The Highs and Lows of The QCD Axion

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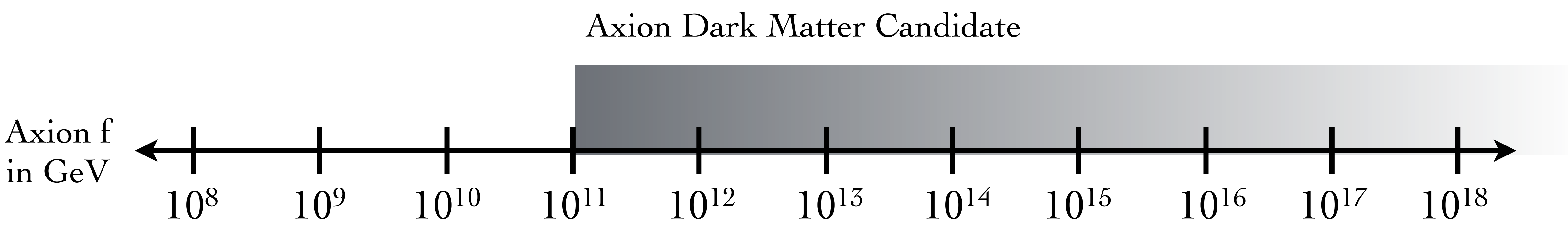
The Parameter Space of the QCD Axion



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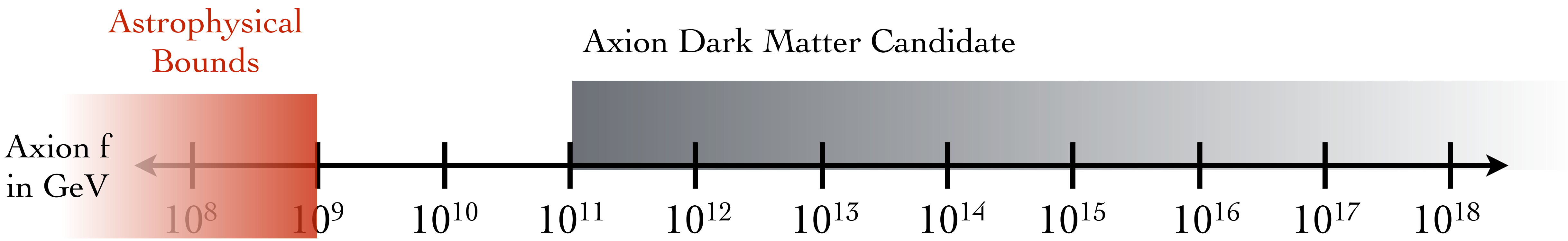

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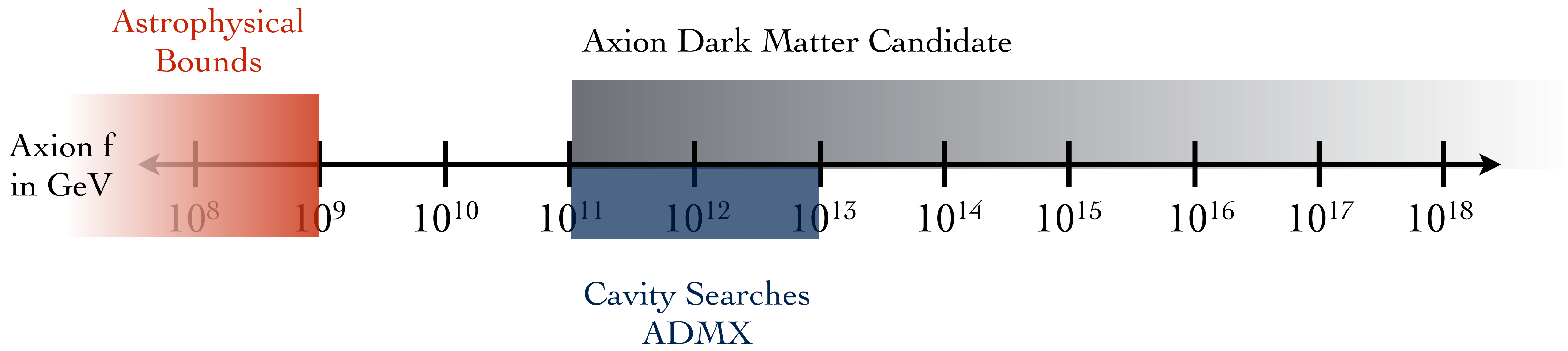

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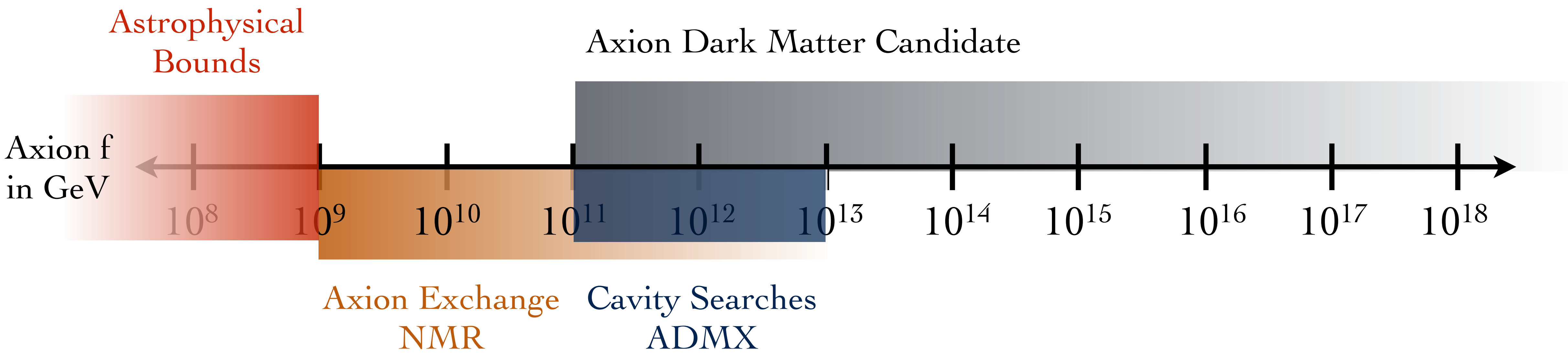
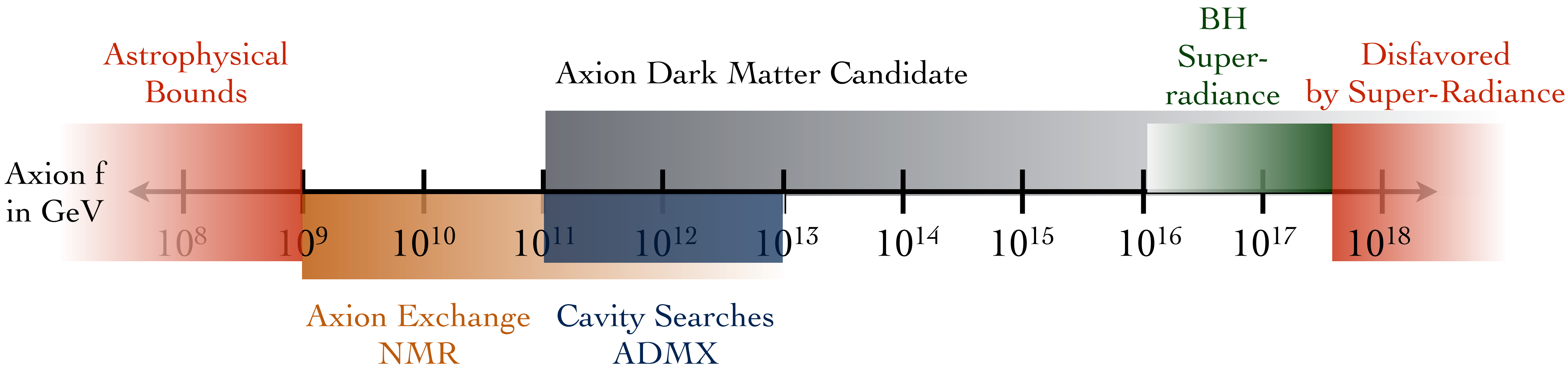


- Axion Force Detection with Nuclear Magnetic Resonance

The Parameter Space of the QCD Axion



- Axion Force Detection with Nuclear Magnetic Resonance

- Axion Signals from Black Hole Super-radiance

Short Range Axion Interactions

- Scalar Axion Coupling

$$\mathcal{L} \supset g_s a \bar{\psi} \psi$$

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

From CP violation in the Standard Model

From CP violation allowed by experiment

- Yukawa Potential Generated by Mass with N nucleons

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

Short Range Axion Interactions

- Pseudo-scalar axion coupling

$$\mathcal{L} \supset \frac{g_p \partial_\mu a}{m_f} \bar{\psi} \gamma^\mu \gamma_5 \psi$$

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

In the non-relativistic limit:

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

- Yukawa Potential Generated by Mass with N spins

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

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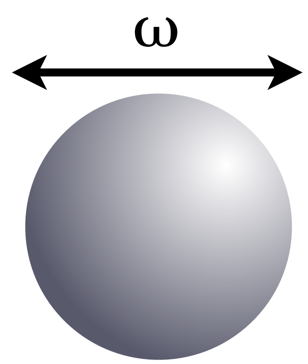
Couplings and potential similar to a magnetic field

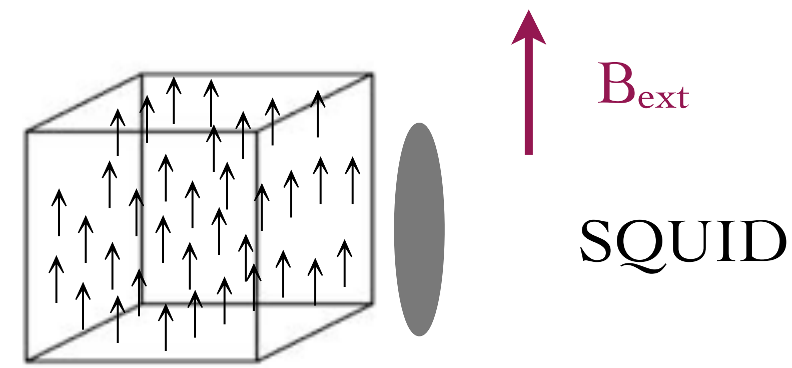
Detection Strategy

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:

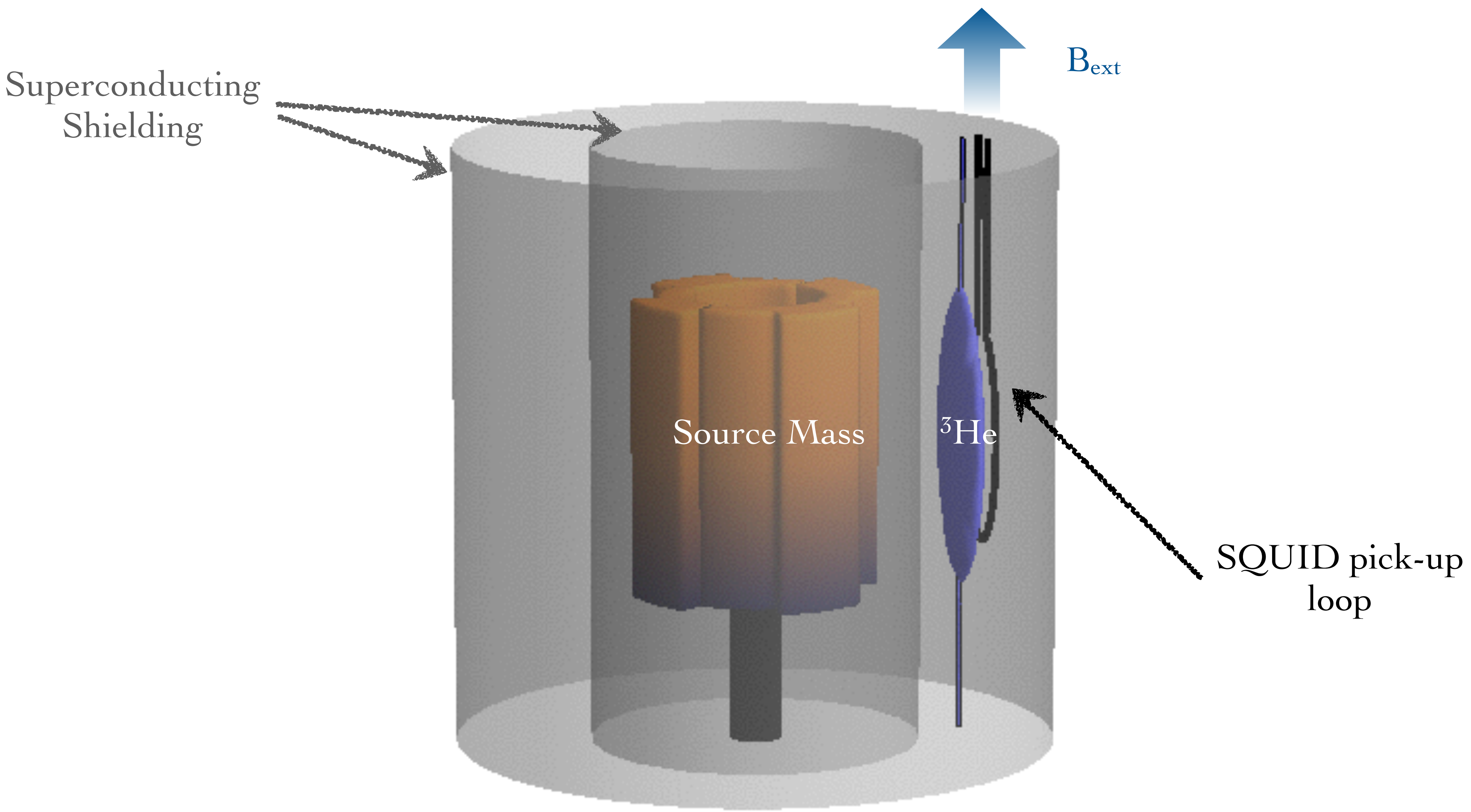
$$\vec{M}(t) = n_{NMR}\, p \vec{\mu}\, \Delta E_{NMR}\, t \sin \omega t$$

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

Experimental Setup



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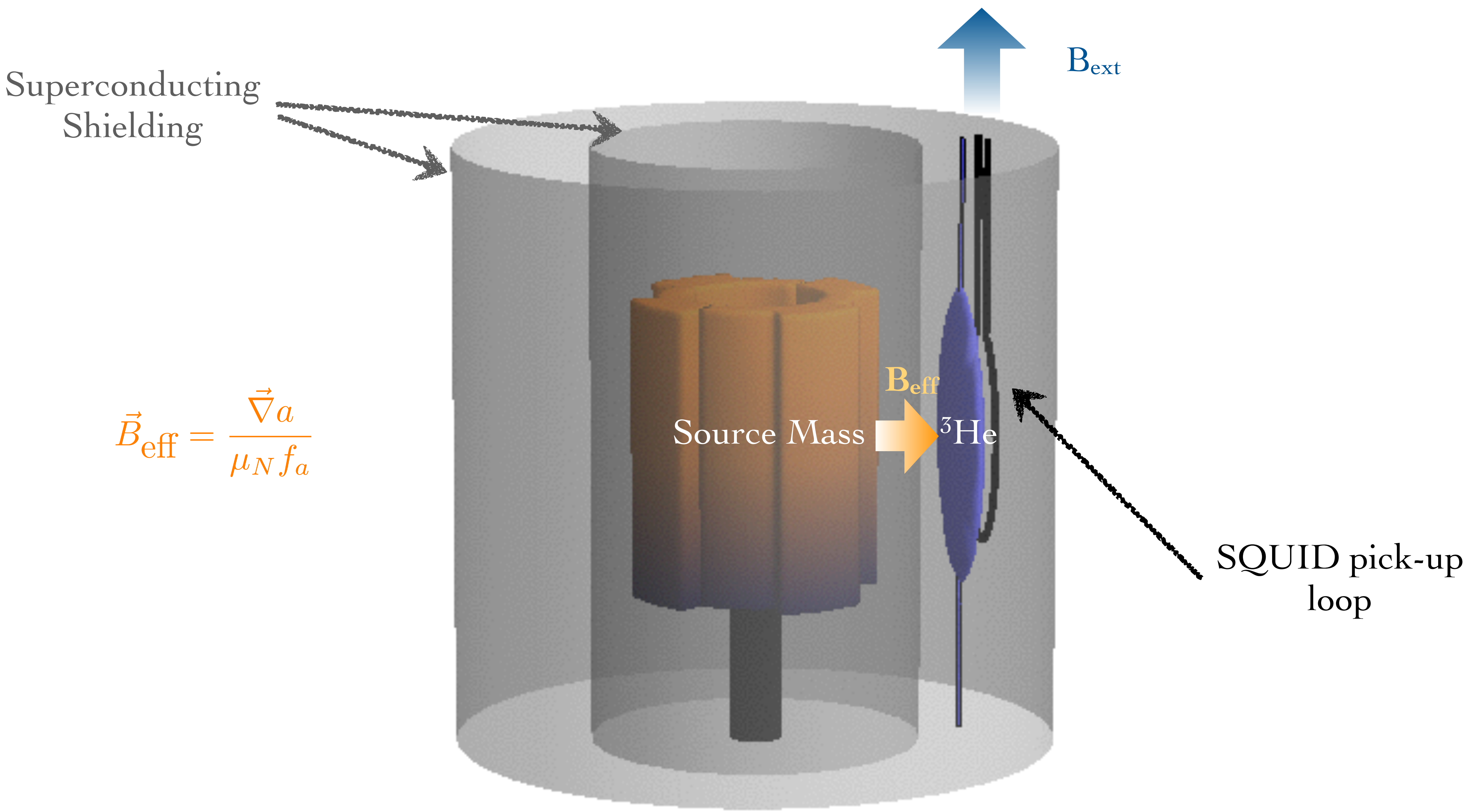
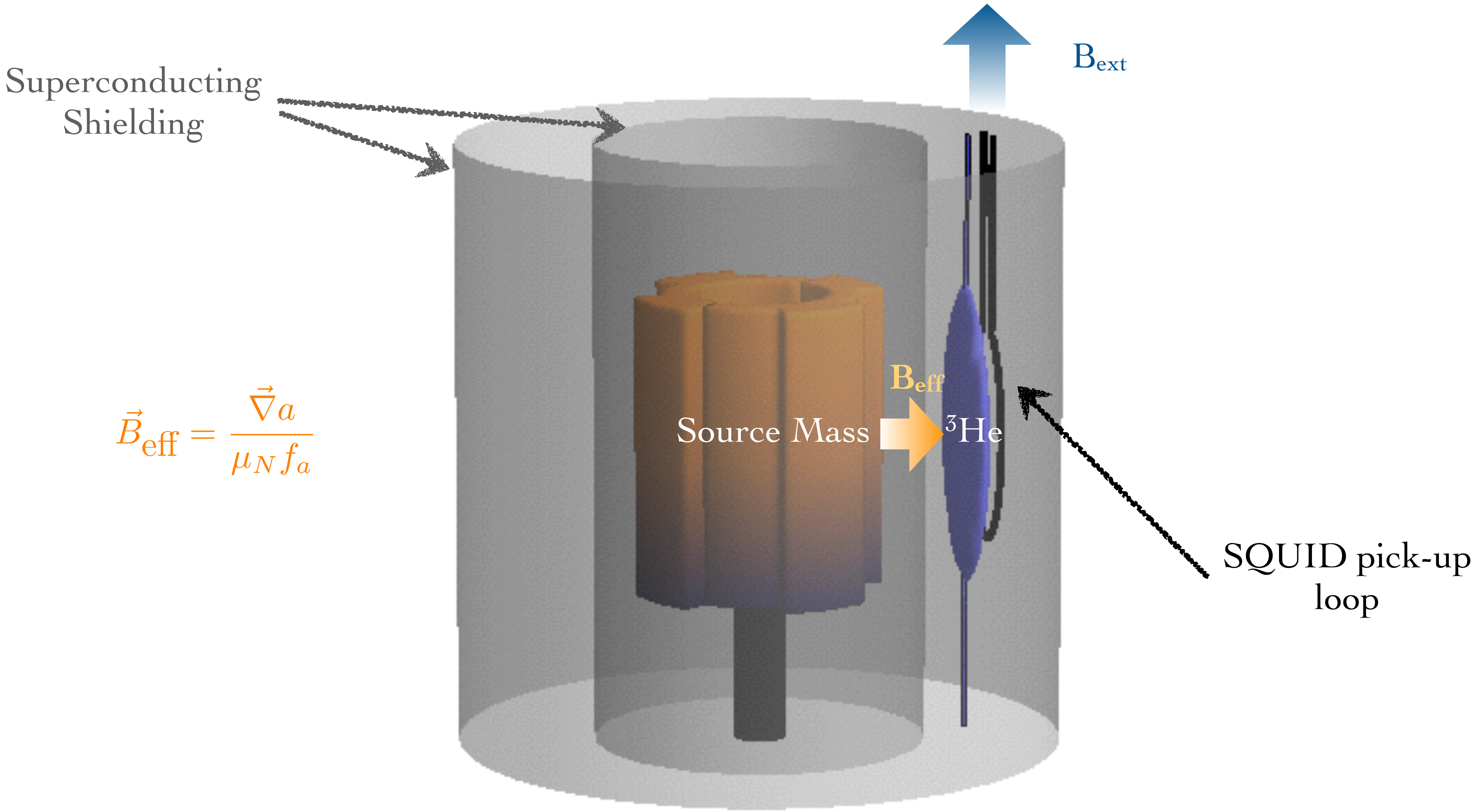


$$\vec{B}_{\text{eff}} = \frac{\vec{\nabla} a}{\mu_N f_a}$$

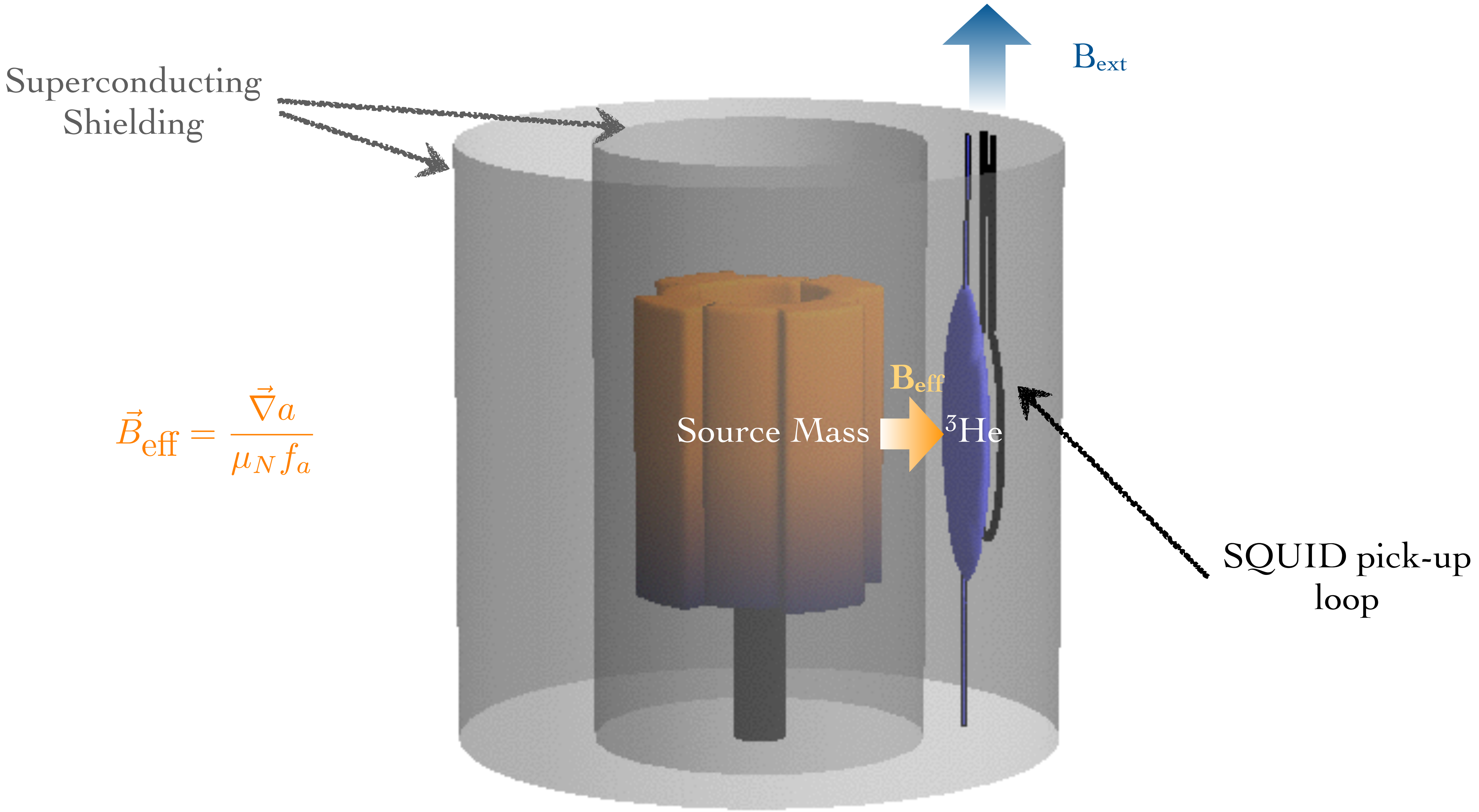
Experimental Setup



$$\vec{B}_{\text{eff}} = \frac{\vec{\nabla} a}{\mu_N f_a}$$

- B_{eff} is different for nucleons and electrons
- B_{eff} doesn't couple to orbital angular momentum
- B_{eff} cannot be screened

Experimental Setup



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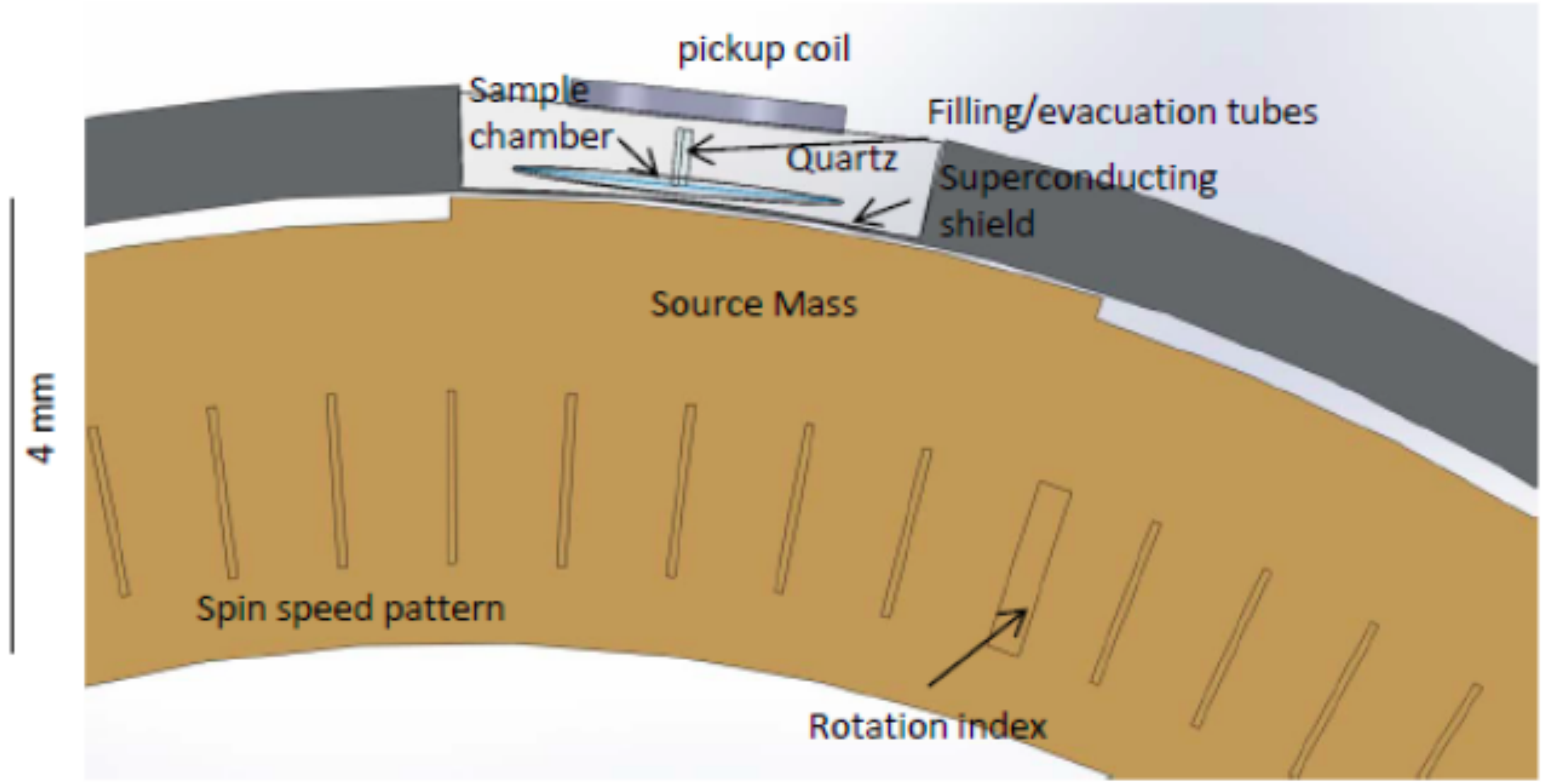
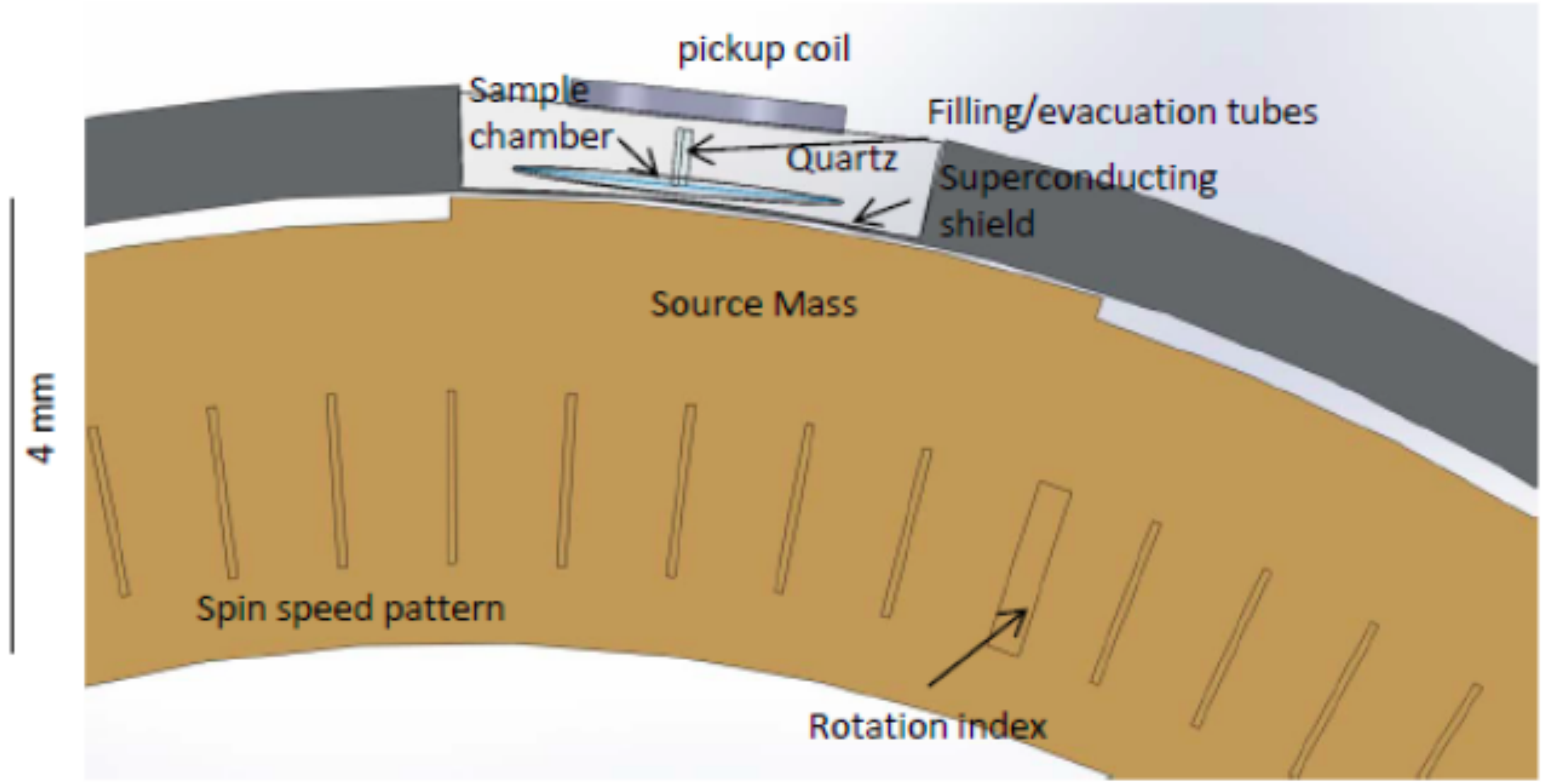
$$B_{\text{min}} \approx p^{-1}\sqrt{\frac{2\hbar}{n_s \mu_{^3\text{He}} \gamma V T_2}} = 10^{-20}\frac{T}{\sqrt{Hz}} \times \left(\frac{1}{p}\right)\left(\frac{1\ \text{cm}^3}{V}\right)^{1/2}\left(\frac{10^{21}\ \text{cm}^{-3}}{n_s}\right)^{1/2}\left(\frac{1000\ \text{sec}}{T_2}\right)^{1/2}$$

Experimental Setup in This Talk



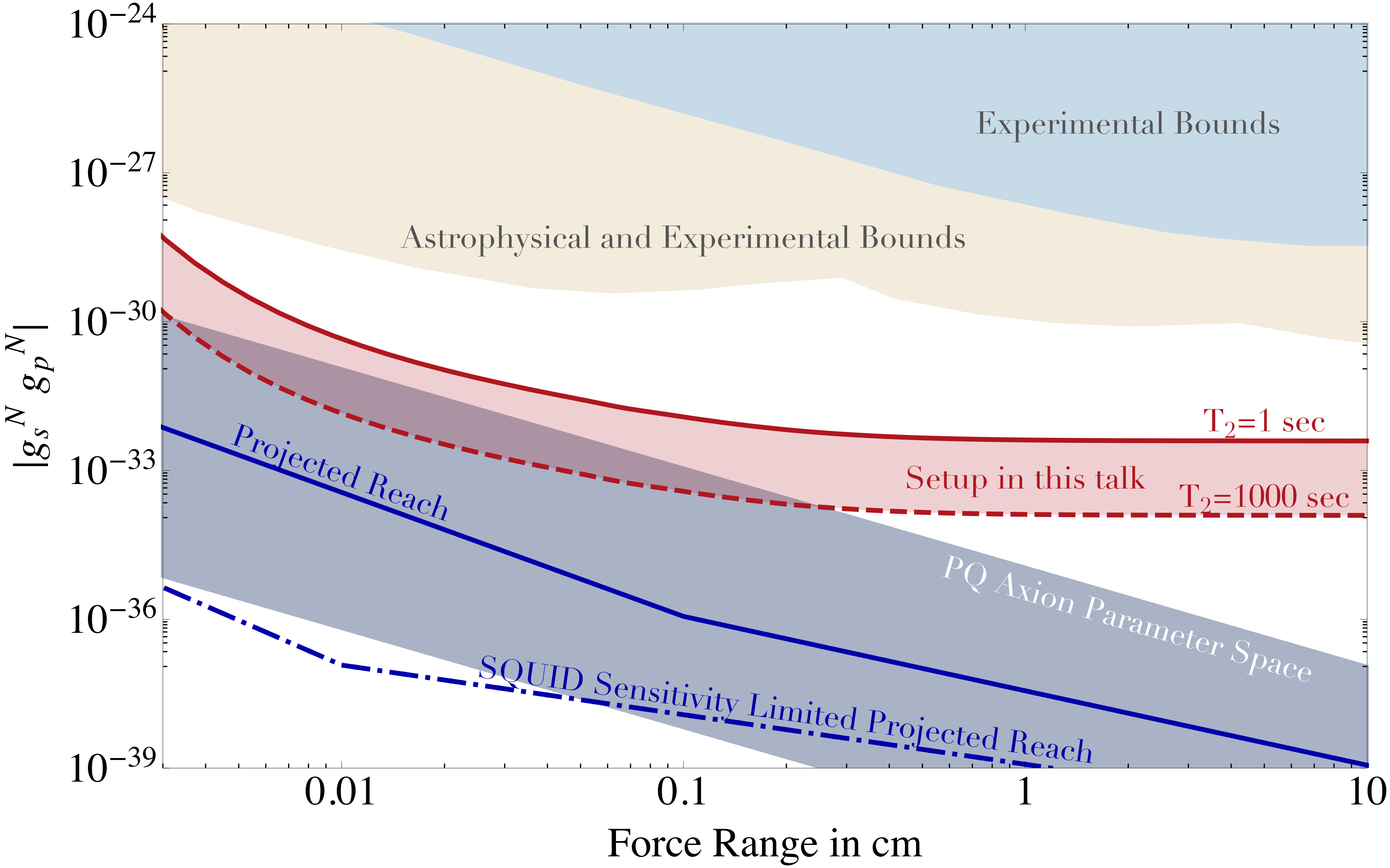
Experimental Setup in This Talk



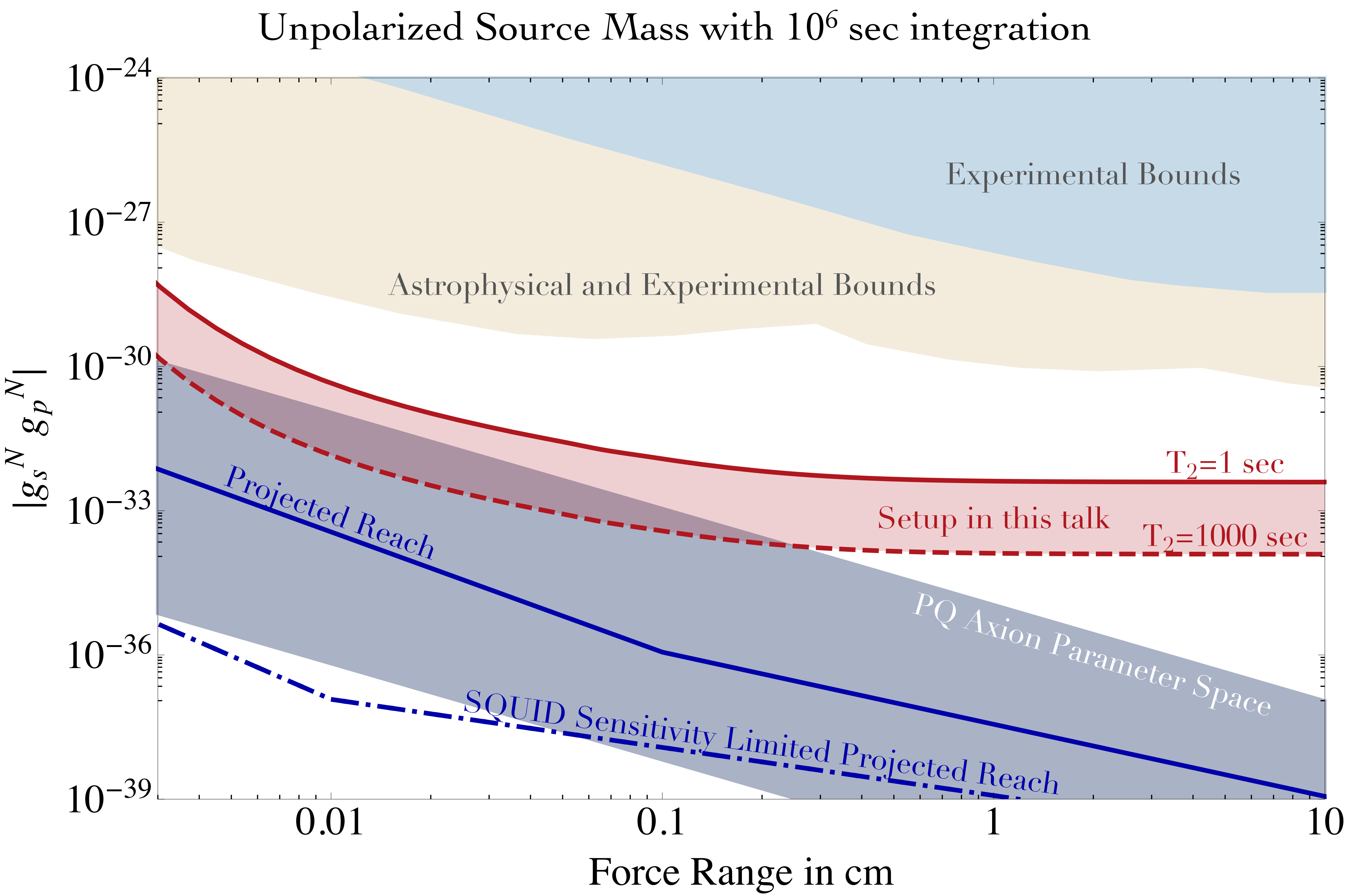
- 10 segments
- 100 Hz Larmor precession frequency for ^{3}He nuclei
- 2×10^{21} / cc ^{3}He polarized spin density
- 10 mm x 3 mm x 150 μm NMR sample size
- Tungsten (or nuclear - electron spin polarized He or Fe) source mass

Monopole-Dipole Interaction Reach

Unpolarized Source Mass with 10^6 sec integration

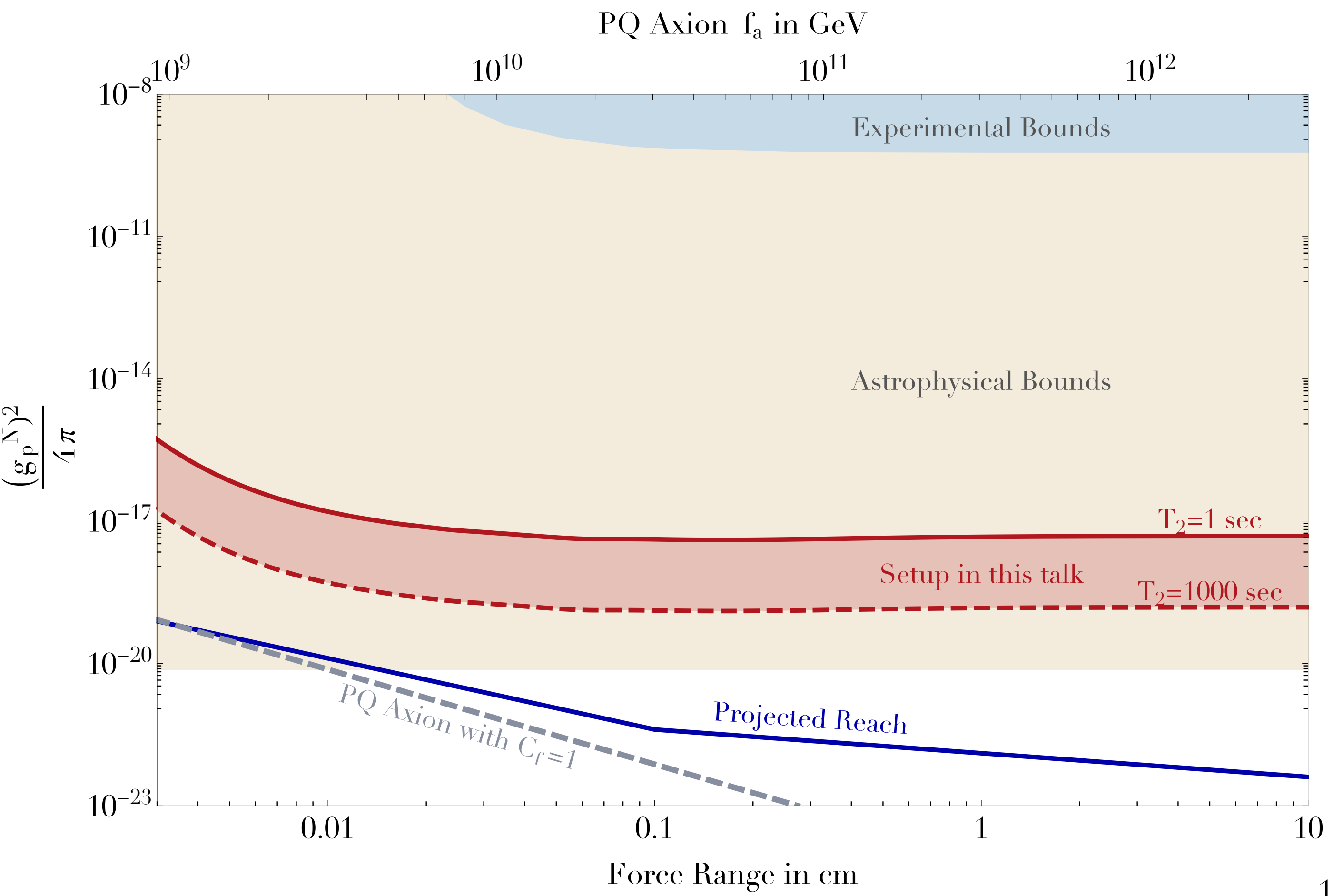


Monopole-Dipole Interaction Reach



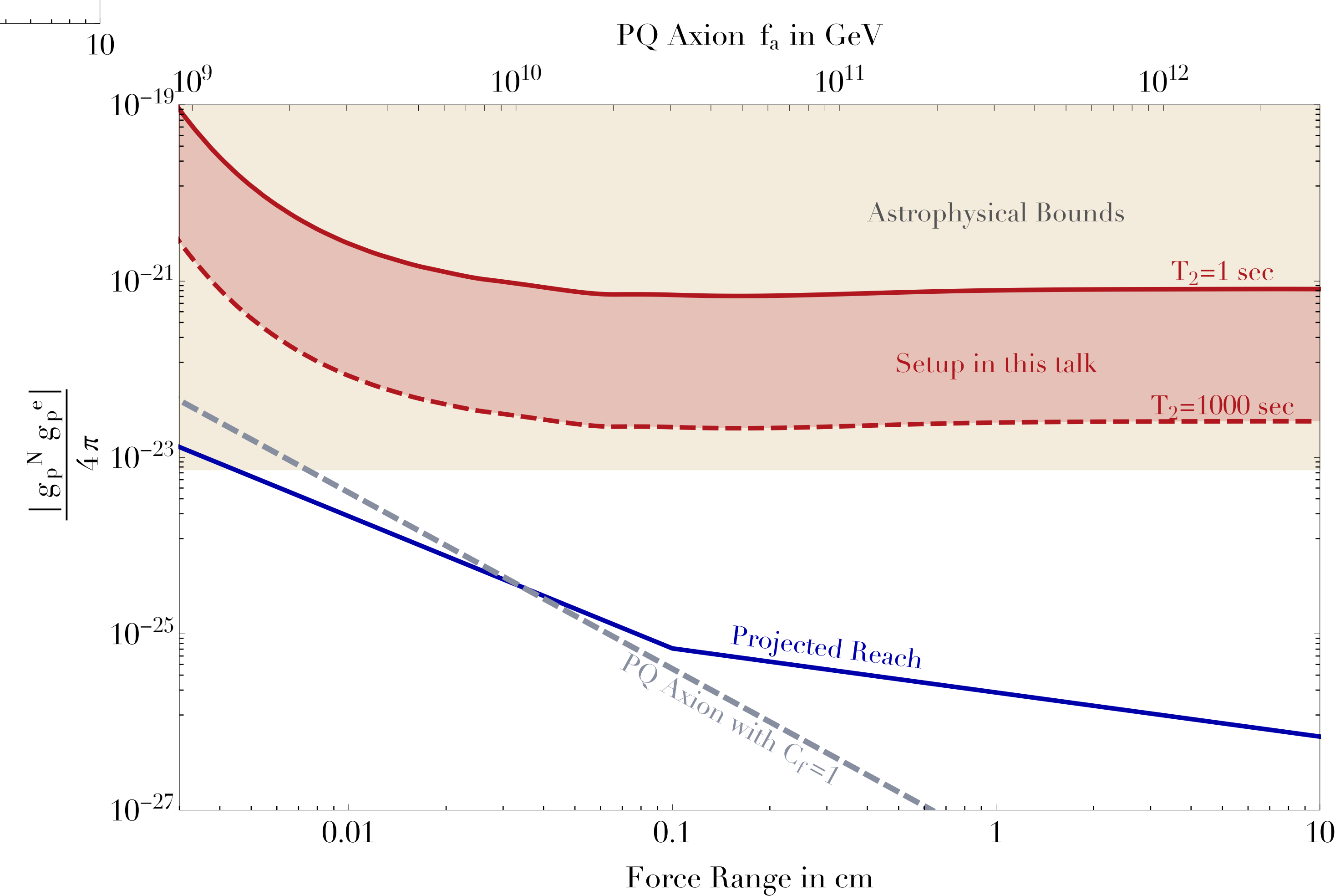
Projected Reach with increase of polarized spin density
and larger NMR sample volume

Dipole-Dipole Interaction Reach



Nuclear Spin Polarized Source Mass with 10^6 sec integration

Electron Spin Polarized Source Mass with 10^6 sec integration

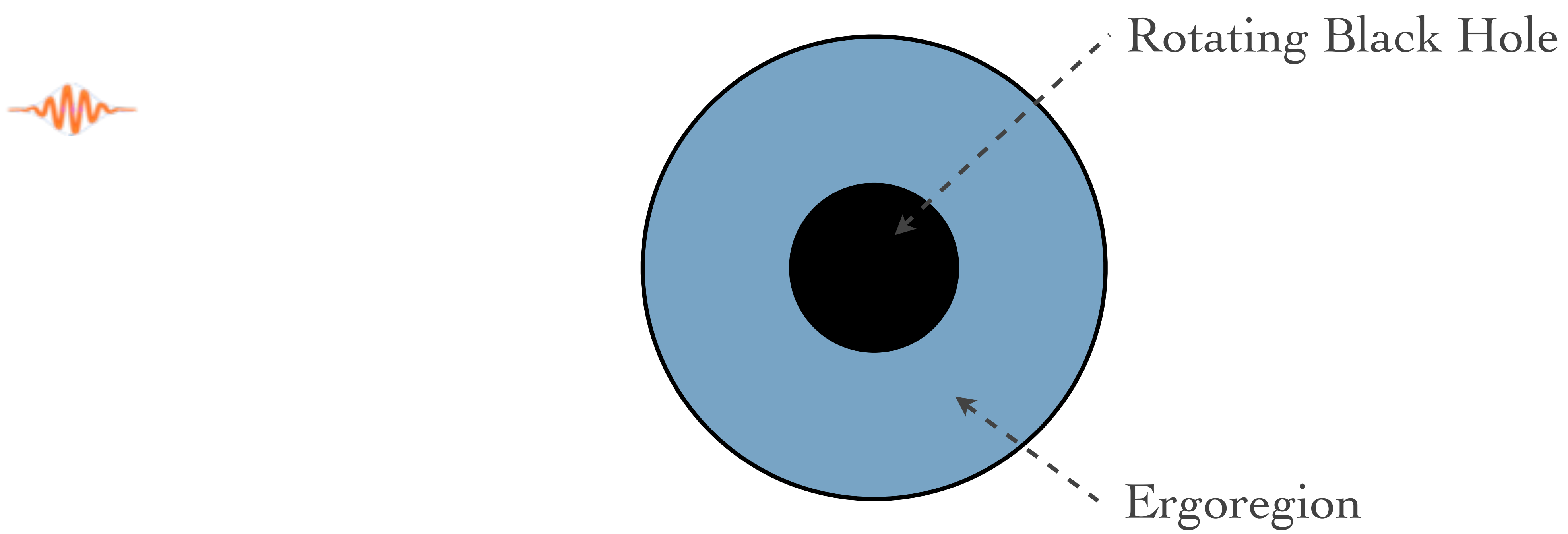


Black Hole Super-Radiance

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

Black Hole Superradiance

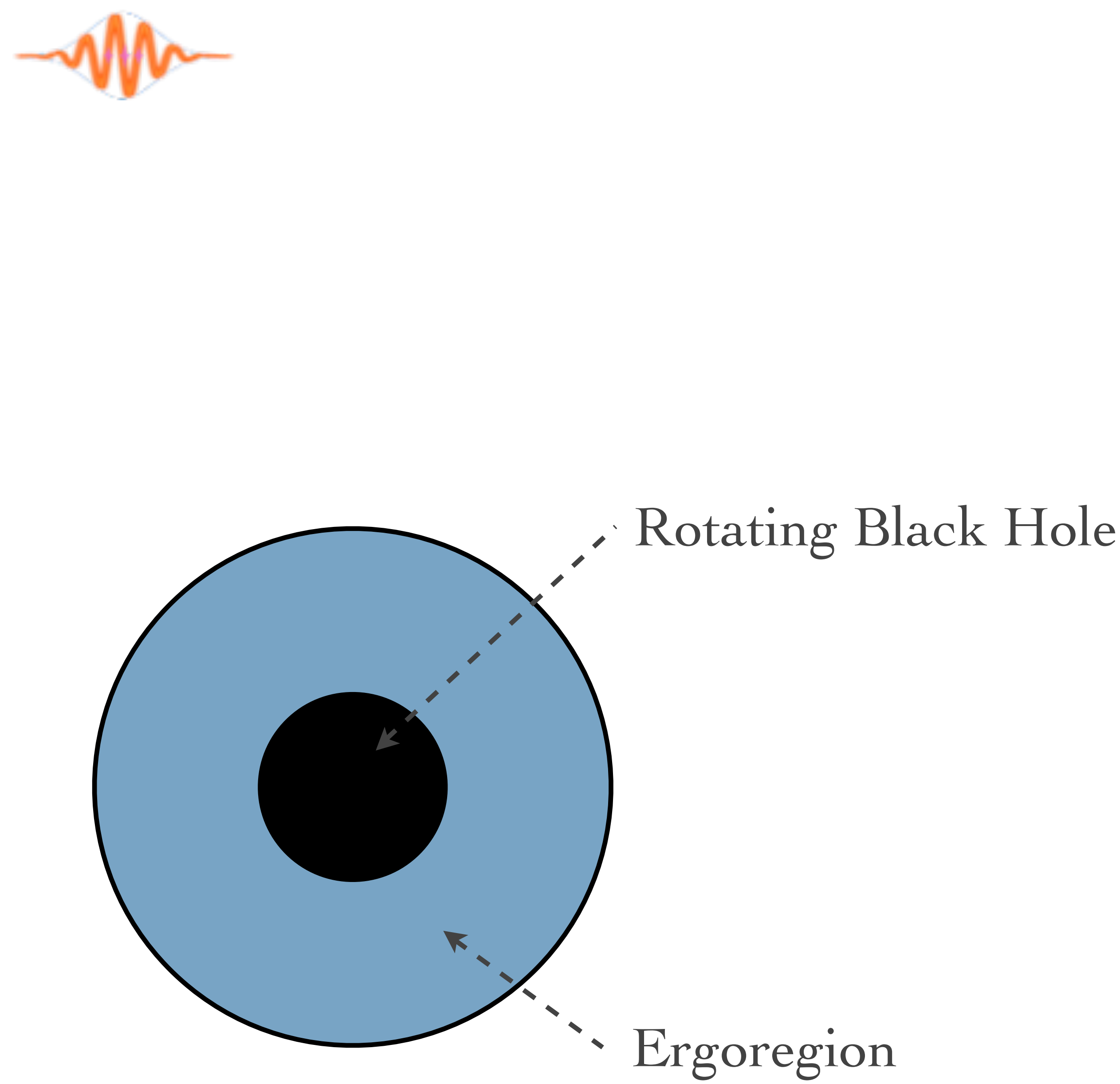
Penrose Process



Ergoregion: Region where even light has to be rotating

Black Hole Superradiance

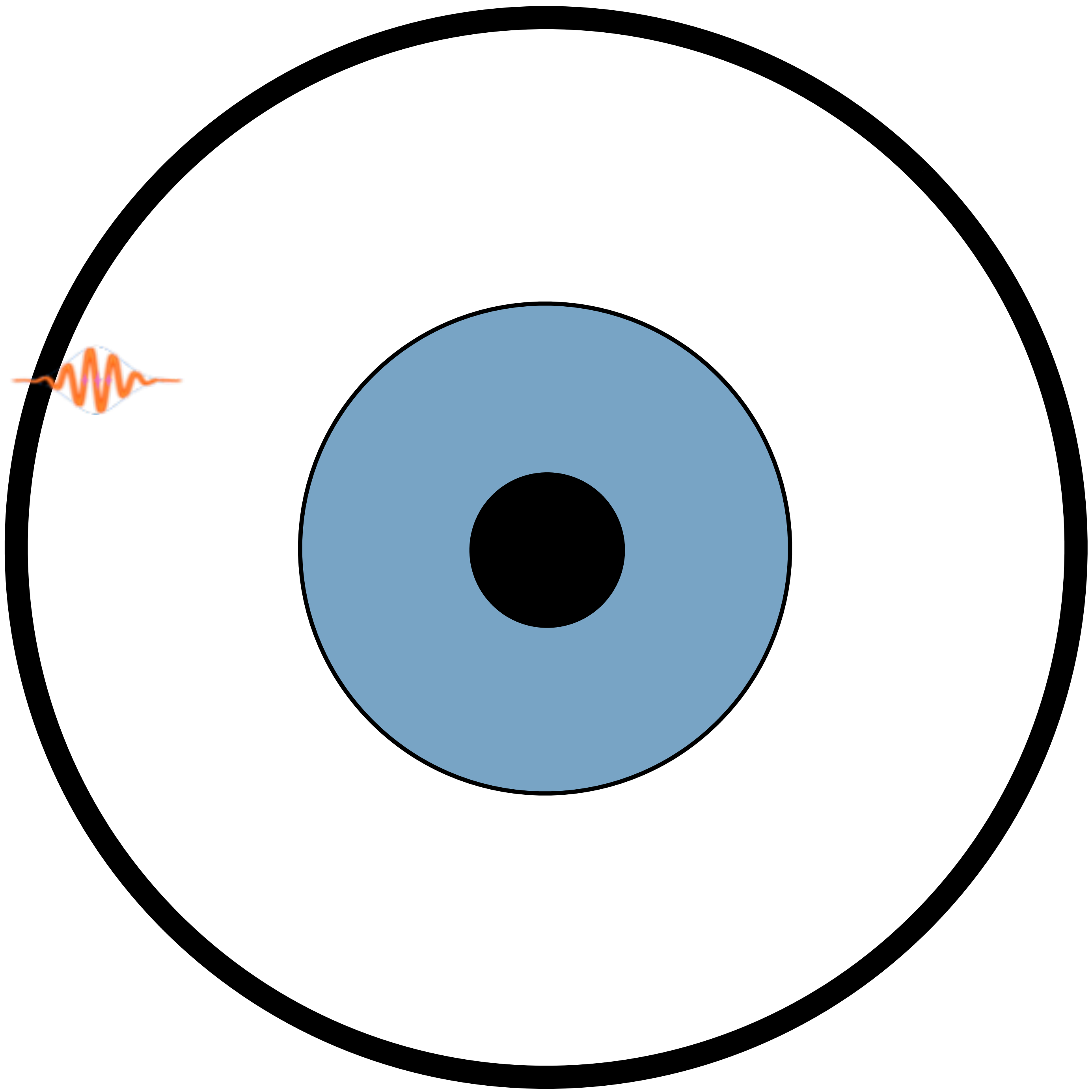
Penrose Process



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

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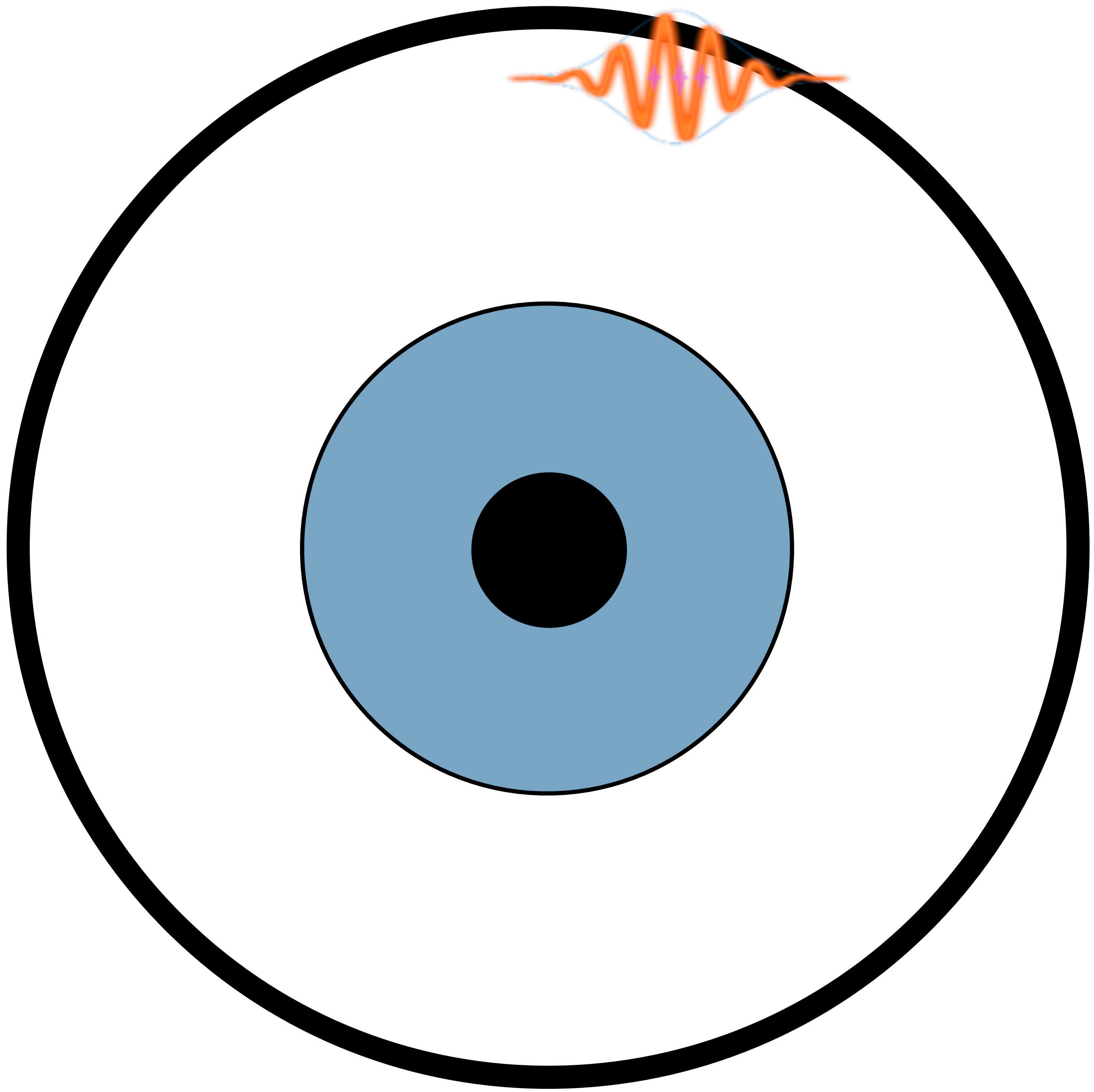

Photons reflected back and forth from the black hole
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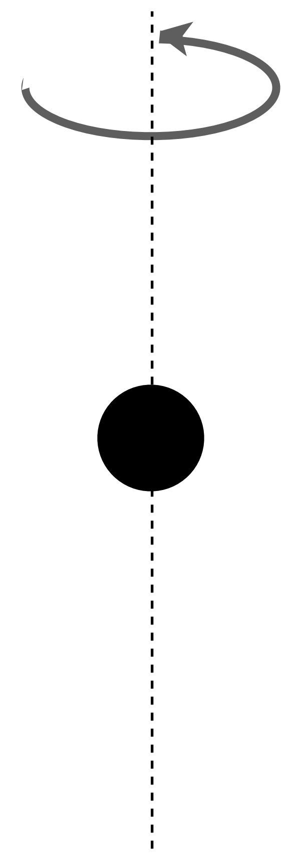
Superradiance for a Massive Boson

Penrose Process

Damour et al; Zouros & Eardley;
Detweiler; Gaina



Particle Compton Wavelength comparable to the size of the Black Hole

Superradiance for a Massive Boson

Damour et al; Zouros & Eardley;
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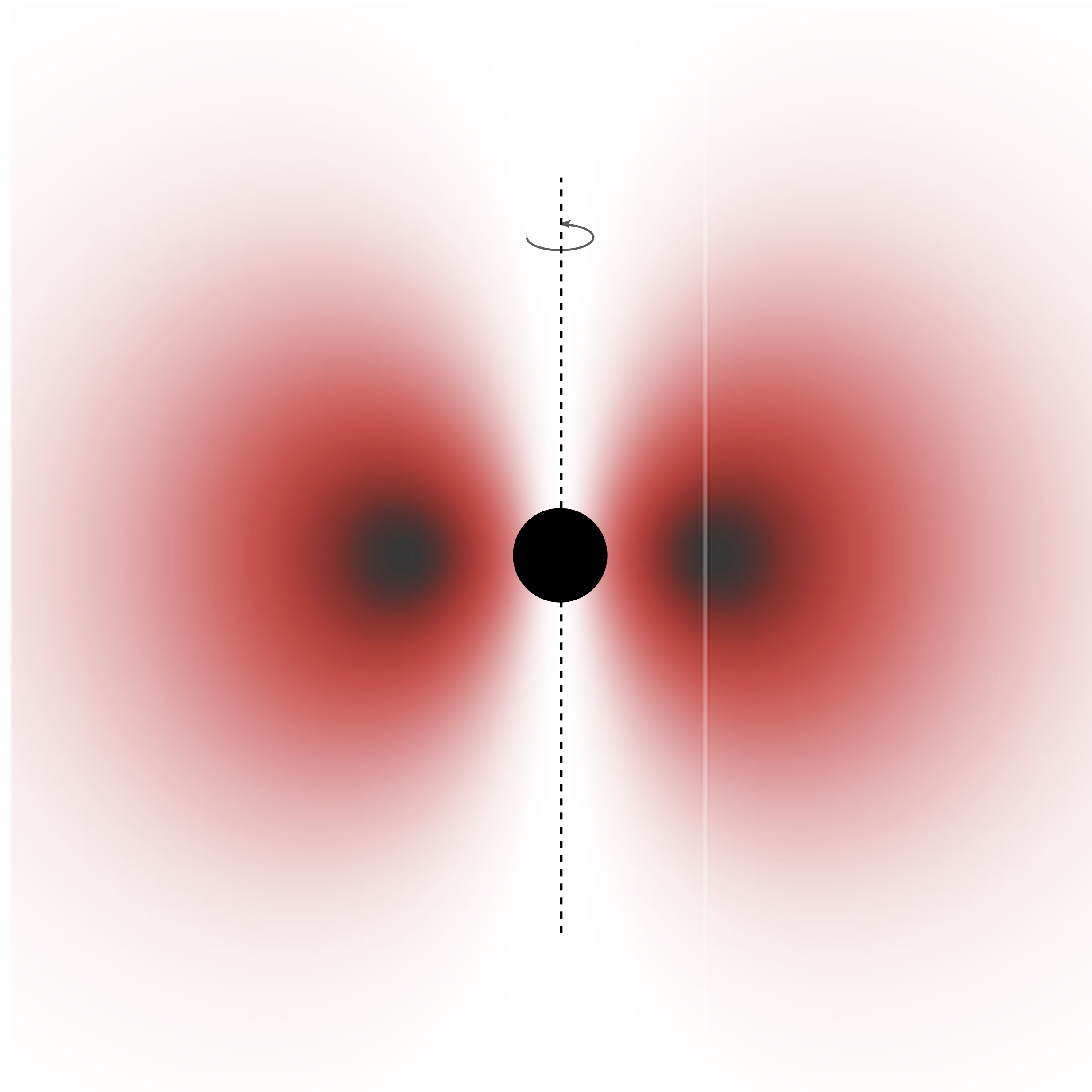
Penrose Process



Particle Compton Wavelength comparable to the size of the Black Hole

Gravitational Atom in the Sky

Away from the Black Hole: Newtonian Potential

The gravitational Hydrogen Atom

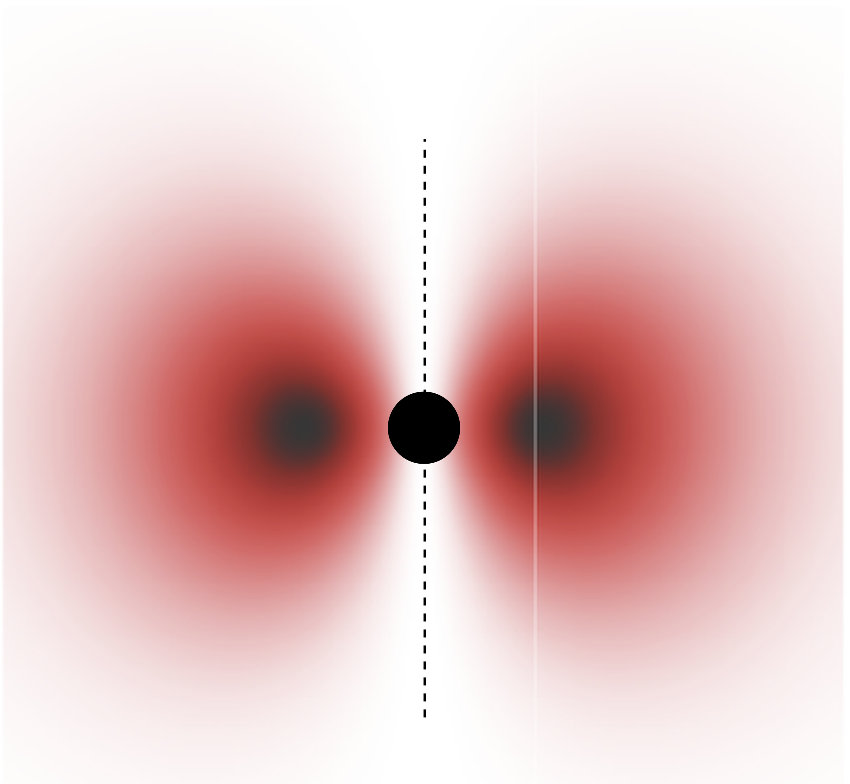
$$\alpha_{EM} = \frac{e^2}{4\pi} \quad \longrightarrow \quad \alpha = G_{\rm N} M_{\rm BH} \mu_a = R_g \mu_a$$

$$E_{\rm binding} = -\frac{\alpha_{EM}^2 m_e}{2n^2} \quad \longrightarrow \quad E_{\rm binding} = -\frac{\alpha^2 \mu_a}{2n^2}$$

fermions $\longrightarrow$ bosons

Occupation number

$1 \longrightarrow 10^{75}$



Superradiance Parametrics

Superradiance Condition

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

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

m : magnetic quantum number

a : BH spin, between 0 and 1

Superradiance Rate

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

When $R_g\ \mu_a >> 1$,

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

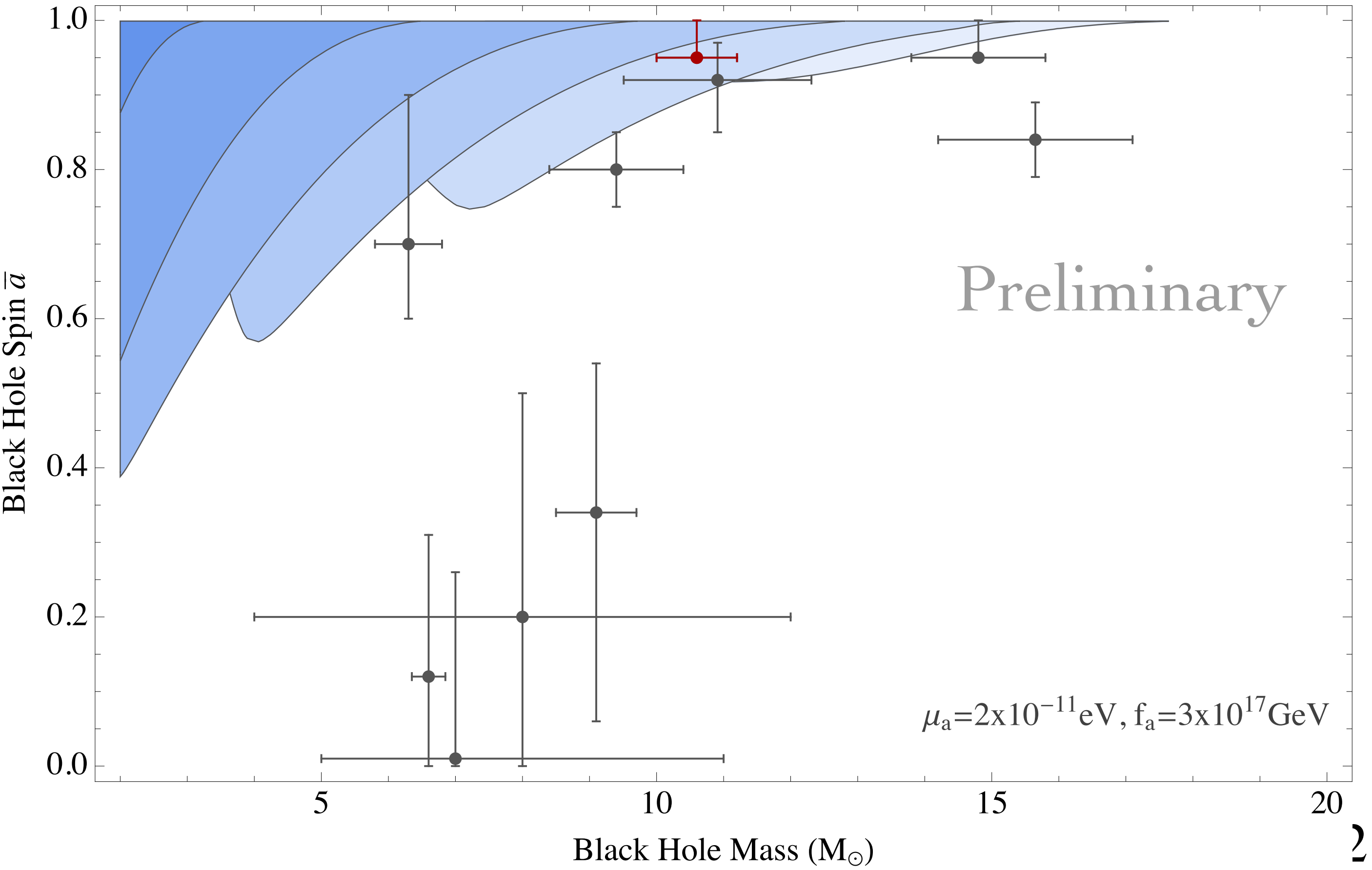
When $R_g\ \mu_a << 1$

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

QCD axion at high f_a matches stellar BH size:

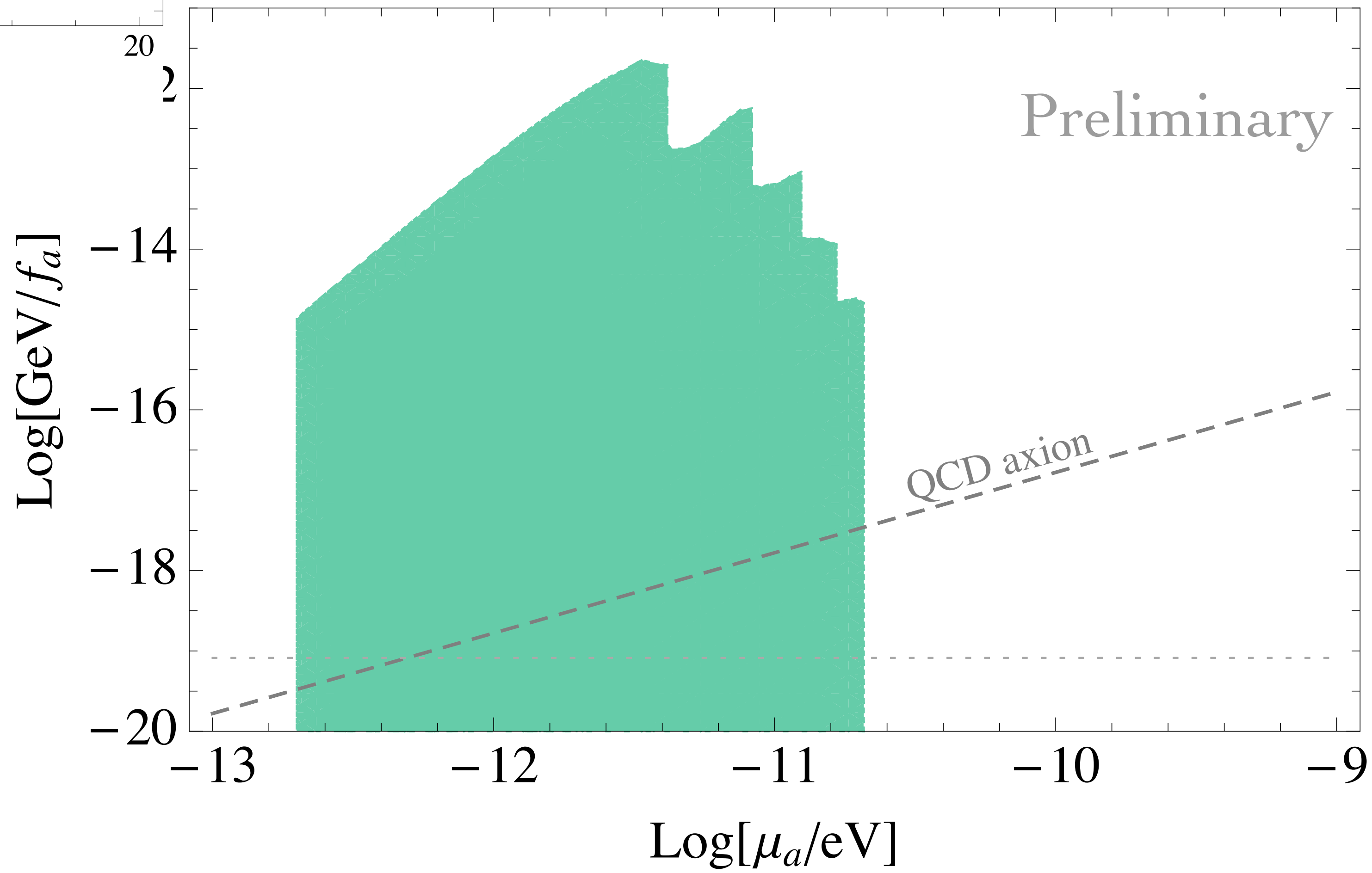
$$\mu_a \sim 6 \times 10^{-11}\ \text{eV}\ \frac{10^{17}\ \text{GeV}}{f_a} \sim (3\ \text{km})^{-1}\ \frac{10^{17}\ \text{GeV}}{\text{f}_\text{a}}$$

Spin-Down of Astrophysical Black Holes



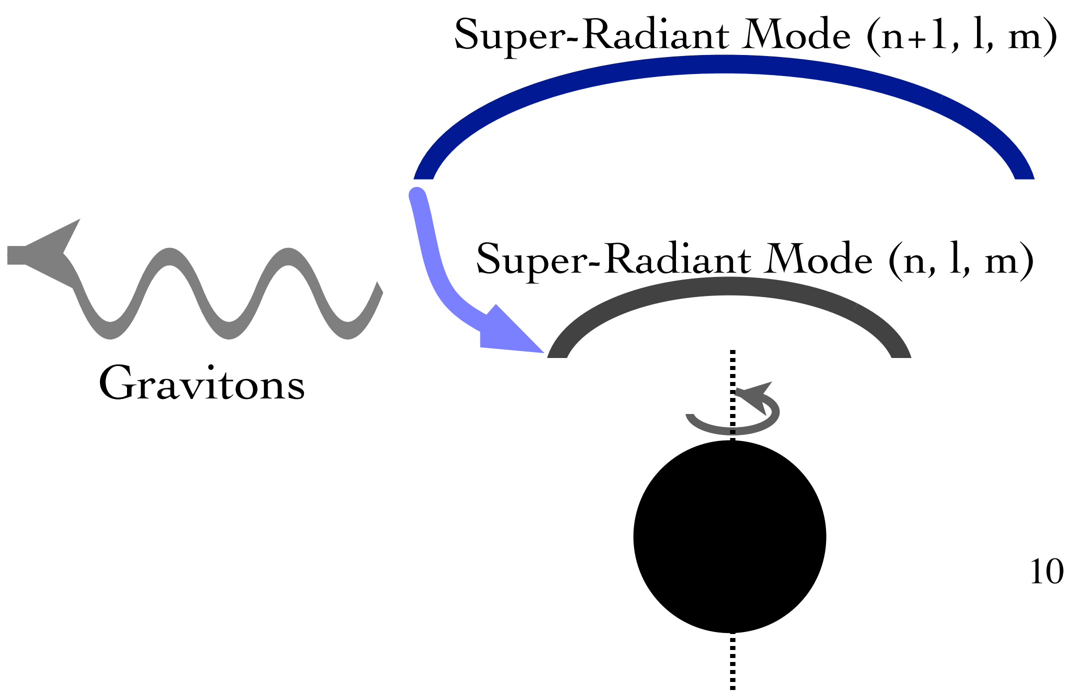
Black-Hole Spin Measurements

Excludes QCD axion f_a above $4{\times}10^{17}$ GeV

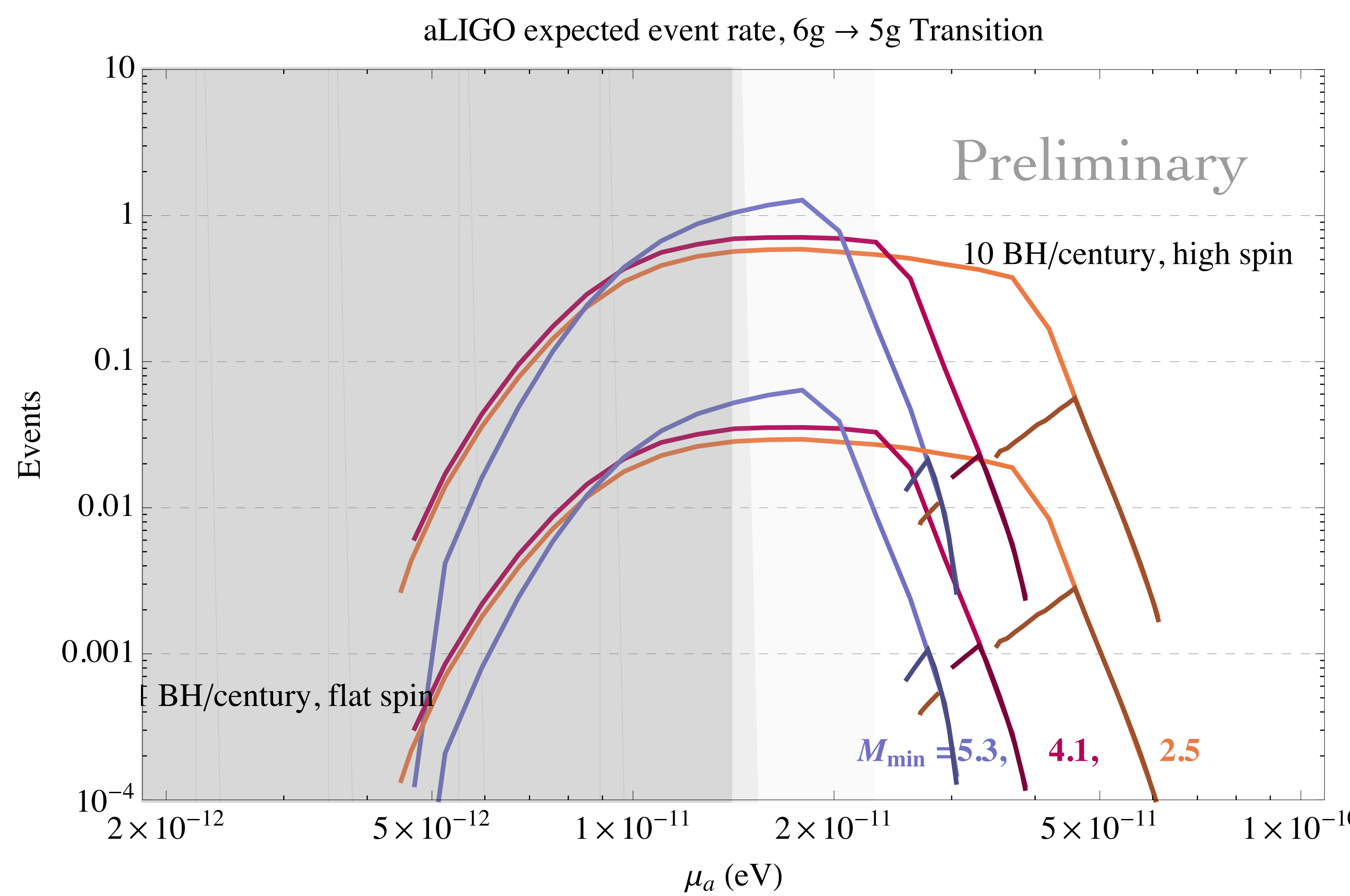


Super-Radiance Signatures

GW transitions

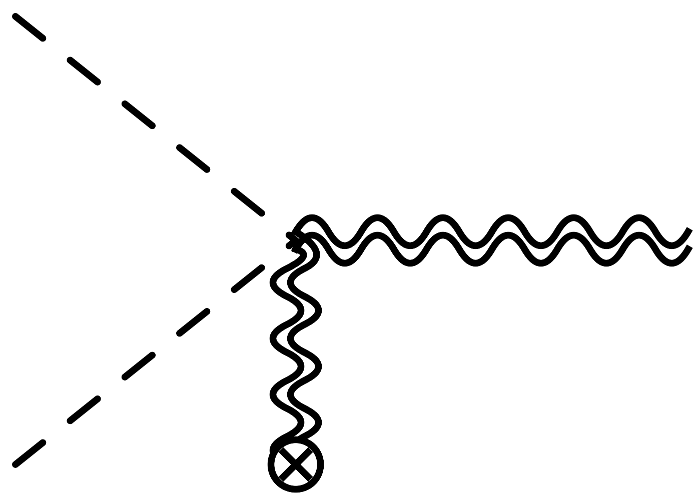


Optimal frequency for LIGO

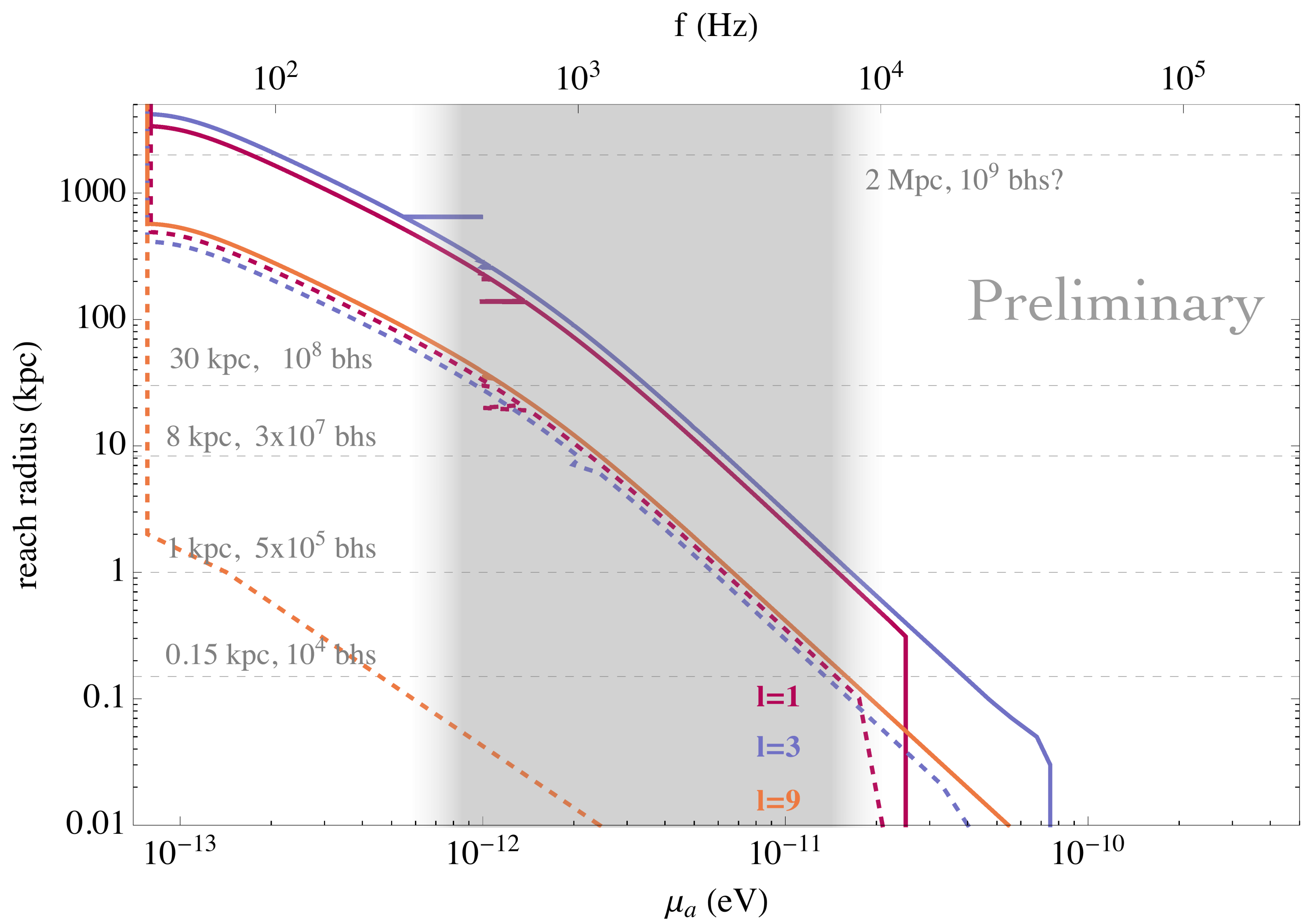


Super-Radiance Signatures

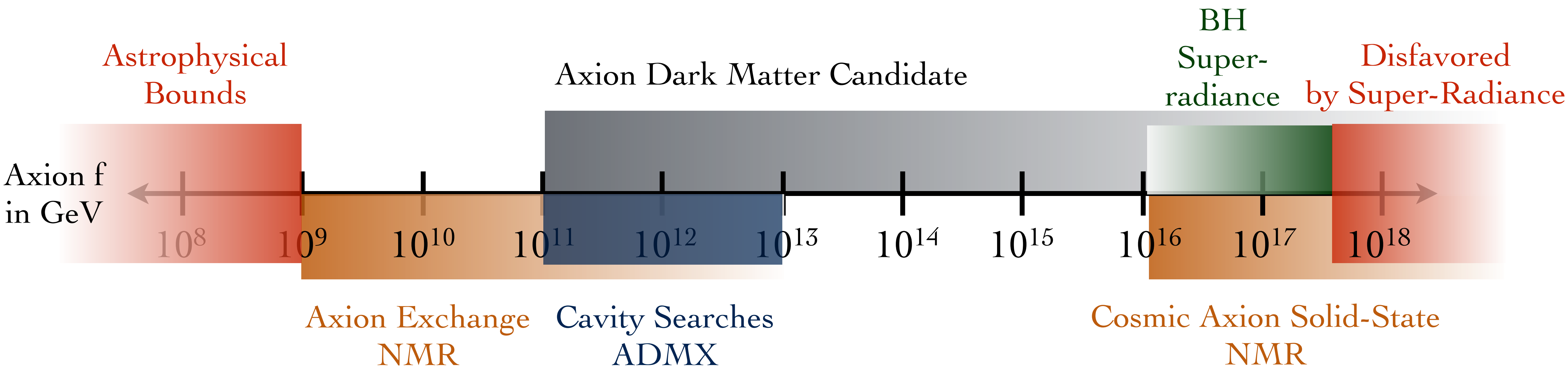
GW annihilations



High frequency GWs (>10 kHz)



New Ideas for Axion Detection



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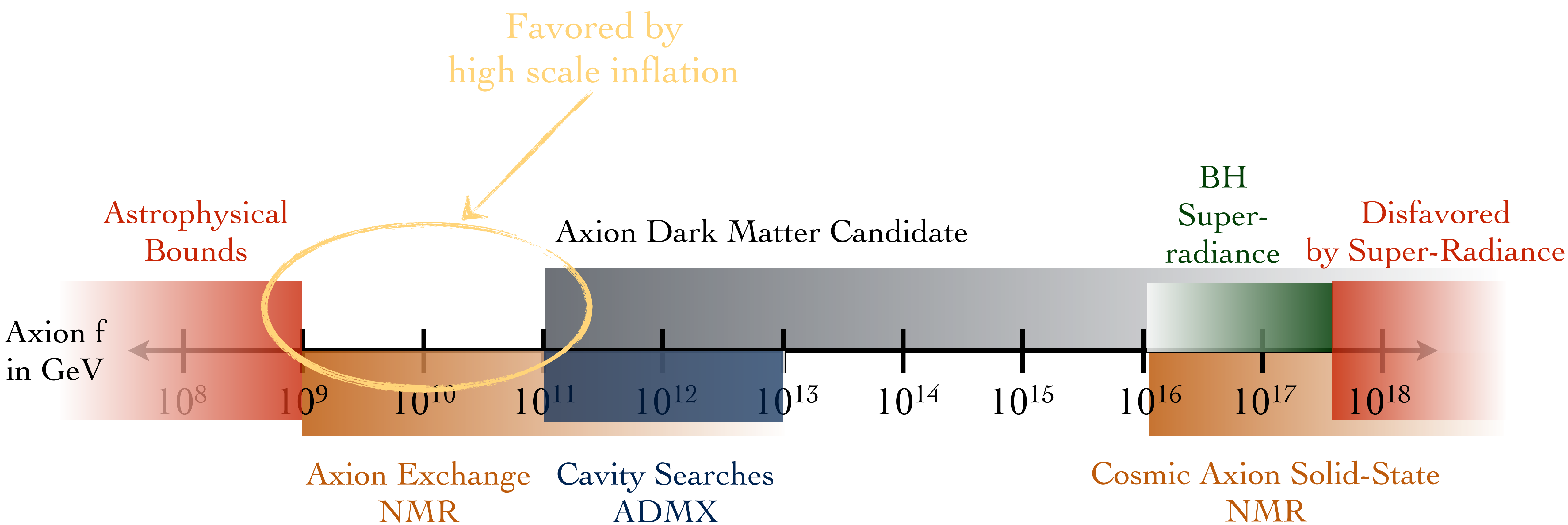

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