



Searching for Dark Particles with Light (and Quantum Technologies)

Christina Gao

New methods and ideas at the frontiers of particle physics



Axion talks in this conference

Astrophysical sources:

- Aggrawal (BH), Balkin (NS), K.Perez (stars), Servant (axion kination)

Dark matter:

- Buschmann (theory), Nita (ADMX), Ouellet (DMRadio), Schutz (axion decay)

Laboratory:

- Perez & Hod (LUXE), Redigolo (flavour exp), **Gao (LSW)**
- + many model-independent searches looking for dark sector particles!

This talk

Laboratory experiment:

- light-shining-through-walls (LSW)
- Axion-photon coupling
- Axion mass: $\lesssim 10 \mu\text{eV} (\text{GHz})$

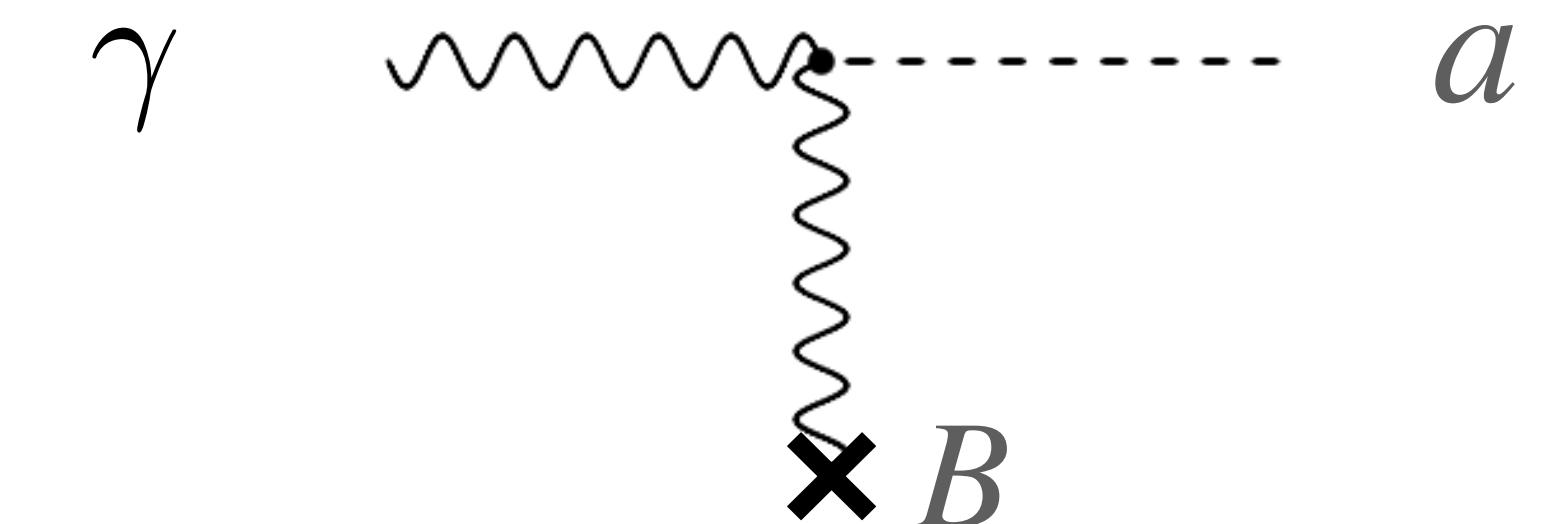
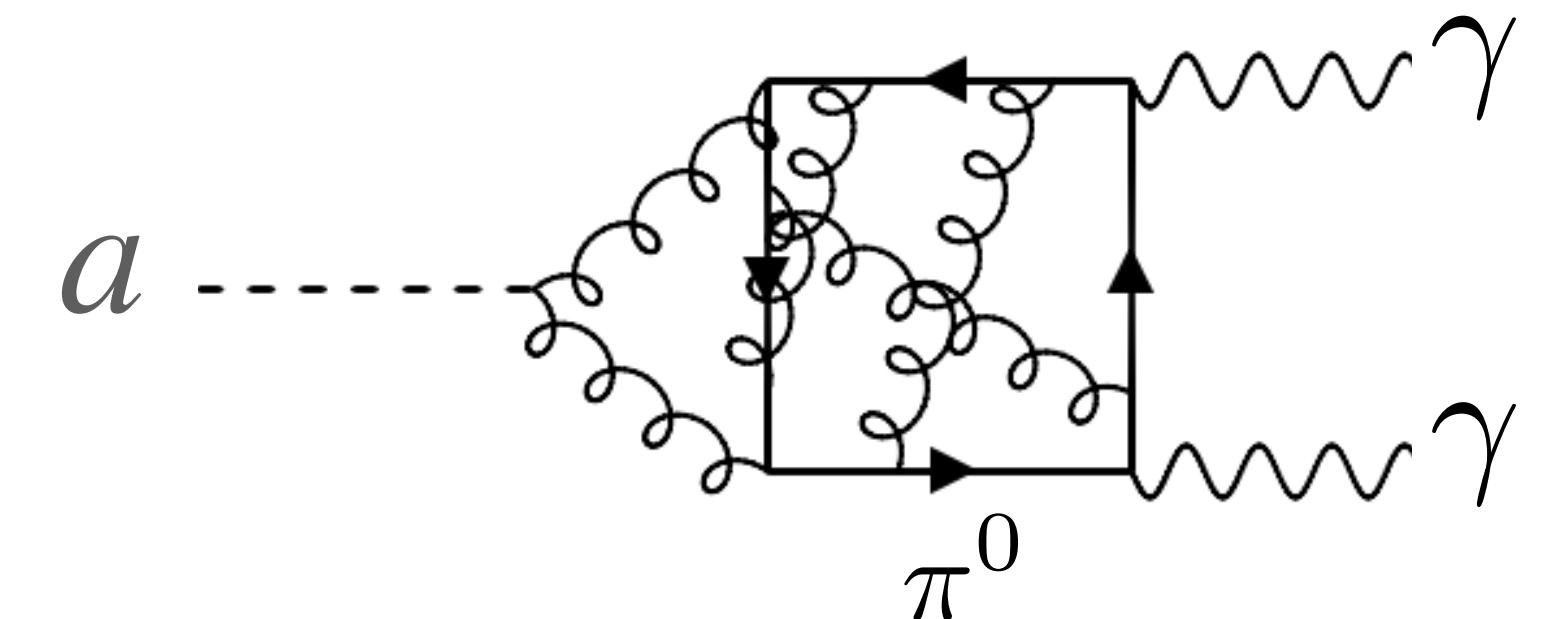
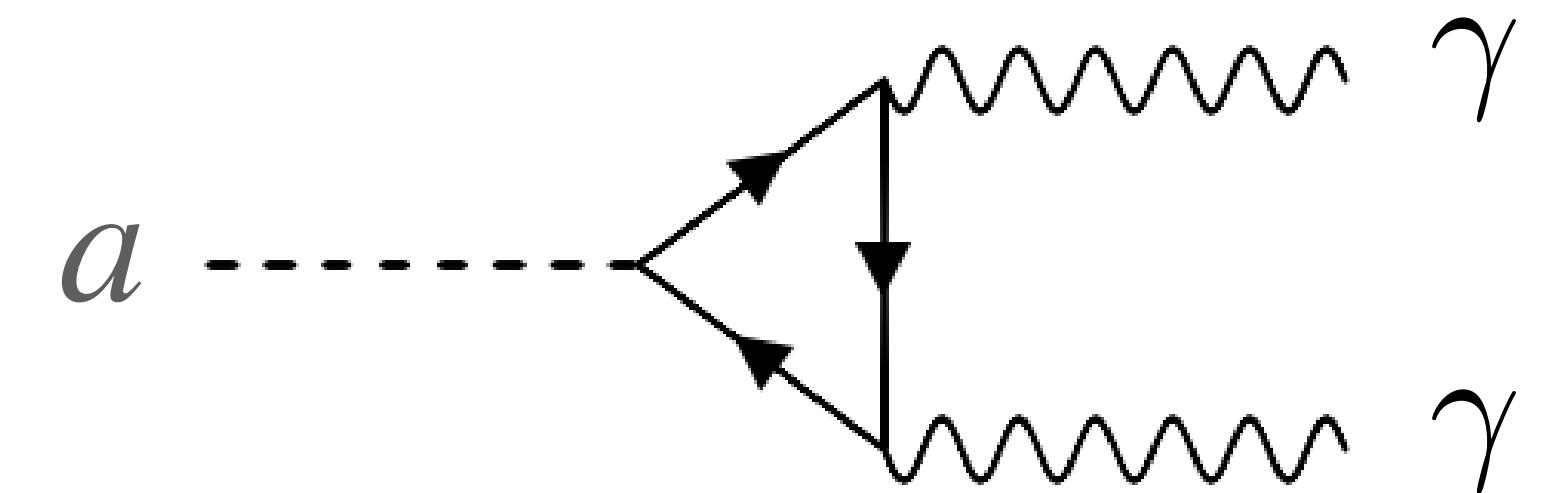
based on **CG & Harnik** (JHEP 2021)

Axion's Two Photon Vertex

$$\mathcal{L}_{\text{int}} \supset -\frac{g}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$
$$= ga E \cdot B$$

$$g \propto 1/f$$

Axion searches usually rely on axion-photon conversion in a background magnetic field.



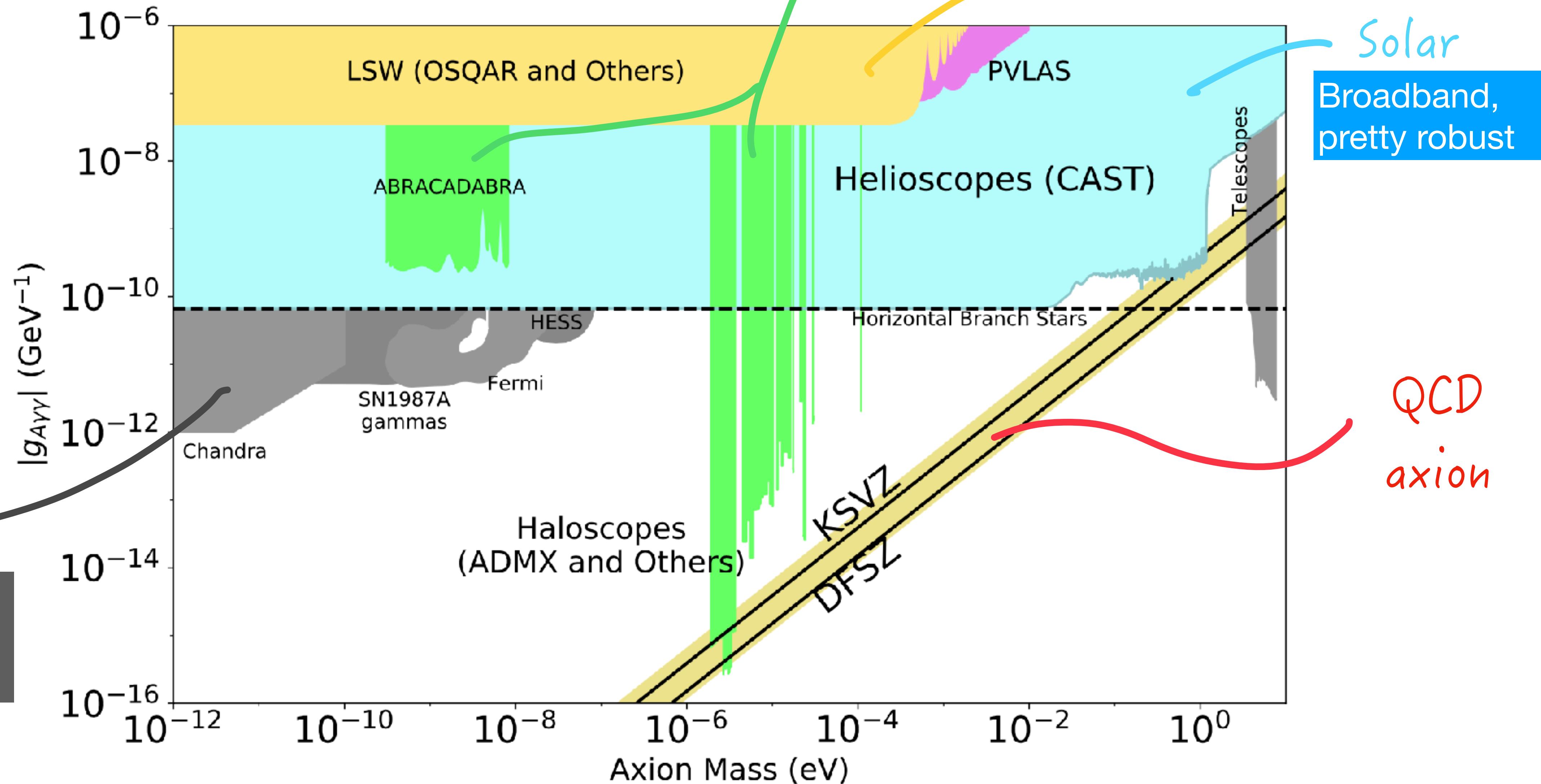
Constraints on axion-photon coupling

From The Review of Particle Physics (2020)

Astro
Relies on
modeling of
astrophysics

Very narrow
bandwidth, requires
scanning

Brady, CG et al (2022)

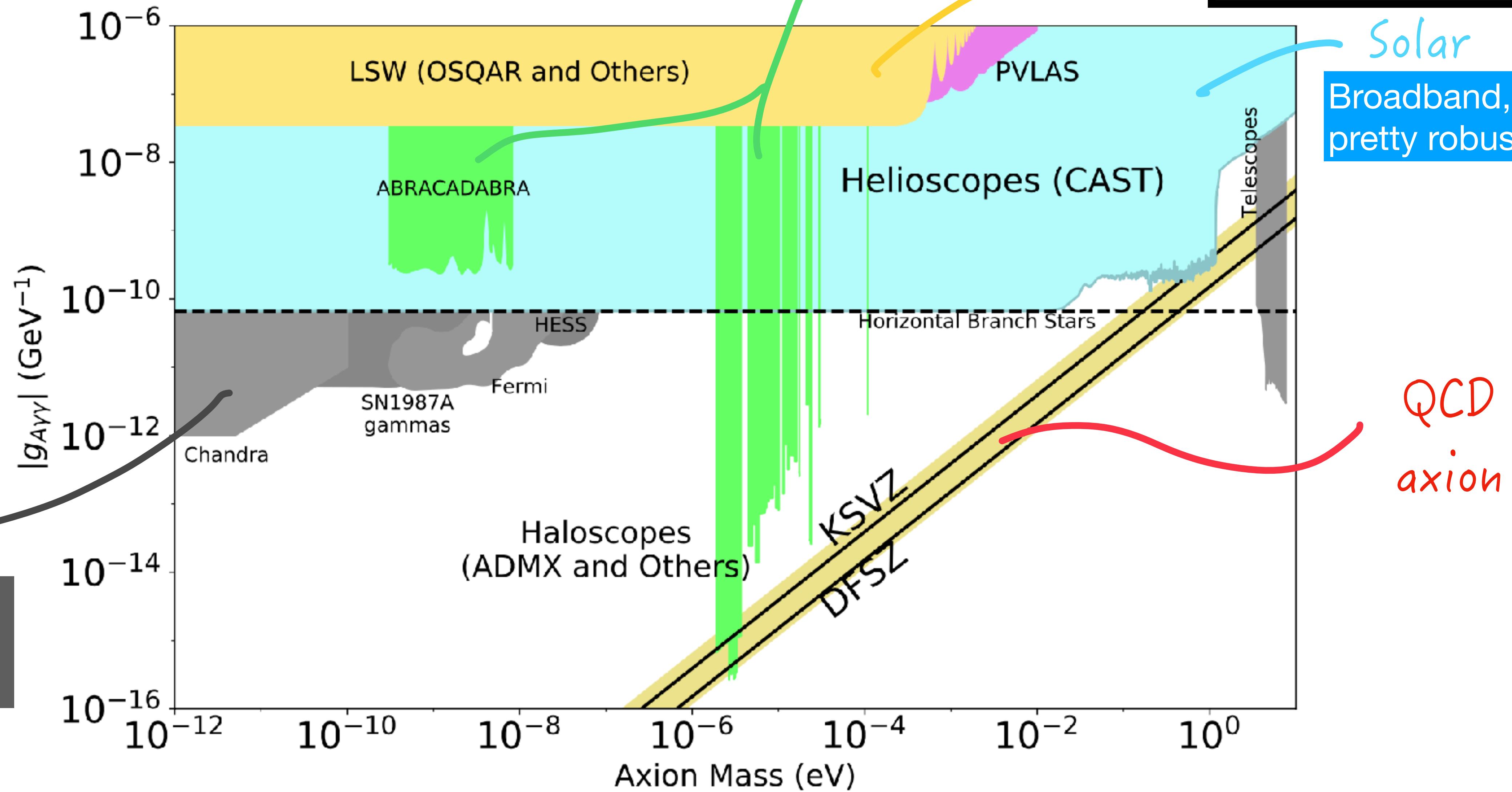


From The Review of Particle Physics (2020)

Relies on
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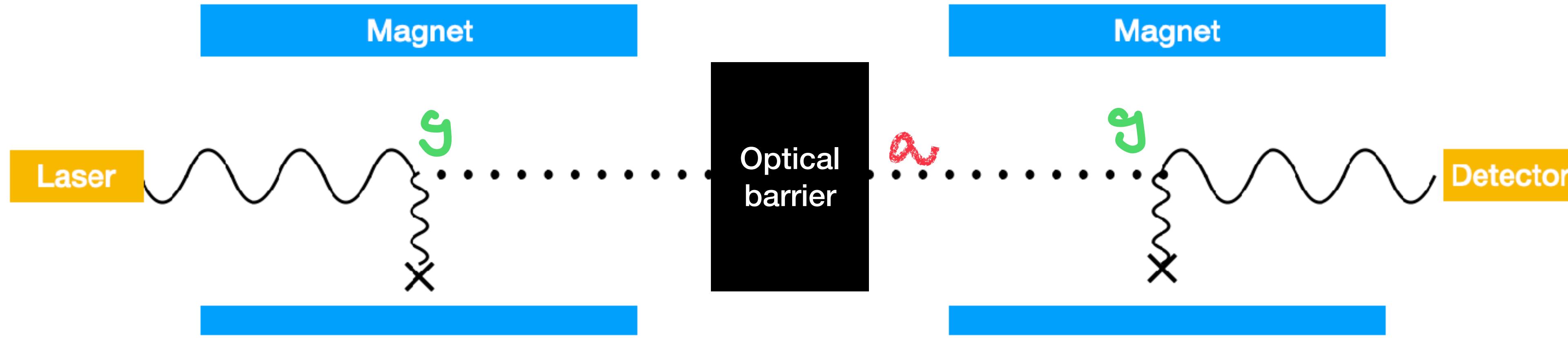
Very narrow bandwidth, requires scanning

Broadband, clean, can be improved by quantum technology!



Light-Shining-Through-Walls (LSW)

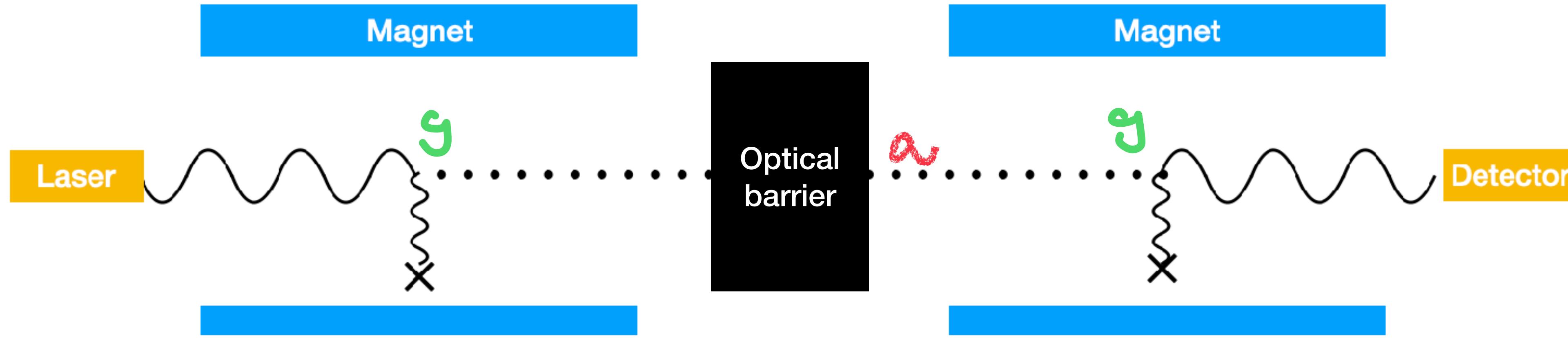
$$g \, a \, E \cdot B$$



- ◆ Tiny signal rate $\propto g^4$
- Want large number of photons to source the axion
- Want a low noise detector

Light-Shining-Through-Walls (LSW)

$$g \, a \, E \cdot B$$



♦ Tiny signal rate $\propto g^4$

- High Quality Cavity {
- Want large number of photons to source the axion
 - Want a low noise detector

Quality Factor of Cavities

$$Q \equiv 2\pi \times \frac{\text{energy stored}}{\text{energy dissipated per cycle}}$$

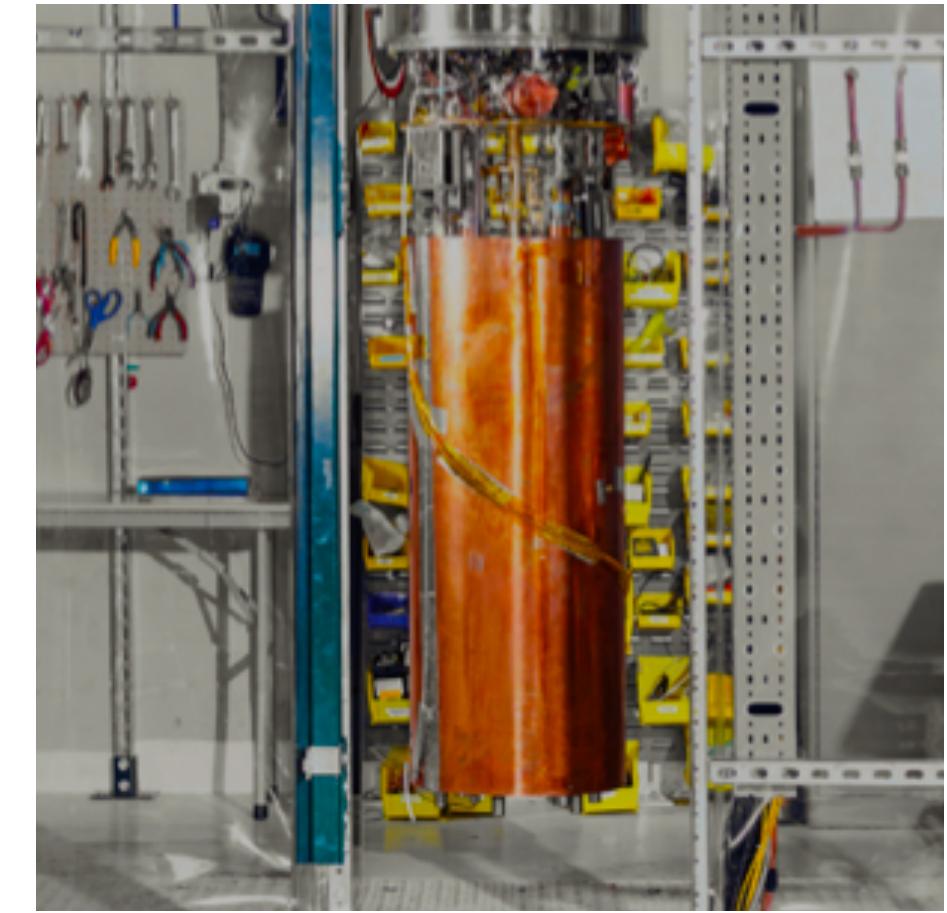
The **higher** the Q is, the **lower** the loss is, and the **larger** the number of photons are stored in a cavity.

Quality Factor of Cavities

Earth Ionosphere
 $Q = 3$



ADMX
 $Q \sim 10^5$



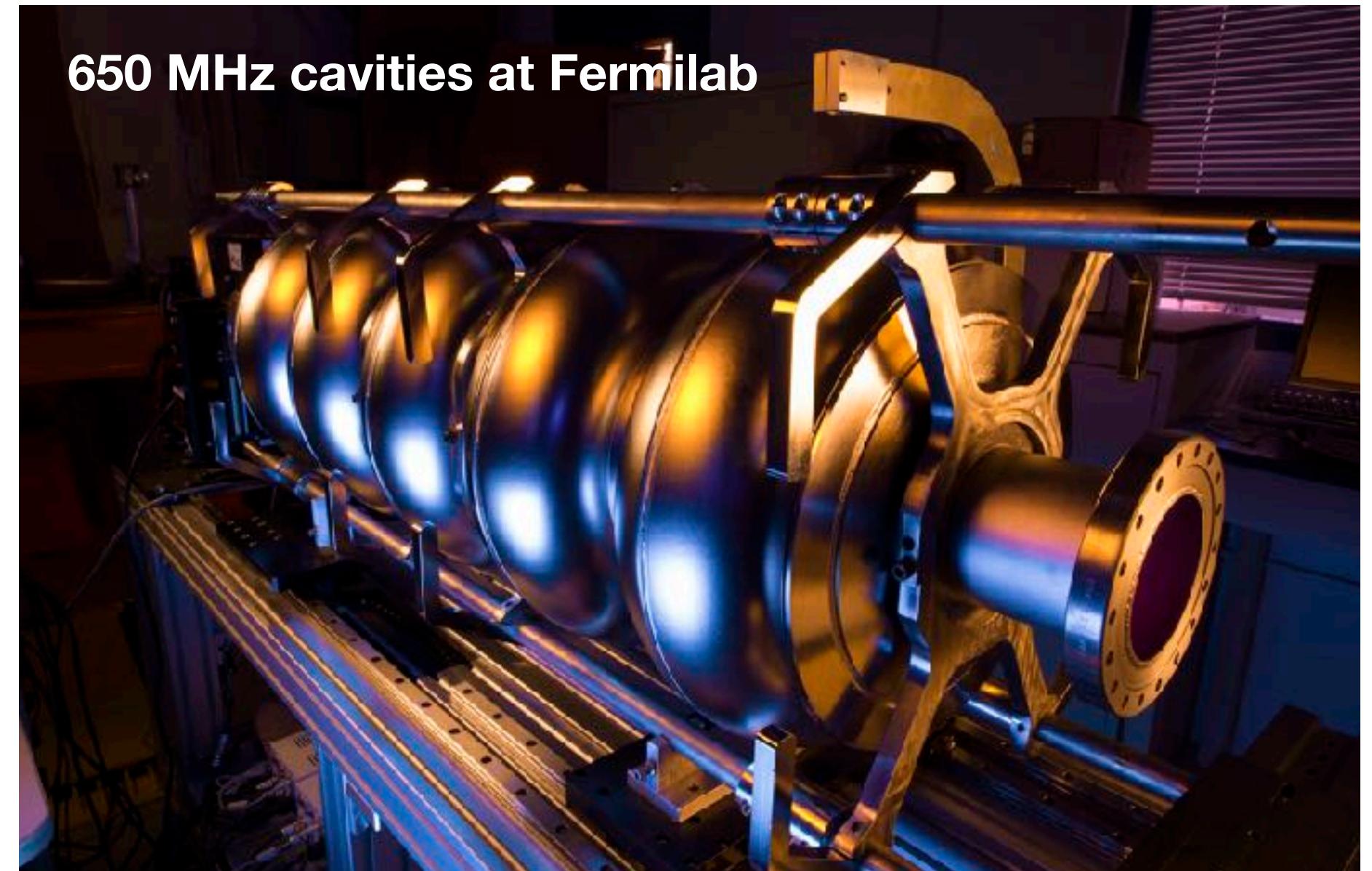
Phys. Rev. Lett. 127 (2021)

High quality cavities have $Q \gtrsim 10^7 \sim 10^{12}$
(depending on the resonant frequencies).

Superconducting Radio-frequency Cavities

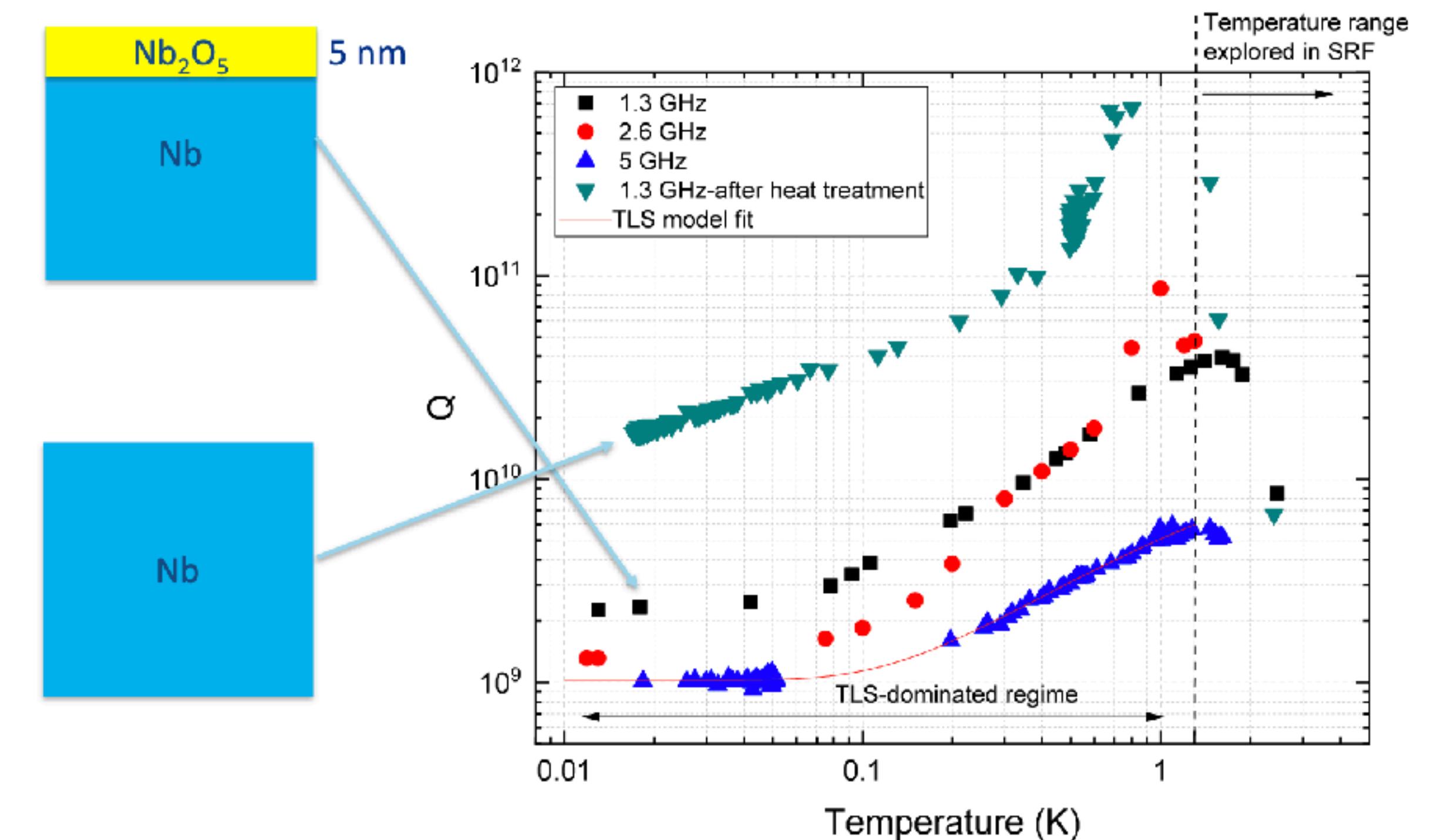
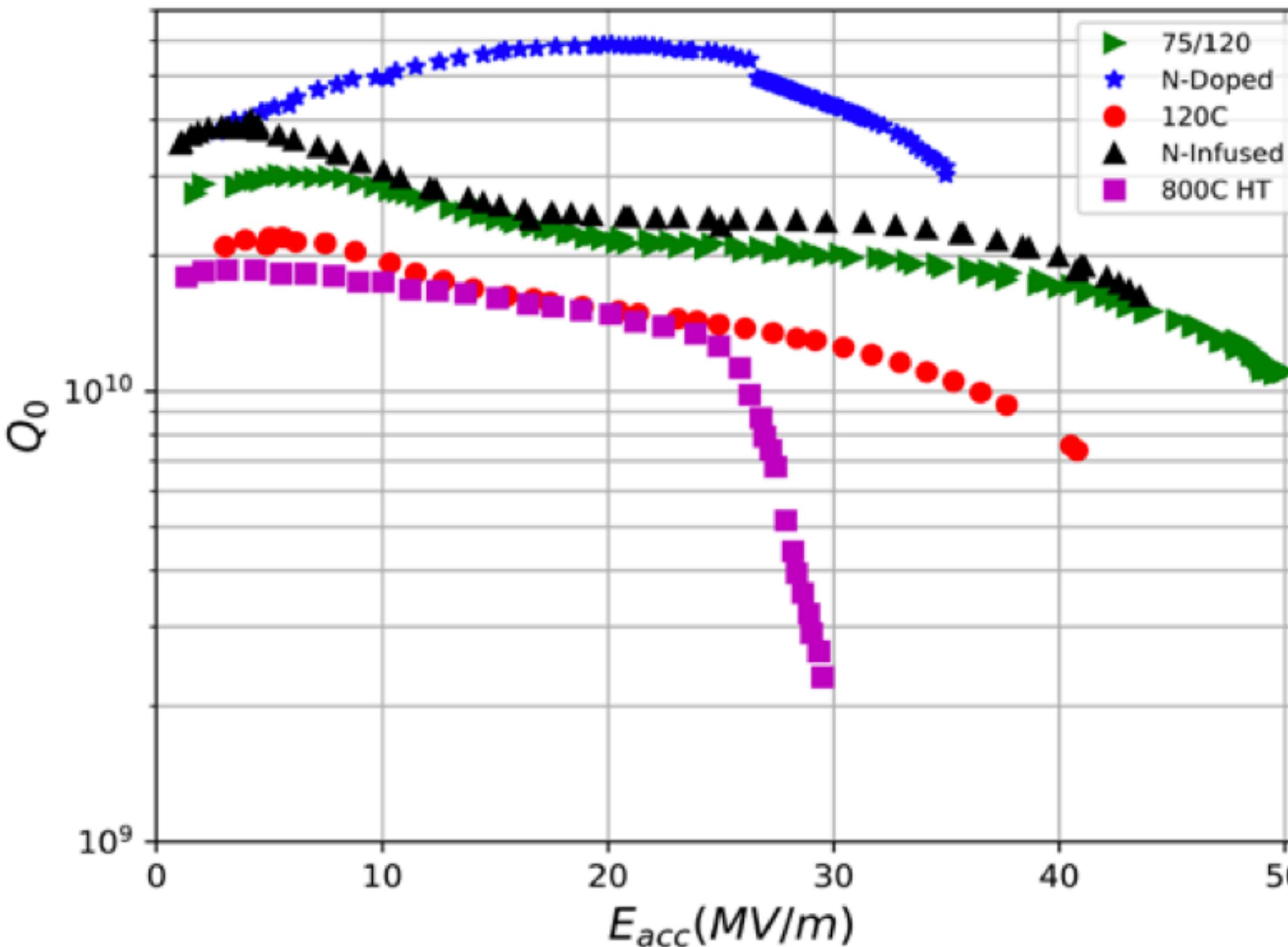
- ♦ Superconducting radio frequency (SRF) cavity has a resonance frequency around GHz ($10\mu\text{eV}$)
- ♦ $Q = 10^{10}$, can store 10^{26} photons with a field of peak amplitude

$$E_{\text{peak}} = 80 \text{ MV m}^{-1}$$



Superconducting Radio-frequency Cavities

$$E_{acc} \sim \frac{1}{2} E_{peak}$$



A. Romanenko and D. I. Schuster
Phys. Rev. Lett. 119, 264801 – Published 28 December 2017

<https://accelconf.web.cern.ch/srf2019/papers/mop031.pdf>

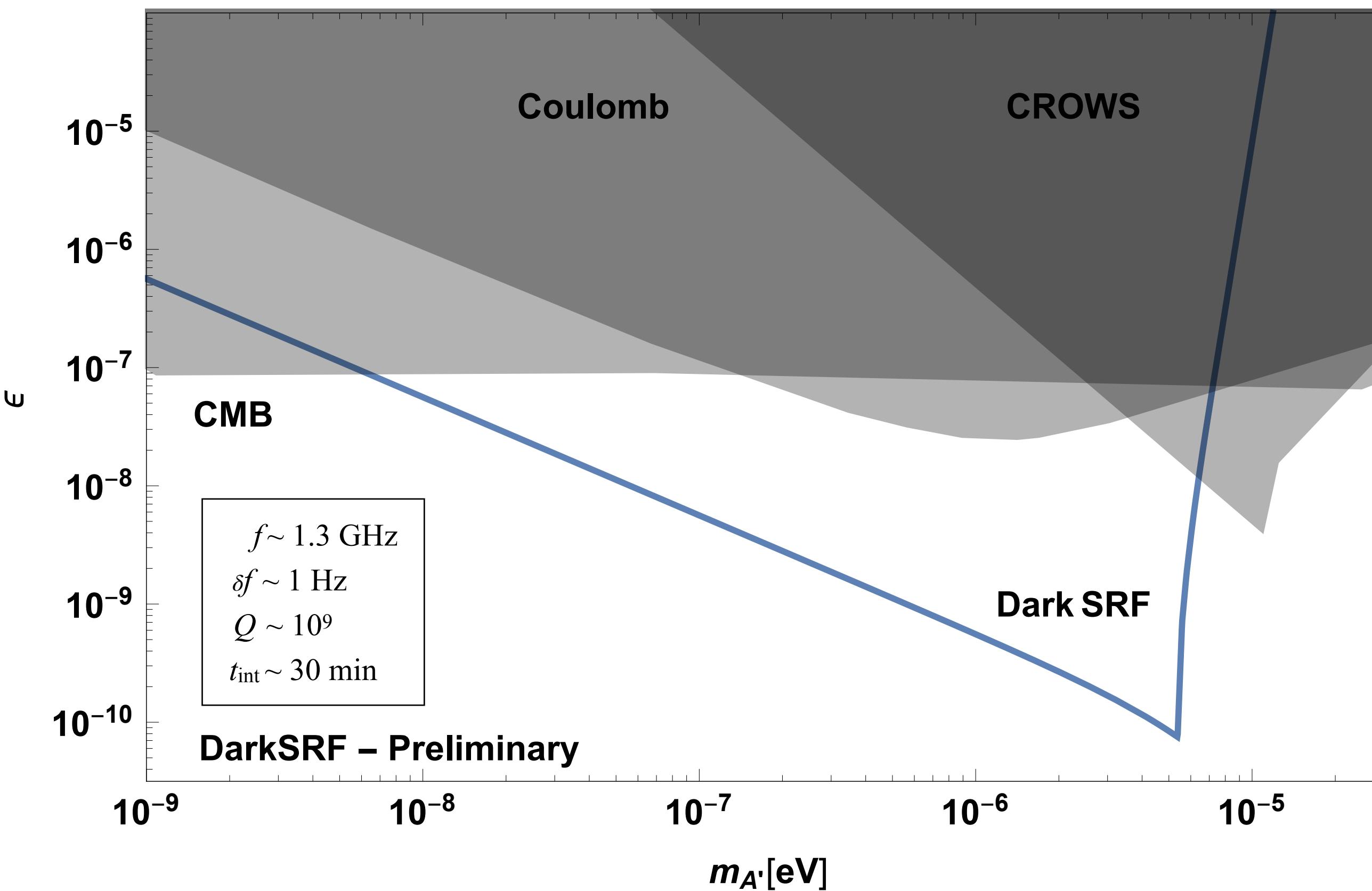
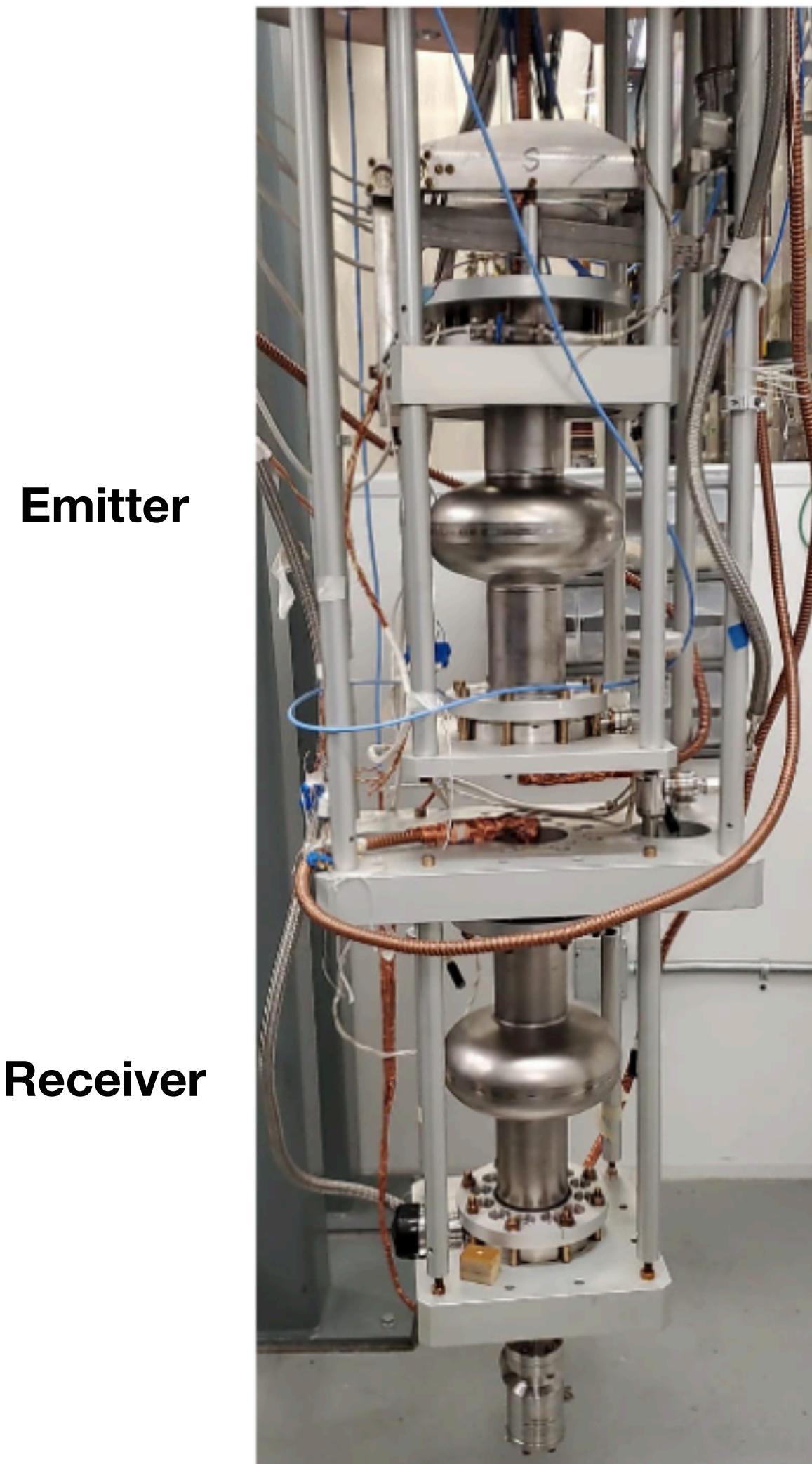
Superconducting Radio-frequency Cavities

Snowmass white paper

**“Searches for New Particles, Dark Matter,
and Gravitational Waves with SRF Cavities”**



SRF Cavities - Dark SRF

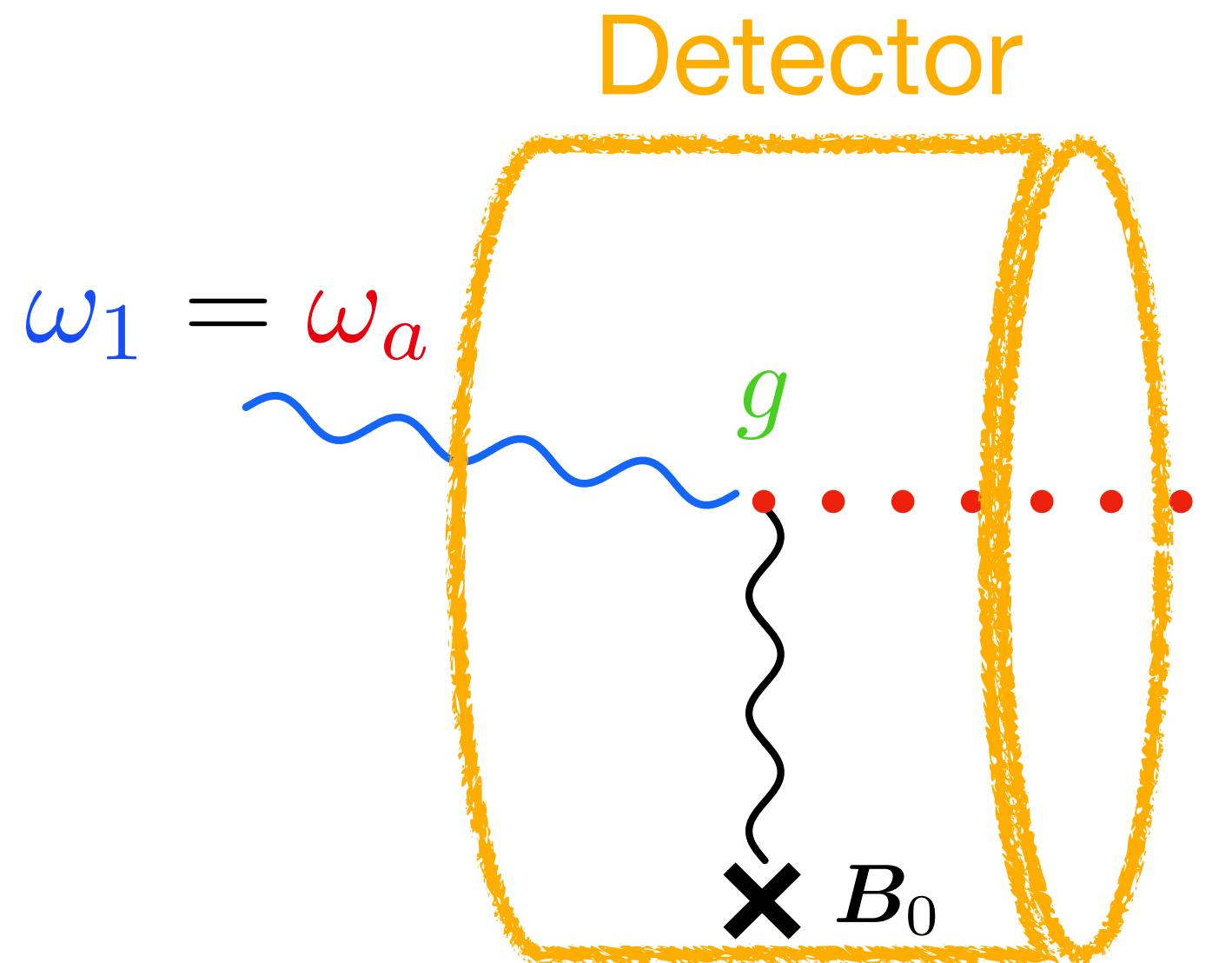


**A dark photon LSW search at Fermilab using SRF cavities.
Demonstrated high Q and frequency control.**

Dark SRF - A. Grasselino, R. Harnik, S. Posen, Z. Liu, A. Romanenko (to appear).

Review of Cavity Axion Searches

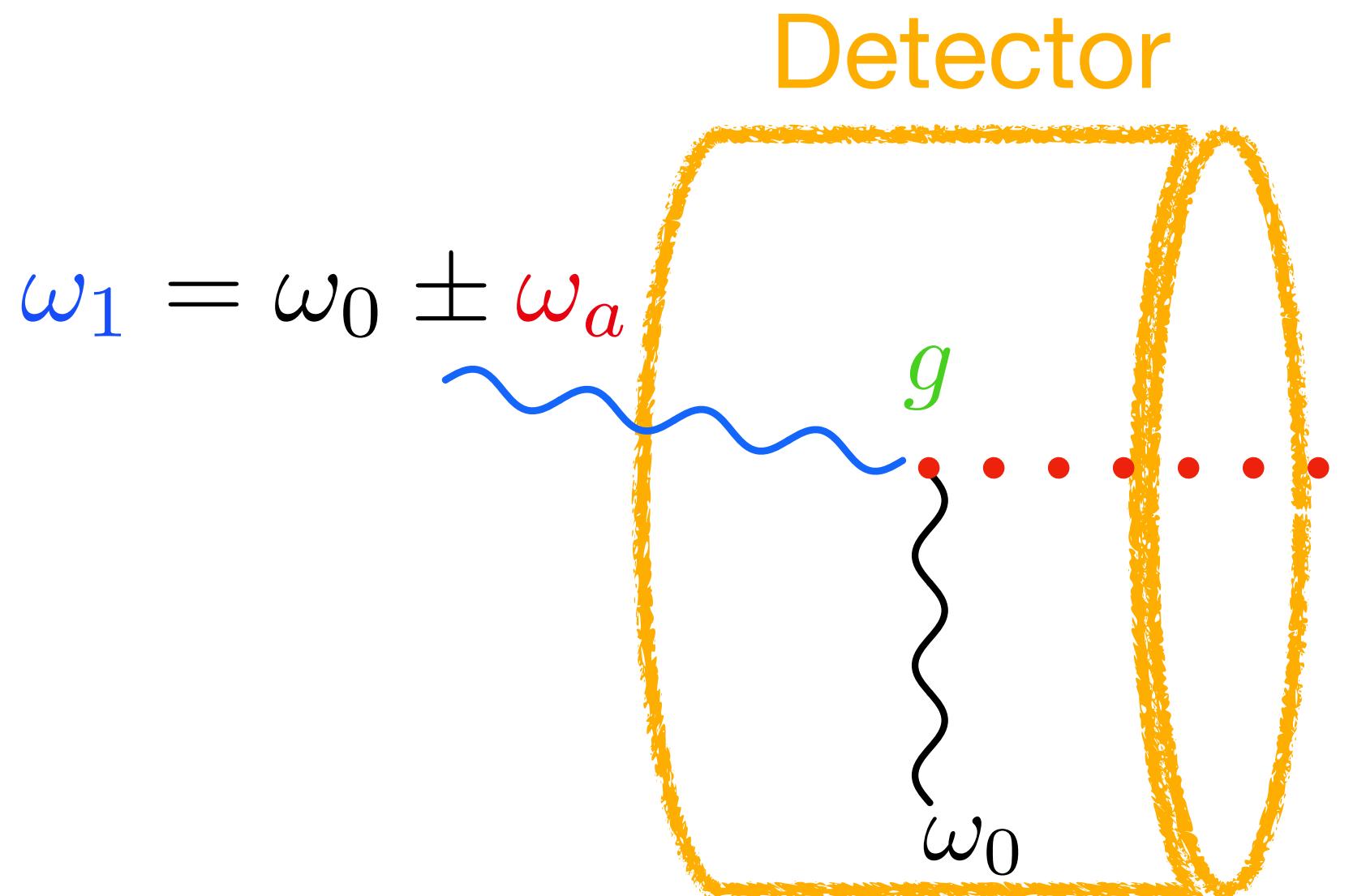
$$g \text{ } a \text{ } E_1 \cdot B_0$$



- ◆ a quiet cavity + static B
- ◆ signal ω_1 is a cavity mode, enhanced by Q .
- ◆ tiny g \Rightarrow large B desired, but large B may penetrate SRF cavity.

Review of Cavity Axion Searches

$$g \textcolor{red}{a} E_1 \cdot B_0$$



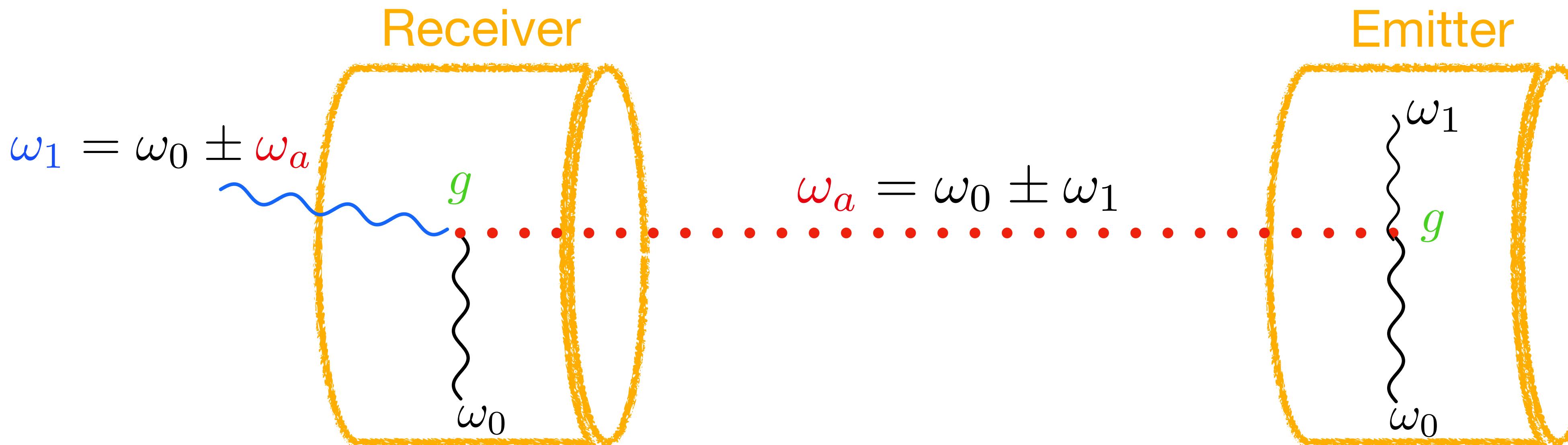
- ◆ static B → **active** cavity mode ω_0
- ◆ signal $\omega_1 = 2\text{nd}$ cavity mode
- ◆ frequency matching: $\omega_1 = \omega_0 \pm \omega_a$
- ◆ new DM axion search strategies

Sikivie (2010), Berlin et. al (2019)

Our proposal

LSW Axion Searches with SRF Cavities

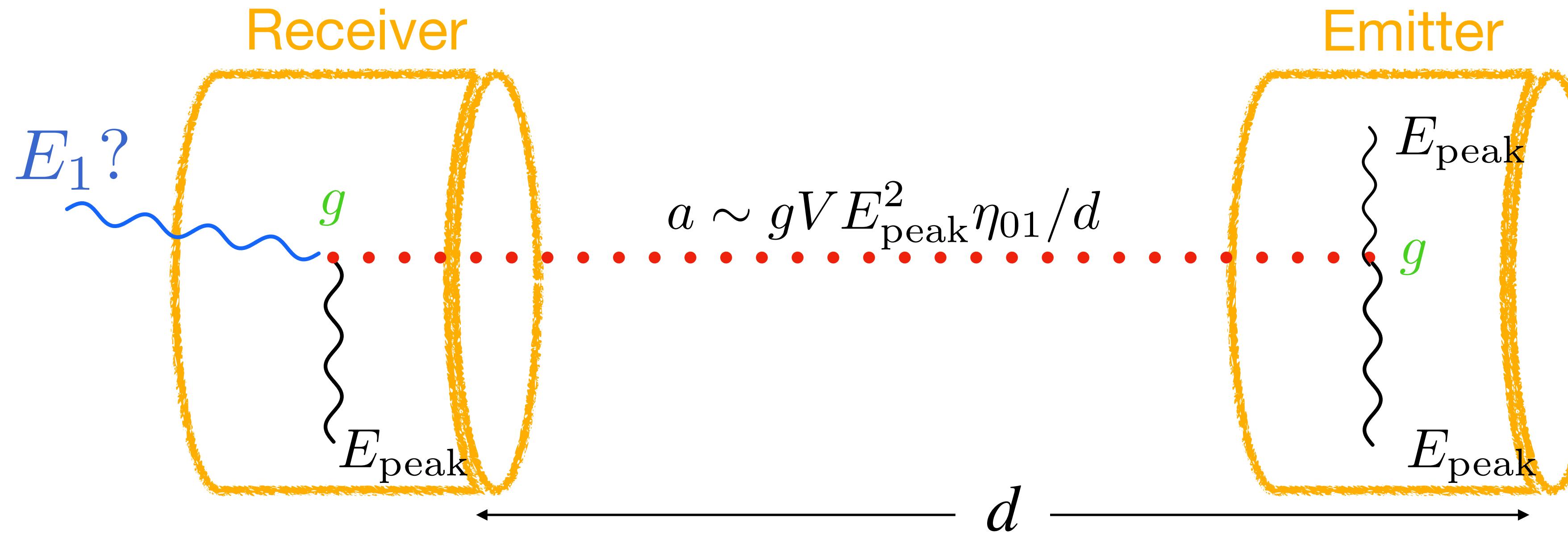
$$g \text{ } a \text{ } E_1 \cdot B_0$$



- ◆ 2 active cavity modes to source axion in the emitter.
- ◆ 3rd active mode in the receiver, satisfying frequency matching.

Signal Power

$$g \textcolor{red}{a} E_1 \cdot B_0$$



$$P_{\text{sig}} = \frac{\text{energy}}{\text{time}} = \frac{1}{\tau_1} \int_V |E_1|^2 \propto \frac{QV^3 g^4 \eta_{01}^4 E_{\text{peak}}^6}{d^2}$$

Q = quality factor

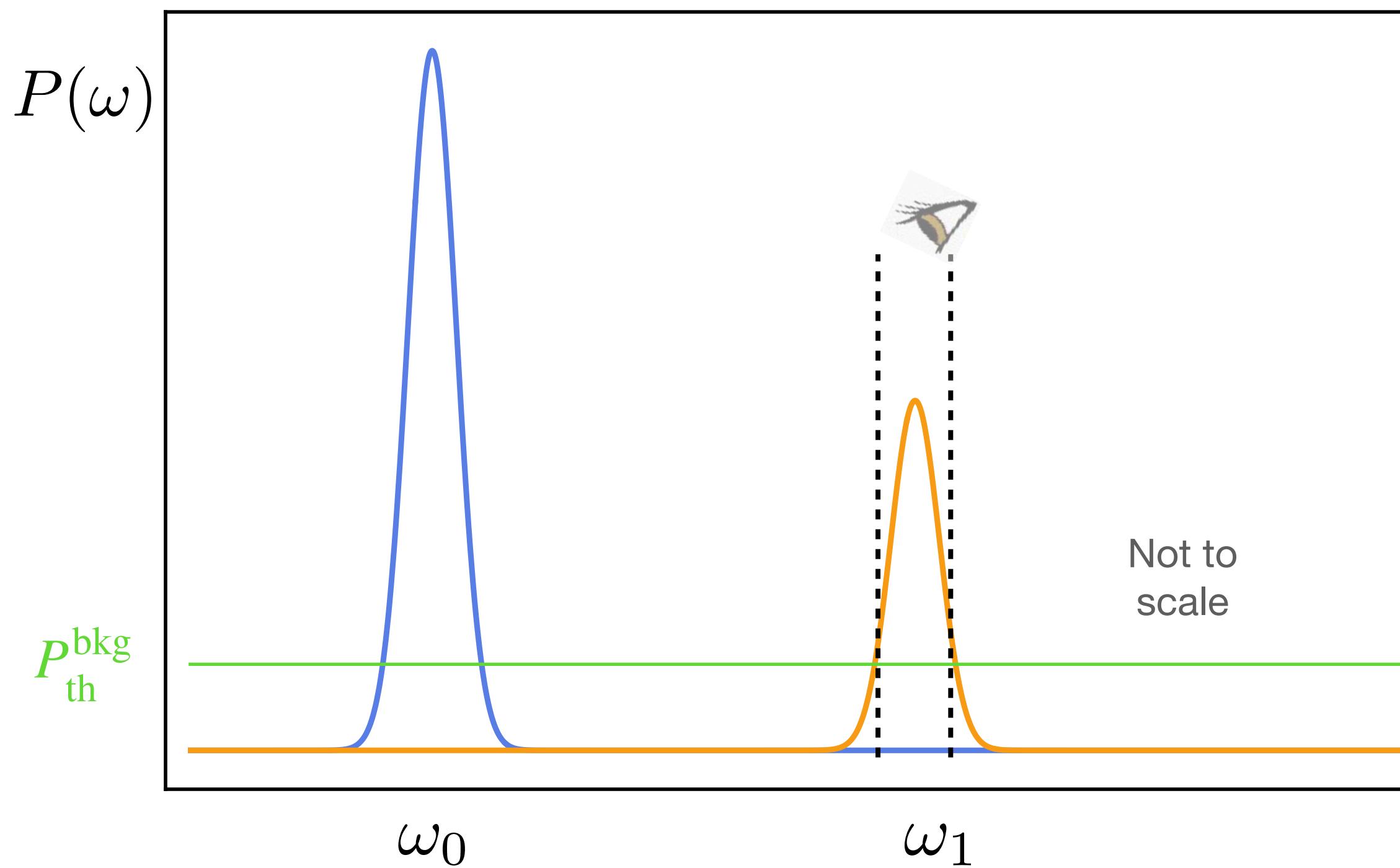
V = volume of cavity

η_{01} = geometric factor

E_{peak} = field amplitude

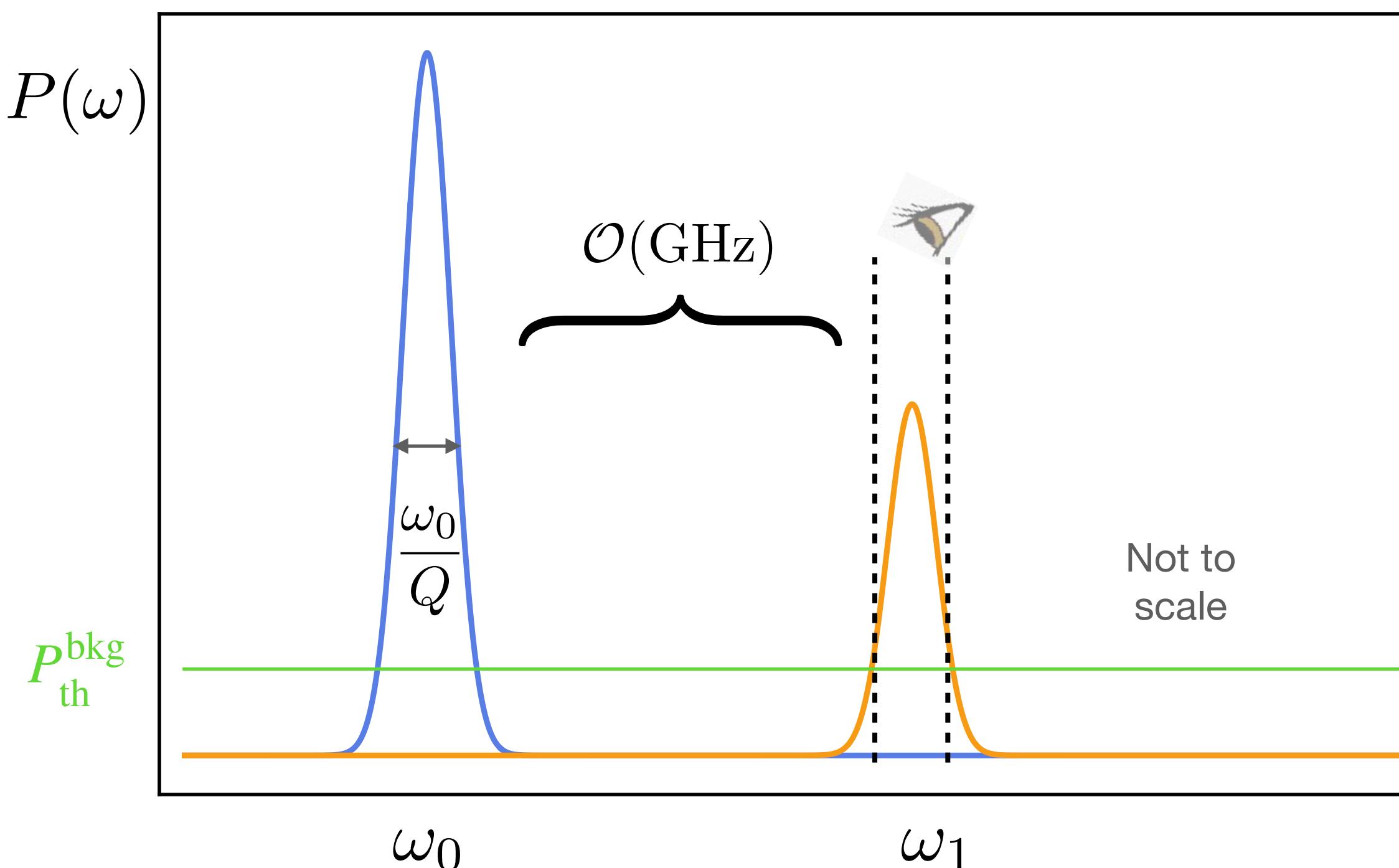
Backgrounds

1. Thermal background, constant over frequency domain: $P_{\text{th}}^{\text{bkg}} = T\Delta\omega_1$



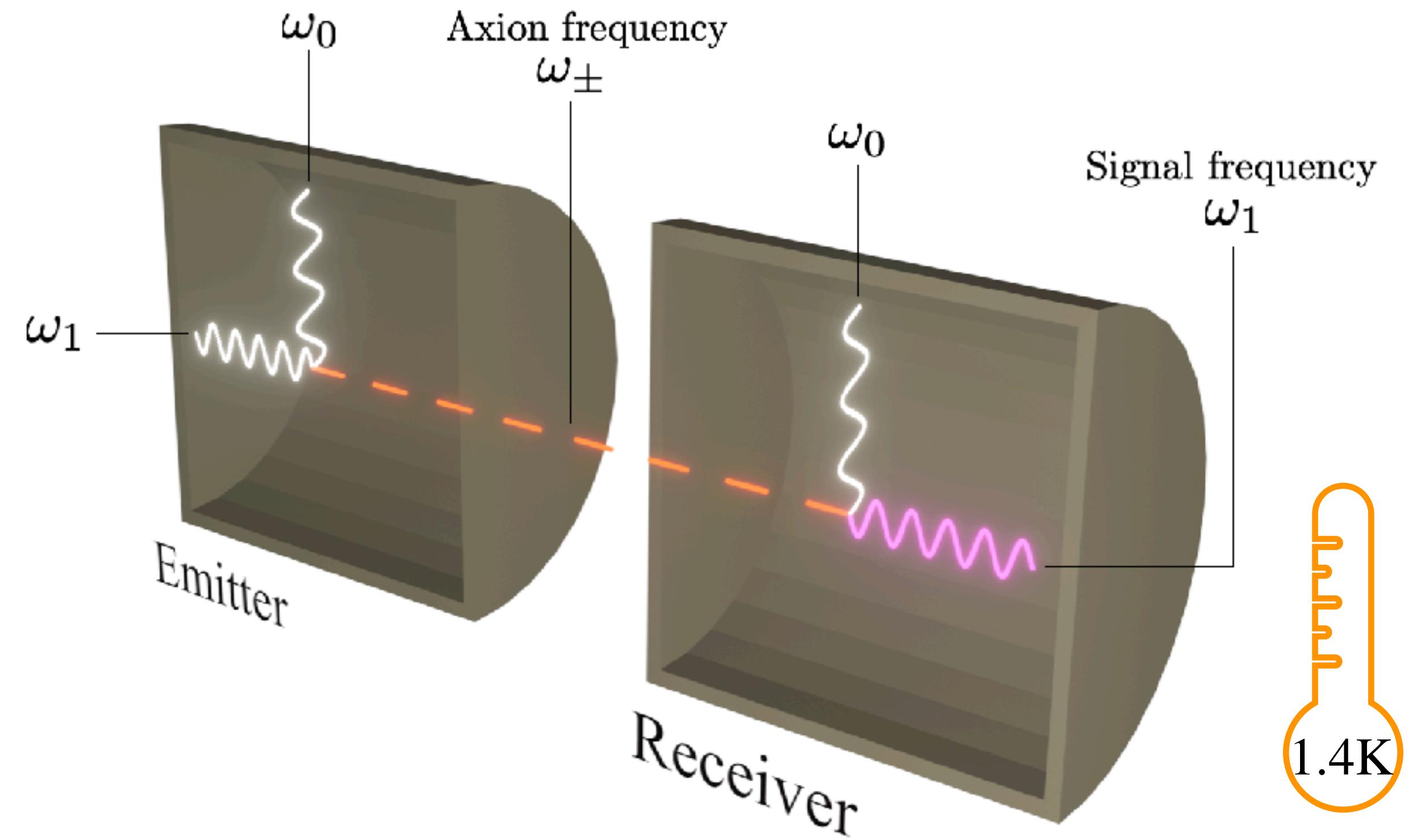
Backgrounds

1. Thermal background, constant over frequency domain: $P_{\text{th}}^{\text{bkg}} = T\Delta\omega_1$
2. Potential leakage background from a large number of spectating photons in the receiver. It can be suppressed, because $|\omega_0 - \omega_1| \gg \Delta\omega_{0,1}$



Setup

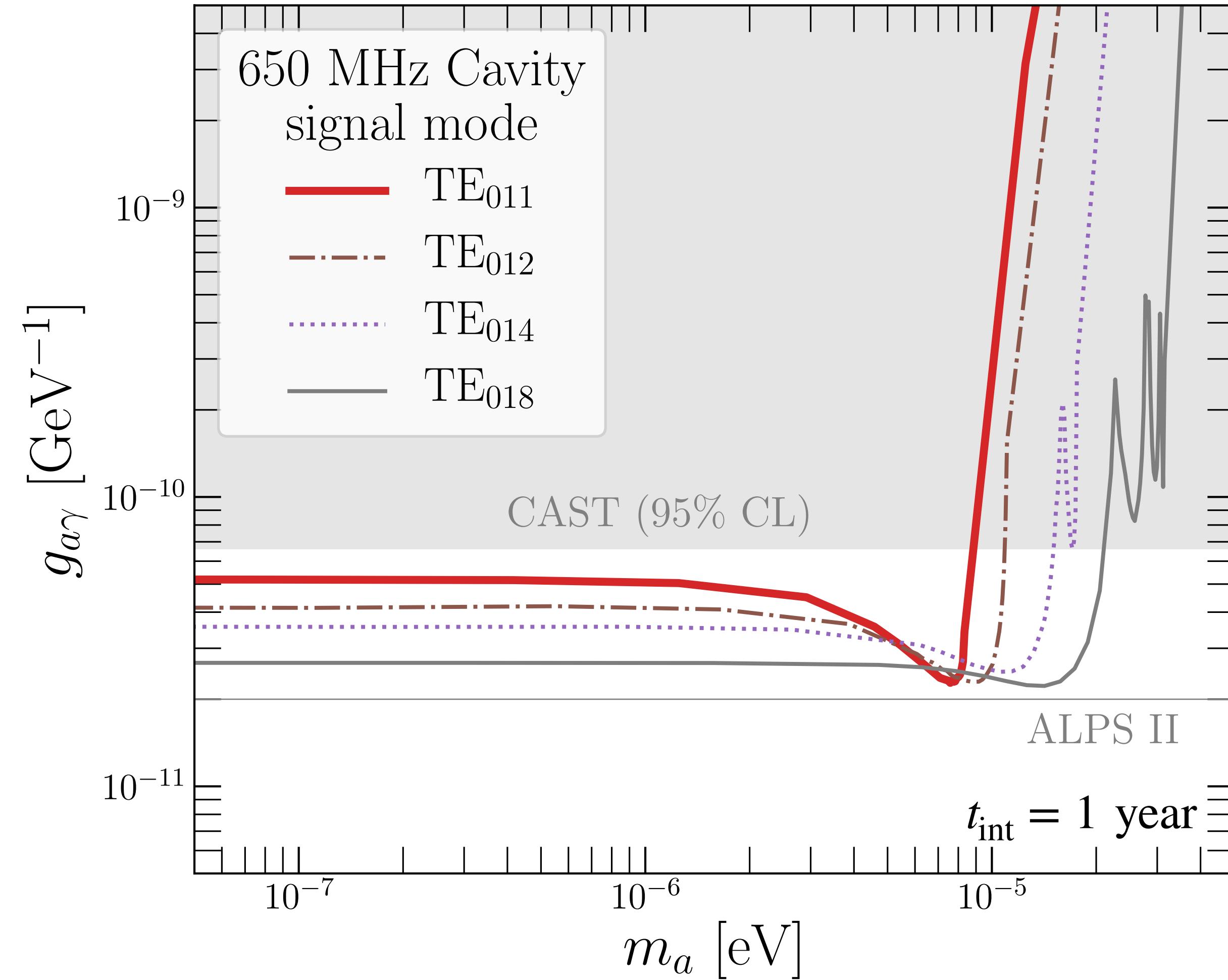
- ♦ Fundamental frequency: 650 MHz
- ♦ Quality factor $Q = 10^{10}$
- ♦ $E_{\text{peak}} = 80 \text{ MVm}^{-1}$ (or 0.26 Tesla) for all active modes



Ongoing work at Fermilab SQMS center.

Z. Bogorad et al 19
R. Janish et al 19

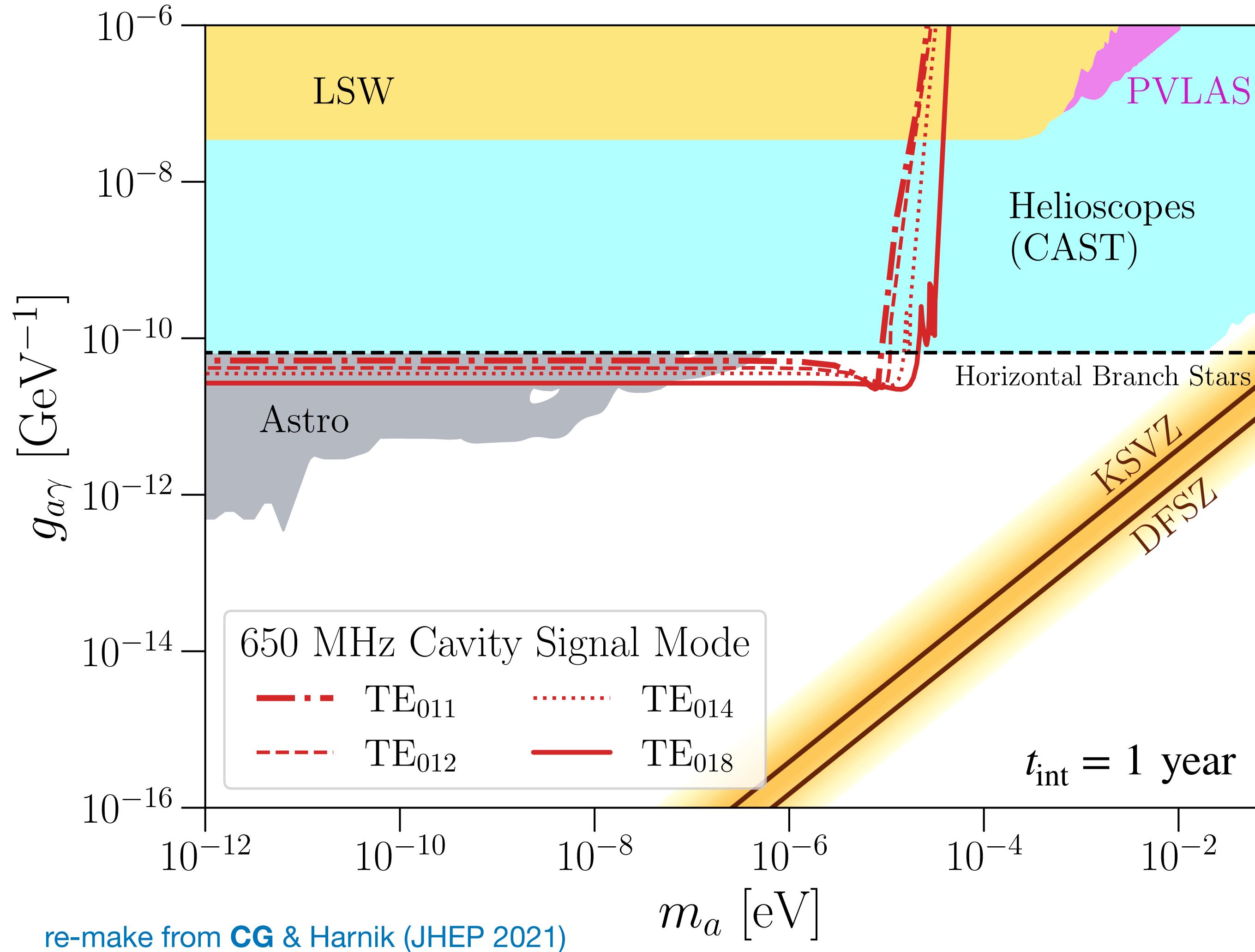
Sensitivity of the LSW Axion Search



$$\text{SNR} = \frac{P_{\text{sig}}}{P_{\text{bkg}}} \sqrt{t_{\text{int}} \Delta \omega_1} > 5$$

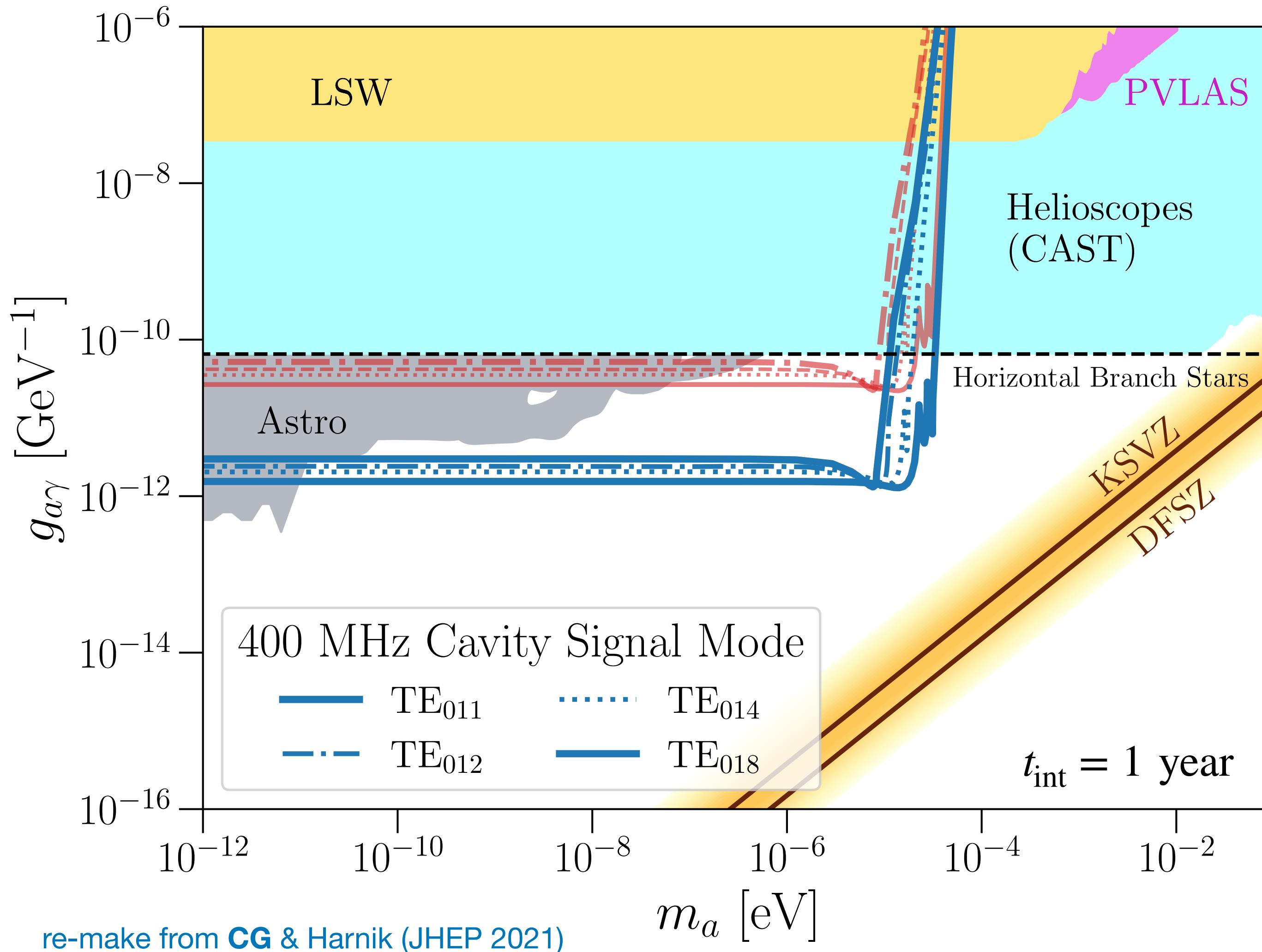
$$Q = 10^{10}$$
$$E_{\text{peak}} = 80 \text{ MVm}^{-1}$$

Sensitivity of the LSW Axion Search



$$Q = 10^{10}$$
$$E_{\text{peak}} = 80 \text{ MVm}^{-1}$$

Sensitivity of the LSW Axion Search



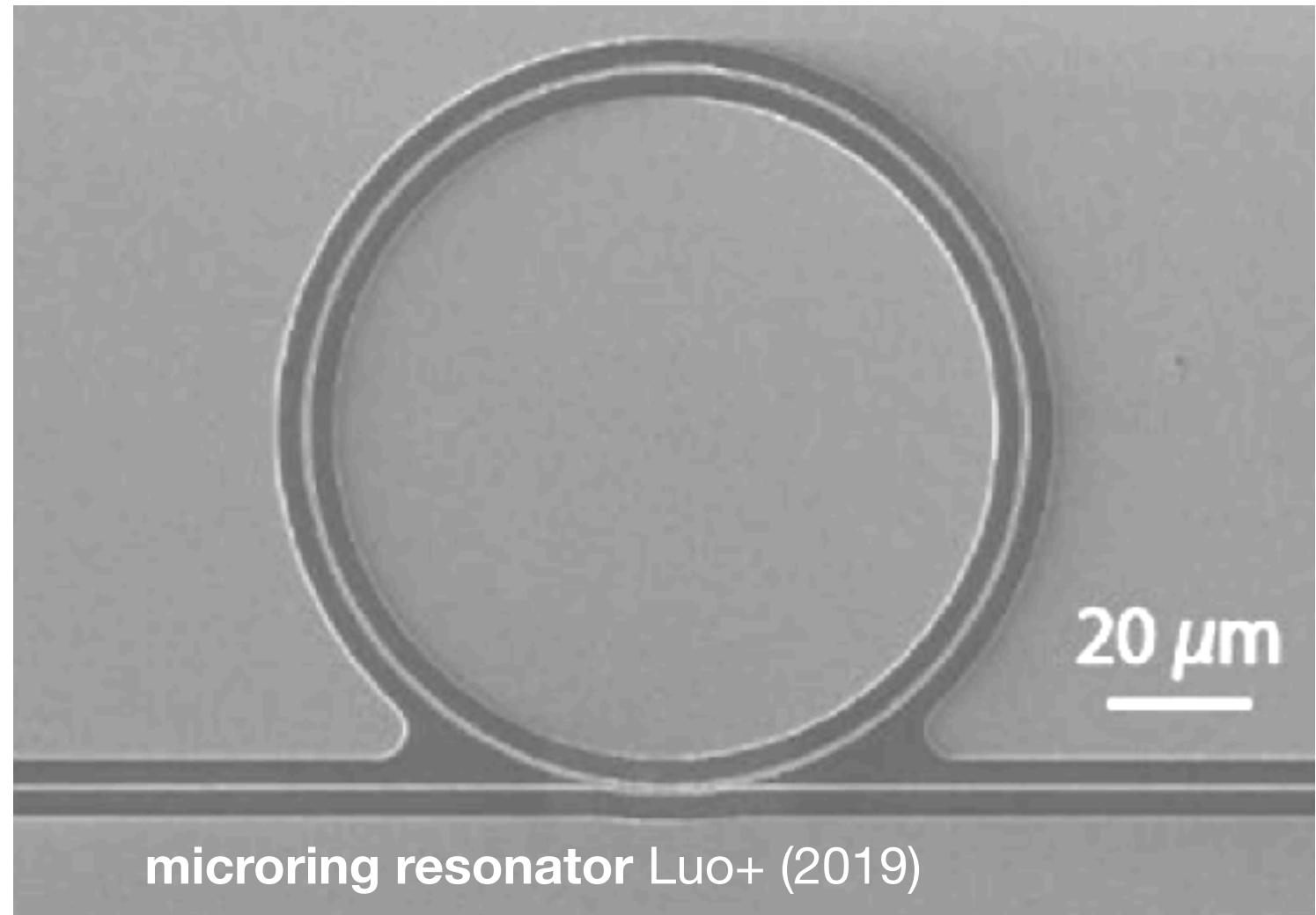
$$P_{\text{sig}} \propto Q V^3 g^4 E_{\text{peak}}^6$$

$$\begin{aligned} Q &= 10^{12} \\ E_{\text{peak}} &= 120 \text{ MVm}^{-1} \end{aligned}$$

$$\begin{aligned} Q &= 10^{10} \\ E_{\text{peak}} &= 80 \text{ MVm}^{-1} \end{aligned}$$

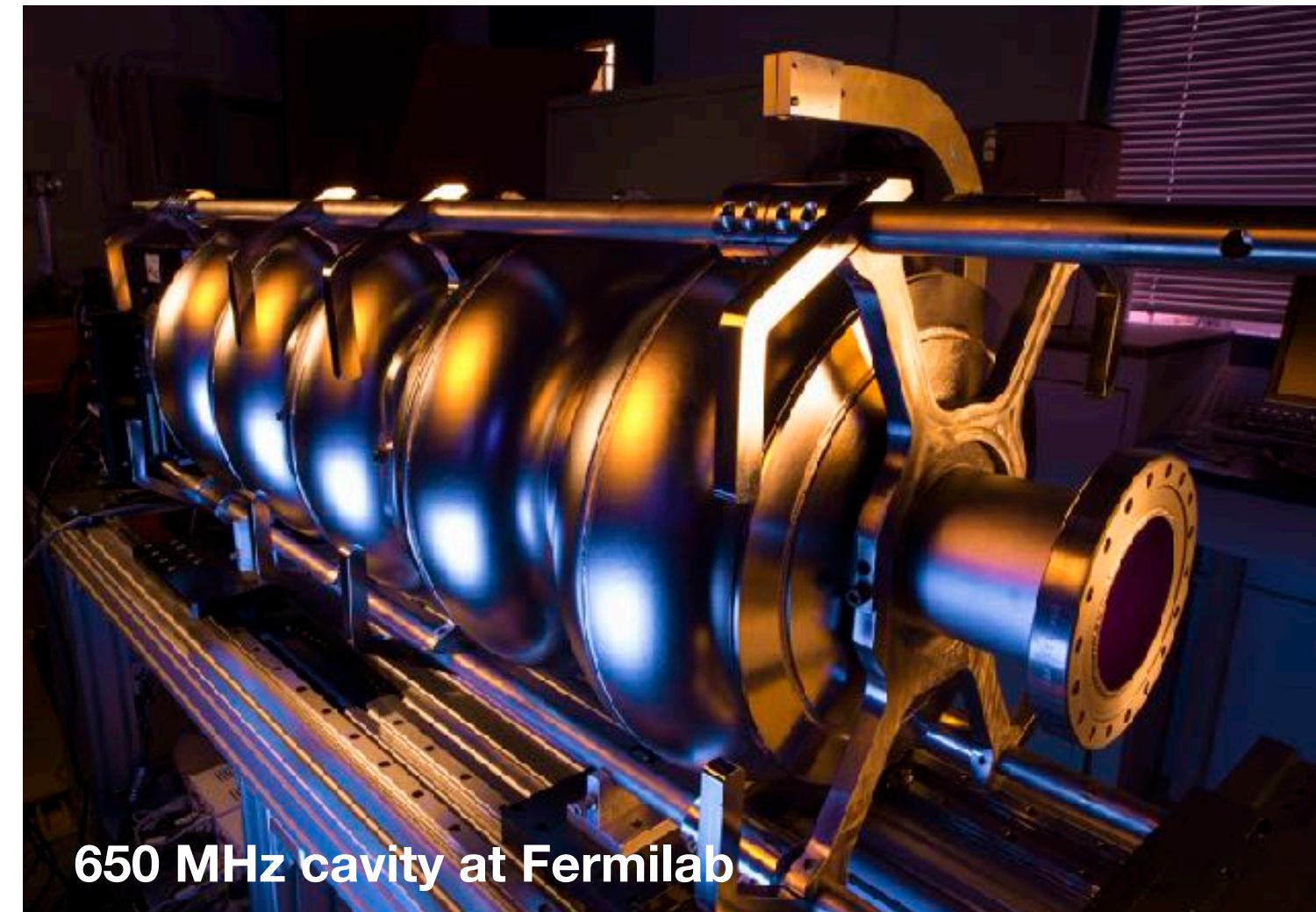
Axion Searches at Optical Frequency

Optical Cavity: eV



microring resonator Luo+ (2019)

SRF Cavity: μeV



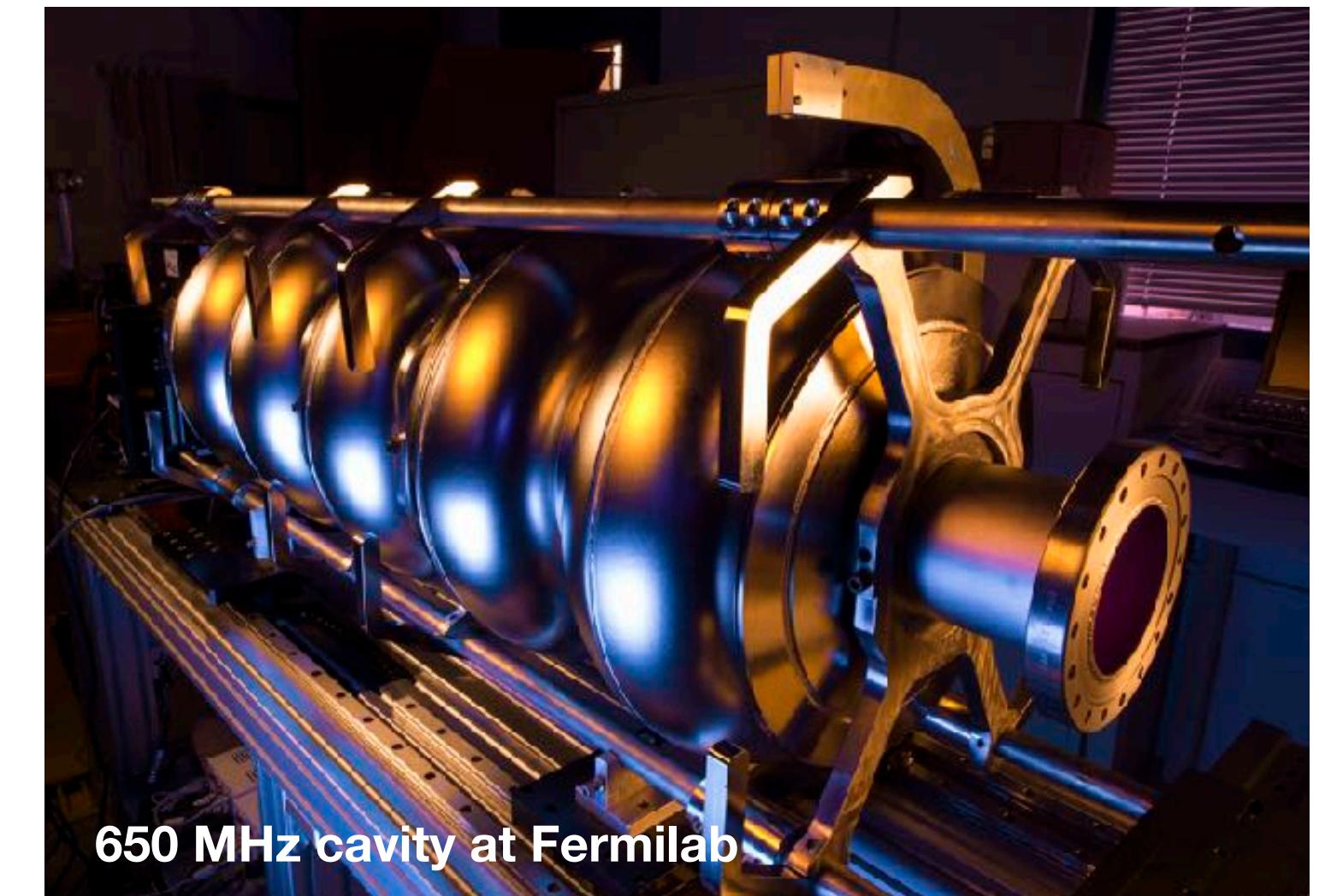
650 MHz cavity at Fermilab

$Q \sim 10^7$
can be mass produced

$Q \sim 10^{10}$
can store 10^{26} photons

Summary

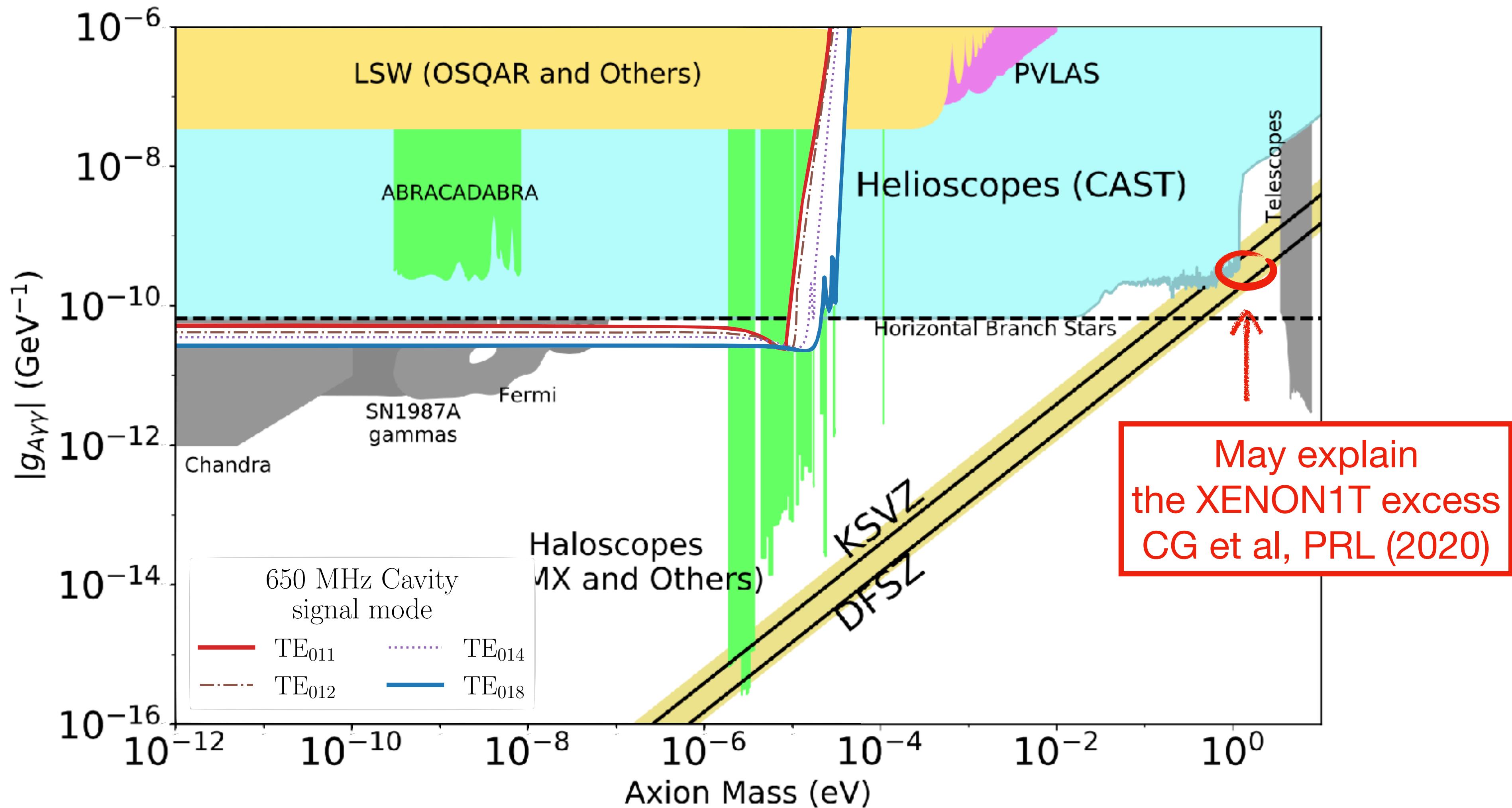
- ◆ SRF cavities \Rightarrow dark particles $\lesssim 10 \mu\text{eV}$.
- ◆ Axion LSW is **broadband** \Rightarrow can cover a large axion mass range with a single experiment.
- ◆ Exciting time to apply quantum technology to new physics searches.



Thank you!

Backup Slides

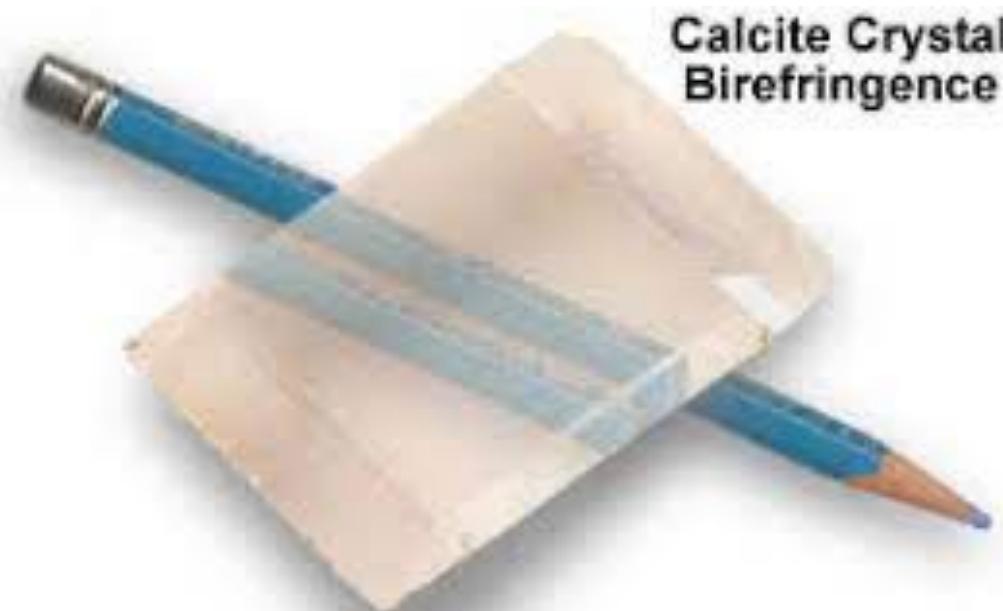
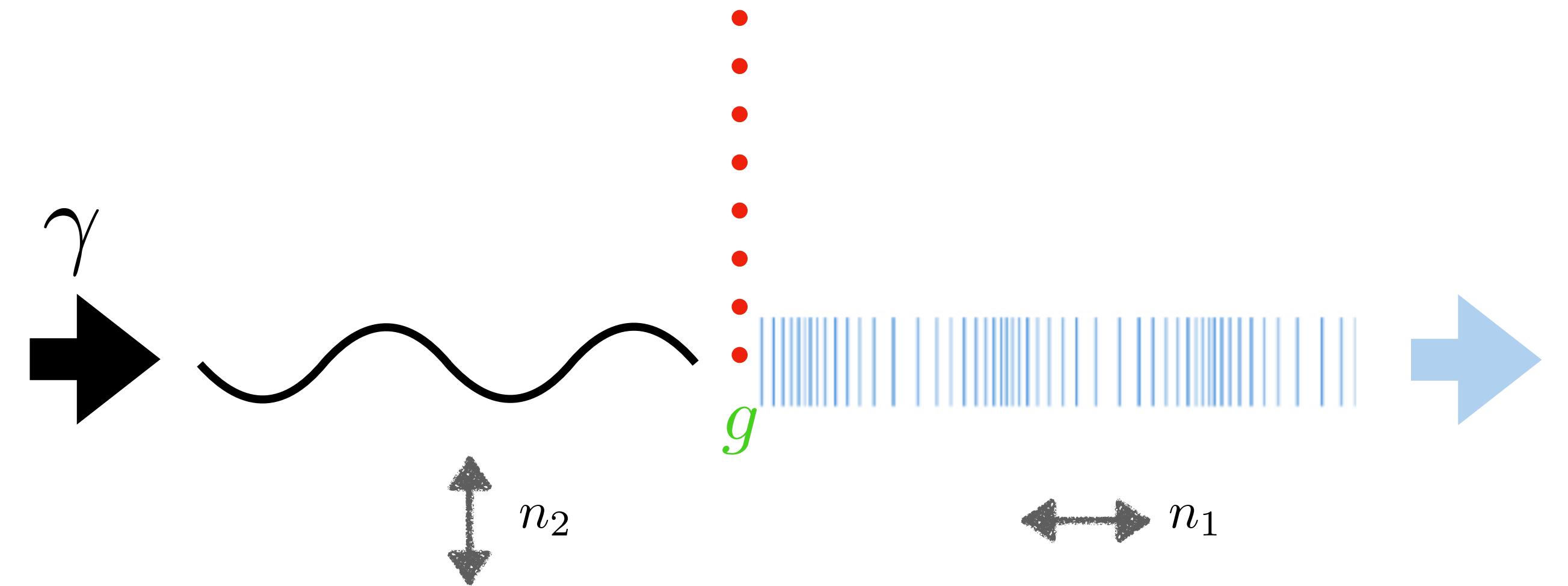
Backup: Axion at Optical Frequency



Backup: Axion Searches at Optical Frequency

- Through **birefringence**

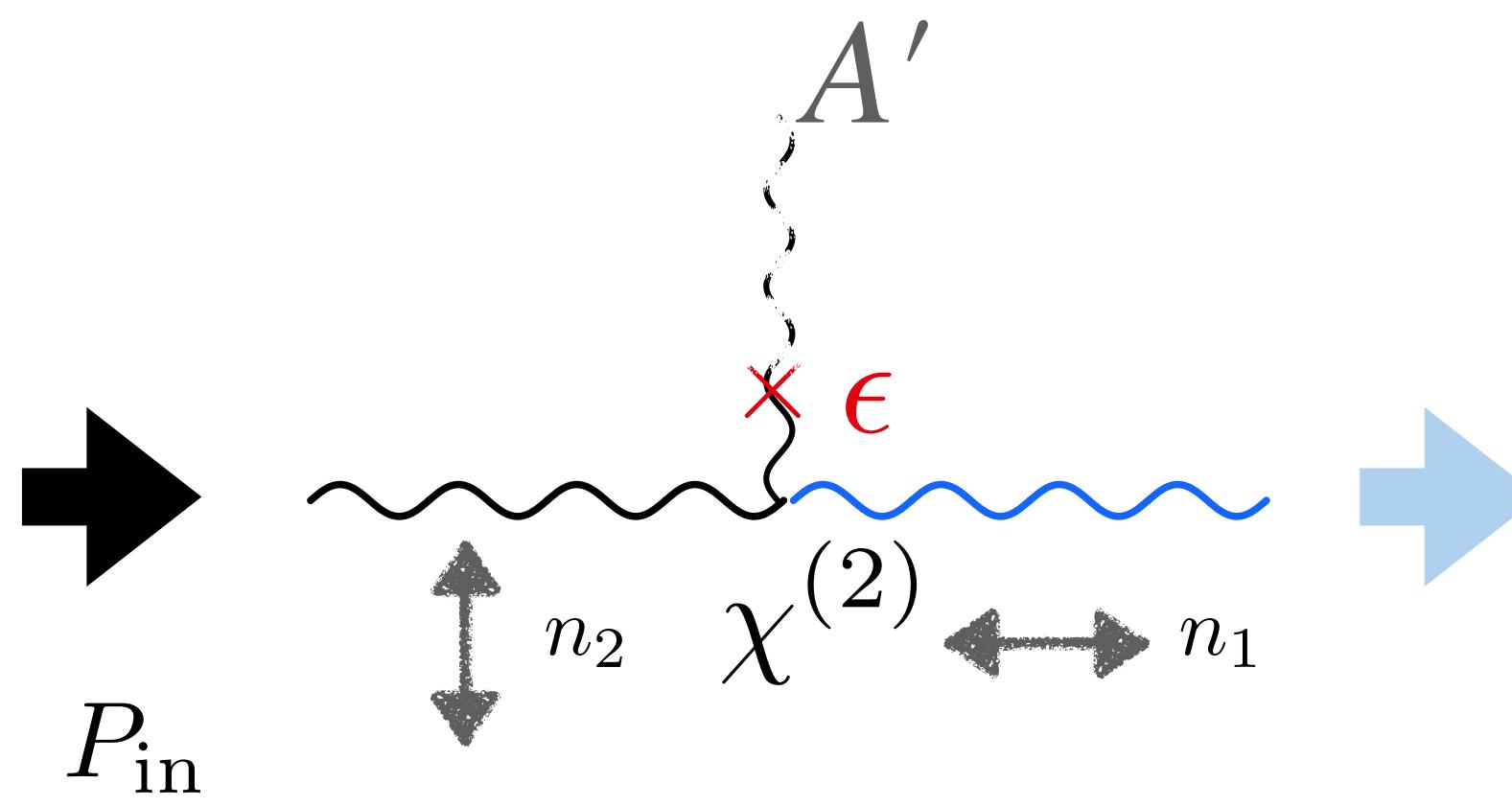
$$\frac{2\pi}{\lambda} = \omega_i n_i, \quad i = 1, 2$$



$$m_a = \frac{2\pi}{\lambda} \left(\frac{1}{n_1} - \frac{1}{n_2} \right)$$

Backup: Searching for Other Dark Particles

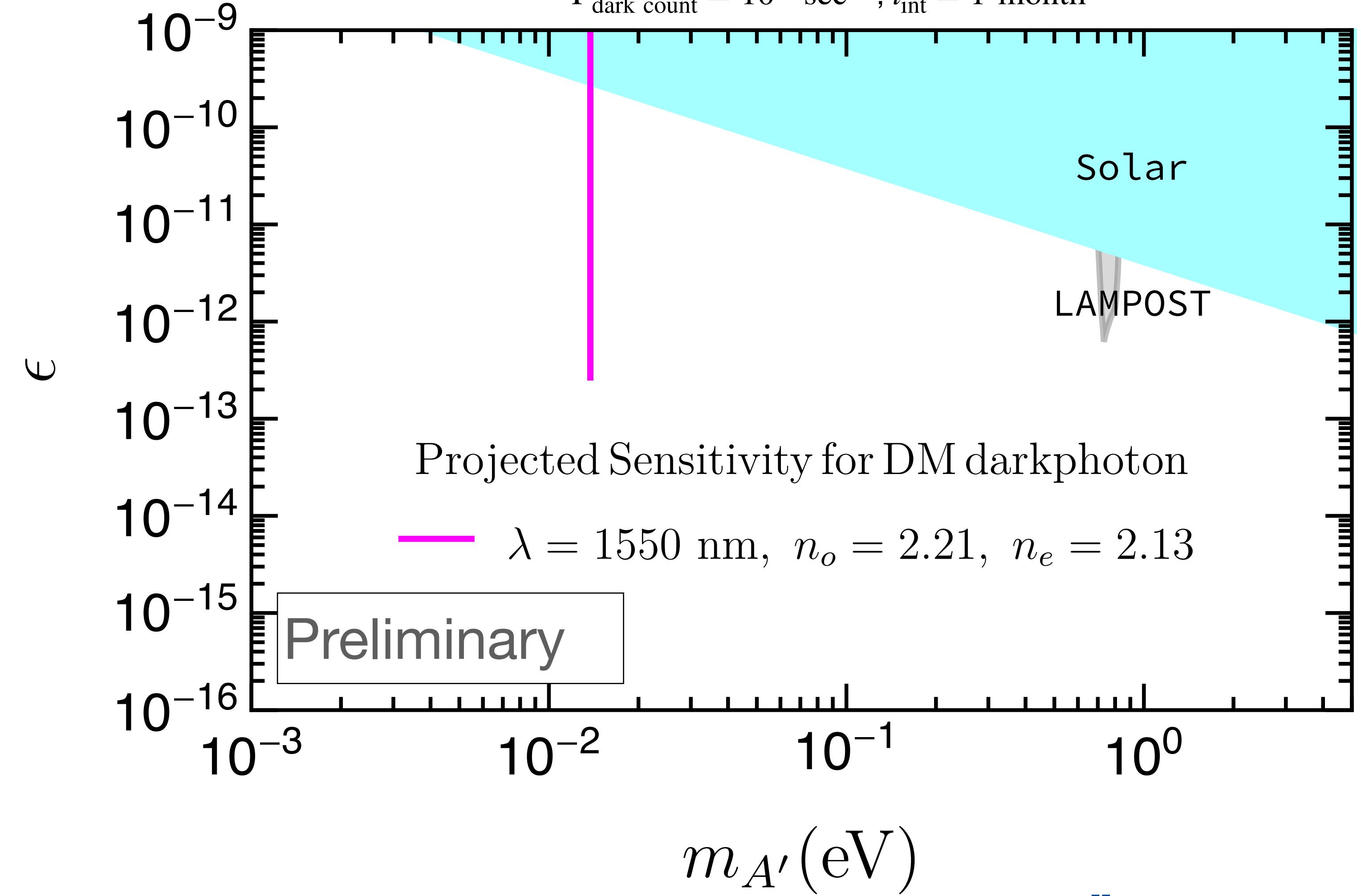
3 photon interaction in LiNbO₃



$$m_{A'} = \frac{2\pi}{\lambda} \left(\frac{1}{n_1} - \frac{1}{n_2} \right)$$

$$\epsilon F'_{\mu\nu} F^{\mu\nu}$$

$Q_{\text{load}} = 10^6$, $\mathcal{F} = 10^3$, $P_{\text{in}} = 0.2\text{W}$, 10^6 optical cavities,
 $\Gamma_{\text{dark count}} = 10^{-6}\text{sec}^{-1}$, $t_{\text{int}} = 1$ month



Backup: Example of Cavity Modes

$$\vec{E}_{0m\ell}^{TM}(\vec{x}, t) = E_0 \begin{pmatrix} -i\frac{\ell\pi}{L} \frac{R}{Z_{0m}} J_1\left(r \frac{Z_{0m}}{R}\right) \\ 0 \\ J_0\left(r \frac{Z_{0m}}{R}\right) \end{pmatrix} e^{i\ell\pi z/L - i\omega_{0m\ell}^{TM}t}$$
$$\omega_{\text{TM}}^{nm\ell} = \sqrt{\left(\frac{Z_{nm}}{R}\right)^2 + \left(\frac{\ell\pi}{L}\right)^2}, \quad \ell = 0, 1, 2, \dots,$$

$$\vec{B}_{0m\ell}^{TM}(\vec{x}, t) = B_0 \begin{pmatrix} 0 \\ -i\omega_{0m\ell}^{TM} \frac{R}{Z_{0m}} J_1\left(r \frac{Z_{0m}}{R}\right) \\ 0 \end{pmatrix} e^{i\ell\pi z/L - i\omega_{0m\ell}^{TM}t}$$

$$\vec{B}_{0m\ell}^{TE}(\vec{x}, t) = B_0 \begin{pmatrix} -i\frac{\ell\pi}{L} \frac{R}{S_{0m}} J_1\left(r \frac{S_{0m}}{R}\right) \\ 0 \\ J_0\left(r \frac{S_{0m}}{R}\right) \end{pmatrix} e^{i\ell\pi z/L - i\omega_{0m\ell}^{TE}t}$$
$$\omega_{\text{TE}}^{nm\ell} = \sqrt{\left(\frac{S_{nm}}{R}\right)^2 + \left(\frac{\ell\pi}{L}\right)^2}, \quad \ell = 1, 2, \dots.$$

$$\vec{E}_{0m\ell}^{TE}(\vec{x}, t) = B_0 \begin{pmatrix} 0 \\ i\omega_{0m\ell}^{TE} \frac{R}{S_{0m}} J_1\left(r \frac{S_{0m}}{R}\right) \\ 0 \end{pmatrix} e^{i\ell\pi z/L - i\omega_{0m\ell}^{TE}t}$$



Backup: Production of Axion from a Cylindrical Cavity

$$\phi(\vec{x}, t) = \phi_+(\vec{x}, t) + \phi_-(\vec{x}, t),$$

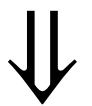
$$\phi_{\pm}(\vec{x}, t) = -g e^{-i\omega_{\pm}t} \int_{V_{pc}} d^3y \frac{e^{ik|\vec{x}-\vec{y}|}}{4\pi|\vec{x}-\vec{y}|} (\vec{E} \cdot \vec{B})_{\omega_{\pm}}$$

With $\text{TM}_{0m\ell}$, $\text{TE}_{0m'\ell'}$:

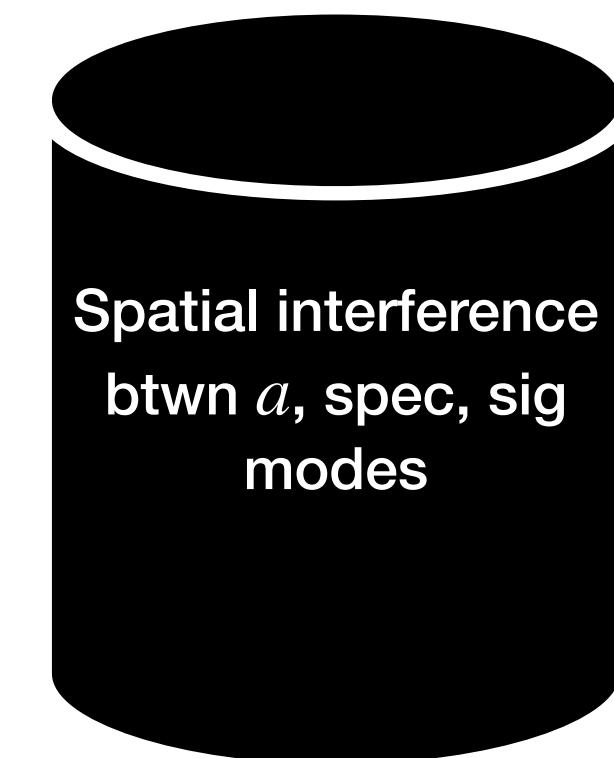
$$(\vec{E} \cdot \vec{B})_{\omega_{\pm}} = \frac{E_{\text{peak}} B_{\text{peak}}}{2} \left(J_0(Z_{0m}r/R) J_0(S_{0m'}r/R) \right. \\ \left. \pm \frac{\omega_{\text{TM}}^{0m\ell} \omega_{\text{TE}}^{0m'\ell'} - k_z^{\ell} k_z^{\ell'}}{(Z_{0m}/R)(S_{0m'}/R)} J_1(Z_{0m}r/R) J_1(S_{0m'}r/R) \right) e^{i\pi(k_z^{\ell} \pm k_z^{\ell'})z}$$

Backup: Signal Field

$$\vec{\nabla}^2 \vec{E} - \partial_t^2 \vec{E} = -g \partial_t (\vec{E} \times \vec{\nabla} a) + g \partial_t (\vec{B} \partial_t a)$$



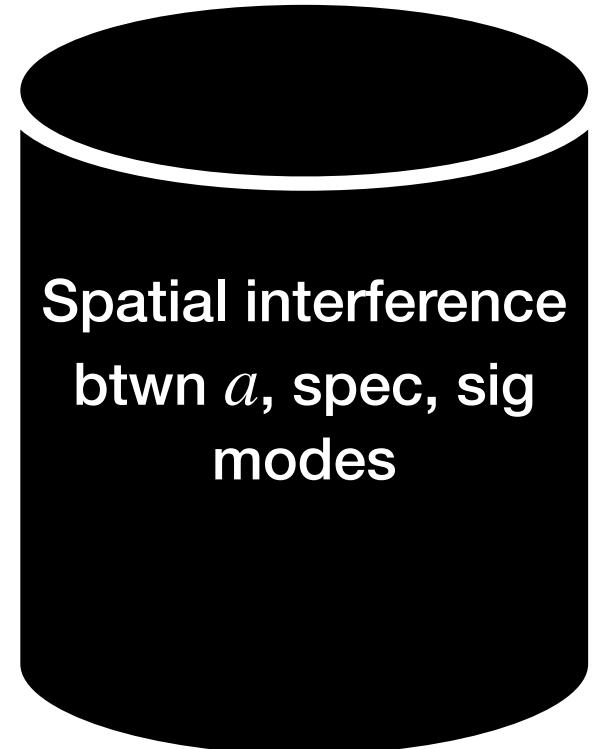
$$\tilde{E}_{sig}(\omega) \sim \frac{E_0 g}{d} \frac{\omega \omega_1}{\omega^2 - \omega_1^2 - i\omega \omega_1 / Q_1} \delta(\omega \pm \omega_0 - \omega_a) \times$$



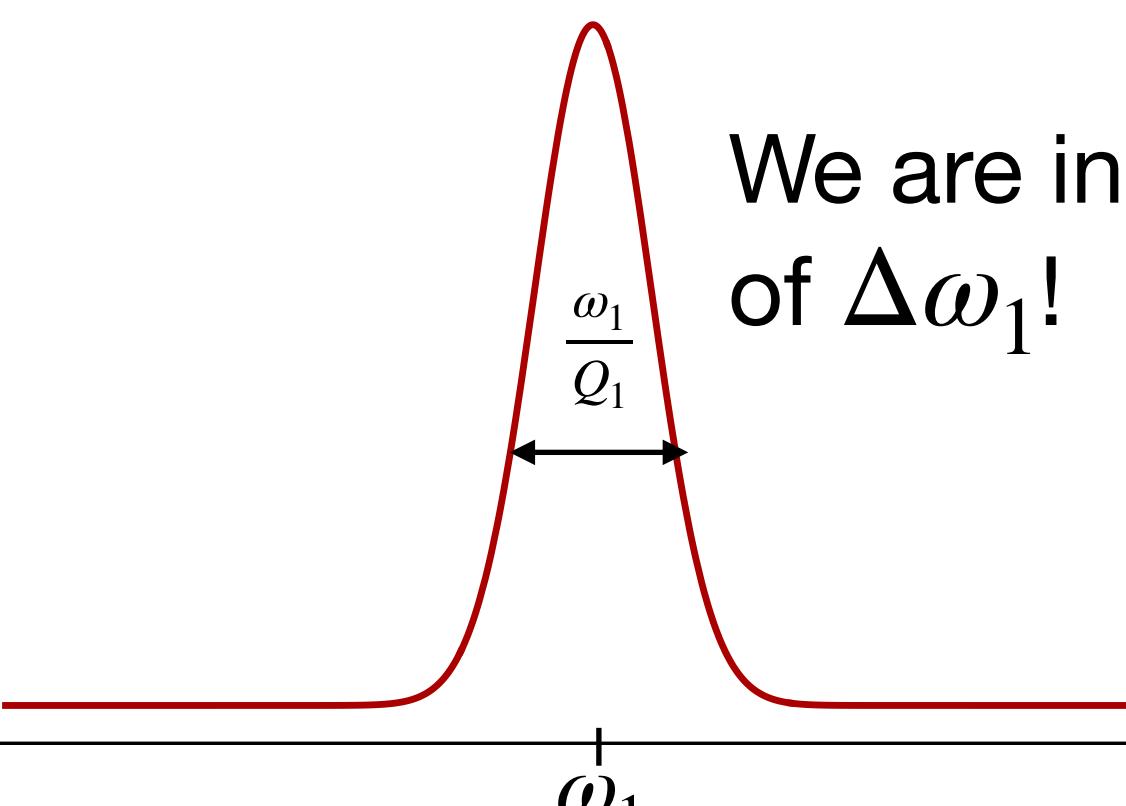
- d = separation between emitter and receiver
- Q_1 = quality factor for signal mode ω_1
- $\omega_1 = \omega_a \pm \omega_0$ will be produced on resonance

Backup: Signal Power

$$P_{sig} = \frac{\omega_1}{Q_1} \int_{V_{Re}} \langle |\vec{E}_{sig}(\vec{x}, t)|^2 \rangle$$
$$= \frac{\omega_1}{Q_1} \int_{V_{Re}} \left| \vec{E}_1(\vec{x}) \right|^2 \times \int_{\omega_1 - \Delta\omega_1/2}^{\omega_1 + \Delta\omega_1/2} \frac{d\omega}{(2\pi)^2} \langle \tilde{e}_1^* \tilde{e}_1(\omega) \rangle$$


Spatial interference
btwn a , spec, sig
modes

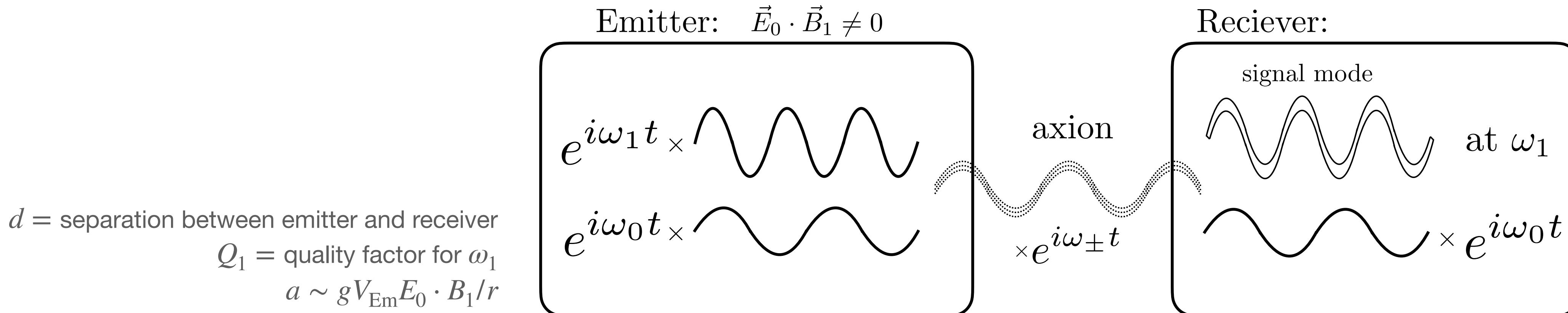
$\vec{E}_{sig} = \int \frac{d\omega}{2\pi} e^{i\omega t} \tilde{E}_{sig}(\omega) = \vec{E}_1(\vec{x}) e_1(t)$

We are in control
of $\Delta\omega_1$!

Backup: Signal Power

Assume that the two modes in the emitter and the spectating mode in the receiver have the same E_{peak} :

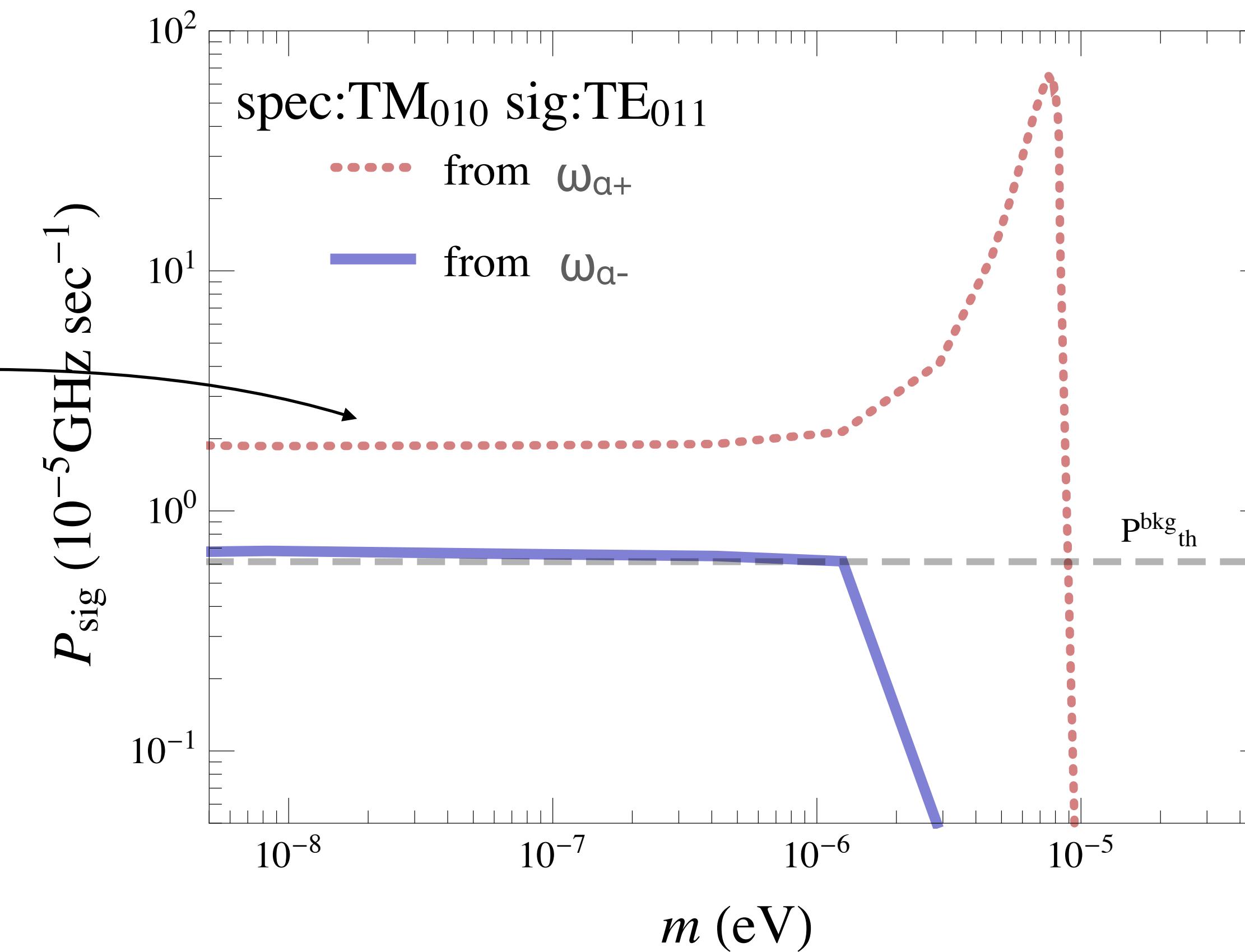
$$P_{\text{sig}} \sim \frac{Q_1}{8\omega_1} V^3 g^4 E_{\text{peak}}^6 \omega_a^2 \frac{\eta_{01}^4}{(4\pi d)^2} \quad 0 < \eta_{01} < 1$$



Backup: Signal Power

$$P_{\text{sig}} \sim \frac{Q_1}{8\omega_1} V^3 g^4 E_{\text{peak}}^6 \omega_a^2 \frac{\eta_{01}^4}{(4\pi d)^2}$$
$$P_{\text{th}}^{\text{bkg}} = T\Delta\omega_1, \quad \Delta\omega_1 = t_{\text{int}}^{-1}$$

200 sig photons
after 1 year!

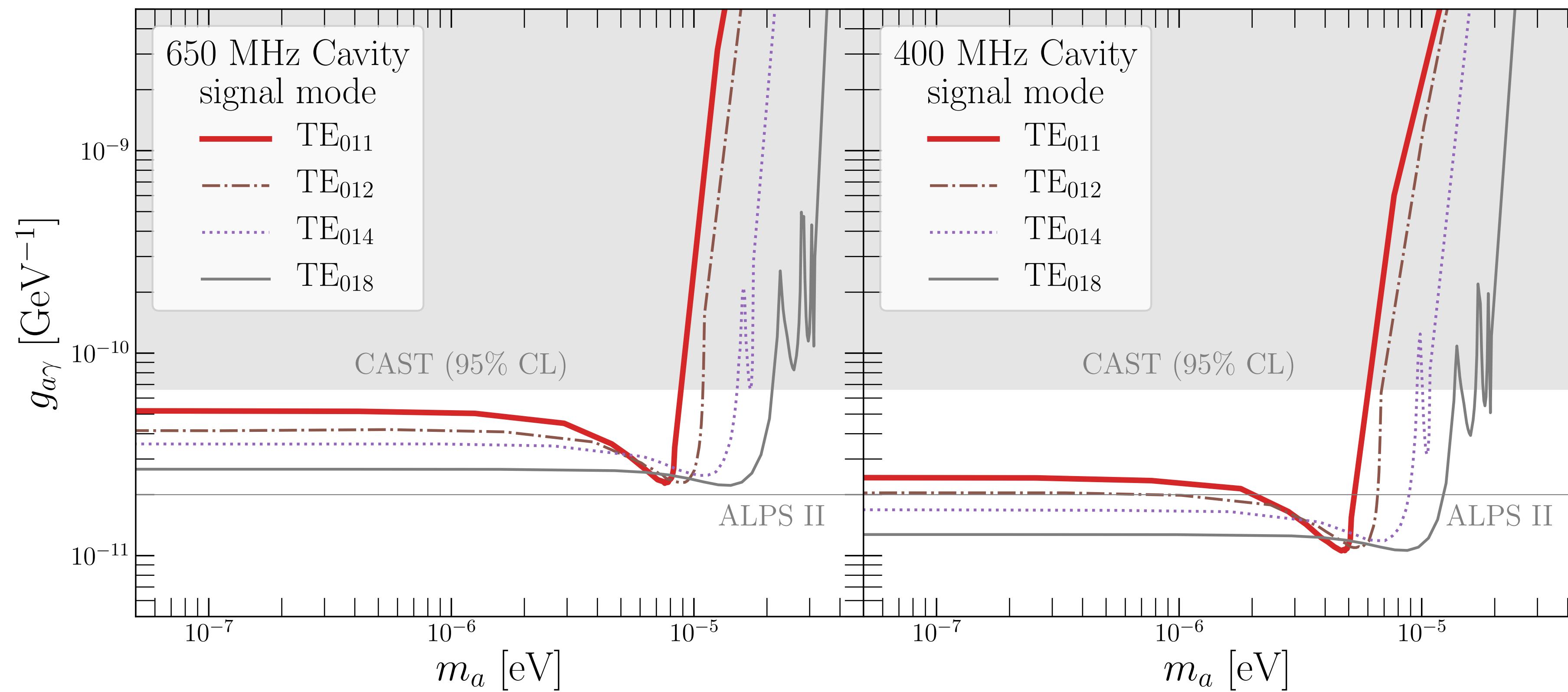


$$g = 5 \times 10^{-11} \text{GeV}^{-1}$$

$$\omega_a = \omega_1 \pm \omega_0$$

Backup: Sensitivity with High Cavity Modes

require $\text{SNR} \sim \frac{P_{\text{sig}}}{P_{\text{bkg}}} \sqrt{t_{\text{int}} \Delta \omega_1} \sim \frac{P_{\text{sig}} t_{\text{int}}}{T} > 5, \quad P_{\text{th}}^{\text{bkg}} = T \Delta \omega_1, \quad \Delta \omega_1 = t_{\text{int}}^{-1}, \quad t_{\text{int}} = 1 \text{ year}$



Backup: LSW w. Resonant Optical Cavities

K. Ehret et al. [ALPS collaboration] 09,10

- Laser frequency matches a cavity mode
- High **finesse** cavity \Rightarrow resonant production of $\sim 10^{19}$ photons
- Realized by ALPS Collaboration, who obtained

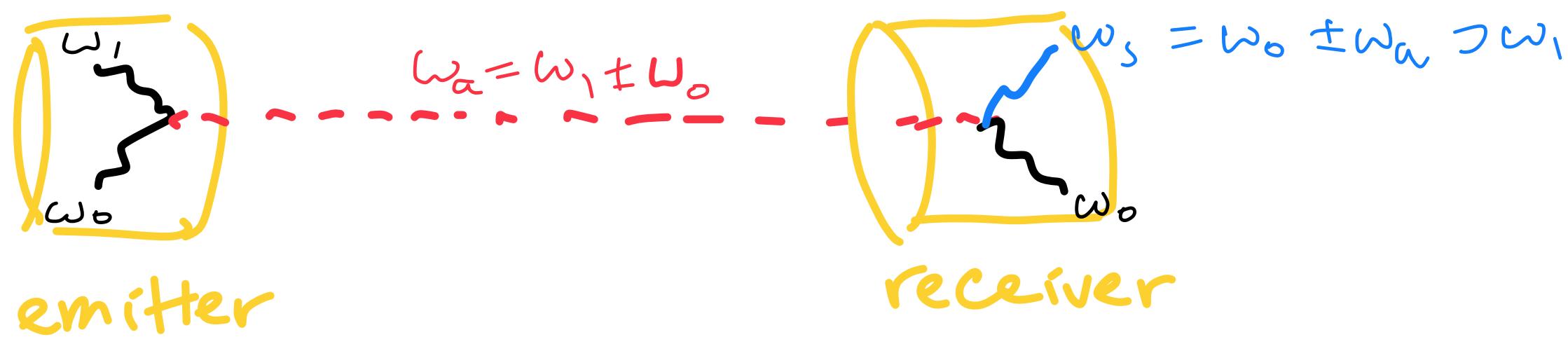
$$g < 7 \times 10^{-8} \text{ GeV}^{-1} \text{ for } m_a < \text{meV}$$

- ALPS II projection:

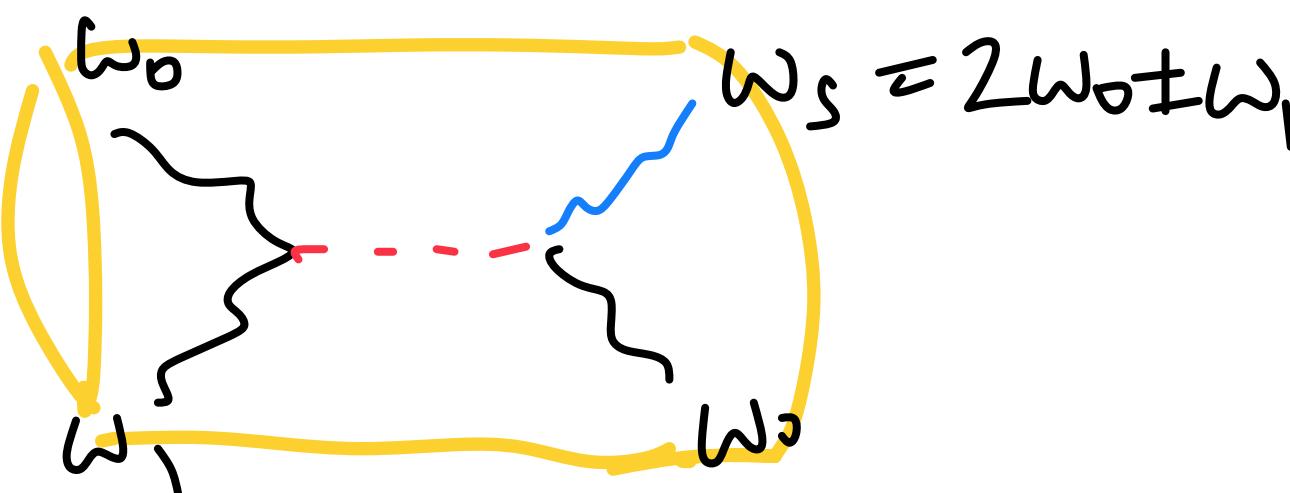
$$\text{CAST (solar axion): } g < 6.6 \times 10^{-11} \text{ GeV}^{-1}$$

$$g < 2 \times 10^{-11} \text{ GeV}^{-1} \text{ for } m_a < \text{meV}$$

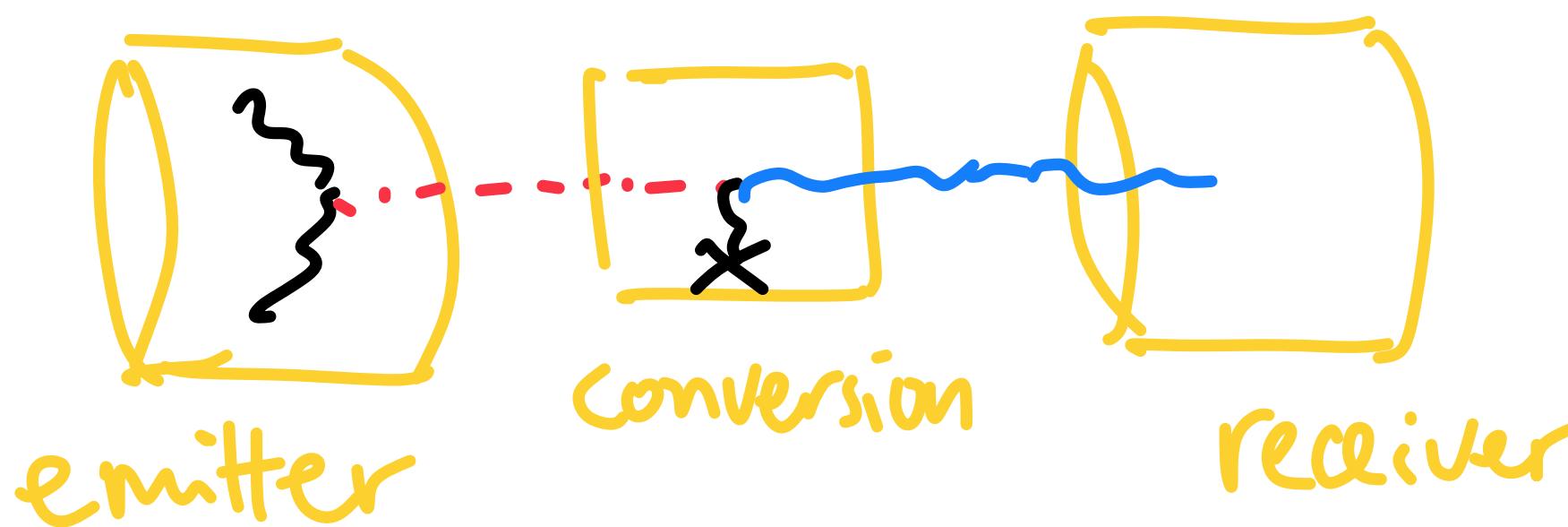
Backup: SRF cavity proposals looking for axions



this work



Z. Bogorad et al 19



R. Janish et al 19