Gravitational-wave echoes

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

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The observational status of black holes (BHs) is now more solid than ever

(Classical) BHs in GR are very economical:

- Arbitrary mass
- Compactness $M/R \sim 1$ ($G=c=1$ units henceforth)
- Sound formation mechanism
- Linearly (at least mode) stable
  [Dafermos & Rodnianski; Clay Math. Proc. (2013)]
- Consistent with all observations

So why questioning the BH picture and testing exotic compact objects (ECOs)?
Testing BHs, why should we care?

- New species of compact objects?
  - Lesson from timeline of particle physics discovery

- The dark matter connection
  - Can ECOs form (part of) the dark matter? (es. boson/axion stars)

- Quantifying the evidence for BHs
  - Lessons from tests of the WEP, etc, how to even formulate the problem?

- Problems on the horizon
  - BH exterior is fine, interior is not $\rightarrow$ singularities, Cauchy horizons, CTCs...
  - BHs are required for self consistency of General Relativity [Cosmic Censorship]
  - Drawbacks: Huge entropy, unitarity loss, thermodynamical instability [Hawking 1972]
Testing BHs, why should we care?

- Resolution of Hawking’s paradox might require drastic changes at the horizon:
  - New physics at the horizon (e.g. firewalls, nonlocality) [Almheri+, Giddings+, 2012-2017]
  - Regular, horizonless compact objects (e.g. fuzzballs) [Mathur, 2007-, Bena+ 2015, Turton, Warner]

- Tunneling probability to quantum state:
  - small amplitude \[ \mathcal{A}_{\text{tunneling}} \sim e^{-\alpha R_s^2/\ell_P^2} \sim e^{-\alpha M^2/h} \]
  - but huge phase space \[ \mathcal{N}_{\text{states}} \sim e^{S_{\text{BH}}} \sim e^{4\pi M^2/h} \]

\[ \mathcal{P}_{\text{tunneling}} \sim \mathcal{A}_{\text{tunneling}} \times \mathcal{N}_{\text{states}} \sim \mathcal{O}(1) \]
Exotic compact objects (ECOs)

Several models/proposals

Different levels of “robustness” and open problems


Phenomenologically:

“Good” ECOs [fluid stars, anisotropic stars, boson stars, oscillatons, ...]

“Bad” ECOs [fuzzballs, gravastars, wormholes, firewalls...]

Two approaches:

Model-dependent and from first principles

Phenomenological and agnostic on the model
GW-based tests of ECOs

~point masses: same signal for all objects

*tidal effects* + *spins deformations*

*absence of horizon absorption effects*

*echoes*

merger
different ringdown, tidal disruption, postmerger,

...
GW spectroscopy

- Post-merger signal → superposition of QNMs

  [e.g. Kokkotas & Schmidt (1999), Berti, Cardoso, Starinets (2009)]

\[ h_+ + i h_\times \sim \sum_i A_i \sin(\omega_i t + \phi_i) e^{-t/\tau_i} \]

- QNMs of Kerr BH in GR depends only mass and spin [no hair] (2+ modes needed)

\[ \omega_{nlm} = \omega_{R}^{\text{Kerr}}(M, \chi) + \delta\omega_R \quad \tau_{nlm} = \tau^{\text{Kerr}}(M, \chi) + \delta\tau \]

- Mode shift (due to different object, different dynamics, or couplings)

- Extra ringdown modes (e.g., extra polarizations, fields, matter) → amplitudes?
QNMs of exotic compact objects

\[ \frac{\partial^2 \Psi}{\partial t^2} - \frac{\partial^2 \Psi}{\partial r^2} + V_{slm}(r_*) \Psi = 0 \]

[\text{e.g. Kokkotas & Schmidt (1999), Berti, Cardoso, Starinets (2009)}]

QNMs exponentially sensitive to boundary conditions
QNMs of exotic compact objects

\[ \frac{\partial^2 \Psi}{\partial t^2} - \frac{\partial^2 \Psi}{\partial r^2_*} + V_{slm}(r_*) \Psi = 0 \]

[e.g. Kokkotas & Schmidt (1999), Berti, Cardoso, Starinets (2009)]

QNMs exponentially sensitive to boundary conditions

Ultracompact stars generically support trapped modes

Chandrasekhar & Ferrari PRSLA (1991)

No horizon \(\rightarrow\) QNM spectrum dramatically different
QNM spectrum of an UCO

Generic feature: low-frequency, long-lived QNMs in the BH limit

\[ f_{\text{QNM}} \sim |\log \epsilon|^{-1} \quad \tau \sim |\log \epsilon|^{2l+3} \quad r_0 = r_+ (1 + \epsilon) \]

QNM spectrum dramatically different \(\rightarrow\) ringdown?
GW echoes

Ringdown of a Schwarzschild BH
(Gaussian perturbation)
Prompt ringdown is identical, but GW “echoes” at late time

Kokkotas 1996; Ferrari & Kokkotas, PRD 2000
Cardoso, Franzin, PP, PRL (2016), Cardoso+ PRD (2016)

\[
\tau_{\text{echo}} = \int_{r_0}^{3M} \frac{dr}{F} \sim \frac{2GM}{c^3} |\log \epsilon|
\]

Delay time → log dependence
GW echoes

Prompt ringdown is identical, but GW “echoes” at late time

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\[ \tau_{\text{echo}} = \int_{r_0}^{3M} \frac{dr}{F} \sim \frac{2GM}{c^3} |\log \epsilon| \]

Delay time \( \rightarrow \) log dependence

Even Planck-scale corrections near horizon are within reach!

\[ r_0 - 2M \sim L_p \approx 10^{-33} \text{ cm} \Rightarrow \tau_{\text{echo}} \sim \frac{GM}{c^3} |\log \epsilon| \sim \mathcal{O}(50 \text{ ms}) \]
Model-independent signatures

- Only a (classical) horizon absorbs everything!

Reflectivity arises in many contexts:

- Stellar-like regular interior
- “Fuzziness”
- Quantum emission from horizon

- Can be modelled by frequency-dependent reflectivity coefficient
GW searches for echoes with LIGO/Virgo

- Tentative evidence in LIGO O1 [Abedi+, 2017, Conklin+ 2018]


- Tentative detection of ~72 Hz echoes @4.2σ in GW170817 [Abedi & Afshordi 1803.10454]

- Absence of statistical evidence in O1 and O2 confirmed by recent analyses [Uchikata+ 1906.00838, Tsang+ 1906.11168]

- Near-horizon quantum (?) structures within reach!

- Negative searches also important → constrain/rule out ECO models
Potential inferences from echoes

→ Remnant has photon sphere but ~ no horizon → neither GR BH nor ordinary NS

Echoes in GW170817-like system would be compatible with

- **Near-horizon quantum structures** [Cardoso+ 2016, Abedi+ 2017, Wang+ 2019, ...]
- **NS with very exotic matter** [Pani-Ferrari 2018, Mannarelli & Tonelli, PRD 2018]
- **Modified theories of gravity** [Conklin+ 2017, Buoninfante+ 2019, Delhom+ 2019]
GW echo modeling

Signal is rich: amplitude/frequency modulation, spin effects, reflectivity...

- Re-processing through a transfer function [Mark+ PRD96 084002 (2017)]

\[ \tilde{Z}^+(\omega) = \tilde{Z}^+_\text{BH}(\omega) + \kappa(\omega) \tilde{Z}^-_{\text{BH}}(\omega) \]

\[ \kappa(\omega) = \frac{\mathcal{T}_{\text{BH}} \mathcal{R}}{1 - \mathcal{R}_{\text{BH}} \mathcal{R}} \]


- Other strategies:
  - Dyson series (potential as a perturbation) [Correia & Cardoso 2018]
  - Resonances (in the transfer function) [Conklin+ 2018-2019]
  - Model-agnostic “wavelets” burst searches [Tsang+ PRD 2018, 1906.11168]
Echo modeling & detectability

Physically-motivated, analytical template:

- Reflectivity can be complex!
- Mixing of polarizations
- Spin-dependent modulation
- Large reflectivity crucial for detection

Waveforms, templates, and movies available @ http://www.DarkGRA.org/gw-echo-catalogue.html
Gravity community is undergoing a revolution

Probing fundamental physics with gravitational observations

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

- Better understanding/modeling is needed (especially of IMR signal)

- Current observations put new constraints on ECO models

- Mimicking BHs is extremely challenging → observational & theoretical issues
Backup slides

“Nothing is More Necessary than the Unnecessary” [cit.]
Echoes VS LISA noise curve

\[ \sqrt{S ; \vert h \vert^2 / f \, [\text{Hz}^{-1}]} \]

- \( R=0 \)
- \( R=1 \)
- \( R=0.99 \)
- \( R=0.9 \)
- \( R=0.5 \)

[Testa & PP (to appear)]
The role of the photon sphere

\[ \mathcal{E} = 1.5, \quad r_{\text{min}} = 4.3M, \quad r_0 - 2M = 10^{-6}M \]

Generic features for ultracompact ECOs (wormholes, gravastars, ultracompact stars, ...)

The ringdown of ECOs without light ring is qualitatively different

GW observations can rule out less compact ECOs without light ring

[Chirenti & Rezzolla, PRD 2016]
Ceci n’est pas un trou noir.
Searching for the absence

When testing *BHs we don’t look for something, but for the absence thereof*

- Surface / internal structure
- Radiation *from* the object
- Hair / multipolar structure
- Tidal Love numbers

BHs are **unique** yet **simple**

- BHs in GR+SM described by 3 parameters → multiple consistency tests

Need models and framework to go beyond null tests