

Title: Dark Matter Search on Chips

Speakers: Christina Gao

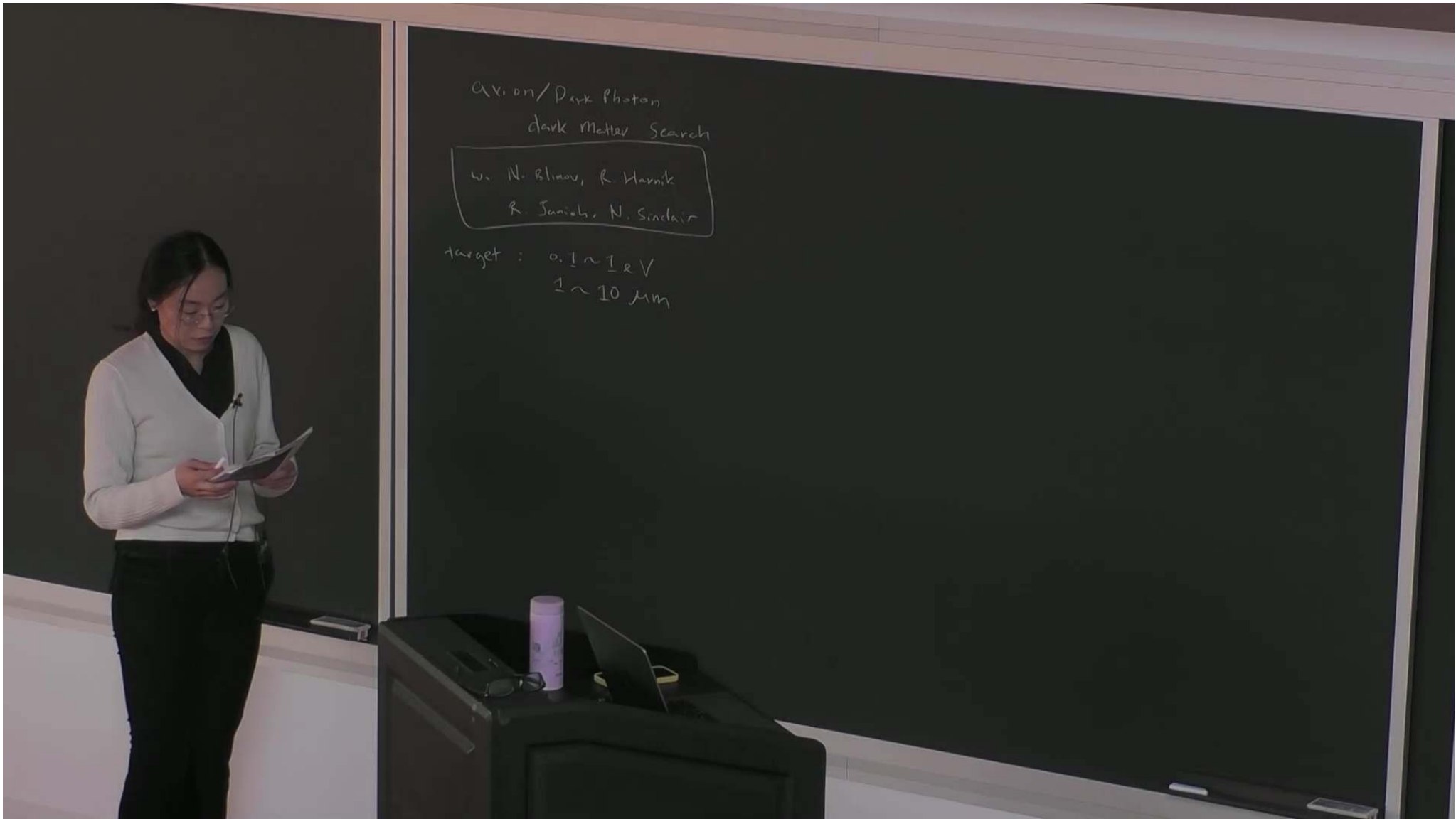
Series: Particle Physics

Date: November 03, 2023 - 1:00 PM

URL: <https://pirsa.org/23110047>

Abstract: Axions and axion-like particles are well motivated candidates for dark matter (DM) and have a signature two photon vertex. The most sensitive axion DM search is at the gigahertz (GHz) regime. It relies on microwave cavities with high quality factors resonantly converting axion DM to cavity photons in the background of a static magnetic field. However, axion DM mass could span a vast range above or below GHz. We describe a new proposal using integrated/on-chip photonic systems to search for axion DM at the optical frequency. This enables the use of waveguides to collect signal photons, which improves the detection efficiency, as well as the use of single photon, micron-sized detector, such as a skipper charge-coupled device, which has a dark count rate as low as $1e-9$ per second per pixel. Furthermore, by coupling a series of resonators of different frequencies to a single receiver bus, the detection can be broadband in terms of the axion masses and has sensitivities to the axion-photon couplings expected for the QCD axion at the axion masses of around 0.2 eV.

Zoom link <https://pitp.zoom.us/j/94515300239?pwd=VVBkaGM5K24yN2F4SFV0MGZ5Vk9LZz09>



Axion/Dark Photon
dark Matter Search

w. N. Blinov, R. Harnik

R. Janich, N. Sinclair

$$g_{ax} \propto \vec{E} \cdot \vec{B}$$

$$= \int F_{\mu\nu} F'^{\mu\nu}$$

target : $0.1 \sim 1 \text{ eV}$
 $1 \sim 10 \text{ mm}$

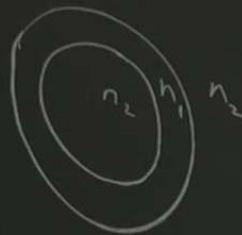
visible, NIR : $\approx 2 \mu\text{m}$
MIR : $2 \sim 5 \mu\text{m}$
LWIR : $< 11 \mu\text{m}$

Optical Resonator:

clad n_2

core n_1

$$\theta > \theta_c = \sin^{-1} \left(\frac{n_2}{n_1} \right)$$



$$L = m \times \frac{\lambda_c}{n_n}$$

axion/ Dark Photon
dark Matter Search

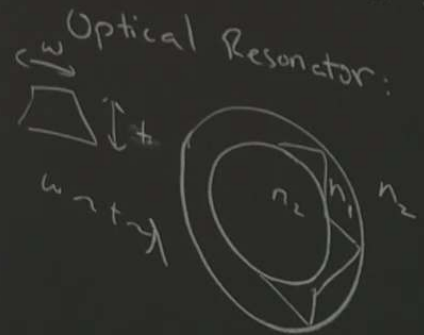
W. N. Rindler-Schjerve, R. Harnik
R. Janish, N. Sinclair

$$g_{ax} \propto \vec{E} \cdot \vec{B}$$

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target : $0.1 \sim 1 \text{ eV}$
 $1 \sim 10 \mu\text{m}$

visible, NIR : $\leq 2 \mu\text{m}$
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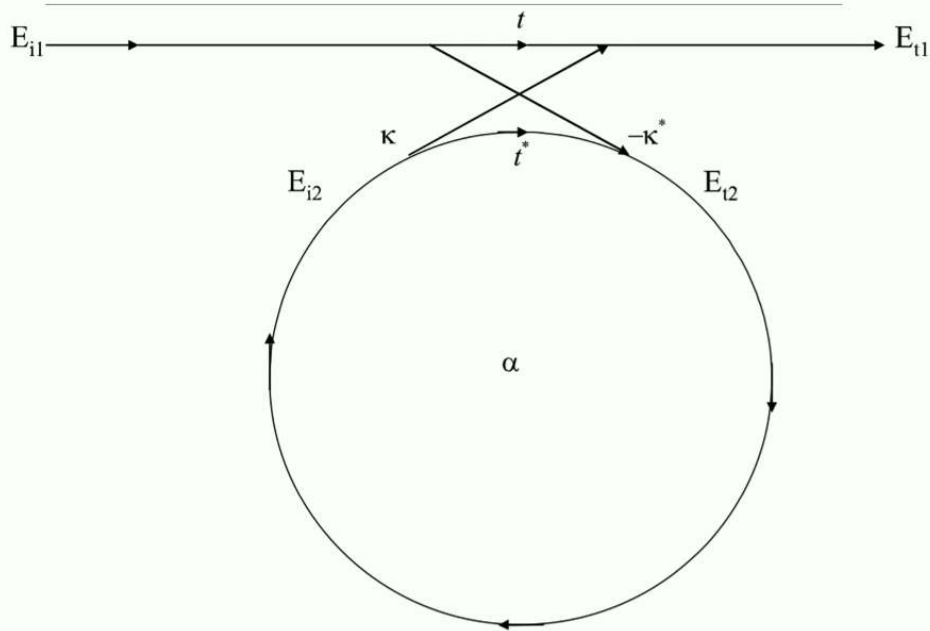
Optical Resonator: clad n_2
core n_1

$$\theta > \theta_c = \sin^{-1} \left(\frac{n_2}{n_1} \right)$$

$$L = m \times \frac{\lambda_0}{n_1}$$

$\mathcal{O}(100)$

Ring Resonator

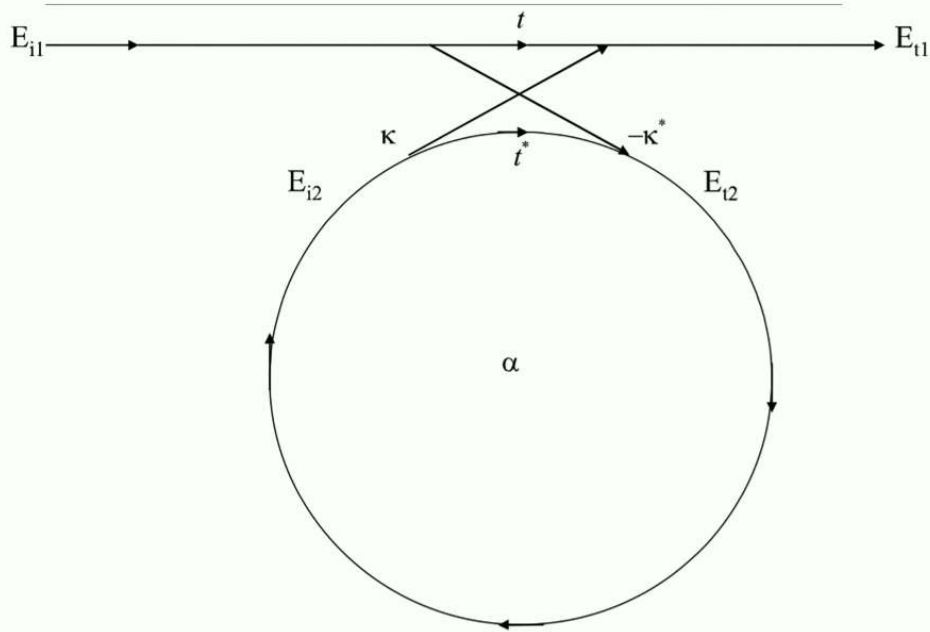


$$\begin{pmatrix} E_{t1} \\ E_{t2} \end{pmatrix} = \begin{pmatrix} t & \kappa \\ -\kappa^* & t^* \end{pmatrix} \begin{pmatrix} E_{i1} \\ E_{i2} \end{pmatrix} \quad |\kappa^2| + |t^2| = 1$$

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

LOSS

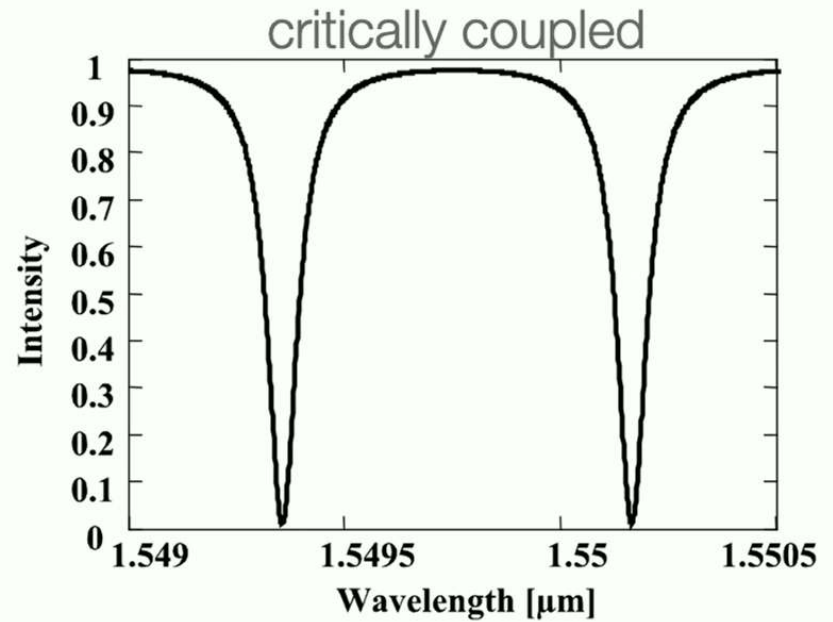
Ring Resonator



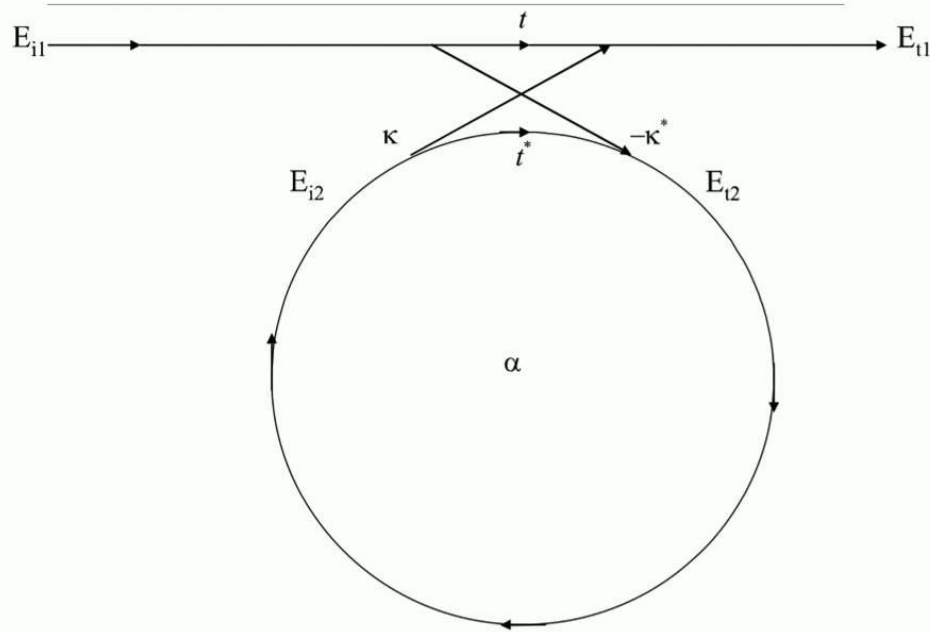
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Loss



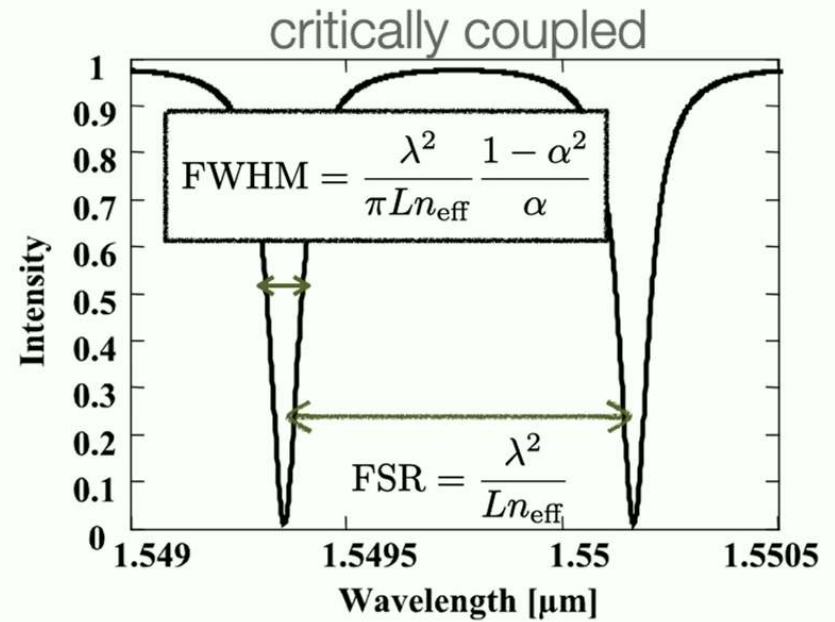
Ring Resonator



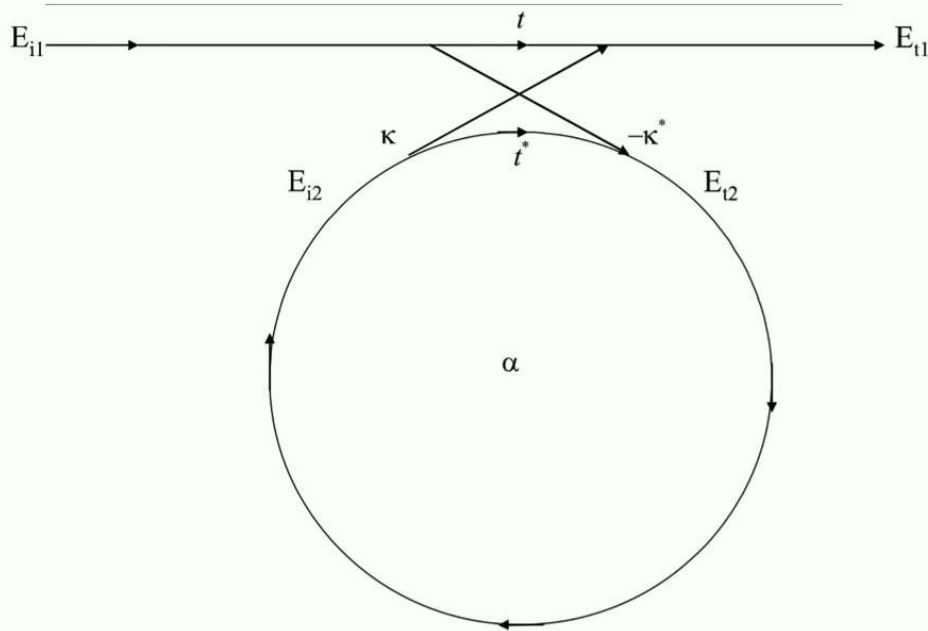
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Loss



Ring Resonator



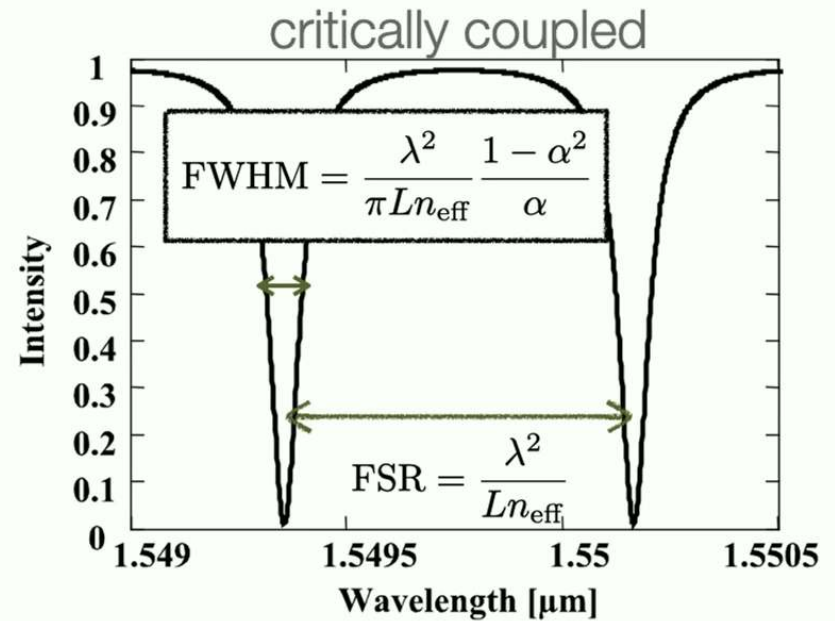
$$Finesse = \frac{FSR}{FWHM} = \frac{1 - \alpha^2}{\alpha\pi}$$

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

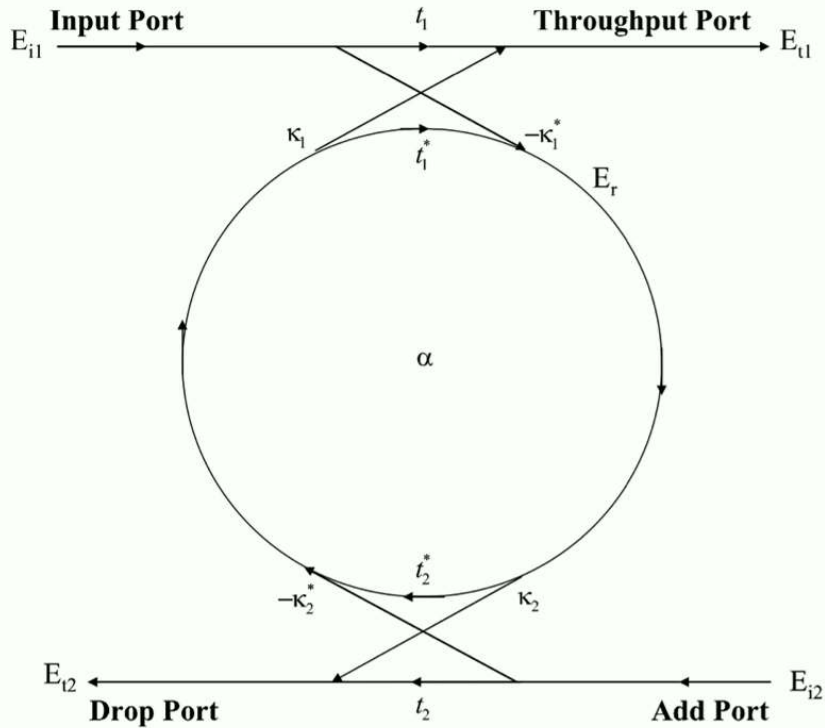
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Loss



Ring Resonator

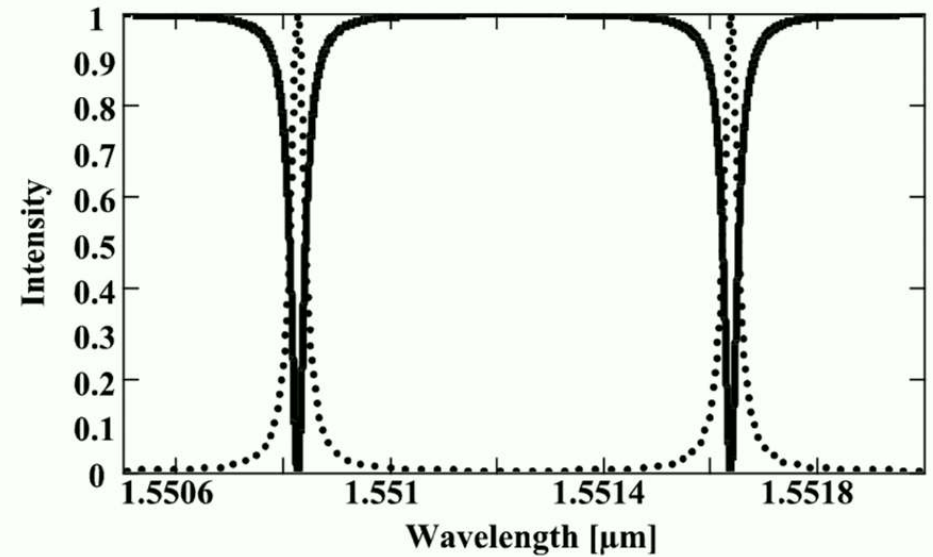


$$Q = \frac{\lambda}{\text{FWHM}} = \frac{n_{\text{eff}}L}{\lambda} \text{ finesse}$$

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

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

LOSS





$$\lambda_{015} = \frac{h}{p} = \frac{2\pi}{m_0} 10^3$$

λ

$$P_{1\text{cavity}}^{\text{crit}} = \frac{P_0 Q}{4} C_i^2 |\eta|^2$$

$$P_0 = \rho_0 v \omega_0$$

$$C_i^2 = \begin{cases} \left(\frac{g_{cr} B}{\omega_0}\right)^2 & \text{axion} \\ x^2/3 & \text{DR} \end{cases}$$

$$|\eta|^2 = \frac{\int \frac{d^3x}{v} \int \frac{d^3x'}{v} E(\alpha) E^*(\alpha') e^{-|x-x'|} \frac{1}{\lambda_{03}^2}}{\int \frac{d^3x}{v} \epsilon |E|^2}$$

$$g_{ax} = \frac{10}{\text{GeV}} \quad \lambda_{\text{DB}} = \frac{h}{p} = \frac{2\pi}{m_D} 10^3$$

$$P_{\text{sig}} \sim \frac{10^{-14}}{\text{sec}} \left(\frac{Q}{10^5} \right)$$

$$\left(\frac{B}{10^7} \right)^2 \left(\frac{V}{100 \text{ Mm}^3} \right)$$

$$P_{\text{cavity}} = \frac{P_0 Q}{4} C_i^2 |\eta|^2$$

$$P_0 \equiv P_0 V \omega_0$$

$$C_i^2 = \begin{cases} \left(\frac{g_{ax} B}{\omega_0} \right)^2 & \text{axion} \\ x^2/3 & \text{DP} \end{cases}$$

$$|\eta|^2 = \frac{\int \frac{dx}{v} \int \frac{dx'}{v} E(x) E^*(x') e^{-\frac{|x-x'|^2}{\lambda_{\text{DB}}^2}}}{\int \frac{dx}{v} \epsilon |E|^2}$$

phase matching
 ~ 0.1

$$g_{ax} = \frac{10}{\text{GeV}}$$

$$\lambda_{\text{ph}} = \frac{h}{p} = \frac{2\pi}{m_D} 10^3$$

$$P_{\text{sig}} \sim \frac{10^{-14}}{\text{sec}} \left(\frac{G}{10^5} \right)$$

$$\left(\frac{B}{10T} \right)^2 \left(\frac{V}{100 \mu\text{m}^3} \right)$$

$$P_{\text{cavity}} = \frac{P_0 Q}{4} c_i^2 |\eta|^2$$

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$$\int \frac{dx}{v} \epsilon |E|^2$$

phase matching
~ 0.1

axion/Dark Photon
dark Matter Search

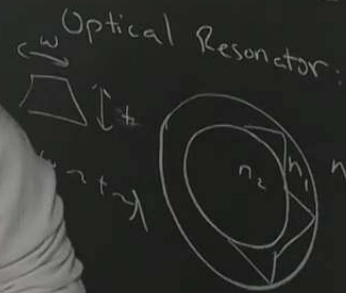
w. N. Blinov, R. Harnik
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$$g_{ax} \propto \vec{E} \cdot \vec{B}$$

$$\sum F_{\mu\nu} F'^{\mu\nu}$$

target : 0.1 ~ 1 eV
1 ~ 10 μm

visible, NIR: < 2 μm
MIR: 2 ~ 5 μm
LWIR: < 11 μm



$$\theta > \theta_c = \sin^{-1} \left(\frac{n_2}{n_1} \right)$$

$$L = \frac{m \lambda_0}{n_1}$$

Q(100)



① phase Match $|\eta|^2 \approx 0.1$

② need # Resonators
 but NOT # Readout $g_{ax} = \frac{10^{-10}}{\text{GeV}}$

③ Going beyond λ_{DB}

$$\lambda_{DB} = \frac{h}{p} = \frac{2\pi}{m_D} 10^3$$

$$P_{sig} \sim \frac{10^{-14}}{\text{sec}} \left(\frac{Q}{10^5} \right)$$

$$\left(\frac{B}{10T} \right)^2 \left(\frac{V}{100 \text{mm}^3} \right)$$

$|\eta|^2$
↓
ph

Periodic Photonic Structure: Bloch Modes

$$\mathbf{E}_{\mathbf{K}} = \mathbf{u}_{\mathbf{K}}(\mathbf{r})e^{\pm i\mathbf{K}\cdot\mathbf{r}}, \quad \mathbf{u}_{\mathbf{K}}(\mathbf{r}) = \mathbf{u}_{\mathbf{K}}(\mathbf{r} + \mathbf{R}) \quad \varepsilon(\mathbf{r}) = \varepsilon(\mathbf{r} + \mathbf{R})$$

Bloch wavevector Lattice vector

Periodic Photonic Structure: Bloch Modes

$$\mathbf{E}_{\mathbf{K}} = \mathbf{u}_{\mathbf{K}}(\mathbf{r})e^{\pm i\mathbf{K}\cdot\mathbf{r}}, \quad \mathbf{u}_{\mathbf{K}}(\mathbf{r}) = \mathbf{u}_{\mathbf{K}}(\mathbf{r} + \mathbf{R}) \quad \varepsilon(\mathbf{r}) = \varepsilon(\mathbf{r} + \mathbf{R})$$

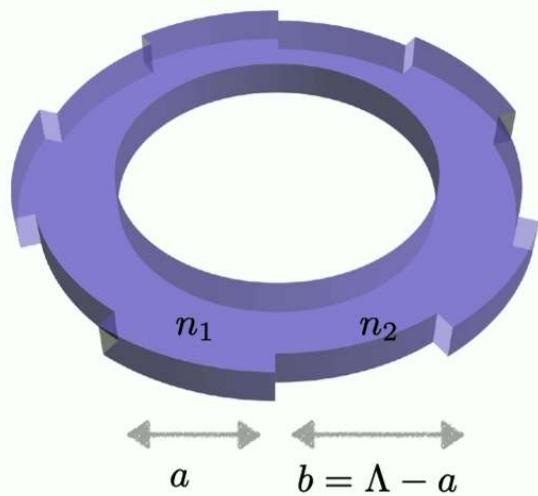
Bloch wavevector
Lattice vector

$$|\eta|^2 \equiv \frac{V^{-2} \int d\mathbf{x}' d\mathbf{x} \mathbf{E}_1^*(\mathbf{x}) \cdot \hat{\mathbf{n}} \mathbf{E}_1(\mathbf{x}') \cdot \hat{\mathbf{n}} e^{-(\mathbf{x}-\mathbf{x}')^2/\lambda_{\text{dB}}^2}}{V^{-1} \int d\mathbf{x} \varepsilon(\mathbf{r}) |\mathbf{E}_1(\mathbf{x})|^2}$$

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

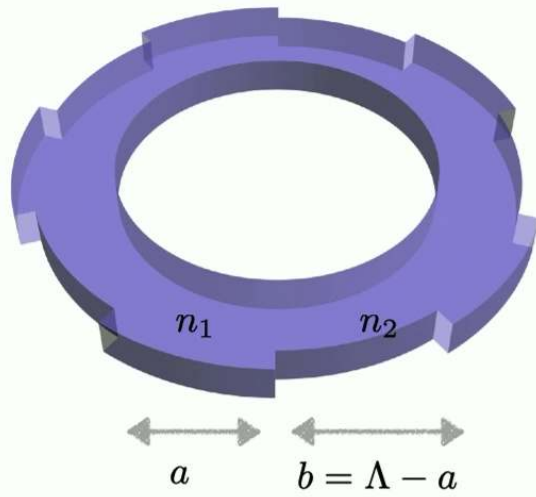
Resonator size $\ll \lambda_{\text{dB}}$

1D Toy Model



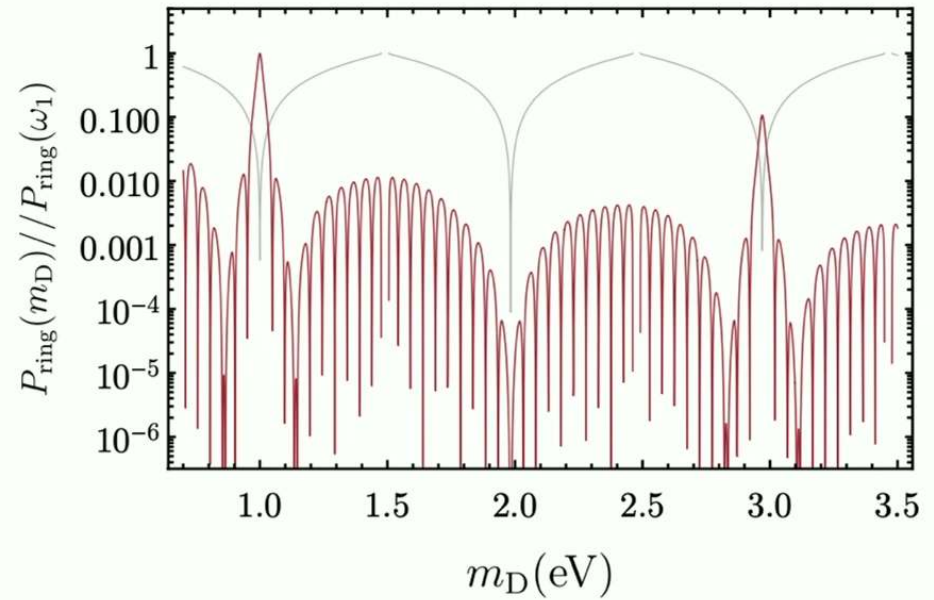
$$\beta_{1,2} = n_{1,2}\omega$$

1D Toy Model

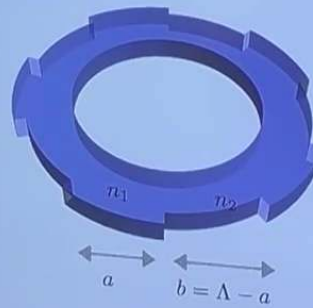


$$\beta_{1,2} = n_{1,2}\omega$$

20 unit cells with finesse 5 ($Q \sim 100$)

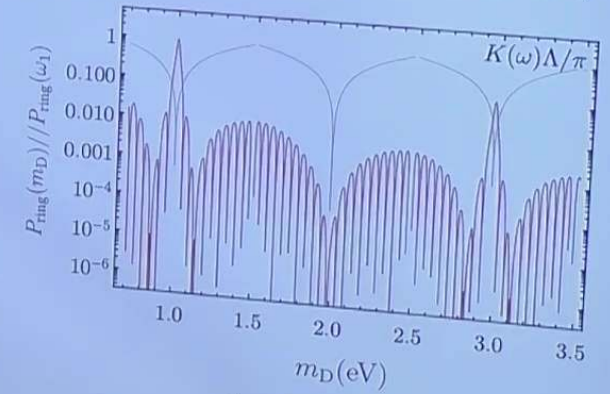


1D Toy Model



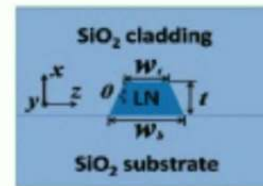
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20 unit cells with finesse 5 ($Q \sim 100$)

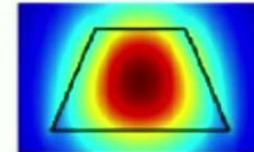


$$\eta_u \sim \frac{1}{n_2} - \frac{1}{n_1}$$

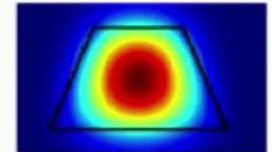
Example: Periodically Grooved LN-on-Insulator Waveguide



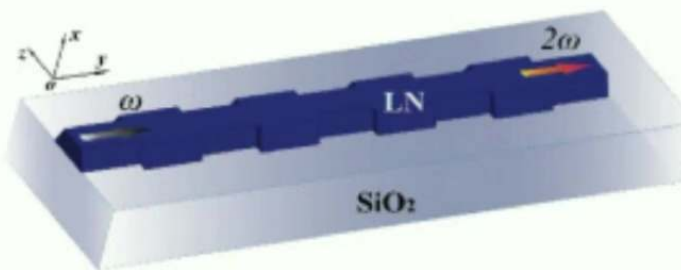
1550nm, TE₁ mode



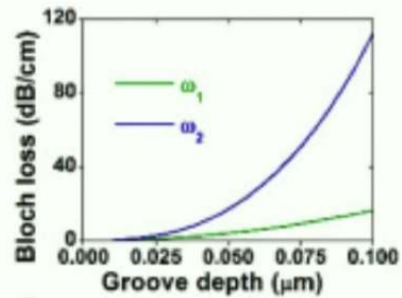
775nm, TE₁ mode



(a)



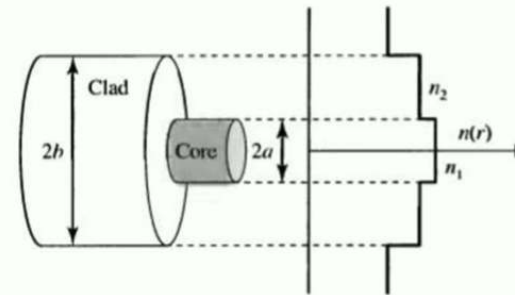
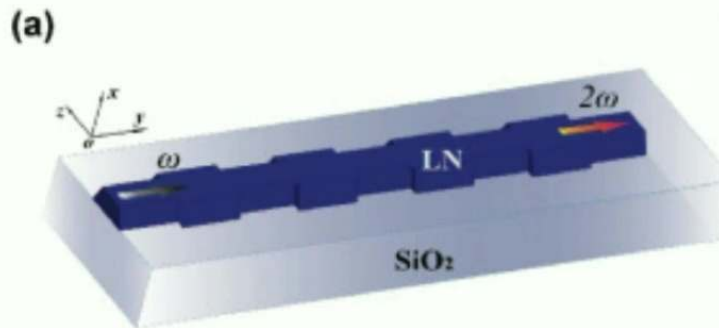
(c)



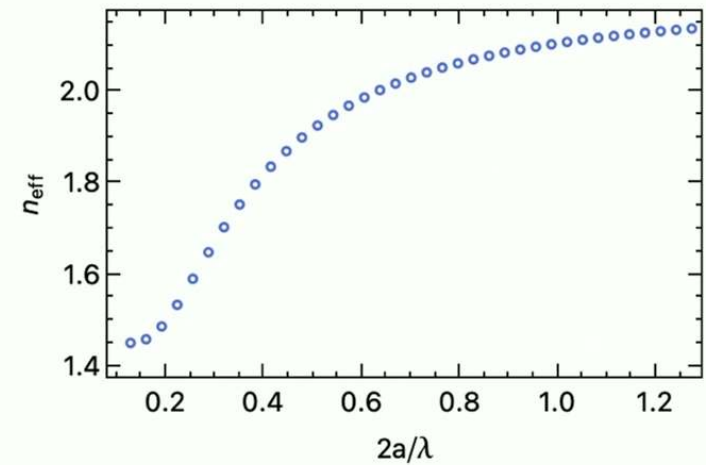
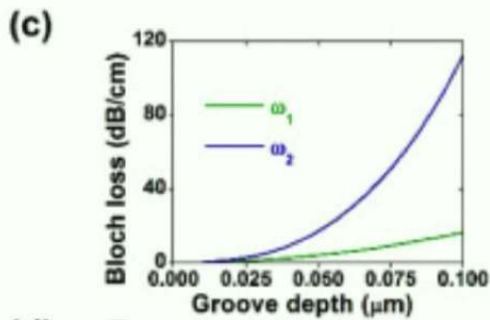
<https://doi.org/10.1364/OE.25.006963>

Effective Index Theory

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



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



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

Surface Scattering Loss

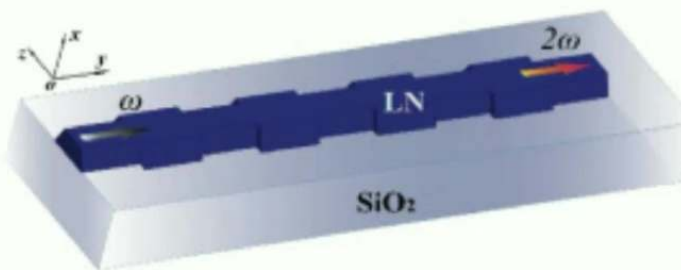
$$P_L = P_0 e^{-\alpha L}$$

Surface Scattering Loss

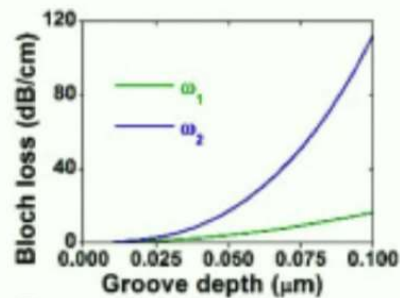
$$Q \approx \frac{\pi n_{\text{eff}}}{\alpha \lambda_0} \sim 10^3 \left(\frac{180 \frac{\text{dB}}{\text{cm}}}{\mathcal{L}} \right) \left(\frac{1.5 \mu\text{m}}{\lambda_0} \right) \left(\frac{n_{\text{eff}}}{2} \right)$$

for $L \ll 1 \text{ cm}$

(a)



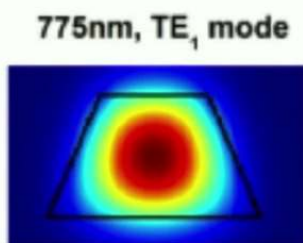
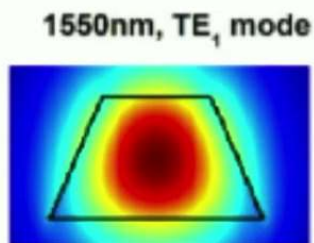
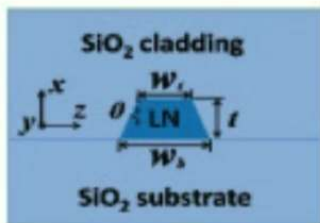
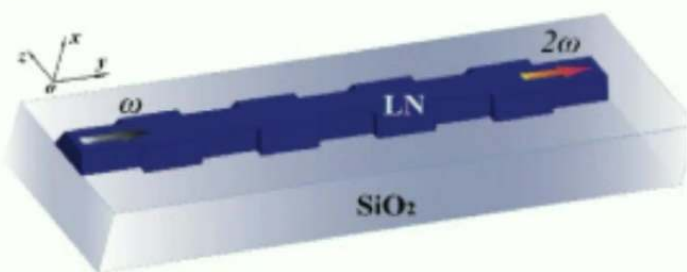
(c)



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

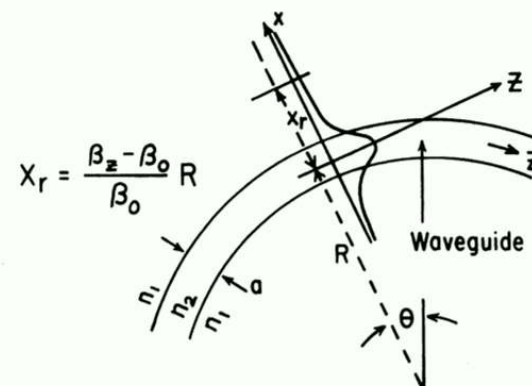
Radiation Loss

(a)



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

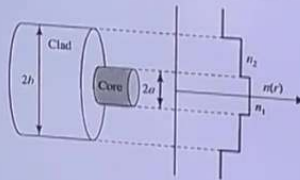
Radiation/bend Loss



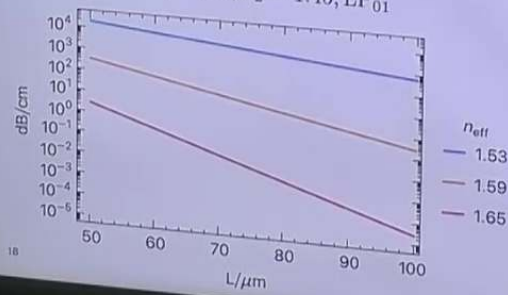
$$\alpha_{\text{rad}} \simeq \frac{P_{\text{loss}}}{P_t} \frac{1}{Z_c}$$

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

Radiation Loss

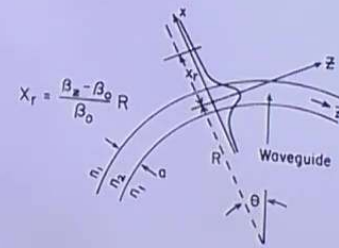


$n_1 = 2.2, n_2 = 1.45, LP_{01}$



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

Radiation/bend Loss



$$\alpha_{\text{rad}} \approx \frac{P_{\text{loss}}}{P_t} \frac{1}{Z_c}$$

Example: Si-on-Insulator Photonic Crystal Ring Resonator

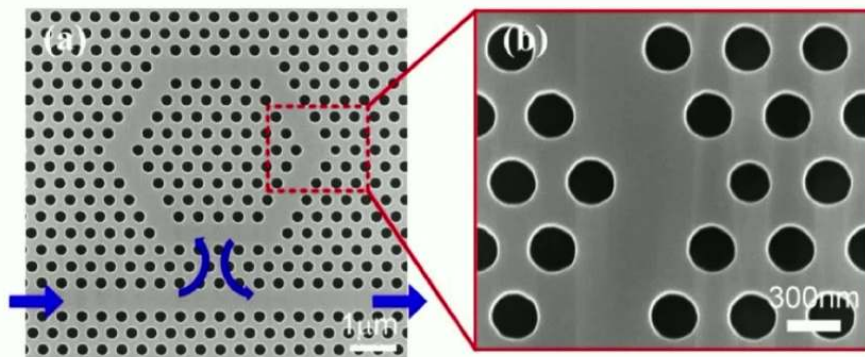
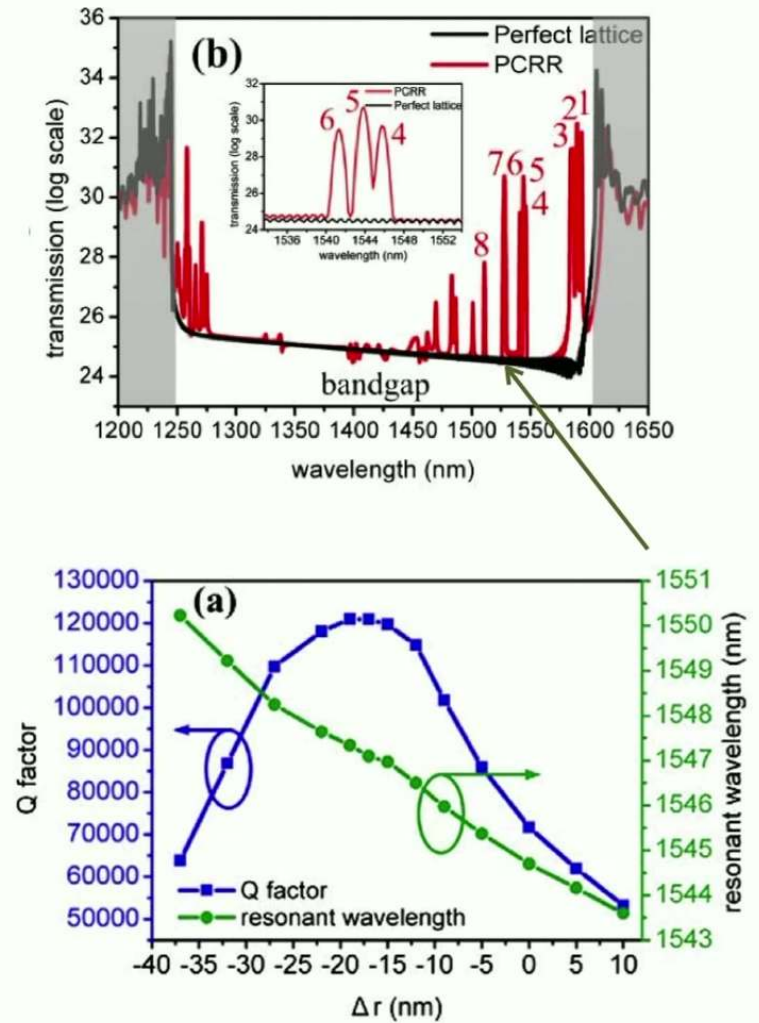


Fig. 4. (a) SEM image of the fabricated modified PCRR. (b) Magnified micrograph of the corner of the modified PCRR.

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

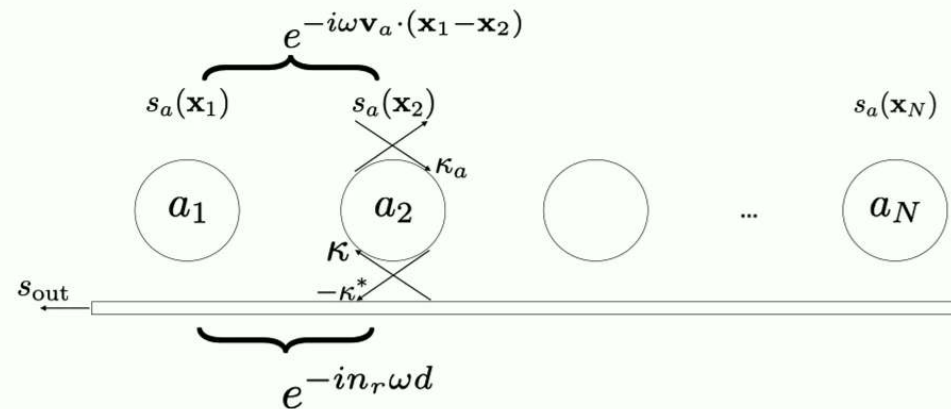
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Coupling N Resonators in Parallel

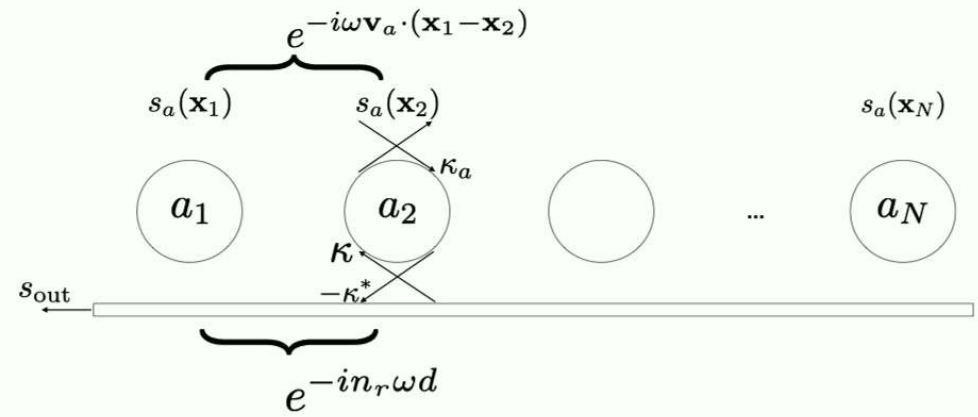
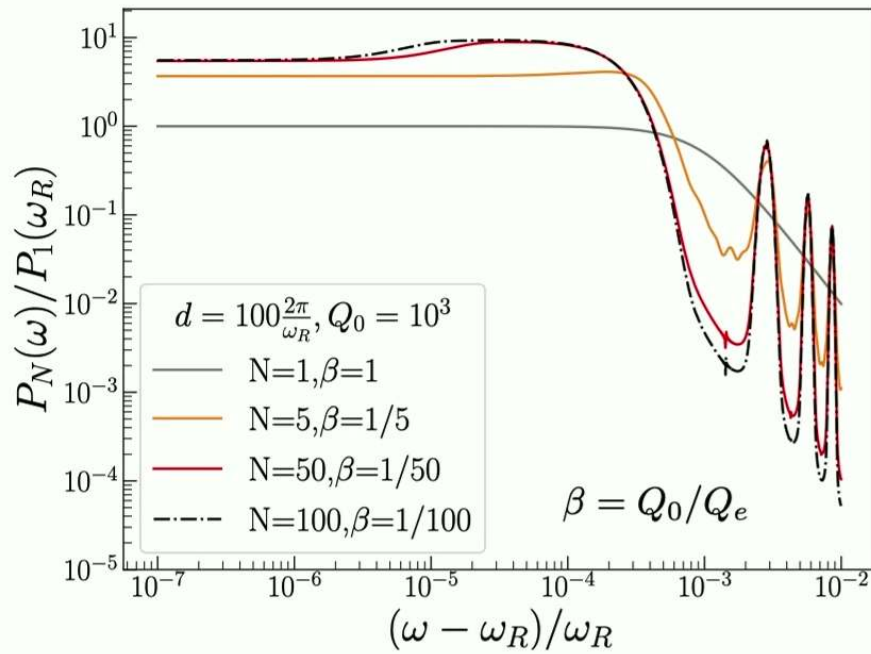
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N Resonators in Parallel



- 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.

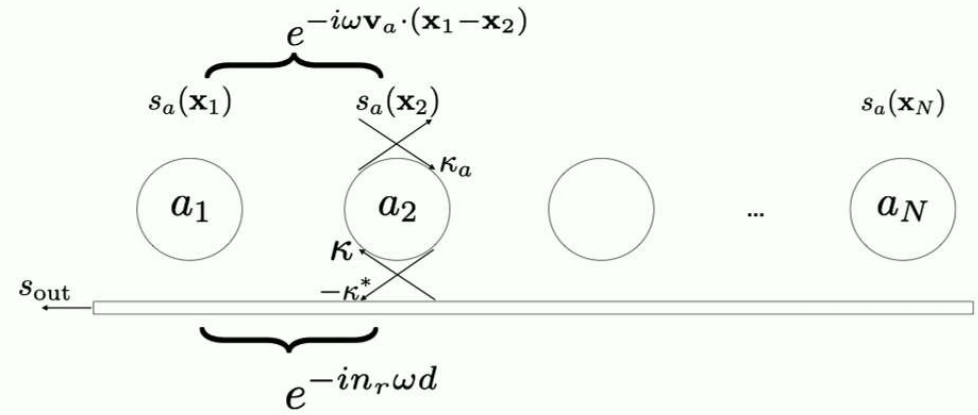
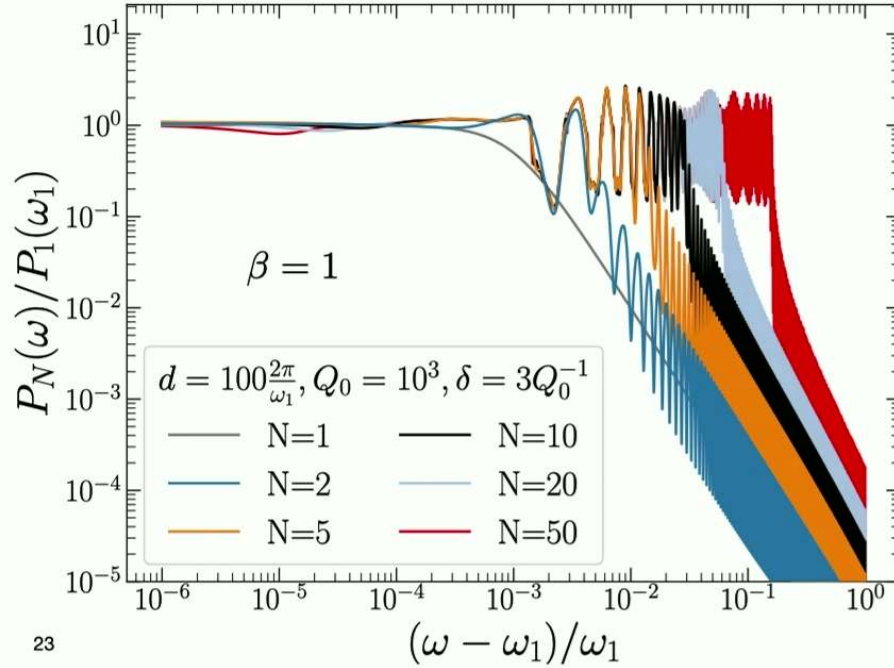
Same Frequency



No gain after going beyond the DM coherence length.

Different Frequencies

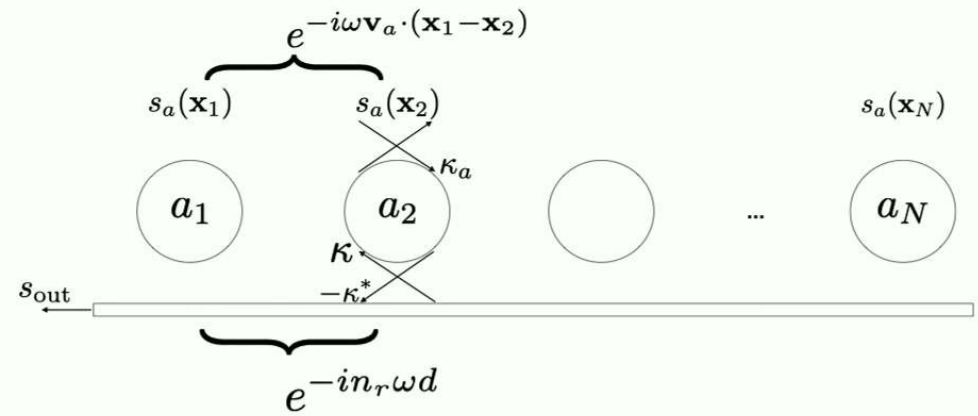
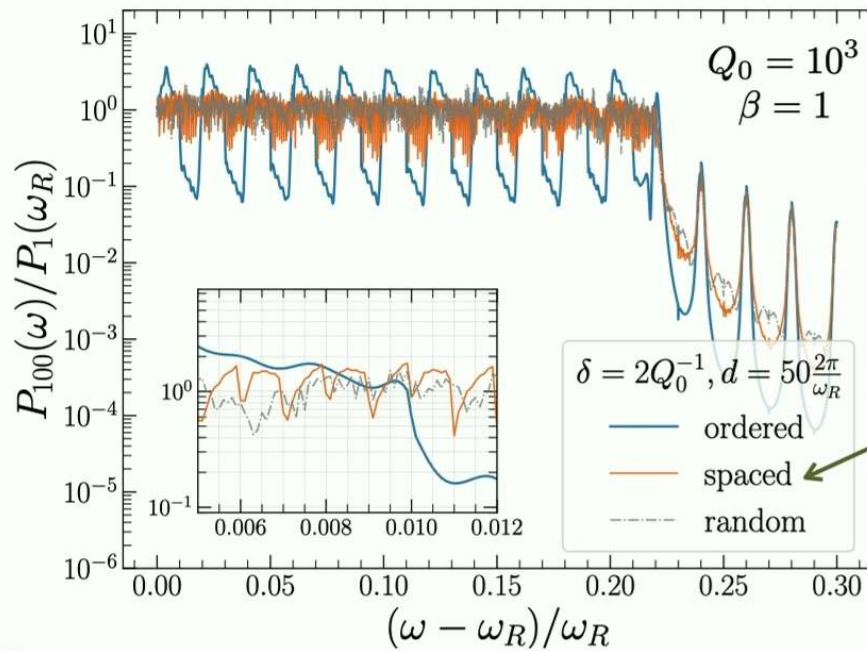
$$\omega_R(1 + \delta)^{i-1}, i = 1, 2, \dots, N$$



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

Different Frequencies

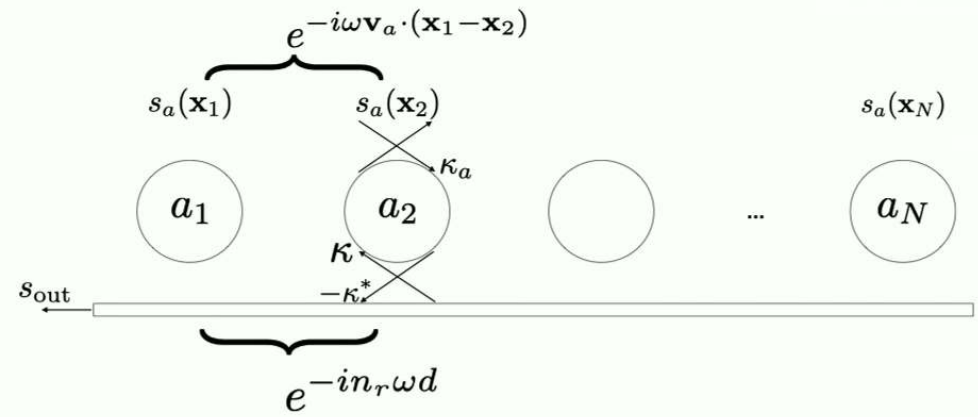
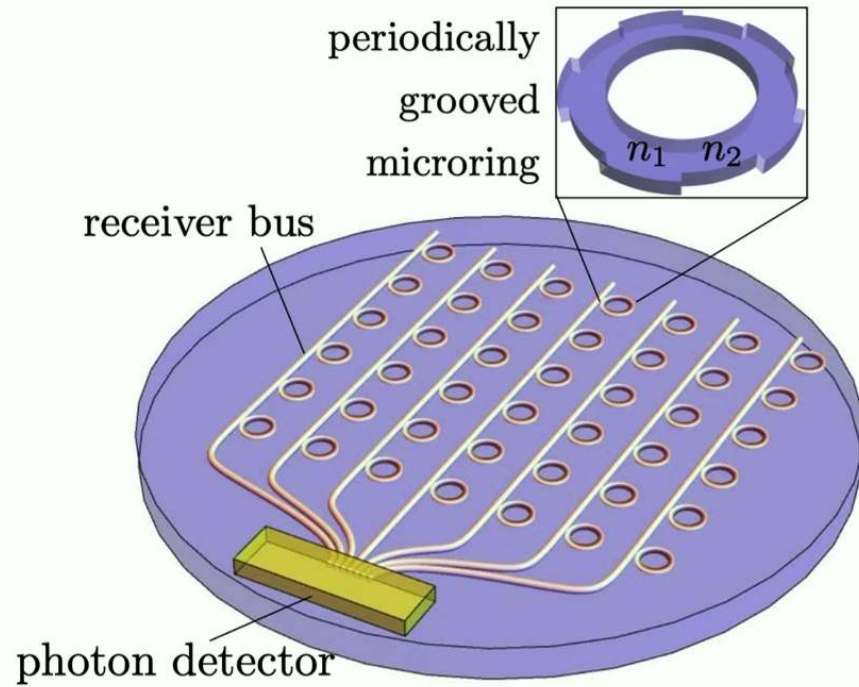
$$\omega_R(1 + \delta)^{i-1}, i = 1, 2, \dots, N$$



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

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

Sketch of the Setup



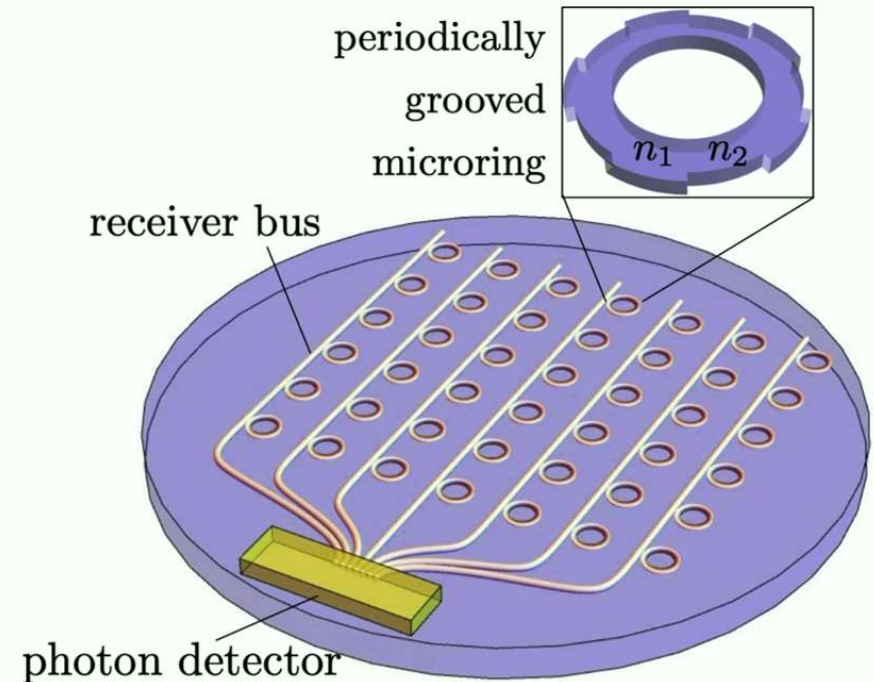
“Active” Fraction of a Chip

$$\xi_{\text{act}} \equiv \frac{V_{\text{int}}}{\frac{1}{4}\pi D^2 t_s} \sim 0.1\% \left(\frac{100}{N_u} \right) \left(\frac{t_w/t_s}{0.01} \right)$$

N_u = # of unit cells in each resonator

t_w = thickness of the resonator

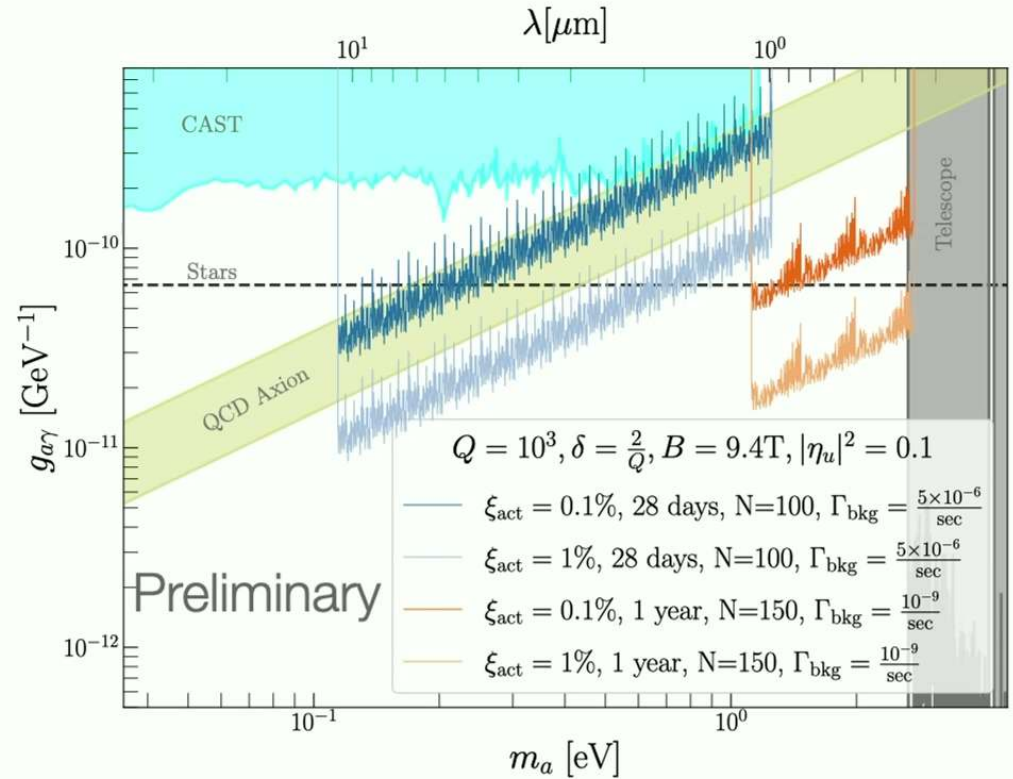
t_s = thickness of the substrate



Axion DM Search Needs a Background Magnetic Field

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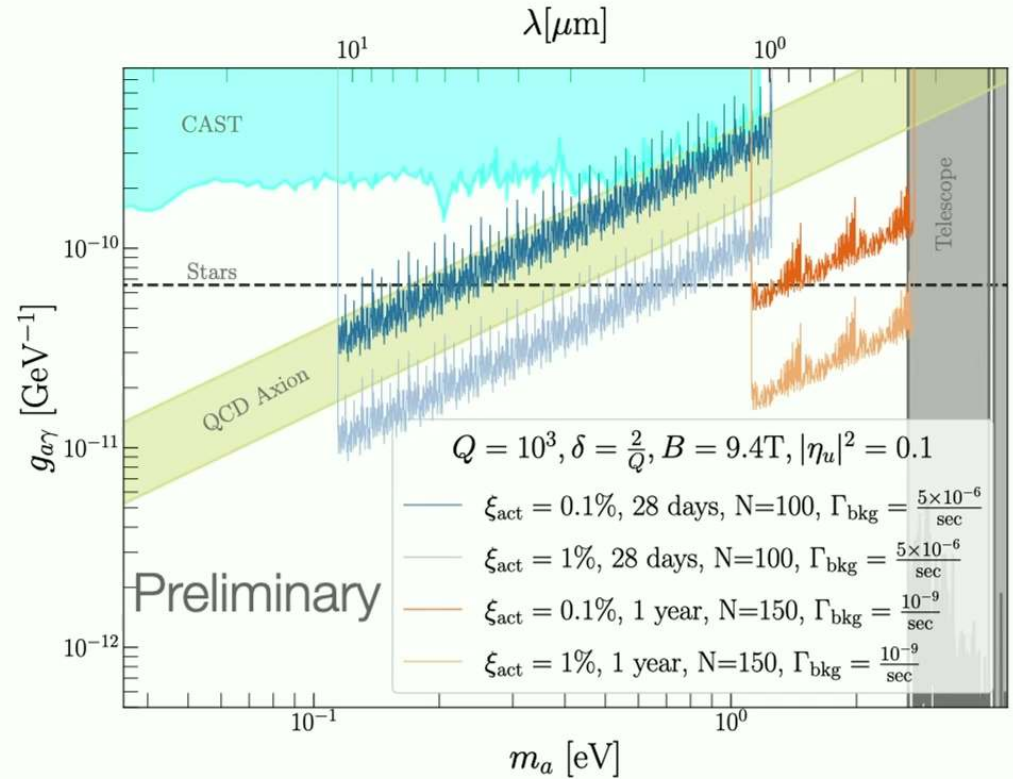
$B(\text{T})$	Bore (mm)	$V_{\text{act}}(\text{cm}^3)$	$B^2 V_{\text{act}}(\text{PeV})$	References
40	34	9×10^{-3}	6.9×10^4	[29]
21	123	0.118	2.5×10^5	[30]
9.4	800	100	4.2×10^7	[31]
11.7	900	127	8.3×10^7	[32]
20 ^a	680	72.6	1.38×10^8	[33]



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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

