



Axion Searches with Two or More Cavities

Christina Gao



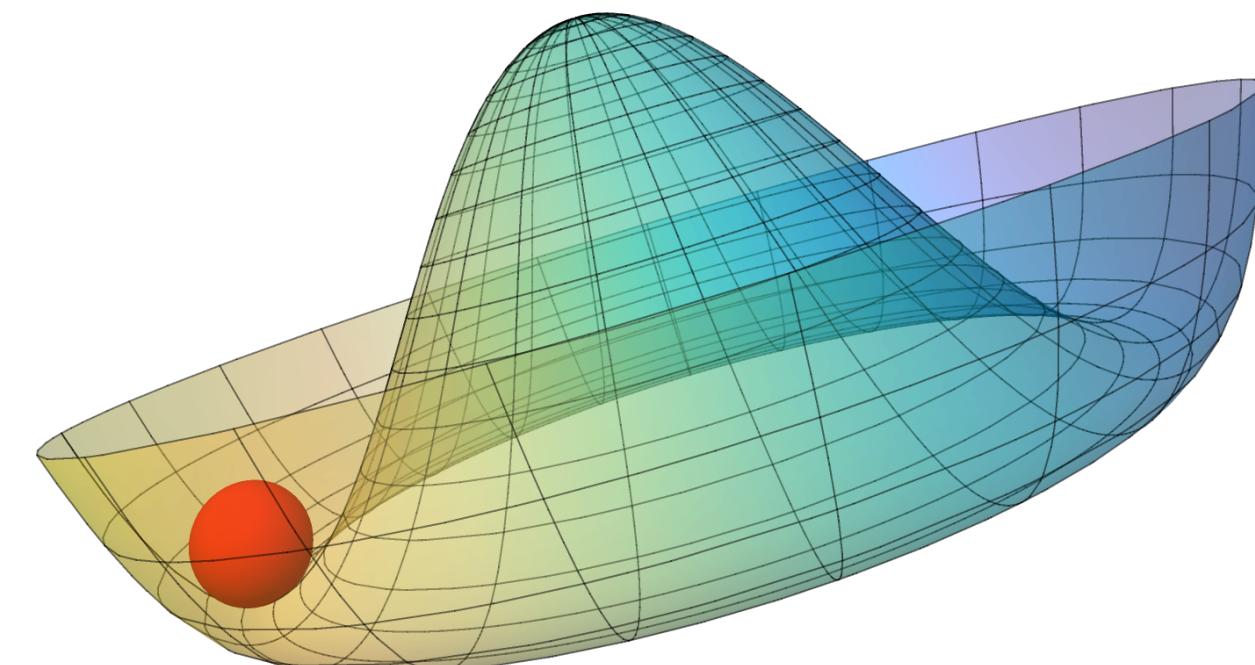
What are Axions?

- Axions are pseudo Goldstone bosons, naturally light.
- Couplings to SM are naturally small.
- QCD axion can solve the strong CP problem.
- String theory predicts many axion-like particles (ALPs).

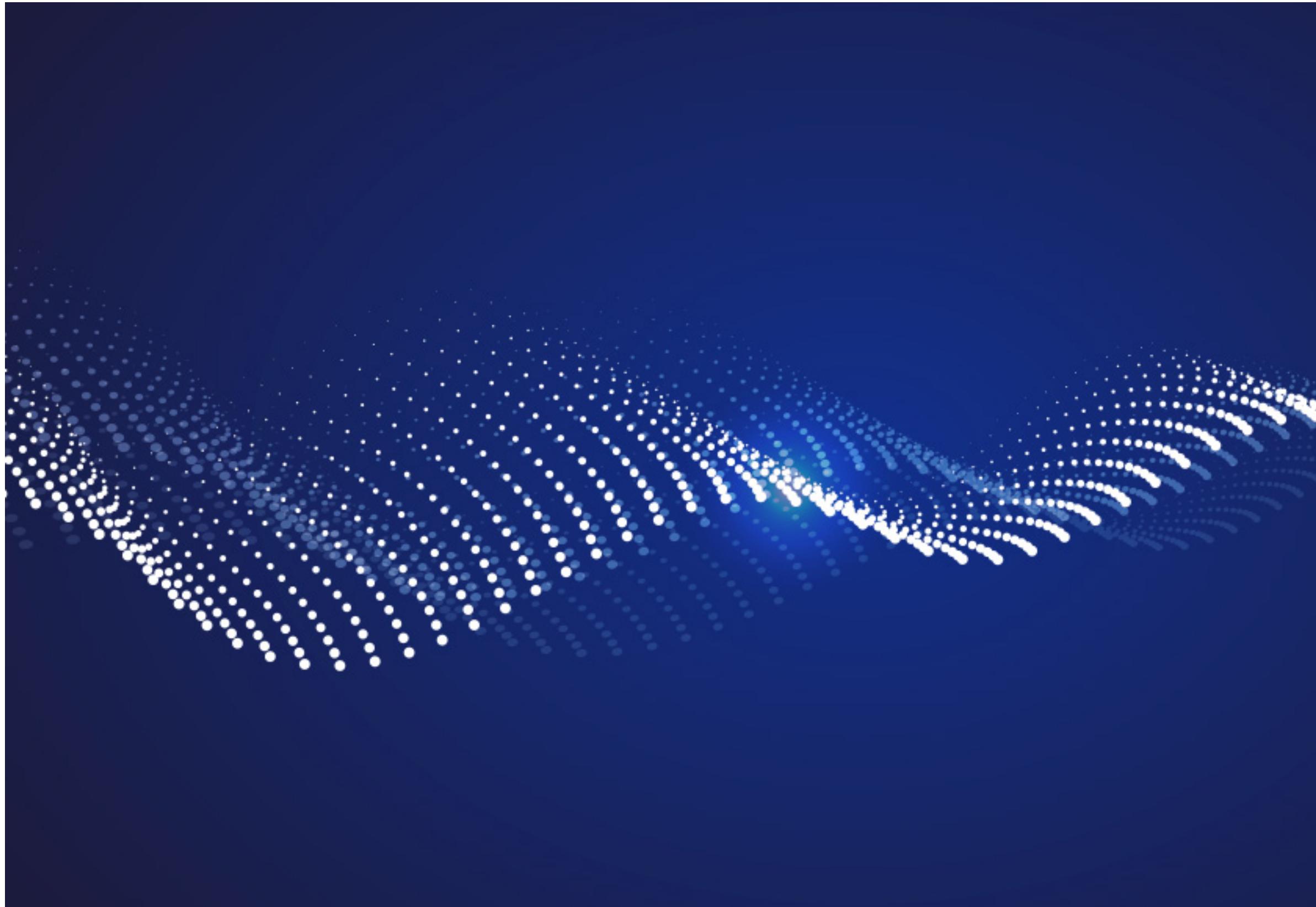
Peccei & Quinn (1977)
Weinberg (1978)
Wilczek (1978)

Kim (1979),
Dine et. al (1981)

Svrcek & Witten (2006), Arvanitaki et. al (2009)



Axions can be Dark Matter (DM)



Preskill et. al (1983), Abbott & Sikivi (1983), Dine & Fischler (1983)

- Large occupation number
- Cold dark matter
- Behave like classical field

$$a_{\text{DM}}(t) \sim a_0 \cos \left((m_a + \frac{1}{2} m_a v^2) t \right)$$

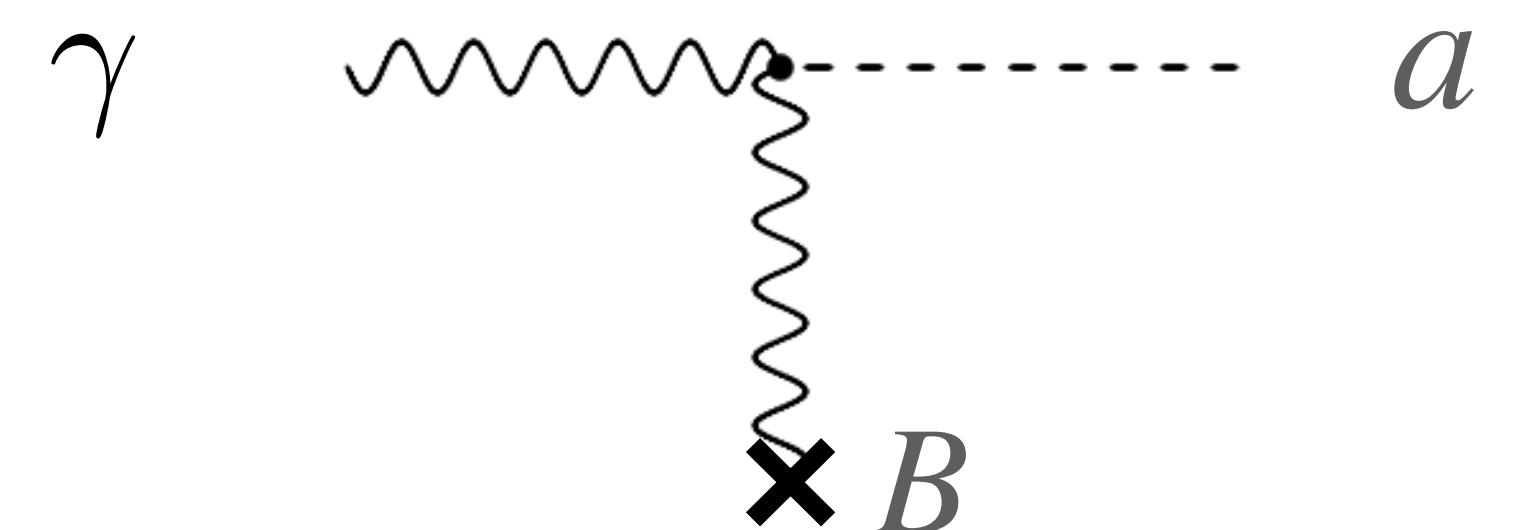
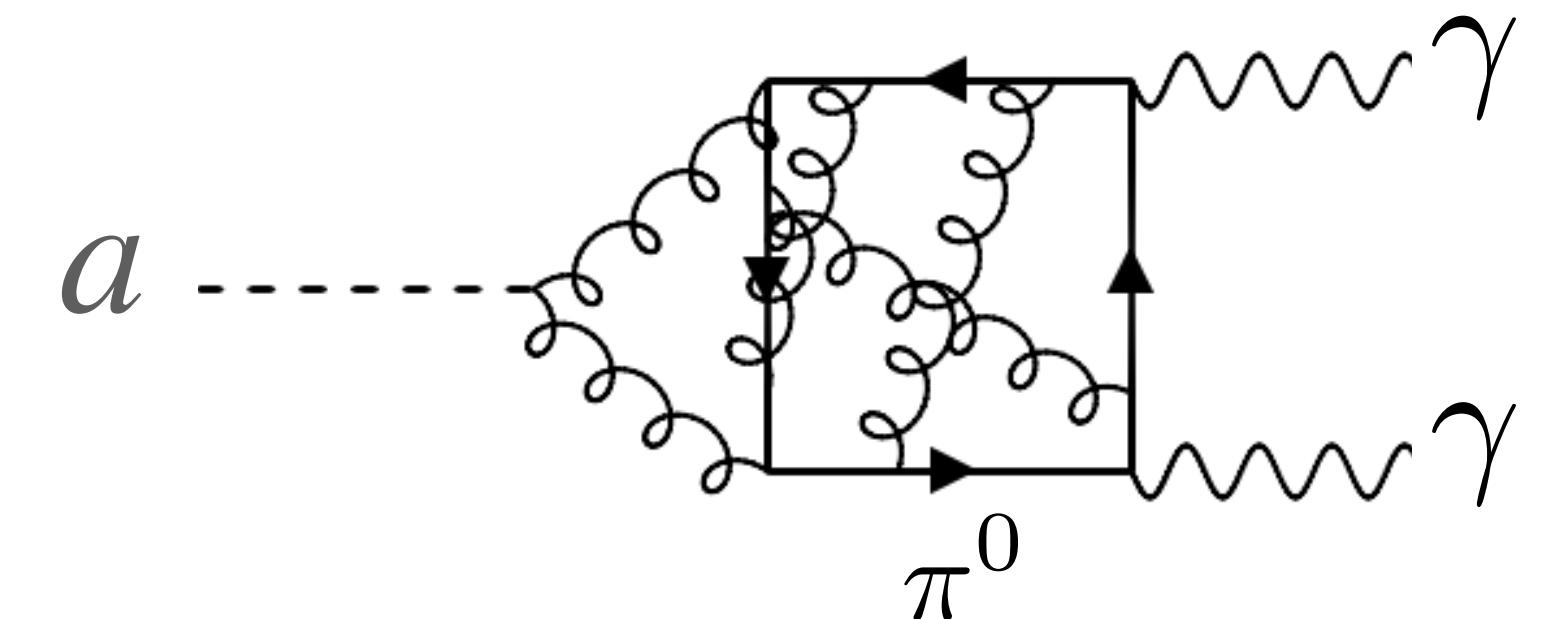
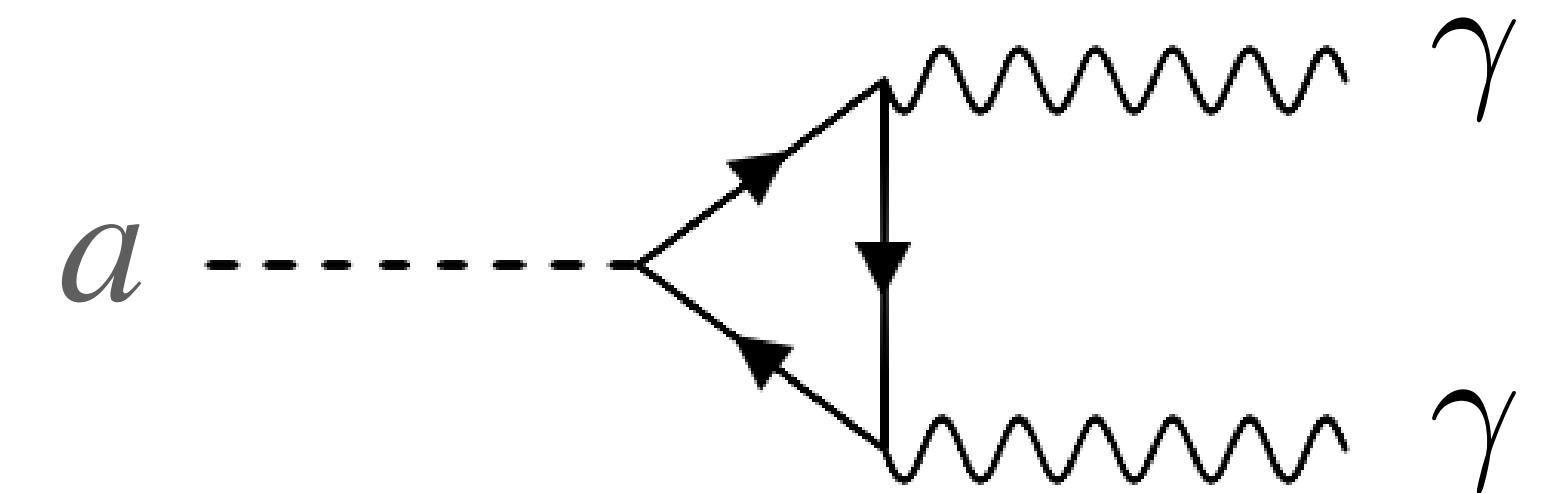
Random variable follows Maxwell distribution

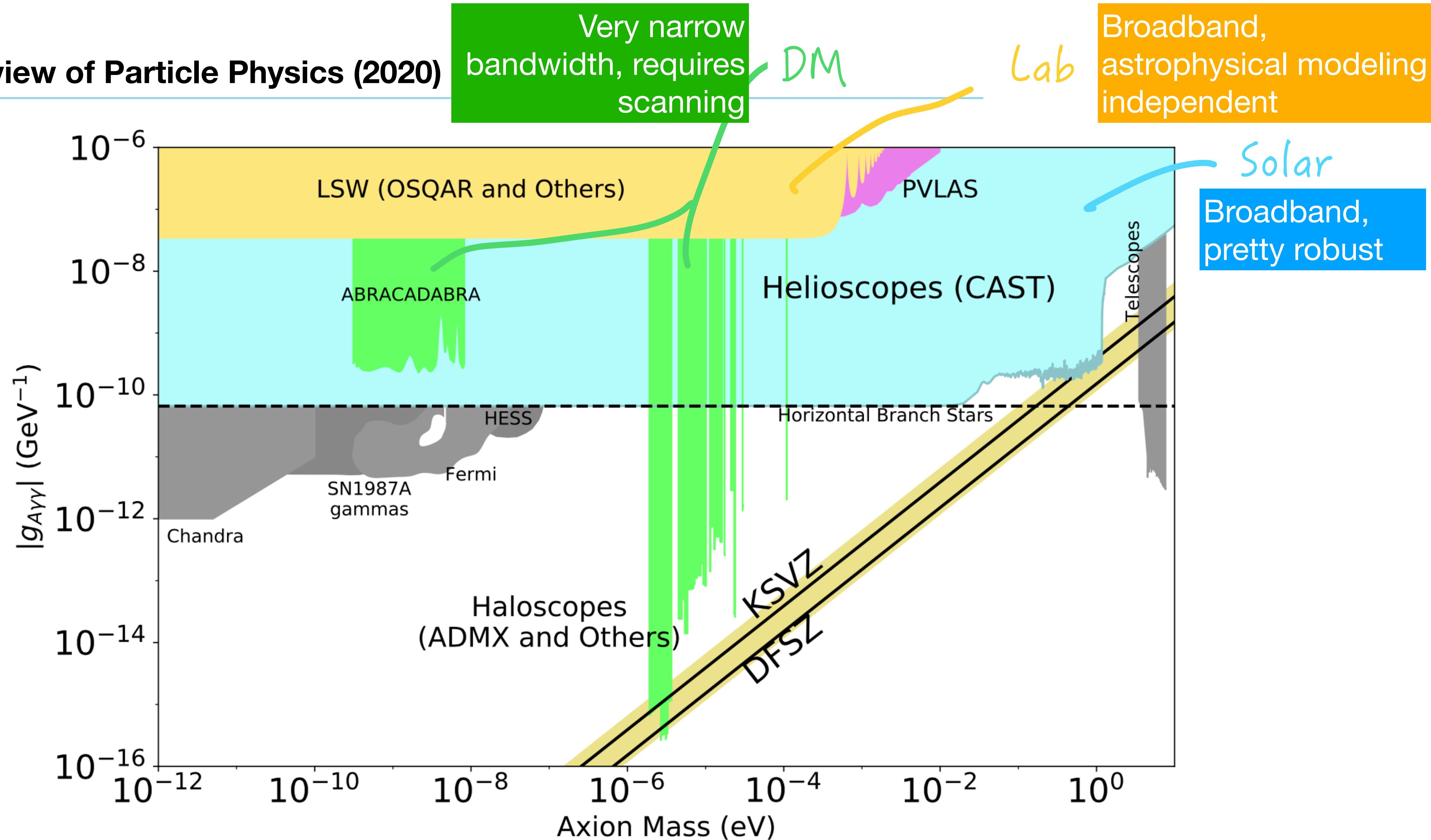
Axion's Two Photon Vertex

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

$$g \propto 1/f$$

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





This talk

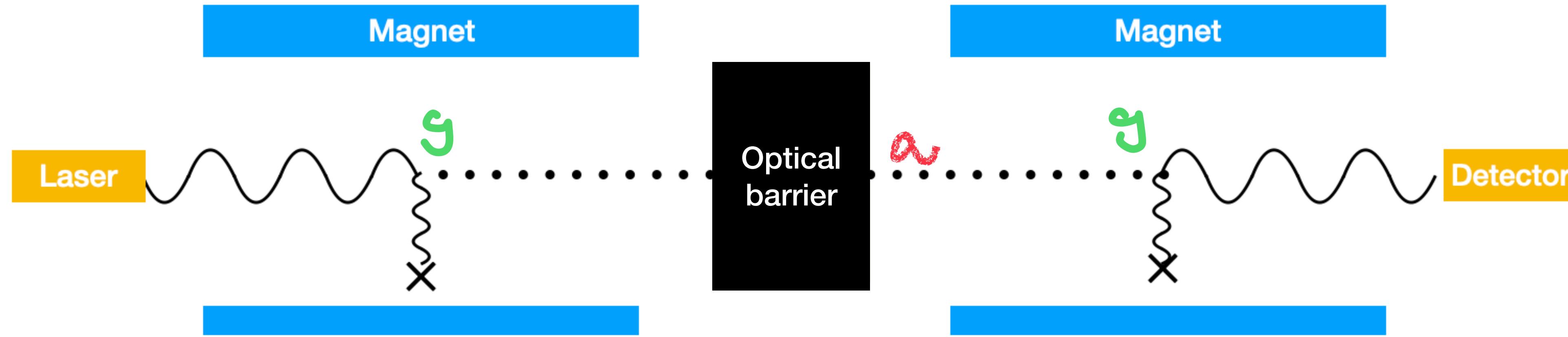
- Axion-photon coupling
- Light-Shining-through-Wall (LSW) using two superconducting radio-frequency (SRF) cavities CG, R. Harnik, JHEP (2021)
- Entangled sensor networks for DM direct detection A.J.Brady, CG, et. al, PRX Quantum (2022)

LSW Axion Searches with Two SRF Cavities

CG, R. Harnik, JHEP (2021)

Light-Shining-Through-Walls (LSW)

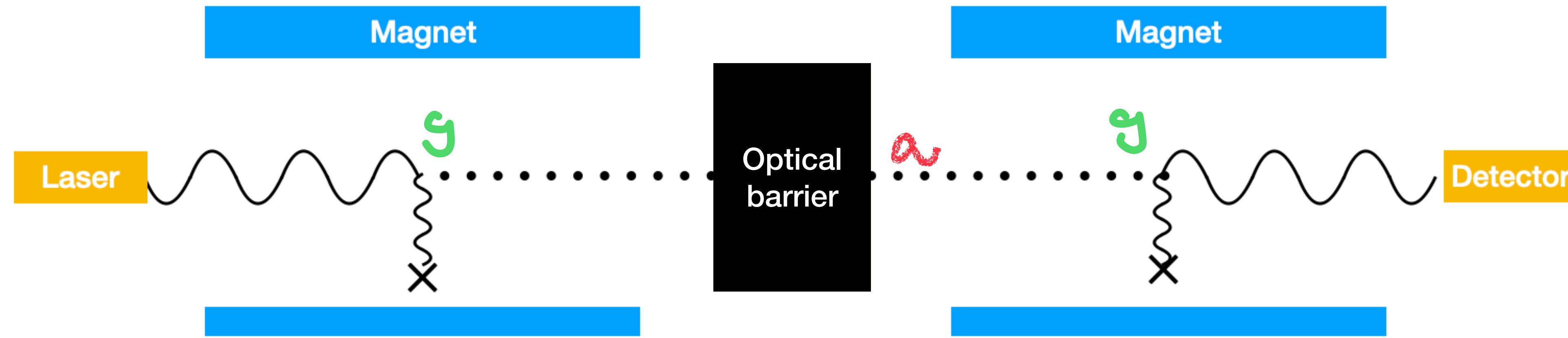
$$g \, a \, E \cdot B$$



- ◆ 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

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

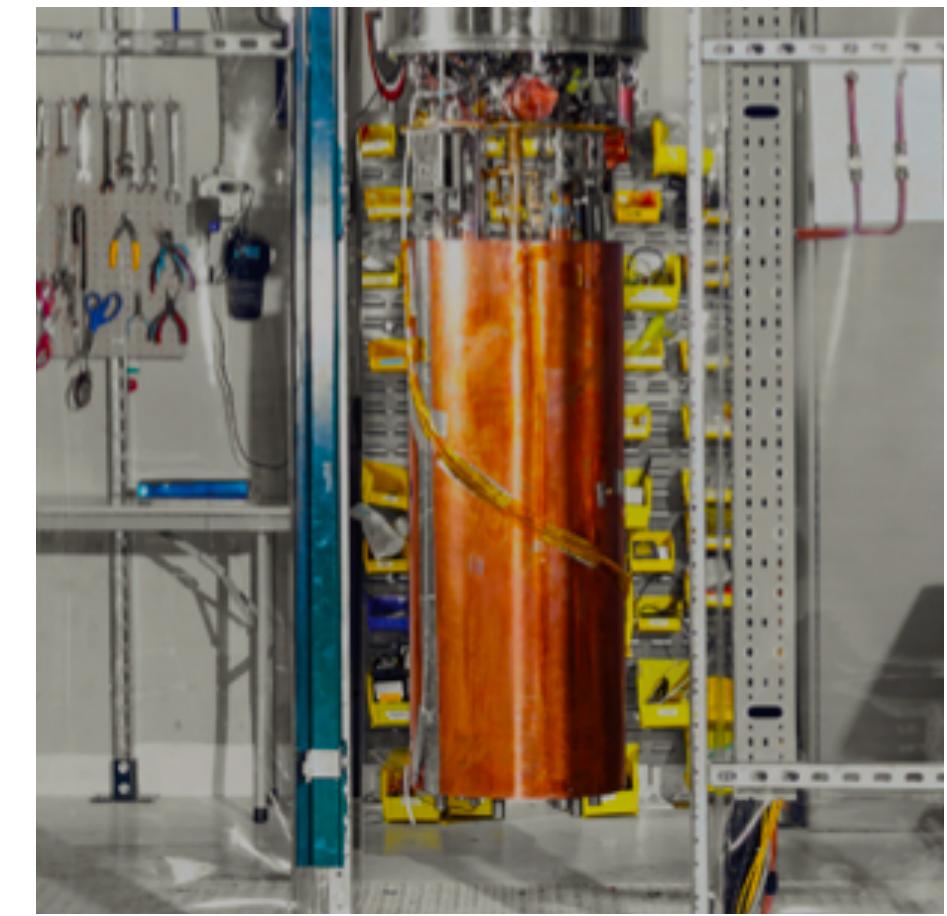
The **higher** the Q is, the **lower** the loss is, and the **larger** the number of photons are stored in a cavity.

Quality Factor of Cavities

Earth Ionosphere
 $Q = 3$



ADMX
 $Q \sim 10^5$



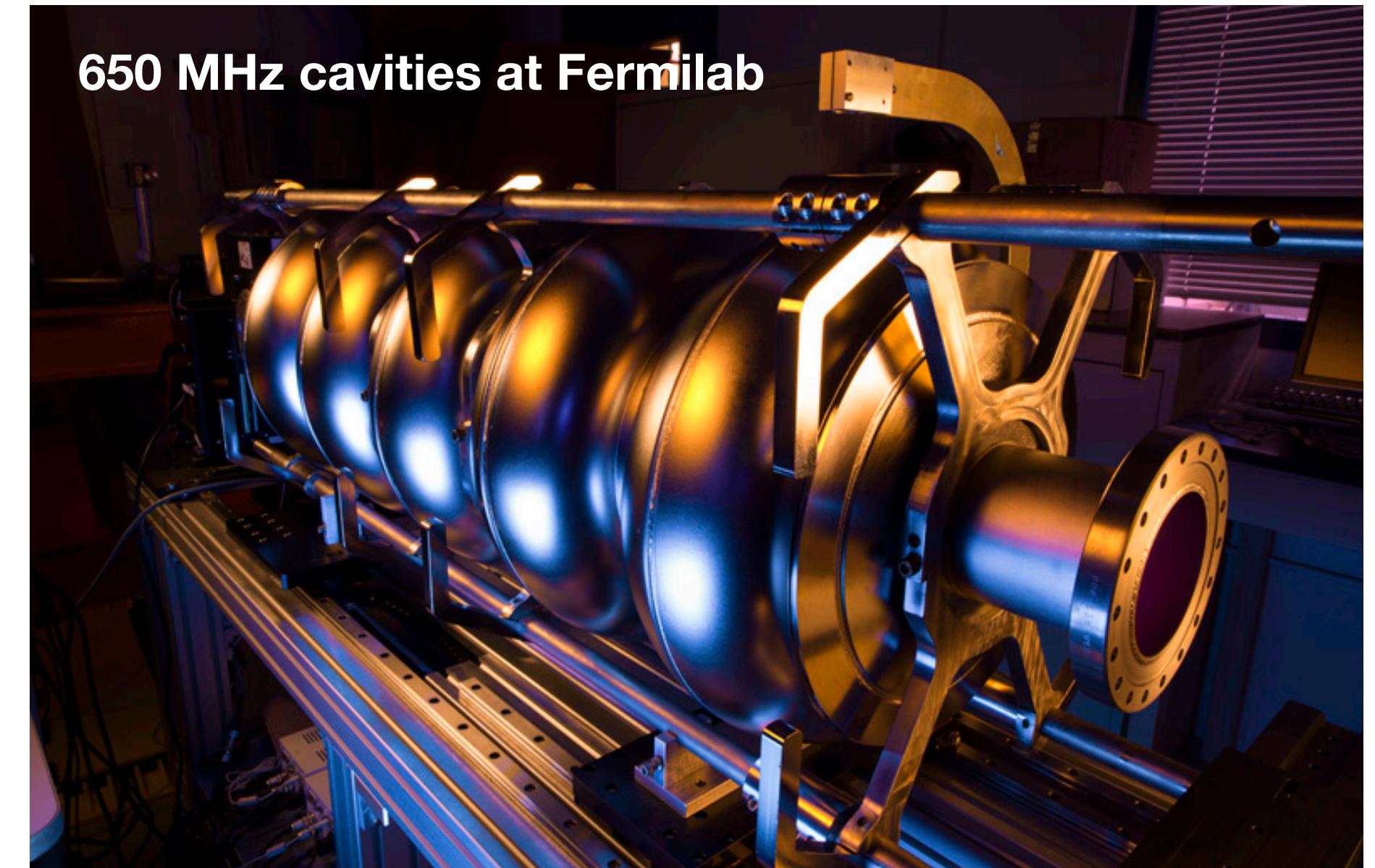
Phys. Rev. Lett. 127 (2021)

High quality cavities have $Q \gtrsim 10^7 \sim 10^{14}$
(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

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

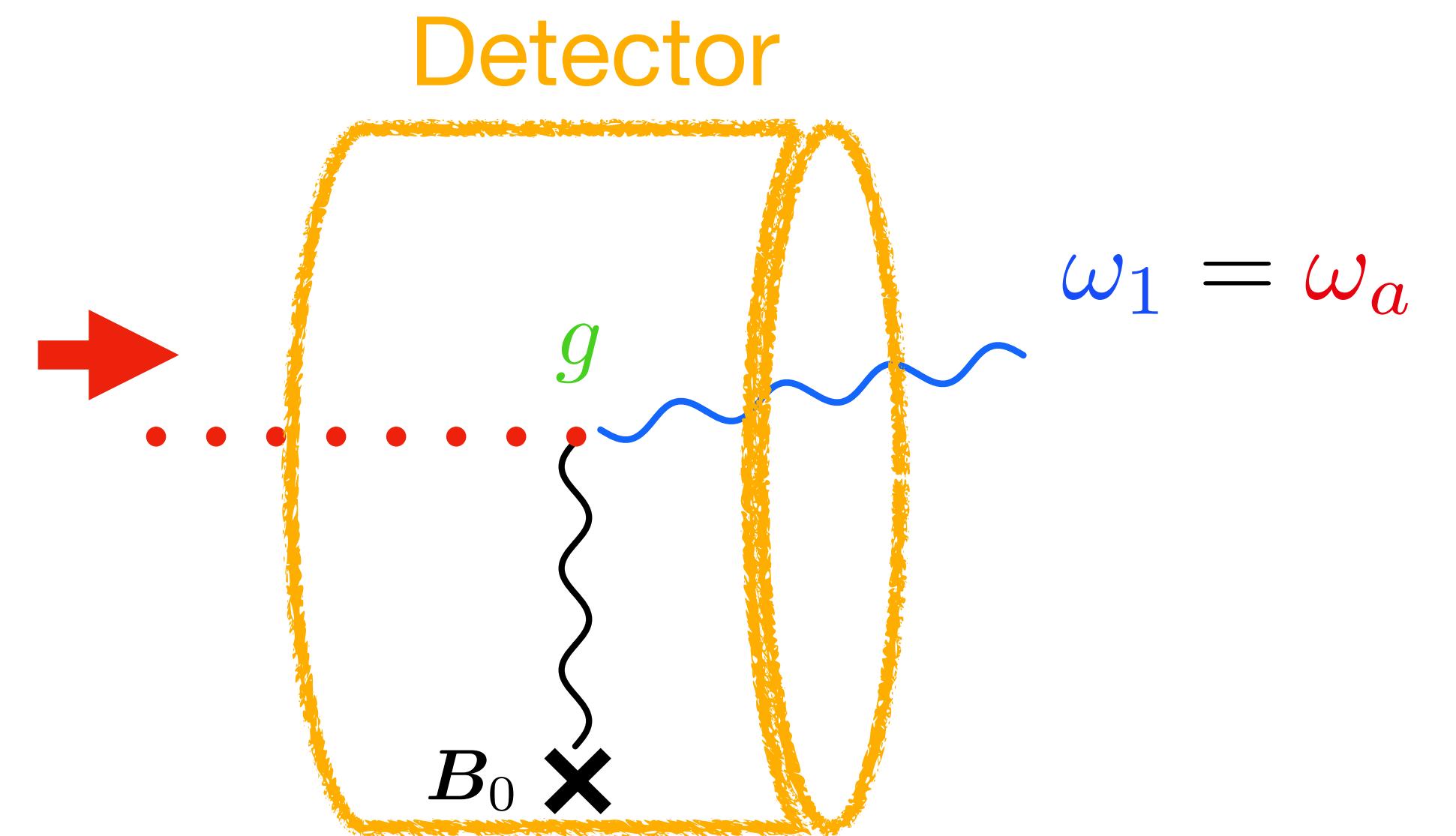


“Searches for New Particles, Dark Matter, and Gravitational Waves with SRF Cavities”

Review of Cavity Axion Searches

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

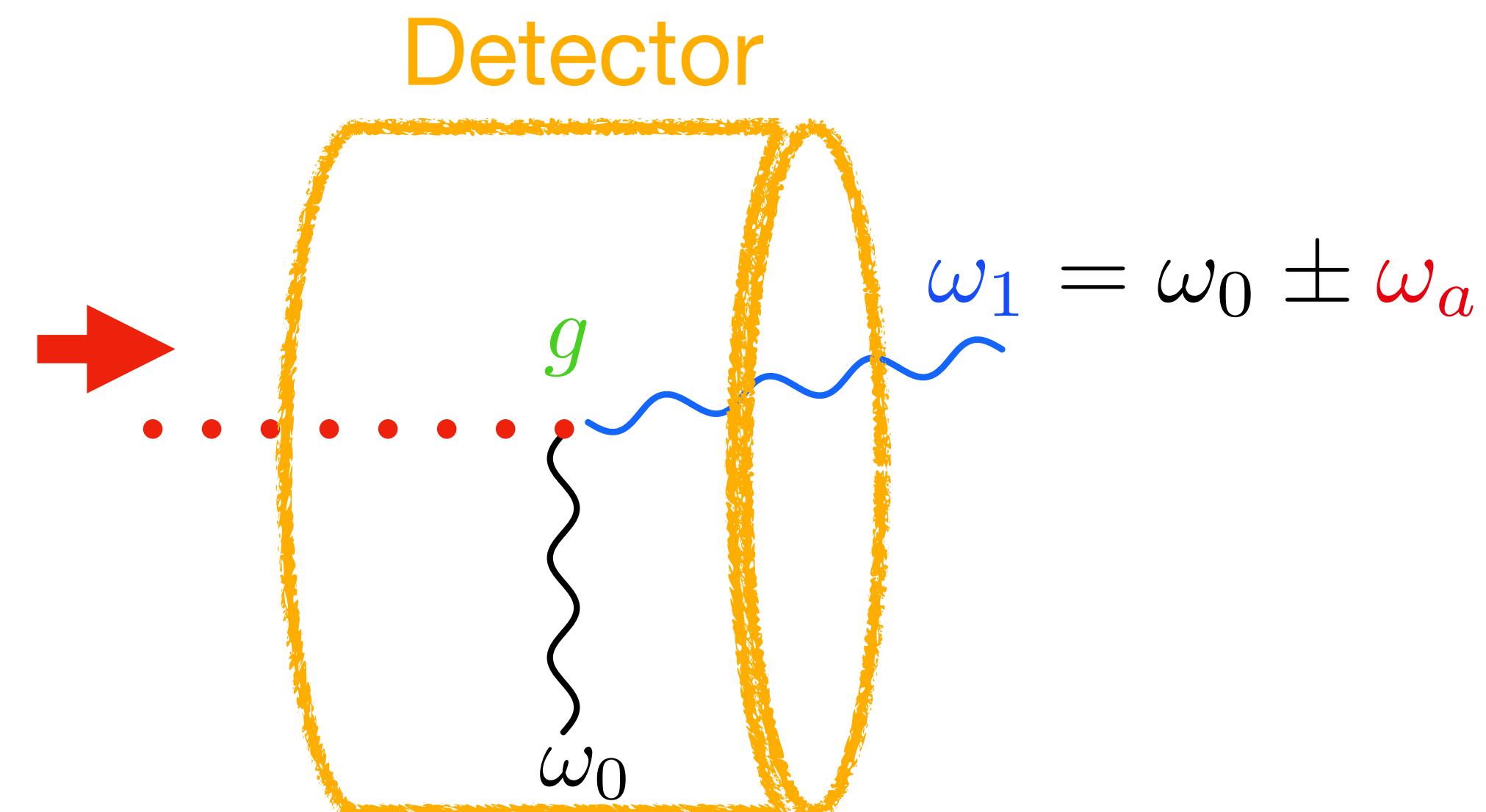
- ♦ a quiet cavity + static B
- ♦ signal ω_1 is a cavity mode, enhanced by Q .
- ♦ tiny g \Rightarrow large B desired, but large B may penetrate SRF cavity.



Review of Cavity Axion Searches

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

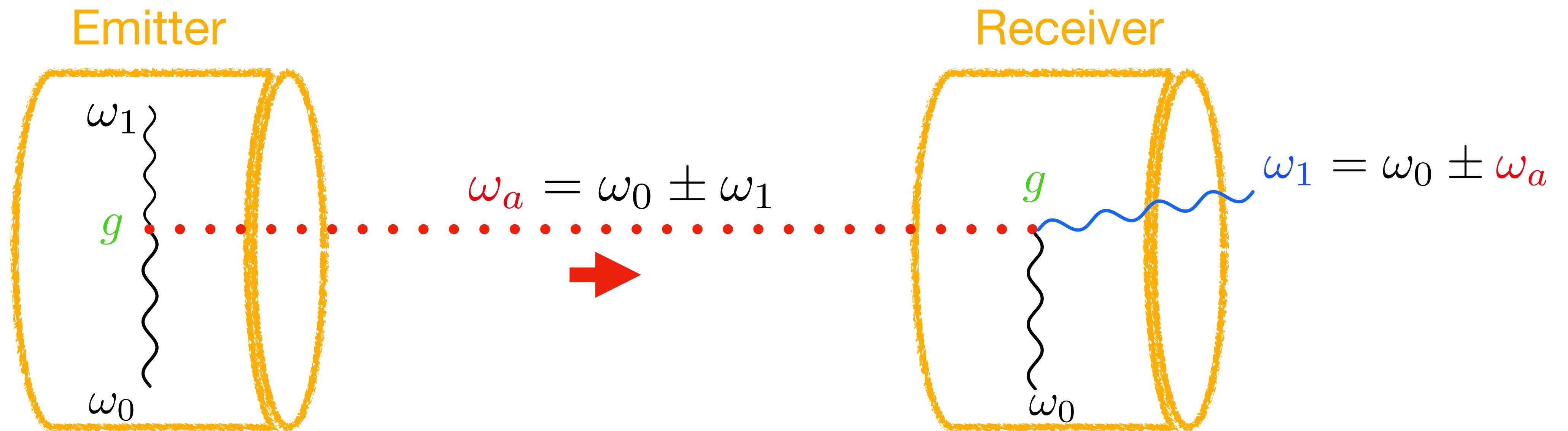
- ♦ static B → **active** cavity mode ω_0
- ♦ signal $\omega_1 = 2\text{nd}$ cavity mode
- ♦ frequency matching:
- ♦ new DM axion search strategies



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

LSW Axion Searches with SRF Cavities

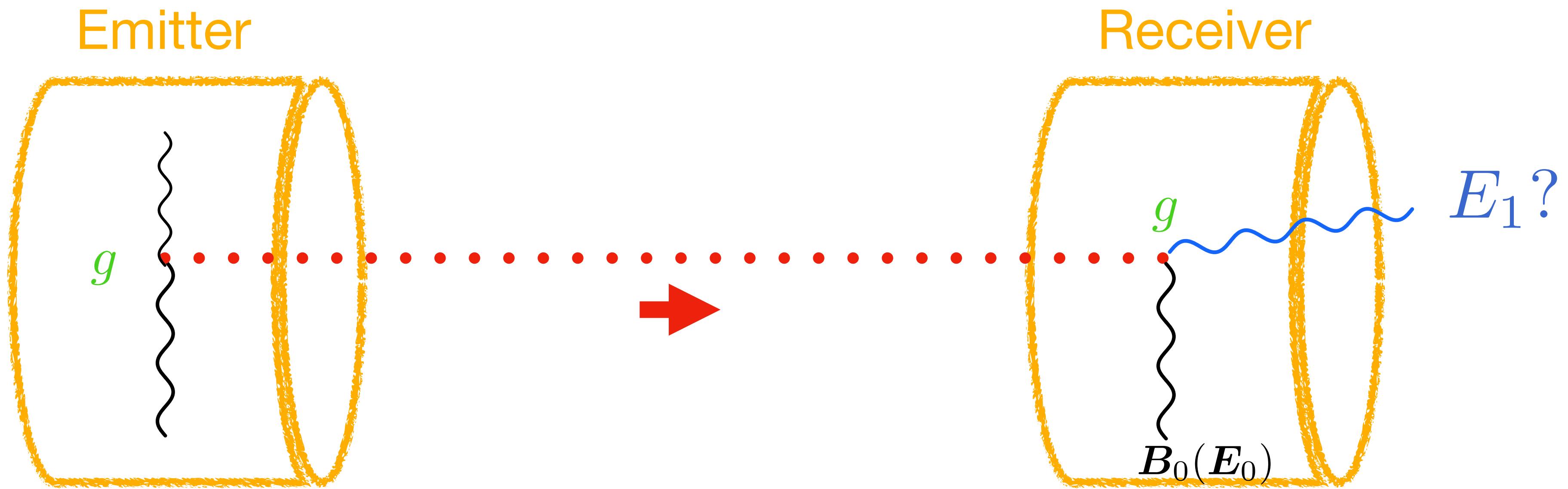
$$g \text{ } a \text{ } E_1 \cdot B_0$$



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

Signal Field

$$g \ a \ E_1 \cdot B_0$$



$$\nabla \cdot \mathbf{E} = -g_{a\gamma} \mathbf{B} \cdot \nabla a$$

$$\nabla \times \mathbf{B} = \partial_t \mathbf{E} - g_{a\gamma} (\mathbf{E} \times \nabla a - \mathbf{B} \partial_t a)$$

$$\nabla \cdot \mathbf{B} = 0$$

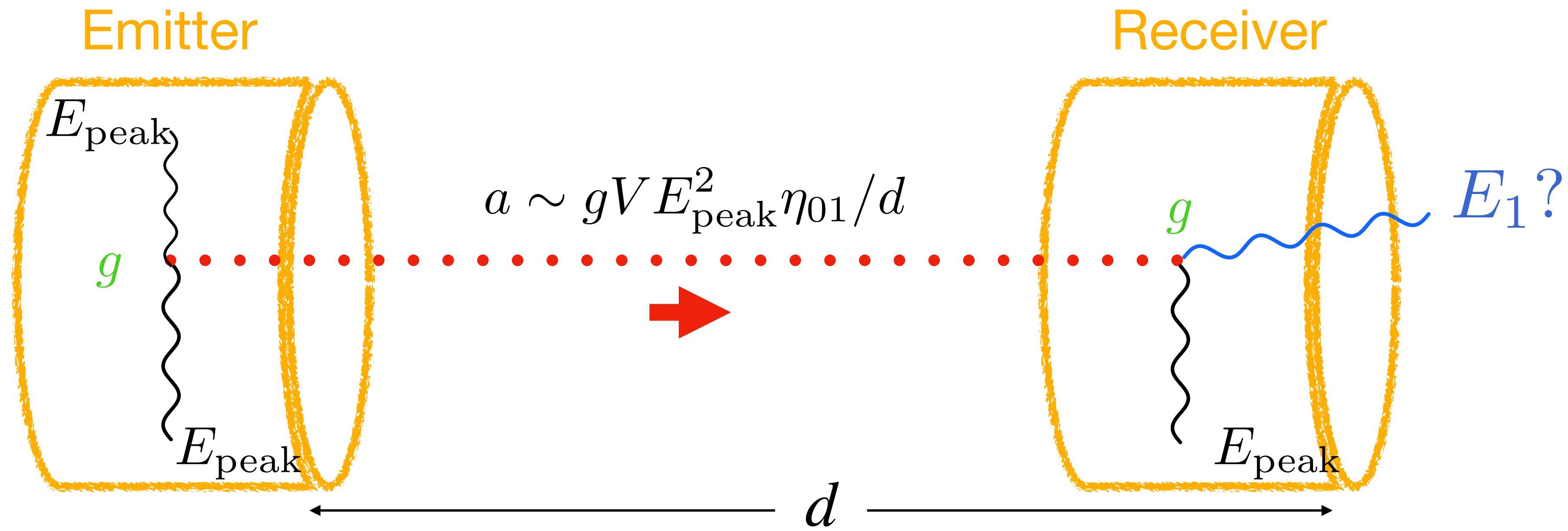
$$\nabla \times \mathbf{E} = -\partial_t \mathbf{B}$$

(under natural unit)



Signal Power

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

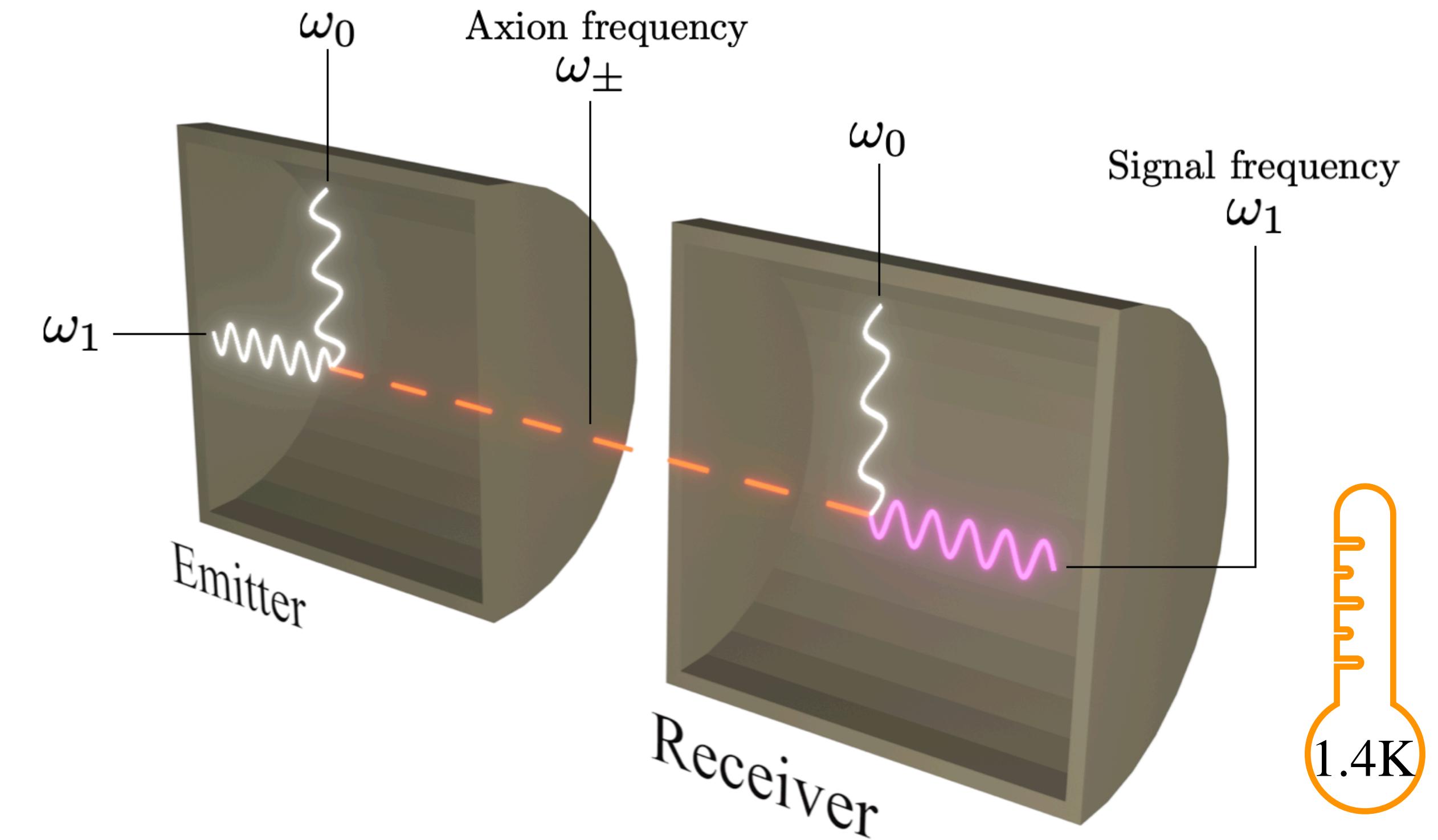


$$P_{\text{sig}} = \frac{\text{energy}}{\text{time}} = \frac{1}{\tau_1} \int_V |E_1|^2 \propto \frac{Q V^3 g^4 \eta_{01}^4 E_{\text{peak}}^6}{d^2}$$

Q = quality factor
 V = volume of cavity
 η_{01} = geometric factor
 E_{peak} = field amplitude

Experimental Setup

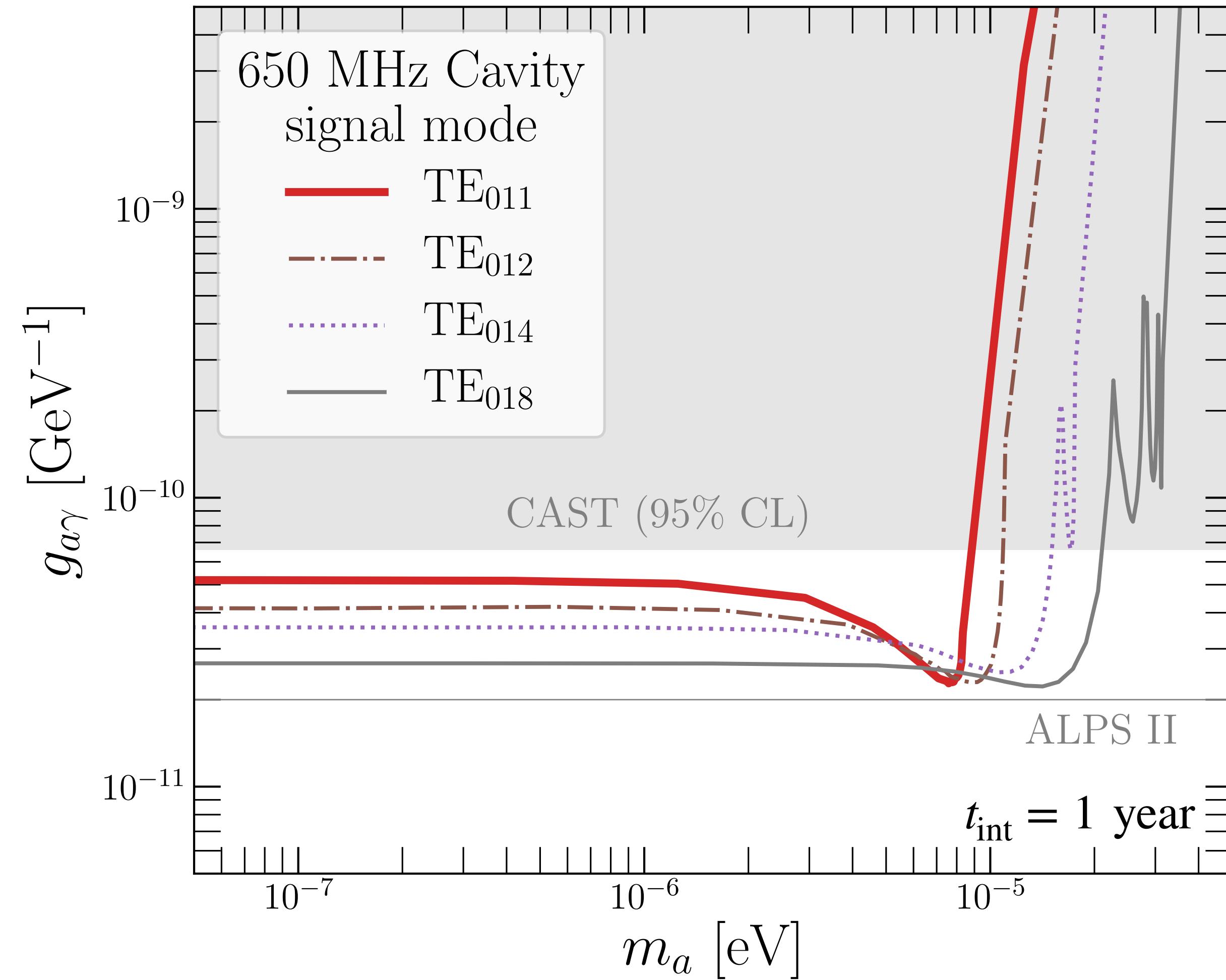
- ♦ Fundamental frequency: 650 MHz
- ♦ Quality factor $Q = 10^{10}$
- ♦ $E_{\text{peak}} = 80 \text{ MVm}^{-1}$ (or 0.26 Tesla) for all active modes



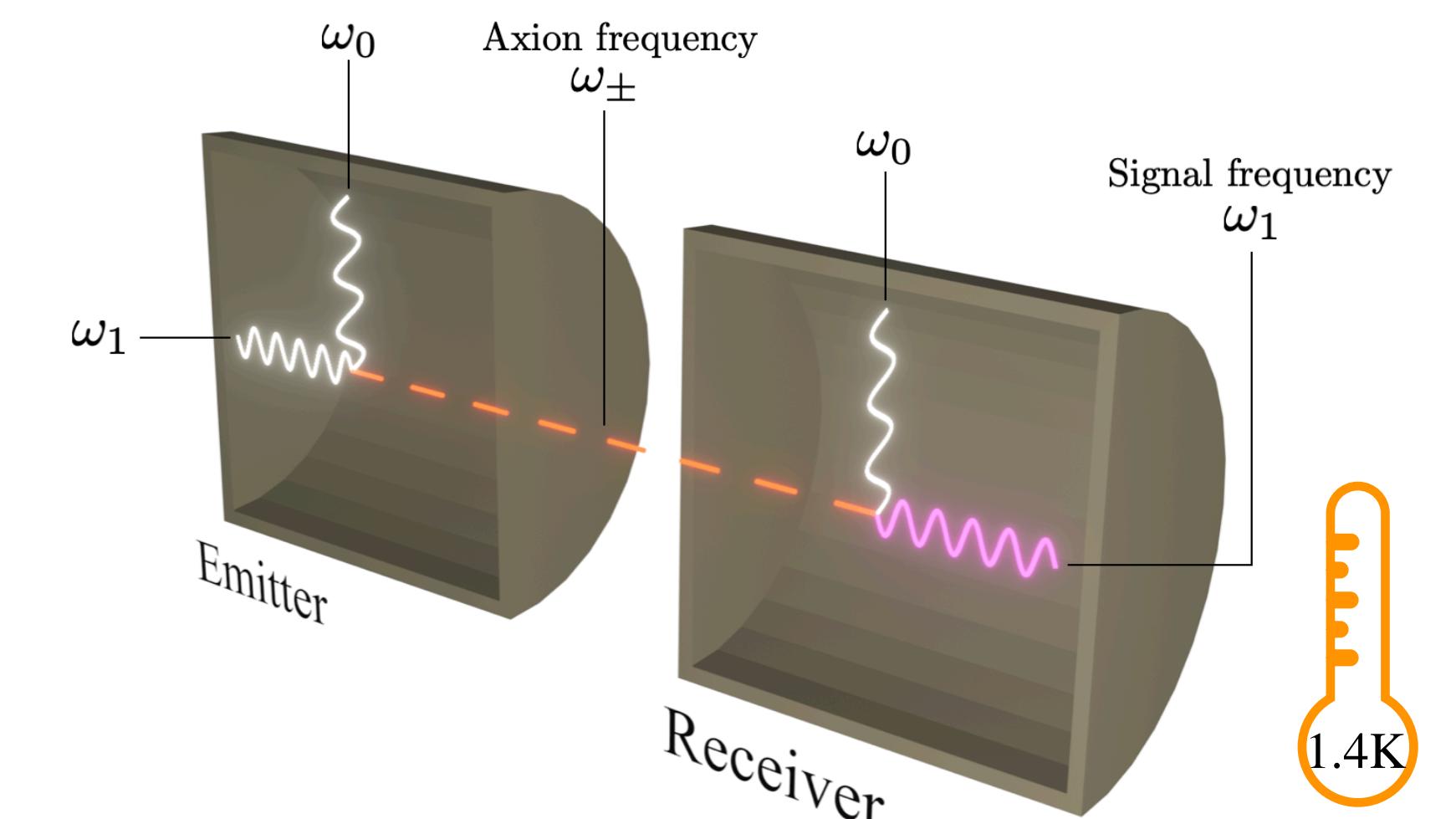
$$\text{SNR} = \frac{P_{\text{sig}}}{P_{\text{bkg}}} \sqrt{t_{\text{int}} \Delta \omega_1}$$

$$P_{\text{bkg}} = \omega_1 \left(\frac{1}{2} + \frac{1}{e^{\frac{\omega_1}{kT}} - 1} \right) \Delta \omega_1$$

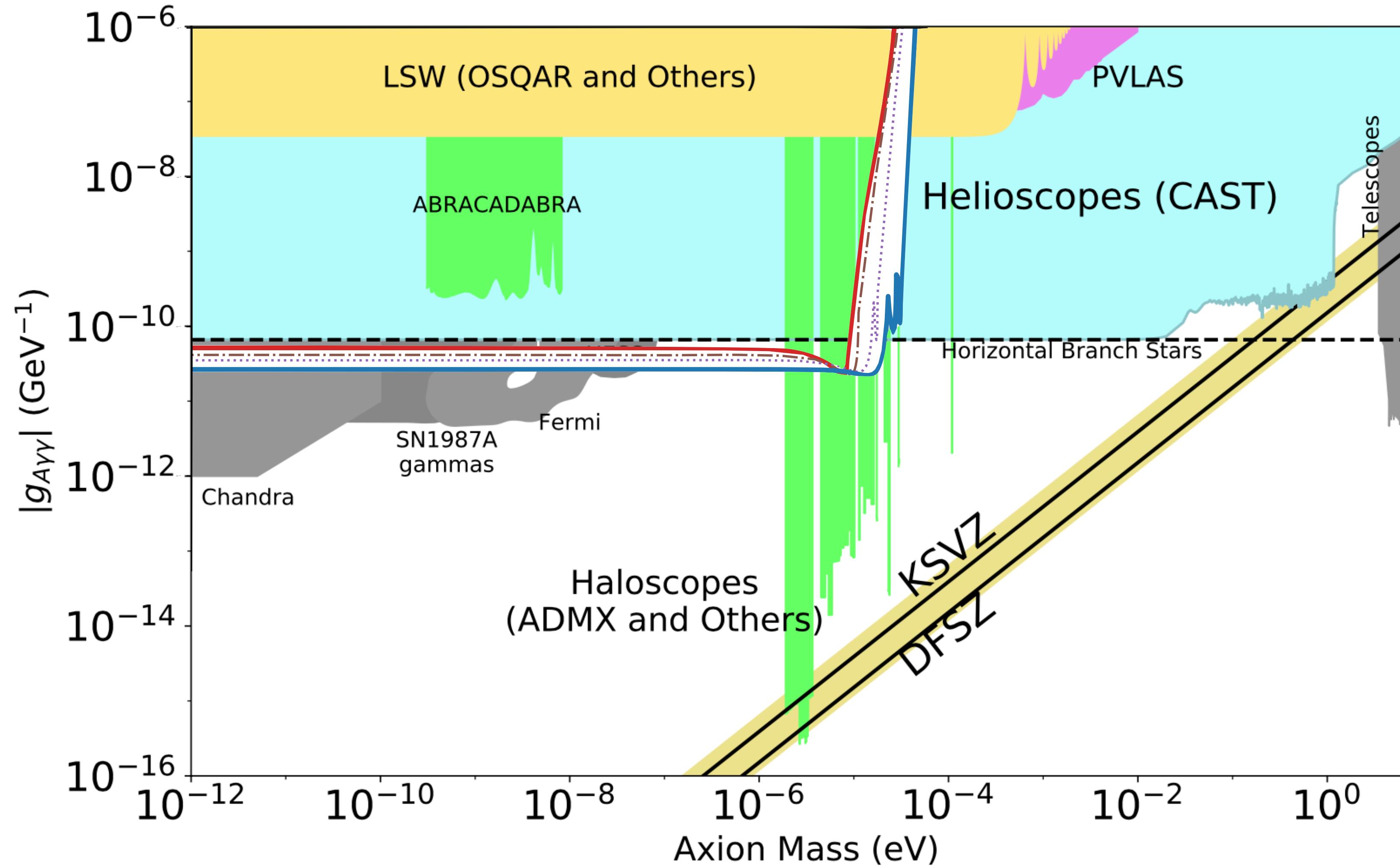
Sensitivity of the LSW Axion Search



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



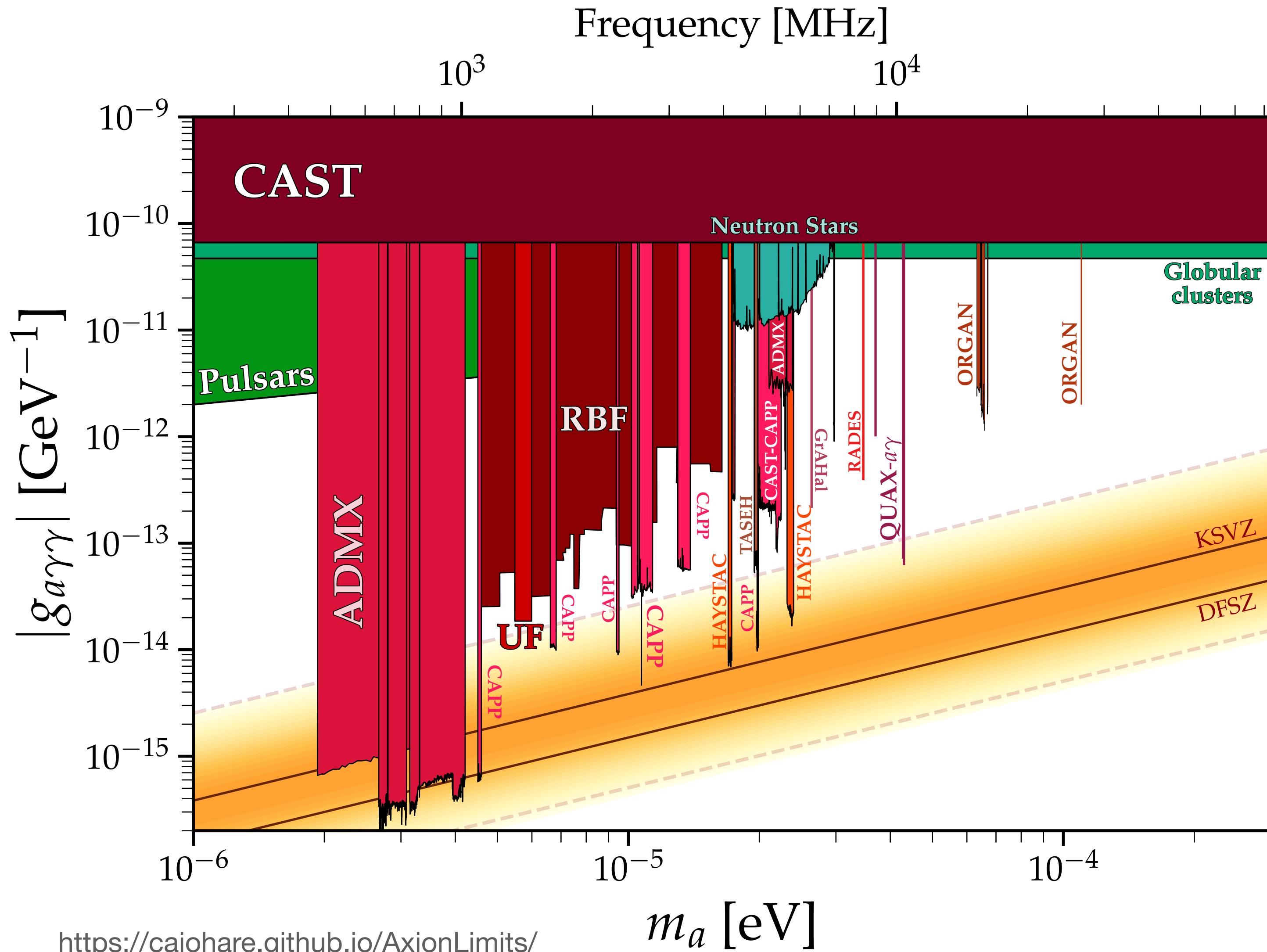
Sensitivity of the LSW Axion Search



Entangled Sensor Network for Axion DM Searches

CG, R. Harnik, Z. Liu,
Q. Zhuang, A. J. Brady, Z. Zhang,
PRX Quantum (2022)

Axion Haloscope Experiments



<https://cajohare.github.io/AxionLimits/>

$$a_{\text{DM}}(t) \sim a_0 \cos \left((m_a + \frac{1}{2} m_a v^2) t \right)$$

$$v \sim 10^{-3} \rightarrow Q_a \sim 10^6$$

- ◆ DM m_a unknown
- ◆ Signal bandwidth small
- ◆ Requires high scan rate



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Scan Rate for Axion DM

$$\frac{d\omega}{dt} \propto \left(\frac{1}{\text{SNR}} \right)^2$$

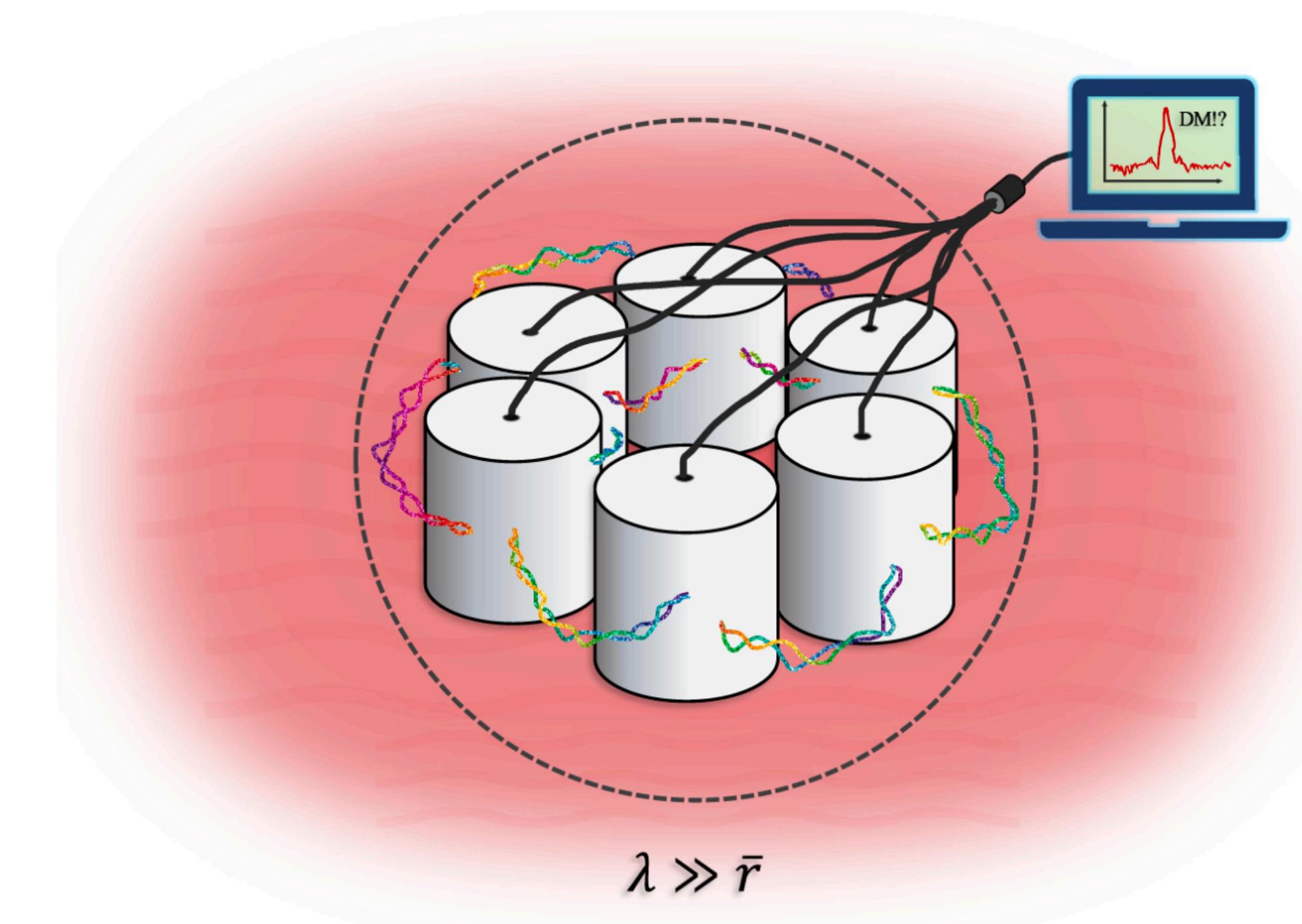
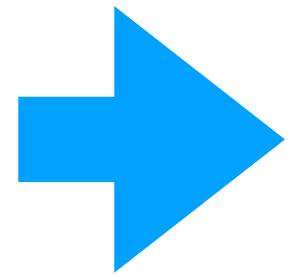
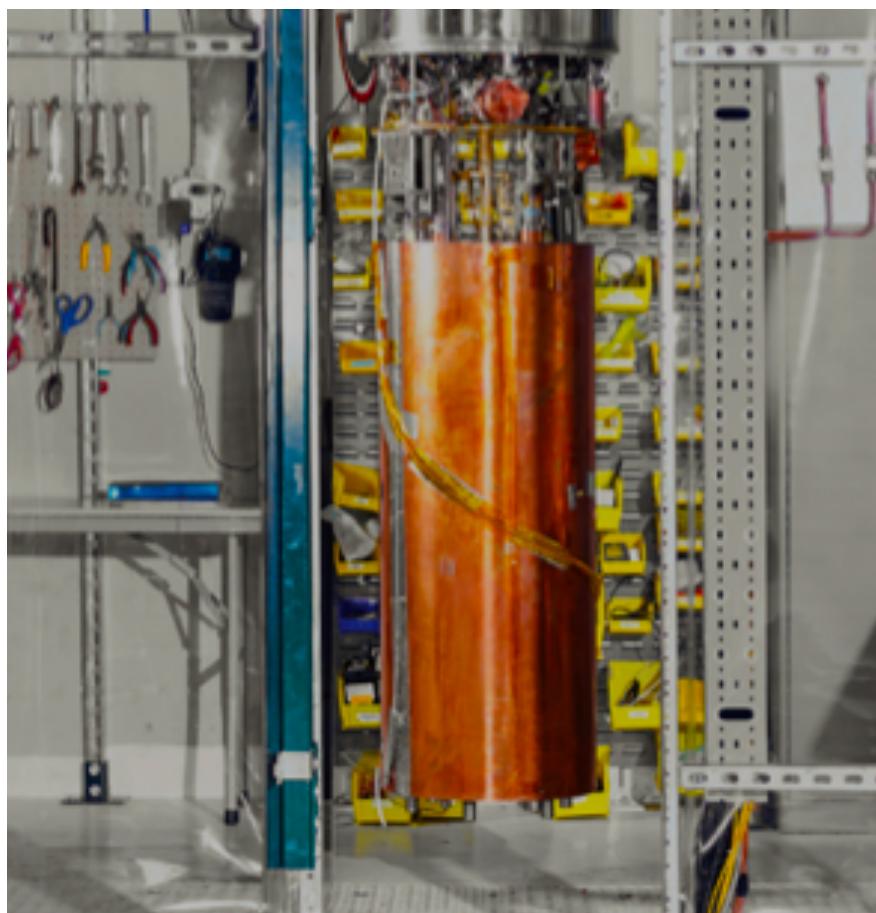
$$\text{SNR} = \frac{P_{\text{sig}}}{P_{\text{bkg}}} \sqrt{t_{\text{int}} B_s}$$

$$P_{\text{bkg}} = \omega_1 \left(\frac{1}{2} + \frac{1}{e^{\frac{\omega_1}{kT}} - 1} \right) B_s$$

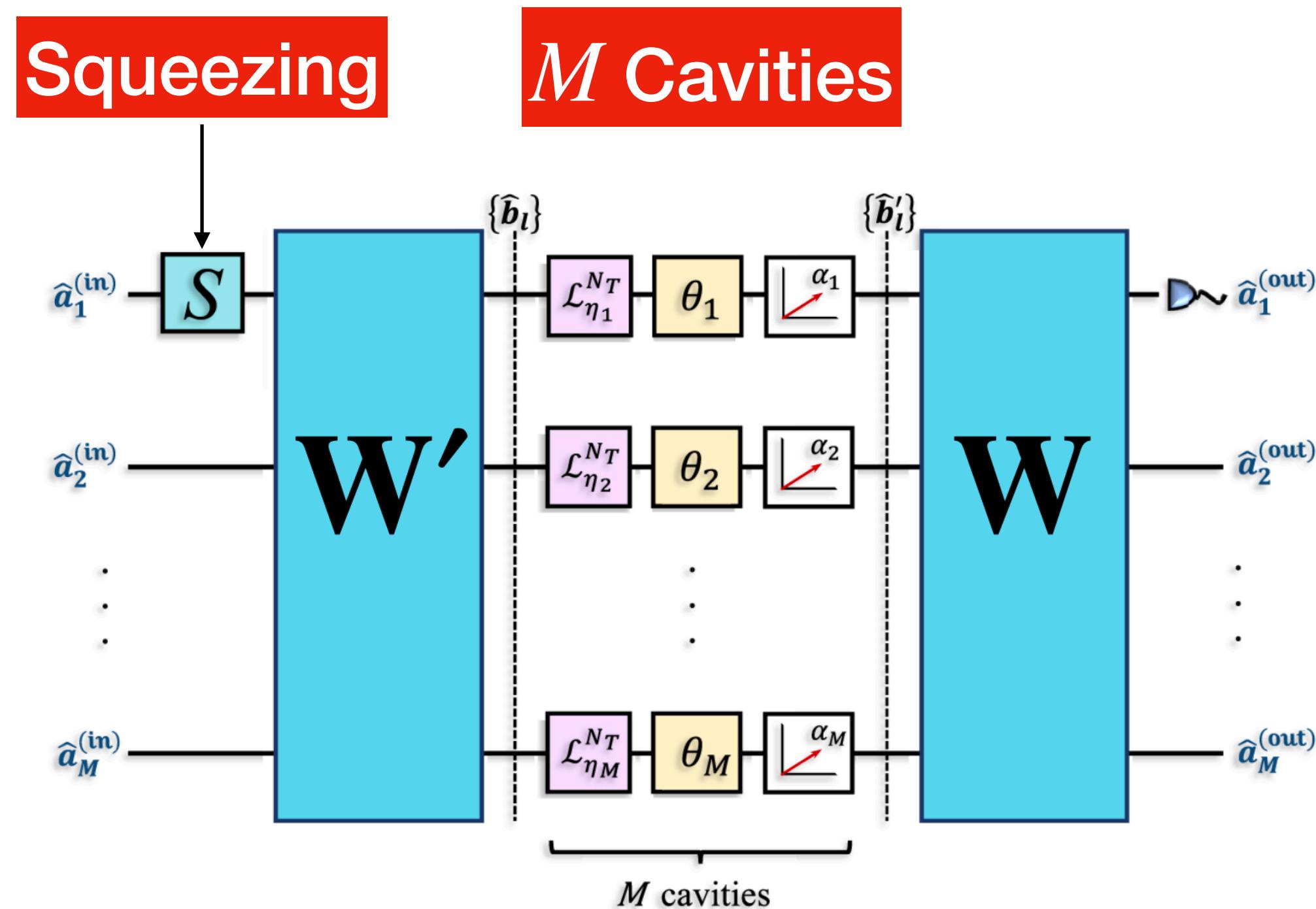
- ◆ To improve scan rate requires
 - Want larger signal rate
 - Want lower background noise

Entangled Sensor Network for Axion DM Searches

CG, R. Harnik, Z. Liu,
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PRX Quantum (2022)



M Entangled Cavities



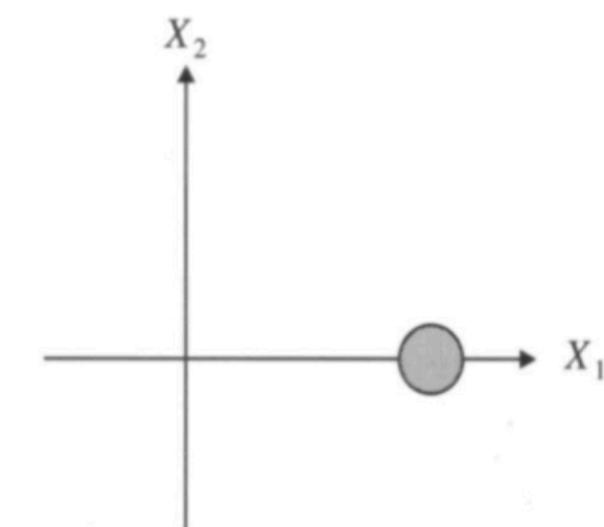
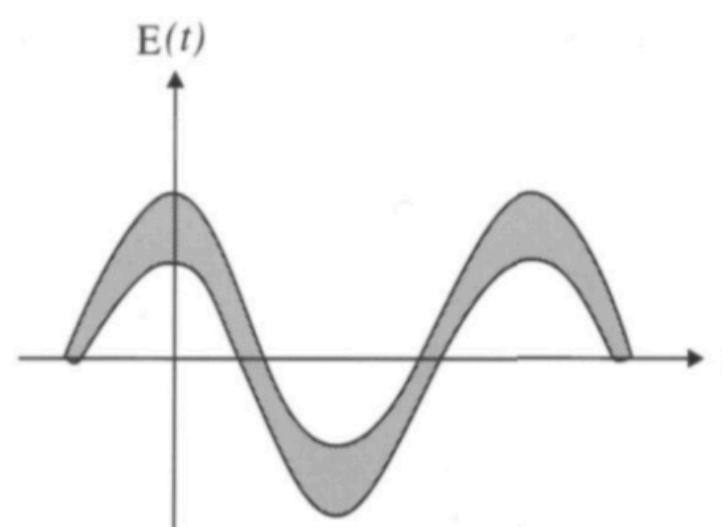
- ◆ Described by input-output theory for driven cavity
- ◆ W, W' = linear networks that couple M cavities in parallel
- ◆ Can add squeezed vacuum to the input

$$N_T \sim \frac{1}{2} + \frac{1}{e^{\frac{\omega}{kT}} - 1}$$

Squeezing

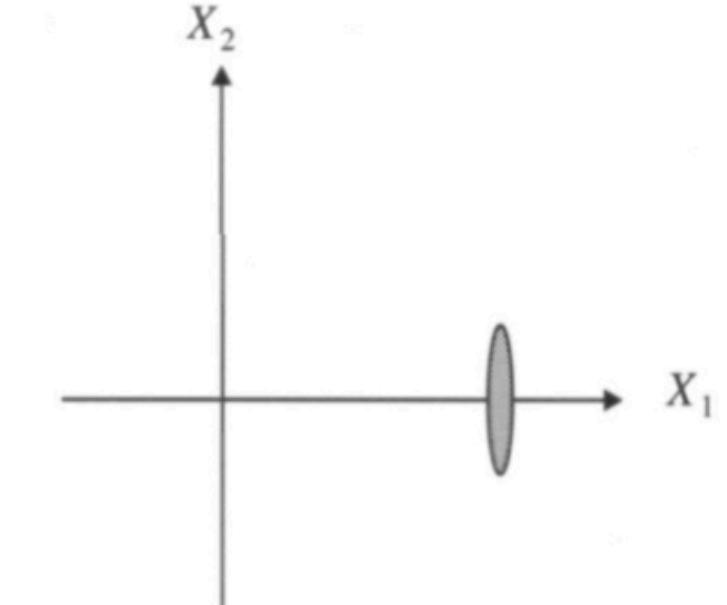
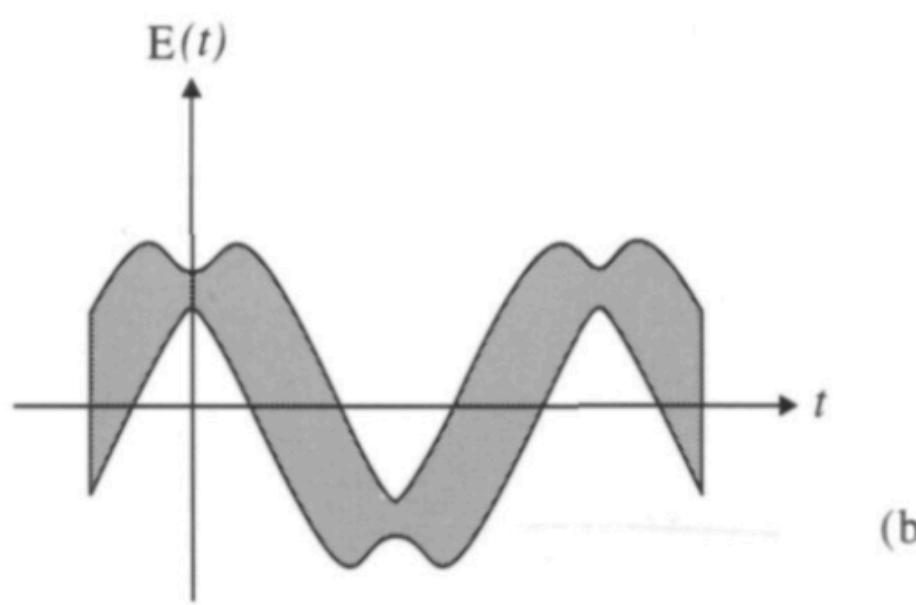
$$[X_1, X_2] = \frac{i}{2}$$

$$\Delta X_1 \Delta X_2 \geq \frac{1}{4}$$

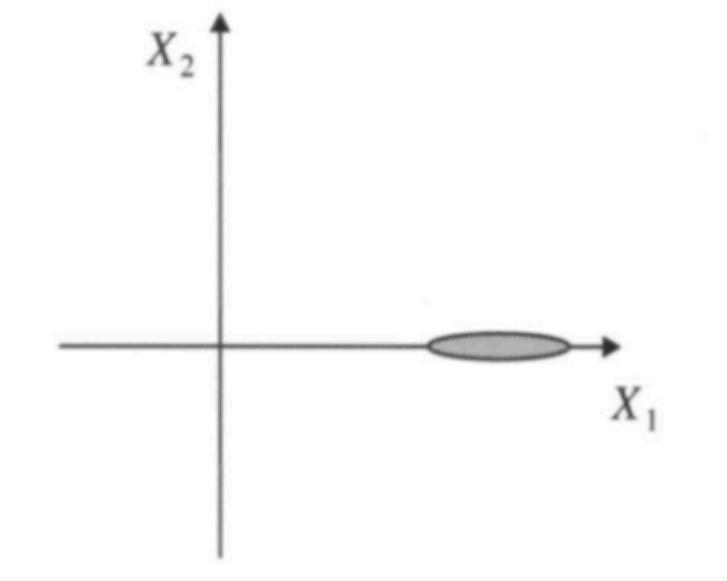
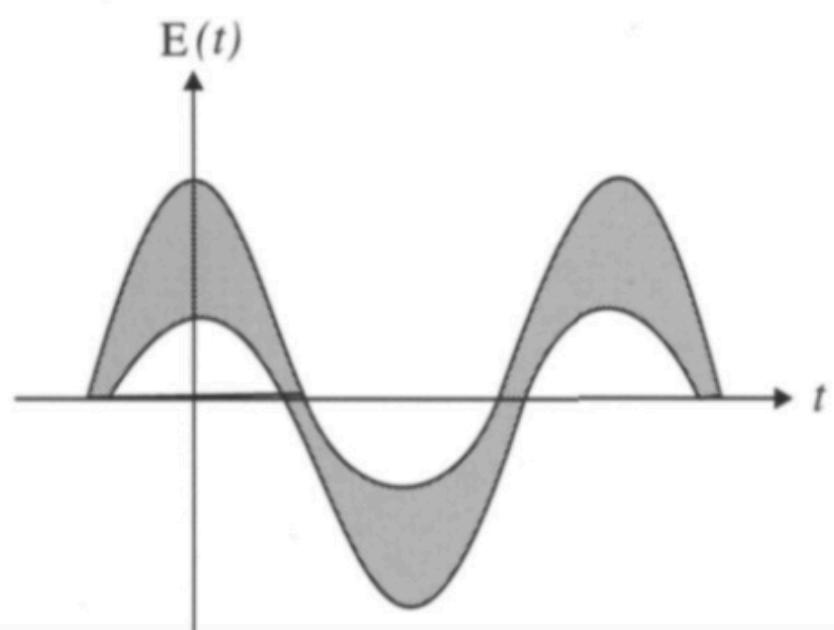


$$E(t) \sim X_1 \cos(\omega t) + X_2 \sin(\omega t)$$

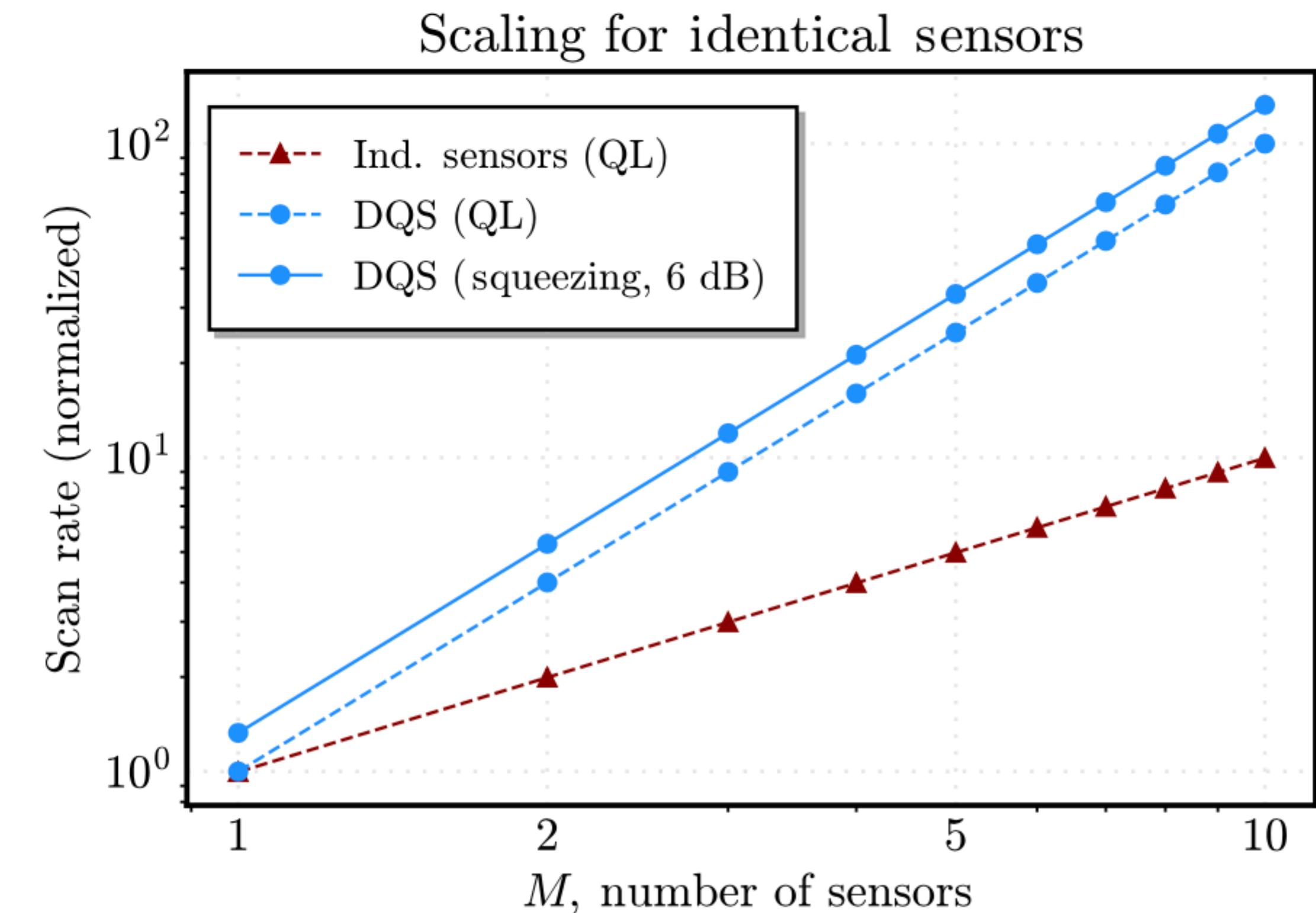
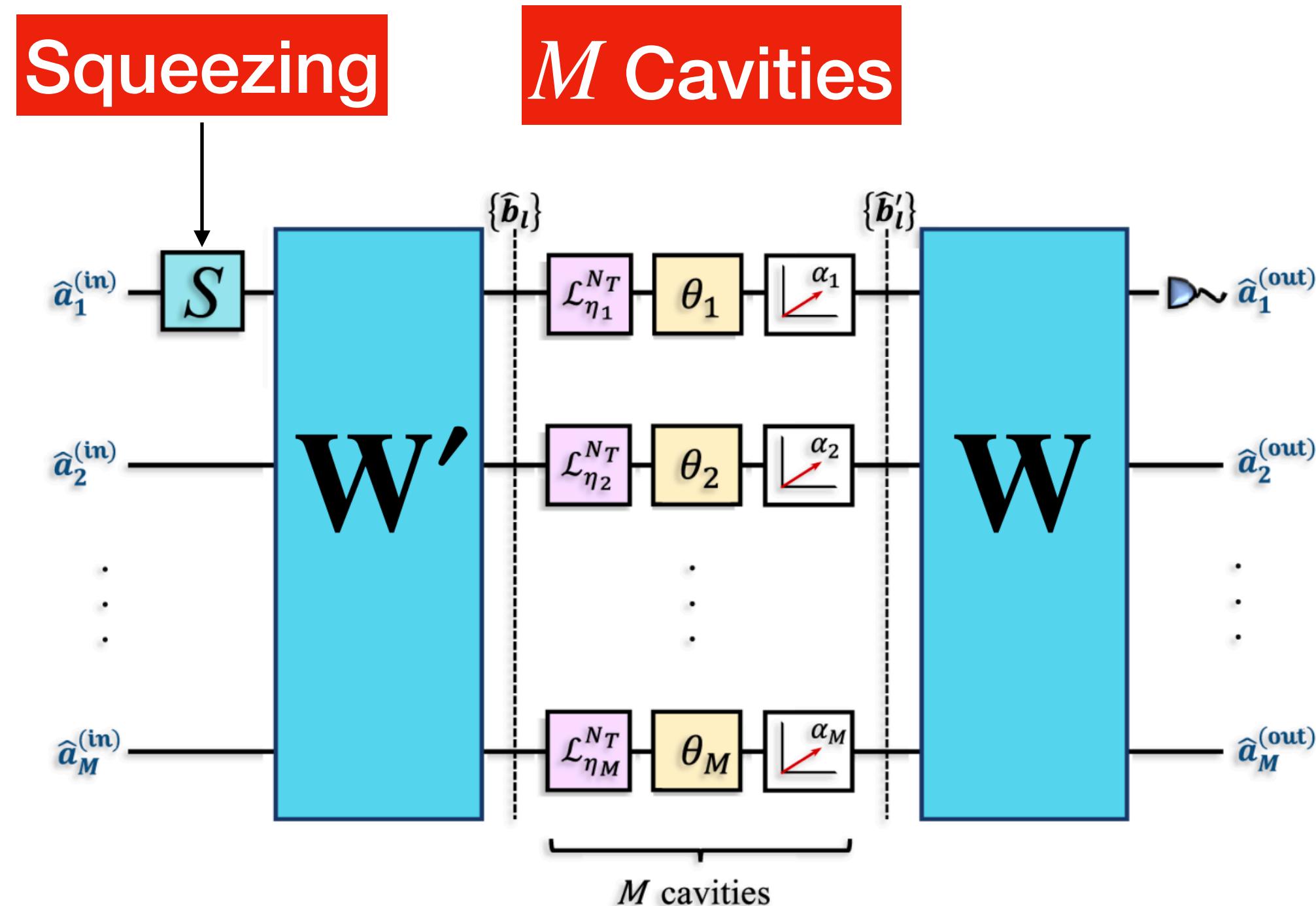
**Squeezing
ΔAmplitude**



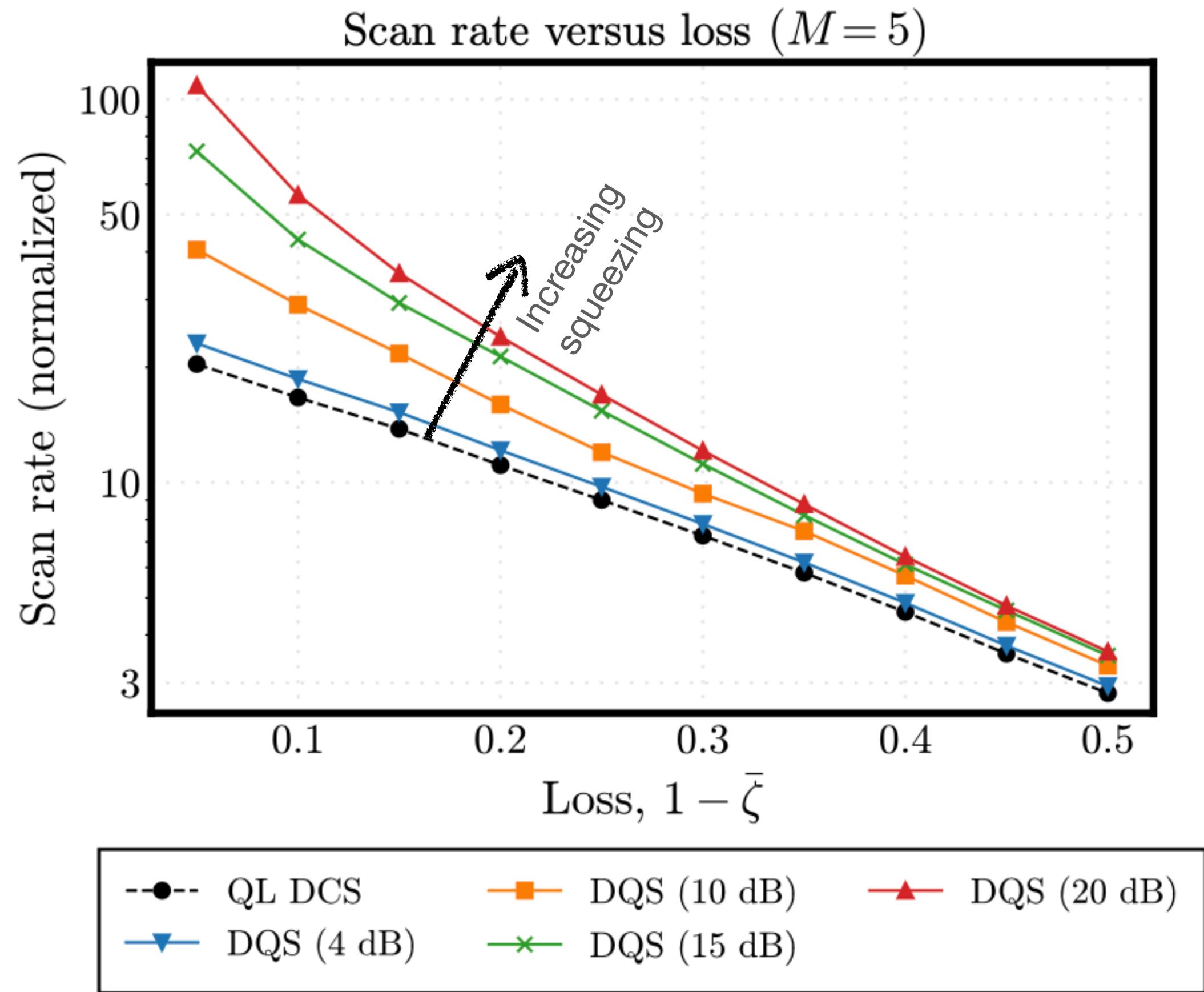
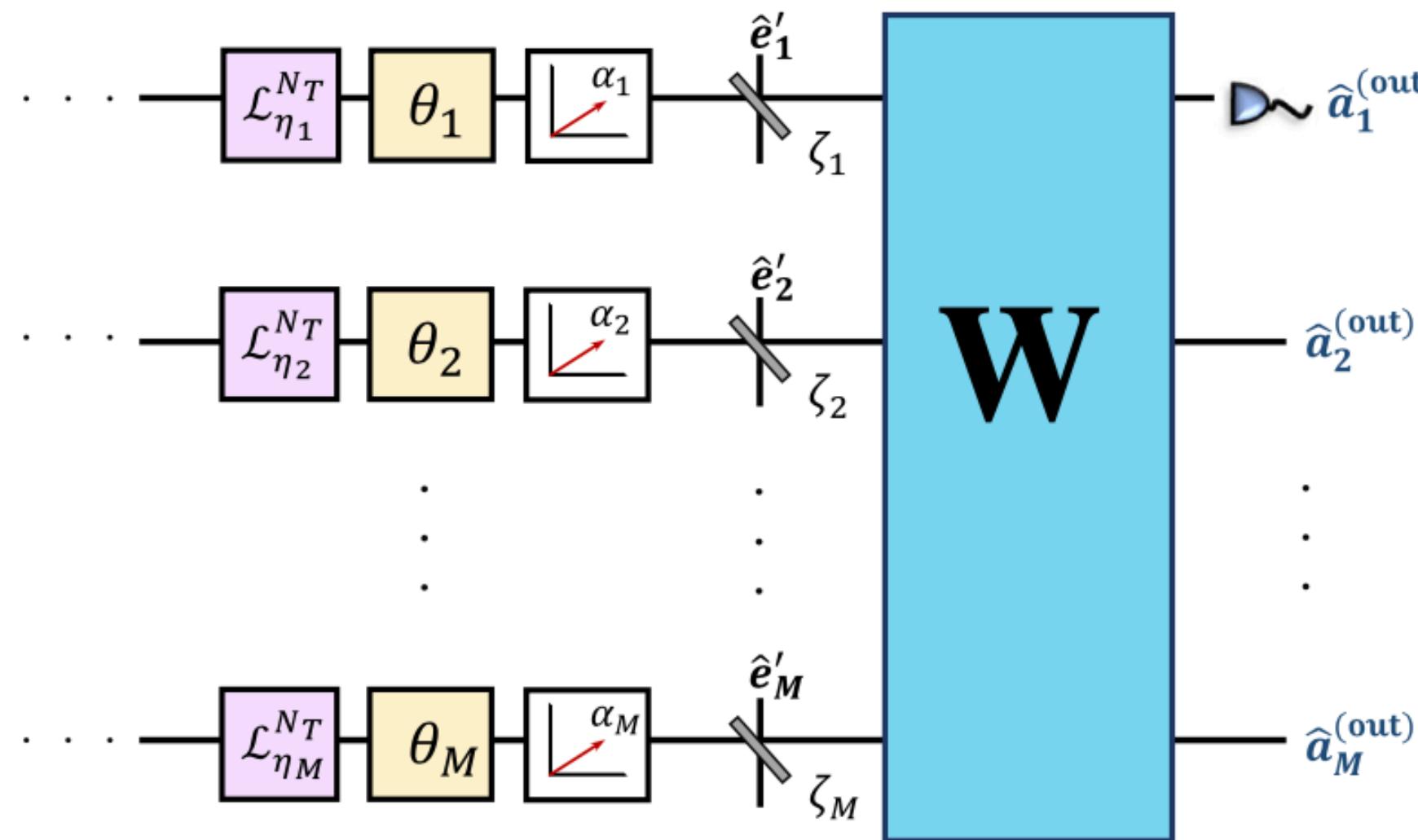
**Squeezing
ΔPhase**



M Entangled Cavities



Entangled Cavities with Losses

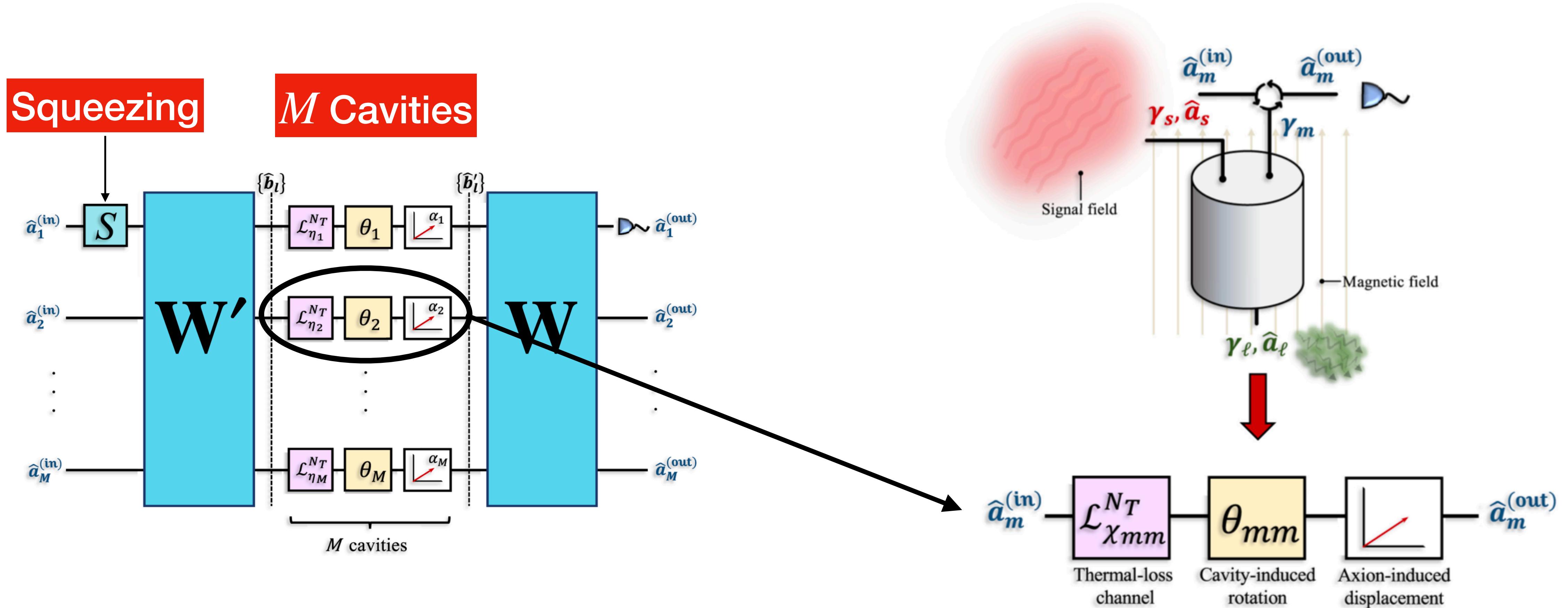


Conclusion

- With the axion-photon coupling, cavity based searches are sensitive to axion masses of 0.1 meV and below.
- LSW search is broadband and can be done using two high Q SRF cavities.
- A network of entangled cavities can increase the scan rate of axion DM search, thus improving the search efficiency.
- Quantum technologies, such as squeezing and entanglement, can benefit new physics searches.

Backups

M Entangled Cavities

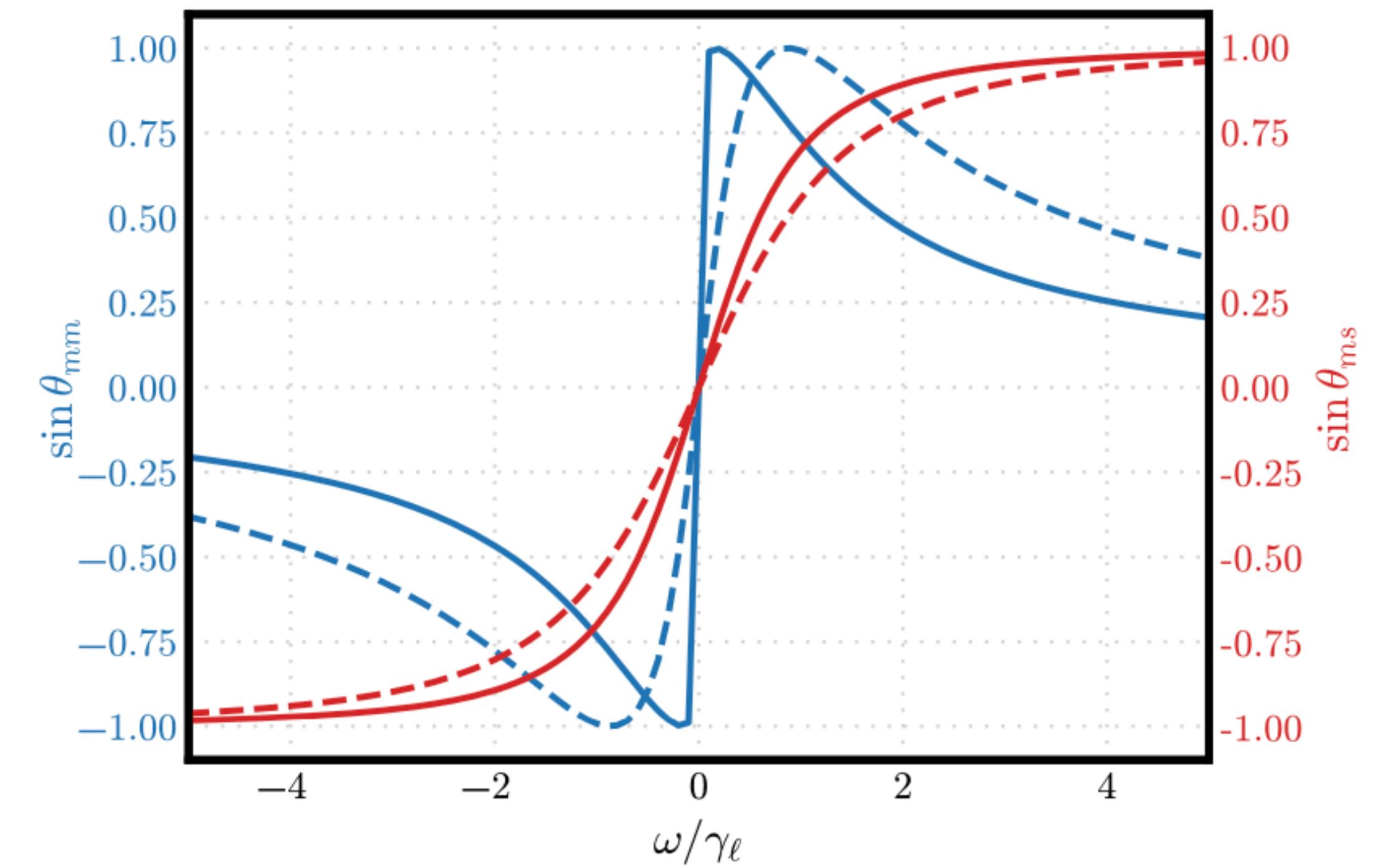
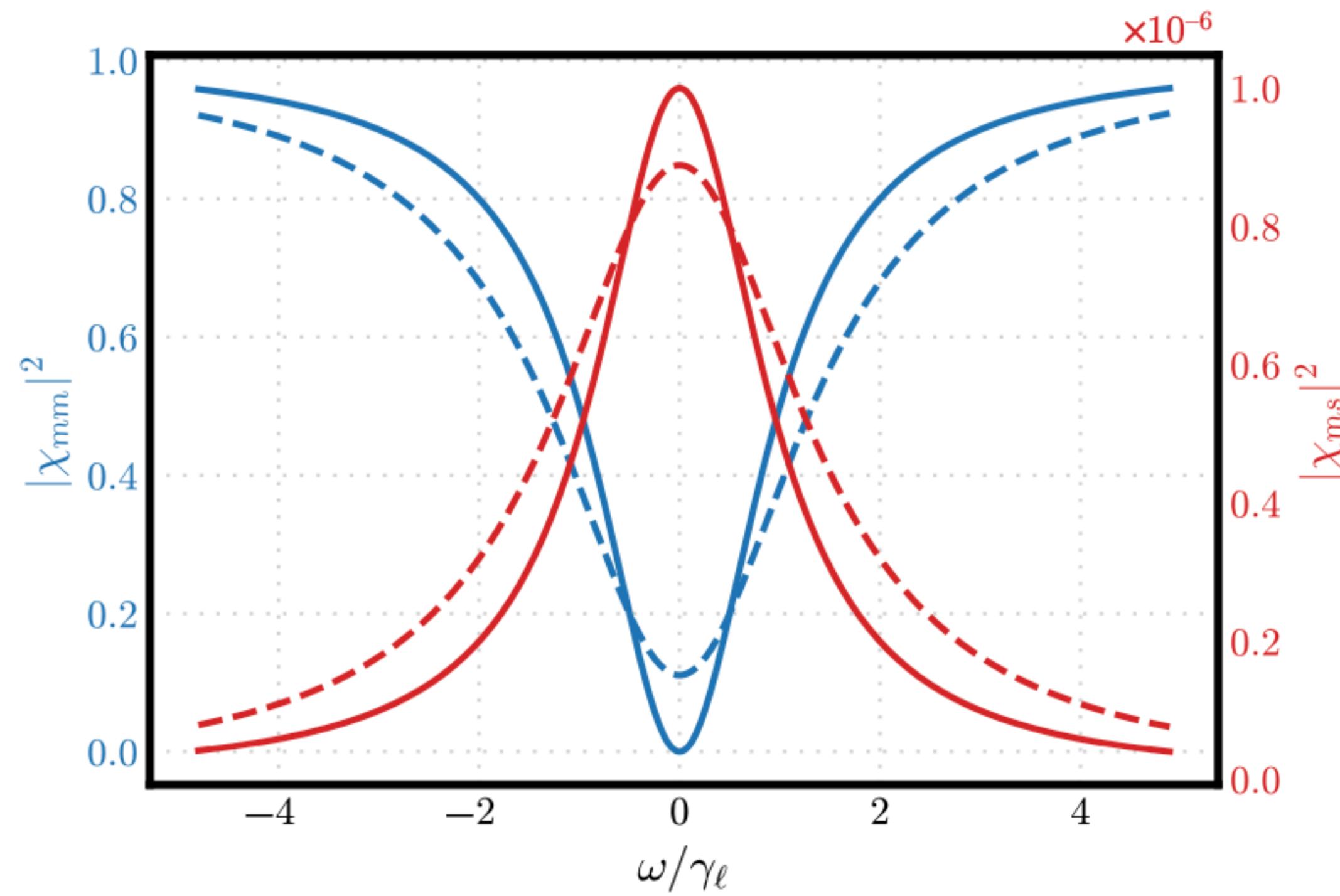


$$\frac{d\hat{a}_{\text{cav}}}{dt} = -\frac{\gamma}{2}\hat{a}_{\text{cav}} + \sum_{j=m,s,\ell} \sqrt{\gamma_j} \hat{a}_j^{(\text{in})} \quad \hat{a}_m^{(\text{out})} = \hat{a}_m^{(\text{in})} + \sqrt{\gamma_m} \hat{a}_{\text{cav}}$$

Susceptibility Matrix

$$\boldsymbol{\mu}_m^{(\text{out})} = |\chi_{mm}| \mathbf{0}(\theta_{mm}) \boldsymbol{\mu}_m^{(\text{in})} + |\chi_{ms}| \mathbf{O}(\theta_{ms}) \boldsymbol{\mu}_s$$

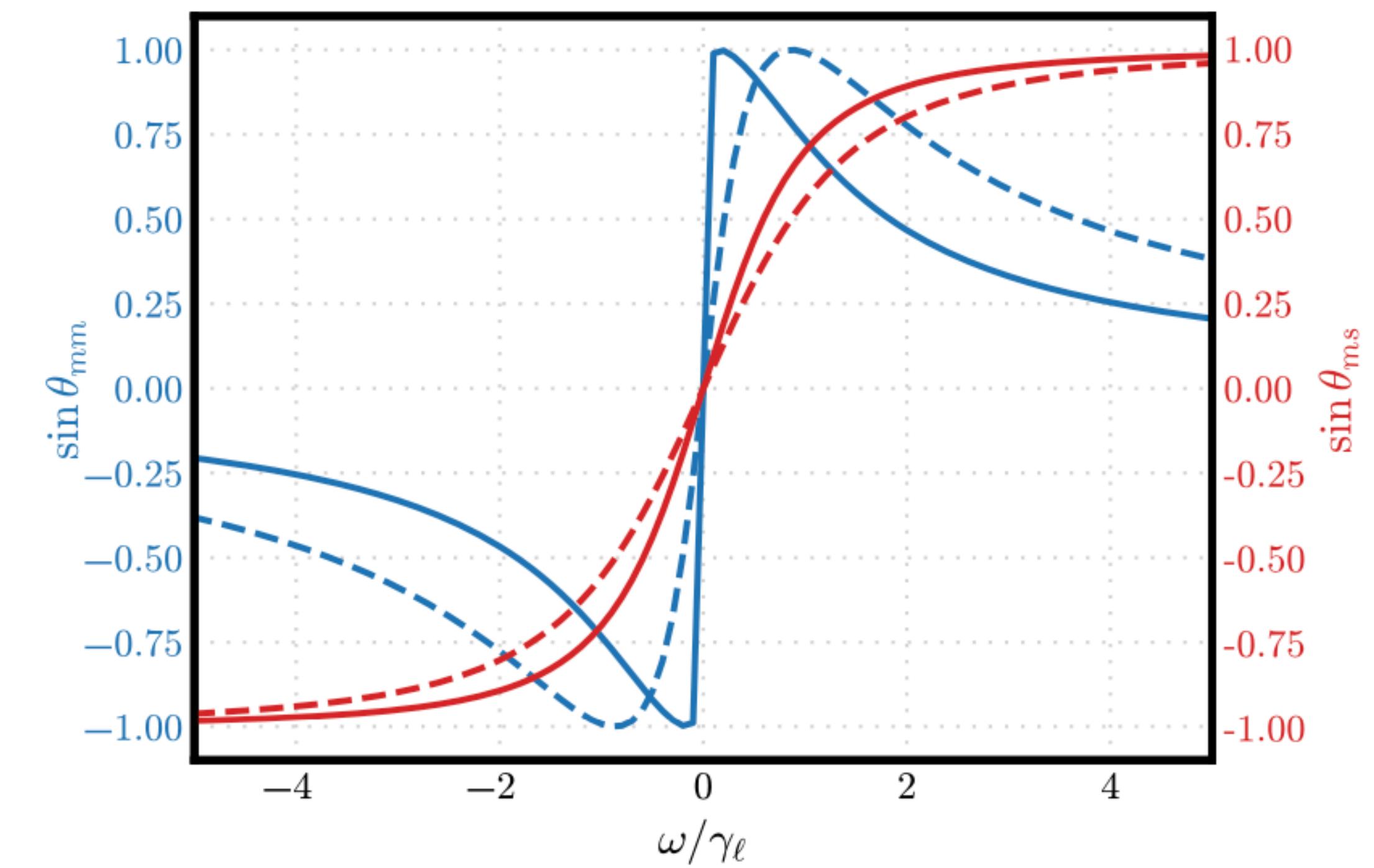
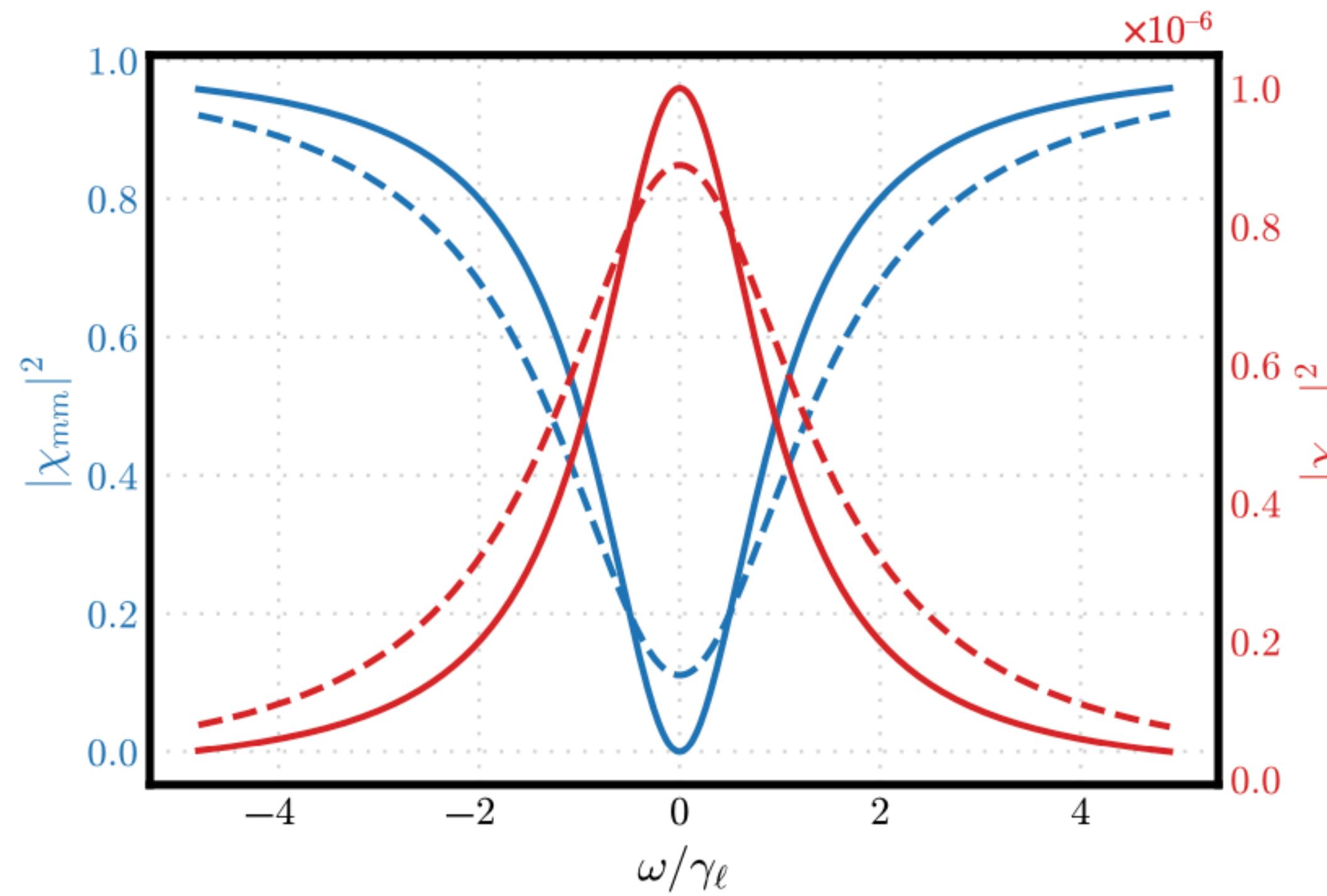
$$\boldsymbol{\sigma}_m^{(\text{out})} = |\chi_{mm}|^2 \mathbf{0}(\theta_{mm}) \boldsymbol{\sigma}_m^{(\text{in})} \mathbf{0}(\theta_{mm})^\top + N_T (1 - |\chi_{mm}|^2) \mathbb{I}_2$$



Squeezing

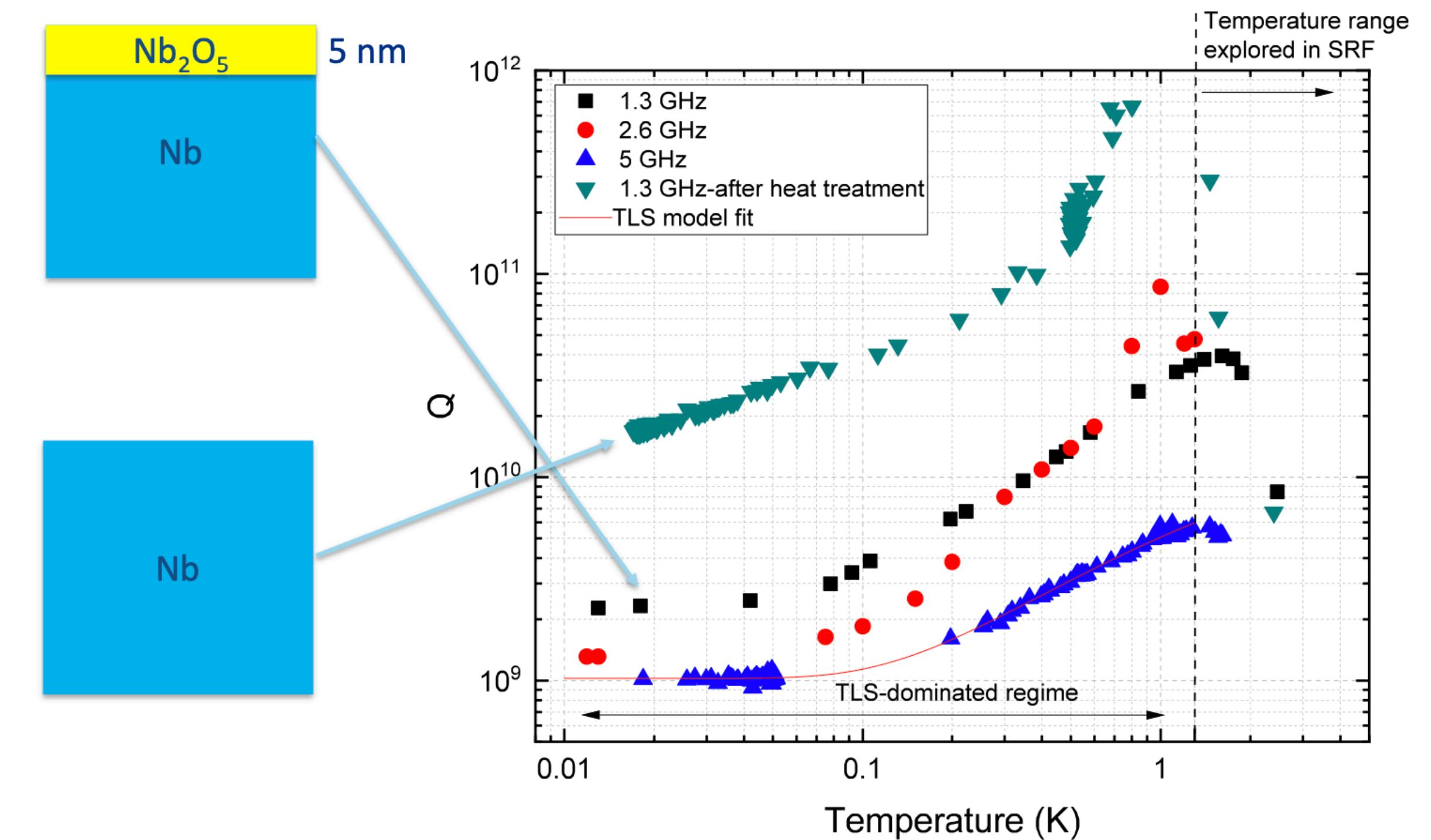
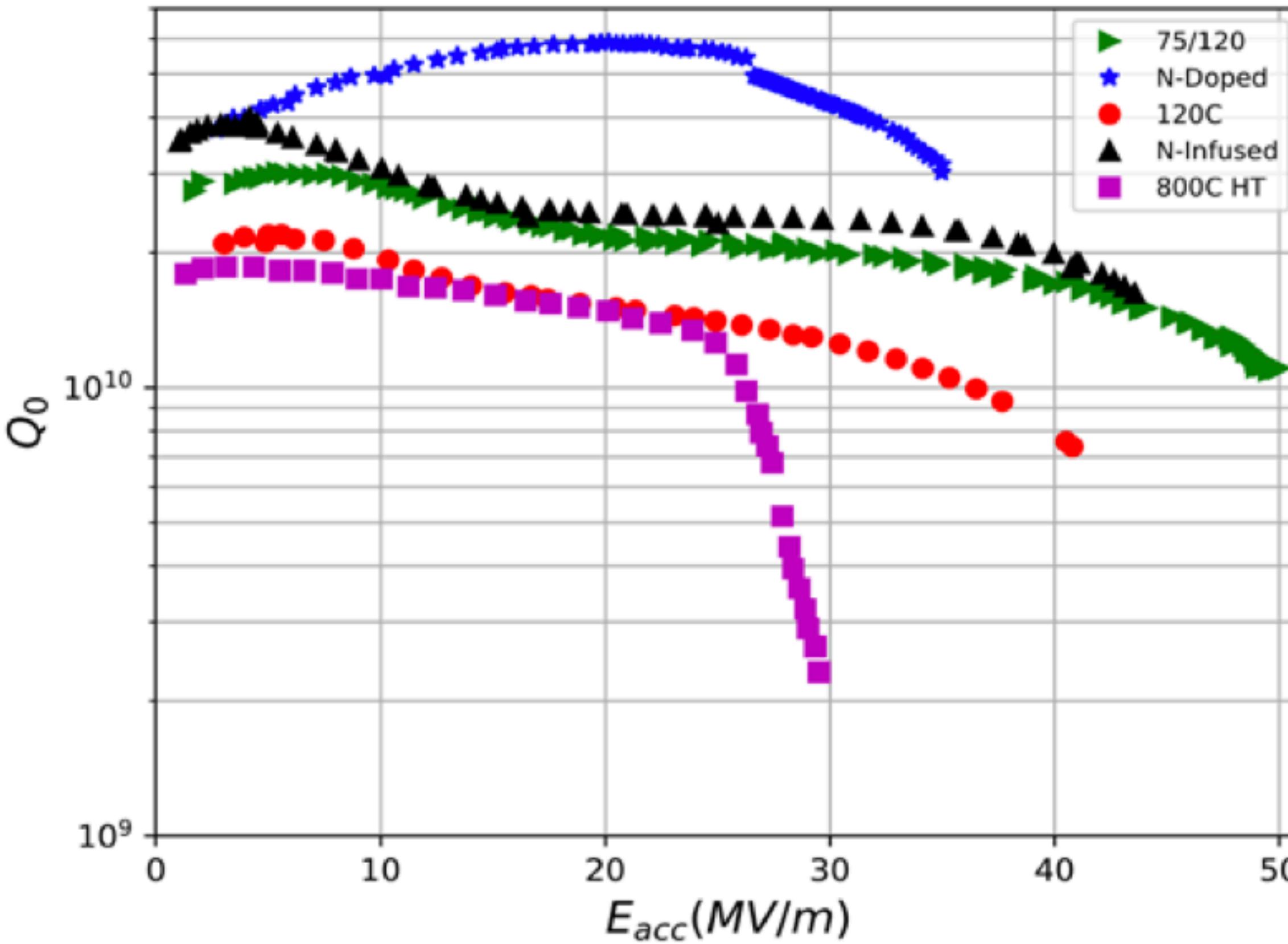
$$\boldsymbol{\mu}_m^{(f)} = |\chi_{ms}| \text{diag}(G, 1/G) \mathbf{O}(\theta_{ms}) \boldsymbol{\mu}_s$$

$$\boldsymbol{\sigma}_m^{(f)} = N_T |\chi_{mm}|^2 \mathbb{I}_2 + N_T (1 - |\chi_{mm}|^2) \text{diag}(G, 1/G)$$



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>