Constraints on Axions from Black Hole mergers and Binary Pulsars

Based on:

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- Blas, López Nacir, Sibiryakov, "Ultra-Light Dark Matter Resonates with Binary Pulsars", 1612.06789

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24 Janvier 2017 - Cosmo Club IPhT/SAP/SPP

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QCD Axions

- QCD axion: one of the best motivated BSM particles
- Solves the strong-CP problem by making the QCD θ angle a dynamical field

$$\mathcal{L}_{\rm SM} \supset \frac{\alpha_s}{8\pi}\frac{a}{f_a}G_{\mu\nu}\tilde{G}^{\mu\nu}$$

- Pseudo-Goldstone boson with mass and couplings fixed by the decay constant f_a

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

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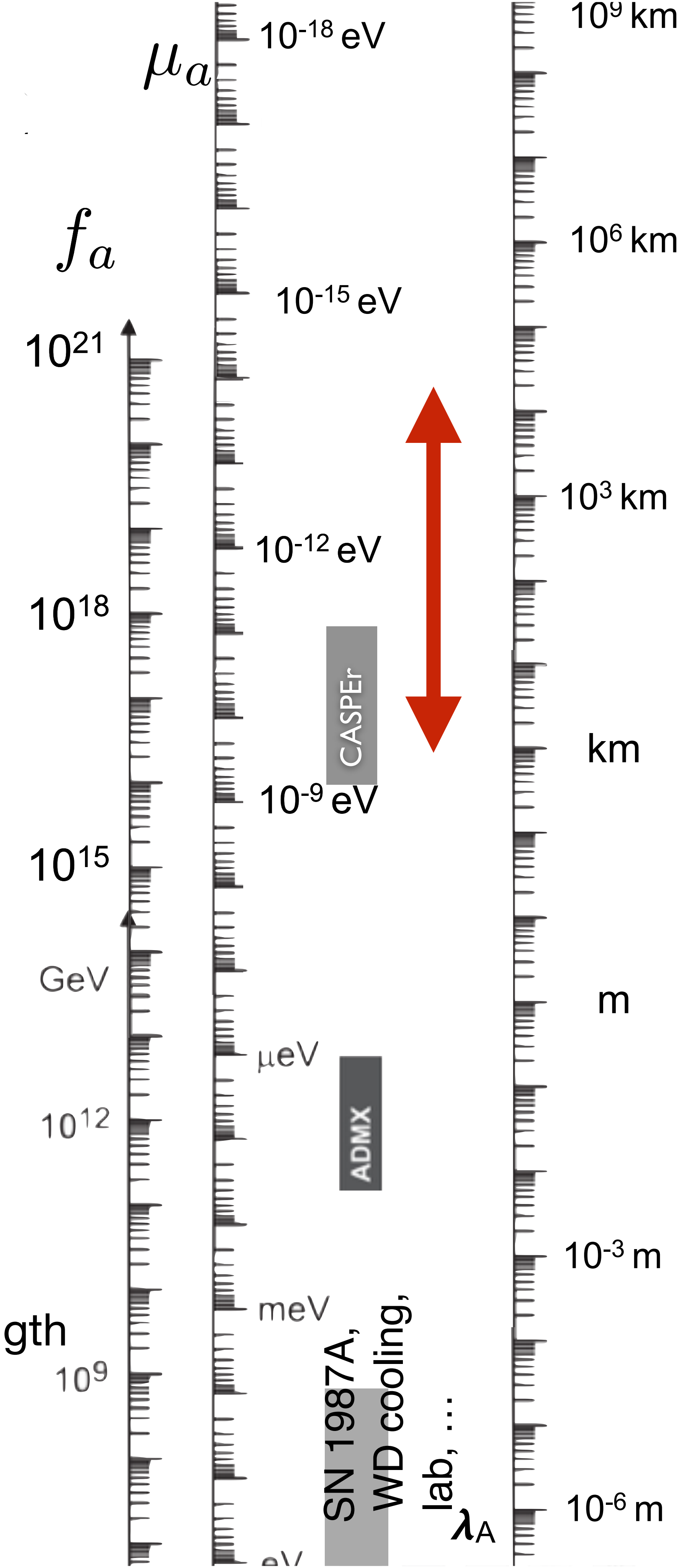
$$\mu_a \sim 6\times 10^{-11}\ {\rm eV}\ \frac{10^{17}\ {\rm GeV}}{f_a}$$

- Very weakly interacting
- Large Compton wavelength

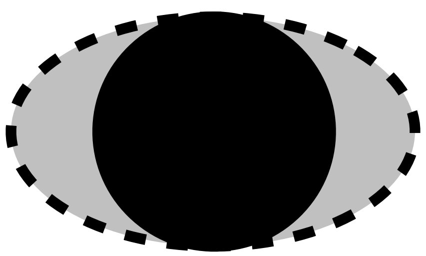
$$\lambda_a \sim 3\,{\rm km}\,\frac{6\times 10^{-11}{\rm eV}}{\mu_a}$$

- Small masses difficult to probe because have very long wavelength
- Current bound only for large masses and model dependent

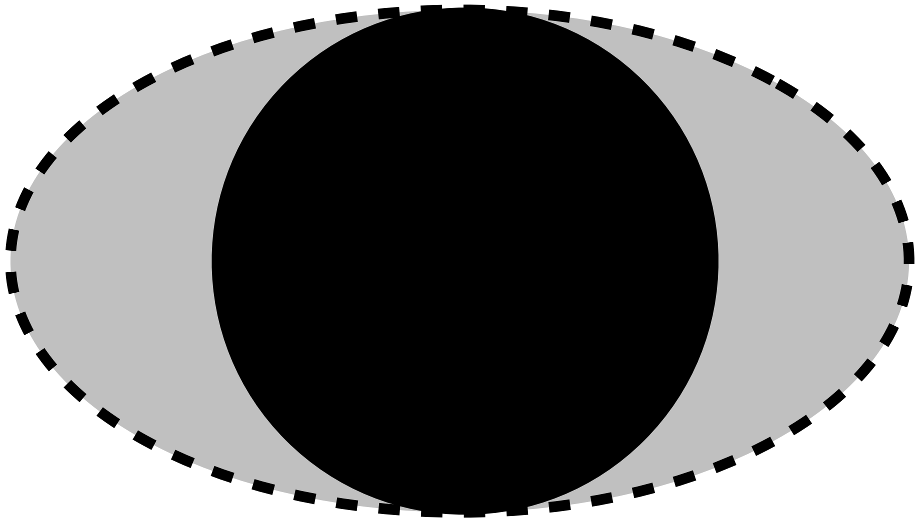


Black Holes

- Black holes can be used as axion detectors: BH size ~ axion Compton wavelength



$$30\ \text{km} \times \frac{M}{10 M_\odot}$$



$$3 \times 10^7\ \text{km} \times \frac{M}{10^7 M_\odot}$$

Stellar black holes:

- ~10^8 - 10^9 in our galaxy
- Sensitive to axion masses ~10^{-13} - 10^{-11} eV

Supermassive black holes:

- Found at the center of galaxies
- Sensitive to axion masses ~10^{-19} - 10^{-16} eV

Gravitational Atom

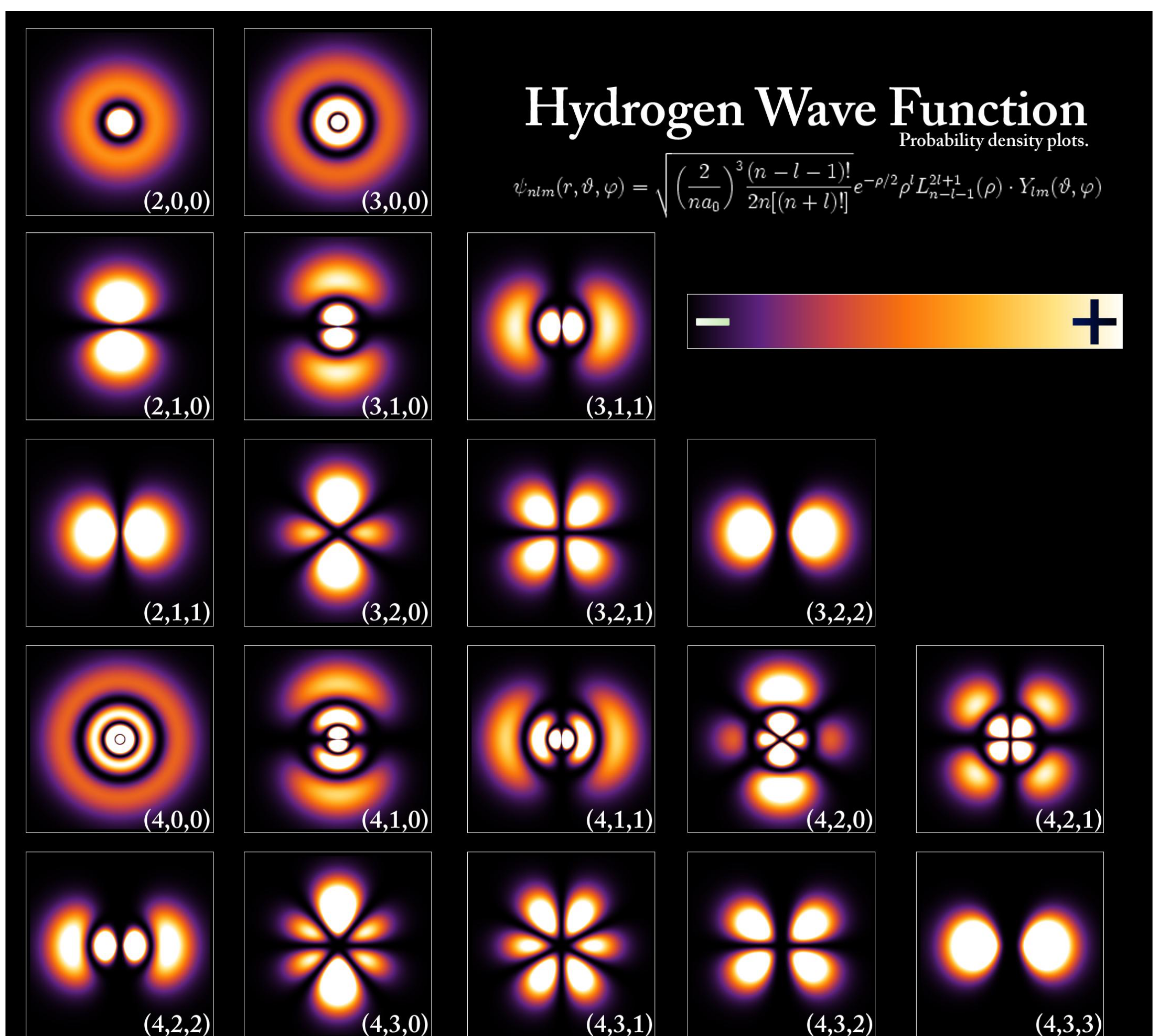
- In analogy with the Hydrogen atom, axions gravitationally bind around a BH and occupy the states characterised by the usual quantum number, n, l and m.

- Fine-structure constant

$$\alpha = \frac{G M_{\mathrm{BH}} \mu_a}{\hbar c} = 0.22 \left(\frac{M_{\mathrm{BH}}}{30 M_{\odot}} \right) \left(\frac{\mu_a}{10^{-12}\,\mathrm{eV}} \right)$$

- Energy level

$$\hbar\omega = \mu_a c^2 \left(1 - \frac{\alpha^2}{2n^2} \right)$$

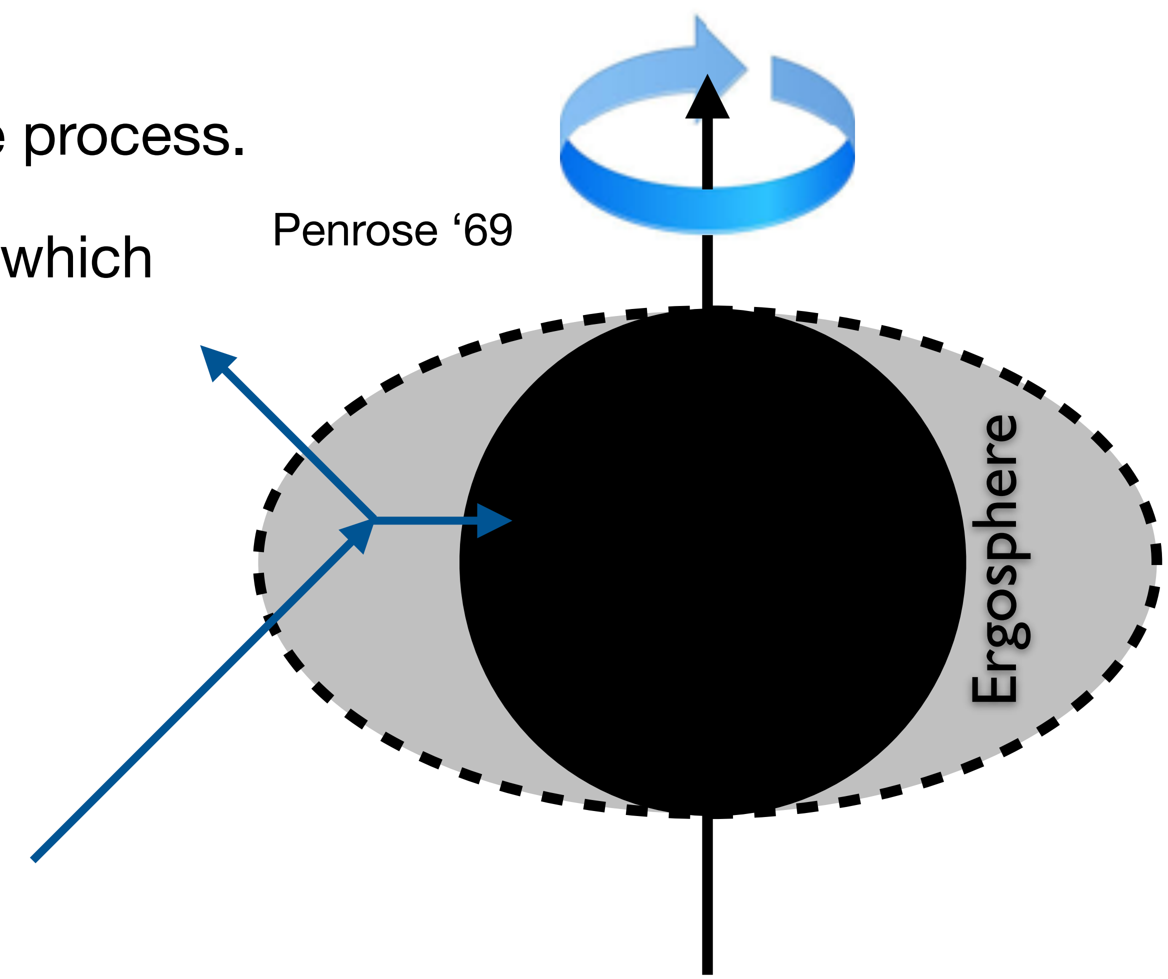


Superradiance

- Superradiance is an ubiquitous kinematic/thermodynamic phenomenon.

- In a BH, it can be explained in terms of Penrose process.
- A rotating BH possesses an ergosphere, inside which no observer can be stationary.

Penrose '69



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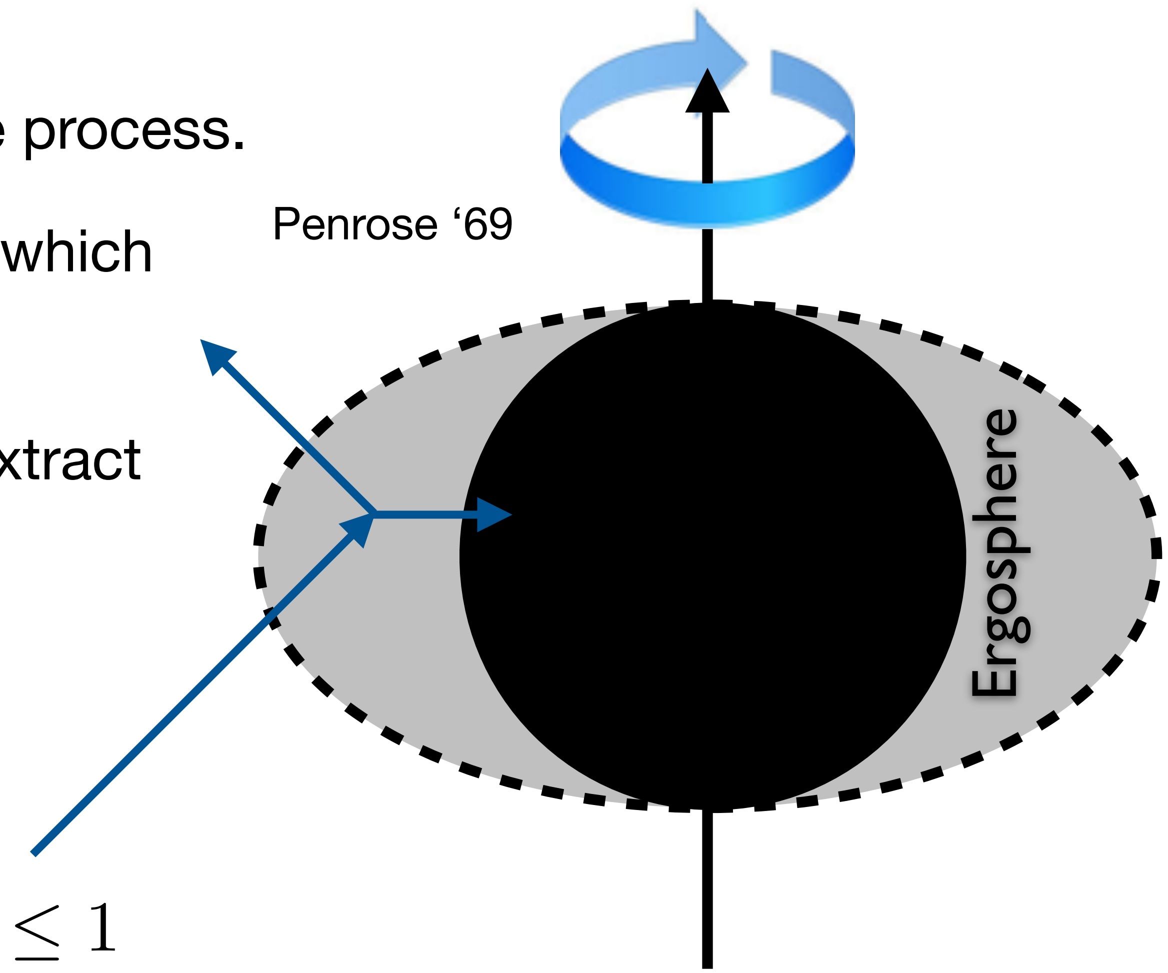
- A rotating BH possesses an ergosphere, inside which no observer can be stationary.
- Particles passing through the ergosphere can extract angular momentum and energy from the BH.
- Superradiant condition: $\omega < m\Omega_{\rm H}$



$$\Omega_{\rm H} = \frac{c^3}{2GM_{\rm BH}} \frac{a_*}{1+\sqrt{1-a_*^2}}\,, \qquad 0 \leq a_* \leq 1$$

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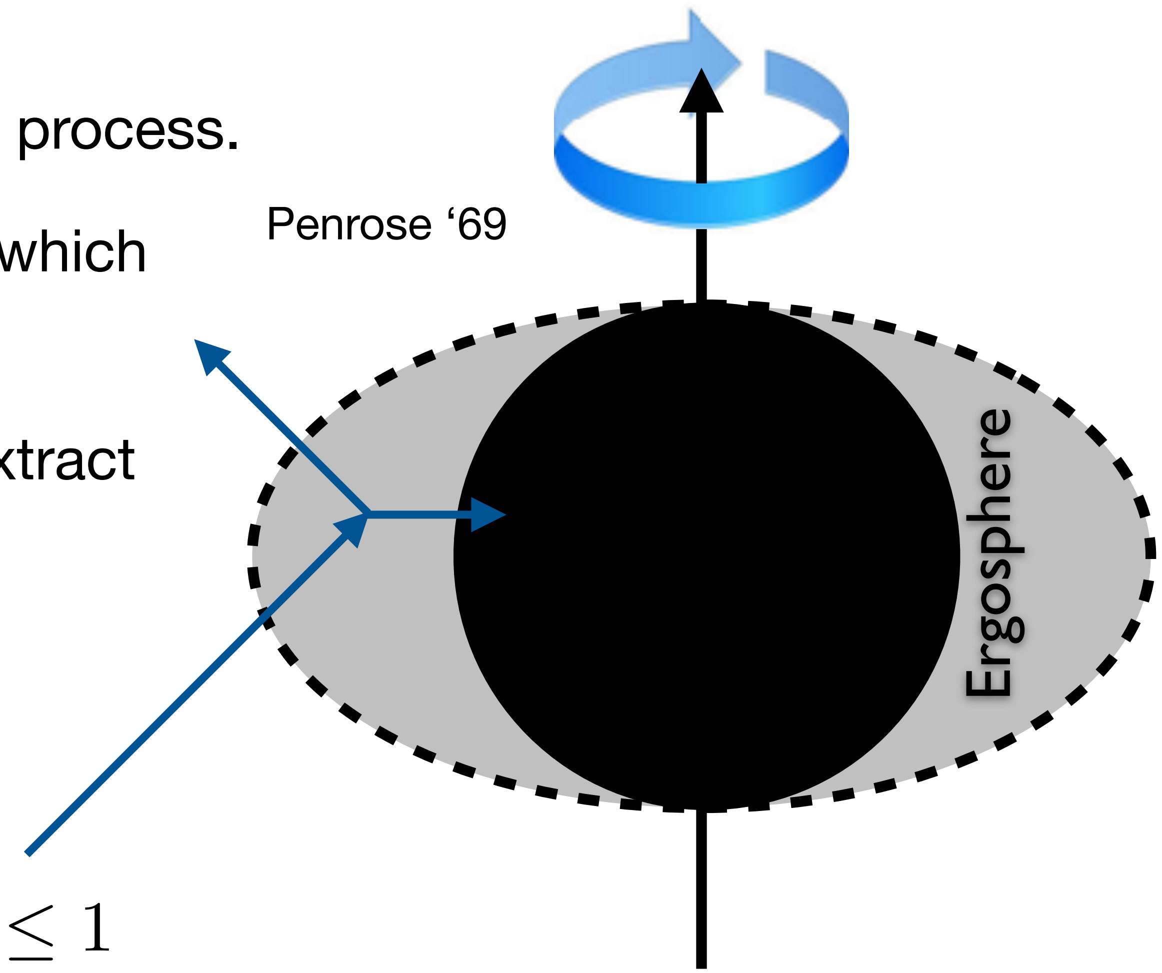

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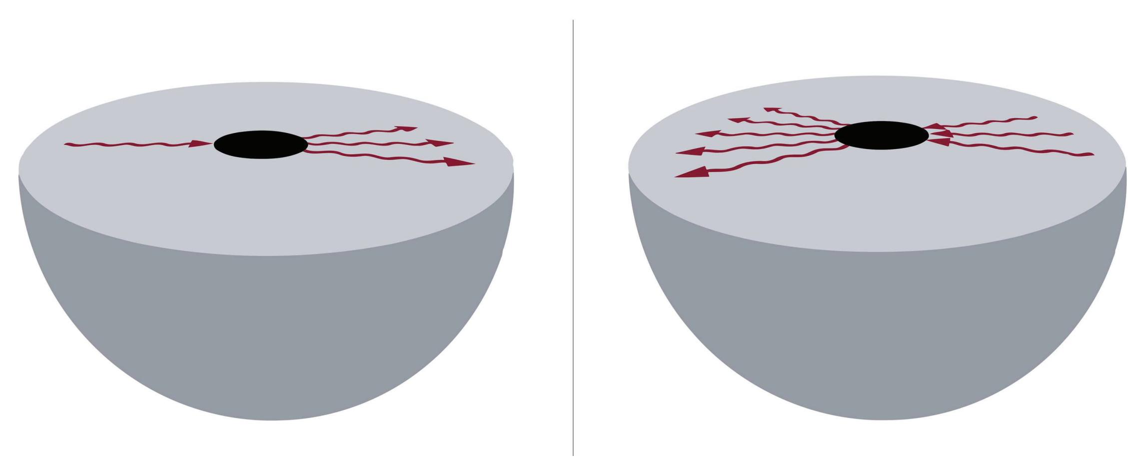
- Very difficult to observe
- If particles (bosons) are confined the process repeats continuously, growing exponentially.



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- Energy level

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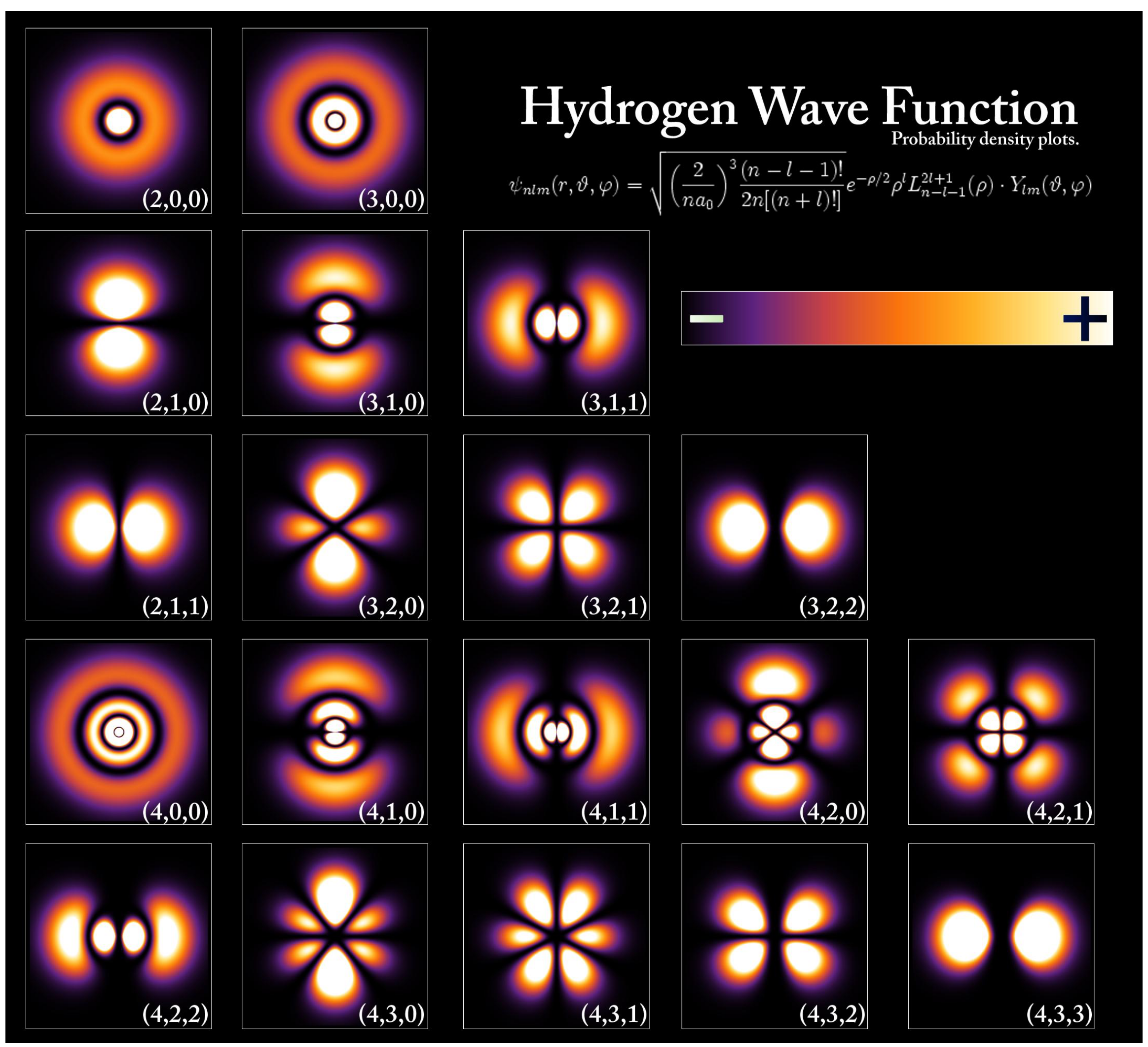


- Particle orbits that satisfy the SR condition are coherently amplified

$$\frac{\alpha}{\ell} \leq \frac{1}{2}$$

- As long as SR condition is satisfied, occupation number grows exponentially

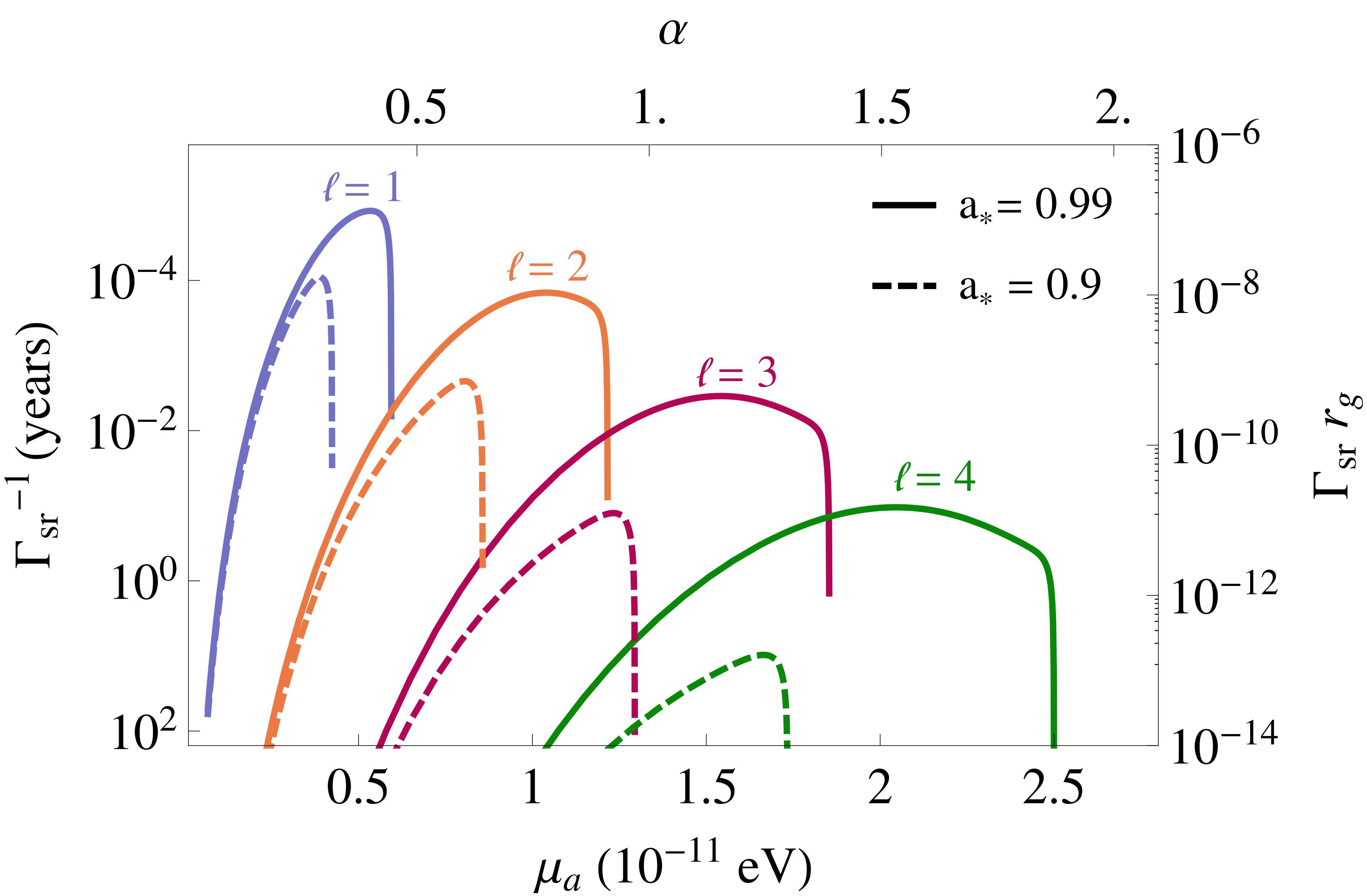
$$\frac{dN}{dt} = \Gamma_{\mathrm{sr}} N$$

$$\Gamma_{\mathrm{sr}} = \mathcal{O}(10^{-7} - 10^{-14}) \mu_a$$

Superradiant rate

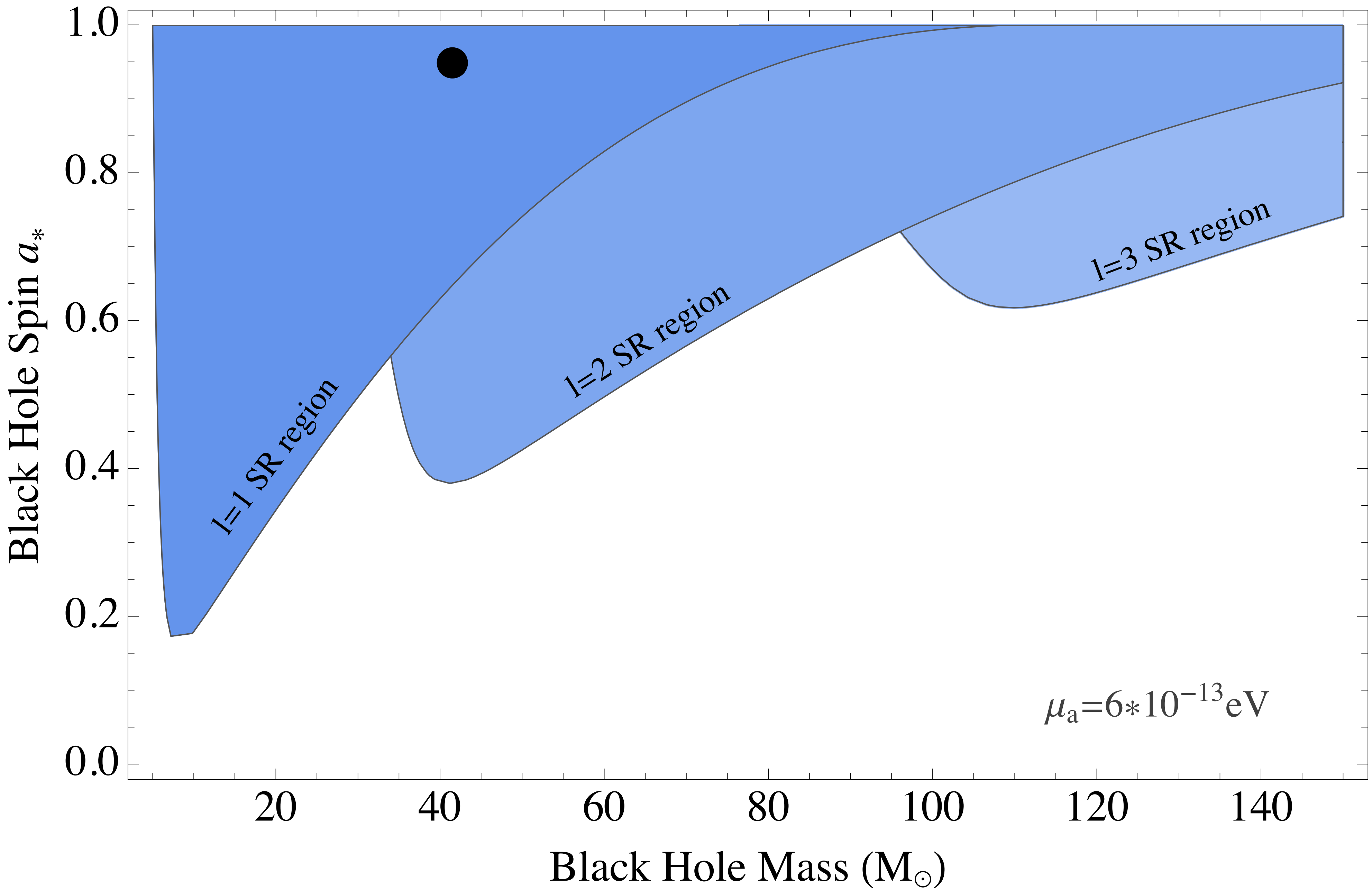
- Superradiance times for the levels l=1 to 4, for m=l and n=l+1, for a BH of mass 10 $M_\odot$.

Arvanitaki, Baryakhtar and Huang '14



Black hole spin decay

- Black hole spin-mass plane.
- Absence of rapidly rotating BH is signal that superradiance has taken place.



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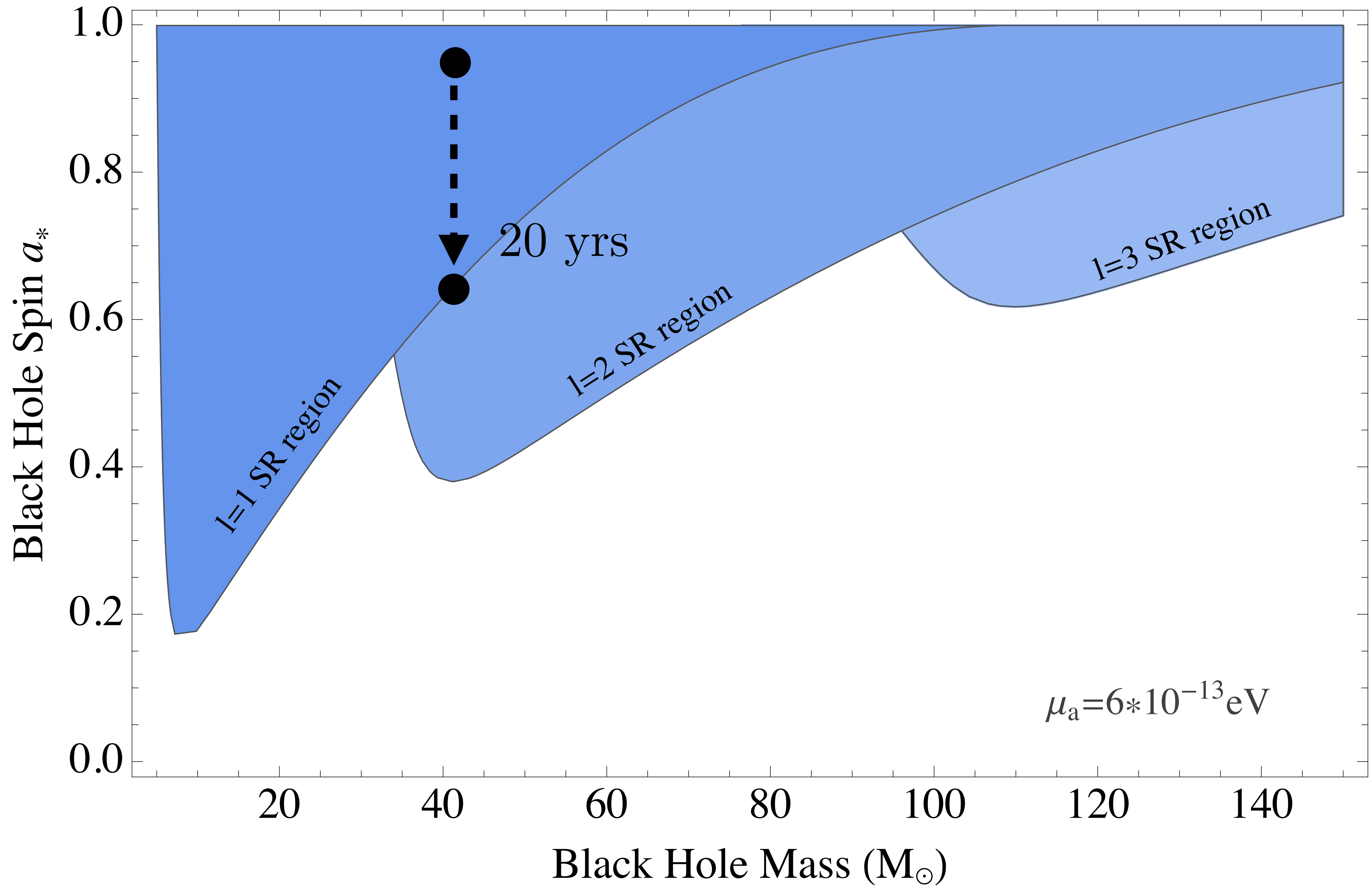

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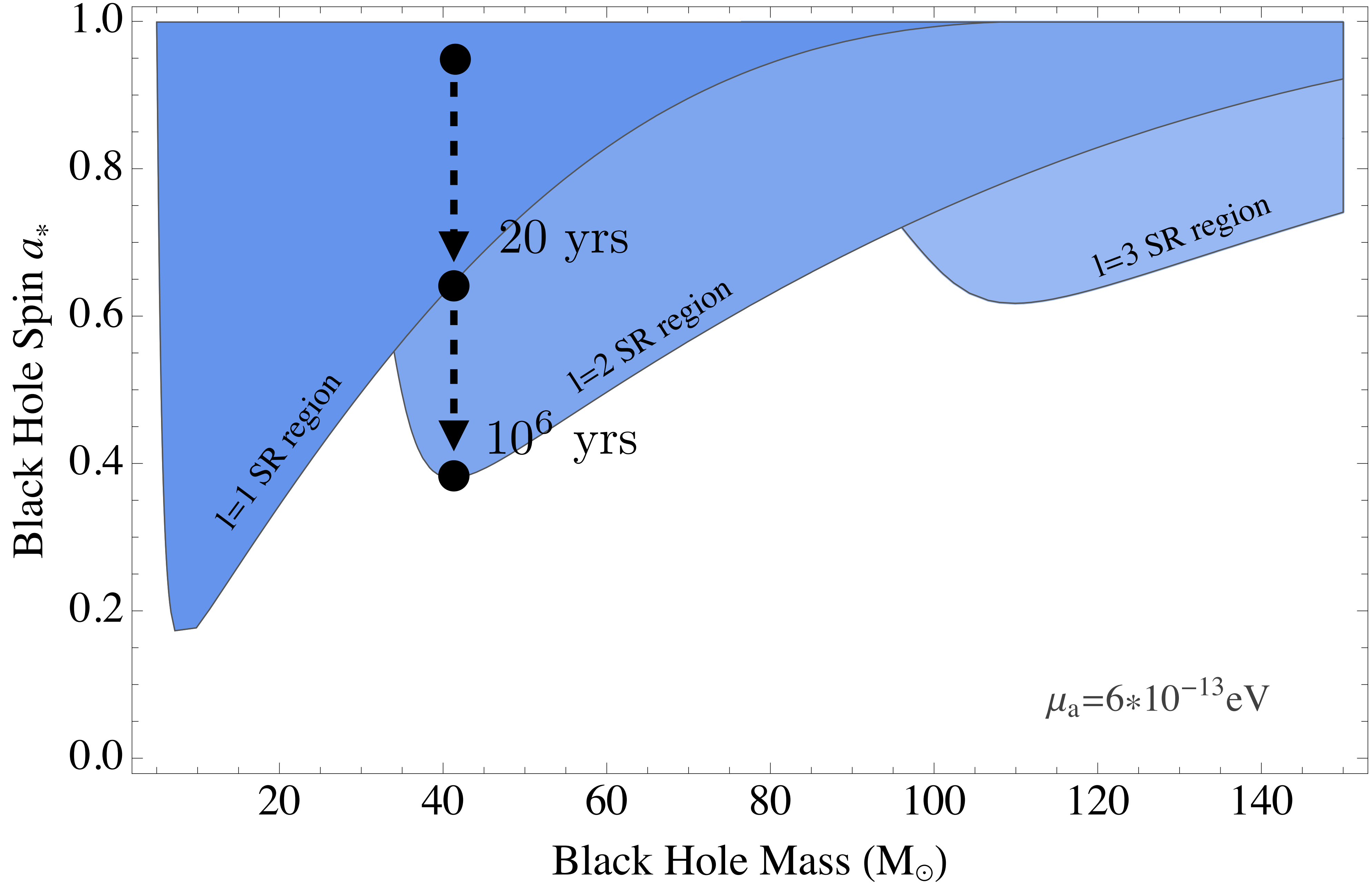
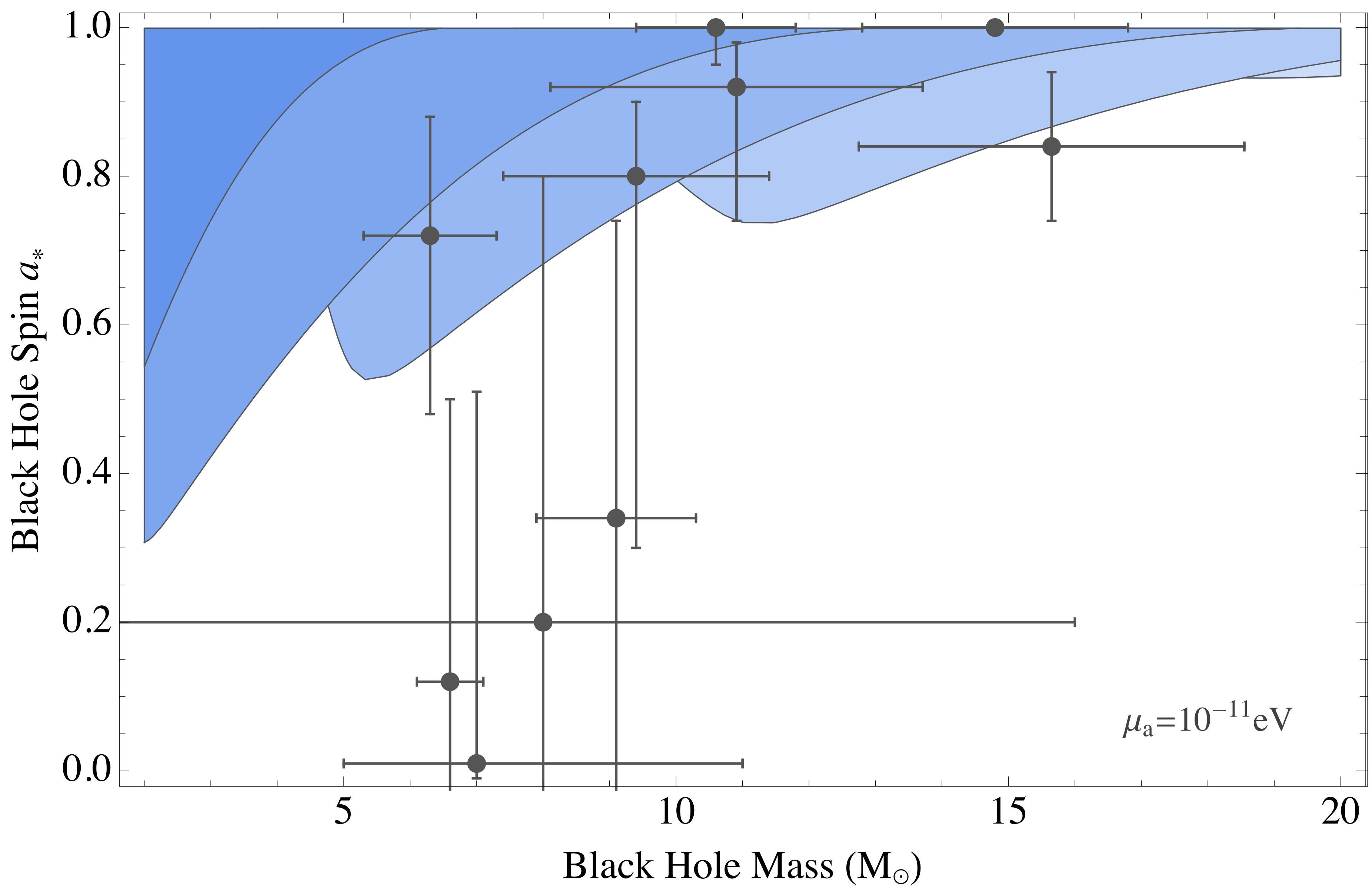


Black hole spin from X-ray

- BH measurements of spin and BH masse in X-ray binaries.

Arvanitaki, Baryakhtar and Huang '14

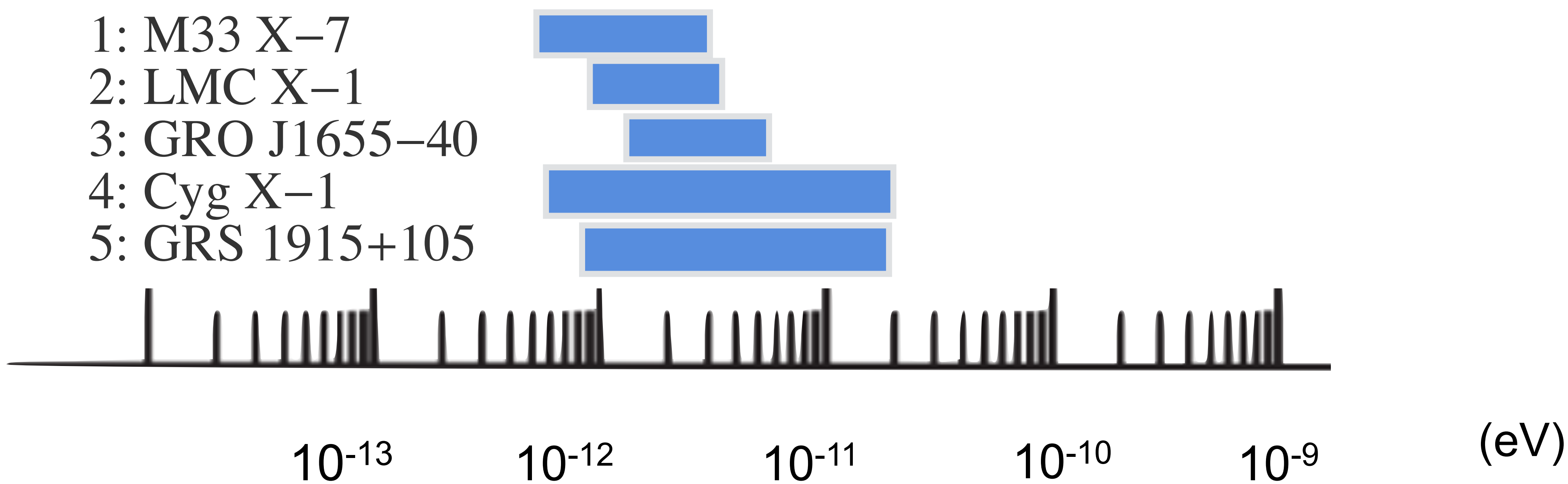


Black hole spin from X-ray

- High-spin measurements disfavor an axion with mass

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

Arvanitaki, Baryakhtar and Huang '14



- The exclusion of these parameter space has not been reached by other approaches.

LIGO and Virgo

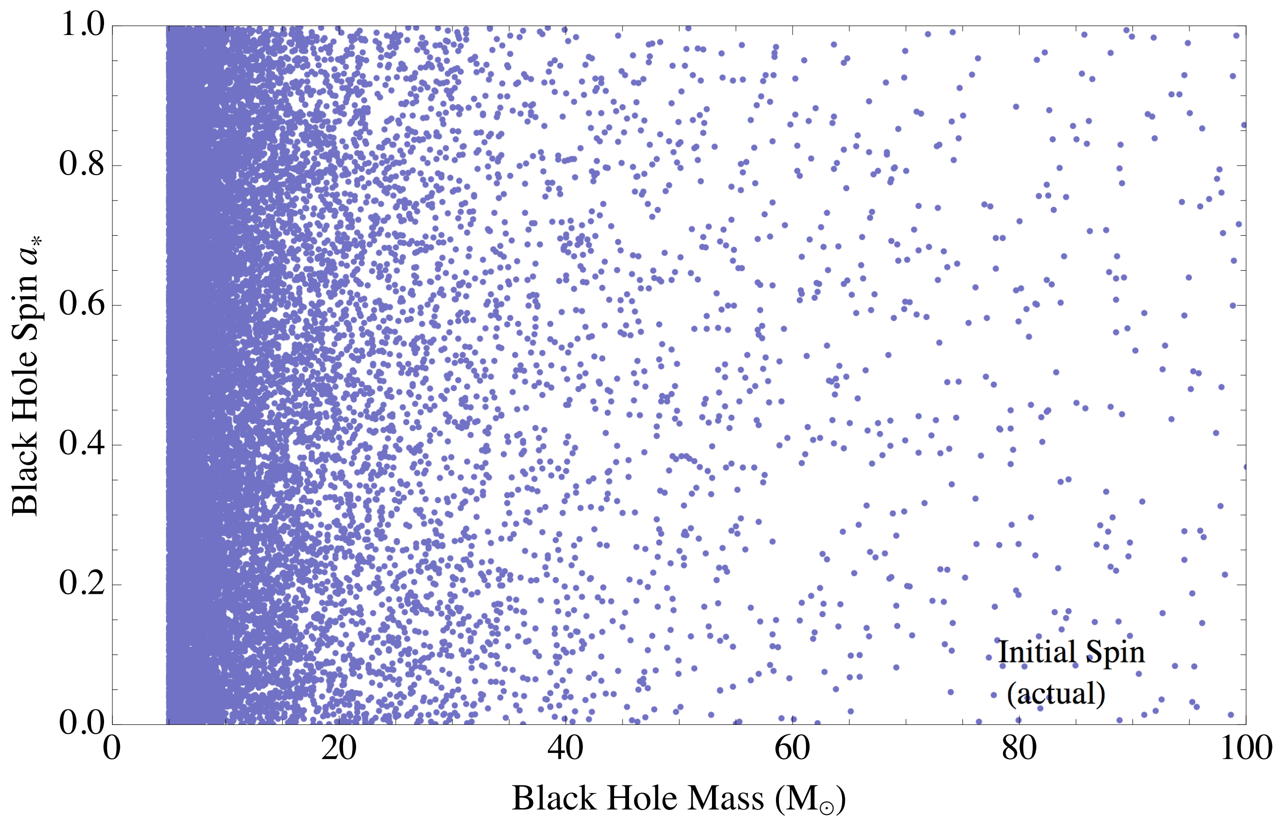
- Expected detection of 40-1500 merger events per year and measure masses and spin.

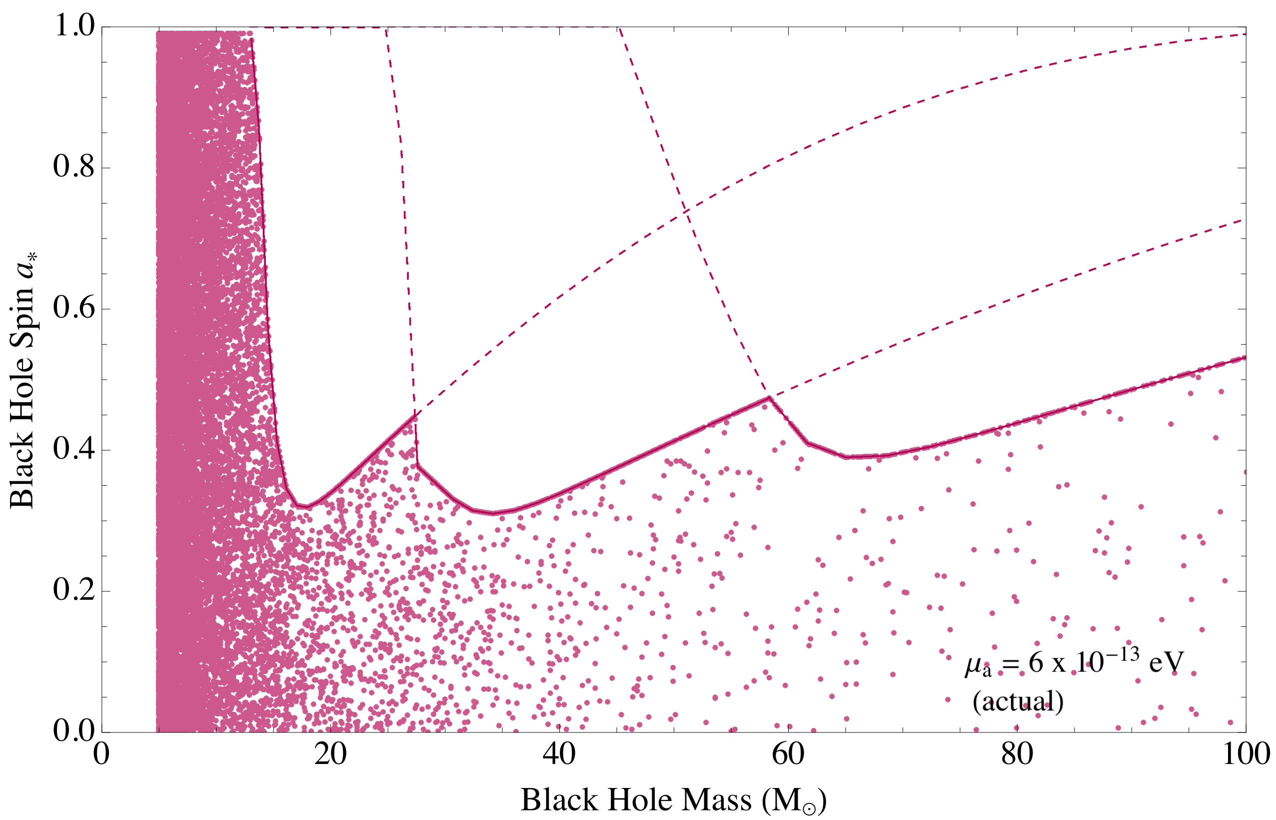
- Example: the final BH from GW150914 has a spin of $0.67^{+0.05}_{-0.07}$ and mass of $61.8^{+4.2}_{-3.5} M_{\odot}$

LIGO ‘16

Expected black hole spin

- Expected distribution of intrinsic spins and masses of merging BHs in the absence (right) and presence (left) of an axion. Flat spin distribution and power-law BH mass. Normalized at 1000 events in LIGO.

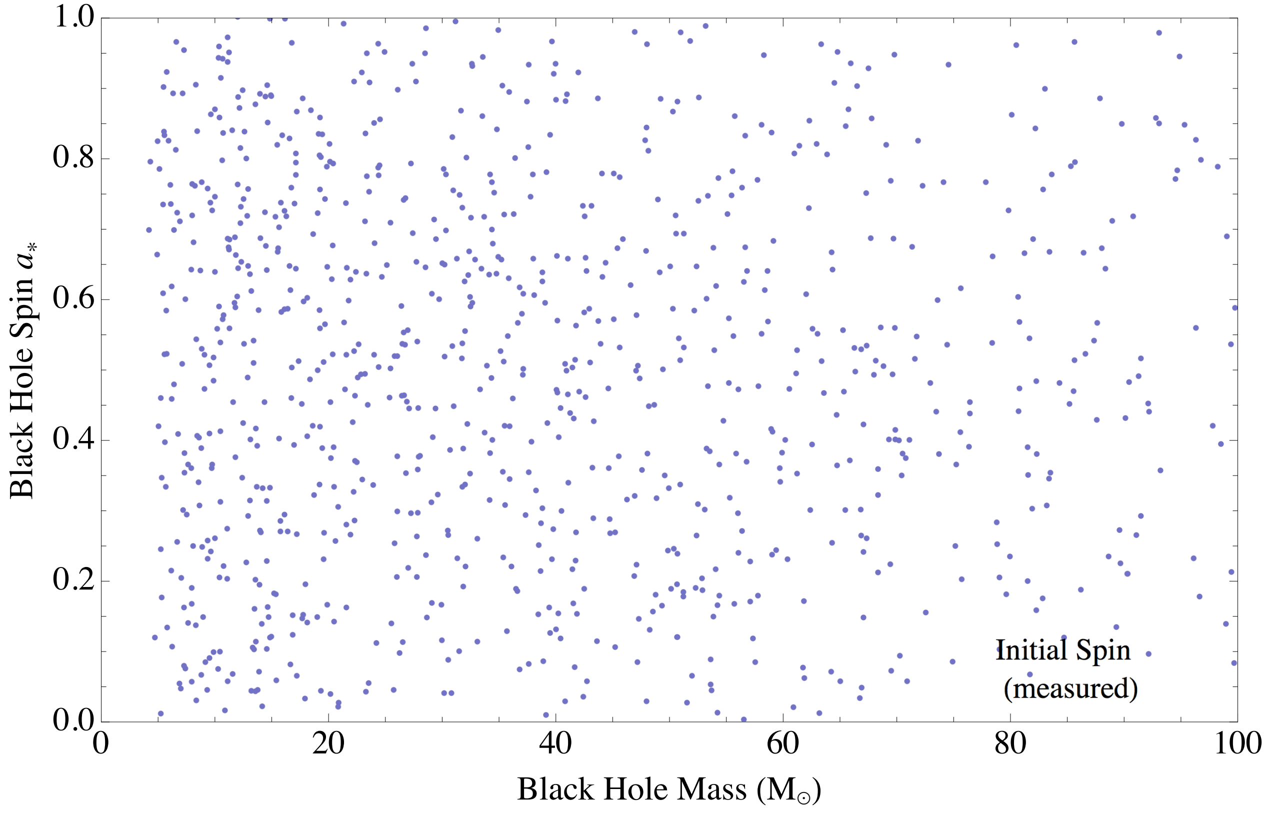


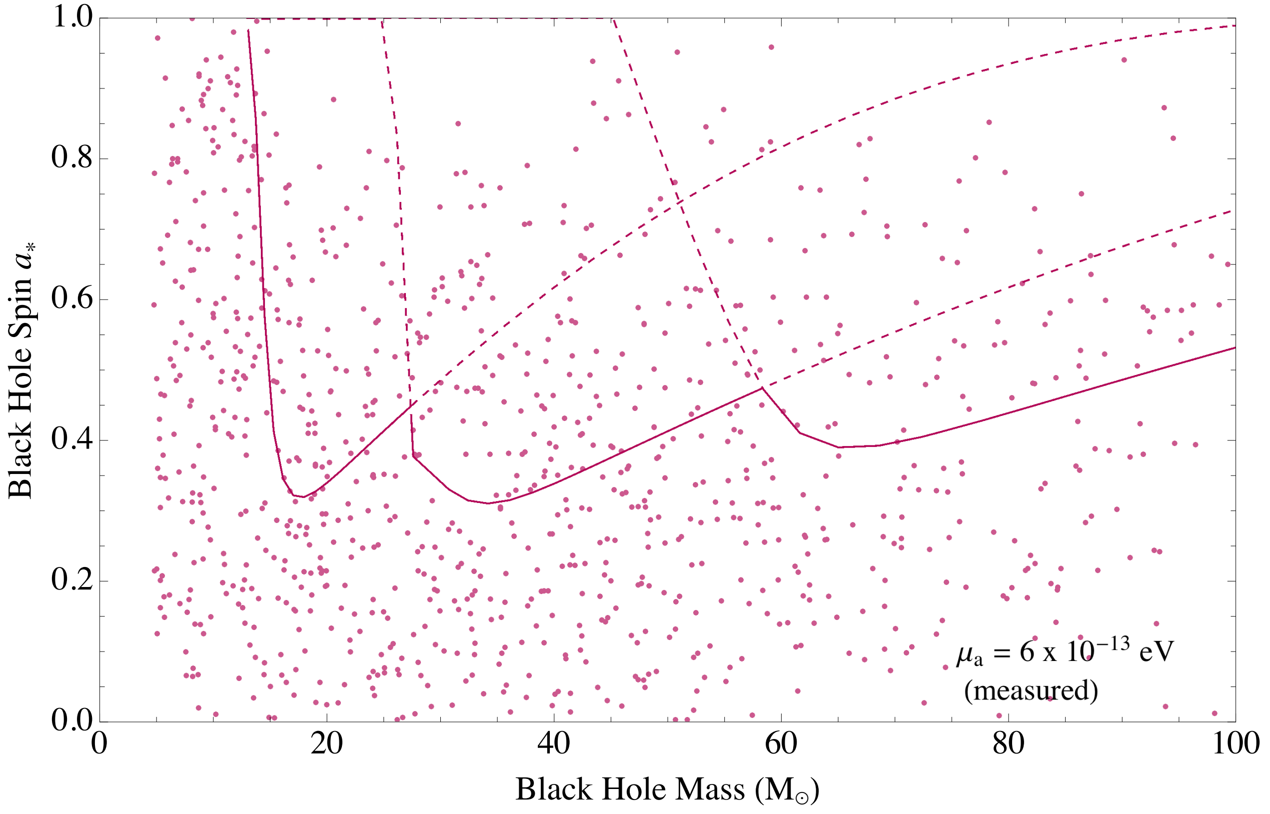


- The theoretical curve assume that BBHs take a Hubble time to merge into account

Measured black hole spin

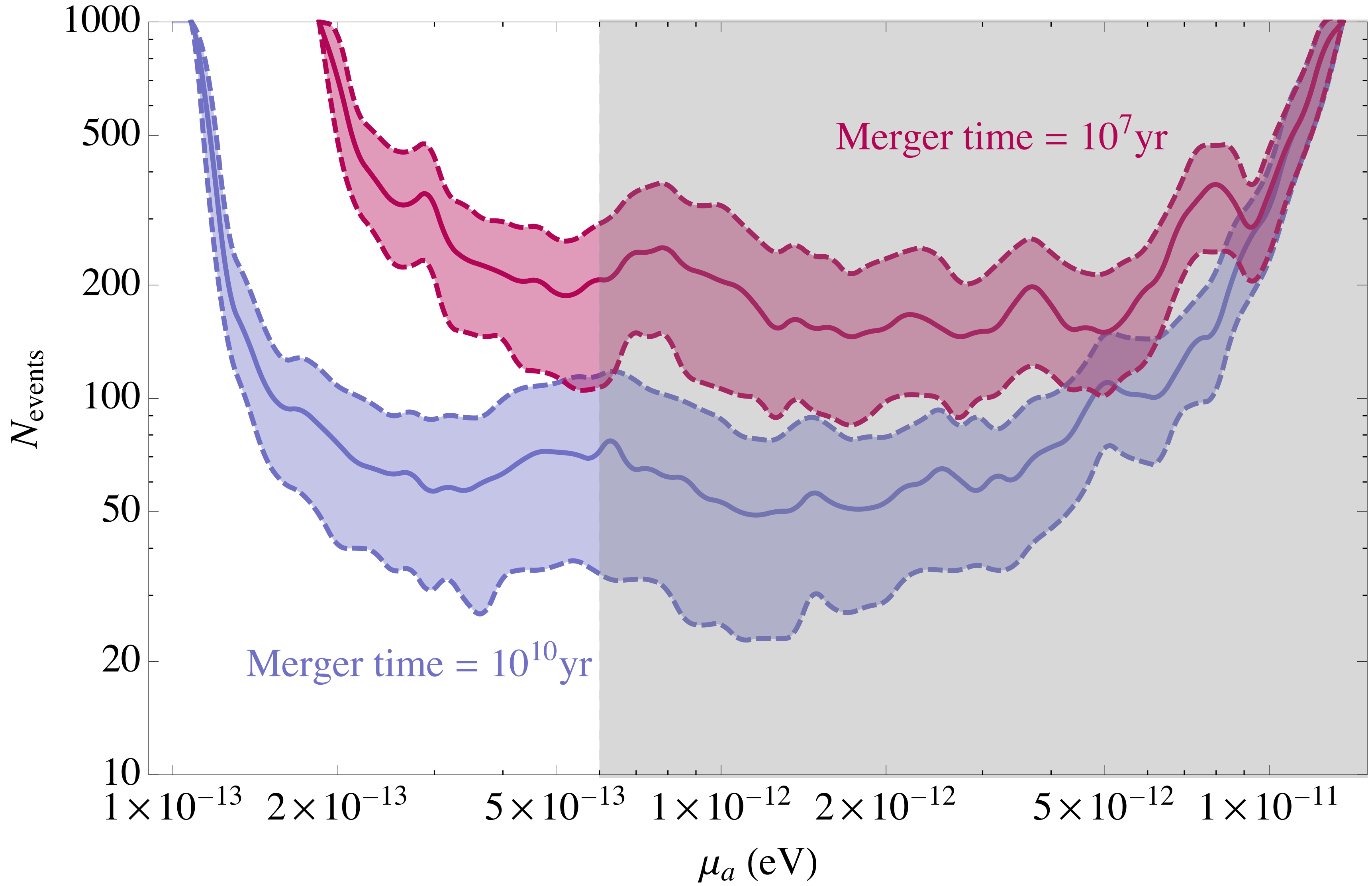
- Measured distribution of intrinsic spins and masses of merging BHs, 10% measurement error in the mass and 0.25 in the spin. Flat spin distribution and power-law BH mass. Normalized at 1000 events in LIGO.





Required events

- Number of observed events required to show (at 2σ) that the BH spin distribution varies with the BH mass as predicted by superradiance.

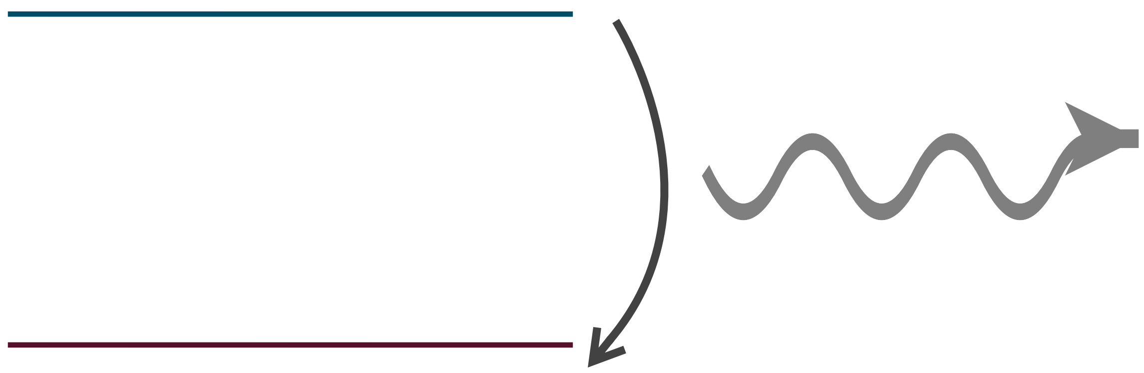


- If merger time is long, few tens of events may be enough.

Gravitational waves signal

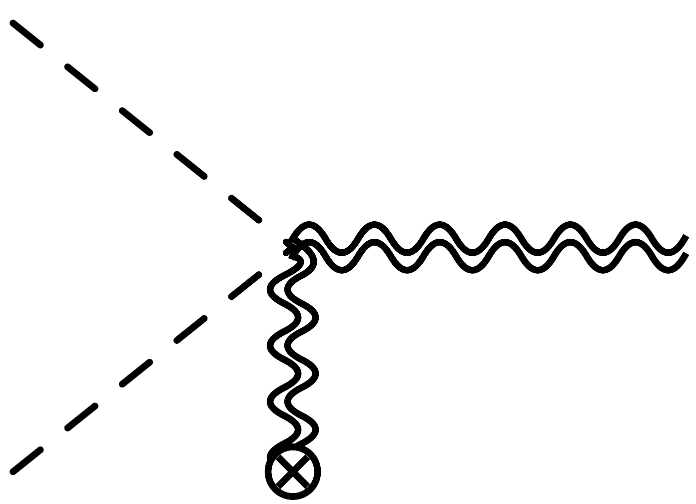
- Monochromatic gravitational waves can be produced due to:

1) Axion transition between levels:



$$f \sim 15 \text{ Hz} \times (\mu_a / 10^{-11} \text{ eV})$$

2) Axion annihilation:

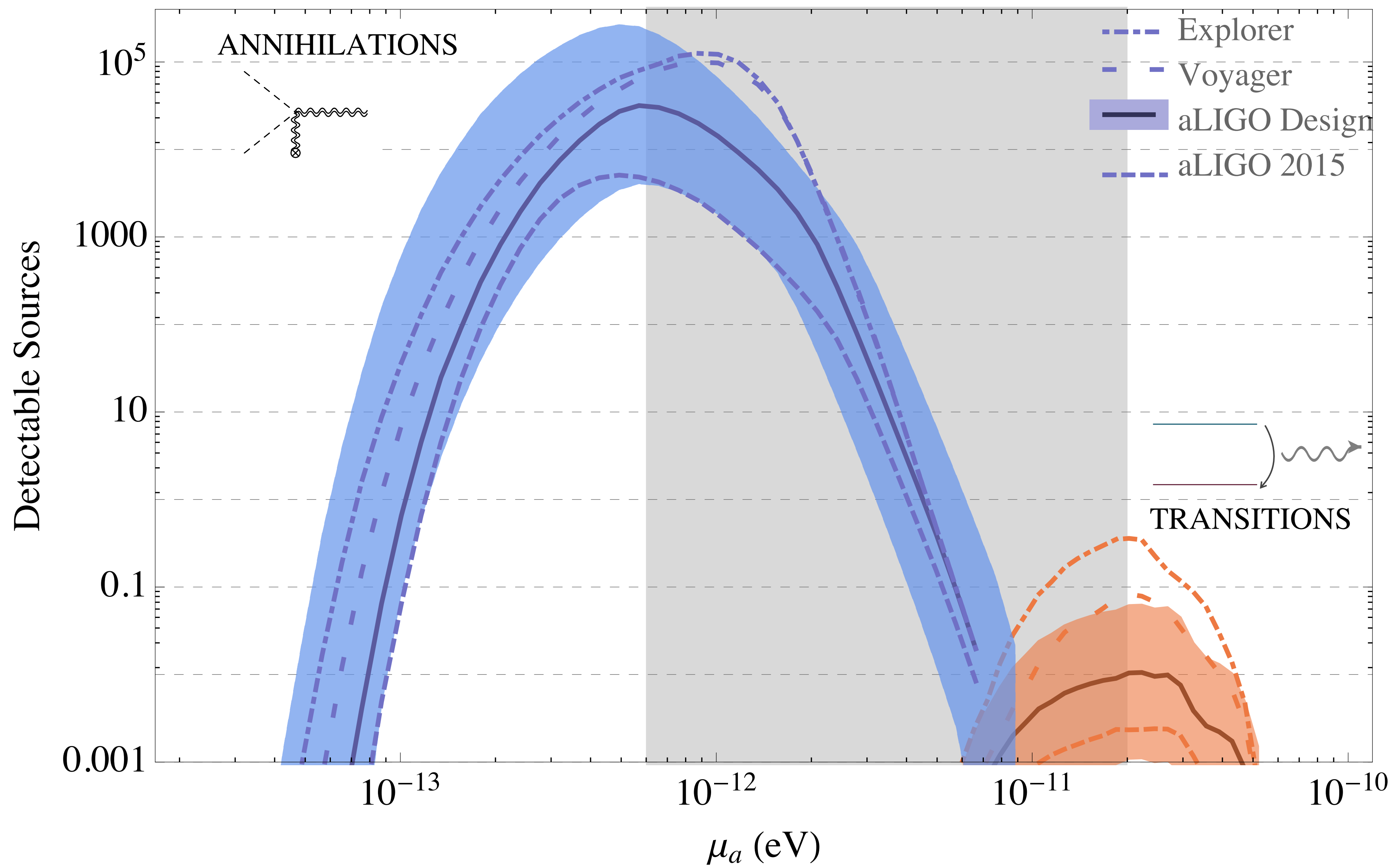


$$f = 10 \text{ kHz} \times (\mu_a / 10^{-11} \text{ eV})$$

- These GW are expected to be monochromatic within a ~3% frequency range, thus distinguishable from other GW of astrophysical sources. Unique signal.

Transition and annihilation

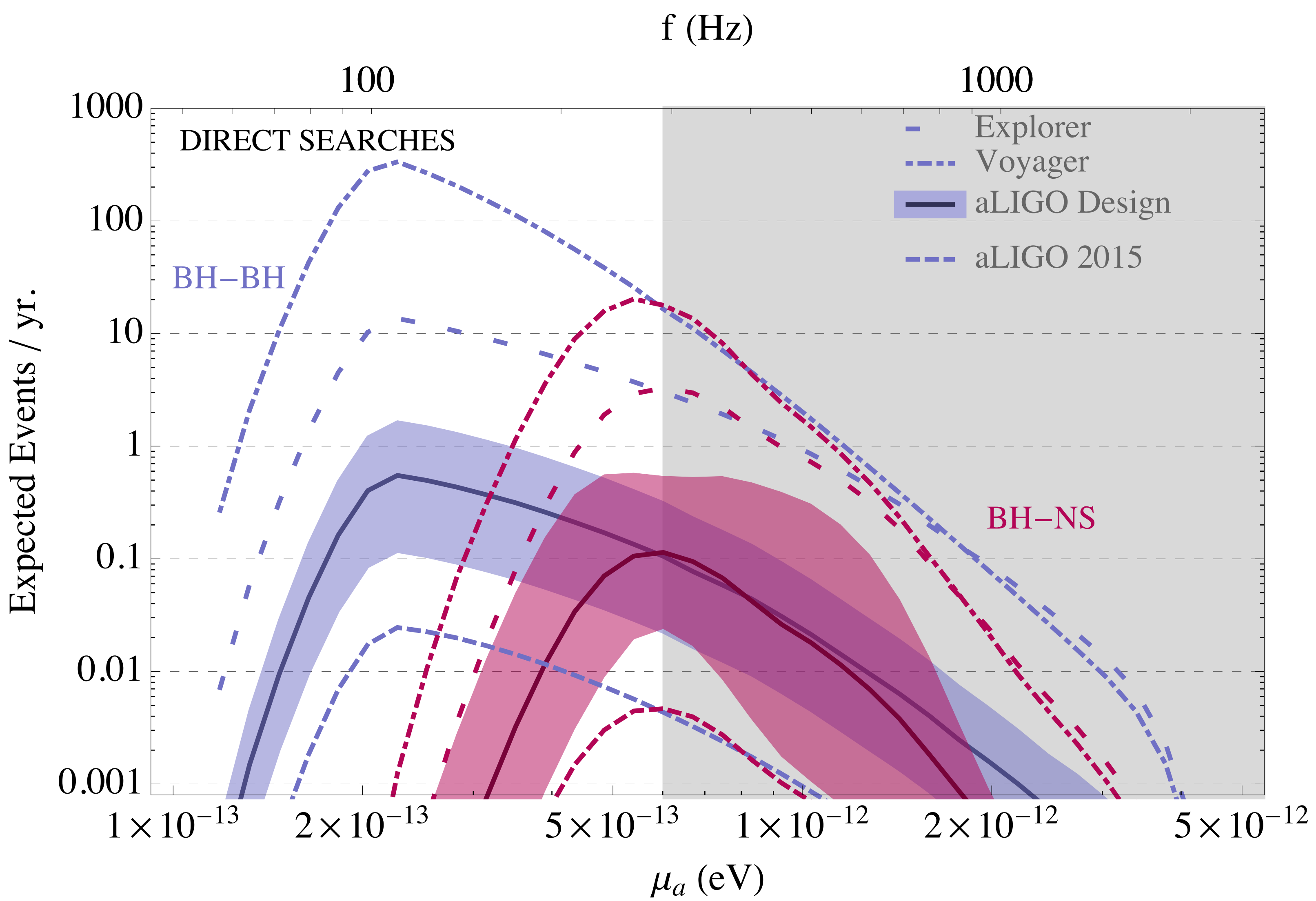
- Transitions: Uncertainty dominated by BH formation rate and spin distribution. Less sensitive to mass distribution
- Annihilation: Uncertainty dominated by BH mass distribution for large BH masses.



- Coherent integration time of 2 days, total integration time 1 year.

Correlating searches

- After a merger at LIGO one can follow-up with continuous wave search to look for superradiant axion growth. More promising for future GW observatories
- Impossible for transition; very long time to populate the levels giving appreciable signal.
- Expected annihilation events by BBH or BH-NS merger products per year.



- Coherent integration time of 10 days for BBH and 1 year for BH-NS.

Conclusions

* Ultra light axions can be probed by astrophysical BHs
* Mechanism applies to other scalar (boson) particles: not necessarily QCD axions, not necessarily DM.
* Advanced LIGO may measure thousands of BH spins and provide evidence of a new particle
* Monochromatic GW signals may be observable from transition and annihilation of axions
* May observe the growth of gravitational atoms in real time after a BBH/ BH-NS merger

Sensitivities