Title: Portents of new physics from extreme gravity

Speakers: William East

Series: Colloquium

Date: May 31, 2023 - 2:00 PM

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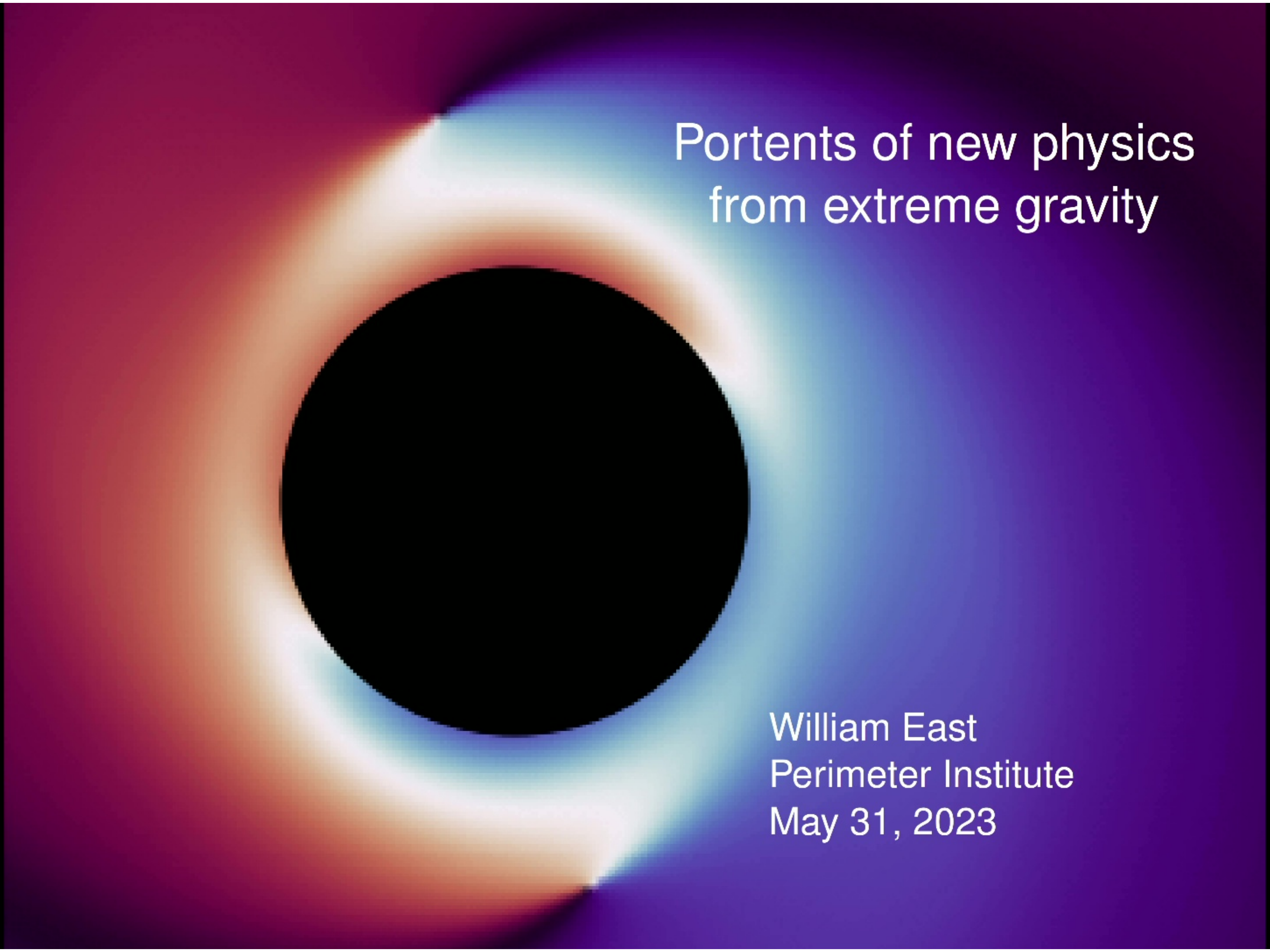
Abstract: Complementing the spectacular breakthroughs in gravitational wave and multi-messenger astronomy, advancements in our theoretical understanding and modelling of the strong gravity are essential to apprehending the nonlinear dynamics of spacetime, and to unlocking the full potential of the observations. I will illustrate the scope of new physics that might be probed by black holes, neutron stars, and other such systems, including testing general relativity and strong gravity signatures of new particles, and describe some recent developments that allow for uncovering novel phenomena and making detailed predictions in this regime.

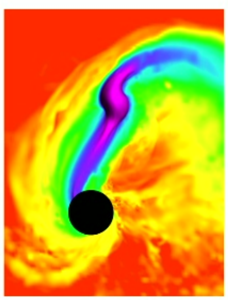
Zoom Link: https://pitp.zoom.us/j/96180256322?pwd=LzEyd3ZBWGdZeDR6MjB1dGpLWFRpUT09

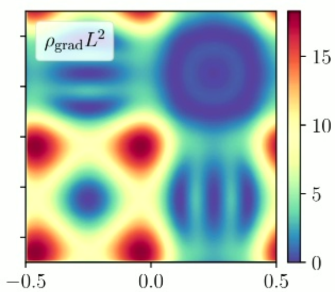

Portents of new physics
from extreme gravity
William East
Perimeter Institute
May 31, 2023

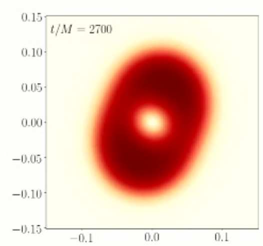
Nonlinear dynamics of spacetime

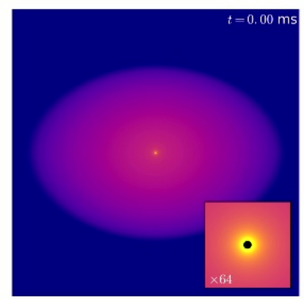
Constellation of questions, and methods for answering them, regarding the nonlinear dynamics of gravity in the strong field regime.

- What does GR predict, and how close are our observations (and approximations) to this prediction?
- How does gravity combine with the nonlinear dynamics of matter/fields to give rise to new phenomena?
- Can we make detailed predictions for new physics/modified gravity?
- What is the ultimate fate of an unstable strongly gravitating system?
- When does general relativity breakdown?
- What happens in the inhomogeneous and strong field regime of cosmology?
- . . .

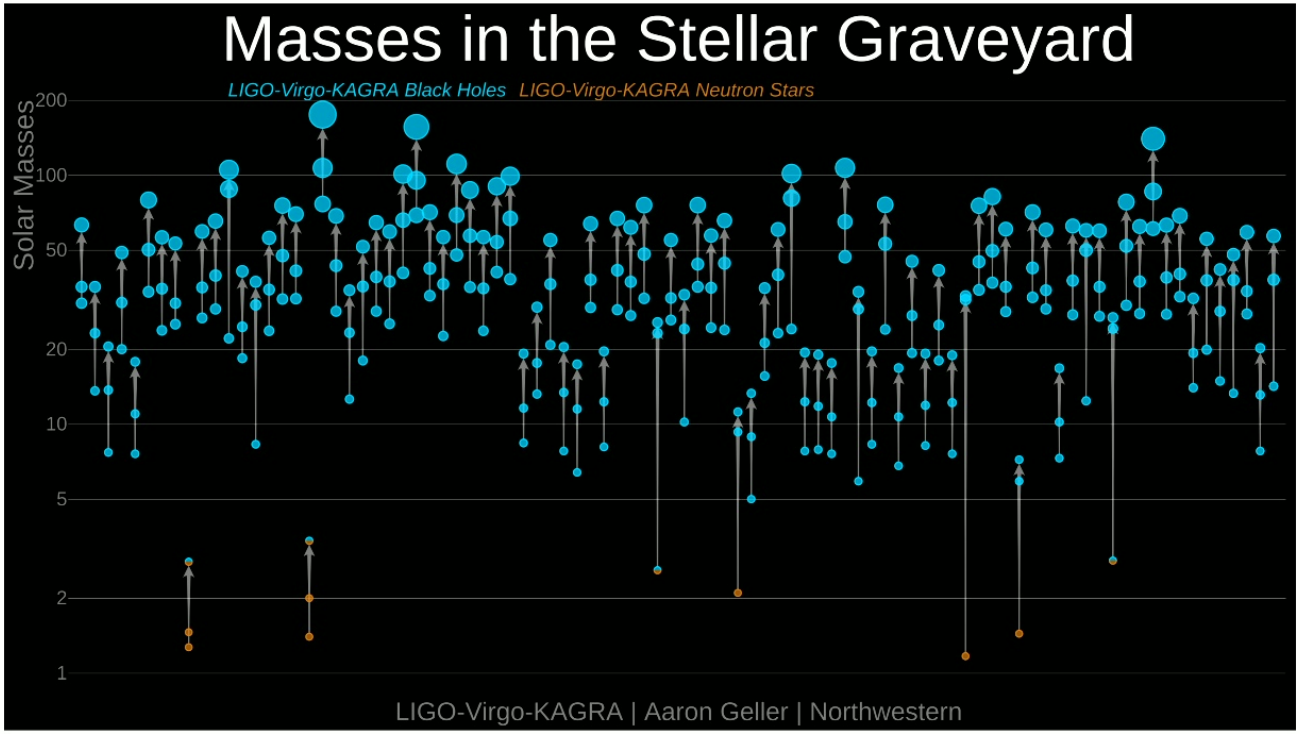








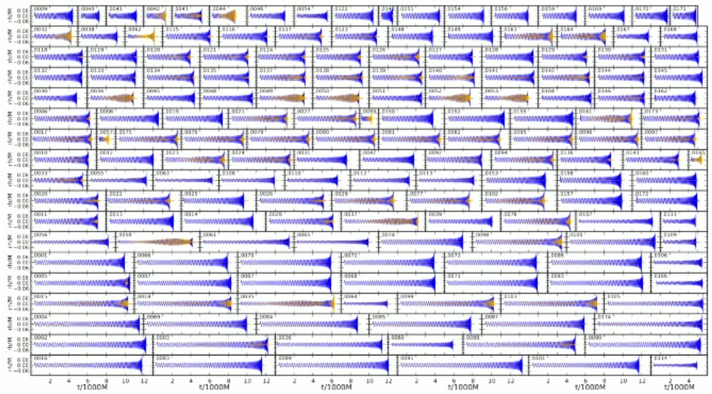
Unveiling black holes and neutron star binaries with gravitational waves



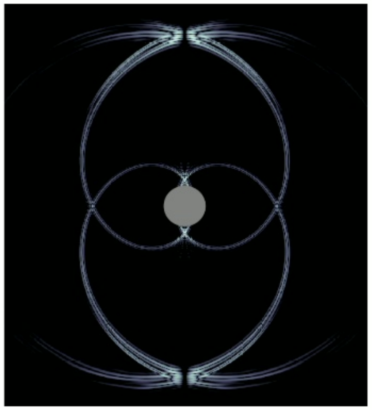
Interplay of theory and observations

Need to understand GR to use (and test) it with observations:

- When and how can one make predictions?
- When does the theory breakdown, and how does that affect predictivity? (cosmic censorship)

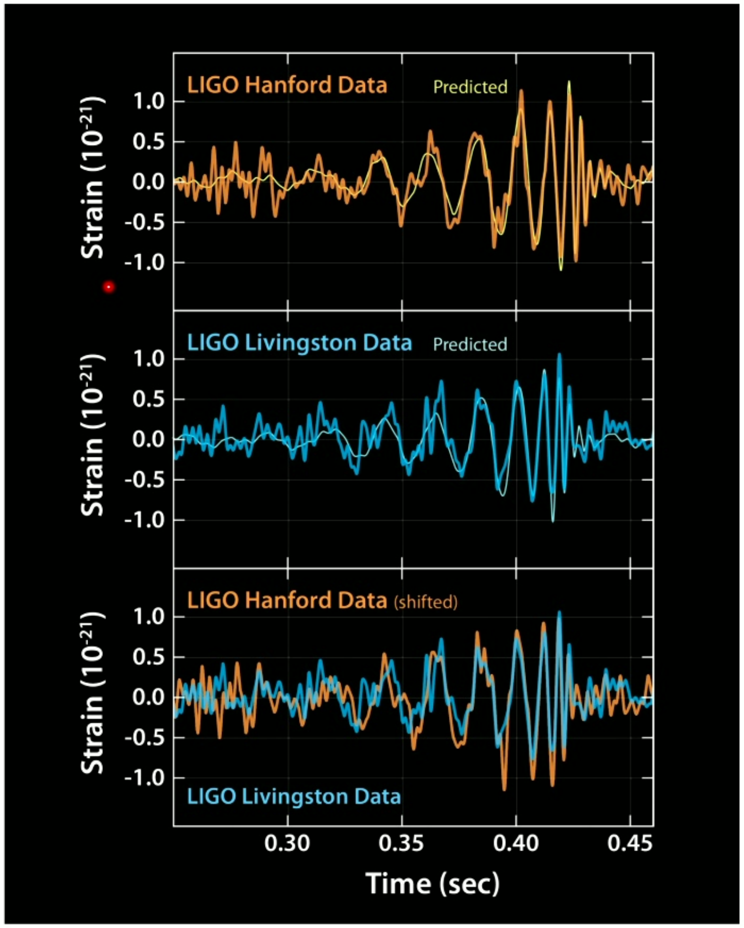


Mroué+ 2013



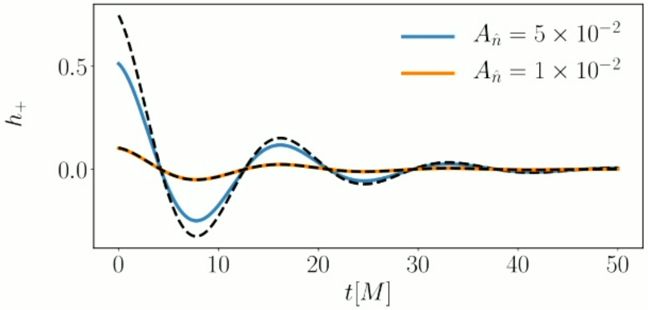
WE 2019

Black hole merger and ringdown



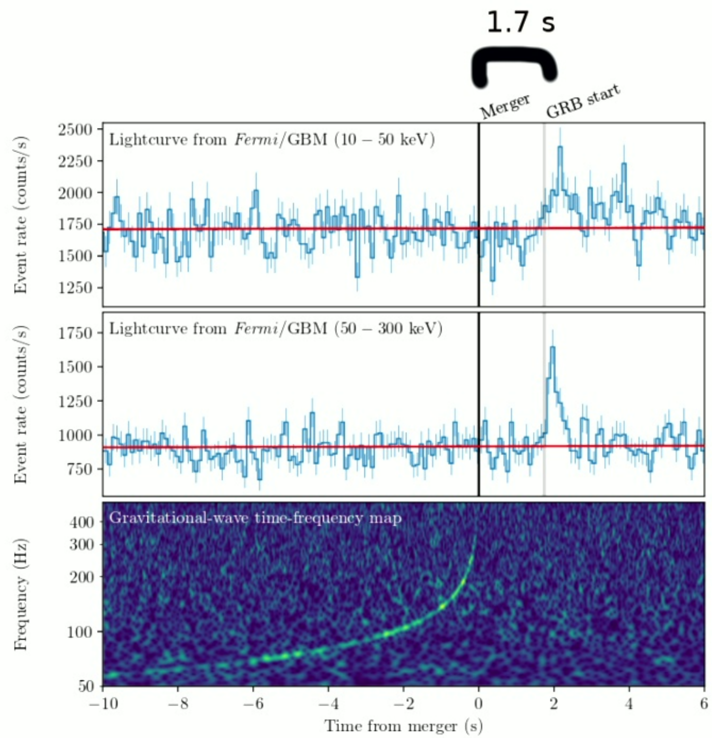
Caltech/MIT/LIGO Lab

- Observations of nonlinear dynamics of spacetime confronted with predictions
- Quasinormal ringdown encodes remnant properties and can be a clean test of GR
- But still debate regarding when ringdown is linear



Sberna, Bosch, WE+ (2022)

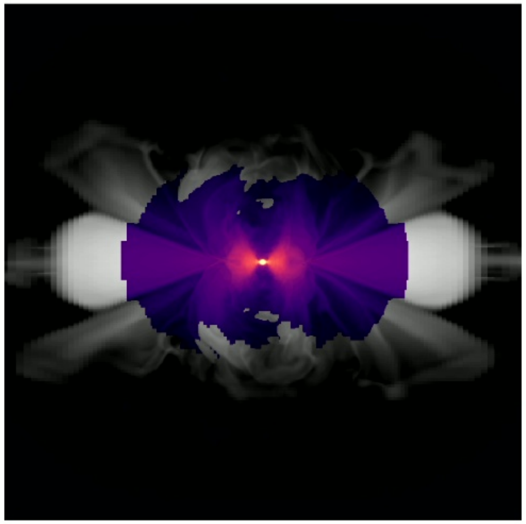
Multimessenger astronomy with neutron star mergers



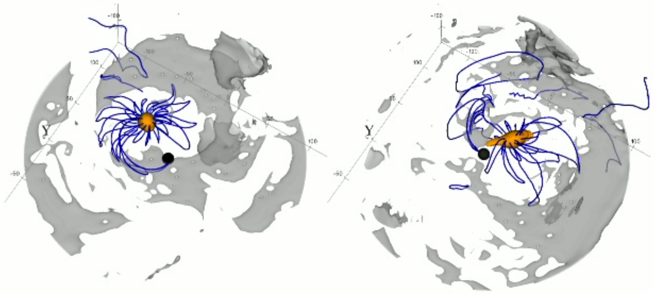
LIGO/Virgo Collaboration+ 2017

- Concurrent observations with range of telescopes.
- Need theory to fill in the gap, and connect the disparate physics.
- In many cases, electromagnetic counterparts only way to identify presence of star (without astrophysical priors)

Electromagnetic transients reveal new aspects



WE+ 2019



WE+ 2021

- Accretion disk and ejected material sensitive to binary parameters and neutron star properties
- Precursor electromagnetic transients from magnetospheric interactions

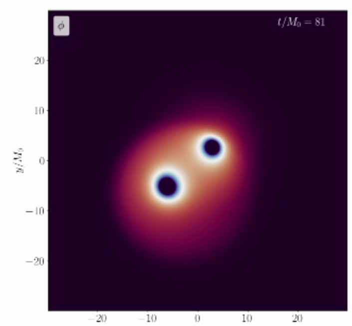
Focus

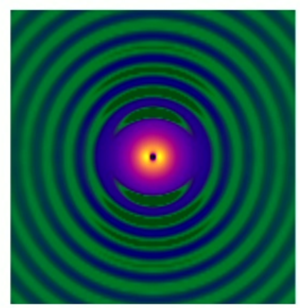
Theme: Making rigorous predictions to provide best chance to find (constrain) new physics.

Two examples:

- Modifications to GR: Non-perturbative calculations of compact object mergers in theories with second-order EOMs.
- Searching for ultralight vector bosons with black hole superradiance: accurate waveforms and including interactions.

Gravitational wave observations are already probing 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

Theory lagging behind: It's unclear whether most of these modifications are on the same theoretical footing as general relativity.

Modified gravity theories

Ideal modified theory:

- Physically motivated
- Gives new phenomenology compared to GR
- Is consistent with current observations while having potential to be tested with near-future observations
- Theory can give full (non-linear) alternative predictions to what happens when compact objects merge.

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

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:

$$\nabla_a \nabla^a x^b = 0 \ .$$

But doesn't work in general for modified theories (*Papallo & Reall 2017*).

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

- Without this property, arbitrary small changes to the initial conditions can lead to solutions that diverge arbitrary fast
- Not just a numerical problem, but something you're forced to confront in simulations.

Possible Approaches for Evolving Modified Gravity Theories

Order-reduction approximation	
Advantage: At each order have same principle structure as Einstein equations *Challenge*: Beyond test field, get secular error effects	
Modify short wavelength behavior of theory	
Advantage: Have well-posed system with same long-wavelength behavior *Challenge*: Have to introduce new short length/timescales ad-hoc	
Solve full equations	
Advantage: No approximations to justify *Challenge*: Restricted to theories/parameters where system is well-posed.	

Question: Can we solve the full equations for strong-field/dynamical systems (e.g. black hole mergers) for theories that modify the structure (principle part) of the Einstein equations?

WE & Ripley (2021)

Nonlinear evolutions beyond Einstein gravity

New scheme for nonlinearly evolving scalar-tensor gravity with second order equations of motion (Horndeski)

- Utilizes new modified harmonic formulation (Kovacs & Reall 2020).
- Deal with breakdown of hyperbolicity in black hole interior with excision.
- Need new gauges, equations now fully nonlinear, violates null convergence condition.

WE & Ripley (2021)

Nonlinear evolutions beyond Einstein gravity

Benchmark theory: 4-derivative, parity-invariant scalar tensor

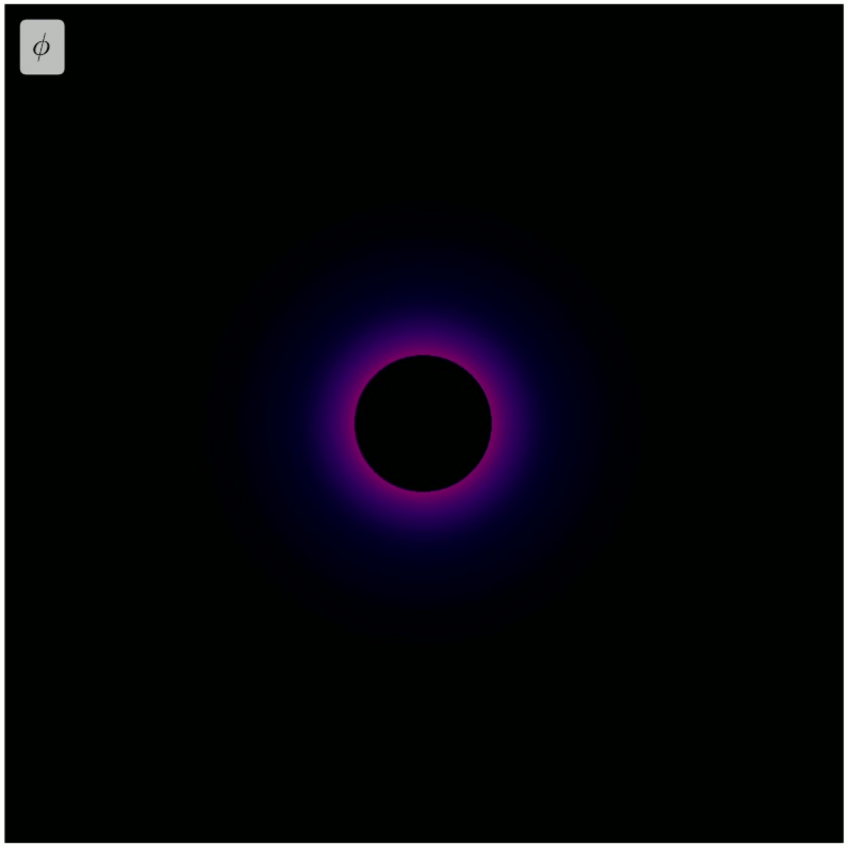
$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}R - \frac{1}{2}(\nabla\phi)^2 - V(\phi) + \alpha(\phi)(\nabla\phi)^4 + \beta(\phi)\mathcal{G}\right]$$

where $\mathcal{G} = R^2 - 4R^{ab}R_{ab} + R^{abcd}R_{abcd}$.
Shift-symmetric Einstein-scalar-Gauss-Bonnet: $\beta(\phi) = \lambda\phi$, $\alpha = V = 0$.

- Black holes have scalar charge, affects inspiral, results on PN expansion, stationary solutions, etc. to compare.

Conclusion: We can evolve binary black hole *(Corman, Ripley, WE 2021; 2023)* and binary neutron star mergers *(WE+ 2022)* in regime where modifications are significant.

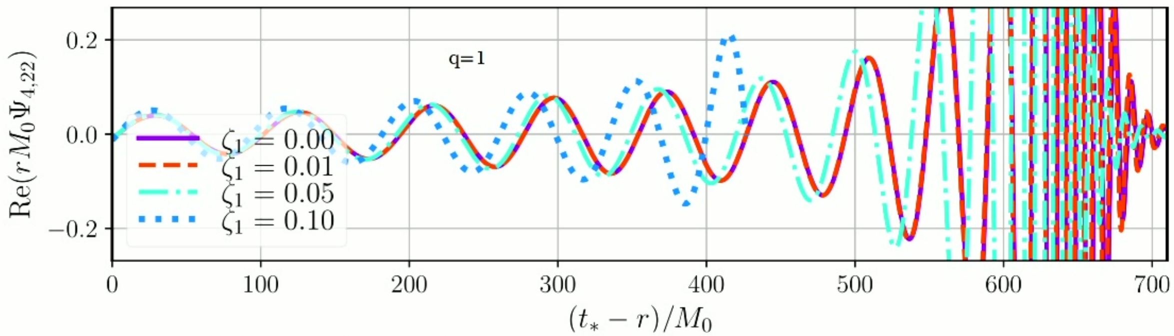
Binary black hole inspirals in modified gravity

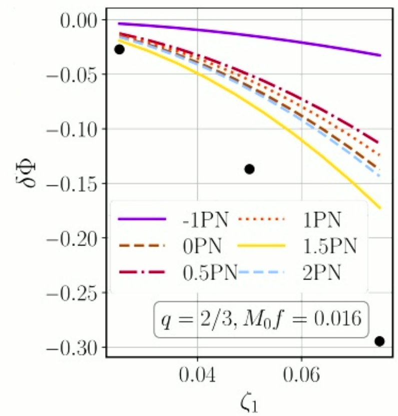


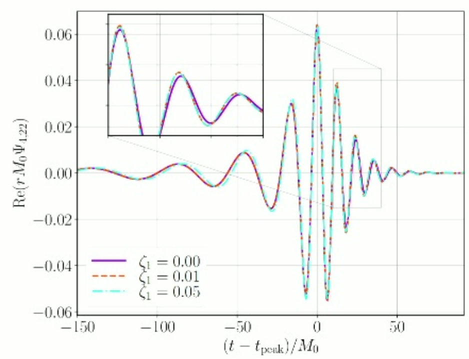
$\zeta_1 = \lambda/m^2 = 0.05$, equal mass

Corman, Ripley & WE 2023

Faster BH-BH inspiral in shift-symmetric ESGB



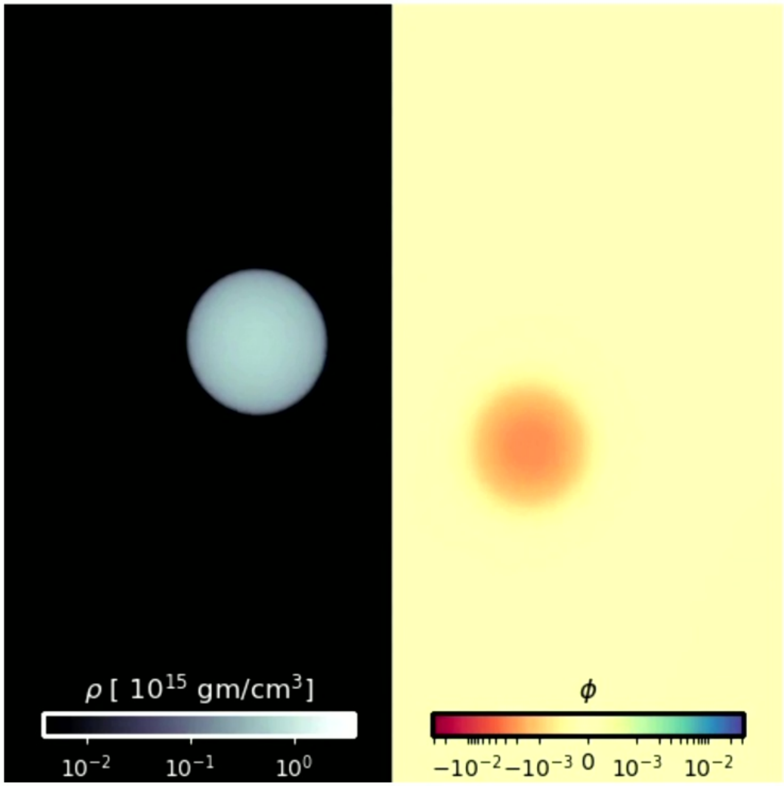




Enhanced orbital dephasing with increasing coupling $\zeta_1 = \lambda/m^2$. Effect on merger waveform amplitude/ringdown mild.

Corman, Ripley & WE 2023

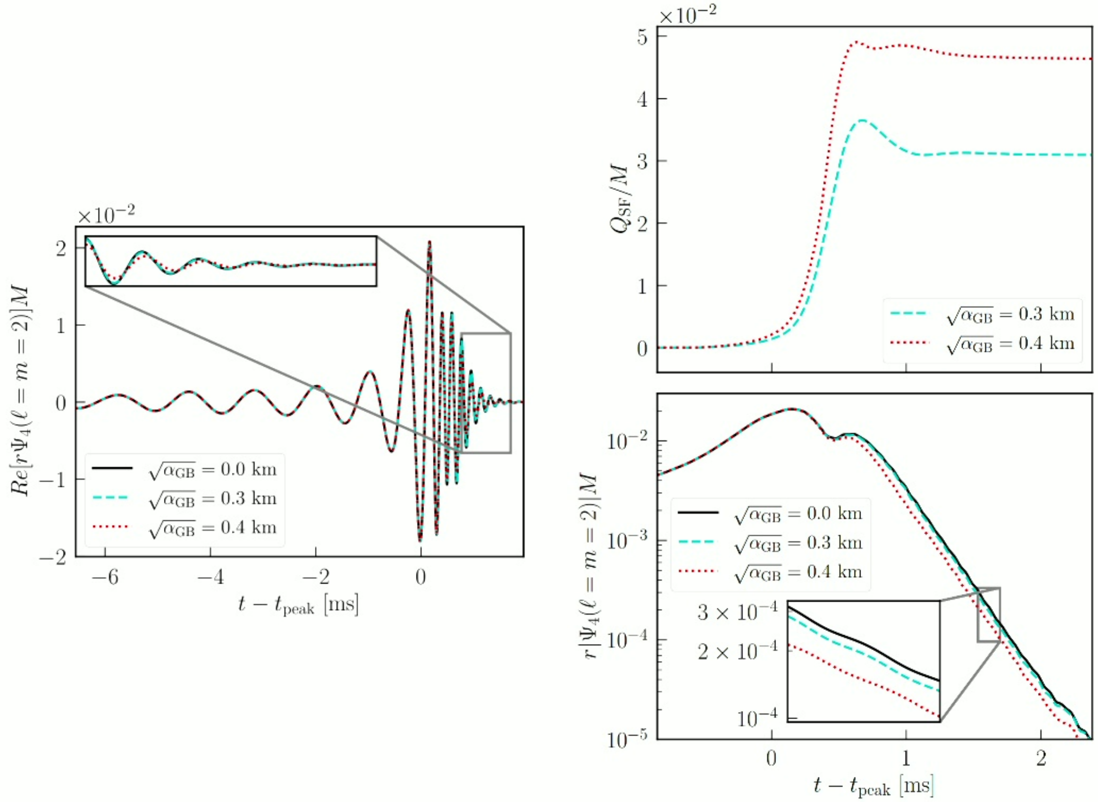
Binary neutron star merger: black hole formation



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

$M = 3.4\ M_{\odot}$, $\sqrt{\alpha_{\rm GB}} = 0.3$ km *WE+ 2022*

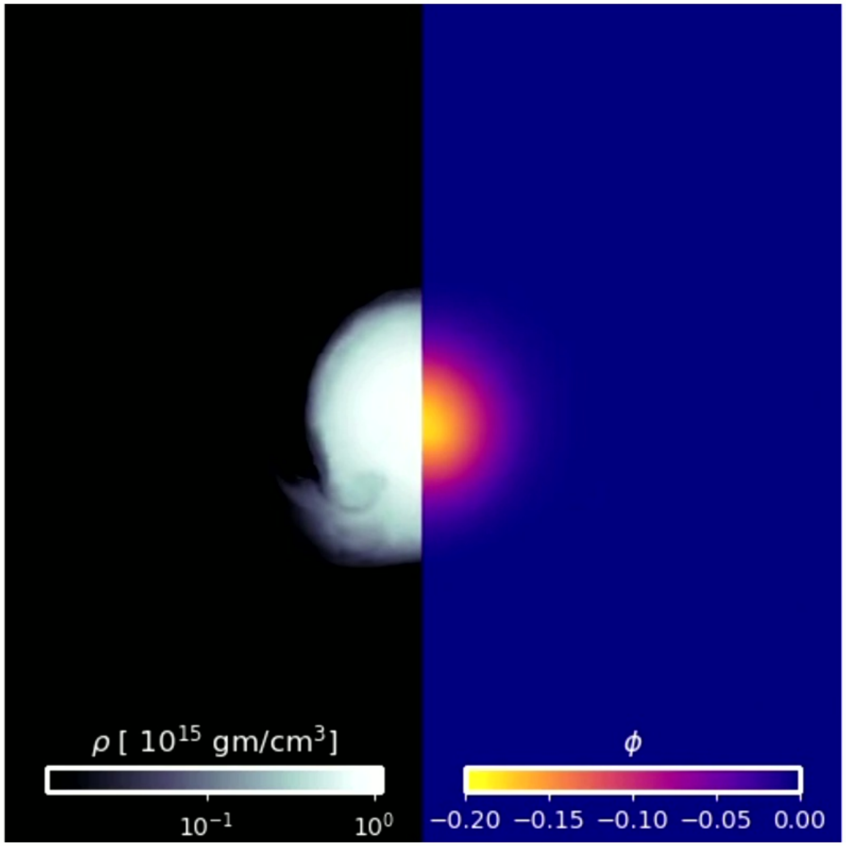
Development of scalar charge in remnant black hole



Modified gravity affects black hole ringdown, but predominantly amplitude (not frequency).

WE+ 2022

Binary neutron star merger: remnant star

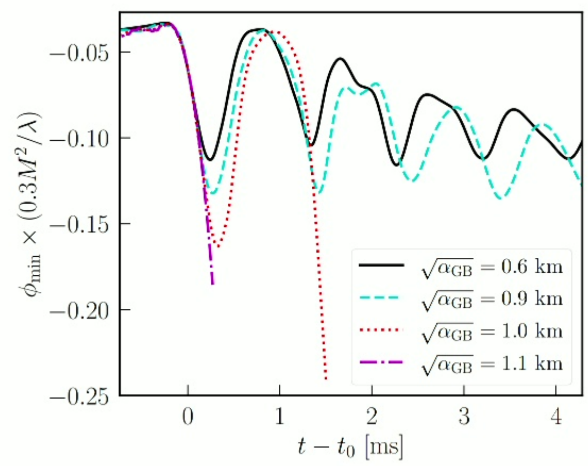


$M = 3.0\ M_{\odot}$, $\sqrt{\alpha_{\rm GB}} = 1.0$ km

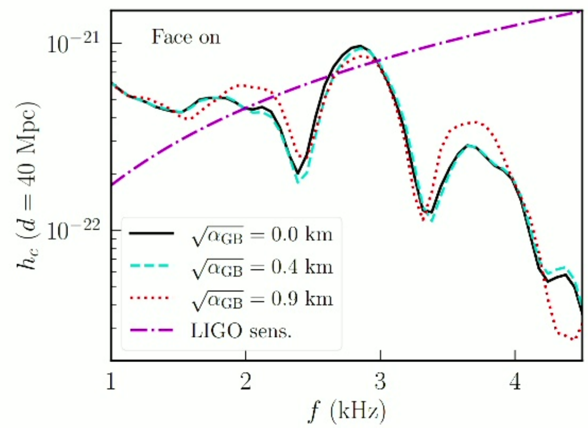
WE+ 2022

Nonlinear scalar field enhancement post-merger

Oscillations in postmerger star can lead to blow up in ϕ, breakdown in evolution.



Dephasing in postmerger oscillations, but in kilohertz frequency regime.



Looking forward

We now have the tools to give complete answer to questions like: *What is the gravitational wave signal from a compact object merger in the class of gravity theories with second order equations of motion?*

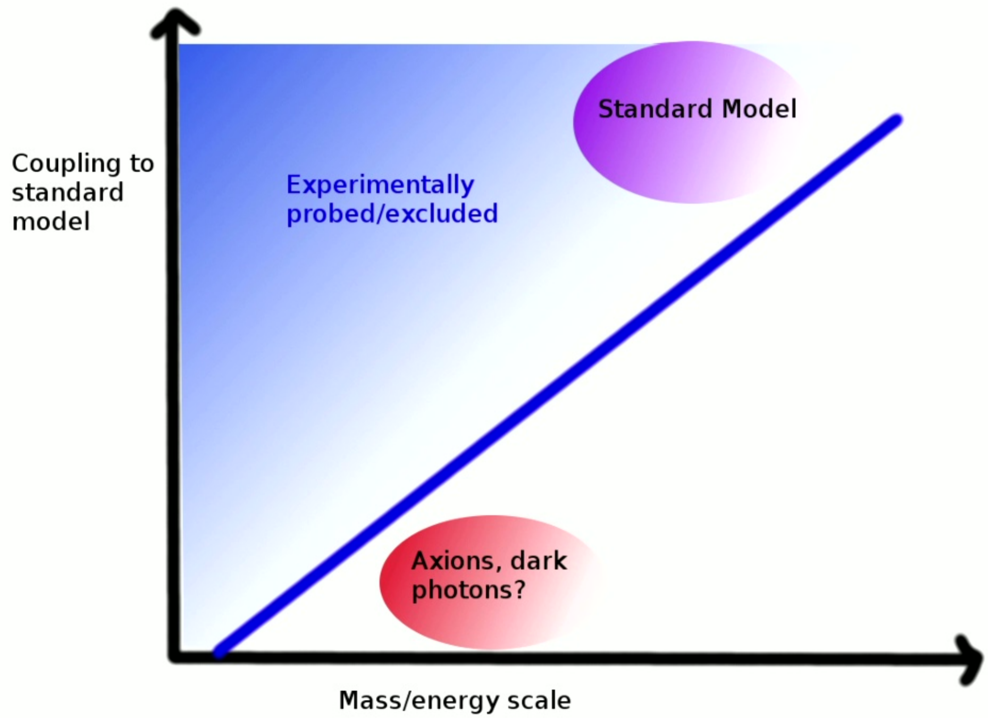
Initial takeaways:

- Currently used approximations under/overestimate modified gravity effects
- Simple tests (e.g. ringdown frequency) may have limited sensitivity

Can now:

- Determine domain where theories are well-posed, and can give predictions for GW observations of compact object mergers.
- Use for benchmarking data analysis methods
- Compare to order-reduction, short-wavelength fixing, other approximations.
- Apply to other settings, e.g. cosmology beyond homogeneity.

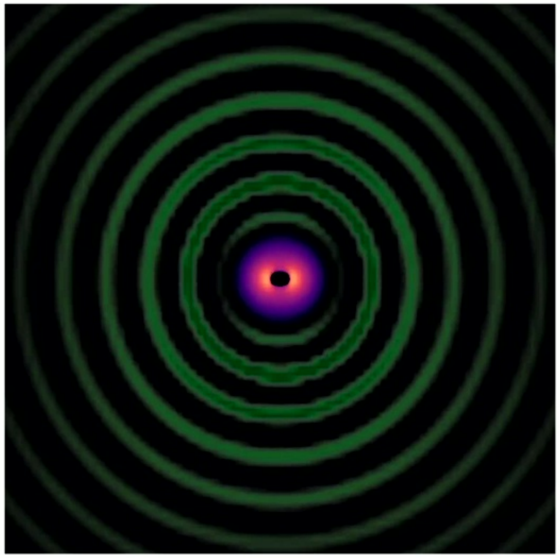
Gravitational wave probe of new particles



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 photons, etc.) with Compton wavelength comparable to black hole radius (Arvanitaki et al.)
- Focus on **ultralight vectors**: faster and louder.



WE (2018)

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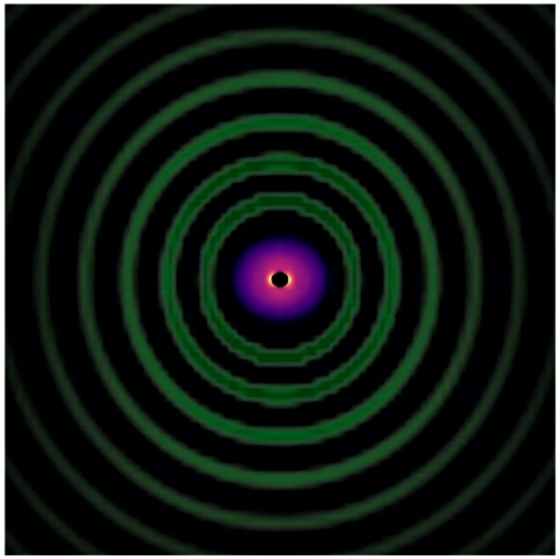
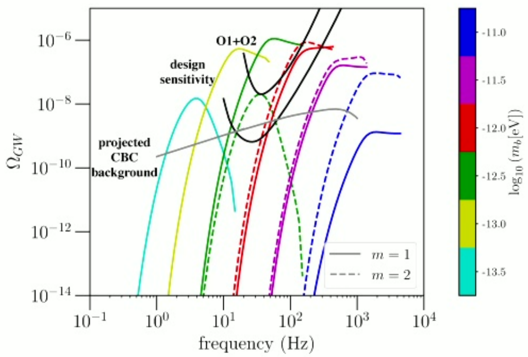


WE (2018)

Observational signatures of ultralight vector superradiance



Tsukada, Brito, WE & Siemonsen (2020)

- Measure black hole spin from merger GWs, or EM observations of accreting BHs.
- Blind GW searches for either resolved or stochastic sources with LIGO-Virgo-KAGRA
- Targeted GW searches–e.g. follow-up black hole merger events. Obviates need to make assumptions on black hole population.

Question: Can we target black hole merger events with LIGO-Virgo-KAGRA? Need to model evolution of GW signal.

Waveform model for black hole superradiance

- Frequency drift as cloud mass evolves
- Not taking this into account limits time GW can be coherently integrated (typically assume $|\dot{f}_{\rm GW}| \lesssim 10^{-11}$ Hz/s).
- Fully relativistic (black hole perturbation): valid for loudest signals
- Scalar and vector bosons

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pip install superrad
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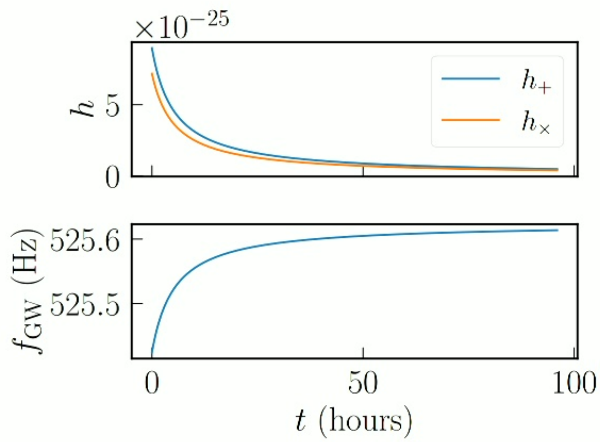
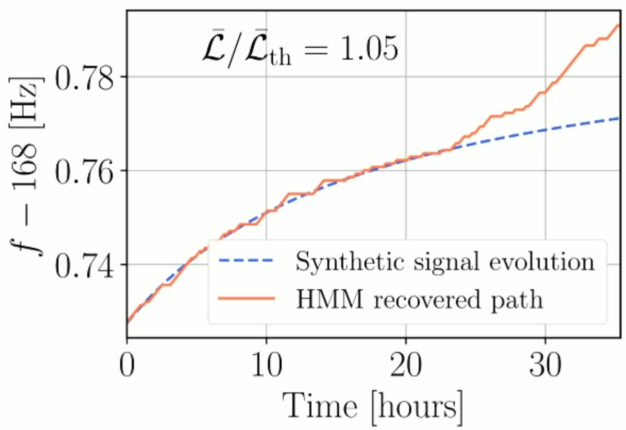


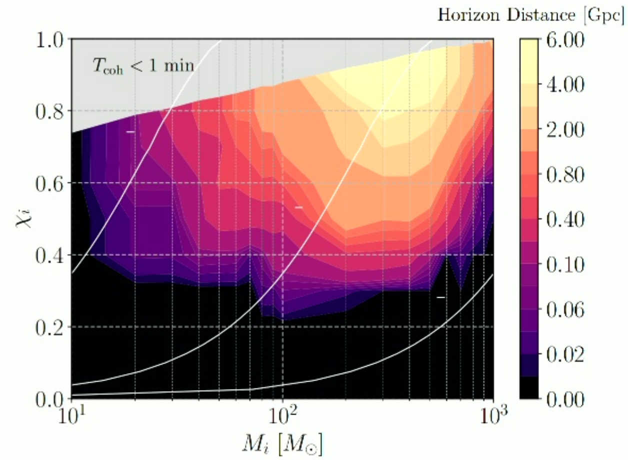
$\mu_{\rm Vec.} = 10^{-12}$ eV; $M_{\rm BH} = 20\ M_\odot$;
$a_{\rm BH} = 0.8$; $d_{\rm Obs} = 100$ Mpc

Siemonsen, May & WE (2022)

Performing follow-up searches of merger events

New long duration search method optimized with signal model.





$M_{\rm BH} = 60\ M_\odot$, $\chi_i = 0.7$, $\alpha_{\rm opt} = 0.176$, and $d = 500$ Mpc

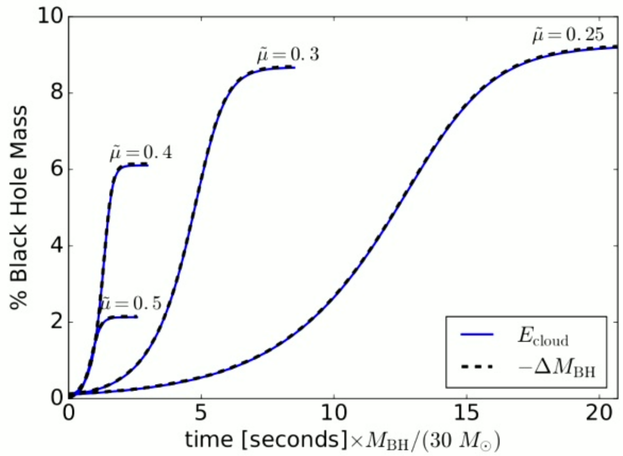
Can reach merger remnants up to $\sim$ Gpc distances with current detectors.

Jones, Sun, Siemonsen, WE+ (2023)

Effect of non-gravitational interactions

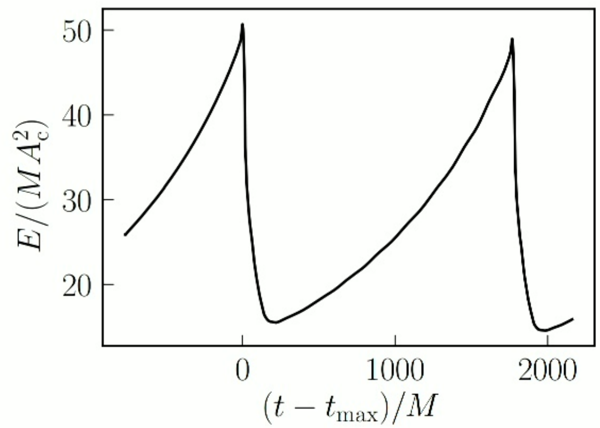
For simple massive boson, superradiance saturates through black hole spin down, cloud dissipates through GWs.

Gravitational backreaction



WE & Pretorius (2017)

Nonlinear boson interactions



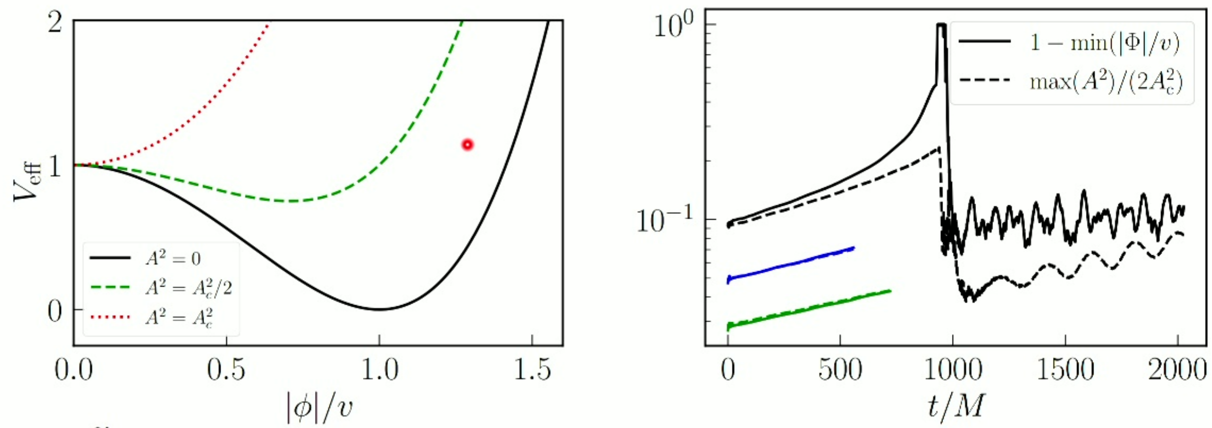
WE (2022)

However, additional interactions may halt growth before gravitational backreaction (cf. bosenova scenario) and/or give rise to additional observables .

Dark Photon with Higgs Mechanism

Model for nonlinear interaction: mass of dark photon arises from (dark) Higgs mechanism:

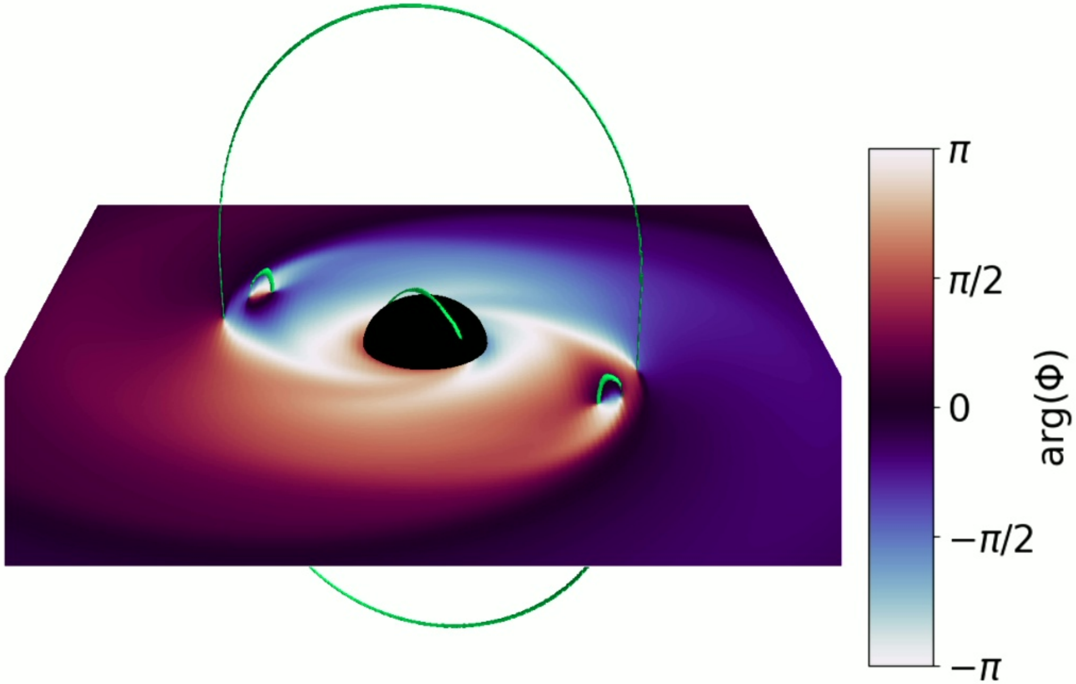
$$\mathcal{L} = -\frac{1}{4}F'_{ab}F'^{ab} - \frac{1}{2}|(\nabla_a - igA_a)\Phi|^2 - \frac{\lambda}{4}\left(|\Phi|^2 - v^2\right)^2 .$$



When $\tilde{A}_a$ small, $|\Phi| \approx v$, and vector has mass $\mu = gv$. When $\tilde{A}^2 \sim A_c^2 := \lambda v^2/g^2$, backreacts on Φ and drives it towards $|\Phi| = 0$.

WE (2022)

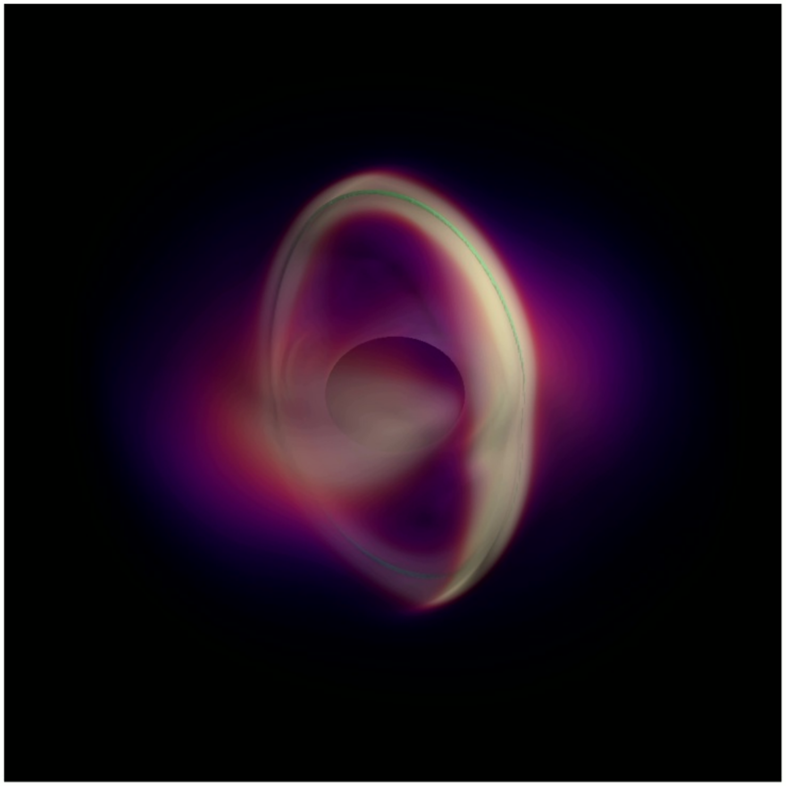
String vortex formation



One dimensional curves where $|\Phi| = 0$ but complex phase goes through 2π.

WE 2022

Stringy bosenova

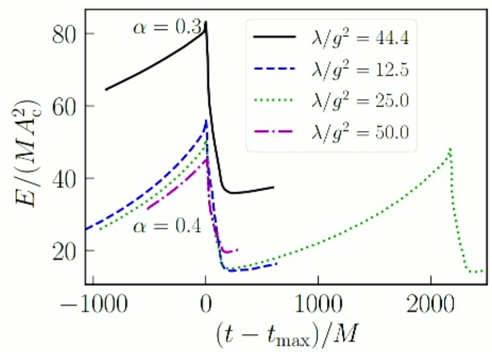


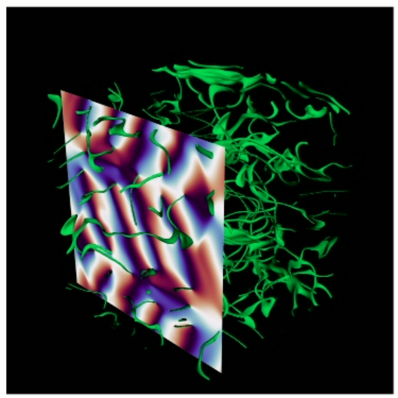
E.g. for $M_{\rm BH} = 60\, M_{\odot}$ and $\mu = 9 \times 10^{-13}$ eV, $v\lambda^{1/4} \lesssim 10$ MeV ($g\lambda^{-1/4} \gtrsim 10^{-19}$).

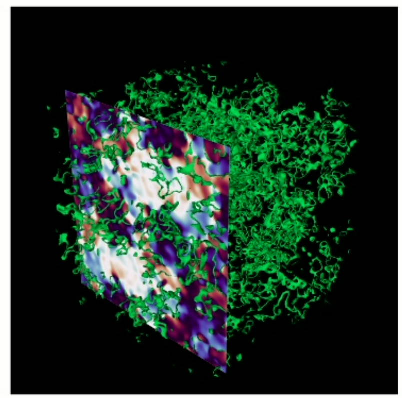
WE 2022

Phenomenology of vortex formation

- Changes saturation of superradiant instability, can lead to episodic bursts.
- Potential signals from gravitational waves or long-lived string loops.
- Related scenario in dark photon dark matter



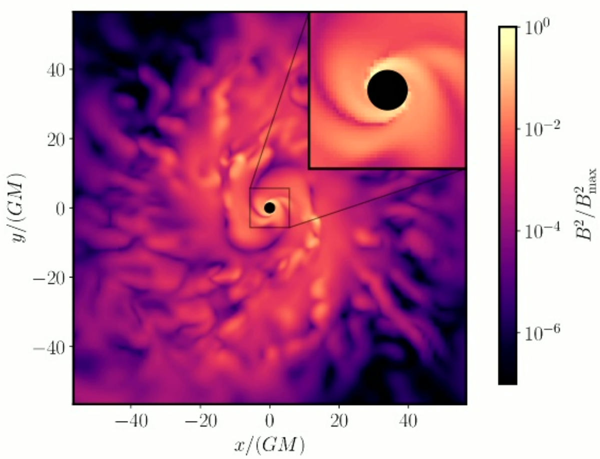


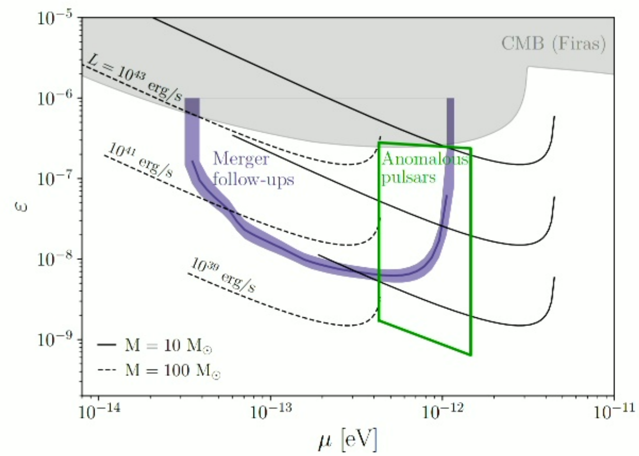


WE, WE & Huang 2022

Outlook

- Gravitational waves are powerful probe of ultralight bosons
- New signal models and search methods will allow for following up merger events with current detectors
- Couplings to standard model and self-interactions may give rise to new observables





Kinetically mixed dark photon clouds sources pulsar-like electromagnetic transient

Siemonsen, Mondino, Egana-Ugrinovic, Huang, Baryakhtar, WE (2023)

Conclusion

We are in a golden age of multimessenger gravitational wave astronomy. Observations and theory allow us to explore the extremes of spacetime!

On the horizon:

- Many more black hole and neutron star mergers, and thus more exceptional cases.
- New probes of fundamental physics.
- The unknown unknowns.

Rich dynamics, in compact object mergers to cosmology, can teach us about the fundamentals of strongly curved spacetime.