# Optical Haloscope Searches for Dark Photons and Axions

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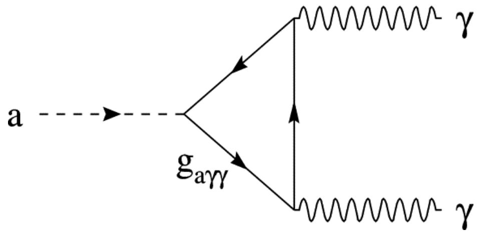
New York University
June 6, 2019

New Directions
in the Search for Light Dark Matter Particles

# Searching for axions



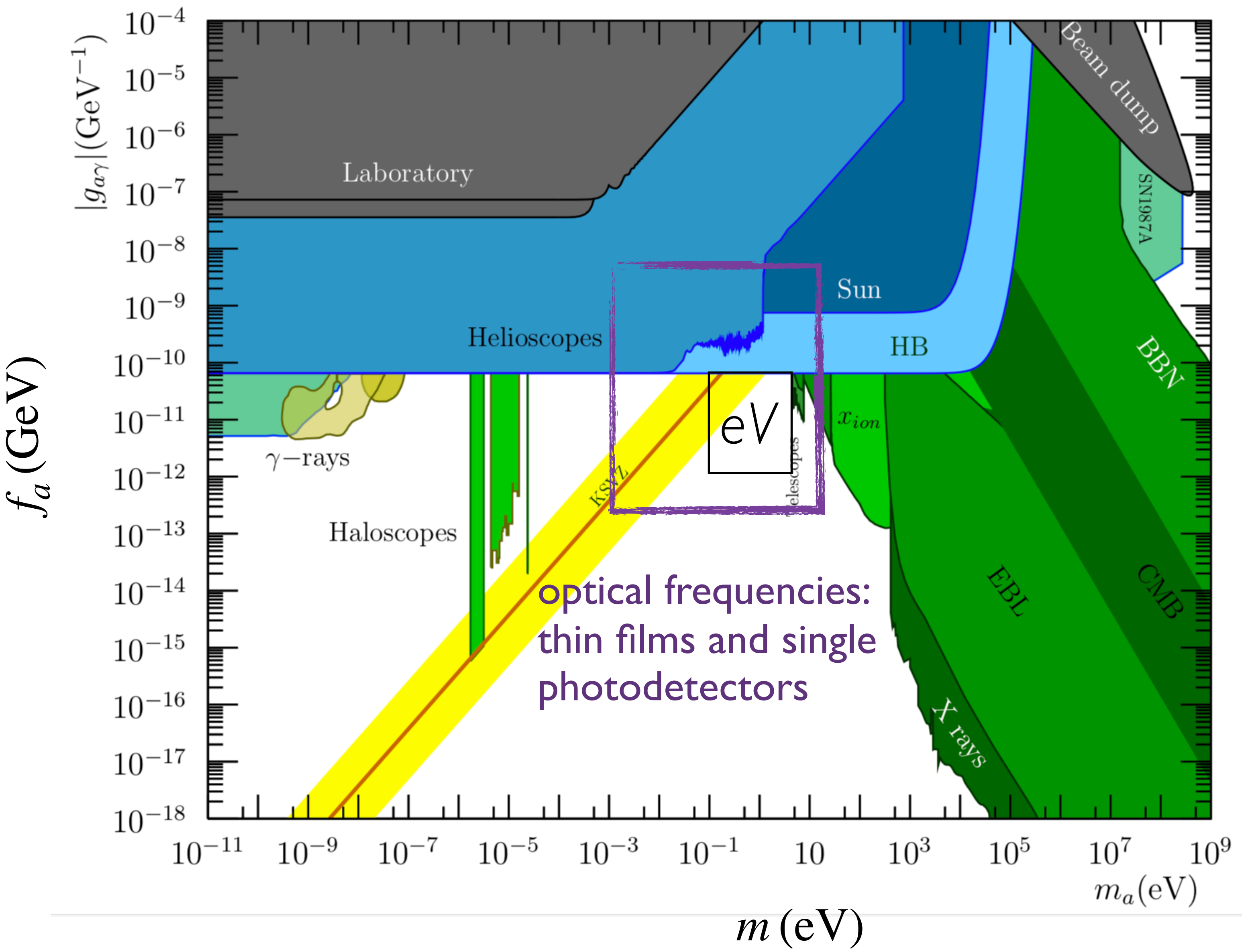
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 + \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 + \frac{g_{a\gamma\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

- QCD axion one of the best-motivated BSM particles

- Solves the Strong-CP problem, DM candidate

- Wide parameter space of weakly coupled, light particles

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



optical frequencies: thin films and single photodetectors

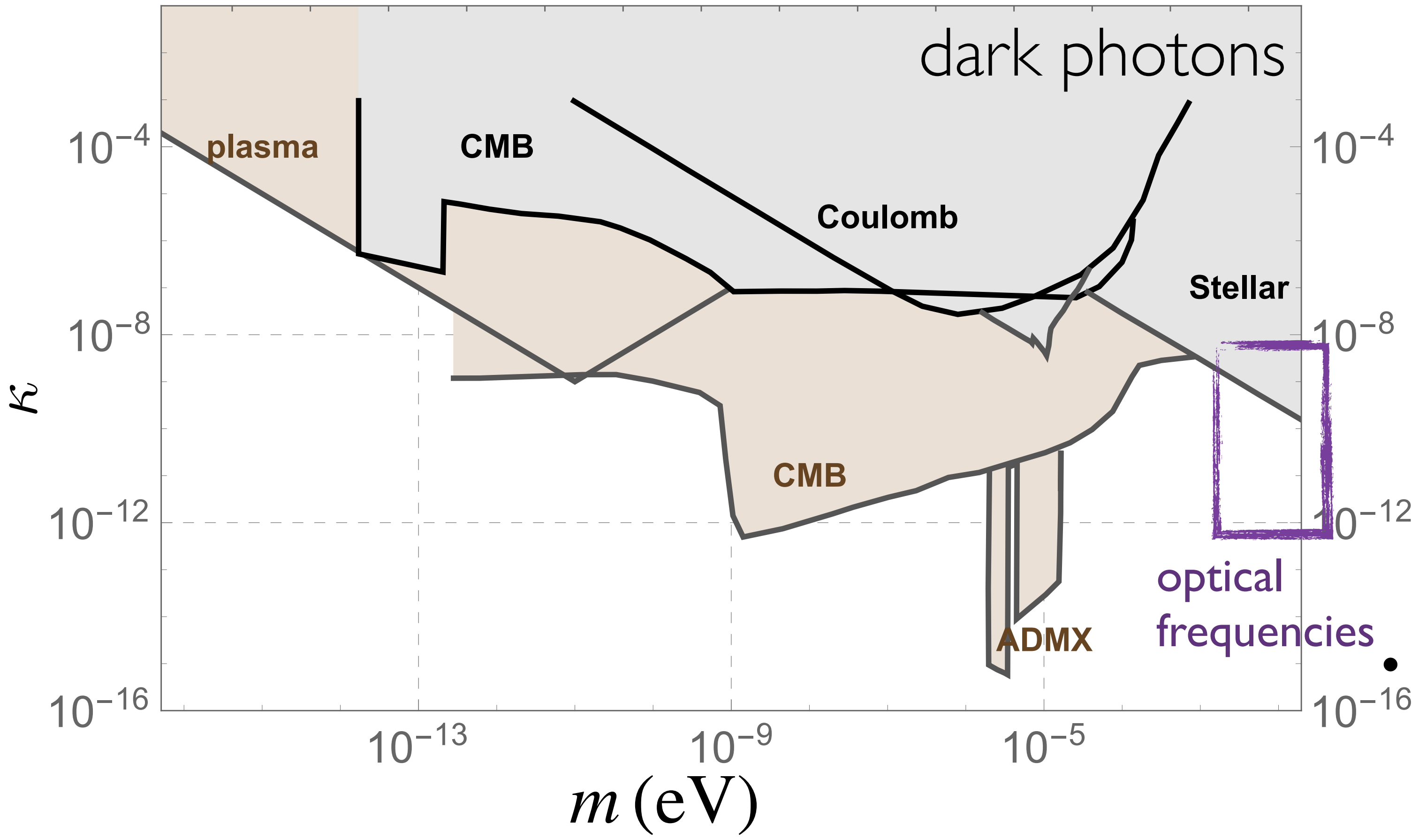
axions

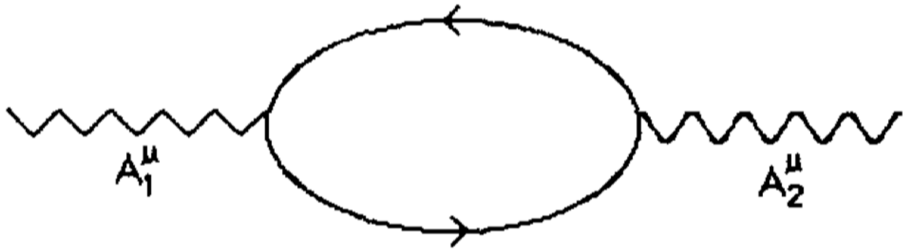
# Searching for Dark Photons

- Long-lived dark matter candidate; produced through inflationary fluctuations at high scales

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

Graham, Mardon, Rajendran [1504.02102]





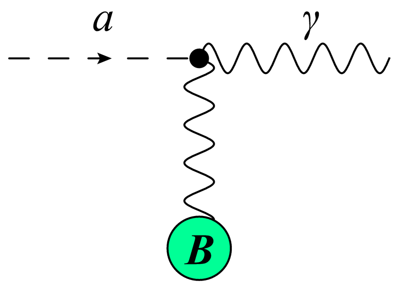
$$-\frac{1}{4}F'^2_{\mu\nu} + \frac{\kappa}{2}F_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}m_A^2 A'^2_\mu$$

- Dark photons mix with SM photon via kinetic term

Holdom PRB166 (1986) 196

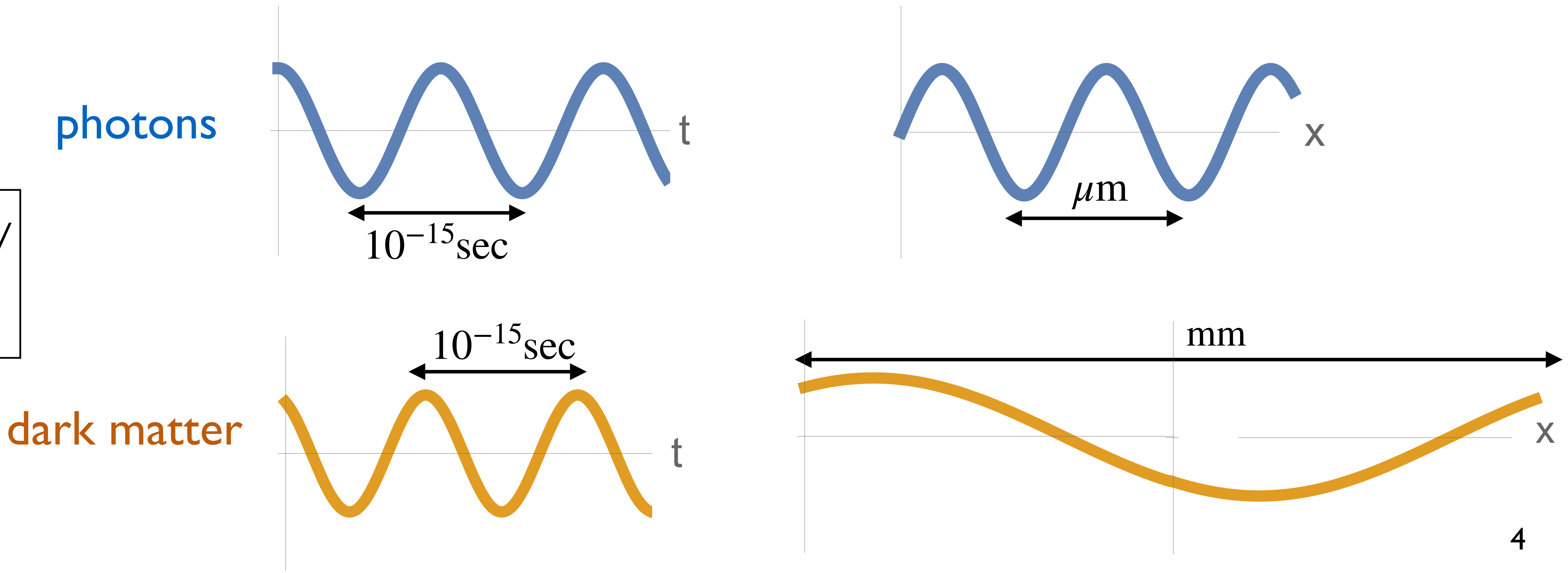
# Light bosonic dark matter

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

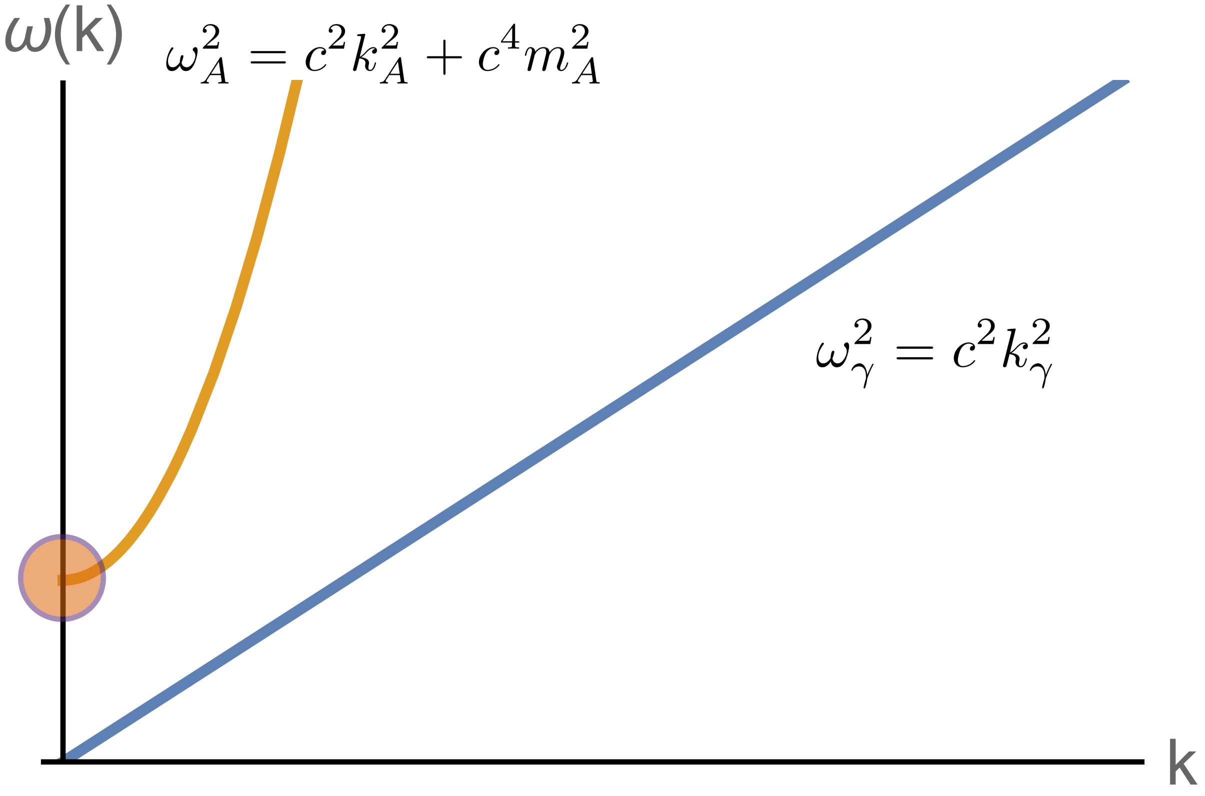


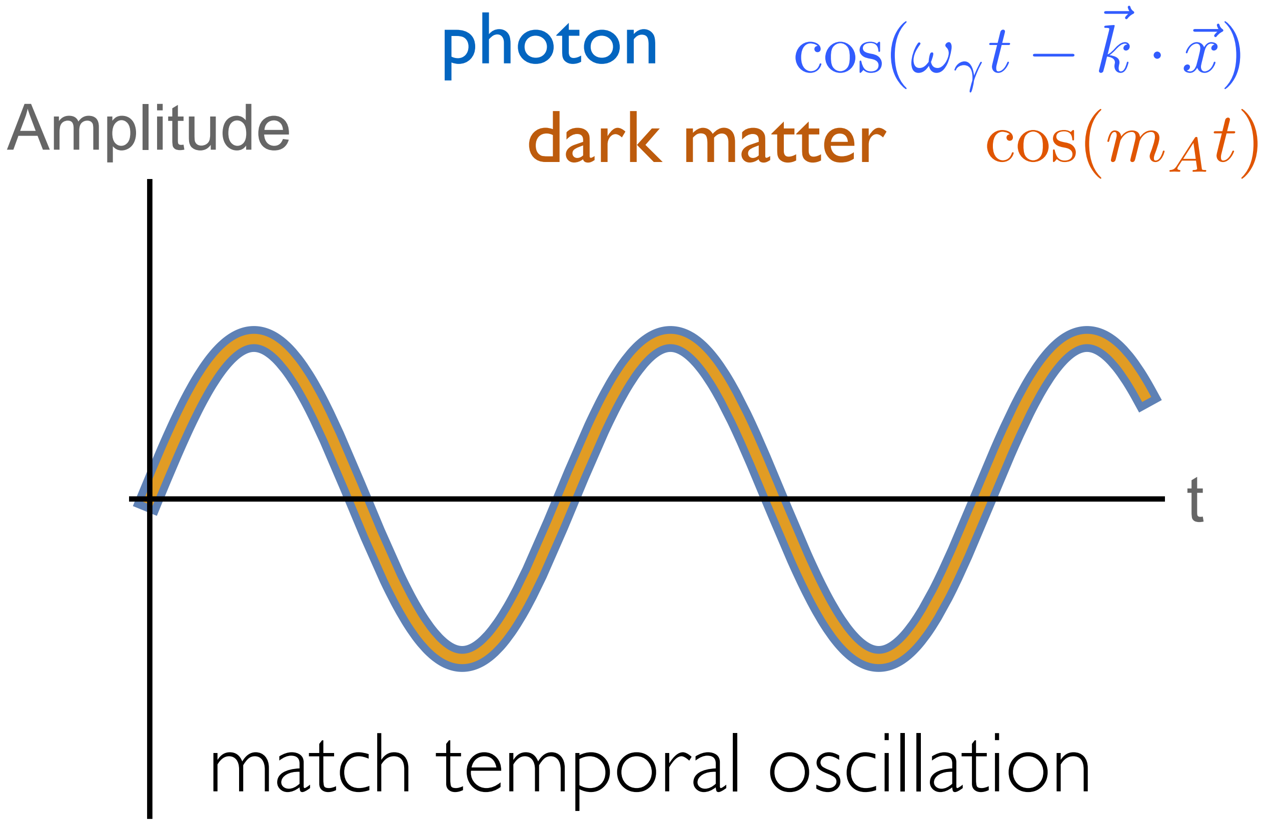
- Can we see axion or dark photon dark matter converting to photons?

for an eV particle:



# Light bosonic dark matter

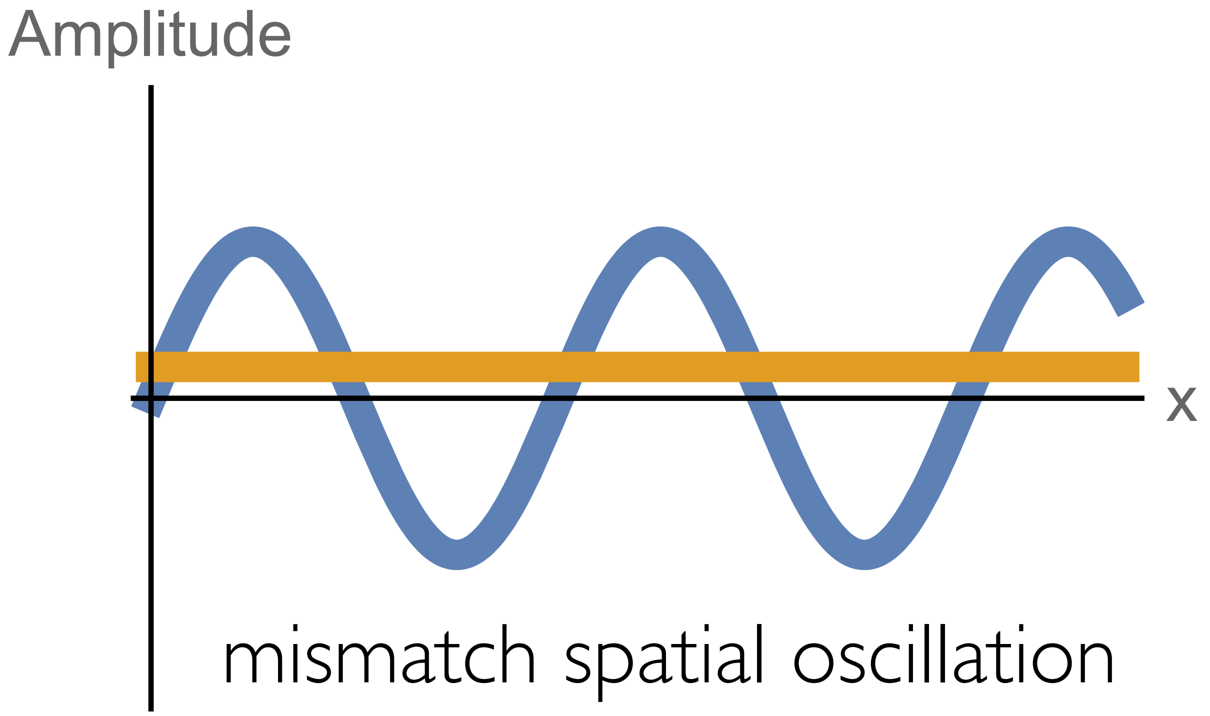




match temporal oscillation

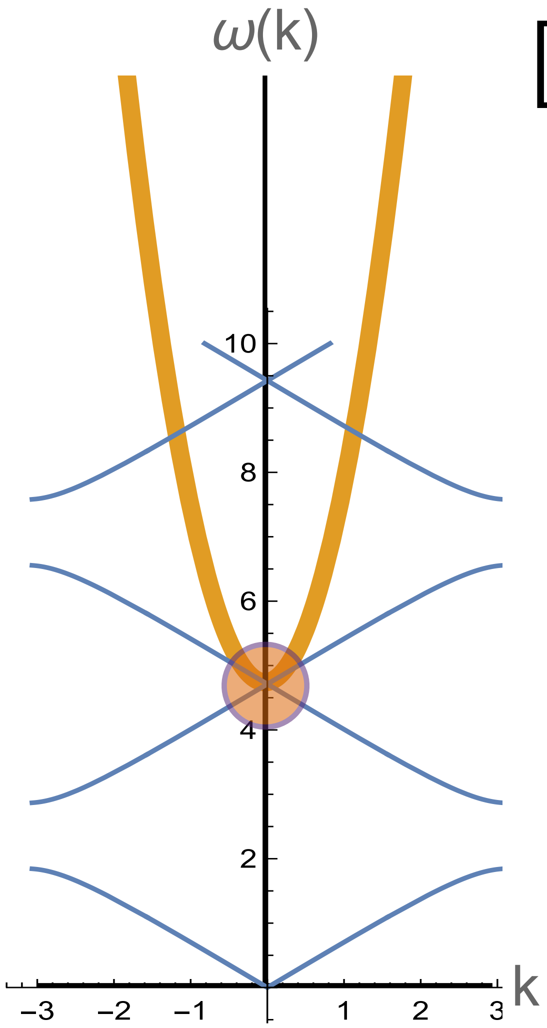
- Mismatch in dispersion relation: **photons** relativistic while **dark matter** is massive with a small velocity in our galaxy
- Impossible to conserve both energy and momentum

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



mismatch spatial oscillation

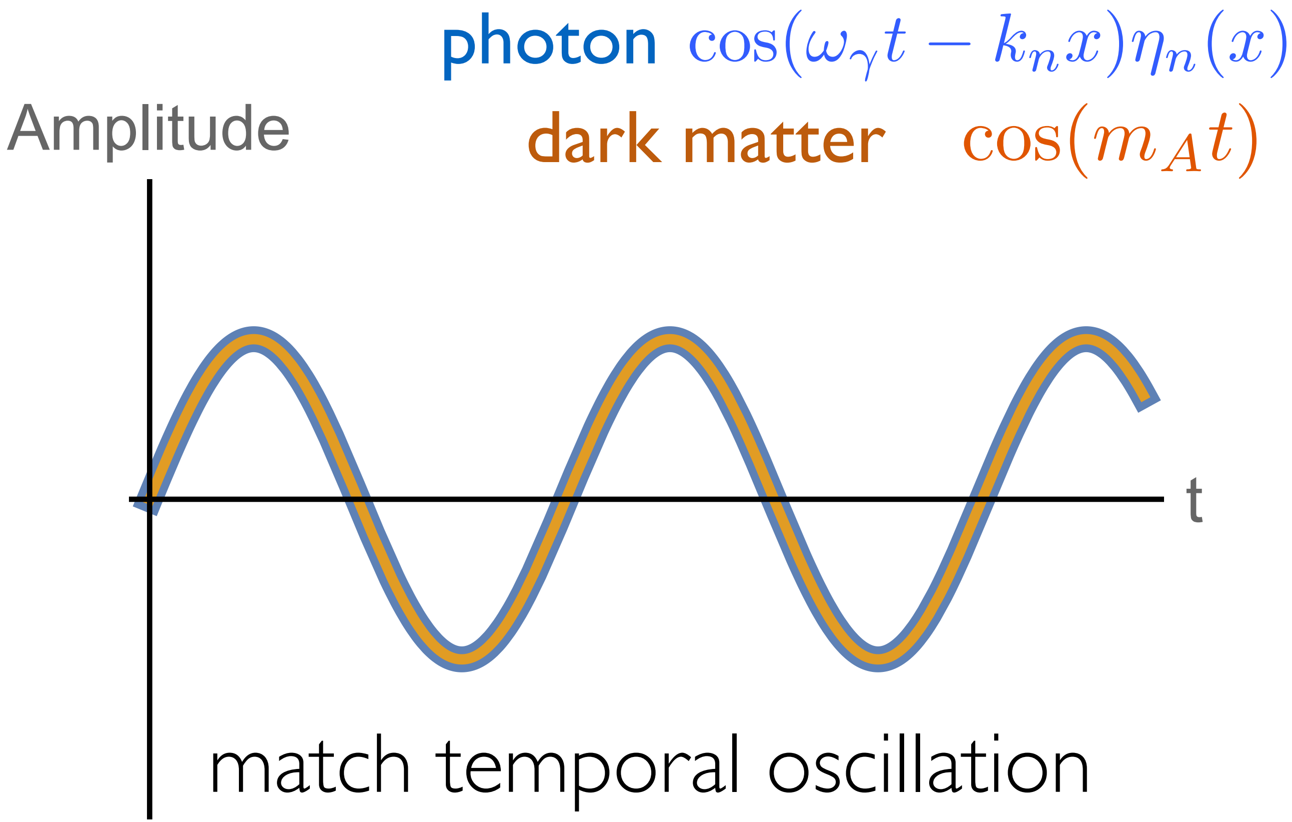
# Dielectric Optical Haloscope



- Add periodicity in one dimension to correct momentum mismatch

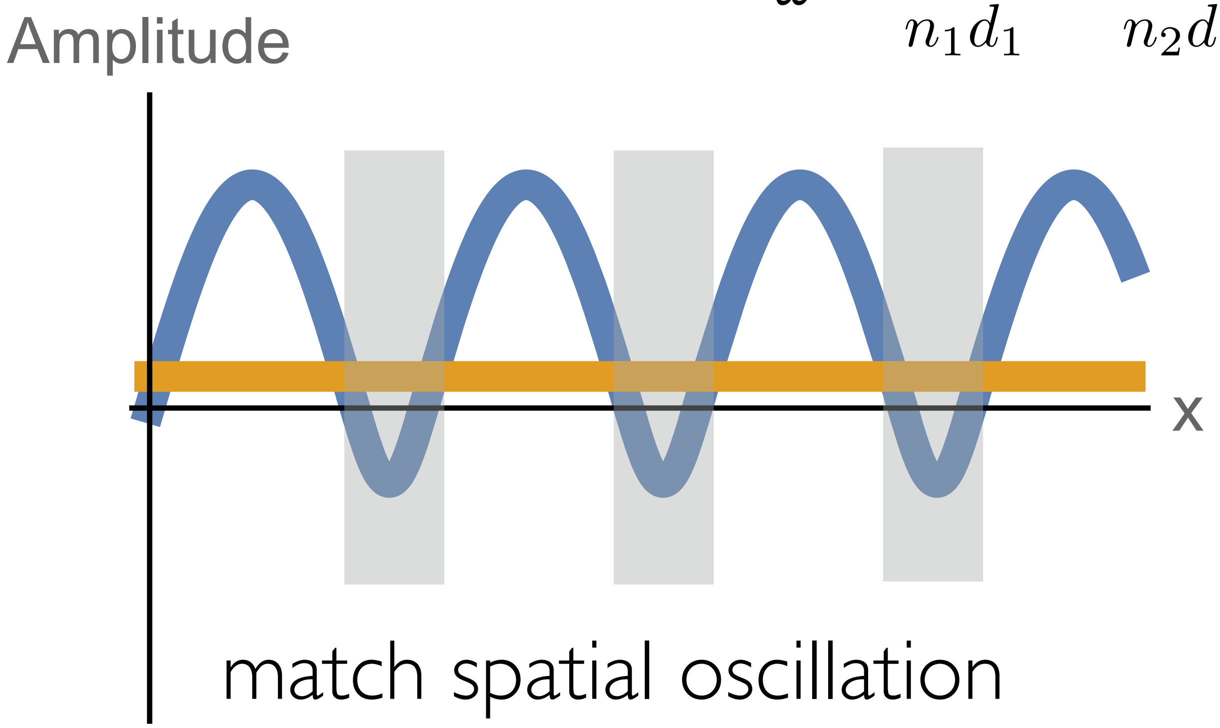
- Periodic index of refraction changes free solutions of photon modes

- Electric field no longer integrates to zero against a constant DM background



match temporal oscillation

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

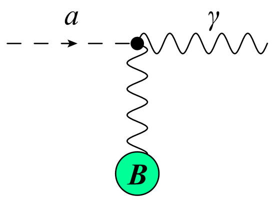


match spatial oscillation

# Dielectric Optical Haloscope

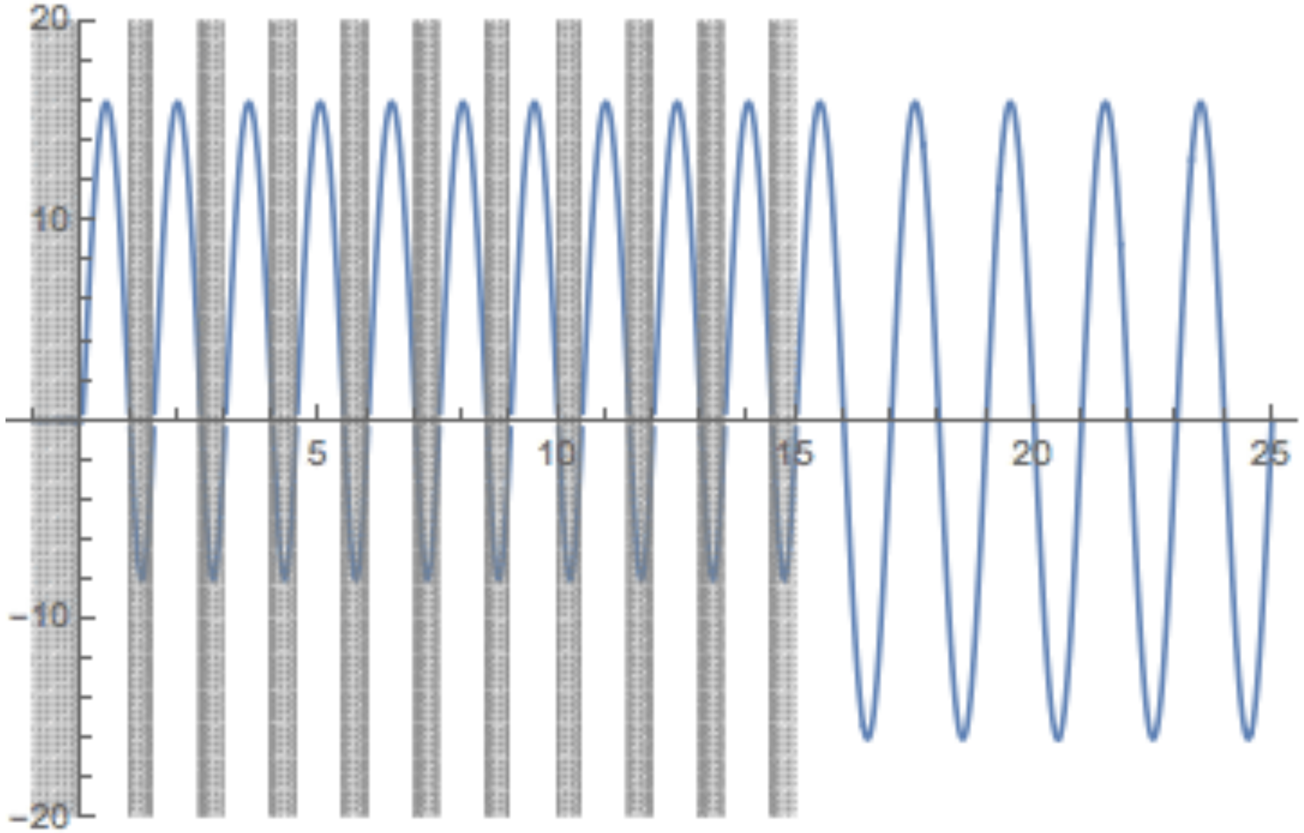
Time varying, spatially homogeneous dark matter sources photons in periodic structure

$$
\begin{aligned}
\nabla \cdot D &= \rho_{dm} \\
\nabla \cdot B &= 0 \\
\nabla \times E + \partial_t B &= 0 \\
\nabla \times H - \partial_t D &= \boxed{J_{dm}}
\end{aligned}
$$



Axion ‘current’ $\boxed{J_a} = g_{a\gamma\gamma}\partial_t a\, B_{ext}$

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

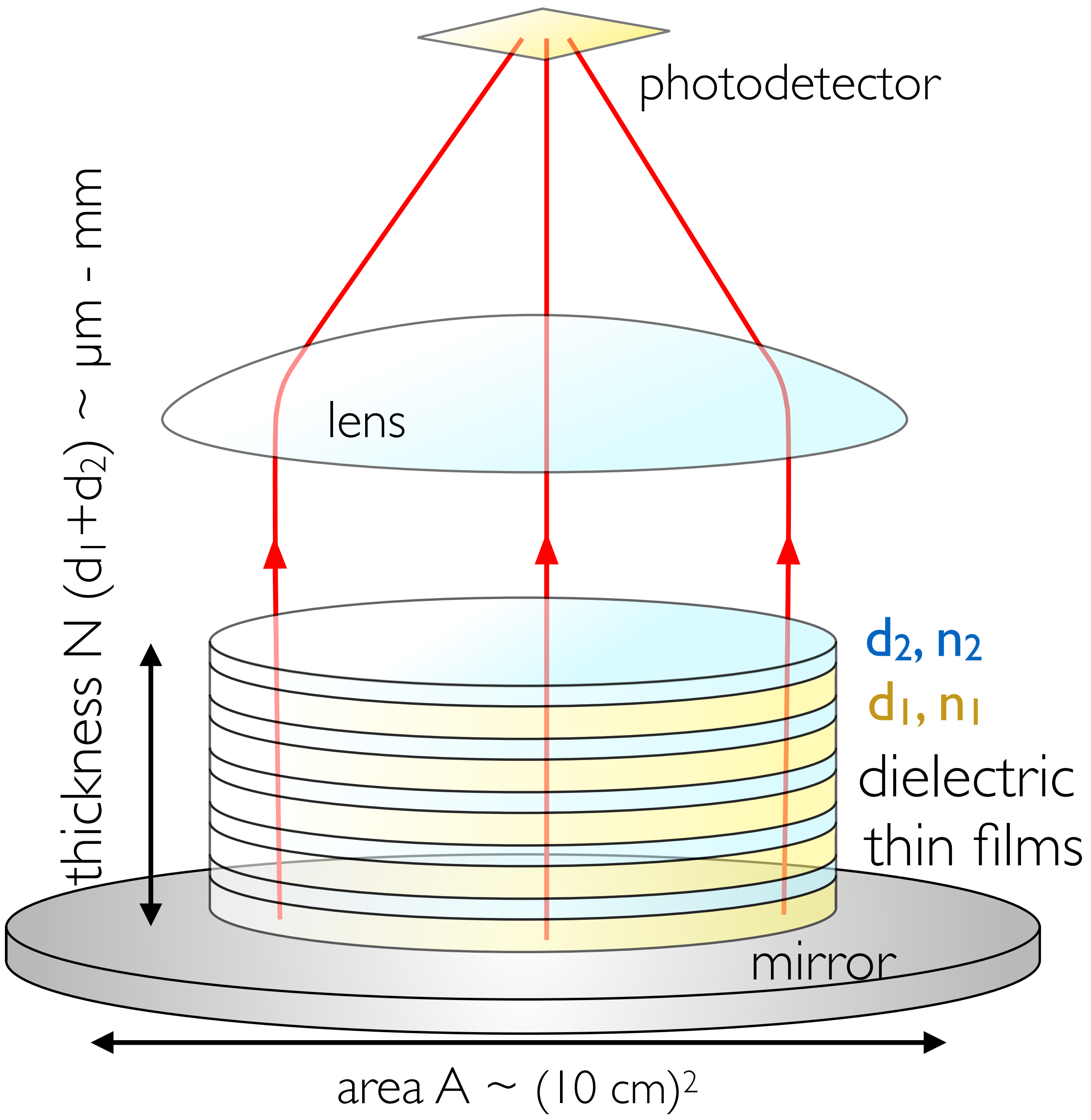


- Outgoing photon energy sourced by dark matter:
$$\omega_\gamma \simeq m_{dm}$$
- Outgoing photon momentum sourced by periodicity: $k_\gamma \simeq \dfrac{\pi}{nd}$
- Emission when DM mass matches periodicity: $m_{dm} \simeq \dfrac{\pi}{nd}$

# Dielectric Optical Haloscope

## Dark photons

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



- 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

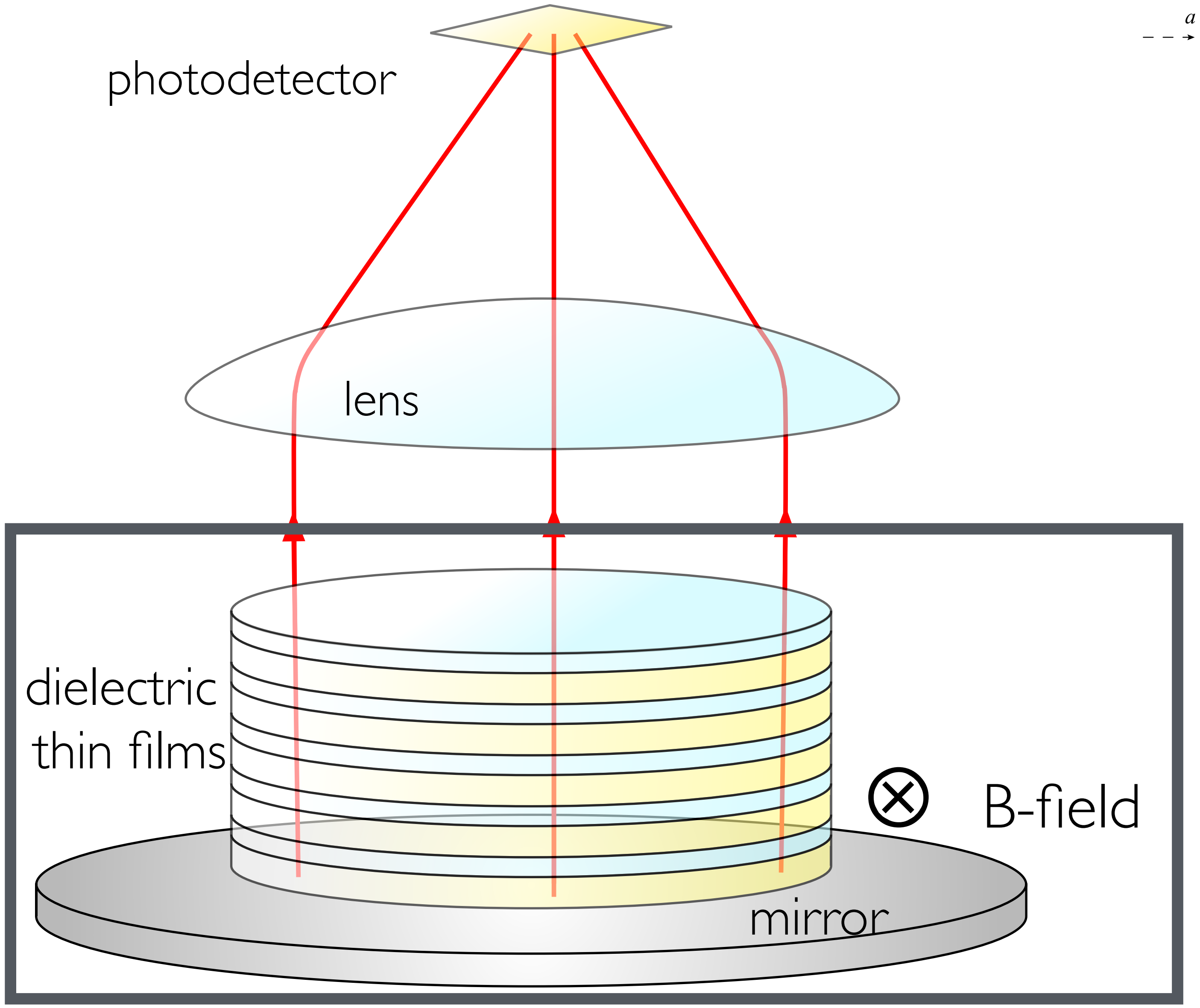
**MB**, J. Huang, R. Lasenby

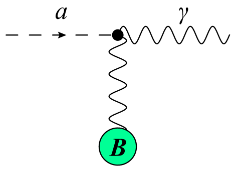
# Dielectric Optical Haloscope

## Axions

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

apply external B field for axion-to-photon conversion





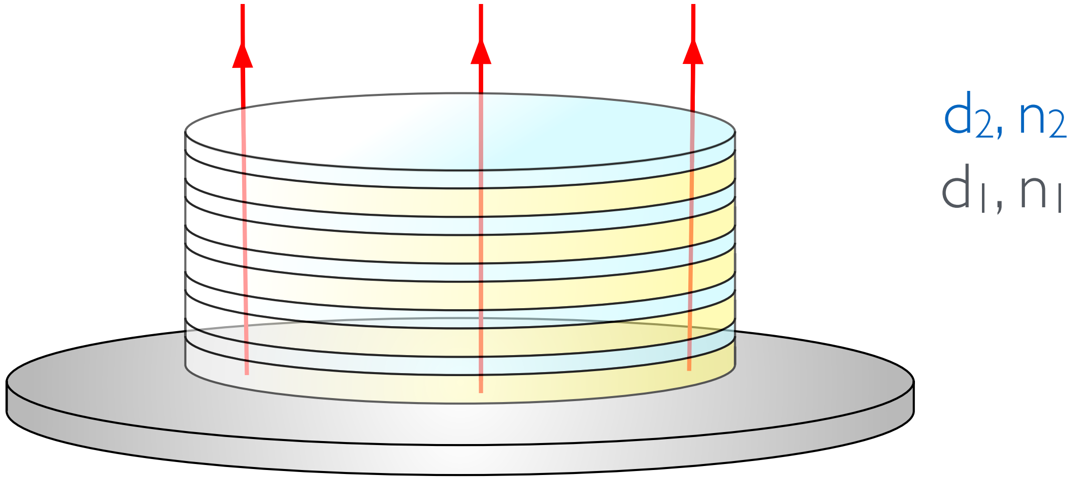
Axion ‘current’ $J_a = g_{a\gamma\gamma} \partial_t a \, B_{ext}$

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

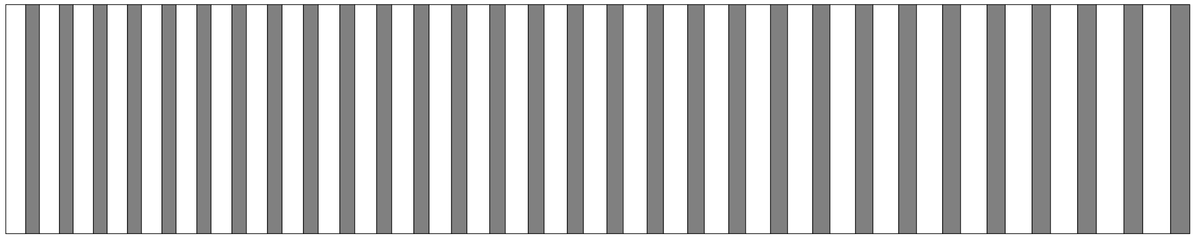
# Dielectric Optical Haloscope

DM mass matched to layer thickness and index of refraction

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

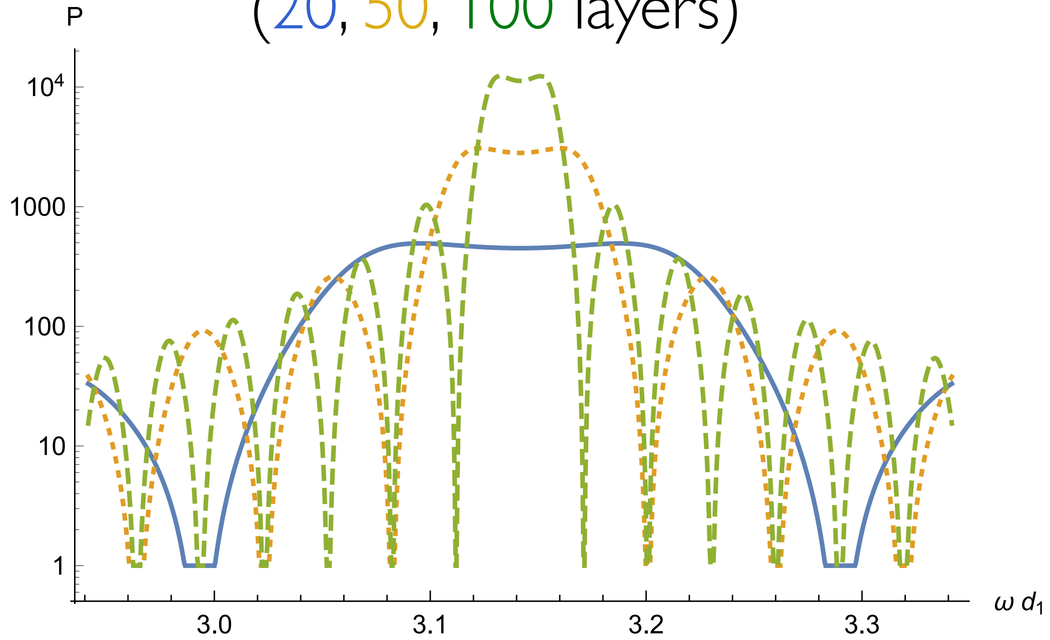


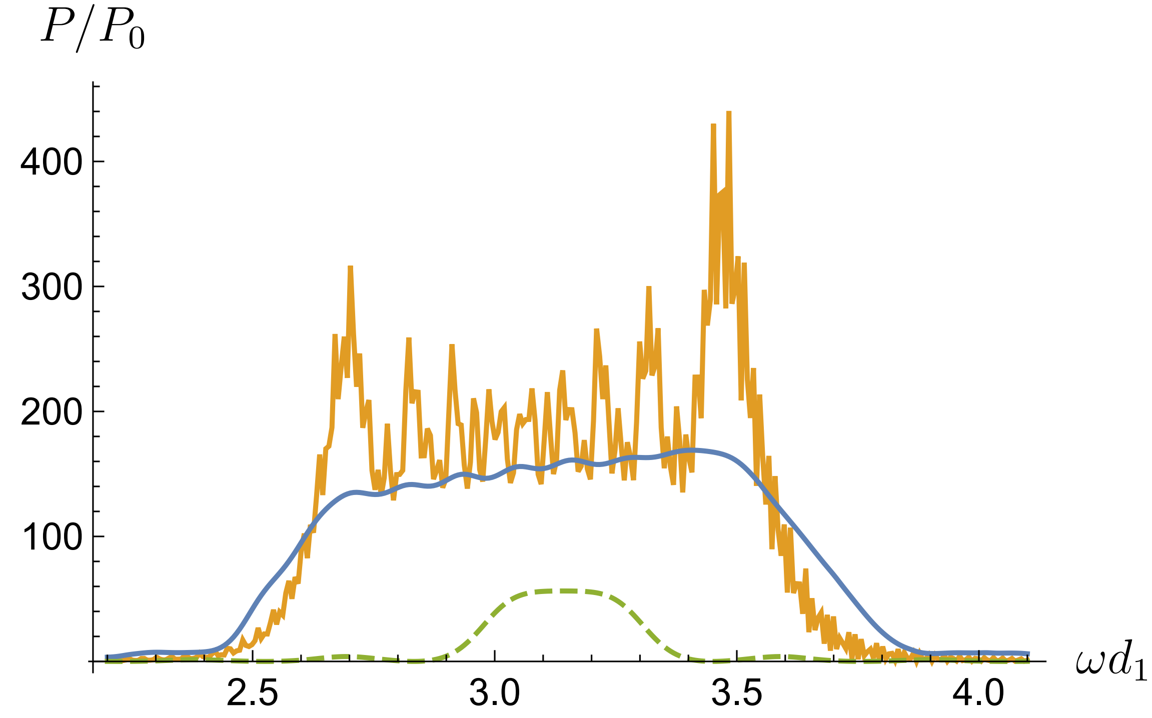
'Chirped' stacks for broader mass coverage:



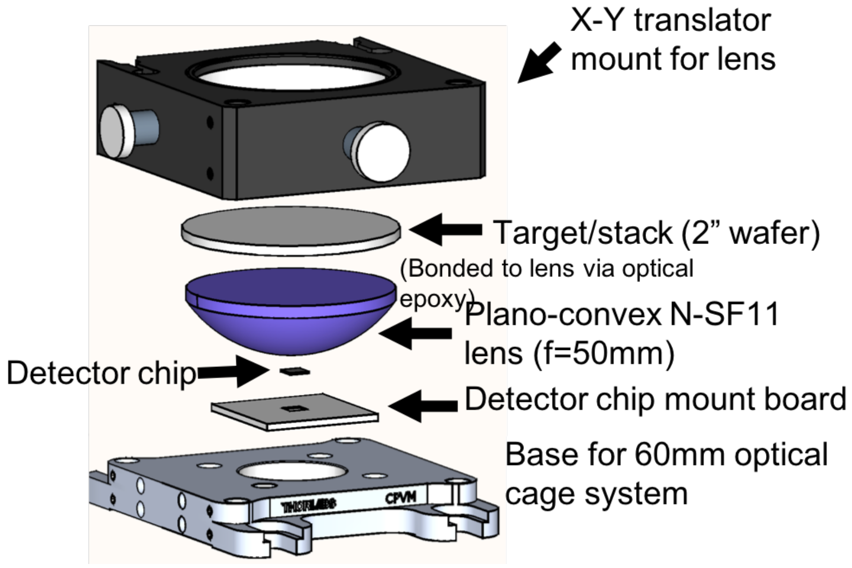
10% - 0.1% coverage per stack $\frac{\Delta\omega}{\omega} \sim \frac{1}{N}$

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





# 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

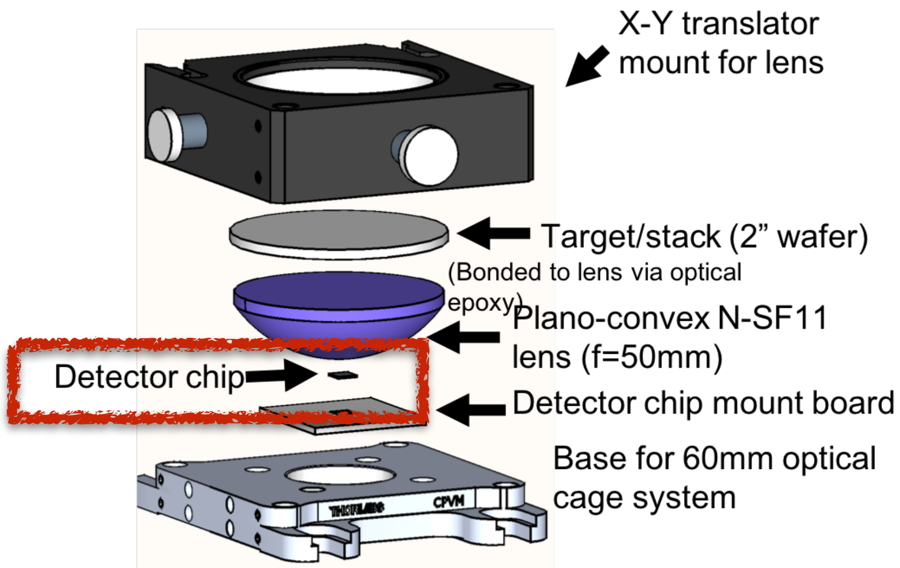
DOE QuantiSED grant, DE-SC0019129 +NIST funds

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

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

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

# Nanowire Detection of Photons from the Dark Side



X-Y translator mount for lens

Target/stack (2" wafer)

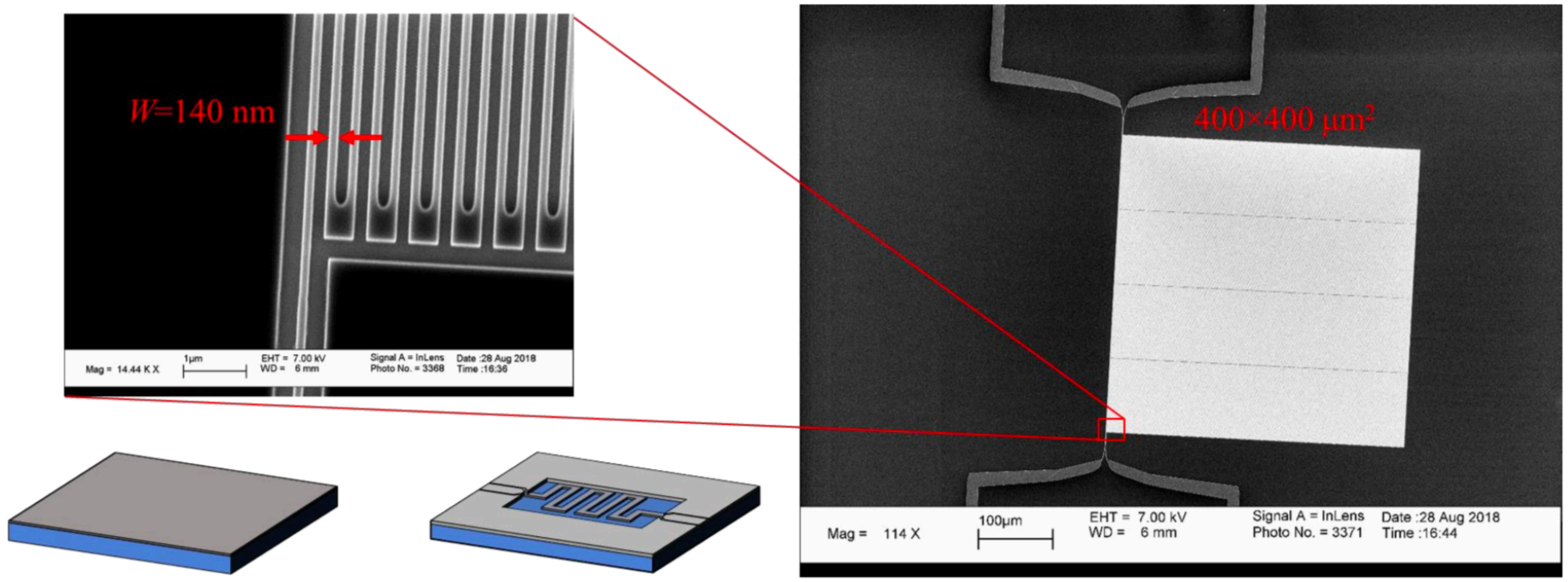
(Bonded to lens via optical epoxy)

Plano-convex N-SF11 lens (f=50mm)

Detector chip

Detector chip mount board

Base for 60mm optical cage system

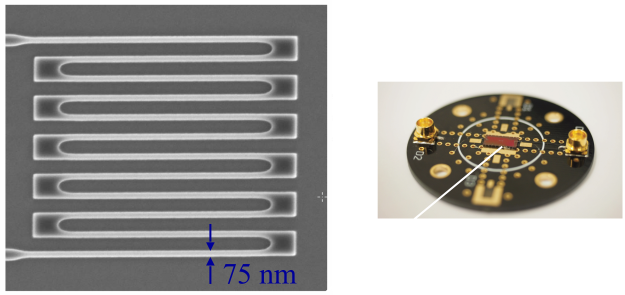


Deposition of 7 nm WSi film on silicon oxide substrate

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

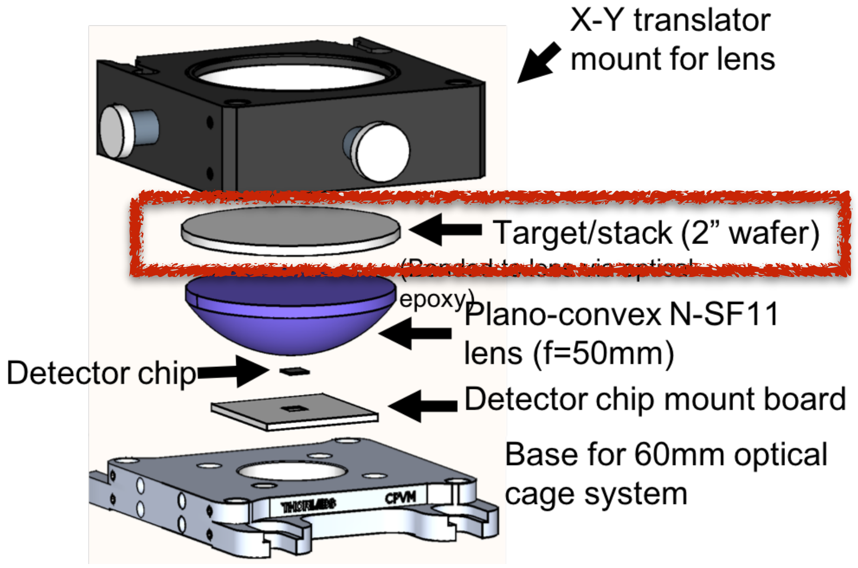
Ilya Charaev, MIT

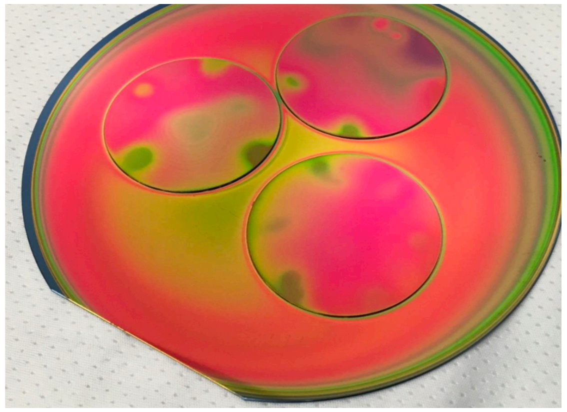
**Detector**

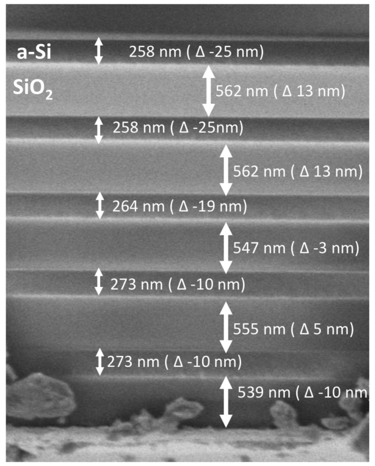


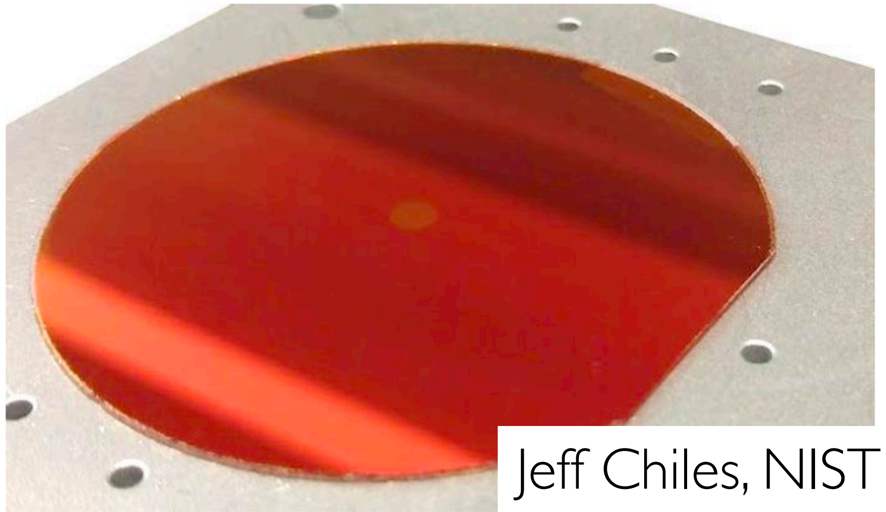
- Use superconducting nanowire single photon detector (SNSPDs)
  - Relatively small area, extremely low dark count rates
  - High efficiency in optical frequency range

# Nanowire Detection of Photons from the Dark Side

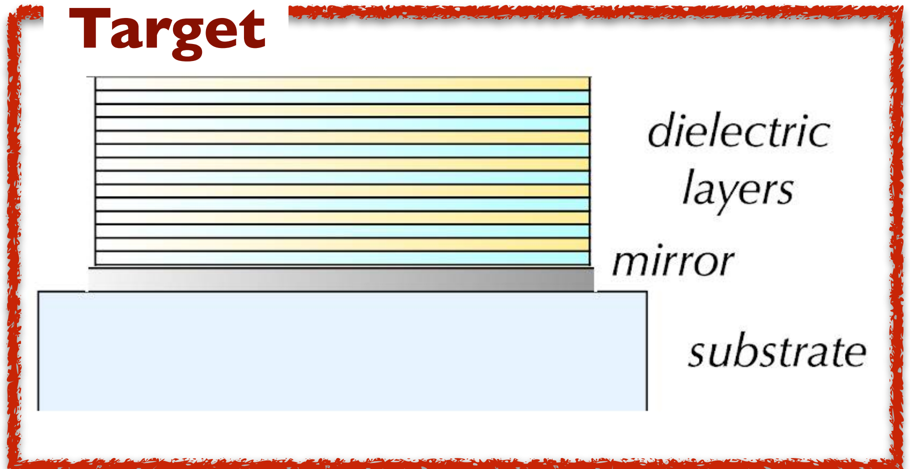






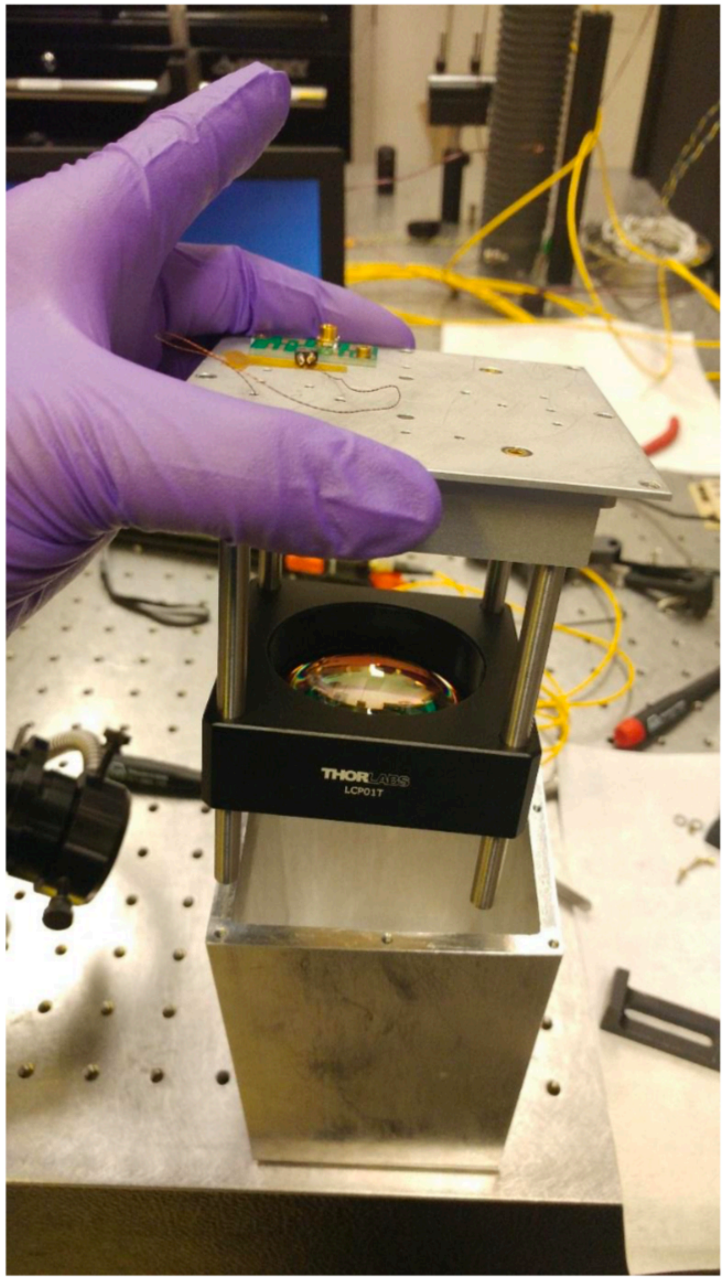


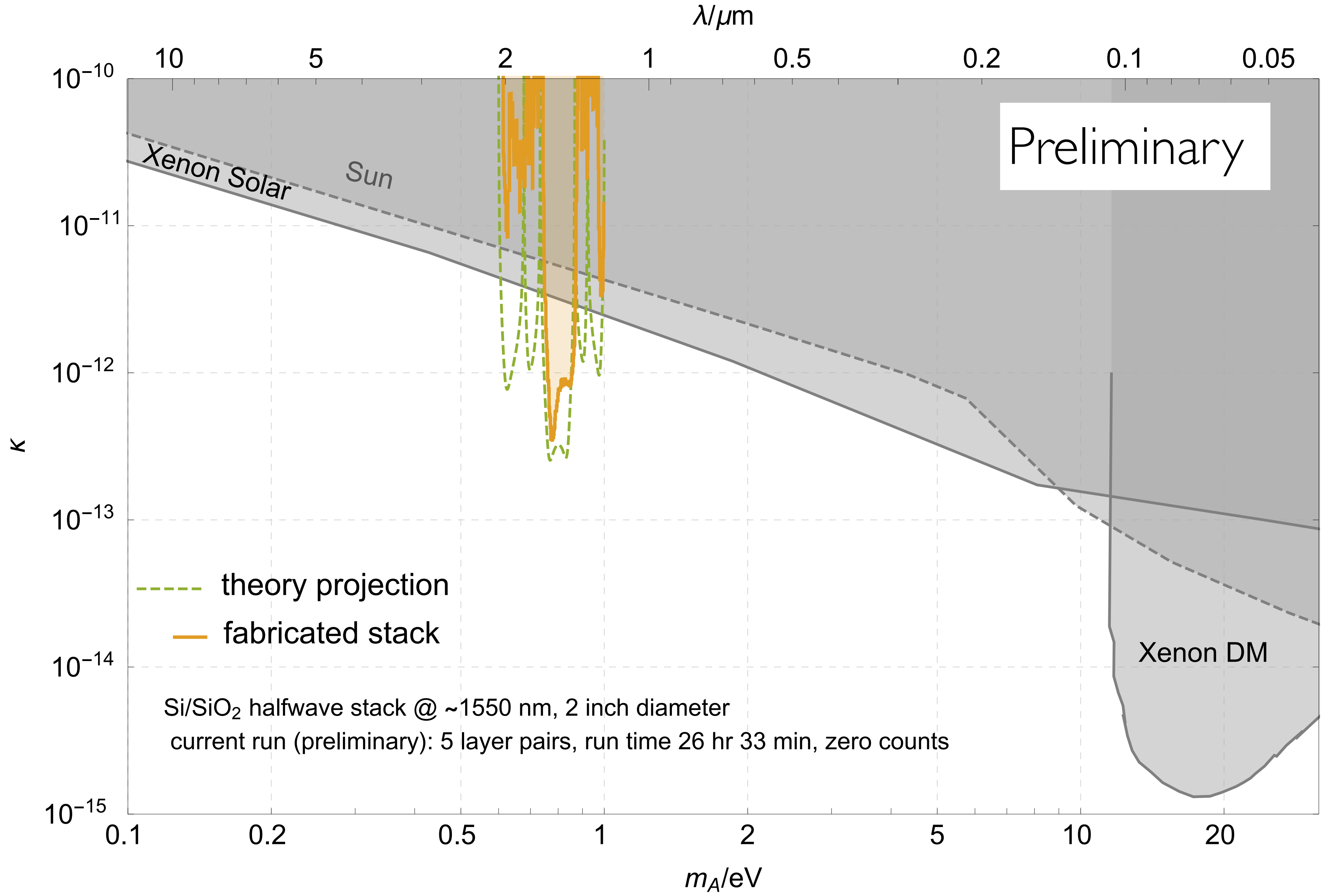
Jeff Chiles, NIST



- Thin film target fabricated via plasma-enhanced chemical vapor deposition
  - Target of 2" diameter, 5 alternating films of Si and $SiO_2$
  - In-house manufacture, quick turnaround for testing

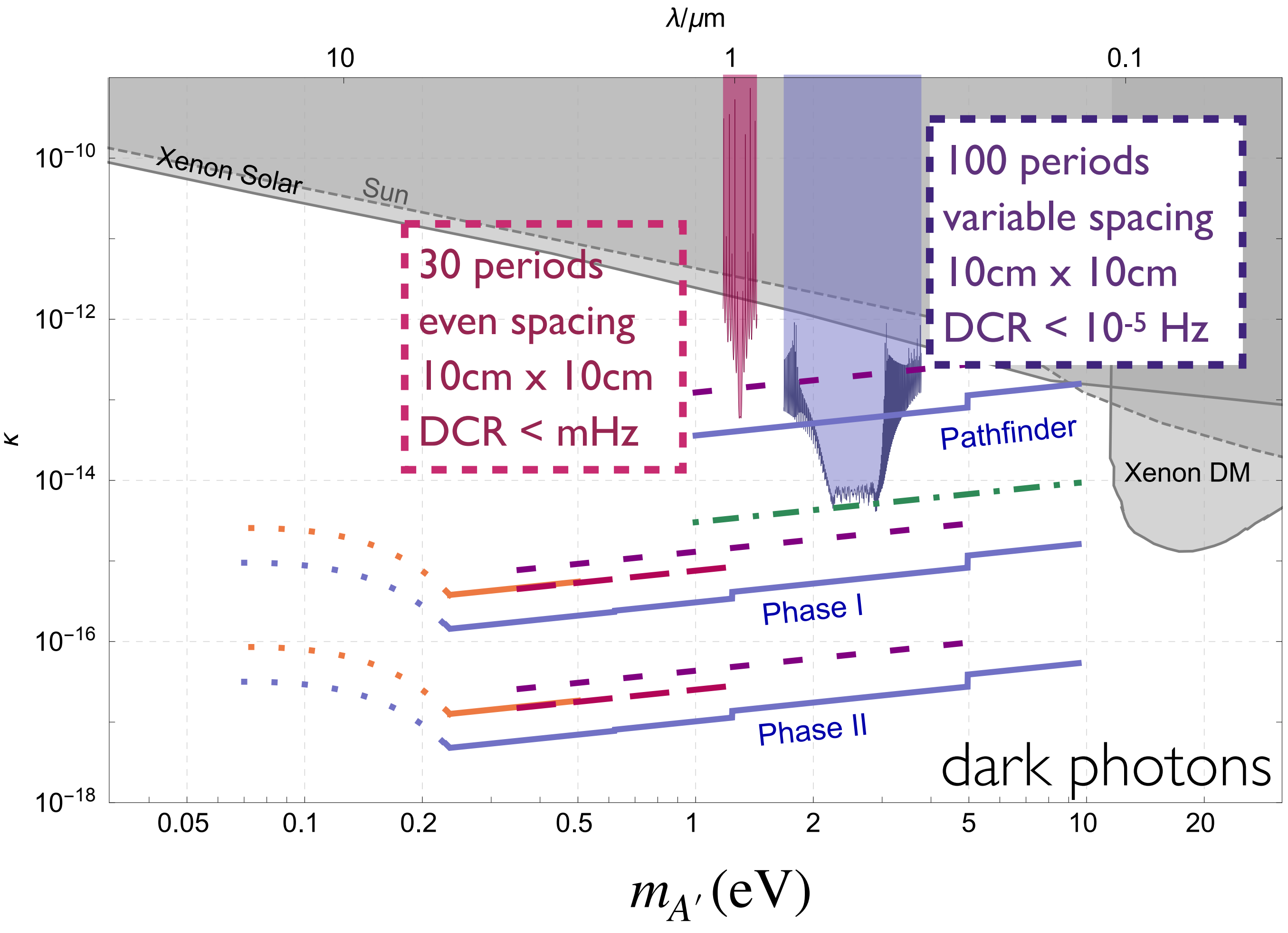
# Nanowire Detection of Photons from the Dark Side

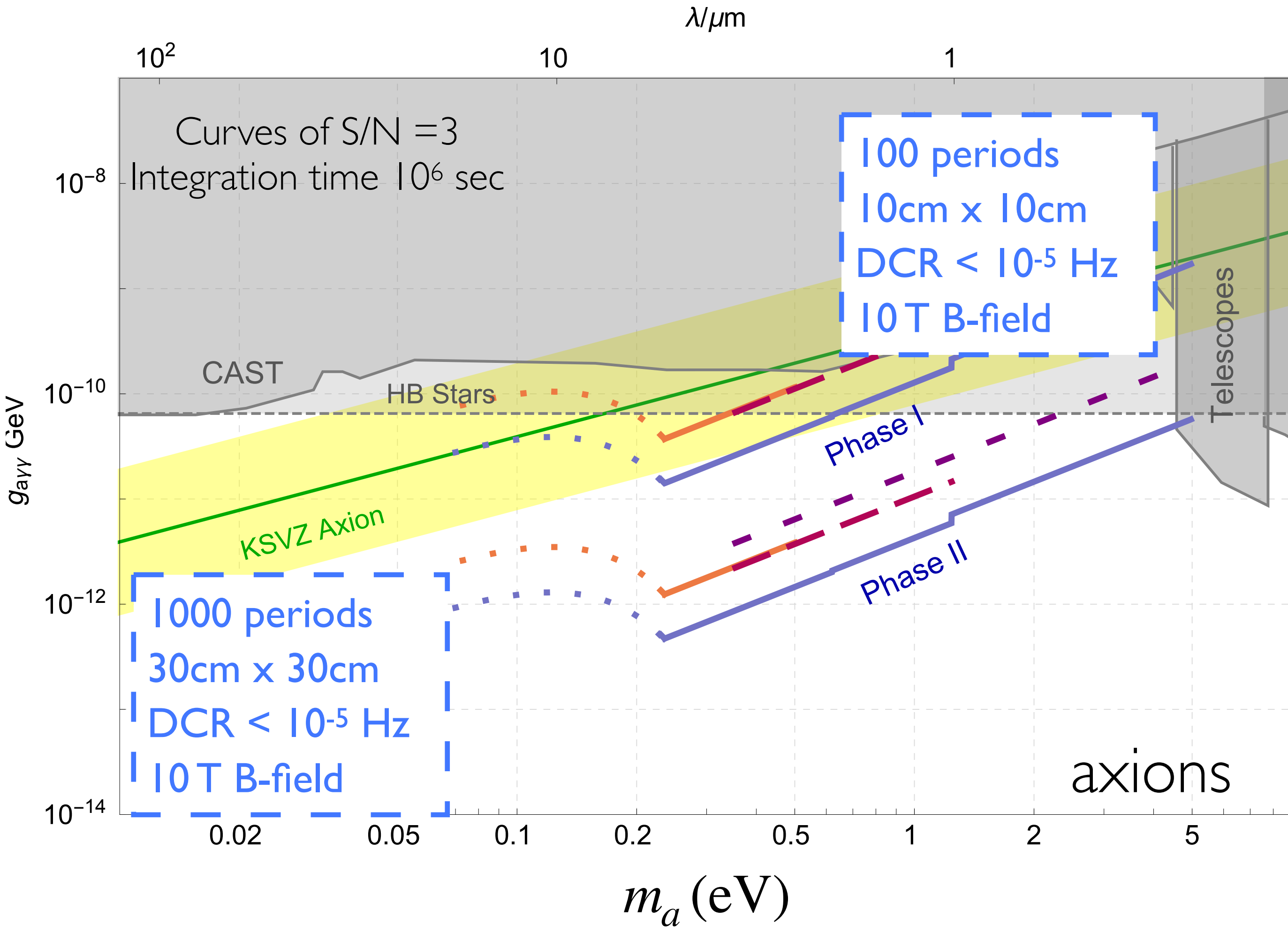




- Prototype can cut into new parameter space with one day of runtime

# Future Reach





Future targets:

**MB**, J. Huang, R. Lasenby

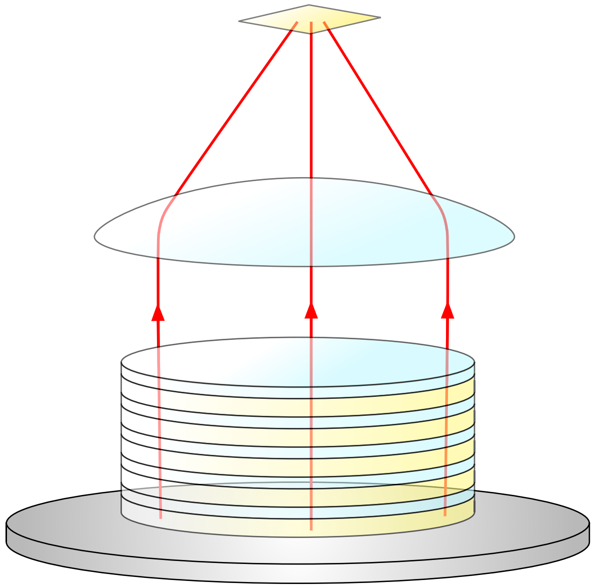
- increase number and area of films for deeper coupling reach
- vary film thickness across the stack for wider frequency coverage
- add large magnetic field for axion search
- adding molecular gas - see Ken Van Tilburg's talk

# Searches with dielectric optical haloscopes

- Axion and dark photon dark matter of ~ eV mass converts to photons efficiently with the help of periodic dielectric materials

- First steps underway, use well-established optics and detector technology

- Can improve on parameter space by orders of magnitude, and perhaps see dark matter



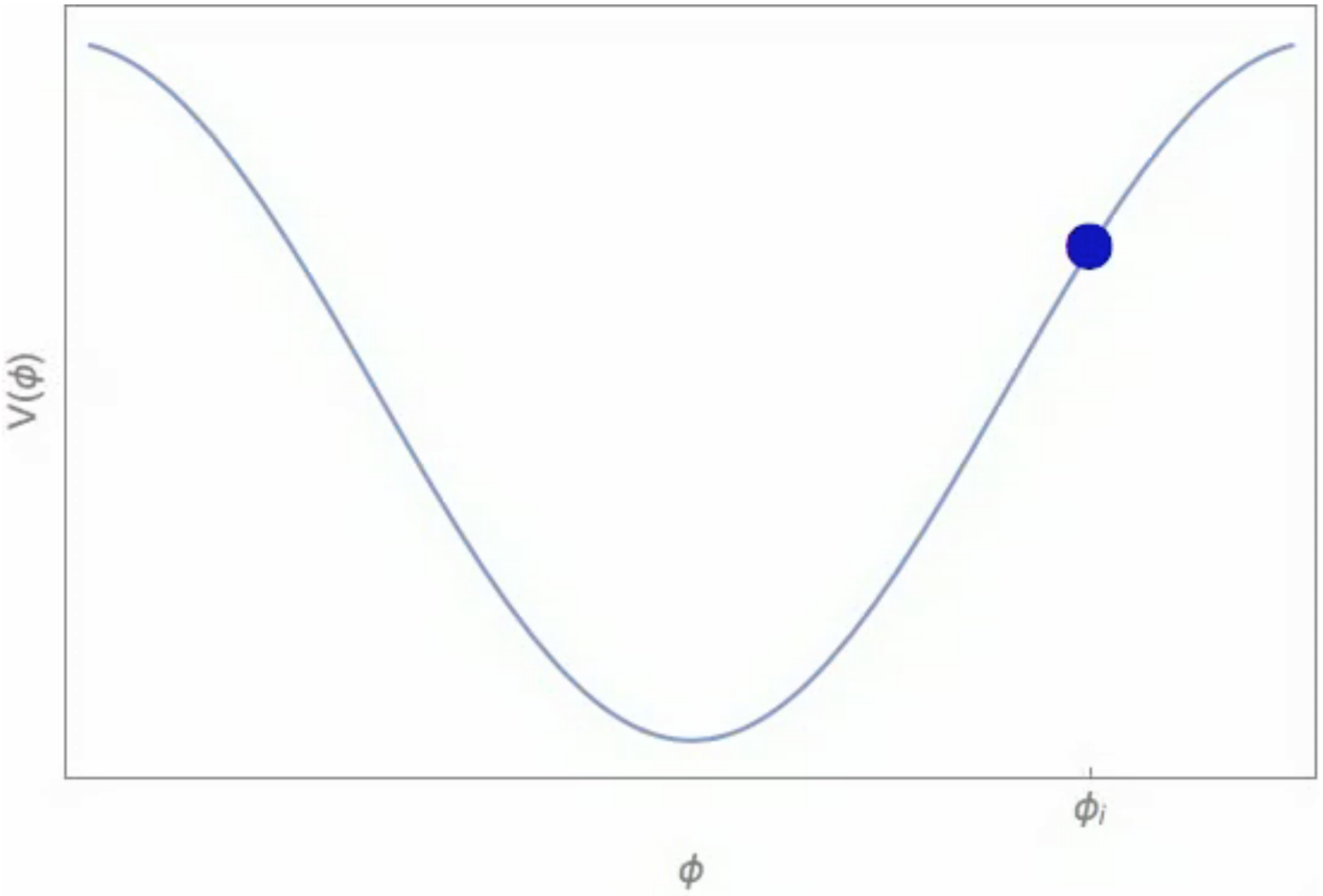
# Extra

# Axion dark matter

- Cosmological evolution of amplitude given by damped harmonic oscillator:

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

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



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

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

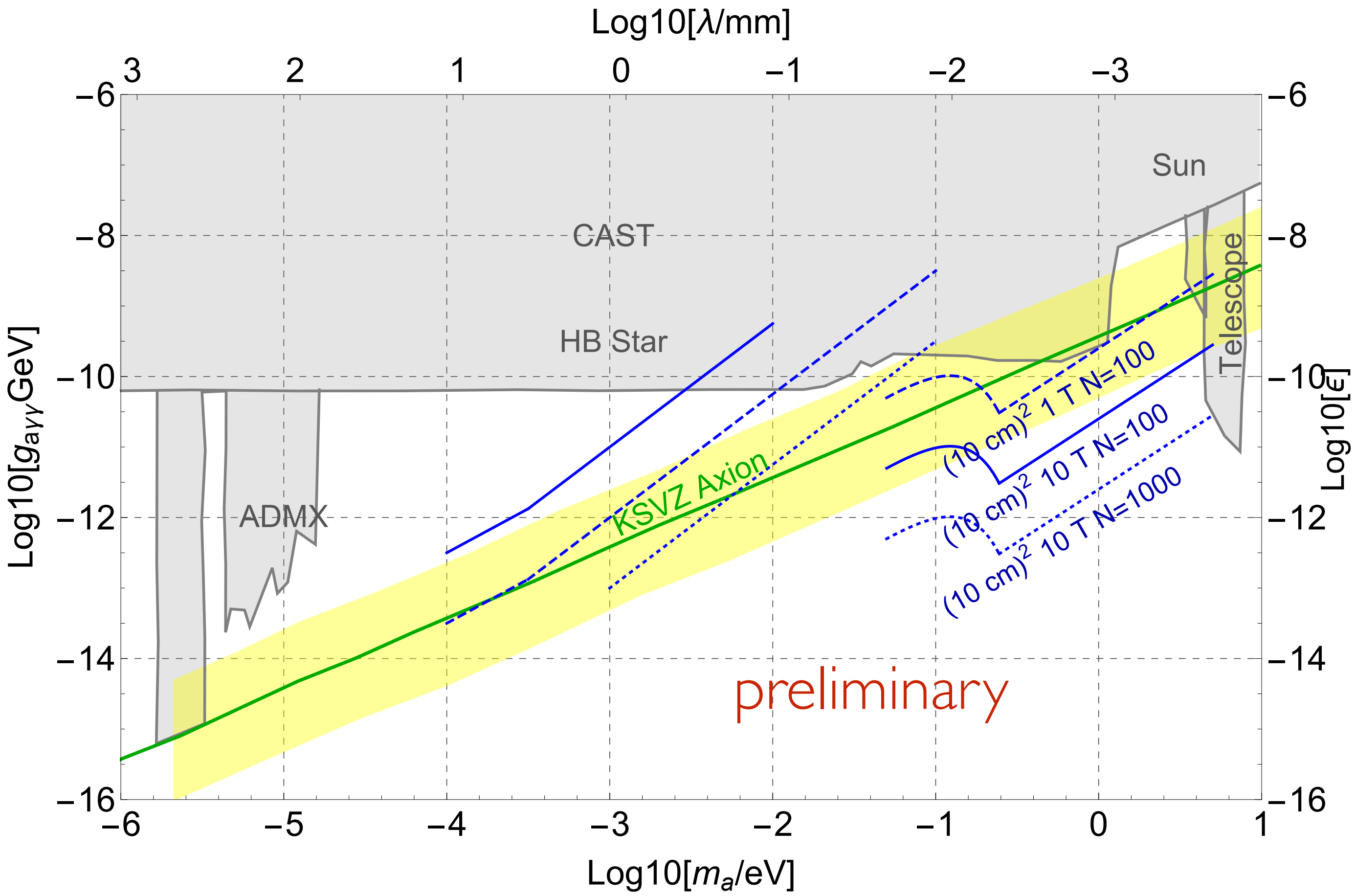
QCD axion

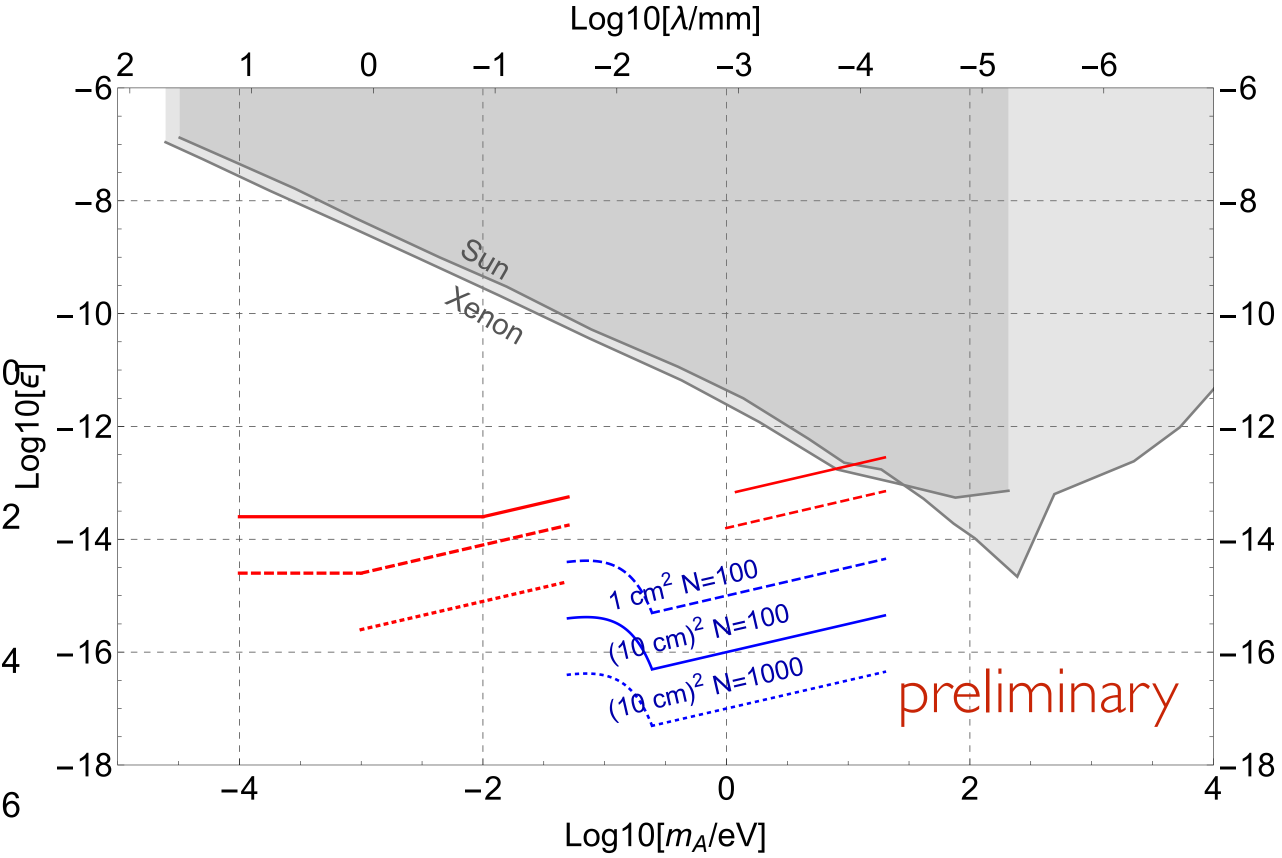
$$\frac{\rho_{\rm a,QCD}}{\rho_{\rm cdm}} \sim \left(\frac{f}{{\rm few} \times 10^{11}{\rm GeV}}\right)^{7/6} \left(\frac{a_i}{f}\right)^2$$

# Seeing dark matter

## Future extensions

Lower masses:

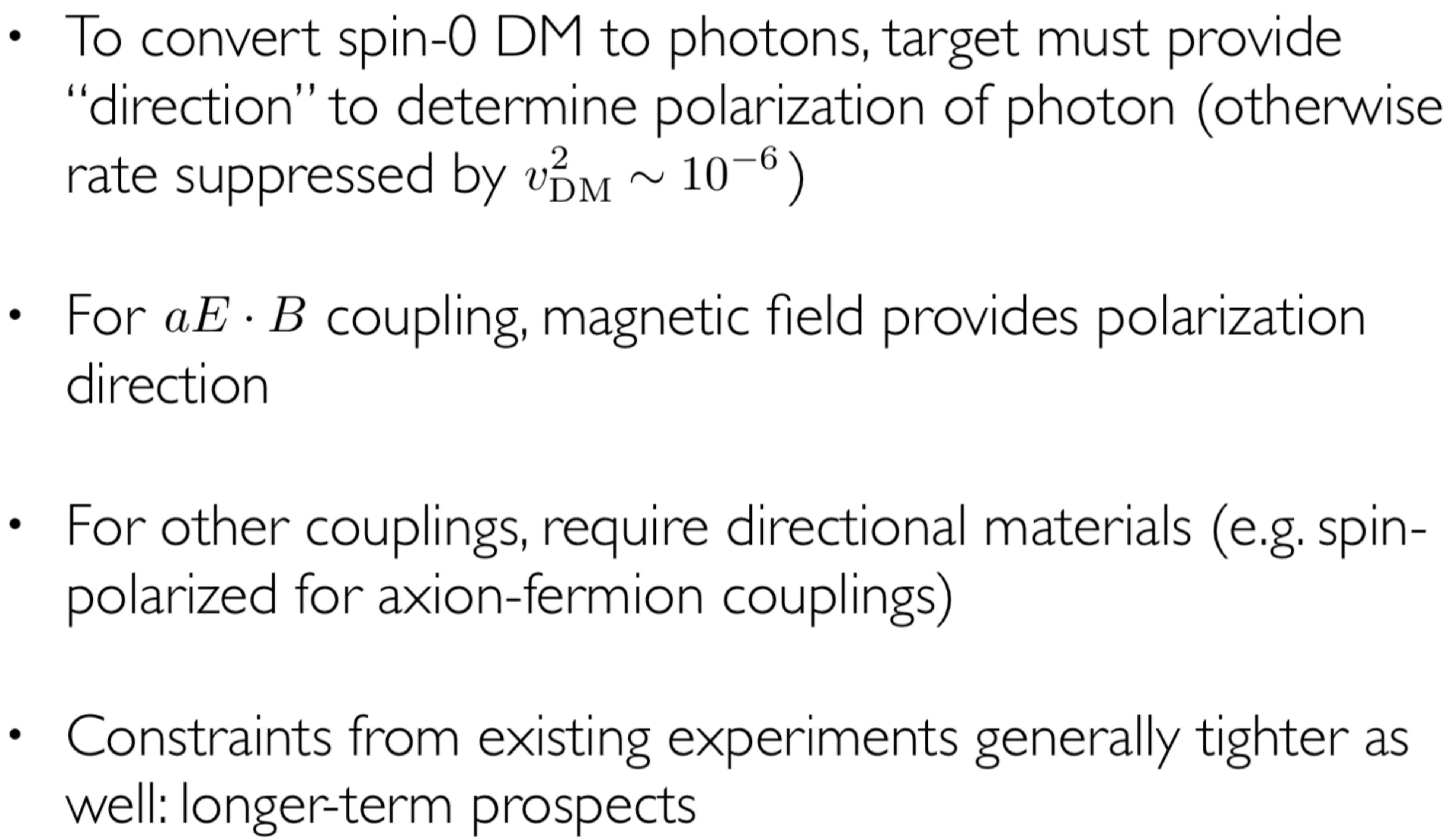




# Seeing dark matter

## Future extensions

Other couplings: scalars, B-L vectors, …



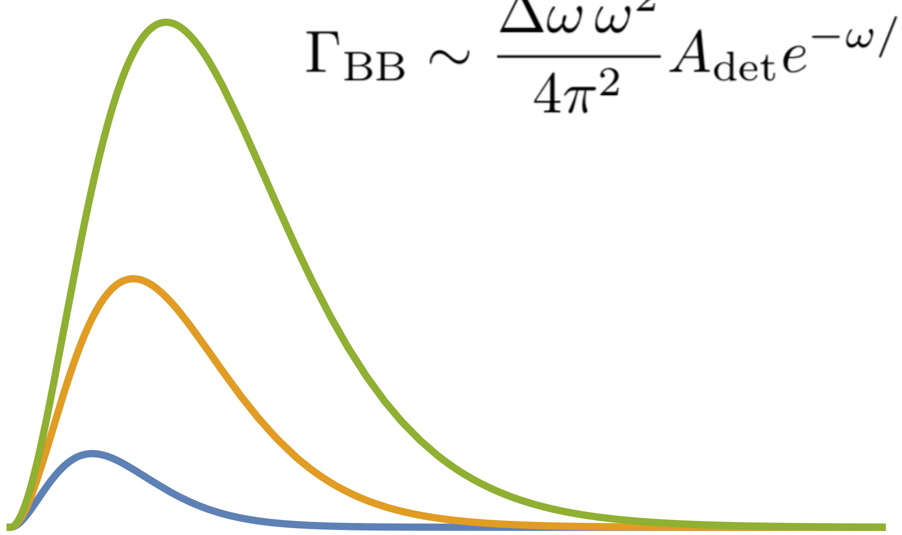
- To convert spin-0 DM to photons, target must provide "direction" to determine polarization of photon (otherwise rate suppressed by $v_{\rm DM}^2 \sim 10^{-6}$)
- For $aE \cdot B$ coupling, magnetic field provides polarization direction
- For other couplings, require directional materials (e.g. spin-polarized for axion-fermion couplings)
- Constraints from existing experiments generally tighter as well: longer-term prospects

Higher number of layers or other improvements to Q-factor, especially in the event of a signal!

# Not seeing dark matter

## Backgrounds

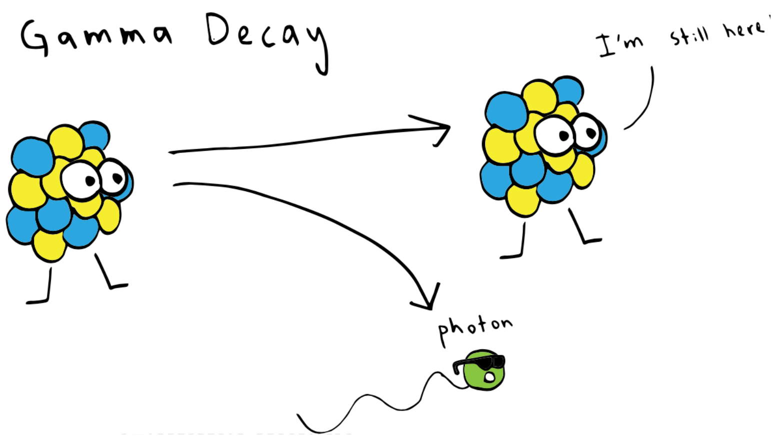
### Blackbody radiation

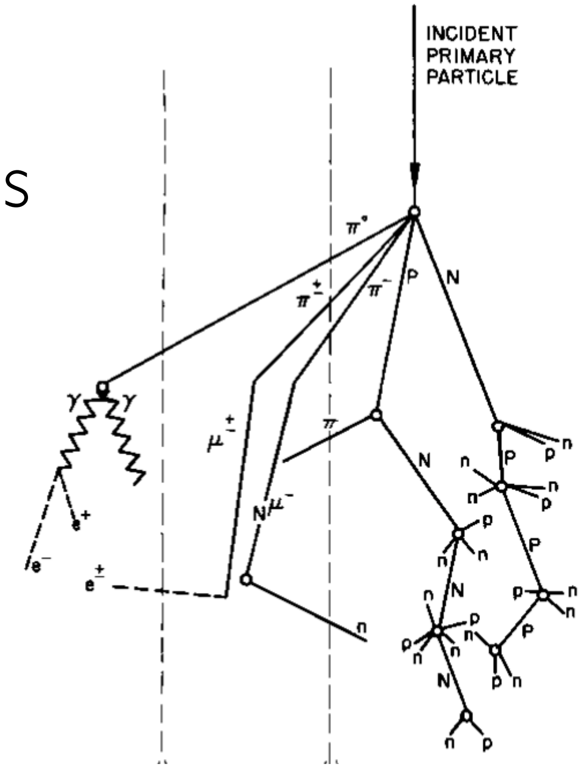


$$\Gamma_{\mathrm{BB}} \sim \frac{\Delta\omega\,\omega^2}{4\pi^2} A_{\mathrm{det}} e^{-\omega/T}$$

- At optical frequencies, black body radiation exponentially suppressed
- Cooling may be necessary

### Radioactivity and Cosmics

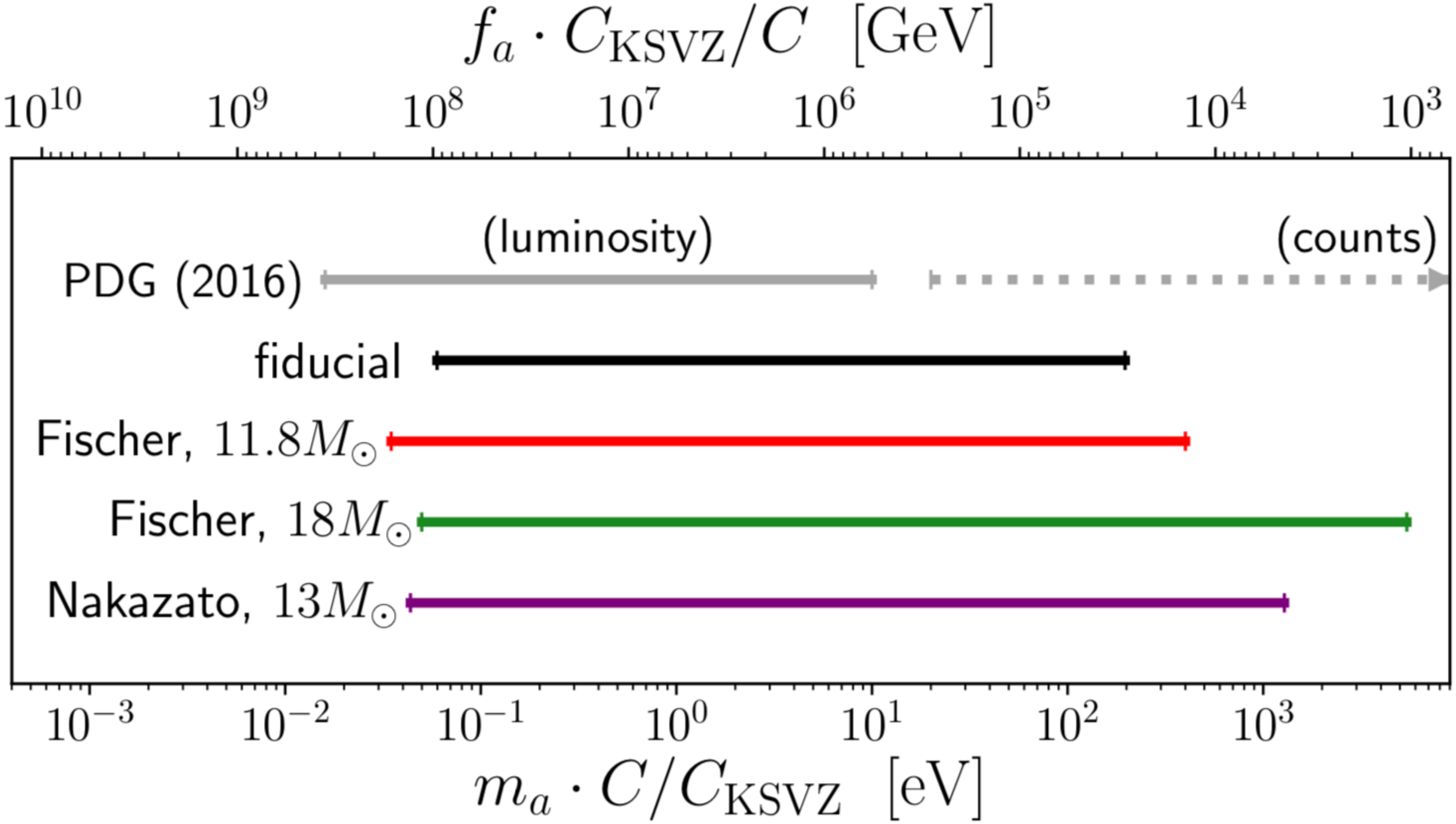




- Radioactive decays in surroundings, cosmic rays can produce energetic photons
- Typically these are high energy compared to signal and/or shower into many particles

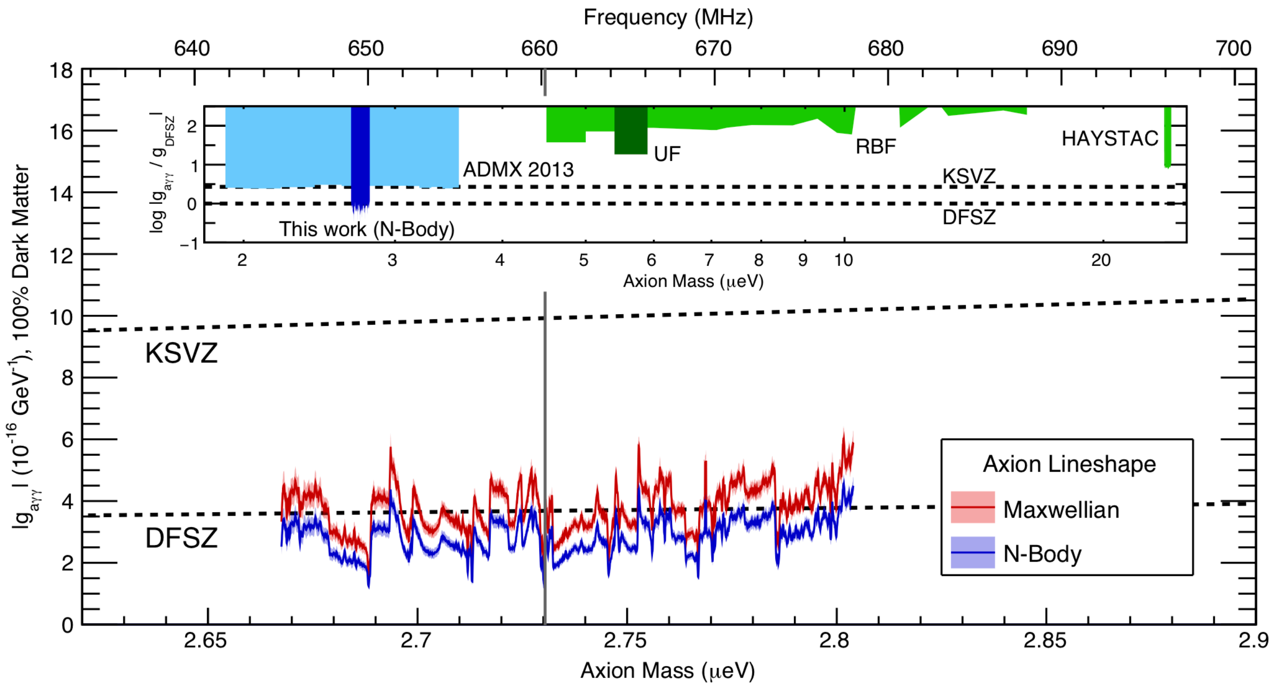
- Backgrounds suppressed by small target volume and very small detector area
- Extra handles from separating target and detector

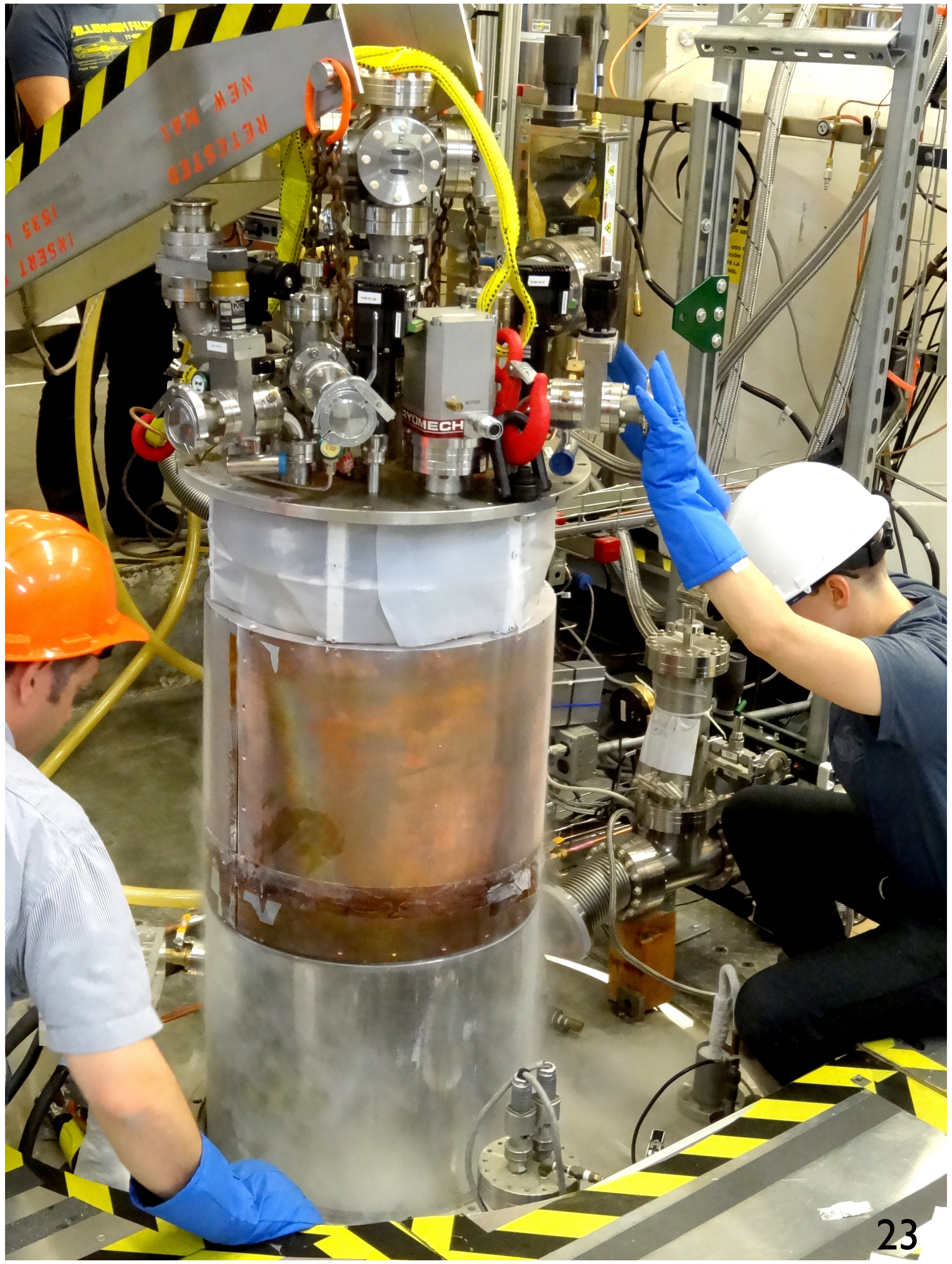
# bounds on QCD axion from supernova



# Axion and dark photon detection

- Similar strategies used in a range of current and proposed experiments:
  - ADMX: cavity with boundary conditions and tunable rod
  - First axion DM experiment to reach motivated photon coupling parameter space



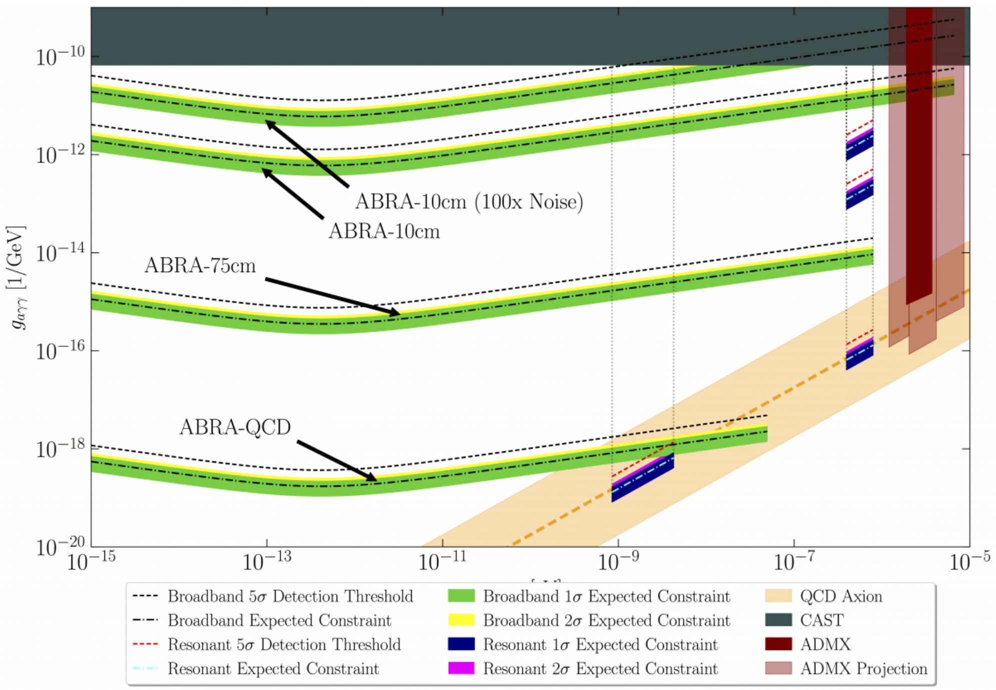


Exploring using periodic structure at higher frequencies (Electric Tiger, ORPHEUS)

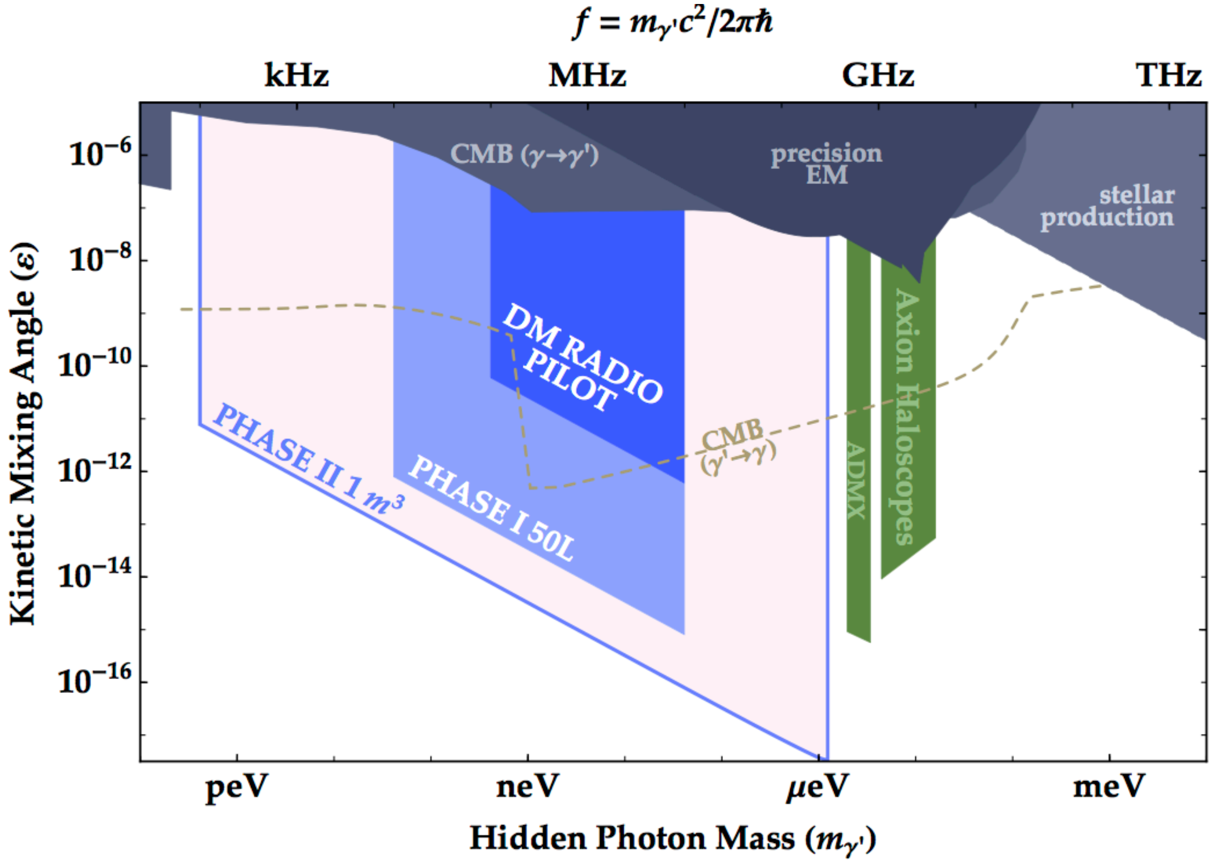
# Axion and dark photon detection

- Similar strategies used in a range of current and proposed experiments:
  - ABRACADABRA

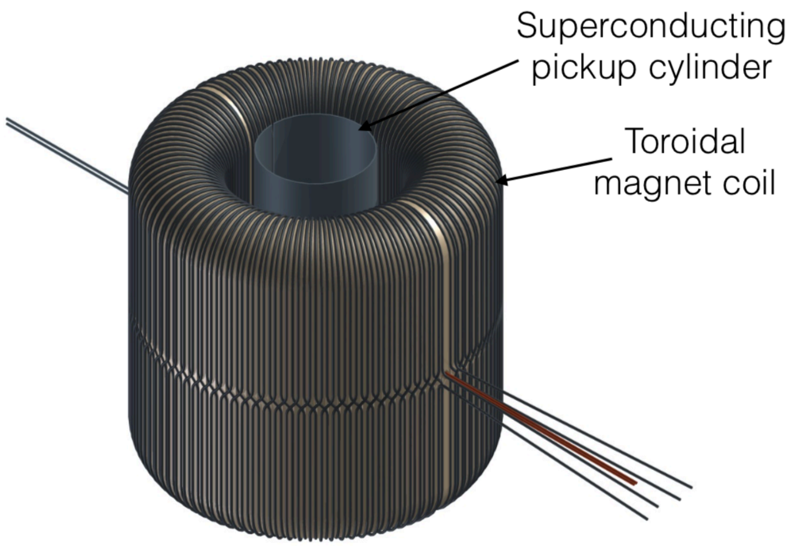
DM Radio

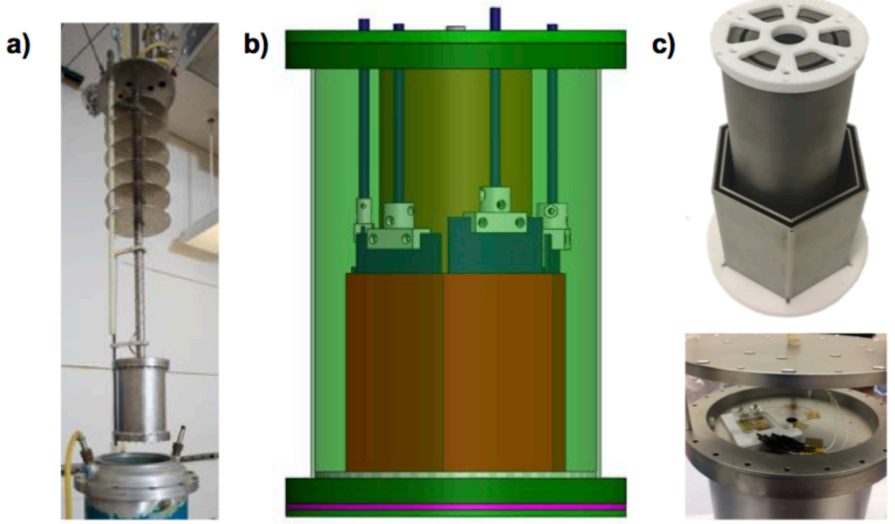


| | | |
|---|---|---|
| Broadband $5\sigma$ Detection Threshold | Broadband $1\sigma$ Expected Constraint | QCD Axion |
| Broadband Expected Constraint | Broadband $2\sigma$ Expected Constraint | CAST |
| Resonant $5\sigma$ Detection Threshold | Resonant $1\sigma$ Expected Constraint | ADMX |
| Resonant Expected Constraint | Resonant $2\sigma$ Expected Constraint | ADMX Projection |



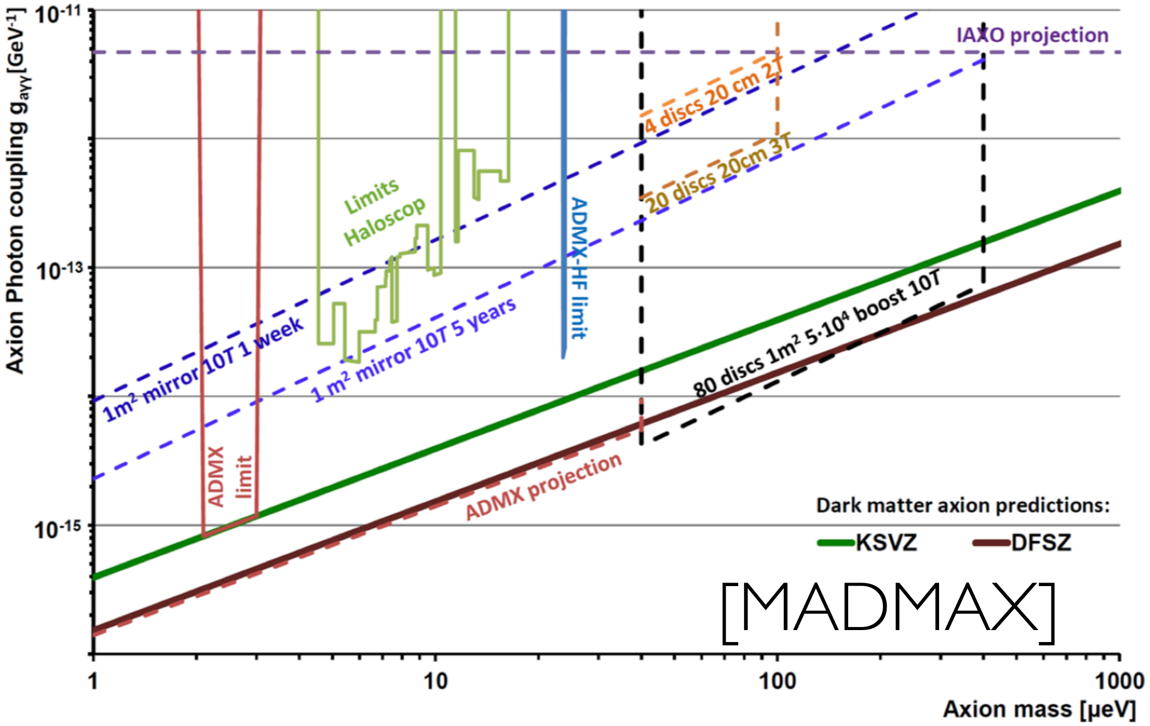
ABRACADABRA-10 cm



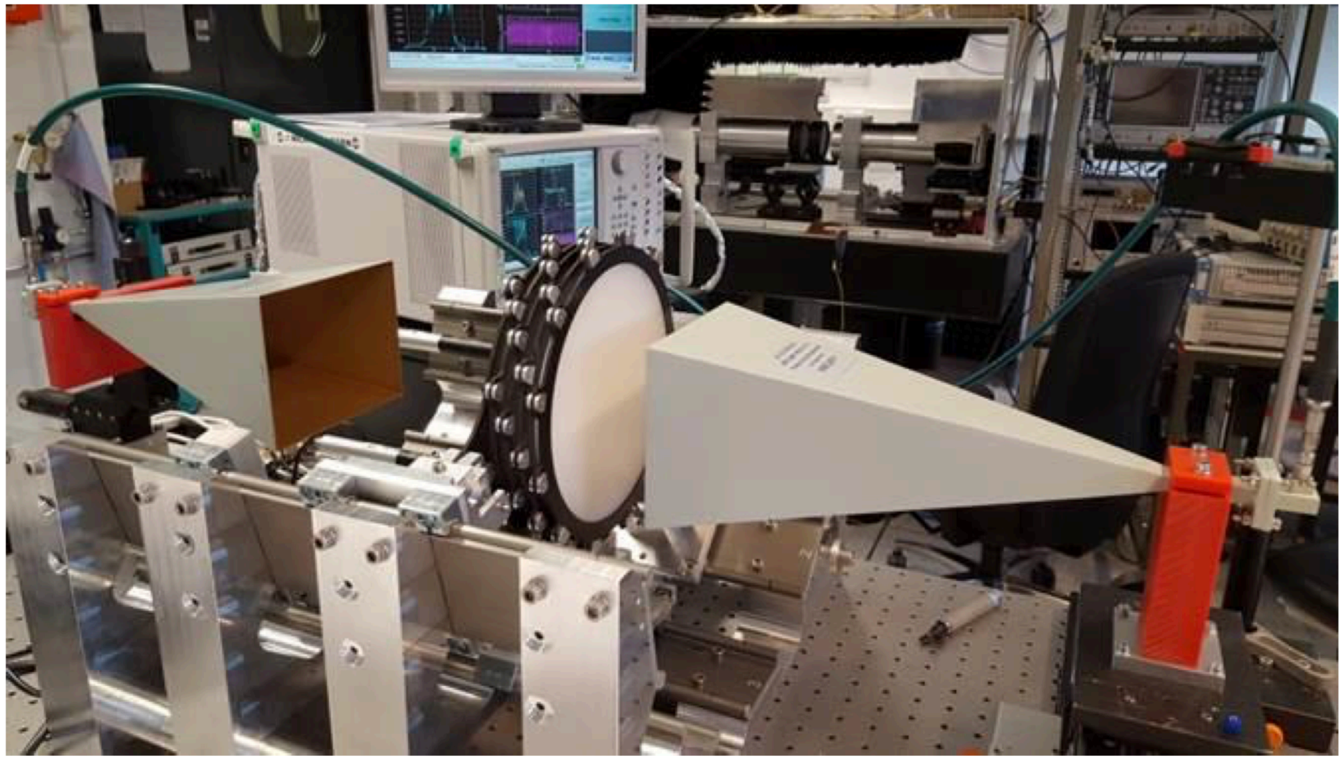


# Axion and dark photon detection

- Similar strategies used in a range of current and proposed experiments:
  - Dish antenna: boundary conditions
  - MADMAX: movable dielectric layers

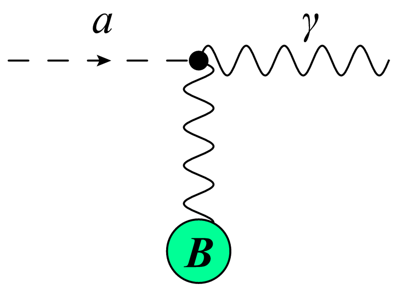


[MADMAX]

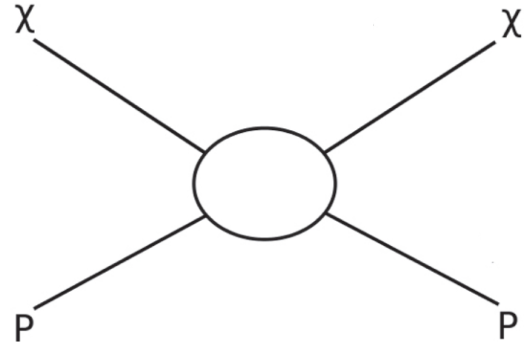


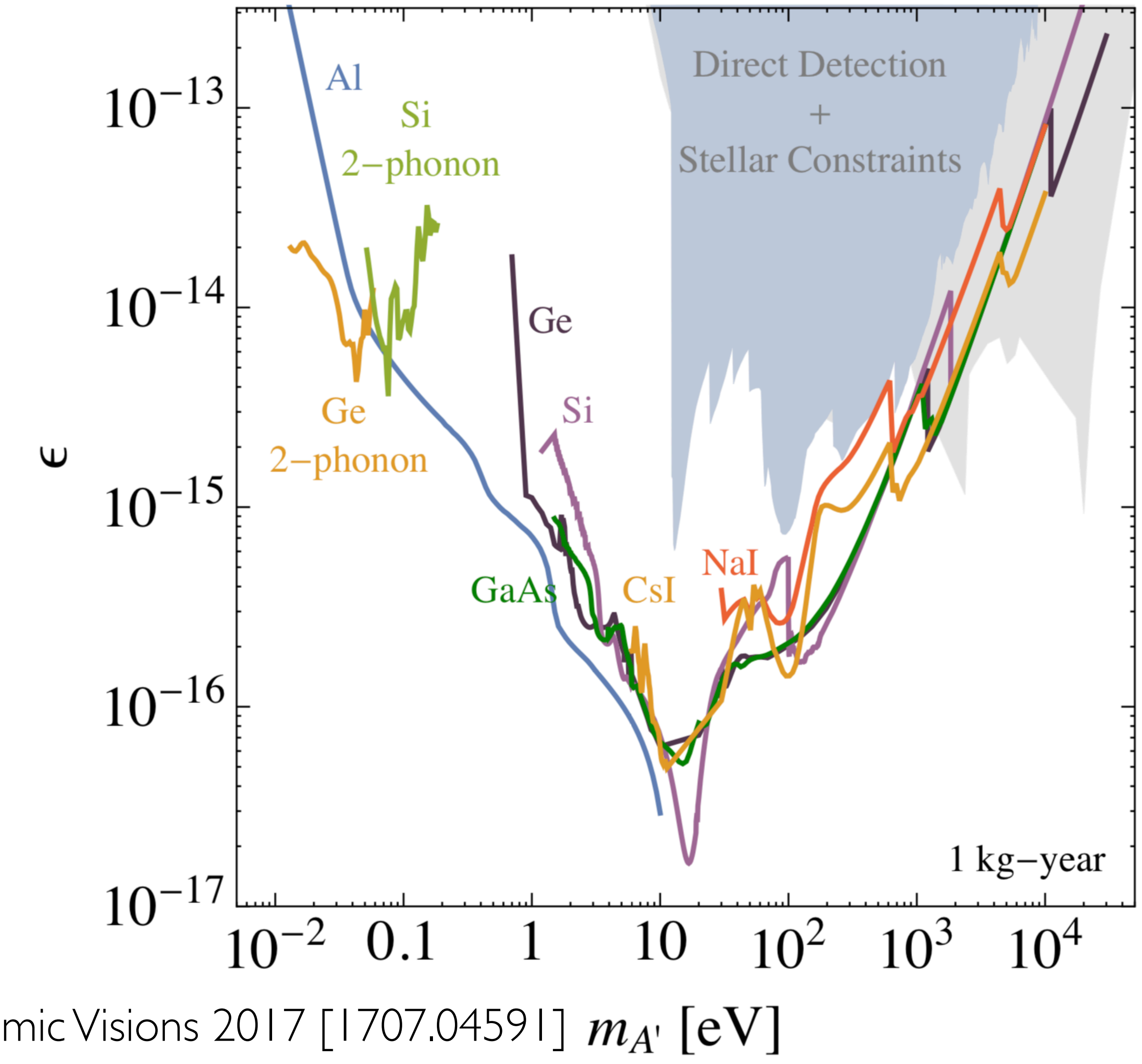
# Axion and dark photon detection

- Bosonic dark matter can be absorbed, imparting entire rest mass, ***m***



- Much more energy transfer to SM particles than kinetic energy from DM scattering, **< *mv^2***





- Direct detection limits from electron excitation or ionization in material

- Also possible to excite phonon modes, etc.

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