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Searching for ultralight bosons with black holes and gravitational waves

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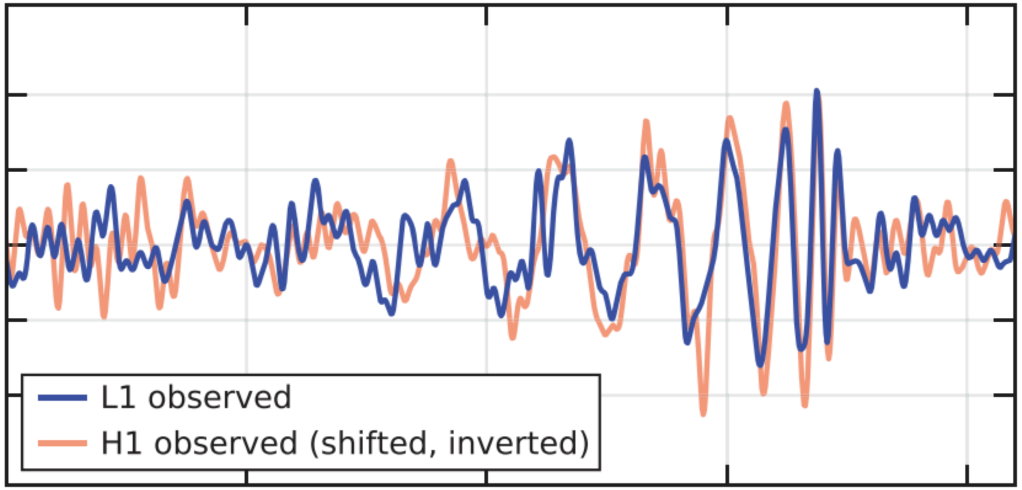
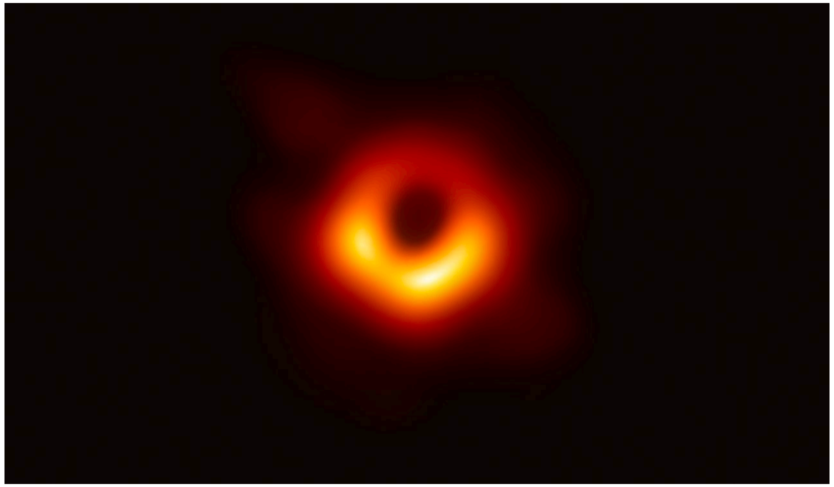
grit
gravitation in técnico

FCT Fundação para a Ciência e a Tecnologia

A new golden age for gravitation



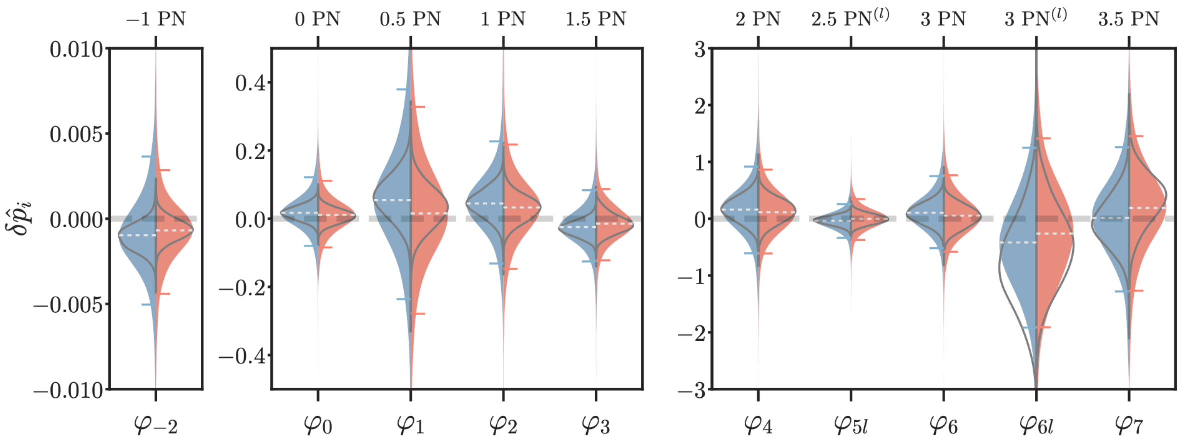
Credit: (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. Lett. 116, 061102


Credit: Event Horizon Telescope collaboration

- A wealth of data, from **gravitational waves** to **EHT observations**, is opening new doors for potential discoveries in regimes completely unexplored up to very recently.
- In the coming years, especially with **LISA** and **third generation gravitational-wave** detectors we will be doing “**precision** gravitational-wave physics” and we will likely be doing **data-driven science**.
- Plenty of room for **unexpected** discoveries.

Fundamental Physics with BHs and GWs

Tests of gravity

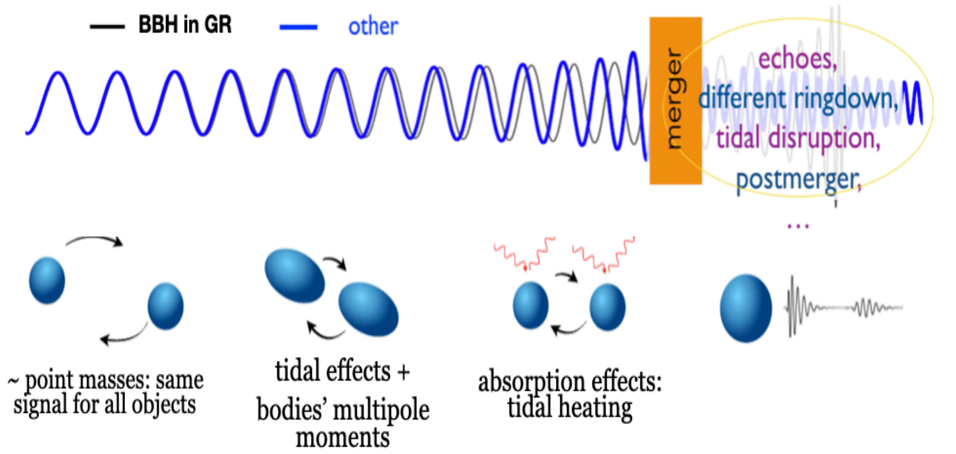


From: LVC, Phys. Rev. D103,122001 (2021)

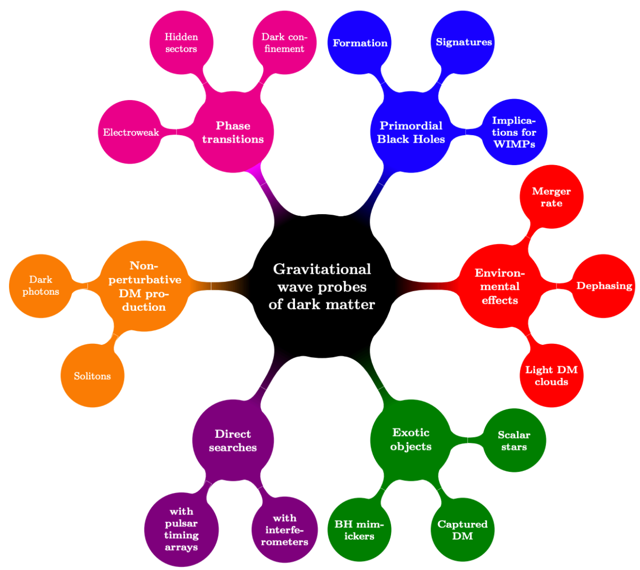
This talk

Tests of compact objects

Credit: Paolo Pani (concept by T. Hinderer and A. Maselli)

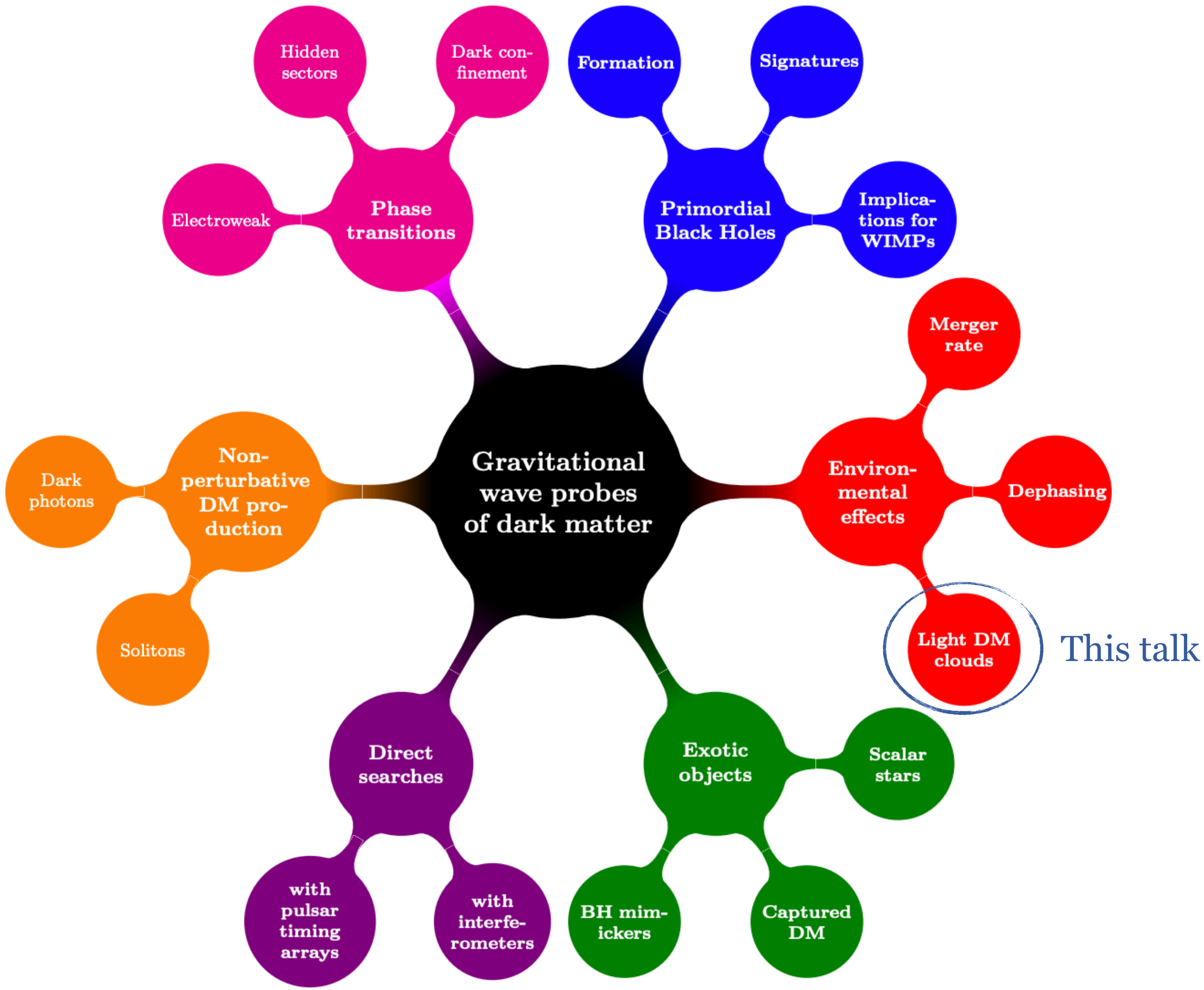


Searches for dark matter & new fields



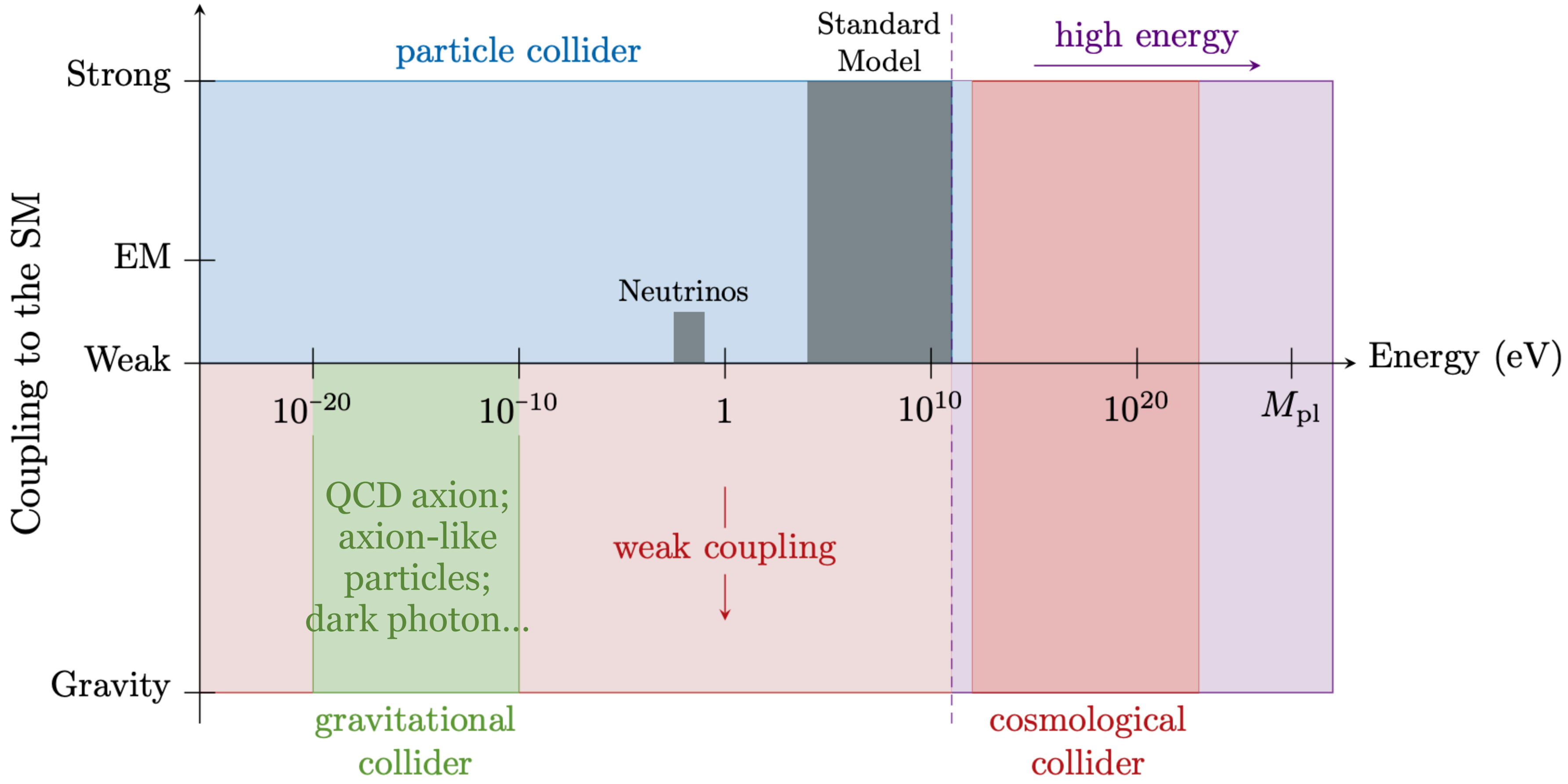
From: Bertone *et al*, arXiv: 1907.10610

Gravitational wave probes of dark matter



From: Bertone *et al*, arXiv: 1907.10610

Ultralight bosons



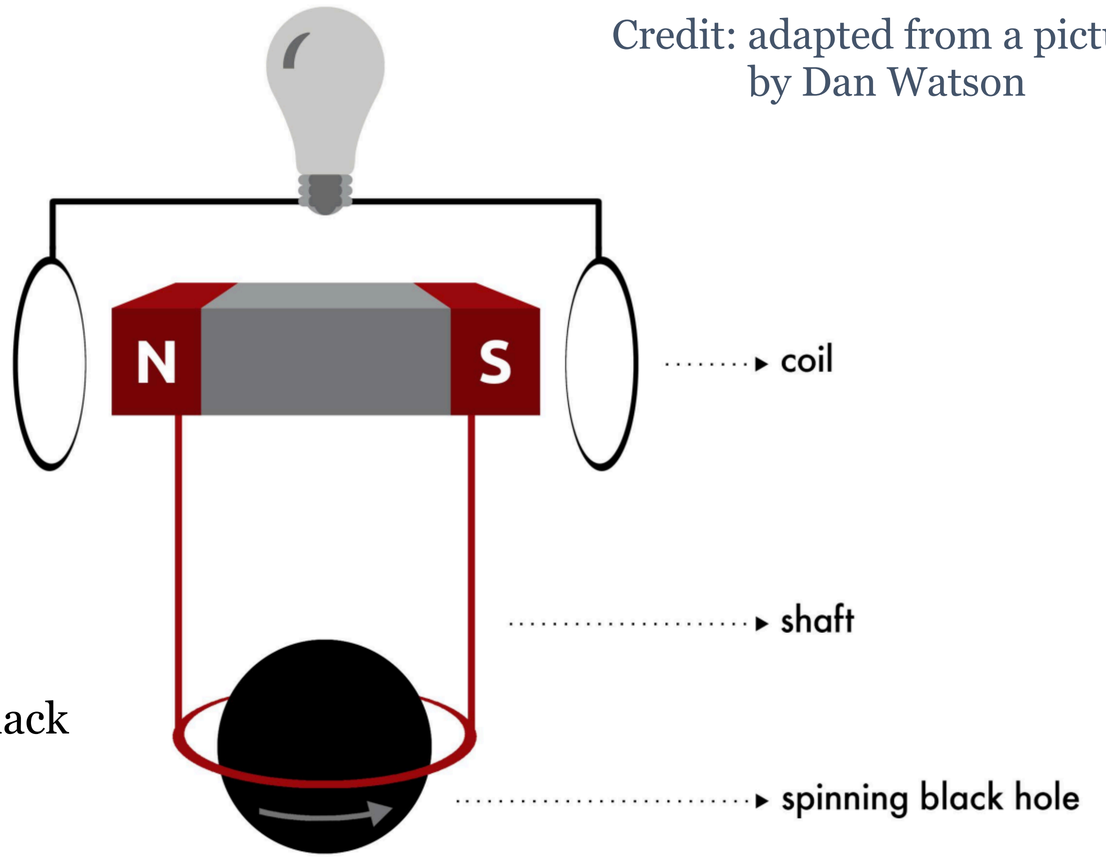
Adapted from: Baumann et al ’20, PRD101, 083019

Bosons with masses $\sim 10^{-20}$ eV – 10^{-11} eV have Compton wavelengths as large as the size of **astrophysical black holes** ranging from $10M_\odot - 10^{10}M_\odot$.

Extracting energy from a spinning black hole

Credit: adapted from a picture by Dan Watson

Rods turn magnet over generating electric current

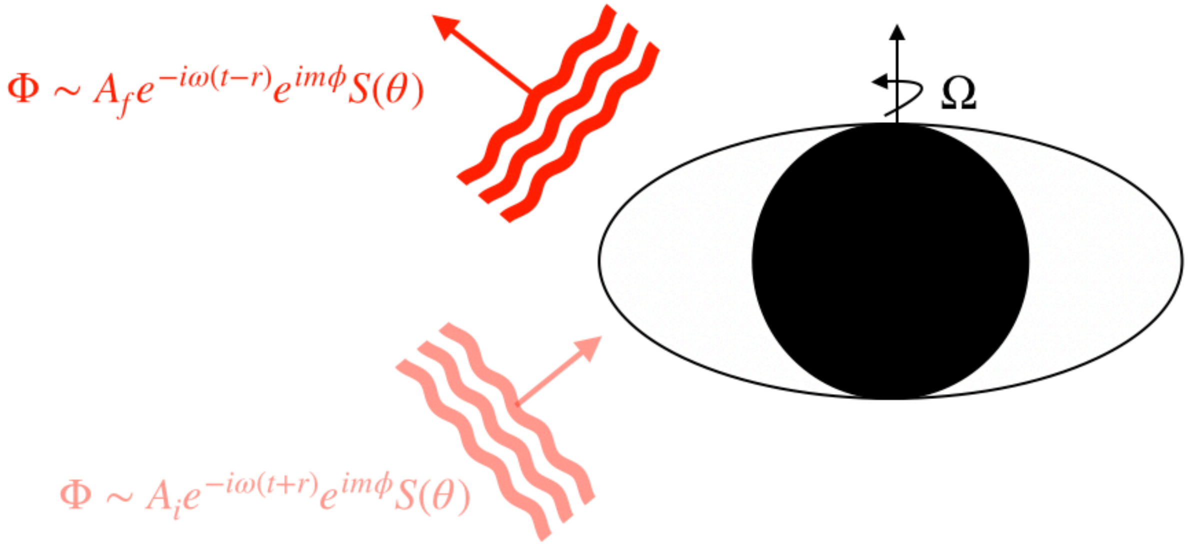


Ends of shaft placed in the **ergoregion** of the spinning black hole, where it is **forced to co-rotate** with the black hole.

Rotational energy can be extracted from spinning black holes, e.g. Penrose process, Blandford-Znajek process & **superradiance**

Black hole superradiance

Zel'dovich, '71; Misner '72; Press and Teukolsky ,'72-74;
Review: RB, Cardoso & Pani "Superradiance" Lect. Notes Phys. 971 (2020), 2nd ed.



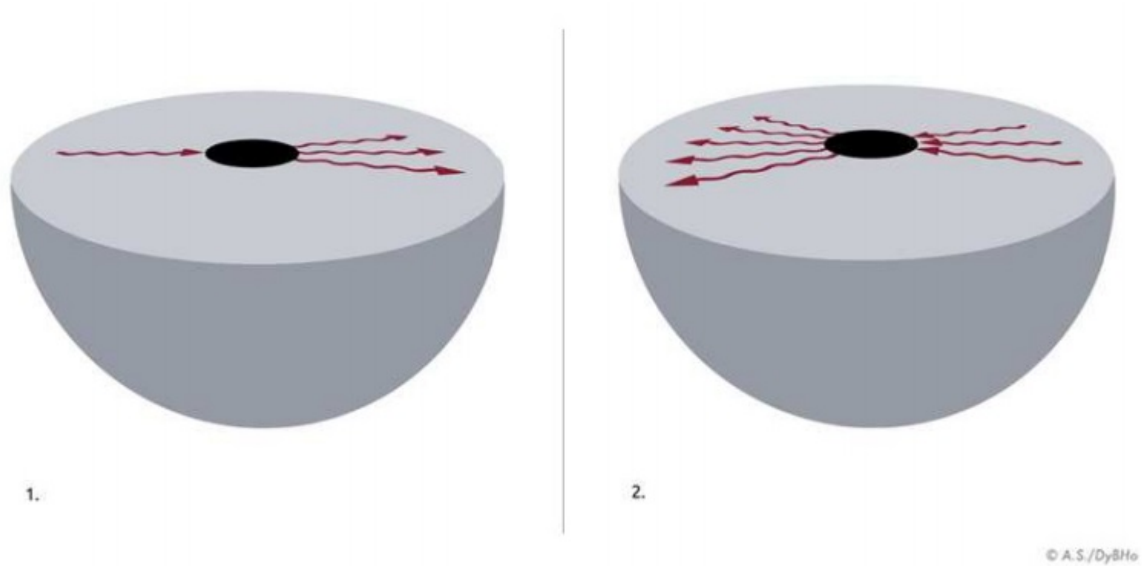
$$\omega/m < \Omega \implies |A_f|^2 > |A_i|^2$$

Superradiant scattering of classical **bosonic** waves ⟹ **Extraction** of energy and angular momentum from the black hole

Black-hole bombs

Press & Teukolsky, ’72; Cardoso *et al* ‘04

Confinement + Superradiance → Superradiant instability



Spinning black holes surrounded by a reflecting mirror are **unstable** against bosonic radiation with frequency:

$$\omega/m < \Omega_H$$

Massive bosonic fields around spinning BHs

Damour '76; Gaina '78; Zouros & Eardley '79; Detweiler '80; Dolan '07; Rosa & Dolan '12; Pani *et al* '12; RB, Cardoso & Pani '13; Baryakthar, Lasenby & Teo '17; East '17; Cardoso *et al* '18; Frolov *et al* '18; Dolan '18; Baumann et al '19; RB, Grillo & Pani '20…

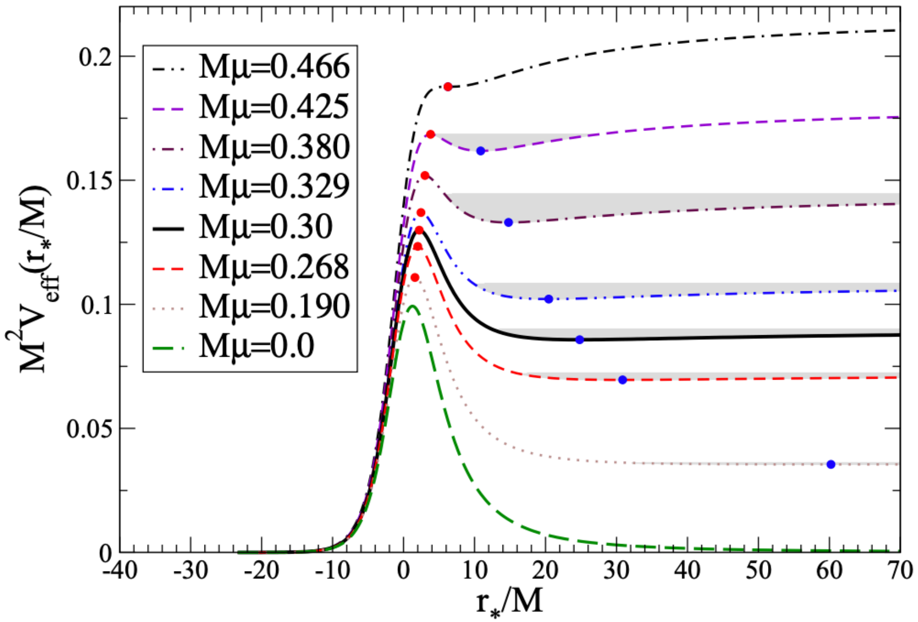
Massive bosonic fields naturally confine waves with frequency $\omega < \mu$.

$$M\mu = \frac{M m_b}{M_{\rm Pl}^2} = R_G/\lambda_C$$

$$\nabla_\mu \nabla^\mu \Phi = \mu^2 \Phi \qquad (\mu \equiv m_b/\hbar)$$

$$\Phi = \Re\left(\frac{\Psi(r)}{r} S_{\ell m\omega}(\theta) e^{-i\omega t + im\varphi}\right)$$

$$\frac{d\Psi}{dr_*^2} + (\omega^2 - V_{\rm eff})\Psi = 0\,, \qquad V_{\rm eff}(r\to\infty) = \mu^2$$



From: Barranco *et al*' 11, PRD84, 083008 (2011)

A (macroscopic) **"gravitational atom"** but with some big differences when compared to the hydrogen atom:

i) **boundary conditions** at the horizon: horizon act as a dissipative membrane

ii) **no Pauli exclusion principle** for bosons

Massive bosonic fields around spinning BHs

Damour ’76; Gaina ’78; Zouros & Eardley ’79; Detweiler ’80; Dolan ’07; Rosa & Dolan ’12; Pani *et al* ‘12; RB, Cardoso & Pani ’13; Baryakthar, Lasenby & Teo ’17; East ’17; Cardoso *et al* ’18; Frolov *et al* ’18; Dolan ’18; Baumann et al ’19; RB, Grillo & Pani ’20…

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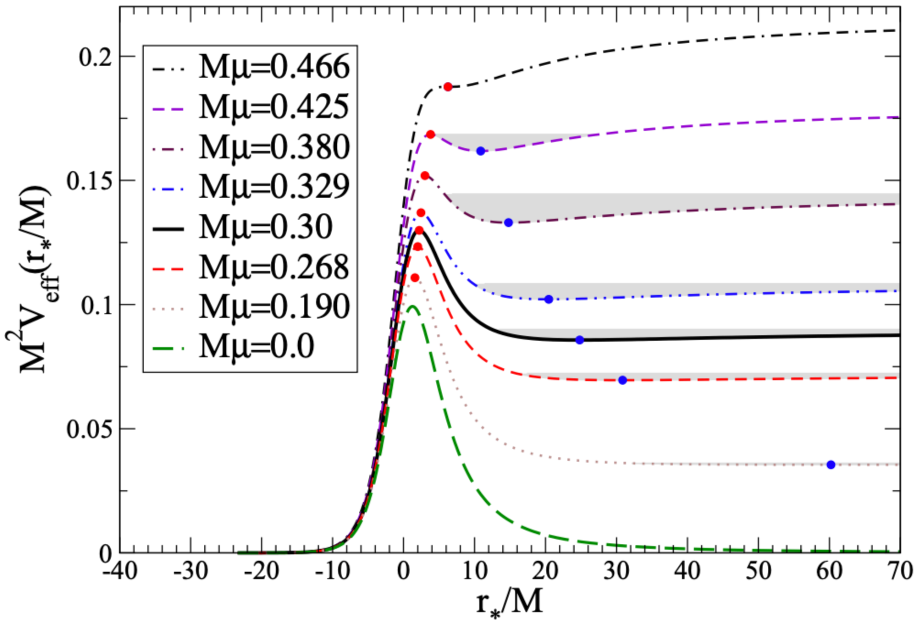


From: Barranco *et al*’ 11, PRD84, 083008 (2011)

$$\omega \equiv \omega_{nlm} + i\Gamma_{nlm}$$

$$\omega_{nlm} \simeq \mu\left(1 - \frac{\alpha^2}{2n^2}\right) + \Delta\omega_{nlm}$$

$$\Gamma_{n\ell m} = \frac{2r_+}{M} C_{n\ell m}(\alpha)\,(m\Omega_{\rm H} - \omega)\,\alpha^{4\ell+5}$$

$$\alpha \equiv M\mu$$

Superradiant instability of massive bosonic fields

Damour '76; Gaina '78; Zouros & Eardley '79; Detweiler '80; Dolan '07; Rosa & Dolan '12; Pani *et al* '12; RB, Cardoso & Pani '13; Baryakthar, Lasenby & Teo '17; East '17; Cardoso *et al* '18; Frolov *et al* '18; Dolan '18; Baumann et al '19; RB, Grillo & Pani '20…

Spinning black holes perturbed by massive bosons can become **unstable** on quite short timescales:

Scalar fields:
$(\nabla_\mu \nabla^\mu \Phi = \mu^2 \Phi)$

$$\tau_{\rm inst}^{\rm spin\,0} \approx 30\,{\rm days}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^9\left(\frac{0.9}{\chi}\right)$$

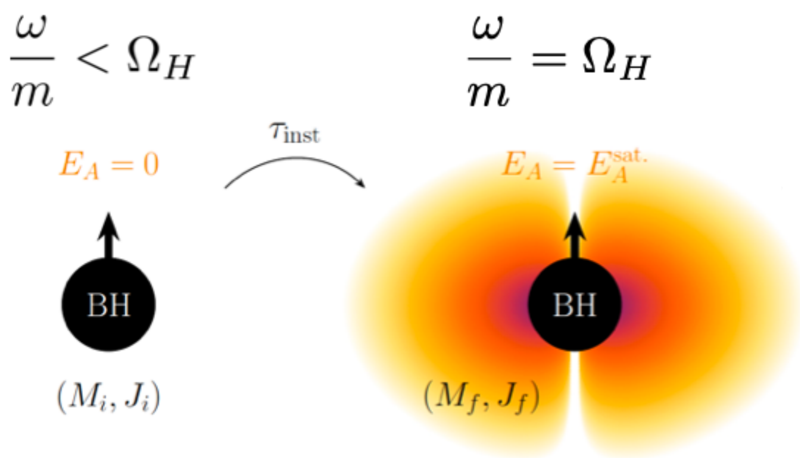
Vector fields:
$(\nabla_\mu F^{\mu\nu} = \mu^2 A^\nu)$

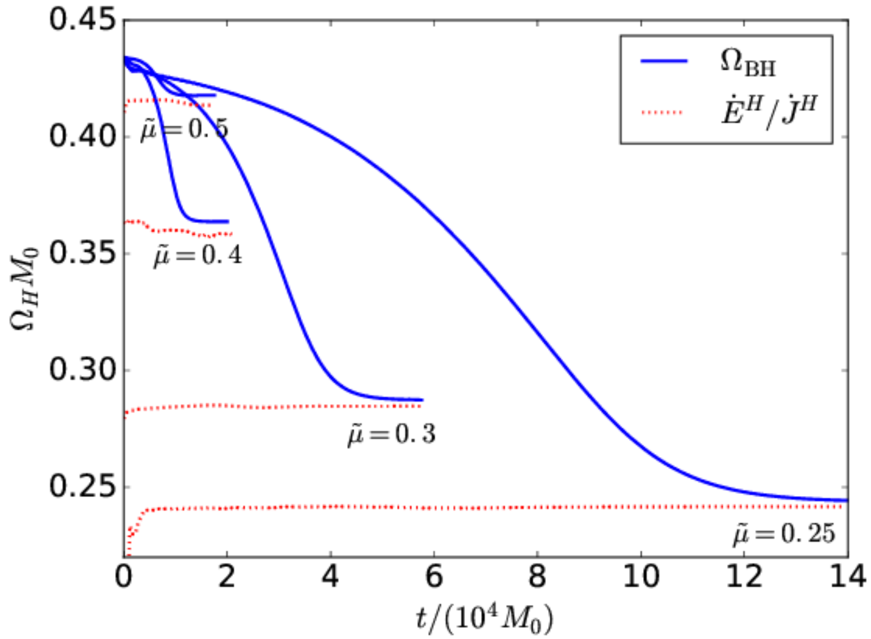
$$\tau_{\rm inst}^{\rm spin\,1} \approx 280\,{\rm s}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^7\left(\frac{0.9}{\chi}\right)$$

$$M\mu \sim 0.1\left(\frac{M}{10M_\odot}\right)\left(\frac{m_b c^2}{10^{-12}{\rm eV}}\right)M_{\rm Pl}^{-2}$$

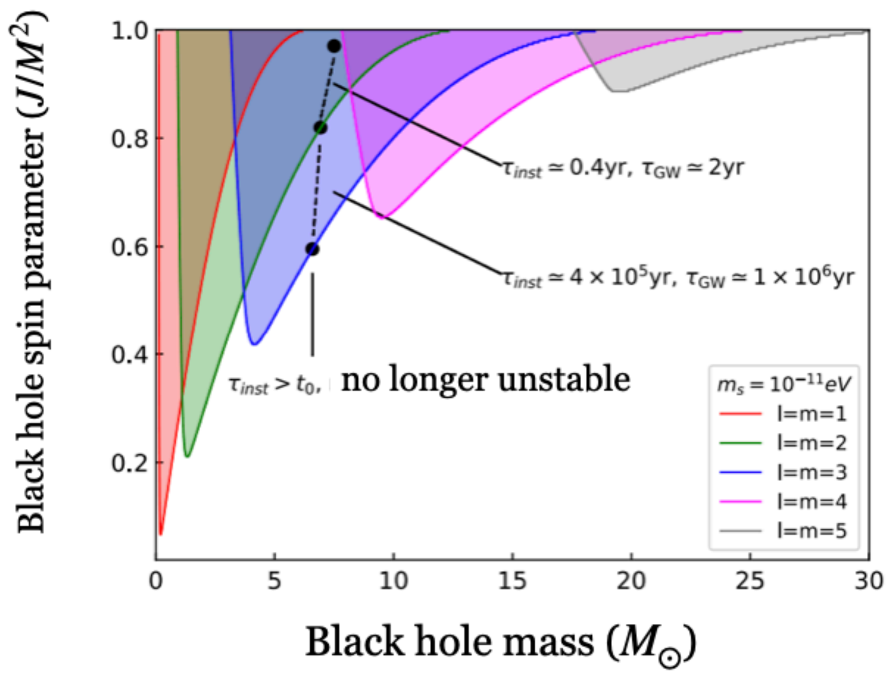
Evolution of the superradiant instability

What happens to a spinning black hole if slightly perturbed by a massive boson field?

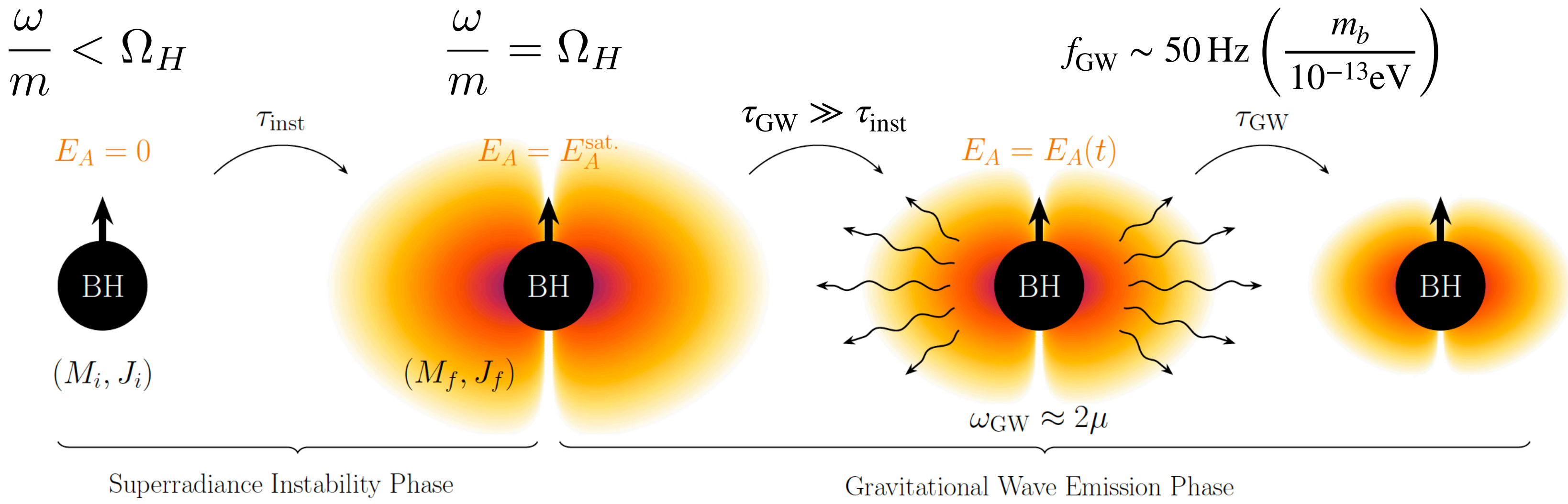




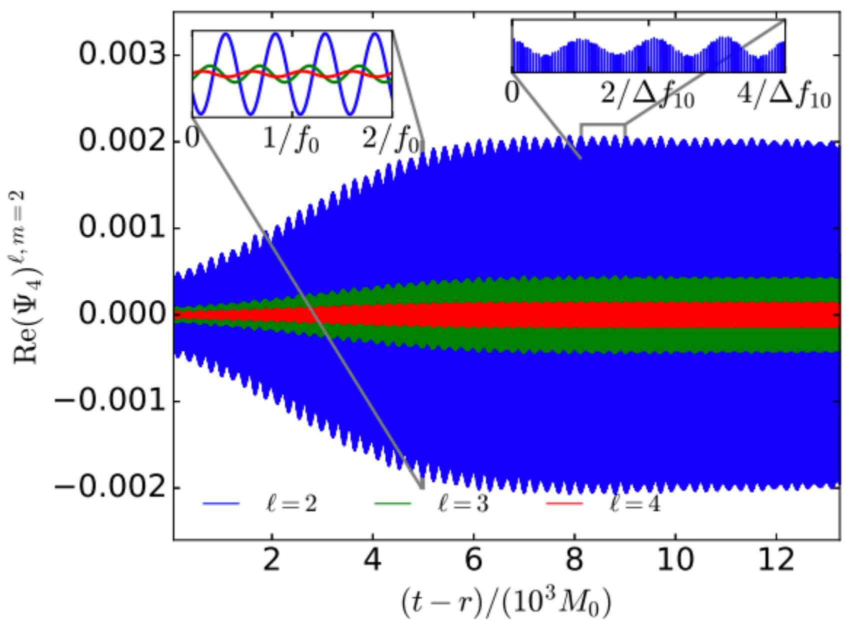
From: East, PRL121, 131104 (2018)



GW emission from the boson cloud



From: East, PRL121, 131104 (2018)



$$\dot{M}_{\rm cloud} \approx -dE_{\rm GW}/dt \implies M_{\rm cloud} = \frac{M_{\rm cloud}^{\rm sat.}}{1 + t/\tau_{\rm GW}}$$

$$\chi \equiv J/M^2$$

$$\tau_{\rm GW}^{\rm spin\,0} \approx 10^5\,{\rm yr}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^{15}\left(\frac{0.5}{\chi_i - \chi_f}\right)$$

$$\tau_{\rm GW}^{\rm spin\,1} \approx 2\ {\rm days}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^{11}\left(\frac{0.5}{\chi_i - \chi_f}\right)$$

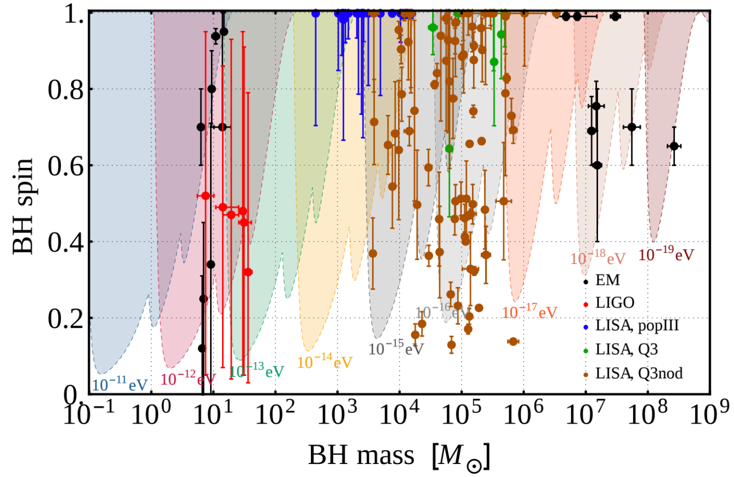
scalars: Yoshino & Kodama '14; RB *et al* '17
vectors: Baryakthar *et al* '17; Siemonsen & East '20

https://github.com/maxisi/gwaxion
https://github.com/richbrito/gw_superradiance

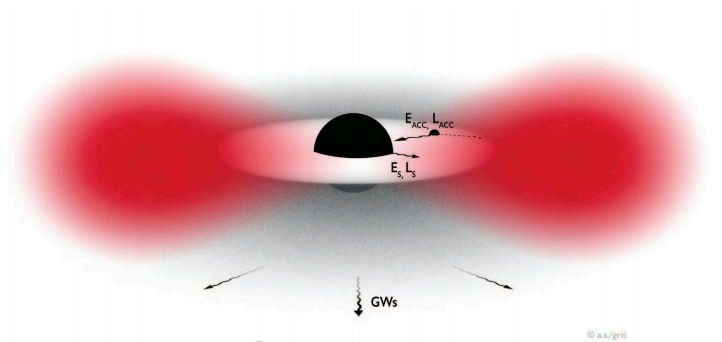
Observables

❖ Indirect constraints through **black hole mass & spin measurements**

From: RB *et al*, PRD96 (2017) 6, 064050

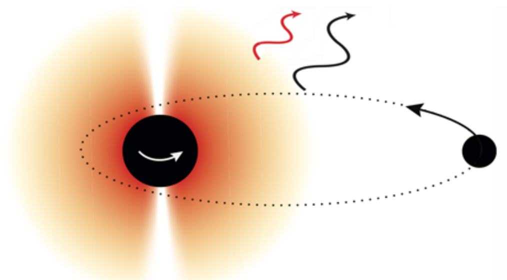


❖ **Direct emission** of continuous gravitational waves from the boson cloud



Credit: Ana Sousa/GRIT

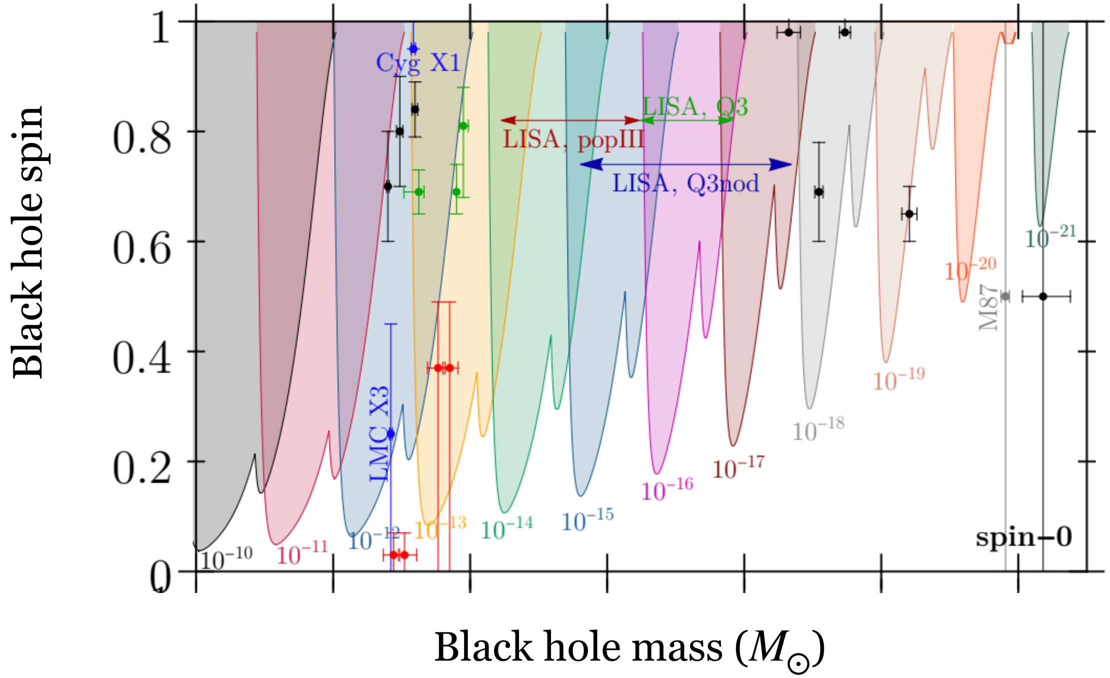
❖ Signatures in **binary systems**: cloud depletion, resonances, dynamical friction, tidal Love numbers, multipolar structure…



Credit: D. Baumann/University of Amsterdam

“Gaps” in the BH mass-spin distribution

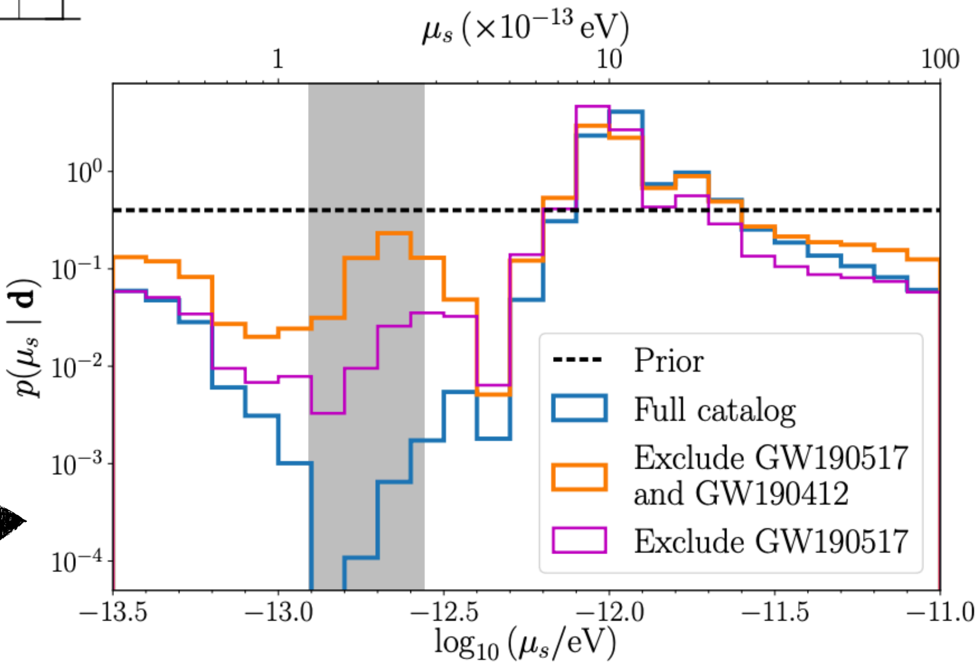
Arvanitaki *et al* ’09; Arvanitaki & Dubovsky ’10; Arvanitaki, Baryakthar & Huan ’15; Pani *et al* ‘12; Baryakthar, Lasenby & Teo ’17; RB *et al* ’17; Cardoso et al ’18; RB, Grillo & Pani ’20; Stott ’20; K. Ng *et al* ’21,…



Lack of highly spinning black holes in particular mass ranges.

BH spin measurements allow to impose constraints on ultralight bosons.

Constraints with GWTC-2 →

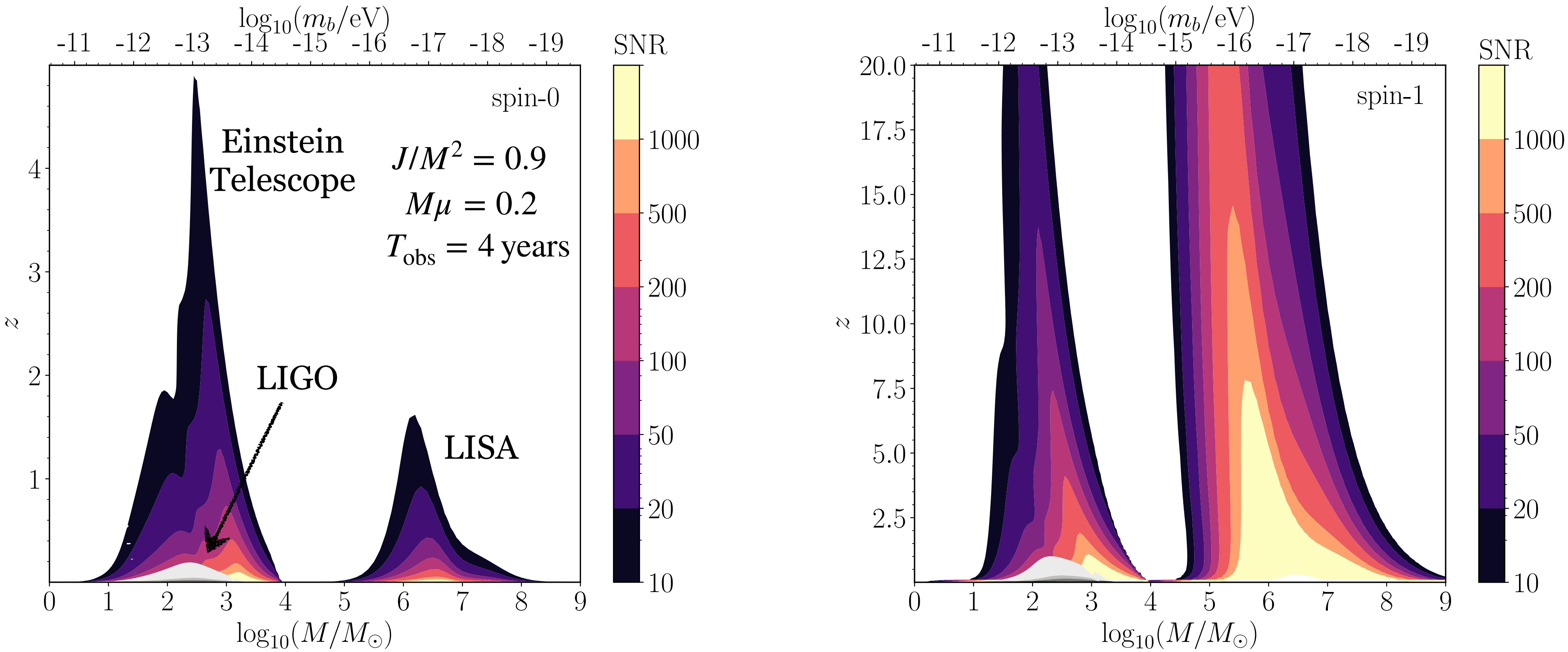


From: K. K. Y. Ng *et al*, PRL 126 (2021), 151102

Direct gravitational-wave searches

Arvanitaki *et al*'09; Yoshino & Kodama '14; Arvanitaki, Baryakhtar & Huang, '15; RB *et al '17;*
Baryakthar, Lasenby & Teo '17; Siemonsen & East '20; RB, Grillo & Pani '20, Zhu *et al* '20...

Bosonic cloud emits **nearly monochromatic long-lived gravitational waves** which could be directly detected.

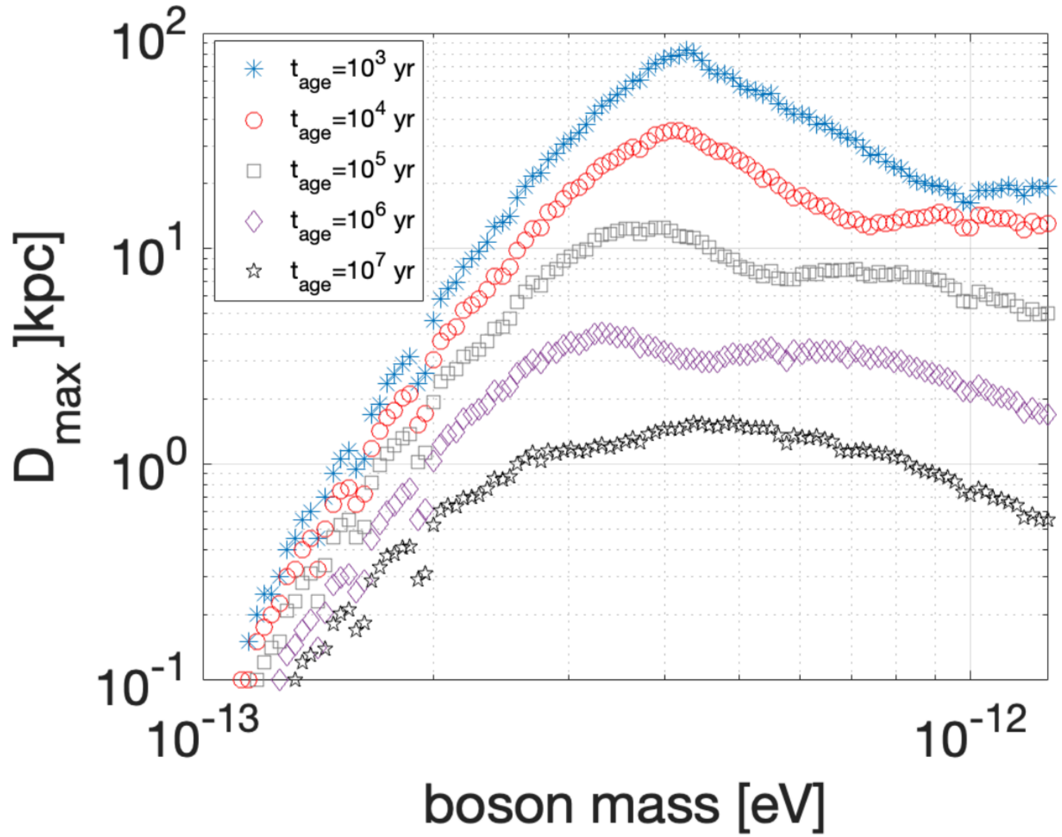


Blind all-sky searches

Arvanitaki, Baryakhtar & Huang, '15; RB *et al* '17; Baryakthar, Lasenby & Teo '17
Palomba *et al*'19; Zhu *et al* '20; LVK '21

- **All-sky "blind" searches** could reveal the presence of a boson cloud around a black hole emitting gravitational waves.

Constraints with LIGO O3



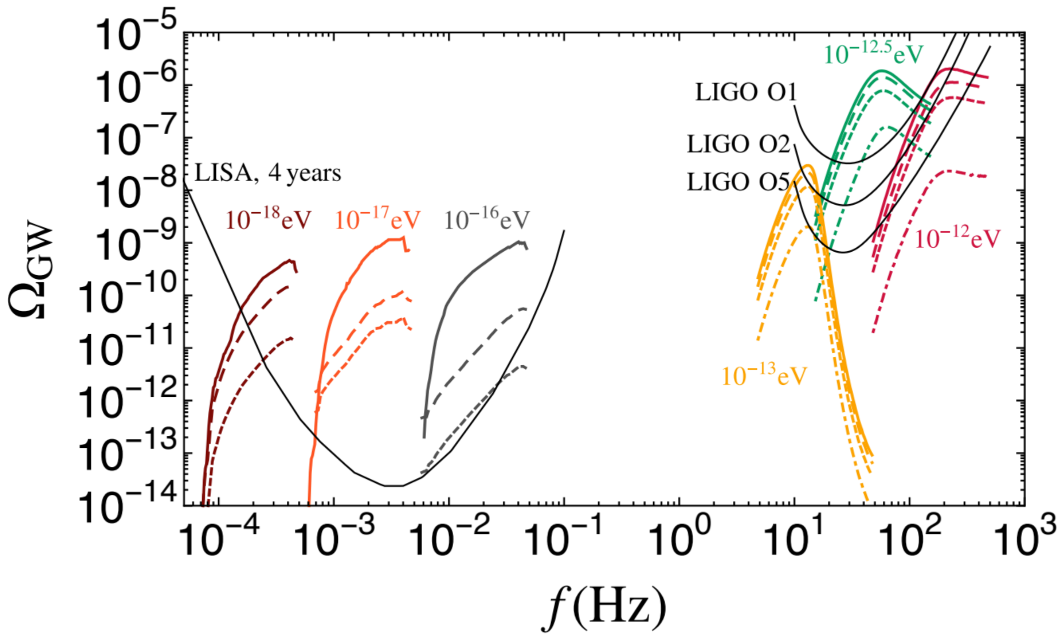
From: LVK Collaboration, arXiv: 2111.15507

Stochastic GW background

RB *et al*, '17; Tsukada *et al* '18-20; Chen, RB & Cardoso '21; Chen, Jiang & Q.-G. Huang '22

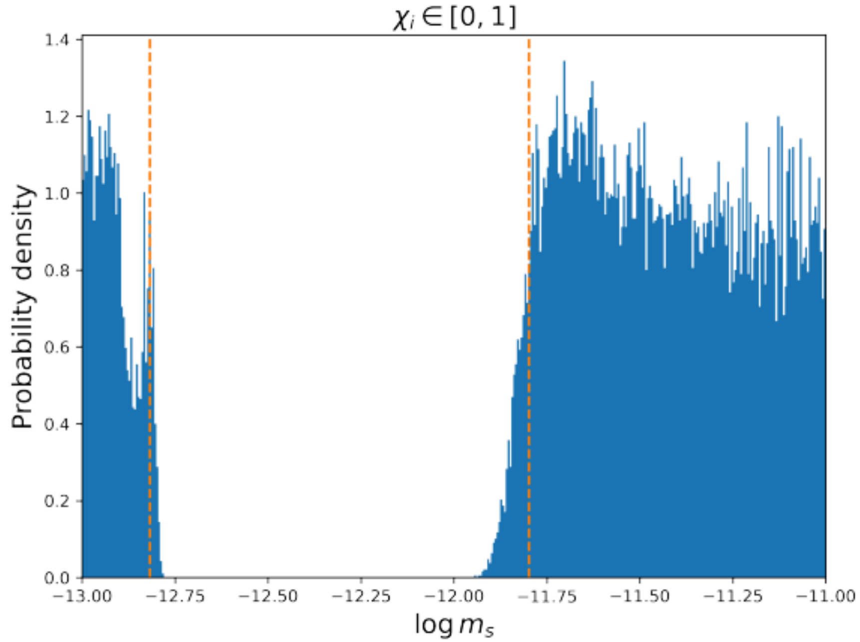
The existence of many unresolved sources can produce a **large stochastic background** of gravitational waves.

From: RB *et al* PRL119 (2017) 13, 131101



(Different line types correspond to different assumptions about black hole population)

From: Chen *et al* arXiv:2204.03482



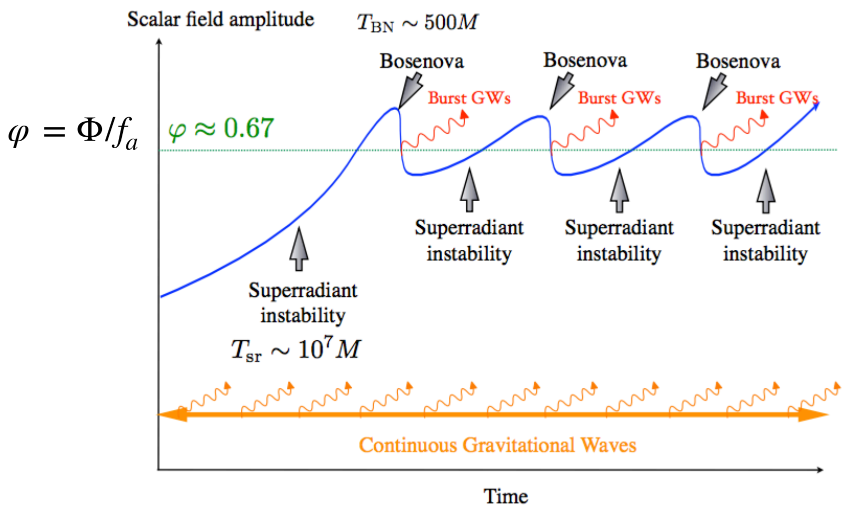
Constraints with LIGO (O1+O2+O3)

Impact of non-gravitational interactions?

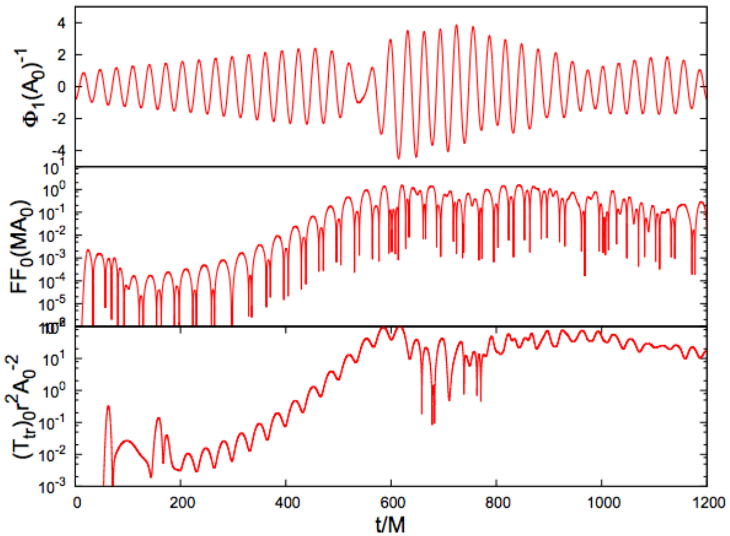
Yoshino & Kodama ’12, Ikeda, RB, Cardoso ’19; Rosa & Kephart ’18; Boskovic *et al* ’19; Fukuda & Nakayama ’19; Baryakhtar *et al* ’20; Omiya *et al* ’20; Omiya *et al* ’2022; Caputo, Witte, Blas & Pani ’21; East ‘22

$$\Box\Phi - \mu^2 f_a \sin(\Phi/f_a) = 0$$

$$\left(\nabla^\mu\nabla_\mu - \mu^2\right)\Phi = \frac{k_{\rm axion}}{2}\,{}^*F^{\mu\nu}F_{\mu\nu}$$
$$\nabla^\nu F_{\mu\nu} = -2k_{\rm axion}\,{}^*F_{\mu\nu}\nabla^\nu\Phi\,.$$



From: Yoshino & Kodama, PTEP (2015) 061E01



Ikeda, RB, Cardoso ’19

- Large enough non-gravitational interactions can quench the growth of the boson cloud and/or strongly slow down black hole spin down.
- Does a bosenova for self-interacting scalar fields ever happen? Baryakhtar *et al* ’20
- Impact of plasma and environment around black holes?

Sen ’18; Boskovic *et al* ’19; Caputo *et al* ‘21

Take-home message

Black-hole superradiance provides an interesting portal to search for ultralight particles with **black-hole** and **gravitational-wave** observations.

	excluded region (in eV)	source	references
*	$5.2 \times 10^{-13} < m_S < 6.5 \times 10^{-12}$	Direct bounds from absence of spin down in Cyg X-1.	[125, 477]
*	$1.1 \times 10^{-13} < m_V < 8.2 \times 10^{-12}$		
*	$2.9 \times 10^{-13} < m_T < 9.8 \times 10^{-12}$		
	$3.8 \times 10^{-14} < m_S < 2 \times 3.4 \times 10^{-11}$	Indirect bounds from BH mass-spin measurements.	[103, 11, 12, 124]
	$5.5 \times 10^{-20} < m_S < 1.3 \times 10^{-16}$		
	$2.5 \times 10^{-21} < m_S < 1.2 \times 10^{-20}$		
	$6.2 \times 10^{-15} < m_V < 3.9 \times 10^{-11}$		[128, 636, 125, 477, 714, 715]
	$2.8 \times 10^{-22} < m_V < 1.9 \times 10^{-16}$		
	$2.2 \times 10^{-14} < m_T < 2.8 \times 10^{-11}$		
	$1.8 \times 10^{-20} < m_T < 1.8 \times 10^{-16}$		
	$6.4 \times 10^{-22} < m_T < 7.7 \times 10^{-21}$		
	$1.2 \times 10^{-13} < m_S < 1.8 \times 10^{-13}$	Null results from blind all-sky searches for continuous GW signals.	[133, 136]
	$2.0 \times 10^{-13} < m_S < 2.5 \times 10^{-12}$		
	m_V: NA		
	m_T: NA		
	$6.4 \times 10^{-13} < m_S < 8.0 \times 10^{-13}$	Null results from searches for continuous GW signals from Cygnus X-1.	[135, 531]
	m_V: NA		
	m_T: NA		
	$2.0 \times 10^{-13} < m_S < 3.8 \times 10^{-13}$	Negative searches for a GW background.	[127, 128, 129, 684]
	0.8×10^{-13} eV $< m_V < 6.0 \times 10^{-13}$ eV		
	m_T: NA		
	$5 \times 10^{-13} < m_S < 3 \times 10^{-12}$	Bounds from pulsar timing.	[123, 277]
	$m_V \sim 10^{-12}$		
	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.	[637, 714]
	$8.5 \times 10^{-22} < m_V < 4.6 \times 10^{-21}$		
	$7.2 \times 10^{-22} < m_T < 2.5 \times 10^{-20}$		

RB, Cardoso & Pani “Superradiance” Lect. Notes Phys. 971 (2020)
https://centra.tecnico.ulisboa.pt/network/grit/files/superradiantbounds

Thank you!

Backup slides

Useful scales

Instability timescale:

$$\tau_{\rm inst}^{\rm scalar} \approx 30\,\text{days}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^9\left(\frac{0.9}{\chi}\right), \quad \tau_{\rm inst}^{\rm vector} \approx 280\,\text{s}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^7\left(\frac{0.9}{\chi}\right)$$

GW emission timescale:

$$\tau_{\rm GW}^{\rm scalar} \approx 10^5\,\text{yr}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^{15}\left(\frac{0.5}{\chi_i-\chi_f}\right), \qquad \tau_{\rm GW}^{\rm vector} \approx 2\,\text{days}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^{11}\left(\frac{0.5}{\chi_i-\chi_f}\right)$$

GW strain:

$$h_+(t) \approx \frac{1}{2(1+t/t_{\rm GW})}h_0(1+\cos^2\iota)\cos\left(2\pi f_{\rm GW}t+\phi\right), \quad h_\times(t) \approx \frac{1}{1+t/t_{\rm GW}}h_0\cos\iota\sin\left(2\pi f_{\rm GW}t+\phi\right)$$

$$h_0^{\rm scalar} \approx 5\times10^{-27}\left(\frac{M}{10M_\odot}\right)\left(\frac{M\mu}{0.1}\right)^7\left(\frac{\rm Mpc}{d}\right)\left(\frac{\chi_i-\chi_f}{0.5}\right), \quad h_0^{\rm vector} \approx 10^{-23}\left(\frac{M}{10M_\odot}\right)\left(\frac{M\mu}{0.1}\right)^5\left(\frac{\rm Mpc}{d}\right)\left(\frac{\chi_i-\chi_f}{0.5}\right)$$

Frequency derivative:

$$\dot f_{\rm GW}^{\rm scalar}(t) \approx 5\times10^{-15}\,\text{Hz/s}\left(\frac{M\mu}{0.1}\right)^{19}\left(\frac{10M_\odot}{M}\right)^2\left(\frac{\chi_i-\chi_f}{0.5}\right)^2\left(\frac{M_{\rm cloud}(t)}{M_{\rm cloud}^{\rm sat}}\right)^2$$

$$\dot f_{\rm GW}^{\rm vector}(t) \approx 10^{-7}\,\text{Hz/s}\left(\frac{M\mu}{0.1}\right)^{15}\left(\frac{10M_\odot}{M}\right)^2\left(\frac{\chi_i-\chi_f}{0.5}\right)^2\left(\frac{M_{\rm cloud}(t)}{M_{\rm cloud}^{\rm sat}}\right)^2$$

Computation of the GW signal in practice

Arvanitaki *et al*'09; Yoshino & Kodama '14; Arvanitaki, Baryakhtar & Huang, '15; RB *et al '17;* Baryakthar, Lasenby & Teo '17; Siemonsen & East '20; RB, Grillo & Pani '20…

At any given time, backreaction of boson field on the geometry is **small**:

- Evolve system **adiabatically** (Brito, Cardoso & Pani '14);
- GW signal can estimated using **BH perturbation theory** (Yoshino & Kodama '14):

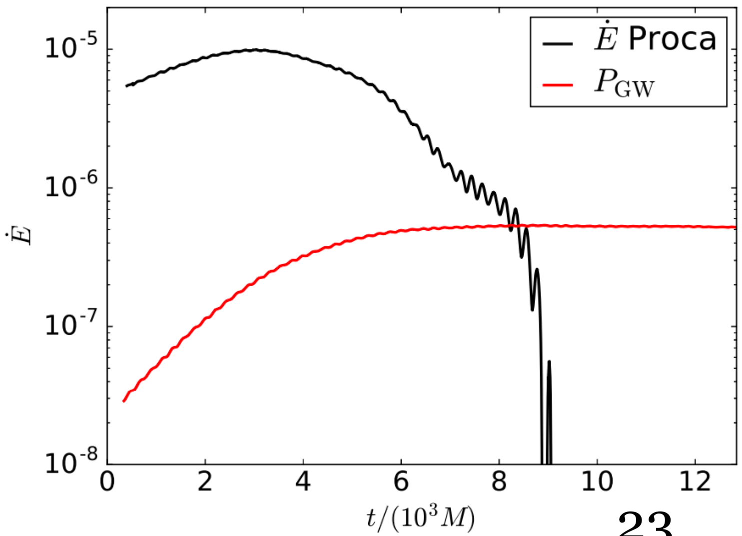
$$\Phi = \epsilon \Re \left(\phi_{lmn}(r) S_{lm}(\theta) e^{im\varphi} e^{i\omega_R t}\right) \qquad T_{\mu\nu} = -\frac{1}{2} g_{\mu\nu} \left(\Phi_{,\alpha}\Phi^{,\alpha} + \mu^2\Phi^2\right) + \Phi_{,\mu}\Phi_{,\nu}$$

$$\mathcal{O}(\epsilon): \ \Box^{(0)} \Phi^{(1)} = \mu^2 \Phi^{(1)}, \qquad \mathcal{O}(\epsilon^2): \ \mathcal{E}^{\rho\sigma}_{\mu\nu} h^{(2)}_{\rho\sigma} = T_{\mu\nu}[\Phi^{(1)}, \Phi^{(1)}]$$

$$\omega_R < m\Omega_H: \ \dot{E}_{\rm cloud} \approx 2\Gamma E_{\rm cloud} \implies E_{\rm cloud} \approx E_0 e^{2\Gamma t}$$

$$\omega_R = m\Omega_H: \dot{E}_{\rm cloud} \approx -P_{\rm GW} \implies E_{\rm cloud} = \frac{E^{\rm sat.}_{\rm cloud}}{1 + t/t_{\rm GW}}$$

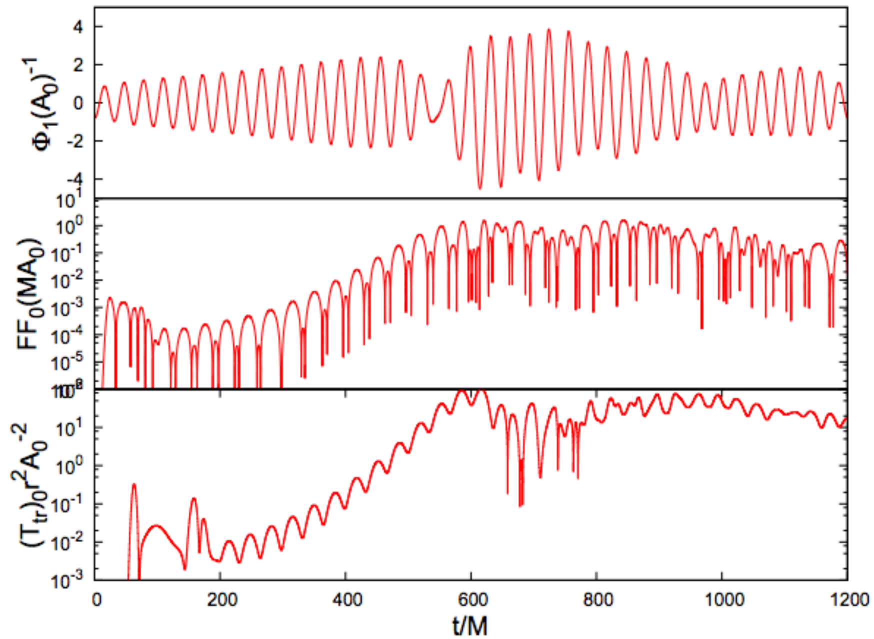
From: East, PRL121, 131104 (2018)



Coupling to photons

Rosa & Kephart '18; Ikeda, RB, Cardoso '18; Boskovic *et al* '18

$$\left(\nabla^\mu\nabla_\mu - \mu^2\right)\Phi = \frac{k_{\rm axion}}{2}\,{}^*F^{\mu\nu}F_{\mu\nu}$$
$$\nabla^\nu F_{\mu\nu} = -2k_{\rm axion}\,{}^*F_{\mu\nu}\nabla^\nu\Phi\,.$$



- Emitted EM radiation oscillates with frequency $\omega_{\rm EM} \sim \mu/2$

- Simulations indicate that EM field grows exponentially whenever:

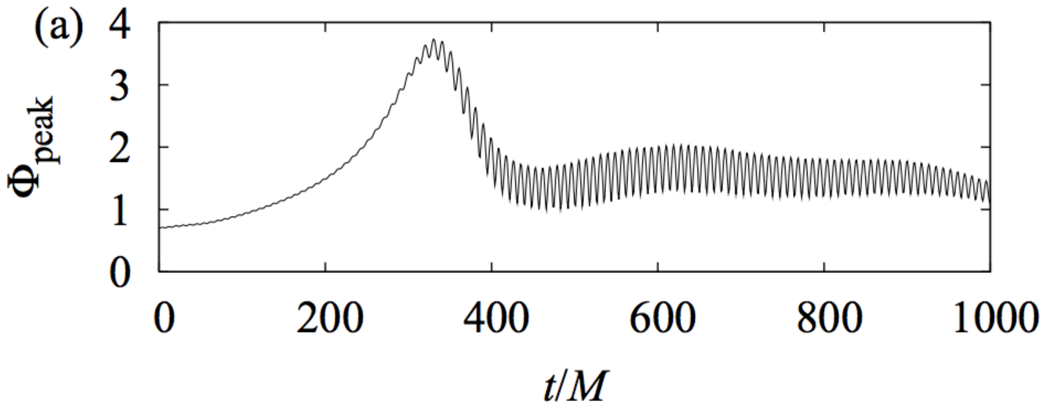
$$k_{axion}^{-1} \lesssim 10^{17}\left(\frac{M_S/M}{0.1}\right)^{1/2}\left(\frac{\mu M}{0.25}\right)^2 \text{GeV}$$

- Can be understood as a parametric resonance (as described by Mathieu's equation). Boskovic *et al* '18

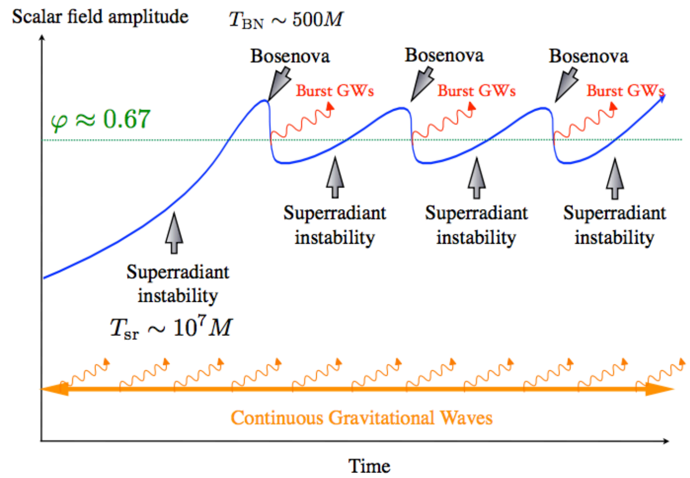
Self-interactions: bosenova

Yoshino & Kodama ’12

$$\Box\Phi - \mu^2 f_a \sin(\Phi/f_a) = 0$$



From: Yoshino & Kodama, Prog.Theor.Phys. 128 (2012) 153-190



From: Yoshino & Kodama, PTEP (2015) 061E01

- Simulations indicate that bosenova occurs when:

$$f_a \lesssim 10^{17} \left(\frac{M_S/M}{0.1}\right)^{1/2} \left(\frac{\mu M}{0.4}\right)^2 \text{GeV}$$

- In a nutshell: self-interactions and non-gravitational couplings may hinder the growth of the cloud above a critical amplitude.