# Dark Matter Searches with Integrated Optics

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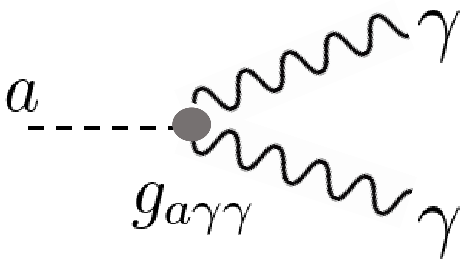
(Fermilab)

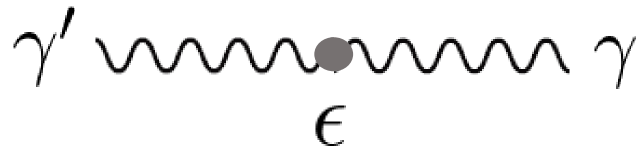
[Blinov, Gao, Harnik, RJ, Sinclair, *in progress*]

# ALPs and Dark Photons

## Photon couplings




ALP




Dark Photon

## High-frequency, wave-like window

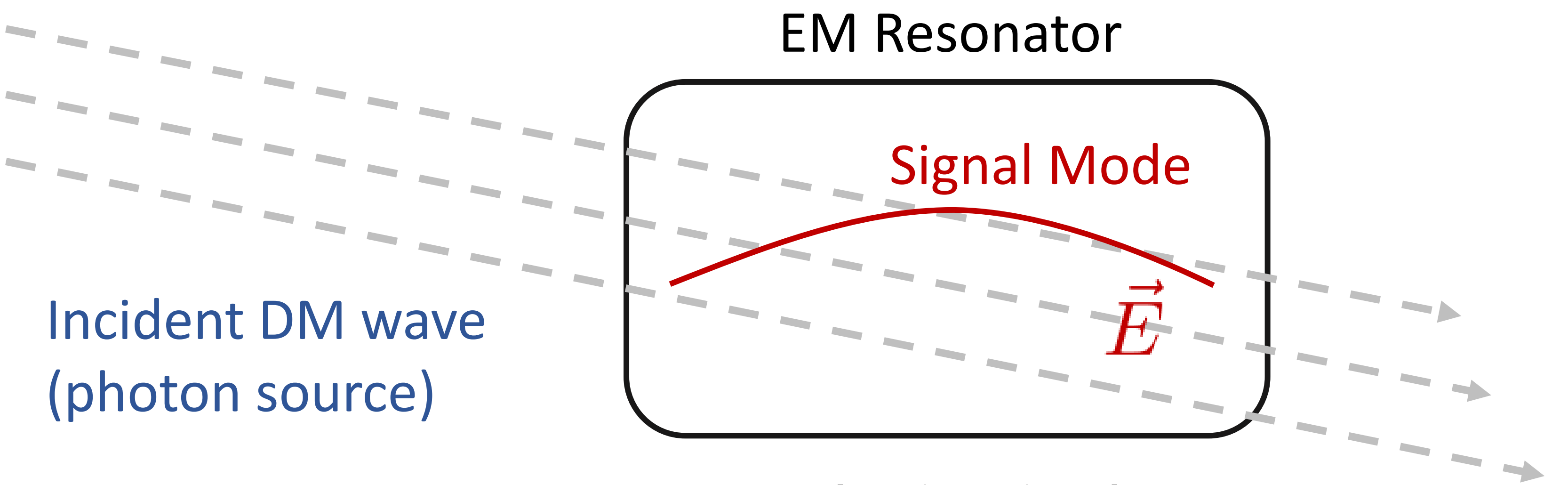
Current bounds from astrophysics and cosmology

$$10^{-4}\ \mathrm{eV} \lesssim m_{dm} \lesssim 5\ \mathrm{eV}$$

DM frequency is in the IR and visible band

DM is an oscillating background field

# Resonant Detection




[Asztalos et al 2010] [Chaudhuri et al 2014]

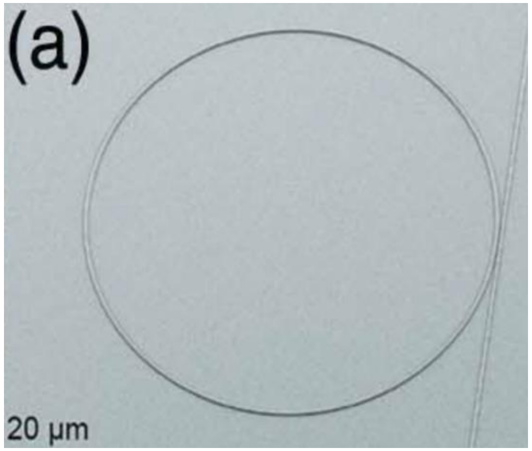
## Resonator size:

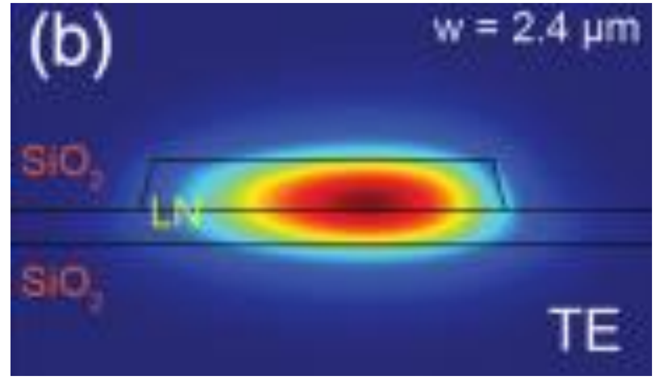
$$10^{-4}\ \text{eV} \lesssim m_{dm} \lesssim 5\ \text{eV}$$

$$\text{cm} \lesssim \lambda \lesssim\ \mu\text{m}$$

Single cavities in this regime are tiny detectors

# Optical Microring Arrays



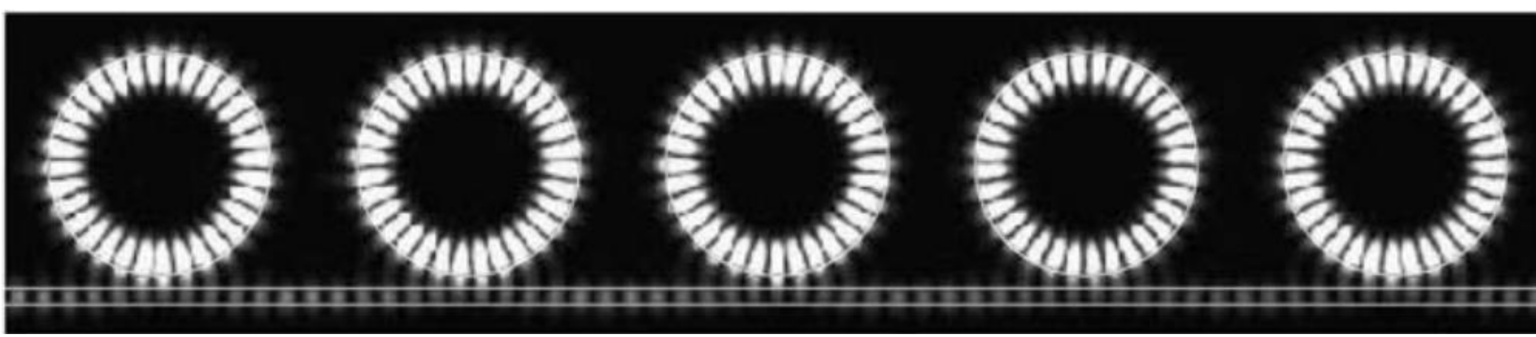

[Zhang et al 2017]

## Integrated Optics

Many optical devices ($10^3$ – $10^4$) mass-produced on single chips

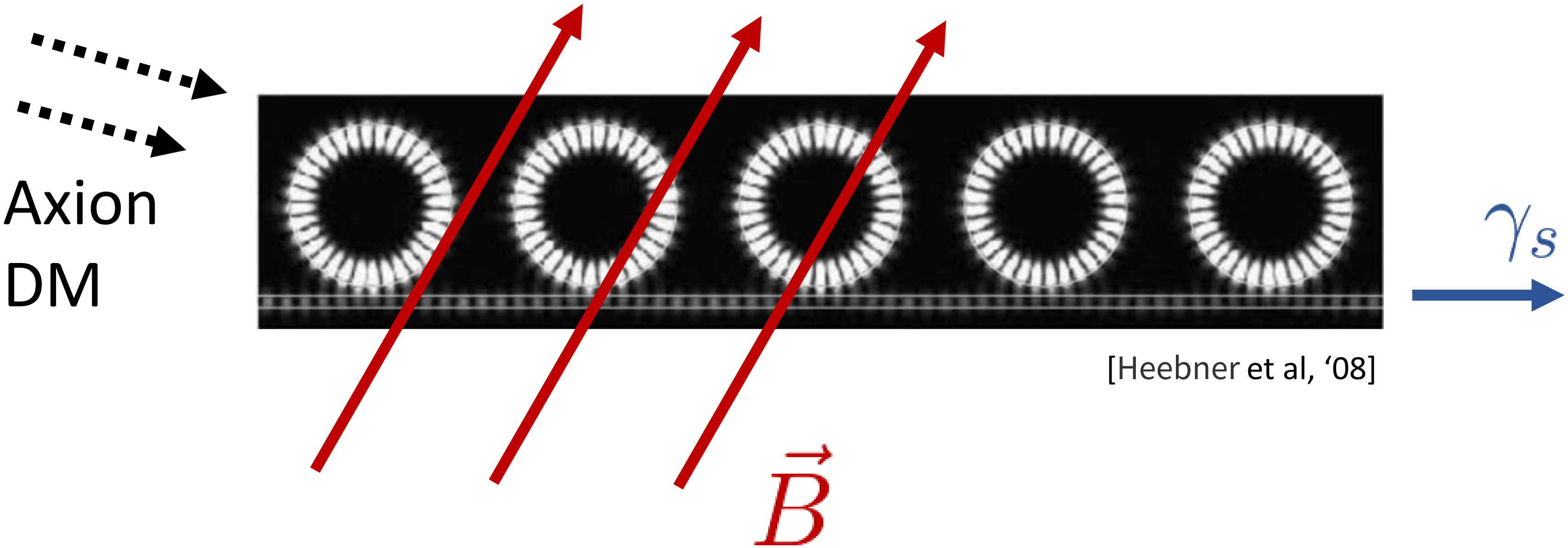
[Smit et al 2019]

Area-limited: $10^6$ cavities per 10 cm x 10 cm chip



[Heebner et al, '08]

# Axion Conversion




[Heebner et al, '08]

## Backgrounds

Non-thermal, $T \ll \omega_s$

Detector dark count (SNSPD): $\lesssim 10^{-5}/\text{sec}$

[Chiles et al, 2110.01582]

# Axion Conversion

## Phase Matching (i.e., Kinematics)

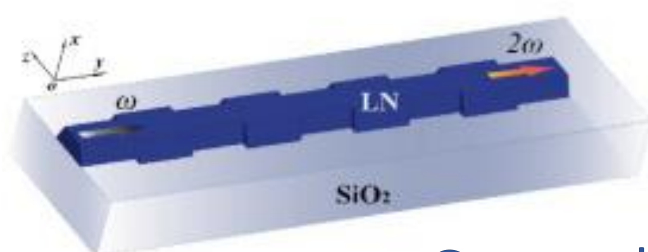
$$\text{Conversion Rate} \sim |\vec{B}_0 \cdot \int d^3x \, a(\vec{x}) \, \vec{E}_s(\vec{x})|^2$$

Nearly uniform DM field

Micron wavelength signal mode

Sinusoidal modes ⟶ no signal

Phase matching: engineer modes to maximize signal

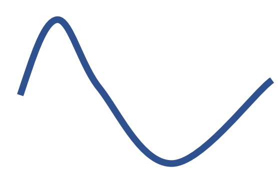



Grooved Cavity

[Wang et al 2017]

⟶

$E_s(x)$

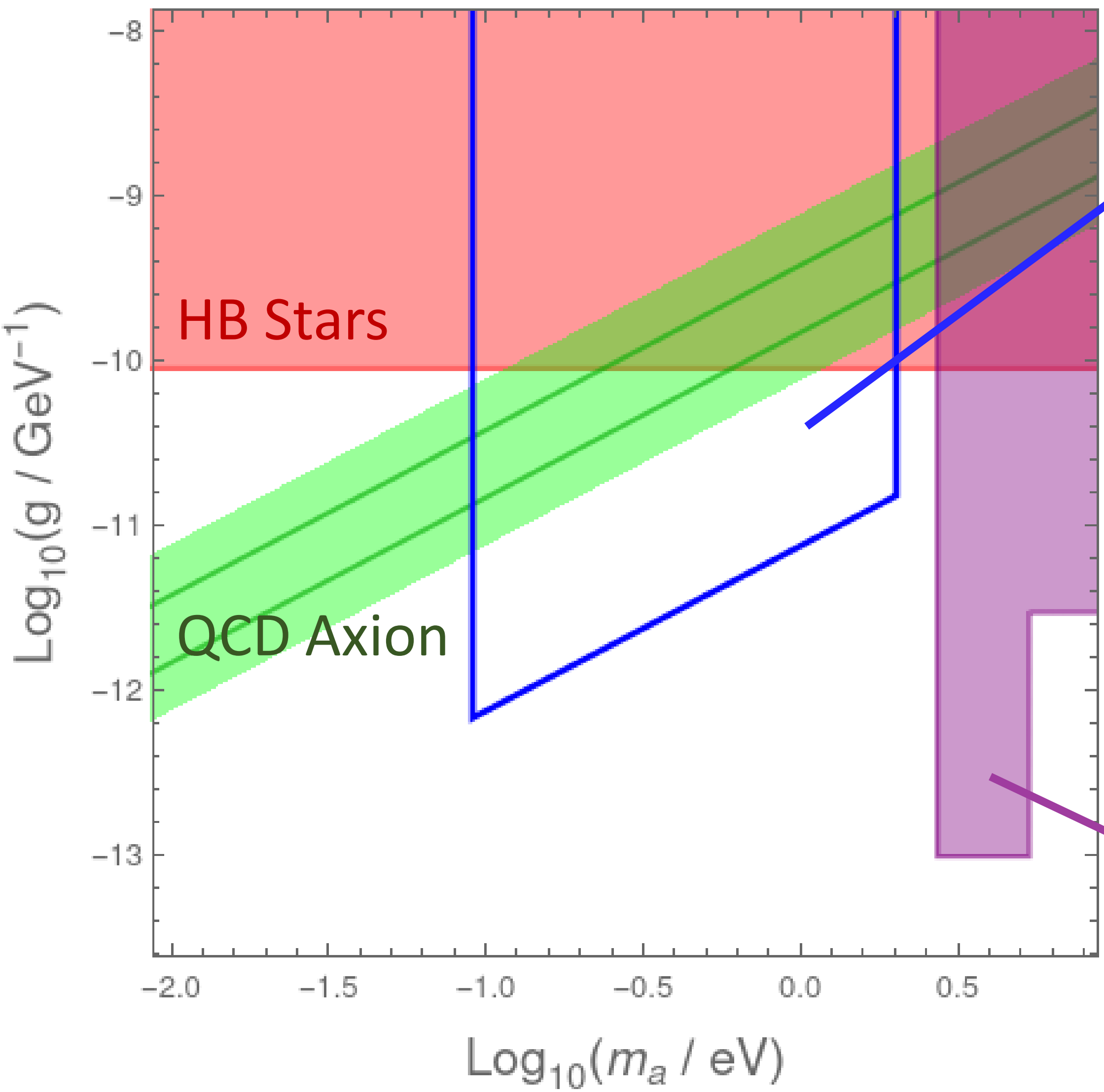


Non-sinusoidal mode

[Chiles et al, 2110.01582]

[Caldwell et al, 1611.05865]

# Axion Conversion




This work:

$$B_0 = 10\,\mathrm{T}$$

$$t_{\mathrm{sb}} = 3 \cdot 10^4\,\mathrm{sec}$$

$$t_{\mathrm{total}} = 30\,\mathrm{yr}$$

$$Q = 10^4$$

$$V = (10\mu\mathrm{m})^2 \times (100\mu\mathrm{m})$$

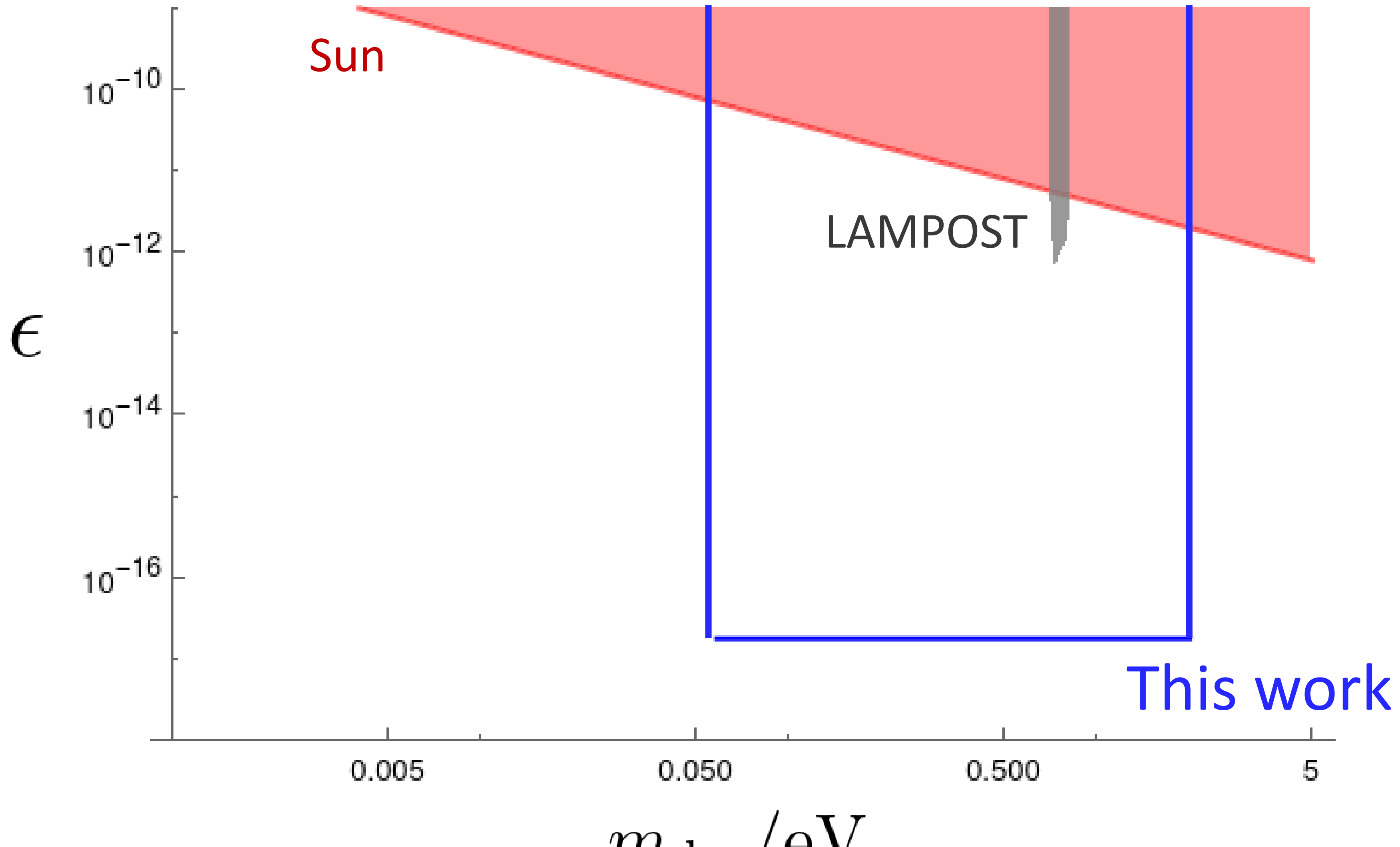
$$N = \frac{10^6}{\mathrm{chip}} \times (10^3\,\mathrm{chips})$$

Indirect (decays) observations

[C. O'Hare, *AxionLimits*]

# Dark Photon Conversion

(search parameters as above)



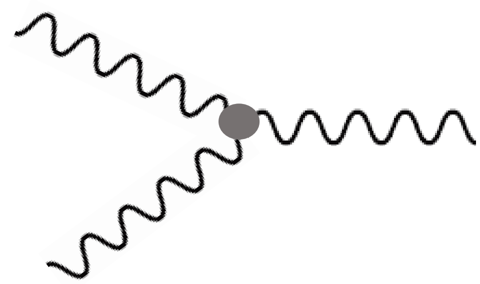

[C. O'Hare, *AxionLimits*]

# Hidden Photons in Nonlinear Media

## Non-linear optical medium

$$\mathcal{L} \supset \varepsilon_0 \chi^{(2)}_{ijk} E_i E_j E_k$$

$$\varepsilon_0 \chi^{(2)} \sim \left(\frac{1}{100\,\mathrm{eV}}\right)^2$$

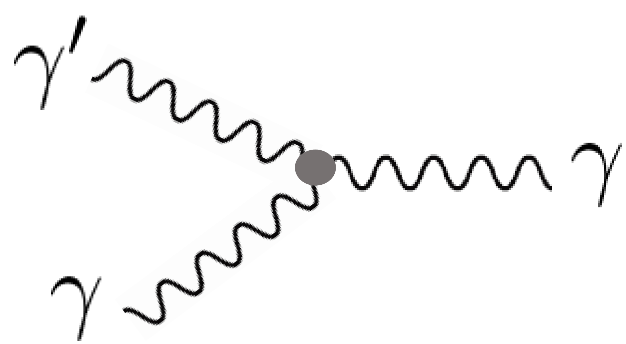


## Kinetically mixed hidden photon

[Estrada et al, 2021.04707]

$$\mathcal{L} \supset -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m^2_{\gamma'} A'_\mu A'^\mu + \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$

$$\Rightarrow \ \mathcal{L} \supset \epsilon\, \varepsilon_0 \chi^{(2)}_{ijk} E_i E_j E'_k$$



# Microring Array DM Search


[Heebner et al, '08]

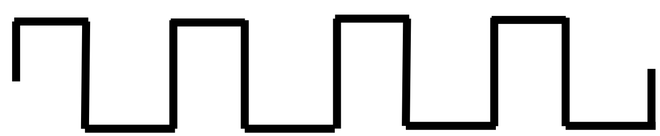
## Up-conversion phase matching [Berlin et al, 2007.15656]

$$\omega_s = \omega_p + m_{dm} \qquad \vec{k}_s = \vec{k}_p$$

Birefringence

Periodic Polling (quasi-phase matching) [Chiles et al, 2110.01582] [Caldwell et al, 1611.05865]

$$\chi^{(2)}(z)$$



# Microring Array DM Search


[Heebner et al, '08]

## Backgrounds

Minimal dark count with SNSPD, $\lesssim 10^{-5}/\mathrm{sec}$

[Chiles et al, 2110.01582]

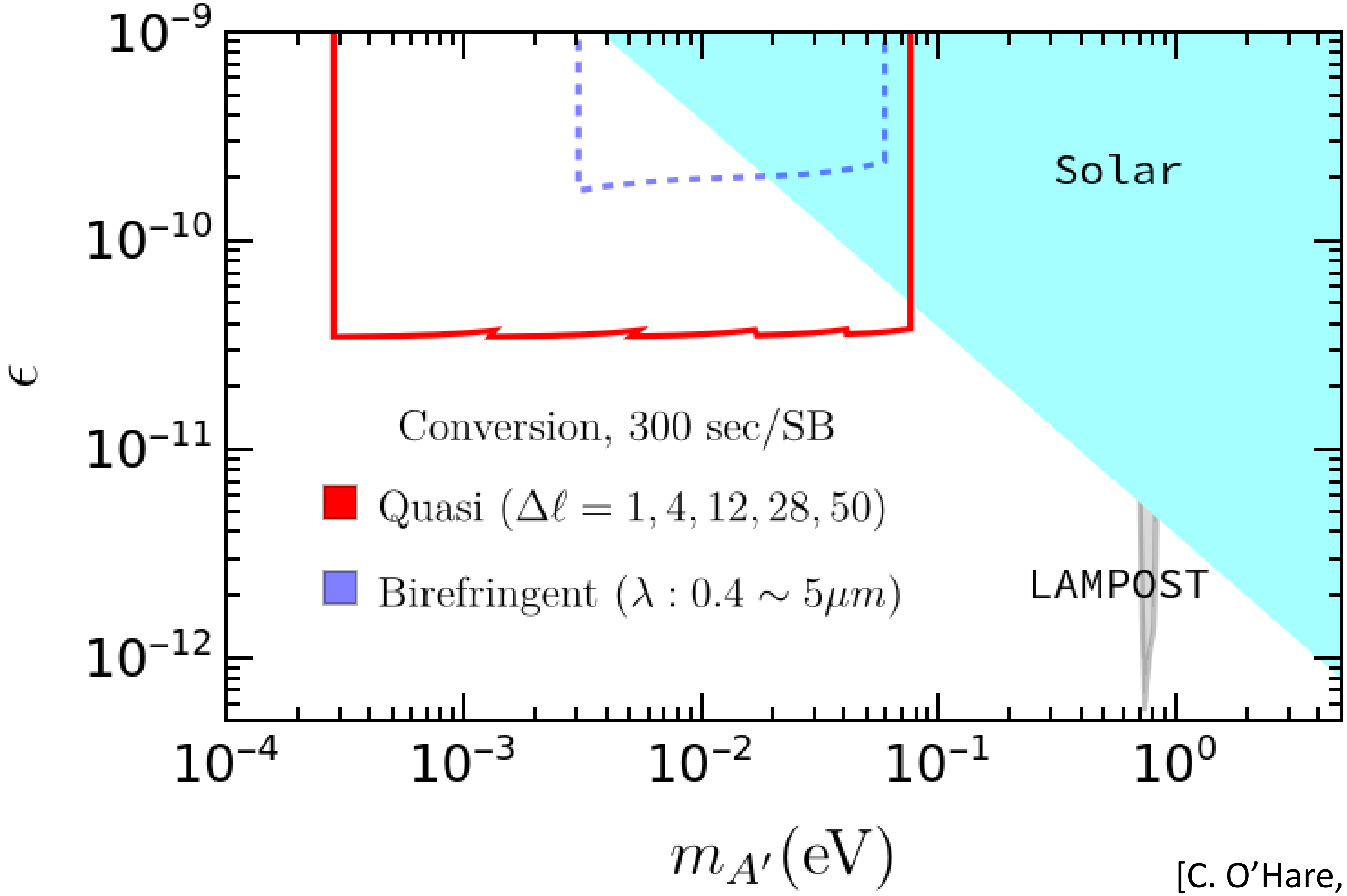
Photon-material scattering

## Mitigation

$\omega_s > \omega_p + T$, polarization flip

# Projected Sensitivity

$$N = 10^3,\ P_{\text{total}} = 1\,\text{kW},\ t_{total} = 1\,\text{year},\ Q = 10^6$$




[C. O'Hare, *AxionLimits*]

# Dark Matter Searches with Integrated Optics

Optical chips allow resonant EM DM searches with large numbers of high-Q, micron-scale resonators

Sensitive to QCD axion and very feeble dark photon kinetic mixings for masses $0.1\ \mathrm{eV} < m_{dm} < 2\ \mathrm{eV}$

Sensitive to up-scattering by dark photons in nonlinear media at smaller masses $10^{-4}\ \mathrm{eV} < m_{dm} < 0.1\ \mathrm{eV}$

This approach to DM direct detection will benefit from future developments in integrated optics

# Dark Matter Searches with Integrated Optics

Extra Slides

# Optical Microring DM Search

## Birefringent phase matching

$$m_{\rm dm} = (\frac{1}{n_s} + \frac{1}{n_p})k = (\frac{n_p}{n_s} + 1)\omega_p \approx 2.04\,\omega_p$$ decay

$$m_{\rm dm} = (\frac{1}{n_s} - \frac{1}{n_p})k = (\frac{n_p}{n_s} - 1)\omega_p \approx 0.04\,\omega_p$$ up-conversion

## Quasi-phase Matching

$$m_{\rm dm} = \frac{1}{n}(k_s - k_p) = \omega_0 N_z$$ up-conversion

$$m_{\rm dm} = \frac{1}{n}(k_s + k_p) = \omega_p + \omega_0 N_z$$ decay

$LiNbO_3$ $\quad n_e = 2.21 \quad n_0 = 2.3$

$$\omega_0 = \frac{2\pi}{n_i L} \approx 6 \cdot 10^{-3}\,{\rm eV}\left(\frac{100\,\mu{\rm m}}{L}\right)$$

# DM + Photon + Photon Interactions

DM Background + "Pump" photon bath ⟶ "Signal" photon

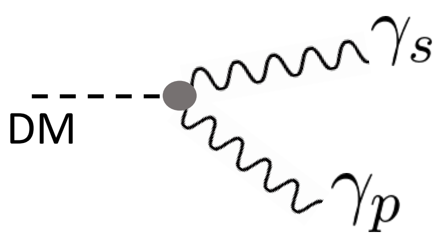
$$\mathcal{L} \supset \epsilon\, \varepsilon_0 \chi^{(2)}_{ijk} E_i E_j E'_k$$

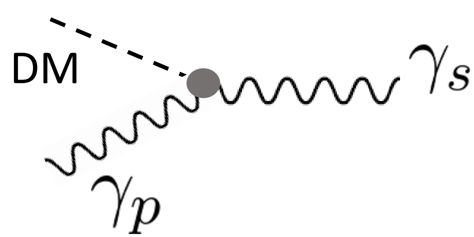
$$\sim \varepsilon_0 \chi^{(2)} \left( b_{dm} a_p^\dagger a_s^\dagger + b_{dm} a_p a_s^\dagger + b_{dm}^\dagger a_p a_s^\dagger \right)$$

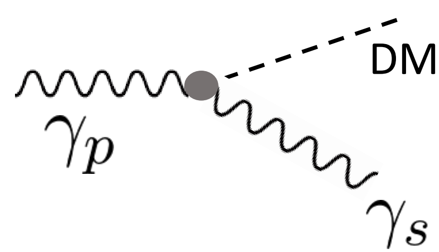
Stimulated Decay

Up-conversion

Down-conversion



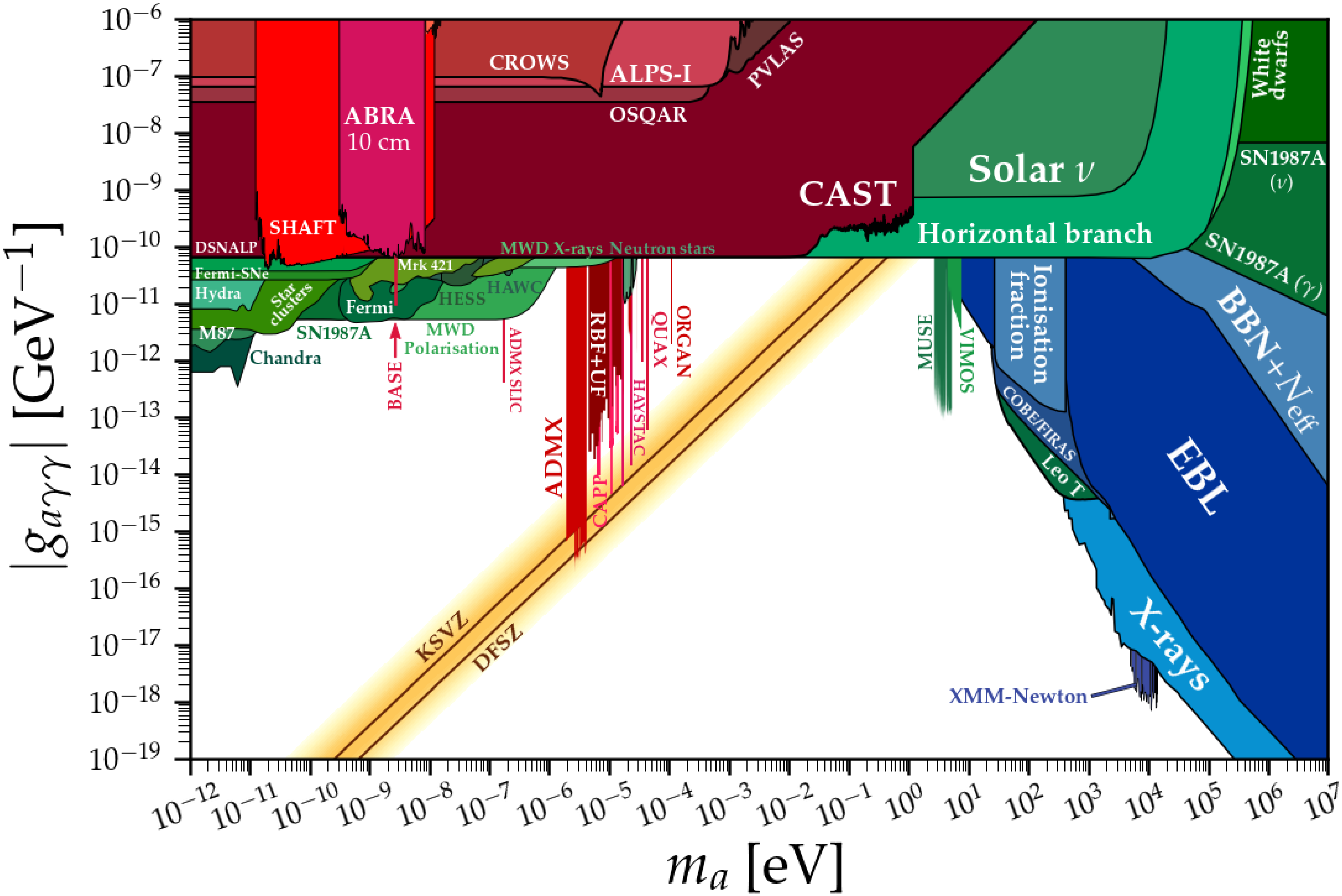




[Gnosh et al, 2008.02729]

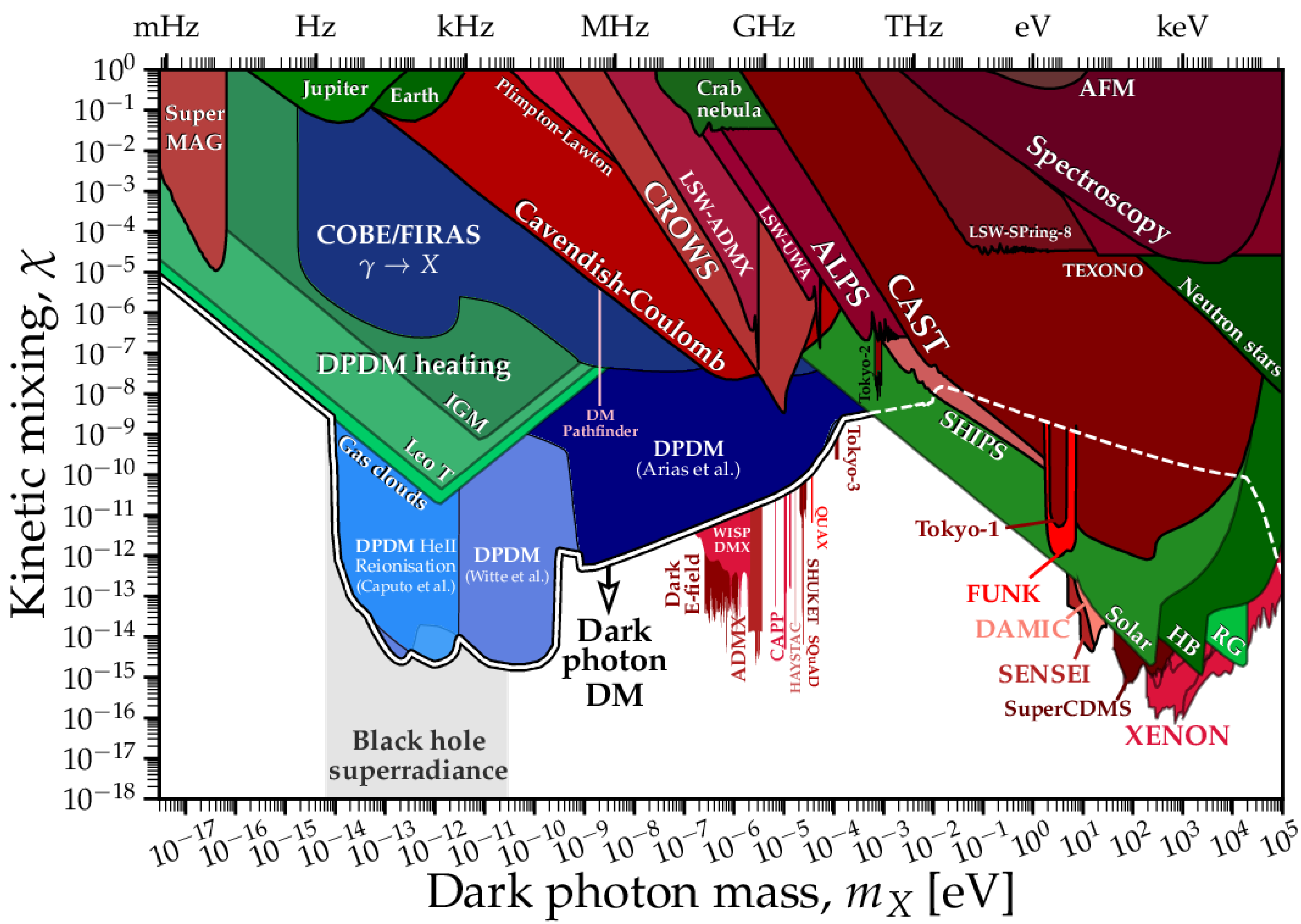
[Berlin et al, 2007.15656]

# Axion Current Limits




[C. O'Hare, https://cajohare.github.io/AxionLimits, 2105.04565]

# Dark Photon Current Limits




[C. O'Hare, https://cajohare.github.io/AxionLimits, 2105.04565]