

# Axion and Dark Photon Detection with Dielectric Haloscopes

Next Frontiers in the Search for Dark Matter



Masha Baryakhtar

NYU

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# Axions as Dark Matter

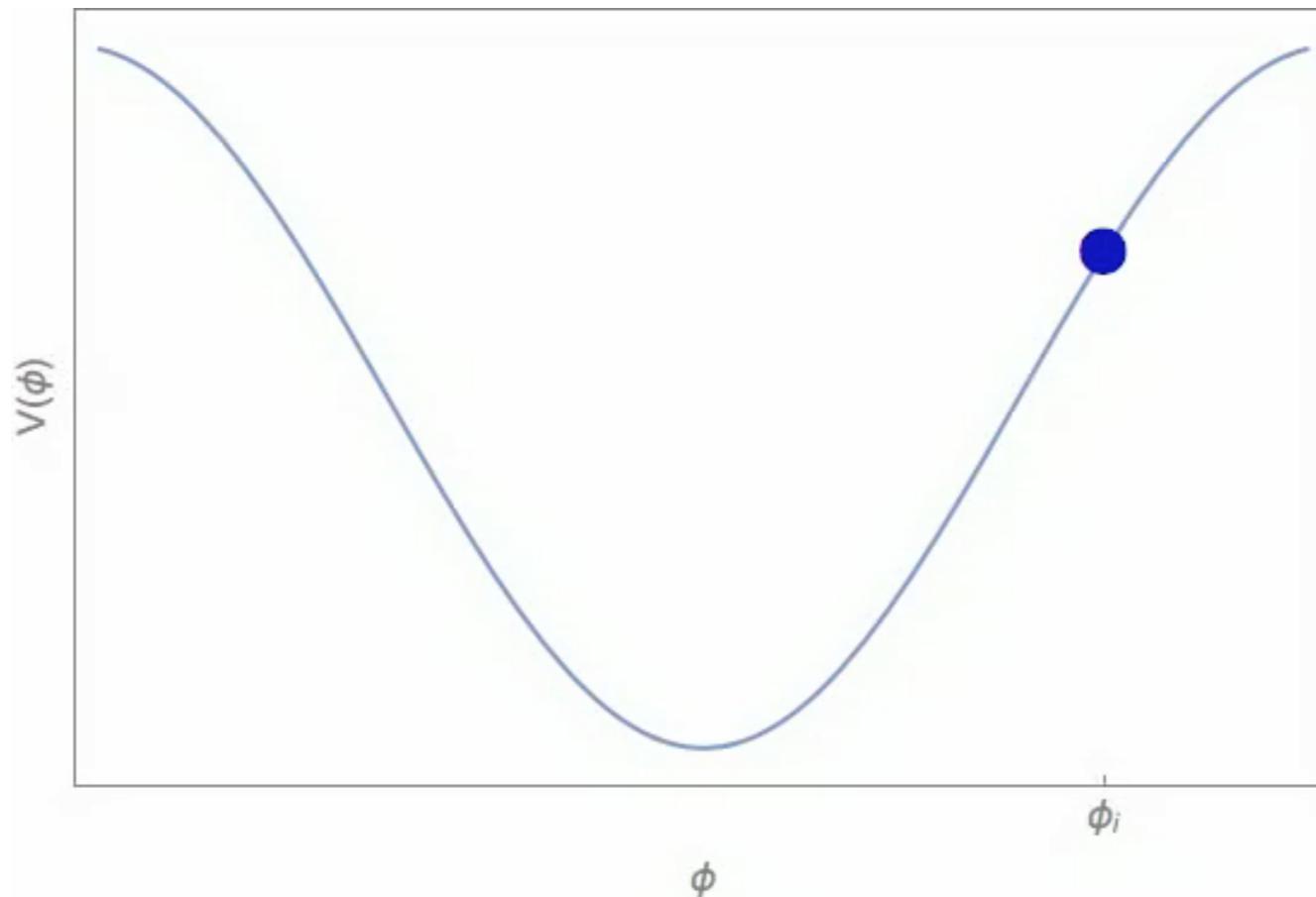
- Proposed to solve the strong-CP problem
- Cosmological evolution of amplitude given by damped harmonic oscillator:

$$\ddot{a} + 3H\dot{a} + m^2a = 0$$

Peccei and Quinn, PRL 38, 1440, 1977  
Weinberg, PRL 40, 223, 1978  
Wilczek, PRL 40, 279, 1978

Preskill, Wise, Wilczek, PR 120B, 127-132, 1983

- Early on,  $H \gg m$ : frozen by Hubble friction
- When  $H < m$ : begins to oscillate and redshift as matter



Predict DM density as a function of  $m, f$ :

$$\frac{\rho_a}{\rho_{cdm}} \sim \left(\frac{m}{eV}\right)^{1/2} \left(\frac{f}{10^{11} \text{GeV}}\right)^2 \left(\frac{a_i}{f}\right)^2$$

QCD axion

$$\frac{\rho_{a,QCD}}{\rho_{cdm}} \sim \left(\frac{f}{\text{few} \times 10^{11} \text{GeV}}\right)^{7/6} \left(\frac{a_i}{f}\right)^2$$

# Cousins of the QCD Axion: Axion-like Particles and Dark Photons

- Complex string compactifications produce multiplicity of light string axions

Kallosh, Linde, Linde, Susskind [9502069]

Svrcek , Witten [0605206]

Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell [0905.4720]

- Gauge fields with an additional index give rise to light dark photons in 4D

Cicoli, Goodsell, Jaeckel, Ringwald [1103.3705]

Arvanitaki, Craig, Dimopoulos, Dubovsky, March-Russell [0909.5440]

- Dark photons produced through inflationary fluctuations at high scales

$$\frac{\rho_{\text{dp}}}{\rho_{\text{cdm}}} \sim \left( \frac{m}{\text{eV}} \right)^{1/2} \left( \frac{H_I}{5 \times 10^{12} \text{GeV}} \right)^2$$

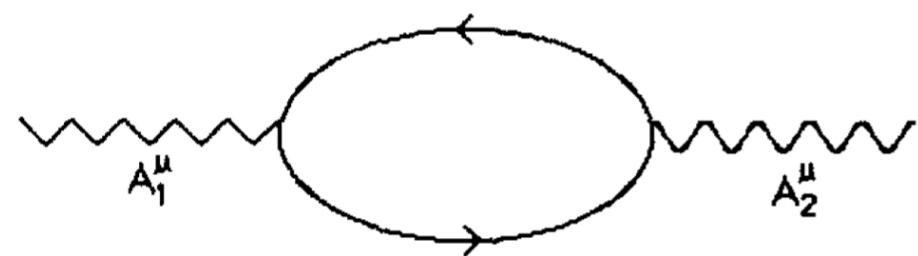
Nelson, Scholtz [1105.2812]

Arias, Cadamuro, Goodsell, Jaeckel, Redondo, Ringwald [1201.5902]

Graham, Mardon, Rajendran [1504.02102]

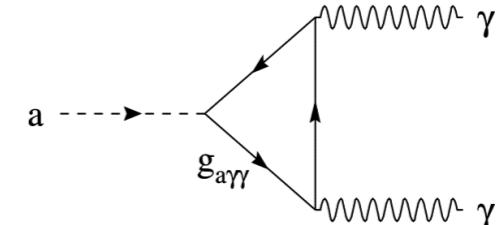
# Axion and Dark Photon Searches

- Wide parameter space of weakly coupled, light particles

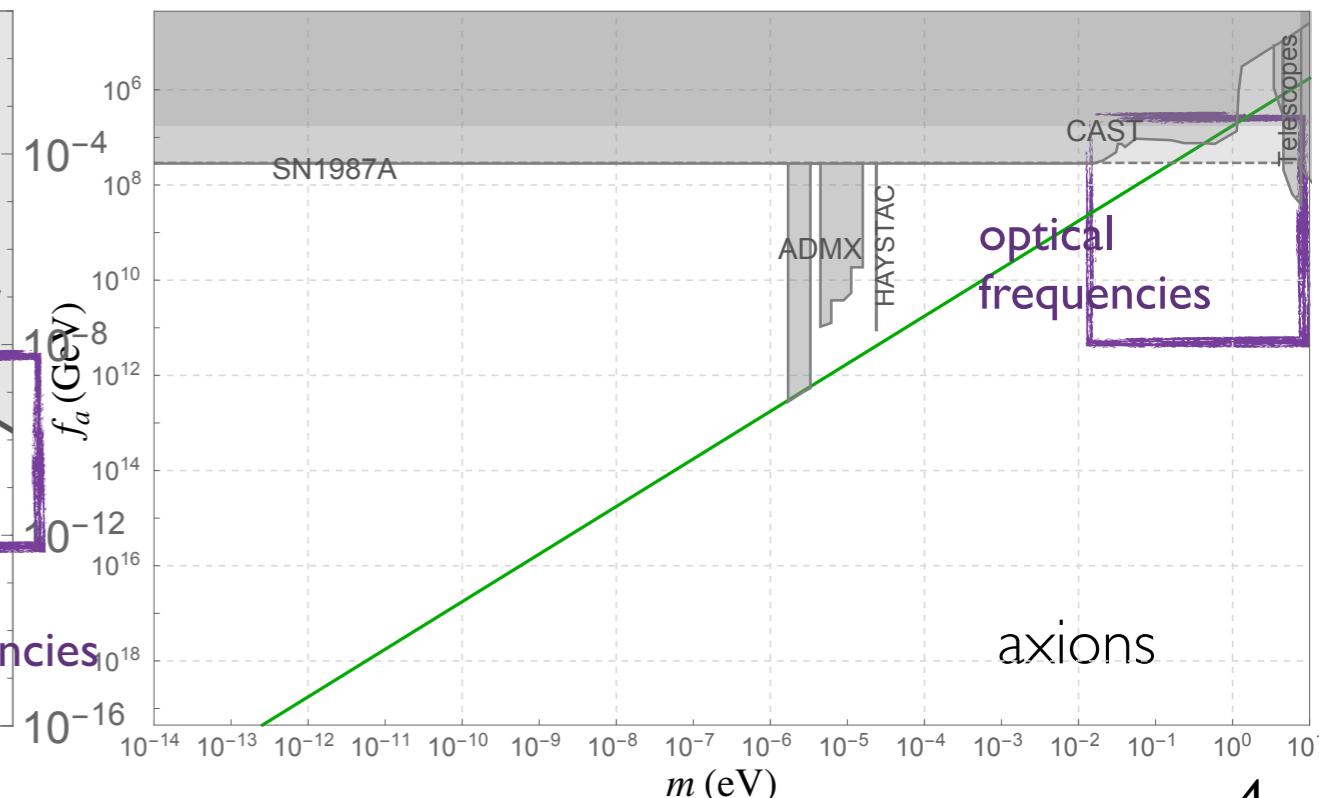
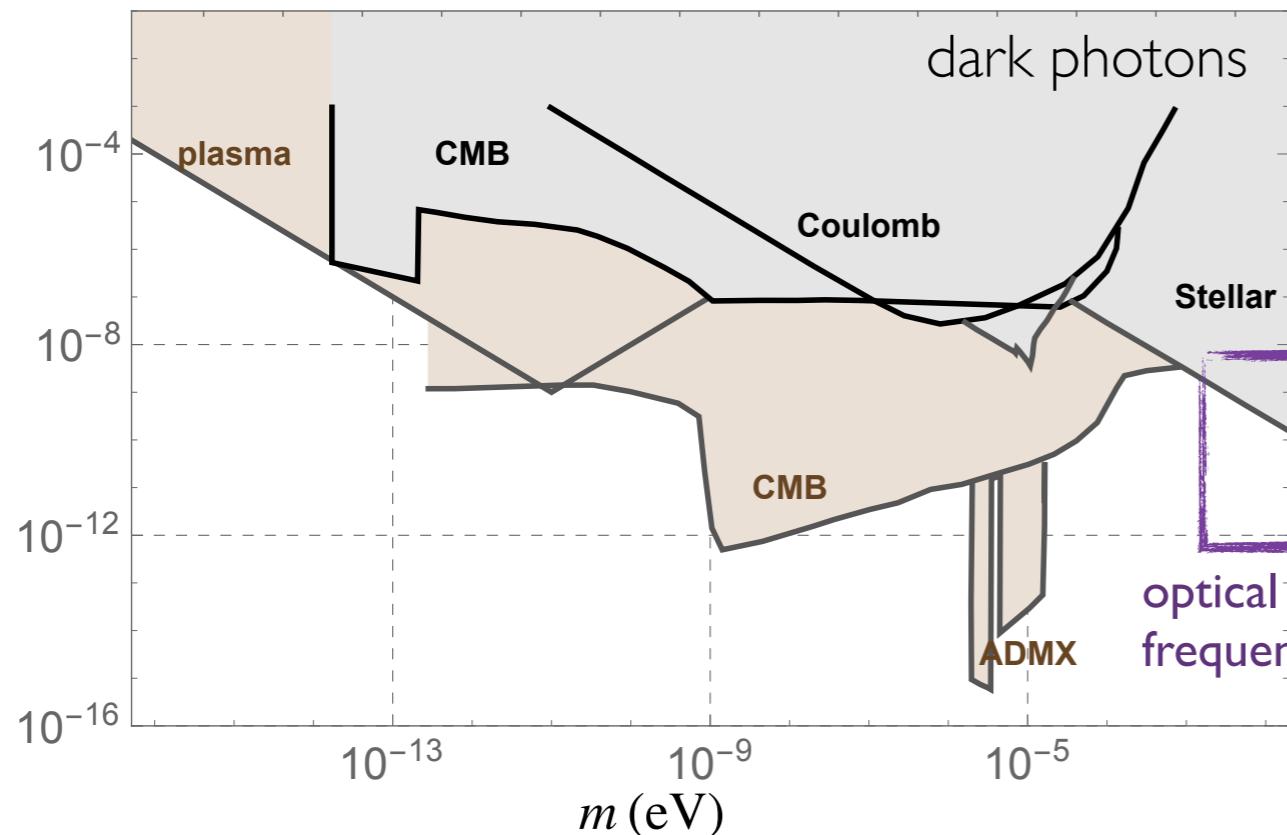


$$-\frac{1}{4}F_{\mu\nu}'^2 + \frac{\kappa}{2}F_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}m_A^2A_\mu'^2$$

- Axions and dark photons generically couple to photons: opens new search strategies with recent technological advances



$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 + \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2a^2 + \frac{g_{a\gamma\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$



# Outline

- Seeing bosonic dark matter
- Searches with dielectric thin films
- Nanowire detection of photons from the dark side

**MB**, J. Huang, R. Lasenby, Phys. Rev. D 98, 035006 (1803.11455)

DOE QuantiSED grant, DE-SC0019129 +NIST funds

*Bosonic Dark Matter Search Using Superconducting Nanowire Single-Photon Detectors*

Experiment: K. Berggren, I. Charaev, A E. Dane (MIT); J. Chiles, S. Nam (NIST)

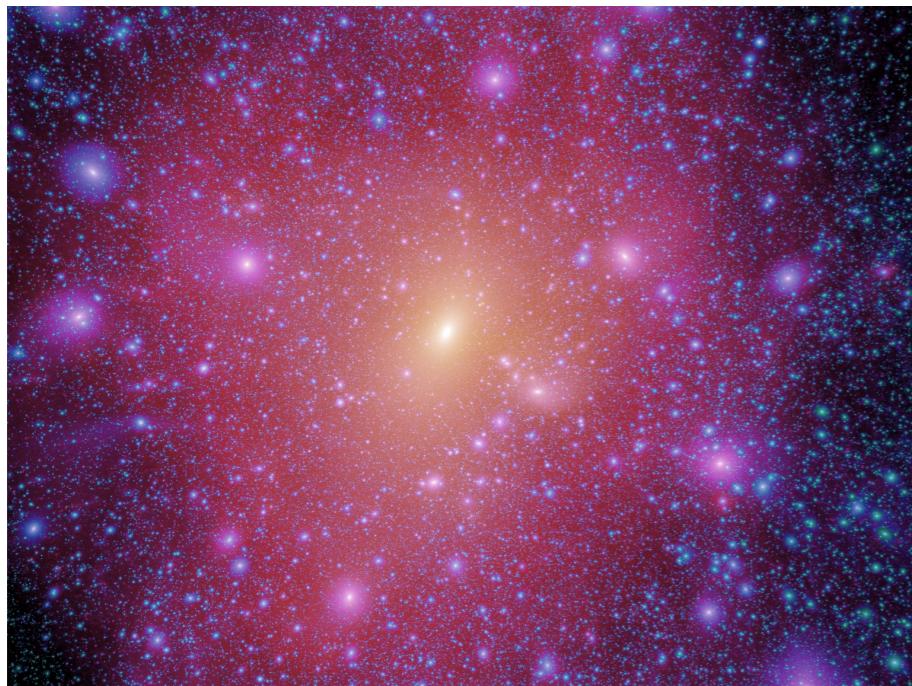
Theory: A. Arvanitaki, J. Huang; **MB**; K. Van Tilburg; R. Lasenby

# Seeing light bosonic dark matter

- Photon can convert into axion (dark photon) and back through E . B (kinetic mixing) term



- Can we see axion or dark photon dark matter converting to photons?



Solar Flux  $\sim 1.4 \text{ kW/m}^2$

$$\rho_{DM} \sim 0.3 \text{ GeV/cm}^3$$

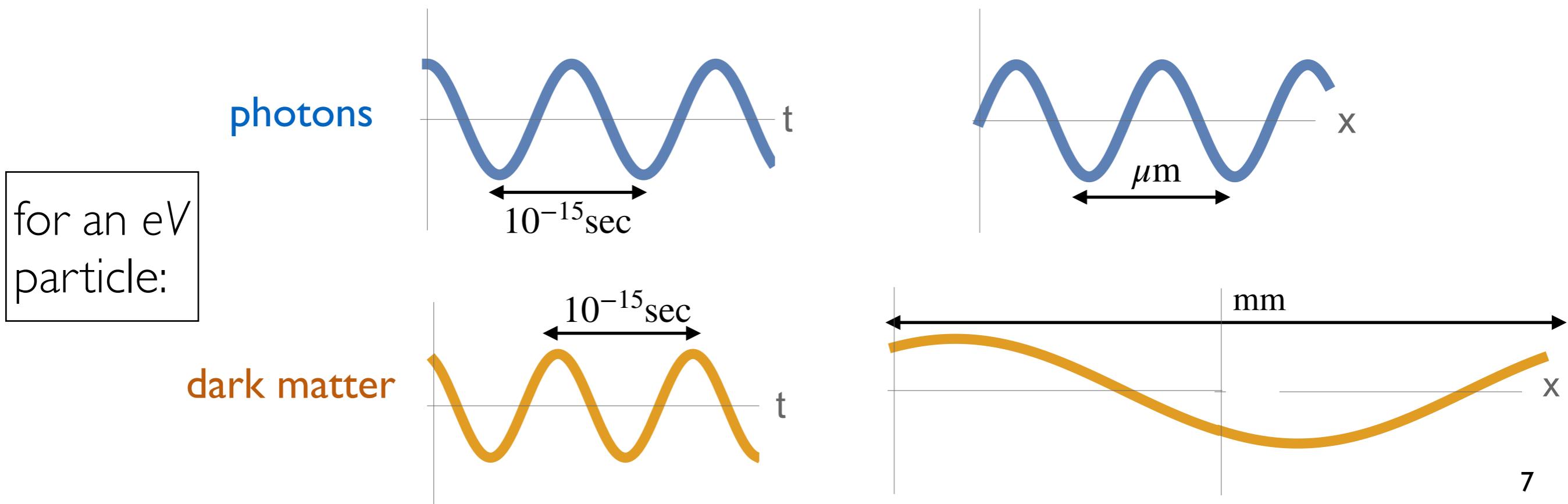
$$\text{Dark Matter Flux} \sim 14 \text{ W/m}^2$$

# Seeing light bosonic dark matter

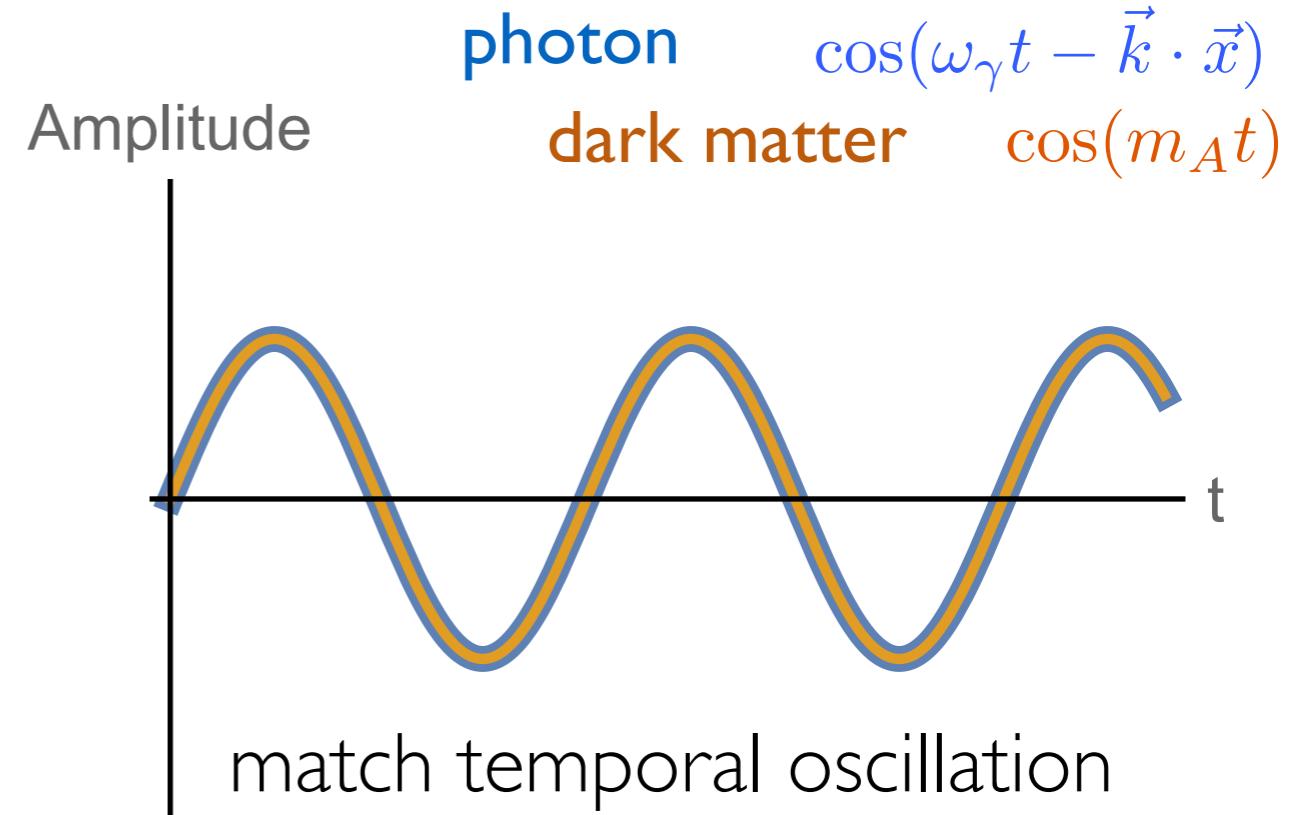
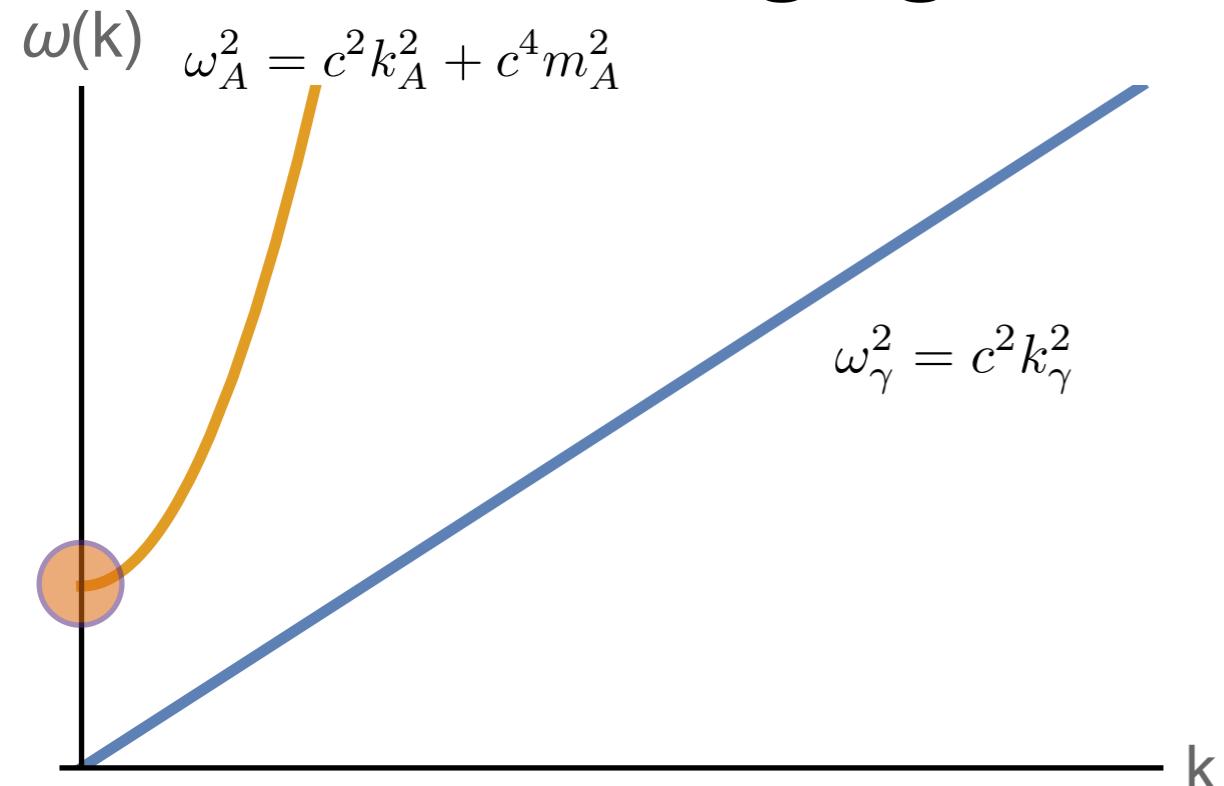
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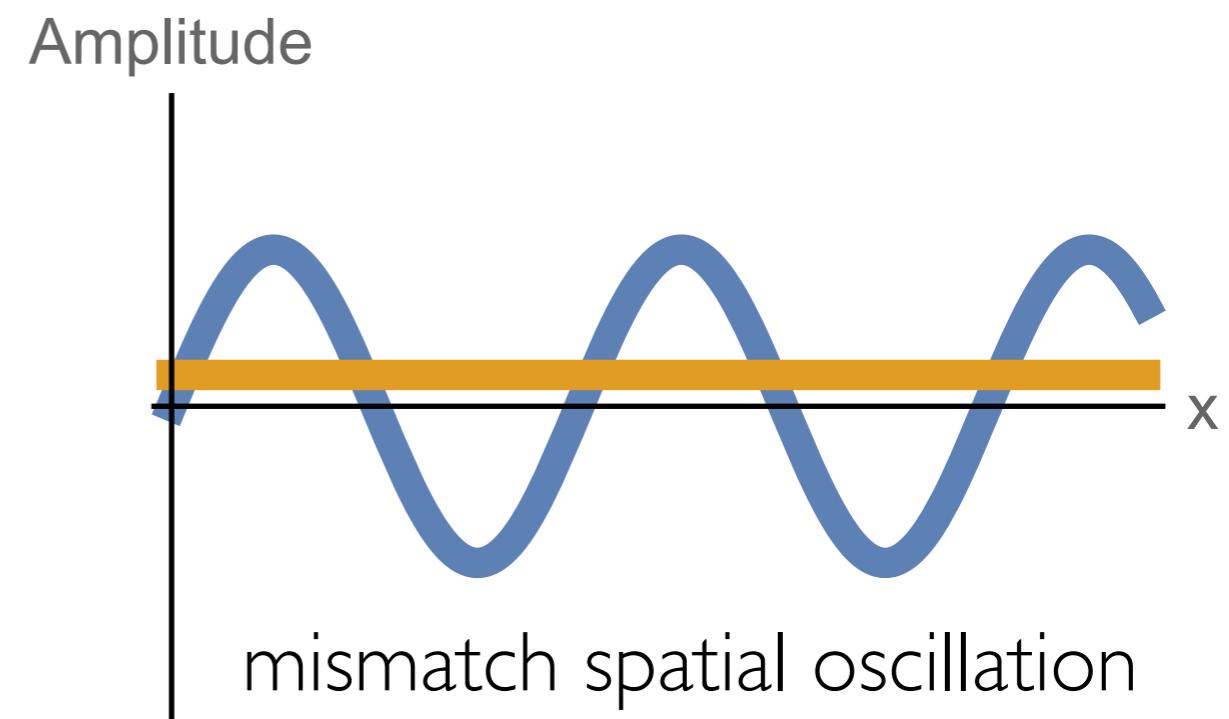


# Seeing light bosonic dark matter



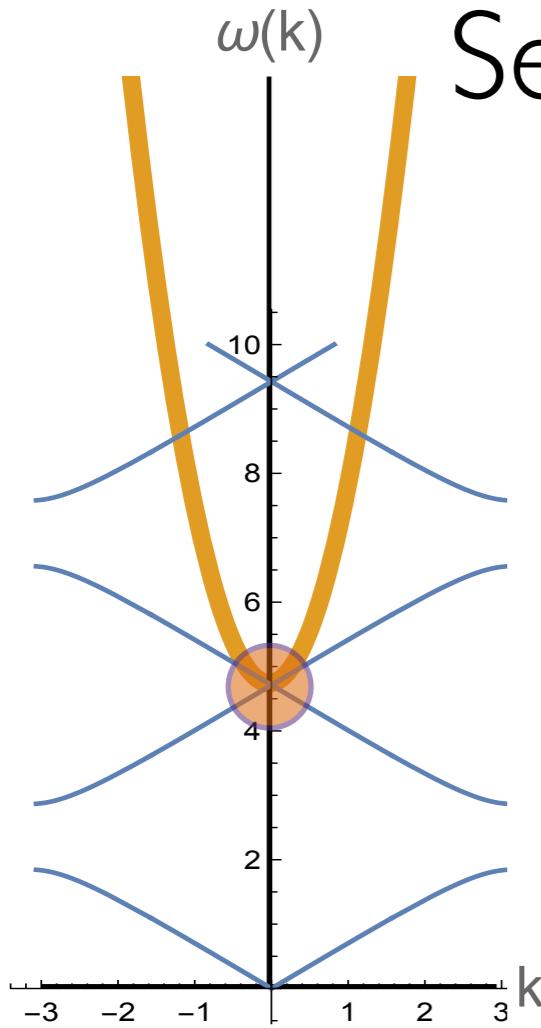
- Mismatch in dispersion relation: **photons** relativistic while **dark matter** is massive with a small velocity in our galaxy
- Impossible to conserve both energy and momentum

$$\omega_A = \omega_\gamma \Rightarrow k_\gamma \sim 0$$

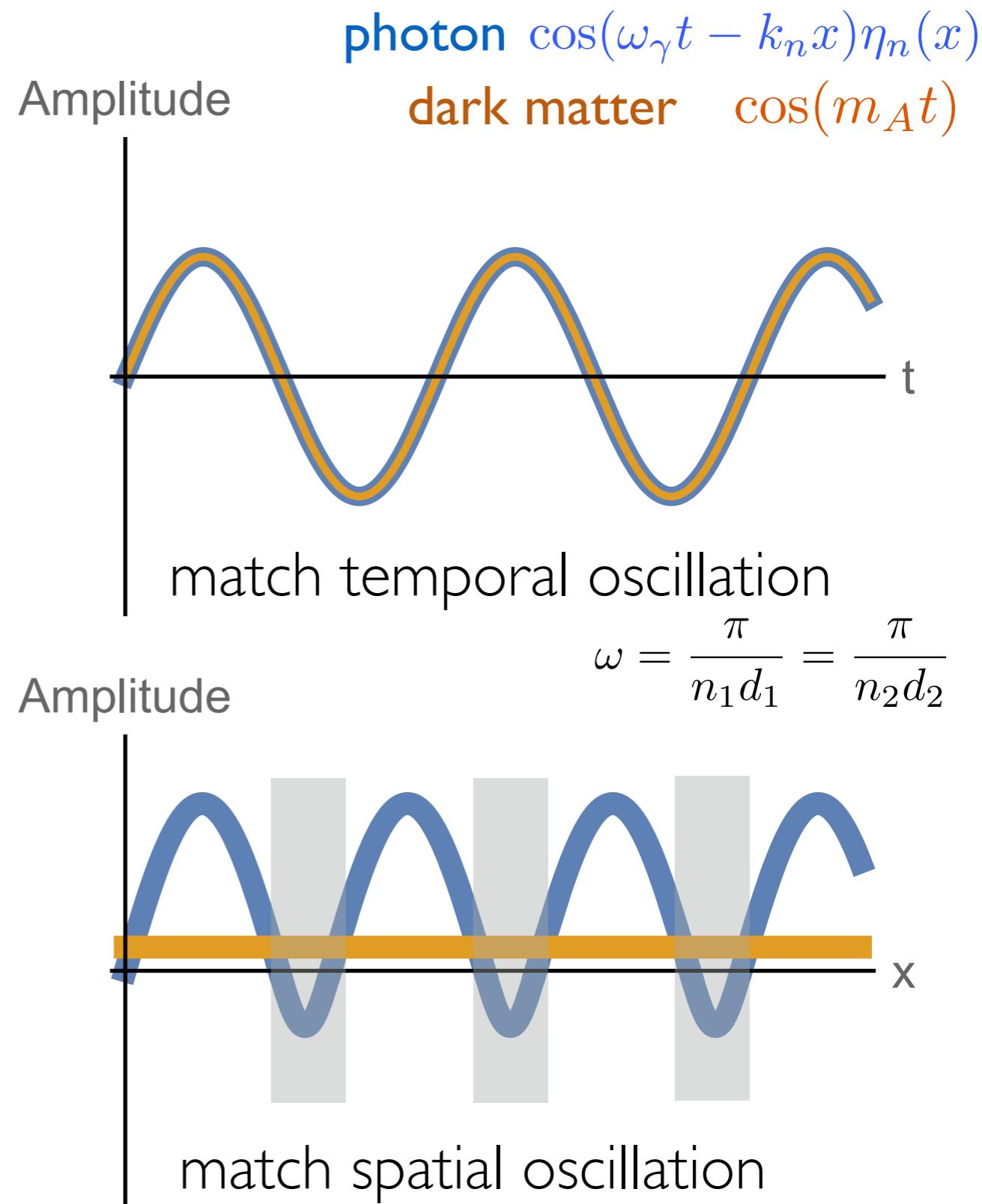


$\omega(k)$ 

# Seeing light bosonic dark matter



- Add periodicity in one dimension to correct momentum mismatch
- Periodic index of refraction changes free solutions of photon modes
- Electric field no longer integrates to zero against a constant DM background



# Seeing light bosonic dark matter

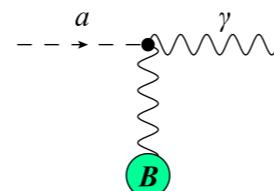
Time varying, spatially homogeneous dark matter sources photons in periodic structure

$$\nabla \cdot D = \rho_{dm}$$

$$\nabla \cdot B = 0$$

$$\nabla \times E + \partial_t B = 0$$

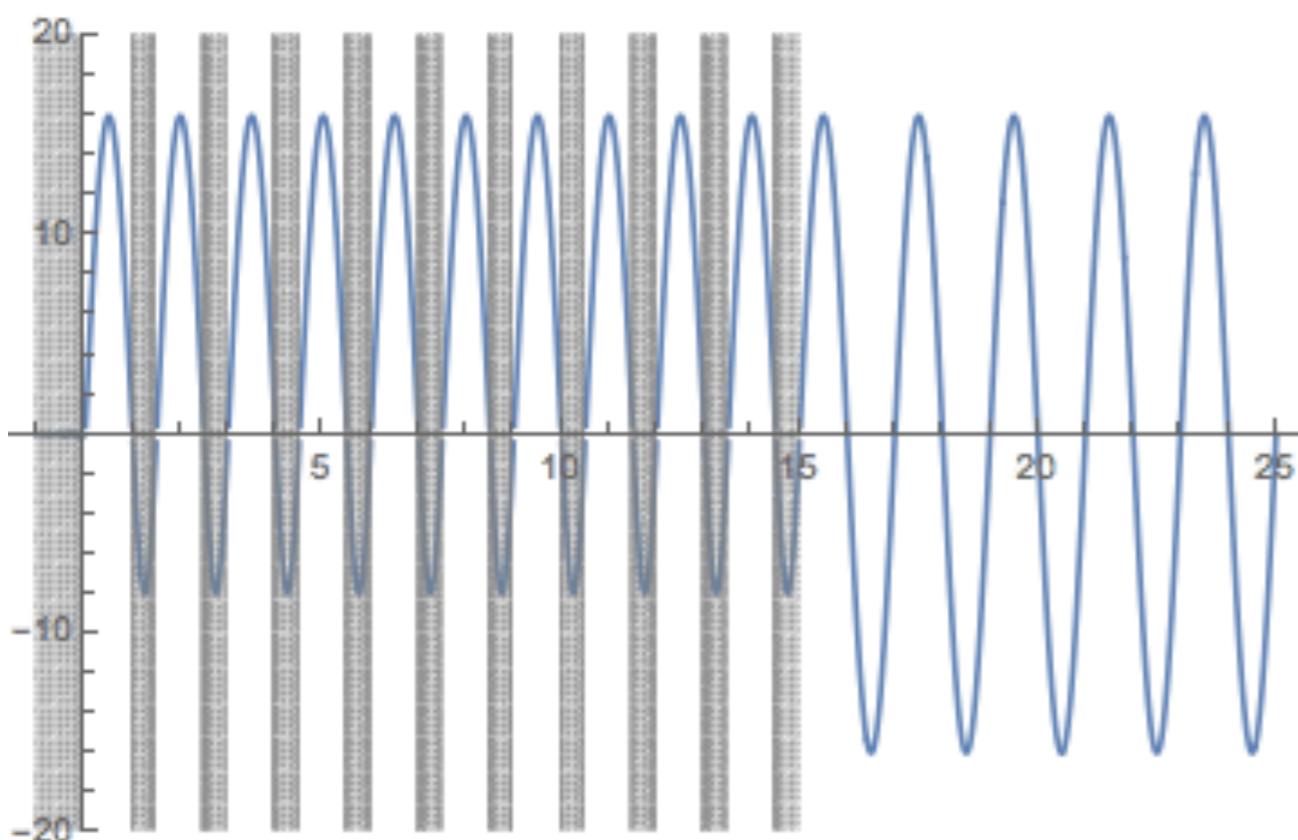
$$\nabla \times H - \partial_t D = J_{dm}$$



Axion 'current'  $J_a = g_{a\gamma\gamma} \partial_t a B_{ext}$

A diagram showing a particle emitting a wavy line labeled 'γ' (dark photon) from a point labeled 'a'. A dashed arrow points towards the particle.

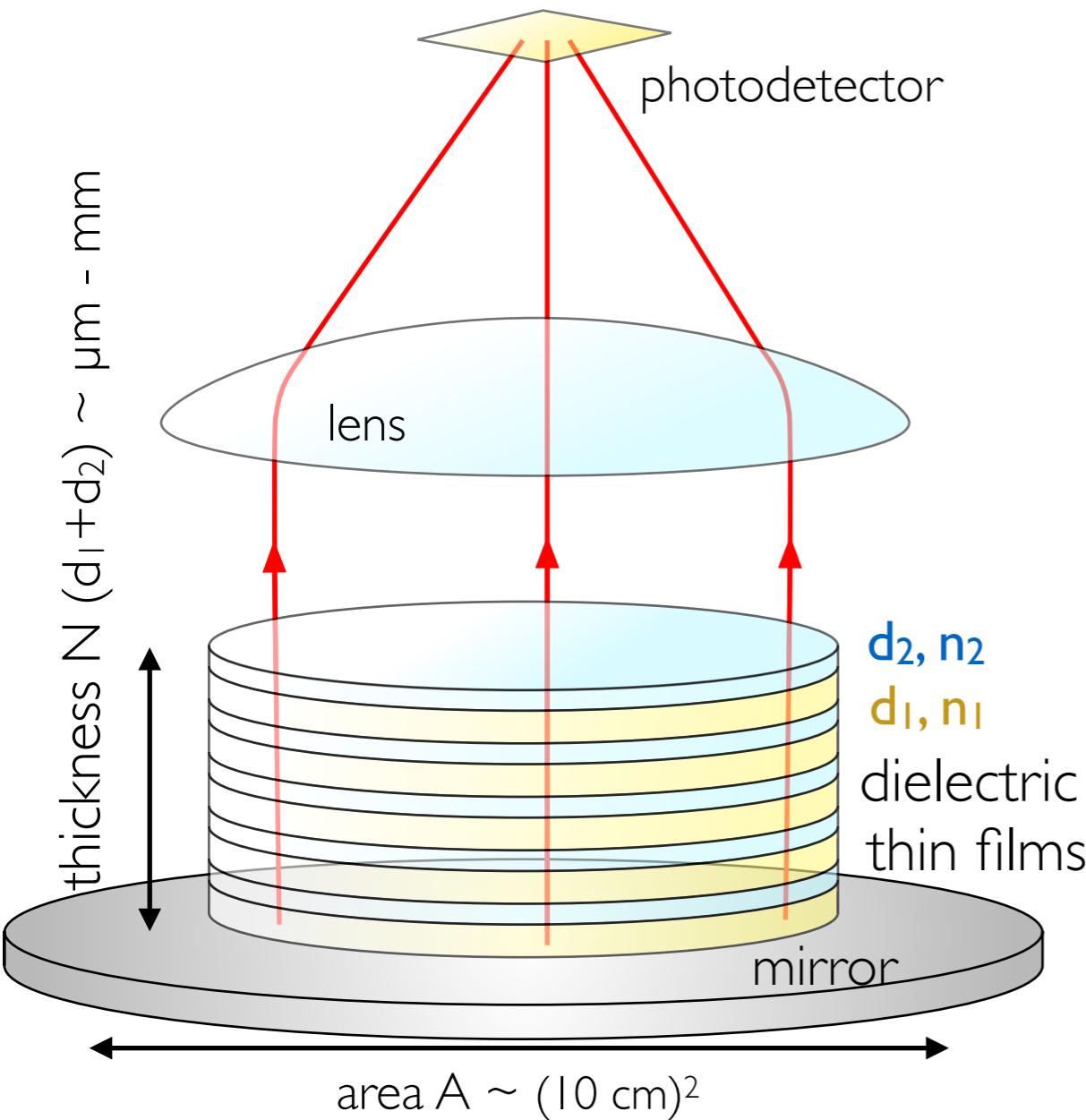
Dark photon 'current'  $J_{A'} = \kappa m_A^2 A'$



- Outgoing photon energy sourced by dark matter:
$$\omega_\gamma \simeq m_{dm}$$
- Outgoing photon momentum sourced by periodicity:
$$k_\gamma \simeq \frac{\pi}{nd}$$
- Emission when DM mass matches periodicity:
$$m_{dm} \simeq \frac{\pi}{nd}$$

# Seeing Dark Photon Dark Matter

$$P \sim \kappa^2 \rho_{dm} A N^2 \left( \frac{n_1^2 - n_2^2}{n_1^2 n_2^2} \right)^2 \sim \left( \frac{\kappa}{10^{-11}} \right)^2 \left( \frac{N}{5} \right)^2 \text{eV/s}$$

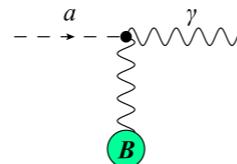
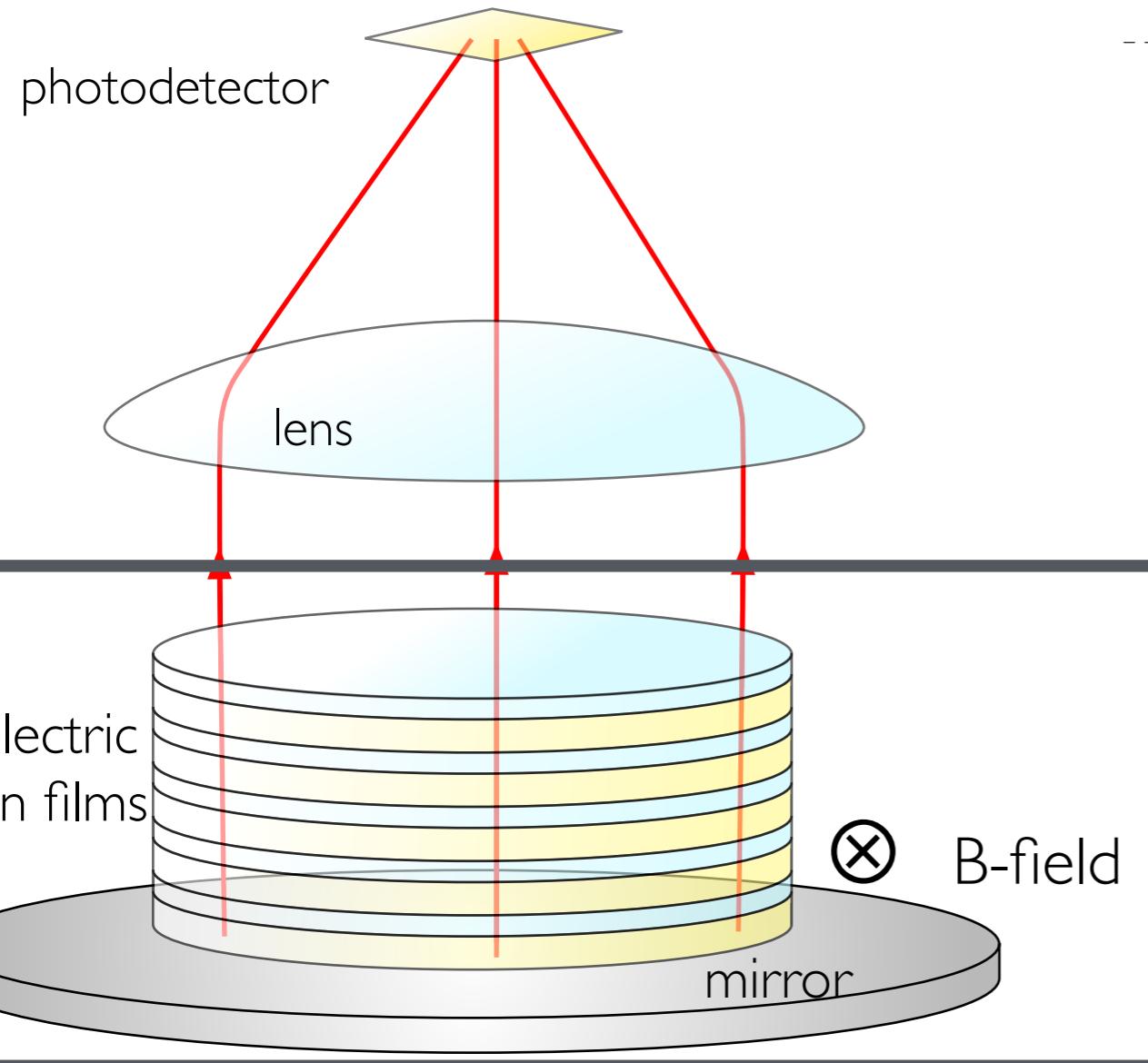


- High index of refraction contrast increases power
  - e.g. **silicon ( $n_2=3.4$ )** and **silica ( $n_1=1.46$ )**
- Large number of layers  $N$  increases power while decreasing mass coverage
  - E&M fields add coherently  $P \sim N^2$
  - $\frac{\Delta\omega}{\omega} \sim \frac{1}{N}$  coverage per stack
- Signal photons perpendicular to thin film stack: efficiently focused onto small photodetector

# Seeing Axion Dark Matter

$$P_a \sim 4g_{a\gamma\gamma}^2 B^2 \frac{\rho_{dm}}{m^2} A N^2 \left( \frac{n_1^2 - n_2^2}{n_1^2 n_2^2} \right)^2$$

apply external B field for axion-to-photon conversion



Axion 'current'

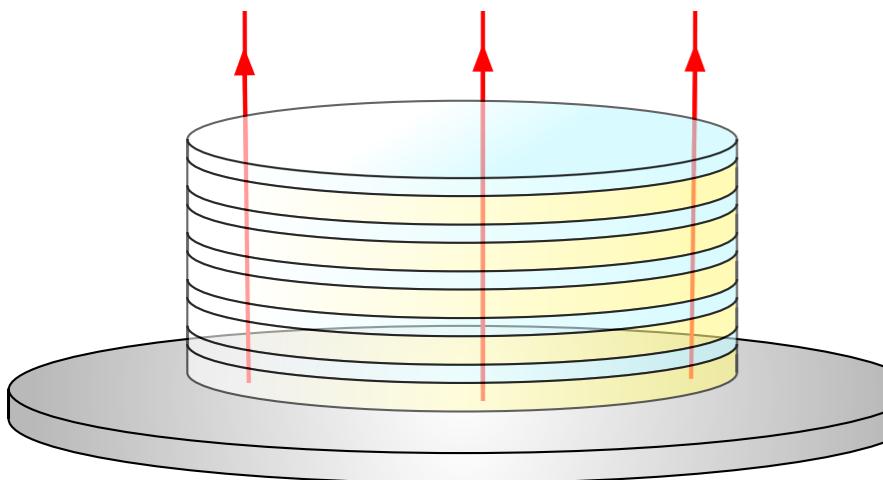
$$J_a = g_{a\gamma\gamma} \partial_t a B_{ext}$$

- Both searches rely on demonstrated, rapidly improving technology:
  - Single photon detectors: Low dark count rates, high efficiency in optical range; energy thresholds  $\sim 100$  meV - eV
  - Dielectric thin films: inexpensive and rapid manufacture with standard methods (CVD, PVD, etc)

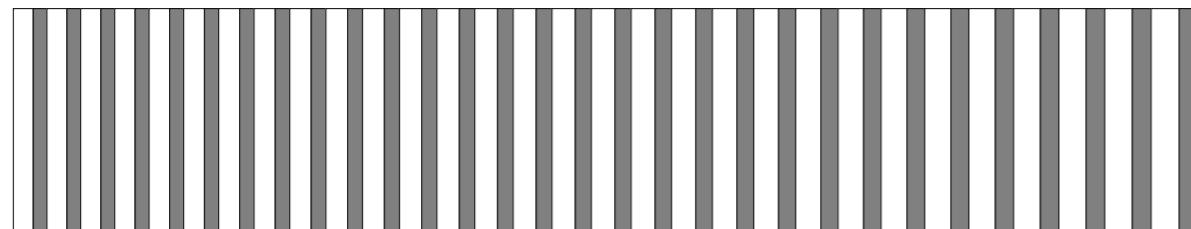
# Dielectric Optical Haloscope

DM mass matched to layer thickness and index of refraction

$$\omega = \frac{\pi}{n_1 d_1} = \frac{\pi}{n_2 d_2}$$



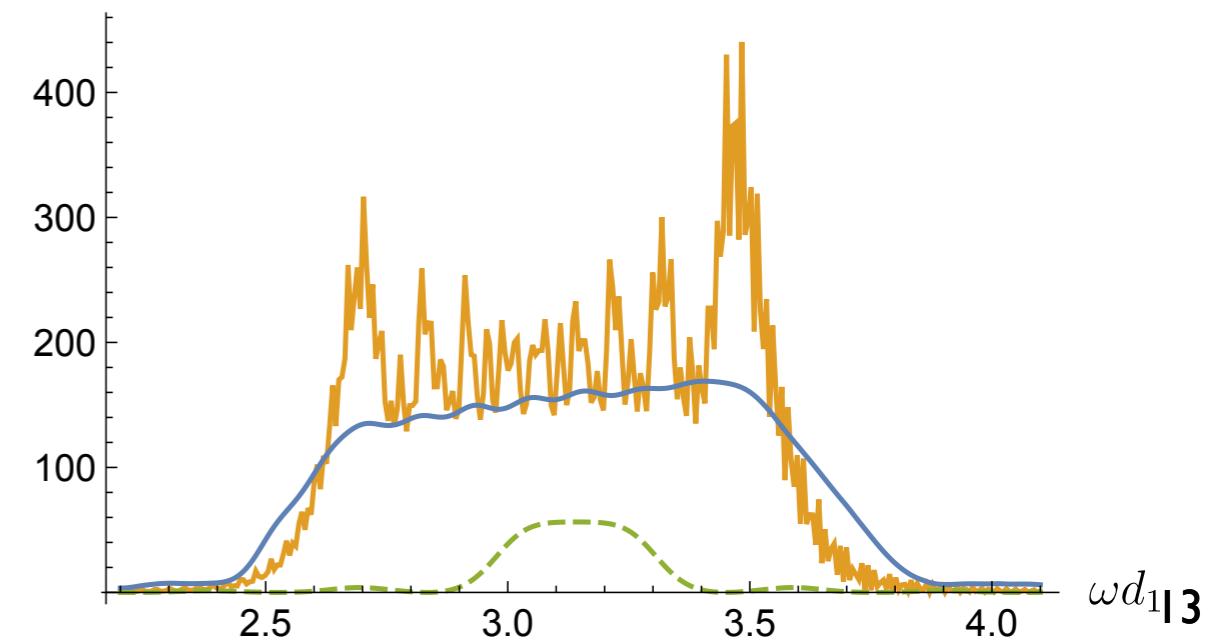
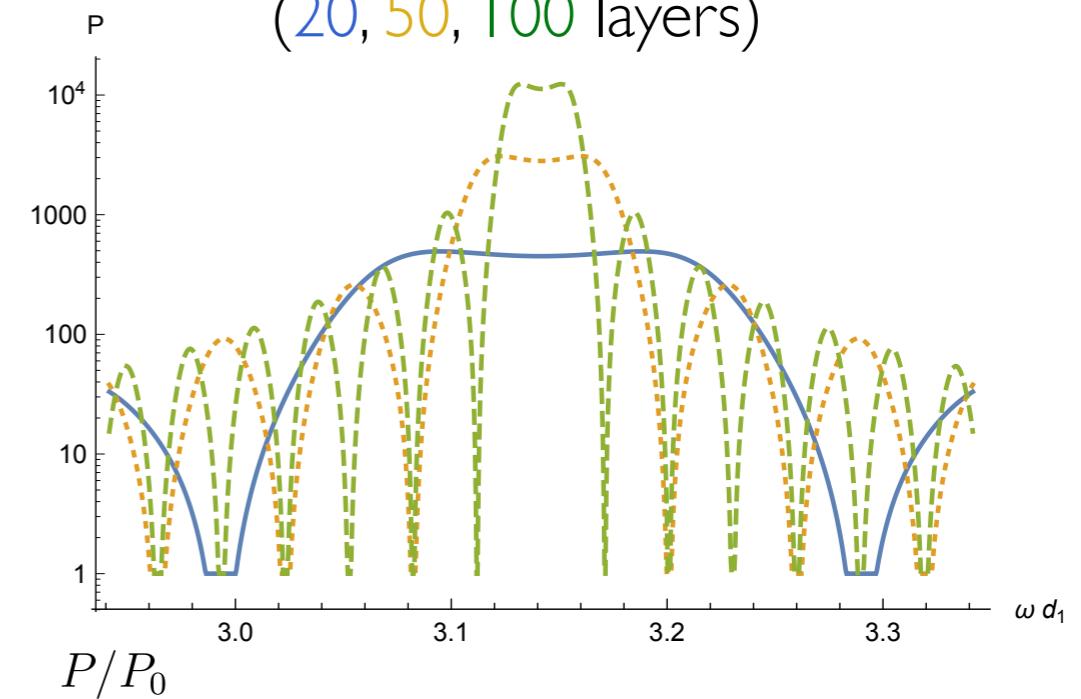
'Chirped' stacks for broader mass coverage:



10% - 0.1% coverage per stack

$$\frac{\Delta\omega}{\omega} \sim \frac{1}{N}$$

Power emitted as a function of frequency  
(20, 50, 100 layers)

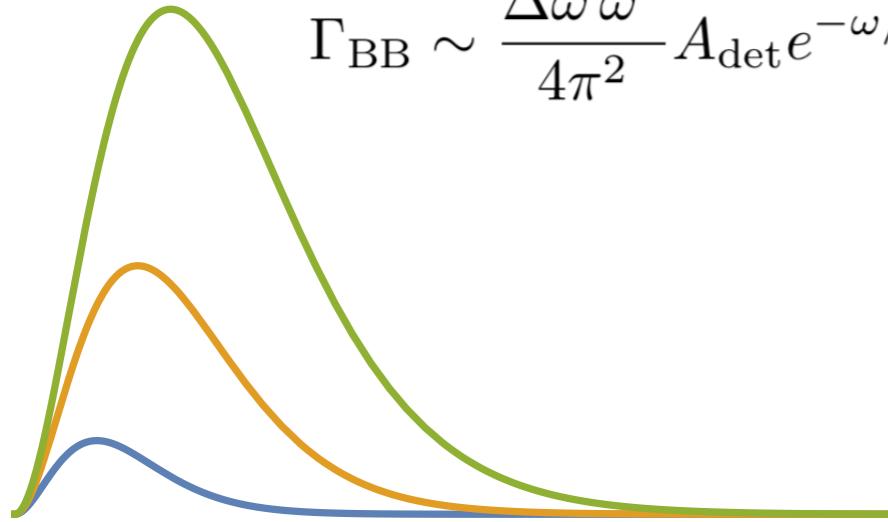


# Not seeing dark matter

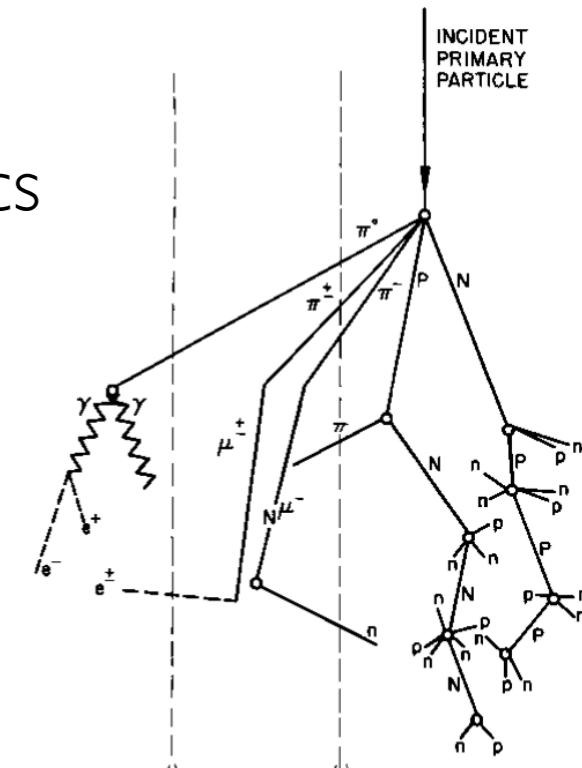
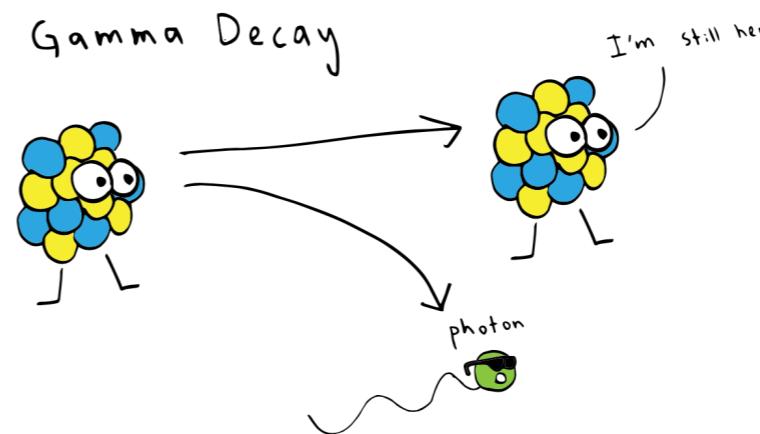
## Backgrounds

### Blackbody radiation

$$\Gamma_{\text{BB}} \sim \frac{\Delta\omega \omega^2}{4\pi^2} A_{\text{det}} e^{-\omega/T}$$

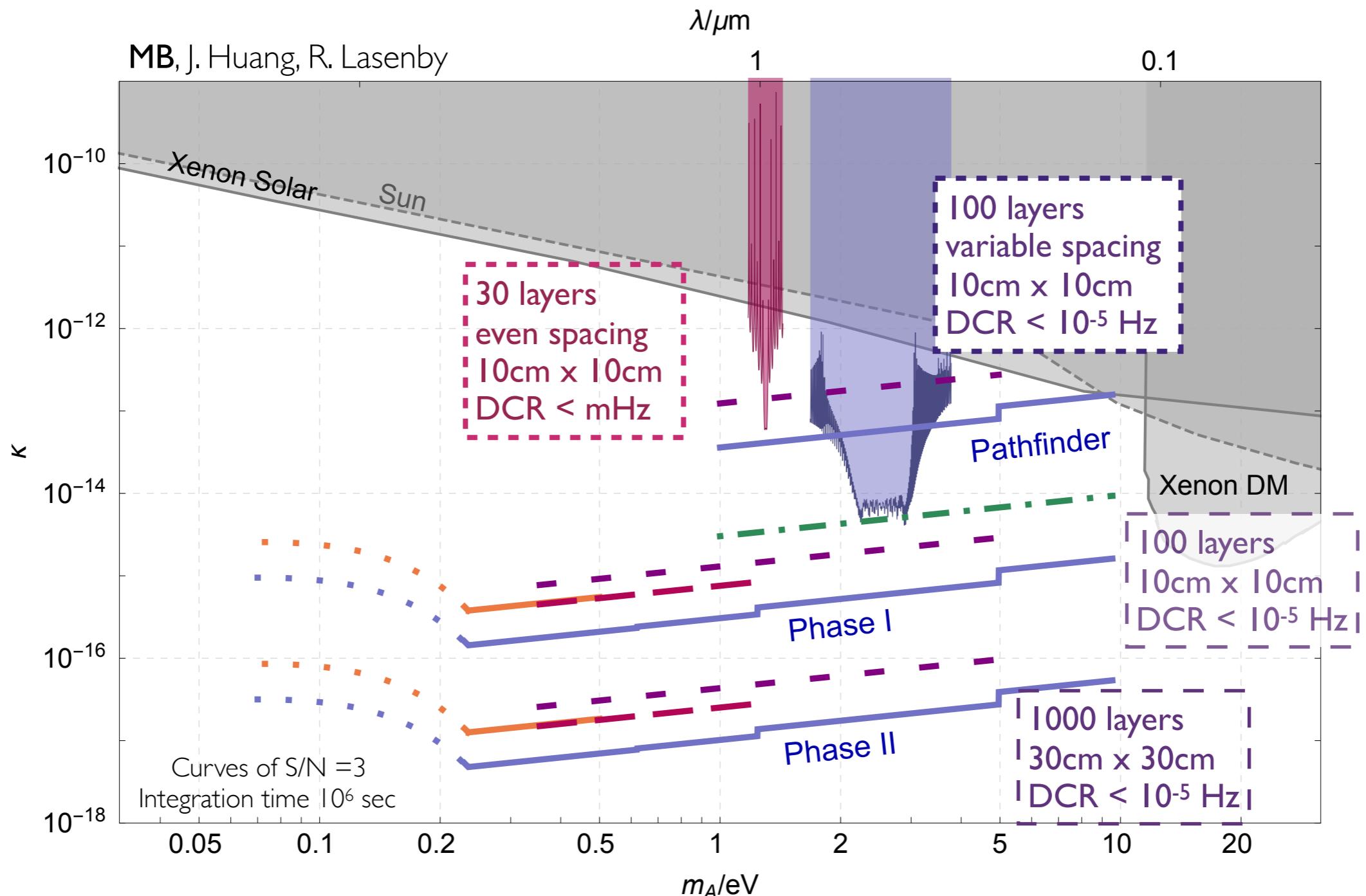


### Radioactivity and Cosmics



- At optical frequencies, black body radiation is exponentially suppressed
- Cooling may be necessary
- Backgrounds suppressed by small target volume, very small detector area, and target/detector separation
- Radioactive decays in surroundings, cosmic rays can produce energetic photons
- Typically these are high energy compared to signal and/or shower into many particles

# Dielectric Optical Haloscope



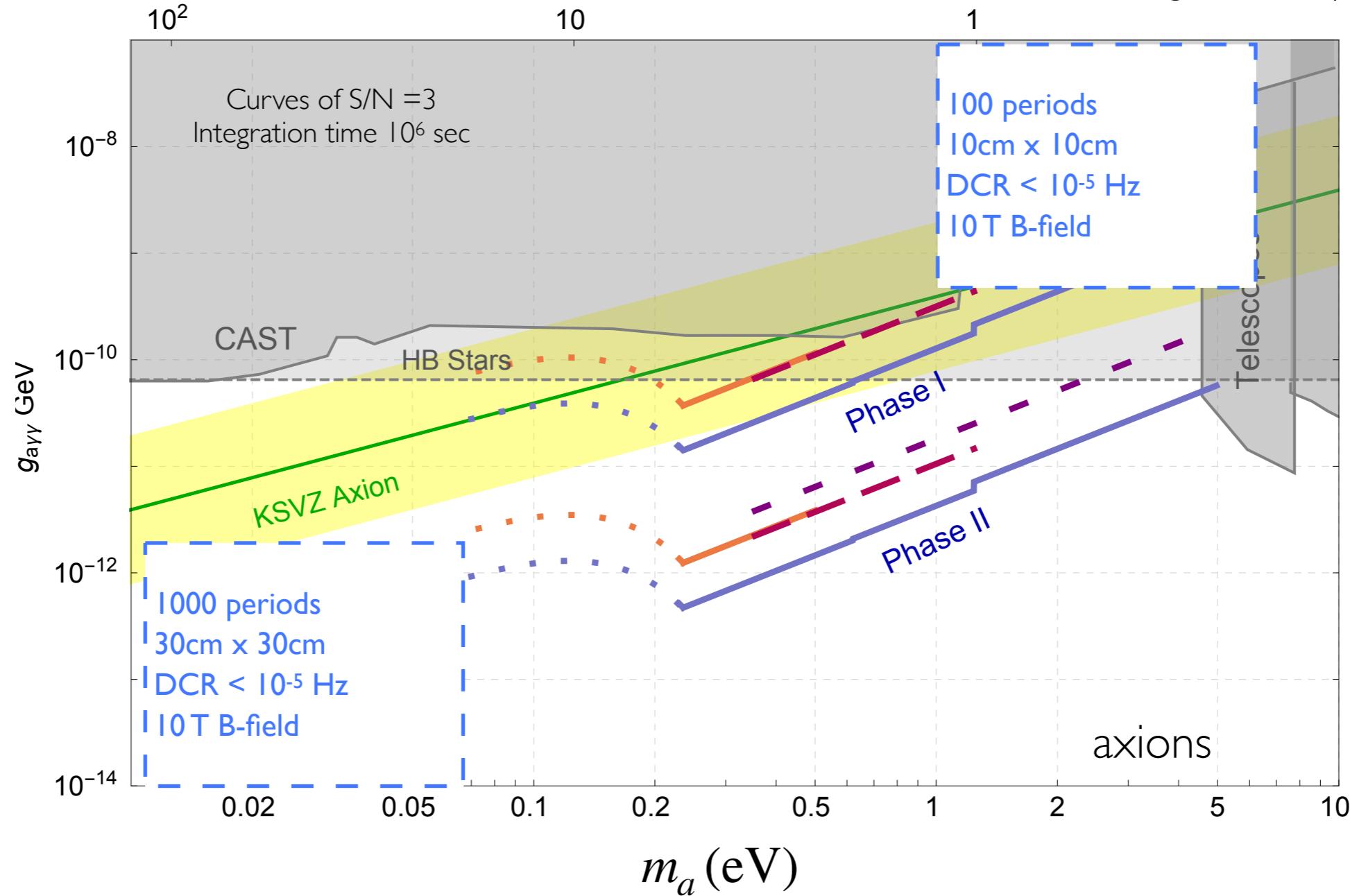
Future targets:

- vary layer thickness across the stack for wider frequency coverage
- increase number and area of layers for deeper coupling reach

# Dielectric Optical Haloscope

$\lambda/\mu\text{m}$

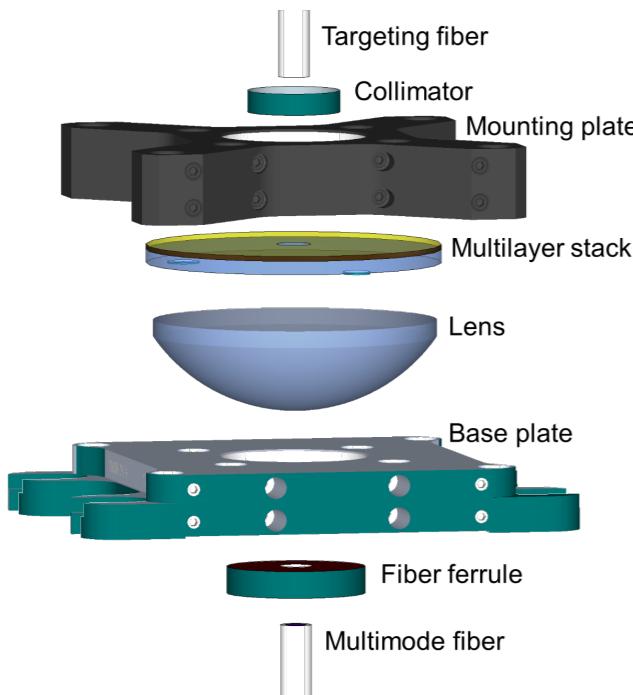
MB, J. Huang, R. Lasenby



Future targets:

- Probing axion couplings using applied magnetic fields

# Nanowire Detection of Photons from the Dark Side



- Prototype experiment currently in progress
- Collaboration with NIST-MIT team
- Set to reach new parameter space on short timescale
- Radioactive & cosmic backgrounds suppressed by small target volume and very small detector area
- Can be characterized by modifying/ removing dielectric target
- For future improvements, veto and/ or discrimination necessary

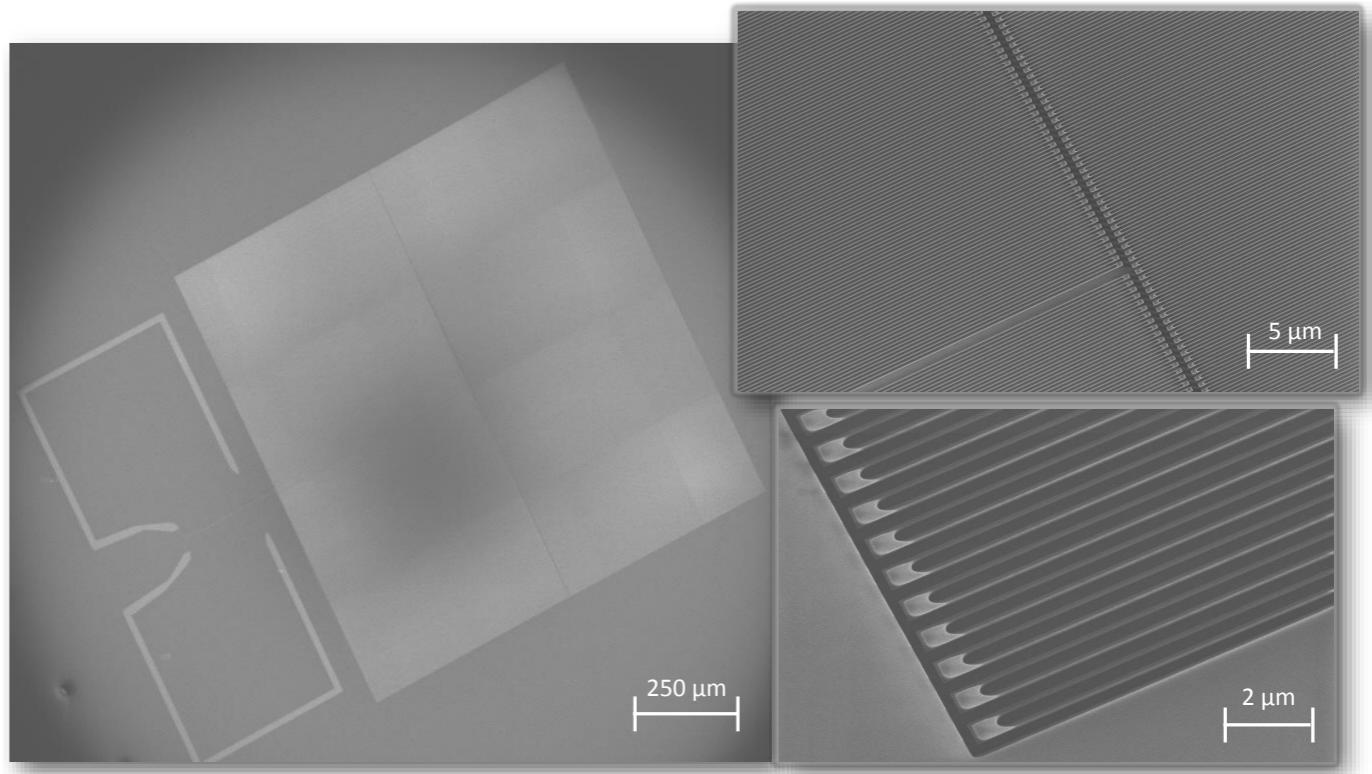
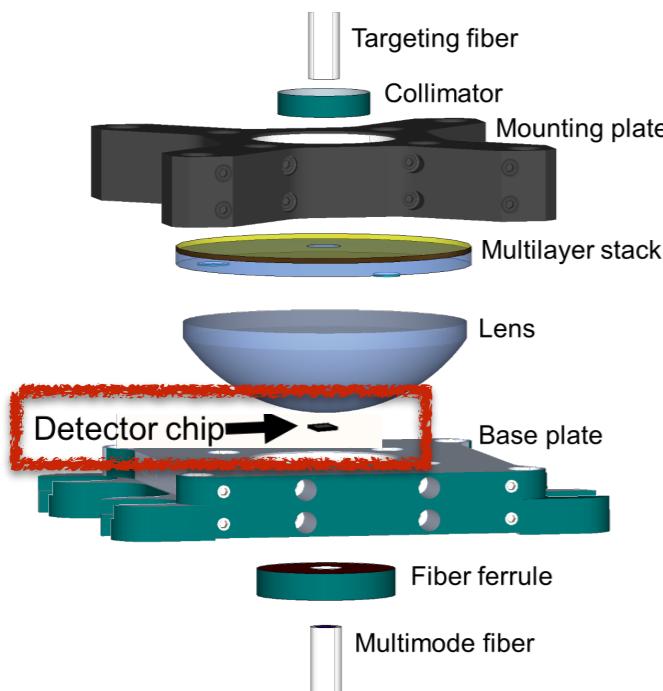
DOE QuantiSED grant, DE-SC0019129 +NIST funds

*Bosonic Dark Matter Search Using Superconducting Nanowire Single-Photon Detectors*

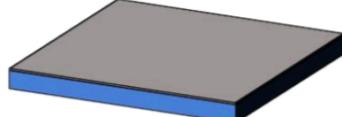
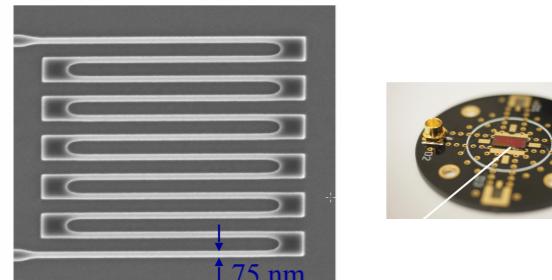
Experiment: K. Berggren, I. Charaev, A E. Dane (MIT); J. Chiles, S. Nam (NIST)

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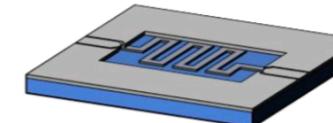
# Nanowire Detection of Photons from the Dark Side



## Detector



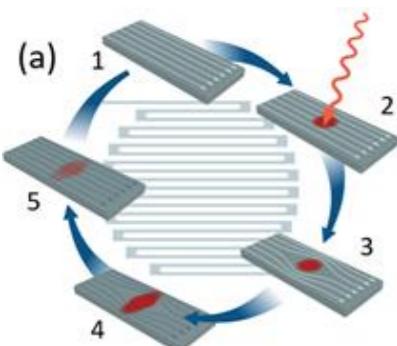
Deposition of 7 nm WSi film  
on silicon oxide substrate



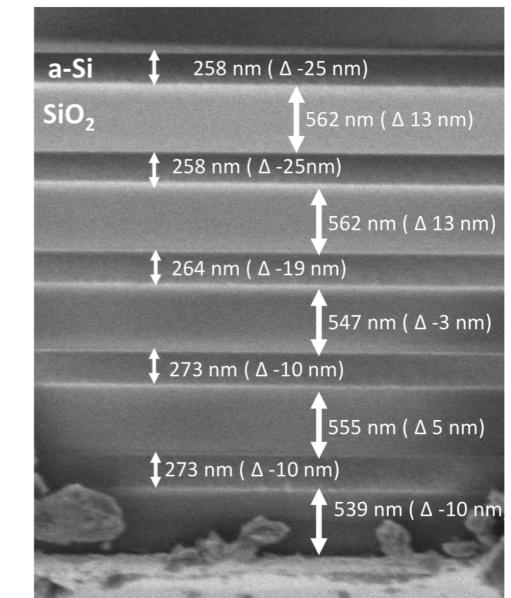
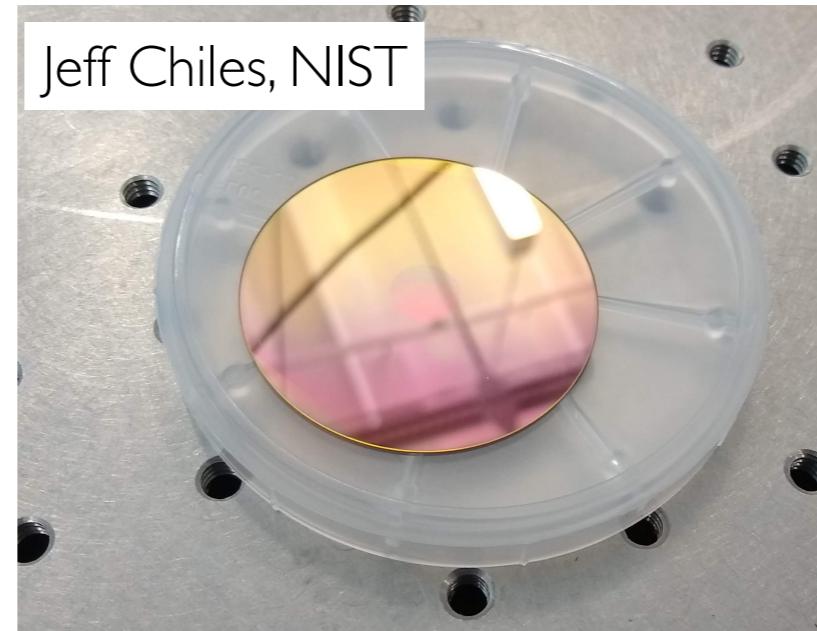
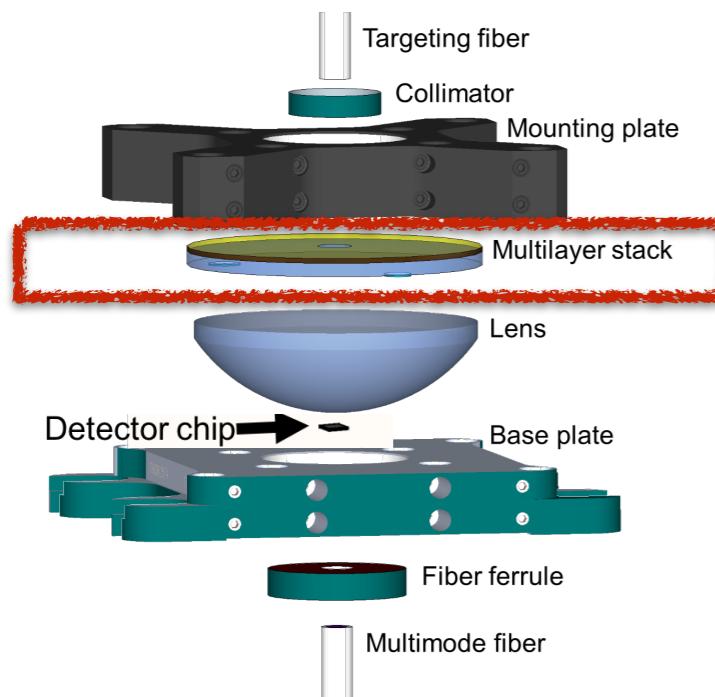
Pattern WSi nanowires  
using e-beam lithography  
and reactive ion etching

Fabricated by Ilya Charaev, MIT

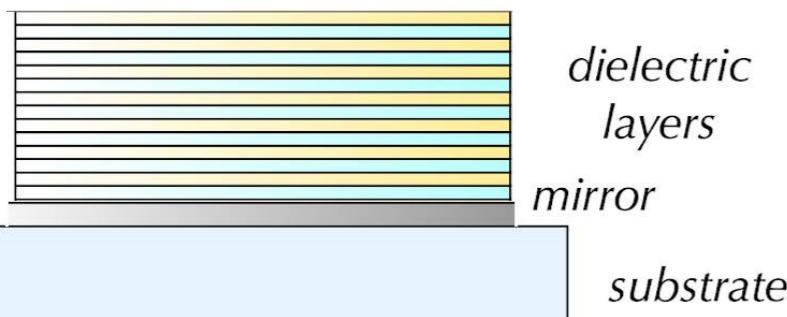
- Use superconducting nanowire single photon detector (SNSPDs)
  - Relatively small area, extremely low dark count rates
  - High efficiency in optical frequency range



# Nanowire Detection of Photons from the Dark Side

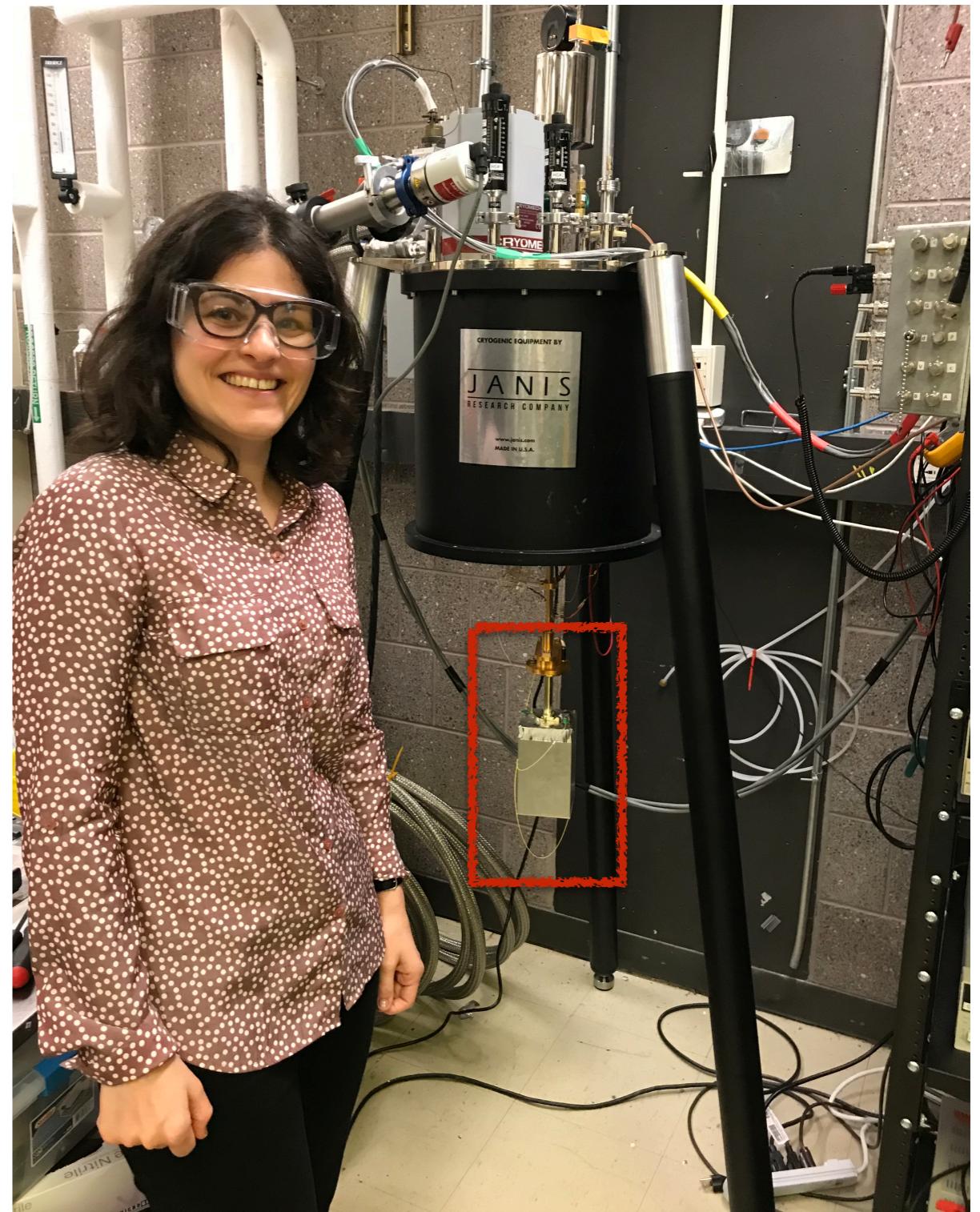
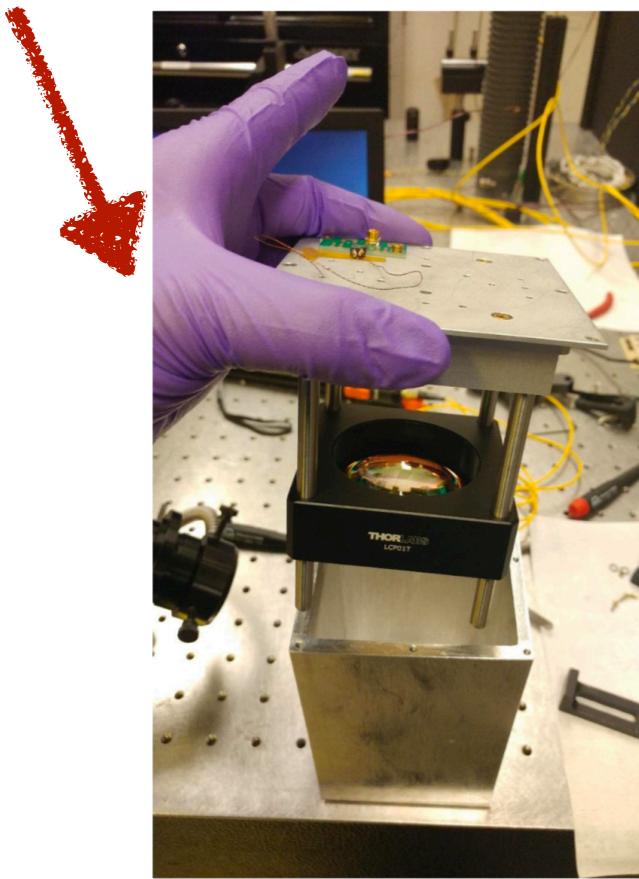
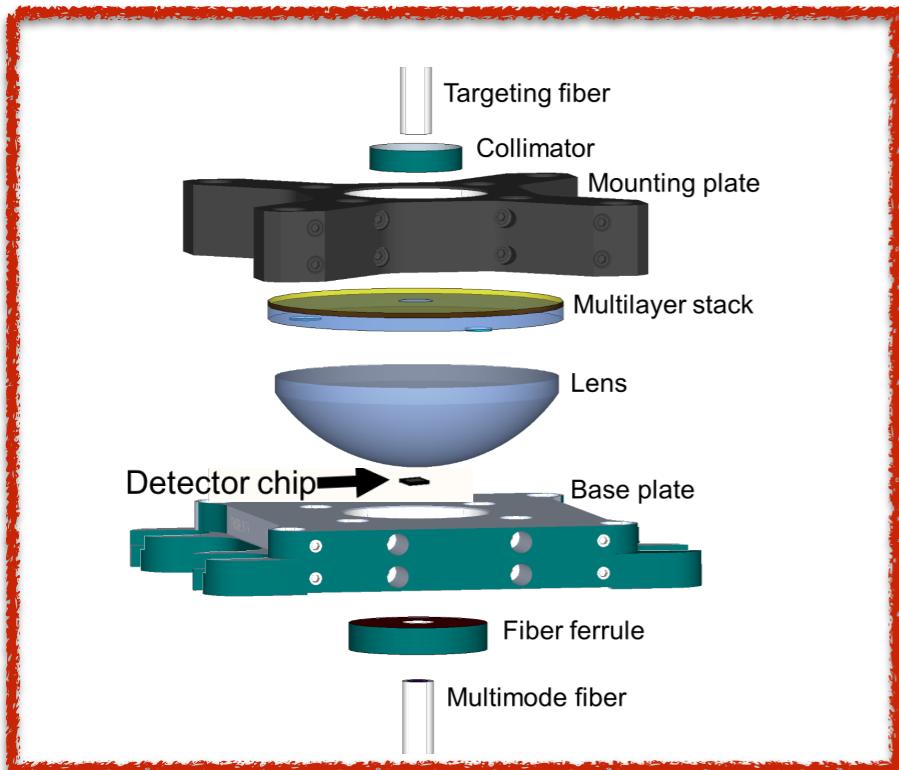


## Target

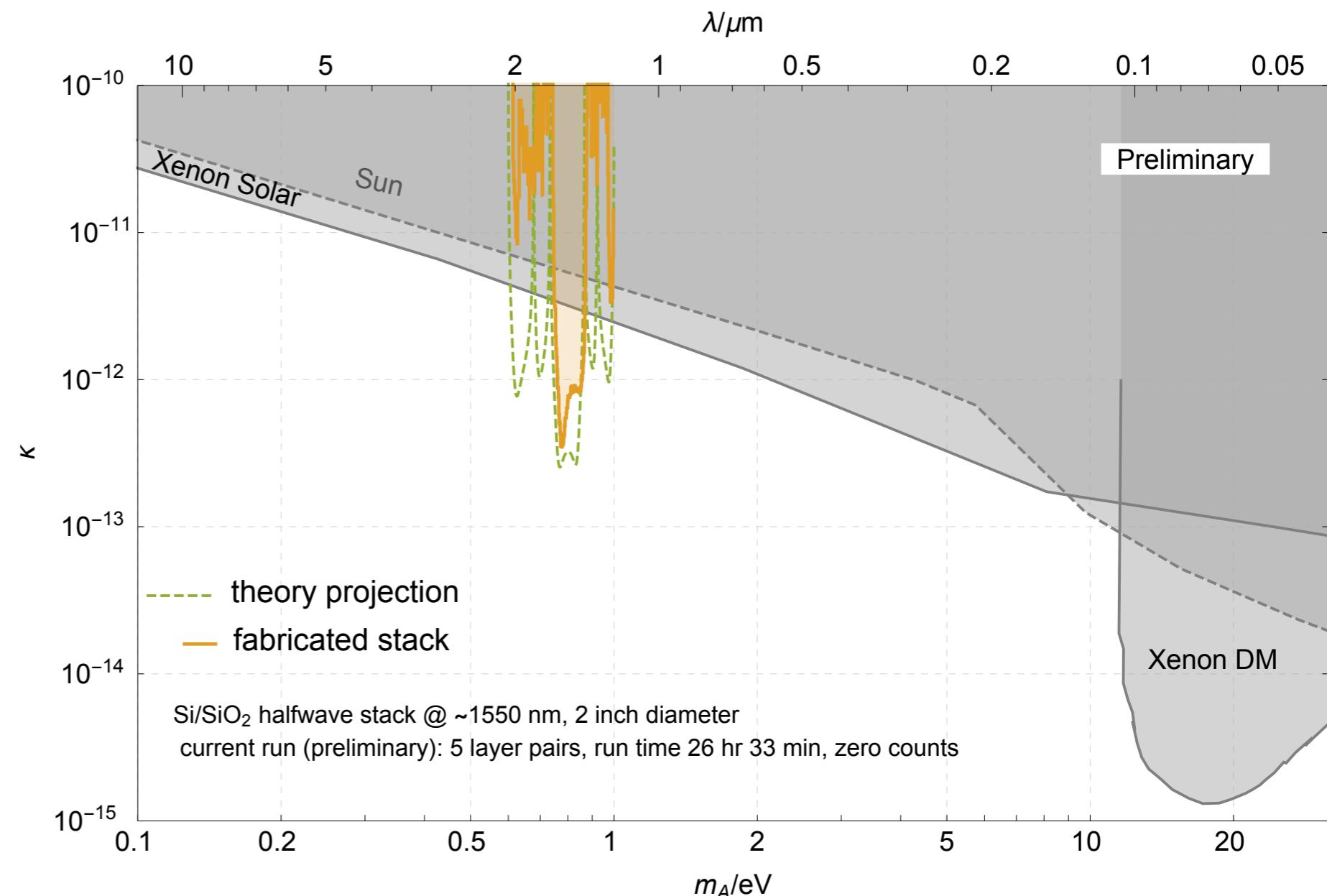
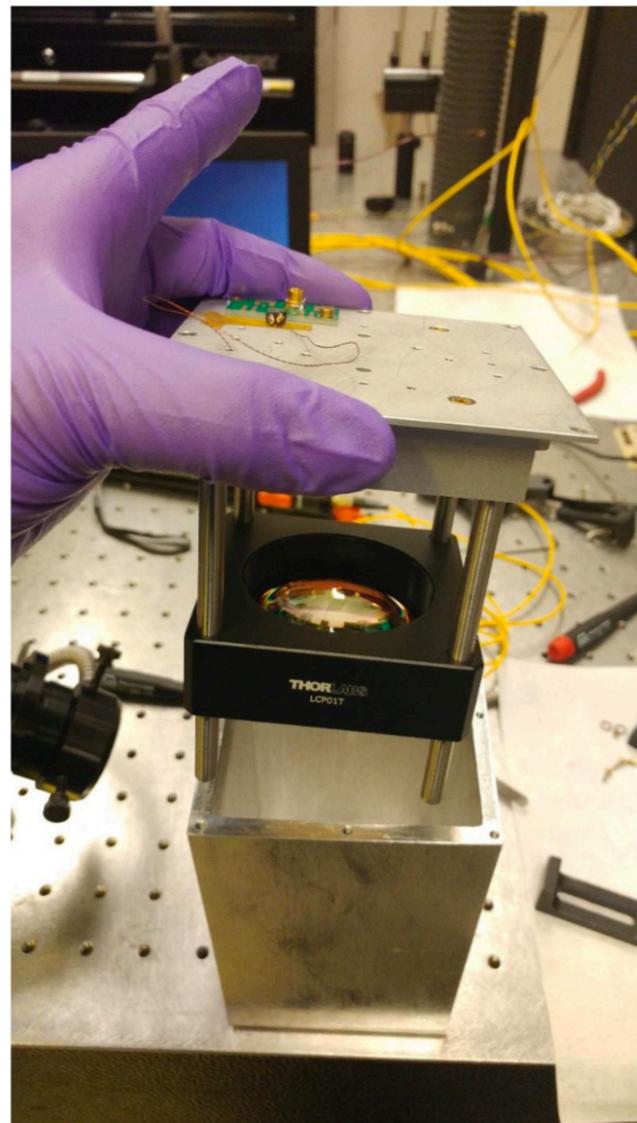


- Thin film target fabricated via plasma-enhanced chemical vapor deposition
  - Target of 2" diameter, 5 alternating films of Si and SiO<sub>2</sub>
  - In-house manufacture, quick turnaround for testing

# Nanowire Detection of Photons from the Dark Side



# Nanowire Detection of Photons from the Dark Side



- Prototype can already cut into new parameter space with one day of runtime
- Currently performing experimental checks
- Longer run time, other frequencies planned

# Axion and Dark Photon Detection with Dielectric Haloscopes

- Axion and dark photon dark matter of  $\sim$  eV mass converts to photons efficiently with the help of periodic dielectric materials
- First steps underway, use well-established optics and detector technology
- Improve on parameter space by orders of magnitude, and perhaps see dark matter

