Physics at the LHC and Beyond

Axion and Dark Photon Direct Detection

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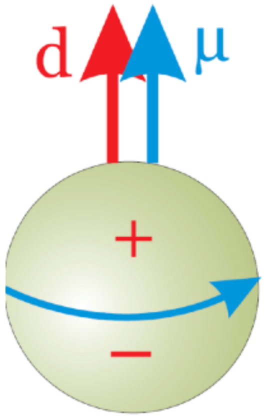
arxiv:1803.11455 MB, Junwu Huang, Robert Lasenby

Outline

- Light bosonic dark matter
- Axion and dark photon detection
- Seeing dark matter

The Strong-CP problem

- Neutron has electric dipole moment, proportional to CP violation in QCD potential



$$V \supset \frac{\alpha_s}{8\pi}\,\theta\, G\tilde{G}$$

- Expect dipole moment to be somewhat smaller than charge separated by neutron size

$$d_n \sim \theta\, 10^{-3} e \cdot R_{neutron} \sim \theta\, 10^{-16} e \cdot cm$$

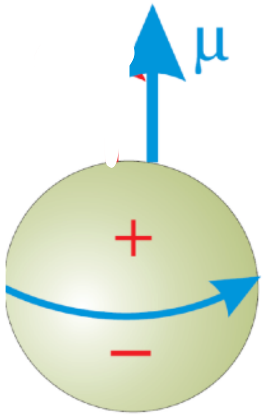
- Experimentally only an upper bound:

$$d_n < 3 \times\ 10^{-26}\ \mathrm{e} \cdot \mathrm{cm}$$

- $\theta < 10^{-10}$ despite CP violation in quark sector

The Strong-CP problem

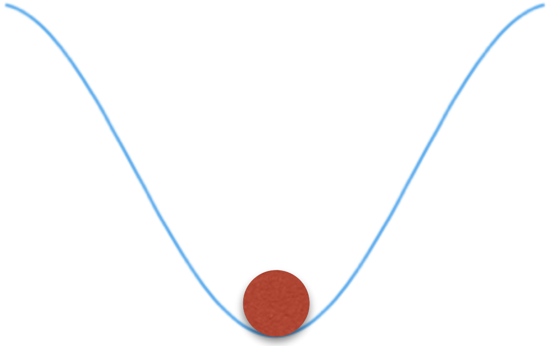
- Solve the problem by promoting $\boldsymbol{\theta}$ to a dynamical field, the axion:



$$V \supset \tfrac{\alpha_s}{8\pi}\,\theta\, G\tilde{G}$$

$$\downarrow$$

$$V \supset \frac{\alpha_s}{8\pi}\left(\frac{\phi}{f}-\theta\right) G\tilde{G}$$



- Goldstone of U(1) symmetry broken at a high scale ***f***
- Periodic potential from nonperturbative QCD effects for the axion, solving the strong-CP problem

$$\Lambda^4\left(1-\cos\left(\frac{\phi-\bar{\theta}}{f}\right)\right)$$

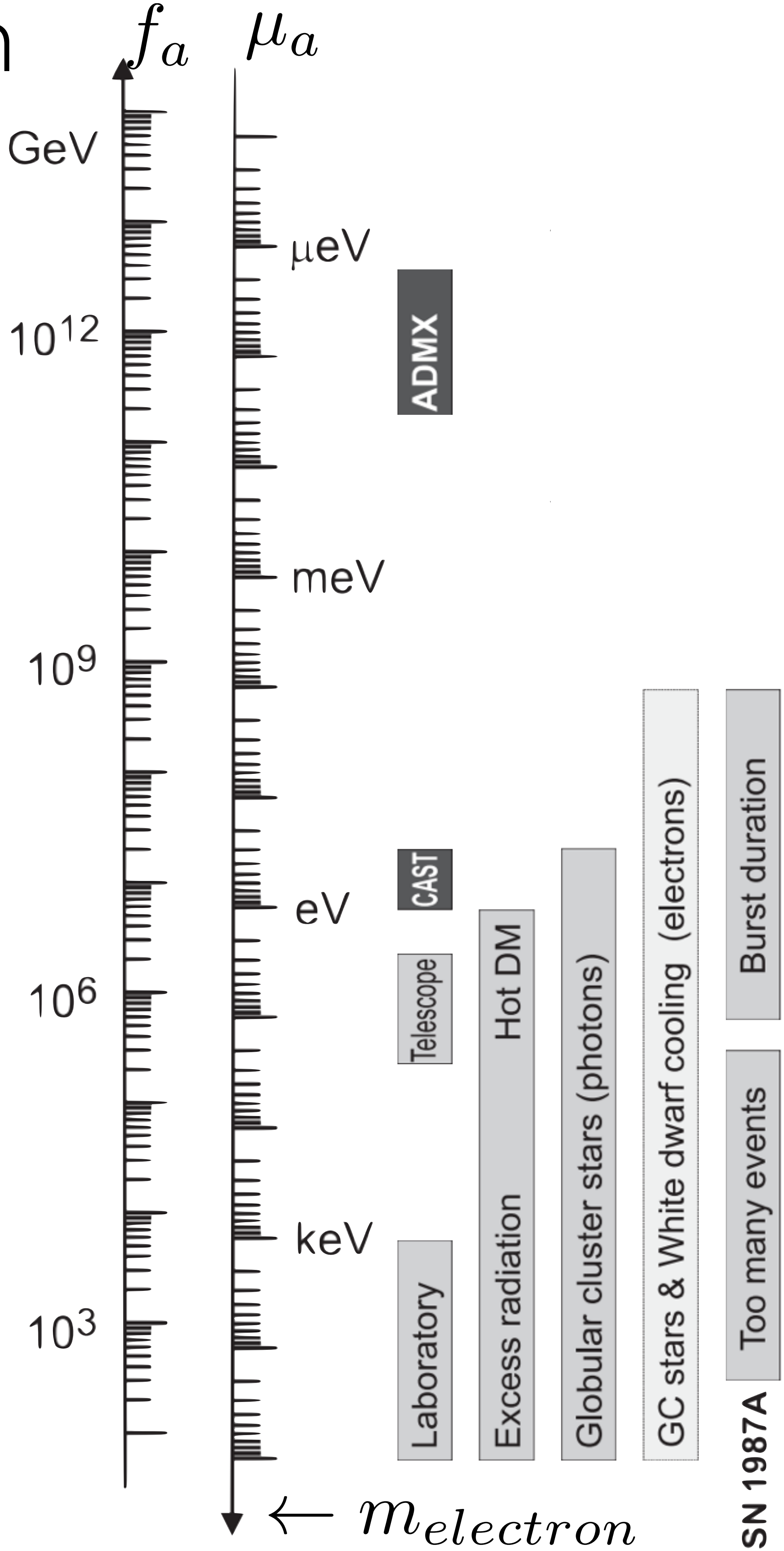
R. Peccei and H. R. Quinn, Phys.Rev.Lett., **38**, 1440 (1977); S. Weinberg, *ibid.*, **40**, 223 (1978); F. Wilczek, *ibid.*, **40**, 279 (1978).

The QCD axion

- Pseudo-goldstone boson with mass and coupling to standard model fields determined by `decay constant' ***f***

$$m_a = 5.70(6)(4)\,\mu\mathrm{eV}\,\left(\frac{10^{12}\mathrm{GeV}}{f_a}\right)$$

- Over a dozen orders of magnitude of coupling strengths and mass scales
- Experiment points to high mass scale of symmetry breaking



The QCD axion

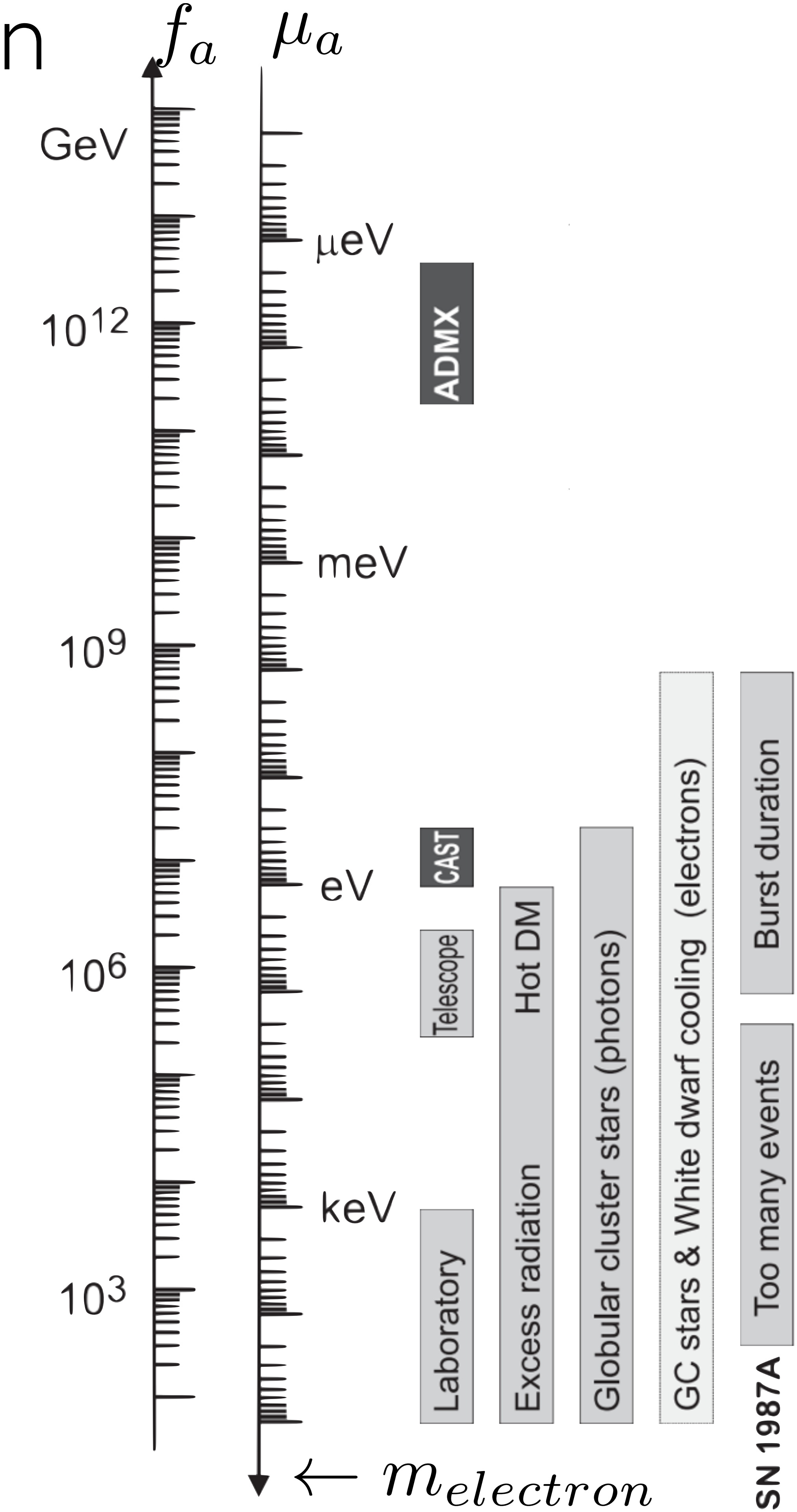
- Should we worry about our understanding of such high scales?
- Global U(1) symmetry can be broken by gravitational effects
- Solution spoiled by planck suppressed operators?

$$V_g(\phi) = \frac{g}{M_{\rm Pl}^{2m+n-4}} |\phi|^{2m} \phi^n + h.c. + c\,,$$

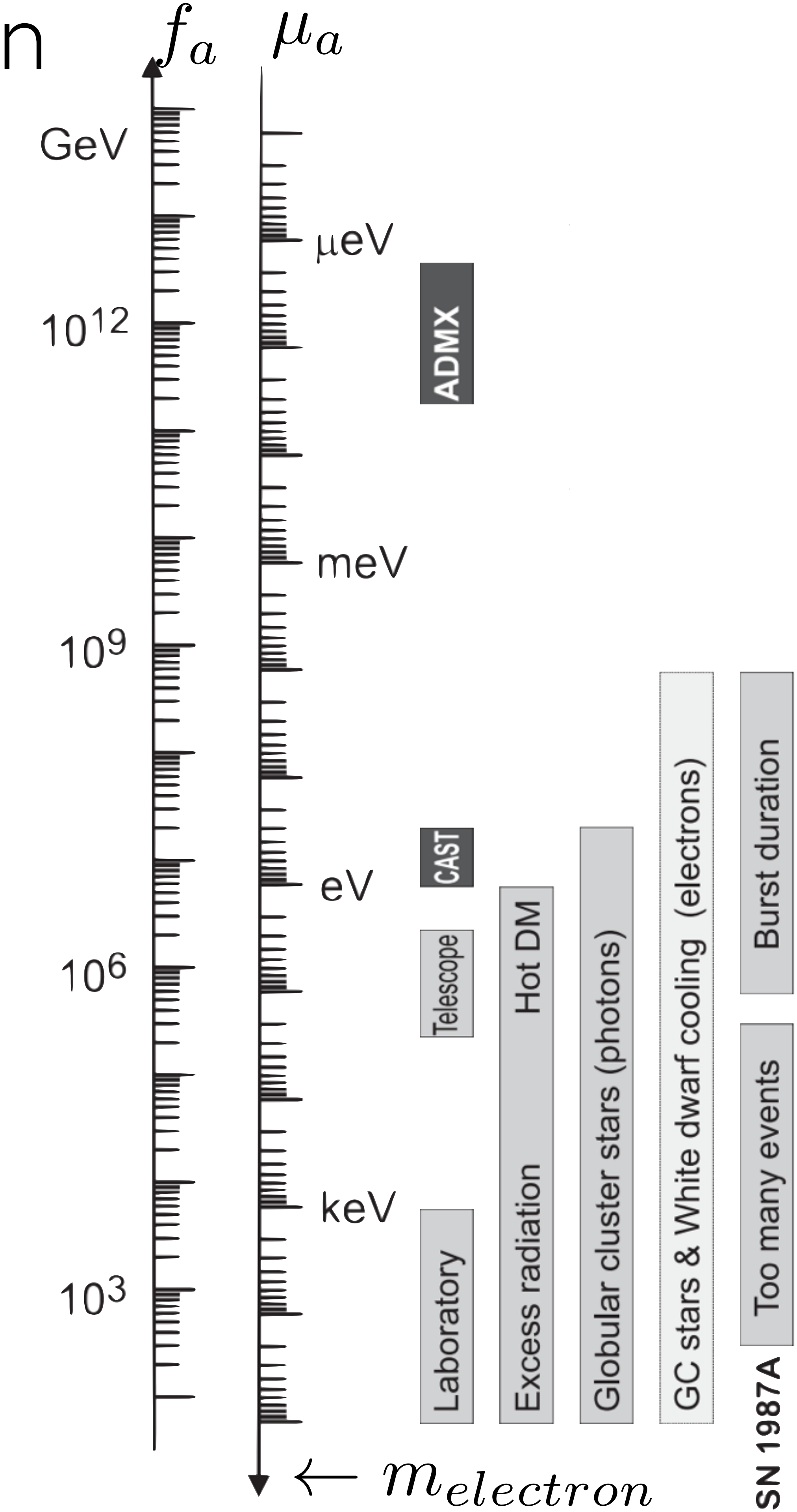
$$(m_a^g)^2 = |g| M_{\rm Pl}^2 \left(\frac{f_{PQ}}{\sqrt{2} M_{\rm Pl}} \right)^{2m+n-2}$$

Kamionkowski, March-Russell [9202003]

Holman, Hsu, Kephart , Kolb, Watkins, Widrow [9203206]



The QCD axion



- Axions in string theory
    - Global symmetry -> gauge symmetry
    - 4D axions appear as zero modes of gauge fields compactified in extra dimensions

Kallosh, Linde, Linde, Susskind [9502069]

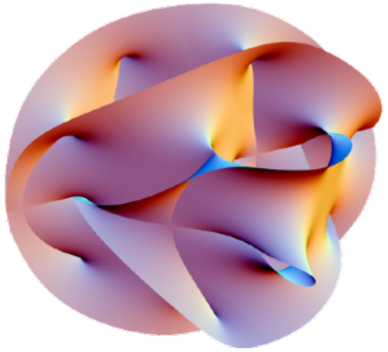
The QCD axion

- In string theory, nonperturbative gravity effects generate a mass, exponentially suppressed:

$$\mu^4 e^{-M_{pl}/f}\left(1-\cos\left(\frac{\phi}{f}\right)\right)$$

- Requiring string theory to produce the QCD axion puts an upper bound on the size of these corrections

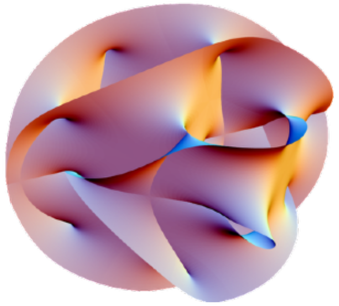
$$\mu^4 e^{-M_{pl}/f} \ll \Lambda^4$$



Svrcek , Witten [0605206]
Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell [0905.4720]

Cousins of the QCD Axion:
String Axions and Dark Photons

- Realistic compactifications in string theory typically have complex manifolds with 100 to 10^5 `holes'
- Number of `holes' ~ number of light axions
- Requirement on QCD axion in string compactifications gives rise to multiplicity of light string axions
- Gauge fields with an additional index gives rise to light dark photons in 4D



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

Cicoli, Goodsell, Jaeckel, Ringwald [1103.3705]

Cousins of the QCD Axion:
String Axions and Dark Photons

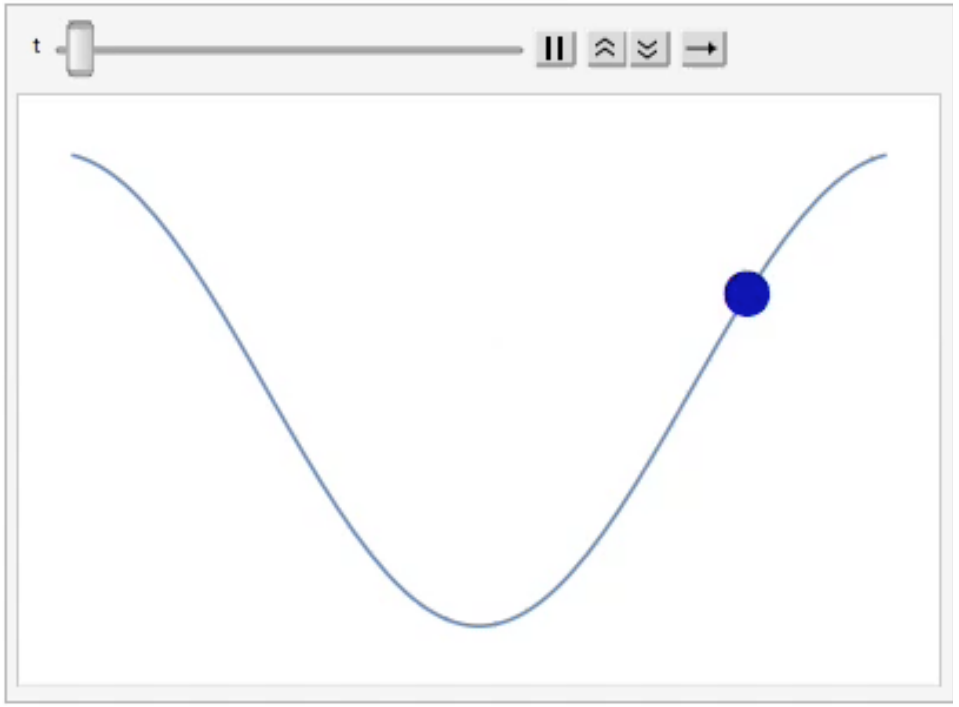
- Axions and dark photons:
    - weakly-interacting
    - stable on cosmological timescales
    - production mechanism for dark matter?

Axion dark matter

- String axion:
  - Cosmological evolution of amplitude given by damped harmonic oscillator:

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

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



Axion dark matter

- String axion:
  - Cosmological evolution of amplitude given by damped harmonic oscillator:

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

  - Early on, H >> m: frozen by Hubble friction
  - When H < m: begins to oscillate and redshift as matter
  - Density today is initial value, redshifted from start of oscillation,

$$\rho_{\rm a} = \boxed{\frac{1}{2}m^2\phi_i^2}\boxed{\left(\frac{a_{\rm osc}}{a_0}\right)^3}$$

This gives the DM density as a function of *m*, *f*:

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

Axion dark matter

- QCD axion:
  - One-to-one relation between ***m*** and ***f***
  - Mass arises from nonperturbative QCD, increases to current value as temperature of the universe drops
  - Contributions to energy density from decays of strings and domain walls if U(1) broken after inflation — potentially dominant?

$$\frac{\rho_{\mathrm{a,QCD}}}{\rho_{\mathrm{cdm}}} \sim \left(\frac{f}{\mathrm{few} \times 10^{11}\mathrm{GeV}}\right)^{7/6} \left(\frac{\phi_i}{f}\right)^2 + (\mathrm{decays})\ ??$$

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

Gorghetto, Hardy, Villadoro [1806.04677]

Dark photon dark matter

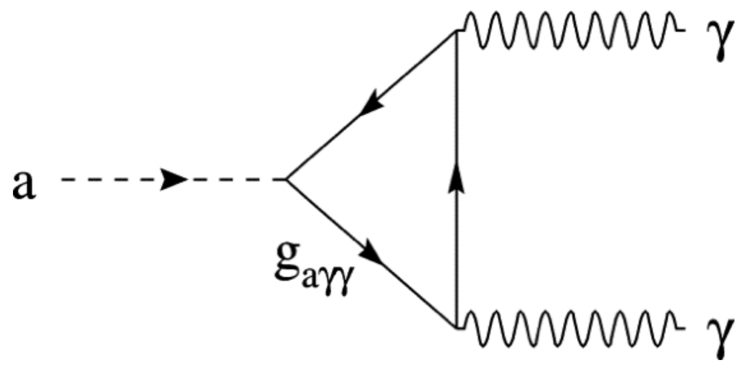
- Vector energy density in zero-momentum mode redshifts faster;
- Sufficient dark photon dark matter can still be produced through inflationary fluctuations if scale of inflation is high,

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

Graham, Mardon, Rajendran [1504.02102]

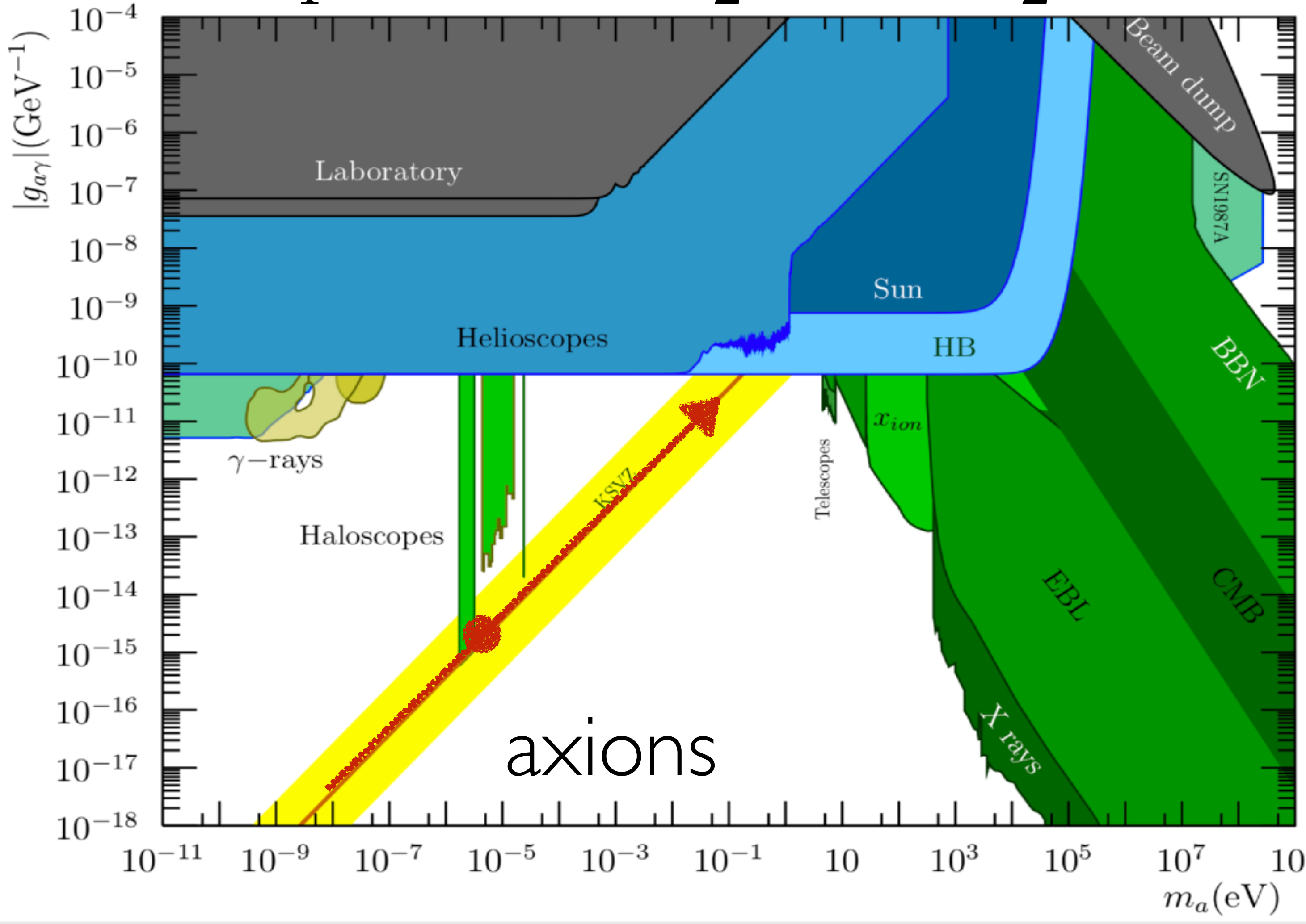
Searching for light bosonic dark matter

- Axions generically couple to photons
- Use this interaction to search for axion dark matter



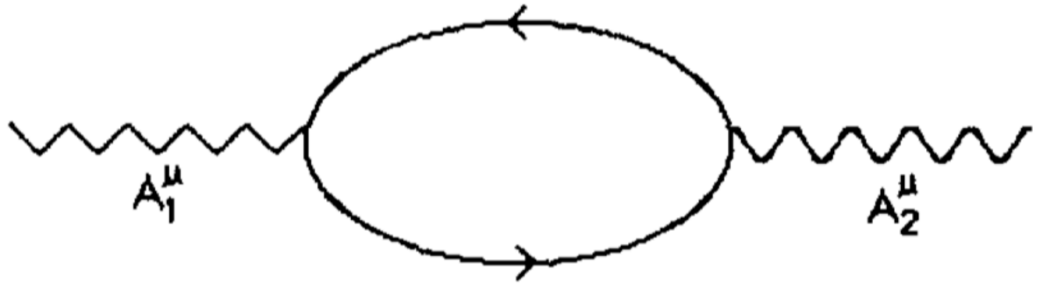
$$g_{a\gamma\gamma} \sim \frac{\alpha}{2\pi}\frac{1}{f_a}$$

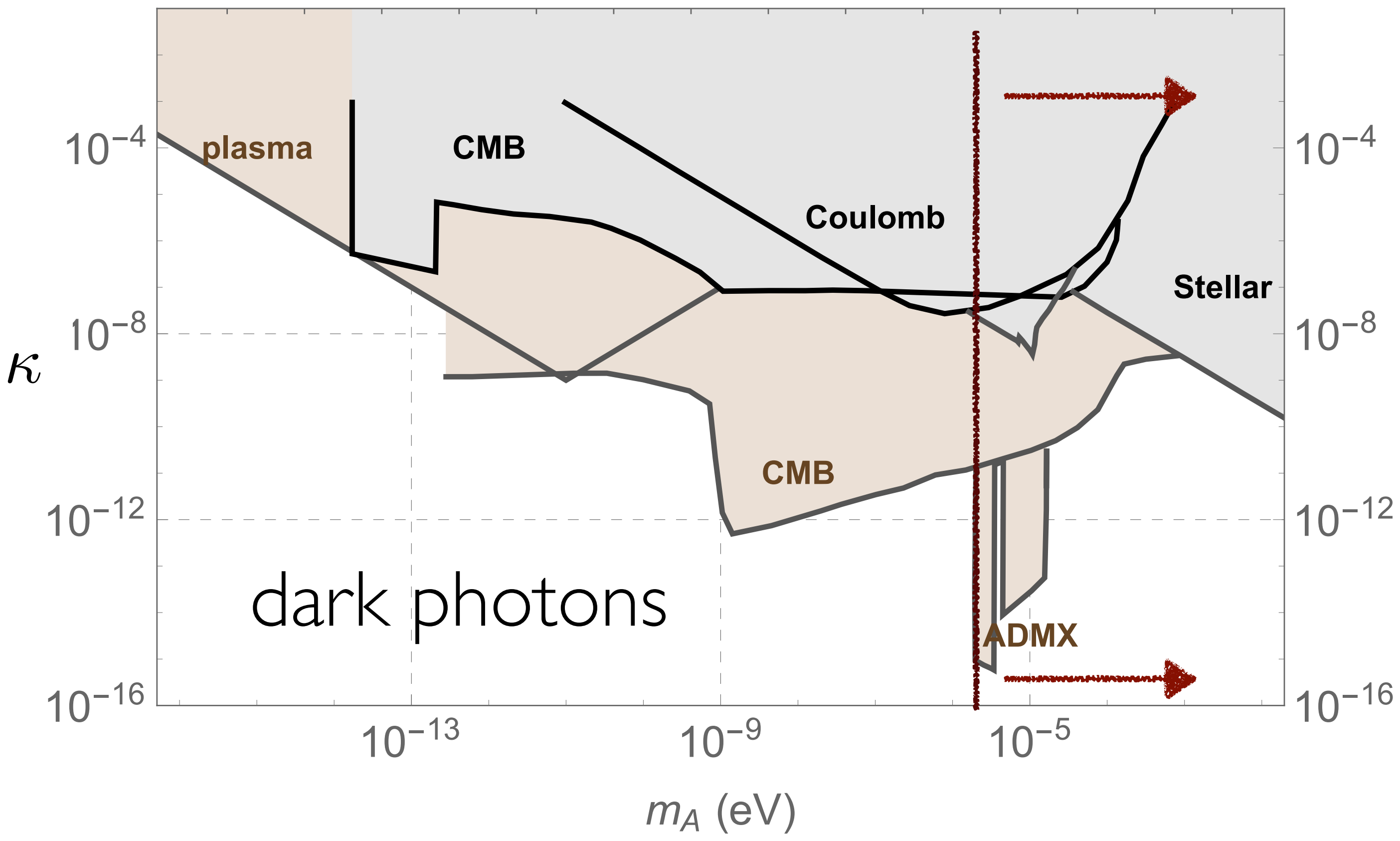
$$\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2$$



Searching for light bosonic dark matter

- Dark photons mix with SM photon via kinetic term
- Can we see dark photon dark matter, perhaps in visible light?





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

Light bosonic dark matter

- Bosonic DM acts as coherent, classical field

$$\phi \sim \phi_0 \cos(\omega t - \vec{k} \cdot \vec{x})$$

- Velocity distribution in our galaxy is virialized, with typical value $v \sim 10^{-3}$
- Approximately monochromatic
  - Coherence length $\ell_{coh} \sim \frac{1}{mv}$
  - Coherence time $t_{coh} \sim \frac{1}{mv^2}$

- Dark matter field amplitude fixed by local DM density $\rho \sim \frac{1}{2} m^2 \phi_0^2$

Outline

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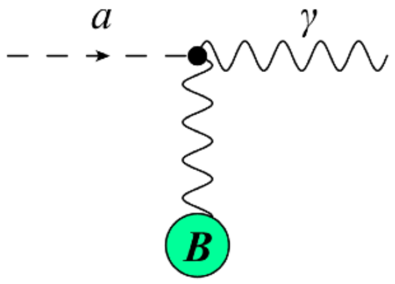
- Axion and dark photon detection
- Seeing dark matter

Searching for light bosonic dark matter

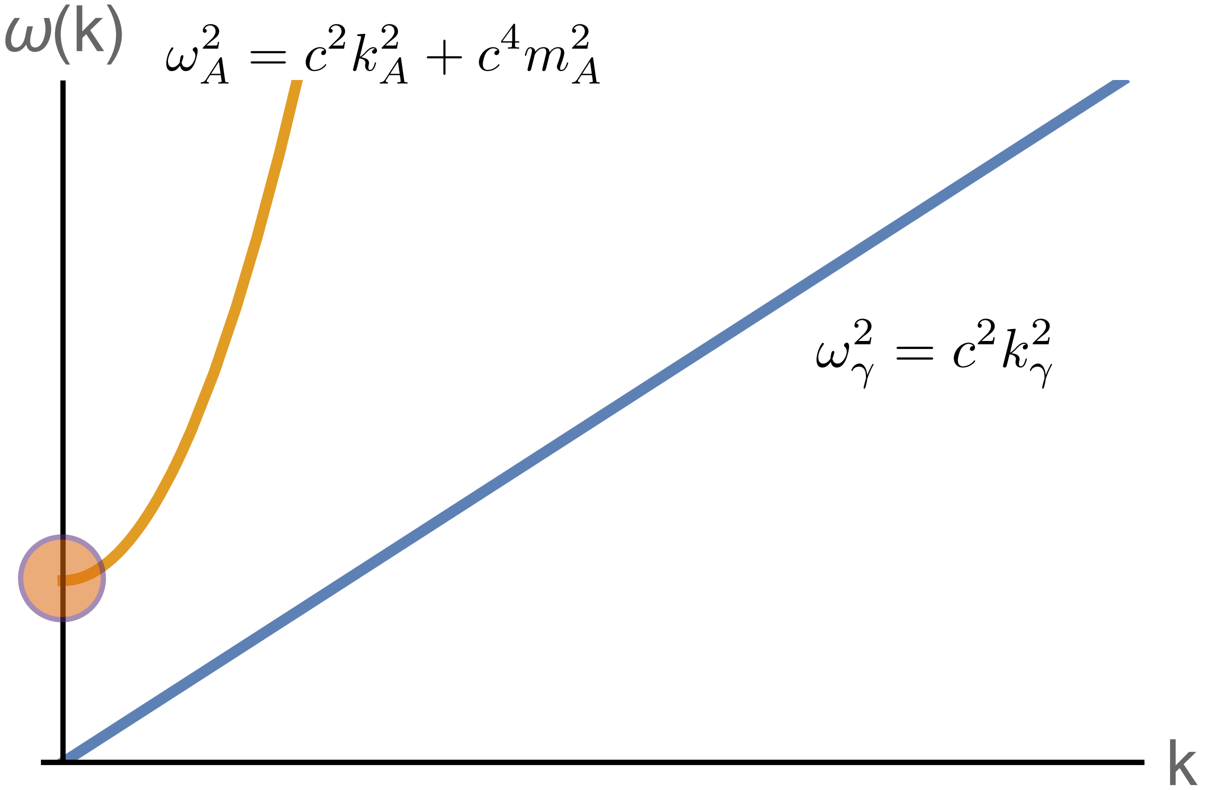
- Photon can convert into axion (dark photon) and back through E . B (kinetic mixing) term



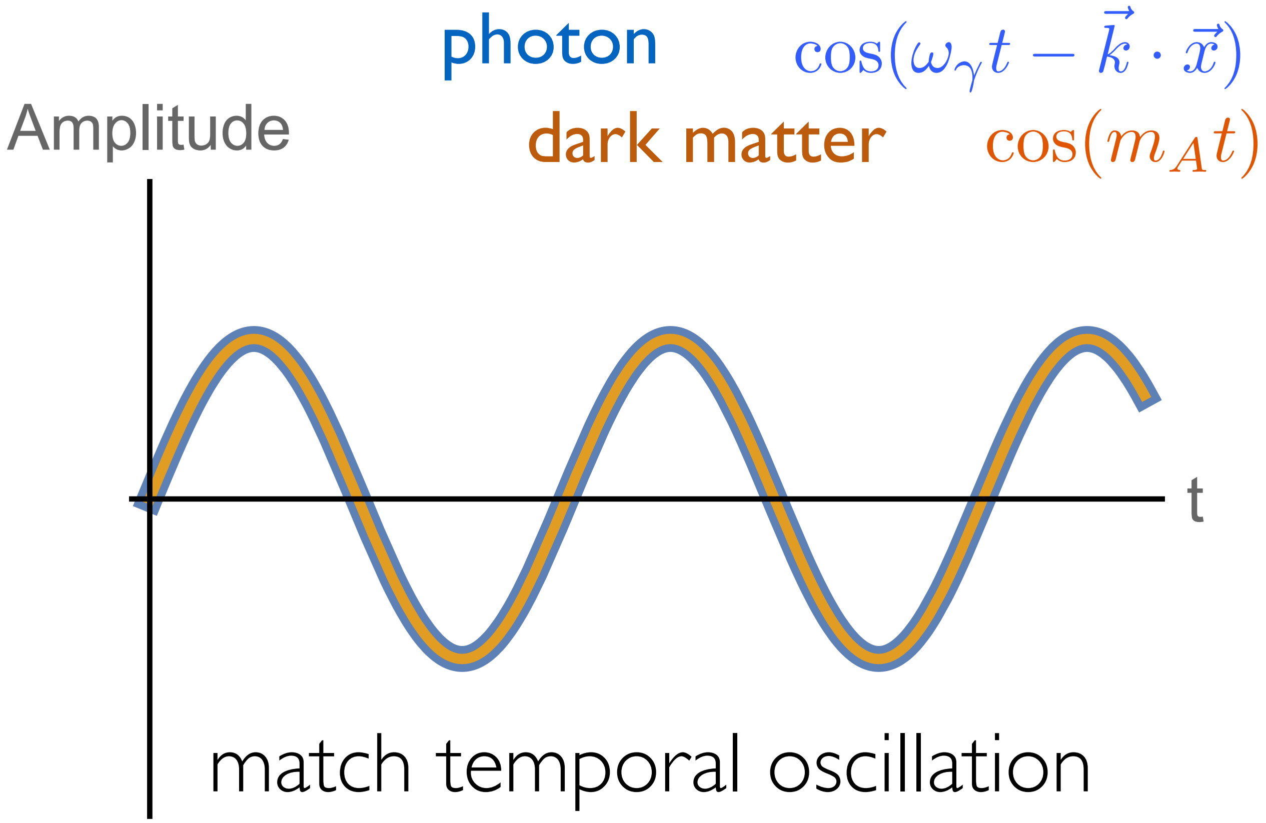
- Why haven't we seen photons from DM conversion?
  - Mismatch in dispersion relation: photons relativistic while dark matter is massive with a small velocity in our galaxy
  - Impossible to conserve both energy and momentum

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

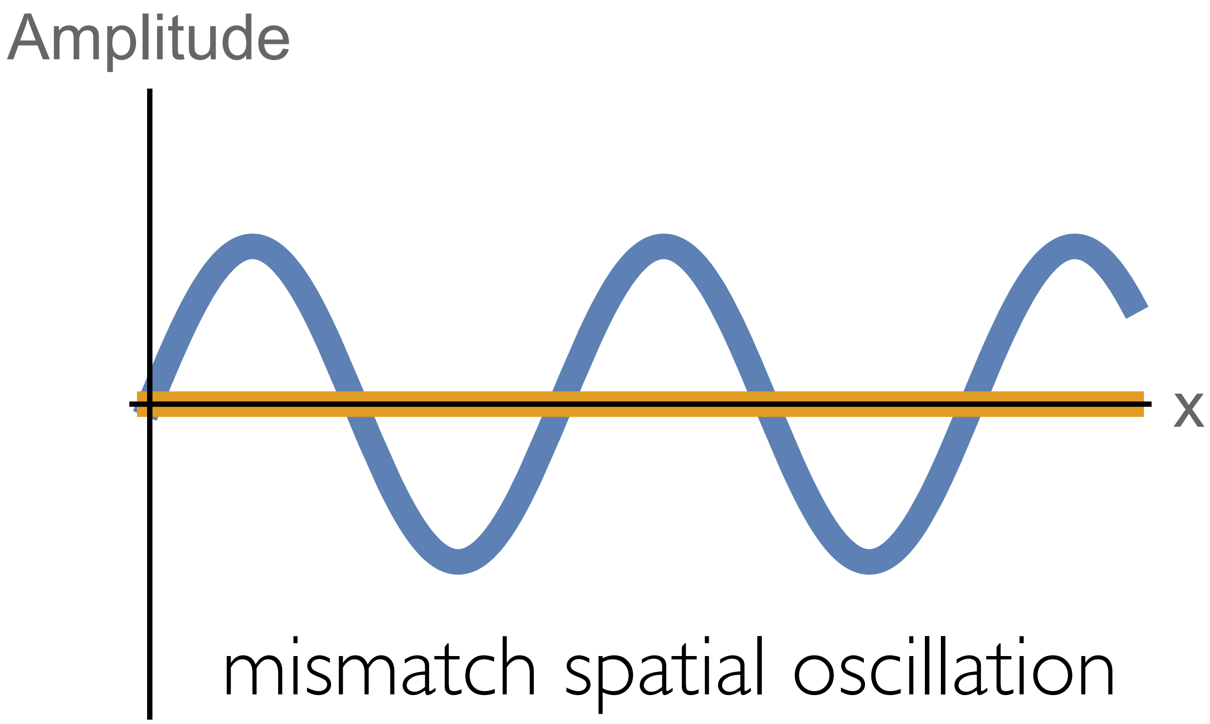
Light bosonic dark matter



Mismatch in dispersion relation: photons relativistic while dark matter nonrelativistic with a small velocity in our galaxy

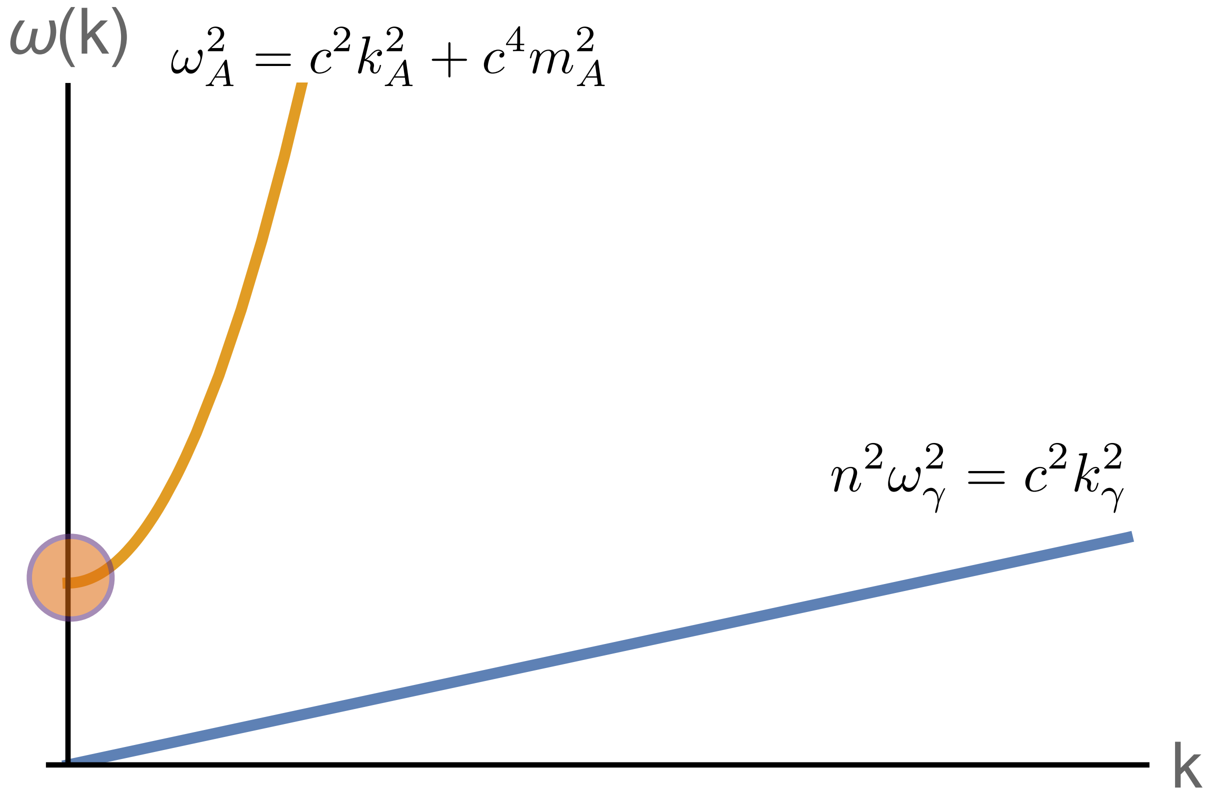


match temporal oscillation



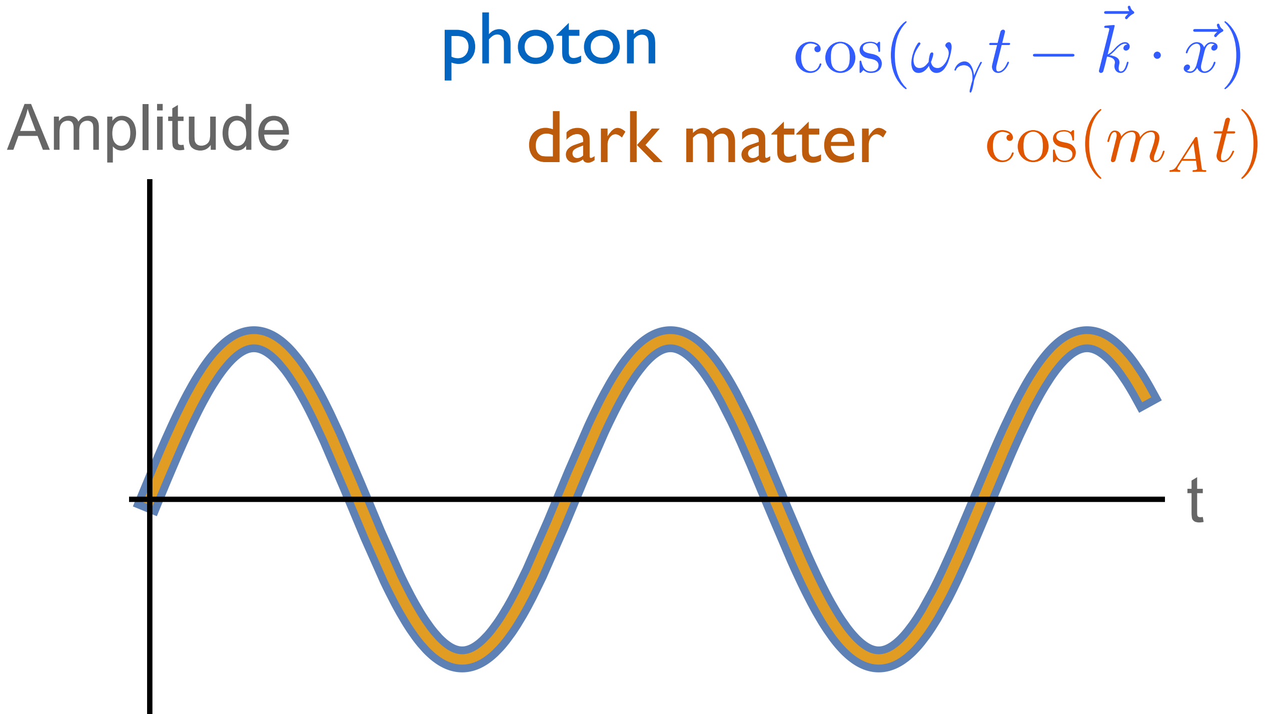
mismatch spatial oscillation

Light bosonic dark matter

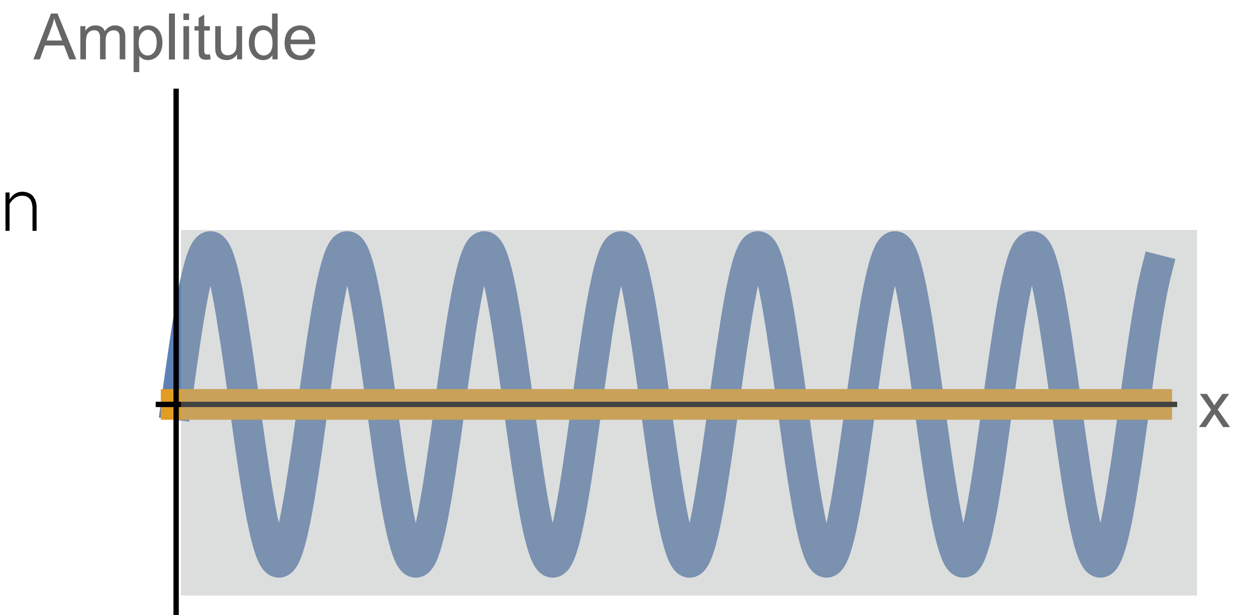


- index of refraction *n* > 1

- possible to change light propagation speed in dielectric materials, but modes still average to zero over dark matter source



match temporal oscillation

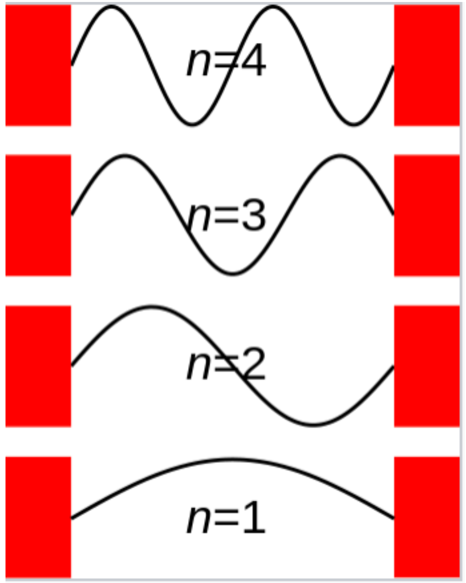


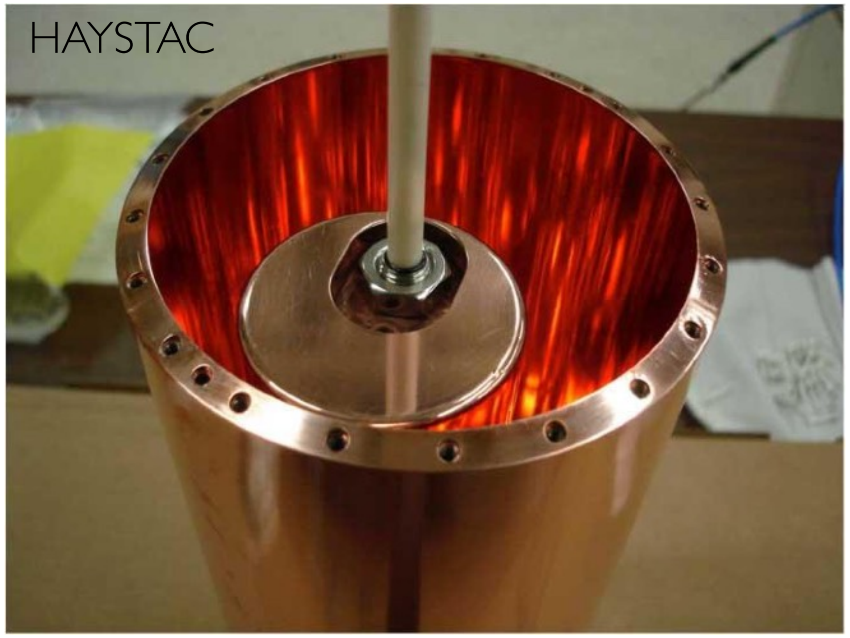
mismatch spatial oscillation

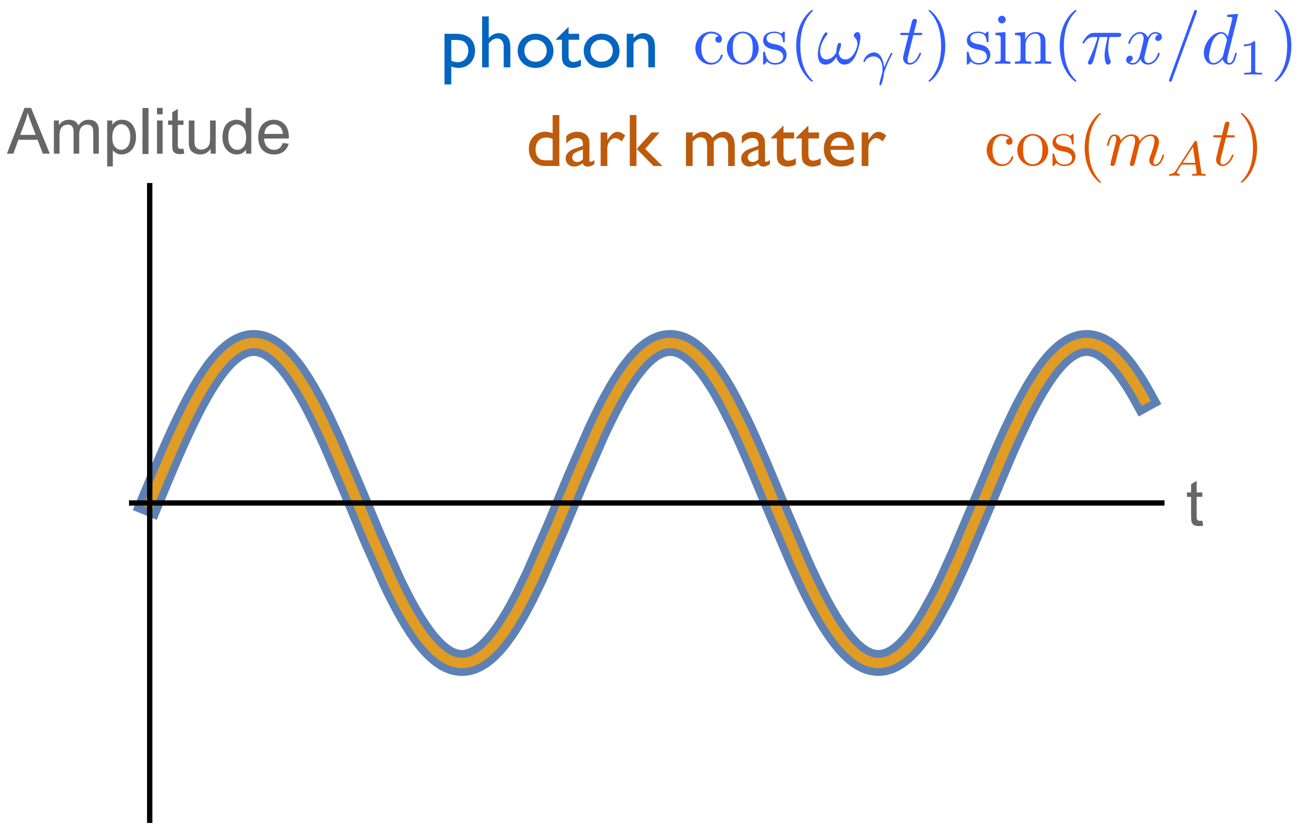
Light bosonic dark matter

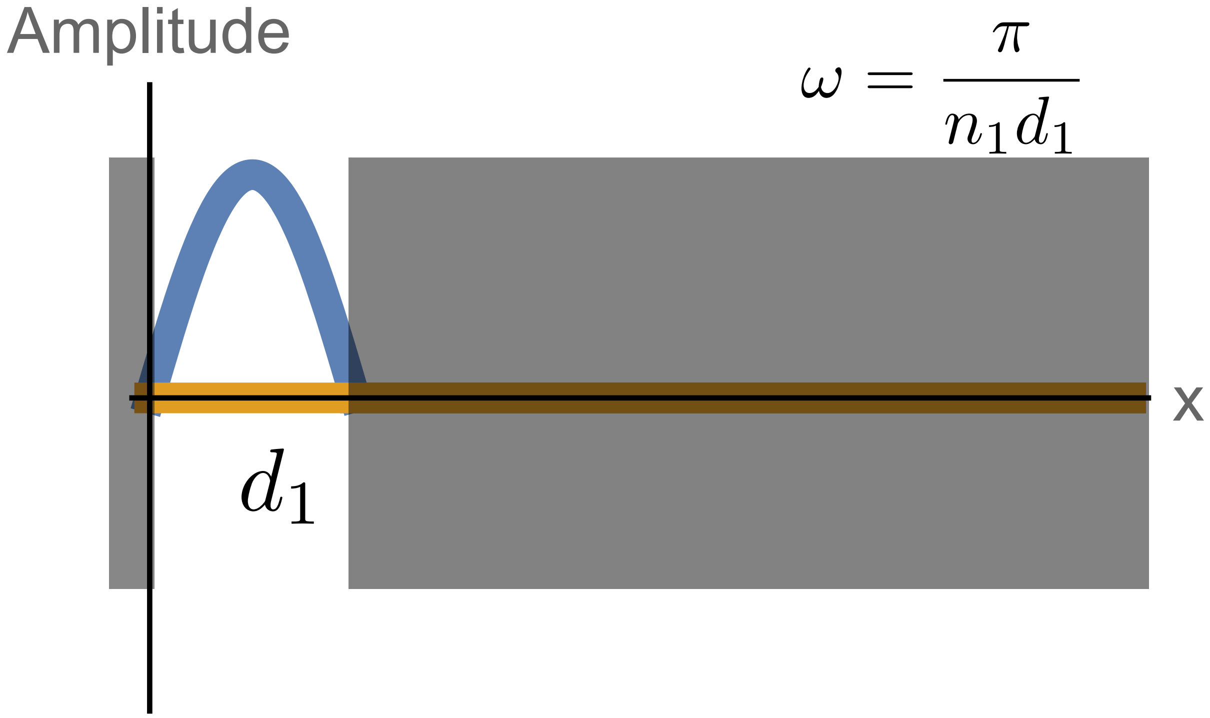
- Boundary conditions: discrete set of allowed frequencies

- Create `gapped modes' for photons

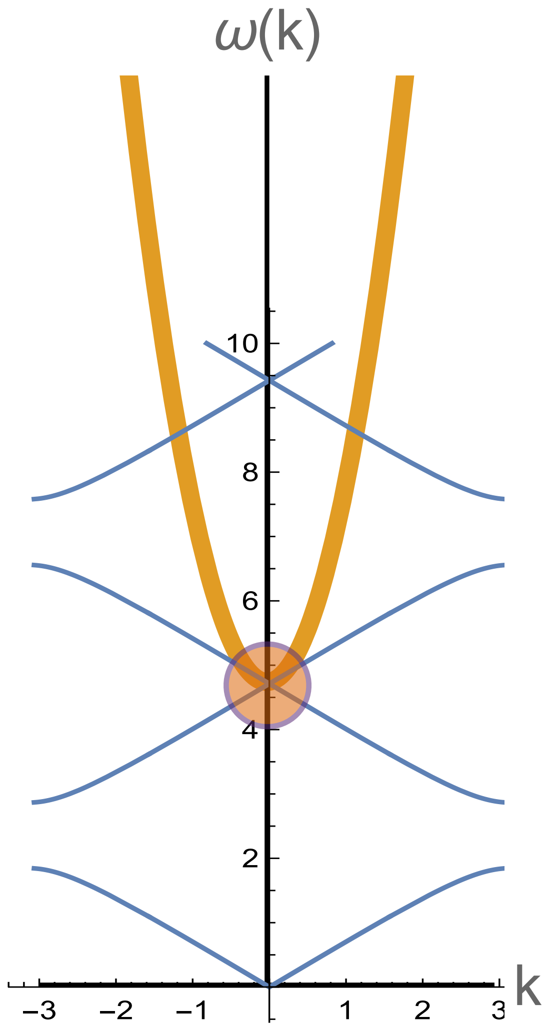


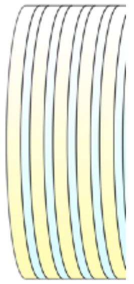






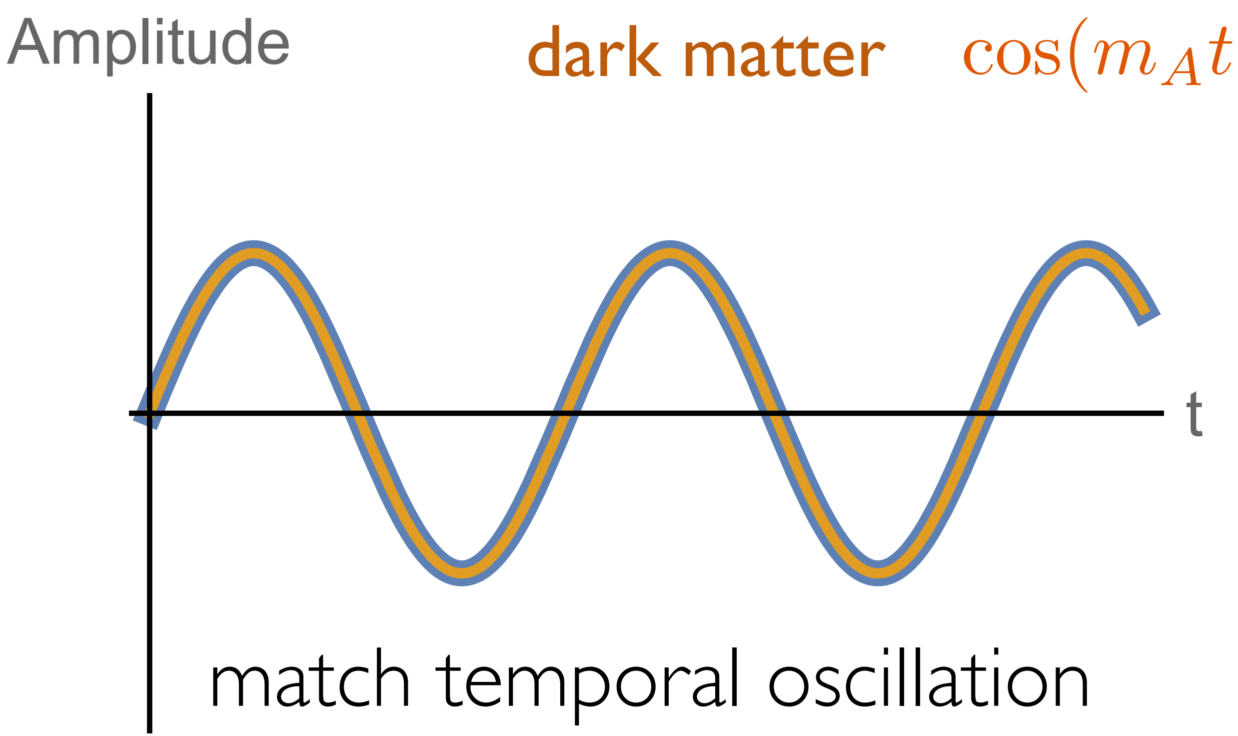
Light bosonic dark matter





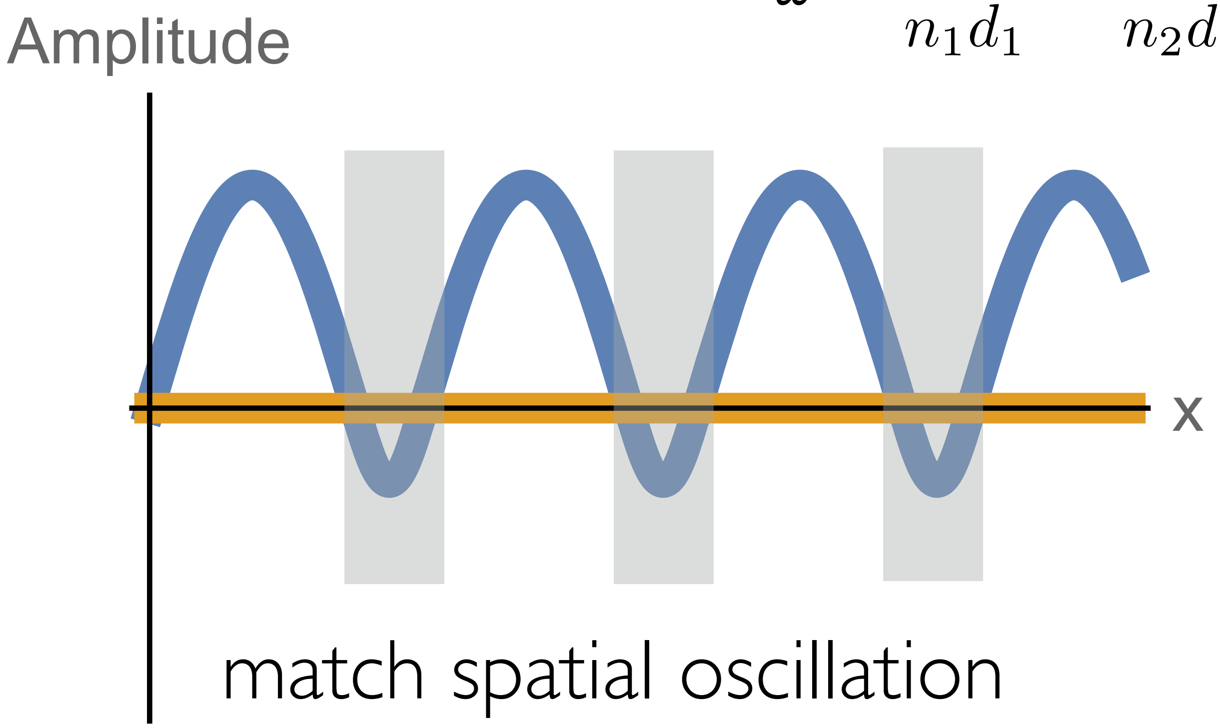
photon $\cos(\omega_\gamma t - k_n x)\eta_n(x)$

dark matter $\cos(m_A t)$



match temporal oscillation

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

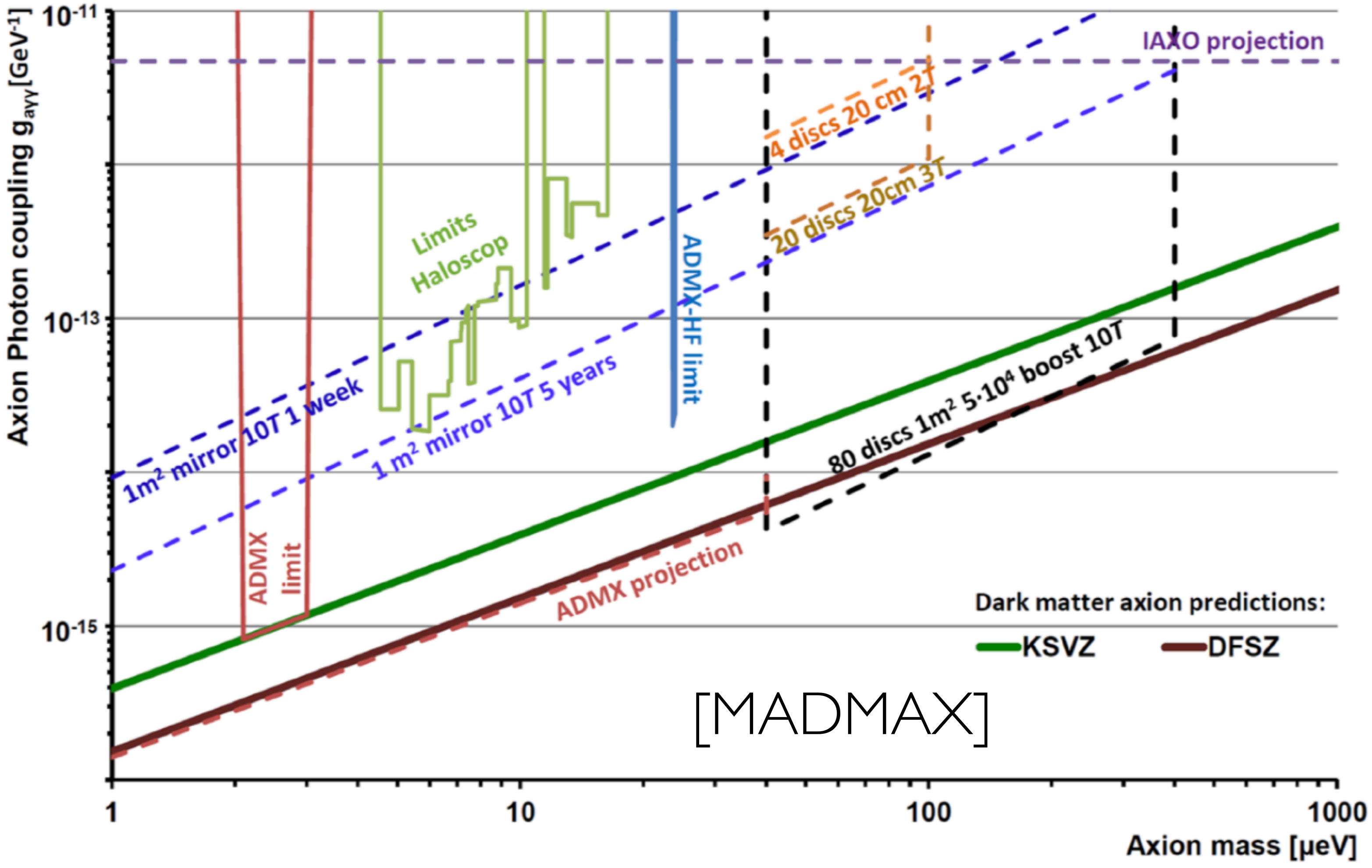


match spatial oscillation

- Add periodicity in one dimension to correct momentum mismatch
- Periodic index of refraction changes free solutions of photon modes
- Nonzero spatial overlap with zero-momentum waves

Light bosonic dark matter

- Similar strategies used in a range of current and proposed experiments:
  - ADMX: cavity with boundary conditions and tunable rod
    - Exploring using dielectrics at higher frequencies
  - Dish antenna: boundary conditions
  - MADMAX: movable dielectric layers

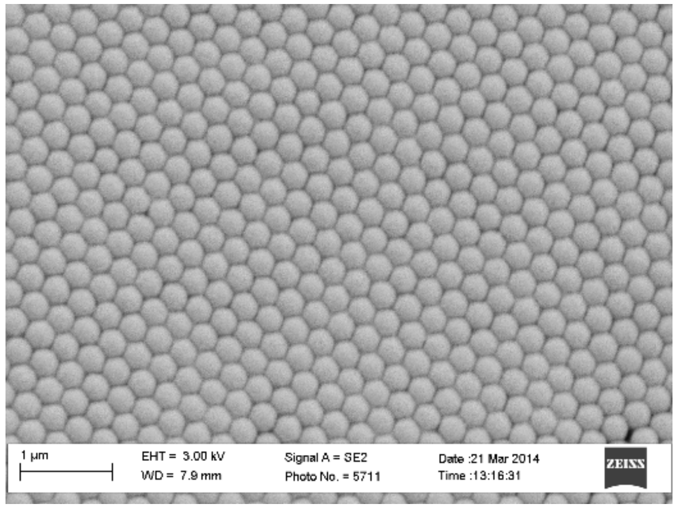


[MADMAX]

Photonic crystals

- Photonic metamaterials — manipulating light

Periodic structures on scales of photon’s wavelength are used to manipulate light (and even occur naturally)




antireflective coatings

- IR to UV frequencies benefit from well-established fields of photonics and single photon detectors

Outline

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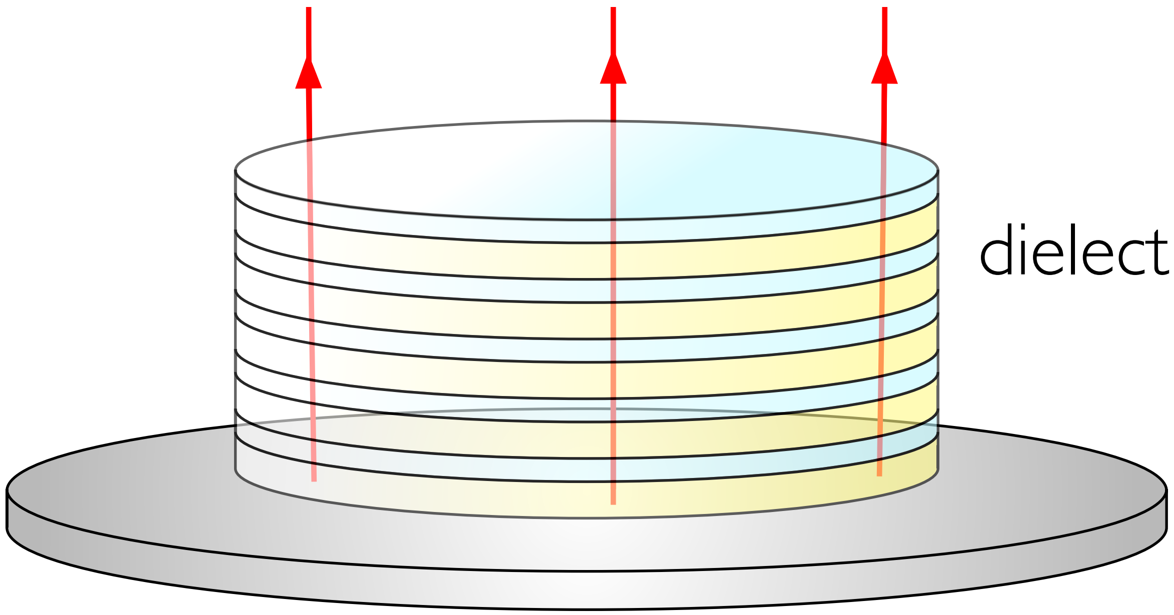
- Seeing dark matter

Seeing dark matter

Experimental Setup

Spatially homogeneous dark matter sources E & B fields in periodic structure

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

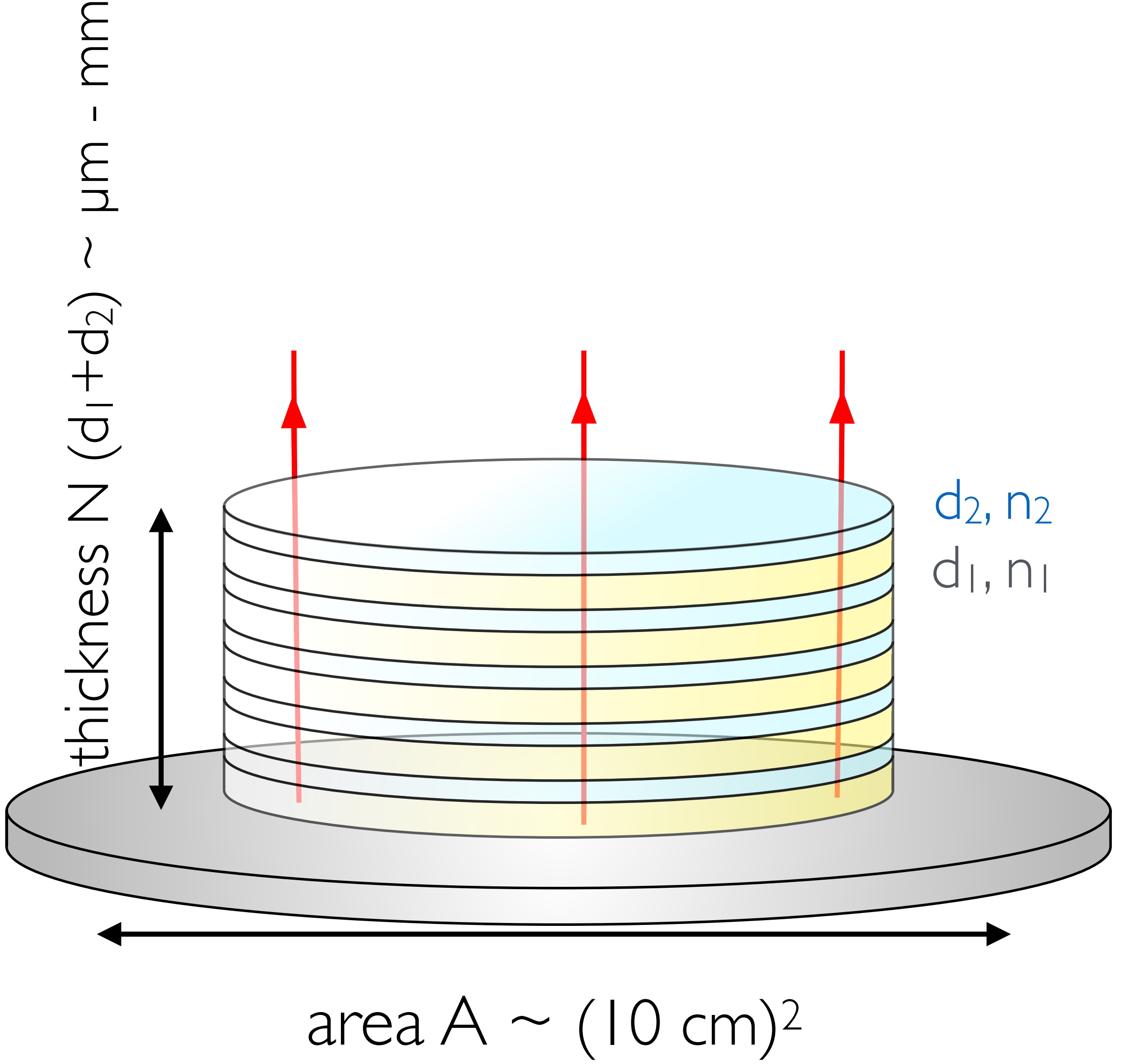


Seeing dark matter

Dark photon dark matter

Power emitted:

$$P \sim \frac{4}{3}\kappa^2 \rho_{dm} \boxed{A}\,\boxed{N^2} \boxed{\left(\frac{n_1^2 - n_2^2}{n_1^2 n_2^2}\right)^2}$$

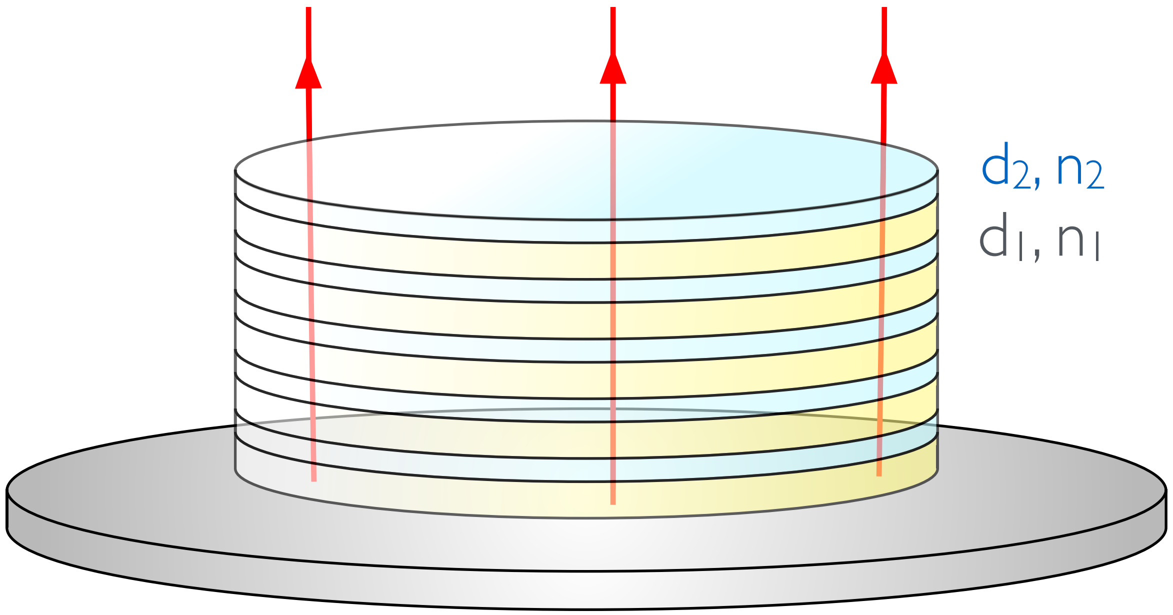


- Power proportional to layer volume, $\boxed{P \sim A/m}$
- E & M fields from each layer add coherently, $\boxed{P \sim N\text{^}2}$
  - N~10-1000 layers
- Maximum power out for maximum contrast: $\boxed{n_1 \sim 1 \text{ , } n_2 >> 1}$
  - e.g. silicon (n=3.4), and silica (n=1.46)

Seeing dark matter

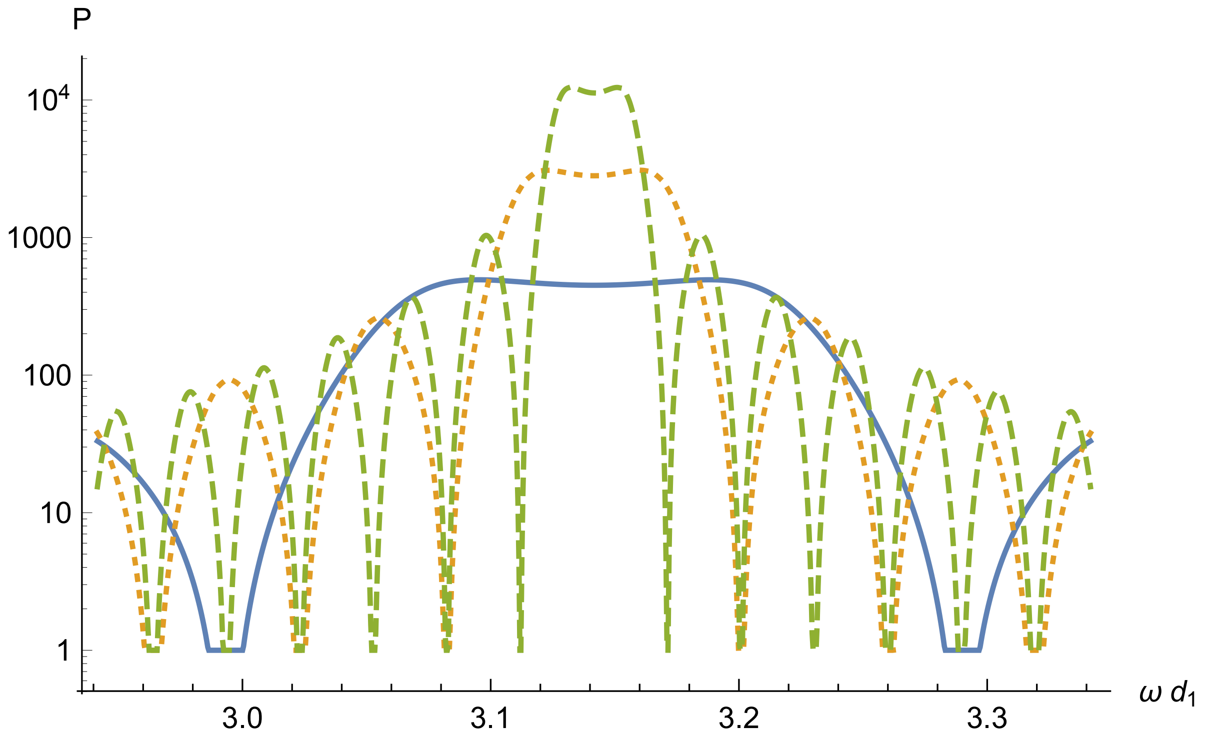
DM mass matched to layer thickness and index of refraction

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



10% - 0.1% coverage per stack

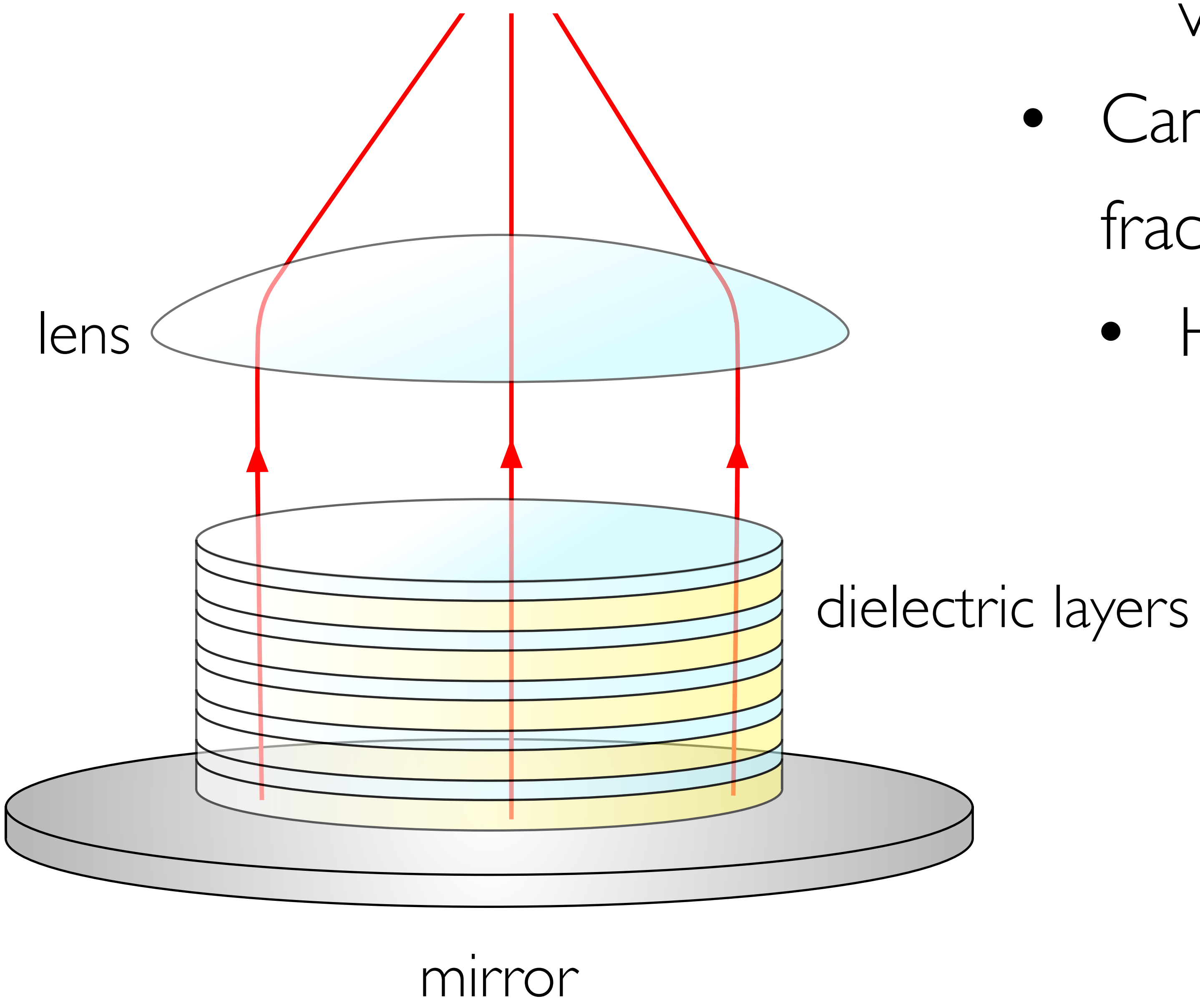
$$\frac{\Delta\omega}{\omega} \sim \frac{1}{N}$$

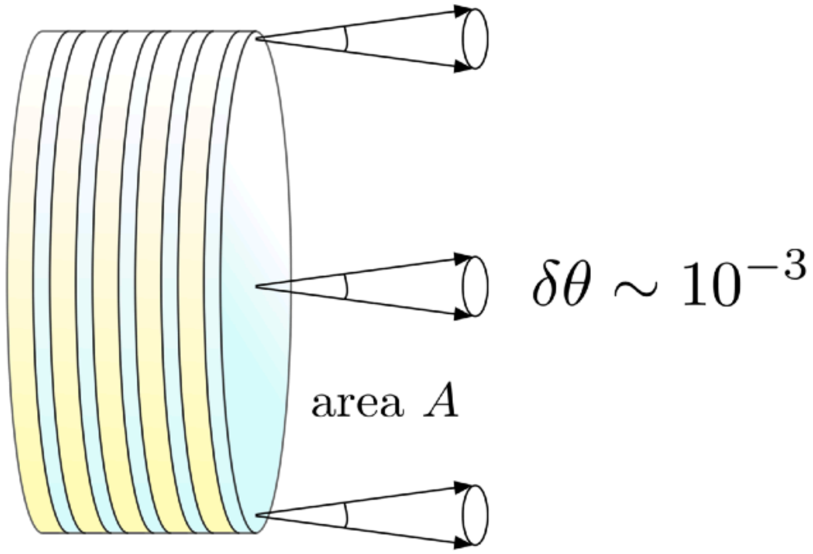


Power emitted as a function of frequency (20, 50, 100 layers)

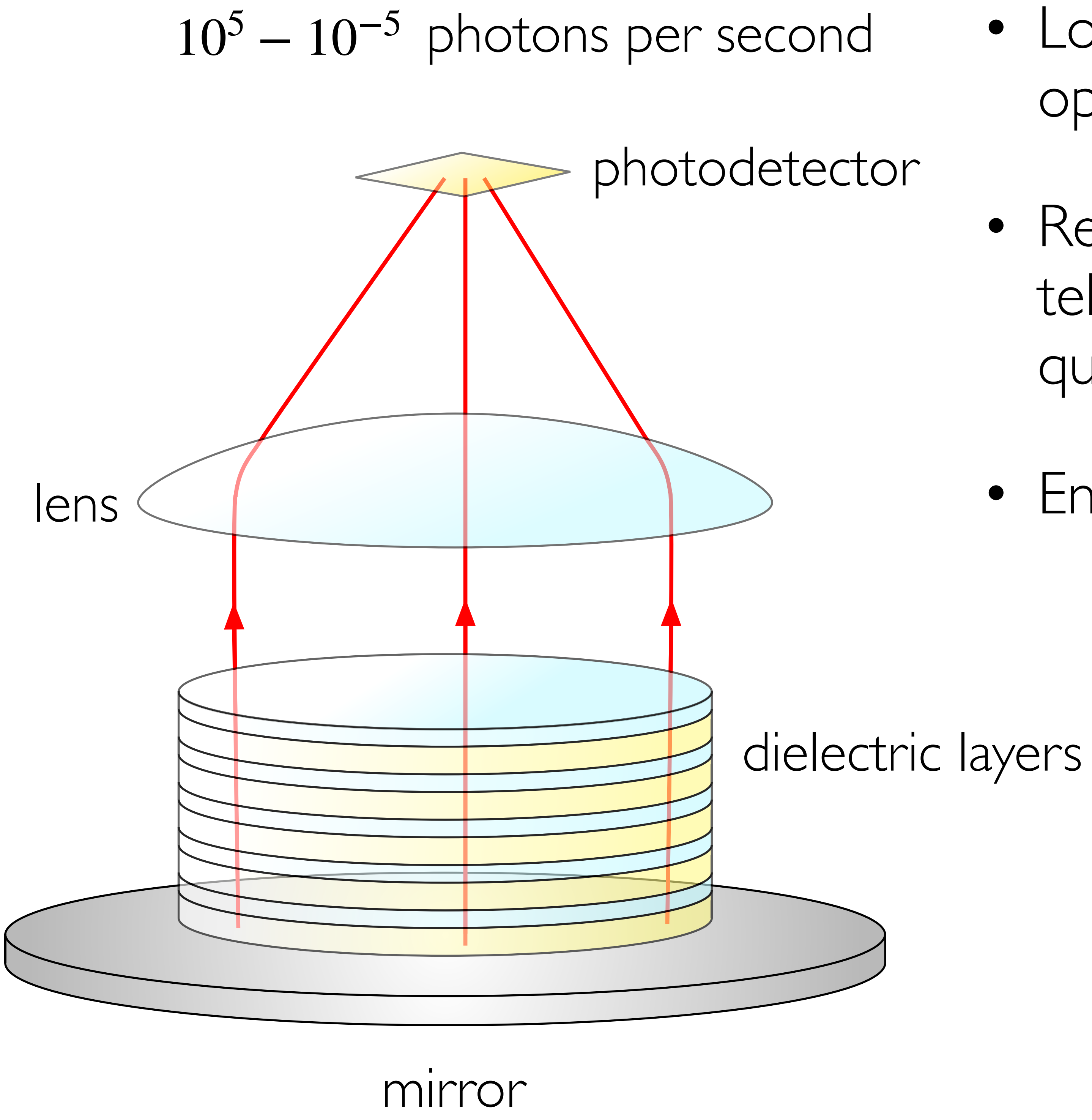
Seeing dark matter

- Signal photons perpendicular to layers
  - Corrections of order the dark matter velocity (and layer imperfections)
- Can be efficiently focused onto small fractional area $dA/A \sim 10^{-6}$
  - Helps background rejection



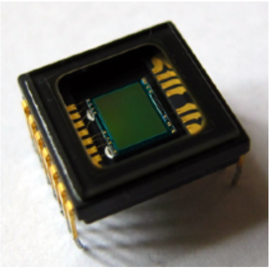


Seeing dark matter



Single photon detectors:

- Low dark count rates, high efficiency in optical range
- Recent rapid improvements for telescopes, direct detection, and quantum computing
- Energy thresholds ~100 meV - eV



CCD camera

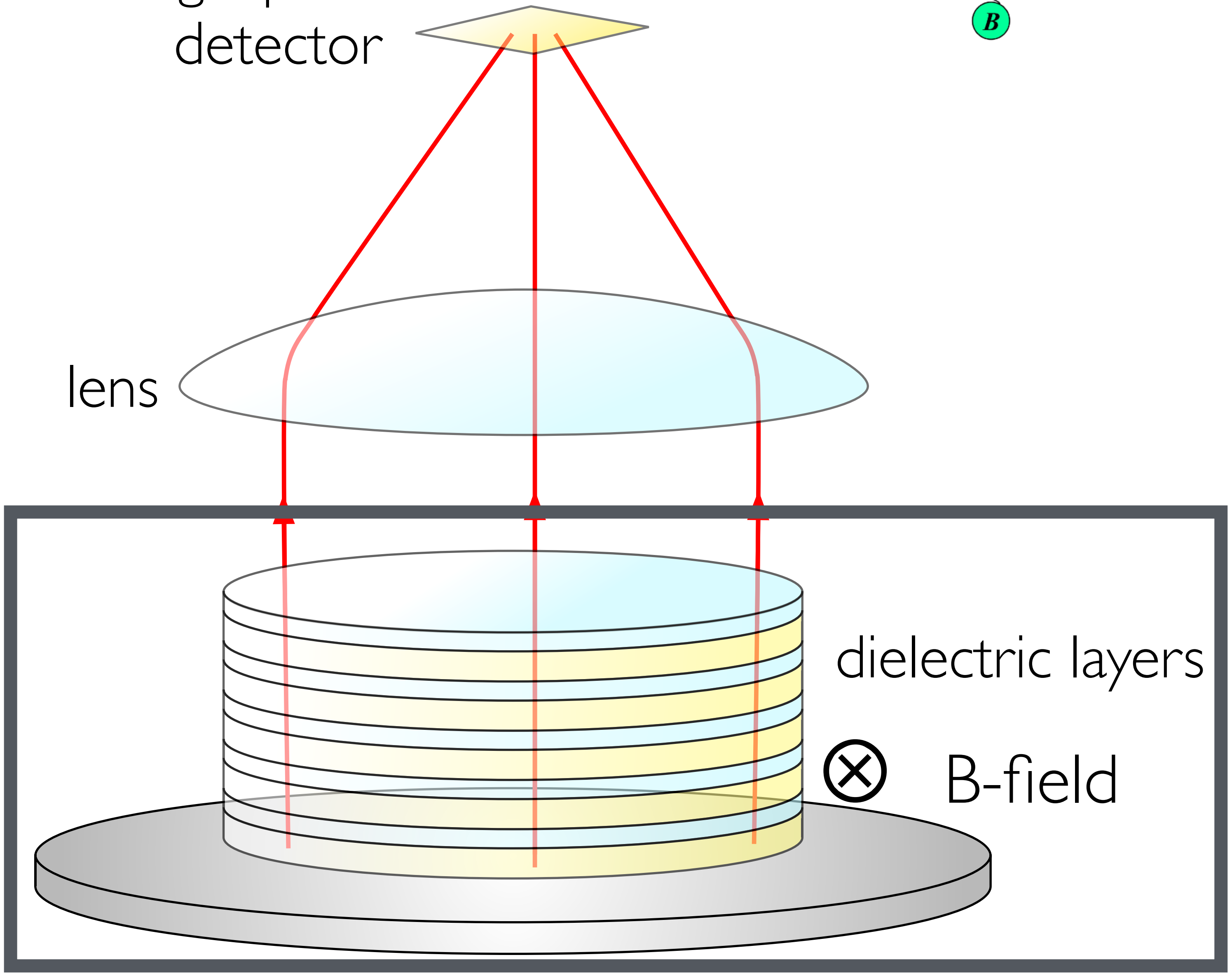
$\Gamma_{\mathrm{CCD}} \lesssim 10^{-2} Hz$ $\eta_{\mathrm{CCD}} \gtrsim 10\%$

TES
(transition edge sensor)

$\Gamma_{\mathrm{TES}} \lesssim 10^{-5} Hz$ $\eta_{\mathrm{TES}} \gtrsim 90\%$

Seeing dark matter

apply external B field for axion-to-photon conversion



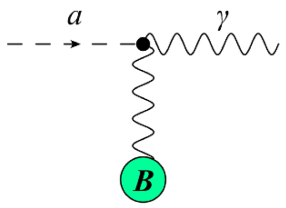
single photon detector

lens

dielectric layers

B-field

mirror



Axion ‘current’

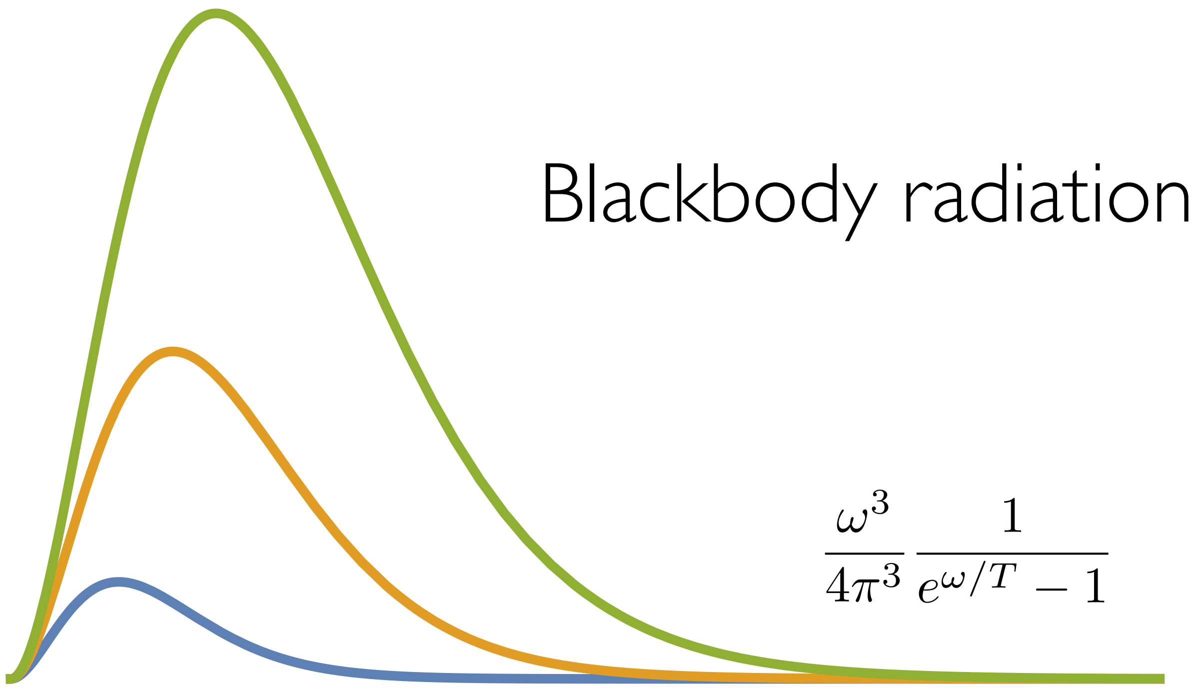
$$J_a = g_{a\gamma\gamma} \partial_t a \, B_{ext}$$

Power emitted:

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

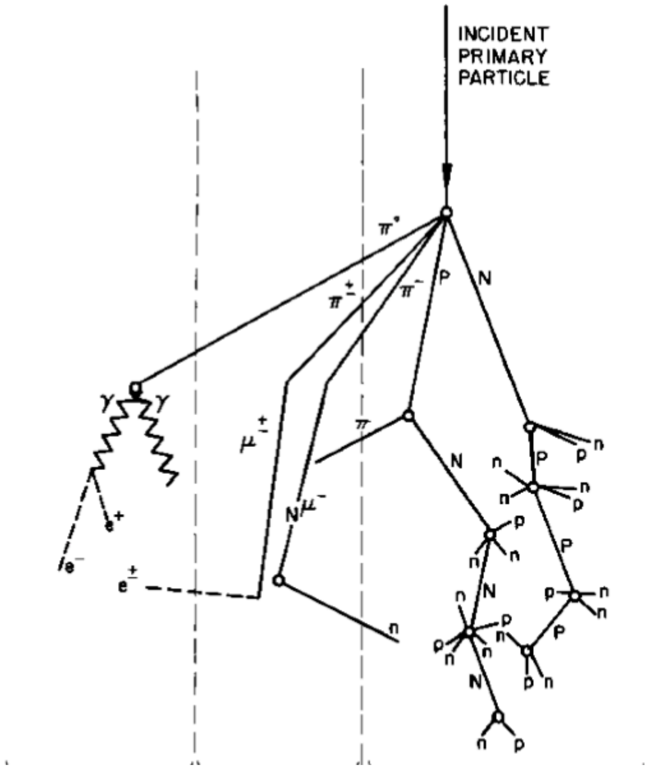
Not seeing dark matter

Backgrounds

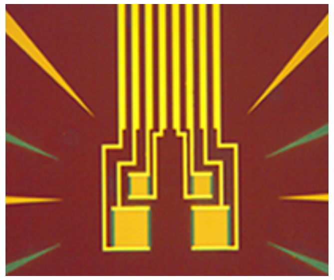


Blackbody radiation

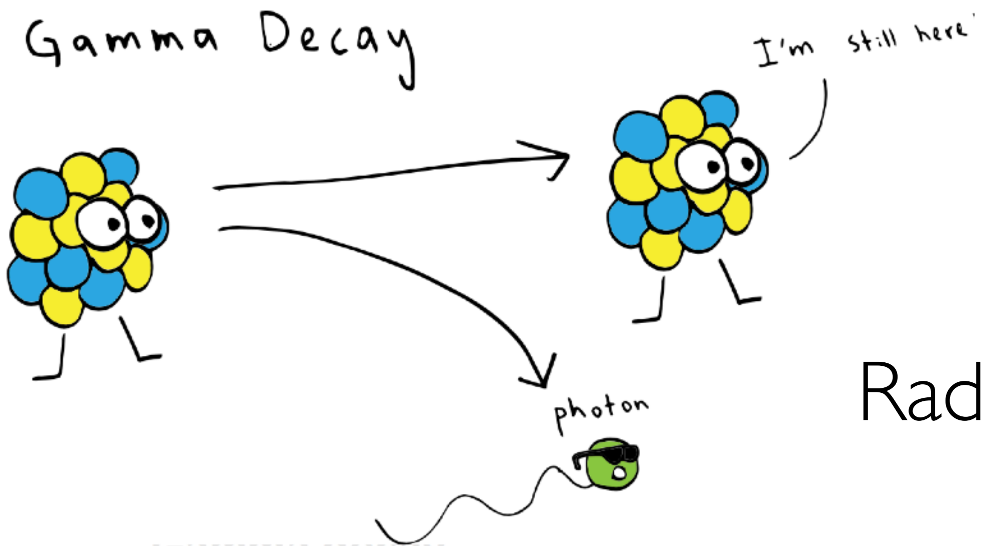
$$\frac{\omega^3}{4\pi^3}\frac{1}{e^{\omega/T}-1}$$



Cosmics



Detector, electronics noise



Radioactivity

Not seeing dark matter

Backgrounds

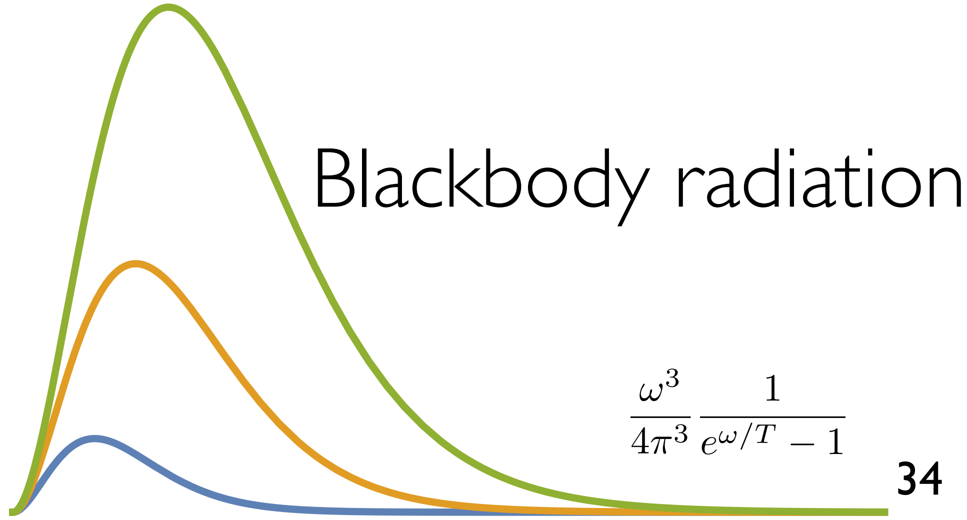
- At these high frequencies, black body radiation is exponentially suppressed

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

- For m > eV, T < 300 K gives rates of mHz or less — room temp sufficient

- For m ~ 50 meV, T < 15 K gives rates of mHz or less — can cool to ~4 K

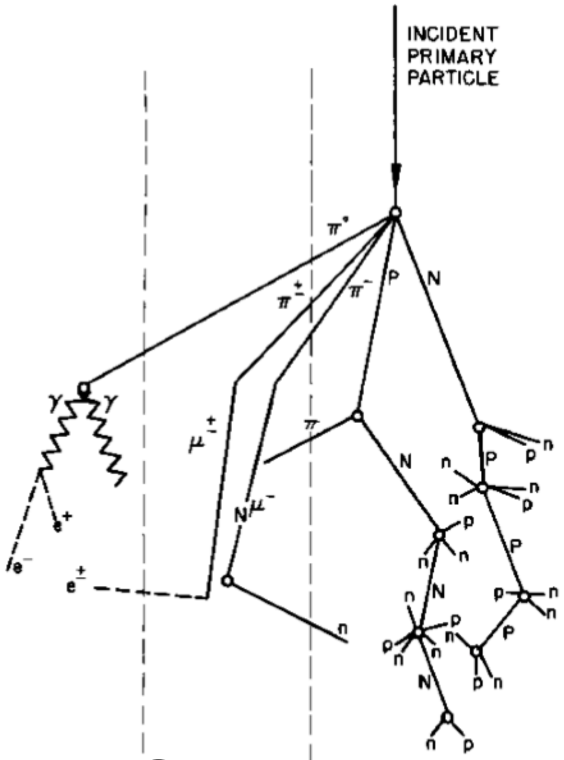
- Sensitive photodetectors may require further cooling



Not seeing dark matter

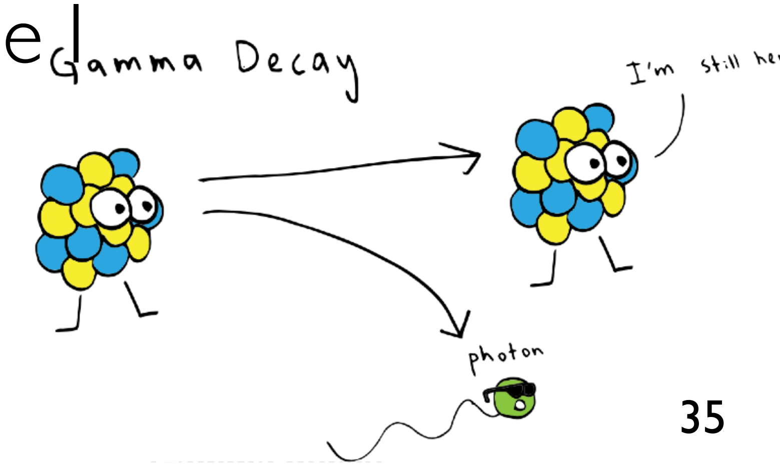
Backgrounds

- Material used in the stack, detector, and surroundings contain radioactive isotopes; unpurified materials can give rates up to 100 Hz
- Cosmic ray muons, 1 Hz / (10cm^2), depositing order 100 keV energy in material
- Typically these are high energy compared to signal and/or shower into many particles
- For prototype, narrow angular acceptance, detector array sufficient
- Shielding and active veto may be necessary for Phase I and II

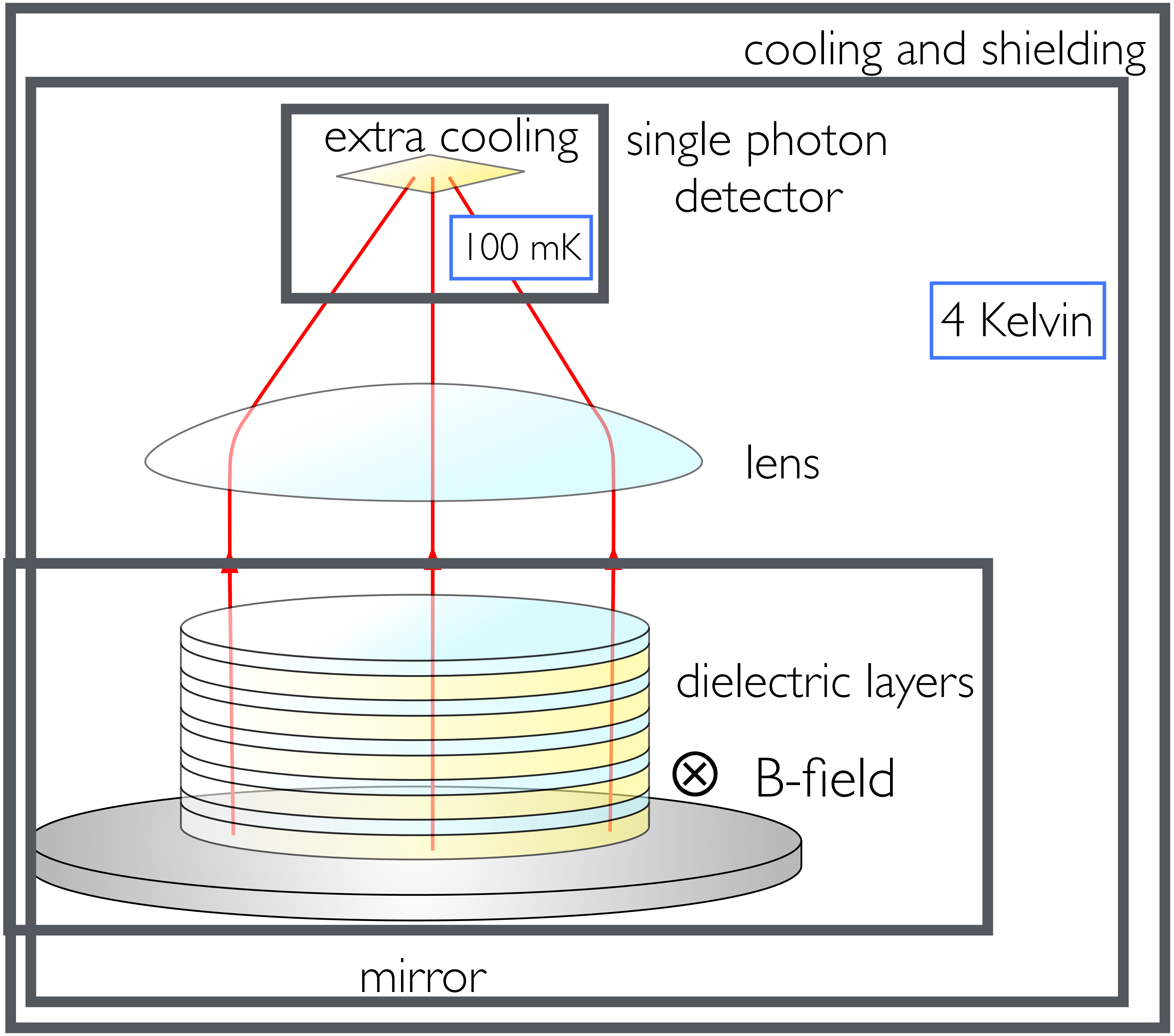


Cosmics

Radioactivity

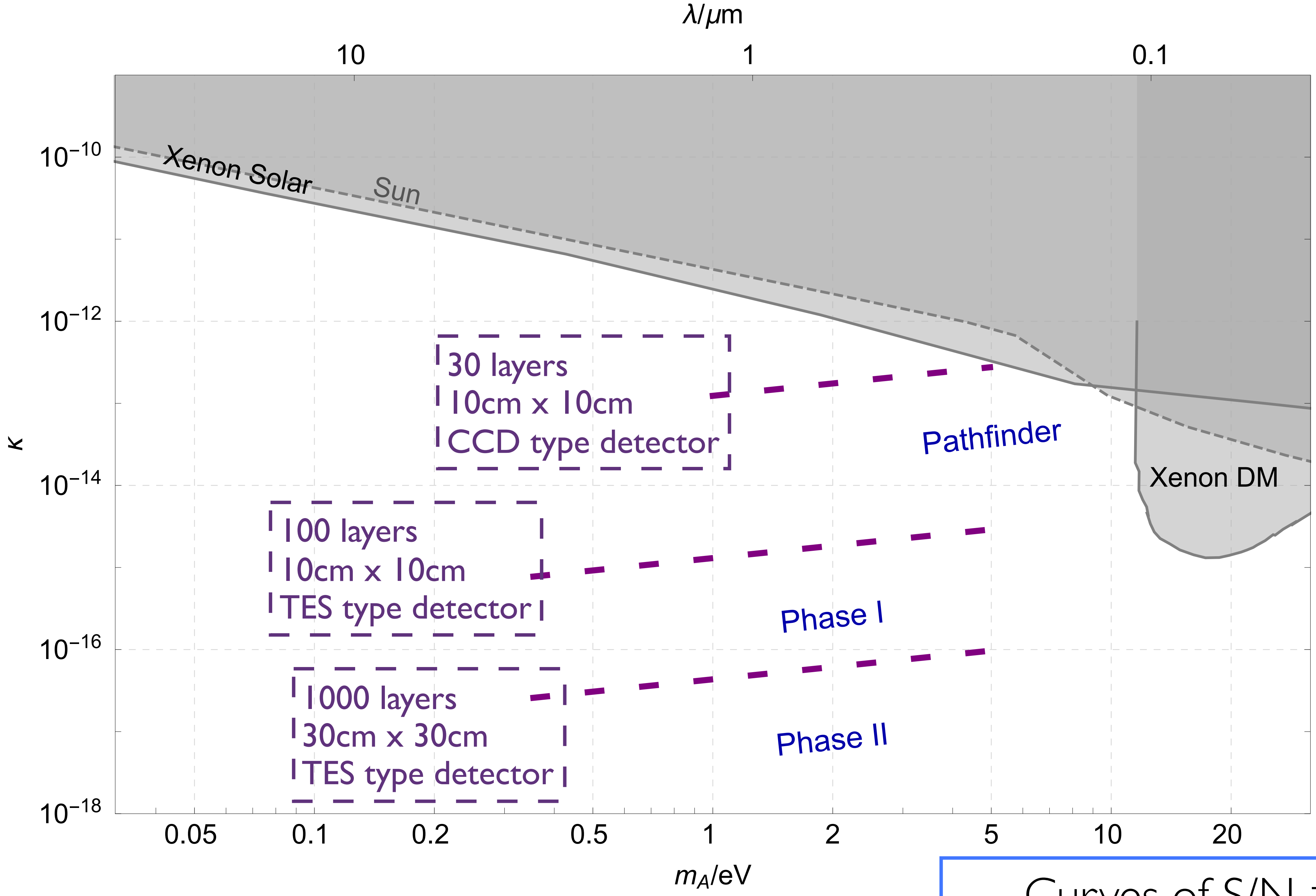


Seeing dark matter



Seeing dark matter

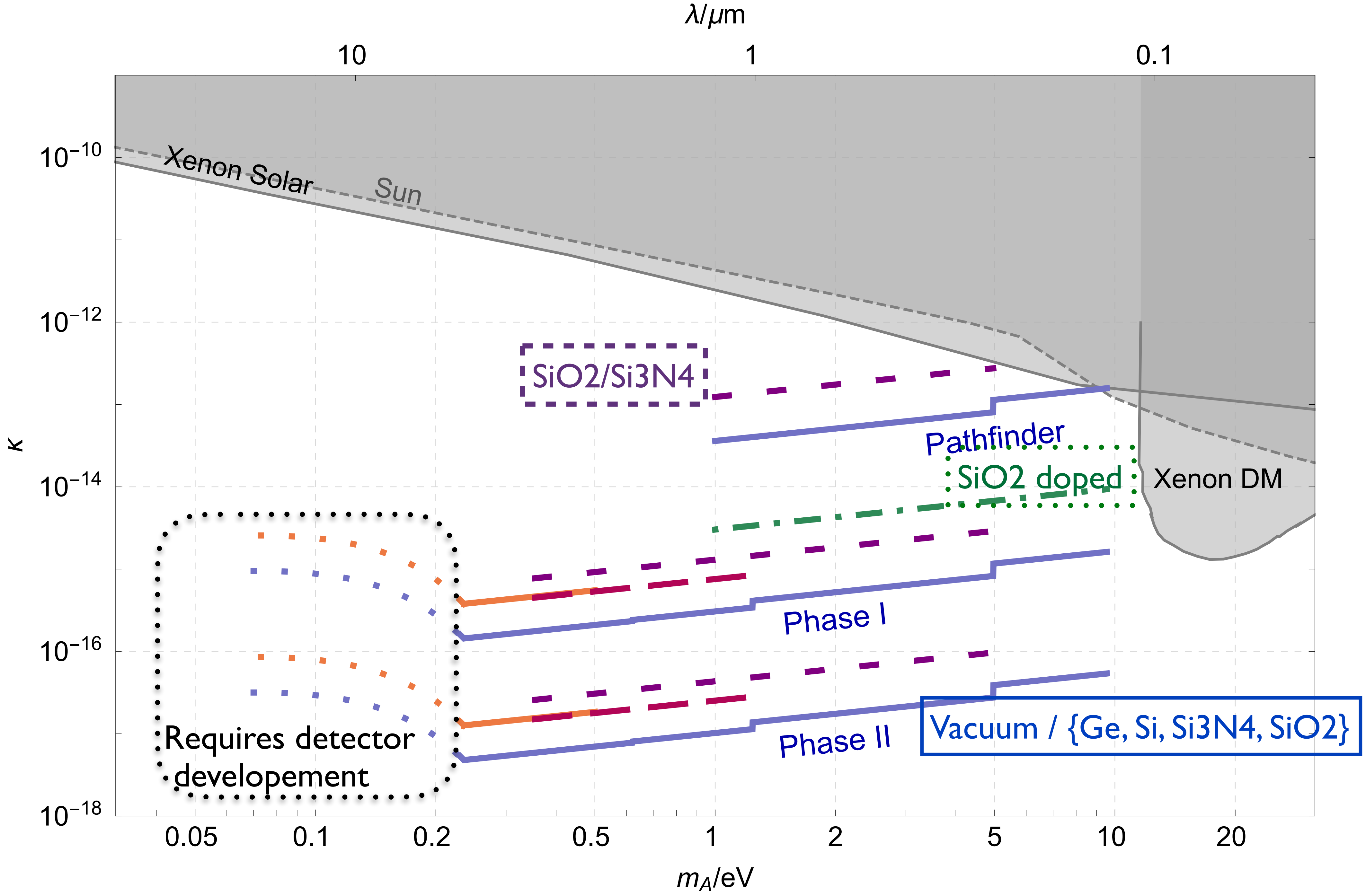
Dark photons



Curves of S/N =3
Integration time 10^6 sec

Seeing dark matter

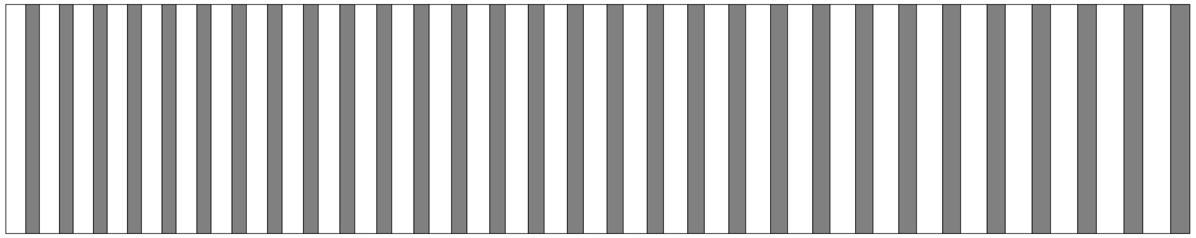
Dark photons

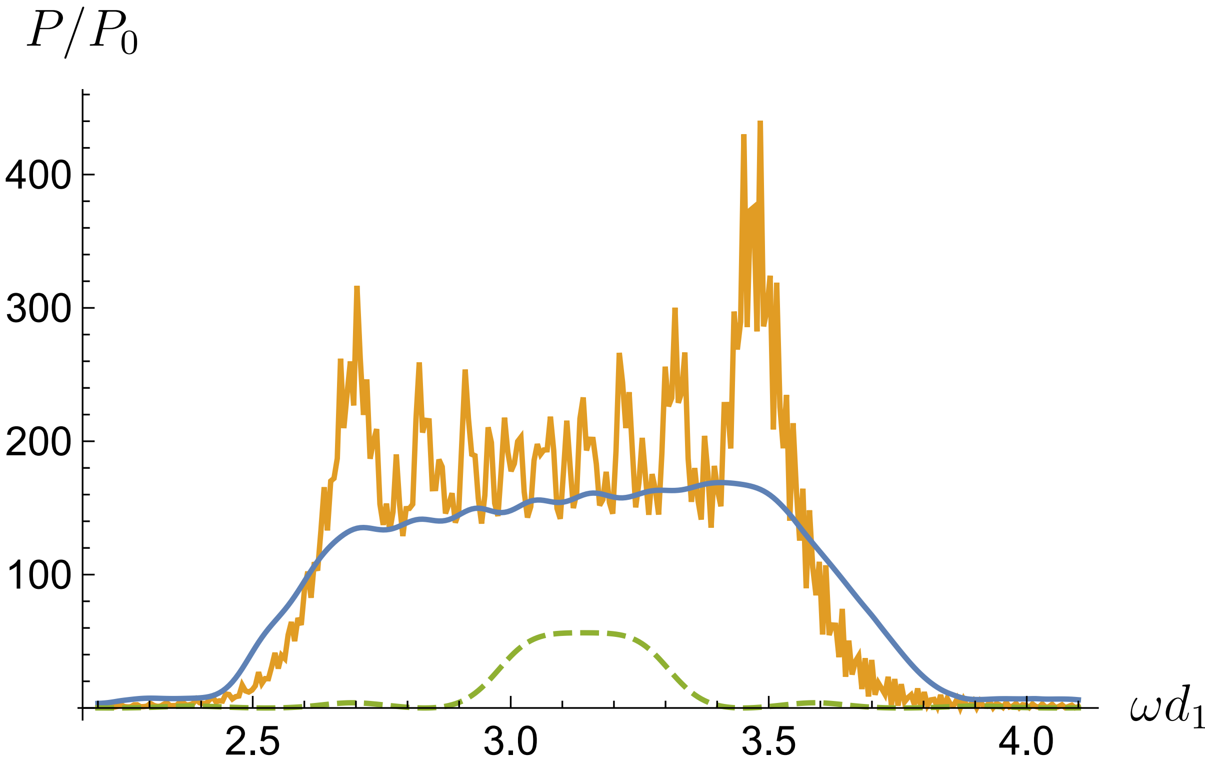


Seeing dark matter

Scanning

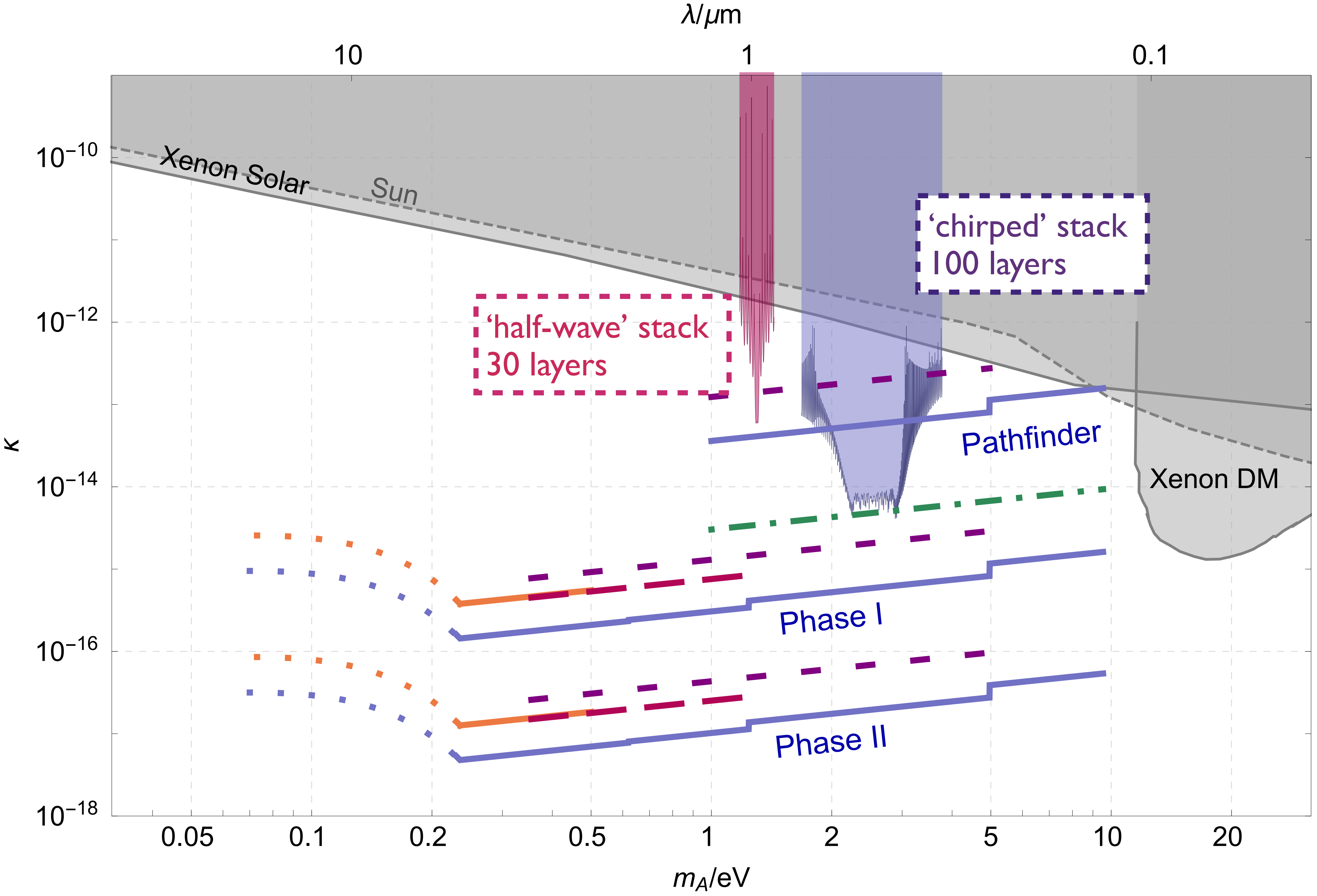
- Backgrounds at optical frequencies can be significantly reduced/vetoed
    - Less important to have a narrow resonance
- Scanning with modification of refractive index or length scales
    - Sub-percent variation in realistic materials
- Building multiple stacks
    - 150-1000 per e-fold
- Building ‘chirped’ stacks:





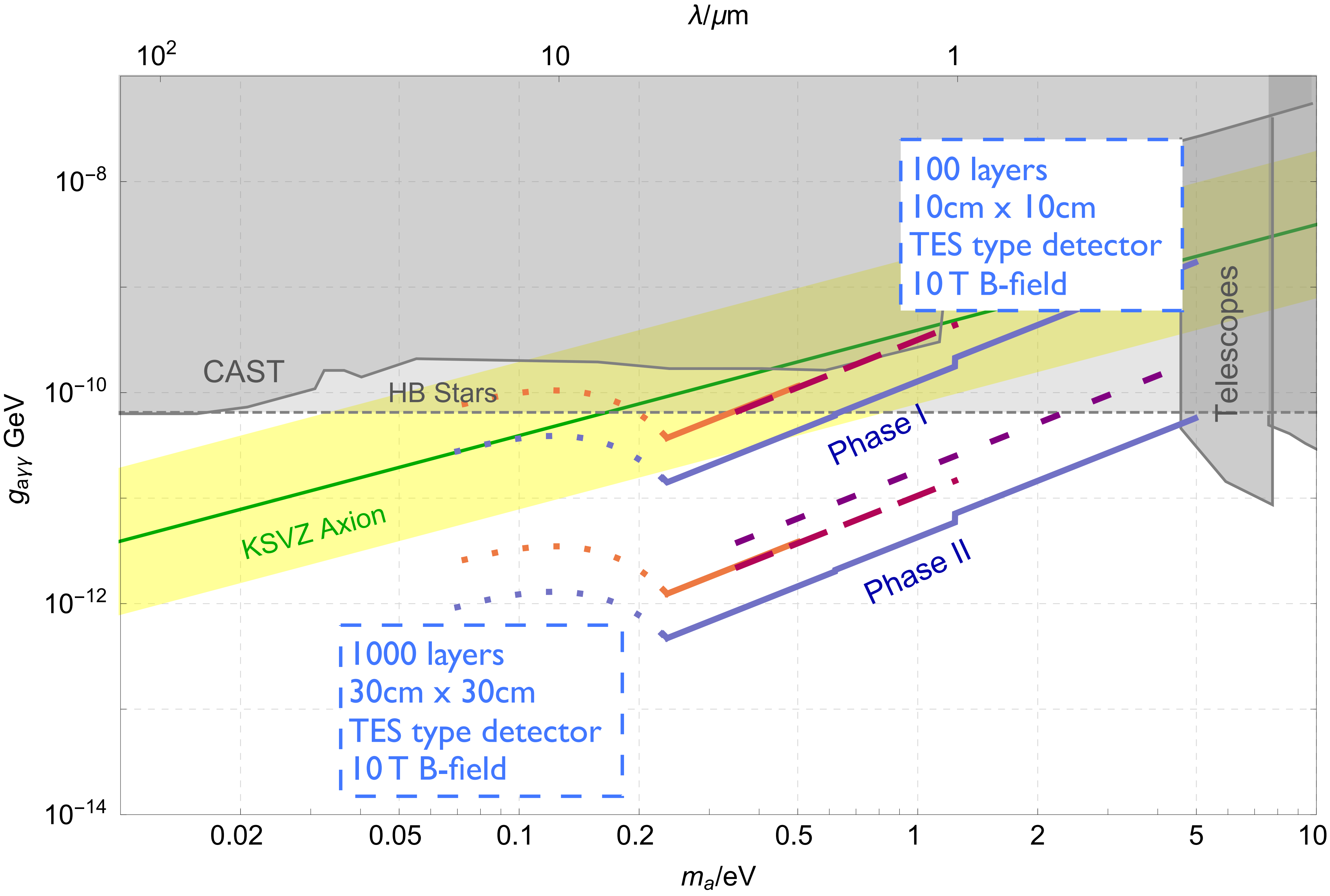
Seeing dark matter

Dark photons



Seeing dark matter

Axions



100 layers
10cm x 10cm
TES type detector
10 T B-field

1000 layers
30cm x 30cm
TES type detector
10 T B-field

Conclusions

- Light axions and dark photons appear in well-motivated extensions of the Standard Model
- Important to pursue broad parameter space for well-motivated dark matter candidates
- Enable conversion to nonrelativistic dark matter to relativistic photons by using periodic structure of dielectric materials
- Relies on well-known optics technology and rapidly developing detectors
- Improve on parameter space by orders of magnitude, and hopefully see dark matter