Title: Discovering the QCD Axion with Black Holes and Gravitational Waves

Date: Oct 28, 2014 01:00 PM

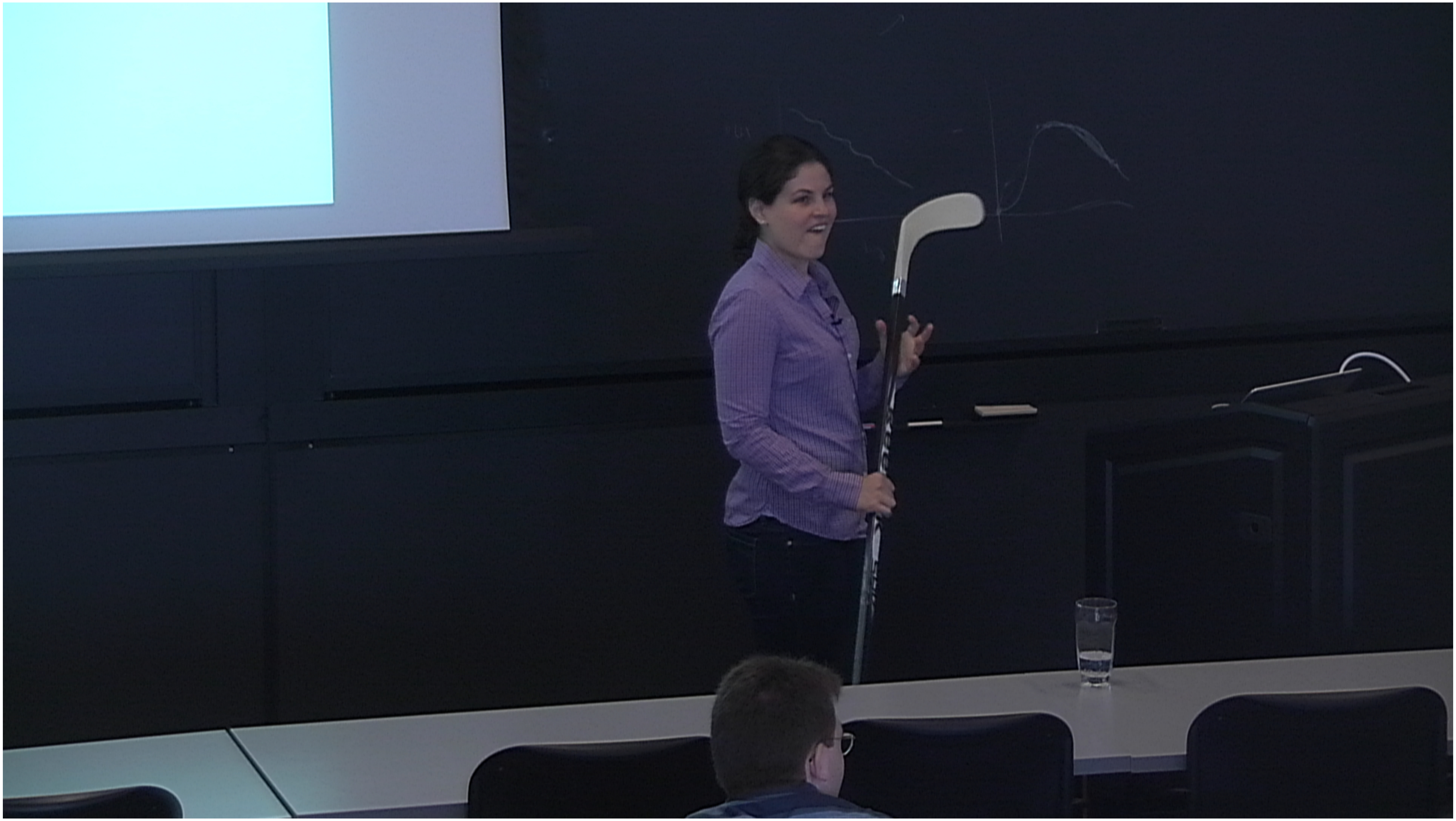
URL: http://pirsa.org/14100049

Abstract: In the next few years, Advanced LIGO will be the first experiment to detect gravitational waves. Through superradiance of stellar black holes, it may also be the first experiment to discover the QCD axion with decay constant around or above the GUT scale. When an axion's Compton wavelength is comparable to the size of a black hole, the axion binds to the black hole, forming a "gravitational atom". Due to superradiance, the number of axions occupying the bound levels grows exponentially, extracting energy and angular momentum from the black hole. I will discuss the promising gravitational wave signals from axions transitioning between levels of the gravitational atom and axions annihilating to gravitons. Events for axions in the range 10^âˆ’13 to 10^âˆ’10 eV can be visible at aLIGO. The signals produced are long-lasting, monochromatic, and can be distinguished from ordinary astrophysical sources. These signatures are also promising for lighter axions at future, lower-frequency, GW observatories. I will also present our updated exclusion on the QCD axion mass range of 6*10^âˆ’13 eV < ma < 1.5*10^âˆ’11 eV imposed by black hole spin measurements.

Discovering the QCD Axion with Black Holes and Gravitational Waves

Masha Baryakhtar
Stanford University

with Xinlu Huang and Asimina Arvanitaki
[arxiv:1410.xxxx]



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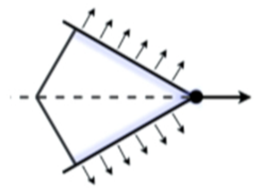
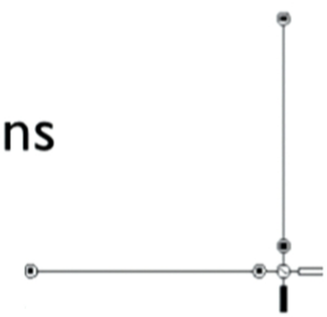
Detecting the QCD Axion with Black Holes and Gravitational Waves

- Introduction
- Superradiance



- Spinning Black Holes

- Gravitational Wave Detection of Axions



Introduction

- The QCD axion is one of the best motivated BSM particles
- Solves the strong-CP problem by making the QCD θ angle a dynamical field,

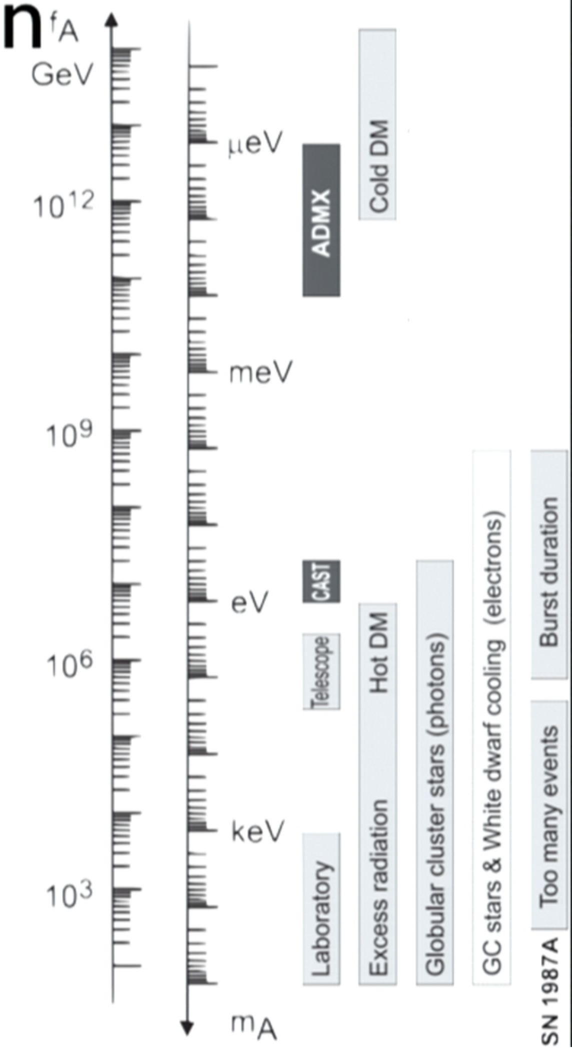
$$L_{\rm SM} \supset \frac{\alpha_s}{8\pi}\frac{a}{f_a} G^a \tilde{G}^a$$

- Pseudo-goldstone boson with mass fixed by the decay constant f_a,

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

Introduction

- Some of the best current limits on axions come from astrophysics
- Current limit: $f_a < 10^9$ GeV from astrophysics and $f_a \sim 10^{11}$ GeV from ADMX (assuming coupling to photons and DM density)



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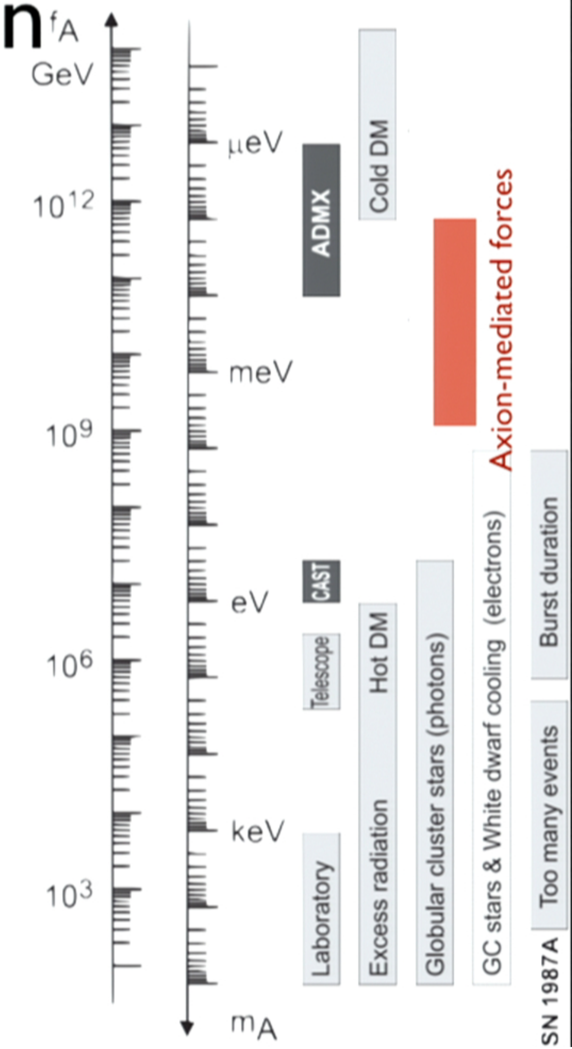
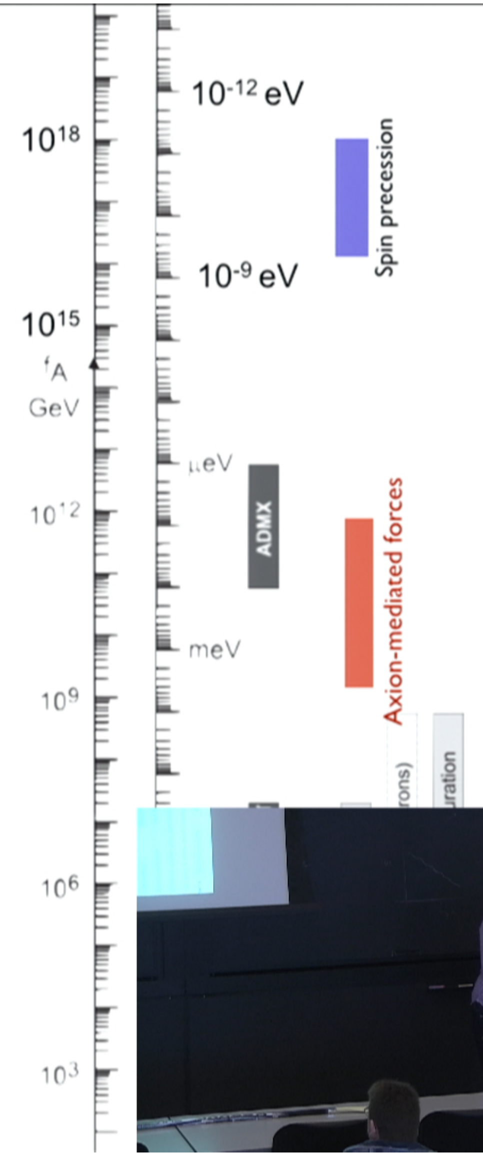


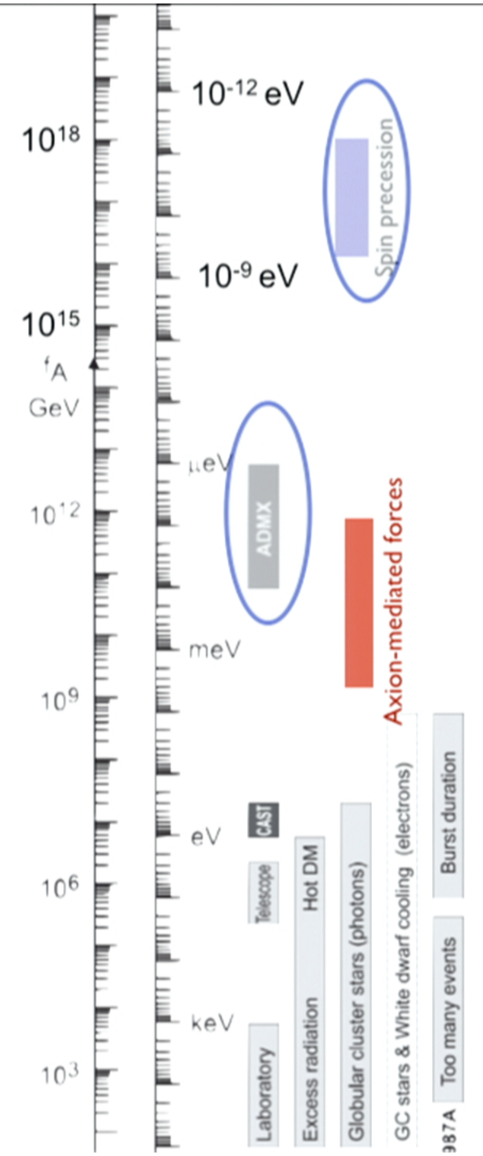
Introduction

- Parameter space is huge and everything should be explored
- Light axions are especially difficult: the coupling is very weak, hard to produce and detect in the lab



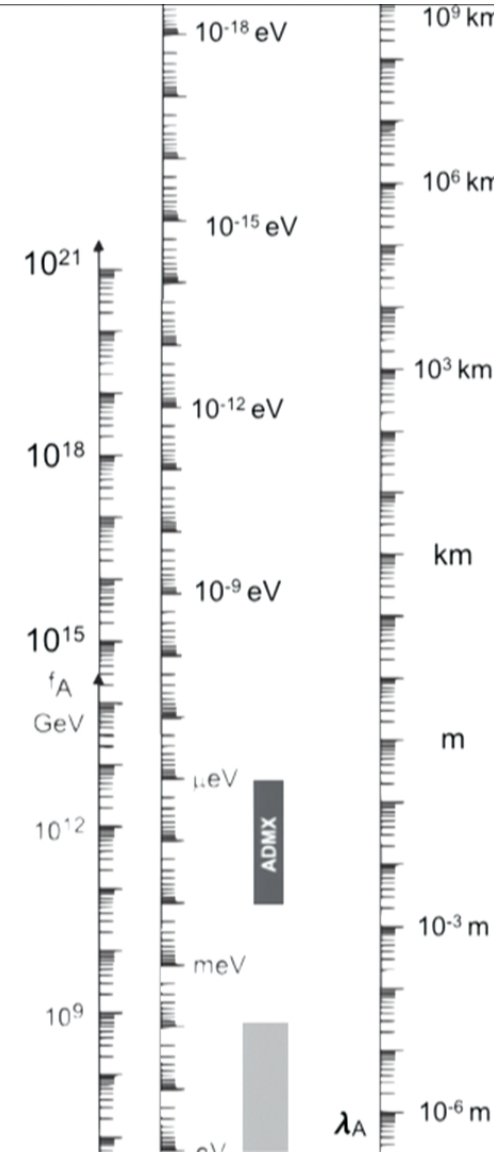
Introduction

- Parameter space is huge and everything should be explored
- Light axions are especially difficult: the coupling is very weak, hard to produce and detect in the lab
- Can rely on 'pre-made' axions, but what if they're not 100% of the dark matter?



Introduction

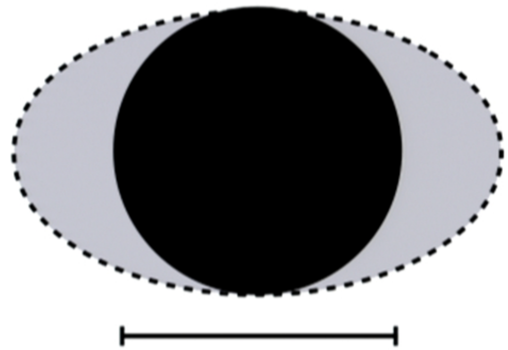
- Parameter space is huge and everything should be explored
- Hard to look at small masses: the coupling is very weak and hard to produce and detect in the lab
- For small masses the physical size of the axion can be too big to fit in a laboratory



Introduction

Black holes are nature's detectors

$(15\ \mathrm{km}) \times (M / 10\ M_\odot)$



$(1.5\times10^{7}\ \mathrm{km}) \times (M / 10^{7}\ M_\odot)$

Stellar black holes:
$\sim10^{8}$-10^{9} in our galaxy
Sensitive to axion masses 10^{-13}-10^{-11} eV

Supermassive black holes:
Found at the centers of galaxies
Sensitive to axion masses 10^{-19}-10^{-16} eV

Superradiance

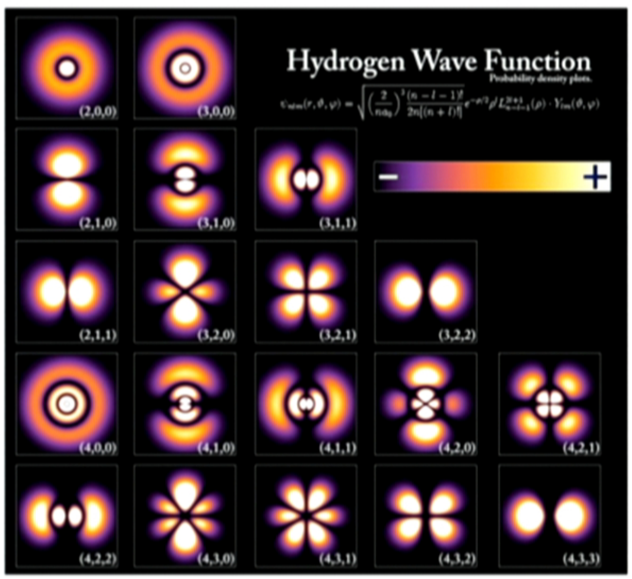
The gravitational hydrogen atom

'Fine structure' constant

$$\alpha = G_{\rm N} M_{\rm BH} \mu_a = \; r_g \, \mu_a$$

Energy levels

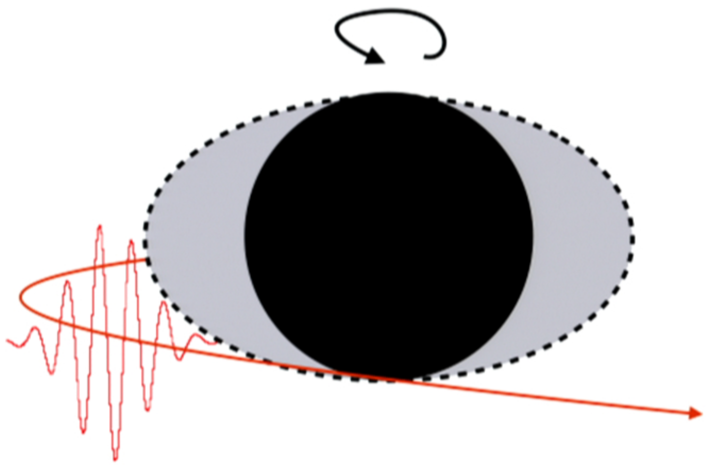
$$\omega = \mu_a \left(1 - \frac{\alpha^2}{2n^2}\right)$$



Through the process of superradiance some of these orbitals will become populated with an exponentially large number of axions

Superradiance

Particle passing through the ergo-region can extract angular momentum and energy from the black hole

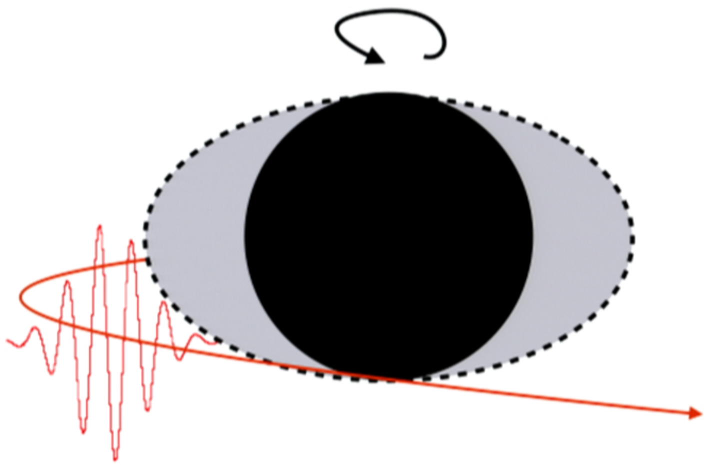


Energy and angular momentum of the BH are extracted through Penrose process

Superradiance

Particle passing through the ergo-region can extract angular momentum and energy from the black hole

Particles trapped in orbit around the BH can repeat this process continuously



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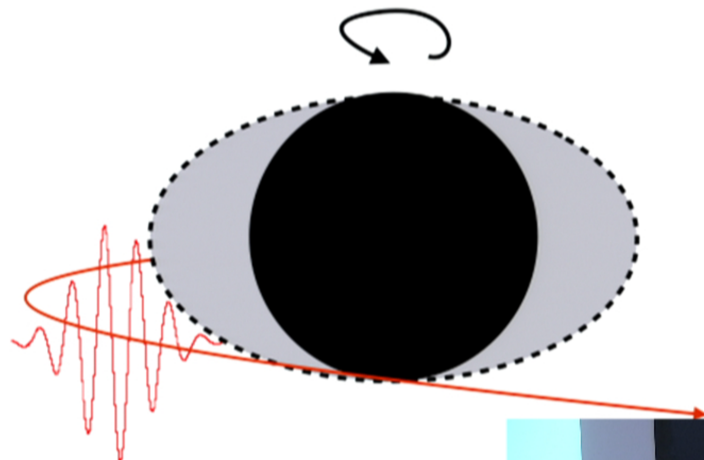


Particles trapped in orbit around the BH can repeat this process continuously

Energy and angular momentum of the BH are extracted throug

Superradiance

Superradiance condition

$$\frac{\omega}{m} < \omega^{+}$$

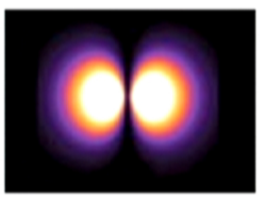
Angular velocity of particle is slower than the black hole angular velocity

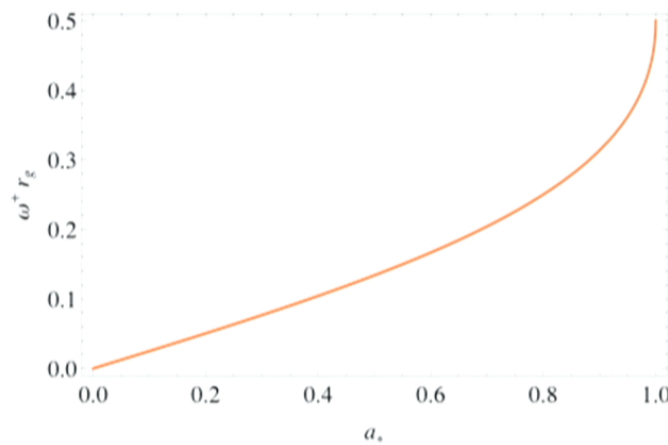
Particle orbits that satisfy the SR condition are coherently amplified

m = magnetic quantum number

$$r_g \equiv G_N M$$

$$\alpha/\ell \leq 1/2$$





Superradiance

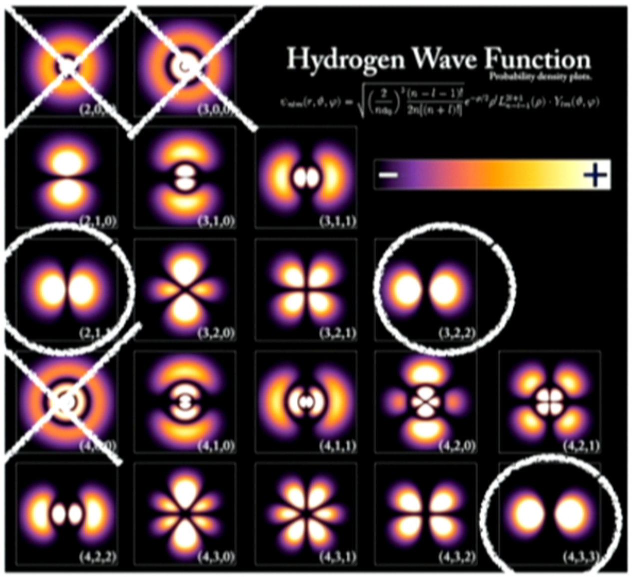
The gravitational Hydrogen Atom

'Fine structure' constant

$$\alpha = G_N M_{BH} \mu_a = r_g \mu_a$$

Energy levels

$$\omega = \mu_a \left(1 - \frac{\alpha^2}{2n^2}\right) - i\Gamma_{sr}$$



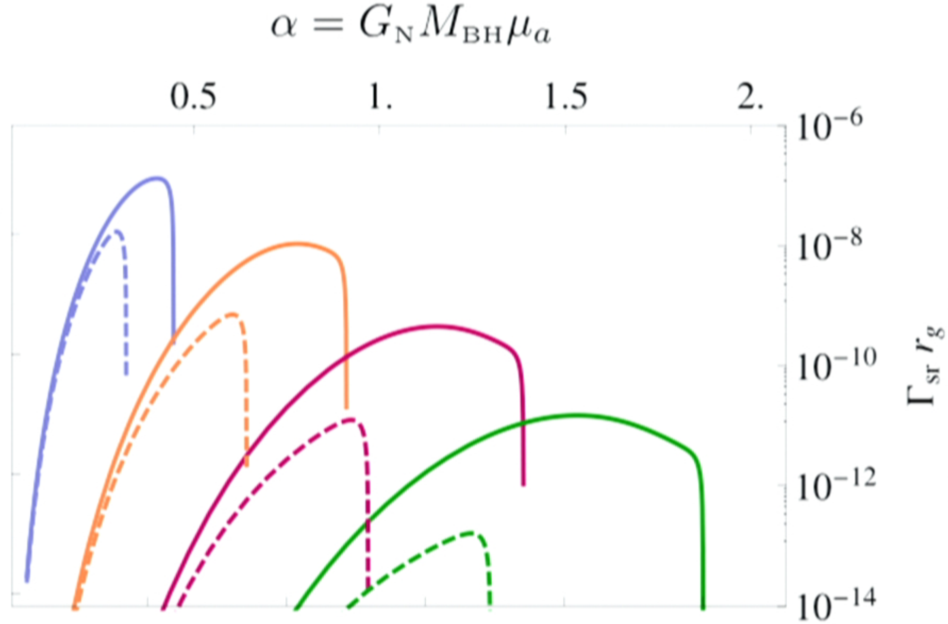
For bosons that satisfy SR condition, occupation number grows exponentially with SR rate

$$\left.\frac{dN}{dt}\right|_{sr} = \Gamma_{sr} N.$$

$$\Gamma_{sr}^{n\ell m}(a_*, \alpha, \mu_a) = \mathcal{O}(10^{-7}\text{–}10^{-14})\, \mu_a$$

Superradiance

- Strong dependence on ℓ
- Steep function of coupling α
- Depends on BH spin a_*
- One superradiance time lasts between 100 s and 100 years



$r_g \equiv G_N M$

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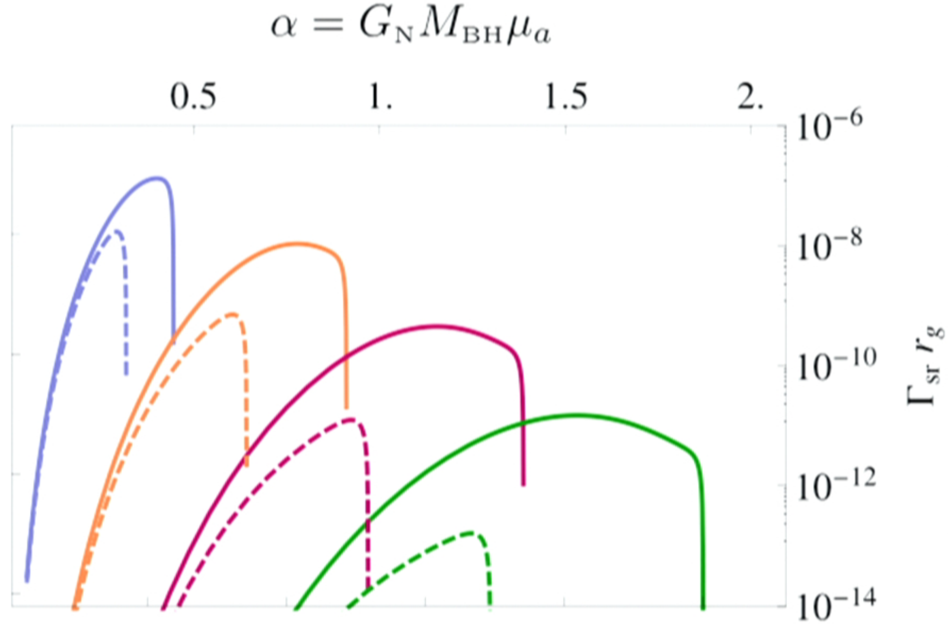
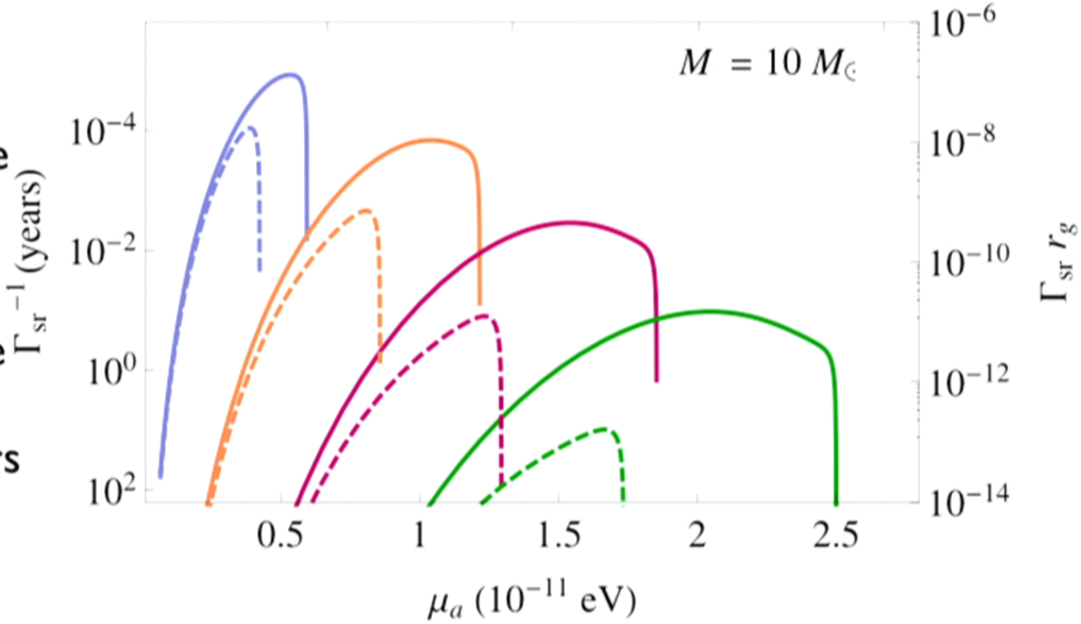


Small α: less wavefunction overlap with BH: power law suppression

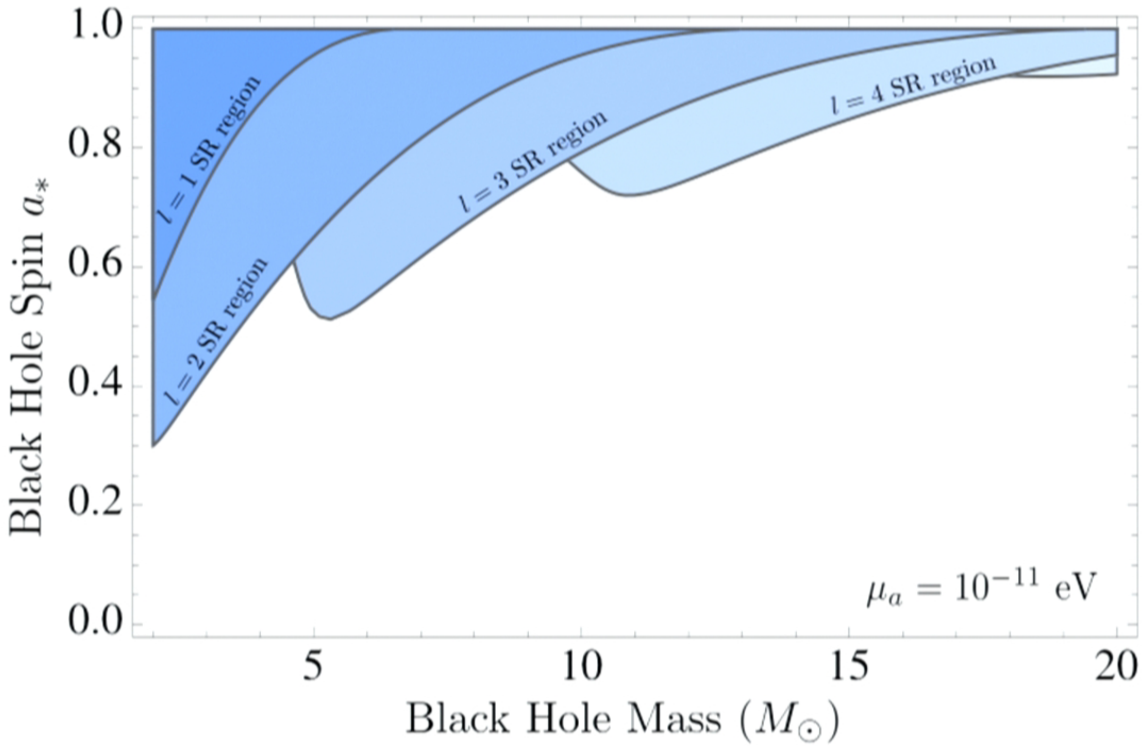
Superradiance

- Steep function of α
- Depends on BH spin a_*
- Strong dependence on ℓ
- One superradiance time lasts between 100 s and 100 years



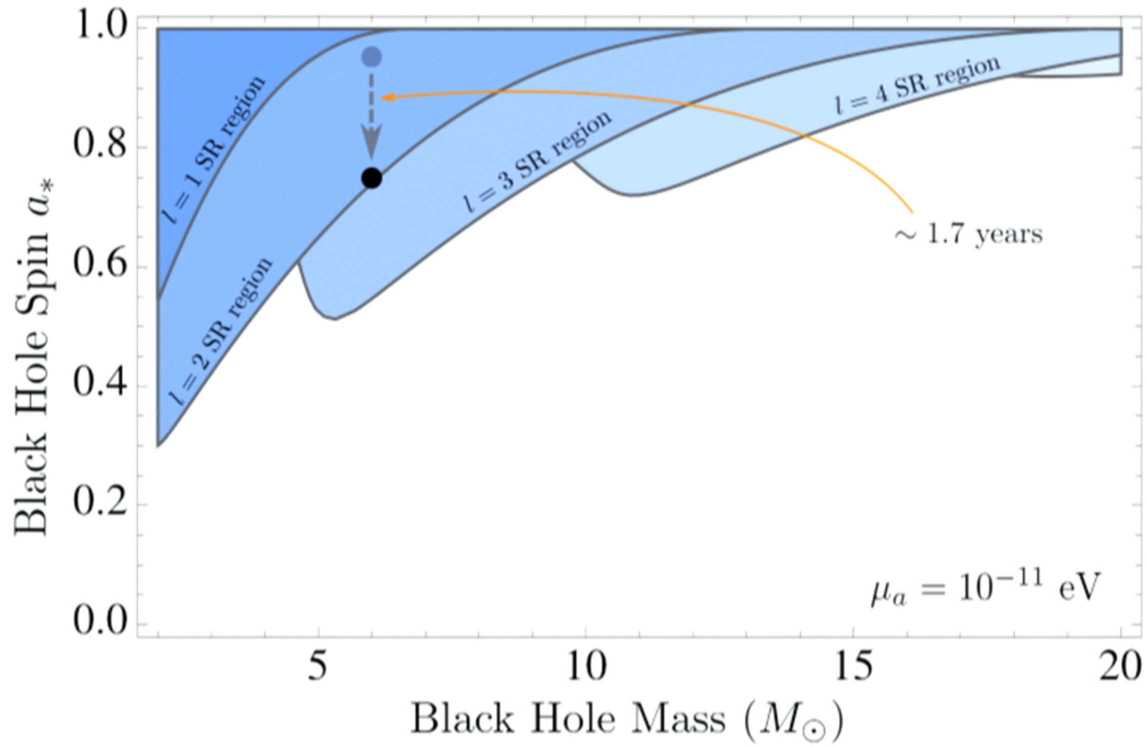
Superradiance

Fixing axion mass, SR affects a range of BH masses and lifetimes



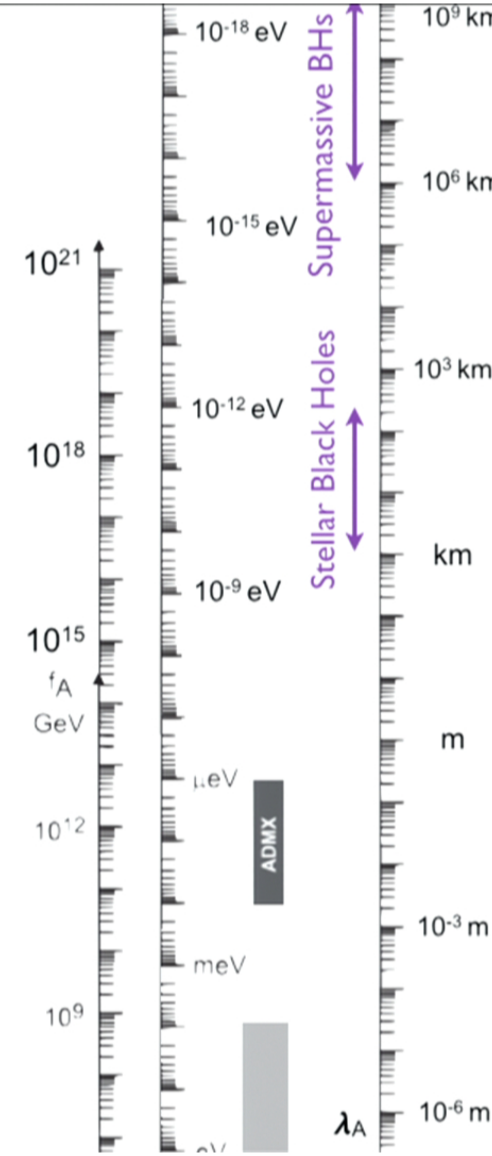
Superradiance

After ~200 SR times, axion cloud grows to macroscopic size ($N=10^{77}$) and the BH quickly loses a fraction of its spin.



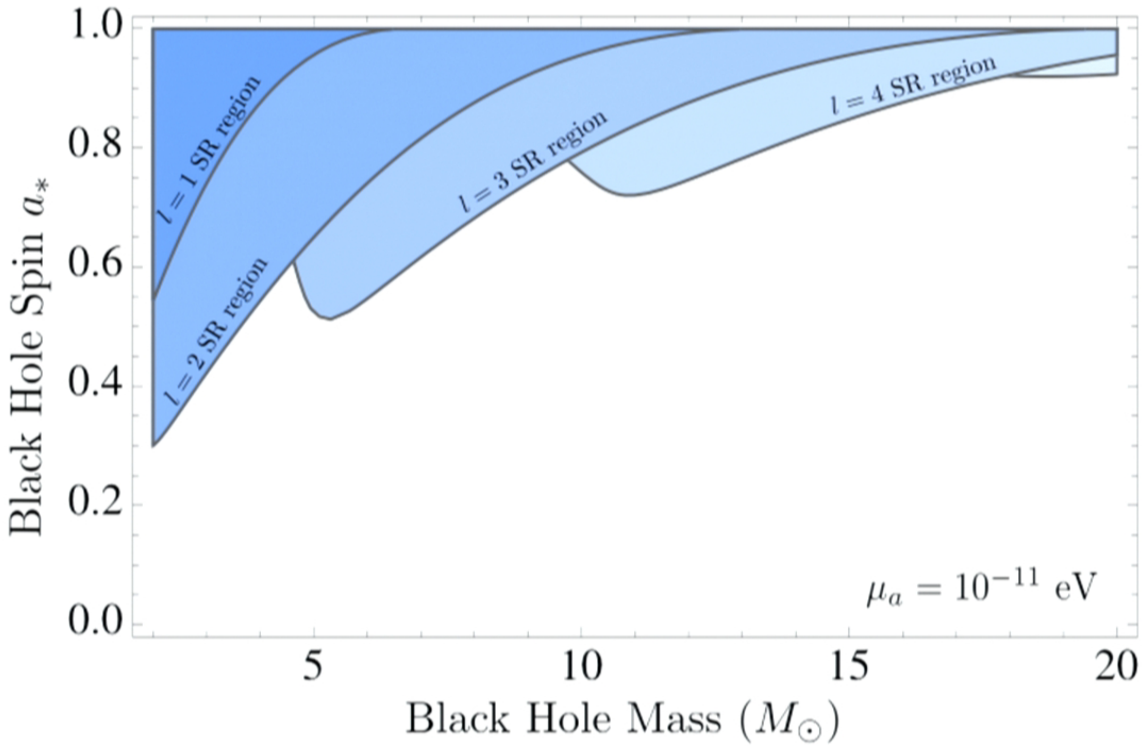
Superradiance

- Black holes are just the right size to explore GUT- to Planck-scale axions
- Does not rely on QCD coupling: can be any other light, weakly coupled boson
- Does not rely on DM density
- Superradiance is a kinematic effect so does not require precise resonance



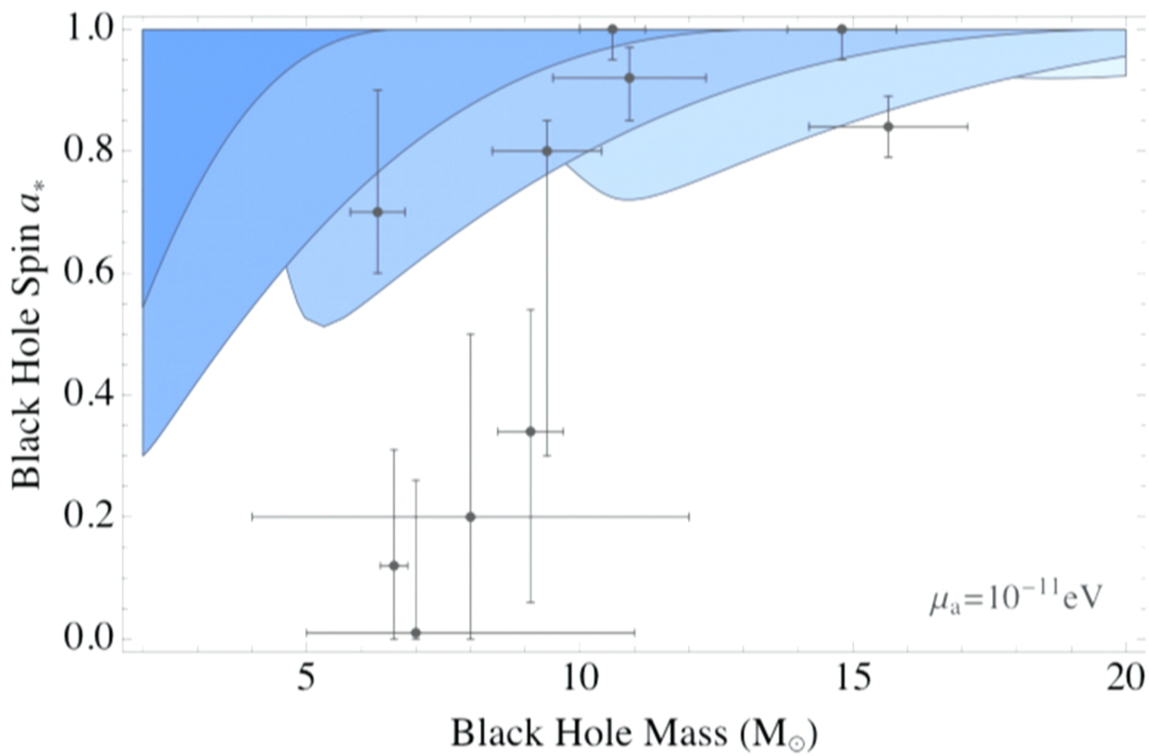
Black Hole Spins

Black hole parameter space affected by superradiance of 10^{-11} eV axion



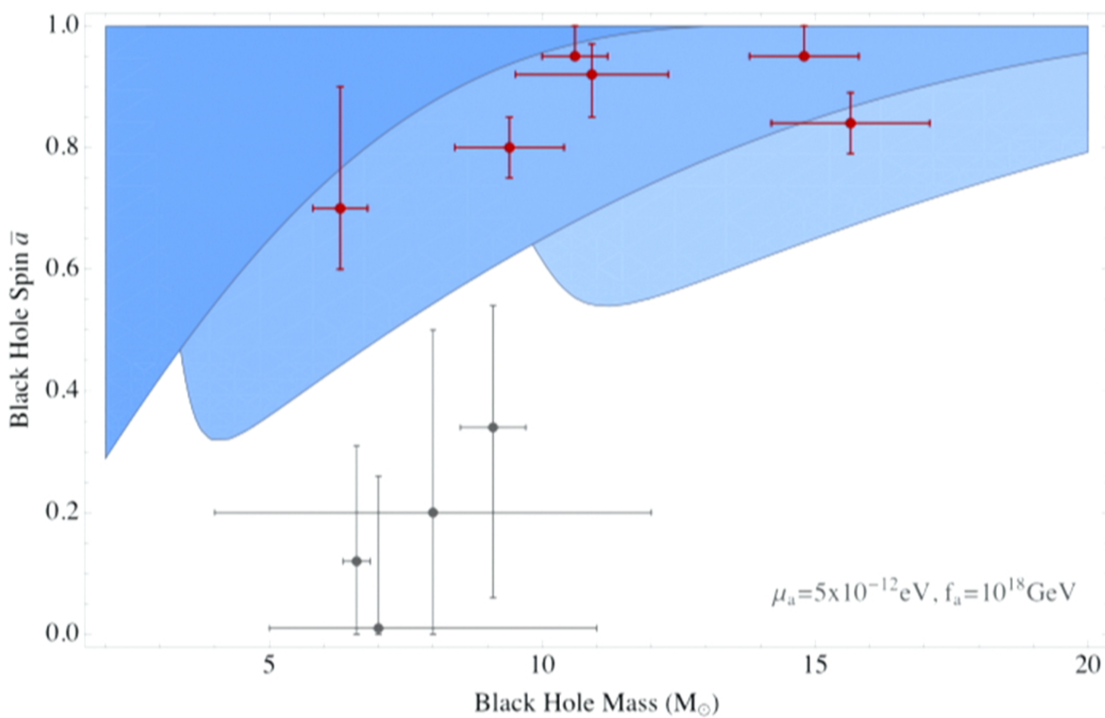
Black Hole Spins

Black hole spin and mass measurements



Black Hole Spins

More constrained at lighter axion mass



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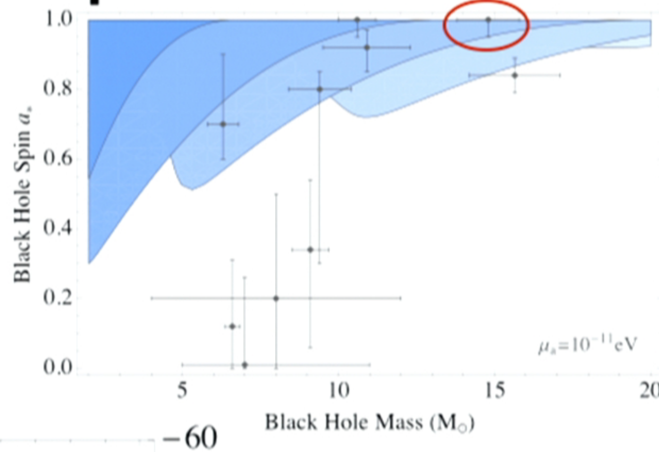
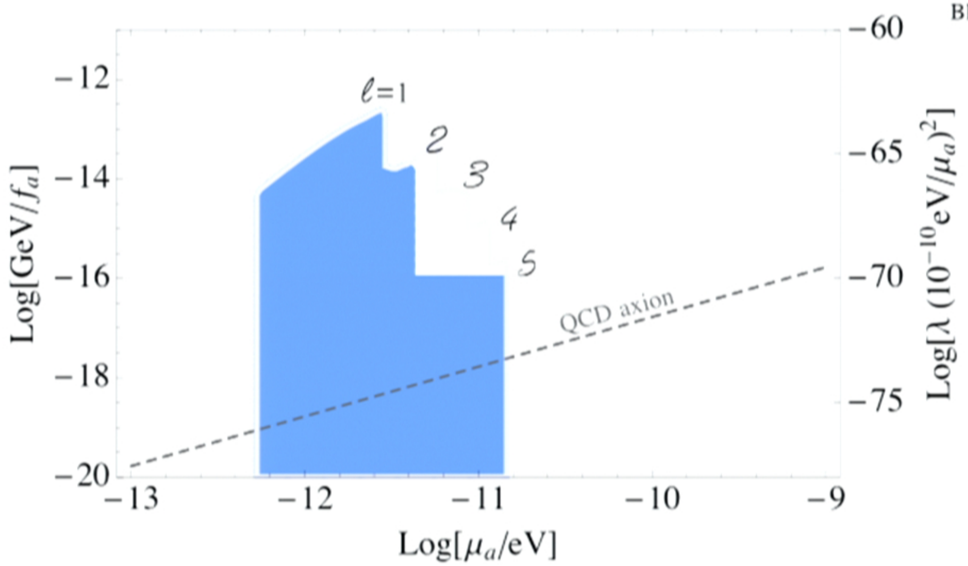
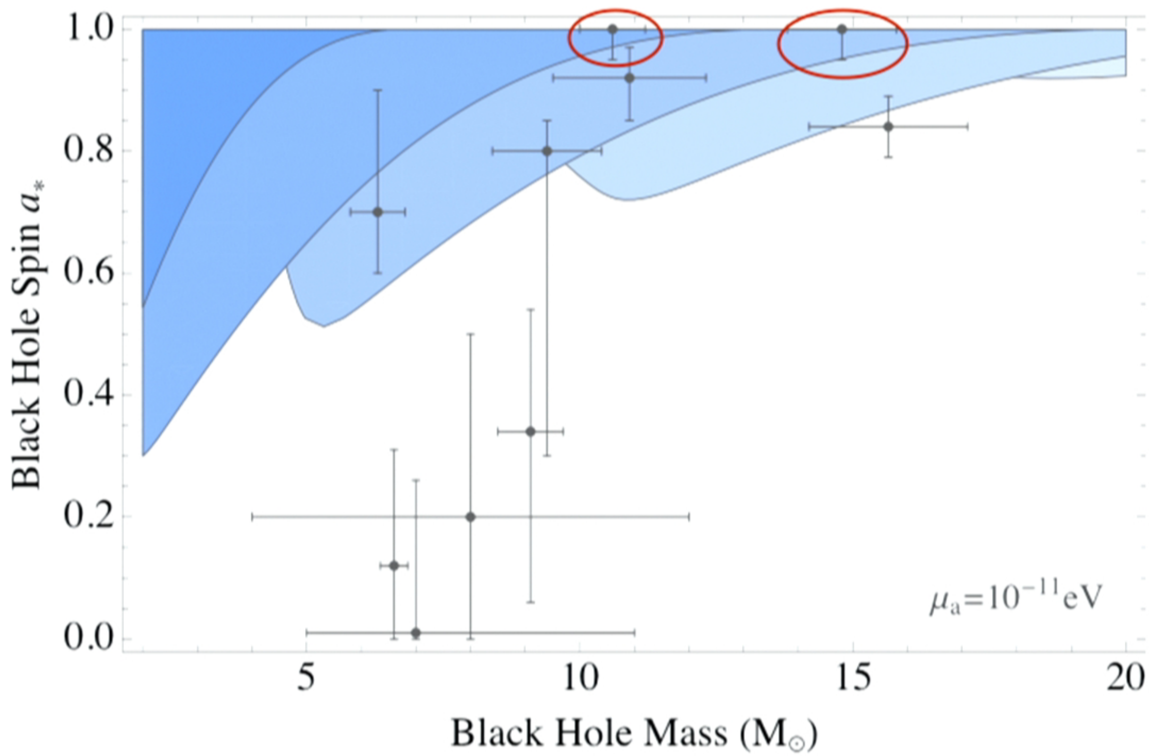


Limit from Cyg X-1



Black Hole Spins

Two black holes exclude this axion mass at 2 sigma



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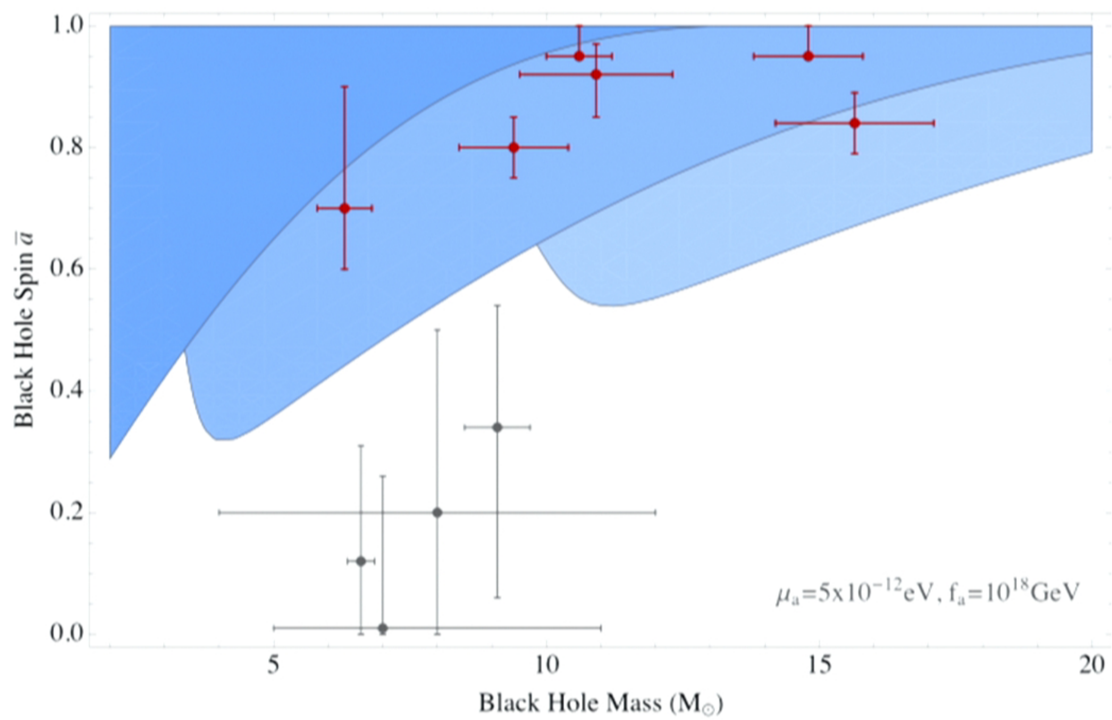
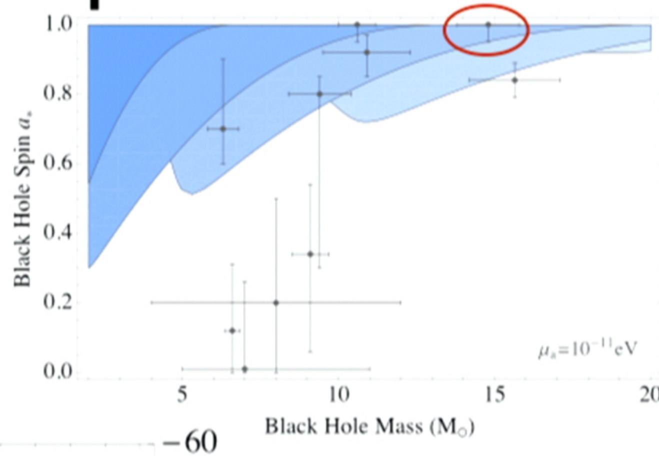


Black Hole Spins



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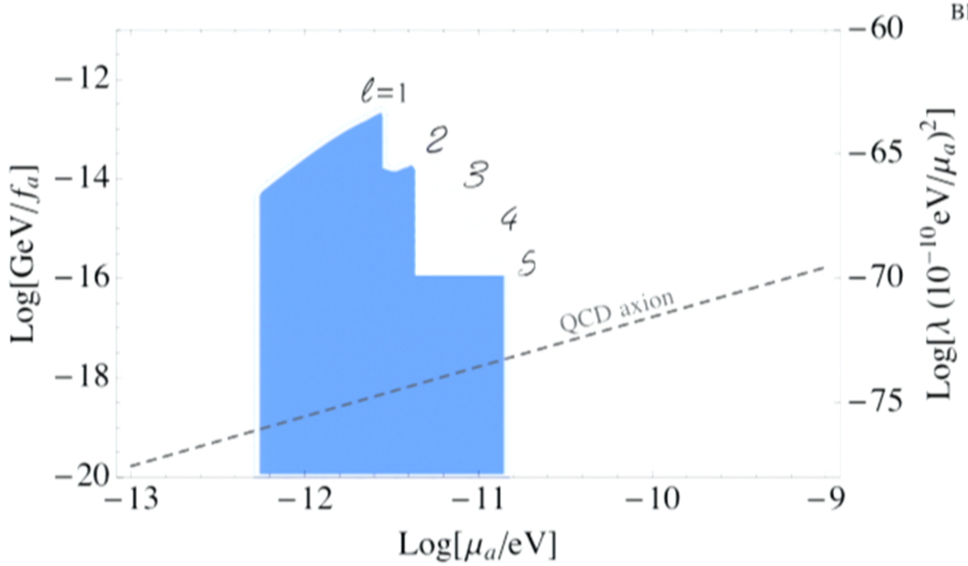
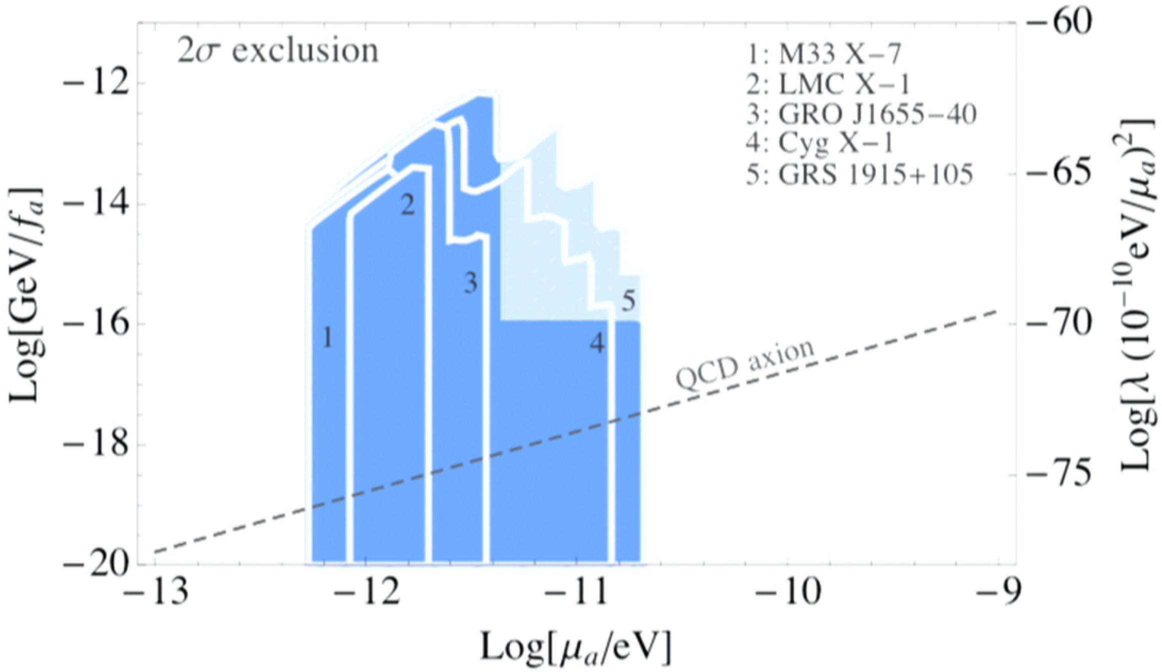


Black Hole Spins

Five currently measured black holes combine to set limit:

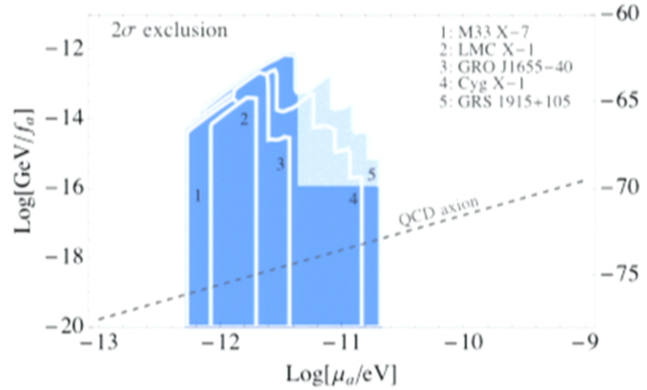
$$1.5 \times 10^{-11} > \mu_a > 6 \times 10^{-13}\,\mathrm{eV}$$

$$4 \times 10^{17} < f_a < 1 \times 10^{19}\,\mathrm{GeV}$$

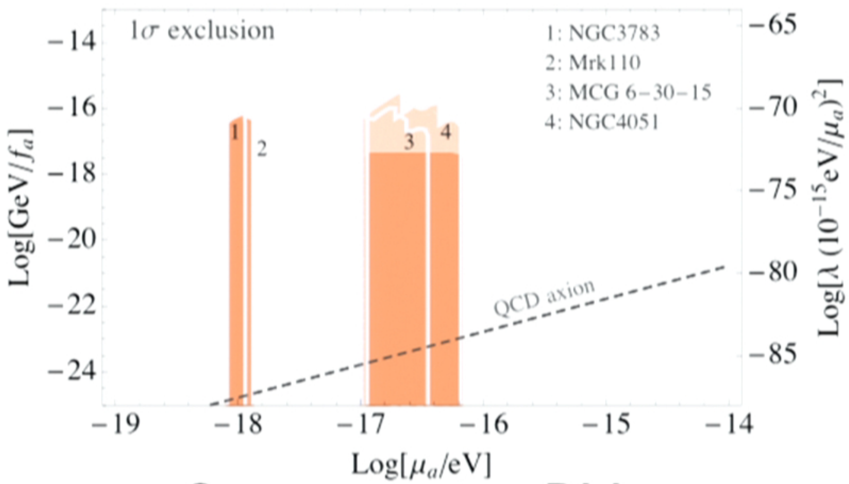


Black Hole Spins

Spin measurements of supermassive BHs have recently become possible and are starting to set limits at lower masses:



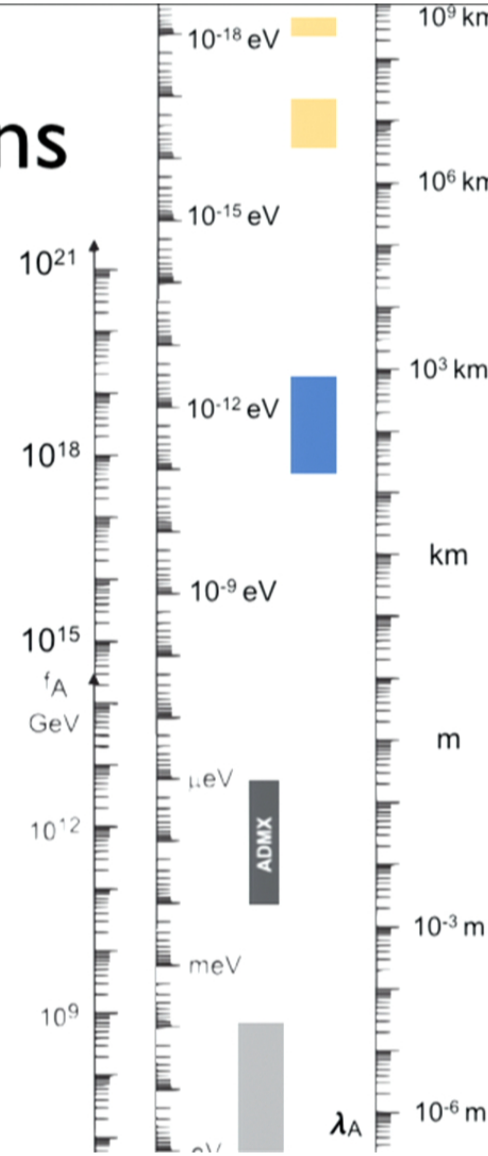
Stellar BHs



Supermassive BHs

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



Gravitational Wave Signals

Advanced LIGO and VIRGO turning on and beginning to collect data in 2015

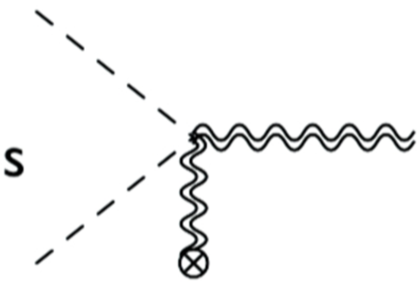
Advanced LIGO

Advanced VIRGO

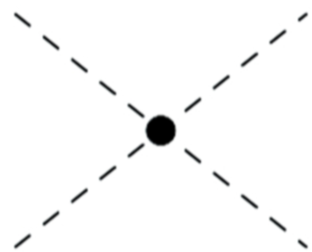
Gravitational Wave Signals

- Transitions between levels

- Annihilations



- Bosenova



Transitions

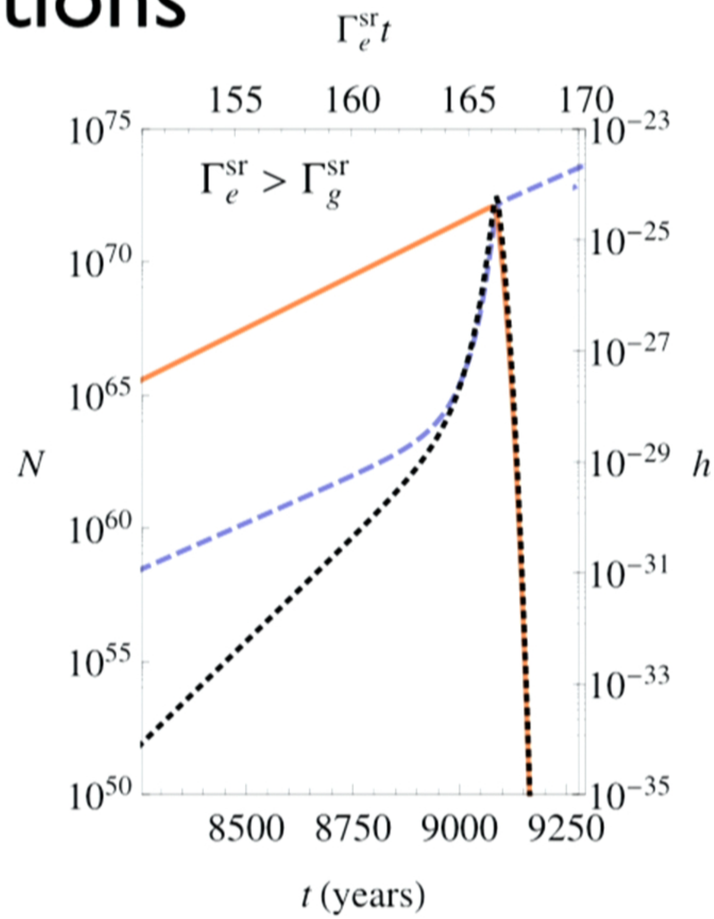
Signal proportional to occupation number of both levels:

$$h_{\rm tr}(t) = \sqrt{\frac{4G_N}{r^2\omega_{\rm tr}}\Gamma_t N_g(t) N_e(t)}$$

Levels evolve as:

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

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



6g → 5g transition around a 10 M⊙ BH with spin a∗ = 0.9, 10 kpc away

Transitions

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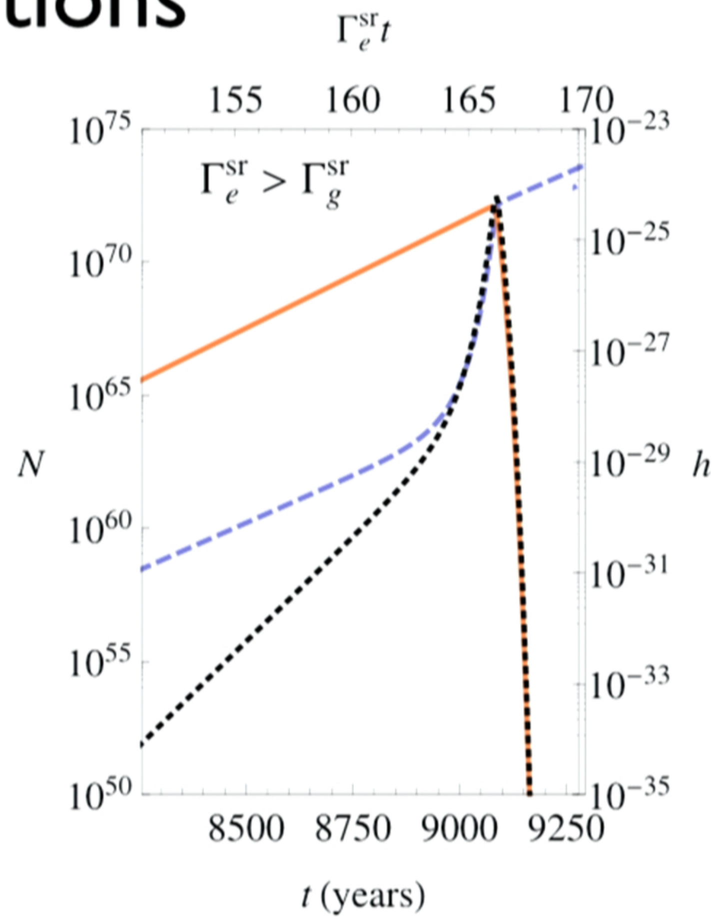
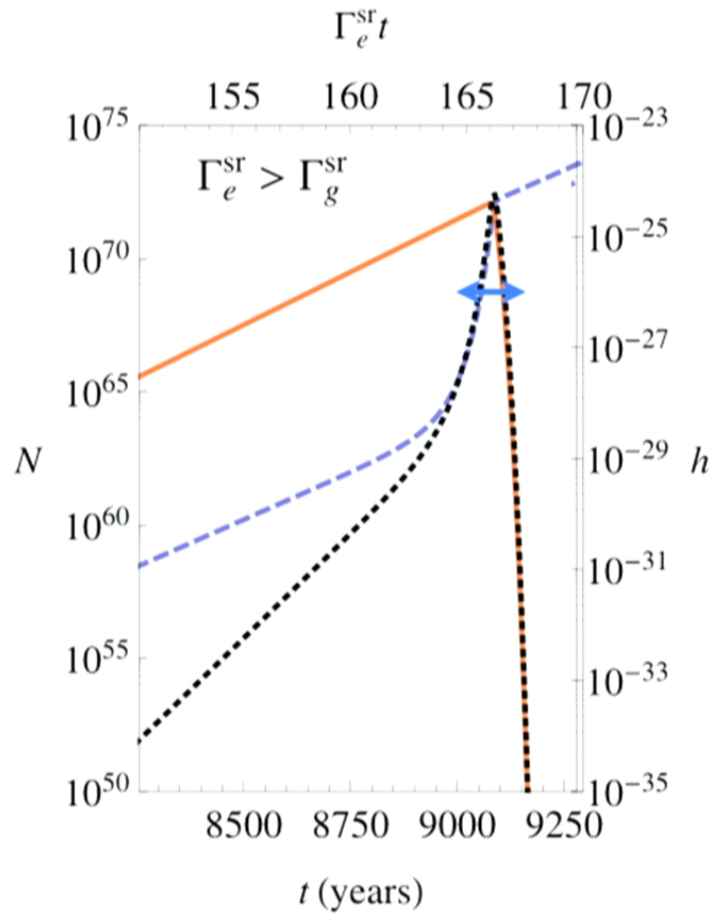


6g → 5g transition around a 10 M⊙ BH with spin a∗ = 0.9, 10 kpc away

Transitions

Signal very monochromatic
with small frequency drift

$$\frac{df}{dt} \simeq 10^{-11}\frac{\mathrm{Hz}}{\mathrm{s}}\left(\frac{f}{35\,\mathrm{Hz}}\right)\left(\frac{M}{10M_{\odot}}\right)\left(\frac{M_{\mathrm{GUT}}}{f_a}\right)^2$$

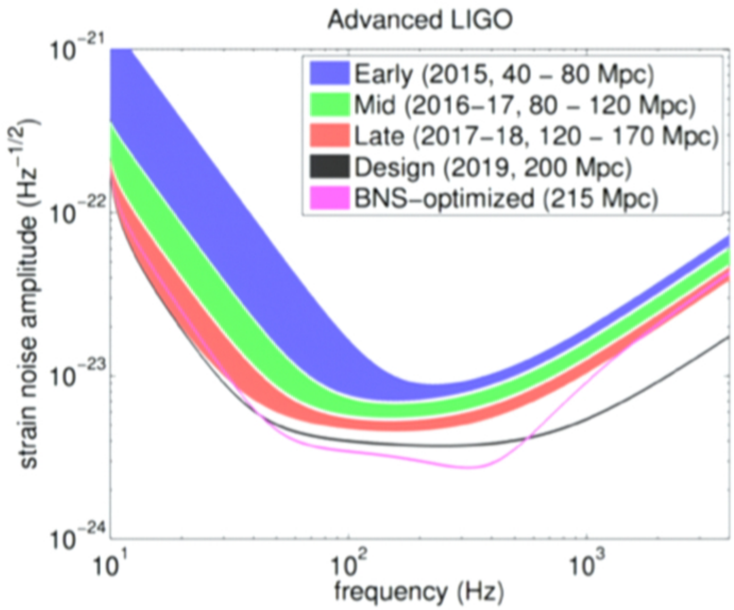


Gravitational Wave Signals

Advanced LIGO sensitivity

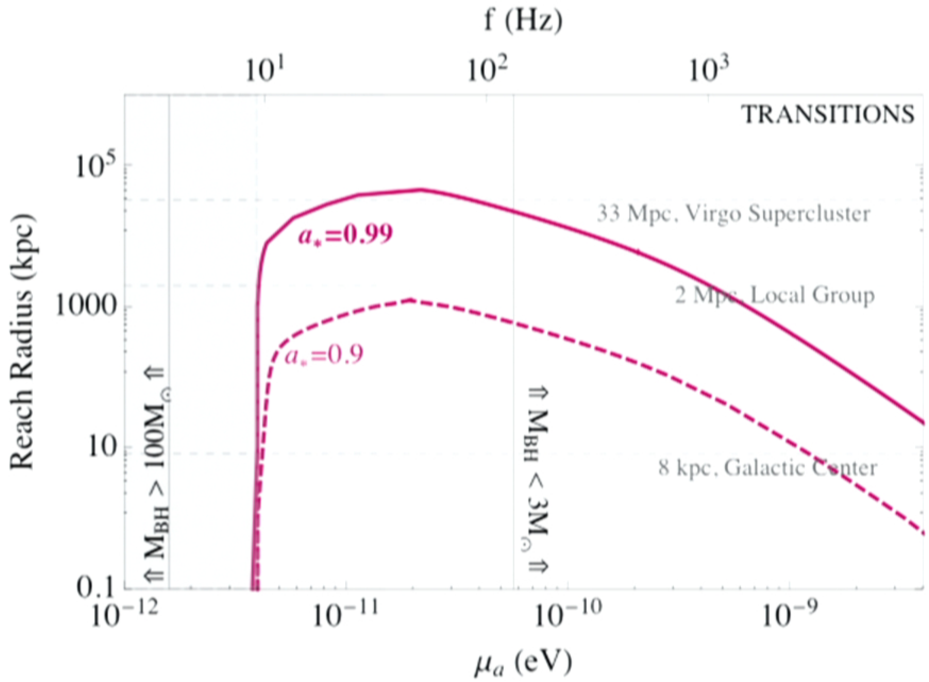
Example searches:

- Focus on in-spiral signals
- Mountains on neutron stars, cosmic strings, ...



Transitions

Optimal reach of advanced LIGO



Using monochromatic search for rotating neutron stars

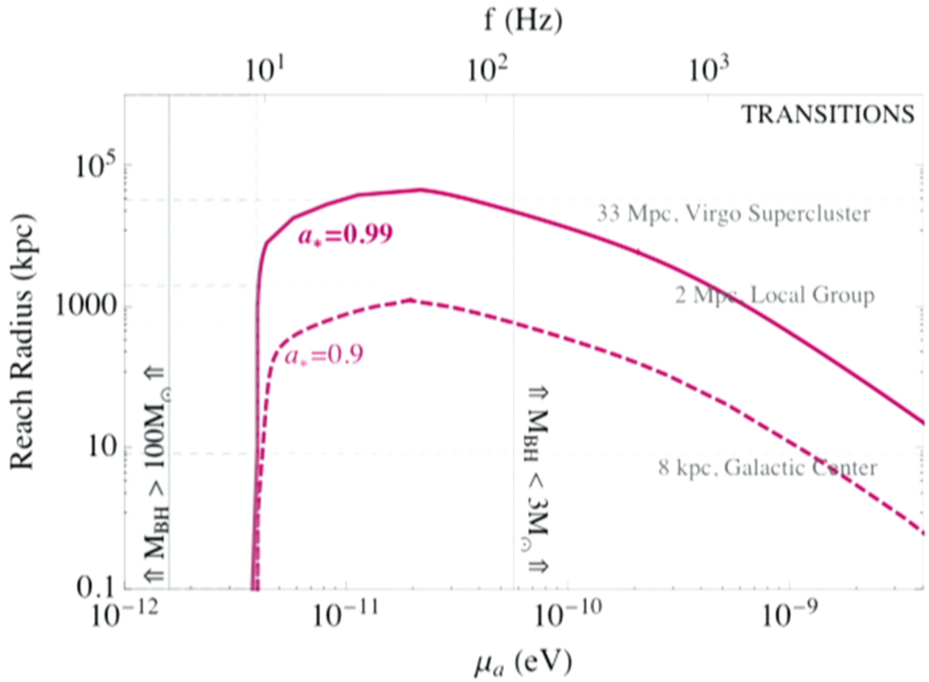
Heavier BHs give bigger signals

Cut off at low masses by LIGO sensitivity

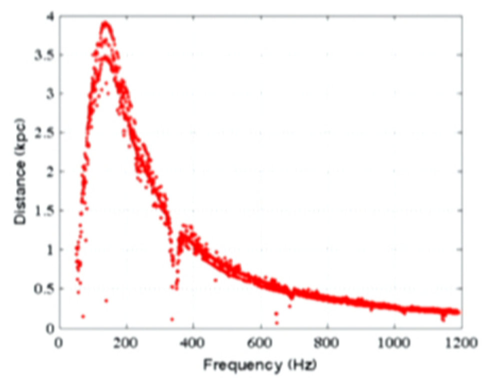
BH with high spin, optimal mass, and is currently superradiating

Transitions

Optimal reach of advanced LIGO



rotating neutron star reach (current LIGO)



Transitions: Event Rates

Signal lasts much longer than a year and generally happens once in the lifetime of a BH

$$\# \text{ of Events} \sim \frac{\tau_{\rm sig}(M, a_*, r)}{(\rm BHFR)^{-1}}$$

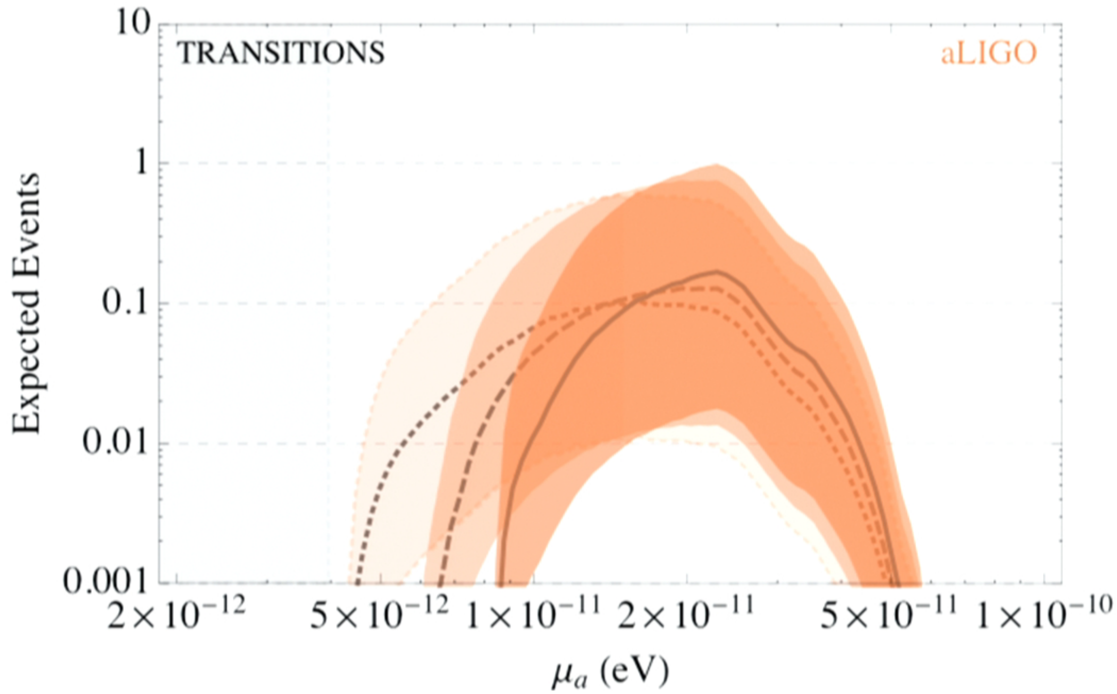
- Black hole formation rate is ~ (0.1 - 1) / century in the Milky Way

$$\tau_{\rm sig}(M, a_*, r) \sim$$ 20 years for axion mass 10-11 eV

$M \to 10\ M_\odot$, $a_* \to 0.9$, $r \to 8$ kpc

Transitions

- Integrating over BH masses and spins gives promising event rates
- Uncertainty dominated by BH formation rate and spin distribution
- Less sensitive to mass distribution



Complementary to spin limits

Transitions

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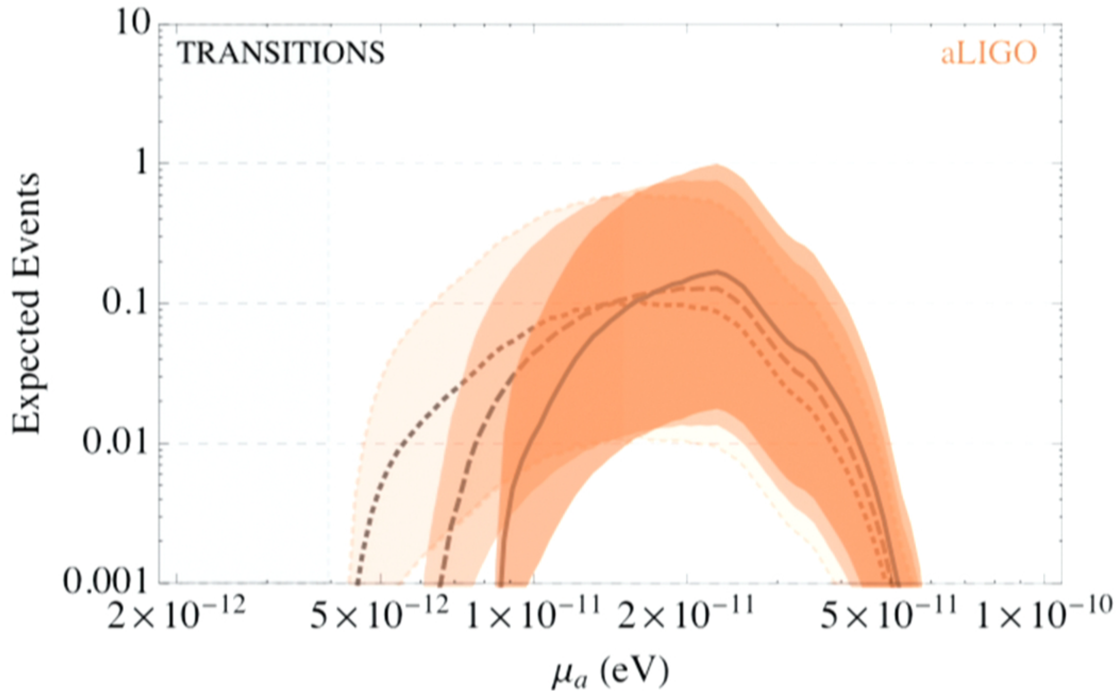
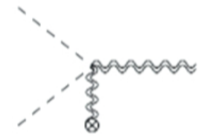
Complementary to spin limits

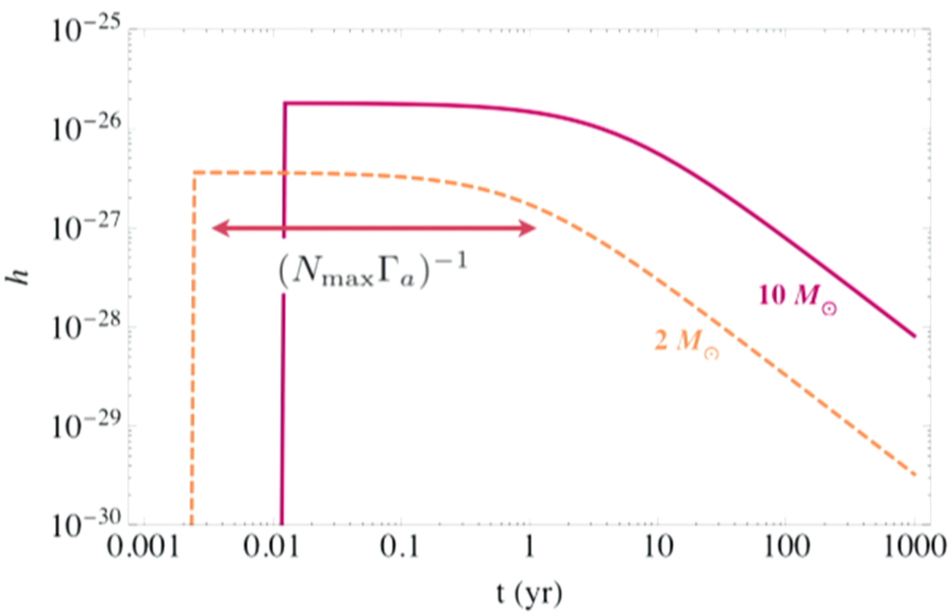


Annihilations



Signal strain proportional to occupation number

$$h(t) = N(t)\sqrt{\frac{4G_N}{r^2\omega_{\text{ann}}}\Gamma_a}$$

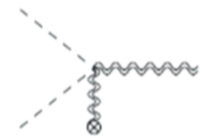


Signals visible from galactic center last 10^3 yrs or more

$\tau_{\text{sig}}(M, a_*, r) \sim 10^3$ yrs

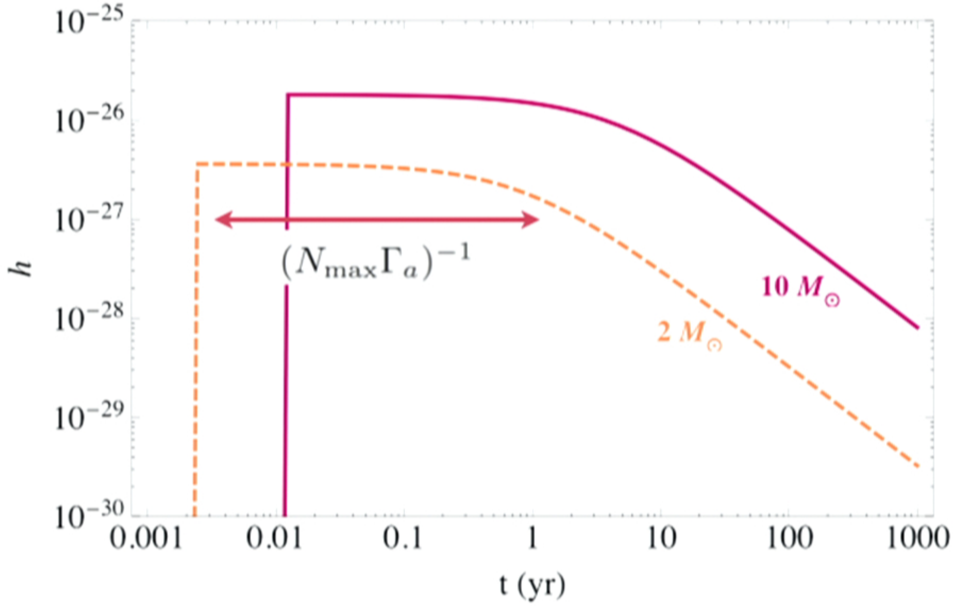
M → 10 M⊙, a_* → 0.9, r → 8 kpc

Annihilations



Signal strain proportional to occupation number

$$h(t) = N(t)\sqrt{\frac{4G_N}{r^2\omega_{\rm ann}}\Gamma_a}$$

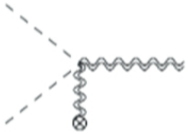


Signals visible from galactic center last 10^3 yrs or more

$\tau_{\rm sig}(M, a_*, r) \sim 10^3$ yrs

10 M⊙ 0.9 8 kpc

Annihilations



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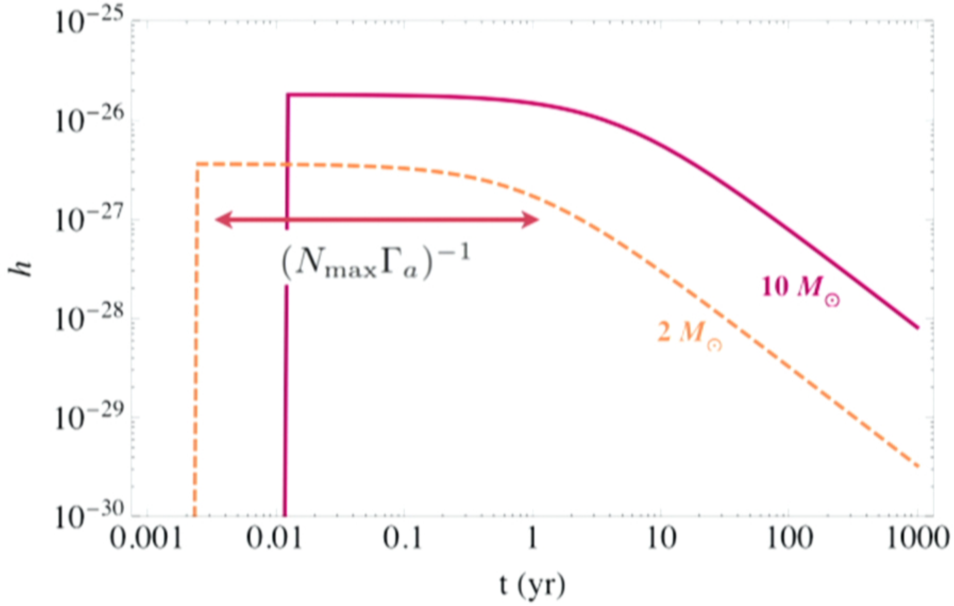

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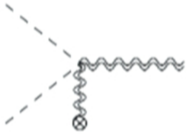
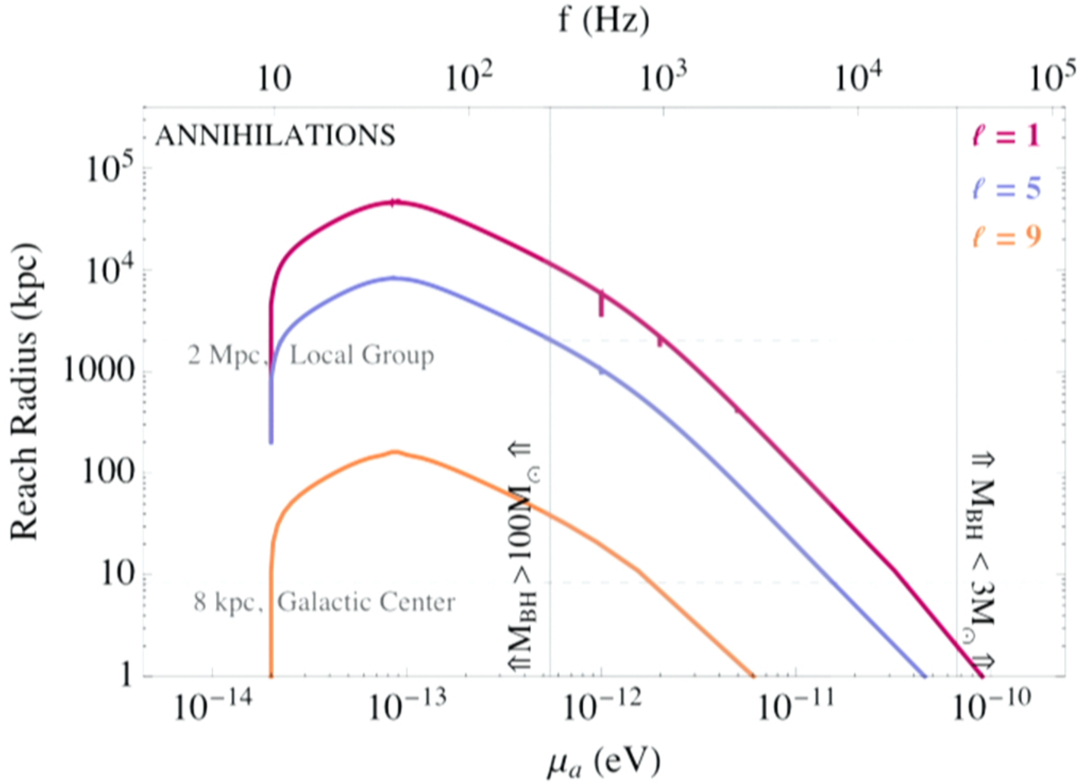
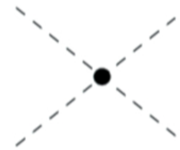


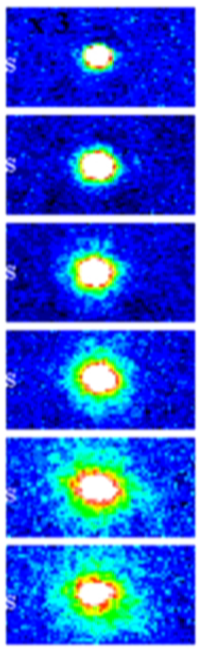


Higher ℓ-levels have lower annihilation rates

Part of parameter space excluded by spin measurements

Bosenova





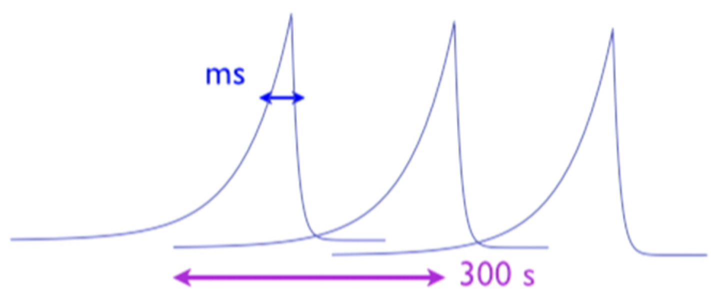
spot.colorado.edu/~cwieman/Bosenova.html

If self-interaction is strong enough, self-interaction of the axion can lead to collapse of the cloud, for

$$f_a \lesssim 2 \times 10^{16}\,\mathrm{GeV}$$

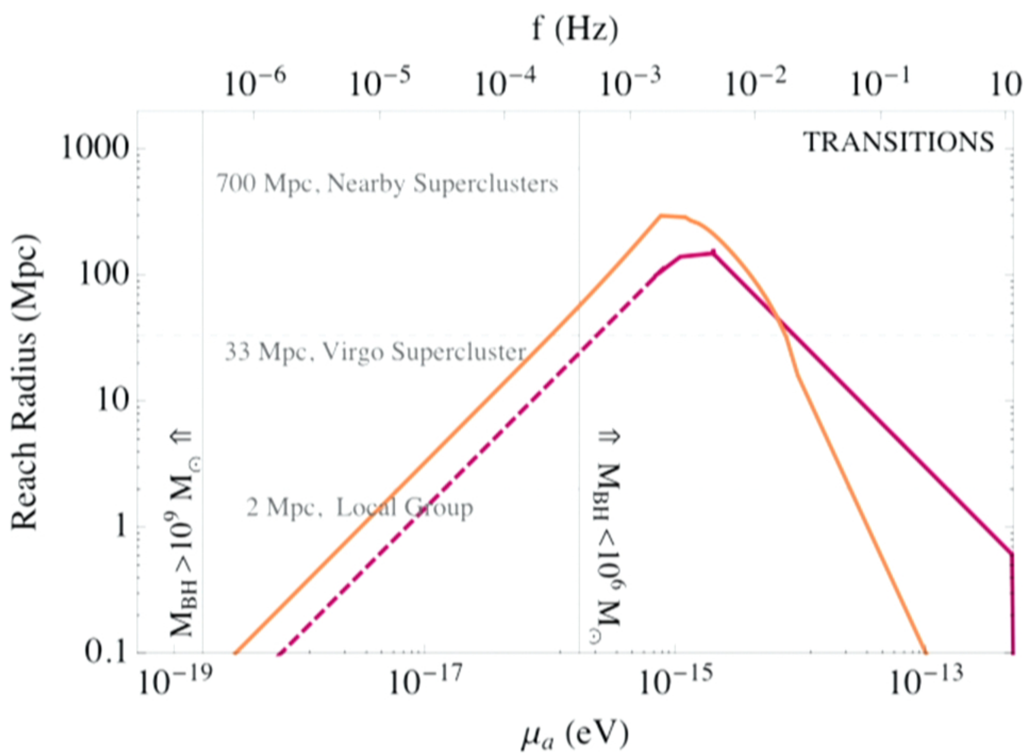
Not relevant for QCD axion but can lead to interesting burst events for other light particles, with strain and frequency

$$h \simeq 10^{-21} \left(\frac{f_a}{f_a^{\max}}\right)^2 \qquad f_{\rm bn} = 30\,\mathrm{Hz}$$



Future GW Detectors

Transitions



Gravitational Wave Signals

Expected event rates at aLIGO and low-f detectors

Source		$N_{\rm low}$	$N_{\rm re}$	$N_{\rm high}$	f (Hz)
$6g \to 5g$ transition	$10\,M_\odot$	0.02	0.2	1	20
$2p$ annihilation	$50\,M_\odot^*$	0.4	4	30	200
$6g \to 5g$ transition	$10^6\,M_\odot$	1	20	500	2×10^{-4}
$2p$ annihilation	$10^6\,M_\odot$	2	20	400	2×10^{-2}
$2p$ annihilation	$10^7\,M_\odot$	900	3×10^4	2×10^7	2×10^{-3}

Conclusions

- Ultra light bosons can be probed by astrophysical black holes
- BH spin measurements exclude previously open parameter space
- Advanced LIGO is coming online next year and will reach target sensitivity in the next 5 years
- GW signals from transitions of GUT scale axions
- GW signals from annihilations of Planck scale axions