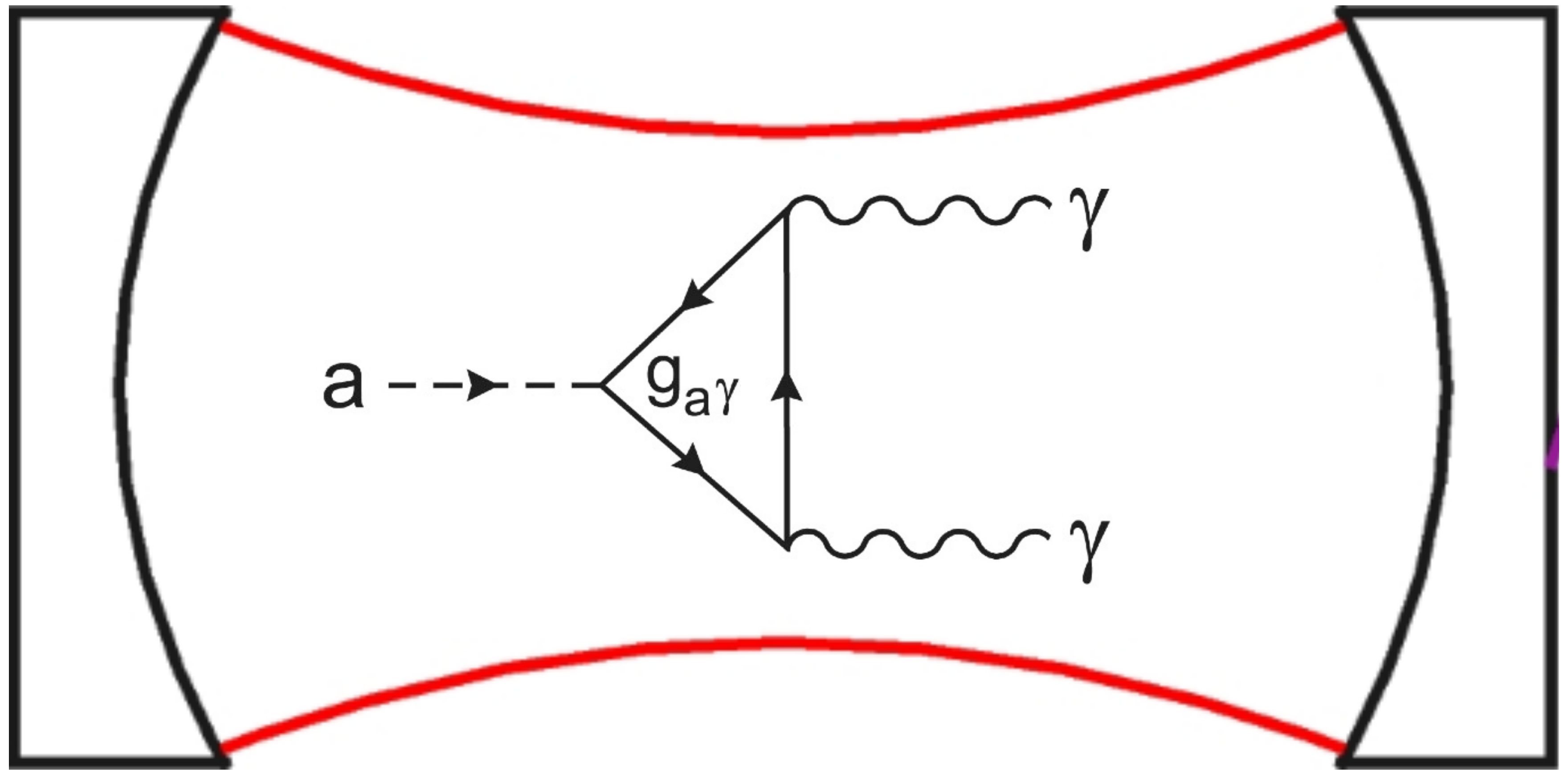
# Resonant enhancement of axion dark matter decay




Nick Houston, Beijing University of Technology

Based on arXiv:2507.18508 with Bilal Ahmad and Yu-Ang Liu,

Axion 2025, nhouston@bjut.edu.cn

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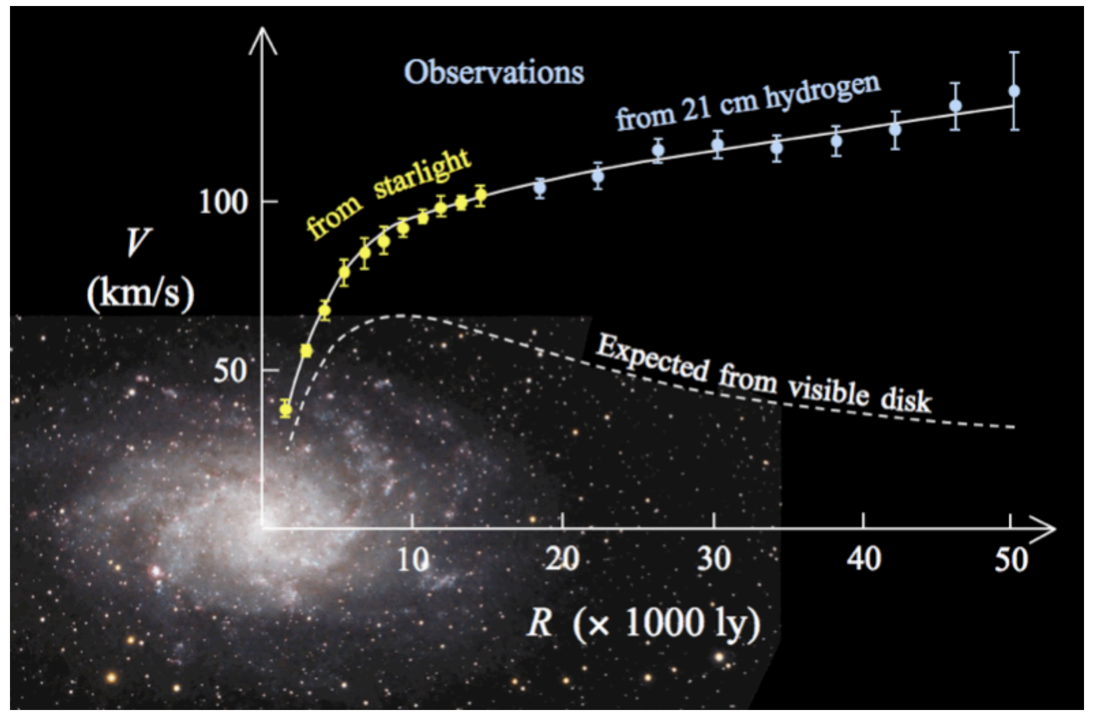
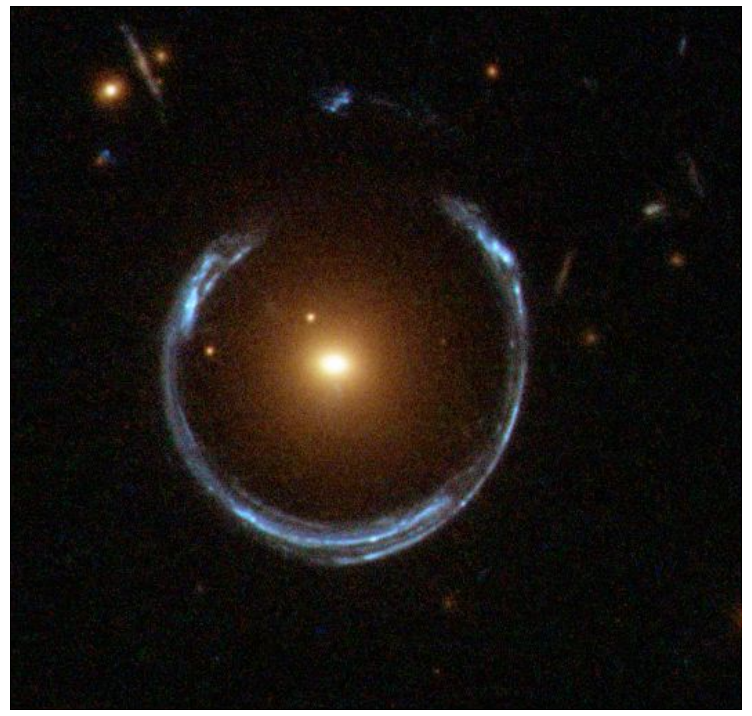
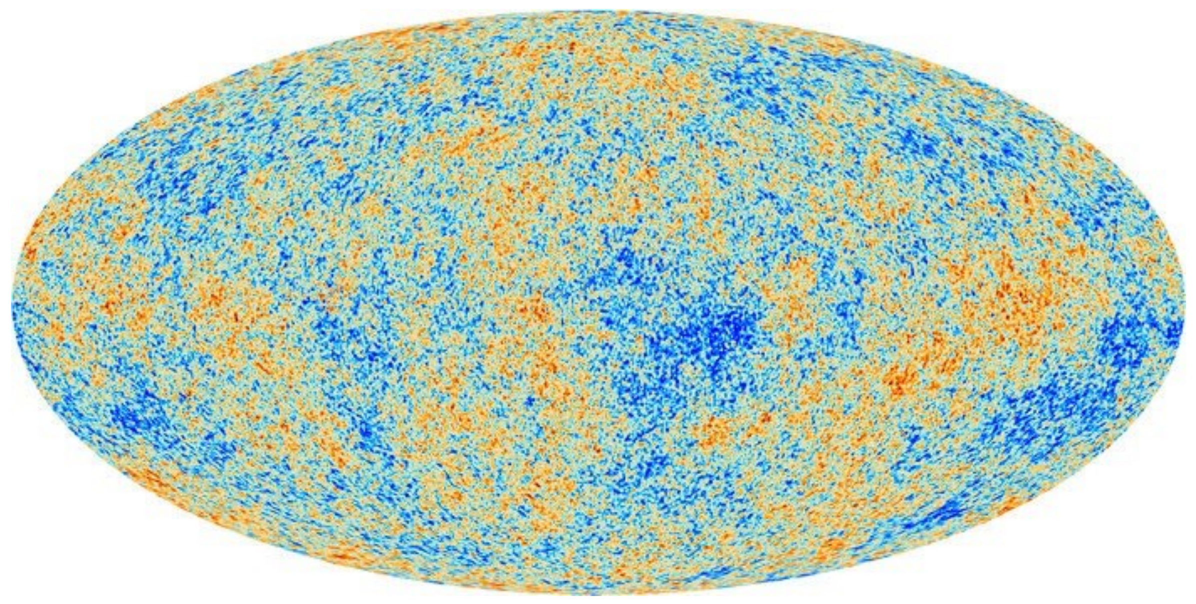






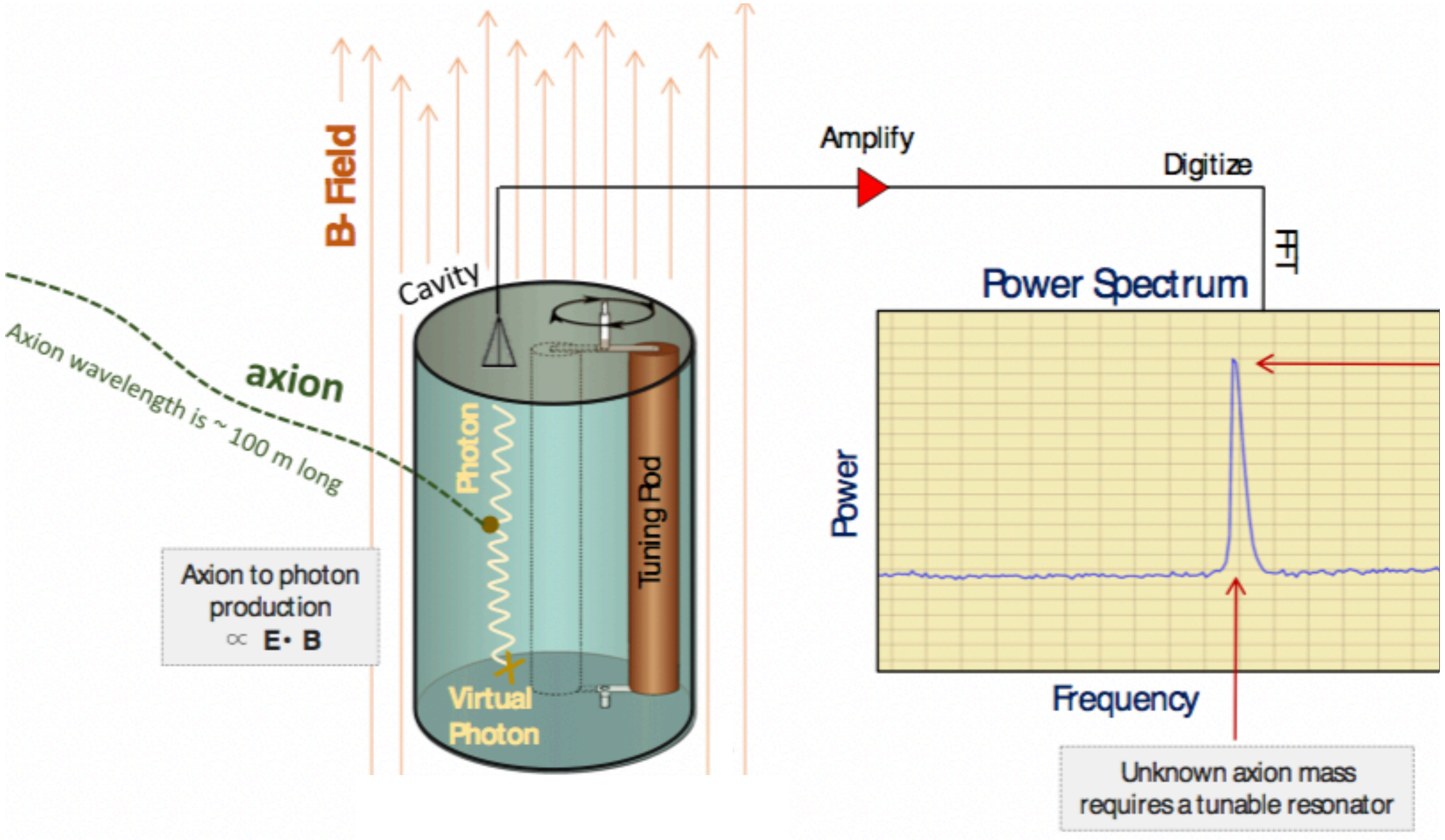
## The big picture

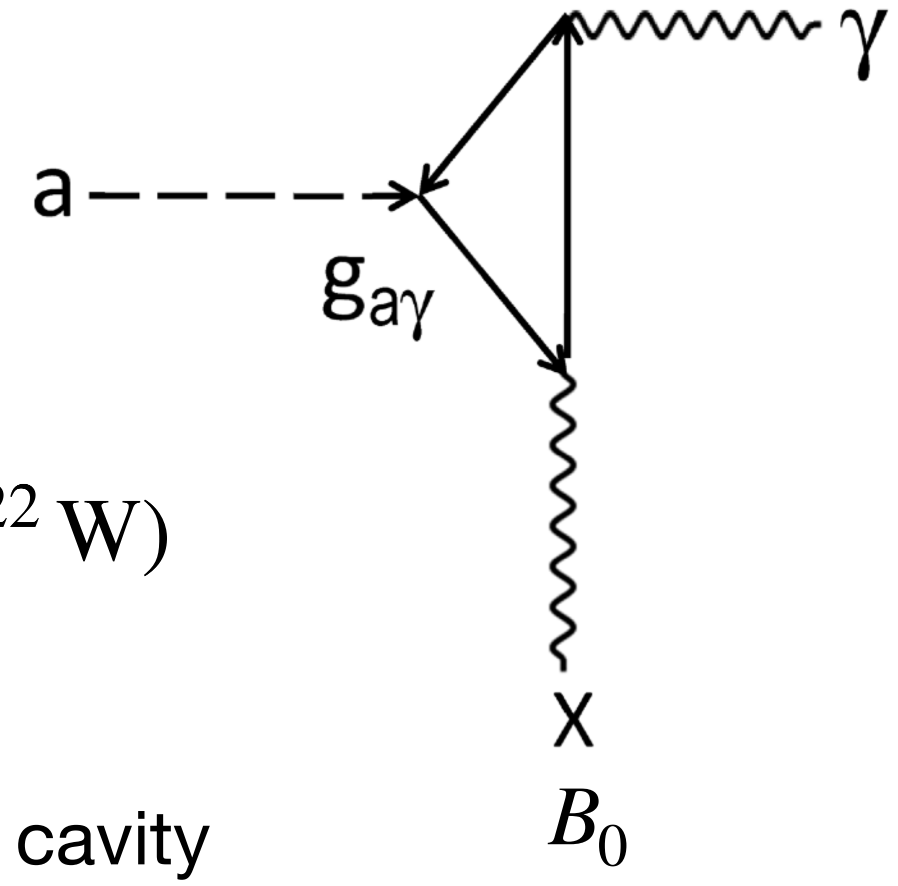
- Very good indirect evidence exists for dark matter, so why hasn’t it been detected?
- This talk is about using a resonant microwave cavity - a haloscope - to search for axion dark matter

## Motivation

- New experimental strategies for axion DM detection

# Key technology: cavity haloscopes




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

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

Why does this enhance detection?

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

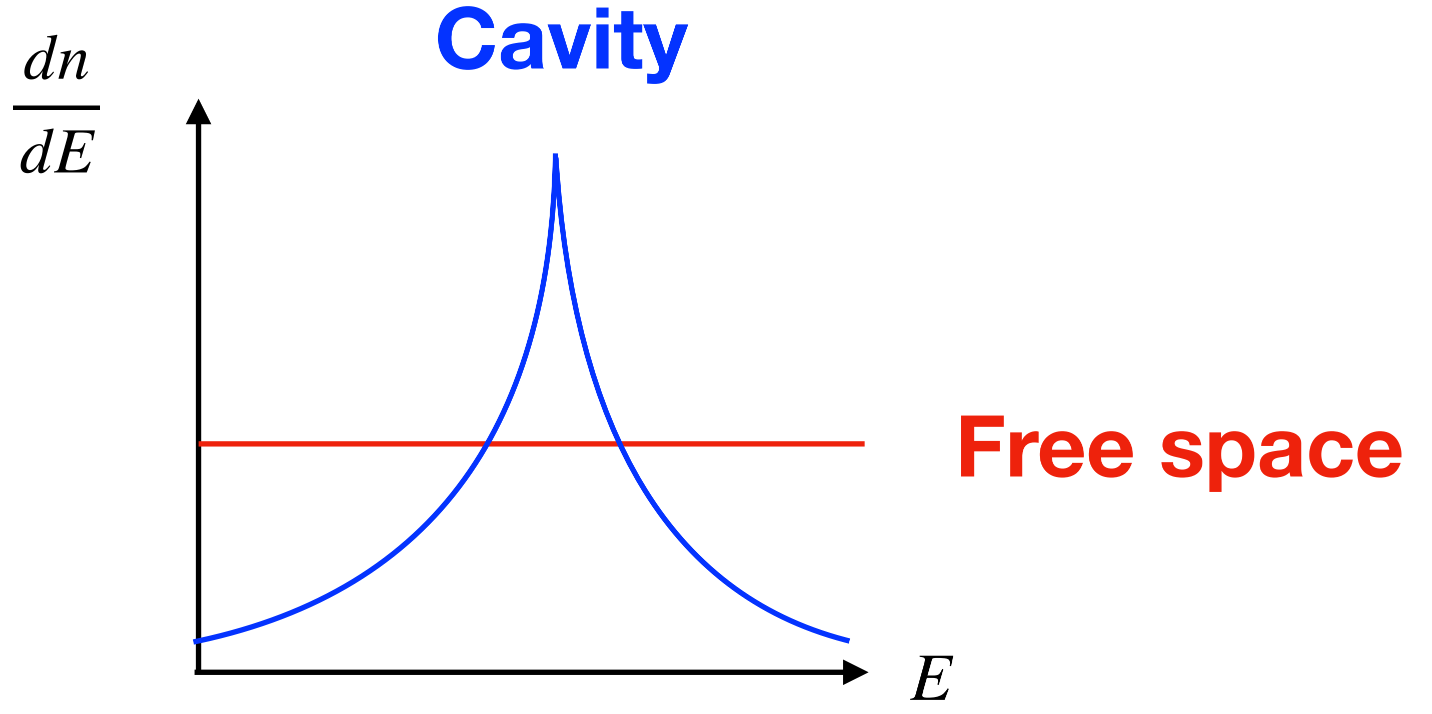
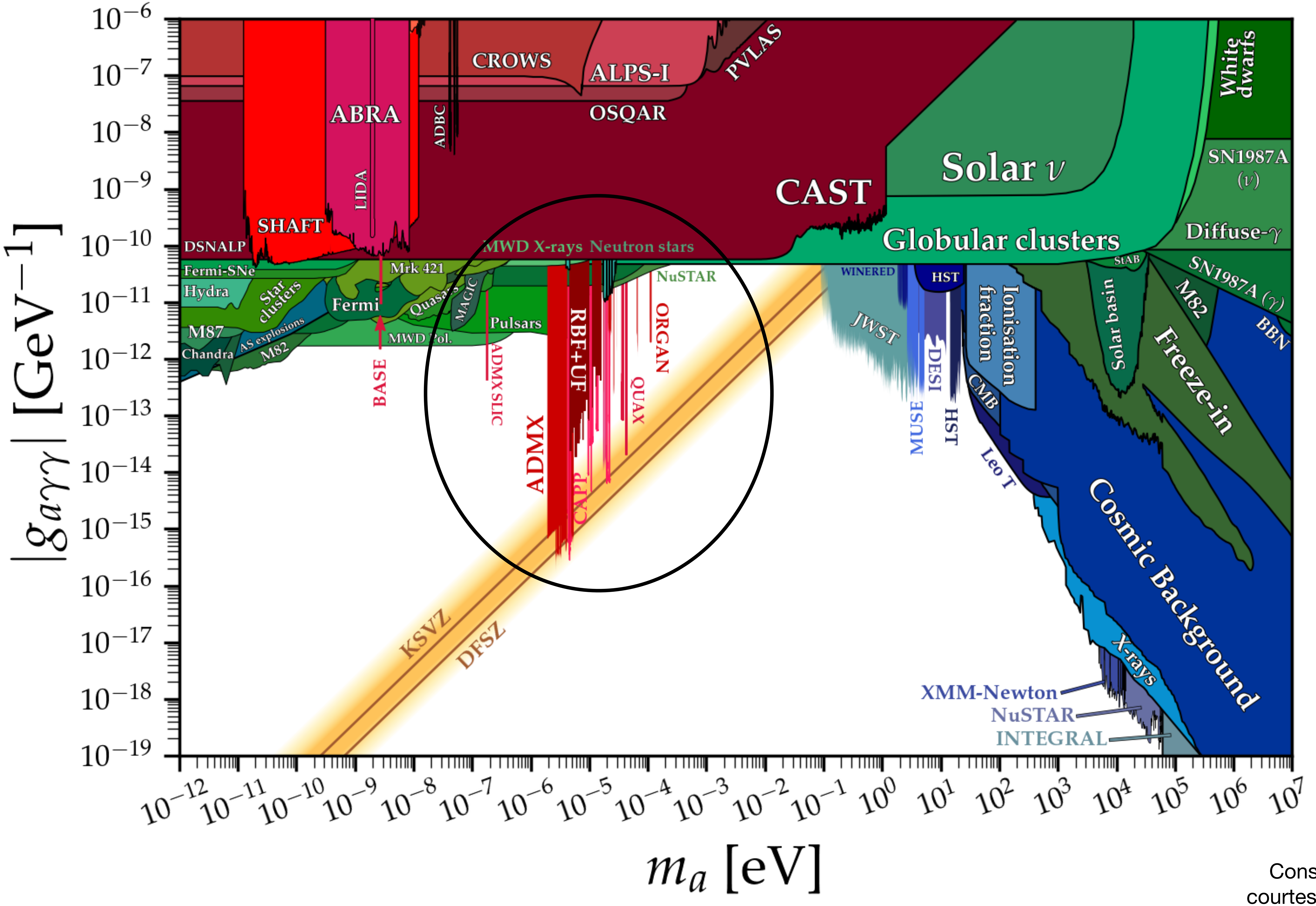
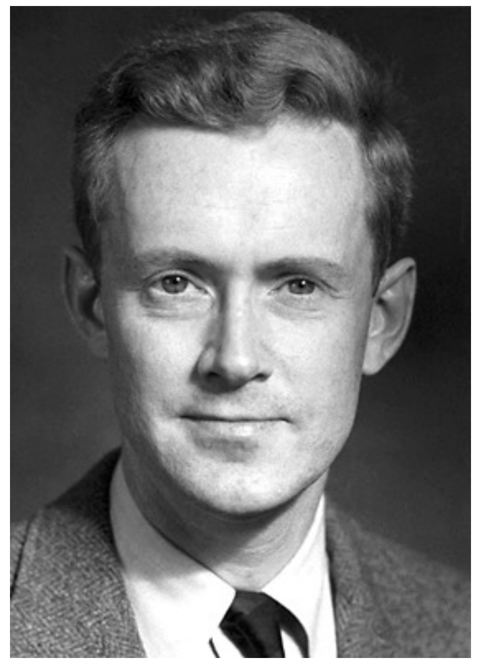



Figure courtesy of C. Boutan




Constraint figures courtesy of Axionlimits

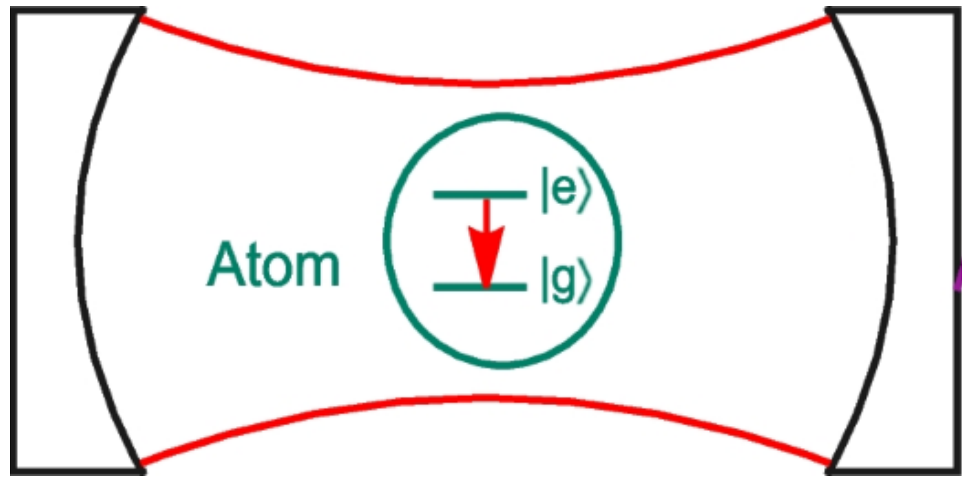
# The Purcell effect



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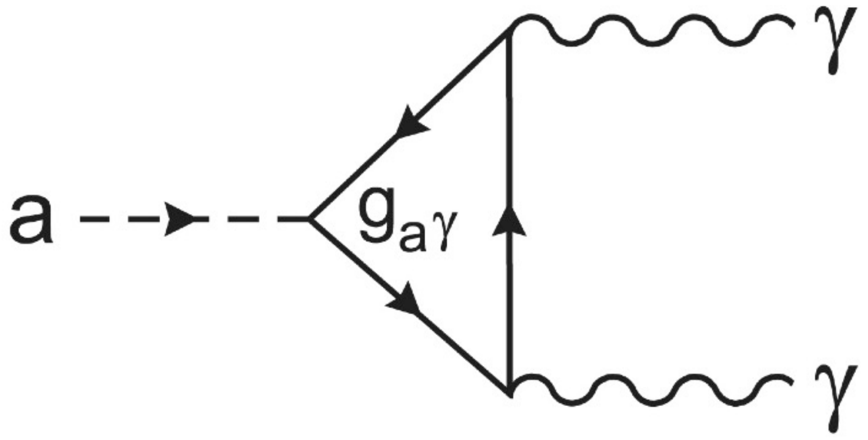
- Axions can decay too. Is this also enhanced? Can we use this to search for DM?

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



# Sanity check

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

$$\dot{n}_a \simeq -\Gamma_{a\to\gamma\gamma} \times n_a \times F_{\text{Purcell}}$$

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

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

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

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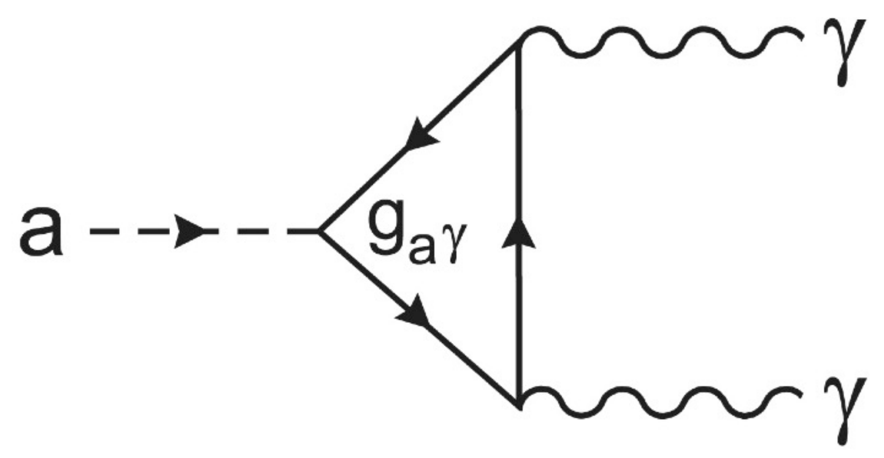
- For stimulated decay though, $\dot{n}_a \simeq -\Gamma_{a\to\gamma\gamma} \times n_a \times F_{\text{Purcell}} \times \boxed{(1+n_\gamma)}$



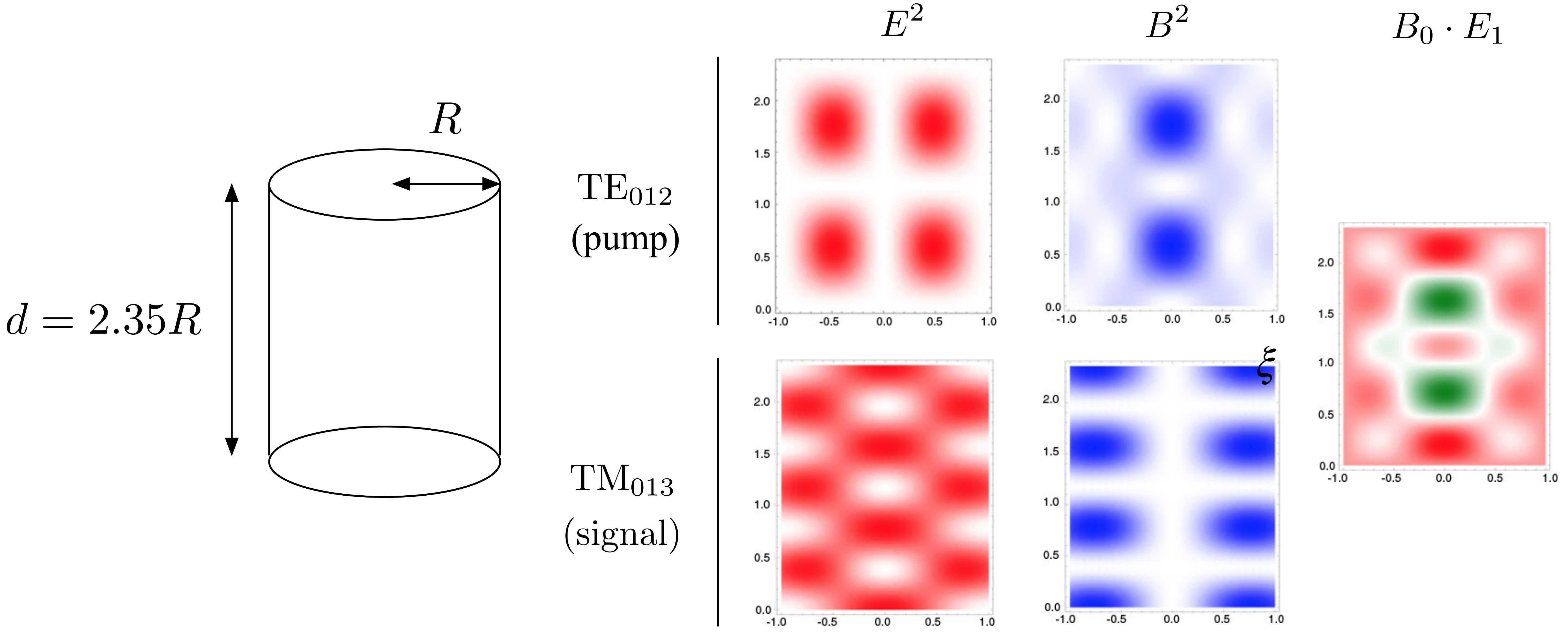

- For high $Q$ cavities, we can have $n_\gamma = \frac{U}{E_\gamma} \simeq 10^{28}\left(\frac{U}{\text{kJ}}\right)\left(\frac{\text{GHz}}{E_\gamma}\right)$

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

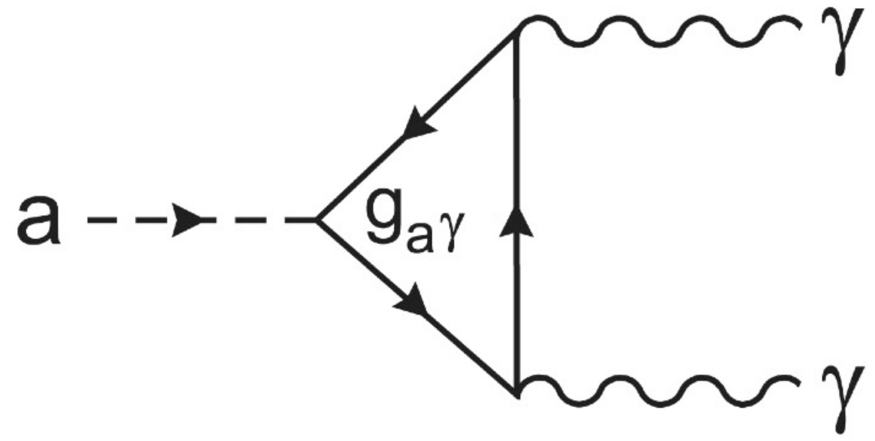
# What would we require?

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

- A cavity with two tunable resonant modes, with $E \cdot B \neq 0$ and good form factor $\xi$ . 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

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

# Let's calculate

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

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

damping term

axion mixing term

pumping term

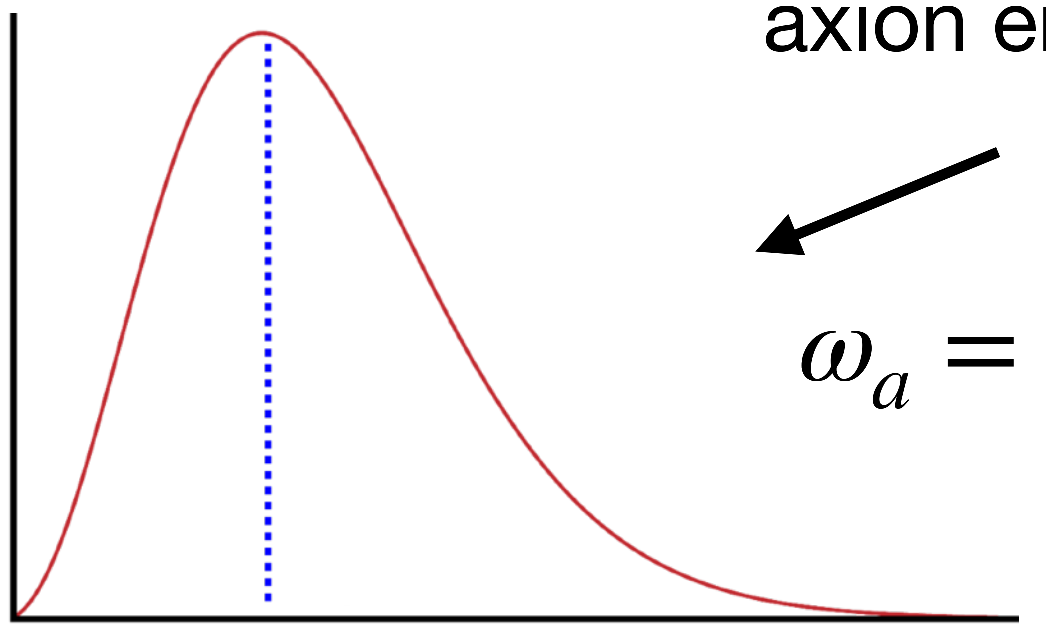
$$< N_s > \equiv \frac{1}{T}\int_0^T dt\ < c_s^\dagger(t)c_s(t) > \simeq \frac{g_{a\gamma}^2|\xi|^2 w_p}{4m_a^2}Q_s\rho_{DM}F_{\rm DM}(w_s + w_p)\Big(1 + < N_p > \Big)$$

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 $Q_{\rm int}$
- Can still be competitive with ordinary Primakoff haloscopes:

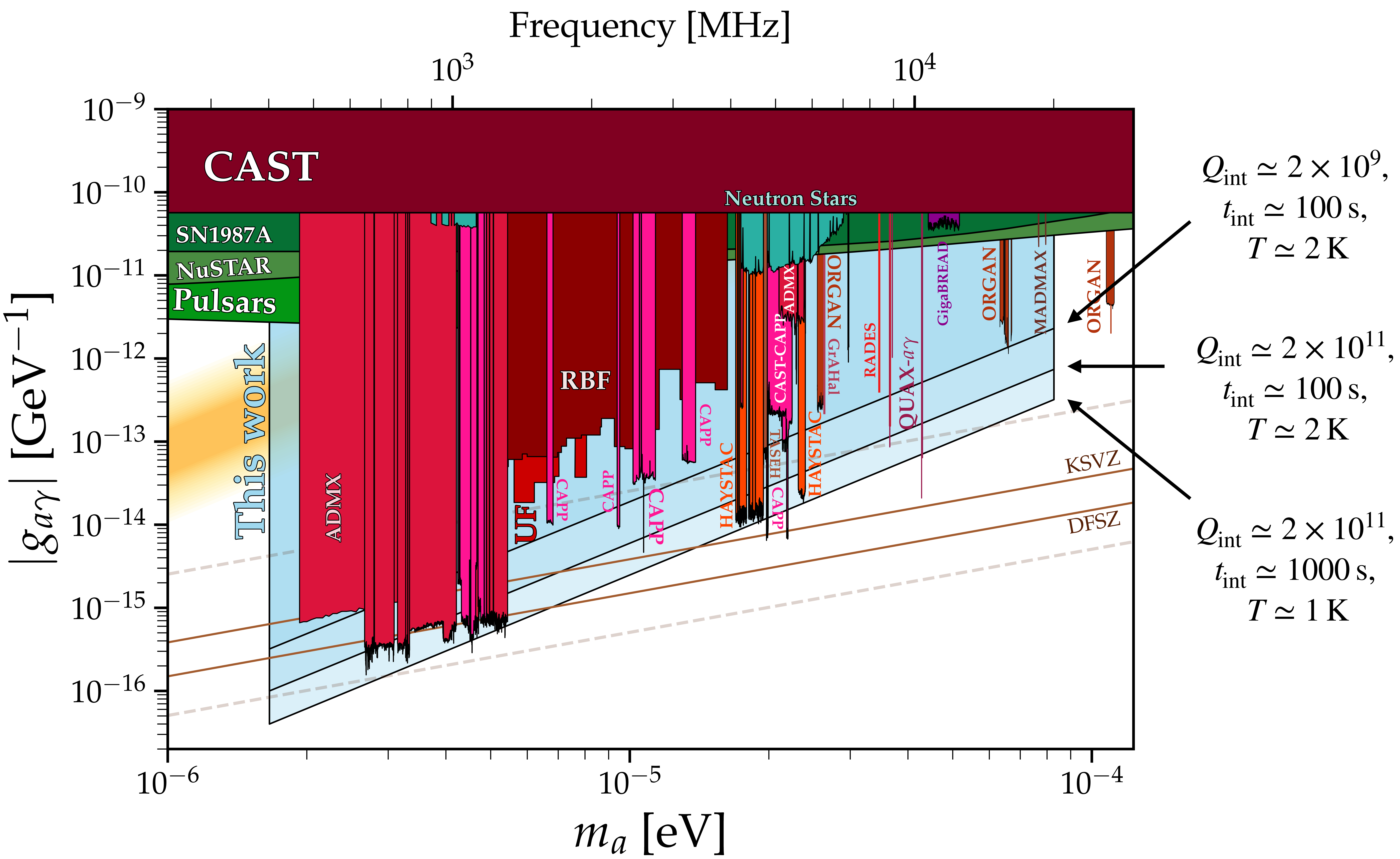
$$g_{a\gamma}^{95\%}\Big|_{\rm Purcell} \simeq \frac{5\times10^{-15}}{\rm GeV}\left(\frac{10^6}{Q_a}\right)^{\frac{1}{2}}\left(\frac{2\times10^{11}}{Q_{\rm int}}\right)^{\frac{1}{4}}\left(\frac{411\,{\rm J}}{U_{\rm max}}\right)^{\frac{1}{2}} \times \text{common factors}$$

**Cavity dependent factor**

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

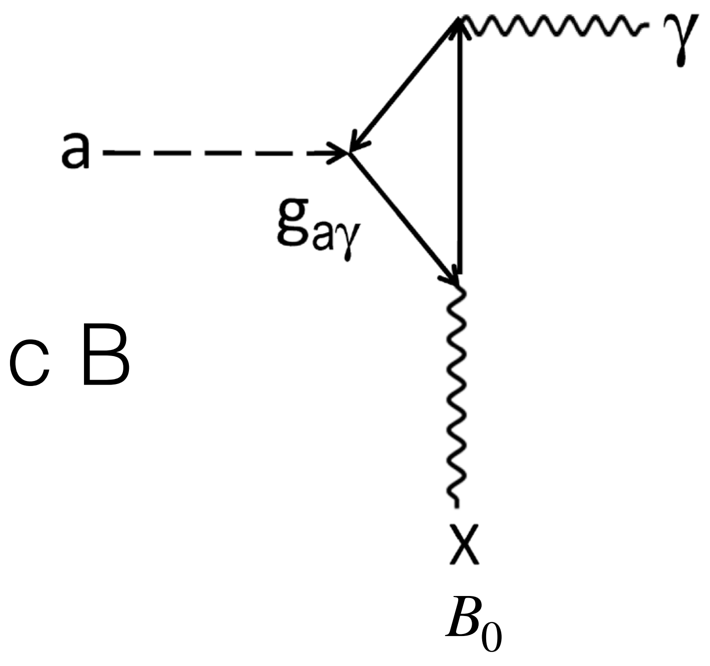
$$\text{common factors} = \left(\frac{m_{\rm a}}{10.7\mu{\rm eV}}\right)^{\frac{3}{4}}\left(\frac{T}{1.2\,{\rm K}}\right)^{\frac{1}{2}}\left(\frac{0.45\,{\rm GeV/cm^3}}{\rho_{\rm a}}\right)^{\frac{1}{2}}\left(\frac{100\,{\rm s}}{t_{\rm int}}\right)^{\frac{1}{4}}$$

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

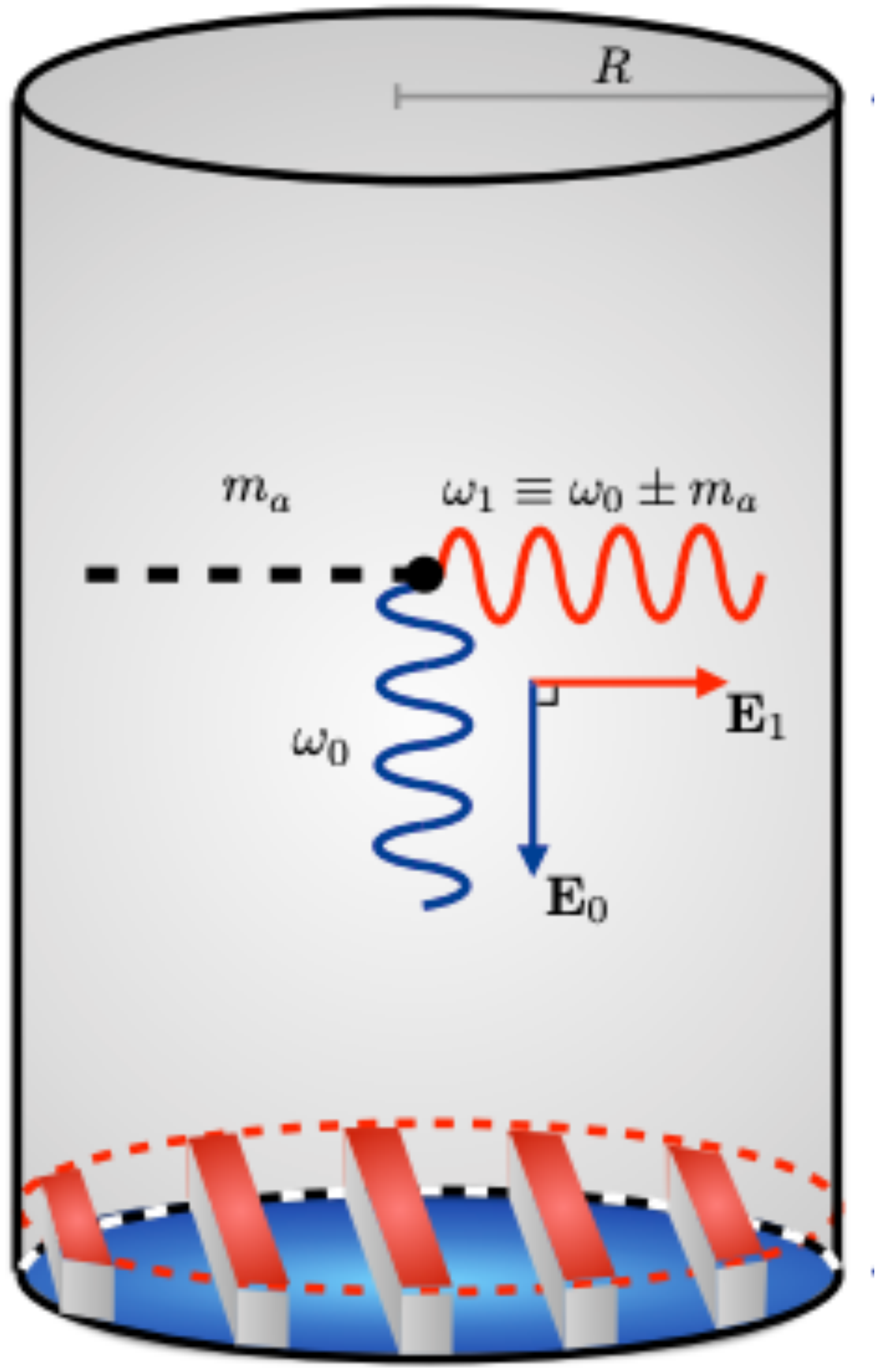


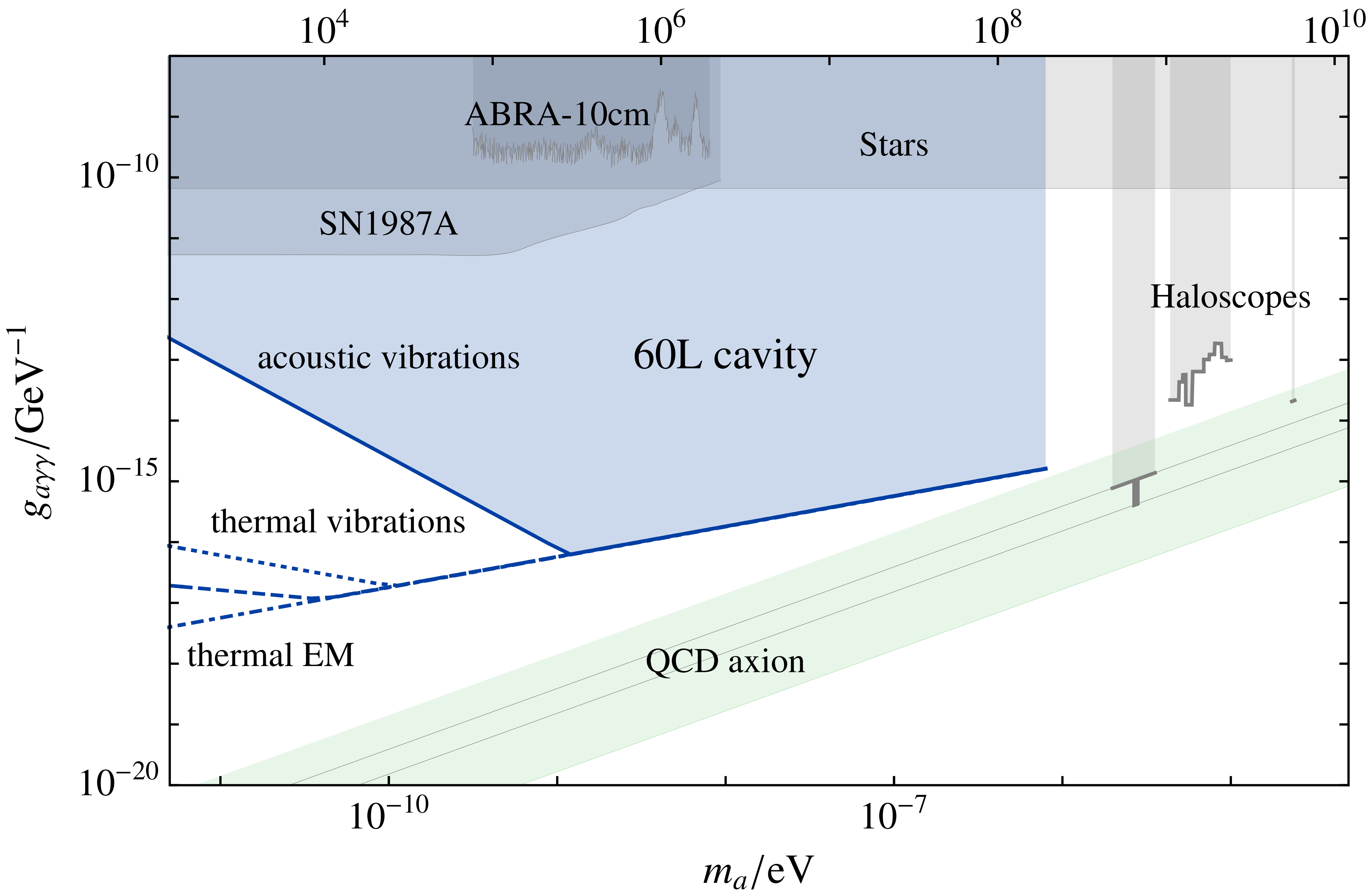
Frequency [MHz]
$10^3$
$10^4$
$10^{-9}$
$10^{-10}$
$10^{-11}$
$10^{-12}$
$10^{-13}$
$10^{-14}$
$10^{-15}$
$10^{-16}$
$|g_{a\gamma}|$ [GeV$^{-1}$]
CAST
Neutron Stars
SN1987A
NuSTAR
Pulsars
This work
ADMX
RBF
UF
CAPP
HAYSTAC
CAST-CAPP
ADMX
TASEH
ORGAN
GrAHal
RADES
QUAX-$a\gamma$
GigaBREAD
MADMAX
KSVZ
DFSZ
$10^{-6}$
$10^{-5}$
$10^{-4}$
$m_a$ [eV]
$Q_{\rm int} \simeq 2\times10^9$,
$t_{\rm int} \simeq 100$ s,
$T \simeq 2$ K
$Q_{\rm int} \simeq 2\times10^{11}$,
$t_{\rm int} \simeq 100$ s,
$T \simeq 2$ K
$Q_{\rm int} \simeq 2\times10^{11}$,
$t_{\rm int} \simeq 1000$ s,
$T \simeq 1$ K

# 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



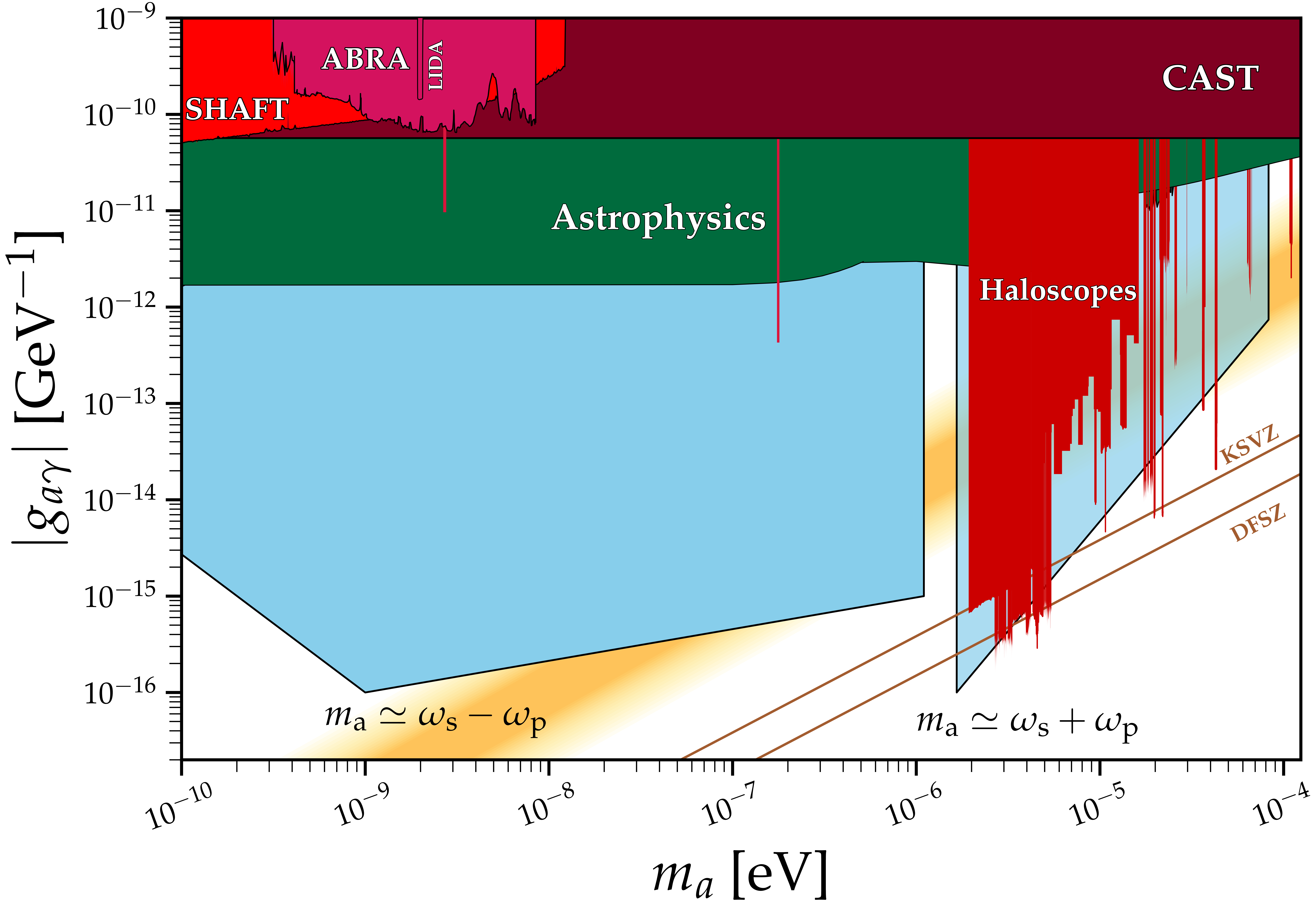




**See Kevin Zhou's talk later today!**

**With a single cavity we can simultaneously search for $m_a = w_s - w_p$ (Primakoff) and $m_a = w_s + w_p$ (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



CAST
ABRA
LIDA
SHAFT
Astrophysics
Haloscopes
KSVZ
DFSZ
$m_a \simeq \omega_s - \omega_p$
$m_a \simeq \omega_s + \omega_p$
$|g_{a\gamma}|$ [GeV$^{-1}$]
$m_a$ [eV]

# Discussion and conclusions

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

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

More details available in arXiv: 2507.18508

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| 1. No $B$ field required<br>2. Can use ultrahigh $Q$ superconducting cavities: higher scan rate<br>3. Can simultaneously search for $m_a = w_1 + w_2$ and $m_a = w_1 - w_2$<br>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<br>2. Need to pump one mode for good sensitivity: require very good pump mode rejection<br>3. Additional cooling needs due to pump power, thermal noise limits sensitivity |

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**Thanks for listening!**