Superradiance and Black Holes

or

How to Extract Energy from Black Holes and Discover New Particles

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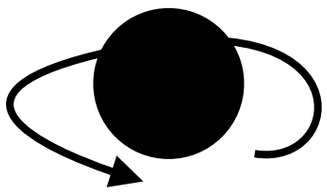
July 13, 2018

Outline

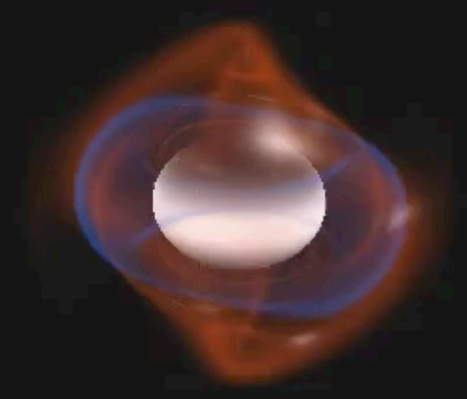
- Superradiance and rotating BHs

- Gravitational Atoms
- Signs of New Particles
  - Black Hole Spindown



  - GW signals

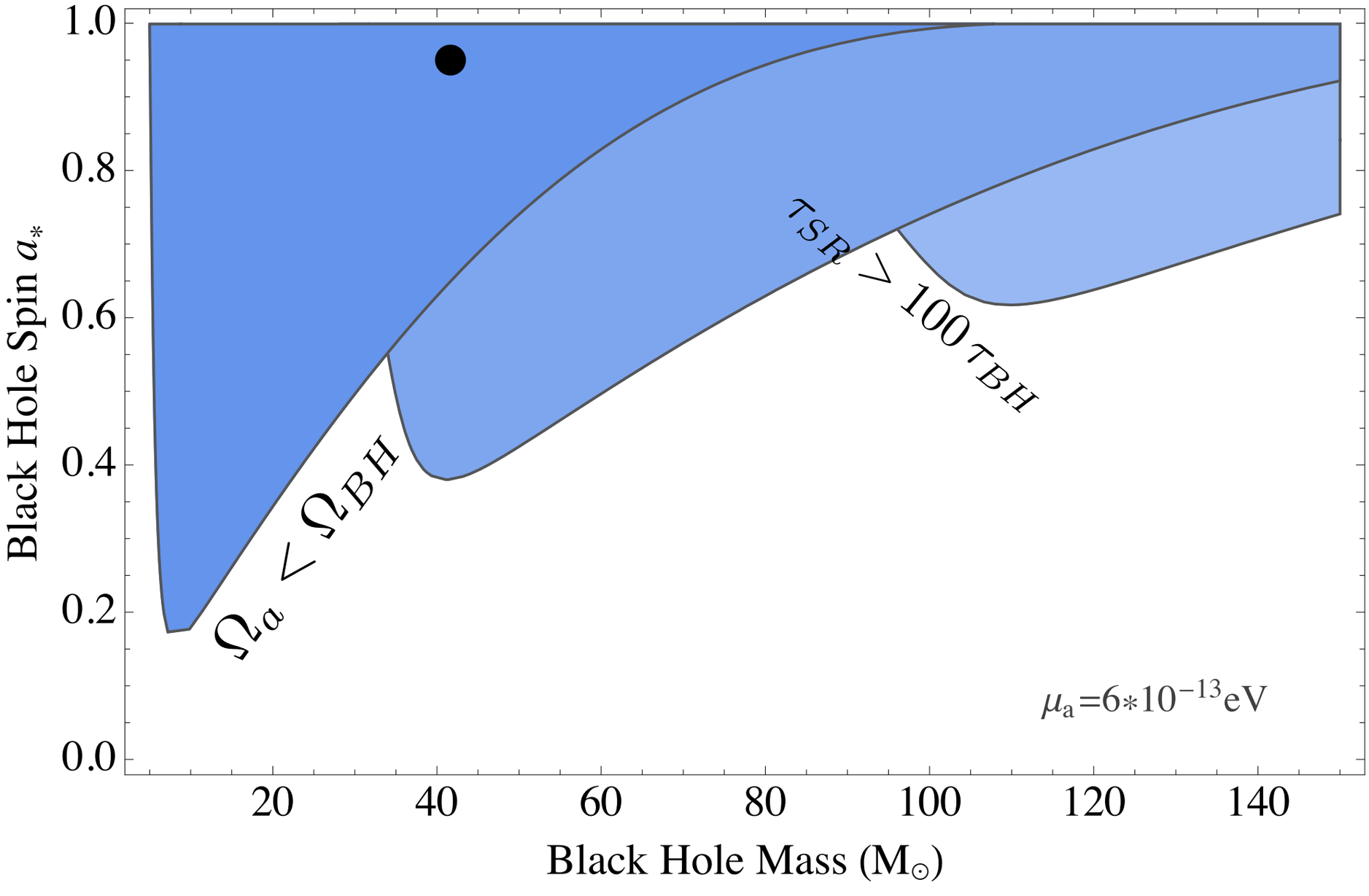
Superradiance and rotating Black Holes



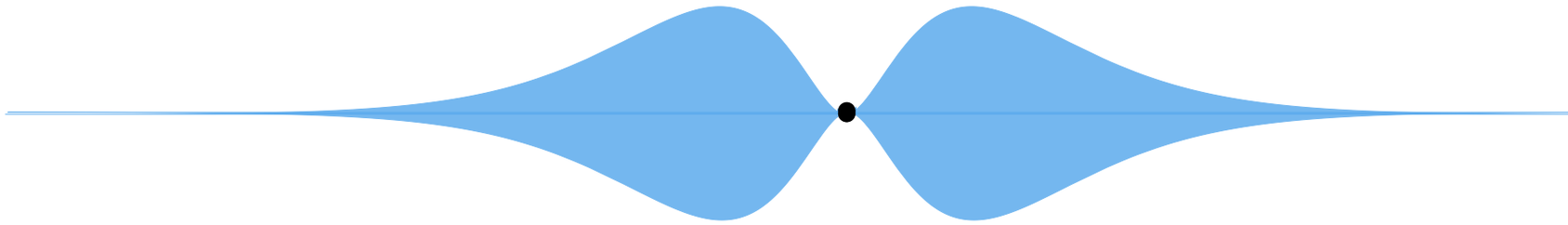
Will East, Superradiant Amplification of Gravitational Waves on a Kerr BH

Superradiance: a stellar black hole history

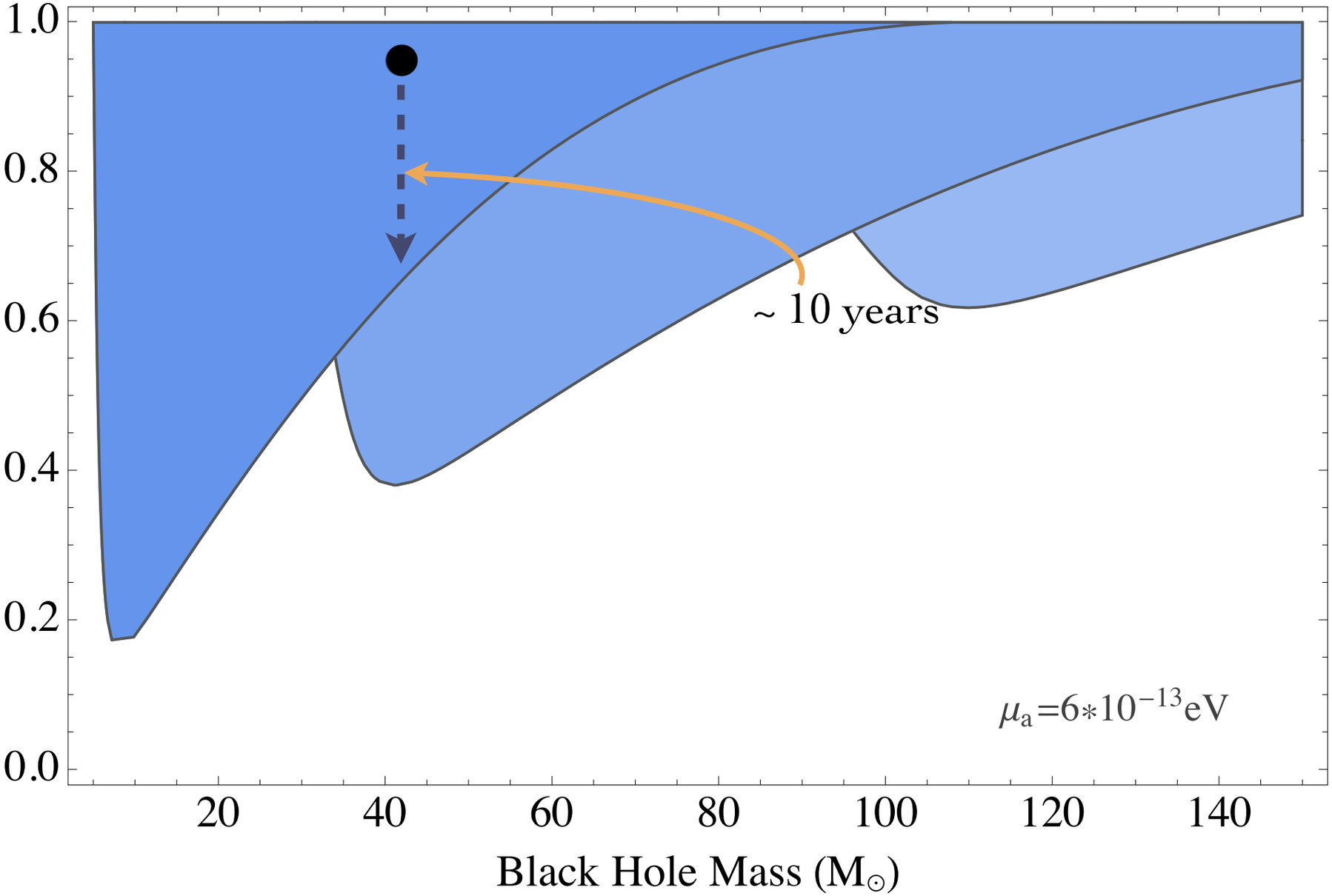
A black hole is born with spin $a_* = 0.95$, $M = 40\ M_\odot$.



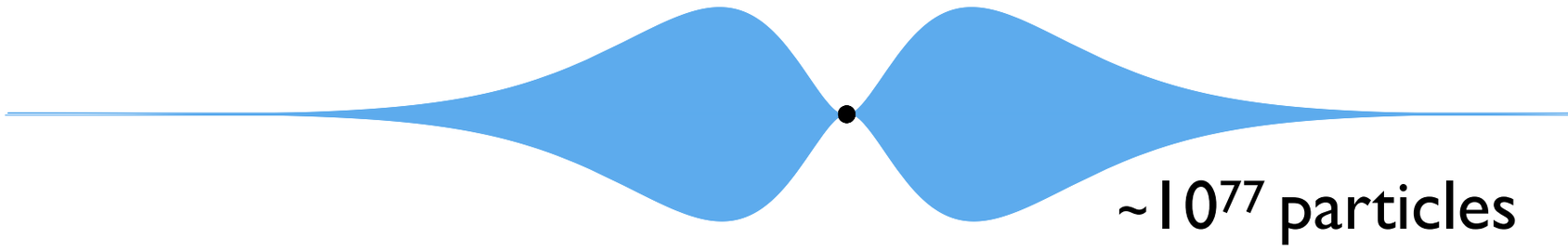
Superradiance: a stellar black hole history



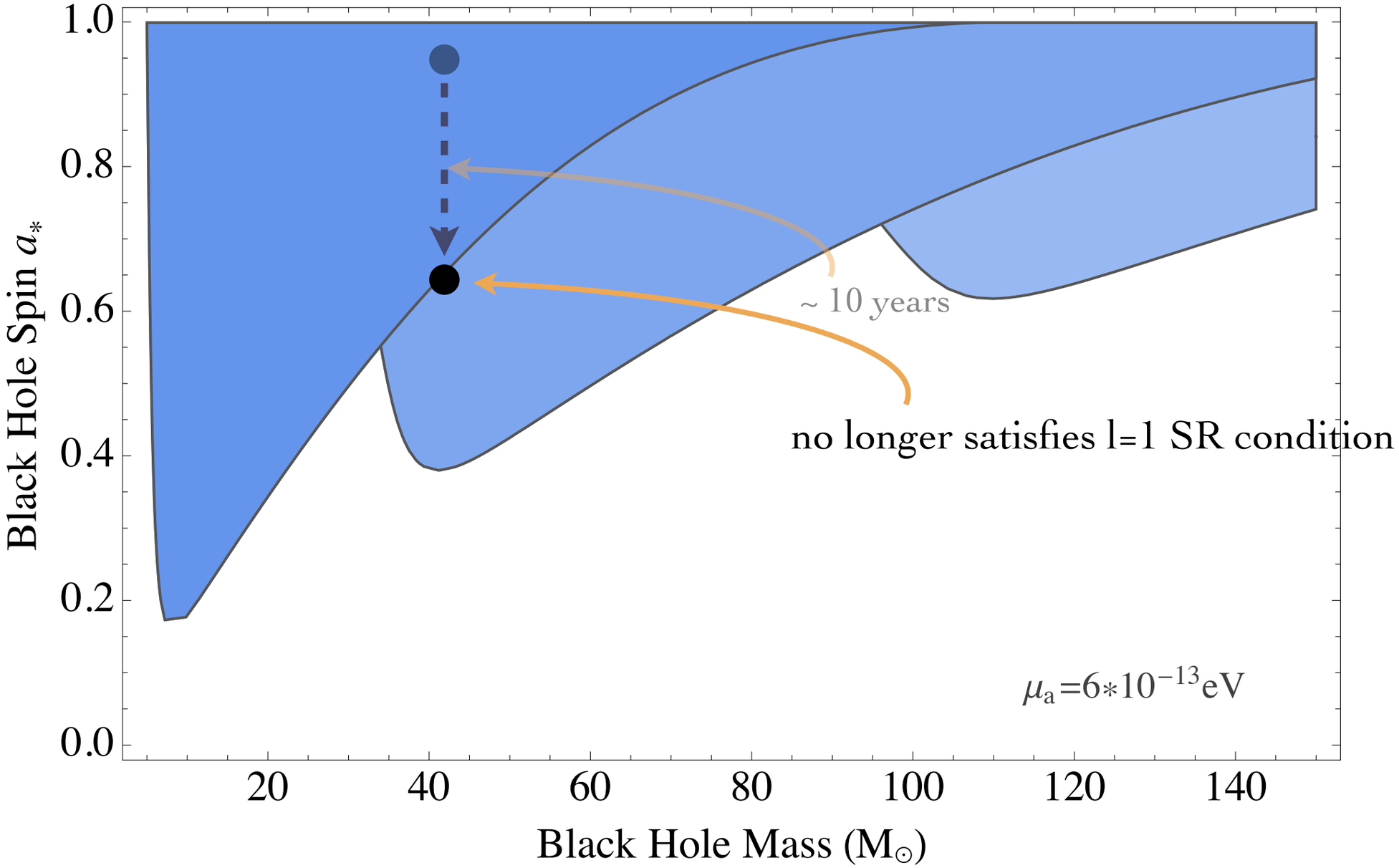
BH spins down and *fastest-growing* level is formed



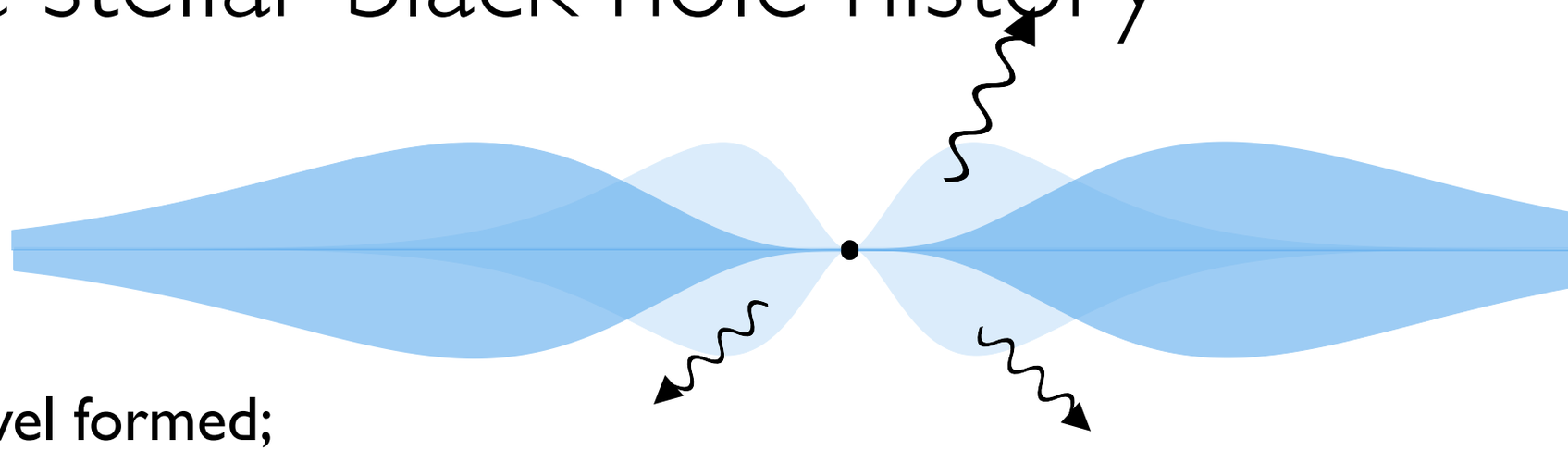
Superradiance: a stellar black hole history



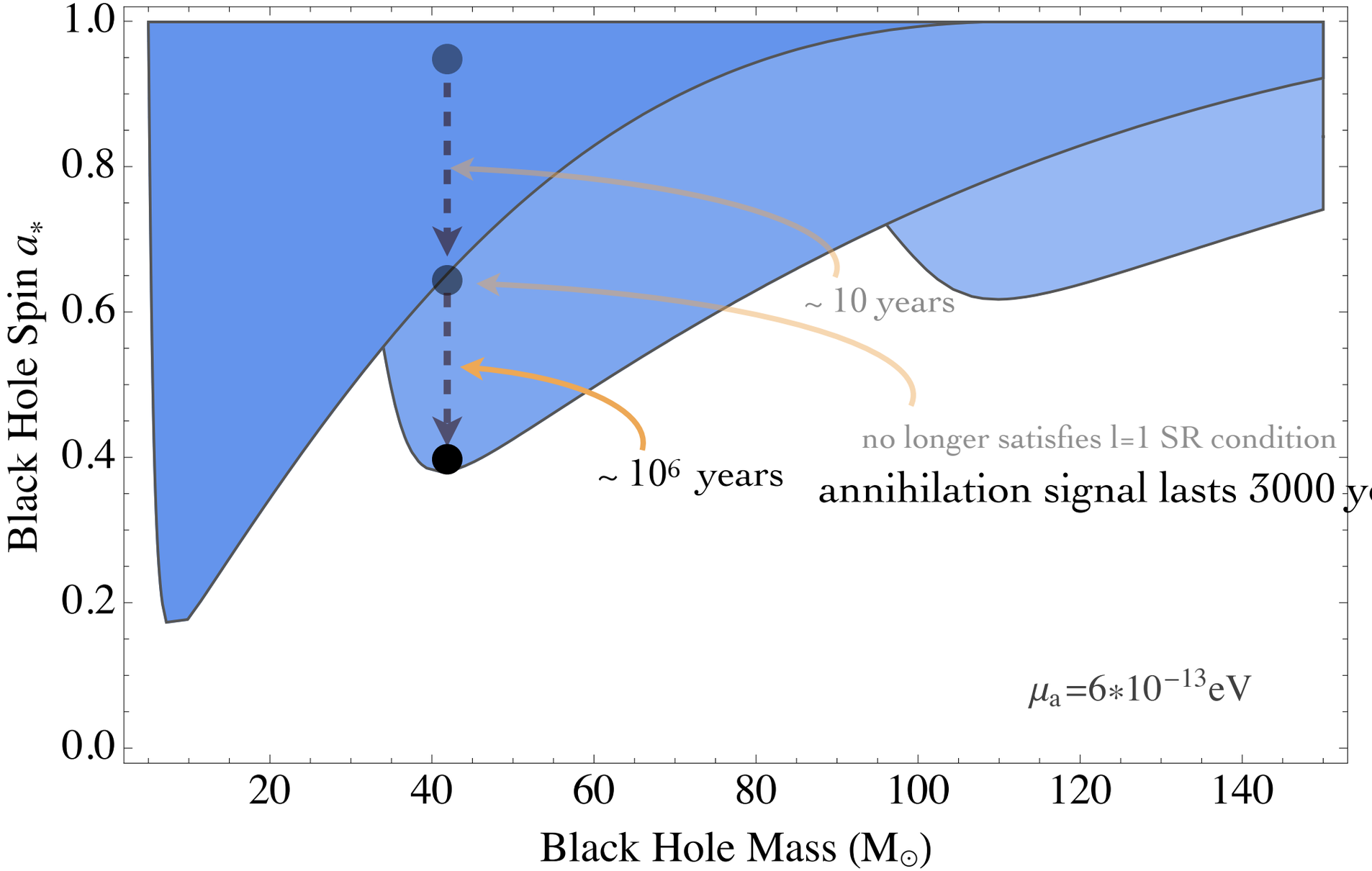
Once BH angular velocity matches that of the level, growth stops



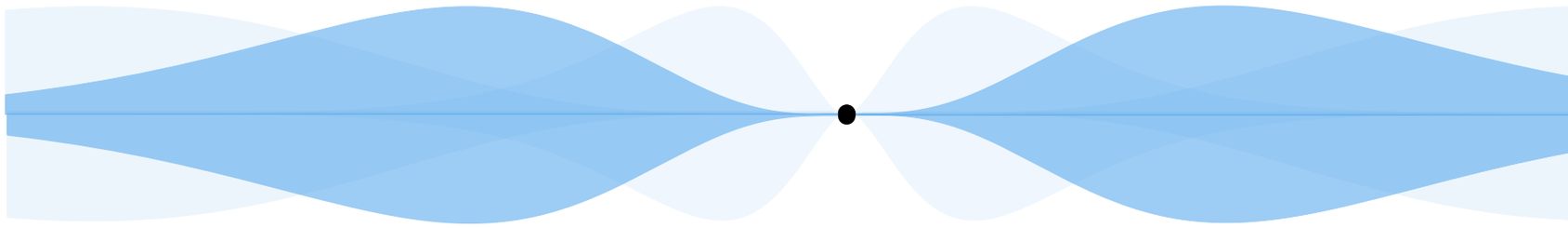
Superradiance: a stellar black hole history



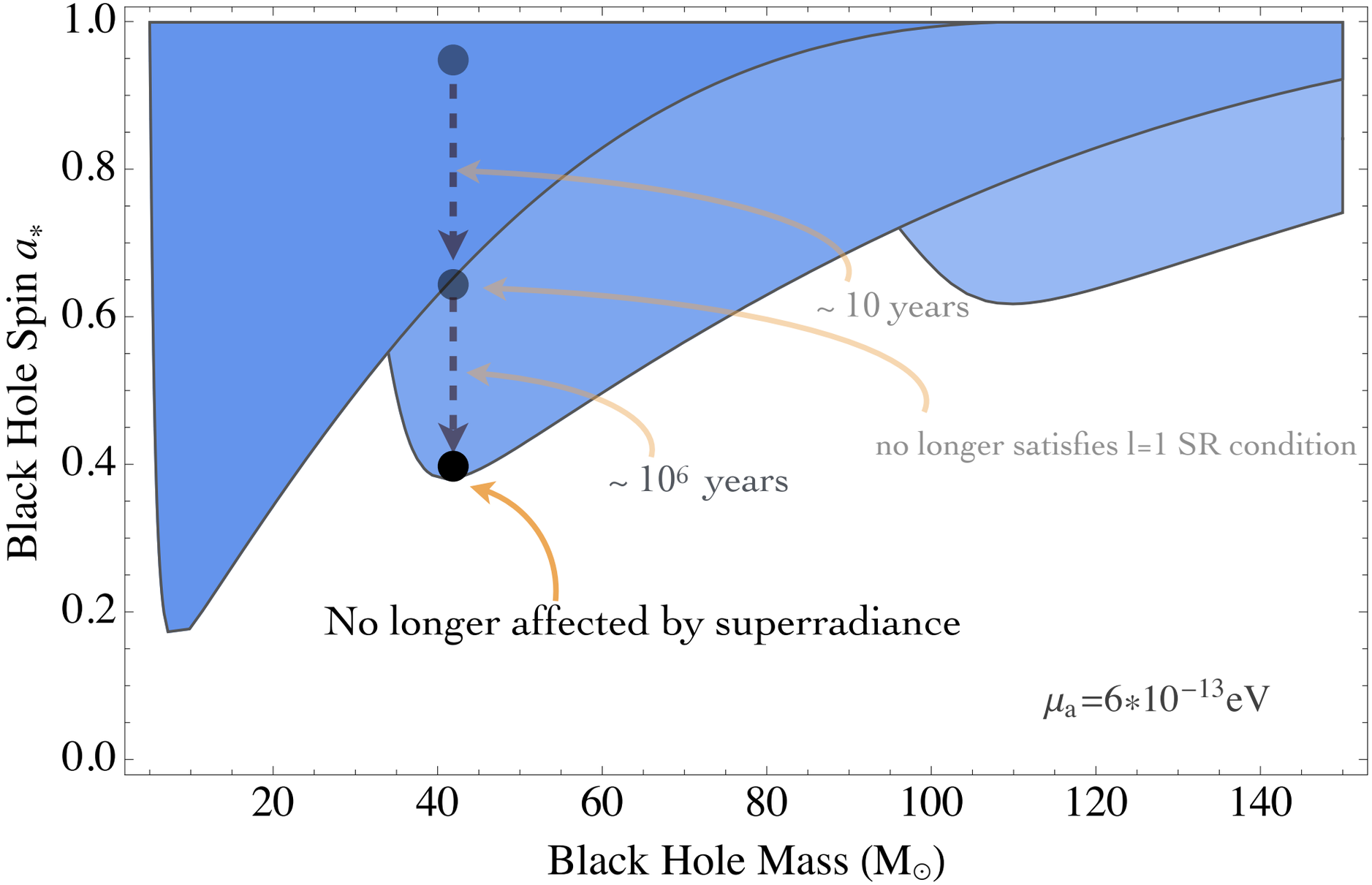
BH spins down and *next* level formed;
annihilations to GWs deplete first level



Superradiance: a stellar black hole history

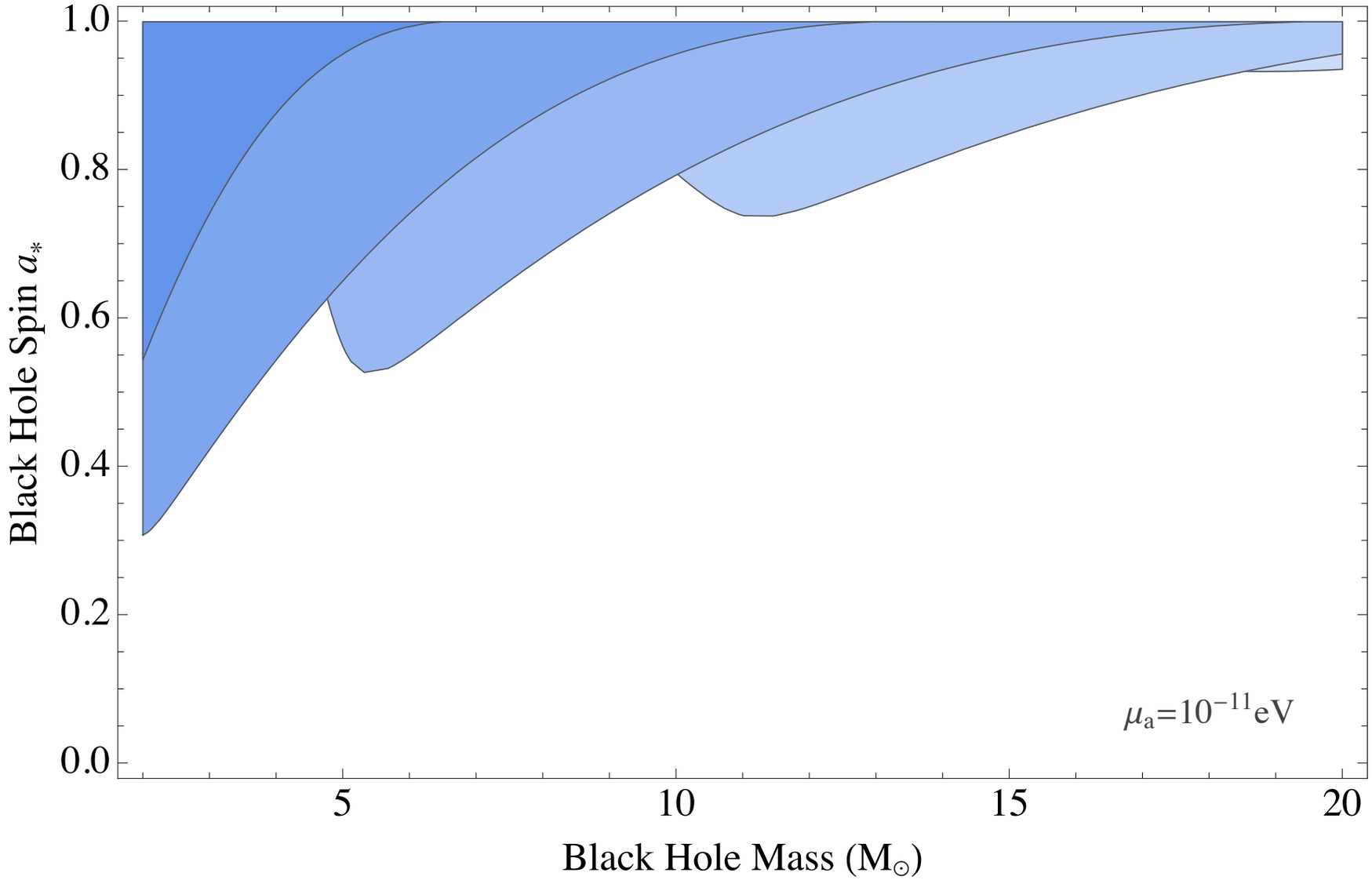


The following level has a superradiance rate exceeding age of BH



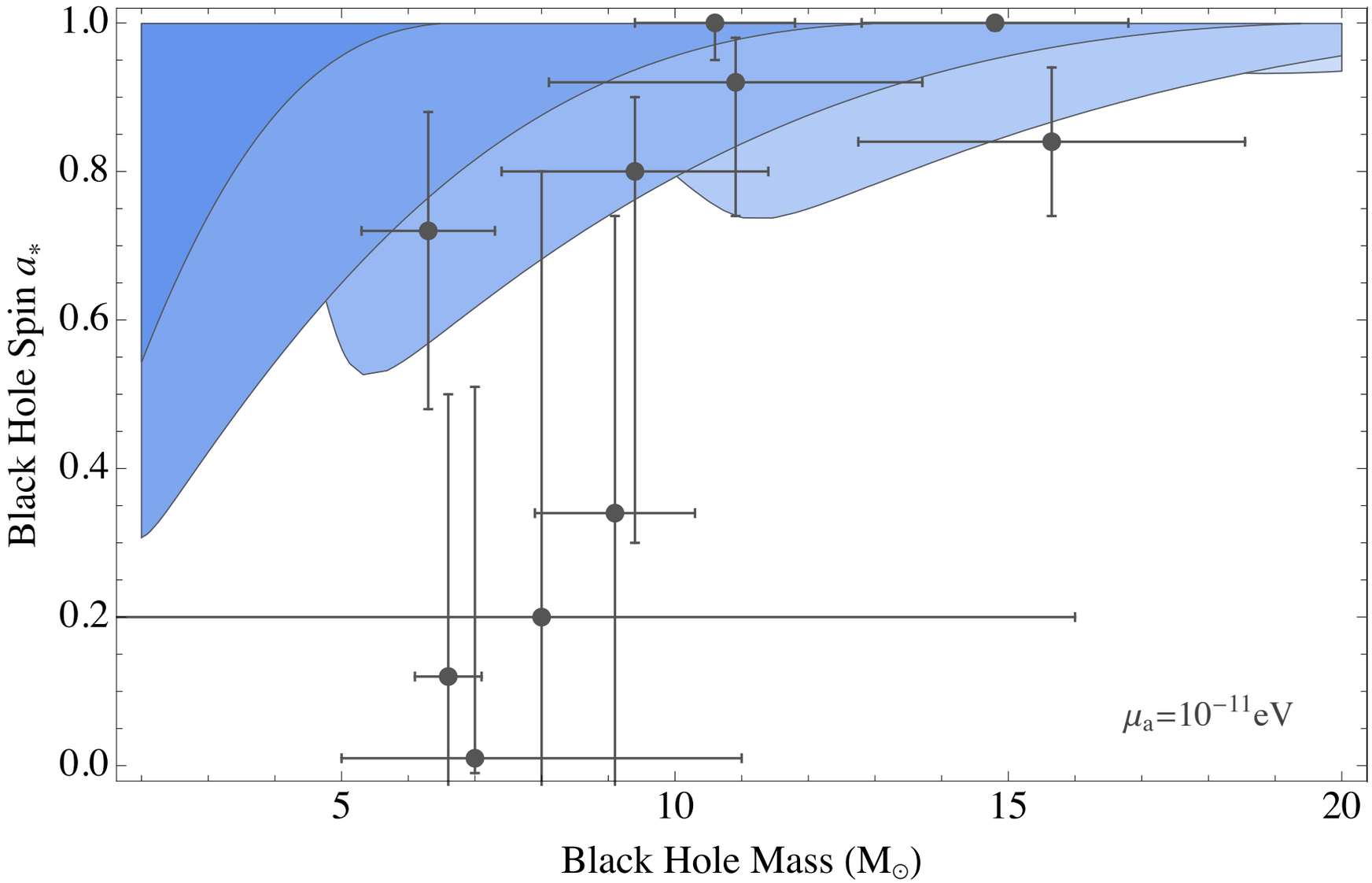
Black Hole Spins

Black hole parameter space affected by superradiance of 10^{-11} eV axion



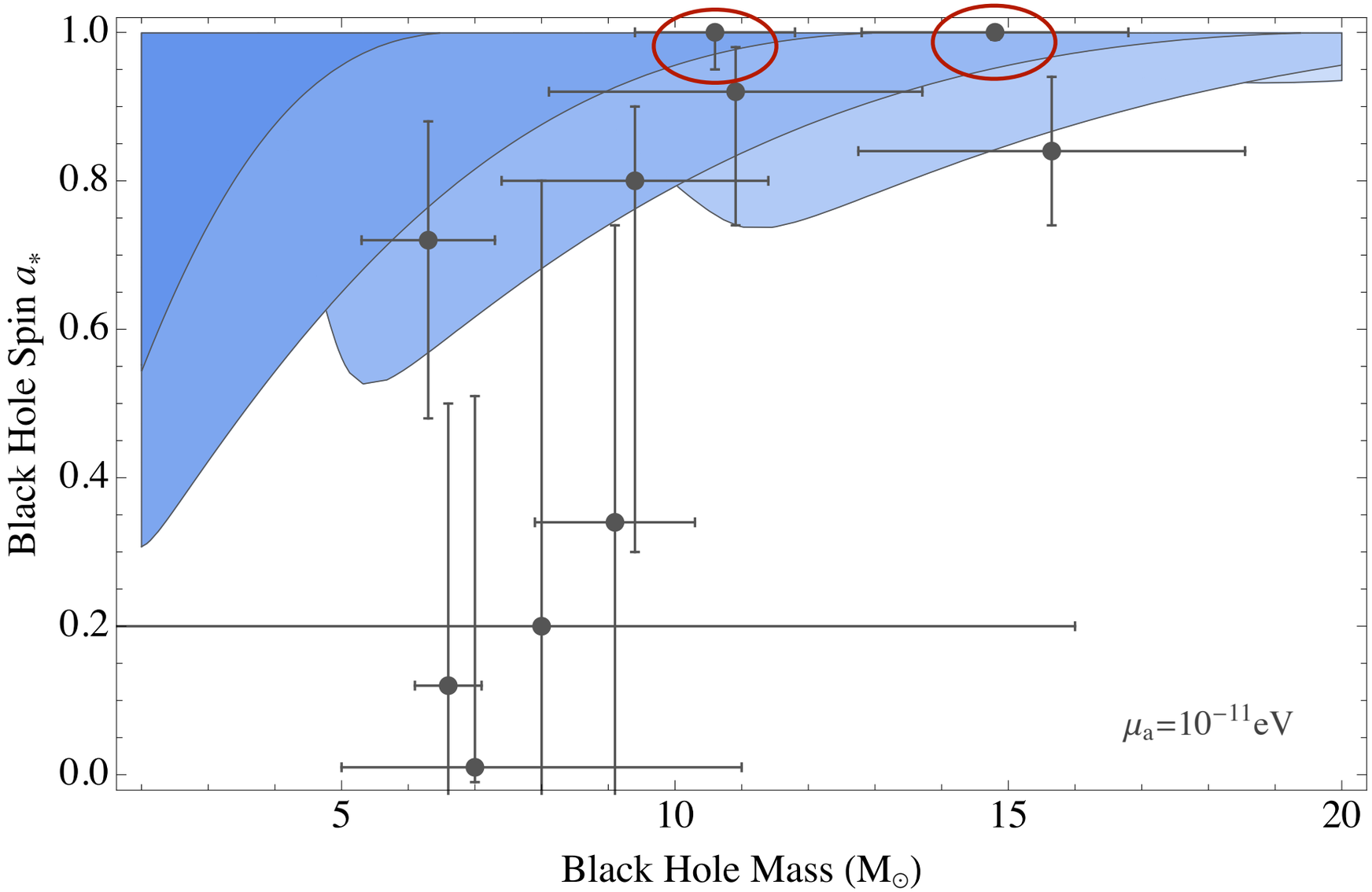
Black Hole Spins

Black hole spin and mass measurements



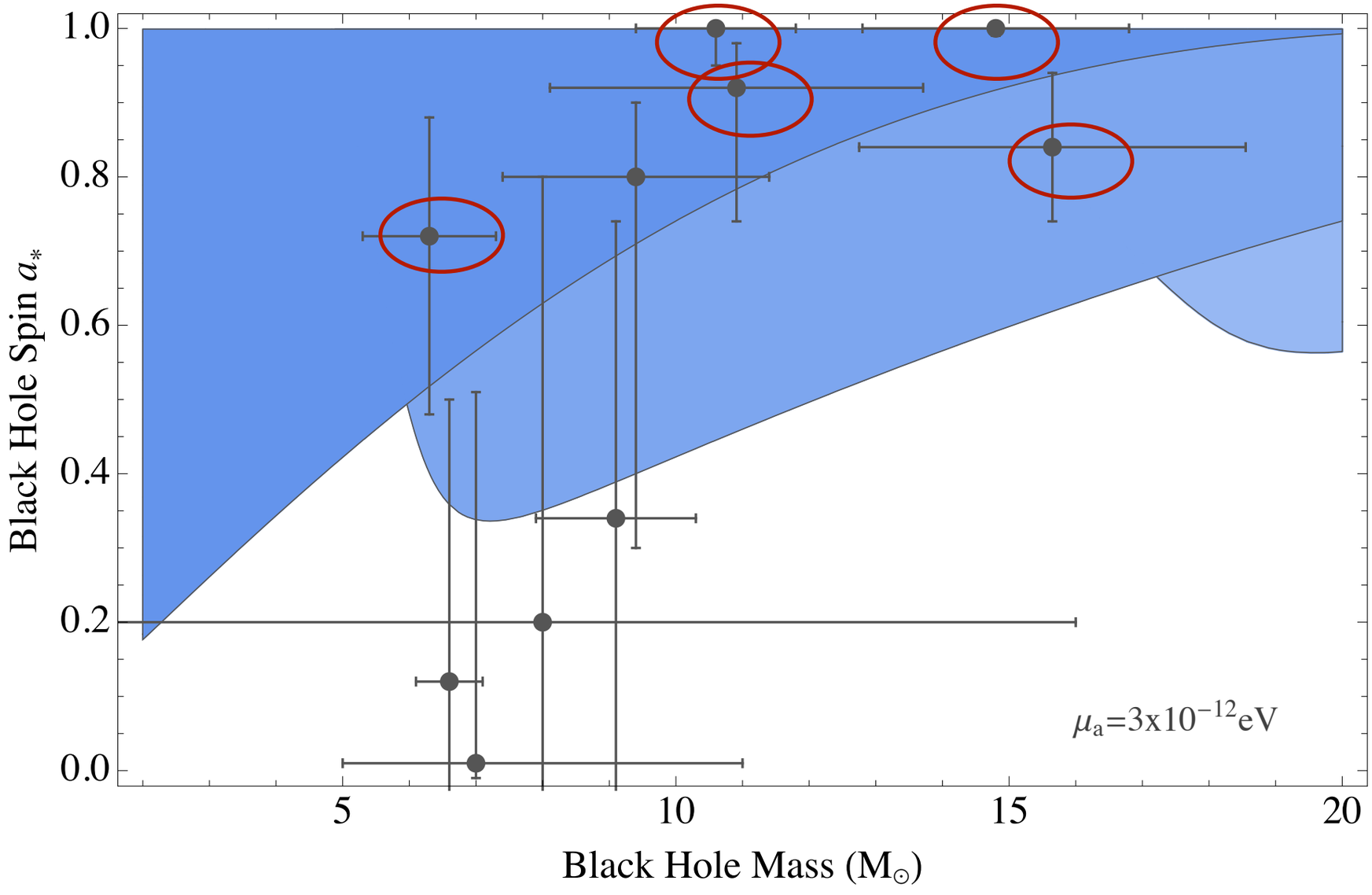
Black Hole Spins

Two black holes disfavor this axion mass



Black Hole Spins

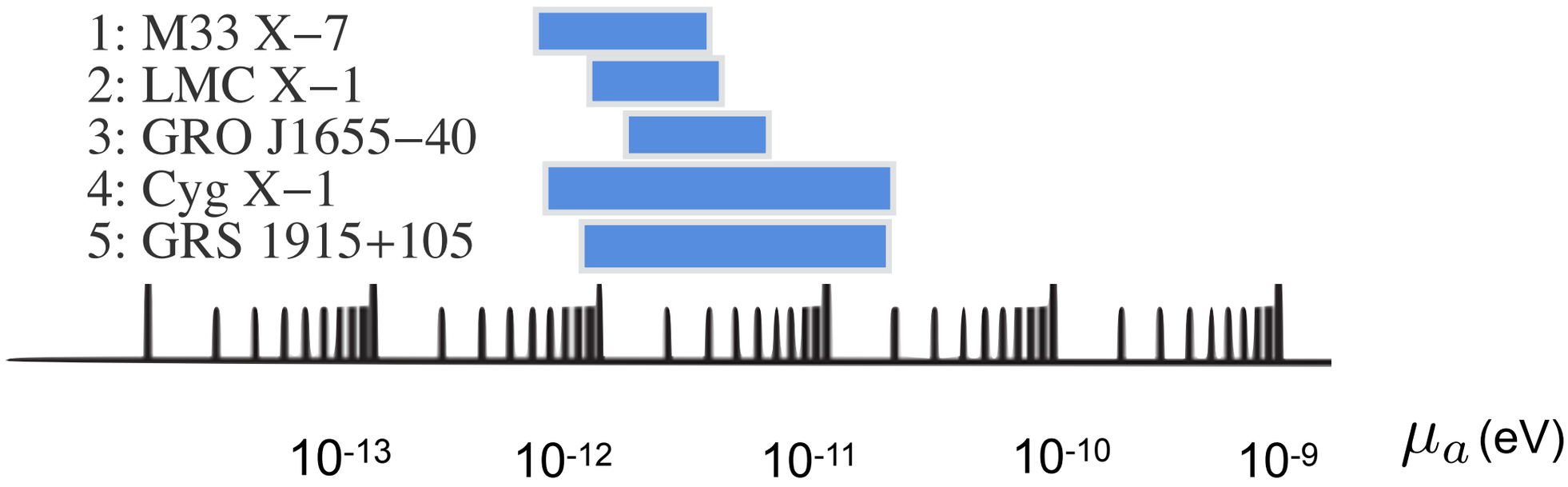
More constrained at lighter axion mass



Black Hole Spins

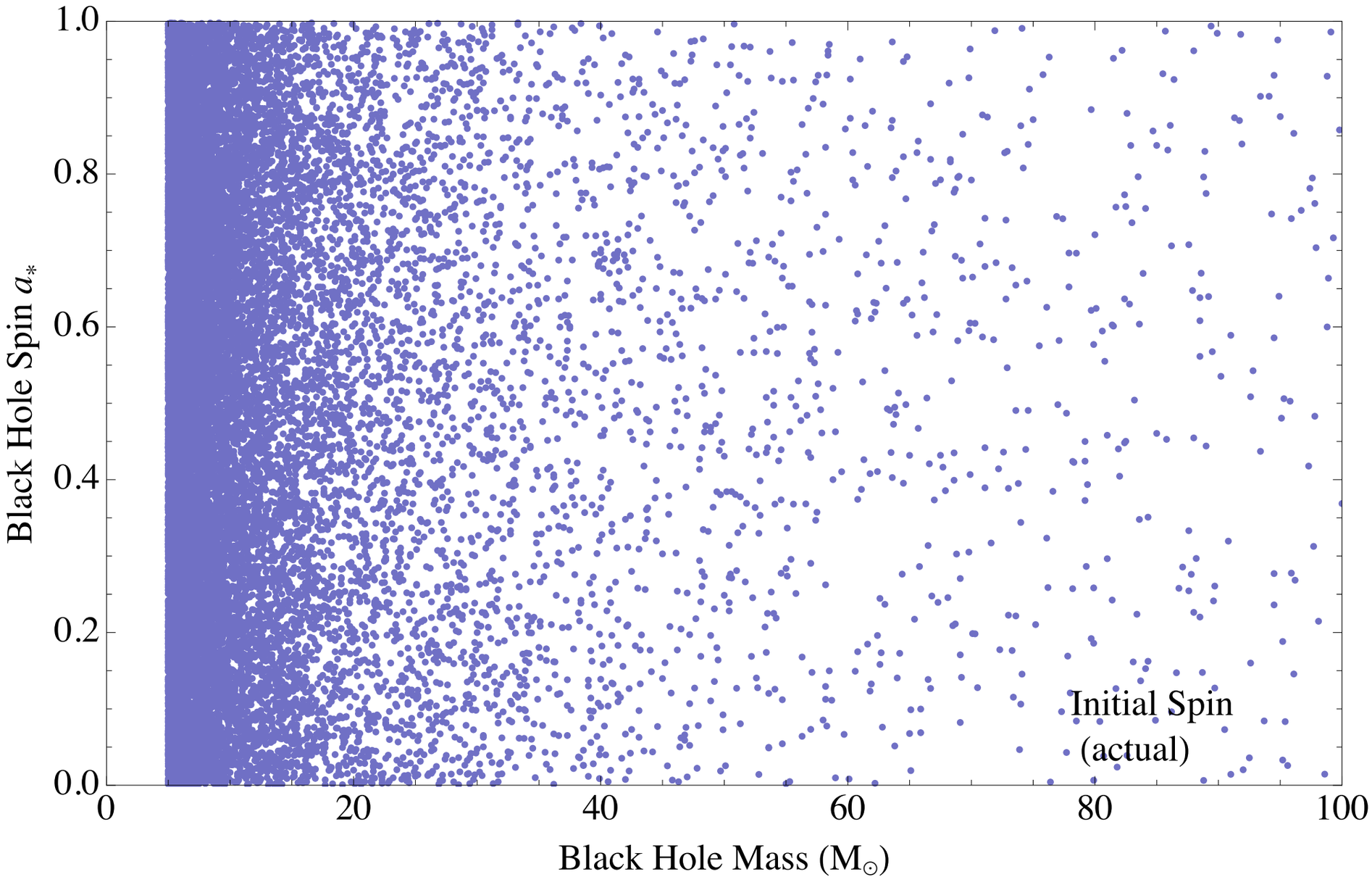
Five currently measured black holes combine to set limit:

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



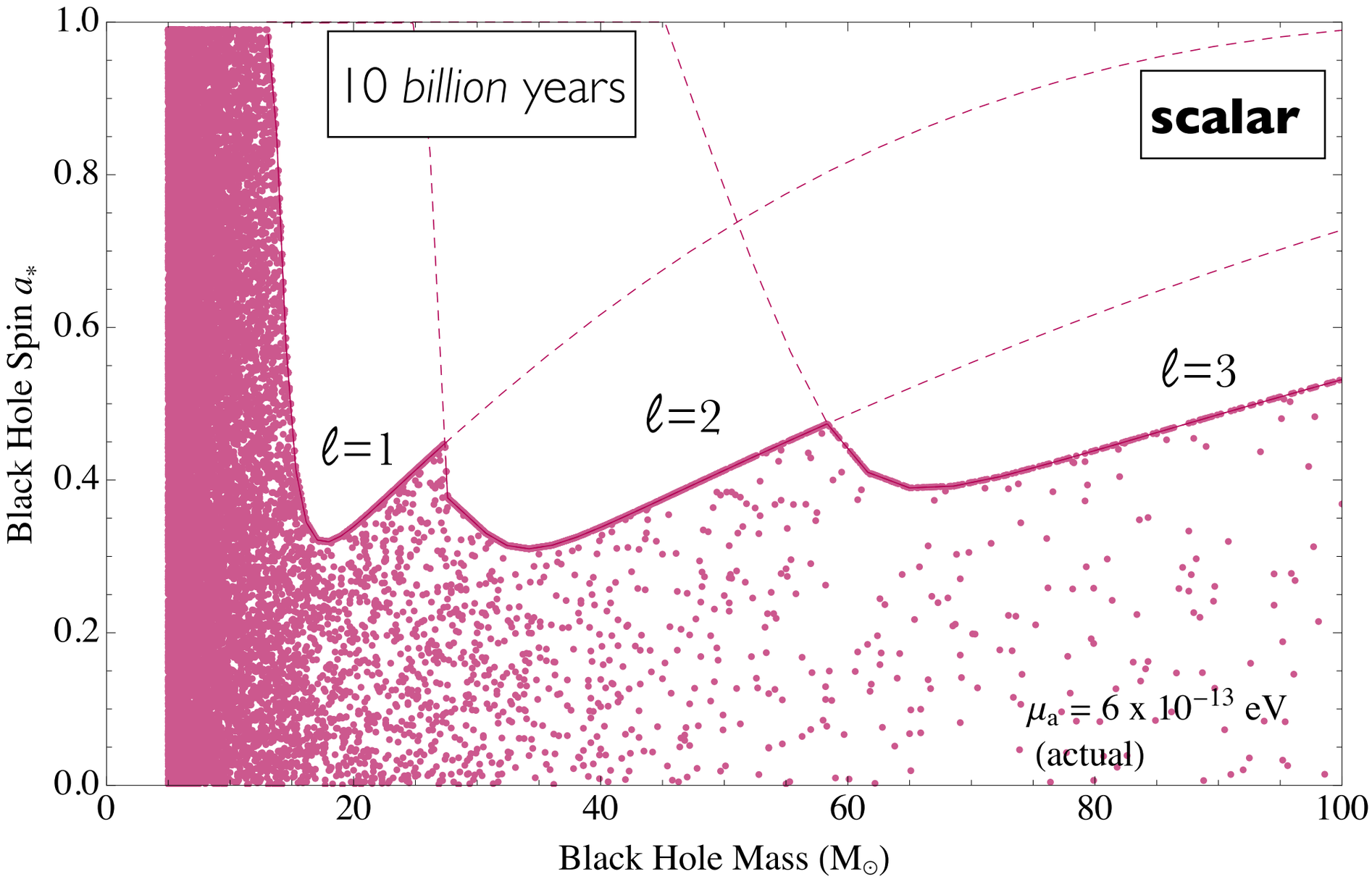
Black Hole Spins
at LIGO

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

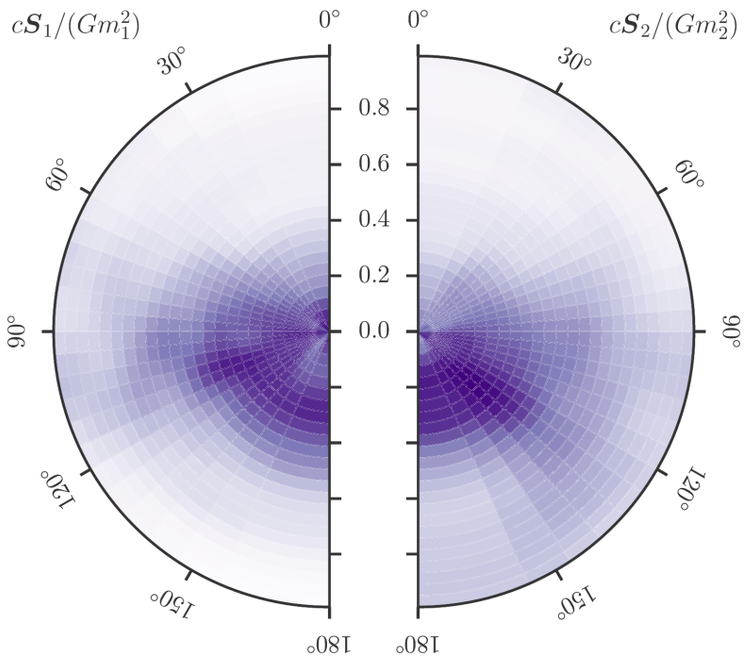


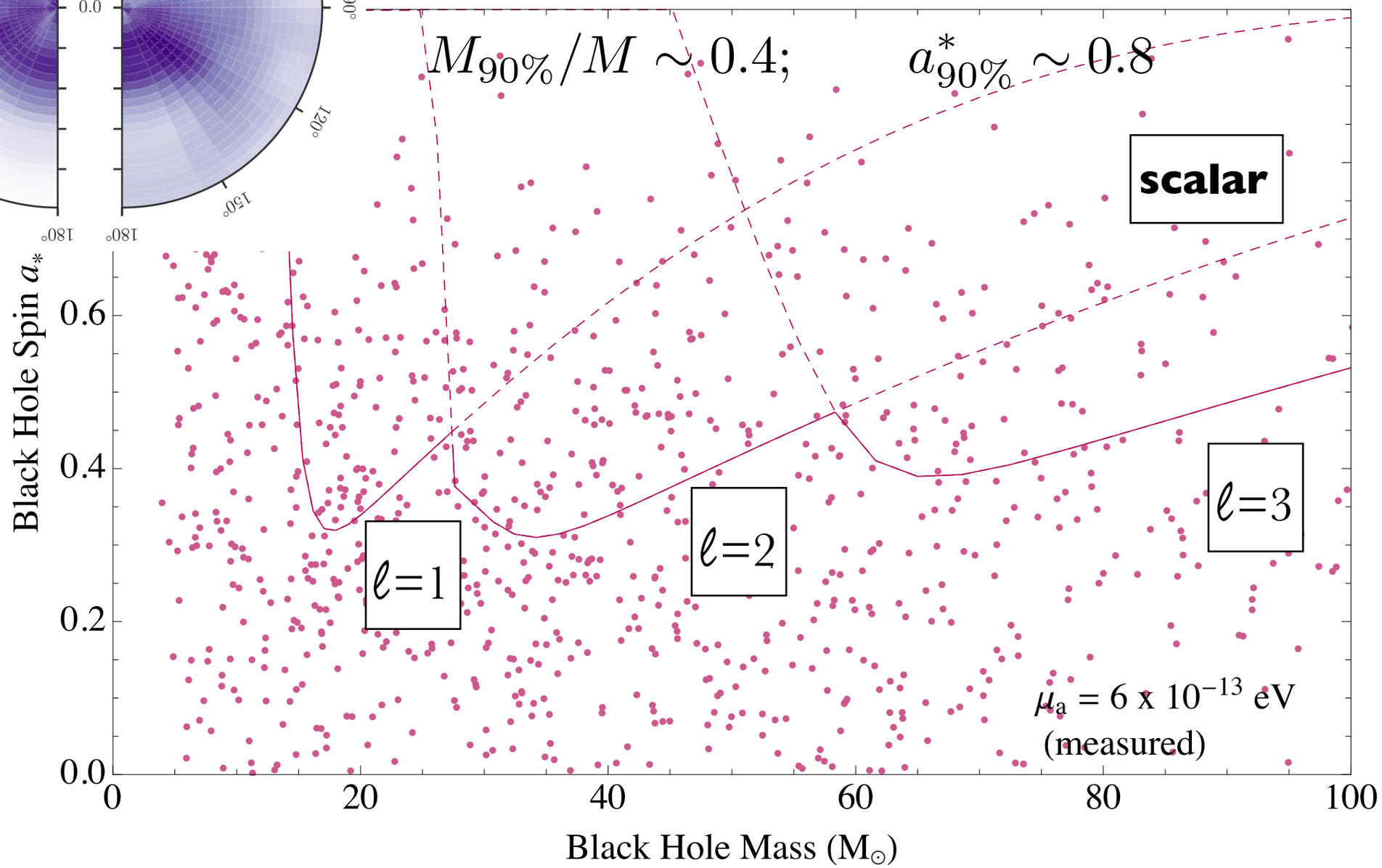
Black Hole Spins
at LIGO

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



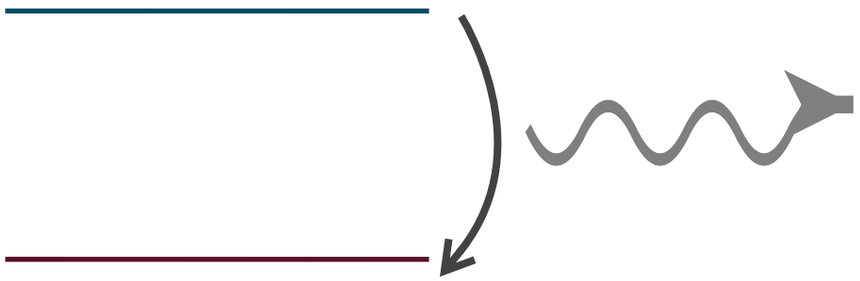


so far:
GW150914
LVT151012
GW151226
GW170104
GW170608
GW170814

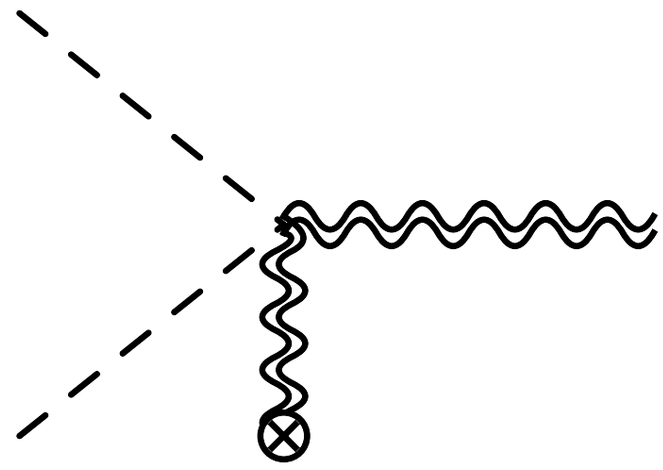
Can find statistical evidence for superradiance-like features with 50-200 merger measurements

Gravitational Wave Signals

- Transitions between levels

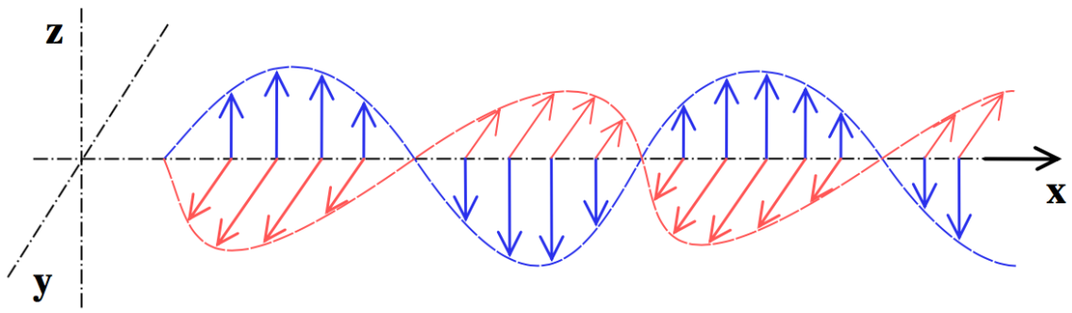


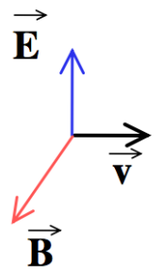
- Annihilations to gravitons



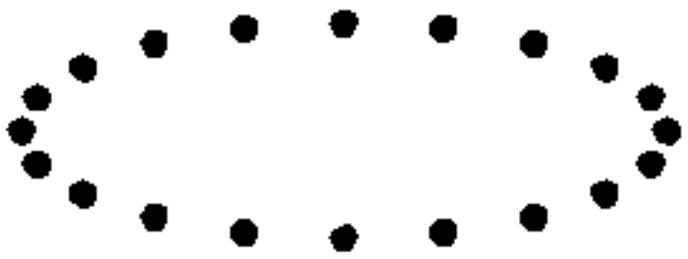
  - Signals coherent, monochromatic, last hours to millions of years

Gravitational Waves





Electromagnetic waves:
displacement of charged particles



Gravitational waves:
displacement of all matter

Gravitational wave strain $h = \left(\frac{4G_N P}{r^2\omega^2}\right)^{1/2} \sim \frac{\Delta L}{L}$

Gravitational Waves

Advanced LIGO

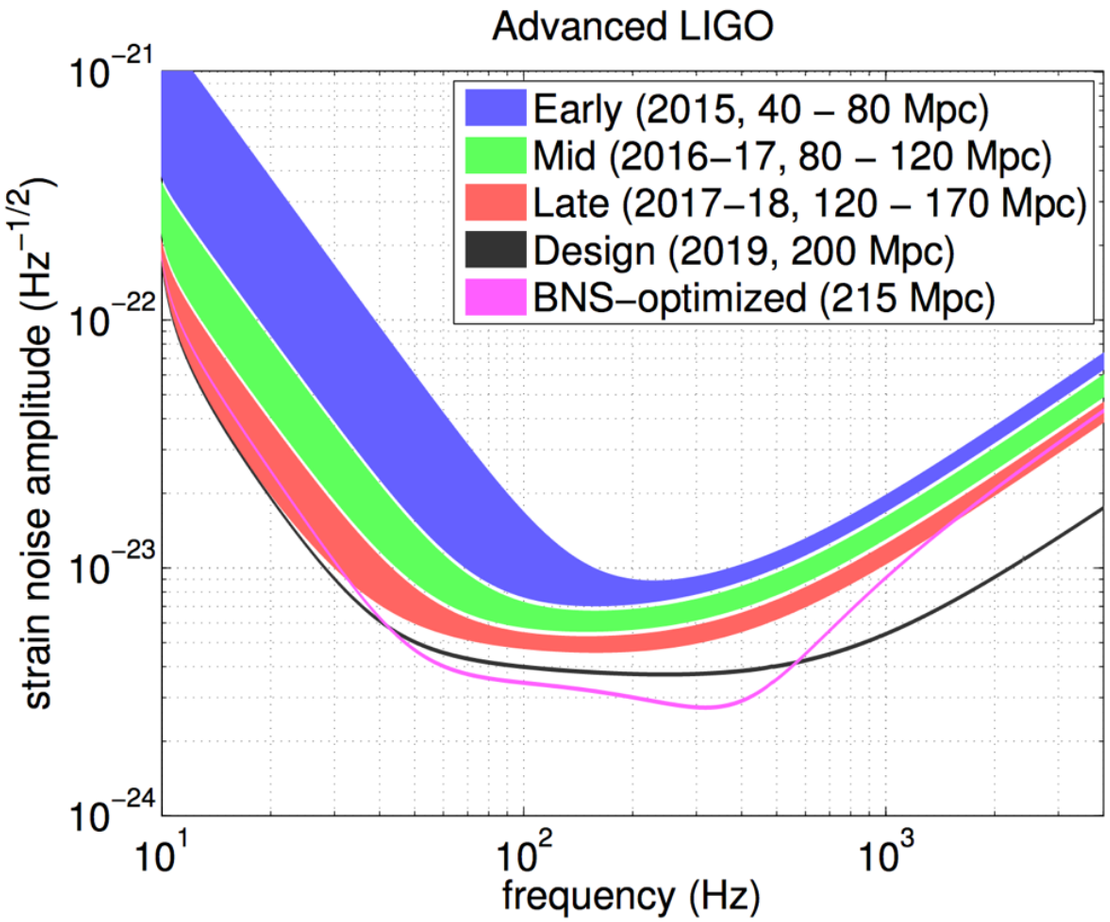
Advanced VIRGO

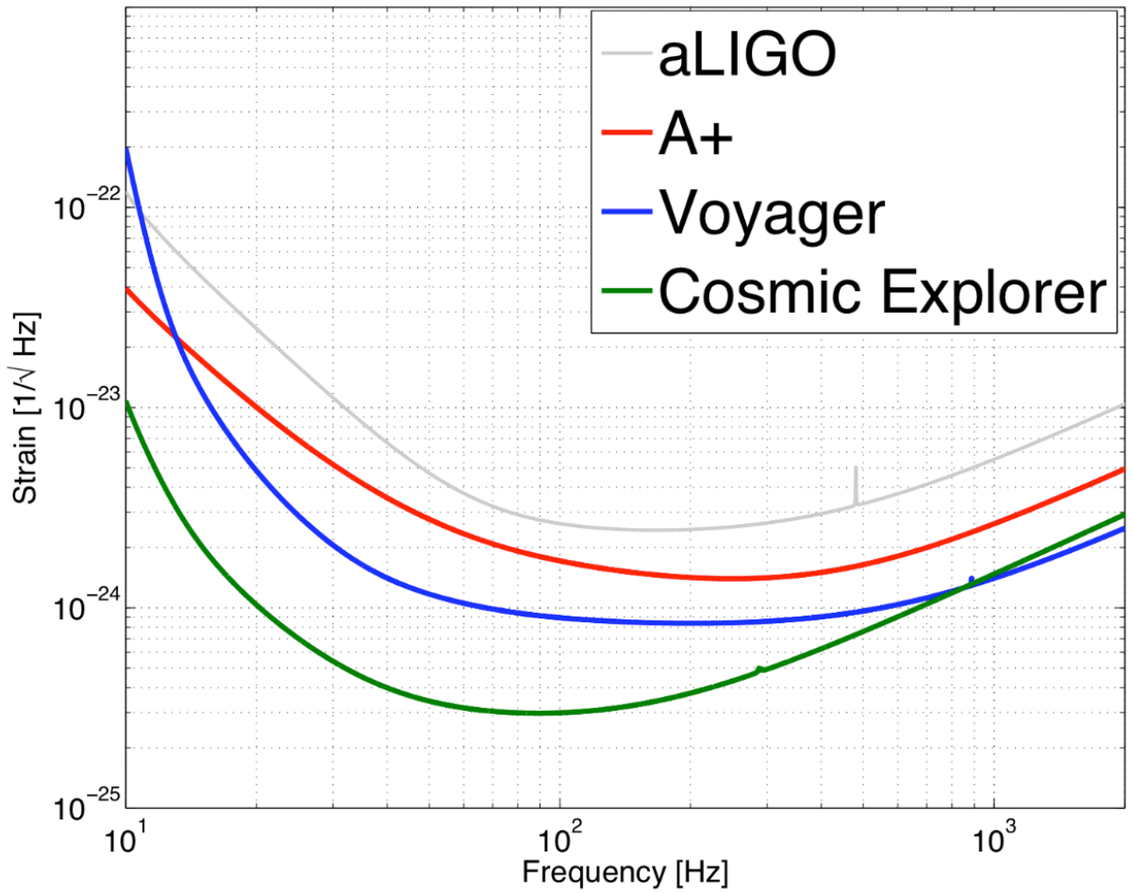
Advanced LIGO and VIRGO already made several discoveries

Goal to reach target sensitivity in the next years

Gravitational Wave Signals

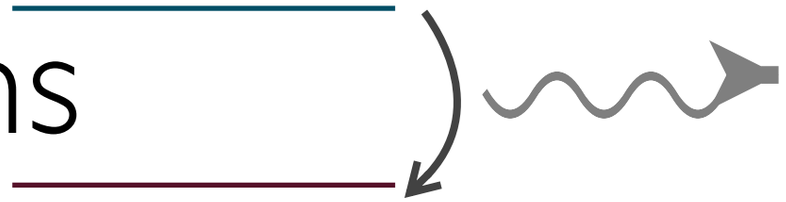
Advanced LIGO sensitivity





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

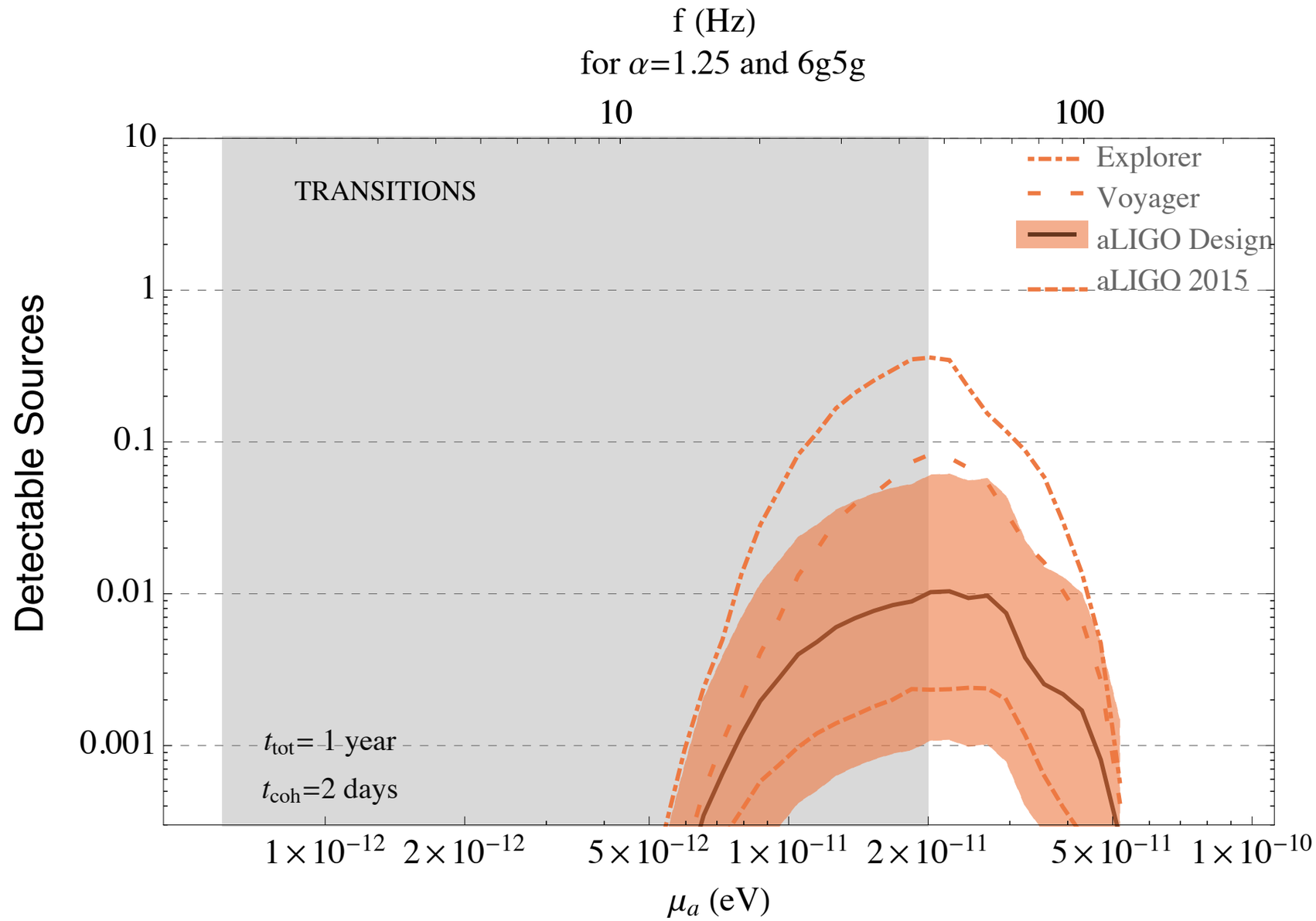
Transitions



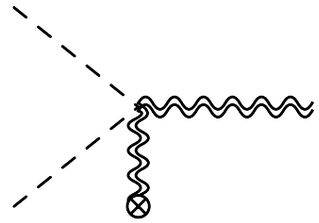
- Integrating over BH masses and spins gives promising event rates
- Uncertainty dominated by BH formation rate and spin distribution

Signals visible from galactic center typically last 10-100 yrs

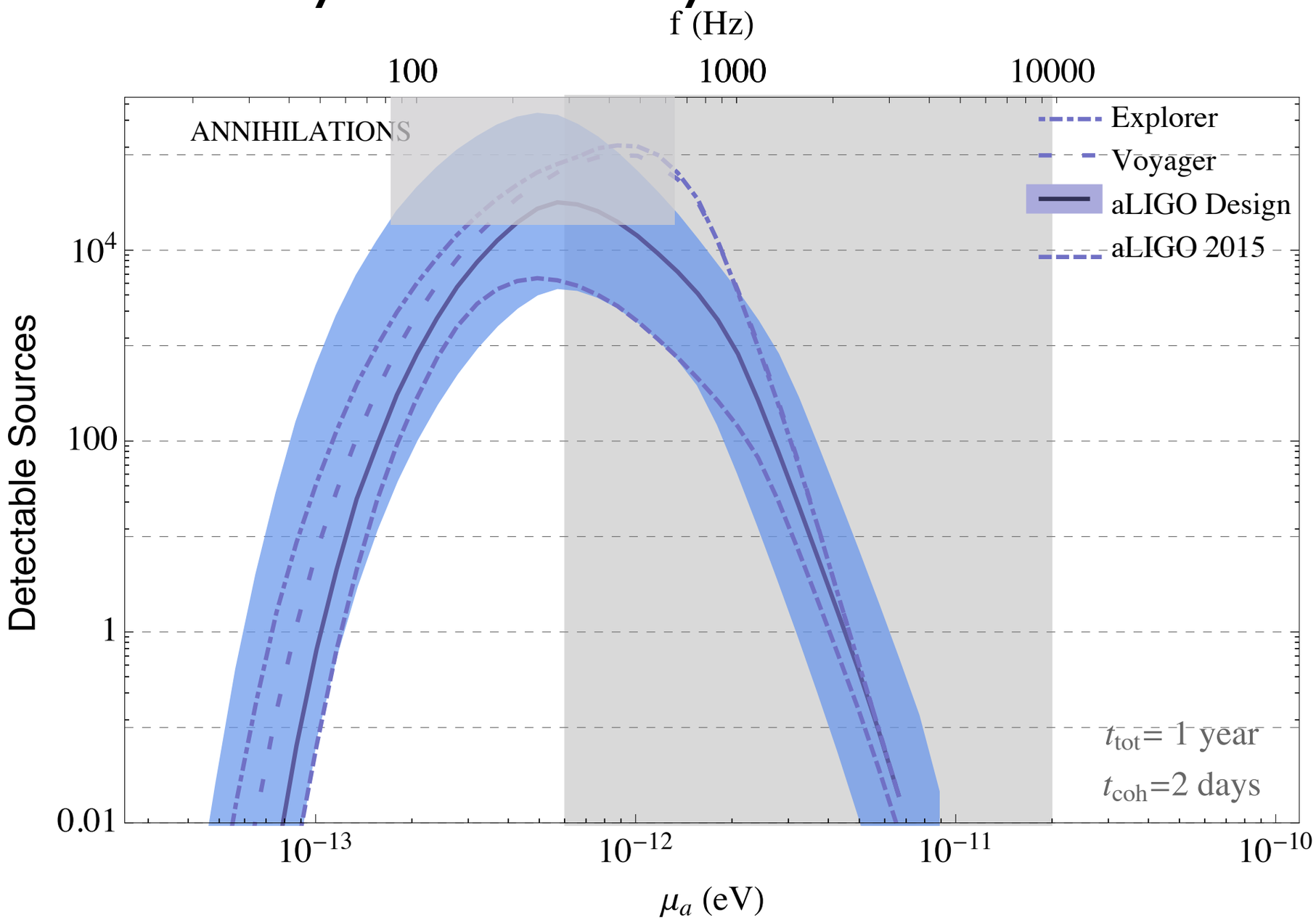
Signals *coherent* and *monochromatic*



Annihilations



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

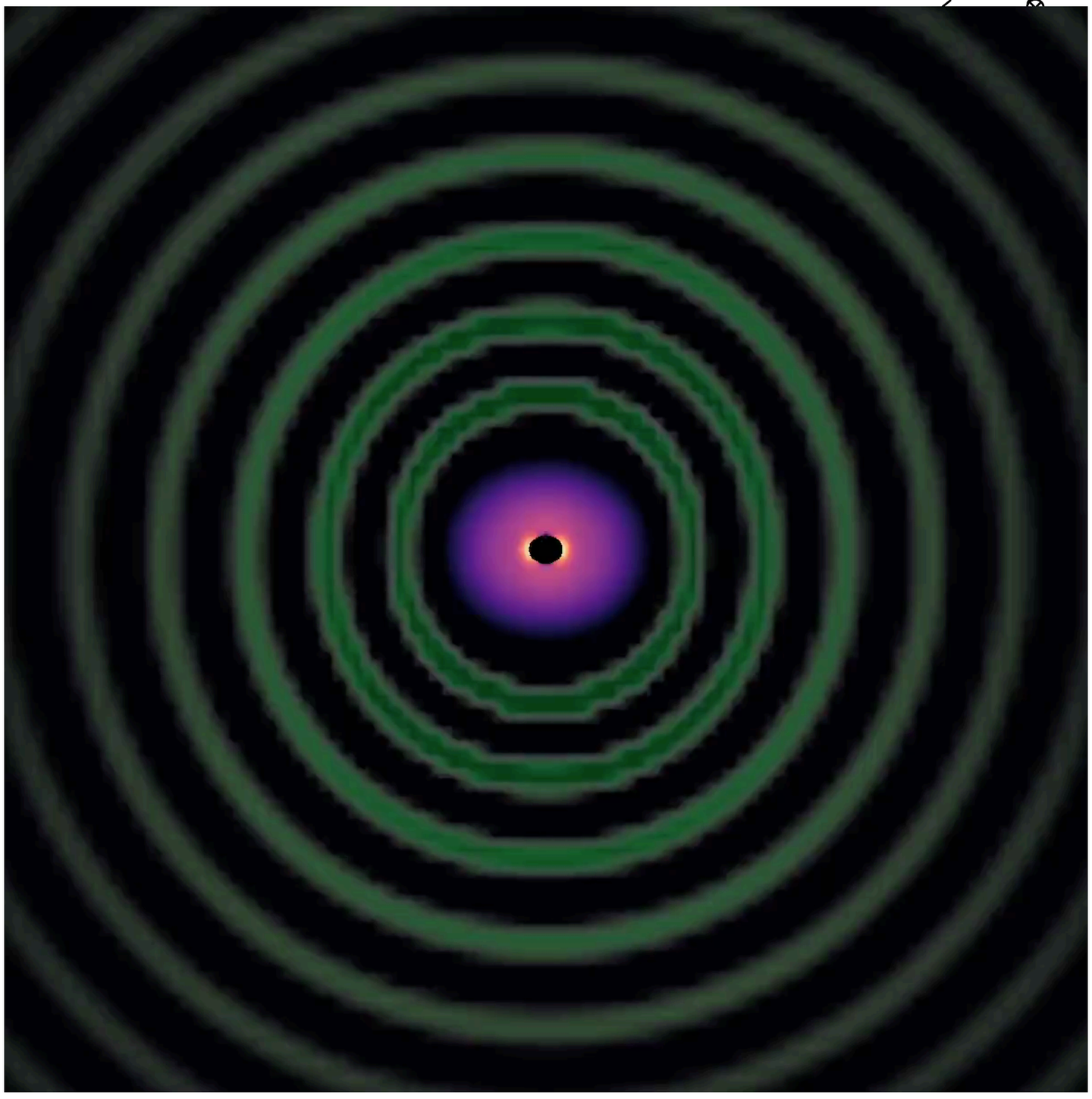


Signals visible from galactic center typically last 10-1000 yrs

Signals *coherent* and *monochromatic*

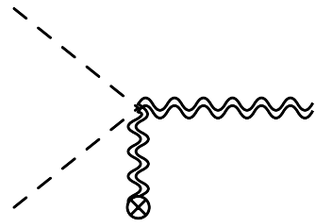
Cross-check spin limits

Annihilations

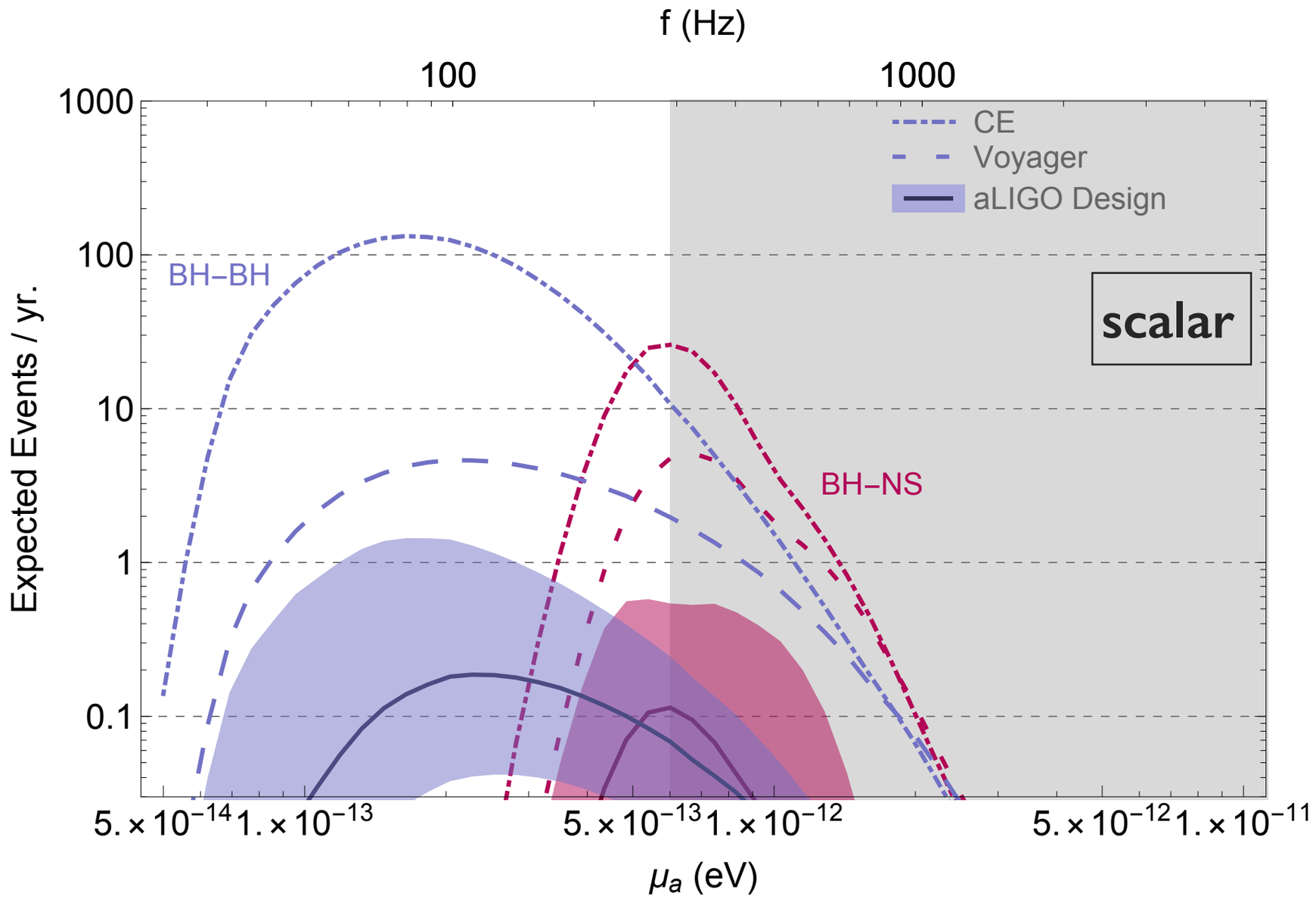


Will East, annihilations of vector field into GWs

Annihilations

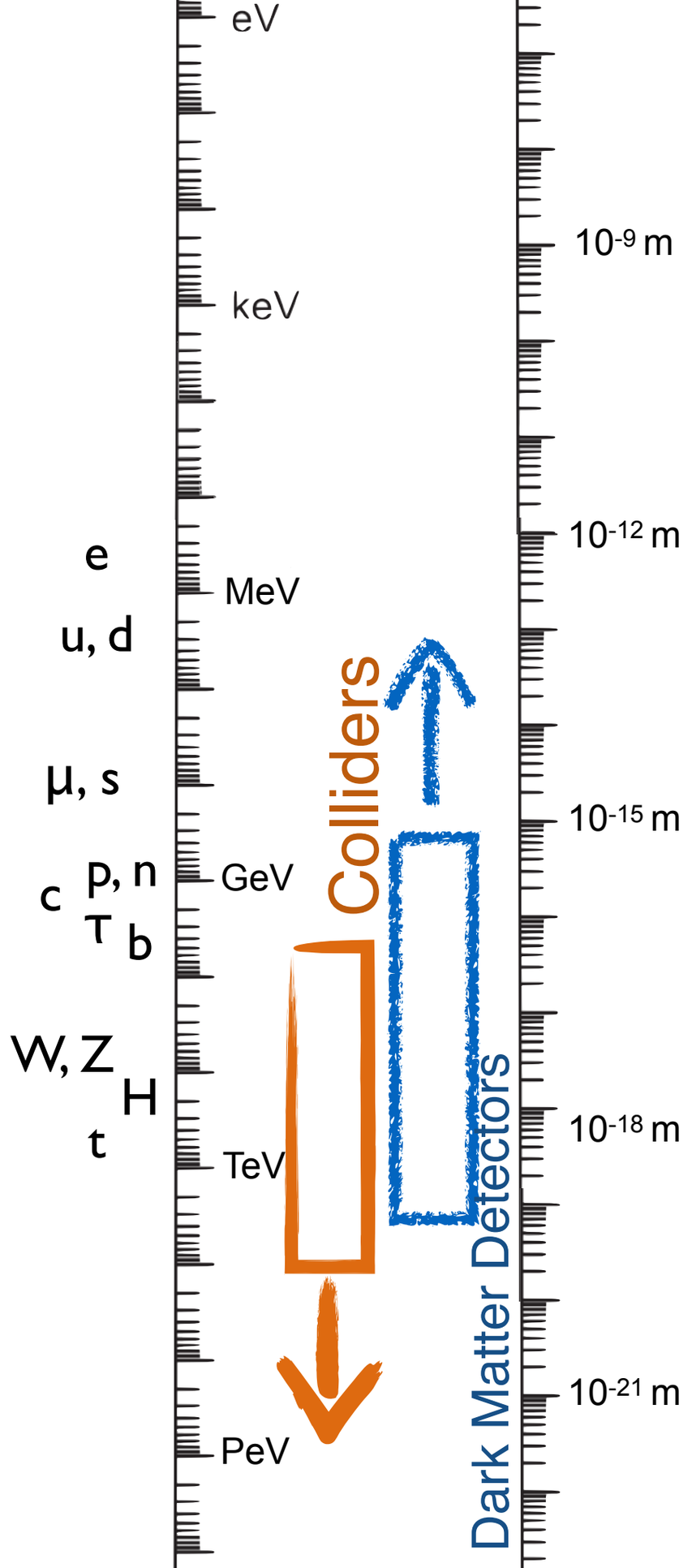


- Mergers at LIGO: a black hole is born!
- Follow up with continuous wave search to see if superradiance creates a cloud of axions around the new BH
- Targeted searches especially promising at future GW observatories



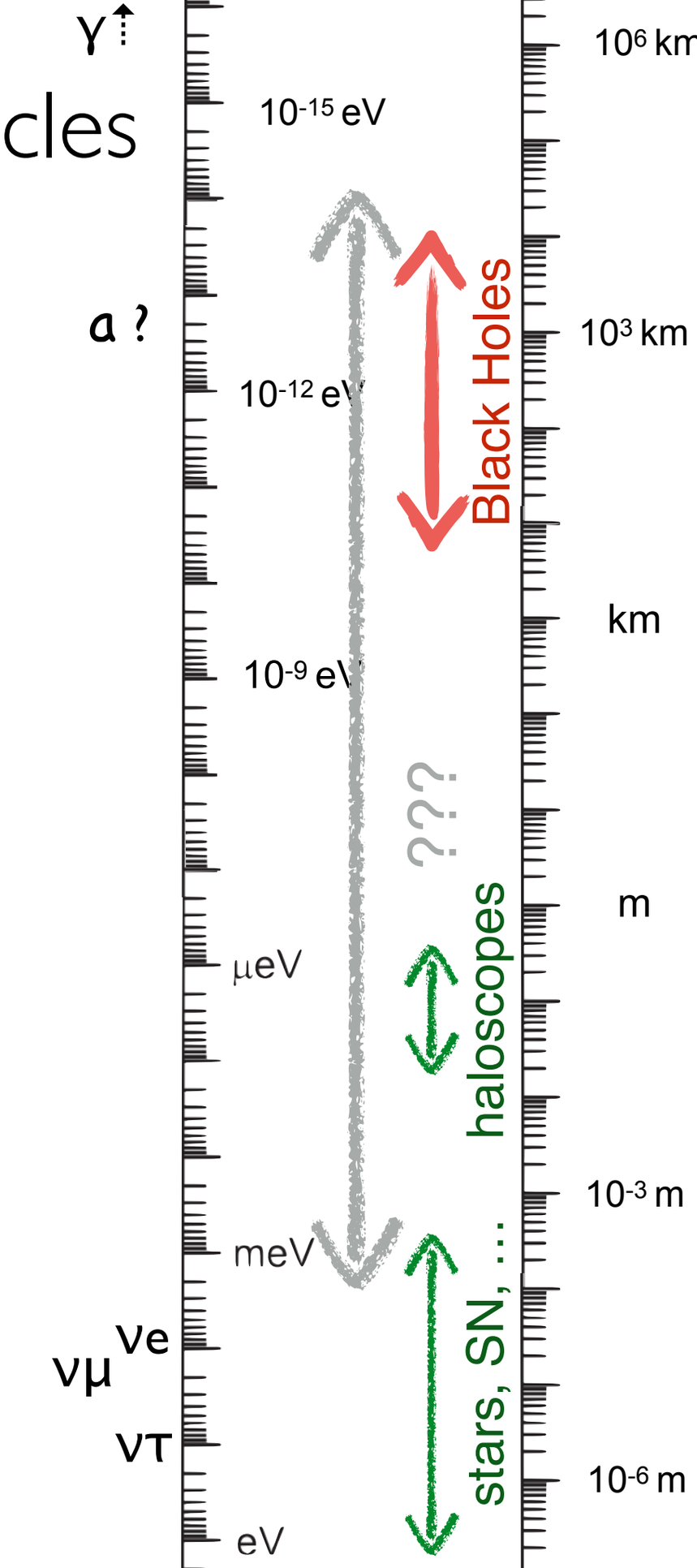
Searching for New Particles

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



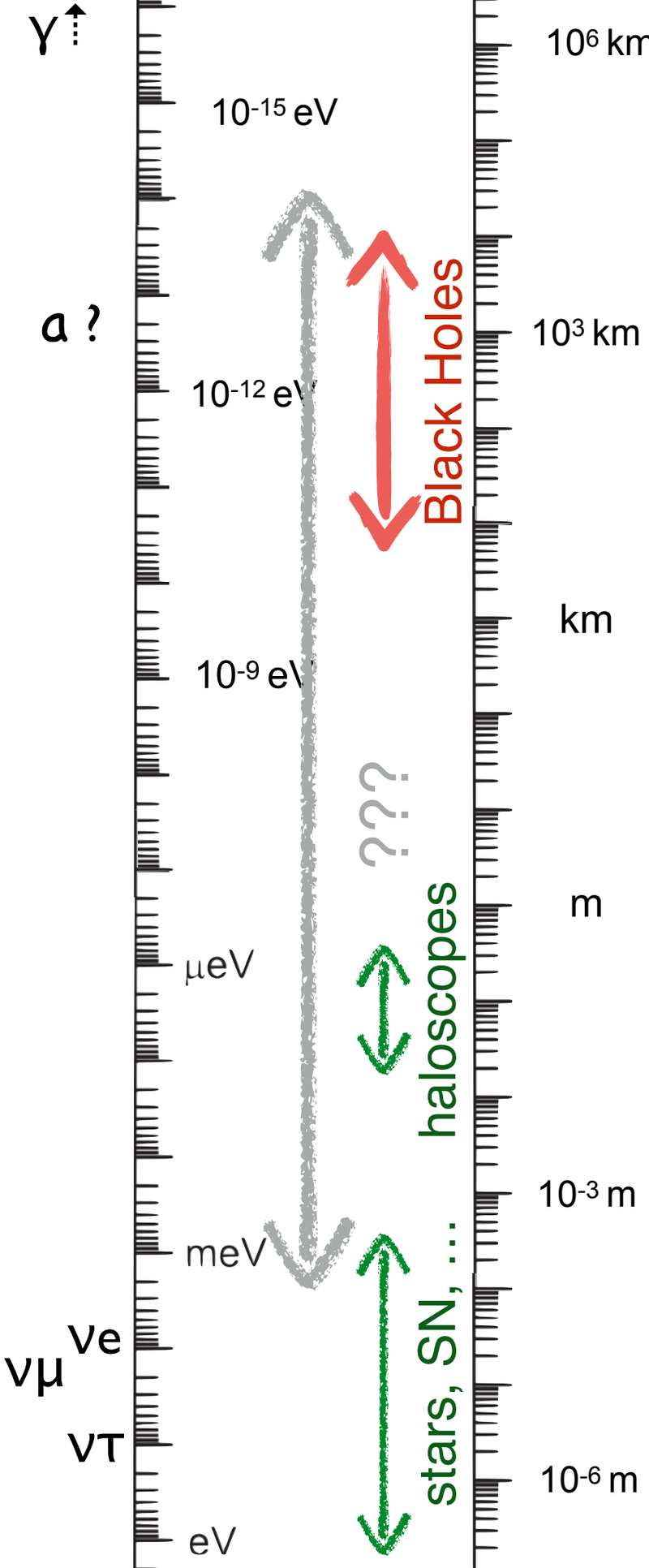
Searching for New (Ultra)Light Particles

- 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



Summary

- Rotational superradiance is a process that extracts energy from lossy, rotating objects
- Rotating black holes are unstable to superradiant energy loss in the presence of light fields
- Ultra light axions 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



Selection of (more or less) Pedagogical References

Classic references

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Superradiance for new particle searches

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- Discovering the QCD Axion with Black Holes and Gravitational Waves - Arvanitaki, Baryakhtar, Huang, Phys.Rev. D91 (2015) no.8, 084011 arXiv:1411.2263
- Black Hole Superradiance Signatures of Ultralight Vectors - Baryakhtar, Lasenby, Teo, Phys.Rev. D96 (2017) no.3, 035019 arXiv:1704.05081
- Superradiant instability of massive vector fields around spinning black holes in the relativistic regime - East, William E. Phys.Rev. D96 (2017) no.2, 024004 arXiv:1705.01544.