Fundamental Physics with GWs

Black holes as imagined by children

TÉCNICO LISBOA

Vitor Cardoso

European Research Council

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

$$
\begin{aligned}
ds^2 \quad = \quad & \frac{\Delta - a^2 \sin^2\theta}{\Sigma} dt^2 + \frac{2a(r^2 + a^2 - \Delta)\sin^2\theta}{\Sigma} dt d\phi \\
& - \frac{(r^2 + a^2)^2 - \Delta a^2 \sin^2\theta}{\Sigma} \sin^2\theta d\phi^2 - \frac{\Sigma}{\Delta} dr^2 - \Sigma d\theta^2 \\
& \Sigma = r^2 + a^2 \cos^2\theta \,, \quad \Delta = r^2 + a^2 - 2Mr
\end{aligned}
$$

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

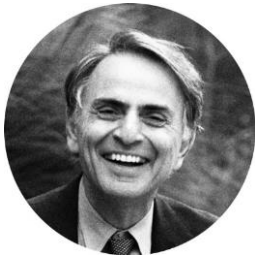
"In my entire scientific life, extending over forty-five years, the most shattering experience has been the realization that an exact solution of Einstein's equations of general relativity provides the *absolutely exact representation* of untold numbers of black holes that populate the universe."

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?
Cardoso+ PRL116: 171101 (2016); Nature Astronomy 1: 586 (2017); Liv. Rev. Rel.22: 1 (2019)

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?
Barack+arXiv:1806.05195; Brito+ PRL119:131101 (2017); Annulli+ PRD102:063022 (2020)

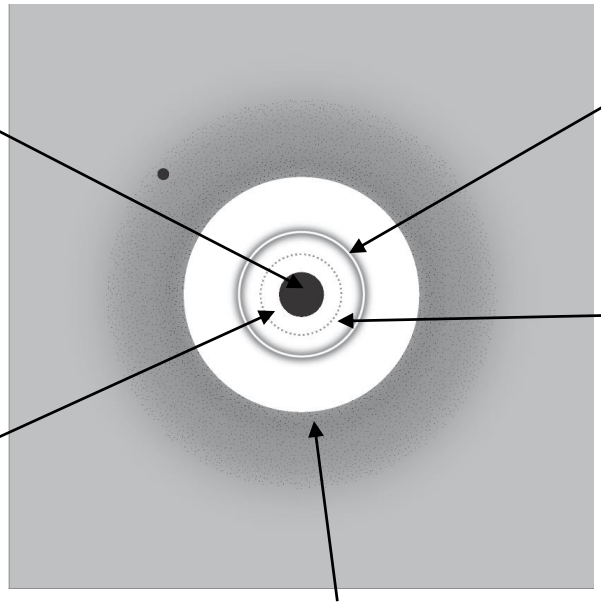
Black holes: the ultimate engine of discovery

Cardoso & Pani, Living Reviews in Relativity (2019)

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

Singularity:
who knows?
quantum gravity?

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



Ergoregion:
energy extraction, superradiance, condensation of light fields

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

Image: Ana Carvalho

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

Evidence for existence of any of these features is welcome

Inspiralling compact objects

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

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

$$h(f, \text{pars}) = A(f, \text{pars}) e^{i\Psi(f, \text{pars})}$$

$$\Psi = \frac{3}{128}\left(G\mathcal{M}\pi f/c^3\right)^{-5/3}\left(\ldots + \alpha_{-4PN}x^{-4} + \ldots + \alpha_{-1PN}x^{-1} + 1 + \alpha_{1PN}x + \ldots\right)$$

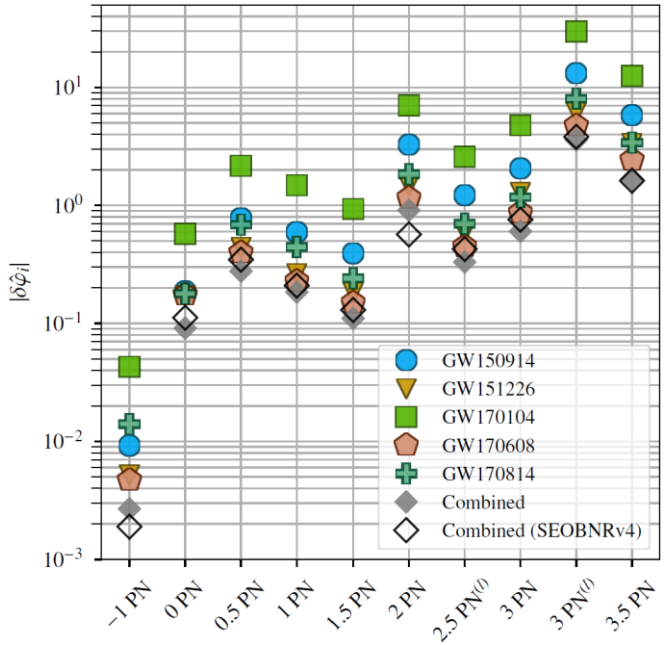
Dipole moment (electric charge)

Graviton mass

$$x = (\pi M f)^{2/3}\,, \quad M = m_1 + m_2\,, \quad \nu = m_1 m_2/M^2\,, \quad \mathcal{M} = \nu^{3/5} M$$

M. Maggiore, Gravitational waves, Volume I

Parametrized tests



LVC arXiv:1903.04467; see arXiv:2010:14529 for latest events

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 chanllenging simulations

Parametrized tests

PN order (ppE b)	Current Constraint	Best (Worst) Constraint	Best (Worst) Source Class
-4 (-13)	–	10^{-25} (10^{-14})	MB (T)
-3.5 (-12)	–	10^{-23} (10^{-14})	MB (T)
-3 (-11)	–	10^{-21} (10^{-12})	MB (T)
-2.5 (-10)	–	10^{-19} (10^{-11})	MB (T)
-2 (-9)	–	10^{-17} (10^{-10})	MB (T)
-1.5 (-8)	–	10^{-15} (10^{-9})	MB (T)
-1 (-7)	2×10^{-11}	10^{-13} (10^{-11})	MB (MBH)
-0.5 (-6)	1.4×10^{-8}	10^{-11} (10^{-8})	MB (T)
0 (-5)	1.0×10^{-5}	10^{-7} (10^{-5})	MBH (T)
.5 (-4)	$4.4 \times 10^{-3*}$	10^{-7} (10^{-5})	MB (T)
1 (-3)	$2.5 \times 10^{-2*}$	10^{-6} (10^{-4})	MB/T (T)
1.5 (-2)	0.15^{*}	10^{-5} (10^{-3})	T (MB)
2 (-1)	0.041^{*}	10^{-4} (10^{-2})	T (MB)

Perkins+ arXiv:2010.09010
MB=Multiband, T=Terrestrial
MBH=spacebased

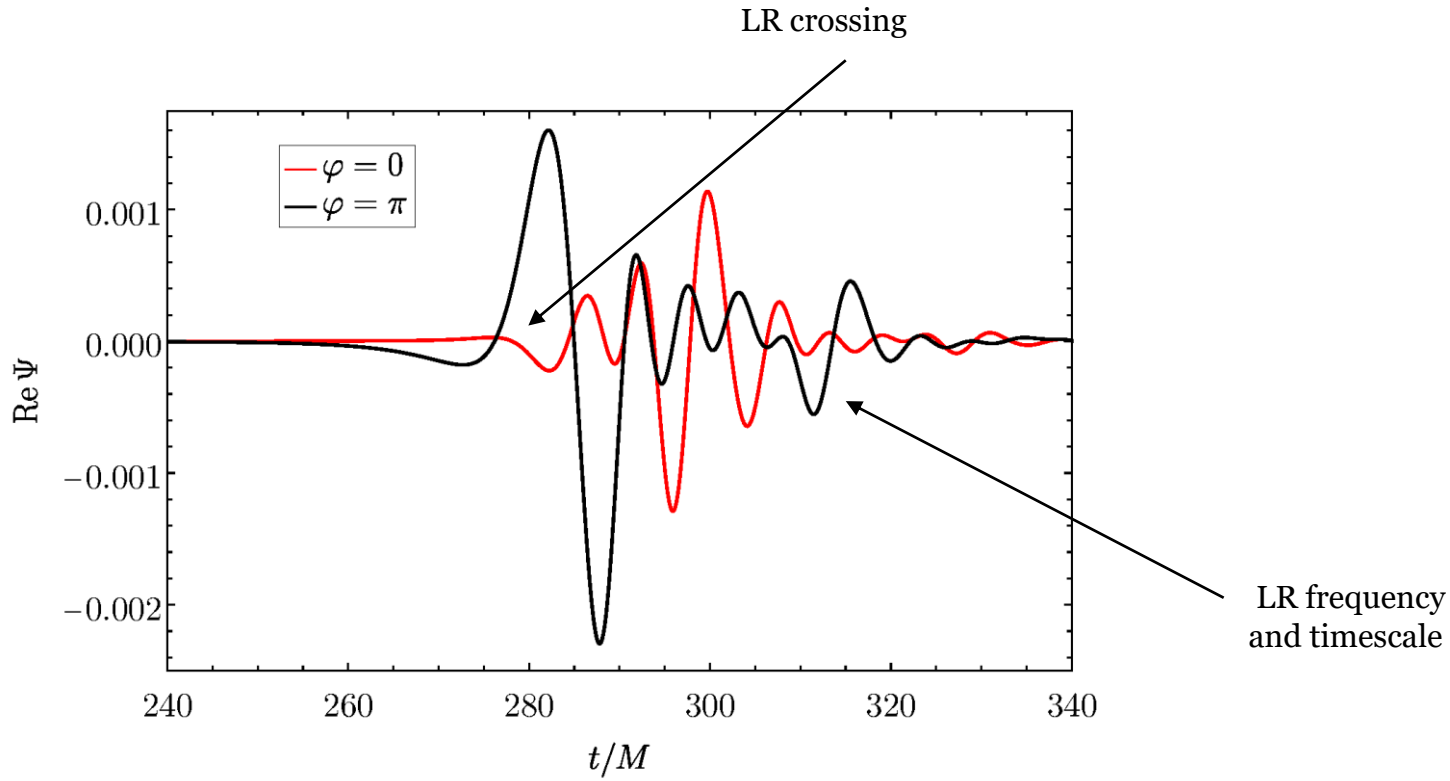
We need ET

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 chanllenging simulations

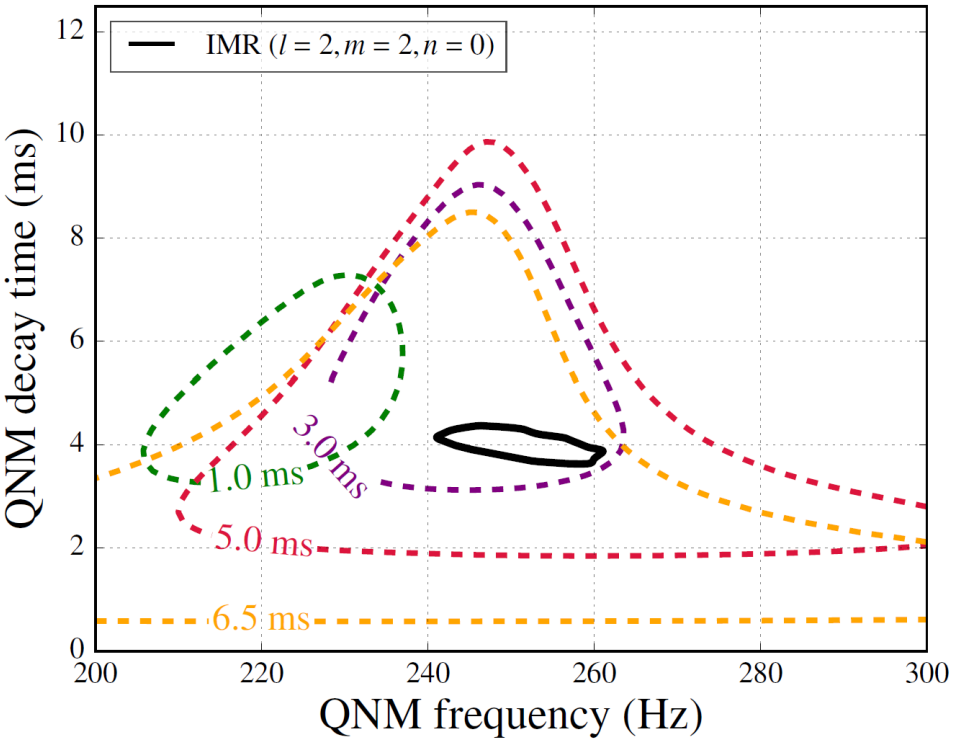
Black hole spectroscopy I

Berti+ PRD73: 064030 (2006); CQG26:163001 (2009); PRL117:10102 (2016)



$$h = \sum_k A_k e^{-\omega_I^{(k)} t} \sin\left(\omega_R^{(k)} t\right)$$

Black hole spectroscopy I



90% posterior distributions.

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

LSC PRL116:221101 (2016); for higher overtones: Bhaibav+PRD97:044048 (2019); Isi+ PRL123:111102 (2019) also recent LIGO/Virgo analysis arXiv:2010.14529

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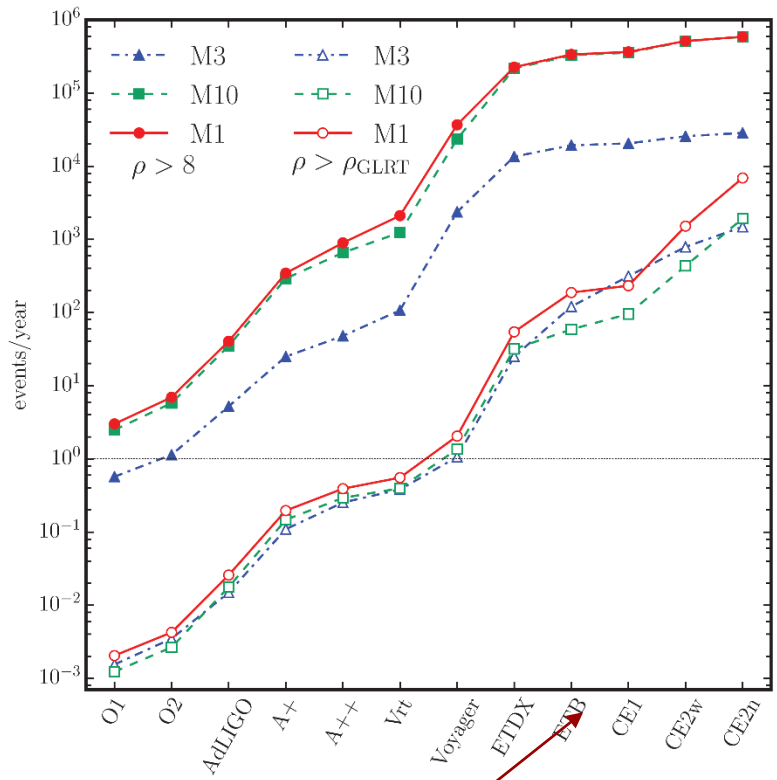
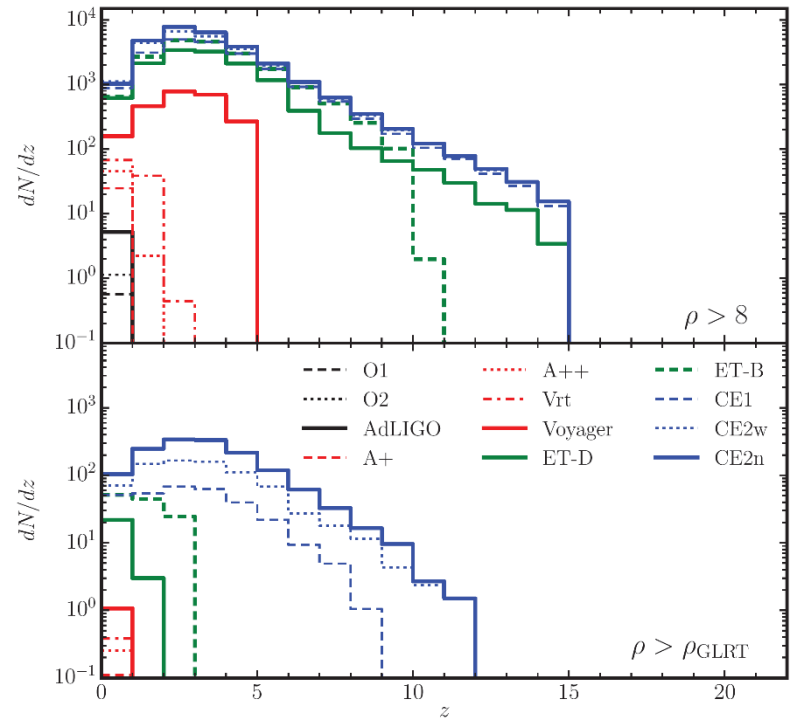


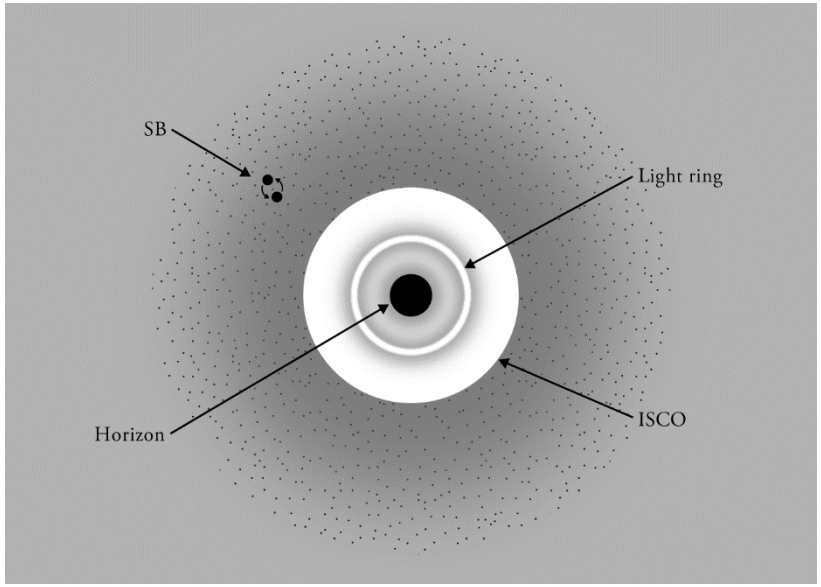


We need ET!

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

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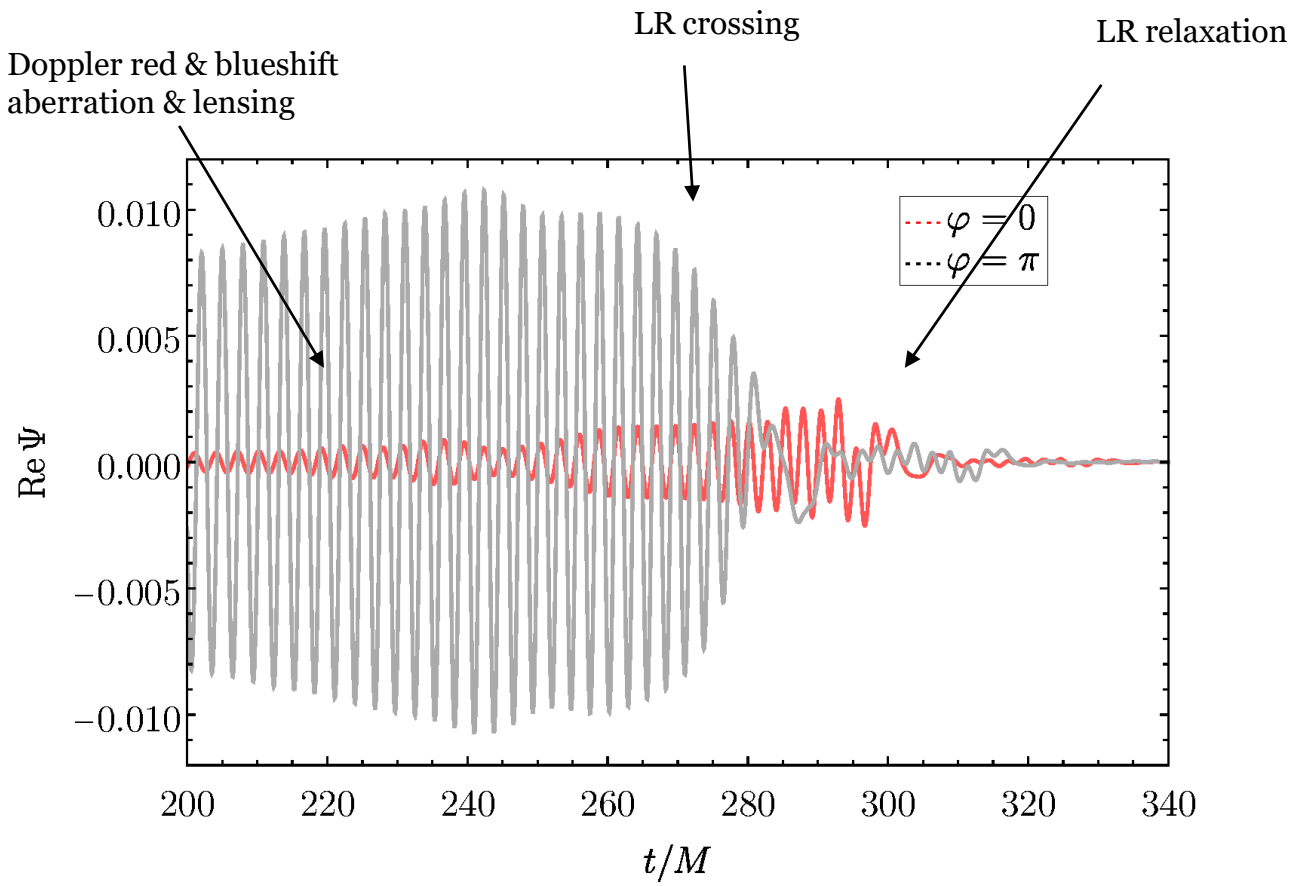


Evidence for horizons: outstanding challenges

Cardoso & Pani, Living Reviews in Relativity 22: 1 (2019)

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?

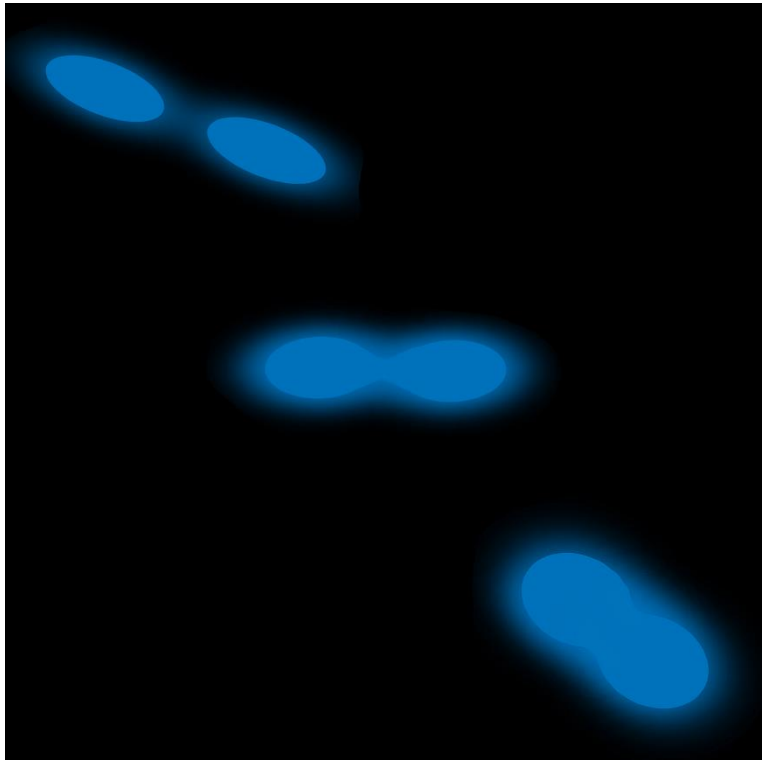
v. Observationally, how close do we get to horizons?

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

GW signal: inspiral

Cardoso & Pani, Living Reviews in Relativity 22: 1 (2019)



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

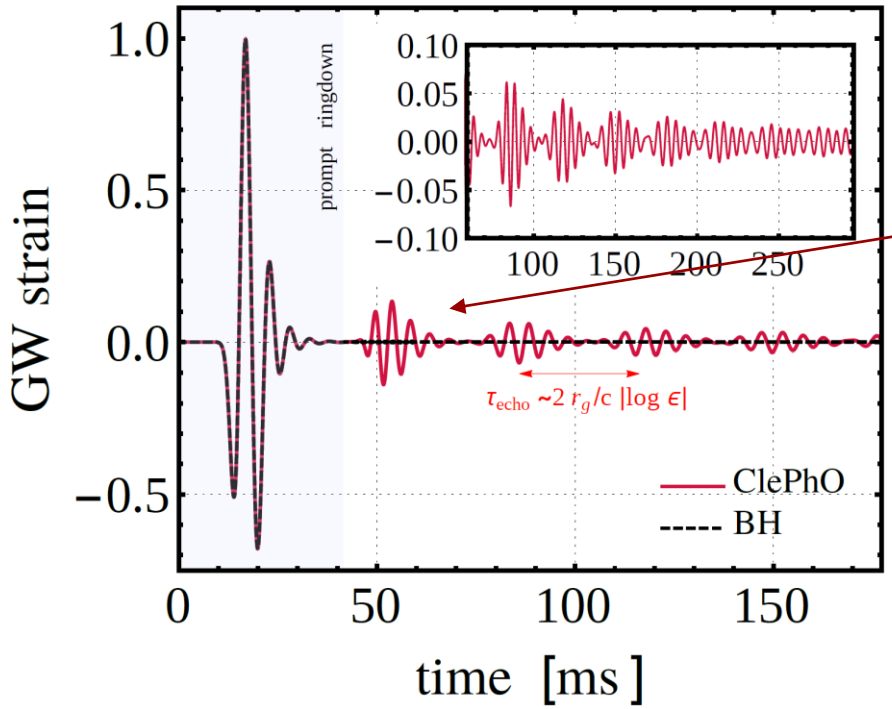
(iii) on amount of radiation absorbed, i.e., tidal heating

$$\tilde{h}(f) = \mathcal{A}(f) e^{i(\psi_{\rm PP} + \psi_{\rm TH} + \psi_{\rm TD})}$$

Cardoso + PRD95:084014 (2017); Sennett + PRD96:024002 (2017)
Maselli+ PRL120:081101 (2018); Cardoso & Pani, Nature Astronomy 1:586 (2017)

Post-merger: echoes

more than just w-modes



We need ET!

Cardoso + PRL116:171101 (2016); Cardoso and Pani, Nature Astronomy 1: 2017; Testa+ 2019
Cardoso and Pani, Living Reviews in Relativity 22:1 (2019)

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

Surprises?

Bekenstein & Mukhanov 1995
Foit & Kleban 2019; Cardoso+ 2019; Agullo+ arXiv:2007.03700

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

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

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

Classical!

Consequences for ringdown, TLNs, tidal heating

$$\alpha_{\rm crit}(a) = 0.0842 + 0.2605a^2 + 0.0320e^{5.3422a^3}$$

TLNs, tidal heating, echoes
Agullo, Cardoso, del Rio, Maggiore, Pullin arXiv:2007.03700

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 ϵ. 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 ν/ν_∞ (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).

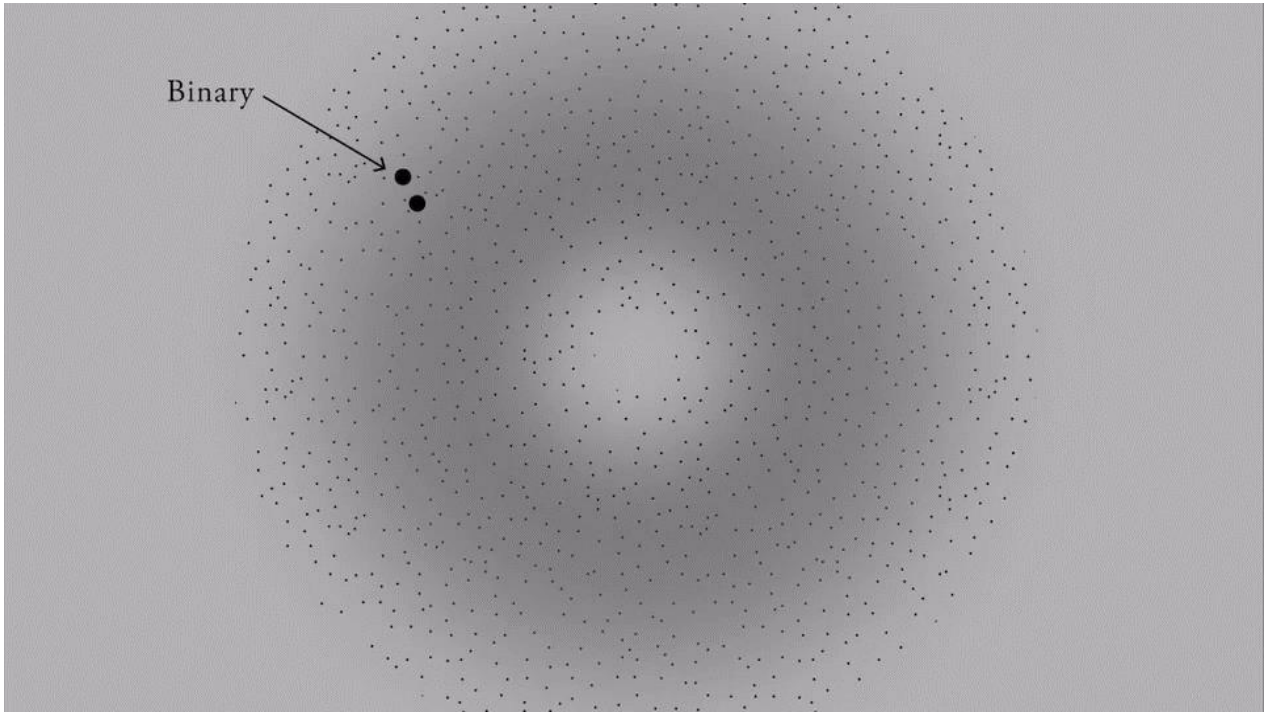
Constraints		Source
$\epsilon(\lesssim)$	$\frac{\nu}{\nu_\infty}(\gtrsim)$	
$\mathcal{O}(1)$	1.4	Sgr A* & M87 (LR cutoff)
$\mathcal{O}(0.01)$	150	GW150914 (merger frequency, ringdown agreement)
10^{-14}	10^{7}	Sgr A* (low luminosity of object compared to disk)
10^{-40}	10^{23}	GW????? (absence of echoes)

Planck-scale physics. Need ET for this.

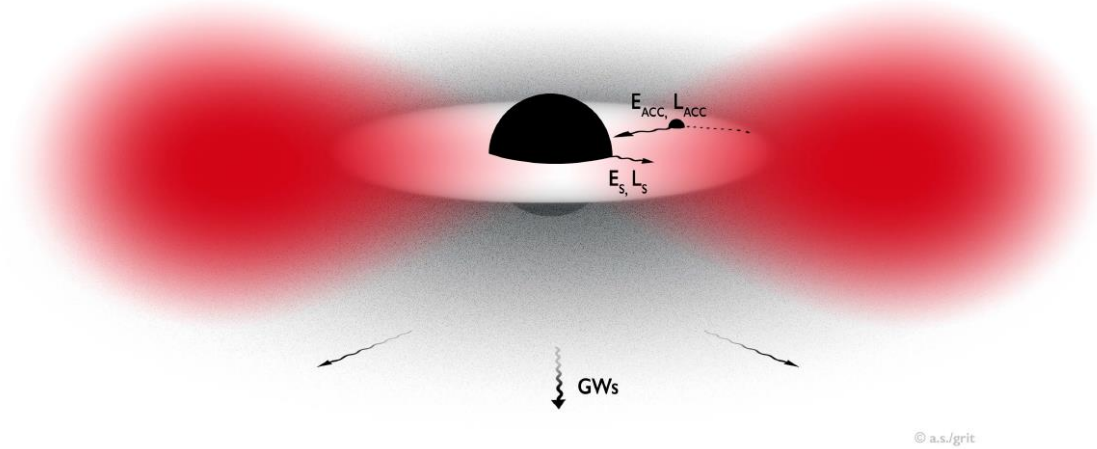
GWs and dark matter

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.
Eda + PRL110:221101 (2013); Macedo + ApJ774:48 (2013); Cardoso + arXiv 1909.05870; Kavanagh + arXiv 2002.12811; Annulli + PRD101:063022 (2020)



GWs and new fundamental fields: superradiance



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

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

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

$$S = -s, -s+1 ..., s-1, s$$

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

Wonderful sources of GWs

Arvanitaki+ 2010, 2011, 2015; Brito+ 2013, 2015, 2017; Baumann+ 2019, 2020
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!

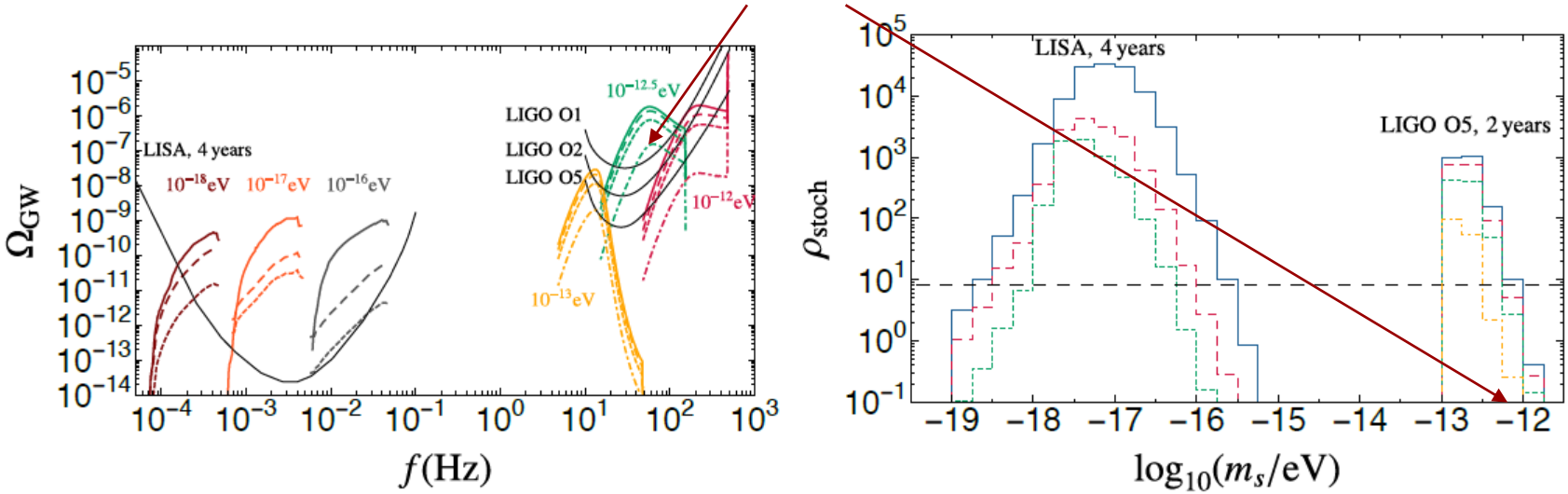


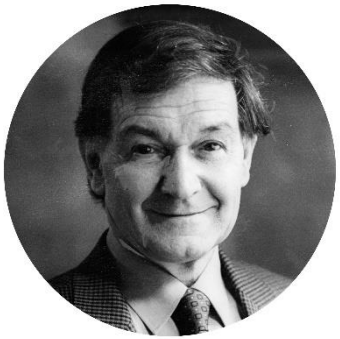
FIG. 2. Left panel: stochastic background in the LIGO and LISA bands. For LISA, the three different signals correspond to the "optimistic" (top), "less optimistic" (middle) and "pessimistic" (bottom) astrophysical models. For LIGO, the different spectra for each scalar field mass correspond to a uniform spin distribution with (from top to bottom) $\chi_i \in [0.8, 1]$, $[0.5, 1]$, $[0, 1]$ 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, $\rho_{\rm stoch} \geq 1$ when a power-law spectrum intersects one of the power-law integrated curves. Right panel: $\rho_{\rm stoch}$ for the backgrounds shown in the left panel. We assumed $T_{\rm obs} = 2$ yr for LIGO and $T_{\rm obs} = 4$ yr for LISA.

Brito + PRL119: 131101 (2017); for vectors: Tsukada + arXiv: 2011.06995
See review Brito, Cardoso & Pani Lecture Notes Physics 971 (2020)
https://centra.tecnico.ulisboa.pt/network/grit/files/superradiantbounds/

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?"

Roger Penrose, Gravitational Collapse: the role of General Relativity (1969)

Thank you

Energy source?

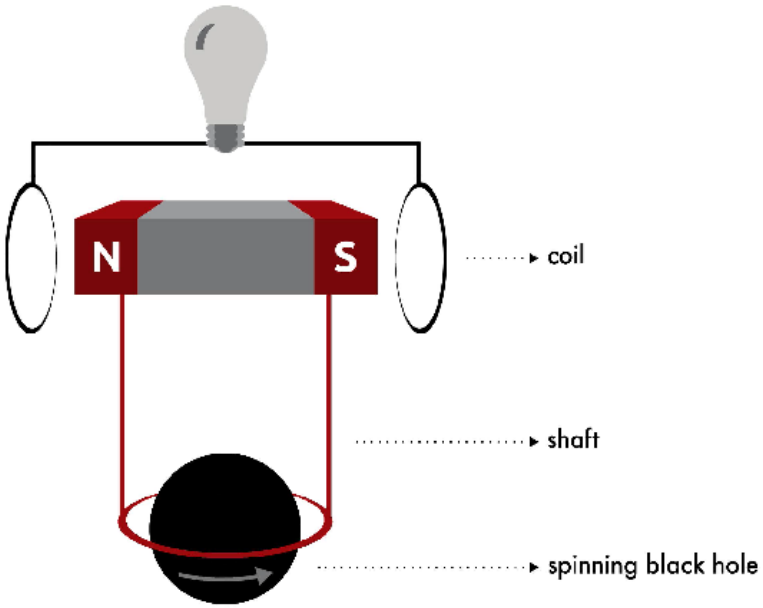


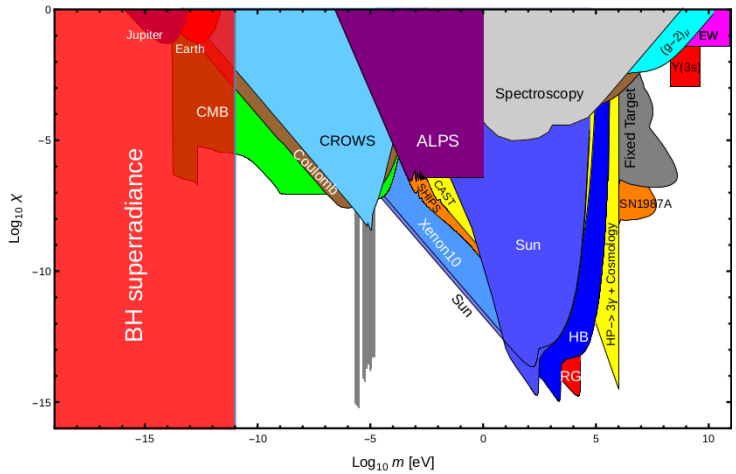
Image: Ana Carvalho

Brito, Cardoso & Pani, *Superradiance* (Springer-Verlag, 2020)

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?

Penrose, Gravitational Collapse: the role of General Relativity (1969)

DM II. Light fields



Cardoso+ 2018, adapted from Sigl (2017) and Jaeckel arXiv:1303.1821

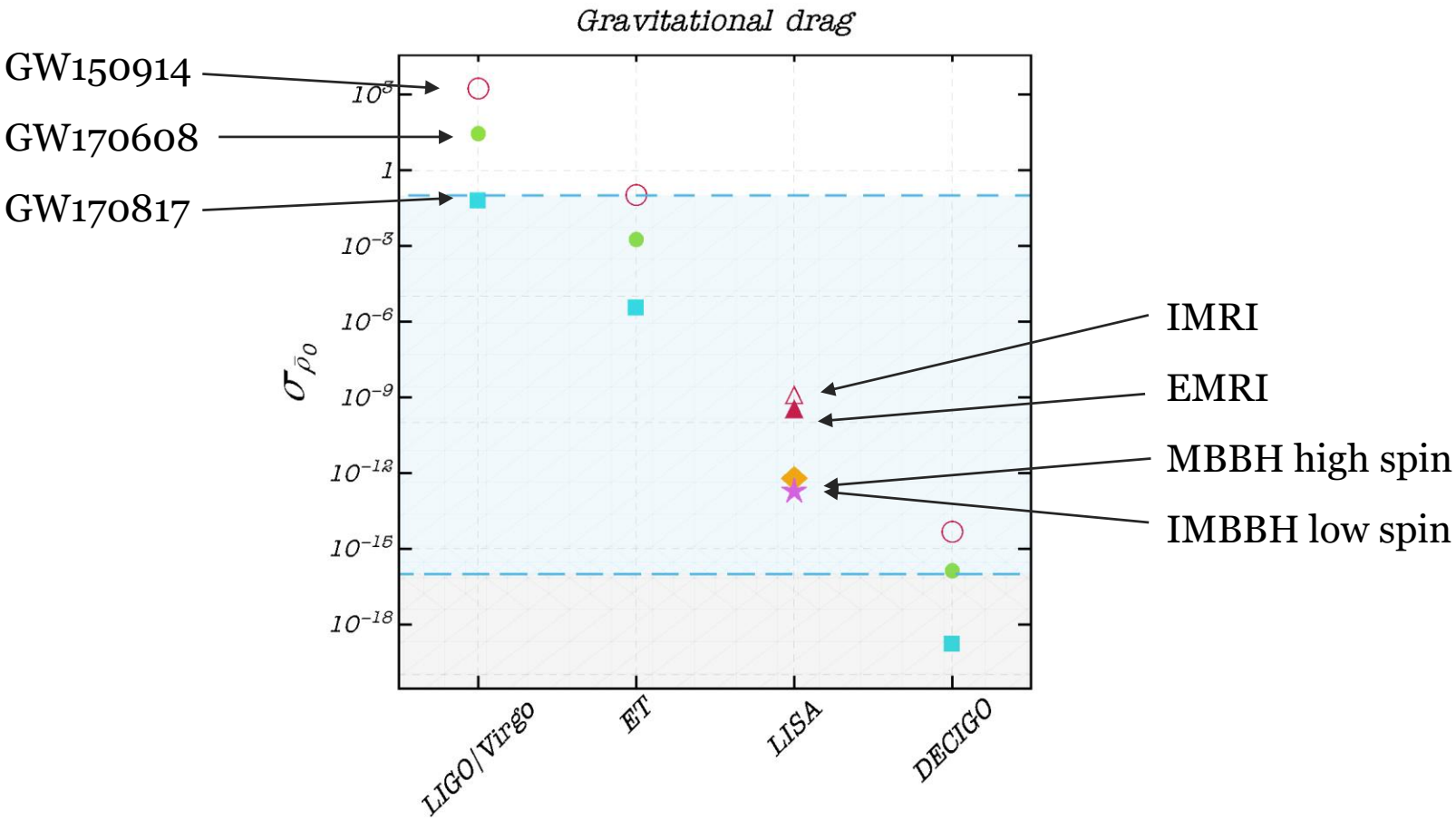
Interesting as effective description; proxy for more complex interactions; arise as interesting extensions of GR* *(BD or generic ST theories, f(R), etc)*

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)

$$\mathcal{L} = \frac{R}{k} - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{2}g^{\mu\nu}\partial_\mu\Psi\partial_\nu\Psi - \frac{\mu_S^2}{2}\Psi\Psi - \frac{k_{\rm axion}}{2}\Psi\ {}^*F^{\mu\nu}F_{\mu\nu}$$

...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

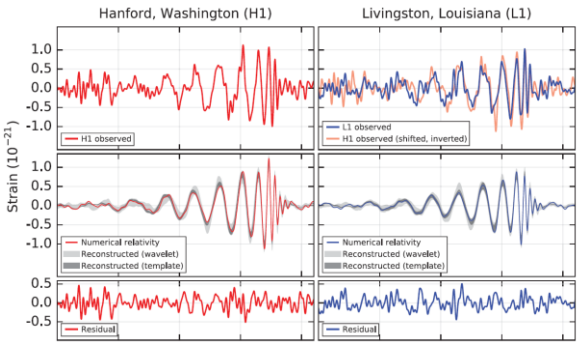
Cardoso & Maselli AA (to appear) arXiv 1909.05870
Also Eda + PRL 110 (2013) 221101; Macedo+ApJ774 (2013) 48; Annulli+ PRD102;063022 (2020)

Constraints on fundamental fields via superradiance

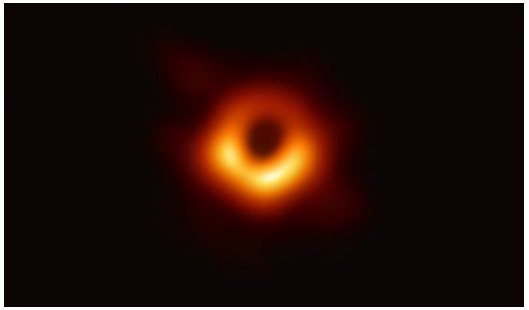
	excluded region (in eV)	source
*	$5.2 \times 10^{-13} < m_S < 6.5 \times 10^{-12}$	Direct bounds from absence of spin down in Cyg X-1.
*	$1.1 \times 10^{-13} < m_V < 8.2 \times 10^{-12}$	
*	$2.9 \times 10^{-13} < m_T < 9.8 \times 10^{-12}$	
	$6 \times 10^{-13} < m_S < 2 \times 10^{-11}$	Indirect bounds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

Brito, Cardoso & Pani Lecture Notes Physics 971 (2020)
https://centra.tecnico.ulisboa.pt/network/grit/files/superradiantbounds/

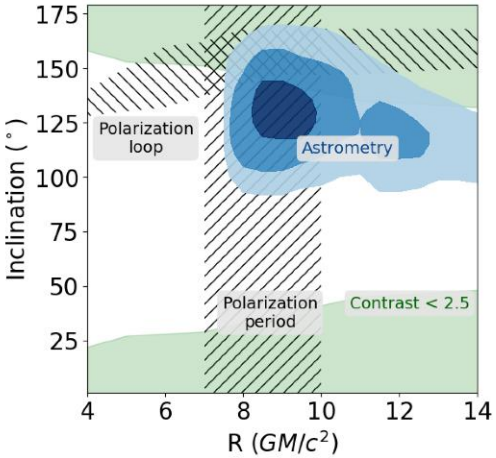
They exist! (?)



LIGO/Virgo Collaboration PRL116:061102 (2016)



EHT Collaboration ApJL 875: 1 (2019)



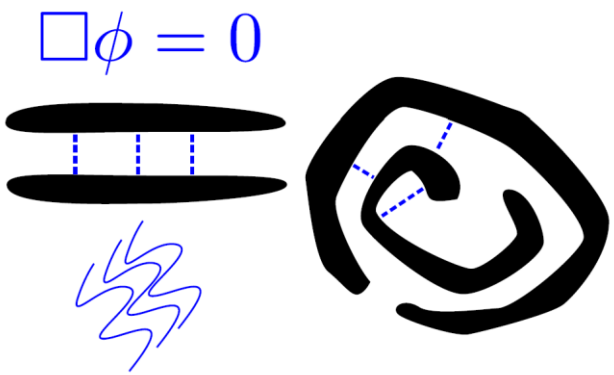
GRAVITY Collaboration AA 635: A143 (2020)

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)

$$\mathcal{E}^{(N)}_{\text{local}}(t) \lesssim \frac{1}{(\log(2+t))^2}\mathcal{E}^{(N)}_{(2)}(0)$$



Burq, Acta Mathematica 180: 1 (1998)

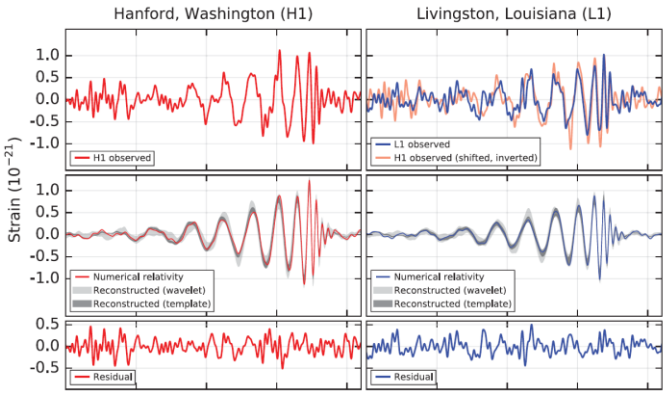
Fundamental questions

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?
Cardoso+ PRL116: 171101 (2016); Cardoso & Pani, Nature Astronomy 1: 586 (2017)

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?
Barack+arXiv:1806.05195; Brito+ PRL119:131101 (2017); Annulli+ PRD102:063022 (2020)



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

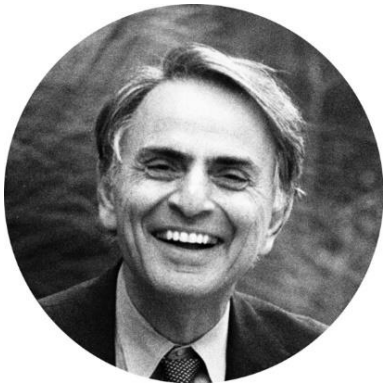
Why is this not enough?

Cardoso & Pani, Living Reviews in Relativity (2019)

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

2. Quantum effects not fully understood. Non-locality to solve information paradox? Is BH just a fuzzball? BH area quantization? (Mathur 2005; Bekenstein & Mukhanov 1995; Giddings 2017)

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.