Axion and hidden photon dark matter detection with multilayer optical haloscopes

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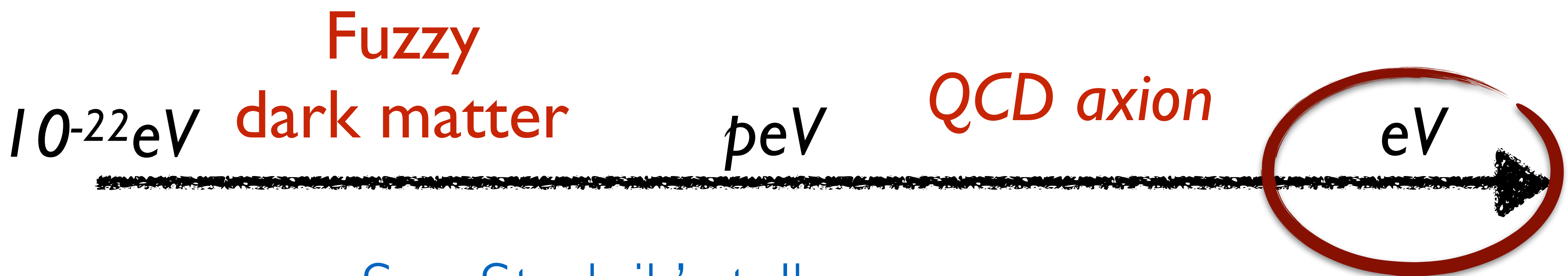
arxiv:1803.11455, Masha Baryakhtar, **JH**, Robert Lasenby

Outline

- Motivations for bosonic Dark Matter searches
- Dark Matter to photon conversion in a photonic crystal
- Experimental setup and reach
- Conclusion

Bosonic dark matter

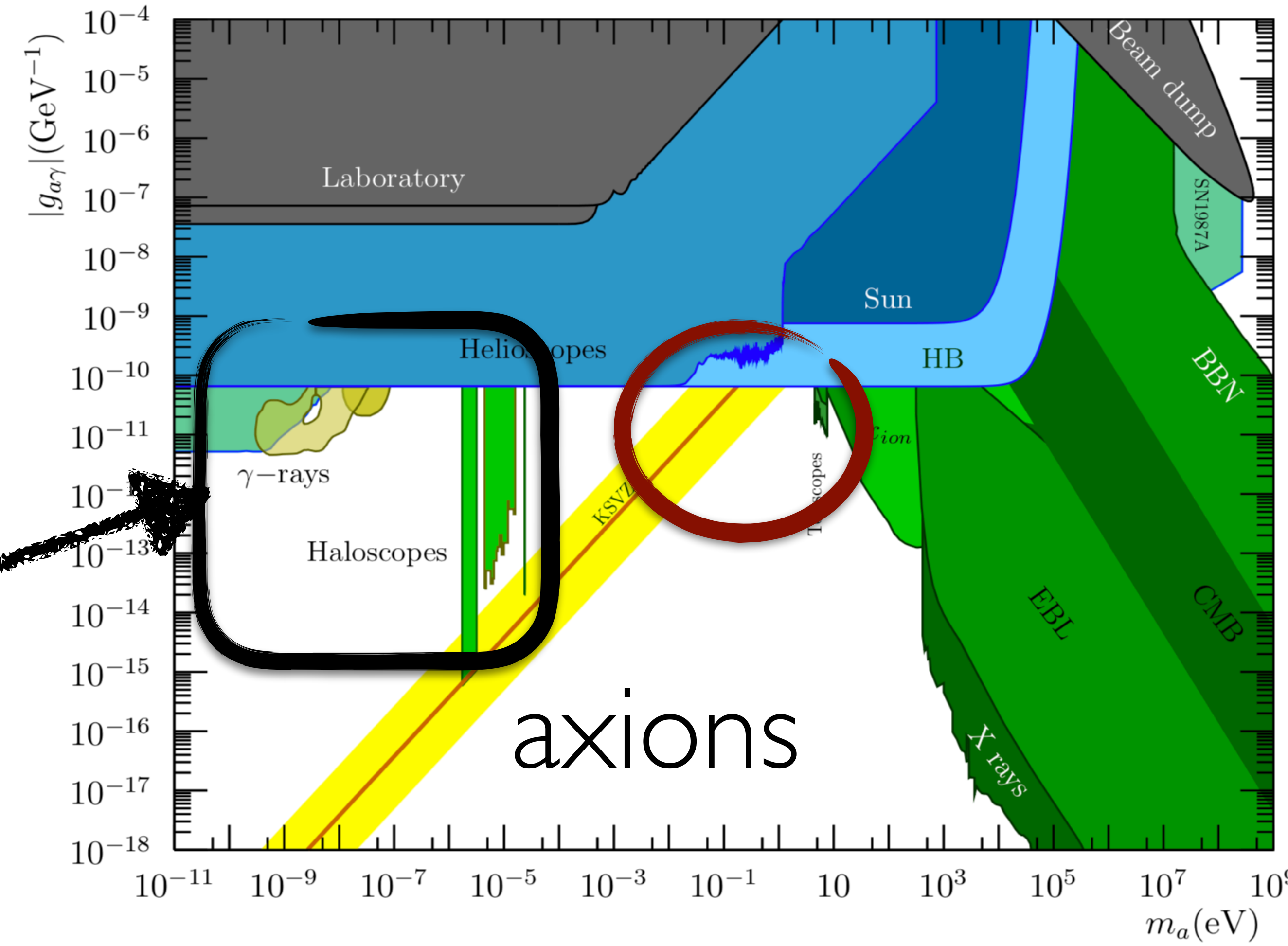


See Stadnik's talk

- Dark matter with $m \lesssim 100\,\mathrm{eV}$must be bosonic, with occupation number > 1 in dense regions
- DM in form of coherent, classical oscillations of field
  coherence length $\sim (v_{\rm DM} m)^{-1} \sim 10^3 m^{-1}$
  coherence time $\sim (v_{\rm DM}^2 m)^{-1} \sim 10^6 m^{-1}$
- Can naturally be produced by amplification of quantum fluctuations during inflation

Axions

- Axion parameter space:
- Axion DM searches:
  - CASPER
  - ABRACADABRA, DM radio
  - ADMX, HAYSTAC
  - MADMAX
  - …



- Axion productions:
  - Misalignment
  - String & domain wall

$$\frac{1}{2}(\partial_\mu a)^2 - V(a) - \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

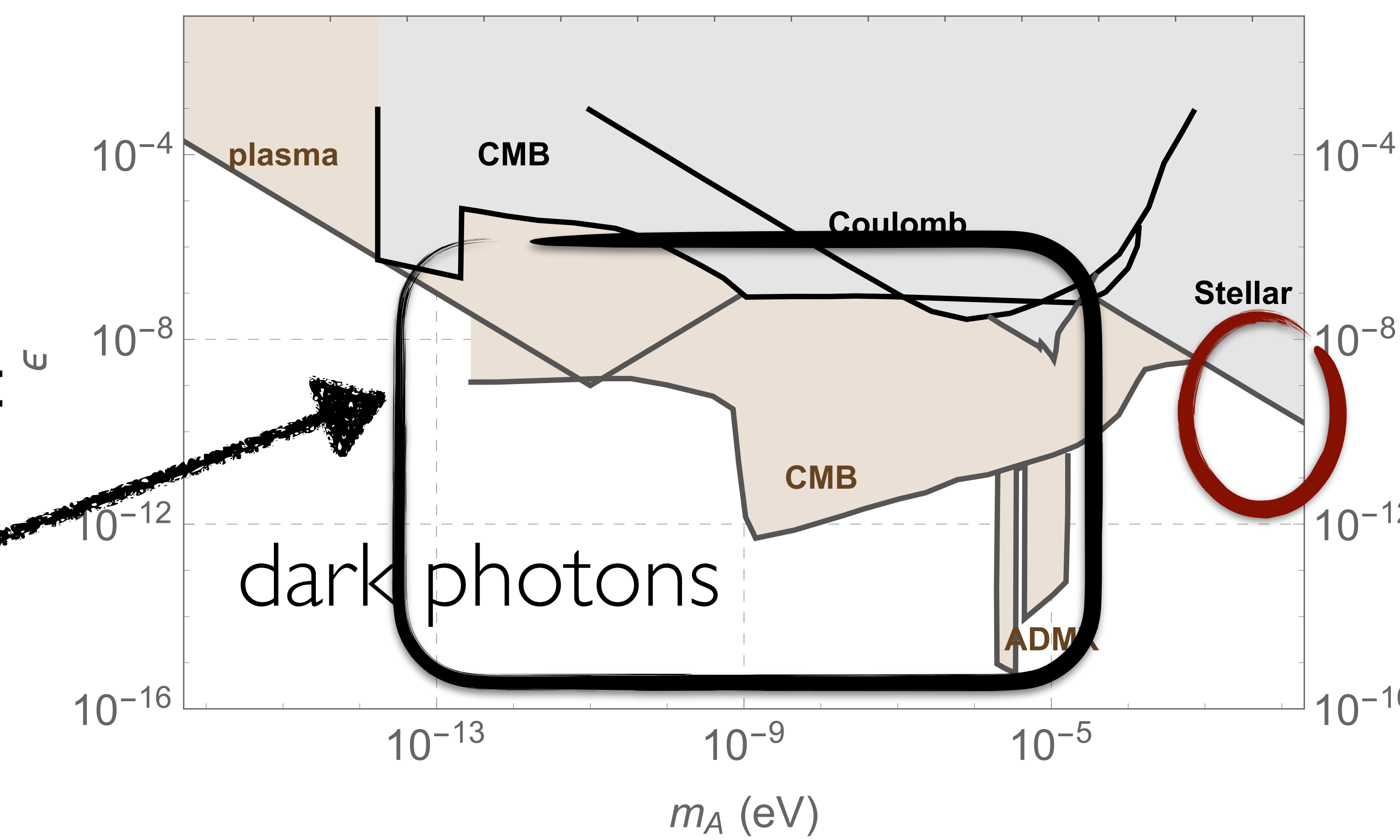
[Borsanyi et al., Nature `16 [1606.0794]]
[G. Grilli di Cortona, E. Hardy, J. Pardo Vega, G.Villadoro [1511.02867]]

See Scherlis's talk

Dark photons

- Dark photon parameter space:

- Dark photon DM searches:
  - DM radio
  - ADMX
  - …



- Dark photon production:

$$-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}-\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu}+\frac{1}{2}m^2A'^2+J^{\mu}_{\rm EM}(A_\mu+\kappa A'_\mu);$$

  - Inflationary production

[P.W. Graham, J. Mardon, S. Rajendran, arXiv:1504.02102]

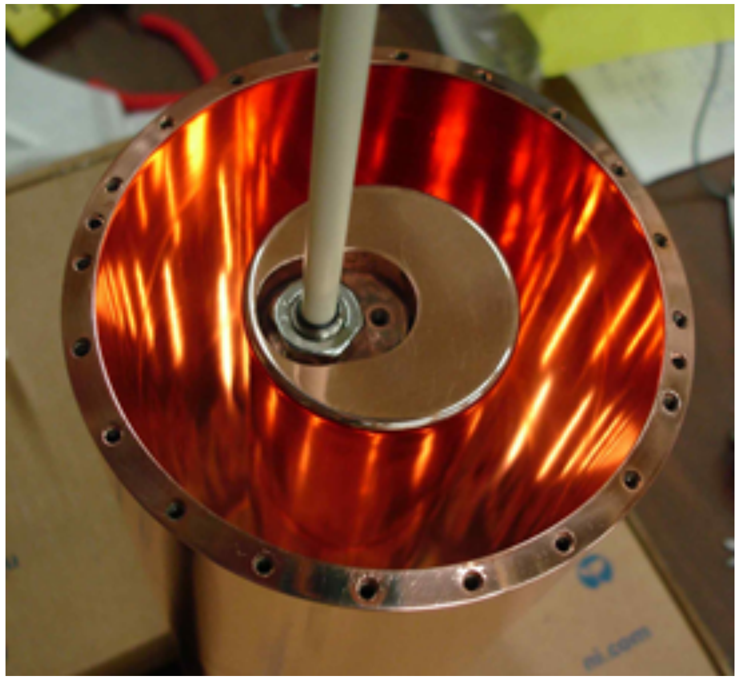
Dark matter searches

- Dark matter scattering

$$\Delta E \sim m_{\rm DM} v_{\rm DM}^2/2$$

- Dark matter absorption/conversion

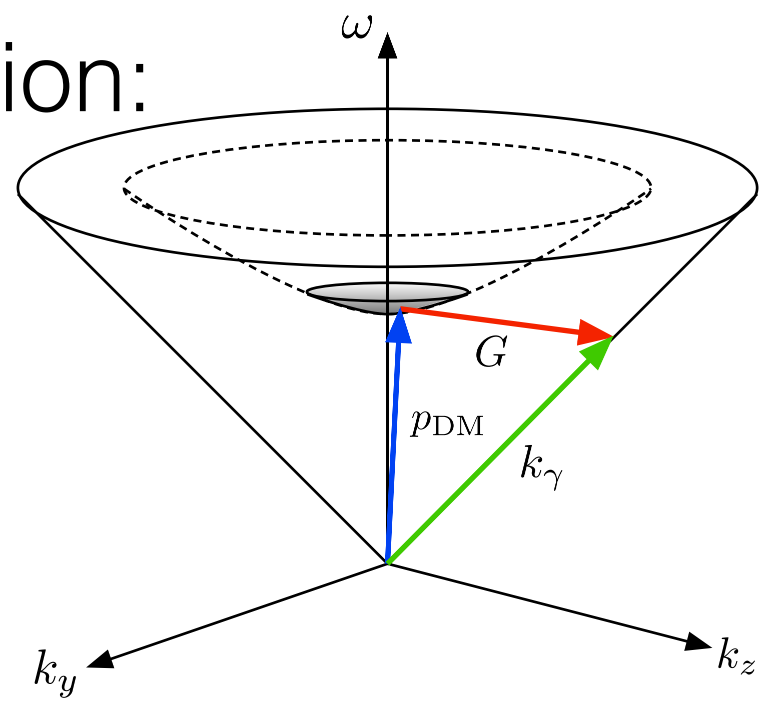
$$\Delta E = m_{\rm DM}$$



Haystac Cavity

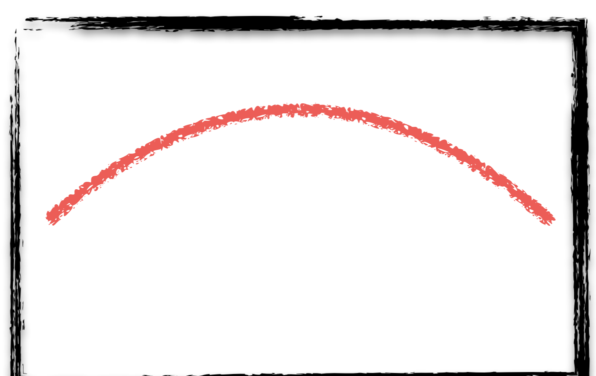
Dark matter conversion to photon

- Challenges for dark matter absorption:



$$p_a = (m_a, m_a \vec{v_a})$$
$$p_\gamma = (m_a, \vec{m_a})$$

- To satisfy energy and momentum conservation, we need the absorption target to have the right periodicity

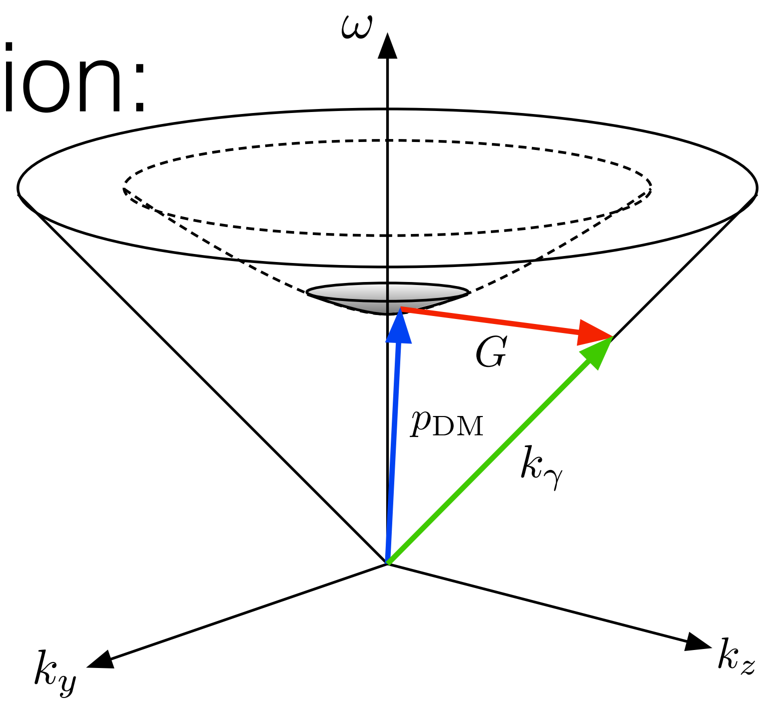


Boundary of a cavity (ADMX)

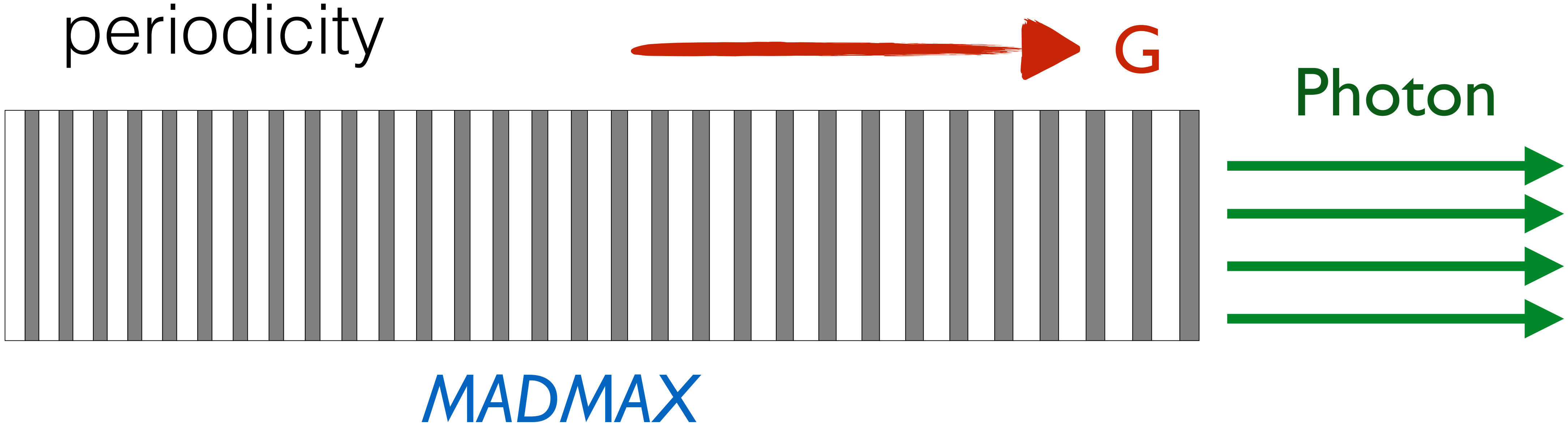
Dark matter absorption

- Challenges for dark matter absorption:

$$p_a = (m_a, m_a \vec{v_a})$$
$$p_\gamma = (m_a, \vec{m_a})$$

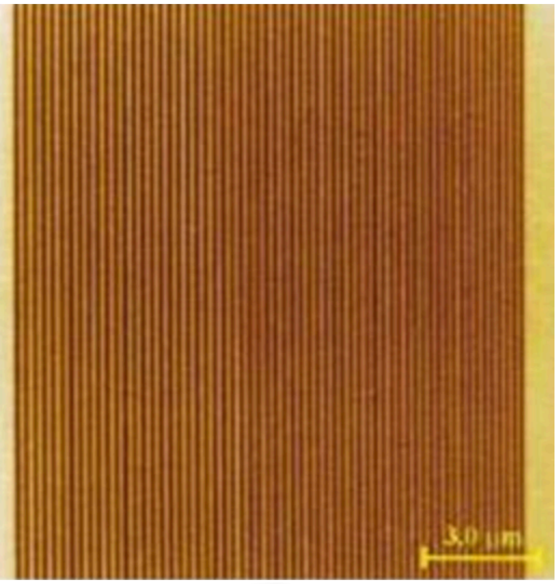


- To satisfy energy and momentum conservation, we need the scattering target to have the right periodicity

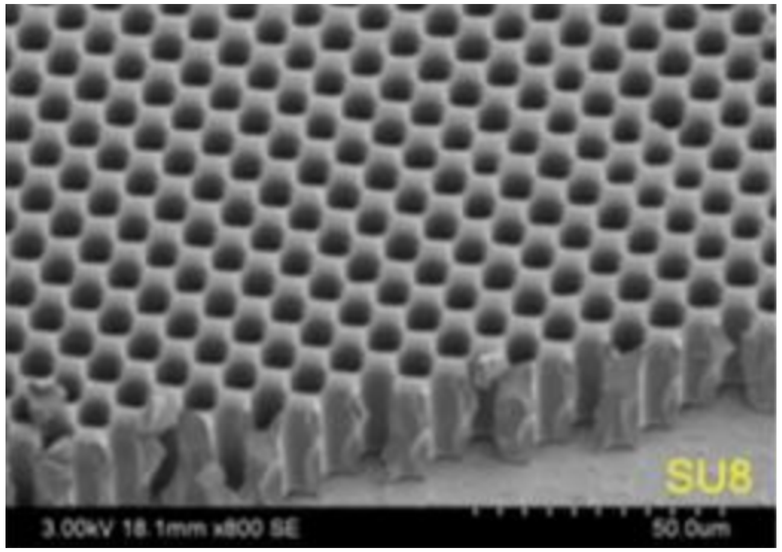


Photonic Crystals

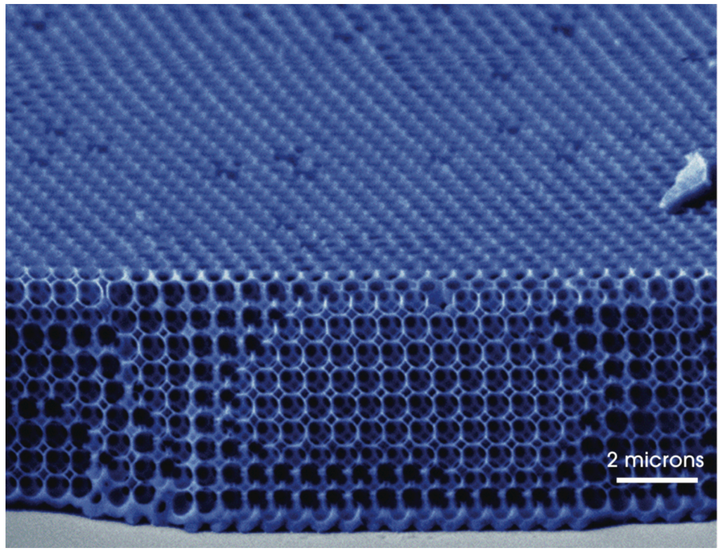
- Materials with periodic optical properties



1D



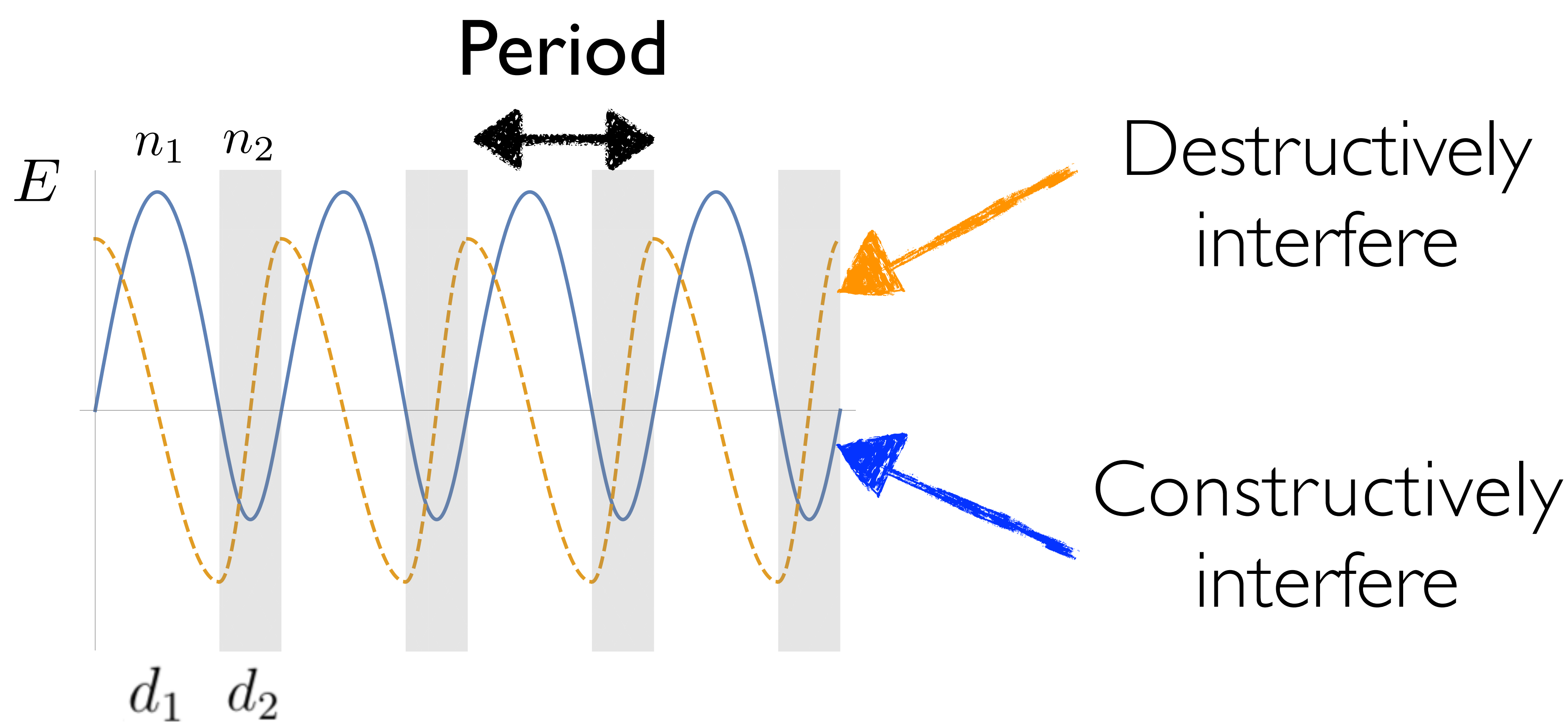
2D



3D

Photon mode

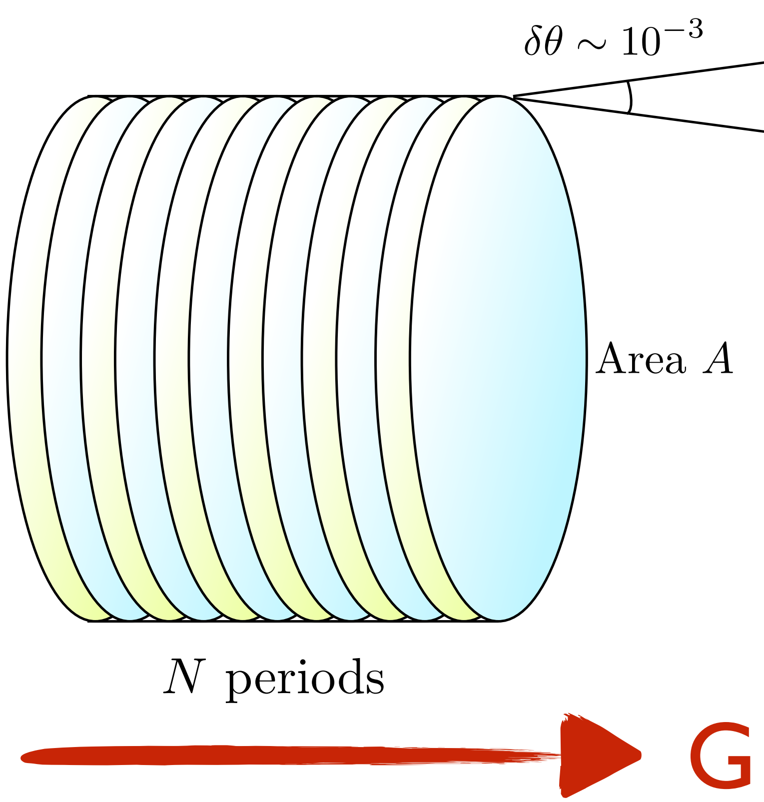
- DM is spatially uniform over the **de Broglie** wavelength
- Photon modes have period of the **Compton** wavelength
- Half wave stack $n_1 d_1 = n_2 d_2 = \lambda_{\text{Compton}}/2$



Coherent absorption

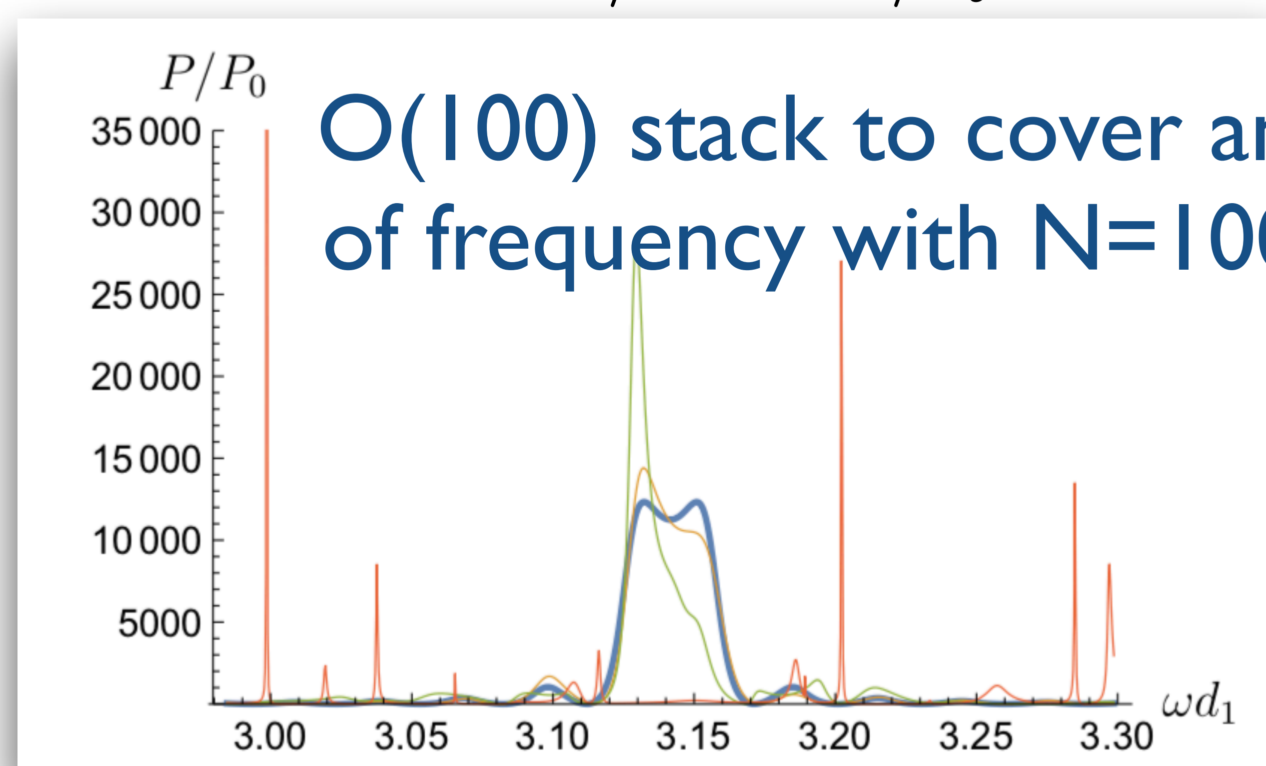
- Converted power (dark photon): $(Q \sim N)$

$$\frac{16}{3}\kappa^2 \rho_{\rm DM} A N^2 \frac{(n_1^2 - n_2^2)^2}{n_1^4 n_2^4}$$



- Coverage over DM mass range $\delta m/m \sim 1/Q$

Scan!

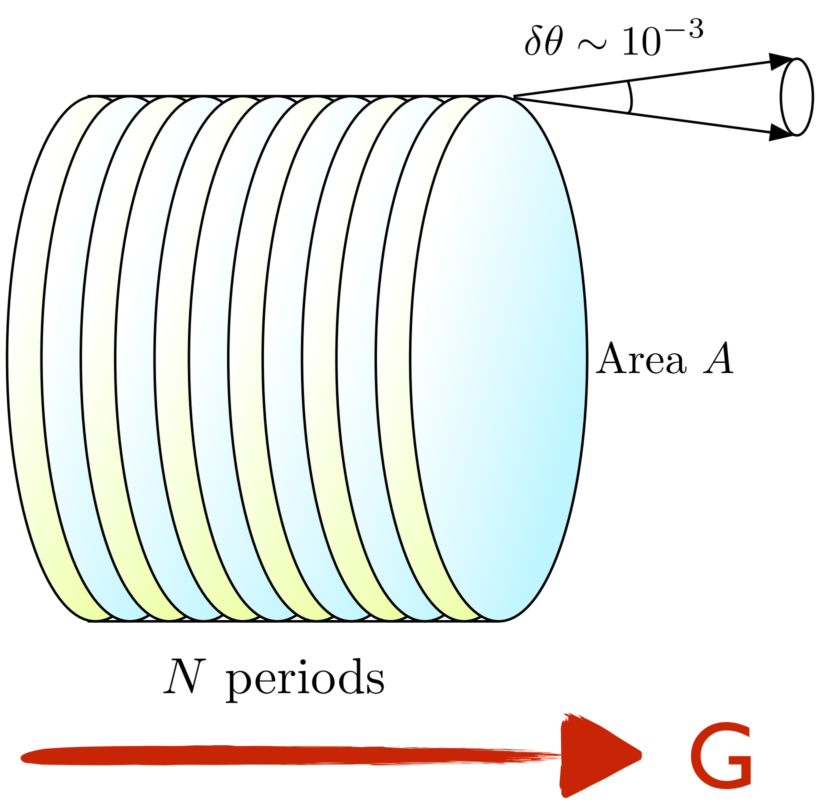


O(100) stack to cover an e-fold of frequency with N=100 stack.

Coherent absorption

- Converted power (dark photon): $(Q \sim N)$

$$\frac{16}{3}\kappa^2\rho_{\rm DM}AN^2\frac{(n_1^2-n_2^2)^2}{n_1^4 n_2^4}$$



- Coverage over DM mass range $\delta m/m \sim 1/Q$

Scan!

- Photons are emitted collimated to the surface

- Photons can be focussed down to area $\sim 10^{-6}A$

Background rejection

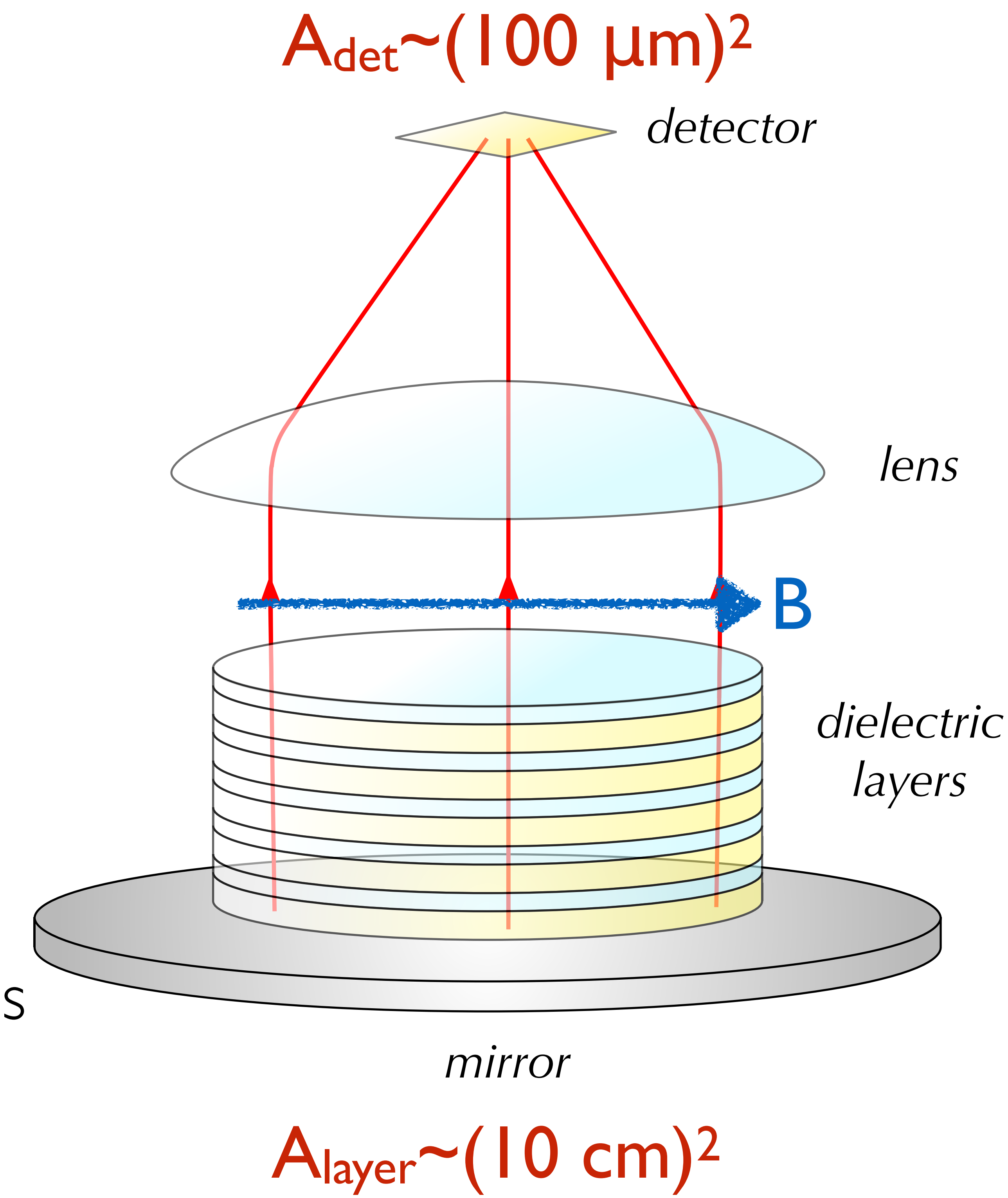
Experimental setup

- Signal photons can be focused into a sensitive photon detector

$$A_{\mathrm{det}} = 10^{-6} A_{\mathrm{layer}}$$

- The Target-Lens-Detector system should be operated in a cryogenic system

- A horizontal magnetic field is needed to look for axions



Notable background

- Blackbody (Thermal)

$$\Gamma_{\rm BB} \sim \frac{\Delta\omega\,\omega^2}{4\pi^2} A_{\rm det}\, e^{-\omega/T} \longrightarrow T \lesssim \omega/40 \approx 300\,{\rm K}\left(\frac{\omega}{\rm eV}\right)$$

- Cosmic ray and Radioactivity

$$\Gamma \sim \mathcal{O}(10)\,{\rm Hz/Target}$$

  - Background reduction by focusing

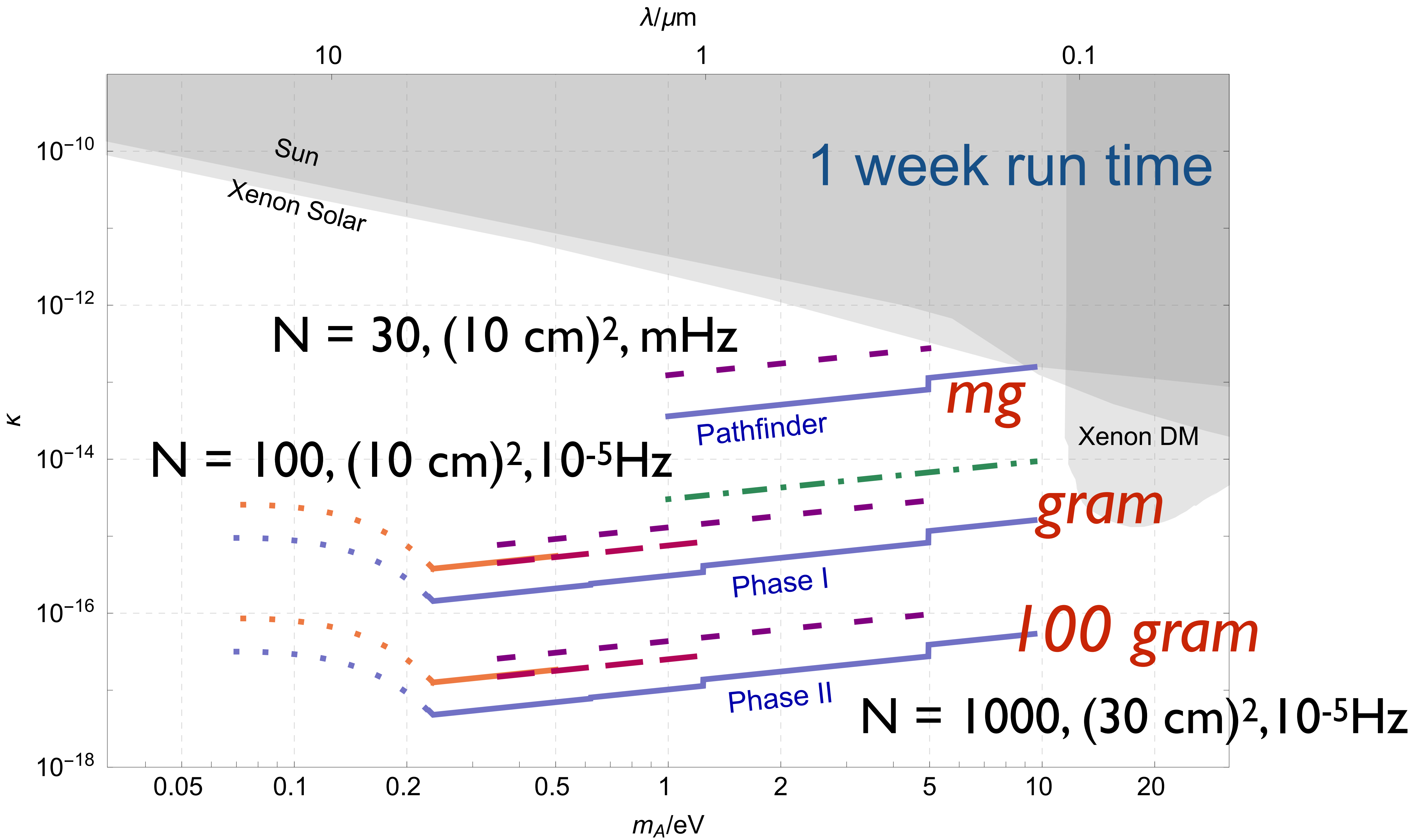
$$\Gamma_{\rm det} \simeq 10^{-6}\Gamma_{\rm Target}$$

  - Active veto of particle shower

- Detector dark count
  - CCD: mHz
  - SCTJ, TES, MKIDs: O(1)/day

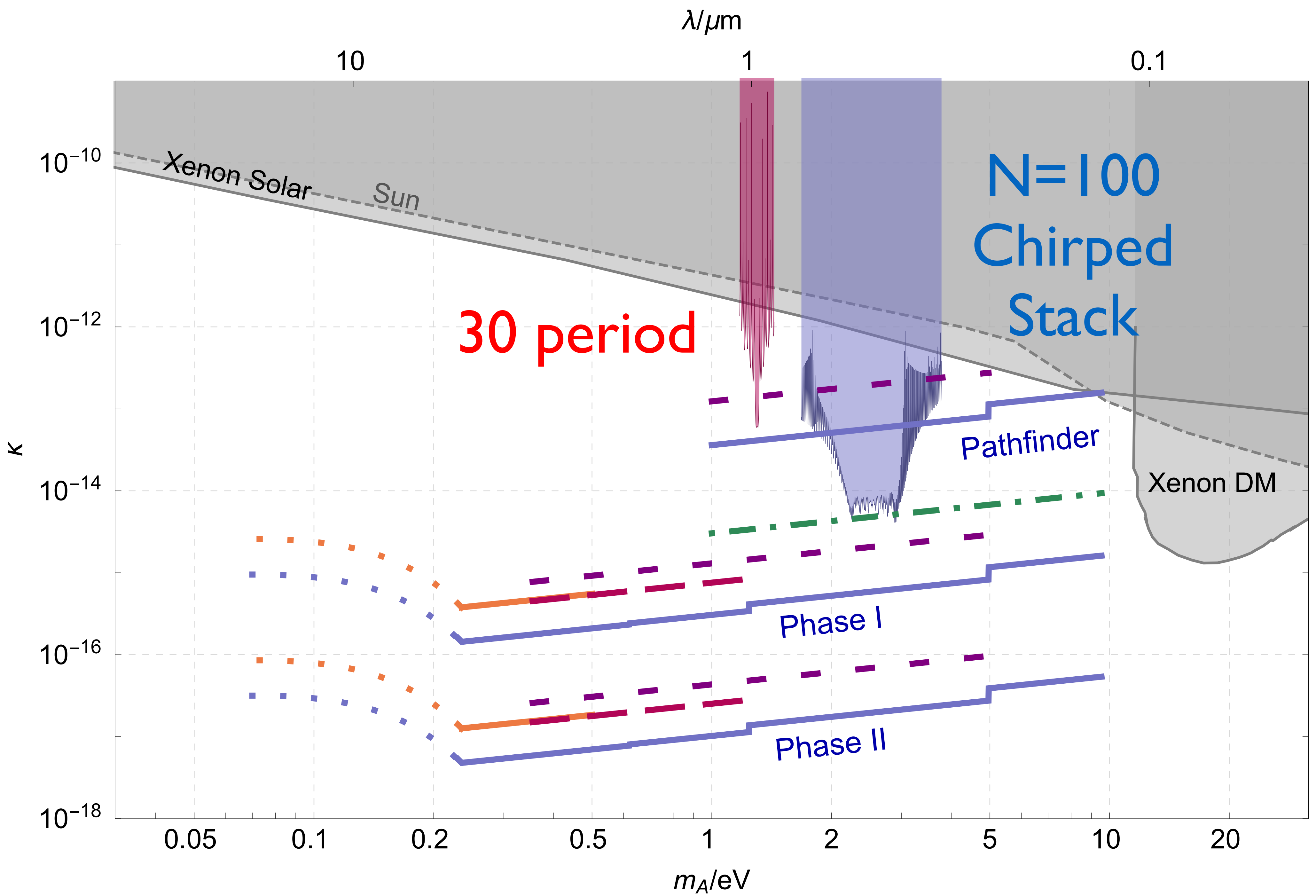
Background rate of 10^{-5} Hz at eV energies

Dark Photon DM



Roughly N stacks are needed to cover an e-fold of masses

Dark Photon DM

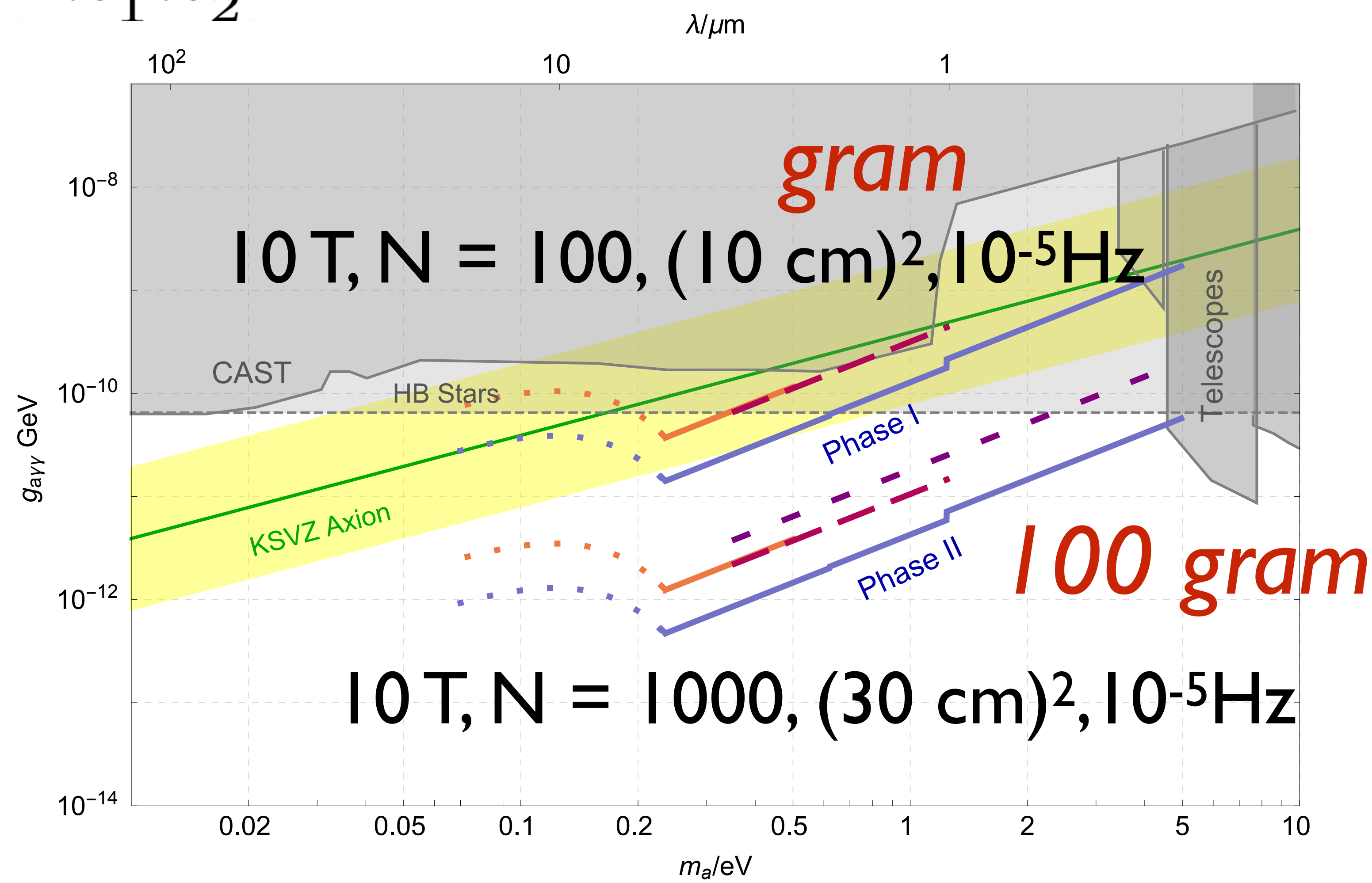


Axion DM

$$8g^2 B_0^2 \frac{\rho_{\rm DM}}{m_0^2} A N^2 \frac{(n_1^2 - n_2^2)^2}{n_1^4 n_2^4}$$ 1 week run time

- Axion-photon coupling $g_{a\gamma\gamma} a\, E \cdot B$ requires background magnetic field

- Existing constraints stronger; need larger target / better detectors



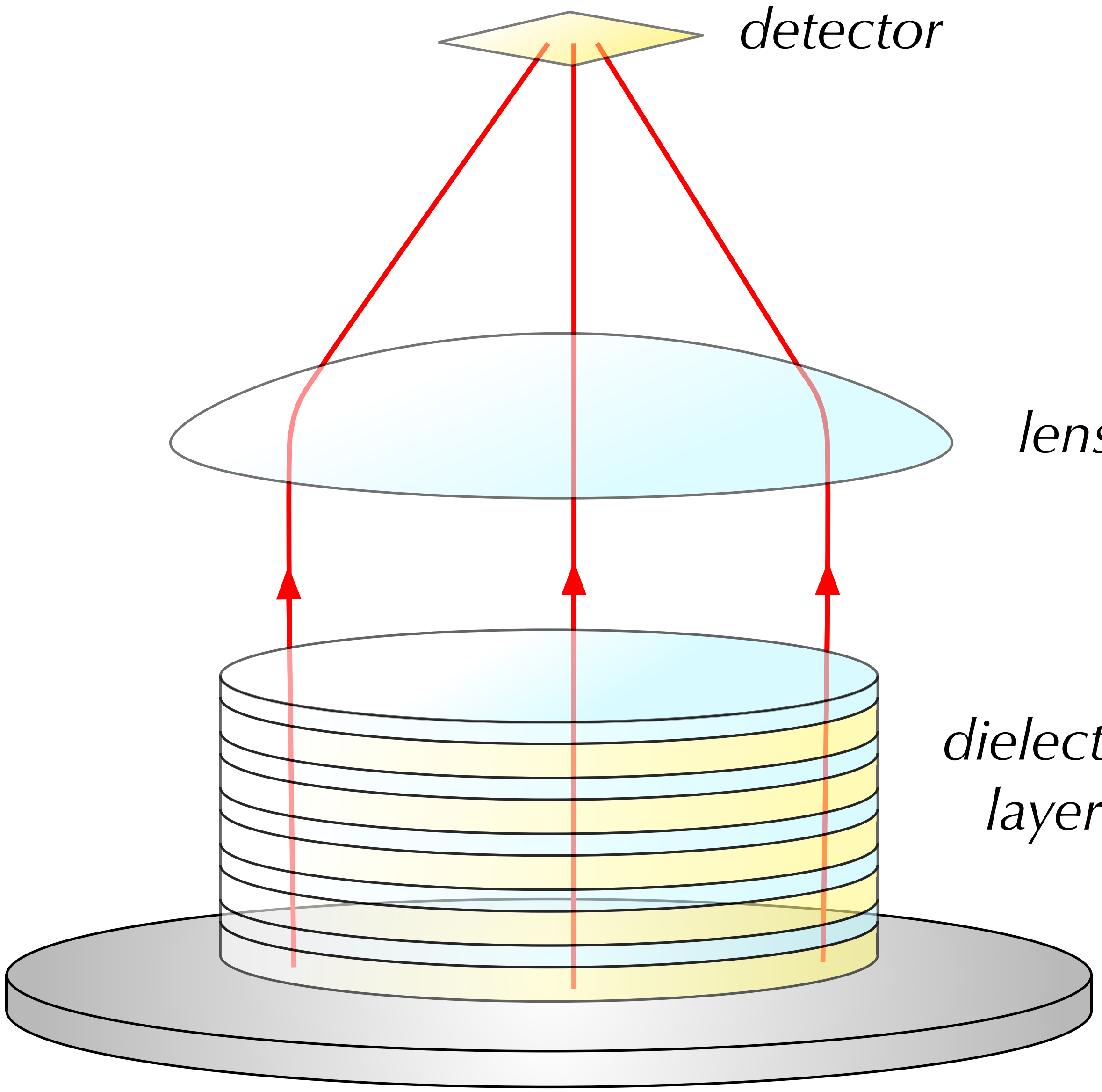
Sub-component of DM

Conclusions

- Photonic crystals can be used to convert non-relativistic axion and dark photon dark matter to photon
- The converted photon can be focused onto very small photon counters
- ***Optimal*** axion and dark photon dark matter reach in the optical/IR range
- Experimental design & set up underway

Thank you!

Light
Axion
Multilayer
Periodic
Optical
Scanning
Targets



Experimental parameters

	Pathfinder	Phase I	Phase II
Signal	Dark Photon	Dark Photon & Axion	Dark Photon & Axion
Range (m_{DM} & $\lambda_{\mathrm{Compton}}$)	$(1\,\mathrm{eV}, 10\,\mathrm{eV})$ $(0.1\,\mu\mathrm{m}, 1\,\mu\mathrm{m})$	$(50\,\mathrm{meV}, 10\,\mathrm{eV})$ $(0.1\,\mu\mathrm{m}, 20\,\mu\mathrm{m})$	$(50\,\mathrm{meV}, 10\,\mathrm{eV})$ $(0.1\,\mu\mathrm{m}, 20\,\mu\mathrm{m})$
Area (A)	$(10\,\mathrm{cm})^2$	$(10\,\mathrm{cm})^2$	$(30\,\mathrm{cm})^2$
Number of periods (N)	30	100	1000
Temperature (T_{layer})	200 K (300 K)	4 K	4 K
Thickness ($d \sim N\lambda$)	$(\sim 3\,\mu\mathrm{m}, \sim 30\,\mu\mathrm{m})$	$(\sim 10\,\mu\mathrm{m}, \sim 2\,\mathrm{mm})$	$(\sim 100\,\mu\mathrm{m}, \sim 20\,\mathrm{mm})$
Stacks per e-fold	150	400	4000
Detector Dark Count (Γ_{DCR})	mHz (e.g. CCD)	10^{-5} Hz (e.g. TES)	10^{-5} Hz (e.g. TES)
Detector Efficiency (η)	0.1	0.9	0.9
Temperature (T_{detector})	200 K	100 mK	100 mK
Magnetic Field (Axion)	N/A	10 T	10 T

mg mass target

g mass target