

Title: Observing Superradiance of Light Vector Particles

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URL: <http://pirsa.org/17020092>

Abstract: <p>We will discuss how the process of superradiance, combined with
gravitational wave measurements, makes black holes into
nature's laboratories to search for new light bosons. We will present
analytic results for superradiance of light vector (spin-1) particles,
valid in the regime where the vector's Compton wavelength is much
larger than the horizon size of a black hole. If superradiance is
efficient, the occupation number of the vectors in the black hole's
vicinity grows exponentially and the black hole spins down. We will
present preliminary signatures of this process, including black hole
spin measurements and gravitational wave signals. Current measurements
of black hole spins disfavor a range of masses of (gravitationally
coupled) vectors. Vectors annihilating to gravitons would emit
strong monochromatic gravitational wave signals, which may be
visible in future LIGO observations. </p>

Black hole superradiance of light vector particles

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February 9, 2017

0905.4720 A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper, J. March-Russell

1004.3558 A. Arvanitaki, S. Dubovsky

1411.2263 A. Arvanitaki, MB, X. Huang

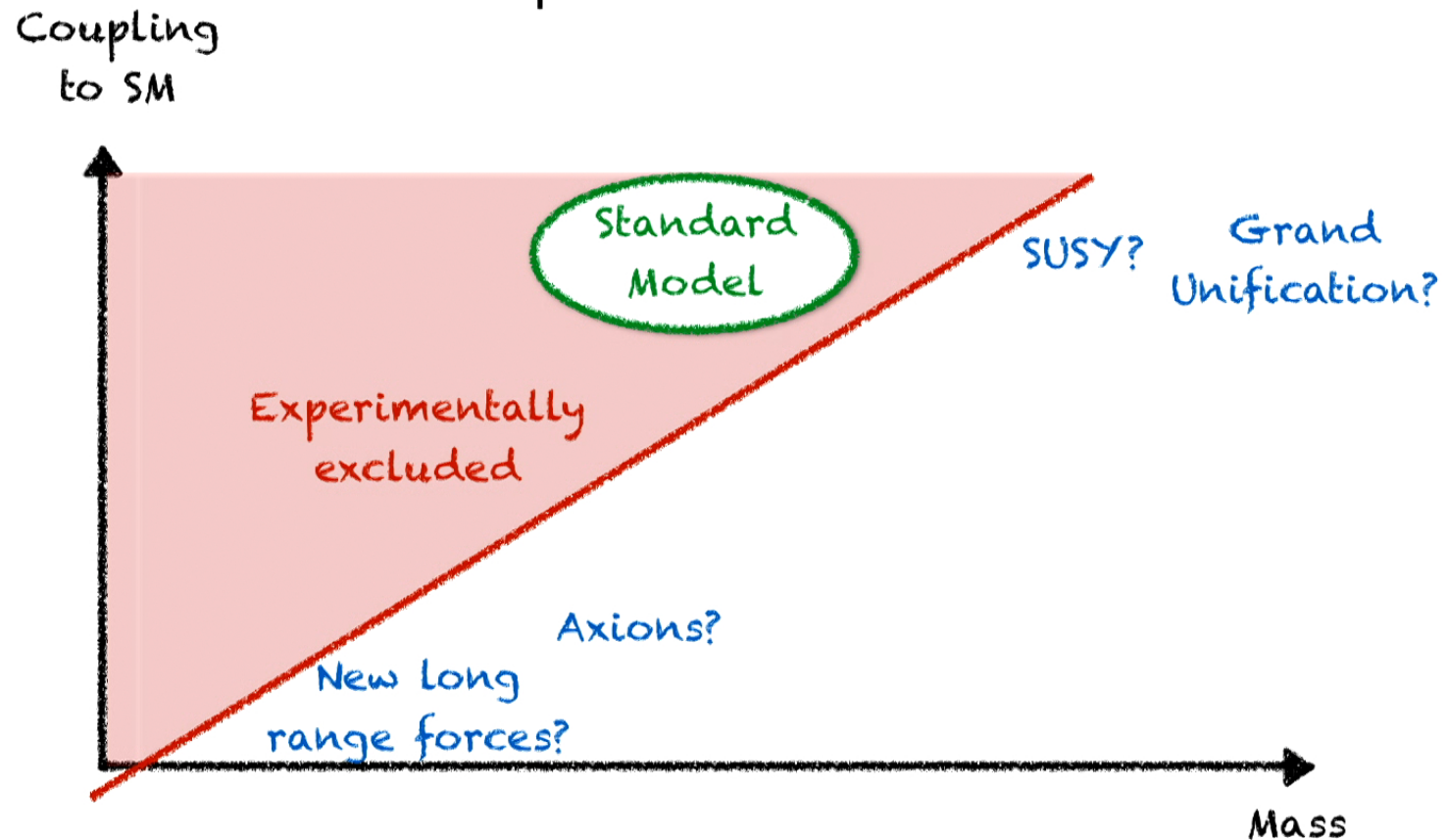
1604.03958 A. Arvanitaki, MB, S. Dimopoulos, S. Dubovsky, RL

17xx.xxxxx MB, RL, M. Teo

Outline

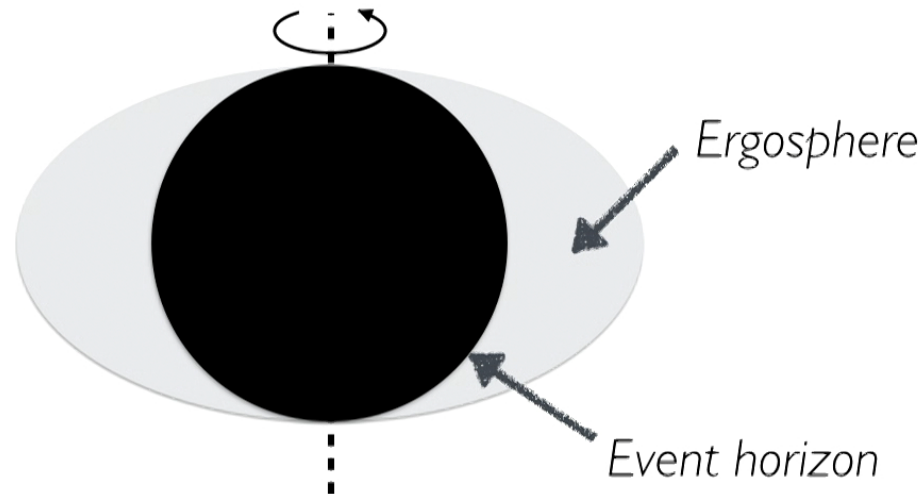
- Energy extraction from black holes
- Black hole superradiance for light scalar/vector particles
- Observational signatures
 - Spin-down of black holes
 - Coherent gravitational wave emission

Light, weakly-coupled new particles



Extracting energy and angular momentum from black holes

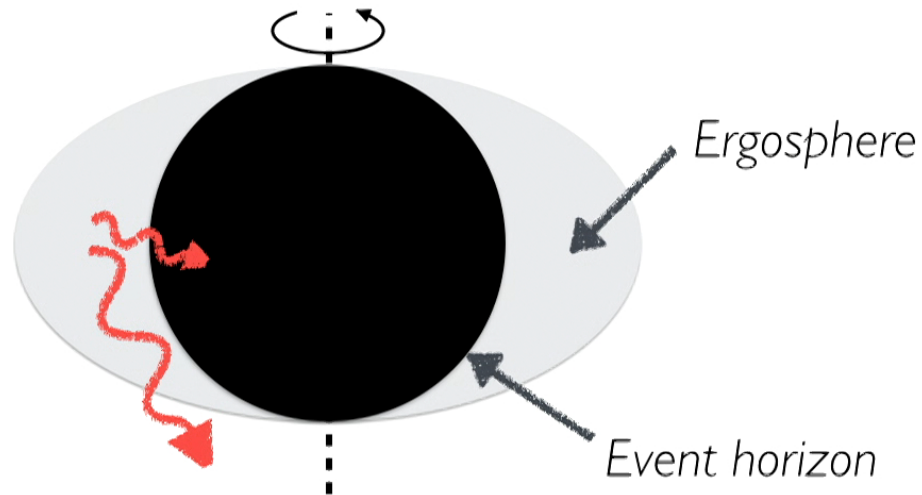
- Spinning BHs have *ergosphere* - region where particles can have negative energy (as viewed from infinity)



- Mechanical Penrose process: throwing negative-energy particle into horizon

Extracting energy and angular momentum from black holes

- Spinning BHs have *ergosphere* - region where particles can have negative energy (as viewed from infinity)



- Wave Penrose process: transmitted wave has negative energy, reflected wave carries extra energy away

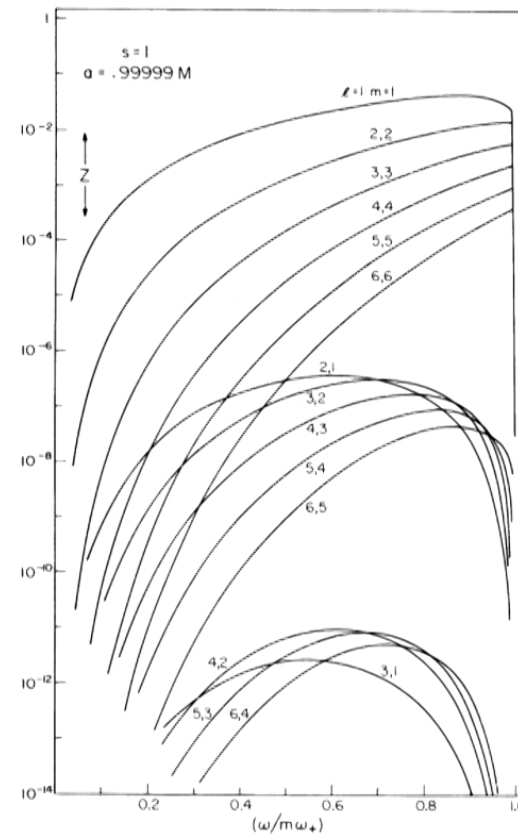
Wave superradiance

- Ingoing flux at horizon can correspond to negative E_∞ flux
- For wave with angular quantum number m ,

$$\varphi \sim e^{i\omega t - im\phi}$$

$$P \sim \varphi_0^2 A_H \omega (\omega - m\Omega_H)$$

- Incoming waves can be scattered with amplification (max 4.4% for spin-1, 138% for spin-2)

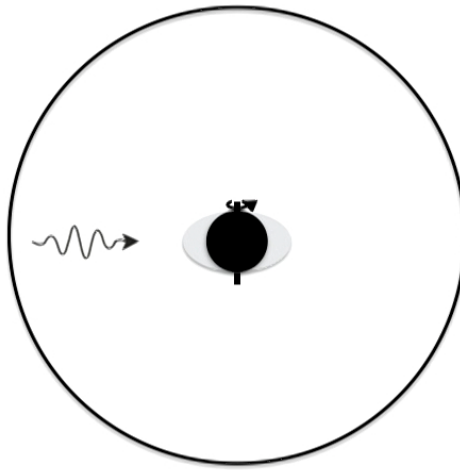


[Teukolsky & Press, 1974]

Black hole bombs and bound states

- “Black hole bomb”: superradiant scattering with a mirror

[Teukolsky & Press, 1972]

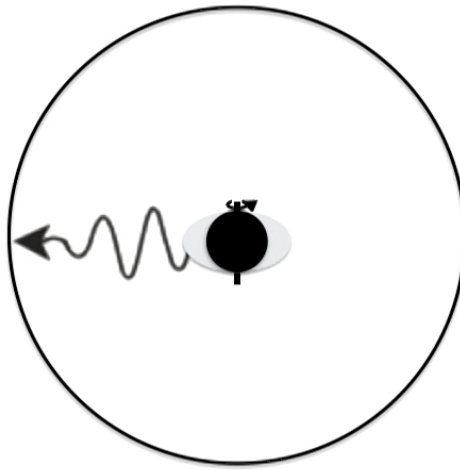


- Massive particles can form bound states around BH, enabling same exponential amplification

Black hole bombs and bound states

- “Black hole bomb”: superradiant scattering with a mirror

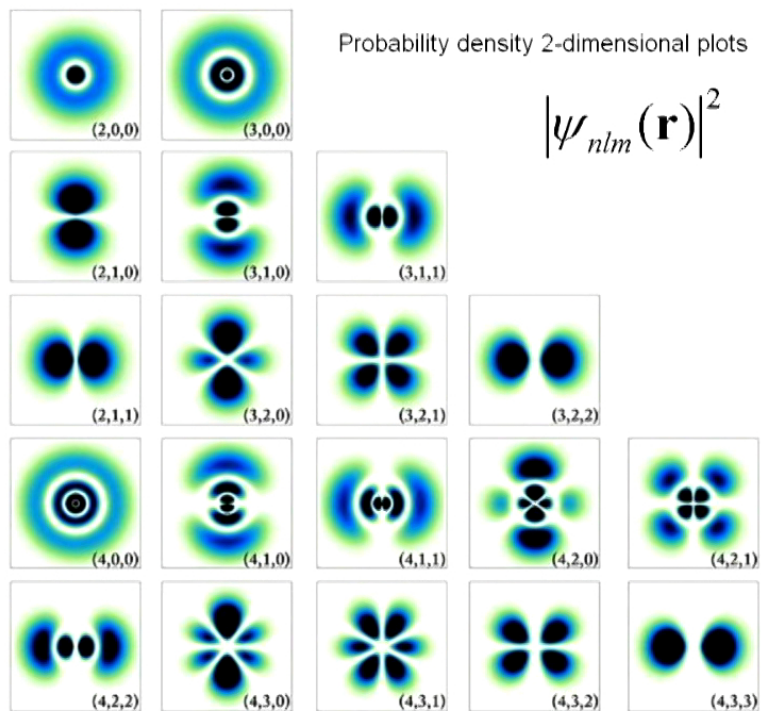
[Teukolsky & Press, 1972]



- Massive particles can form bound states around BH, enabling same exponential amplification

Non-relativistic bound states

- For small mass, bound state spectrum is hydrogen-like



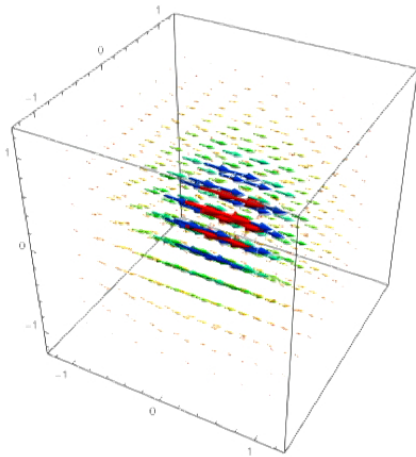
$$\alpha \equiv GM\mu = r_g\mu$$

$$\omega_n \simeq \mu \left(1 - \frac{\alpha^2}{2n^2} \right)$$

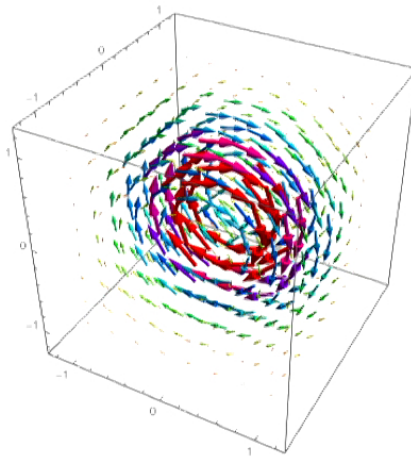
$$r_n \sim \frac{n^2}{\mu\alpha} \sim 4 - 400r_g$$

Vector bound states

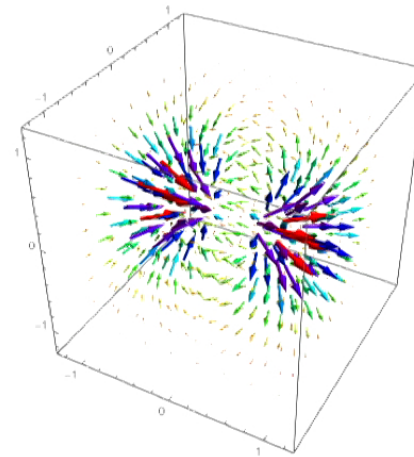
Hydrogen-like radial profile, vector spherical harmonic angular



$$j = 1, l = 0$$



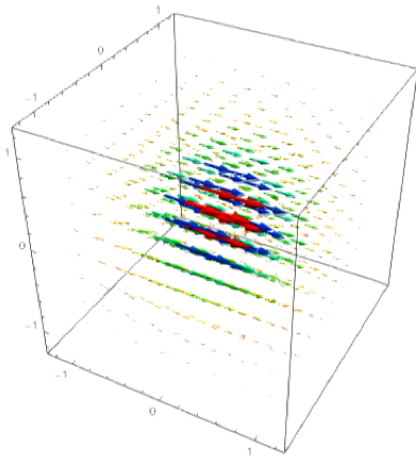
$$j = 1, l = 1$$



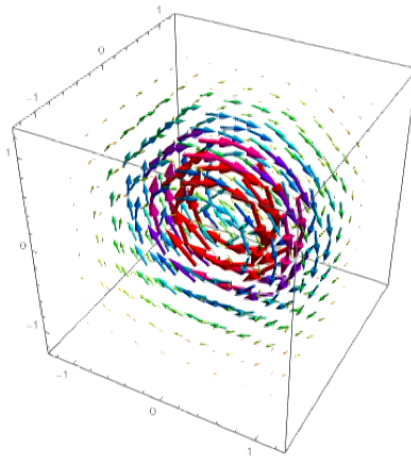
$$j = 1, l = 2$$

Vector bound states

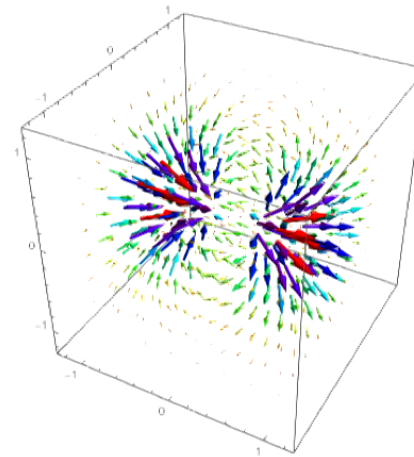
Hydrogen-like radial profile, vector spherical harmonic angular



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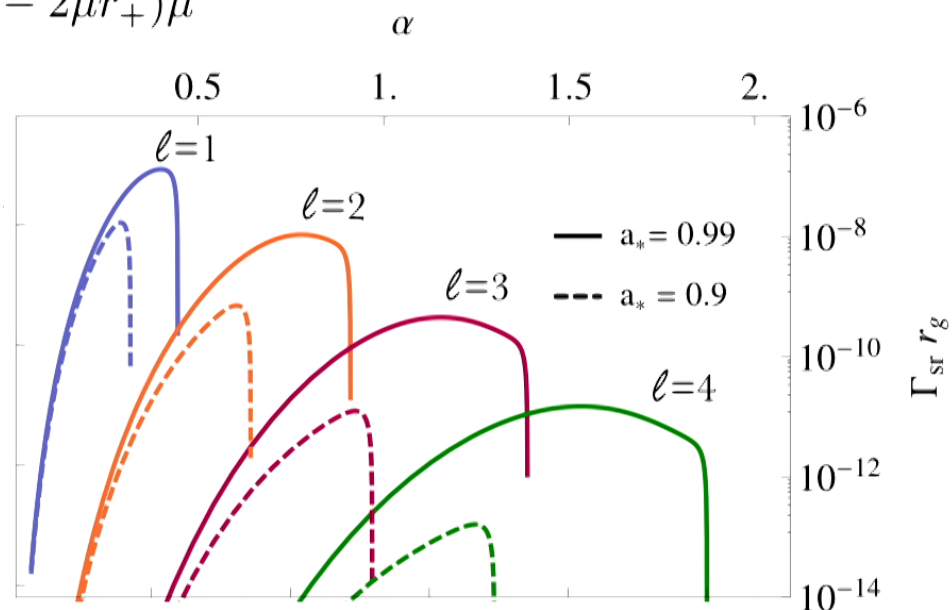
$$j = 1, l = 1$$



$$j = 1, l = 2$$

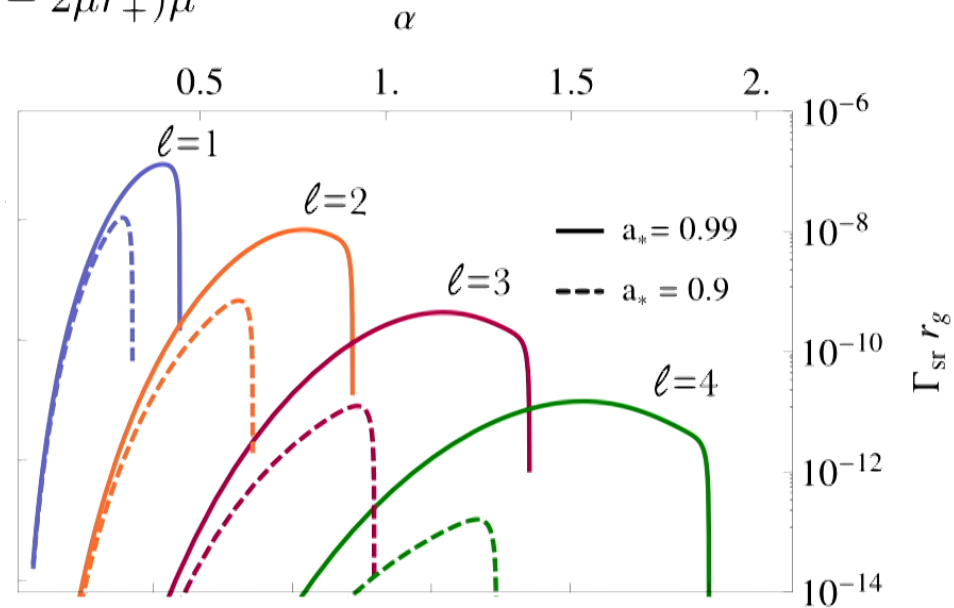
Superradiant growth rates

- For scalar field, energy flux across horizon $\sim A_H \varphi_H^2 \omega (\omega - m \Omega_H)$
- Smaller α , larger $l \Rightarrow$ amplitude near horizon suppressed
 $\text{Im}(\omega) \sim \alpha^{4l+4} (a_* m - 2\mu r_+) \mu$



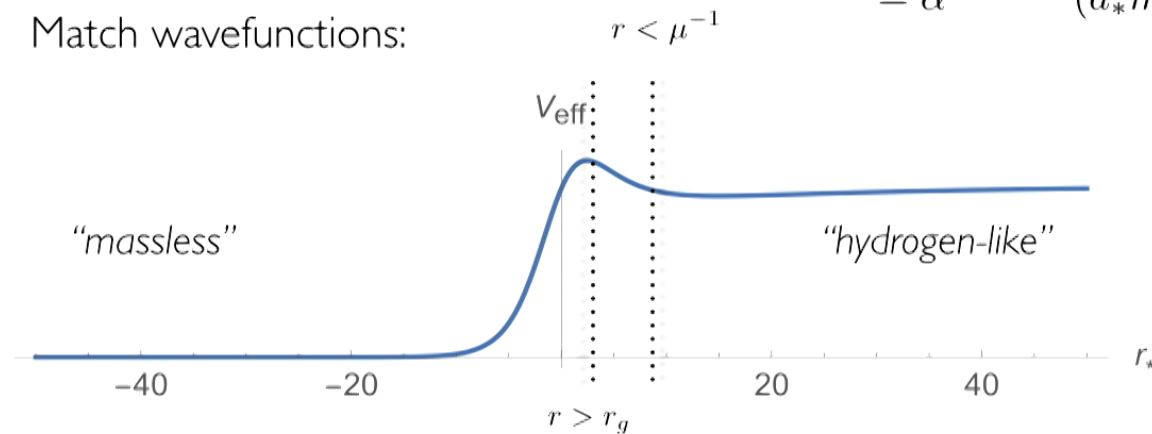
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Vector superradiance rates

- For vector with $j = l + S$, growth rate is $\text{Im}(\omega) \sim \alpha^{4l+2S+4}(a_* m - 2\mu r_+) \mu$
 $= \alpha^{2l+2j+4}(a_* m - 2\mu r_+) \mu$
- Match wavefunctions:



e.g. scalar in Schwarzschild: $V_{\text{eff}}(r) = \left(1 - \frac{2r_g}{r}\right) \left(\mu^2 + \frac{l(l+1)}{r^2} + 2\frac{r_g}{r^3}\right)$

- Massless vector absorption controlled by $\mathbf{j}$, not by $\mathbf{l}$

Vector superradiance rates

- For massless boson, absorption probability is

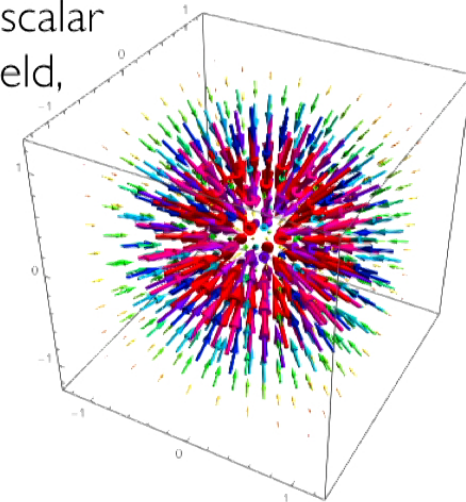
$$\mathbb{P}_{\text{abs}} = \left(\frac{(j-s)!(j+s)!}{(2j)!(2j+1)!!} \right)^2 \prod_{n=1}^j \left[1 + \left(\frac{\omega - m\Omega}{n\kappa} \right)^2 \right] 2 \left(\frac{\omega - m\Omega}{n\kappa} \right) \left(\frac{A\kappa}{2\pi} \omega \right)^{2j+1}$$

- Split light vector into transverse (“massless vector”) and longitudinal (“massless scalar”) modes. Massless scalar component corresponds to A_0 part of vector field,

$$D_\mu A^\mu = 0 \Rightarrow \partial_i A_i \simeq \partial_0 A_0$$

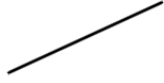
- e.g. monopole mode: $A_0 \sim \frac{1}{\mu a_0} |A_i|_{a_0} Y^{00}$

Decay “through scalar mode” with $\Gamma \simeq \frac{3}{2} \alpha^7 \mu$



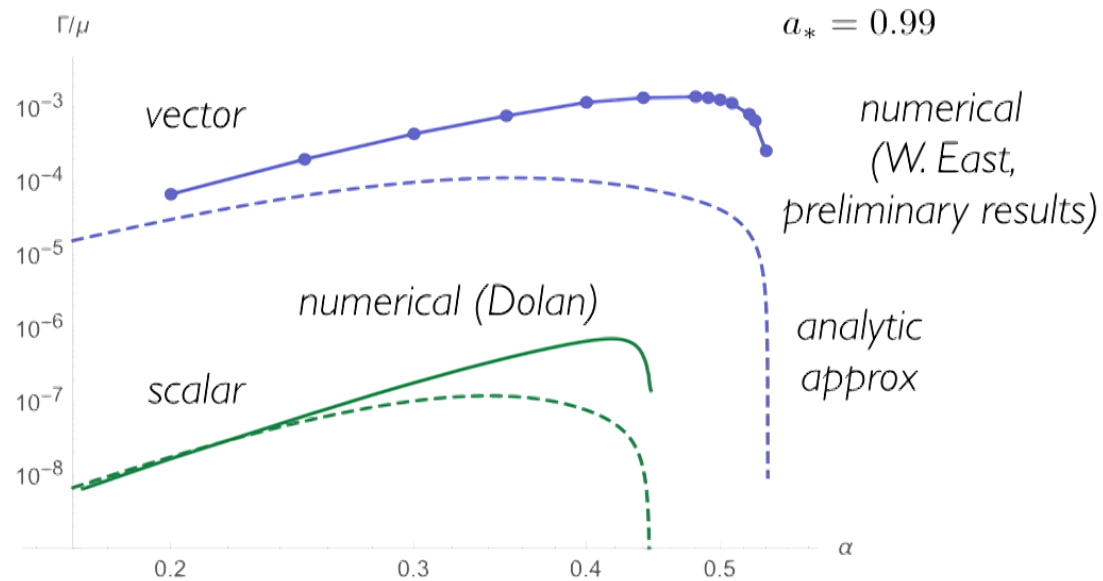
$$j = 0, l = 1$$

Vector superradiance rates

	$l = j - 1$	$l = j$	$l = j + 1$
Leading growth via:	vector	vector	scalar (+vector)
$j = 0$			$-\frac{3}{2}\alpha^7\mu + \dots$
$j = 1$	$\frac{8}{3}a_*\alpha^6\mu + \dots$	$\frac{1}{6}a_*\alpha^8\mu + \dots$	$\frac{16(15 + \sqrt{6})}{177147}a_*\alpha^{10}\mu + \dots$
$j = 2$	$\frac{1}{180}a_*\alpha^{10}\mu + \dots$	$\frac{16}{98415}a_*\alpha^{12}\mu + \dots$	$\frac{140 + 3\sqrt{5}}{110592000}a_*\alpha^{14}\mu + \dots$

For comparison, scalar has fastest growth rate $\frac{1}{24}a_*\alpha^8\mu + \dots$

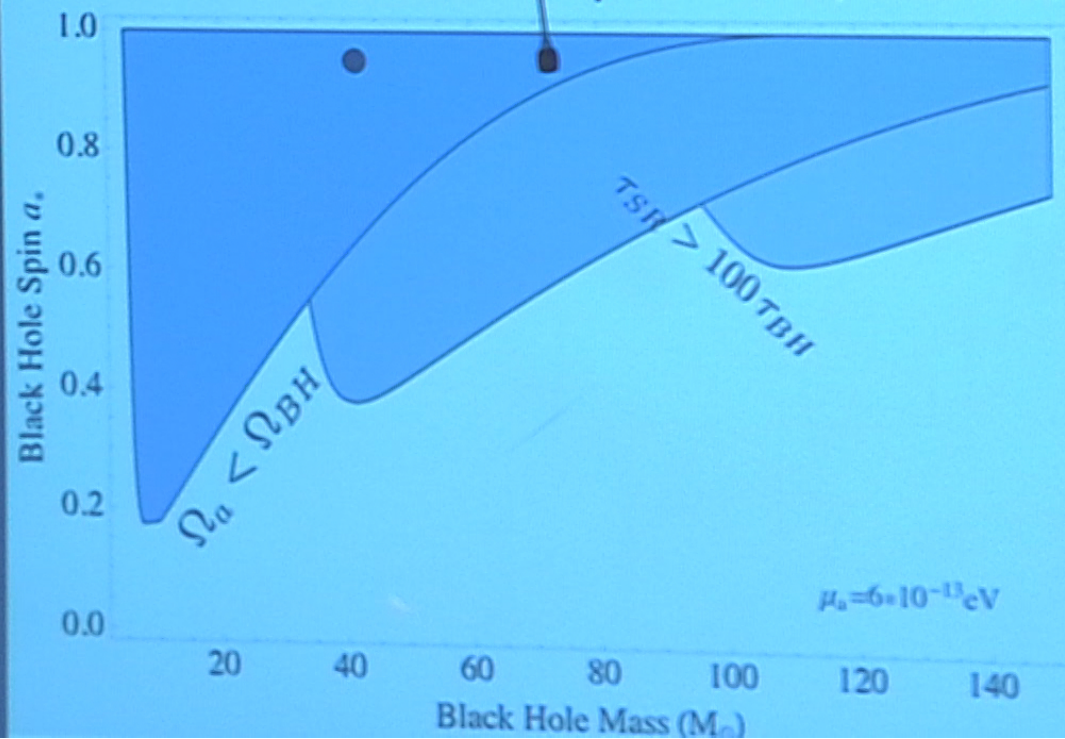
Vector superradiance rates



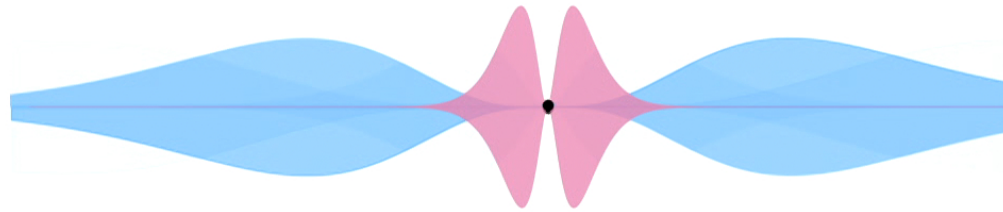
- Analytic expression is accurate to leading order in α , for given a_*
- Not a small a_* approximation

Superradiance: a history

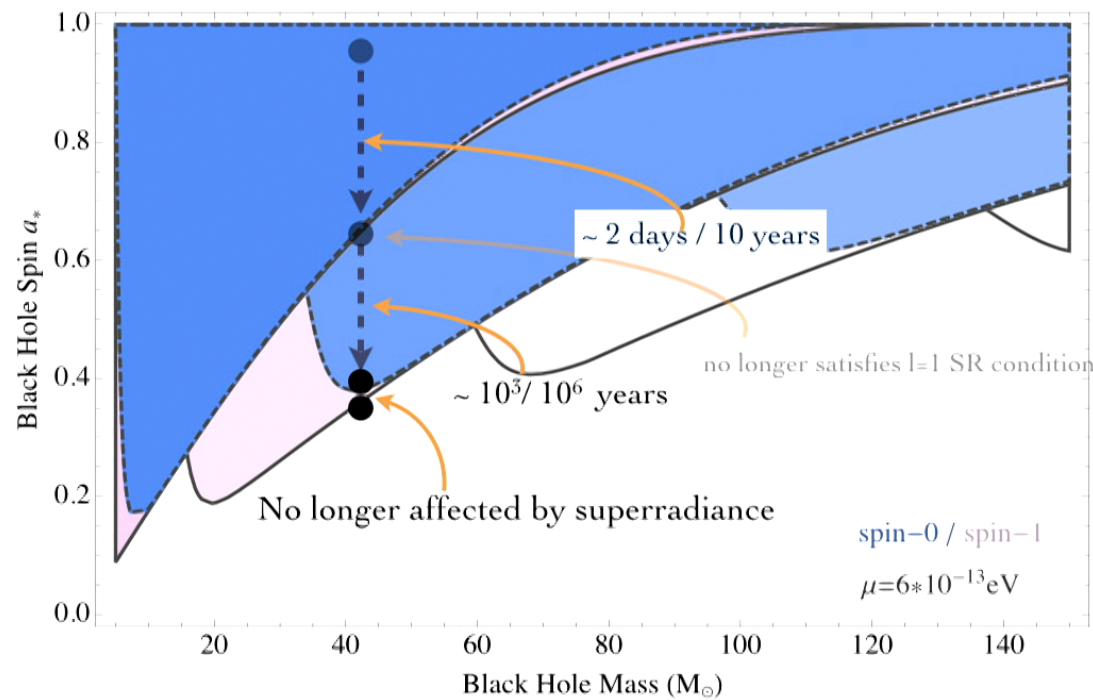
A black hole is born with spin $a^* = 0.95$, $M = 40 M_\odot$.



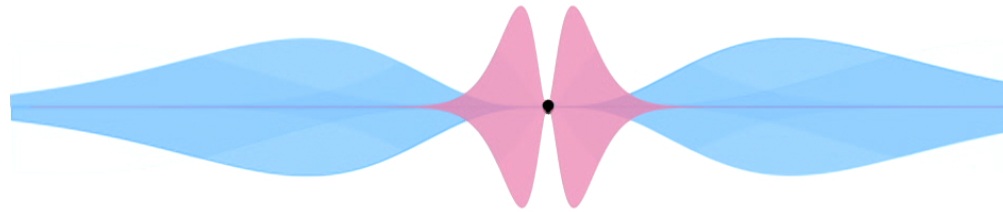
Superradiance: a history



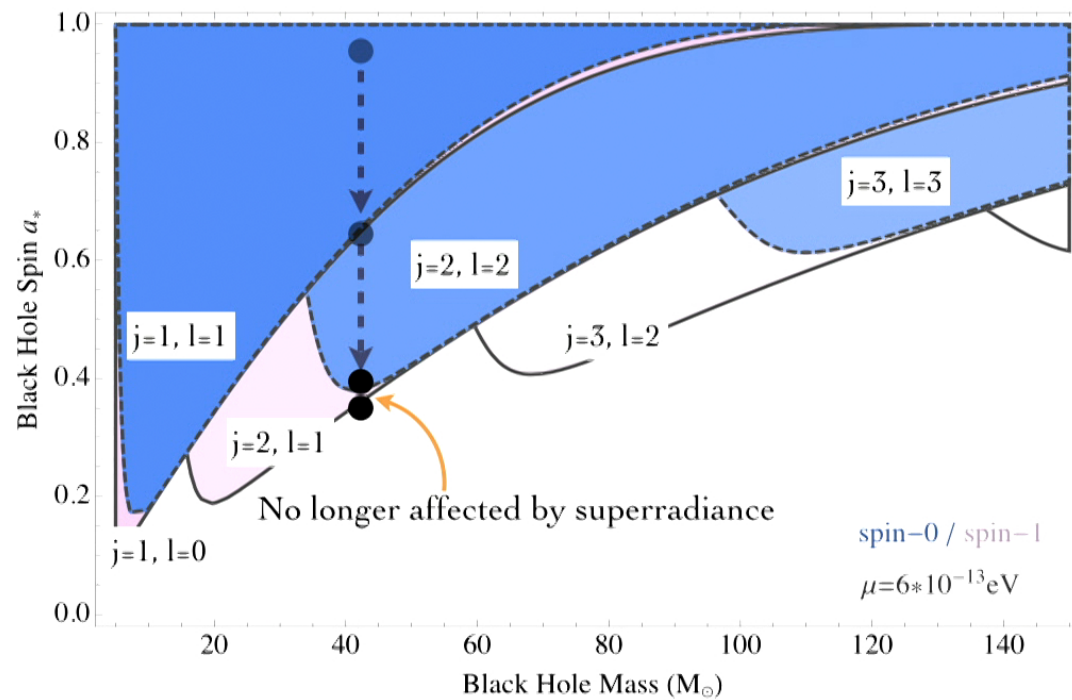
Spin 1 particles: faster superradiance rate for the same mass particle



Superradiance: a history



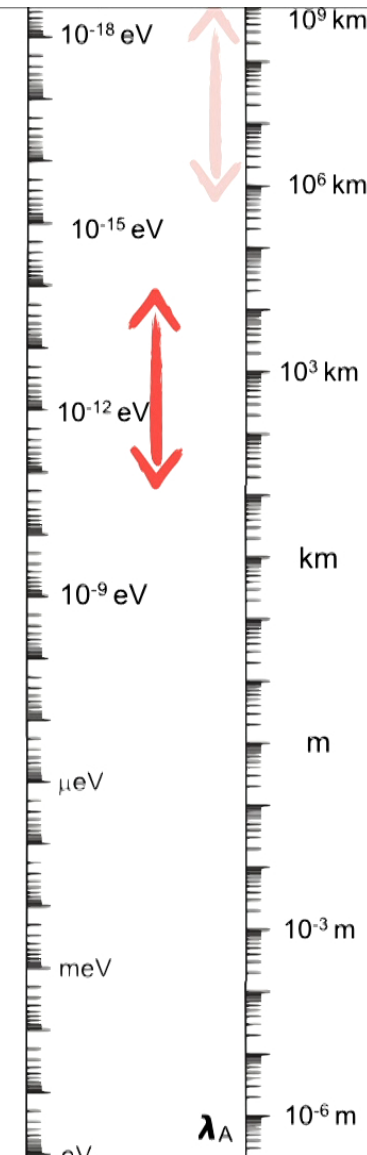
Spin 1 particles: faster superradiance rate for the same mass particle



Vectors can have higher total angular momentum for a given orbital angular momentum

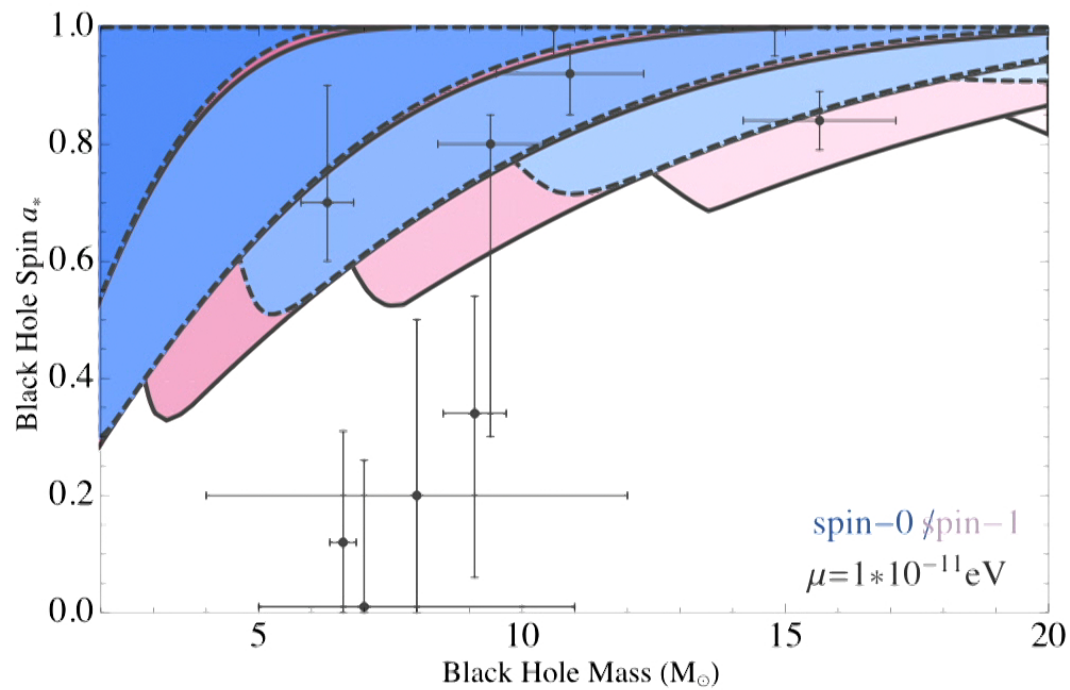
Black hole superradiance for light particles

- Gravitational coupling: can be any light, weakly coupled boson
- $$\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}\mu_a^2\phi^2$$
- $$-\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}\mu_V^2 A_\mu'^2$$
- Depends on particle mass and spin
 - Does not rely on DM density
 - Superradiance is a kinematic effect so does not require precise resonance



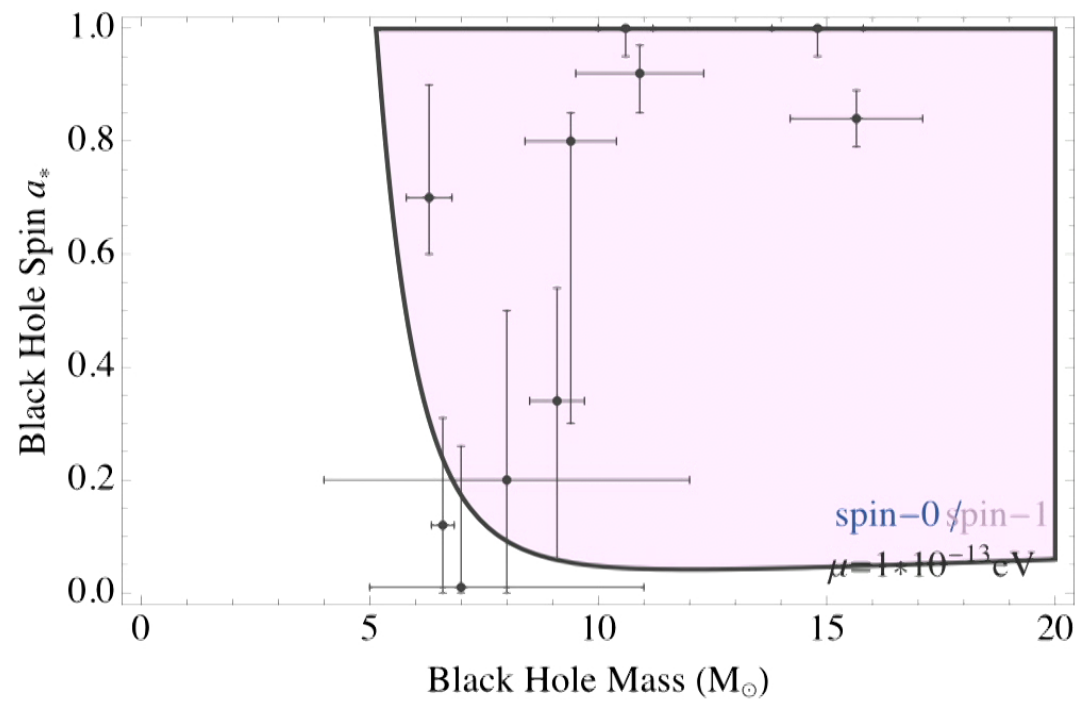
Black Hole Spins

Black hole spin and mass measurements



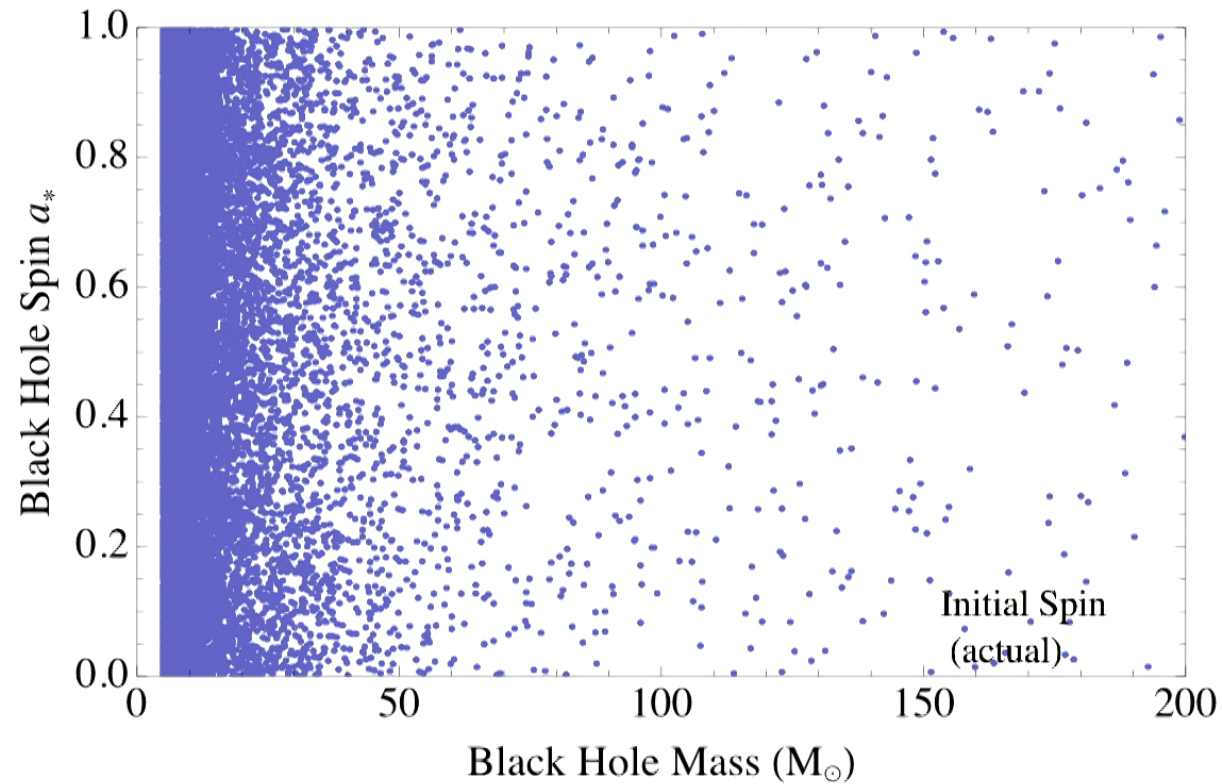
Black Hole Spins

At even lighter masses, constraint is relaxed; SR time is too long



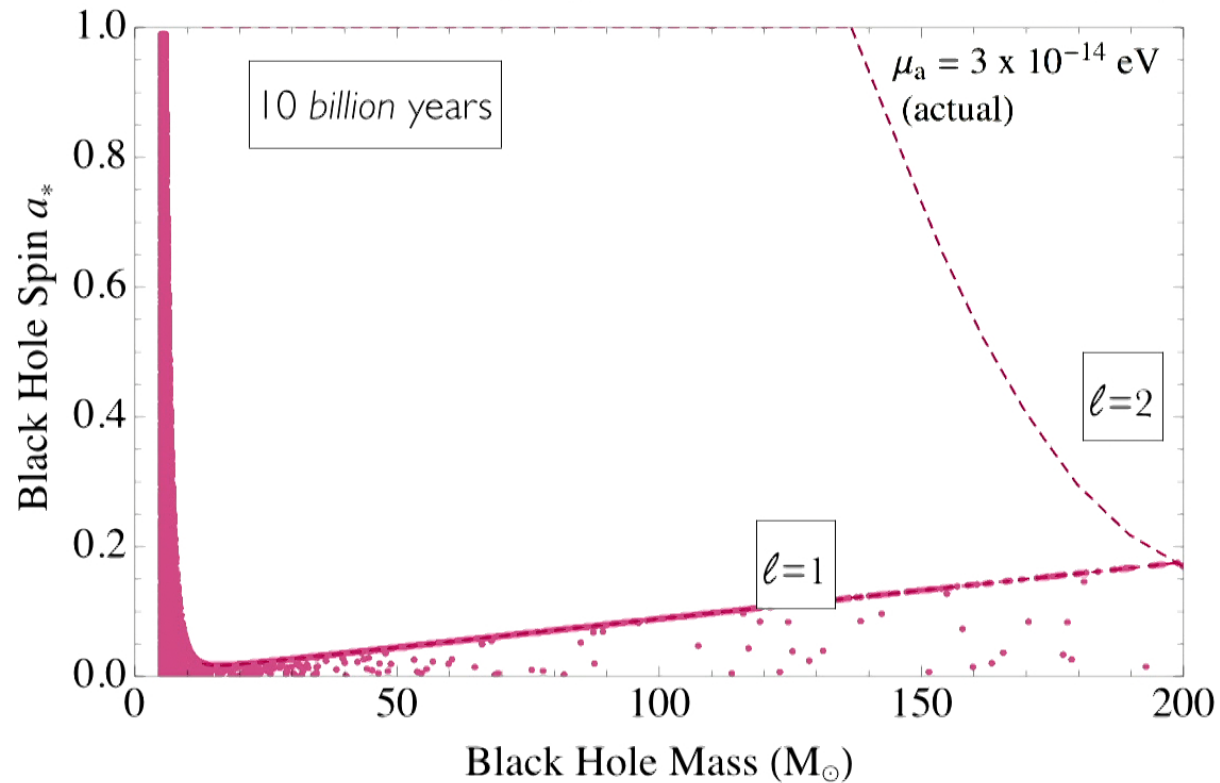
Black Hole Spins at LIGO

9-240 BBHs/Gpc³/yr. — 1000s of BHs merging in
low-redshift universe —



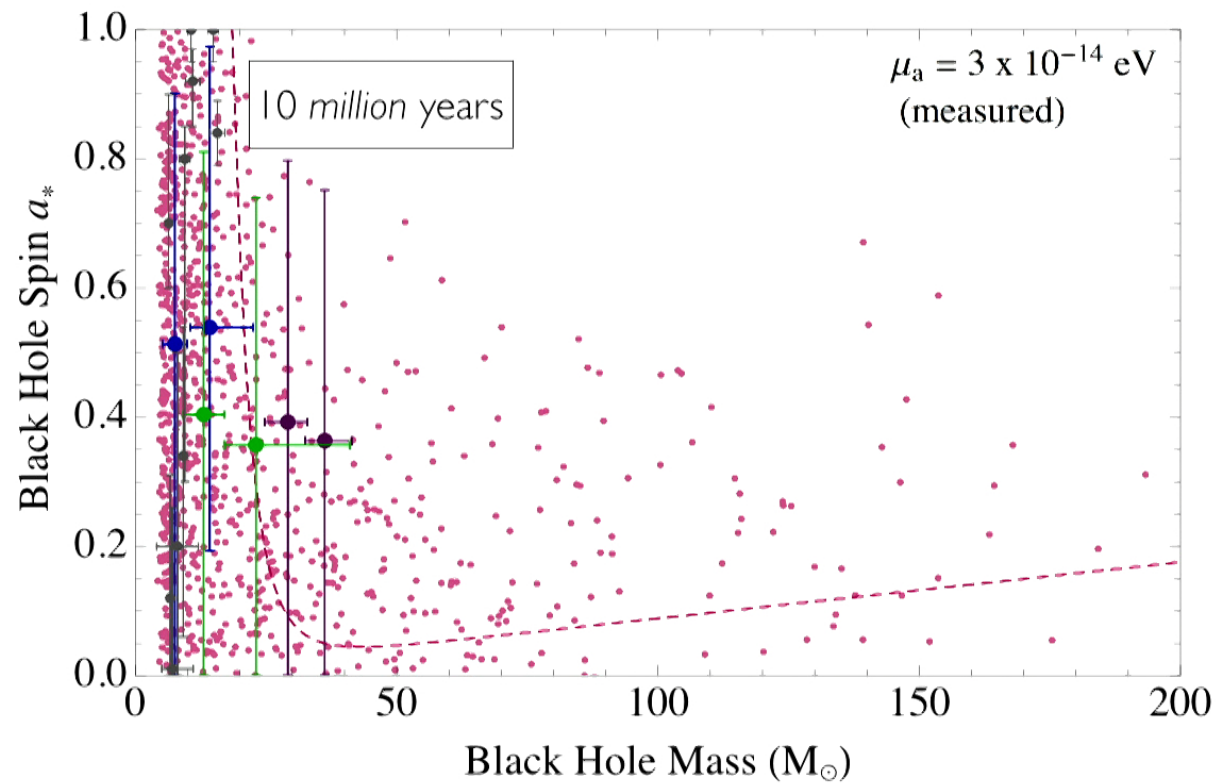
Black Hole Spins

If light vector exists, many of these will spin down due to superradiance, limited by age and radius of binary system



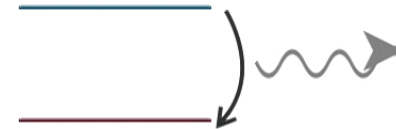
Black Hole Spins

May see spin-down of black holes at LIGO outside of excluded region



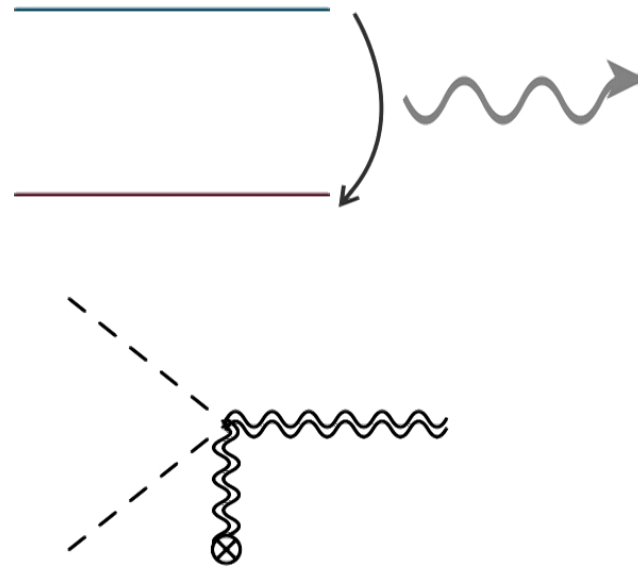
Outline

- Energy extraction from black holes
- Black hole superradiance for light scalar/vector particles
- Observational signatures
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- Coherent gravitational wave emission

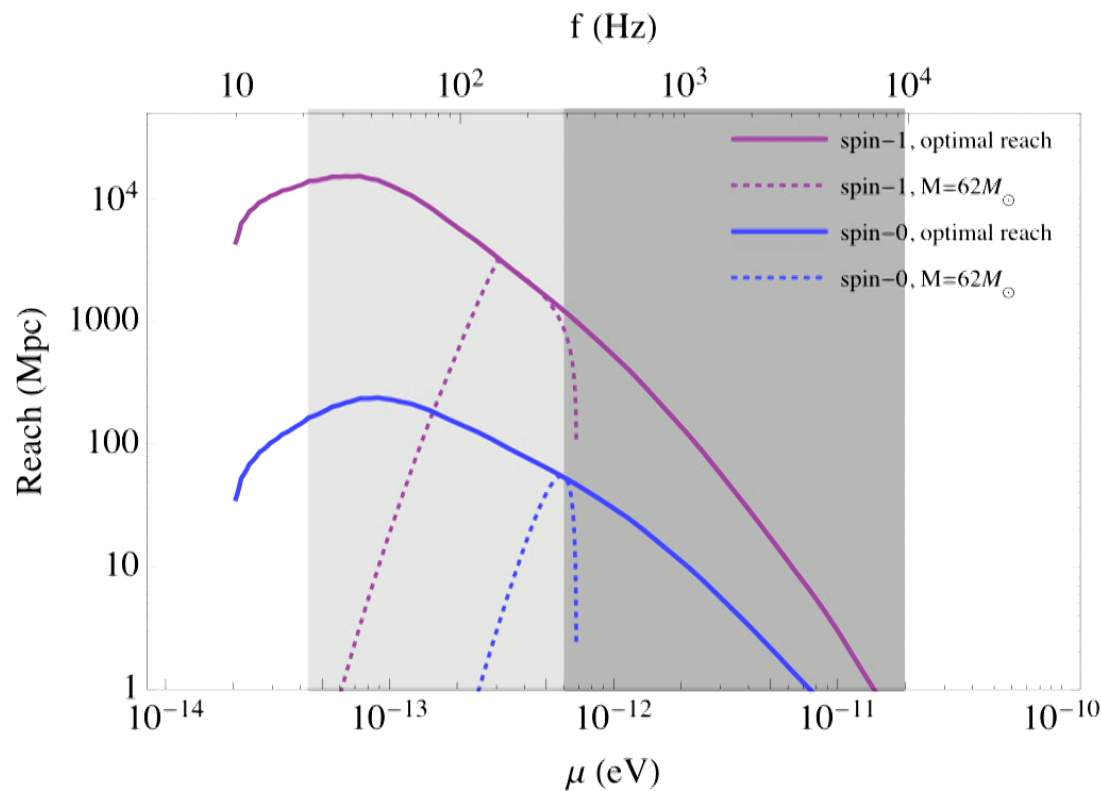
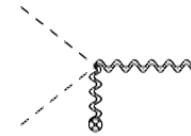


Gravitational Wave Signals

- Transitions between levels
- Annihilations to gravitons



Annihilations



Most of parameter space excluded by spin measurements

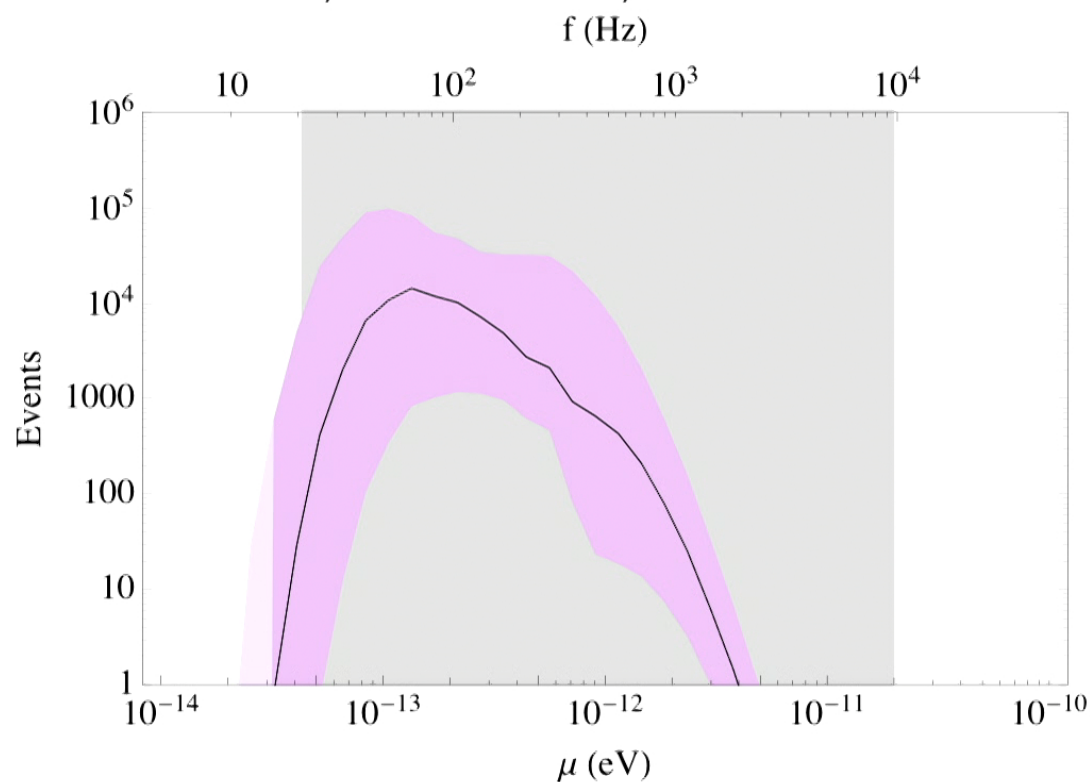
Realistically, limited by number of heavy black holes ($> 100 M_{\text{sun}}$)

Spin-1 particle annihilations give higher rates, although stronger constraints

Annihilations



- Event rates up to 10,000 — can be observed and studied in detail
- Uncertainty dominated by BH mass distribution at higher masses



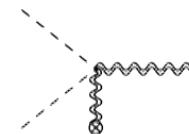
Long, weak signals
visible from galactic
center, limited by
LIGO noise floor

Shorter signals visible
from ~ 1000 Mpc

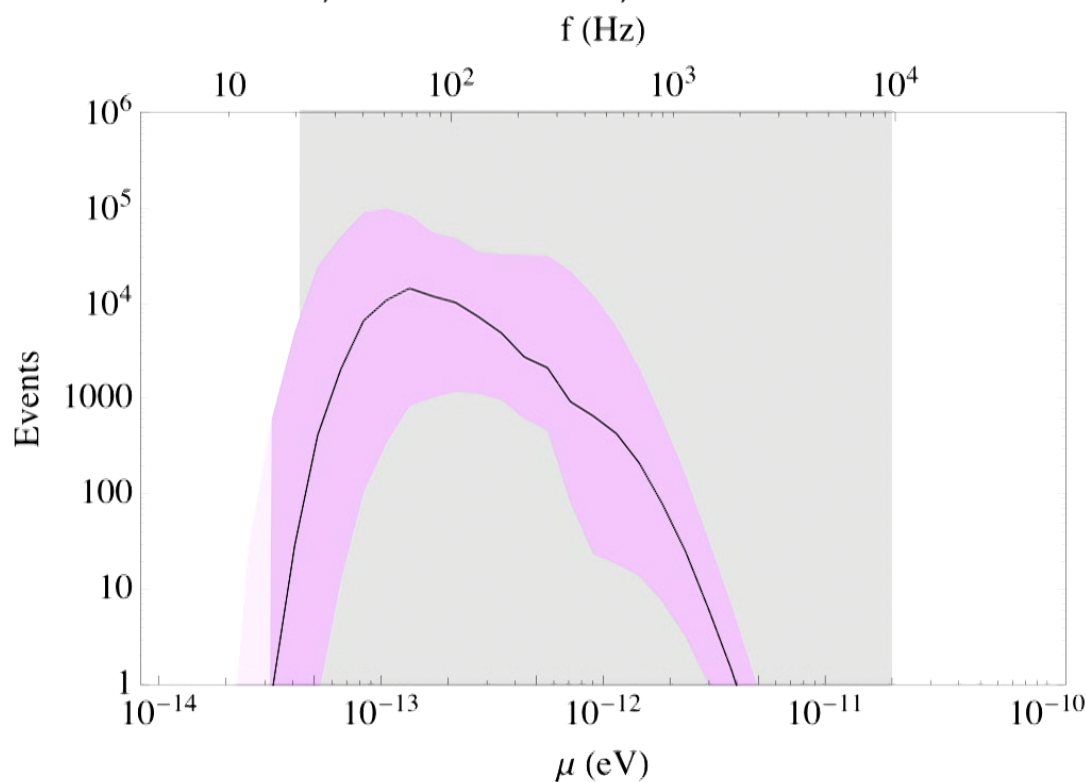
Signals coherent
and
monochromatic

Cross-check
spin limits

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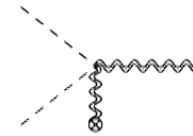
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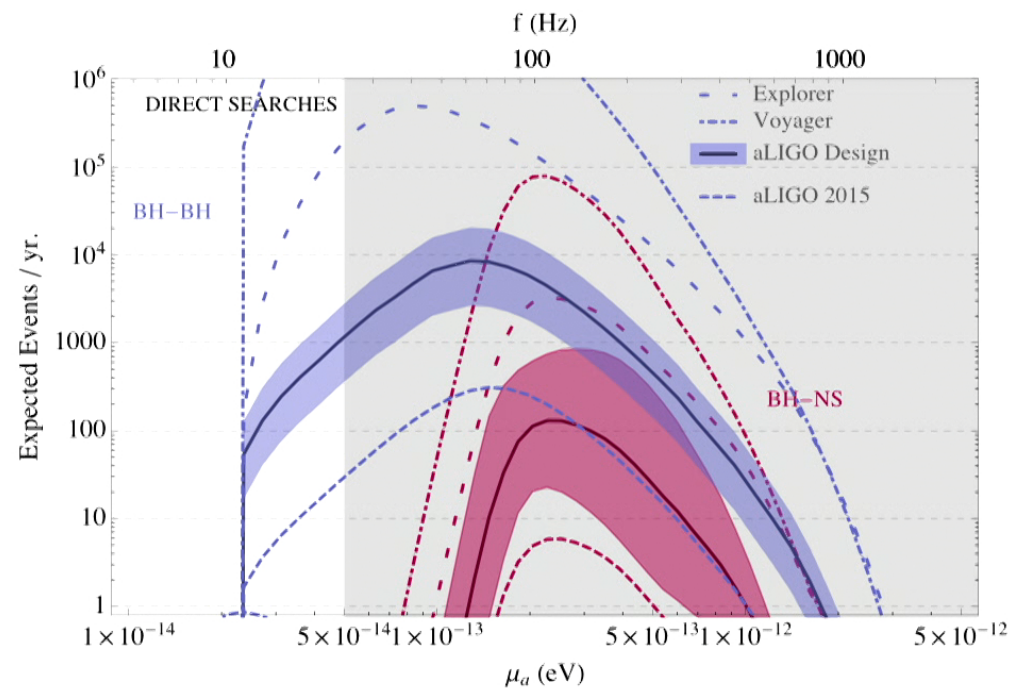
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Annihilations



- Mergers at LIGO: a black hole is born!
- Follow up with continuous wave search to see if superradiance creates a cloud of axions around the new BH



Conclusions

- Ultra light vectors can be constrained or discovered by measurements of astrophysical black holes
- Independent of background density and coupling
- BH spin measurements exclude previously open parameter space
- Advanced LIGO may measure thousands of BH spins and provide evidence of a new light particle
- Continuous GW signals may be observable from annihilations of vectors
- May observe growth of gravitational atom after a merger in real time

