Fundamental Physics with GWs

Black holes as imagined by children

Vitor Cardoso
Black holes: the ultimate engine of discovery

Theorem (Carter 1971; Robinson 1975; Chrusciel and Costa 2012):
A stationary, asymptotically flat, vacuum BH solution must be Kerr

\[
    ds^2 = \frac{\Delta - a^2 \sin^2 \theta}{\Sigma} dt^2 + \frac{2a(r^2 + a^2 - \Delta) \sin^2 \theta}{\Sigma} dt d\phi \\
    - \frac{(r^2 + a^2)^2 - \Delta a^2 \sin^2 \theta}{\Sigma} \sin^2 \theta d\phi^2 - \frac{\Sigma}{\Delta} dr^2 - d\theta^2
\]

\[\Sigma = r^2 + a^2 \cos^2 \theta, \quad \Delta = r^2 + a^2 - 2Mr\]

Describes a rotating BH with mass M and angular momentum \( J = aM \), iff \( a < M \)

“In my entire scientific life, extending over forty-five years, the most shattering experience has been the realization that an exact solution of Einstein’s equations of general relativity provides the absolutely exact representation of untold numbers of black holes that populate the universe.”

*S. Chandrasekhar*, The Nora and Edward Ryerson lecture, Chicago April 22 1975
Black holes: the ultimate engine of discovery
Cardoso & Pani, Living Reviews in Relativity (2019)

BH exterior is pathology-free, interior is not. How are singularities resolved? Do they impact on BH exterior? Are singularities always covered?

“Extraordinary claims require extraordinary evidence.”
Carl Sagan

Quantum effects not fully understood. “Fuzzballs,” “gravastars,” extra dimensions,...do black holes offer glimpses to quantum gravity?
Mathur 2005; Bekenstein & Mukhanov 1995; Giddings 2017; Foit & Kleban 2019; Agullo+ 2020

Is the final - or initial - object really a black hole?

Is it a Kerr black hole? Can we constrain alternatives?
Berti+ PRL117: 101102 (2016); Cardoso & Gualtieri CQG33:174001 (2016)

Can GWs from BHs inform us on fundamental fields/DM?
Black holes: the ultimate engine of discovery
Cardoso & Pani, Living Reviews in Relativity (2019)

Answer requires understanding of theoretical framework, PDEs, precise modelling, challenging simulations & challenging data analysis techniques

Image: Ana Carvalho

Singularity: who knows? quantum gravity?

Horizon: one-way membrane. Dresses singularity. Echoes, tidal Love numbers, quantum imprints?

Ergoregion: energy extraction, superradiance, condensation of light fields

Innermost Stable Circular Orbit (ISCO): cutoff for Standard Model particles, accretions disks

Light ring (photon sphere): GW relaxation signal, spectroscopy, strong-field tests

Evidence for existence of any of these features is welcome
Inspiralling compact objects

Binding Energy: \( E_b = -\frac{GM\mu}{2L} + \text{other interactions} \)

Quadrupole emission: \( \dot{E} = -\frac{32}{5} \frac{G\mu^2 L^4 \Omega^6}{c^5} + \text{other emission channels} \)

\[
h(f, \text{pars}) = A(f, \text{pars}) e^{i\Psi(f, \text{pars})} \\
\Psi = \frac{3}{128} \left( \frac{GM \pi f}{c^3} \right)^{-5/3} \left( \ldots + \alpha_{-4PN} x^{-4} + \ldots + \alpha_{-1PN} x^{-1} + 1 + \alpha_{1PN} x + \ldots \right)\]

\[
x = (\pi M f)^{2/3}, \quad M = m_1 + m_2, \quad \nu = m_1 m_2 / M^2, \quad \mathcal{M} = \nu^{3/5} M
\]
**Parametrized tests**

Any specific theory bound to affect all PPN parameters. Some of these - extra dimensions, varying-G, graviton mass, etc, derived with hand-waving arguments, blind to full theory.

In other words, need to know full waveform, which requires precise modelling and challenging simulations.
Any specific theory bound to affect all PPN parameters. Some of these - extra dimensions, varying-G, graviton mass, etc, derived with hand-waving arguments, blind to full theory.

In other words, need to know full waveform, which requires precise modelling and challenging simulations.
Black hole spectroscopy I


\[ h = \sum_{k} A_k e^{-\omega_{l}^{(k)} t} \sin \left( \omega_{R}^{(k)} t \right) \]
Black hole spectroscopy I

90% posterior distributions.

Black solid is 90% posterior of QNM as derived from the posterior mass and spin of remnant.

We need ET!

Left: Rates of binary BH mergers that yield detectable ringdown signals (filled symbols) and allow for spectroscopic tests (hollow symbols).

Right: Same for redshift distribution.
Black hole spectroscopy II
Duque+ (in preparation)
Black hole spectroscopy II
Duque+ (in preparation)
Evidence for horizons: outstanding challenges


i. Well-posed alternatives yielding ultracompact solutions?
ii. Formation mechanism for alternatives?
iii. Are these BH mimickers dynamically stable? Timescales?
iv. How do they look like? Is GW or EM signal similar to BHs?
v. Observationally, how close do we get to horizons?

Quantifying evidence for horizons similar to quest to quantify equivalence principle

Answer requires understanding of theoretical framework, PDEs, precise modelling, challenging simulations & challenging data analysis techniques
Nature of inspiralling objects is encoded

(i) in way they respond to own field (multipolar structure)

(ii) in way they respond when acted upon by external field of companion – through their tidal Love numbers (TLNs), and

(iii) on amount of radiation absorbed, i.e., tidal heating

\[ \tilde{h}(f) = A(f)e^{i(\psi_{PP} + \psi_{TH} + \psi_{TD})} \]
Post-merger: echoes 
more than just w-modes

We need ET!

Searches for echoes were conducted by the LIGO/Virgo Collaboration arXiv:2010:14529
Surprises?

Bekenstein & Mukhanov 1995

i. Postulate some area quantization

\[ A = \alpha l_p^2 N = \alpha \frac{\hbar G}{c^2} N \]

\[ \Delta A = \alpha \frac{\hbar G}{c^3} \Delta N = 32\pi \frac{G^2}{c^4} M \Delta M \]

ii. Compute absorbed energy of graviton

\[ \Delta M = \alpha \frac{c\hbar}{32\pi G} \frac{\Delta N}{M} \]

\[ \omega_n = \frac{\Delta M c^2}{\hbar} = \frac{n\alpha}{32\pi} \frac{c^3}{MG} \]

Consequences for ringdown, TLNs, tidal heating

\[ \alpha_{\text{crit}}(a) = 0.0842 + 0.2605a^2 + 0.0320e^{5.3422a^3} \]

TLNs, tidal heating, echoes
The evidence for black holes
Cardoso and Pani, Living Reviews in Relativity (2019)

Table 1: *How well does the BH geometry describe dark compact objects in our universe?* Table quantifies the answer *by excluding* the presence of surfaces in the spacetime. Deviation from Kerr geometry is assumed to occur close horizon and is measured with a dimensionless quantity $\epsilon$. For $\epsilon = 0$ the spacetime is described by vacuum GR all the way to the horizon. Constraint also translated as blueshift of a radial-directed photon $\nu/\nu_\infty$ (on the equatorial plane, measured by locally non-rotating observers) as it travels from large distances to the last point down to which observations are compatible with vacuum. Constraints derived from a variety of observations and tests (Cardoso+Pani, LLR 2019).

<table>
<thead>
<tr>
<th>$\epsilon(\lesssim)$</th>
<th>$\frac{\nu}{\nu_\infty}(\lesssim)$</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{O}(1)$</td>
<td>1.4</td>
<td>Sgr A* &amp; M87 (LR cutoff)</td>
</tr>
<tr>
<td>$\mathcal{O}(0.01)$</td>
<td>150</td>
<td>GW150914 (merger frequency, ringdown agreement)</td>
</tr>
<tr>
<td>$10^{-14}$</td>
<td>$10^7$</td>
<td>Sgr A* (low luminosity of object compared to disk)</td>
</tr>
<tr>
<td>$10^{-40}$</td>
<td>$10^{23}$</td>
<td>GW????? (absence of echoes)</td>
</tr>
</tbody>
</table>

Planck-scale physics. Need ET for this.
GWs and dark matter

DM not strong-field phenomenon, but GW observations may reveal a “mundane” explanation in terms of heavy BHs. 

*Bird + PRL116:201301 (2016)*

Inspiral occurs in DM-rich environment and may modify the way inspiral proceeds, given dense-enough media: accretion and gravitational drag play important role.

GWs and new fundamental fields: superradiance

\[ \nabla_\gamma \nabla^\gamma \Psi = \mu^2 \Psi, \quad \nabla_\gamma F^{\gamma \nu} = \mu^2 A^\nu, \quad \nabla_\gamma \nabla^\gamma h_{\mu \nu} = \mu^2 h_{\mu \nu} \]

\[ \Psi \sim e^{-i\omega t} Y_{lm} \]

\[ \omega \sim \mu + i(m\Omega_H - \mu)(M\mu)^{4l+5+S} \]

\[ S = -s, -s + 1,..., s - 1, s \]

\[ \tau \sim 100 \left( \frac{10^6 M_\odot}{M} \right)^8 \left( \frac{10^{-16} \text{eV}}{\mu} \right)^9 \text{ seconds} \]

Wonderful sources of GWs
Brito, Cardoso, Pani, Lecture Notes Physics 971 (2020)
Wonderful sources for different GW-detectors

For model-independent bounds $10^{-13} - 10^{-11}$ eV need ET!

---

**FIG. 2.** Left panel: stochastic background in the LIGO and LISA bands. For LISA, the three different signals correspond to the “optimistic” (top), “less optimistic” (middle) and “pessimistic” (bottom) astrophysical models. For LIGO, the different spectra for each scalar field mass correspond to a uniform spin distribution with (from top to bottom) $\chi \in [0.8, 1], [0.5, 1], [0, 1]$ and $[0, 0.5]$. The black lines are the power-law integrated curves of Ref. [61], computed using noise PSDs for LISA [9], LIGO’s first two observing runs (O1 and O2), and LIGO at design sensitivity (O5) [62]. By definition, $\rho_{\text{stoch}} \geq 1$ when a power-law spectrum intersects one of the power-law integrated curves. Right panel: $\rho_{\text{stoch}}$ for the backgrounds shown in the left panel. We assumed $T_{\text{obs}} = 2$ yr for LIGO and $T_{\text{obs}} = 4$ yr for LISA.

See review Brito, Cardoso & Pani Lecture Notes Physics 971 (2020)
Conclusions: exciting times!

Gravitational wave astronomy will become a precision discipline, mapping compact objects throughout the entire visible universe.

Black holes remain the most outstanding object in the universe. BH spectroscopy will allow to test GR and provide strong evidence for the presence of horizons... improved sensitivity pushes putative surface closer to horizon, like probing short-distance structure with accelerators. BHs can play the role of perfect laboratories for particle physics, or high energy physics.

“I only wish to make a plea for “black holes” to be taken seriously and their consequences to be explored in full detail. For who is to say, without careful study, that they cannot play some important part in the shaping of observed phenomena?”

Thank you
I only wish to make a plea for “black holes” to be taken seriously and their consequences to be explored in full detail. For who is to say, without careful study, that they cannot play some important part in the shaping of observed phenomena?

DM II. Light fields

Interesting as effective description; proxy for more complex interactions; arise as interesting extensions of GR* (BD or generic ST theories, f(R), etc)

Bosons do exist (Higgs) and lighter versions may as well Peccei-Quinn (interesting because not invented to solve DM problem), axiverse (moduli and coupling constants in string theory)

\[ \mathcal{L} = \frac{R}{k} - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{1}{2} g^{\mu\nu} \partial_{\mu} \Psi \partial_{\nu} \Psi - \frac{\mu_{S}^{2}}{2} \Psi \Psi - \frac{k_{\text{axion}}}{2} \Psi^{*} F^{\mu\nu} F_{\mu\nu} \]

...and one or more could be a component of DM. D. Marsh, Phys. Repts. 2016
Small Compton wavelength: heavy DM

Effect is -5.5 PN on GW phase

Cardoso & Maselli AA (to appear) arXiv 1909.05870
Constraints on fundamental fields via superradiance

<table>
<thead>
<tr>
<th>excluded region (in eV)</th>
<th>source</th>
</tr>
</thead>
<tbody>
<tr>
<td>(5.2 \times 10^{-13} &lt; m_S &lt; 6.5 \times 10^{-12})</td>
<td>Direct bounds from absence of spin down in Cyg X-1.</td>
</tr>
<tr>
<td>(1.1 \times 10^{-13} &lt; m_V &lt; 8.2 \times 10^{-12})</td>
<td></td>
</tr>
<tr>
<td>(2.9 \times 10^{-13} &lt; m_T &lt; 9.8 \times 10^{-12})</td>
<td></td>
</tr>
<tr>
<td>(6 \times 10^{-13} &lt; m_S &lt; 2 \times 10^{-11})</td>
<td>Indirect bounds from BH mass-spin measurements.</td>
</tr>
<tr>
<td>(7 \times 10^{-20} &lt; m_S &lt; 1 \times 10^{-16})</td>
<td></td>
</tr>
<tr>
<td>(2 \times 10^{-14} &lt; m_V &lt; 1 \times 10^{-11})</td>
<td></td>
</tr>
<tr>
<td>(1 \times 10^{-20} &lt; m_V &lt; 9 \times 10^{-17})</td>
<td></td>
</tr>
<tr>
<td>(6 \times 10^{-14} &lt; m_T &lt; 1 \times 10^{-11})</td>
<td></td>
</tr>
<tr>
<td>(3 \times 10^{-20} &lt; m_T &lt; 9 \times 10^{-17})</td>
<td></td>
</tr>
<tr>
<td>(1.2 \times 10^{-13} &lt; m_S &lt; 1.8 \times 10^{-13})</td>
<td>Null results from blind all-sky searches for continuous GW signals.</td>
</tr>
<tr>
<td>(2.0 \times 10^{-13} &lt; m_S &lt; 2.5 \times 10^{-12})</td>
<td></td>
</tr>
<tr>
<td>(m_V: NA)</td>
<td></td>
</tr>
<tr>
<td>(m_T: NA)</td>
<td></td>
</tr>
<tr>
<td>(5.8 \times 10^{-13} &lt; m_S &lt; 8.6 \times 10^{-13})</td>
<td>Null results from searches for continuous GW signals from Cygnus X-1.</td>
</tr>
<tr>
<td>(m_V: NA)</td>
<td></td>
</tr>
<tr>
<td>(m_T: NA)</td>
<td></td>
</tr>
<tr>
<td>(2.0 \times 10^{-13} &lt; m_S &lt; 3.8 \times 10^{-13})</td>
<td>Negative searches for a GW background.</td>
</tr>
<tr>
<td>(m_V: NA)</td>
<td></td>
</tr>
<tr>
<td>(m_T: NA)</td>
<td></td>
</tr>
<tr>
<td>(5 \times 10^{-13} &lt; m_S &lt; 3 \times 10^{-12})</td>
<td>Bounds from pulsar timing.</td>
</tr>
<tr>
<td>(m_V \sim 10^{-12})</td>
<td></td>
</tr>
<tr>
<td>(m_T: NA)</td>
<td></td>
</tr>
<tr>
<td>(2.9 \times 10^{-21} &lt; m_S &lt; 4.6 \times 10^{-21})</td>
<td>Bounds from mass and spin measurement of M87 with EHT.</td>
</tr>
<tr>
<td>(8.5 \times 10^{-22} &lt; m_V &lt; 4.6 \times 10^{-21})</td>
<td></td>
</tr>
<tr>
<td>(*1.0 \times 10^{-21} &lt; m_T &lt; 8.2 \times 10^{-21})</td>
<td></td>
</tr>
</tbody>
</table>
They exist! (?)


GRAVITY Collaboration AA 635: A143 (2020)
IIIb. Stability of objects with photospheres

Static objects: No uniform decay estimate with faster than logarithmic decay can hold for axial perturbations of ultracompact objects.

Keir CQG33: 135009 (2016); Cardoso + PRD90:044069 (2014)

\[ E_{\text{local}}^{(N)}(t) \lesssim \frac{1}{(\log(2+t))^2} E_{(2)}^{(N)}(0) \]

\[ \Box \phi = 0 \]

Fundamental questions

Is it a Kerr black hole? Can we constrain alternatives?
*Berti*+ *PRL117: 101102 (2016)*; *Cardoso & Gualtieri CQG33:174001 (2016)*

Is the final - or initial - object *really* a black hole?

Do black holes offer glimpses to quantum gravity?
*Bekenstein & Mukhanov 1995; Foit & Kleban 2019; Agullo+ 2020*

Can GWs from BHs inform us on fundamental fields/DM?

Answer requires understanding of theoretical framework, PDEs, precise modelling, challenging simulations & challenging data analysis techniques
Why is this not enough?

Cardoso & Pani, Living Reviews in Relativity (2019)

1. BH exterior is pathology-free, interior is not.


3. Tacitly assumed quantum effects at Planck scales. Planck scale could be significantly lower (Arkani-Hamed+ 1998; Giddings & Thomas 2002). Even if not, many orders of magnitude standing, surprises can hide.

“Extraordinary claims require extraordinary evidence.”
Carl Sagan

4. Dark matter exists, and interacts gravitationally. Are there compact DM clumps?

5. Physics is experimental science. We can test exterior. Aim to quantify evidence for horizons. Similar to quantifying equivalence principle.