Testing the nature of compact objects with gravitational waves

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Why?

- **Paradigm:** any compact object heavier than few $M_{\text{sun}}$ must be a black hole (BH)
- Observations of exotic compact objects (ECOs) would imply new physics / new matter
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1. BHs and neutron stars might co-exist with other “species”
   - ECOs might explain LIGO/Virgo *mass-gap* events (GW190814, GW190521)
   - ECOs can form in GR with new (dark?) matter fields (e.g. boson/axion stars)
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2. Strong theoretical motivation (singularity and/or information-loss problems):
   - New physics at the horizon (e.g. firewalls, nonlocality) [Almheri+, Giddings+, 2012-2017]
   - Regular, horizonless compact objects (e.g. fuzzballs) [Mathur+, Bena+, Bianchi+, Giusto+, ...]
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3. At the very least: quantify the “BH-ness” of GW sources across mass ranges
The zoo of ECOs

Solutions to GR with exotic matter sources
(e.g. anisotropic stars, boson stars, axion stars, gravastars, wormholes)

Solutions to modified gravity
(e.g. fuzzballs/microstates, 2-2 holes, superspinars, wormholes)

- No sharp distinction in some cases

- Some ECOs require modified gravity only in the interior / close to the horizon → assuming GR in the exterior is often a good approx.

- Here we focus on GW phenomenology *agnostically*

Quantifying the shades of darkness
Quantifying the shades of darkness

Compactness

$\epsilon$

$\epsilon$

$\epsilon$

$r_0 = r_+(1 + \epsilon)$
Quantifying the shades of darkness

\( R \)

Reflectivity

Compactness

\[ r_0 = r_+(1 + \epsilon) \]
Quantifying the shades of darkness

![Black hole diagram]

Reflectivity

Compactness

$\epsilon = 0 \quad R = 0$

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Quantifying the shades of darkness

\[ R \]

Reflectivity

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Black hole

Compactness

\[ r_0 = r_+ (1 + \epsilon) \]

~Small compactness
No absorption
(e.g. boson stars)
Quantifying the shades of darkness

- Small compactness
  - No absorption
  - (e.g. boson stars)

- Small compactness
  - Large absorption
  - (e.g. diffuse fuzzballs)

**Reflectivity**

**Compactness**

$\mathcal{R}$

$\epsilon = 0 \quad \mathcal{R} = 0$

$r_0 = r_+ (1 + \epsilon)$
Quantifying the shades of darkness

Large compactness
No absorption
(e.g. gravastars)

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~Small compactness
Large absorption
(e.g. diffuse fuzzballs)

Black hole
$\epsilon = 0 \quad R = 0$

Compactness
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Quantifying the shades of darkness

$\mathcal{R}$

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Black hole

Large compactness
No absorption
(e.g. gravastars)

Small compactness
No absorption
(e.g. boson stars)

Large compactness
Large absorption
(e.g. tight fuzzballs)

Small compactness
Large absorption
(e.g. diffuse fuzzballs)

$r_0 = r_+ (1 + \epsilon)$
Quantifying the shades of darkness

How do current and future observations constrain this parameter space?

Large absorption (e.g. tight fuzzballs)
Large absorption (e.g. diffuse fuzzballs)

Black hole

$\epsilon = 0 \quad R = 0$

$r_0 = r_+ (1 + \epsilon)$

Reflectivity

Compactness
A compass to navigate the ECO atlas

Buchdhal’s theorem
\[ \epsilon > \frac{1}{8} \]

1. Rotating or deformed objects
2. Dissipative fluids
   - Multi-fluids
   - Other matter fields
3. Exotic matter
4. Perfect fluid
5. Decreasing density
6. Staticity
7. Classical
8. Anisotropic fluids
   - Scalar or EM fields
9. ECOs in modified gravity
   - Semi-classical effects
   - Quantum gravity
Evading Buchdhal: anisotropic stars

\[ T_{\mu\nu} = T_{\mu\nu}^{\text{ISO}} + \sigma_1 k_\mu k_\nu + \sigma_2 \xi_\mu \xi_\nu + \sigma_3 \eta_\mu \eta_\nu \]

- Covariant framework for anisotropic fluids in GR, ready for 3+1 simulations
- Consistent proxy for ultracompact objects
- Satisfy WEC and SEC; highly-anisotropic configurations violate DEC
- Display all ECO typical phenomenology
Shadows: BH vs Boson Star

- Telling the shadow of a boson star from a Kerr BH is very challenging
- Lot of dirty astrophysics [Gralla 2019-2020]
- Tests based on shadows can at most constrain $\rightarrow \epsilon \sim O(1)$
GW-based tests of ECOs

~point masses: same signal for all objects

tidal effects + spins deformations

absence of horizon absorption effects

merge

different ringdown, tidal disruption, postmerger,

... echoes
ECO spectroscopy

- **Prompt ringdown**: superposition of quasinormal modes (QNMs)
  [e.g. Kokkotas & Schmidt (1999), Berti, Cardoso, Starinets (2009)]
  
  \[ h_+ + i h_\times \sim \sum_i A_i \sin(\omega_i t + \phi_i) e^{-t/\tau_i} \]

- 3G/LISA → O(100-1000) events/yr allowing for BH spectroscopy
  [Berti+ (2016)]

- Overtones also important → multimode/multitone analysis?

- **ECO smoking guns in the prompt ringdown** (shared with modified gravity):
  - Shift of the entire QNM spectrum
  - Extra ringdown modes (e.g., extra polarizations, matter modes) → amplitudes?
  - Isospectrality breaking

- Ringdown parametrizations sufficient for null-hypothesis tests
How does an ECO ringdown?

- Neglecting spin and assuming GR in the exterior → Schwarzschild
- Interior modeled extending the BH membrane paradigm [Damour, Thorne, ...]
- Boundary conditions → viscosity of a fictitious fluid \( \eta_{\text{BH}} = \frac{1}{16\pi} \)

Region not excluded by GW150914

- Axial and polar modes are not isospectral but harder to resolve
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A factor 10 increase in the SNR would constrain the whole region!
[Elisa Maggio – prelim. res.]

- Axial and polar modes are not isospectral but harder to resolve
For ultracompact ECOs ($\varepsilon<0.01$) prompt ringdown is identical to BHs but GW “echoes” at later times

- Only (classical) horizons absorb everything!

- Reflectivity arises in many contexts:
  - Stellar-like regular interior
  - “Fuzziness”
  - Quantum emission from horizon

- Lot of progress on echo waveform modeling and searches [Abedi+, Universe (2020)]
Coherent, analytical template in the FD:

- complex reflectivity
- mixing of polarizations
- spin-dependent modulation
- Many more features than templates used in current searches

Waveforms, templates, and movies available @ http://www.DarkGRA.org/gw-echo-catalogue.html

Near-horizon corrections are within reach!

- Large reflectivity crucial for detection with LIGO/Virgo
- Much better prospects with 3G and LISA
Post-Newtonian inspiral: BH vs ECO

\[ \tilde{h}(f) = A(f)e^{i(\psi_{PP} + \psi_{TH} + \psi_{TD})} \]

1PN = \frac{v^2}{c^2}

Blanchet, Living Rev. Relativity 17, 2 (2014)
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- **2PN:** Point-particle phase depends on **multipole moments** of the bodies

- Tests of the BH no-hair theorem [Hansen 1974]

\[ M^\ell_{\text{Kerr}} + iS^\ell_{\text{Kerr}} = M^{\ell+1} (i\chi)^\ell \]

Mass moments Spin moments
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Mass moments \quad Spin moments

- **ECOs** (axisymmetric case):

\[ M_\ell = M_\ell^{\text{Kerr}} + \delta M_\ell \quad S_\ell = S_\ell^{\text{Kerr}} + \delta S_\ell \]

- 3G/LISA can constrain mass quadrupole \((M_2)\) and spin octupole \((S_3)\) [Krishnendu+ 2018]

- In the BH limit \(\rightarrow\) **“hair conditioner”** [Raposo, PP, Emparan, PRD 2019]

\[ \frac{\delta M_\ell}{M^{\ell+1}} \rightarrow a_\ell \frac{\chi^{\ell}}{\log \epsilon} + b_\ell \epsilon + \ldots \quad \frac{\delta S_\ell}{M^{\ell+1}} \rightarrow c_\ell \frac{\chi^{\ell}}{\log \epsilon} + d_\ell \epsilon + \ldots \]

(assumes exterior is \(\sim\) GR and curvature near the surface is small)
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- (Stationary) ECOs can break: [fuzzballs: Bianchi+ 2007.01743, 2008.01445; boson stars: Herdeiro+ 2008.10608]
  - equatorial symm.: e.g. $S_2 \neq 0$, $M_3 \neq 0$
  - axial symm.: e.g. $M_{20} \neq 0$, $M_{21} \neq 0$, $M_{22} \neq 0$
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Embedding diagrams by G. Raposo
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Fuzzballs (in N=2 supergravity):

  - certain multipole ratios are \( \sim \) universal [Bena-Mayerson PRL 2006.10750, 2007.09152]
  - certain multipole invariants are minimum for BHs [Bianchi+ PRL 2007.01743, 2008.01445]

Lot of progress: current waveforms should be extended beyond Kerr symmetries
Post-Newtonian inspiral: BH vs ECO

\[ \tilde{h}(f) = A(f)e^{i(\psi_{PP} + \psi_{TH} + \psi_{TD})} \]

2.5 log PN: tidal heating [Alvi PRD 2001, Poisson, PRD 2009]

- BHs absorb radiation at horizon
- Tidal heating is \sim absent for ECOs
- Small even for 3G for q\sim 1 \rightarrow IMRIs or LISA

Post-Newtonian inspiral: BH vs ECO

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- **2.5 log PN: tidal heating** [Alvi PRD 2001, Poisson, PRD 2009]
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- **5PN: tidal deformability and Love numbers** [Flanagan & Hinder, PRD77 021502 2008]
  - Love = 0 for a BH in GR [Damour ‘86, Binnington-Poisson PRD 2009; Damour-Nagar PRD 2009; PP+, PRD 2015]
    (but see Le Tiec-Casal 2007.00214 and Chia 2010.07300 for spinning BHs!)
  - Love \neq 0 for ECOs and BHs in modified gravity [Porto+ Fortsch. Phys. 2016, Cardoso+, PRD 2017]
  - 3G/LISA will be able to distinguish BHs from any boson star model [Cardoso+, PRD 2017]
  - In several ECO models Love scales logarithmically → strong constraints [Maselli+, 2018-2019]
BH vs Boson Stars: coherent model

\[ \mathcal{L} = \frac{R}{16\pi G} - \partial_\mu \phi \partial^\mu \phi^* - m^2 |\phi|^2 + \lambda |\phi|^4 + \gamma |\phi|^6 + \ldots \]

Coherent inspiral waveform → all deviations from Kerr (multipoles, tidal, etc) depend only on masses & spins and on the theory’s coupling constants

▶ Tidal deformability strongest, but coherent model significantly improves the constraints

▶ Constraining power of current detectors is marginal: merger detections in 3G/LISA are required to constrain boson-star couplings

[Pacilio+ 2007.05264 PRD 2020]
ECO tests with EMRIs/IMRIs

- EMRIs are unique probes of both multipolar structure and dynamics

- ECO corrections are amplified for small mass-ratio, lessons form EMRIs:
  - Spin-induced multipole moments $\rightarrow \delta \tilde{M}_2 \sim 10^{-4}$ [Barack-Cutler, PRD 2007, Babak+ 2017]
  - Tidal heating $\rightarrow$ large for highly-spinning objects $\rightarrow |\mathcal{R}|^2 \lesssim 10^{-4}$ [Datta+ PRD 2020]
  - Tidal Love numbers $\rightarrow \tilde{\Lambda} \sim 10^{-5}$ [Pani & Maselli 2019]
  - Tests of the Kerr bound ($\chi<1$) could be much simpler and accurate with EMRIs if one can measure the spin of the secondary [Piovano, Maselli, PP, 2003.08448, 2004.02654]

- ECO tests with EMRIs/IMRIs $\rightarrow$ many challenges in modeling, parameter estimation, rates, etc...
Conclusion & Open problems

- Future detectors have superior potential to search for departures from classical BHs → discovery opportunity for new physics

- Very least: orders of magnitude improvements on current constraints

- Dramatic improvements on ECOs on all fronts in the last few years

- Better understanding/modeling is needed (simulations, coalescence, inspiral-merger-ringdown waveforms, and theoretical issues)

- Testing quantum gravity? In the search of a log...

Comprehensive living review: Cardoso & Pani, 1904.05363
for description of the effects, caveats, constraints, and references