

Title: Searching for Ultralight Particles with Gravitational Waves

Date: Jun 11, 2018 02:00 PM

URL: <http://pirsa.org/18060047>

Abstract:

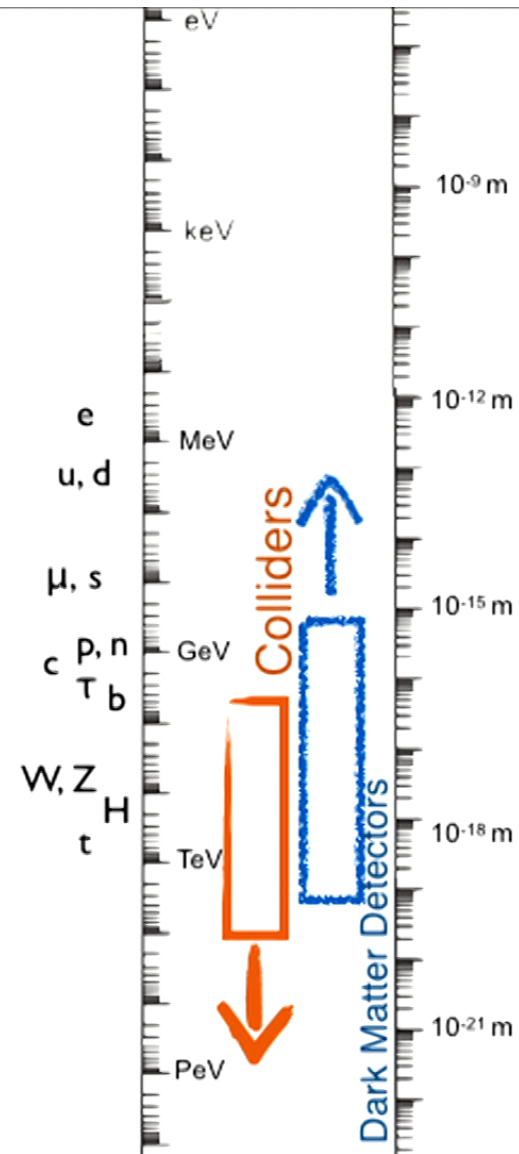
Searching for Ultralight Particles with Gravitational Waves

Masha Baryakhtar
Perimeter Institute
June 11, 2018



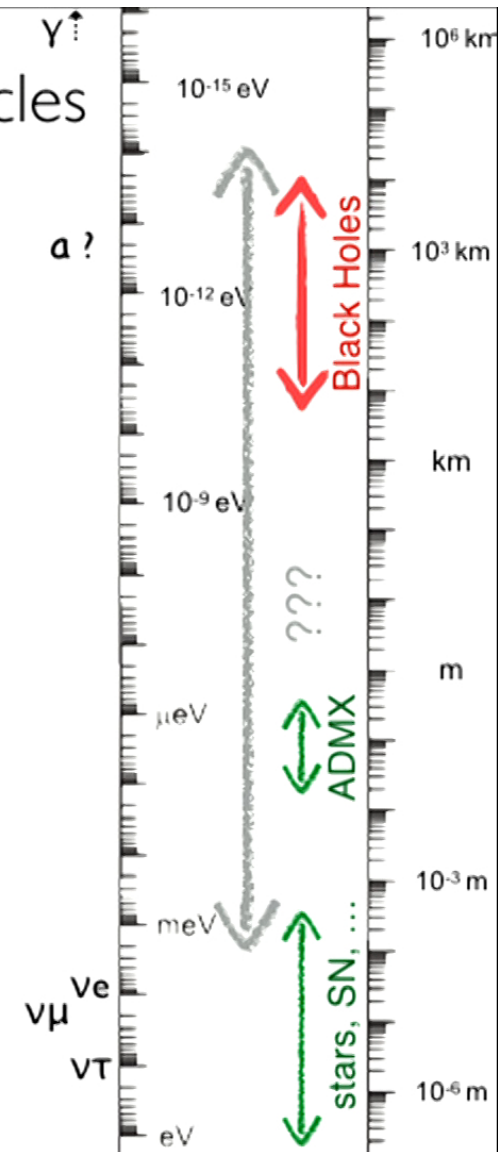
Searching for New Particles

- Going beyond the Standard Model of particle physics — going to higher energies?
- Some of the outstanding problems motivate going to lower energies



Searching for New (Ultra)Light Particles

- Going beyond the Standard Model of particle physics — going to higher energies?
- Some of the outstanding problems motivate going to lower energies
- Dark matter, strong-CP problem, ...
 - QCD axion
 - Dilatons, moduli, dark photons, ...
 - Very weakly interacting
 - Long wavelength



Searching for New (Ultra)Light Particles

- The QCD axion is one of the best motivated BSM particles
- Solves the strong-CP problem

$$\mathcal{L} \supset \frac{\alpha_s}{8\pi} \theta G\tilde{G}$$

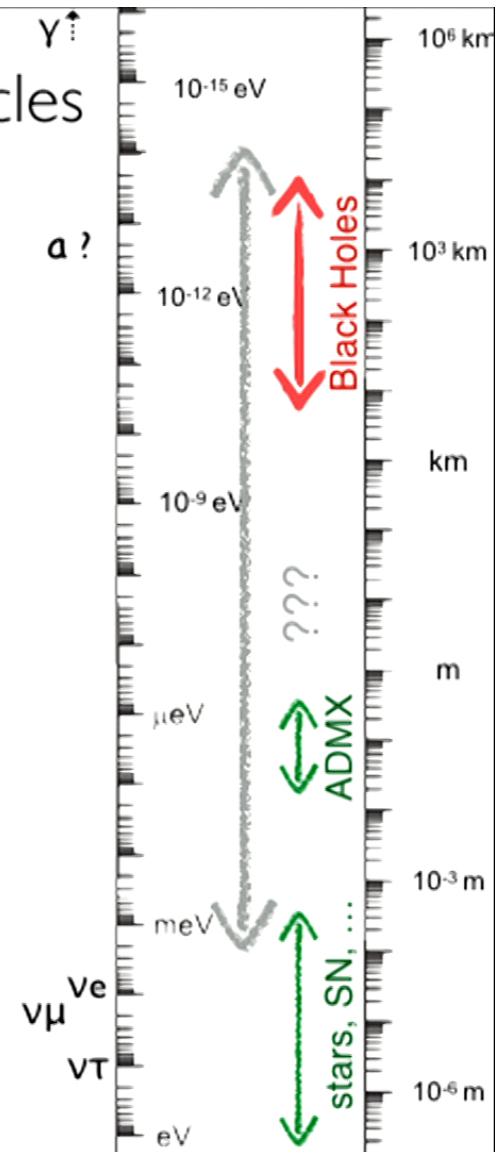
↓

$$\mathcal{L} \supset \frac{\alpha_s}{8\pi} \frac{a}{f_a} G\tilde{G}$$

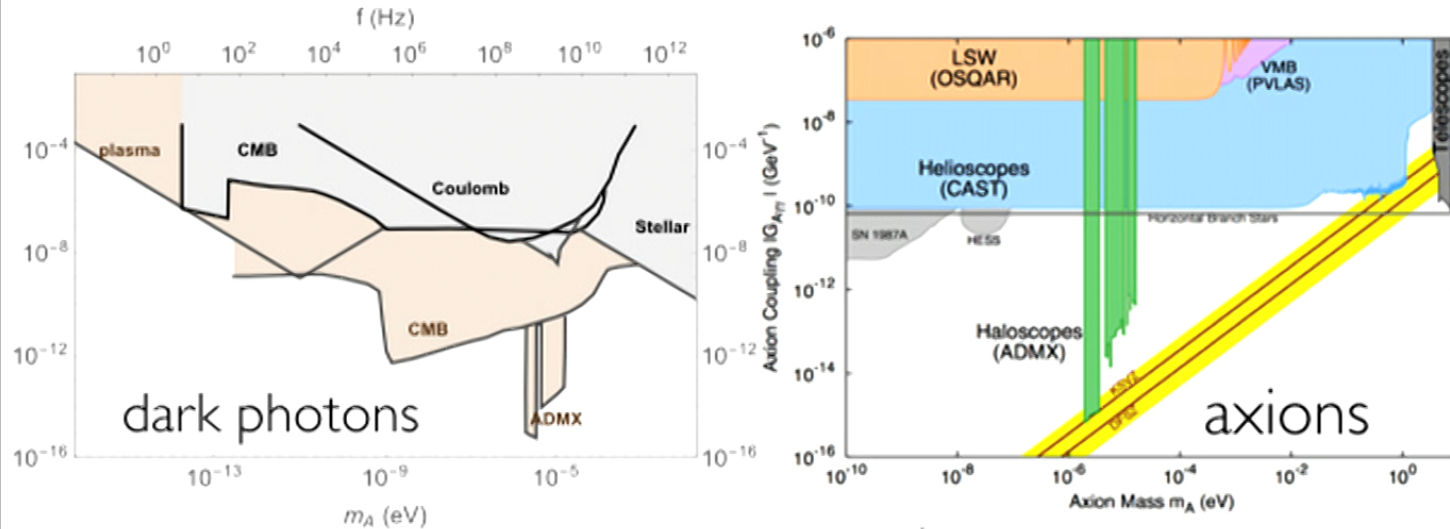
- Very weakly interacting
- Large compton wavelength

$$\mu_a \sim 6 \times 10^{-11} \text{ eV} \frac{10^{17} \text{ GeV}}{f_a} \quad \lambda_a \sim 3 \text{ km} \frac{6 \times 10^{-11} \text{ eV}}{\mu_a}$$

R. Peccei and H. R. Quinn, Phys.Rev.Lett., **38**, 1440 (1977); S. Weinberg, *ibid.*, **40**, 223 (1978); F. Wilczek, *ibid.*, **40**, 279 (1978).



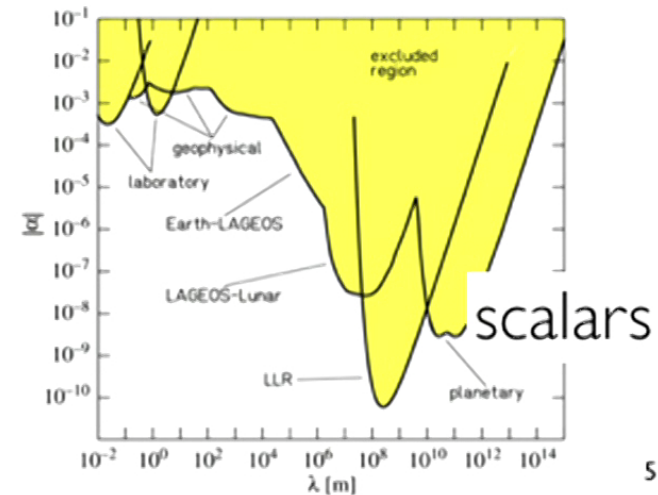
Searching for Ultralight particles



Spin 0 and spin 1, weakly interacting

$$\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}\mu_a^2\phi^2$$

$$-\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}\mu_V^2 A_\mu'^2$$



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Outline

- Black Hole Superradiance



- Spinning Black Holes



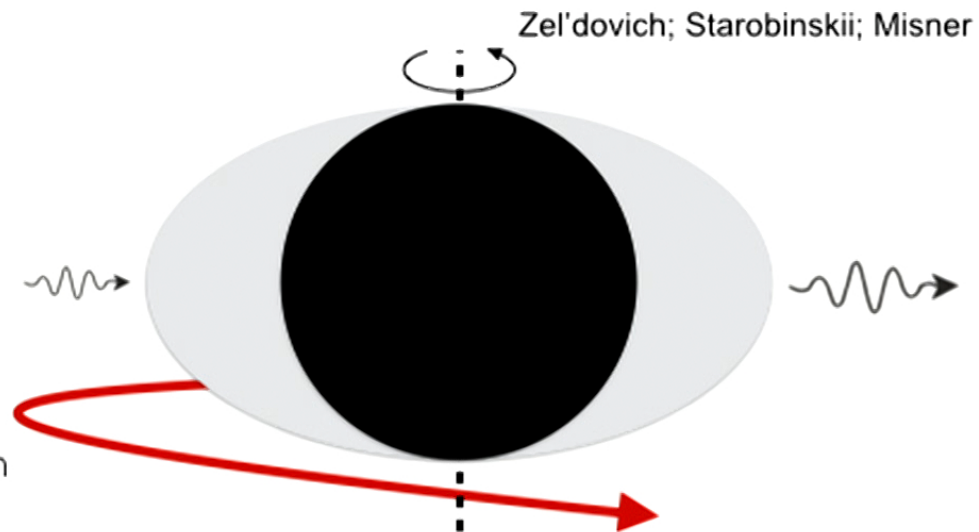
- Gravitational Wave Signals



Superradiance

A wave scattering off a rotating object can increase in amplitude by extracting angular momentum and energy.

Growth proportional to probability of absorption when rotating object is at rest: dissipation necessary to change the wave amplitude



Superradiance condition:

Angular velocity of wave slower than angular velocity of BH horizon,

$$\Omega_a < \Omega_{BH}$$

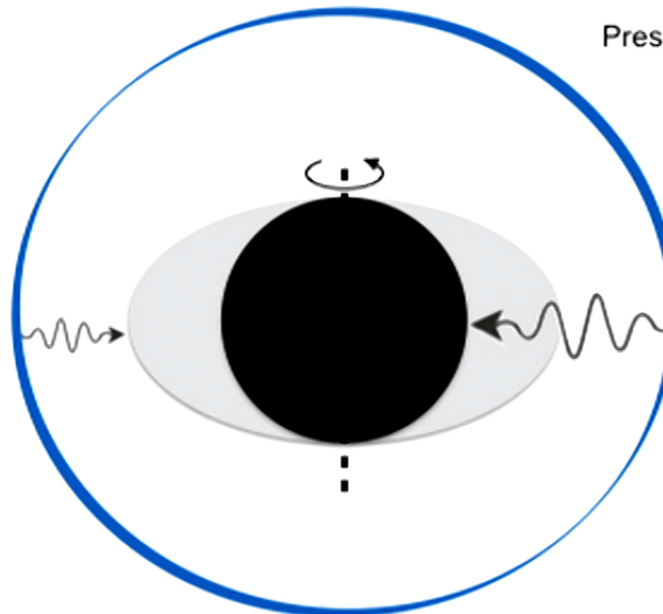
Superradiance

Particles/waves trapped in orbit around the BH repeat this process continuously

Press & Teukosky

"Black hole bomb":
exponential instability when
surround BH by a mirror

Kinematic, not resonant
condition



Superradiance condition:

Angular velocity of wave slower than angular velocity of BH horizon,

$$\Omega_a < \Omega_{BH}$$

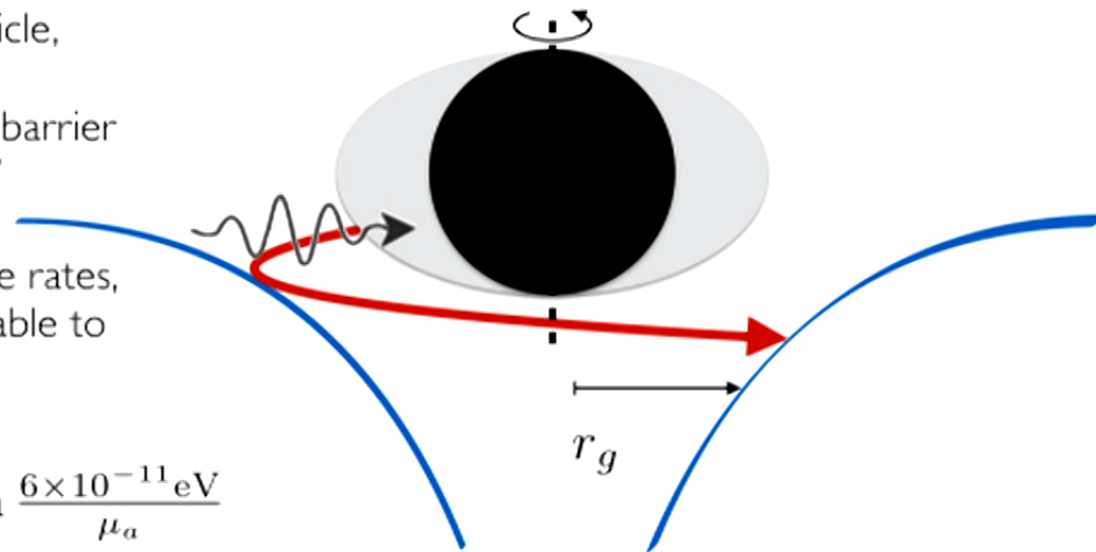
Superradiance

$$V(r) = -\frac{G_N M_{BH} \mu_a}{r}$$

For a massive particle,
e.g. axion,
gravitational potential barrier
acts as "mirror"

For high superradiance rates,
"mirror" size comparable to
BH size:

$$r_g \lesssim \mu_a^{-1} \sim 3 \text{ km} \frac{6 \times 10^{-11} \text{ eV}}{\mu_a}$$



[Zouros & Eardley'79; Damour et al '76; Detweiler'80; Gaina et al '78]

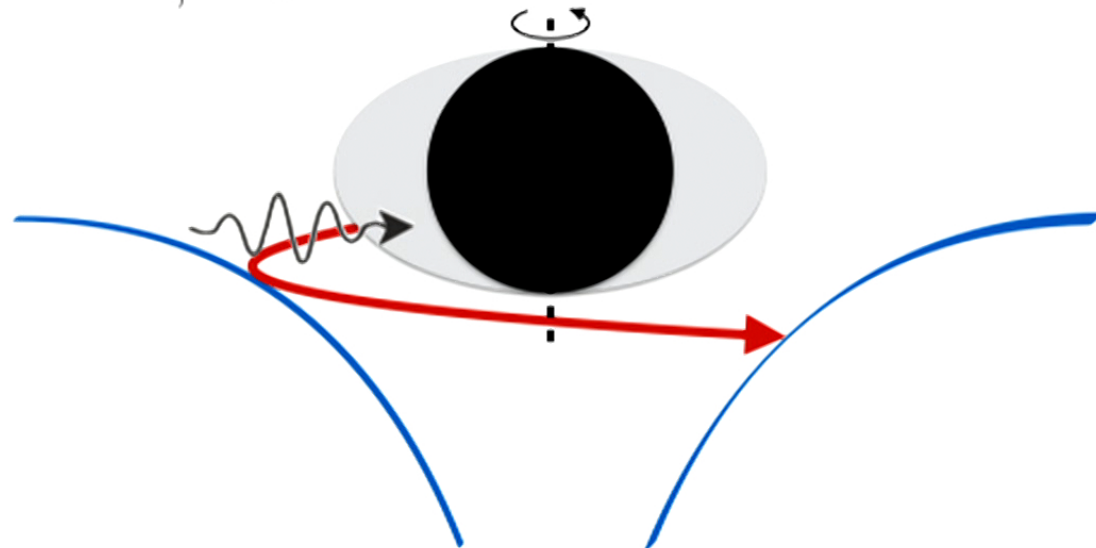
[Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell 2009; Arvanitaki, Dubovsky 2010]

Superradiance

For a massive particle,
"mirror" is created by
potential barrier

$$V(r) = -\frac{G_N M_{BH} \mu_a}{r}$$

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



Angular velocity of wave slower than angular velocity of BH horizon,

Superradiance condition: $\frac{\omega_a}{m} < \Omega_{BH}$ (m = magnetic quantum number)

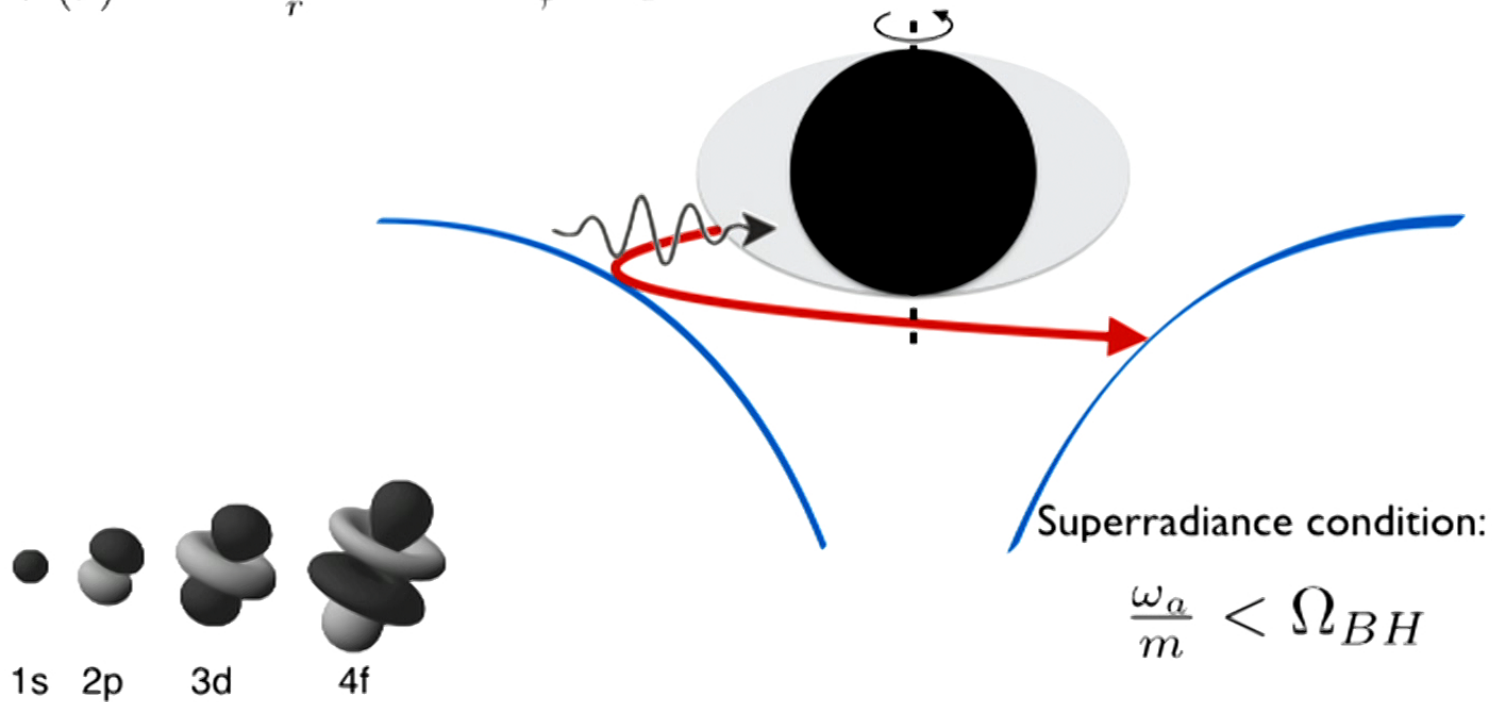
12

Superradiance

For a massive particle,
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$$V(r) = -\frac{G_N M_{BH} \mu_a}{r}$$

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



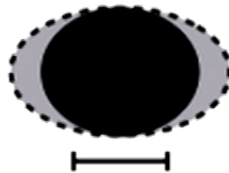
(m = magnetic quantum number)₁₃

Black holes and gravitational atoms

Black holes are nature's detectors

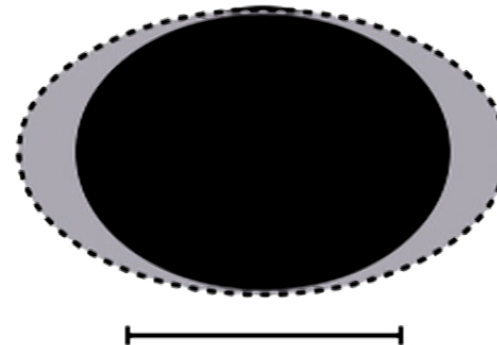
Supermassive black holes:

Stellar black holes:



$$(15 \text{ km}) \times (M / 10 M_{\odot})$$

$\sim 10^8 - 10^9$ in our galaxy
Sensitive to axion masses $10^{-13} - 10^{-11} \text{ eV}$



$$(1.5 \times 10^7 \text{ km}) \times (M / 10^7 M_{\odot})$$

Found at the centers of galaxies
Sensitive to axion masses $10^{-19} - 10^{-16} \text{ eV}$

Superradiance: Gravitational Atoms

$$V(r) = -\frac{G_N M_{BH} \mu_a}{r}$$

Hydrogen atoms

Gravitational 'atoms'

`Fine structure constant`

$$\alpha_{em}$$

$$\alpha = G_N M_{BH} \mu_a = r_g \mu_a$$

Radius

$$r_B = \frac{n^2}{\alpha_{em} m_e}$$

$$r_c \sim \frac{n^2}{\alpha \mu_a} \sim 4 - 400 r_g$$

Occupation number

$$N = 1$$

$$N \sim 10^{70} - 10^{80}$$

— classical field

Boundary conditions

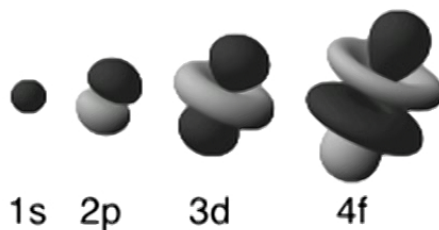
regular at origin

ingoing at horizon

Energy levels

$$m_e \left(1 - \frac{\alpha_{em}^2}{2n^2} \right)$$

$$\mu_a \left(1 - \frac{\alpha^2}{2n^2} + i\Gamma_{sr} \right)$$



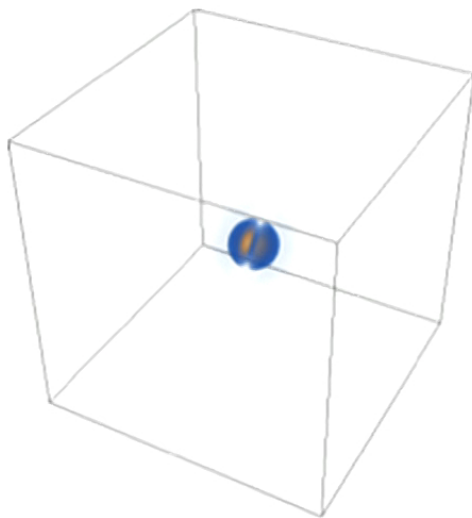
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$$\frac{\omega_a}{m} < \Omega_{BH}$$

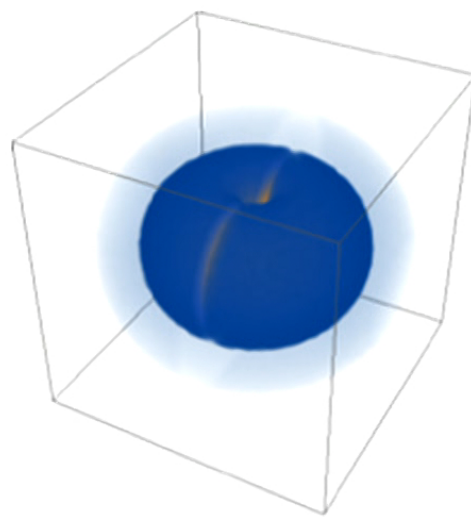
(m = magnetic quantum number)

15

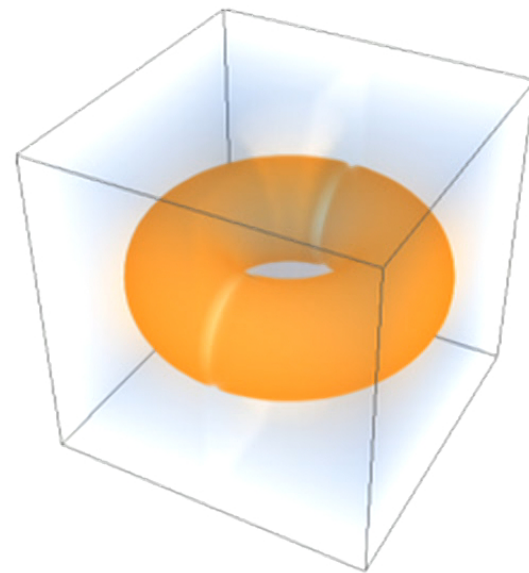
Gravitational Atoms: Scalar bound states



$l = 0$



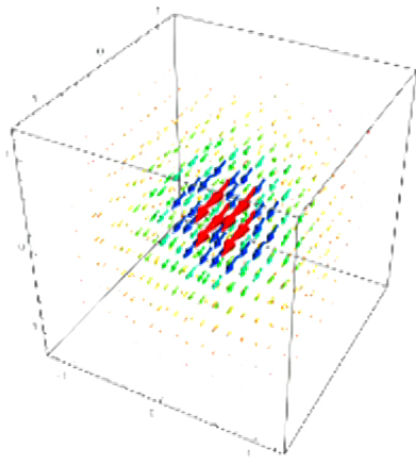
$l = 1$



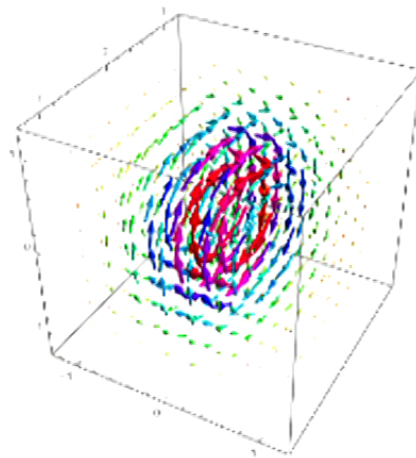
$l = 2$

Superradiance: Vector Gravitational Atoms

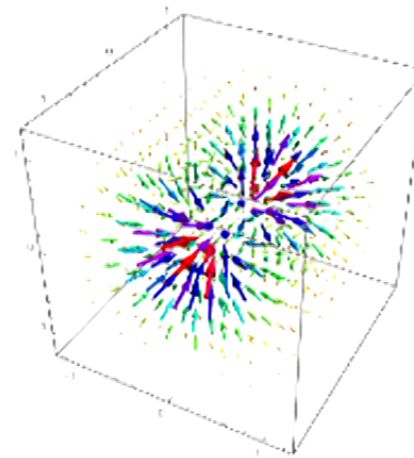
Hydrogen-like radial profile, vector spherical harmonic angular



$$j = 1, l = 0$$



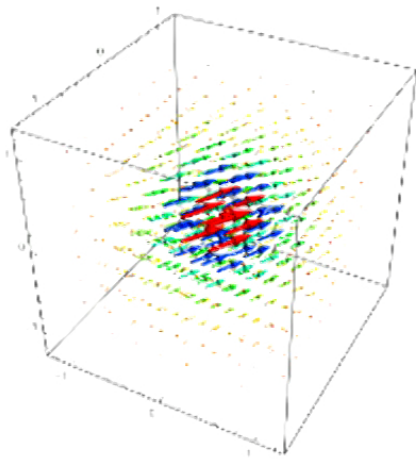
$$j = 1, l = 1$$



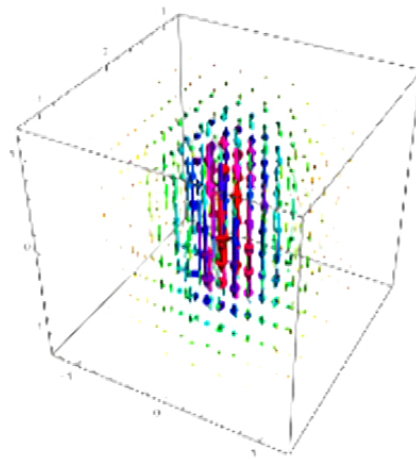
$$j = 1, l = 2$$

Superradiance: Vector Gravitational Atoms

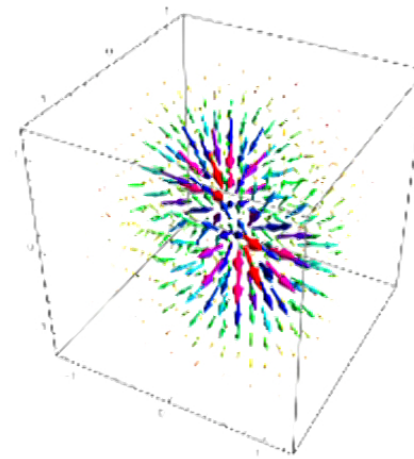
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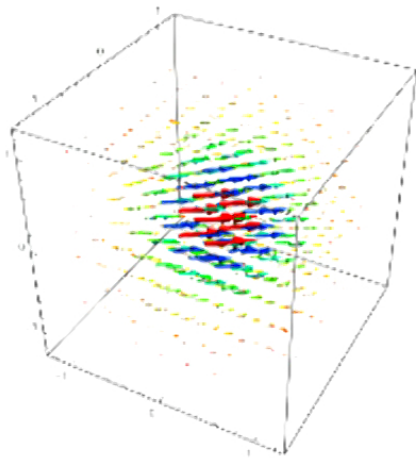
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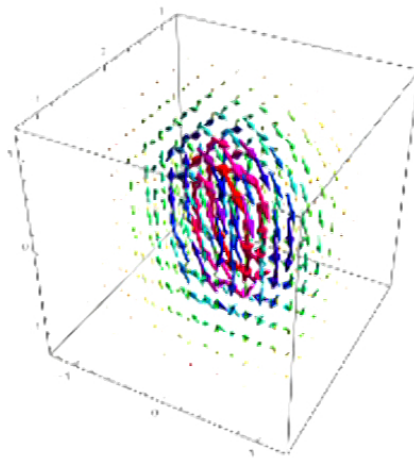
$$j = 1, l = 2$$

Superradiance: Vector Gravitational Atoms

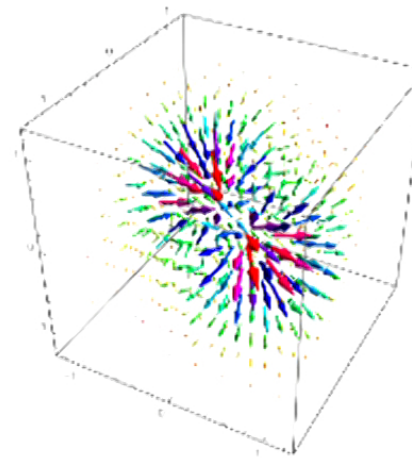
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$$j = 1, l = 0$$



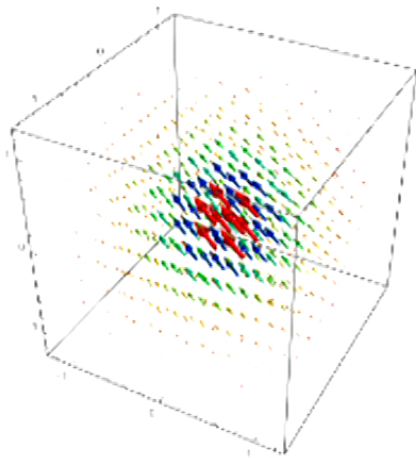
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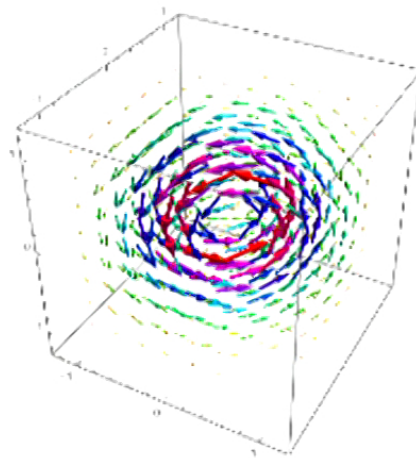
$$j = 1, l = 2$$

Superradiance: Vector Gravitational Atoms

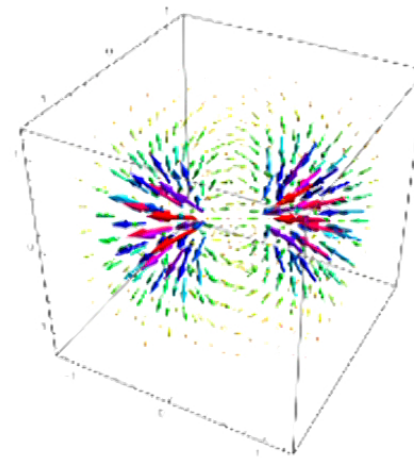
Hydrogen-like radial profile, vector spherical harmonic angular



$$j = 1, l = 0$$



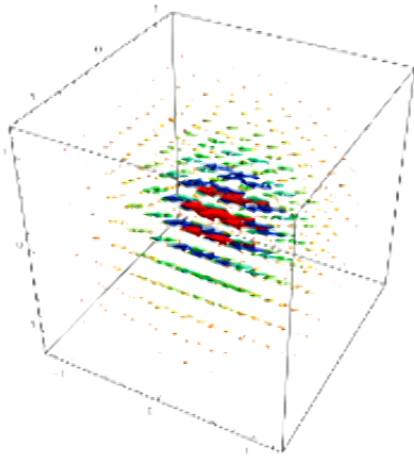
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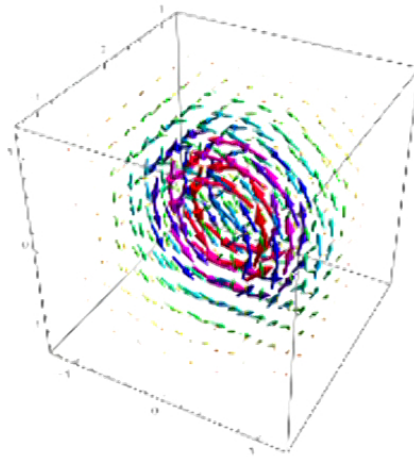
$$j = 1, l = 2$$

Superradiance: Vector Gravitational Atoms

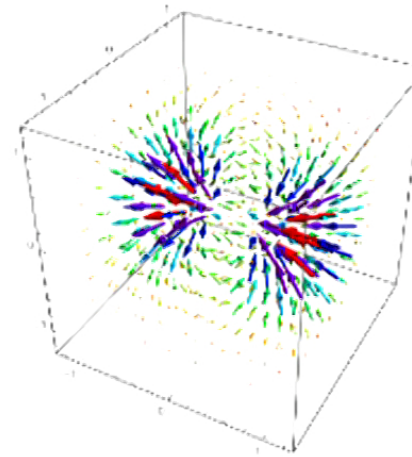
Hydrogen-like radial profile, vector spherical harmonic angular



$$j = 1, l = 0$$



$$j = 1, l = 1$$



$$j = 1, l = 2$$

Gravitational Atoms

$$V(r) = -\frac{G_N M_{BH} \mu_a}{r}$$

Hydrogen atoms

Gravitational 'atoms'

`Fine structure constant`

$$\alpha_{em}$$

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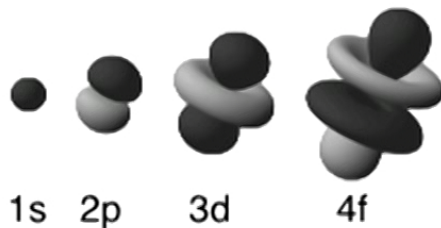
regular at origin

ingoing at horizon

Energy levels

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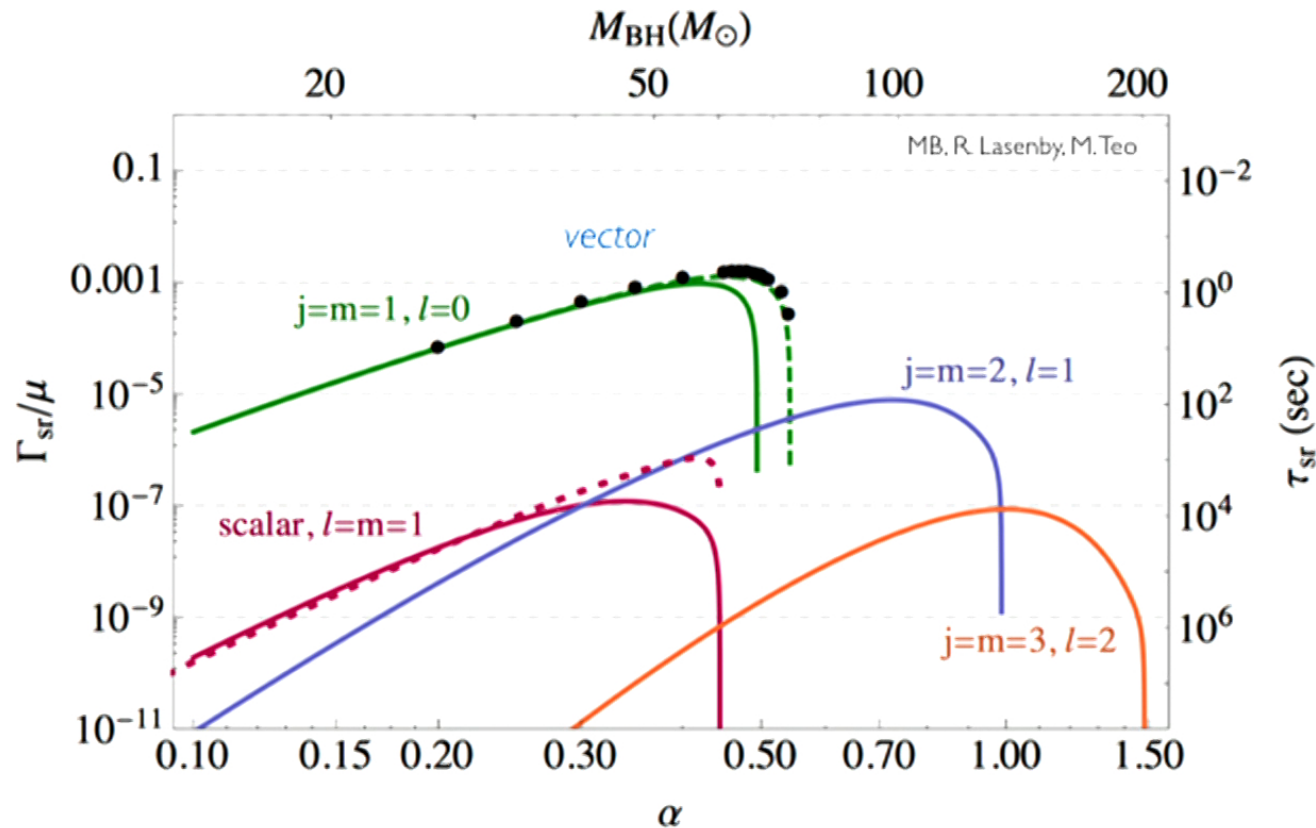
$$\mu_a \left(1 - \frac{\alpha^2}{2n^2} + i\Gamma_{sr} \right)$$



$$\Gamma_{sr}^{nlm} \sim \mu_a \alpha^{4l+4} (m\Omega_{BH} - \mu_a) r_+ C_{nlm} \lesssim 10^{-6} \mu_a$$

↑
(scalar) particle mass

Analytic superradiance rates



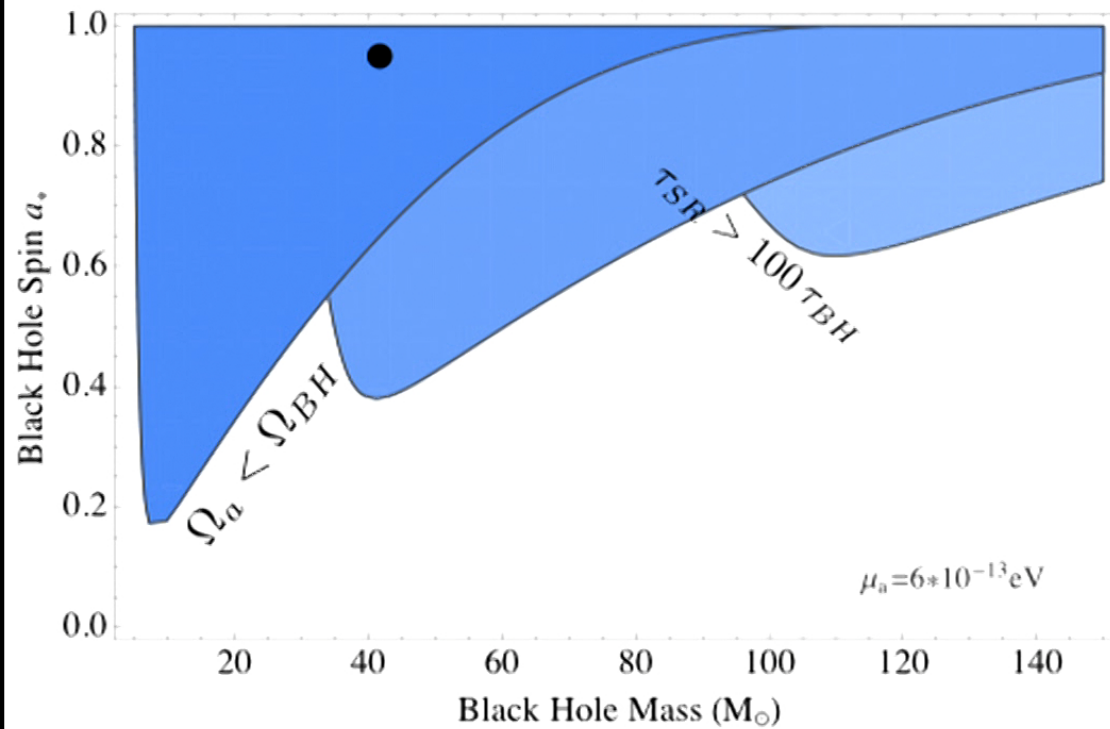
- For massless boson, scattering probability depends on $\mathbf{j}$, wavefunction value depends on $\mathbf{l}$

$$\Gamma_{sr}^{nlm} \sim \mu \alpha^{2l+2j+4} (m\Omega_{BH} - \mu) r_+ C_{njl m} \lesssim 10^{-3} \mu$$

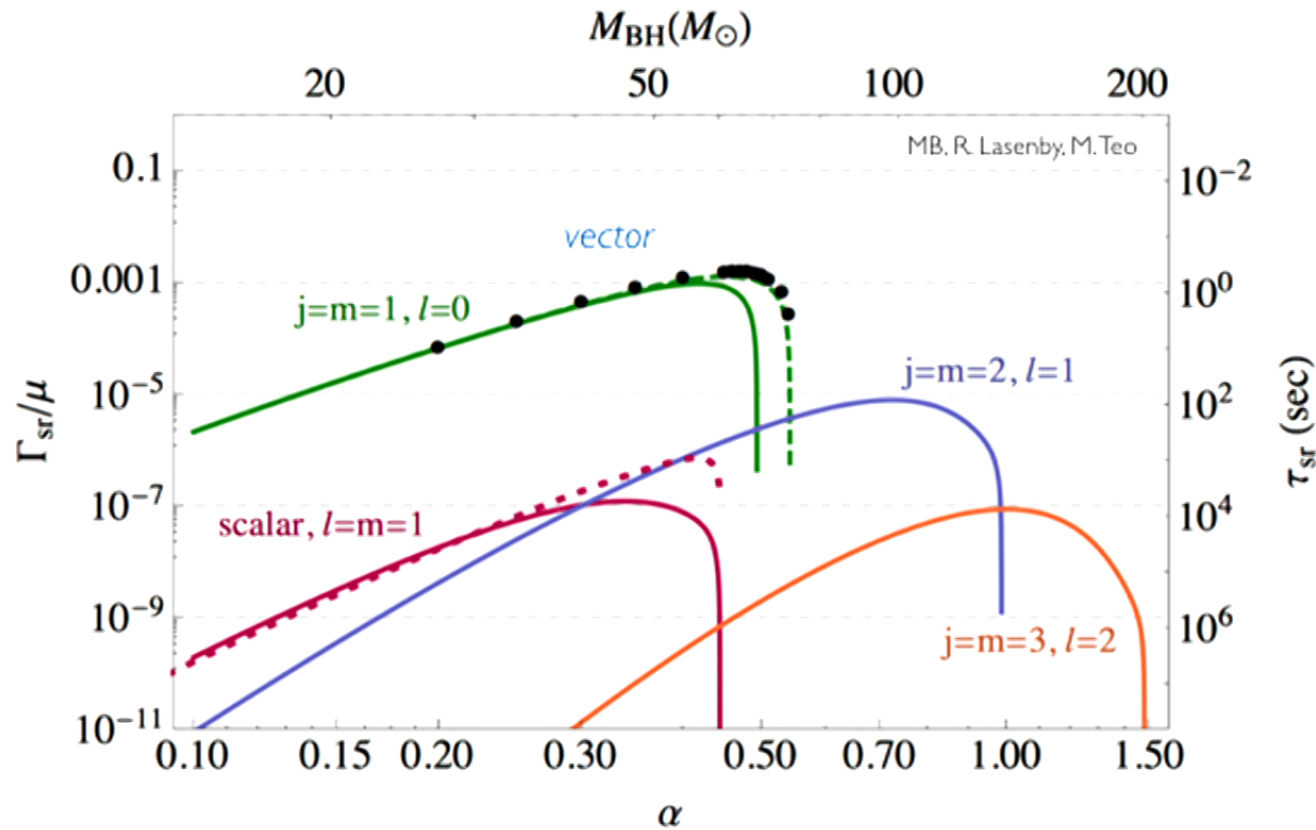
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Superradiance: a stellar black hole history

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



Analytic superradiance rates

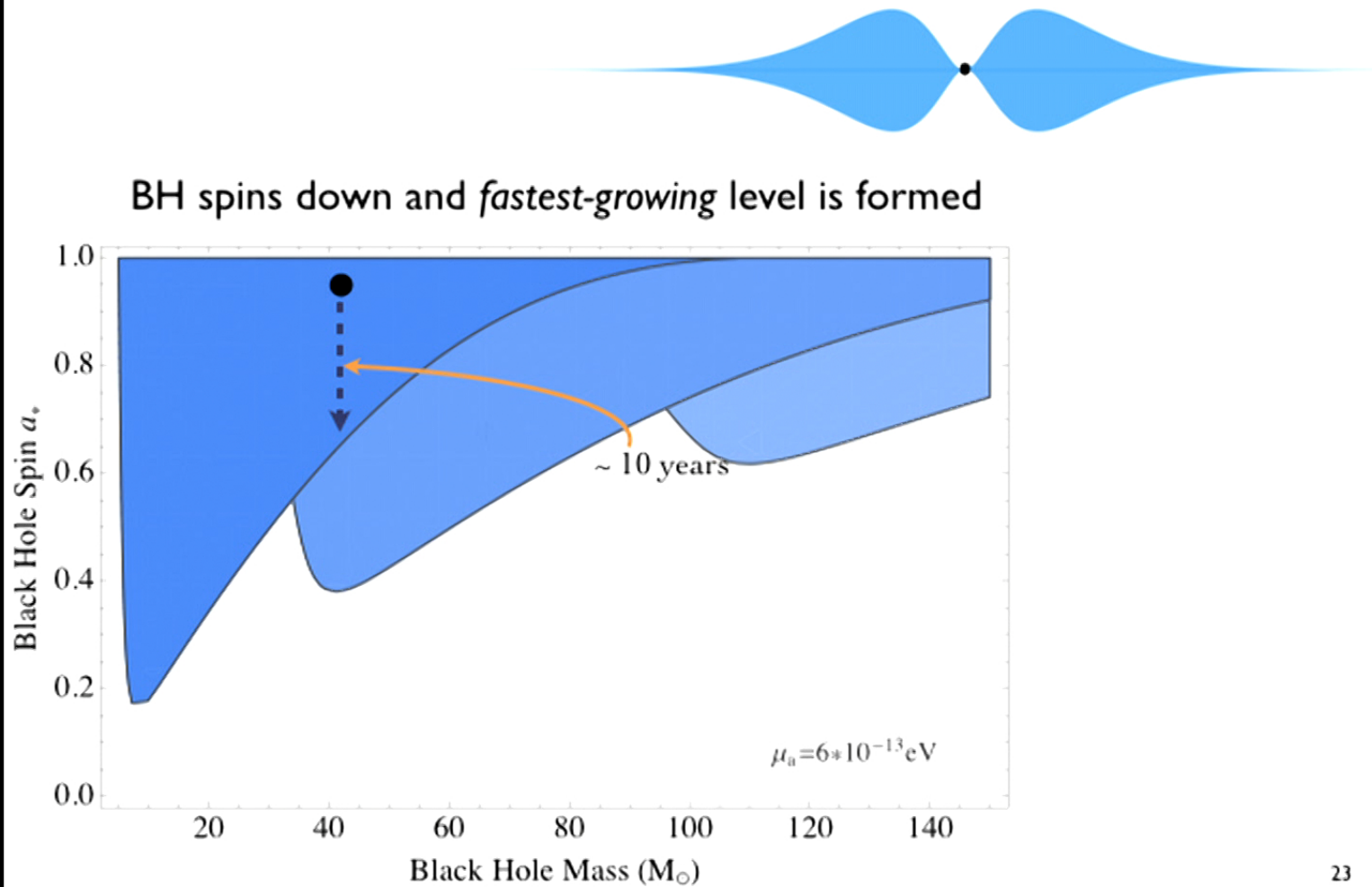


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21

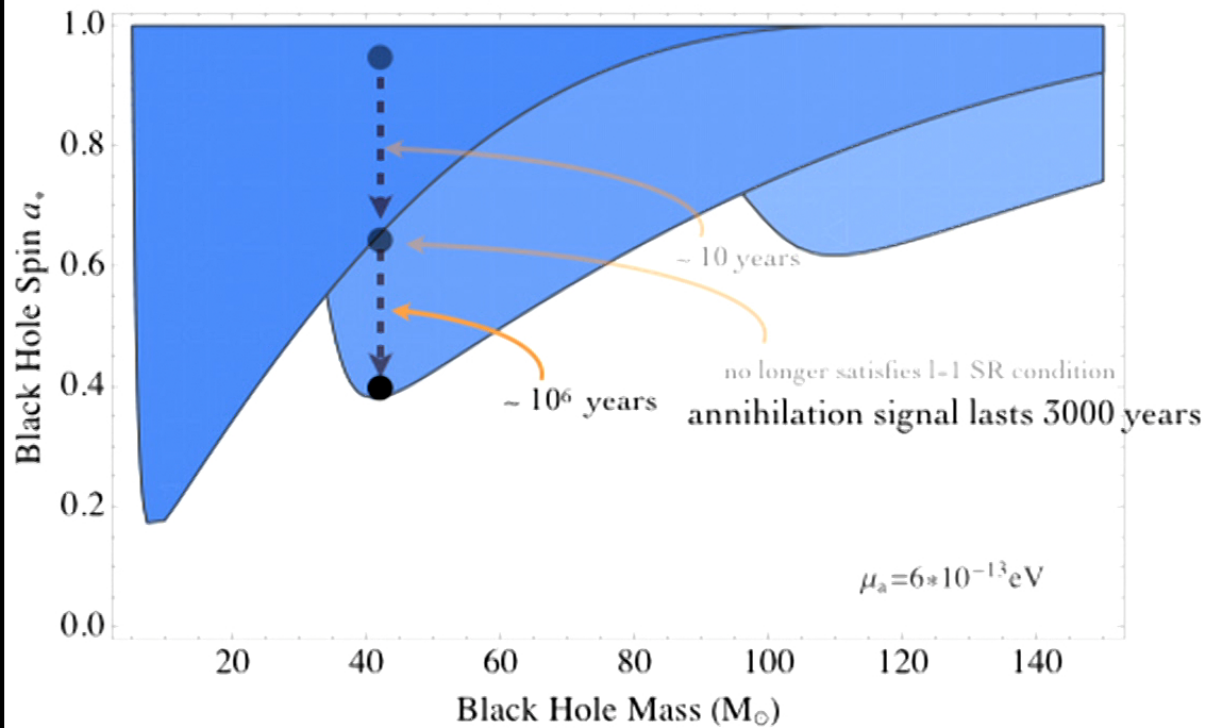
Superradiance: a stellar black hole history



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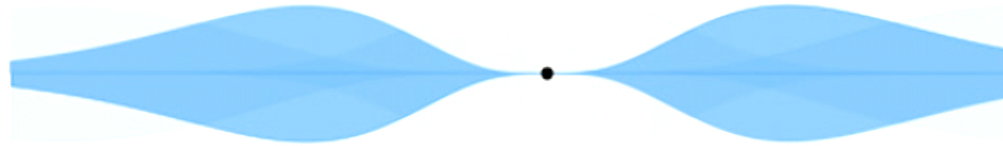
Superradiance: a stellar black hole history

BH spins down and *next level* formed;
annihilations to GWs deplete first level

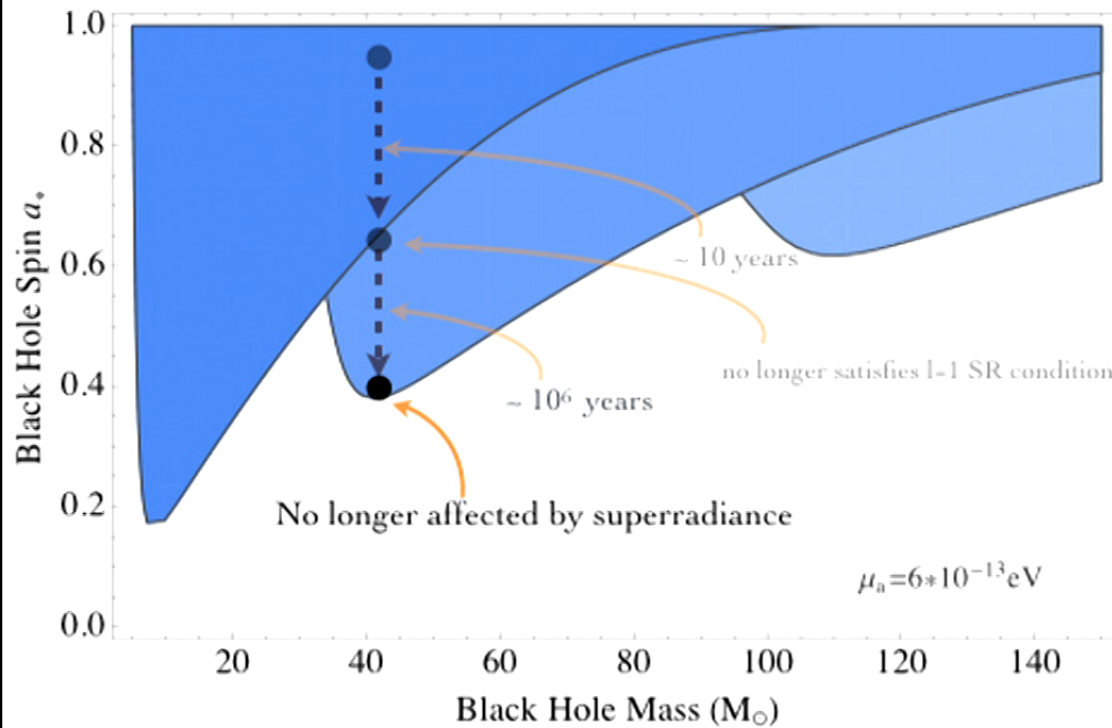


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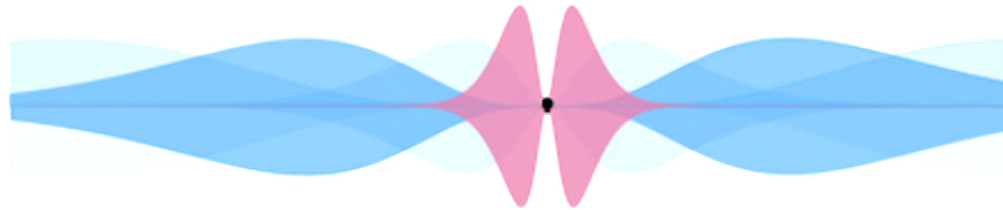
Superradiance: a stellar black hole history



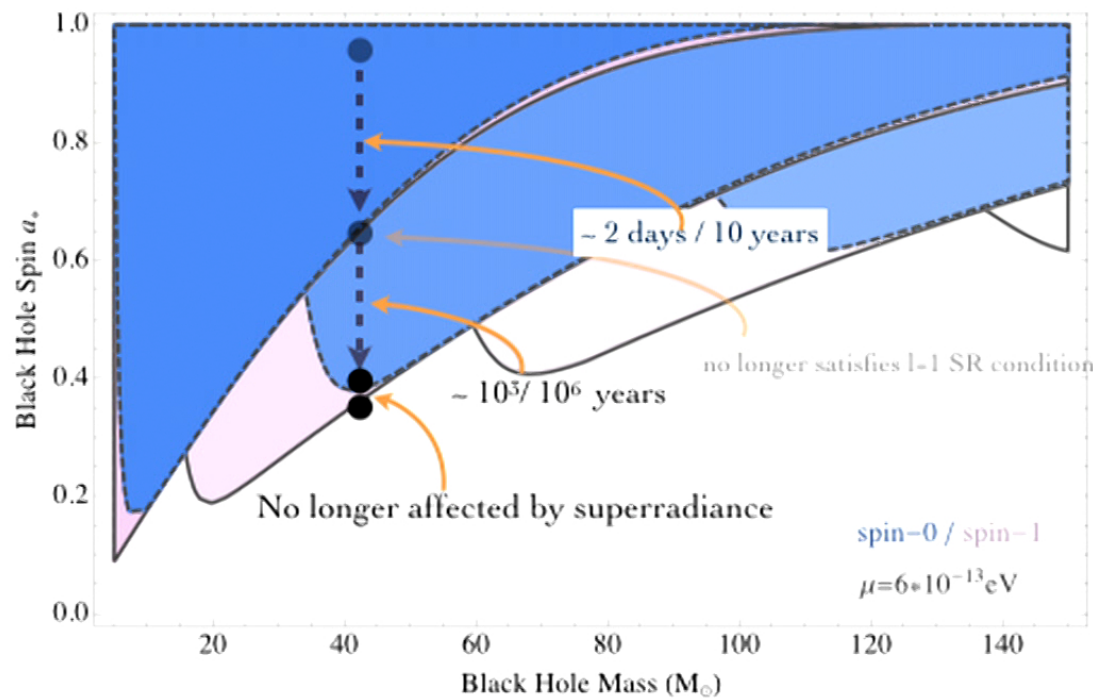
The following level has a superradiance rate exceeding age of BH



Superradiance: a stellar black hole history



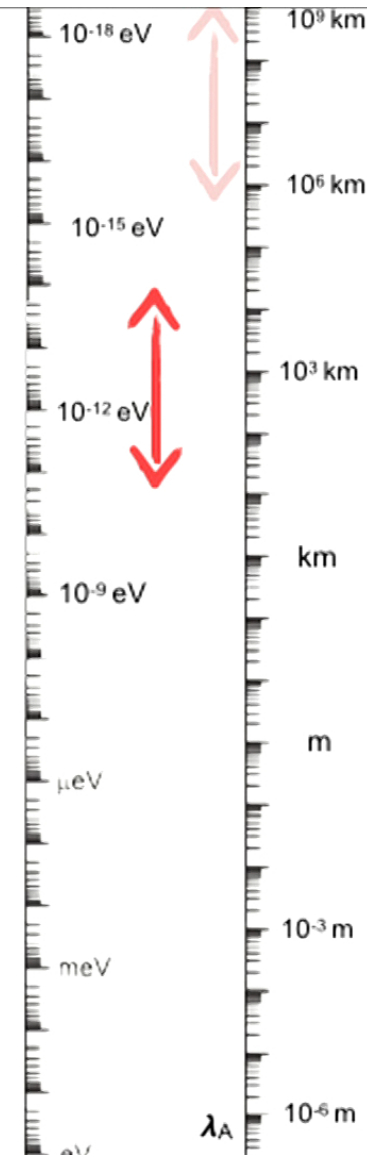
Spin 1 particles: faster superradiance rate for the same mass particle



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
- Depends on particle mass and spin
- Does not rely on DM density
- Superradiance is a kinematic effect so does not require precise resonance



Outline

- Black Hole Superradiance



- Spinning Black Holes



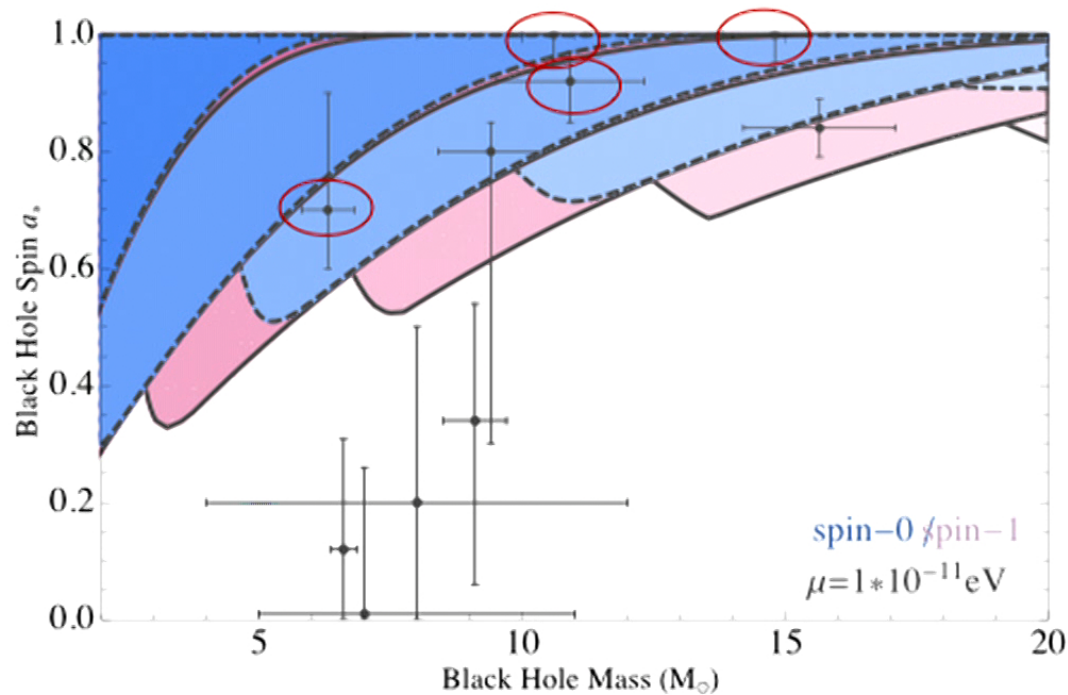
- Gravitational Wave Signals



Black Hole Spins

Black hole spin and mass measurements from X-ray binaries:

several black holes disfavor this scalar/vector mass

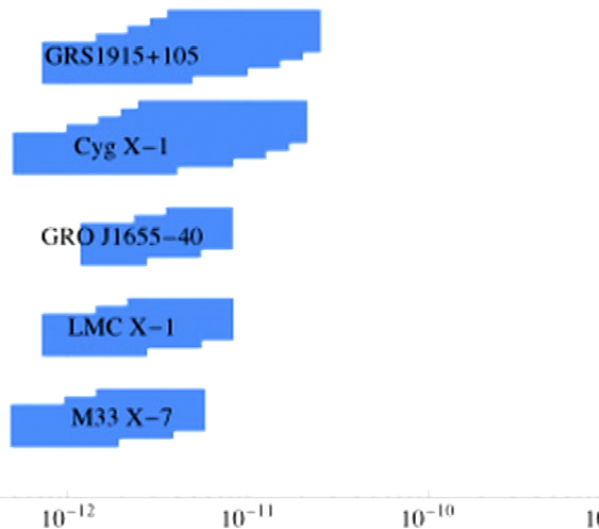


Black Hole Spins

Five stellar black holes and four SMBHs combine to disfavor the range:

scalar

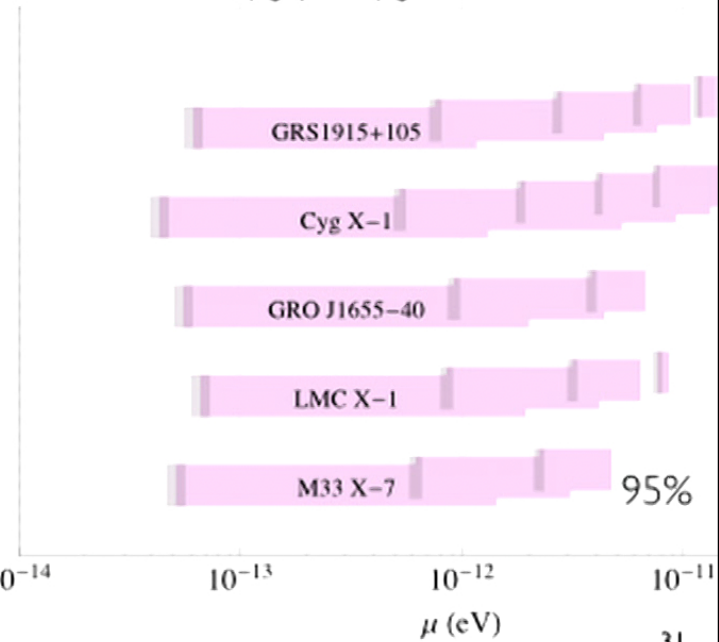
$$2 \times 10^{-11} > \mu_a > 6 \times 10^{-13} \text{ eV}$$



$$3 \times 10^{17} < f_a < 1 \times 10^{19} \text{ GeV}$$

vector

$$2 \times 10^{-11} \gtrsim \mu_V \gtrsim 5 \times 10^{-14} \text{ eV}$$



95%

μ (eV)

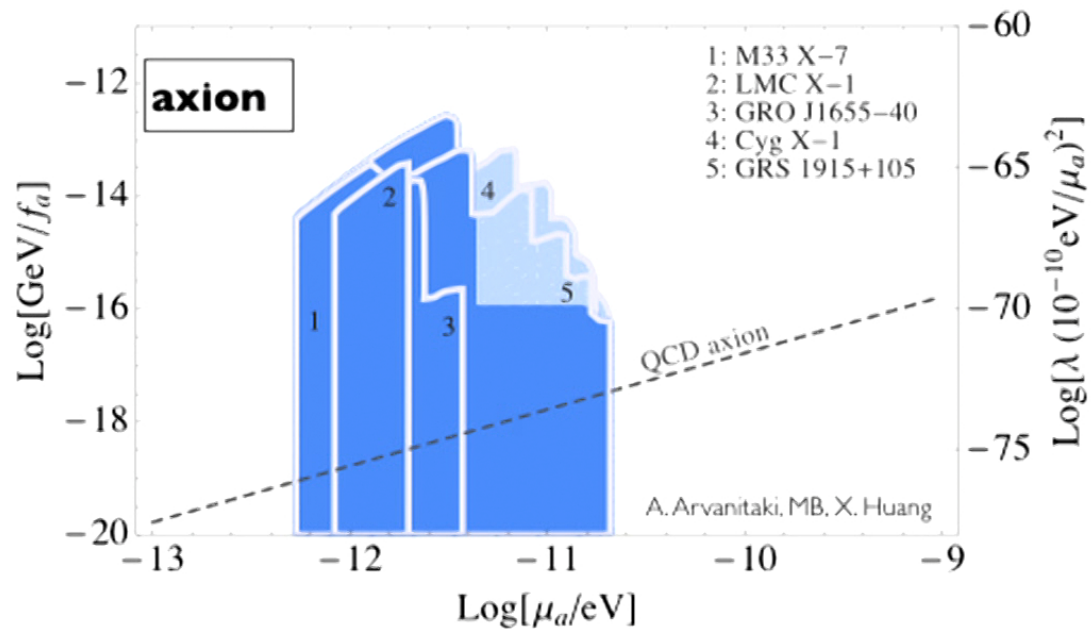
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Black Hole Spins, coupling

Five currently measured black holes combine to set limit:

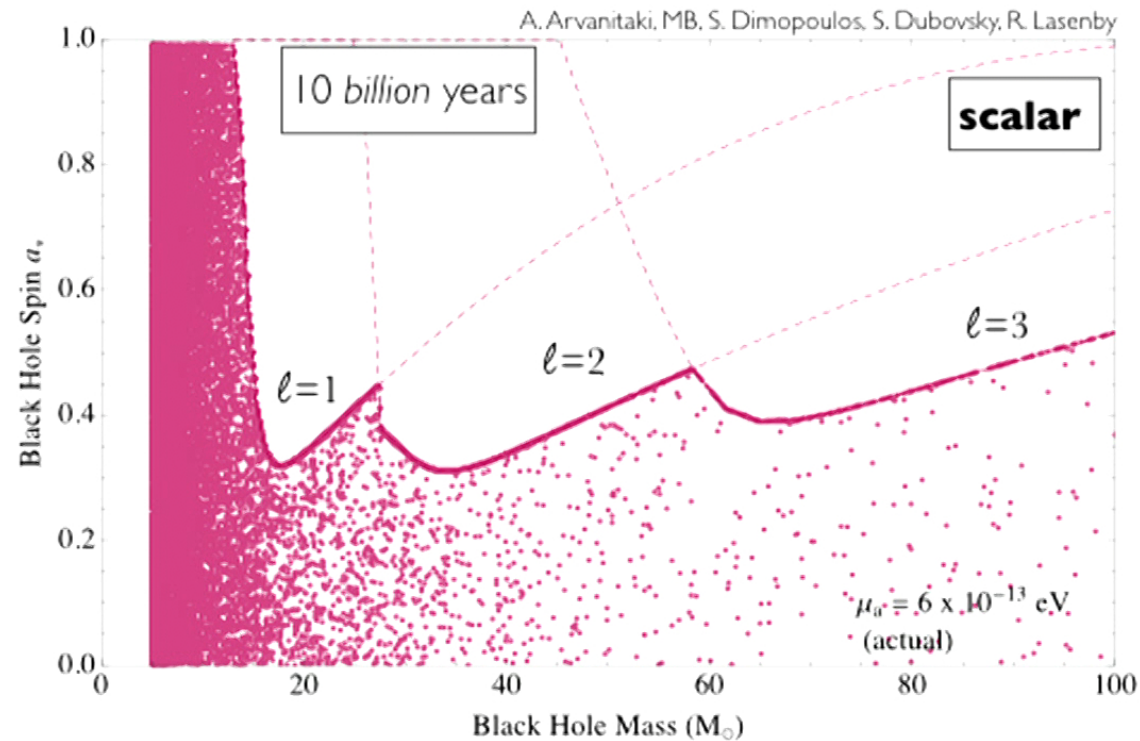
$$2 \times 10^{-11} > \mu_a > 6 \times 10^{-13} \text{ eV}$$

$$3 \times 10^{17} < f_a < 1 \times 10^{19} \text{ GeV}$$



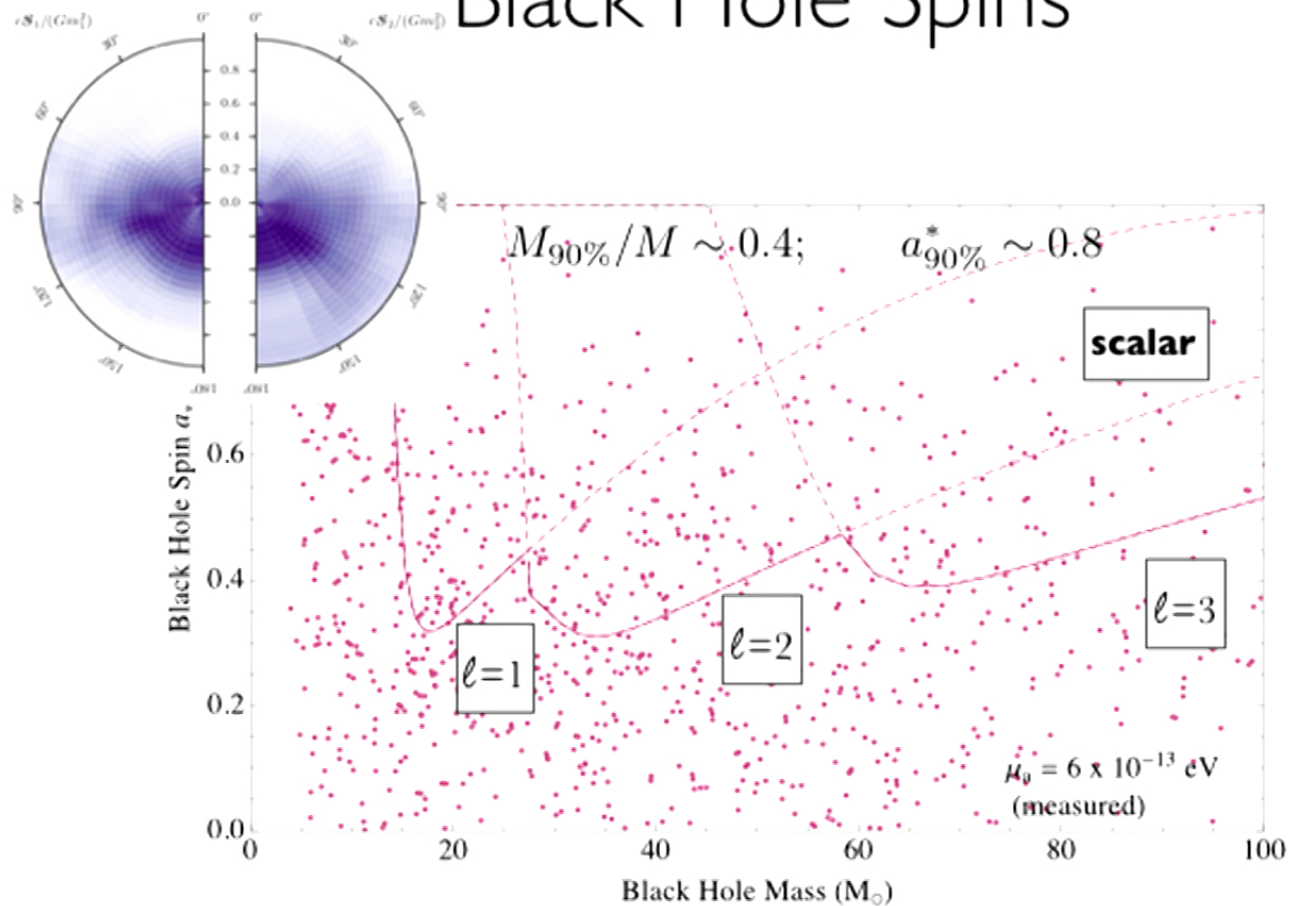
Black Hole Spins at LIGO

If light axion exists, many initial BHs would have low spin due to superradiance, limited by age and radius of binary system



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Black Hole Spins



so far:
 GW150914
 LVT151012
 GW151226
 GW170104
 GW170608
 GW170814

Can find statistical evidence for superradiance-like features with
 50-200 merger measurements

Outline

- Black Hole Superradiance



- Spinning Black Holes



- Gravitational Wave Signals

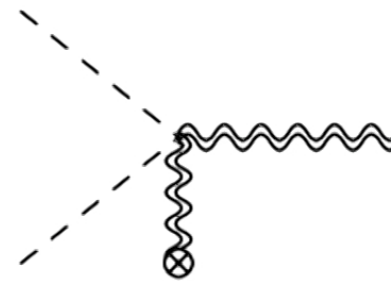


Gravitational Wave Signals

- Transitions between levels



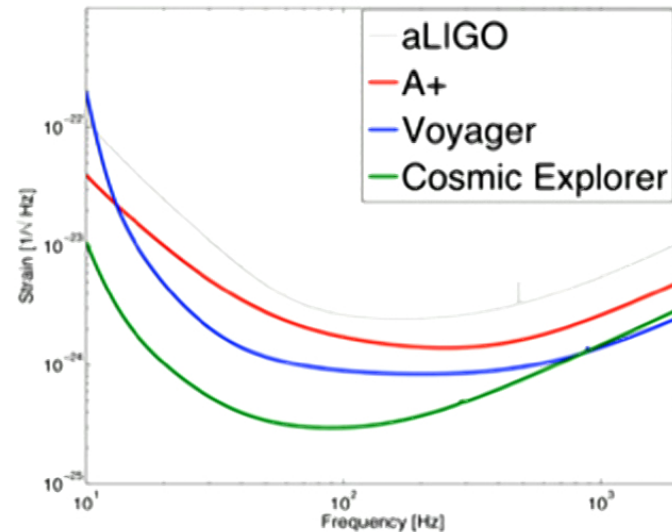
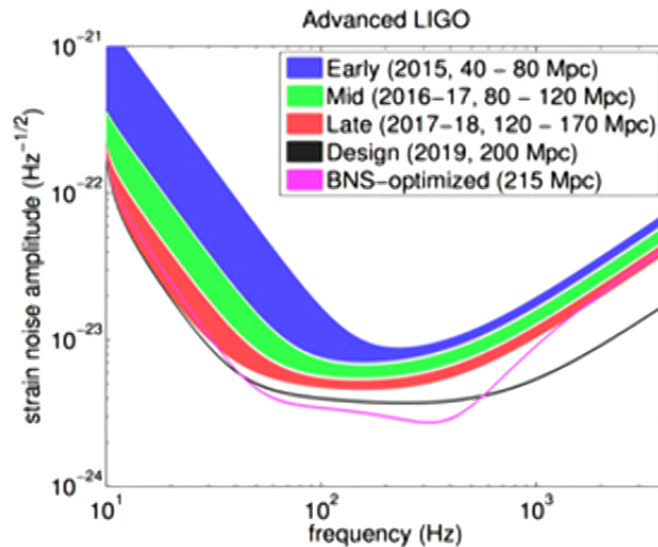
- Annihilations to gravitons



- Signals coherent, monochromatic, last hours to millions of years

Gravitational Wave Signals

Advanced LIGO sensitivity



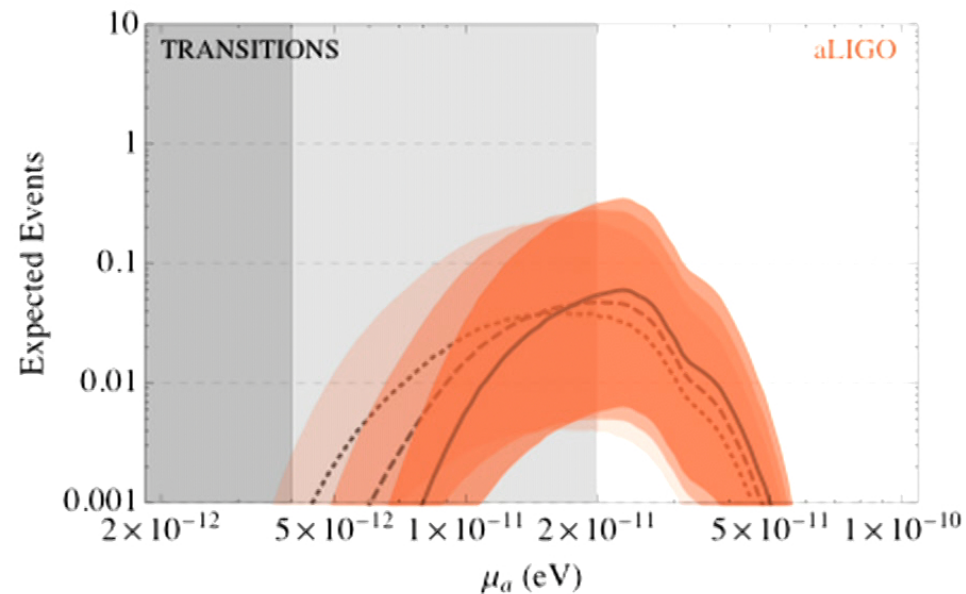
- Fits into searches for **long, continuous, monochromatic** gravitational waves
- Currently looking for “mountains” on neutron stars



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Transitions

- Integrating over BH masses and spins gives promising event rates
- Uncertainty dominated by BH formation rate and spin distribution
- Less sensitive to mass distribution

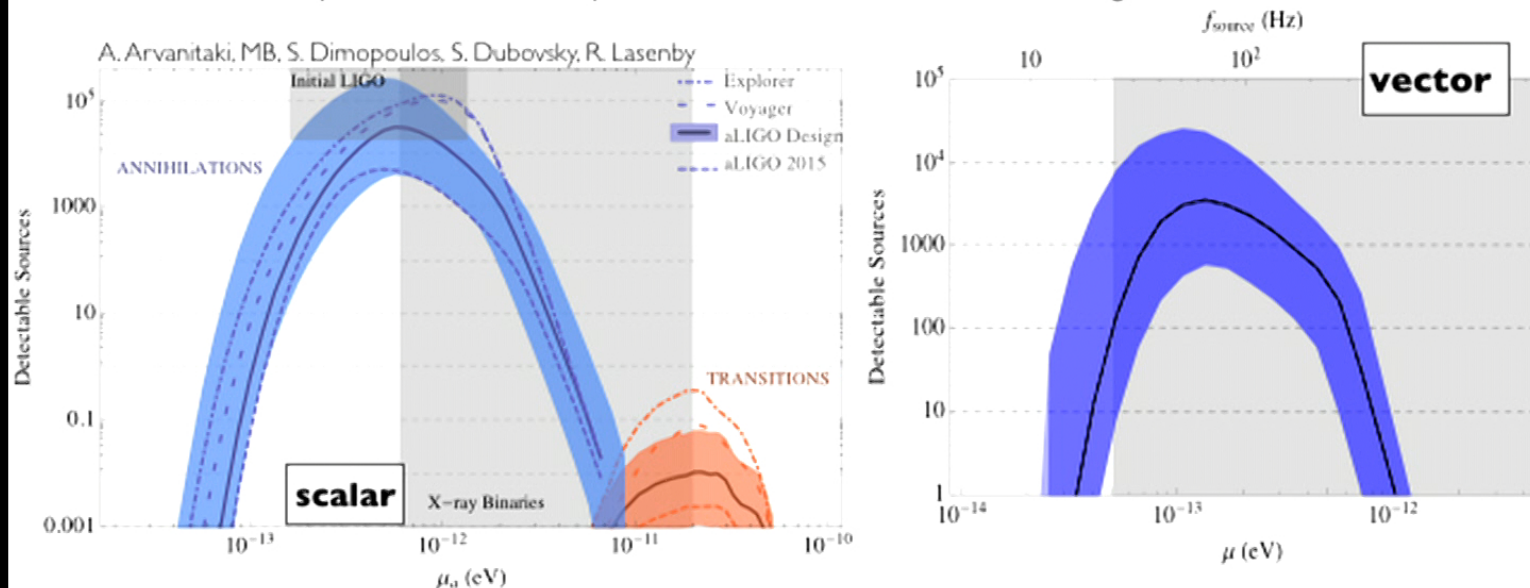


Complementary
to spin limits

Annihilations



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

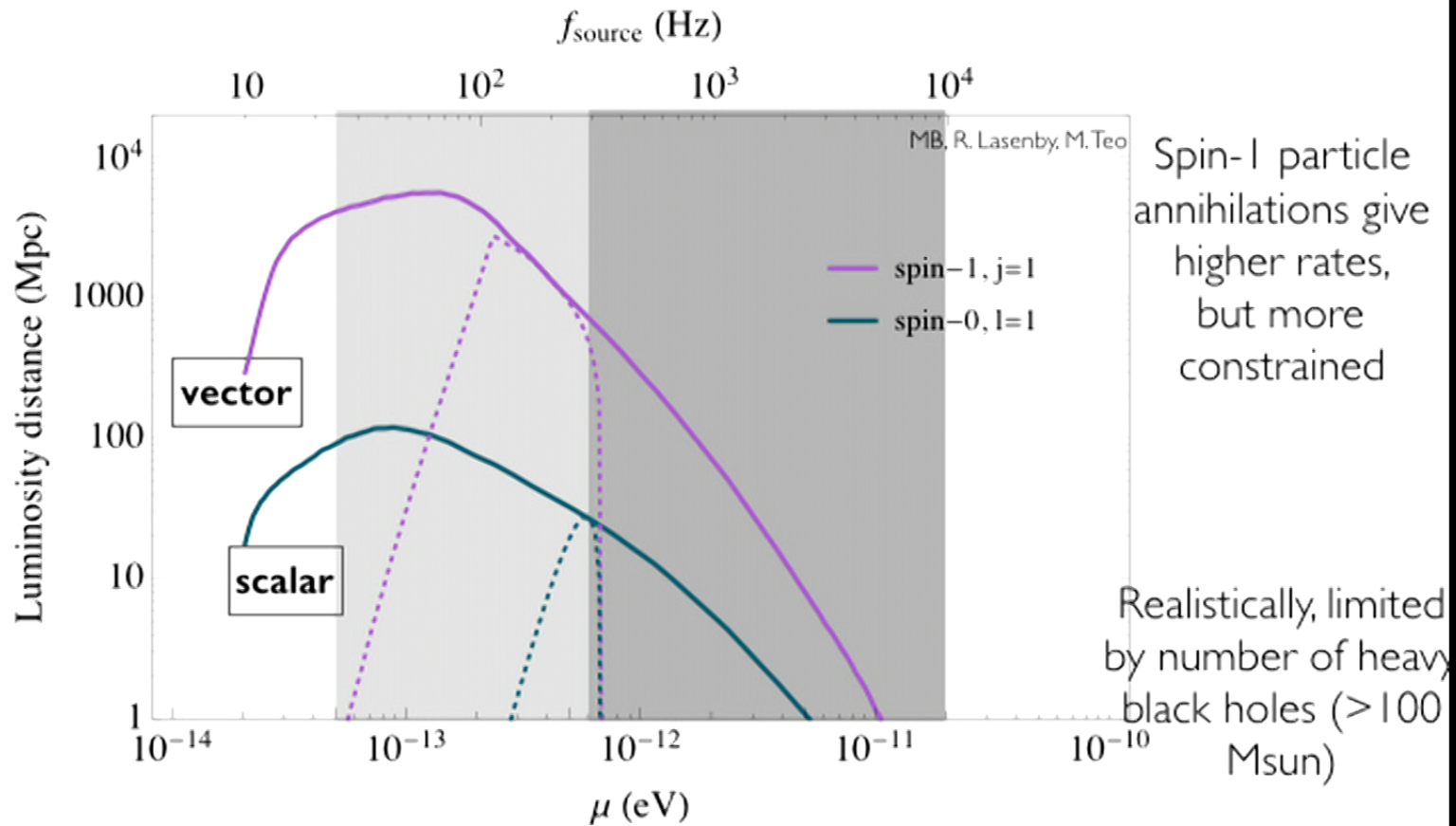


Long, weak signals
visible from galactic
center; limited by
LIGO noise floor

Signals coherent and monochromatic: Fits
into searches for **long, continuous,
monochromatic** gravitational waves
("mountains" on neutron stars)

Cross-check
spin limits

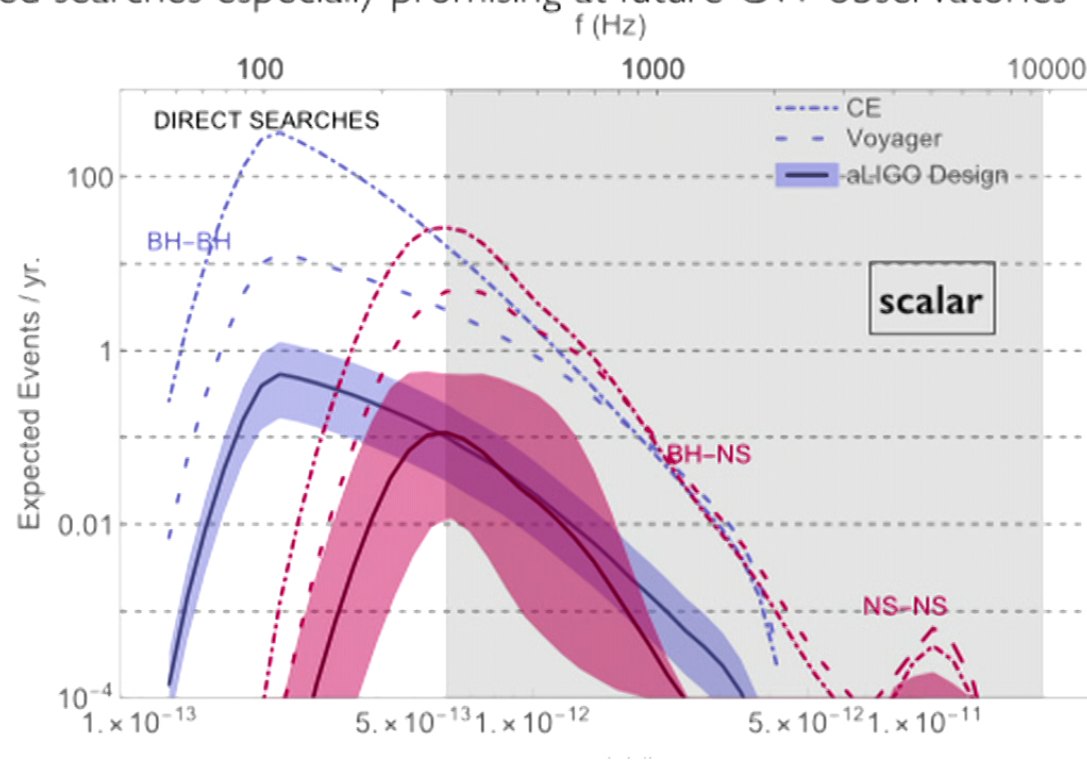
Annihilations



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
- Targeted searches especially promising at future GW observatories

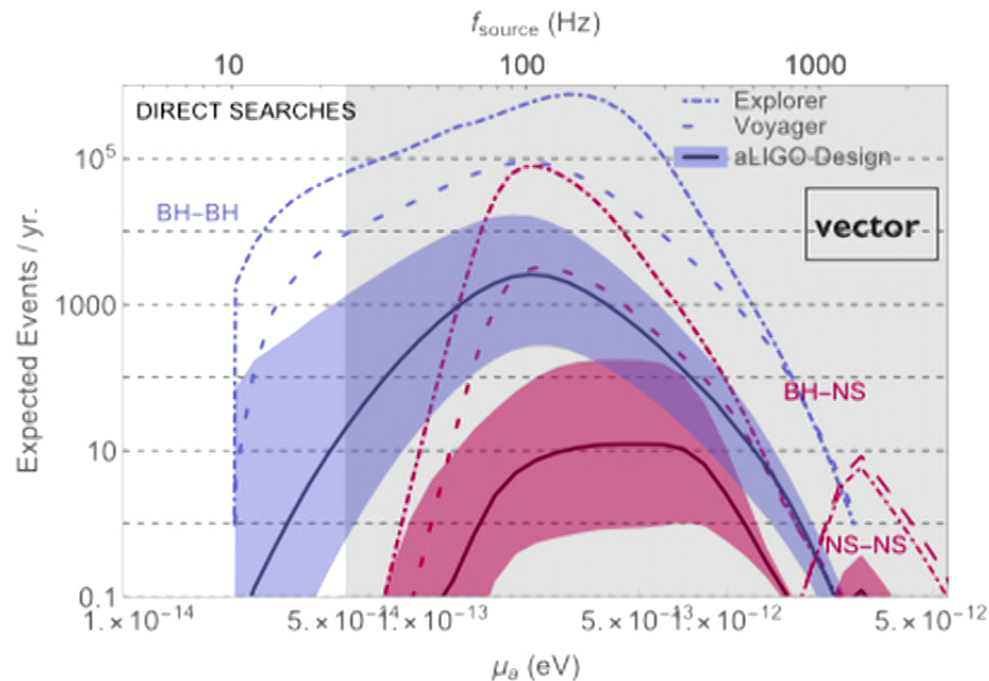


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Annihilations



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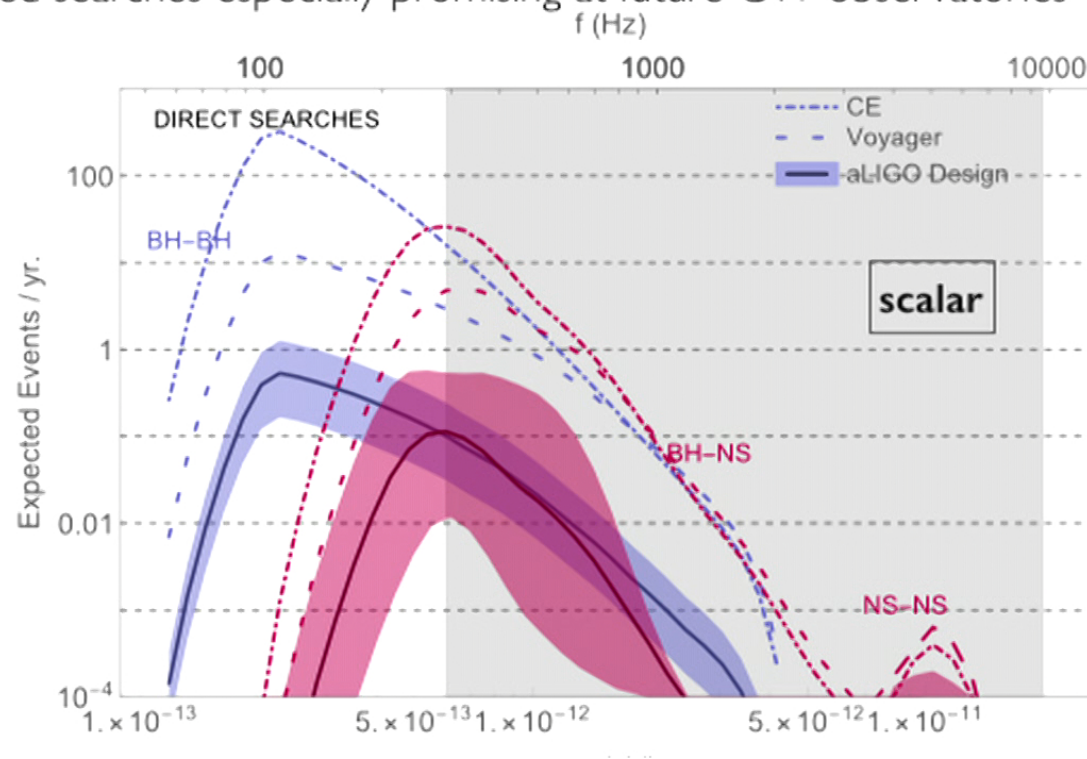


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Annihilations



- 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
- Targeted searches especially promising at future GW observatories



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Conclusions

- Ultra light axions, scalars, 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 scalars or vectors
- May observe growth of gravitational atom after a merger in real time

