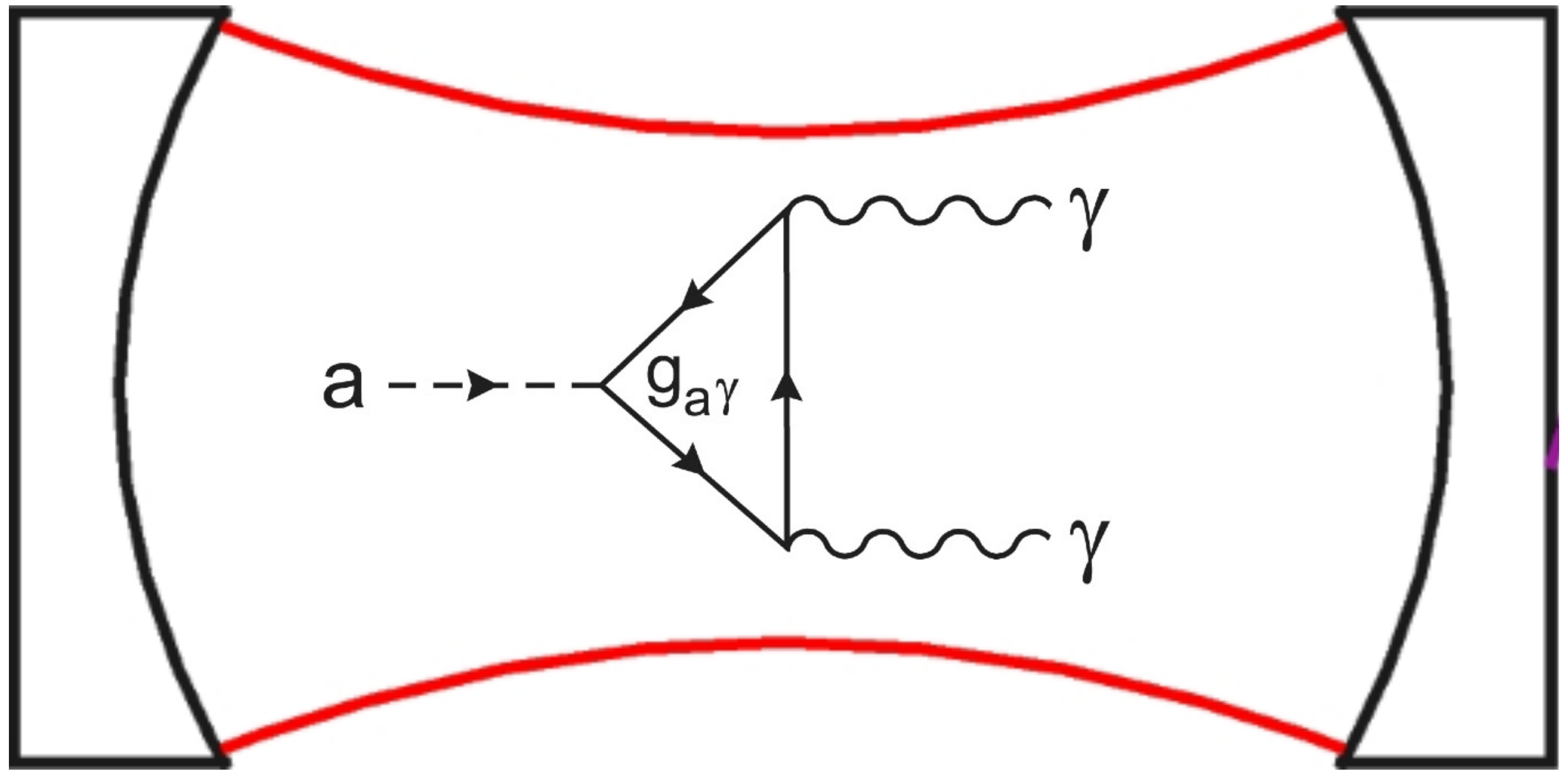
Resonant enhancement of axion dark matter decay



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Axion 2026, Qingdao

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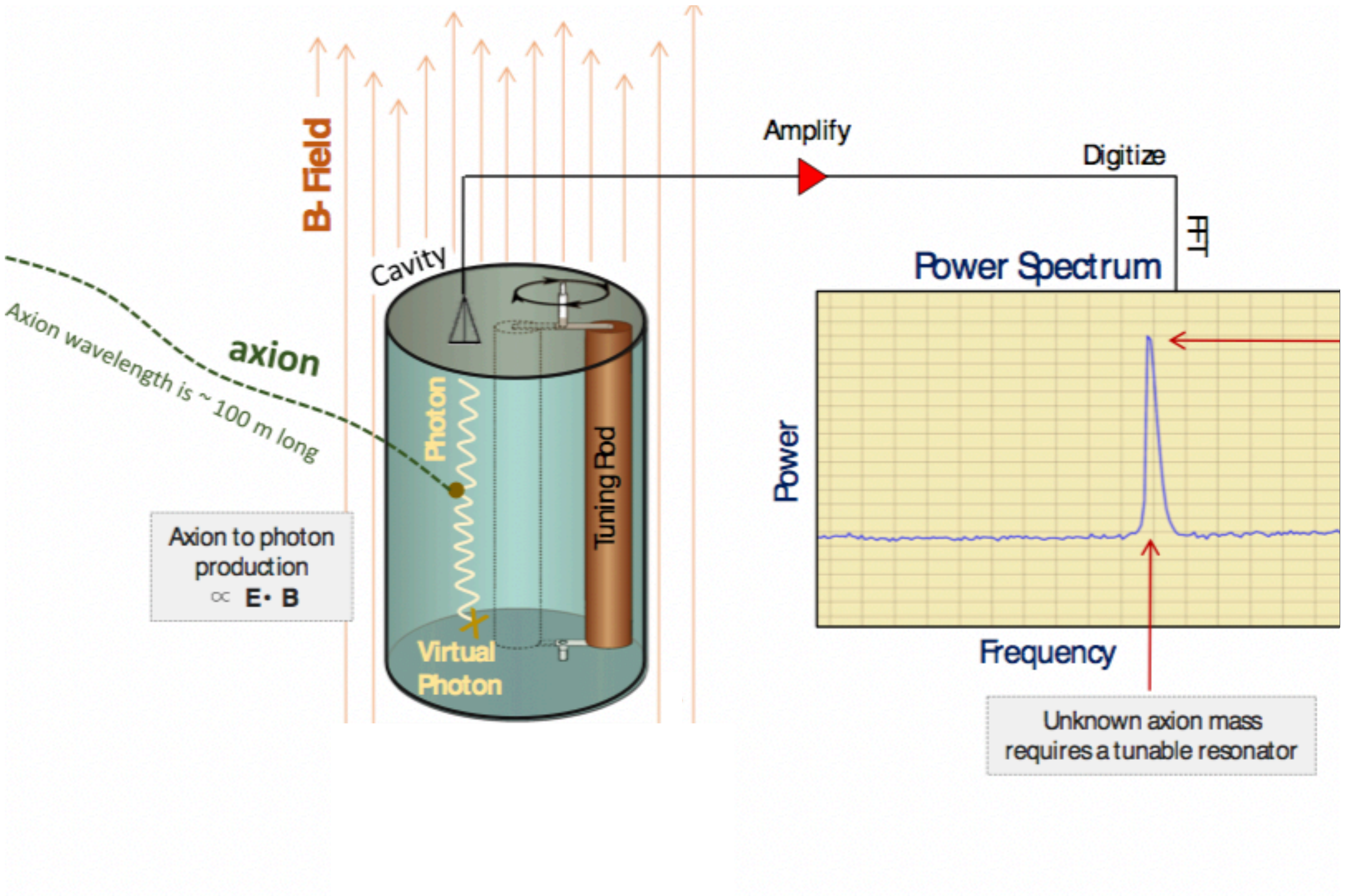
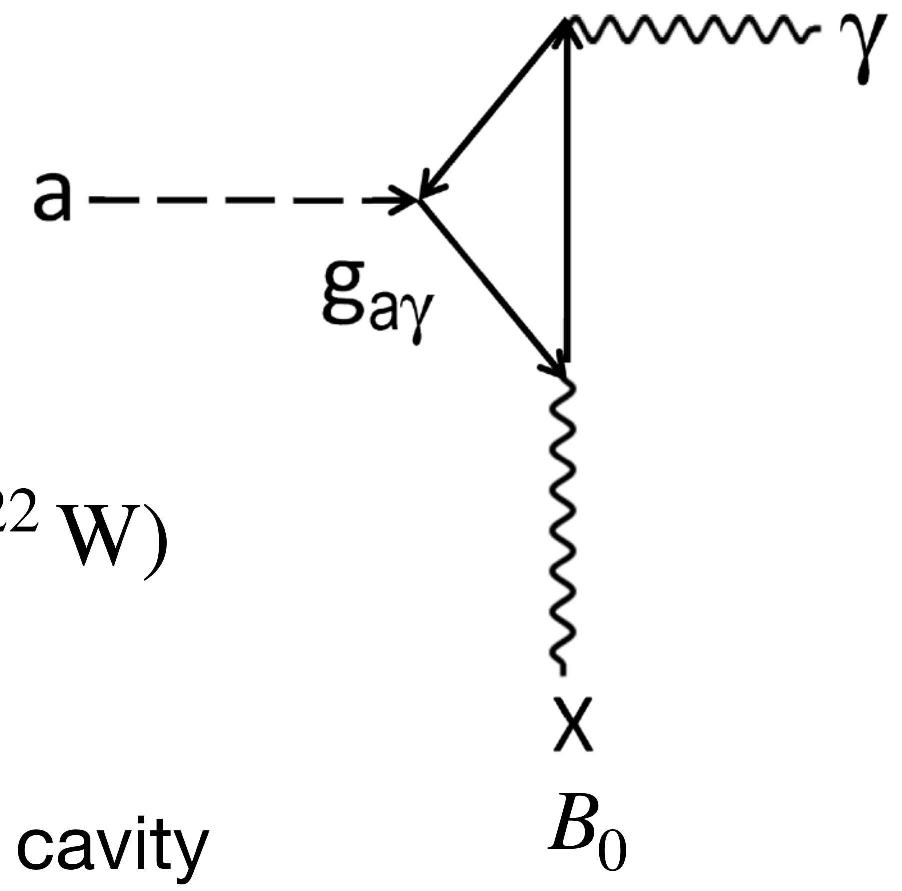
Key technology: cavity haloscopes



$$P_{signal} \simeq \mathcal{O}(10^{-22}\,\mathrm{W})$$



Noise floor from cavity blackbody radiation, plus added Johnson noise from the receiver chain

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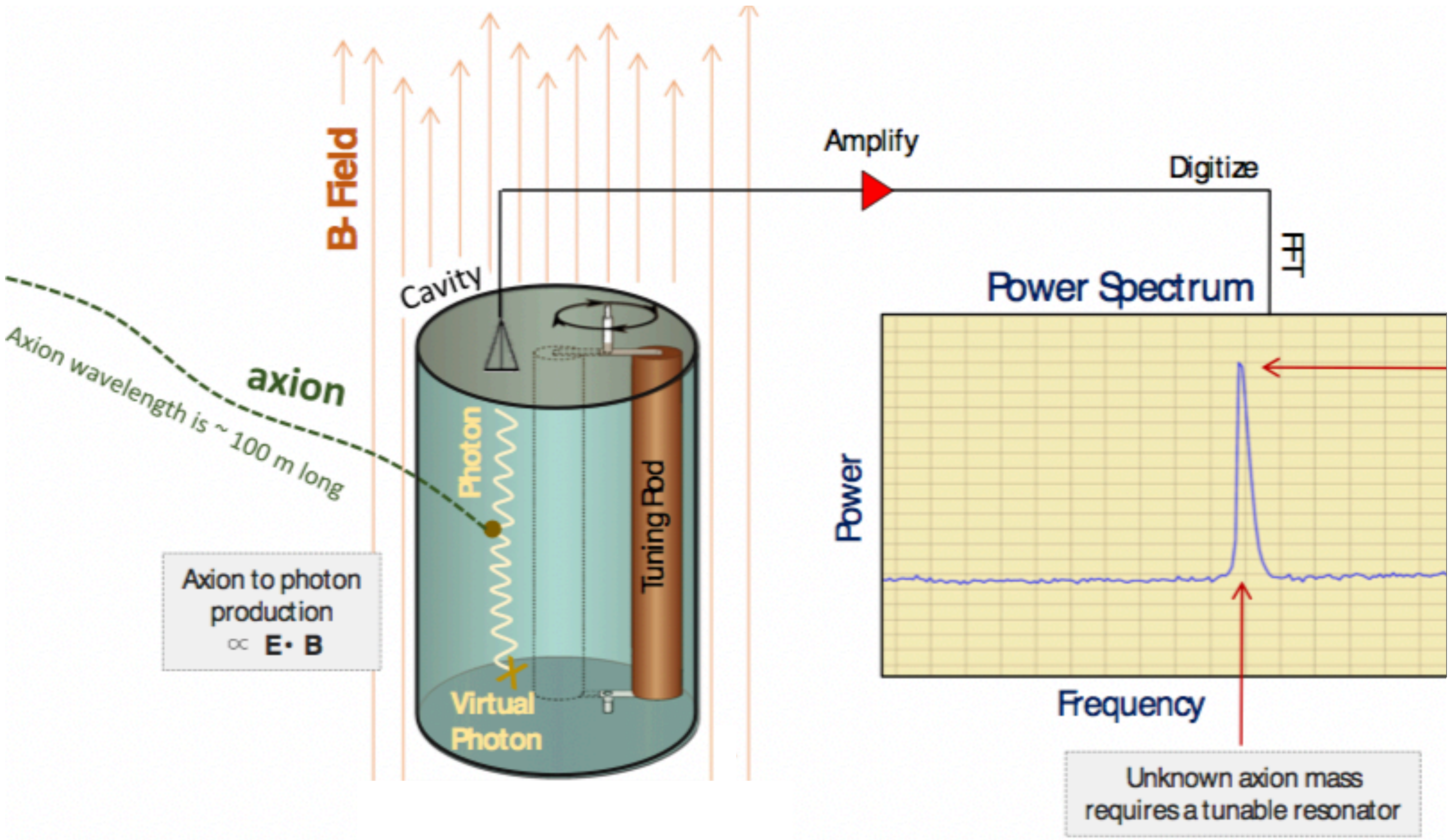

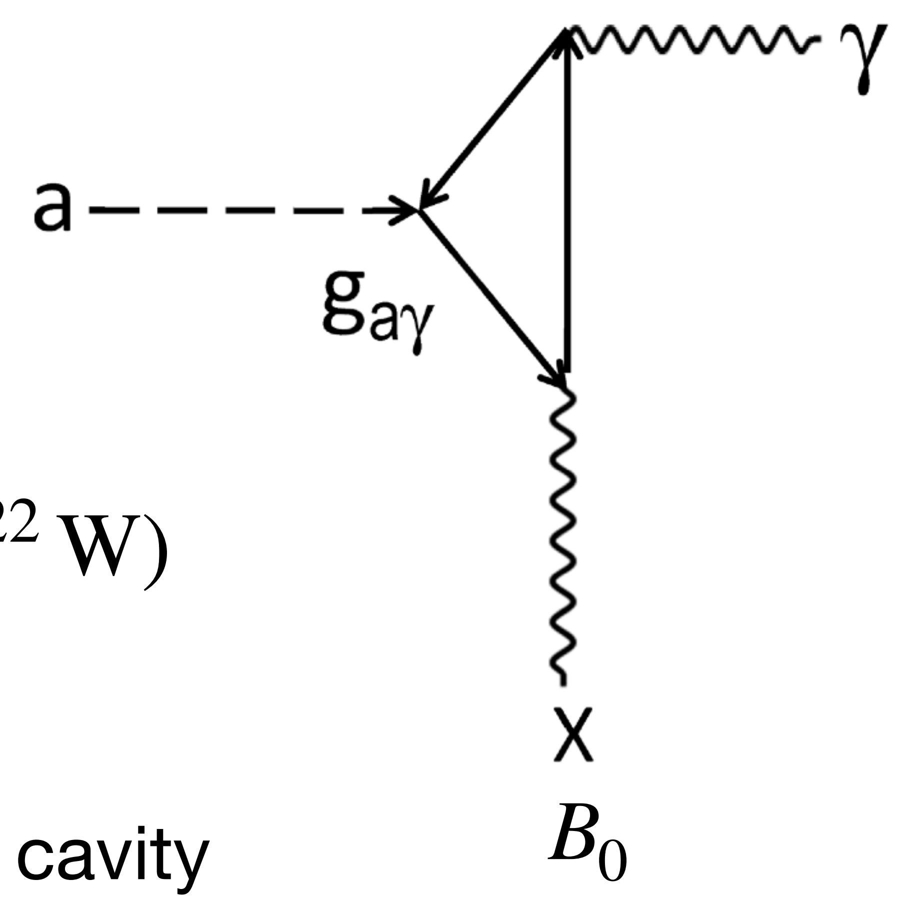

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Noise floor from cavity blackbody radiation, plus added Johnson noise from the receiver chain

Why does this enhance detection?

$$\Gamma_{a\to\gamma} \simeq 2\pi |<f|H_{int}|i>|^2 \left(\frac{dn}{dE}\right)$$

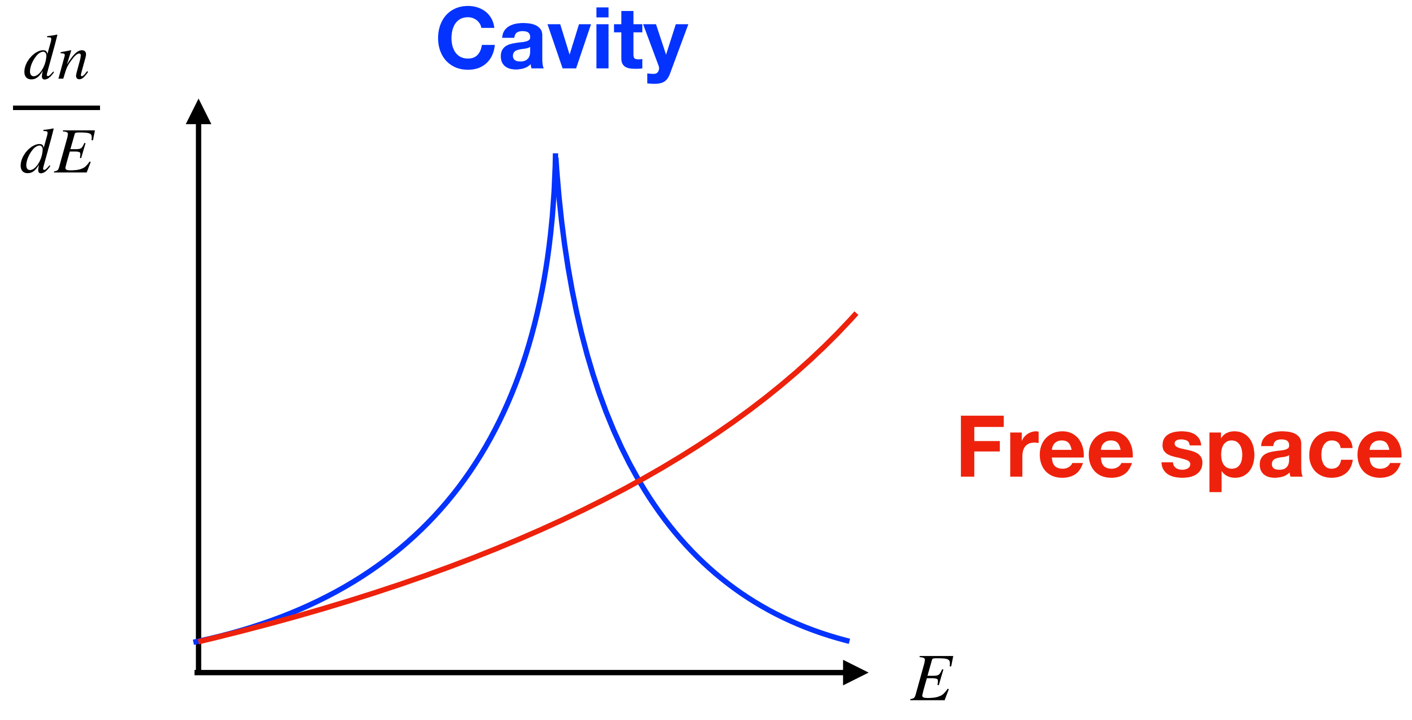
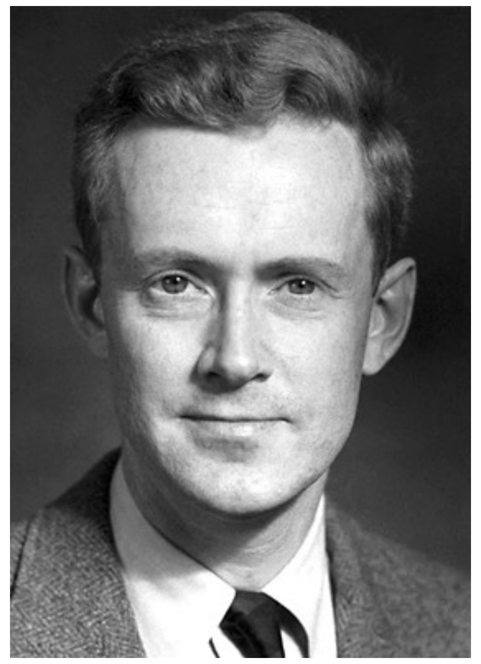


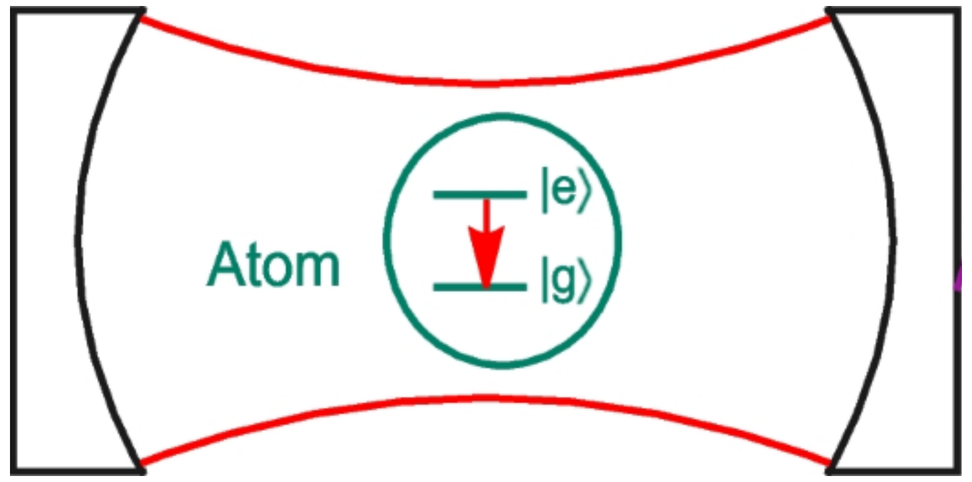
Figure courtesy of C. Boutan

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

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

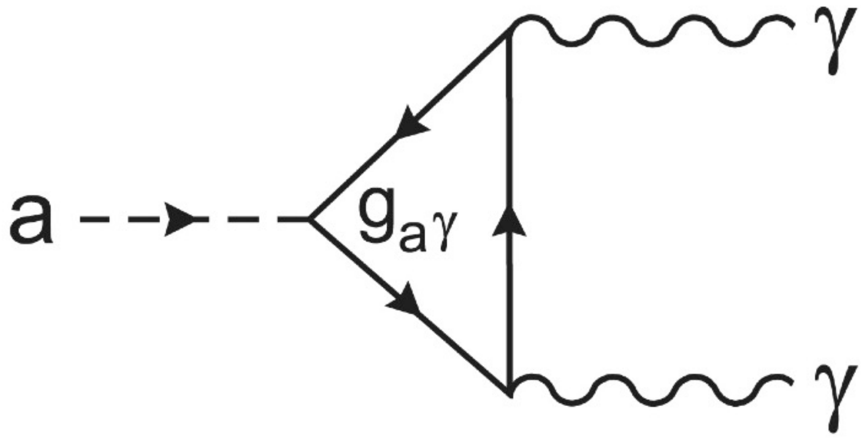


Spontaneous emission probabilities at radio frequencies

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

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

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



Feasibility

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

$$\text{decays/s} \simeq \Gamma_{a\to\gamma\gamma} \times N_a \times F_{\text{Purcell}}$$

$$\left(F_{\text{Purcell}} = \frac{\tau_{\text{free}}}{\tau_{\text{cavity}}} \right)$$

$$\simeq \frac{g_{a\gamma}^2 m_a^3}{64\pi} \times \frac{\rho_{DM} V}{m_a} \times \frac{3\lambda^3}{4\pi^2}\left(\frac{Q}{V}\right)$$

$$\simeq \frac{10^{-24}}{s}\left(\frac{g_{a\gamma}}{10^{-16}/\text{GeV}}\right)^2 \left(\frac{\text{GHz}}{m_a}\right)\left(\frac{Q}{10^{11}}\right)\left(\frac{\rho_{DM}}{0.4\,\text{GeV/cm}^3}\right)$$

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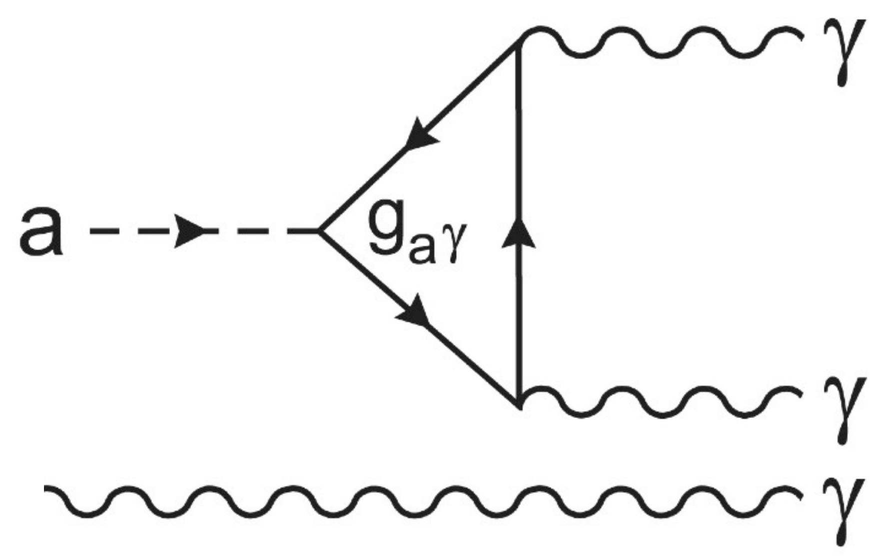
- For stimulated decay though, $\text{decays/s} \simeq \Gamma_{a\to\gamma\gamma} \times N_a \times F_{\text{Purcell}} \times (1 + N_\gamma)$

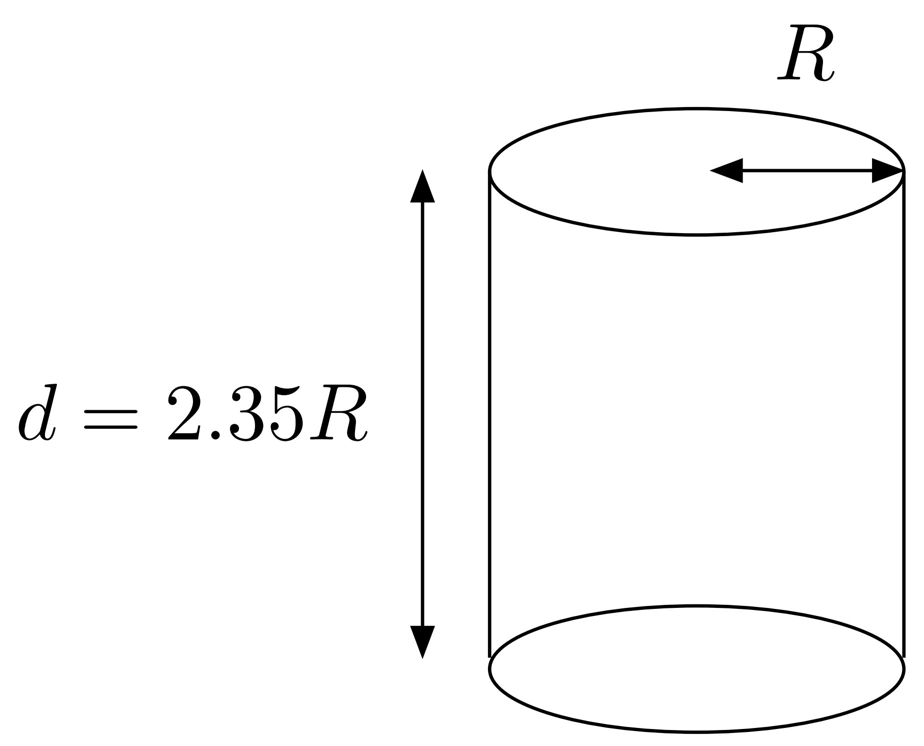


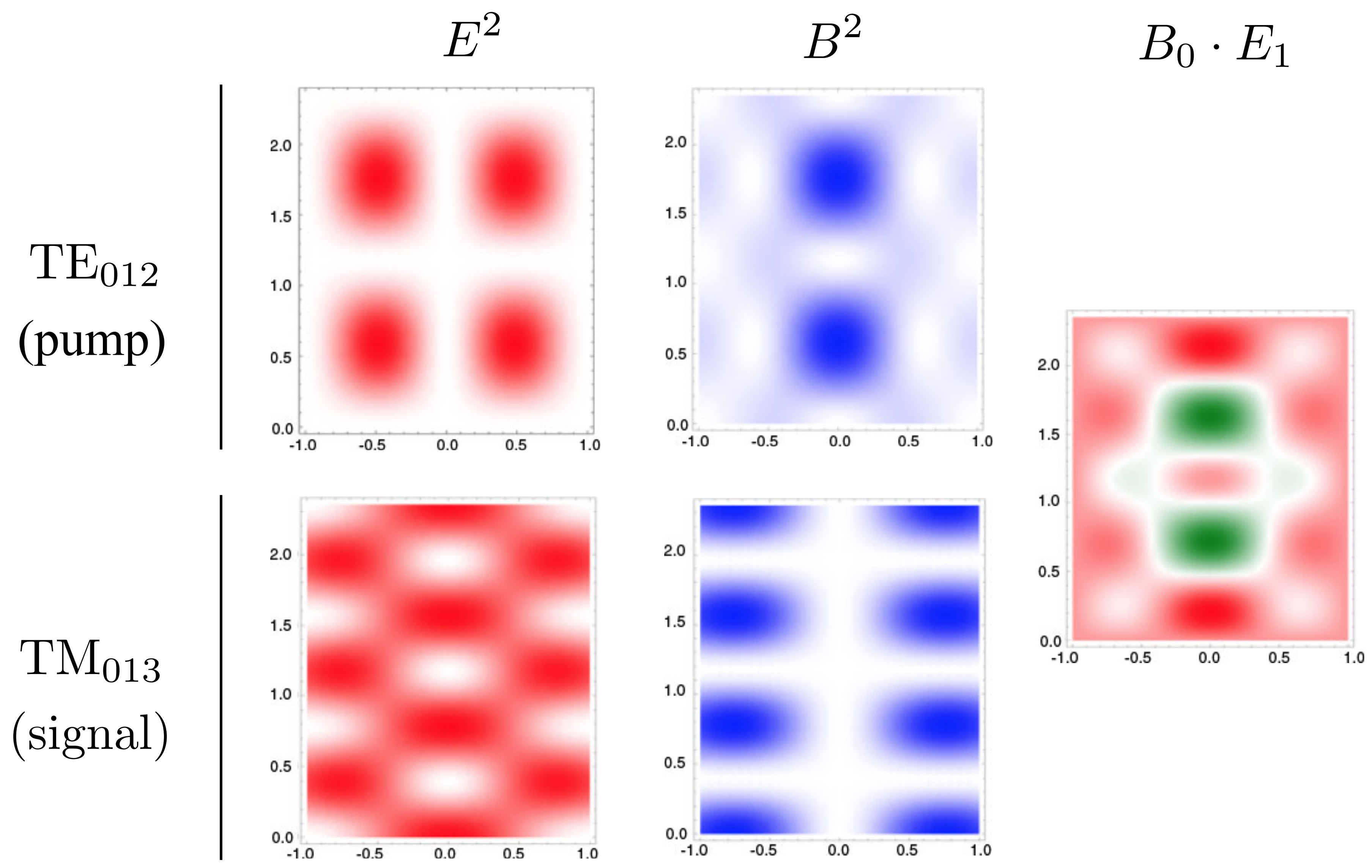
- For ultrahigh Q cavities, we can have $N_\gamma = \frac{U}{E_\gamma} \simeq 10^{28}\left(\frac{U}{\text{kJ}}\right)\left(\frac{\text{GHz}}{E_\gamma}\right)$

$$10^{-24} \times 10^{28} = 10^4 \ \textbf{decays/s}$$

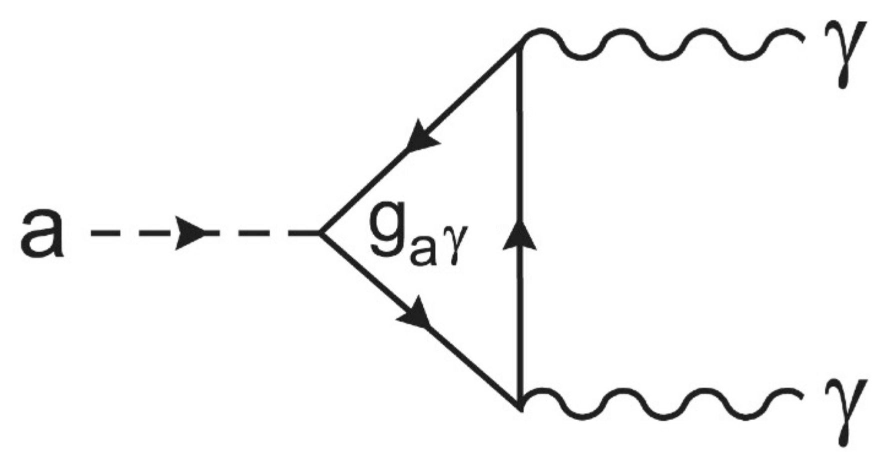
What would we require?

- A high Q cavity with two resonant modes (pump and signal), satisfying $E \cdot B \neq 0$





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

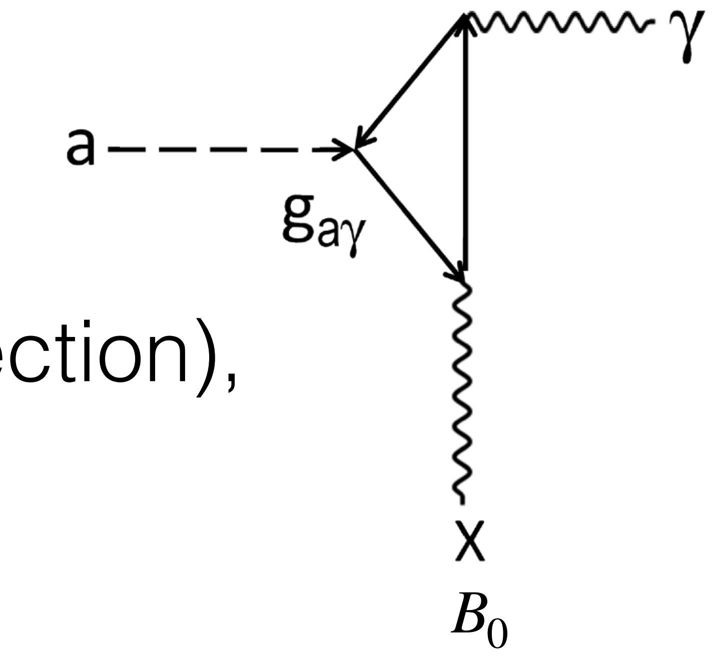


$$\xi \equiv \frac{\left| \int_V \mathbf{E}_1^* \cdot \mathbf{B}_0 \right|}{\sqrt{\int_V |\mathbf{E}_1|^2} \sqrt{\int_V |\mathbf{B}_0|^2}} \leq 1$$

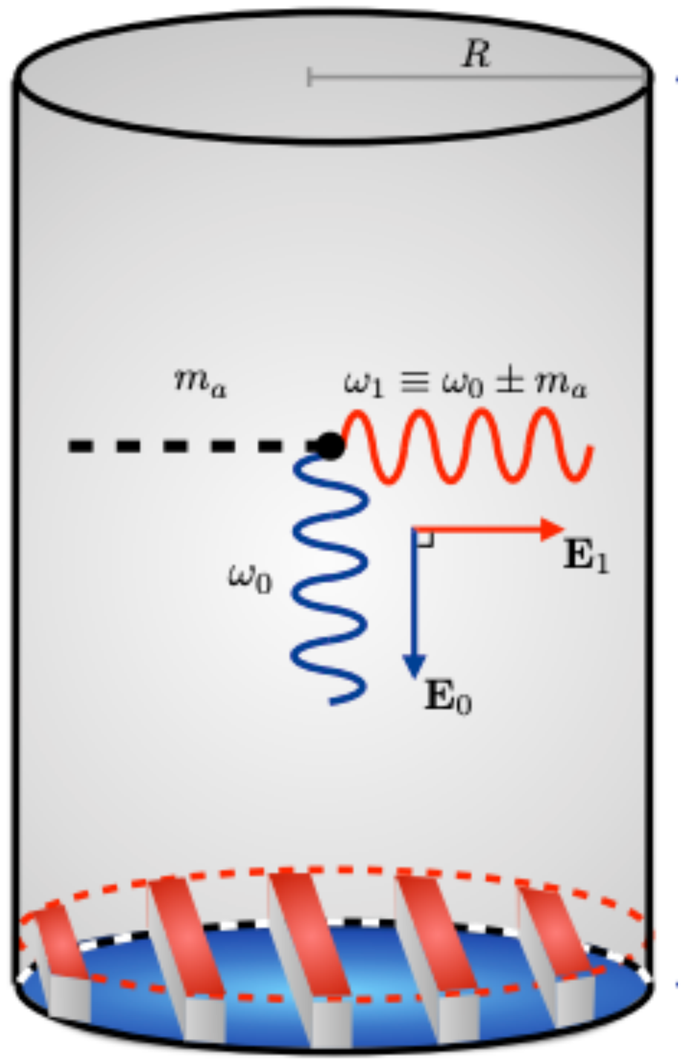
- Spontaneous and stimulated decay both possible: in the latter case we pump one mode, and so need to be able to reject pump output, and cool the cavity effectively

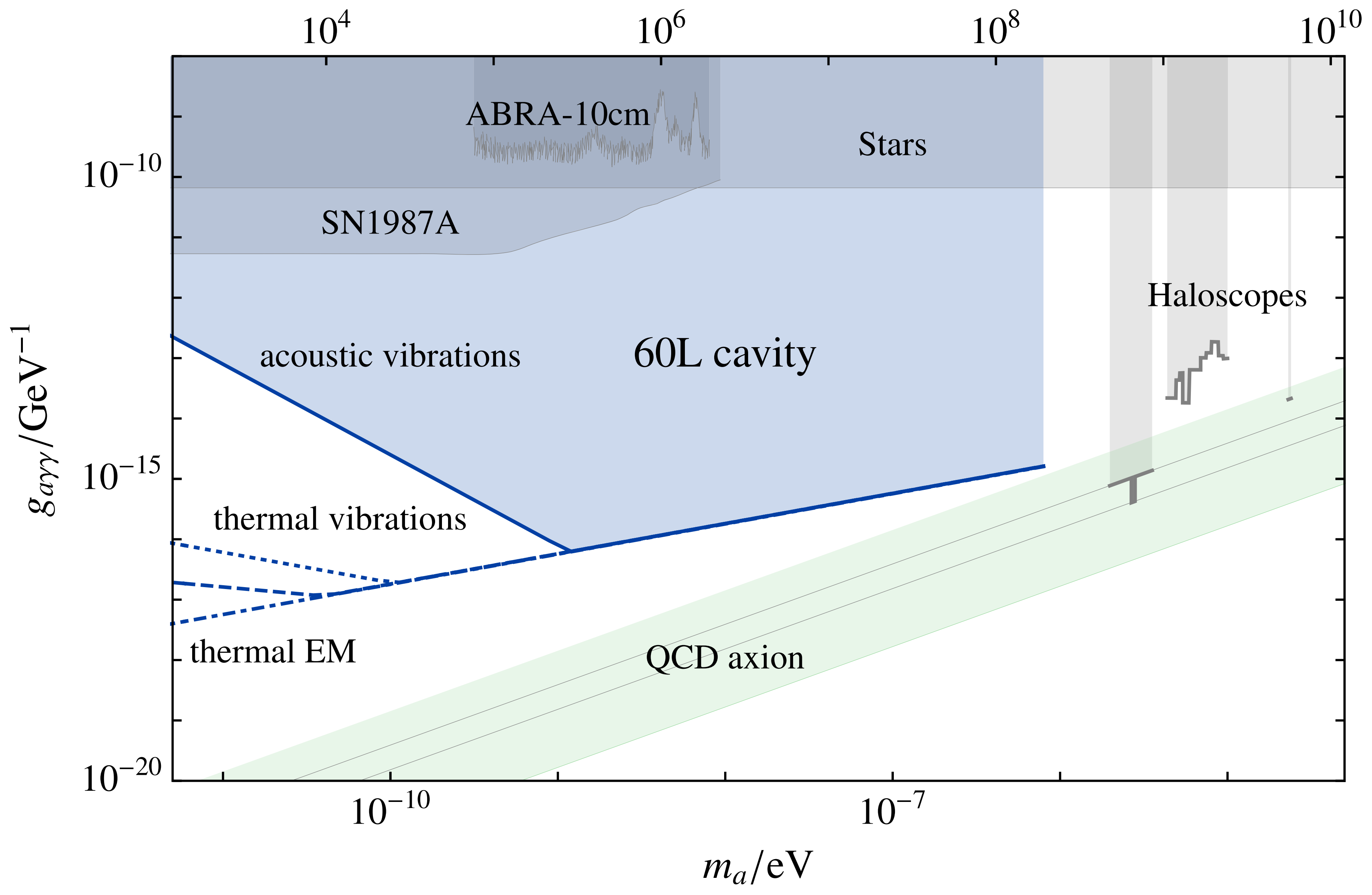
"Microwave cavity searches for low-frequency axion dark matter", R. Lasenby, 1912.11056

Is this experimentally feasible?



- Dual-mode cavity Primakoff experiments have actually already been explored ('axion heterodyne detection), where instead of a static B field, we use the B field of the pump mode





The only difference here is actually kinematic: heterodyne experiments are sensitive to $m_a = w_s - w_p$, axion decay is sensitive to $m_a = w_s + w_p$. With a single cavity we can simultaneously search for both!

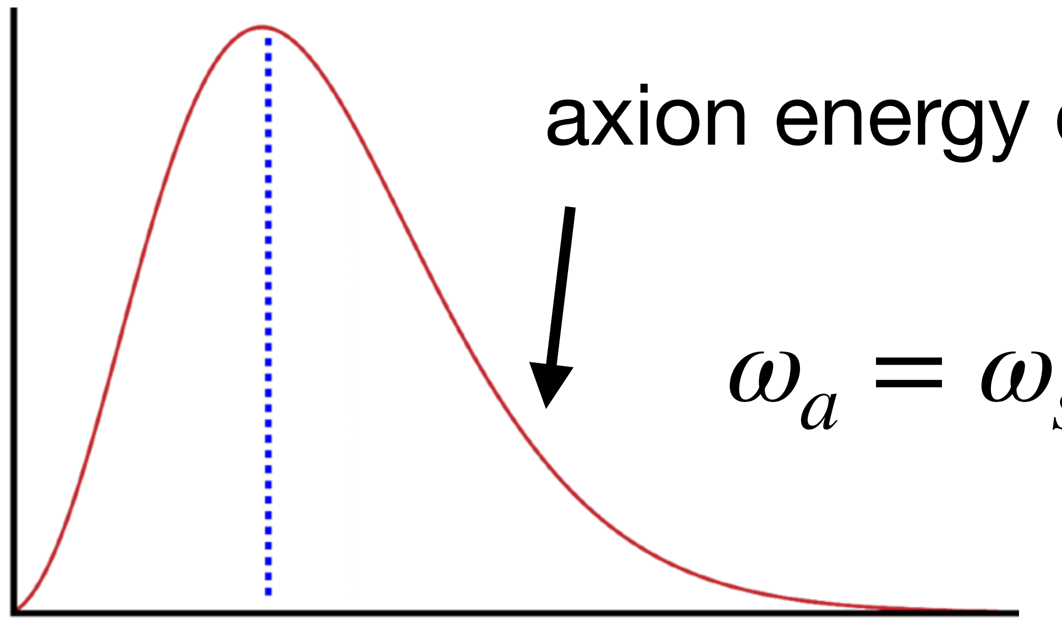
"Microwave cavity searches for low-frequency axion dark matter", R. Lasenby, 1912.11056 , "Axion Dark Matter Detection by Superconducting Resonant Frequency Conversion", A. Berlin *et al,* 1912.11048

Let's calculate

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

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

number of signal photons



axion energy distribution

$\omega_a = \omega_s + \omega_p$

spontaneous decay

Number of pump mode photons, giving stimulated decay

No B field required - can use ultrahigh Q superconducting cavities

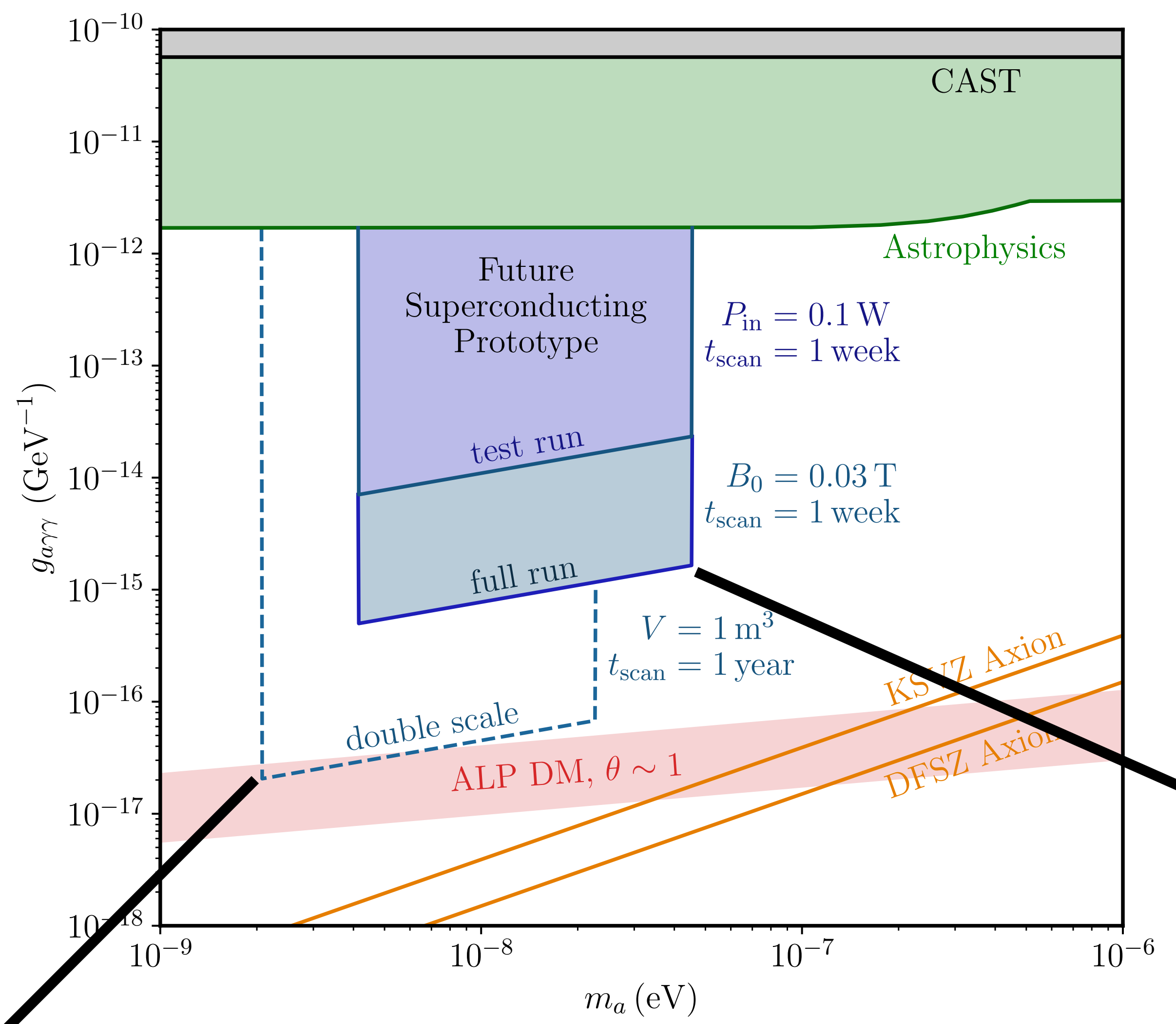
- V dependence? Naively: $\langle N_s \rangle \propto N_{\rm axions} F_{\rm Purcell} \propto \rho_{DM} V \times Q/V$, however max($N_p$) $\sim V$

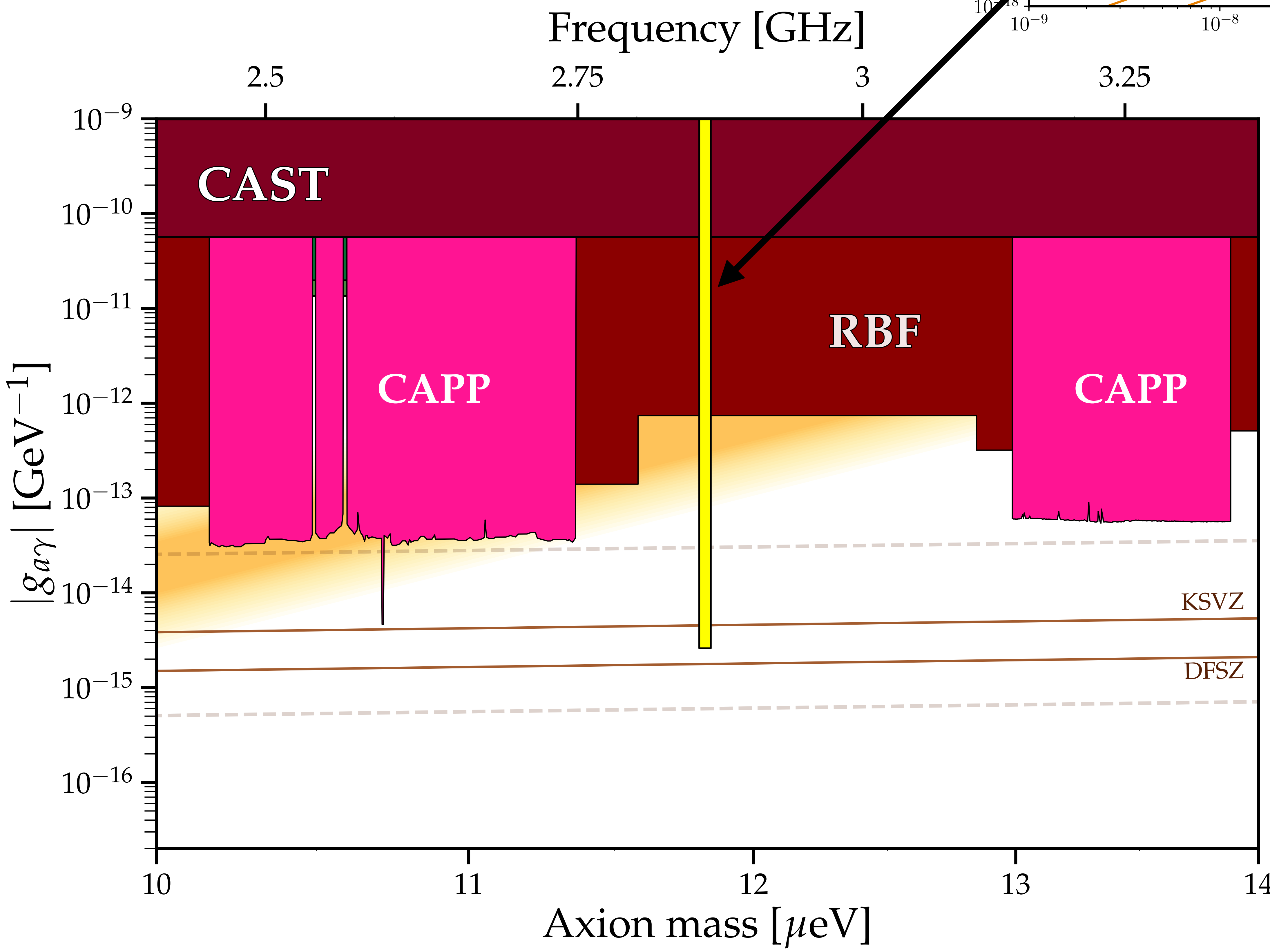
Repurposing heterodyne axion experiments

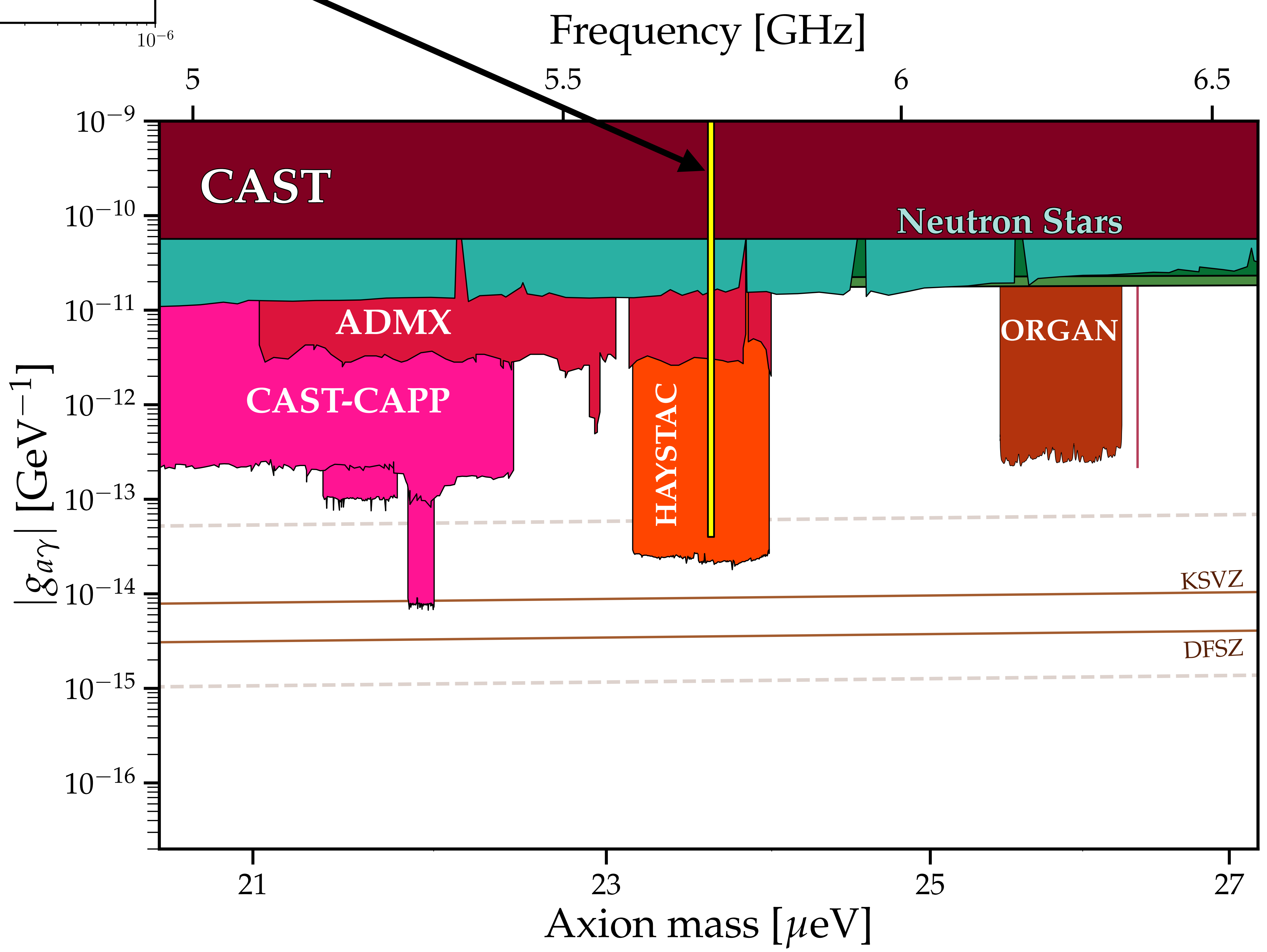
"A Prototype Hybrid Mode Cavity for Heterodyne Axion Detection", Z. Li et al, 2507.07173

- 'Heterodyne' experiments search for $m_a = w_s - w_p$

- These experiments are also sensitive to $m_a = w_s + w_p$

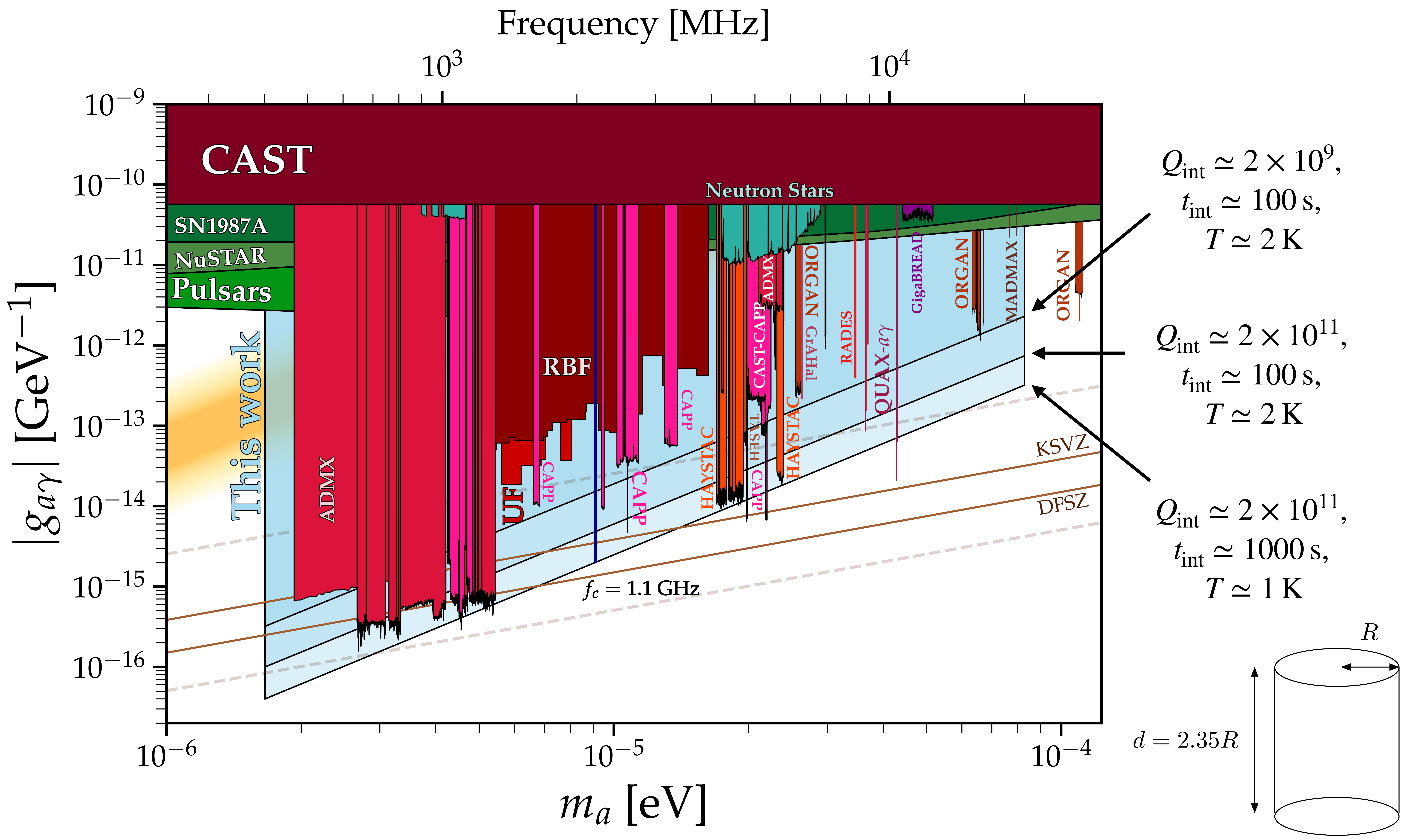






- Development underway at SLAC, Fermilab, CERN, Peking. UPLOAD (Australia) already has results (2301.06778)

- Pro: 'free'. Con: tuning range



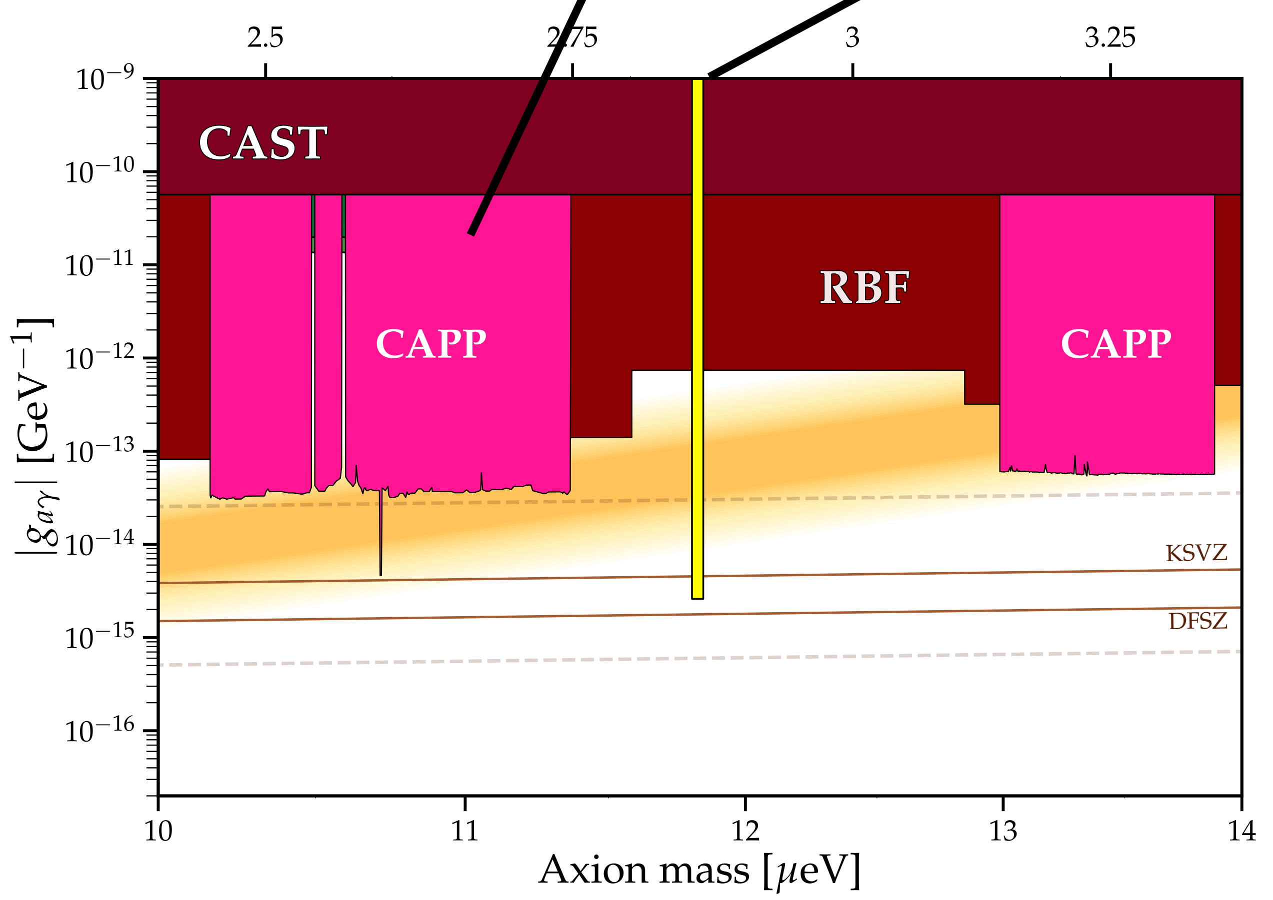
Frequency [MHz]
10^3
10^4
CAST
Neutron Stars
SN1987A
NuSTAR
Pulsars
This work
ADMX
RBF
UF
CAPP
HAYSTAC
CAST-CAPP
ADMX
TASEH
ORGAN
GrAHal
RADES
QUAX-$a\gamma$
GigaBREAD
ORGAN
MADMAX
ORGAN
KSVZ
DFSZ
$f_c = 1.1$ GHz
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
$Q_{\rm int} \simeq 2 \times 10^9$, $t_{\rm int} \simeq 100$ s, $T \simeq 2$ K
$Q_{\rm int} \simeq 2 \times 10^{11}$, $t_{\rm int} \simeq 100$ s, $T \simeq 2$ K
$Q_{\rm int} \simeq 2 \times 10^{11}$, $t_{\rm int} \simeq 1000$ s, $T \simeq 1$ K
R
$d = 2.35R$

What about a dedicated experiment?

- $m_a = w_s + w_p \sim \mathcal{O}(\mathrm{GHz})$, similar to existing Primakoff haloscopes. Where is the advantage?

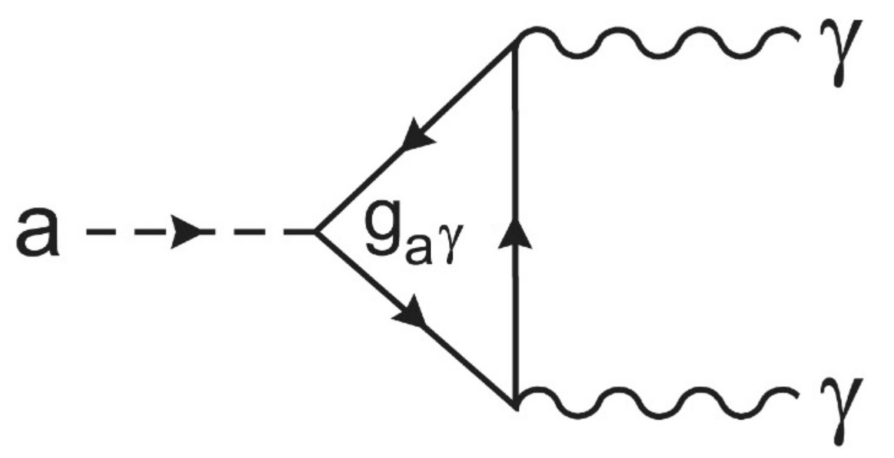
$$\left.\frac{df}{dt}\right|_{\mathrm{CAPP}} \simeq 0.1\mathrm{GHz/yr}\left(\frac{Q_L}{10^5}\right)\left(\frac{B_0}{7.2\,\mathrm{T}}\right)^4\left(\frac{11\mu\mathrm{eV}}{m_a}\right)^2\left(\frac{V}{1.12\,\mathrm{L}}\right)^2\left(\frac{1.2\mathrm{K}}{T_{sys}}\right)^2$$

$$\left.\frac{df}{dt}\right|_{\mathrm{Purcell}} \simeq \mathrm{GHz/yr}\left(\frac{Q_{\mathrm{int}}}{2\times 10^{11}}\right)\left(\frac{<N_p>}{2\times 10^{26}}\right)^2\left(\frac{2\mathrm{K}}{T_{sys}}\right)^2$$



Assuming $g_{a\gamma} = g_{KSVZ}$, SNR = 2, optimal β, standard Q_a and ρ_{DM}

This method also produces pairs of entangled photons.
- quantum sensing enhancement?



Any other benefits?

Frequency scaling

$m_a \sim f$
$V \sim f^{-3}$
$Q \sim f^{-2/3}$
$T_{sys} \sim f$

- Primakoff haloscopes typically scale poorly with increasing frequency:

$$\frac{df}{dt} = g_{a\gamma}^4 \frac{\rho_a^2}{m_a^2} \frac{1}{\mathrm{SNR}^2} \frac{B_0^4 V^2 \xi^2}{T_{sys}^2} \frac{\beta^2}{(1+\beta)^2} Q_a \min(Q_L, Q_a) \sim f^{-10.66}$$

- Typically necessitates multi-cavity setups, higher order modes, dielectric/plasma haloscopes

However, the Purcell/heterodyne approach separates m_a and f

- We can work at a frequency which is experimentally more convenient
- For $\omega_s \simeq n \times \omega_p$ a 1 GHz experiment probes $n+1$ GHz axions. Scan rate benefit can be $\mathcal{O}(n^7)$!
- Analysis required here to determine optimal approach

Discussion and conclusions

We propose a novel dark matter search strategy: cavity enhanced axion decay

Pros	Cons
1. No B field, allowing ultrahigh Q superconducting cavities	1. Must work with two cavity modes - additional cavity design constraints and tuning complexity
2. Can simultaneously search for $m_a = w_s + w_p$ and $m_a = w_s - w_p$, using heterodyne experiments 'for free'	2. Must pump one mode for good sensitivity: require good pump mode rejection and cavity cooling
3. With plausible parameters, can probe a classic region for QCD axion DM, with enhanced high frequency performance	

Questions

How much tuning is possible? What would an optimal cavity enhanced axion decay experiment look like?

More details available in arXiv: 2507.18508

Thanks for listening!