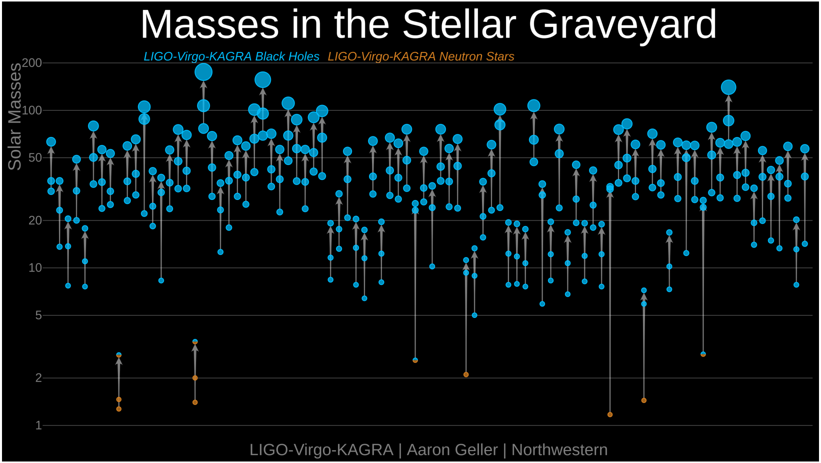
Unveiling ultralight bosons through black hole superradiance

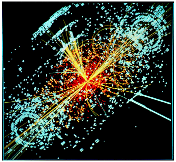
William East (Perimeter)
Fundamental physics
& GW detectors (Pollica)
September 18, 2024

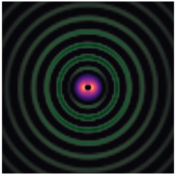
Unveiling dark objects with gravitational waves

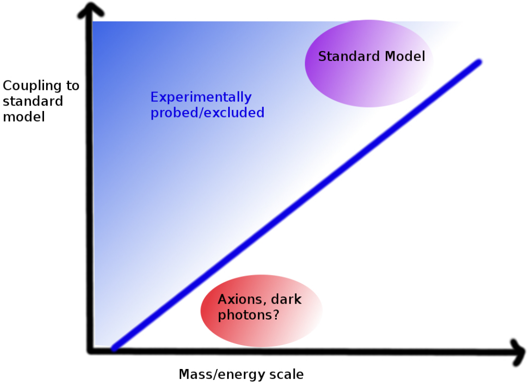


Gravitational waves have already revealed new populations of black holes and neutron stars. How can we use them to look for dark particles?

Gravitational wave probe of new particles







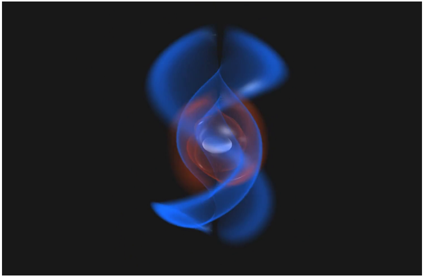
Strong gravity effects can probe new part of parameter space where particles are weakly coupled to standard model

Black hole superradiance

- For a black hole with an impinging wave with frequency ω

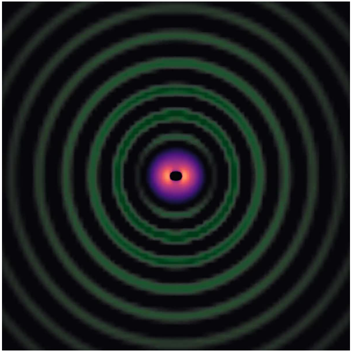
$$\delta\mathrm{Area} \propto \delta\mathrm{M_{BH}}(1 - m\Omega_{\mathrm{BH}}/\omega)$$

- Black hole thermodynamics: $\delta\mathrm{Area} \propto \delta\mathrm{Entropy} \geq 0$. Hence $\delta M_{\mathrm{BH}} < 0$ when $\omega < m\Omega_{\mathrm{BH}}$.
- Rotational energy of black holes can be liberated. For maximally spinning, up to 29% of black hole's mass in principle (or up to 10% at fixed ω).

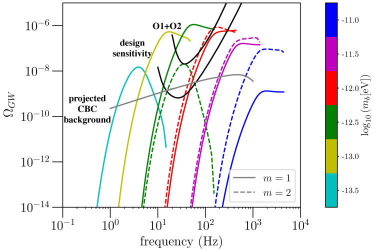


Superradiant instability: realizing the black hole bomb

- Massive bosons can form bound states, when frequency $\omega < m\Omega_{\rm BH}$ grow exponentially in time.
- Search for new ultralight bosonic particles with Compton wavelength comparable to black hole radius
- Occurs for ultralight scalar and vector bosons, e.g. QCD axion, string axiverse, dark photons. (And ultralight spin-2 fields?)



Observational signatures of ultralight boson superradiance



Tsukada, Brito, WE & Siemonsen (2020)

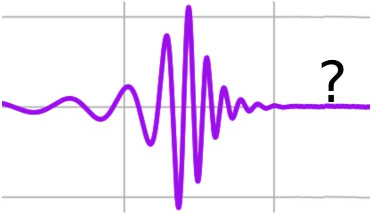
- Measure black hole spin from merger GWs, or EM observations of accreting BHs. *(Baryakhtar+ 2017; Ng+ 2021)*

  ◇ Can rule out certain mass ranges

- Blind GW searches for either resolved or stochastic sources *(Brito+ 2017; Tsukada+ 2019; Zhu+ 2020; LVK 2022)*

  ◇ Constraints rely on population assumptions, including BH spin

Observational signatures of ultralight boson superradiance



- Targeted GW searches–e.g. follow-up black hole merger events. *(Isi+ 2019; Ghosh+ 2019; Sun+ 2020; Chan+ 2022; Jones+2023)*

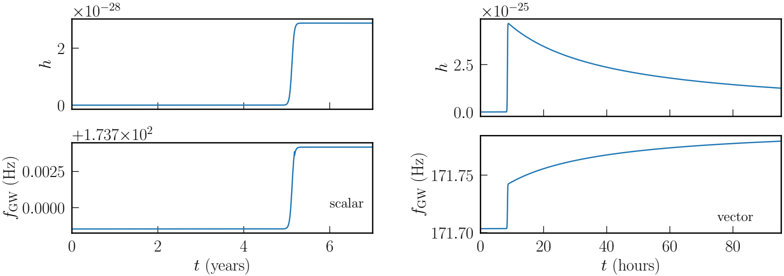
  ◇ Obviates need to make assumptions on black hole population.

  ◇ However characteristically occur at large distances.

Question: Can we target black hole merger events in near term? Need to model evolution of GW signal.

Gravitational waveform from black hole superradiance

- Cloud grows exponentially, then dissipates over longer timescale through GWs
- Vector bosons louder and faster
- GW frequency increases with time (c.f. a neutron star spinning down)



$\mu = 3.6 \times 10^{-13}$ eV with GW150914-like BH with $M = 62\ M_{\odot}$, $a_* = 0.67$, $d = 410$ Mpc

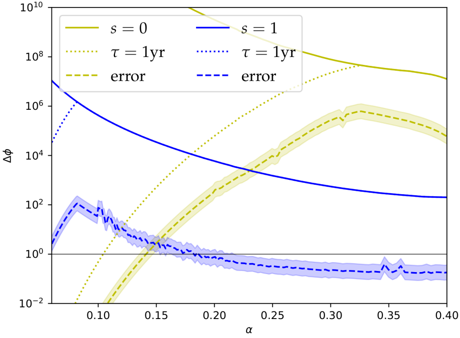
Siemonsen, May & WE (2022)

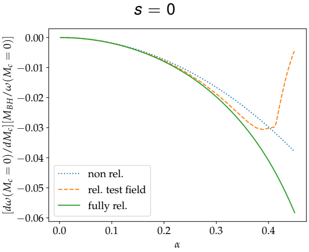
`pip install superrad`

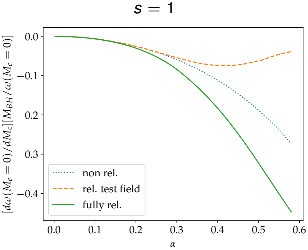
`www.bitbucket.org/weast/superrad`

Gravitational waveform from black hole superradiance

Frequency drift and phase shift due to changing cloud mass.







$\alpha \equiv \mu \times M_{\rm BH}$

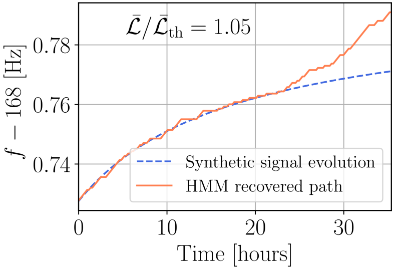
Full-GR/oscillation averaged self-gravity

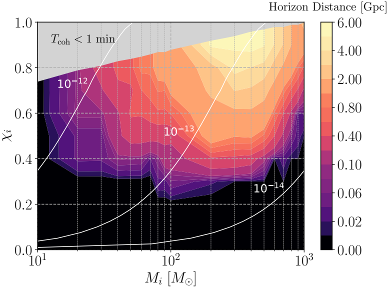
Taillte May, Siemonsen, & WE (in prep.)

With relativistic corrections, nearing phase coherent regime.

Performing follow-up searches of merger events

New long duration search method (based on Viterbi) optimized with signal model.





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

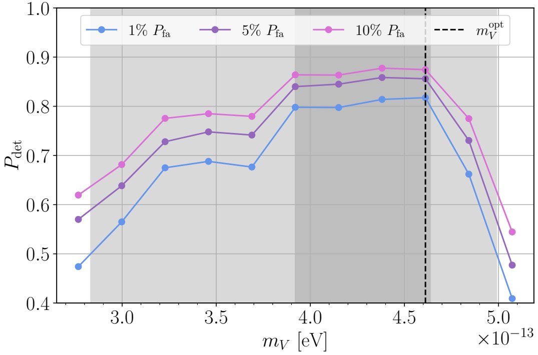
Can reach merger remnants up to $\sim$ Gpc distances with current generation of detectors.

(Typically requires matched-filtered SNR to be $\gtrsim$ 15–25.)

Jones, Sun, Siemonsen, WE+ (2023)

Performing follow-up searches of merger events

Can place constraints in absence of signal, folding in remnant property uncertainities.



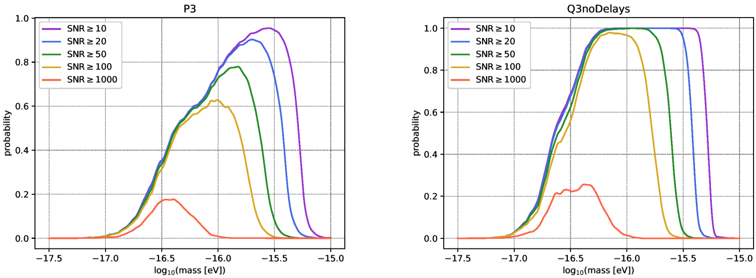
Mock Data: GW170814 posteriors from GWOSC, $M_{\rm BH} = 53.2^{+3.2}_{-3.3}\ M_{\odot}$, $\chi = 0.72^{+0.07}_{-0.05}$ but assuming 40% closer and O3 sensitivity.

Jones, Siemonsen, Sun, & WE (in prep.)

Performing follow-up searches of merger events

Can also follow-up supermassive black hole mergers with LISA.

[In addition to stochastic or resolved sources of GWs in space-based detectors (*Brito+ 2017*) and possibility of effects in binaries (*Bauman+ 2019*).]



Probability of ultralight vector signal from merger remnant in light-seed (left) and heavy seed (right) population models.

Giannakoudi+ in prep

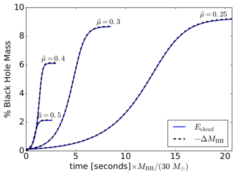
Effect of non-gravitational interactions

Questions to address:

- Do interactions halt superradiant growth?
- Is the process gradual or violent (cf. bosenova scenario)?
- When do they give rise to additional observables?

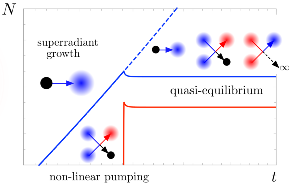
(Arvanitaki+ 2010; Yoshino+ 2012; Baryakhtar+ 2020; Omiya+ 2022; Clough+ 2022; Spieksma+ 2023; . . .)

Gravitational



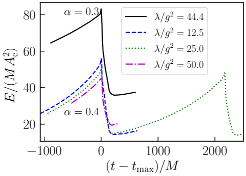
WE+ (2017)

Quartic scalar



Baryakhtar+ (2021)

Higgs-Abelian interaction

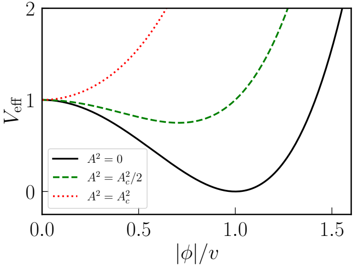


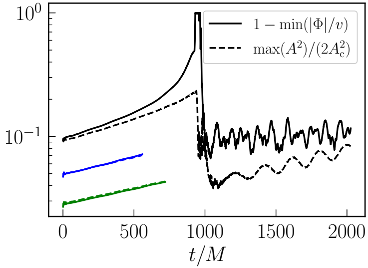
WE (2022)

Dark Photon with Higgs Mechanism

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

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

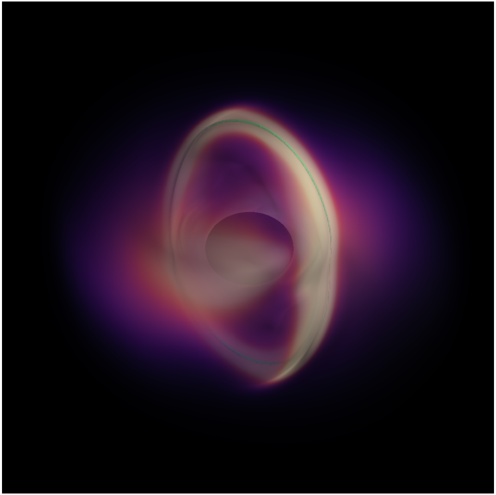




When $\tilde{A}_a$ small, $|\Phi| \approx v$, and vector has mass $\mu = gv$. When $\tilde{A}^2 \sim A_c^2 := \lambda v^2/g^2$, backreacts on Φ and drives it towards $|\Phi| = 0$.

WE (2022)

Stringy bosenova



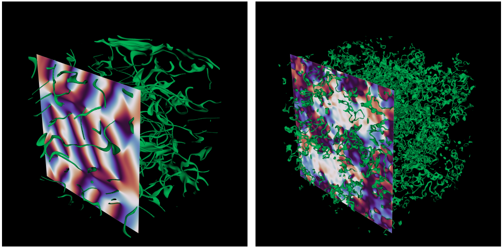
E.g. for $M_{\rm BH} = 60\ M_{\odot}$ and $\mu = 9 \times 10^{-13}$ eV,

happen when $v\lambda^{1/4} \lesssim 10$ MeV ($g\lambda^{-1/4} \gtrsim 10^{-19}$).

WE 2022

Phenomenology of vortex formation

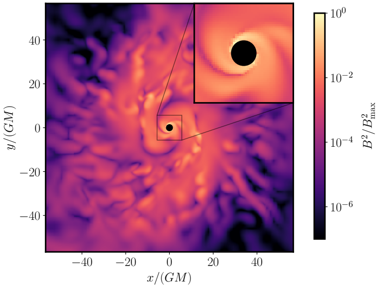
- Changes saturation of superradiant instability, can lead to episodic bursts.
- Potential signals from gravitational waves or long-lived string loops.
- GW frequencies in wide range, nHz to $\sim$ 10 MHz for super to stellar mass black holes *Brzeminski et al. (2024)*
- Related scenario in dark photon dark matter

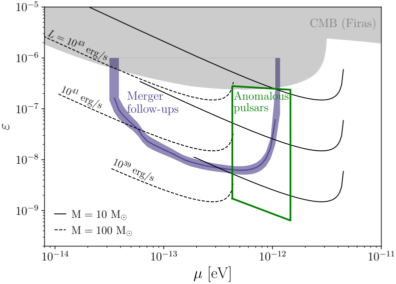


WE & Huang 2022; See also Brzeminski et al. 2024

Multimessenger signals from dark photon superradiance (see Cristina Mondino's talk last week)

Coupling to standard model: kinetic mixing with photon $\mathcal{L} \supset \varepsilon F'_{ab} F^{ab}/2$





Superradiant cloud can rise to turbulent pair plasma, lead to pulsar-like electromagnetic transient counterpart to GWs with $L \lesssim 10^{43}$ erg/s.

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

What about massive spin-2 instability around black holes?

Massive spin-2 fields also considered in beyond-GR gravity and dark matter models.

Black hole superradiant instability should be faster/louder.

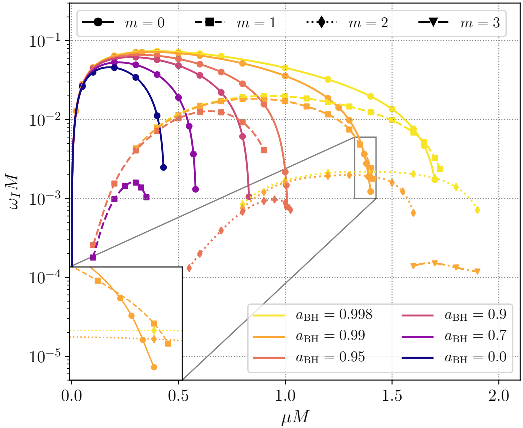
Linear theory of massive spin-2 field (Fierz-Pauli, 1939) on Ricci-flat background:

$$\Box H_{ab} = \mu^2 H_{ab} - 2R_{acbd}H^{cd}, \;\; H^a_a = \nabla_a H^{ab} = 0$$

Extending to nonlinear level to determine backreaction highly non-trivial—enter regime of modified gravity.

Massive spin-2 linear instability

Spin-2 superradiant instability is faster (c.f. $\omega_I M \lesssim 10^{-3}$ for spin-1) but even faster mono-polar ($m = 0$) instability.



WE & Siemonsen 2024; See also Brito+ 2020, Dias+ 2023

What is fate of monopolar instability of massive spin-2?

Massive spin-2 field has same *Gregory-Laflamme instability* as a black string in 5D GR with $k \to \mu$. *(Babichev+; Brito+ 2013)*

Determining backreaction requires nonlinear theory:

- Nonlinear massive bi-gravity *(de Rham+ 2011, Hassan+ 2012)*: Removes BD ghost at nonlinear level. Not yet known how to make well-posed.
- Quadratic (aka fourth order or Stelle) gravity is well-posed *(Noakes 1983)*, but has Hamiltonian that is unbounded from below as dictated by Ostrogradsky's theorem.

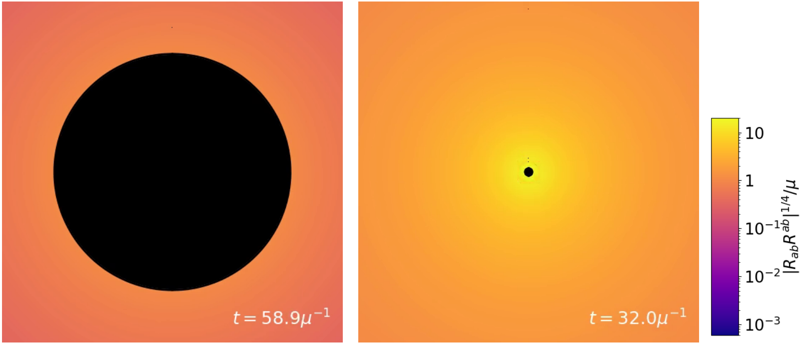
$$S = \int d^4x\sqrt{-g}\left(R - \frac{1}{2\mu^2}C^{abcd}C_{abcd}\right)$$

Can use as simple model of backreaction.

"Ghosts!"

Backreaction of spin-2 monopolar instability

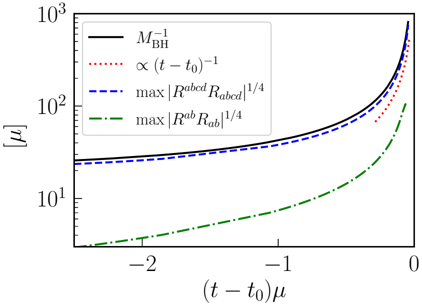
Two different possibilities for same black hole:
$(M_{\rm BH}^{t=0} = (20\mu)^{-1})$

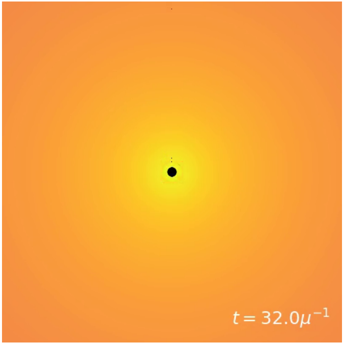


WE & Siemonsen 2024

Backreaction of spin-2 monopolar instability

As black hole shrinks, curvature blows up:





Black hole shrinks to zero mass, giving mild naked singularity (similar to Gregory-Laflamme instability of 5D black string).

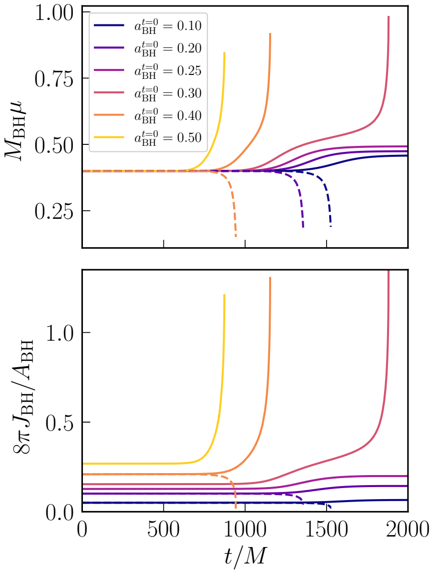
WE & Siemonsen 2024

Massive spin-2 instability

What happens to spinning black holes?

Decreasing mass leads the black hole to spin down.

Increasing mass can lead to a *super-extremal* horizon ($J_{\rm BH} > 8\pi A_{\rm BH}$).



Outlook

Gravitational waves and compact objects are a powerful probe of the dark sector. Black hole superradiance can reveal ultralight bosons:

- New signal models and search methods will allow for following up merger events with current and future detectors.
- Couplings to standard model and self-interactions may give rise to new observables
- Massive spin-2 case can be quite different

Understanding dynamics and observational signals gives strongest constraints, and sheds new light on fundamentals of dynamical spacetime.