Searching for ultra-light new particles with black holes

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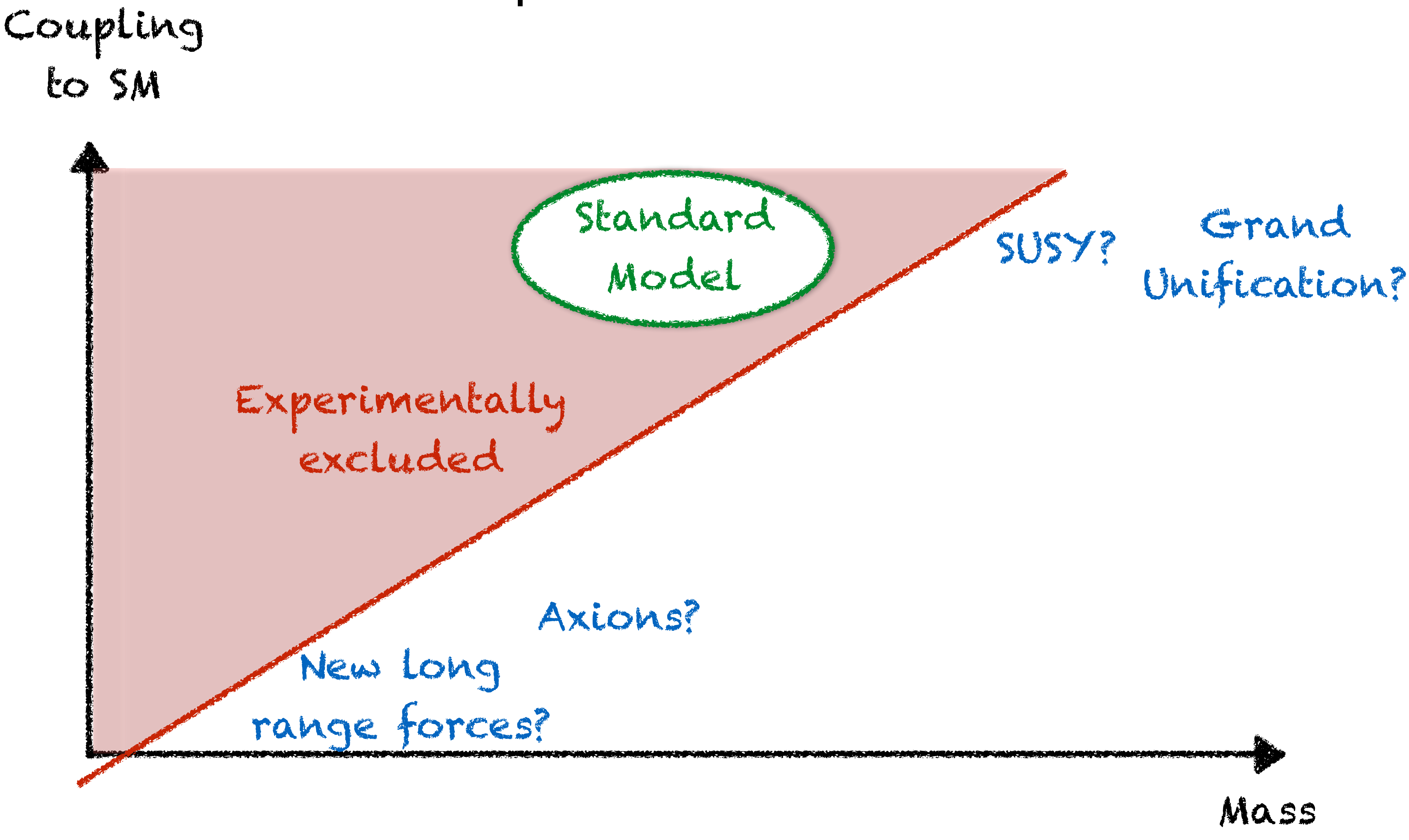
1004.3558 A. Arvanitaki, S. Dubovsky
1411.2263 A. Arvanitaki, M. Baryakhtar, X. Huang
1604.03958 A. Arvanitaki, M. Baryakhtar, S. Dimopoulos, S. Dubovsky, RL
16xx.xxxxx M. Baryakhtar, RL
. . .

Outline

- Light, weakly-coupled new particles — motivation & constraints
- Black hole superradiance — particle production by energy extraction
- Observational signatures
  - Spin-down of black holes
  - Coherent gravitational wave emission

Light, weakly-coupled new particles



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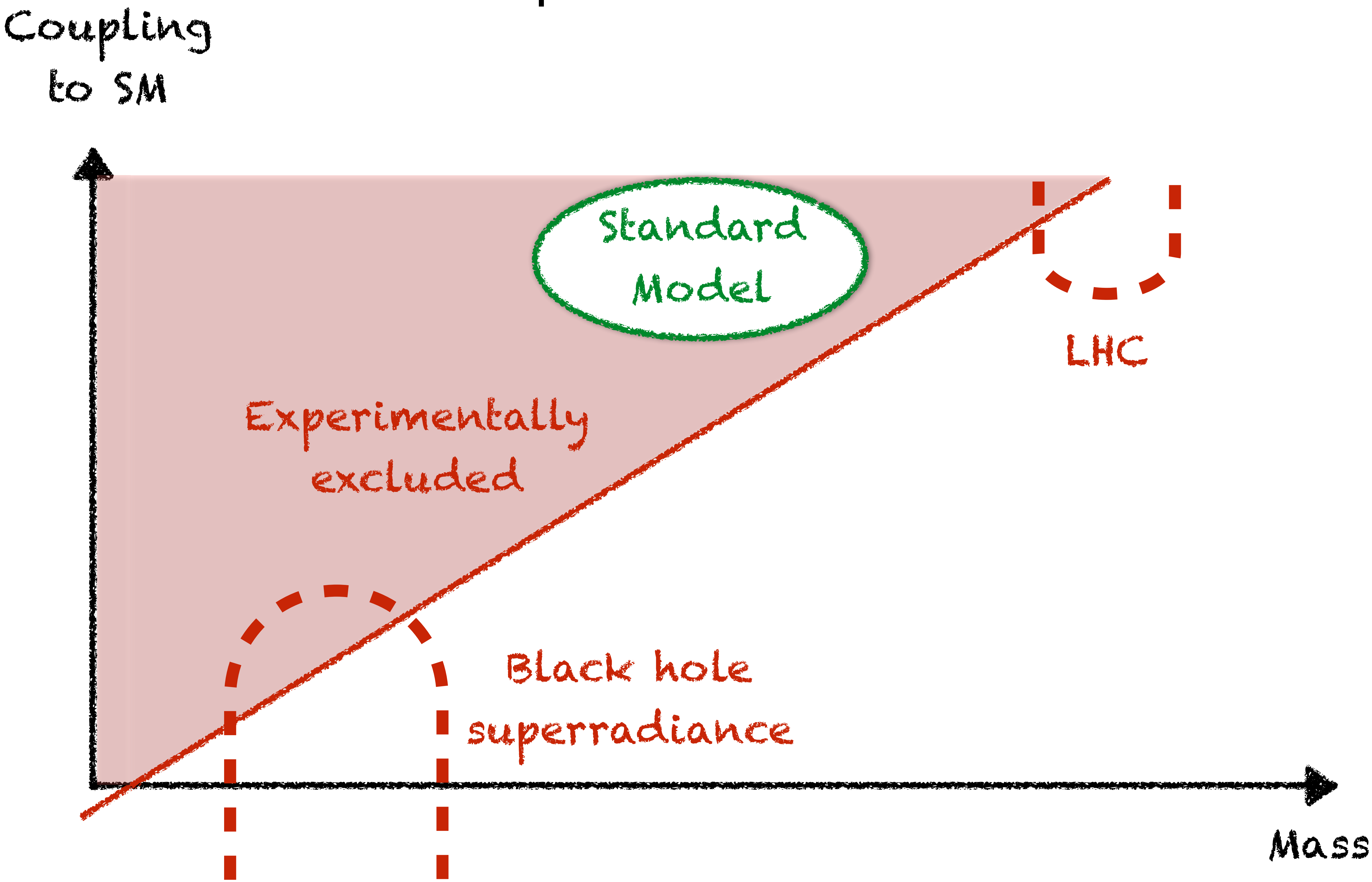
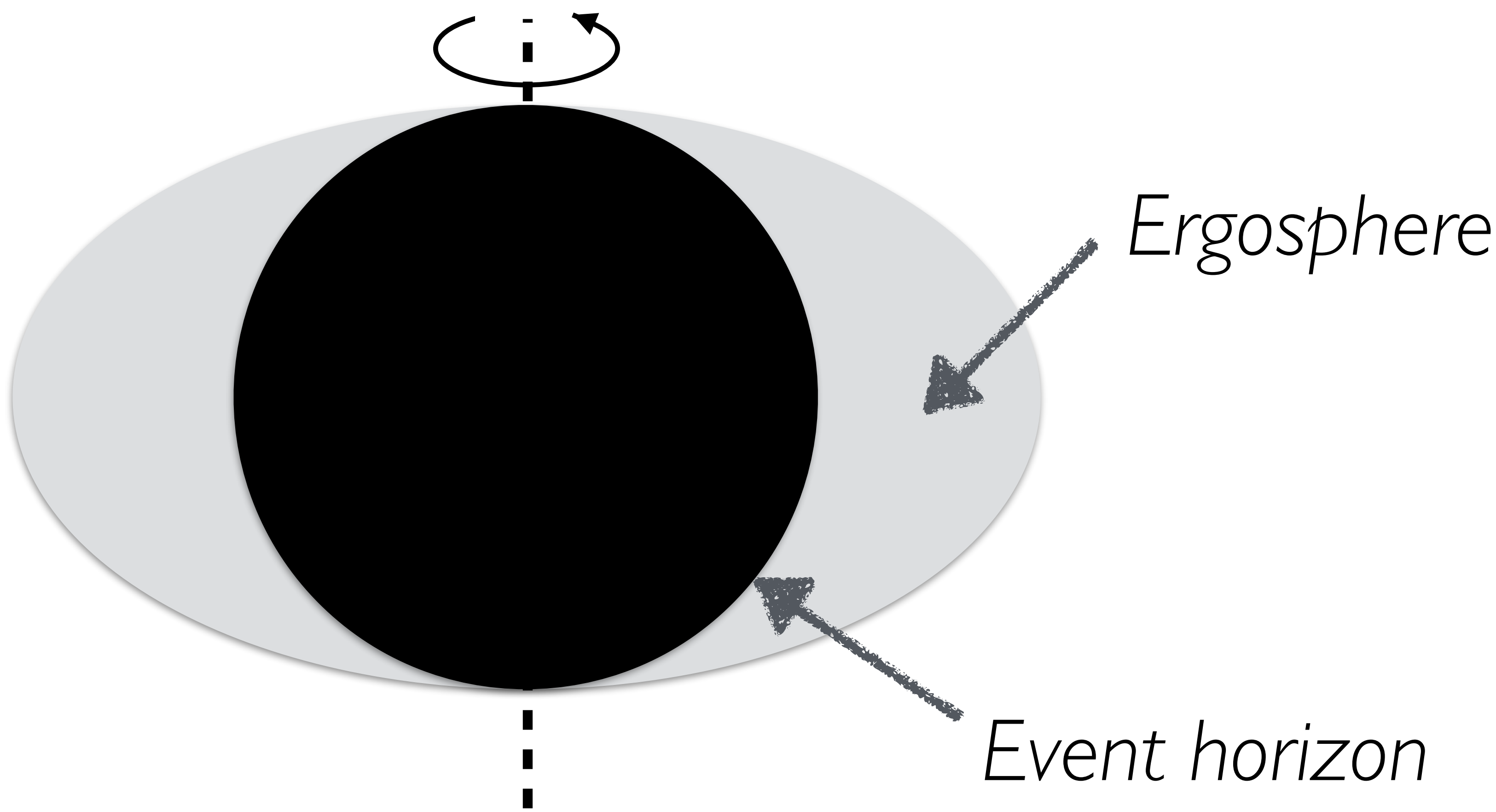


Gravitational production of light particles

- New particles *must* couple to SM through gravity
- Problem: astrophysically, spacetime curvature scale $\gtrsim \mathrm{km}$ => effective source density very low
  - e.g. BH Hawking temperature, $T_H = 1/(8\pi GM) \sim 10^{-8}\,\mathrm{K}$
- Take advantage of coherence enhancement: classical energy extraction from spinning BHs

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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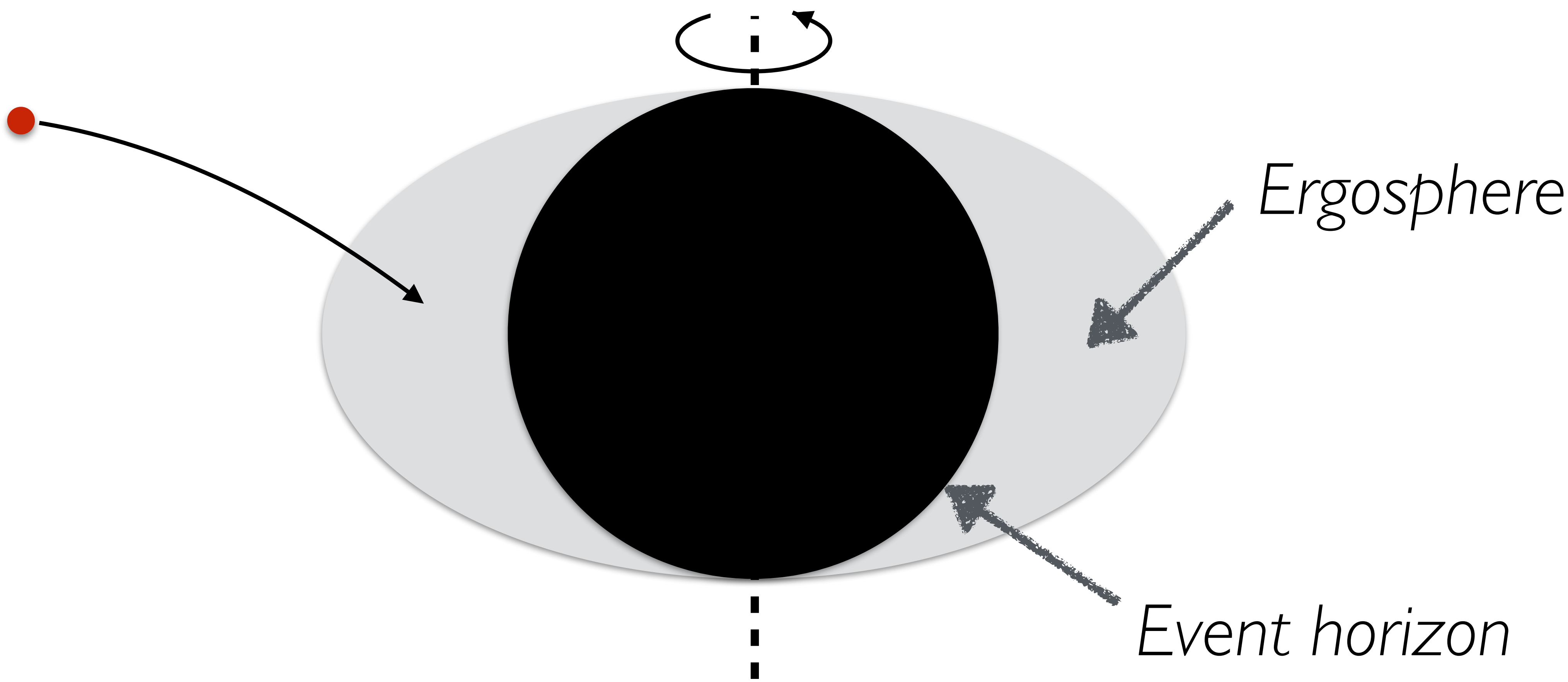

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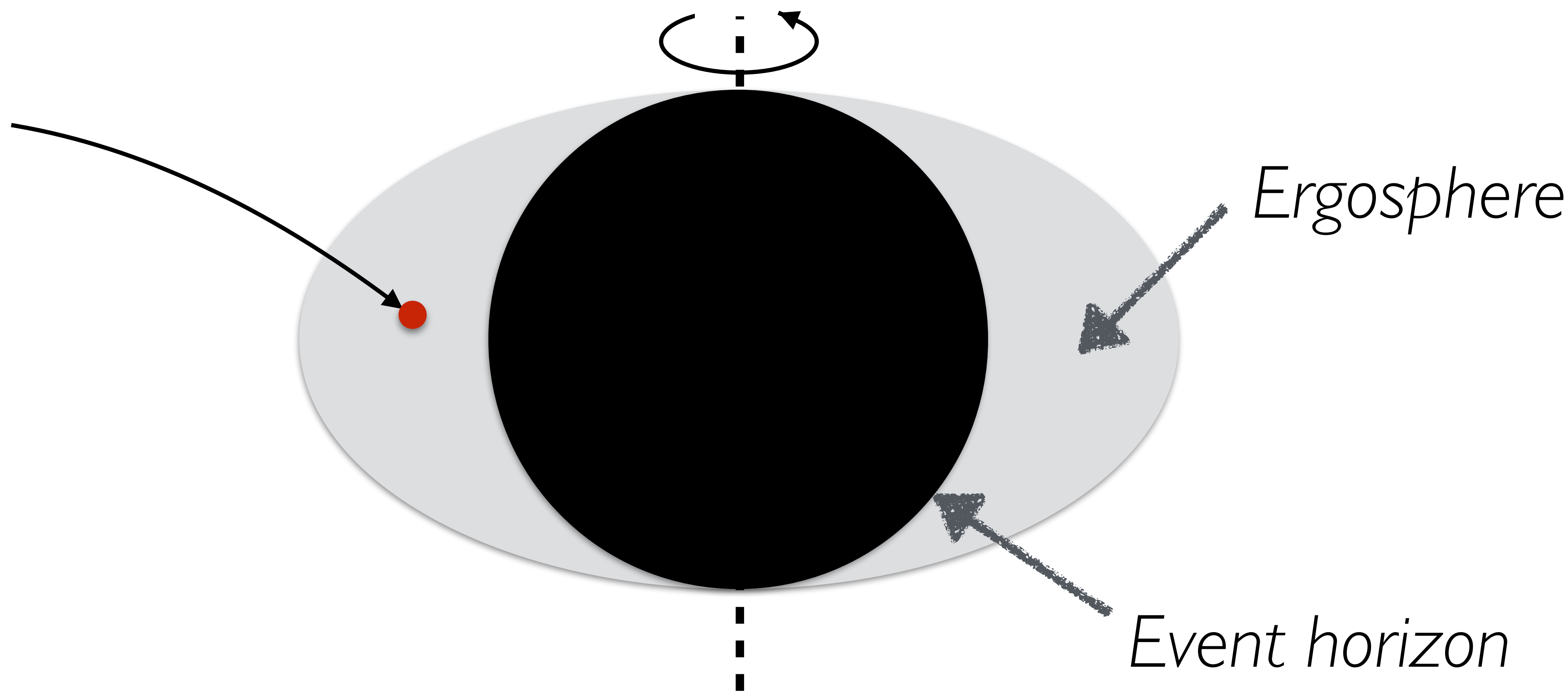

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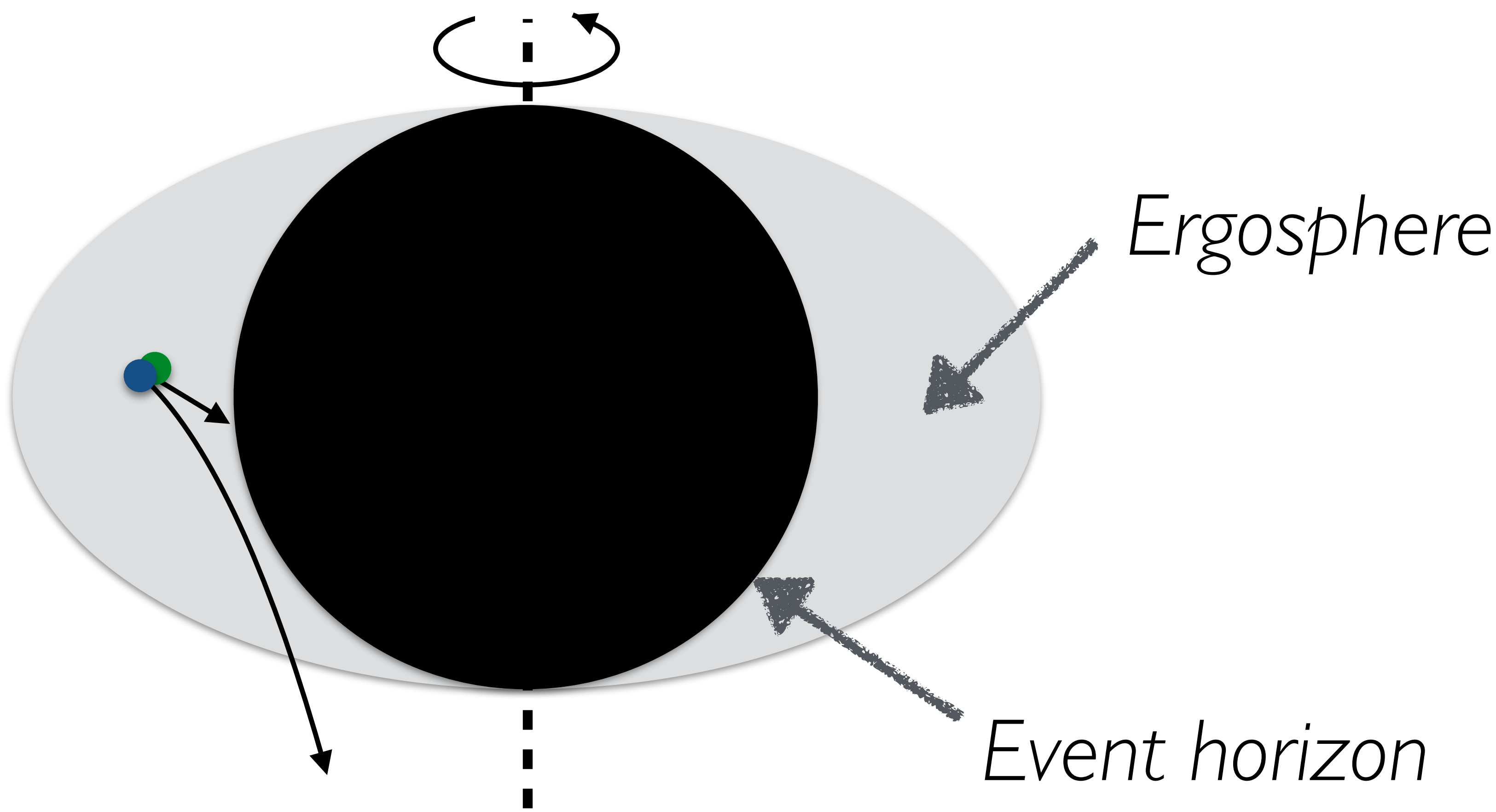

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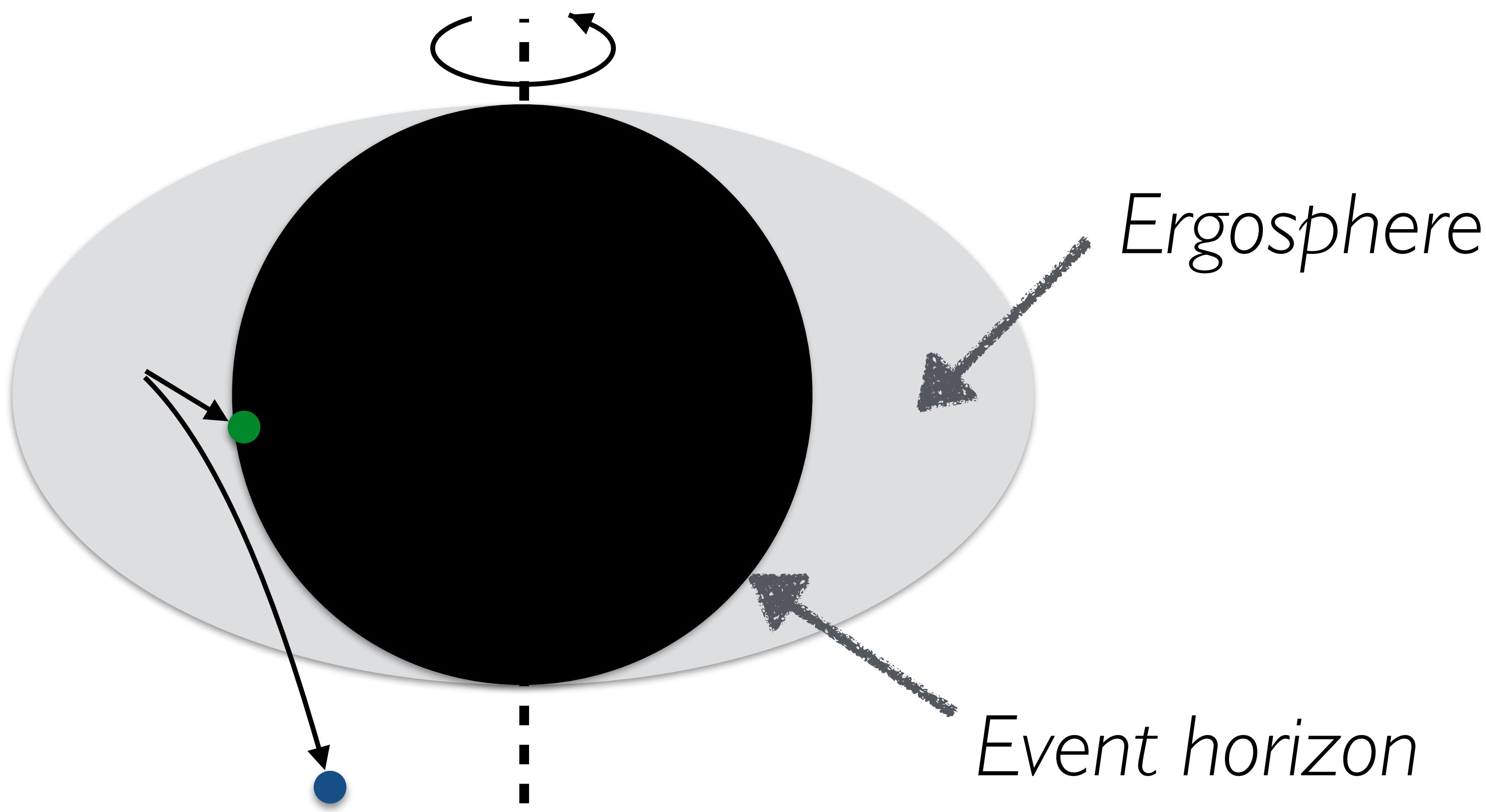

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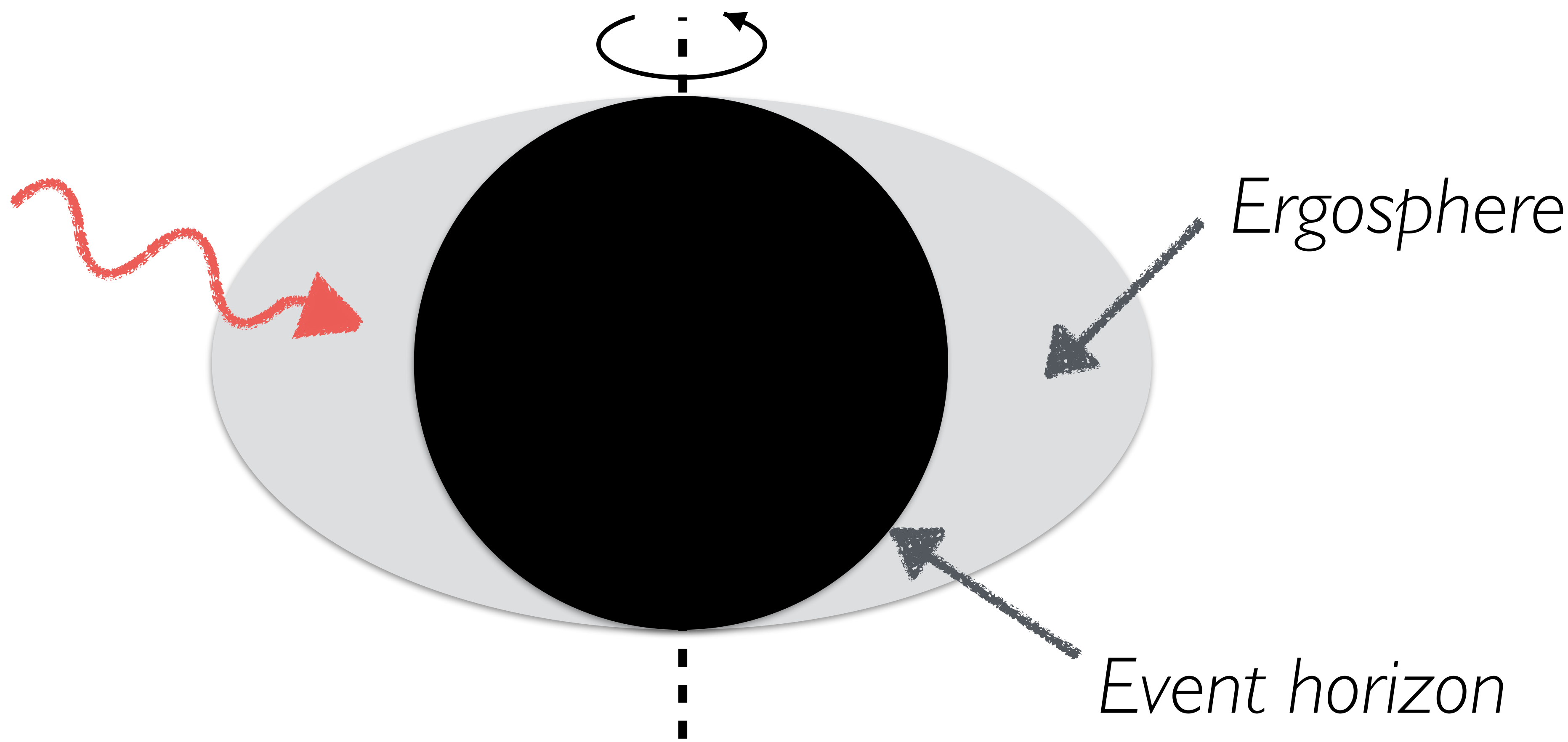

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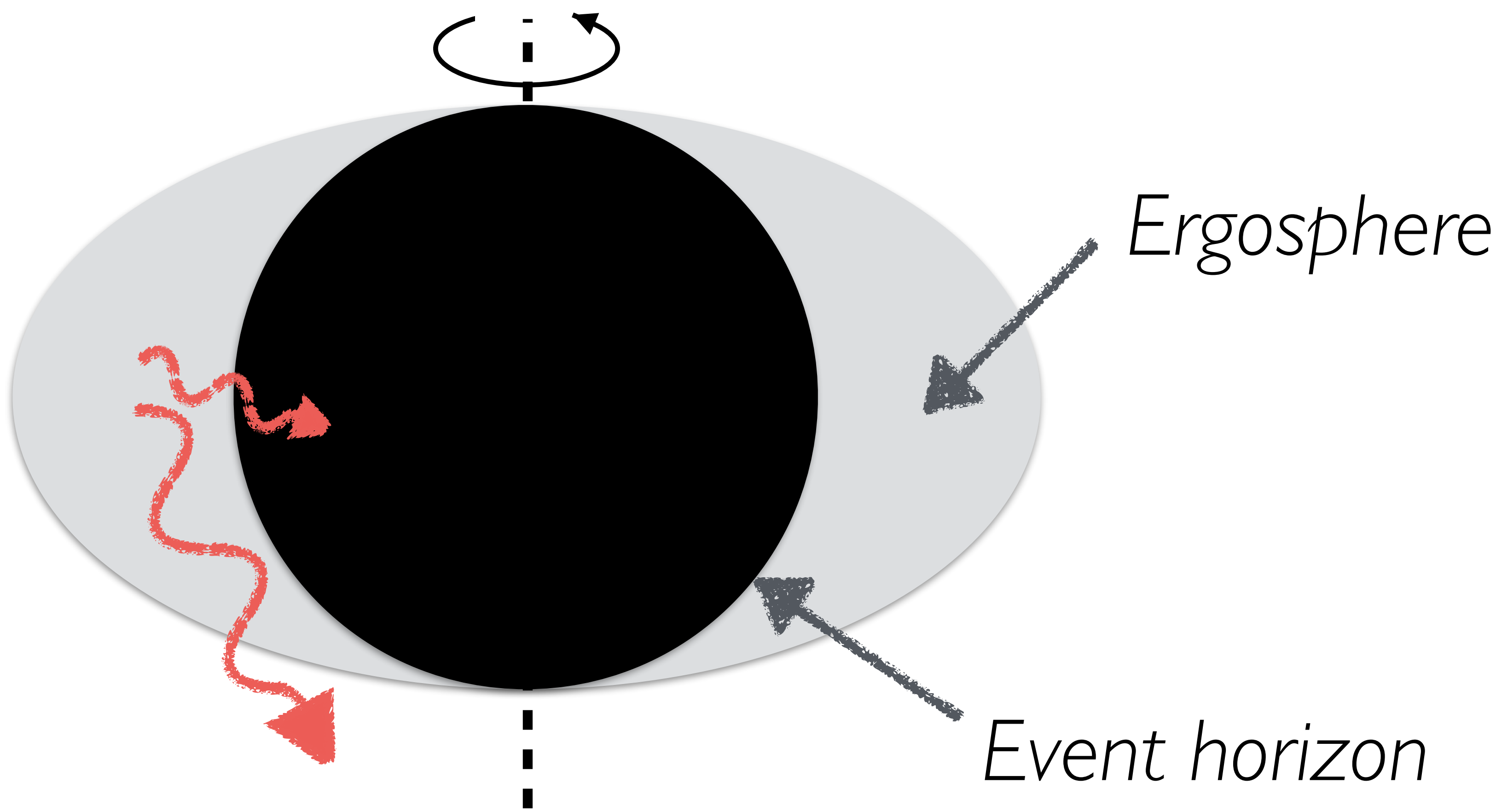

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Wave superradiance

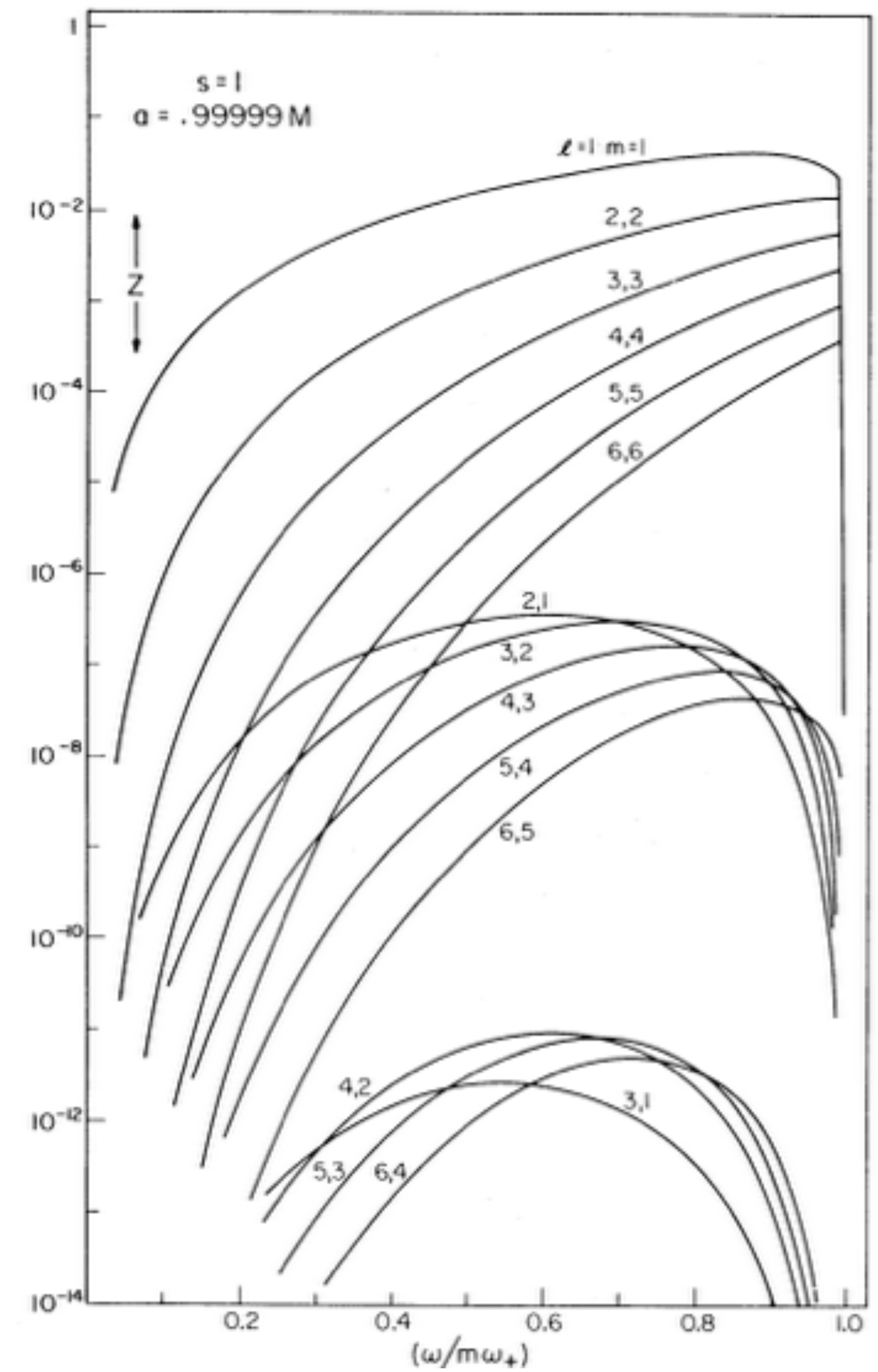
- Ingoing flux at horizon can correspond to negative E_∞ flux

- For wave with angular quantum number m,

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

$$P = \frac{1}{2}\varphi_0^2 A_H \omega(\omega - m\Omega_H)$$

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



[Teukolsky & Press, 1974]

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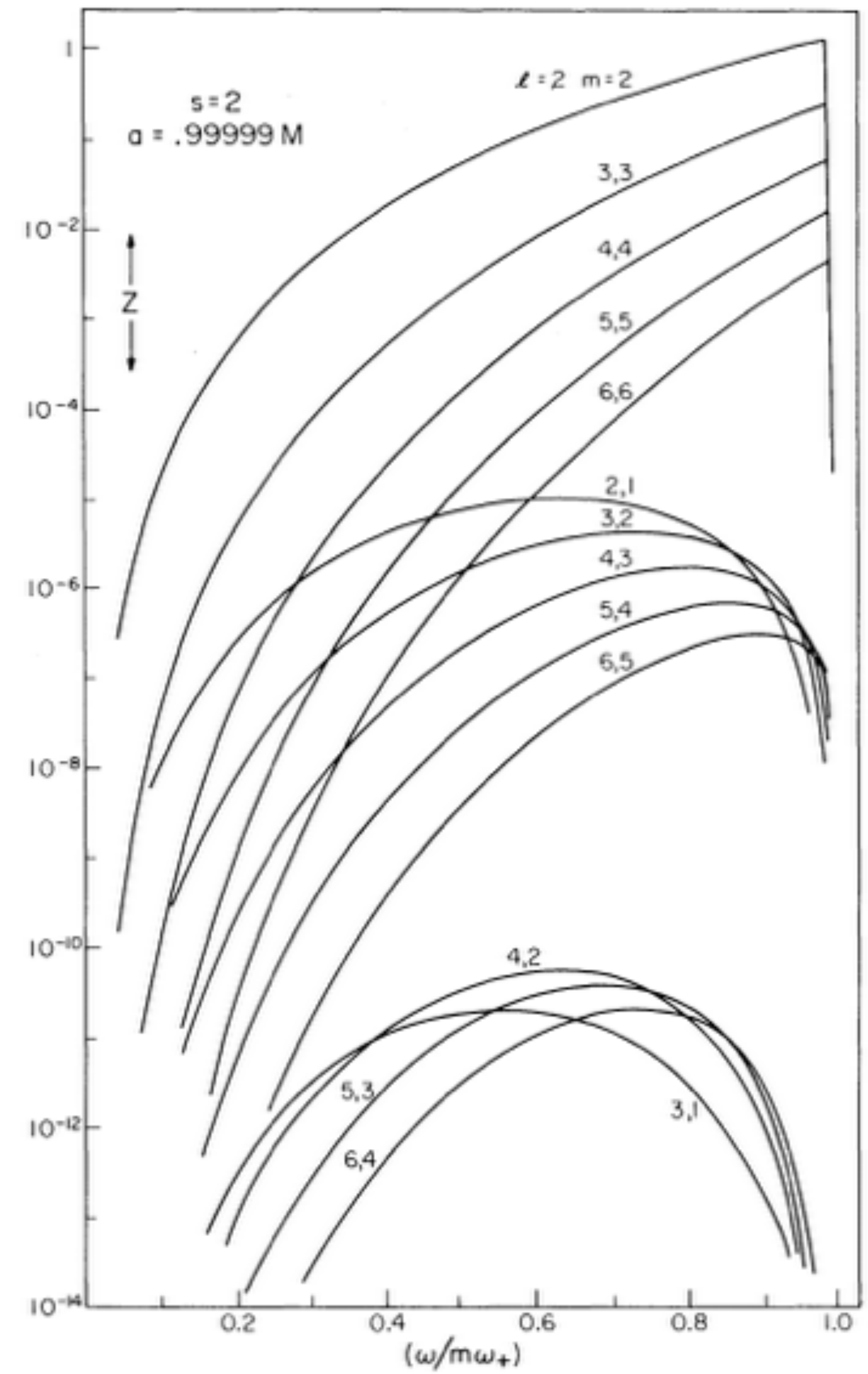
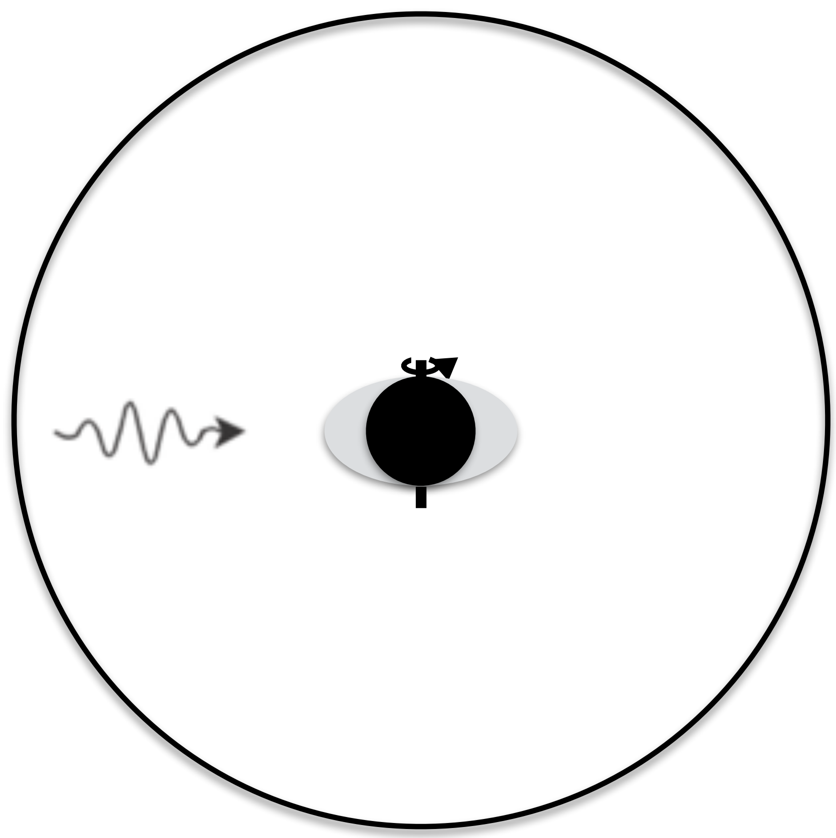


[Teukolsky & Press, 1974]

Black hole bombs and bound states

- "Black hole bomb" : superradiant scattering with a mirror

[Teukolsky & Press, 1972]



- Massive particles can form bound states around BH, enabling same exponential amplification

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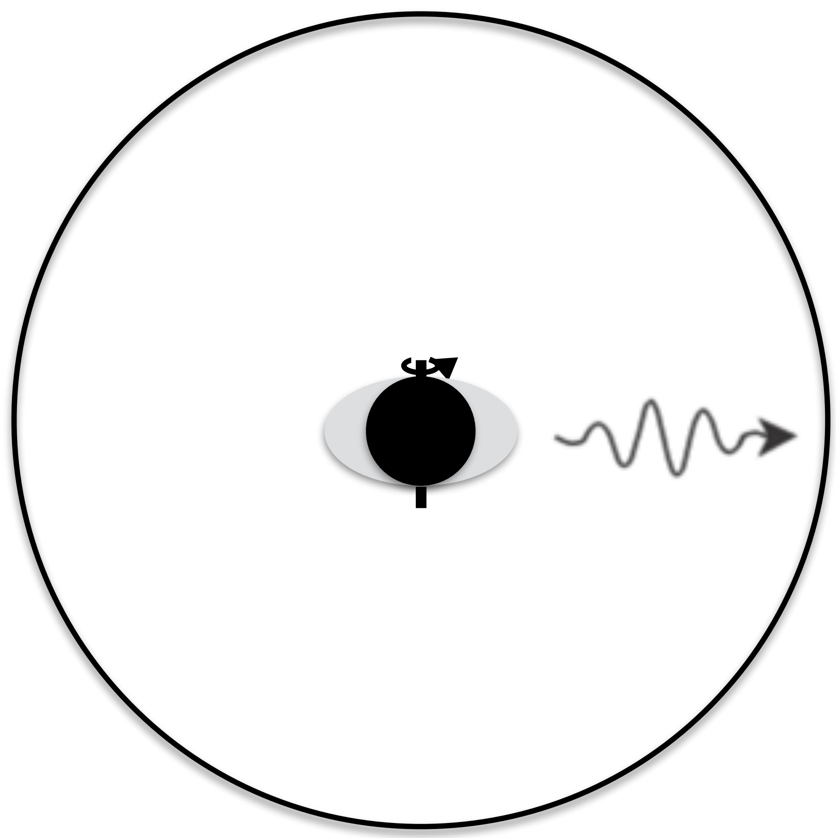

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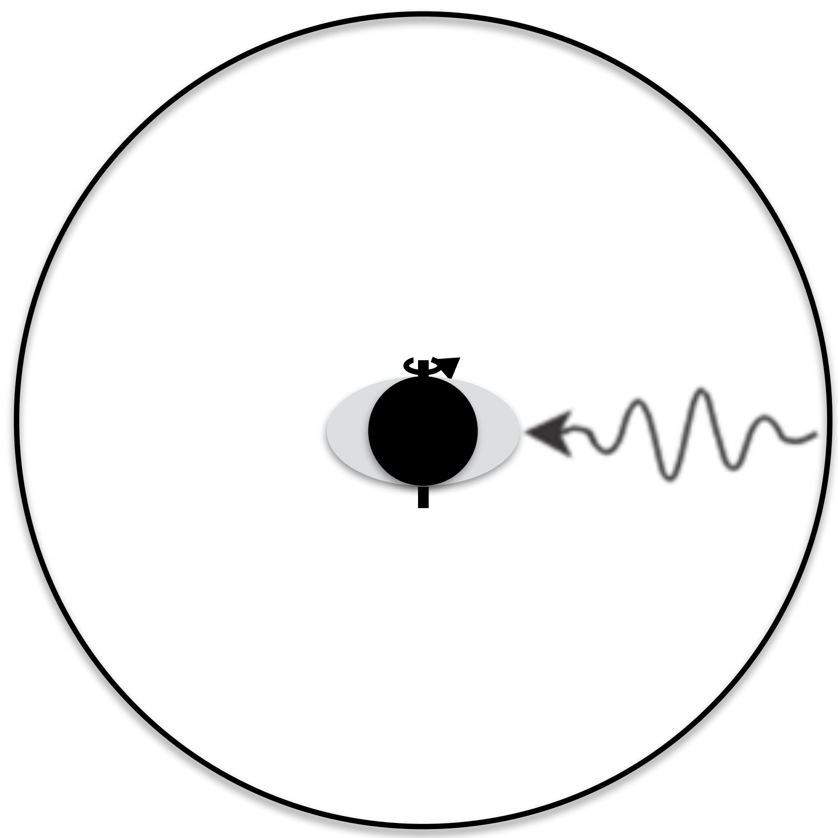

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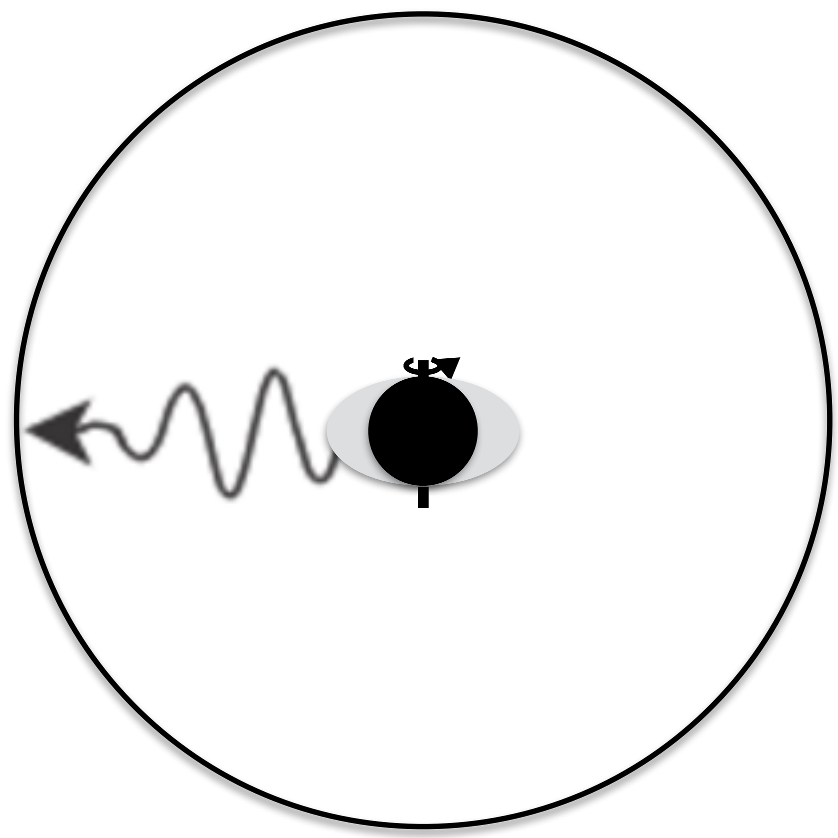

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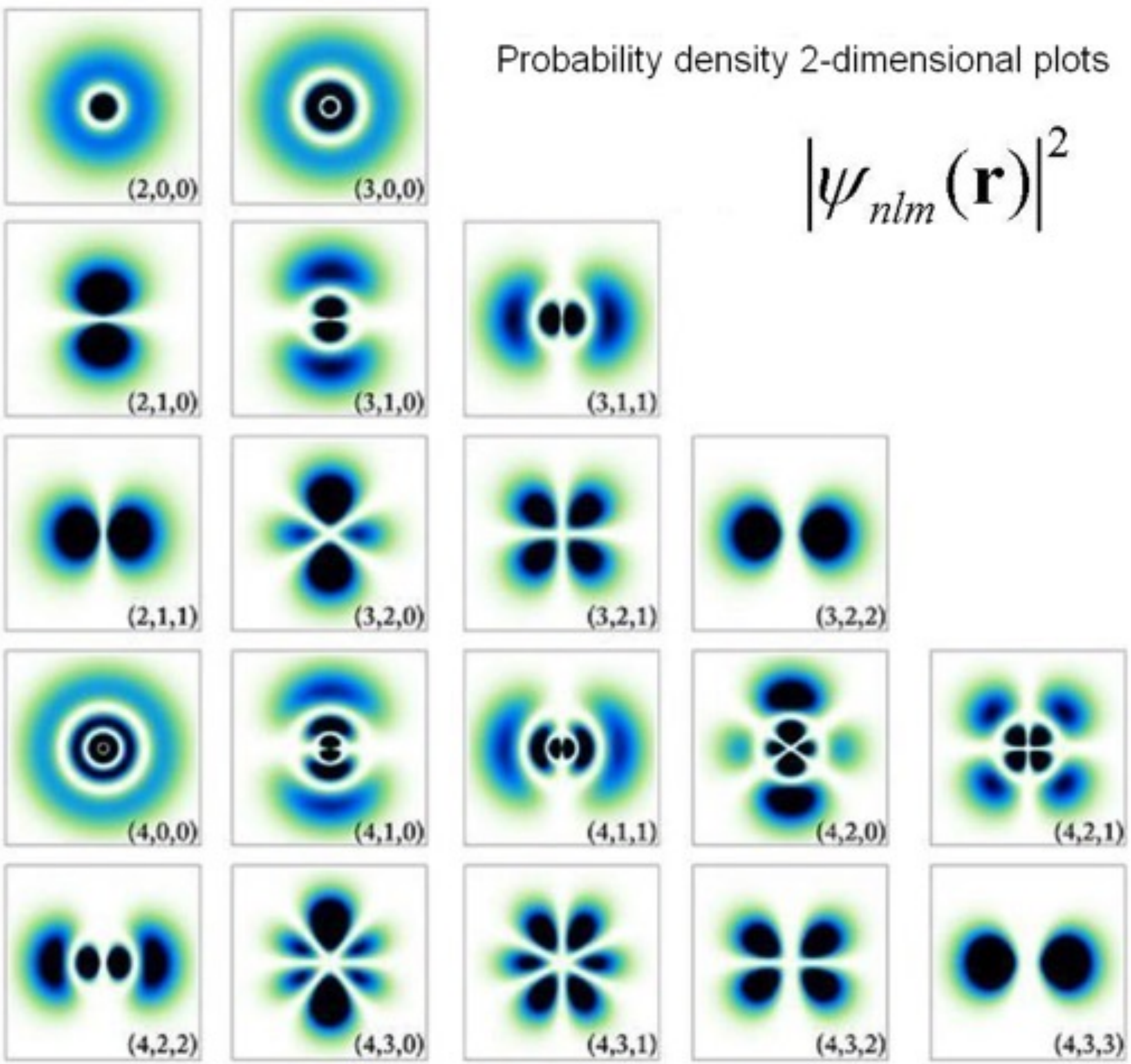
(Pseudo)scalar bound states

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



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

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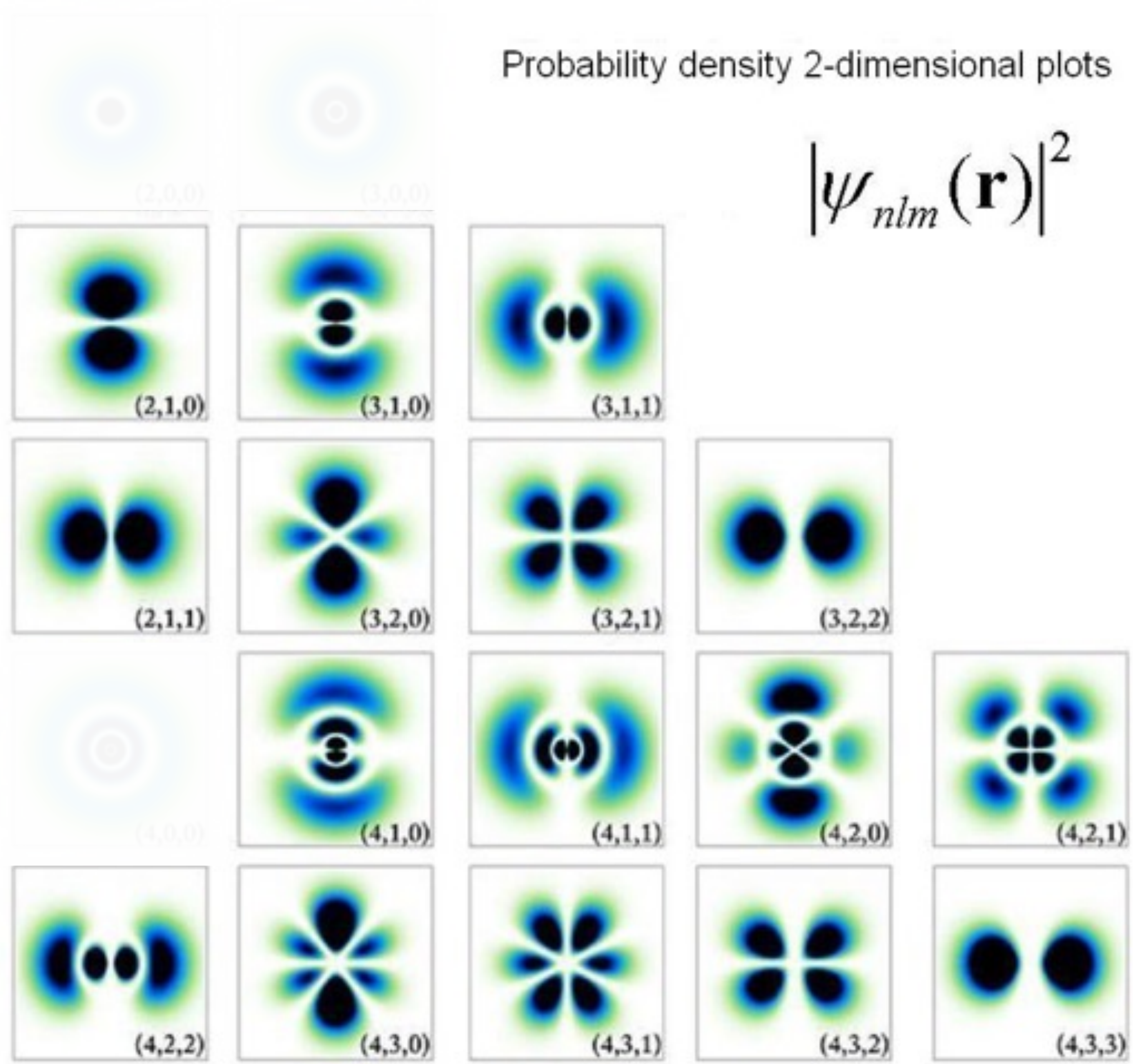

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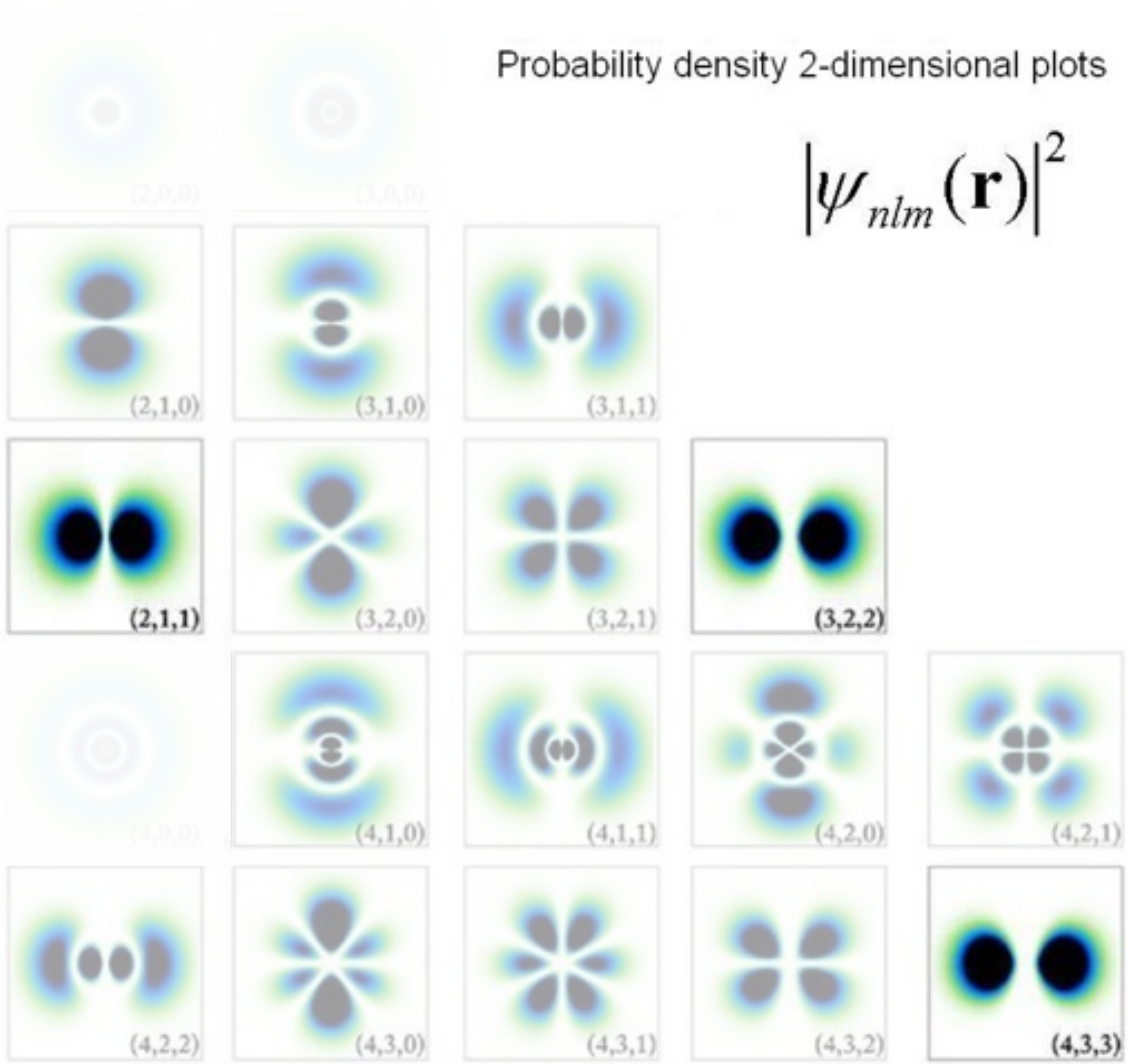

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Superradiant growth rates

- Smaller alpha, larger l ⇒ amplitude near horizon suppressed

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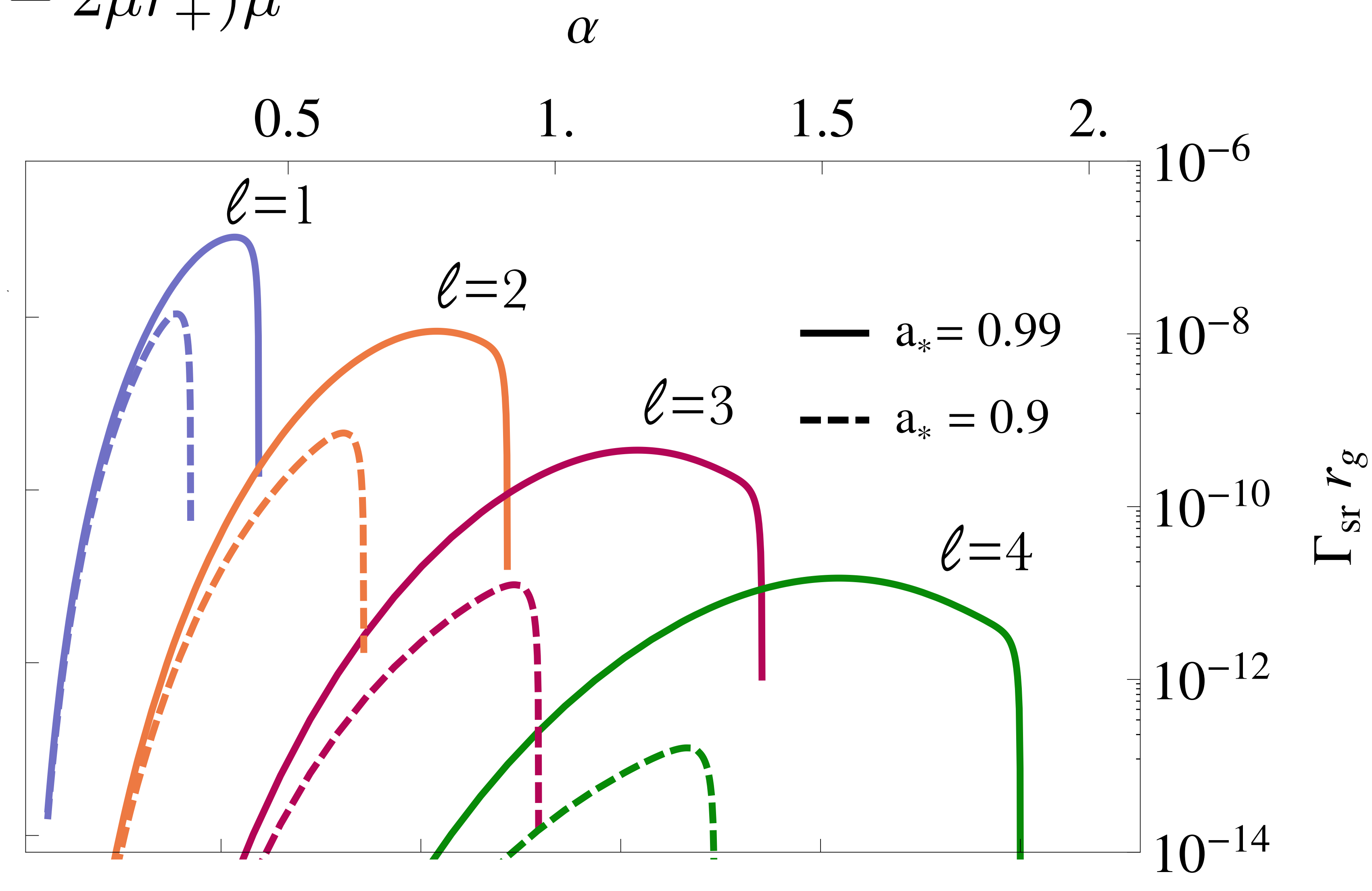

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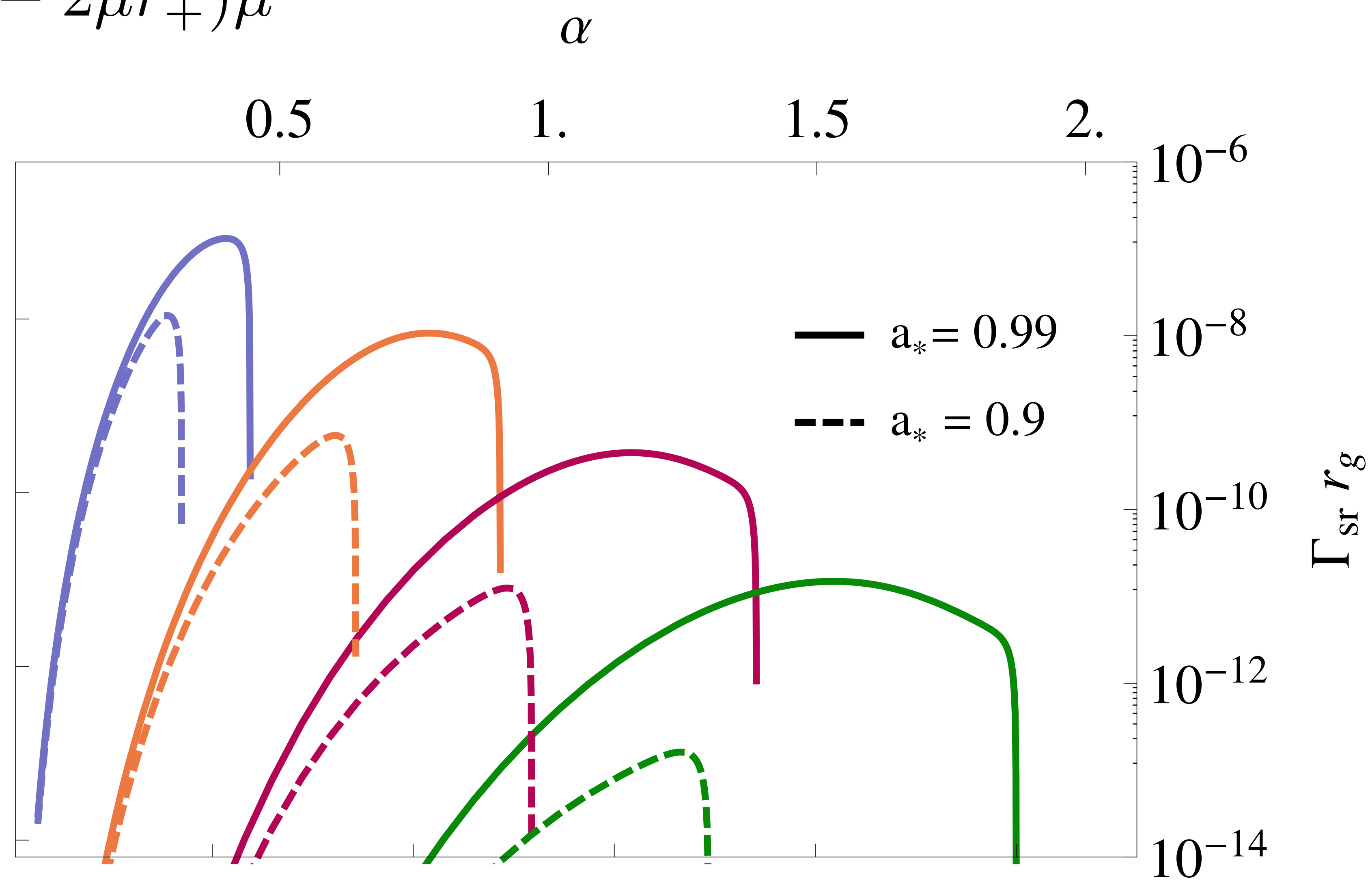
- If $\alpha/l > 1/2$ then angular phase velocity faster than horizon, so mode is decaying
- Fastest growth rate for $\mu \sim 1/(GM_{\mathrm{BH}})$



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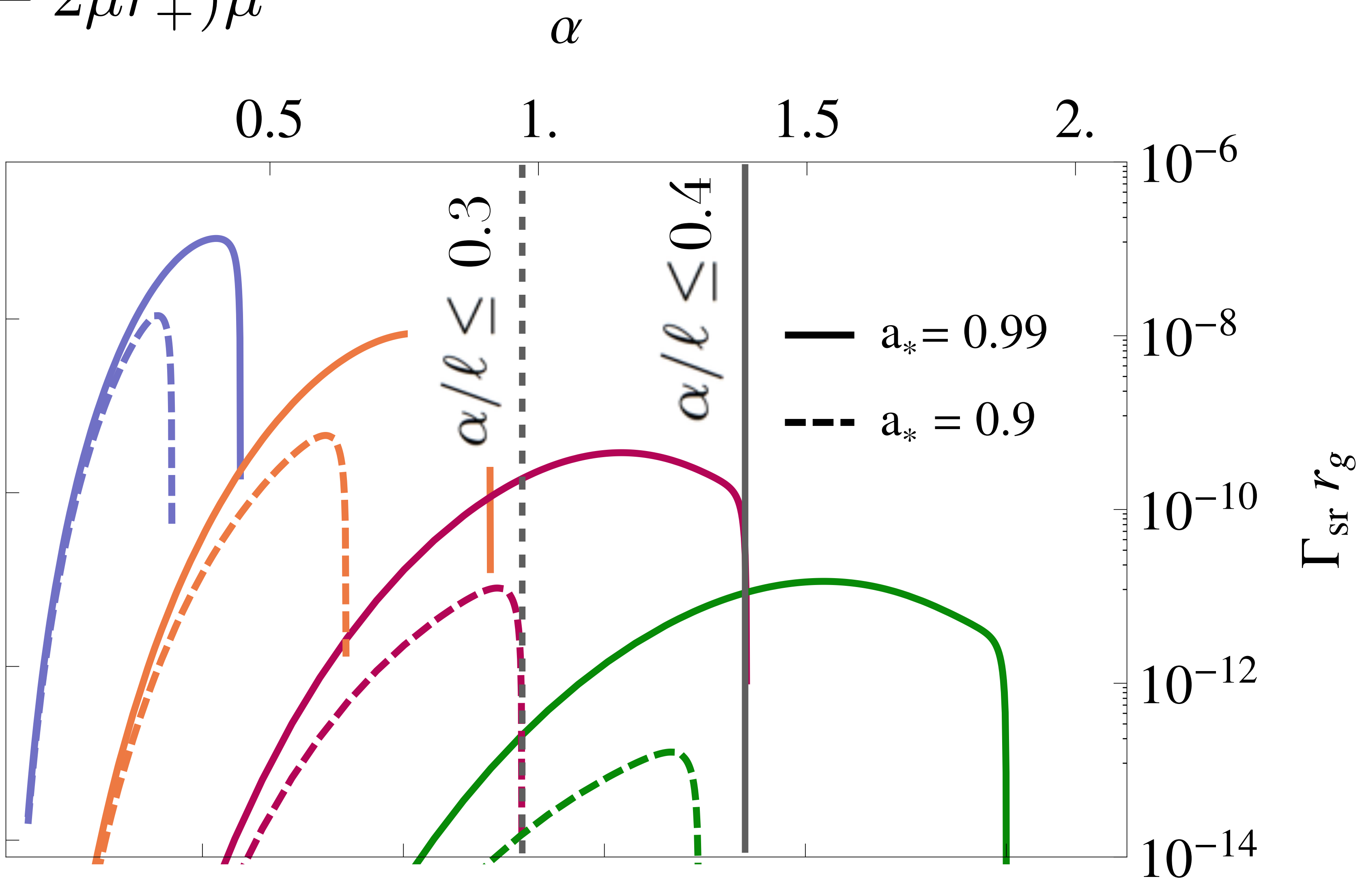

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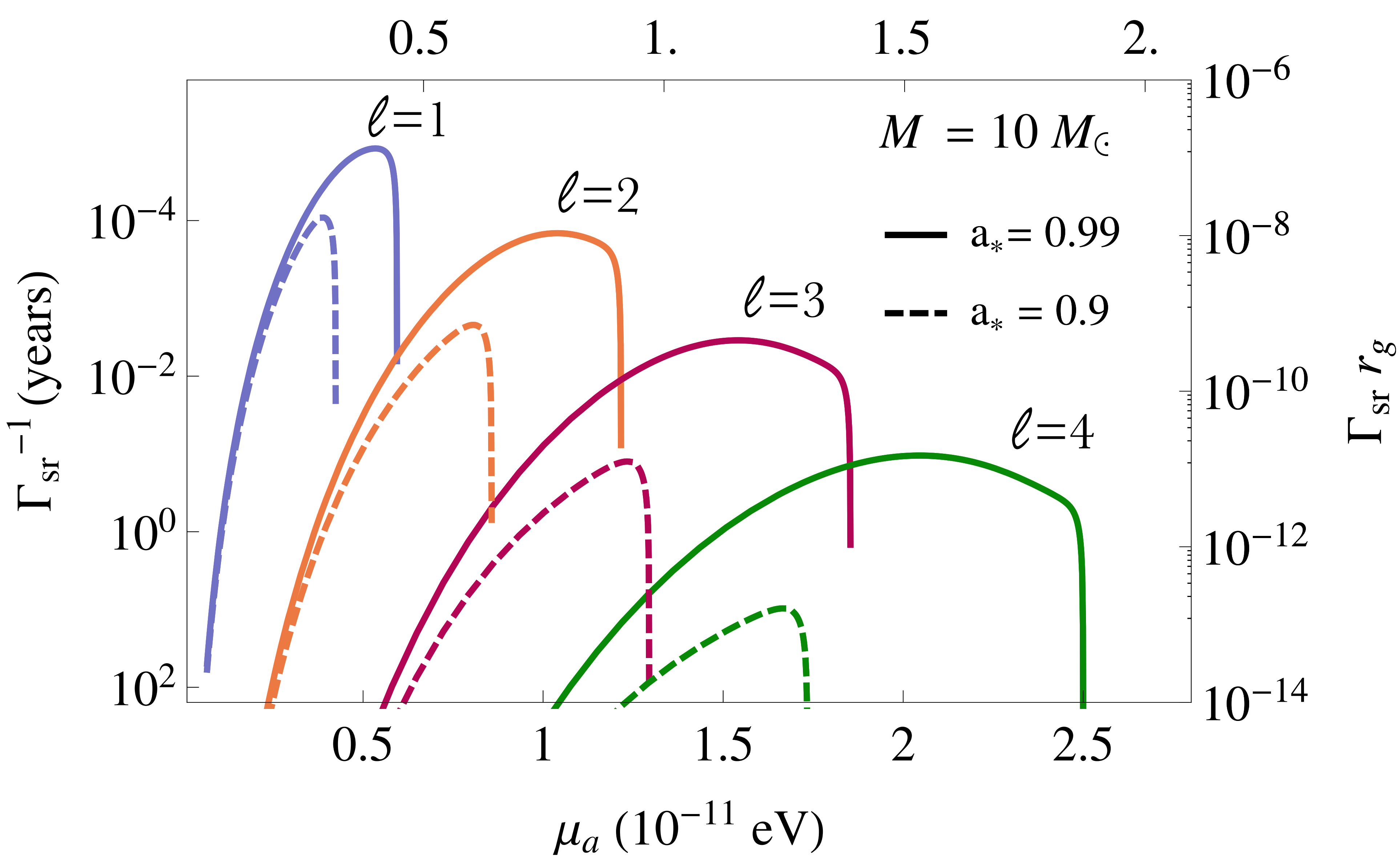
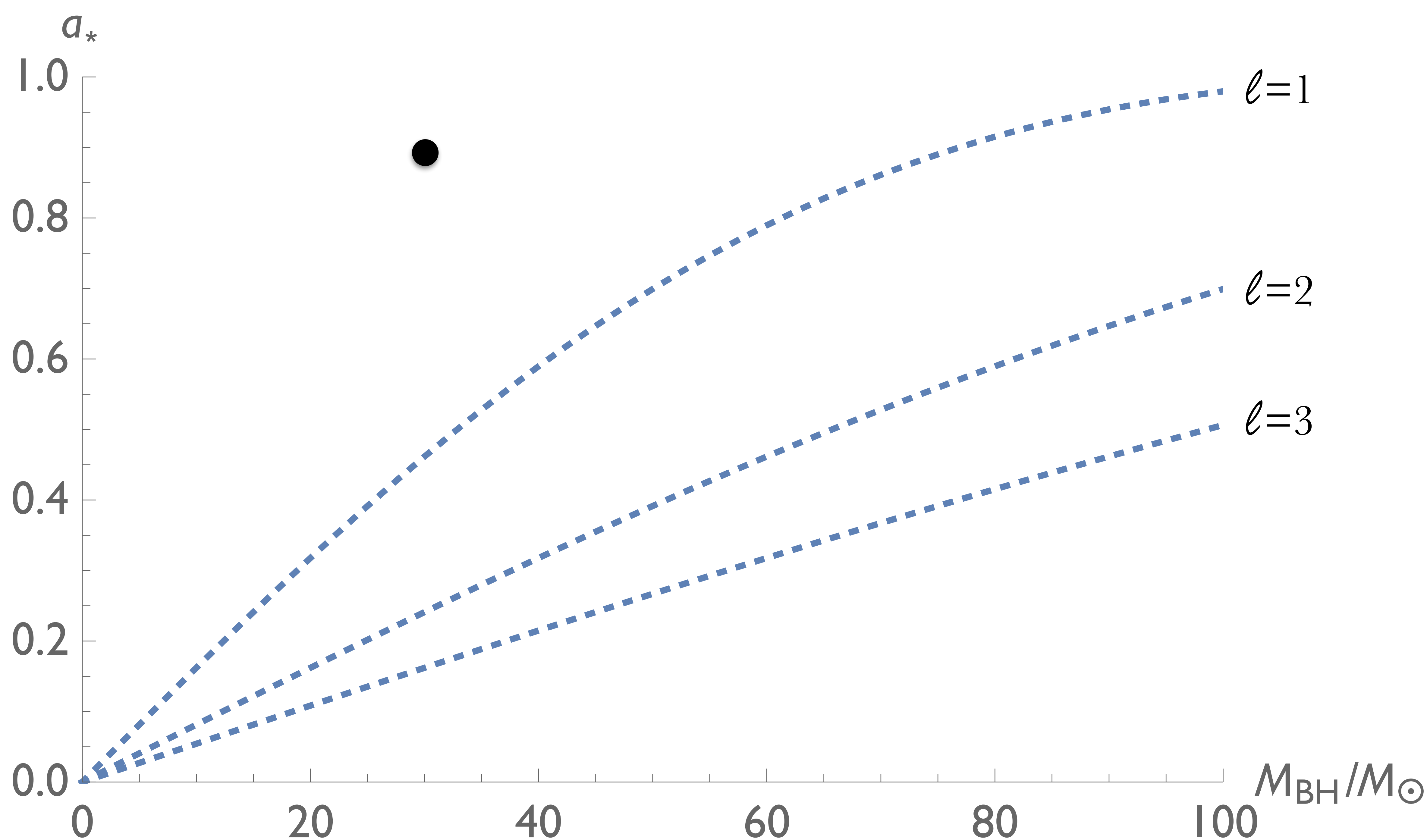
- For stellar BH, e-folding times in plot ~100 sec - 100 yr



Black hole spin-down



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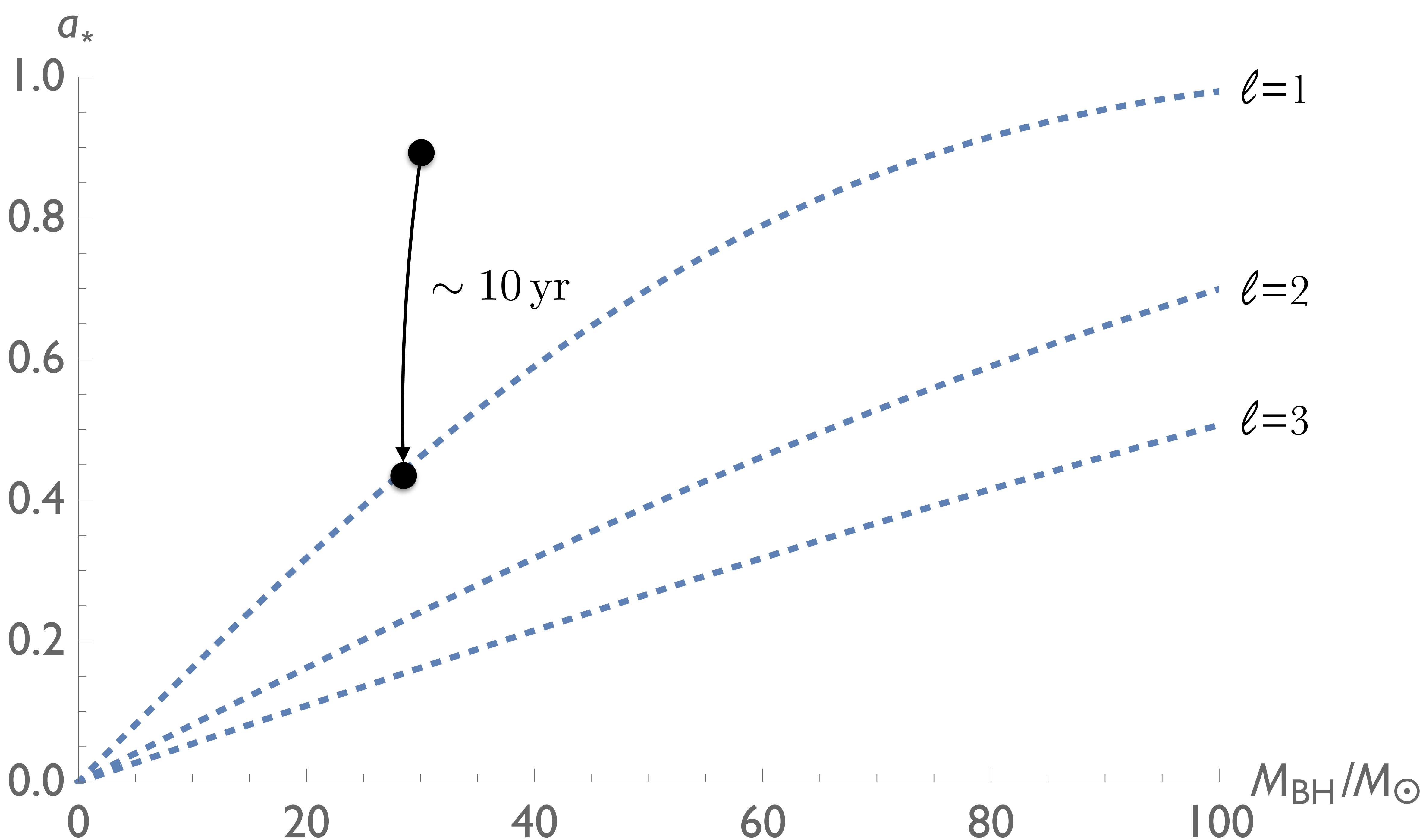

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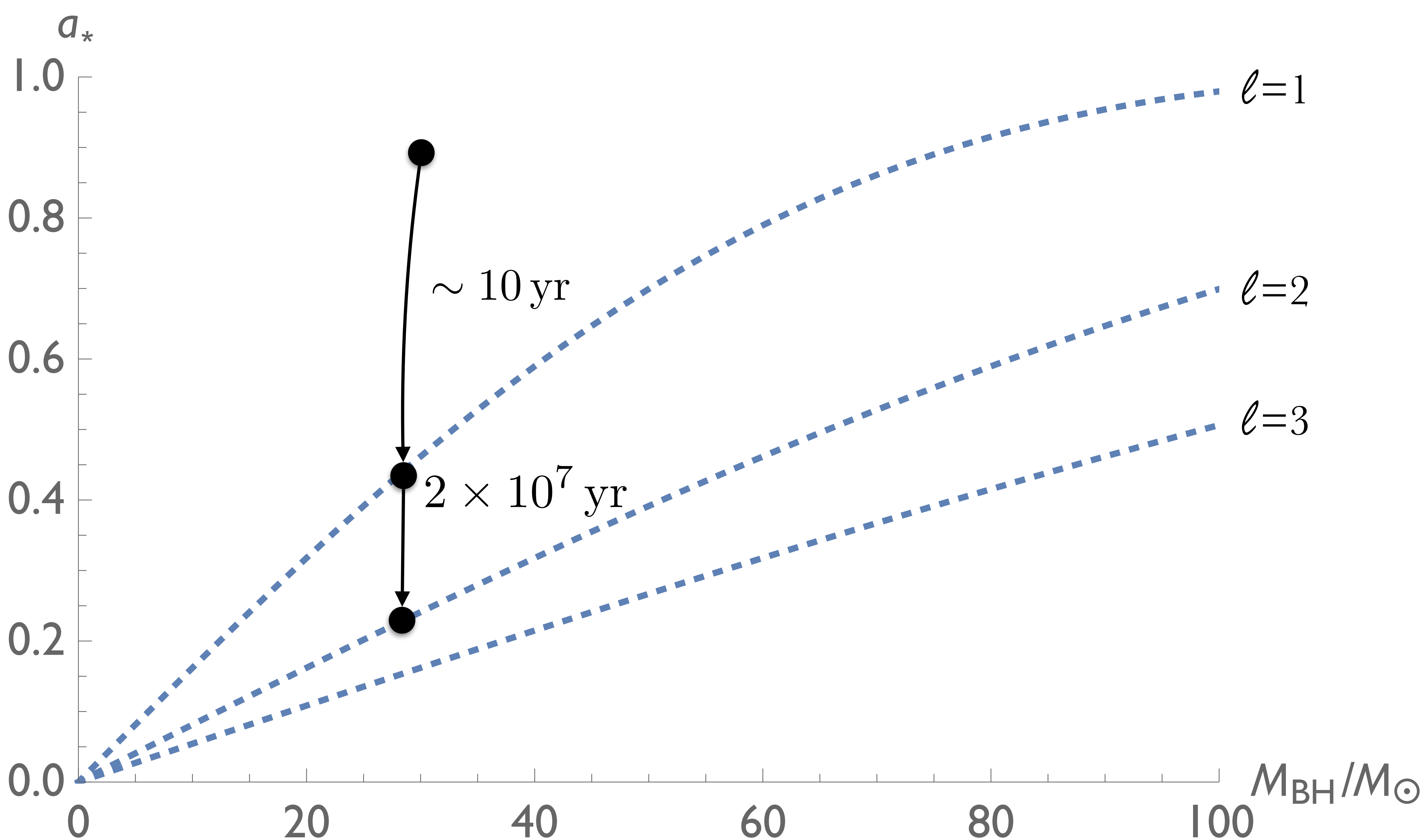

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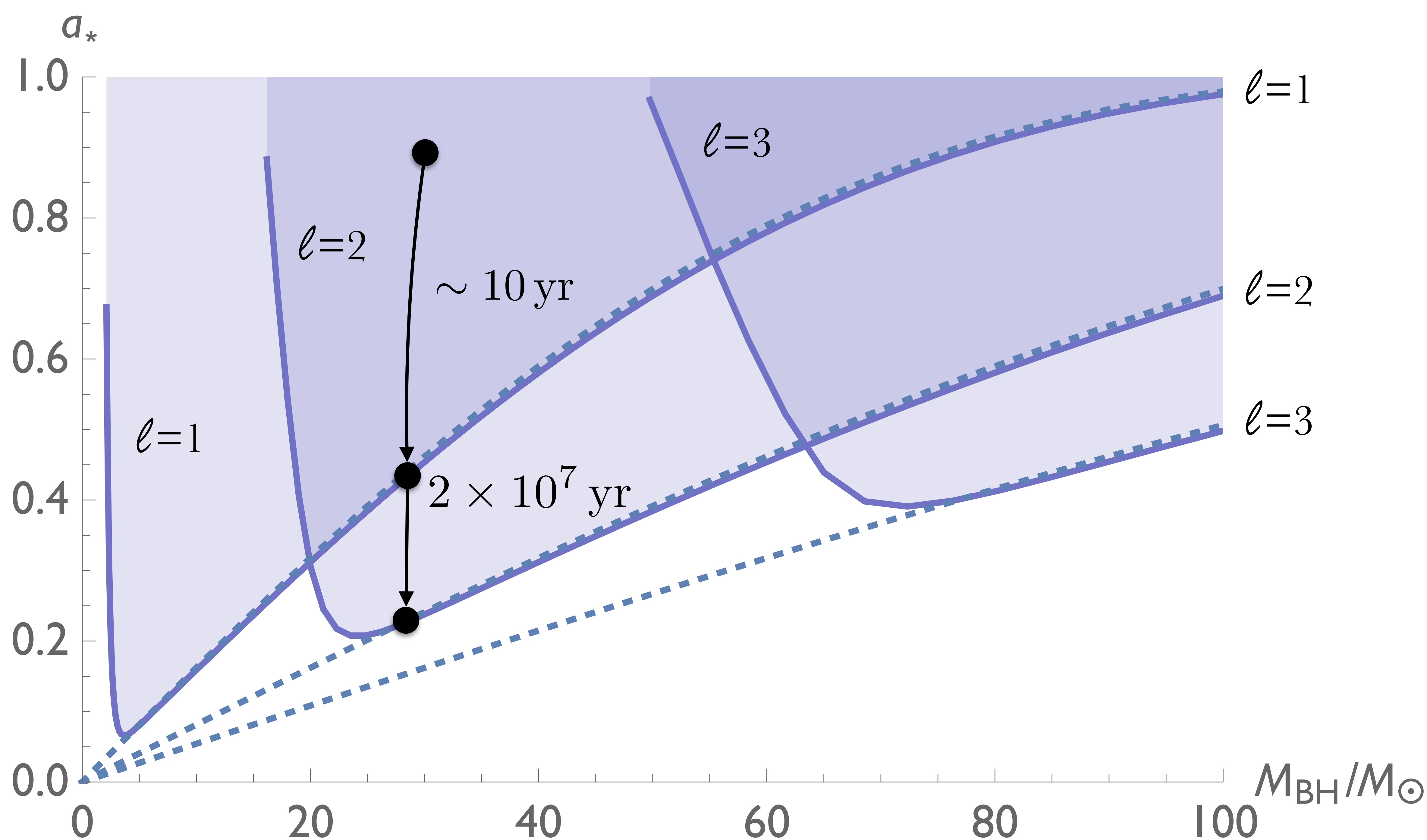
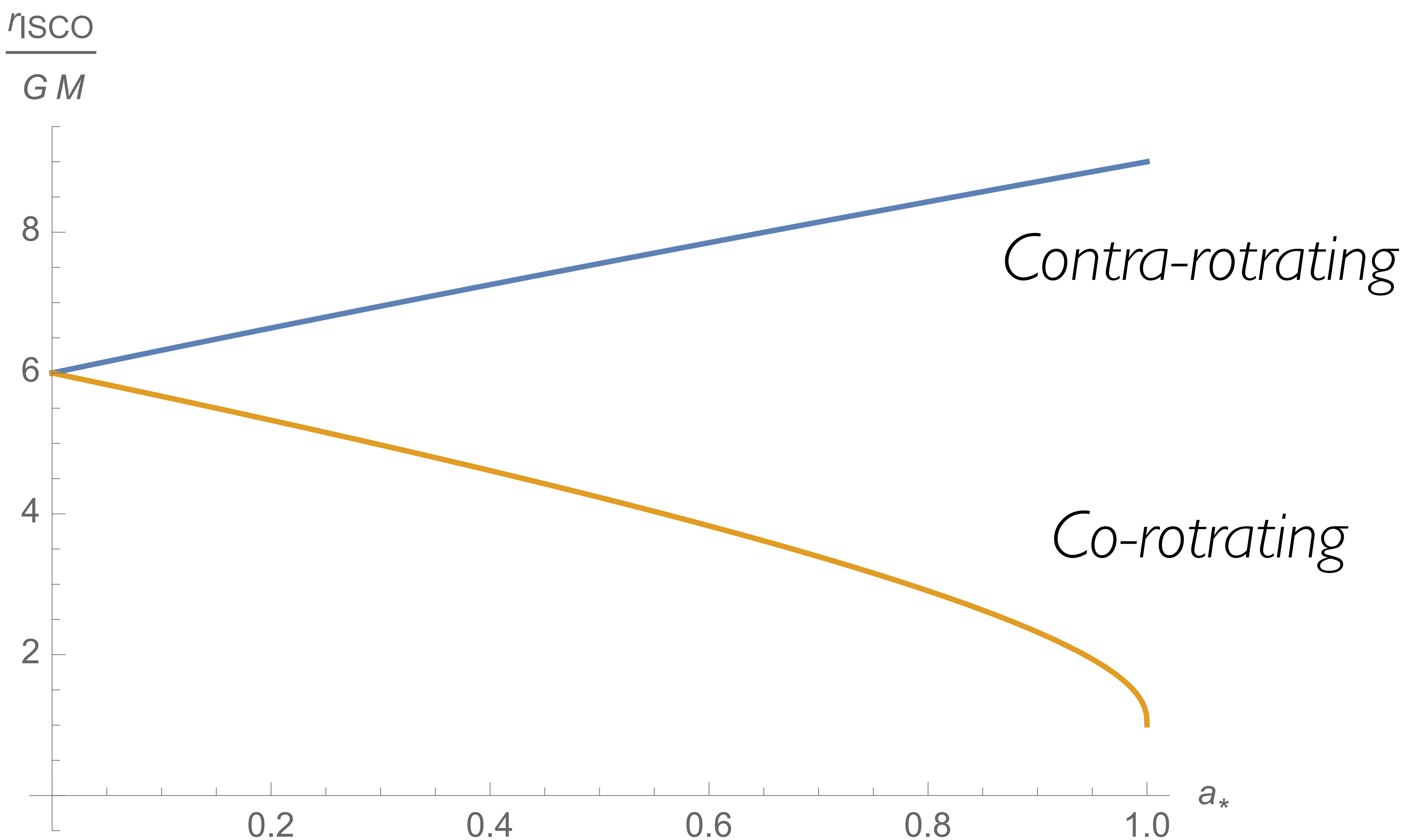


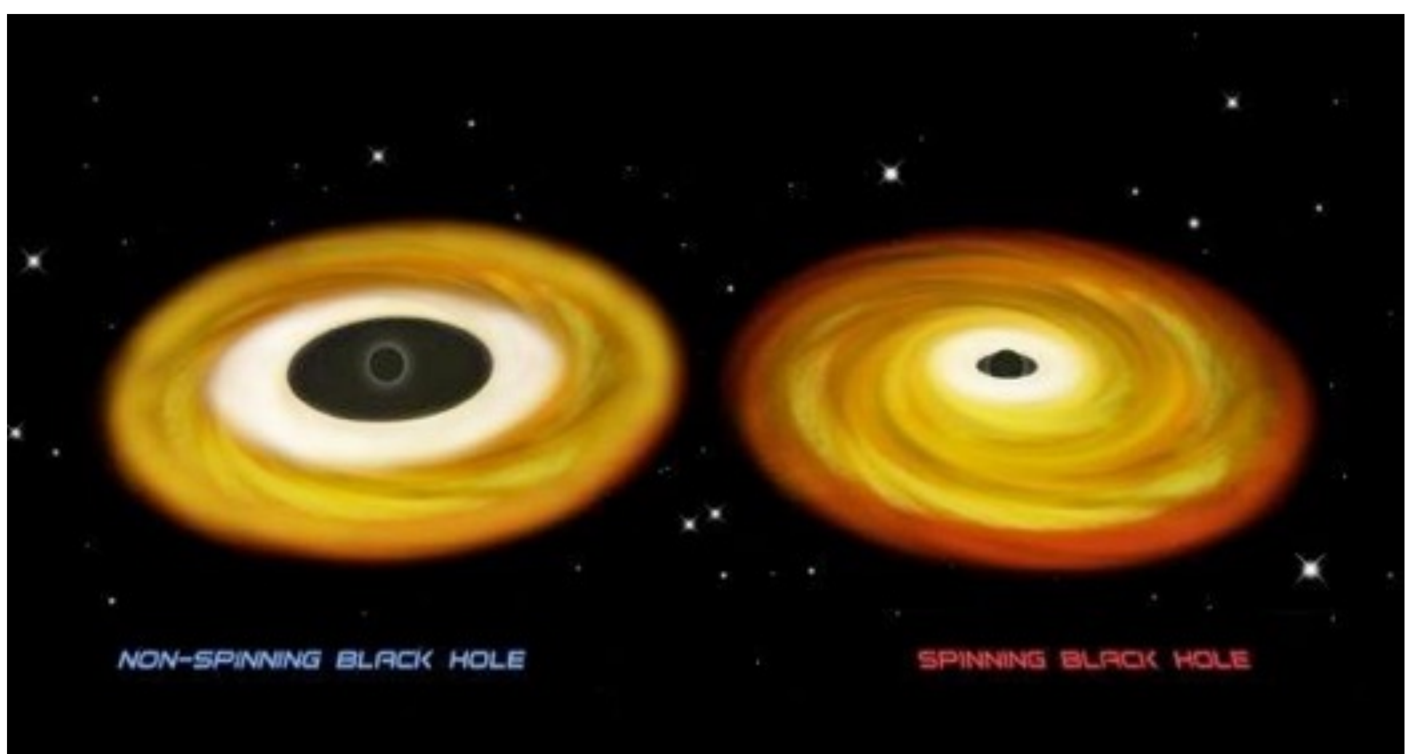
Exclusions from BH spin measurements

- Higher BH spin => innermost stable orbit at smaller radius



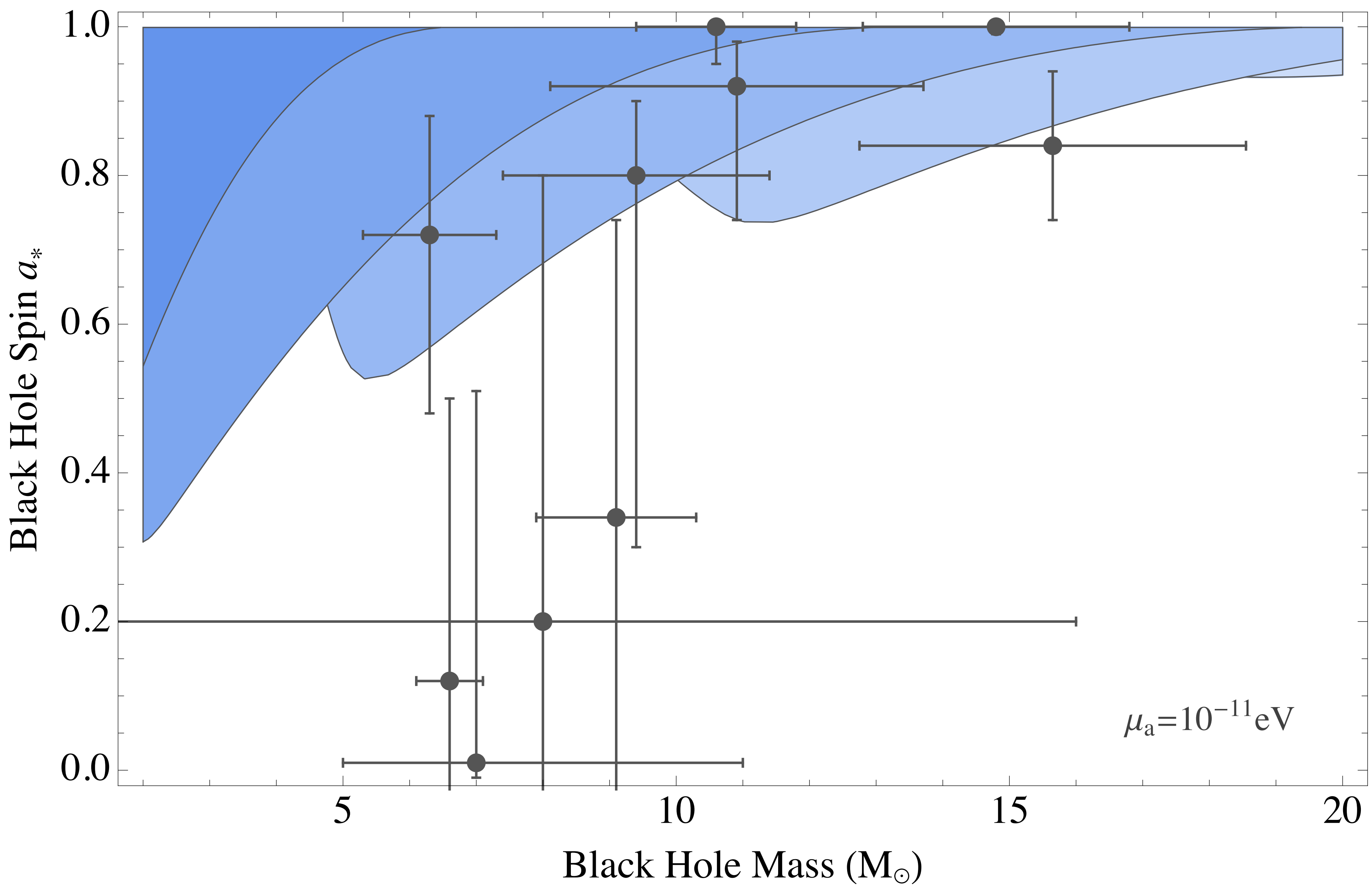
Exclusions from BH spin measurements

- Higher BH spin => innermost stable orbit at smaller radius
- Accretion disk can get closer to BH
- Detect X-rays from accretion disk, infer disk properties



X-ray spin measurements

Spin measurements from different black holes:



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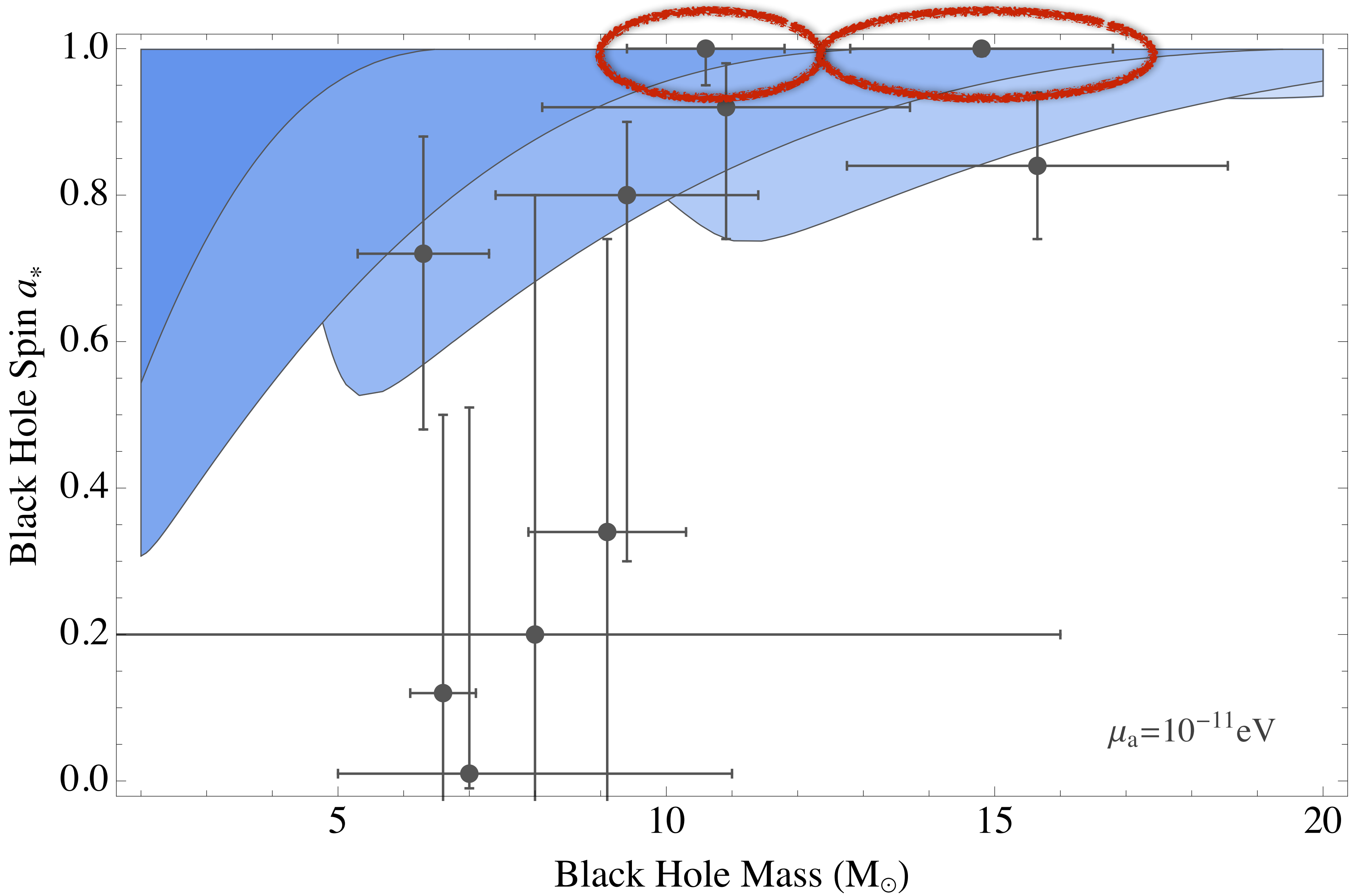

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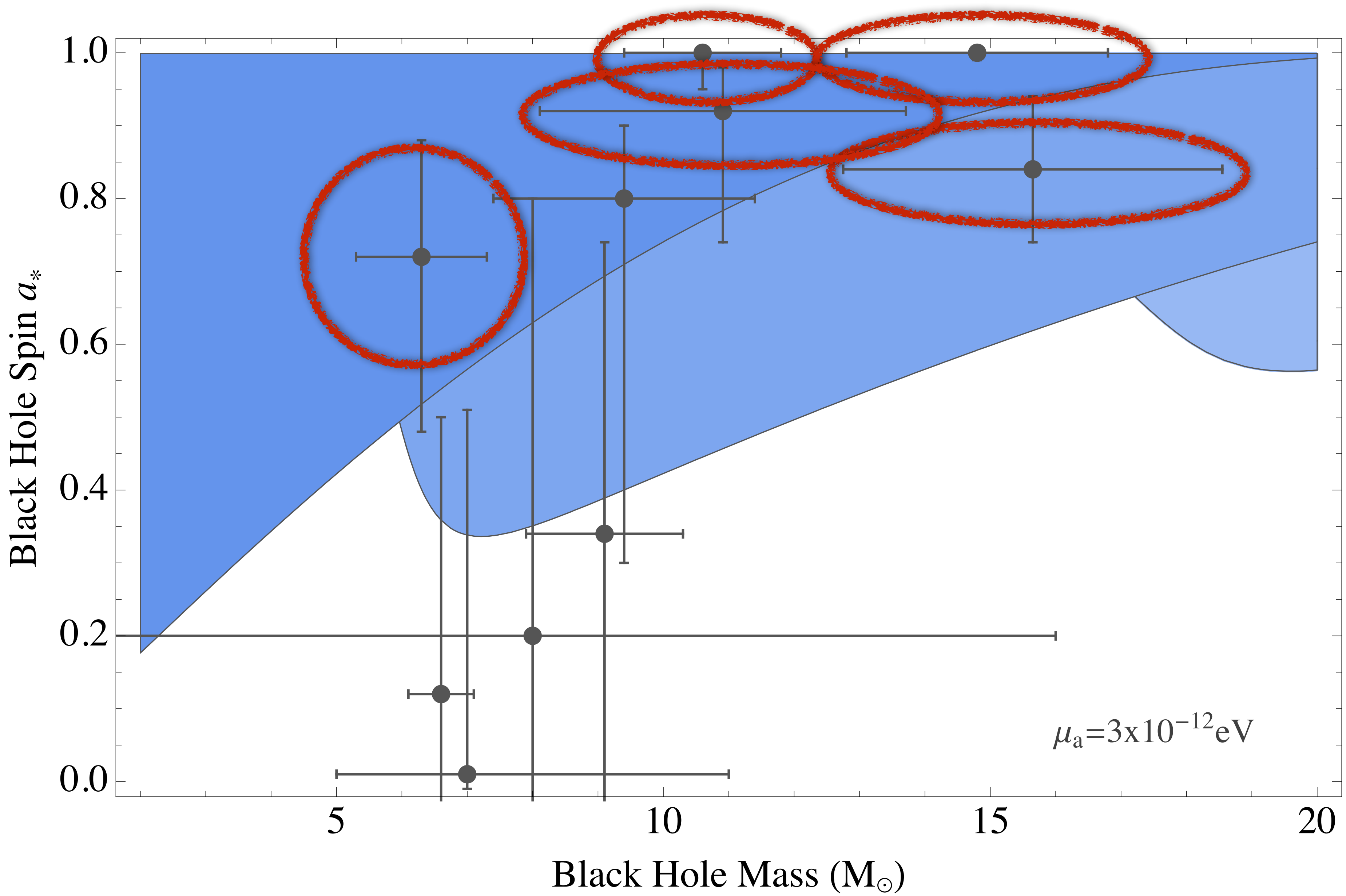
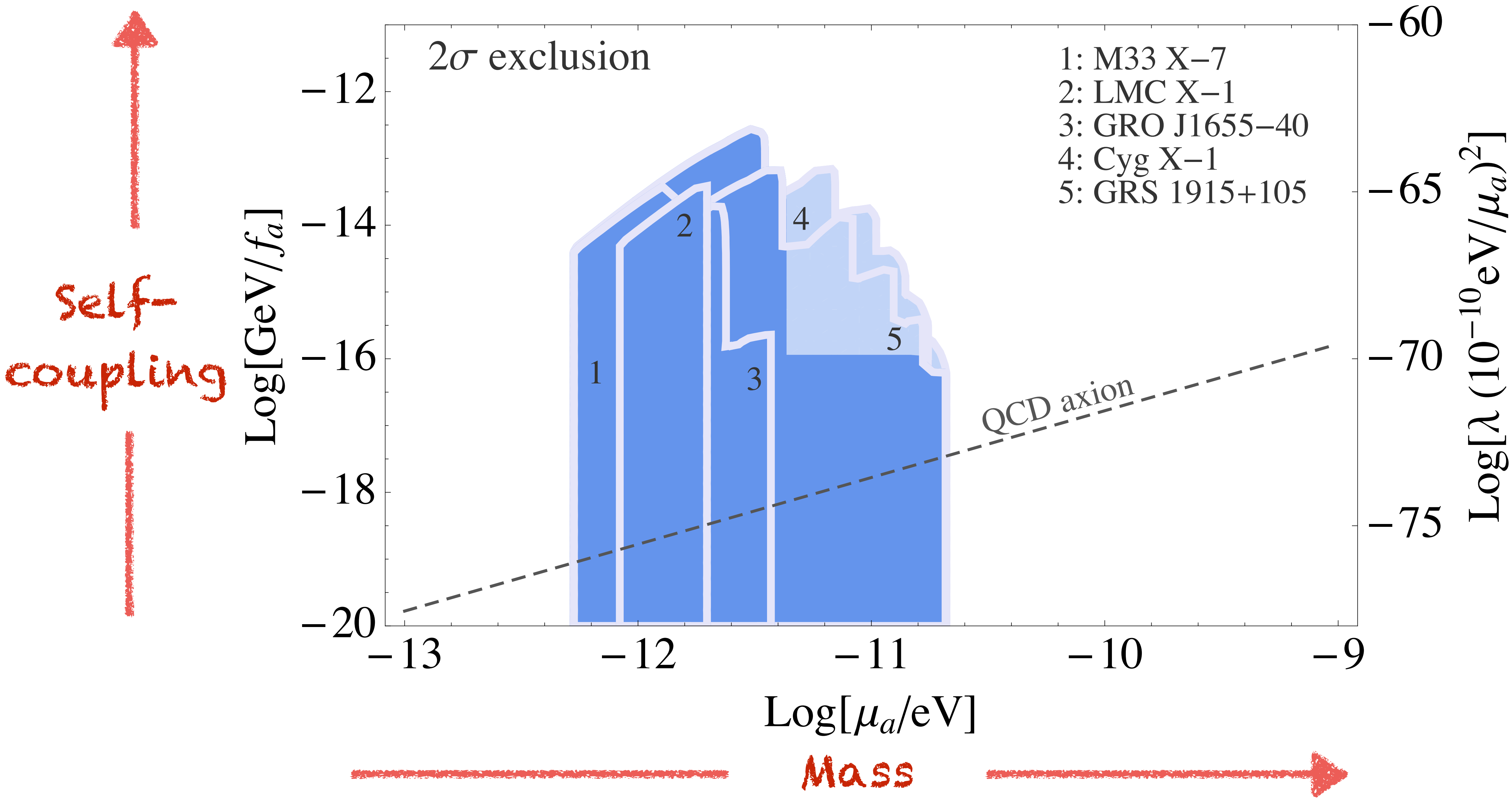


Light particle exclusion limits

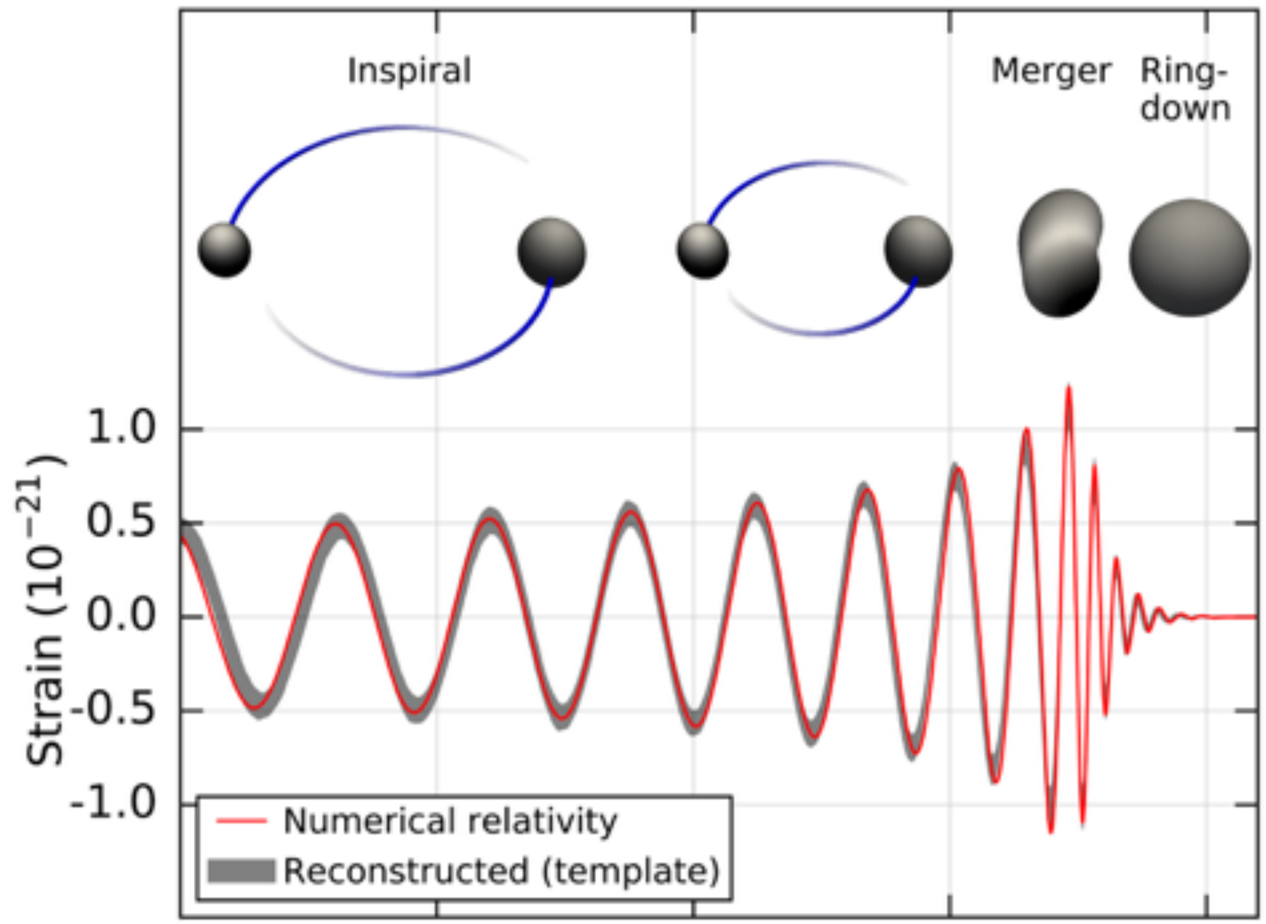
Large self-coupling => bosonic cloud growth cut off



Binary black hole mergers

[Abbot et al, 2016]

- LIGO GW150914: first direct detection of gravitational waves!
- From 2.5 events so far, infer merger rate of 9-240 / Gpc yr
- At design sensitivity, 70-1200 visible mergers / year!

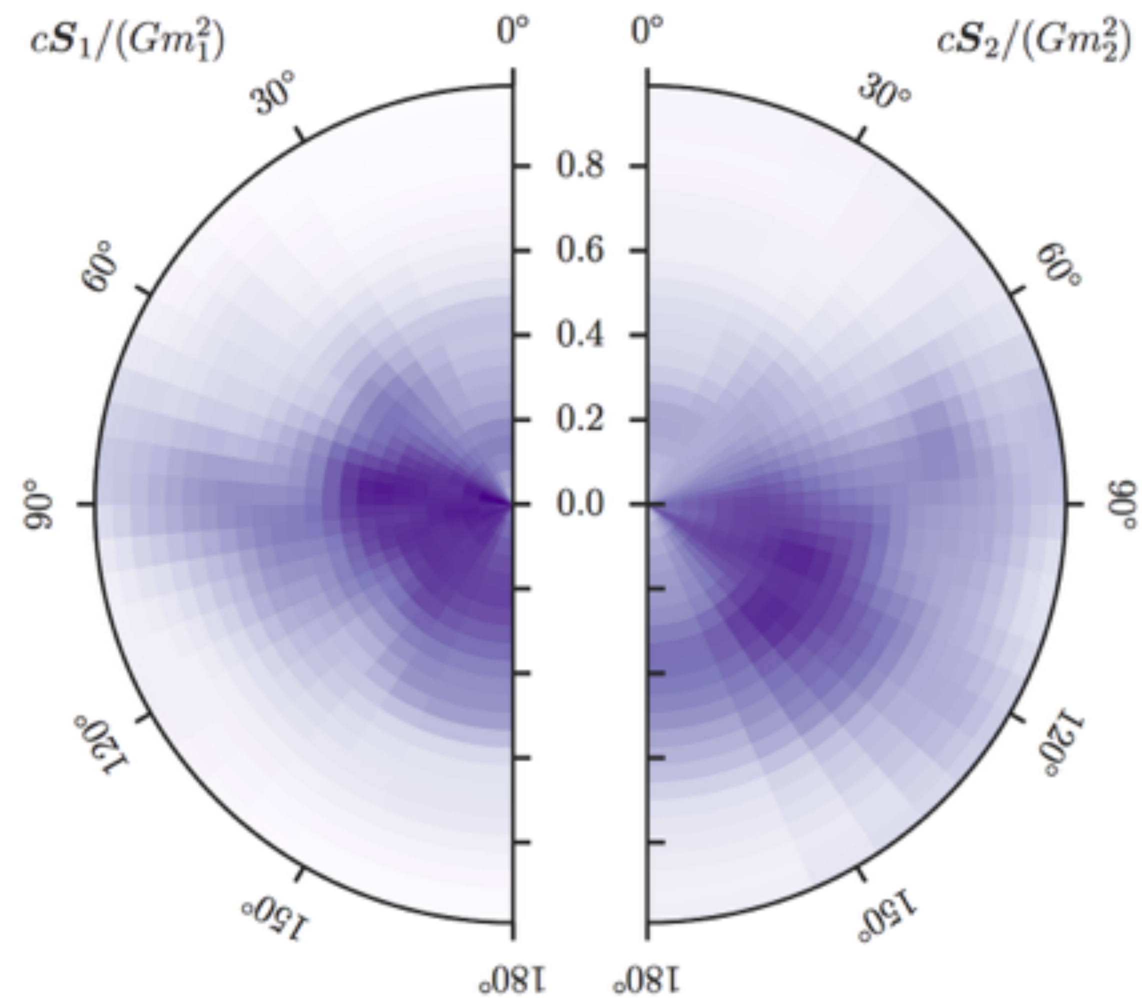


Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

BBH spin measurements

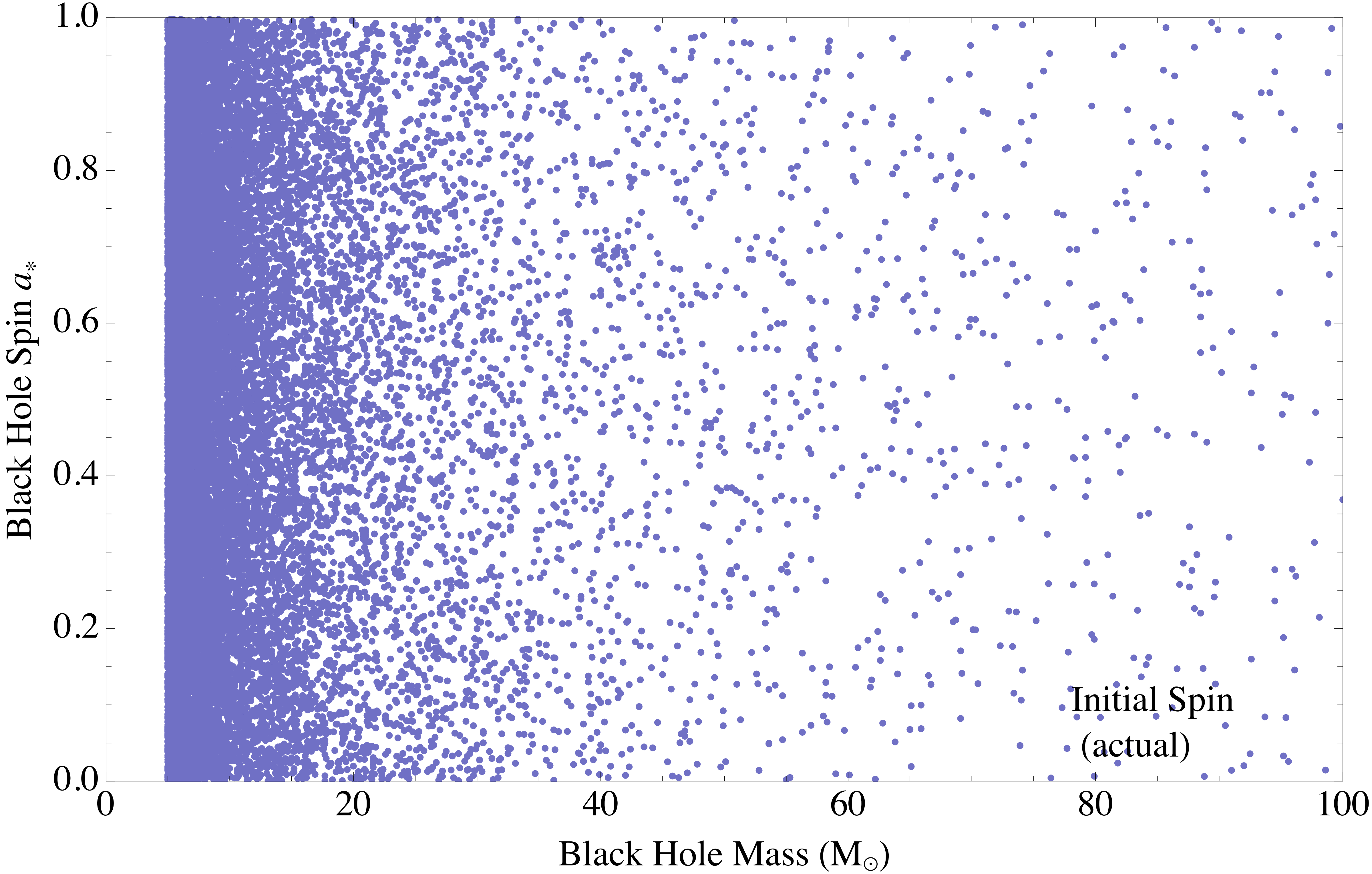
[Abbot et al, 2016]

- Spin-orbit interaction => BH spin components parallel to orbital axis affect inspiral waveform
- Spin components misaligned with orbital axis can cause precession, modulating inspiral waveform
- Intrinsic spins contribute to spin of final BH, which is constrained by merger and ringdown waveform



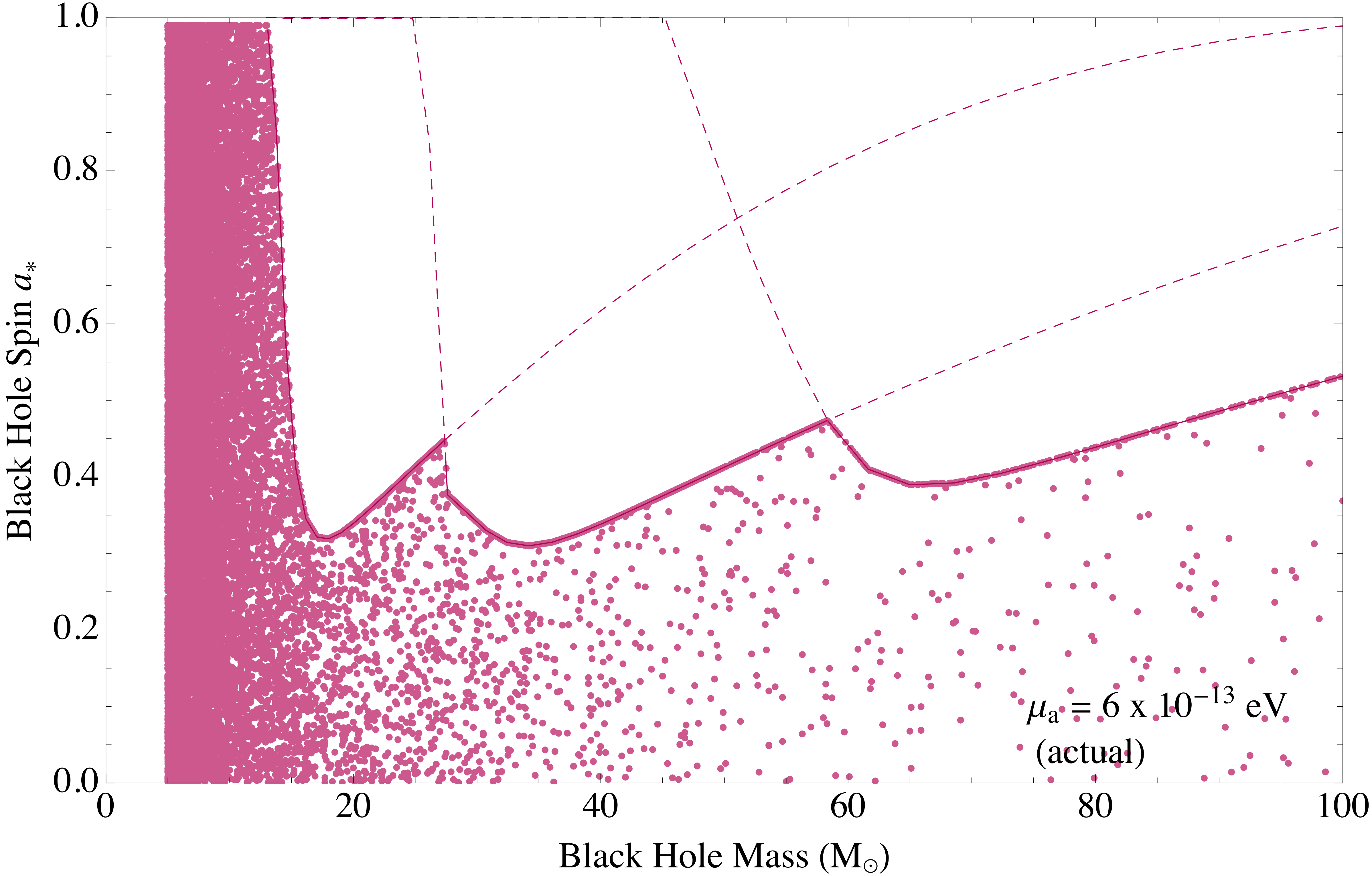
- GW150914: if spins are aligned, obtain $a_1 < 0.2\,,\ a_2 < 0.3\,(90\%)$

Spin-down



1.0
0.8
0.6
0.4
0.2
0.0
Black Hole Spin a_*
0
20
40
60
80
100
Black Hole Mass ($M_\odot$)
Initial Spin
(actual)

Spin-down



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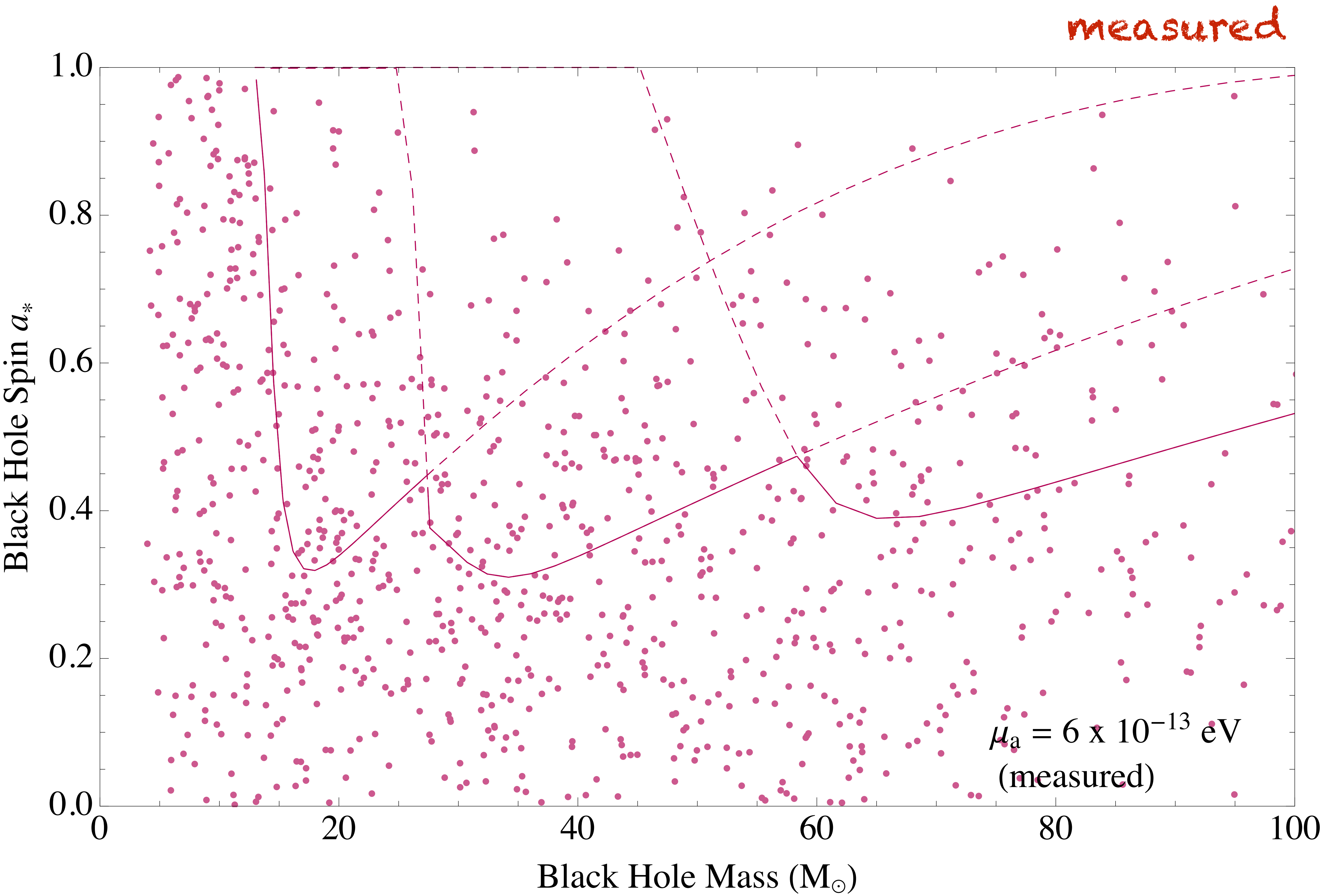
Black Hole Spin a_*
Black Hole Mass ($M_\odot$)
$\mu_a = 6 \times 10^{-13}$ eV
(actual)

Spin-down


measured
1.0
0.8
0.6
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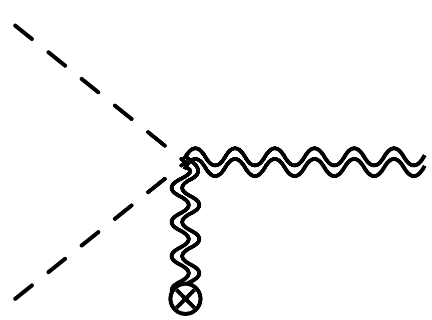
(measured)

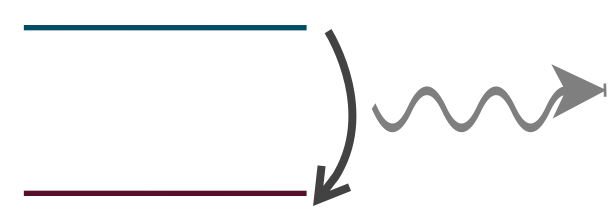
Gravitational radiation from bound states

- Bosonic cloud corresponds to classical scalar field oscillations => oscillating energy-momentum
- Oscillating $T_{\mu\nu} = \nabla_\mu \varphi \nabla_\nu \varphi - g_{\mu\nu}\left(\ldots\right)$ sources gravitational radiation
- Decomposing into levels, have $\varphi = \frac{1}{\sqrt{2\mu}} \sum_i \sqrt{N_i} \psi_i e^{-i\omega_i t} + \mathrm{h.c.}$

$$T_{ij} = \frac{1}{2\mu}\Big(N_1 (\nabla_i \psi_1)(\nabla_j \psi_1) e^{-2i\omega_1 t} + \sqrt{N_1 N_2} (\nabla_i \psi_1^*)(\nabla_j \psi_2) e^{-i(\omega_2 - \omega_1)t} + \ldots\Big)$$



"Annihilations"



"Transitions"

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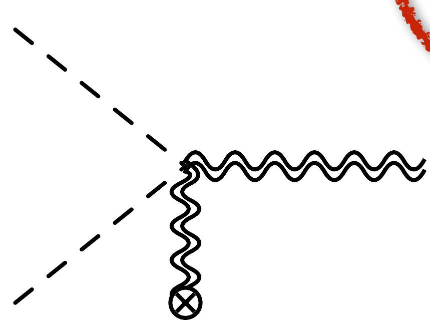

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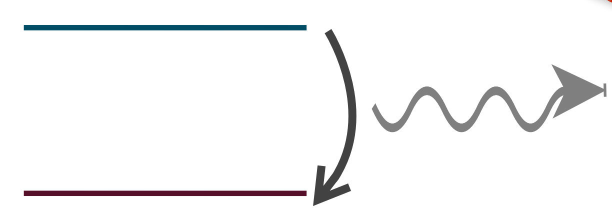


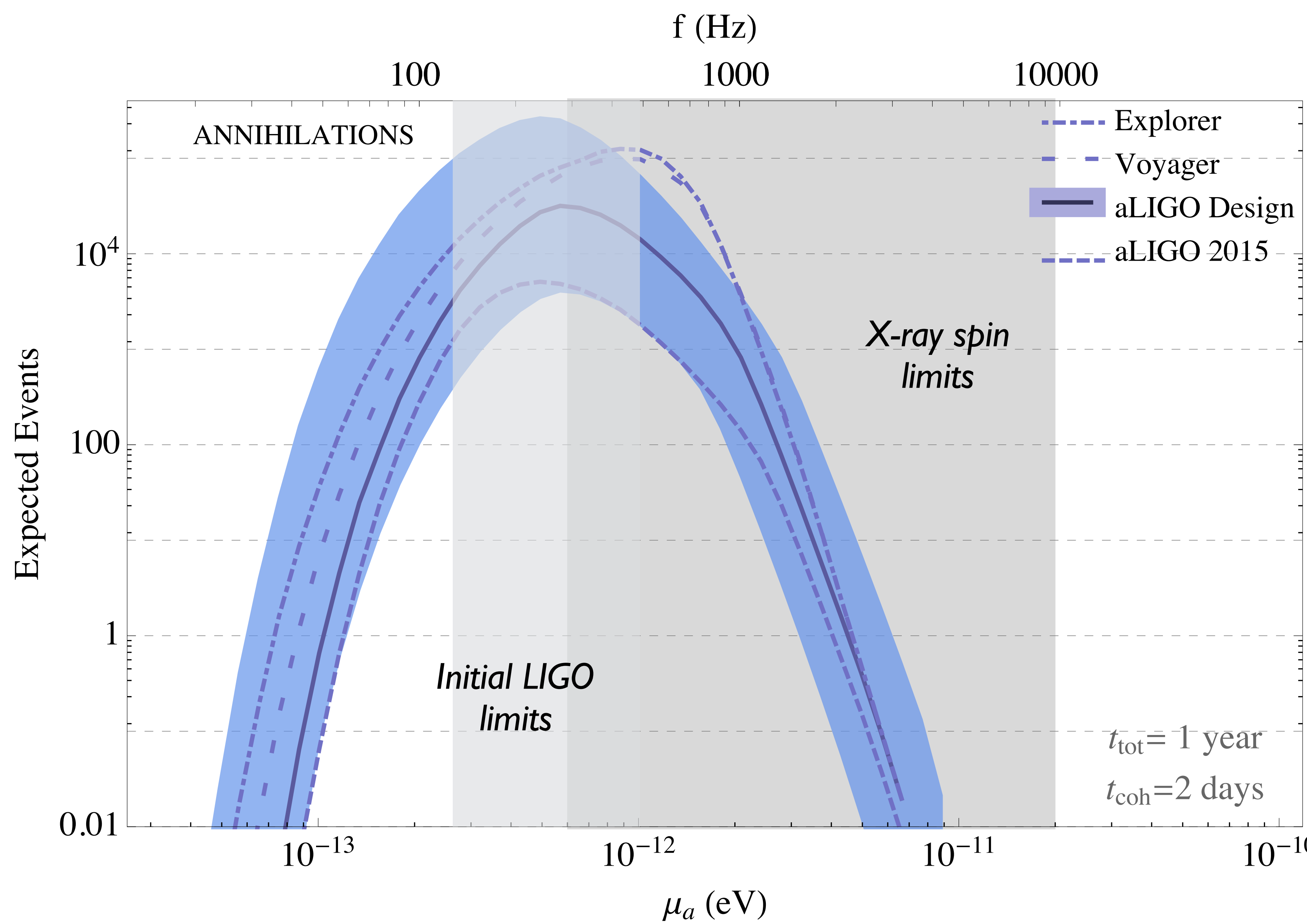
"Transitions"

All-Sky GW search

- From each BH with a cloud, expect GWs from annihilations at frequency

$$\omega \simeq 2\mu \left(1 - \frac{\alpha^2}{2n^2}\right) = 2\mu\,(1 - [0, 0.03])$$

- Coherent, monochromatic signals, very slow frequency drift
- Signals from different black holes clustered just below $\omega = 2\mu$
- Expected signals determined by BH mass and spin distribution - potentially hundreds eventually visible!
- Most signals from BHs in our galaxy

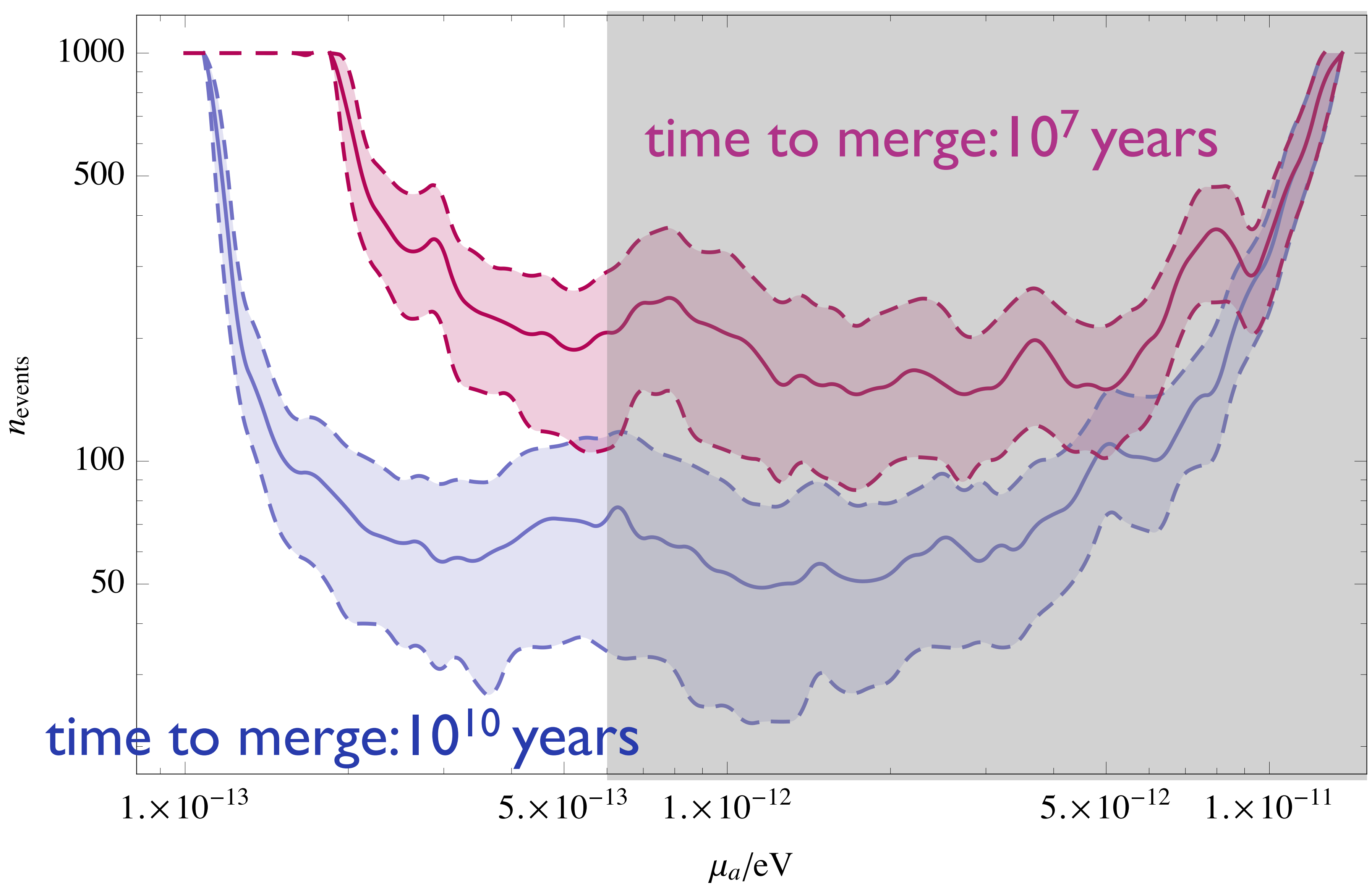


Summary

- Black hole superradiance is a unique probe of light, weakly-coupled bosons
- Gravitational wave detectors can probe SR in multiple, complementary ways:
  - Monochromatic GWs from cloud
  - Statistics of BH spins, measured in mergers
  - Signals possible in near future!
- Observations of supermassive black holes, via telescopes and future lower-frequency GW detectors, can constrain lower-mass bosons
  - Less clean astrophysical environment - further investigation required

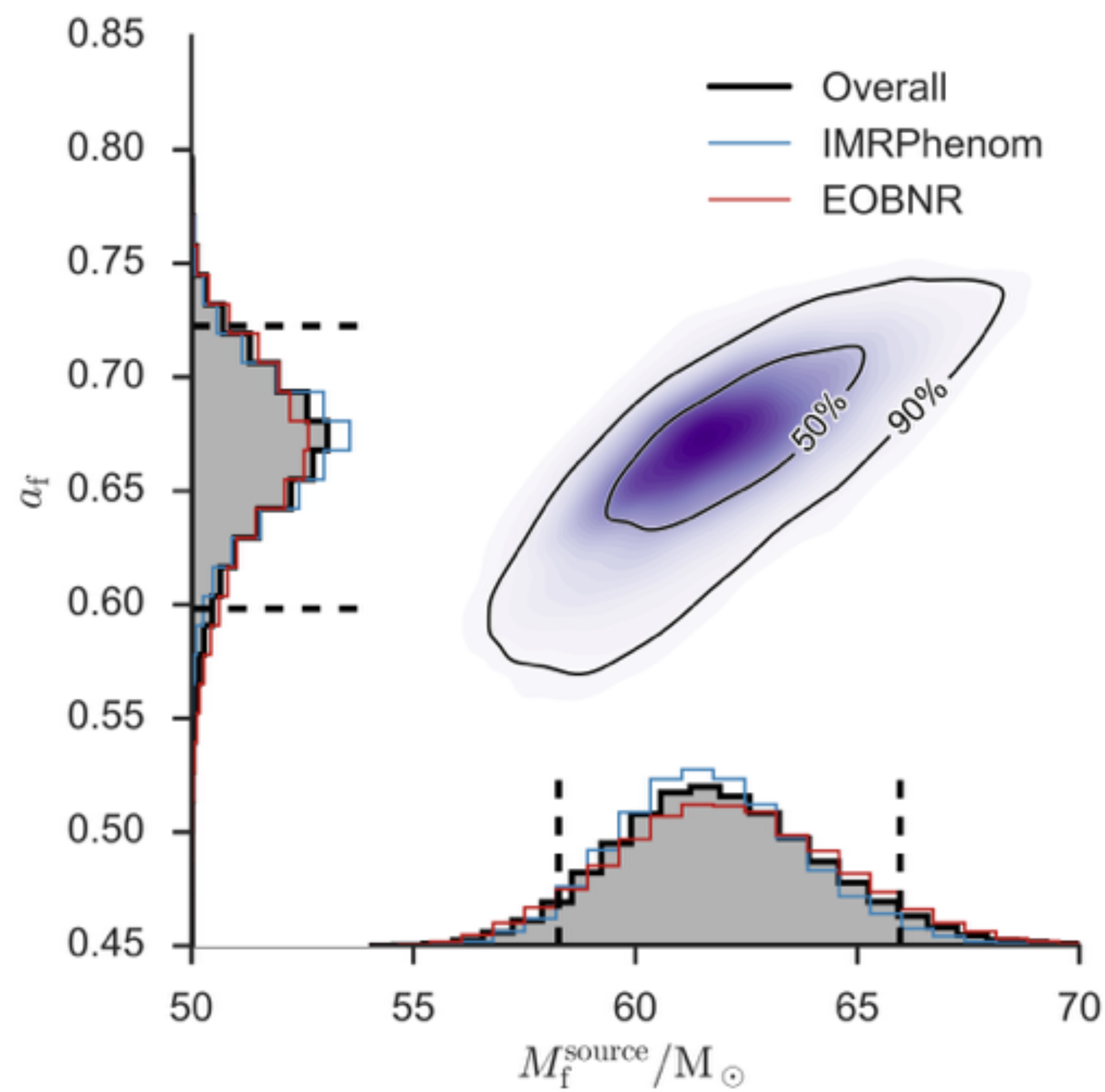
Statistical evidence

- Could obtain statistical evidence for structure in mass-spin plane with 50-200 measurements



GWs from newly formed BHs

- Measure parameters of newly-formed BH => prediction for SR process, given axion mass
- Axion cloud takes days/years to grow
- Typical reach ~ 30 Mpc for annihilation GW signals
- e.g. if GW150914 had been < 10 Mpc away, potentially observable signal



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