Title: Searching for Light Bosons with Black Hole Superradiance

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Abstract:

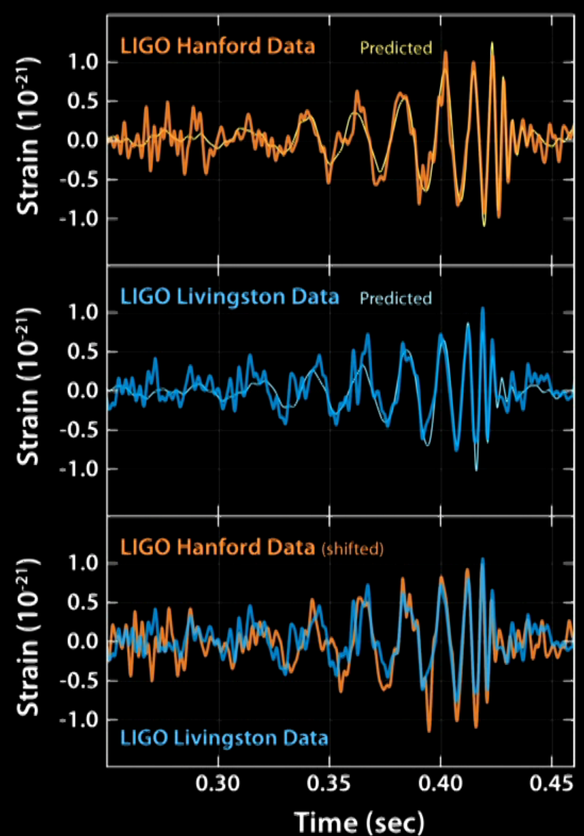
SEARCHING FOR LIGHT BOSONS WITH BLACK HOLE SUPERRADIANCE

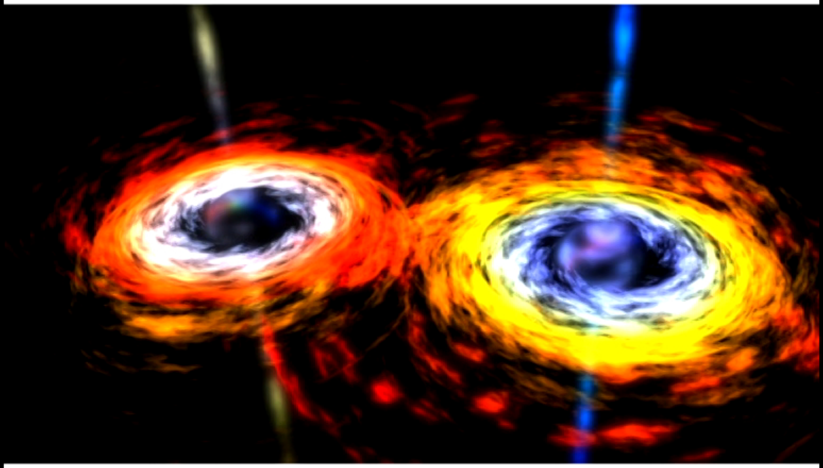
Savas Dimopoulos
Stanford University

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

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

September 14, 2015, 9:50:45 Greenwich Time





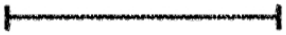
The Dawn of the Gravitational Wave Astronomy

- The Violent Universe: Mergers, phase transitions, inflation

- New precision science: many mergers per day, lots of data per merger

- How about Beyond the Standard Model Physics?

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

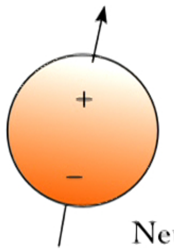
Focus on stellar black holes

Outline

- Theoretical Motivation for Light Bosons
- Black Hole Superradiance

Why is the Electric Dipole Moment of the Neutron Small?

The Strong CP Problem and the QCD axion



Neutron
EDM

$$\frac{g_s^2}{32\pi^2}\theta_s \vec{E}_s \cdot \vec{B}_s$$

EDM ~ e fm θ_s

Experimental bound: $\theta_s < 10^{-10}$

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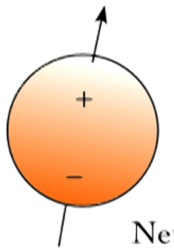

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Solution:
θ_s ~a(x,t) is a dynamical field, an axion

Axion mass from QCD:

$$\mu_a \sim 6 \times 10^{-13} \mathrm{eV} \frac{10^{19}\ \mathrm{GeV}}{f_a} \sim (300\ \mathrm{km})^{-1} \frac{10^{19}\ \mathrm{GeV}}{f_a}$$

f_a : axion decay constant

Mediates new forces and can be the dark matter

The Many Universes of String Theory

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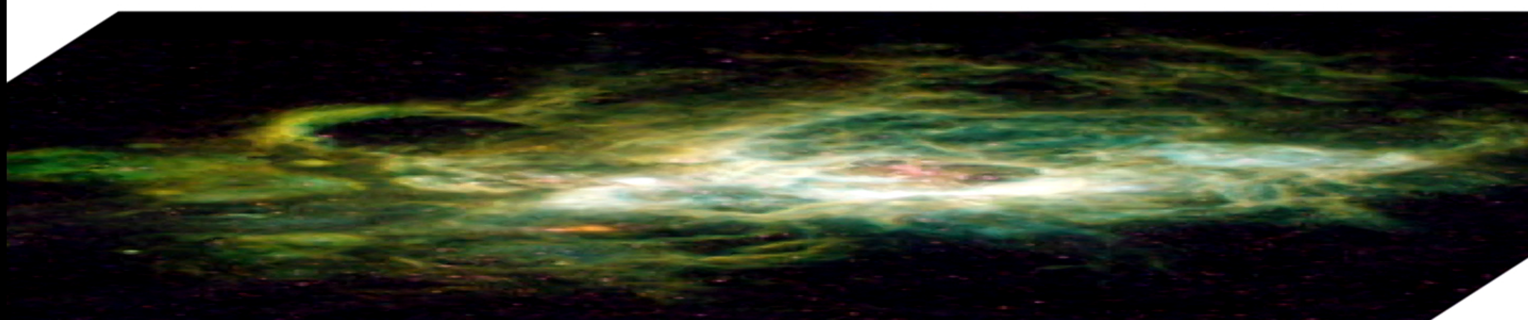

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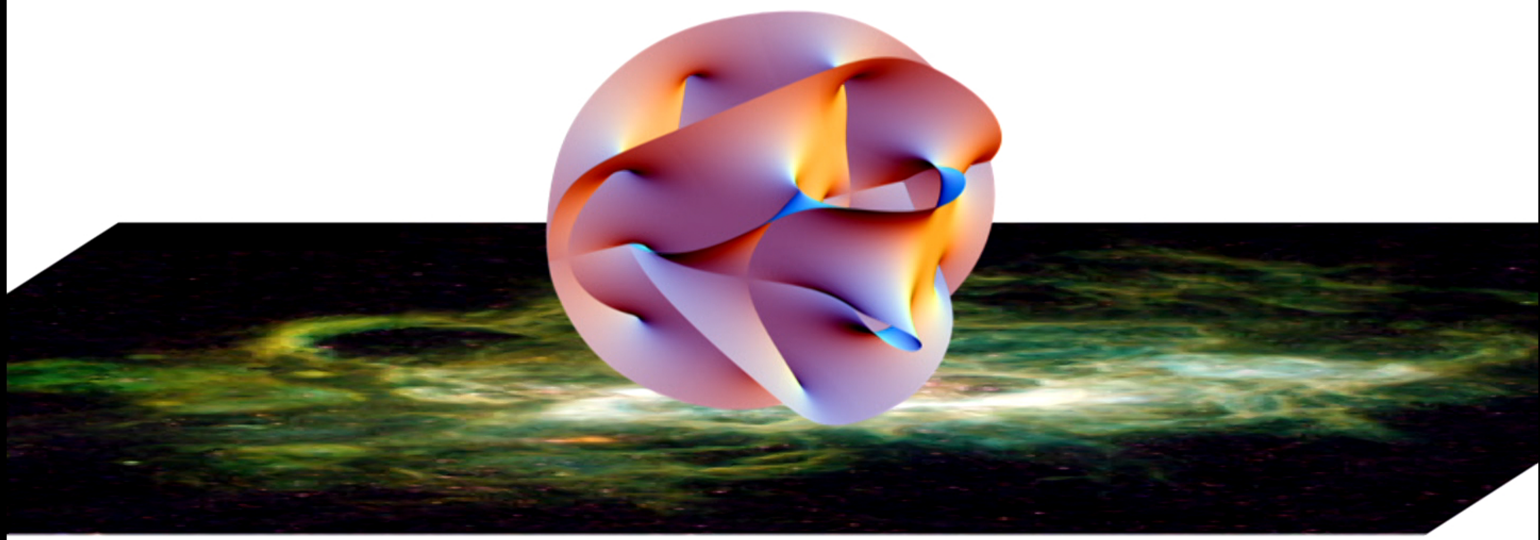

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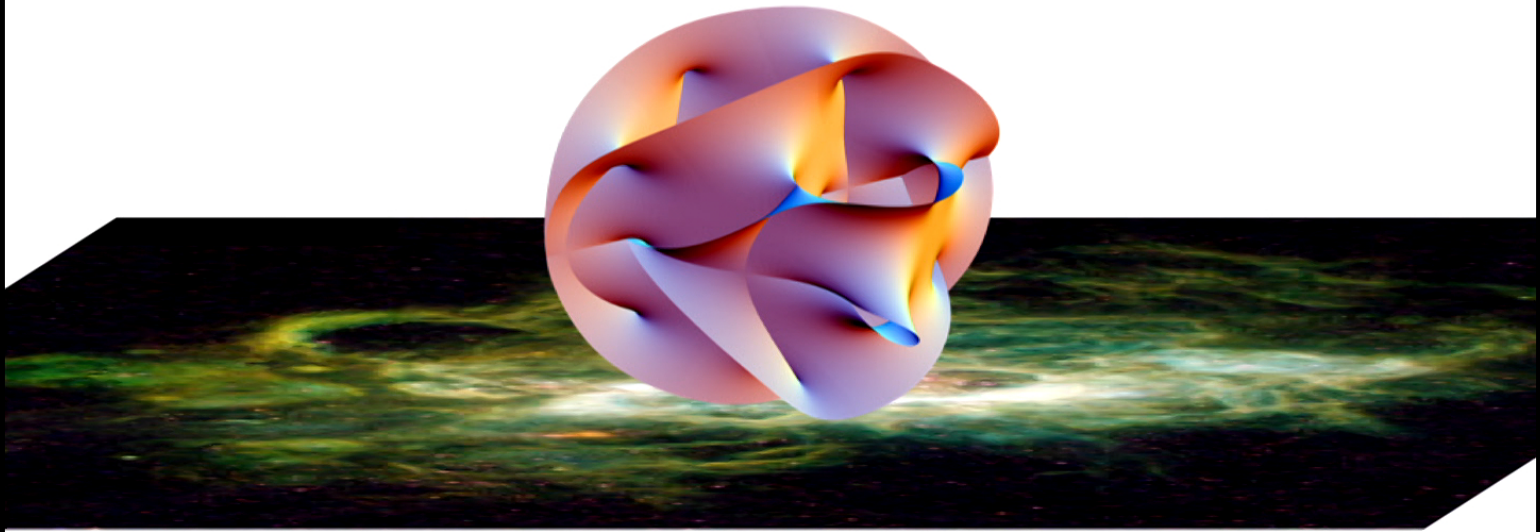

Extra dimensions of String Theory imply a Plenitude of Universes

Laws of Nature depend on the shape of the extra dimensions

Non-trivial gauge configurations

The Aharonov-Bohm Effect

Solenoid

Taking an electron around the solenoid

$$e \int A_\mu dx^\mu = e \times \text{Magnetic Flux}$$

while

$$\vec{B} = 0$$

Energy stored only inside the solenoid

Non-trivial gauge configuration far away carries no energy

Non-trivial gauge configurations

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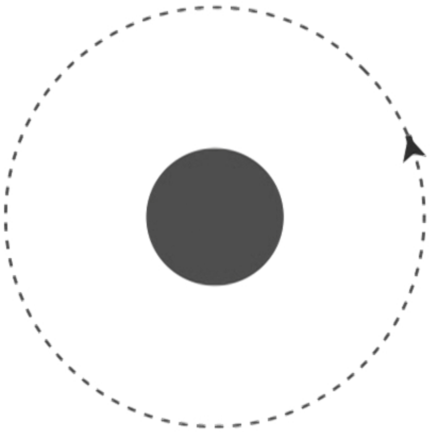

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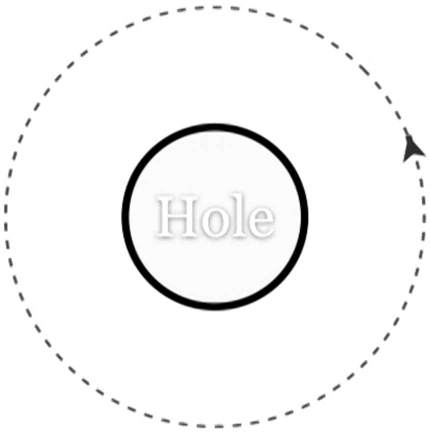

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Non-trivial topology:
"Blocking out" the core still leaves a non-trivial gauge, but no mass

A Plenitude of (Nearly) Massless Particles

- Spin-0 non-trivial gauge field configurations: String Axiverse
- Spin-1 non-trivial gauge field configurations: String Photiverse
- Fields that determine the shape and size of extra dimensions as well as values of fundamental constants: Dilatons, Moduli, Radion
- Higher dimensional graviton or modifications of gravity at short distances

Mass acquired by non-perturbative effects

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- Particle Mass $\sim M_{\text{Planck}} e^{-\frac{2h}{e^2}}$

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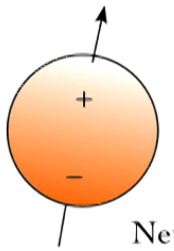

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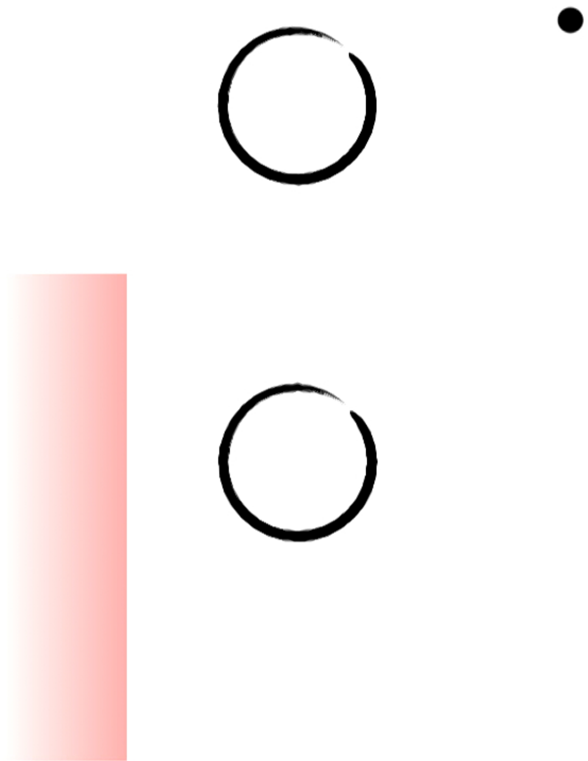
Super-Radiance Cartoon

Super-radiant scattering of a massive object

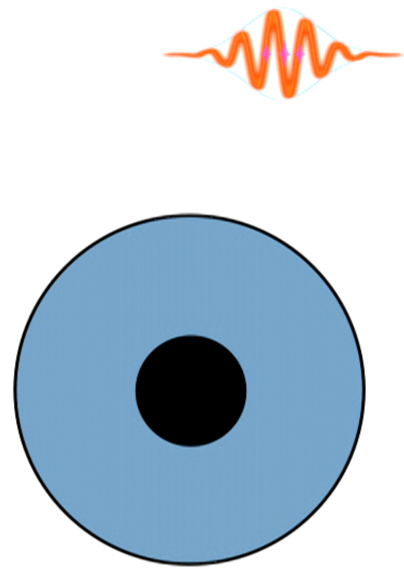
Super-Radiance Cartoon



Super-radiant scattering of a wave

Black Hole Bomb

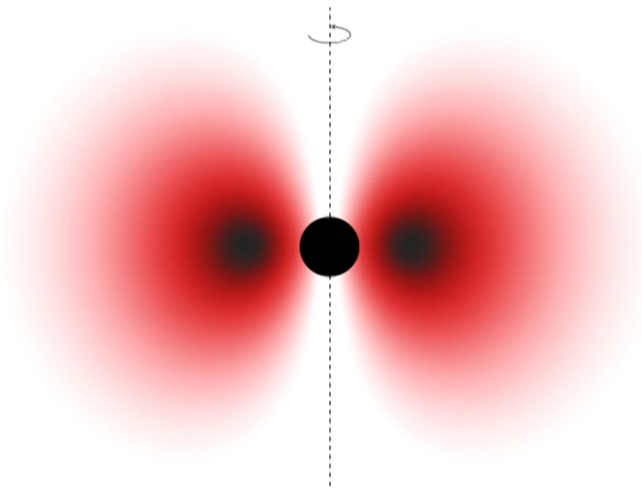
Press & Teukolsky 1972



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

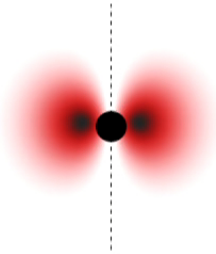
Superradiance for a massive boson

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



Particle Compton Wavelength comparable to the size of the Black Hole

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 $E_{\rm binding} = -\frac{\alpha^2 \mu_a}{2n^2}$

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

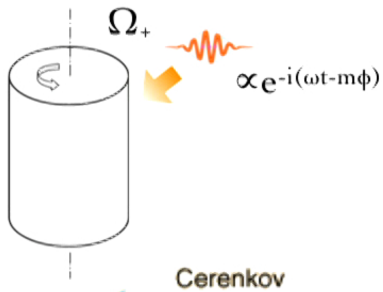
$\omega_{\text{axion}} < m\,\Omega_+$ *Note: This is *a kinematic* condition

m : magnetic quantum number

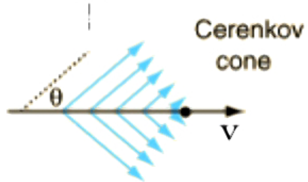
Ω_+ : angular velocity of the BH

Universal Phenomenon:

Superluminal rotational motion of a conducting cylinder



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



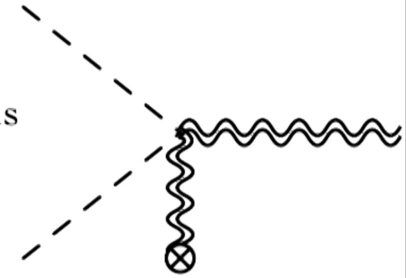
Condition can be extracted from requiring that $dA_{BH} > 0$

Evolution of Superradiance for an Axion

Superradiance instability

Gravity wave transitions of axions between levels

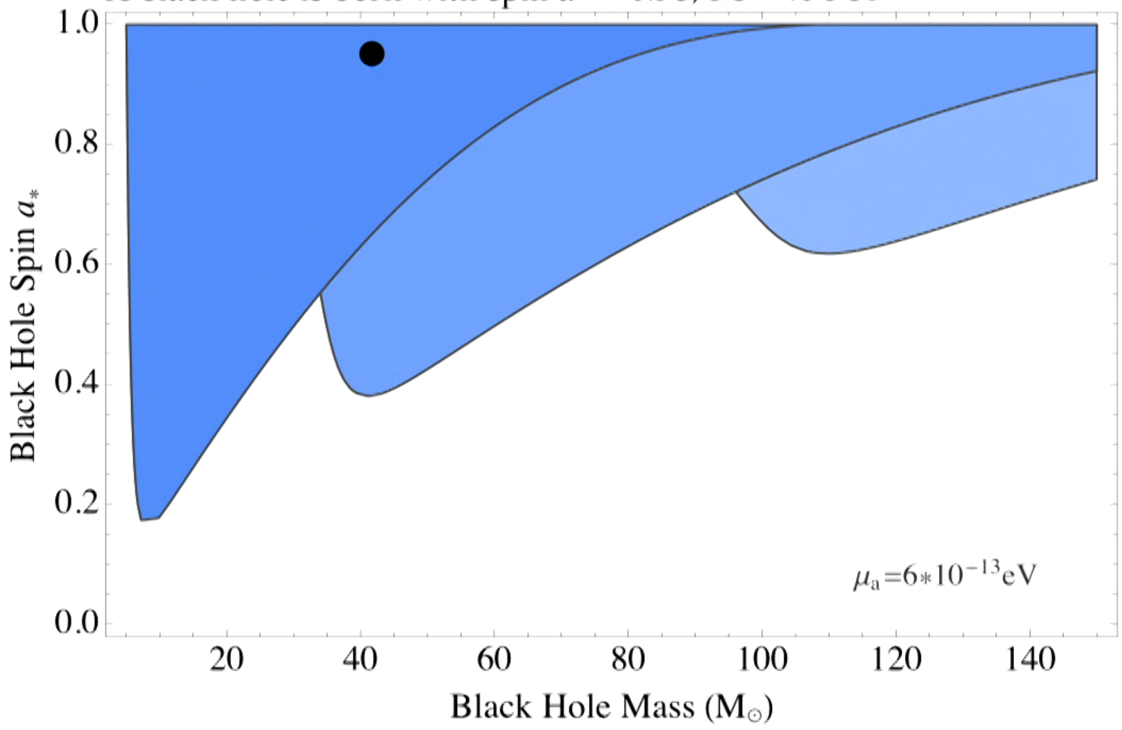
Gravity wave emission through axion annihilations



Superradiance: A stellar Black Hole History

•

A black hole is born with spin a* = 0.95, M = 40 M⊙



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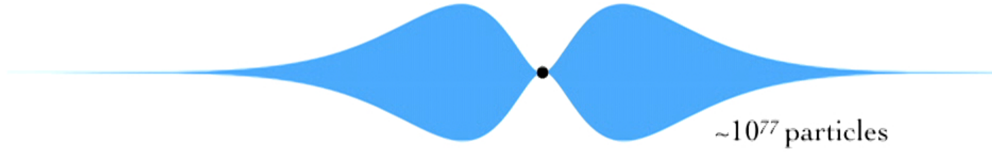
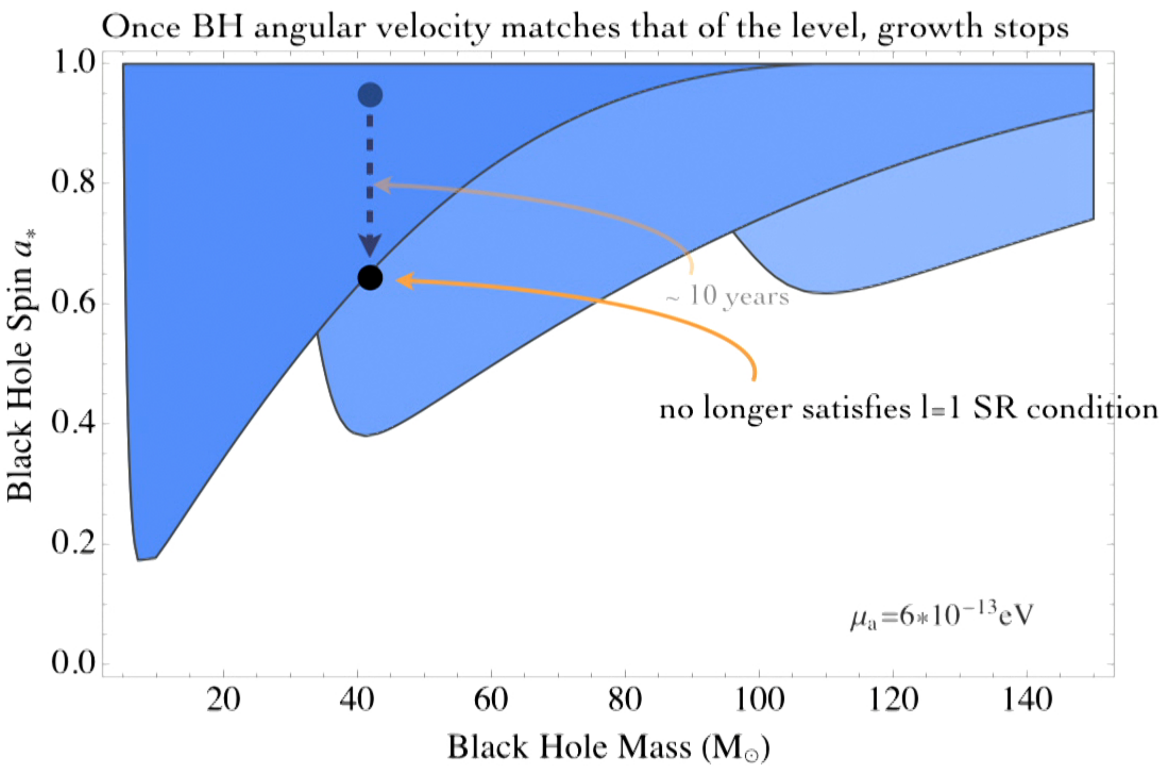
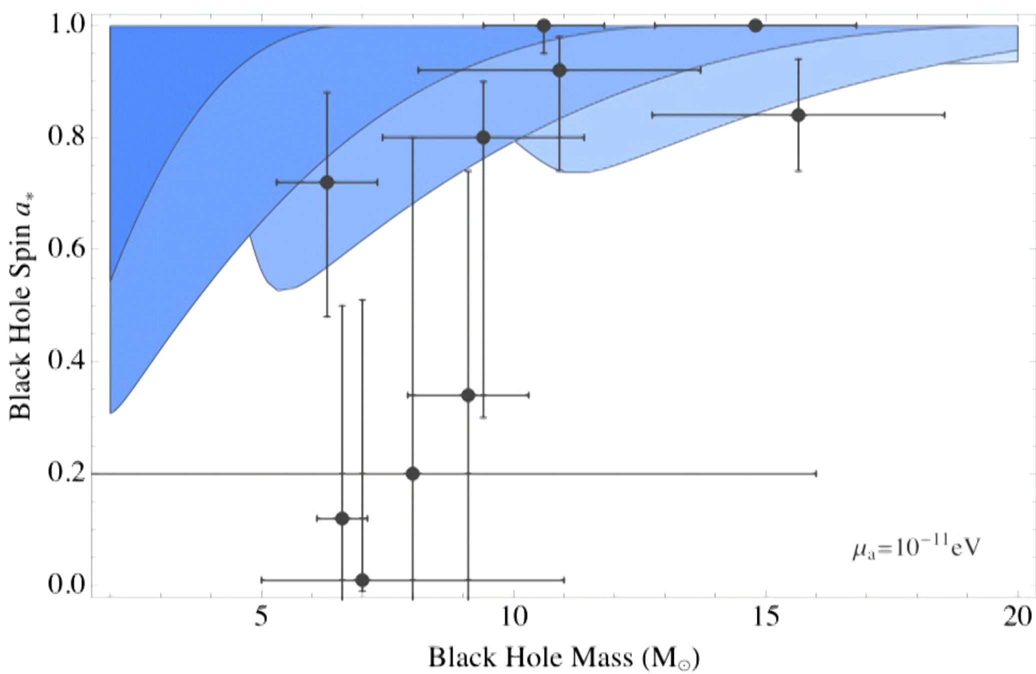




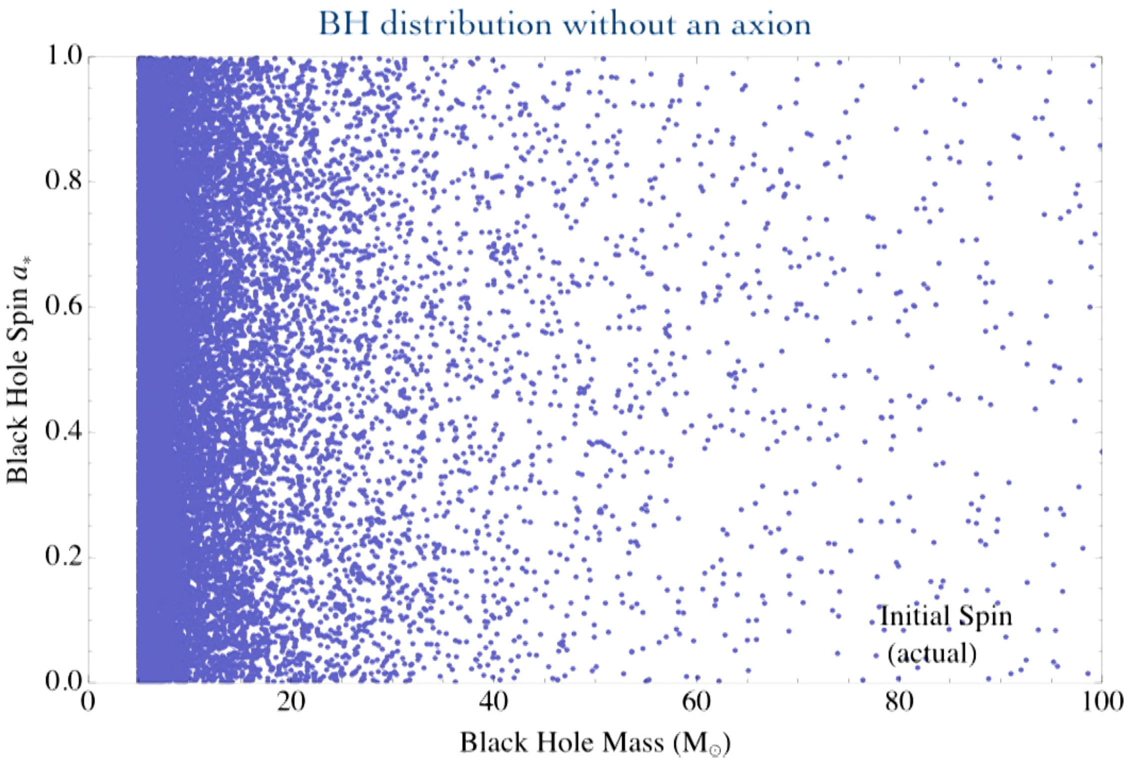
Spin-Down of Astrophysical Black Holes



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



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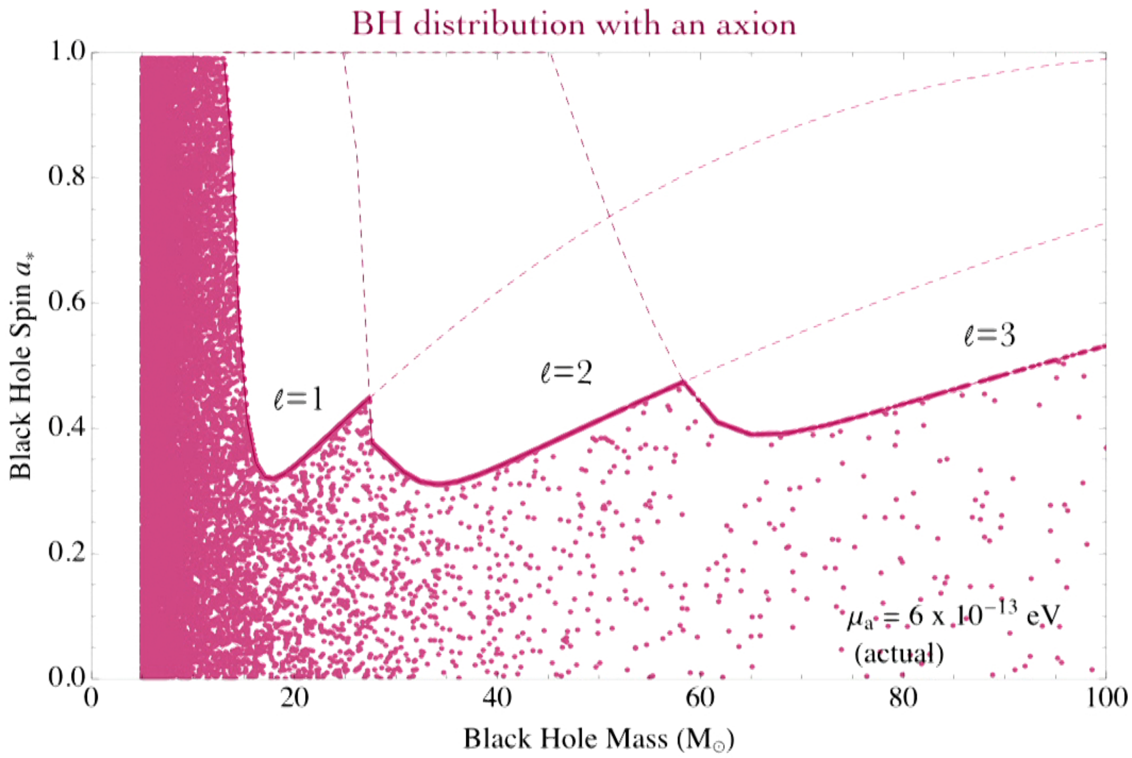
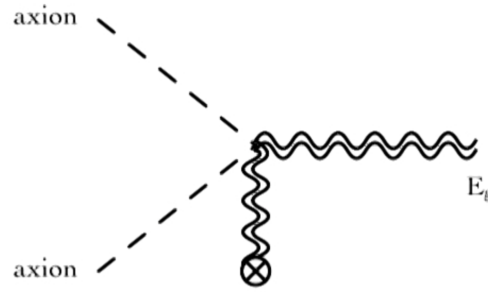


Super-Radiance Signatures

GW annihilations



$E_{graviton} \approx 2\ m_{axion}$

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

High frequency GWs

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

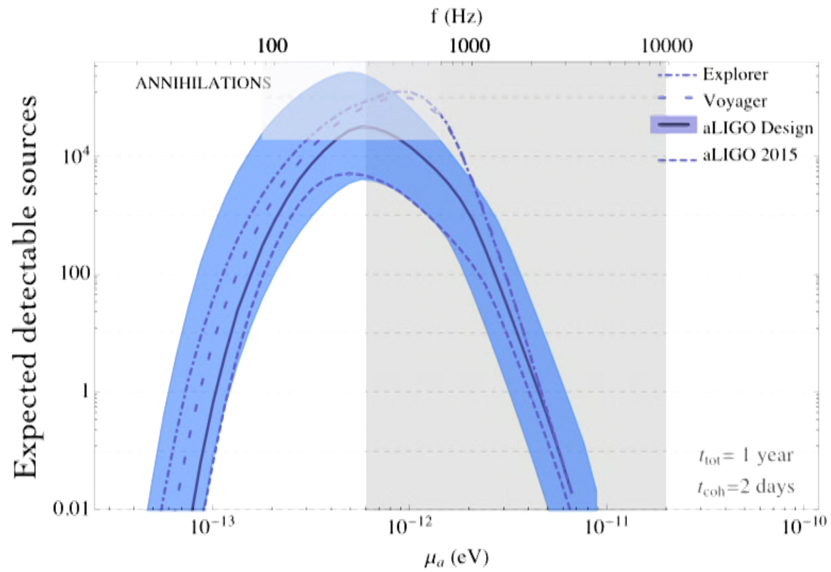
$$h_{\text{peak}} \simeq 10^{-22} \left(\frac{1\,\text{kpc}}{r}\right) \left(\frac{\alpha/\ell}{0.5}\right)^{\frac{p}{2}} \frac{\alpha^{-\frac{1}{2}}}{\ell} \left(\frac{M}{10 M_\odot}\right)$$

- Signal frequency drifts upwards with time

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

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

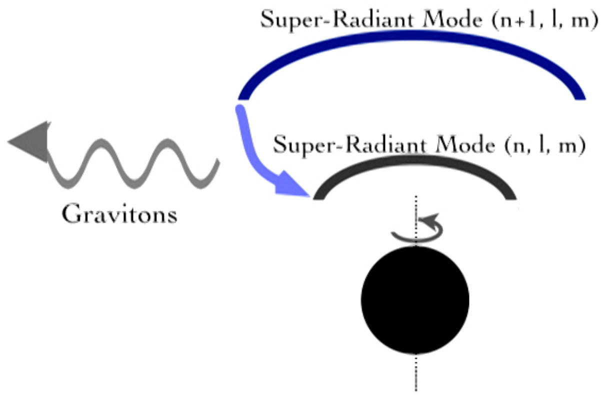
Optimistic: 90% above spin of 0.9 and 0.9 BH/century

Super-Radiance Signatures

GW transitions

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

Optimal frequency for LIGO



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

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

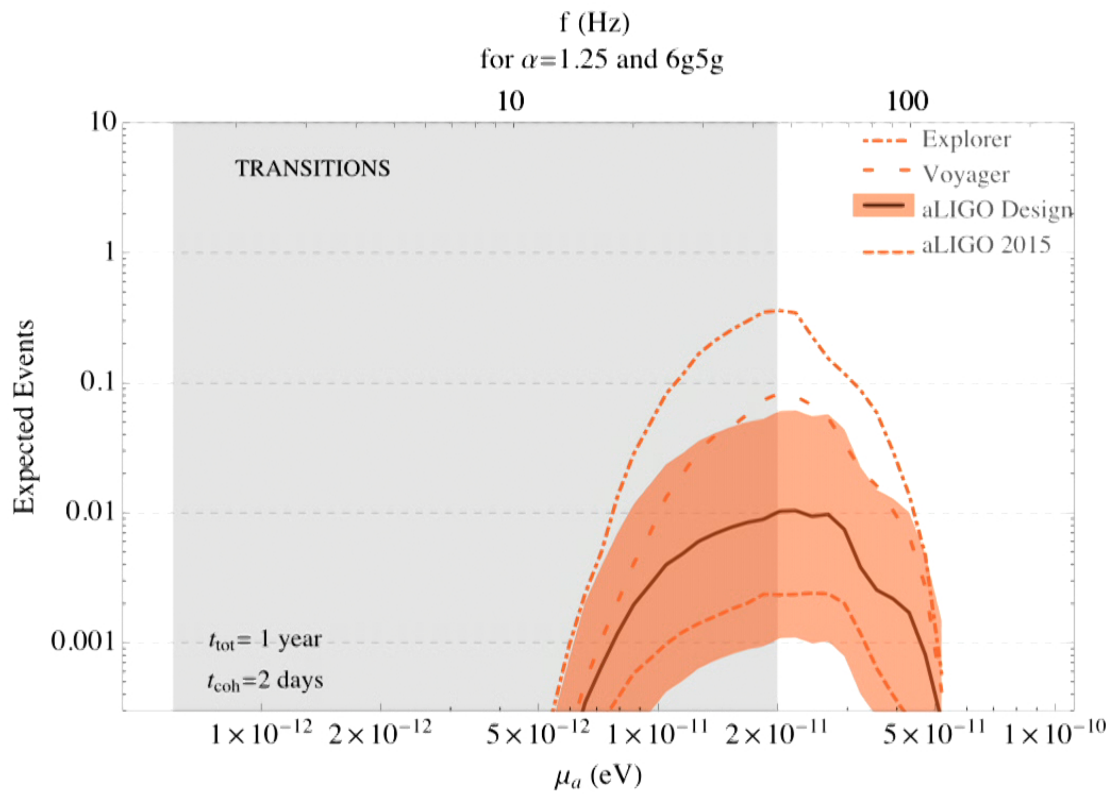
h ~ 3x10^{-25} for a BH 10 kpc away

- Signal frequency drifts upwards with time

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

Transition Events Estimates

- Lower number of observable sources due to signal duration



Real-Time Superradiance

Black Holes produced from mergers are point sources candidates