STRONG GRAVITY UNIVERSE
SÃO MIGUEL, JULY 3-7, 2017

Black hole superradiance of ultralight particles

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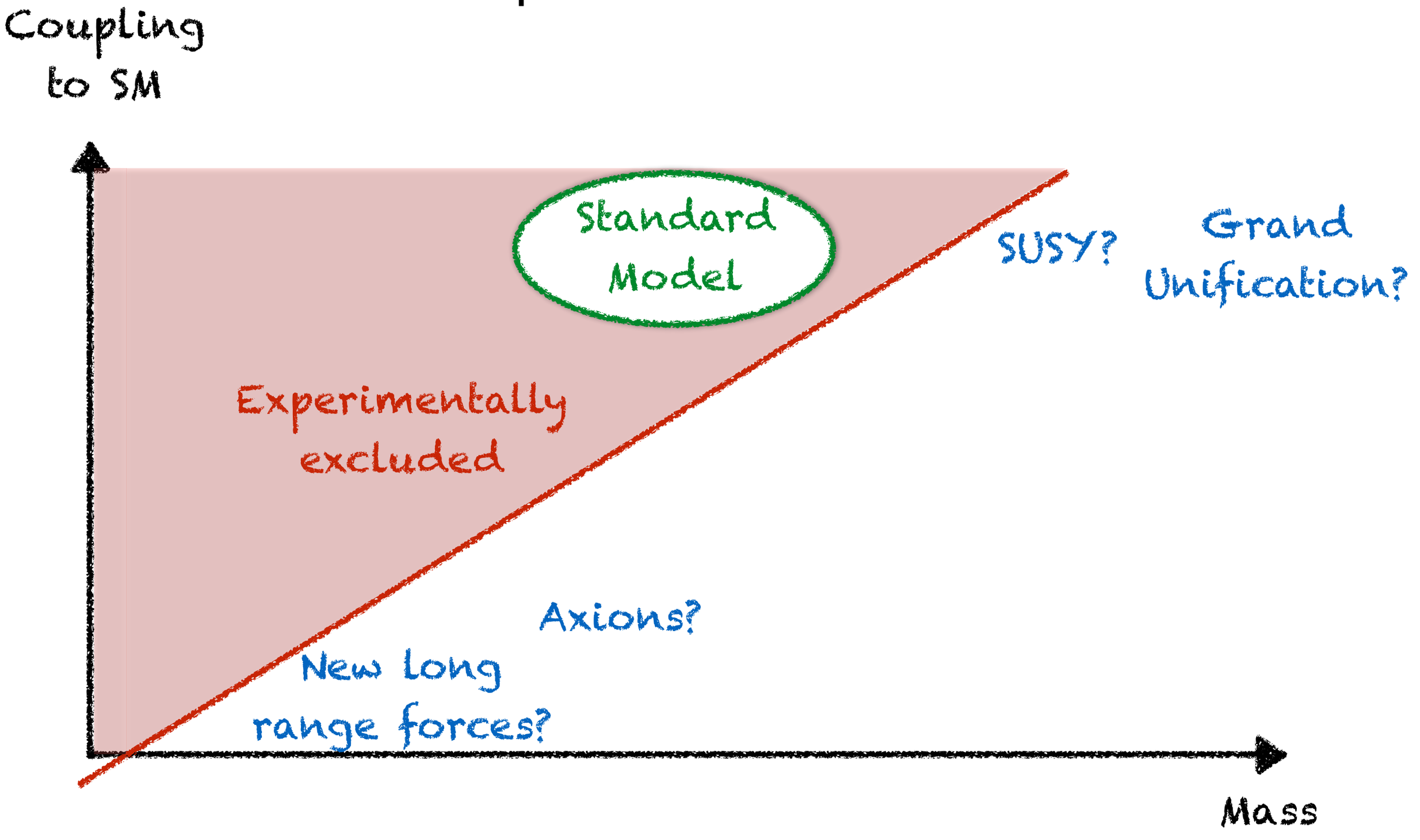
July 5, 2017

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, RL
arxiv: 1704.05081 MB, RL, M. Teo

Outline

- Energy extraction from black holes
- Black hole superradiance for light scalar/vector particles
- Observational signatures
  - Spin-down of black holes
  - Coherent gravitational wave emission

Light, weakly-coupled new particles



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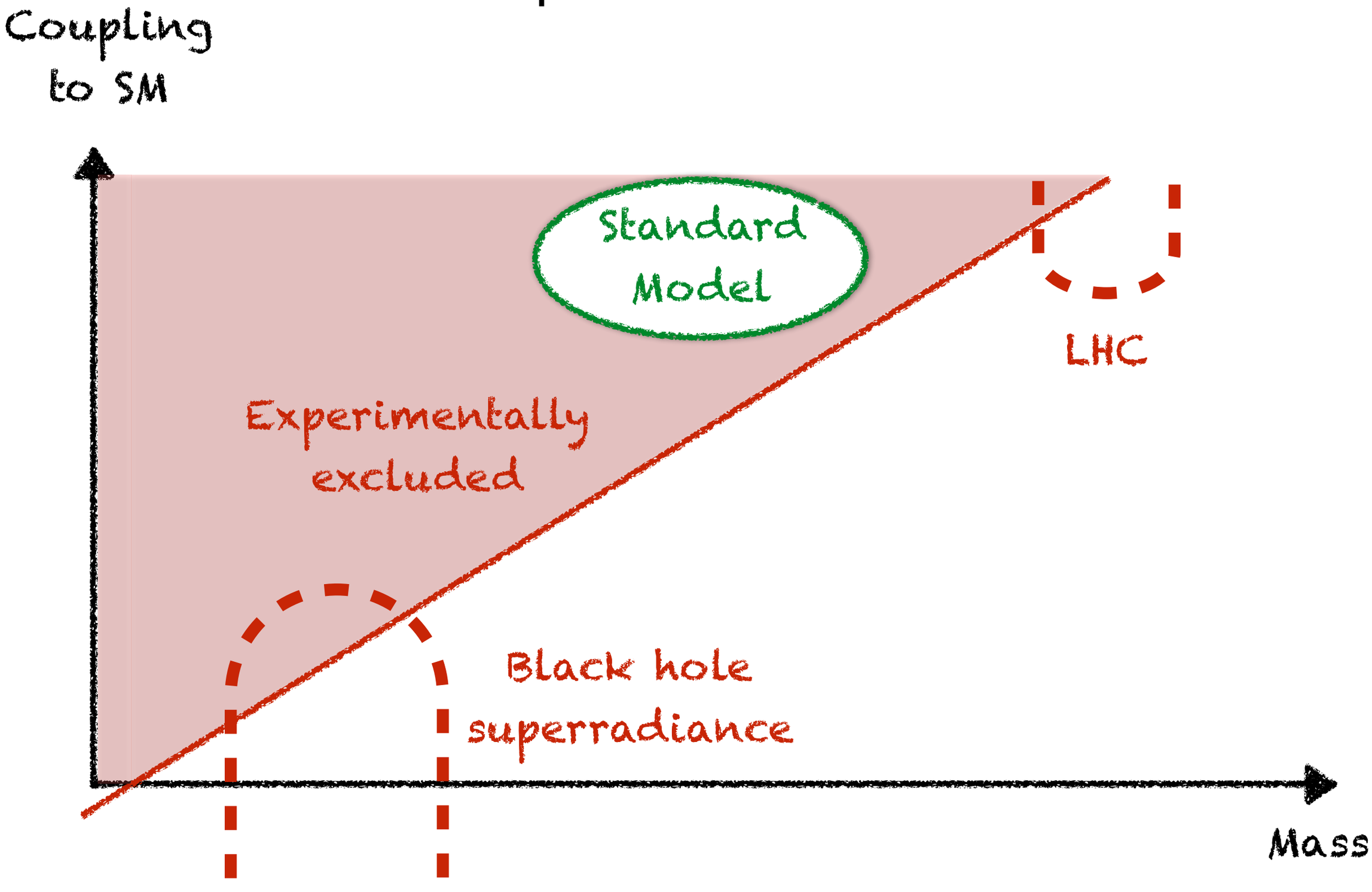
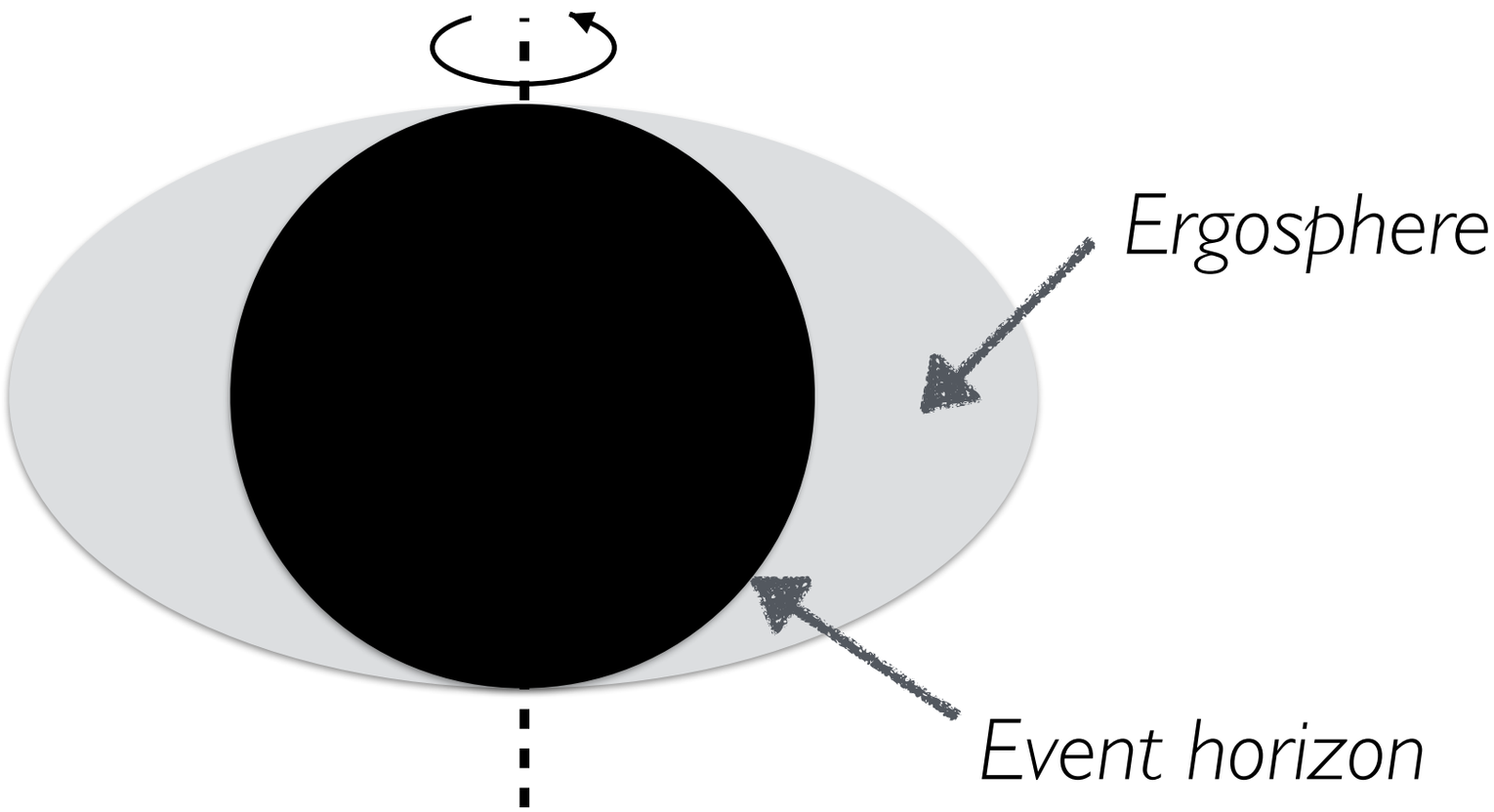


Extracting energy and angular momentum from black holes

- Spinning BHs have *ergosphere* - region where particles can have negative energy (as viewed from infinity)



- Mechanical Penrose process: throwing negative-energy particle into horizon

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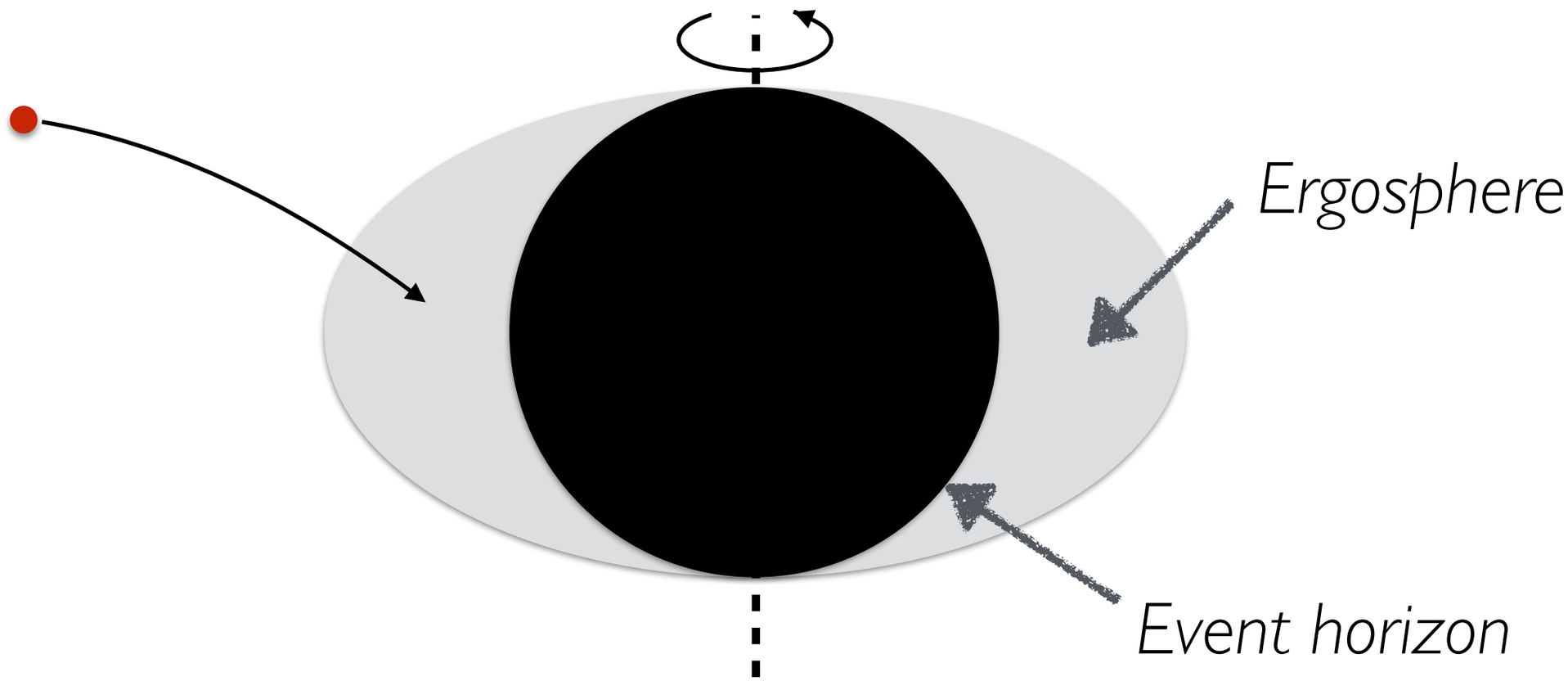

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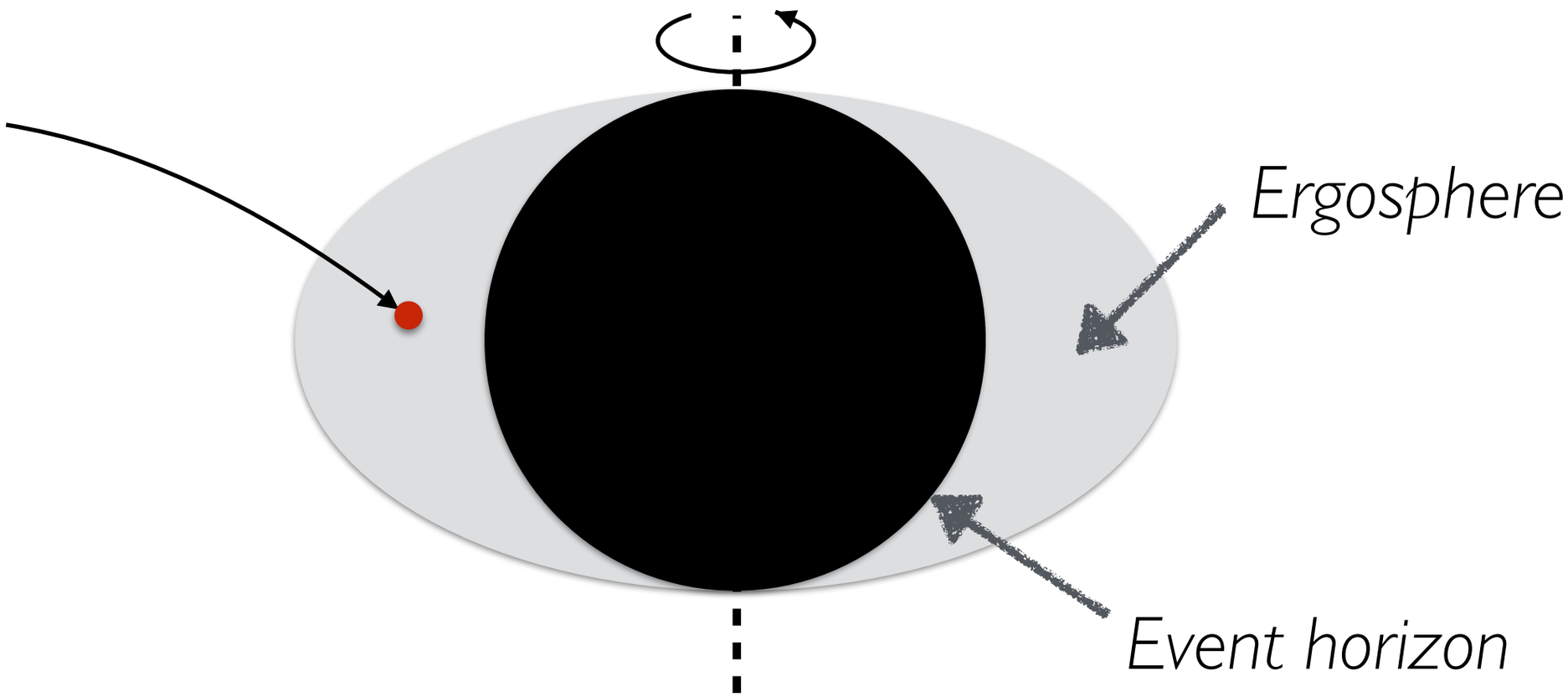

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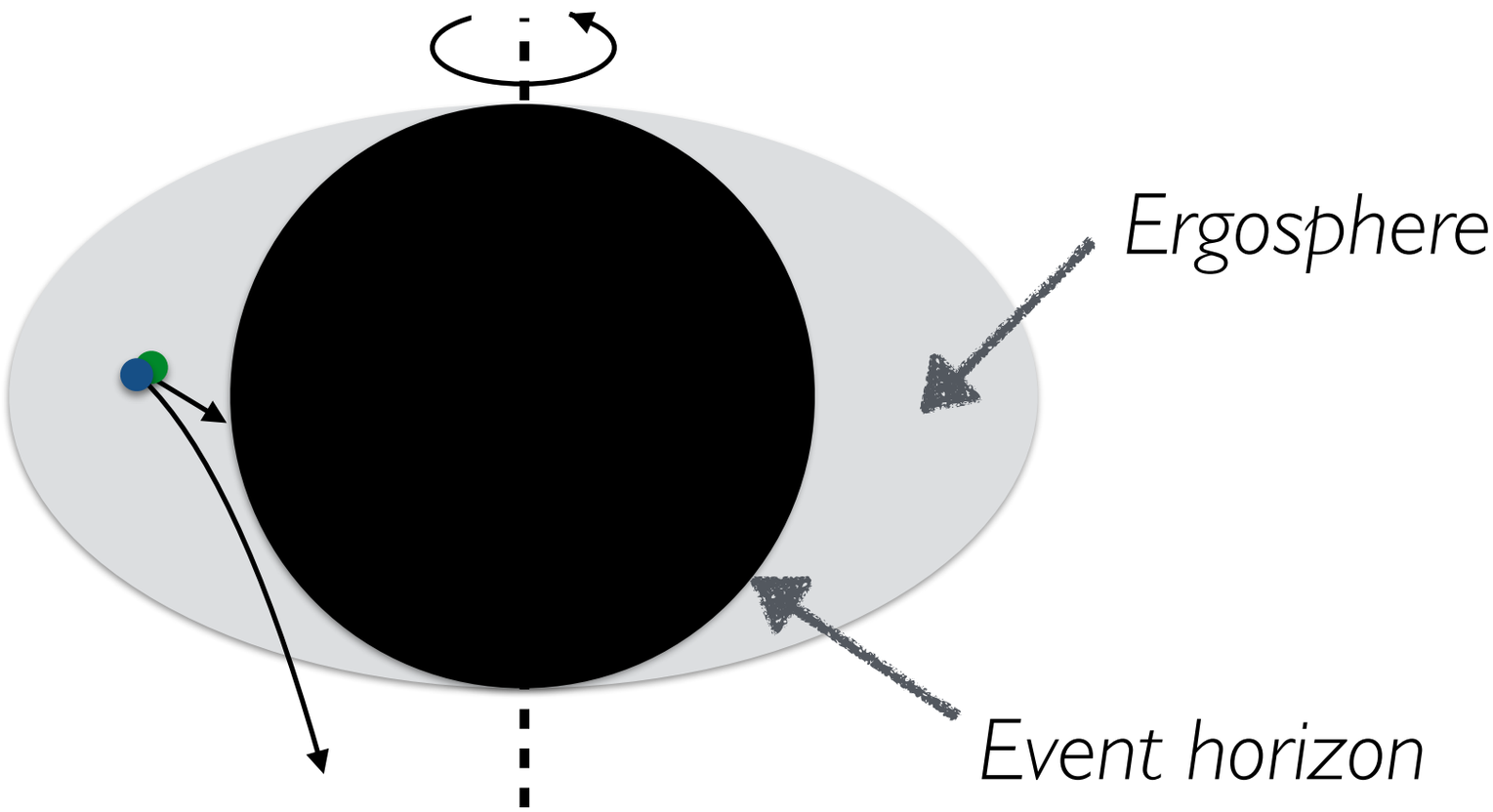

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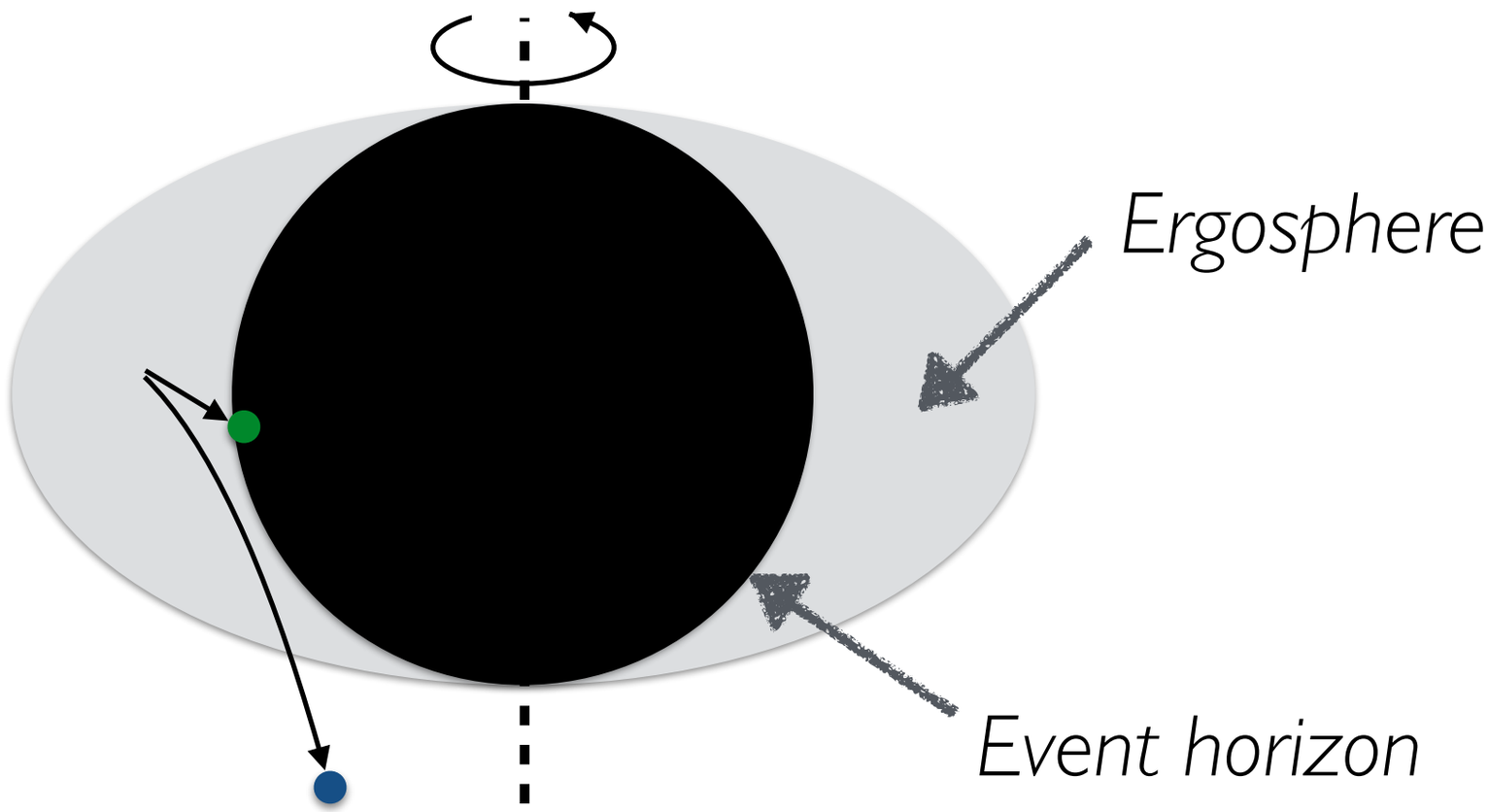

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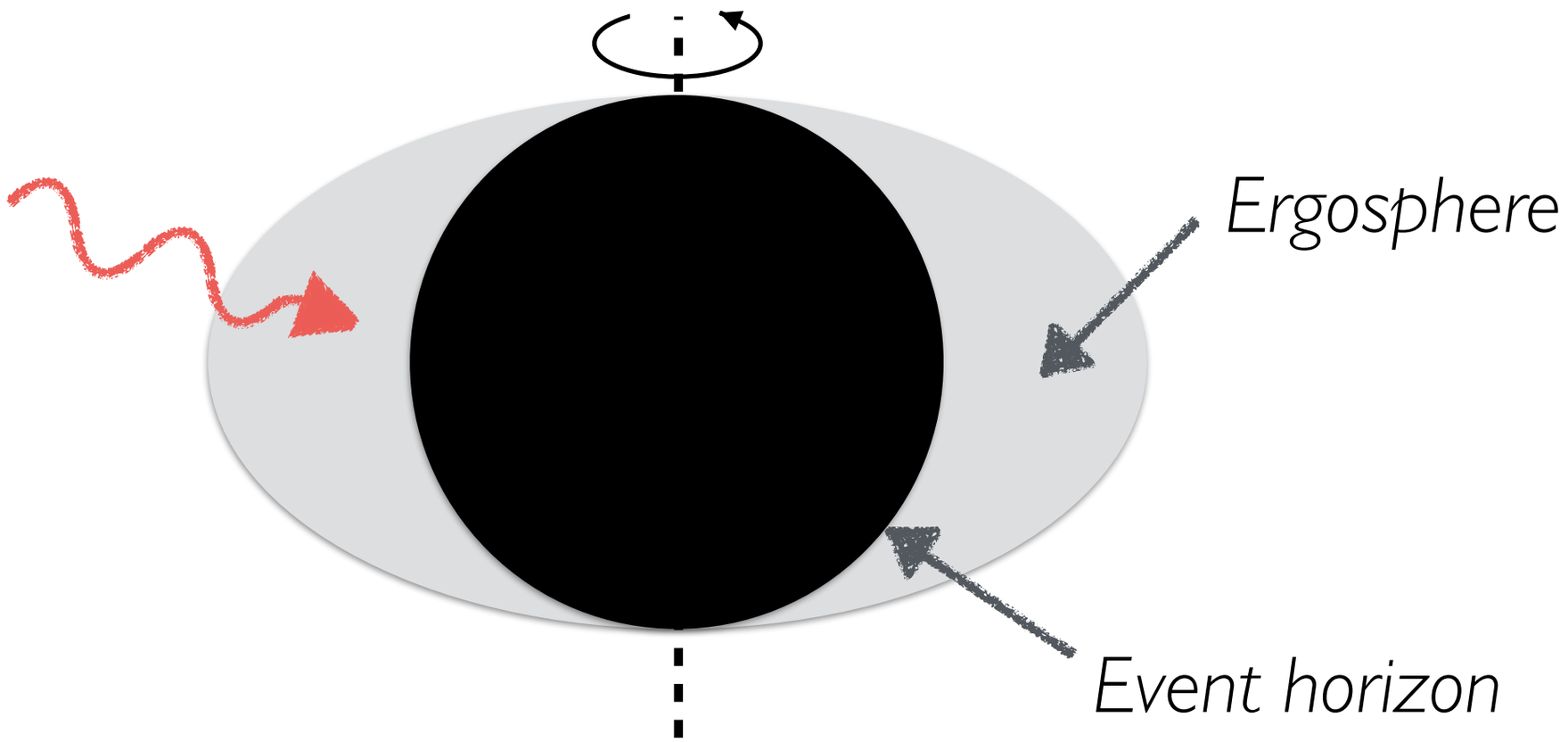

- *Wave* Penrose process: transmitted wave has negative energy, reflected wave carries extra energy away

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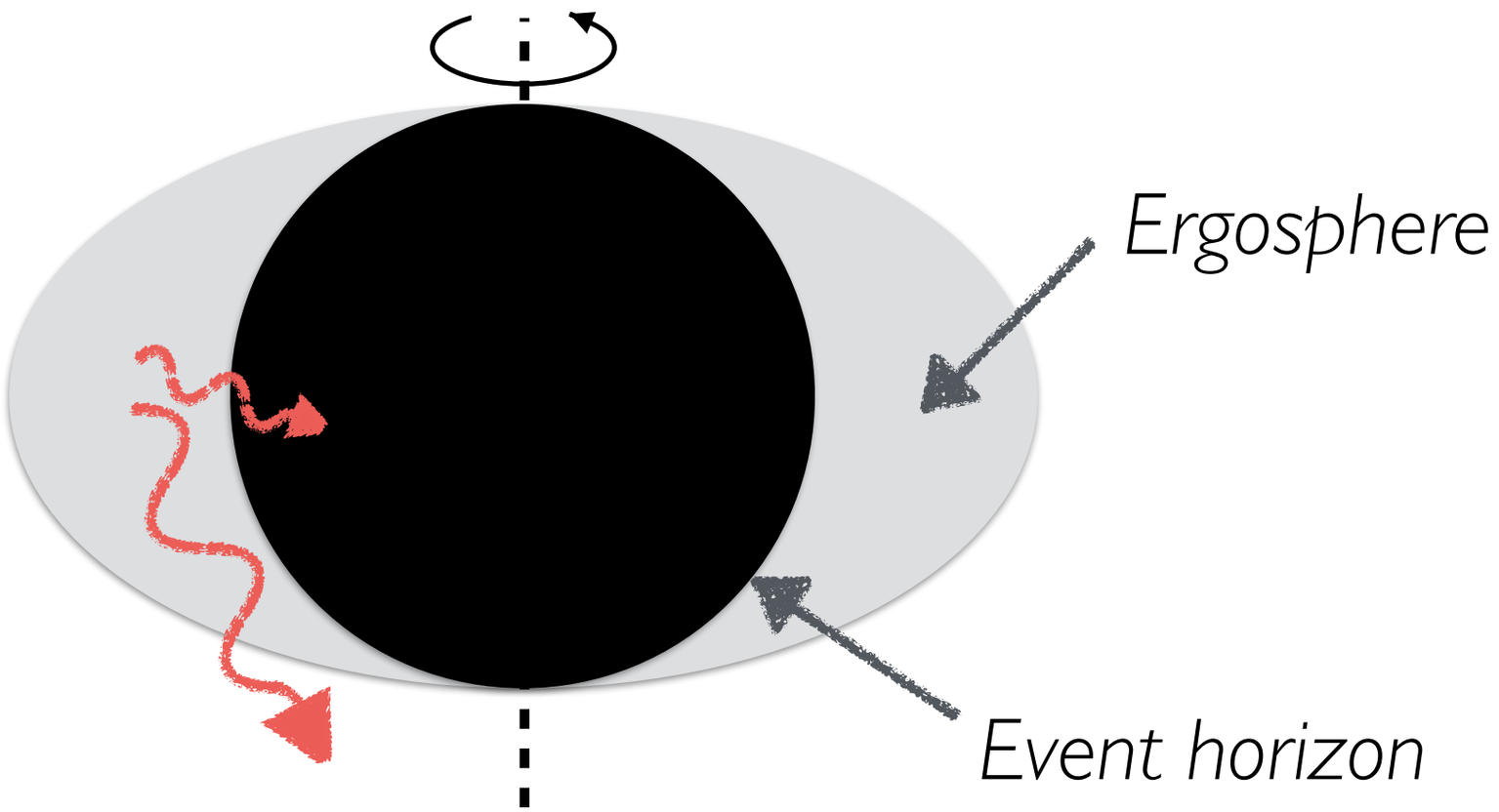


- *Wave* Penrose process: transmitted wave has negative energy, reflected wave carries extra energy away

Wave superradiance

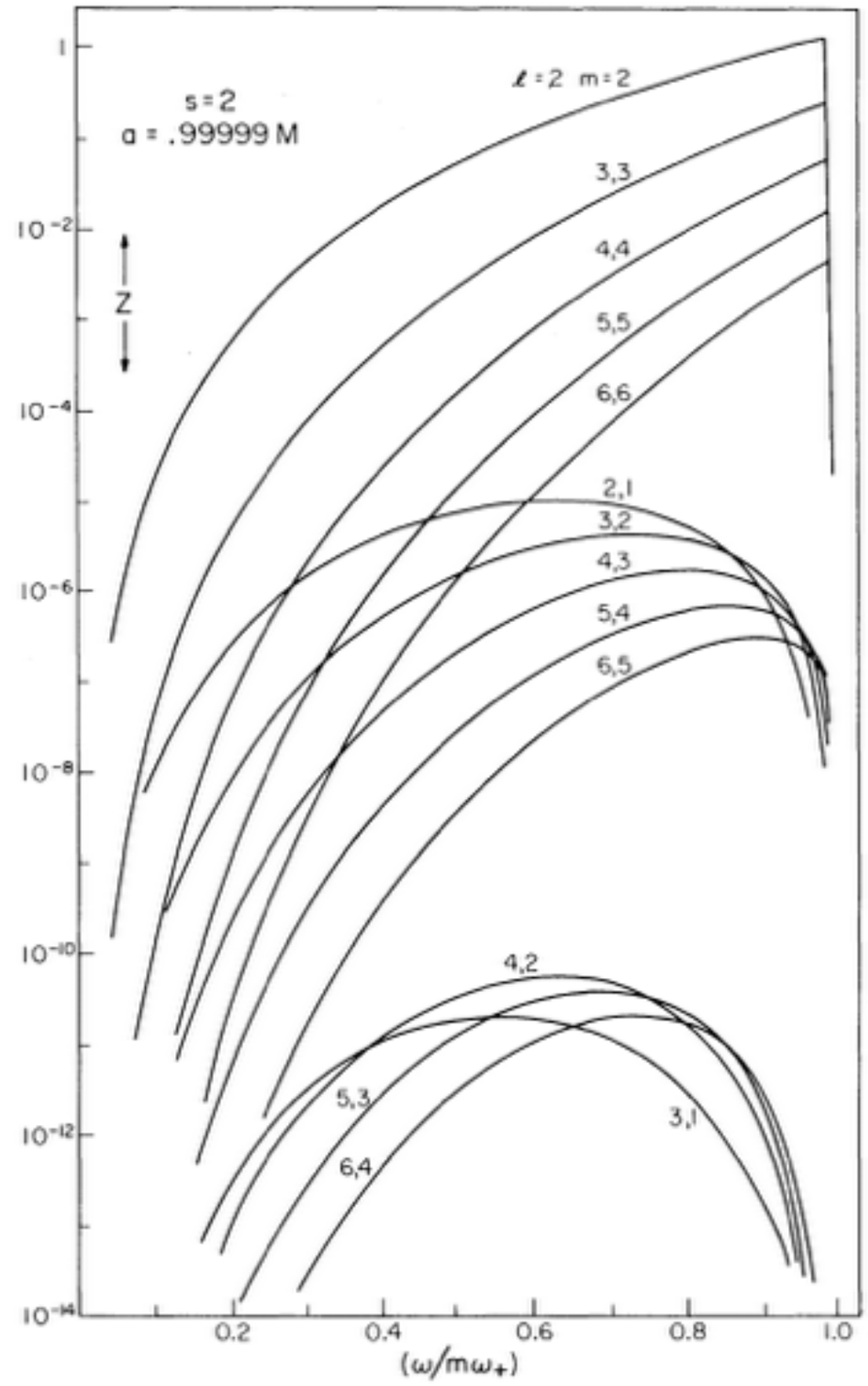
- Ingoing flux at horizon can correspond to negative E_∞ flux

- For wave with angular quantum number m,

$$\varphi \sim e^{i\omega t - im\phi}$$

$$P \sim \varphi_0^2 A_H \omega(\omega - m\Omega_H)$$

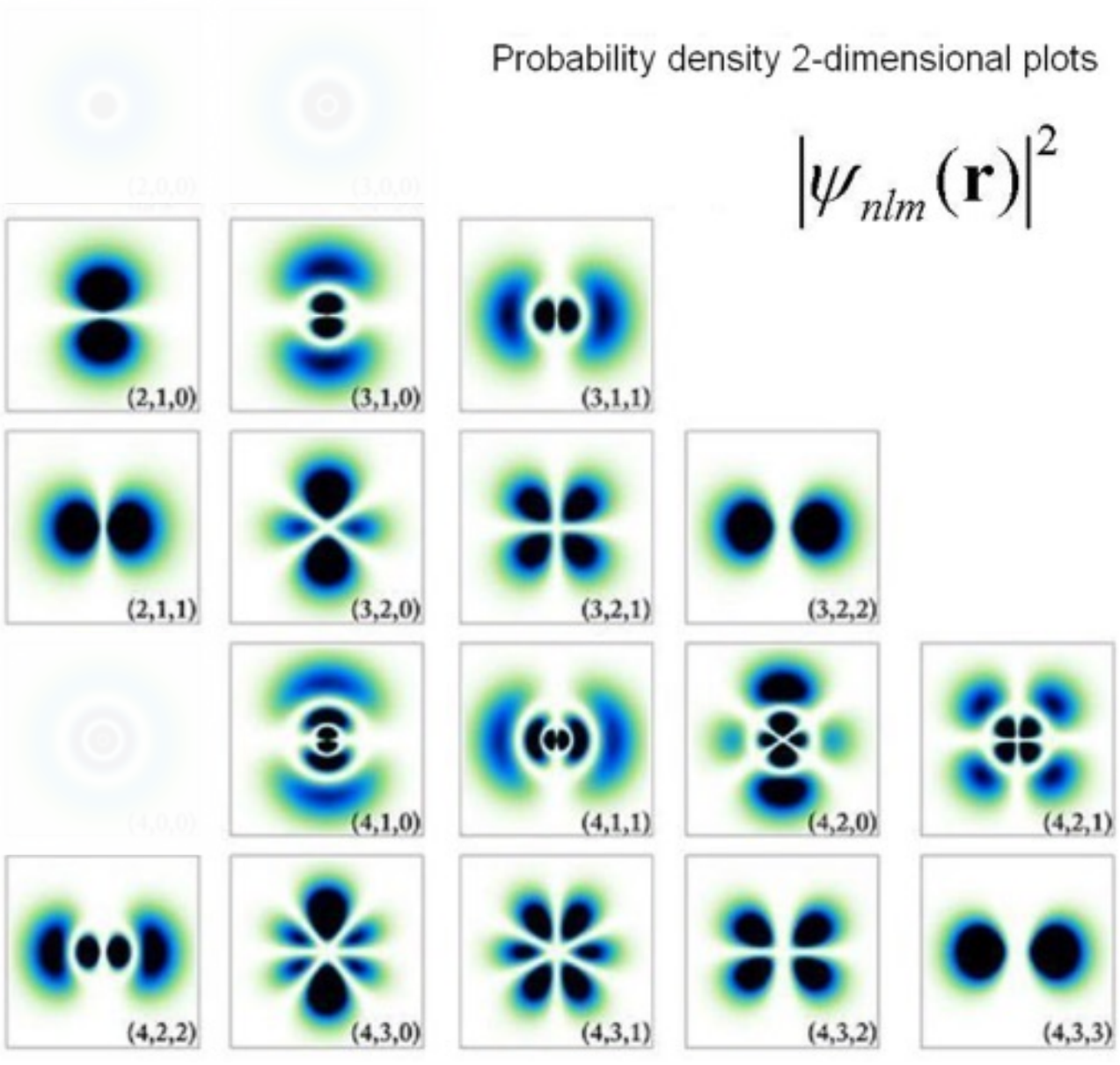
- Incoming waves can be scattered with amplification (max 4.4% for spin-1, 138% for spin-2)



[Teukolsky & Press, 1974]

Non-relativistic bound states

- For small mass, bound state spectrum is hydrogen-like



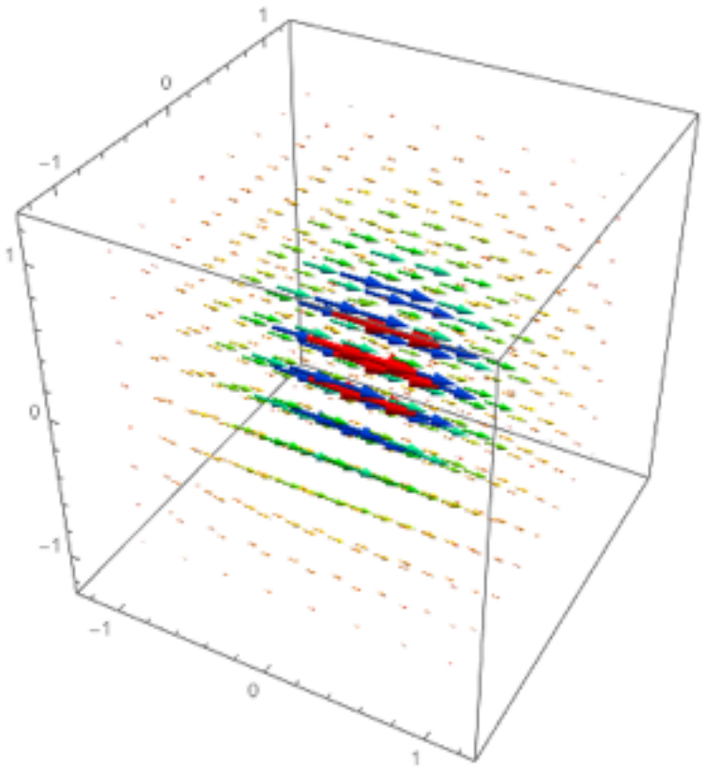
$$\alpha \equiv GM\mu = r_g\mu$$

$$\omega_n \simeq \mu\left(1 - \frac{\alpha^2}{2n^2}\right)$$

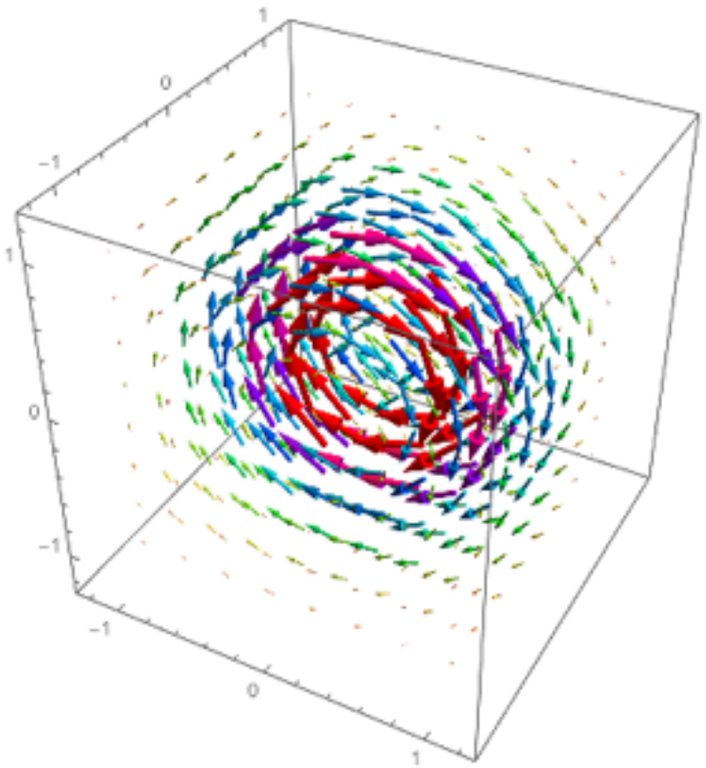
$$r_n \sim \frac{n^2}{\mu\alpha} \sim 4 - 400 r_g$$

Vector bound states

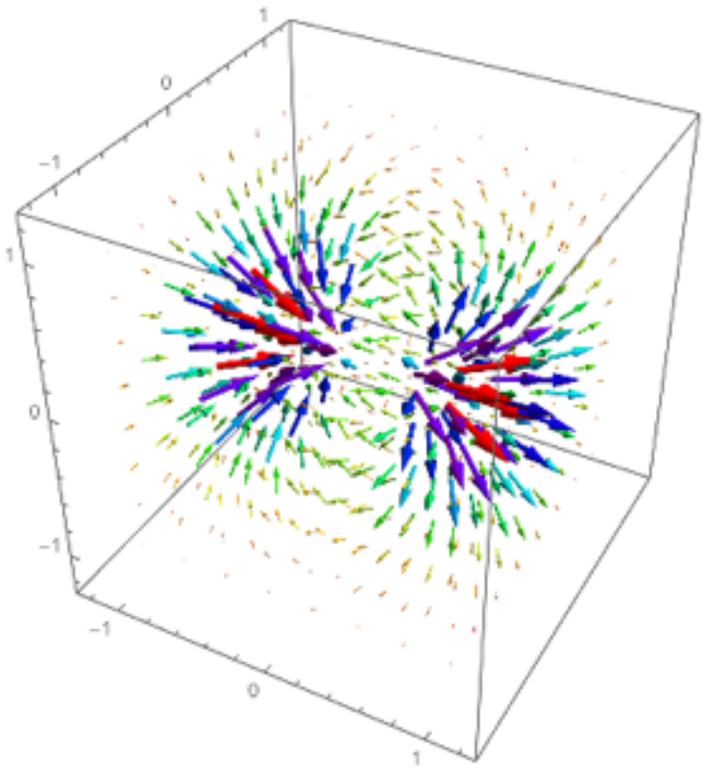
Hydrogen-like radial profile, vector spherical harmonic angular



$j = 1, l = 0$



$j = 1, l = 1$



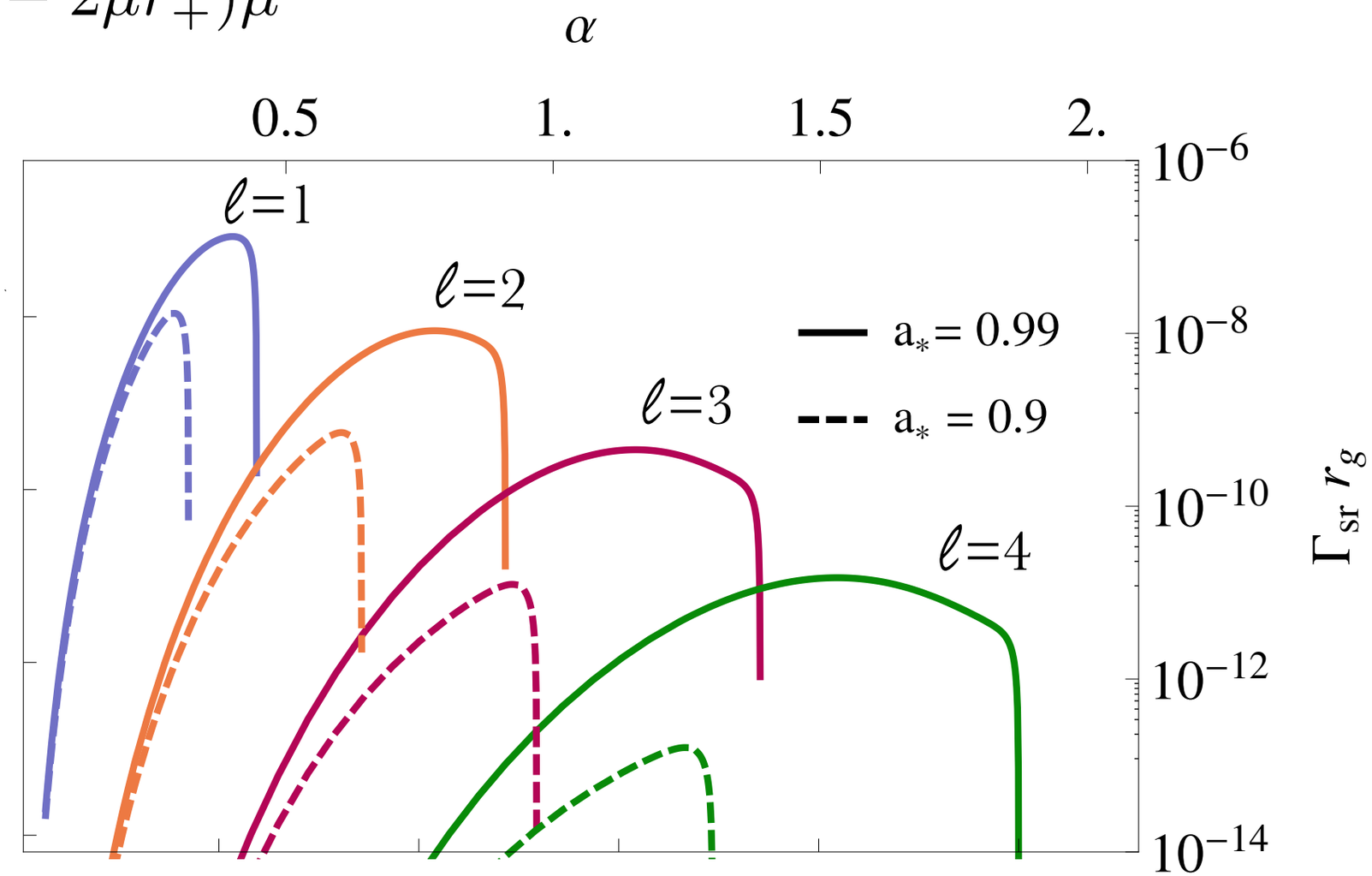
$j = 1, l = 2$

Superradiant growth rates (scalars)

- For scalar field, energy flux across horizon $\sim A_H \varphi_H^2 \omega(\omega - m\Omega_H)$

- Smaller alpha, larger l $\Rightarrow$ amplitude near horizon suppressed

$$\mathrm{Im}(\omega) \sim \alpha^{4l+4}(a_* m - 2\mu r_+)\mu$$



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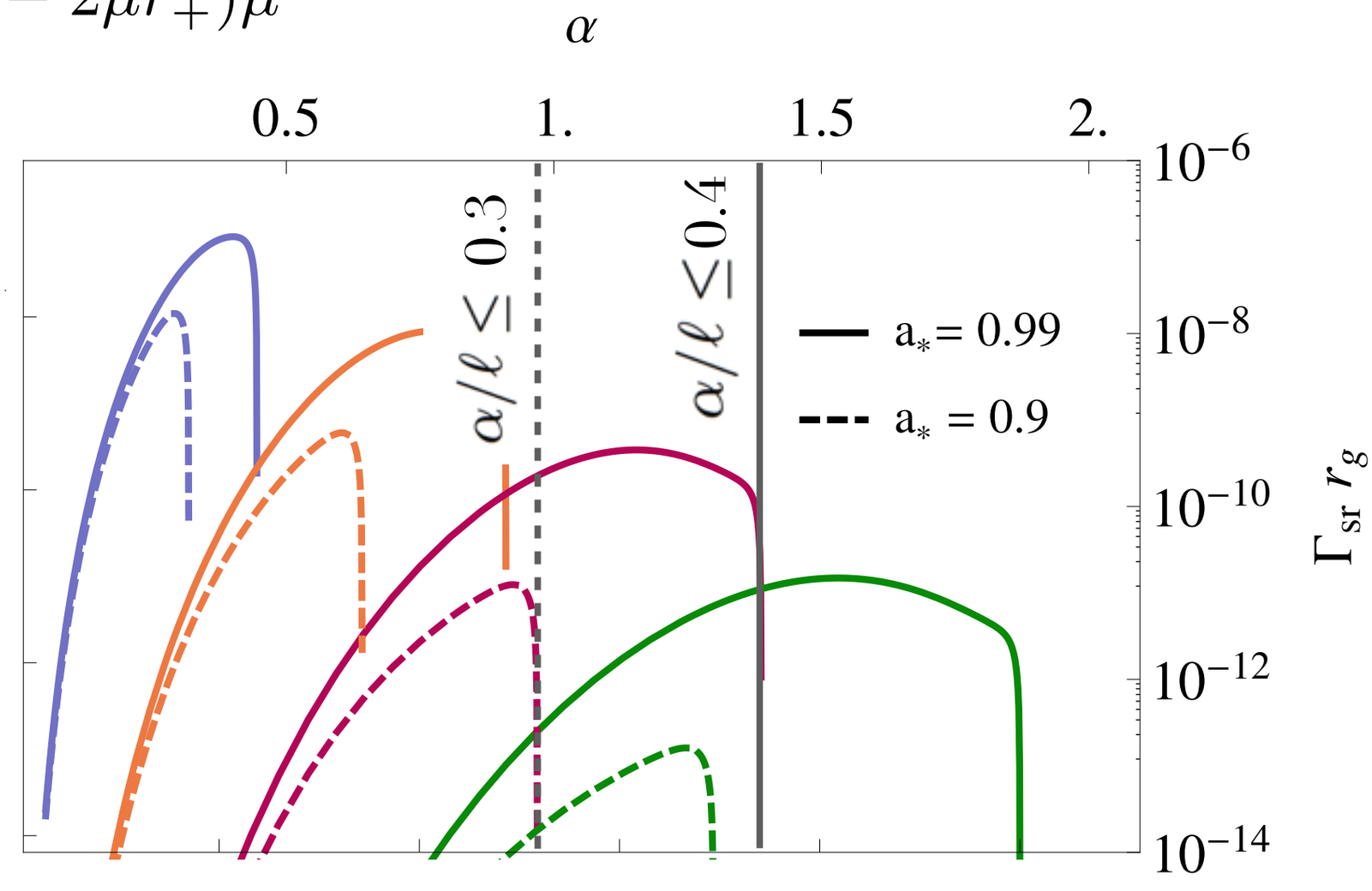
- If $\alpha/m > 1/2$ then angular phase velocity faster than horizon, so mode is decaying

- Fastest growth rate for $\mu \sim 1/(GM_{\rm BH})$



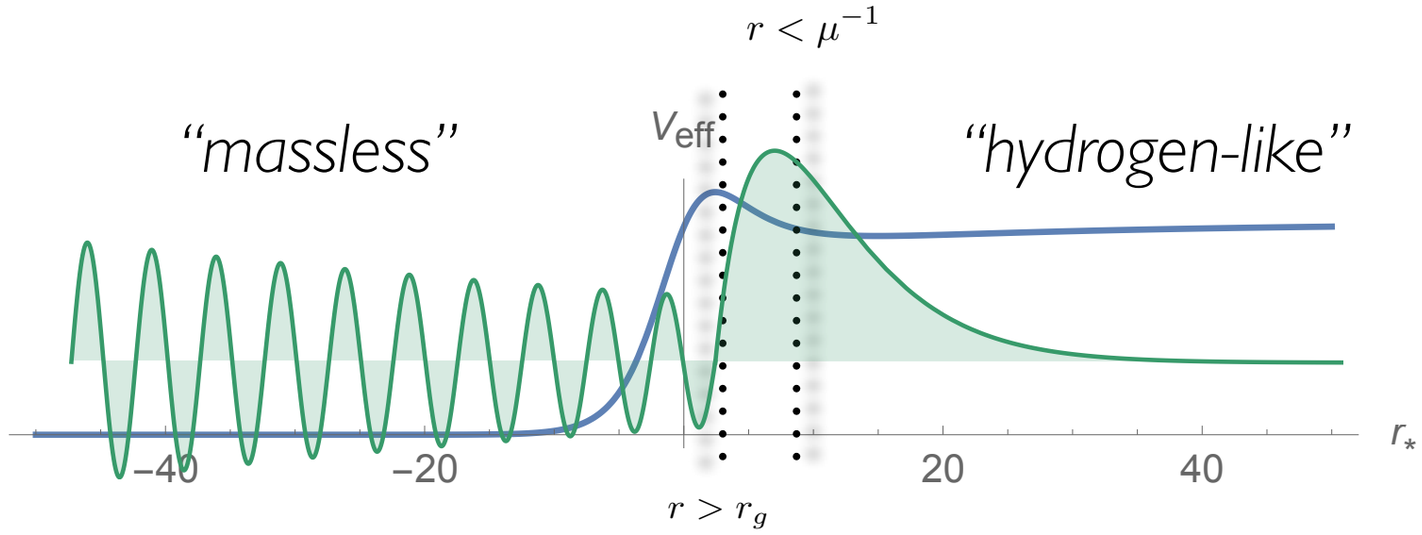
Superradiant growth rates (vectors)

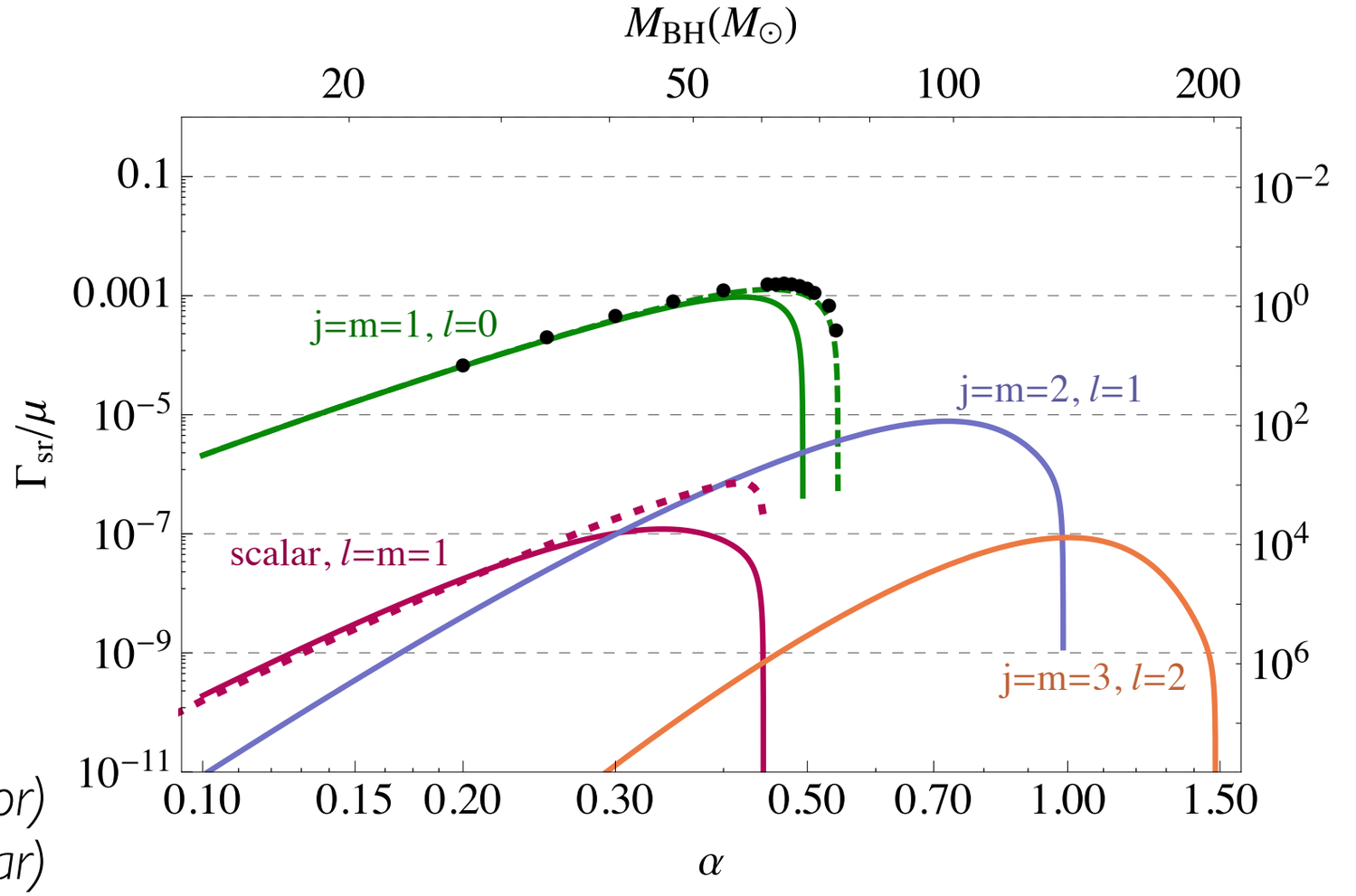
- At small α , vector growth rate is

$$\mathrm{Im}(\omega) \sim \alpha^{2l+2j+4}(a_* m - 2\mu r_+)\mu$$

- Match hydrogen-like bound state to "relativistic" wave near horizon

- j=1, l=0 state grows faster than scalar

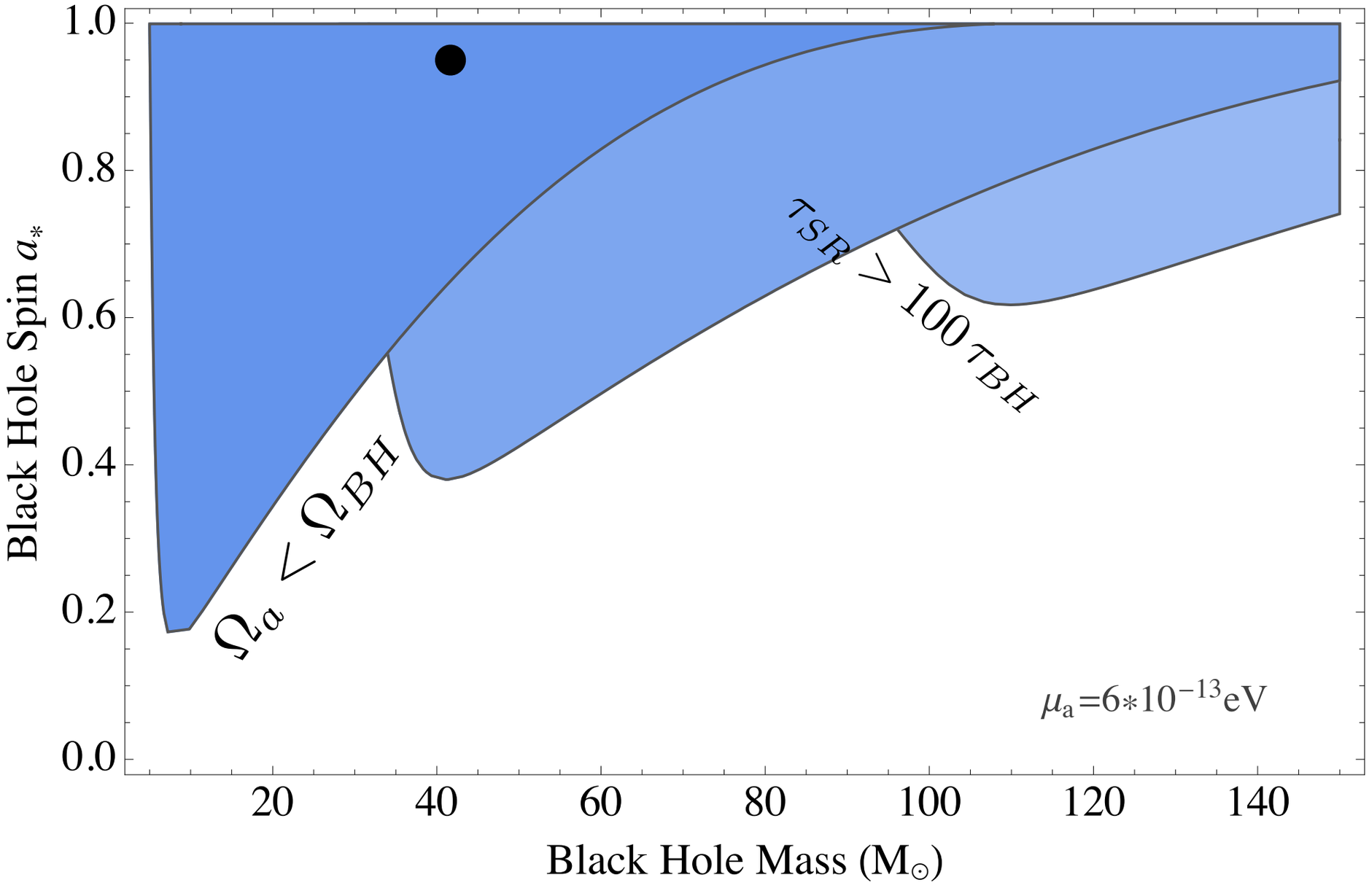




Numerical results:
[East, 1705.01544] (vector)
[Dolan, 0705.2880] (scalar)

Superradiance: a history

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



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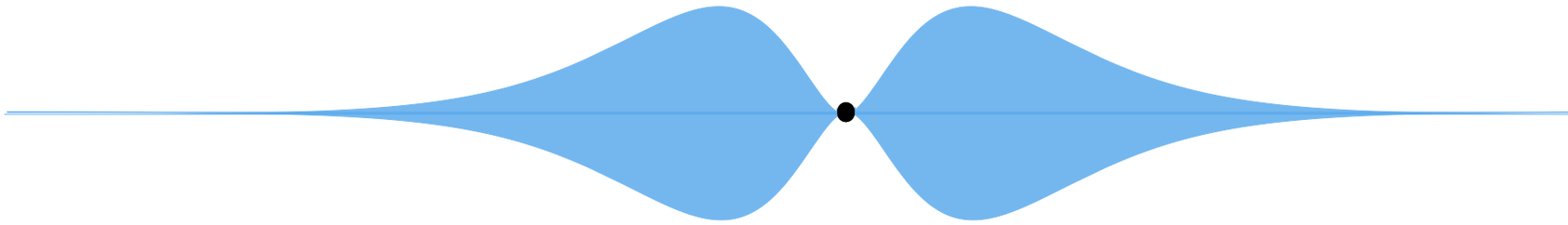
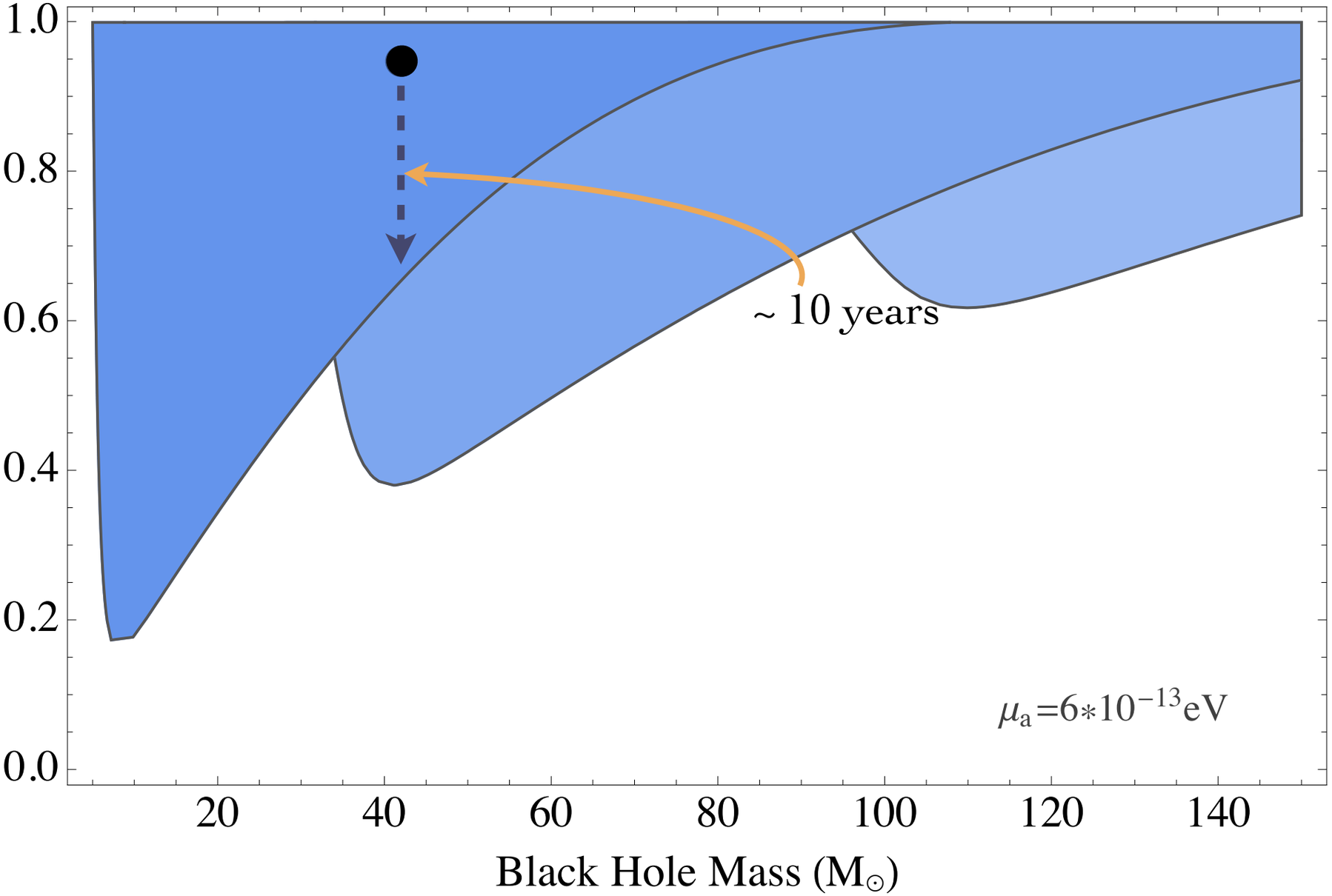


BH spins down and *fastest-growing* level is formed



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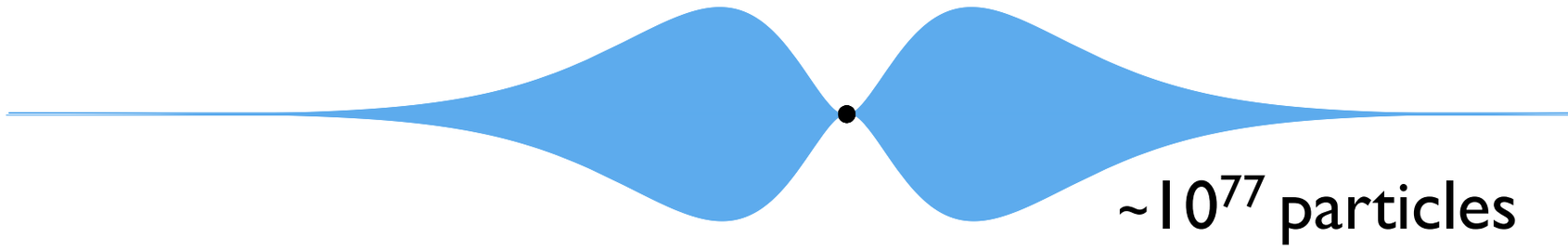
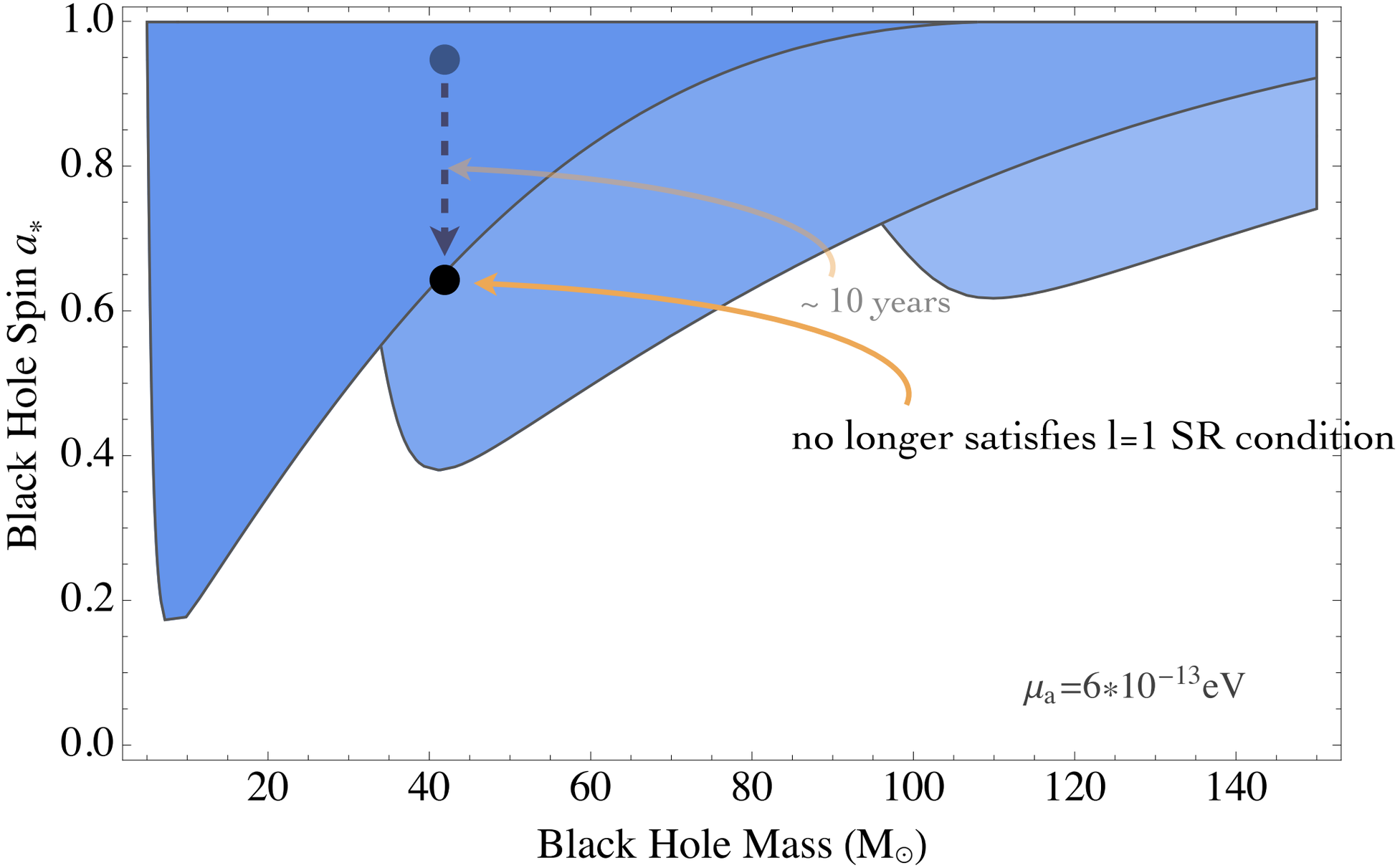


Once BH angular velocity matches that of the level, growth stops



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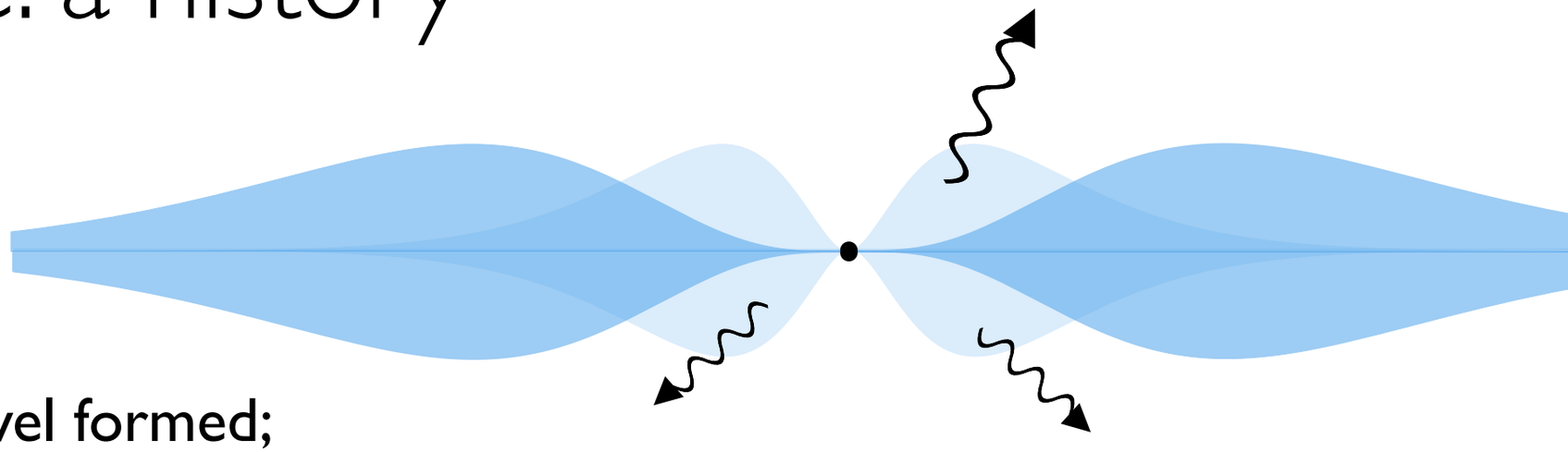
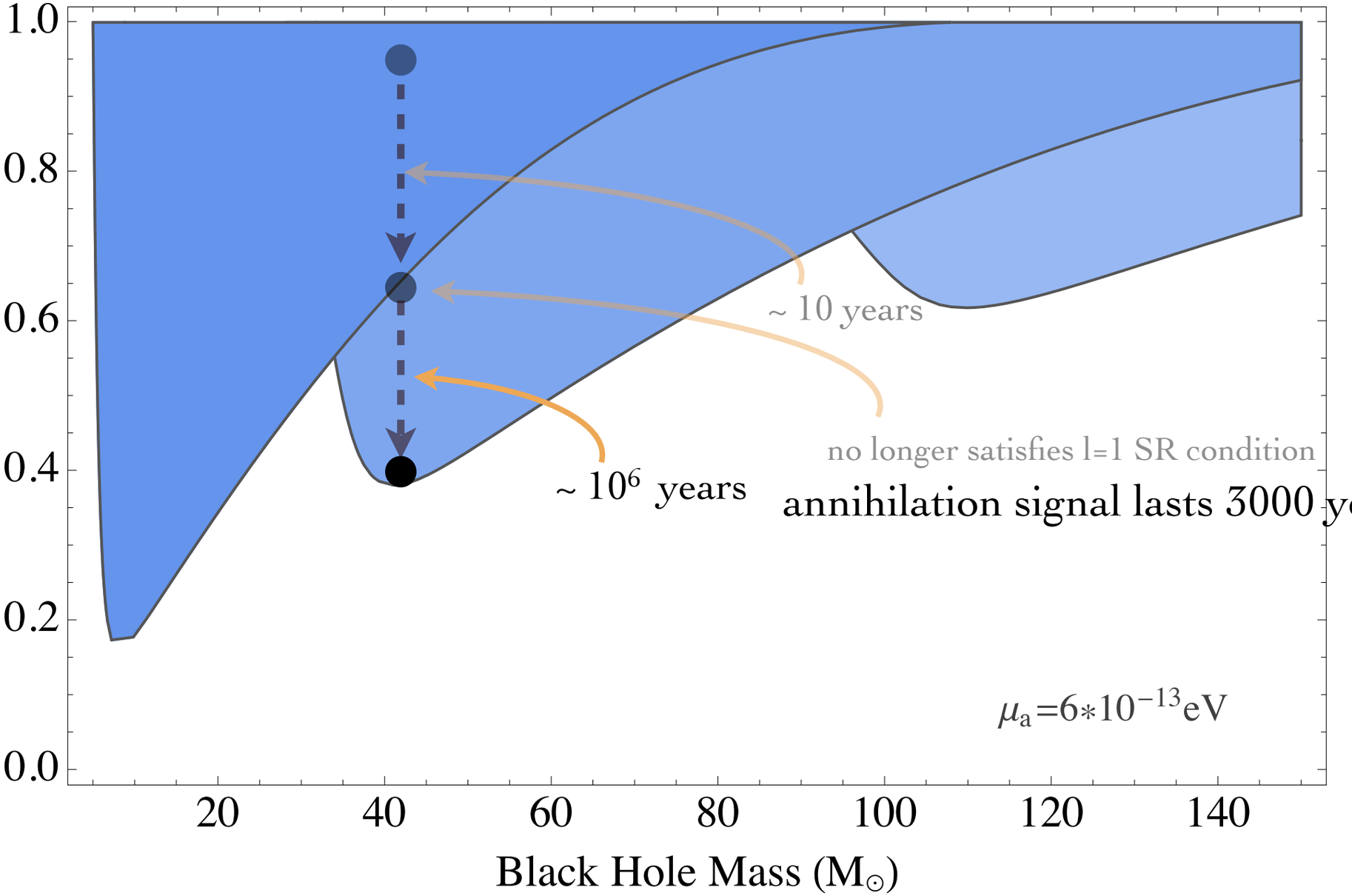


BH spins down and *next* level formed;
annihilations to GWs deplete first level



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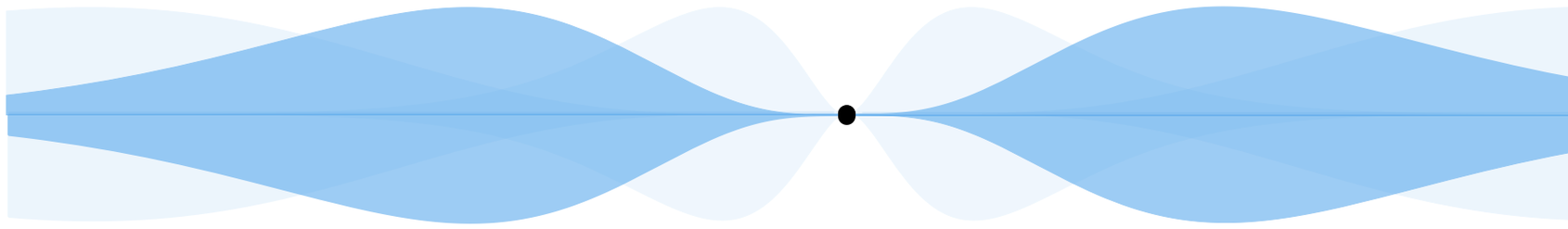
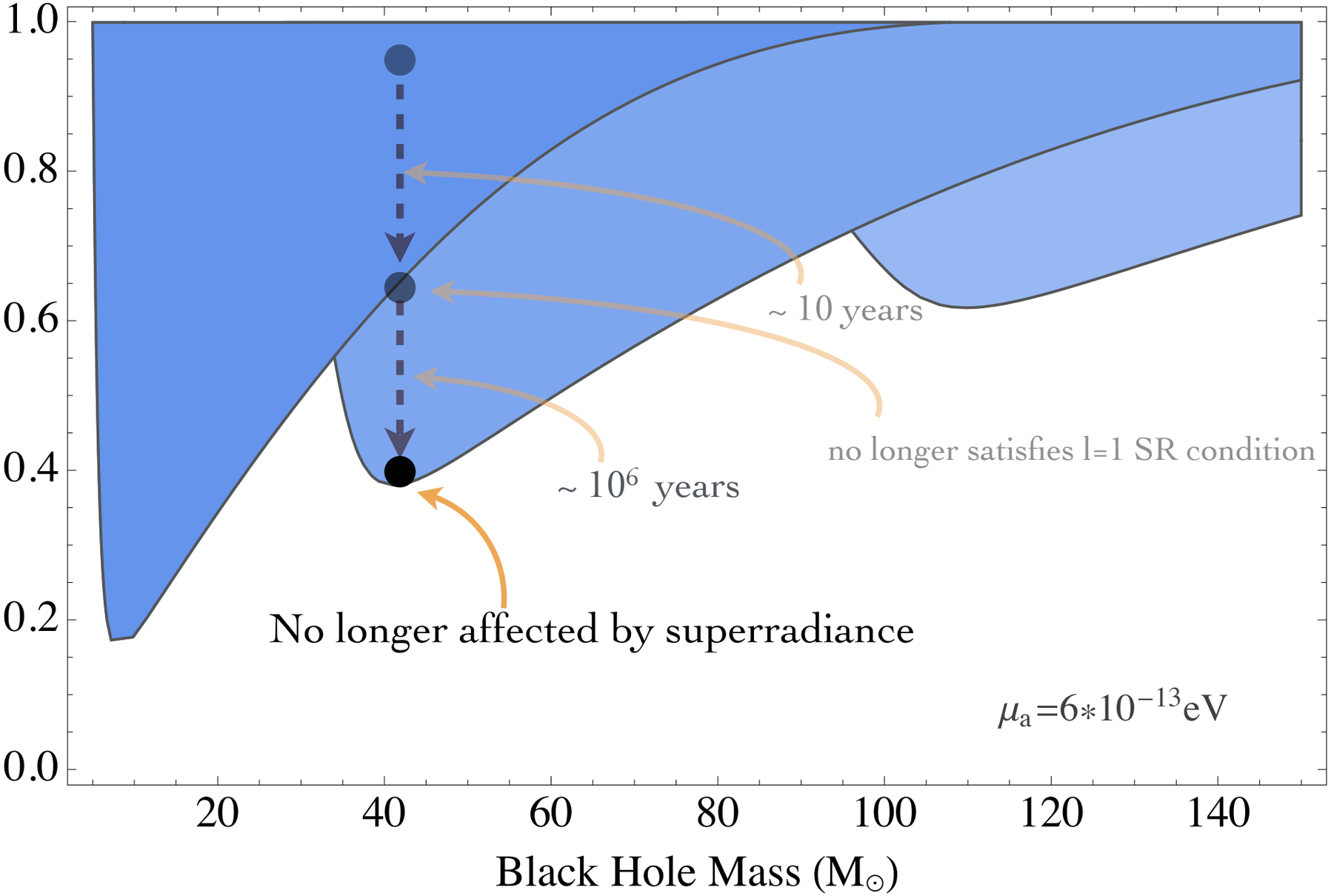


The following level has a superradiance rate exceeding age of BH



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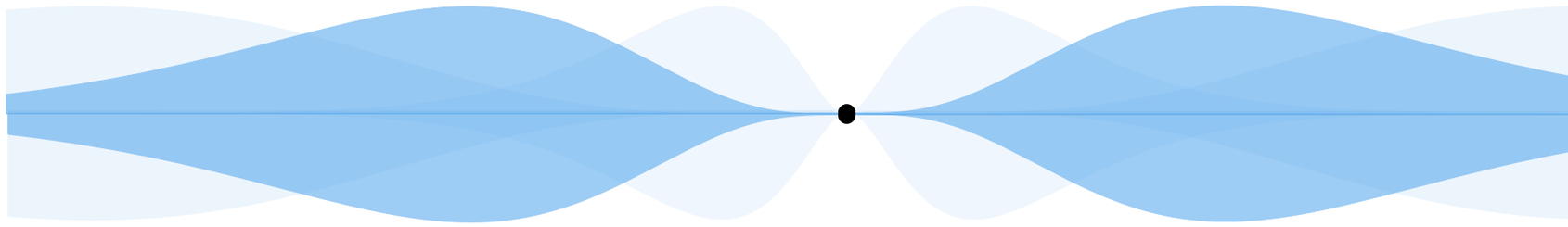
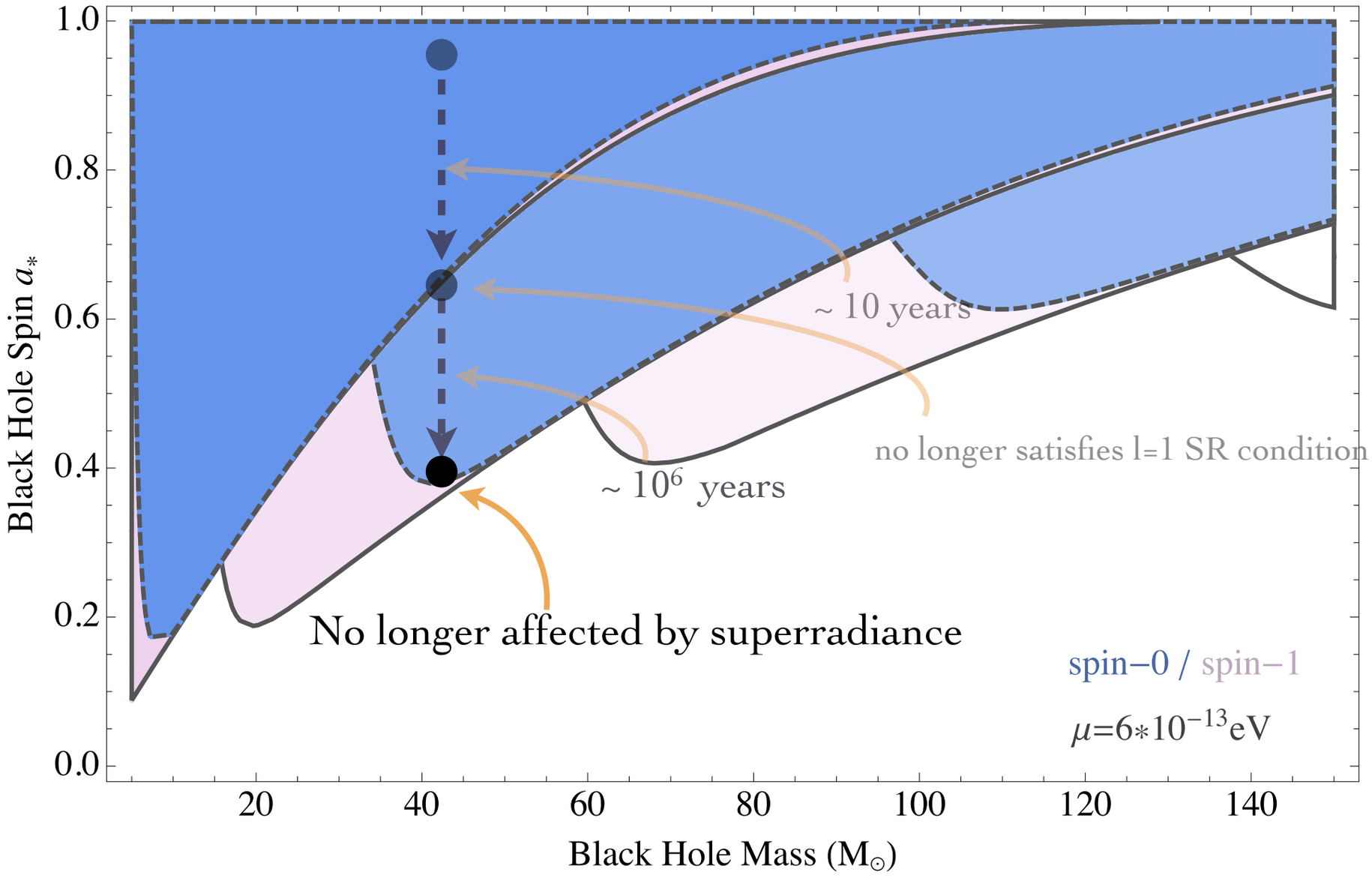


Spin 1 particles: faster superradiance rate for the same mass particle



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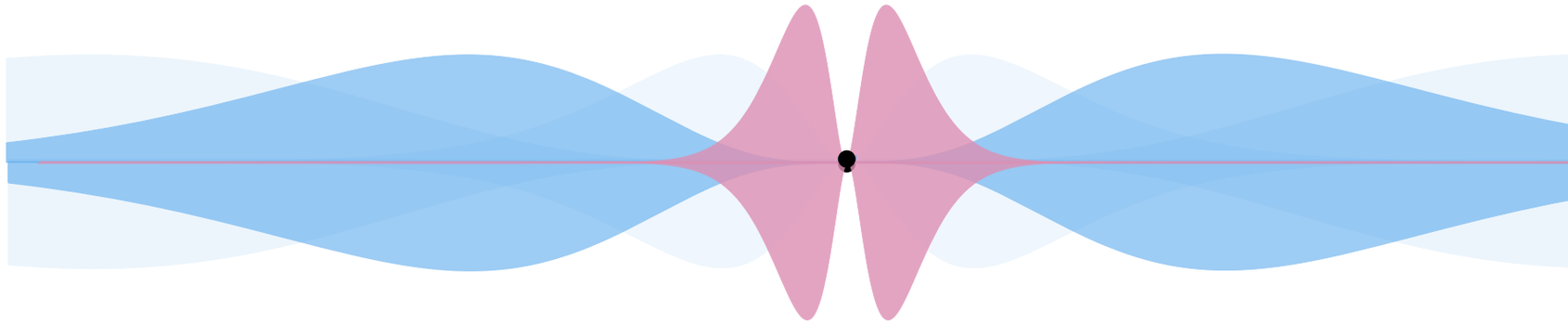

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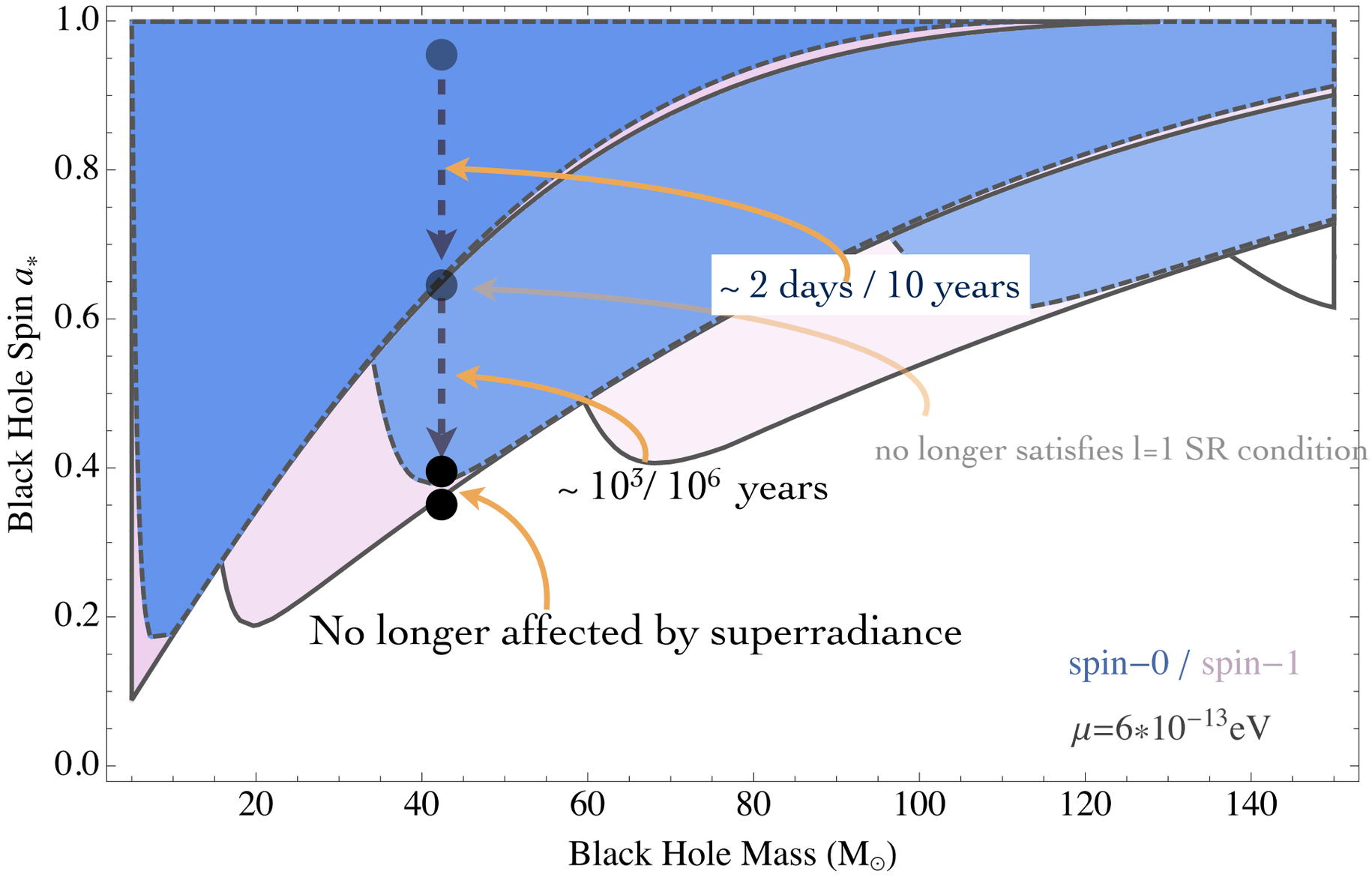

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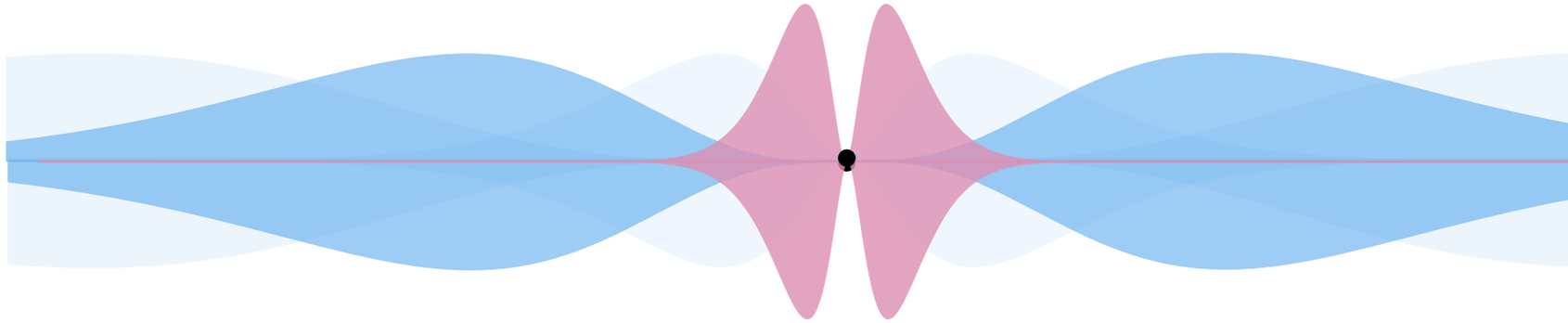

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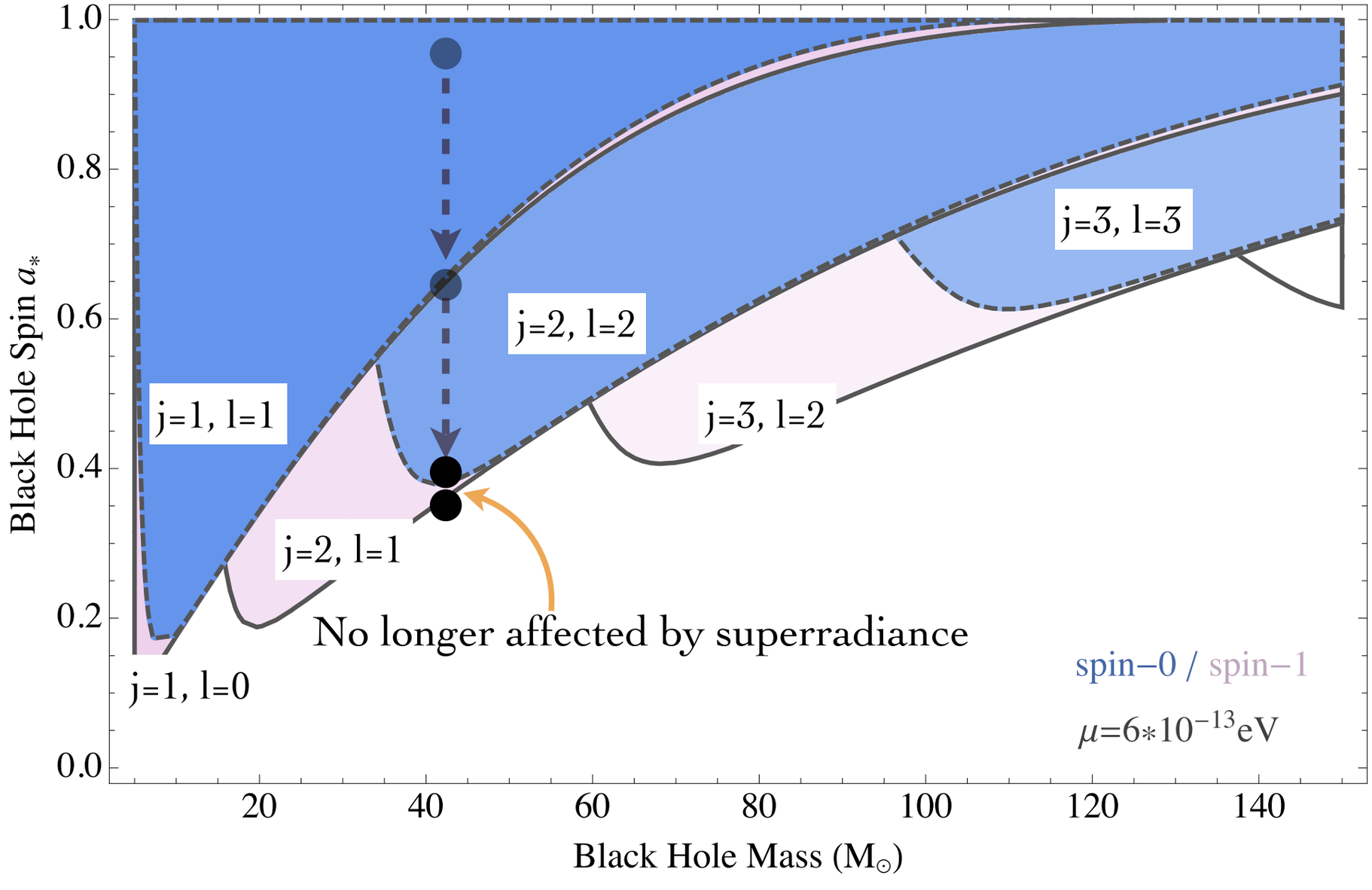


Vectors can have higher total angular momentum for a given orbital angular momentum

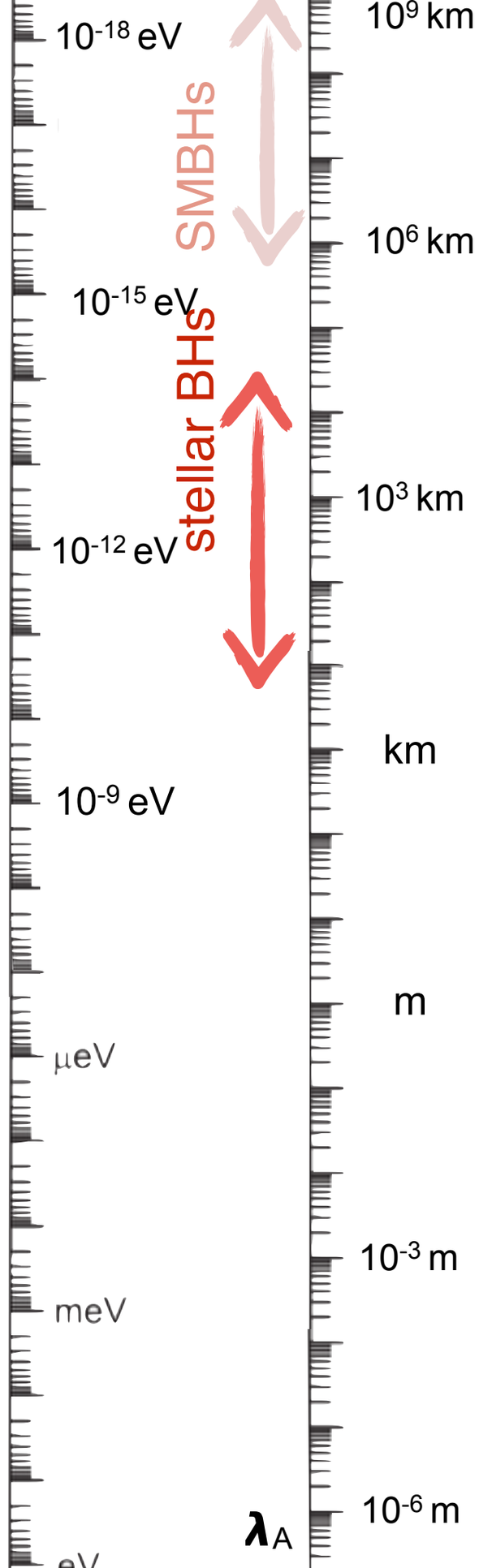
Black hole superradiance for light particles

- Gravitational coupling: can be any light, weakly coupled boson

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

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

- Depends on particle mass and spin
- Does not rely on DM density
- Superradiance is a kinematic effect so does not require precise resonance



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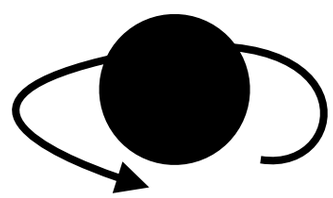
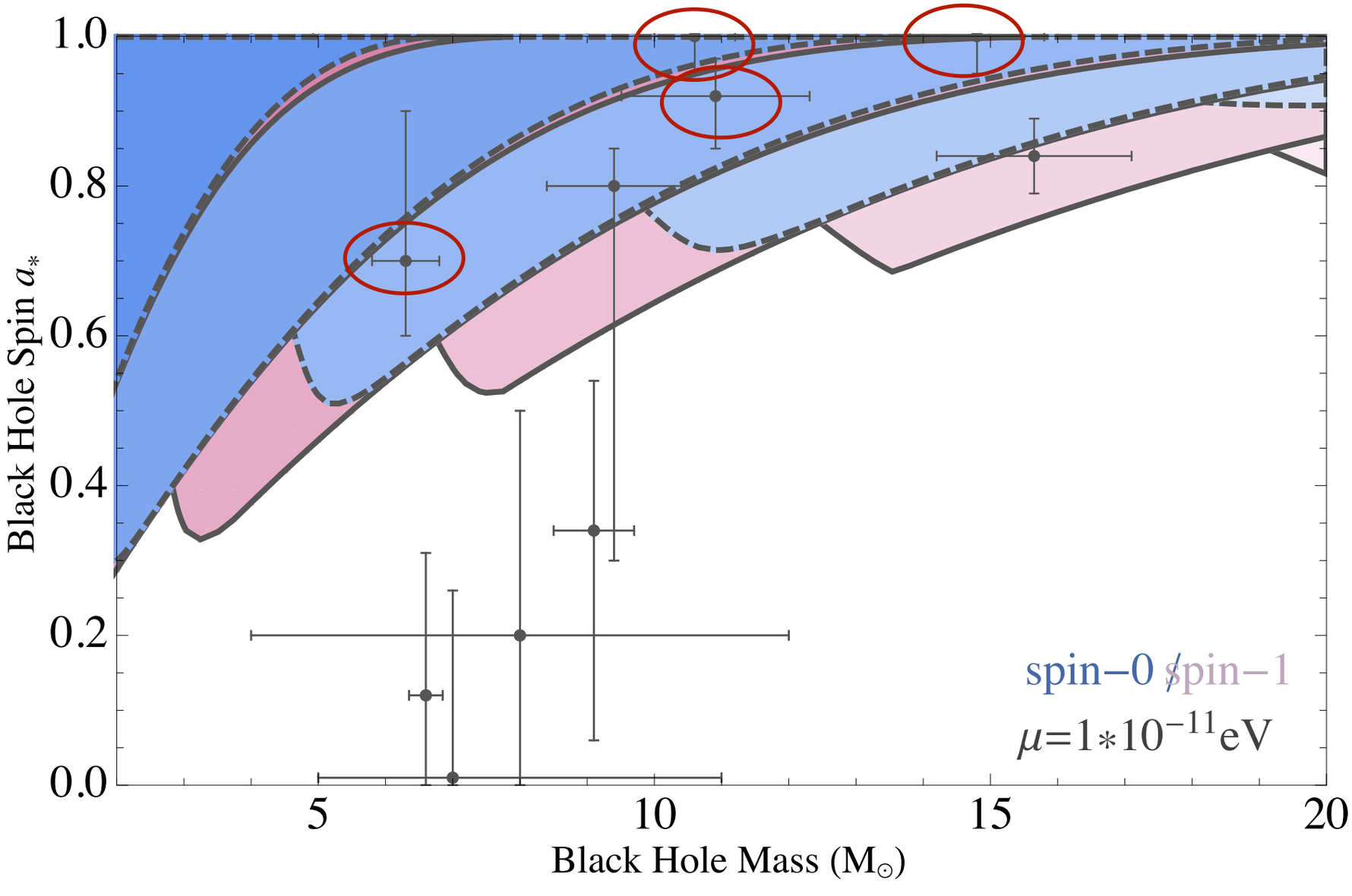
  - Spin-down of black holes 
  - Coherent gravitational wave emission

Black Hole Spins

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

several black holes disfavor this scalar/vector mass



Black Hole Spins

In the presence of a light boson, a black hole will spin down, if:

1. There is enough time,

$$\Gamma_m \gtrsim \frac{1}{\tau_{\rm BH}} \log N_m$$

BH lifetime and accretion time are long compared to time to grow the full cloud (~100 SR times)

scalar

$$\alpha \gtrsim 0.02 \left(\frac{4\times10^7\,{\rm yr}}{\tau_{\rm BH}}\right)^{1/8} \left(\frac{10^{-12}\,{\rm eV}}{\mu}\right)^{1/8}$$

vector

$$\alpha \gtrsim 0.002 \left(\frac{4\times10^7\,{\rm yr}}{\tau_{\rm BH}}\right)^{1/6} \left(\frac{10^{-12}\,{\rm eV}}{\mu}\right)^{1/6}$$

2. Perturbations are small,

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

Companion star/BH/accretion disk can mix growing and decaying modes through non axisymmetric gravitational potential

scalar

$$\alpha \gtrsim 0.05 \left(\frac{10^6 r_g}{R}\right)^{4/15} \left(\frac{M'}{M_{\rm BH}}\right)^{2/15}$$

vector

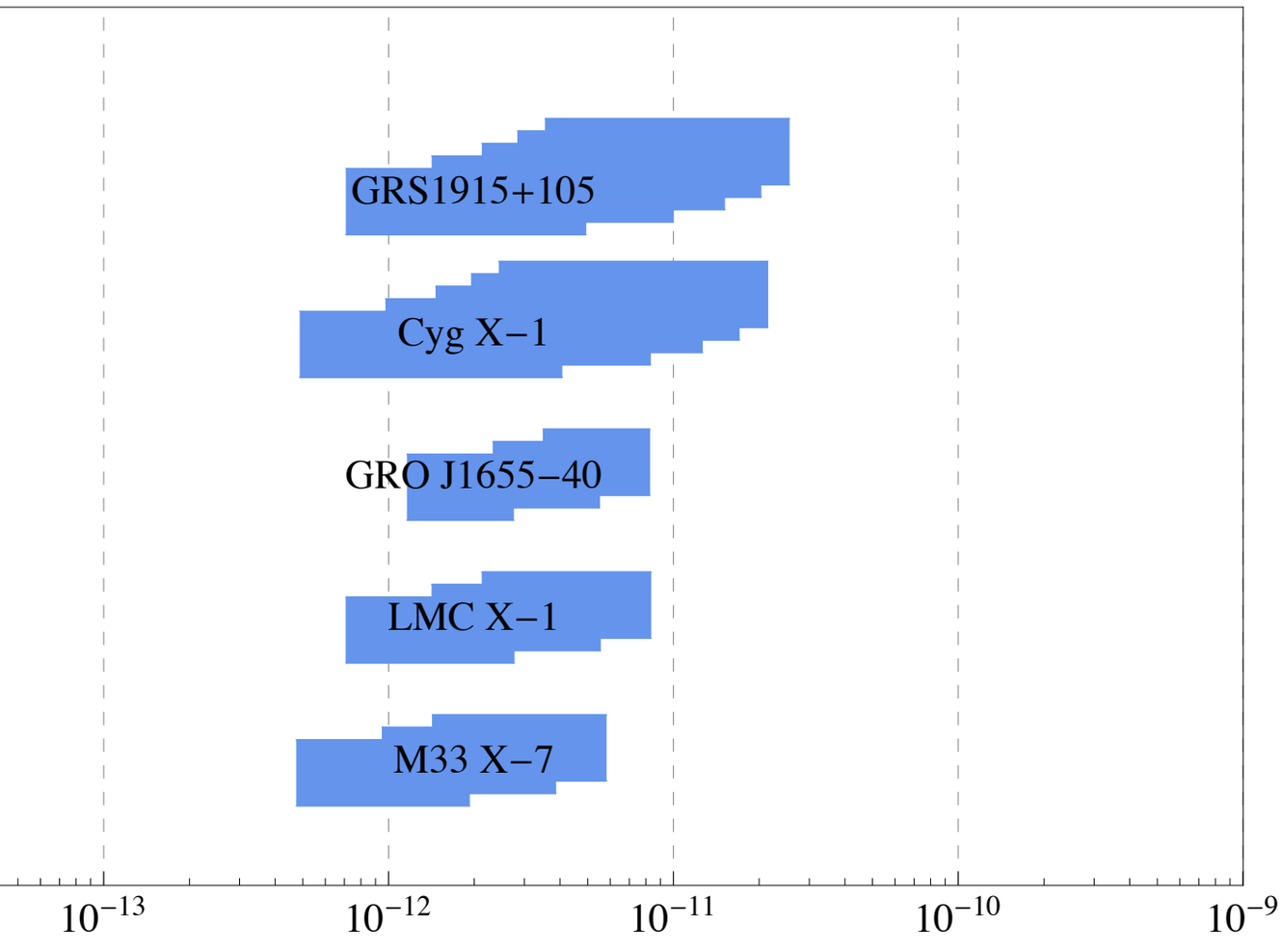
$$\alpha \gtrsim 0.001 \left(\frac{10^6 r_g}{R}\right)^{4/7} \left(\frac{M'}{M_{\rm BH}}\right)^{2/7}$$

Black Hole Spins

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

scalar

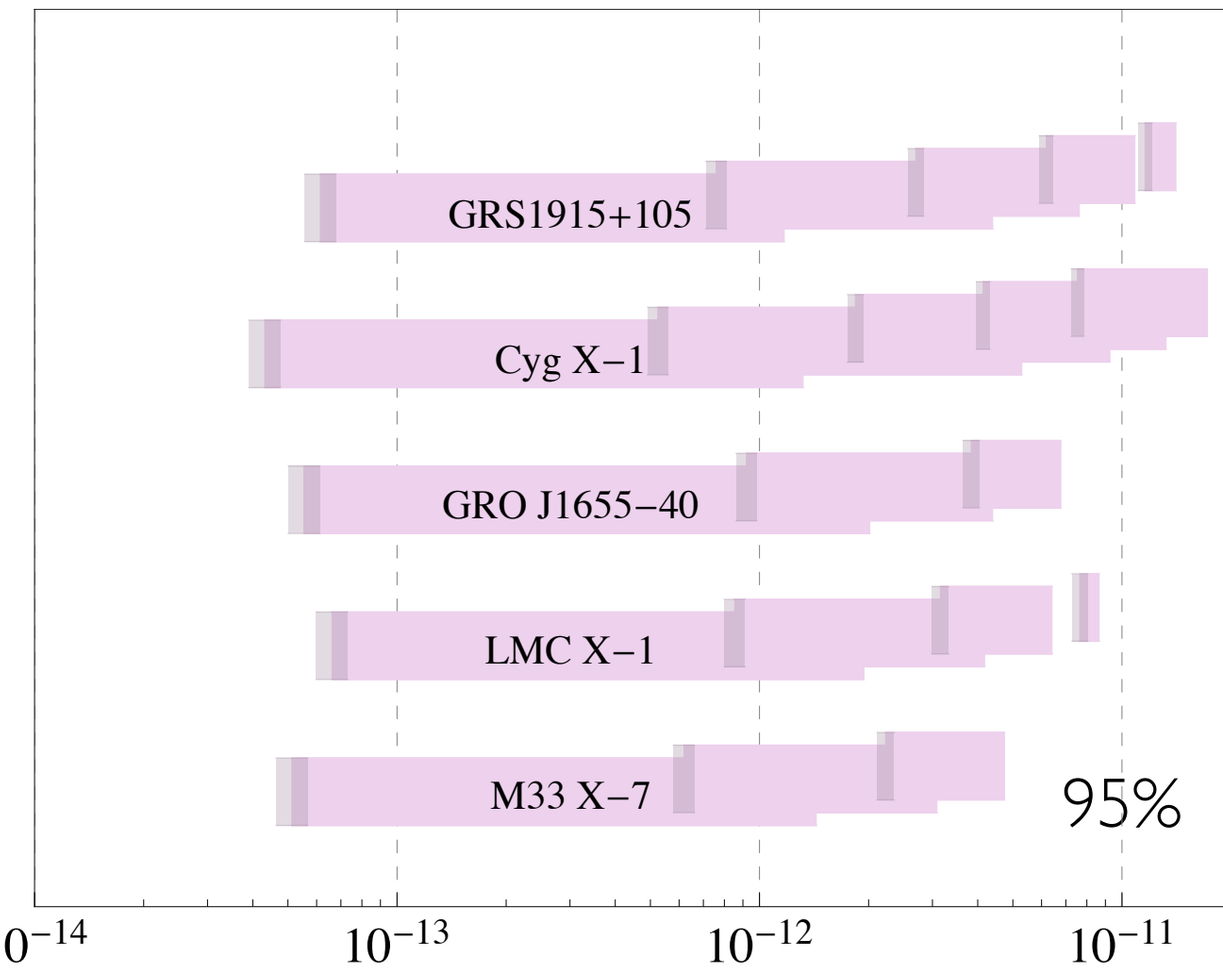
$$2 \times 10^{-11} > \mu_a > 6 \times 10^{-13} \text{ eV}$$



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

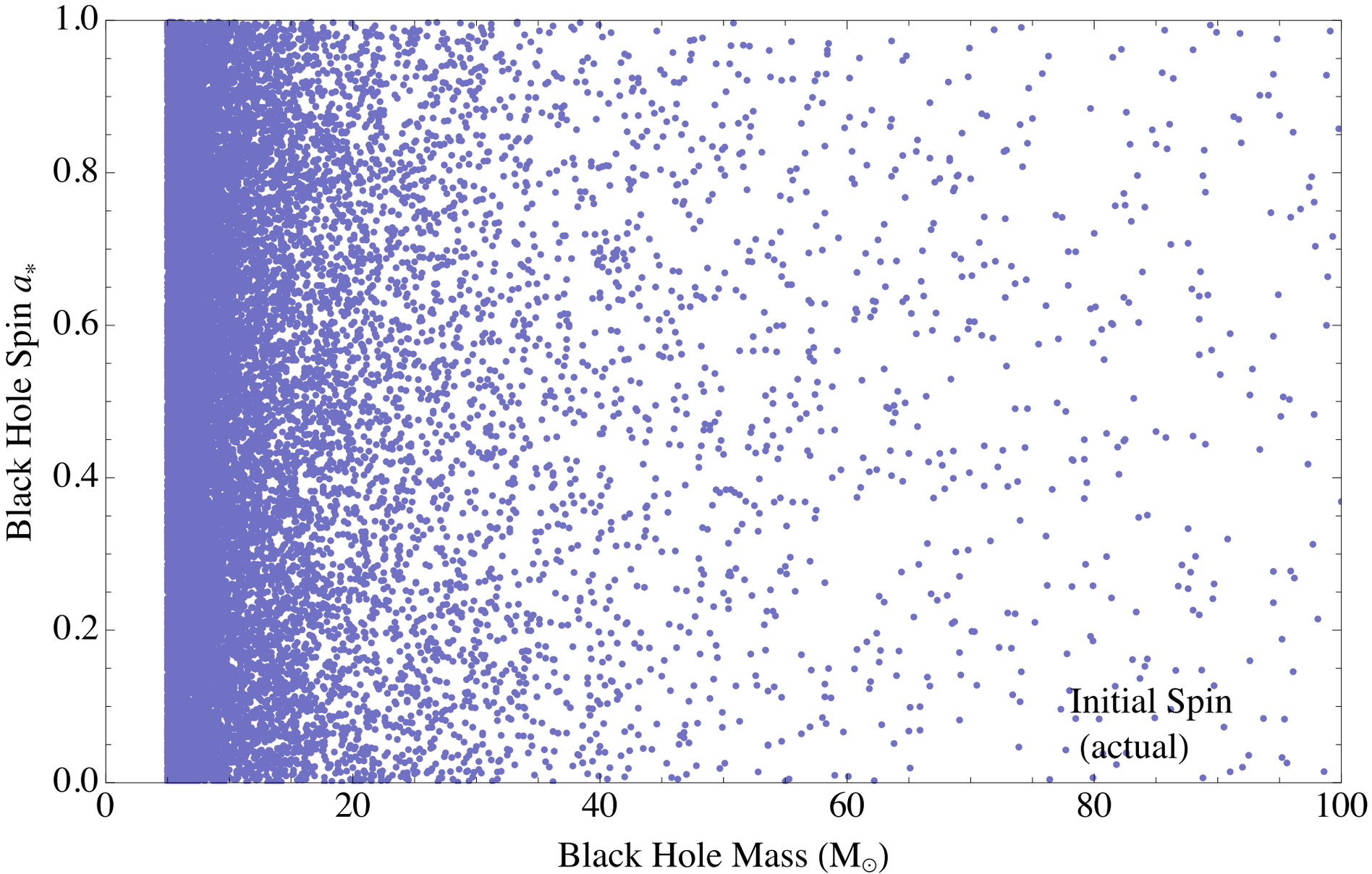
vector

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



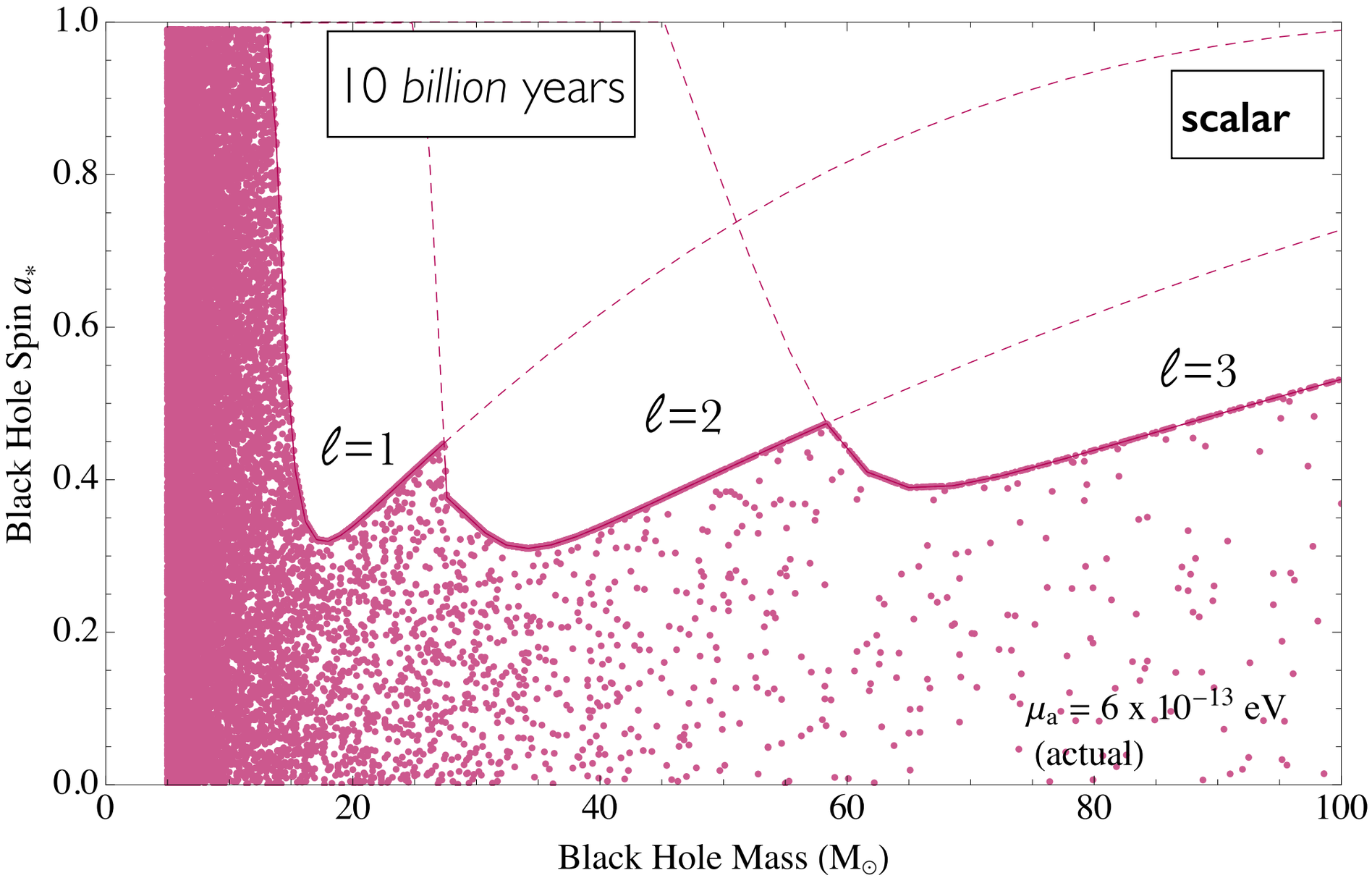
Black Hole Spins
at LIGO

12-213 BBHs/Gpc^3/yr. — 1000s of BHs merging in low-redshift universe —



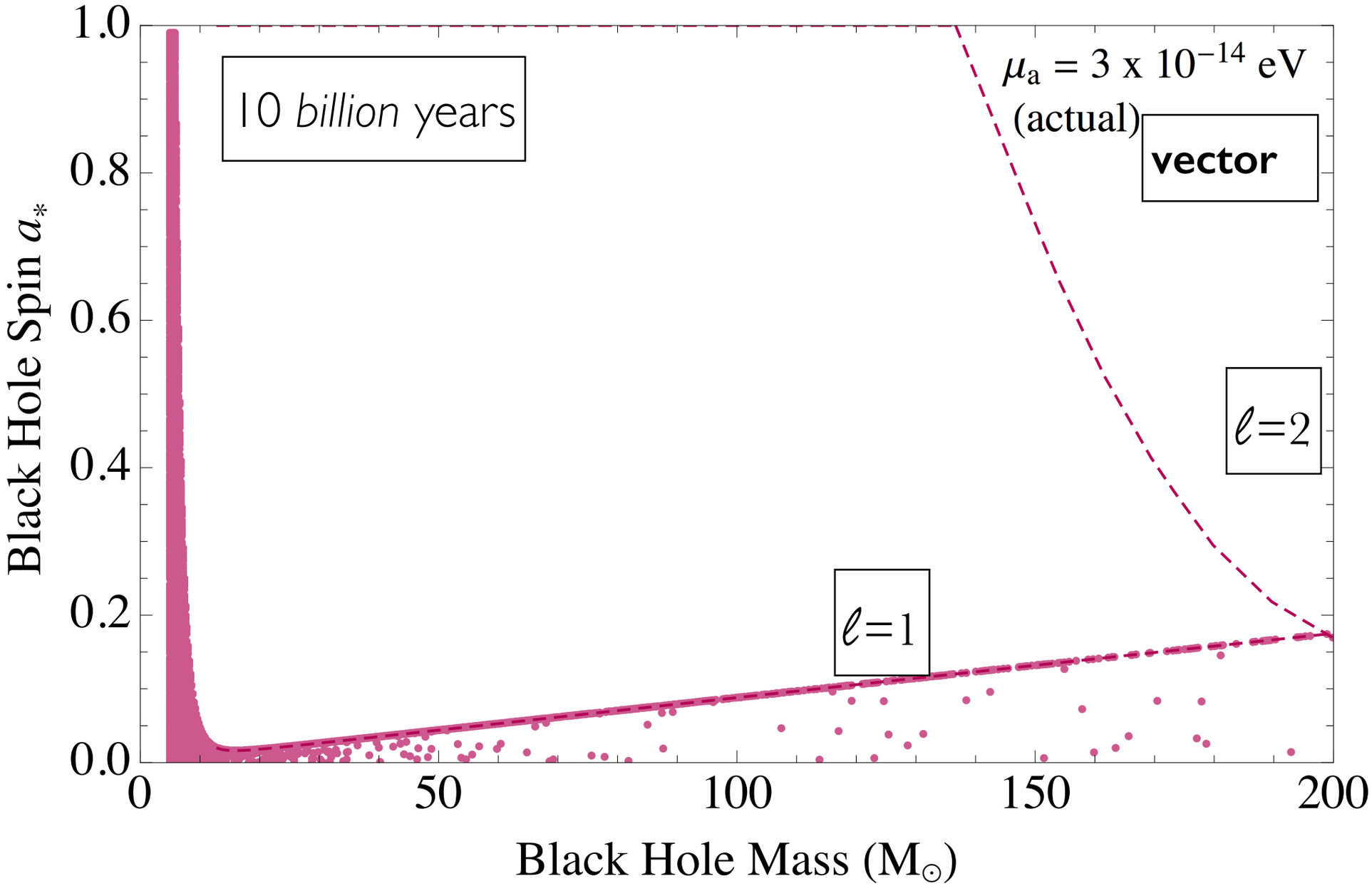
Black Hole Spins

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



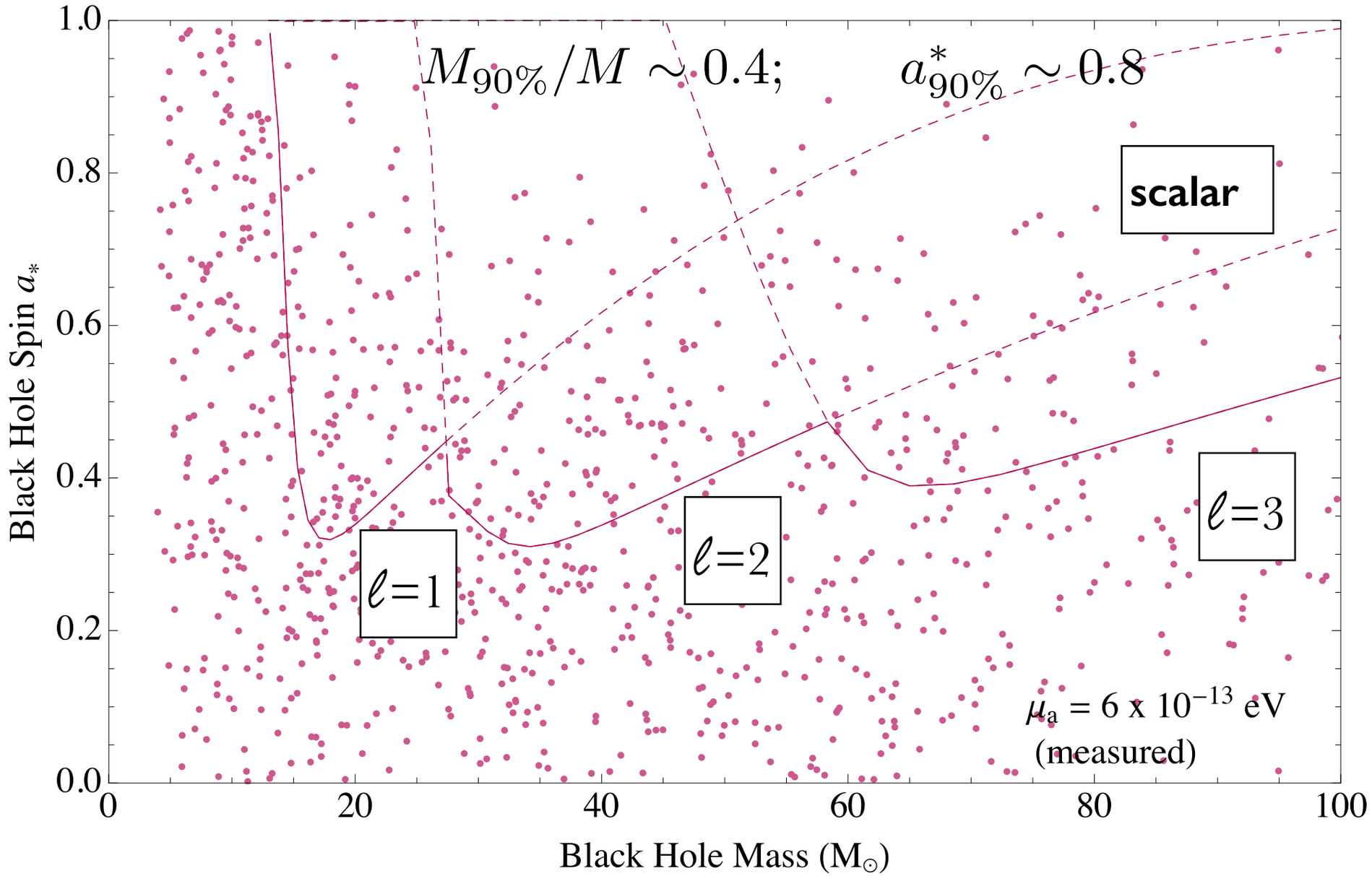
Black Hole Spins

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



Black Hole Spins

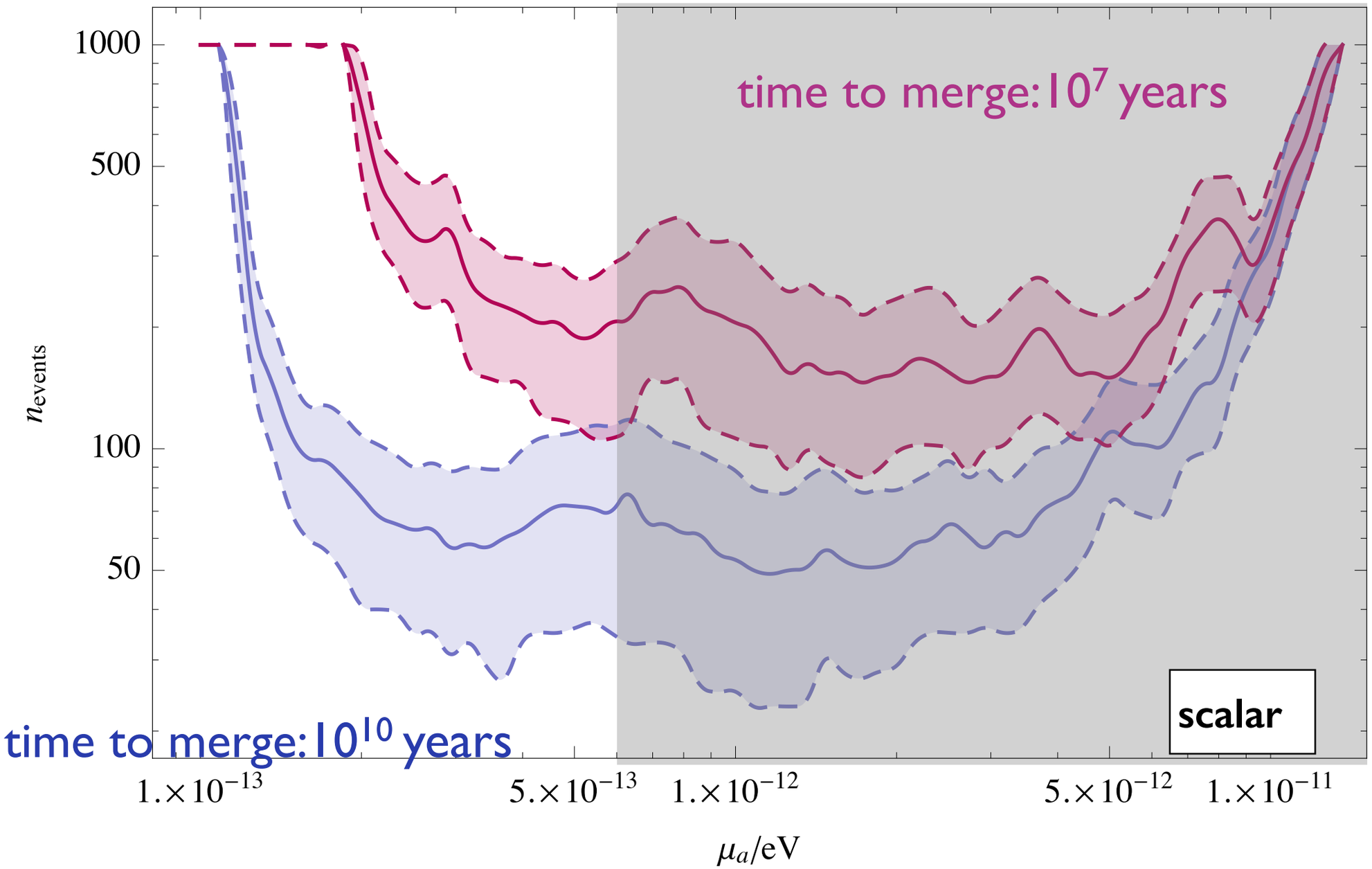
LIGO may measure hundreds of BHs in spin-mass plane



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

Black Hole Spins

Can find statistical evidence for variation in spin-mass distribution in a range of BH masses with 50-200 measurements:



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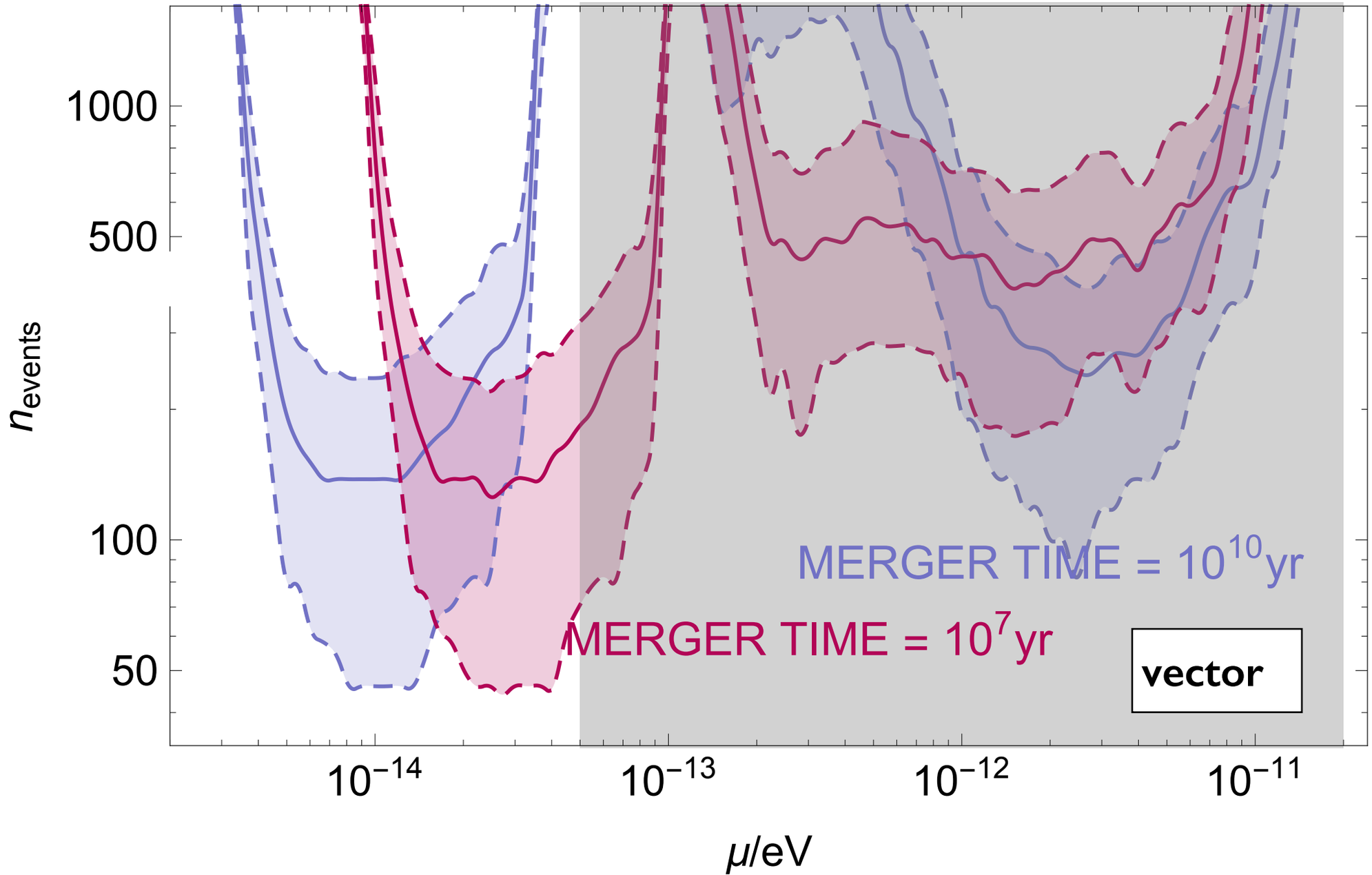
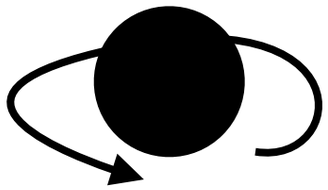
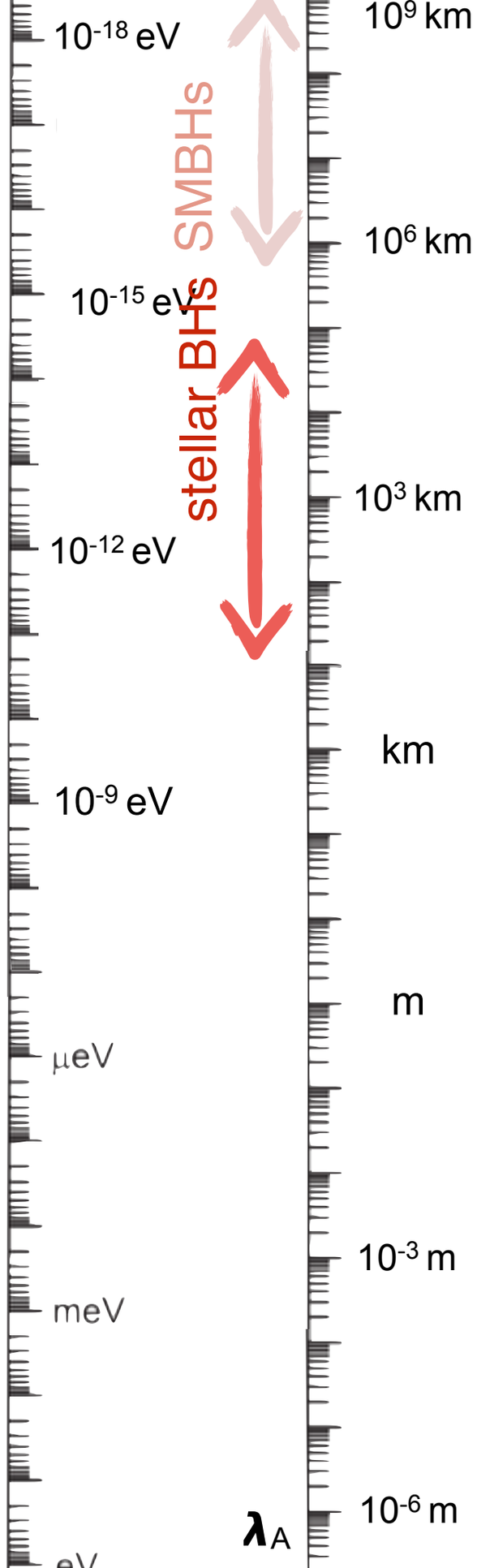




Black Hole Spins

- Astrophysical black holes are great at diagnosing presence of new light particles
- With existing data already possible to set new limits on parameter space
- Upcoming LIGO BH spin data can be used to find evidence of axions

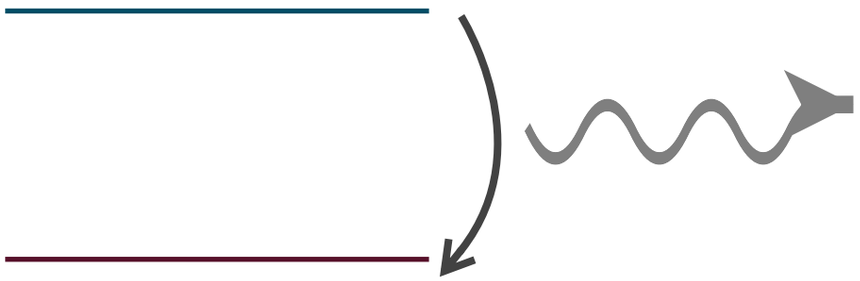


Outline

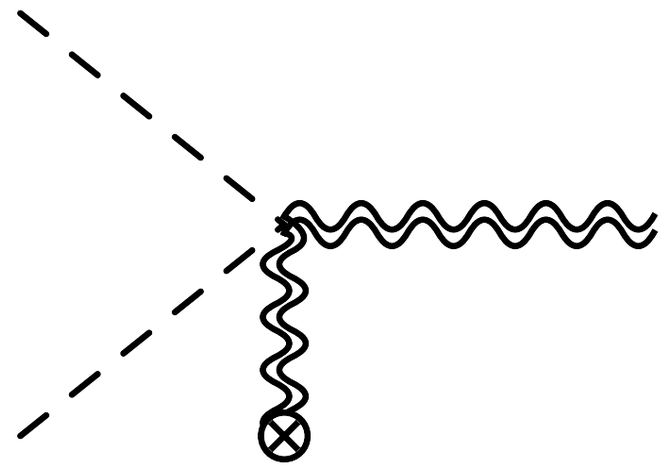
- Energy extraction from black holes
- Black hole superradiance for light scalar/vector particles
- Observational signatures
  - Spin-down of black holes
  - Coherent gravitational wave emission

Gravitational Wave Signals

- Transitions between levels

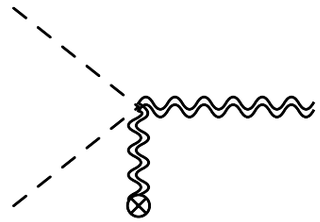


- Annihilations to gravitons

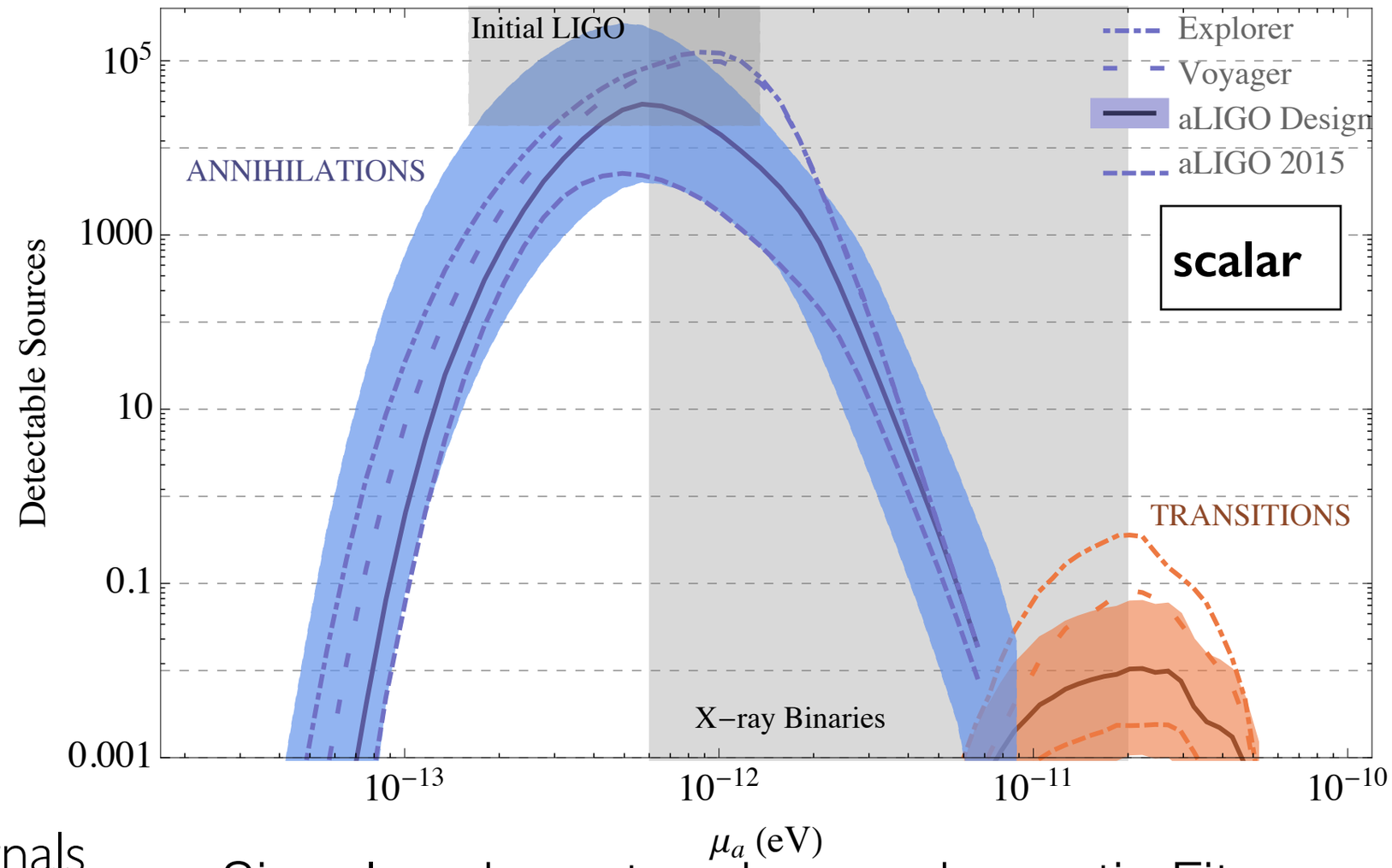


  - Signals coherent, monochromatic, last hours to millions of years

Annihilations



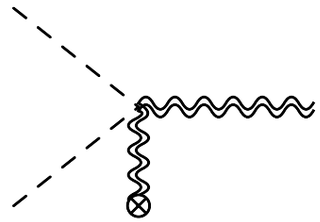
- Event rates up to 10,000 — can be observed and studied in detail
- Uncertainty dominated by BH mass distribution at higher masses



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

Signals coherent and monochromatic:Fits into searches for **long, continuous, monochromatic** gravitational waves (“mountains” on neutron stars)

Annihilations



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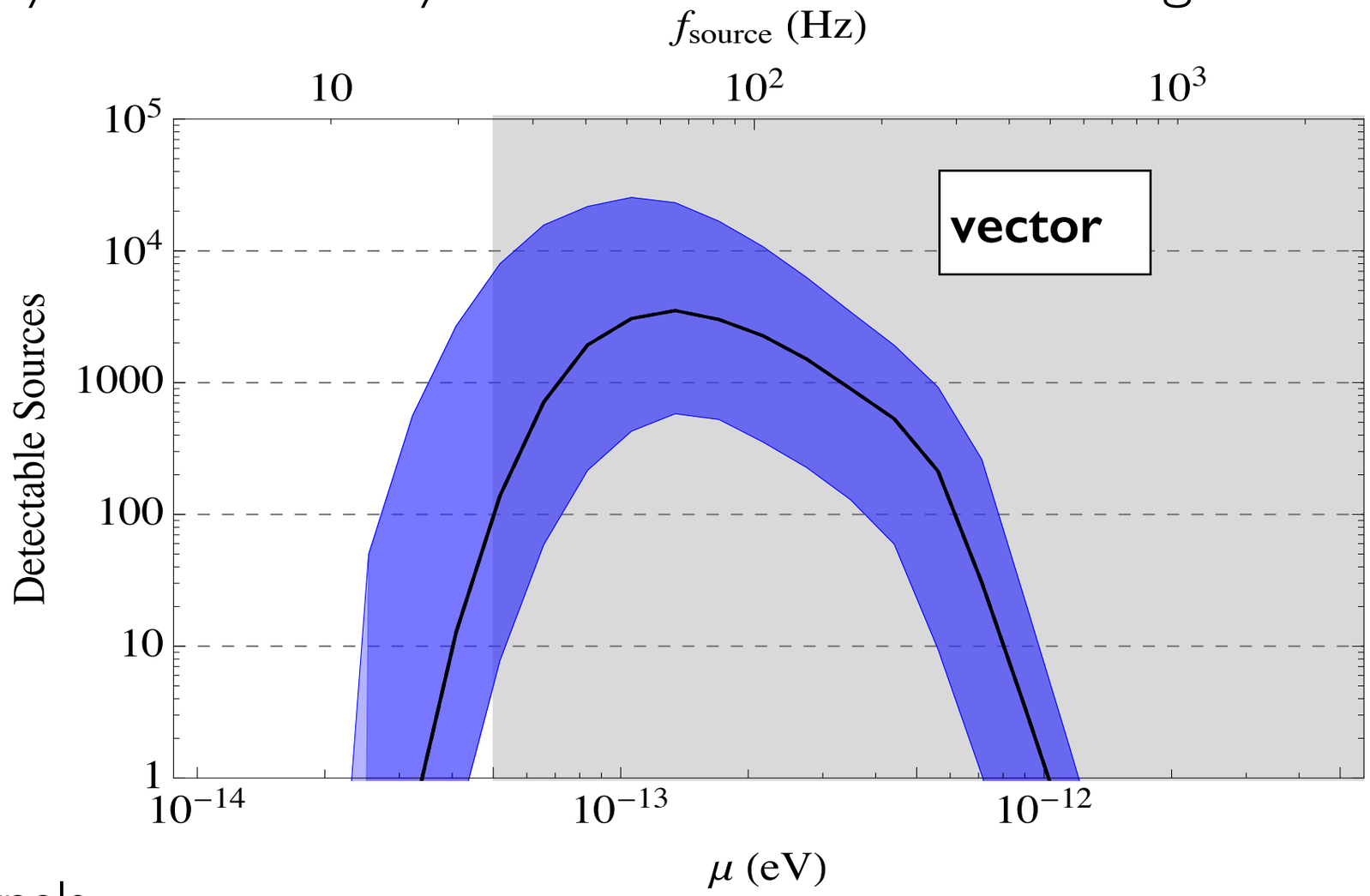

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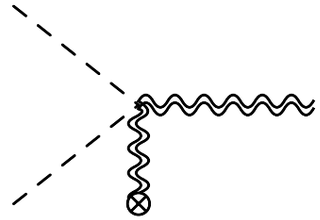
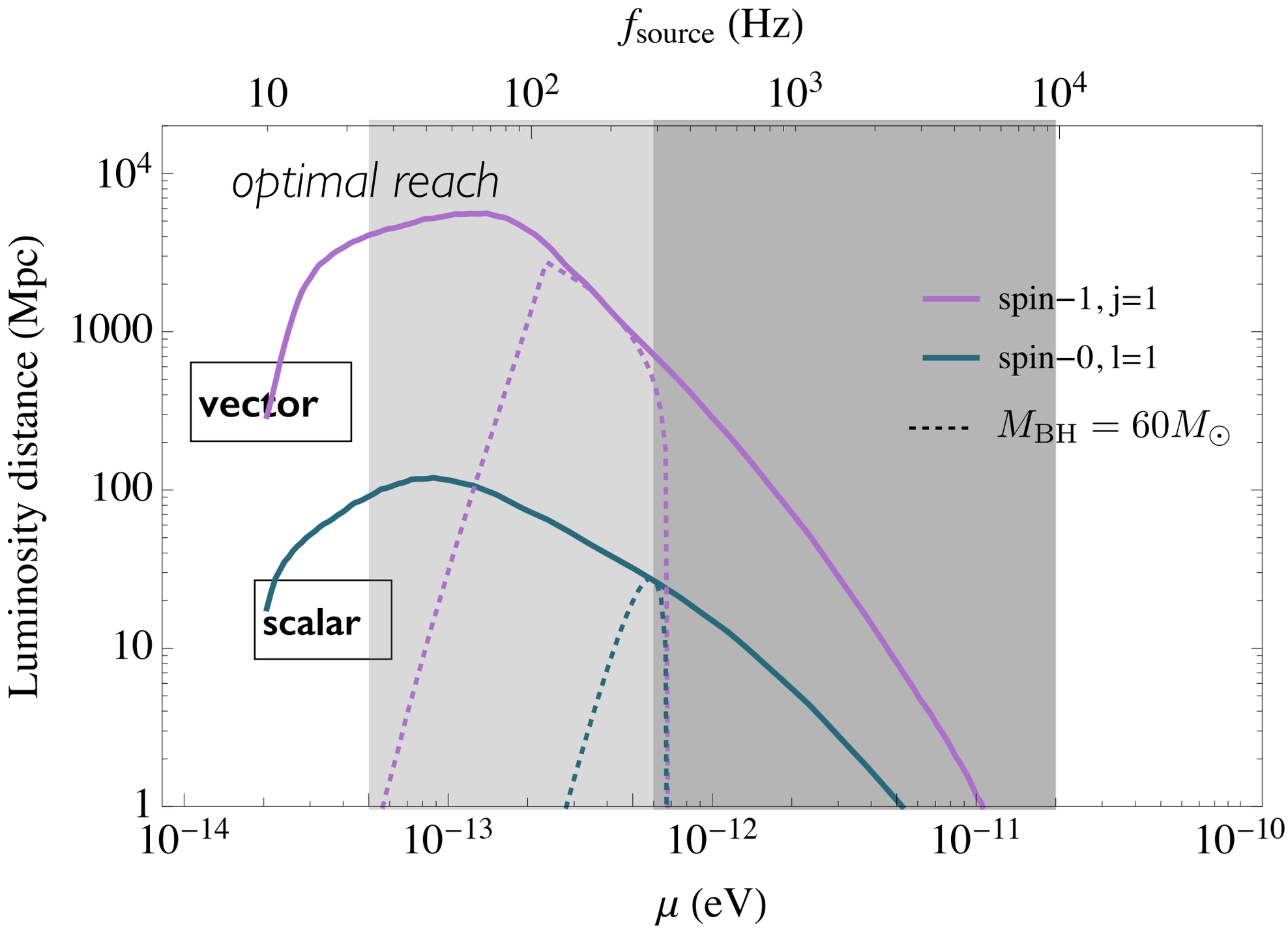
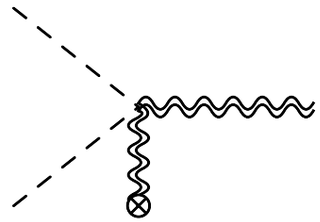




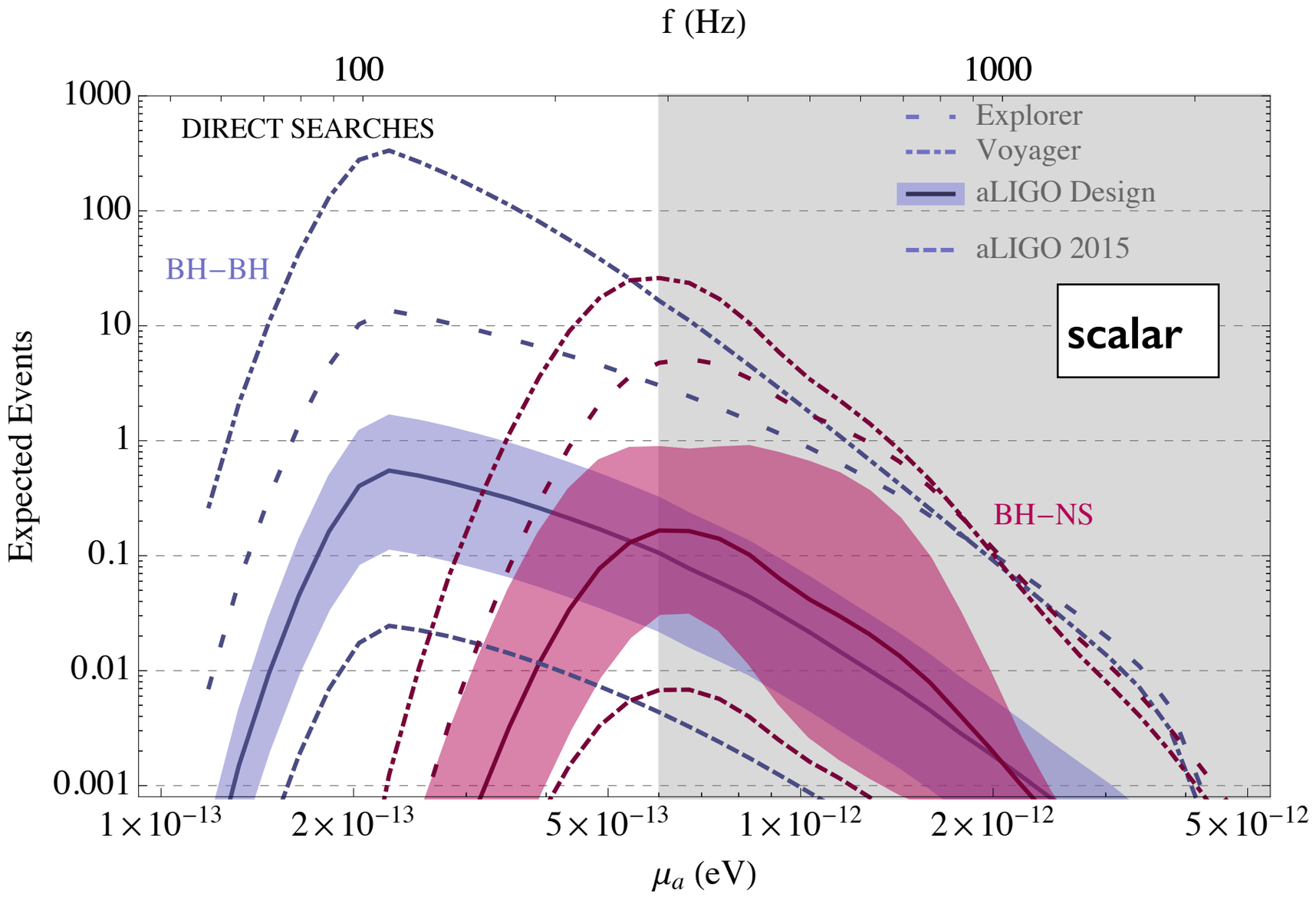
Spin-1 particle annihilations give higher rates, but more constrained

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

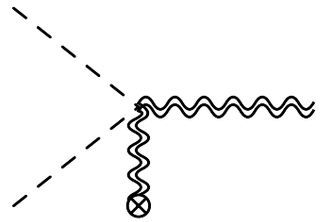
Annihilations



- 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



Annihilations



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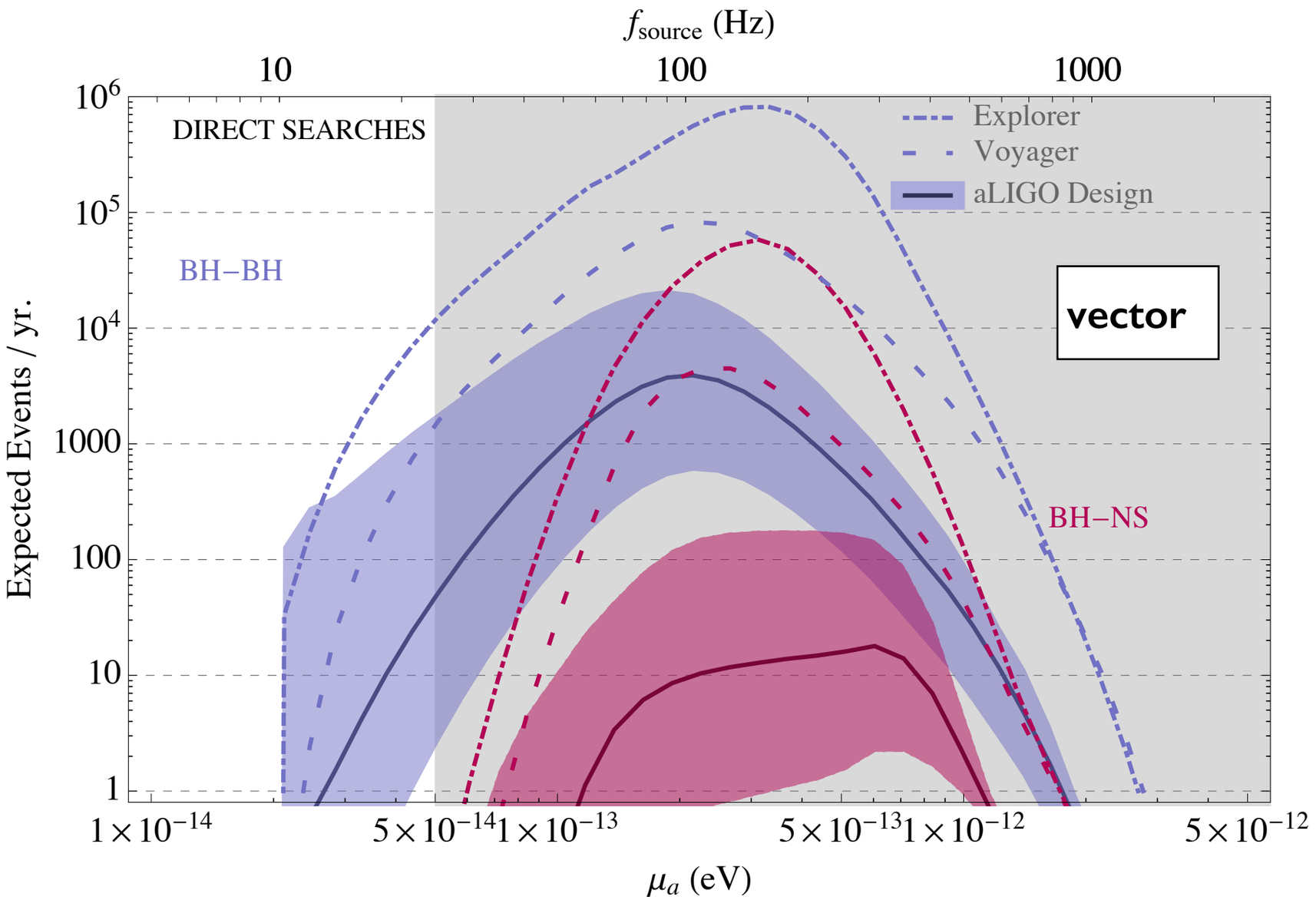
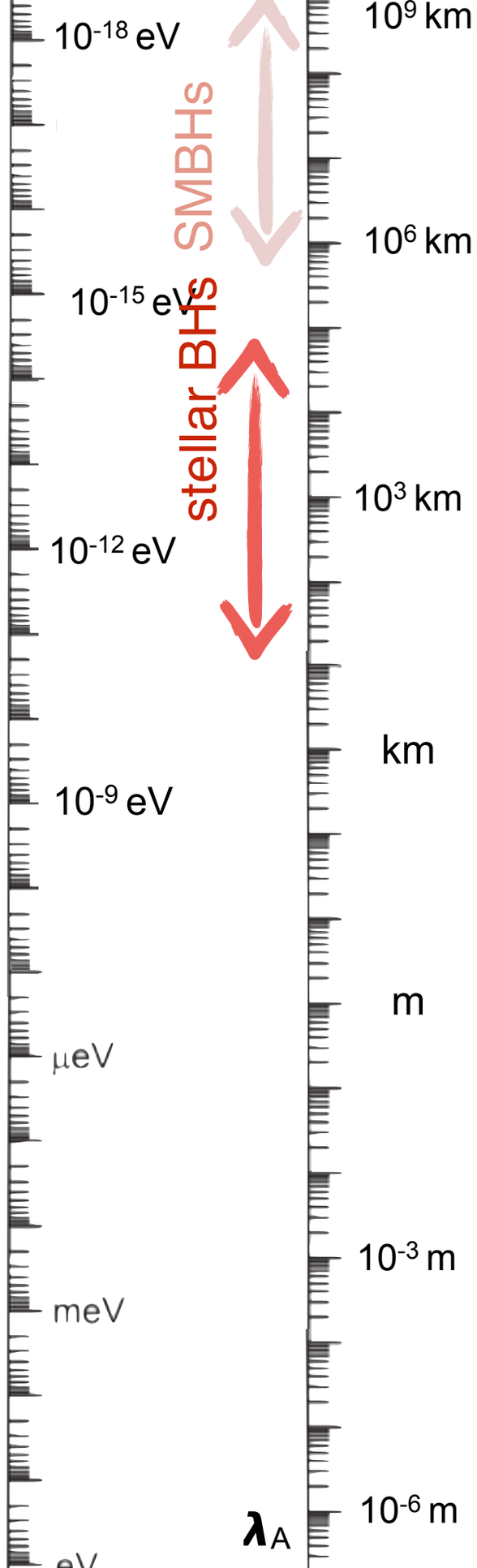


Conclusions

- Ultra light axions, scalars, vectors, can be constrained or discovered by measurements of astrophysical black holes
- Independent of astrophysical abundance 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 annihilations of scalars or vectors
- May observe growth of gravitational atom after a merger in real time

Thank you!



Extra

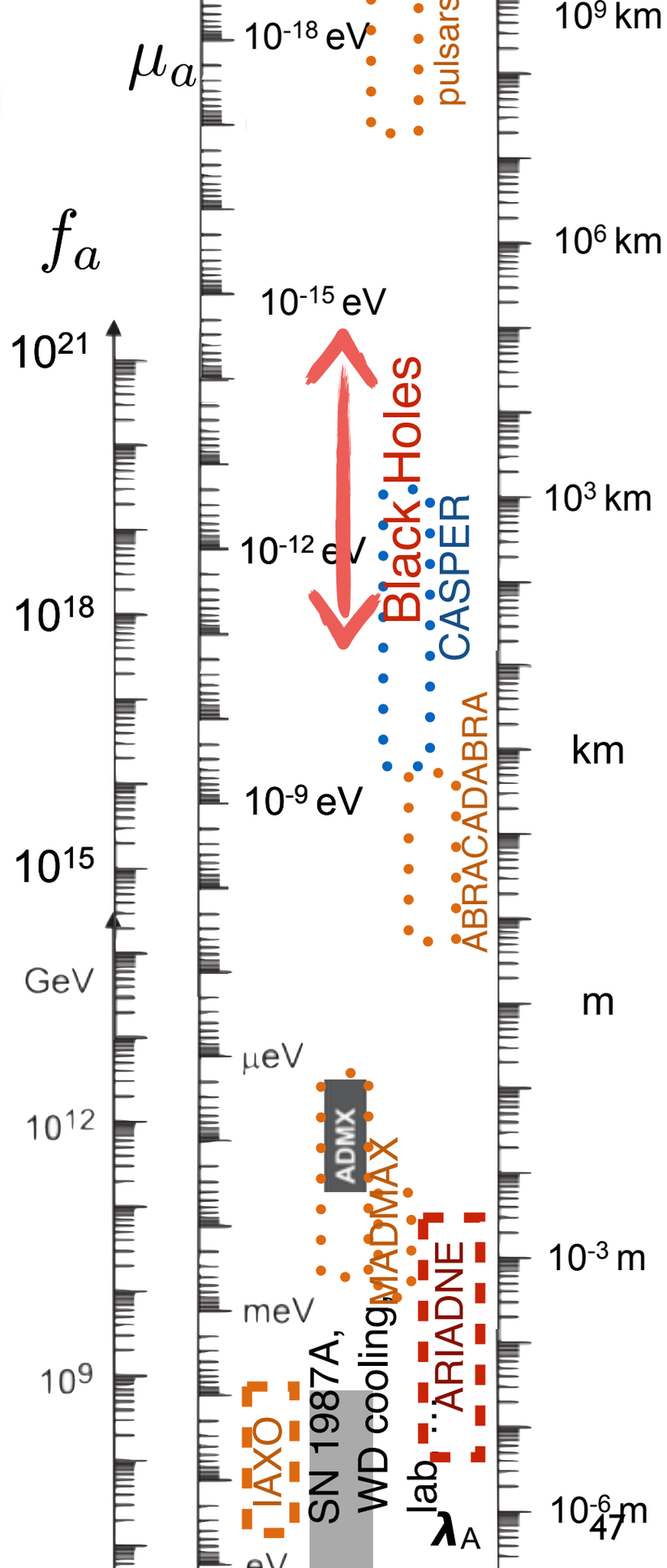
Searching for the QCD axion

- 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,

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

- Very weakly interacting
- Large compton wavelength

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



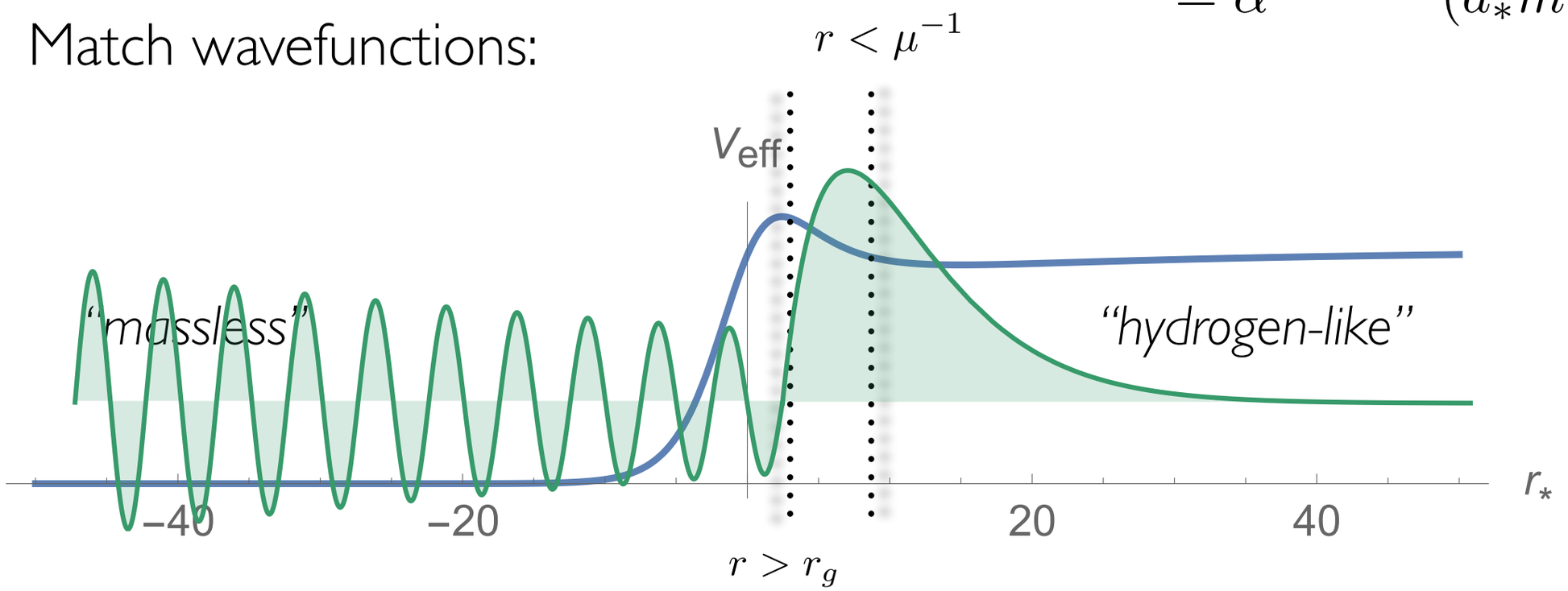
R. Peccei and H. R. Quinn, Phys.Rev.Lett., **38**, 1440 (1977); S. Weinberg, *ibid.*, **40**, 223 (1978); F. Wilczek, *ibid.*, **40**, 279 (1978).

Vector superradiance rates

- For vector with $j = l + S$, growth rate is $\mathrm{Im}(\omega) \sim \alpha^{4l+2S+4}(a_* m - 2\mu r_+)\mu$

$$= \alpha^{2l+2j+4}(a_* m - 2\mu r_+)\mu$$

- Match wavefunctions:



e.g. scalar in Schwarzschild: $V_{\rm eff}(r) = \left(1 - \frac{2r_g}{r}\right)\left(\mu^2 + \frac{l(l+1)}{r^2} + 2\frac{r_g}{r^3}\right)$

- Massless vector absorption controlled by ***j***, not by ***l***

Vector superradiance rates

- For massless boson, absorption probability is

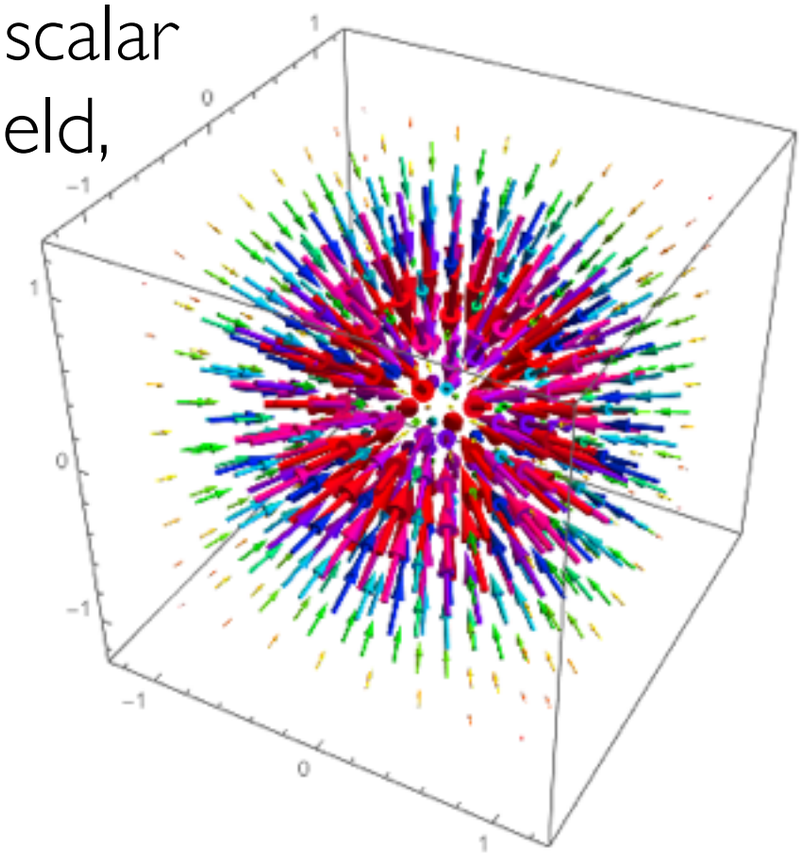
$$\mathbb{P}_{\rm abs} = \left(\frac{(j-s)!(j+s)!}{(2j)!(2j+1)!!}\right)^2 \prod_{n=1}^{j}\left[1+\left(\frac{\omega-m\Omega}{n\kappa}\right)^2\right] 2\left(\frac{\omega-m\Omega}{n\kappa}\right)\left(\frac{A\kappa}{2\pi}\omega\right)^{2j+1}$$

- Split light vector into transverse ("massless vector") and longitudinal ("massless scalar") modes. Massless scalar component corresponds to A_0 part of vector field,

$$D_\mu A^\mu = 0 \Rightarrow \partial_i A_i \simeq \partial_0 A_0$$

- e.g. monopole mode: $A_0 \sim \frac{1}{\mu a_0}|A_i|_{a_0} Y^{00}$

  Decay "through scalar mode" with $\Gamma \simeq \frac{3}{2}\alpha^7 \mu$



$j = 0, l = 1$

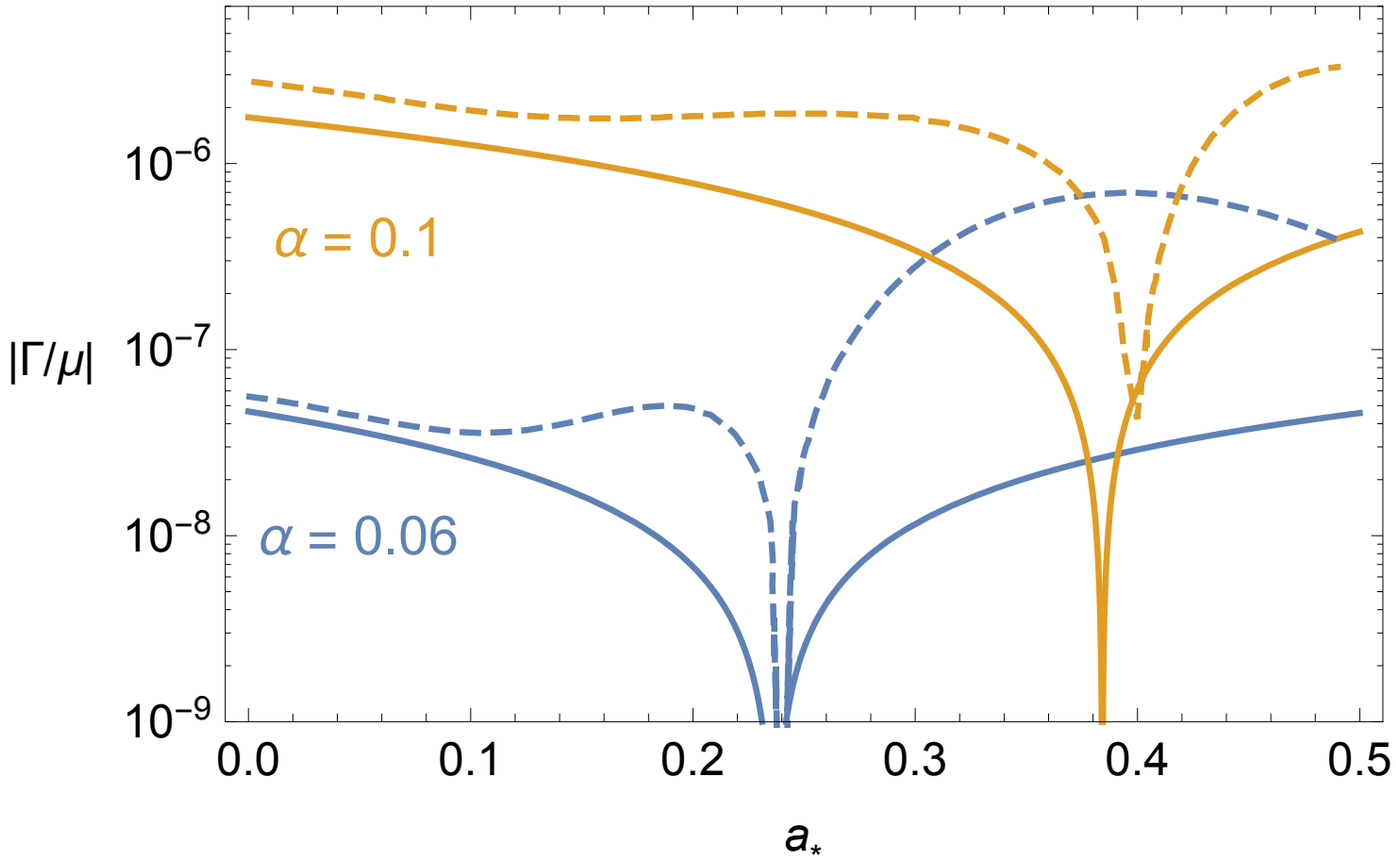
Vector superradiance rates

	vector			**scalar**
	$l = j-1$	$l = j$	$l = j+1$	l
Leading growth via:	*vector*	*vector*	*scalar (+vector)*	***scalar***
$j = 0$			$-\frac{3}{2}\alpha^7\mu + \ldots$	$-8\alpha^5\mu$
$j = 1$	$4a_*\alpha^6\mu + \ldots$	$\frac{1}{6}a_*\alpha^8\mu + \ldots$	$\sim a_*\alpha^{10}\mu + \ldots$	$\frac{1}{24}a_*\alpha^8\mu + \ldots$
$j = 2$	$\sim a_*\alpha^{10}\mu + \ldots$	$\sim a_*\alpha^{12}\mu + \ldots$	$\sim a_*\alpha^{14}\mu + \ldots$	$\sim a_*\alpha^{12}\mu + \ldots$

Vector rates are faster for the same total angular momentum, and more robust to perturbations

Other vector SR calculations

- Slow-rotation approximation *[Pani et al]*; expansion around Schwarzschild ($a_* \ll 1$), rather than $\alpha \ll 1$



solid: $\alpha \ll 1$

dashed: $a_* \ll 1$

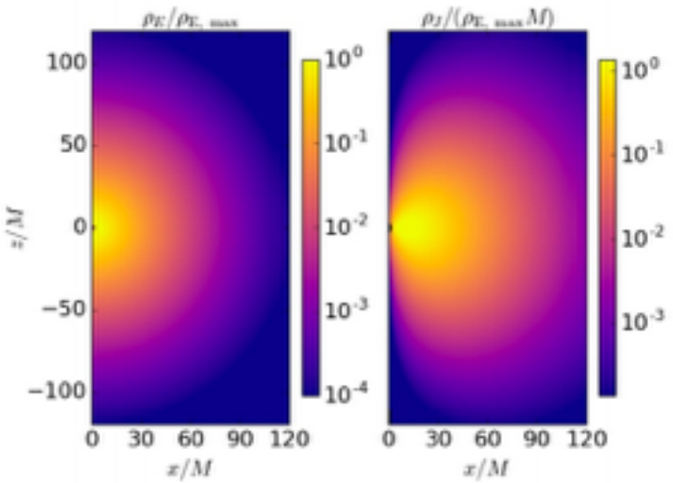
$$j = m = 1,\ \ell = 0$$

Other vector SR calculations

$a_* = 0.99 \quad j = m = 1,\ \ell = 0$

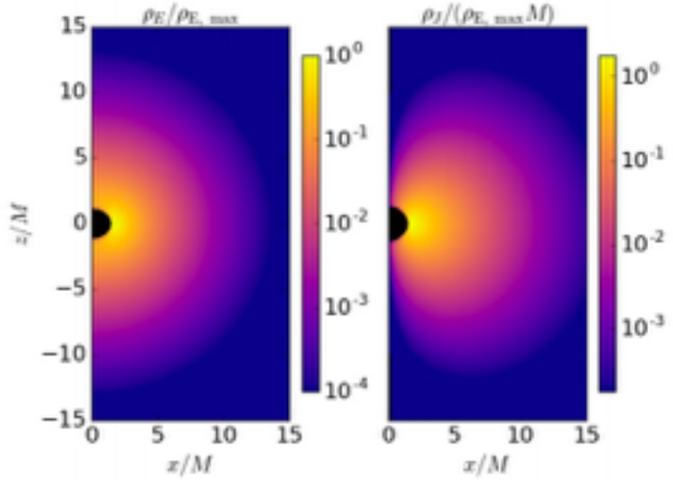
- East *[1705.01544]*: time-domain calculations of Proca field on Kerr background

$\alpha = 0.2$

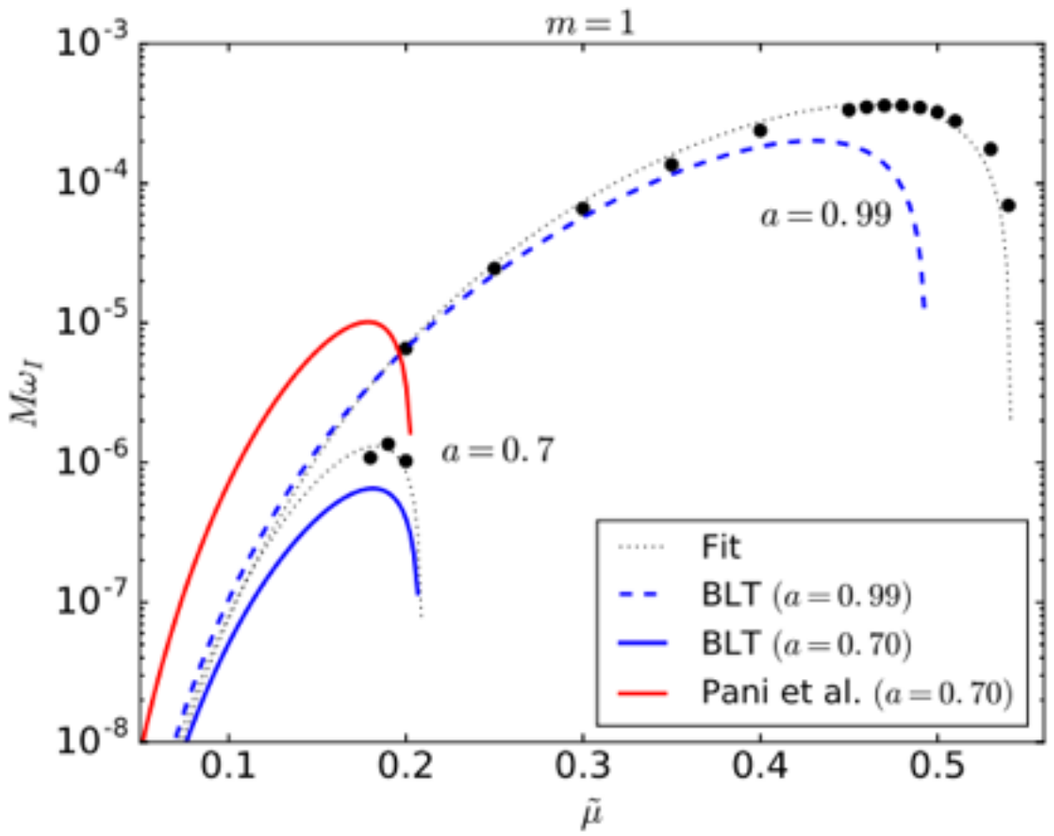


- East & Pretorius *[1704.04791]*: full non-linear Kerr + Proca evolution

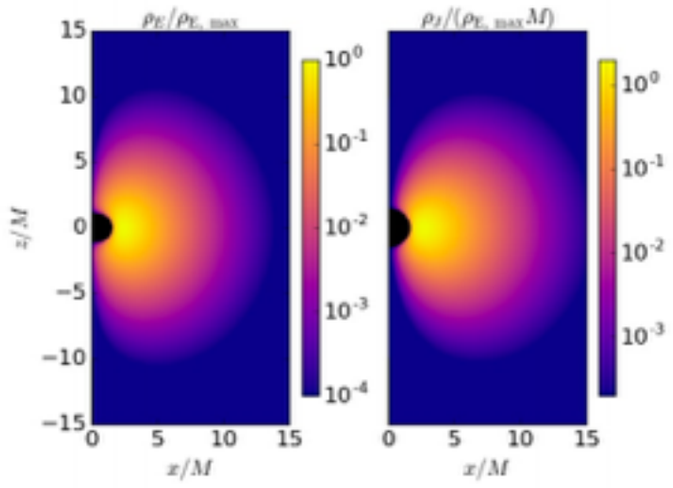
$\alpha = 0.5$



- Good agreement with small-α growth rates:



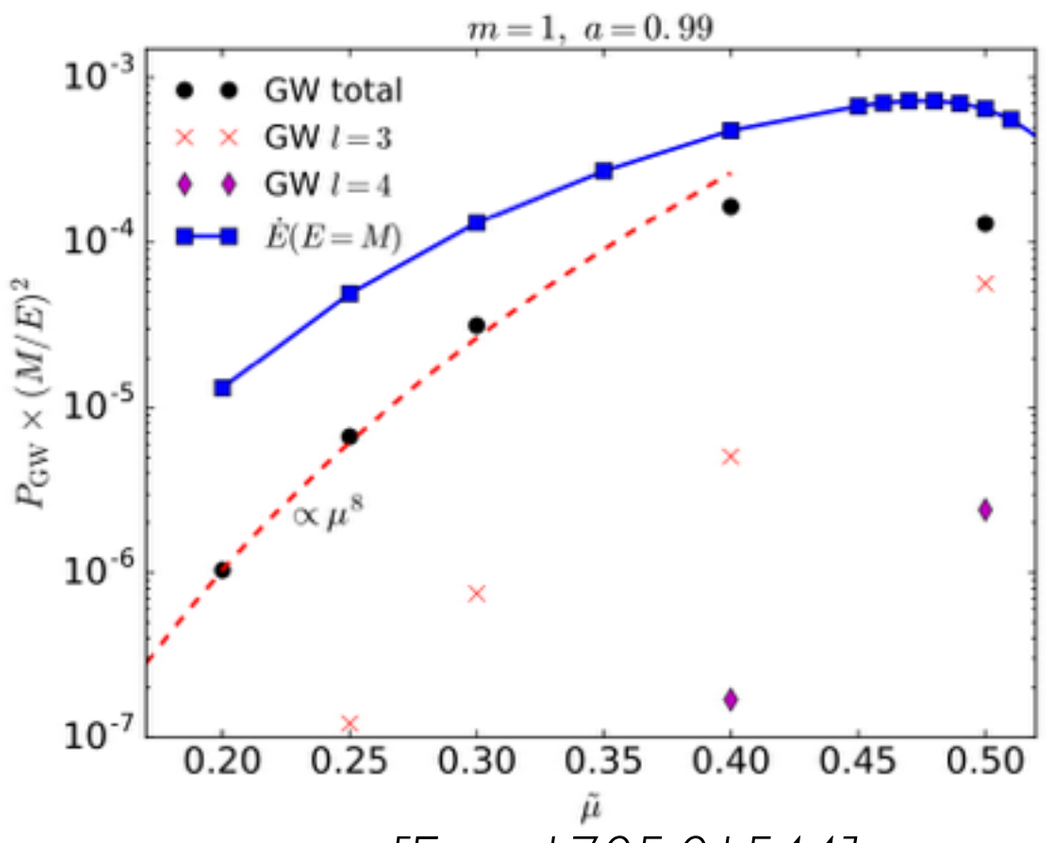
$\alpha = 0.95$



Annihilation to gravitons

$$P_{\rm scalar} \simeq 0.02\alpha^{16}\frac{GN^2}{r_g^4} \simeq N_{\rm max}\mu\left(\frac{N}{N_{\rm max}}\right)^2 0.02\alpha^{16}\mu$$

$$P_{\rm vector} \simeq 60\alpha^{12}\frac{GN^2}{r_g^4}$$

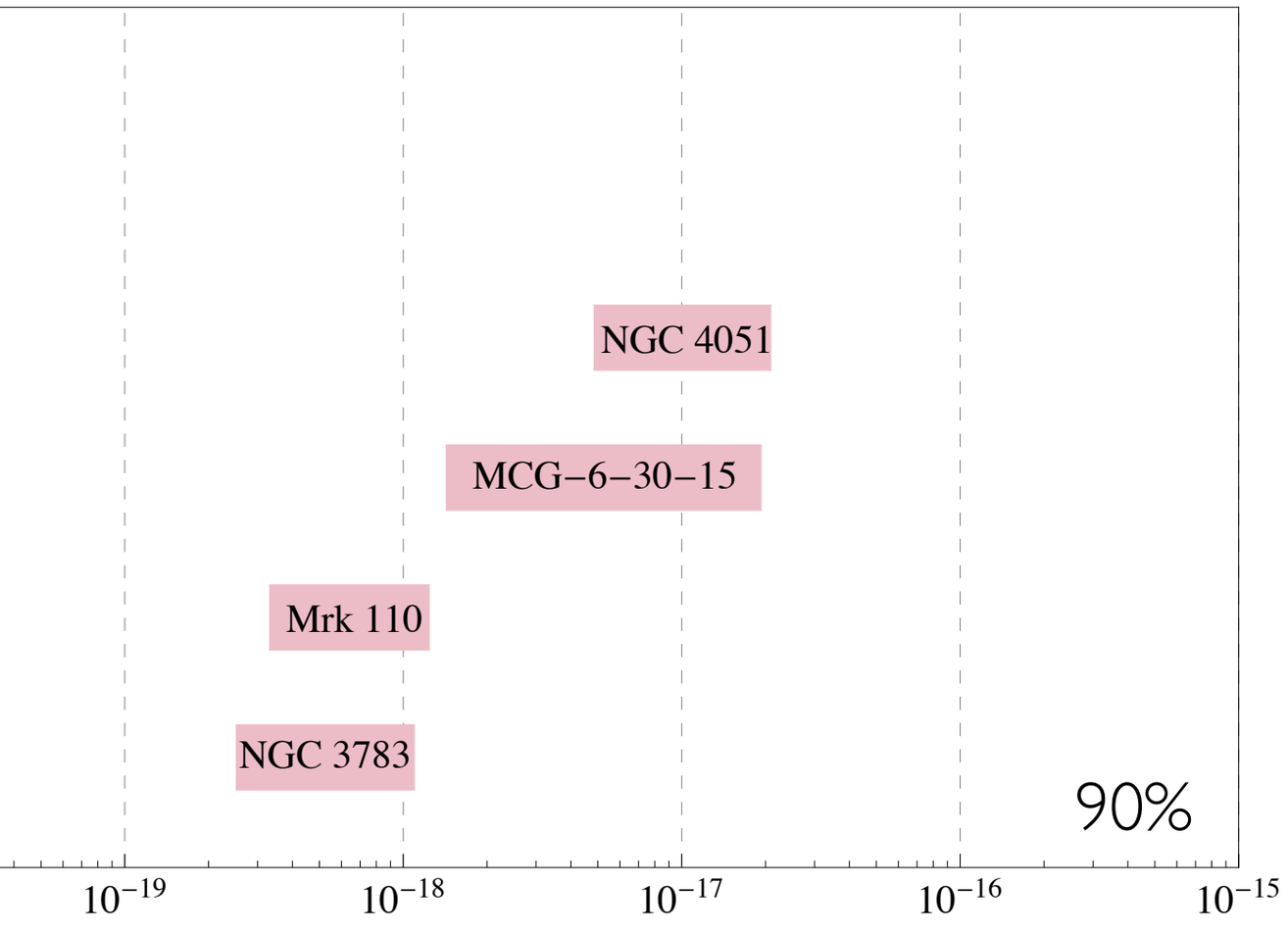


[East, 1705.01544]

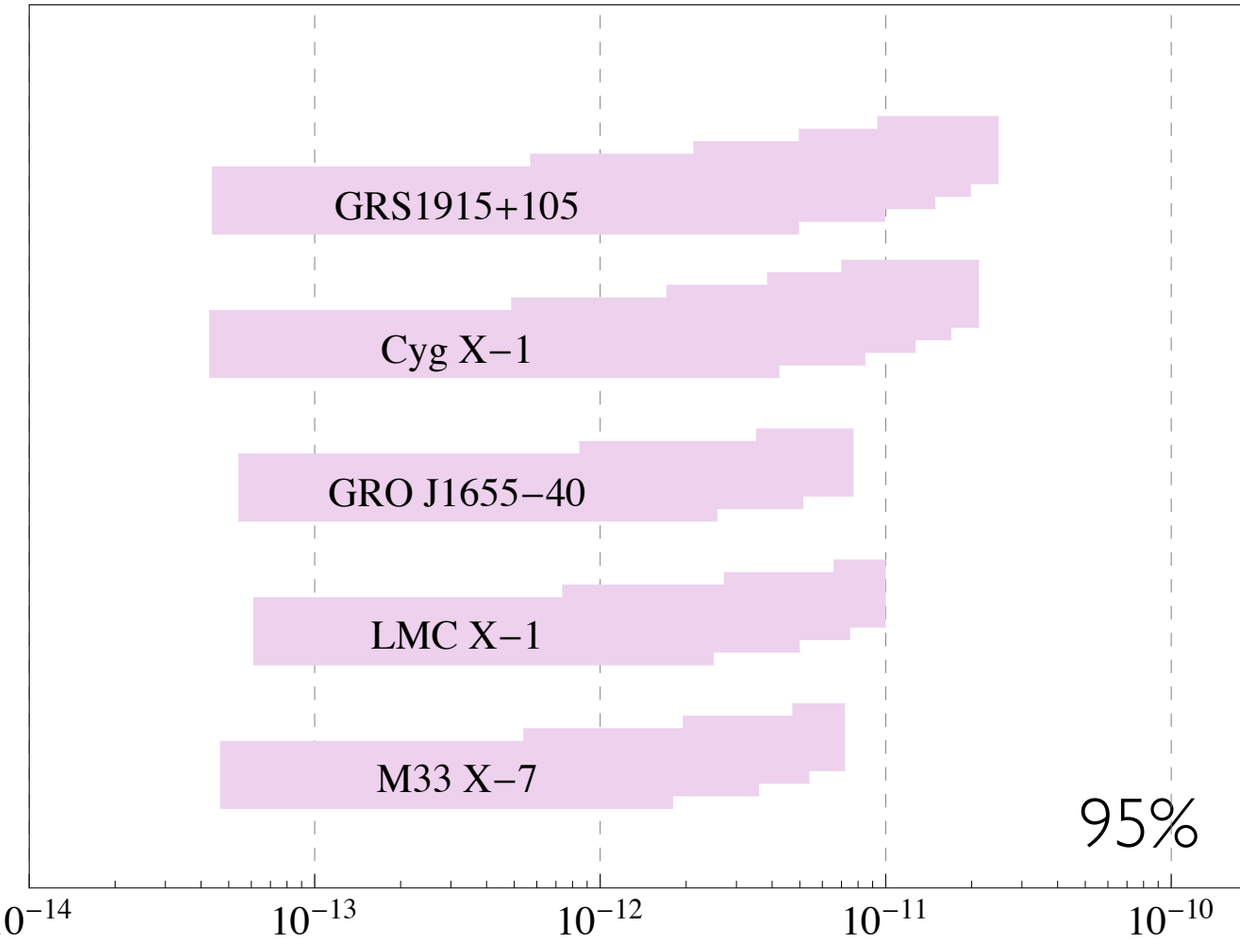
Black Hole Spins

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

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

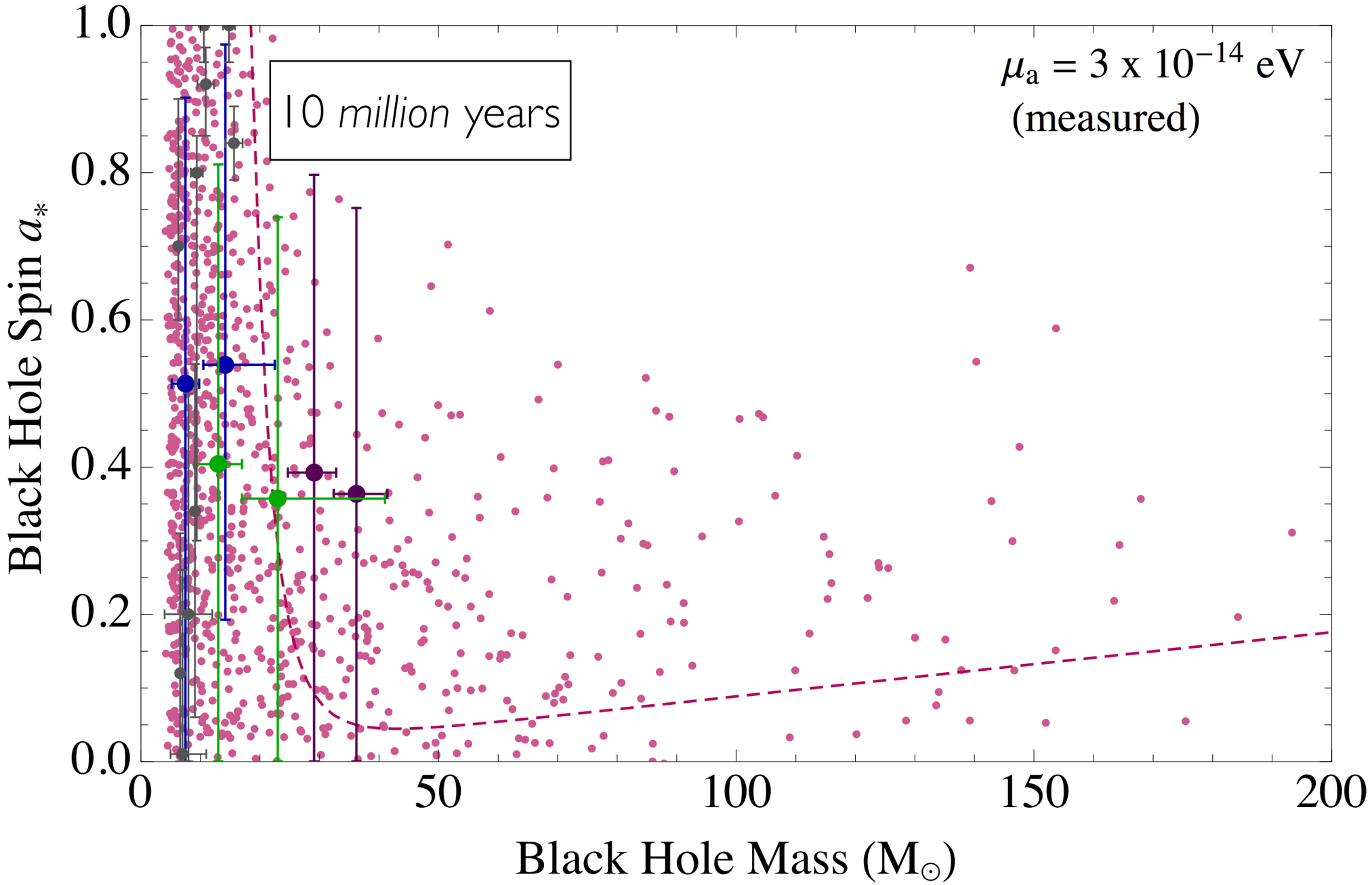


$2 \times 10^{-11} \gtrsim \mu_V \gtrsim 5 \times 10^{-14}\mathrm{eV}$



Black Hole Spins

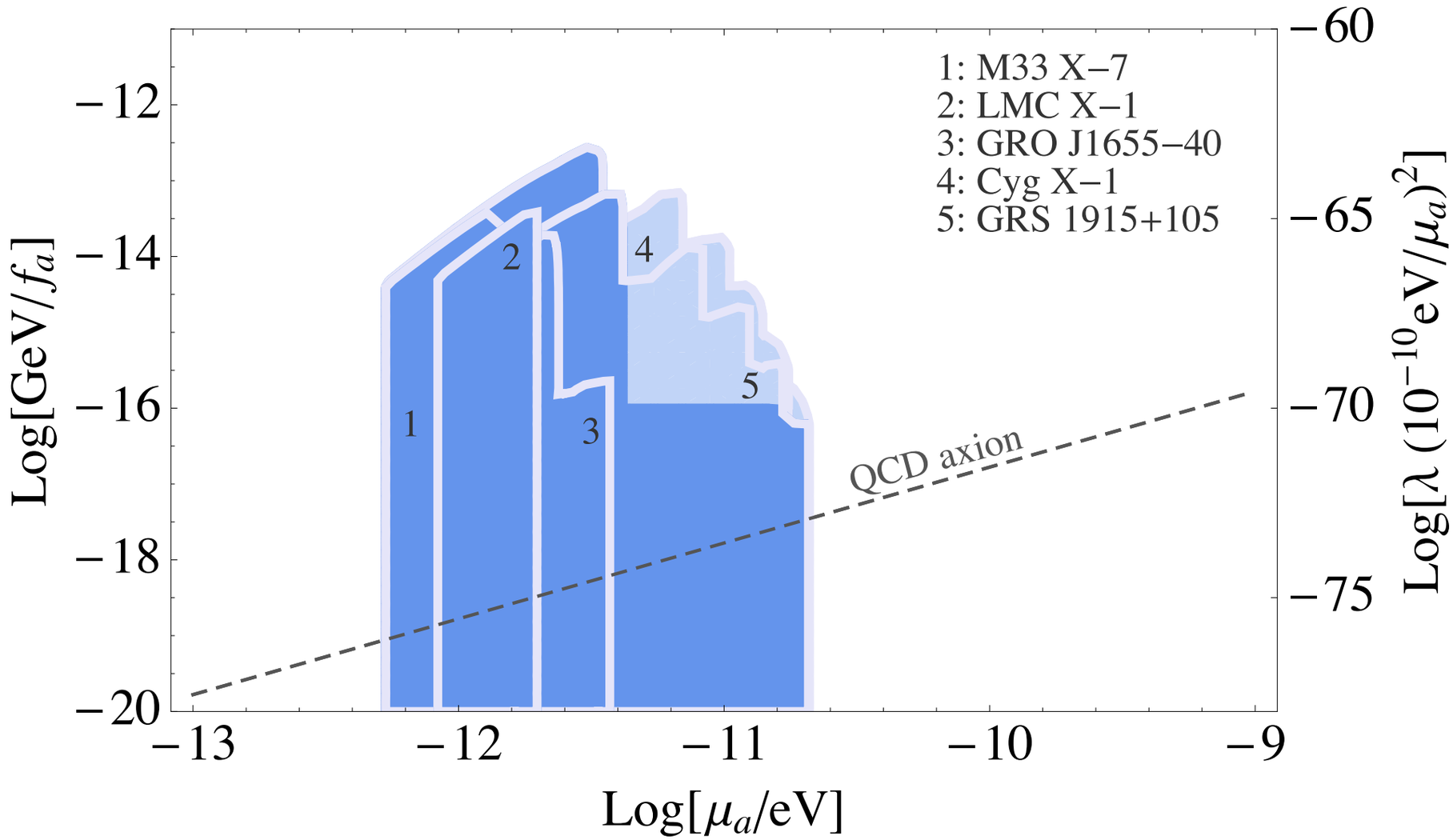
May see spin-down of black holes at LIGO outside of excluded region



Black Hole Spins, coupling

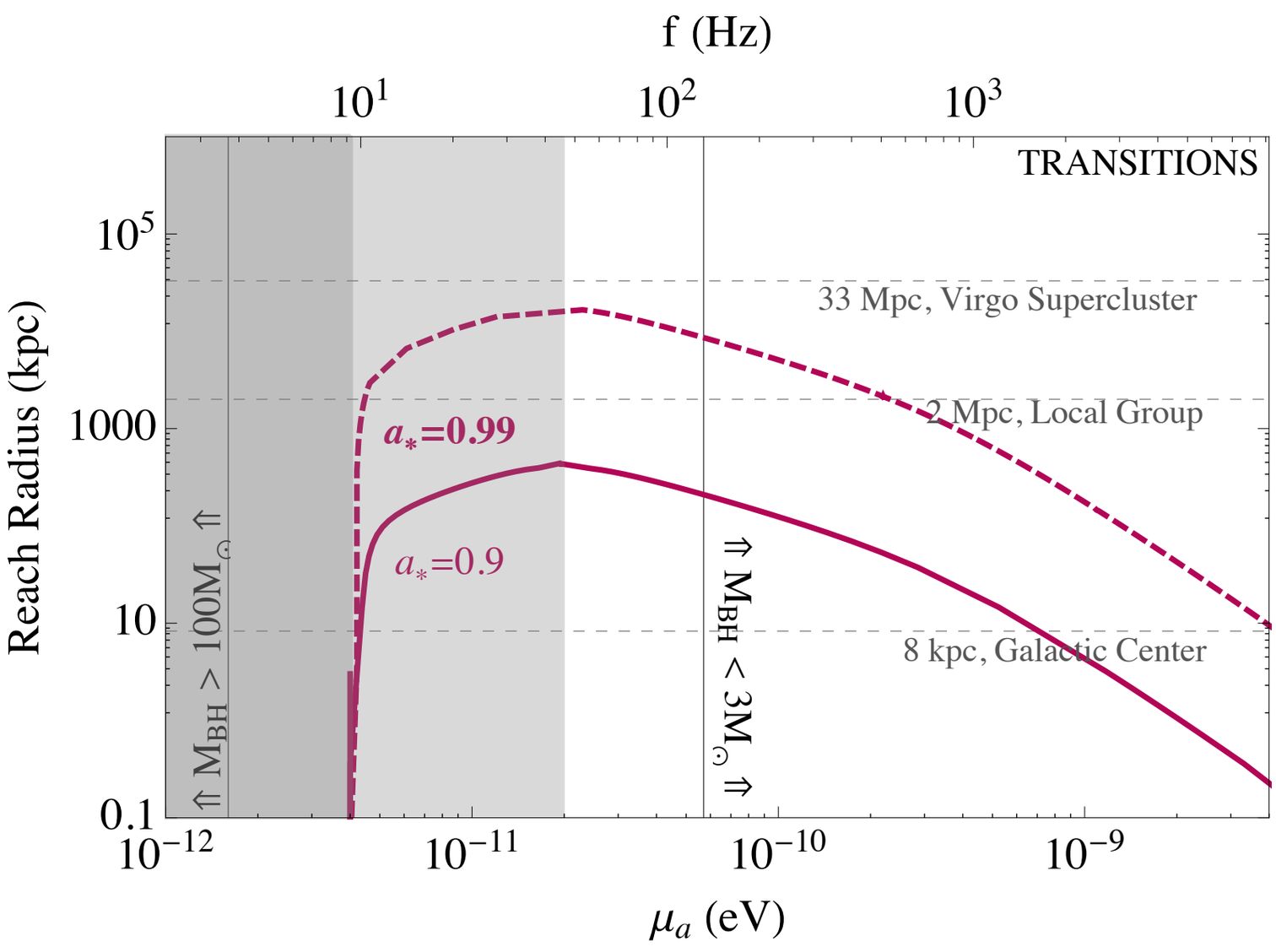
Five currently measured black holes combine to set limit:

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



Transitions

Optimal reach of advanced LIGO



Using monochromatic search for rotating neutron stars

Heavier BHs give bigger signals

Cut off at low masses by LIGO sensitivity

Signals visible from galactic center typically last 10-100 yrs

BH with high spin, optimal mass, and is currently superradiating

Gravitational Wave Signals

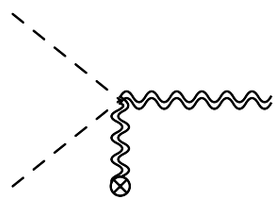
Transitions

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

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

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

Annihilations



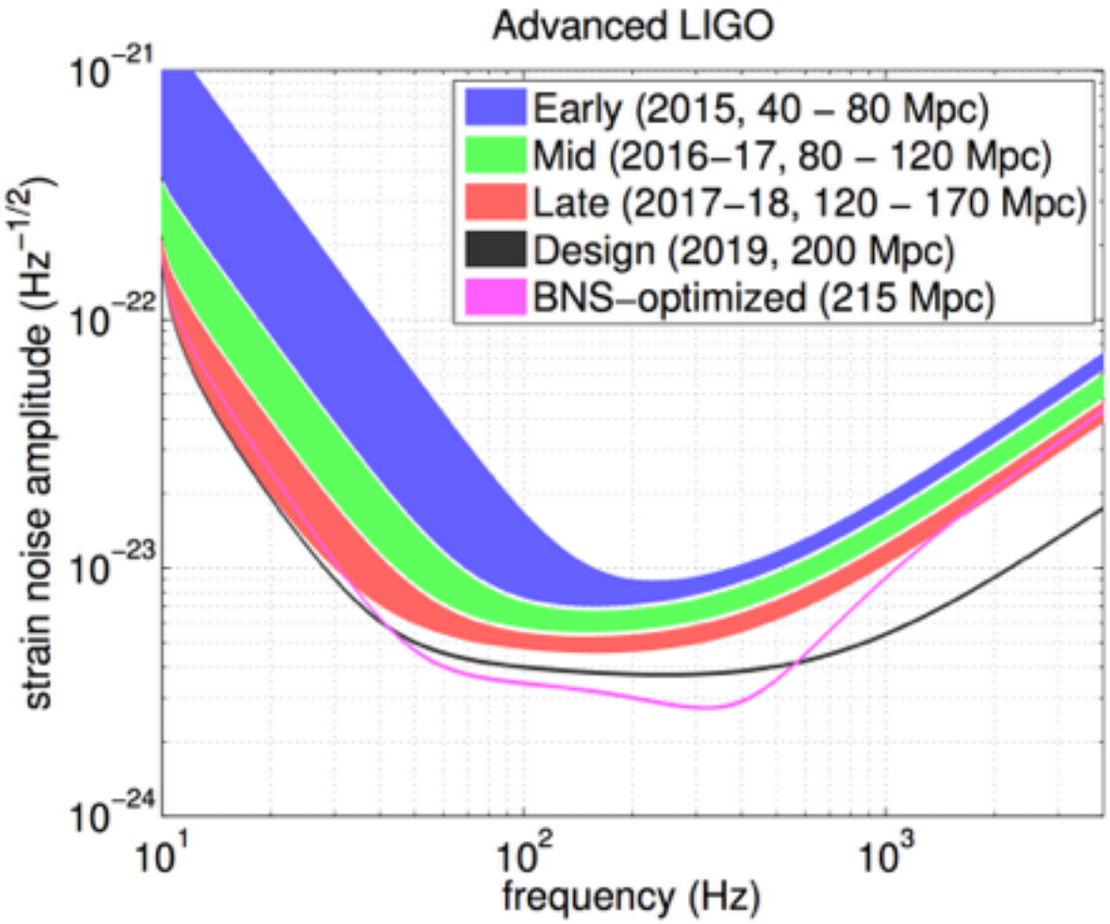
$$\frac{dN}{dt} = \Gamma_{\rm sr} N - \Gamma_a N^2$$

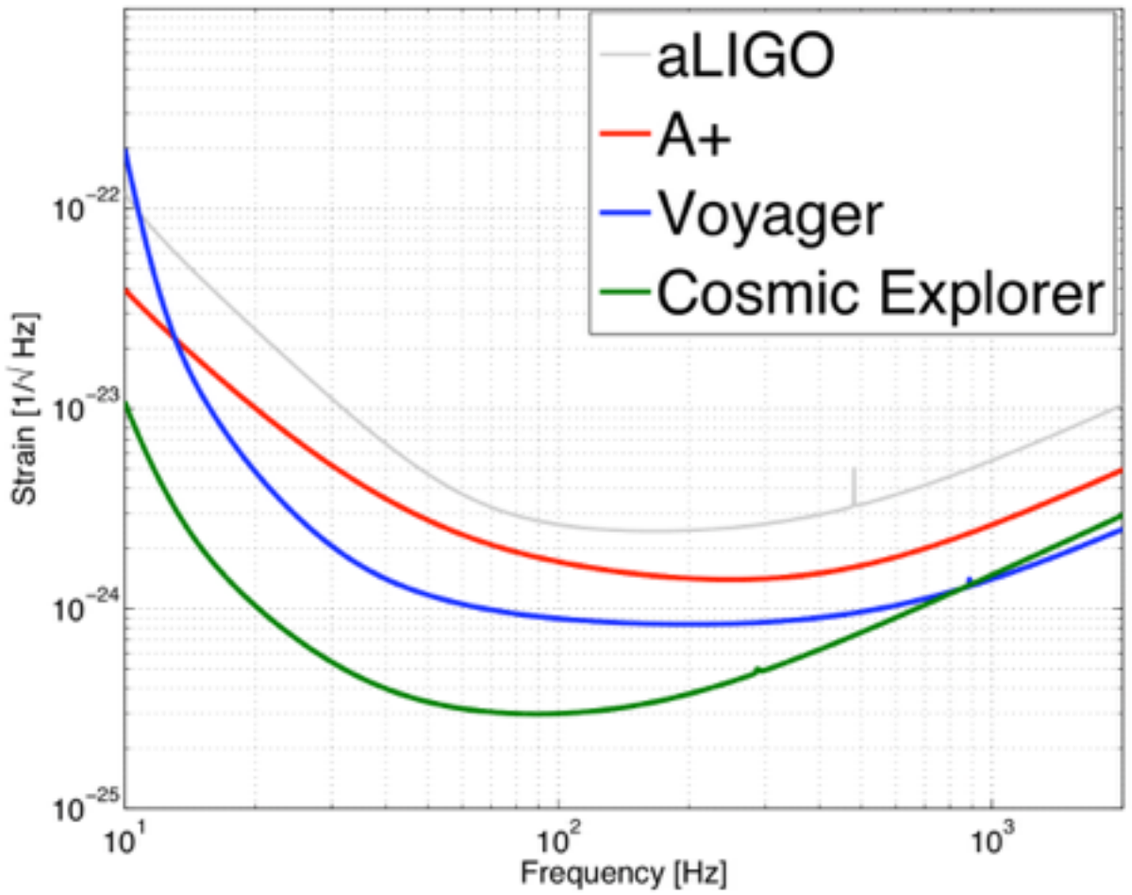
$$\frac{df}{dt} \simeq 10^{-12}\ \frac{\rm Hz}{\rm s} \left(\frac{f}{\rm kHz}\right) \left(\frac{M_{\rm Pl}}{f_a}\right)^2 \left(\frac{10^3\ {\rm yr}}{T}\right)$$

$$\dot{f} \simeq 10^{-8} {\rm Hz/sec} \times \left(\frac{\mu}{10^{13}\,{\rm eV}}\right) \left(\frac{\alpha}{0.2}\right)^3 \frac{250\,{\rm hr}}{t_{\rm sig}}\,.$$

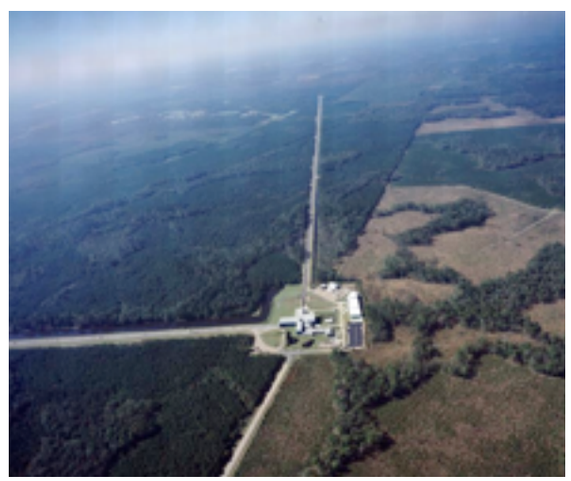
Gravitational Wave Signals

Advanced LIGO sensitivity

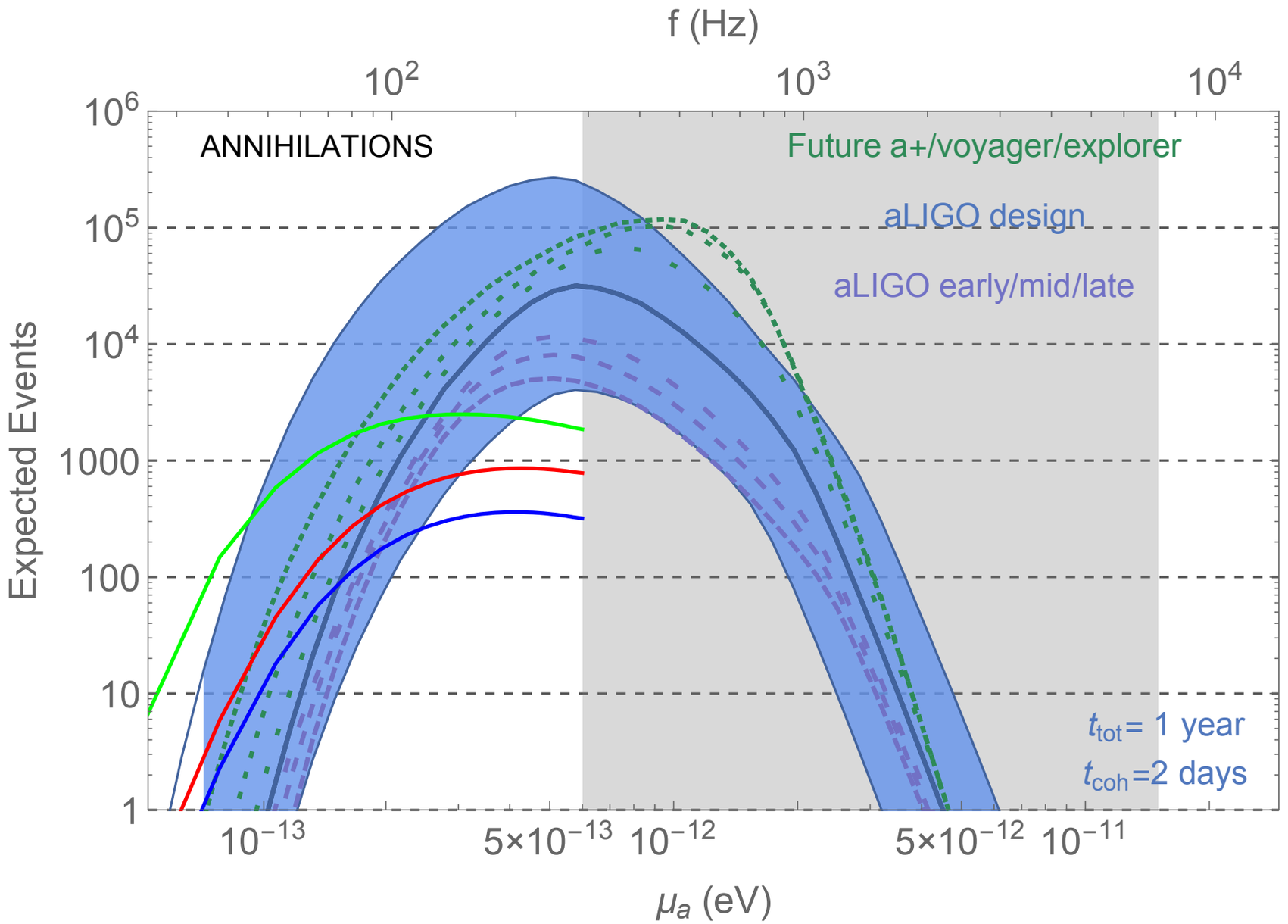




- Fits into searches for **long, continuous, monochromatic** gravitational waves
- Currently looking for "mountains" on neutron stars



Gravitational Wave Signals stochastic bkgd



Black Hole Environment

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

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

Black holes themselves are perfectly axisymmetric

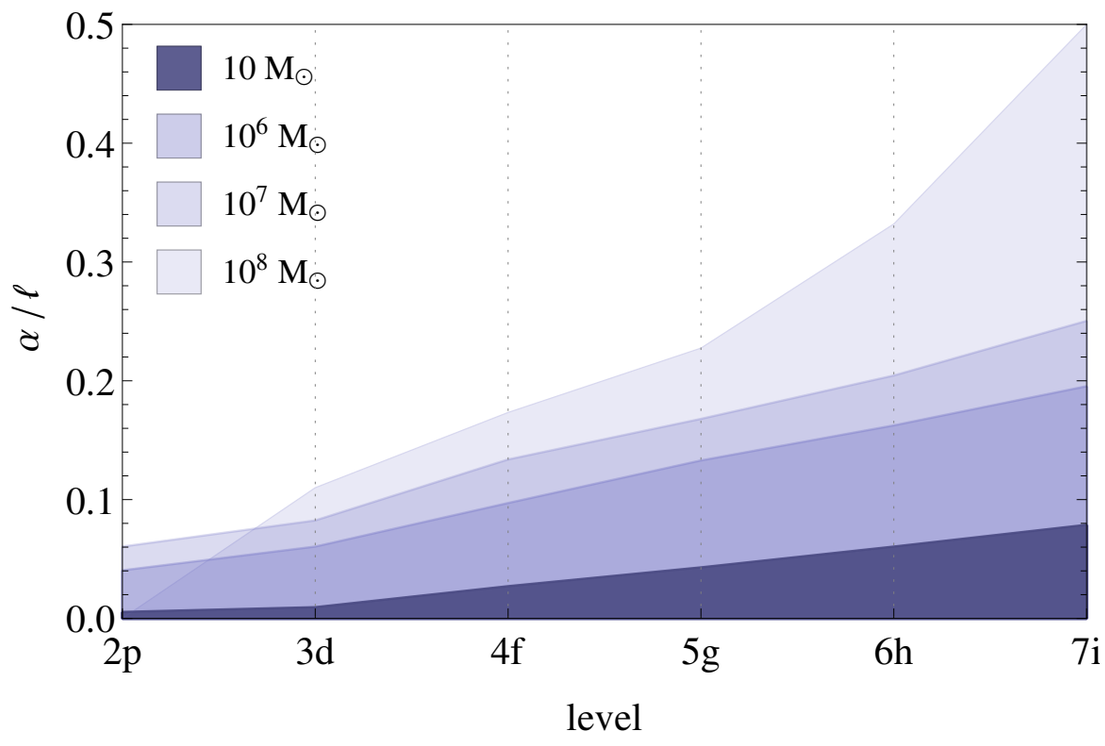
Environments of BHs are very clean

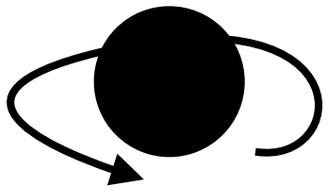
If present, companion star/accretion disk can slightly constrain small coupling parameter space

Companion star

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

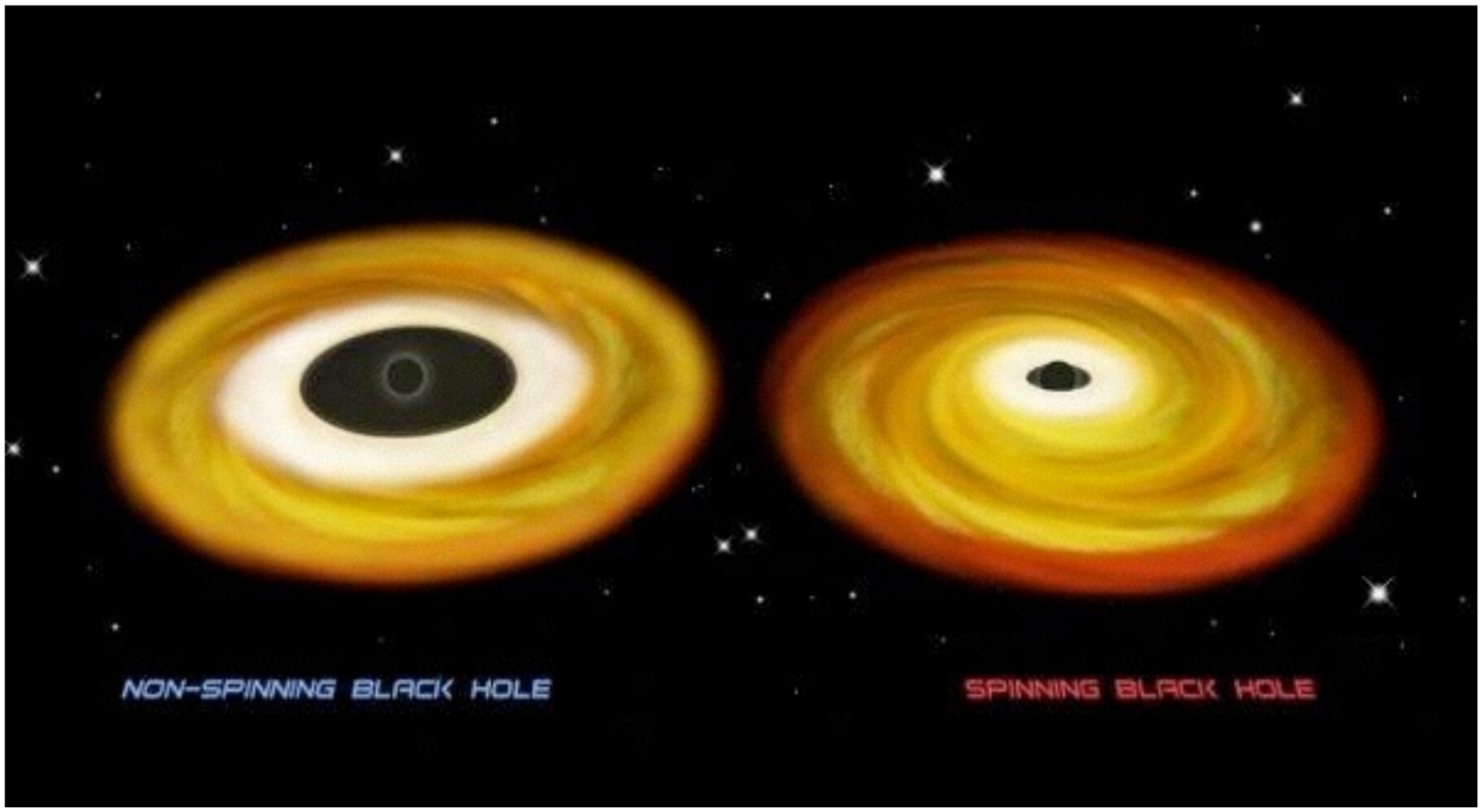
Accretion disk



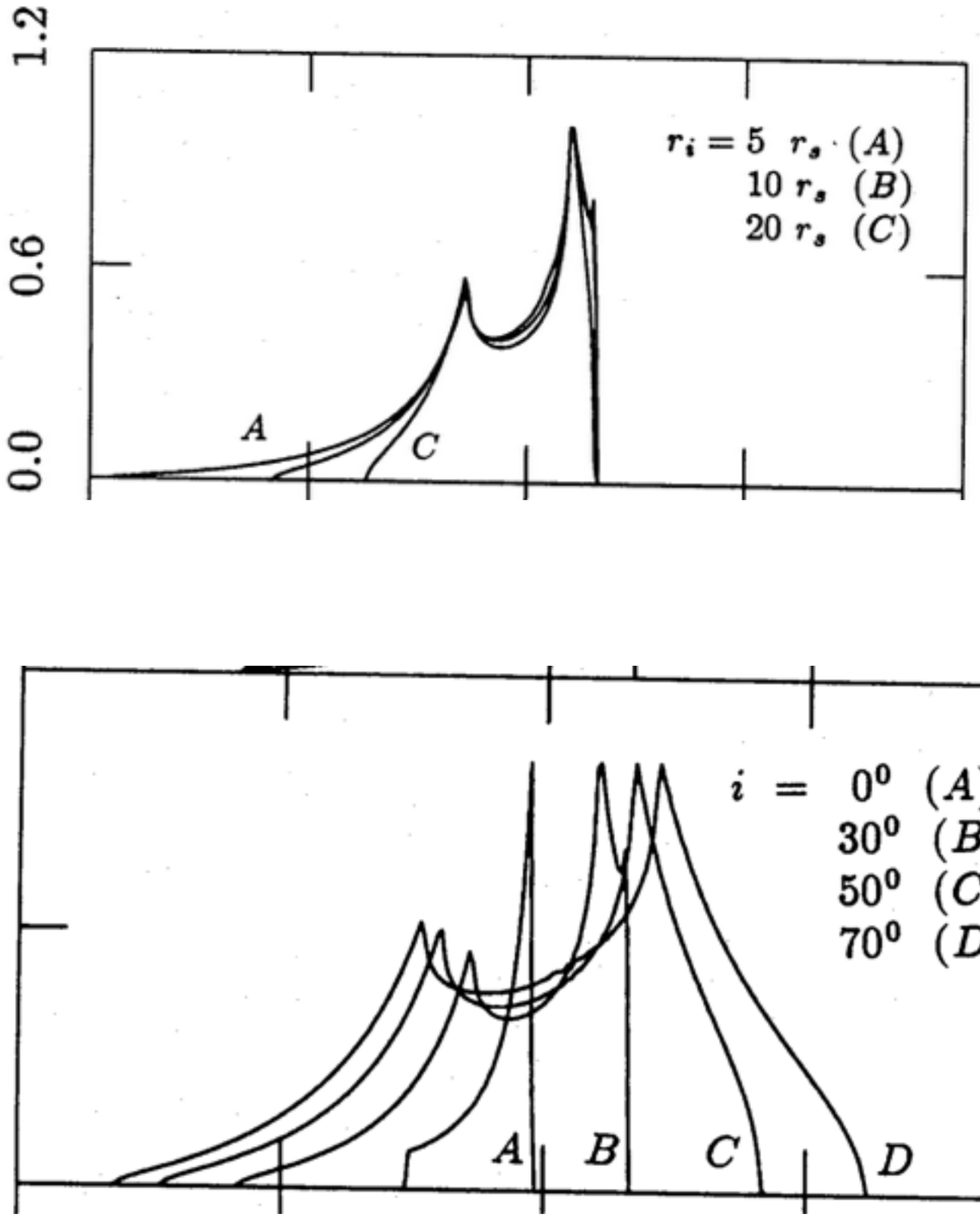


Black Hole Spins

- Two leading methods: continuum fitting and X-ray reflection
- Based on finding the innermost stable orbit of the accretion disk
- Uncertainty dominated by observational errors; smaller at extremal spins



Xray line BH spin measurement



Continuum measurement

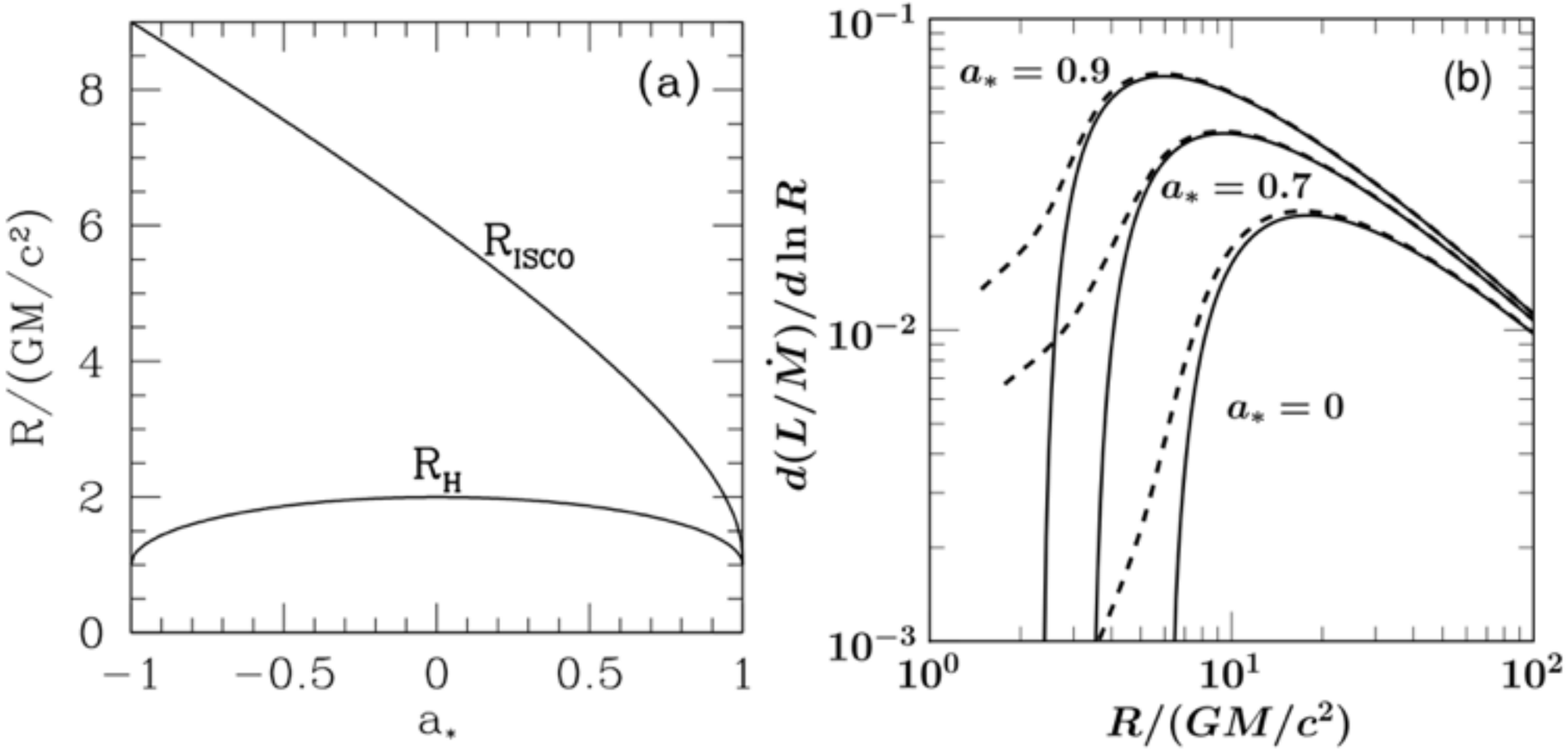


Fig. 3 (a) Radius of the ISCO $R_{\rm ISCO}$ and of the horizon $R_{\rm H}$ in units of GM/c^2 plotted as a function of the black hole spin parameter a_*. Negative values of a_* correspond to retrograde orbits. Note that $R_{\rm ISCO}$ decreases monotonically from $9GM/c^2$ for a retrograde orbit around a maximally spinning black hole, to $6GM/c^2$ for a non-spinning black hole, to GM/c^2 for a prograde orbit around a maximally spinning black hole. (b) Profiles of $d(L/\dot{M})/d\ln R$, the differential disk luminosity per logarithmic radius interval normalized by the mass accretion rate, versus radius $R/(GM/c^2)$ for three values of a_*. Solid lines are the predictions of the NT model. The dashed curves from Zhu et al. (2012), which show minor departures from the NT model, are discussed in Section 5.2.

Black Hole Spins

#	Object	Mass ($M_\odot$)	Spin	Age (yrs)	Period (days)	$M_{\text{comp. star}}$ ($M_\odot$)
1	GRS1915+105	$12.4^{+2.0}_{-1.8}$ [33]	> 0.95 [34, 35]	$3 - 5 \times 10^9$ [36]	33.85 [37]	0.47 ± 0.27 [37]
2	Cyg X-1	14.8 ± 1.0	> 0.99 [38]	$4.8 - 7.6 \times 10^6$ [39]	5.599829 [40]	17.8 [40]
3	GRO J1655-40	6.3 ± 0.5	$0.72^{+.16}_{-.24}$ [35]	$3.4 - 10 \times 10^8$ [41]	2.622 [41]	2.3 - 4 [41]
4	LMC X-1	10.91 ± 1.4	$0.92^{+.06}_{-.18}$ [42]	$5 - 6 \times 10^6$ [43]	3.9092 [44]	31.79±3.48 [44]
5	M33 X-7	15.65 ± 1.45	$0.84^{+.10}_{-.10}$[35]	$2 - 3 \times 10^6$ [45]	3.4530 [46]	$\gtrsim 20$ [46]

#	Object	Mass ($10^6\ M_\odot$)	Spin
1	Ark 120	150 ± 19	$0.64^{+0.19}_{-0.11}$
2	Mrk 79	52.4 ± 14.4	0.7 ± 0.1
3	NGC 3783	29.8 ± 5.4	> 0.88
4	Mrk 110	25.1 ± 6.1	> 0.89
5	Mrk 335	14.2 ± 3.7	$0.83^{+0.09}_{-0.13}$
6	MCG-6-30-15	$2.9^{+0.18}_{-0.16}$	> 0.98
7	NGC 4051	1.91 ± 0.78	> 0.99