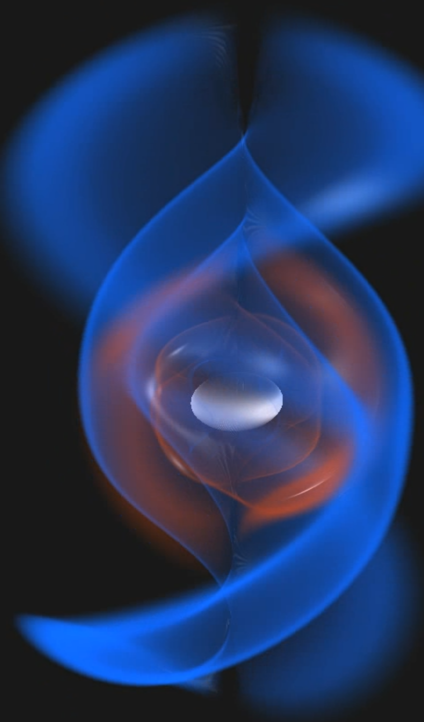
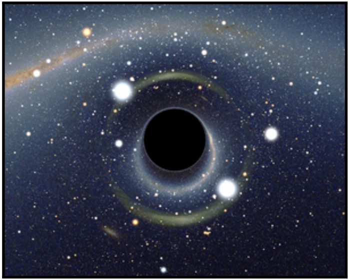


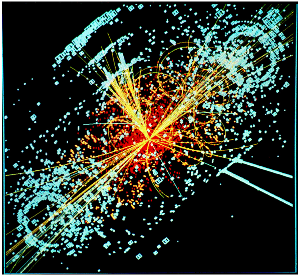
Strong field dynamics of bosonic fields: Looking for new particles and modified gravity

William East, Perimeter Institute
ICERM Workshop
October 26, 2020

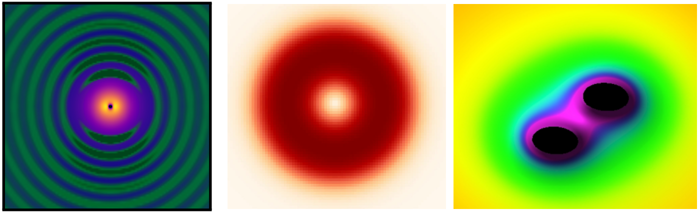
Introduction

- How can we use gravitational waves to look for new matter?
- Can we come up with alternative predictions for black holes and/or GR to test against observations?
- Need understanding of relativistic/nonlinear dynamics for maximum return



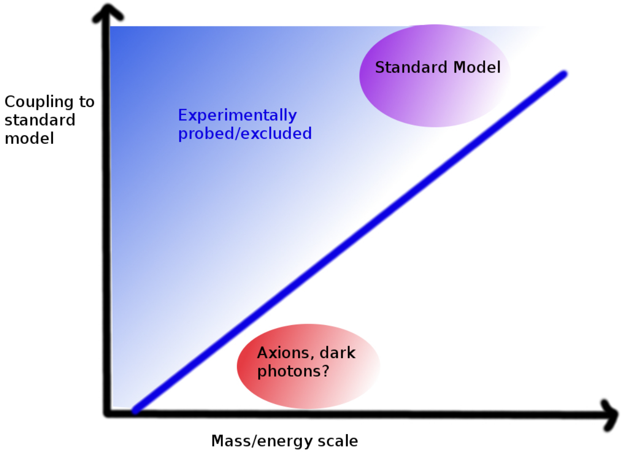


Three examples with bosonic fields



Black hole superradiance, boson stars, and modified gravity with non-minially coupled scalar fields

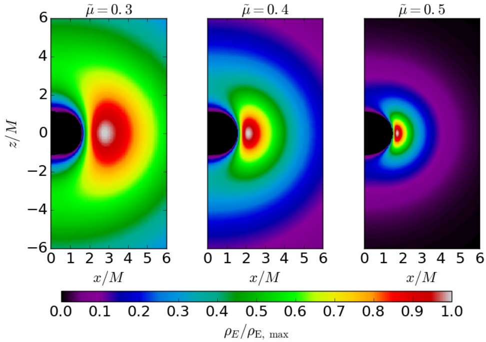
Gravitational wave probe of new particles



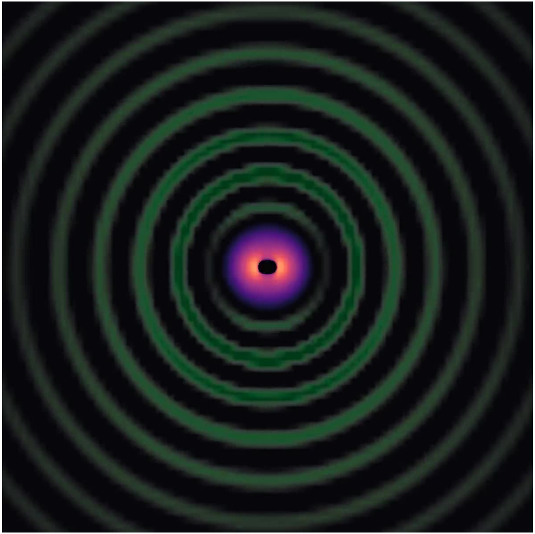
Search new part of parameter space: ultralight particles weakly coupled to standard model

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.)

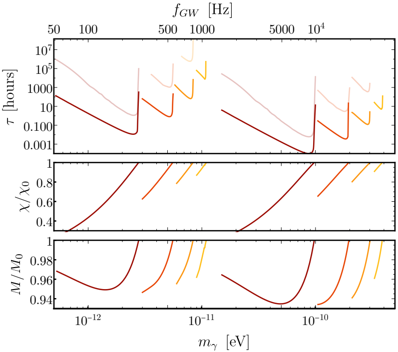


Boson clouds emit gravitational waves



WE (2018)

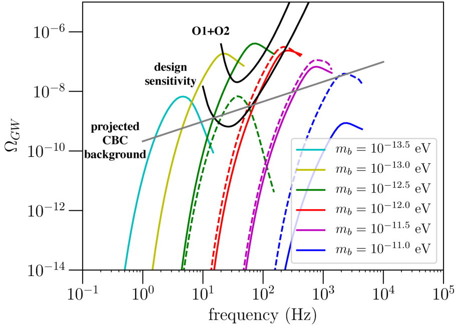
Boson clouds emit gravitational waves

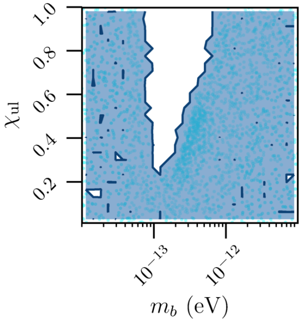


Siemonsen & WE (2020)

- Can do targeted searches–e.g. follow-up black hole merger events, or “blind" searches
- Look for either resolved or stochastic sources with LIGO (Baryakthar+ 2017; Zhu+ 2020; Brito+ 2017; Tsukada+ 2019)

Stochastic gravitational wave background

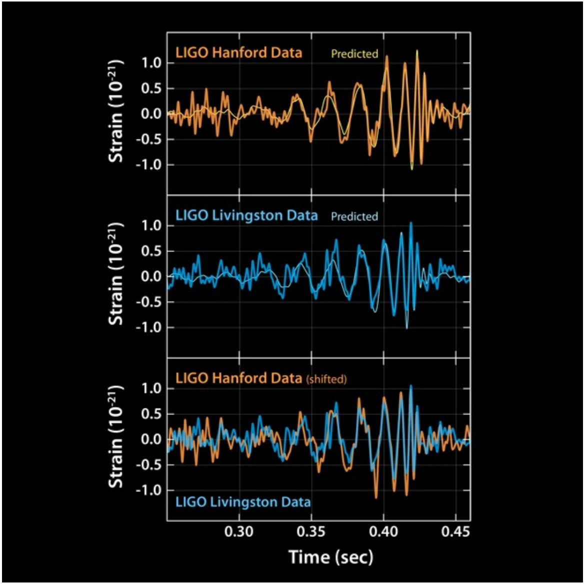




Can already place constraints on vector bosons with LIGO O1+O2 (with moderate assumptions on black hole spin)

Tsukada, Brito, WE, & Siemonsen (in prep.)

Testing the black hole paradigm

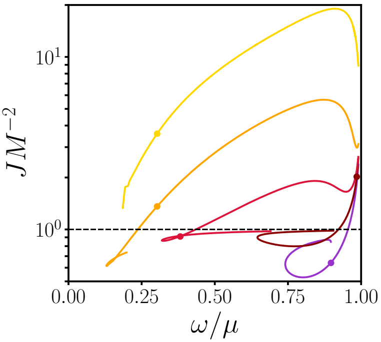


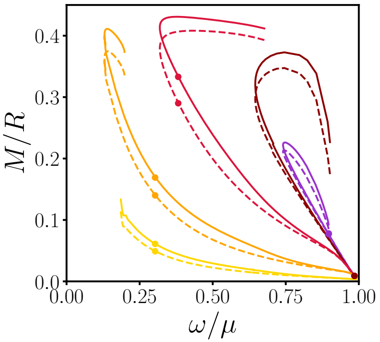
Caltech/MIT/LIGO Lab

- Black hole seems to fit. . .
- But are there horizonless objects that can give similar behavior?

Boson stars

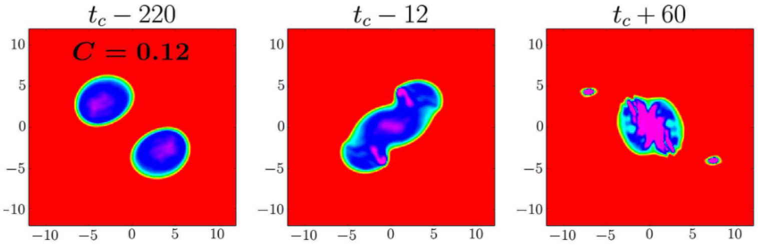
- Are easy to evolve (c.f. gravastars, constant density stars, etc.).
- Can be ultracompact.
- Can be rapidly spinning.
- Can have stable photon orbits, ergospheres, etc.
- But are they stable?





Rotating boson star stability

Maybe not. . .

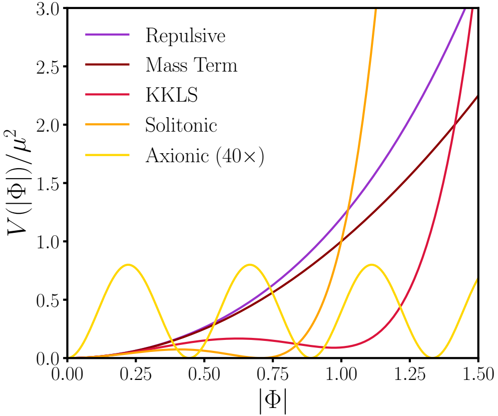


Palenzuela et al. (2017)

Also Sanchis-Gual et al. (2019): Rotating stars are unstable for massive scalar bosons; Rotating massive vector stars are more stable. (See J. Font's talk)

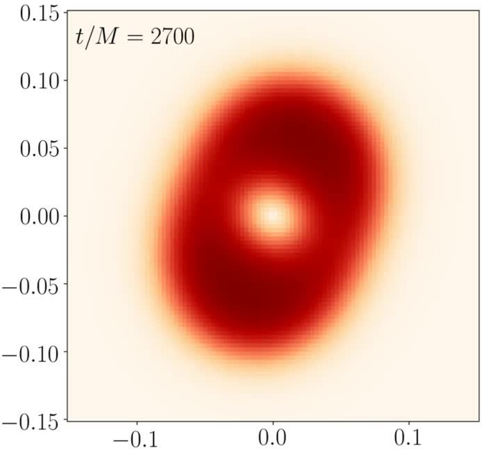
Boson stars

Use 3D full GR evolutions to study stability of complex scalar boson stars with nonlinear interactions, $\Box\Phi = V'(\Phi)$ with V' nonlinear.



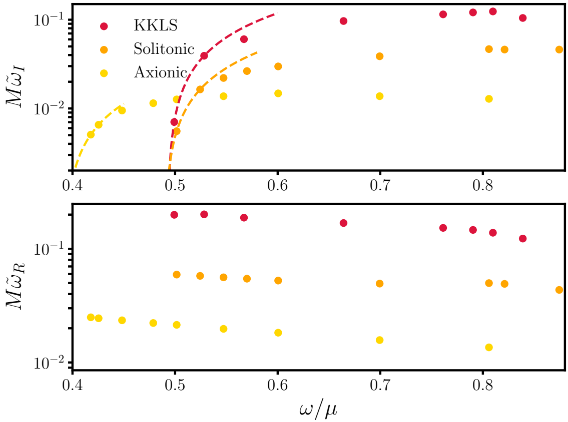
Nils Siemonsen & WE (in prep.)

Non-axisymmetric instability



Example of rotating axionic boson star

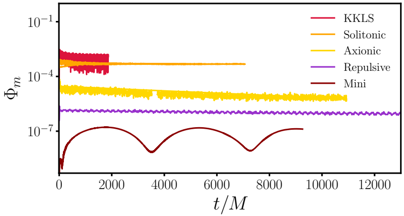
Unstable and stable boson stars



With nonlinear coupling, instability shuts off in relativistic regime for some cases.

Siemonsen & WE (in prep.)

Boson stars: outlook



Siemonsen & WE (in prep.)

- Class of rotating scalar boson stars stable on long timescales
- Can study mergers of these as point of comparison to black holes.
- Longer timescale instabilities (e.g. ergoregion, light ring, etc.)?

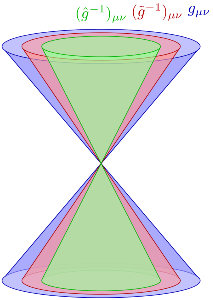
Modifying general relativity

$$S = \frac{1}{8\pi} \int d^4x\sqrt{-g}(\frac{1}{2}R - \frac{1}{2}(\nabla\phi)^2 - V(\phi) + \alpha(\phi)(\nabla\phi)^4 + \beta(\phi)\mathcal{G}$$
$$+ \gamma(\phi)\, {}^*R^{abcd}R_{abcd} + (R^{abcd}R_{abcd})^2/\Lambda^6 + \ldots)$$

- Some modifications no longer have 2nd order equations of motion
- In that case one has no choice but to use order-reduction (see M. Okounkova's talk) or modify short wavelength behavior (e.g. Cayuso & Lehner, 2020)
- For those with 2nd order equations (Horndeski theories) <u>may</u> be well-posed, but usually aren't in commonly used formulations (Papallo & Reall).

Modification to generalized harmonic — Kovacs & Reall (2020)

Introduce auxiliary metrics that determine gauge and constraint propagation.



Equations of motion will still be strongly hyperbolic for Horndeski theories with $\lambda \ll L^2$.

Non-perturbative dynamics of Horndeski

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

- Focus on Einstein-dilaton Gauss Bonnet

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

- Representative example of Horndeski, violates null convergence condition
- Can leverage experience regarding hyperbolicity in spherically symmetric case (Ripley & Pretorius)

See also Helvi Witek's talk in previous workshop for test field case.

EDGB equations in modified harmonic

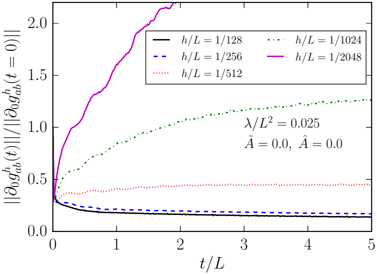
Evolution variables $\{g_{ab}, \partial_t g_{ab}, \phi, \partial_t \phi\}$

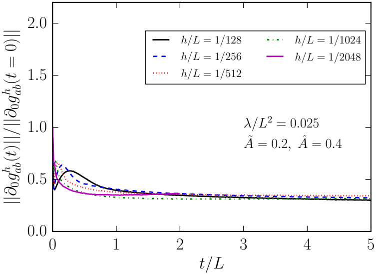
$$\begin{pmatrix} A_{ab}{}^{ef} & B_{ab} \\ C^{ef} & D \end{pmatrix} \partial_t^2 \begin{pmatrix} g_{ef} \\ \phi \end{pmatrix} + \begin{pmatrix} F^{(g)}_{ab} \\ F^{(\phi)} \end{pmatrix} = 0$$

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

- In modified harmonic formulation, principal matrix no longer diagonal. In Horndeski, C^{ef} and B_{ab} non-zero, and matrix involves second-derivatives.
- Carry over experience with constraint damping, gauge conditions, from generalized harmonic.
- Black hole excision essential.

Harmonic vs. auxiliary metric harmonic

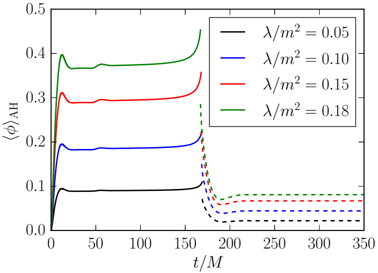


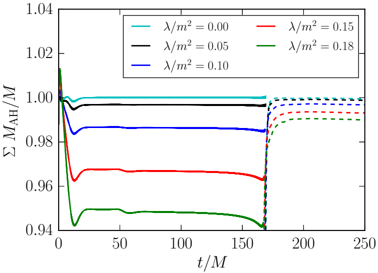


Use of auxiliary metrics removes frequency dependence growth.

WE & Ripley in prep.

Black hole collisions

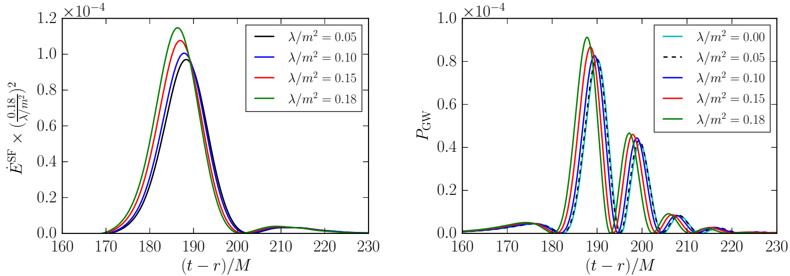




Black holes scalarize while shrinking, and then collide.

WE & Ripley in prep.

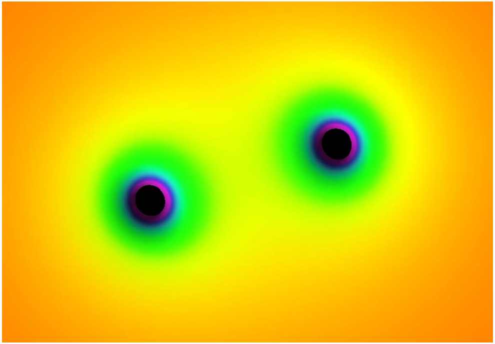
Black hole collisions: radiation



Scalar and gravitational wave radiation in full EDGB.

WE & Ripley in prep.

Binary black hole inspiral



To do:

- Determine domain where theories are well-posed, and can give predictions for GW observations (case-by-case).
- Compare to order-reduction, other approximations that may not capture secular/non-perturbative effects.

Conclusion

Gravitational waves provide new probes of fundamental physics that may be inaccessible to terrestrial experiments.

- Place interesting constraints on new particles with current, upcoming observations
- Can use boson stars to test limits of horizonless compact objects
- Make non-perturbative predictions for modified gravity theories (and determine where this is possible)

Understanding of detailed dynamics, targeted analyses important.