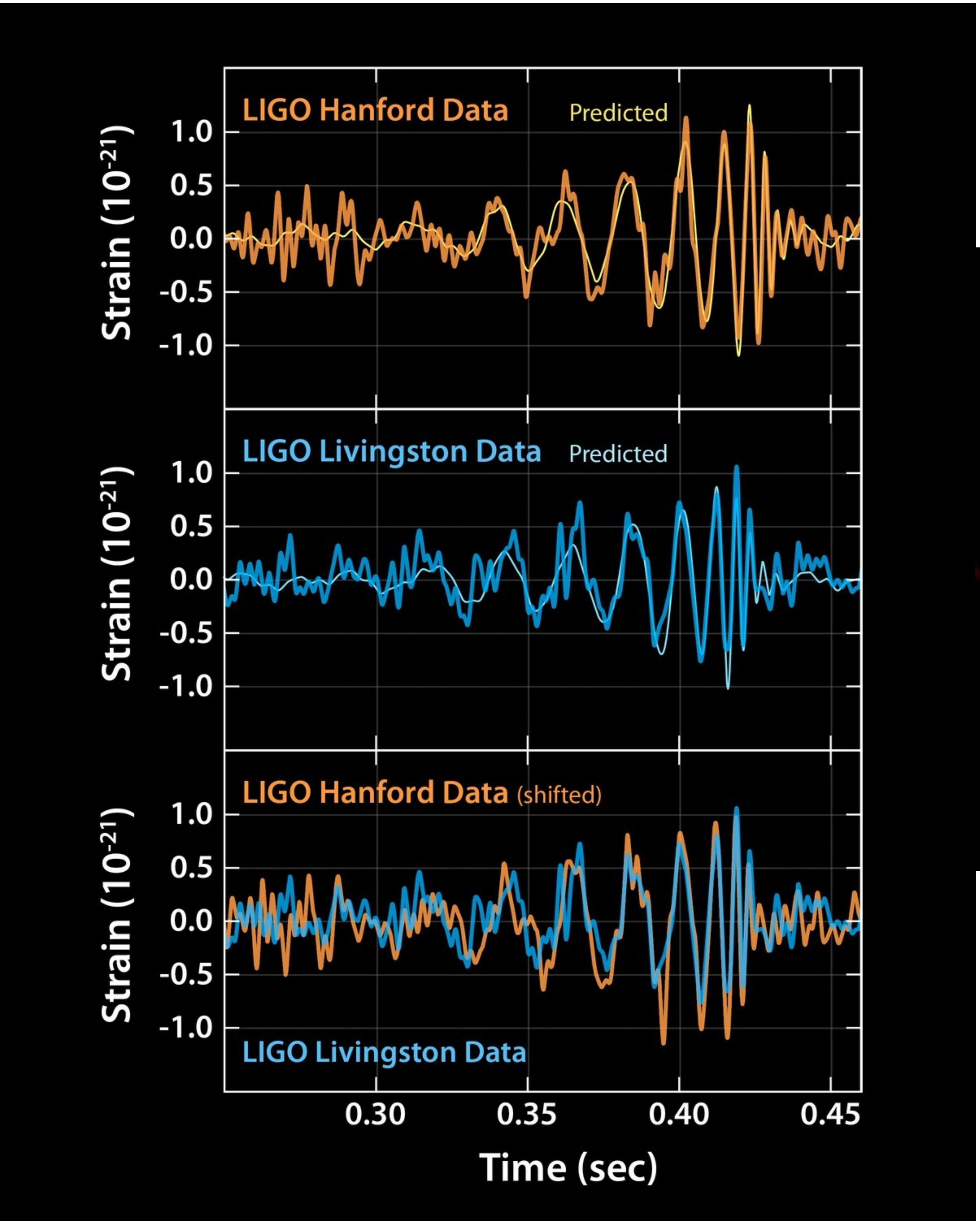
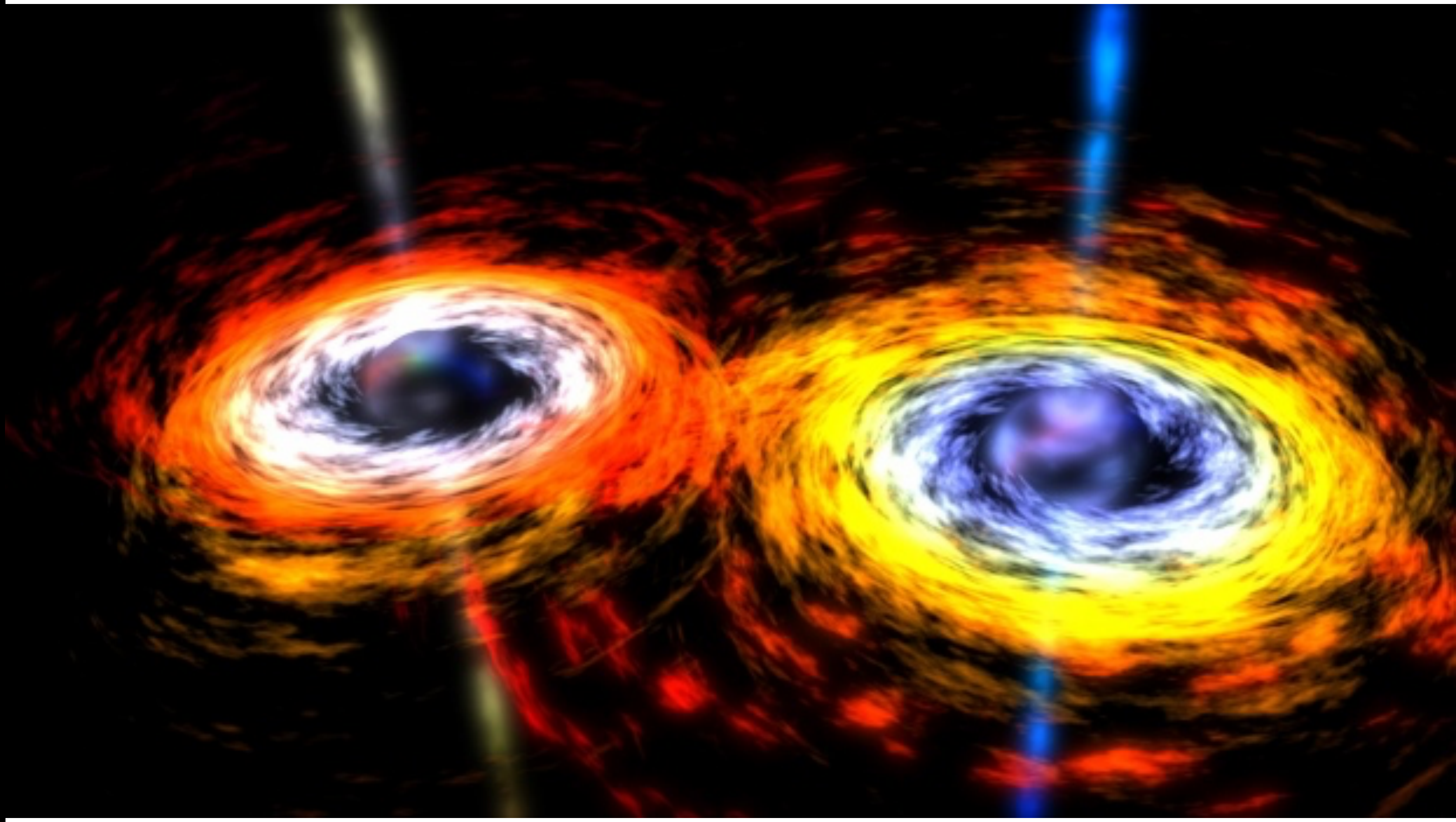
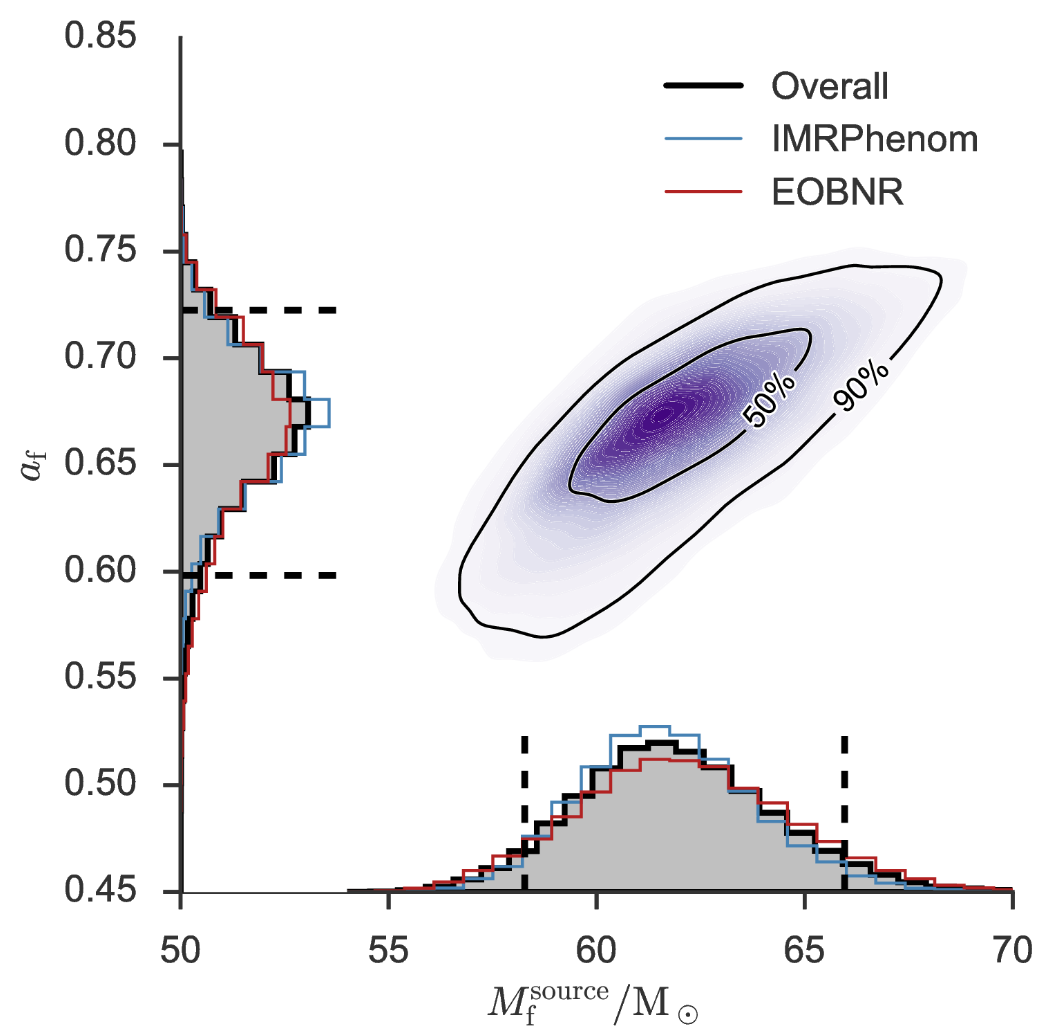
September 14, 2015





Properties of GW150914



Effective inspiral spin parameter $\chi_{\rm eff}$	$-0.09^{+0.19}_{-0.17}$	$-0.03^{+0.14}_{-0.15}$	$-0.06^{+0.17\pm0.01}_{-0.18\pm0.07}$
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Taken from 1602.03840

New Era

- New telescope
- The violent Universe
    - Black Hole mergers, phase transitions, inflation
- New precision science
    - ~one merger per day — a lot of data per merger
- BSM physics?

New spectroscopy

Black Holes as Nature's Detectors

(15 km) x (M / 10 M⊙)

Range of astrophysical Black Holes:
few M⊙ to 10^{10} M⊙
Sensitive to boson masses 10^{-20}-10^{-10} eV

Focus on stellar black holes

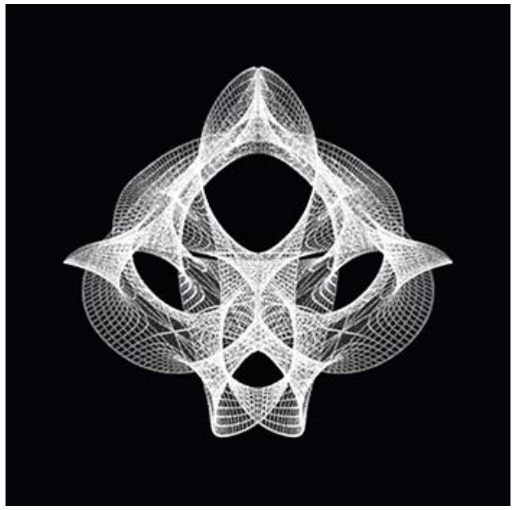
Why is this interesting?

- The Strong CP problem and the QCD axion

$$\mu_a \sim 6 \times 10^{-11}\ \text{eV}\ \frac{10^{17}\ \text{GeV}}{f_a} \sim (3\ \text{km})^{-1}\ \frac{10^{17}\ \text{GeV}}{\mathrm{f_a}}$$

- The String Axiverse

Arvanitaki, SD, Dubovsky, Kaloper, March-Russell (2009)



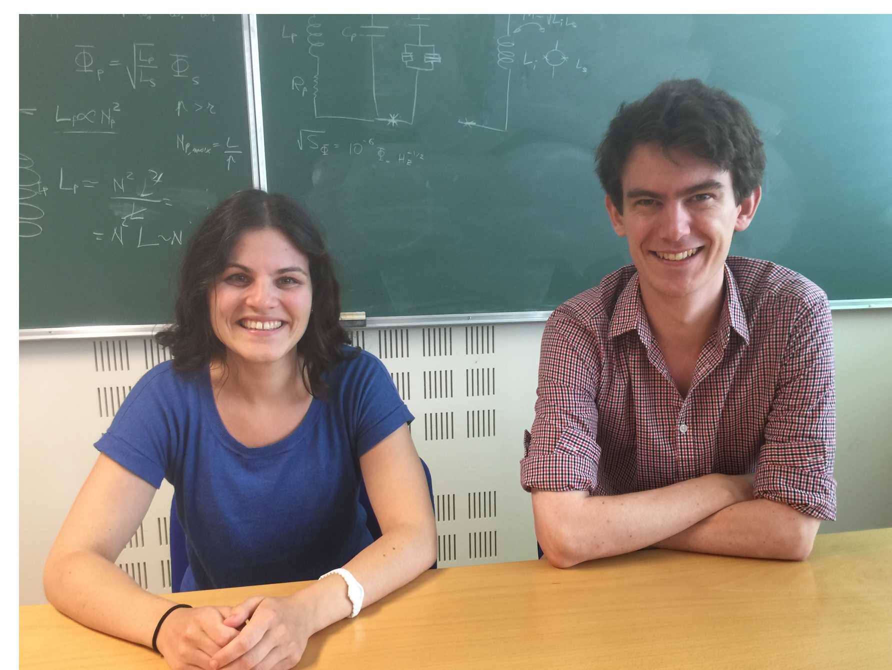
- Superradiance probes any boson in the right mass range

Black Holes and The QCD Axion at Advanced LIGO

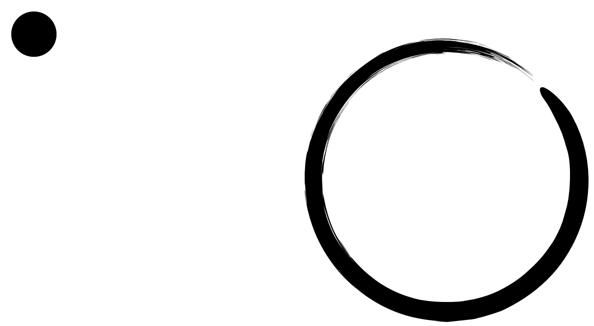
Savas Dimopoulos
Stanford University

with
Arvanitaki, Dubovsky, Kaloper, March-Russell (2009)
Baryakhtar, Lasenby, Arvanitaki, Dubovsky(2016)

also based on
Arvanitaki, Dubovsky (2010)
Arvanitaki, Baryakhtar, X. Huang (2014)

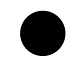


Super-Radiance Cartoon



Super-radiant scattering of a massive object

Super-Radiance Cartoon



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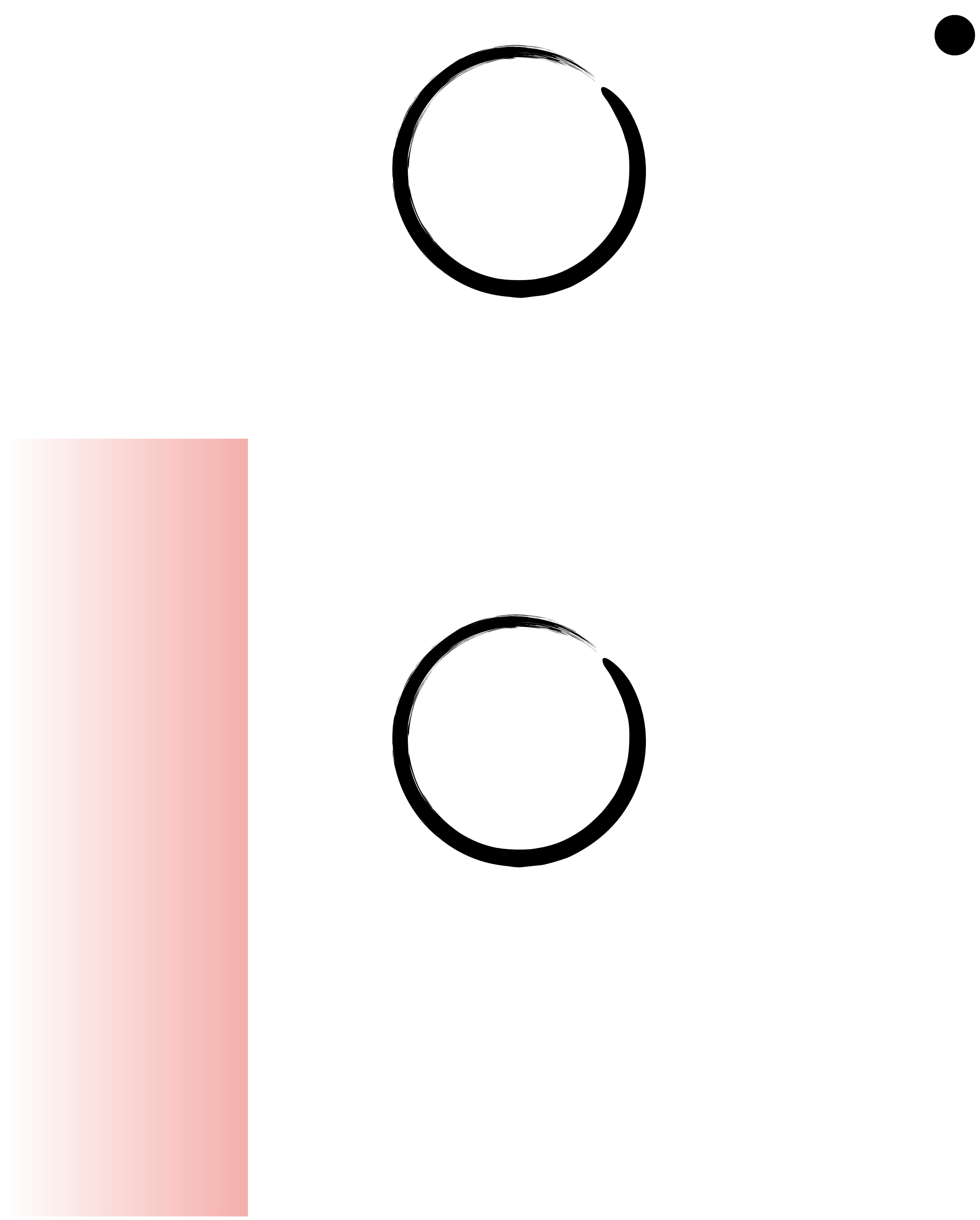
Super-Radiance Cartoon



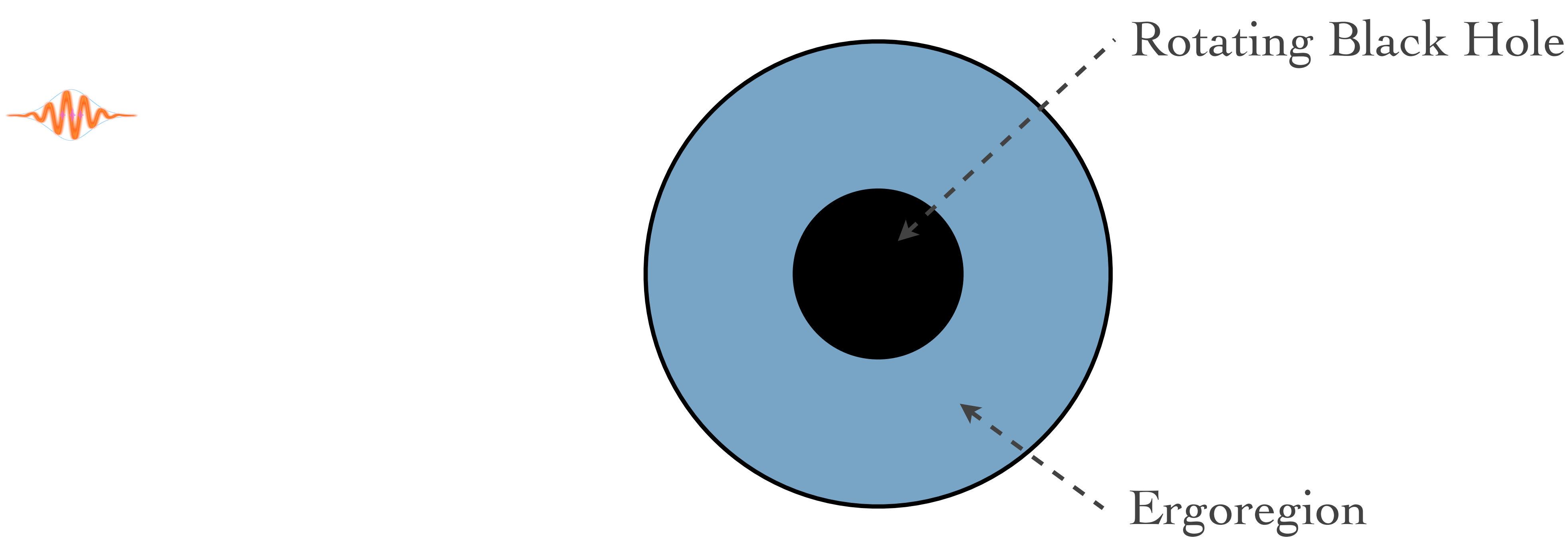
Super-radiant scattering of a wave

Super-Radiance Cartoon

Super-radiant scattering of a wave

Black Hole Superradiance

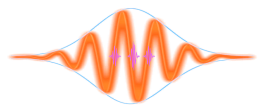
Penrose Process

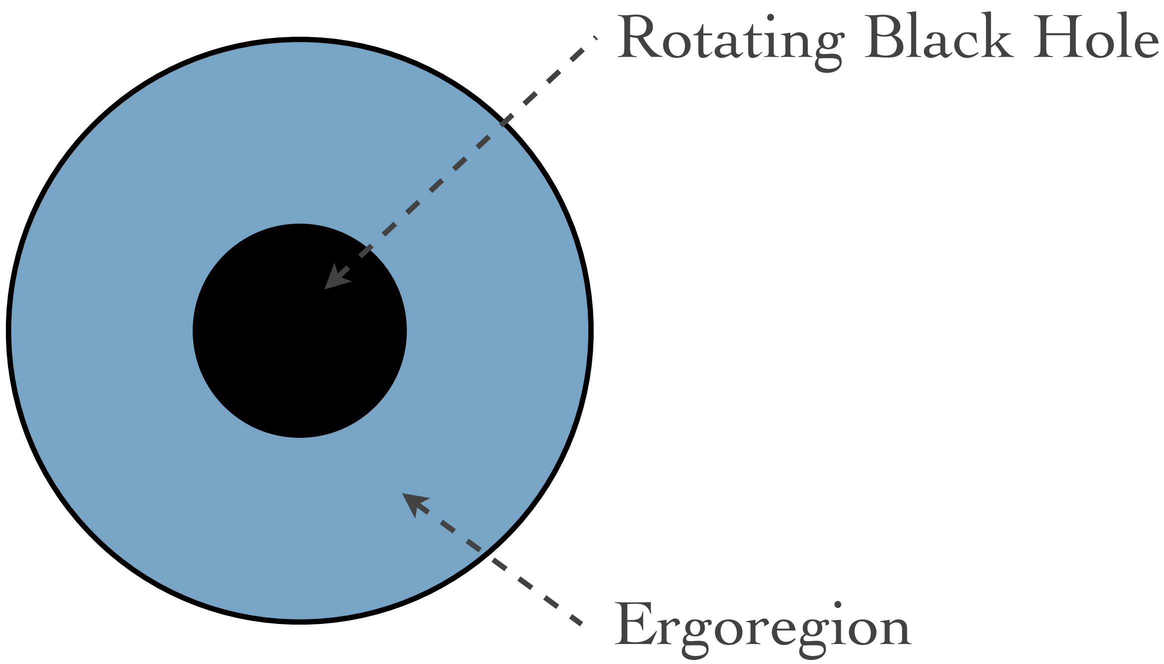


Ergoregion: Region where even light has to be rotating

Black Hole Superradiance

Penrose Process

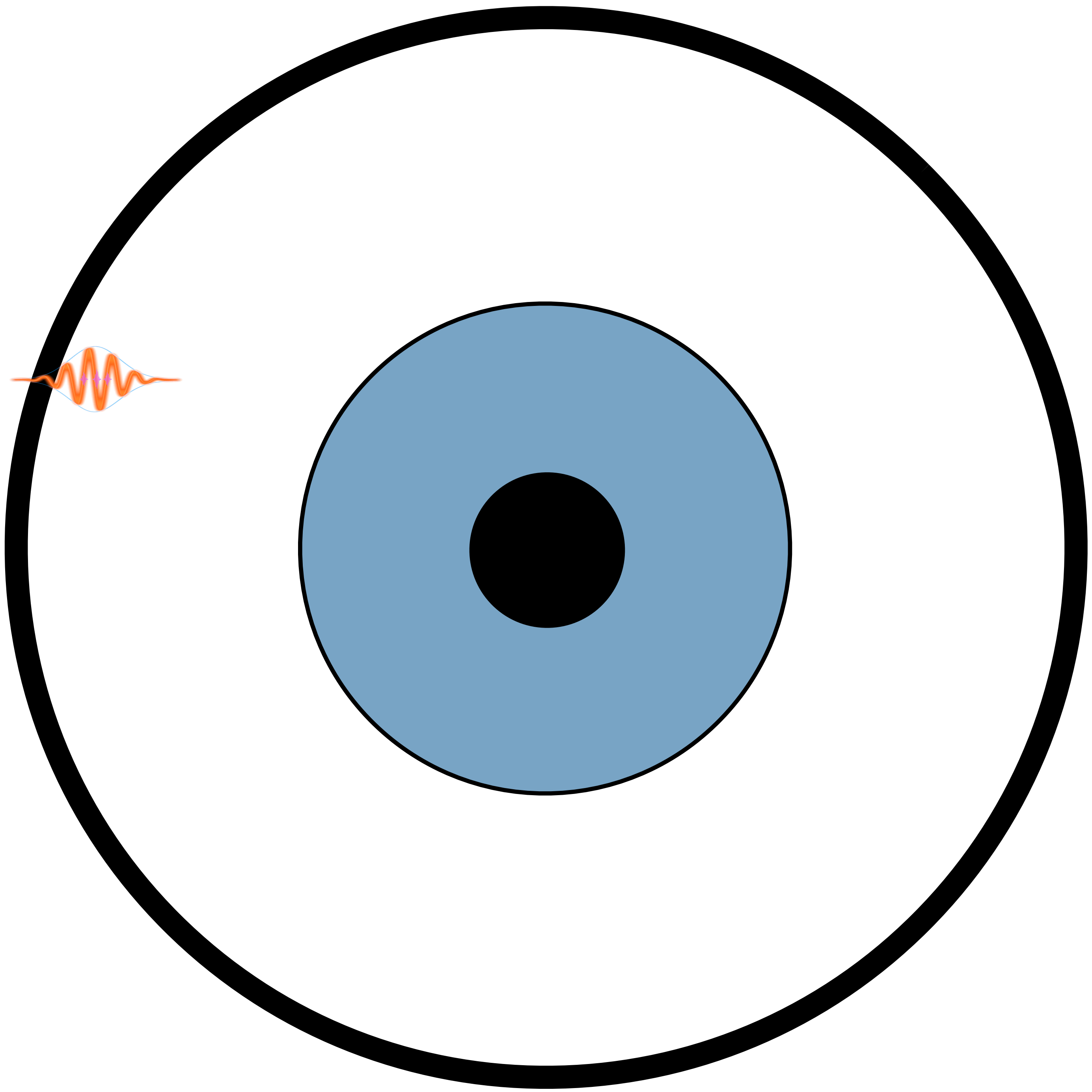




Extracts angular momentum and mass from a spinning black hole

Black Hole Bomb

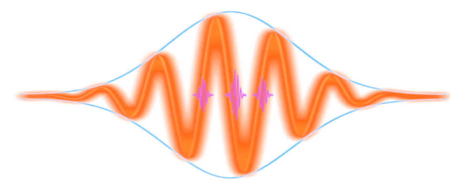
Press & Teukolsky 1972

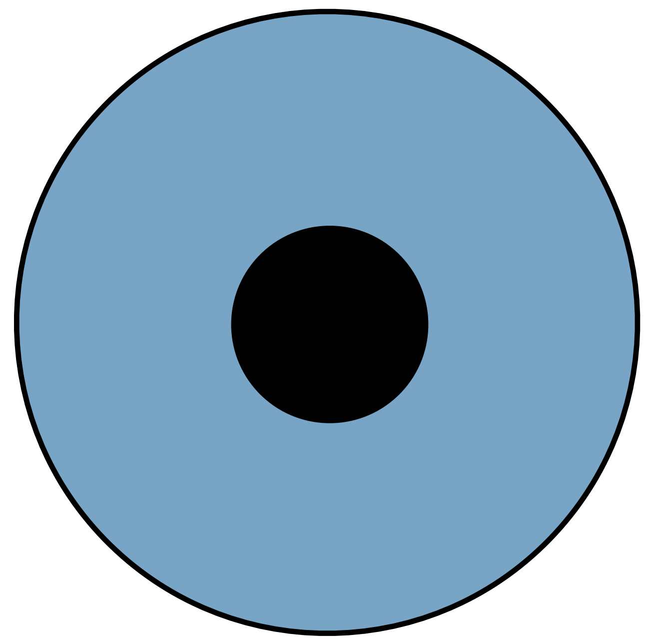


Photons reflected back and forth from the black hole and through the ergoregion

Black Hole Bomb

Press & Teukolsky 1972

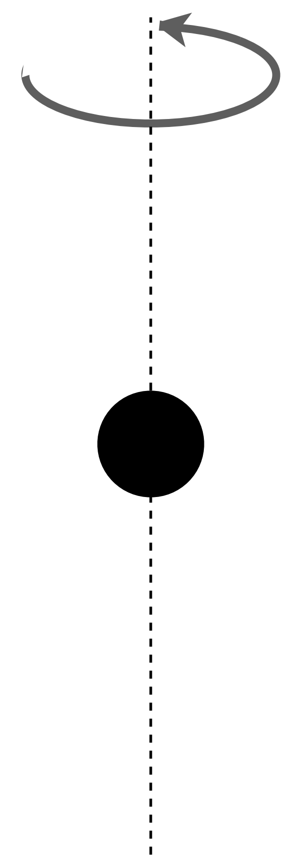




Photons reflected back and forth from the black hole
and through the ergoregion

Superradiance for a massive boson

Damour et al; Zouros & Eardley;
Detweiler; Gaina (Early 70s)



Particle Compton Wavelength comparable to the size of the Black Hole

Superradiance for a massive boson

Damour et al; Zouros & Eardley;
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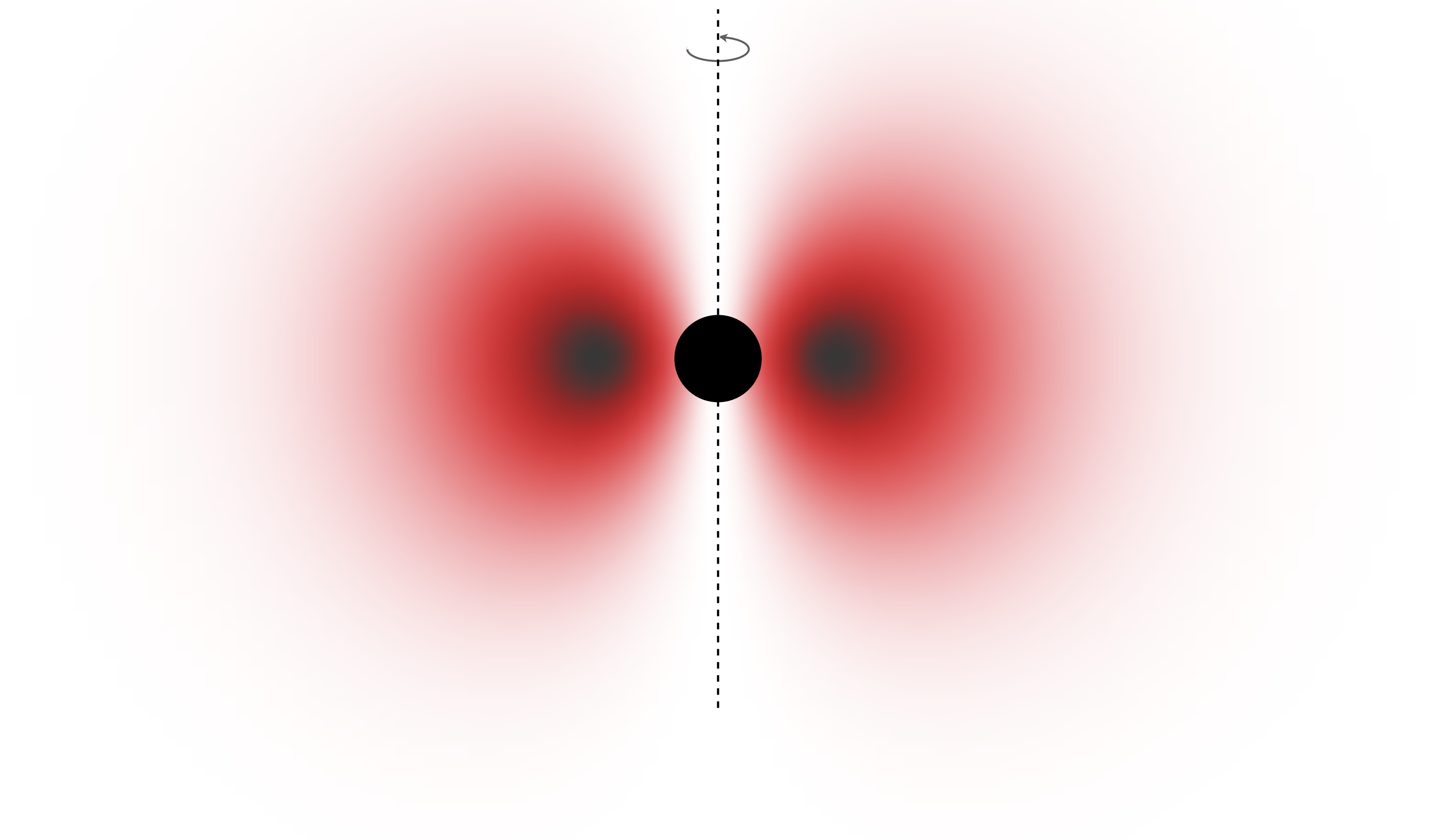
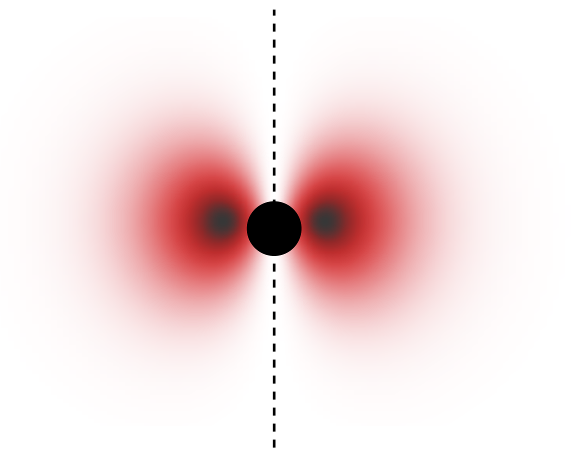


Particle Compton Wavelength comparable to the size of the Black Hole

Gravitational Atom in the Sky



The gravitational Hydrogen Atom

Fine-structure constant: $\alpha = G_{\rm N} M_{\rm BH} \mu_a = R_g \mu_a$

Principal (n), orbital (l), and magnetic (m) quantum number for each level $E_{\rm binding} = -\dfrac{\alpha^2 \mu_a}{2n^2}$

Main differences from hydrogen atom:

Levels occupied by bosons - occupation number >10^{77}

In-going Boundary Condition at Horizon

Key Points About Superradiance

- For light axions(weak coupling) equation identical to Hydrogen atom

- Boundary conditions different:
  - Regular at the origin ⟶ Ingoing (BH is absorber)
  - Hermitian ⟶ Non-hermitian

Superradiance Parametrics

Superradiance Condition

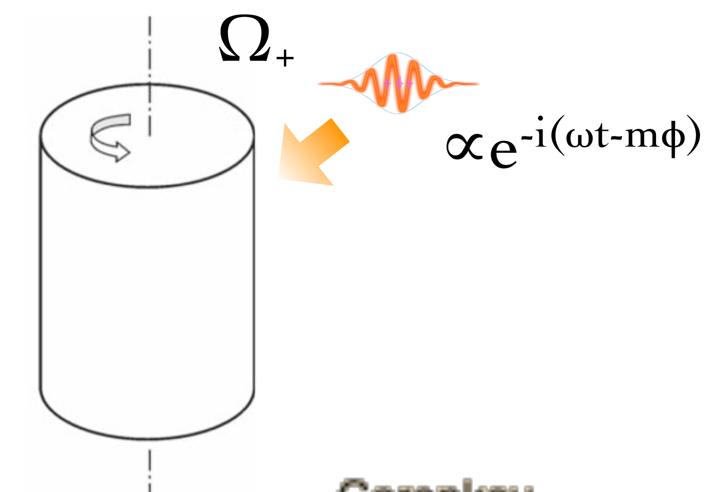
$$\omega_{\text{axion}} < m \; \Omega_+$$

m : magnetic quantum number

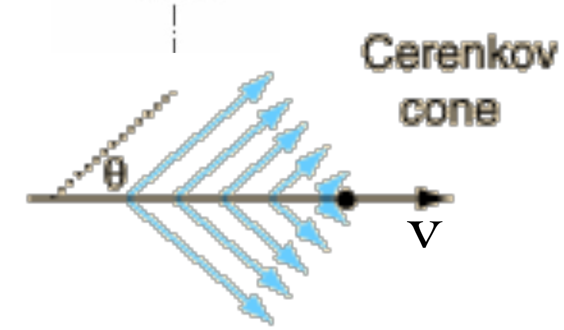
Ω_+ : angular velocity of the BH

Universal Phenomenon:

Superluminal rotational motion of a conducting cylinder



Superluminal linear motion - Cherenkov radiation $1/n(\omega) < v$



Condition can be extracted from requiring that $dA_{BH} > 0$

Superradiance Parametrics

Superradiance Rate

$\tau_{sr} \sim 0.6 \times 10^7 R_g$ for $R_g \mu_a \sim 0.4$

As short as 100 sec vs $\tau_{accretion} \sim 10^8$ years

When $R_g \mu_a >> 1$,

$$\tau_{sr} = 10^7 e^{3.7(\mu_a R_g)} R_g$$

When $R_g \mu_a << 1$

$$\tau_{sr} = \left(\frac{24}{a}\right)(\mu_a R_g)^{-9} R_g$$

Evolution of Superradiance for an Axion

Superradiance instability

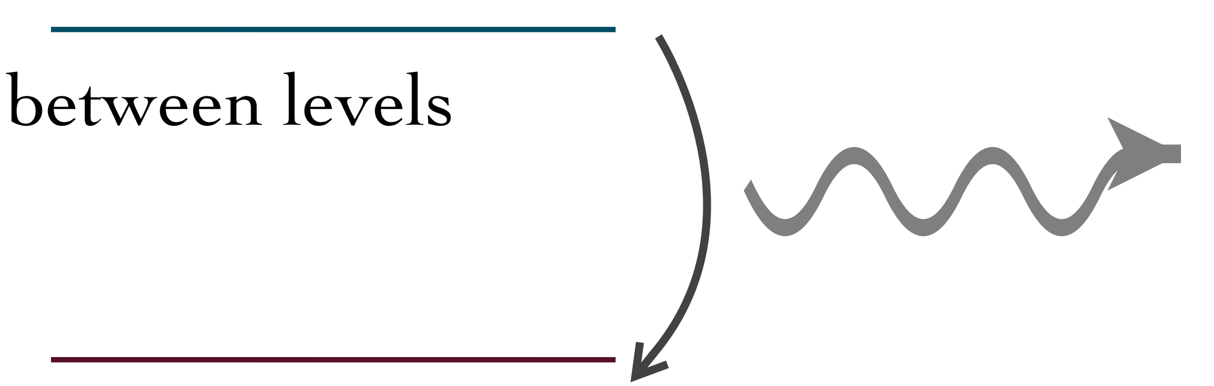
Self interactions

Evolution of Superradiance for an Axion

Superradiance instability

Self interactions

Gravity wave transitions of axions between levels



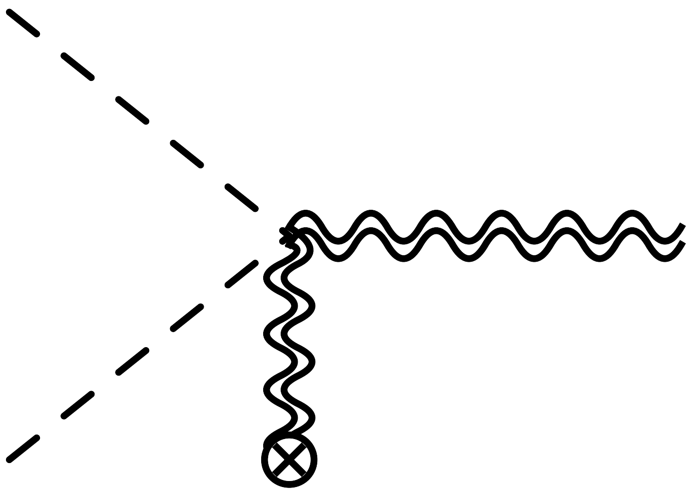
Evolution of Superradiance for an Axion

Superradiance instability

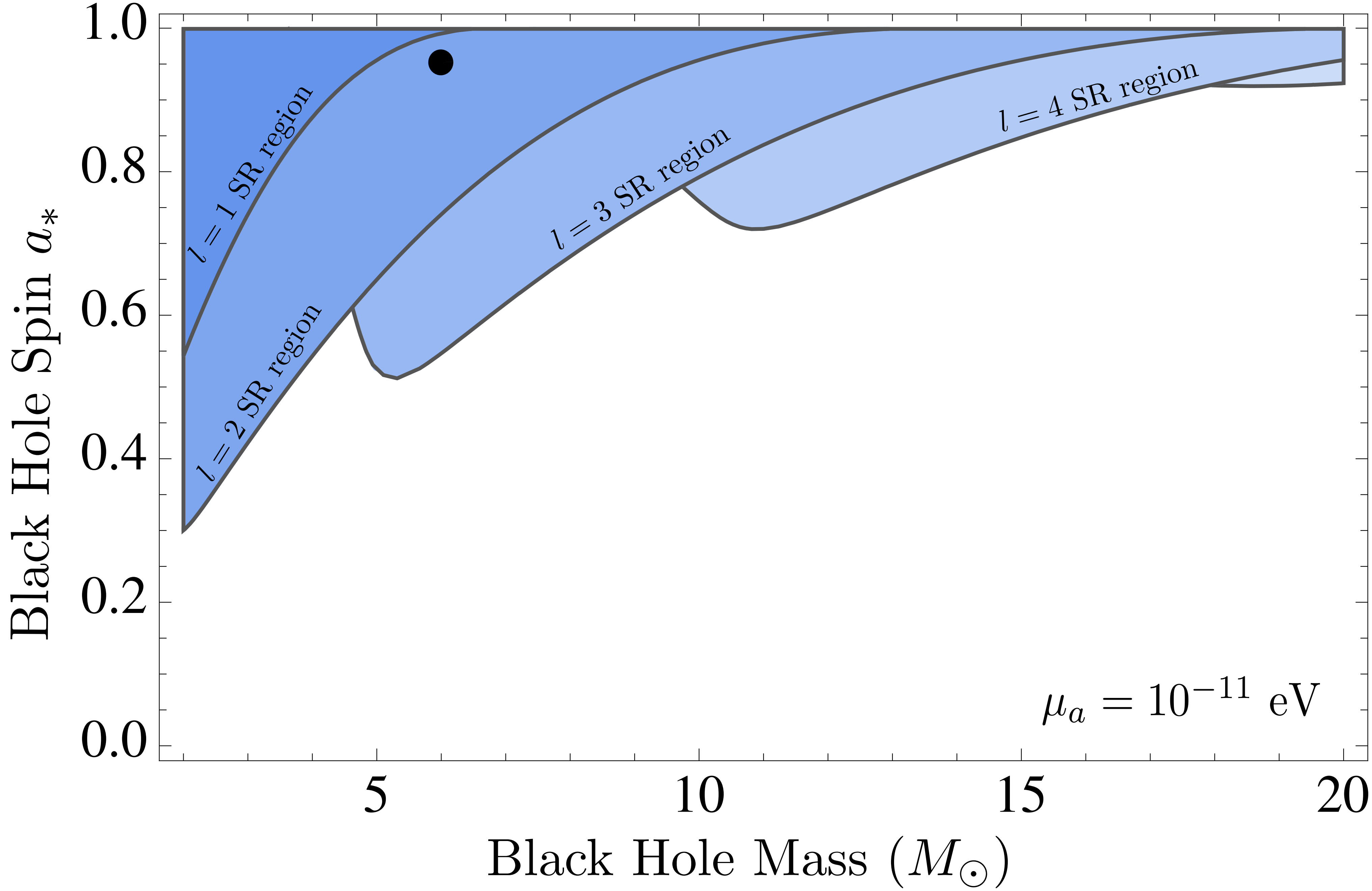
Self interactions

Gravity wave transitions of axions between levels

Gravity wave emission through axion annihilations



Superradiance Evolution



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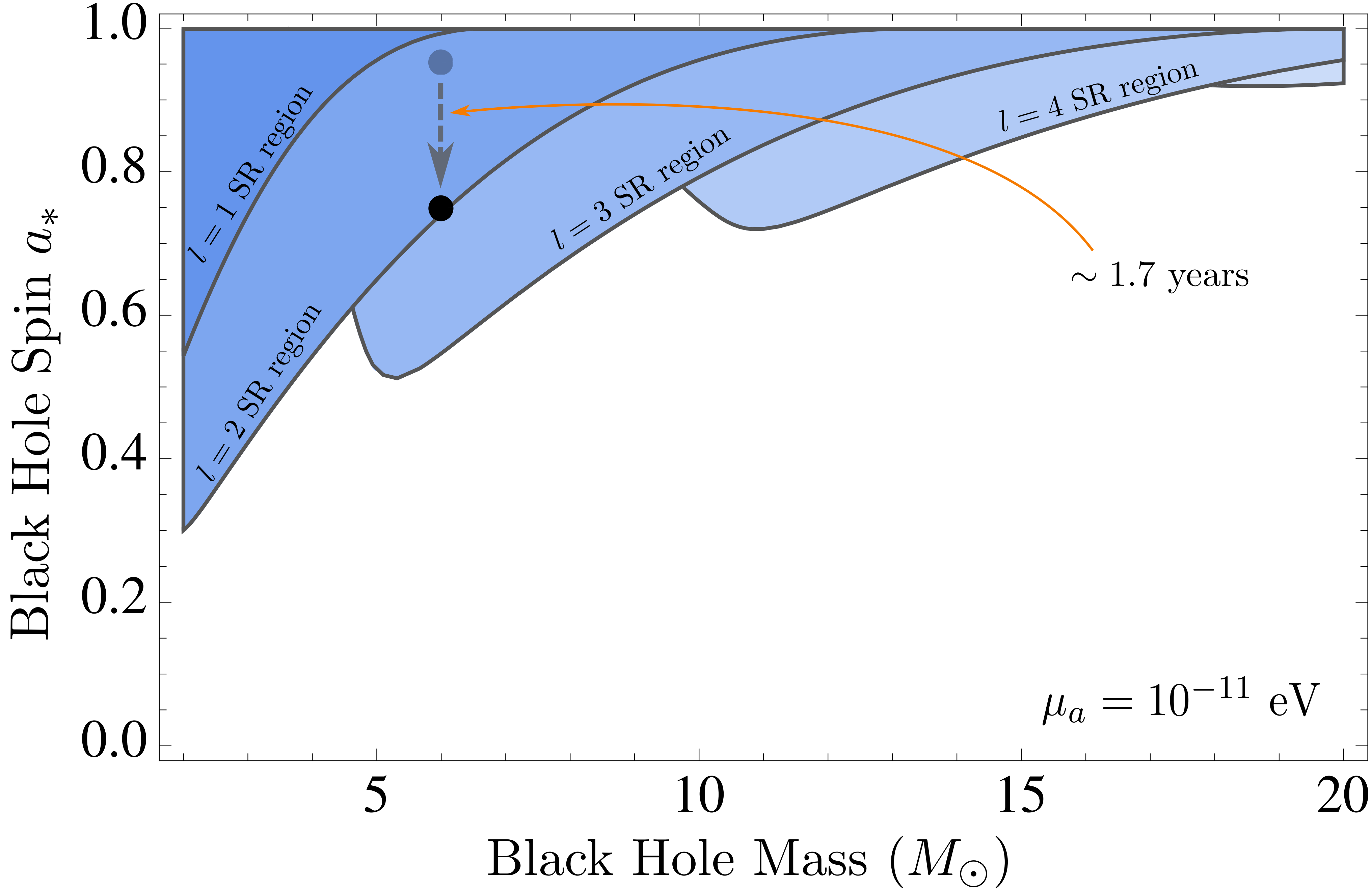

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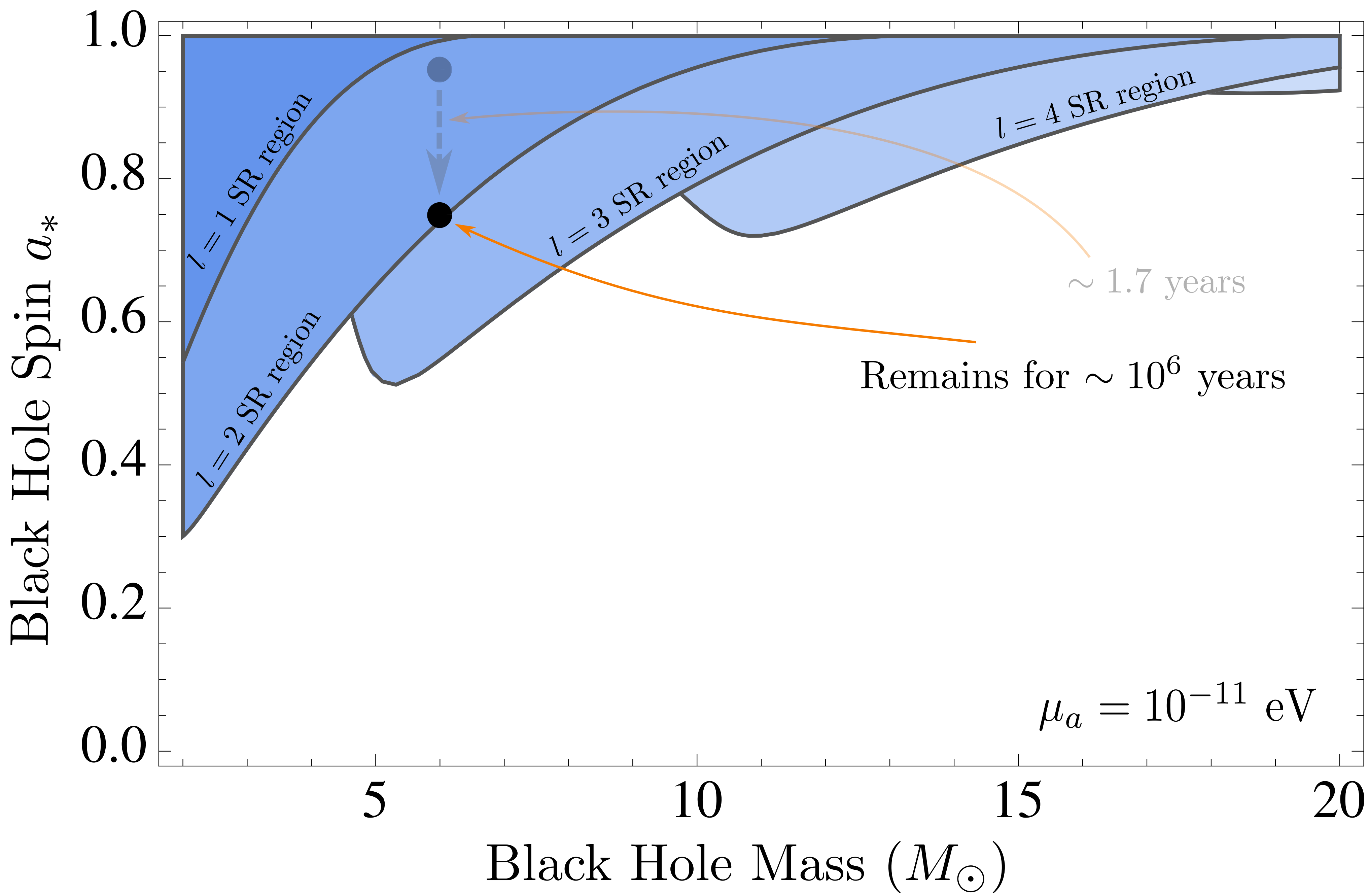

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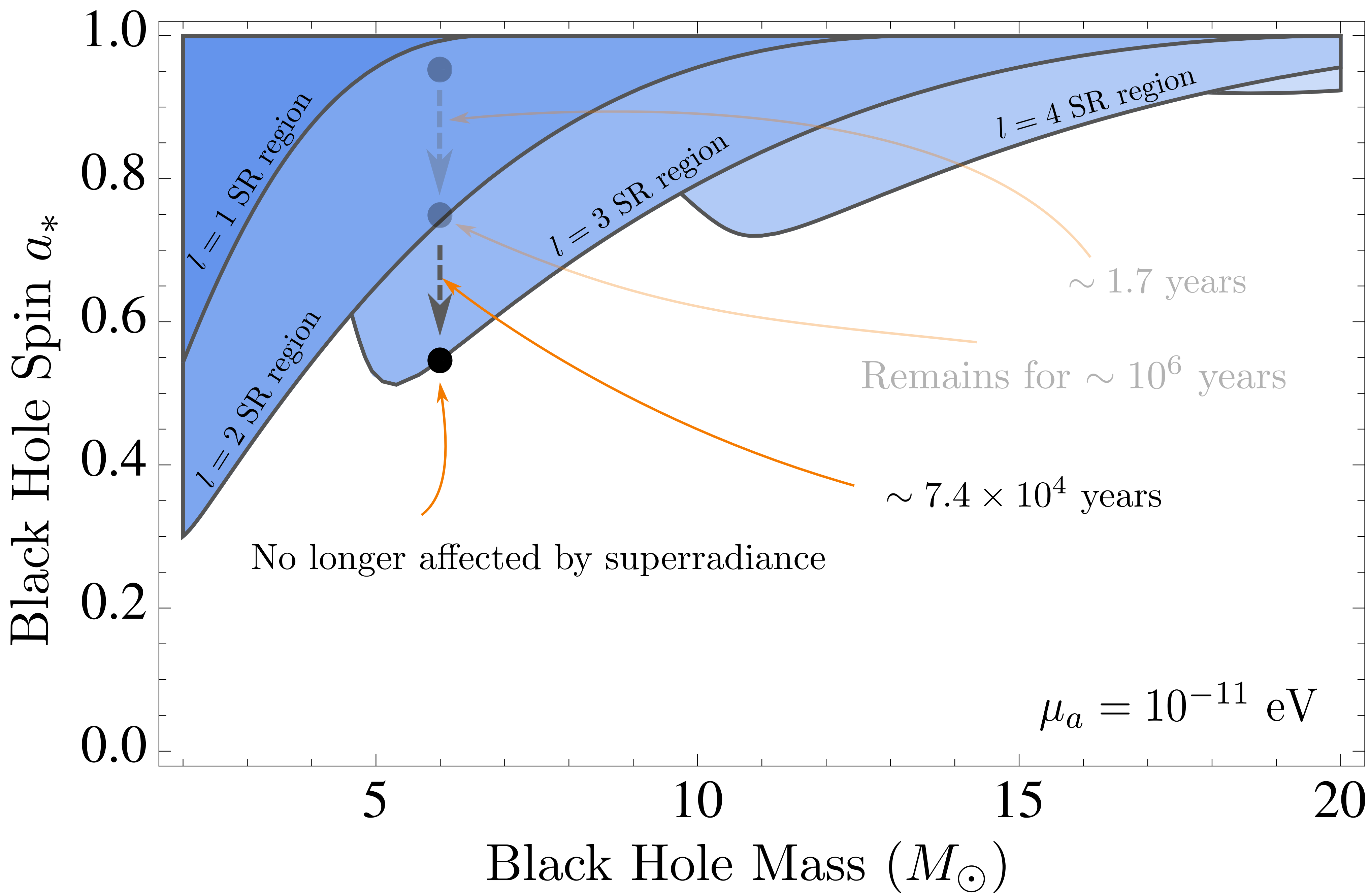
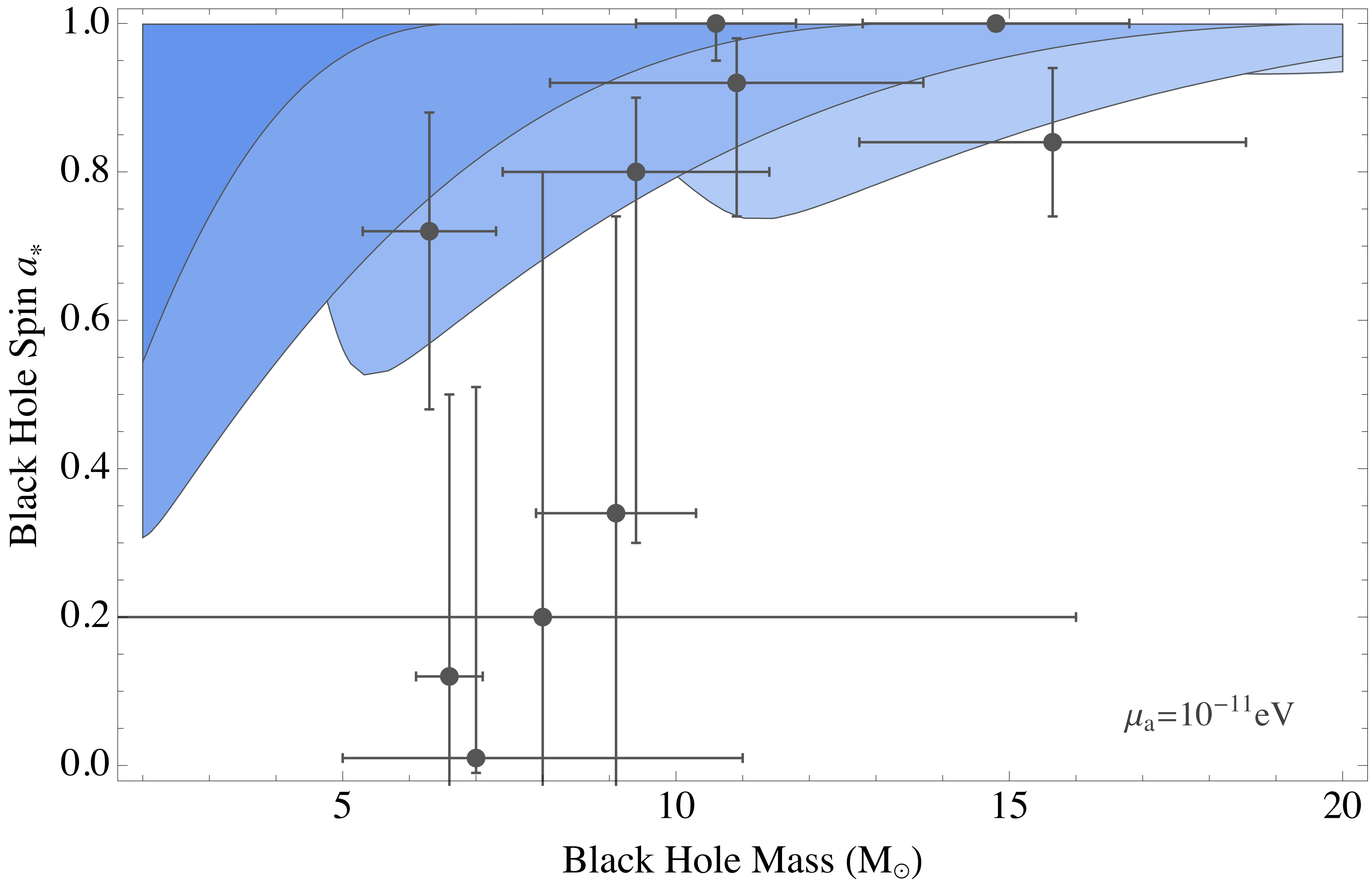


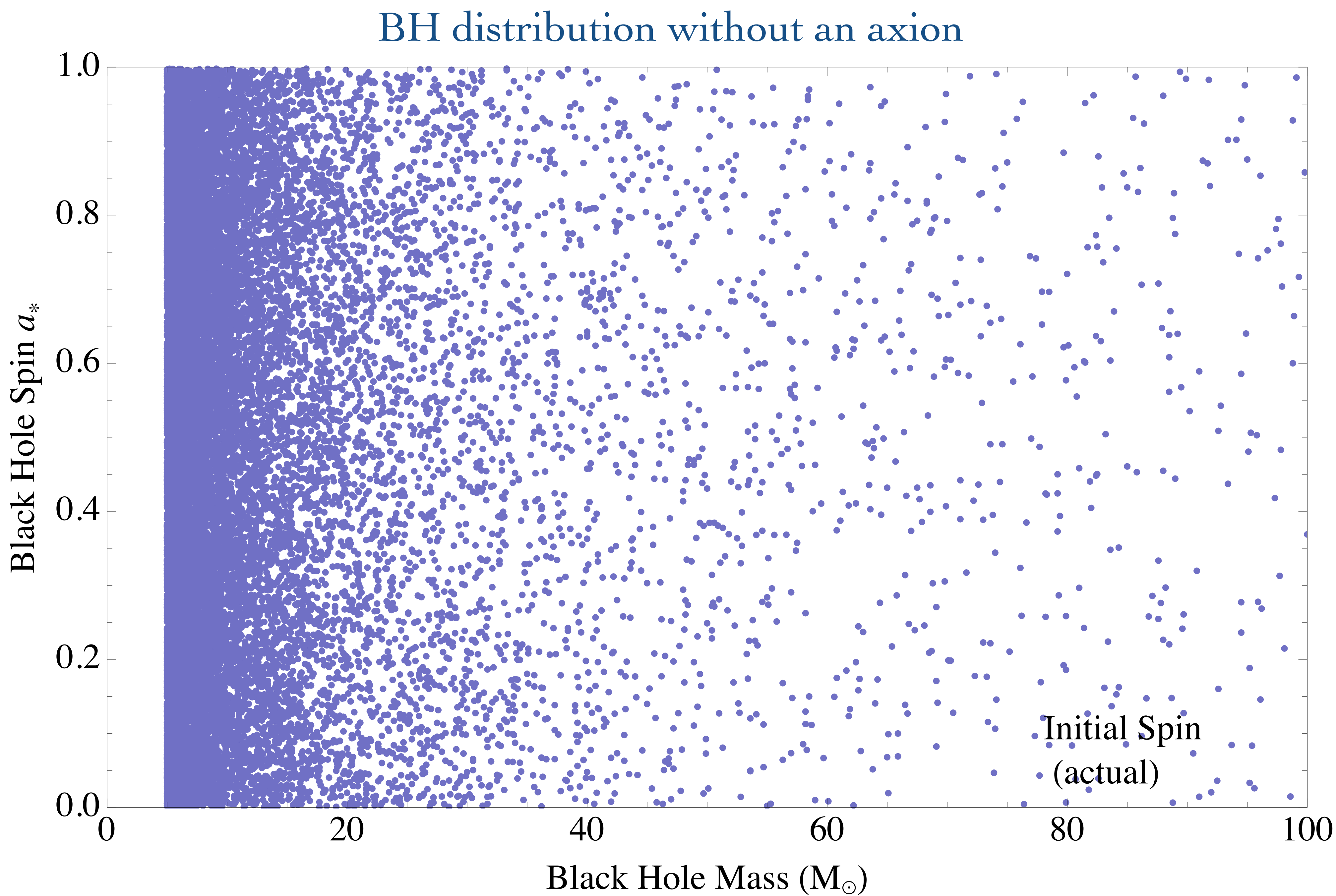
Spin-Down of Astrophysical Black Holes



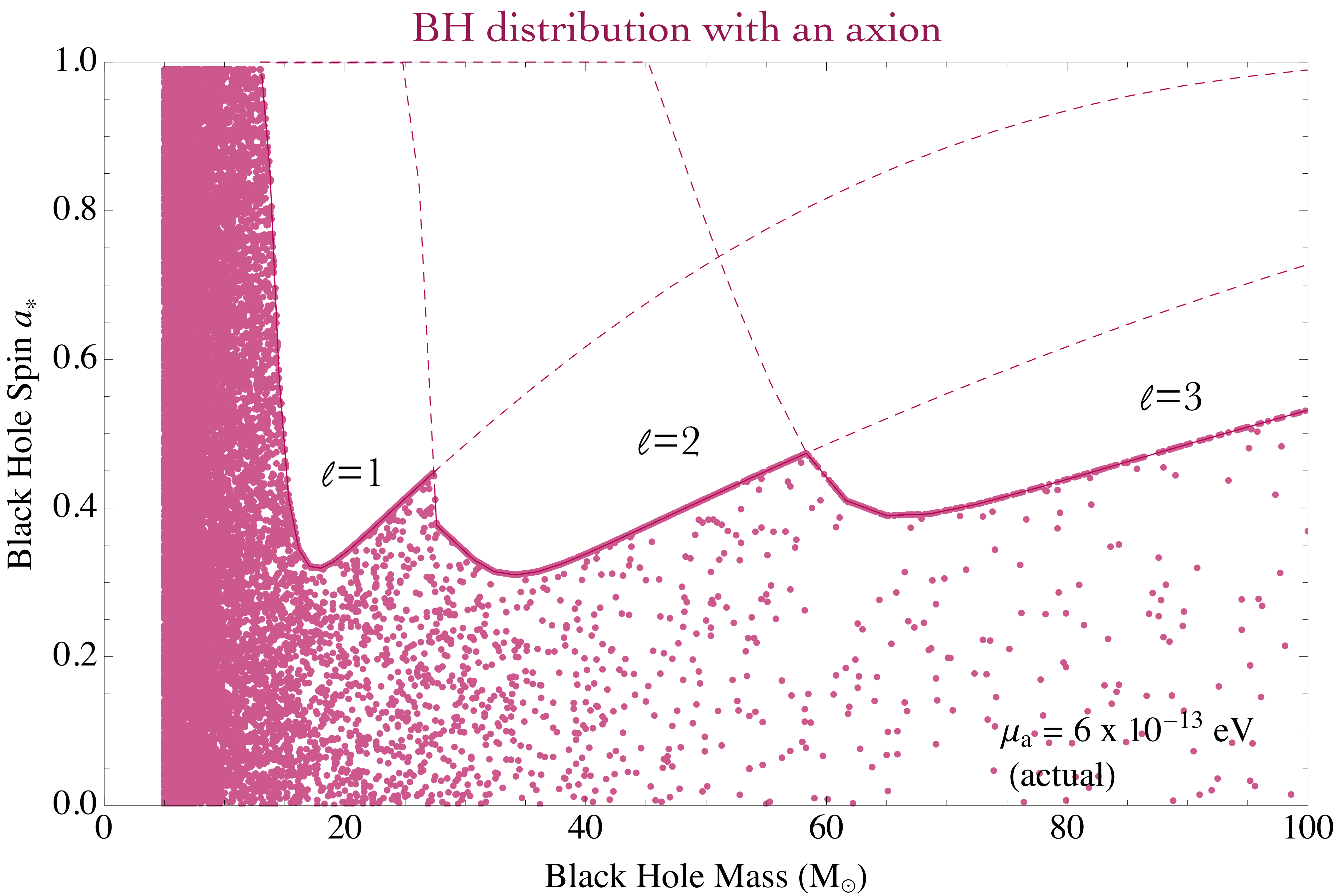
Range of the QCD axion excluded by current measurements

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

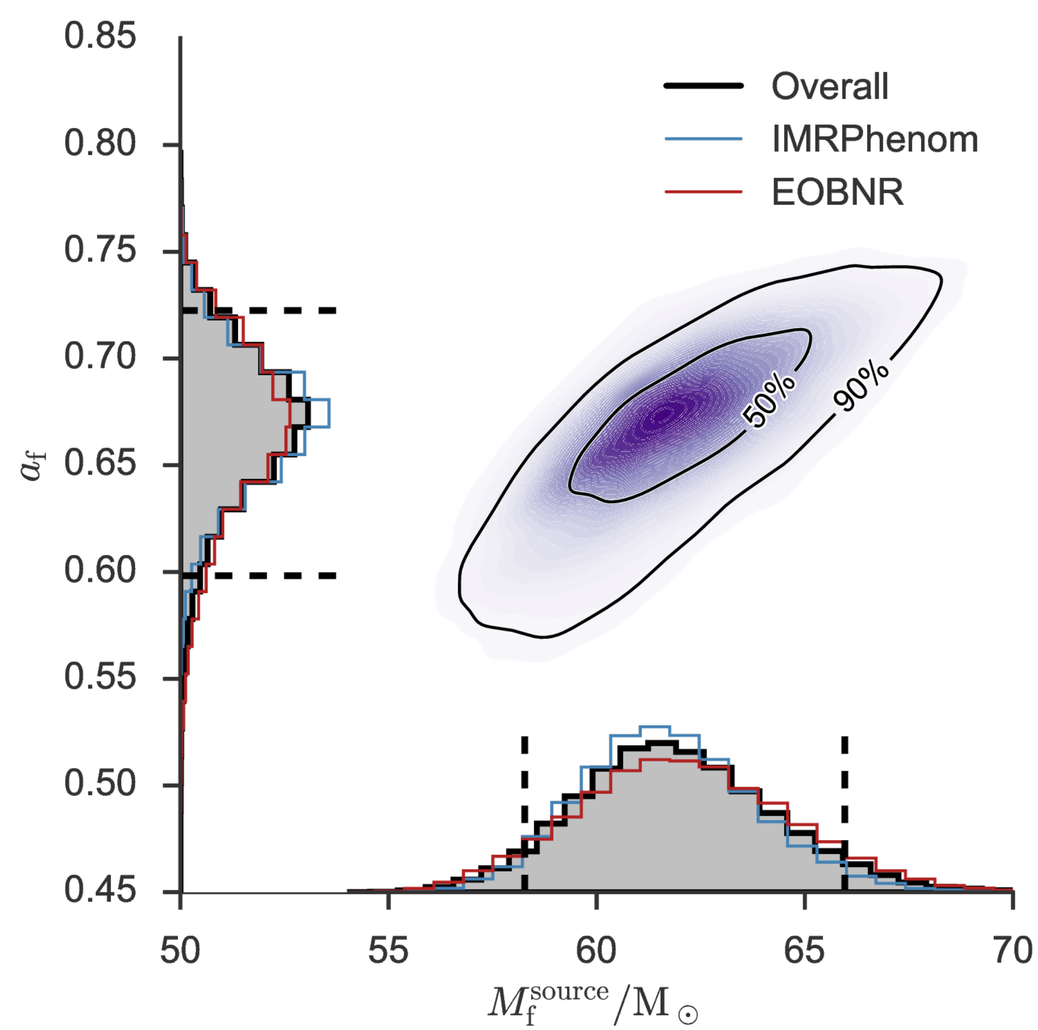
Black Hole Spins at aLIGO



Black Hole Spins at aLIGO



Properties of GW150914



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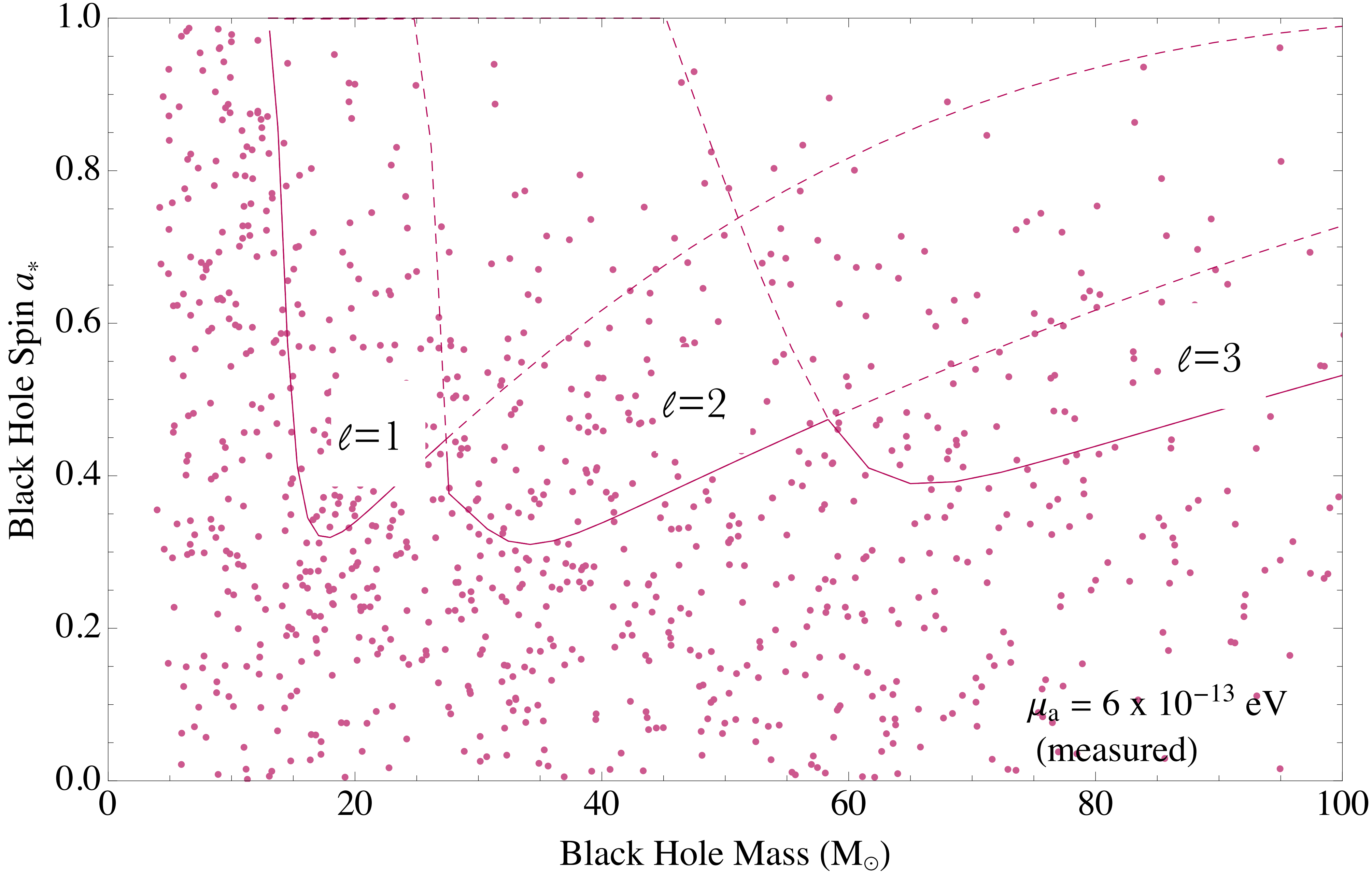
Taken from 1602.03840

Black Hole Spins at aLIGO

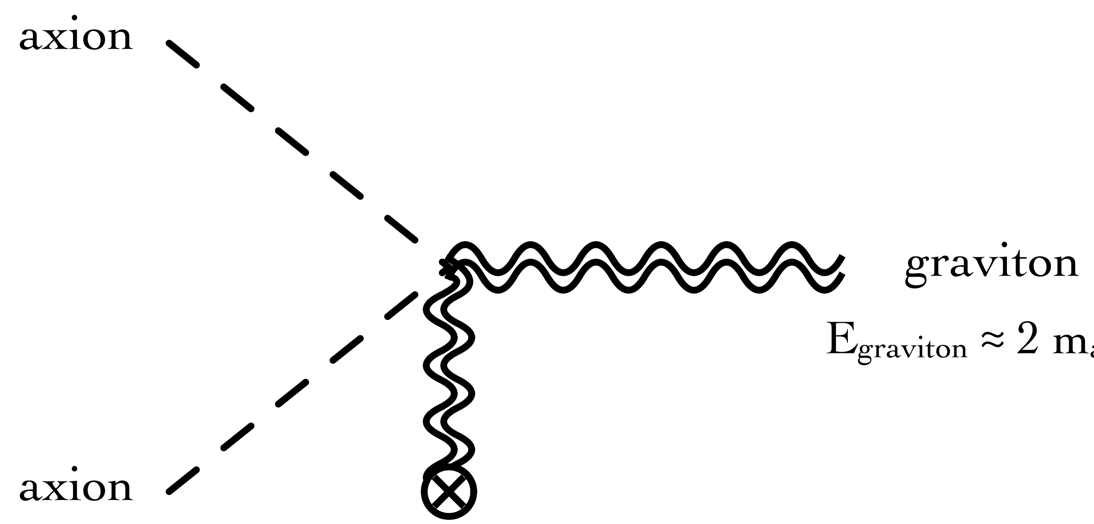
BH distribution with an axion
including errors

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



Super-Radiance Signatures

GW annihilations



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

$E_{graviton} \approx 2\ m_{axion}$ High frequency GWs

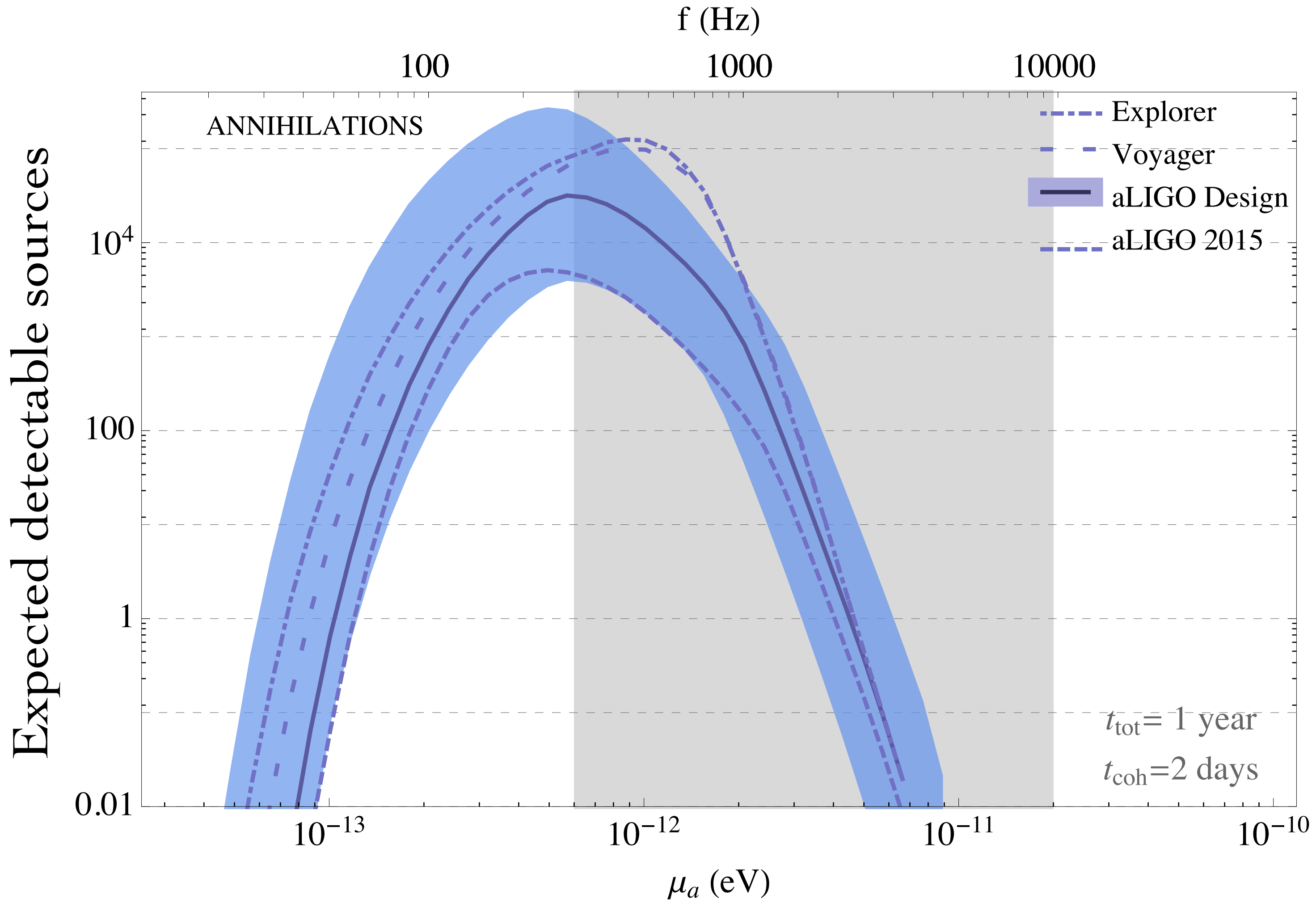
- Signal enhanced by the square of the occupation number of the state

$$h_{\mathrm{peak}} \simeq 10^{-22}\left(\frac{1\,\mathrm{kpc}}{r}\right)\left(\frac{\alpha/\ell}{0.5}\right)^{\frac{p}{2}}\frac{\alpha^{-\frac{1}{2}}}{\ell}\left(\frac{M}{10M_{\odot}}\right)$$

- Signal duration determined by the annihilation rate (can last thousands of years)

Expected Events from Annihilations

- Large uncertainties coming from tails of BH mass distribution



Pessimistic: flat spin distribution and 0.1 BH/century

Realistic: 30% above spin of 0.8 and 0.4 BH/century

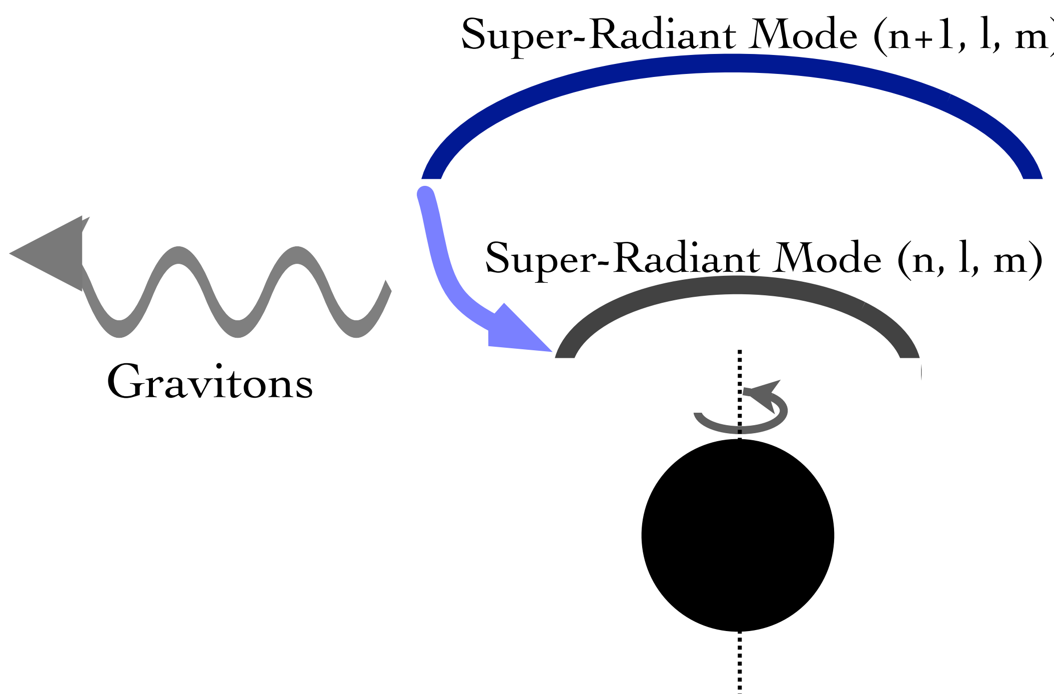
Optimistic: 90% above spin of 0.9 and 0.9 BH/century

Super-Radiance Signatures

GW transitions

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

Optimal frequency for LIGO



- Signal enhanced by the occupation numbers of excited and ground states

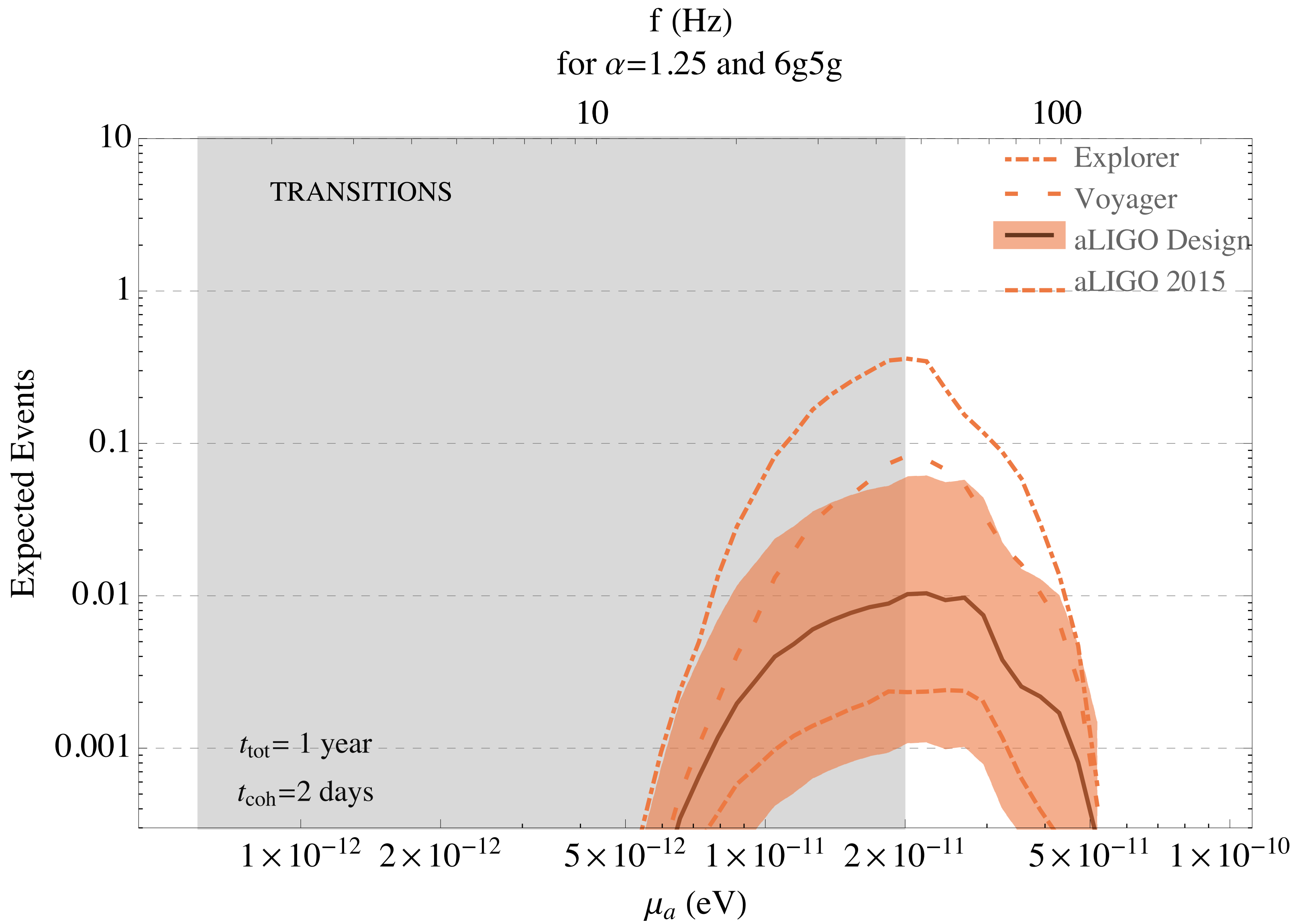
- Signal strength determined by the occupation number of the excited state

  $h \sim 3 \times 10^{-25}$ for a BH 10 kpc away

- Signal duration determined by the superradiance rate (1-100 years duration)

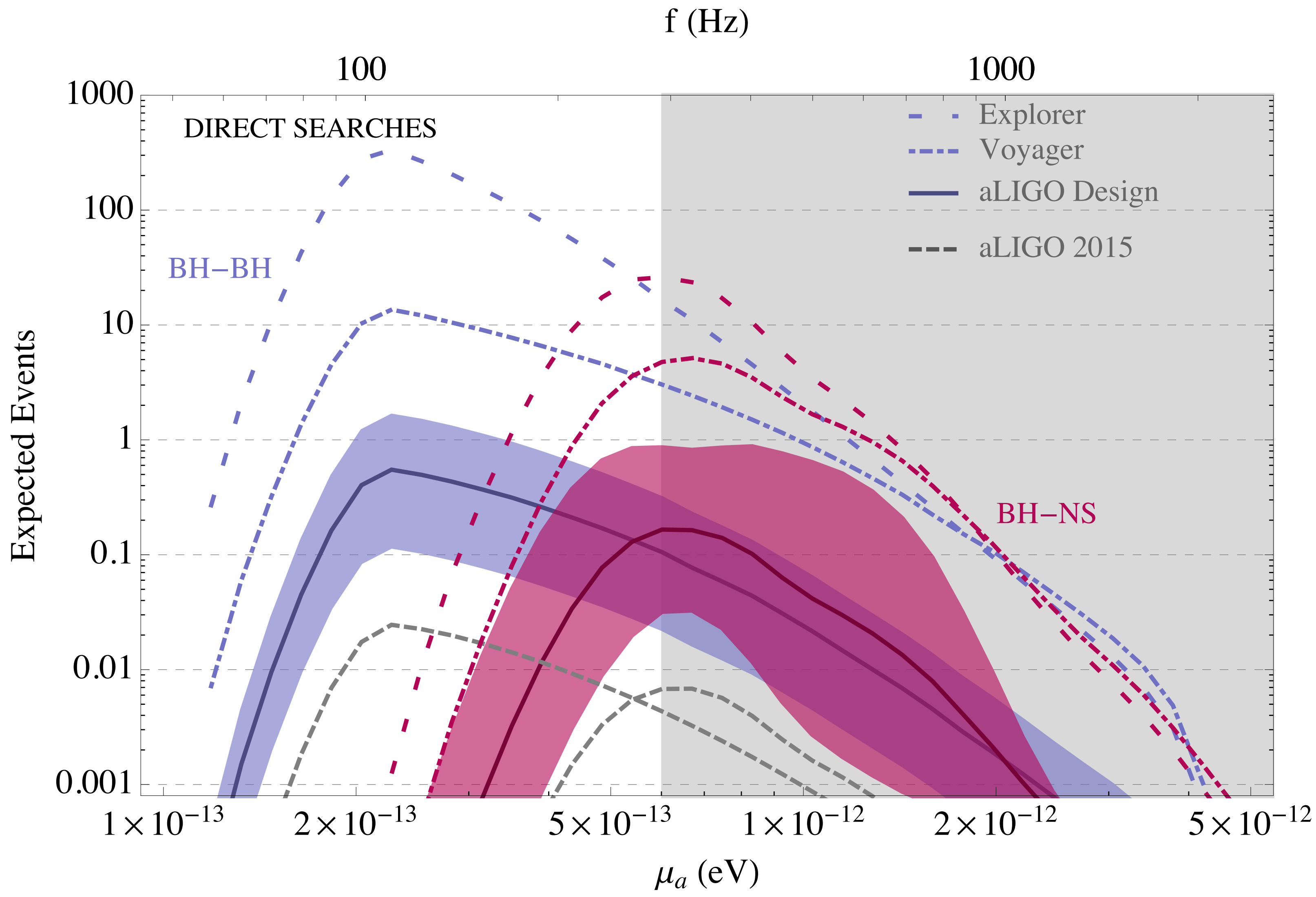
Transition Events Estimates

- Lower number of observable sources due to signal duration



Real-Time Superradiance

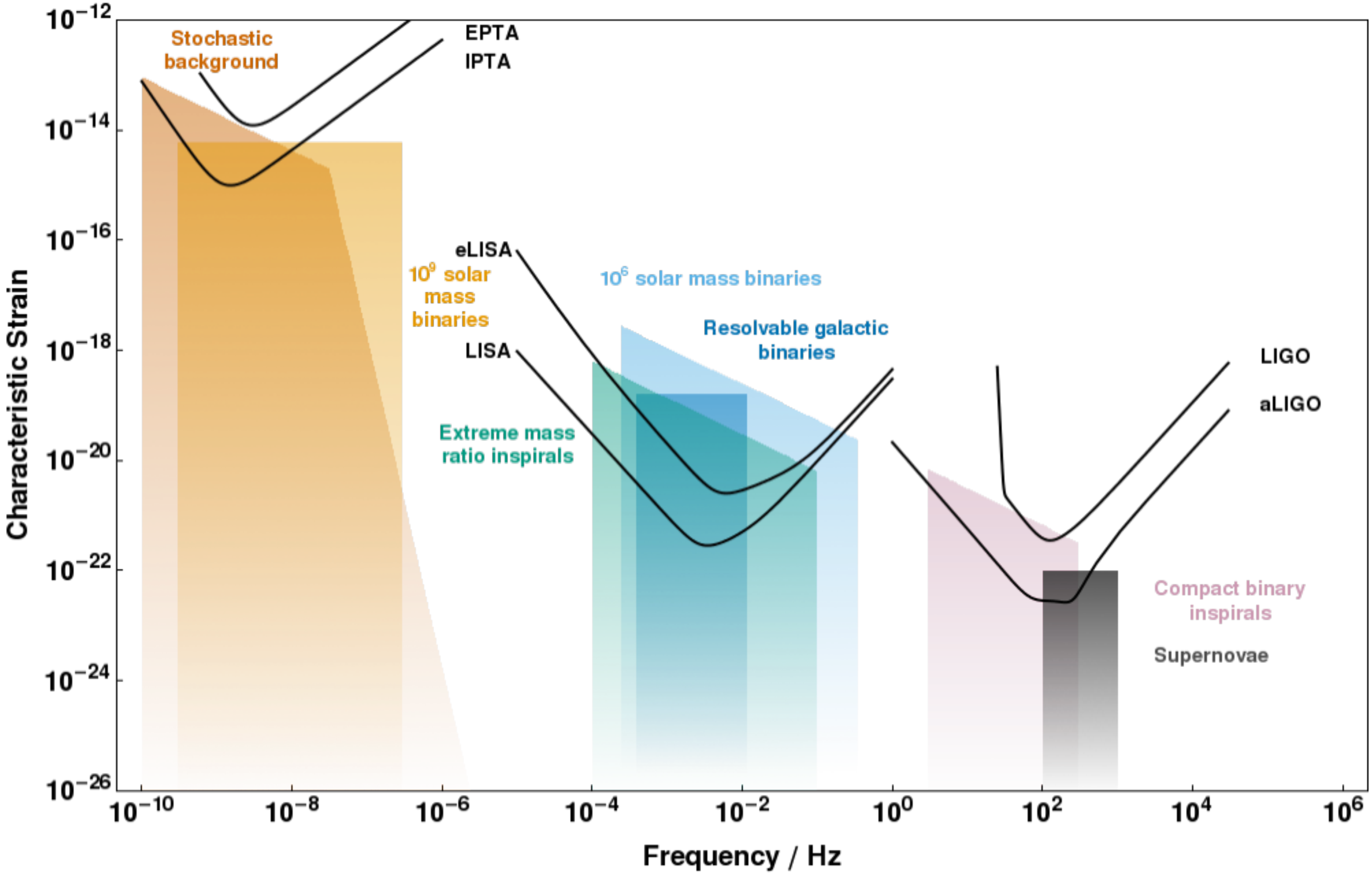
Black Holes produced from mergers are point sources candidates



Superradiance Prospects

- Probes axions between 10^{-20} and 10^{-10} eV independent of DM abundance
- Spin-mass distribution measured from mergers may reveal the presence of an axion
- Blind searches at aLIGO for annihilations most promising for lighter axions
- Merger events allow to follow SR in real time

Just The Beginning



Super Radiance Effect: Increased Progress Towards International Peace

TROUGH GROUP PRACTICE OF THE TRANSCENDENTAL MEDITATION AND TM-SIDHI PROGRAM