Dark Matter Searches on a Photonic Chip

Christina Gao DPF-PHENO 2024

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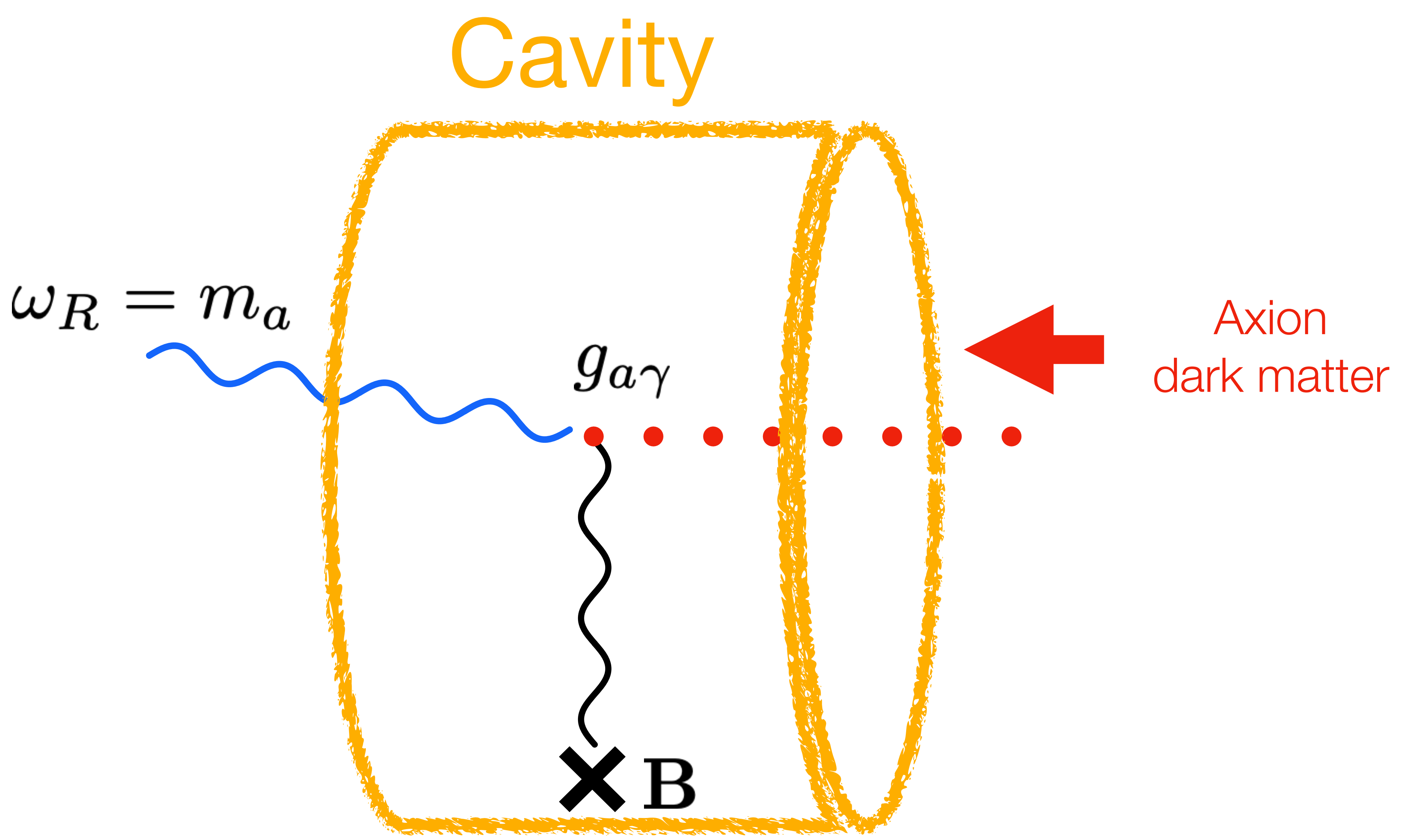
N. Blinov (York University);
N. Sinclair (Harvard)

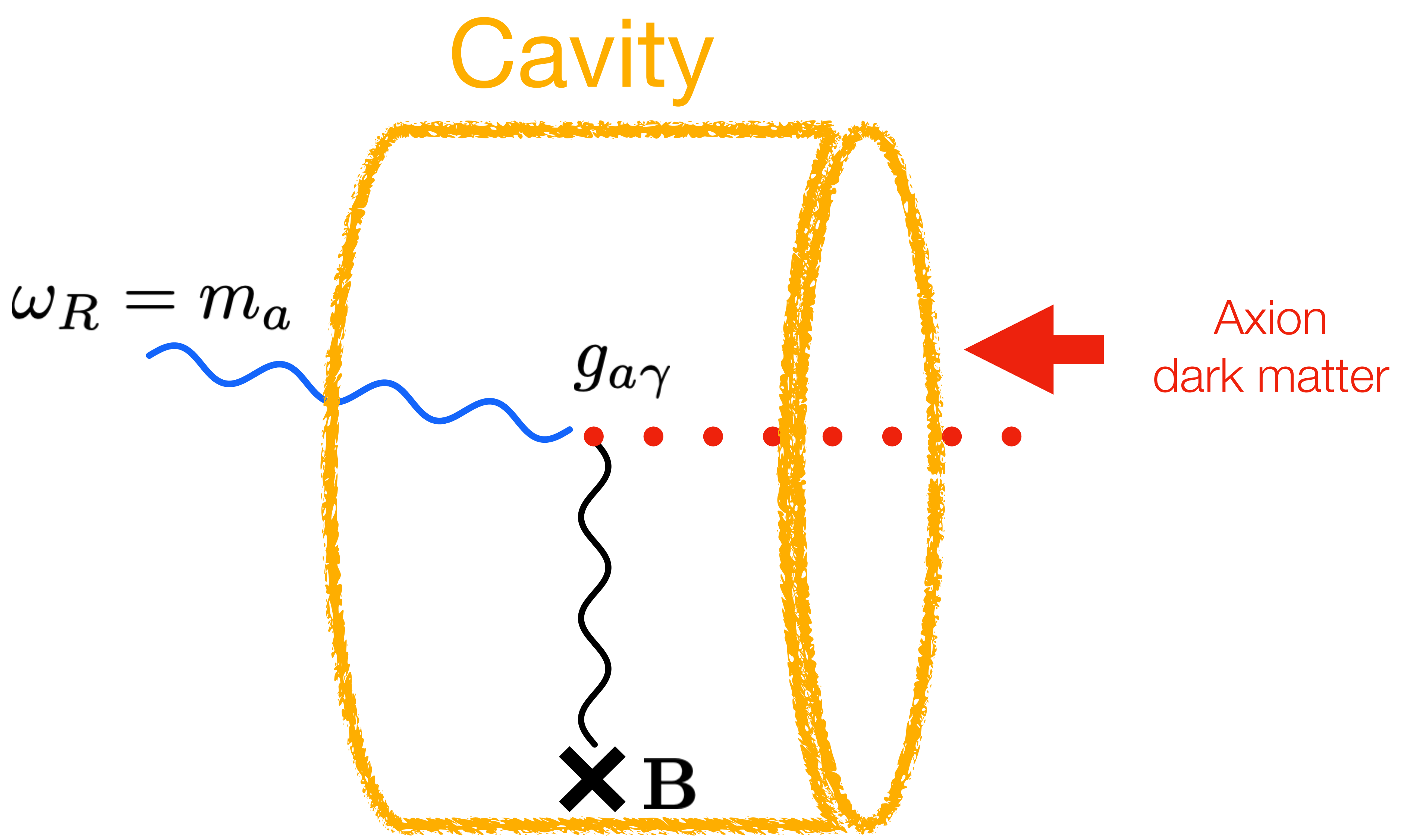
arXiv:2401.17260

Dark Matter Detection using Cavities



Axion	$g_{a\gamma} a \mathbf{E} \cdot \mathbf{B}$
Dark photon	$\frac{1}{2} \chi F'_{\mu\nu} F_{\mu\nu}$

Dark Matter Detection using Cavities



Axion $g_{a\gamma} a \mathbf{E}\cdot\mathbf{B}$

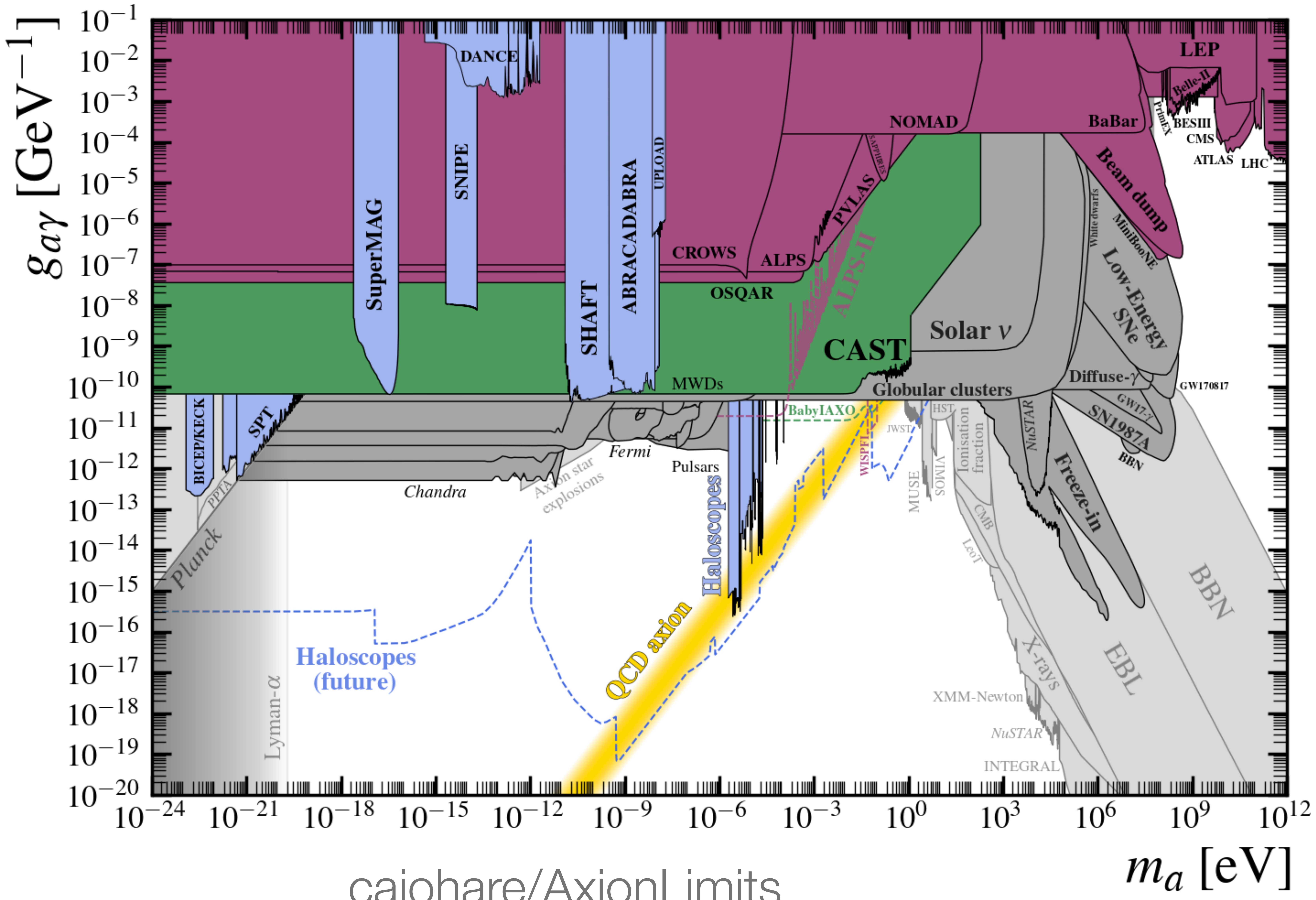
Dark photon $\frac{1}{2}\chi F'_{\mu\nu}F_{\mu\nu}$

quality factor

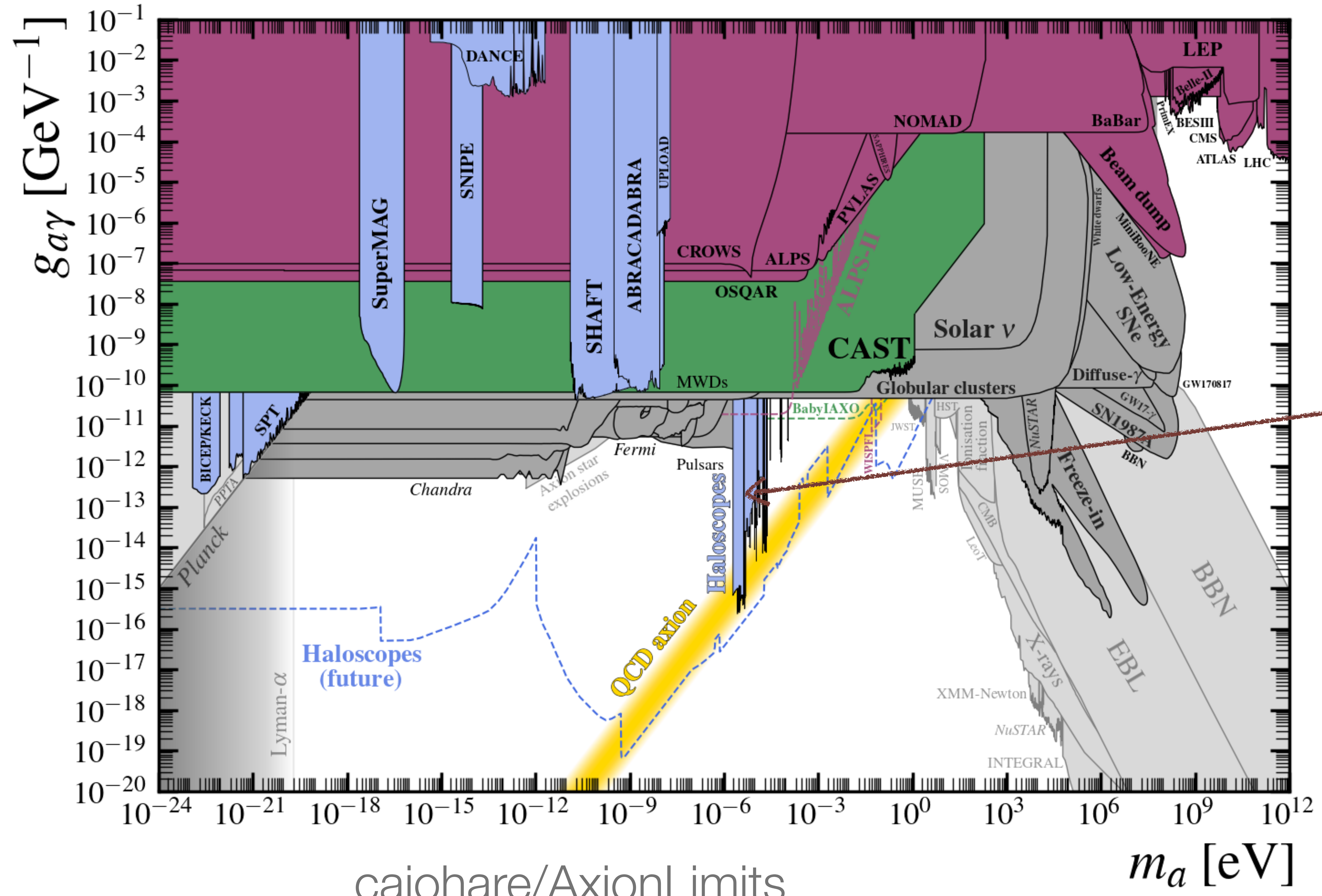
effective DM current

$$P_{\rm sig} \simeq \frac{Q}{m_{\rm D}} J_{\rm D}^2 |\eta|^2 V$$

momentum conservation

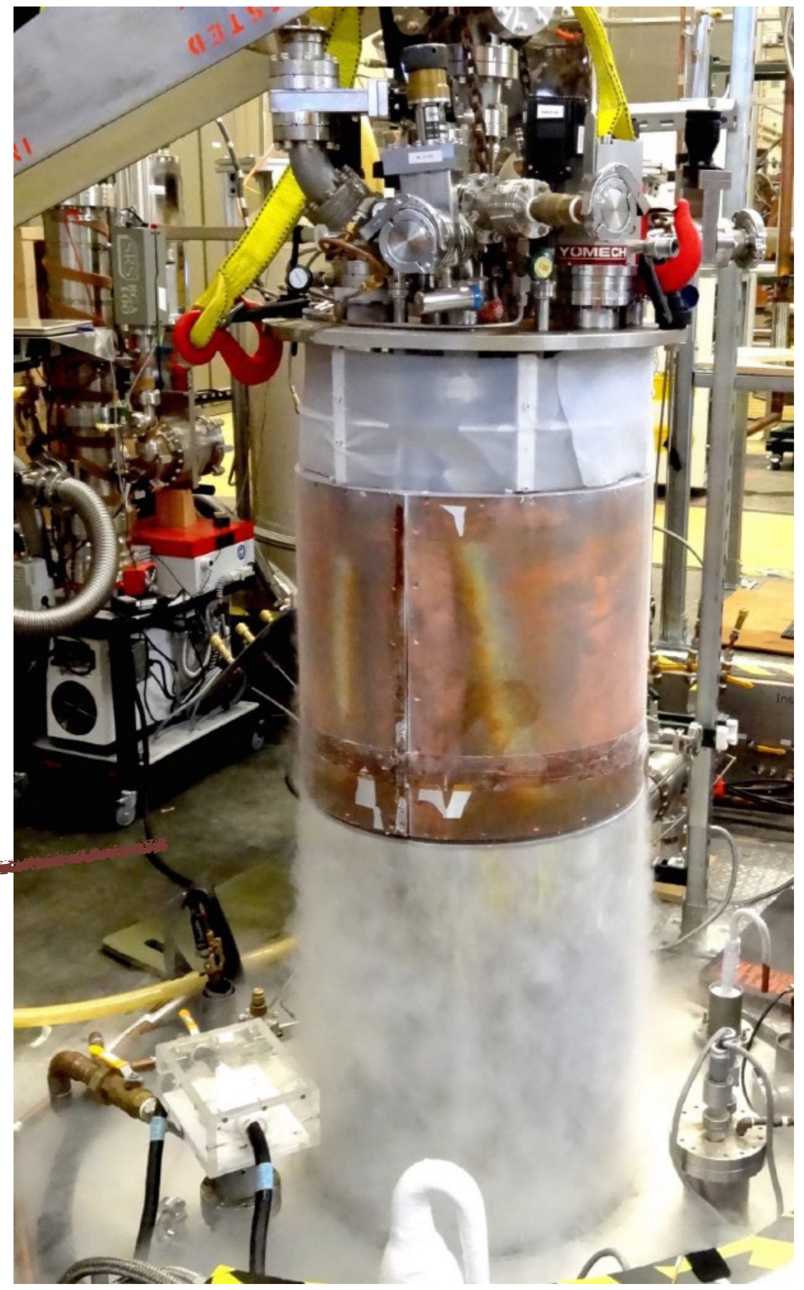


cajohare/AxionLimits



cajohare/AxionLimits

https://news.fnal.gov/2019/11/admx-experiment-places-worlds-best-constraint-on-dark-matter-axions/



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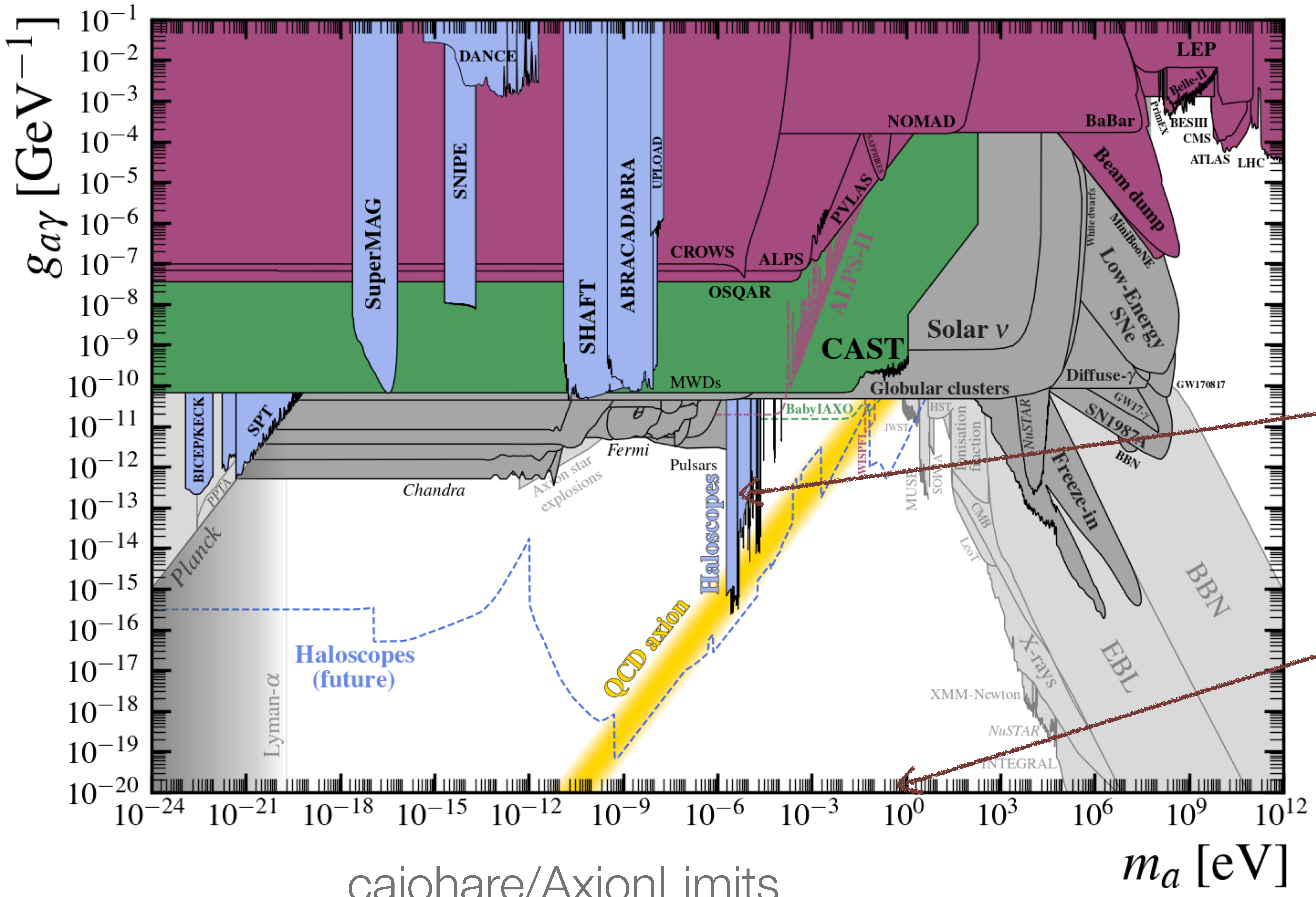
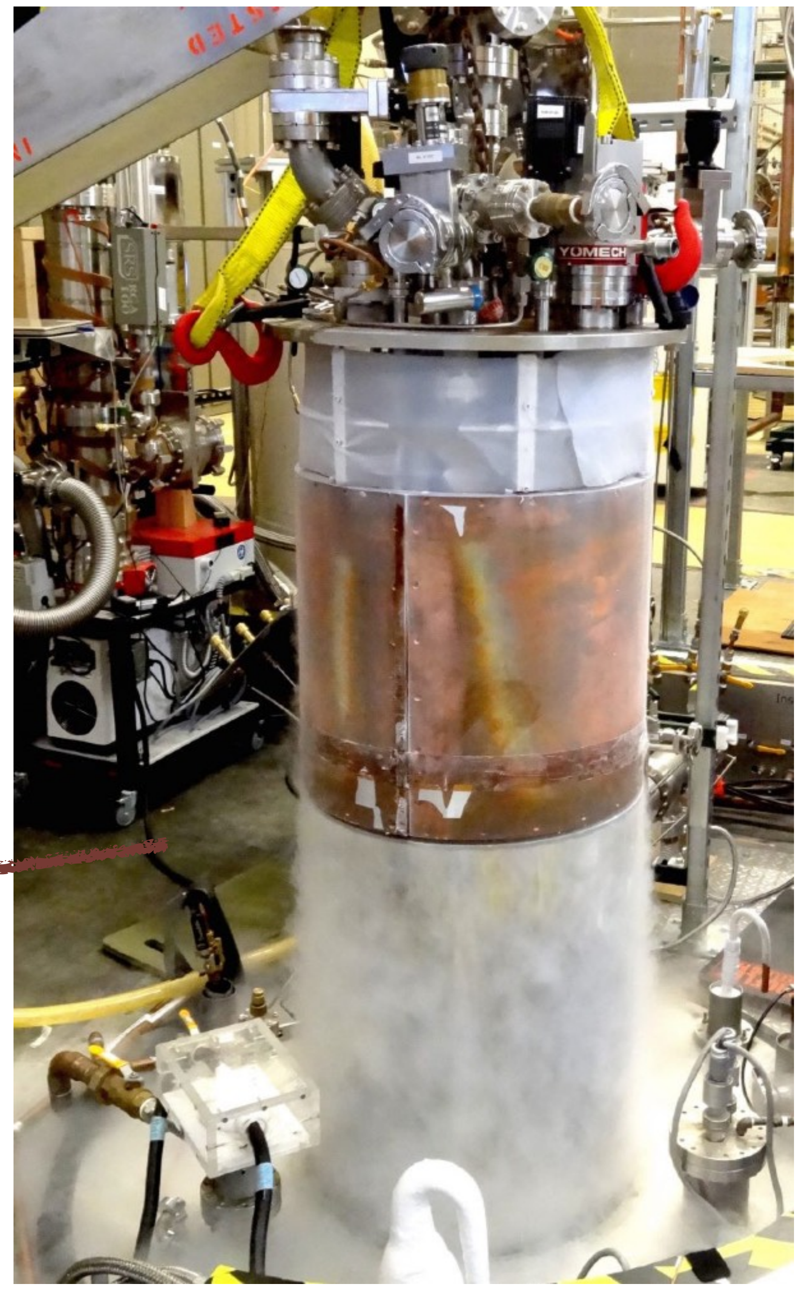
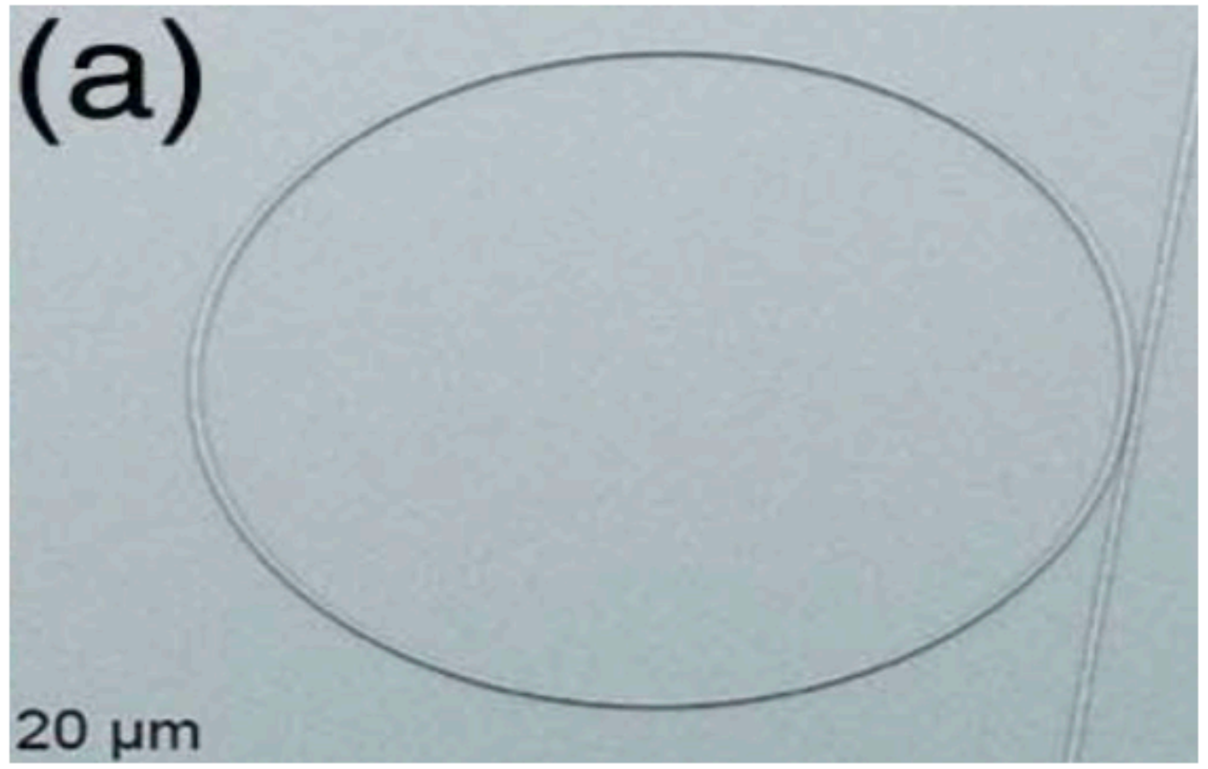


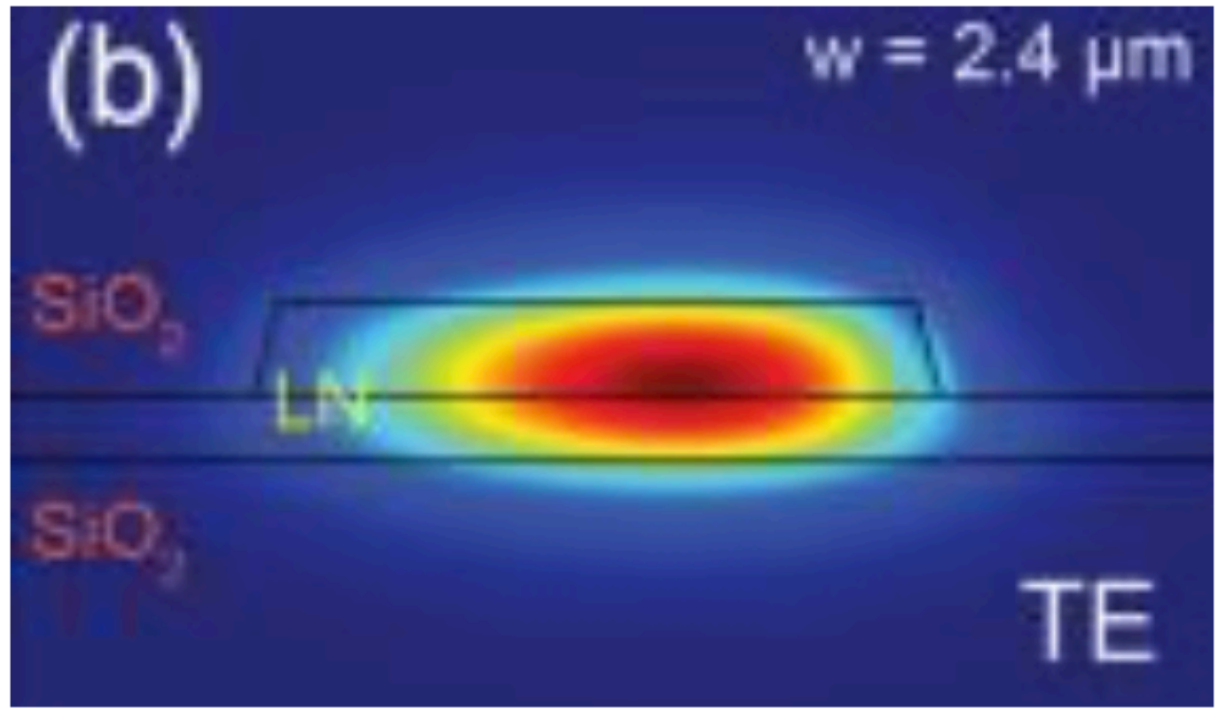


our proposal

cajohare/AxionLimits

Ring Resonator: eV axion/DP

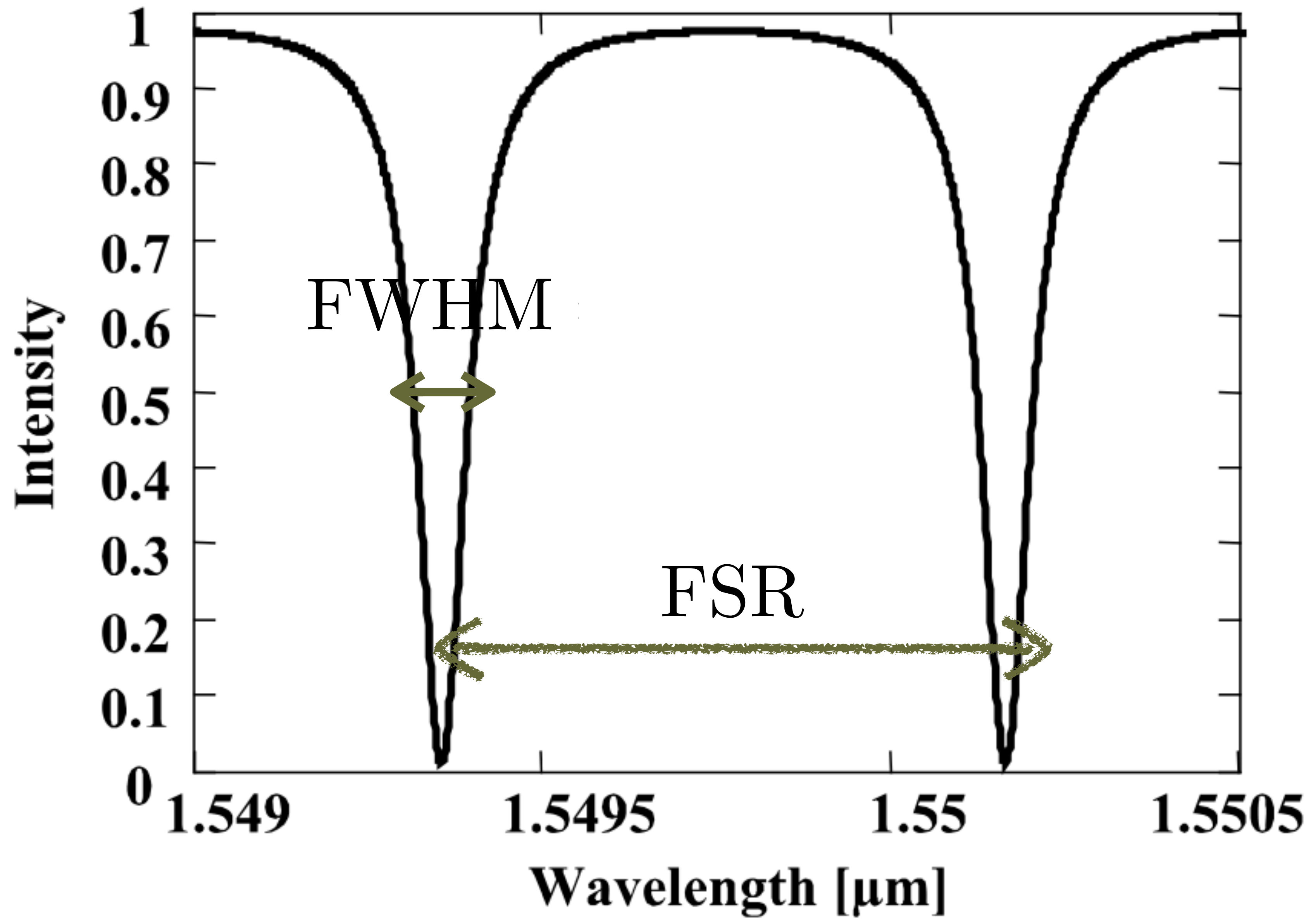




[Zhang et al 1712.04479]

$$\lambda \sim \mu\text{m} \sim {m_a}^{-1}$$

$$L \sim 100\mu\text{m}$$



$$Finesse = \frac{\text{FSR}}{\text{FWHM}}$$

$$Q = \frac{\lambda}{\text{FWHM}} = \frac{n_{\text{eff}} L}{\lambda} finesse$$

Ring Resonator: eV axion/DP

Axion $g_{a\gamma} a \mathbf{E} \cdot \mathbf{B}$

Dark photon $\frac{1}{2} \chi F'_{\mu\nu} F_{\mu\nu}$

New Challenges:

- Phase matching
- Large Q
- Large V

quality factor

effective DM current

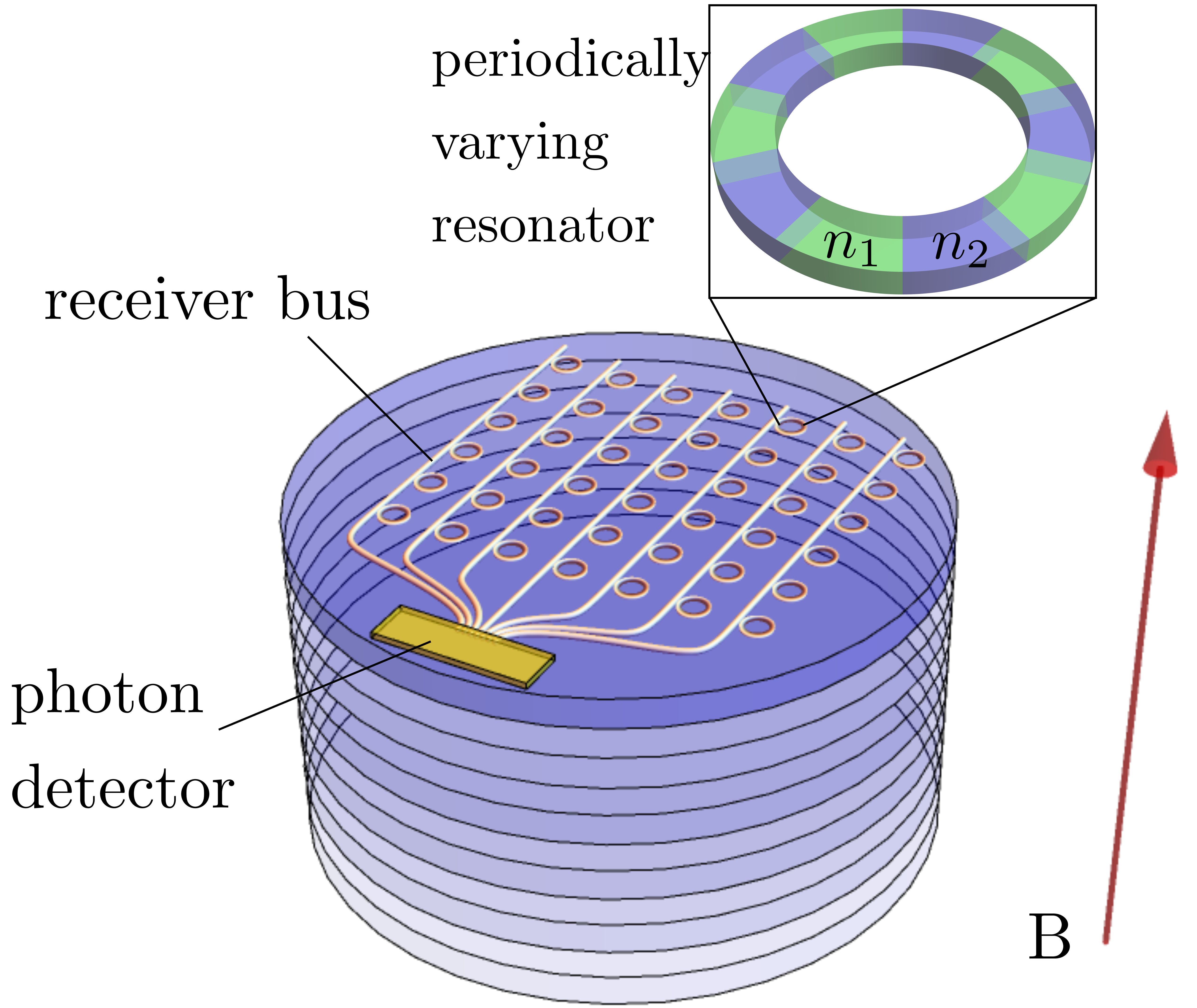
$$P_{\text{sig}} \simeq \frac{Q}{m_{\text{D}}} J_{\text{D}}^2 |\eta|^2 V$$

momentum conservation

Our Proposal

New Challenges:

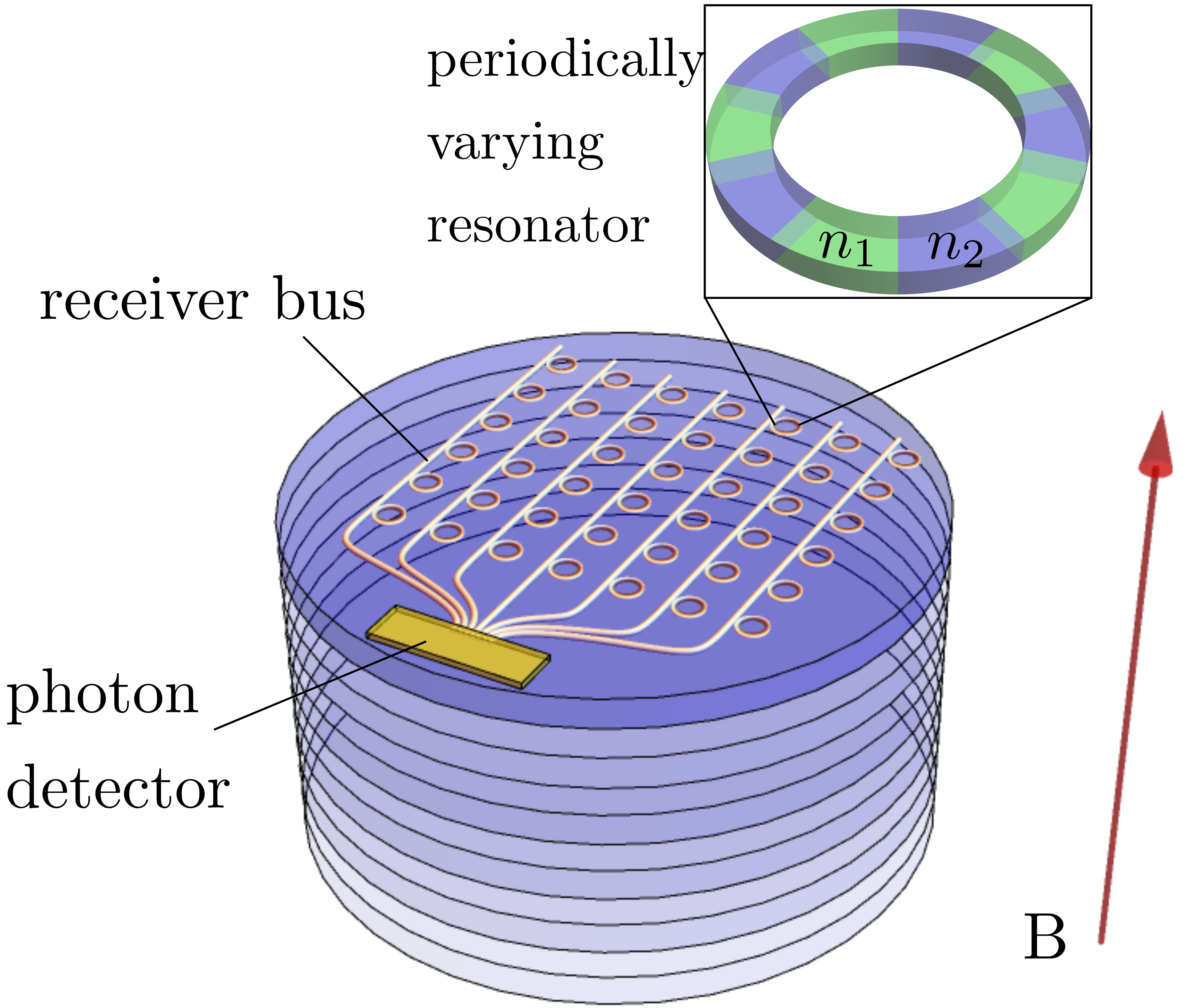
- Phase matching
- Large Q
- Large V



Our Proposal

New Challenges:

- Phase matching   Photonic Crystal
- Large Q   Bound States in Continuum
- Large V   Sensor Network



Our Proposal

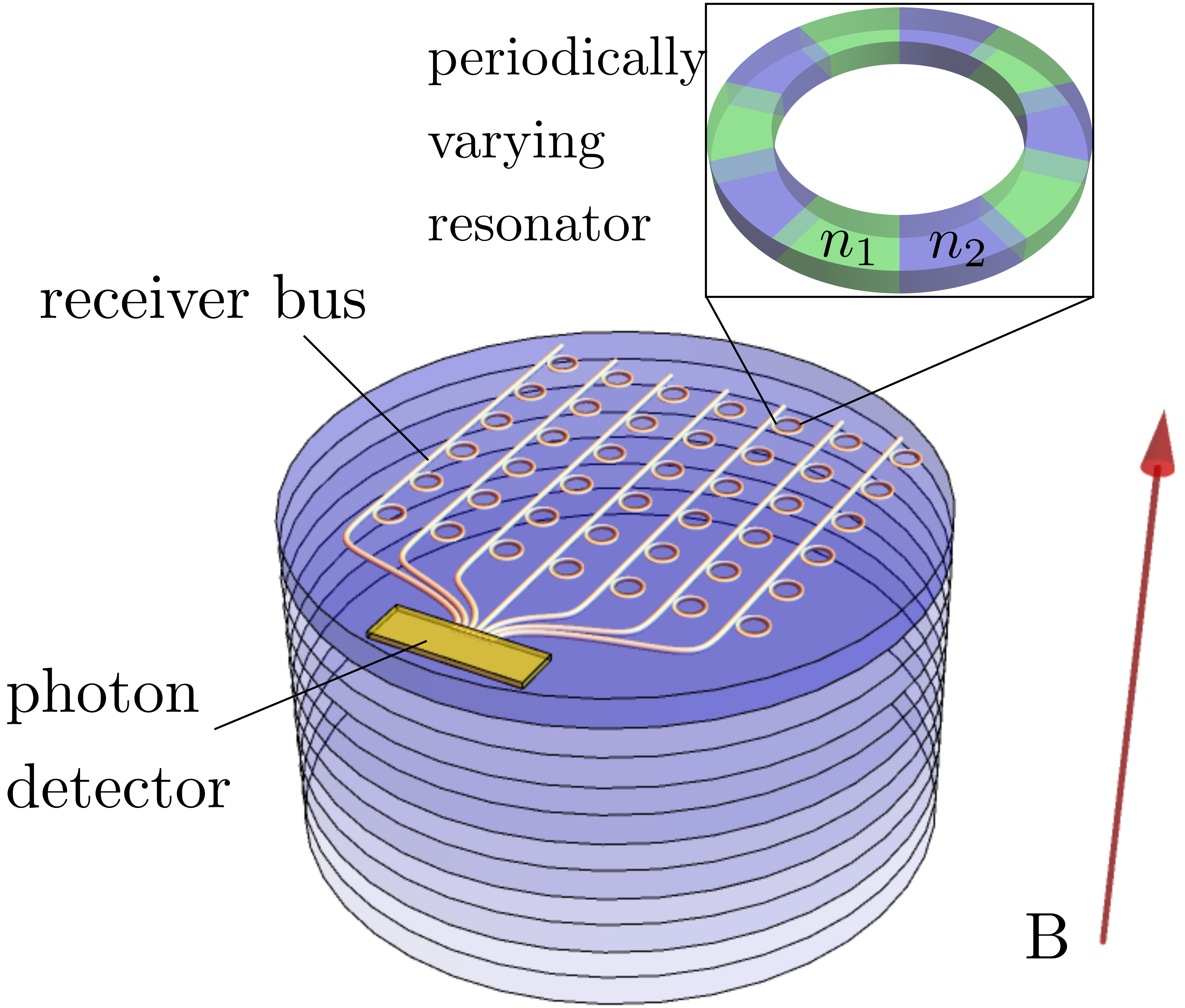
New Challenges:

"UV"

- Phase matching — Photonic Crystal
- Large Q — Bound States in Continuum

"IR"

- Large V — Sensor Network



Phase Matching (Momentum Conservation)

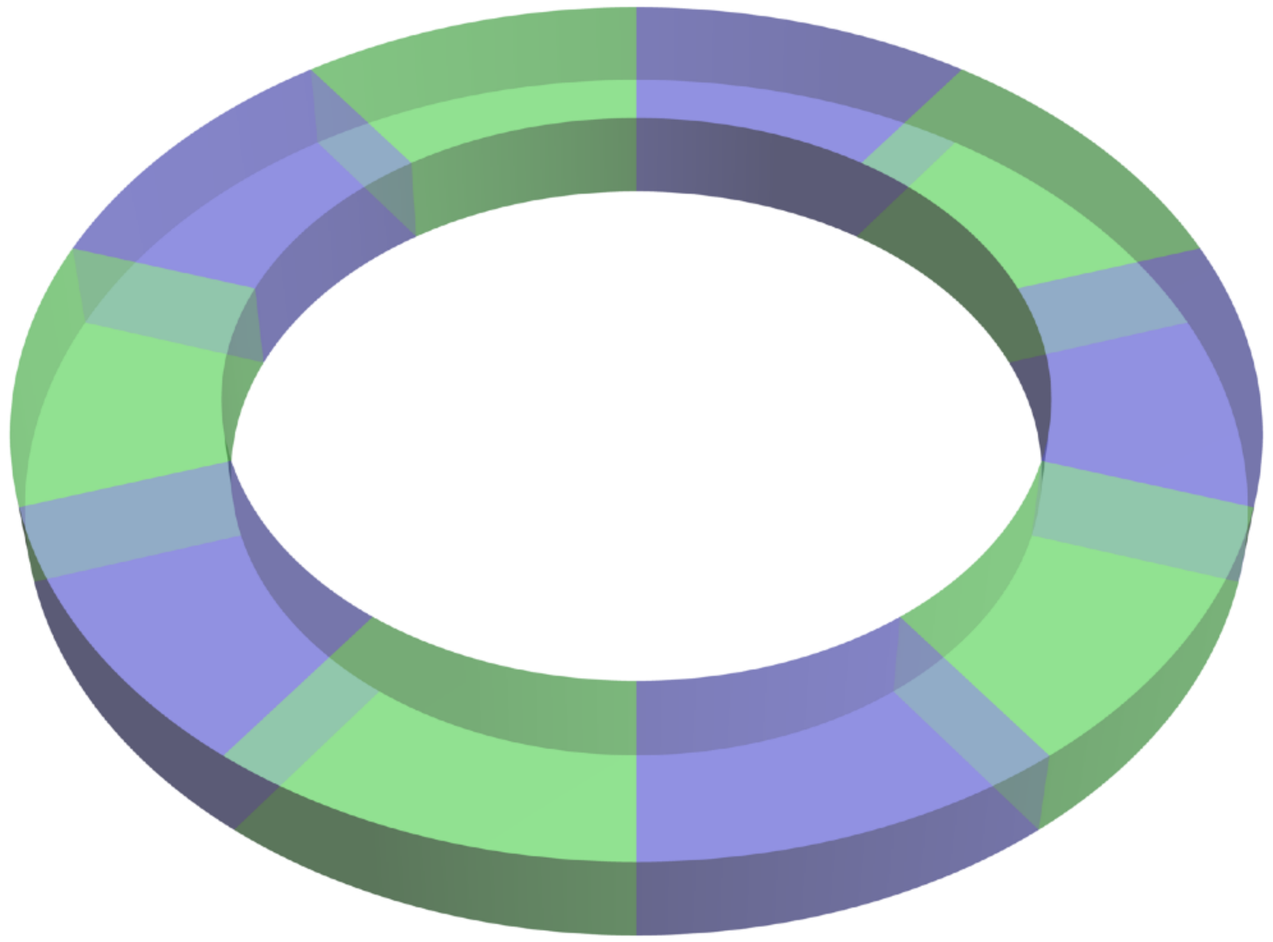
Periodic Photonic Structure: Bloch Modes

Resonator size << λ_{dB}

$$\varepsilon(\mathbf{r}) = \varepsilon(\mathbf{r} + \mathbf{R})$$

$$\mathbf{E_K} = \mathbf{u_K}(\mathbf{r}) e^{\pm i \mathbf{K} \cdot \mathbf{r}} \; , \quad \mathbf{u_K}(\mathbf{r}) = \mathbf{u_K}(\mathbf{r} + \mathbf{R})$$

Bloch wavevector   Lattice vector



e.x. $N_u = 5$

Periodic Photonic Structure: Bloch Modes

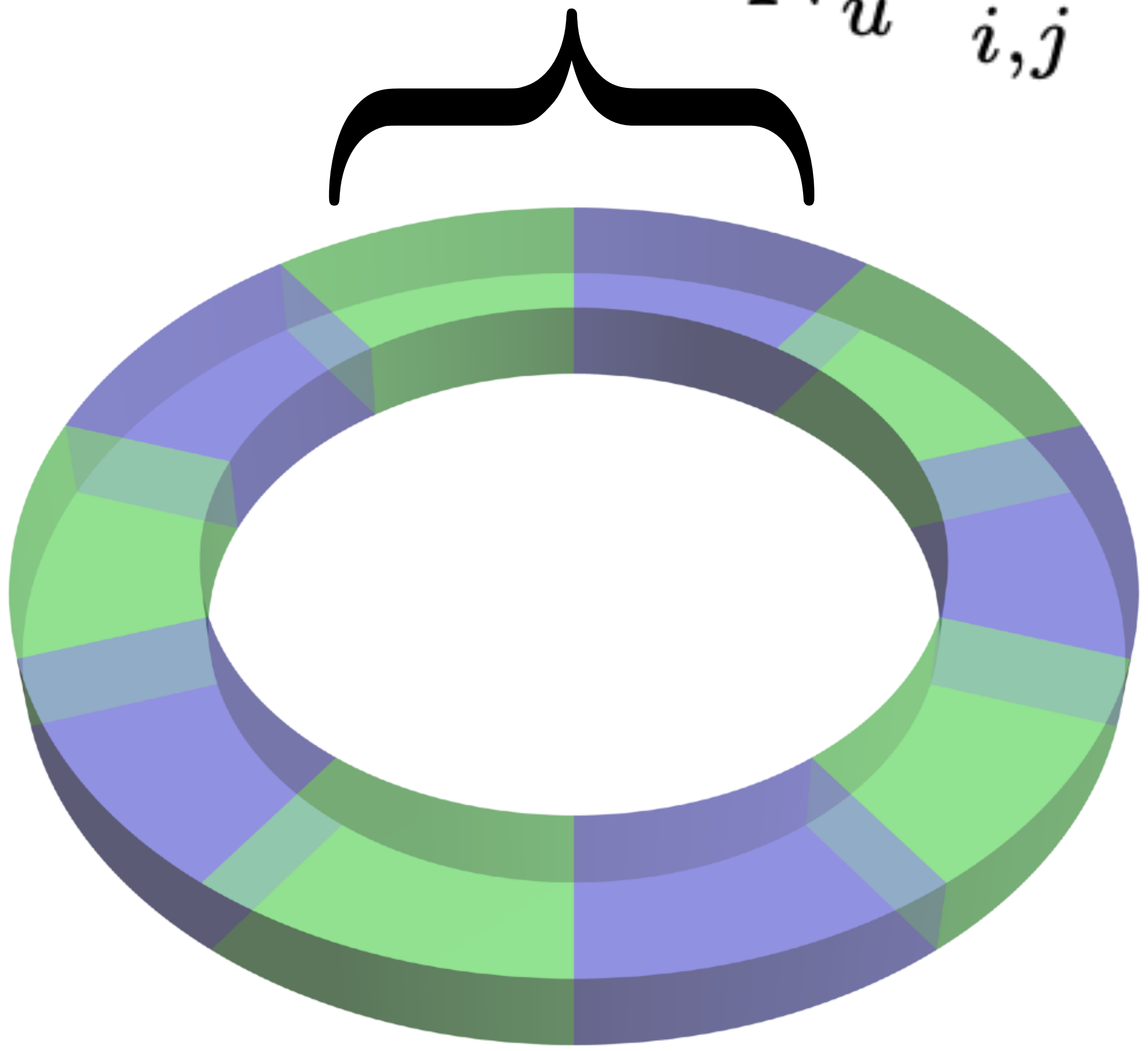
Resonator size << $\lambda_{\rm dB}$

$$\varepsilon(\mathbf{r}) = \varepsilon(\mathbf{r}+\mathbf{R})$$

$$\mathbf{E_K} = \mathbf{u_K}(\mathbf{r})e^{\pm i\mathbf{K}\cdot\mathbf{r}} \;, \quad \mathbf{u_K}(\mathbf{r}) = \mathbf{u_K}(\mathbf{r}+\mathbf{R})$$

Bloch wavevector   Lattice vector

$$|\eta|^2 = |\eta_u|^2 \frac{1}{N_u^2} \sum_{i,j} e^{-i\mathbf{K}\cdot(\mathbf{R}_i - \mathbf{R}_j)}$$



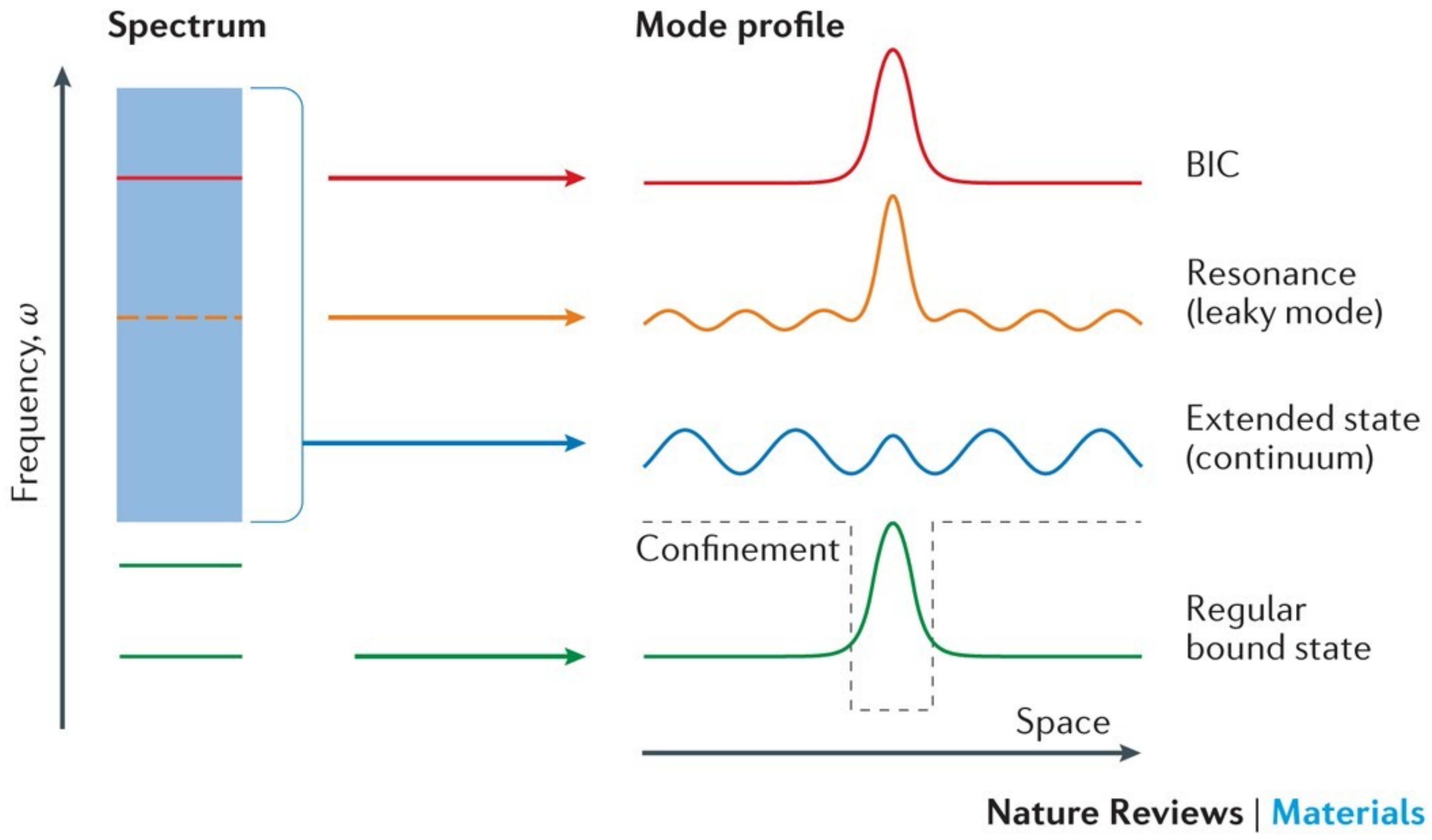
e.x. $N_u = 5$

DM couples to $K \approx 0$ modes

What about Q?

Bound States in Continuum

[Nature Reviews Materials](#)
volume
1, Article number: 16048 (2016)



Bound States in Continuum

[Nature Reviews Materials](#)
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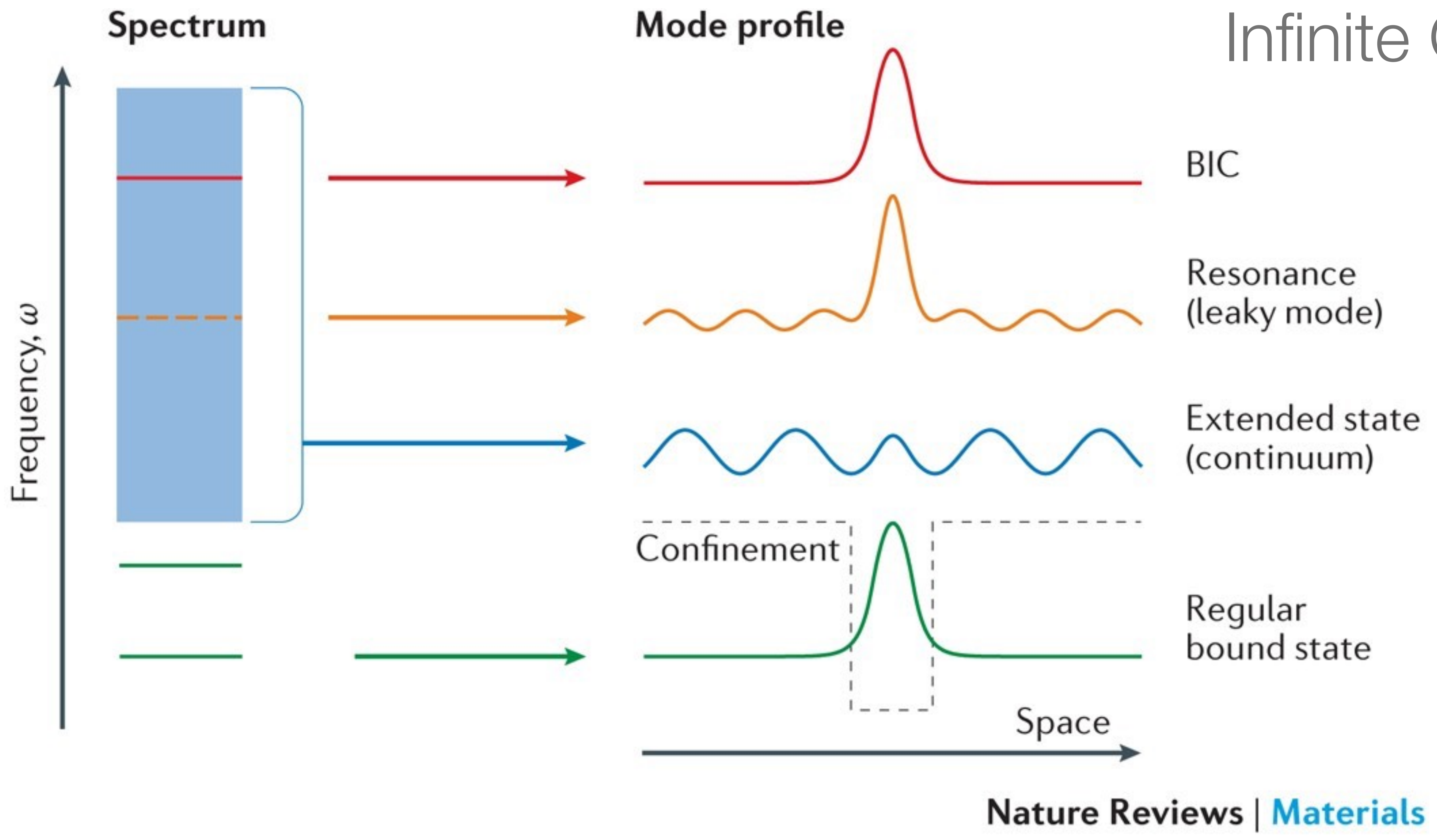
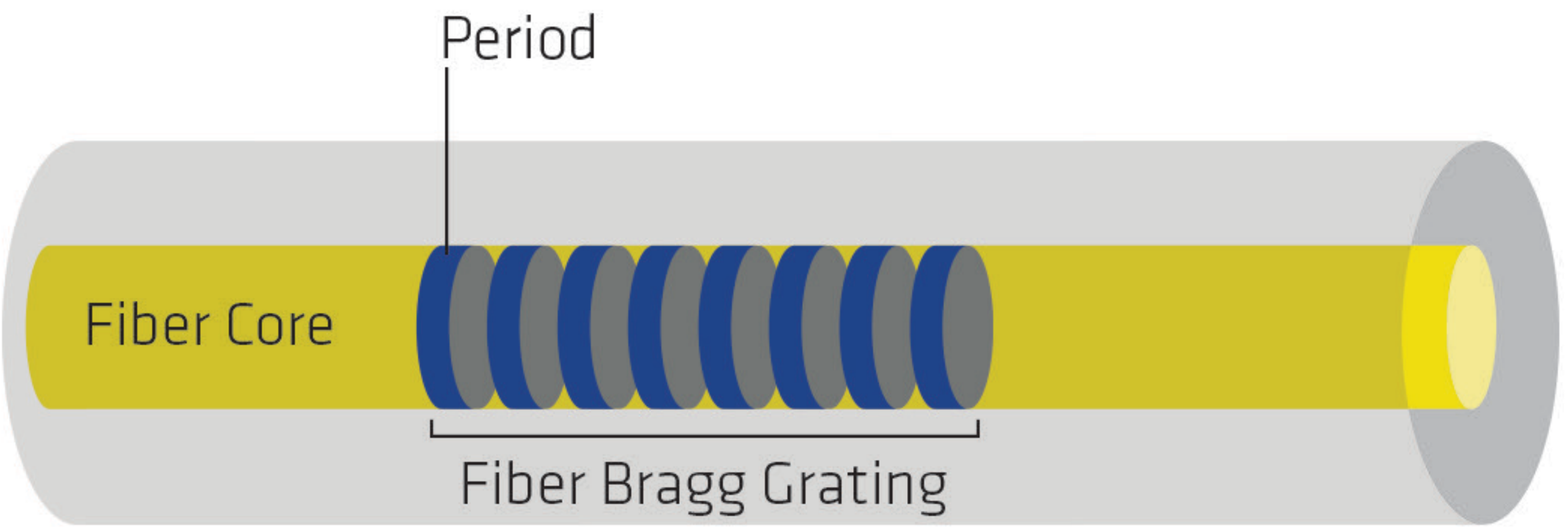
Infinite Q for perfect BIC



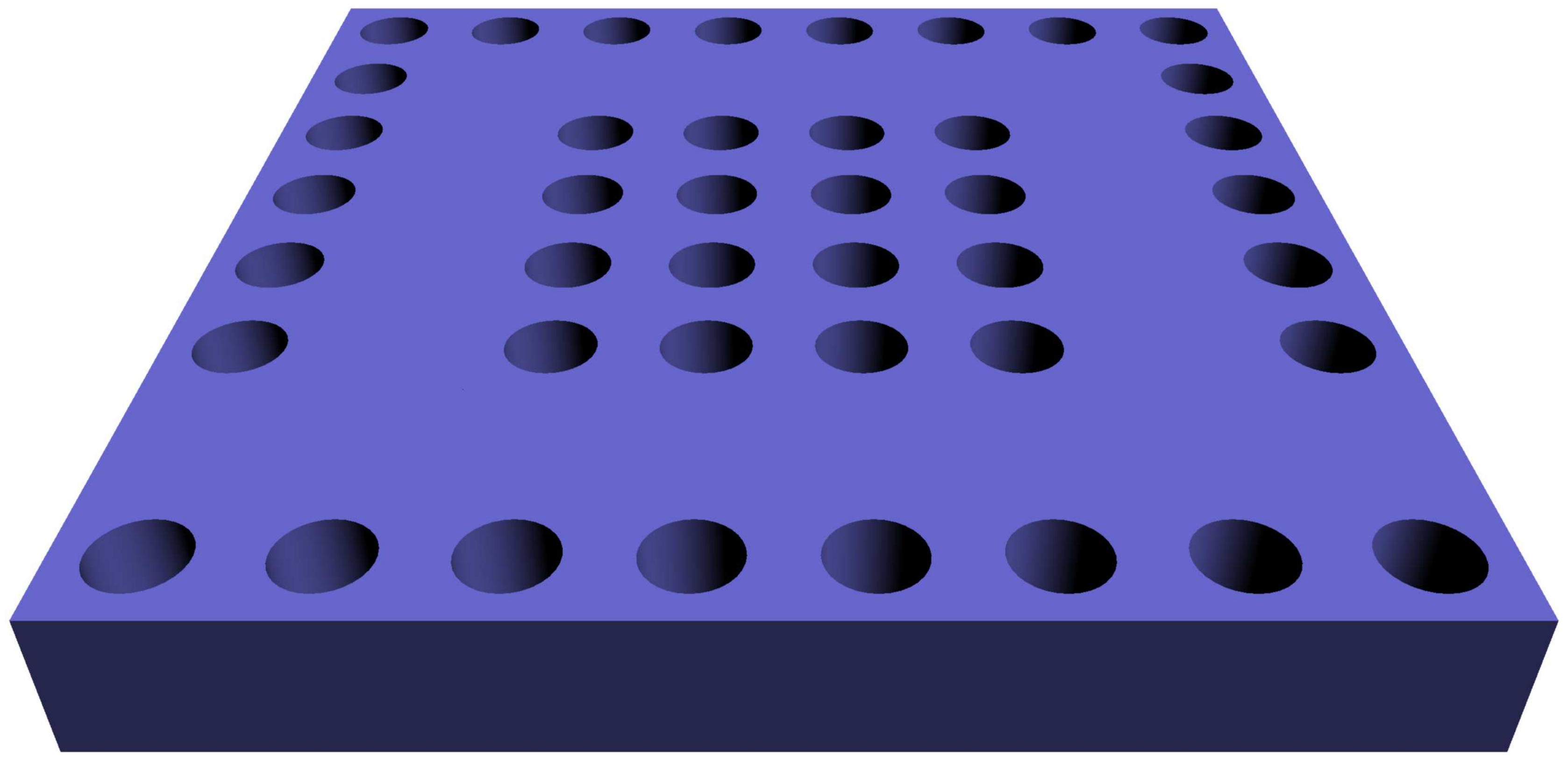
1D and 2D BIC Examples

$$|\eta|^2 = |\eta_u|^2 \frac{1}{N_u^2} \sum_{i,j} e^{-i\mathbf{K}\cdot(\mathbf{R}_i - \mathbf{R}_j)}$$

https://www.teraxion.com/en/company/fiberbragggrating/



Patterned slab

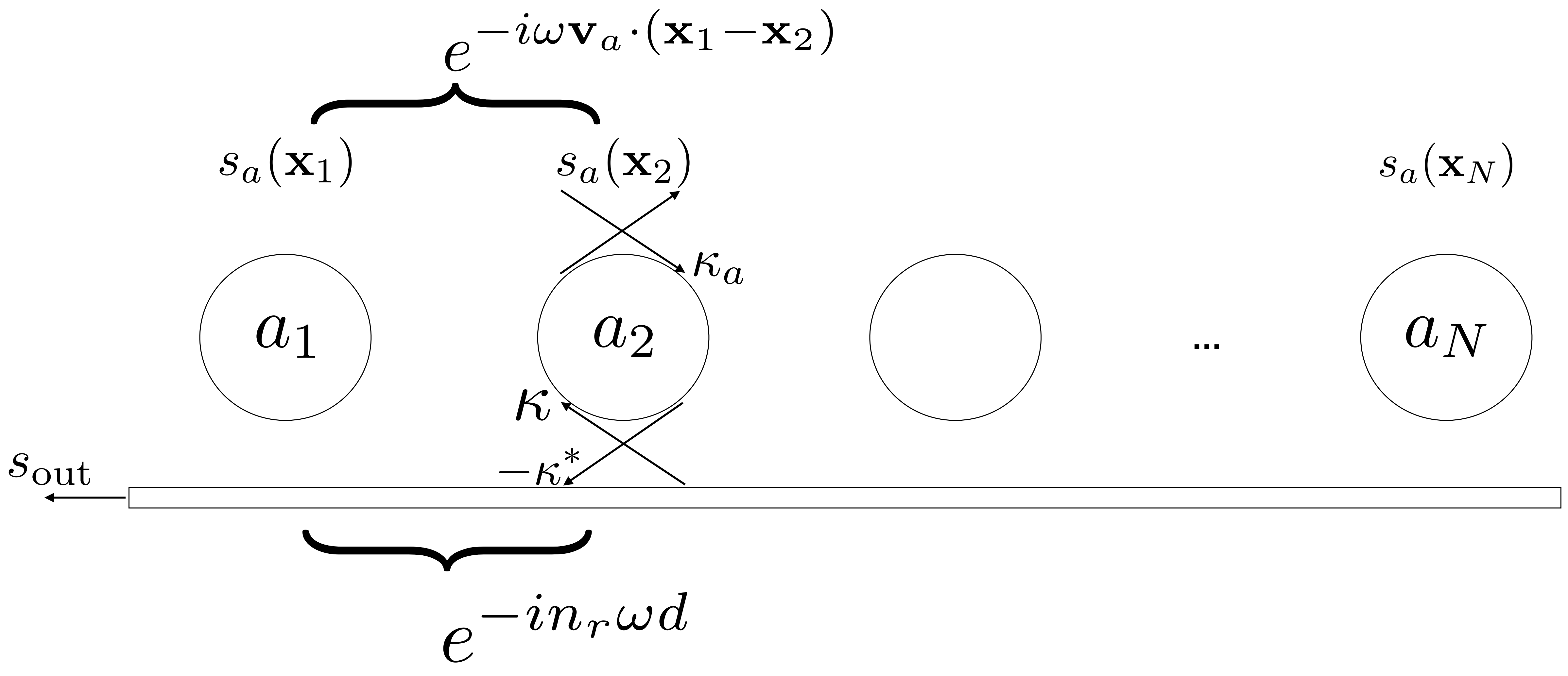


$$|\eta_u| : 0.01 \sim 0.1$$

Not optimized

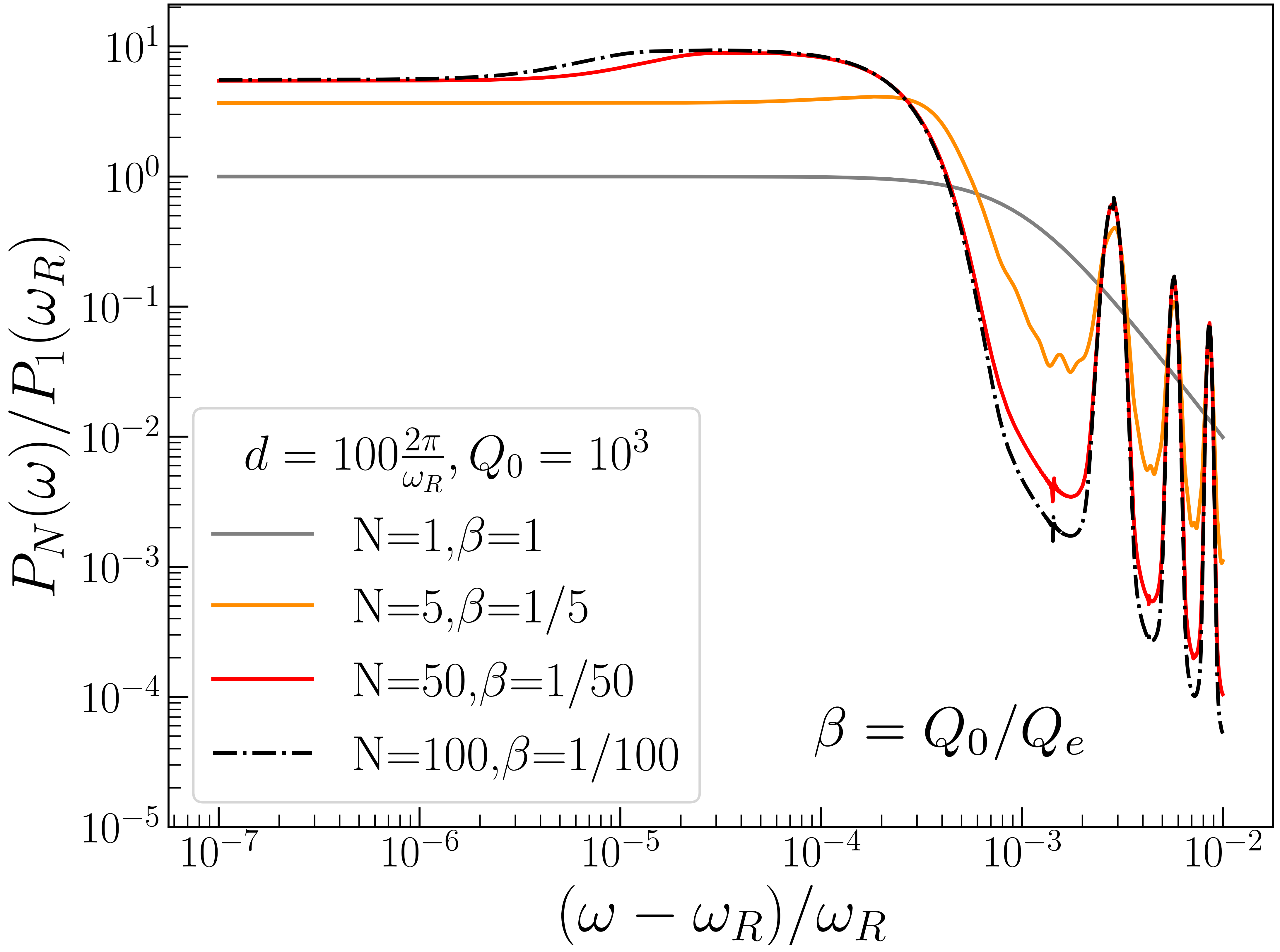
Coupling N Resonators in Series

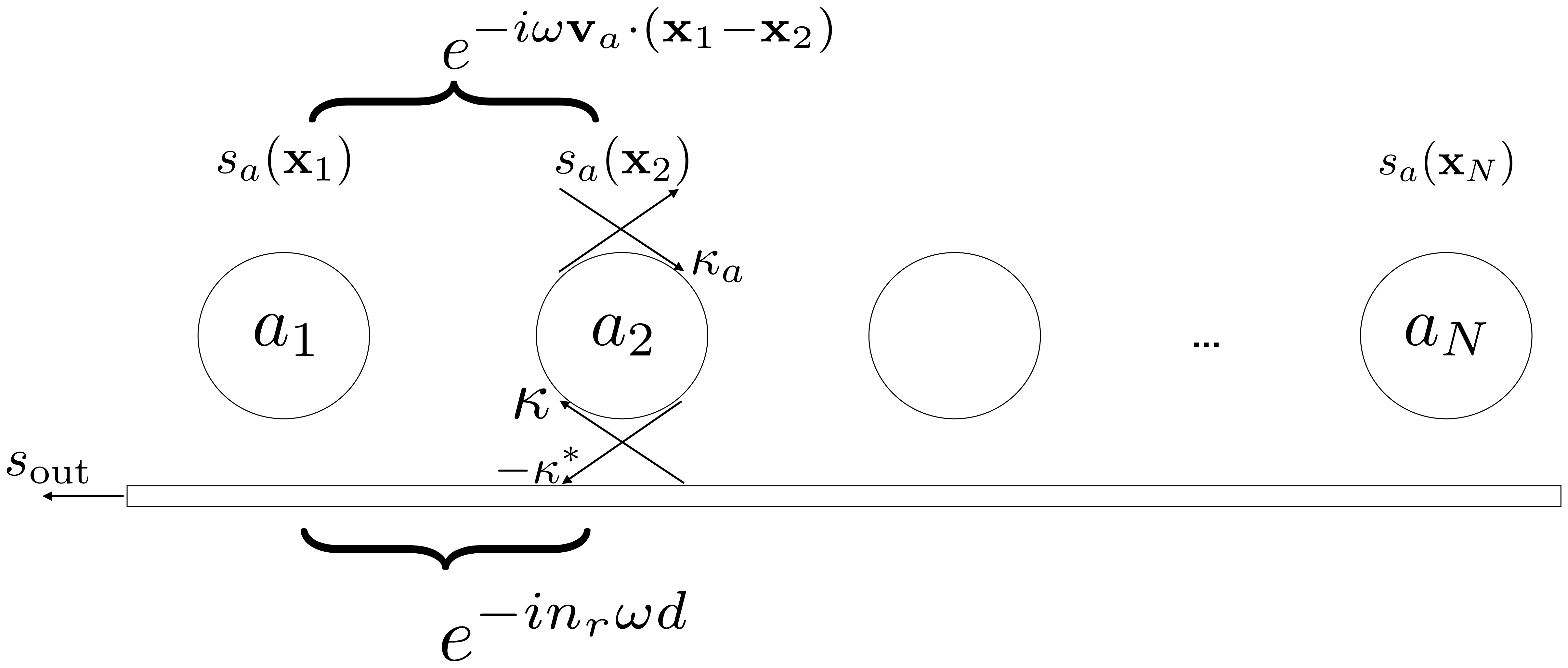
N Resonators in Series



- Solve the output using Heisenberg Langevin equations
- Gaussian distribution of $\mathbf{v}_a$ is assumed.
- DM sources a standing wave that can couple to either left or right-traveling wave in the bus.

Same Frequency

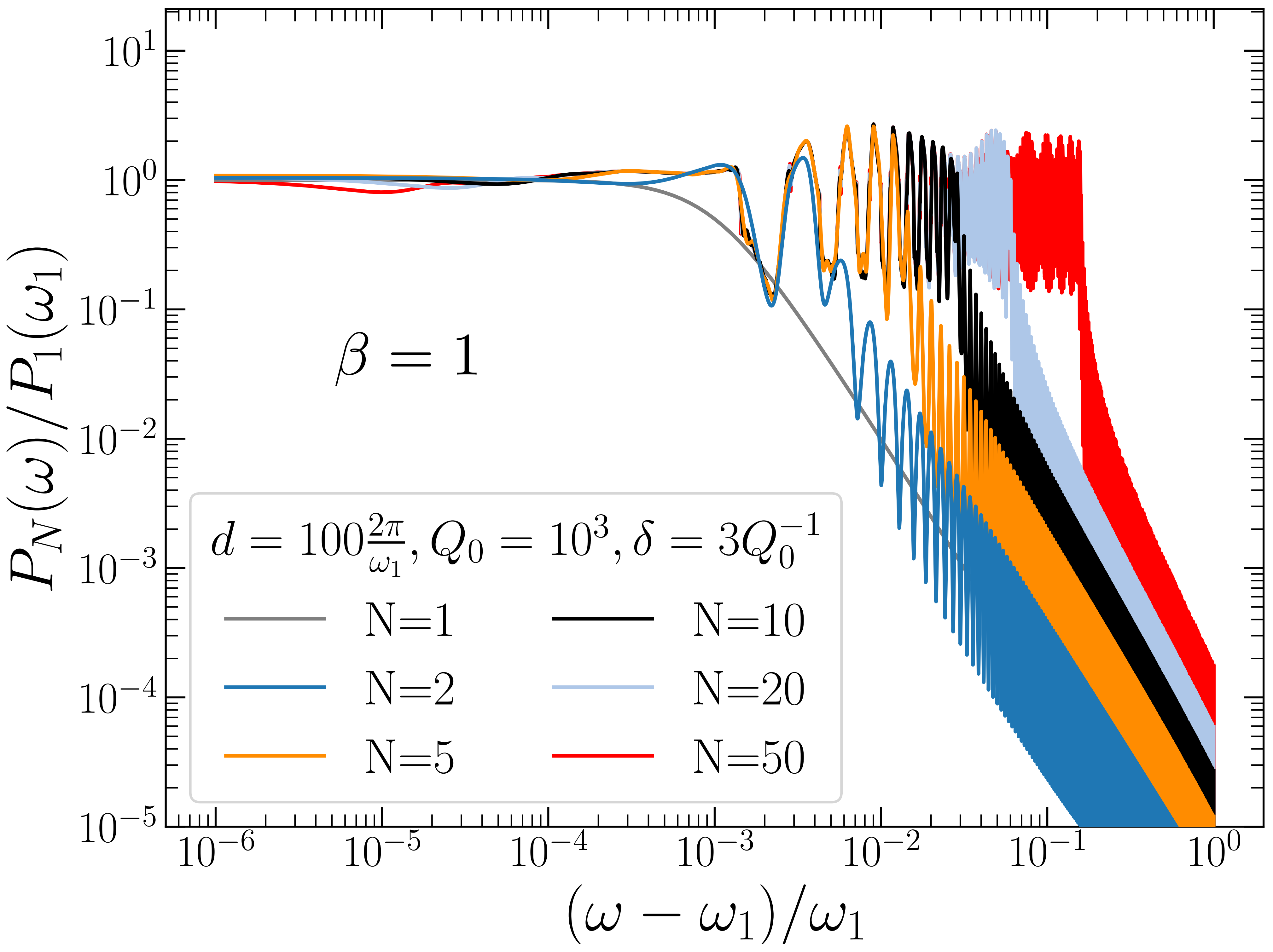


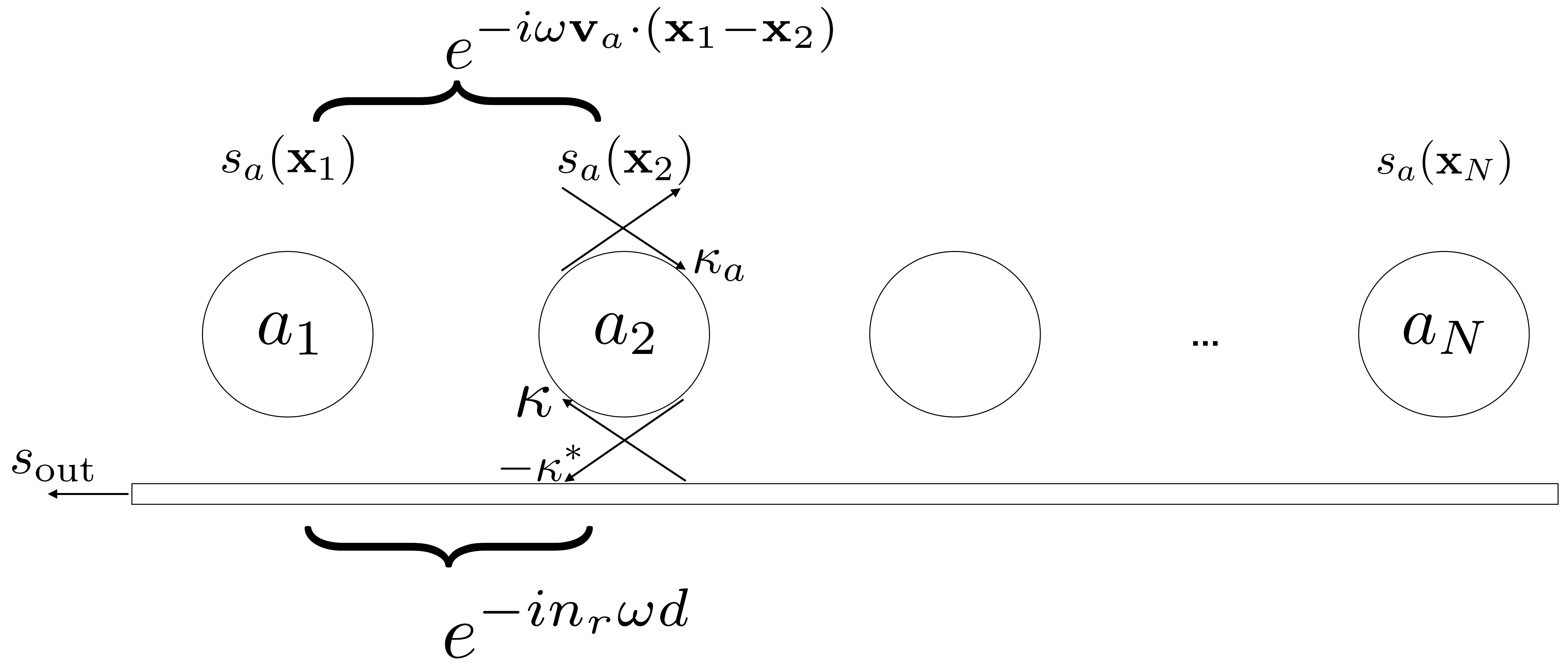


No gain after going beyond the DM coherence length.

Different Frequencies

$$\omega_R(1+\delta)^{i-1}, i = 1, 2, \cdots, N$$





Signal width grows like $\delta \times Q_0$.

Projected Sensitivity

Axion DM Search Needs a Background Magnetic Field

$$\xi_{\rm act} \equiv \frac{V_{\rm int}}{\pi D^2 t_s/4} \sim 1\% \left(\frac{100}{N_u}\right)\left(\frac{t_w/t_s}{0.1}\right)$$

B (T)	Bore (mm)	$V_{\rm act}$ (cm^3)	$B^2 V_{\rm act}$ (kJ)	References
40	34	9×10^{-2}	0.11	[70]
21	123	1.18	0.40	[71]
9.4	800	1000	67.3	[72]
11.7	900	1270	133	[73]
20[a]	680	726	221	[74]

Above ~1.1 eV, Skipper CCD

Below ~1.1 eV, Superconducting Nanowire Single Photon Detector

$$\mathrm{SNR} = \frac{\Gamma_{\rm sig} t_{\rm int}}{\mathrm{Max}\left[1, \Gamma_{\rm bkg} t_{\rm int}\right]^{1/2}}$$

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↓

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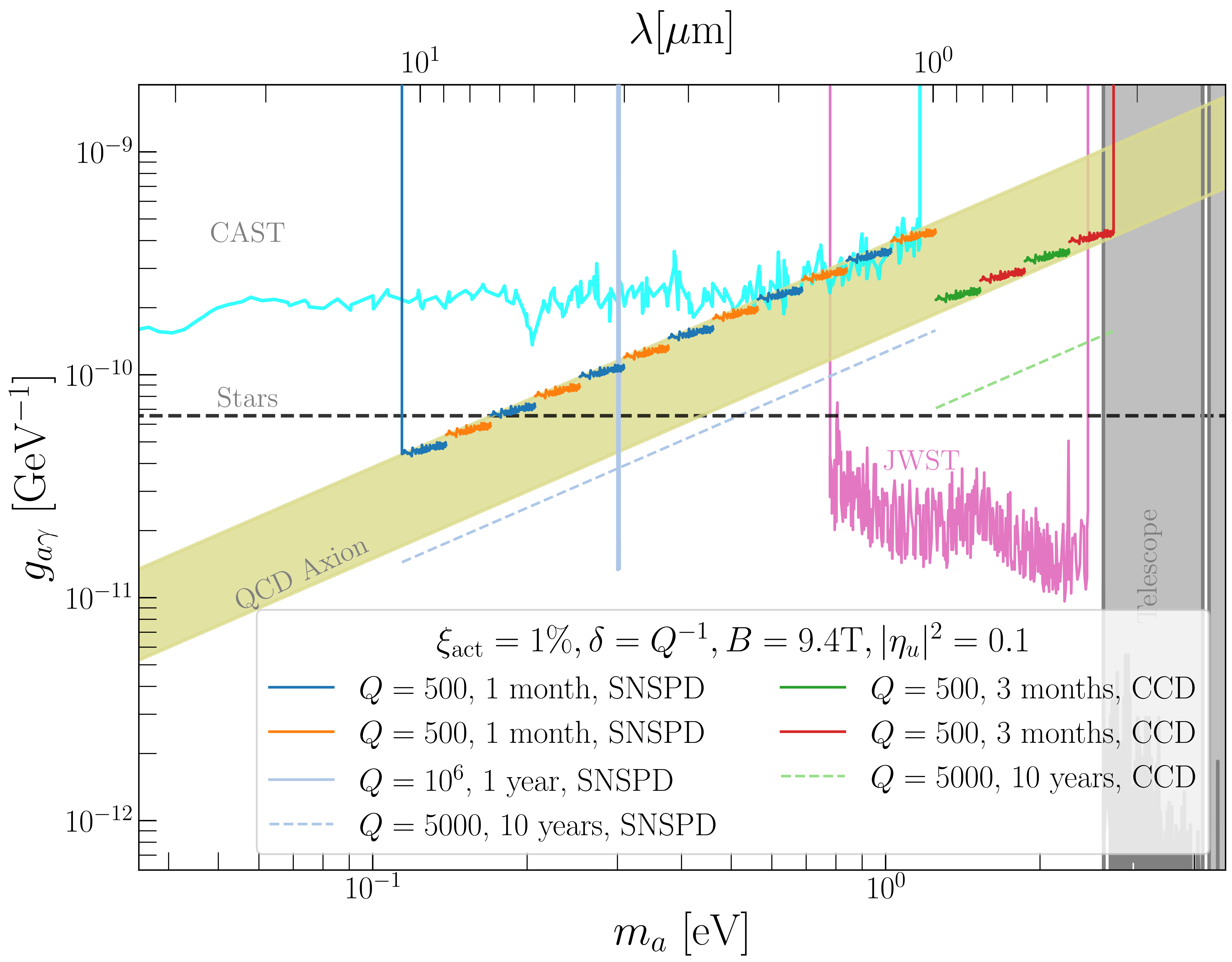
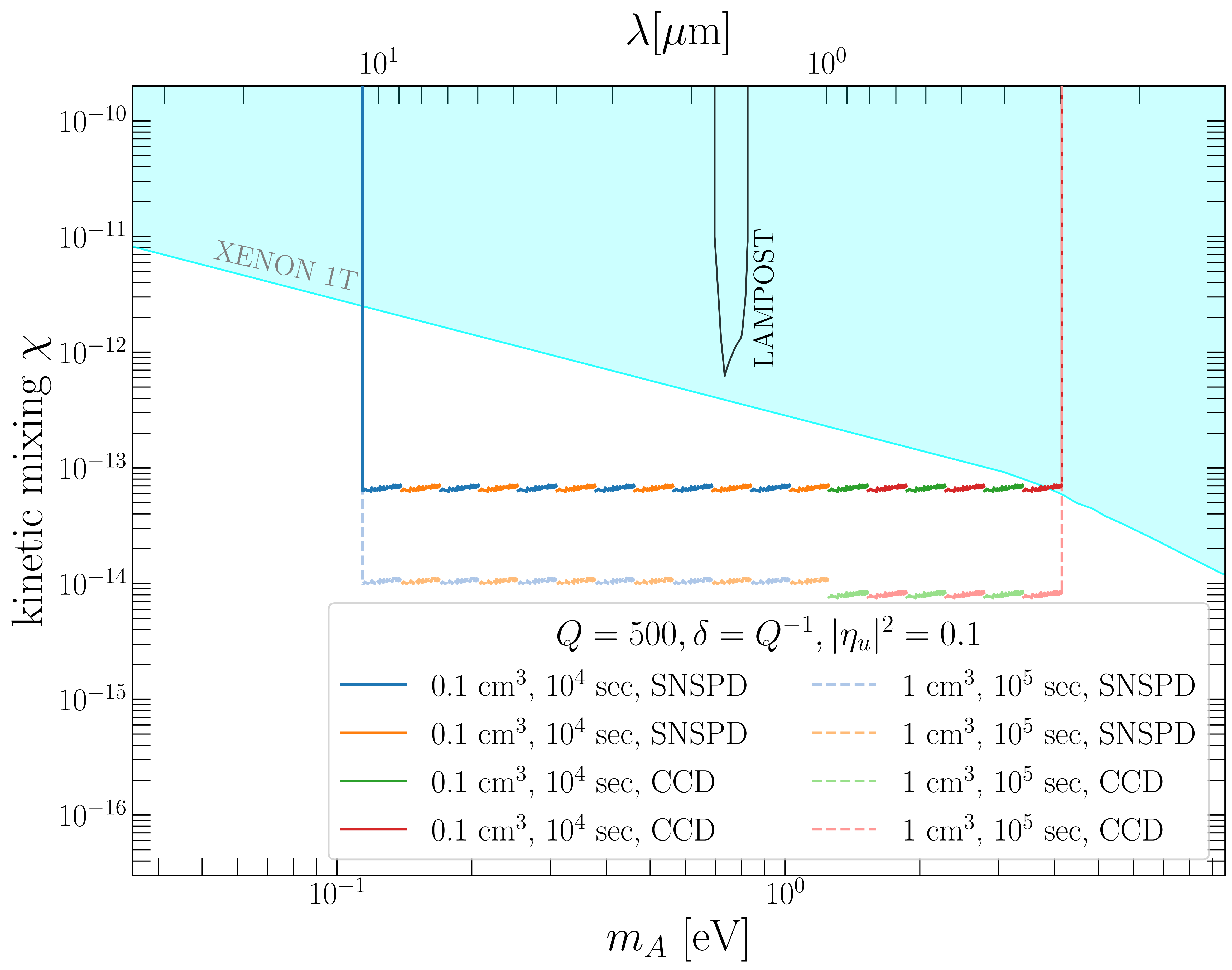


Conclusion & Future

- Integrated Photonics can be applied in the DM direct detection at optical frequencies.
- Photonic Crystal Cavities constitute the best option to phase match. 2D and 3D photonic crystals, though harder to mass produce, could provide better phase matching and volume filling.
- Optical resonators' properties may undergo significant changes under cryogenic temperatures.

Dark photon-photon kinetic mixing



Backups

Dark matter candidates

Ultralight dark matter (e.g. axion, dark photon)

Weakly interacting massive particles (WIMP)

Ultraheavy dark matter (e.g. black holes)

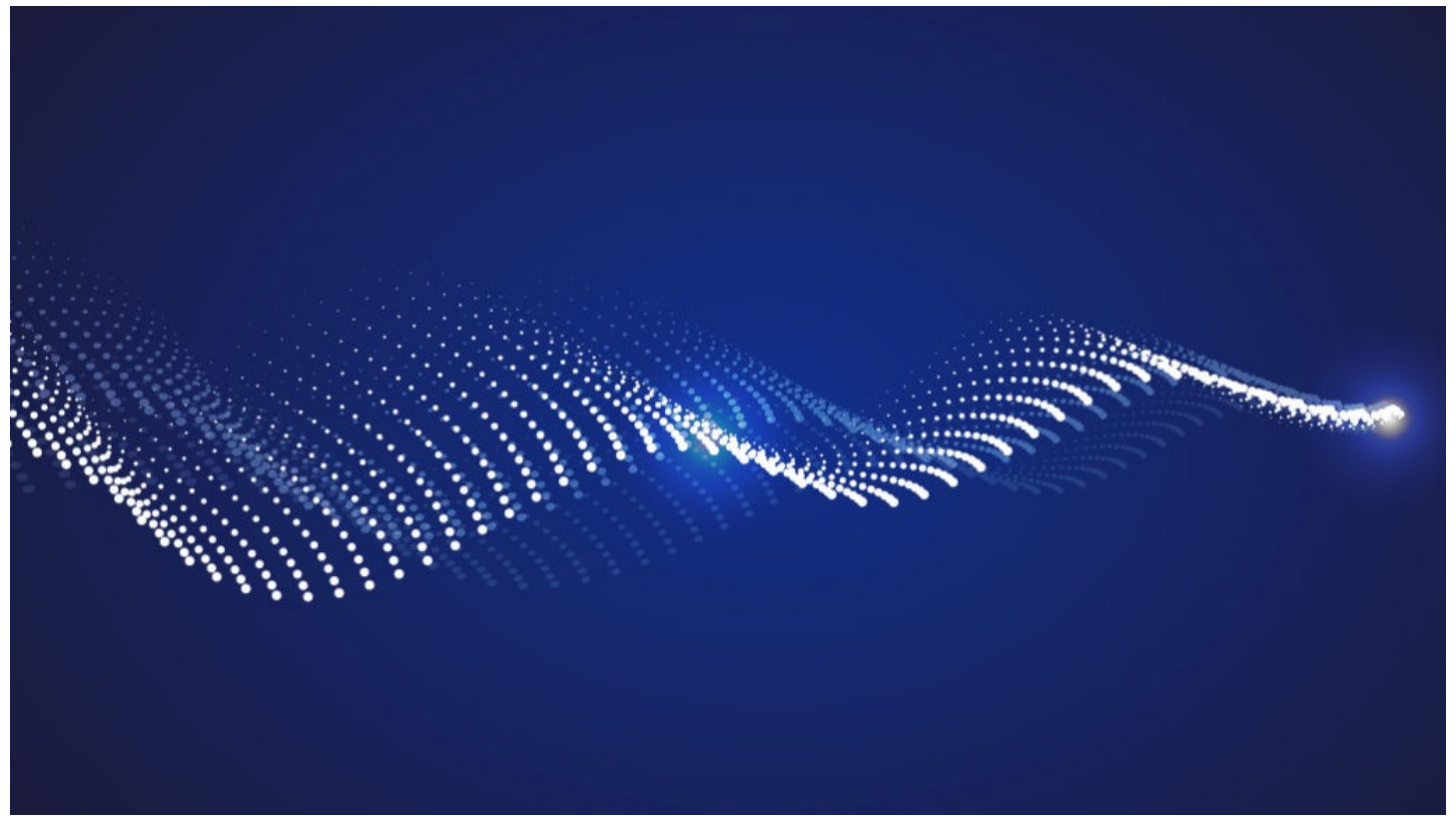
Wavelength fits in a galaxy

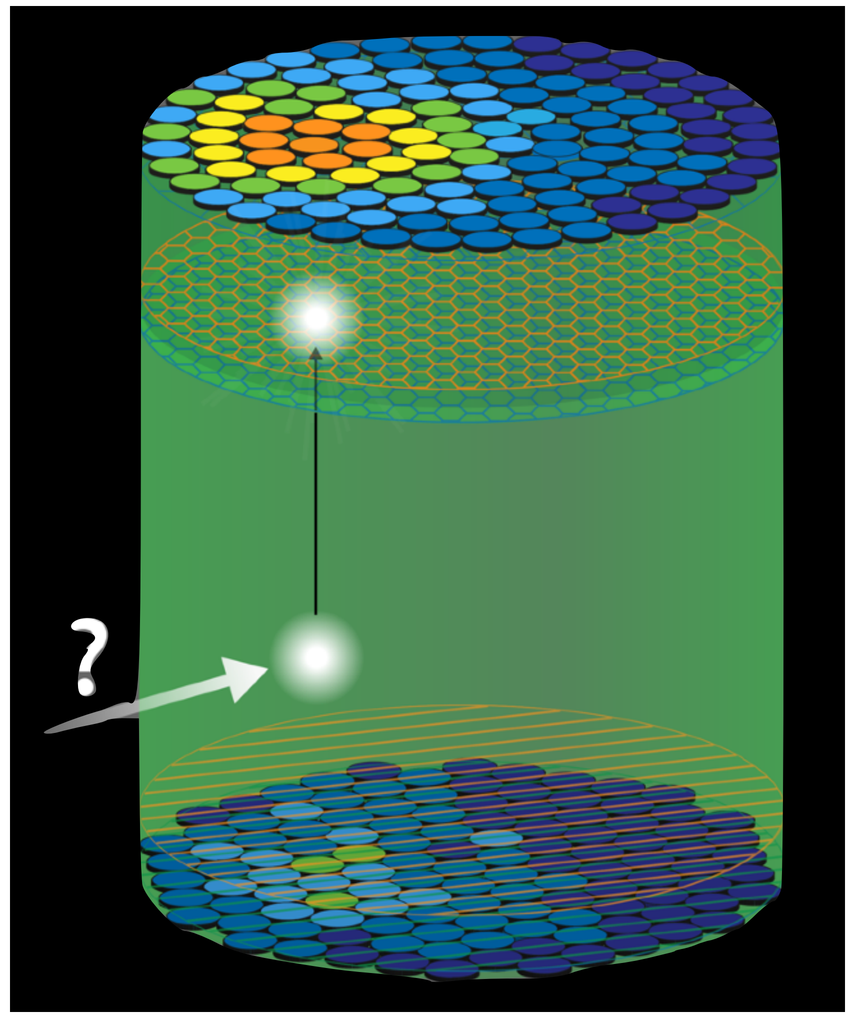
10^{-22} eV — 1 eV

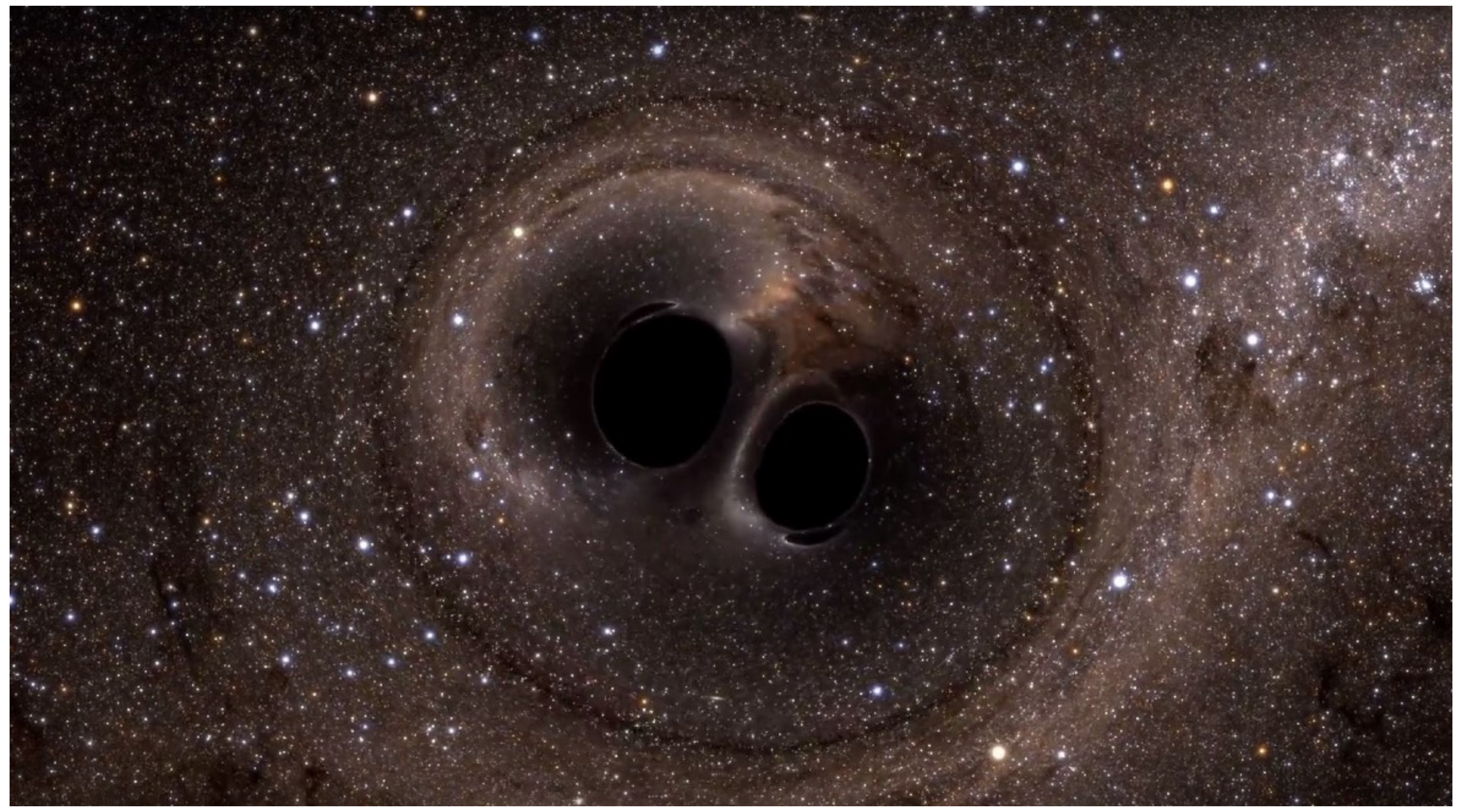
10^{9} eV — 10^{13} eV

Planck mass

10^{50} eV — 10^{53} eV







Example: Si-on-Insulator Photonic Crystal Ring Resonator

https://doi.org/10.1364/OL.39.001282

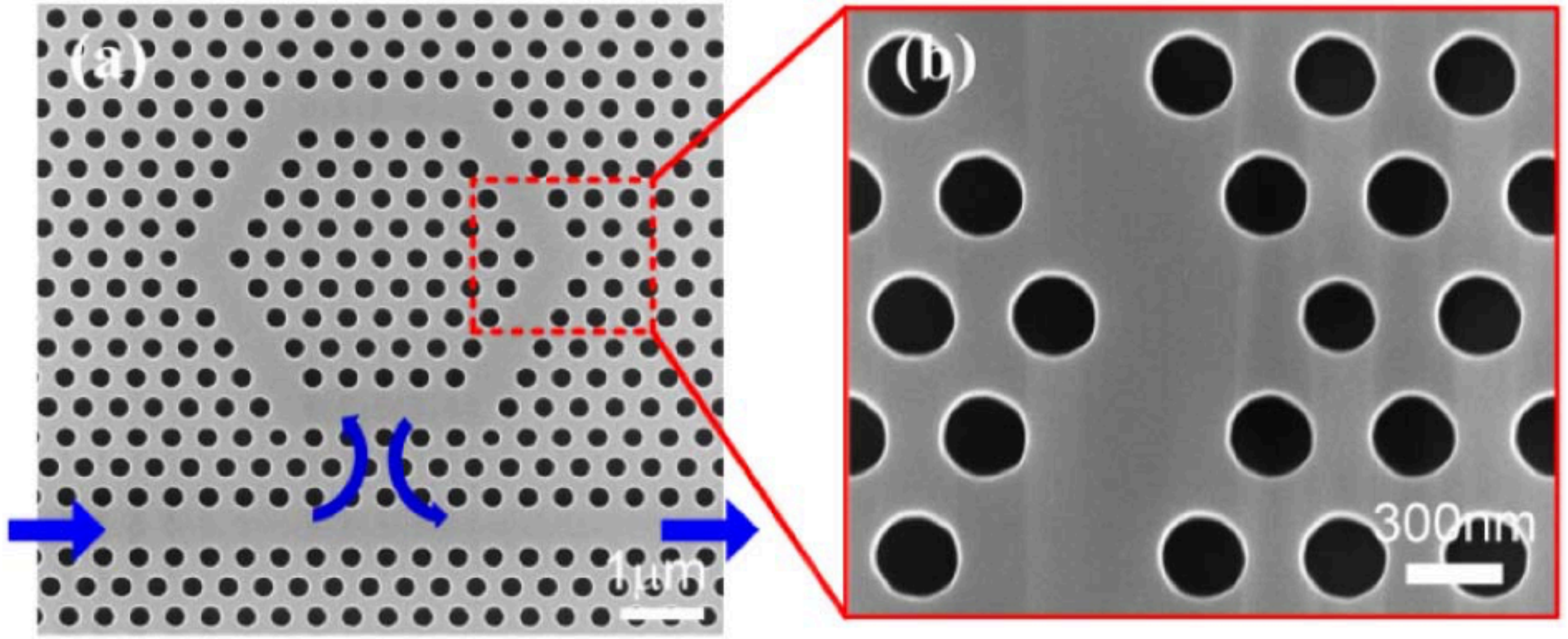
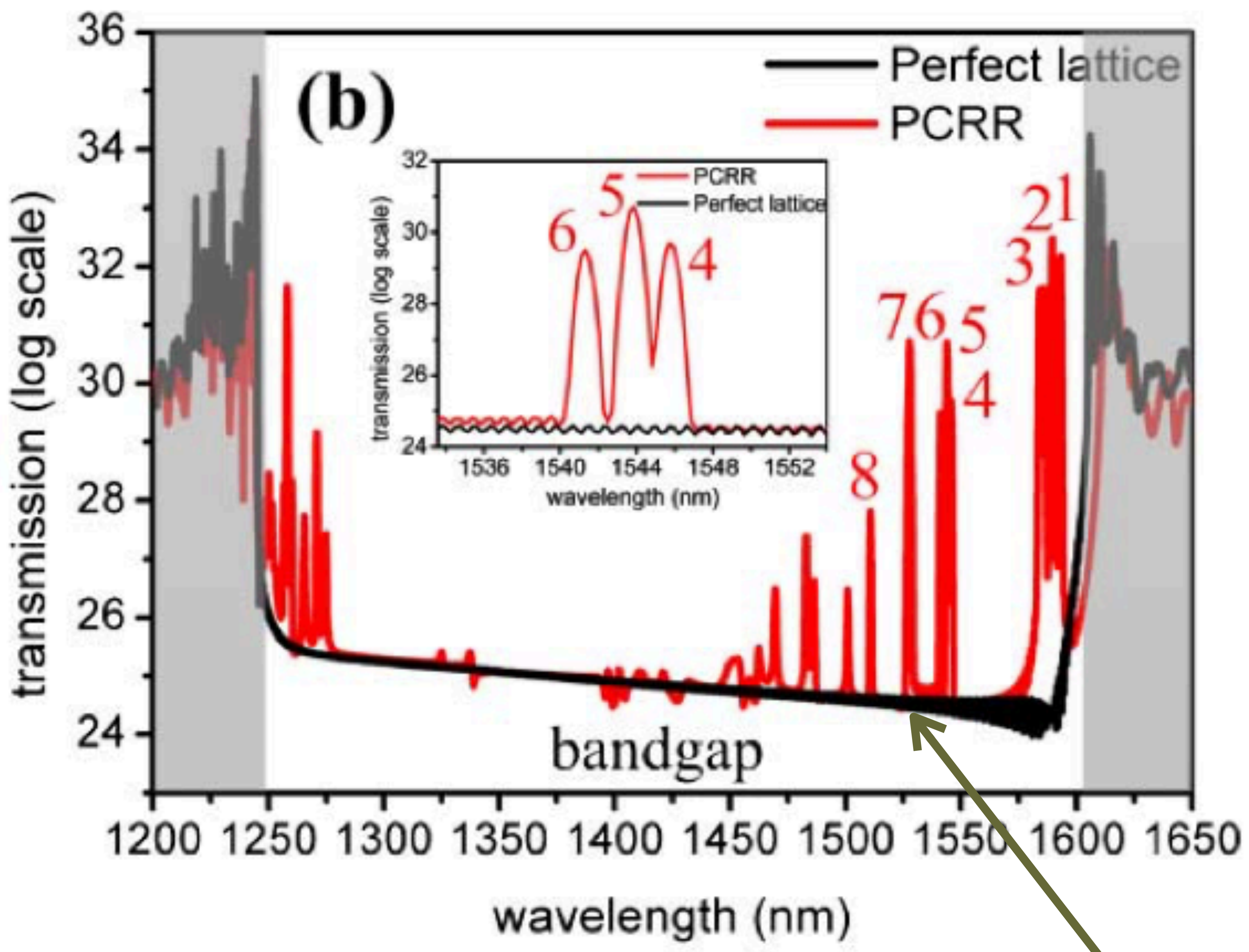
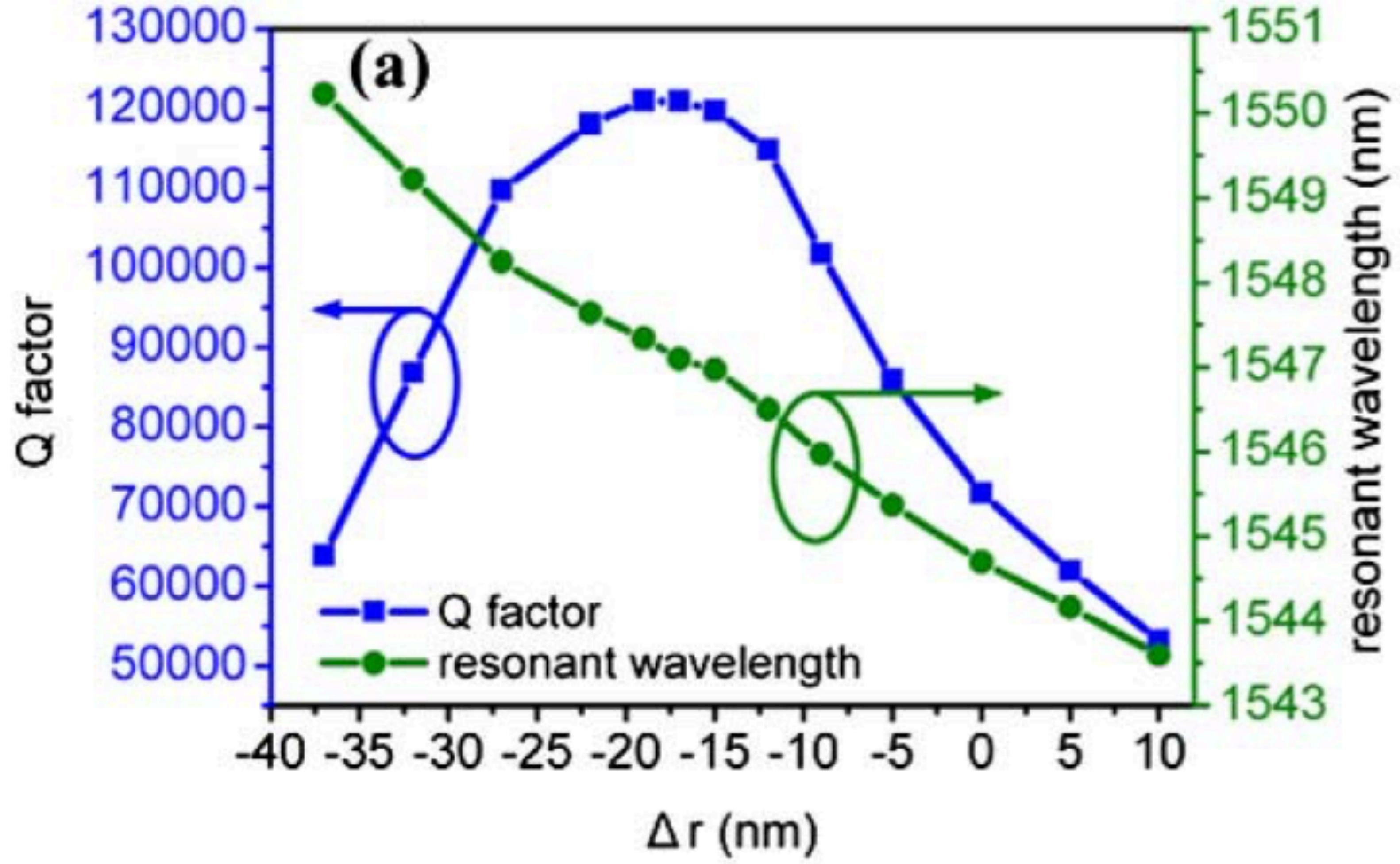
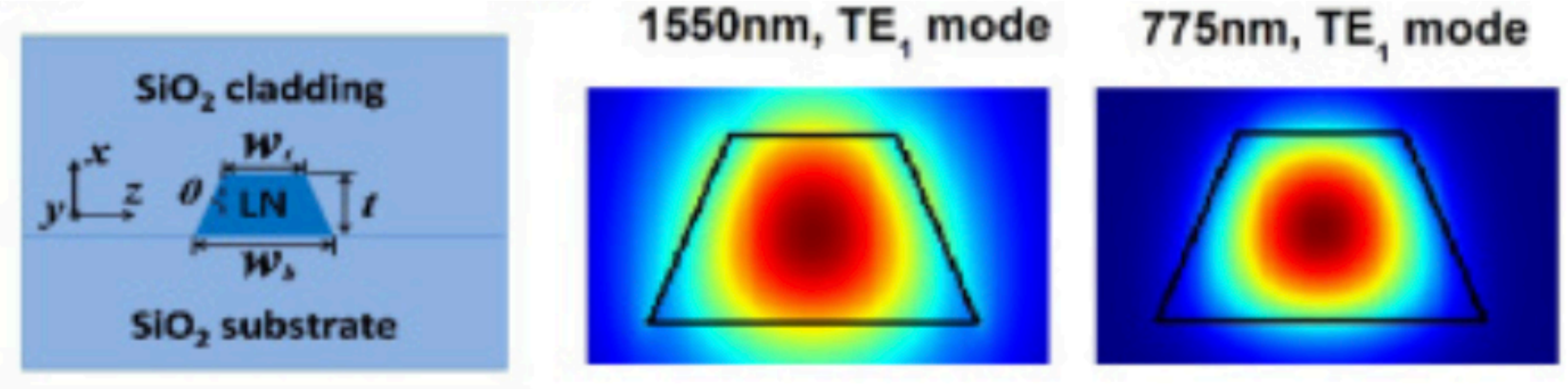


Fig. 4. (a) SEM image of the fabricated modified PCRR. (b) Magnified micrograph of the corner of the modified PCRR.

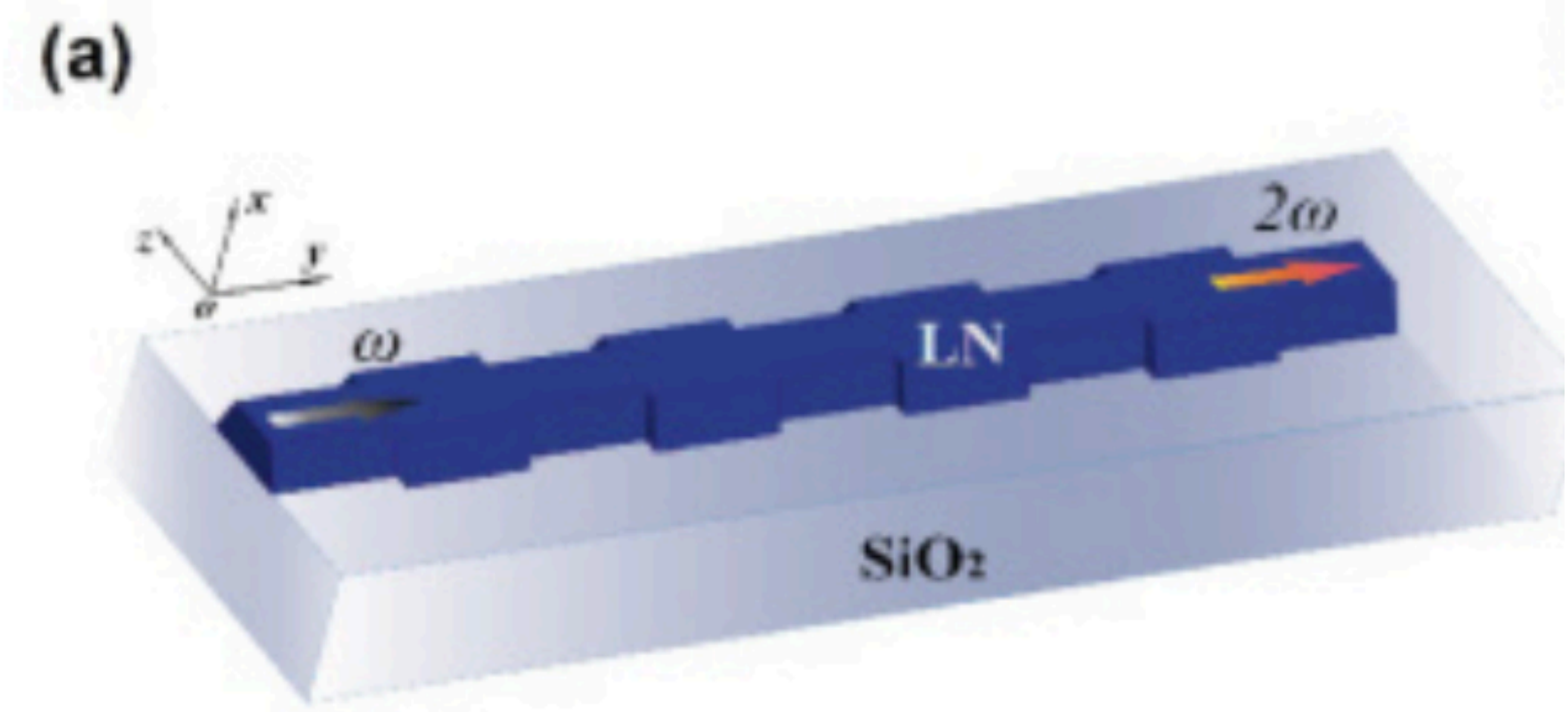


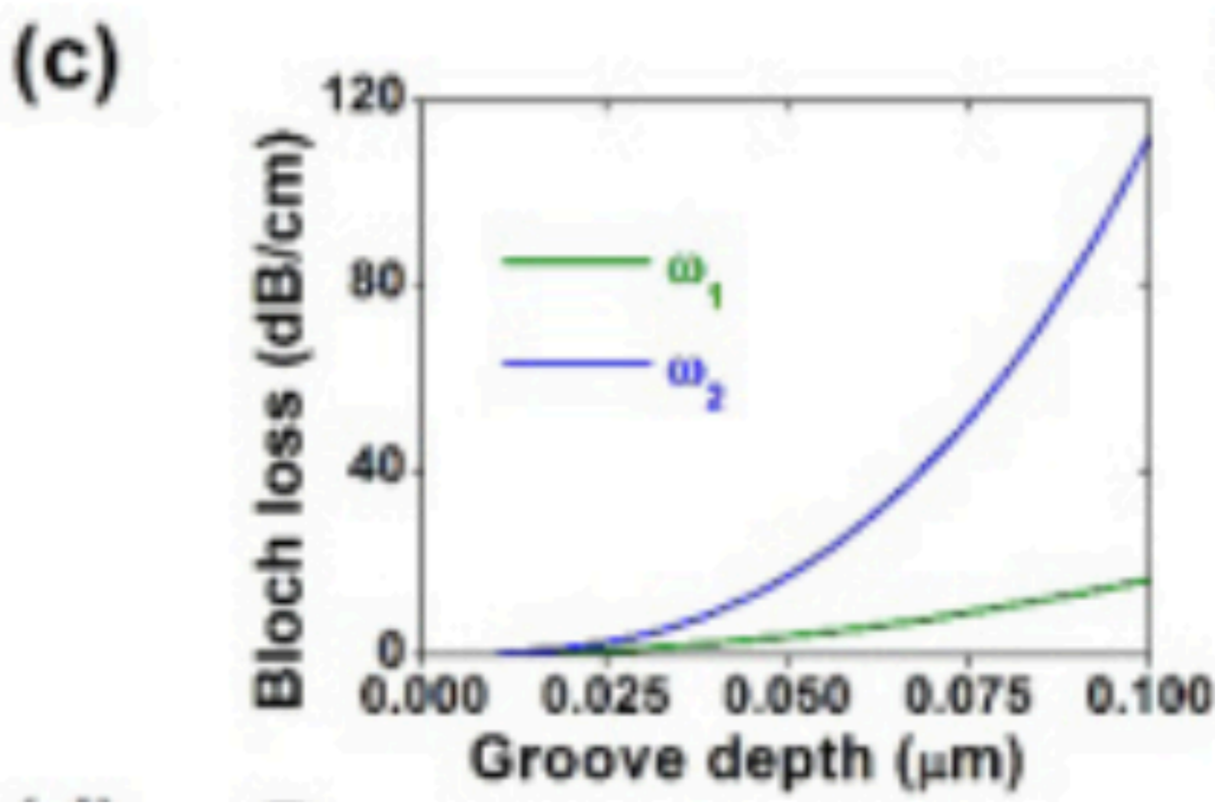


Example: Periodically Grooved LN-on-Insulator Waveguide



https://doi.org/10.1364/OE.25.006963





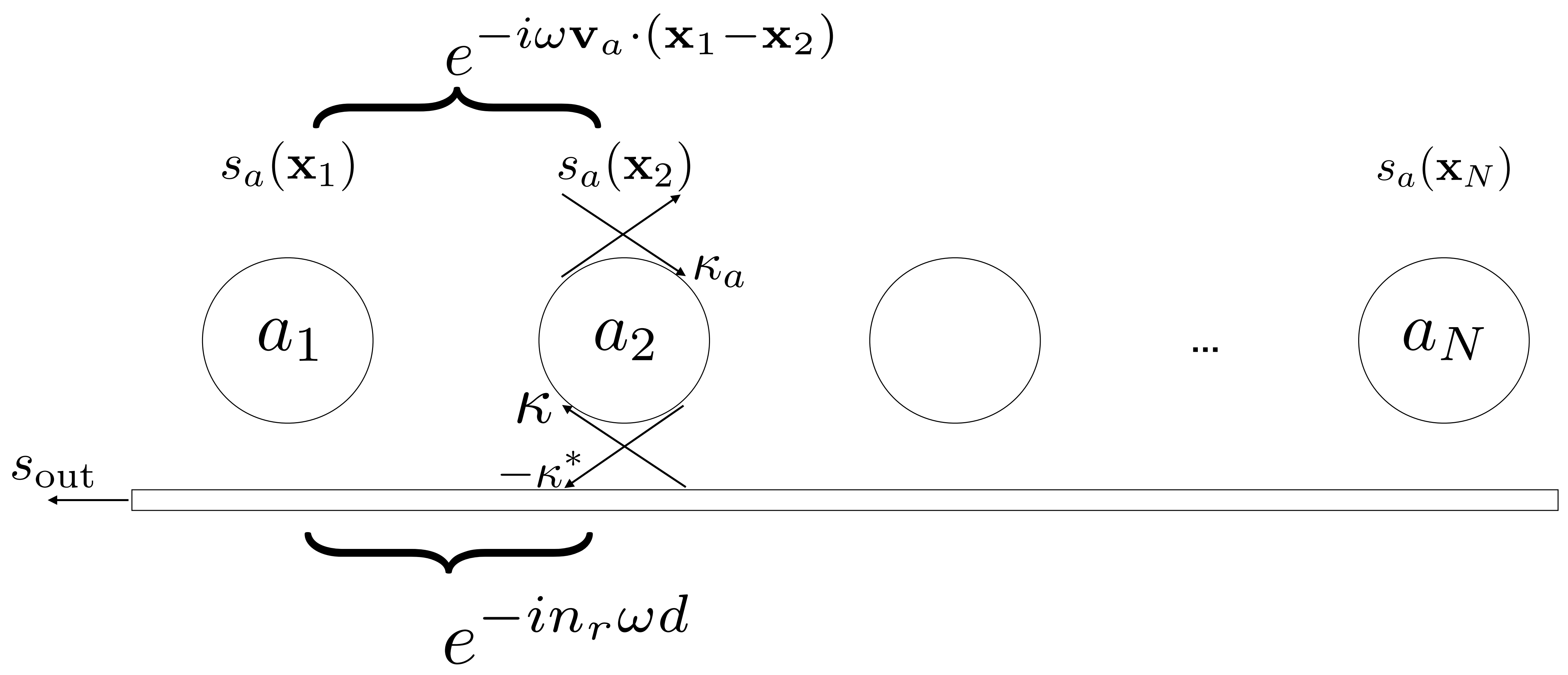
Q can be affected by:

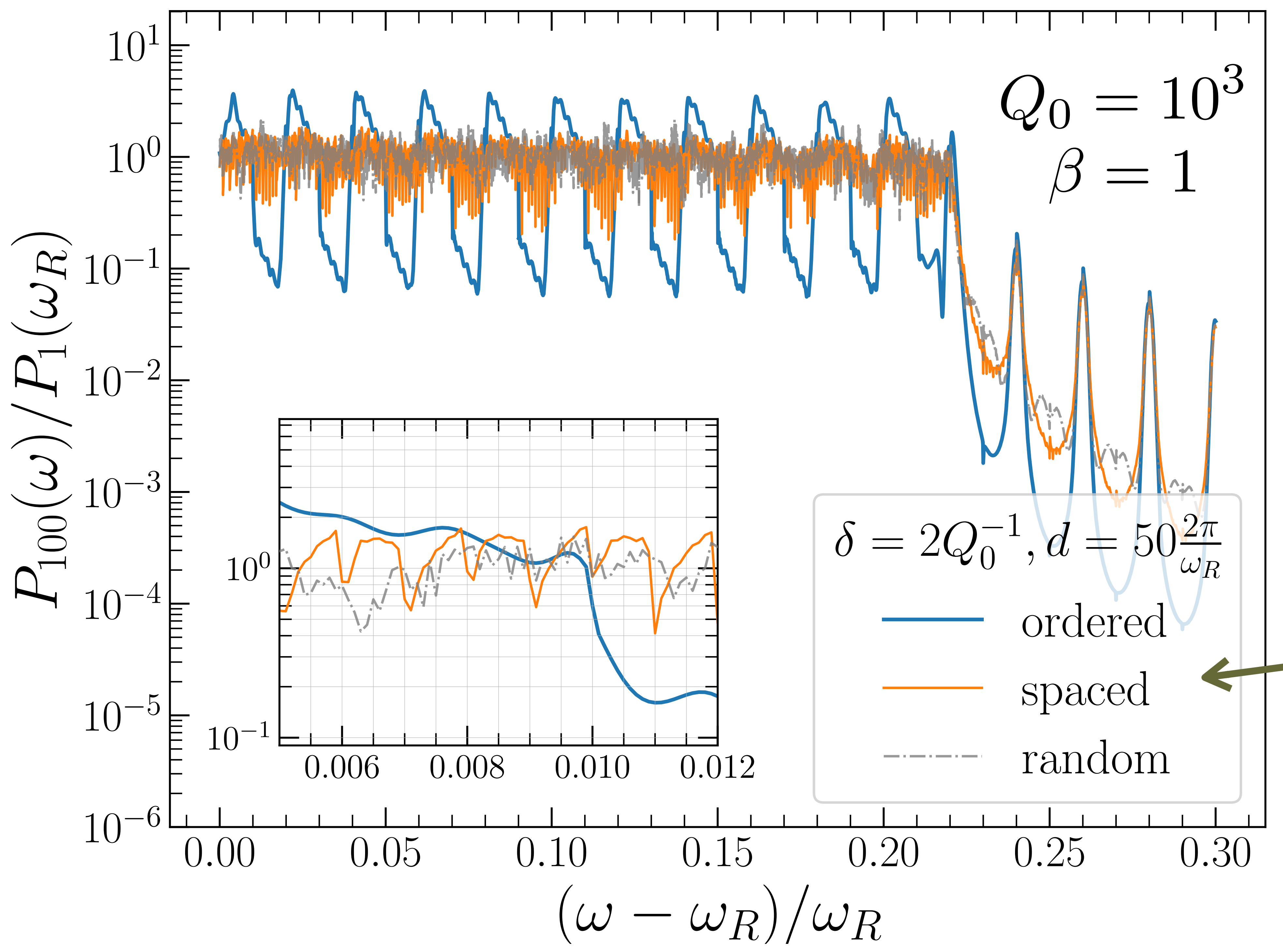
- Surface/volume scattering loss
- Bending/radiation loss
- Absorption by the material

$$Q \approx \frac{\pi n_{\rm eff}}{\alpha \lambda_0} \sim 10^3 \left(\frac{180\,\frac{\rm dB}{\rm cm}}{\mathcal{L}}\right)\left(\frac{1.5\mu{\rm m}}{\lambda_0}\right)\left(\frac{n_{\rm eff}}{2}\right)$$

Different Frequencies

$$\omega_R(1+\delta)^{i-1}, i = 1, 2, \cdots, N$$



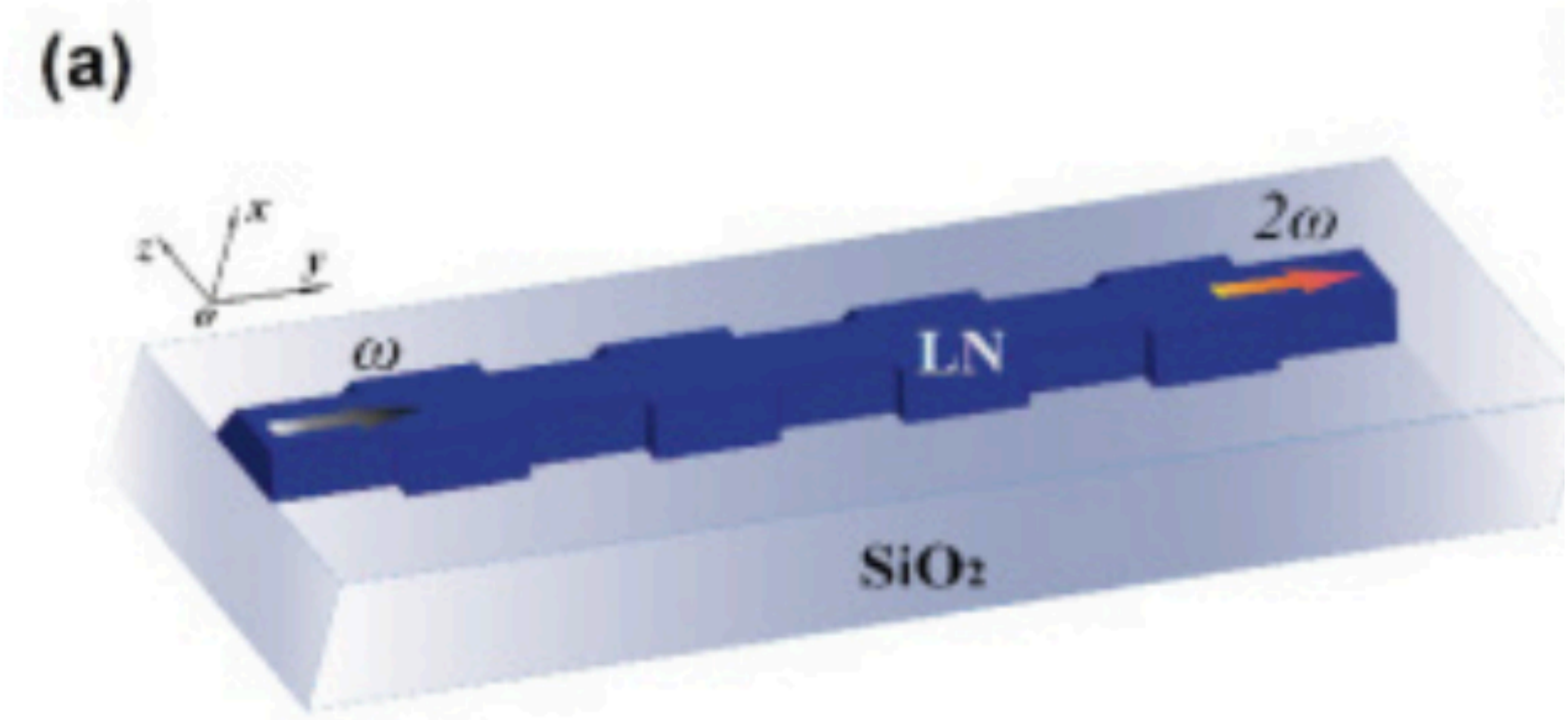


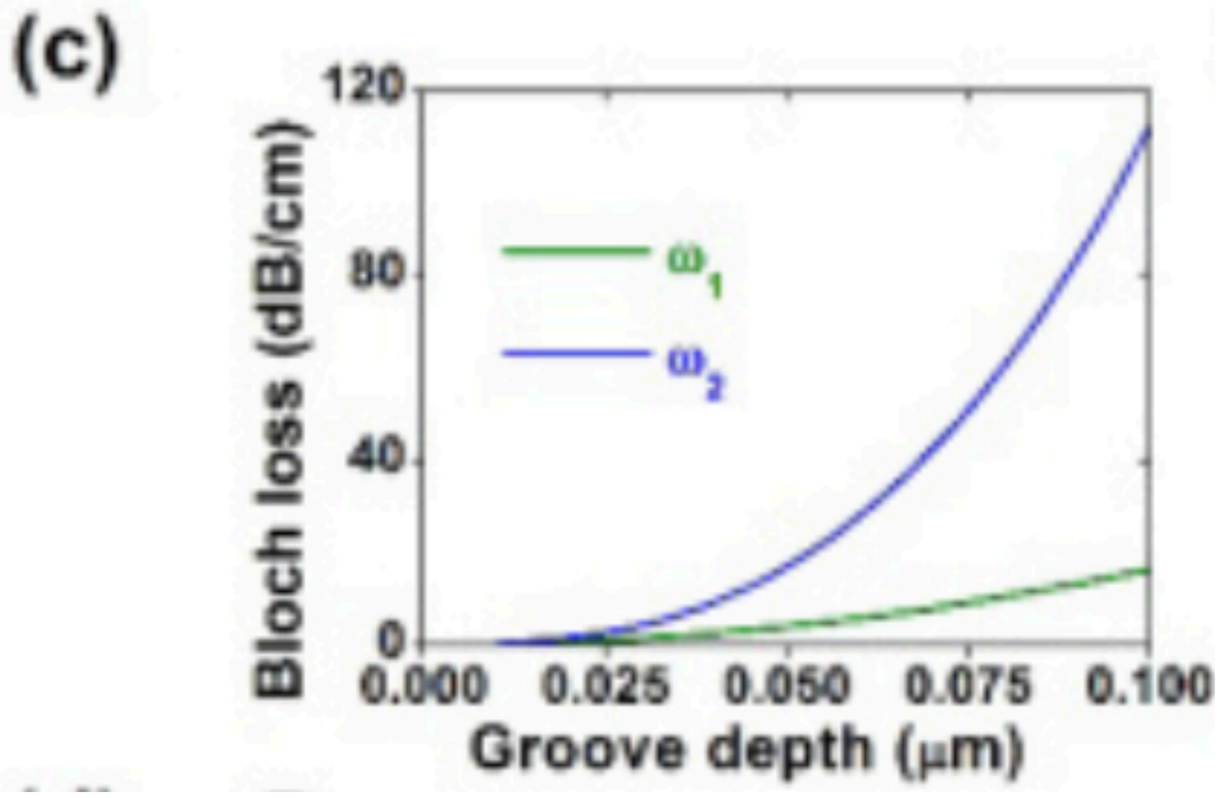
For lth resonator $\omega_R(1+\delta)^{g(l)}$

$$g(l) = \begin{cases} \lfloor \frac{l}{10} \rfloor + \frac{N}{10}((l \bmod 10) - 1) + 1 & l \bmod 10 \neq 0 \\ (l + 9N)/10 & l \bmod 10 = 0 \end{cases}$$

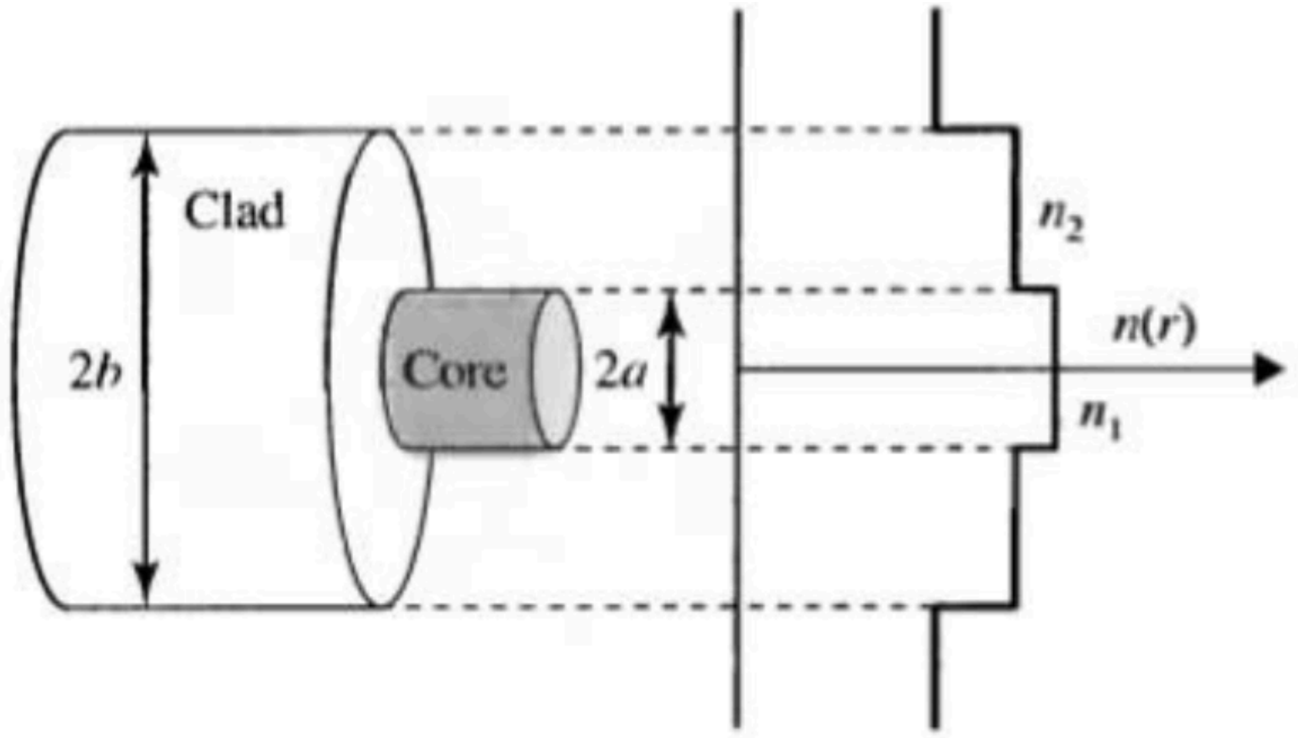
Effective Index Theory

https://doi.org/10.1364/OE.25.006963

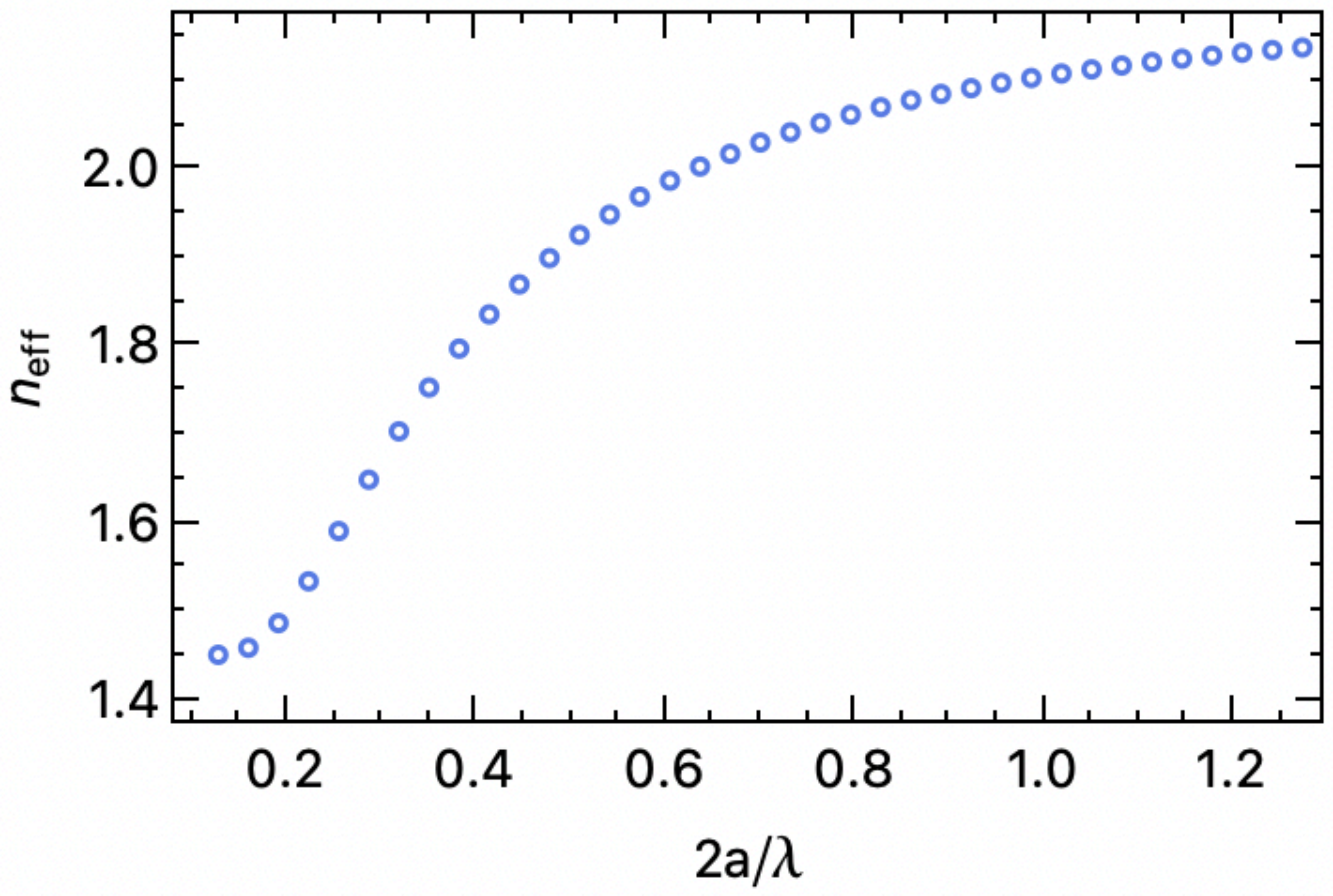




How big can n_{eff} be changed by grooving?

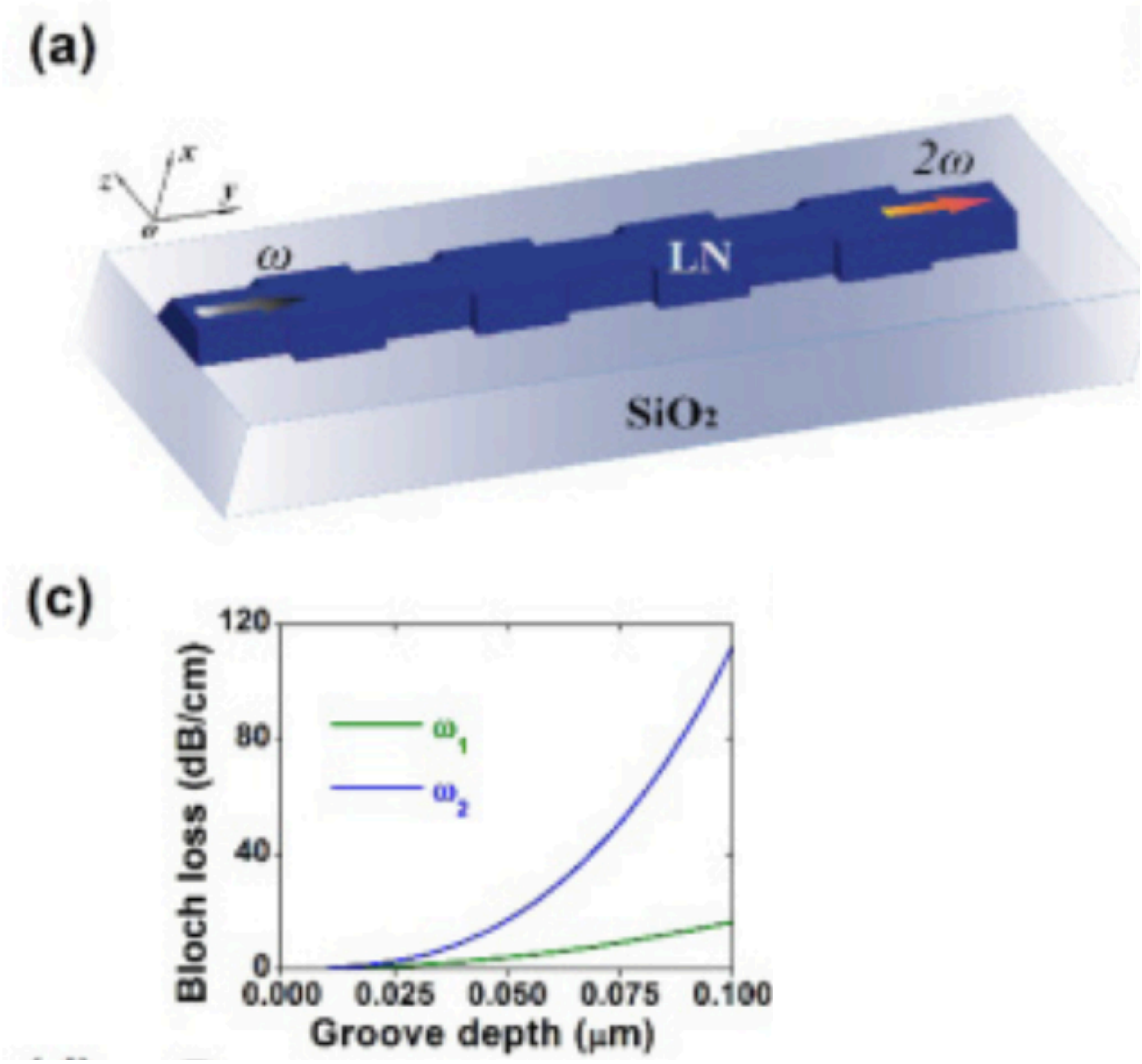


$$n_1 = 2.2, n_2 = 1.45, \mathrm{LP}_{01}$$



Surface Scattering Loss

https://doi.org/10.1364/OE.25.006963



$$P_L = P_0 e^{-\alpha L}$$

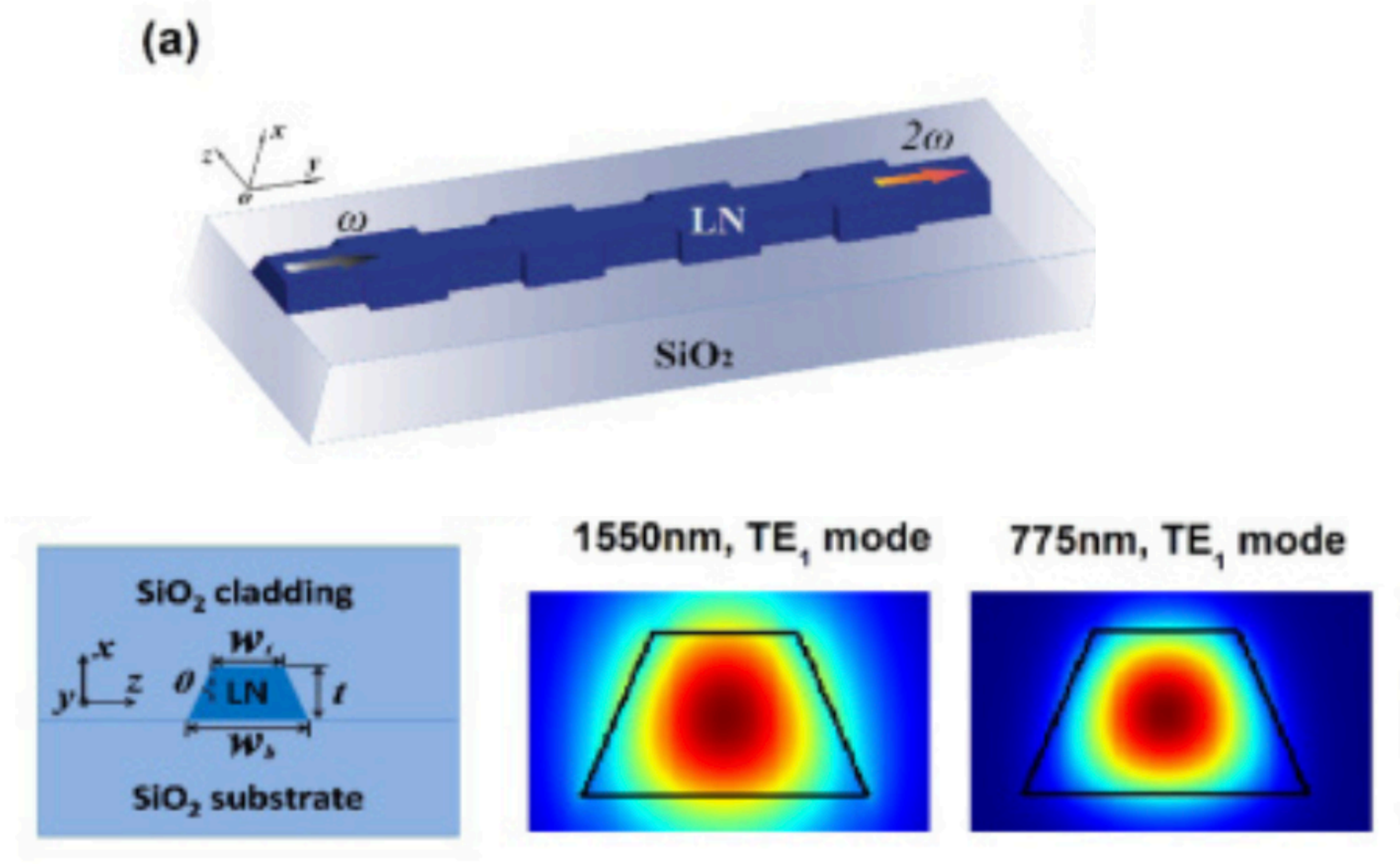
Surface Scattering Loss

$$Q \approx \frac{\pi n_{\text{eff}}}{\alpha \lambda_0} \sim 10^3 \left(\frac{180\, \frac{\text{dB}}{\text{cm}}}{\mathcal{L}} \right) \left(\frac{1.5\mu\text{m}}{\lambda_0} \right) \left(\frac{n_{\text{eff}}}{2} \right)$$

for L << 1 cm

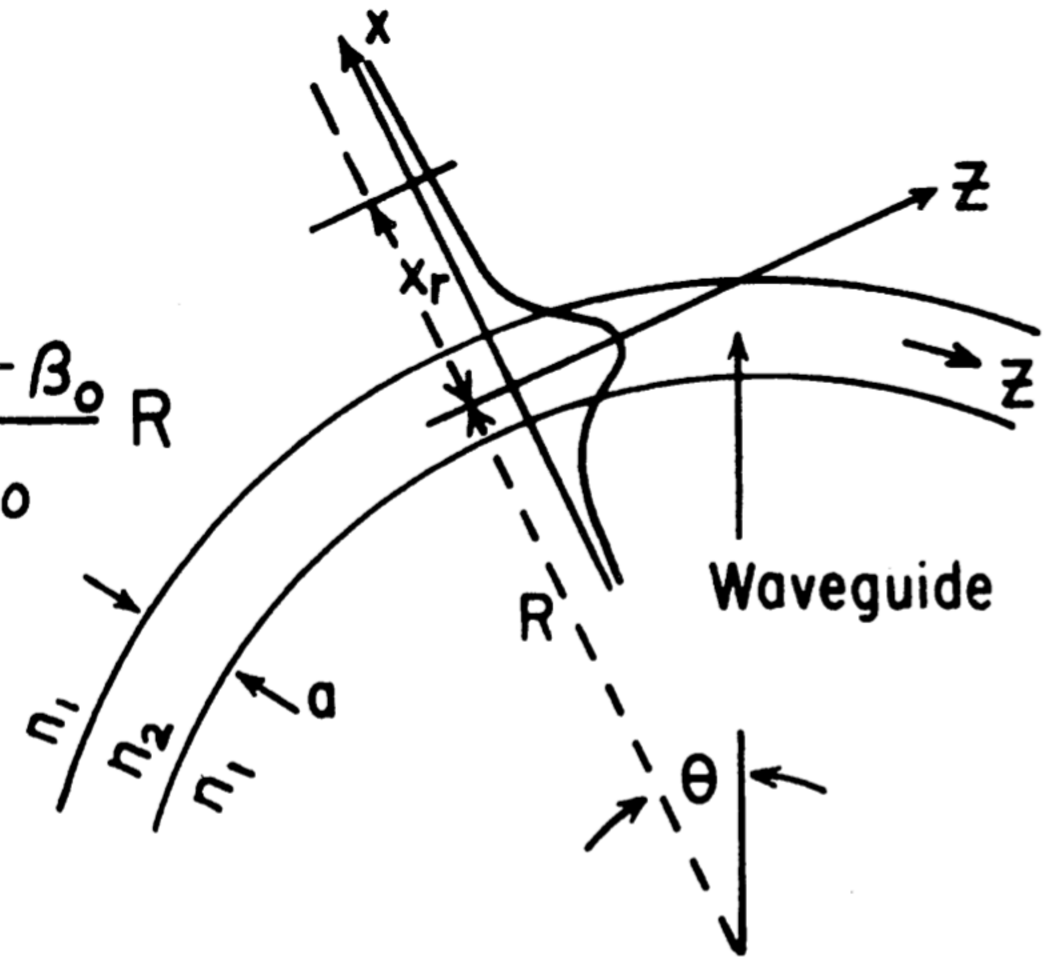
Radiation Loss

https://doi.org/10.1364/OE.25.006963



$$P_L = P_0 e^{-\alpha L}$$

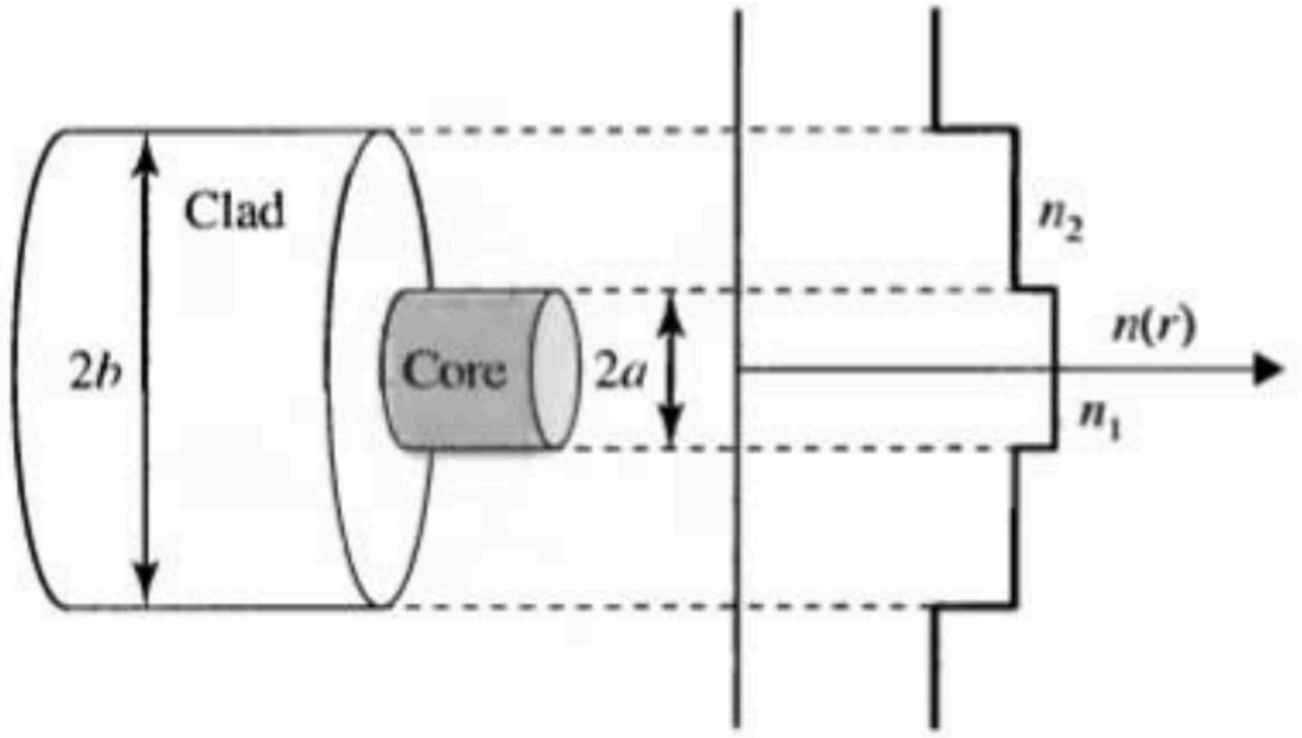
Radiation/bend Loss



$$x_r = \frac{\beta_z - \beta_0}{\beta_0} R$$

$$\alpha_{\rm rad} \simeq \frac{P_{\rm loss}}{P_{\rm t}} \frac{1}{Z_c}$$

Radiation Loss



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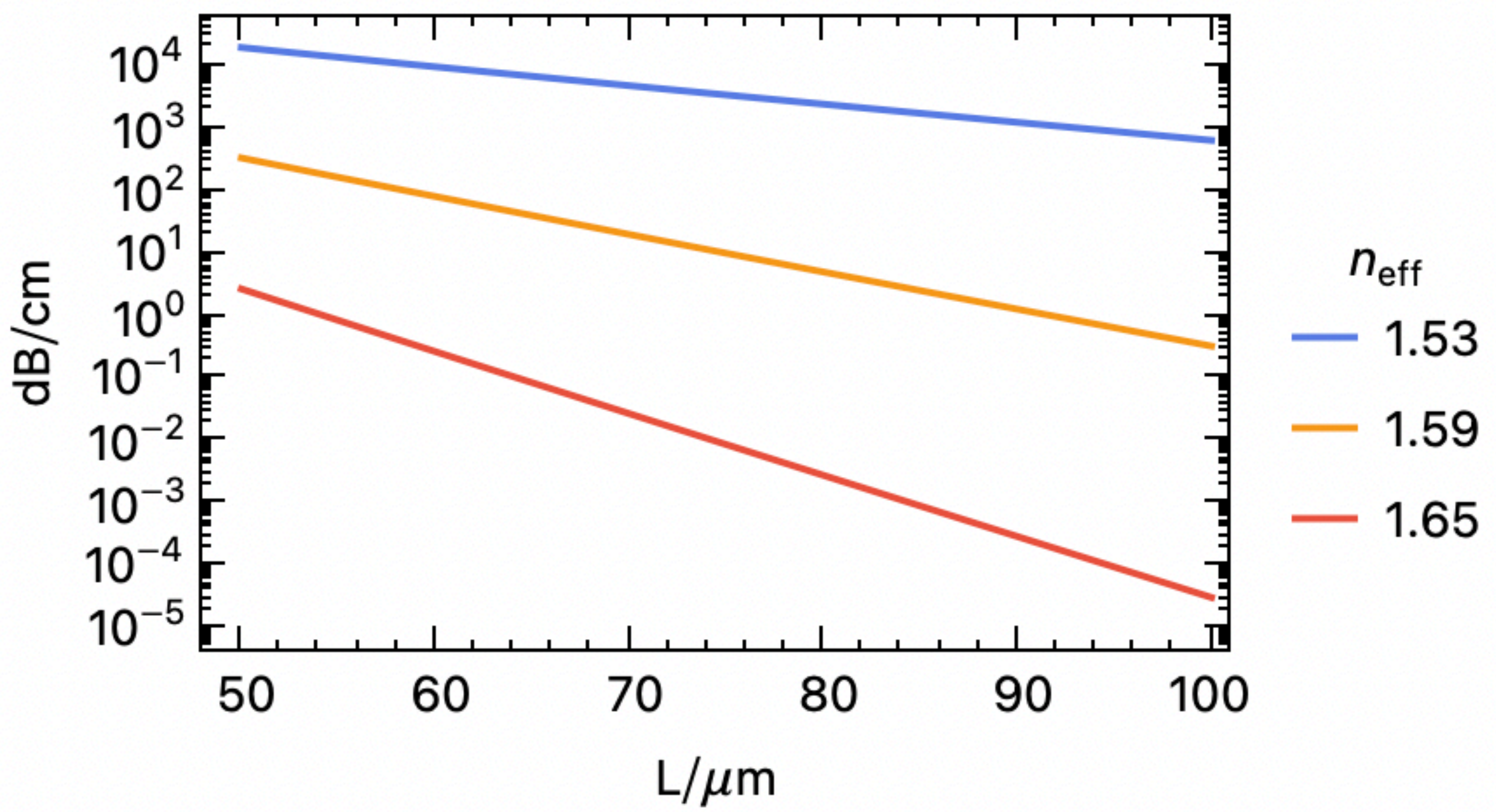
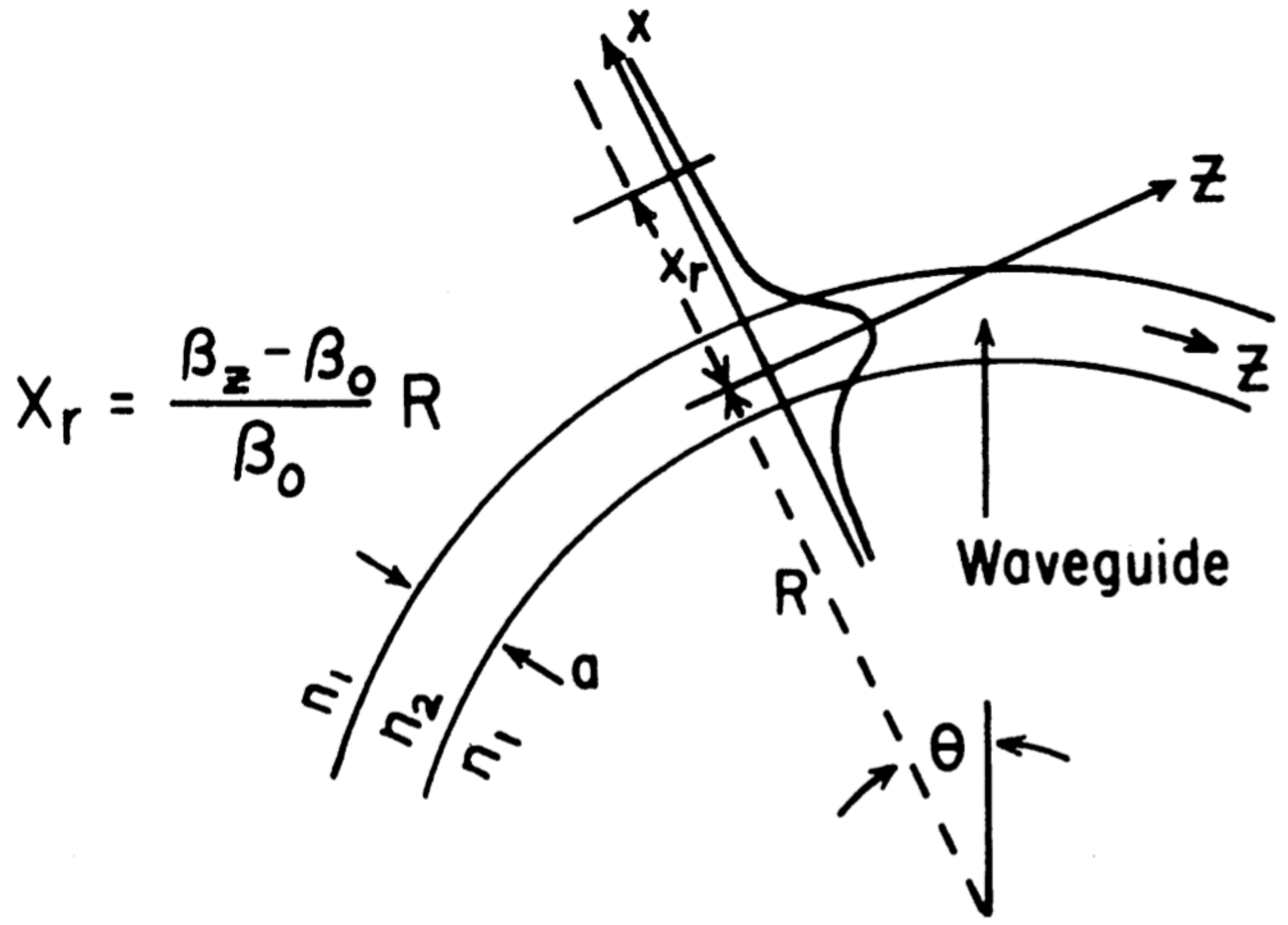


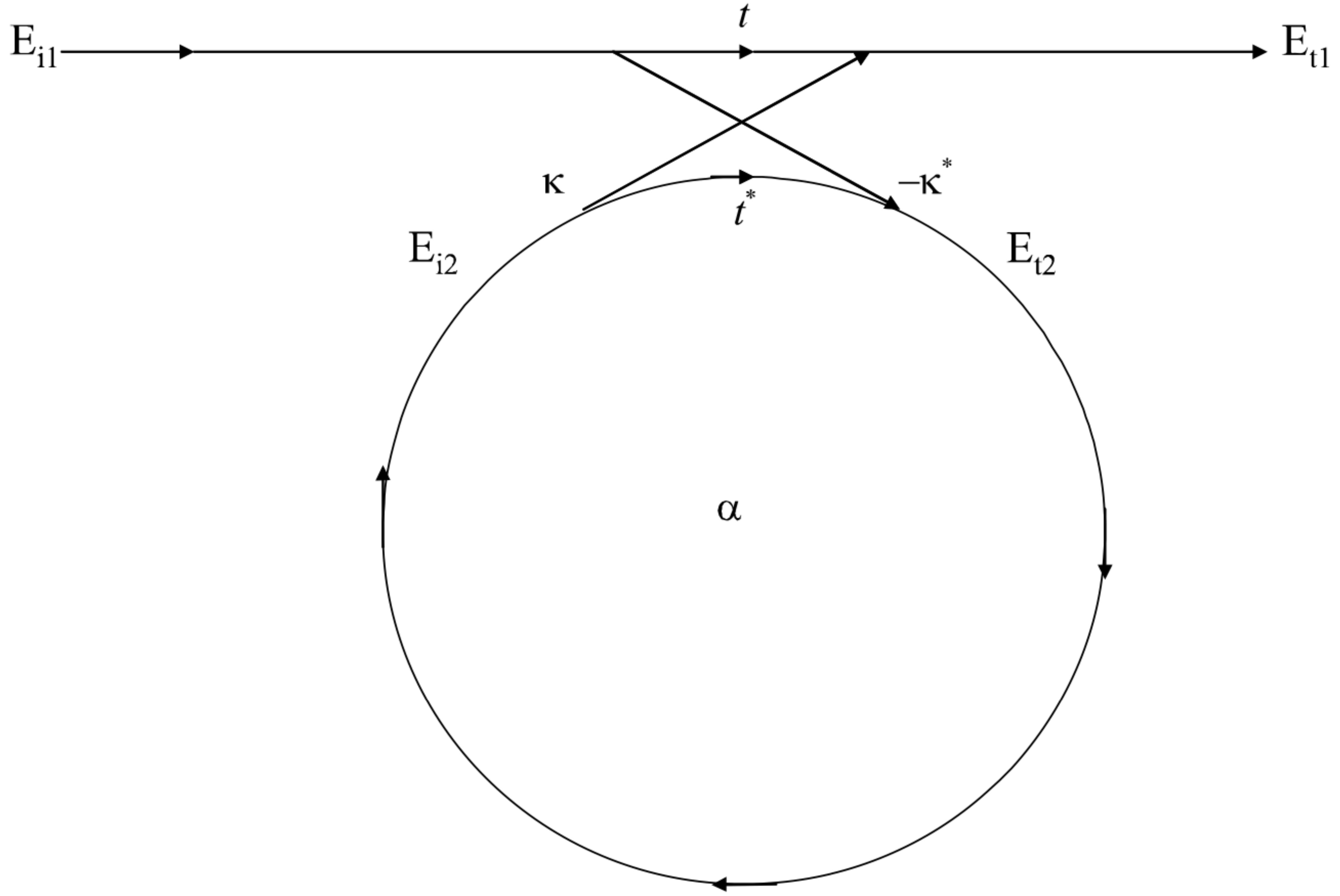
$$P_L = P_0 e^{-\alpha L}$$

Radiation/bend Loss



$$\alpha_{\mathrm{rad}} \simeq \frac{P_{\mathrm{loss}}}{P_{\mathrm{t}}} \frac{1}{Z_c}$$

Ring Resonator

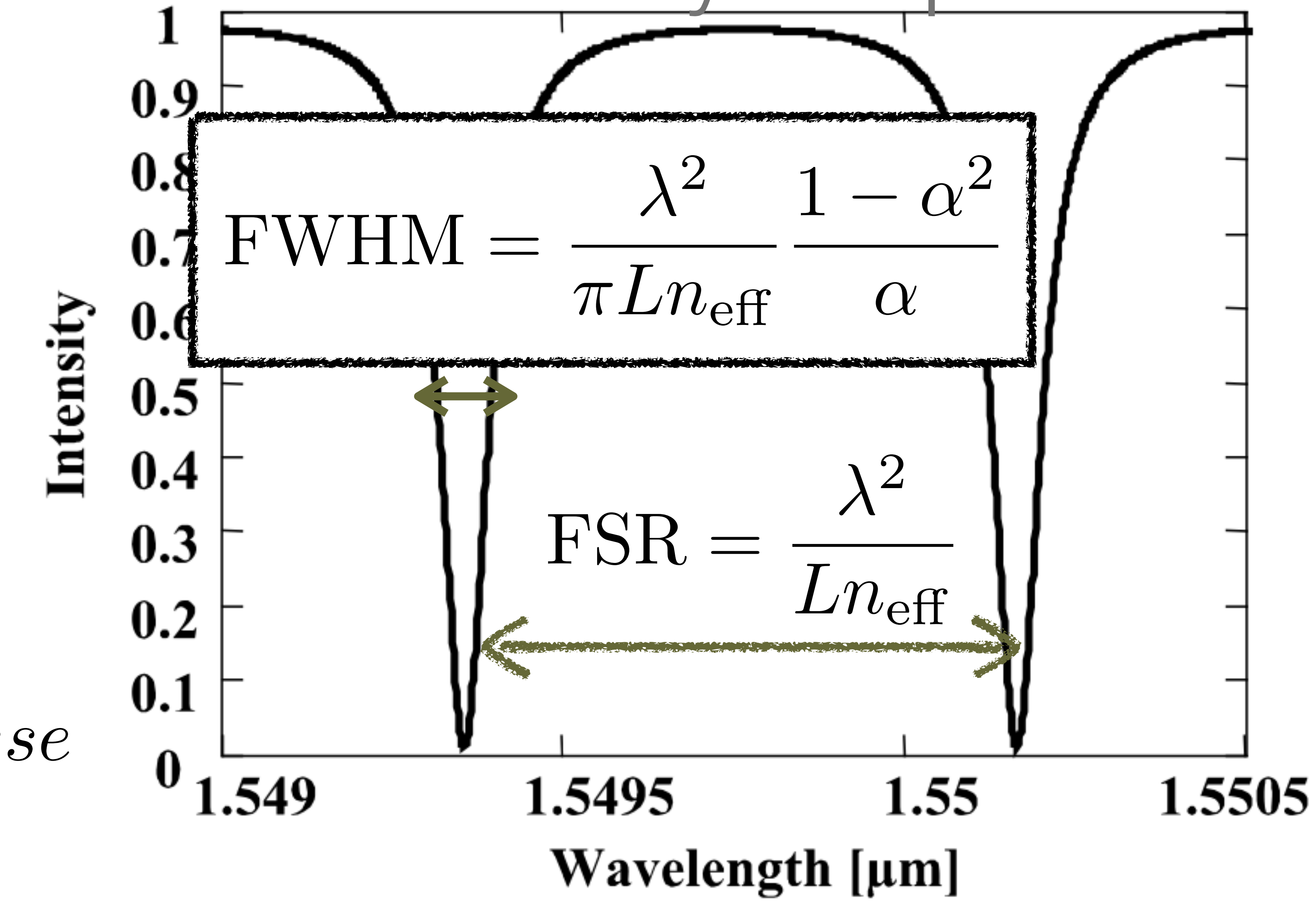


$$\begin{pmatrix} E_{t1} \\ E_{t2} \end{pmatrix} = \begin{pmatrix} t & \kappa \\ -\kappa^* & t^* \end{pmatrix} \begin{pmatrix} E_{i1} \\ E_{i2} \end{pmatrix} \qquad |\kappa^2| + |t^2| = 1$$

$$E_{i2} = \alpha \cdot e^{j\theta} E_{t2} \qquad \theta \approx n_{\text{eff}} \omega L$$

Loss

critically coupled

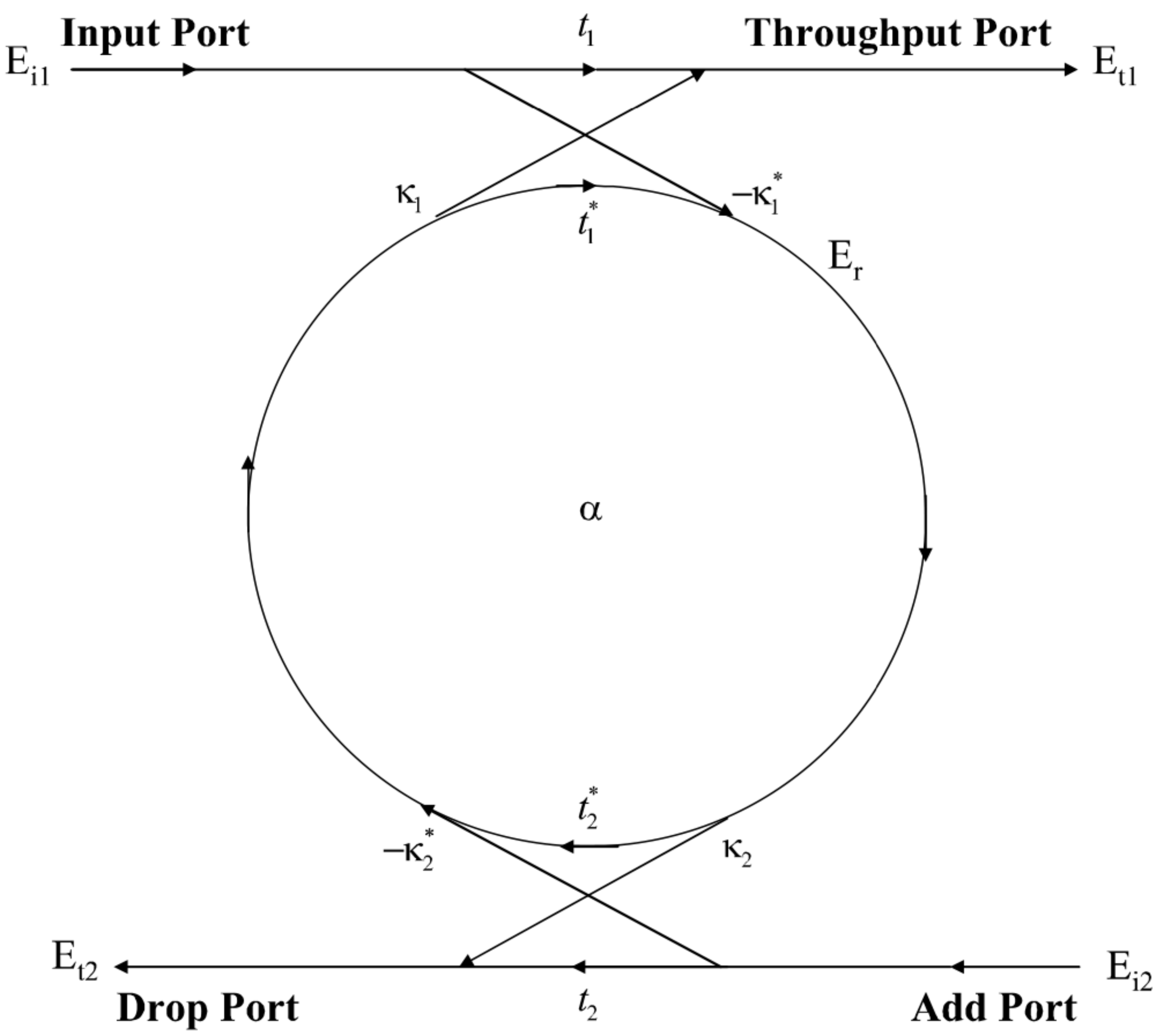


$$\text{FWHM} = \frac{\lambda^2}{\pi L n_{\text{eff}}} \frac{1-\alpha^2}{\alpha}$$

$$\text{FSR} = \frac{\lambda^2}{L n_{\text{eff}}}$$

$$Finesse = \frac{\text{FSR}}{\text{FWHM}} = \frac{1-\alpha^2}{\alpha\pi} \qquad Q = \frac{\lambda}{\text{FWHM}} = \frac{n_{\text{eff}} L}{\lambda} finesse$$

Ring Resonator



$$\begin{pmatrix} E_{t1} \\ E_{t2} \end{pmatrix} = \begin{pmatrix} t & \kappa \\ -\kappa^* & t^* \end{pmatrix} \begin{pmatrix} E_{i1} \\ E_{i2} \end{pmatrix} \qquad |\kappa^2| + |t^2| = 1$$

$$E_{i2} = \alpha \cdot e^{j\theta} E_{t2} \qquad \theta \approx n_{\text{eff}} \omega L$$

Loss

critically coupled