Searching for Ultralight Particles with Black Holes and Gravitational Waves

Masha Baryakhtar
Perimeter Institute
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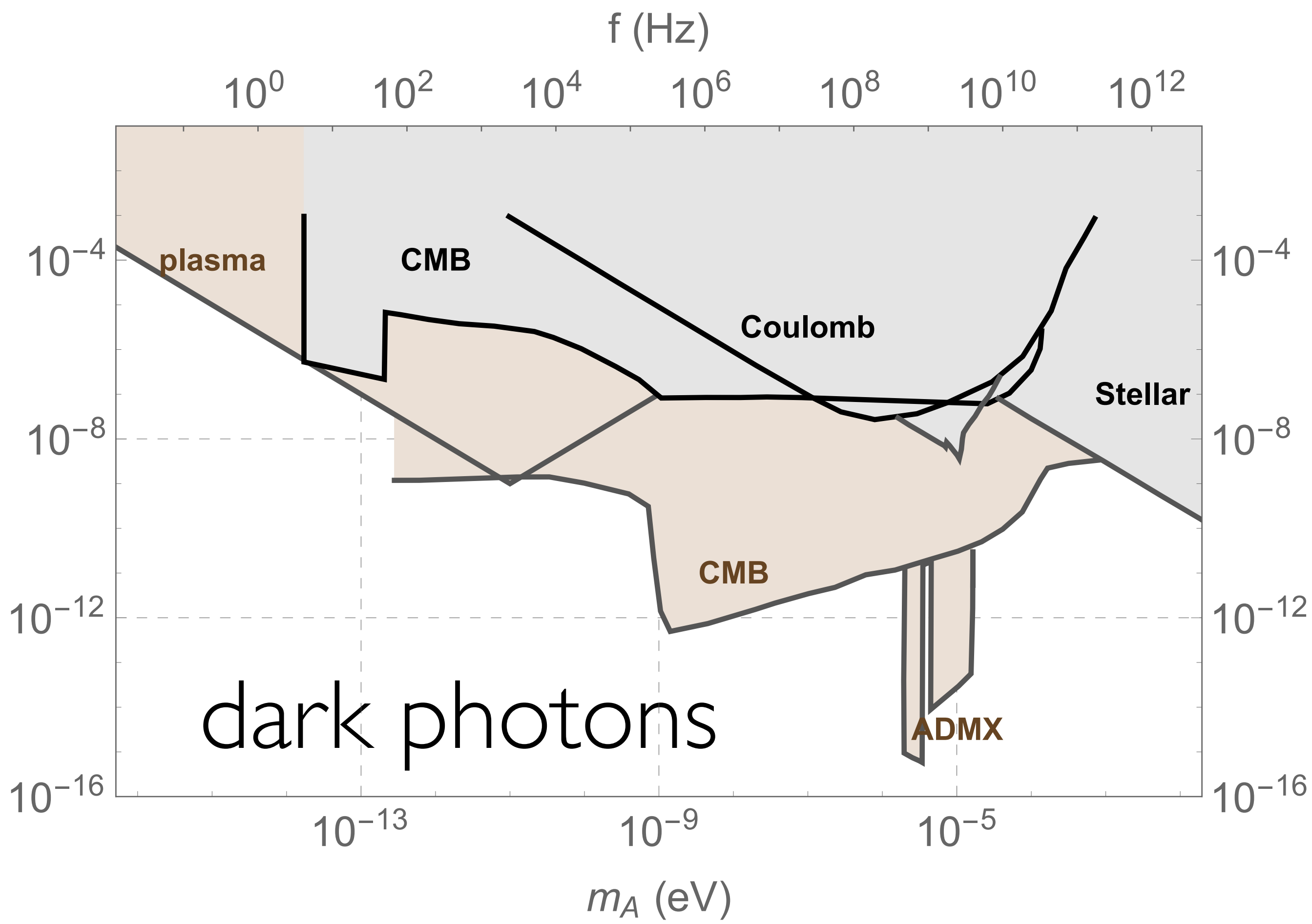
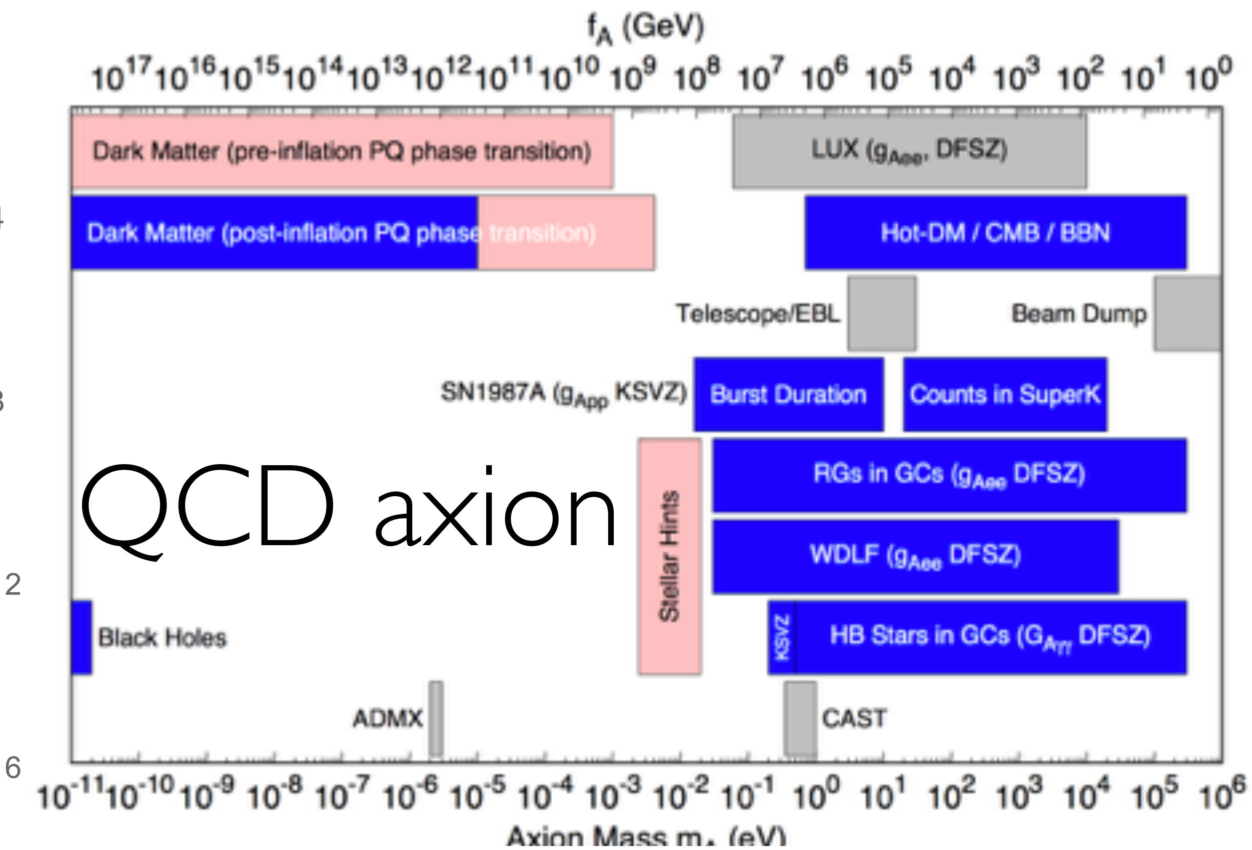
Phys.Rev. D91 (2015) no.8, 084011 A. Arvanitaki, MB, X. Huang
Phys.Rev. D95 (2017) no.4, 043001 A. Arvanitaki, MB, S. Dimopoulos, S. Dubovsky, R. Lasenby
Phys.Rev. D96 (2017) no.3, 035019 MB, R. Lasenby, M. Teo

Searching for Ultralight particles

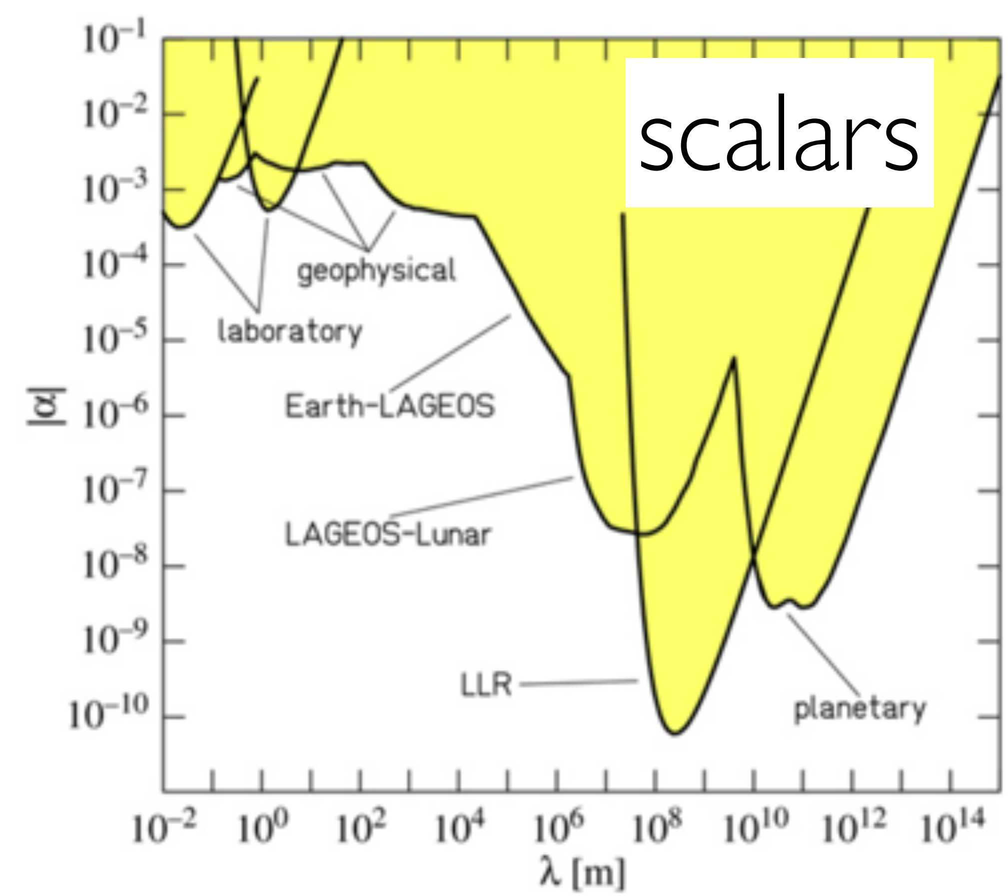




Spin 0 and spin 1, weakly interacting

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

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



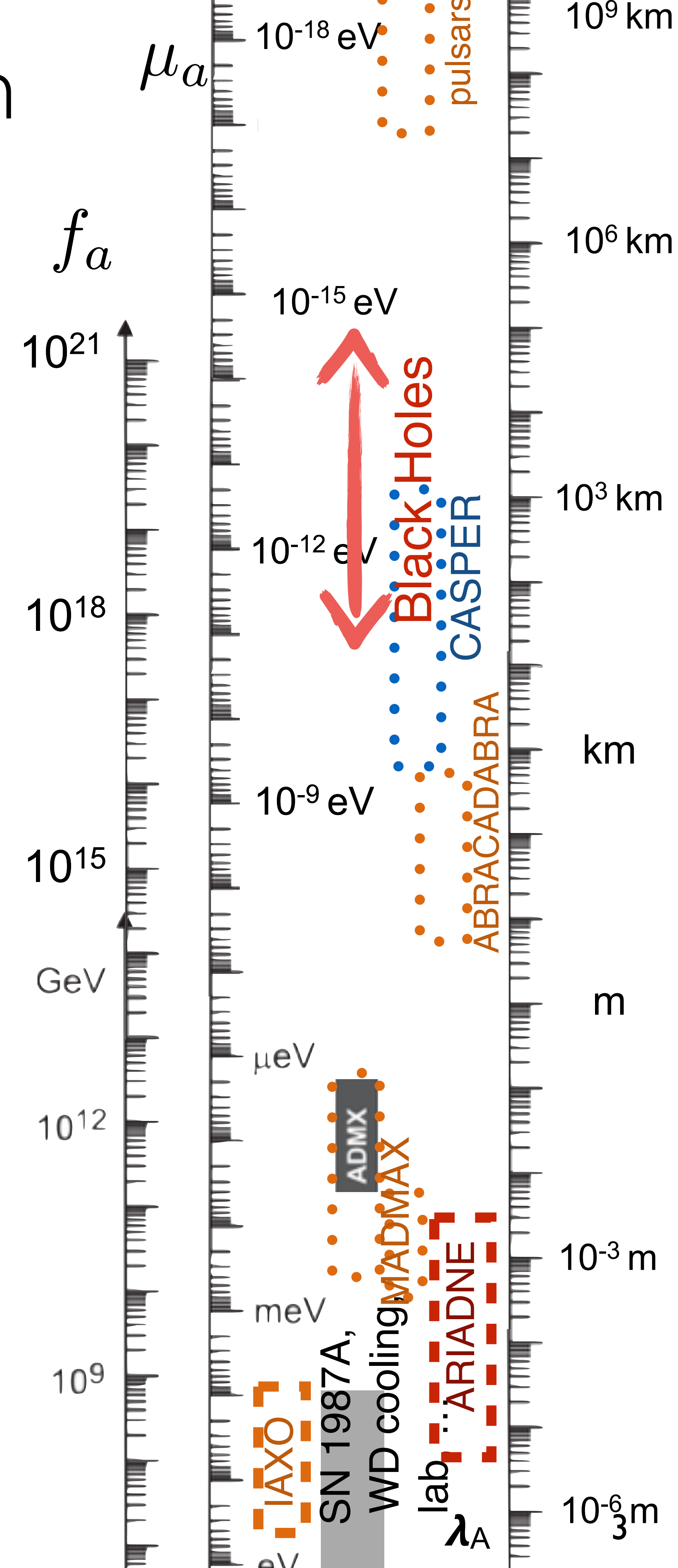
Searching for the QCD axion

- 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

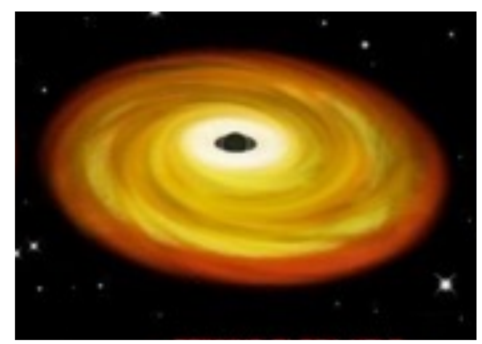
$$\lambda_a \sim 3\,\text{km}\ \frac{6\times10^{-11}\text{eV}}{\mu_a}$$



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

Outline

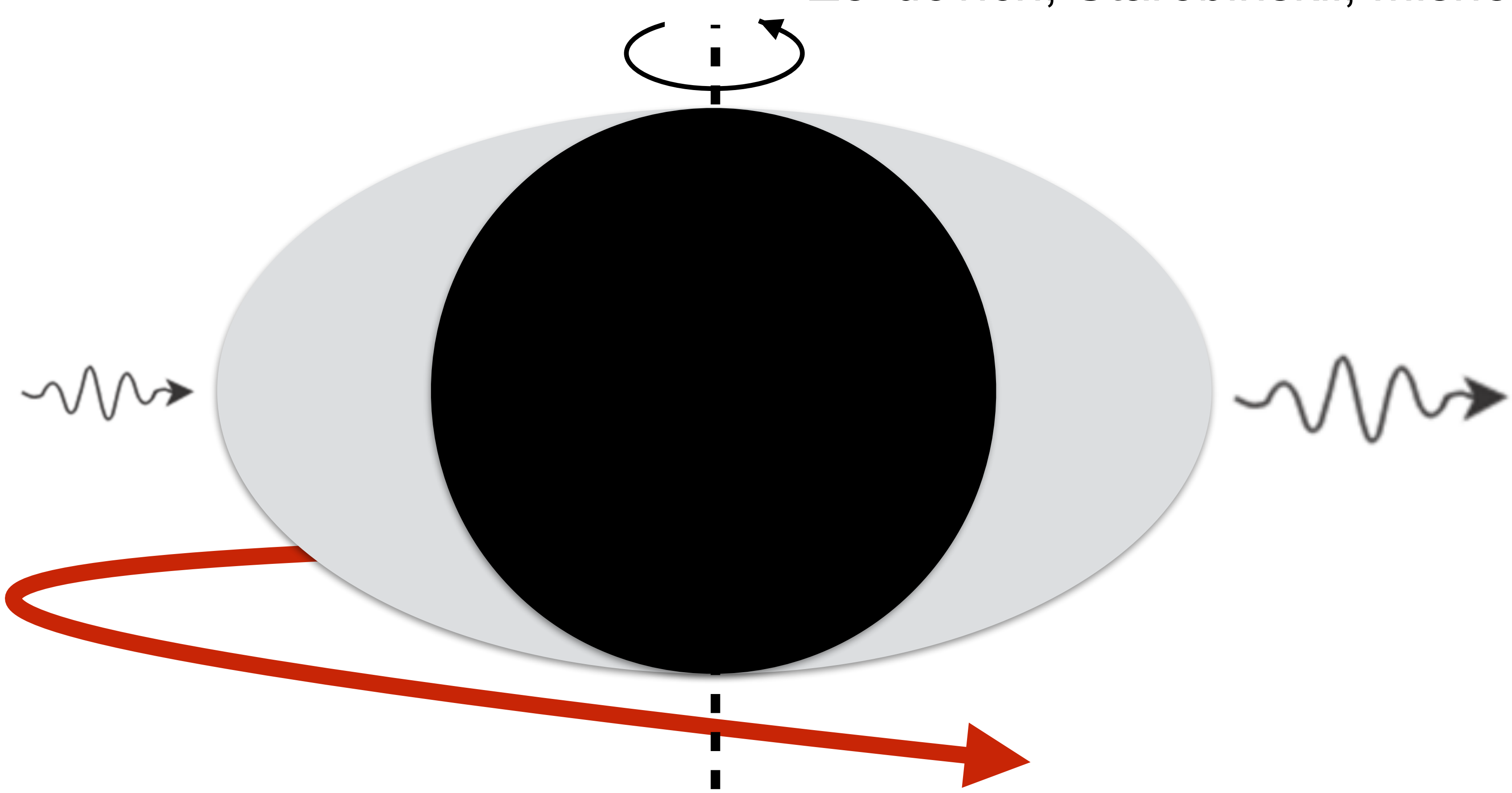
- Black Hole Superradiance



- Spinning Black Holes
- Gravitational Wave Signals

Superradiance

Zel'dovich; Starobinskii; Misner



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:

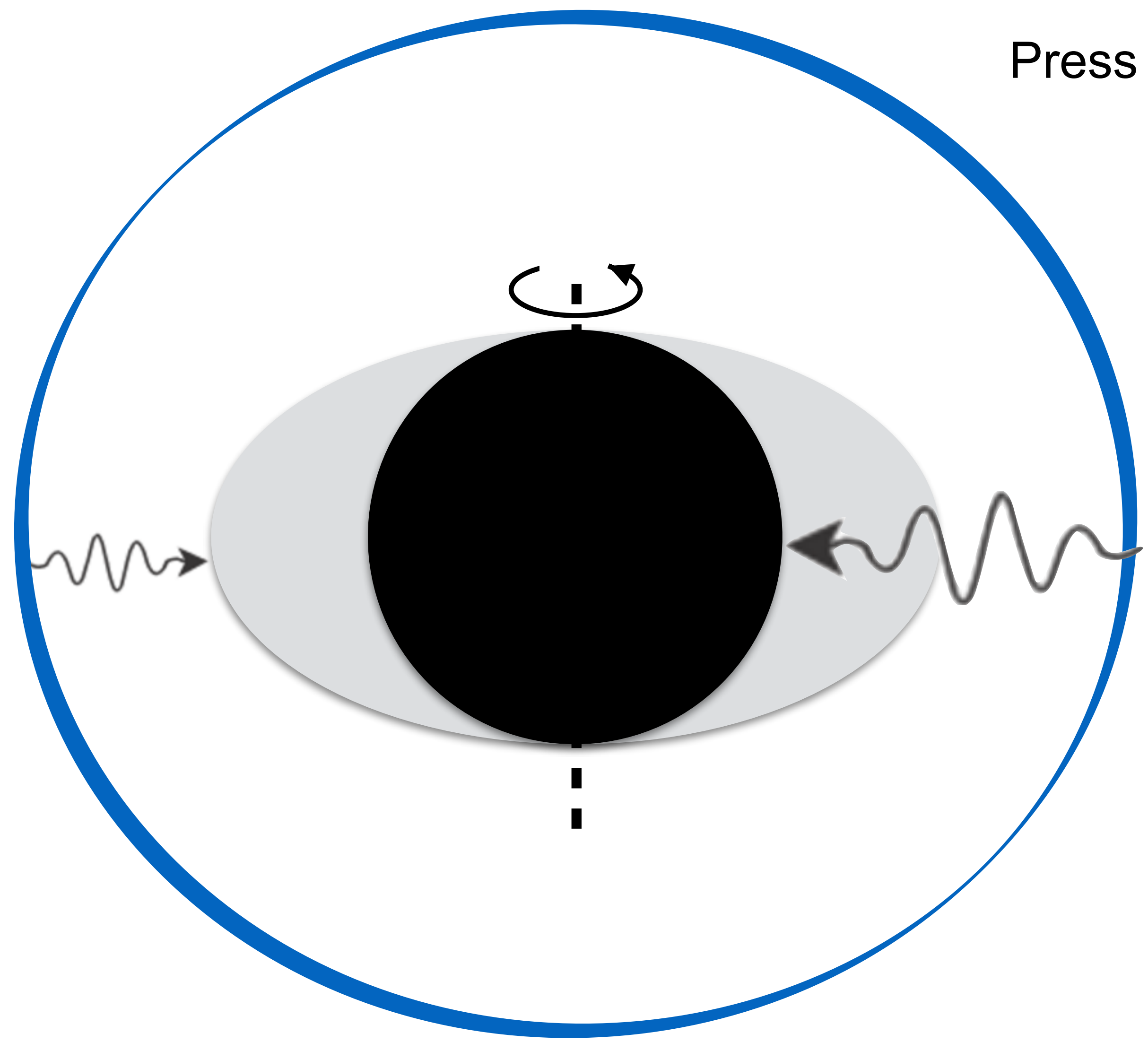
Angular velocity of wave slower than angular velocity of BH horizon,

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

Superradiance

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

Press & Teulkosky



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

Kinematic, not resonant condition

Superradiance condition:

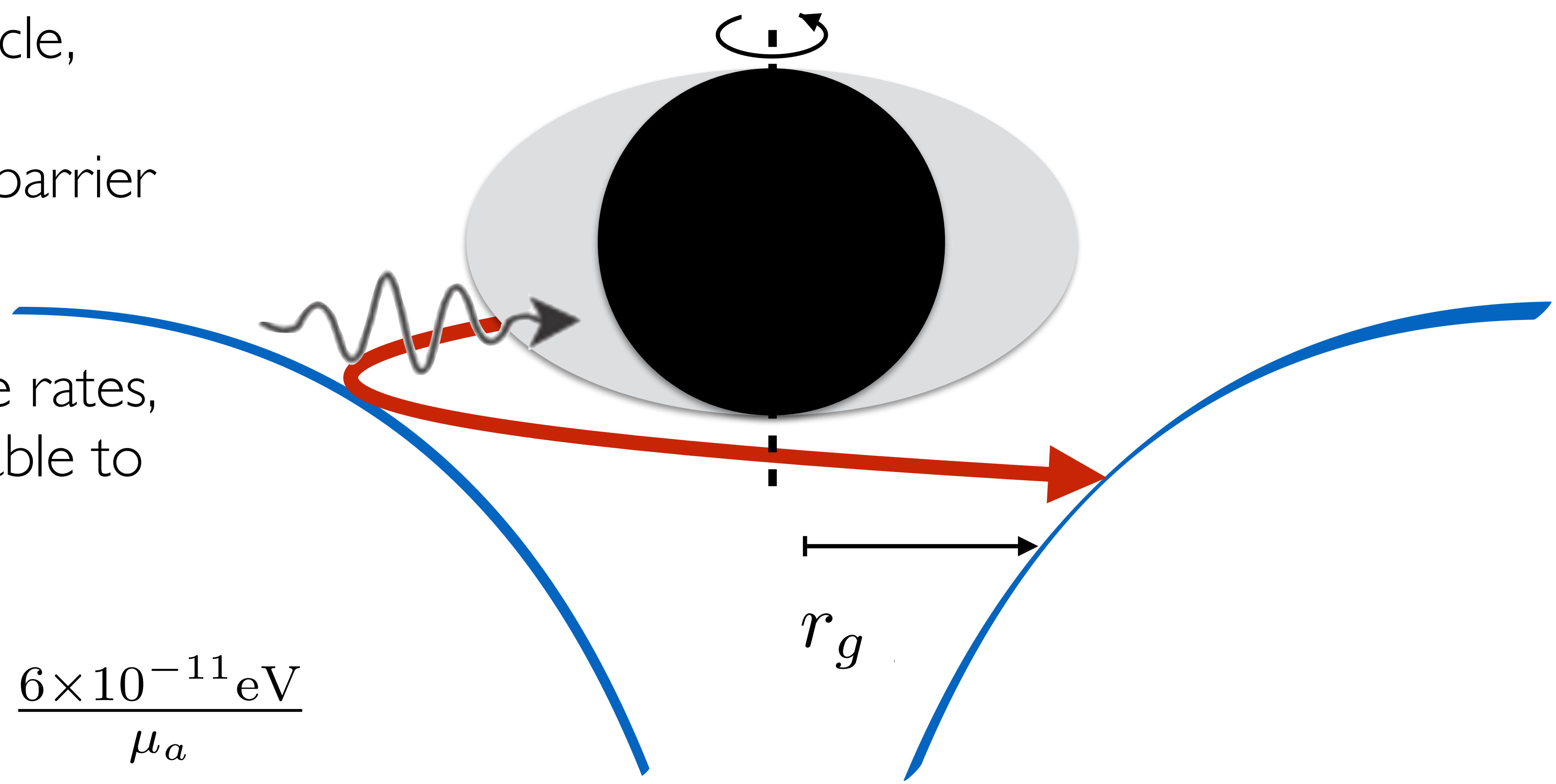
Angular velocity of wave slower than angular velocity of BH horizon,

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

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:

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

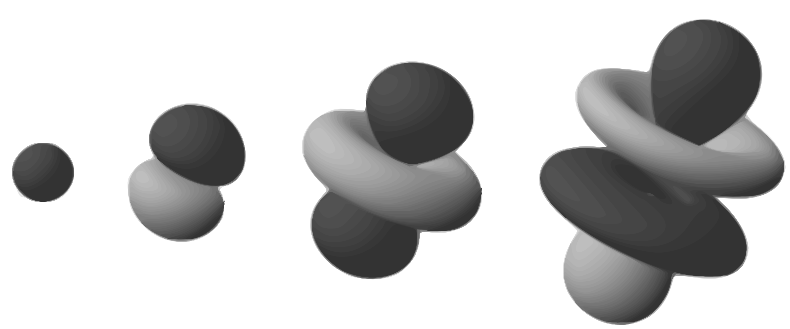
[Zouros & Eardley'79; Damour et al '76; Detweiler'80; Gaina et al '78]

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

Superradiance:
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	$r_B = \frac{n^2}{\alpha_{em} m_e}$	$r_c \sim \frac{n^2}{\alpha\mu_a} \sim 4 - 400 r_g$
Occupation number	$N = 1$	$N \sim 10^{70} - 10^{80}$ — classical field
Boundary conditions	regular at origin	ingoing at horizon
Energy levels	$m_e\left(1 - \frac{\alpha_{em}^2}{2n^2}\right)$	$\mu_a\left(1 - \frac{\alpha^2}{2n^2} + i\Gamma_{sr}\right)$



1s 2p 3d 4f

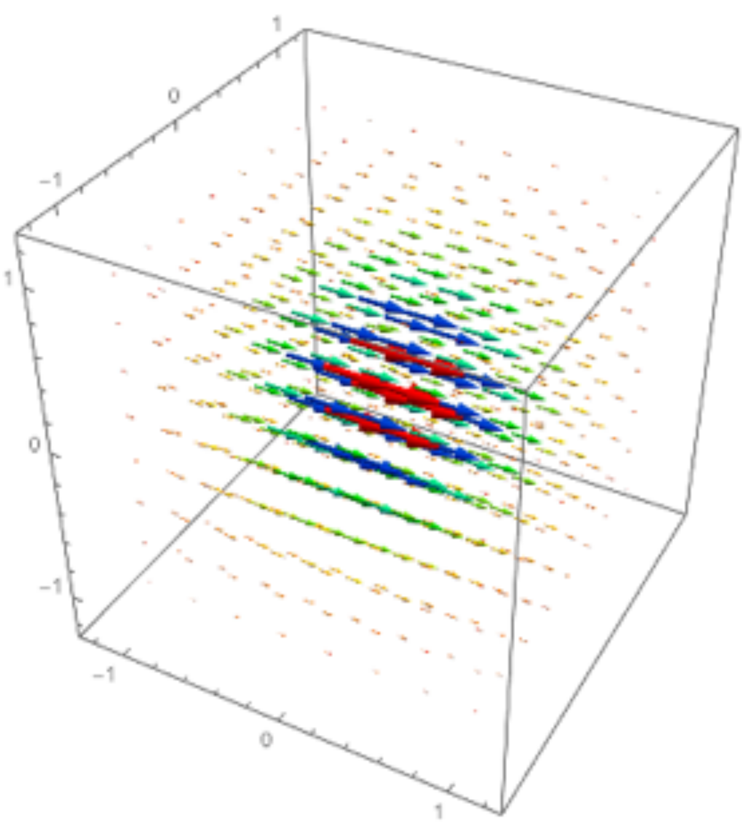
Superradiance condition:

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

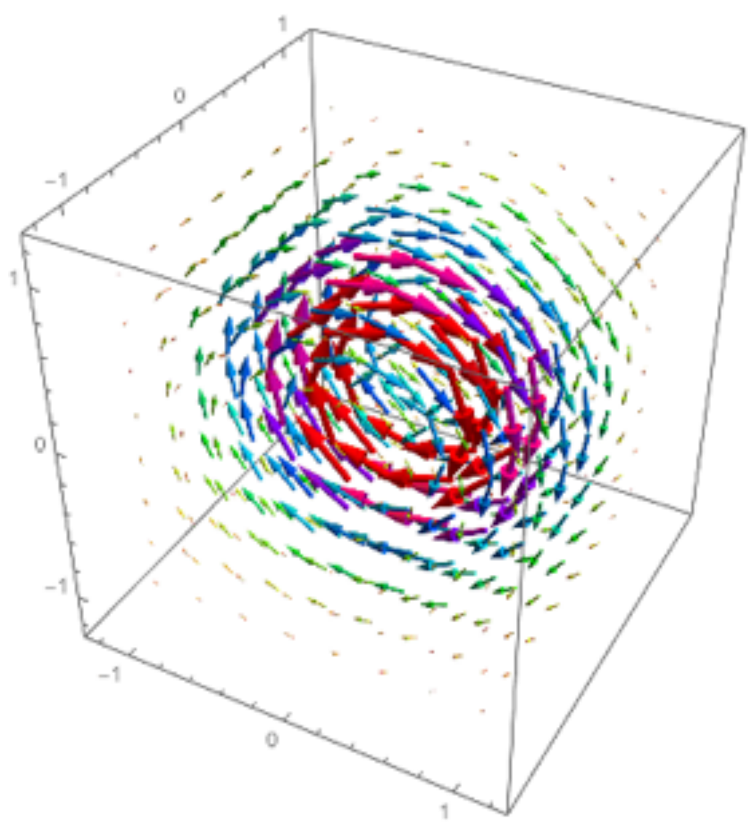
(m = magnetic quantum number)

Superradiance:
Vector Gravitational Atoms

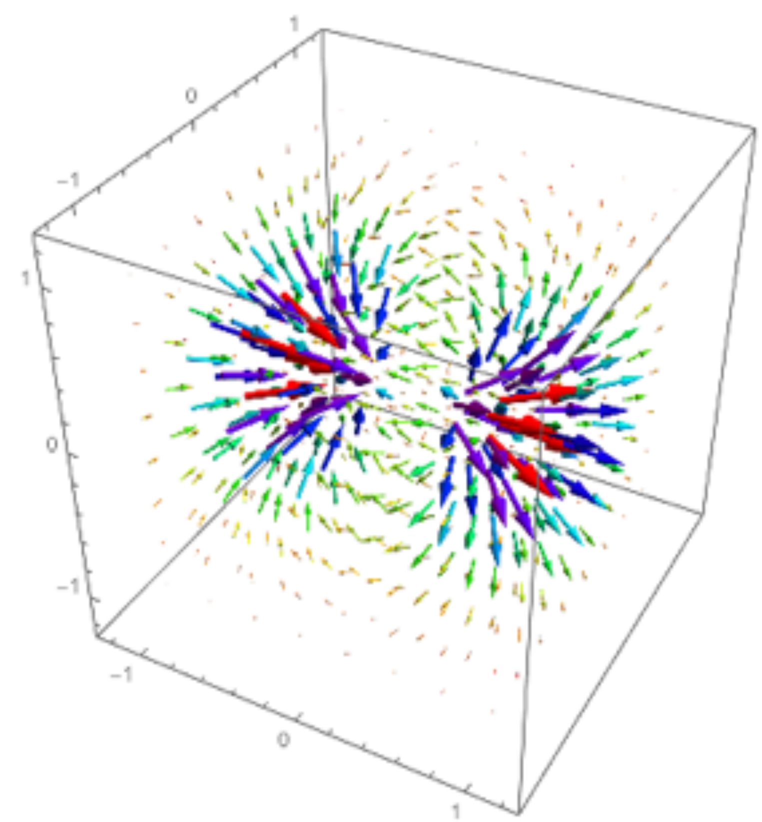
Hydrogen-like radial profile, vector spherical harmonic angular



$j = 1, l = 0$



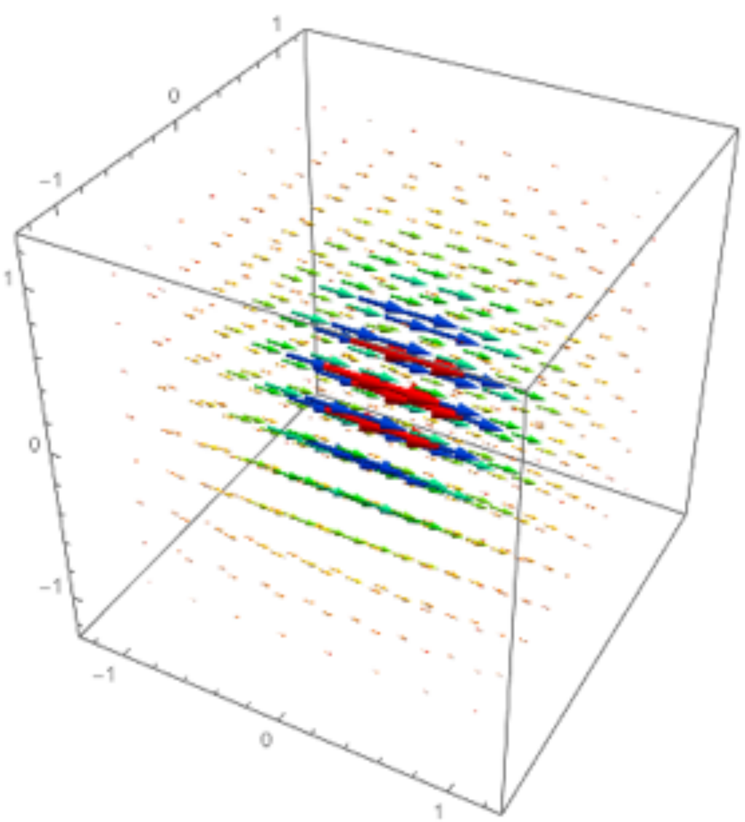
$j = 1, l = 1$



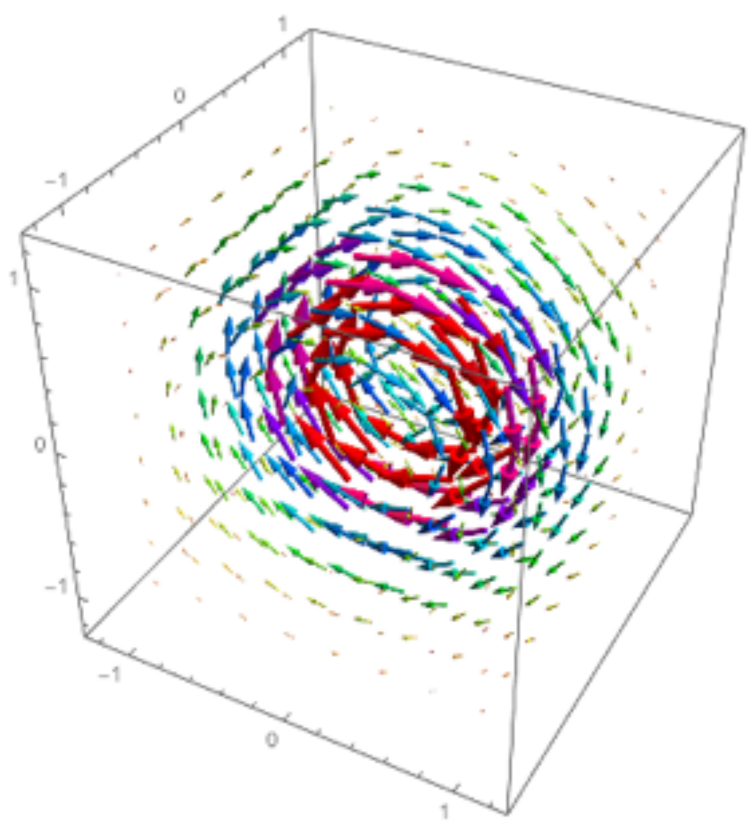
$j = 1, l = 2$

Superradiance:
Vector Gravitational Atoms

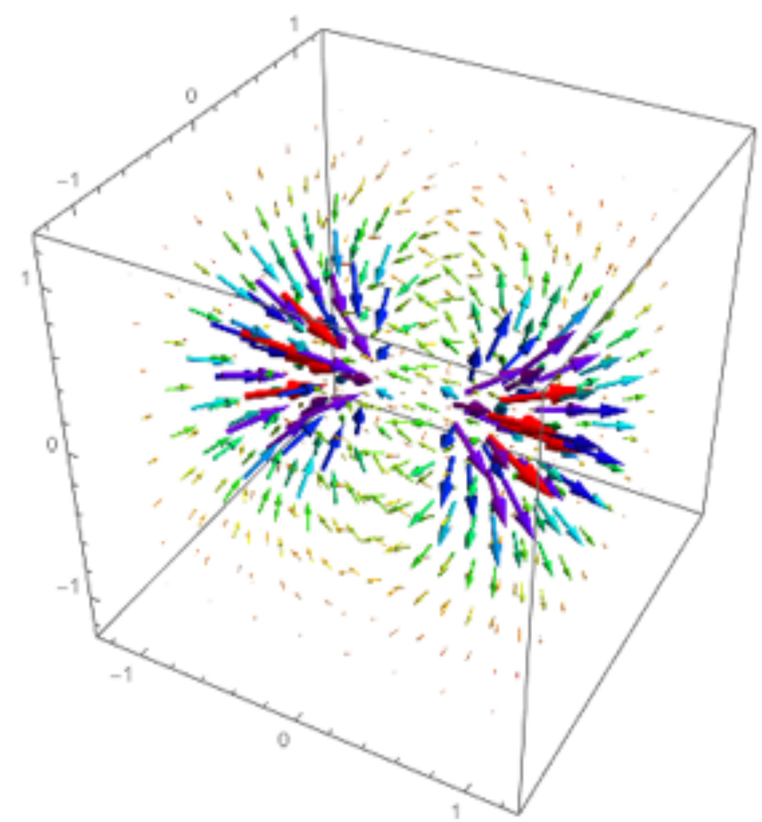
Hydrogen-like radial profile, vector spherical harmonic angular



$j = 1, l = 0$

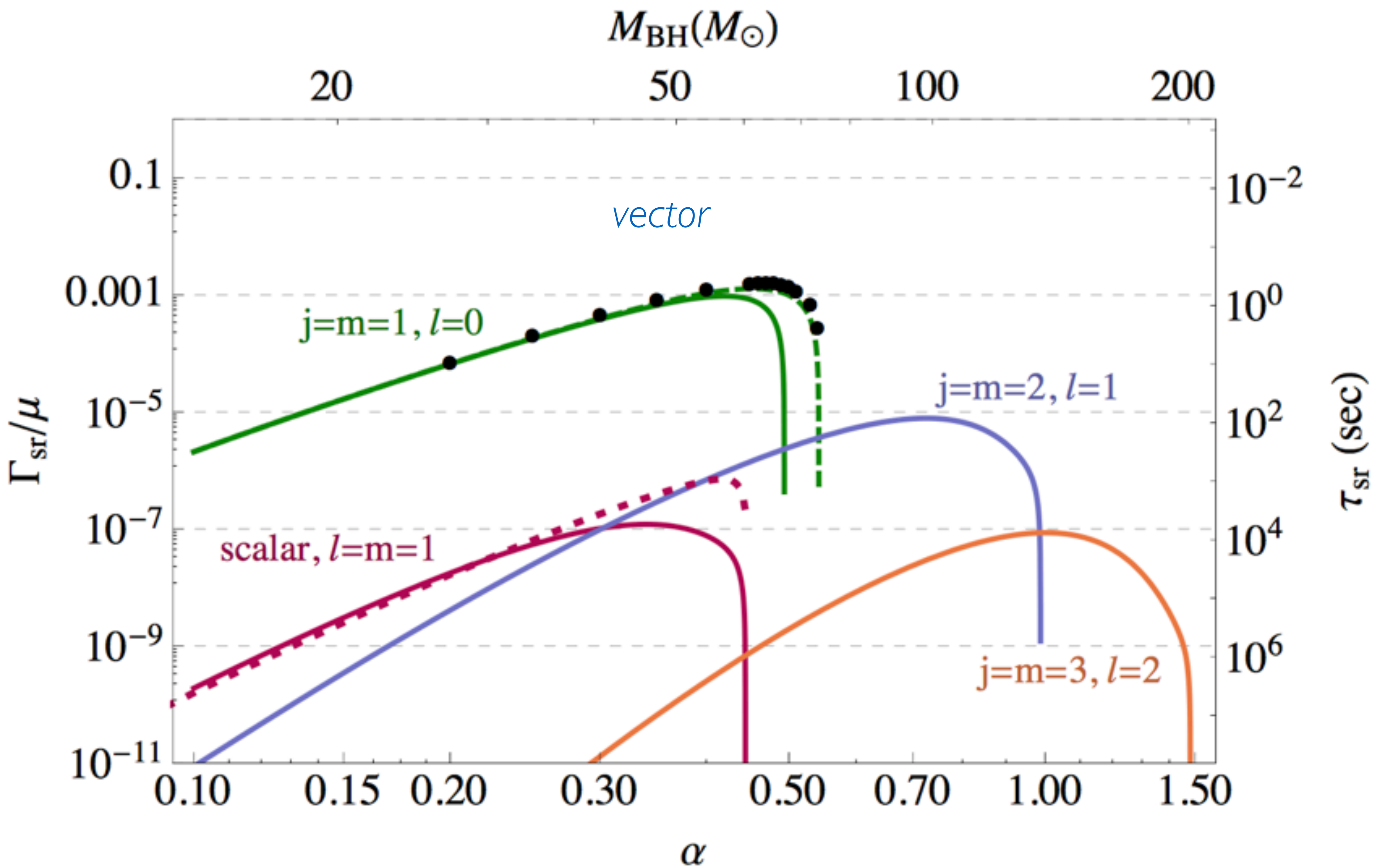


$j = 1, l = 1$



$j = 1, l = 2$

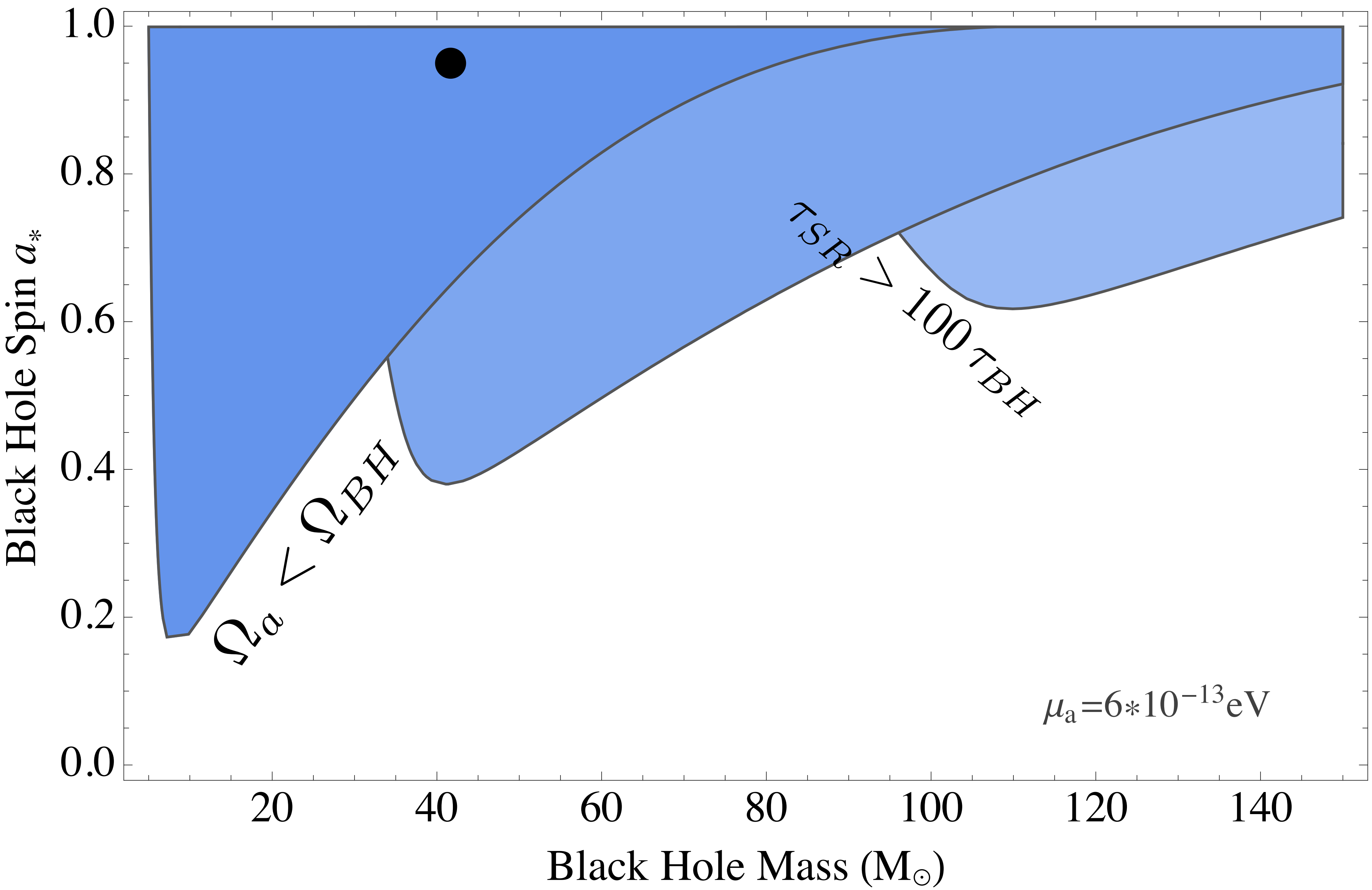
Superradiance:
Growth rates



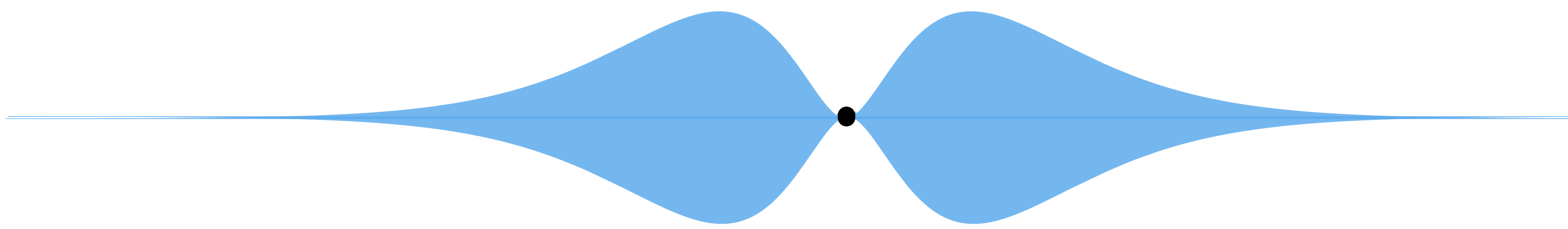
- Superradiance condition depends on **total** angular momentum ***j***
- *Radial wavefunction depends on **orbital** angular momentum **l***

Superradiance: a stellar black hole history

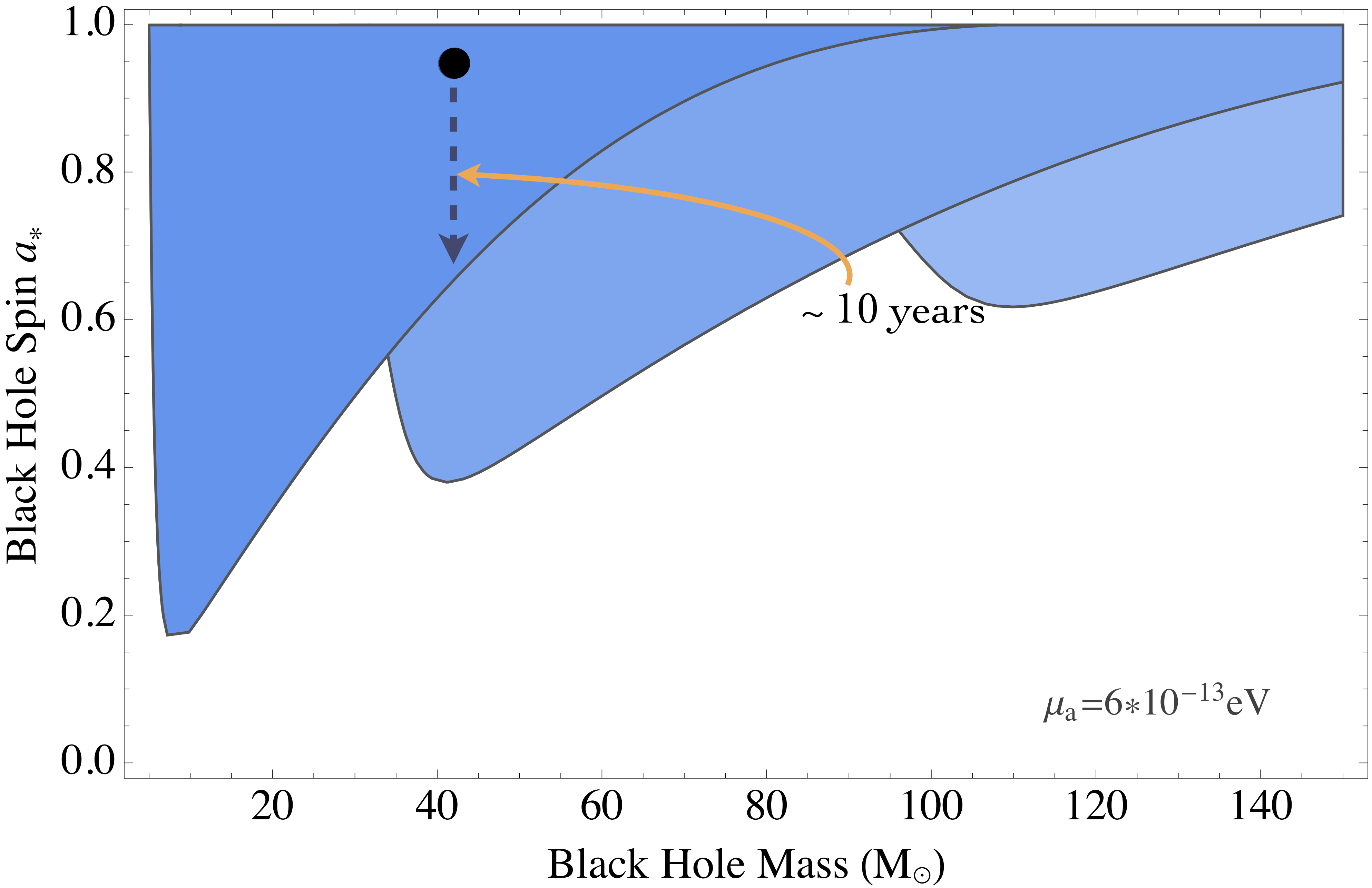
A black hole is born with spin a* = 0.95, M = 40 M☉.



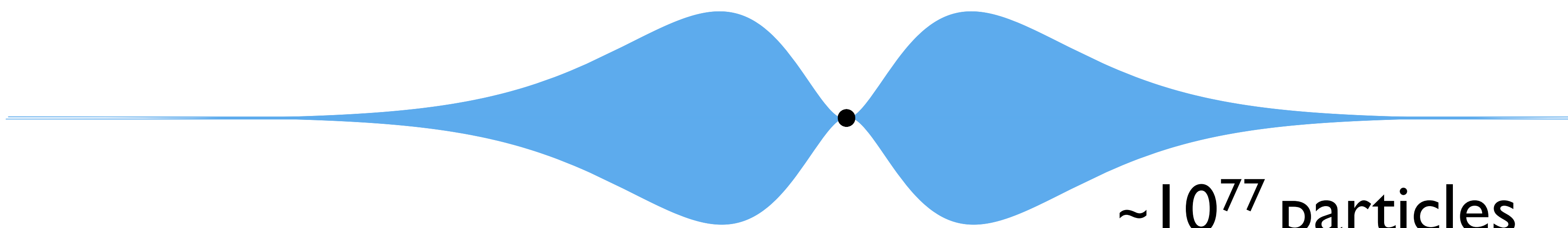
Superradiance: a stellar black hole history



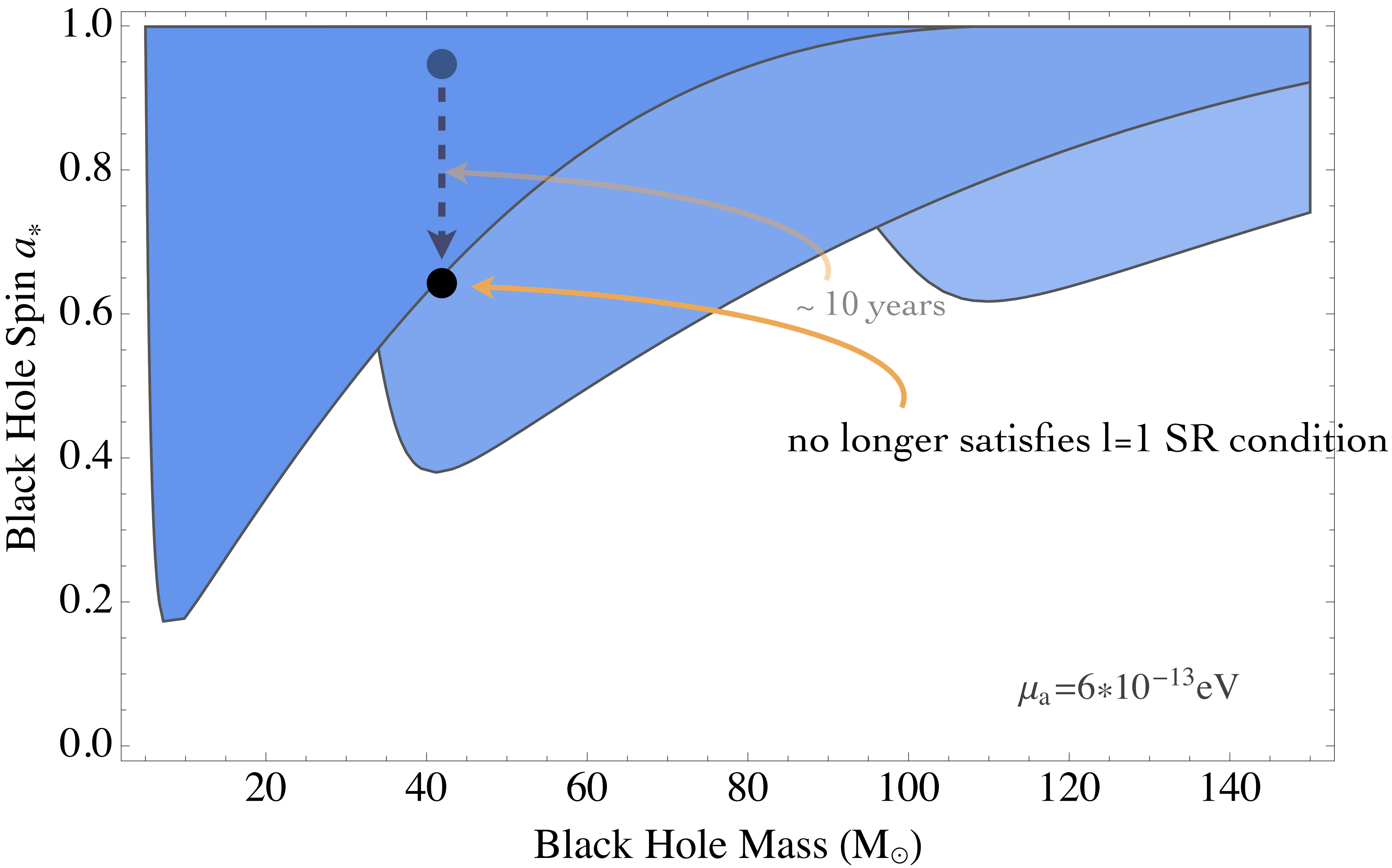
BH spins down and *fastest-growing* level is formed



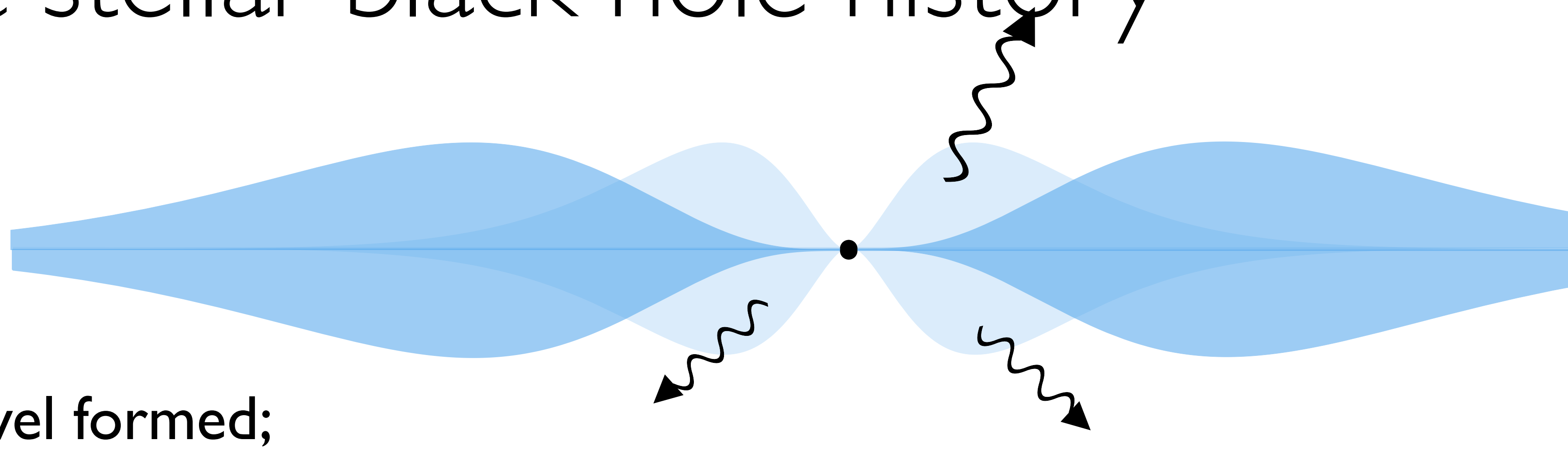
Superradiance: a stellar black hole history



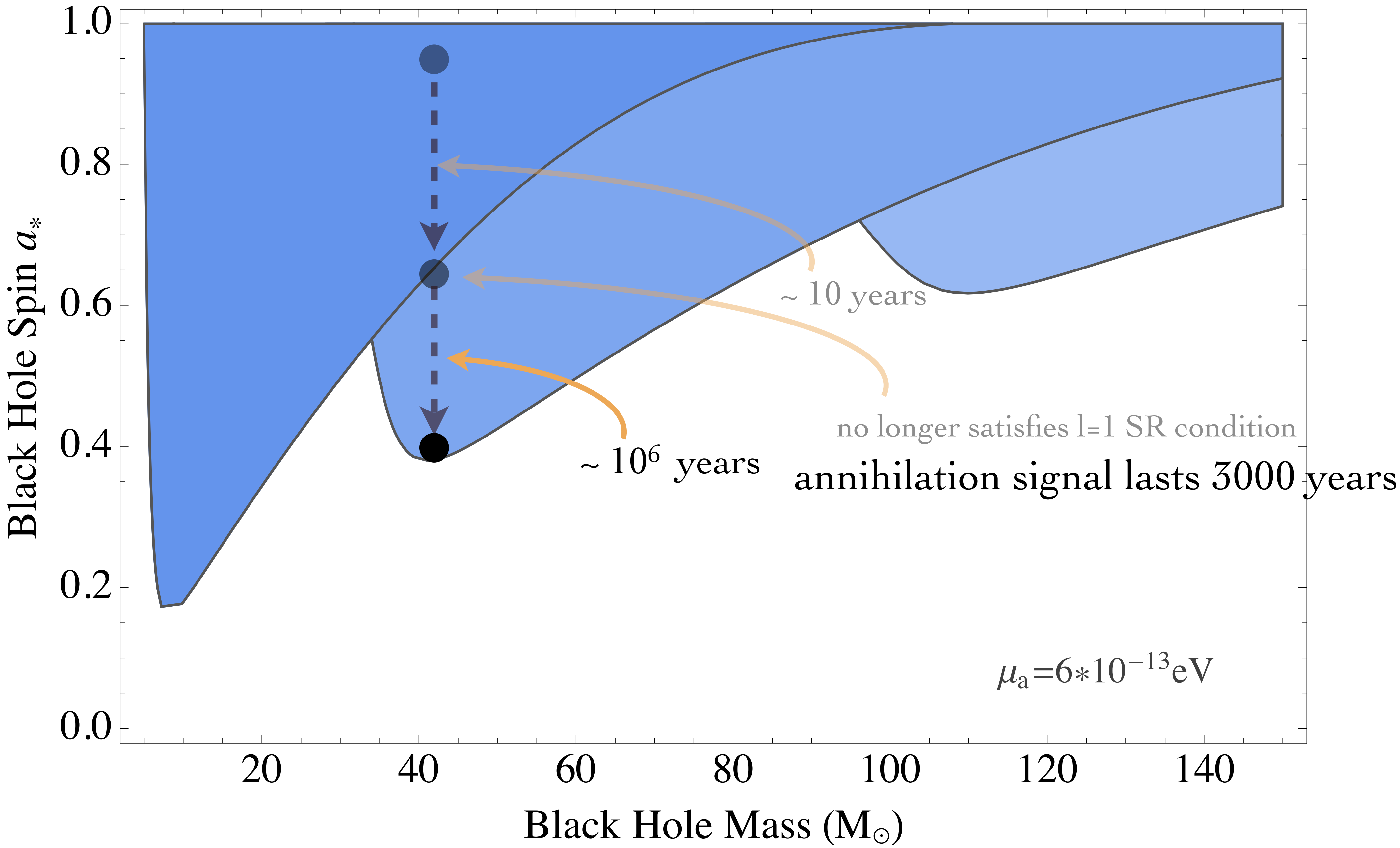
Once BH angular velocity matches that of the level, growth stops



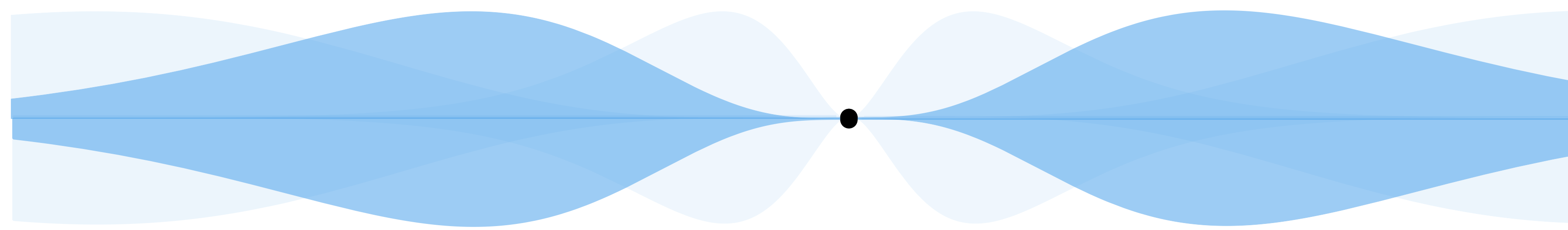
Superradiance: a stellar black hole history



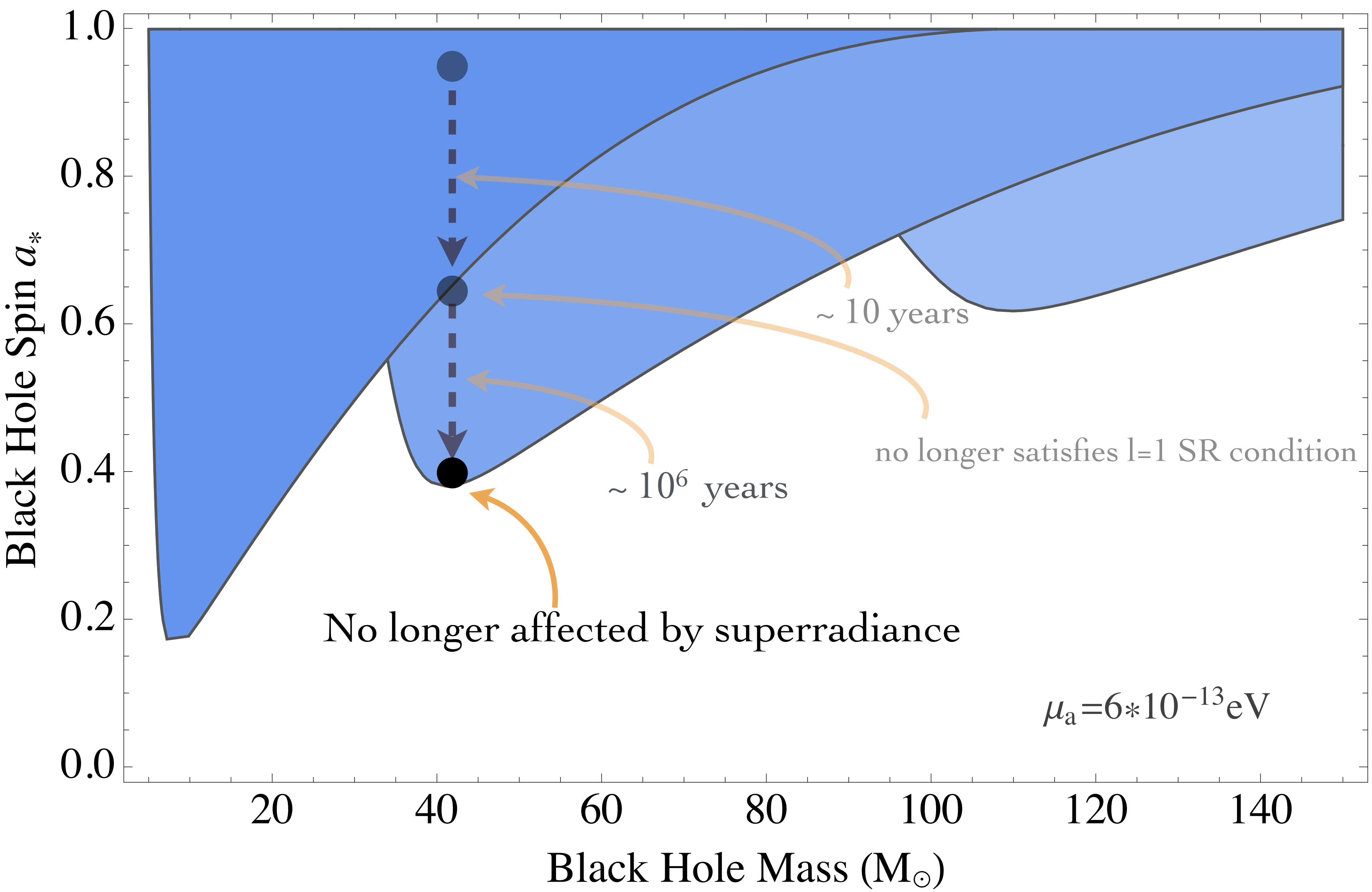
BH spins down and *next* level formed;
annihilations to GWs deplete first level



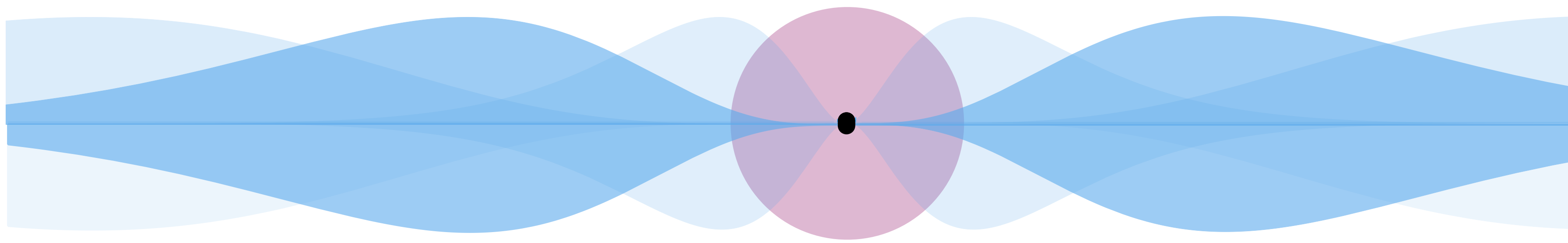
Superradiance: a stellar black hole history



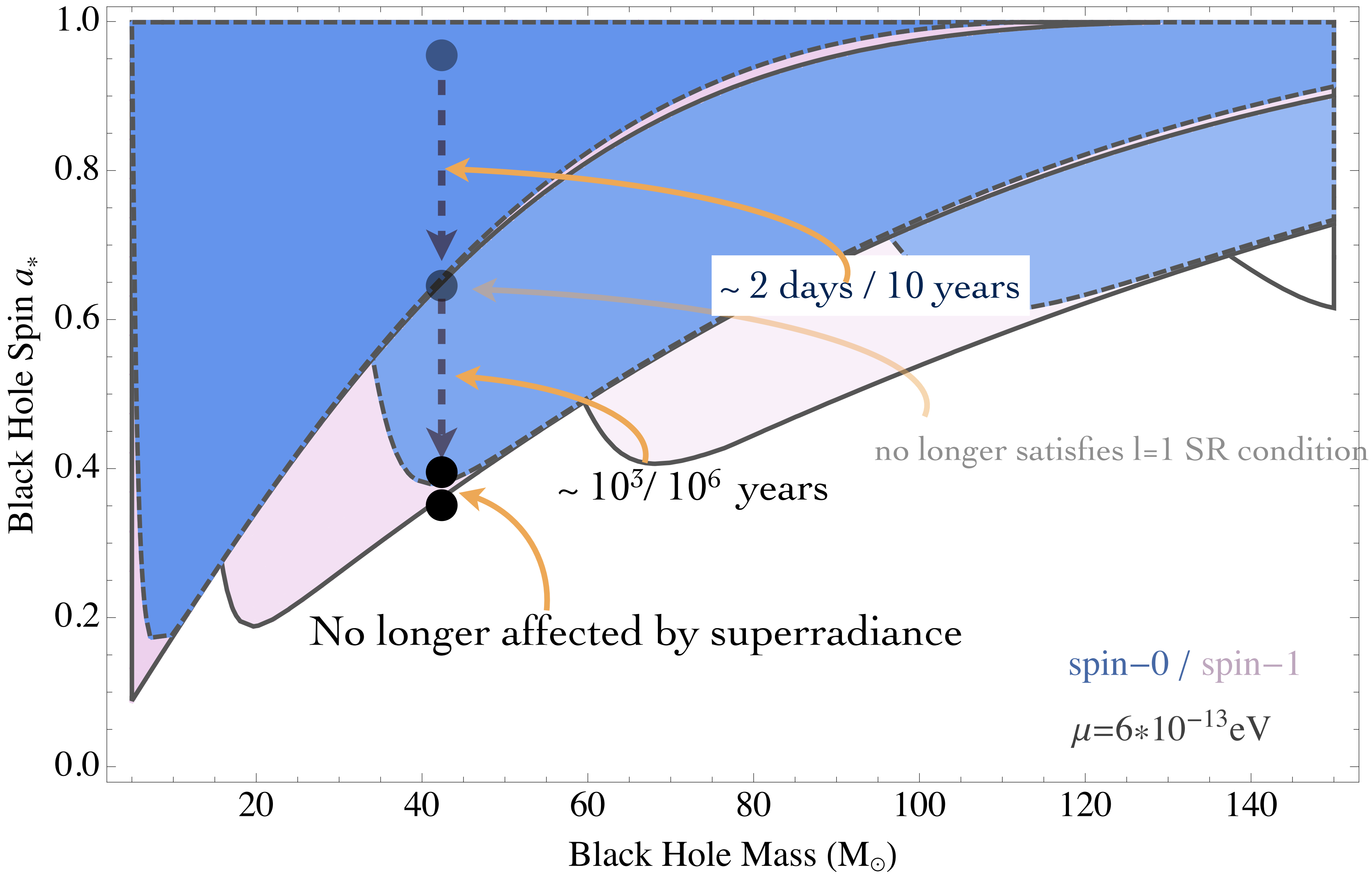
The following level has a superradiance rate exceeding age of BH



Superradiance: a stellar black hole history



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

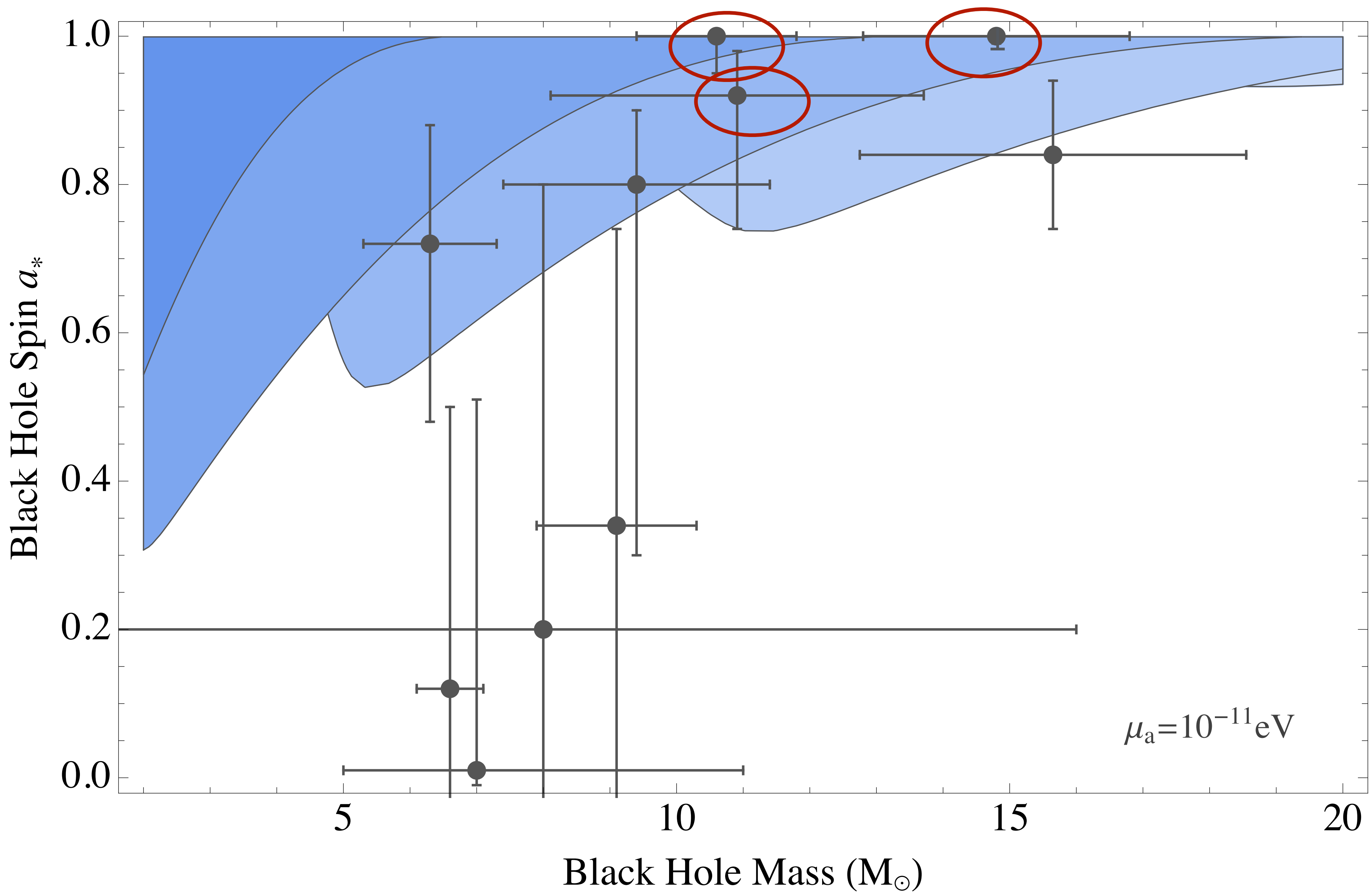


Vectors can have higher total angular momentum for a given orbital angular momentum

Black Hole Spins

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

several black holes disfavor this axion mass



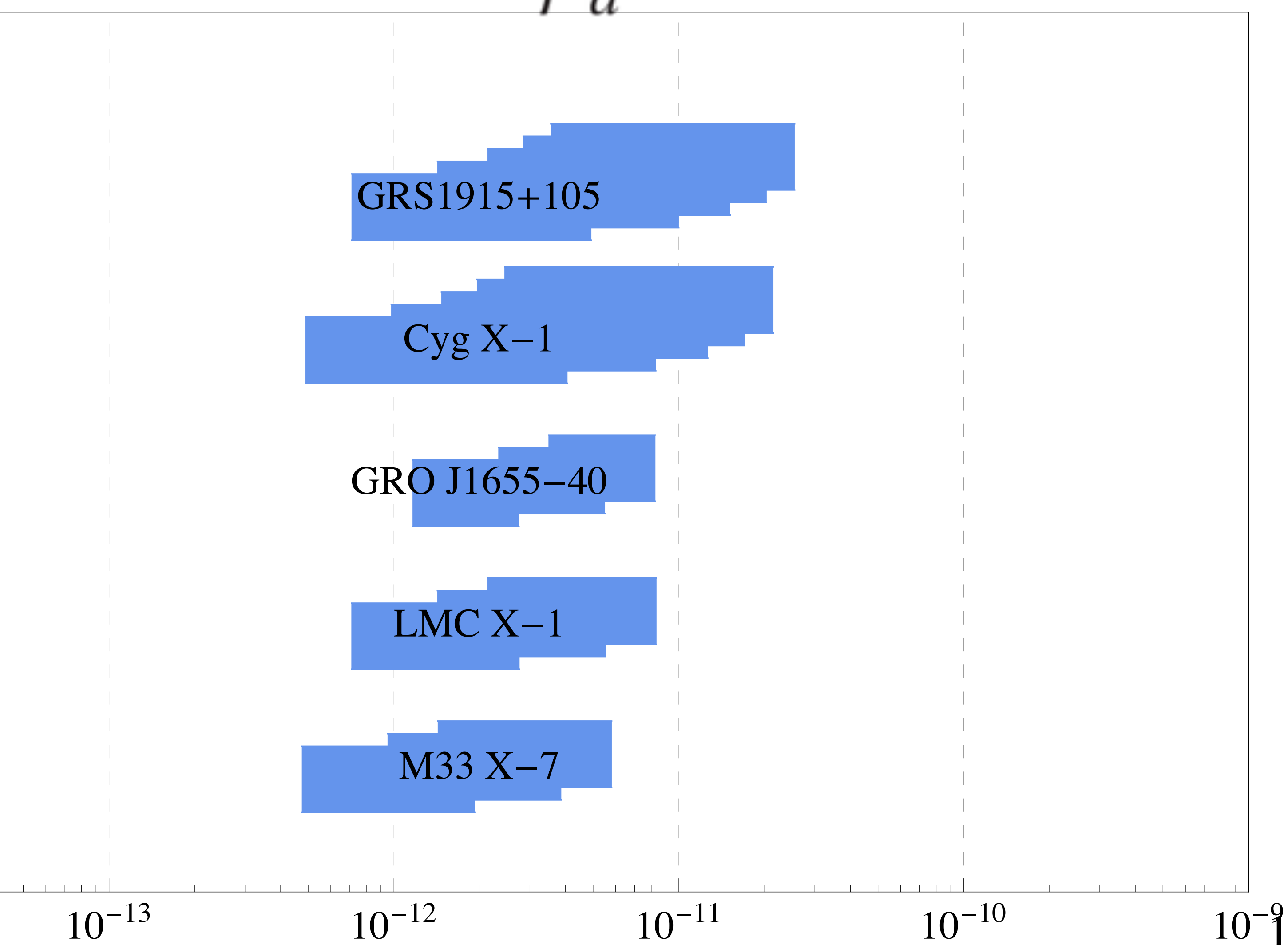
Black Hole Spins

Five stellar black holes combine to disfavor the range:

scalar

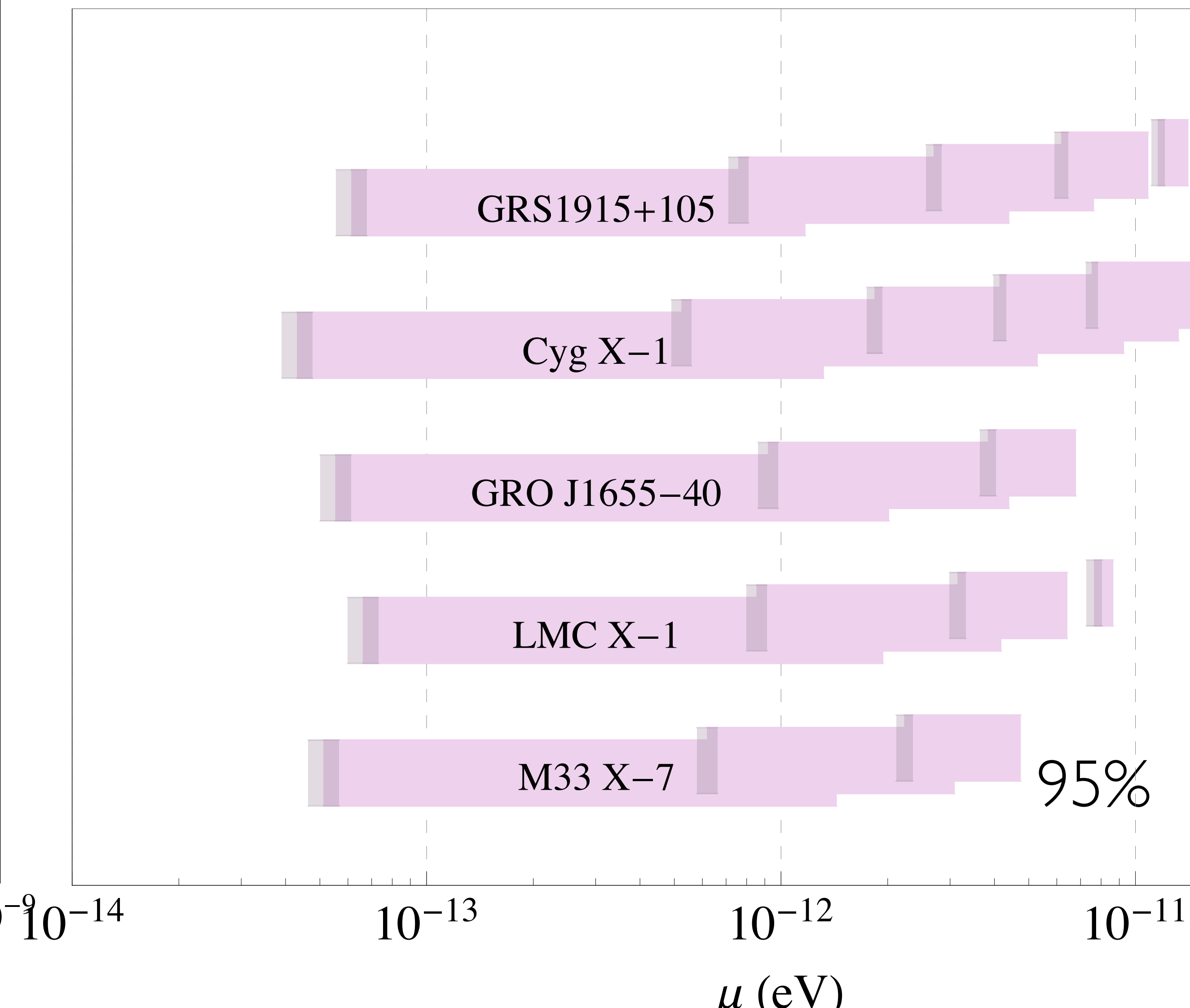
vector

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



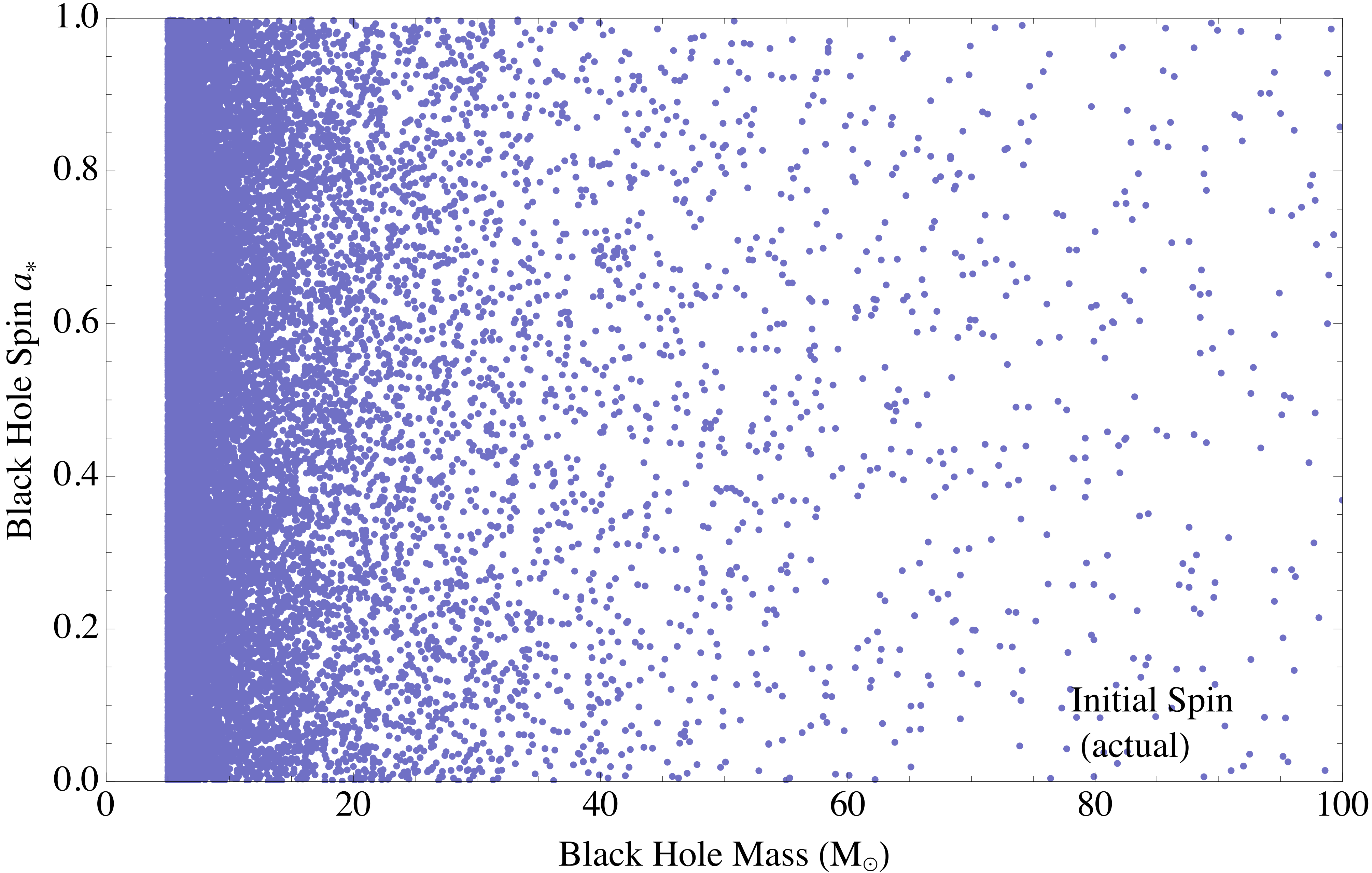
$$3 \times 10^{17} < f_a < 1 \times 10^{19}\ \text{GeV}$$

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



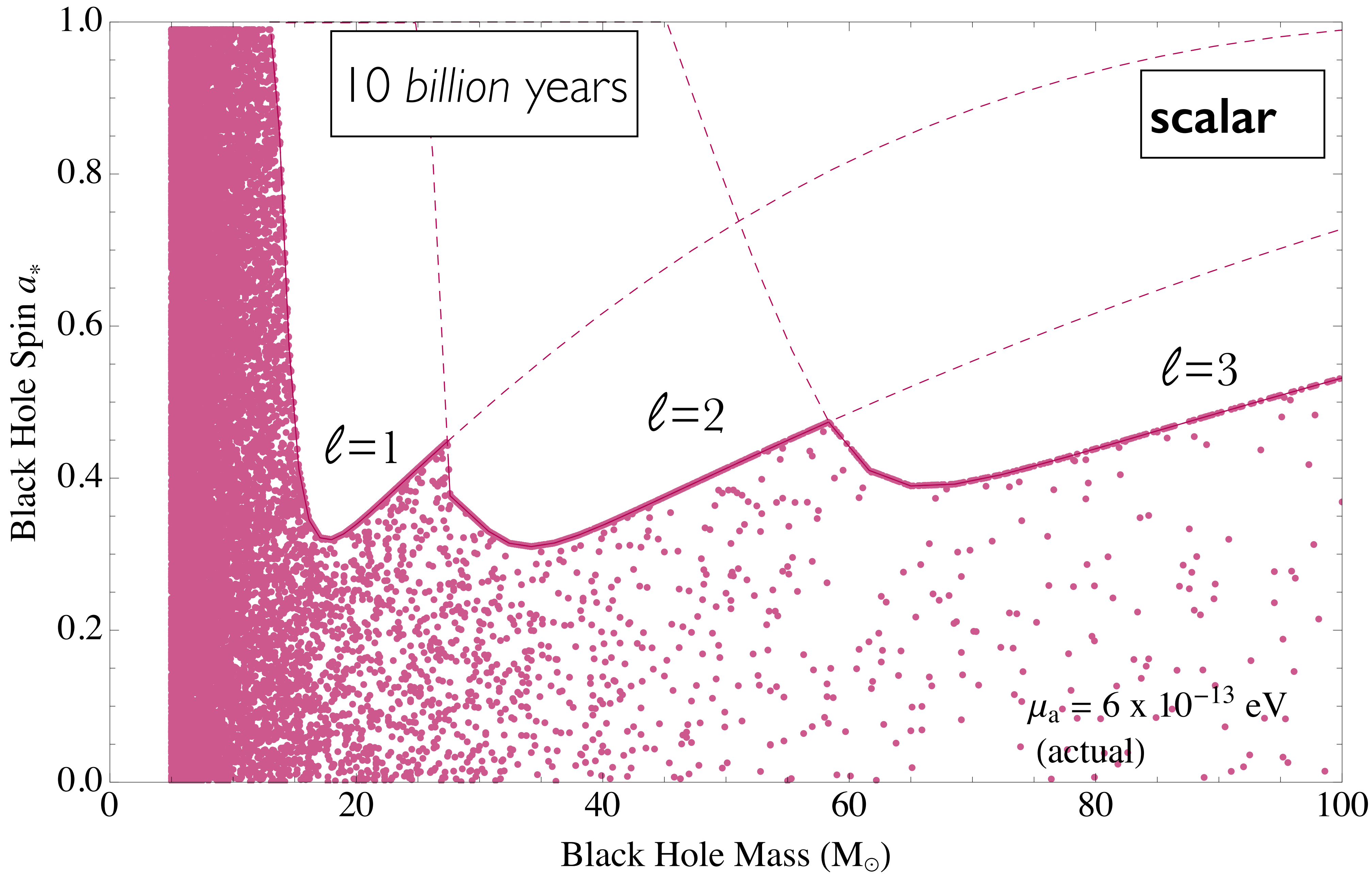
Black Hole Spins
at LIGO

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



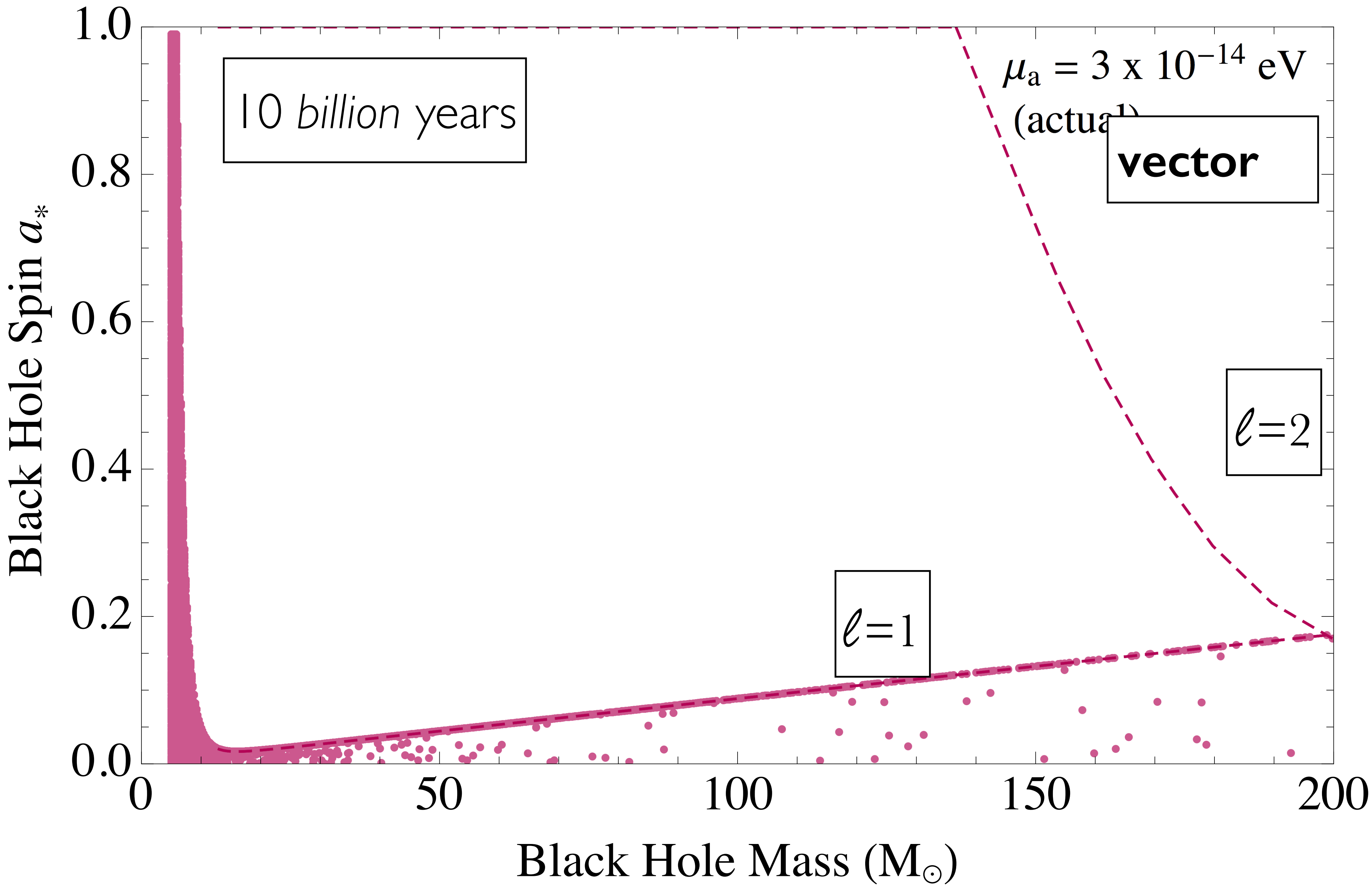
Black Hole Spins
at LIGO

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



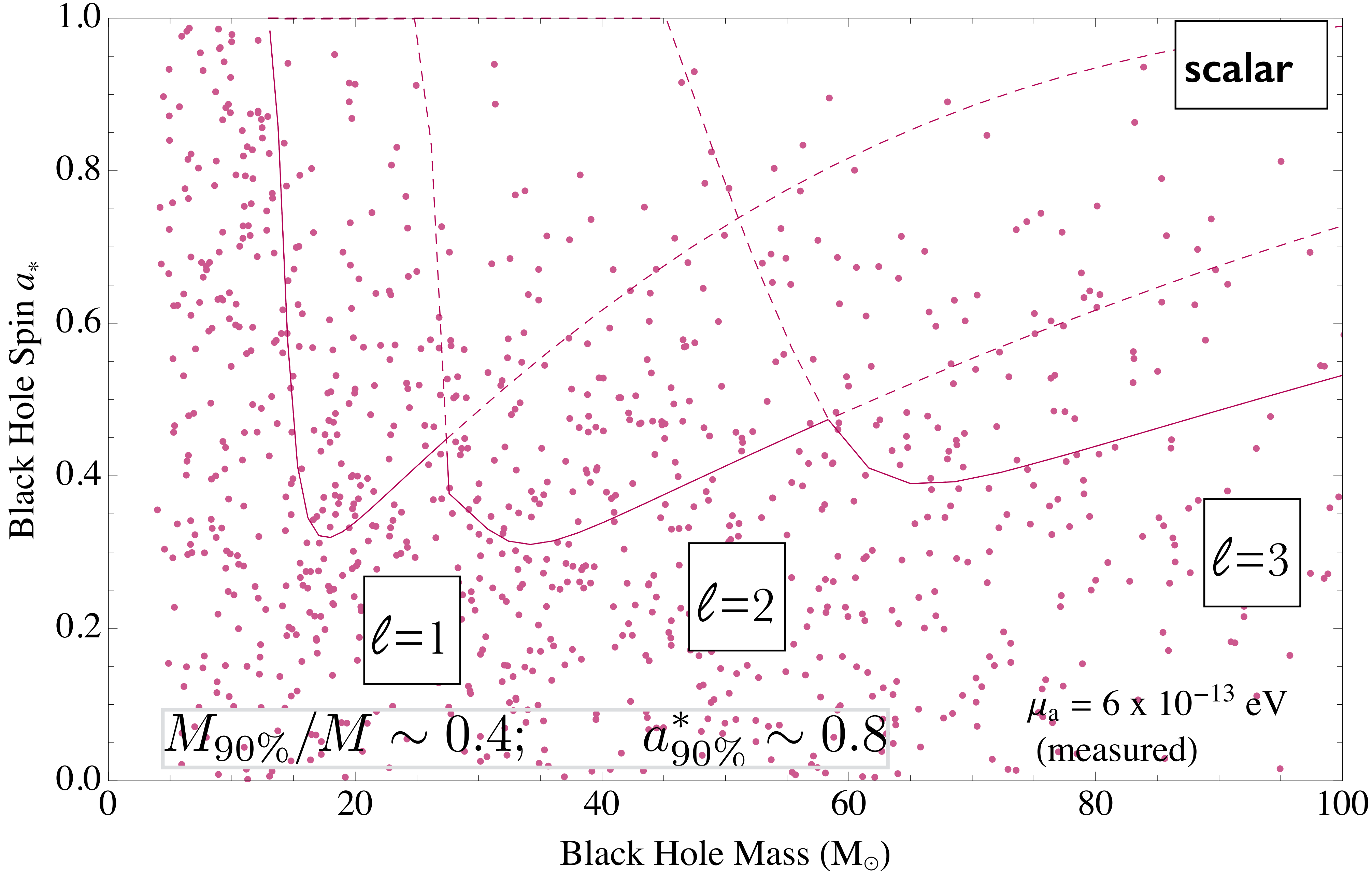
Black Hole Spins at LIGO

For light vector, the spindown is even more dramatic, limited by age binary system; first level not affected by mixing



Black Hole Spins

Initial BH spins measured with large uncertainty;

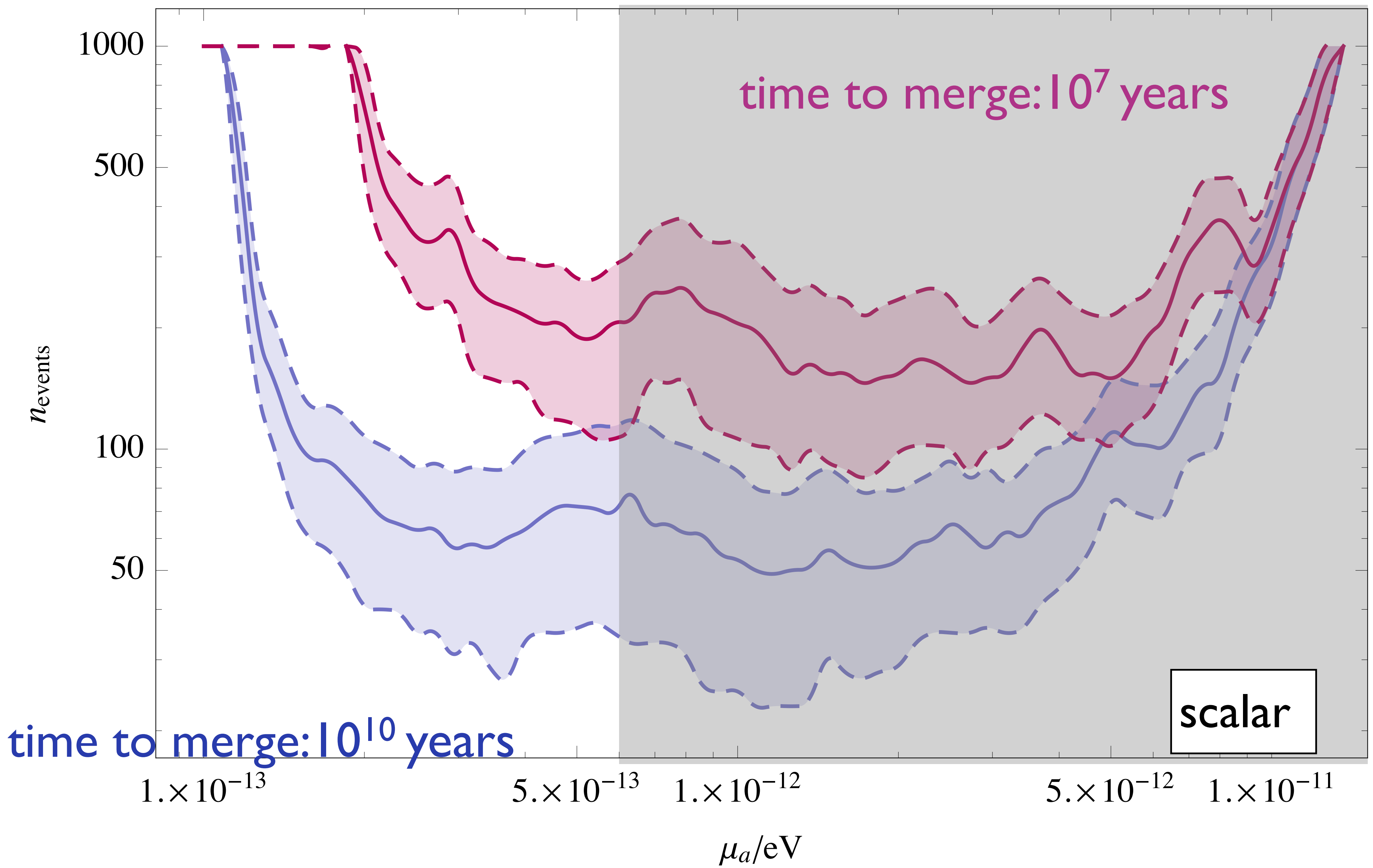


so far:
GW150914
LVT151012
GW151226
GW170104
GW170608
GW170814

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

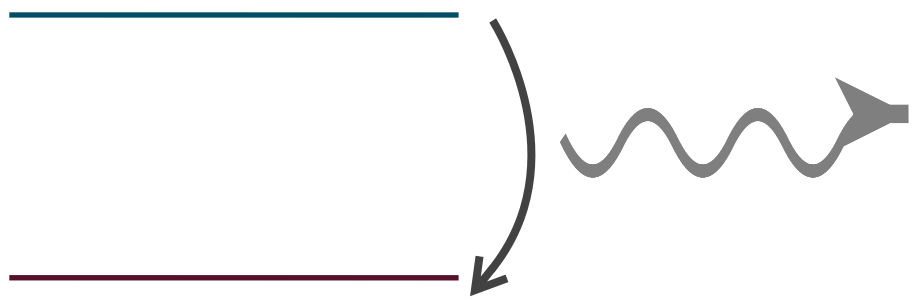
Black Hole Spins

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

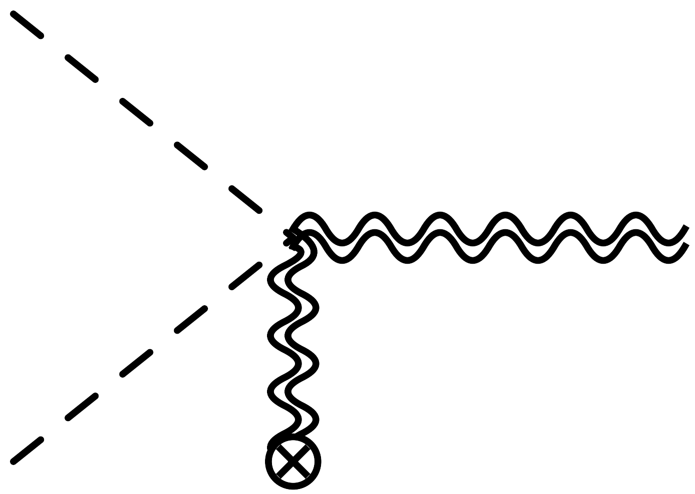


Gravitational Wave Signals

- Transitions between levels

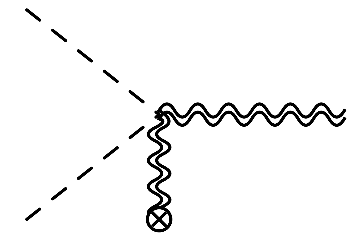


- Annihilations to gravitons

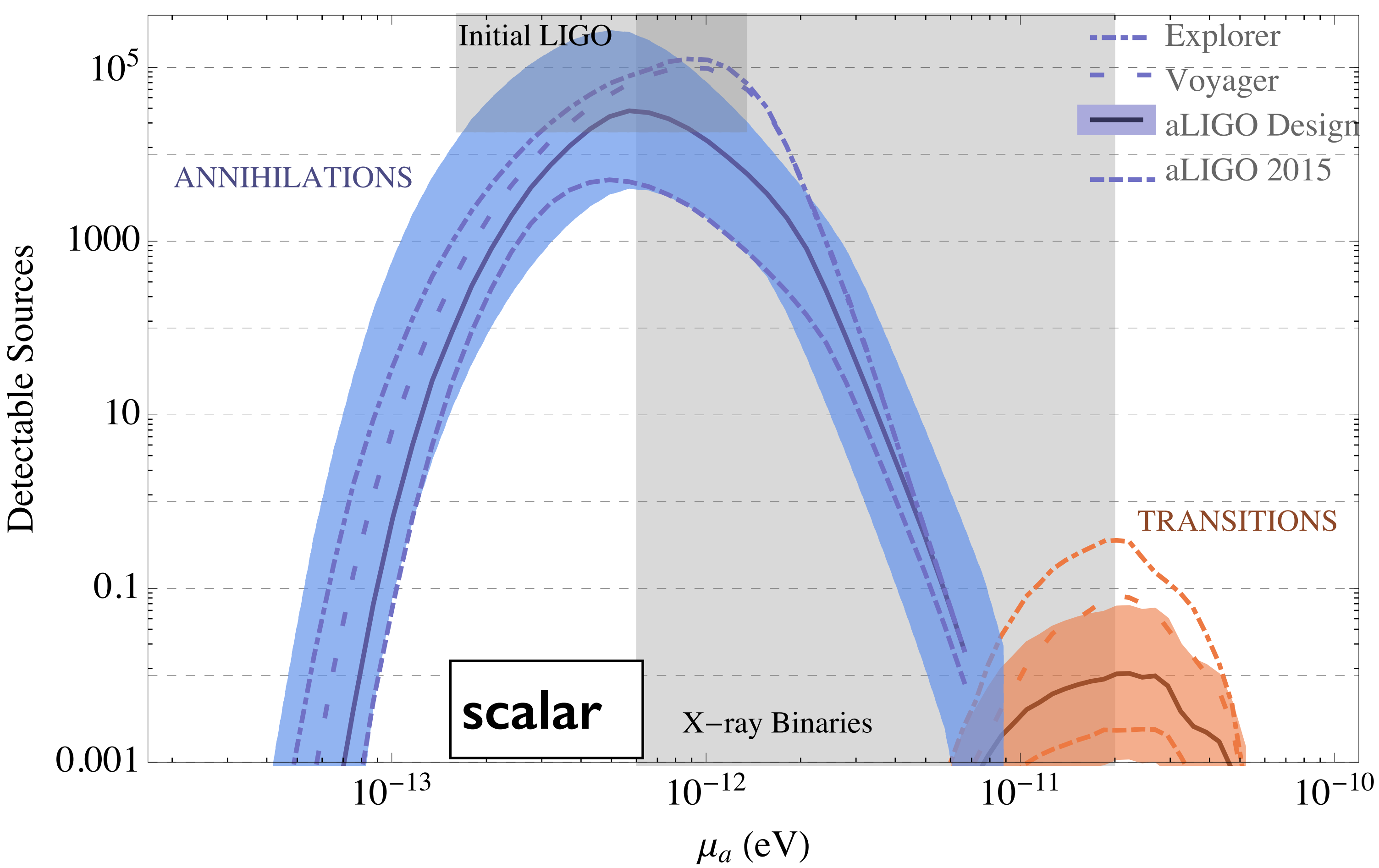


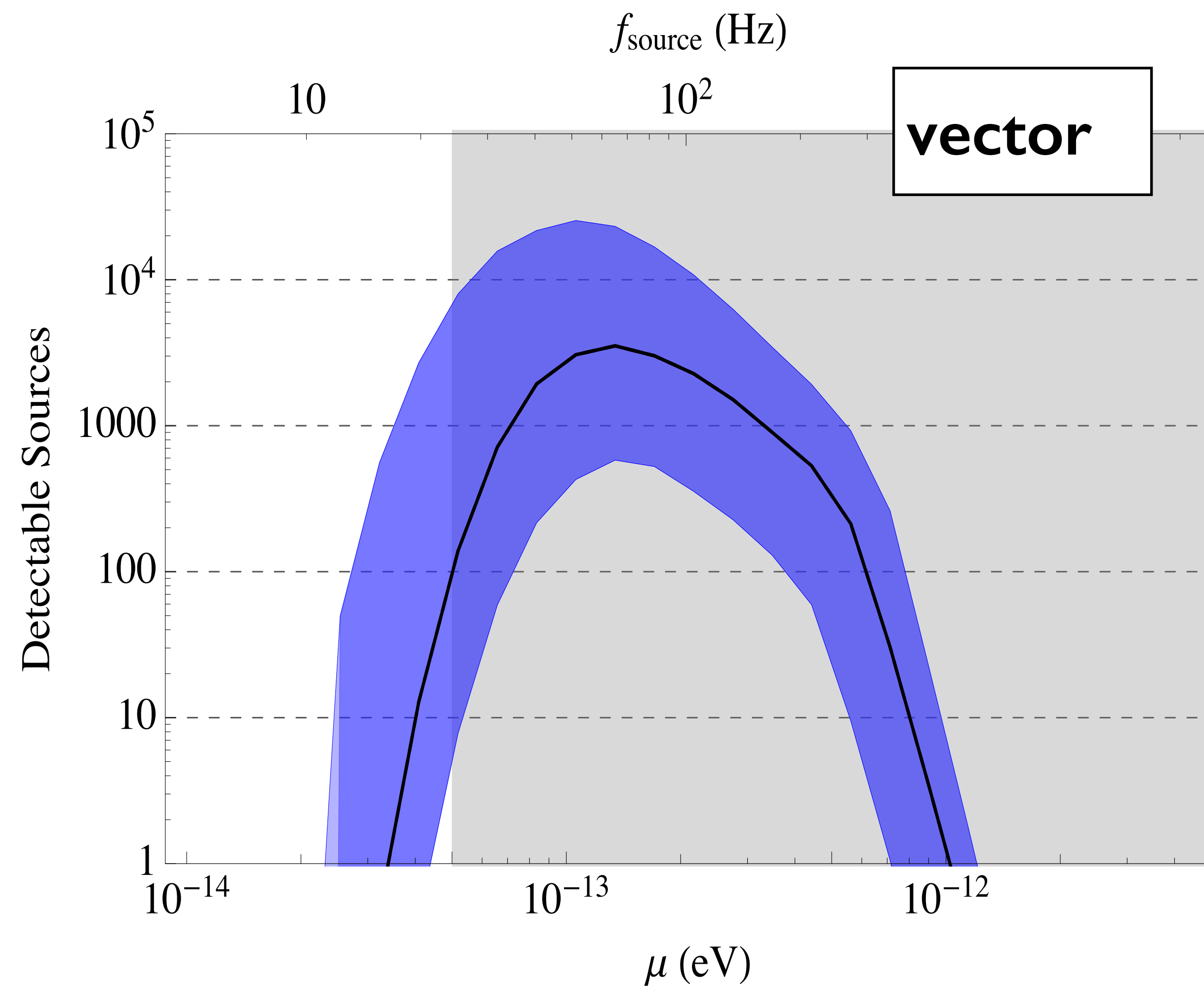
  - Signals coherent, monochromatic, last hours to millions of years

Annihilations



- Up to 10,000 detectable sources — can be studied in detail
- Uncertainty dominated by BH mass distribution at higher masses



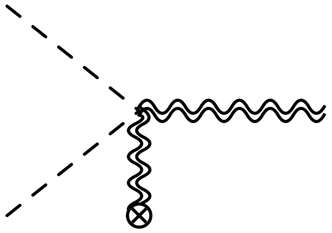


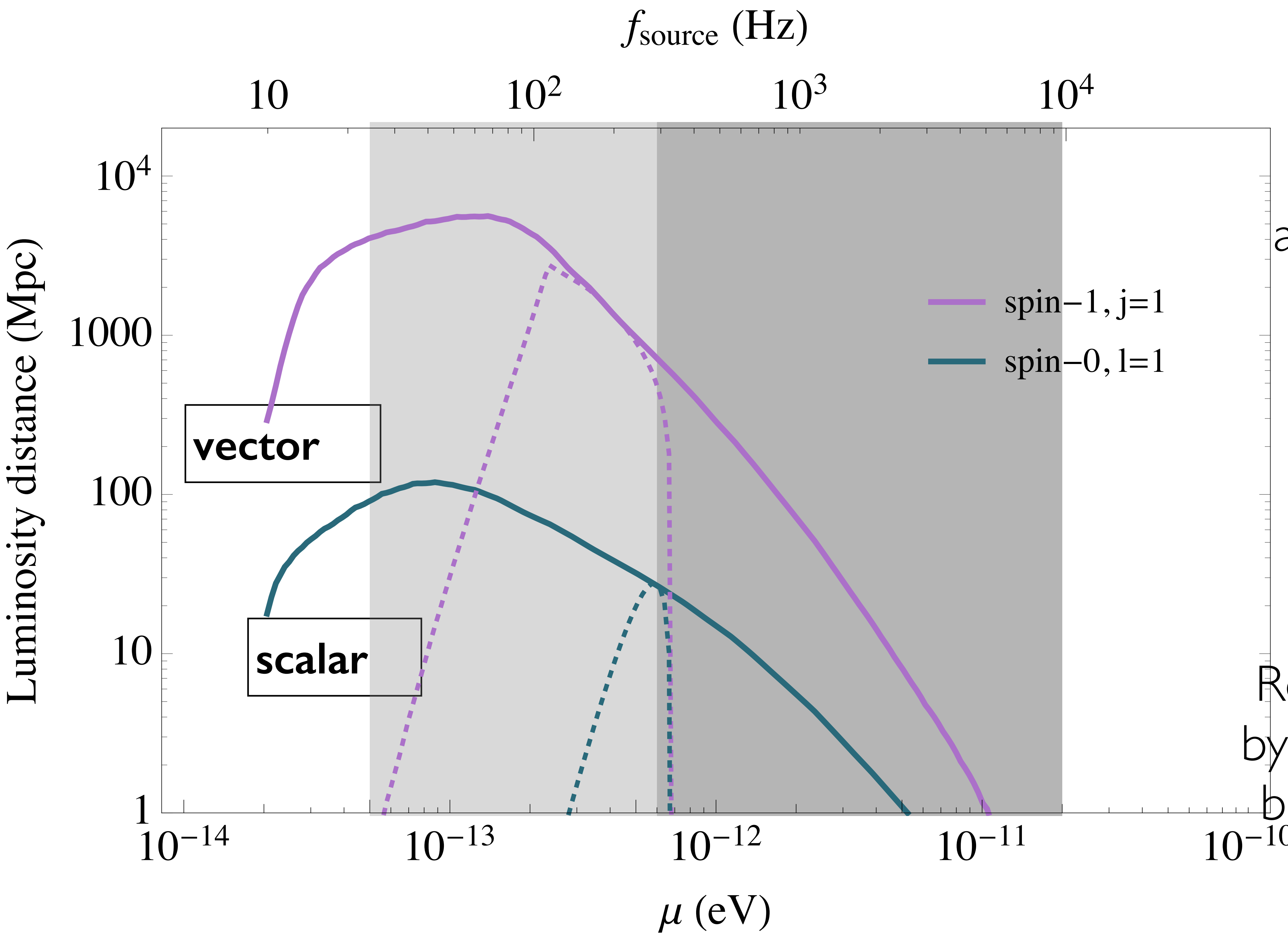
Long, weak signals visible from galactic center, limited by LIGO noise floor

Signals coherent and monochromatic: analogous to searches for **continuous, monochromatic** gravitational waves ("mountains" on neutron stars)

Cross-check spin limits

Annihilations

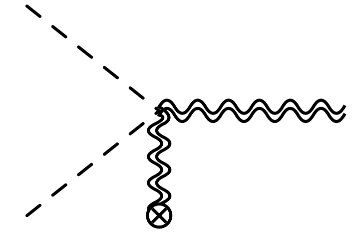




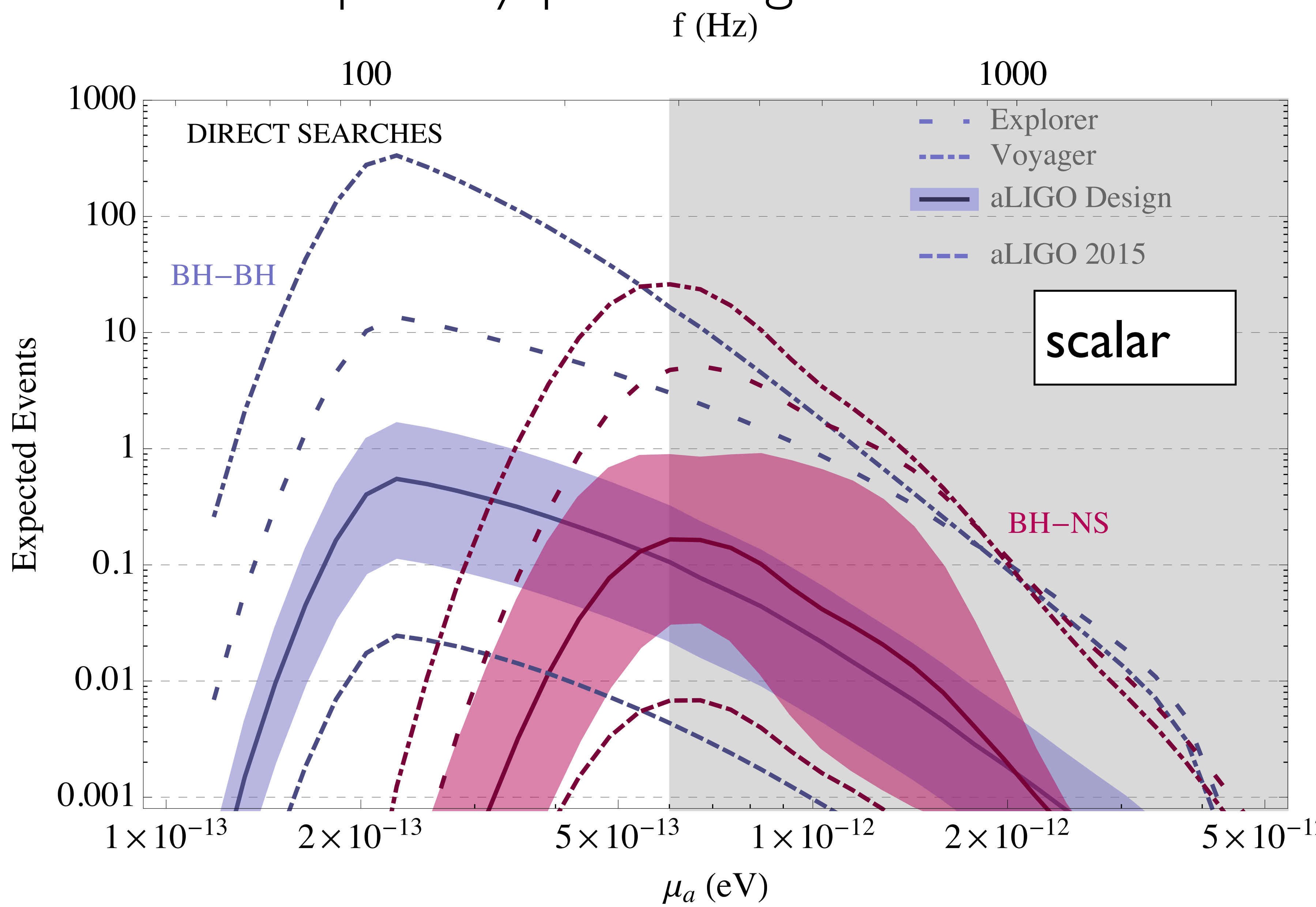
Spin-1 particle annihilations give higher rates, but more constrained

Realistically, limited by number of heavy black holes (>100 Msun)

Annihilations

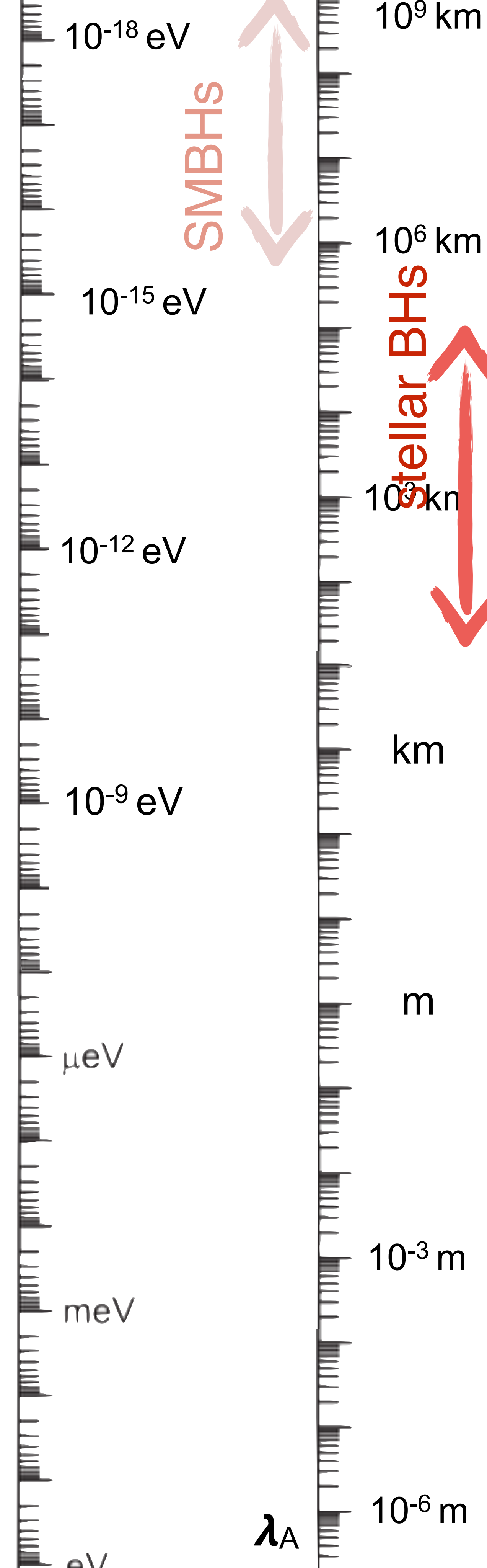


- Mergers at LIGO: a black hole is born!
- Follow up with continuous wave search to see if superradiance creates a cloud of axions around the new BH
- Targeted searches especially promising at future GW observatories



Conclusions

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



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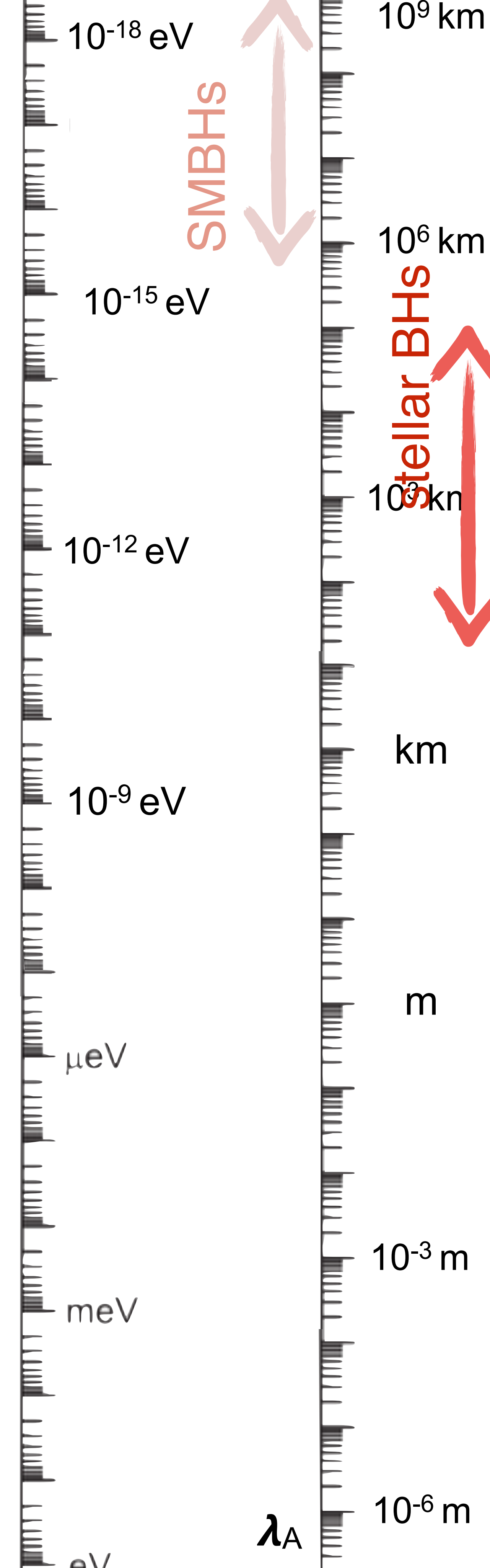
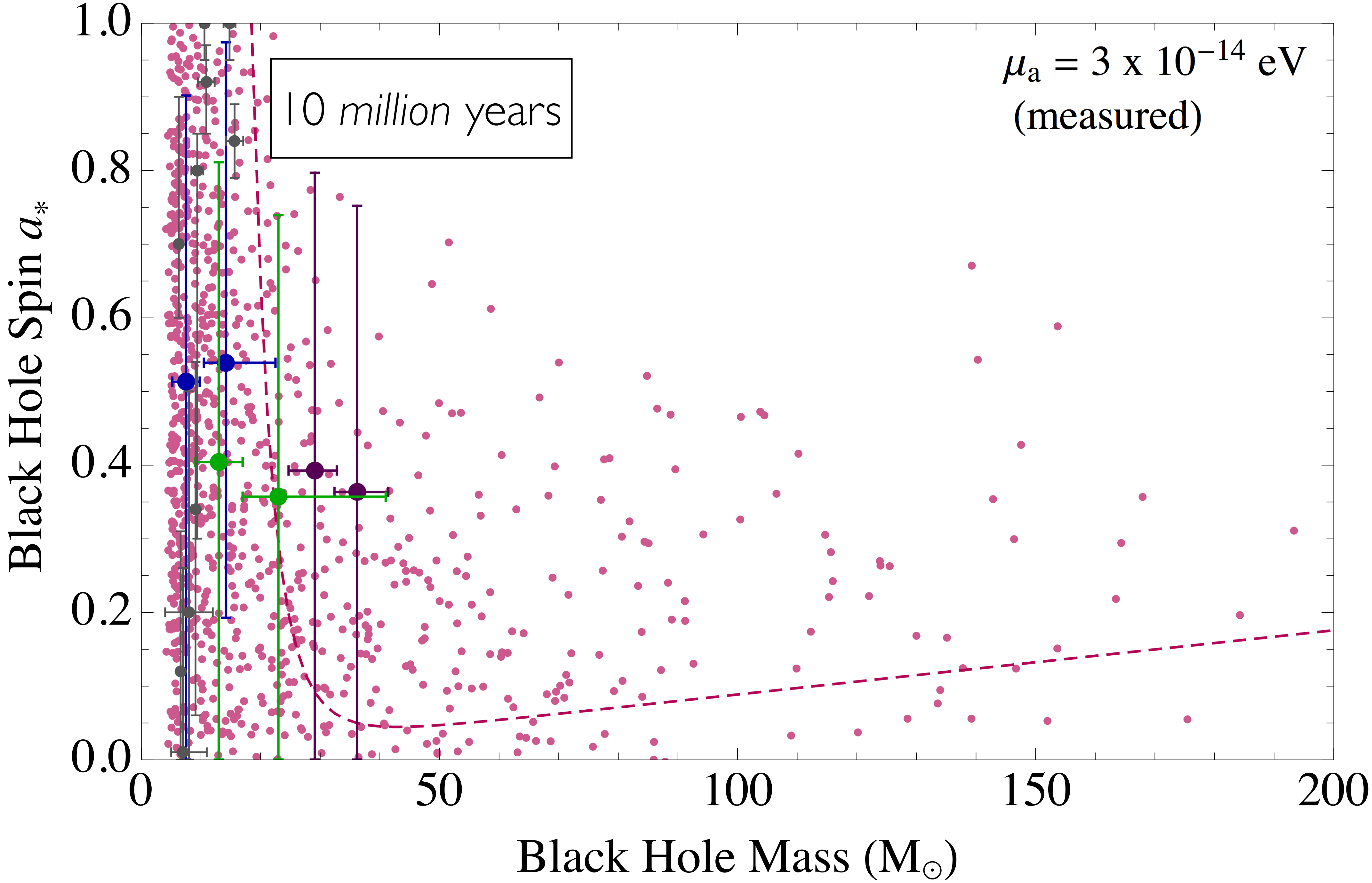
Thank you!



Extra

Black Hole Spins

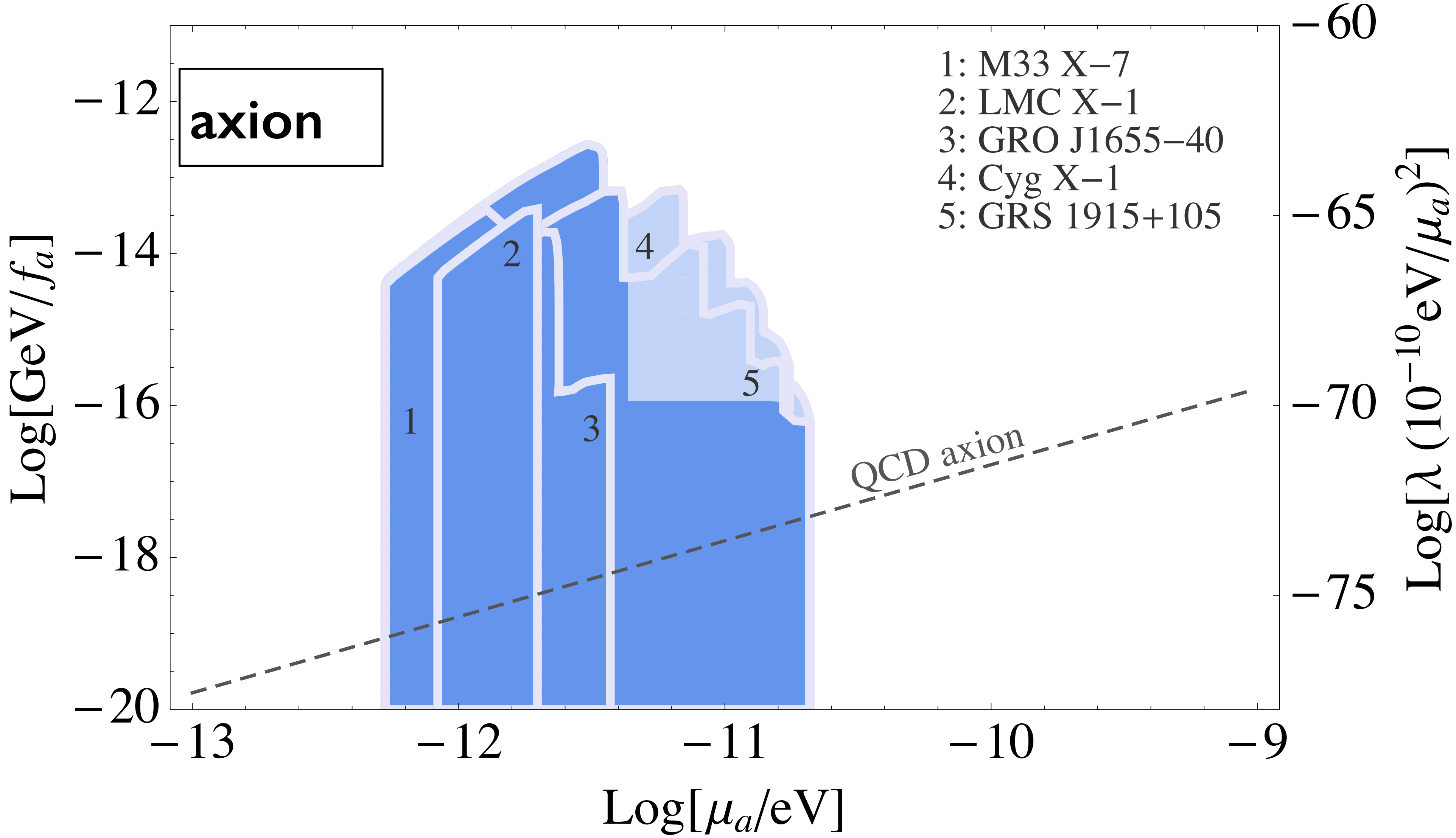
May see spin-down of black holes at LIGO outside of excluded region



Black Hole Spins, coupling

Five currently measured black holes combine to set limit:

$$2 \times 10^{-11} > \mu_a > 6 \times 10^{-13} \text{ eV}$$
$$3 \times 10^{17} < f_a < 1 \times 10^{19} \text{ GeV}$$

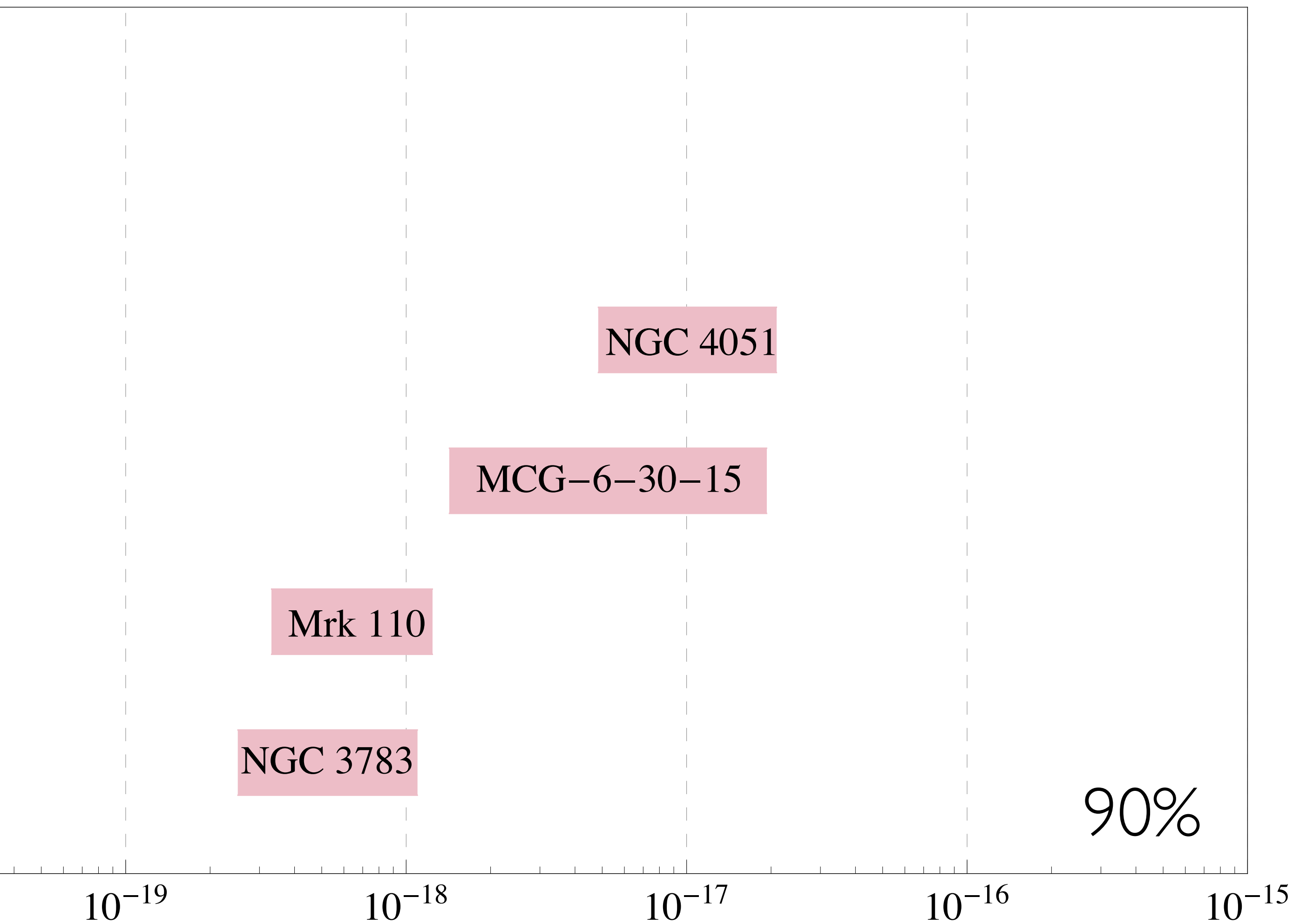


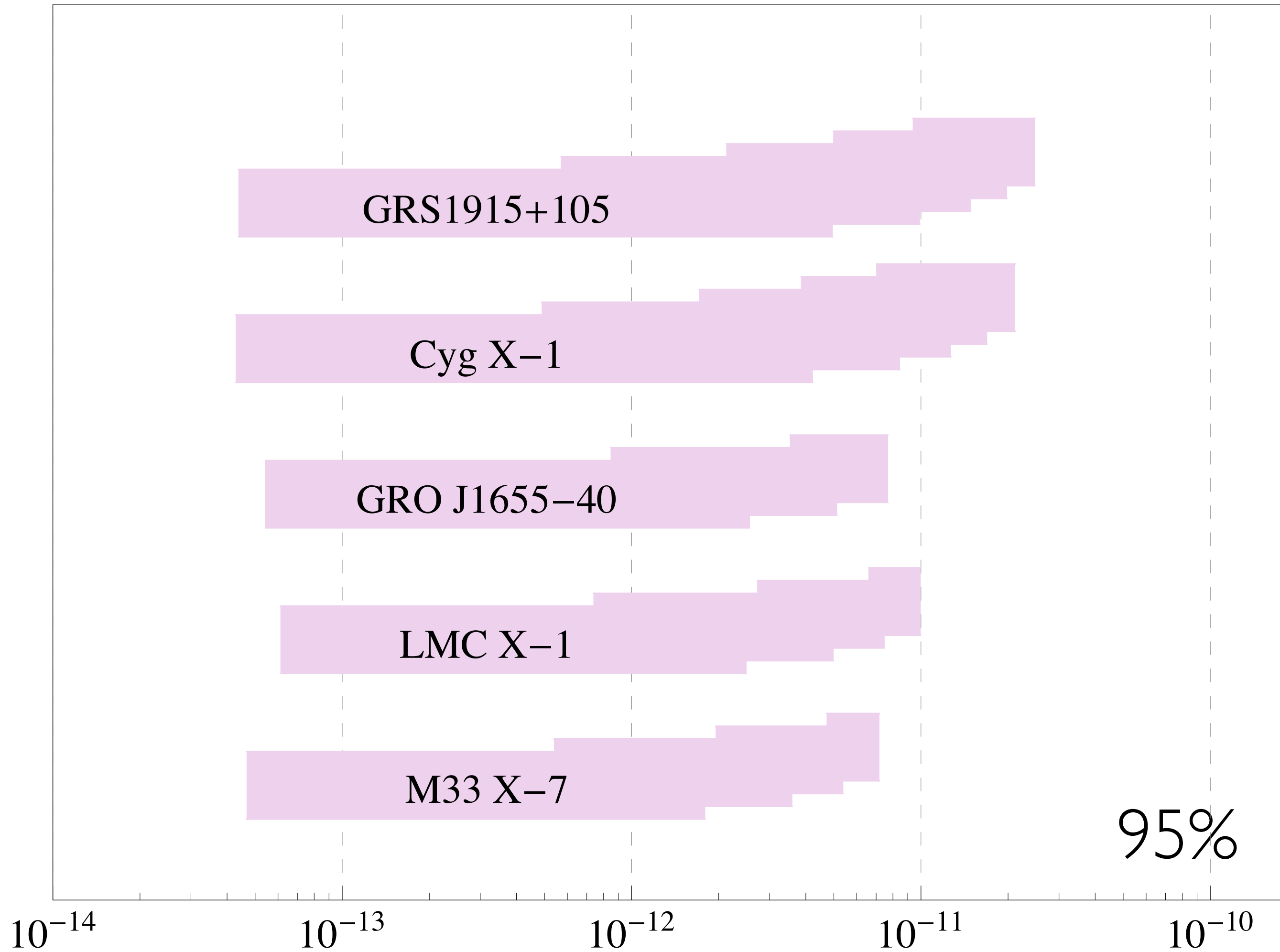
Black Hole Spins

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

$$2.5 \times 10^{-19} < \mu_V < 2.1 \times 10^{-17}\text{eV}$$

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





Black Hole Spins

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