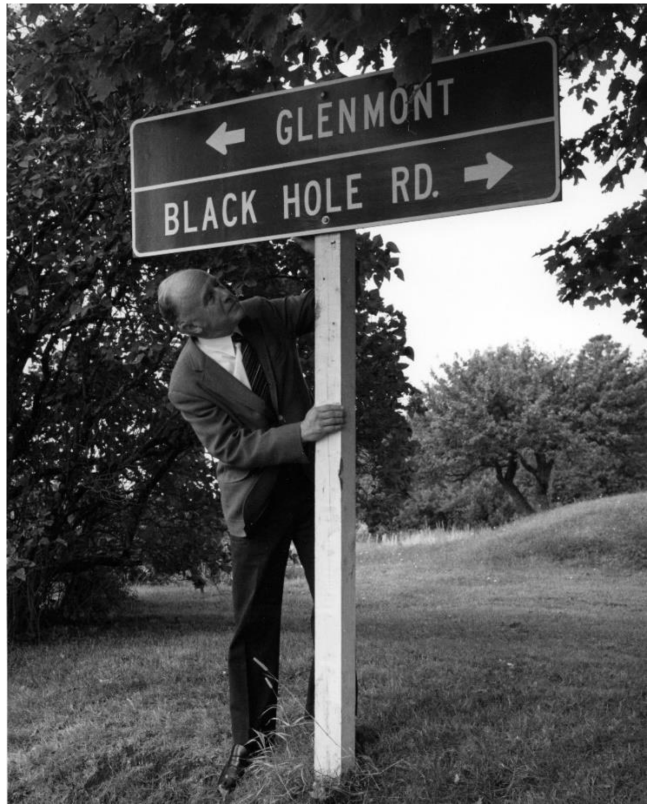
Black holes as (fundamental) physics laboratories



Vitor Cardoso (Lisbon)

TÉCNICO LISBOA
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grit
gravitation in técnico
European Research Council
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1919. May 29 eclips confirms that gravity “bends” light


REVOLUTION IN SCIENCE.

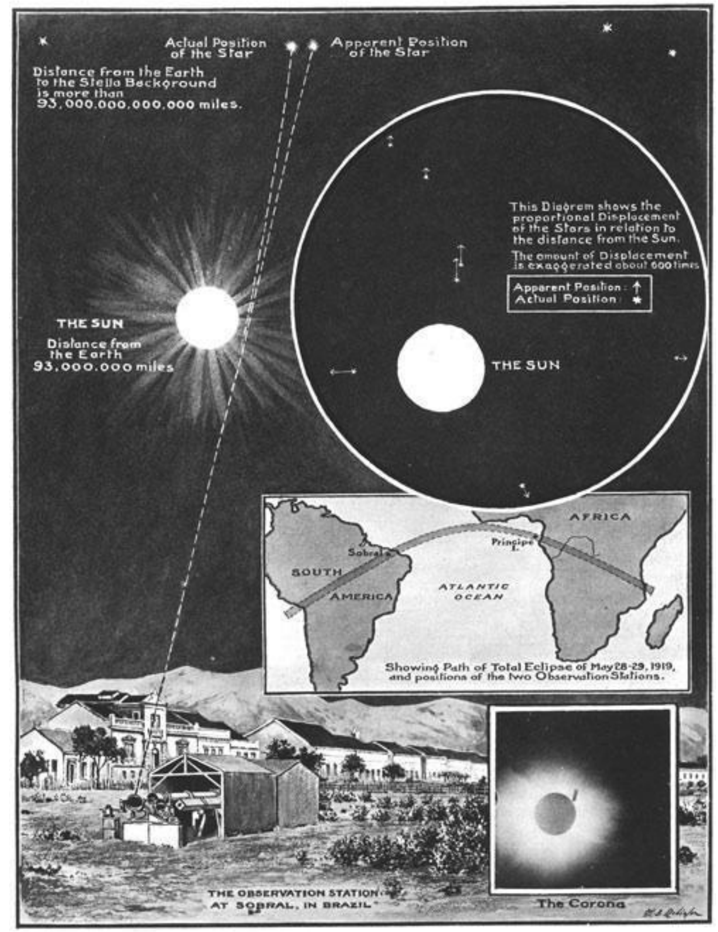
NEW THEORY OF THE UNIVERSE.

NEWTONIAN IDEAS OVERTHROWN.

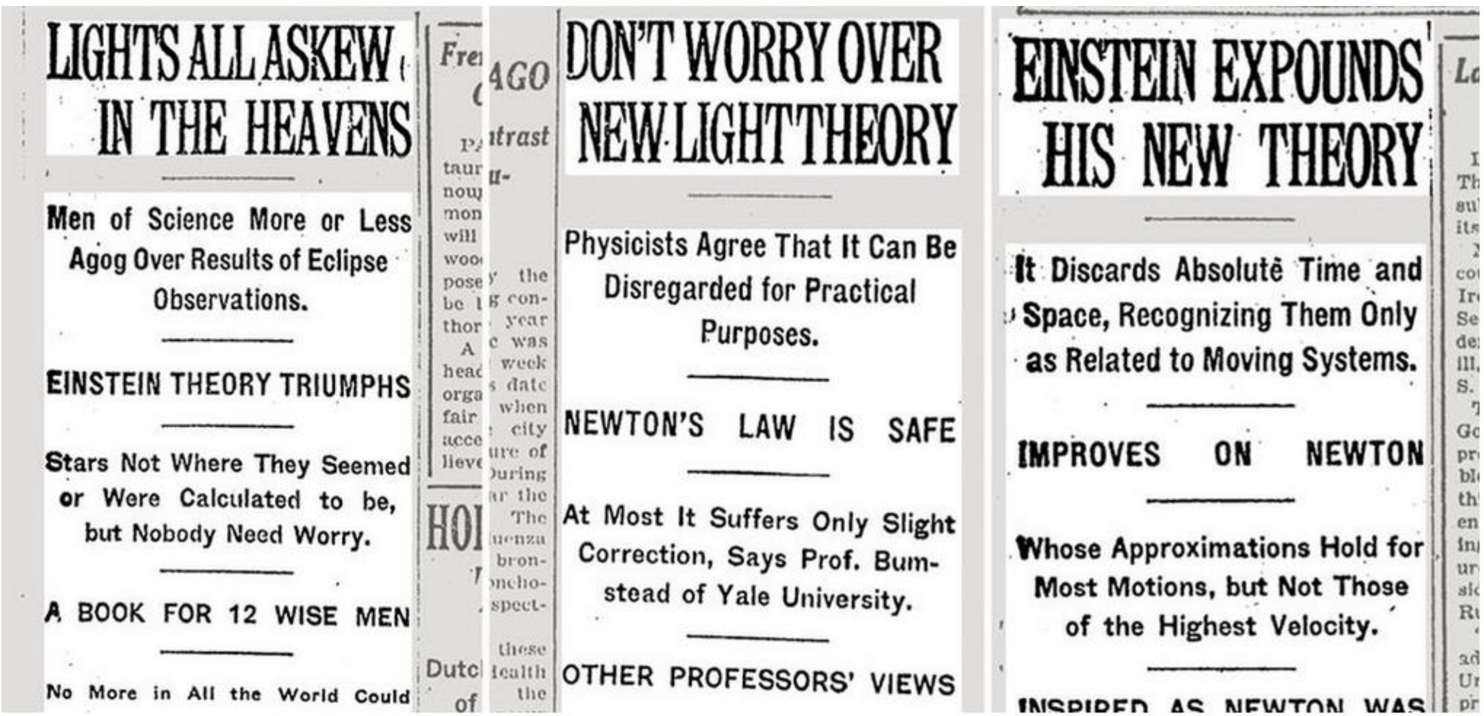
Yesterday afternoon in the rooms of the Royal Society, at a joint session of the Royal and Astronomical Societies, the results obtained by British observers of the total solar eclipse of May 29 were discussed.

The greatest possible interest had been aroused in scientific circles by the hope that rival theories of a fundamental physical problem would be put to the test, and there was a very large attendance of astronomers and physicists. It was generally accepted that the observations were decisive in the verifying of the prediction of the famous physicist, Einstein, stated by the President of the Royal Society as being the most remarkable scientific event since the discovery of the predicted existence of the planet Neptune. But there was differ-

‘Times of London‘, Nov 7 1919



'Illustrated London News‘, Nov 22 1919


LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

No More in All the World Could

DON'T WORRY OVER NEW LIGHT THEORY

Physicists Agree That It Can Be Disregarded for Practical Purposes.

NEWTON'S LAW IS SAFE

At Most It Suffers Only Slight Correction, Says Prof. Bumstead of Yale University.

OTHER PROFESSORS' VIEWS

EINSTEIN EXPOUNDS HIS NEW THEORY

It Discards Absolute Time and Space, Recognizing Them Only as Related to Moving Systems.

IMPROVES ON NEWTON

Whose Approximations Hold for Most Motions, but Not Those of the Highest Velocity.

INSPIRED AS NEWTON WAS

Articles in The Times from Nov. 10, 1919, left; Nov. 16, 1919, center; and Dec. 3, 1919.

"I made at once by good luck a search for a full solution. A not too difficult calculation gave the following result: ..."

K. Schwarzschild to A. Einstein (Letter dated 22 December 1915)

Solution re-discovered by many others:

J. Droste, May 1916 (part of PhD thesis under Lorentz): Same coordinates, more elegant

P. Painlevé, 1921, A. Gullstrand, 1922: P-G coordinates
(not realized solution was the same)

...and many others

Uniqueness: the Kerr solution

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

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

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

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

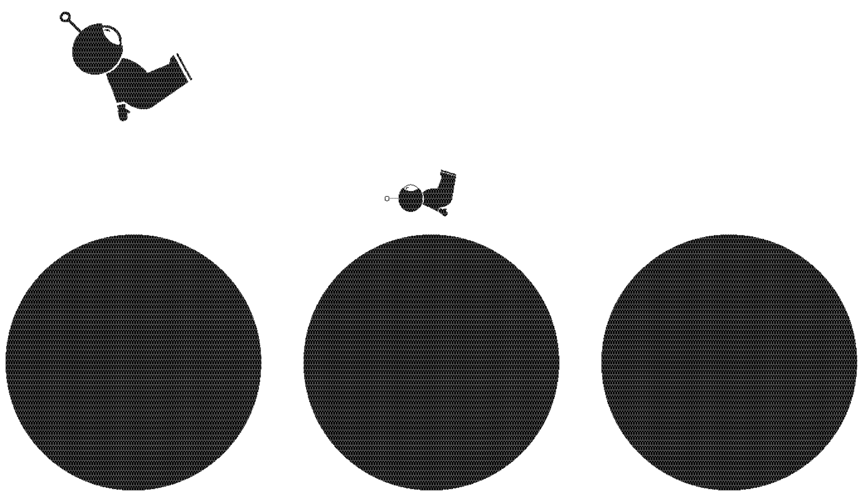
Black holes have no hair

J. A. Wheeler 1971

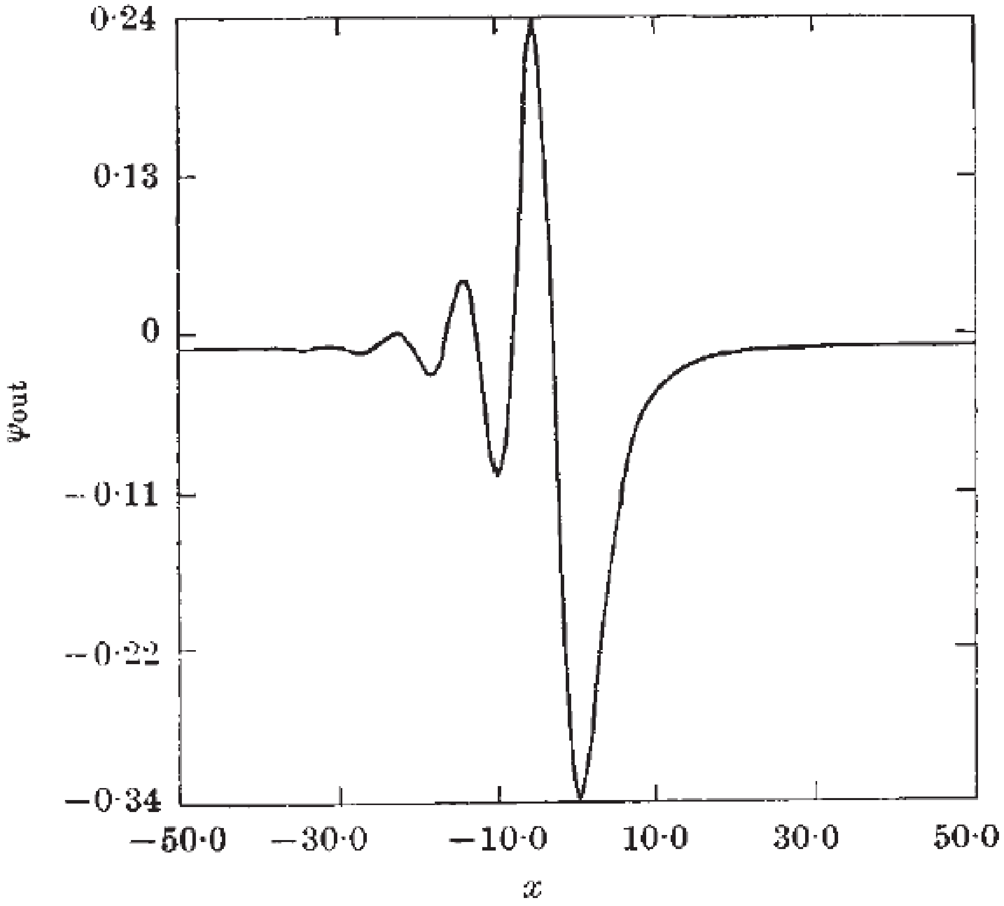
One star of matter and another of anti-matter produce the same BH.

BH shares 3 common quantities with progenitor (when no radiative processes):

mass, rotation (and electric charge)

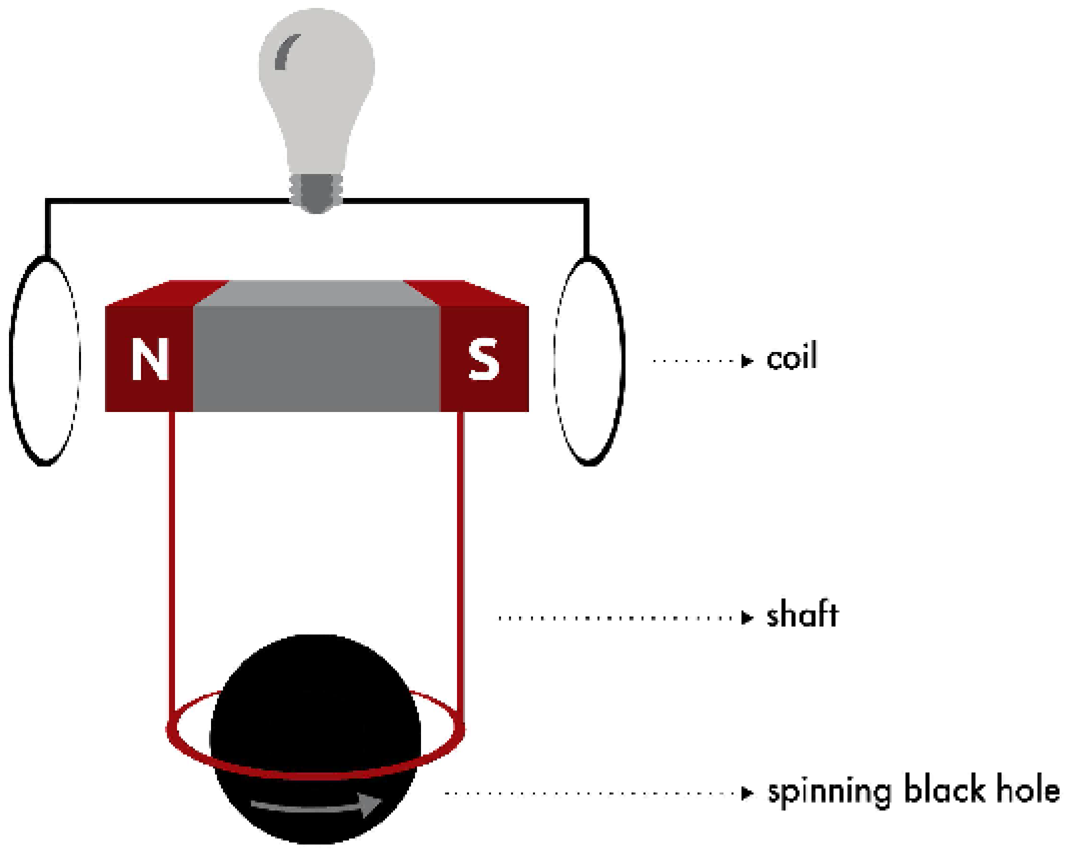


Hair loss: the characteristic modes of black holes



C.V.Vishveshwara, Nature 227: 938 (1970)
Data and routines at blackholes.ist.utl.pt

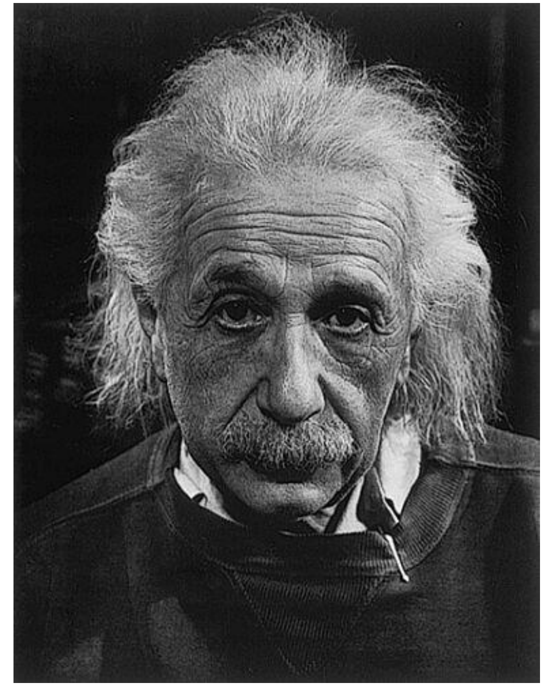
Energy source?



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

Brito, Cardoso & Pani, *Superradiance* (Springer-Verlag 2015)

In 1916, Einstein shows that GWs are a consequence of the linear theory.



$$ds^2 = -c^2 dt^2 + (1 + h_+) dx^2 + (1 - h_+) dy^2 + 2h_\times dx dy + dz^2$$

$$\partial_z^2 h_{+,\times} - \frac{1}{c^2} \partial_t^2 h_{+,\times} = 0$$

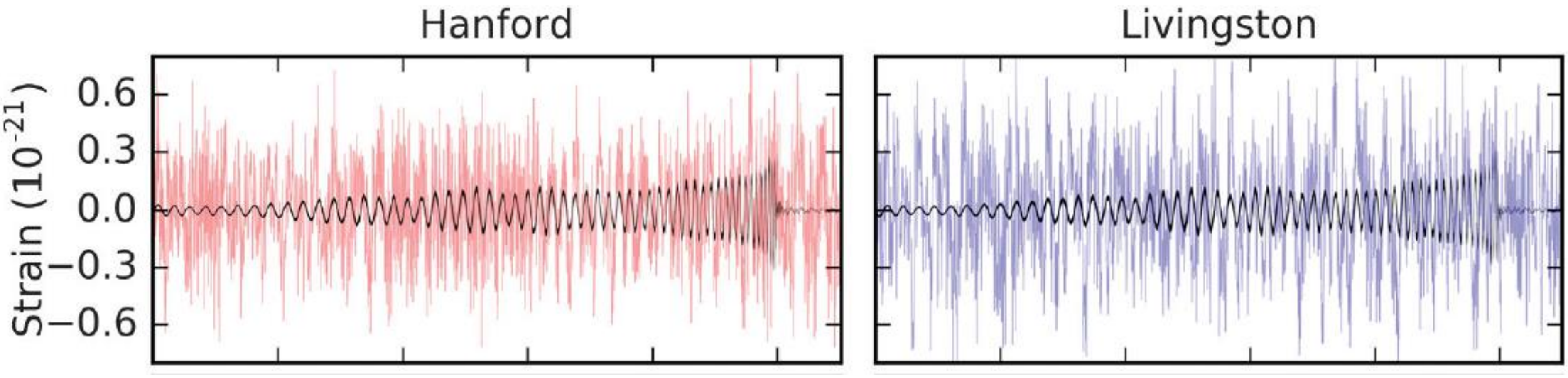
GWs travel at the speed of light

“Wir müssen wissen, wir werden wissen.”

(We must know, we will know)

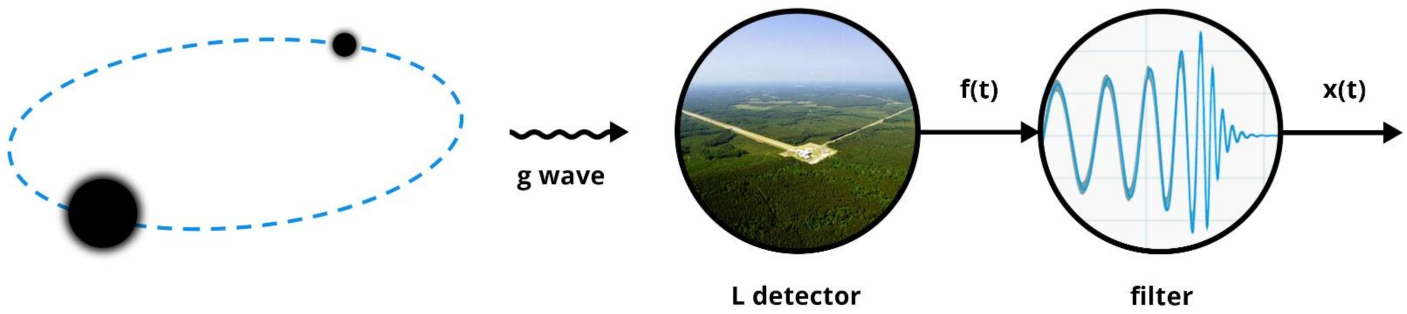
The 2017 Nobel Physics award to Weiss, Thorne and Barish

The needle in the haystack problem



The LIGO Collaboration, PRL116:241103 (2016)

Matched-Filtering

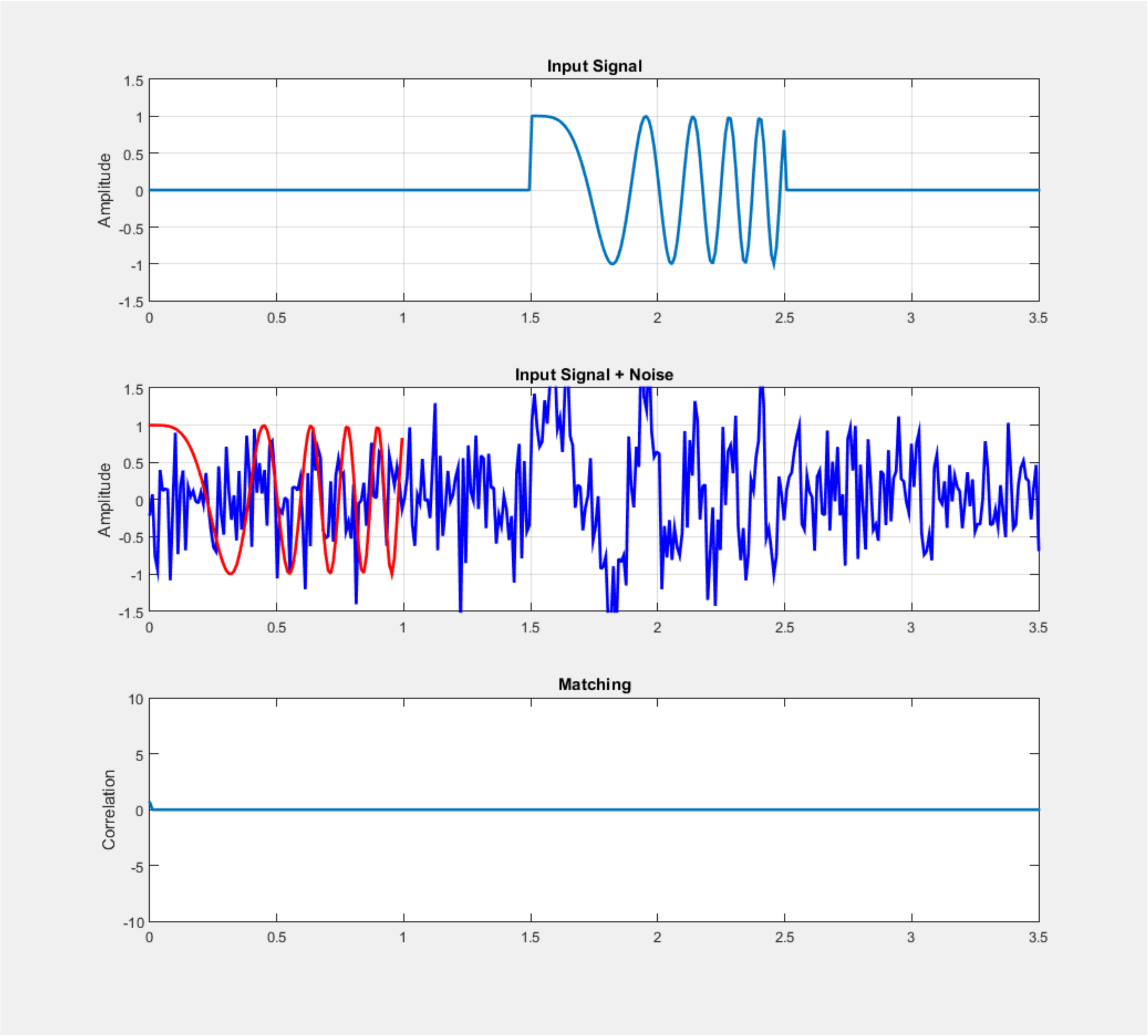


The detector output $f(t) = h(t) + n(t)$

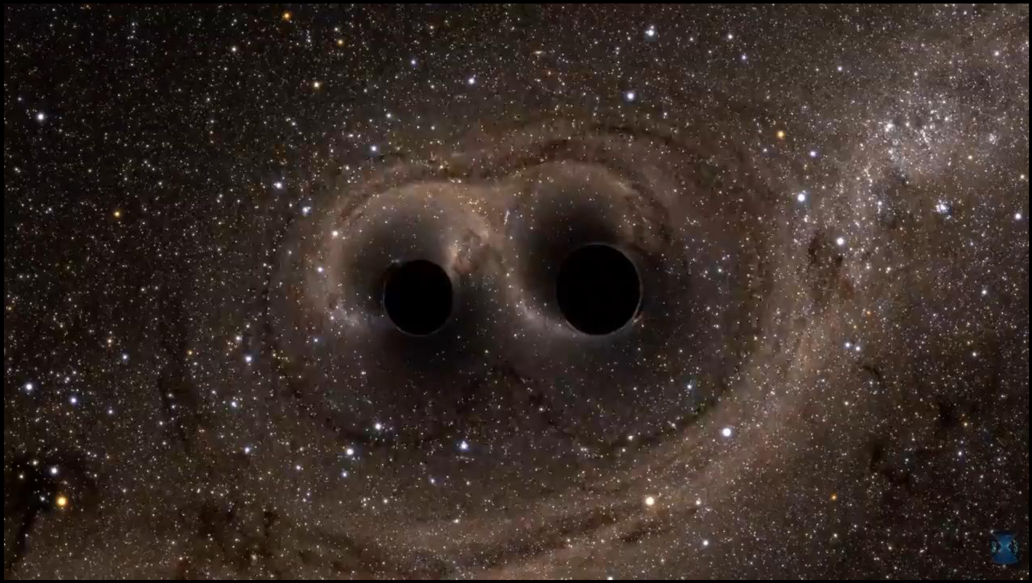
where n(t) is the noise. For stationary Gaussian noise, process signal with filter K(t) against data stream producing number

$$\frac{S}{N} = \frac{\text{expected value of X with signal}}{\text{rms value of X with no signal}} = \frac{\langle X \rangle}{\sqrt{\langle X^2 \rangle_{h=0}}}$$

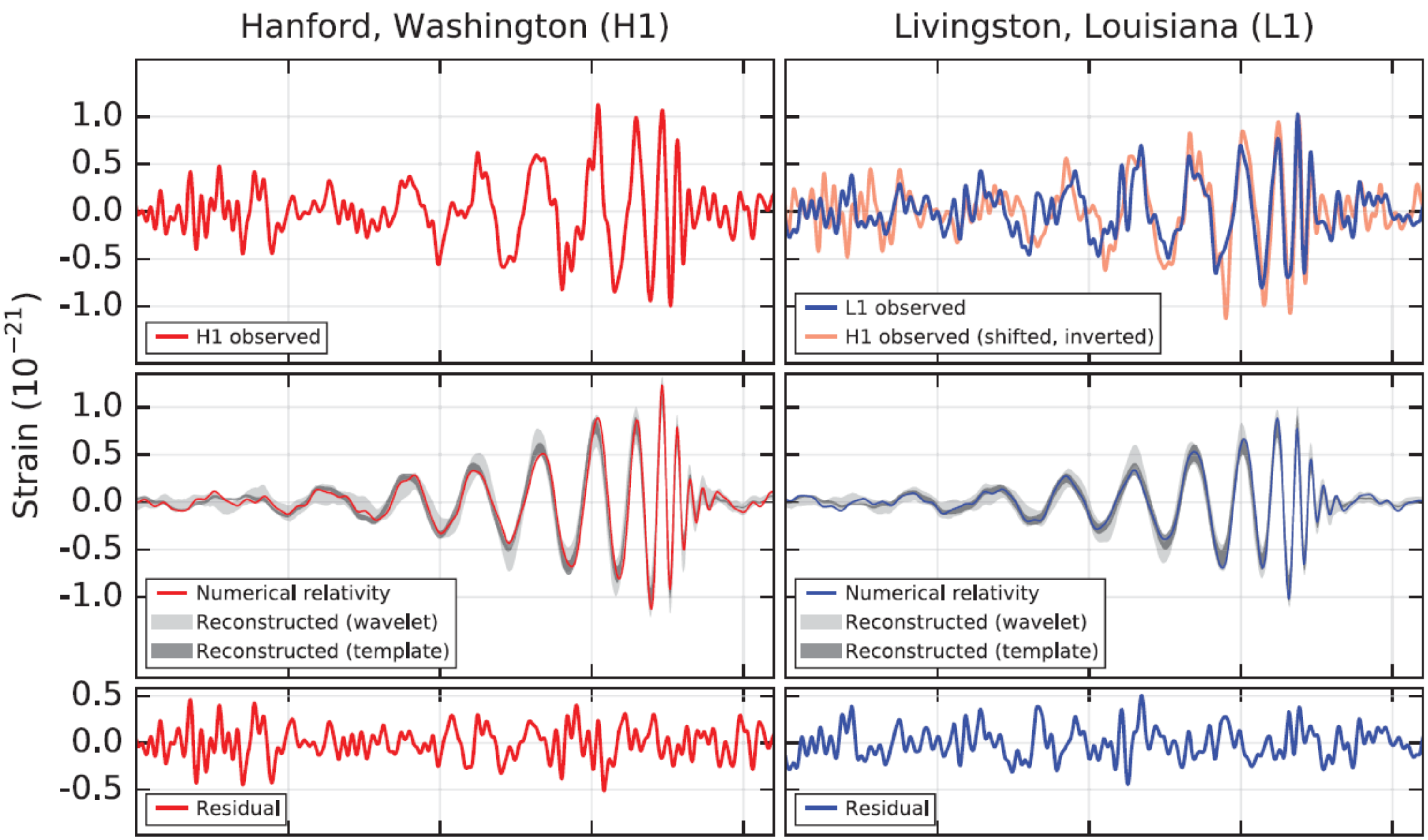
Optimum filter K maximizes SNR and is the signal h itself!



3% Mismatch: 10% lost events!....LIGO used ~250000 templates for CBC searches




GW150914: a binary BH system, as seen with GWs



Abbott + Phys.Rev.Lett.116:061102 (2016)

Fundamental questions

a. BH seeds, BH demography, galaxy co-evolution (how many, where, how?)
See review Barack+ arXiv:1806.05195

b. What is the graviton mass or speed?
Baker+ PRL119: 251301 (2017); See review Barack+ arXiv:1806.05195

c. Is cosmic censorship preserved?
Sperhake+ PRL103:131102 (2009); Cardoso+ PRL120:031103 (2018)

d. Is it a Kerr black hole? Can we constrain alternatives?
Berti+ 2016; Cardoso & Gualtieri 2016

e. Can GWs from BHs inform us on fundamental fields/DM?
Arvanitaki+ PRD95: 043001 (2016); Brito+ PRL119:131101 (2017)

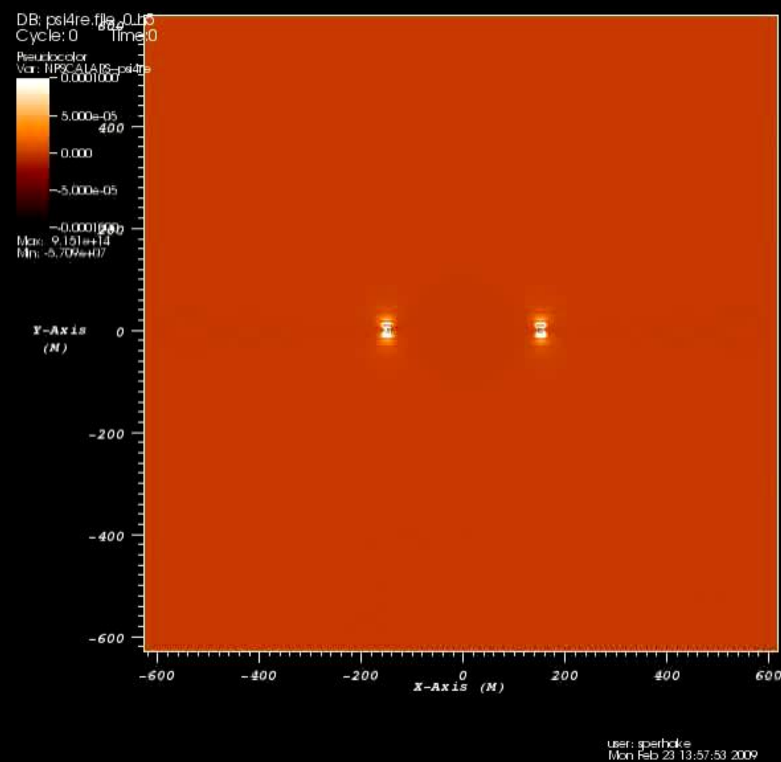
f. Is the final - or initial - object really a black hole?
Cardoso+ PRL116: 171101 (2016); Nature Astronomy 1: 586 (2017); Tsang+ (2018)

(Weak) Cosmic Censorship violations?

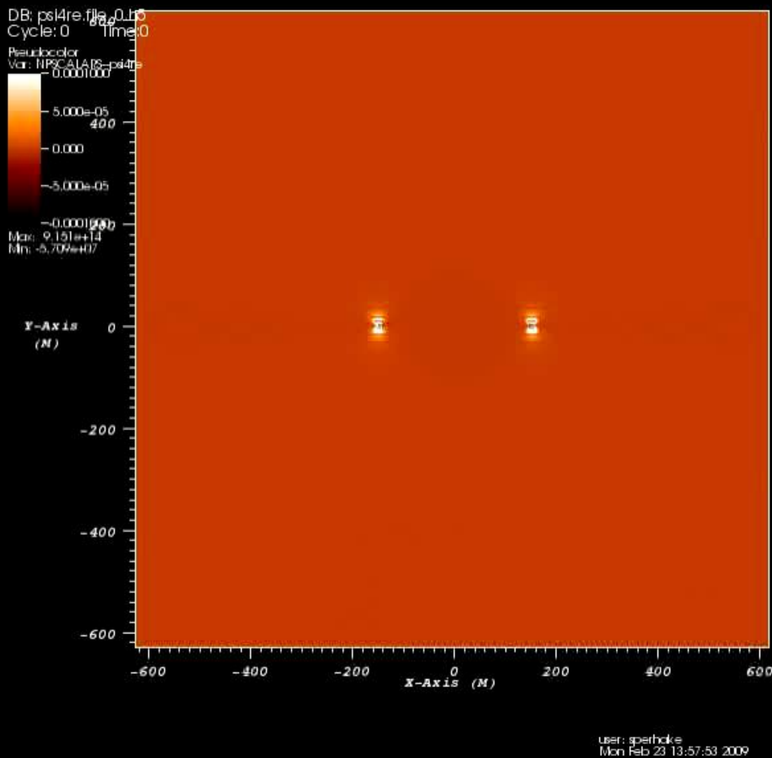
$$M,\ J$$

$$\frac{cJ}{GM^2} \leq 1 \qquad \text{or} \qquad a \leq M$$

Black holes have small angular momentum (very compact objects)



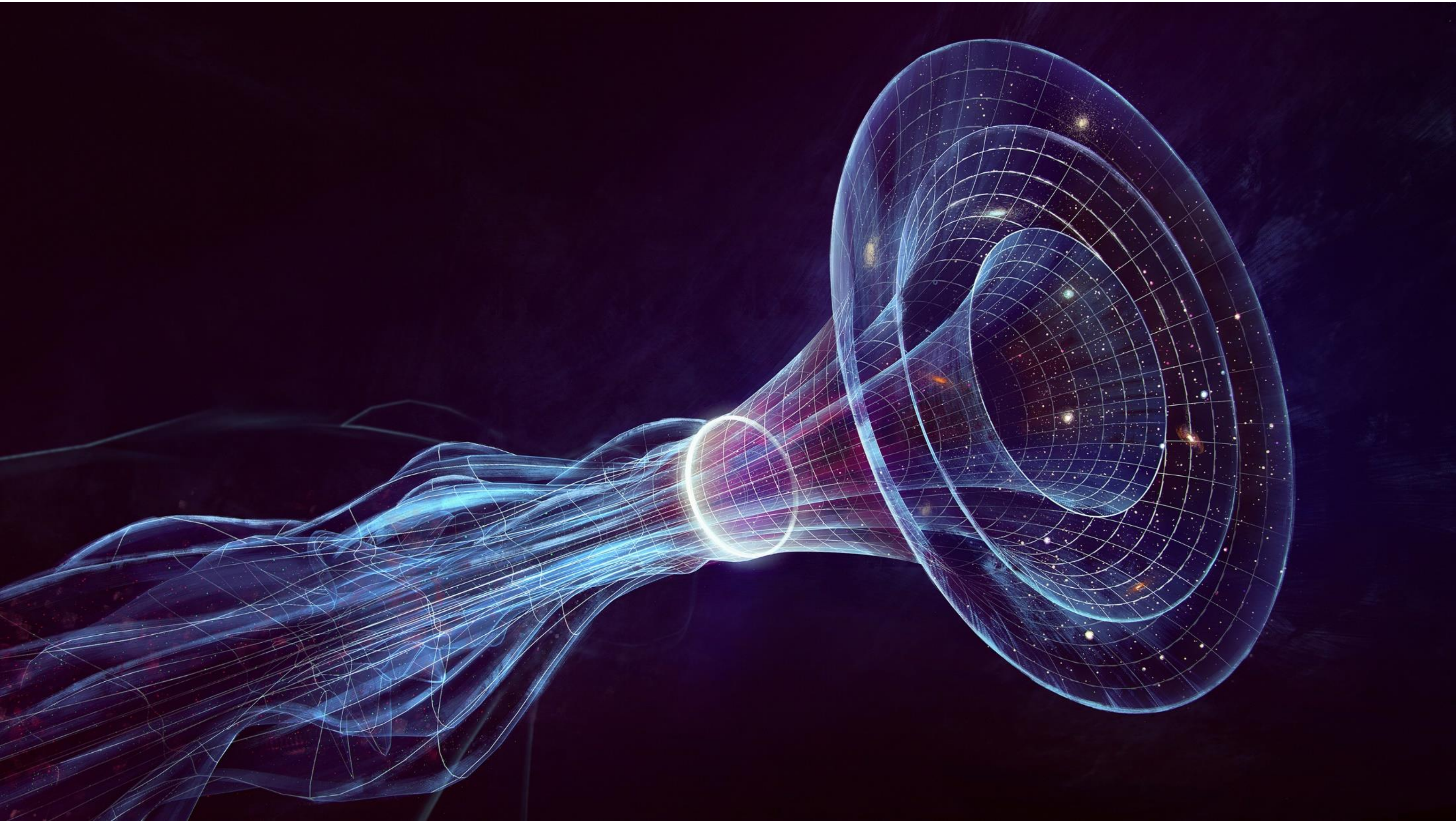
Sperhake + PRL103:131102 (2009)



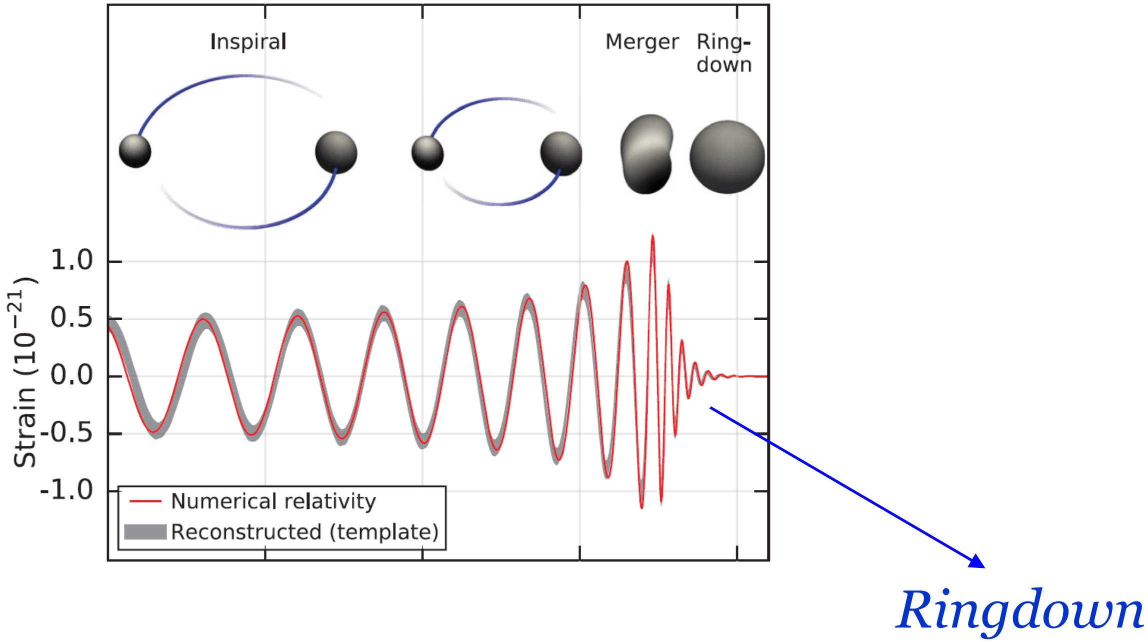
Sperhake + PRL103:131102 (2009)

The inside story: (strong) Cosmic Censorship violations!

Cardoso+ PRL120 (2018) 031103

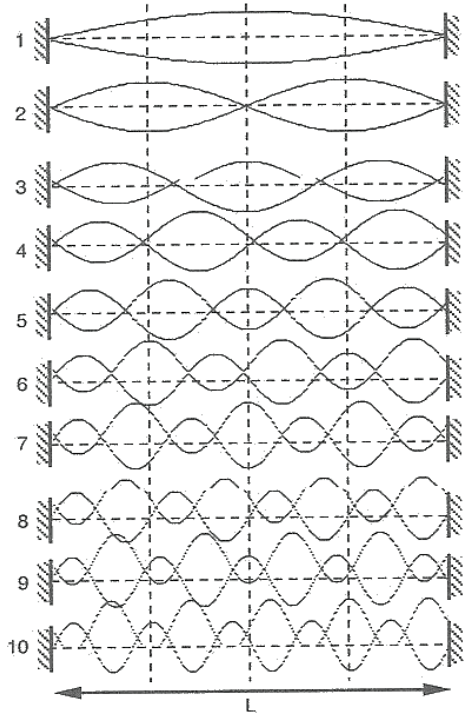


BH spectroscopy: testing the Kerr nature



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

Tests of the no-hair hypothesis



$$f = \frac{nv}{2L}\,, \quad n = 1,\, 2,\, 3...$$

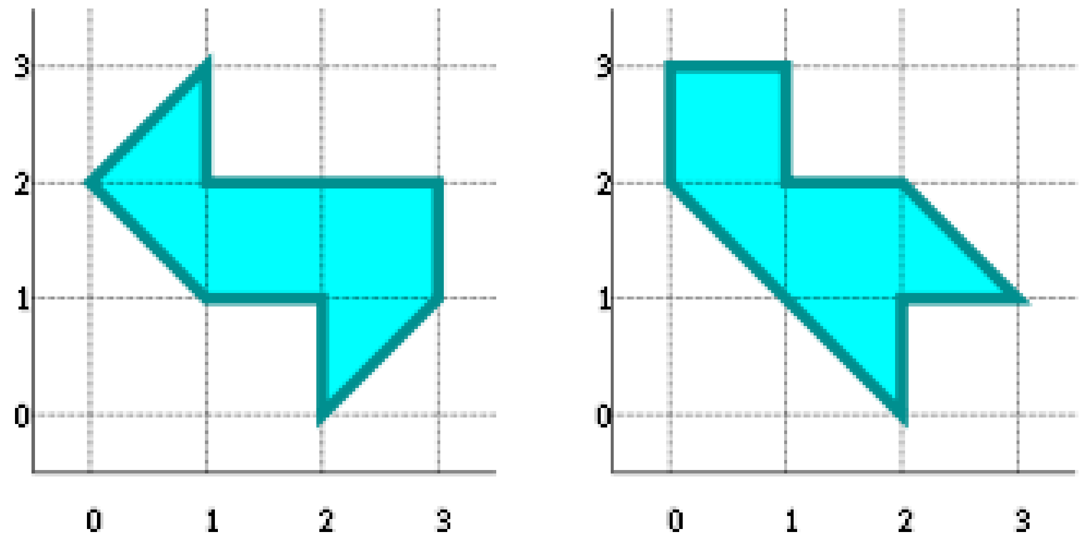
Measure fundamental mode, determine length L.
Measure first overtone, test if it's a string...

“Can one hear the shape of a drum?”

Mark Kac, American Mathematical Monthly, *1966*

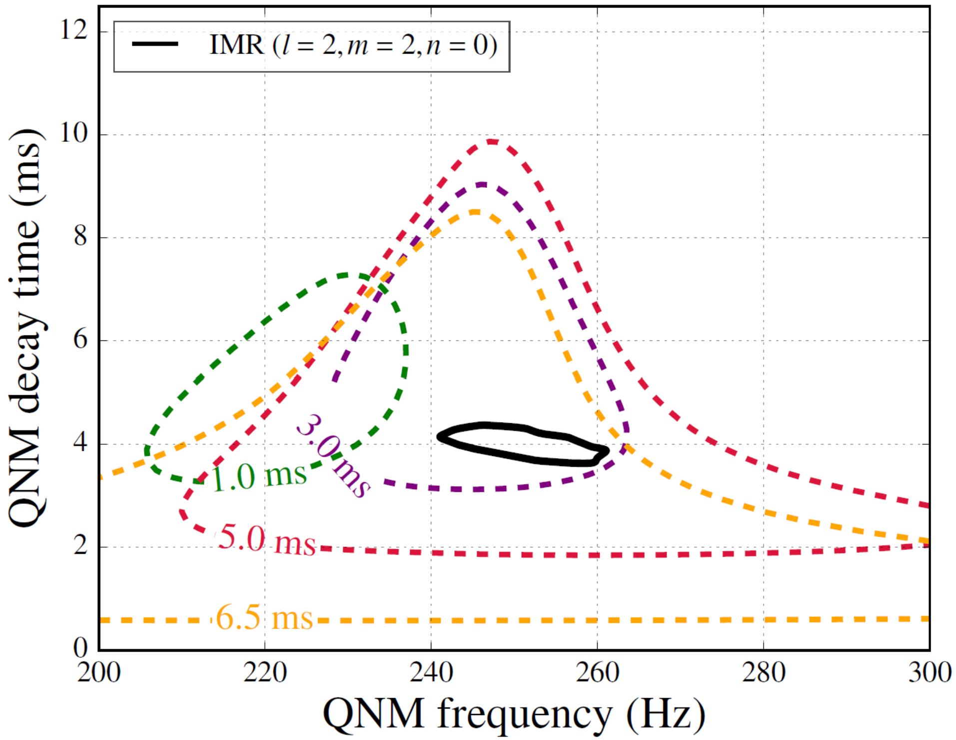
$$N(\lambda) = \sum_{\lambda_n < \lambda} 1 \sim \frac{|\Omega|}{2\pi}\lambda$$

H. Weyl 1911



Gordon, Webb & Wolpert, Inventiones Mathematicae 1992

One and two-mode estimates



90% posterior distributions.

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

LSC PRL116:221101 (2016); see Bhaibav+PRD97:044048 (2019); Isi+ PRL123:111102 (2019)

Results not affected by environment

i. GWs are redshifted and lensed in "usual", EM way (use geometric optics)

ii. GWs do not couple to perfect, homogeneous fluids

iii. Viscosity: $L_{att} = \frac{c^6}{32\pi\eta\, G} = 10^{18}\,\frac{1poise}{\eta}$ light years

iv. Medium of oscillators $L_{att} = \frac{1}{n\sigma} = 10^{28}$ light years or so

(if all our galaxy consists of BHs of roughly 10 solar masses)

Kip Thorne, Gravitational Radiation (Les Houches 1984); Grishchuk, Polnarev 1980; Barausse+ PRD89:104059 (2014); Annulli+ PRD99:044038 (2019)

GWs and dark matter I

Dark matter is not a strong-field phenomenon, but GW observations may reveal a more "mundane" explanation in terms of heavy BHs

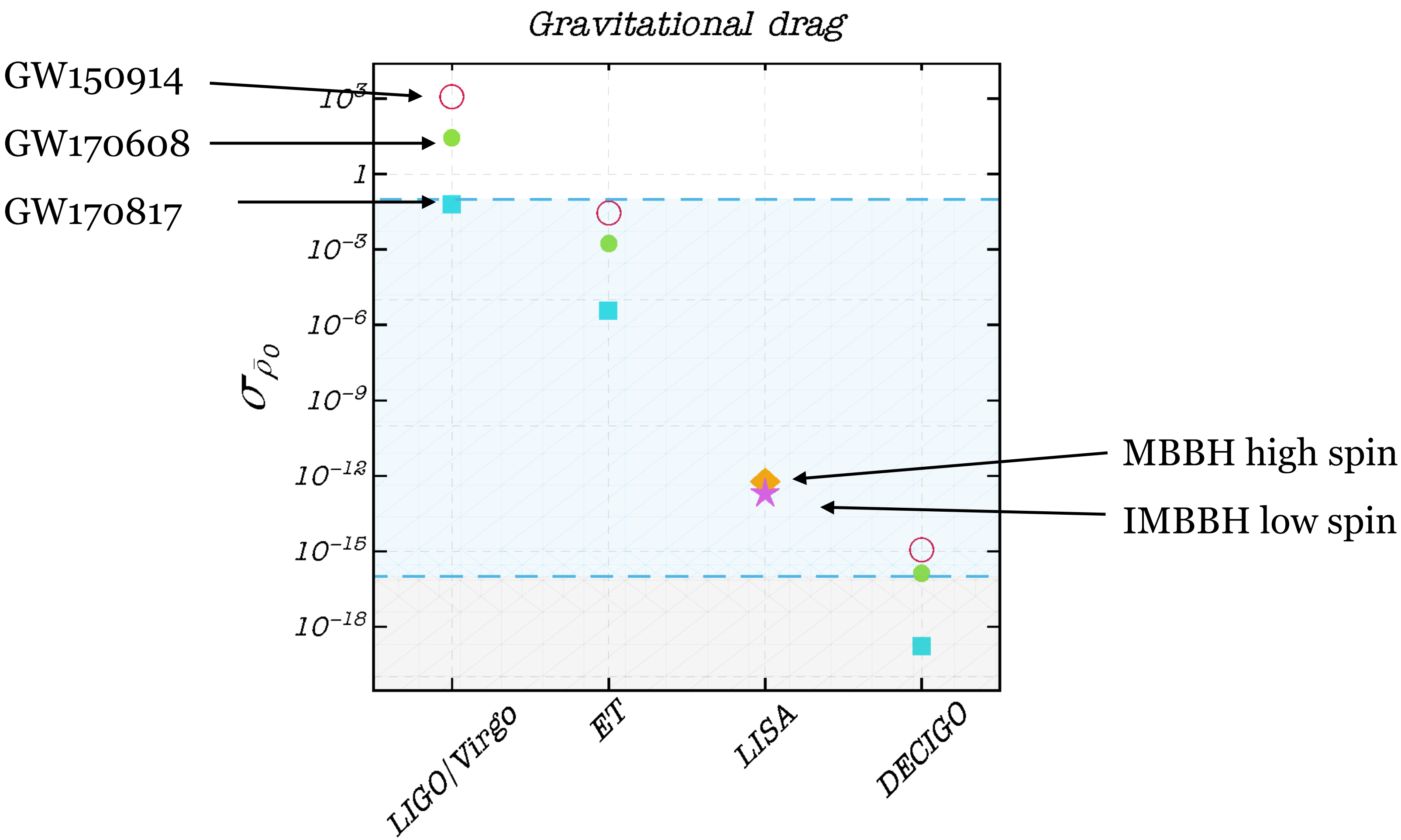
Bird + PRL116:201301 (2016)

II

Inspiral occurs in dark-matter 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)

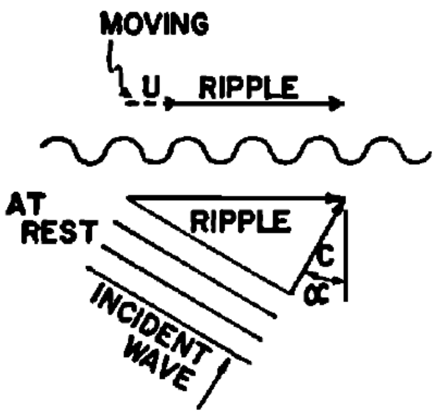
Bertone+ arXiv:1907.10610



Cardoso & Maselli arXiv 1909.05870,
Also Eda + PRL 110 (2013) 221101; Macedo+ApJ774 (2013) 48

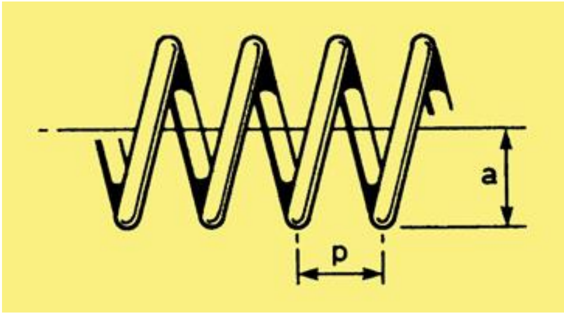
III. Light fields and DM: superradiance

Zel'dovich JETP Lett. 14:180 (1971)

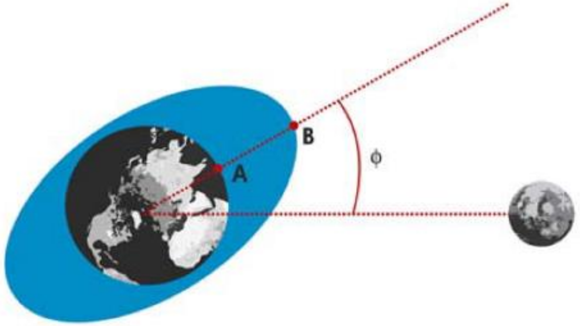


Ribner, J. Acous. Soc. Amer.29 (1957)

Tamm & Frank, Doklady AN SSSR 14 (1937)

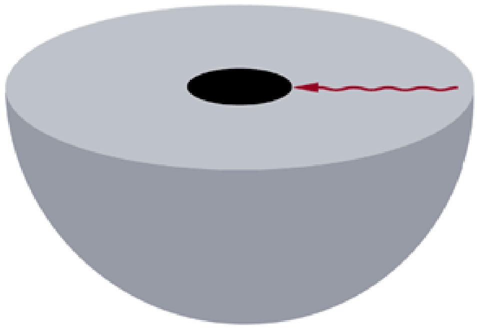


Pierce (& Kompfner), Bell Lab Series (1947)
Ginzburg, anomalous Doppler year



G. H. Darwin, Philos. Trans.
R. Soc. London 171 (1880)

Bombs and superradiant instabilities

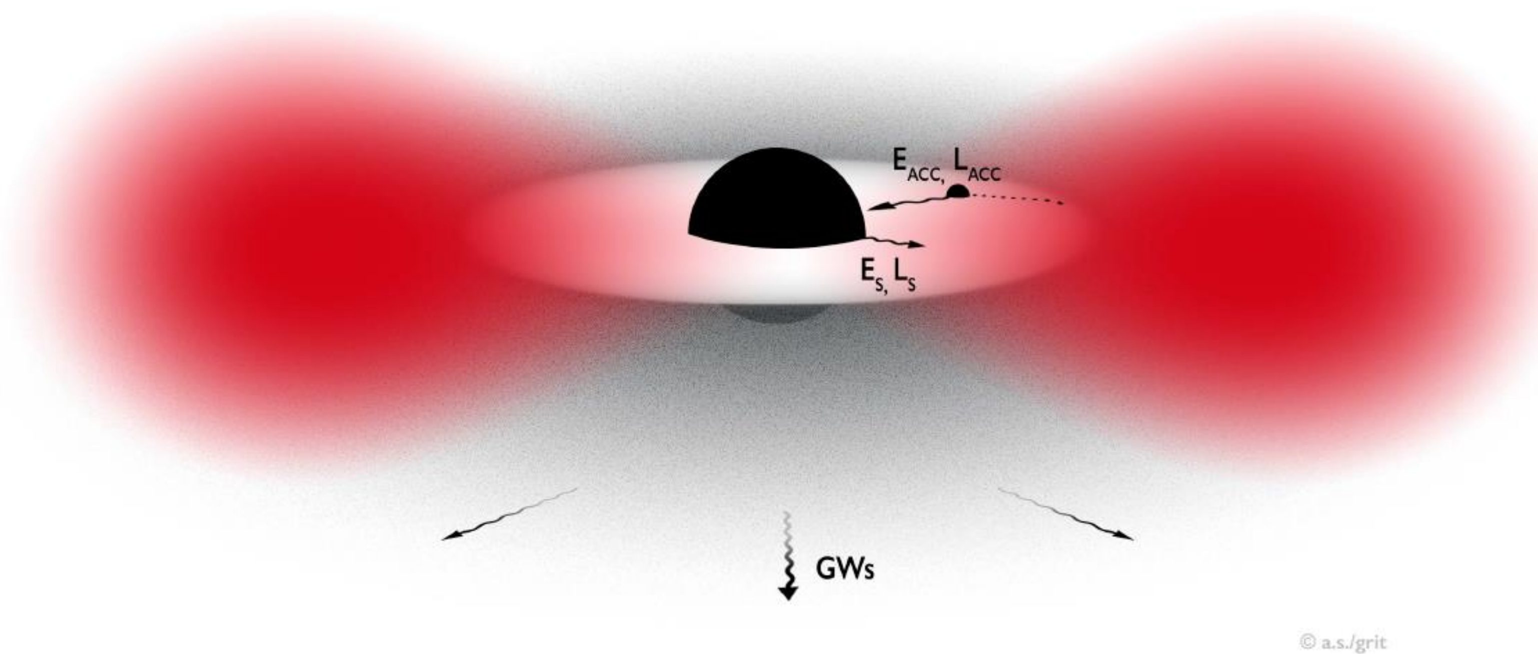


$$\tau \sim 100 \left(\frac{10^6 M_\odot}{M}\right)^8 \left(\frac{10^{-16}\text{eV}}{\mu}\right)^9 \text{ seconds}$$

Massive "states" around Kerr are linearly unstable

Detweiler PRD22 (1980) 2323

See review Brito, Cardoso, Pani, Lect. Notes Phys. 906: 1 (2015); arXiv:1501.06570

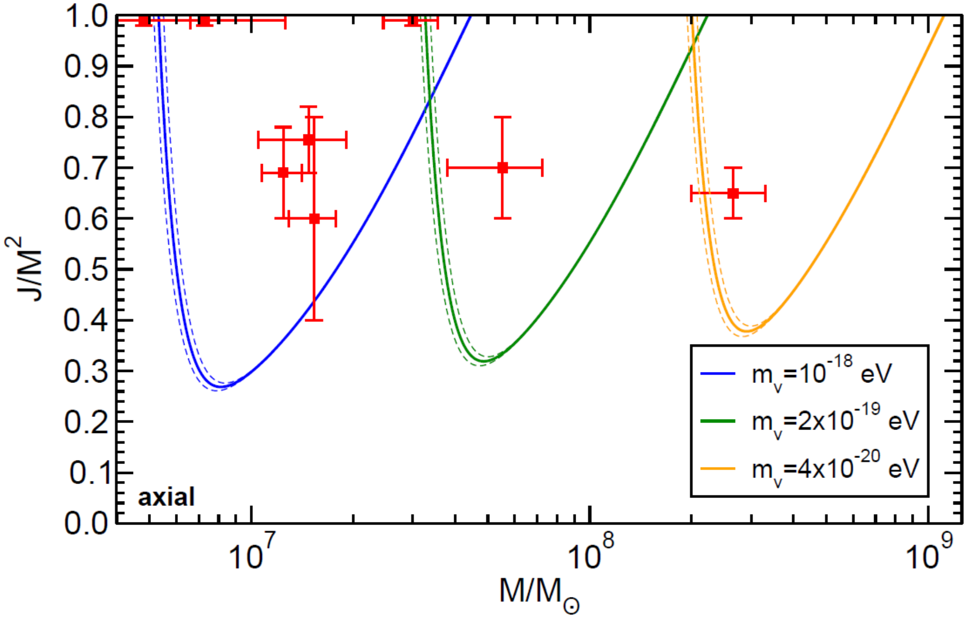


Wonderful sources of GWs

Arvanitaki & Dubovsky PRD83: 044026 (2011); Brito+ Lecture Notes Physics 906: 1-237 (2015)

Bounding the boson mass with EM observations

Pani + PRL109, 131102 (2012)

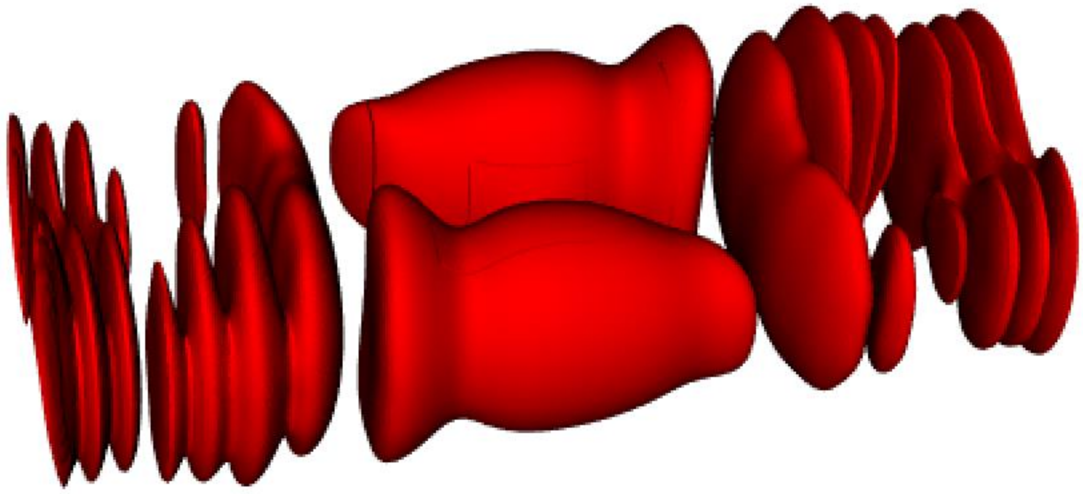


Bound on photon mass is model-dependent: details of accretion disks or intergalactic matter are important... but gravitons interact very weakly!

$$m_g < 5 \times 10^{-23}\,\mathrm{eV}$$

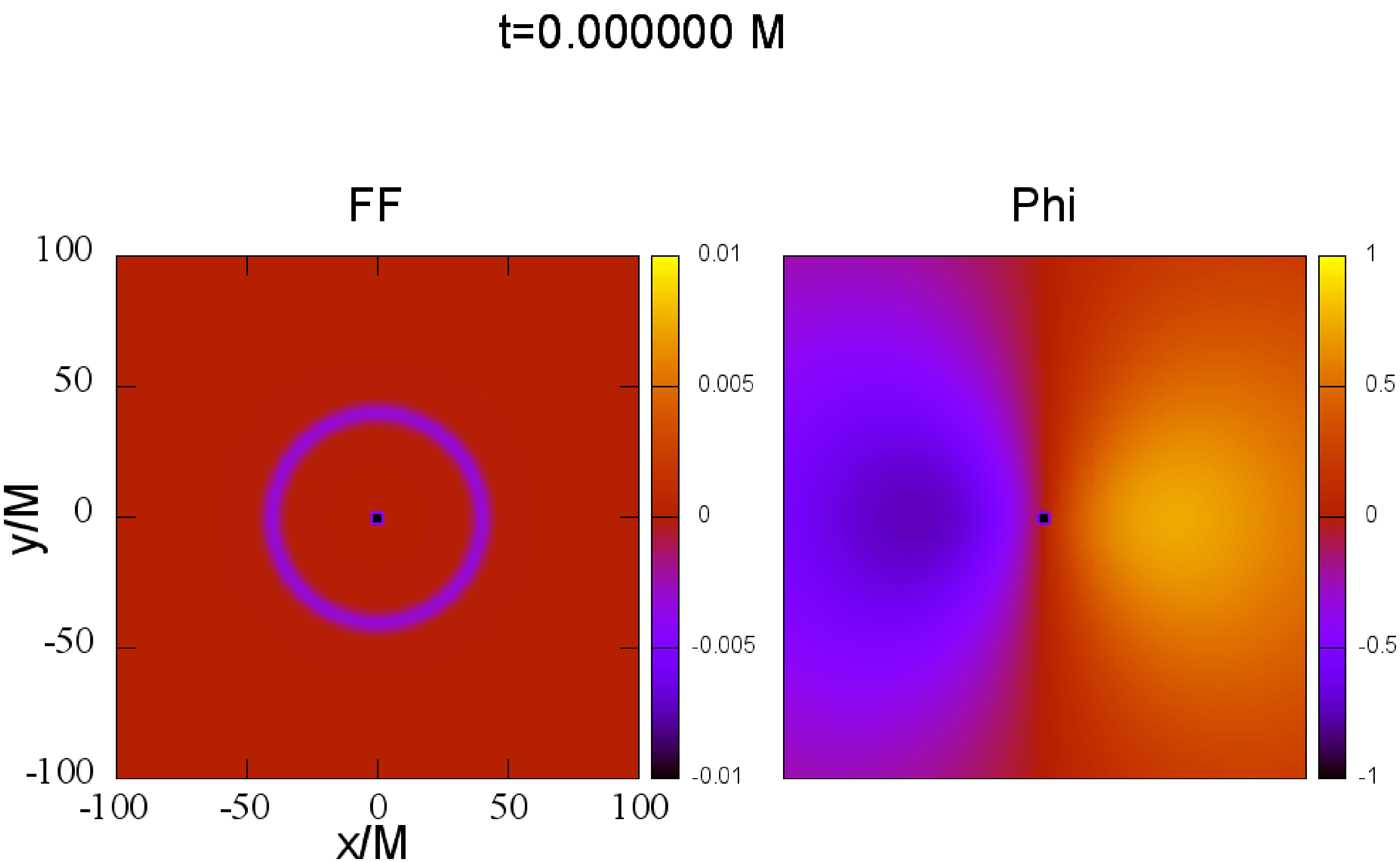
Brito + PRD88:023514 (2013); Review of Particle Physics 2014

Tidal effects, etc



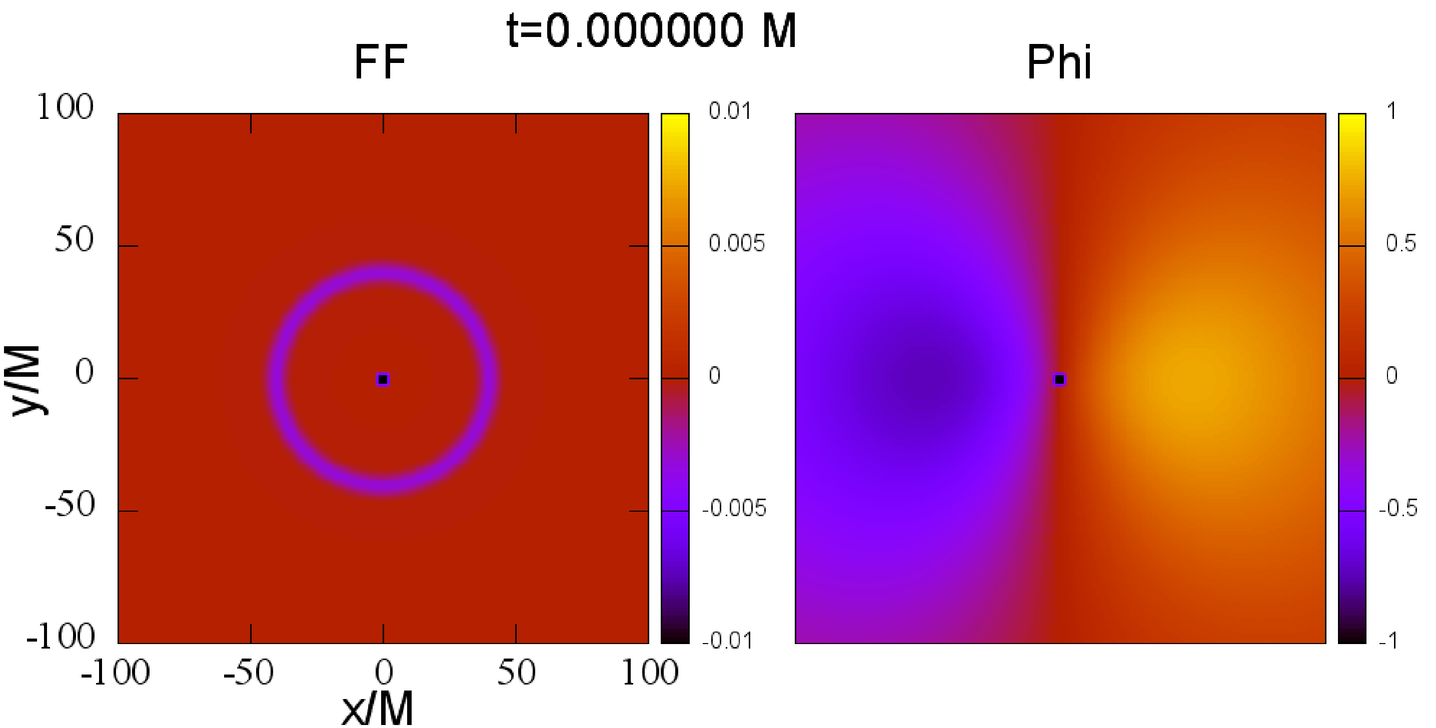
Baumann + PRD99 (2019) 044001; Cardoso+ (in progress)

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



Ikeda + PRL122: 081101 (2019)

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



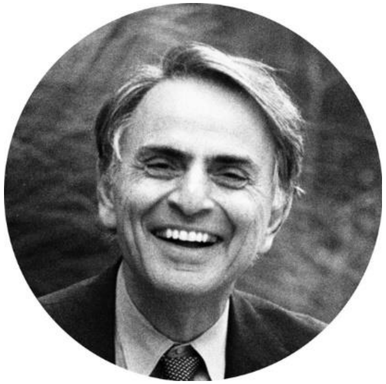
Ikeda + PRL122: 081101 (2019)

The evidence for black holes

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

2. Quantum effects not fully understood. Non-locality to solve information paradox? Hard-surface to quantize BH area (Bekenstein & Mukhanov 1995)

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 (Bekenstein & Mukhanov 1995).

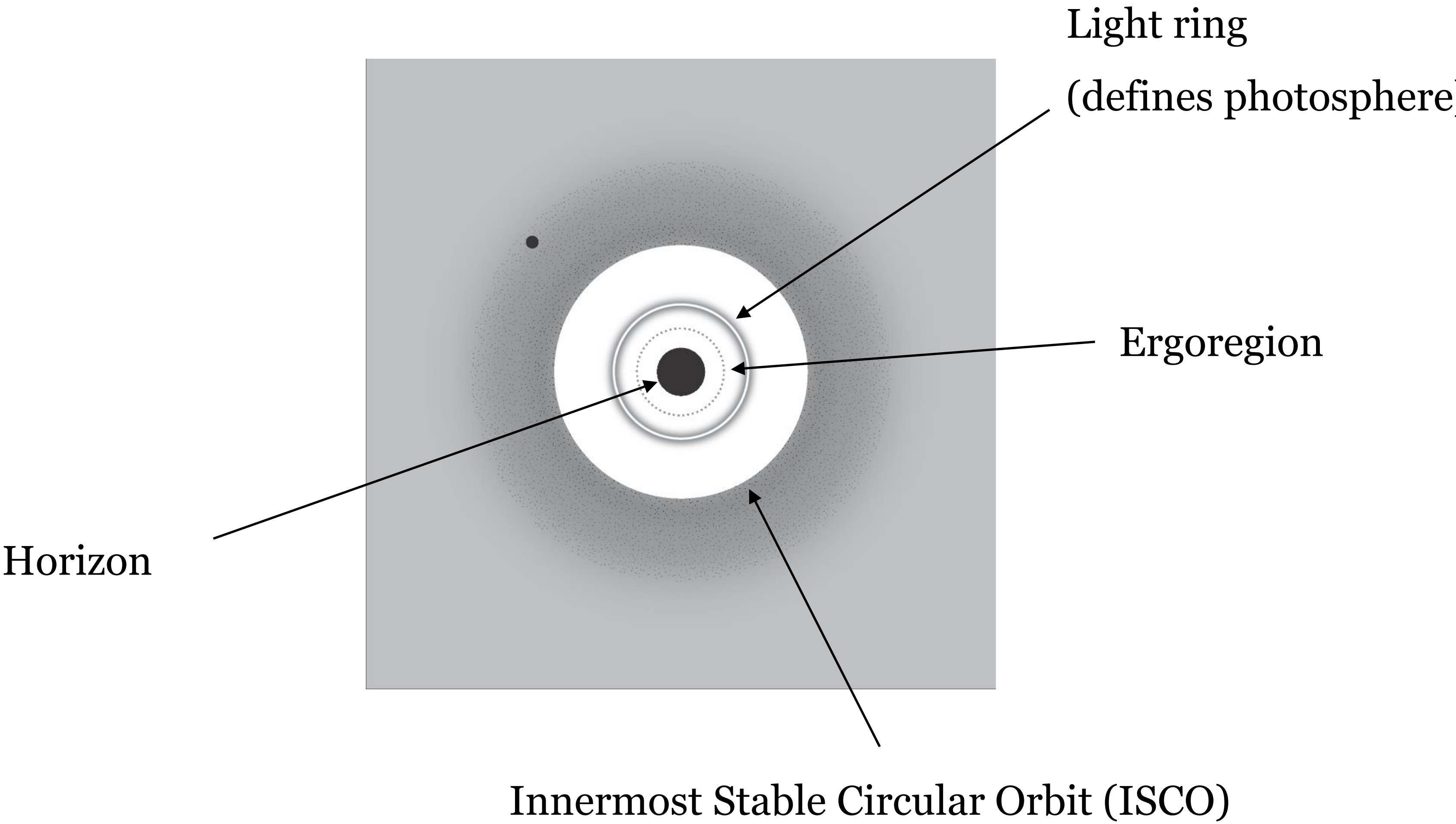


"*Extraordinary claims require extraordinary evidence.*"
Carl Sagan

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.

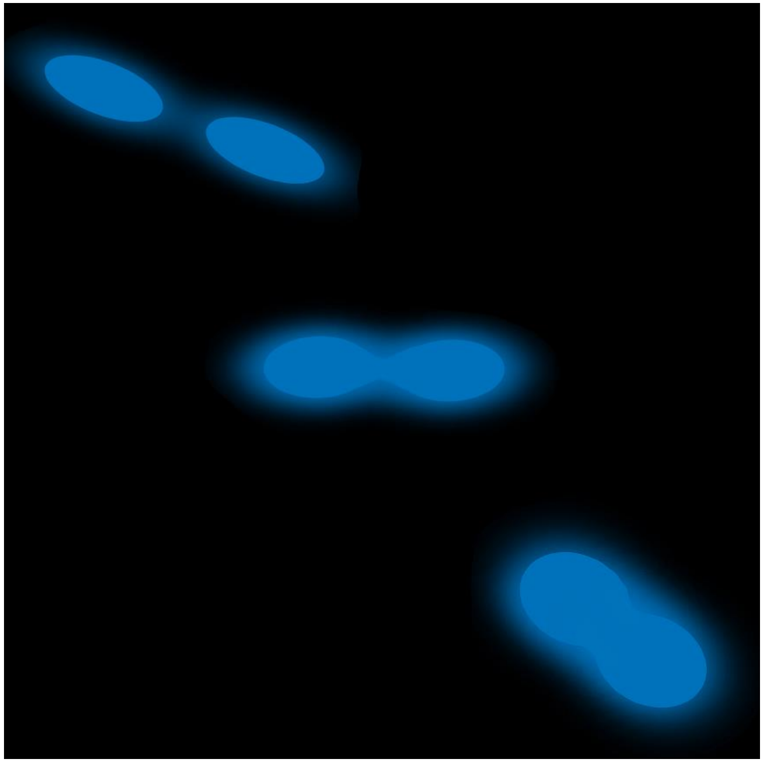
Black holes are black



Cardoso & Pani, Nature Astronomy 1: 586 (2017)
Living Reviews in Relativity 22: 1 (2019)

Image: Ana Carvalho

GW signal



Nature of inspiralling objects is encoded

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

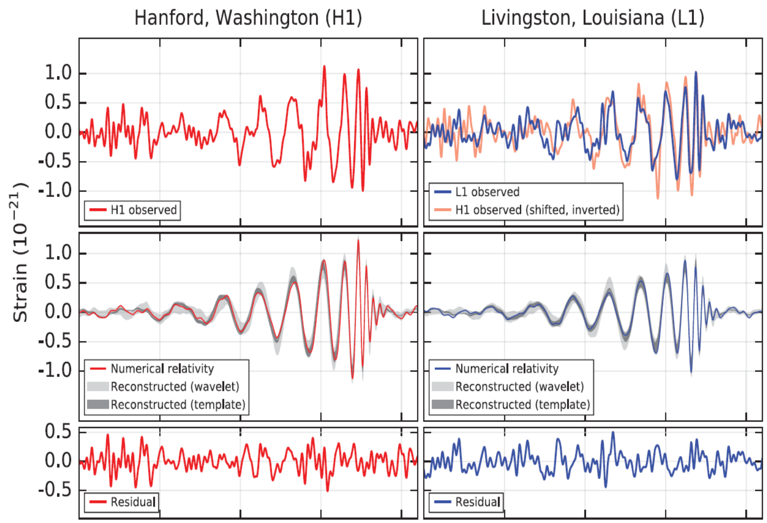
(ii) in way they respond when acted upon by external field of companion – through their tidal Love numbers (TLNs), and

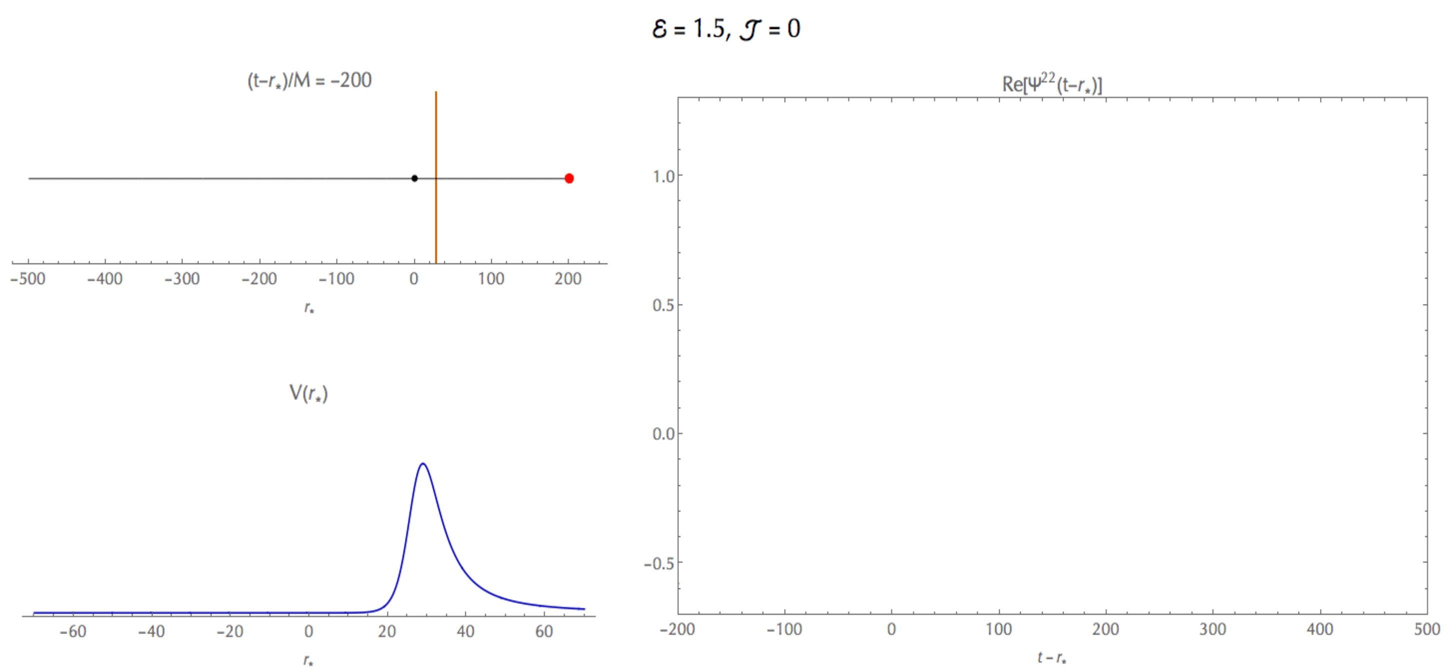
(iii) on amount of radiation absorbed, i.e., tidal heating

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

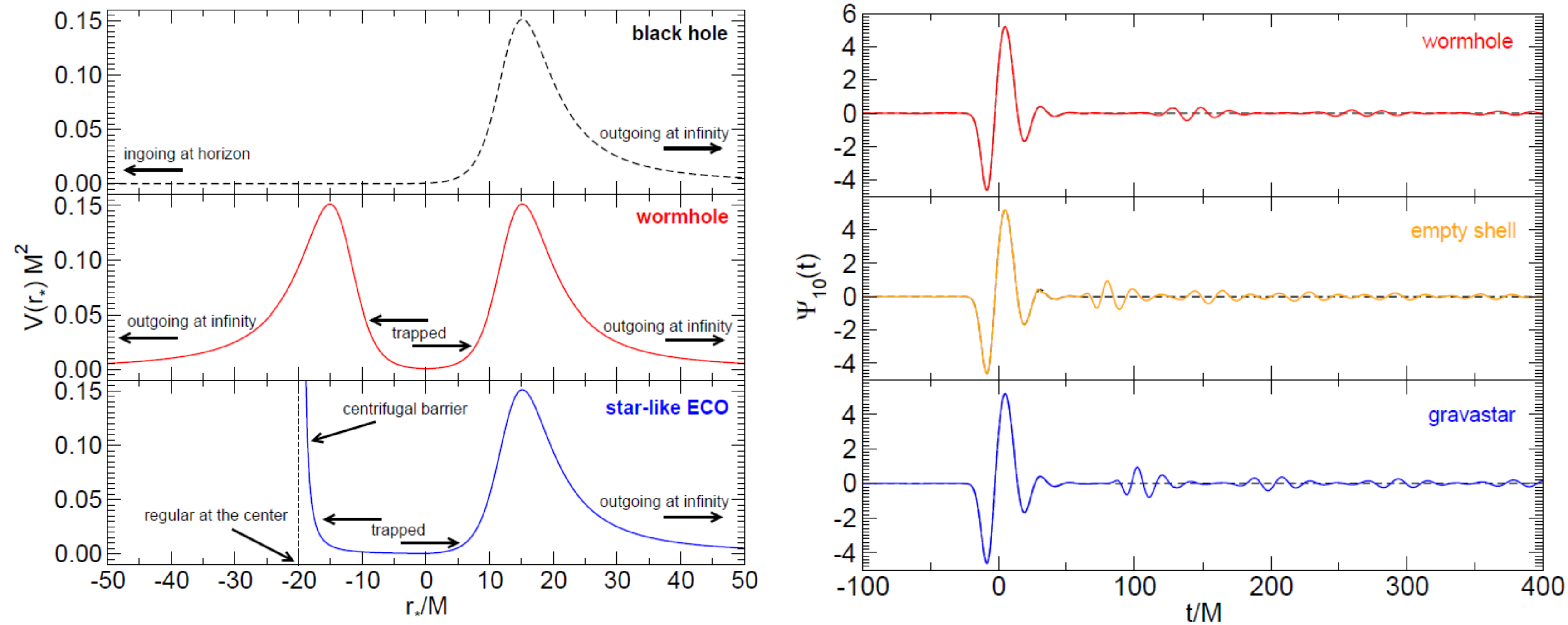
Cardoso + PRD95:084014 (2017); Sennett + PRD96:024002 (2017)
Maselli+ PRL120:081101 (2018); Johnson-McDaniel+arXiv:1804.08026

Post-merger ringdown and echoes





Echoes



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

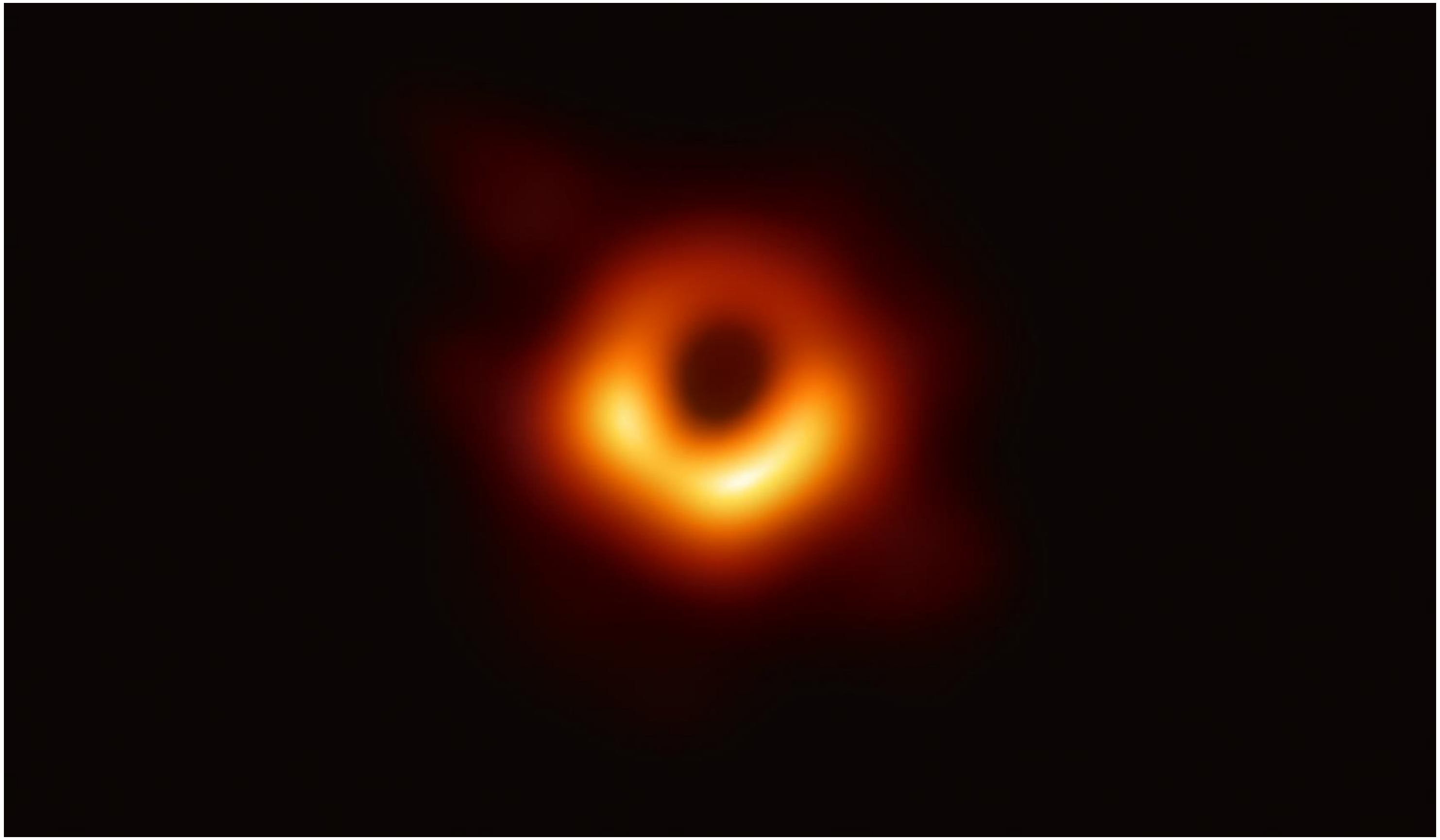
Conclusions: exciting times!

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.

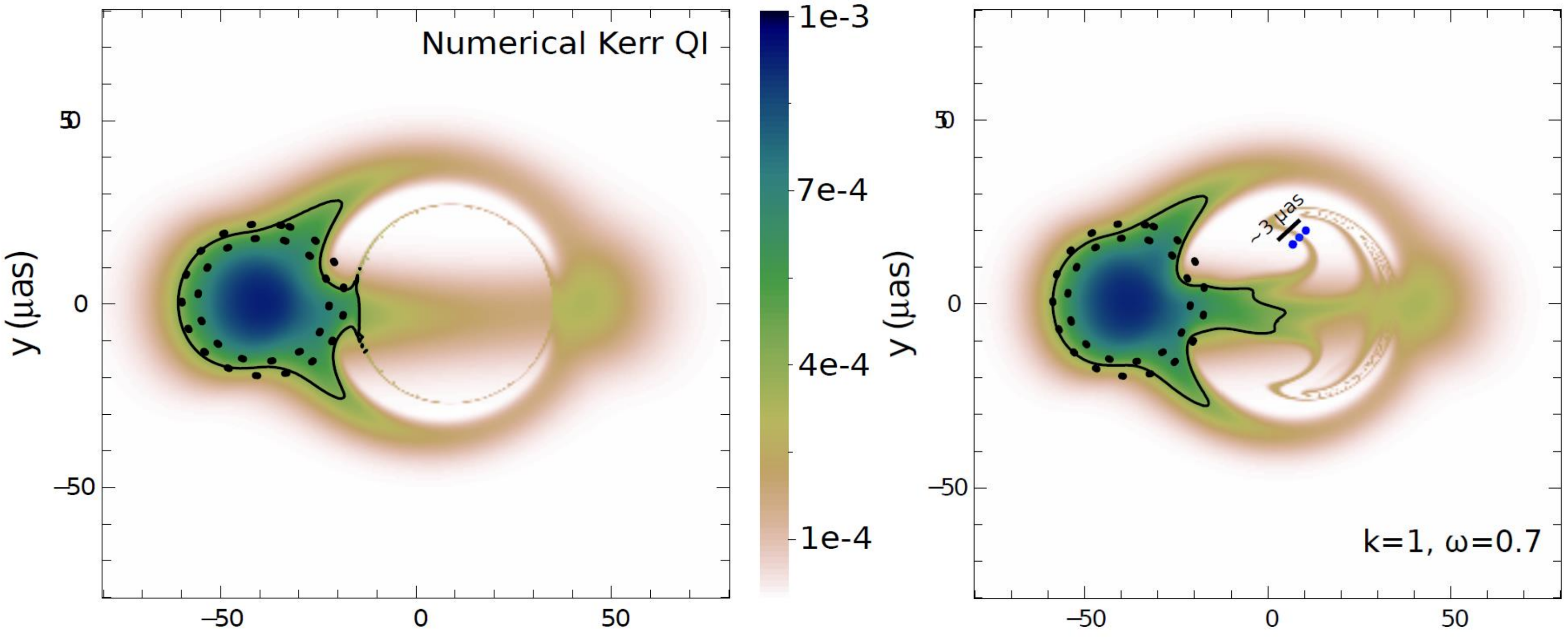
Thank you

Images of black holes?



EHT Collaboration ApJL 875: 1 (2019)

Shadows



Vincent+ CQG 33:105015 (2016)

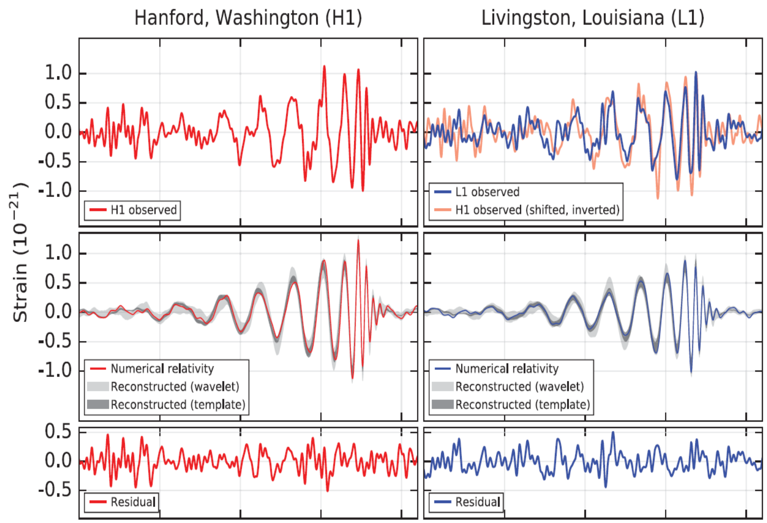
The evidence for black holes

Cardoso and Pani, Living Reviews in Relativity 22: 1 (2019); *arXiv:1904.05363*

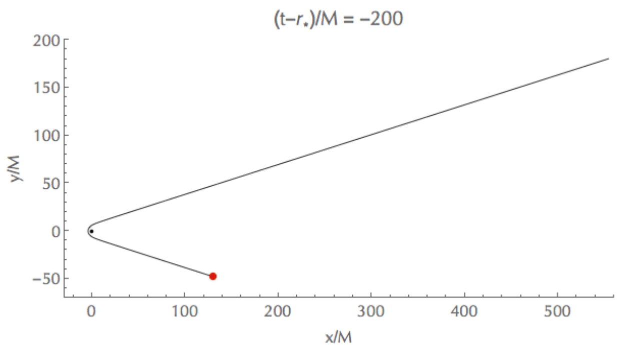
	Constraints		Source
	$\epsilon(\lesssim)$	$\frac{\nu}{\nu_\infty}(\gtrsim)$	
1.	$\mathcal{O}(1)$	1.4	Sgr A* & M87
2.	$\mathcal{O}(0.01)$	10	GW140915
3.	$10^{-4.4}$	158	All with $M > 10^{7.5} M_\odot$
4.	10^{-14}	10^7	Sgr A*
5.	10^{-40}	10^{20}	All with $M < 100 M_\odot$

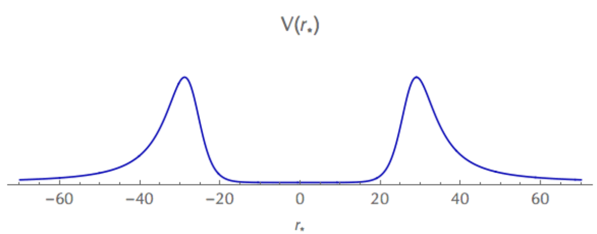
	Effect and caveats
1.	Uses detected structure in "shadow" of SgrA and M87.
	Spin effects are poorly understood; systematic uncertainties not quantified.
2.	Uses same ringdown as BH and lack of echoes.
	?
3.	Lack of optical/UV transients from tidal disruption events.
	Assumes: all objects are horizonless, have a hard surface, spherical symmetry, and isotropy.
4.	Uses absence of relative low luminosity from Sgr A*, compared to disk.
	Spin effects and interaction of radiation with matter poorly understood; assumes spherical symmetry.
5.	Uses absence of GW stochastic background (from ergoregion instability).
	Assumes: hard surface (perfect reflection); exterior Kerr; all objects are horizonless.

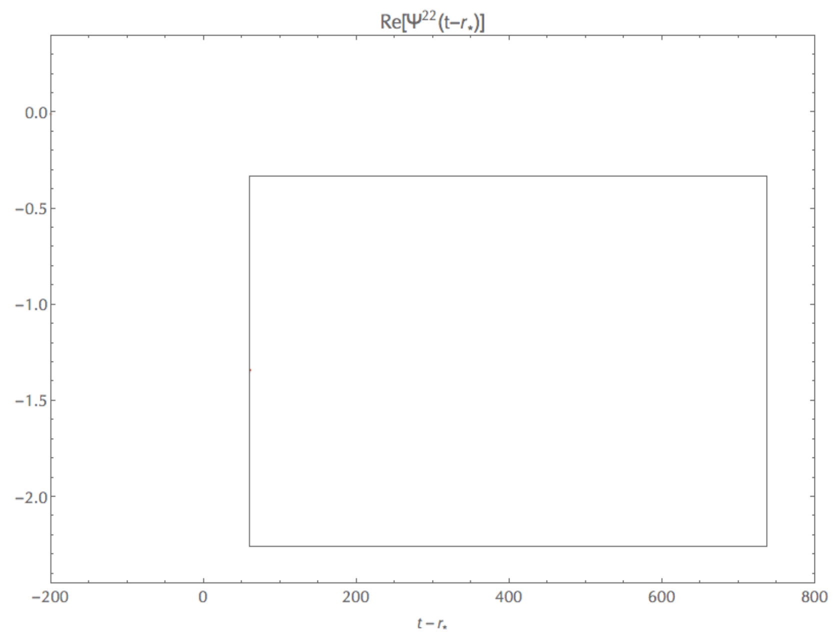
Scattering echoes



$\mathcal{E}$ = 1.5, r_{min}=4.3M, $r_0 - 2M = 10^{-6}M$







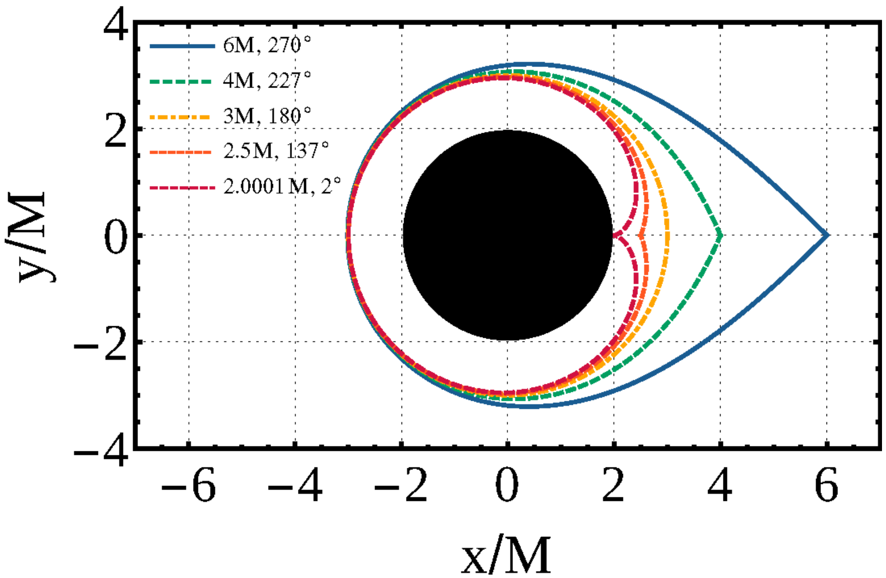
iv. EM constraints

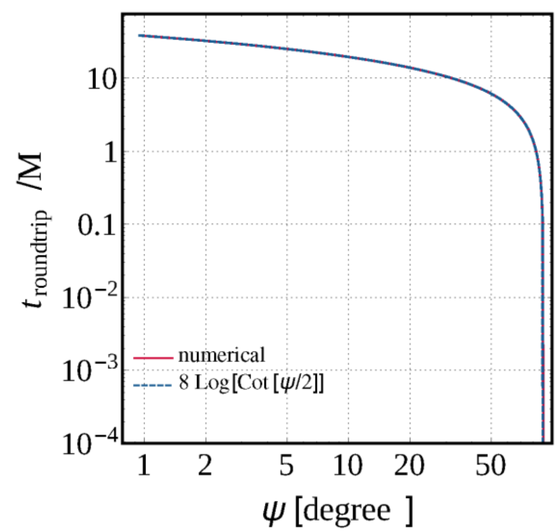
$$r = 2M\,(1+\epsilon)$$

$\epsilon \lesssim 10^{-5}$ Absence of transients from tidal disruptions

$\epsilon \lesssim 10^{-35}$ Dark central spot on SgrA

Carballo-Rúbio, Kumar, PRD97:123012 (2018)
Broderick, Narayan CQG24:659 (2007)





Lensing has to be properly included, as well as emission into other channels

Abramowicz, Kluzniak, Lasota 2002; Cardoso, Pani Nature Astronomy 1 (2017)

Wonderful sources for different GW-detectors!

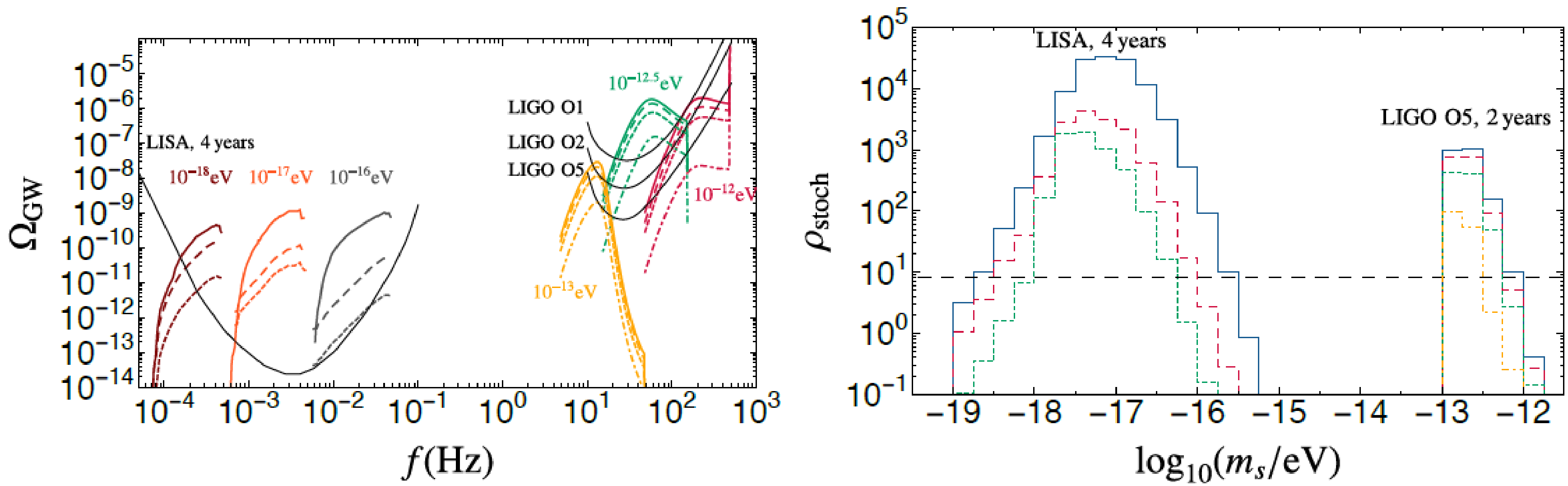


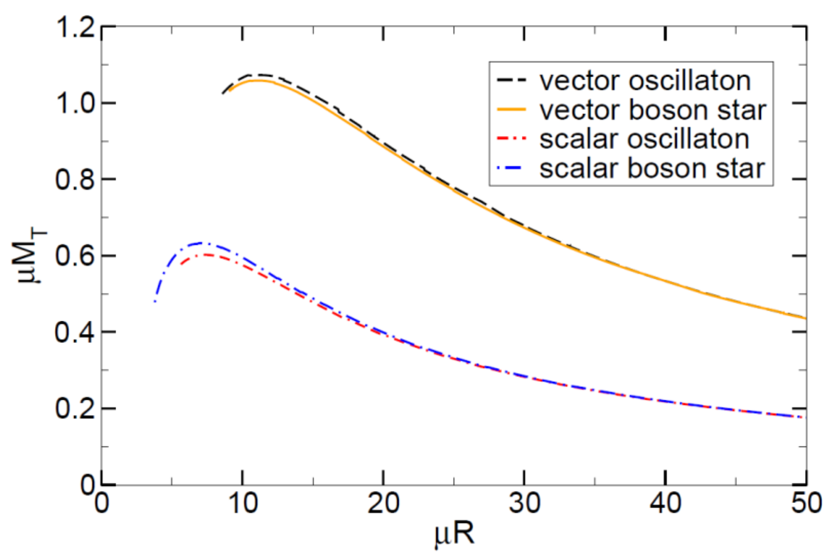
FIG. 2. Left panel: stochastic background in the LIGO and LISA bands. For LISA, the three different signals correspond to the “optimistic” (top), “less optimistic” (middle) and “pessimistic” (bottom) astrophysical models. For LIGO, the different spectra for each scalar field mass correspond to a uniform 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.

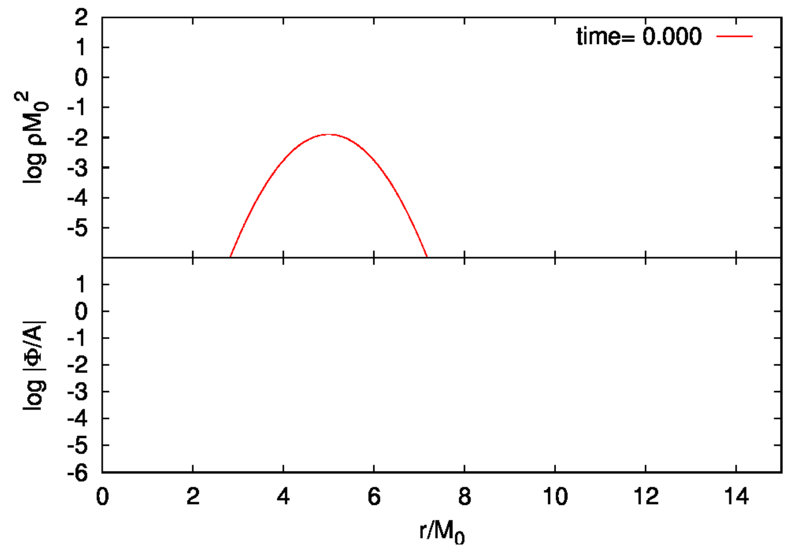
Brito + Phys.Rev.Lett. 119: 131101 (2017); arXiv 1706:05097

ii. Formation

Boson stars, fermion-boson stars, oscillatons

(Kaup '68; Ruffini, Bonazzolla '69; Colpi+ 1986; Tkachev '91; Okawa+ 2014; Brito+ 2015)





$$\frac{M_{\rm max}}{M_\odot} = 8 \times 10^{-11} \frac{\rm eV}{m_B c^2}$$

Challenge: repeat for anisotropic stars, wormholes, gravastars, etc

$$h_{+,\times} = \frac{2Gm\eta}{c_0^2 r}\left(\frac{Gm\omega}{c_0^3}\right)^{2/3}\left\{H^{(0)}_{+,\times} + x^{1/2}H^{(1/2)}_{+,\times} + xH^{(1)}_{+,\times} + x^{3/2}H^{(3/2)}_{+,\times} + x^2 H^{(2)}_{+,\times}\right\}$$

G is Newton's constant, c_0 is speed of light

m is total mass, η is chirp mass, r is distance to source

ω is orbital frequency

x is velocity

c,s are cos and sin of inclination angle

ψ is, up to a constant, the orbital phase

$$\phi(t) = \phi_c - \frac{1}{\eta}\left\{\Theta^{5/8} + \left(\frac{3715}{8064} + \frac{55}{96}\eta\right)\Theta^{3/8} - \frac{3\pi}{4}\Theta^{1/4} + \left(\frac{9275495}{14450688} + \frac{284875}{258048}\eta + \frac{1855}{2048}\eta^2\right)\Theta^{1/8}\right\}$$

Blanchet, Iyer, Will, Wiseman, *CQG13:575 (1996)*

$$
\begin{aligned}
H_+^{(0)} &= -(1+c^2)\cos 2\psi \ , \\
H_+^{(1/2)} &= -\frac{s}{8}\frac{\delta m}{m}\Bigg[(5+c^2)\cos\psi - 9(1+c^2)\cos 3\psi\Bigg] \ , \\
H_+^{(1)} &= \frac{1}{6}\Bigg[(19+9c^2-2c^4) - \eta(19-11c^2-6c^4)\Bigg]\cos 2\psi \\
&\quad - \frac{4}{3}s^2(1+c^2)(1-3\eta)\cos 4\psi \ , \\
H_+^{(3/2)} &= \frac{s}{192}\frac{\delta m}{m}\Bigg\{\Bigg[(57+60c^2-c^4) - 2\eta(49-12c^2-c^4)\Bigg]\cos\psi \\
&\quad - \frac{27}{2}\Bigg[(73+40c^2-9c^4) - 2\eta(25-8c^2-9c^4)\Bigg]\cos 3\psi \\
&\quad + \frac{625}{2}(1-2\eta)s^2(1+c^2)\cos 5\psi\Bigg\} - 2\pi(1+c^2)\cos 2\psi \ , \\
H_+^{(2)} &= \frac{1}{120}\Bigg[(22+396c^2+145c^4-5c^6) + \frac{5}{3}\eta(706-216c^2-251c^4 + \\
&\qquad - 5\eta^2(98-108c^2+7c^4+5c^6)\Bigg]\cos 2\psi \\
&\quad + \frac{2}{15}s^2\Bigg[(59+35c^2-8c^4) - \frac{5}{3}\eta(131+59c^2-24c^4) \\
&\qquad + 5\eta^2(21-3c^2-8c^4)\Bigg]\cos 4\psi \\
&\quad - \frac{81}{40}(1-5\eta+5\eta^2)s^4(1+c^2)\cos 6\psi \\
&\quad + \frac{s}{40}\frac{\delta m}{m}\Bigg\{\Bigg[11+7c^2+10(5+c^2)\ln 2\Bigg]\sin\psi - 5\pi(5+c^2)\cos\psi
\end{aligned}
$$