SAPIENZA
UNIVERSITÀ DI ROMA

MARIE CURIE ACTIONS

Searching for ultralight bosons with black-hole superradiance and gravitational waves

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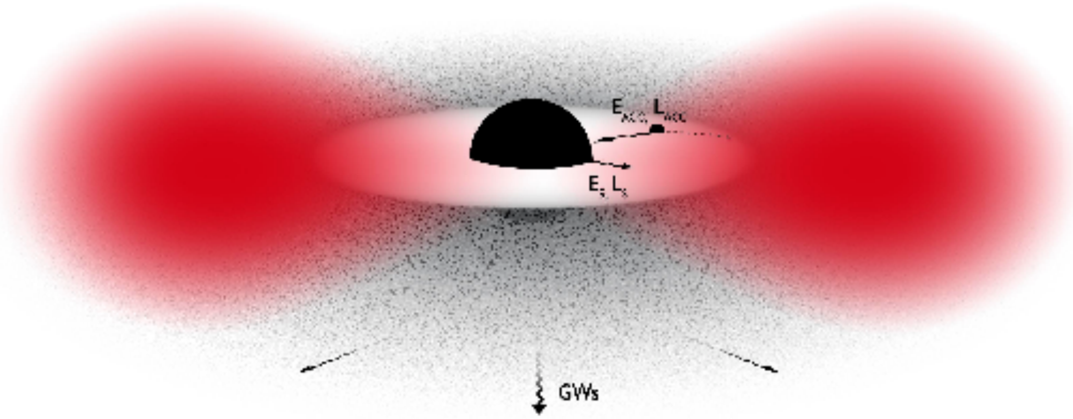
IBS-ICTP Workshop on Axion-Like Particles
11th November 2019



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Ultralight bosons

- Ultralight bosons (masses < 1 eV) are ubiquitous in extensions of the Standard Model: QCD axion, string axiverse, string photiverse, dark photons, …
- Natural weak coupling to Standard Model particles: compelling dark-matter candidates alternative to WIMPs.
- For most of the talk I will neglect self-interactions and non-gravitational interactions.

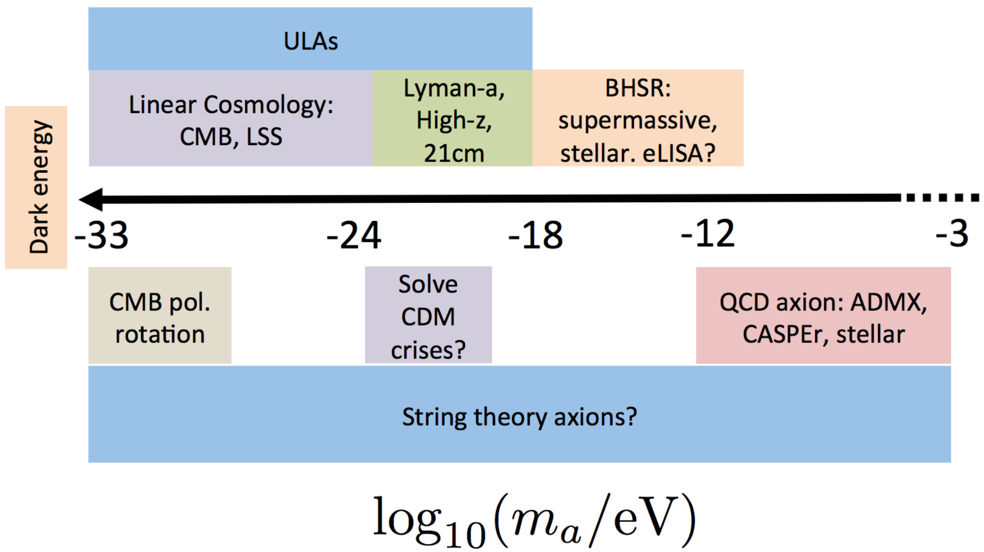
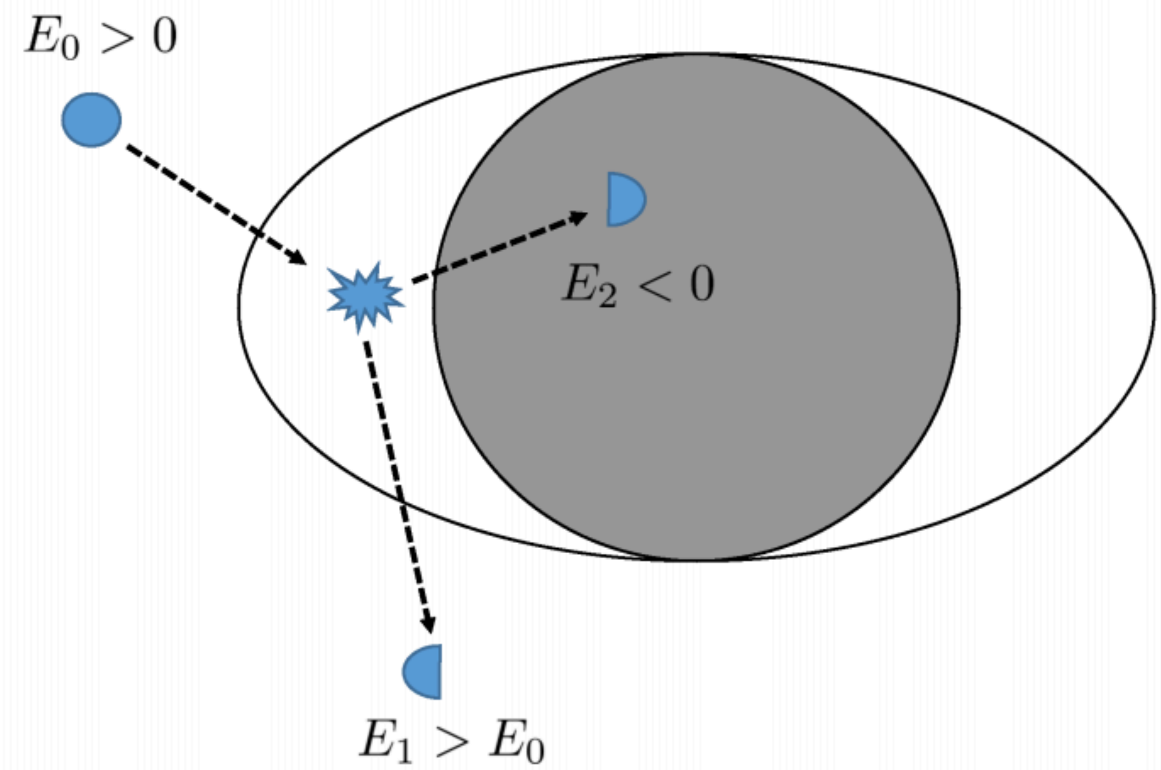


Figure 1: Summary of constraints and probes of axion cosmology.

From: D. Marsh, Phys. Rept. 643 (2016)

Penrose process

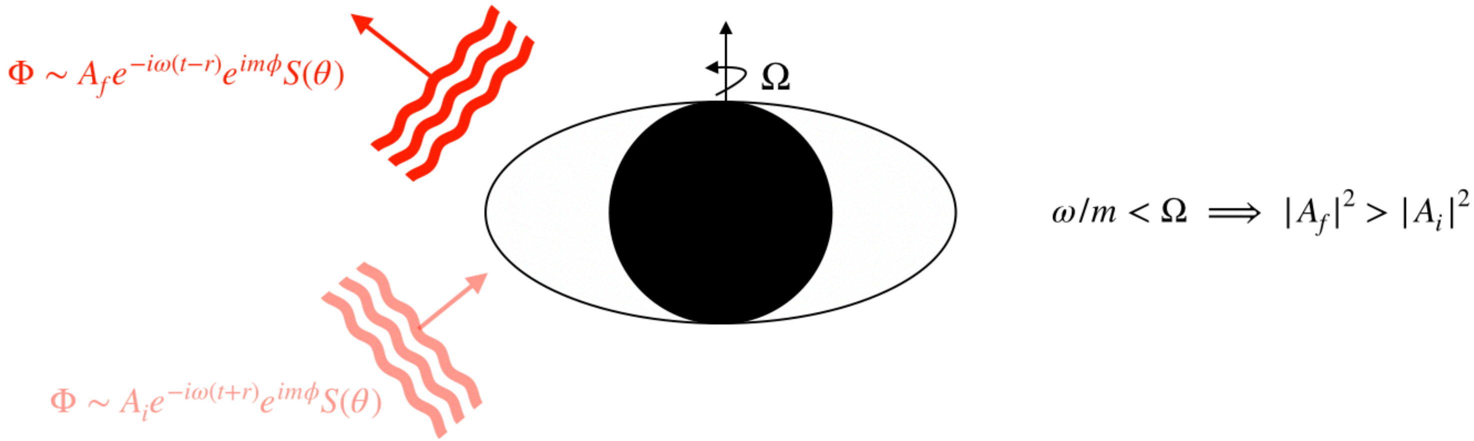
Penrose '69



Energy and angular momentum can
be extracted from Kerr black holes.

Superradiance

Zel'dovich, '71; Misner '72; Press and Teukolsky ,'72-74; Review: RB, Cardoso & Pani '15



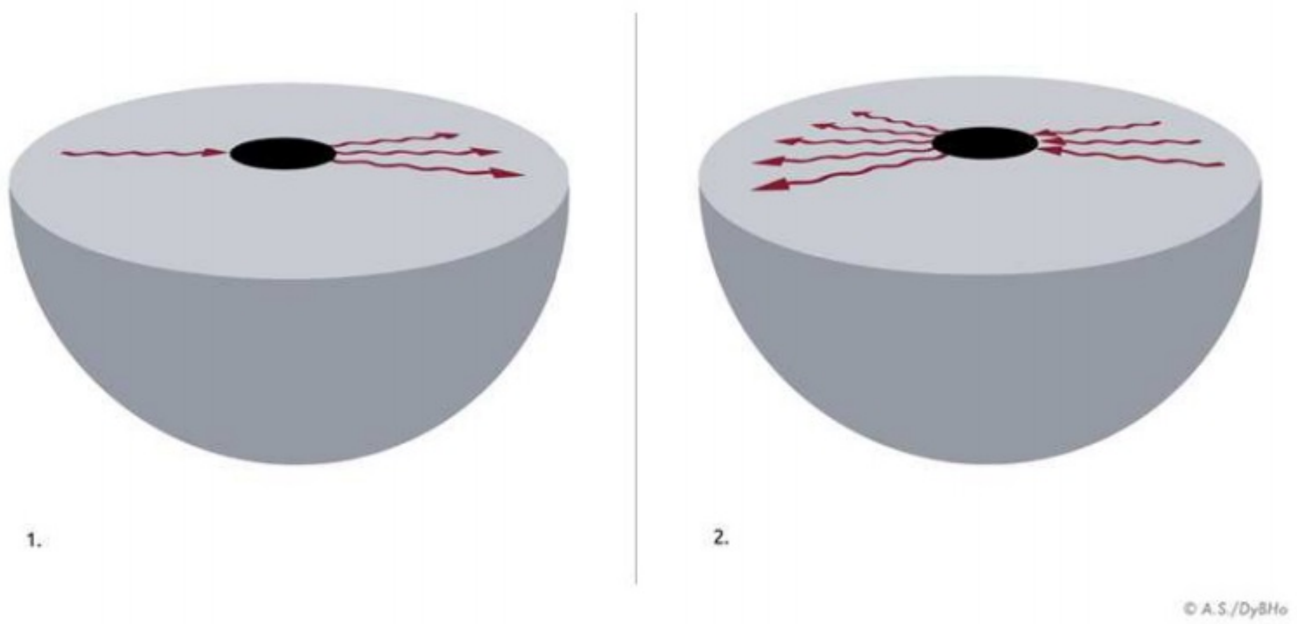
Superradiant scattering of **bosonic** waves ⟹ Extraction of energy and angular momentum from the black hole

❖ Requires the presence of an ergoregion i.e. region with "negative energy states".

Superradiant instability: black-hole bombs

Press & Teukolsky, ’72

Confinement + Superradiance $\longrightarrow$ Superradiant instability



Kerr surrounded by a perfectly reflecting mirror is unstable against bosonic radiation with frequency:

$$\omega < m\Omega_H$$

Massive bosonic fields around Kerr

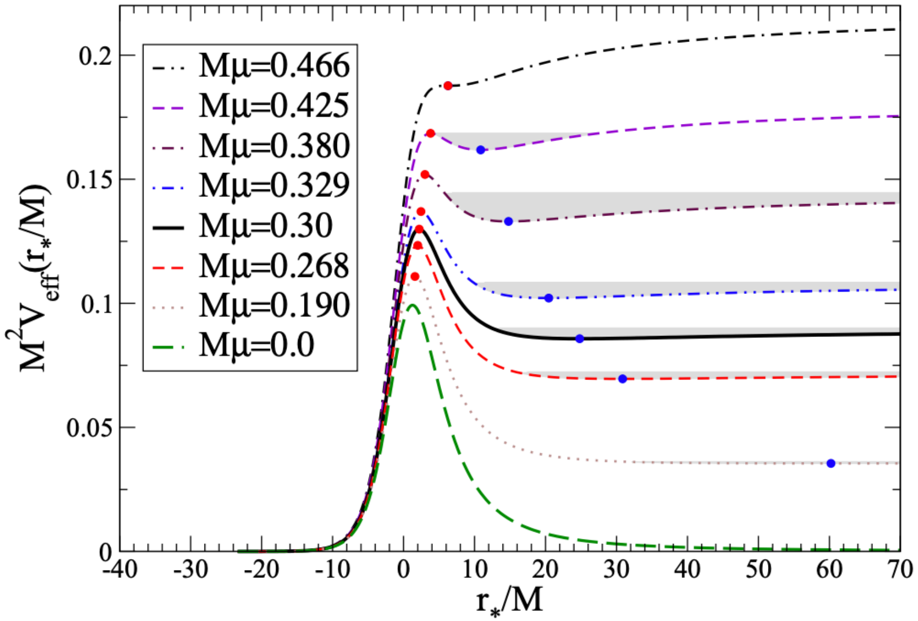
Damour '76; Zouros & Eardley '79; Detweiler '80; Dolan '07; Pani *et al* '12; RB, Cardoso & Pani '13; Baryakthar, Lasenby & Teo '17; East '17; Cardoso *et al* '18; Frolov, Krtous, Kubizník & Santos '18,...

The Yukawa potential of a **massive bosonic field** naturally confines low-frequency waves with $\omega < \mu$ that can satisfy the condition $\omega < m\Omega_H$.

$$\Box\Phi - \mu^2\Phi = 0 \quad \text{with} \quad \mu = \lambda\!\!\!{}^{-}{}^{-1}$$

$$\Phi(t,r,\theta,\phi) = \sum_{jm} e^{-i\omega t}\frac{\phi(r)}{r}Y_{jm}(\theta,\phi)$$

$$\frac{d^2\phi}{dr_*^2} + V_{\text{eff}}\phi = 0$$



From: Barranco et al'*11*

Kerr BHs can be **unstable** in the presence of massive bosons (can be generalized to any boson spin).

“Gravitational atom”

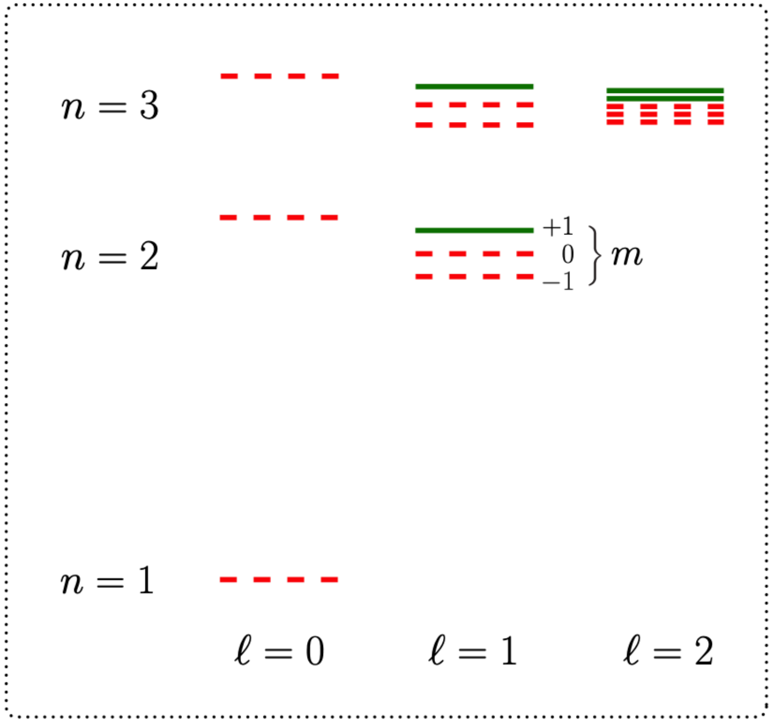
Detweiler ’80; Dolan ’07; Arvanitaki et al ’09; Baumann, Chia, Porto ’18, ...

$$\Phi(t, r, \theta, \phi) = \Psi(r) e^{-i\omega t + im\phi} P_l(\cos\theta)$$

$$\downarrow \quad \alpha \equiv \frac{r_g}{2\lambda\!\!\!^{-}_b} \ll 1$$

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

$$\Delta\omega_{n\ell m} = \mu \left(-\frac{\alpha^4}{8n^4} + \frac{(2\ell - 3n + 1)\,\alpha^4}{n^4(\ell + 1/2)} + \frac{2\tilde{a} m \alpha^5}{n^3 \ell(\ell + 1/2)(\ell + 1)} \right)$$



From: Baumann, Chia, Porto ’18

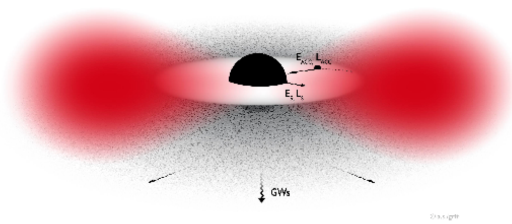
Boundary conditions at the horizon -> problem is non-Hermitian (dissipative):

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

Results for arbitrary α and black-hole spin can be obtained numerically. (Dolan ’07, ...)

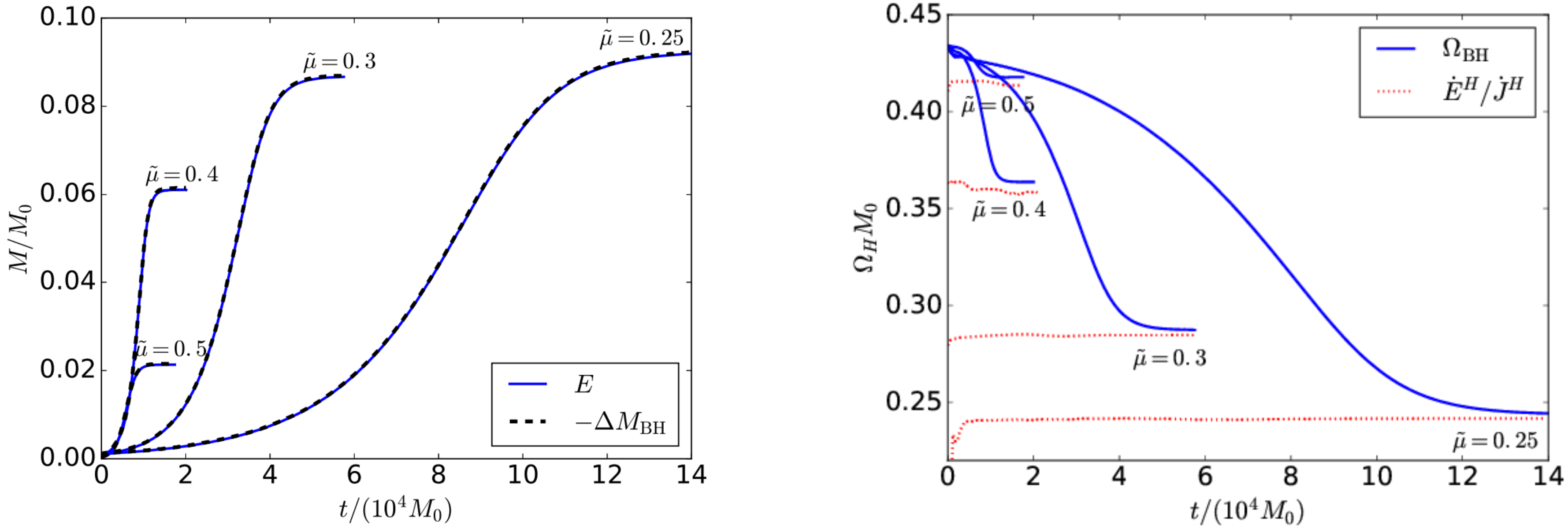
Evolution of the superradiant instability?

- During the instability phase black hole slowly loses spin and mass until it reaches saturation $\omega_R = m\Omega_H$.



- Formation of long-lived bosonic condensates around rotating BHs.

- Numerical simulations confirm linear/adiabatic predictions. East'18; East & Pretorius, '17; RB, Cardoso & Pani '15

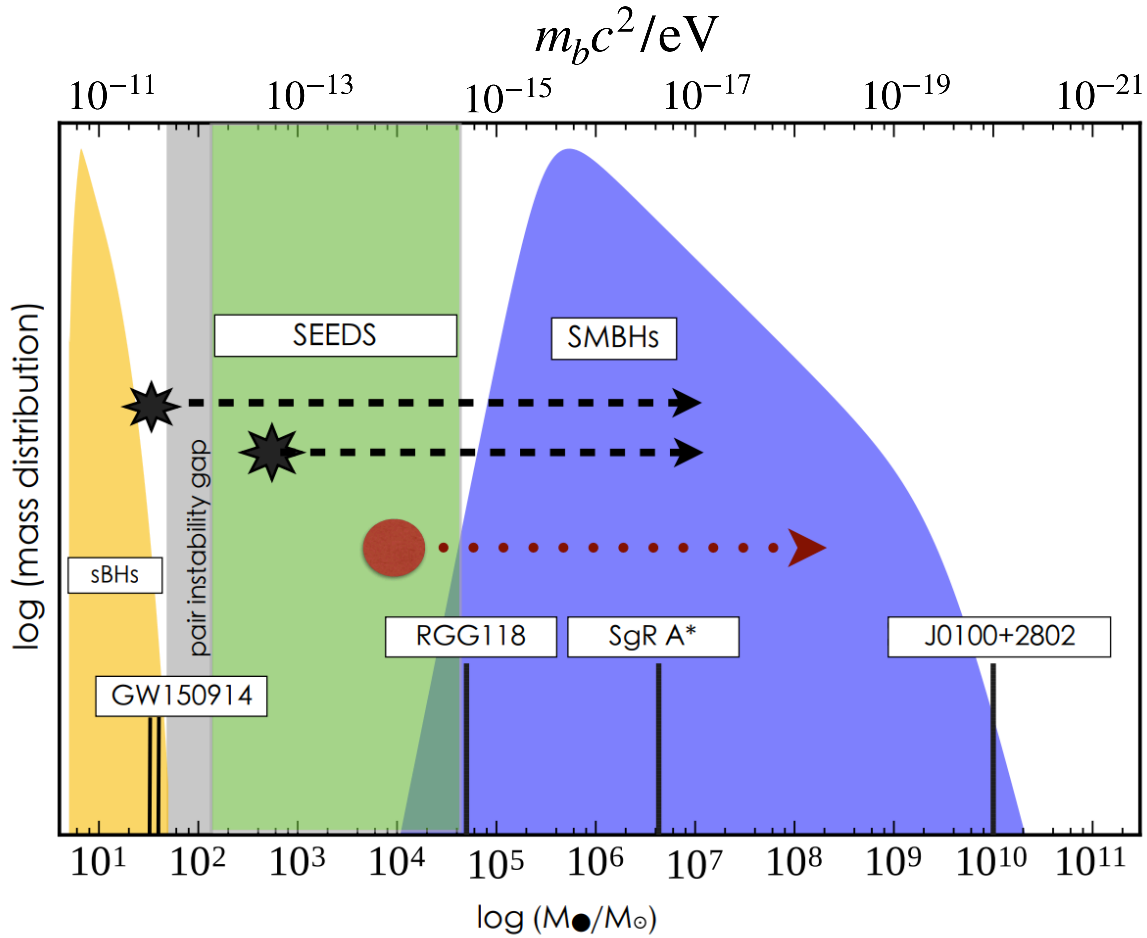


From: East & Pretorius, PRL119 (2017) no.4, 041101

Astrophysical Relevance?

- Strongest growth rate if $a/M \sim 1$ and $2\alpha \sim \left(\frac{M}{70M_\odot}\right)\left(\frac{m_b c^2}{10^{-12}\mathrm{eV}}\right) \sim \mathcal{O}(1)$

- Shortest instability timescale:
  scalars: $\tau \sim 50\,(M/M_\odot)$ s **vectors:** $\tau \sim 5\,(M/M_\odot)$ ms

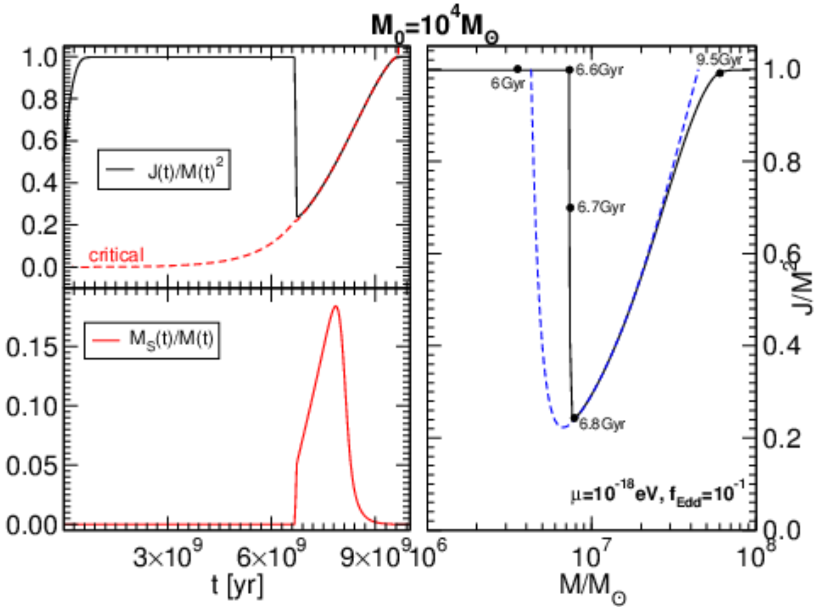


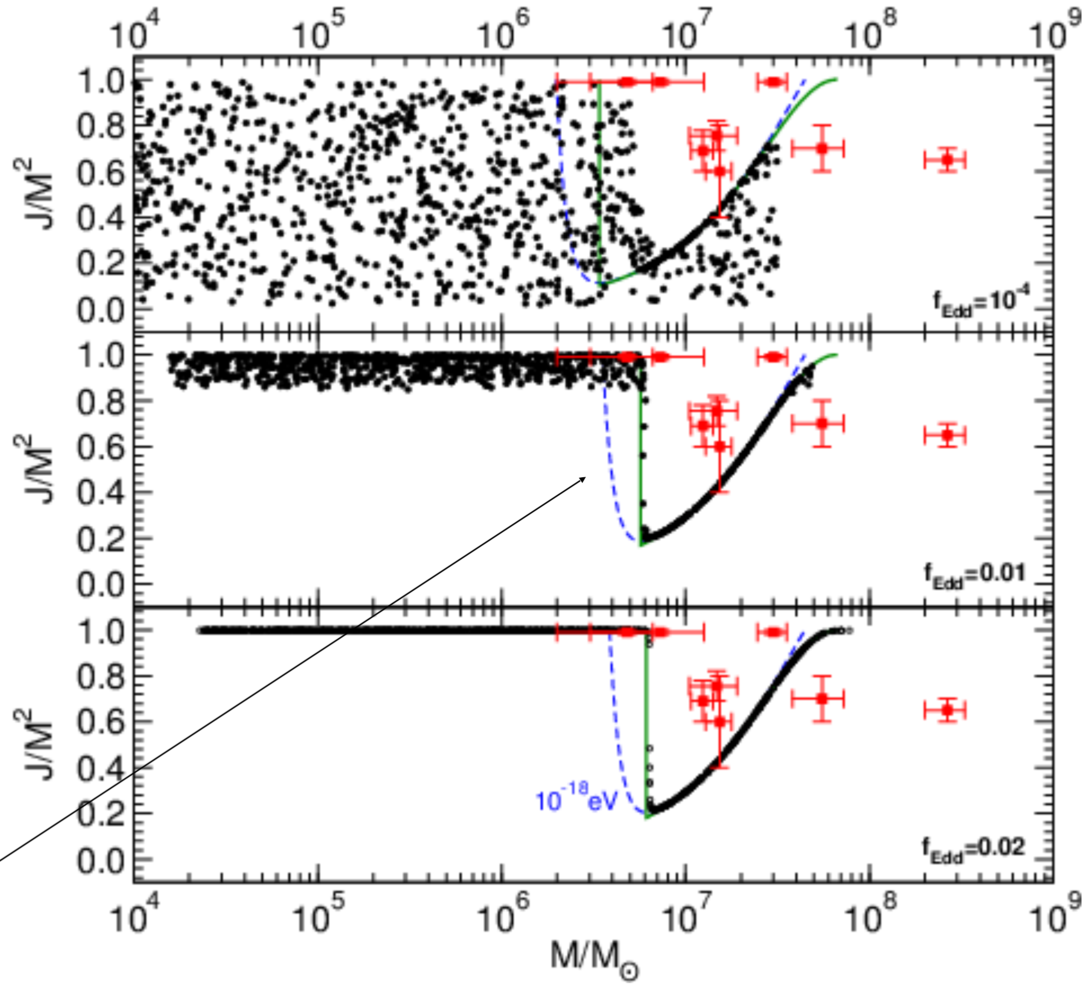
Adapted from: Barack *et al*, arXiv:1806.05195

Detecting or constraining the existence of ultralight bosons by measuring black hole masses and spins

Gaps in the mass vs spin plane

Arvanitaki, Dimopoulos, Dubovsky, Kaloper & March-Russell ’09; Arvanitaki & Dubovsky, ’10;
RB, Cardoso & Pani ‘14





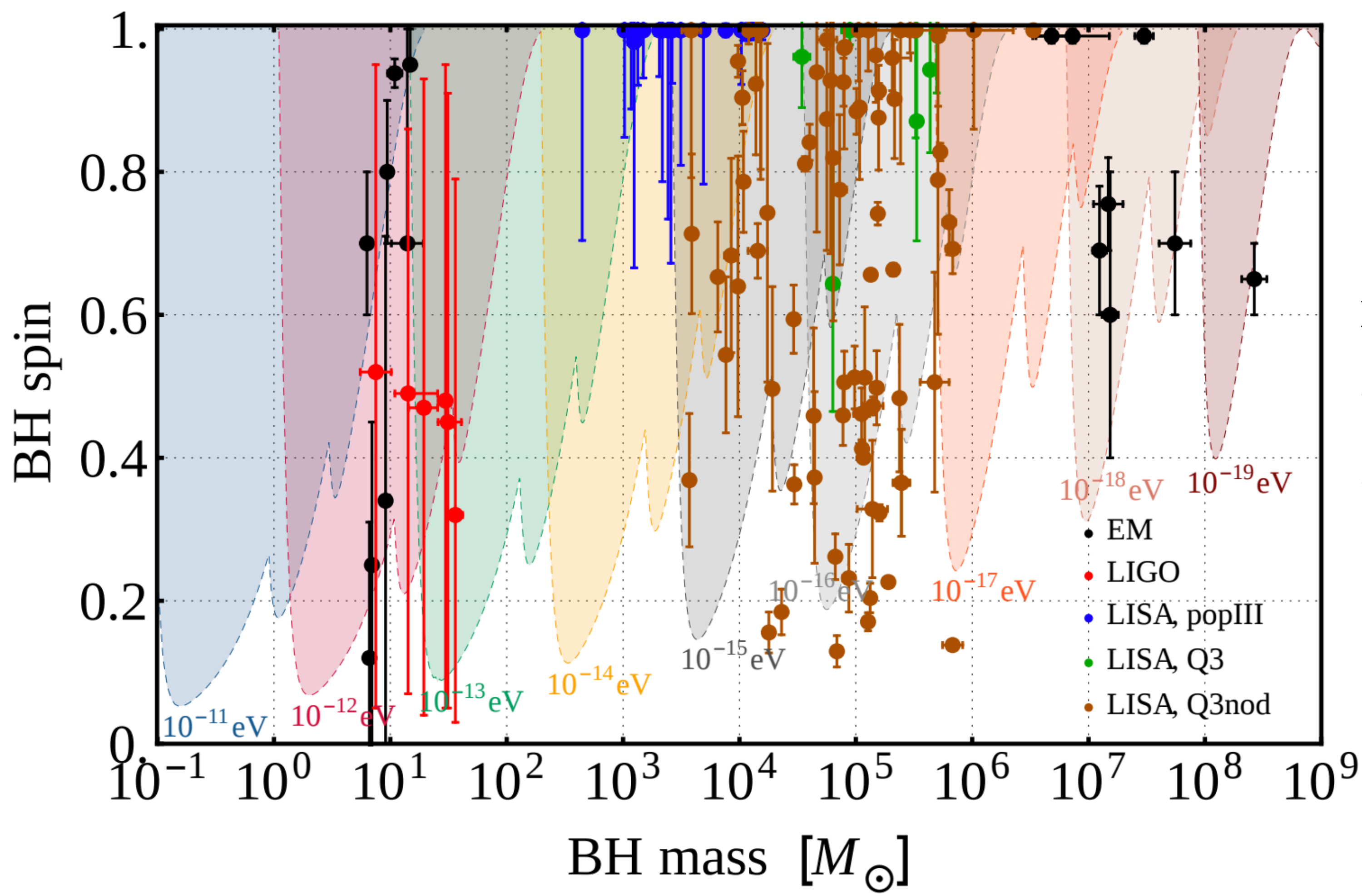
❖ Observations of astrophysical black holes, with precise measurement of mass and spin, could give indications of new physics.

$$\tau_{\rm instability} \approx \tau_{\rm accretion}$$

$$\tau_{\rm accretion} \sim 4.5 \times 10^7 {\rm yr}/f_{\rm Edd}$$

Gaps in the mass vs spin plane

RB, Ghosh, Barausse, Berti, Cardoso, Dvorkin, Klein, Pani, '17



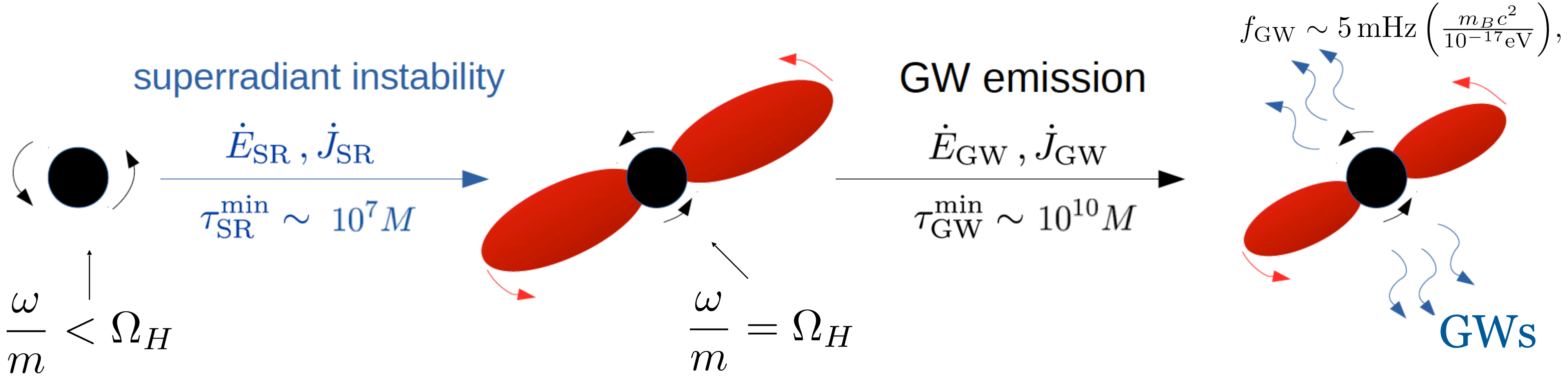
popIII=light seeds
Q3-d=heavy seeds, delays
Q3-nod=heavy seeds, no delays

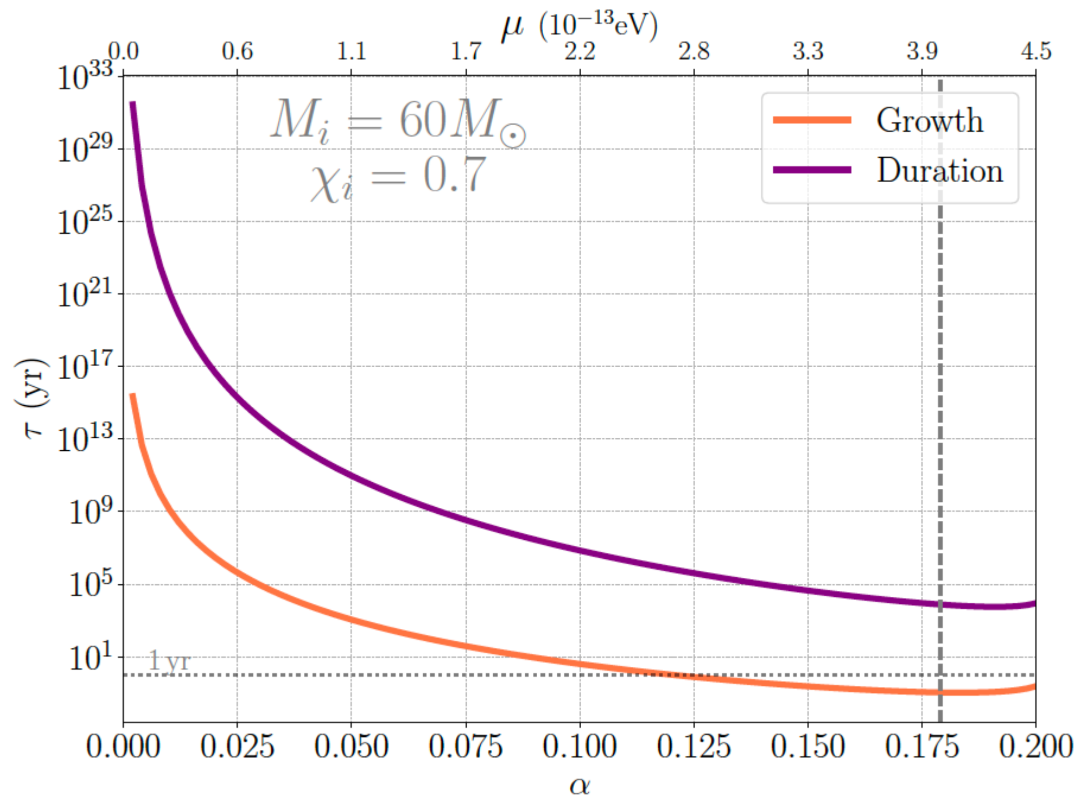
- LISA will be able to measure black hole masses and spins with very good precision therefore providing a unique opportunity to detect or constrain ultralight bosons.

Direct detection of ultralight bosons through the detection of gravitational waves

Continuous gravitational wave sources

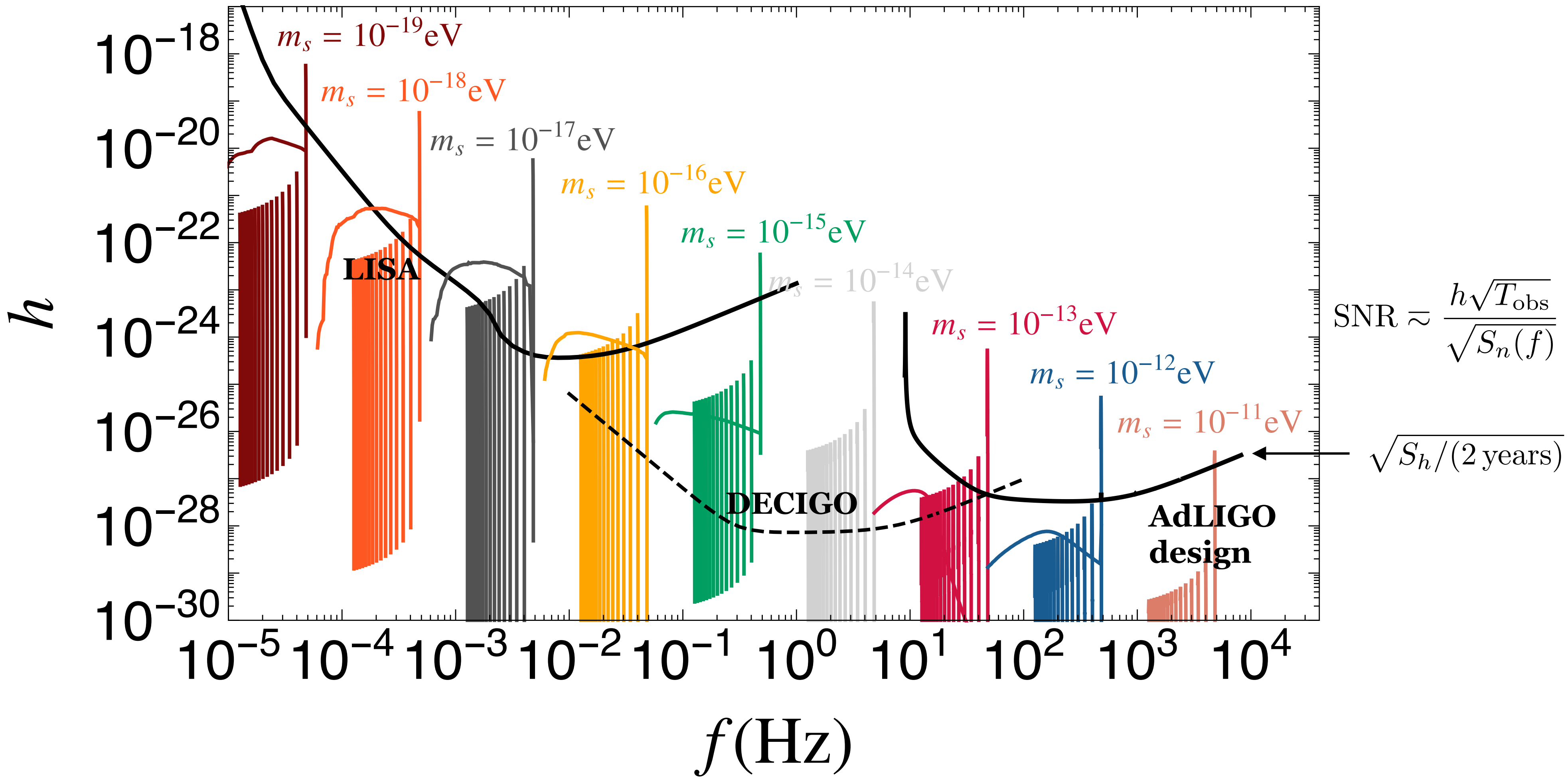
Arvanitaki, Dimopoulos, Dubovsky, Kaloper & March-Russell '09; Arvanitaki & Dubovsky, '10; Yoshino & Kodama '14; Arvanitaki, Baryakhtar & Huang, '15; ...





Multi-band GW searches

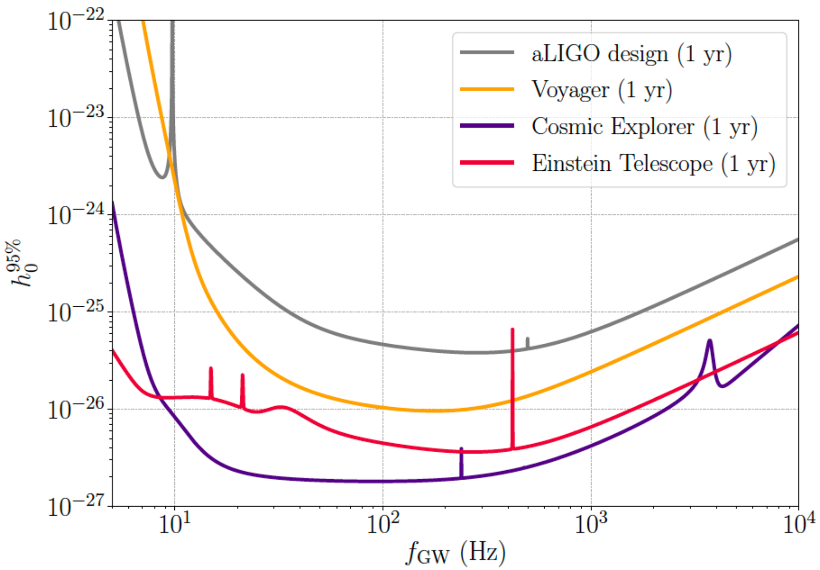
Arvanitaki, Baryakhtar & Huang, '15,
RB, Ghosh, Barausse, Berti, Cardoso, Dvorkin, Klein, Pani, '17

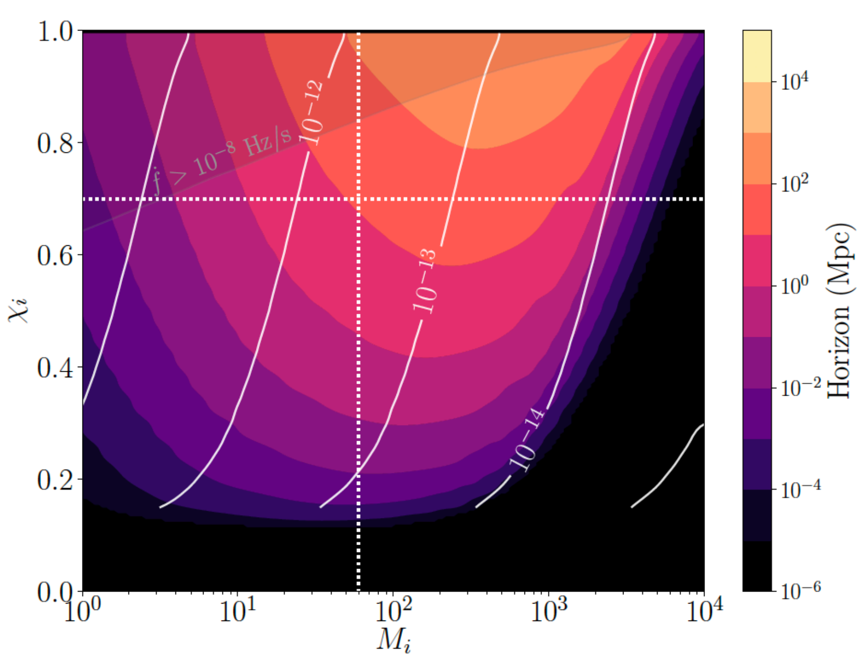


Vertical lines: **a/M=0.9; z=0.01-3.01** (right to left), α grows along vertical lines

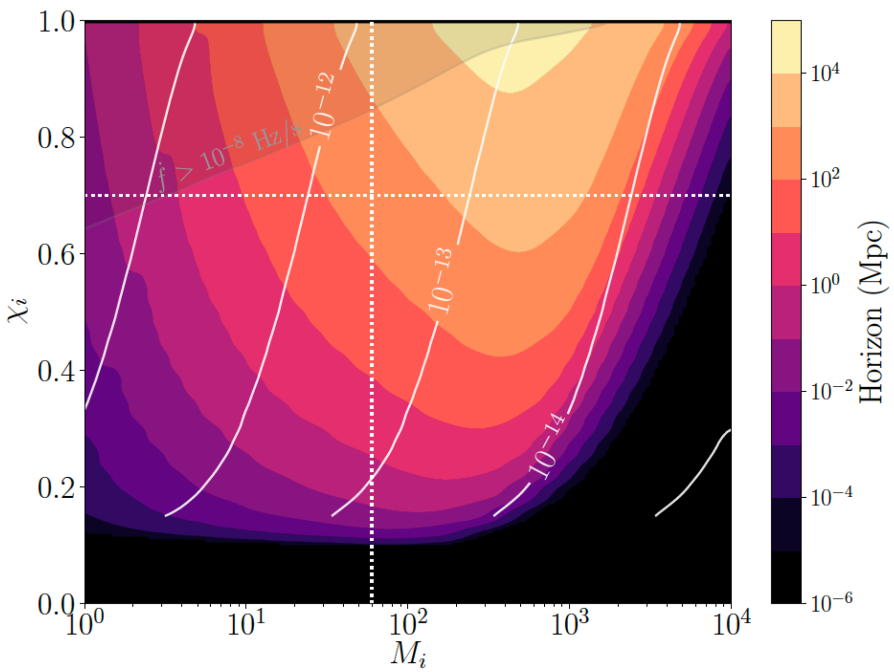
Detection horizons

M. Isi, L. Sun, RB, A. Melatos, ’18; see also S. D’Antonio *et al* ‘18





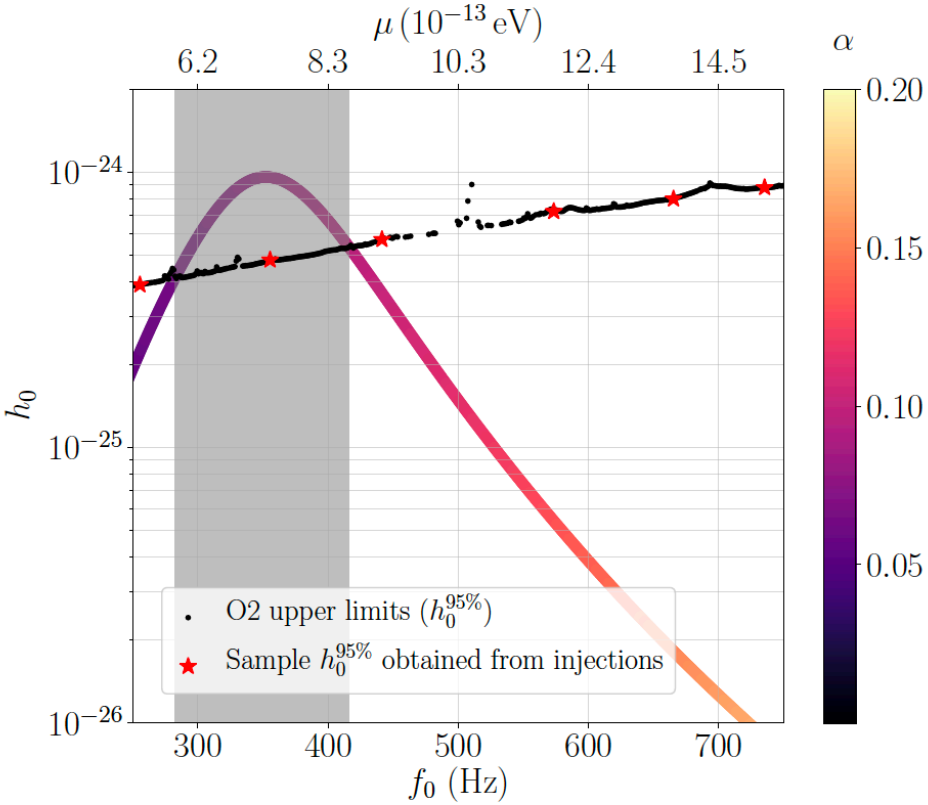
(a) aLIGO design

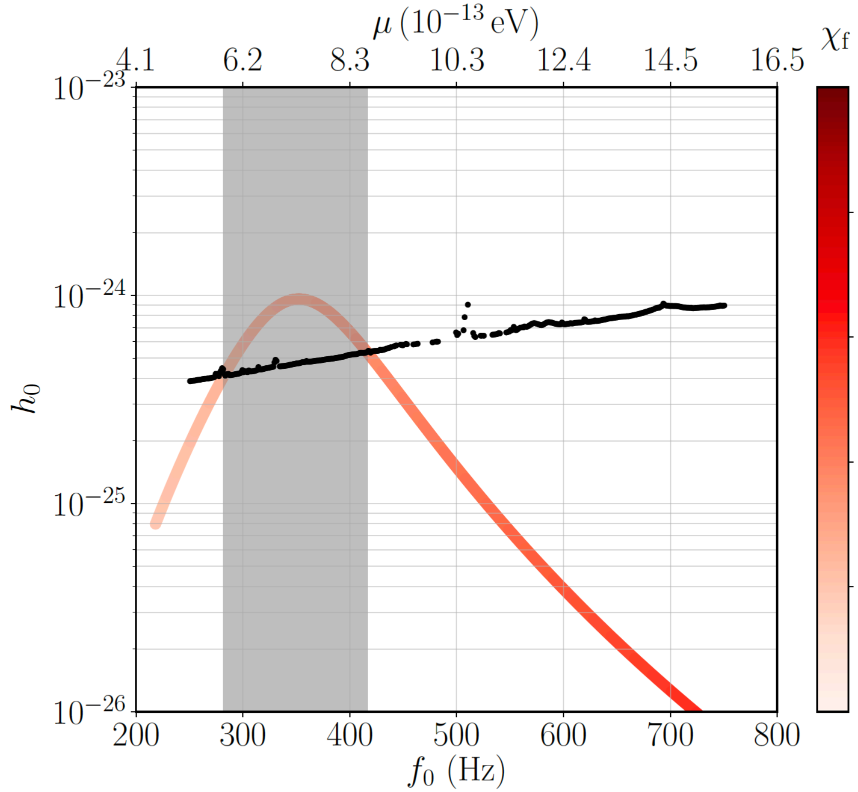


(c) Cosmic Explorer

Directed searches at Cygnus X-1

L. Sun, RB & M. Isi '19

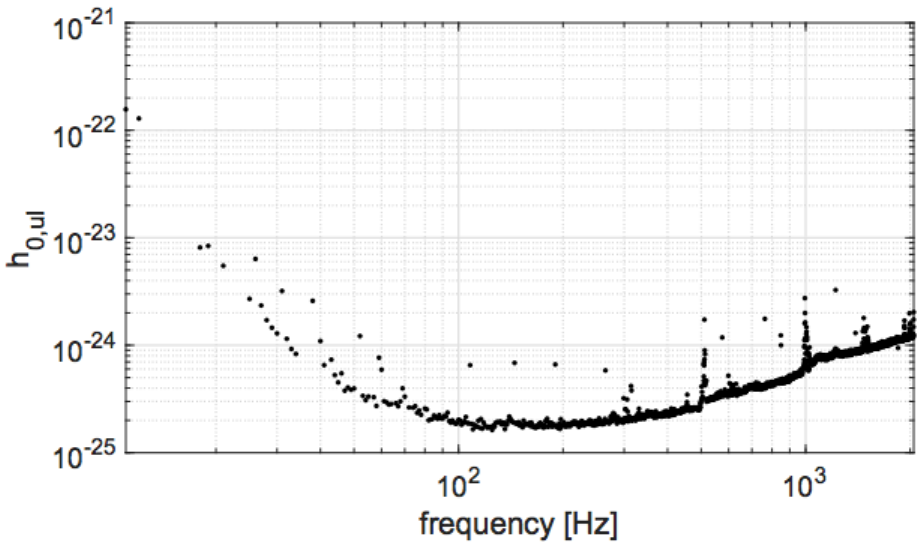


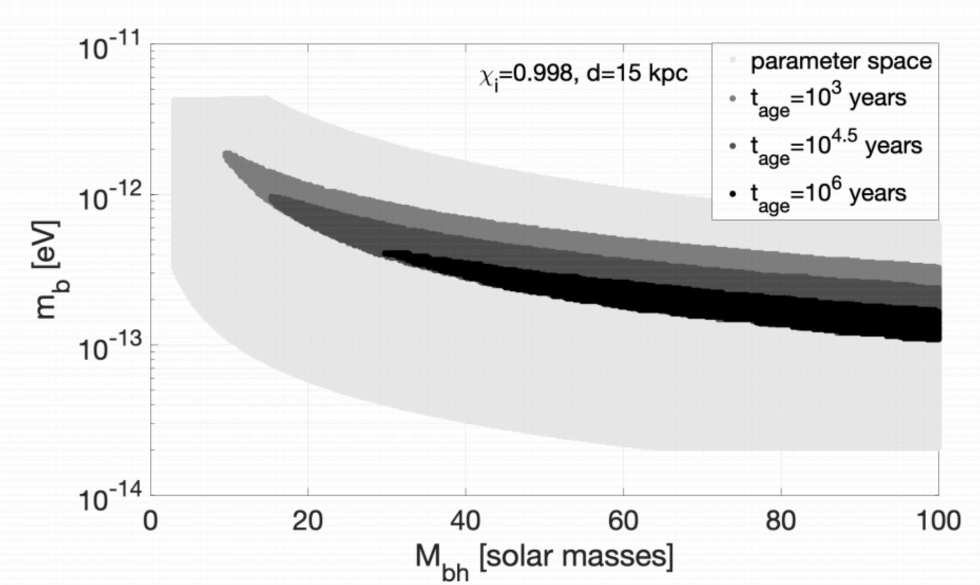


- Cygnus X-1 is a black hole in a X-ray binary at ~ 1.86 kpc with mass $\sim 15 M_\odot$ and was born $\sim 5 \times 10^6$ years ago.
- Note that current spin measurements seem to indicate $\chi \geq 0.95$ (although there are modelling uncertainties in this measurement).
- Directed searches at the remnants of binary black hole mergers free from uncertainties on BH spin and formation age. Large distances and poor sky localization are the main obstacle. M. Isi, L. Sun, RB, A. Melatos, '18; Ghosh *et al* '18

Constraints from all-sky searches

- Aside from known black holes there are many more in the Universe that we do not see. Estimated 10^8 black holes in our galaxy.
- All-sky "blind" searches could reveal the presence of a boson cloud around a black hole emitting gravitational waves. Arvanitaki, Baryakhtar & Huang, '15; RB et al '17





From: Palomba *et al*' PRL123 (2019) 171101

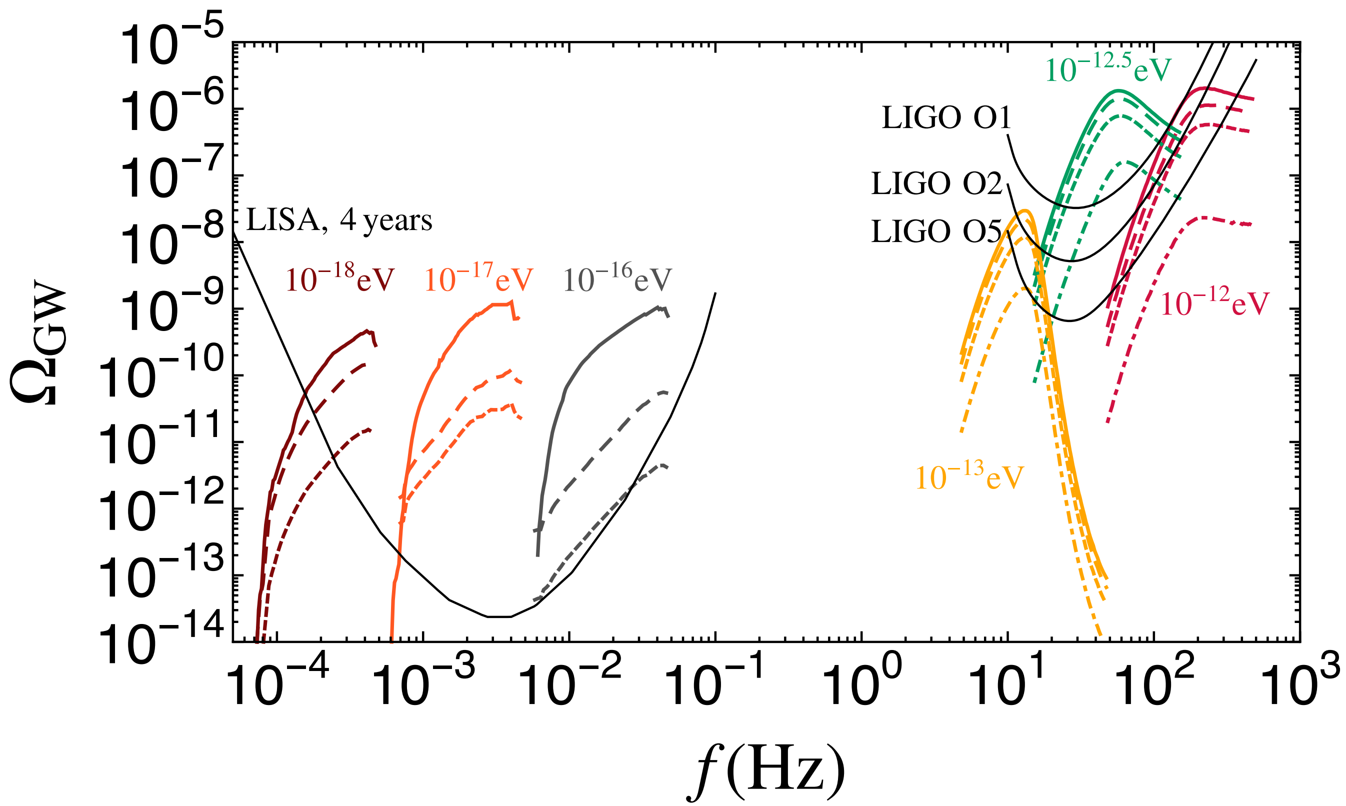
Assuming ~$\mathcal{O}(1)$ BH born every thousand years, latest LIGO upper limits indicates that lack of detections disfavours the range:

$\sim [1.1 \times 10^{-13}, 4 \times 10^{-13}]$ eV assuming high initial BH spins

$\sim [1.2 \times 10^{-13}, 1.8 \times 10^{-13}]$ eV assuming moderate initial BH spins

Stochastic Background

RB, Ghosh, Barausse, Berti, Cardoso, Dvorkin, Klein, Pani, '17



$$dE_s/df_s \approx E_{\rm GW}\delta(f(1+z)-f_s)$$

$$\Omega_{\rm GW}^{\rm iso}(f) = \frac{f}{\rho_c}\int {\rm d}z \frac{{\rm d}t}{{\rm d}z}\int {\rm d}M\, {\rm d}\chi p(\chi)\frac{{\rm d}\dot{n}}{{\rm d}M}\frac{{\rm d}E_s}{{\rm d}f_s}$$

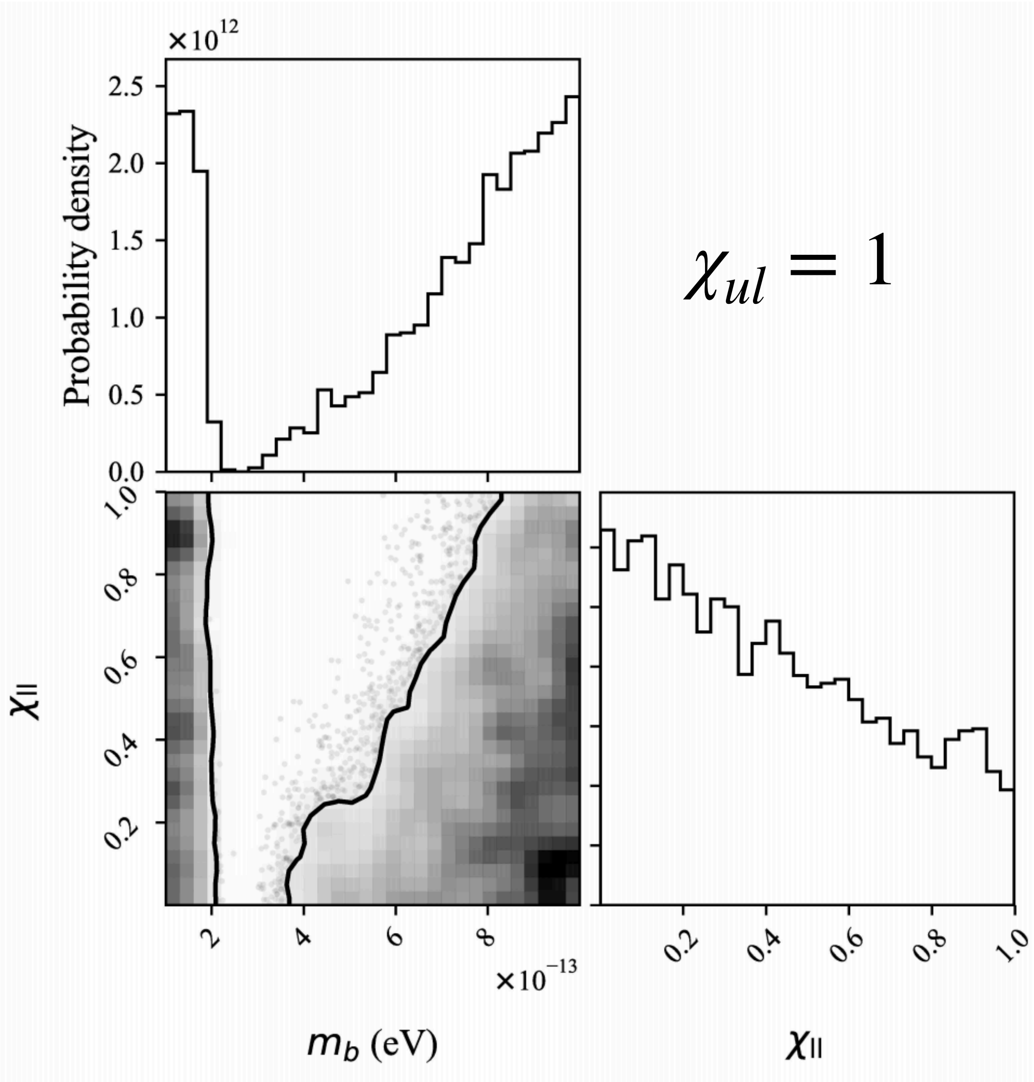
$$E_{\rm GW} = \int_0^{\Delta t} dE/dt$$

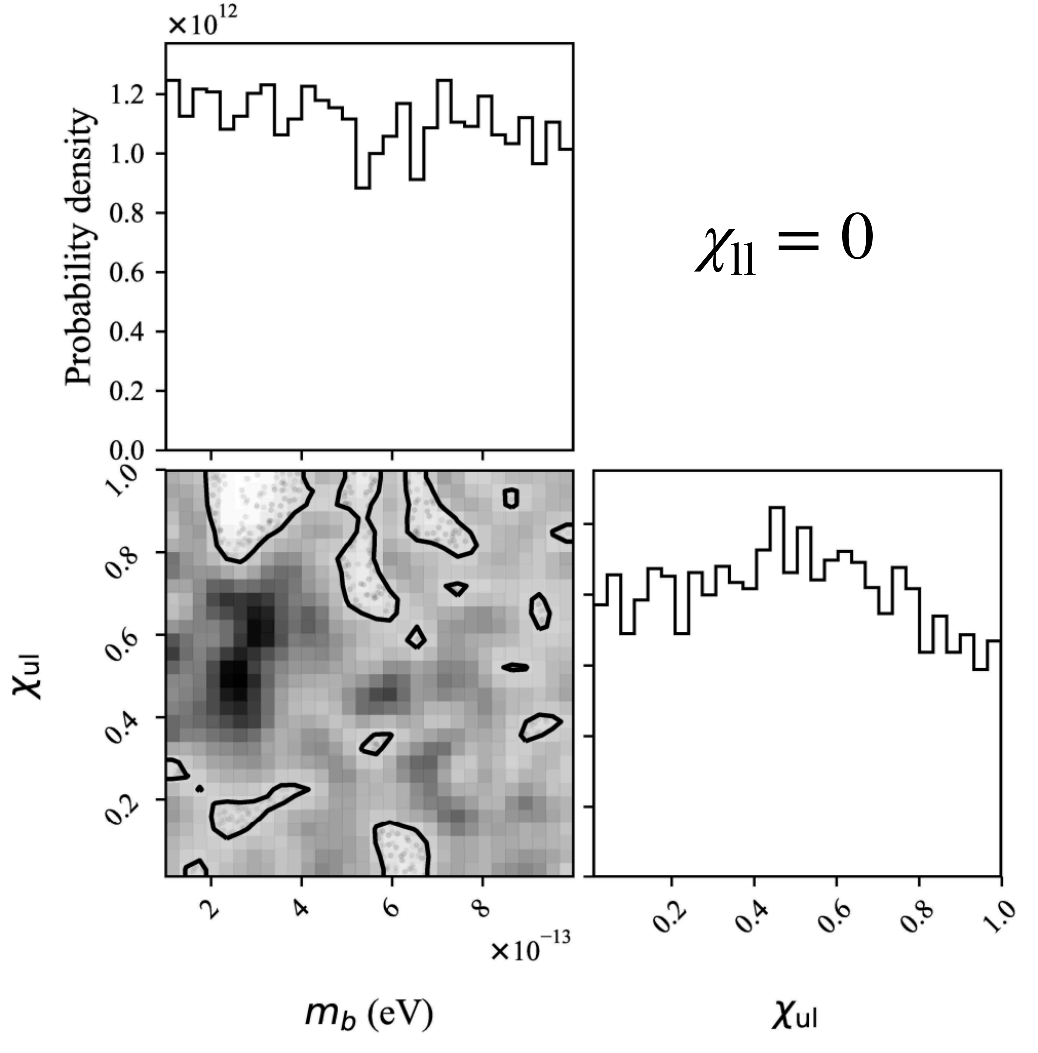
- The existence of many unresolved sources produces a **large stochastic background** with uncertainties mostly dominated by the BH spin distribution.

Constraints from AdLIGO's first observing run

L. Tsukada, T. Callister, A. Matas, P. Meyers, '18

$$p(\chi) \begin{cases} 0 & (\chi < \chi_{\rm ll}, \chi_{\rm ul} < \chi) \\ \frac{1}{\chi_{\rm ul} - \chi_{\rm ll}} & (\chi_{\rm ll} \le \chi \le \chi_{\rm ul}) \end{cases}$$



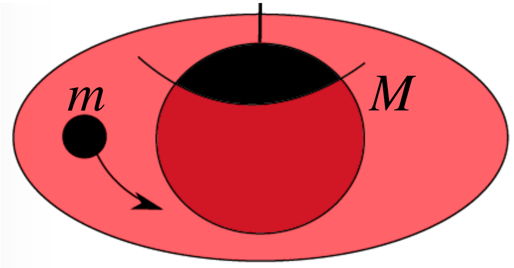


Binary black hole systems as ultralight boson detectors

Detecting boson clouds with extreme-mass-ratio-inspirals

Hannuksela, Wong, RB, Berti, Li ’18

$$\frac{dE_{\rm orbit}}{dt} = -\frac{dE_{\rm gw}}{dt}$$



Credit: O. Hannuksela

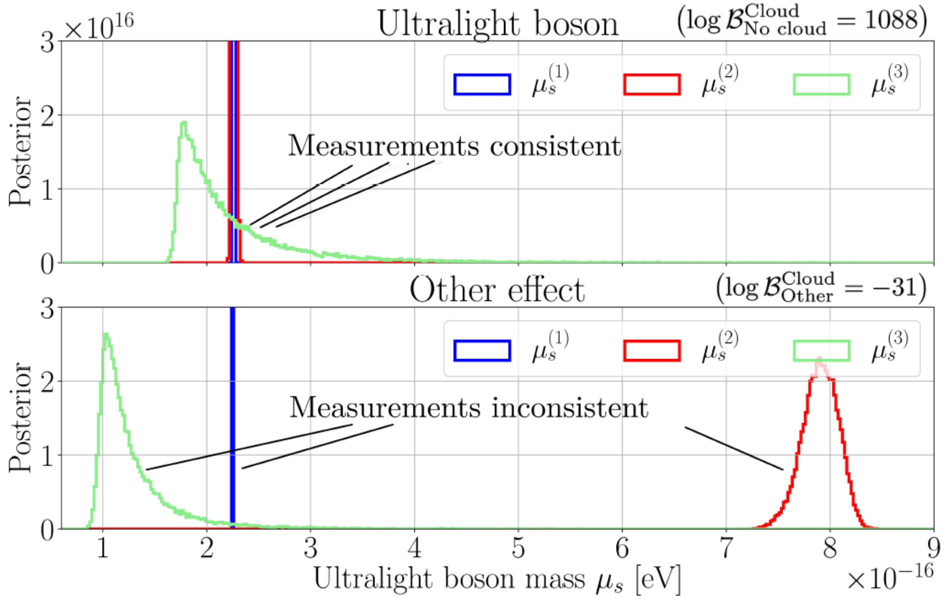
$$\frac{dE_{\rm orbit}}{dt} = \frac{d}{dt}\left(\frac{1}{2}mv^2 + m\Phi(r)\right), \quad \Phi(r) = -M/r + \Phi_b(r)$$

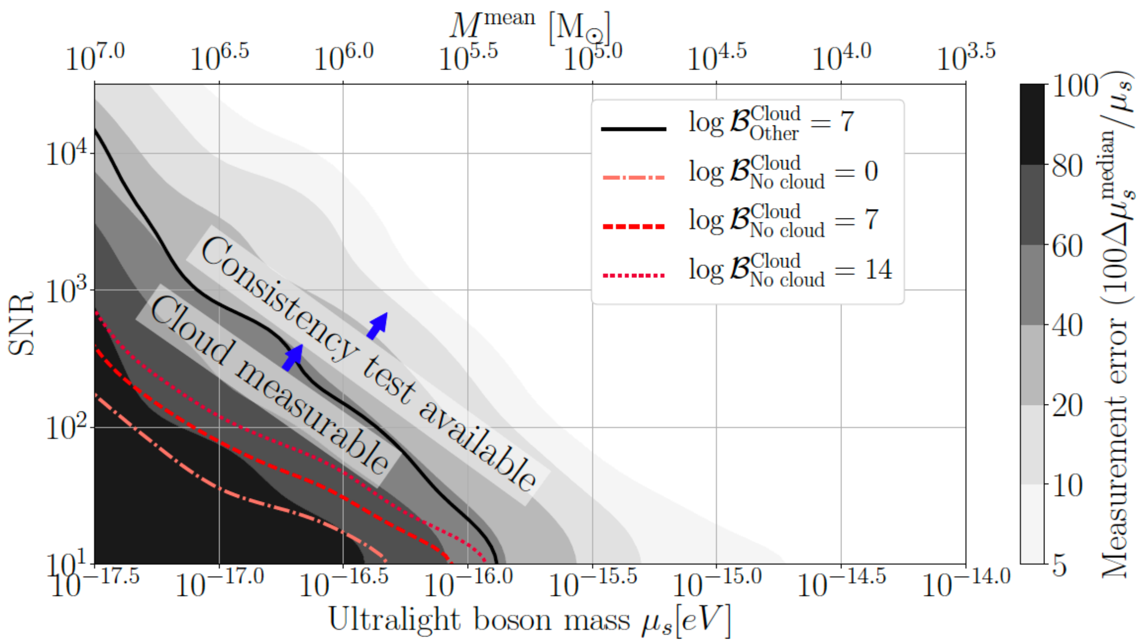
$$\Phi_b(r) \simeq A^2 e^{-Br} F(M, r, B)$$

(i) $$\mu_s^{(1)} \simeq \frac{a}{2Mr_+}$$

(ii) $$\mu_s^{(2)} = (M/B)^{-1/2}$$

(iii) $$\mu_s^{(3)} \simeq 2\left[\frac{\pi A^2}{MM_s}\left(\sqrt{1+\frac{2M_s}{A^2M\pi}}-1\right)\right]^{1/2}$$





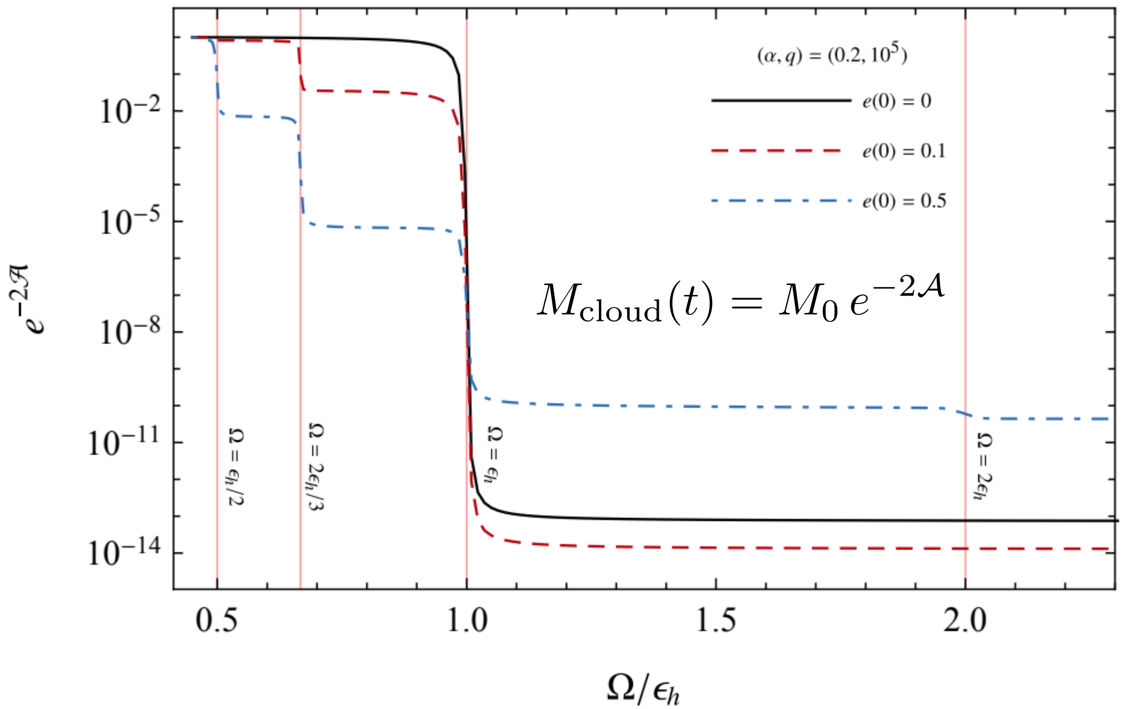
Clouds in a binary system: level-mixing

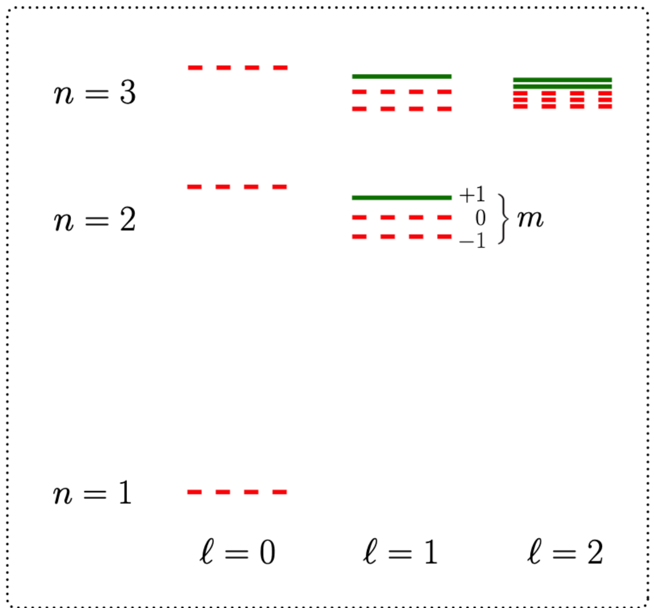
Baumann, Chia, Porto ’18; see also Berti, RB, C. Macedo, G. Raposo & J.L.Rosa ‘19

- When the BH carrying the cloud is part of a binary system, the companion induces a tidal field in the cloud.

- Can induce transitions between modes at (multiples of) orbital frequencies that match the energy split between those modes.

- Transitions to a decaying mode can lead to a partial or total depletion of the cloud. Could lead to interesting signatures in gravitational waves, but needs further investigation.





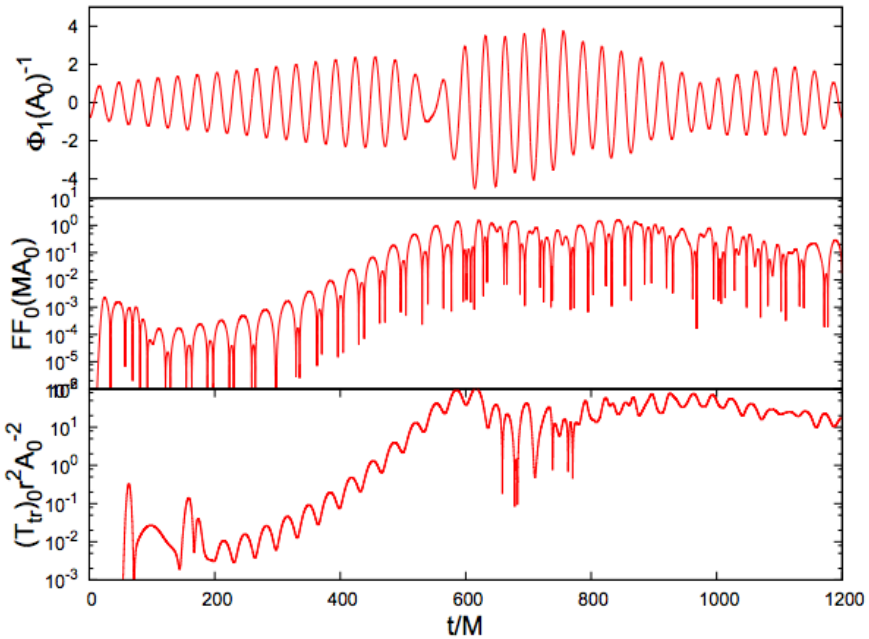
Non-gravitational couplings and self-interactions

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:

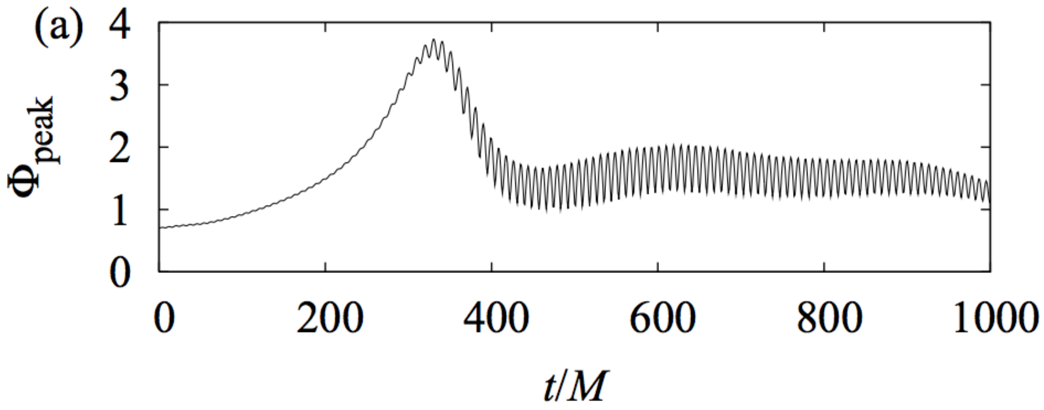
$$k_{axion}^{-1} \lesssim 10^{17}\left(\frac{M_S/M}{0.1}\right)^{1/2}\left(\frac{\mu M}{0.25}\right)^{2}\,\mathrm{GeV}$$

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

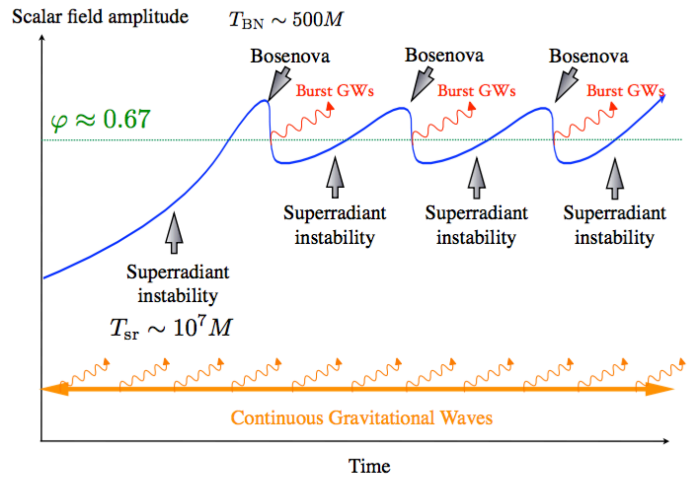
Self-interactions: bosenova

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.

Conclusions

- Superradiant instabilities provide an interesting arena to use black holes as "particle detectors" and search for ultralight particles.

- Several observational channels: black-hole spin measurements; continuous gravitational-waves; stochastic gravitational-wave background, black-hole binaries…

- Self-interactions and couplings to photons may also provide interesting signatures but further work is needed to fully understand their impact and consequences for observations.

Thank you!

Thank you!

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