Absorbing bosonic dark matter with periodic dielectrics

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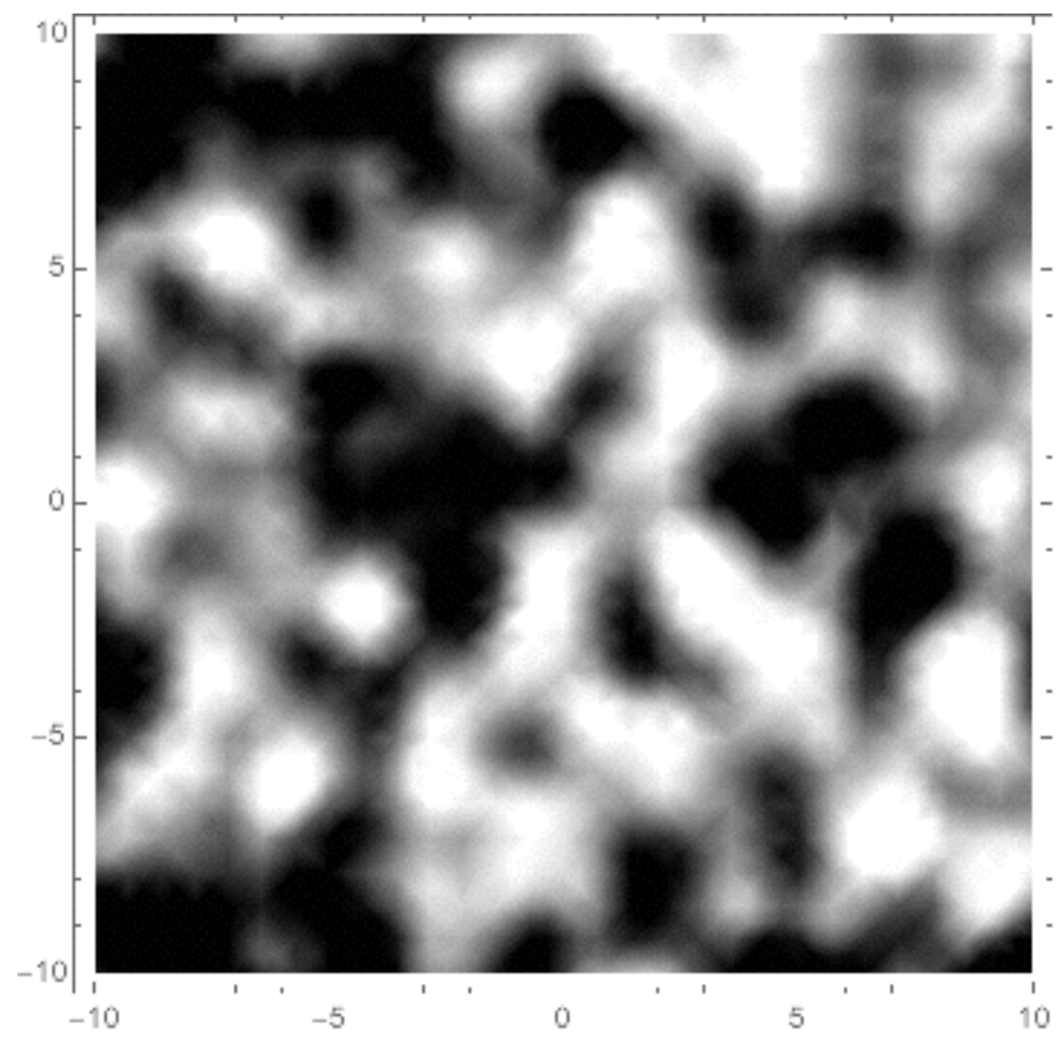
1803.11455 - M. Baryakhtar, J. Huang, RL

Light bosonic dark matter

- Dark matter mass could be anywhere within ~ 50 orders of magnitude, from $10^{-22}\,\mathrm{eV}$ to Planck scale
- For masses $\lesssim 100\,\mathrm{eV}$, DM must be bosonic (Pauli exclusion), and must be produced non-thermally
- Many such DM candidates, and early-universe production mechanisms, in BSM theories:
  - Axions, hidden photons, light moduli $\ldots$
  - Purely gravitational production during inflation, production during phase transitions, $\ldots$
- Direct detection experiments very different to WIMPs

Bosonic dark matter fields

- Bosonic DM expected to be coherent, classical-like oscillations of field
- Virialized velocity distribution within galaxies, $v \sim 10^{-3}$
  - Approximately Gaussian random field, with coherence length ~ $(mv)^{-1}$, coherence time ~ $(mv)^{-2}$



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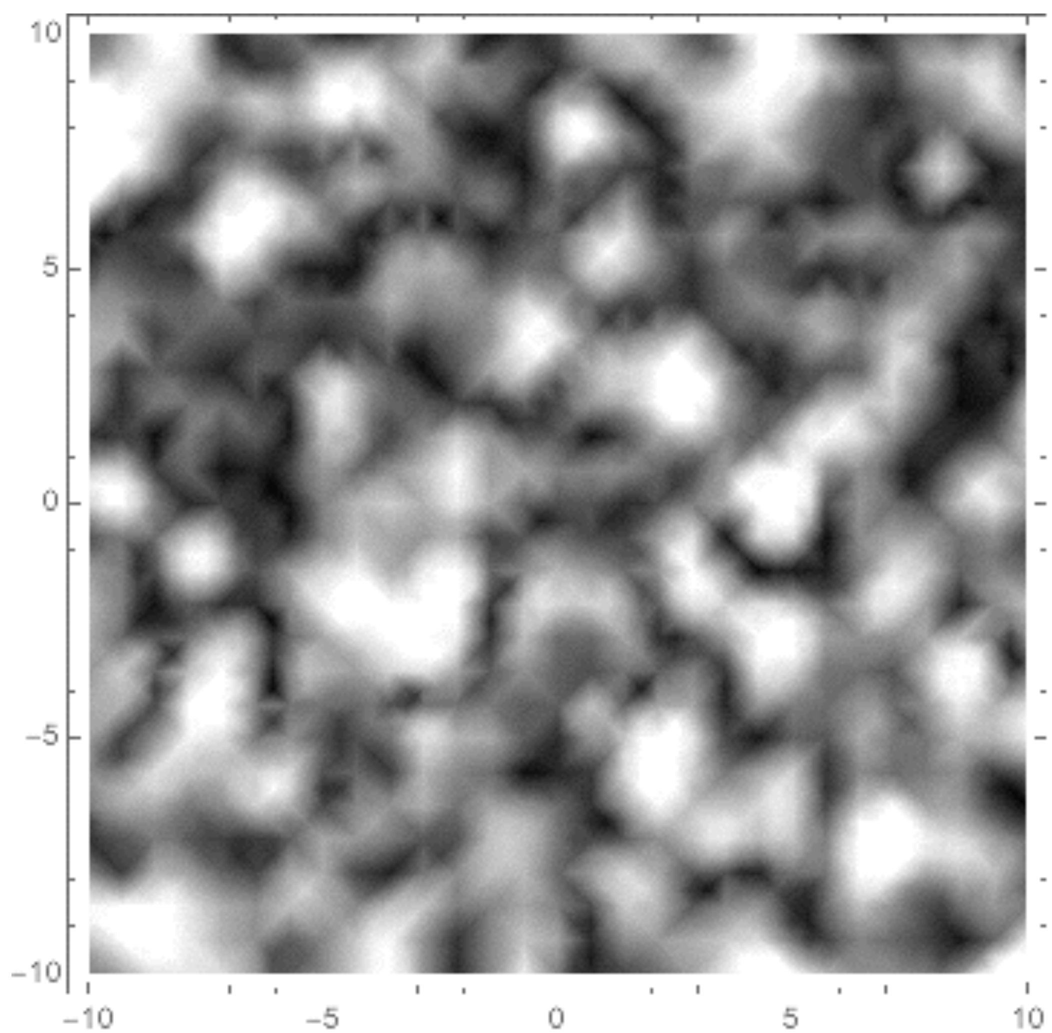
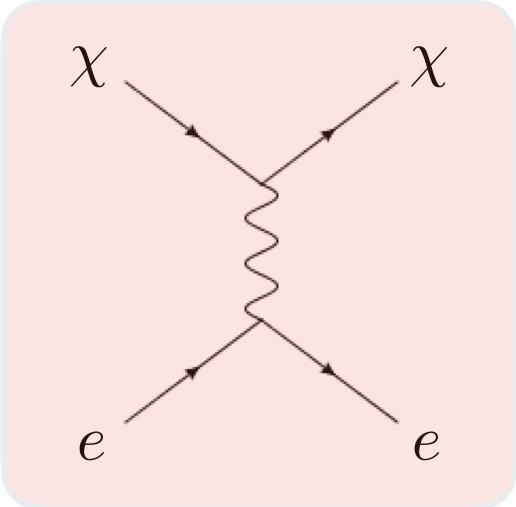
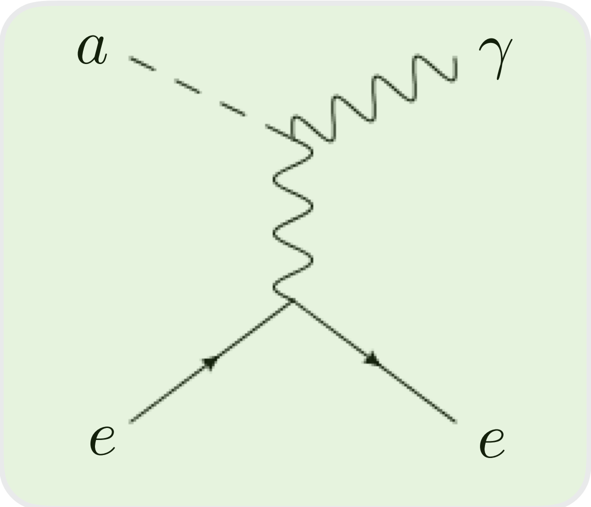


Bosonic dark matter detection

- Detect heavy and/or fermionic DM through scattering



- Many light DM candidates can be absorbed



- Convert whole energy (including rest mass) of DM, versus just kinetic energy
- Existing experiments:
  ADMX for axions,
  Xenon for dark photons, …

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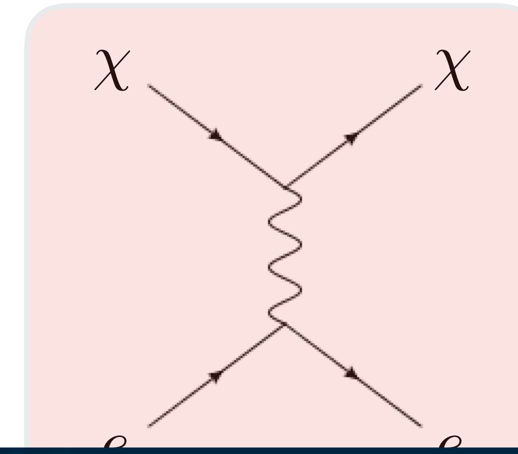

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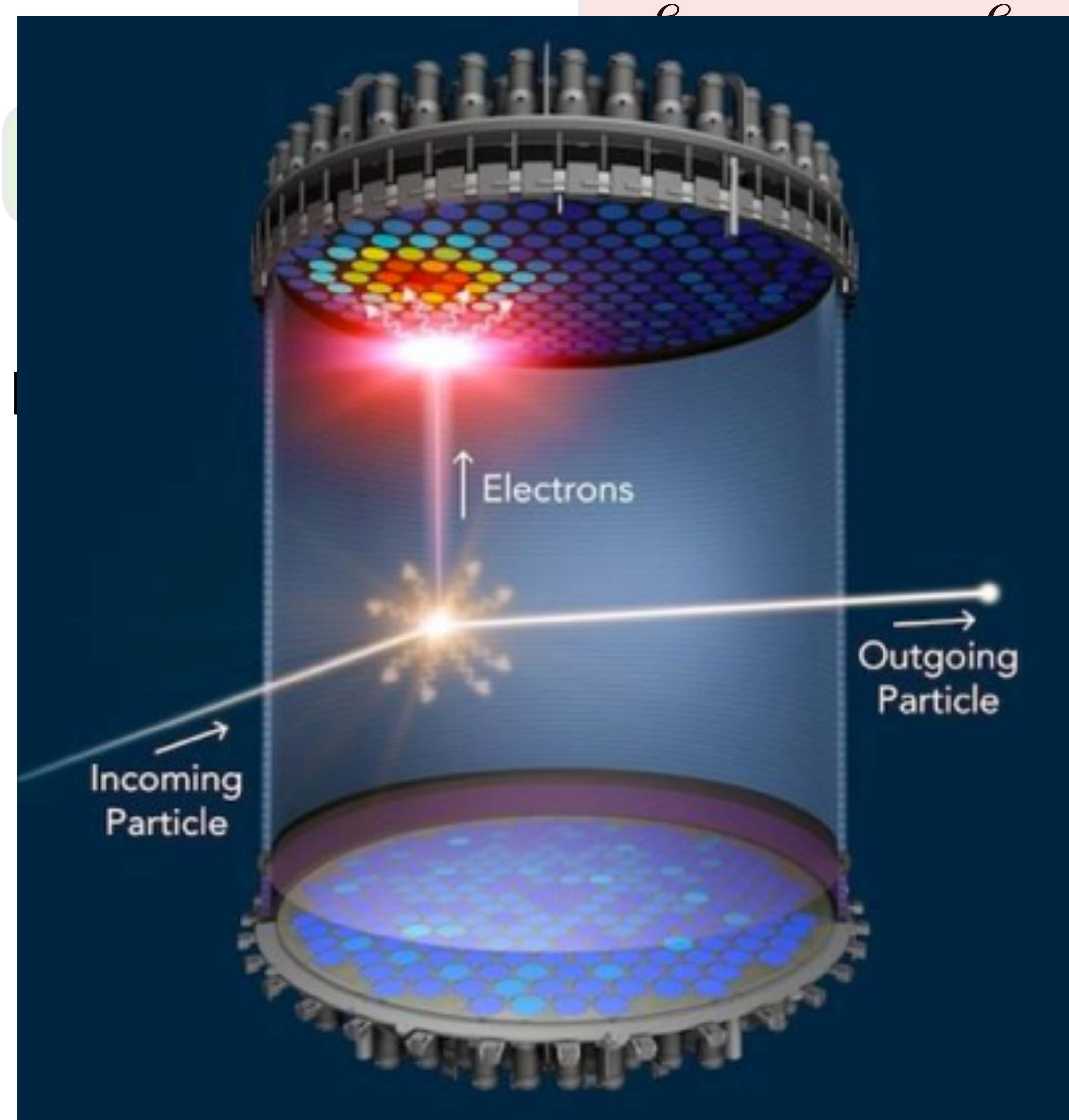

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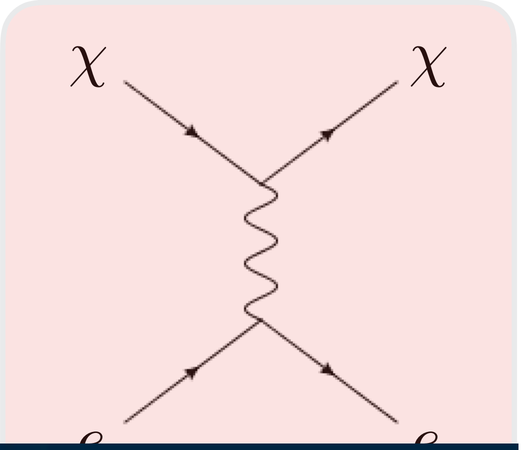

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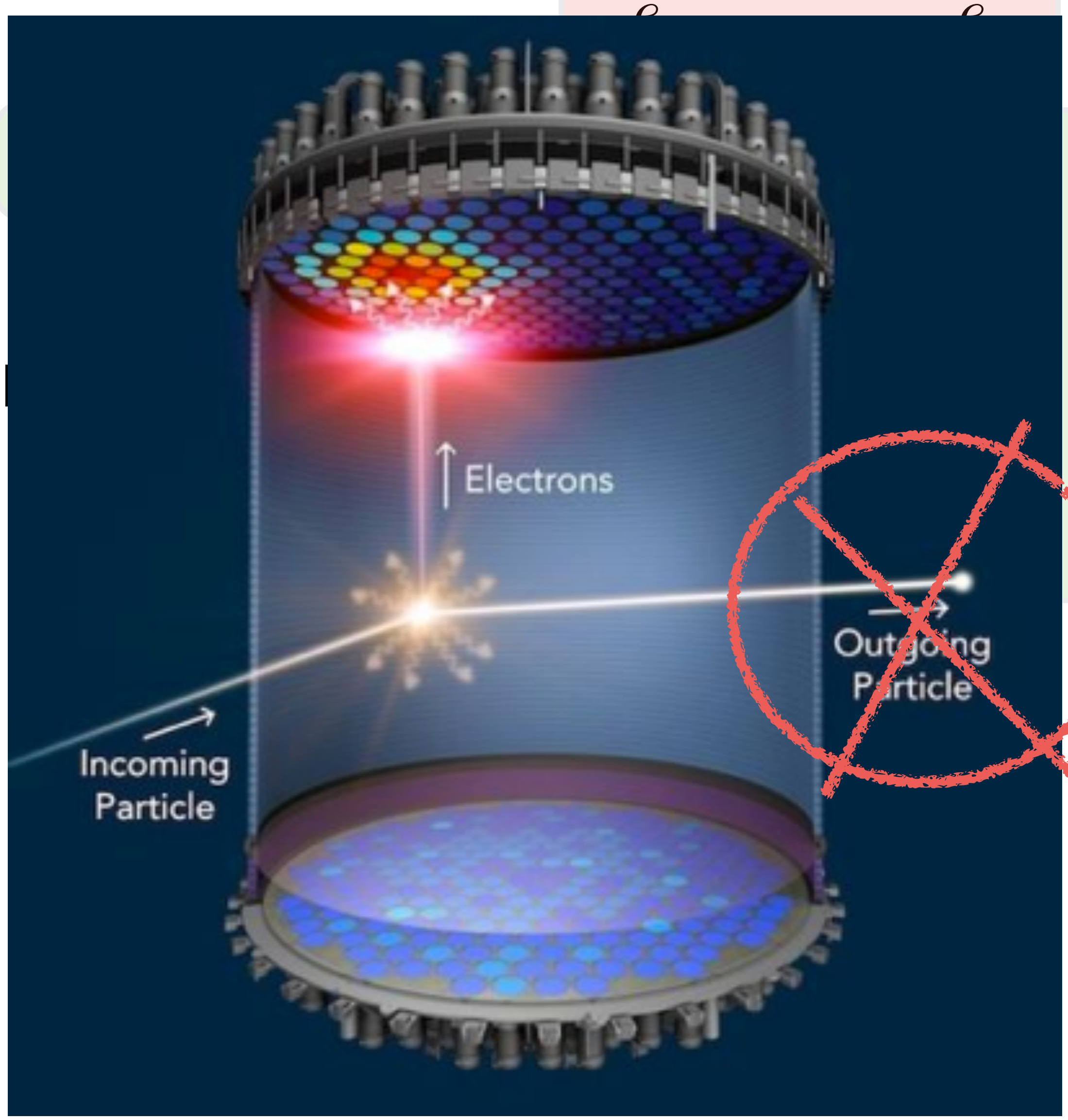

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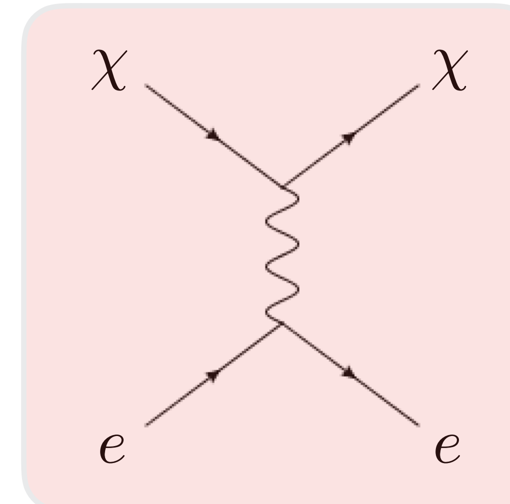

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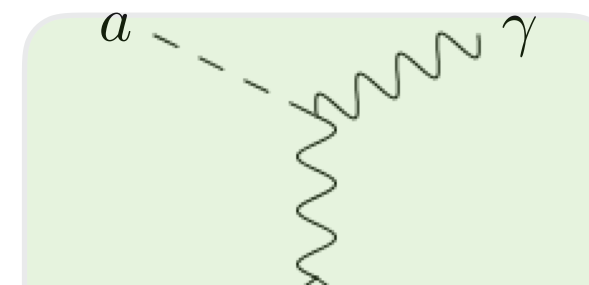

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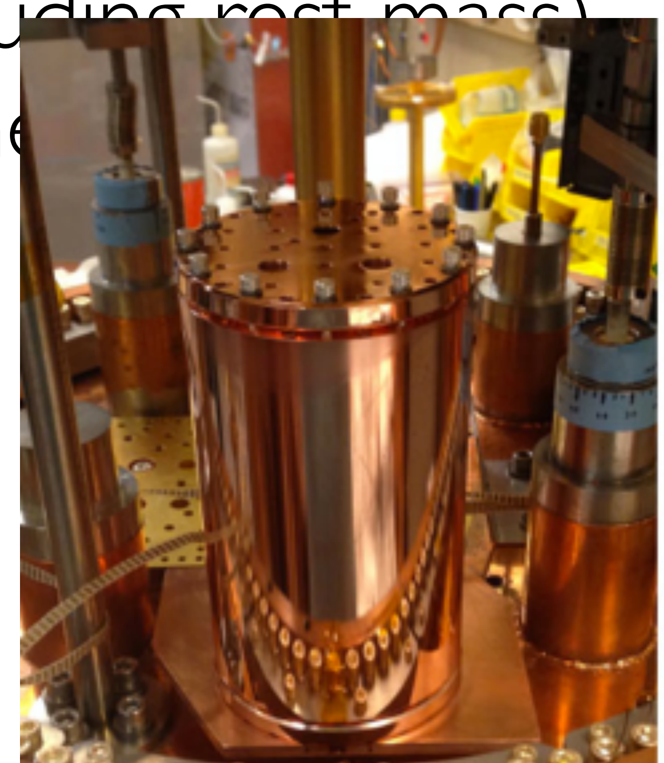
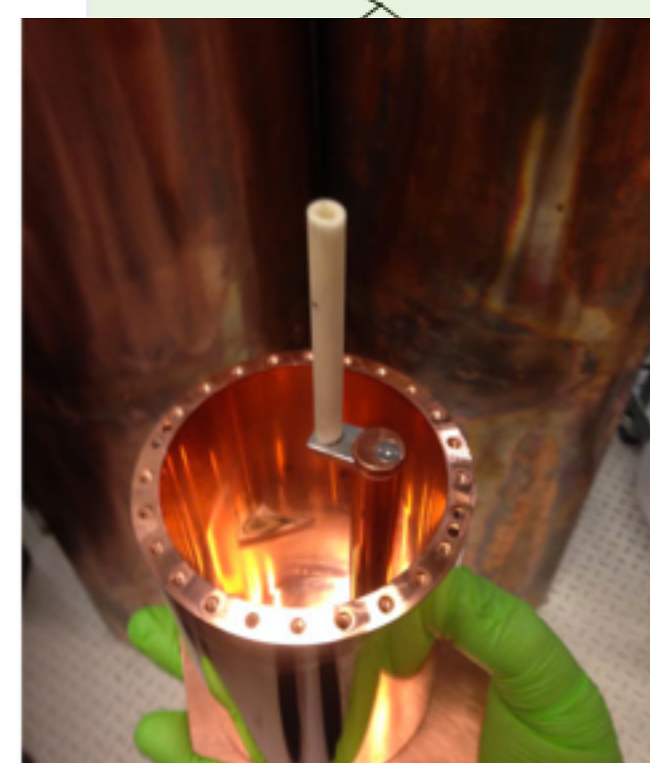
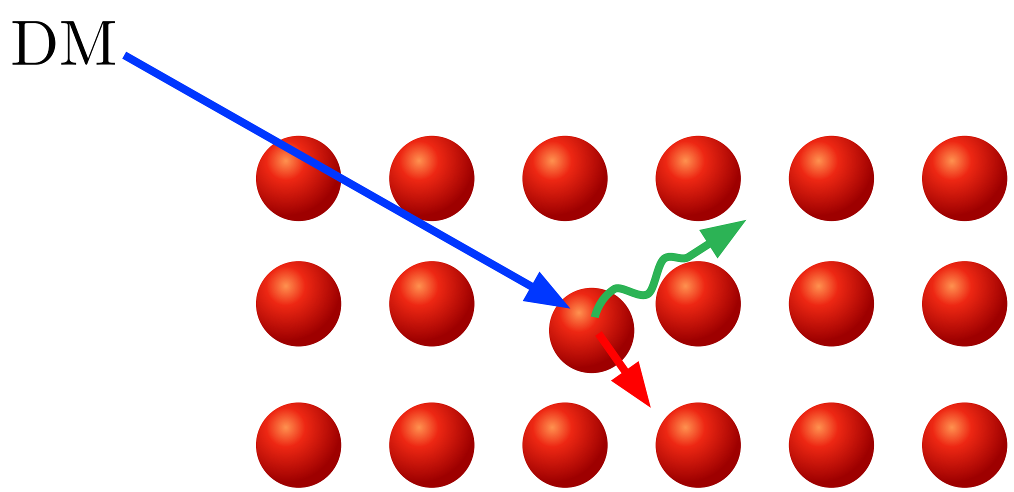


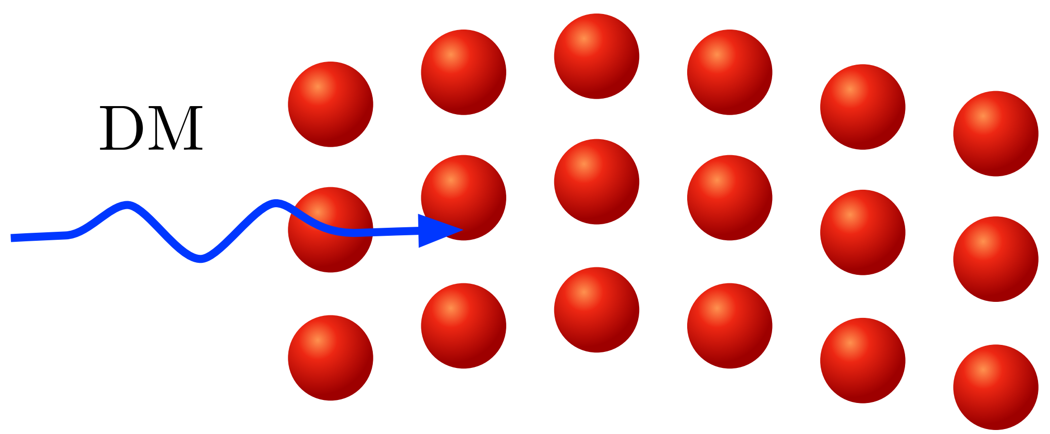


Coherent absorption

- Incoherent vs coherent absorption:



Localized excitations

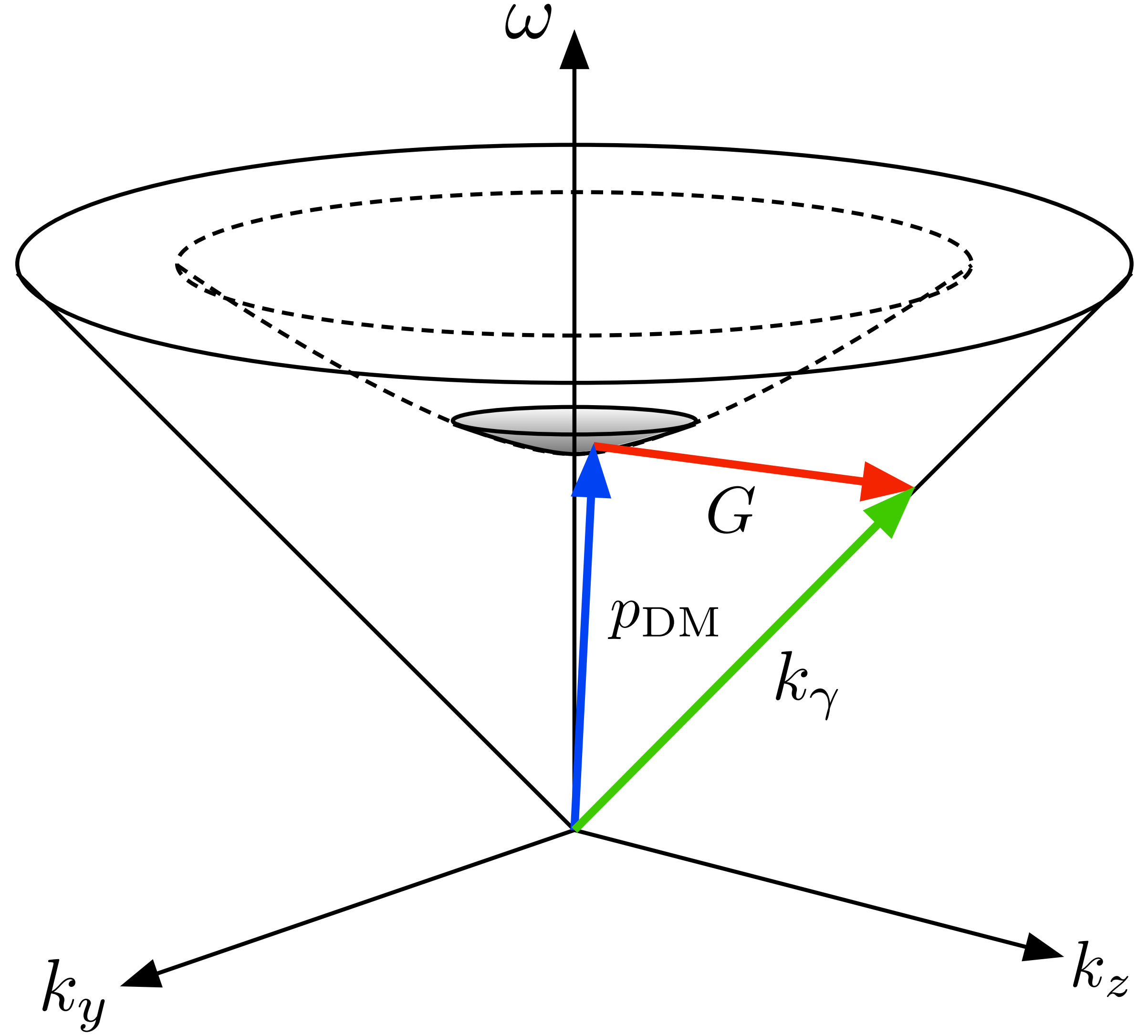


Collective excitations (photons, phonons, etc)

- Coherent absorption can take advantage of large target volume, while still absorbing into specific modes

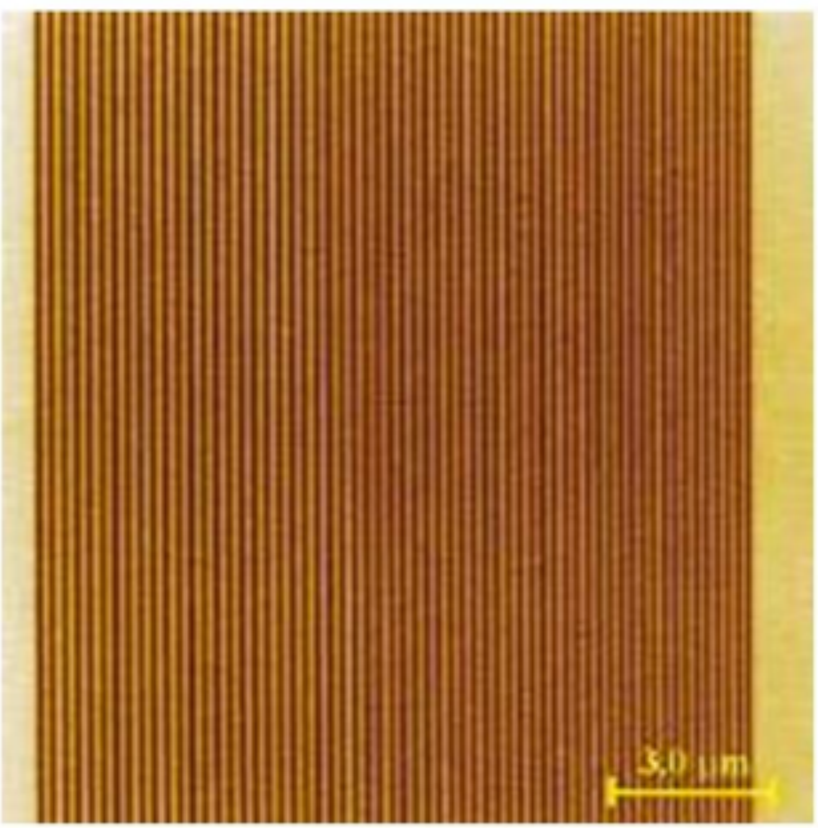
Coherent absorption

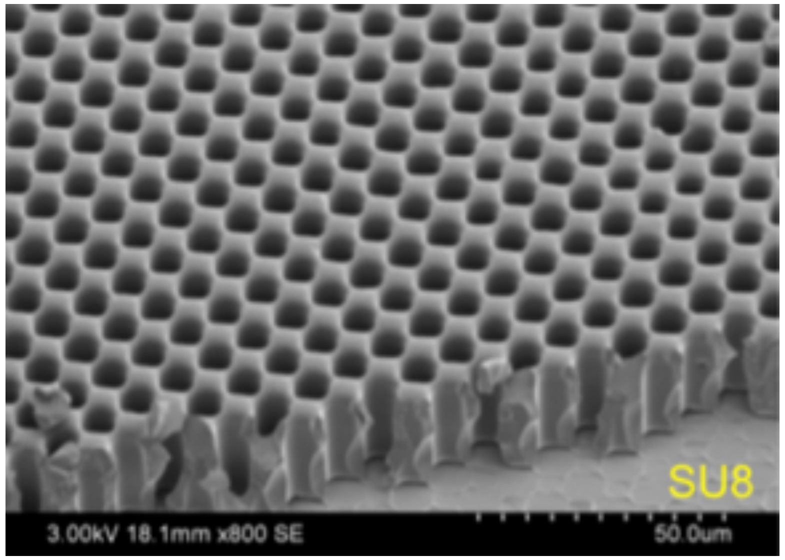
- Photons often a good signal - easily manipulated and detected
- In large target, photons are relativistic - momentum mismatch with DM:

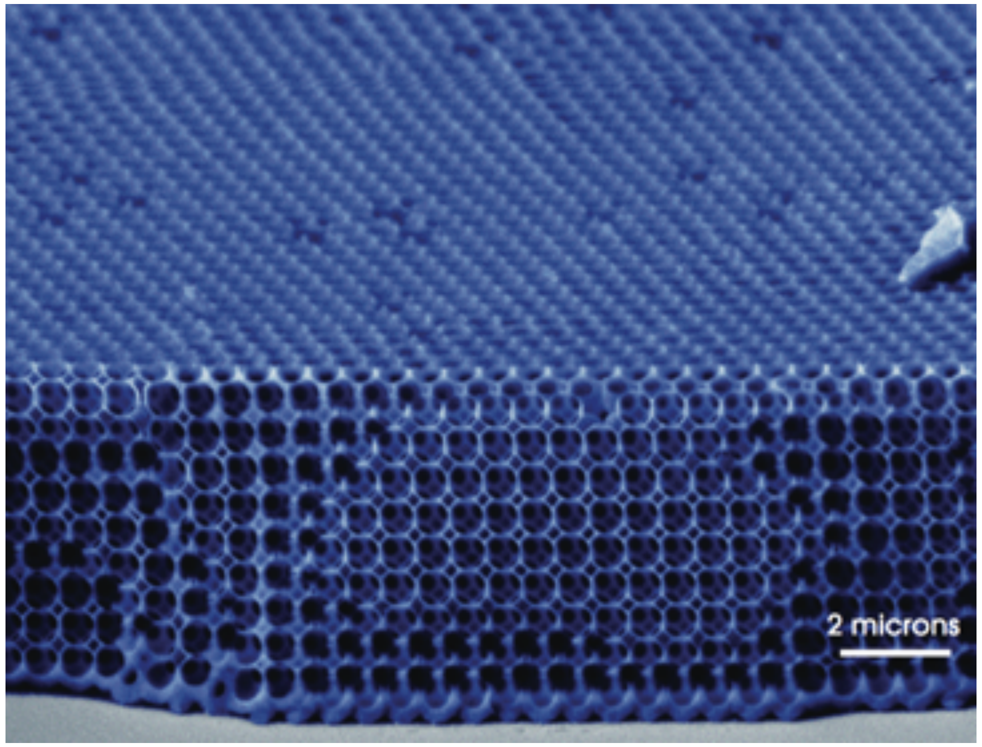


Photonic materials

- Materials with periodic optical properties



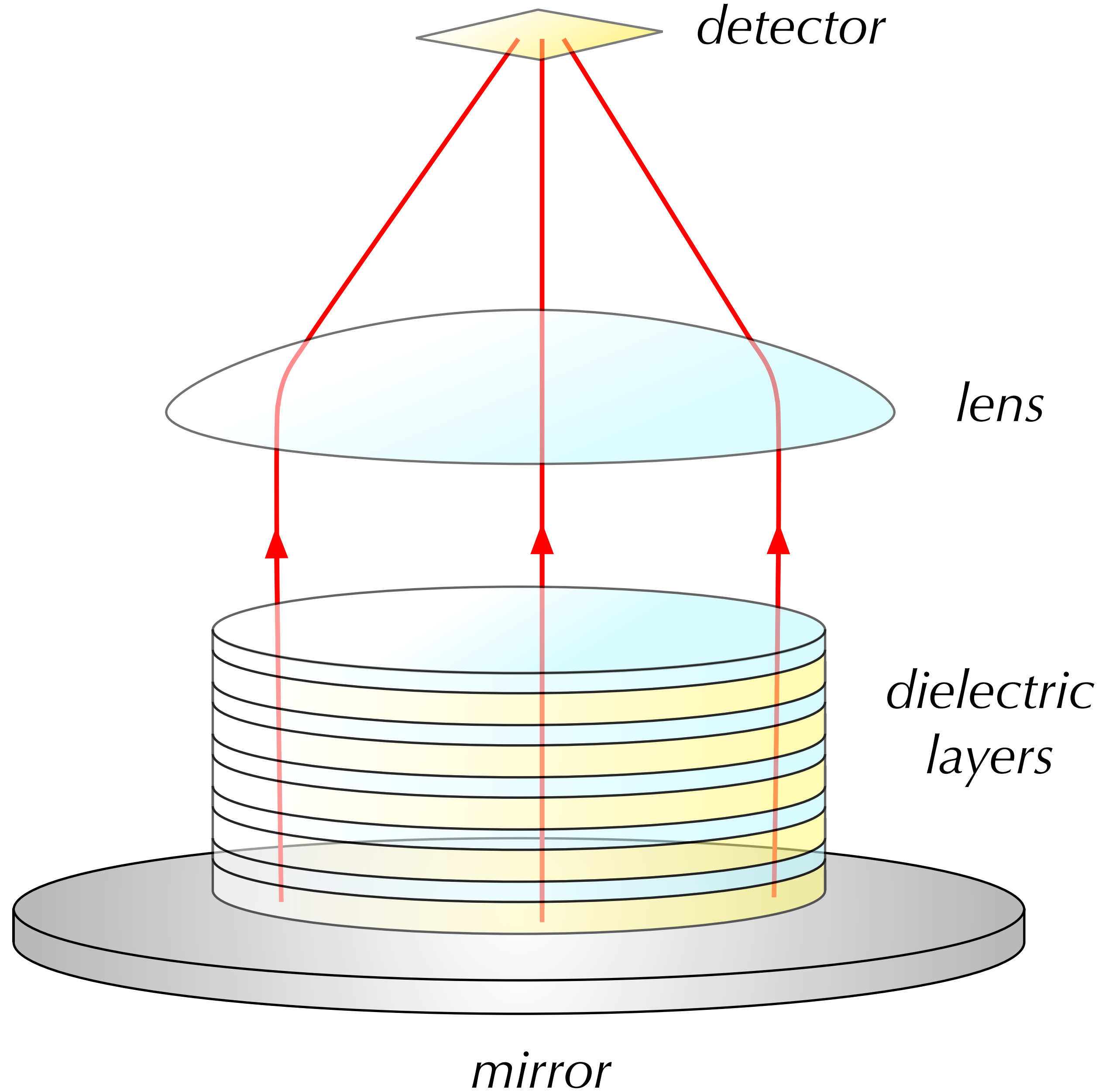




1D ***2D*** ***3D***

Dielectric haloscopes

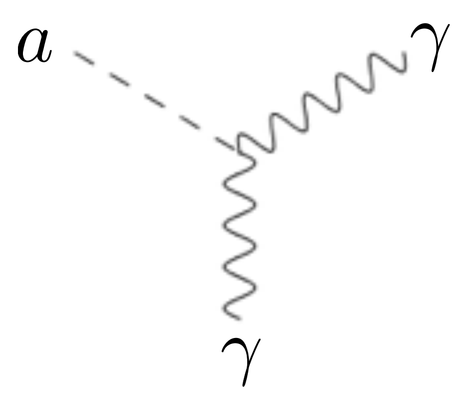
- DM can Bragg-convert in medium, producing photons:



Axion conversion

- Axion-photon coupling

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m^2 a^2 - \frac{1}{4} g a F_{\mu\nu}\tilde{F}^{\mu\nu}$$
$$= \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m^2 a^2 + g a E \cdot B,$$



- Modifies Maxwell equations to

$$\nabla \cdot E = \rho - g \nabla a \cdot B \qquad \nabla \times B = \partial_t E + J + g(\dot{a} B + \nabla a \times E)$$

- Instantaneous power transfer

$$P_{\mathrm{DM}\to\mathrm{SM}} \simeq \int dV\, E \cdot (g \dot{a} B)$$

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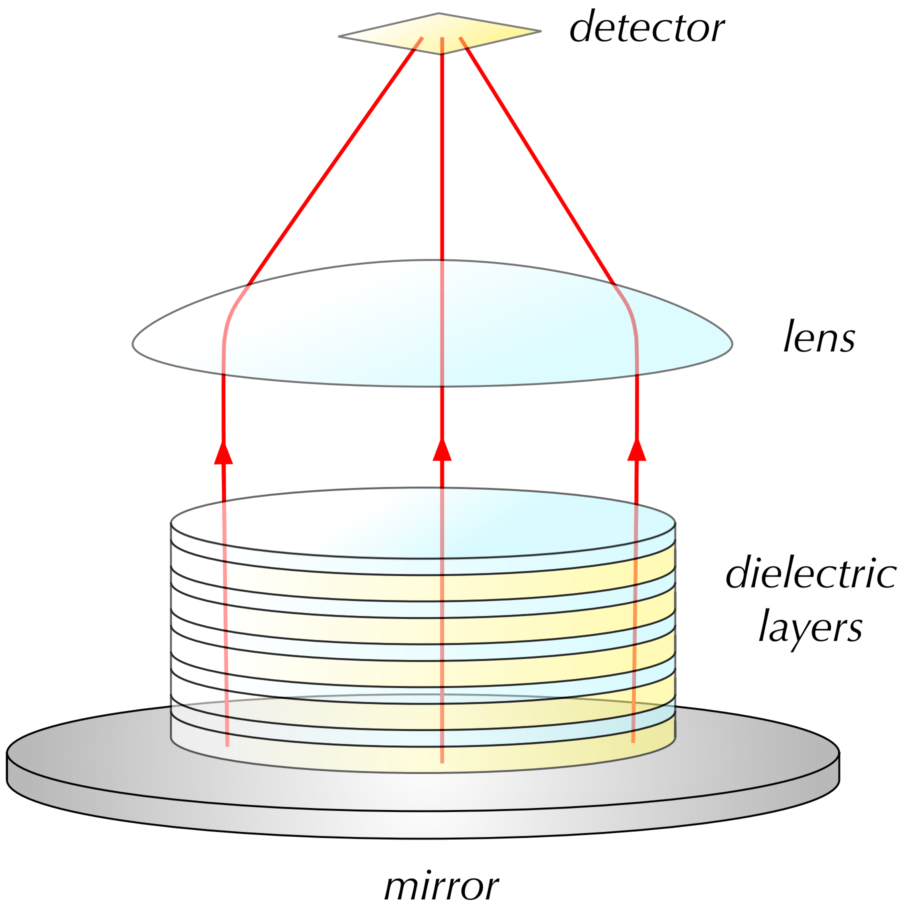

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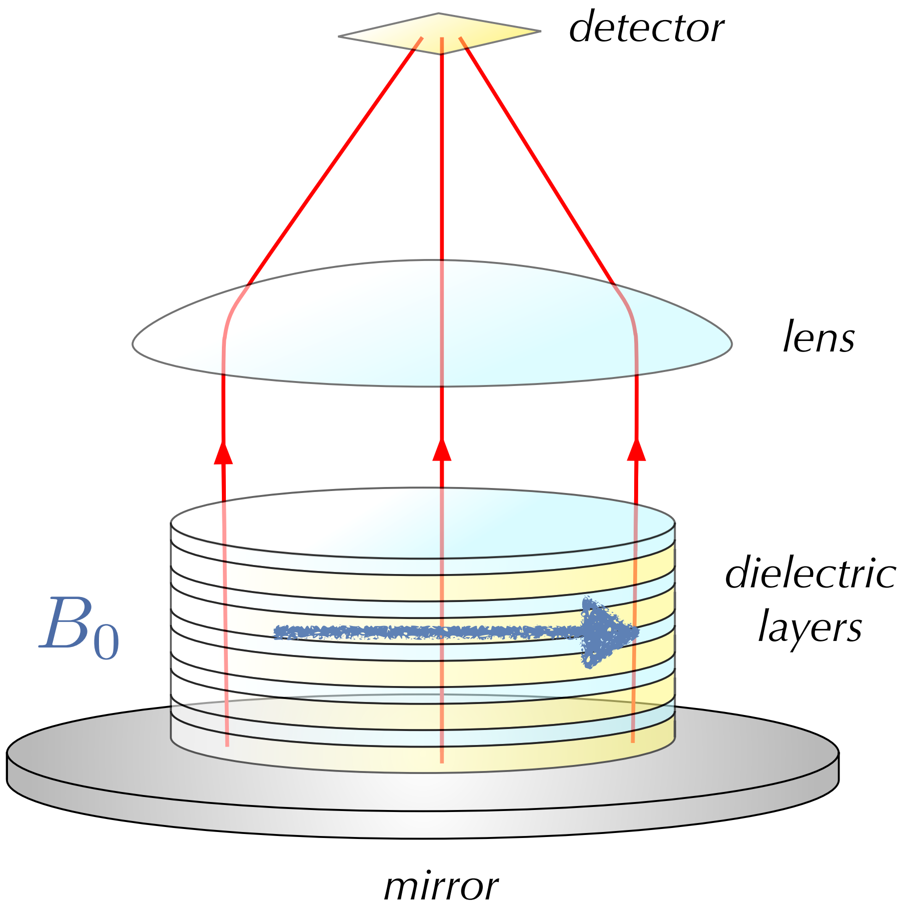

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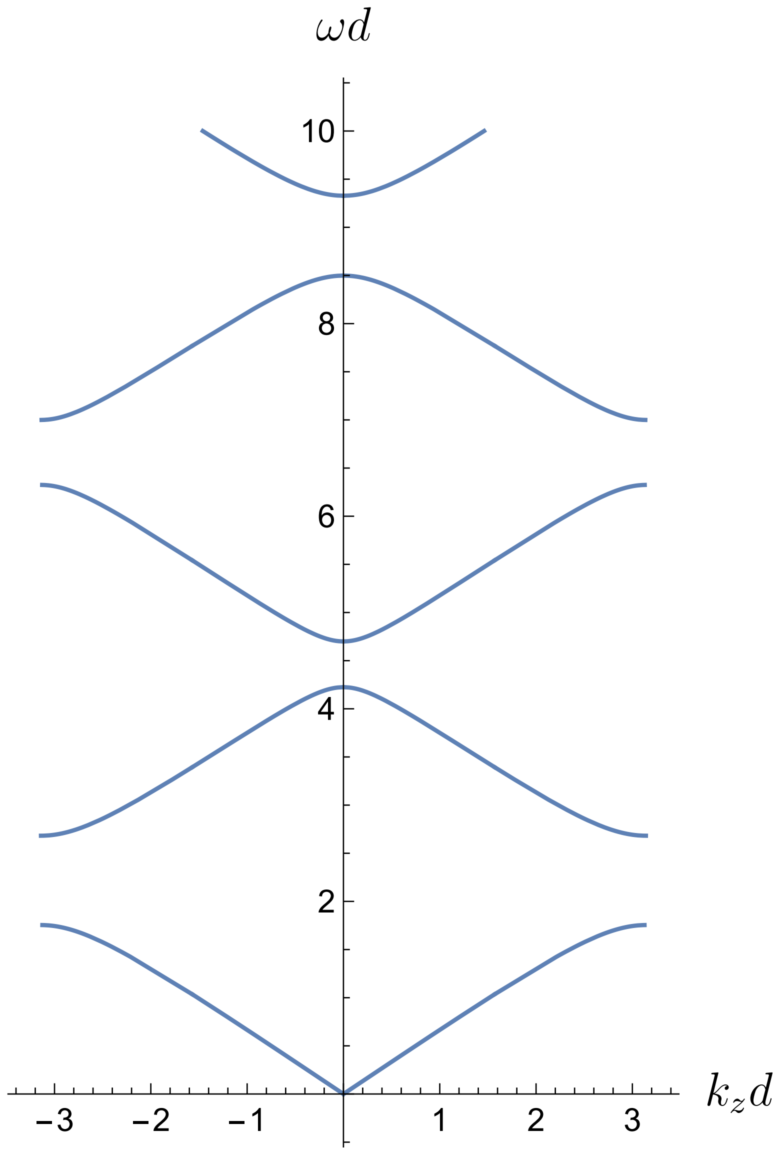
Photon modes

- In infinite periodic material, have photon Bloch modes
  $E(\vec{r}) = e^{i\vec{k}\cdot\vec{r}} u_{\vec{k}}(z)$



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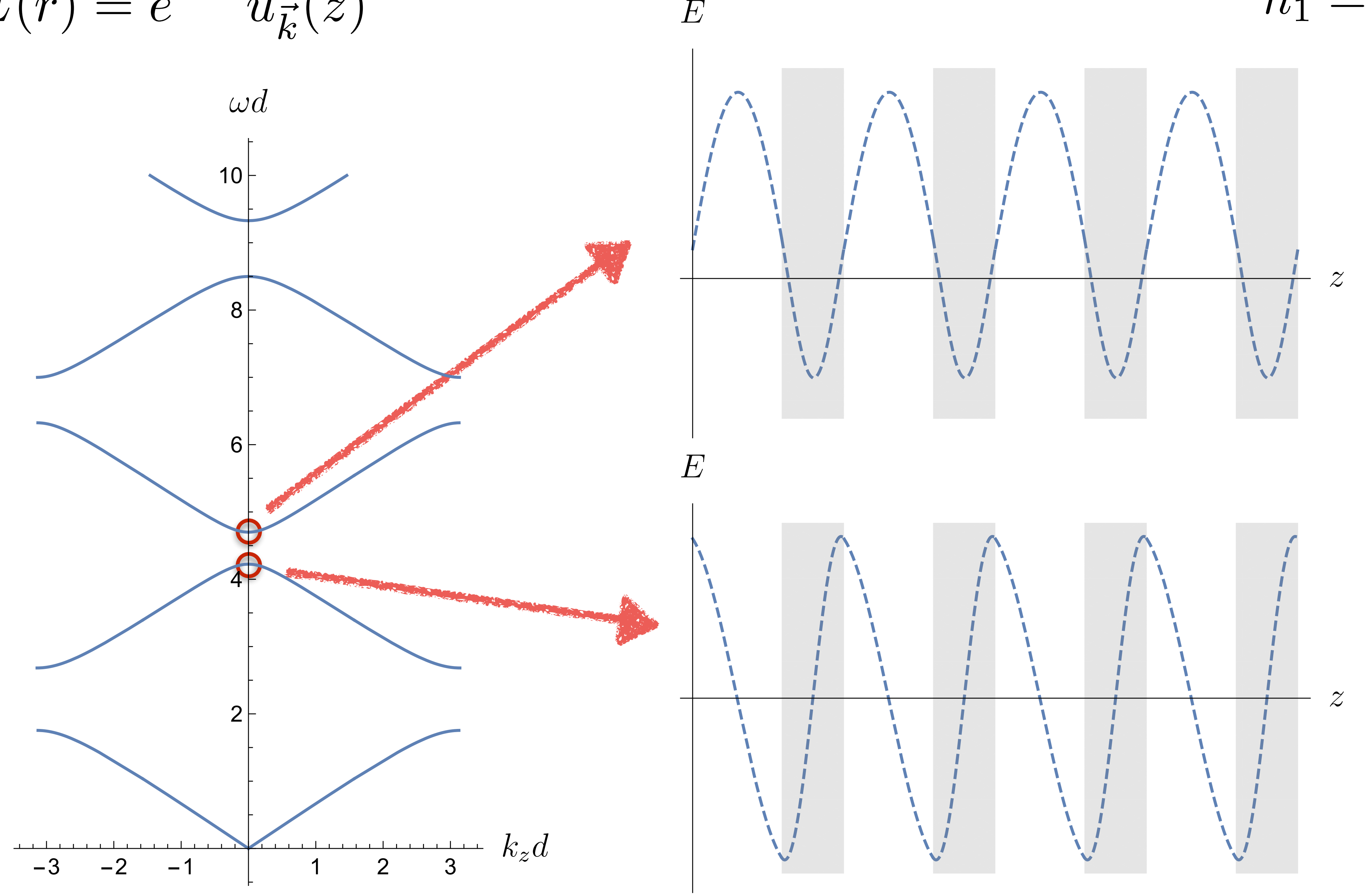
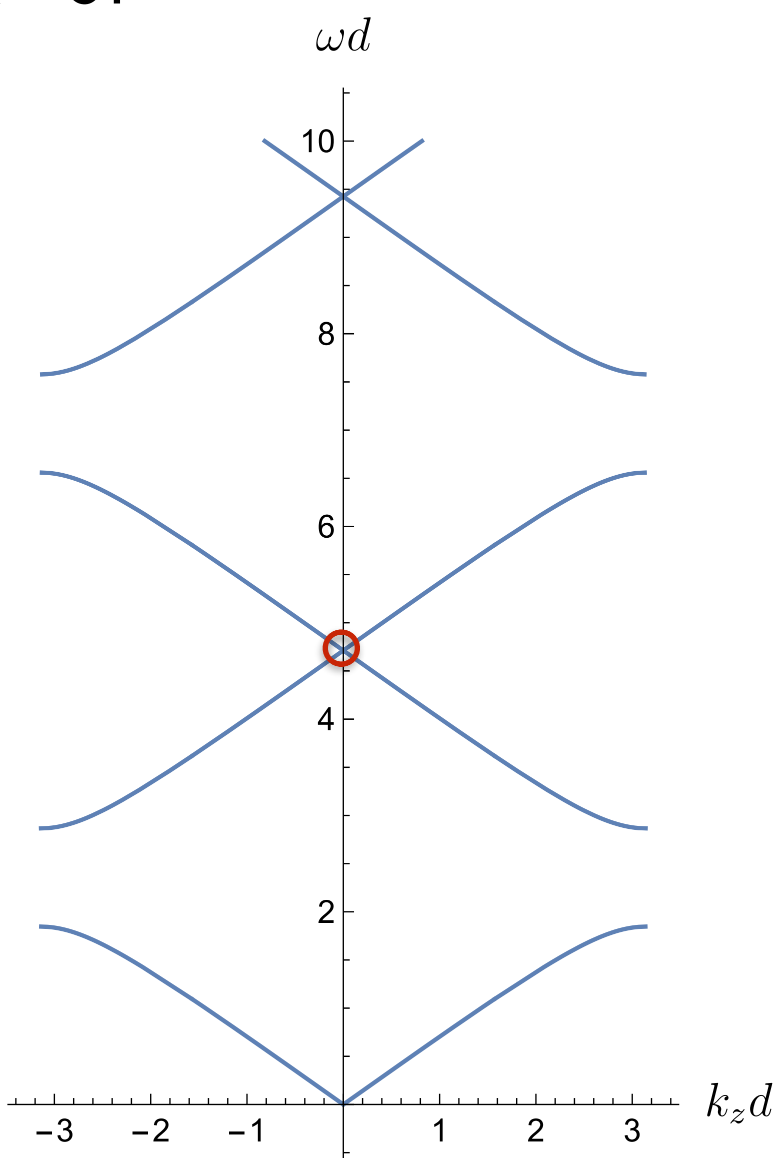


Half-wave stack

- For equal phase depths, $n_1 d_1 = n_2 d_2$, have no bandgaps at k=0:



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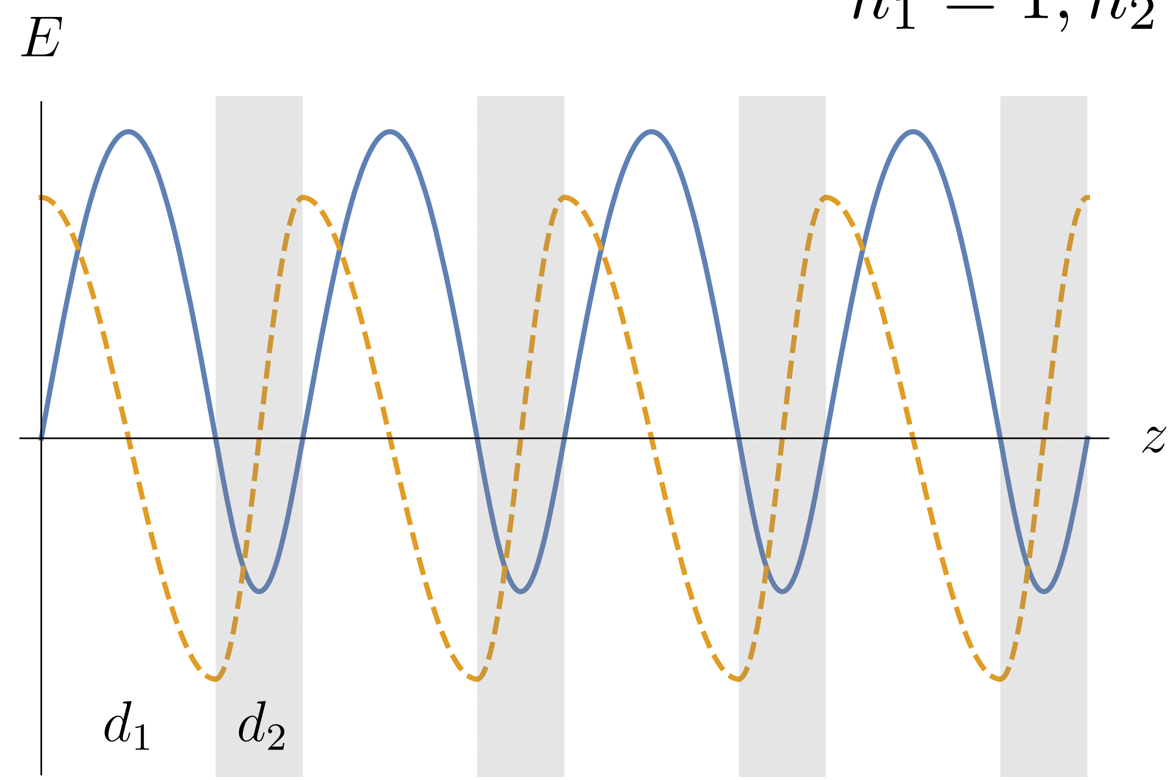

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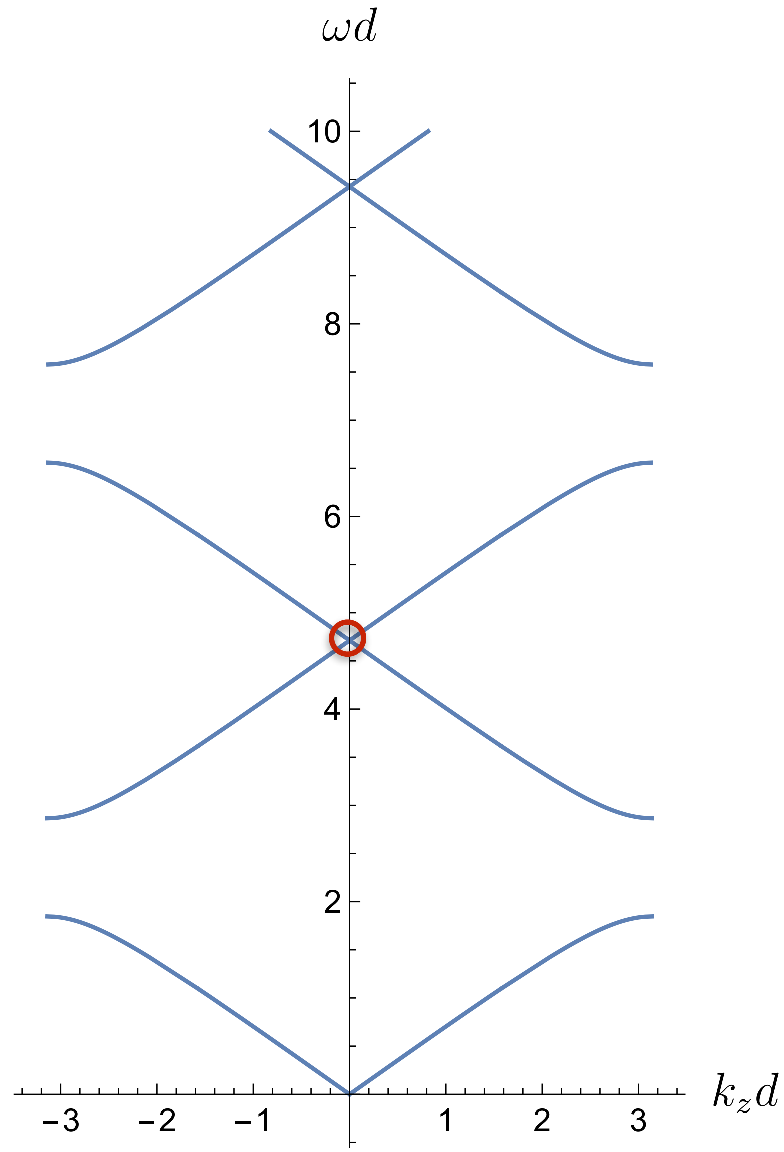

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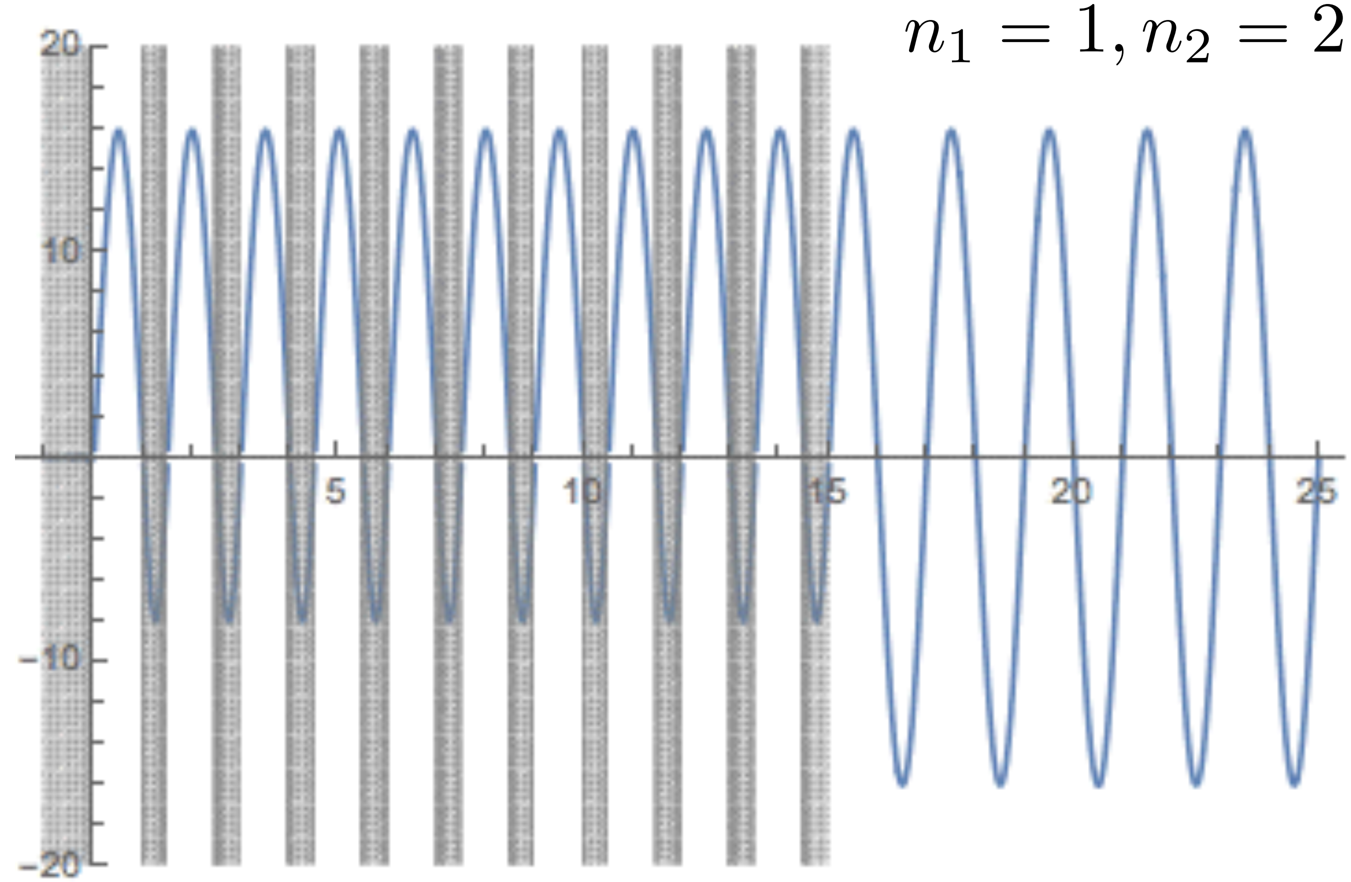

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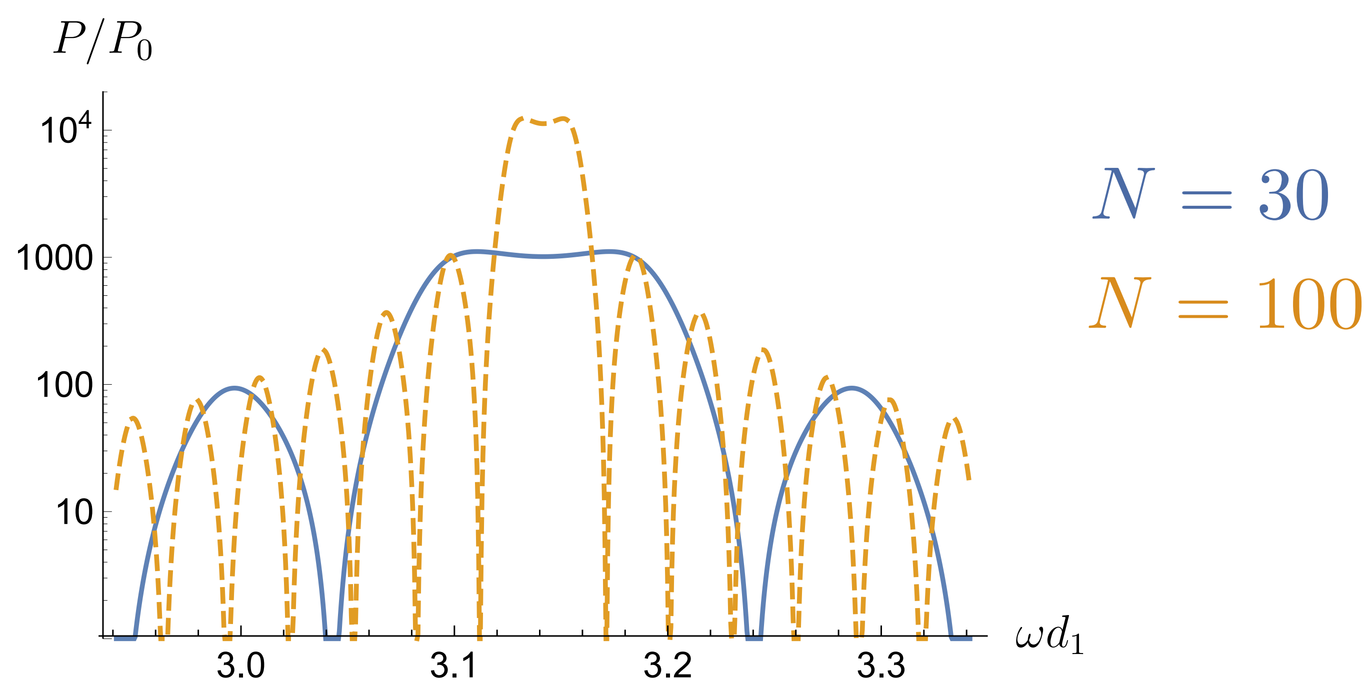
Converted power

- For stack of N periods, with area A, converted power from DM at half-wave frequency is

$$P_{\rm abs} \simeq g^2 B_0^2 \frac{\rho_{\rm DM}}{m^2} Q A N \left(\frac{1}{n_1} + \frac{1}{n_2}\right)\left(\frac{1}{n_2} - \frac{1}{n_1}\right)^2$$

- For "open cavity", $Q \propto N$
- Frequency coverage:



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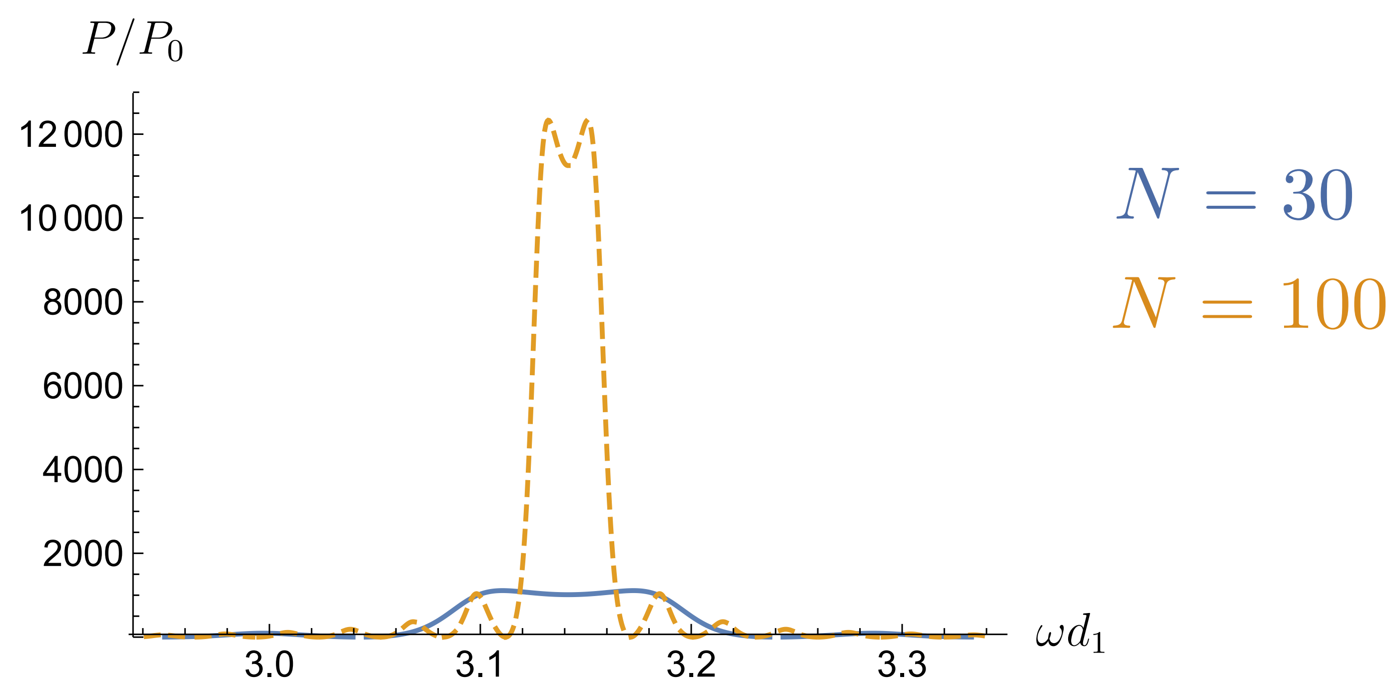

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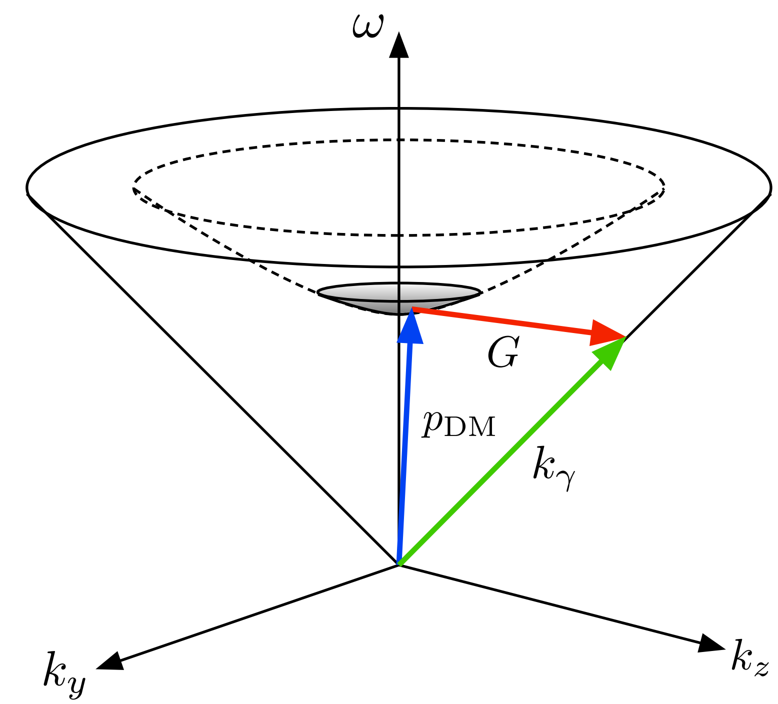
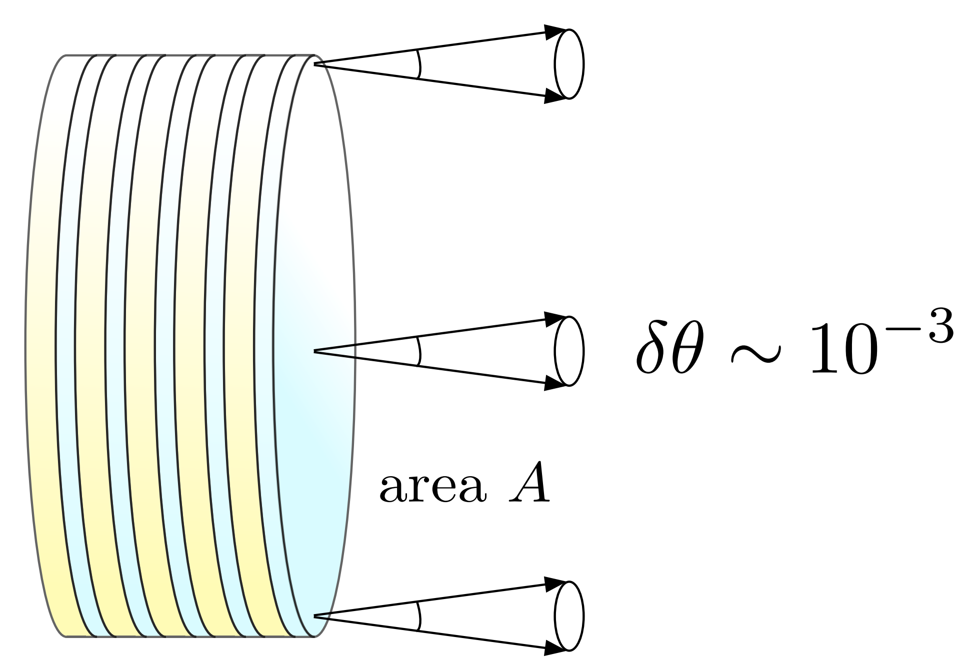
Collimated emission

- Material periodicity "donates" momentum in parallel direction, doesn't affect DM momentum in perpendicular directions

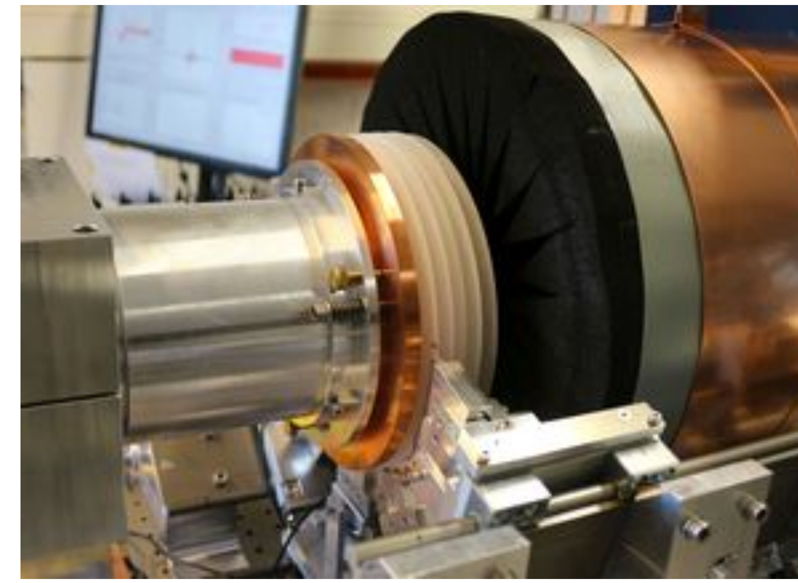


- Converted photons emitted in narrow cone around layer normal, opening angle $\sim v^{-1} \sim 10^{-3}$

- Allows focussing down to area $\sim 10^{-6} A$



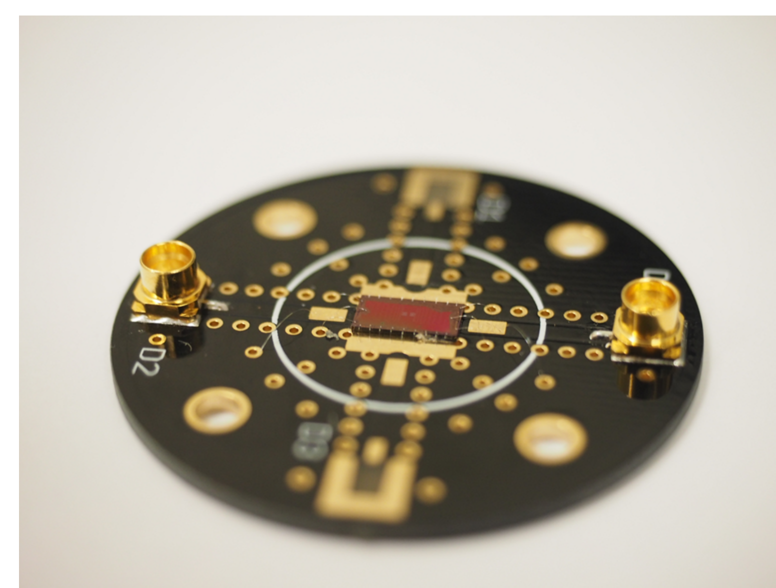
Optical-frequency absorption



- Analogous scheme proposed at microwave frequencies: MADMAX experiment
- At higher frequencies, photon detection becomes much harder …
- until we reach near-IR/optical frequencies!
- Experimental challenges:
  - low noise photon detection
  - background suppression (thermal, radioactive, cosmic)
  - fabrication and scanning

Photon detection

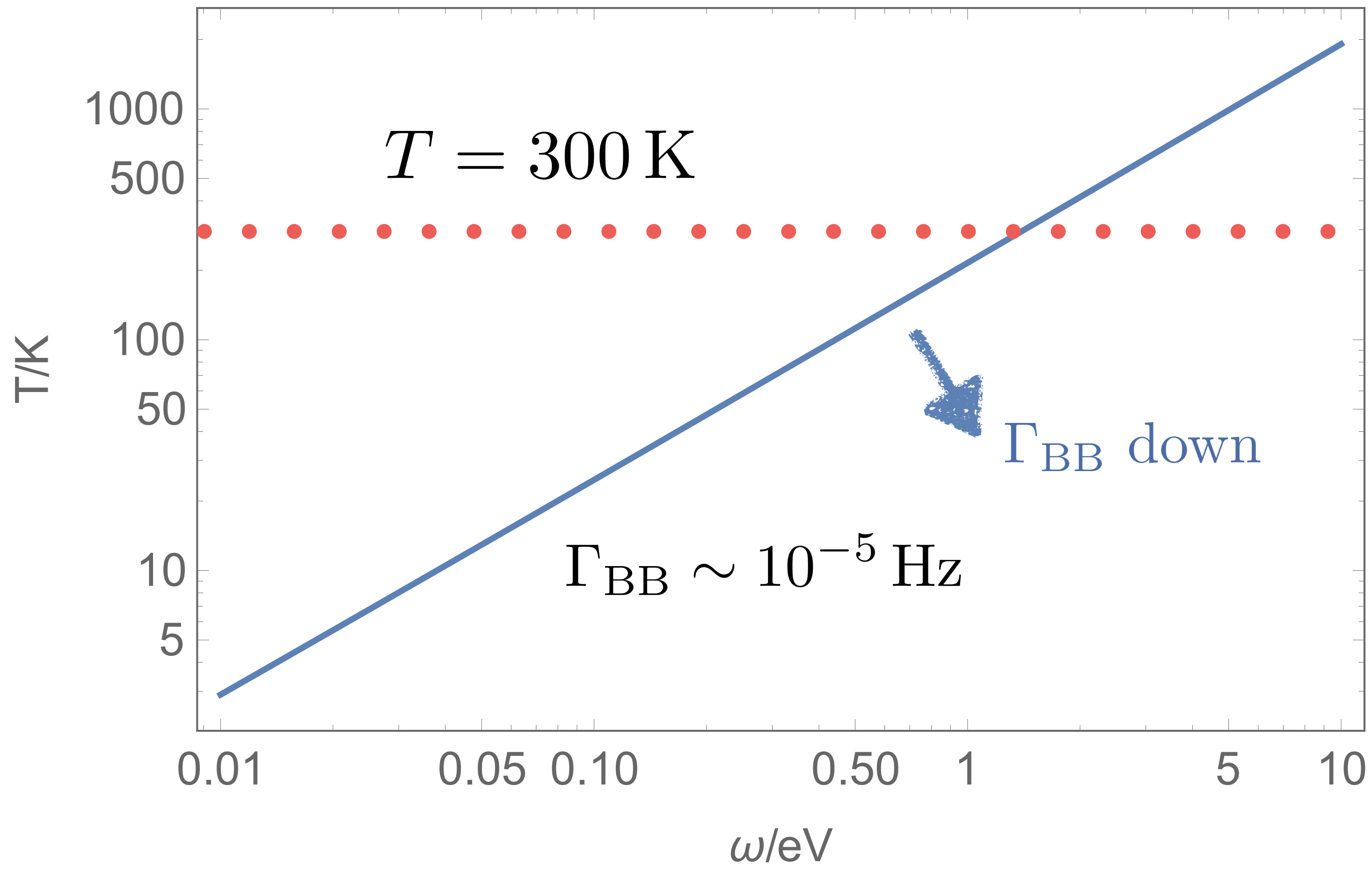
- Collimated emission means that emitted photons can be focused down to area $\sim 10^{-6}$ of layers' area
  - e.g. $(100\,\mu\mathrm{m})^2$ detector for $(10\,\mathrm{cm})^2$ layers
- Enables use of small, low-noise detectors
  - Widely-available: PMT, CCD
    $\mathrm{DCR} \sim 10^{-3}\,\mathrm{Hz}$
  - Lower-noise superconducting detectors: TES, MKID, nanowires
    $\mathrm{DCR} < 10^{-5}\,\mathrm{Hz}$



Thermal backgrounds

- Blackbody photons: if detector's field of view is at temperature T, number of blackbody photons hitting detector is

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



$A_{\rm det} = (100\,\mu{\rm m})^2$

Radioactivity / cosmic rays

- Materials of target, shielding, detector etc will contain some radioactive isotopes; unpurified materials could result in $\sim 100 \text{ decays / sec}$
- Cosmic ray muons: flux $\sim 1/(10\,\text{cm}^2\,\text{sec})$, each deposits energy in target $\sim 1 - 100\,\text{keV}$
- All of these events much more energetic than signal photons, and unless they shower into very many particles, unlikely to hit small detector
- Characterise these backgrounds: active veto / purification / shielding if necessary

Dark photon conversion

- Simplest form of spin-1 DM interaction is coupling to EM current:

$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2A'^2 + J_{\mathrm{EM}}(A + \kappa A')$$

- Also least constrained by current experiments, because of mixing with photon

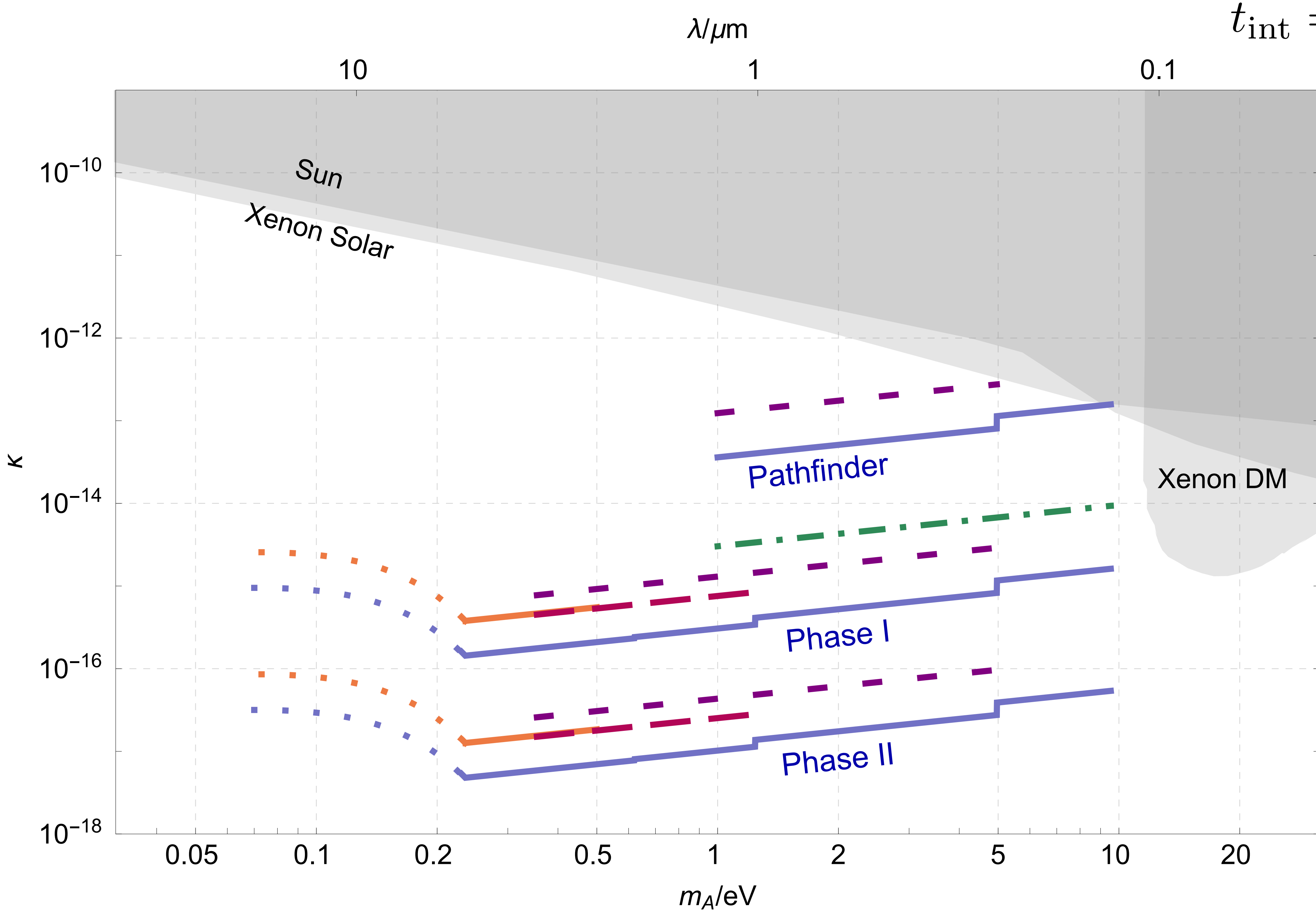
- Non-relativistic dark photon DM oscillation acts like effective current density, $J_{A'} \simeq \kappa m \partial_t A'$

- Comparing to "axion current" $J_a \simeq g\dot{a}B_0$, dark photons convert to photons in dielectric layers, even without magnetic field

$$P_{\mathrm{abs}} \simeq \frac{2}{3}\kappa^2 m \rho_{\mathrm{DM}} QAN \left(\frac{1}{n_1} + \frac{1}{n_2}\right)\left(\frac{1}{n_2} - \frac{1}{n_1}\right)^2$$

Dark photon sensitivity

$t_{\rm int} = 10^6\,{\rm sec}$



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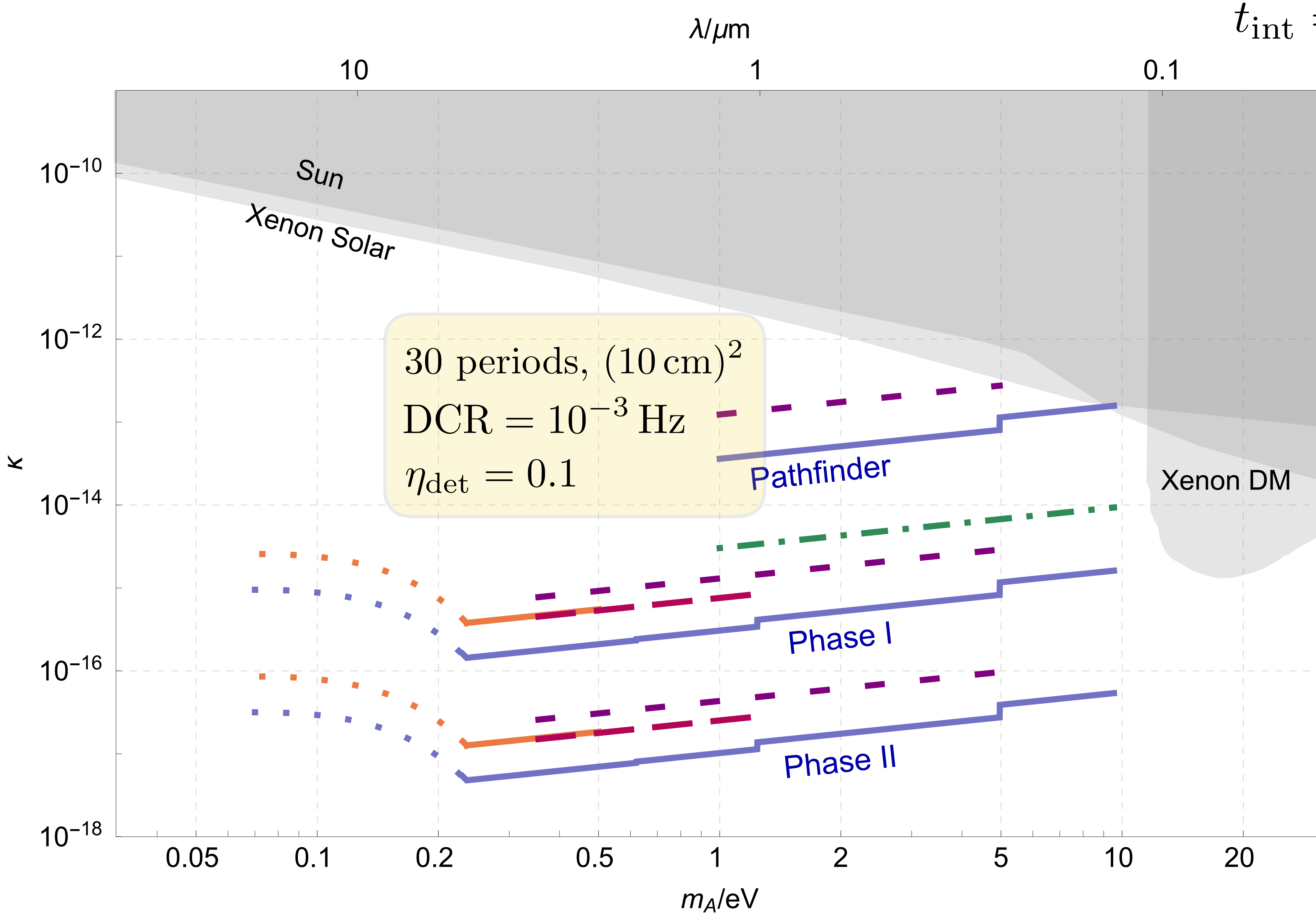

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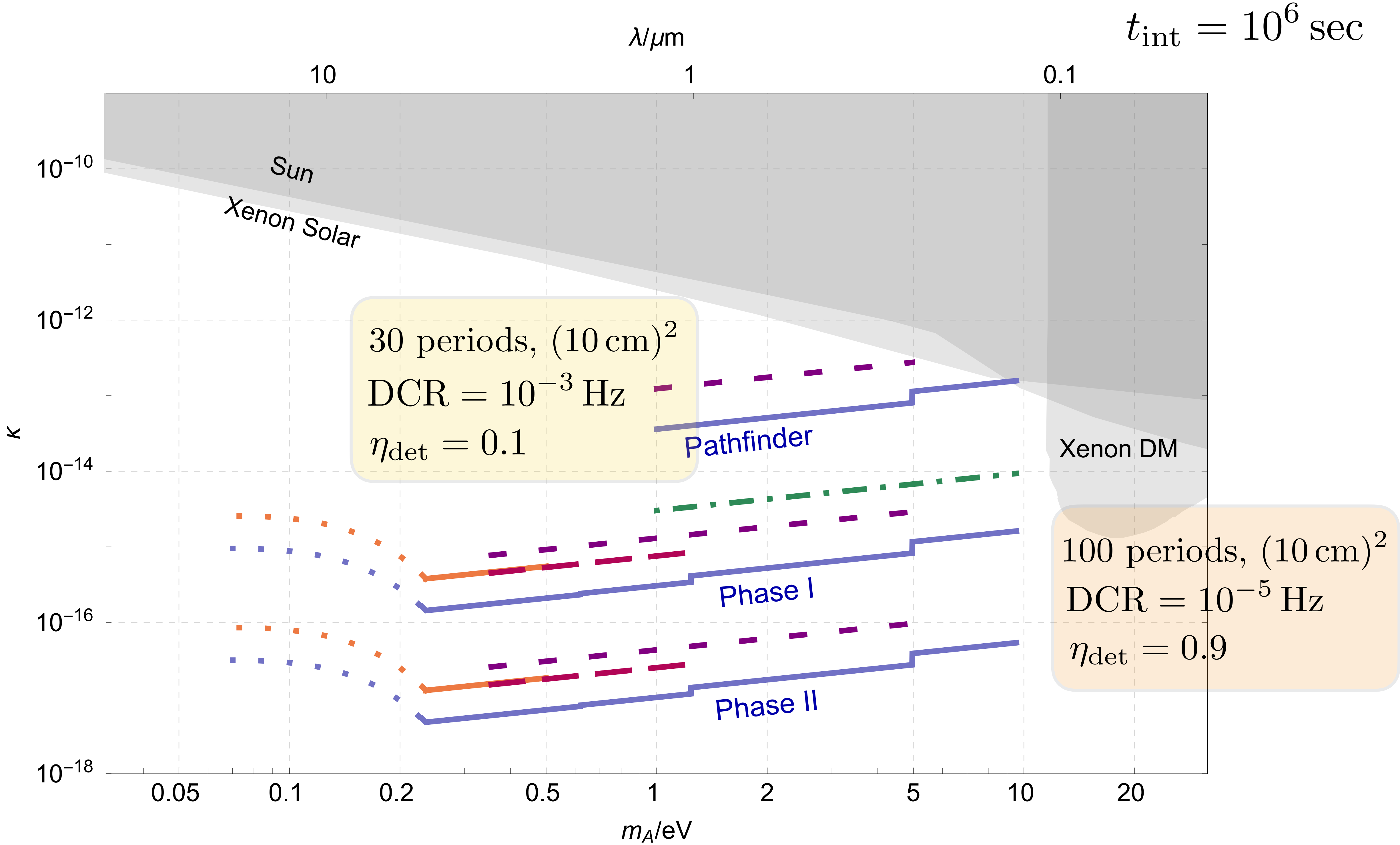

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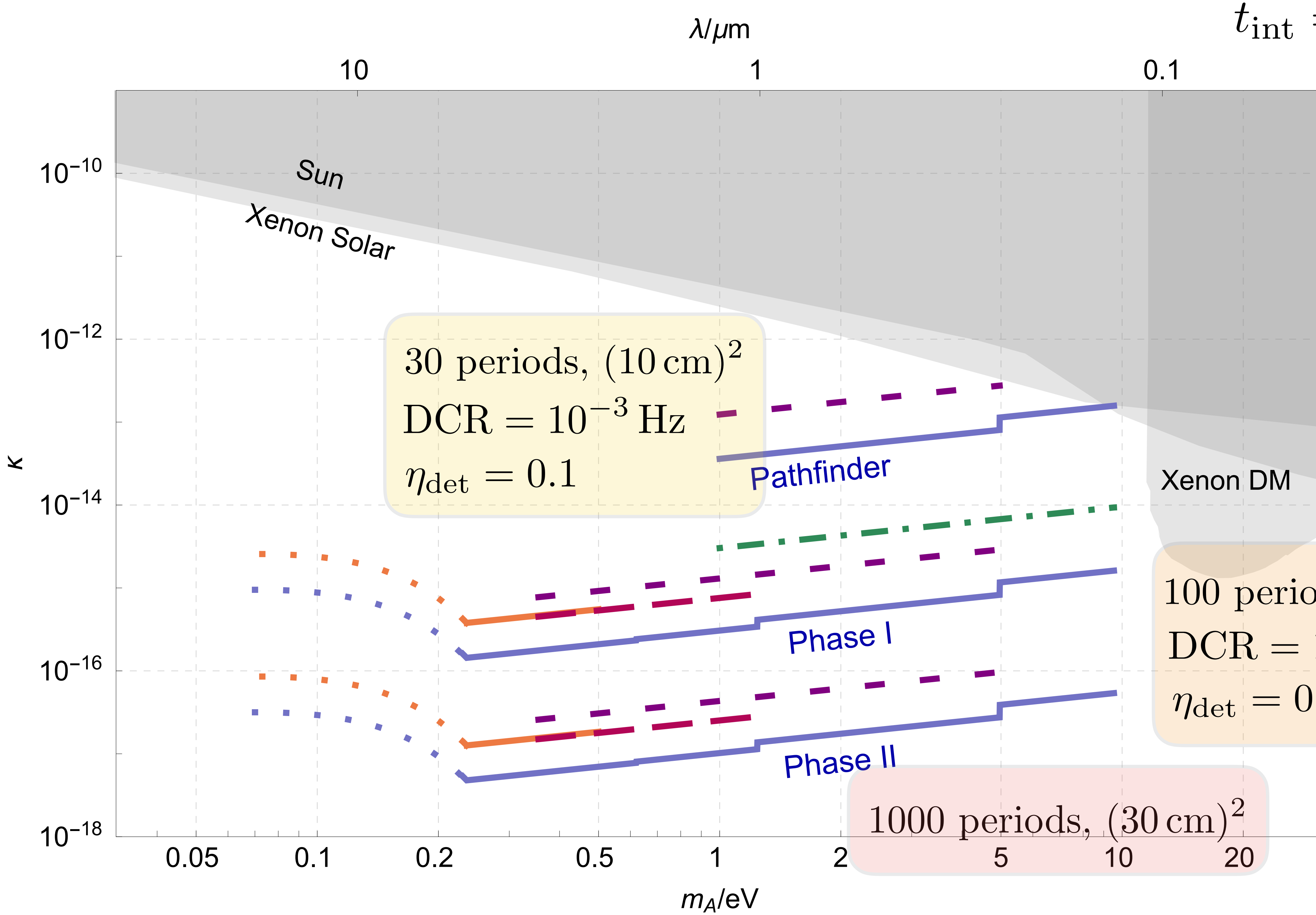
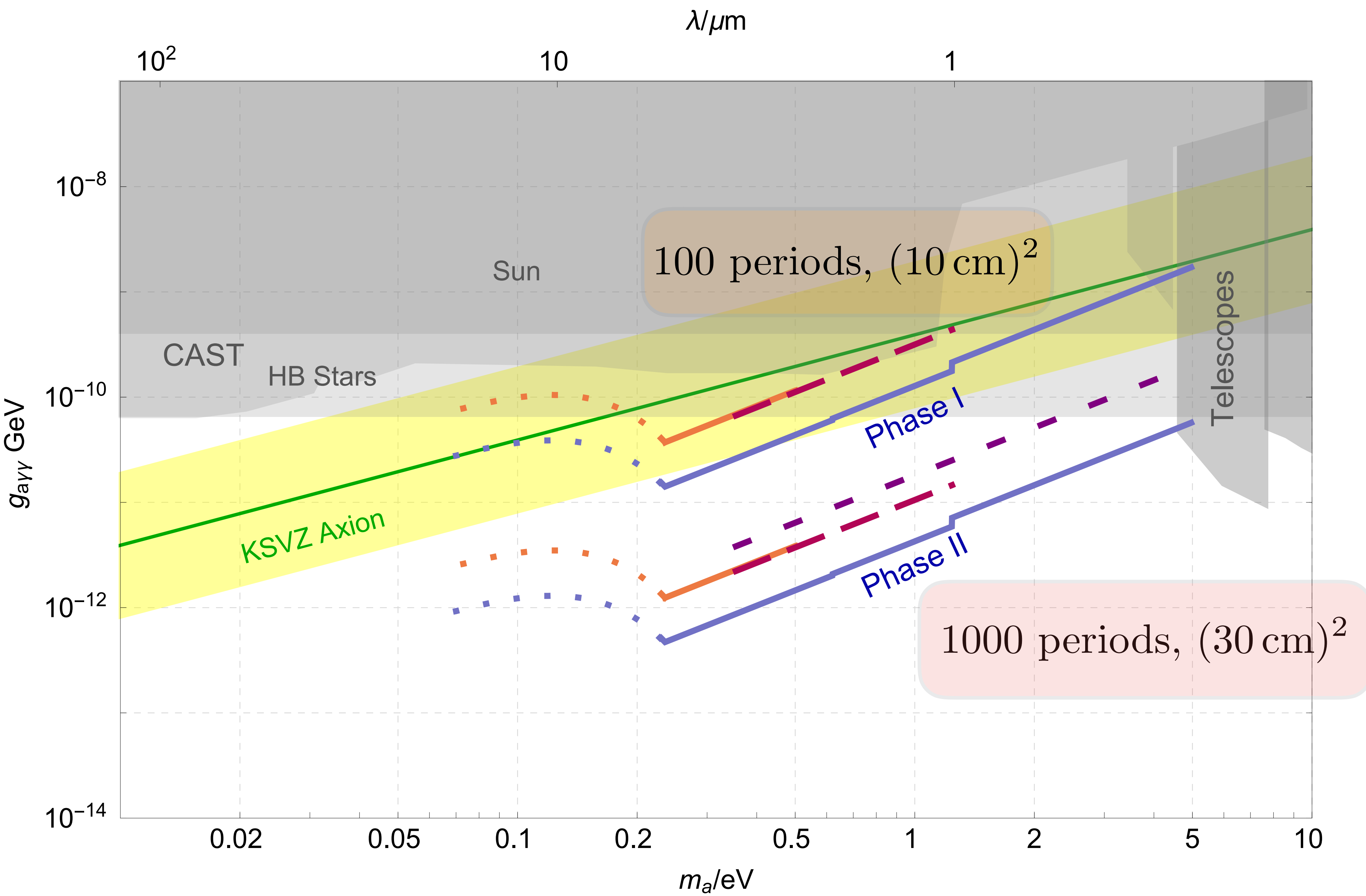


30 periods, $(10\,\rm cm)^2$
$\rm DCR = 10^{-3}\,Hz$
$\eta_{\rm det} = 0.1$

100 periods, $(10\,\rm cm)^2$
$\rm DCR = 10^{-5}\,Hz$
$\eta_{\rm det} = 0.9$

1000 periods, $(30\,\rm cm)^2$

Axion sensitivity



$t_{\rm int} = 10^6\,{\rm sec}$

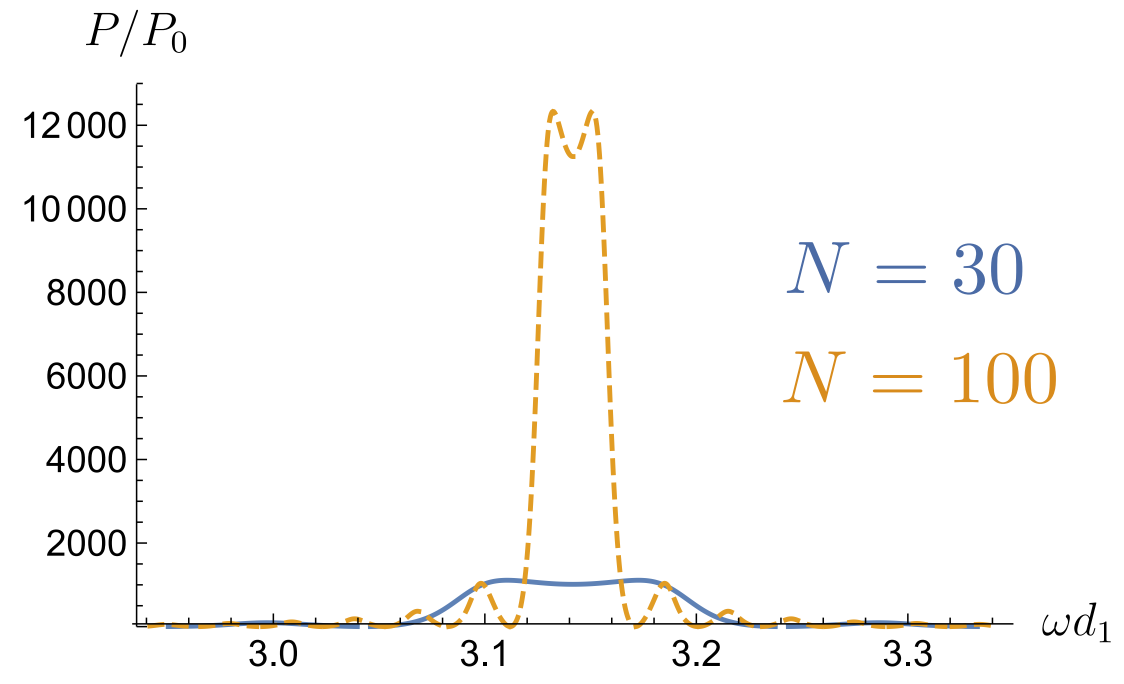
$B_0 = 10\,{\rm T}$

${\rm DCR} = 10^{-5}\,{\rm Hz}$

$\eta_{\rm det} = 0.9$

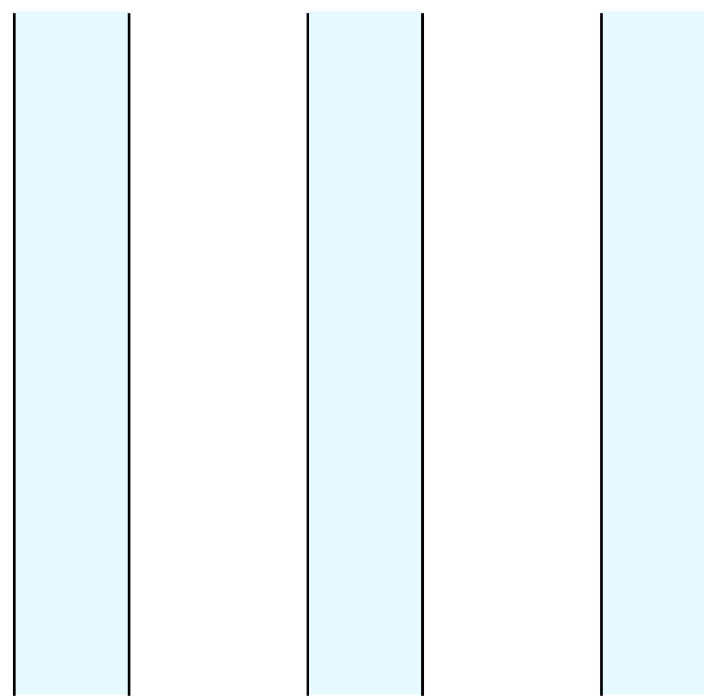
Scanning

- For half-wave stack, $P_{\rm abs} \propto N^2$ but bandwidth $\delta\omega/\omega \sim 1/N$
- Increasing conversion rate requires more layers, but this decreases the mass range covered by a given stack
- What happens for other configurations?



Frequency-averaged power

- Imagine short "pulse" $a(t)$ of DM field



- In general, frequency-averaged power converted is

$$P_{\rm av} \simeq (g a_0 B_0)^2 A \sum_i \left(\frac{1}{n_1} + \frac{1}{n_2}\right)\left(\frac{1}{n_2} - \frac{1}{n_1}\right)^2$$

independent of layer thicknesses and spacings!

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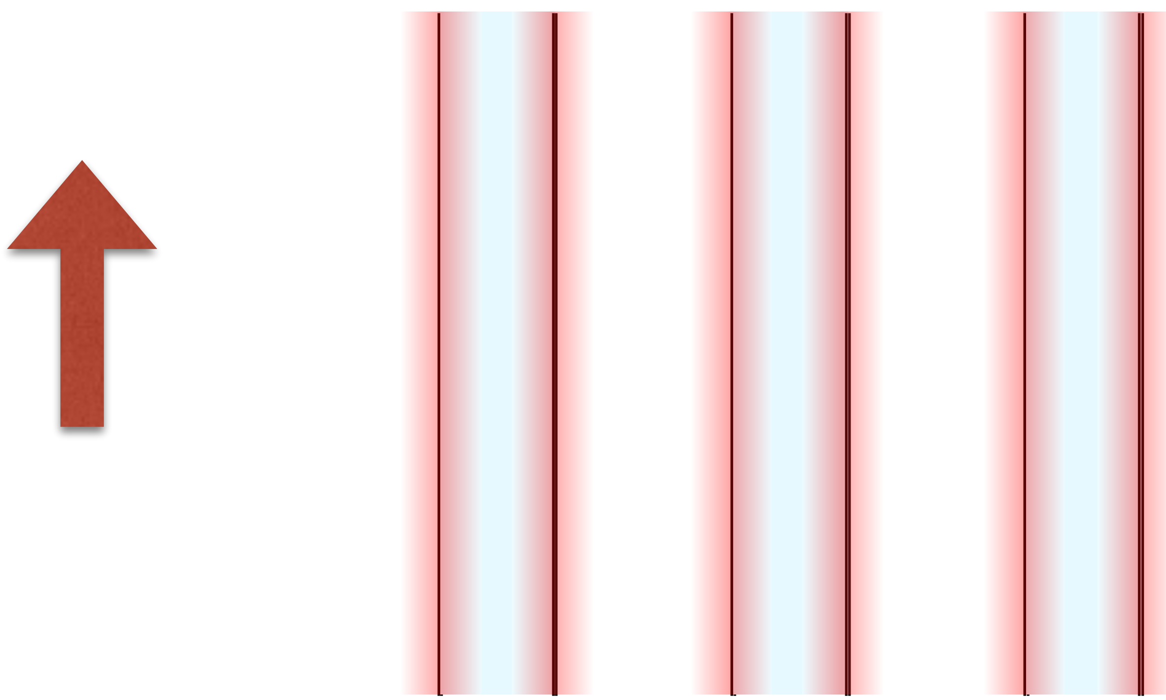

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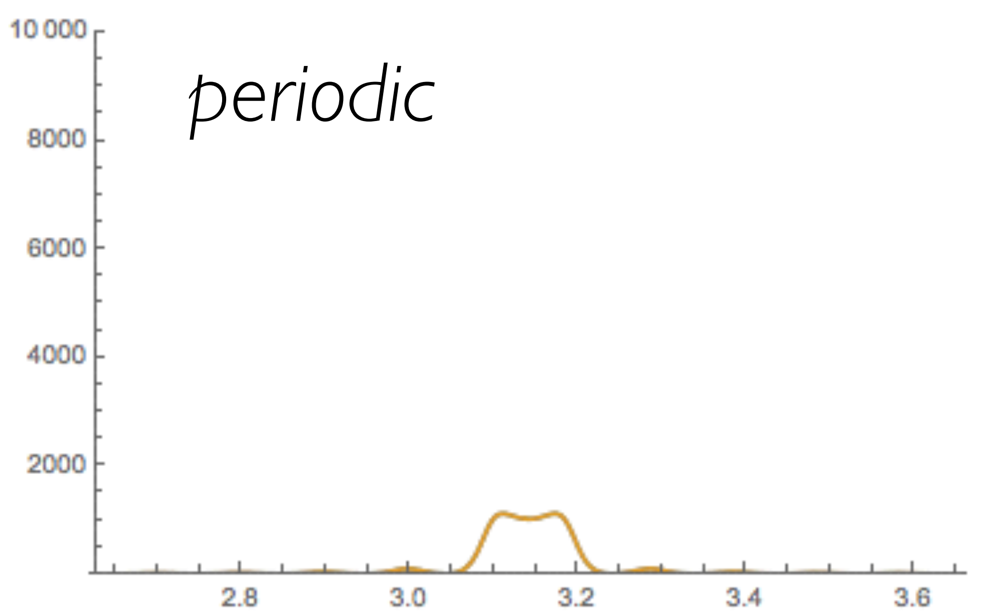
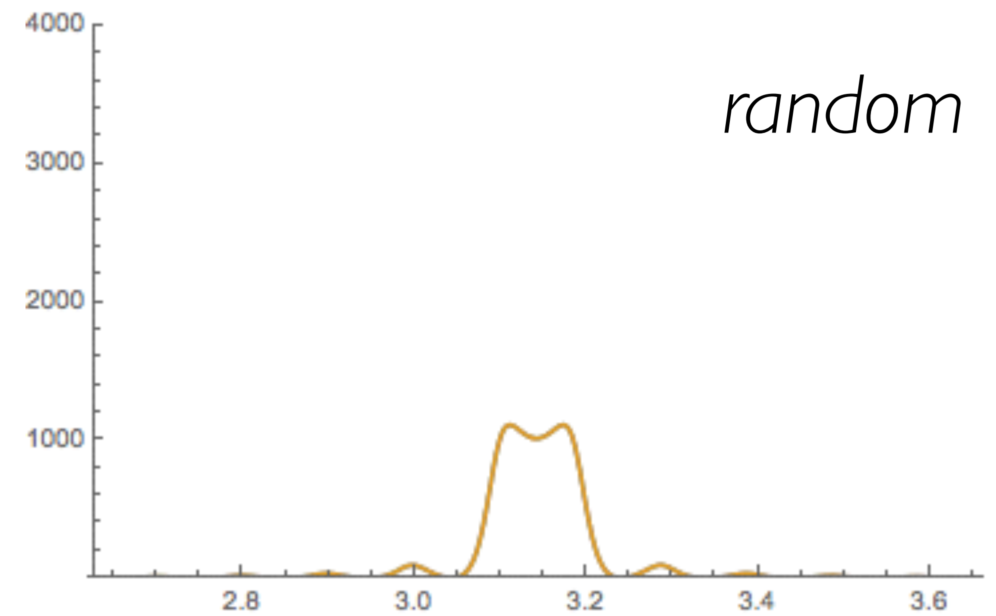
Scanning

- Converted power as a function of frequency is strongly affected by structure:



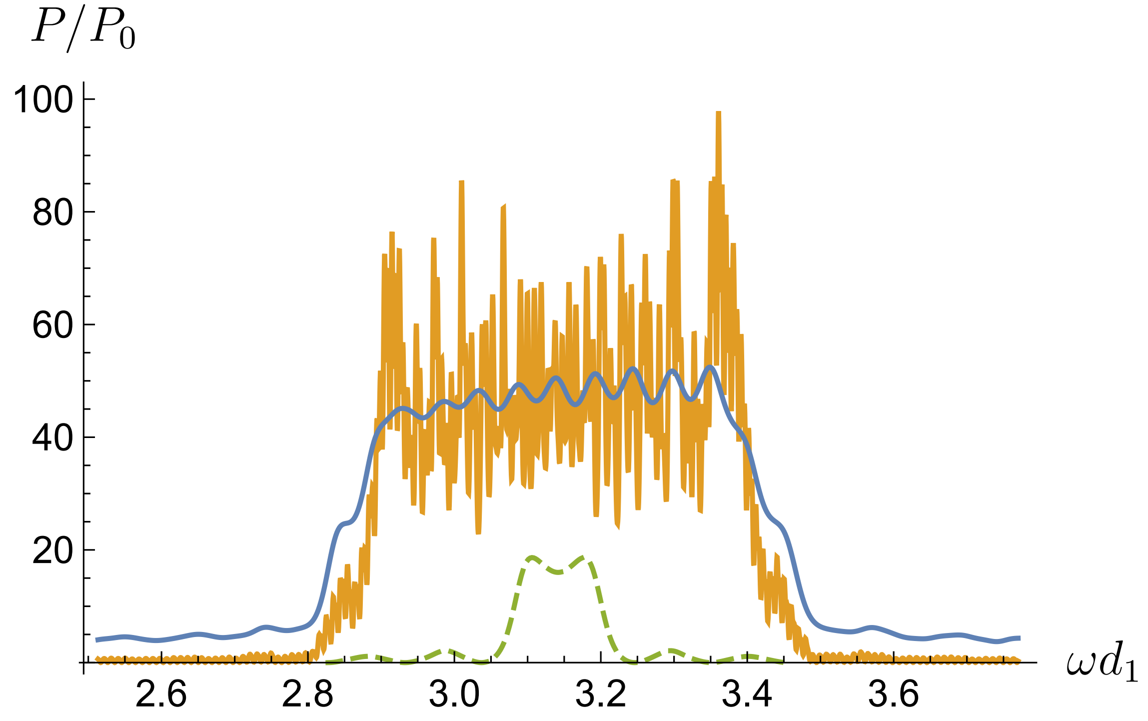


- For periodic layers, half-wave stack has broadest frequency profile

- To increase conversion rate, want more layers, but this tends to decrease bandwidth - need to scan somehow

Scanning

- If experiment not background-free, signal-to-noise improved by scanning a narrow frequency profile
- At optical frequencies, backgrounds are low - bigger issue is expense of fabricating different configurations
- Possibilities:
  - Altering refractive indices
  - Combining stacks of different periodicities



Other DM candidates

- 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

Summary

- Detection of bosonic DM at higher frequencies is an important gap in the experimental program
- Coherent absorption has attractive features; for absorption to photons, it requires wavelength-scale structure in the target
- Layered dielectrics are a simple way to absorb DM candidates with couplings to photons
- Pilot experimental proposals are being worked on!
- Extending downwards to lower frequencies?

Extending to lower frequencies

- At energies below $\sim 0.2\,\mathrm{eV}$, single-photon detection becomes significantly more difficult
- Well-motivated parameter space
  - a generic QCD axion has $m \lesssim 0.06\,\mathrm{eV}$ from SN1987a bounds
  - post-inflationary QCD axion DM at masses $\gtrsim 10^{-5}\,\mathrm{eV}$
  - dark photons from higher-scale inflation, $m \gtrsim 10^{-5}\,\mathrm{eV}$
- Bolometric detectors exist, with $\mathrm{NEP} \sim 10^{-20}\mathrm{W}/\sqrt{\mathrm{Hz}}$
- KSVZ axion gives converted power $10^{-22}\,\mathrm{W} \simeq \mathrm{meV/sec}$ from 1000 layers, of area $(10\,\mathrm{cm})^2$, in a $10\,\mathrm{T}$ magnetic field
- No known fundamental obstacles to improved superconducting detectors for this frequency range