Axion Searches with Twin Superconducting Radio-frequency Cavities

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To appear soon

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Outline

- Introduction
- Current Constraints on Axion-Like Particle Parameters
- Review of Laboratory Searches
- Our Proposal
- Case Study

Strong CP Problem

- QCD vacuum allows a CP violating term

$$\mathscr{L}_\theta = \frac{\theta}{32\pi^2} \mathrm{Tr}\, G_{\mu\nu}\tilde{G}^{\mu\nu}$$

- Measurement of neutron EDM $\Rightarrow \theta \lesssim 10^{-10}$

- Strong CP problem: why is θ vanishingly small?

QCD Axion

- Introduce a new chiral symmetry $U(1)_{PQ}$
- $\theta \Rightarrow$ axion ϕ = NGB after SSB of $U(1)_{PQ}$ at f
- Below Λ_{QCD}, QCD instantons generate a potential

$$V \sim m_u \Lambda_{QCD}^3 \left(1 - \cos(\phi/f)\right)$$

- $\langle \phi \rangle = 0$, solving the strong CP problem!

Axion Like Particles

- NGBs from SSB of global $U(1)$ at scale f
- Shift symmetry $\Rightarrow f^{-1}\partial_\mu \phi \mathcal{O}_{SM}$
- Non-perturbative effects ⇒ periodic $V(\phi/f)$
- e.g. axions from string theory = KK zero modes of the anti-symmetric tensors on the compactified dimensions.

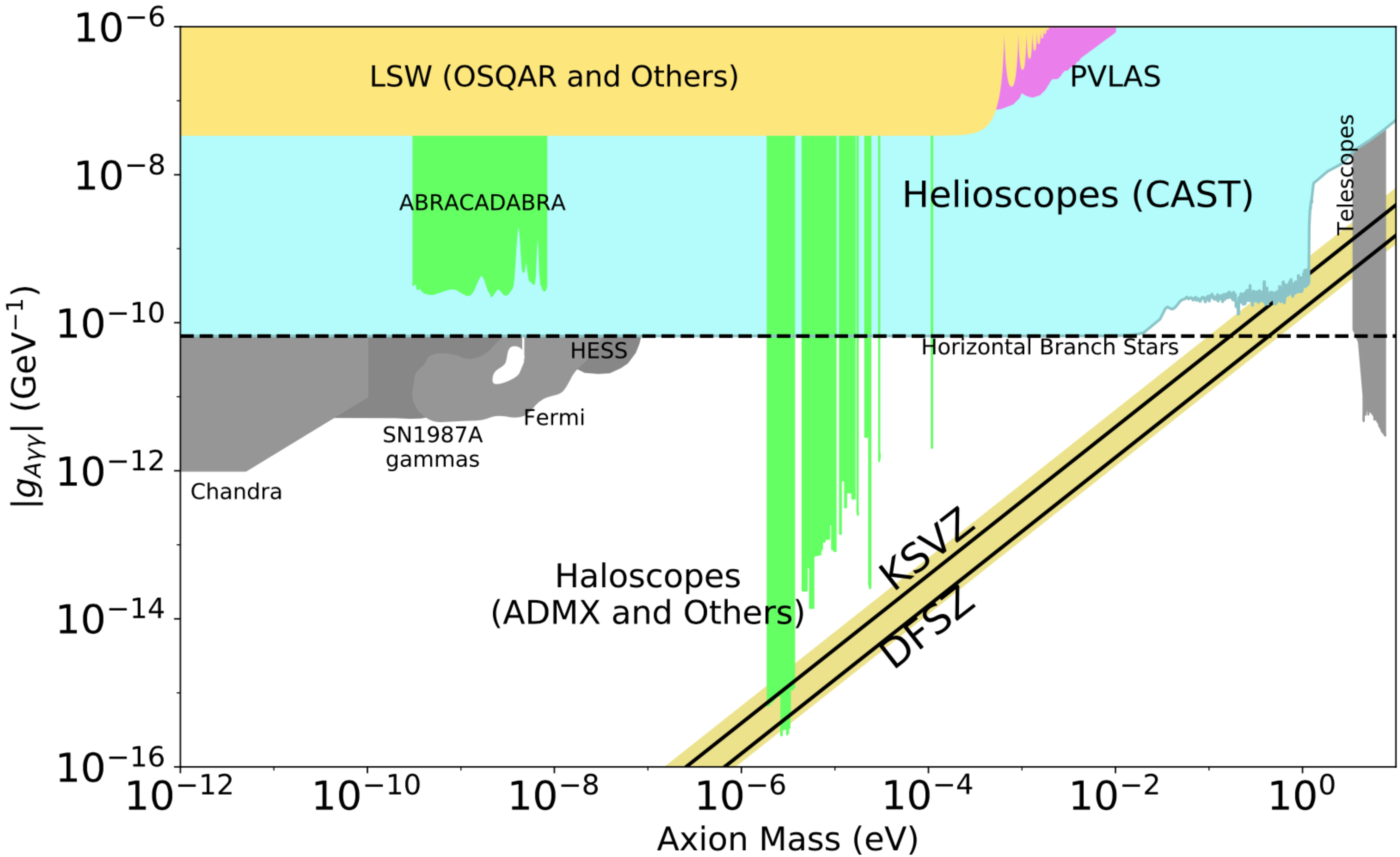
ALP's Two Photon Vertex

$$\mathscr{L}_{int} \supset -\frac{g}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} = g\phi \overrightarrow{E} \cdot \overrightarrow{B}, \quad g \propto 1/f$$

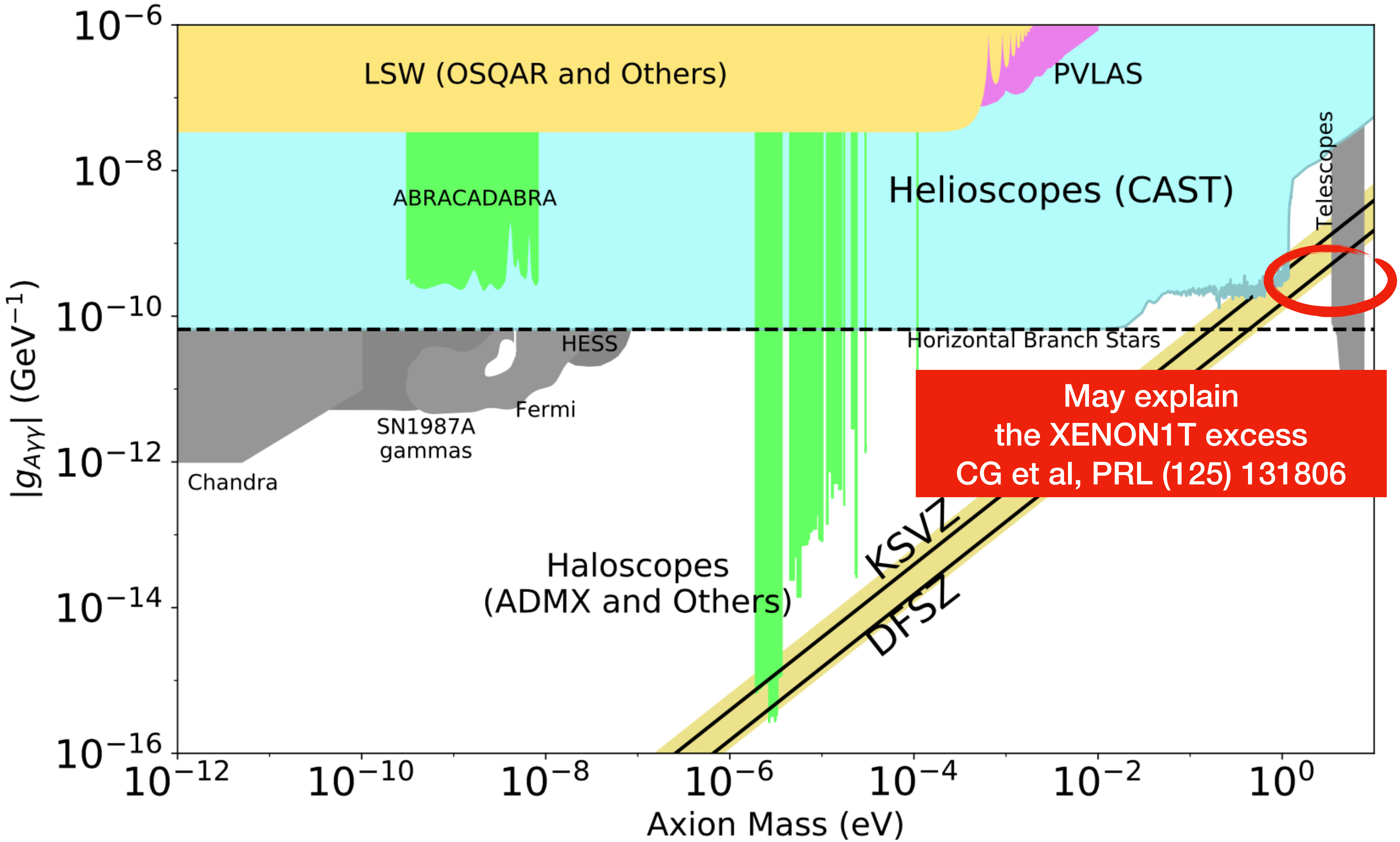
- Primakoff process in the stellar cores leads to excessive energy loss $\Rightarrow$ constaining g for $m_a < T_{\text{core}}$
- Search for solar axion and DM axion relies on axion-photon conversion in a static magnetic field

Current Constraints on $m_a - g$

from The Review of Particle Physics (2020)

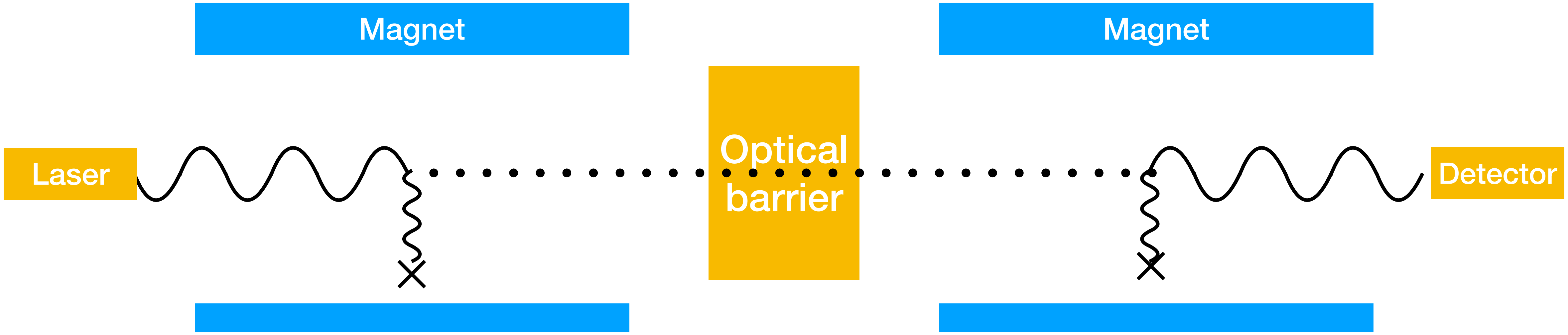


from The Review of Particle Physics (2020)



Laboratory Experiments

Light-Shining-Through-Walls (LSW)



- Static B $\Rightarrow$ $\mathscr{L}_{int} \supset - ig\omega \overrightarrow{B}_{\text{ext}} \cdot \overrightarrow{A}\phi$, a mass mixing term
- Best LSW limit achieved by OSQAR Collaboration:

$$g < 3.5 \times 10^{-8}\,\text{GeV}^{-1} \text{ for } m_\phi < 0.3\,\text{meV}$$

Resonant Optical Cavities

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

$$g < 7 \times 10^{-8}\,\mathrm{GeV}^{-1} \text{ for } m_\phi < \mathrm{meV}$$

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

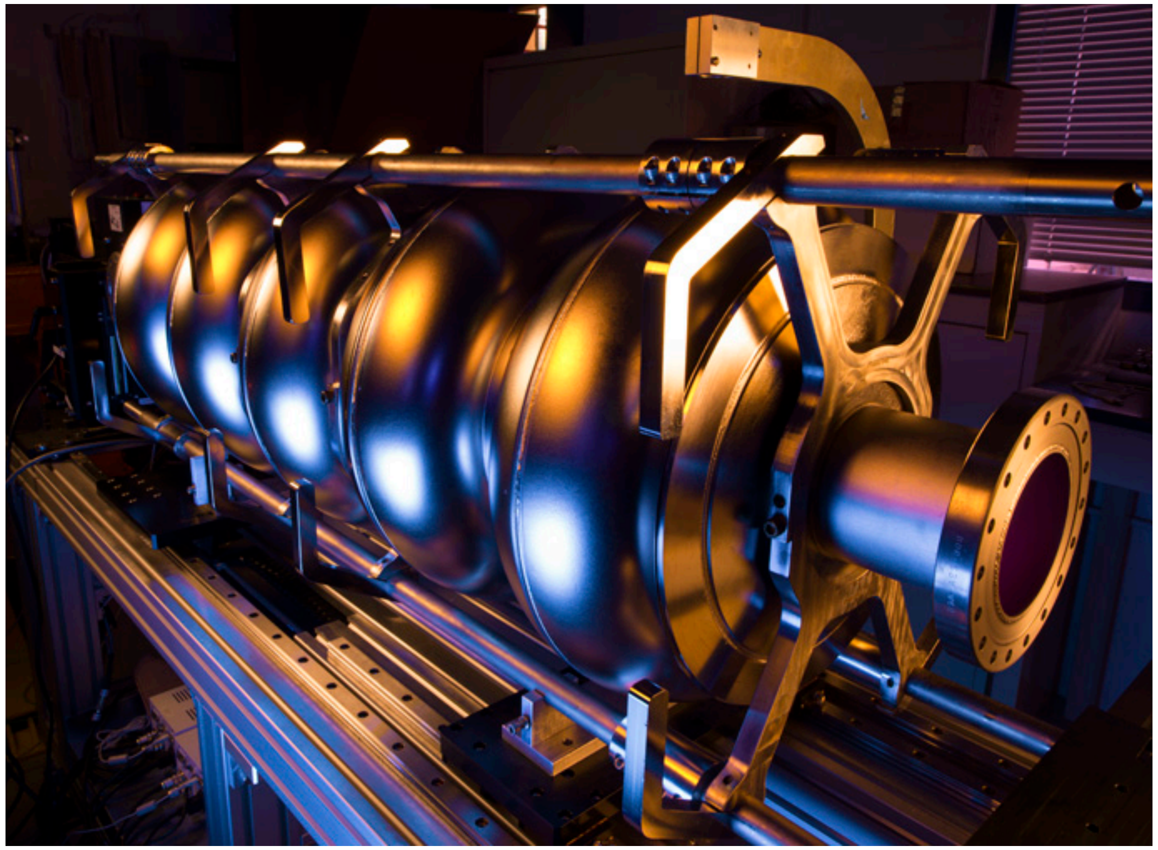
Superconducting Radio-Frequency (SRF) Cavities

- High ***quality factor*** $Q \gtrsim 10^{10}$ when cooled to $\mathcal{O}(1\mathrm{K})$
- Resonant production of $\sim 10^{28}$ photons in a GHz cavity with a peak field of $80\,\mathrm{MVm}^{-1}$

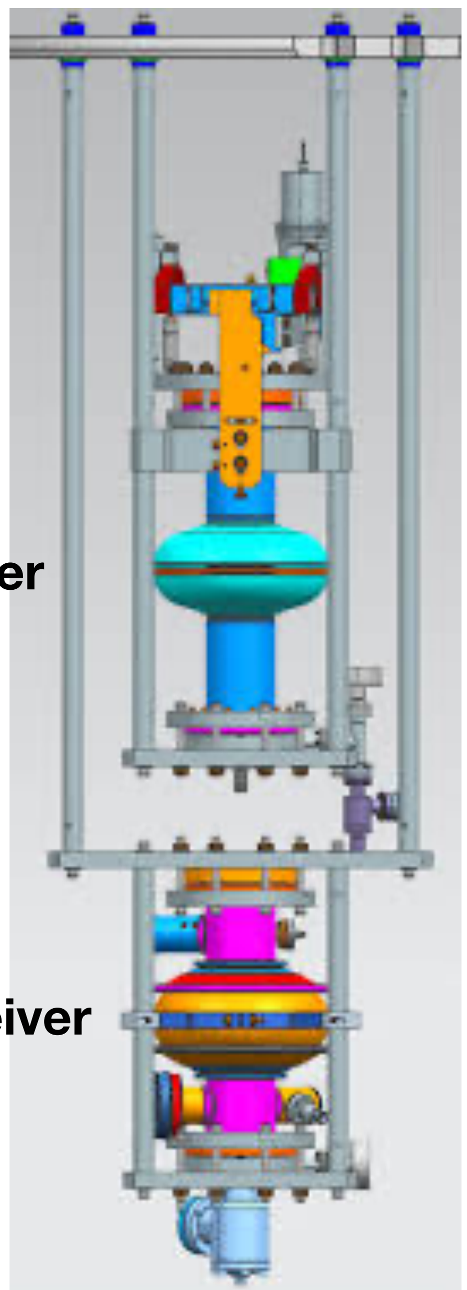
~ O(10 cm)

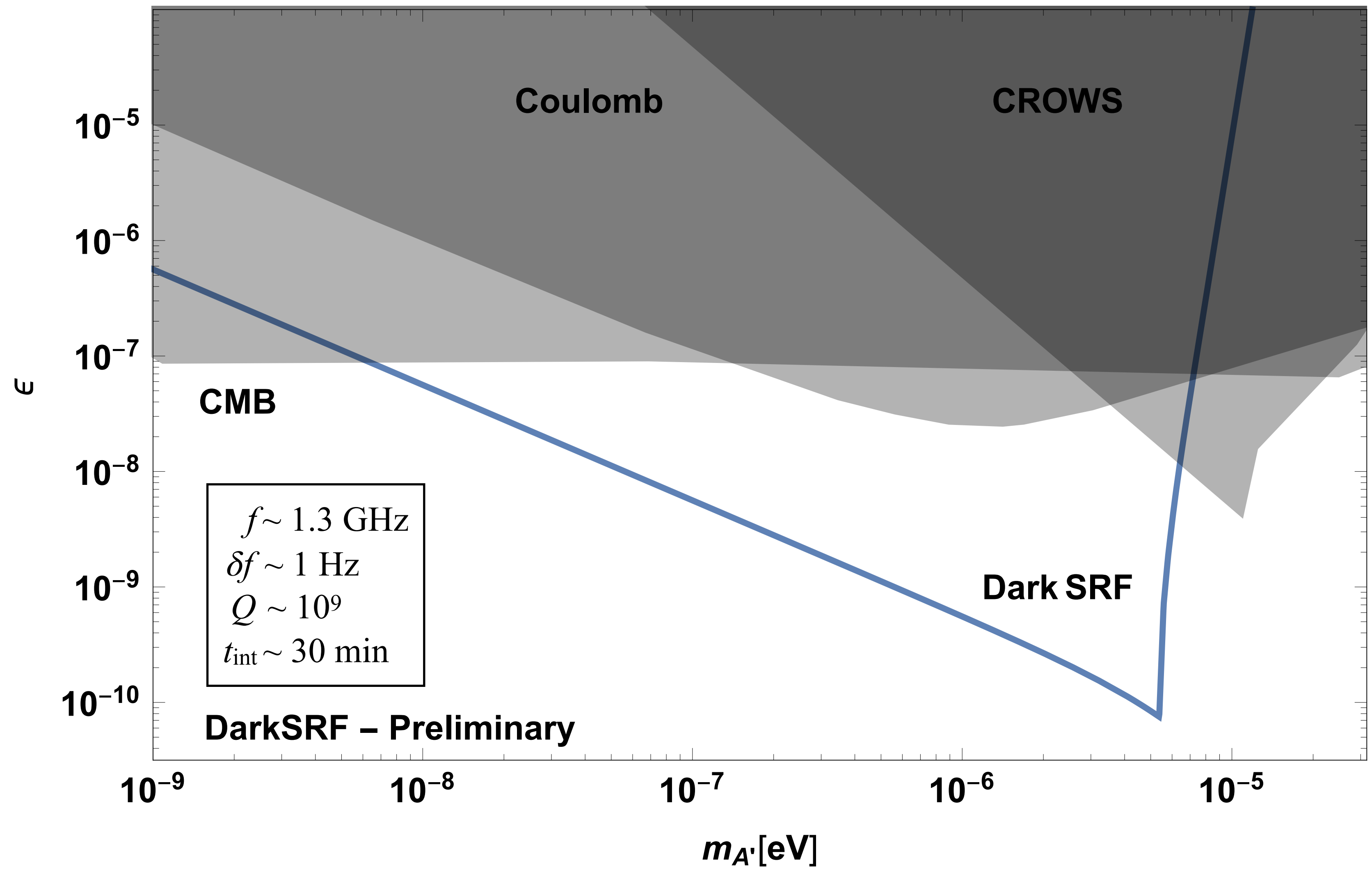
- Active field of research thanks to accelerator physics!

650 MHz multi-cell cavity at Fermilab



SRF Cavities - Dark SRF



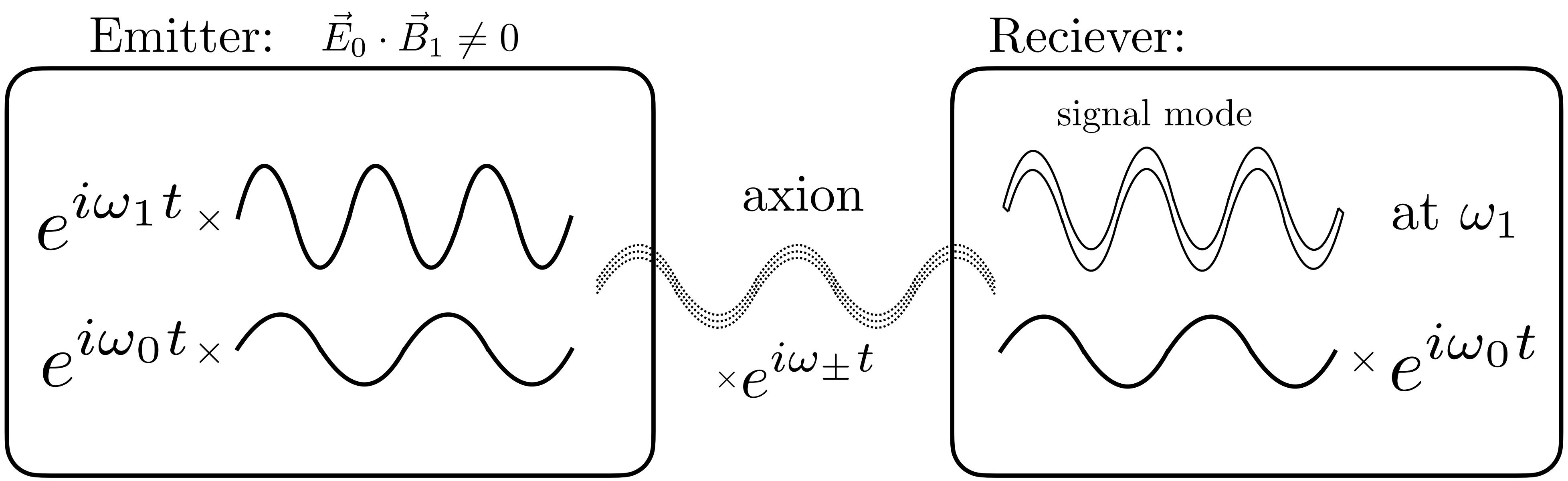


A dark photon LSW search at Fermilab using SRF cavities. Demonstrated high Q and frequency control.

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

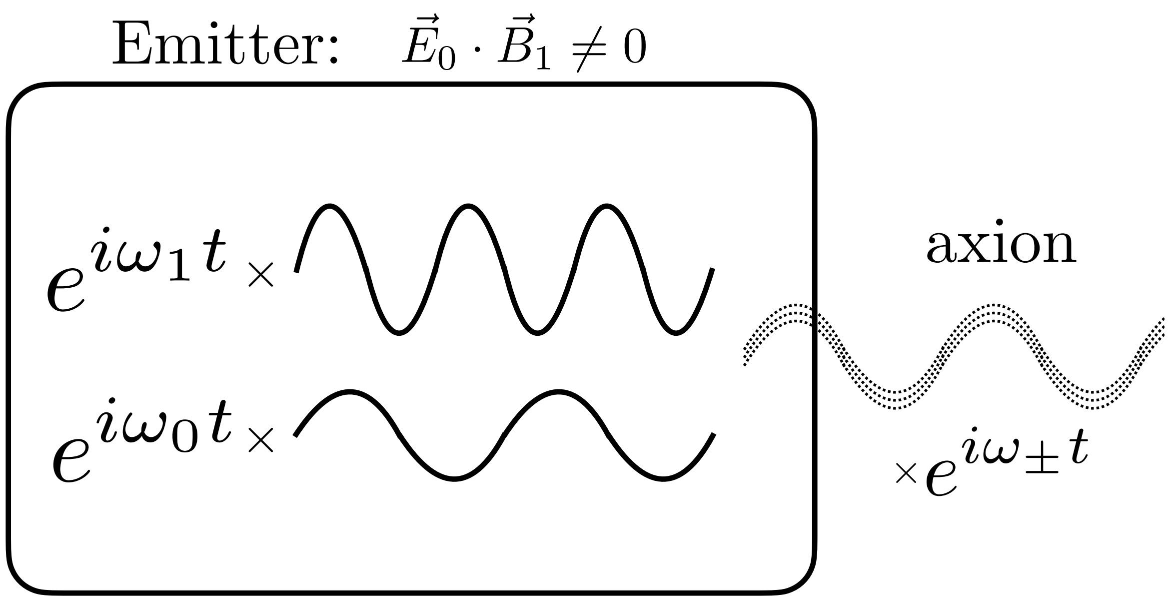
Our Proposal

Executive Summary



- SRF cavity loses high Q under large constant magnetic field.
- Static magnetic field in the previous LSW setup is replaced by an oscillatory field.
- Axion with $\omega_\phi = \omega_1 \pm \omega_0$ is produced in the emitter.
- Axion can convert to a cavity mode with a frequency $\omega_\phi \pm \omega_0$. In particular, it can resonantly produce a field at ω_1.

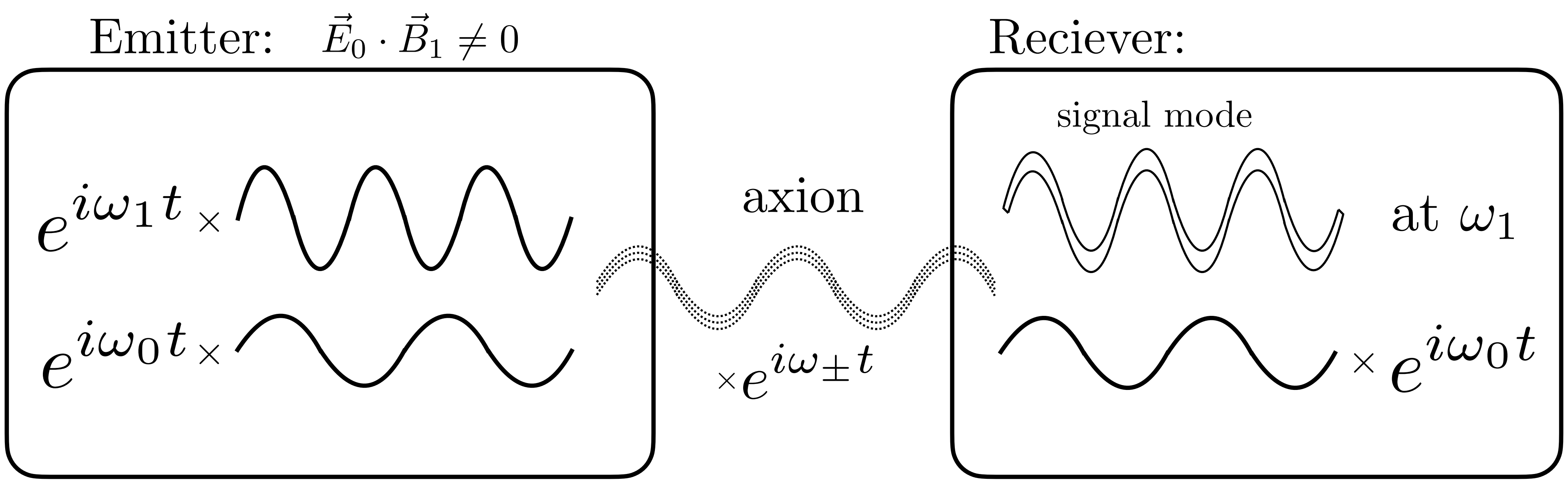
Production



$$\mathscr{L}_{int} \supset g\phi \overrightarrow{E} \cdot \overrightarrow{B}$$

- Use two oscillatory cavity modes to source axion R. Janish et al, 19
- $\phi \sim g V_{\mathrm{Em}} E_0 \cdot B_1 / r$ with $\omega_\phi = \omega_\pm = \omega_1 \pm \omega_0$

Detection



- Pick one of the two production modes to be the spectating mode in the receiver

- Detection with frequency conversion

P. Sikivie, 10
Berlin et al, 19
Z. Bogorad et al, 19

Maxwell Equation

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

$$\Downarrow$$

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

Spatial interference btwn ϕ, spec, sig modes

distance between emitter and receiver

Quality factor for ω_1

$\omega_1 = \omega_\phi \pm \omega_0$ will be produced on resonance.

How large is Signal?

Spatial

interference btwn ϕ, spec, sig modes

$$\sim d\left(\frac{\alpha}{\omega_1} + \frac{\beta}{\omega_1/\omega_\phi} + \frac{\gamma}{\omega_1^2}\right)$$

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

Observable: Power

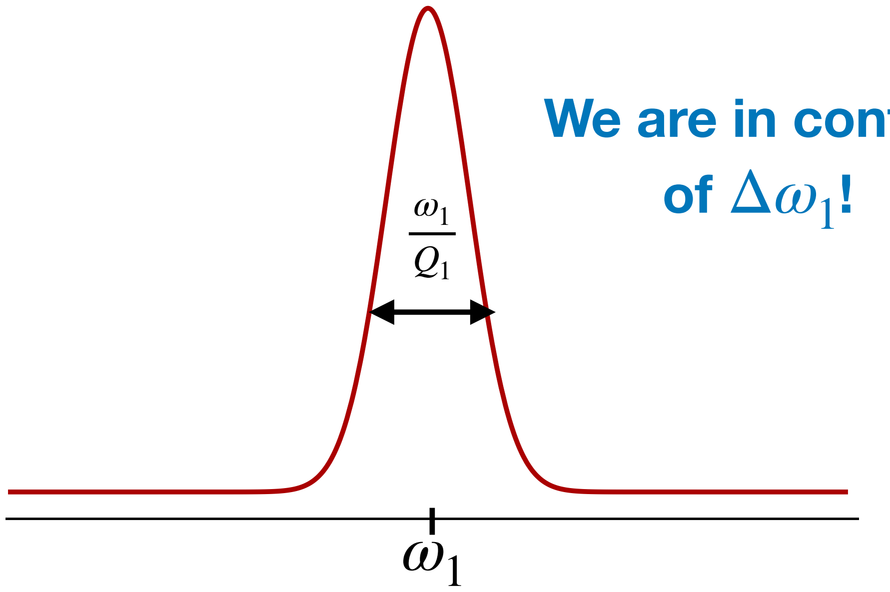
$$P_{sig} = \frac{\omega_1}{Q_1} \int_{V_{\rm Re}} \langle | \vec{E}_{sig}(\vec{x}, t) |^2 \rangle$$

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

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

Spatial

interference btwn ϕ, spec, sig modes

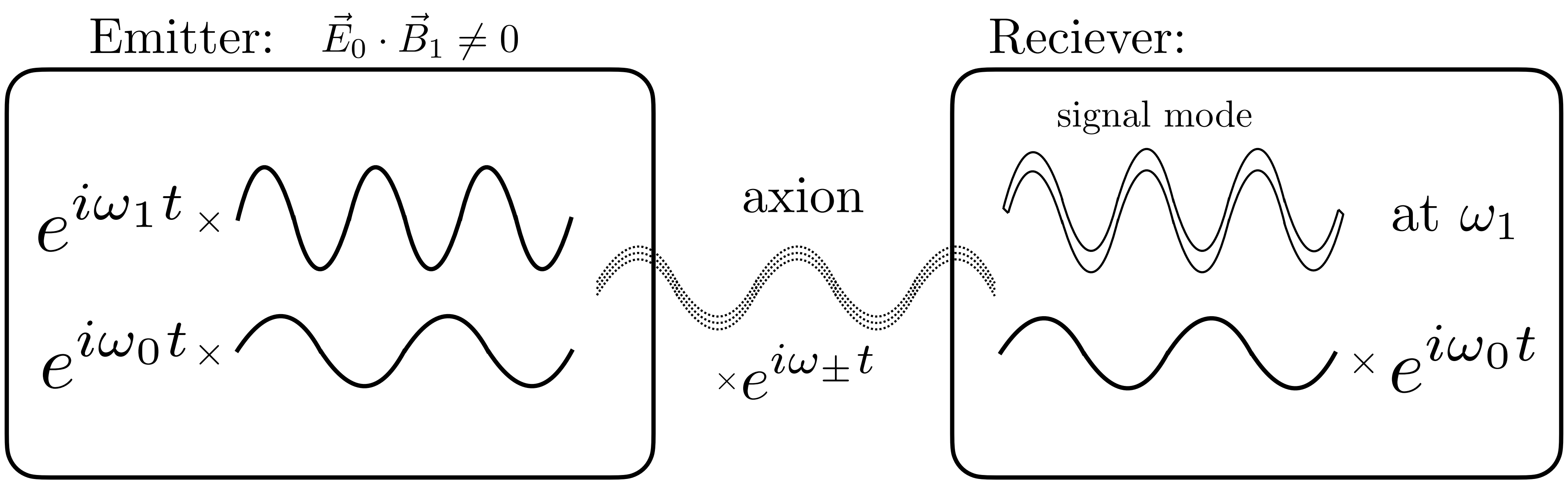


We are in control of $\Delta\omega_1$!

Observable: Power

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

$$P_{sig} \sim \frac{Q_1}{8\omega_1} V^3 g^4 E^6_{\text{peak}} \omega_\phi^2 \frac{\eta_{01}^4}{(4\pi d)^2} \qquad 0 < \eta_{01} < 1$$



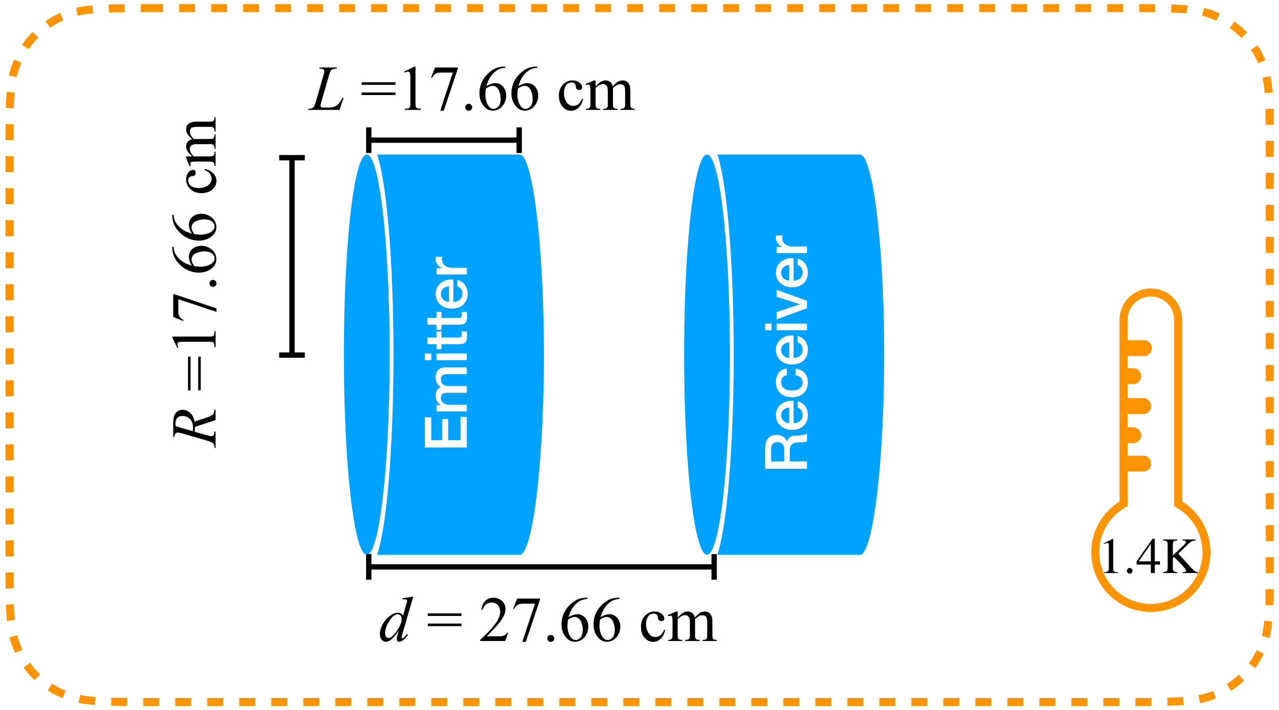
Backgrounds

1. Thermal background, constant over frequency domain. (We assume that this is the dominant background in the case study later.)

2. Leakage backgrounds from a large number of spectating photons in the receiver. They can potentially leak to signal mode, but can be effectively mitigated as long as we choose the appropriate signal mode, and only look at ***a small window around the signal mode***.

Case Study with GHz Cylindrical SRF Cavities

Setup



$$\phi_\pm \propto e^{ikz - i\omega_\pm t}/d$$

$$\vec{\nabla}\phi_\pm \sim k\phi_\pm \hat{z}$$

$$k = \sqrt{\omega_\pm^2 - m^2}$$

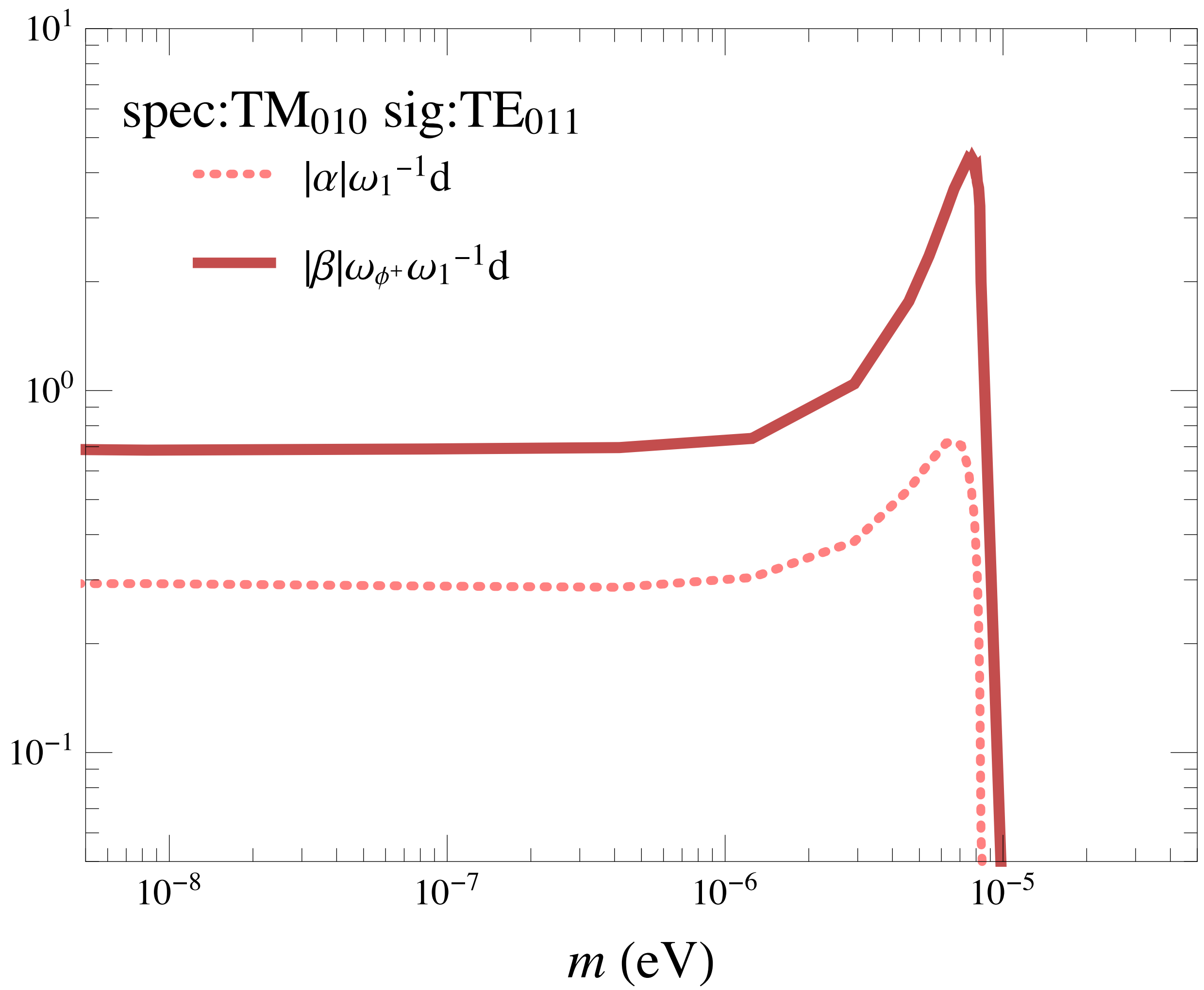
- Fundamental frequency of the cavity = 650 MHz
- Use TM_{010} mode and TE_{011} mode $\propto e^{i\pi z/L}$
- Quality factor $Q = 10^{10}$
- $E_{\text{peak}} = 80\,\mathrm{MVm}^{-1}$ for both modes in the emitter and the spectating mode in the receiver

Spatial Interference

$$\sqrt{P_{sig}} \sim \frac{E_0 g}{d} \times d\left(\frac{\alpha}{\omega_1} + \frac{\beta}{\omega_1/\omega_\phi} + \frac{\gamma}{\omega_1^2}\right)$$

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

$$\int_V \vec{E}_1 \cdot \left[-\partial_t(\vec{E}_0 \times \vec{\nabla}\phi) + \partial_t(\vec{B}_0 \partial_t \phi) - \vec{\nabla}(\vec{B}_0 \cdot \vec{\nabla}\phi)\right]$$



$$\phi_\pm \propto e^{iz\sqrt{\omega_\pm^2 - m^2}}$$

$$\mathrm{TE}_{011} \propto e^{iz\pi/L}$$

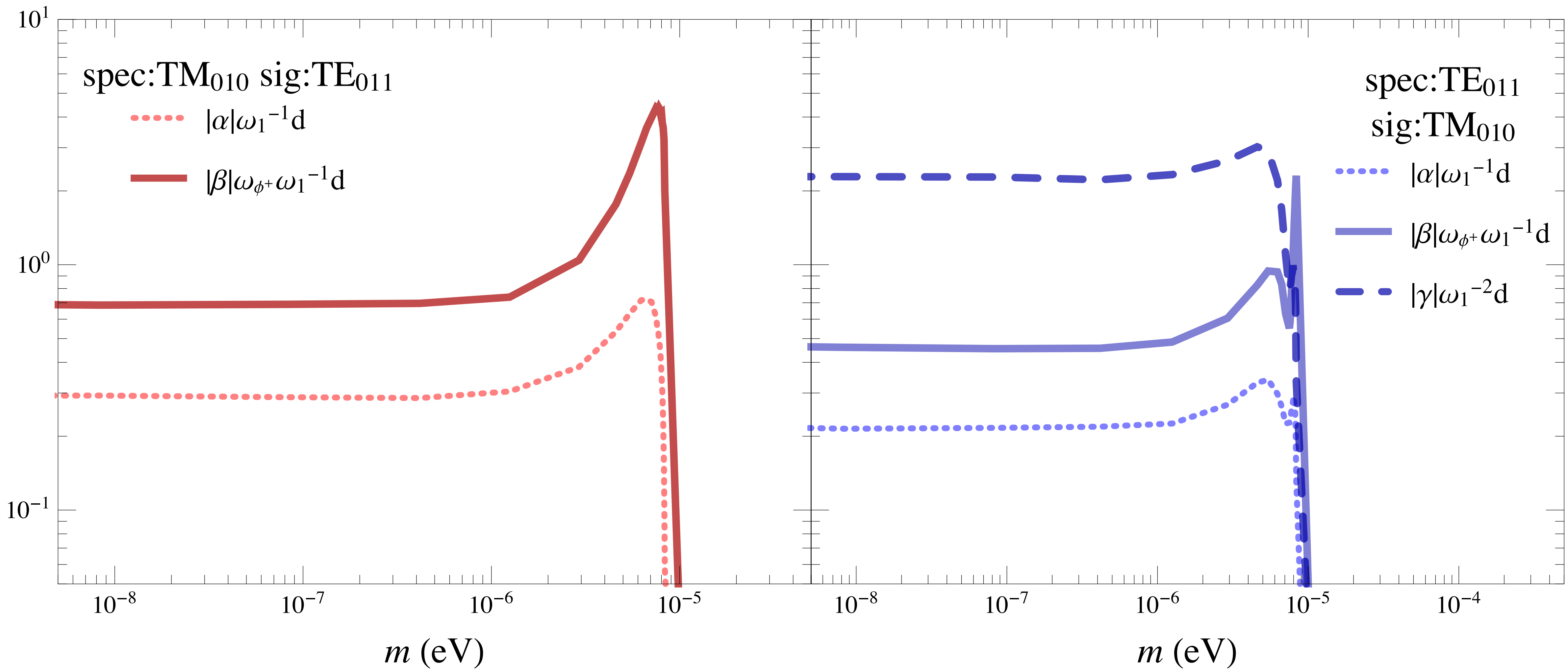
TM_{010} is constant in z

Spatial Interference

$$\sqrt{P_{sig}} \sim \frac{E_0 g}{d} \times d\left(\frac{\alpha}{\omega_1} + \frac{\beta}{\omega_1/\omega_\phi} + \frac{\gamma}{\omega_1^2}\right)$$

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

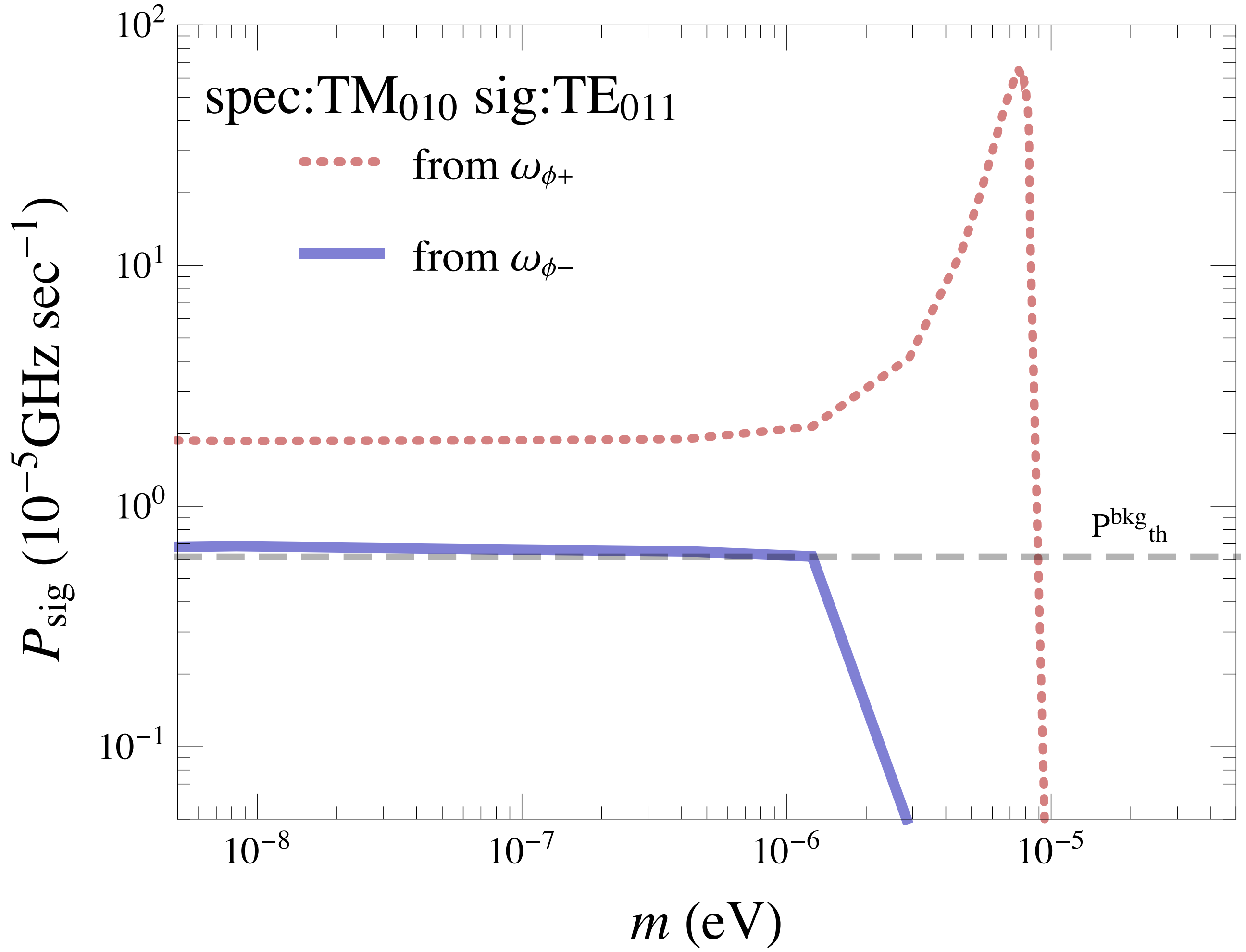
$$\int_V \vec{E}_1 \cdot \left[-\partial_t(\vec{E}_0 \times \vec{\nabla}\phi) + \partial_t(\vec{B}_0 \partial_t \phi) - \vec{\nabla}(\vec{B}_0 \cdot \vec{\nabla}\phi)\right]$$



Signal Power

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

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

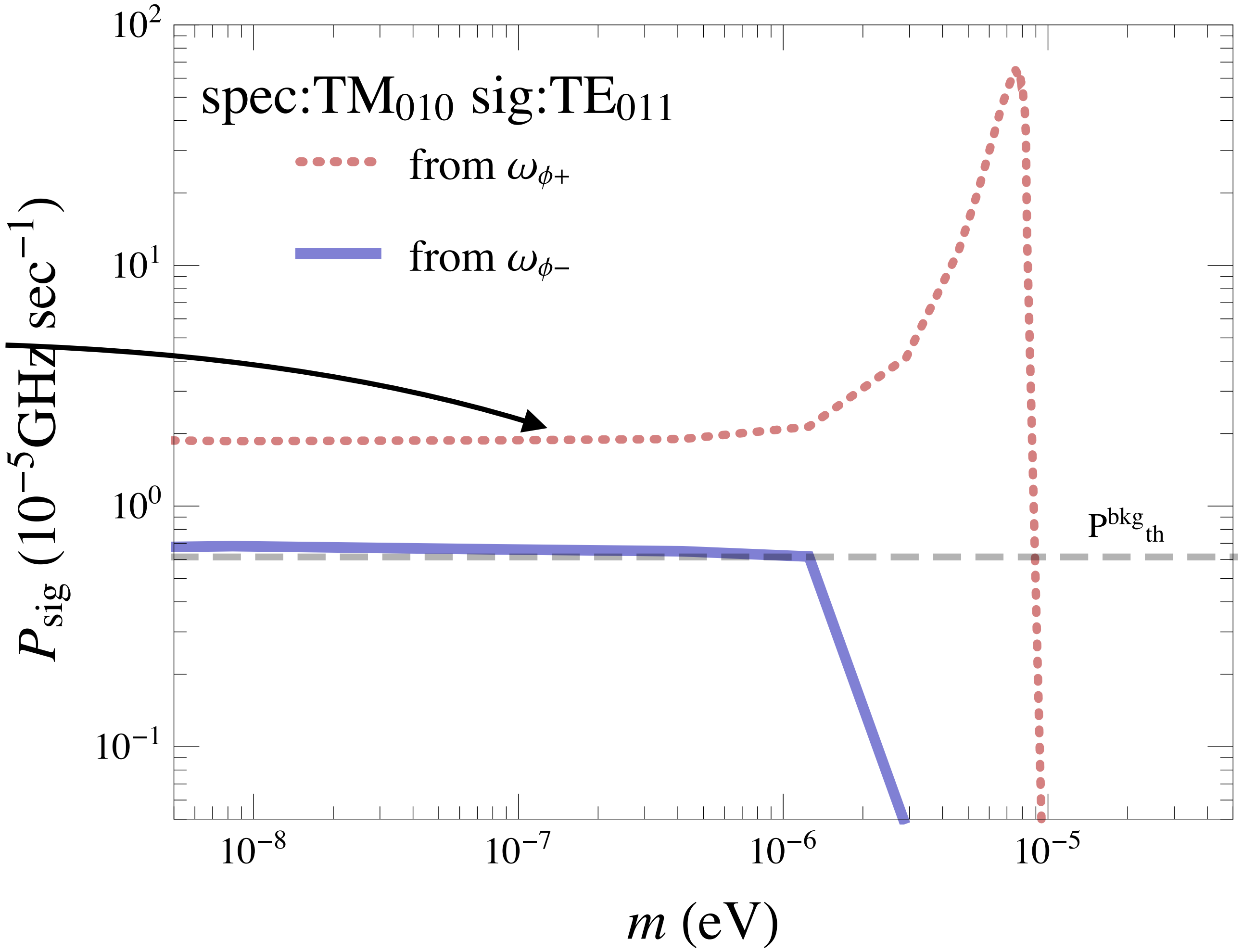


Signal Power

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

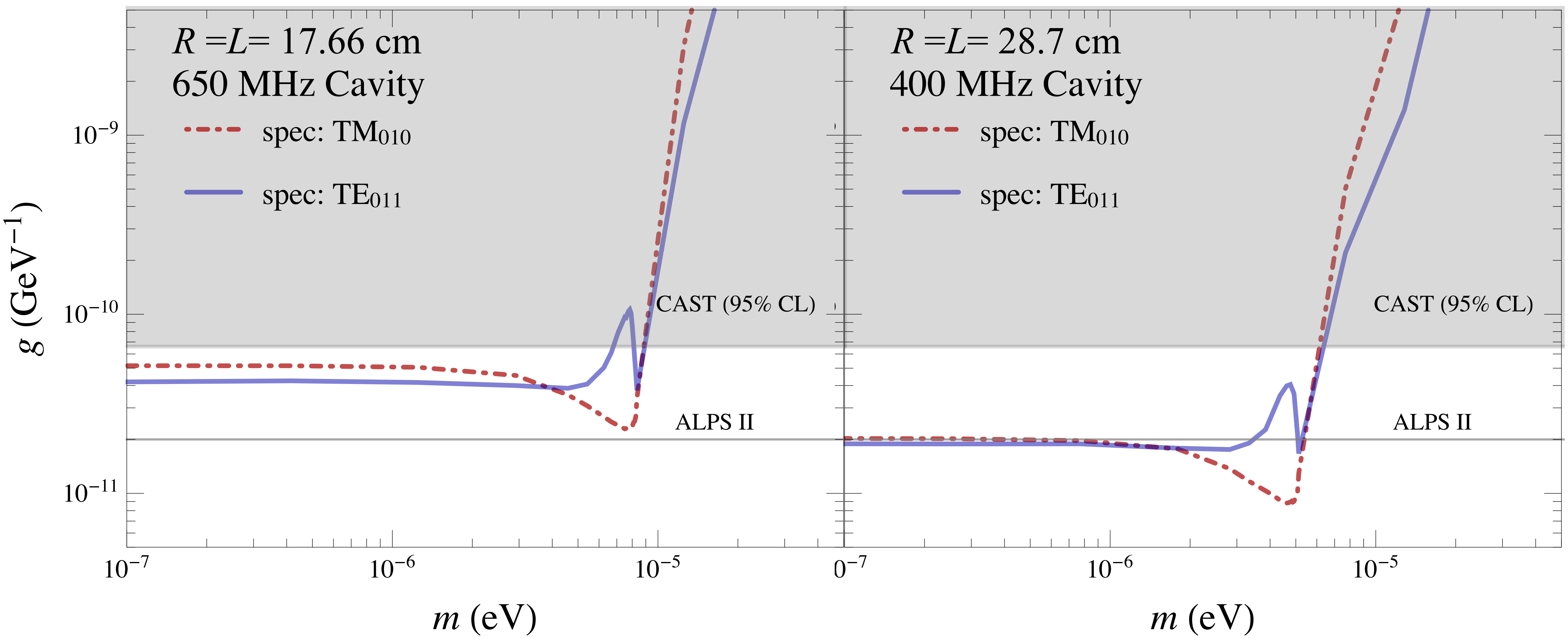
$$g = 5 \times 10^{-11}{\rm GeV}^{-1}$$

200 sig photons after 1 year!



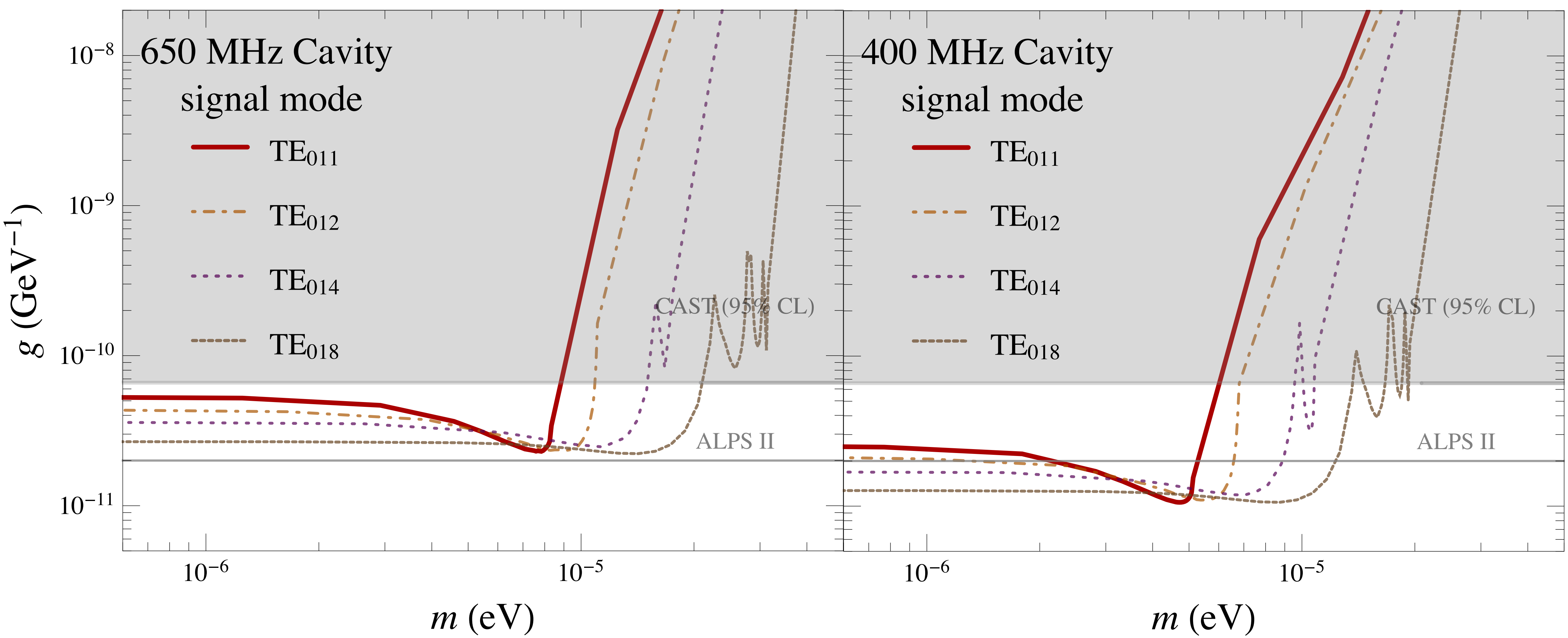
Sensitivity with Low Cavity Modes

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



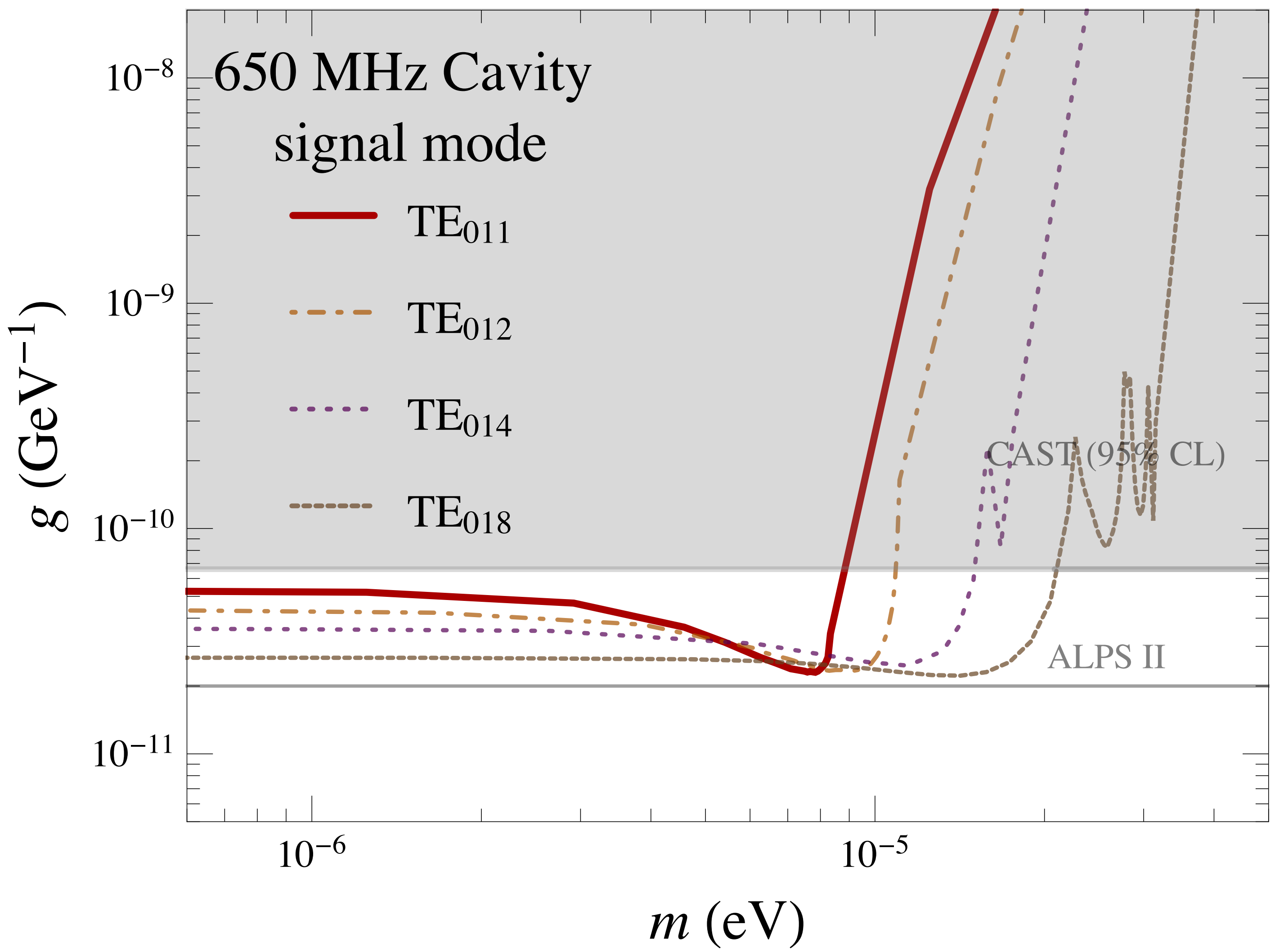
Sensitivity with High Cavity Modes

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



Sensitivity with High Cavity Modes

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



Higher cavity modes

- gain access to larger masses
- have a better sensitivity in the massless limit
- but, Q may worsen under large peak field

Conclusion

- We propose a LSW axion search strategy using SRF cavities in the GHz range.
- The case study shows that for $m_\phi \lesssim 10\,\mu\mathrm{eV}$, our estimated sensitivity on g can be comparable to that projected by ALPSII.
- Exciting opportunity to apply quantum technology.

Thank you, everyone!

Special thanks to:

- Sam Posen, Ryan Janish for helpful discussions,
- Albert Stebbins, Aaron Chou for a tour to see real cavities,
- Roni Harnik, for being so much fun to work with, and
- Yiming Zhong, for everything!

Backups

Maxwell Equations w. axionic interaction

$$\vec{\nabla} \times \vec{E} = -\partial_t \vec{B}, \qquad \vec{\nabla} \cdot \vec{E} = -g\vec{B} \cdot \vec{\nabla}\phi,$$

$$\vec{\nabla} \times \vec{B} = \partial_t \vec{E} - g(\vec{E} \times \vec{\nabla}\phi - \vec{B}\partial_t\phi), \qquad \vec{\nabla} \cdot \vec{B} = 0,$$

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

- Non-linear eom for $\overrightarrow{E}$ (or $\overrightarrow{B}$)
- Can be solved perturbatively at $\mathcal{O}(g)$

Signal can be obtained by solving Maxwell Equations

~ g × **Spectating** field × Axion field

Signal field at $\mathscr{O}(g)$

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

- If ϕ is DM, $\overrightarrow{\nabla}\phi$ is small.
- All of RHS can be important for lab-produced ϕ.

Signal Field

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

$$\mathbb{E}_1\tilde{e}_1(\omega) = \frac{-i\omega g\mathbb{E}_0}{\omega^2-\omega_1^2-i\omega\omega_1/Q_1}\times\int\frac{d\omega'}{2\pi}\tilde{e}_0(\omega-\omega')\tilde{f}(\omega')(\alpha+\beta\omega'+\frac{1}{\omega}\gamma),$$

$$\alpha \equiv \frac{\int_V \vec{E}_1^*\cdot(\vec{E}_0\times\vec{\nabla}\Phi)}{\sqrt{\int_V|\vec{E}_1|^2}\sqrt{\int_V|\vec{E}_0|^2}},\qquad \beta \equiv \frac{\int_V \vec{E}_1^*\cdot(\vec{B}_0\Phi)}{\sqrt{\int_V|\vec{E}_1|^2}\sqrt{\int_V|\vec{B}_0|^2}},\qquad \gamma \equiv \frac{\int_V \vec{E}_1^*\cdot(\vec{\nabla}(\vec{B}_0\cdot\vec{\nabla}\Phi))}{\sqrt{\int_V|\vec{E}_1|^2}\sqrt{\int_V|\vec{B}_0|^2}}.$$

Examples of Cylindrical Cavity Modes

$$\vec{E}^{TM}_{0m\ell}(\vec{x},t) = E_0 \begin{pmatrix} -i\frac{\ell\pi}{L}\frac{R}{Z_{0m}}J_1\left(r\frac{Z_{0m}}{R}\right) \\ 0 \\ J_0\left(r\frac{Z_{0m}}{R}\right) \end{pmatrix} e^{i\ell\pi z/L - i\omega^{TM}_{0m\ell}t}$$

$$\omega^{nm\ell}_{\rm TM} = \sqrt{(\frac{Z_{nm}}{R})^2 + (\frac{\ell\pi}{L})^2}, \quad \ell = 0,1,2,\cdots,$$

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

$$\vec{B}^{TE}_{0m\ell}(\vec{x},t) = B_0 \begin{pmatrix} -i\frac{\ell\pi}{L}\frac{R}{S_{0m}}J_1\left(r\frac{S_{0m}}{R}\right) \\ 0 \\ J_0\left(r\frac{S_{0m}}{R}\right) \end{pmatrix} e^{i\ell\pi z/L - i\omega^{TE}_{0m\ell}t}$$

$$\omega^{nm\ell}_{\rm TE} = \sqrt{(\frac{S_{nm}}{R})^2 + (\frac{\ell\pi}{L})^2}, \quad \ell = 1,2,\cdots.$$

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

Production of Axion from a Cylindrical Cavity

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

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

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

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

Leakage Backgrounds

Leakage backgrounds from a large number of spectating photons in a GHz cavity. They can potentially leak to signal mode due to:

- An imperfect driving current that sources the spec mode;
- Non-linear effects caused by impurities on the walls of cavity.

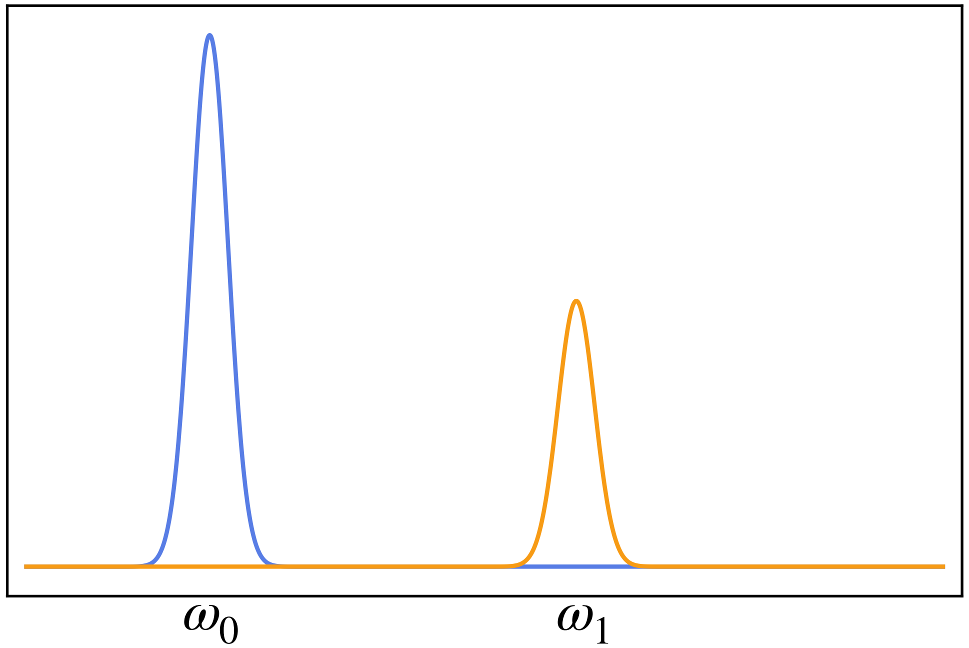
Both effects can be studied with an effective local current density $\vec{J} = \vec{j}(\vec{x})g(t)$ within the cavity:

$$
\begin{aligned}
(\partial_t^2 - \vec{\nabla}^2)\vec{B} &= \vec{\nabla} \times \vec{J} \\
(\partial_t^2 - \vec{\nabla}^2)\vec{E} &= \partial_t \vec{J}
\end{aligned}
$$

Leakage from Driving Source

$$\overrightarrow{J} = \vec{j}(\overrightarrow{x})g(t), \quad \tilde{g}(\omega) \sim e^{i\omega_0 t}$$

$$\mathbb{E}_0\tilde{e}_0(\omega) = \frac{i\omega_0}{\omega^2 - \omega_0^2 - i\omega\omega_0/Q_0}\frac{\frac{1}{V}\int \vec{E}_0^* \cdot \vec{j}}{\sqrt{\frac{1}{V}\int |\vec{E}_0|^2}}\tilde{g}(\omega)\,,$$



Leakage to signal: $$\mathbb{E}_1\tilde{e}_1(\omega) = \frac{i\omega_0}{\omega^2 - \omega_1^2 - i\omega\omega_1/Q_1}\frac{\frac{1}{V}\int \vec{E}_1^* \cdot \vec{j}}{\sqrt{\frac{1}{V}\int |\vec{E}_1|^2}}\tilde{g}(\omega),$$

Leakage from Non-linear Effects

- Spectator mode ω_0 may have a spatial overlap with impurities on the cavity wall, cause a localized current
$\overrightarrow{J}_{\text{impurity}} = \vec{j}(\overrightarrow{x})g(t), \quad \tilde{g}(\omega) \sim e^{i\omega_{\text{imp}}t}$

- Classical level, ω_{imp} equals integer multiples of ω_0

- Can be suppressed by choosing the signal mode so that their spatial overlap vanishes

Leakage to signal: $$\mathbb{E}_1\tilde{e}_1(\omega) = \frac{i\omega_0}{\omega^2 - \omega_1^2 - i\omega\omega_1/Q_1} \frac{\frac{1}{V}\int \vec{E}_1^* \cdot \vec{j}}{\sqrt{\frac{1}{V}\int |\vec{E}_1|^2}} \tilde{g}(\omega),$$