Searching for the QCD Axion with Black Holes and Gravitational Waves

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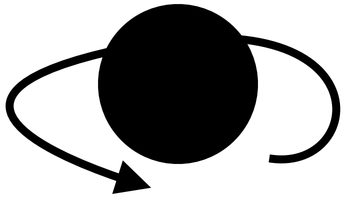
1411.2263/Phys.Rev. D91 (2015) 084011 A. Arvanitaki, MB, X. Huang
1604.03958 A. Arvanitaki, MB, S. Dimopoulos, S. Dubovsky, R. Lasenby

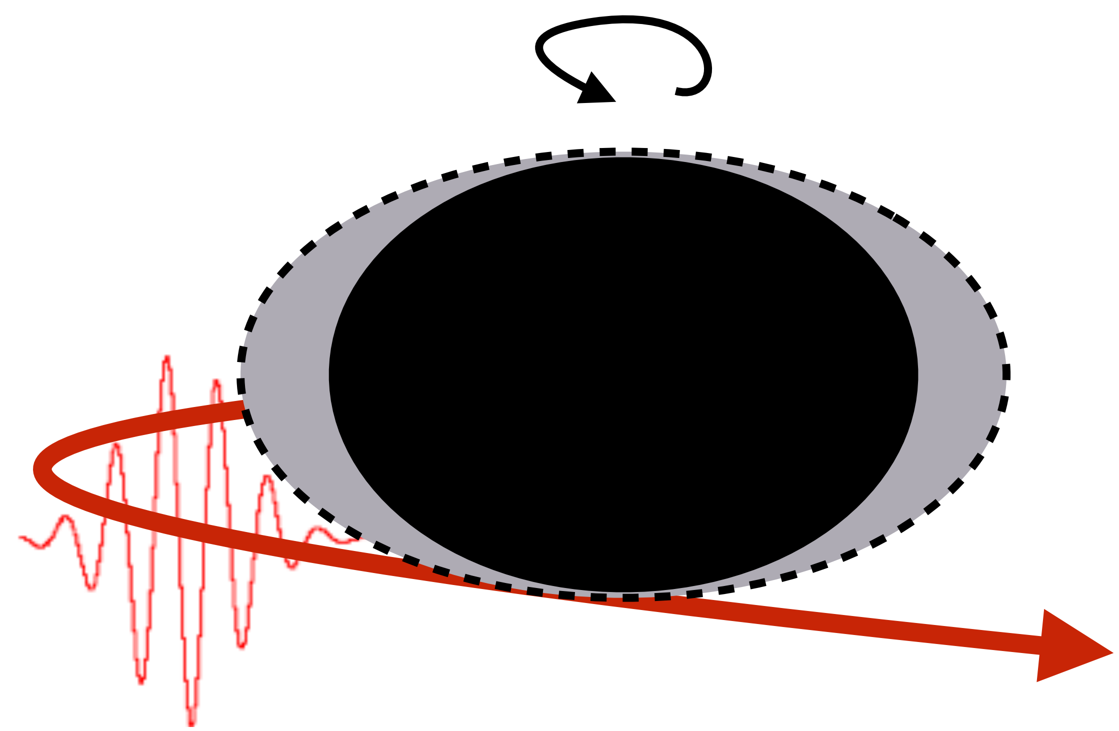
Outline

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

Gravitational Atoms and Superradiance

Wave scattering in the ergoregion can extract angular momentum and energy from the black hole

Wave packets trapped in orbit around the BH can repeat this process continuously



Superradiance condition:

Angular velocity of wave slower than angular velocity of BH horizon

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

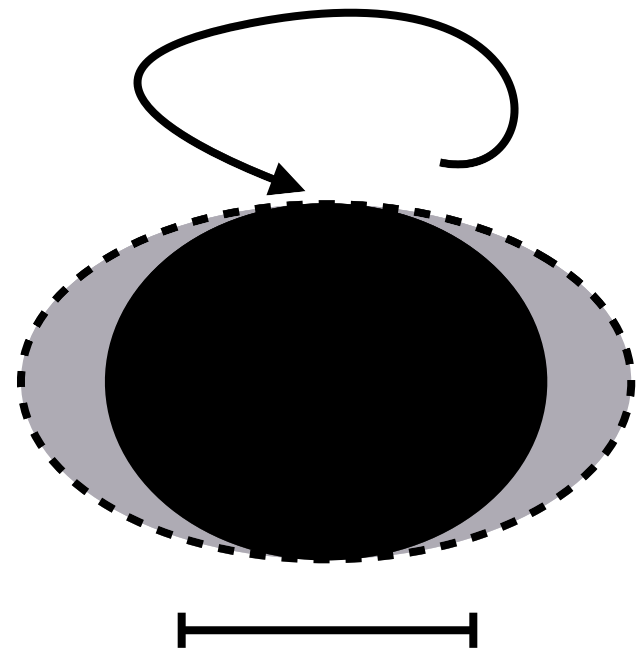
(m = magnetic quantum number)

States that satisfy the SR condition are amplified

Kinematic, not resonant condition

Gravitational Atoms and Superradiance

Stellar-mass black holes, formed in star collapse

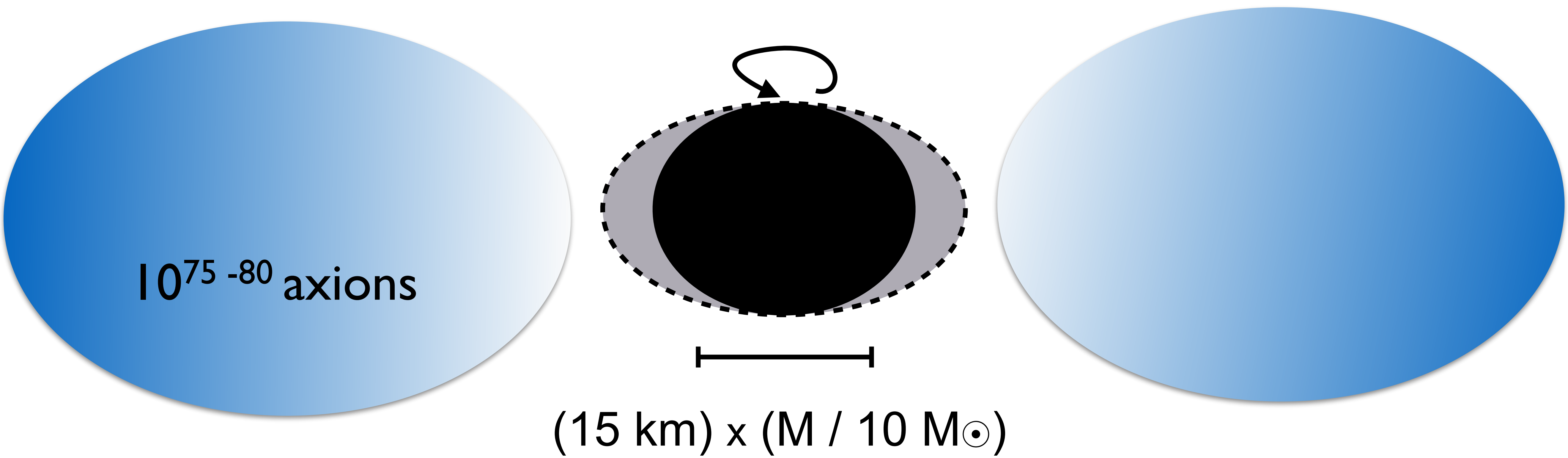


(15 km) x (M / 10 $M_\odot$)

Sensitive detectors of bosons of mass ~10^{-14}-10^{-10} eV

Gravitational Atoms and Superradiance

Stellar-mass black holes, formed in star collapse



Sensitive detectors of bosons of mass ~10^{-14}-10^{-10} eV

For bosons that satisfy SR condition, $\frac{\omega_a}{m} < \Omega_{BH}$

occupation number grows exponentially with SR rate, $N(t) \sim \exp(\Gamma_{sr} t)$

$$\Gamma_{sr}^{nlm} \sim \mu_a \, \alpha^{4l+4}(m\Omega_{BH} - \mu_a) r_+ C_{nlm} \sim \; \mathcal{O}(10^{-7}\text{–}10^{-14}) \, \mu_a$$

$$\alpha = G_{\rm N} M_{\rm BH} \mu_a = \; r_g \, \mu_a$$

Searching for the QCD axion

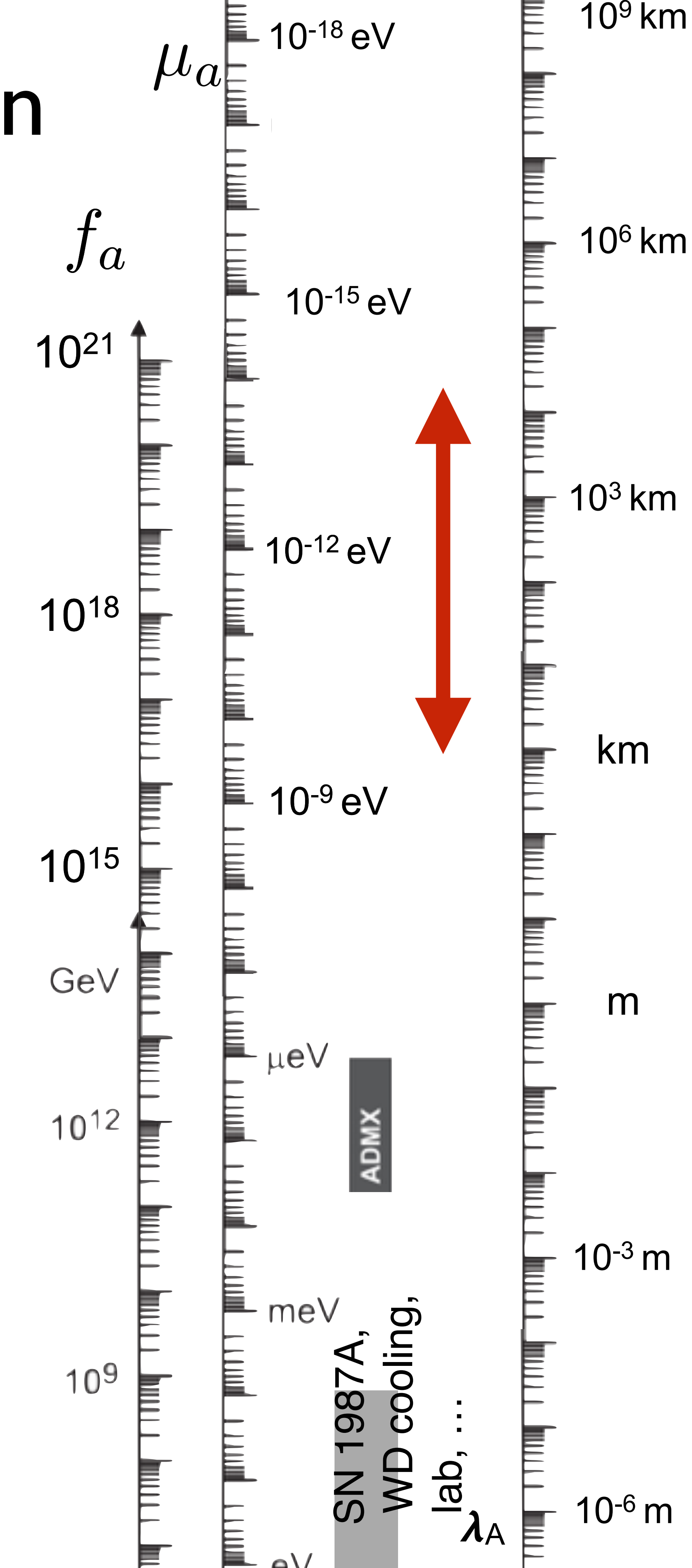
- The QCD axion is one of the best motivated BSM particles
- Solves the strong-CP problem
- Pseudo-goldstone boson with mass and couplings fixed by the decay constant f_a,

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

- Very weakly interacting
- Large compton wavelength

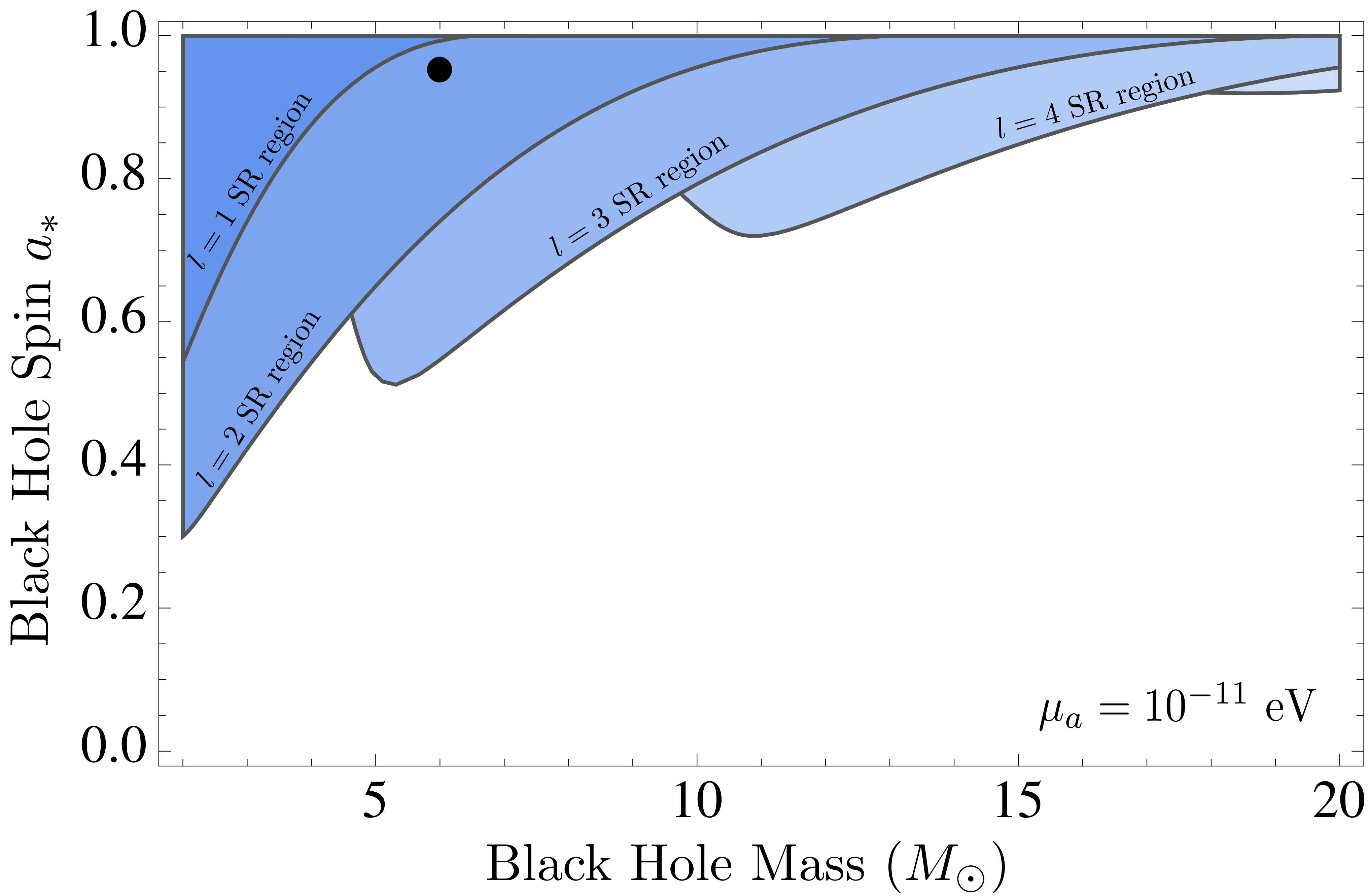
$$\lambda_a \sim 3\,\text{km}\,\frac{6{\times}10^{-11}\text{eV}}{\mu_a}$$

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



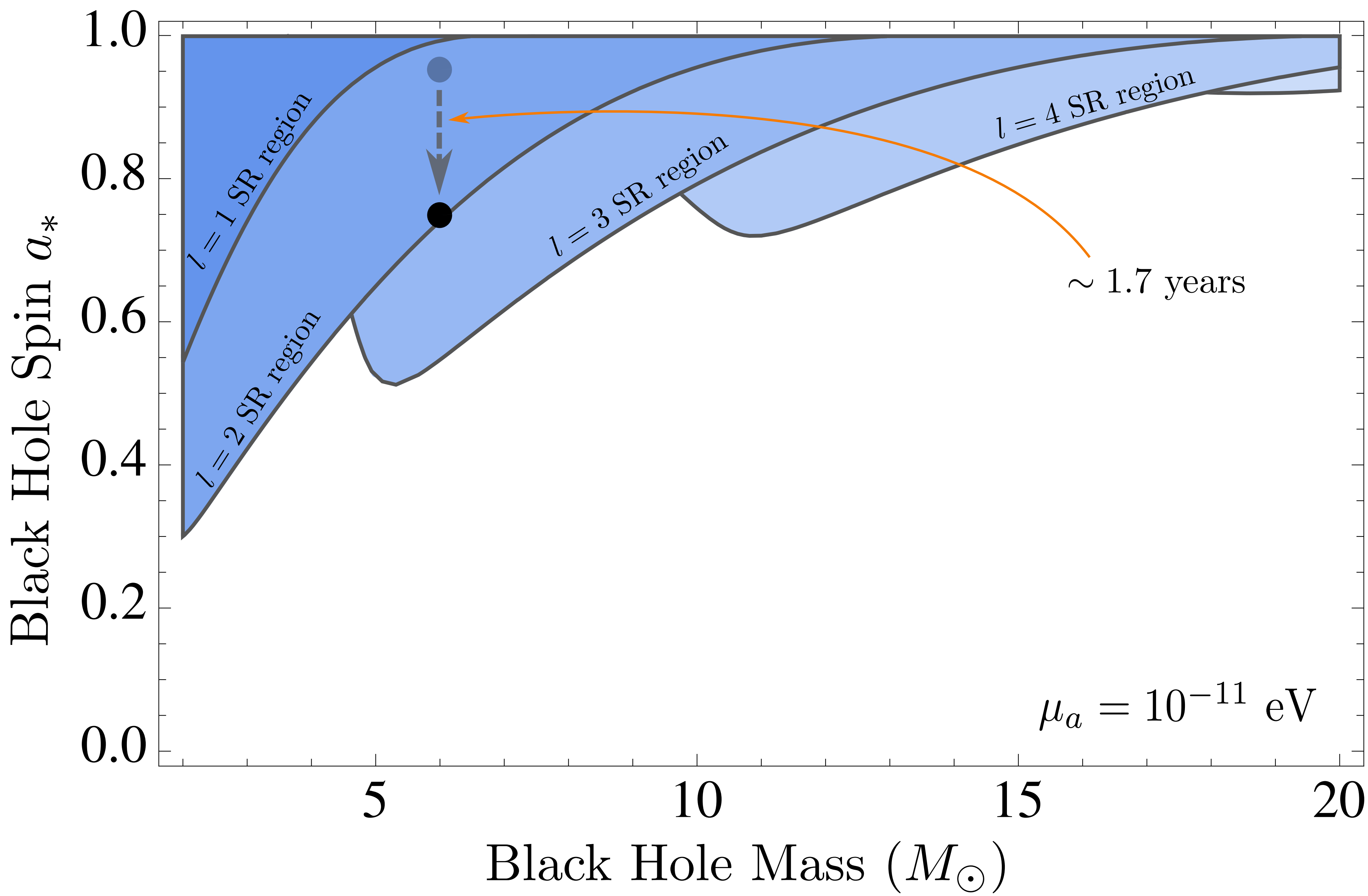
Superradiance

A black hole is born with spin a* = 0.95, M = 6 M⊙.



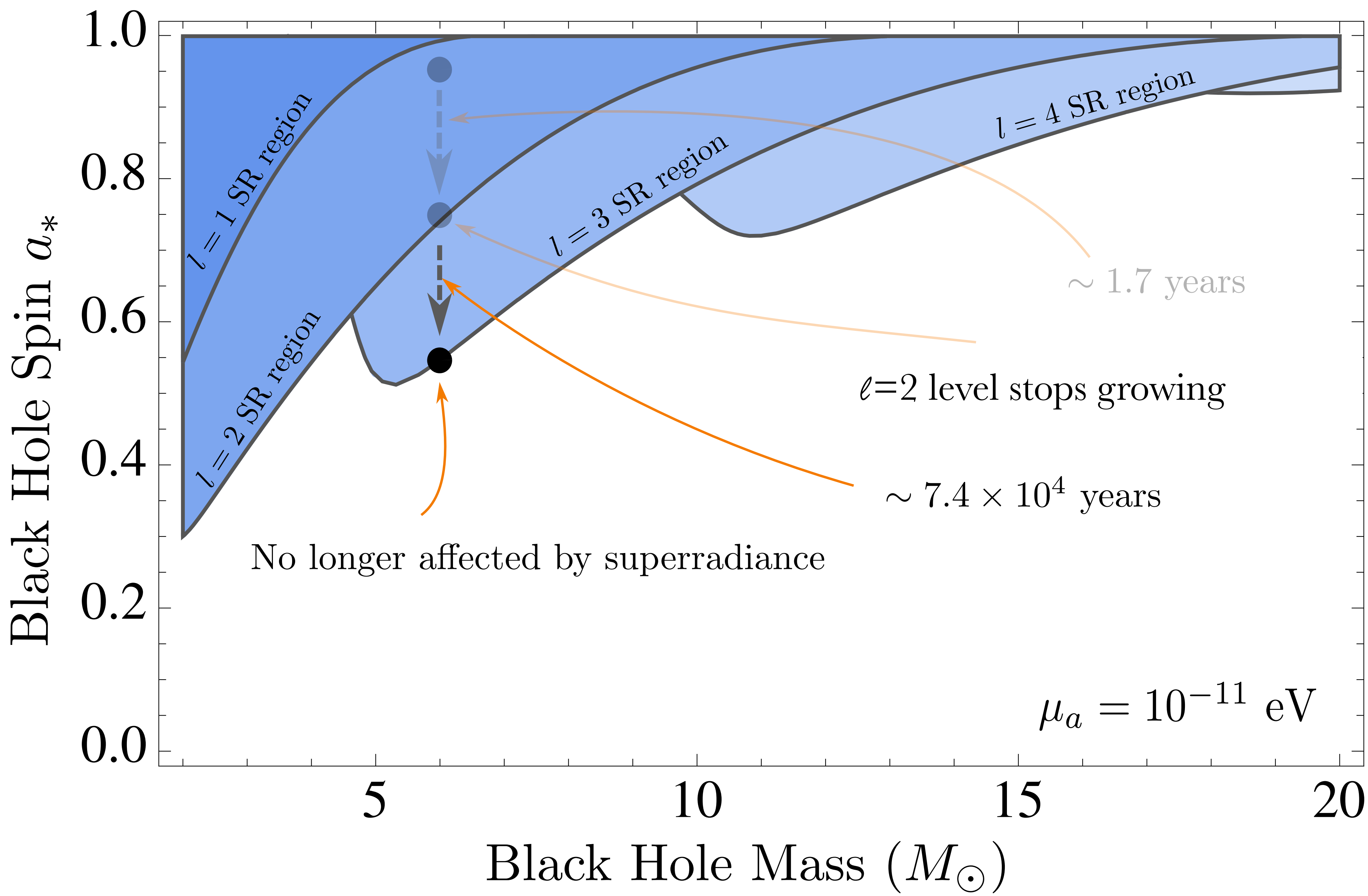
Superradiance

After ~200 SR times, axion cloud grows to macroscopic size ($N=10^{77}$) and the BH quickly loses a fraction of its spin.



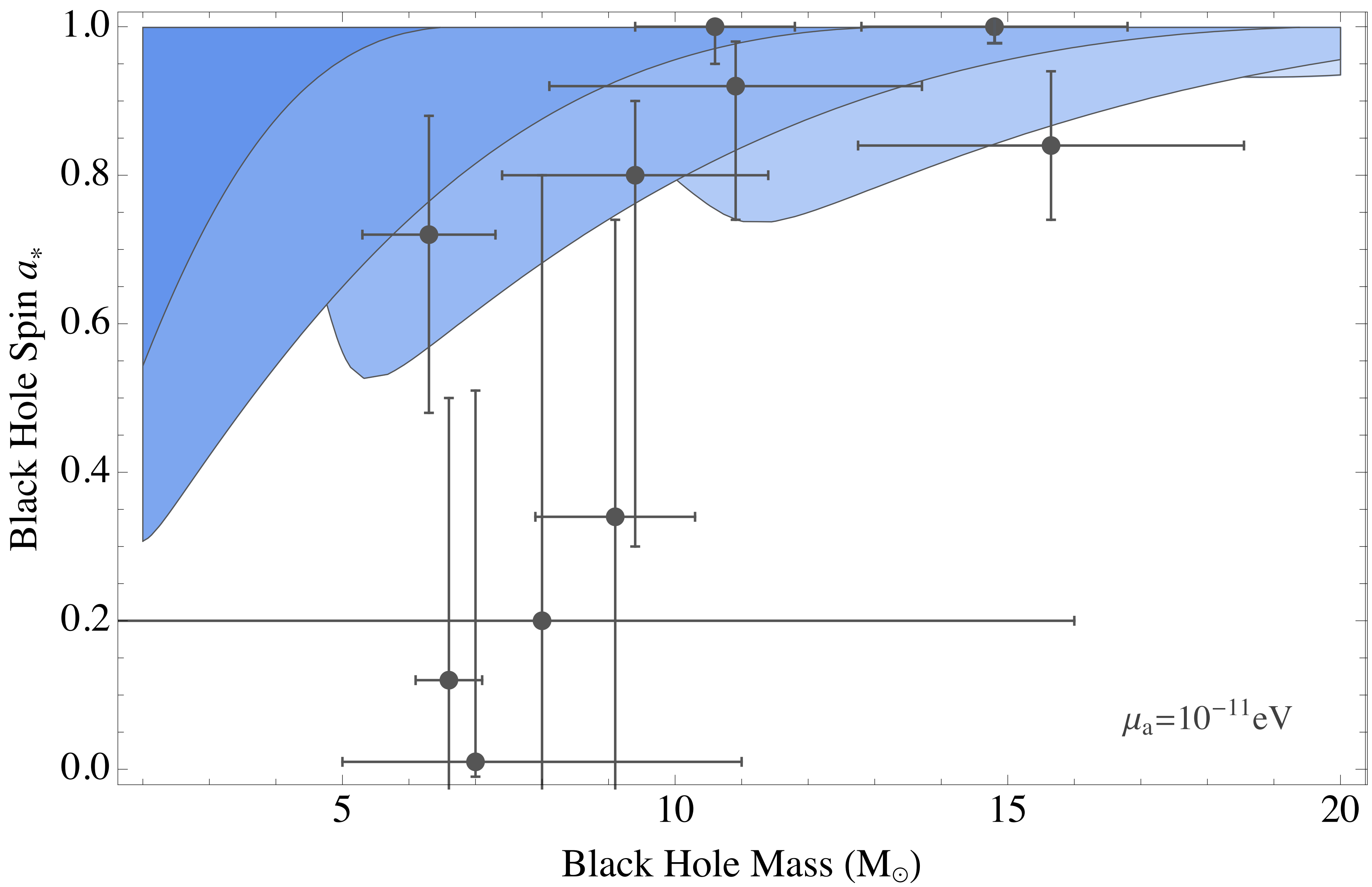
Superradiance

The next level takes a longer time to grow, ~10^5 yrs. Once the BH reaches the next boundary, it is no longer affected by SR.



Black Hole Spins

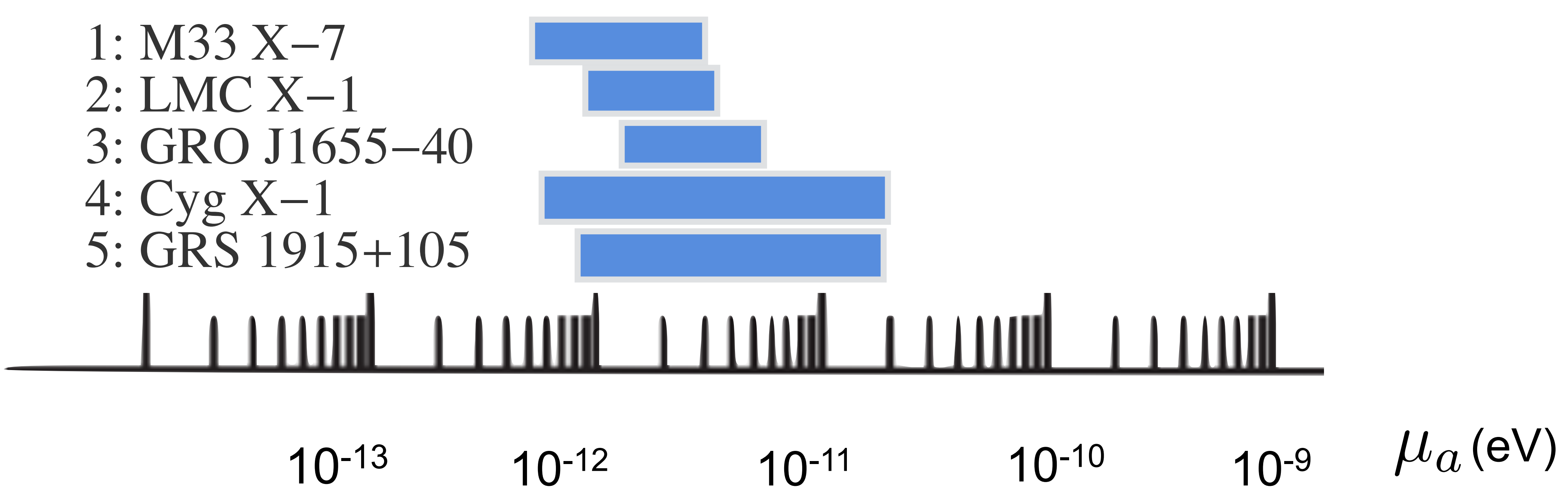
Black hole spin and mass measurements



Black Hole Spins

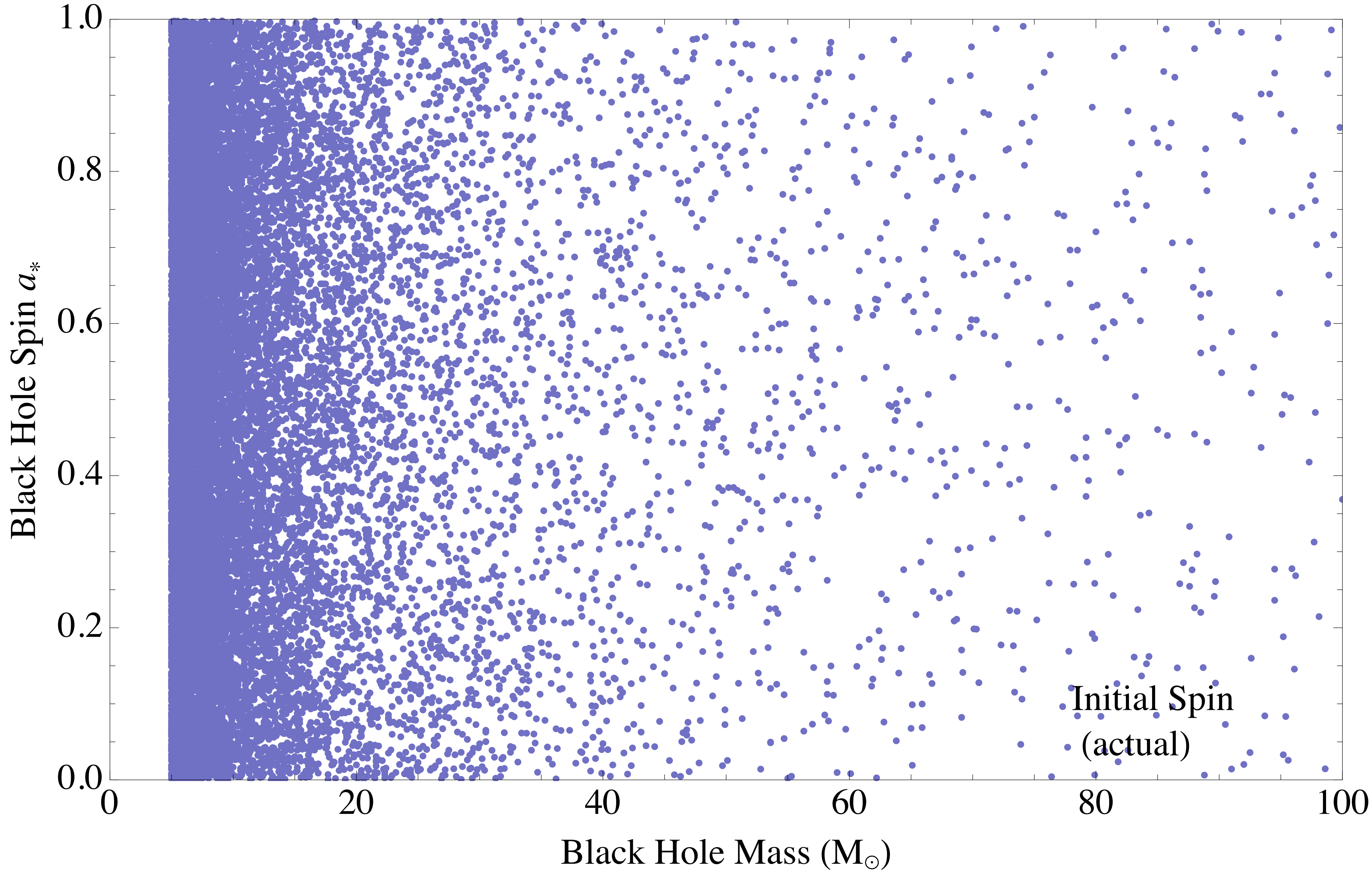
Five currently measured black holes combine to set limit:

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



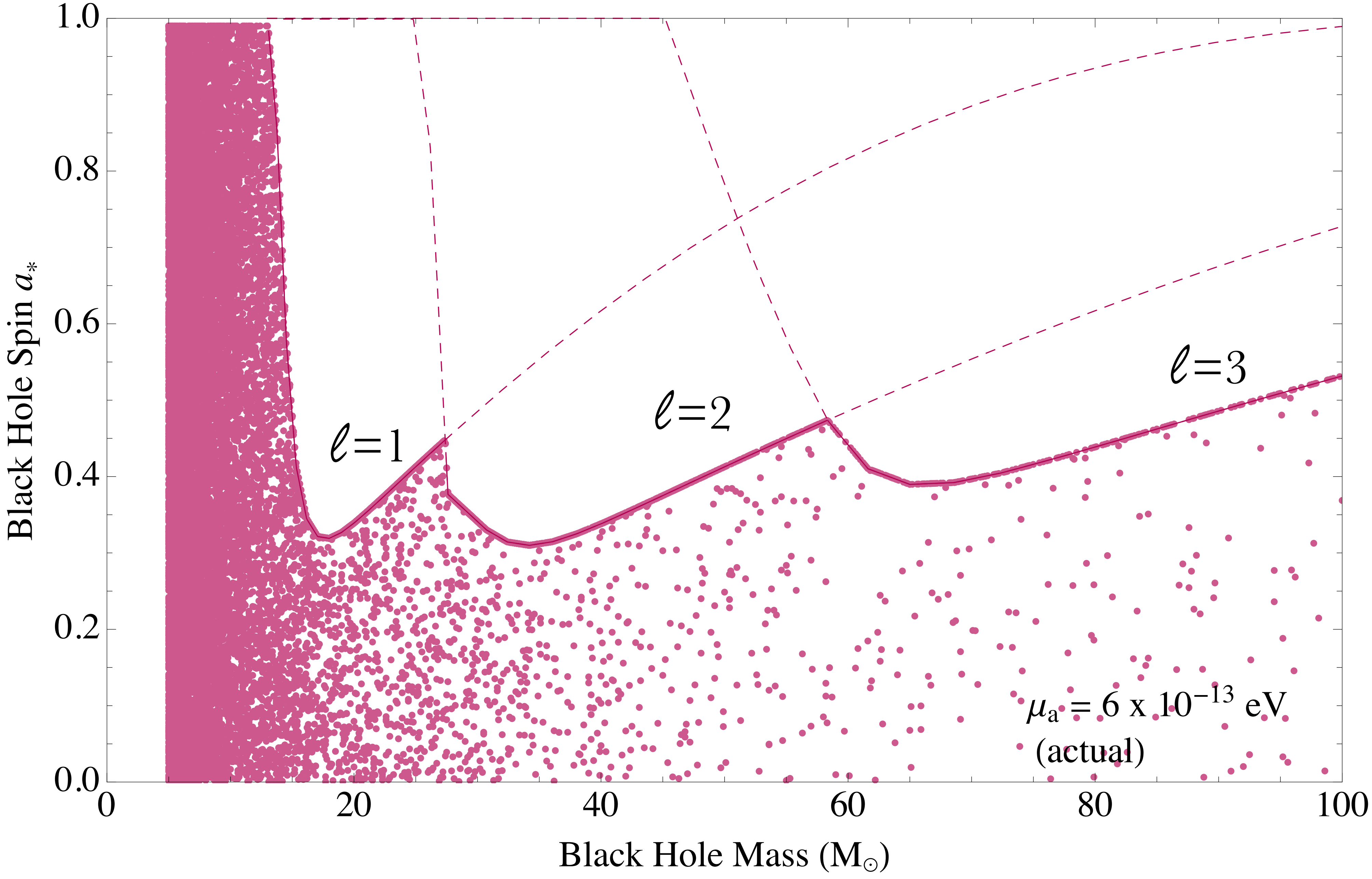
Black Hole Spins
at LIGO

9-240 BBHs/Gpc^3/yr. — 1,000s of BHs merging in low-redshift universe —



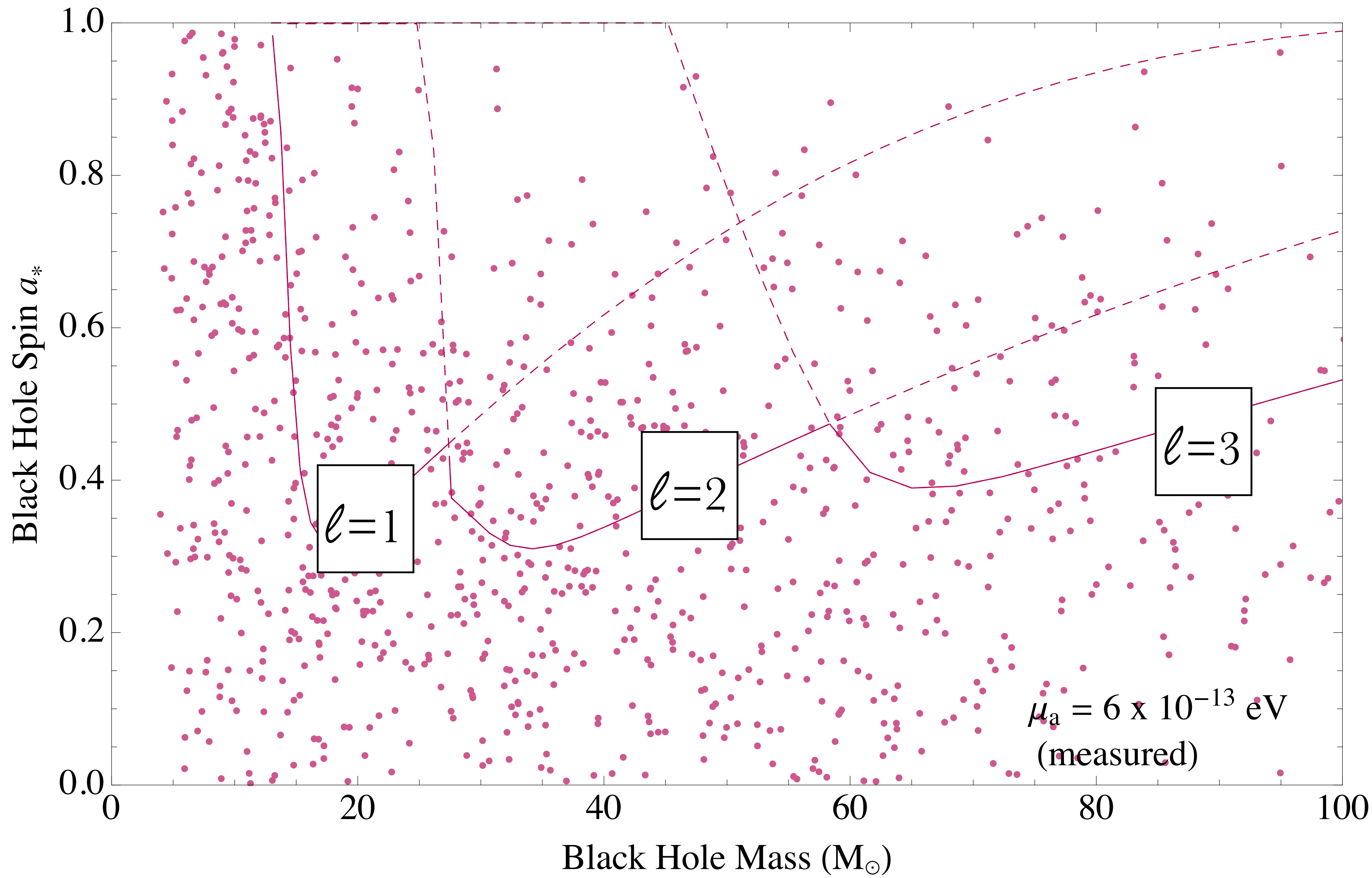
Black Hole Spins

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



Black Hole Spins

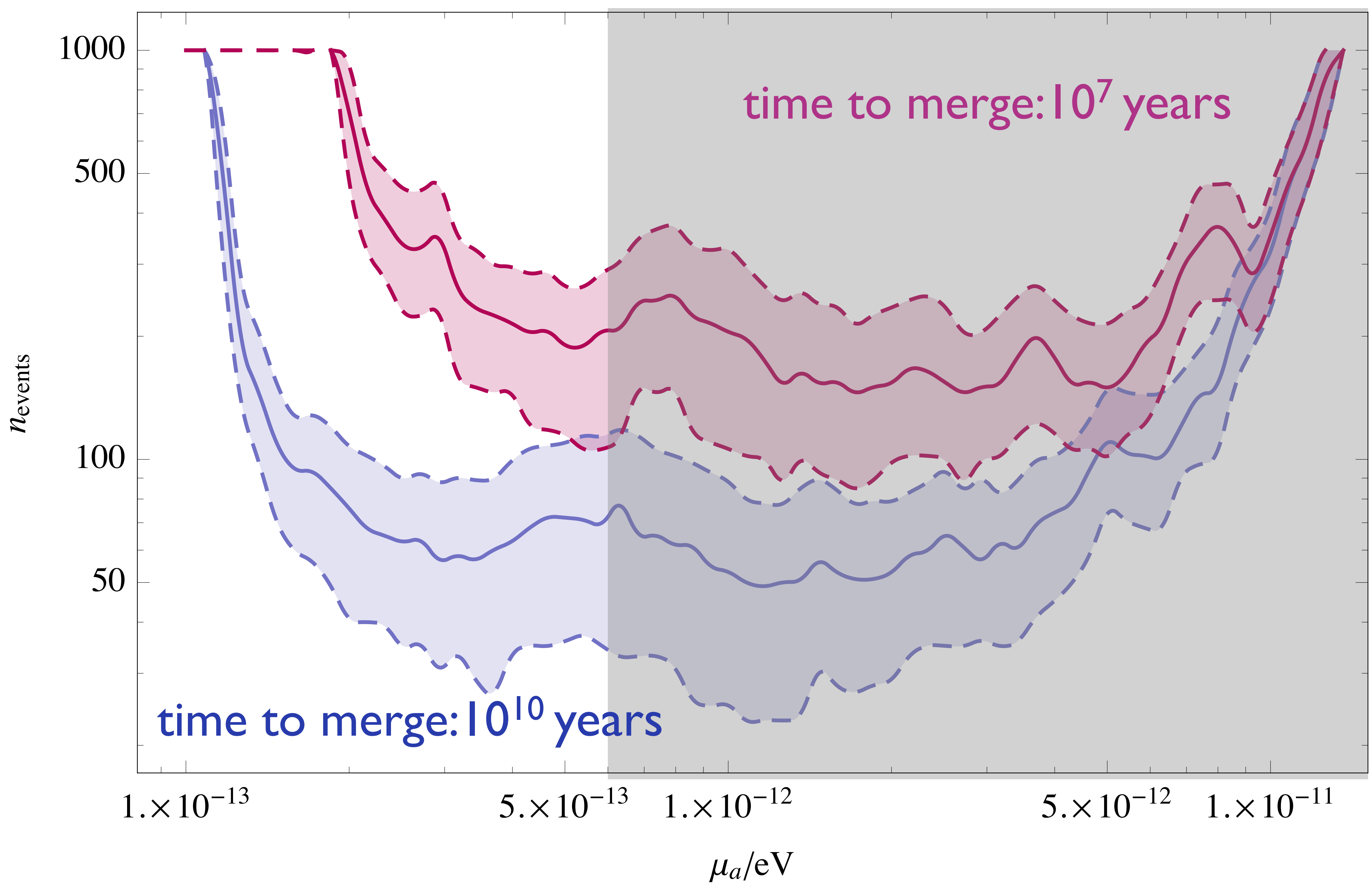
LIGO may measure hundreds of BHs in spin-mass plane (spin error is expected to be large)



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

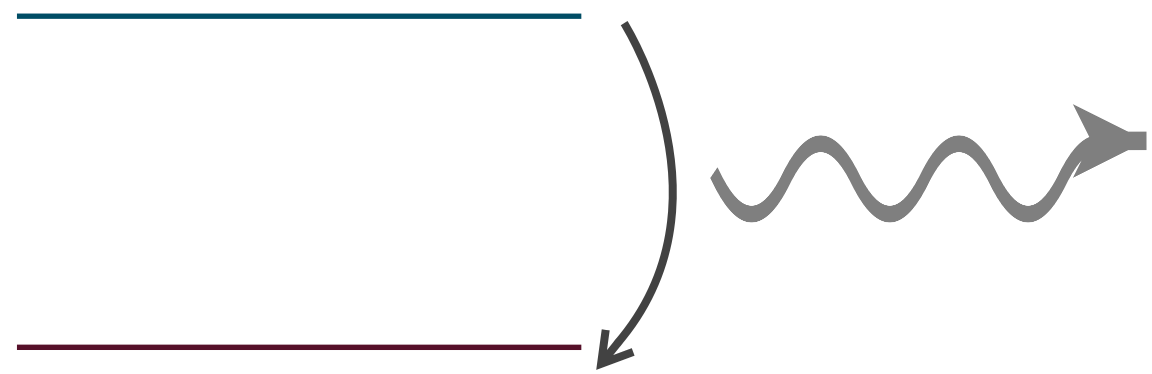
Black Hole Spins

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

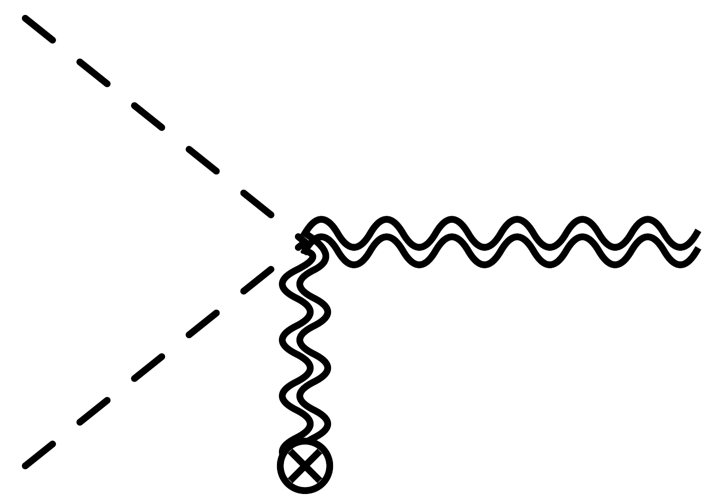


Gravitational Wave Signals

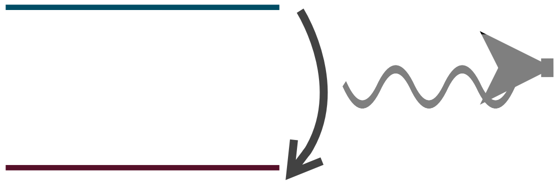
- Transitions between levels

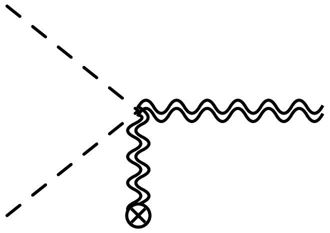


- Annihilations to gravitons

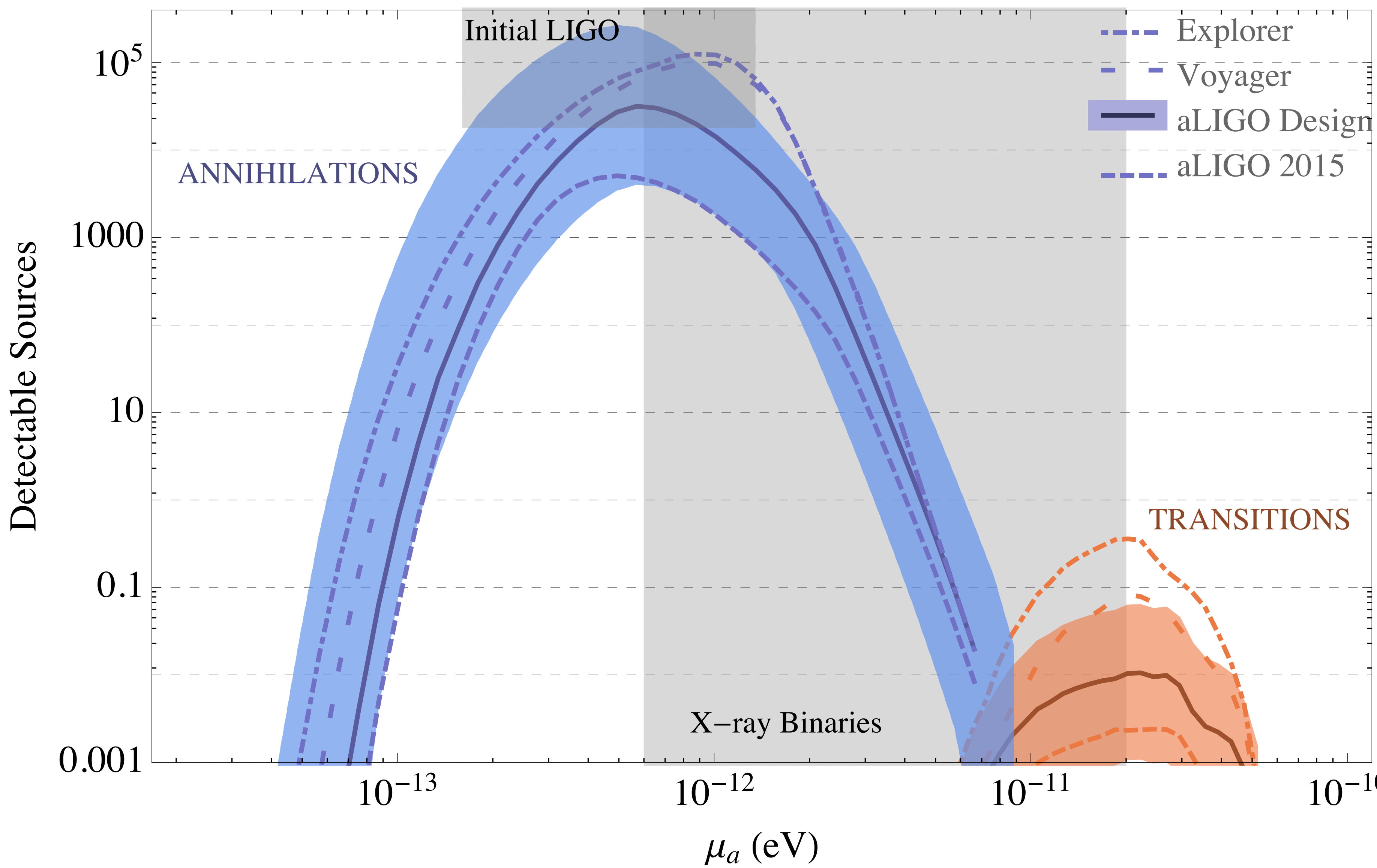


Gravitational Wave Signals





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

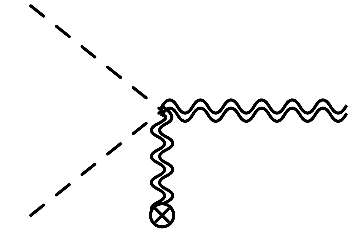


Signals visible from galactic center typically last 10-1000 yrs

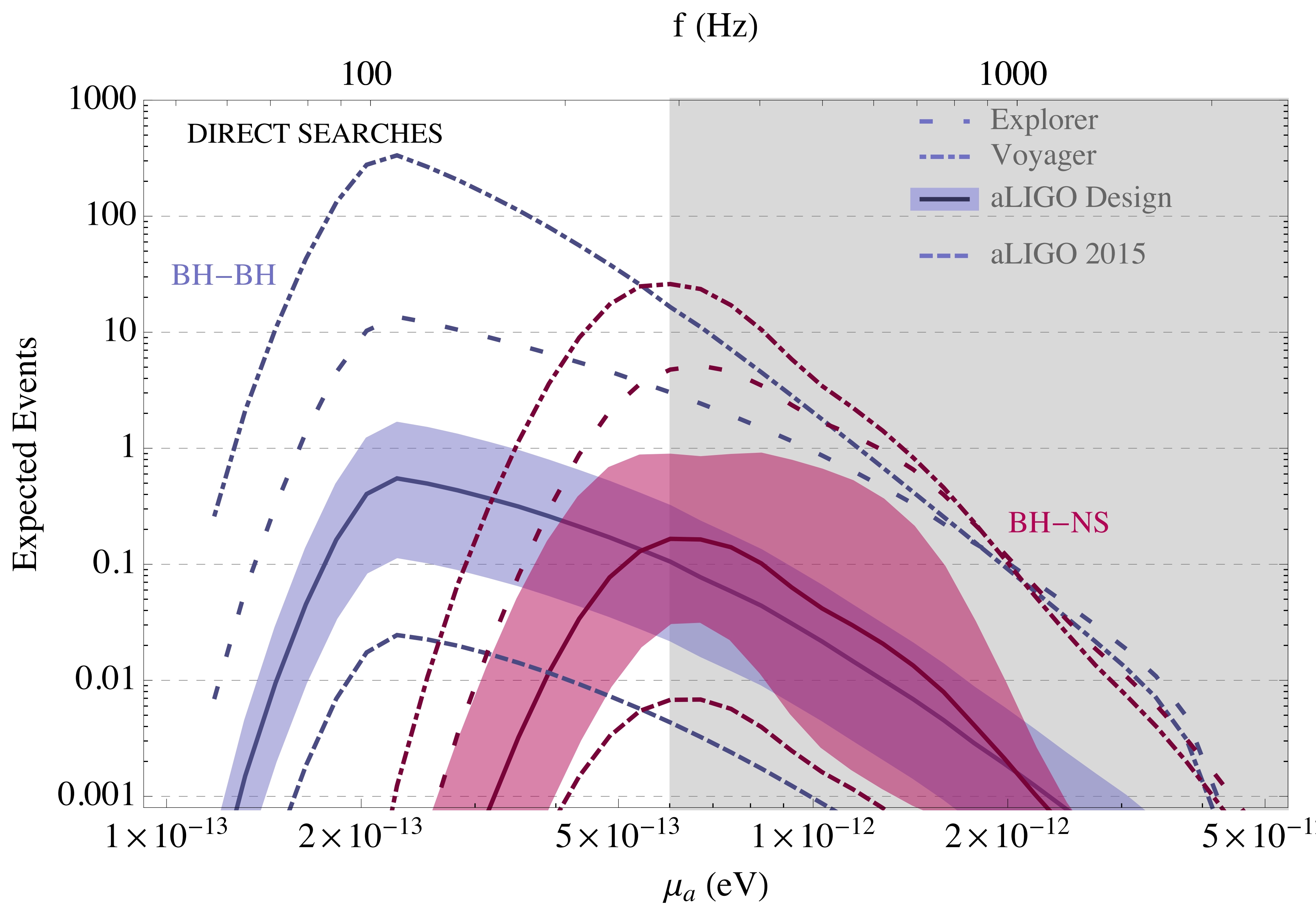
Signals *coherent* and *monochromatic*

Cross-check spin limits

Gravitational Wave Signals

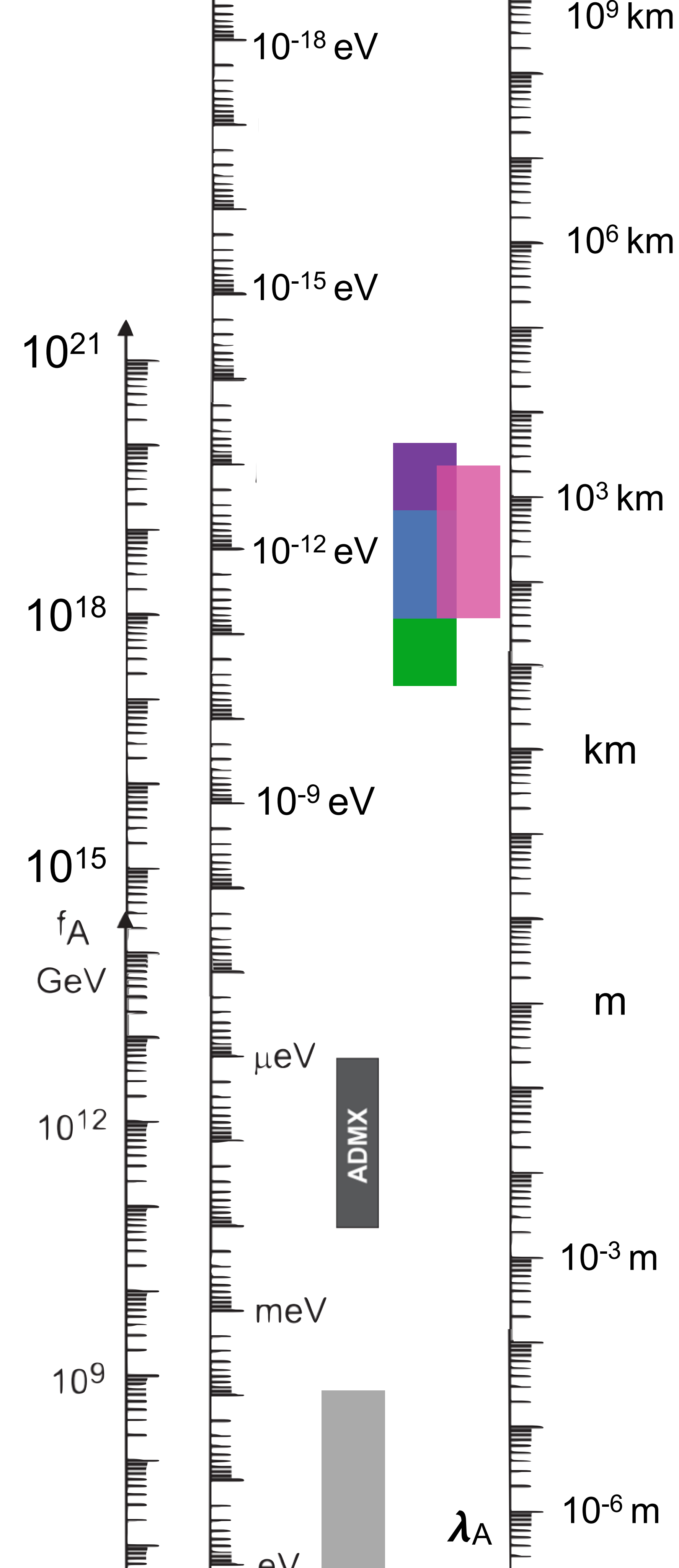


- Mergers at LIGO: a black hole is born!
- Follow up with continuous wave search to see if superradiance creates a cloud of axions around the new BH
- Targeted searches especially promising at future GW observatories



Conclusions

- Ultra light axions can be probed by astrophysical black holes
- Does not rely on DM density
- 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 in real time after a BBH/ BH-NS merger



Thank you!

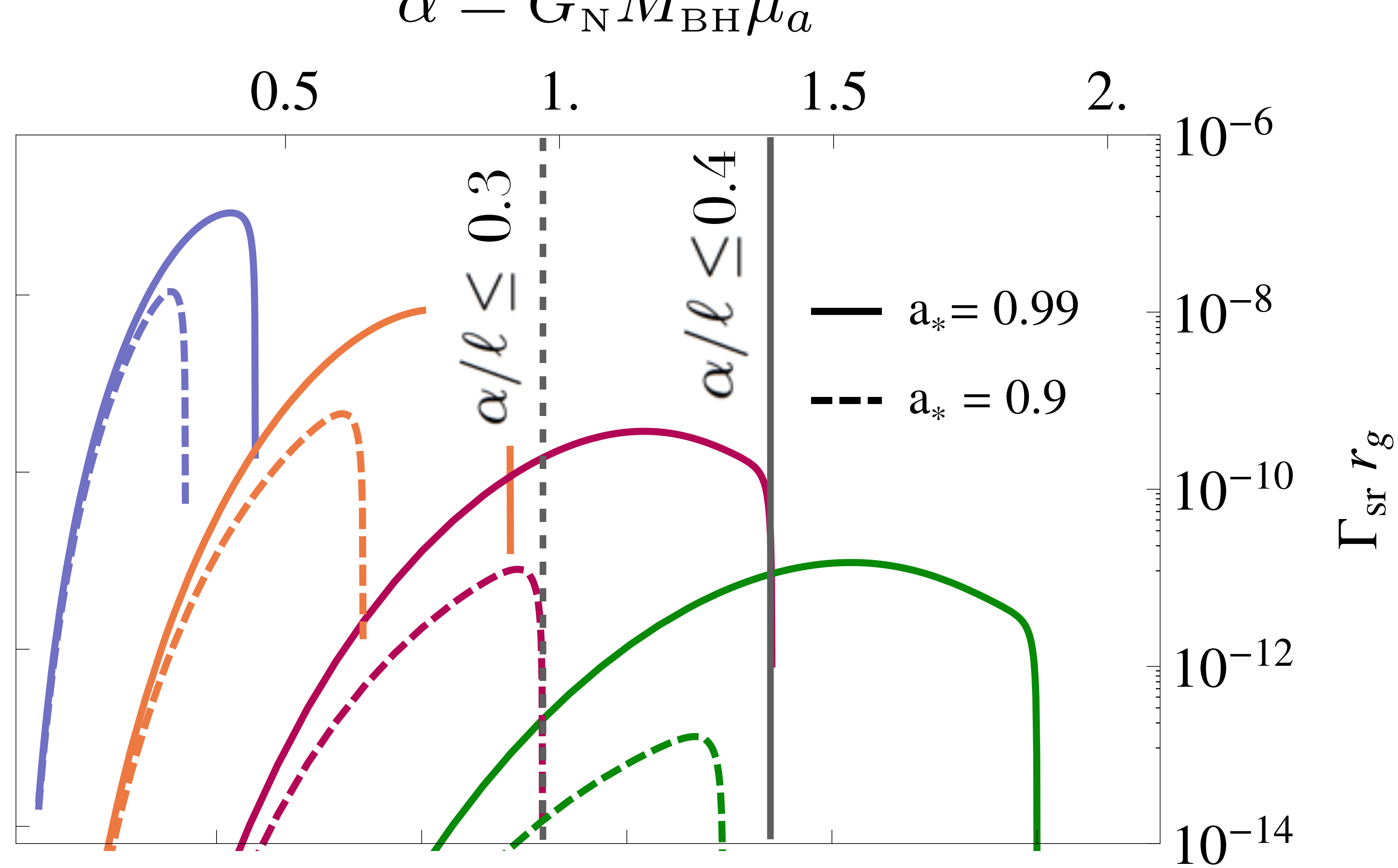
Backup

Superradiance

SR boundary function of α and spin a_*: $\alpha/\ell \leq 1/2$

$$\frac{\omega}{m} < \omega^+, \quad \omega^+ \equiv \frac{1}{2}\left(\frac{a_*}{1+\sqrt{1-a_*^2}}\right) r_g^{-1}$$

- Strong dependence on ℓ
- Steep function of coupling α
- Depends on BH spin a_*
- One superradiance time lasts between 100 s and 100 years



$r_g \equiv G_N M$

Black Hole Spins

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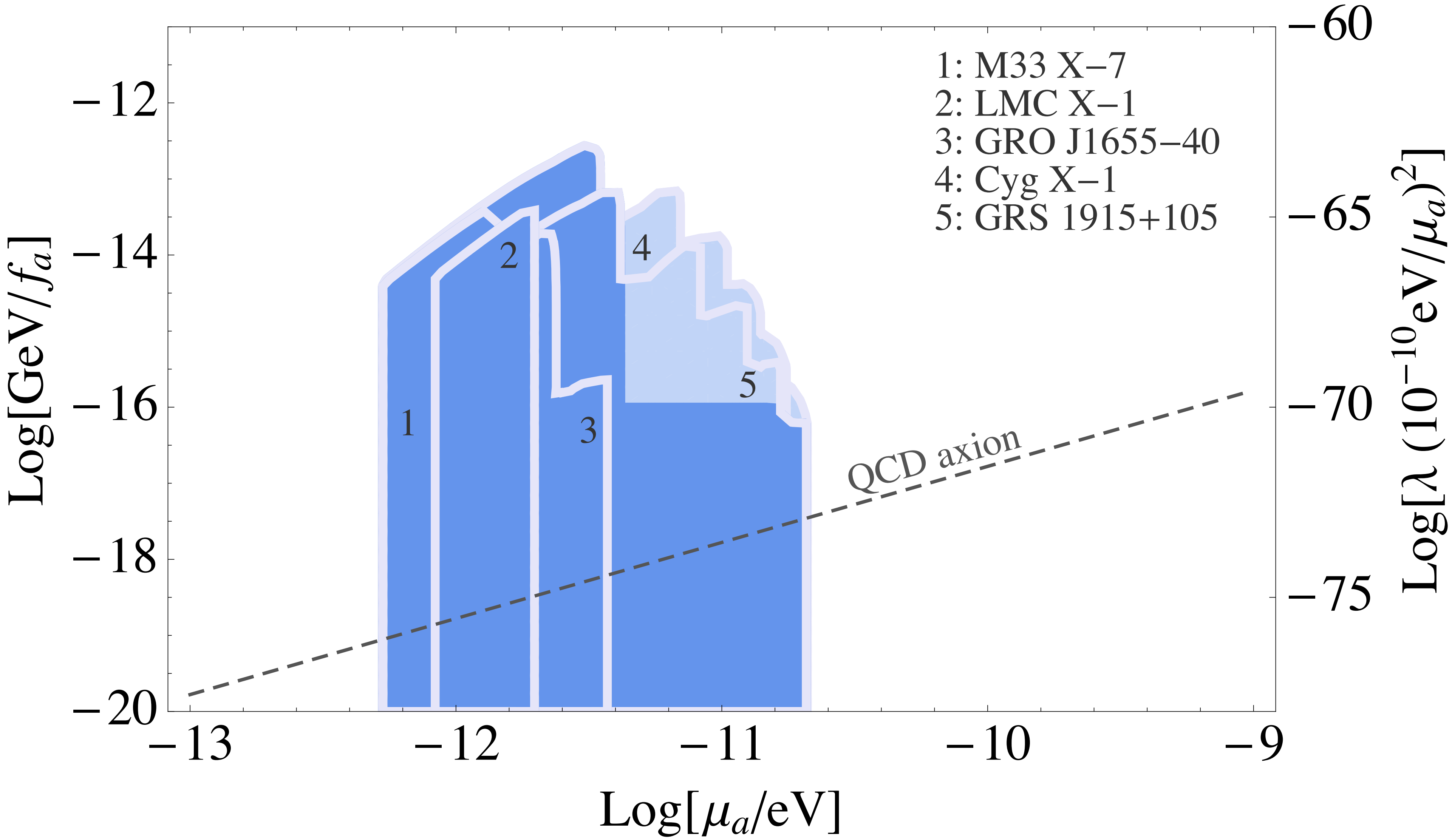
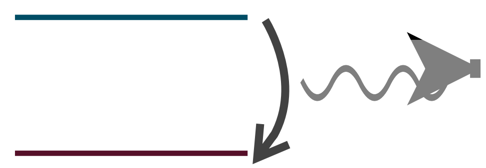


Gravitational Wave Signals

Transitions

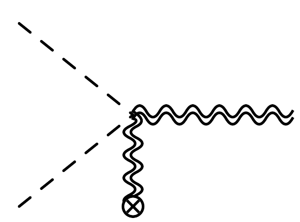


$$\frac{dN_e}{dt} = \Gamma_e^{\rm sr} N_e - \Gamma_t N_e N_g$$

$$\frac{dN_g}{dt} = \Gamma_g^{\rm sr} N_g + \Gamma_t N_g N_e$$

$$\frac{df}{dt} \simeq 10^{-11}\ \frac{\rm Hz}{\rm s} \left(\frac{f}{90\ {\rm Hz}}\right)\left(\frac{M}{10 M_\odot}\right)\left(\frac{10^{17}\ {\rm GeV}}{f_a}\right)^2 \left(\frac{5\ {\rm yr}}{T}\right)^2$$

Annihilations



$$\frac{dN}{dt} = \Gamma_{\rm sr} N - \Gamma_a N^2$$

$$\frac{df}{dt} \simeq 10^{-12}\ \frac{\rm Hz}{\rm s} \left(\frac{f}{\rm kHz}\right)\left(\frac{M_{\rm Pl}}{f_a}\right)^2 \left(\frac{10^3\ {\rm yr}}{T}\right)$$

Black Hole Environment

Perturbations from non-axisymmetric matter can lead to level mixing, disrupting SR.

$$\left|\frac{\Gamma_{\rm dump}^{n'\ell'm'}}{\Gamma_{\rm sr}^{n\ell m}}\right|^{1/2}\left|\frac{\langle\psi_{\rm dump}^{n'\ell'm'}|\delta V(\vec{r})|\psi_{\rm sr}^{n\ell m}\rangle}{\Delta E}\right| < 1,$$

Black holes themselves are perfectly axisymmetric

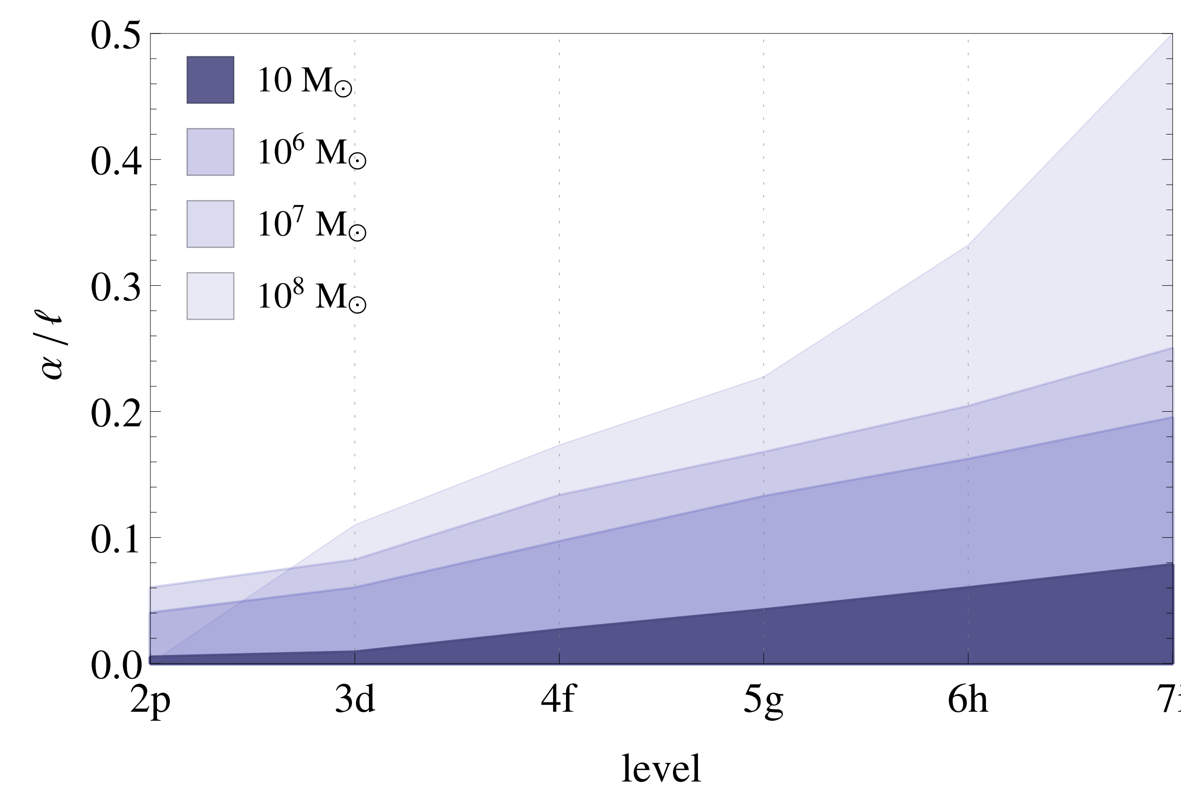
Environments of BHs are very clean

If present, companion star/accretion disk can slightly constrain small coupling parameter space

Companion star

$$\left(\frac{\alpha}{\ell}\right) > (0.05)\left(\frac{M_*}{M}\right)^{1/8}\left(\frac{M}{10M_\odot}\right)^{1/6}\left(\frac{\rm day}{T}\right)^{1/6}$$

Accretion disk



BH data

No.	Object	Mass ($M_\odot$)	Spin	Age (yrs)	Period (days)	$M_{\text{comp star}}$ ($M_\odot$)	$\dot{M}/\dot{M}_E$
1	M33 X-7	15.65 ± 1.45	$0.84^{+0.10}_{-0.10}$ [53]	3×10^6 [54]	3.4530 [55]	$\gtrsim 20$ [55]	$\gtrsim 0.1$ [55]
2	LMC X-1	10.91 ± 1.4	$0.92^{+0.06}_{-0.18}$ [56]	5×10^6 [54]	3.9092 [57]	31.79 ± 3.48 [57]	0.16 [57]
3	GRO J1655 − 40	6.3 ± 0.5	$0.72^{+0.16}_{-0.24}$ [53]	3.4×10^8 [58]	2.622 [58]	2.3–4 [58]	$\lesssim 0.25$ [59]
4	Cyg X-1	14.8 ± 1.0	> 0.99 [60]	4.8×10^6 [61]	5.599829 [54]	17.8 [54]	0.02 [54]
5	GRS1915 + 105	10.1 ± 0.6	> 0.95 [53,62]	4×10^9 [63]	33.85 [64]	0.47 ± 0.27 [64]	$\gtrsim 1$ [64].

No.	Object	Mass ($10^6 M_\odot$)	Spin
1	NGC 3783	29.8 ± 5.4	>0.88
2	Mrk 110	25.1 ± 6.1	>0.89
3	MCG-6-30-15	$2.9^{+0.18}_{-0.16}$	>0.98
4	NGC 4051	1.91 ± 0.78	>0.99

BH distributions

- Spin:
  - 90% above 0.8
  - 30% above 0.8
  - flat distribution
- Formation rate:
  - 0.9/century
  - 0.38/century
  - 0.08/century
- Mass distributions
  - width 2.8/4.7/7.9
  - cutoff 30/80/160