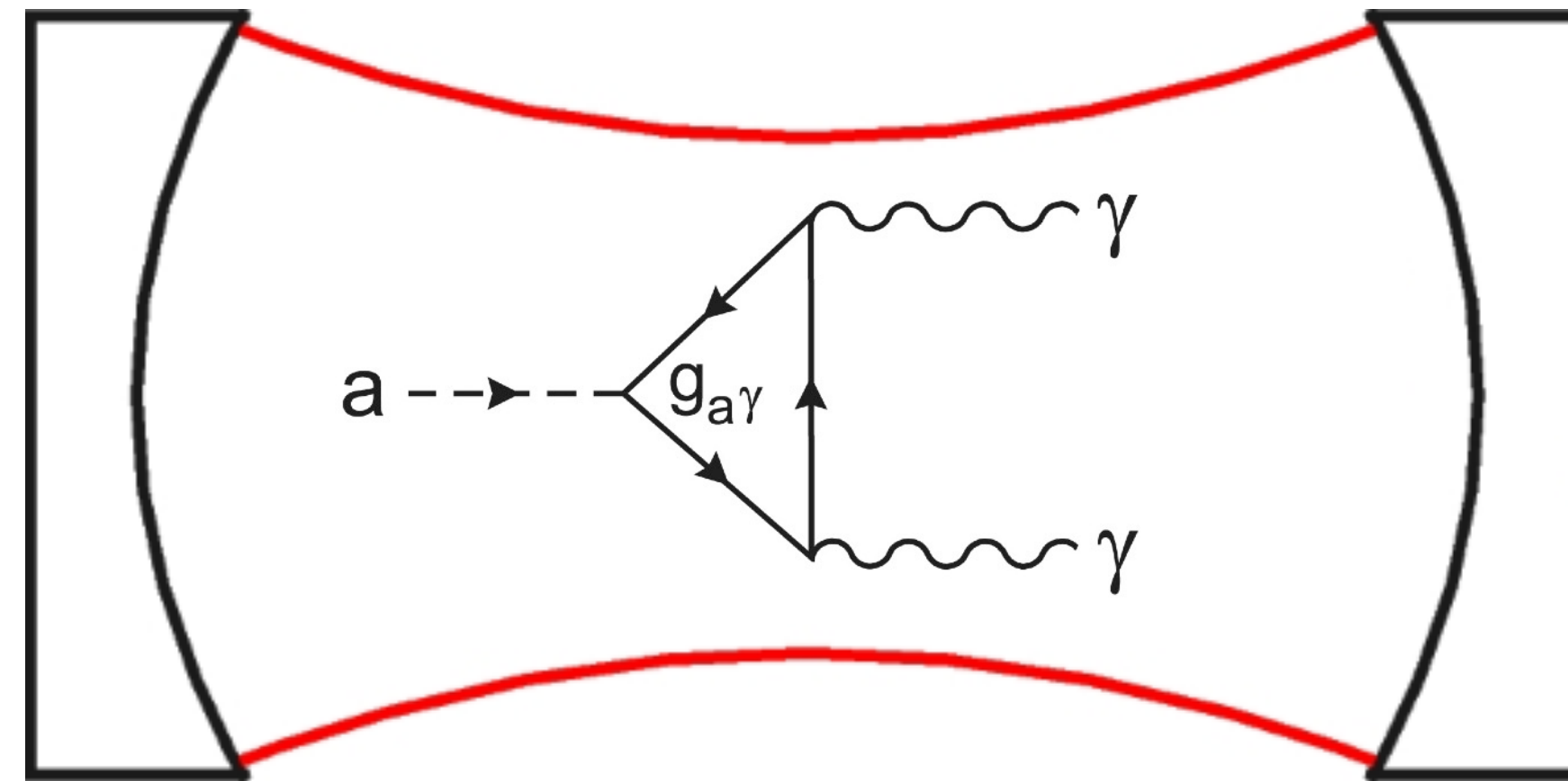


Resonant enhancement of axion dark matter decay



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Based on arXiv:2507.18508 with Bilal Ahmad and 刘宇昂,

第四届高能物理理论与实验融合发展研讨会, Sept 25, nhouston@bjut.edu.cn

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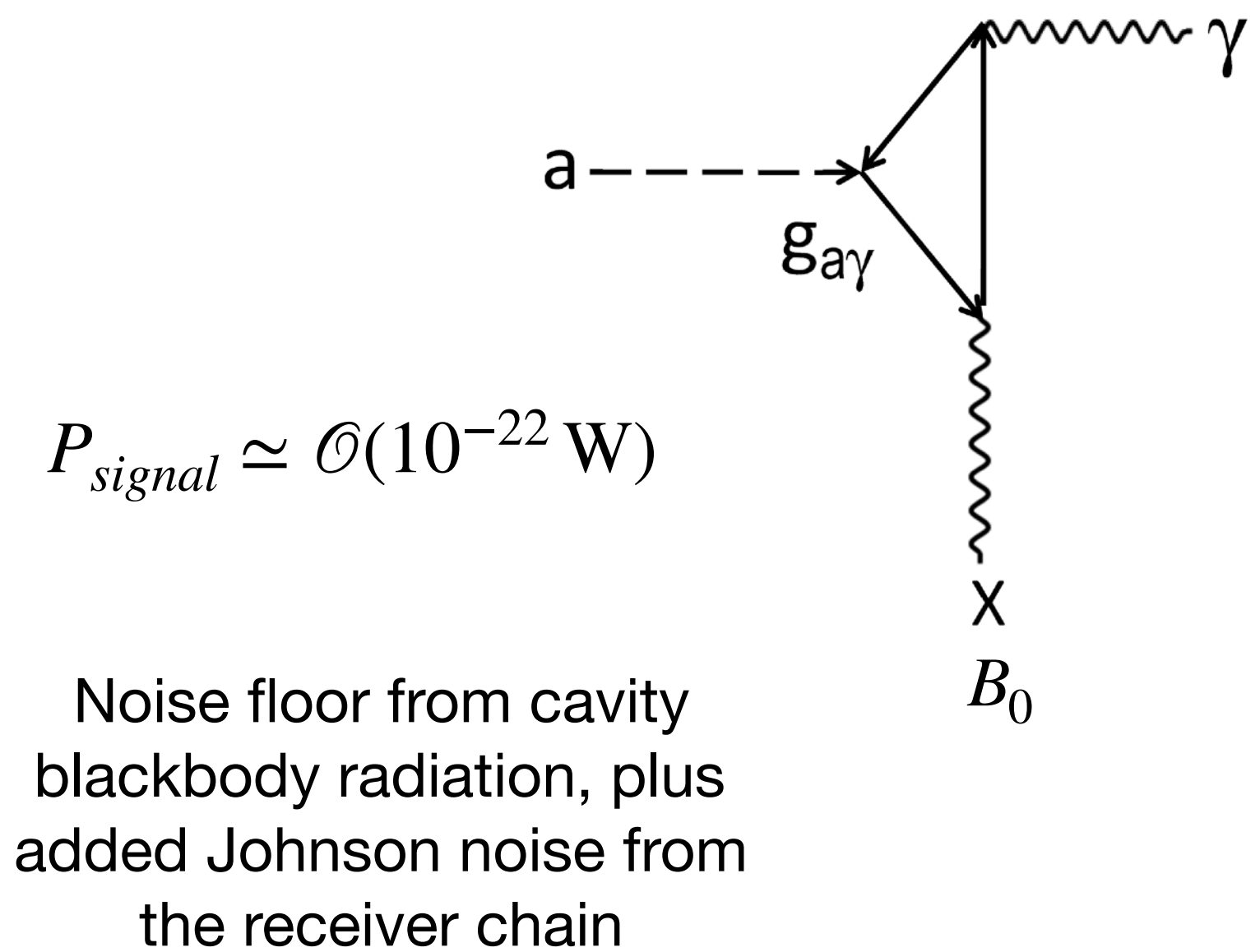
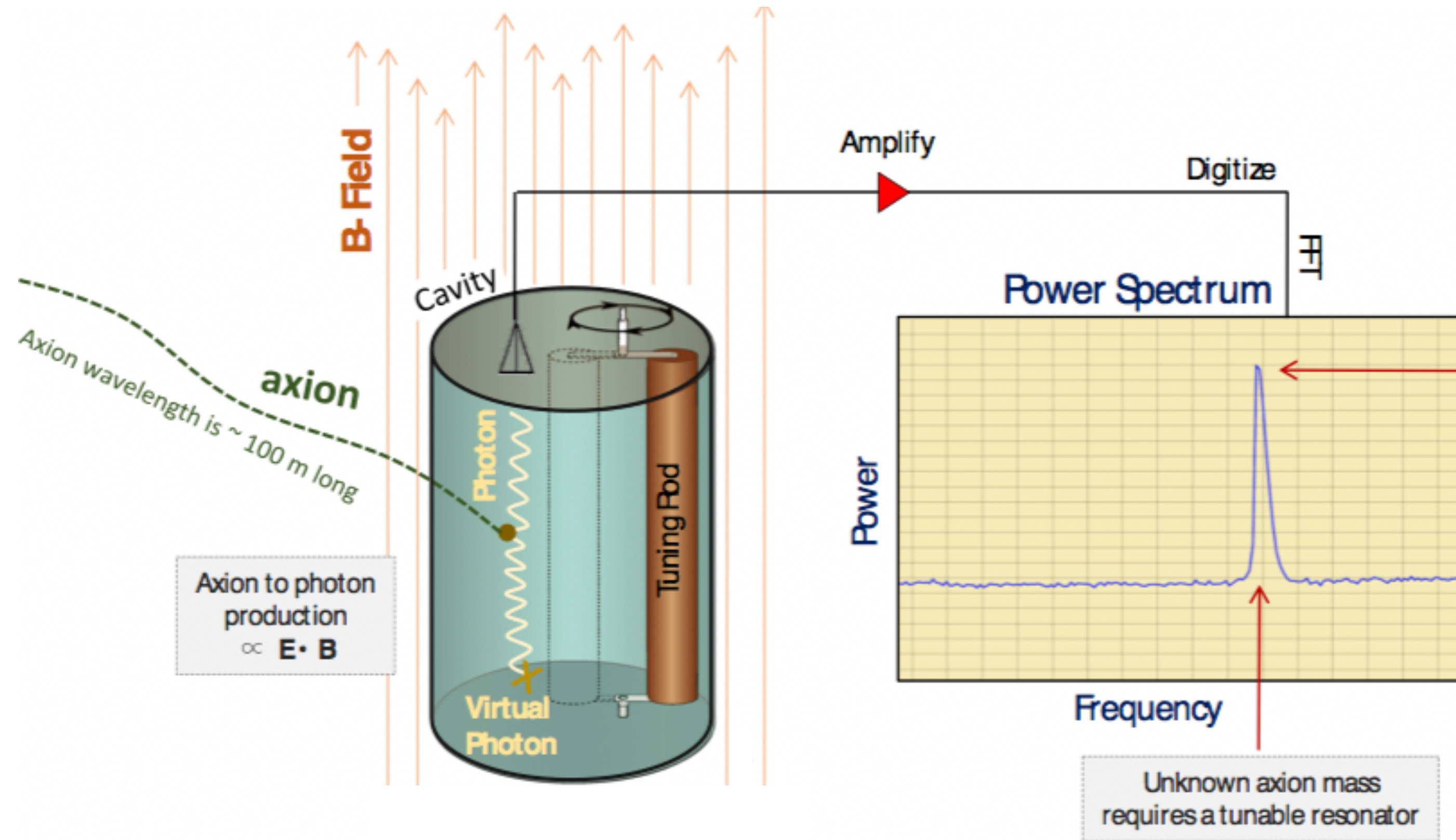
The big picture

- Very good indirect evidence exists for dark matter, so why hasn't it been detected?
- This talk is about using a resonant microwave cavity - a haloscope - to search for axion dark matter

Motivation

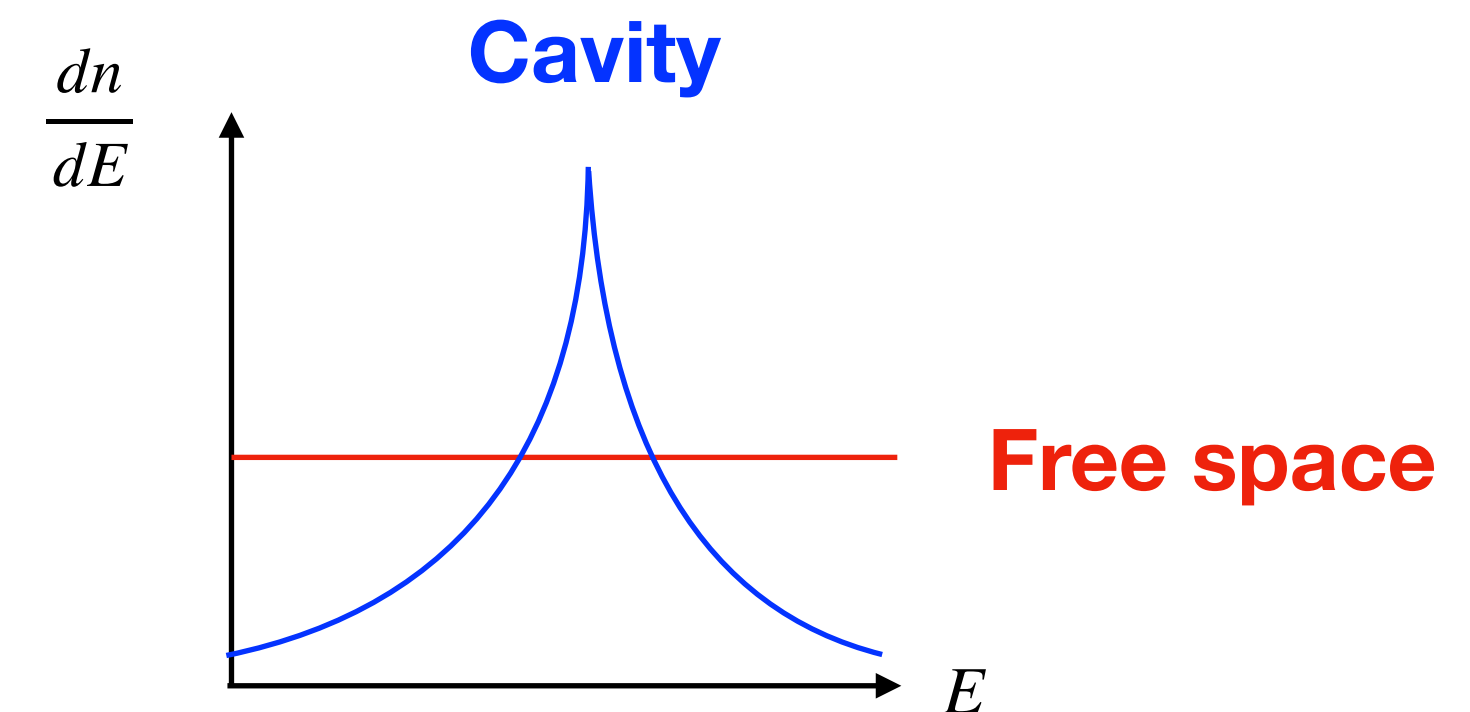
- New experimental strategies for axion DM detection

Key technology: cavity haloscopes



Why does this enhance detection?

$$\Gamma_{a \rightarrow \gamma} \simeq 2\pi \left| \langle f | H_{\text{int}} | i \rangle \right|^2 \times \left(\frac{dn}{dE} \right)$$

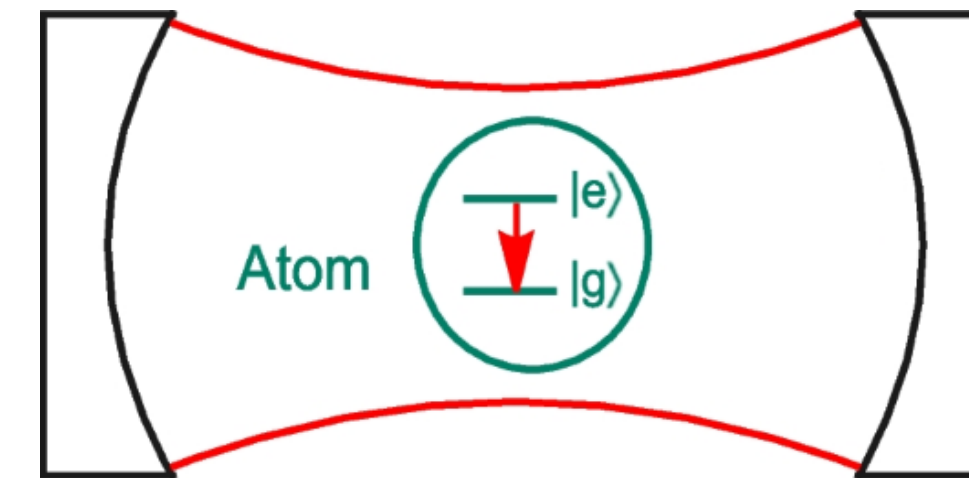




The Purcell effect

- This enhancement can be understood as a specific example of a general effect
- Purcell found that for atoms inside a resonant cavity, spontaneous emission rates are enhanced by

$$F_{\text{Purcell}} = \frac{\tau_{\text{free}}}{\tau_{\text{cavity}}} = \frac{3\lambda^3}{4\pi^2} \left(\frac{Q}{V} \right)$$



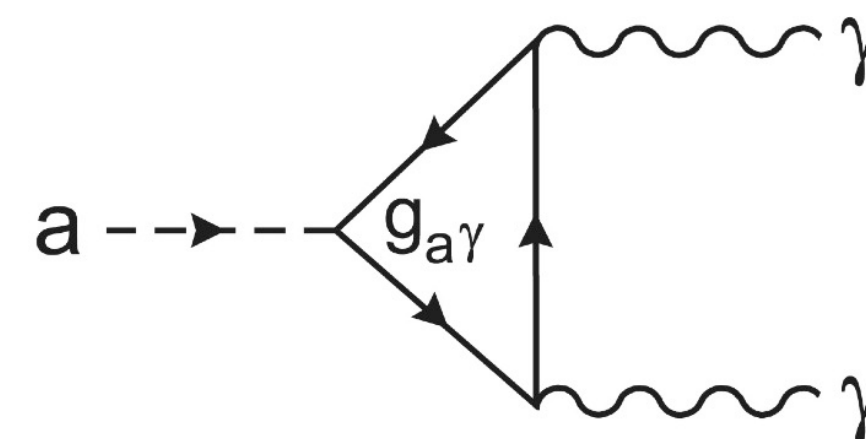
Spontaneous emission probabilities at radio frequencies

EM Purcell - Confined electrons and photons: new physics and ...,

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- Axions can decay too. Is this also enhanced? Can we use this to search for DM?

$$\mathcal{L} = g_{a\gamma} a \vec{E} \cdot \vec{B}$$



Sanity check

- Axion DM must have a lifetime $\gg$ the age of the Universe. Can we really enhance its decay to observable levels?

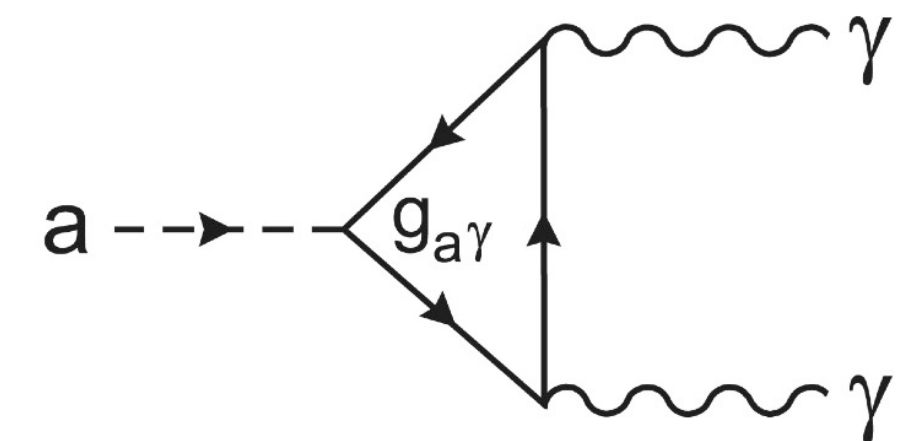
$$\begin{aligned}
 \dot{n}_a &\simeq - \underbrace{\Gamma_{a \rightarrow \gamma\gamma}}_{\text{blue}} \times \underbrace{n_a}_{\text{green}} \times \underbrace{F_{\text{Purcell}}}_{\text{red}} & \left(F_{\text{Purcell}} = \frac{\tau_{\text{free}}}{\tau_{\text{cavity}}} \right) \\
 &= - \underbrace{\frac{g_{a\gamma}^2 m_a^3}{64\pi}}_{\text{blue}} \times \underbrace{\frac{\rho_{DM} V}{m_a}}_{\text{green}} \times \underbrace{\frac{3\lambda^3}{4\pi^2} \left(\frac{Q}{V} \right)}_{\text{red}} \\
 &\simeq - \frac{10^{-24}}{s} \left(\frac{g_{a\gamma}}{10^{-16}/\text{GeV}} \right)^2 \left(\frac{\text{GHz}}{m_a} \right) \left(\frac{Q}{10^{11}} \right) \left(\frac{\rho_{DM}}{0.4 \text{ GeV/cm}^3} \right)
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 \end{aligned}$$

- For stimulated decay though, $\dot{n}_a \simeq - \Gamma_{a \rightarrow \gamma\gamma} \times n_a \times F_{\text{Purcell}} \times \boxed{(1 + n_\gamma)}$



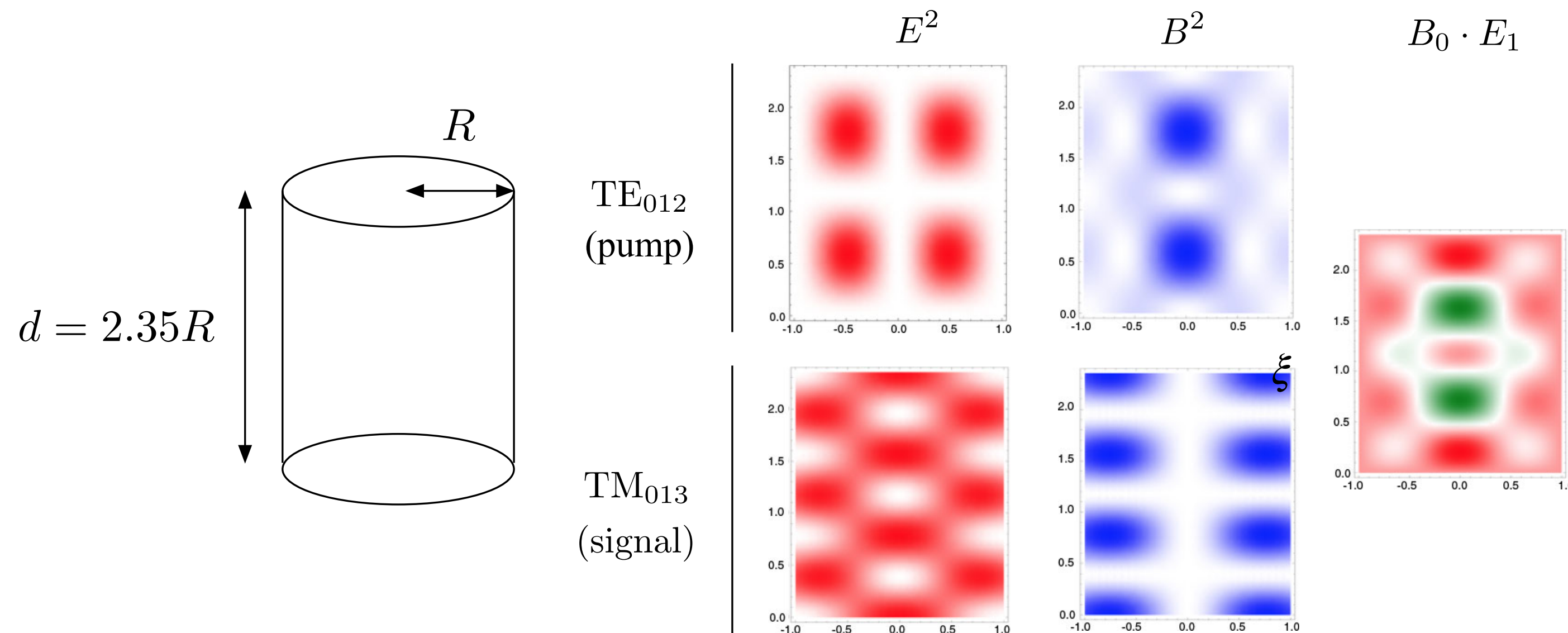
- For high Q cavities, we can have $n_\gamma = \frac{U}{E_\gamma} \simeq 10^{28} \left(\frac{U}{\text{kJ}} \right) \left(\frac{\text{GHz}}{E_\gamma} \right)$

$$10^{-24} \times 10^{28} = 10^4 \text{ stimulated decays/s, looks good}$$

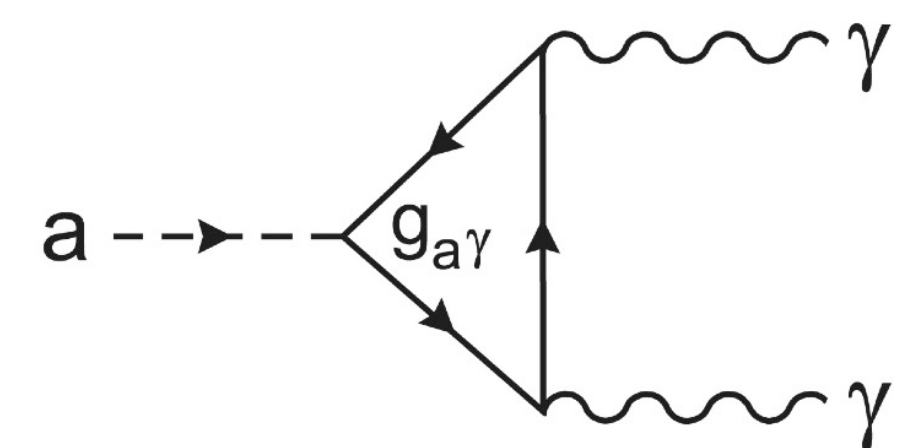
What would we require?

$$\mathcal{L} = g_{a\gamma} a \vec{E} \cdot \vec{B}$$

- A cavity with two tunable resonant modes, with $\vec{E} \cdot \vec{B} \neq 0$ and good form factor ξ . E.g.



$$\xi \equiv \frac{\left| \int_V \mathbf{E}_1^* \cdot \mathbf{B}_0 \right|}{\sqrt{\int_V |\mathbf{E}_1|^2} \sqrt{\int_V |\mathbf{B}_0|^2}} \leq 1$$



- Good news: no magnetic field, so can use ultrahigh Q superconducting cavities
- Spontaneous and stimulated decay both possible: in the latter case we pump one mode, and so need to be able to reject pump output, and cool the cavity effectively

Let's calculate

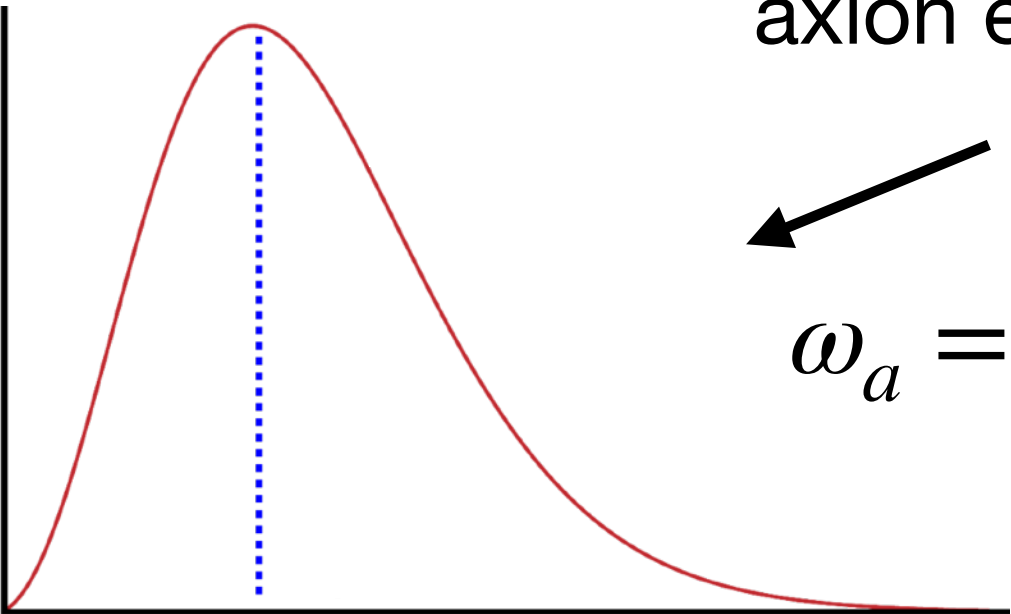
- Use input/output formalism for pump and signal mode creation/annihilation operators (c_s, c_p)

$$\frac{dc_s(t)}{dt} = i [H, c_s(t)] \simeq \left(w_s - \frac{i\omega_s}{2Q_s} \right) c_s(t) - \frac{g_{a\gamma} \sqrt{w_s w_p} \xi}{2} a(t) c_p^\dagger(t) - \sqrt{\frac{\omega_s}{Q_s}} b_{\text{in}}(t),$$

damping term
axion mixing term
pumping term

$$\langle N_s \rangle \equiv \frac{1}{T} \int_0^T dt \langle c_s^\dagger(t) c_s(t) \rangle \simeq \frac{g_{a\gamma}^2 |\xi|^2 w_p}{4m_a^2} Q_s \rho_{DM} F_{DM}(w_s + w_p) \left(1 + \langle N_p \rangle \right)$$

number of photons in signal mode
axion energy distribution
spontaneous decay
stimulated decay



$\omega_a = \omega_s + \omega_p$

Purcell vs Primakoff

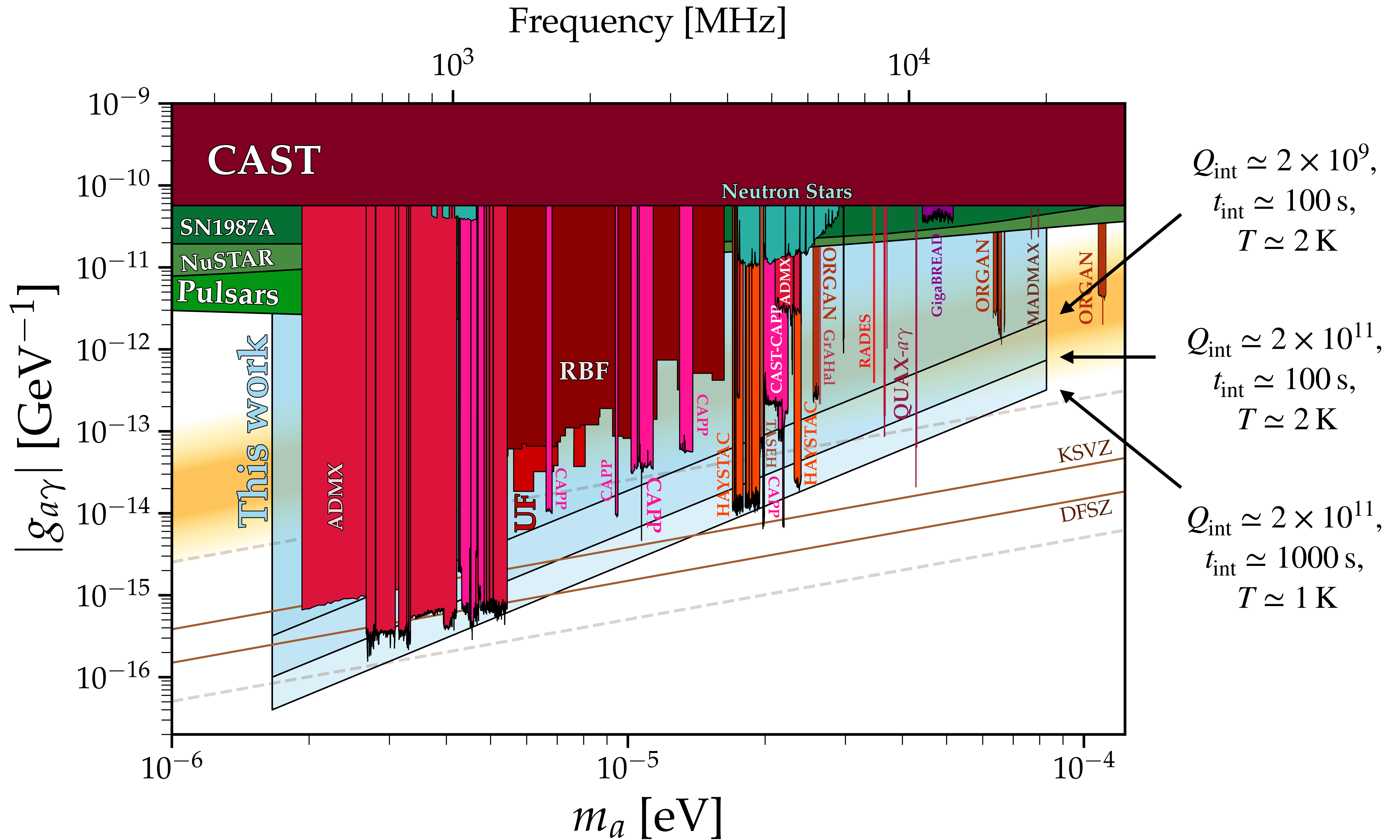
- Since $Q_s \gg Q_a$ we only receive a fraction of the total power available.
- However, we also have two Q enhancements: cavity gives $\min(Q_a, Q_s)$ and $\langle N_p \rangle$ gives Q_{int}
- Can still be competitive with ordinary Primakoff haloscopes:

$$g_{a\gamma}^{95\%} \Big|_{\text{Purcell}} \simeq \frac{5 \times 10^{-15}}{\text{GeV}} \left(\frac{10^6}{Q_a} \right)^{\frac{1}{2}} \left(\frac{2 \times 10^{11}}{Q_{\text{int}}} \right)^{\frac{1}{4}} \left(\frac{m_a}{10.7 \mu\text{eV}} \right)^{\frac{3}{2}} \times \text{common factors}$$

$$g_{a\gamma}^{95\%} \Big|_{\text{CAPP-PACE}} \simeq \frac{10^{-14}}{\text{GeV}} \left(\frac{10^5}{Q_L} \right)^{\frac{1}{2}} \left(\frac{1.1 \text{ L}}{V} \right)^{\frac{1}{2}} \left(\frac{7.2 \text{ T}}{B_0} \right) \times \text{common factors}$$

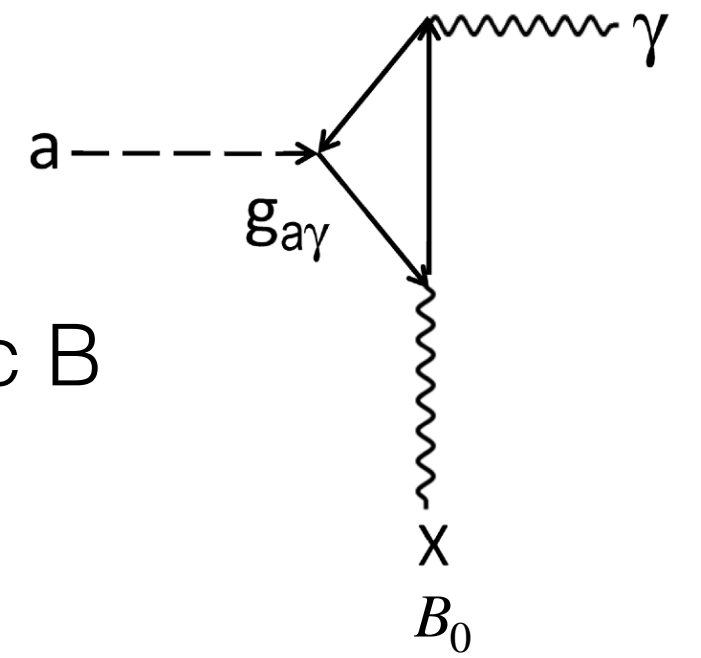
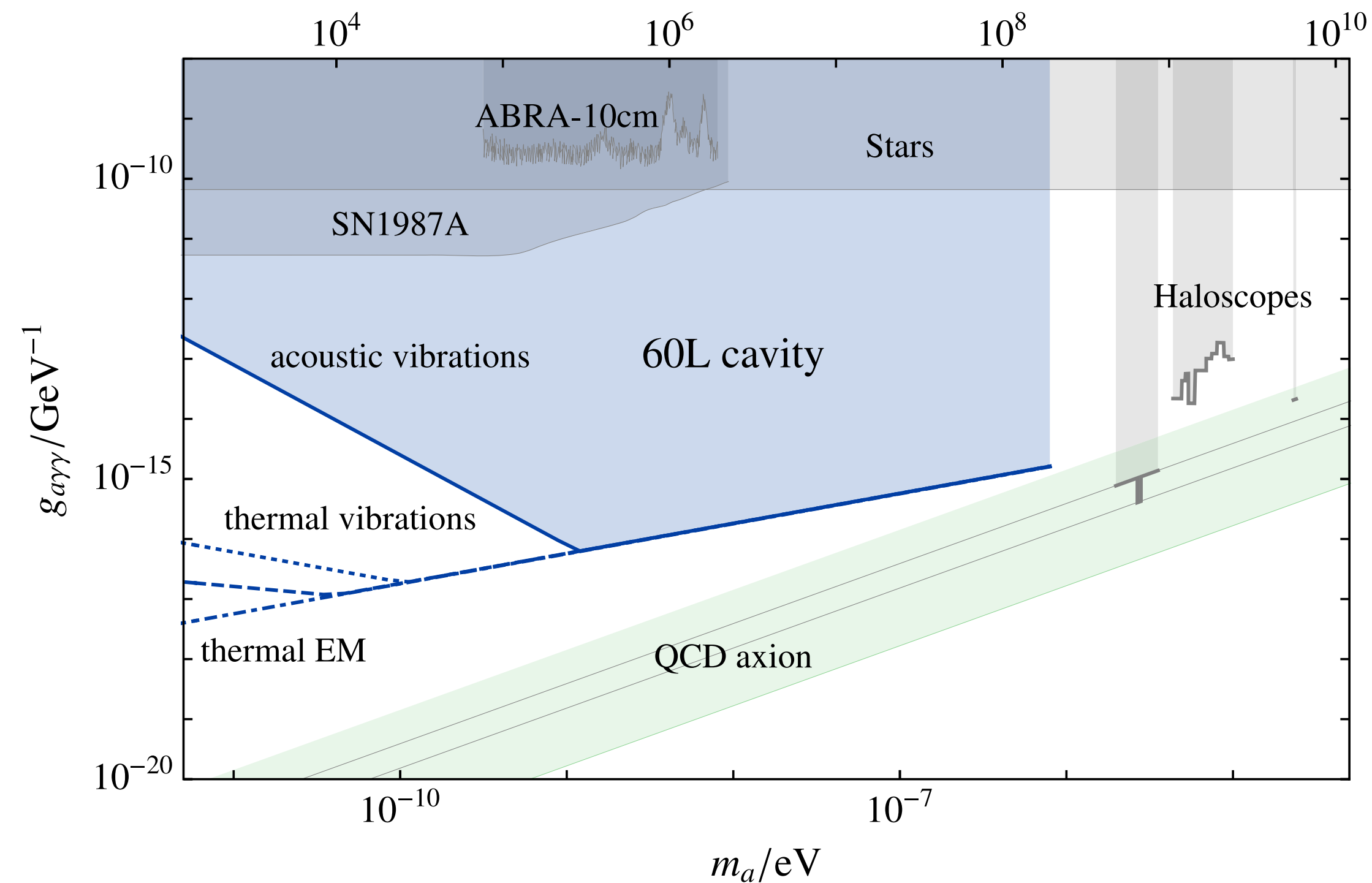
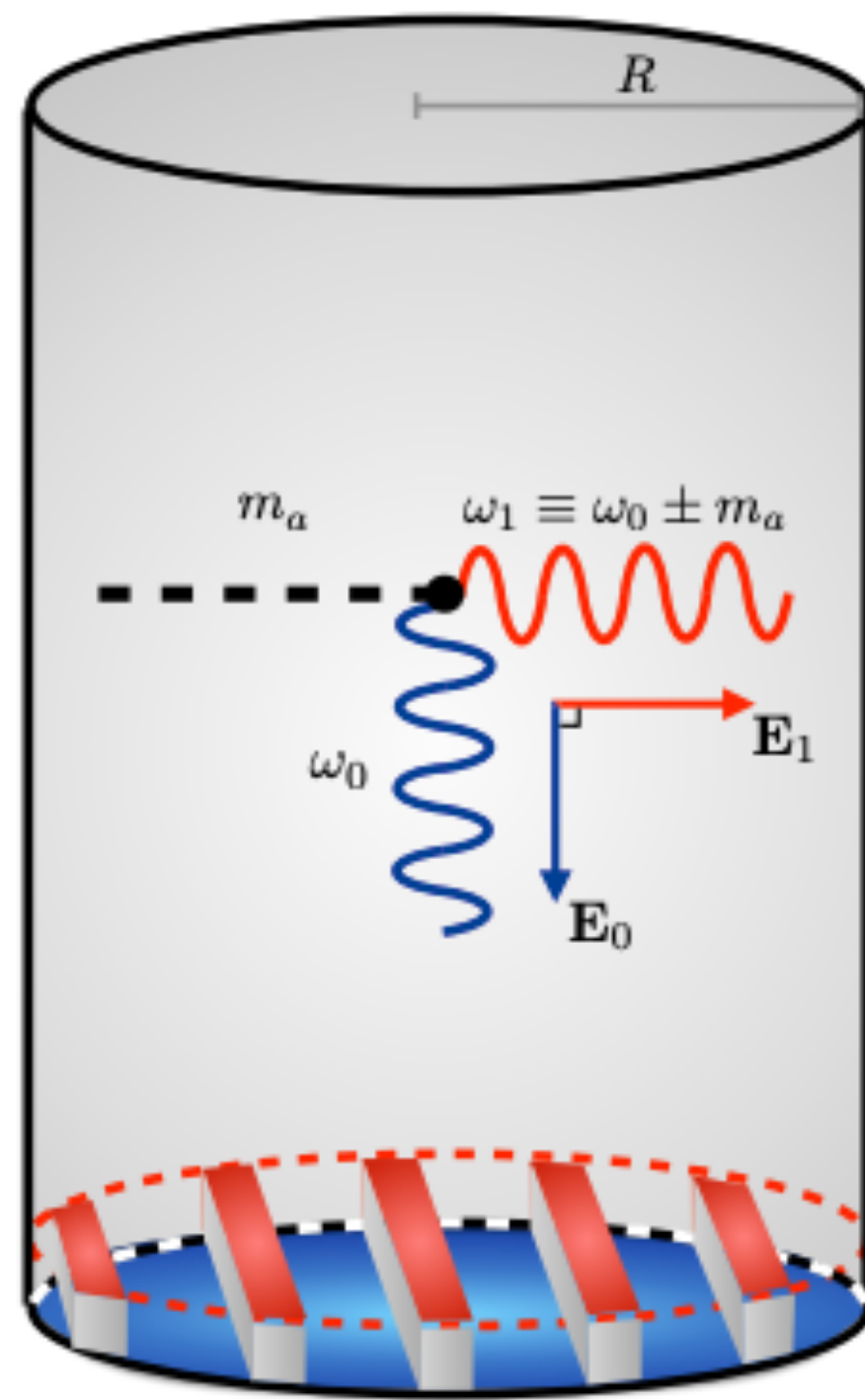
$$\text{common factors} = \left(\frac{m_a}{10.7 \mu\text{eV}} \right)^{\frac{3}{4}} \left(\frac{T}{1.2 \text{ K}} \right)^{\frac{1}{2}} \left(\frac{0.45 \text{ GeV/cm}^3}{\rho_a} \right)^{\frac{1}{2}} \left(\frac{100 \text{ s}}{t_{\text{int}}} \right)^{\frac{1}{4}}$$

Due to ultrahigh Q , our scan rate is also 40 X faster



Heterodyne axion detection

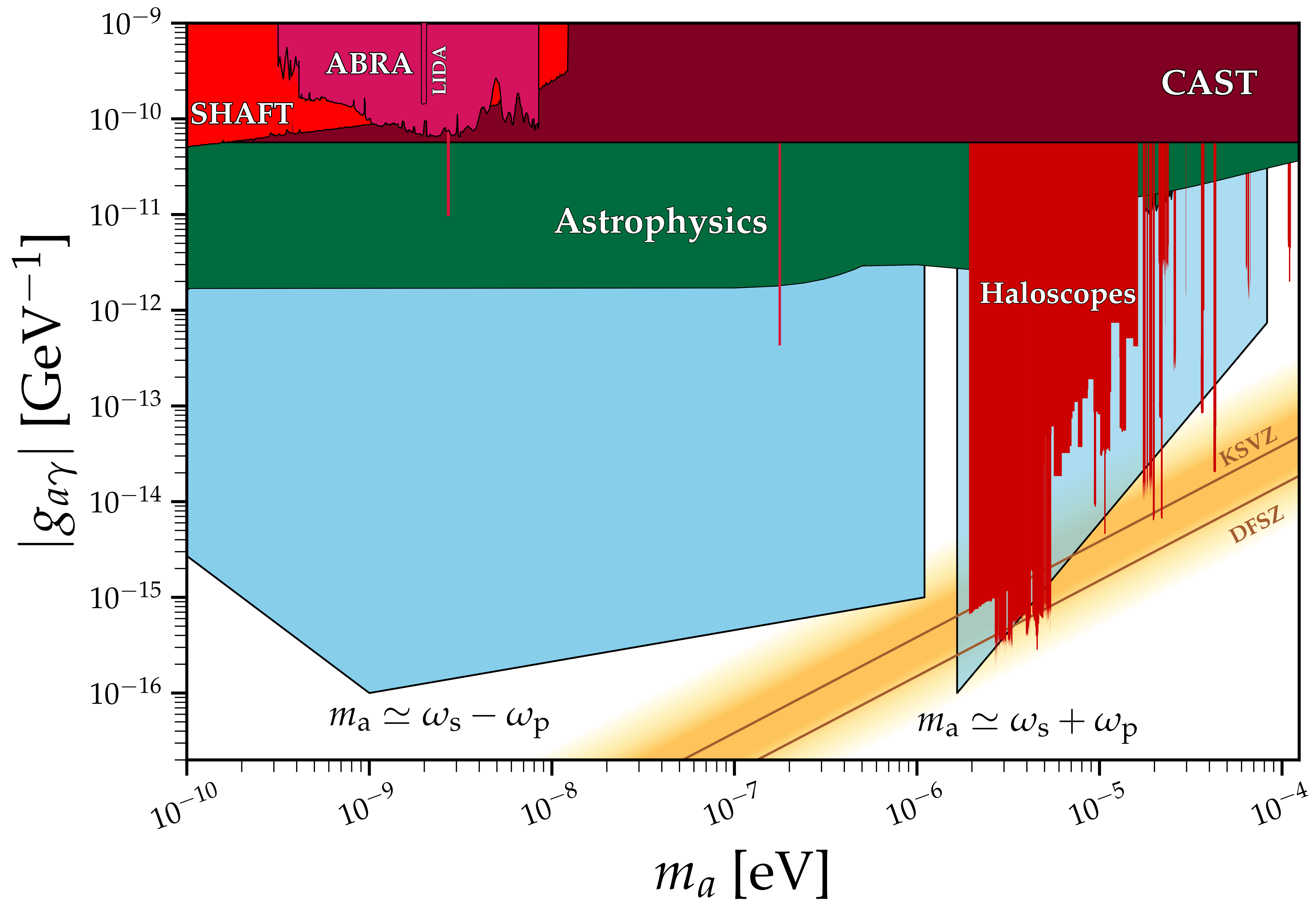
- Dual-mode cavity Primakoff experiments have actually already been explored, where instead of a static B field, we use the B field of the pump mode



With a single cavity we can simultaneously search for $m_a = \omega_s - \omega_p$ (Primakoff) and $m_a = \omega_s + \omega_p$ (Purcell)

Prototype research and development underway at SLAC, CERN, Peking

“Microwave cavity searches for low-frequency axion dark matter”, R. Lasenby, 1912.11056 , “Axion Dark Matter Detection by Superconducting Resonant Frequency Conversion”, A. Berlin *et al*, 1912.11048



Discussion and conclusions

We propose a novel axion search strategy: resonantly enhanced spontaneous and stimulated decay

Pros	Cons
1. No B field required 2. Can use ultrahigh Q superconducting cavities: higher scan rate 3. Can simultaneously search for $m_a = w_1 + w_2$ and $m_a = w_1 - w_2$ 4. With plausible parameters, can probe the most favoured region for QCD axion DM	1. Must work with two cavity modes - additional cavity design constraints and tuning complexity 2. Need to pump one mode for good sensitivity: require very good pump mode rejection 3. Additional cooling needs due to pump power, thermal noise limits sensitivity

More details available in arXiv: 2507.18508

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Thanks for listening!