Testing Gravity 2017

Searching for Ultralight Particles with Black Holes and Gravitational Waves

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Phys.Rev. D91 (2015) no.8, 084011 A. Arvanitaki, MB, X. Huang

Phys.Rev. D/arxiv: 1604.03958 A. Arvanitaki, MB, S. Dimopoulos, S. Dubovsky, R. Lasenby

arxiv: 1702.xxxxx MB, R. Lasenby, M. Teo

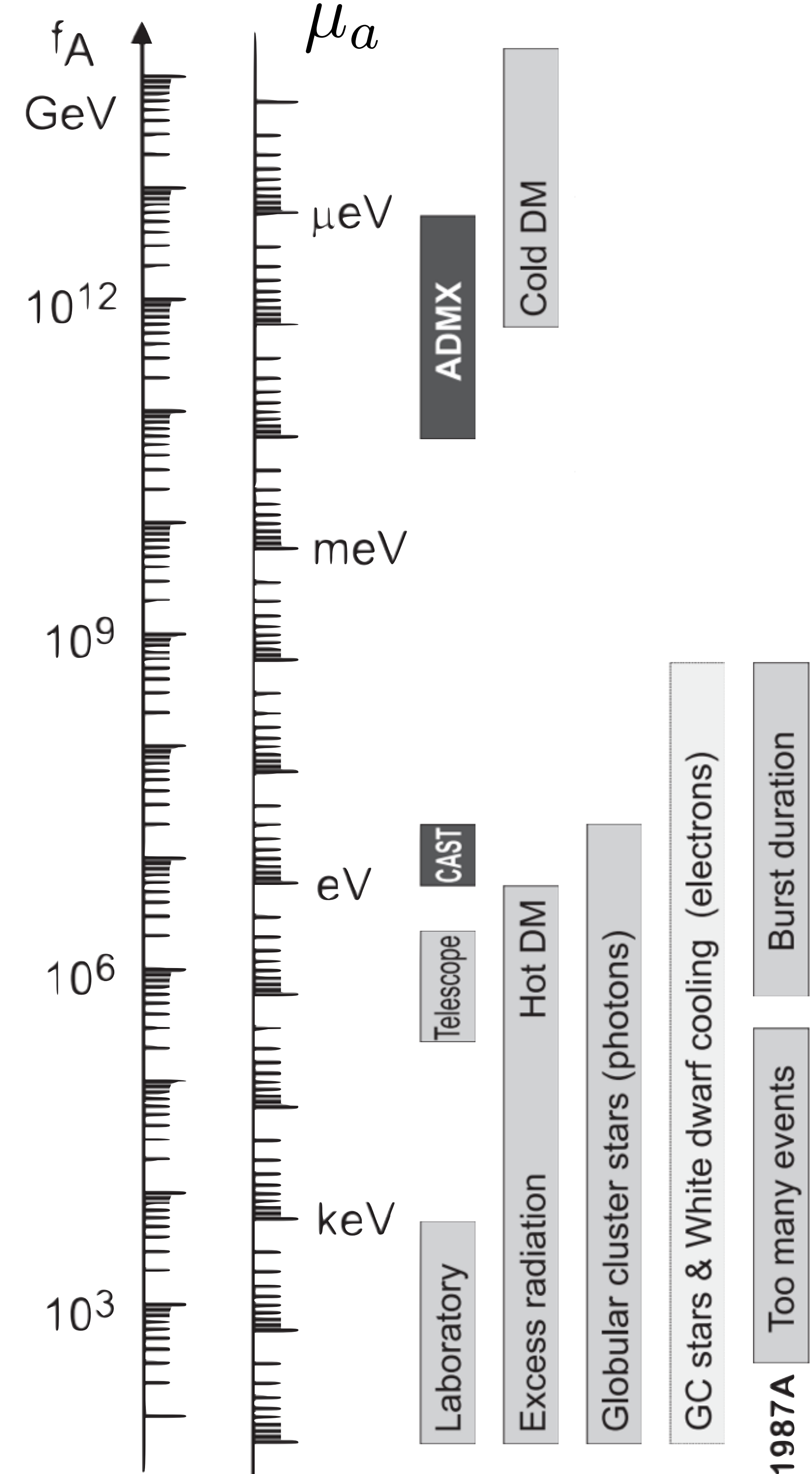
Searching for Ultralight Particles: the QCD axion

- The QCD axion is one of the best motivated BSM particles
- Solves the strong-CP problem
- Pseudo-goldstone boson with mass and couplings fixed by the decay constant f_a,

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

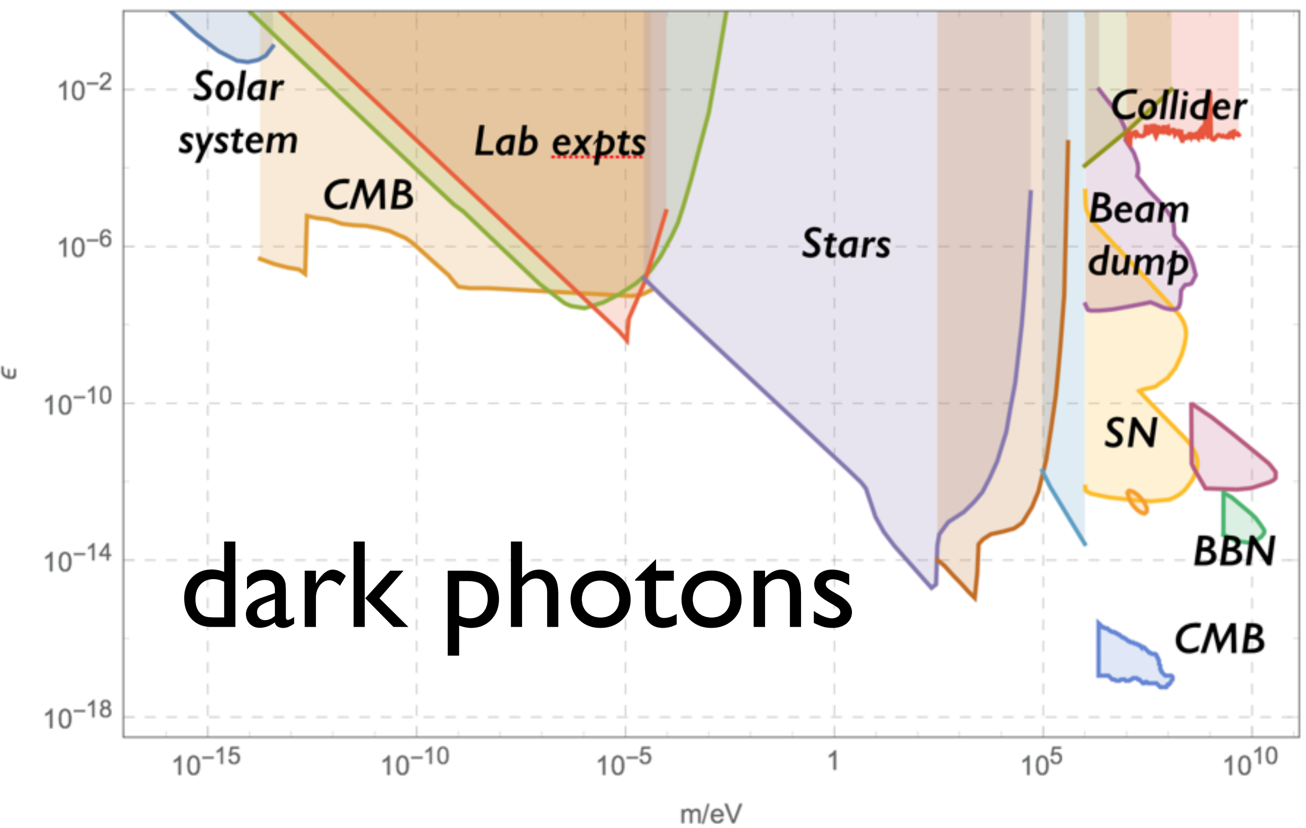
- Very weakly interacting
- Large compton wavelength

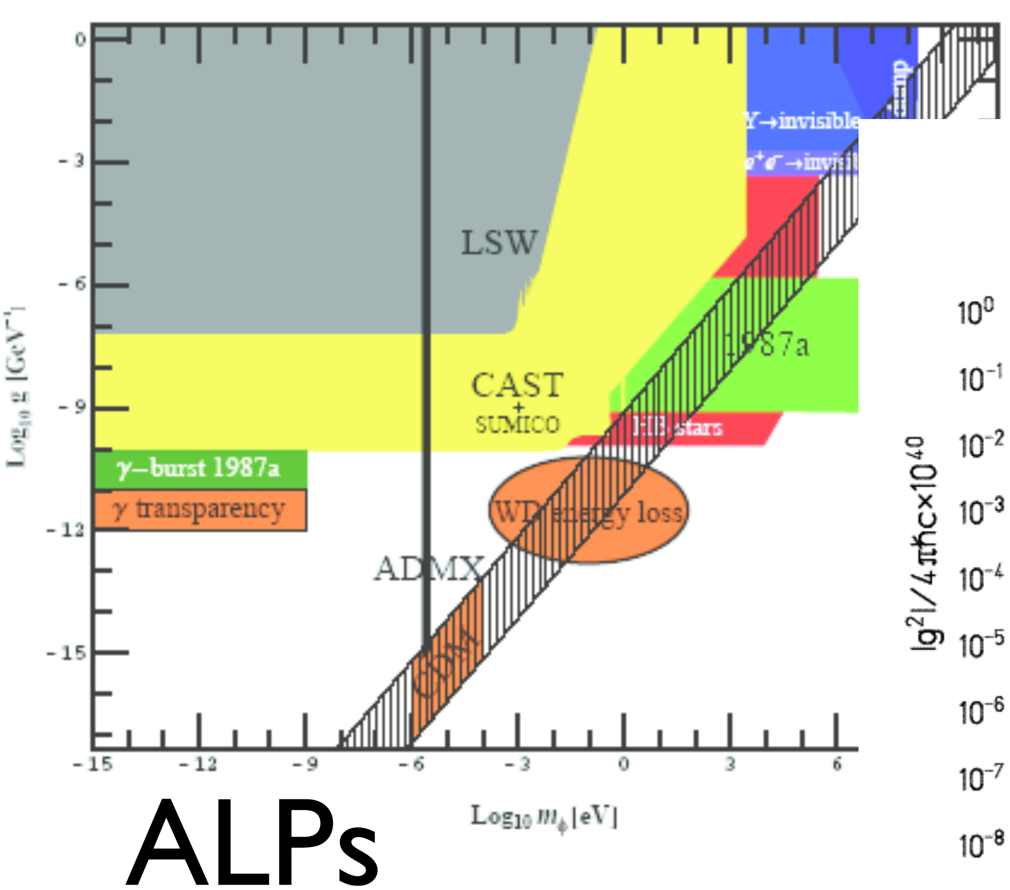
$$\lambda_a \sim 3\,\text{km}\,\frac{6\times 10^{-11}\text{eV}}{\mu_a}$$

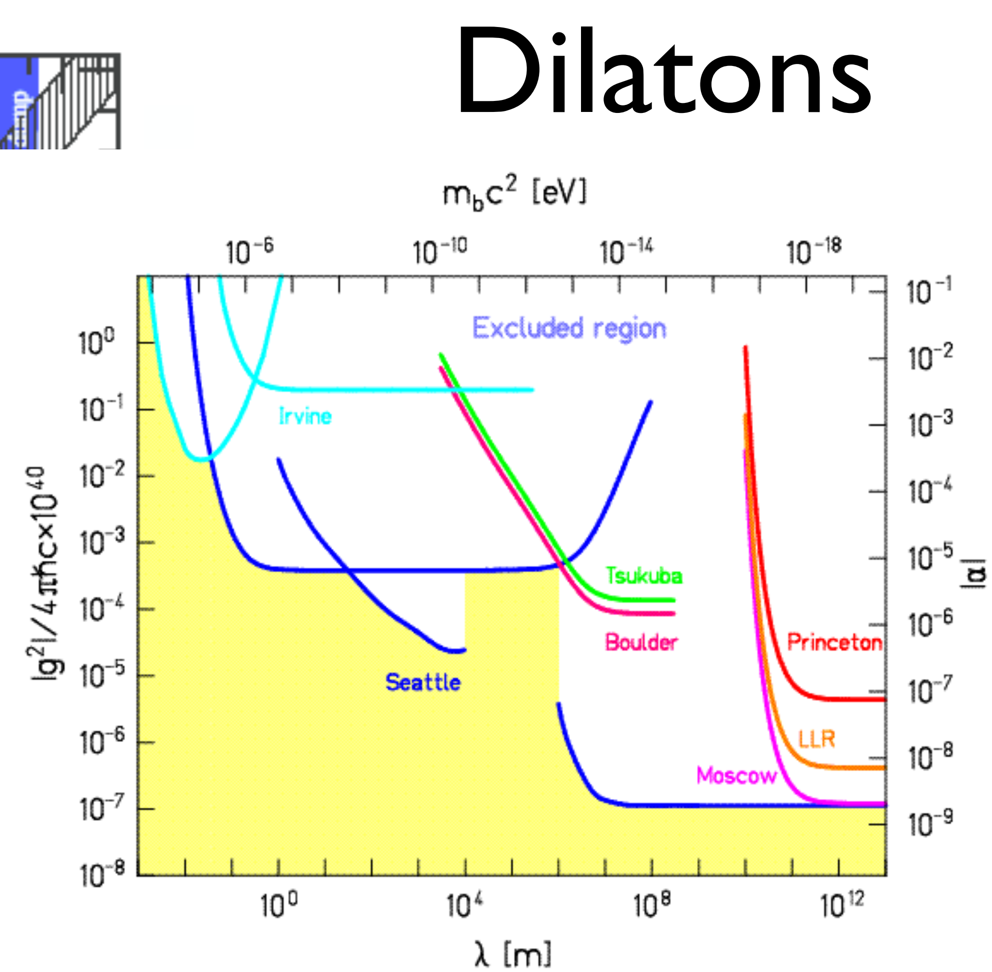


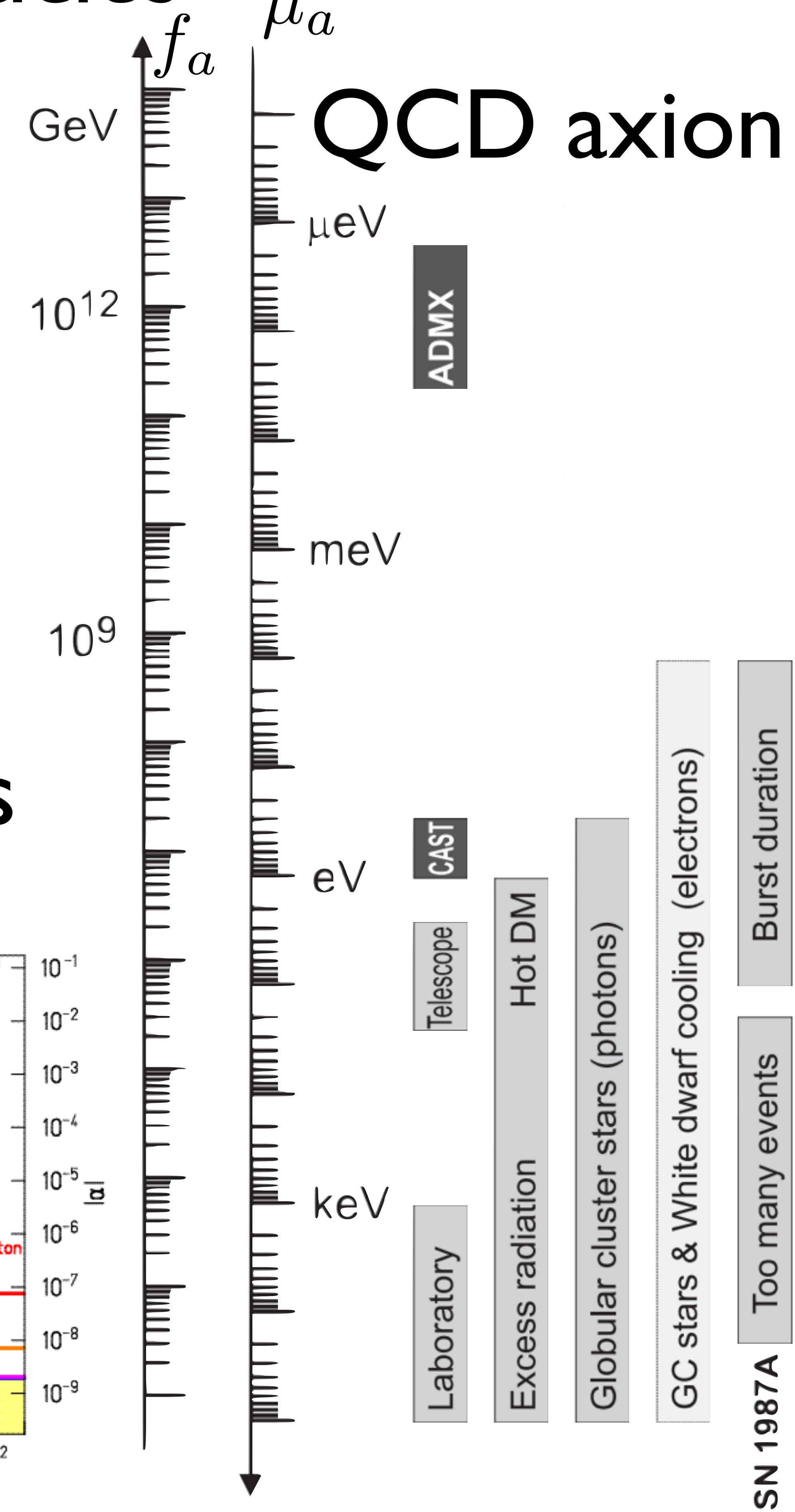
R. Peccei and H. R. Quinn, Phys.Rev.Lett., **38**, 1440 (1977); S. Weinberg, *ibid.*, **40**, 223 (1978); F. Wilczek, *ibid.*, **40**, 279 (1978).

Searching for Ultralight Particles









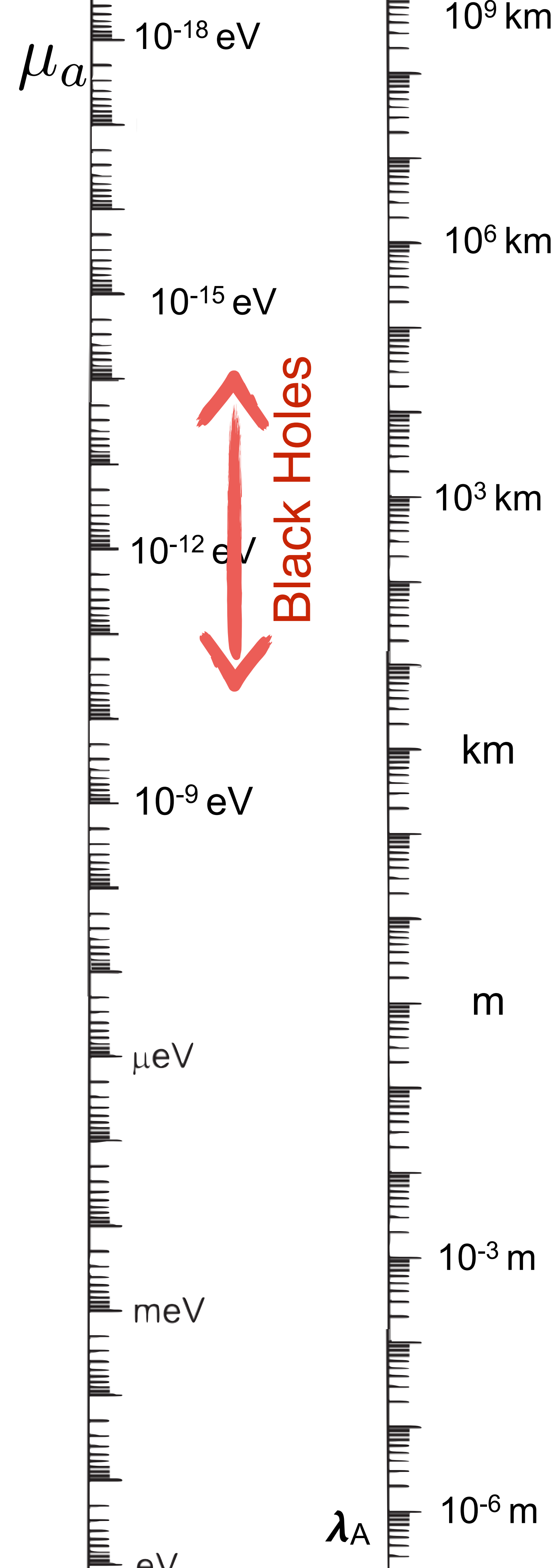
Searching for Ultralight Particles

- Spin 0 and spin 1, weakly interacting

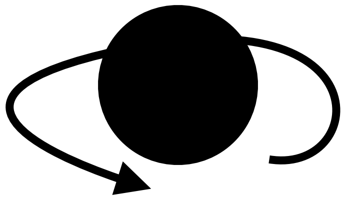
$$\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}\mu_a^2\phi^2$$

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

$$\lambda_a \sim 3\,\mathrm{km}\,\frac{6\times10^{-11}\mathrm{eV}}{\mu_a}$$



Outline

- Gravitational Atoms and Superradiance 
- Spinning Black Holes 
- Gravitational Wave Detection of Axions 

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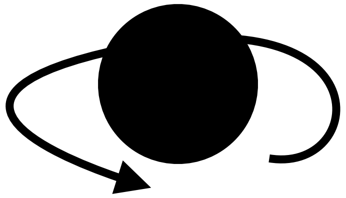
- Spinning Black Holes 
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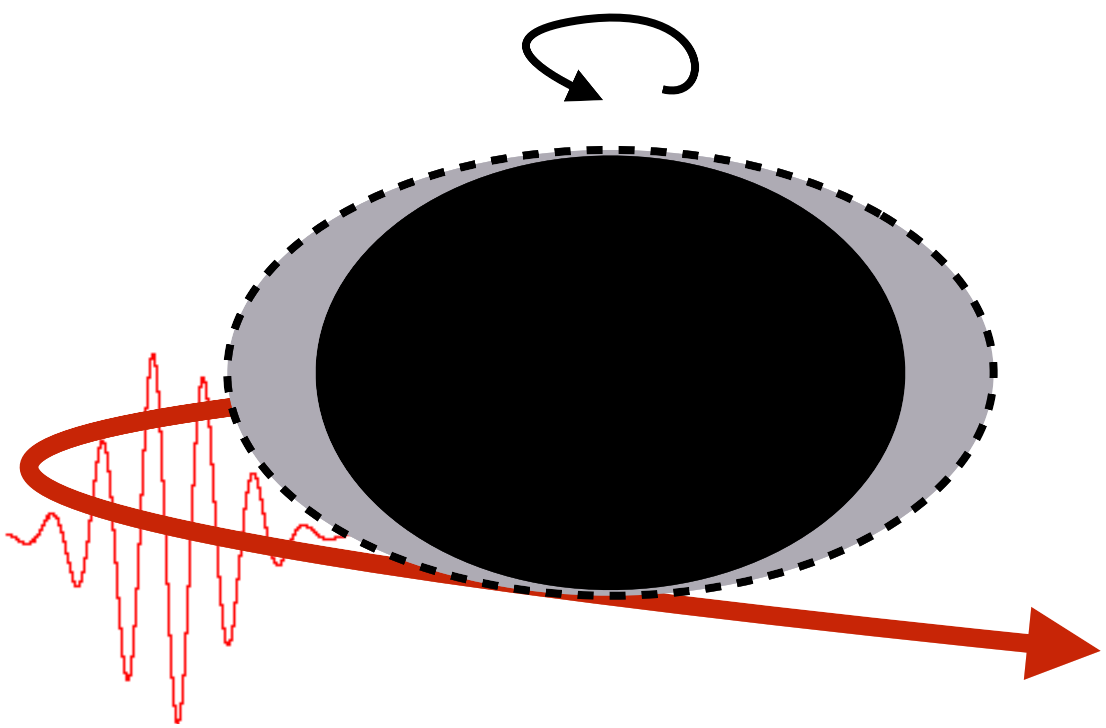
Superradiance

Zel'dovich; Starobinskii; Misner

Initially slow particle scattering off rotating black hole speeds up by extracting angular momentum and energy from the BH;

Waves similarly increase in amplitude



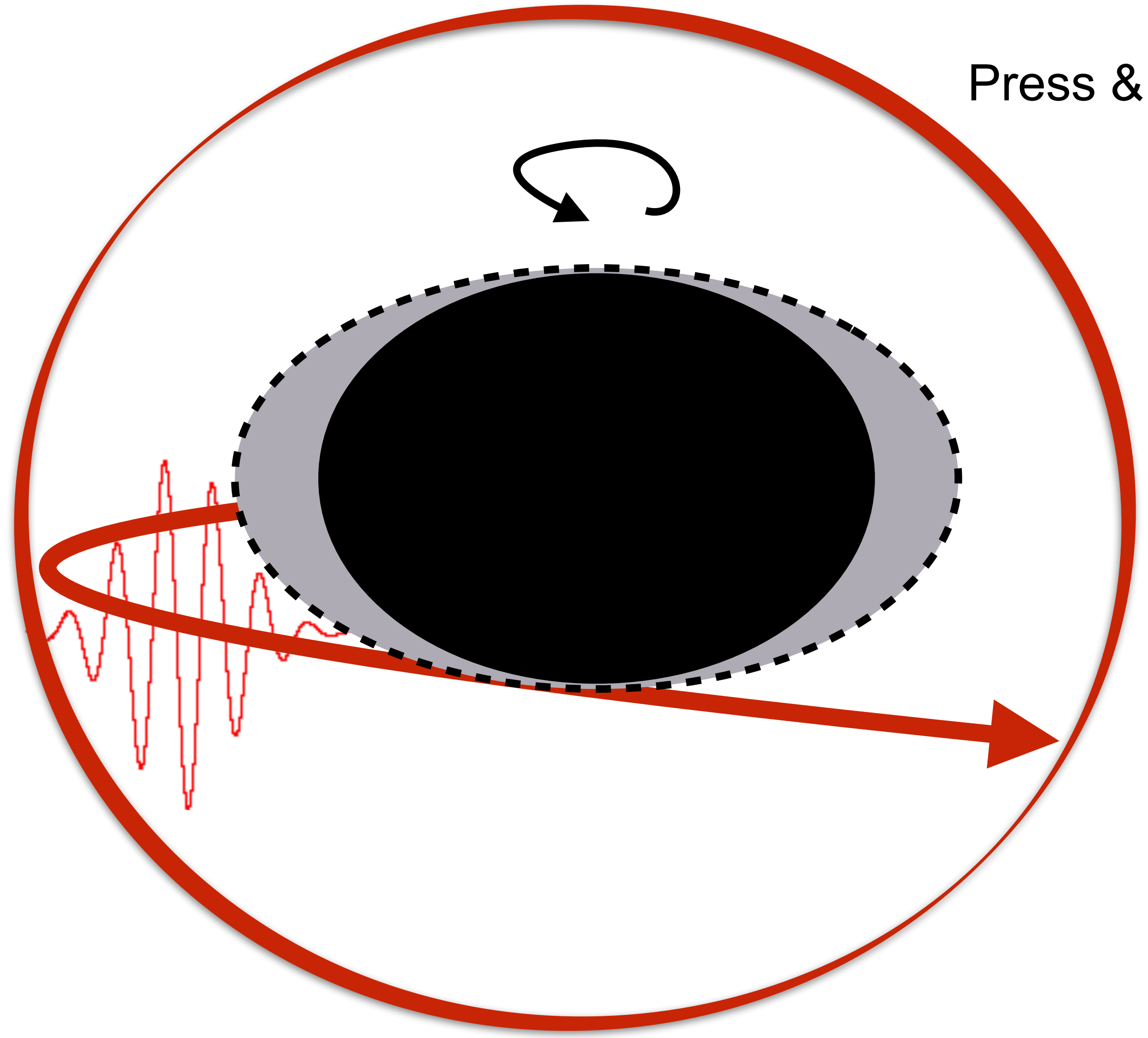
Superradiance condition:

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 & Teulkosky ‘72

“Black hole bomb” exponential instability when surround BH by a mirror

Kinematic, not resonant condition

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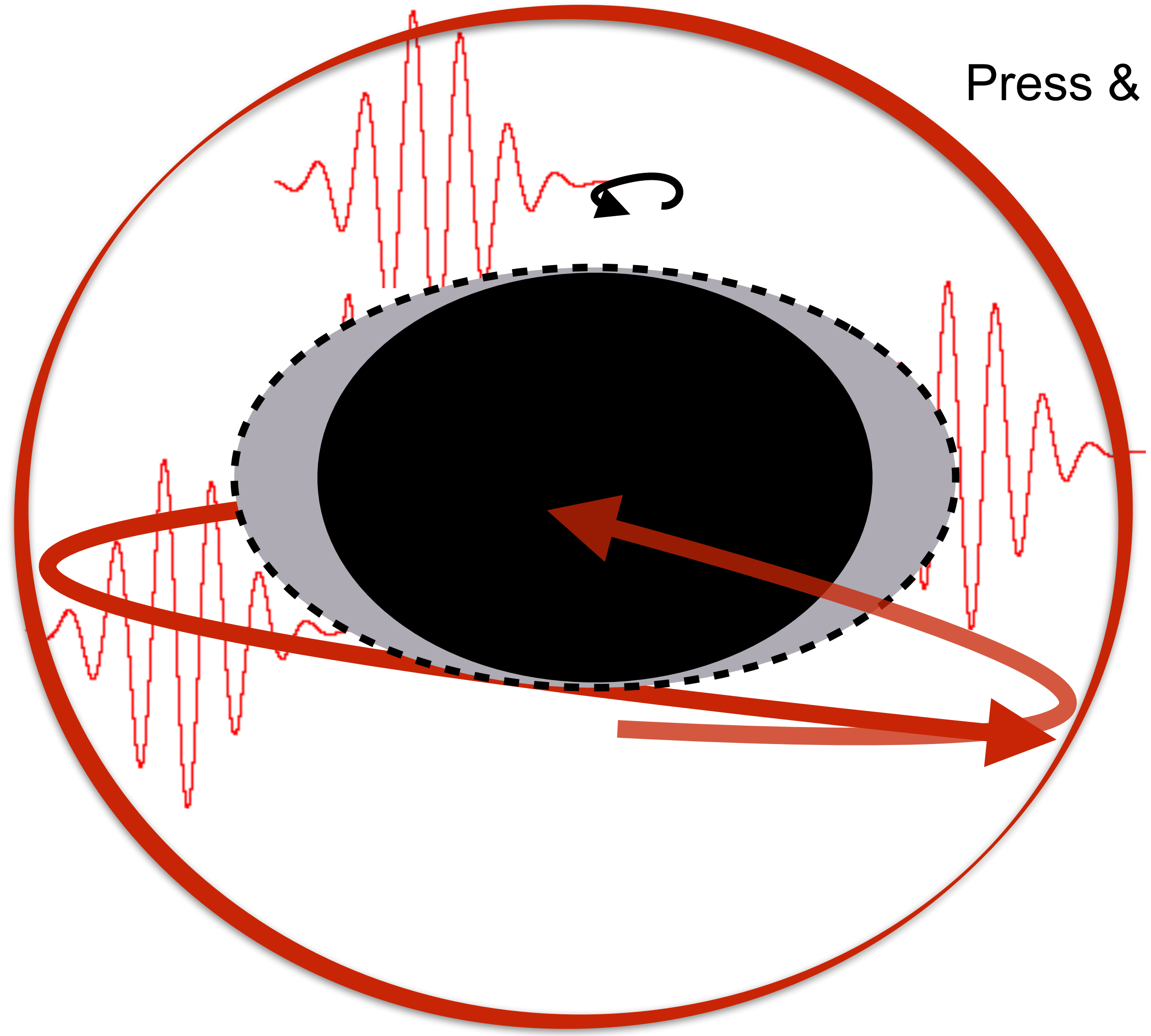

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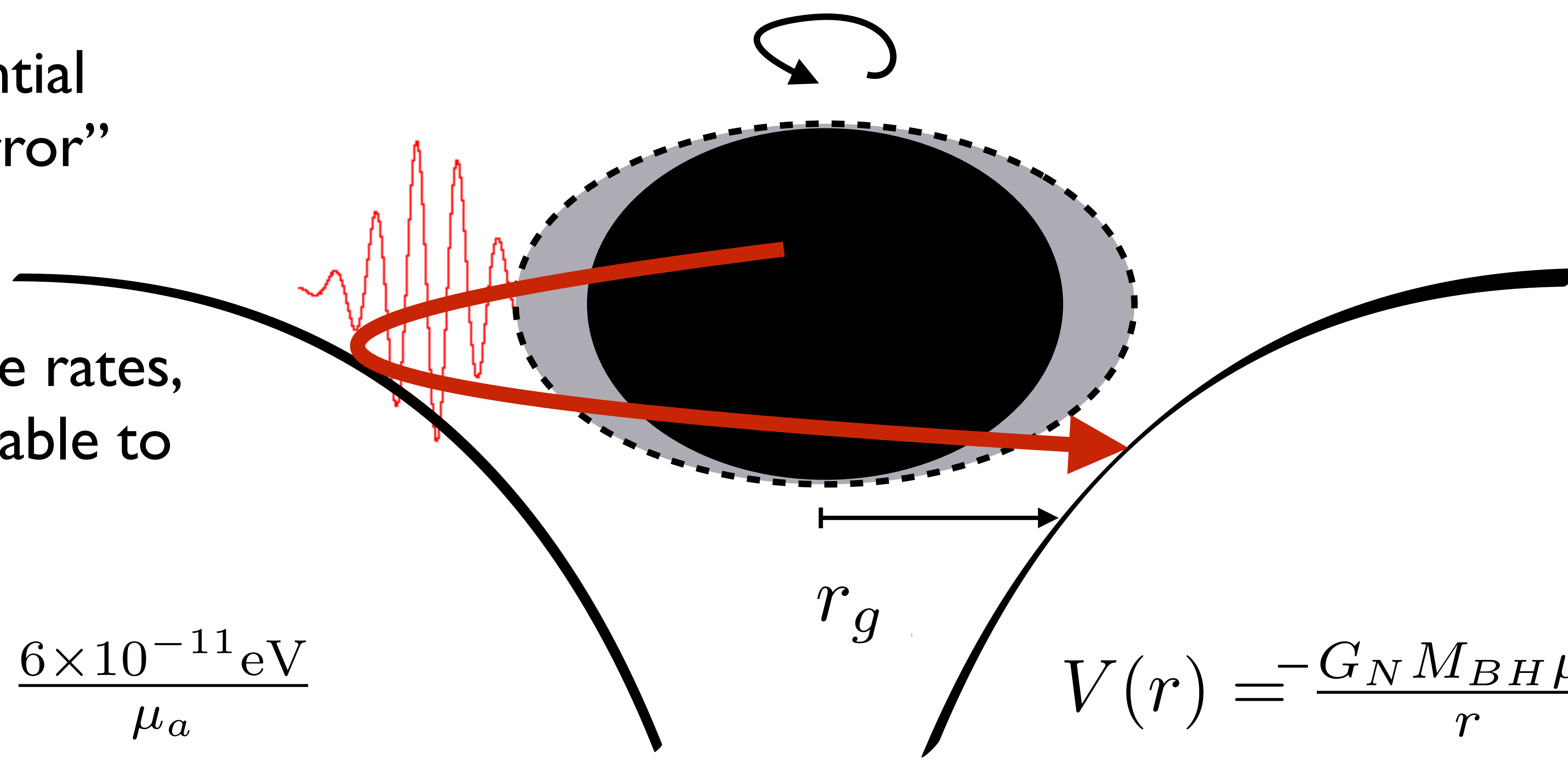
Gravitational Atoms

For a massive particle, “mirror” is created by potential barrier

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



For high superradiance rates, “mirror” size comparable to BH size:

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

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

Zouros & Eardley’79; Detweiler’80; Gaina et al ’78;

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

Gravitational Atoms

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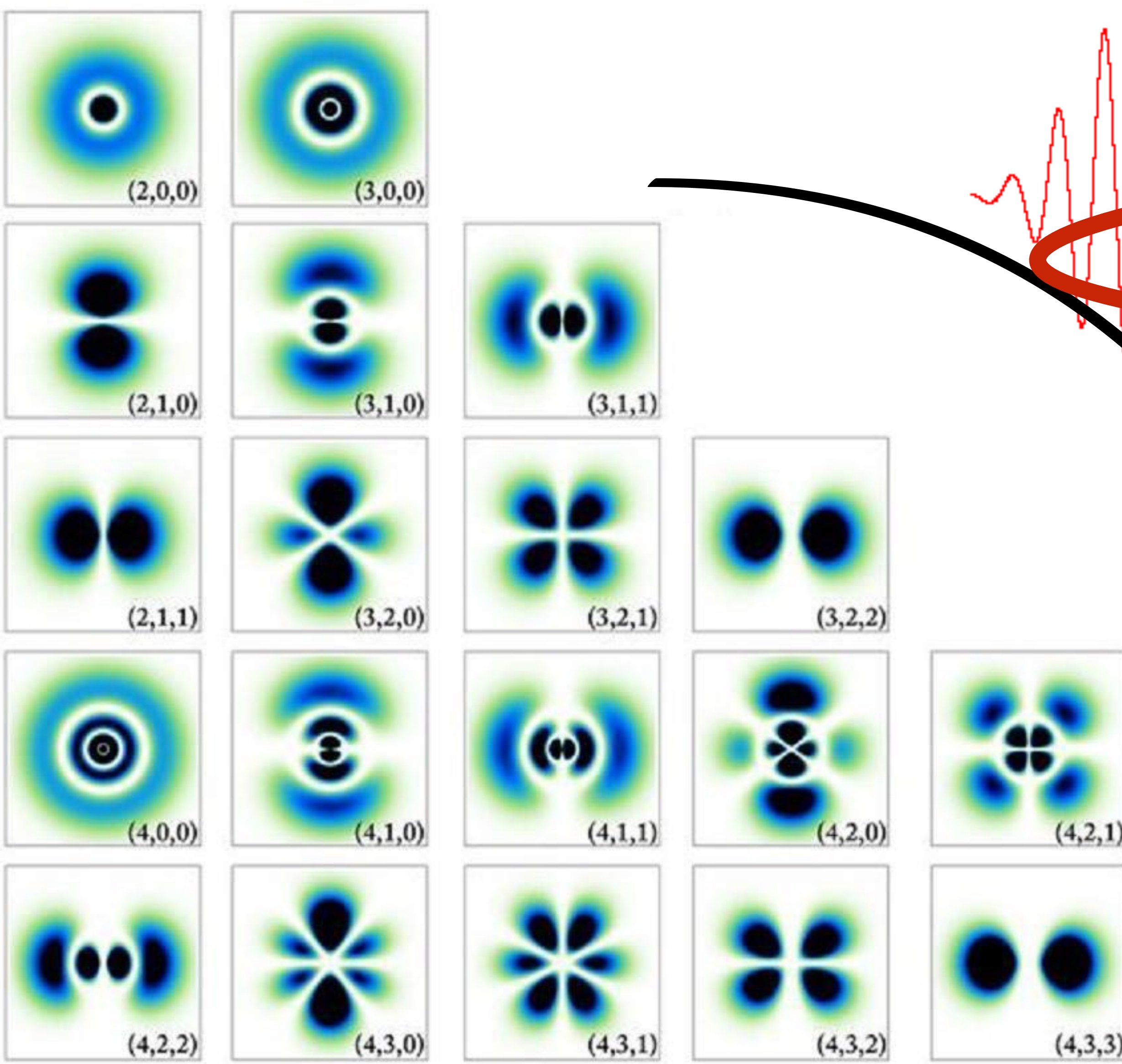
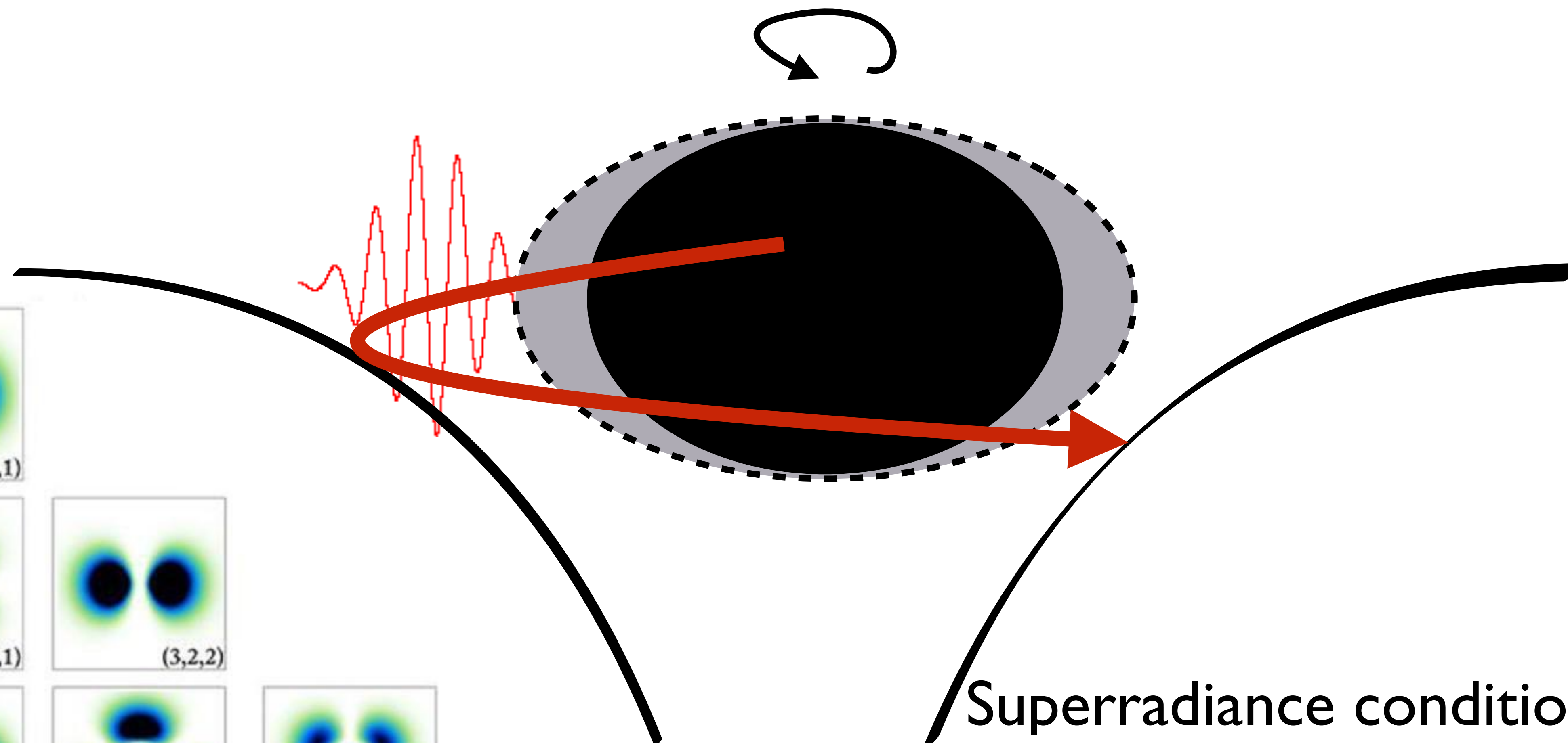




Superradiance condition:

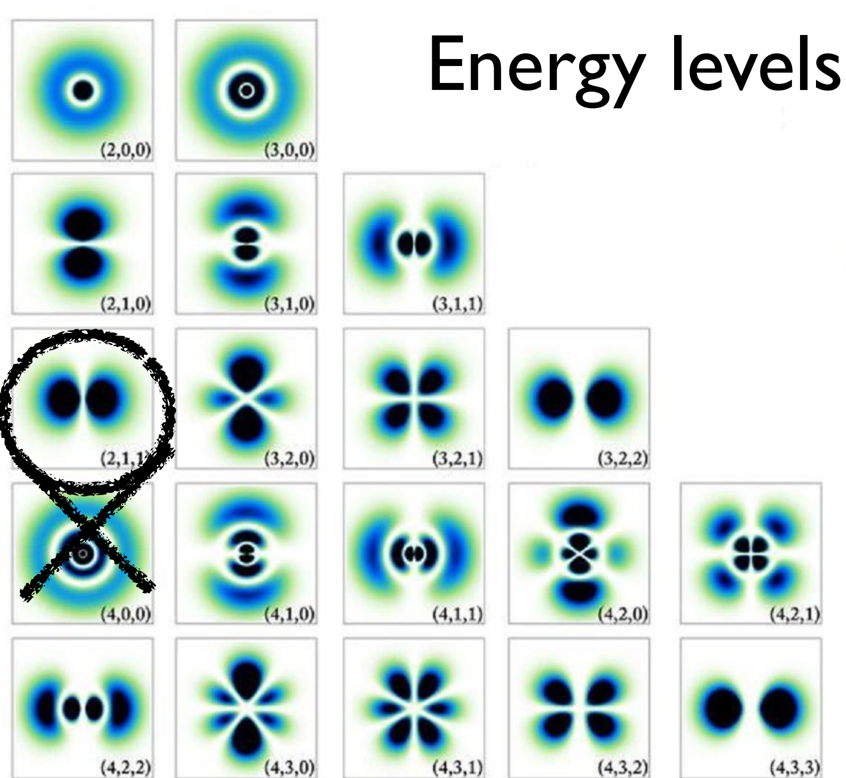
$$\frac{\omega_a}{m} < \Omega_{BH}$$

(m = magnetic quantum number)

Gravitational Atoms

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

	Hydrogen atoms	Gravitational atoms
`Fine structure constant`	α_{em}	$\alpha = G_{\rm N} M_{\rm BH} \mu_a = r_g \mu_a$
Radius	$r_B = \dfrac{n^2}{\alpha_{em} m_e}$	$r_c \sim \dfrac{n^2}{\alpha \mu_a} \sim 4 - 400 r_g$
Occupation number	$N = 1$	$N \sim 10^{70} - 10^{80}$
Boundary conditions	regular at origin	ingoing at horizon
Energy levels	$m_e \left(1 - \dfrac{\alpha_{em}^2}{2n^2}\right)$	$\mu_a \left(1 - \dfrac{\alpha^2}{2n^2} + i\Gamma_{sr}\right)$



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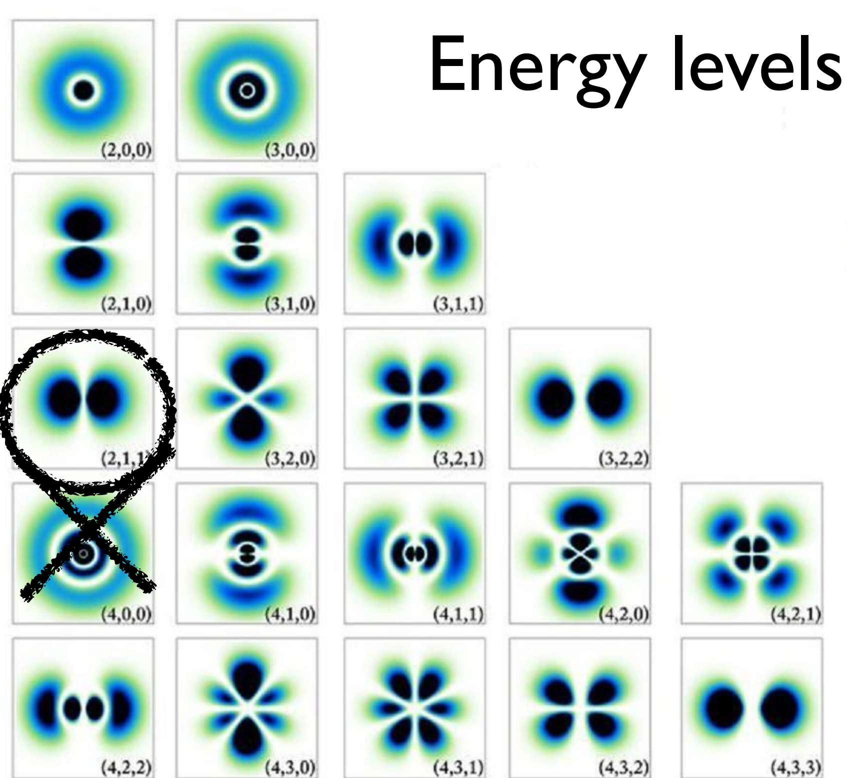


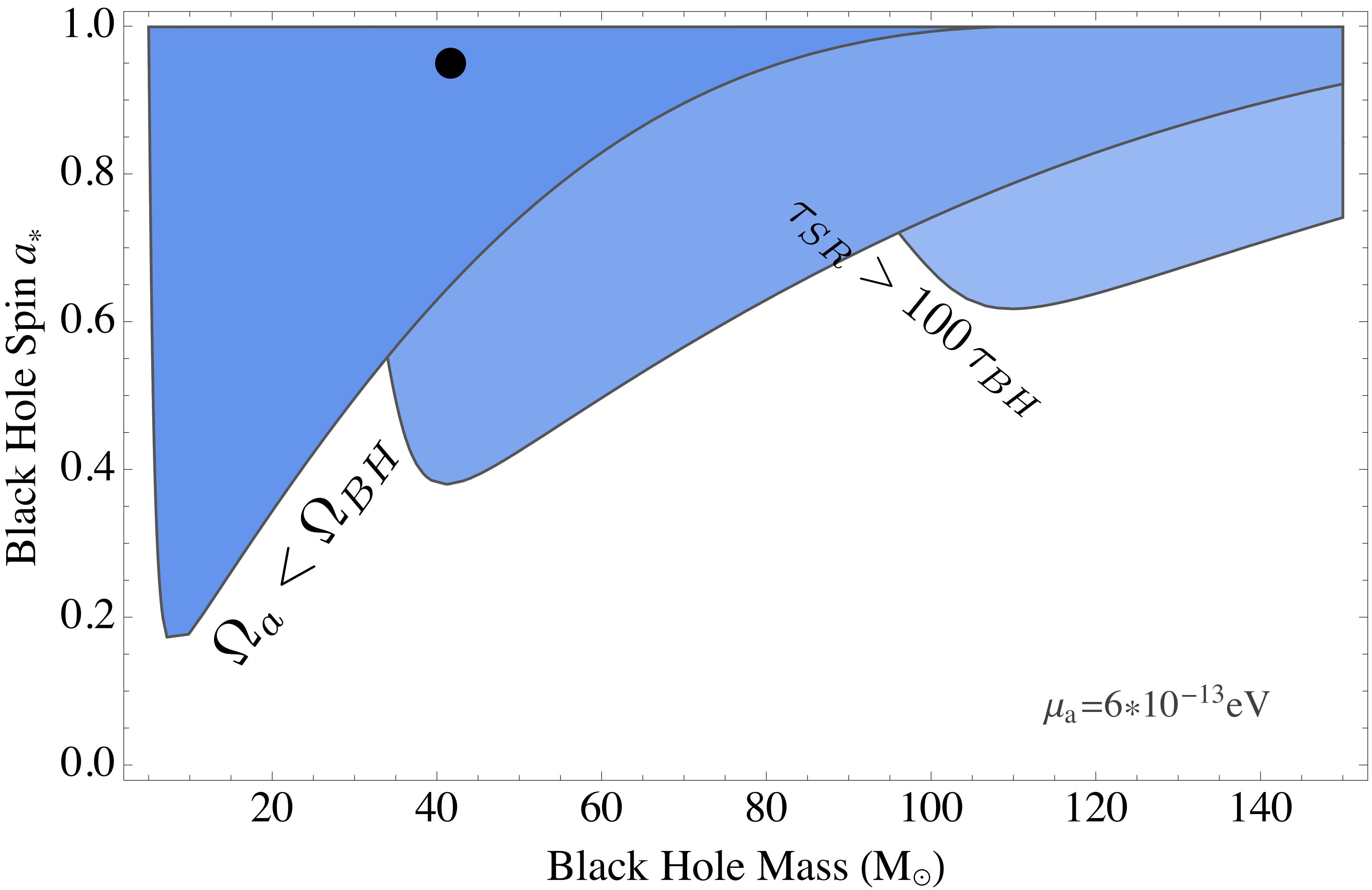
$$\Gamma_{sr}^{nlm} \sim \mu_a \, \alpha^{4l+4} (m\Omega_{BH} - \mu_a) r_+ C_{nlm} \sim$$

$$\sim \mathcal{O}(10^{-7}\text{–}10^{-14})\, \mu_a$$

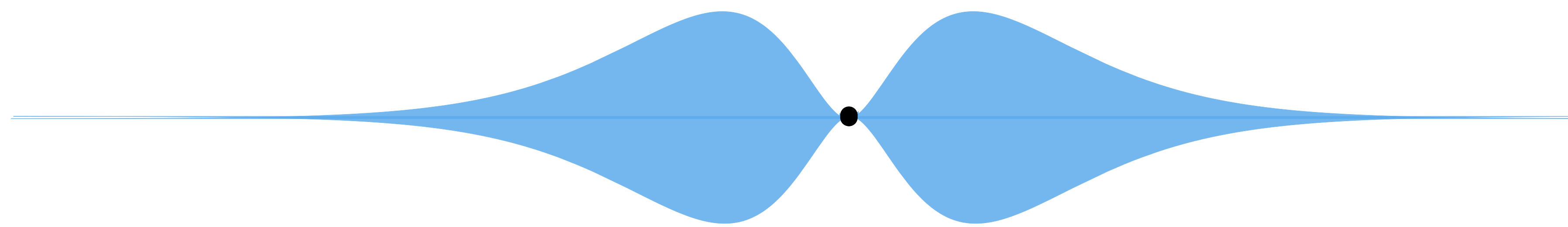
exponential growth $\quad N(t) \sim e^{\Gamma_{sr} t}$

Superradiance: a history

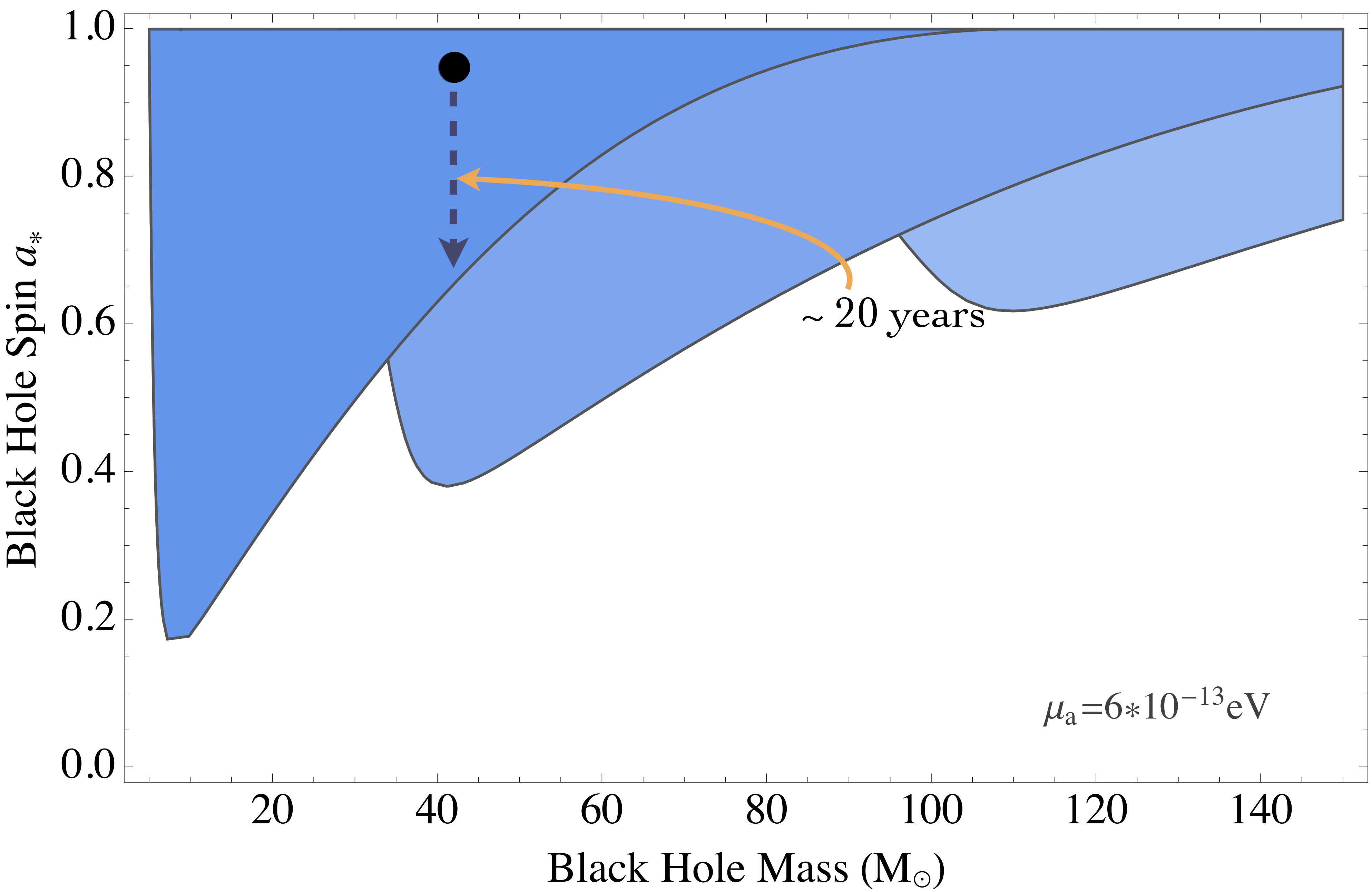
A black hole is born with spin a* = 0.95, M = 40 M⊙.



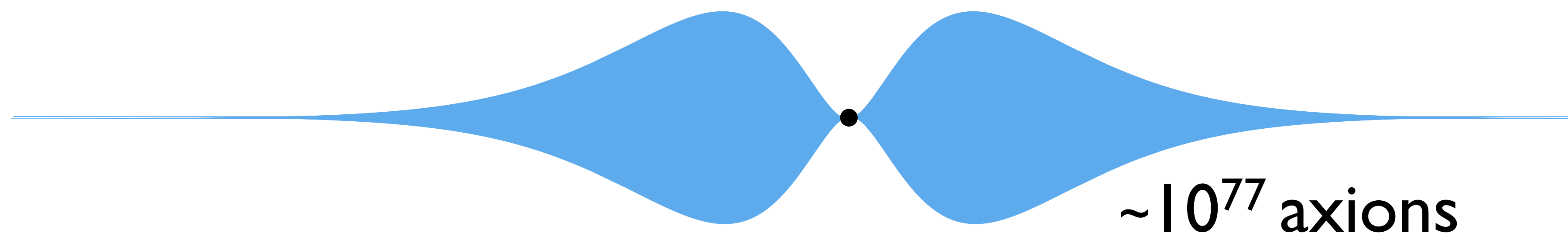
Superradiance: a history



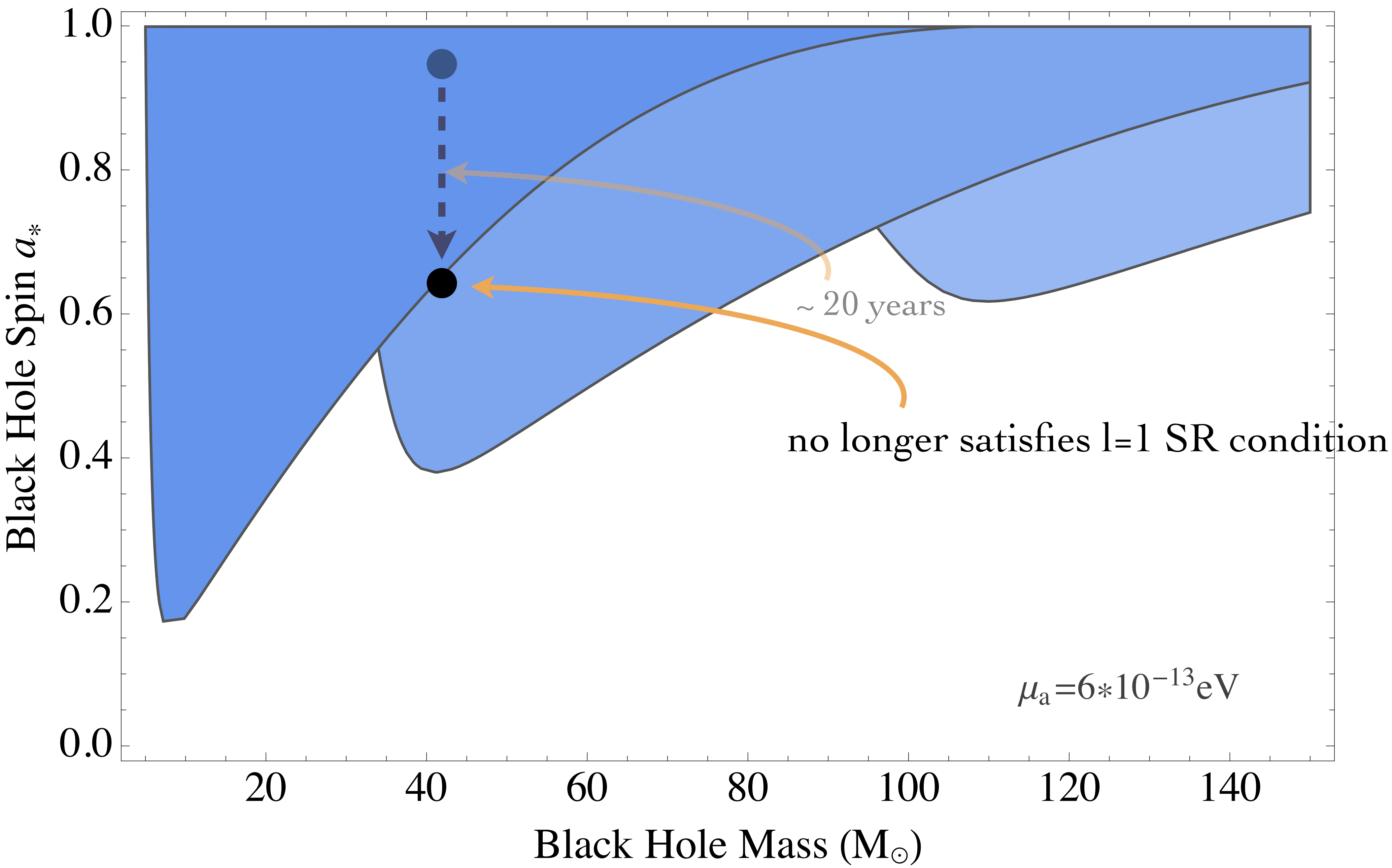
BH spins down and *fastest-growing* level of axions is formed



Superradiance: a history



Once BH angular velocity matches that of the level, growth stops



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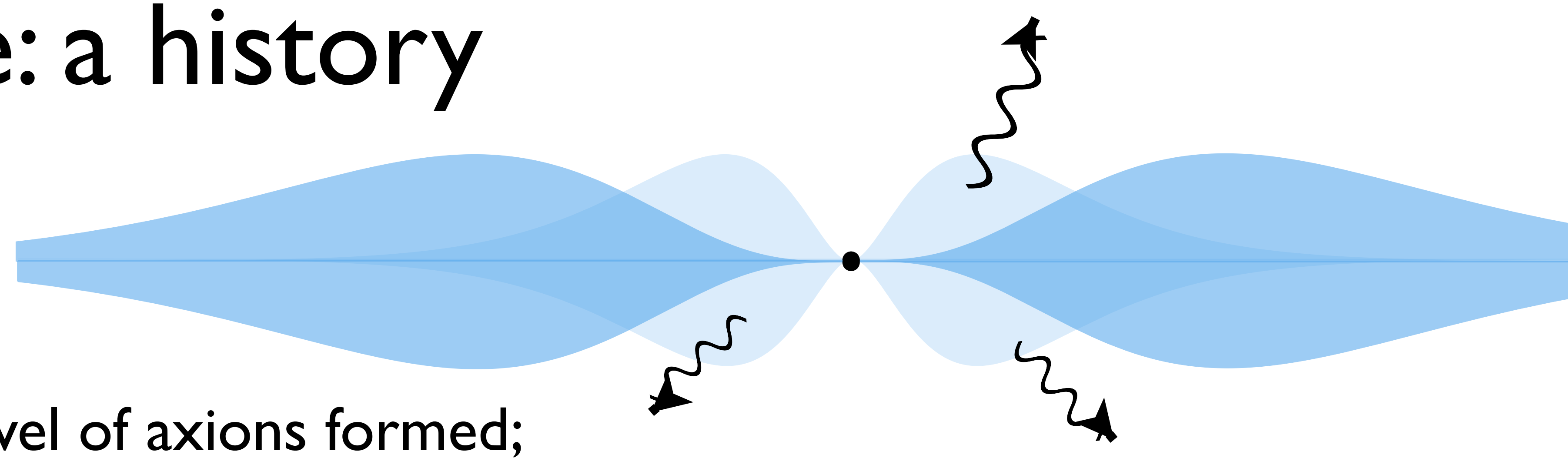
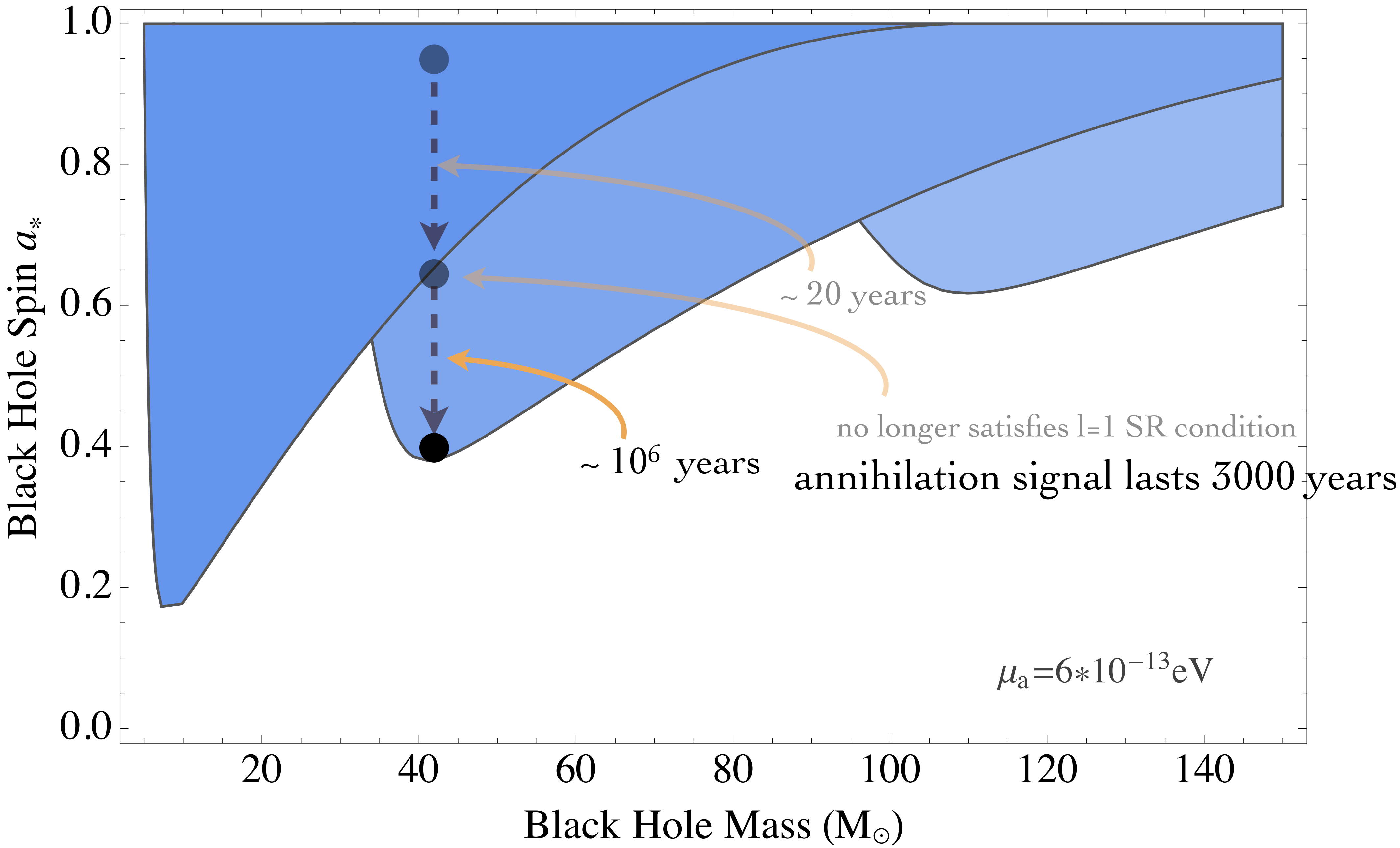
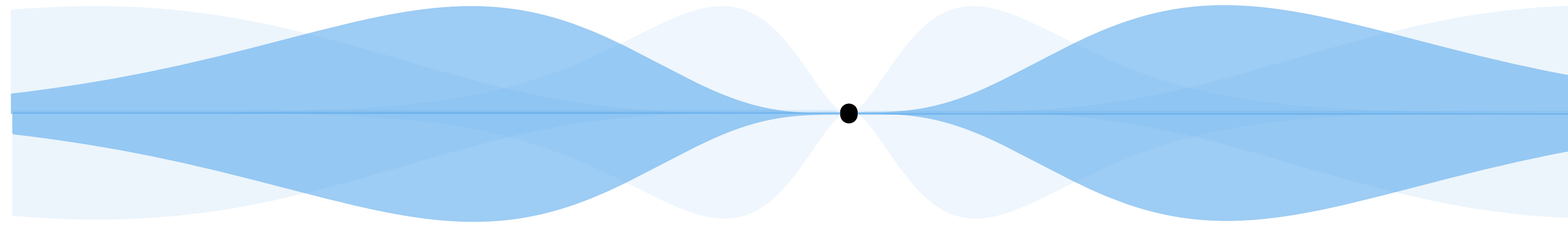


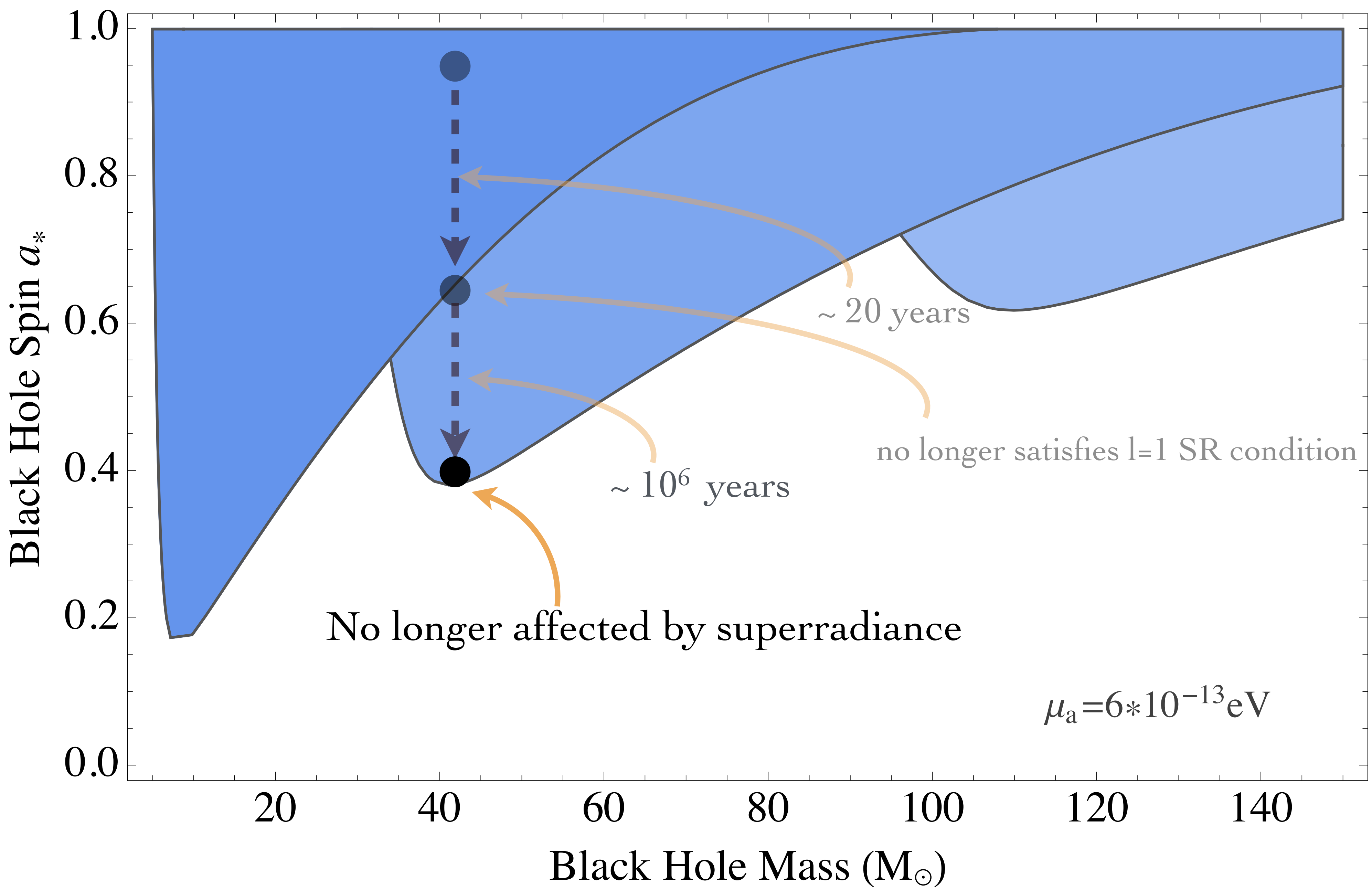
BH spins down and *next* level of axions formed; annihilations to GWs deplete first level



Superradiance: a history



The following level has a superradiance rate exceeding age of BH



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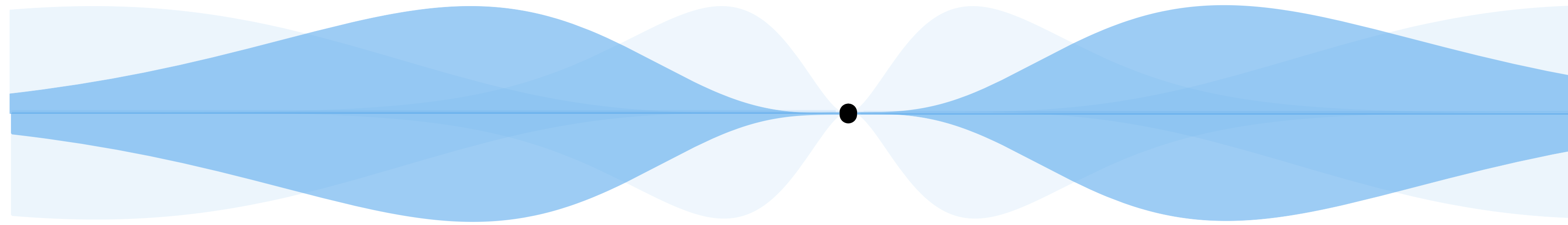
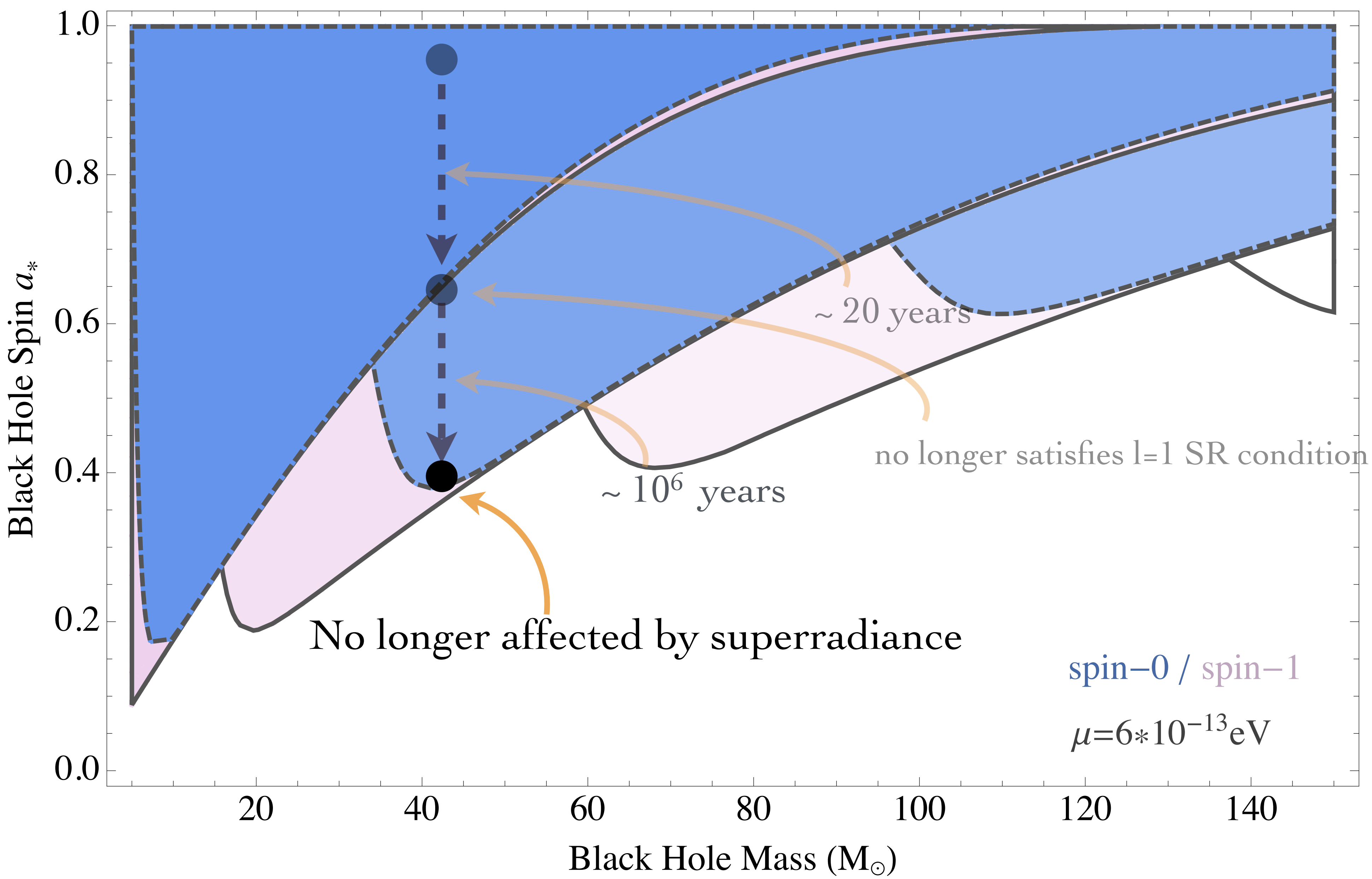


Spin 1 particles: faster superradiance rate for the same mass particle



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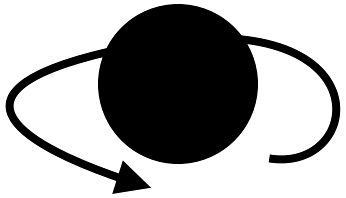
- Spinning Black Holes 
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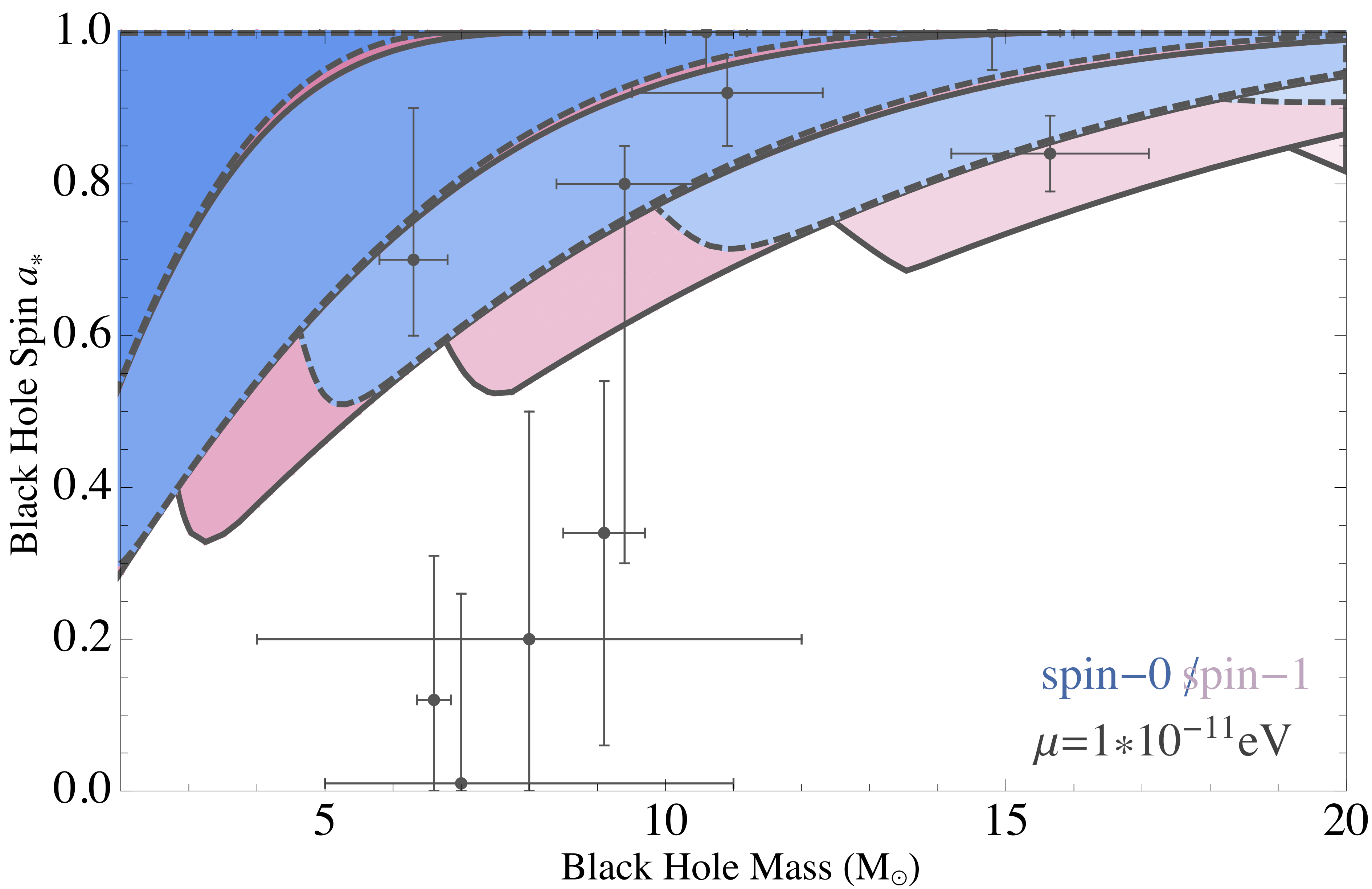
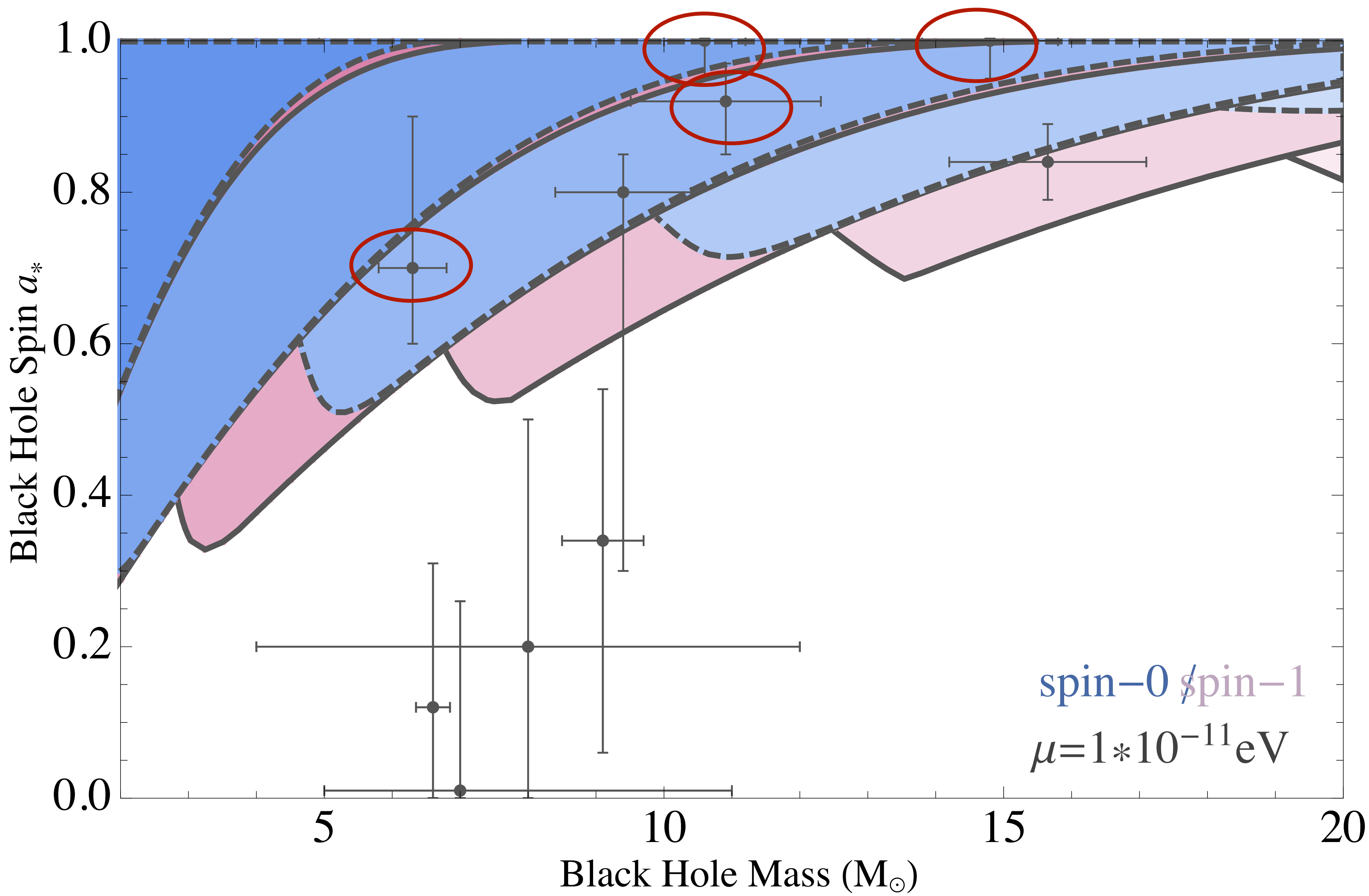
Black Hole Spins

Black hole spin and mass measurements



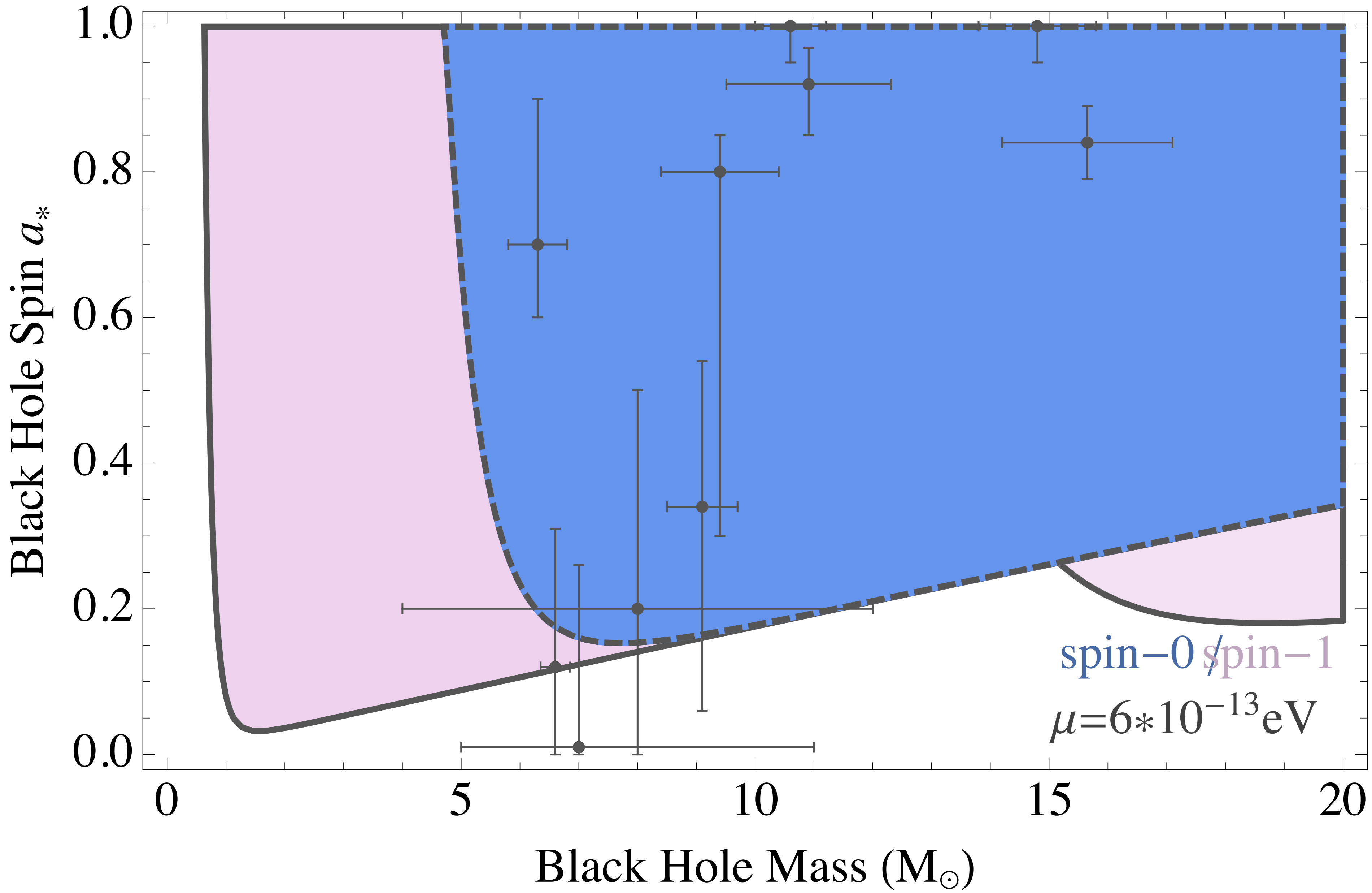
Black Hole Spins

Several black holes disfavor this axion mass, more for vector



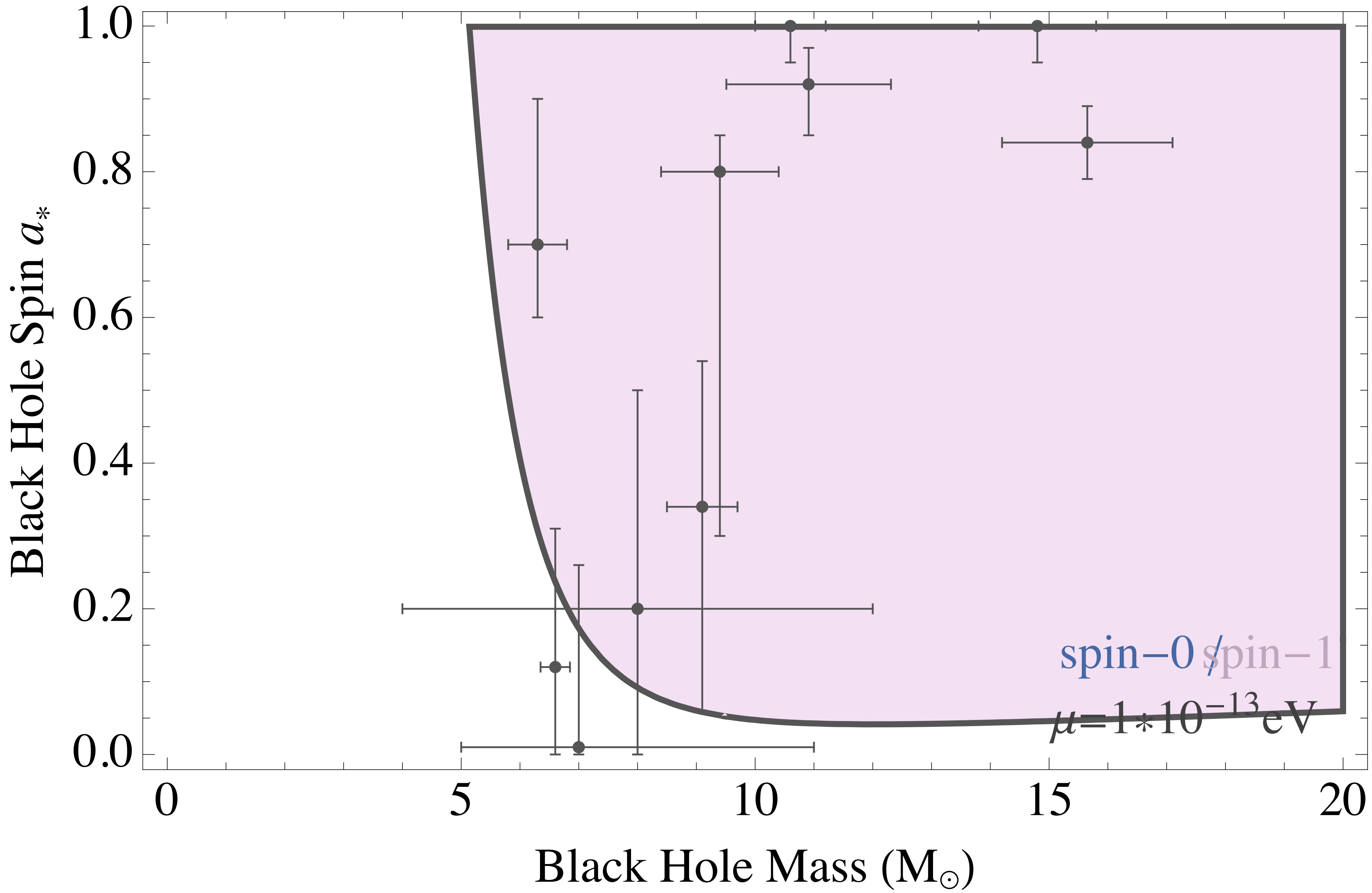
Black Hole Spins

More constrained at lighter masses



Black Hole Spins

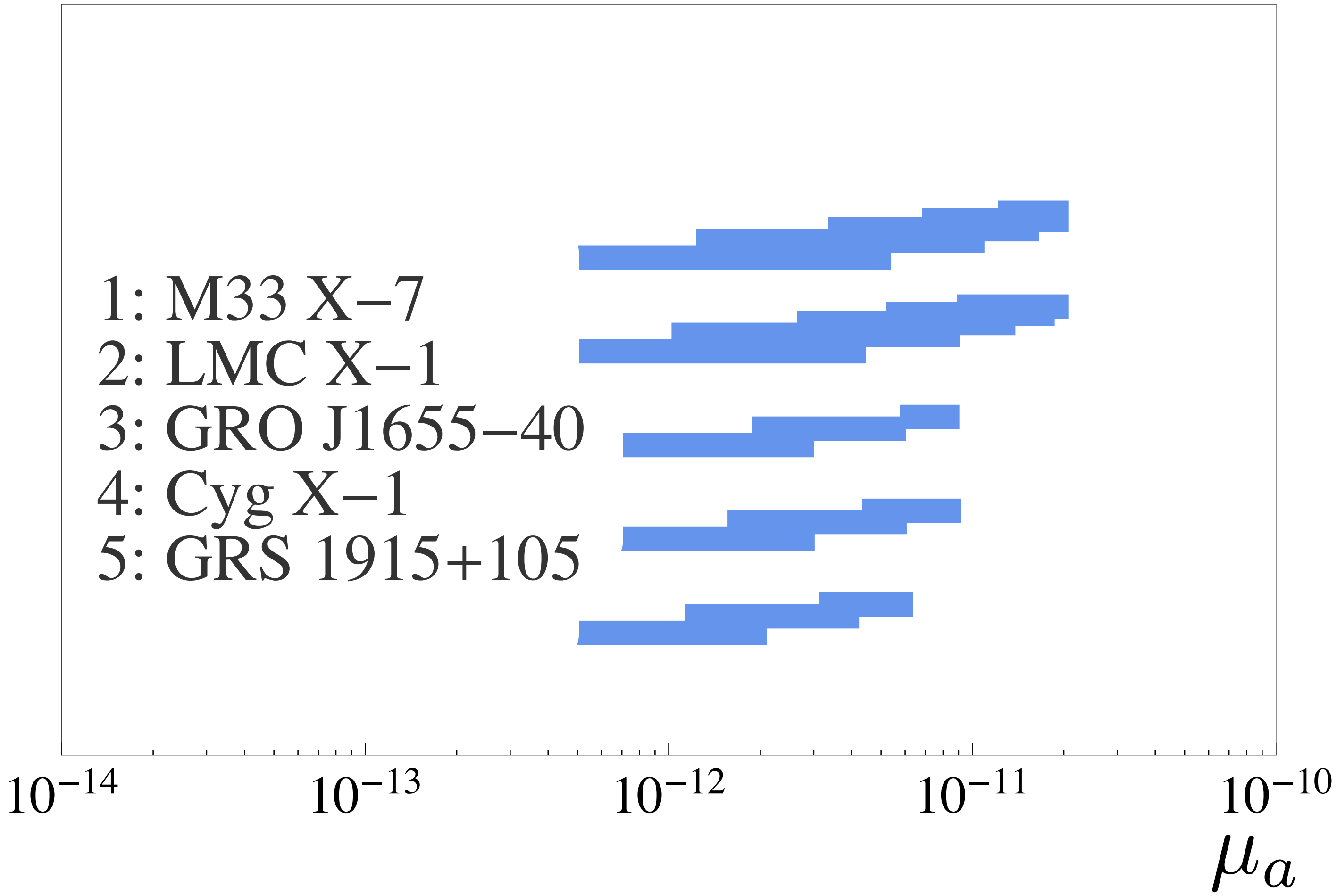
At even lighter masses, constraint is relaxed; SR time is too long



Black Hole Spins

Five currently measured black holes combine to exclude the range:

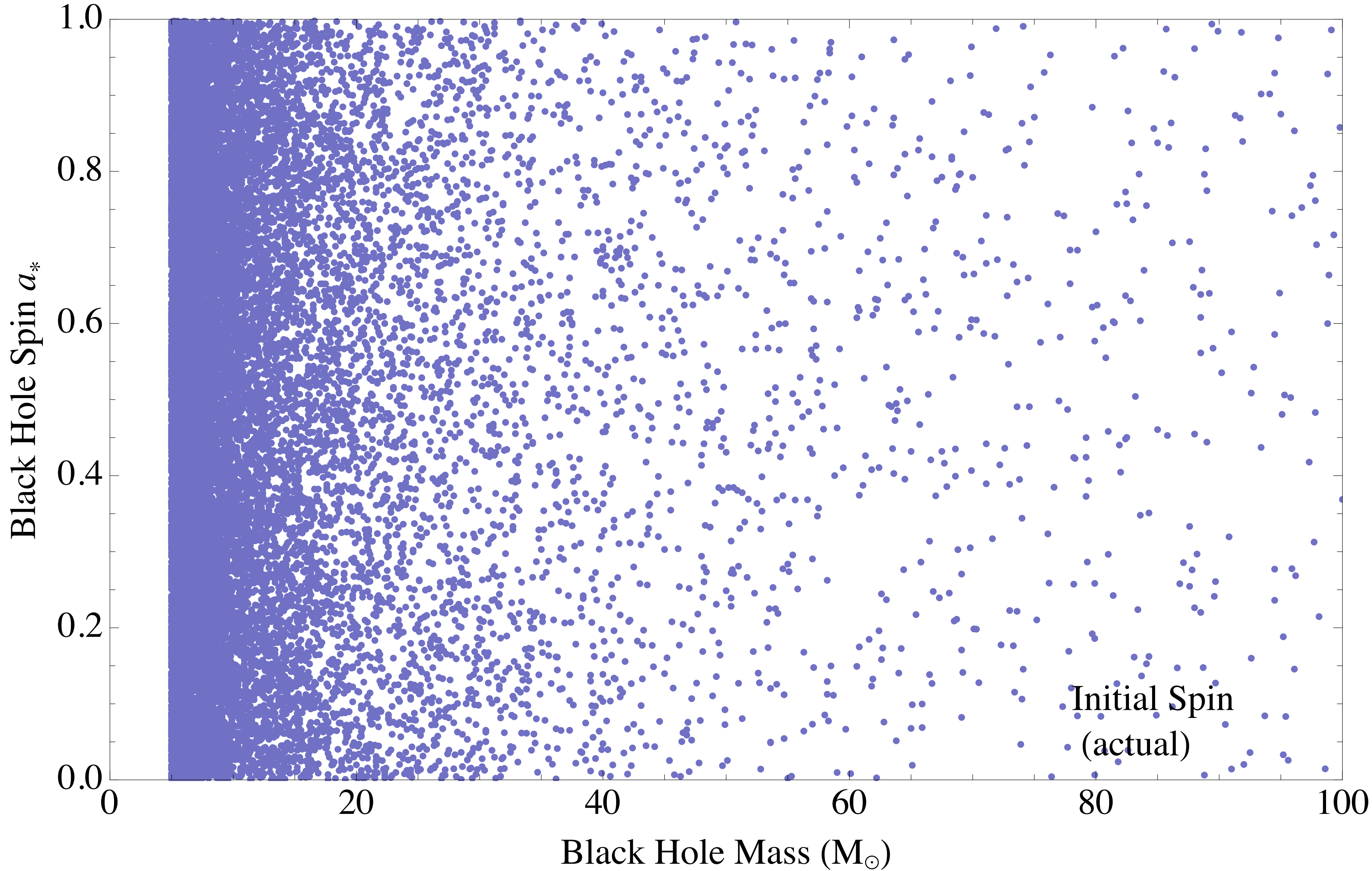
$$2 \times 10^{-11} > \mu_a > 6 \times 10^{-13} \text{ eV}$$



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

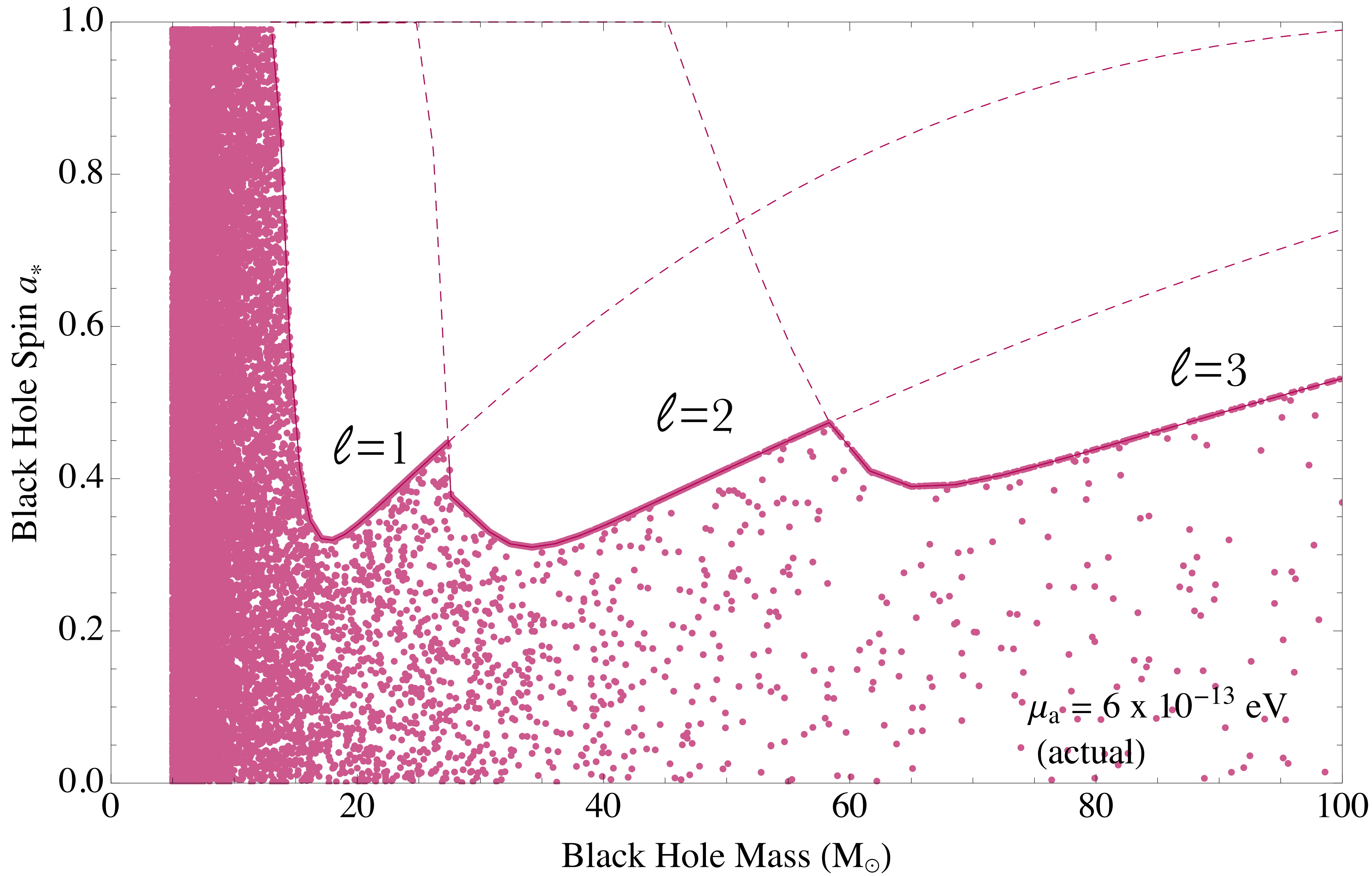
Black Hole Spins
at LIGO

9-240 BBHs/Gpc^3/yr. — 1000s of BHs merging in low-redshift universe —



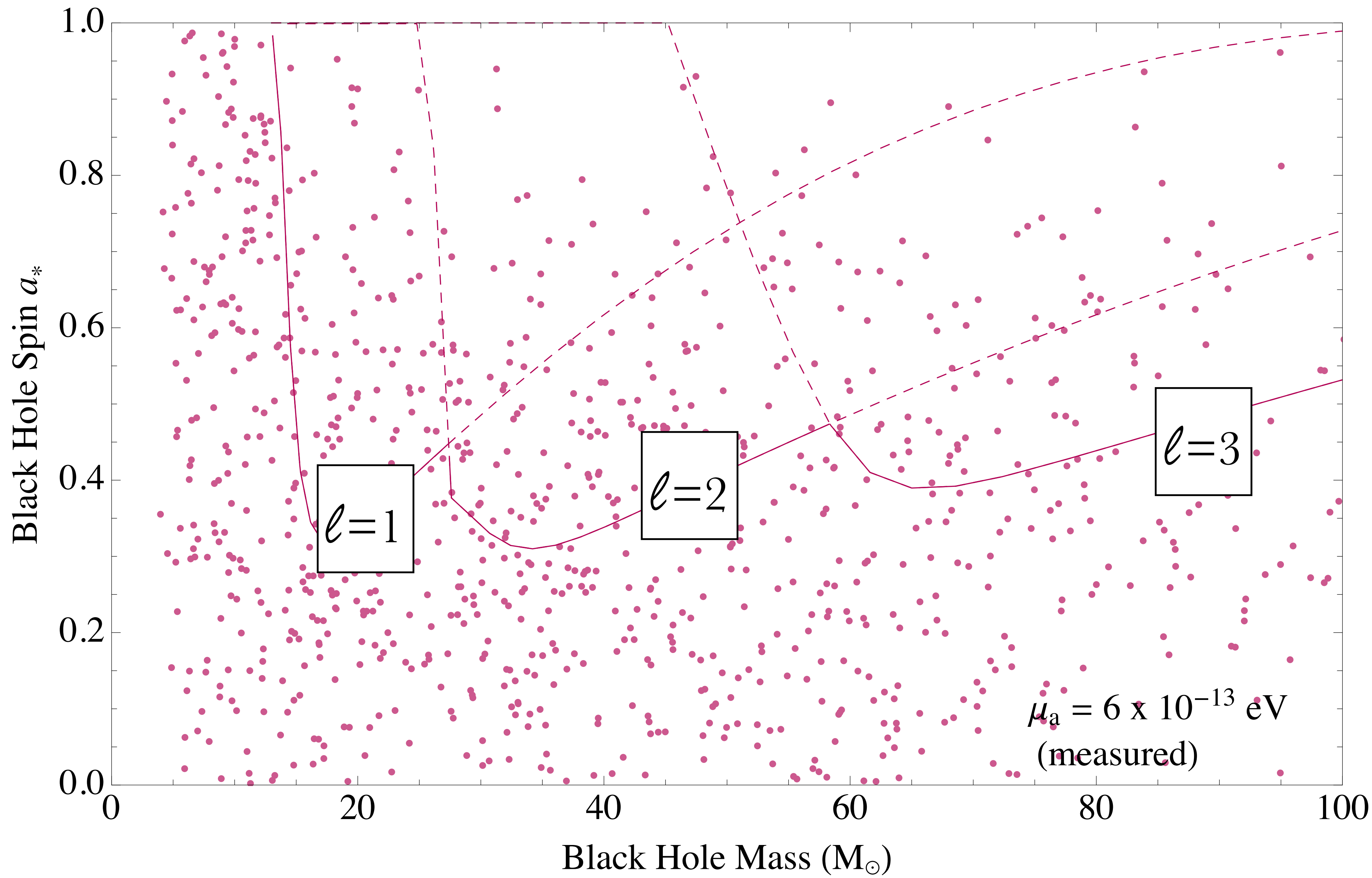
Black Hole Spins

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



Black Hole Spins

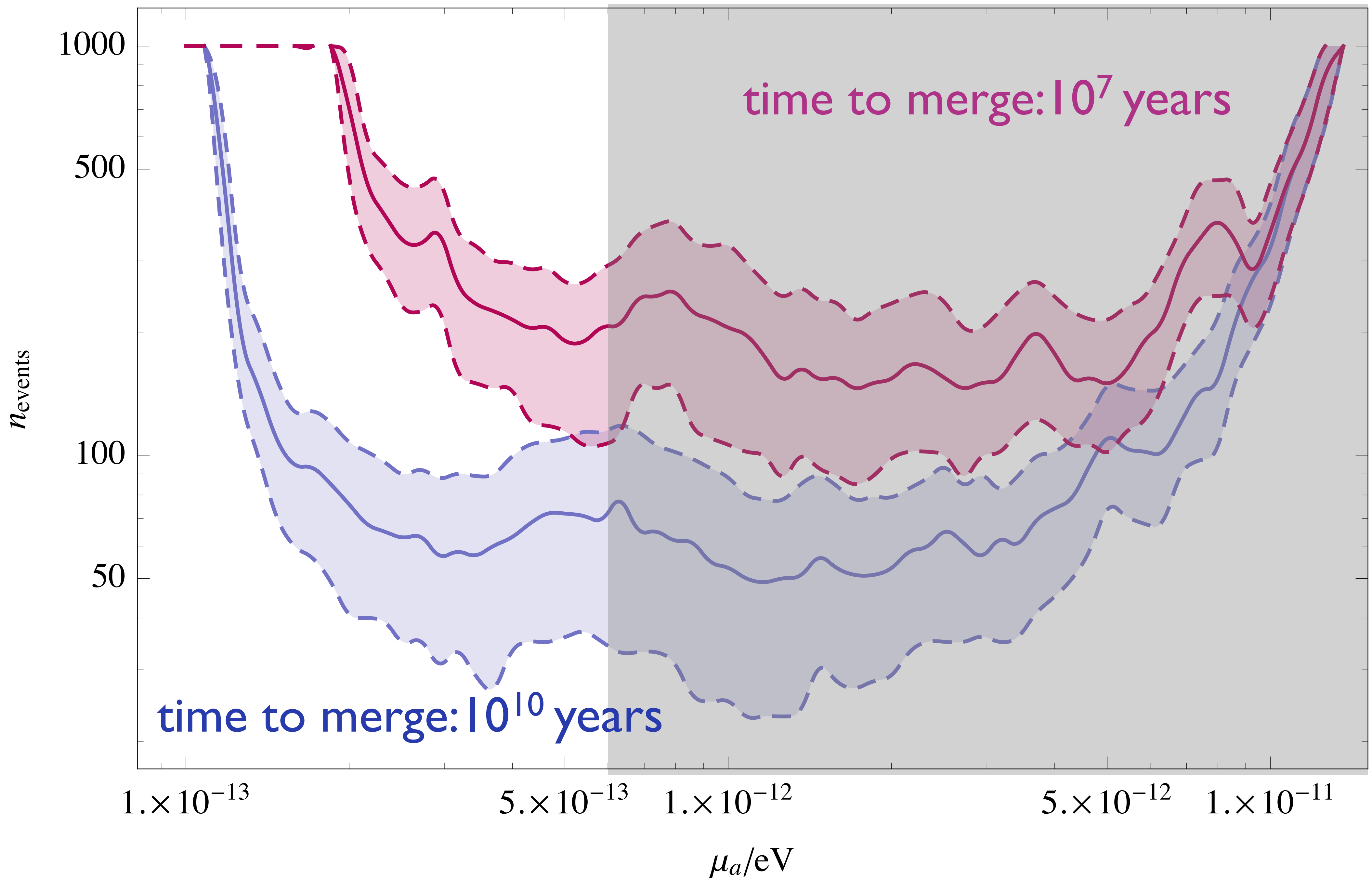
LIGO may measure hundreds of BHs in spin-mass plane (spin error is expected to be large)



$\sigma_M/M \sim 0.1; \qquad \sigma_{a_*} \sim 0.25$

Black Hole Spins

Can find statistical evidence for deficit of high spins in a range of BH masses with 50-200 measurements:



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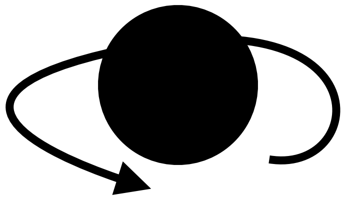
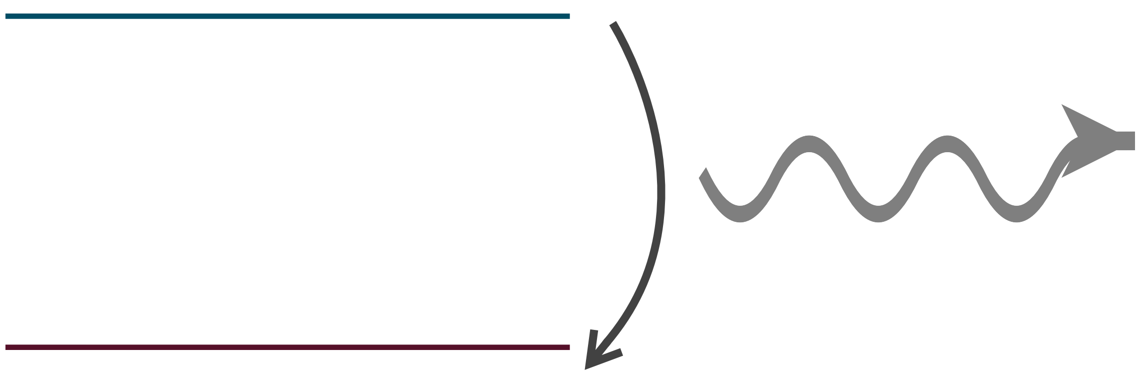


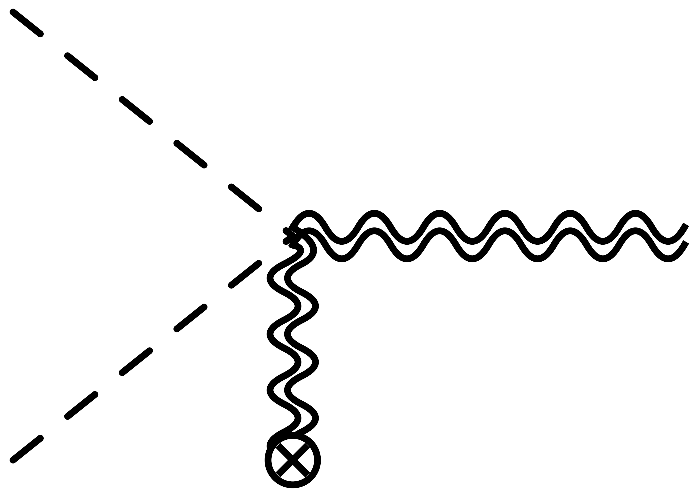
- Gravitational Wave Detection of Axions

Gravitational Wave Signals

- Transitions between levels



- Annihilations to gravitons



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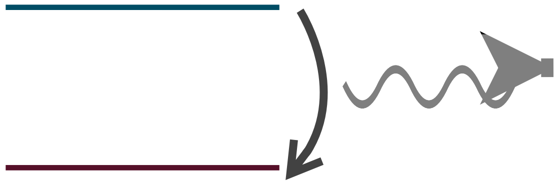
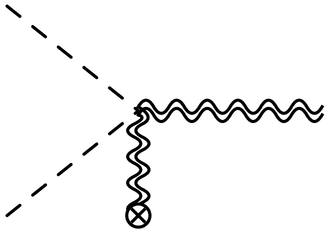
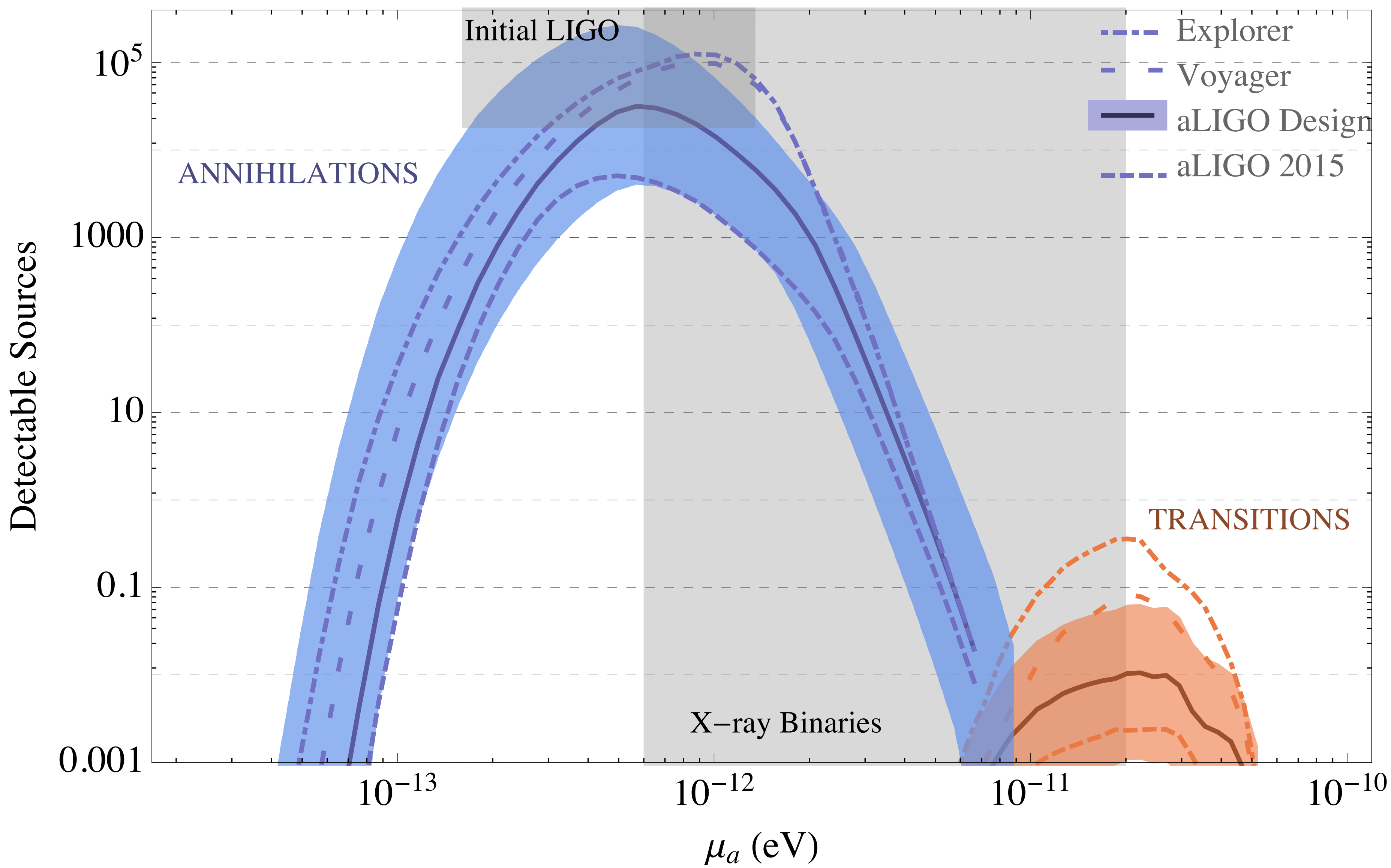




- Event rates up to 10,000 — can be observed and studied in detail
- Uncertainty dominated by BH mass distribution at higher masses

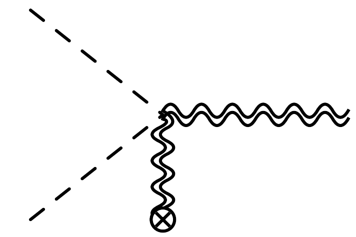


Signals visible from galactic center typically last 10-1000 yrs

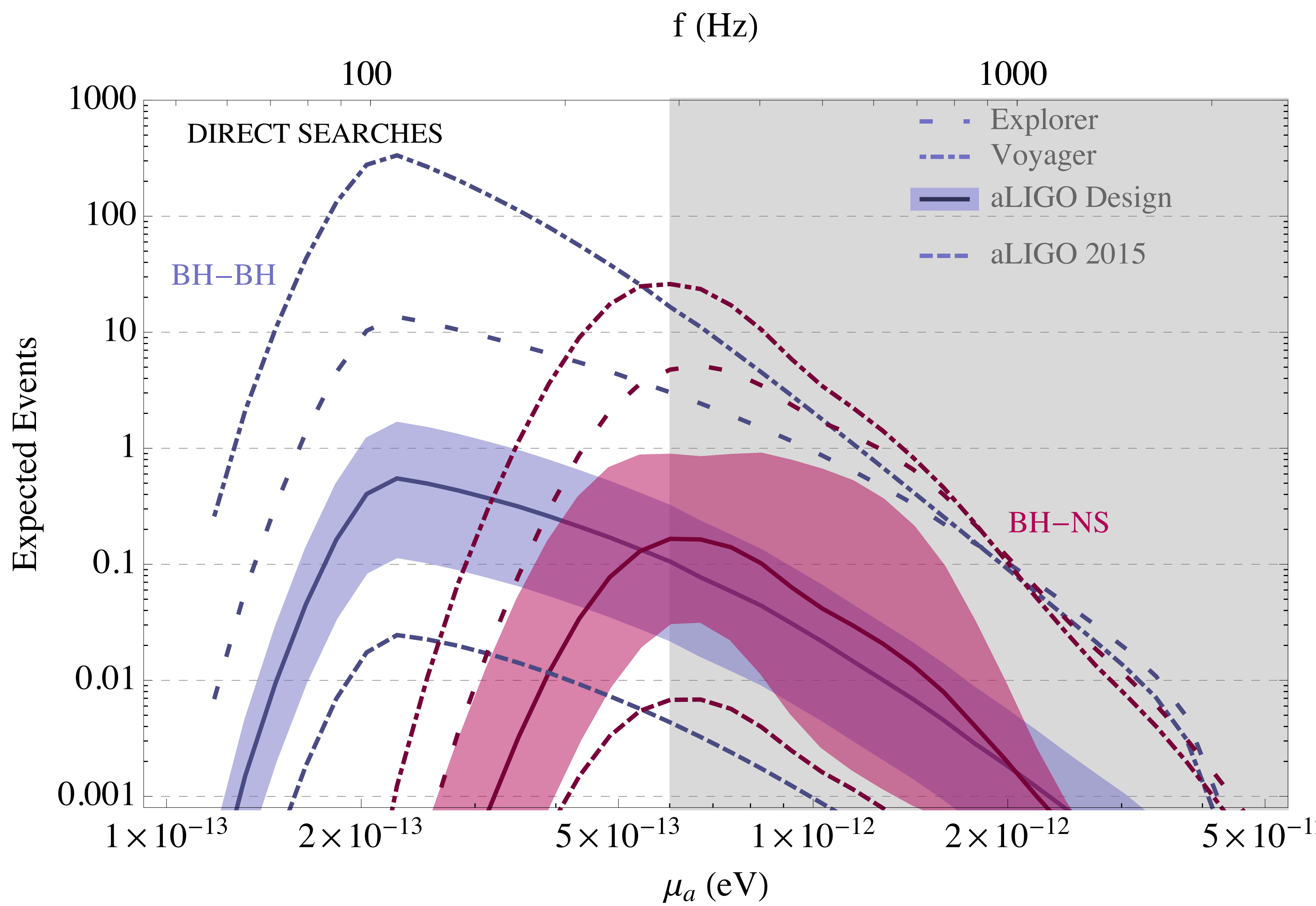
Signals *coherent* and *monochromatic*

Cross-check spin limits

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



Conclusions

- Ultra light axions and vectors can be constrained or detected 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 transitions and annihilations of axions
- May observe growth of gravitational atom after a merger in real time

Thank you!