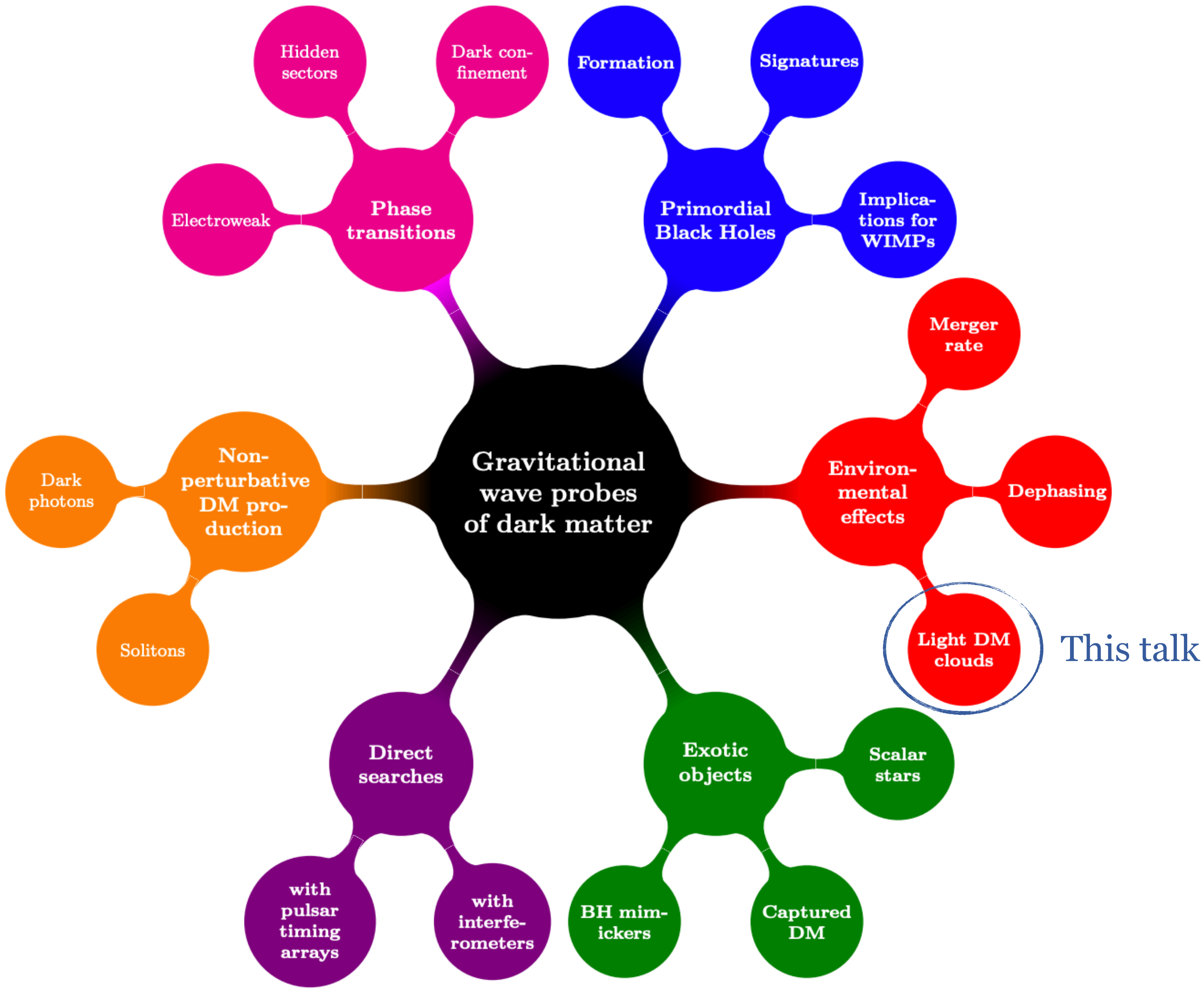
Probing ultralight bosons with black-hole superradiance:

Where do we stand and where do we go?

Richard Brito
CENTRA
Instituto Superior Técnico, Universidade de Lisboa

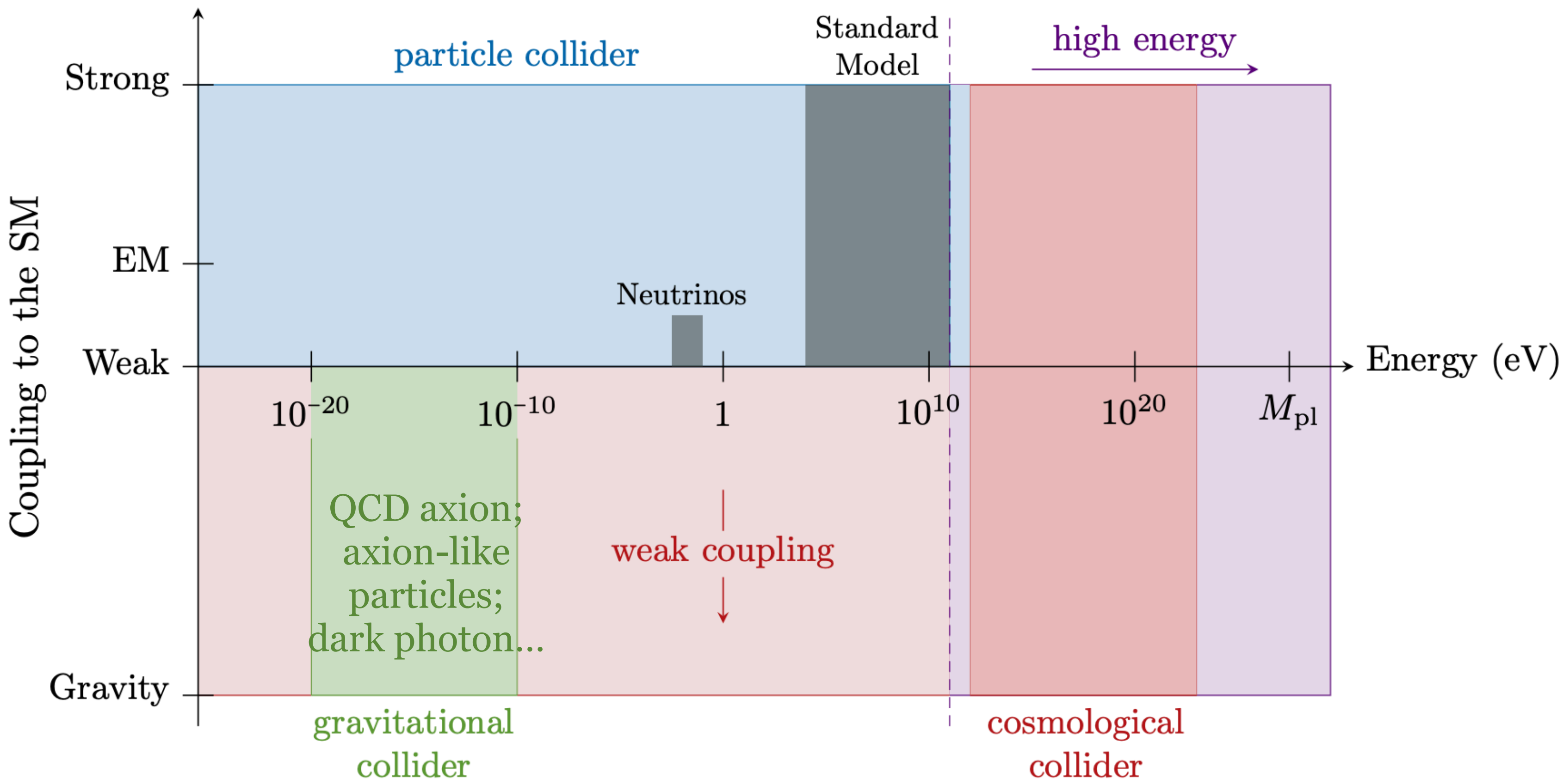
Gravitational wave probes of dark matter



From: Bertone *et al*, arXiv: 1907.10610

Ultralight bosons

$$\mathscr{L} = \frac{R}{16\pi} - \frac{1}{2}\nabla^\mu\Phi\nabla_\mu\Phi - \frac{\mu_S^2}{2}\Phi^2 - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{2}\mu_V^2 A_\nu A^\nu + \mathscr{L}_{\rm EH}(H) - \frac{\mu_T^2}{4}\left(H^{\mu\nu}H_{\mu\nu} - H^2\right)$$

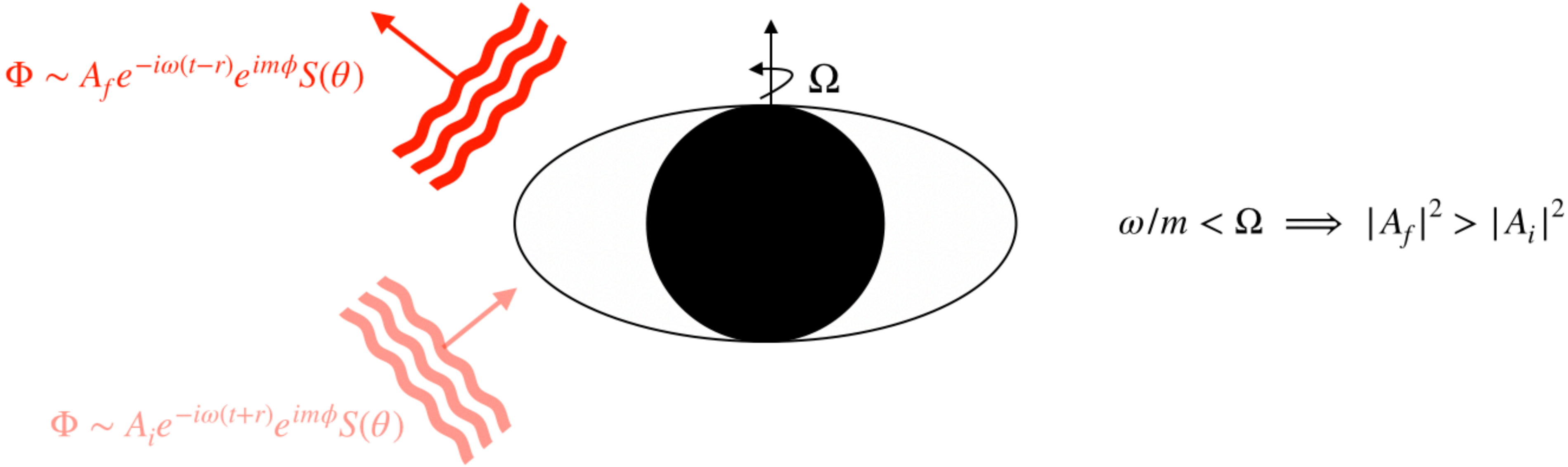


Adapted from: Baumann, Chia, Porto & Stout, PRD101, 083019 (2020)

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 black hole

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



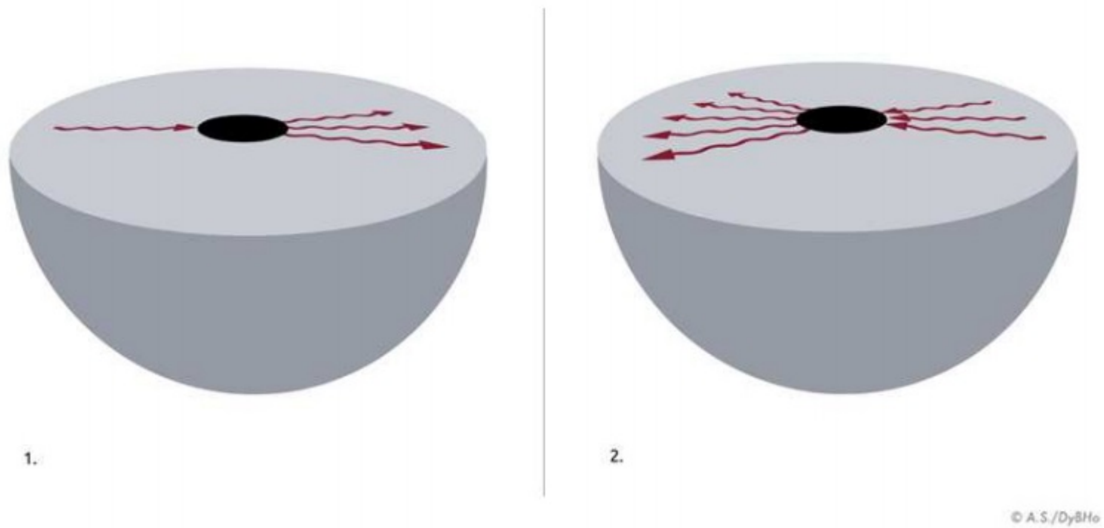
Superradiant scattering of classical **bosonic** waves ⟹ **Extraction** of energy and angular momentum from the black hole

Rotational energy can be extracted from spinning black holes.

Black-hole bombs

Press & Teukolsky, '72; Cardoso *et al* '04
Review: RB, Cardoso & Pani "Superradiance" Lect. Notes Phys. 971 (2020), 2nd ed.

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…

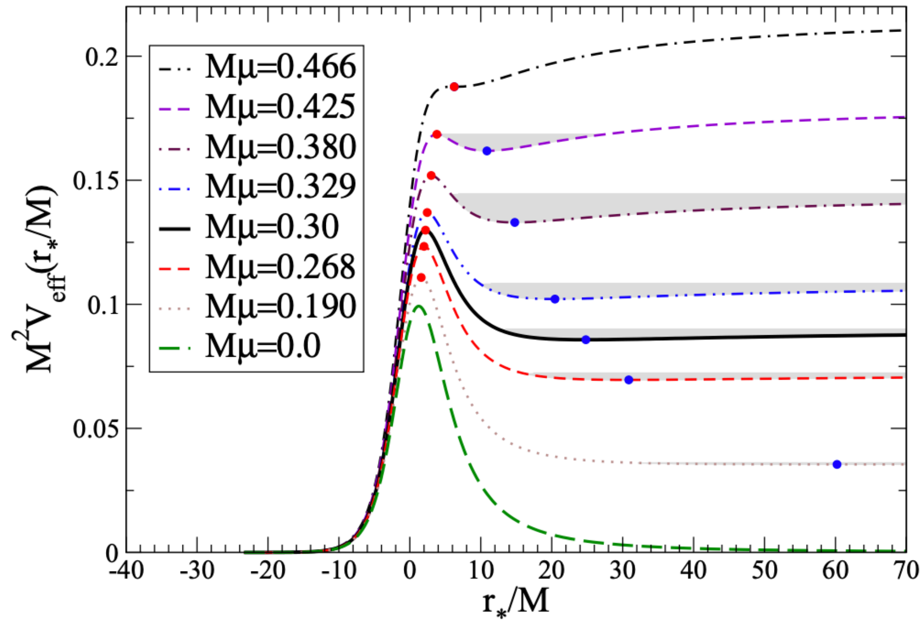
Massive bosonic fields naturally confine waves with frequency $\omega < \mu$.

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

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

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

$$\frac{d\Psi}{dr_*^2} + (\omega^2 - V_{\rm eff})\Psi = 0$$



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

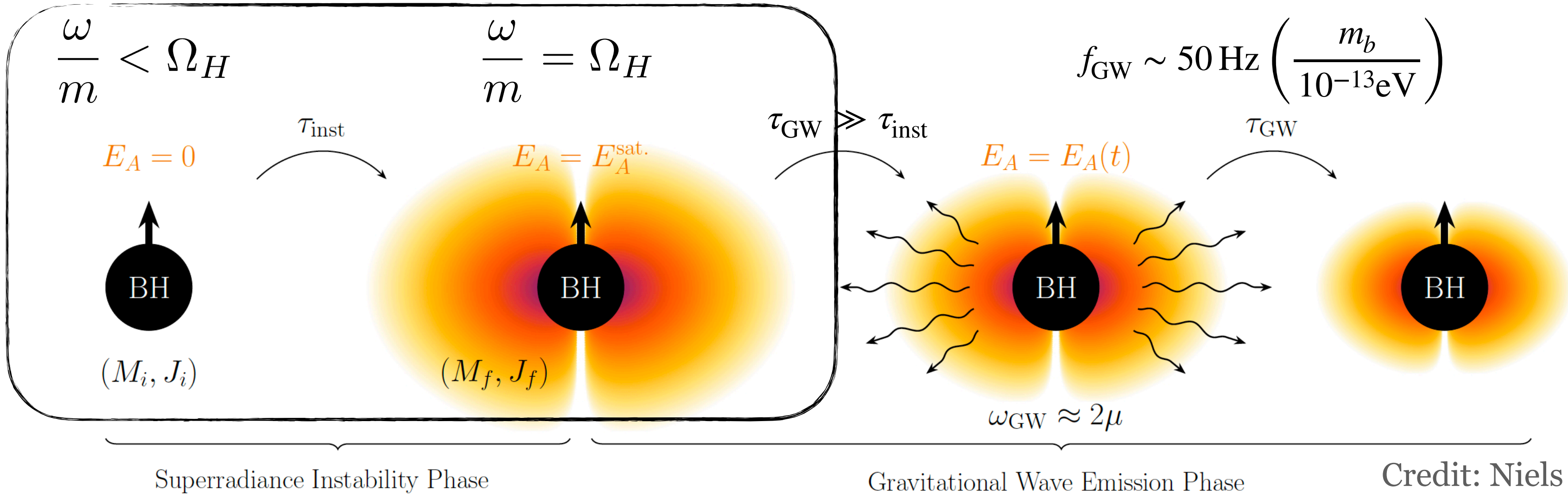
A (macroscopic) **"gravitational atom"** but with some big differences when compared to the hydrogen atom:

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

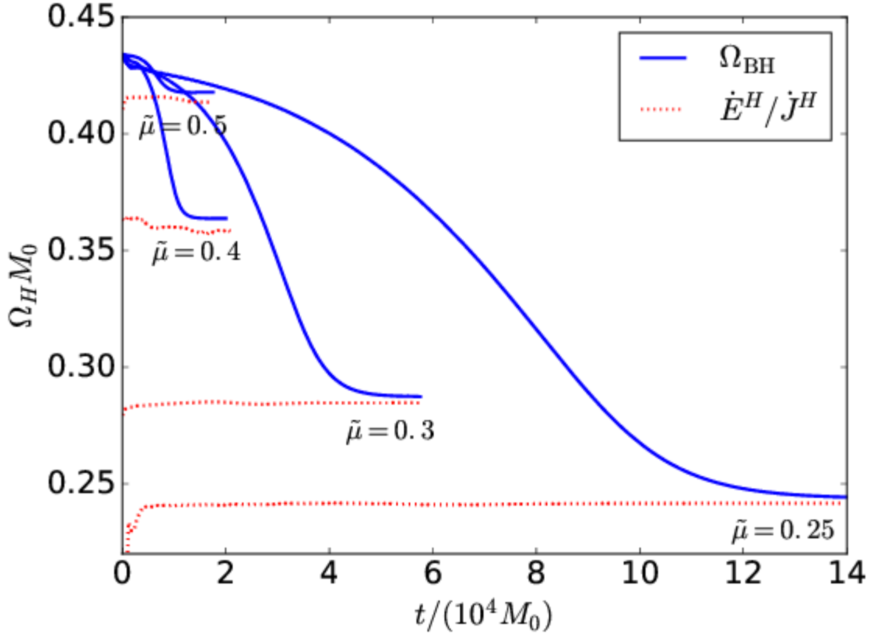
ii) depending on the BH spin, modes can either **decay** or grow **exponentially**

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

Evolution of the superradiant instability



Credit: Niels Siemonsen



From: East, PRL121, 131104 (2018)

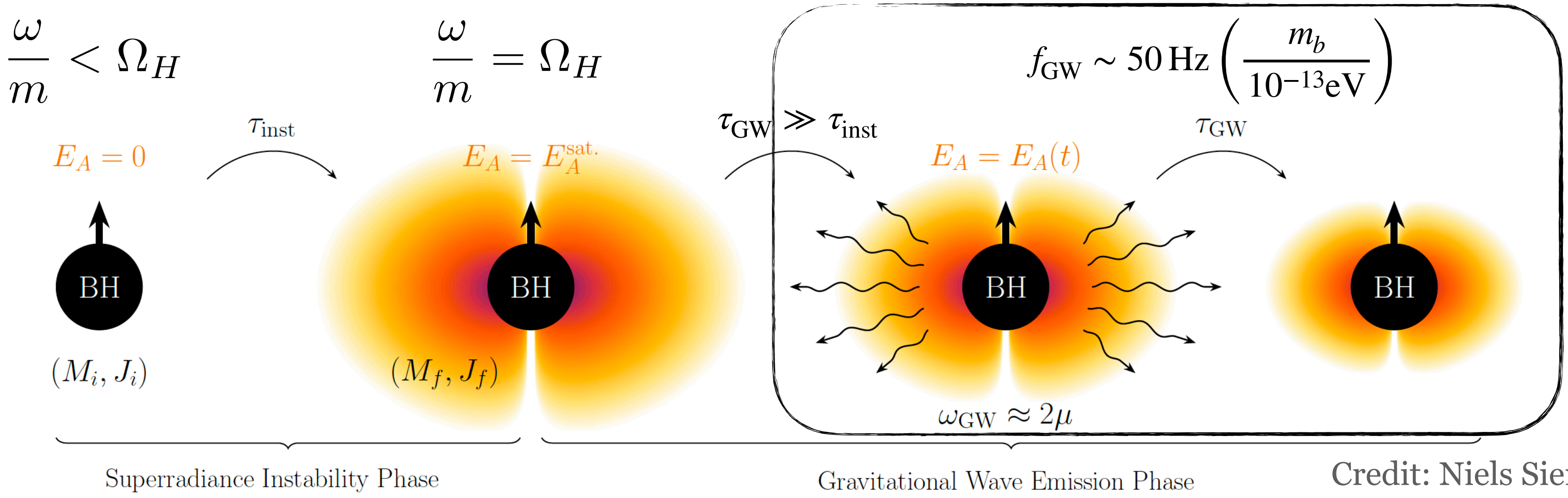
Massive scalar fields: $(\nabla_\mu \nabla^\mu \Phi = \mu^2 \Phi)$ $\quad \tau_{\rm inst}^{\rm spin\,0} \approx 30\,{\rm days}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^9\left(\frac{0.9}{J/M^2}\right)$

Massive vector fields: $(\nabla_\mu F^{\mu\nu} = \mu^2 A^\nu)$ $\quad \tau_{\rm inst}^{\rm spin\,1} \approx 280\,{\rm s}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^7\left(\frac{0.9}{J/M^2}\right)$

Open problem: superradiant instability of **massive tensors** for generic BH spins and generic $M\mu$ (estimates available for $J/M^2 \ll 1$ or $M\mu \ll 1$).

RB, Cardoso & Pani '13; RB, Grillo & Pani '20

Evolution of the superradiant instability



Credit: Niels Siemonsen

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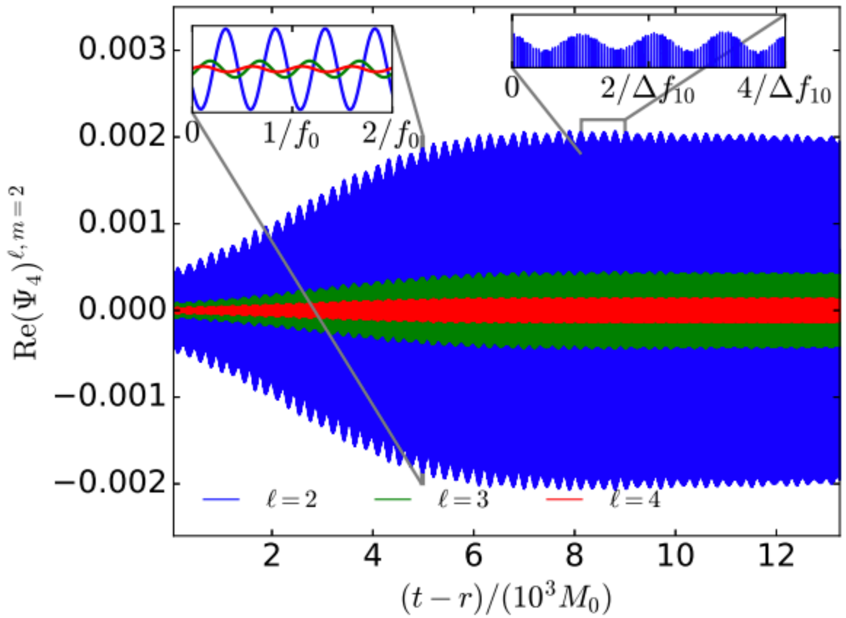


$$\dot{M}_{\rm cloud} \approx -dE_{\rm GW}/dt \implies M_{\rm cloud} = \frac{M_{\rm cloud}^{\rm sat.}}{1+t/\tau_{\rm GW}}$$

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

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

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

scalars: Yoshino & Kodama '14; RB *et al* '17
vectors: Baryakthar *et al* '17; Siemonsen & East '20
Tensors (for $M\mu \ll 1$): RB, Grillo & Pani '20

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

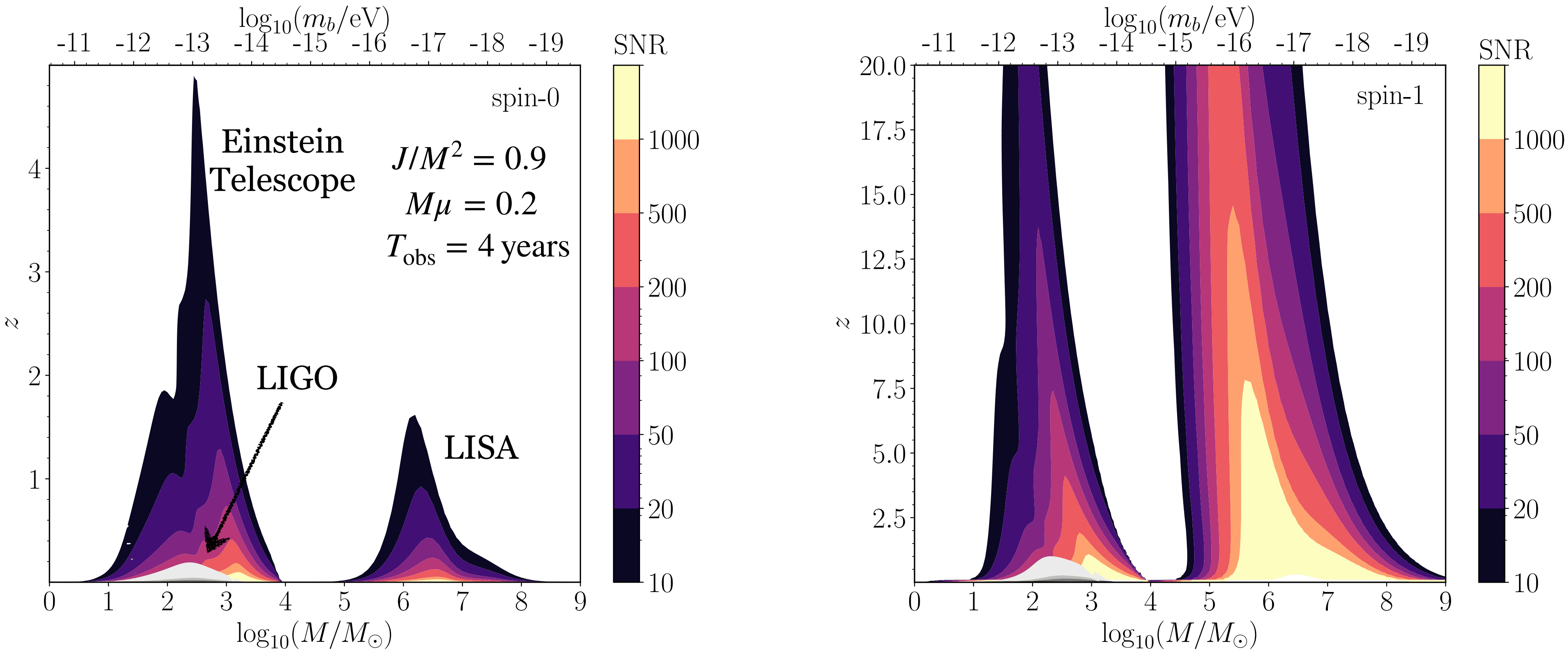
Direct gravitational-wave searches

Arvanitaki, Baryakhtar & Huang, '15; Arvanitaki *et al* '16; RB *et al '17;* Baryakthar, Lasenby & Teo '17; Isi *et al* '19; Ghosh *et al,* '19*;* Sun, RB & Isi '20; RB, Grillo & Pani '20, Zhu *et al* '20, Palomba *et al*'19; Zhu *et al* '20*;* LVK '21

Bosonic clouds emit **nearly monochromatic long-lived gravitational waves** which could be directly detected.

(For latest search in LIGO O3 data see: LVK Collaboration, arXiv: 2111.15507)

See also Piccinni's talk

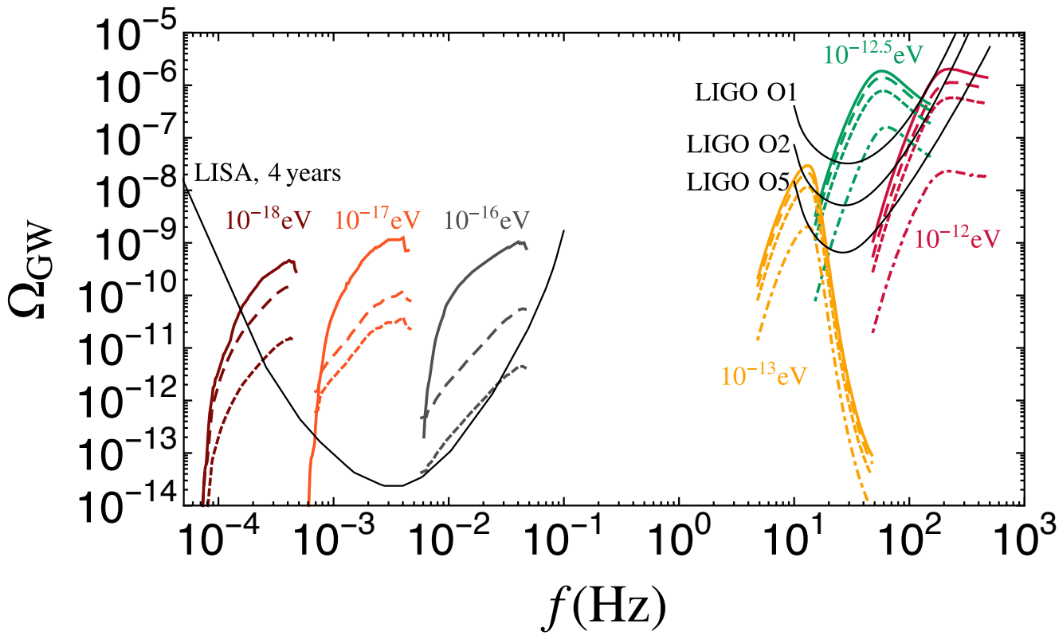


Stochastic GW background

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

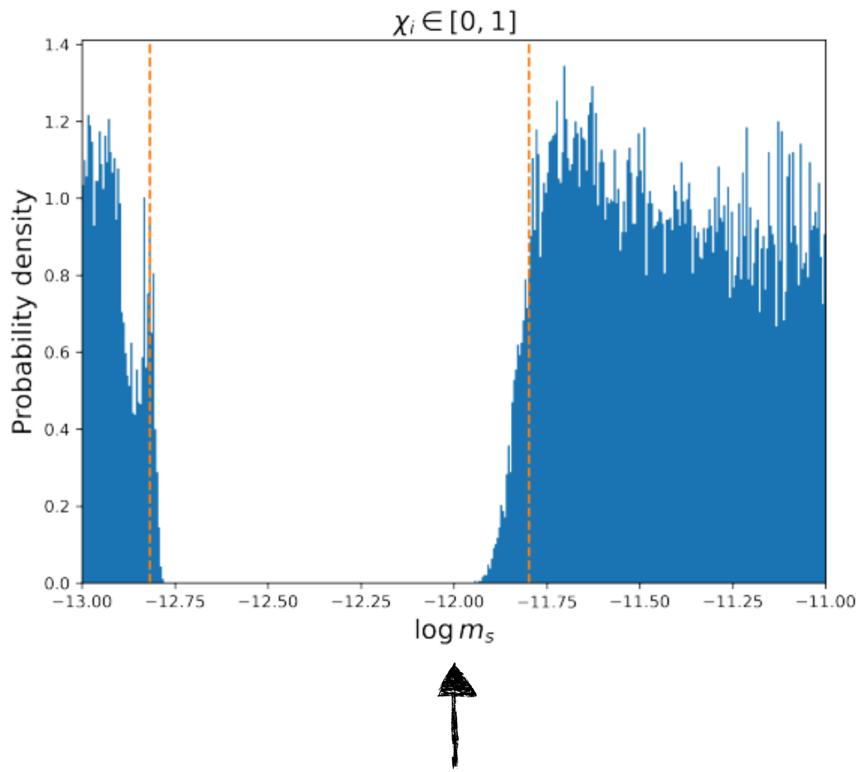
The existence of many unresolved sources can produce a **large stochastic background** of gravitational waves.

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)

Observational bounds so far

	excluded region (in eV)	source	references
*	$5.2\times10^{-13} < m_S < 6.5\times10^{-12}$	Direct bounds from absence of spin down in Cyg X-1.	[125, 477]
*	$1.1\times10^{-13} < m_V < 8.2\times10^{-12}$		
*	$2.9\times10^{-13} < m_T < 9.8\times10^{-12}$		
	$3.8\times10^{-14} < m_S < 2\times3.4\times10^{-11}$	Indirect bounds from BH mass-spin measurements.	[103, 11, 12, 124]
	$5.5\times10^{-20} < m_S < 1.3\times10^{-16}$		
	$2.5\times10^{-21} < m_S < 1.2\times10^{-20}$		
	$6.2\times10^{-15} < m_V < 3.9\times10^{-11}$		[128, 636, 125, 477, 714, 715]
	$2.8\times10^{-22} < m_V < 1.9\times10^{-16}$		
	$2.2\times10^{-14} < m_T < 2.8\times10^{-11}$		
	$1.8\times10^{-20} < m_T < 1.8\times10^{-16}$		
	$6.4\times10^{-22} < m_T < 7.7\times10^{-21}$		
	$1.2\times10^{-13} < m_S < 1.8\times10^{-13}$	Null results from blind all-sky searches for continuous GW signals.	[133, 136]
	$2.0\times10^{-13} < m_S < 2.5\times10^{-12}$		
	m_V: NA		
	m_T: NA		
	$6.4\times10^{-13} < m_S < 8.0\times10^{-13}$	Null results from searches for continuous GW signals from Cygnus X-1.	[135, 531]
	m_V: NA		
	m_T: NA		
	$2.0\times10^{-13} < m_S < 3.8\times10^{-13}$	Negative searches for a GW background.	[127, 128, 129, 684]
	$0.8\times10^{-13}\,\text{eV} < m_V < 6.0\times10^{-13}\,\text{eV}$		
	m_T: NA		
	$5\times10^{-13} < m_S < 3\times10^{-12}$	Bounds from pulsar timing.	[123, 277]
	$m_V \sim 10^{-12}$		
	m_T: NA		
	$2.9\times10^{-21} < m_S < 4.6\times10^{-21}$	Bounds from mass and spin measurement of M87 with EHT.	[637, 714]
	$8.5\times10^{-22} < m_V < 4.6\times10^{-21}$		
	$7.2\times10^{-22} < m_T < 2.5\times10^{-20}$		

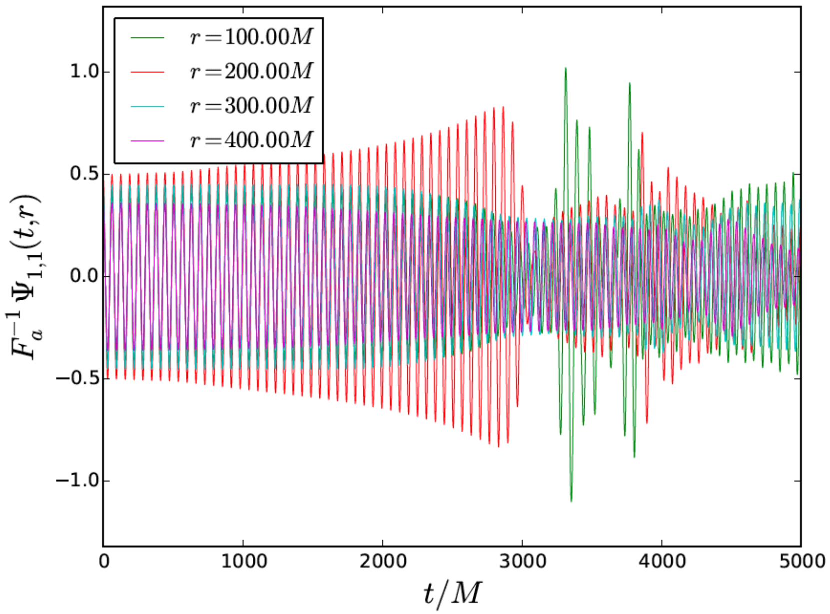
RB, Cardoso & Pani “Superradiance” Lect. Notes Phys. 971 (2020)

There are **caveats** for all these bounds.

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

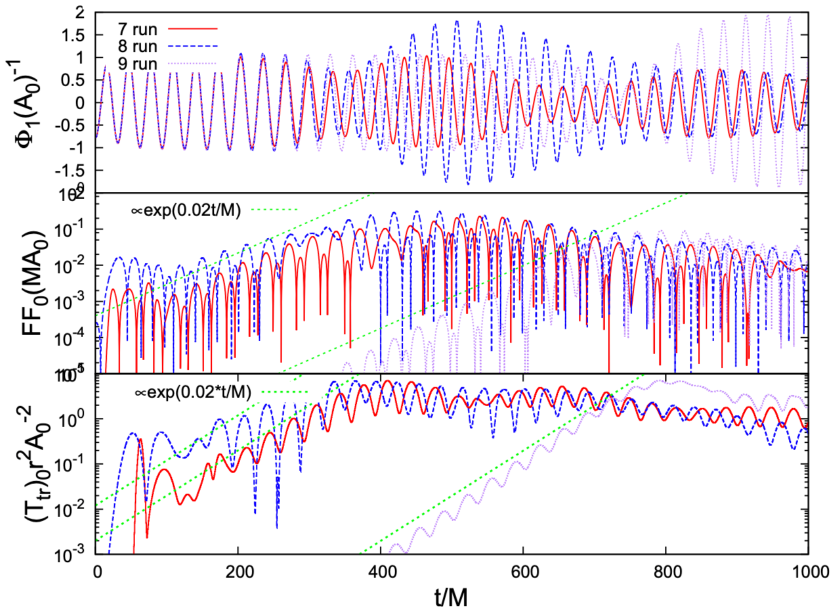
$$\Box\Phi - \mu^2 f_a \sin(\Phi/f_a) = 0$$



Credit: T. Ikeda, unpublished
See also Yoshino & Kodama ’12,’15, Baryakhtar *et al* '20

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

$$\nabla^\nu F_{\mu\nu} = -2k_{\rm axion}\,{}^*F_{\mu\nu}\nabla^\nu\Phi\,.$$



Ikeda, RB, Cardoso ’19; Boskovic *et al* ‘19

$$f_a \lesssim 10^{16}\left(\frac{M_{\rm cloud}/M}{0.1}\right)^{1/2}\left(\frac{\mu M}{0.1}\right)\,\mathrm{GeV}$$

$$k_{\rm axion}^{-1} \lesssim 10^{16}\left(\frac{M_{\rm cloud}/M}{0.1}\right)^{1/2}\left(\frac{\mu M}{0.1}\right)^2\,\mathrm{GeV}$$

Non-gravitational interactions may **hinder** the growth of the cloud and affect observational bounds. However they may also potentially lead to **novel** signatures.

See also Cannizzaro’s related talk

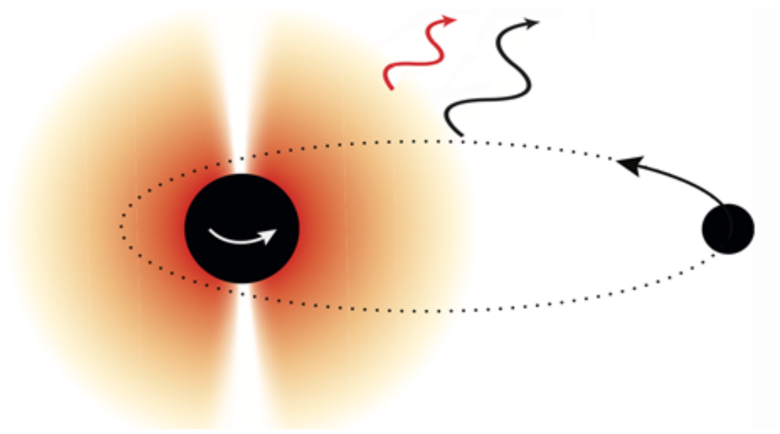
Needs to be much better understood.

Boson clouds in binary systems

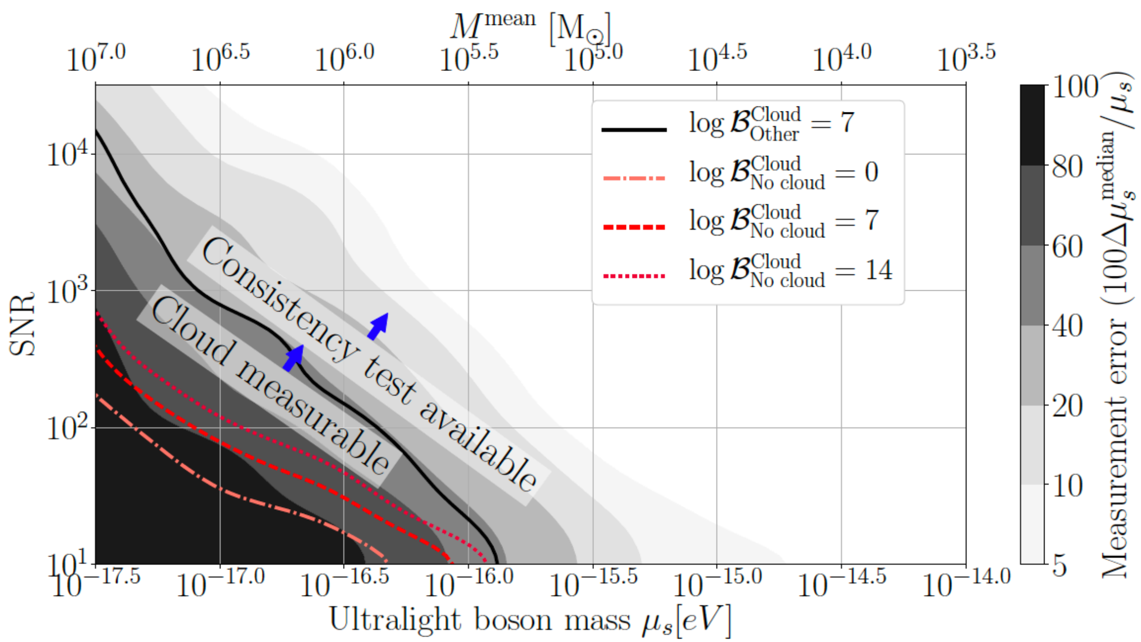
Baumann *et al* '19,'20, '21; Zhang & Yang '19; Hannuksela *et al* '19;
Berti *et al* '19; Cardoso, Duque & Ikeda '20; De Luca & Pani '21, ...

Several effects **induced** by the presence of the cloud studied in the last few years:

floating/kicking orbits, dynamical friction/ionisation, accretion, tidal Love numbers **(see De Luca's talk)**, multipole moments, ...



Credit: D. Baumann/University of Amsterdam



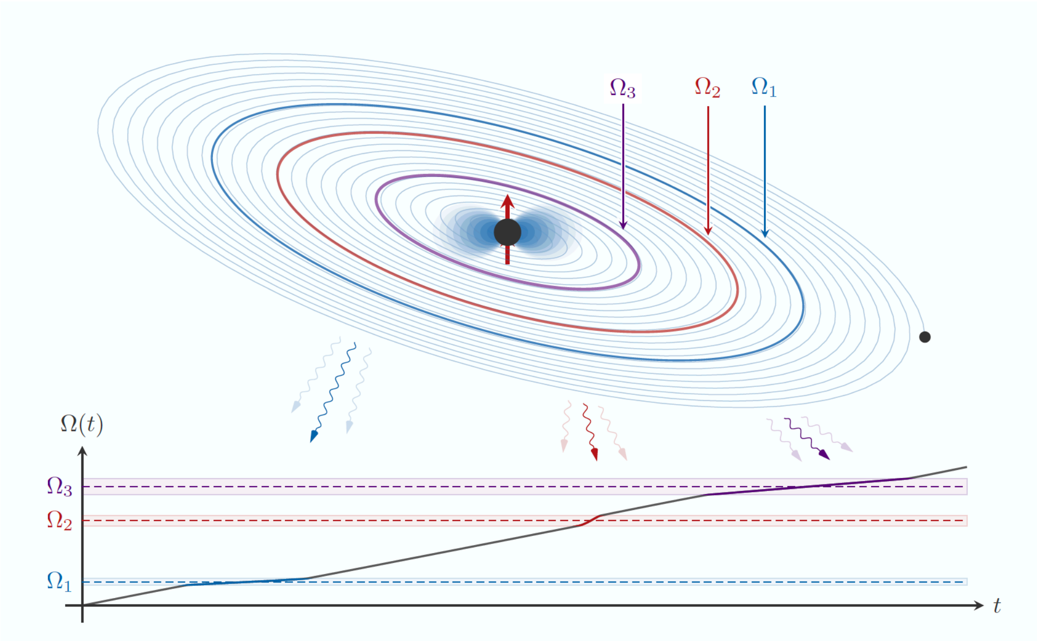
From: Hannuksela *et al*, Nature Astronomy 3, 447 (2019)

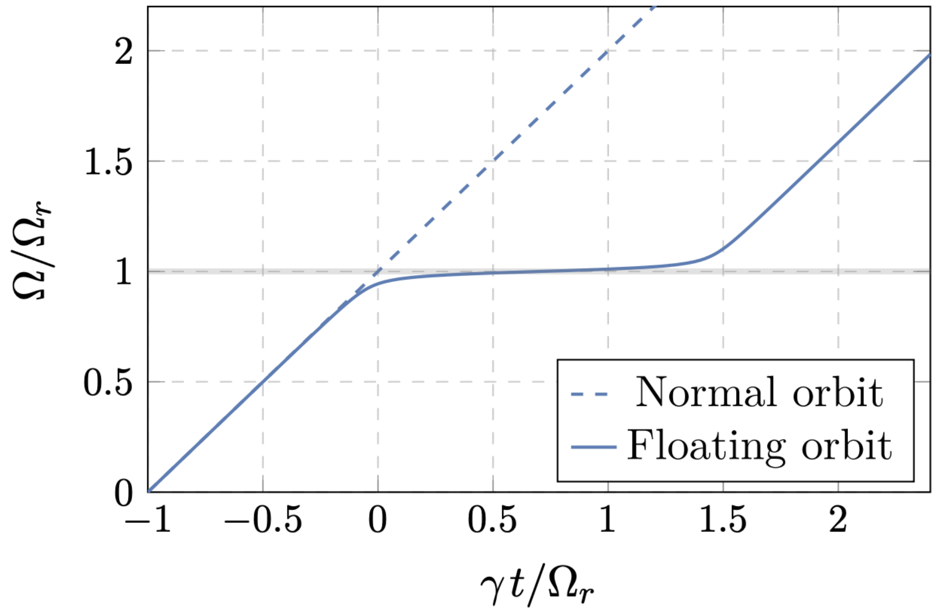
Very ***crude*** analysis for EMRIs shows that presence of a boson cloud could be detected in **GW signal emitted by BH binary**.

(even neglecting relevant effects such as dynamical friction)

Signatures in binary systems: Resonances

Baumann, Chia & Porto ‘18; Baumann, Chia, Porto & Stout ‘19





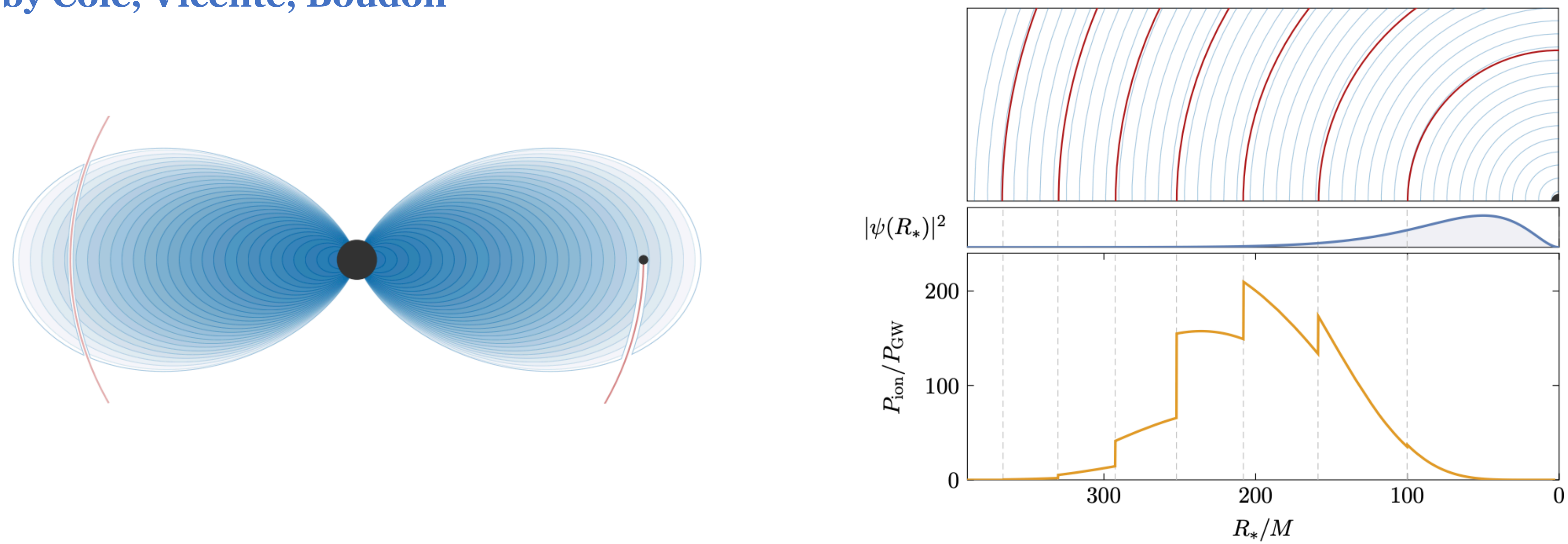
From: Baumann, Chia, Porto & Stout, PRD101, 083019 (2020)

- At specific **orbital frequencies** matching energy split between some levels of “gravitational atom”, **floating** or **sinking orbits** can occur.
- Boson cloud may be partially or totally **depleted** in the process.

Signatures in binary systems: Ionization & Accretion

Baumann, Bertone, Stout & Tomaselli, '21, '22

See Tomaselli's talk and related talks by Cole, Vicente, Boudon



From: Baumann, Bertone, Stout & Tomaselli, arXiv:2112.14777

- Black hole moving inside cloud will also **ionize** boson cloud and **accrete** the boson cloud.
- Backreaction on the orbit induces **additional *forces*** ("dynamical friction" and accretion) that **affects** binary evolution.
- **Needs** to be taken into account to fully characterise binary evolution.

Conclusions

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

However there are many interesting problems to be (further) explored in future:

- Better understanding of the **impact of non-gravitational interactions** on superradiant instabilities
- Better understanding of the **impact of black-hole environment** on superradiant instabilities
- Modelling **black hole binaries** with boson clouds beyond non-relativistic approximations and explore detectability in future detectors in more detail
- Superradiant instability of **massive spin-2 fields** for arbitrary spins
- Is there an **analog** of the superradiant instability for **binary systems**? If yes, signatures and impact for binary evolution?

(Wong '19; Bernard *et al* '19; Ikeda *et al* '21; Ribeiro, Zilhão & Cardoso '22)

...

Thank you!