Massively Multiplexed Dark Matter Searches with Integrated Photonics

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Ryan Janish

(Fermilab)

[Nikita Blinov, Christina Gao, Roni Harnik, RJ, Neil Sinclair, *2401.17260*]

E Pluribus Unum

DM Power from many resonators: $P \sim \frac{Q}{m} J_{\mathrm{dm}}^2 |\eta|^2 V N$

E Pluribus Unum

DM Power from many resonators: $P \sim \frac{Q}{m} J_{\rm dm}^2 |\eta|^2 V N$

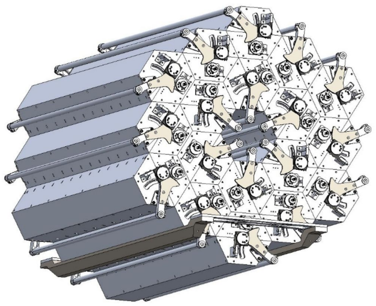
RF multi-cavity searches $(m \lesssim 35\,\mu\mathrm{eV})$

ADMX-G2

4 cavity array

ADMX-EFR

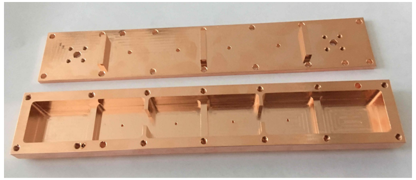
18 cavity array



[Adams et al 2203.14923]

RADES

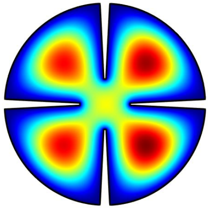
Linear multicell



[Melcon et al 2002.07639]

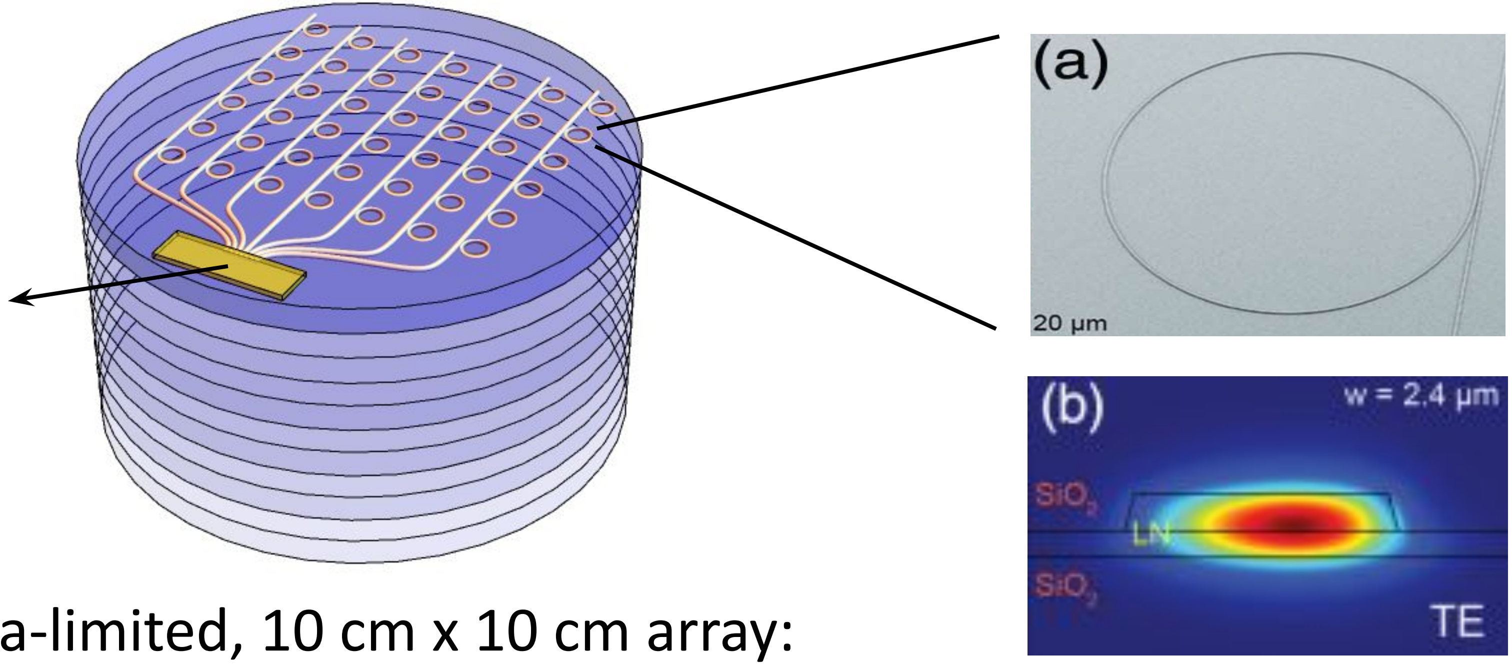
CAPP Pizza

Radial multicell



[Jeong et al 2205.01319]

Photonic Micro-resonator Arrays



Photon Counter

[Zhang et al 1712.04479]

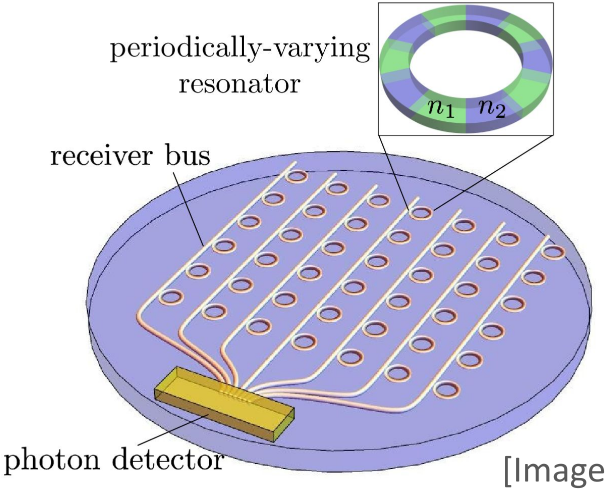
Area-limited, 10 cm x 10 cm array:

$$N \sim \left(\frac{10\,\mathrm{cm}}{100\,\mu\mathrm{m}}\right)^2 \sim 10^6$$

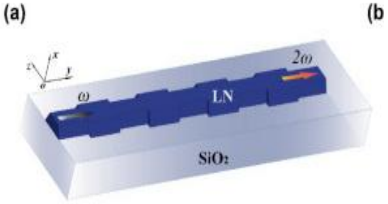
Phase Matching

or Momentum Conservation or Mode Overlap or …

Periodic microring



[Image: Christina Gao]

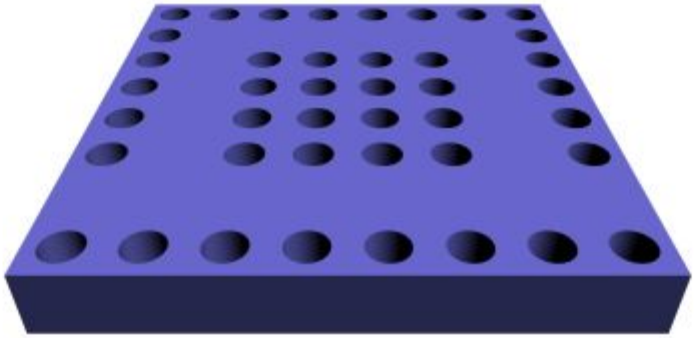


[Wang et al 1610.04197]

$$|\eta| \sim 0.1$$

Photonic crystal resonator

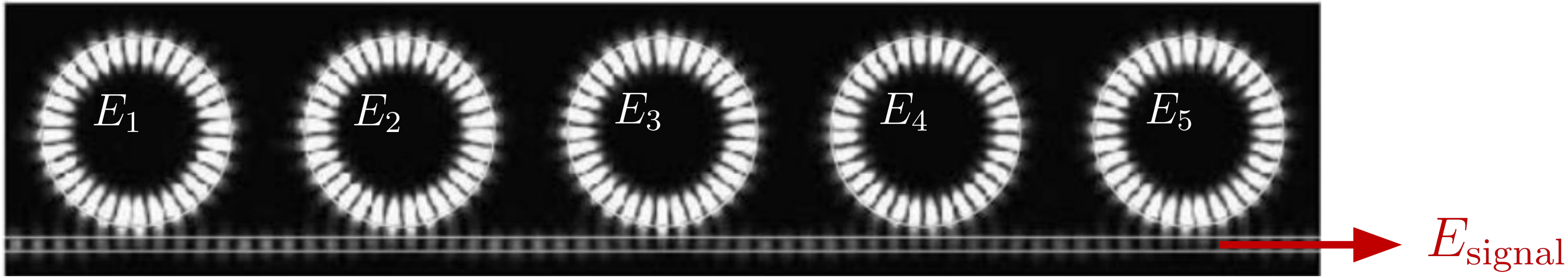
[Fan and Joannopoulos, 2002]



[Image: Nikita Blinov]

$$|\eta| \sim 0.01$$

Power Combining

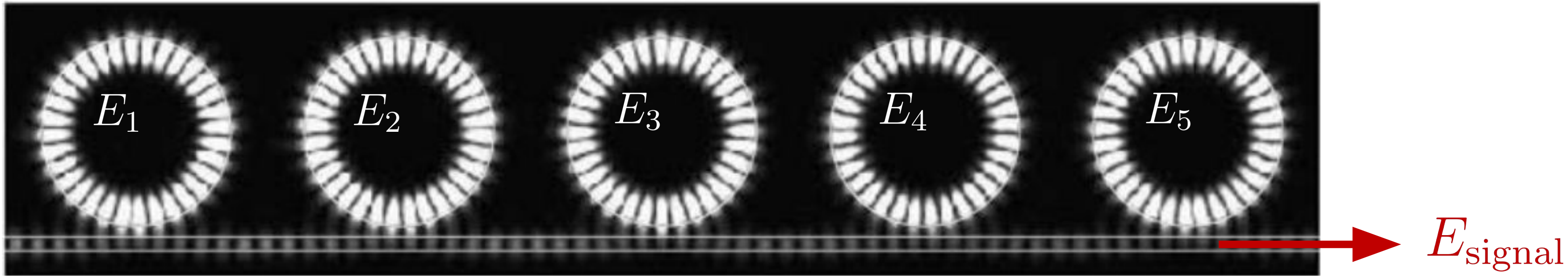


[Heebner et al, '08]

$$P_{\mathrm{signal}} \leq N P_0$$

$$P_0 = \frac{Q}{m} J_{\mathrm{dm}}^2 |\eta|^2 V$$

Power Combining



[Heebner et al, ‘08]

$$P_{\text{signal}} \leq N P_0$$

$$P_0 = \frac{Q}{m} J_{\text{dm}}^2 |\eta|^2 V \quad \Rightarrow$$

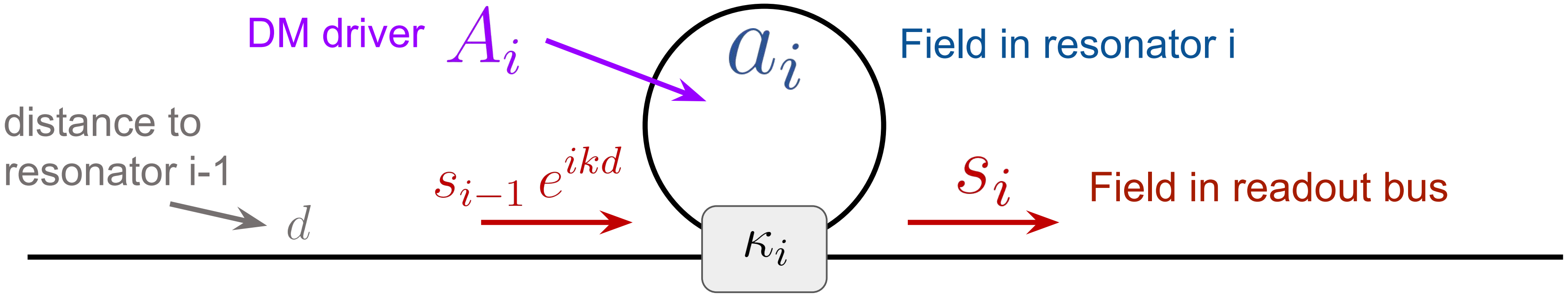
Individual resonator:

$$P_{\text{drive}} \sim E J_{\text{dm}} V$$

$$P_{\text{loss}} \sim |E|^2 V \frac{\omega}{Q}$$

$$P_{\text{out}} \leq P_0$$

Coupled Mode Theory with DM



DM driver A_i

a_i Field in resonator i

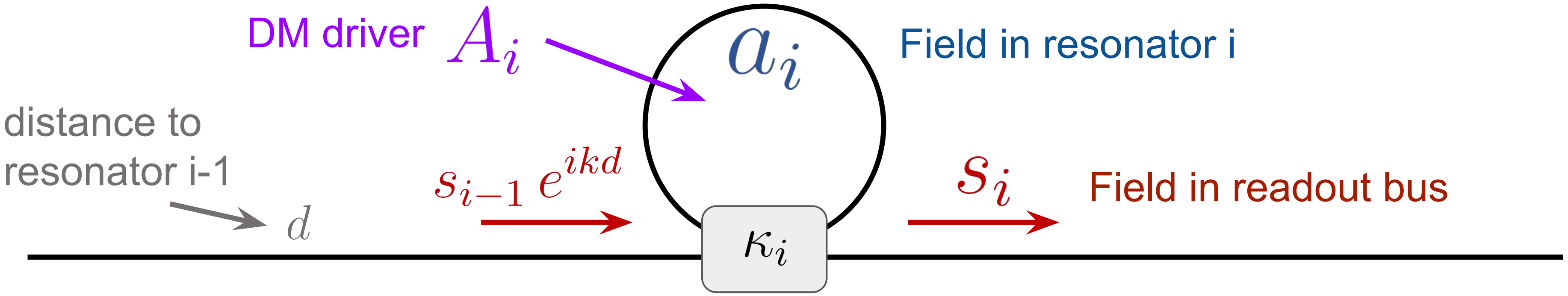
distance to resonator i-1 d

$s_{i-1}\,e^{ikd}$

κ_i

s_i Field in readout bus

Coupled Mode Theory with DM



DM driver A_i

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$s_{i-1}\, e^{ikd}$

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s_i Field in readout bus

$$\dot{a}_i = \left(i\omega_i \underline{- \frac{\omega_i}{2Q_i} - \frac{1}{2}|\kappa_i|^2} \right) a_i - \kappa_i^* s_{i-1} e^{ikd} + A_i$$

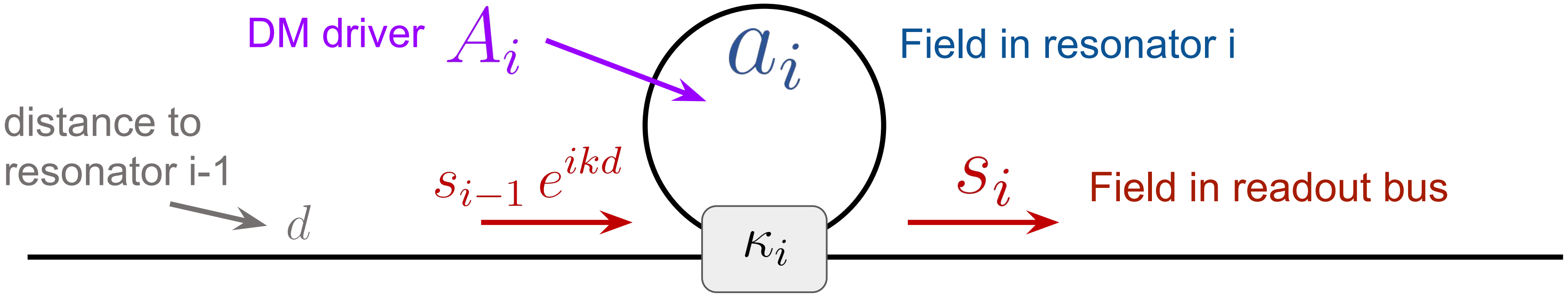
Resonance

Loaded quality factor

Driven by readout bus and DM

from Maxwell: $A_i = -\frac{\omega}{2\omega_i} J_{\rm dm}^2 \eta_i$

Coupled Mode Theory with DM



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s_i Field in readout bus

$$\dot{a}_i = \left(i\omega_i - \frac{\omega_i}{2Q_i} - \frac{1}{2}|\kappa_i|^2 \right) a_i - \kappa_i^* s_{i-1} e^{ikd} + A_i$$

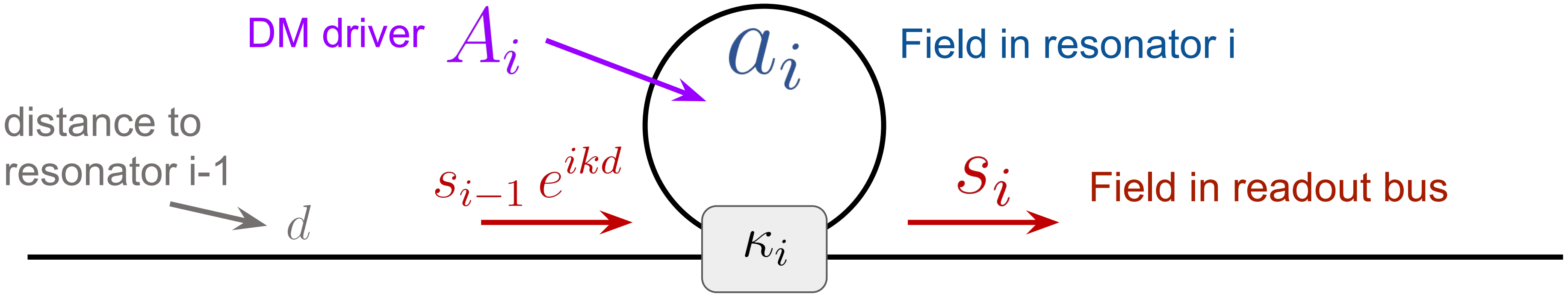
$$s_i = s_{i-1}\, e^{ikd} + \kappa_i\, a_i$$

Outgoing bus field

Incident bus field

Input from resonator

Coupled Mode Theory with DM

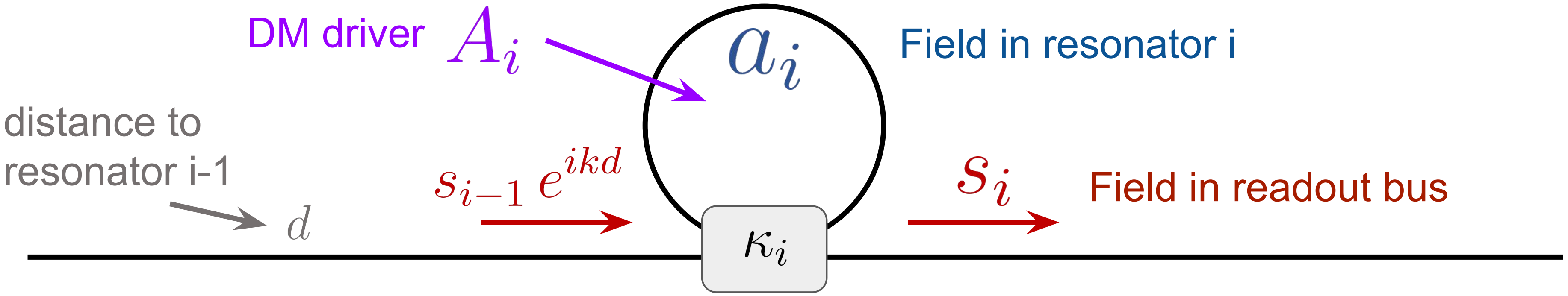


$$\dot{a}_i = \left(i\omega_i - \frac{\omega_i}{2Q_i} - \frac{1}{2}|\kappa_i|^2 \right) a_i - \kappa_i^* s_{i-1} e^{ikd} + A_i$$

$$s_i = s_{i-1}\, e^{ikd} + \kappa_i\, a_i$$

$$s_0 = 0 \qquad P_{\text{sig}} = |s_N|^2$$

Coupled Mode Theory with DM

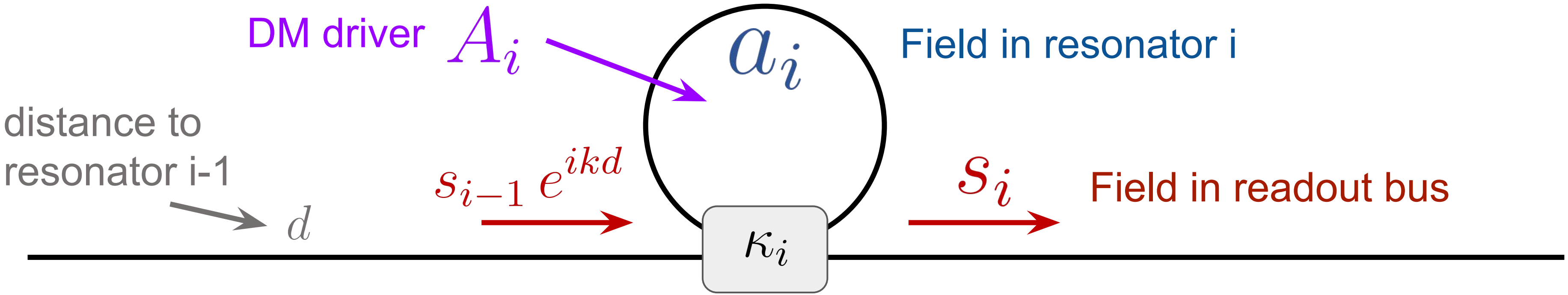


$$s_i = s_{i-1}\,e^{ikd} + \kappa_i\,a_i$$

Bus couples to *one* of N normal modes of the chain of resonators

$$s_n = \sum \kappa_i e^{ikz_i} a_i = \langle b|a\rangle$$

Coupled Mode Theory with DM



DM driver A_i

a_i

Field in resonator i

distance to resonator i-1

d

$s_{i-1}\, e^{ikd}$

κ_i

s_i

Field in readout bus

$$s_i = s_{i-1}\, e^{ikd} + \kappa_i\, a_i$$

Bus couples to *one* of N normal modes of the chain of resonators

$$s_n = \sum \kappa_i e^{ikz_i} a_i = \langle b | a \rangle$$

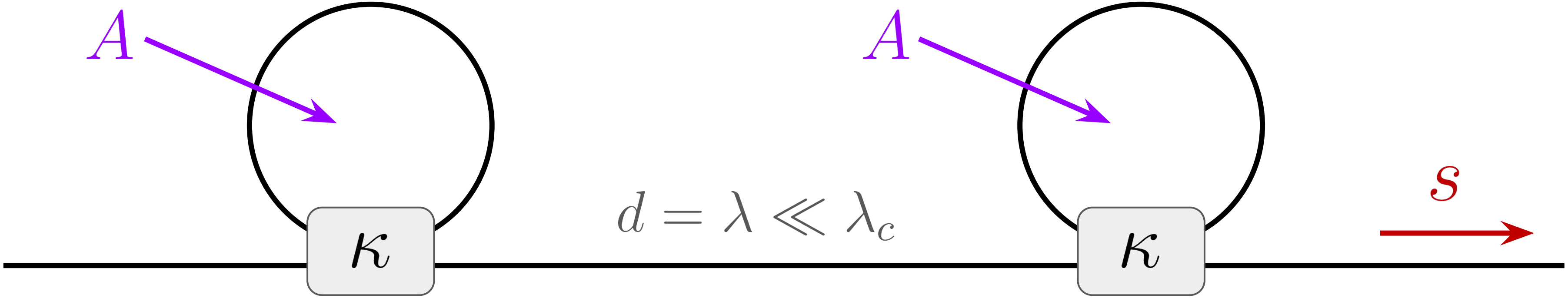
$$|b\rangle = (\kappa_1^* e^{-ikz_1}, \kappa_2^* e^{-ikz_2}, \ldots)$$

Readout mode

$$|a\rangle = (a_1, a_2, \ldots)$$

Resonator state

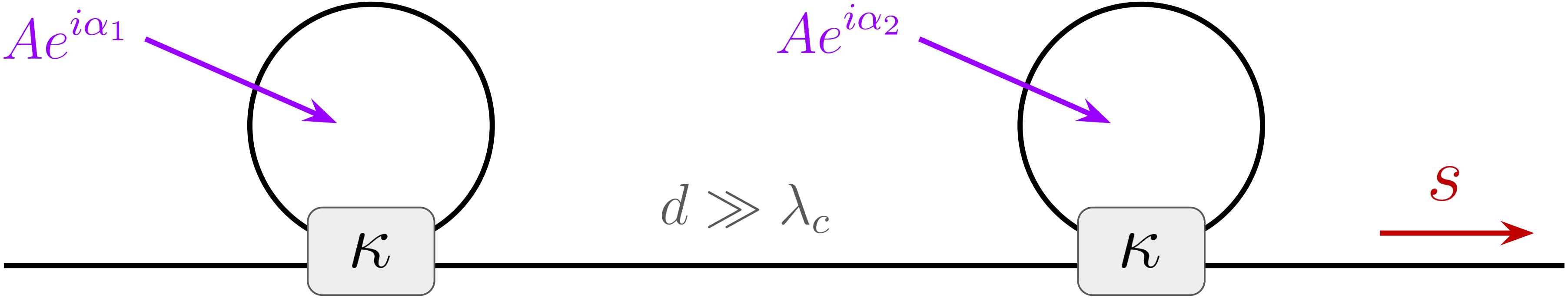
DM Coherence



$$|\text{readout}\rangle \propto |a\rangle \qquad |\langle\text{readout}|a\rangle|^2 \sim N^2\kappa^2|a|^2$$

$$P_{\text{signal}} \sim NP_0$$

DM Coherence



$$|\text{readout}\rangle \not\propto |a\rangle \longrightarrow \left|\frac{\langle \text{readout}|a\rangle_{\text{incoherent}}}{\langle \text{readout}|a\rangle_{\text{coherent}}}\right|^2 \sim \frac{1}{N}$$

$$P_{\text{signal}} \sim P_0$$

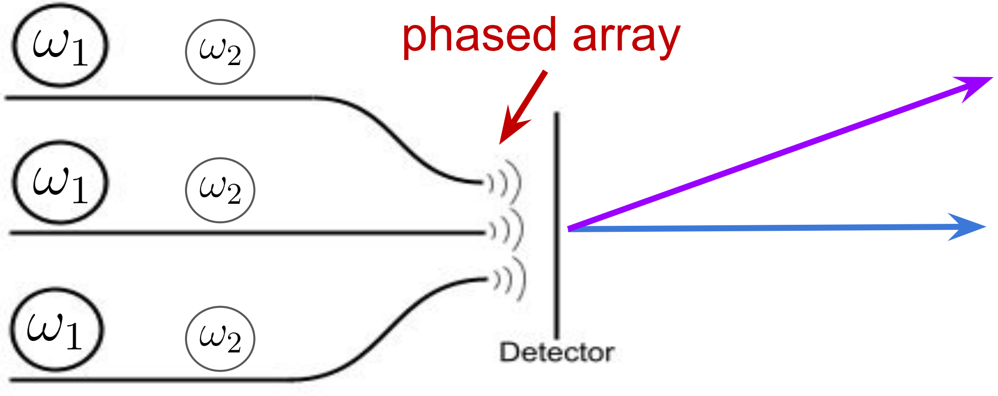
Multimode Readout

For incoherently driven resonators: $\sum_{\text{normal modes}} P_n = NP_0$

Multimode Readout

For incoherently driven resonators: $$\sum_{\text{normal modes}} P_n = NP_0$$

Spatial combining



phased array

resonators with successive phase shift

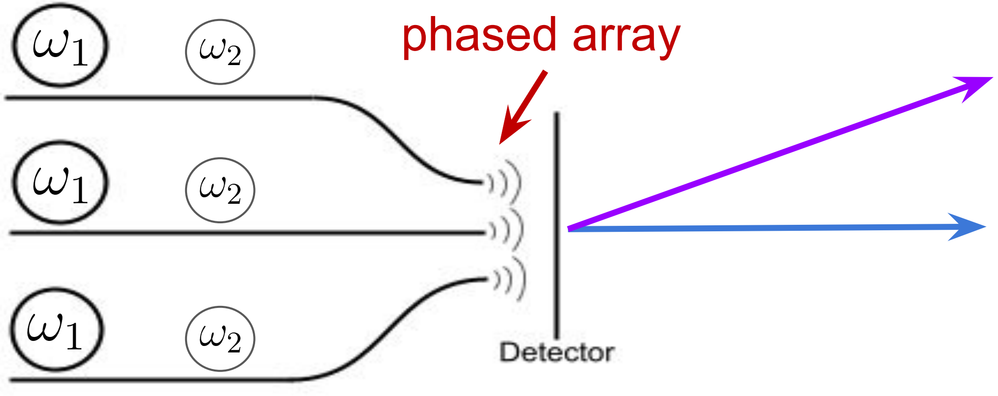
resonators in phase

Multimode Readout

For incoherently driven resonators:

$$\sum_{\text{normal modes}} P_n = NP_0$$

Spatial combining



phased array

resonators with
successive phase shift

resonators in phase

Other techniques

Frequency modulation
Nontrivial waveguide dispersion
Frequency-dependent coupling phases

Detectors

Dark count per detection area (SNSPD or Skipper CCD):

$$\frac{\Gamma_{\mathrm{dc}}}{A} \approx \frac{4 \cdot 10^{-4}}{\sec \mathrm{cm}^2}$$

Required detector size for phased array readout:

Common frequency resonators per bus

$$A \approx \frac{N_r}{N_c N_\omega}\left(\frac{2\pi}{\omega}\right) \approx 40\,\mathrm{cm}^2 \left(\frac{N_r}{10^9}\right)\left(\frac{100}{N_\omega}\right)\left(\frac{100}{N_c}\right)$$

Total number of resonators

Distinct frequencies per bus

Scan Strategy

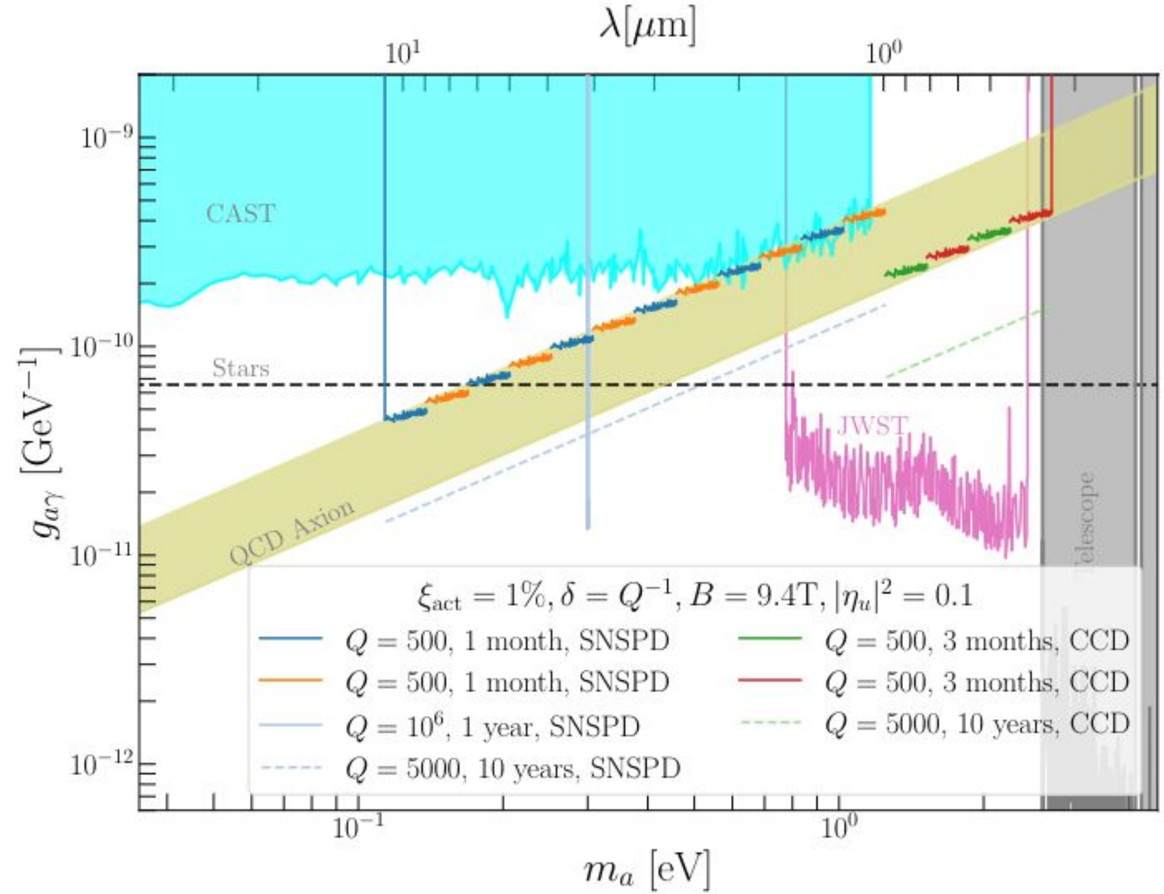
$$\mathrm{SNR} = \frac{\Gamma_{\mathrm{sig}} t_{\mathrm{int}}}{\mathrm{Max}\left[1, \Gamma_{\mathrm{bkg}} t_{\mathrm{int}}\right]^{1/2}}$$

Cover 0.1 eV to 2 eV in one year:

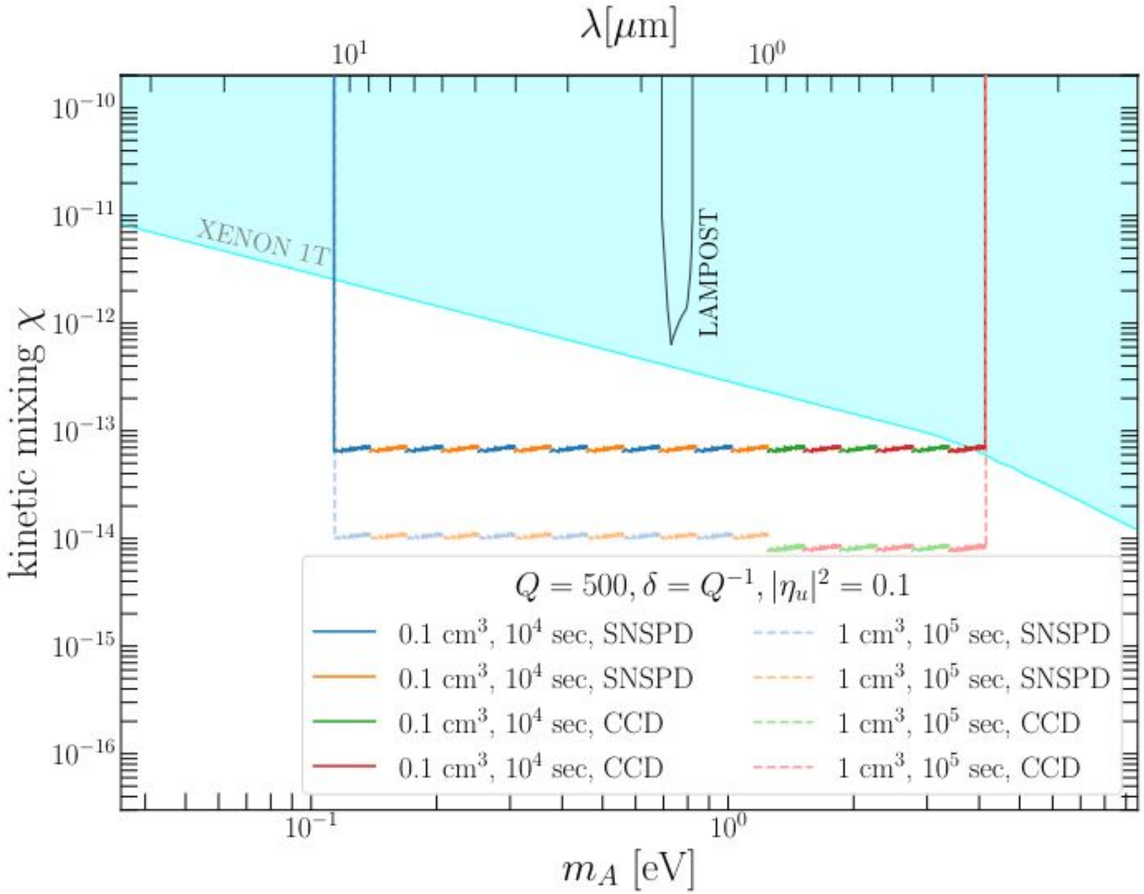
$$\left(\frac{\Delta m}{m}\right)_{\mathrm{run}} \approx 0.2 \left(\frac{500}{Q}\right)\left(\frac{N_\omega}{100}\right)$$

$$N_{\mathrm{runs}} \approx \frac{Q}{N_\omega} \ln\left(\frac{\omega_1}{\omega_2}\right) \approx 16 \left(\frac{Q}{500}\right)\left(\frac{100}{N_\omega}\right)$$

ALP DM Detection Reach



Dark Photon DM Detection Reach



Conclusions

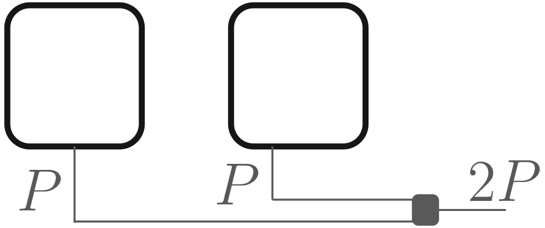
Integrated photonics is a rich platform for DM searches

Scalable, existing fabrication infrastructure, low loss, empirically characterizable, ultra-low dark count detection, tunable search strategies

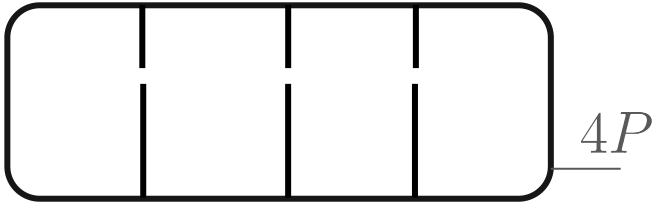
More detailed design and development work to be done (e.g., incoherent power combining strategies)

Resonant Cavity Detection for Large DM Mass

Multicell or Multiple Cavities

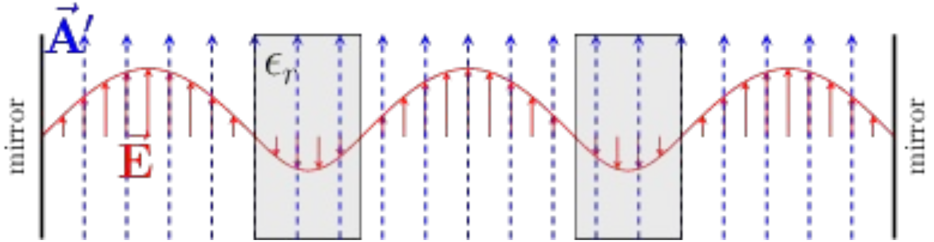


(ADMX-4) [Yang et al, 2020]



[Jeong et al, 1710.06969]
(RADES) [Melcon et al, 1803.01243]

Phase-matched excited modes



(ADMX-Orpheus) [Cervantes et al, 2204.09475]
(MADMAX) [Majorovits et al, 1712.01062]
(LAMPOST) [Chiles et al, 2110.01582]

$$\int d^3x\, \hat{E} \cdot \vec{J}_{\rm dm} \neq 0$$

Signal and Noise

$$\Gamma_1 = \frac{Q J_{\rm dm}^2 V}{8\omega^2} |\eta|^2 \left(\frac{m^2/4Q}{(\omega - m)^2 + m^2/4Q^2} \right)$$

$$|\eta|^2 = \frac{\left| \int d^3x \hat{E} \cdot \hat{n} \right|^2}{V \int d^3x \, |\hat{E}|^2}$$

Signal and Noise

Signal from one resonator:

$$\Gamma_{\rm dp} \approx \frac{10^{-2}}{\rm sec}\left(\frac{0.2\rm eV}{m}\right)^2\left(\frac{\epsilon}{10^{-10}}\right)^2$$

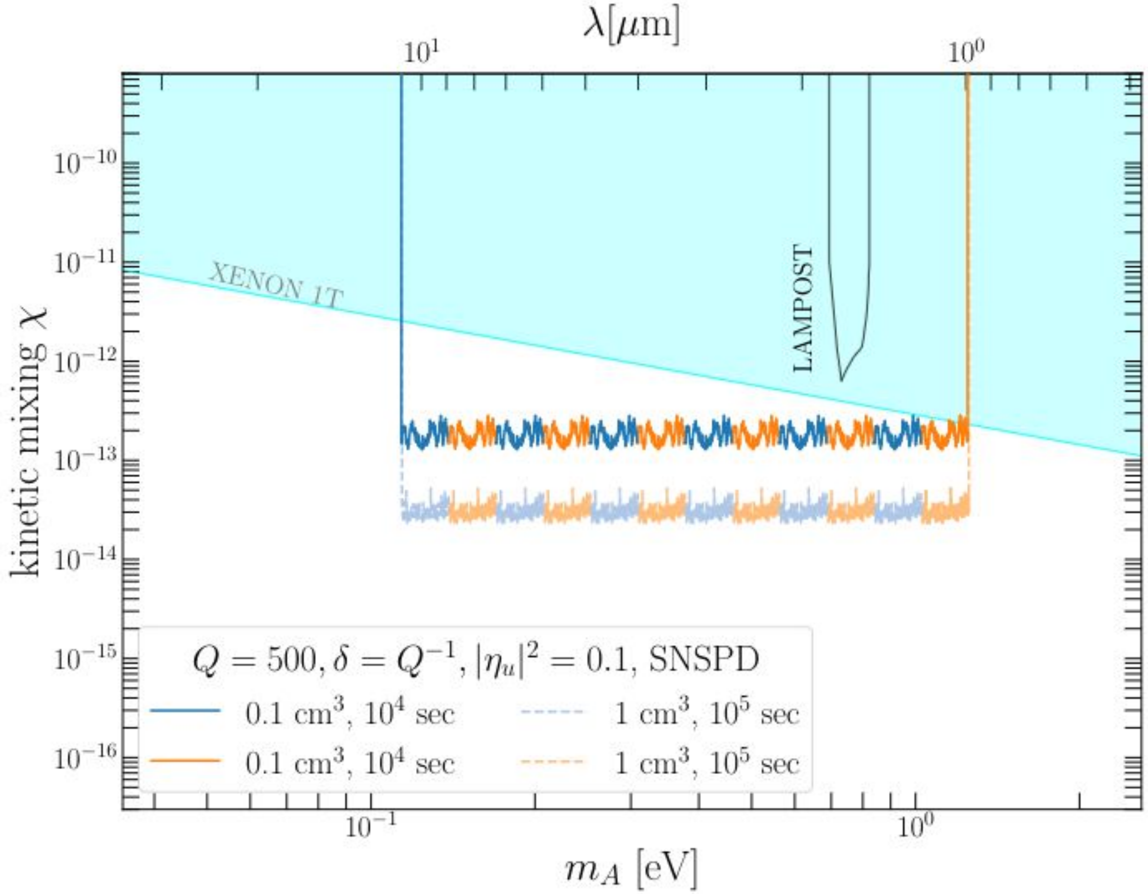
$$\Gamma_{\rm alp} \approx \frac{10^{-11}}{\rm sec}\left(\frac{0.2\rm eV}{m}\right)^4\left(\frac{g}{10^{-10}\rm GeV^{-1}}\right)^2\left(\frac{B}{9.4\,\rm T}\right)^2$$

Assuming:

$$Q = 5\cdot 10^3 \qquad |\eta|^2 = 0.1$$

$$V = \left(\frac{\pi}{\omega}\right)\left(\frac{2\pi}{\omega}\cdot 100\right)\times 10\,\mu\rm m$$

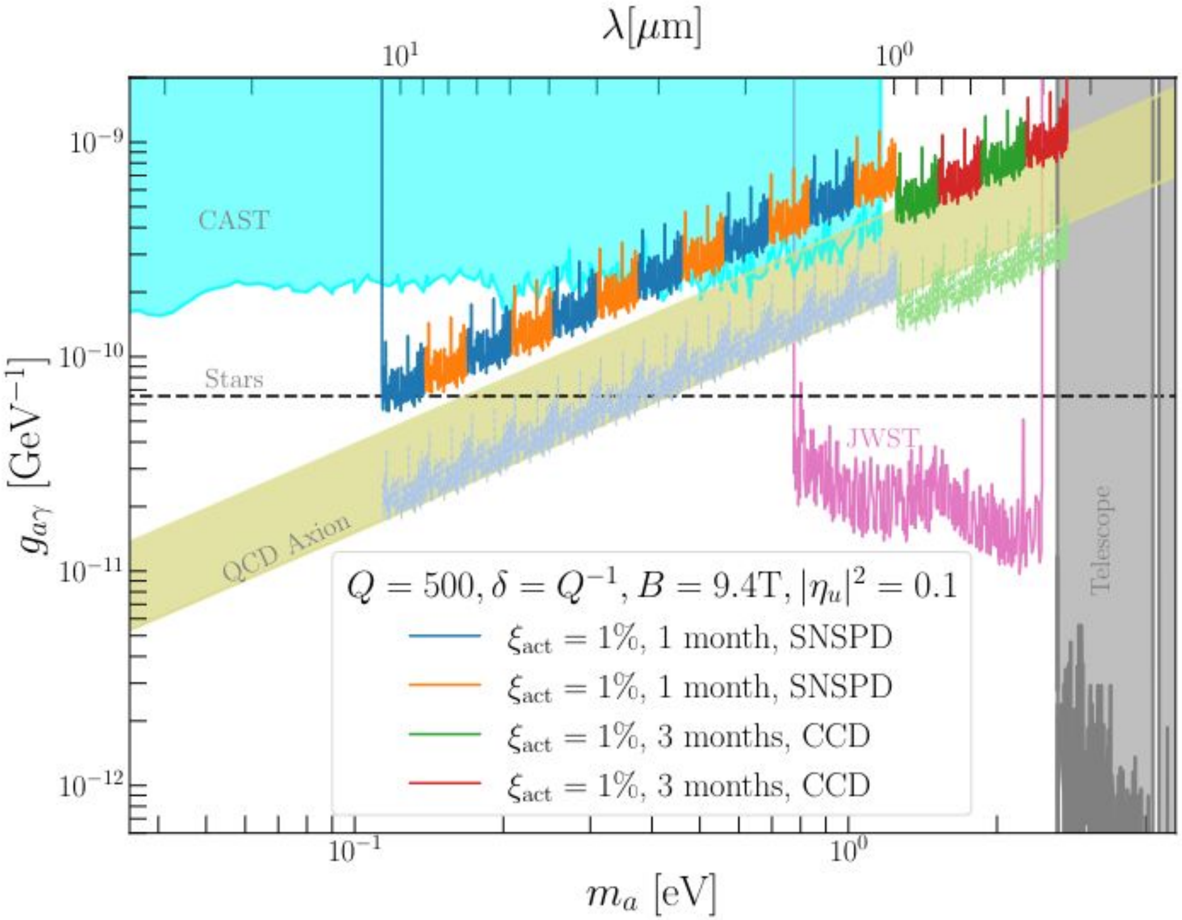
Dark Photon DM Detection Reach



XENON1T
[An et al 2006.13929]

LAMPOST
[Chiles et al 2110.01582]

Axion-like Particle DM Detection Reach



CAST
[CAST 1705.02290]

JWST
[Janish and Pinetti 2310.15395]

Telescope
[Grin et al 0611502]
[Todarello et al 2307.07403]

Stars
[Dolan et al 2207.03102]