Superradiance & ALPs

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Image: Jacques Henri Lartigue

Standard Model not the final word

Death and the Miser, by Frans Francken the Young

Galaxy interactions

Gravitational lensing

Rotation curves

Velocities of galaxies in clusters

Structure formation

...

Uniqueness: the Kerr solution

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

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

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

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

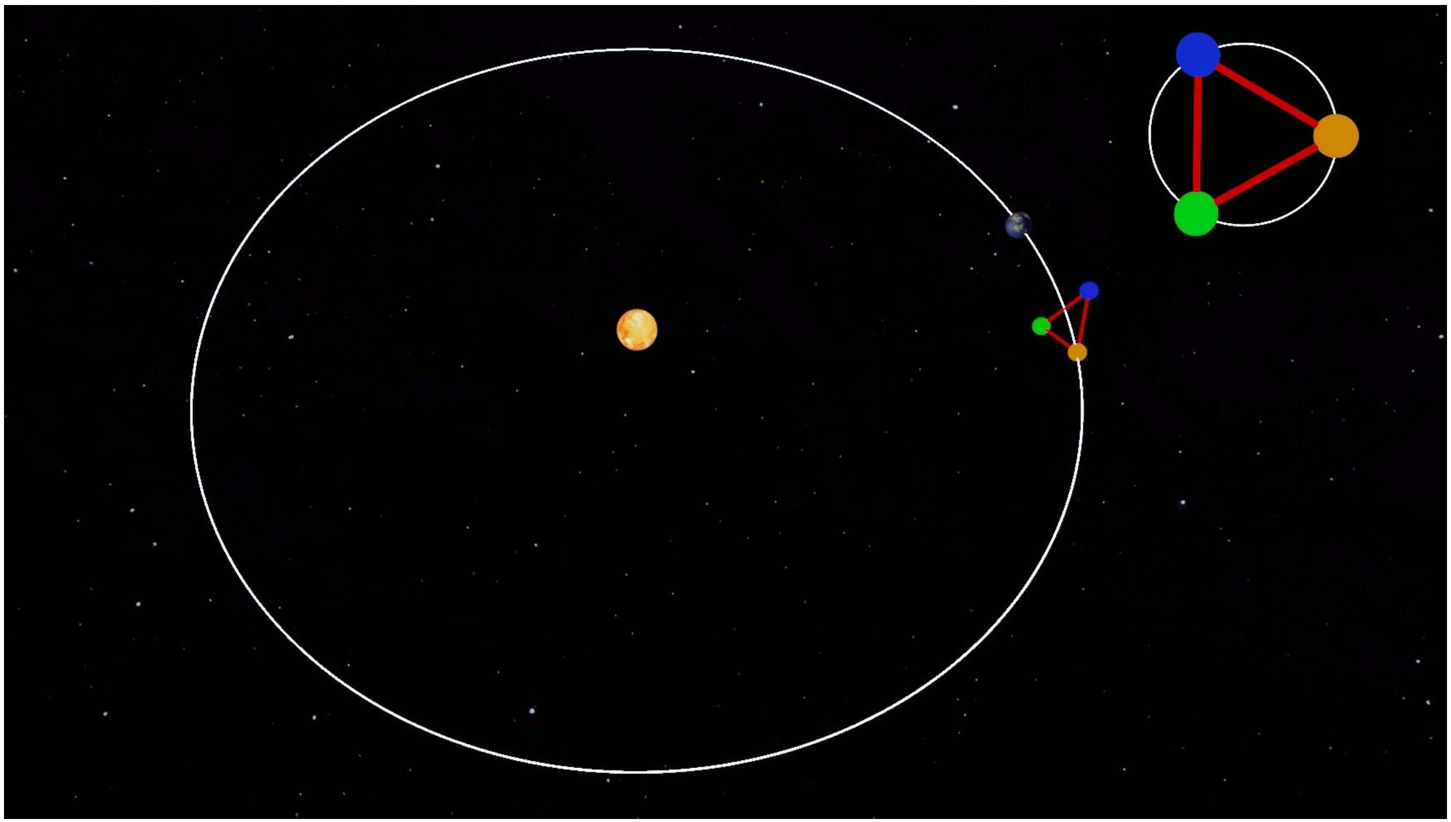
“In my entire scientific life, extending over forty-five years, the most shattering experience has been the realization that an exact solution of Einstein’s equations of general relativity provides the *absolutely exact representation* of untold numbers of black holes that populate the universe.”

S. Chandrasekhar, The Nora and Edward Ryerson lecture, Chicago April 22 1975

They exist!

Zoheyr Doctor / University of Oregon / LIGO-Virgo Collaboration

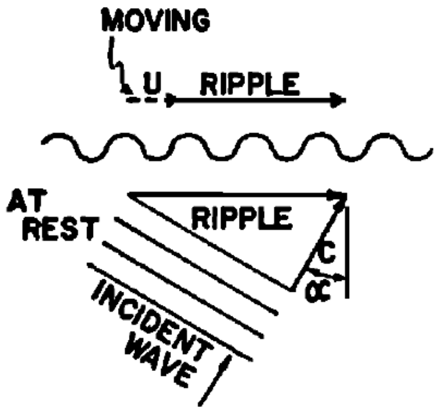
Observing from space with LISA
(Laser Interferometer Space Antenna)



The most amazing space mission ever conceived!

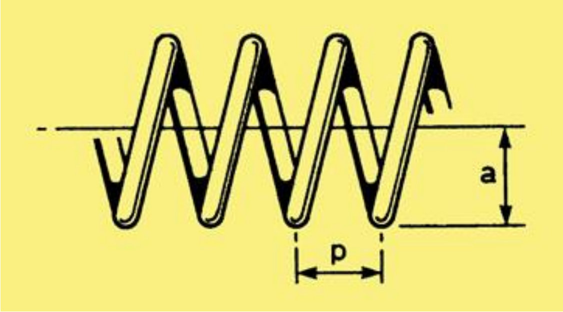
Superradiance

Zel'dovich JETP Lett. 14:180 (1971)
review of all known results in Brito+ Lect. Notes Phys. 971 (2020)

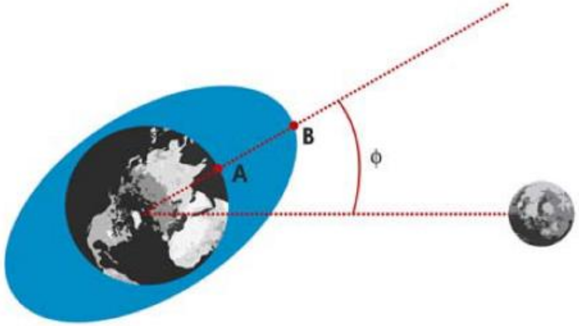


Ribner, J. Acous. Soc. Amer. 29 (1957)

Tamm & Frank, Doklady AN SSSR 14 (1937)

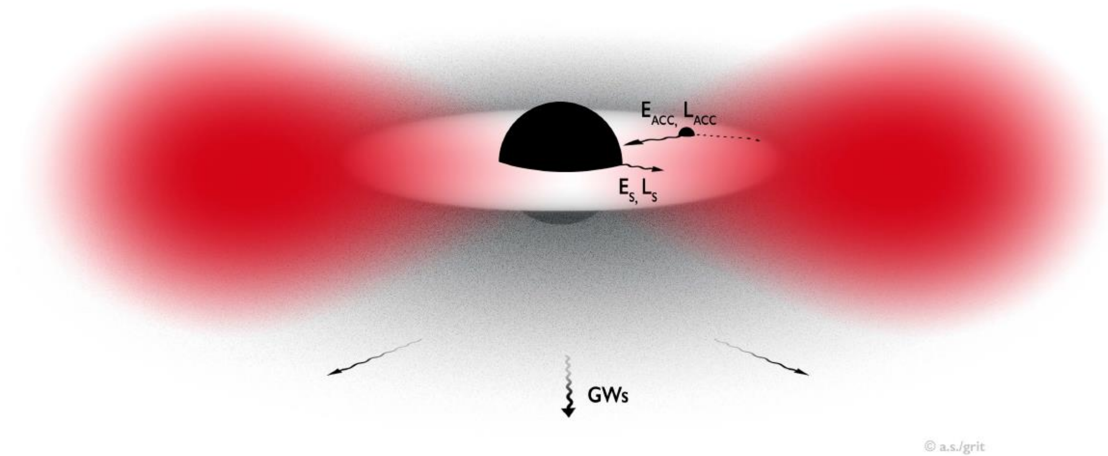


Pierce (& Kompfner), Bell Lab Series (1947)
Ginzburg, anomalous Doppler year



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

Fundamental light fields: particle detectors in the sky



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

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

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

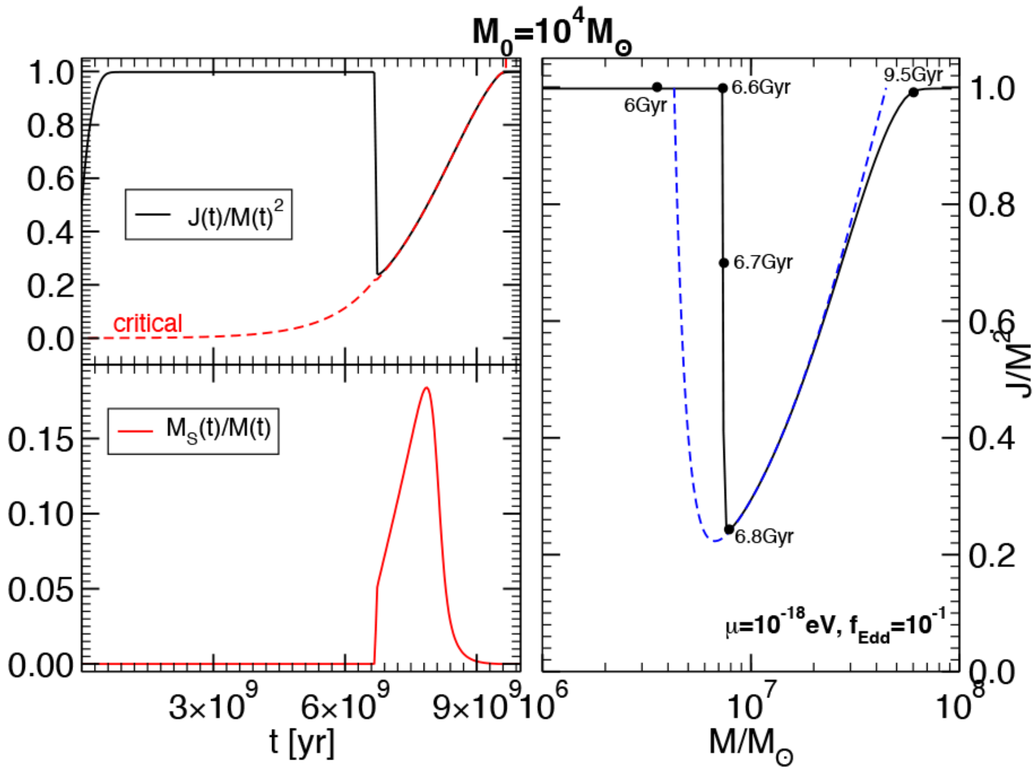
$$S = -s, -s+1..., s-1, s$$

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

Wonderful sources of GWs

Brito, Cardoso, Pani, Lecture Notes Physics 971 (2020)

Fundamental fields: particle detectors in the sky

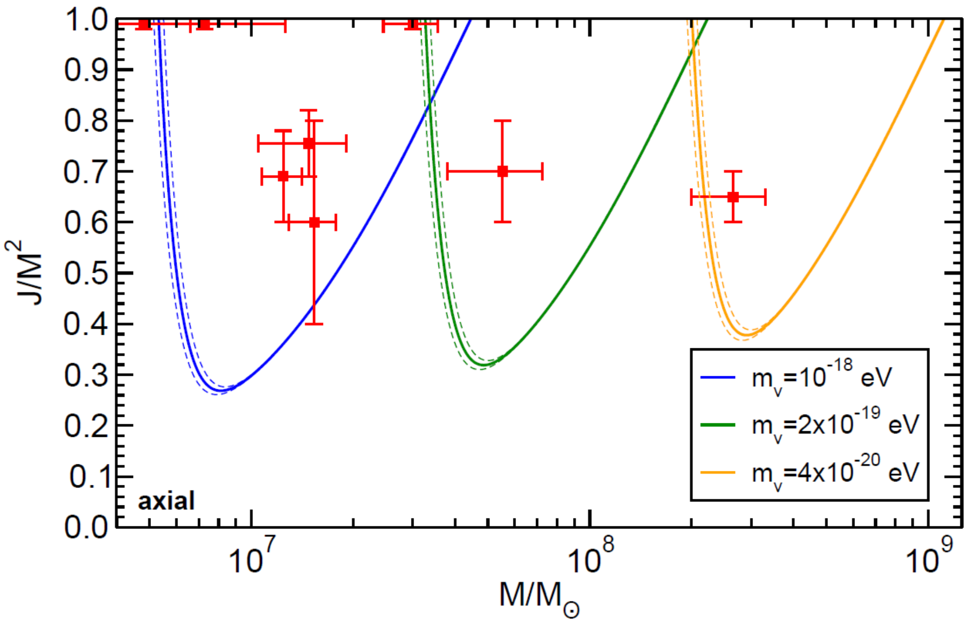


Evolution of BH mass and spin due to superradiance, accretion of gas and emission of GWs. The initial BH mass M0 = 10^4M⊙ and the initial BH spin = 0.5. The BH enters the instability region at about t ~ 6Gyr, when its mass ~ 10^7M⊙ and spin is quasi-extremal. Left shows dimensionless spin and critical superradiant threshold; left bottom shows mass of scalar cloud; right panel shows trajectory of BH in Regge plane. Dashed line denotes depleted region as estimated by linearized analysis.

Brito + CQG32: 134001 (2015)

Bounding the boson mass with EM observations

Pani + PRL109, 131102 (2012)



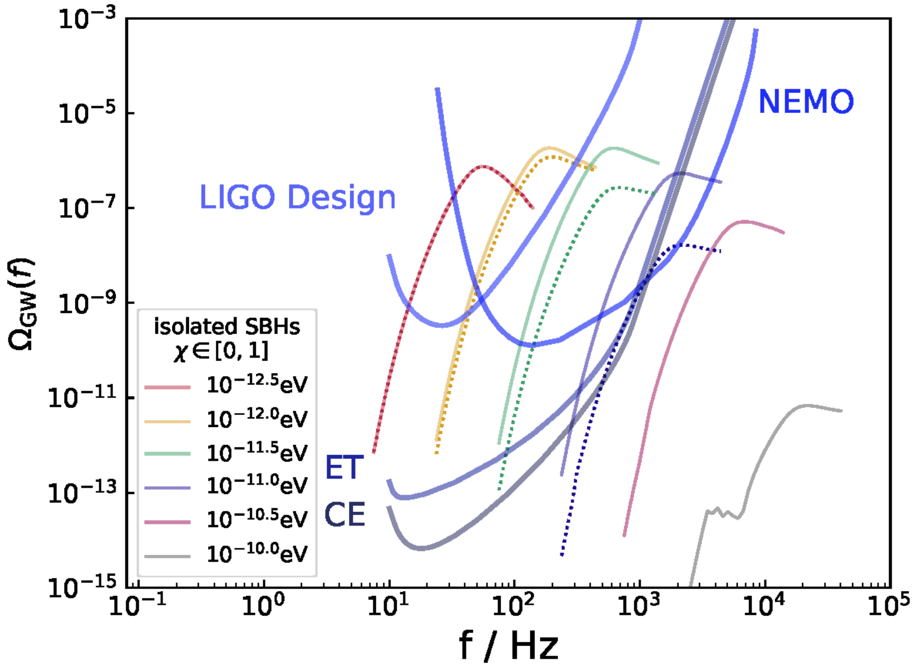
Bound on photon mass is model-dependent: details of accretion disks or intergalactic matter are important… but gravitons interact very weakly!

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

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

Wonderful sources for different GW-detectors

Arvanitaki+ PRD91: 084011 (2015); Brito + PRL119: 131101 (2017); Yuan + PRD 104:044011 (2021)



Dotted lines only include m = 1 mode, solid lines include all modes. Plot also shows power-law integrated sensitivity curves. Assume four-year-detection and two co-aligned and co-located identical detectors for NEMO/CE/ET.

Also LIGO Scientific Collaboration arXiv:2111.15507;
For LISA see Brito + PRL119: 131101 (2017); PRD96:064050 (2017)

Wonderful sources for different detectors

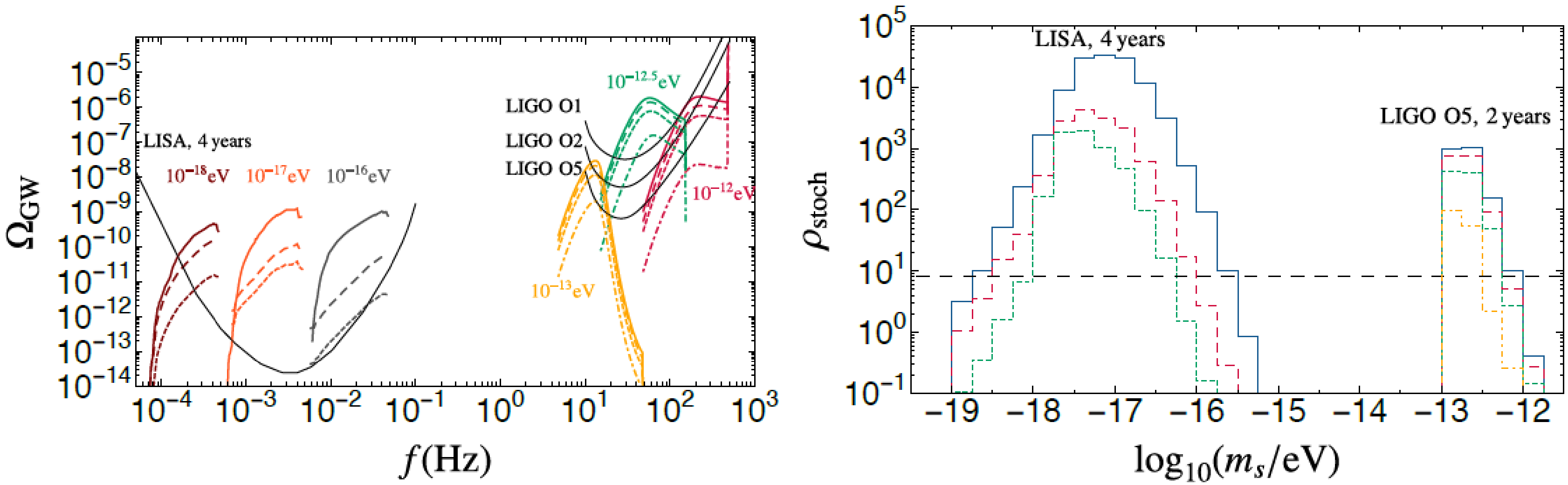
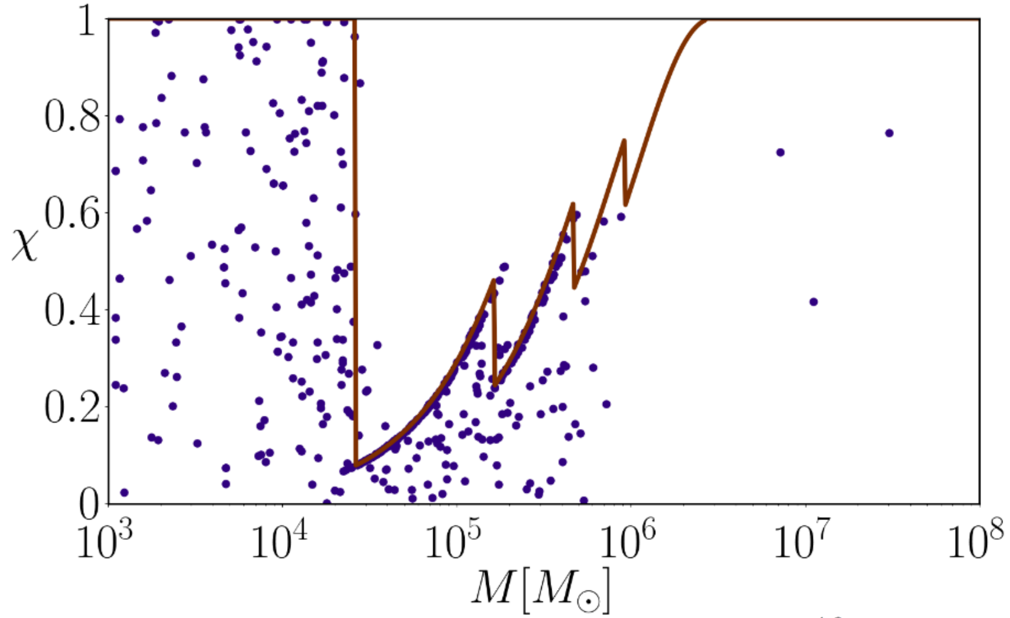


FIG. 2. Left panel: stochastic background in the LIGO and LISA bands. For LISA, the three different signals correspond to the "optimistic" (top), "less optimistic" (middle) and "pessimistic" (bottom) astrophysical models. For LIGO, the different spectra for each scalar field mass correspond to a uniform 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 $T_{\rm obs} = 2\,{\rm yr}$ for LIGO and $T_{\rm obs} = 4\,{\rm yr}$ for LISA.

Brito + PRL119: 131101 (2017); Tsukada + arXiv: 2011.06995; Yuan + arXiv:2106.00021

Signatures in Regge plane



Two-year simulation for LISA and a boson with $10^{-16}\,\mathrm{eV}$. Saw-tooth due to different m harmonics. Final estimate from LISA: $(0.88 - 1.35) \times 10^{-16}\,\mathrm{eV}$

Brito + PRL119: 131101 (2017); PRD96:064050 (2017)

Constraints on fundamental fields via superradiance

Review in Brito+ Lect. Notes Phys.971 (2020)

Resolvable events from single sources

Arvanitaki+ PRD91 (2015) 084011; Brito CQG32 (2015)134001; Brito+PRD96:064050; D'Antonio+PRD98 (2018)103017; Isi+ PRD99 (2019)084042; Palomba+ PRL123 (2019) 171101

Stochastic background

Brito+PRL119: 131101 (2017); PRD96:064050 (2017); Tsukada+PRD99 (2019) 103015; LLIGO/Virgo PRD100 (2019) 061101

Accurate measurements of BH spin (via EM or GW measurements)

Pani+ PRL 109 (2012) 131102; Brito+PRD88 (2013) 023514

Spin distribution

Arvanitaki+ PRD83 (2011) 044026; Brito CQG32 (2015)134001; Brito+PRL119: 131101 (2017); PRD96:064050 (2017);

Polarization of light if field is axionlike

Plascencia+JCAP1804 (2018) 059; Chen+ arXiv:1905.02213

Motion of stars close to supermassive BHs

Ferreira+PRD96 (2017)083017; Boskovic+PRD98 (2018) 024037; Davoudiasl+PRL123 (2019)021102; Bar+ JCAP1907 (2019)045; GRAVITY MNRAS 524:1075 (2023)

Constraints on fundamental fields via superradiance

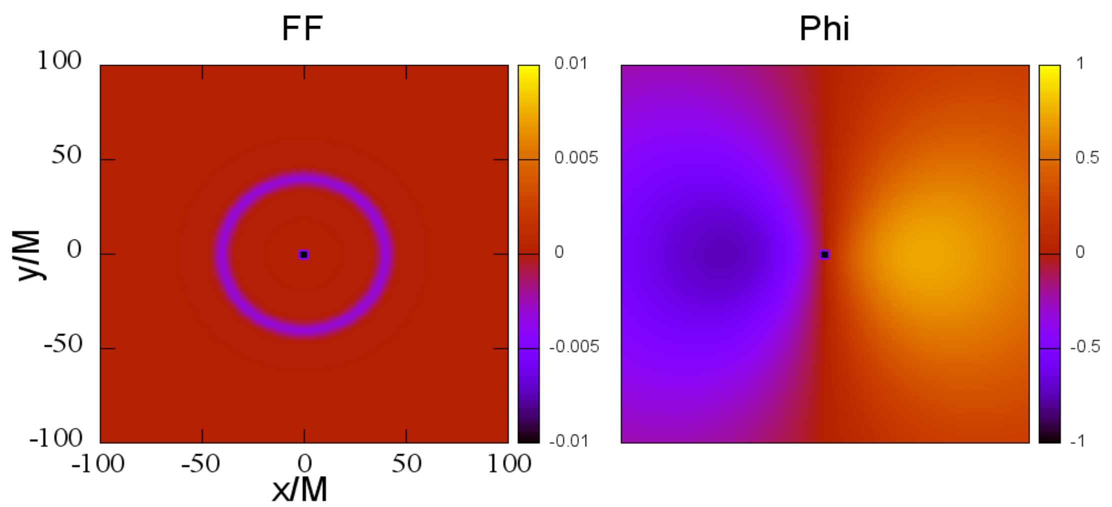
Review in Brito+ Lect. Notes Phys.971 (2020); Updated constraints to appear soon

	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.
	$8.5 \times 10^{-22} < m_V < 4.6 \times 10^{-21}$	
*	$1.0 \times 10^{-21} < m_T < 8.2 \times 10^{-21}$	

Couplings to Standard Model

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

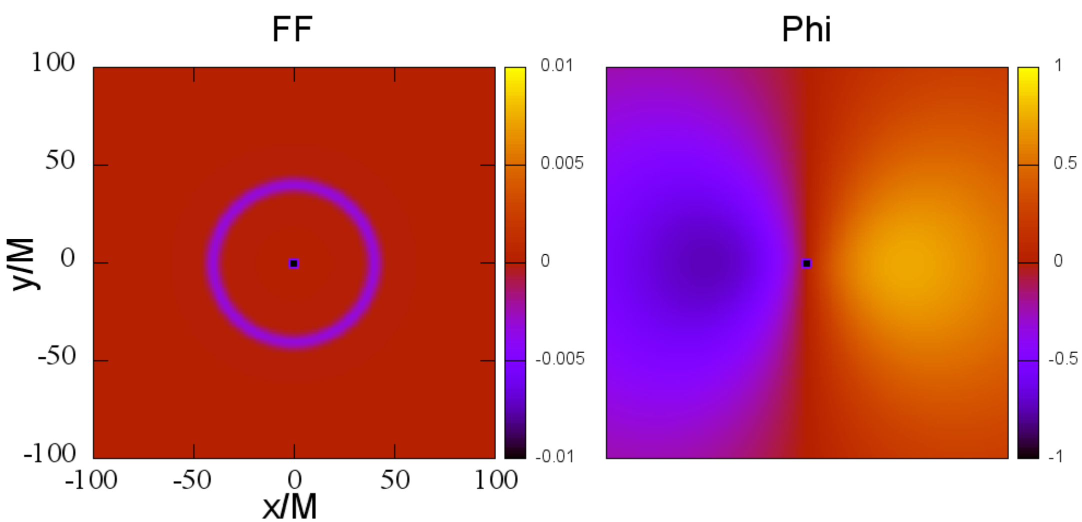
Boskovic+ PRD99:035006 (2019); Ikeda+ PRL122:081101 (2019); Spieksma+ PRD108:063013 (2023)



Couplings to Standard Model

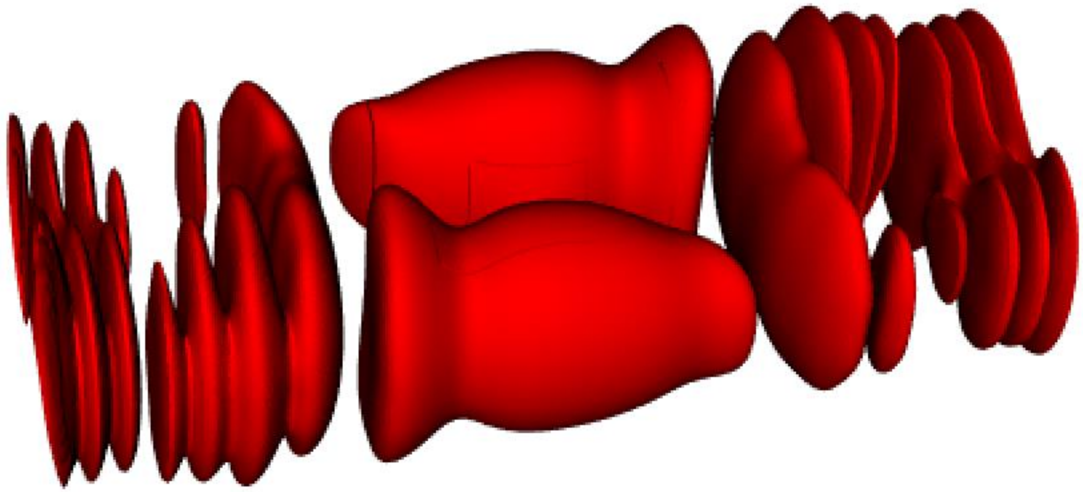
$$\mathcal{L} = \frac{R}{k} - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{2}g^{\mu\nu}\partial_\mu\Psi\partial_\nu\Psi - \frac{\mu_S^2}{2}\Psi\Psi - \frac{k_{\rm axion}}{2}\Psi\, {}^*F^{\mu\nu}F_{\mu\nu}$$

Boskovic+ PRD99:035006 (2019); Ikeda+ PRL122:081101 (2019); Spieksma+ PRD108:063013 (2023)



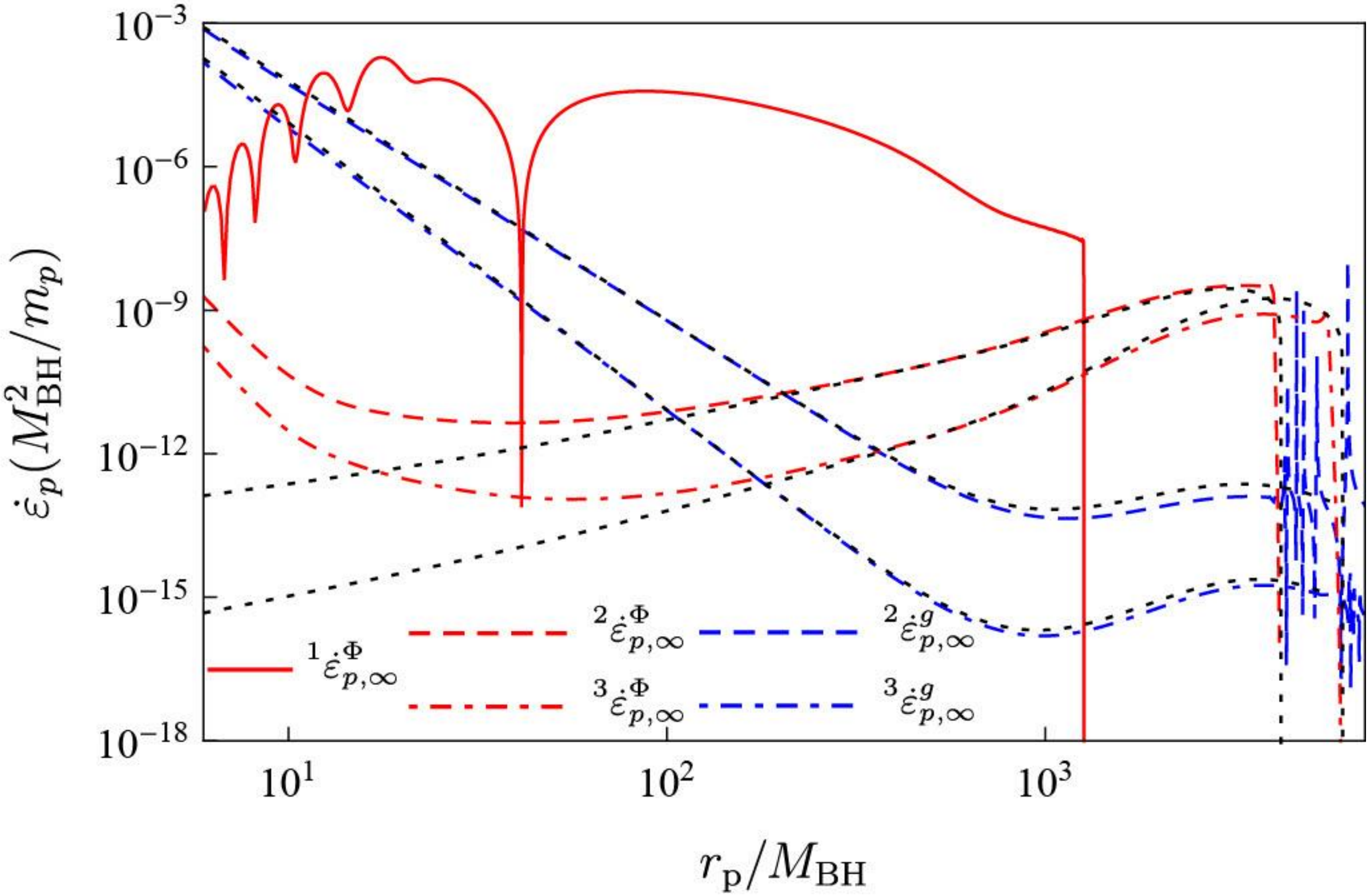
$$k_{\rm axion} > 3\times10^{-18}\left(\frac{M_{BH}}{100\ M_S}\right)^{1/2}(\mu M)^{-1}\ GeV^{-1}$$

Tidal disruption of clouds



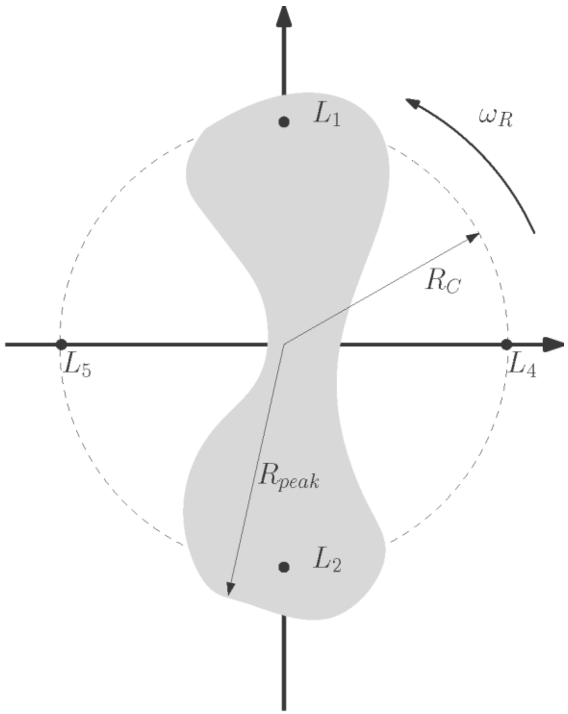
Cardoso+ PRD101: 064054 (2020)

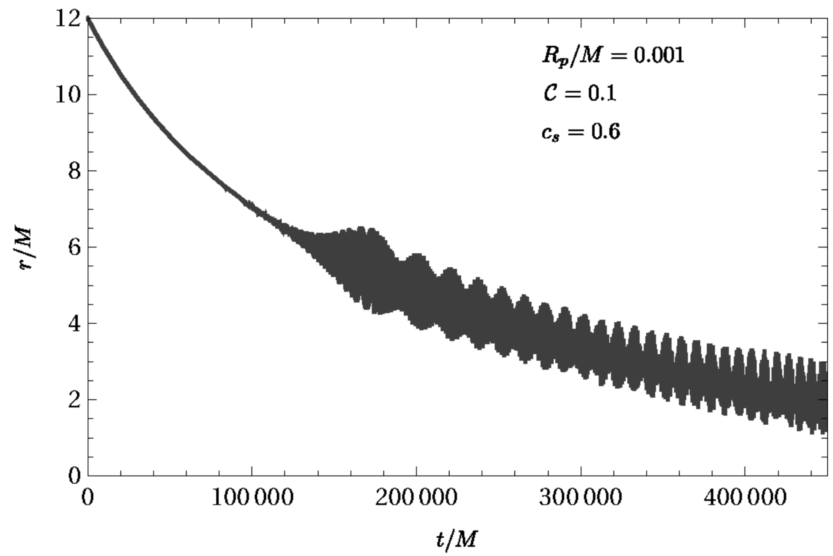
Ionization, friction, tidal capture Tomaselli + JCAP 07 (2023) 070
GW+self force…



Duque+ arXiv:2312.06767

Orbital motion of stars and planets: floating, resonances



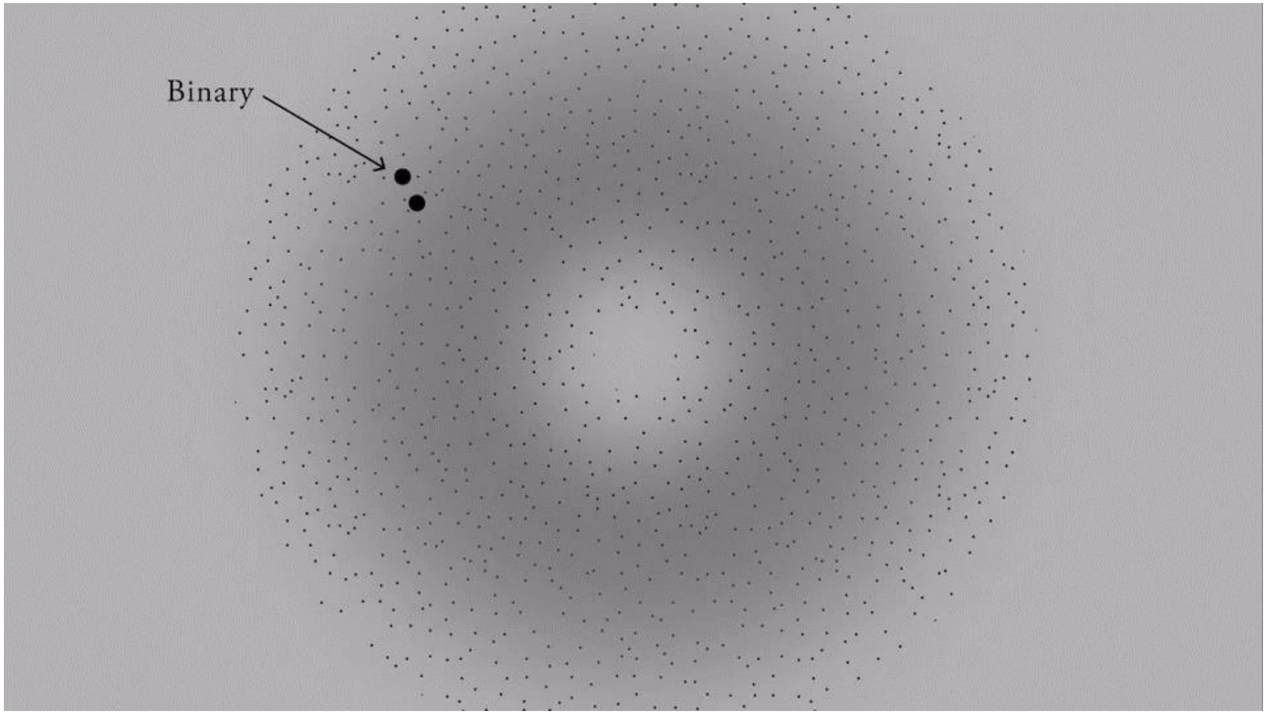


Cardoso+ PRL107: 241101 (2011); PRD96:083017 (2017); Boskovic+ PRD98:024037 (2018)

Dark matter

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 + AA644: A147 (2020)
Kavanagh + arXiv 2002.12811; Annulli + PRD102: 063022 (2020); Duque + arXiv:2312.06767



Precision physics: the inspiral phase

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

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

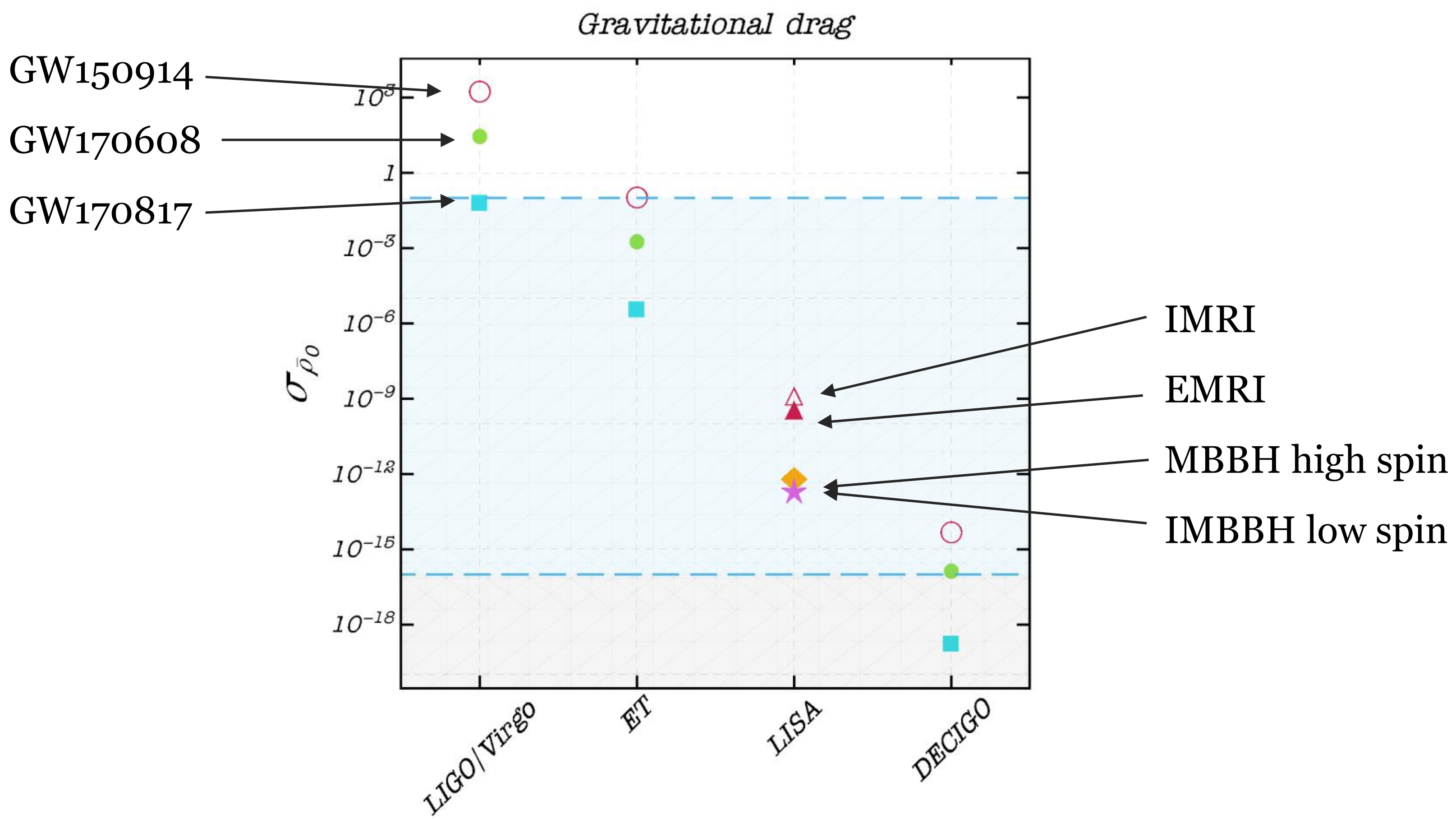
ψ is, up to a constant, the orbital phase

Θ= η/(5m)(to-t)

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

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

Small Compton wavelength: heavy DM



Effect is -5.5 PN on GW phase

Cardoso & Maselli AA644: A147 (2020) arXiv 1909.05870
Also Eda + PRL 110 (2013) 221101; Macedo+ApJ774 (2013) 48; Annulli+ PRD102;063022 (2020)

Some challenges

Couplings (Maxwell, neutrinos)

Ikeda+ PRL122:081101 (2018); Yifan Chen + in preparation

Tensor fields (requires non-linearities)

Brito+ PRD88:064006 (2013); PRL124:211101 (2020)

Self-interactions

Yoshino & Kodama CQG 32:214001 (2015)

Plasmas

Cardoso + MNRAS503:563 (2021); Cannizzaro + PRD 103:124018 (2021)
Spieksma + PRD108:063013 (2023); Cannizzaro +, to appear

Stars: do they superradiate?

Cardoso+PRD91:124026 (2015)
PRD95:124056 (2017);
Chadha-Day + JCAP12: 008 (2022)

Binaries: do they superradiate?

Wong PRD101:124049 (2020); Ikeda+ PRD103:024020 (2021);
Baumann+ PRD99 (2019) 044001; Cardoso+ PRD101 (2020) 064054

Big Jay Mc Neely, Photograph by Bob Willoughby

"Imagine being able to see the world but you are deaf, and then suddenly someone gives you the ability to hear things as well — you get an extra dimension of perception"

B. Schutz, BBC

Thank you

Energy source?

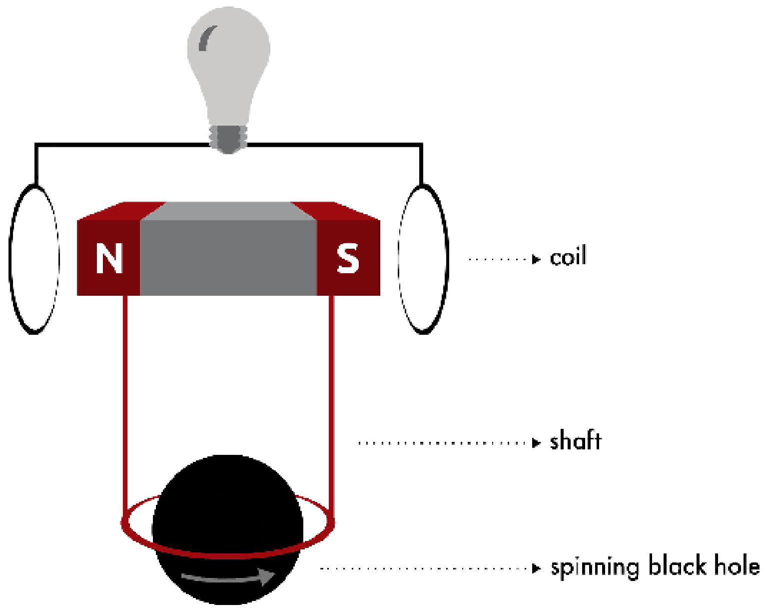


Image: Ana Carvalho

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)