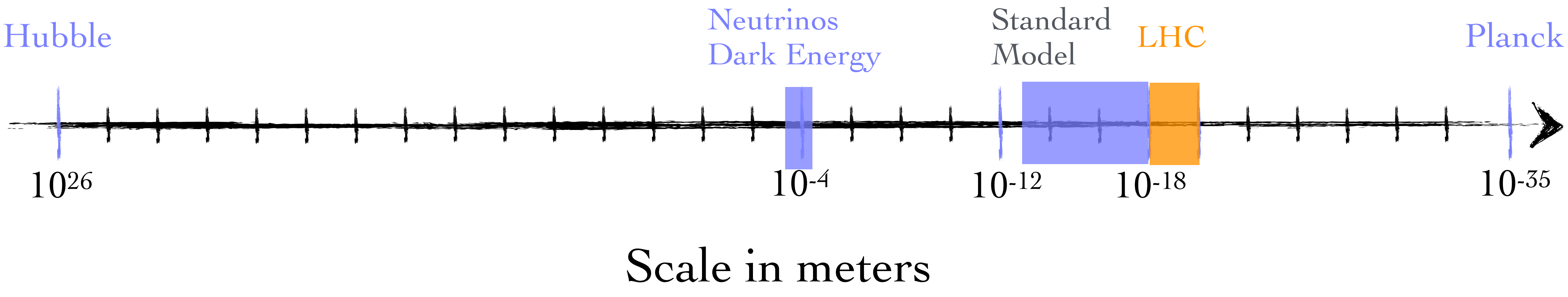
Searching for New Physics Without Colliders

Savas Dimopoulos
Stanford University

The Length Scales in the Universe



80% of the energy scale left to explore

Dark Matter, Strong CP, String theory

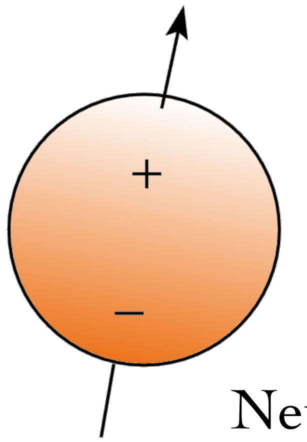
suggests there is more

Outline

- Theoretical Motivation for Light Bosons
- Black Hole Superradiance
- Atom Interferometry and Atomic Clocks

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

Peccei Quinn,
Weinberg,
Wilczek

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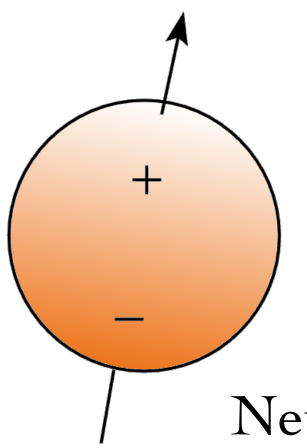


Neutron EDM

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

EDM ~ e fm θ_s

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

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

Peccei Quinn, Weinberg, Wilczek

Axion mass from QCD:

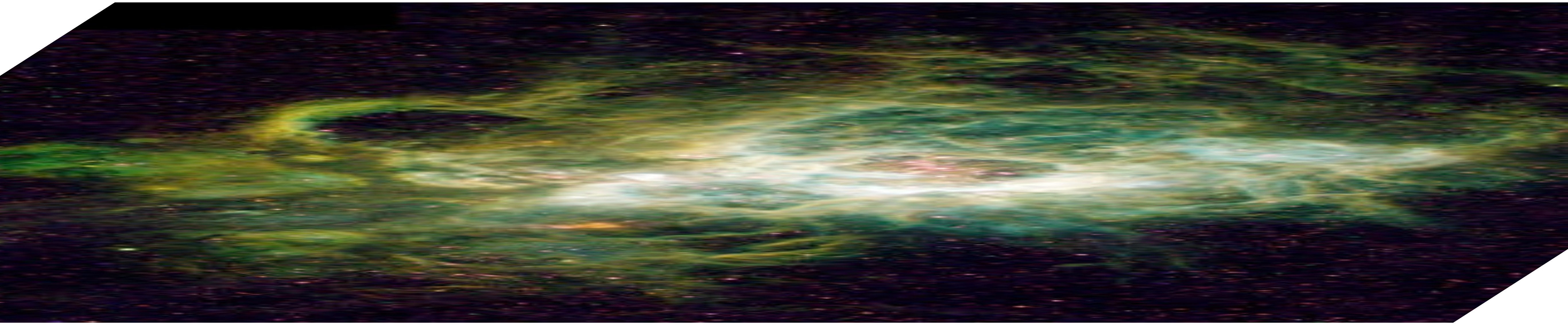
$$\mu_a \sim 6 \times 10^{-13}\text{eV}\frac{10^{19}\ \text{GeV}}{f_a} \sim (300\ \text{km})^{-1}\frac{10^{19}\ \text{GeV}}{f_a}$$

f_a : axion decay constant

Mediates new forces and can be the dark matter

The Many Universes of String Theory

The Many Universes of String Theory



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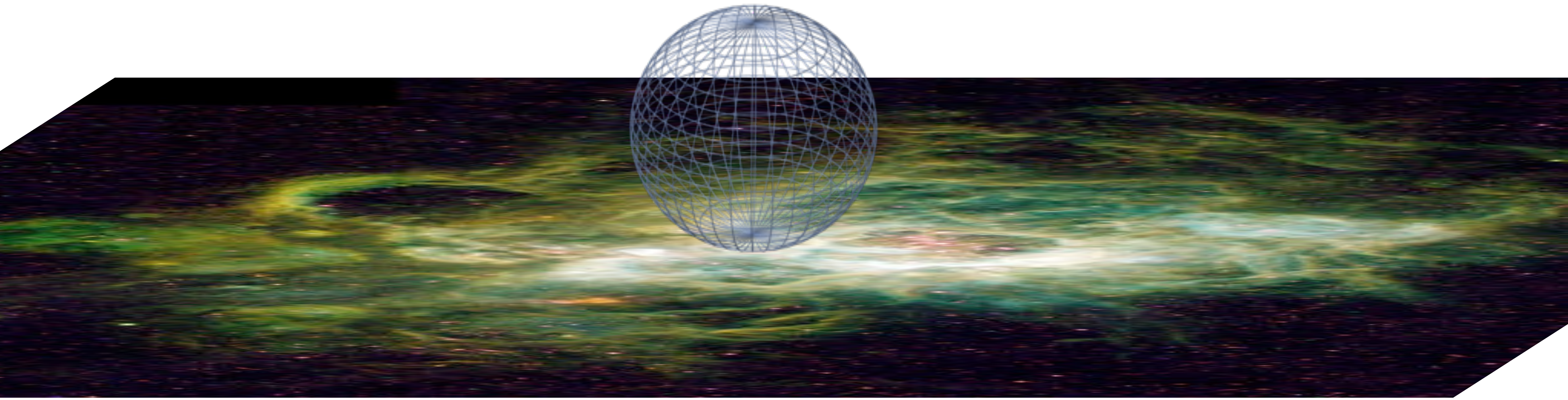

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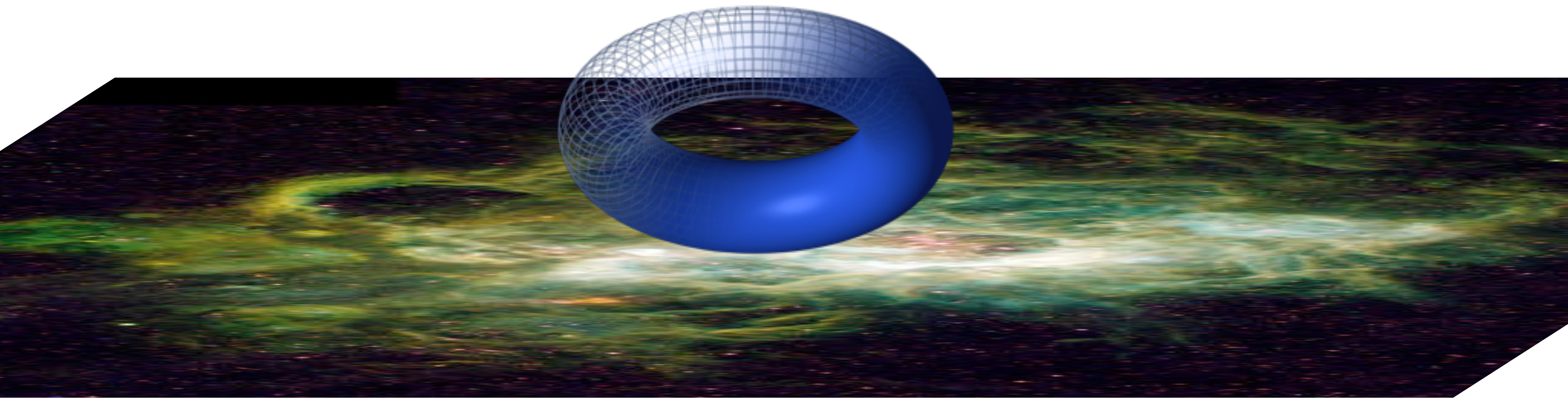

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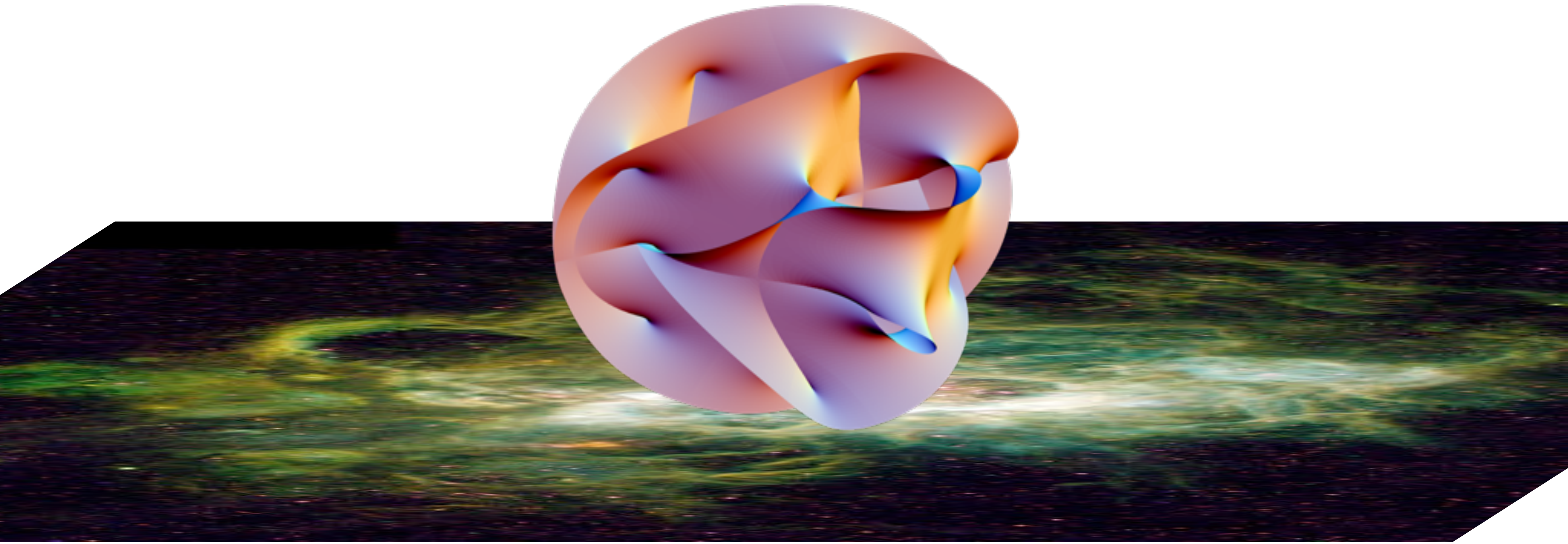

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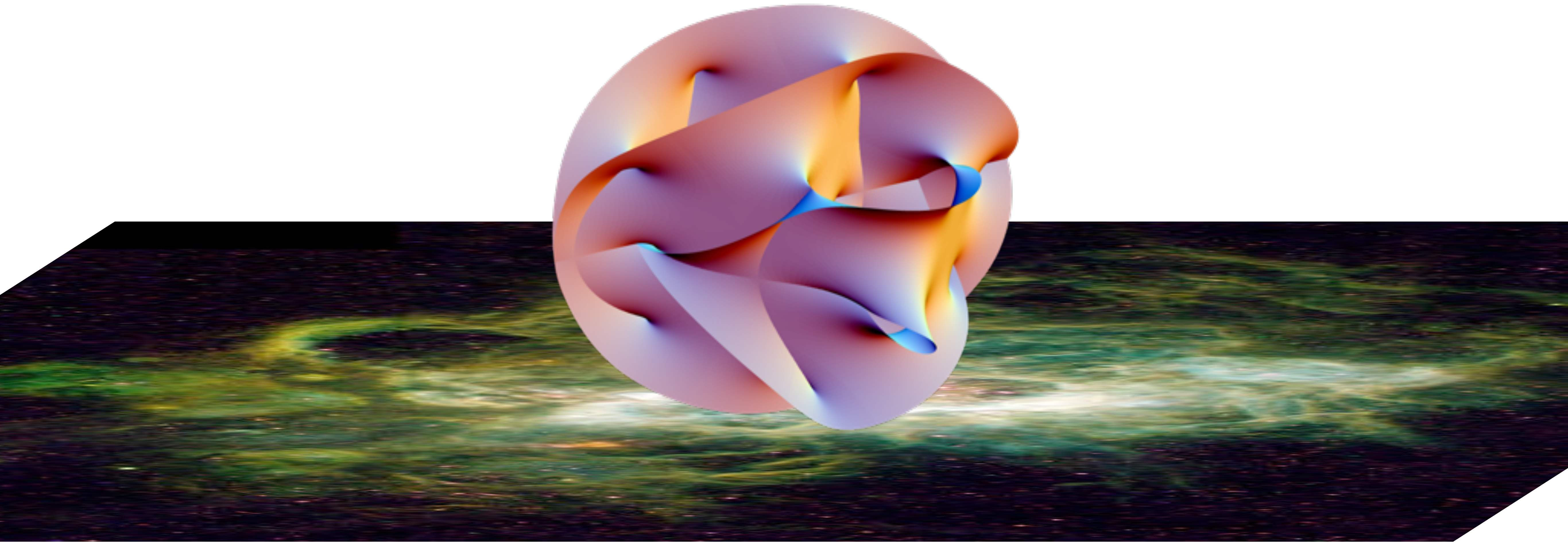
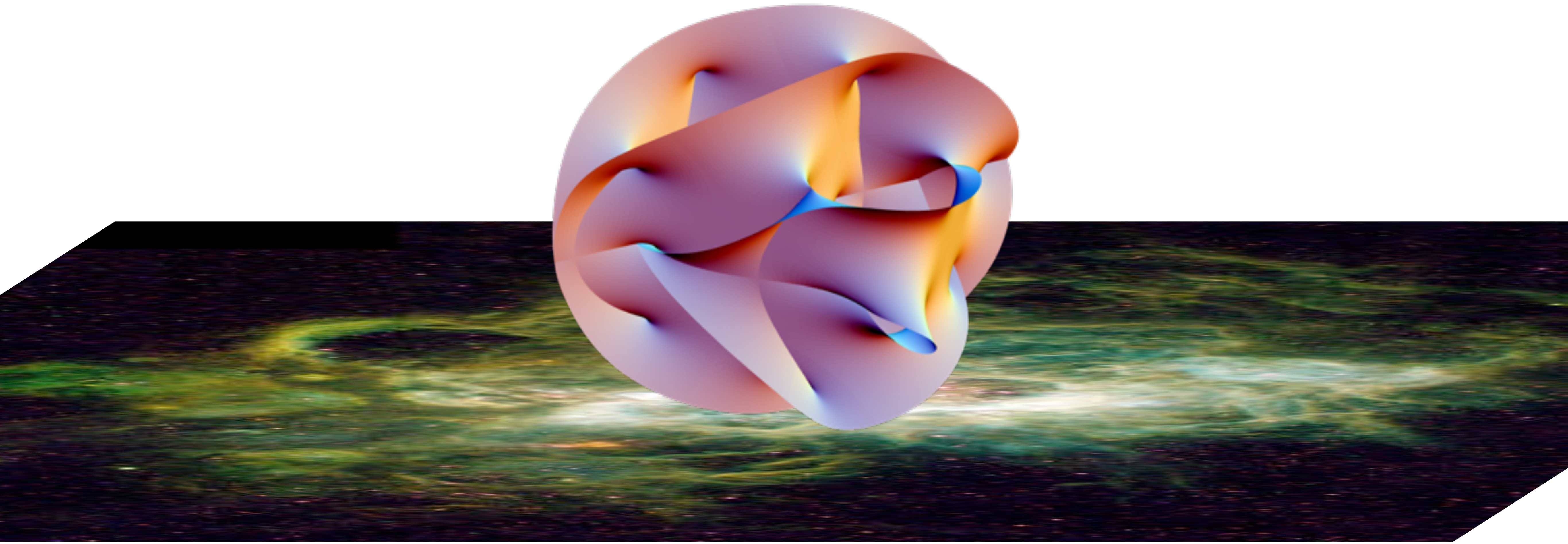


Extra dimensions of String Theory imply a Plenitude of Universes

Laws of Nature depend on the shape of the extra dimensions

The Many Particles in String Theory

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



Extra dimensions of String Theory imply a Plenitude of Universes

Complexity of Extra dimensions implies a Plenitude of Particles

Discovery of these particles would be indirect evidence for the Multiverse

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

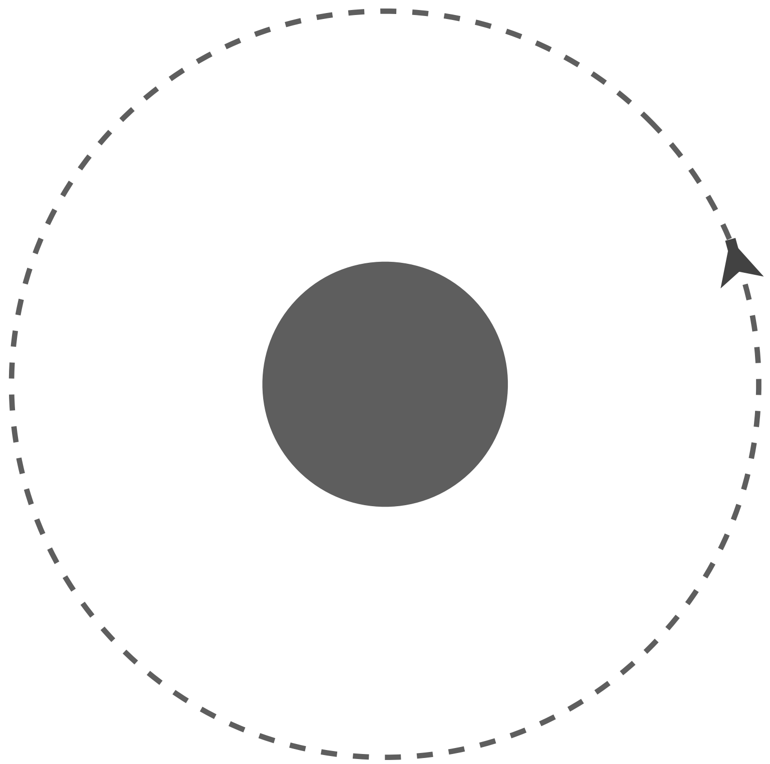
$$\vec{B} = 0$$

Energy stored only inside the solenoid

Non-trivial gauge configuration far away carries no energy

Non-trivial gauge configurations

The Aharonov-Bohm Effect



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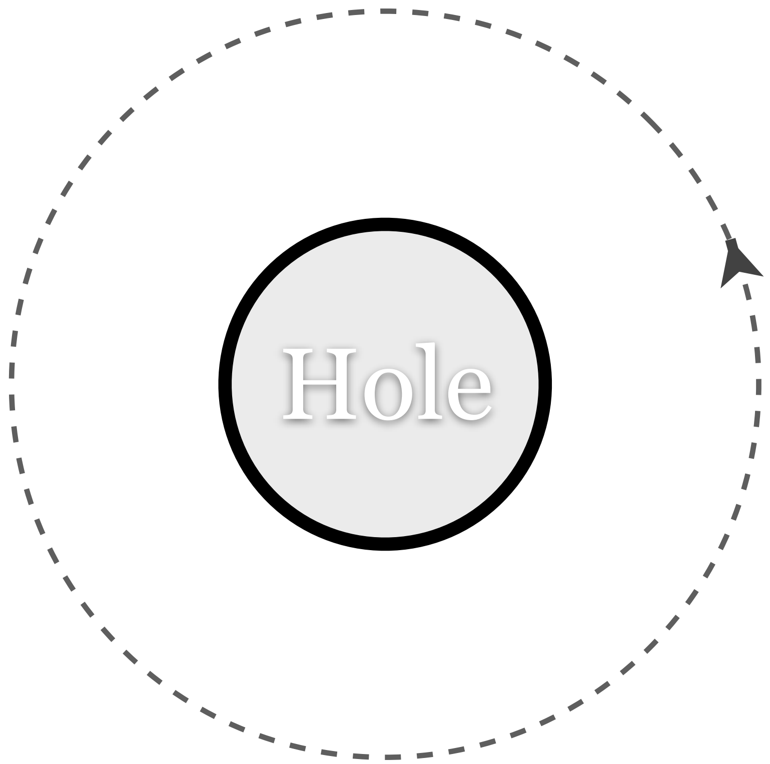

Taking an electron around the solenoid

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

while

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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

- Particle Mass $\sim \dfrac{M_{\text{Planck}}^2 e^{-S/2}}{f_a}$

String Axion mass and the QCD axion

$$\text{Particle Mass} \sim \frac{M_{\text{Planck}}^2 e^{-S/2}}{f_a}$$

Requirements on string theory for QCD axion
to solve the strong CP problem

$\theta_{QCD} < 10^{-10}$

String corrections < $10^{-10} \times$ QCD

$M_{Planck}{}^4 \ e^{-S} < 10^{-10} \times m_\pi{}^2 f_\pi{}^2$

$S \gtrsim 200$ $S \sim 2\pi / \alpha$

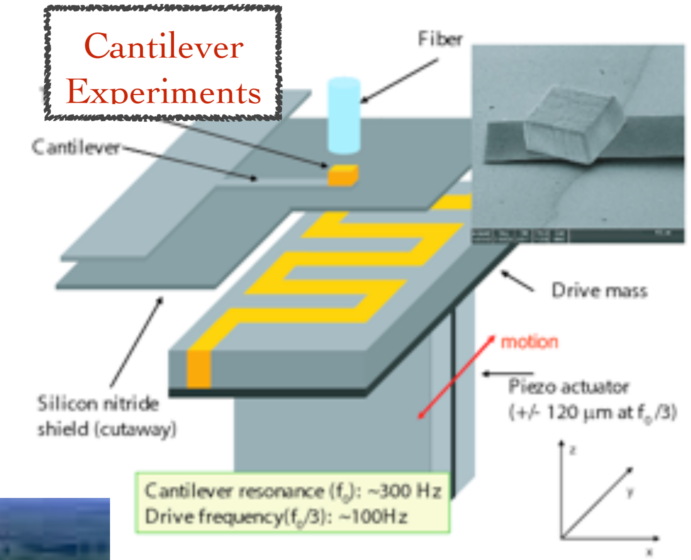
The QCD axion should not be special

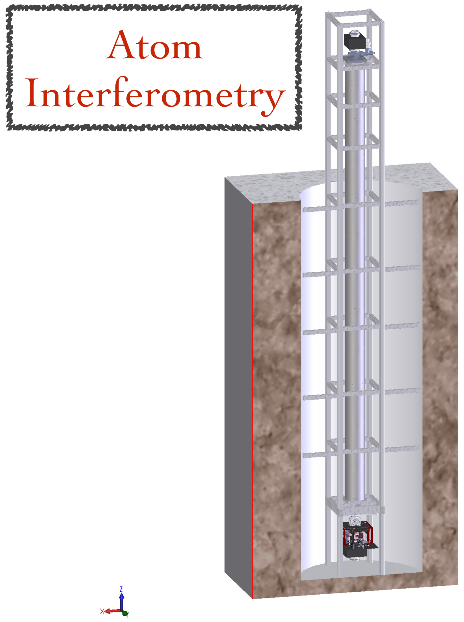
There could be **many** light axions

The Precision Frontier

- Axion Dark Matter Detection
- Axion Force Detection

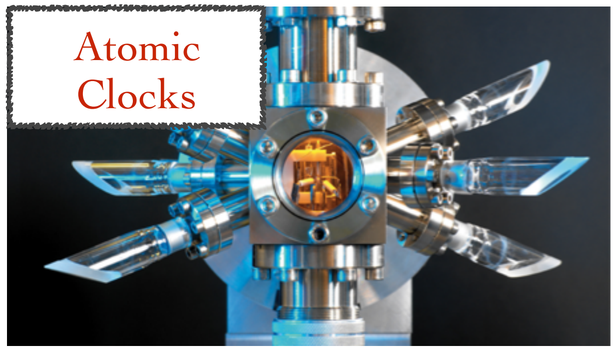
- Short Distance Tests of Gravity
- Extra Dimensions





- Equivalence principle at 15 decimals
- Gravitational Wave detection at low frequencies
- EDM searches
- Tests of Atom Neutrality at 30 decimals

- Setting the Time Standard
- Variation of Fundamental Constants
- Dilaton Dark Matter Detection



Outline

- Theoretical Motivation for Light Bosons

- **Black Hole Superradiance**

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

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

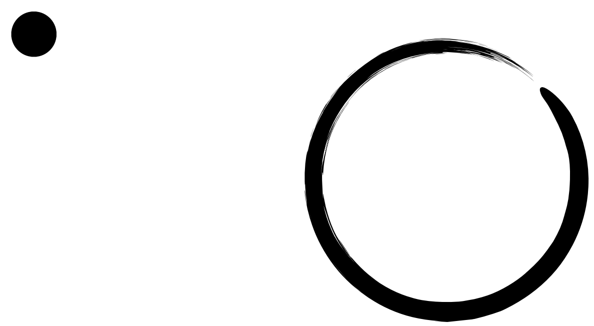
Black Holes as Nature's Detectors

(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

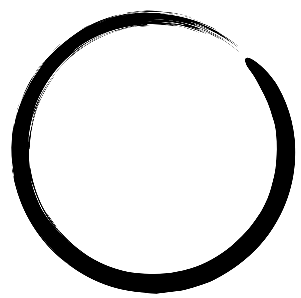
Focus on stellar black holes

Super-Radiance Cartoon



Super-radiant scattering of a massive object

Super-Radiance Cartoon



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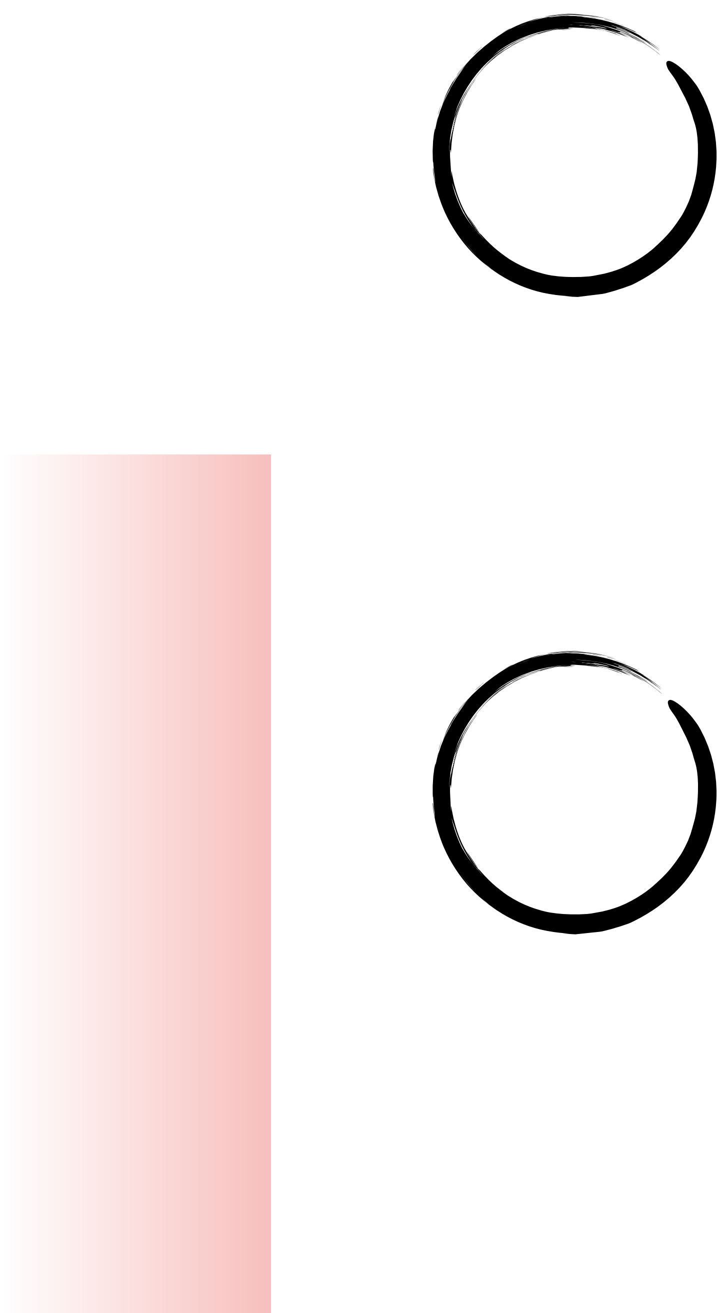


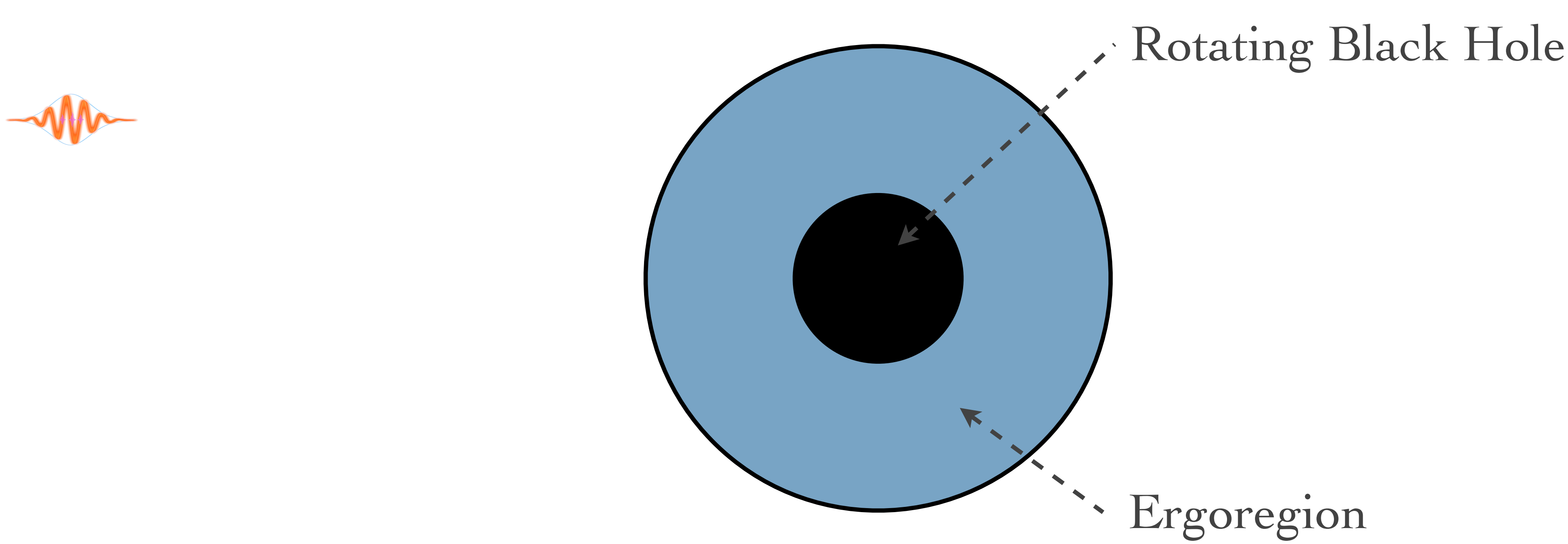
Super-radiant scattering of a wave

Super-Radiance Cartoon

Super-radiant scattering of a wave

Black Hole Superradiance

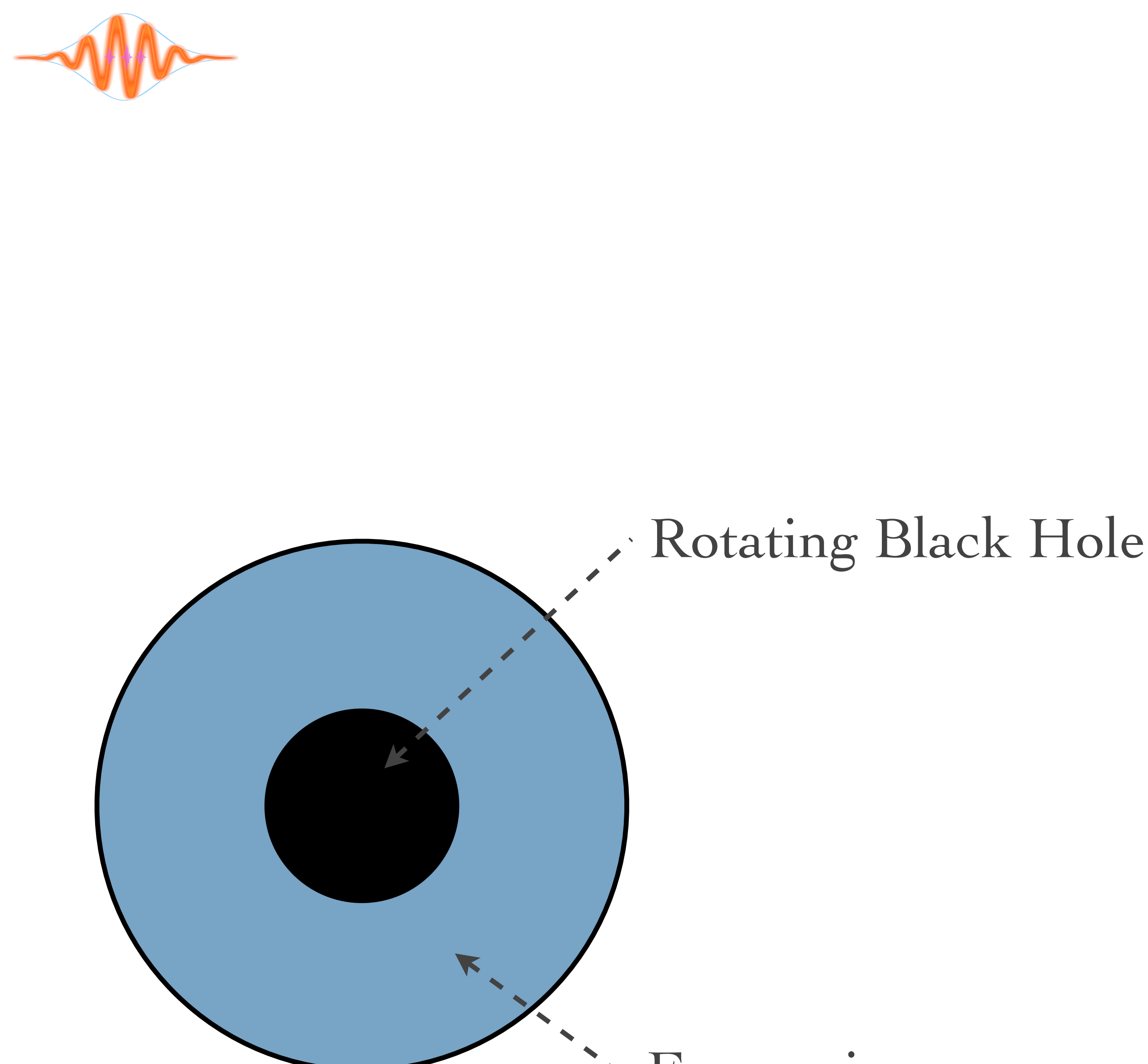
Penrose Process



Ergoregion: Region where even light has to be rotating

Black Hole Superradiance

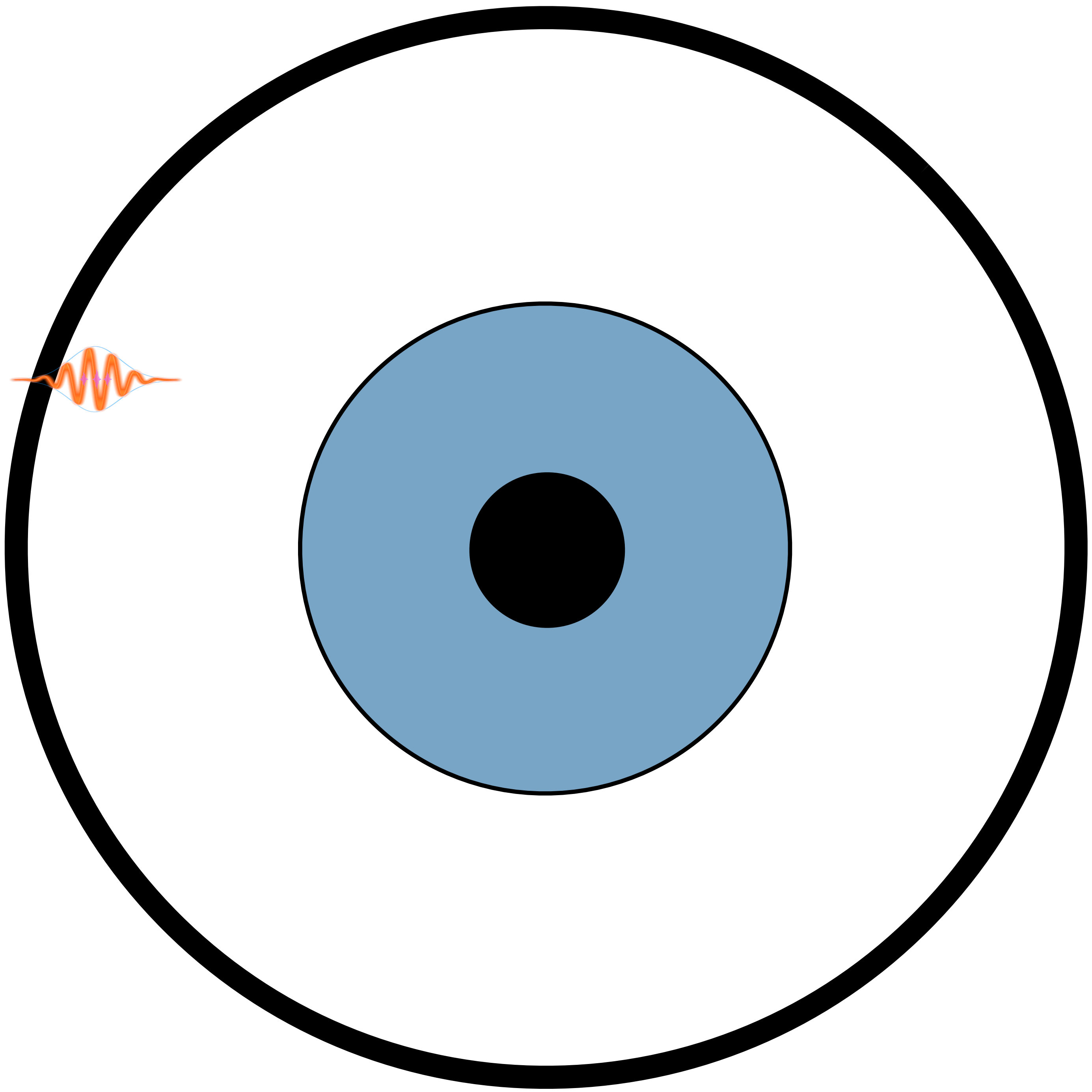
Penrose Process



Extracts angular momentum and mass from a spinning black hole

Black Hole Bomb

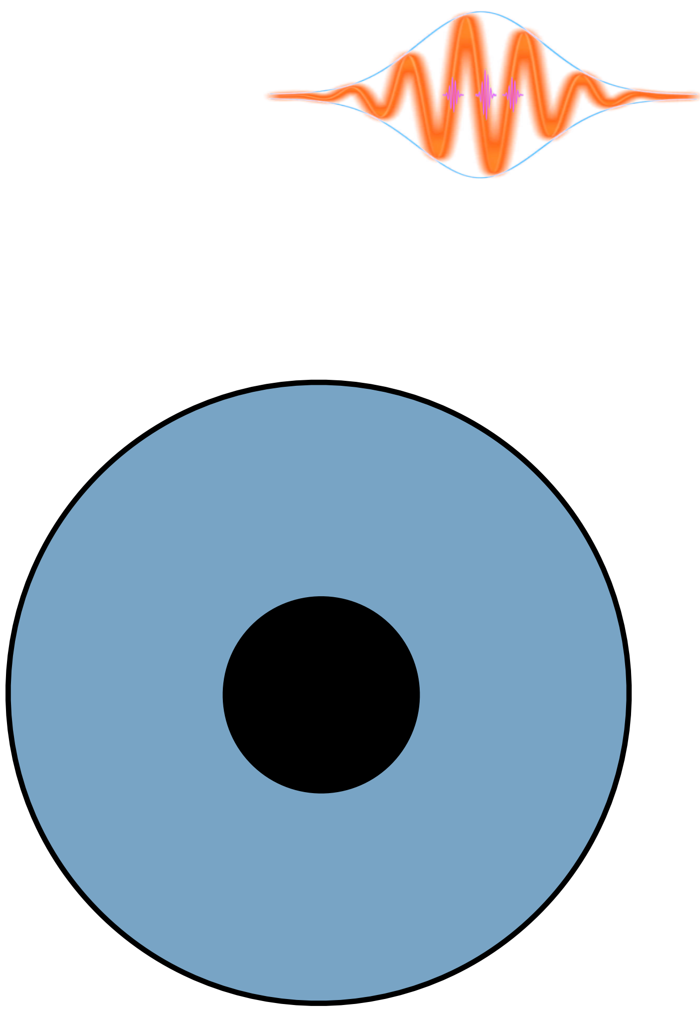
Press & Teukolsky 1972



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

Black Hole Bomb

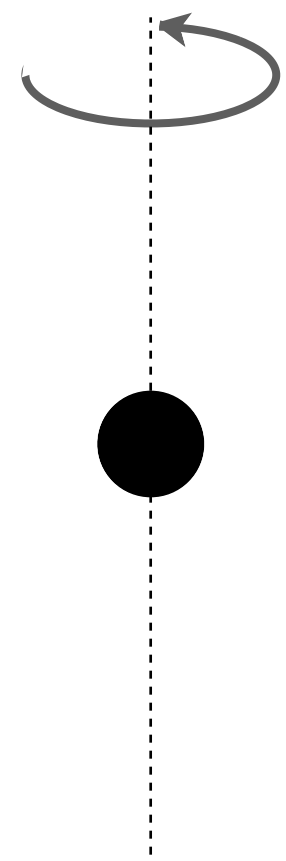
Press & Teukolsky 1972



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

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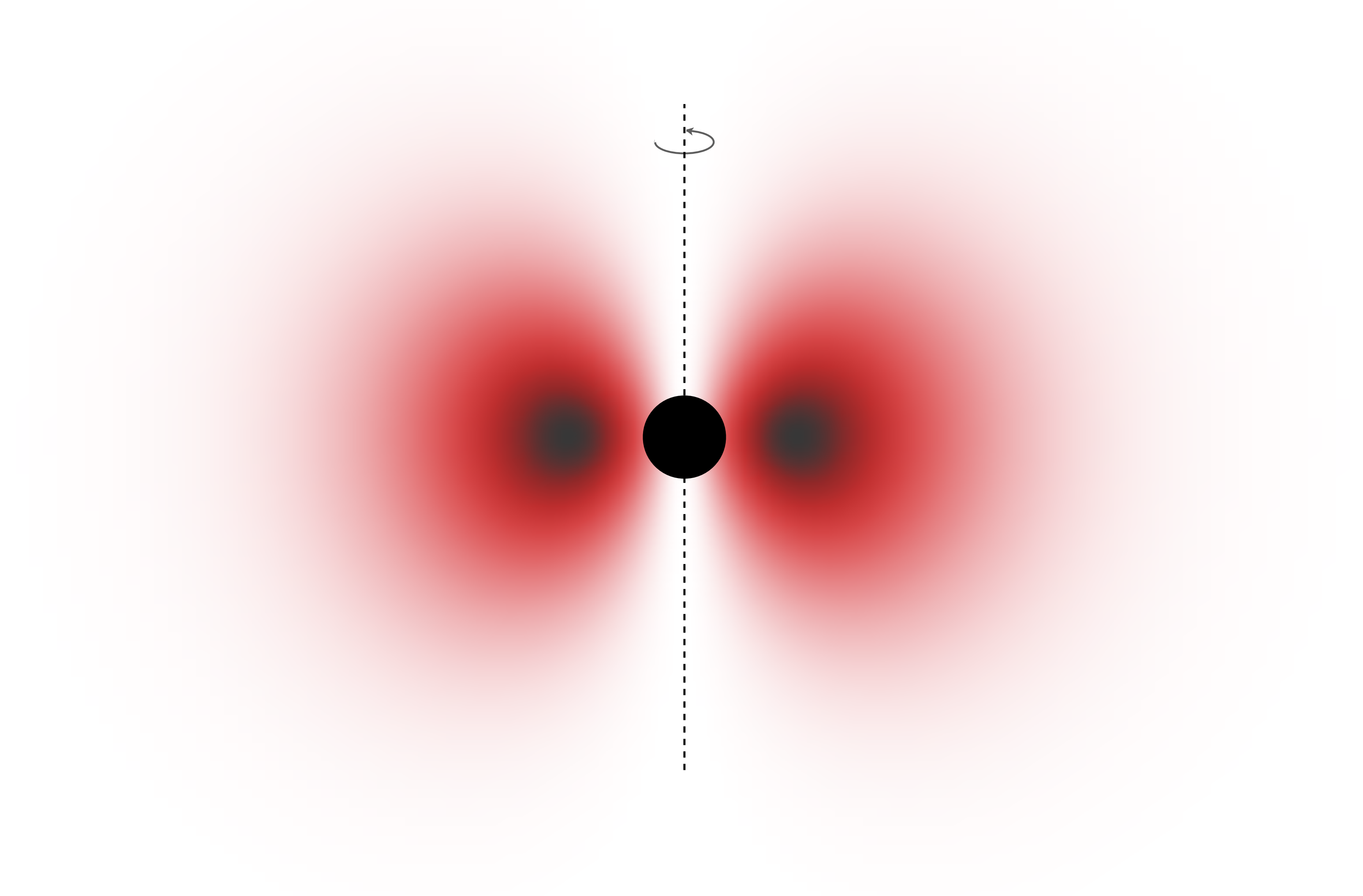
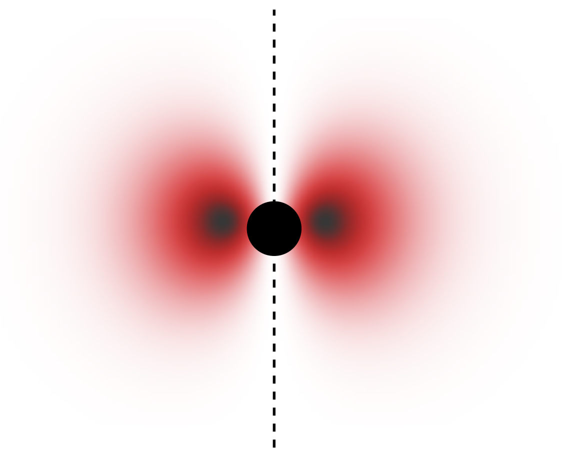


Particle Compton Wavelength comparable to the size of the Black Hole

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

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

$$\omega_{\rm axion} < m\,\Omega_+$$

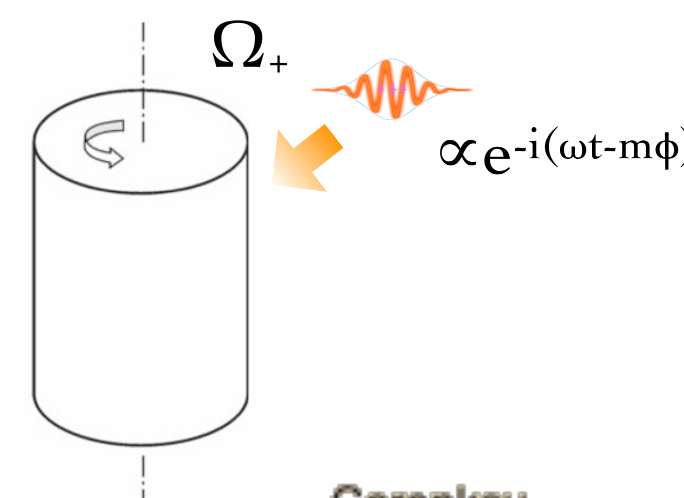
*Note: This is *a kinematic* condition

m : magnetic quantum number

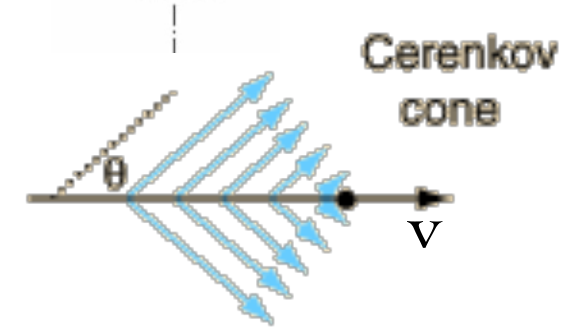
Ω_+ : angular velocity of the BH

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 $dA_{BH} > 0$

Superradiance Parametrics

Superradiance Rate

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

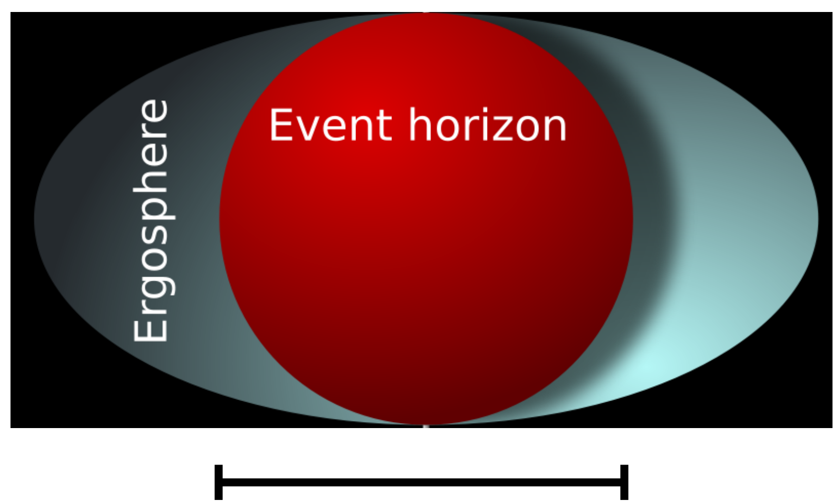
Can be as short as 100 sec

When $R_g\, \mu_a >> 1$,

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

When $R_g\, \mu_a << 1$

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



R_g between 1-100 km

QCD axion at high f_a matches stellar BH size:

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

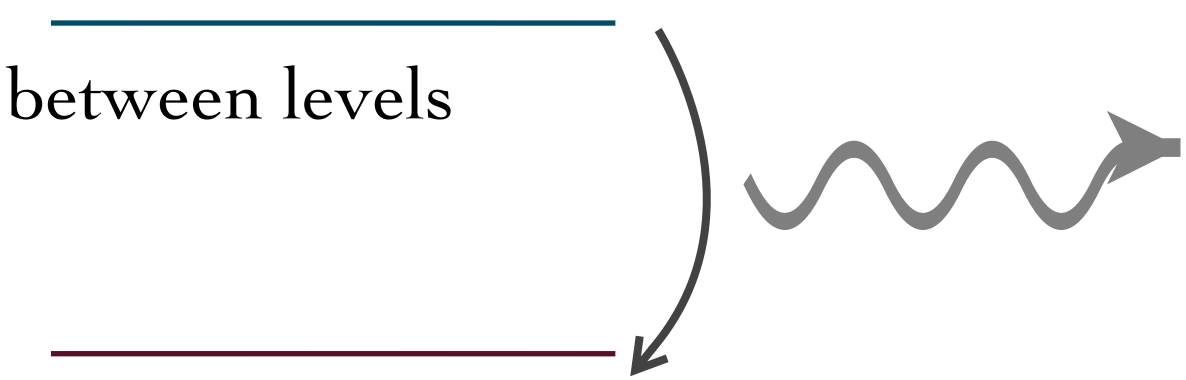
Evolution of Superradiance for an Axion

Superradiance instability, BH spin down

Evolution of Superradiance for an Axion

Superradiance instability, BH spin down

Gravity wave transitions of axions between levels

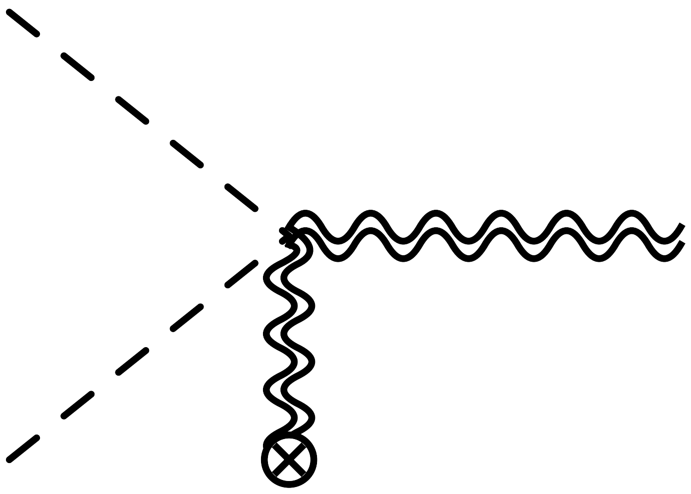


Evolution of Superradiance for an Axion

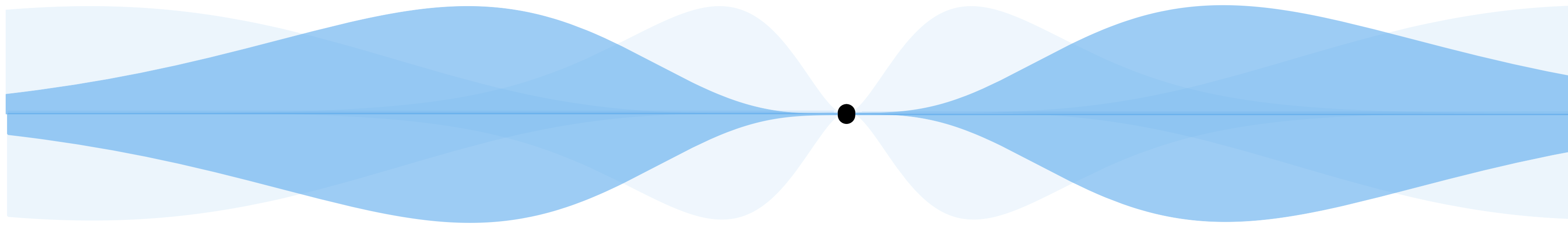
Superradiance instability, BH spin down

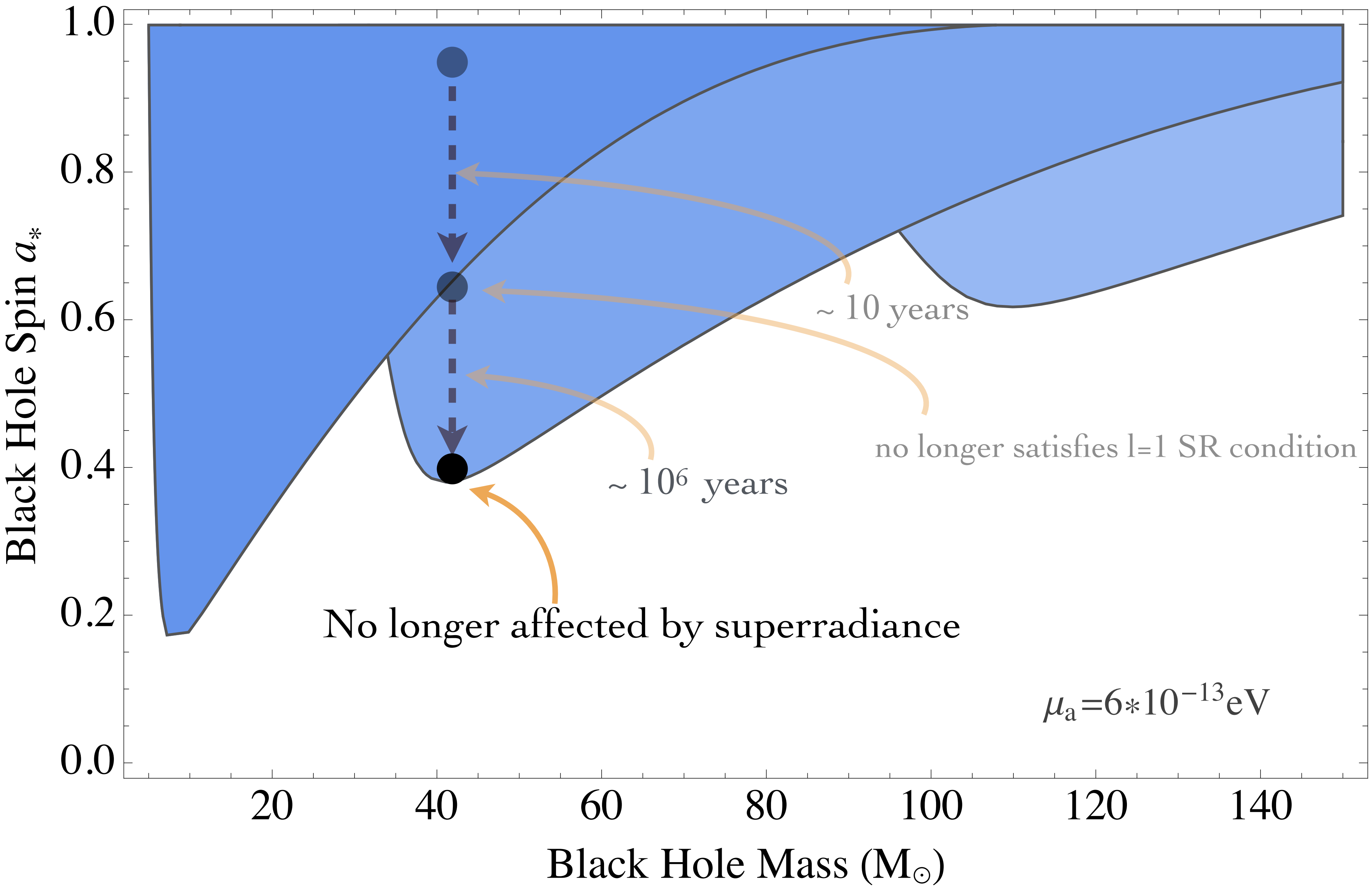
Gravity wave transitions of axions between levels

Gravity wave emission through axion annihilations

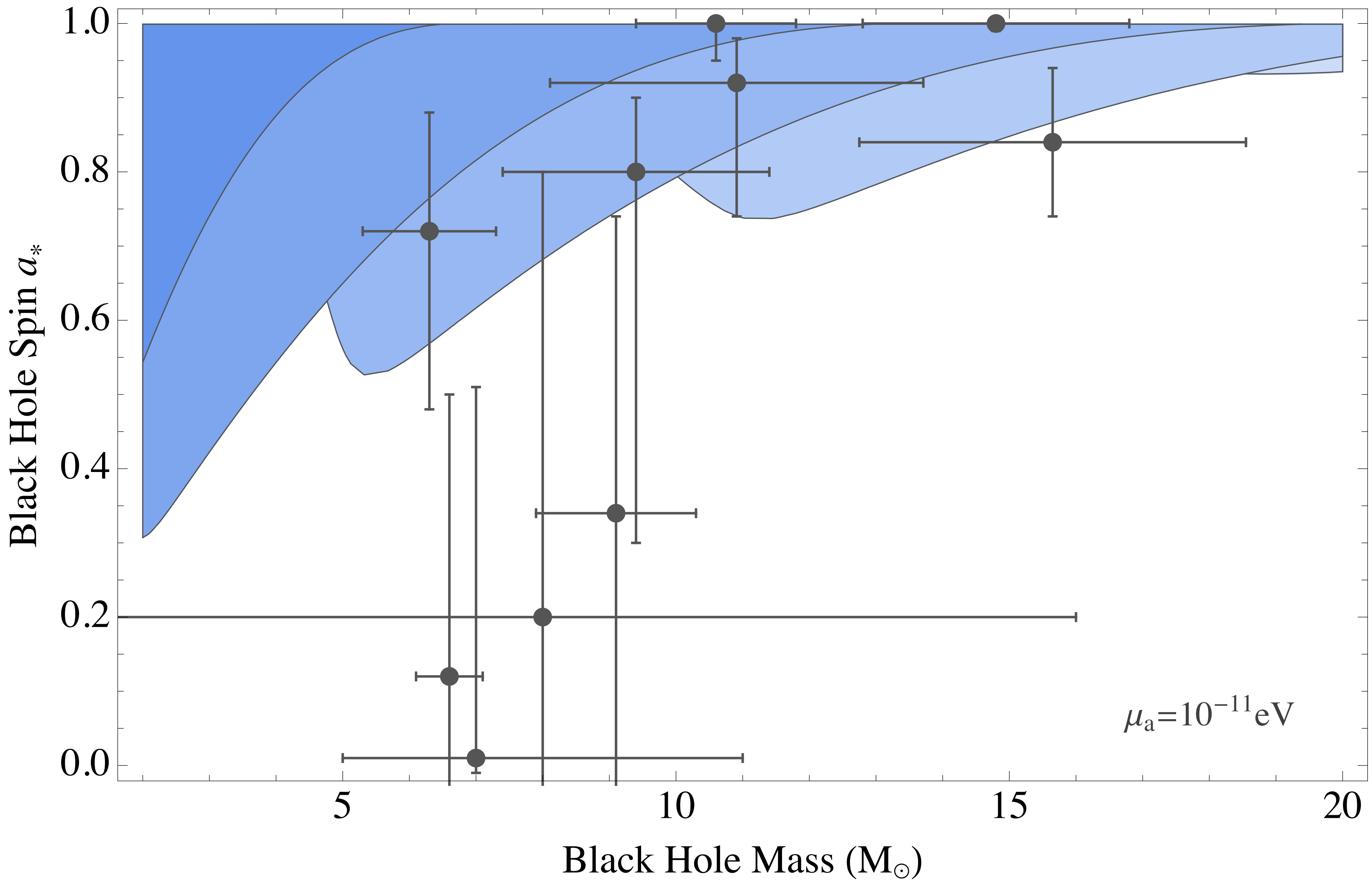


Superradiance: A stellar Black Hole History





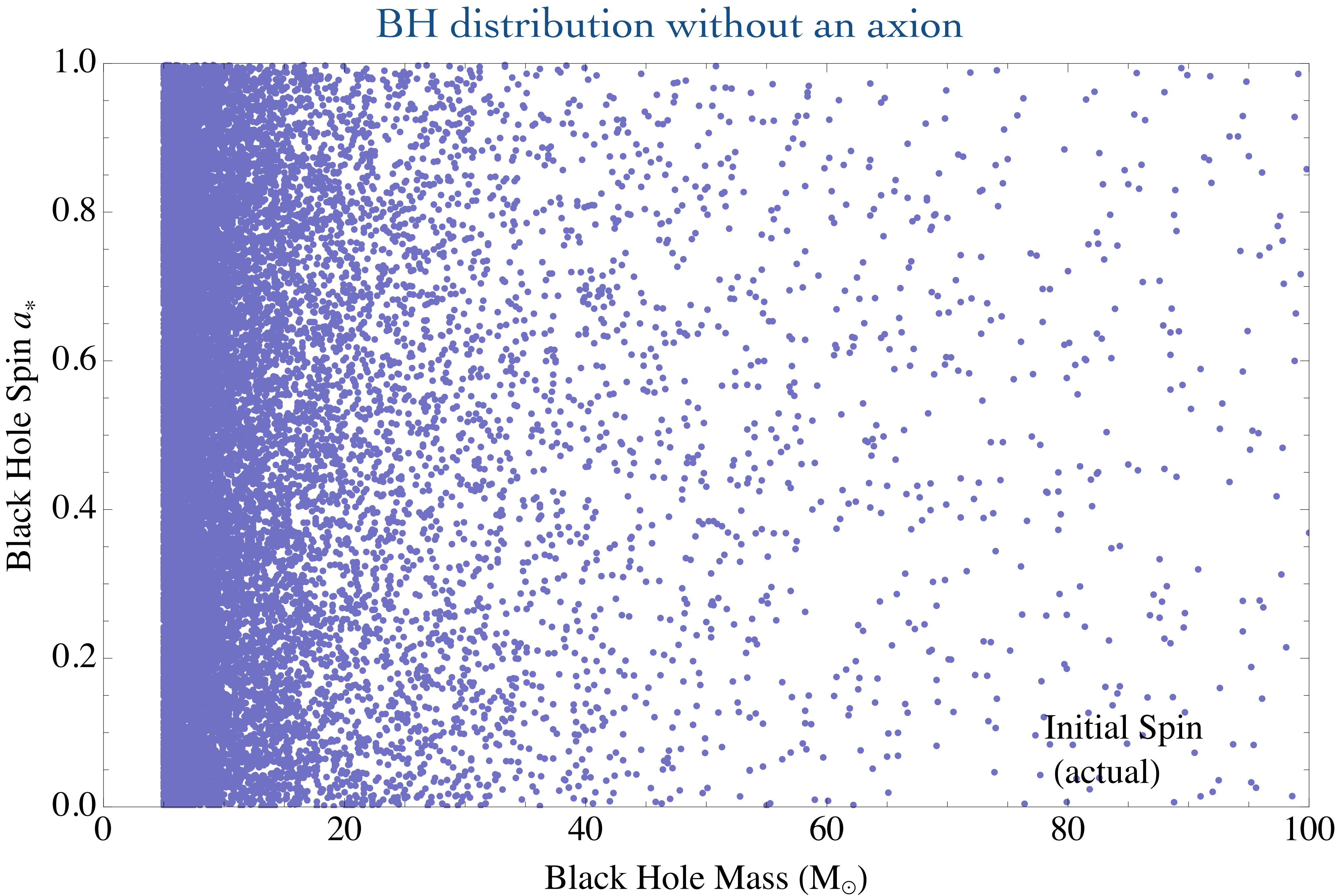
Spin-Down of Astrophysical Black Holes



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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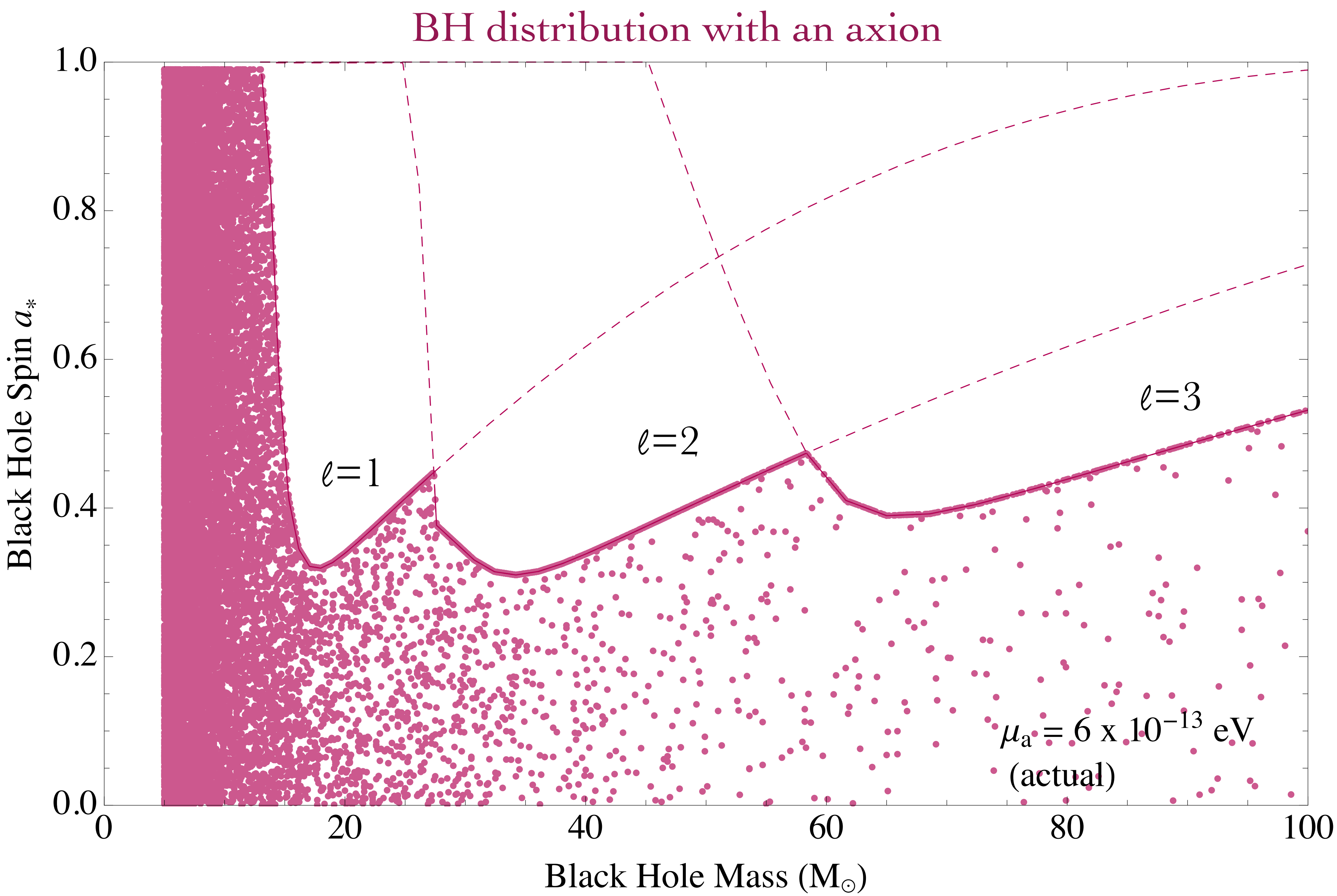
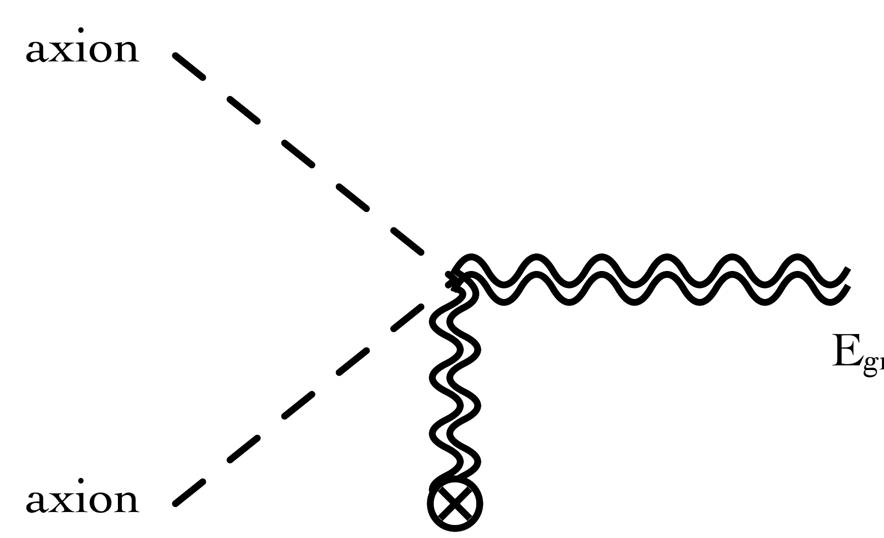


Direct Super-Radiance Signatures

GW annihilations



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

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

High frequency GWs

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

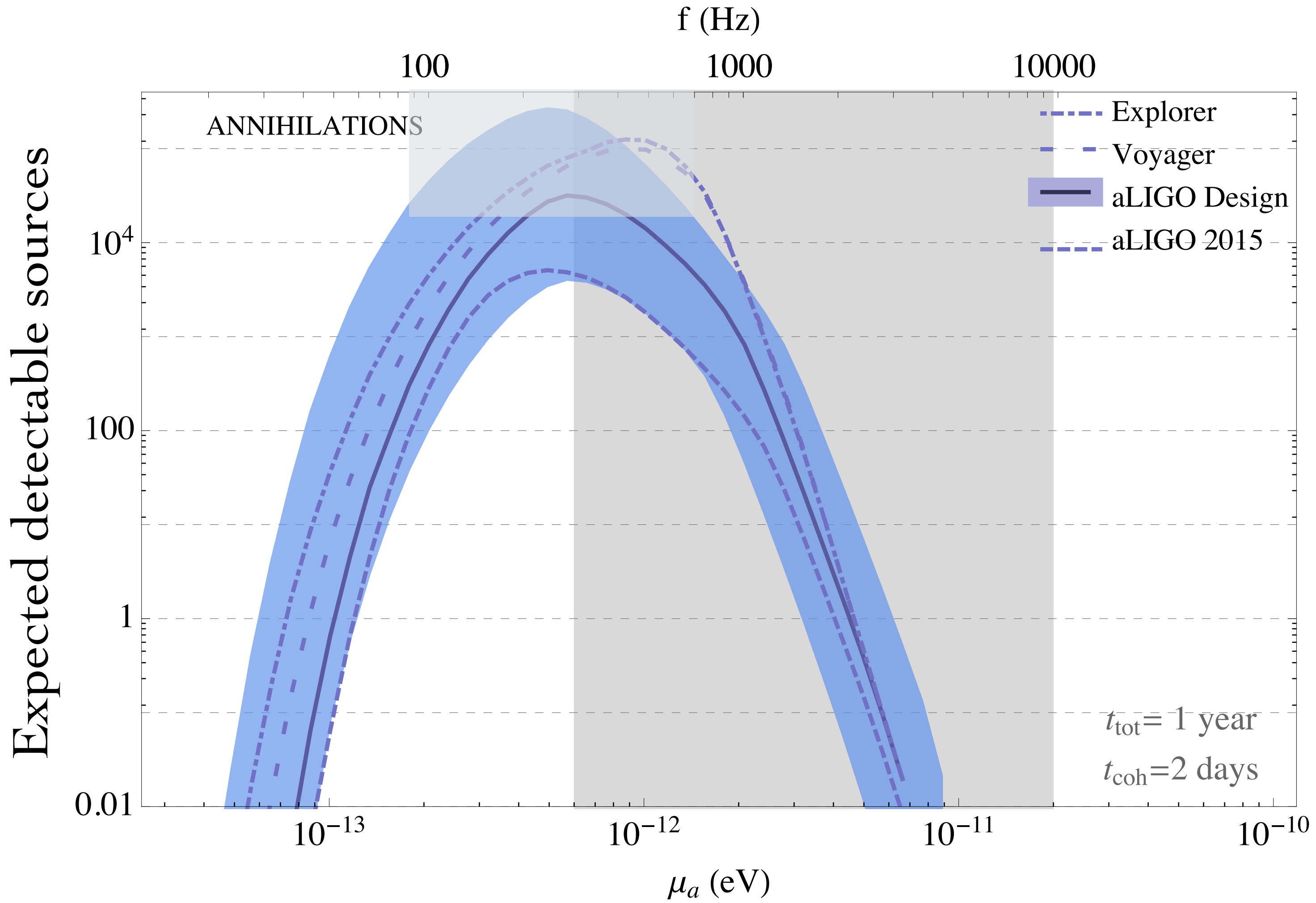
$$h_{\rm peak} \simeq 10^{-22} \left(\frac{1\,\mathrm{kpc}}{r}\right) \left(\frac{\alpha/\ell}{0.5}\right)^{\frac{p}{2}} \frac{\alpha^{-\frac{1}{2}}}{\ell} \left(\frac{M}{10 M_\odot}\right)$$

- Signal frequency drifts upwards with time

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

Expected Events from Annihilations

- Large uncertainties coming from tails of BH mass distribution



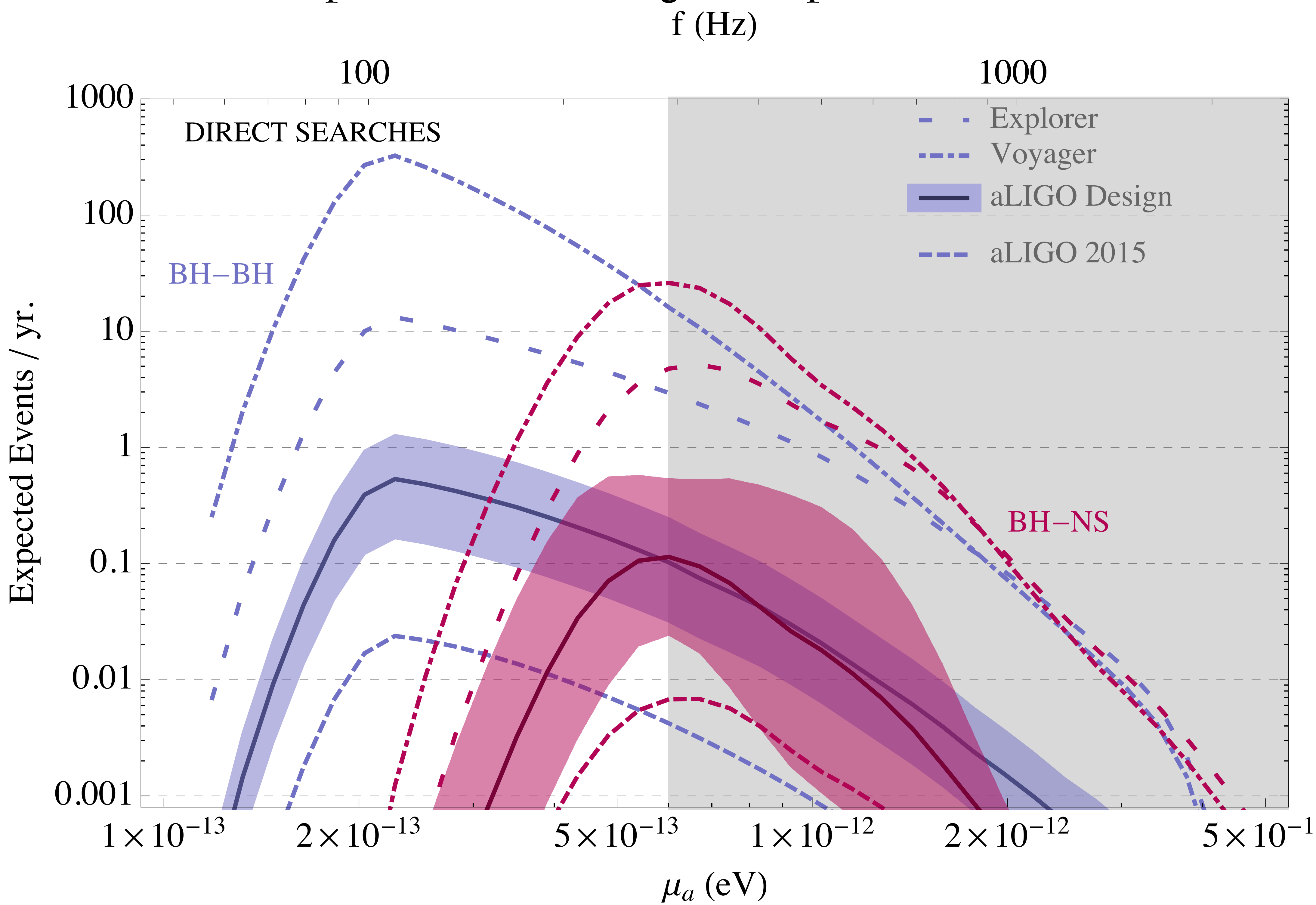
Pessimistic: flat spin distribution and 0.1 BH/century

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

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

Real-Time Superradiance

Black Holes produced from mergers are point sources candidates



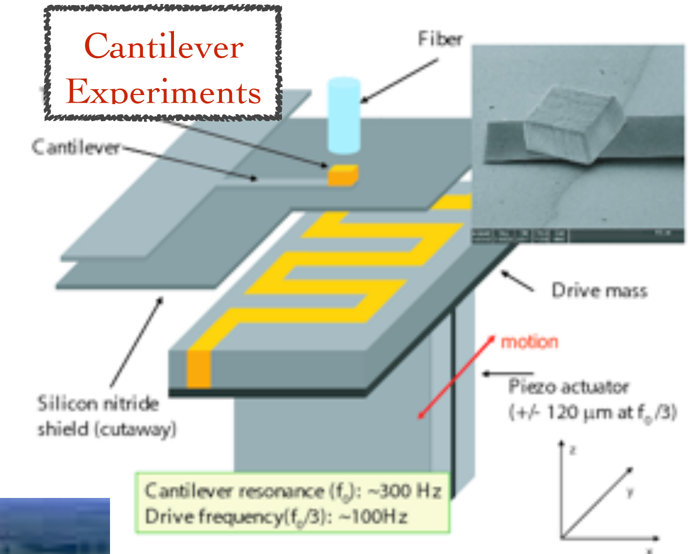
Superradiance Prospects

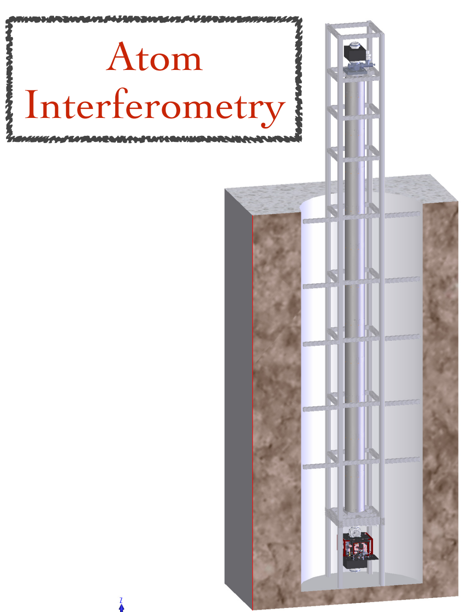
- Probes axions between 10^{-20} and 10^{-10} eV independent of DM abundance
- Spin-mass distribution measured from mergers may reveal the presence of an axion
- Blind searches at aLIGO for annihilations most promising for lighter axions
- Merger events allow to follow SR in real time

The Precision Frontier

- Axion Dark Matter Detection
- Axion Force Detection

- Short Distance Tests of Gravity
- Extra Dimensions





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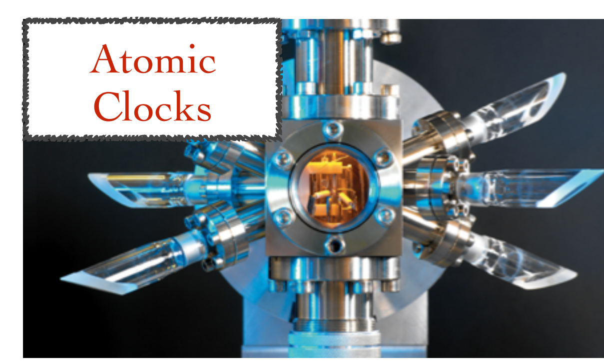

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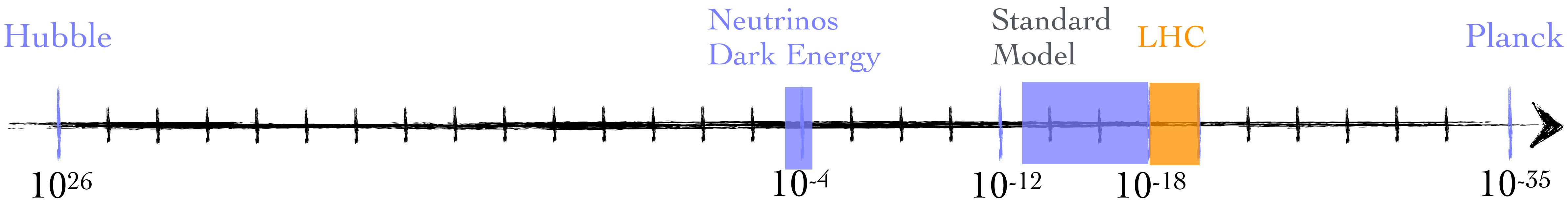

Scale in meters

There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy.