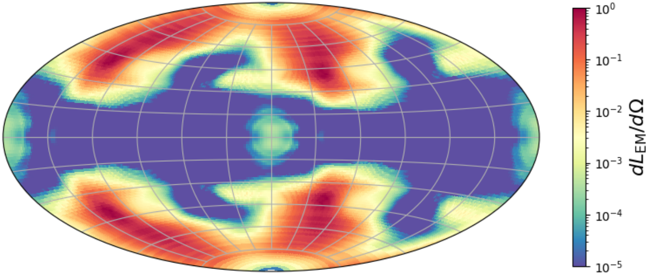
$$\mathcal{L}_{\rm mass} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\mu^2}{2}A'_{\mu}A'^{\mu} + J_{\mu}(A^{\mu} + \varepsilon A'^{\mu})$$

- Ultralight boson clouds have oscillating dark electric field that weakly couples to electrons.
- For allowed ϵ, can create plasma through pair production



Preliminary results: Nils Siemonsen, M. Baryakhtar, WE, D. Egana-Ugrinovic, J. Huang, C. Mondino

New Pulsar from dark photon?



- Can lead to pulsar-like electromagnetic transient
- Oscillation and decay timescales will match boson/black hole mass.

Preliminary results: Nils Siemonsen, M. Baryakhtar, WE, D. Egana-Ugrinovic, J. Huang, C. Mondino

Outlook

- Gravitational waves are powerful probe of ultralight bosons
- With detailed understanding of relativistic dynamics can maximize sensitivity and extend results
- Signals in some regimes motivate thinking about new searches (e.g. intermediate timescales to continuous and merger signals)
- Couplings to standard model and self-interactions may give rise to new observables