Title: Fundamental Physics Without Colliding Particles

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Abstract:

Fundamental Physics Beyond Colliding Particles

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Perimeter Institute


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...To Detecting Fields


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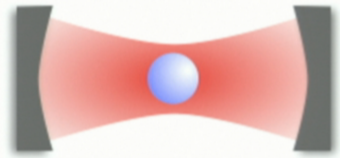
...To Detecting Fields

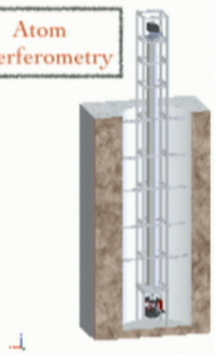
- Axion Dark Matter Detection
- Axion Force Detection

- Short Range Forces
- Gravitational Wave detection at high frequencies
- Tests of Quantum Mechanics

Optically Levitated Objects



Atom Interferometry

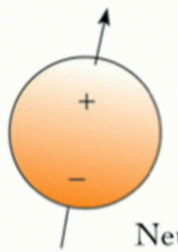


- Equivalence principle at 15 decimals
- Gravitational Wave detection at low frequencies
- EDM searches
- Tests of Atom Neutrality at 30 decimals

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

Why is the Electric Dipole Moment of the Neutron Small?

The Strong CP Problem and the QCD axion



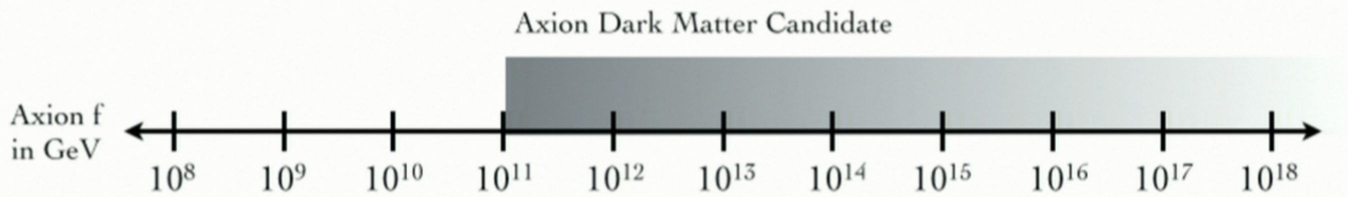
Neutron EDM

EDM ~ e fm θ_{QCD}

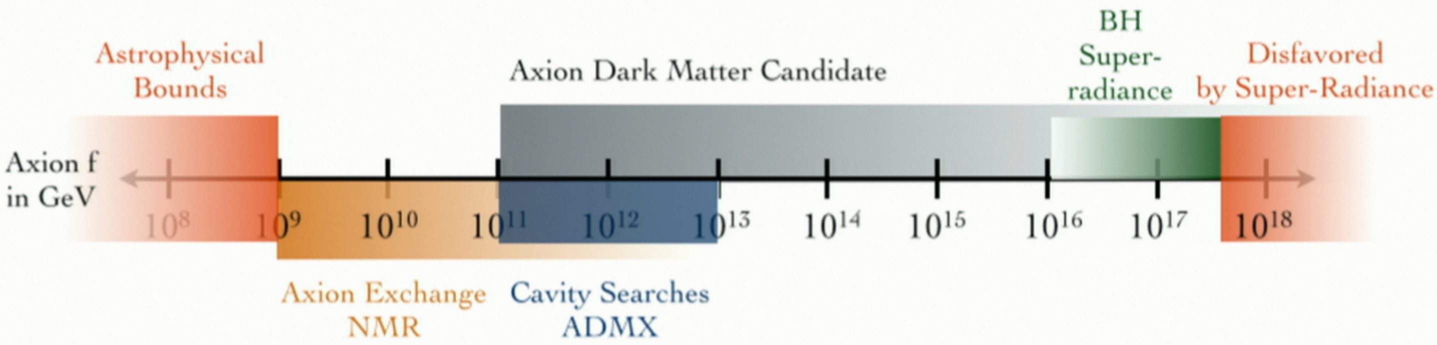
$$L_{\rm SM} \supset \frac{g_s^2}{32\pi^2}\theta_{\rm QCD} G^a \tilde{G}^a$$

Experimental bound: $\theta_{QCD} < 10^{-10}$

The Parameter Space of the QCD Axion



The Parameter Space of the QCD Axion



- Axion Force Detection with Nuclear Magnetic Resonance

  Force range between 30 μm and 3 cm

- Axion Signals from Black Hole Super-radiance

Axion wavelength between 300 m and 300 km

Short Range Interactions of the Axion

Monopole-Dipole Interaction

Mass with N nucleons

Spin

Interaction energy between mass and spin:

$$\frac{g_p \vec{\nabla} a}{m_f} \cdot \vec{\sigma}$$

Potential generated by the mass:

$$a(r) \approx \frac{g_s N}{4\pi} \frac{e^{-m_a r}}{r}$$

Coupling constant of the fermion's spin

$$g_p \approx 10^{-9} \left(\frac{m_f}{1\ \text{GeV}}\right) \left(\frac{10^9\ \text{GeV}}{f_a}\right)$$

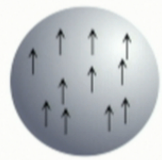
$$\boxed{6 \times 10^{-27} \left(\frac{10^9\ GeV}{f_a}\right)} \lesssim g_s \lesssim \boxed{10^{-21} \left(\frac{10^9\ GeV}{f_a}\right)}$$

From CP violation in the Standard Model

From CP violation allowed by experiment

Short Range Interactions of the Axion

Dipole-Dipole Interaction



N spins

Spin

Interaction energy between mass and spin:

$$\frac{g_p \vec{\nabla} a}{m_f} \cdot \vec{\sigma}$$

Potential generated by N spins:

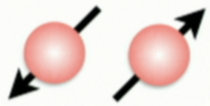
$$a(r) \approx \frac{g_p N}{4\pi m_f} \frac{e^{-m_a r}}{r^2} (\vec{\sigma} \cdot \hat{r})$$

Coupling constant of the fermion's spin

$$g_p \approx 10^{-9} \left(\frac{m_f}{1 \text{ GeV}} \right) \left(\frac{10^9 \text{ GeV}}{f_a} \right)$$

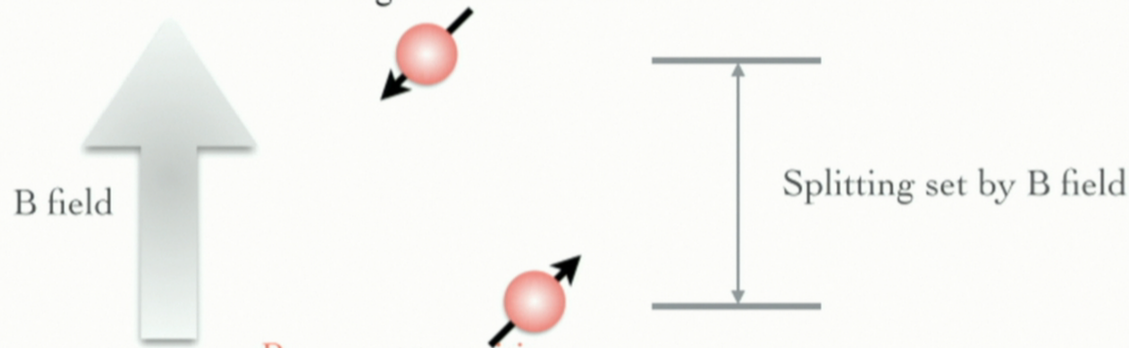
Precision Magnetometry

Nuclear Magnetic Resonance

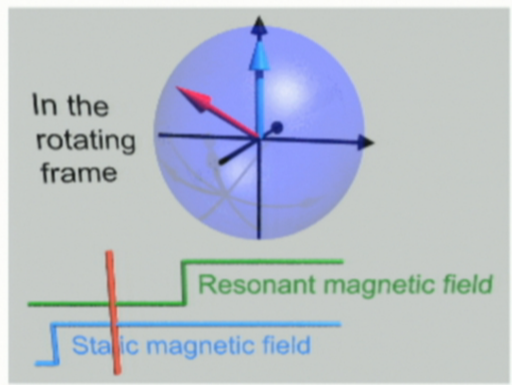


Precision Magnetometry

Nuclear Magnetic Resonance



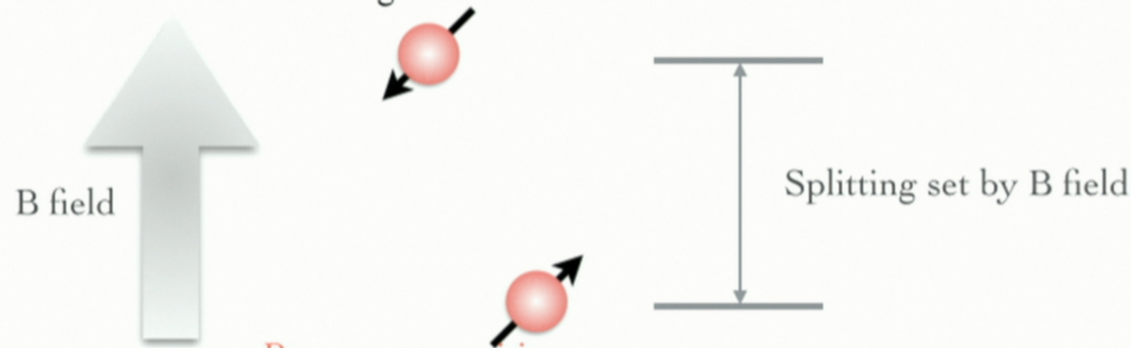
Resonant transition:
Perturbation at the splitting frequency of the spins



In the classical picture: Spins precessing around the perturbing magnetic field

Precision Magnetometry

Nuclear Magnetic Resonance



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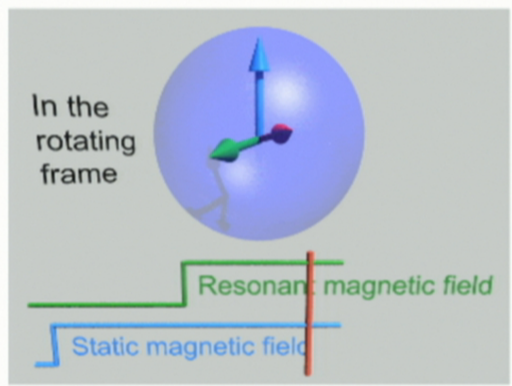
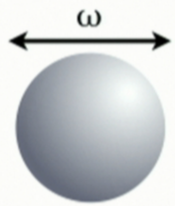


In the classical picture: Spins precessing around the perturbing magnetic field

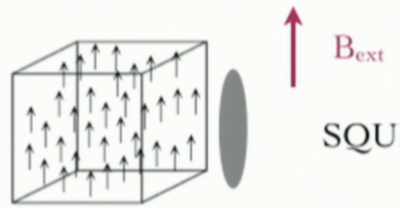
Detection Strategy

Just like a magnetic field

AA and Geraci (2014)



Oscillating Source Mass



NMR

$$\Delta E_{NMR} = \frac{g_p \vec{\nabla} a}{m_f} \cdot \vec{\sigma}$$

On resonance:

$$\vec{M}(t) = n_{NMR}\ p\vec{\mu}\ \Delta E_{NMR}\ t \sin \omega t$$

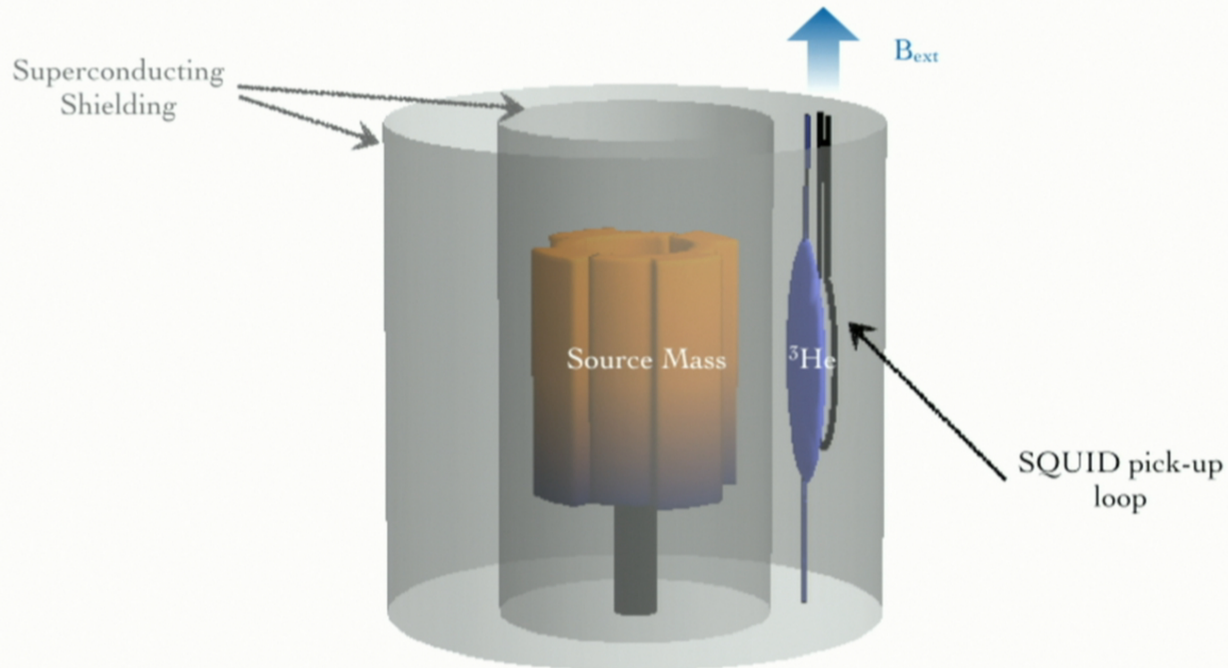
Signal grows till T_2

p: polarized fraction, n_{NMR}: density of spin in the detector, T_2: spin relaxation time

- Unpolarized Source Mass
- Polarized Source Mass

ARIADNE:

Axion Resonant InterAction DetectioN Experiment



$B_{min} = 10^{-16}$ T/(Hz)$^{1/2}$ for SQUIDs

ARIADNE:

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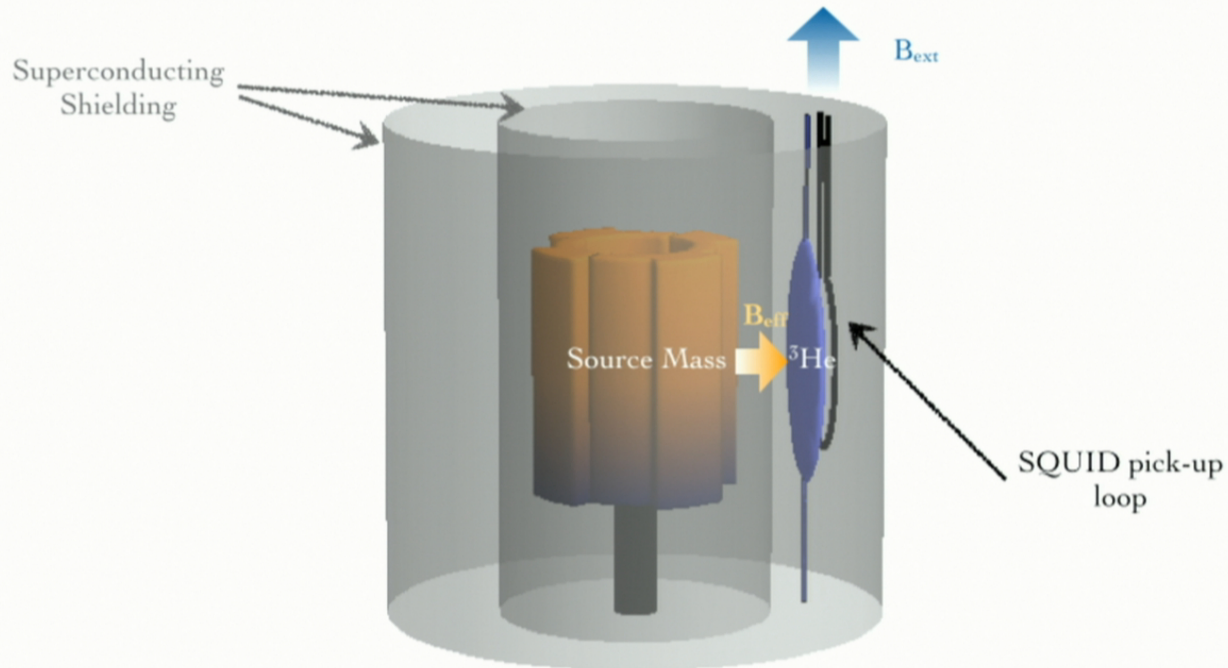

$B_{min} = 10^{-16}$ T/(Hz)$^{1/2}$
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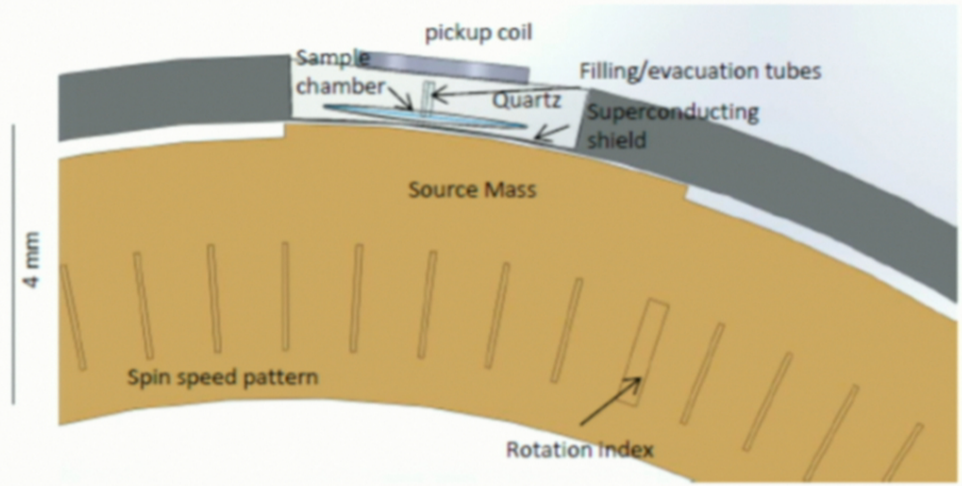
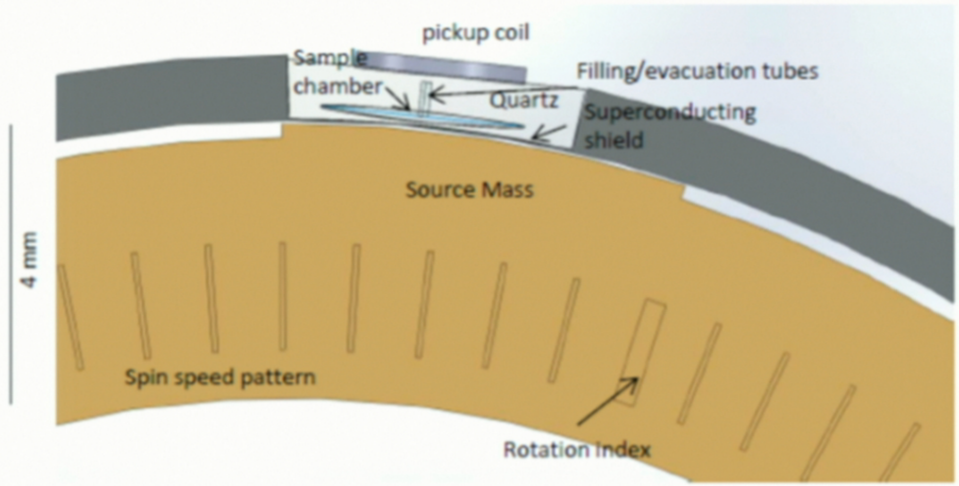
ARIADNE


pickup coil
Sample chamber
Filling/evacuation tubes
Quartz
Superconducting shield
Source Mass
4 mm
Spin speed pattern
Rotation index

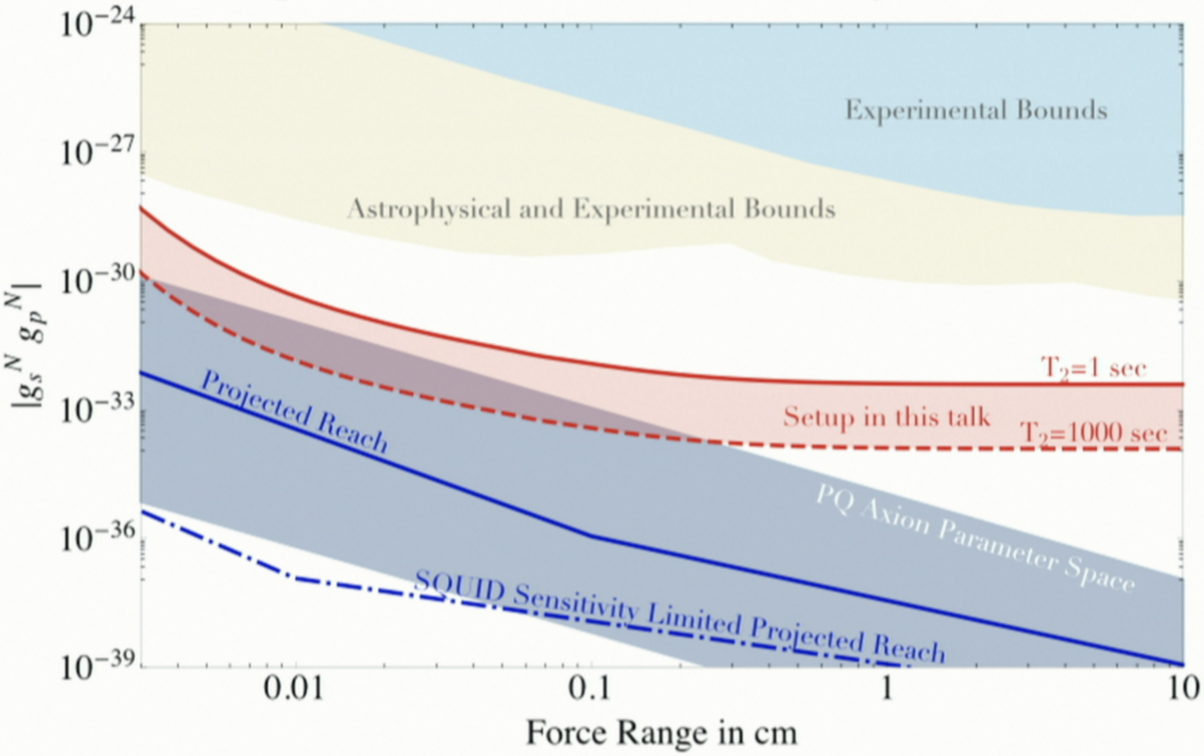
ARIADNE



- 10 segments
- 100 Hz Larmor precession frequency for ^{3}He nuclei
- 2×10^{21} / cc ^{3}He polarized spin density
- 10 mm x 3 mm x 150 μm NMR sample size
- Tungsten (or nuclear - electron spin polarized He or Fe) source mass

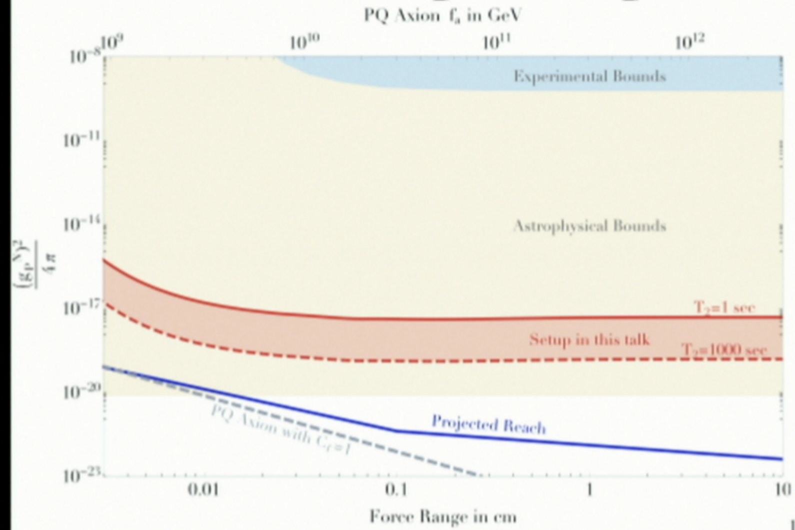
Monopole-Dipole Interaction Reach

Unpolarized Source Mass with 10^6 sec integration



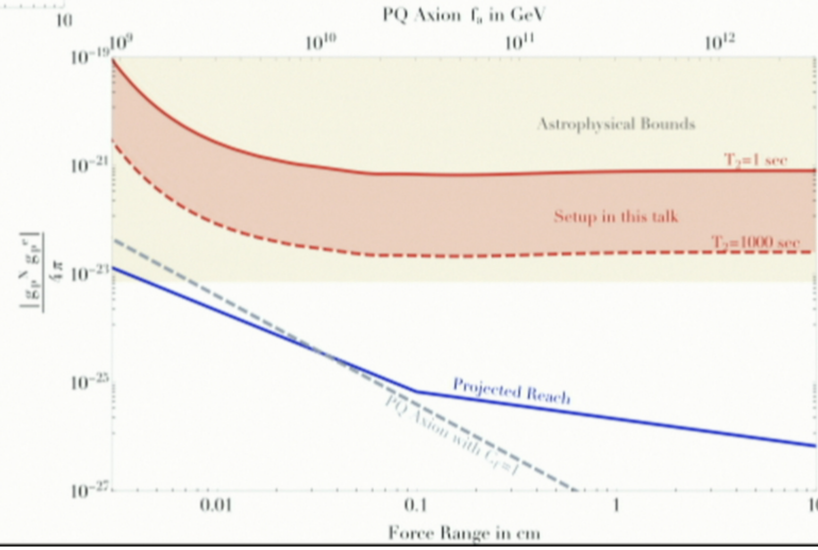
Projected Reach with increase of polarized spin density
and larger NMR sample volume

Dipole-Dipole Interaction Reach



Nuclear Spin Polarized Source Mass
with 10^6 sec integration

Electron Spin Polarized Source Mass
with 10^6 sec integration

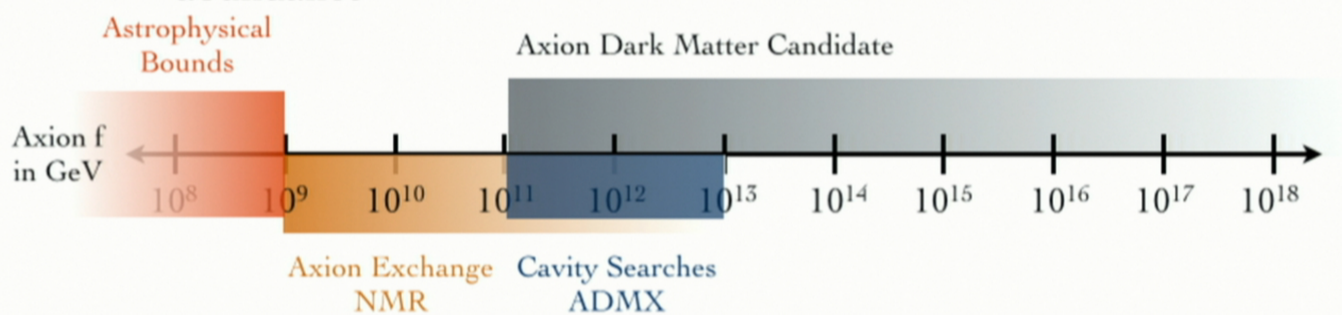


Summary of axion force experiment

- Probes both monopole-dipole and dipole-dipole axion interactions

- Systematics controlled better due to signal modulation

- Covers the traditional axion window independently of the axion abundance

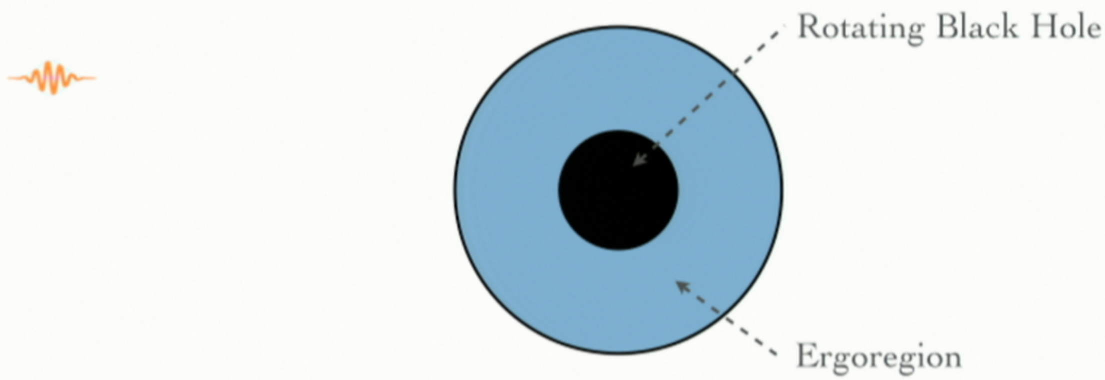


Black Hole Super-Radiance

with Sergei Dubovsky (2010)
and Masha Baryakhtar and Xinlu Huang (to appear)

Black Hole Superradiance

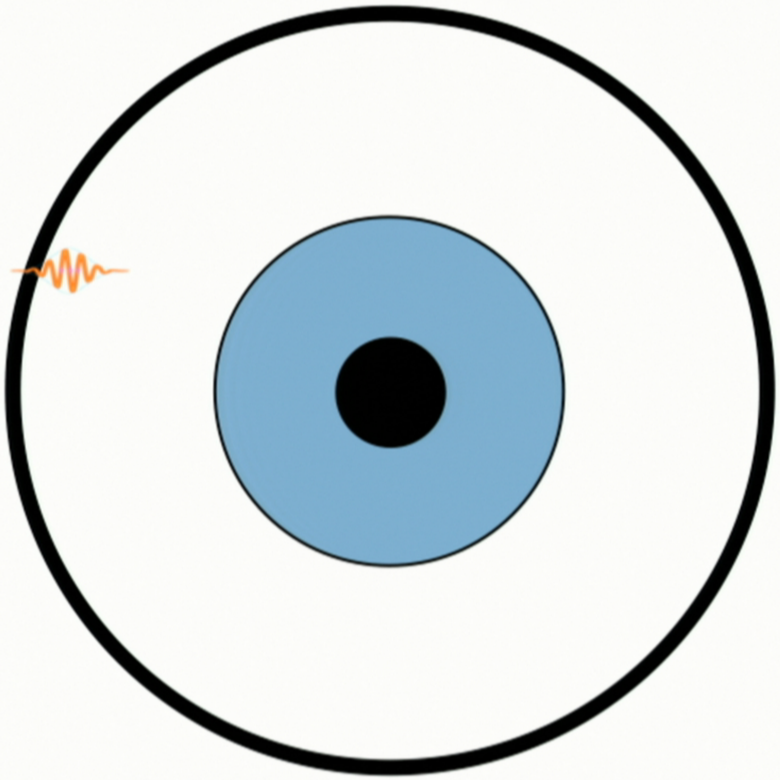
Penrose Process



Ergoregion: Region where even light has to be rotating

Black Hole Bomb

Press & Teukolsky 1972

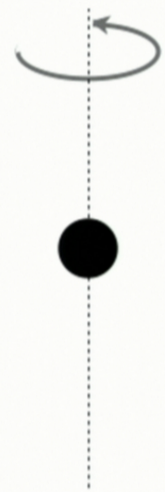


Photons reflected back and forth from the black hole
and through the ergoregion

Superradiance for a Massive Boson

Penrose Process

Damour et al; Zouros & Eardley;
Detweiler; Gaina



Particle Compton Wavelength comparable to the size of the Black Hole

Superradiance Parametrics

Superradiance Condition

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

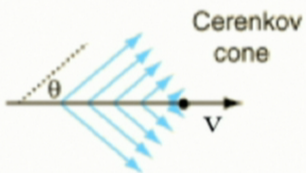
$$\mu_a + E_{\rm binding} < m\frac{a}{2R_g(1+\sqrt{1-a^2})}$$

m : magnetic quantum number

a : BH spin, between 0 and 1

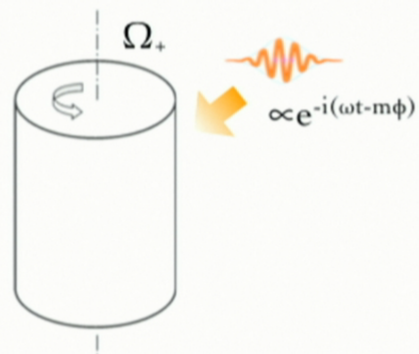
Just like Cherenkov Radiation

Emission of radiation due to superluminal motion



$\cos\theta < v/n$

Superluminal linear motion



Superluminal rotational motion


Ω
rotational motion
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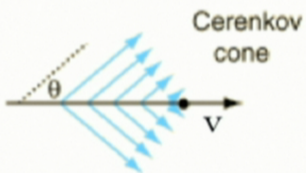

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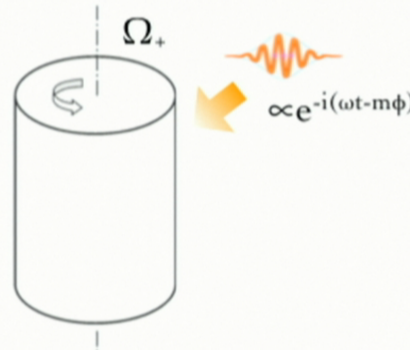

Superluminal rotational motion

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 $R_g\ \mu_a << 1$

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

QCD axion at high f_a matches stellar BH size:

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

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Why are black holes the best superradiance probe?

- Superradiance is a kinematic effect

  It will happen whenever the condition is satisfied

- Black Holes are relativistic

  The superradiance rate can be as small as 100 sec

- Black Holes have quiet environments

  Eddington accretion time scale 10^8 years

Evolution of Superradiance for an Axion

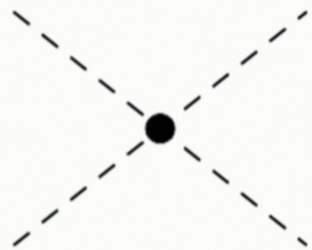
Superradiance instability

Evolution of Superradiance for an Axion

Superradiance instability

Black Hole Accretion $\tau_{accretion} \sim 10^8$ years

Axion self-interactions
"Bosenova"



Evolution of Superradiance for an Axion

Superradiance instability

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Gravity wave transitions of axions between levels

Evolution of Superradiance for an Axion

Superradiance instability

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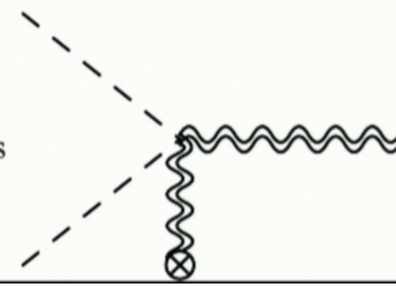
Axion self-interactions

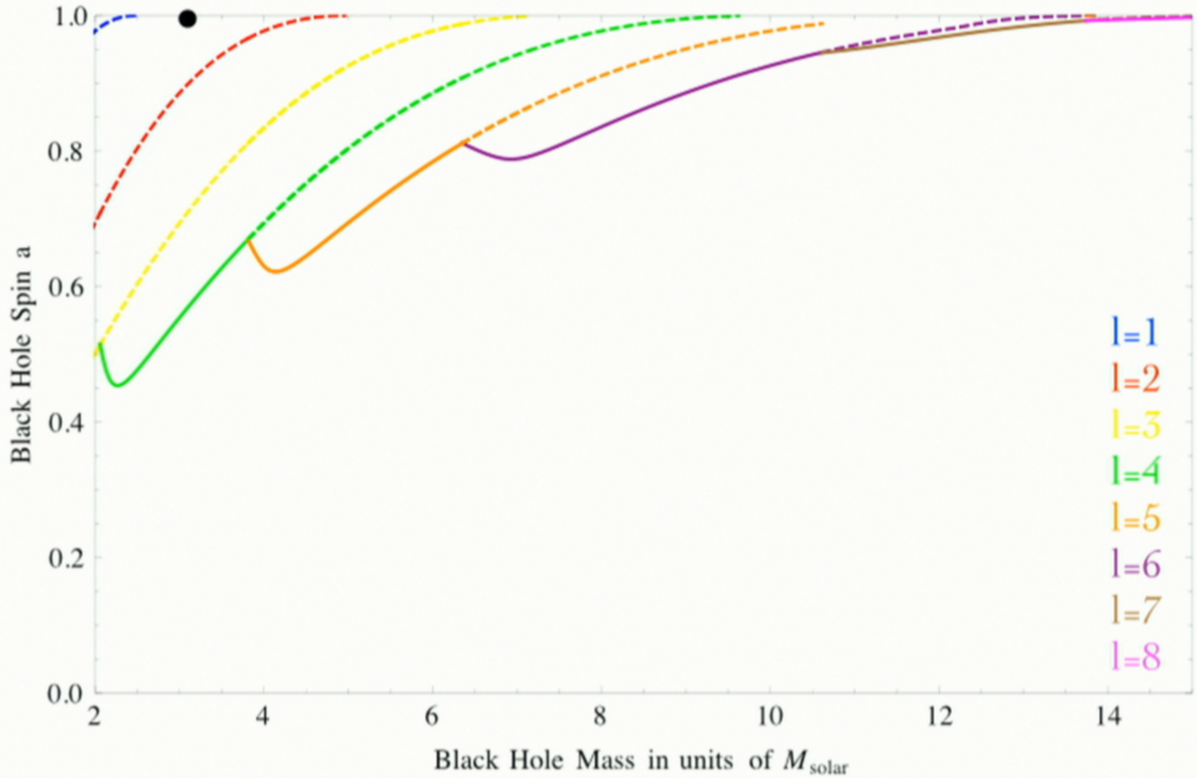
"Bosenova"

Gravity wave transitions of axions between levels

Gravity wave emission through axion annihilations

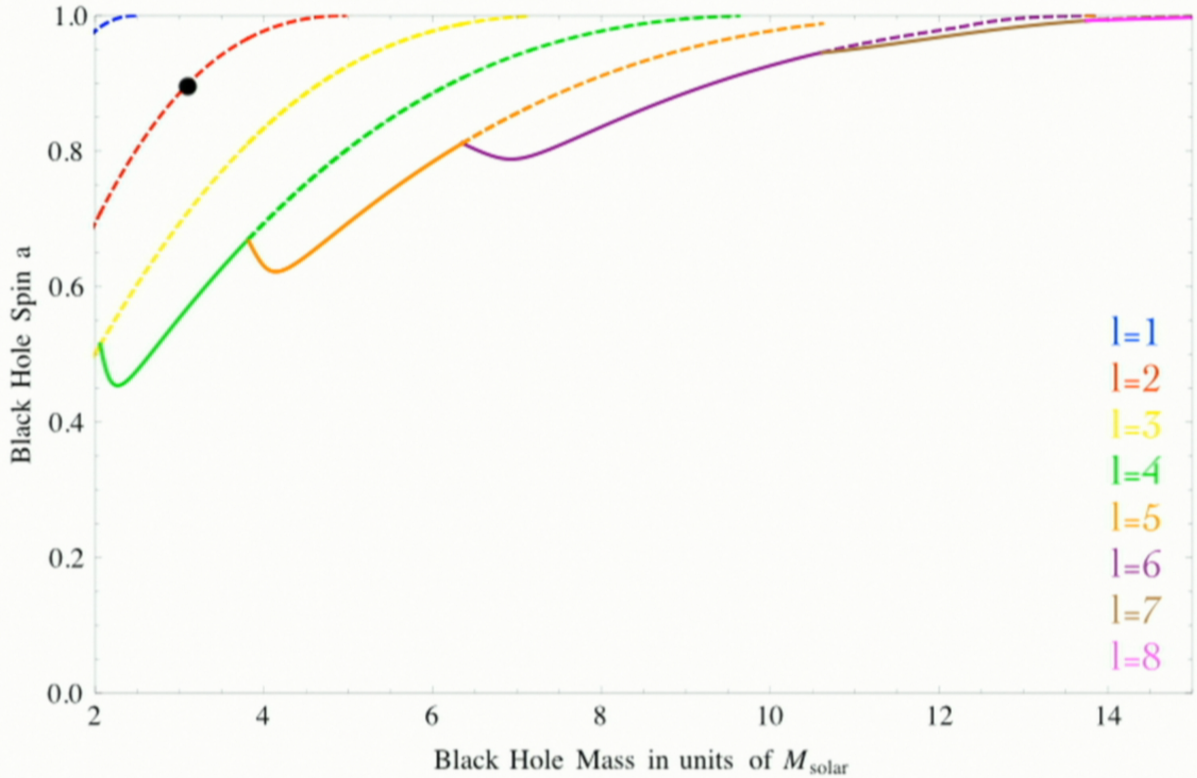


Evolution of Superradiance



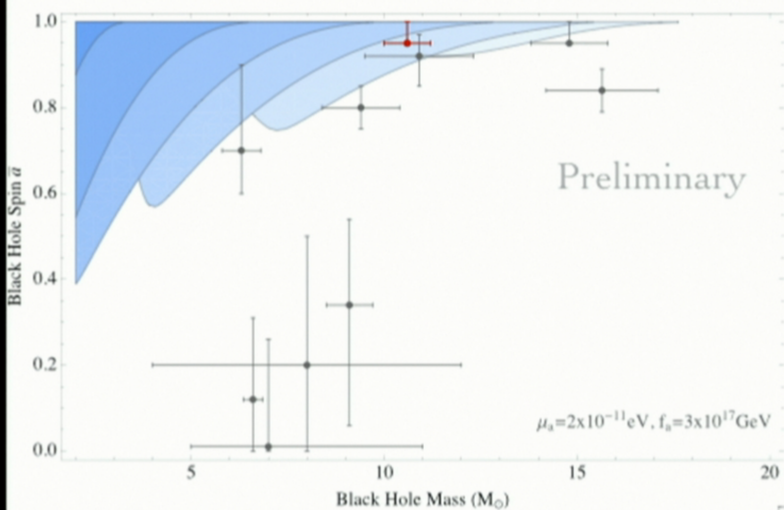
Maximum superradiance rate for level with min. l,max. m

Evolution of Superradiance



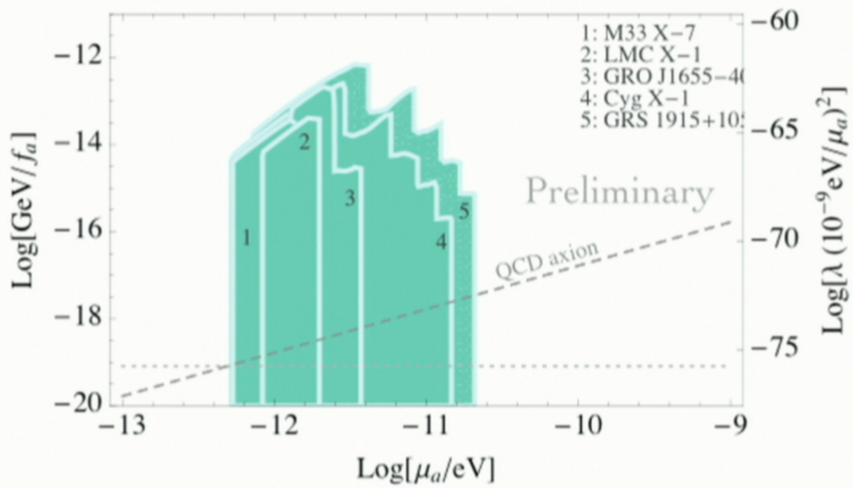
l+1 level grows

Spin-Down of Astrophysical Black Holes



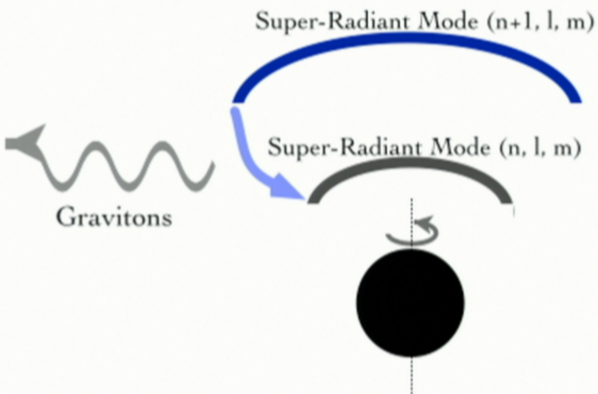
Black-Hole Spin Measurements

For the QCD axion:
4×10^{17} GeV< f_a < 10^{19} GeV excluded

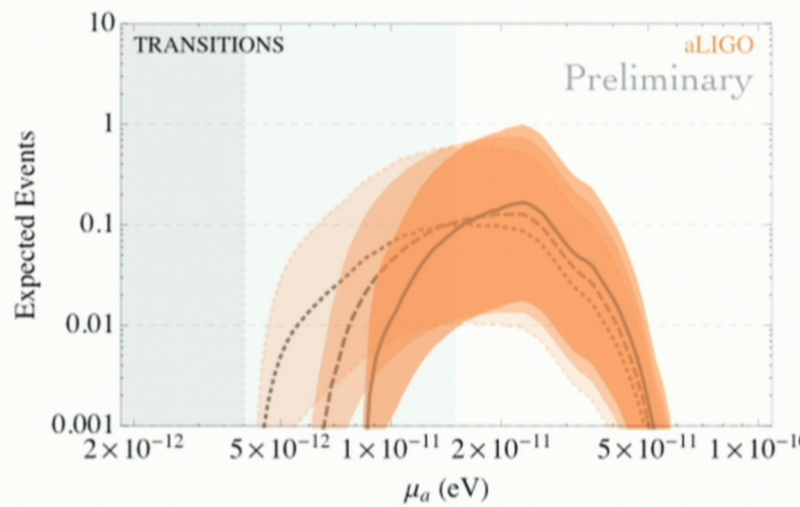


Super-Radiance Signatures

GW transitions

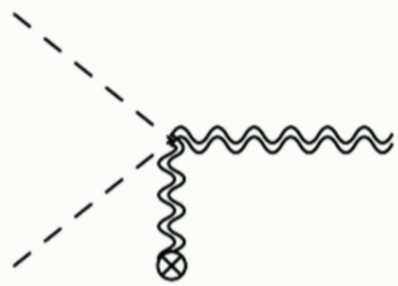


Optimal frequency for LIGO

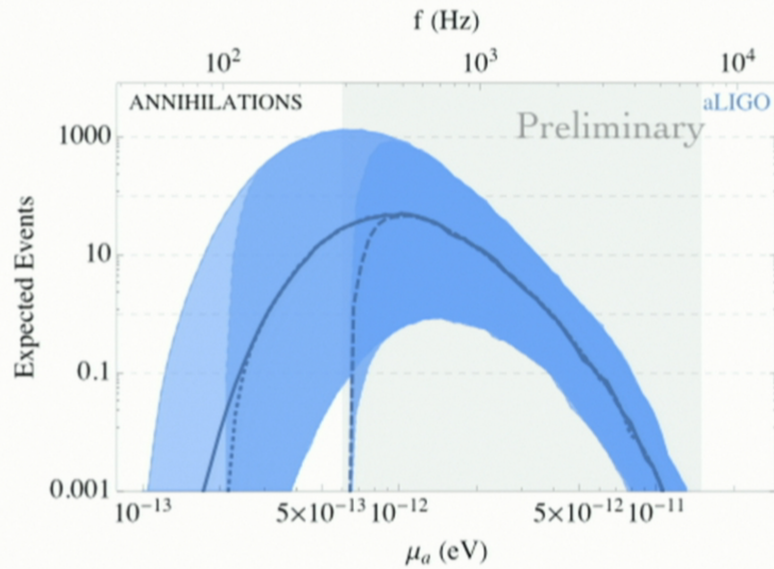


Super-Radiance Signatures

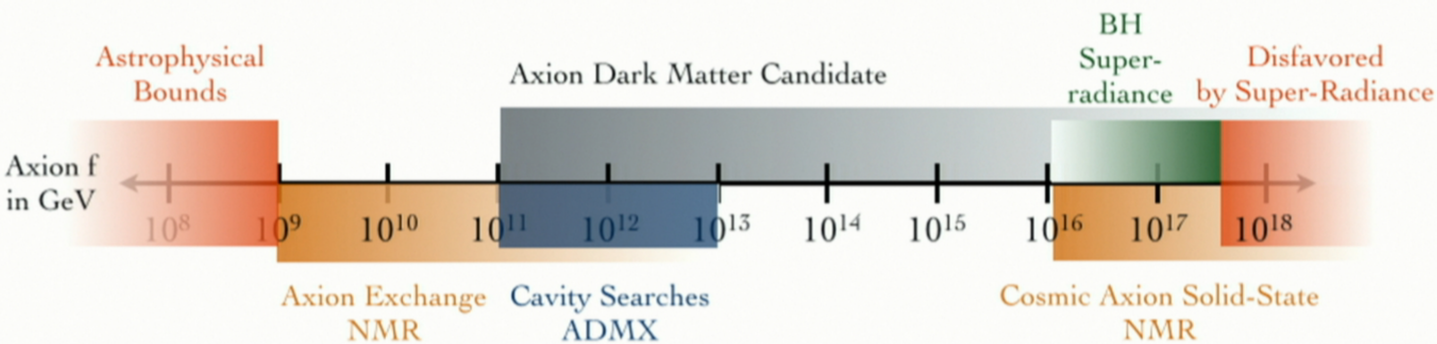
GW annihilations



High frequency GWs



New Ideas for Axion Detection



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