Axion and hidden photon dark matter detection with multilayer optical haloscopes

Junwu Huang
Perimeter Institute
November, 2018

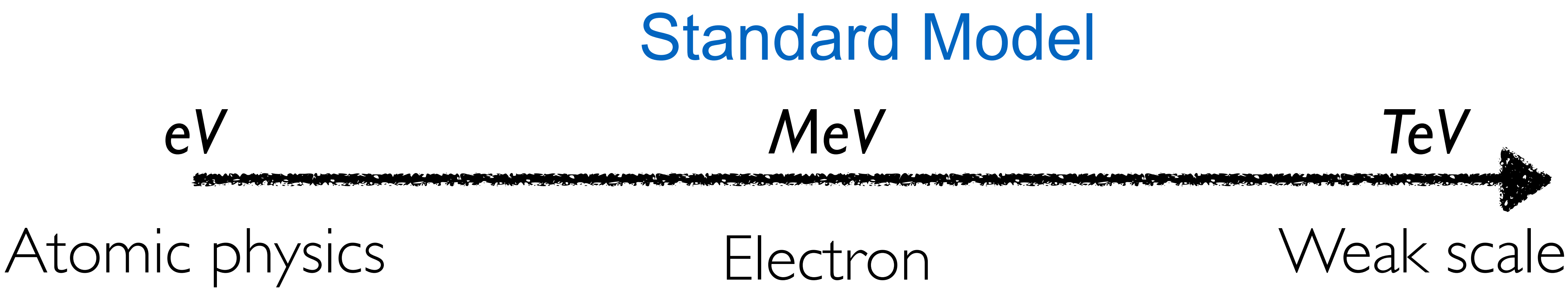
arxiv:1803.11455, Masha Baryakhtar, **JH**, Robert Lasenby,
and with Karl Berggren (MIT), Jeff Chiles and Saewoo Nam (NIST), and
with Ben Mazin, Nathaniel Craig, Miguel Daal and David Weld (UCSB)

Outline

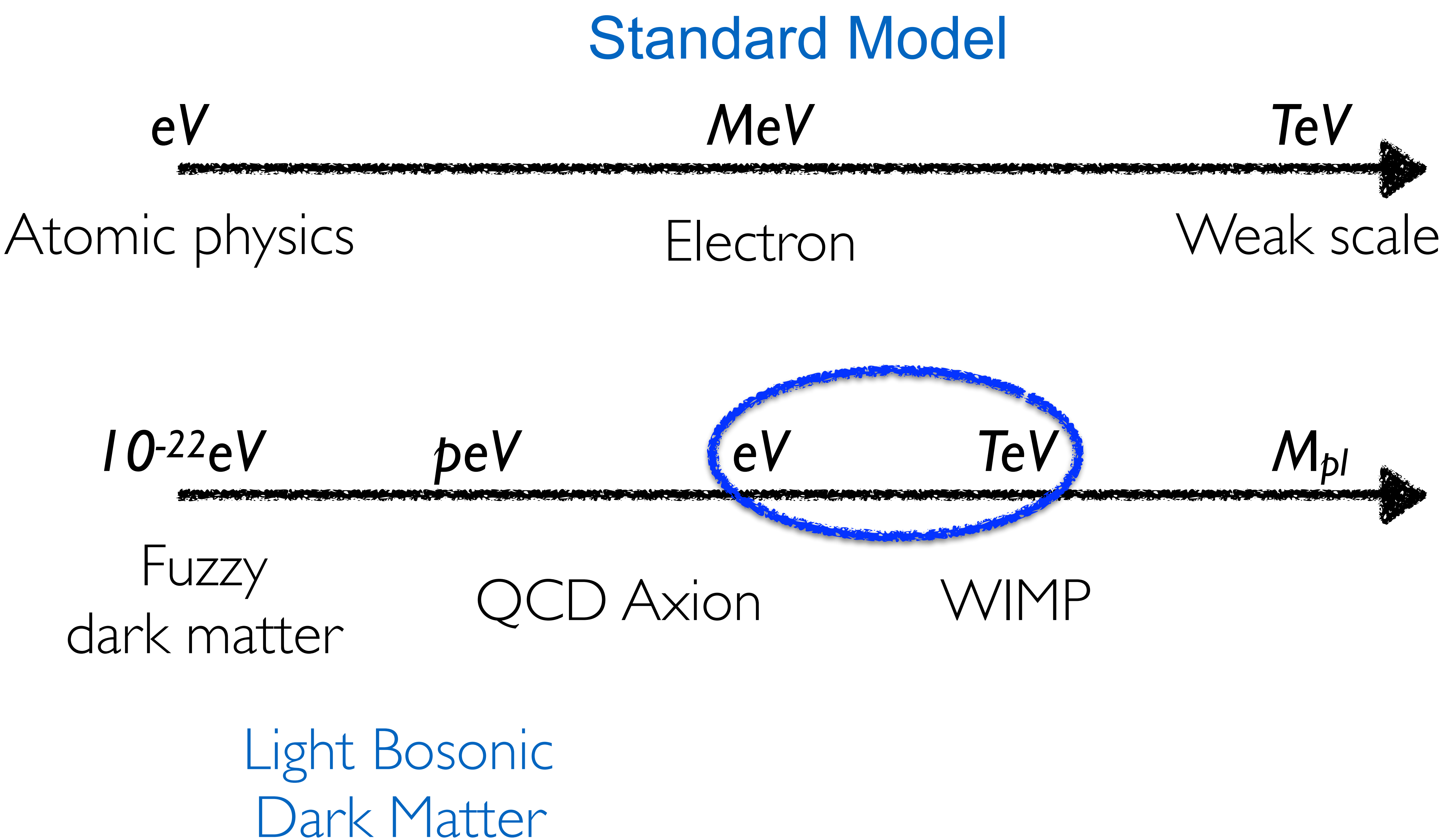
- Motivations for bosonic Dark Matter searches
- Dark Matter to photon conversion in a photonic crystal
- Experimental setup and reach
- Conclusion

Bosonic Dark Matter searches

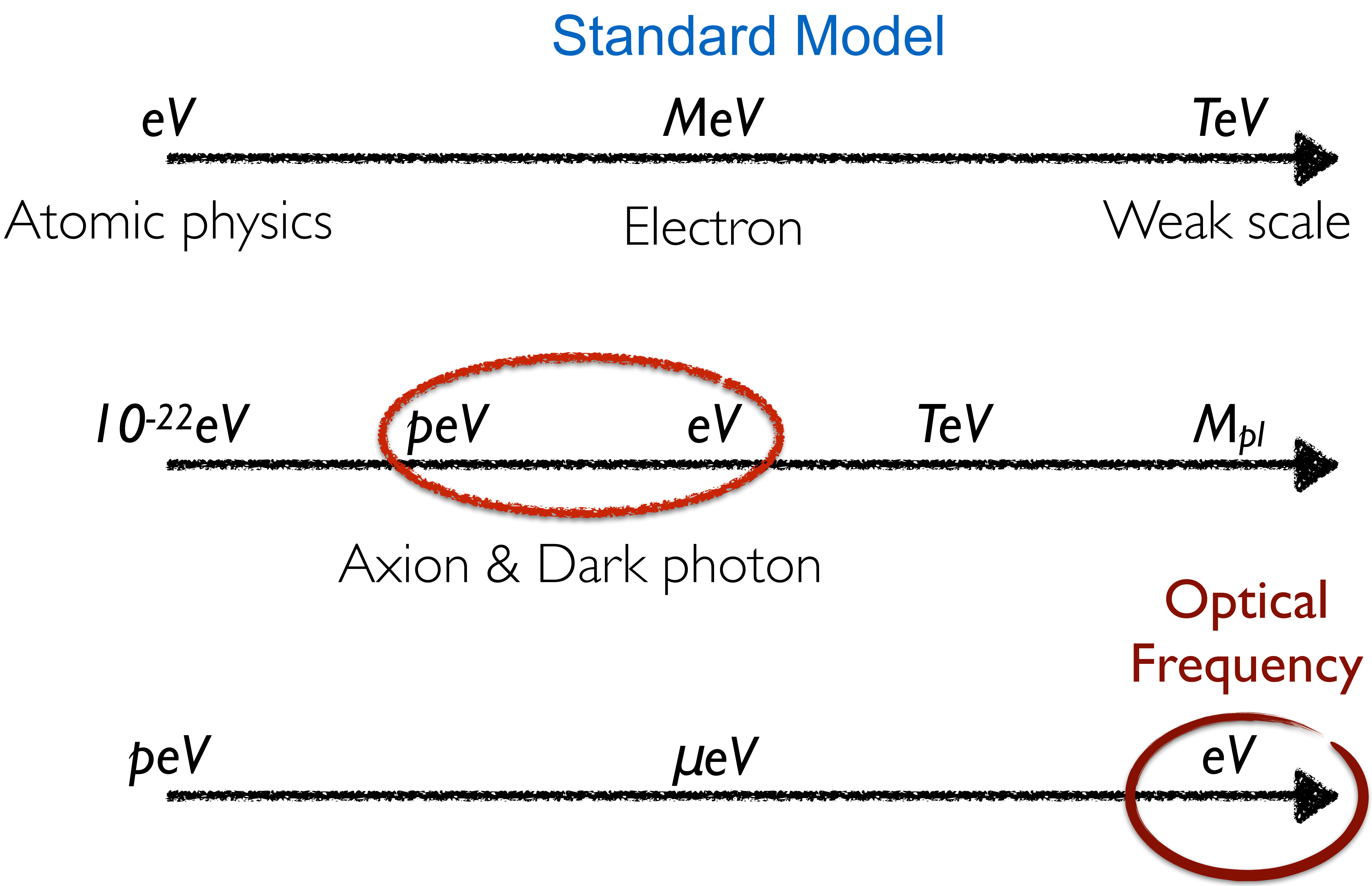
Standard Model



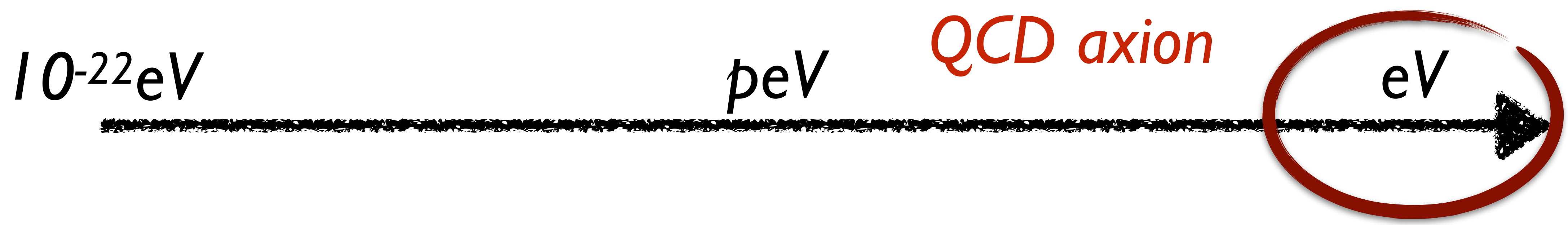
Dark matter


Standard Model
eV
MeV
TeV
Atomic physics
Electron
Weak scale
10^{-22}eV
peV
eV
TeV
M_{pl}
Fuzzy dark matter
QCD Axion
WIMP
Light Bosonic Dark Matter

Dark matter


Standard Model
eV
MeV
TeV
Atomic physics
Electron
Weak scale
10-22eV
peV
eV
TeV
Mpl
Axion & Dark photon
Optical Frequency
peV
μeV
eV

Bosonic DM properties

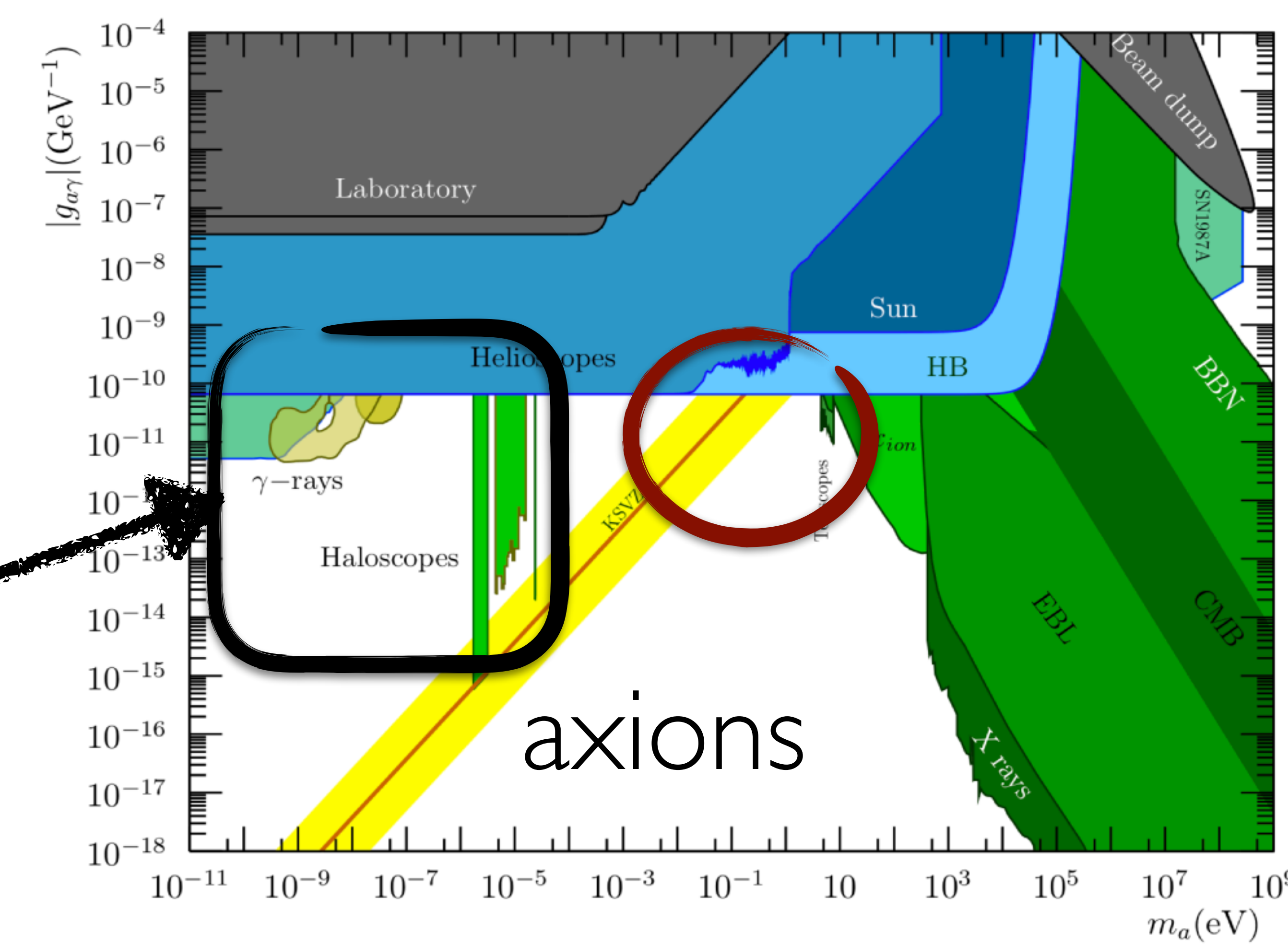


- Dark matter with $m \lesssim 100\,\mathrm{eV}$ must be bosonic, with occupation number > 1 in dense regions

- DM in form of coherent, classical oscillations of field
  coherence length $\sim (v_{\mathrm{DM}} m)^{-1} \sim 10^3 m^{-1}$
  coherence time $\sim (v_{\mathrm{DM}}^2 m)^{-1} \sim 10^6 m^{-1}$

Axions

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



- Axion productions:
  - Misalignment
  - String & domain wall

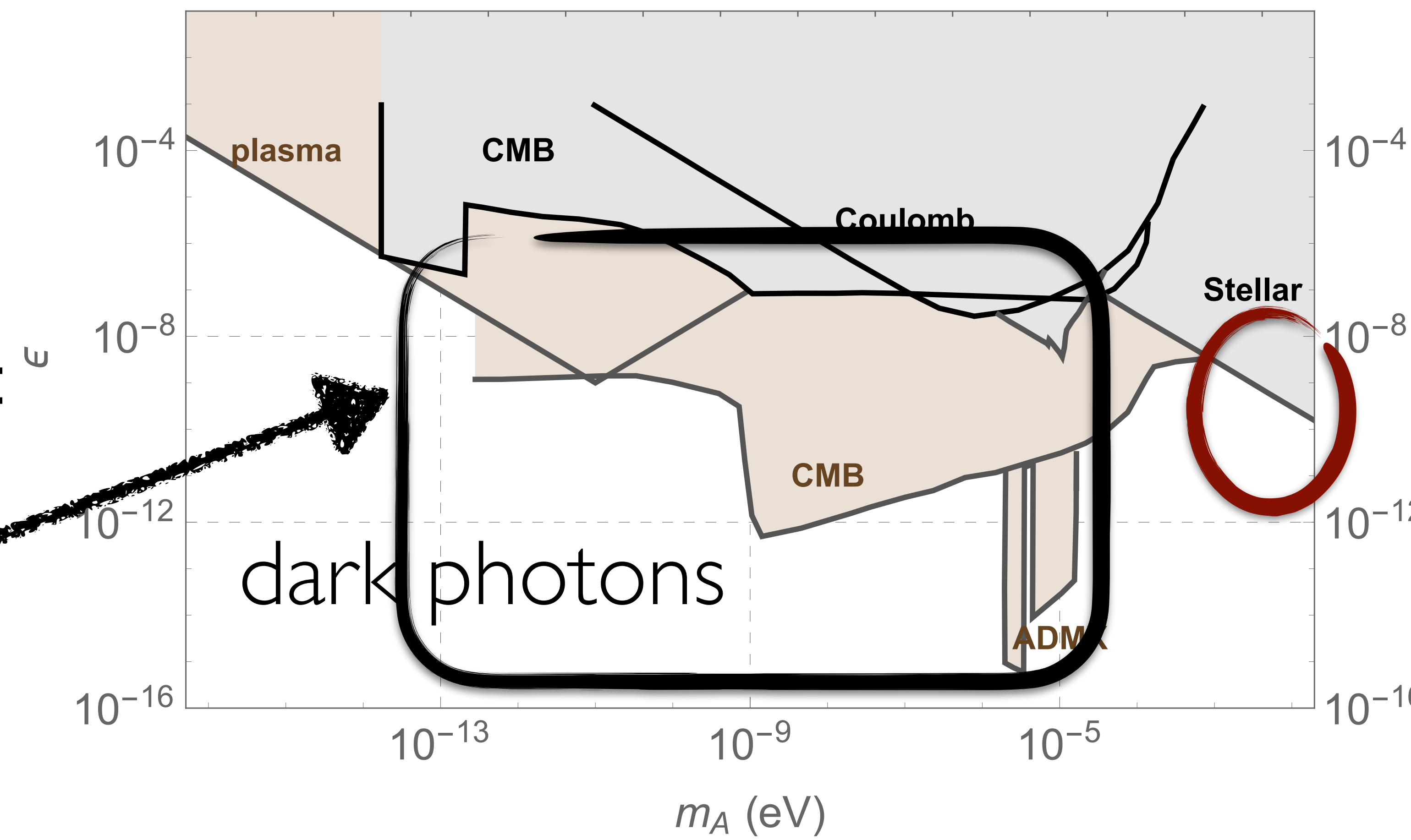
$$\frac{1}{2}(\partial_\mu a)^2 - V(a) - \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

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

Dark photons

- Dark photon parameter space:

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



- Dark photon production:

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

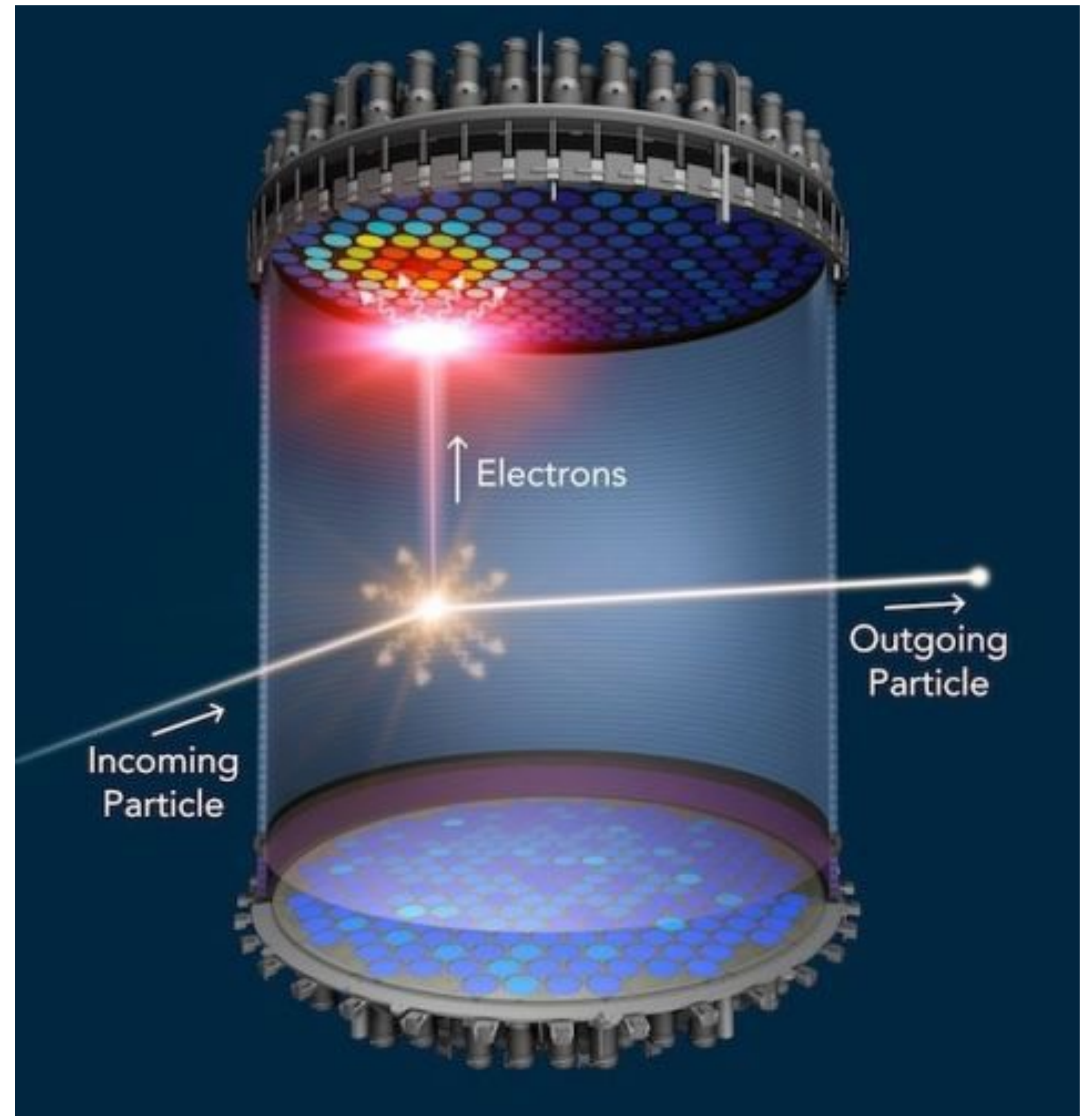
  - Inflationary production

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

Dark matter searches

- Dark matter scattering

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



Xenon

Dark matter searches

- Dark matter scattering

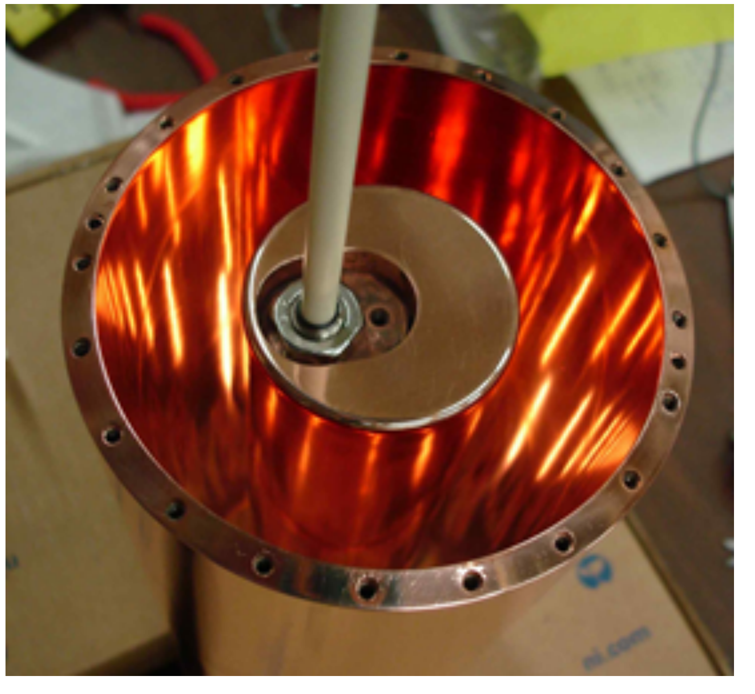
$$\Delta E \sim m_{\rm DM} v_{\rm DM}^2/2$$

$$\Delta \vec{p} \sim m_{\rm DM} v_{\rm DM}$$

- Dark matter absorption/conversion

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

$$\Delta \vec{p} \sim m_{\rm DM} v_{\rm DM}$$



Haystac

Dark matter searches

- Dark matter scattering

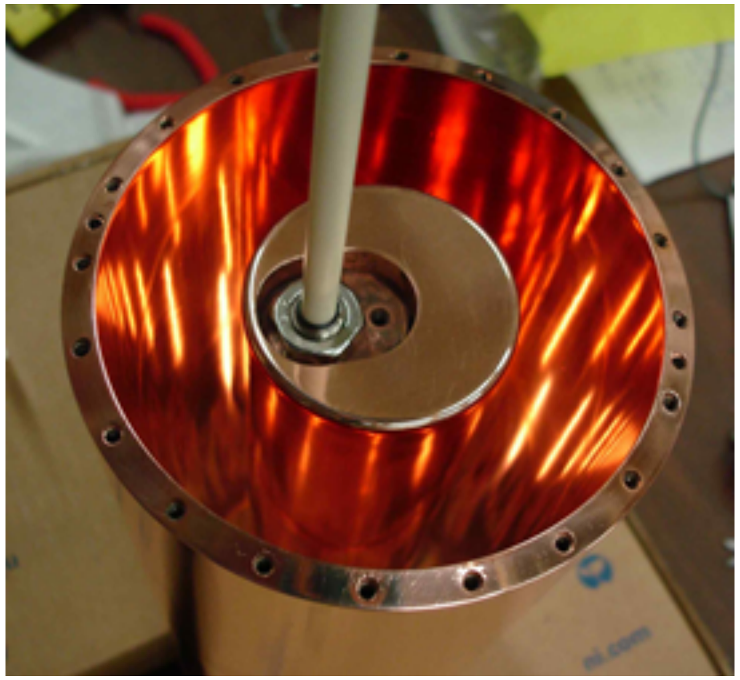
$$\Delta E \sim m_{\mathrm{DM}} v_{\mathrm{DM}}^2/2$$

$$\Delta \vec{p} \sim m_{\mathrm{DM}} v_{\mathrm{DM}}$$

- Dark matter absorption/conversion

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

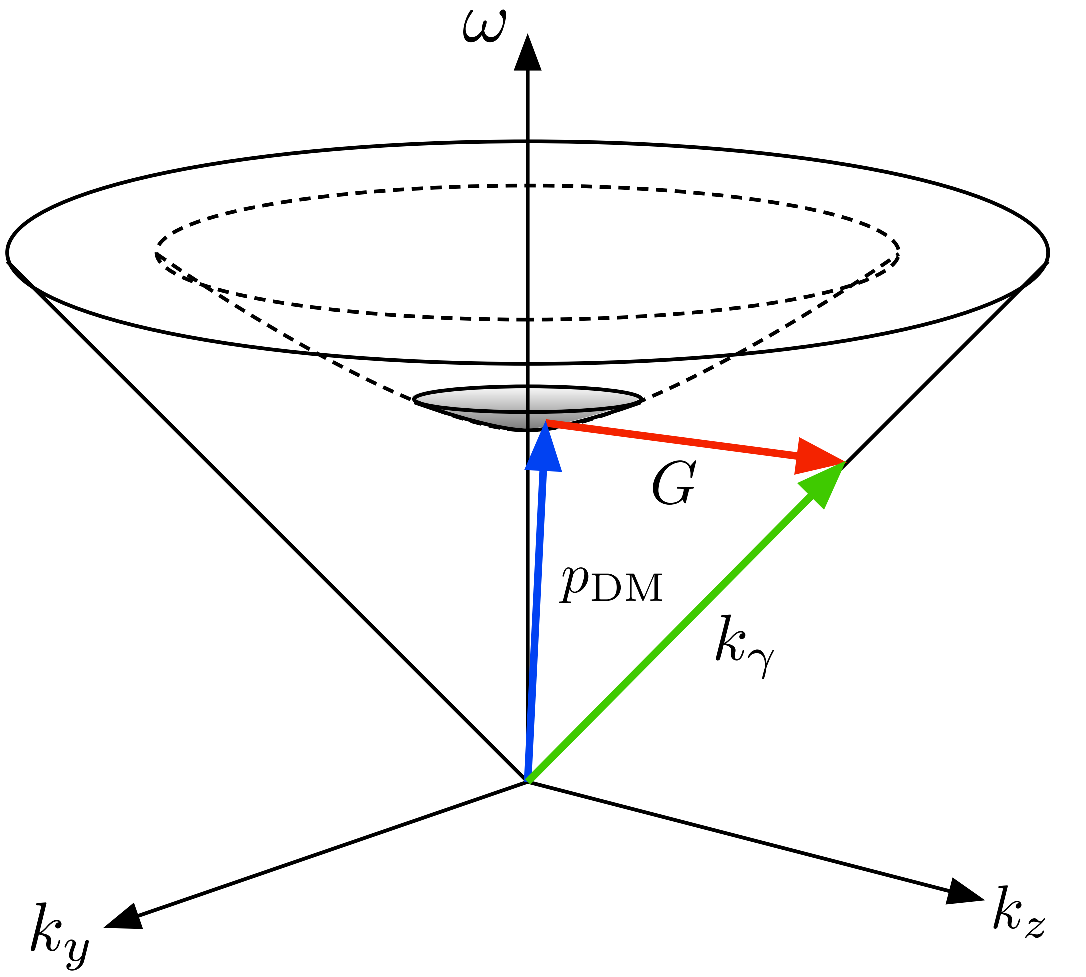
$$\Delta \vec{p} \sim m_{\mathrm{DM}} v_{\mathrm{DM}}$$



Dark matter absorption

- Challenges for dark matter absorption:

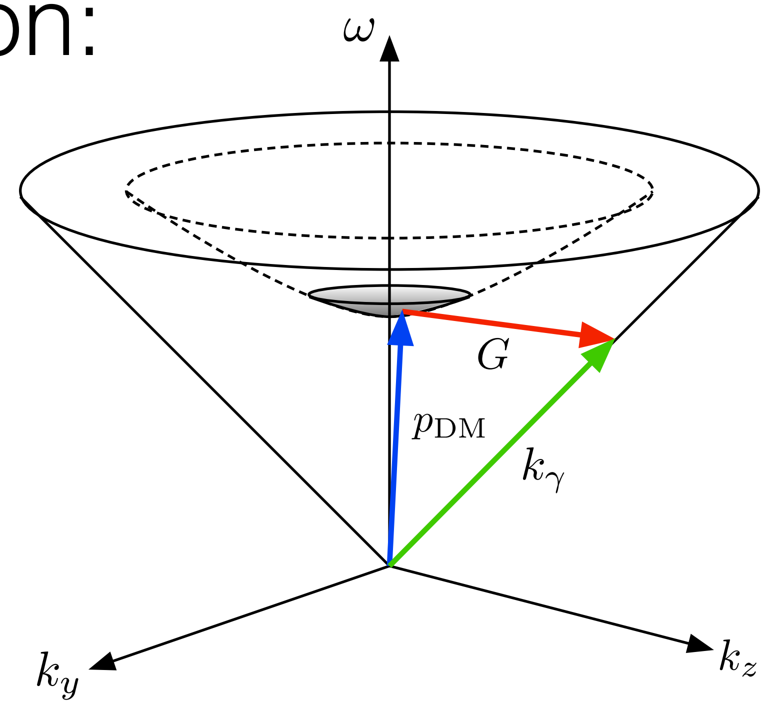
$$p_a = (m_a, m_a \vec{v_a})$$
$$p_\gamma = (m_a, \vec{m_a})$$



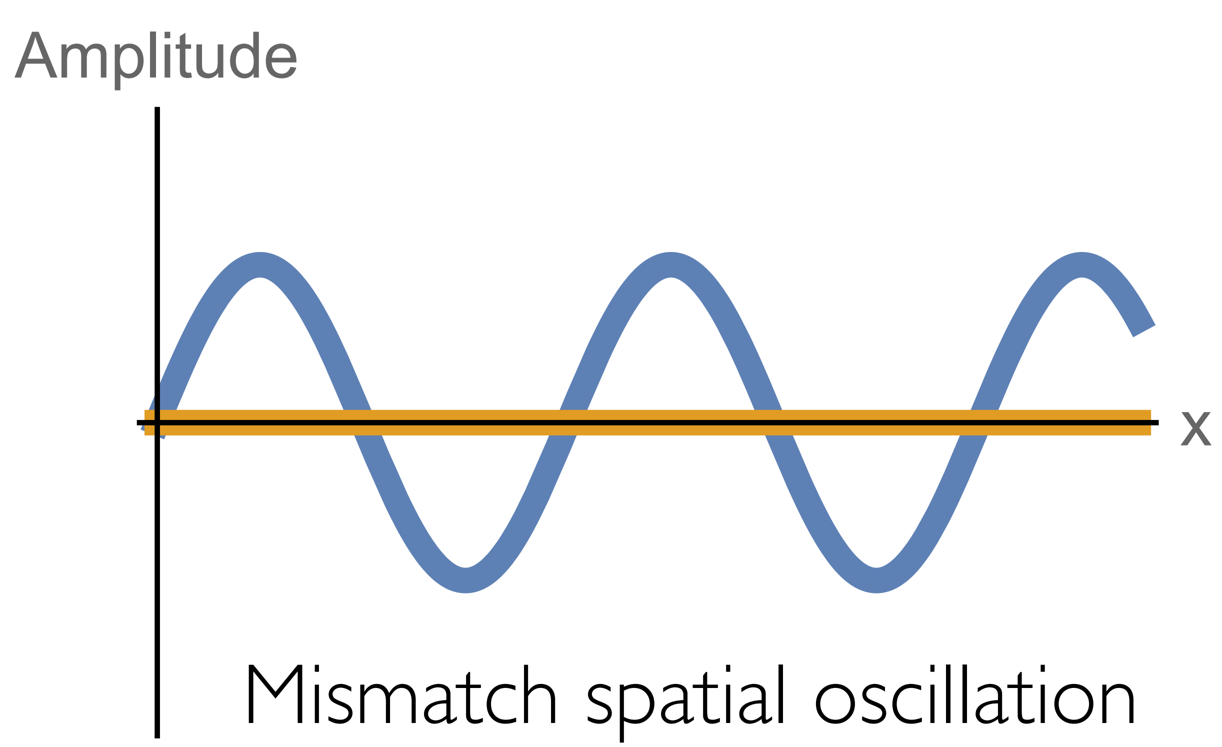
Dark matter conversion to photon

- Challenges for dark matter absorption:

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



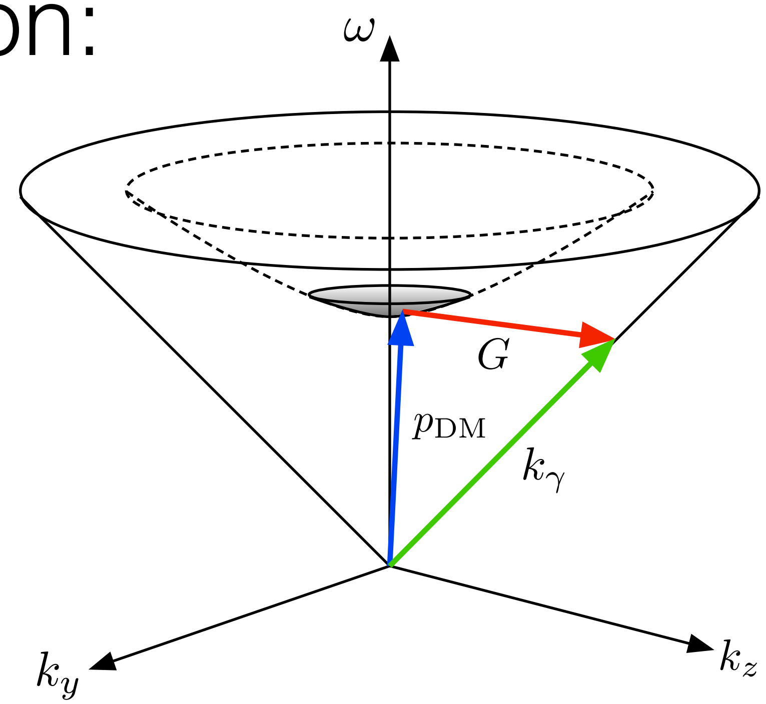
- Position space cancellation



Dark matter:
oscillate on 1/mv scales
Photon:
oscillate on 1/m scales

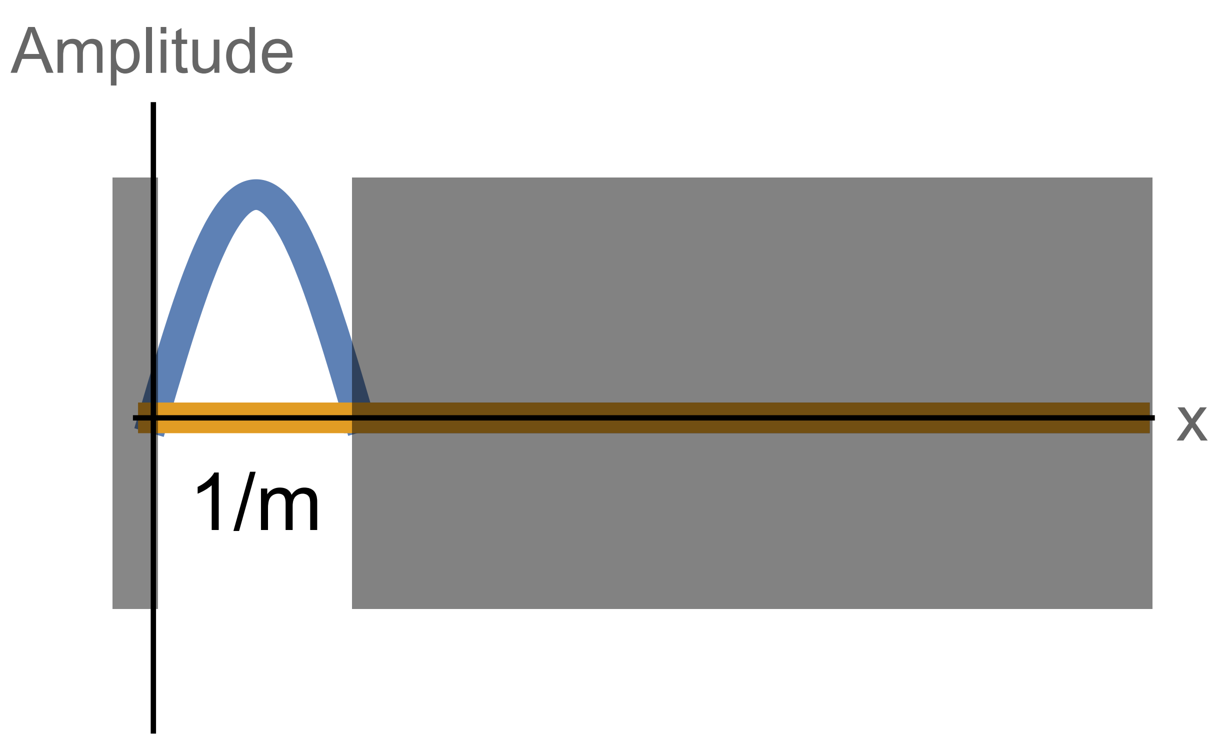
Dark matter conversion to photon

- Challenges for dark matter absorption:



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

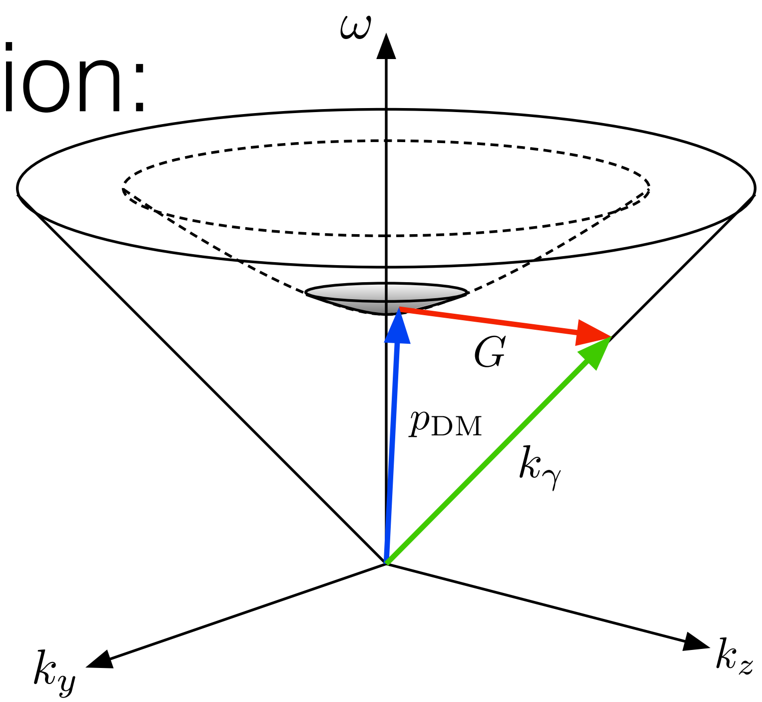
- Introduce boundary (Type I)



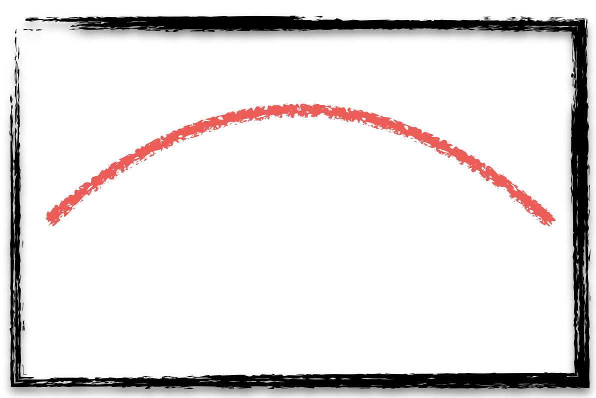
Dark matter conversion to photon

- 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

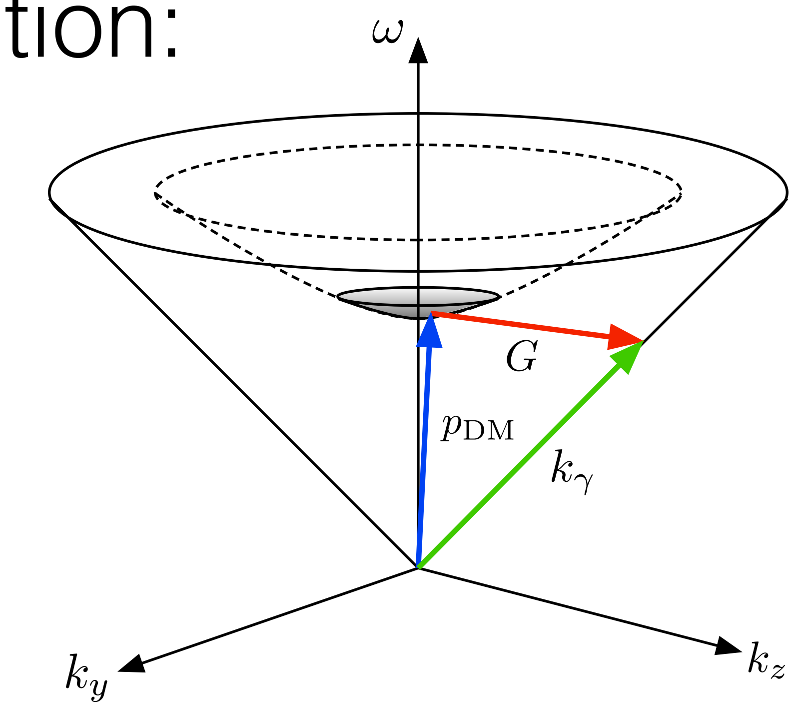


Boundary of a cavity (ADMX)

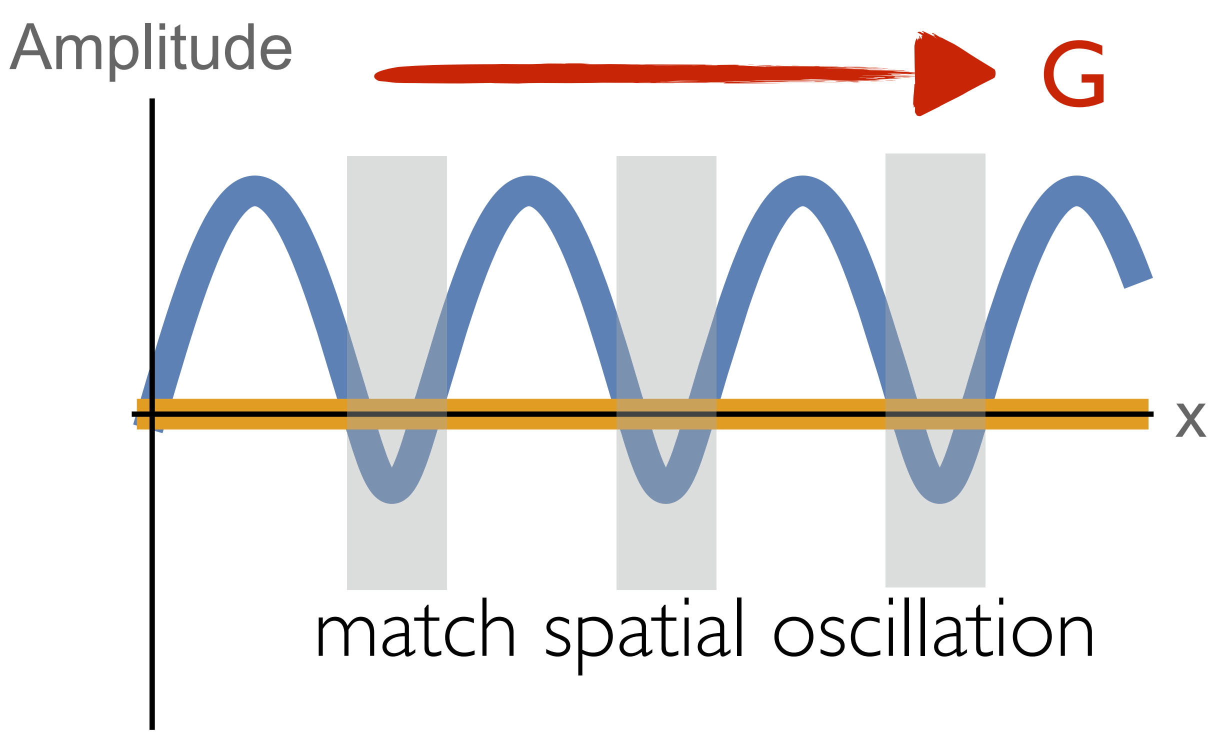
Dark matter absorption

- Challenges for dark matter absorption:

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



- Introduce periodicity (Type II)

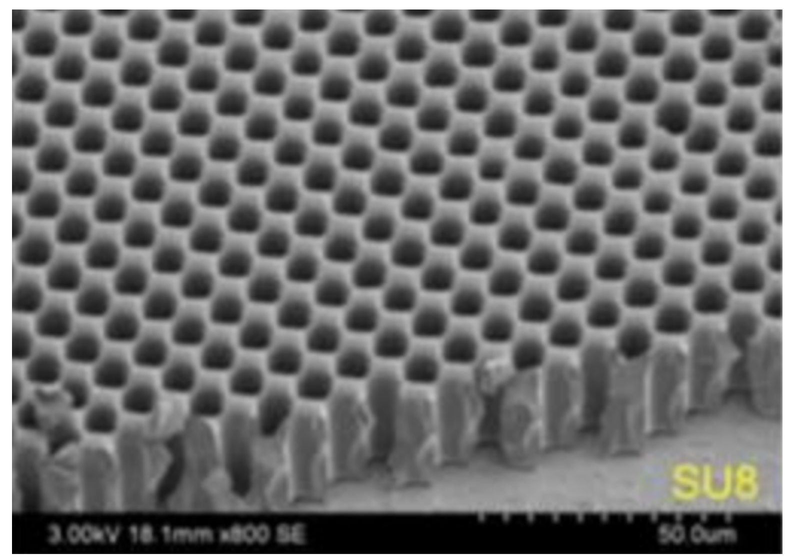


Photonic Crystal
as a target

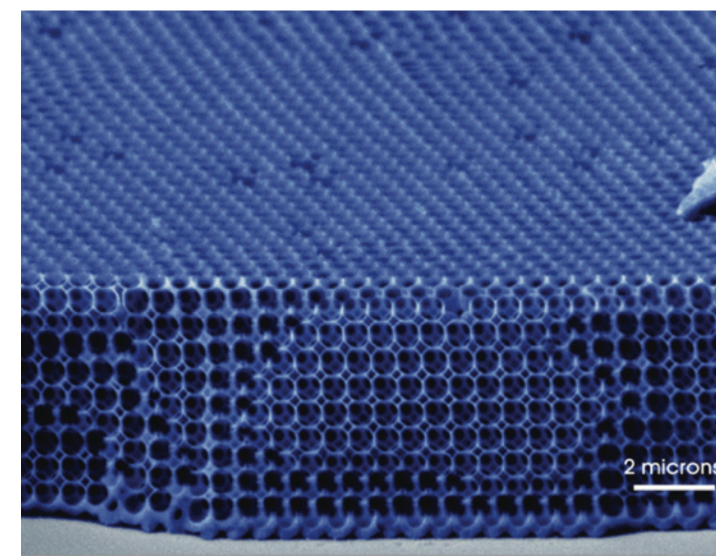
Photonic Crystals

- Materials with periodic optical properties

1D



2D

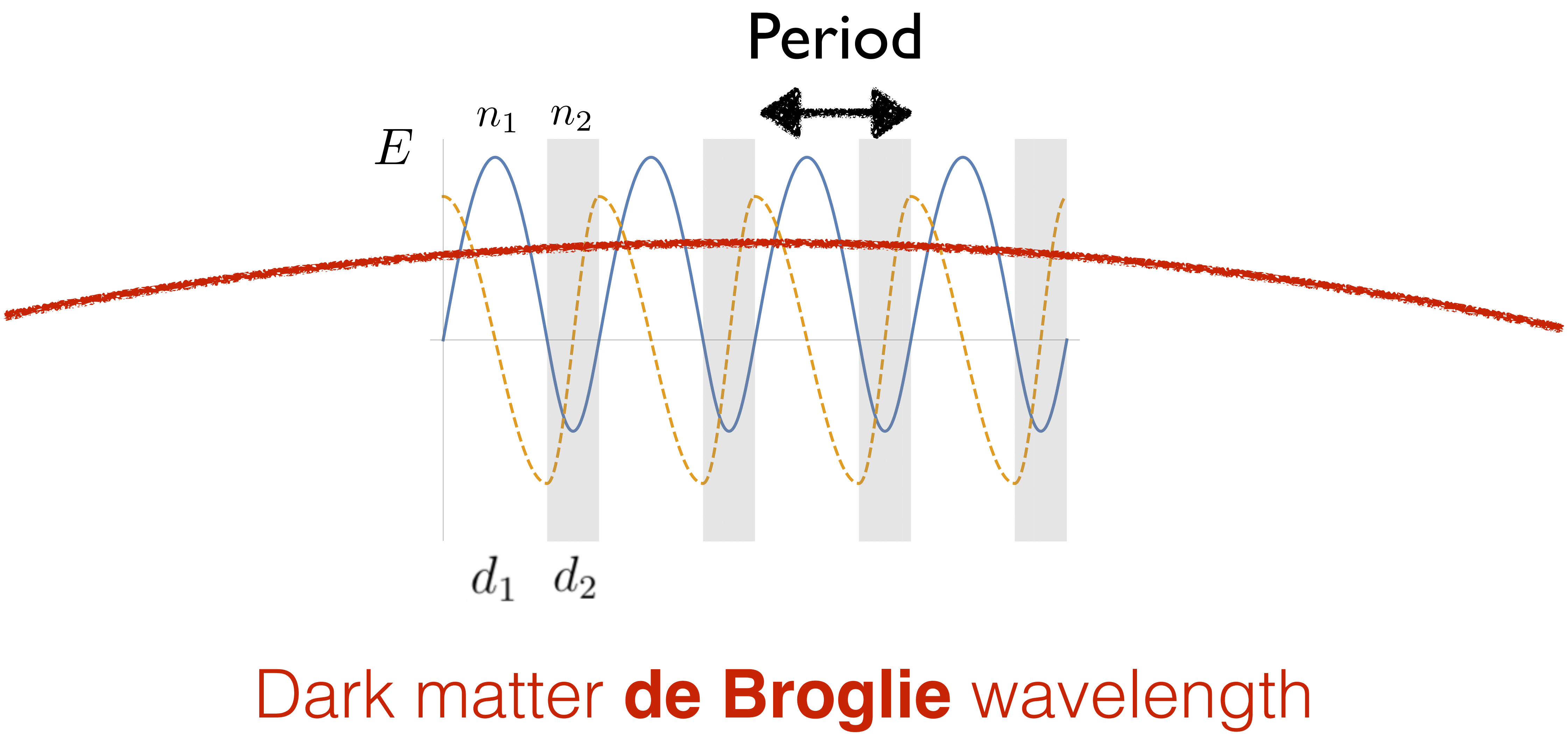


3D

Eli Yablonovitch, EECS, Berkeley

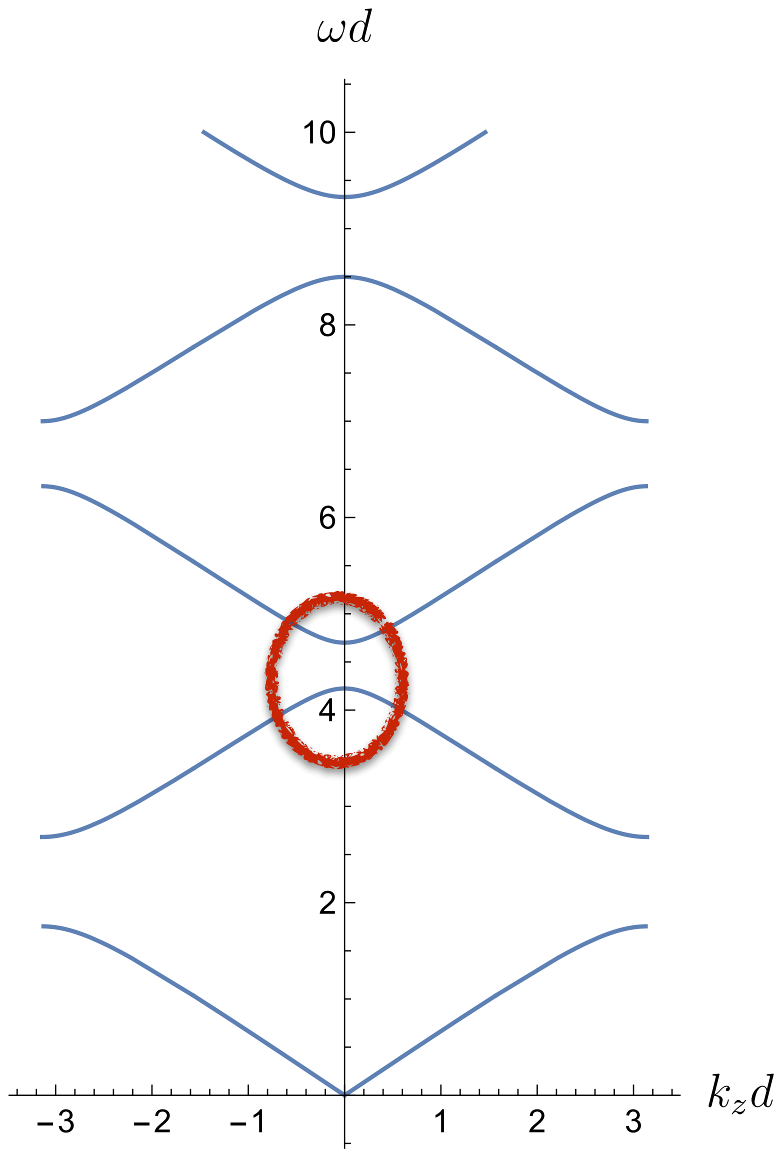
Photon mode

- DM is spatially uniform over the **de Broglie** wavelength
- Photon modes have period of the **Compton** wavelength



Photon modes

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

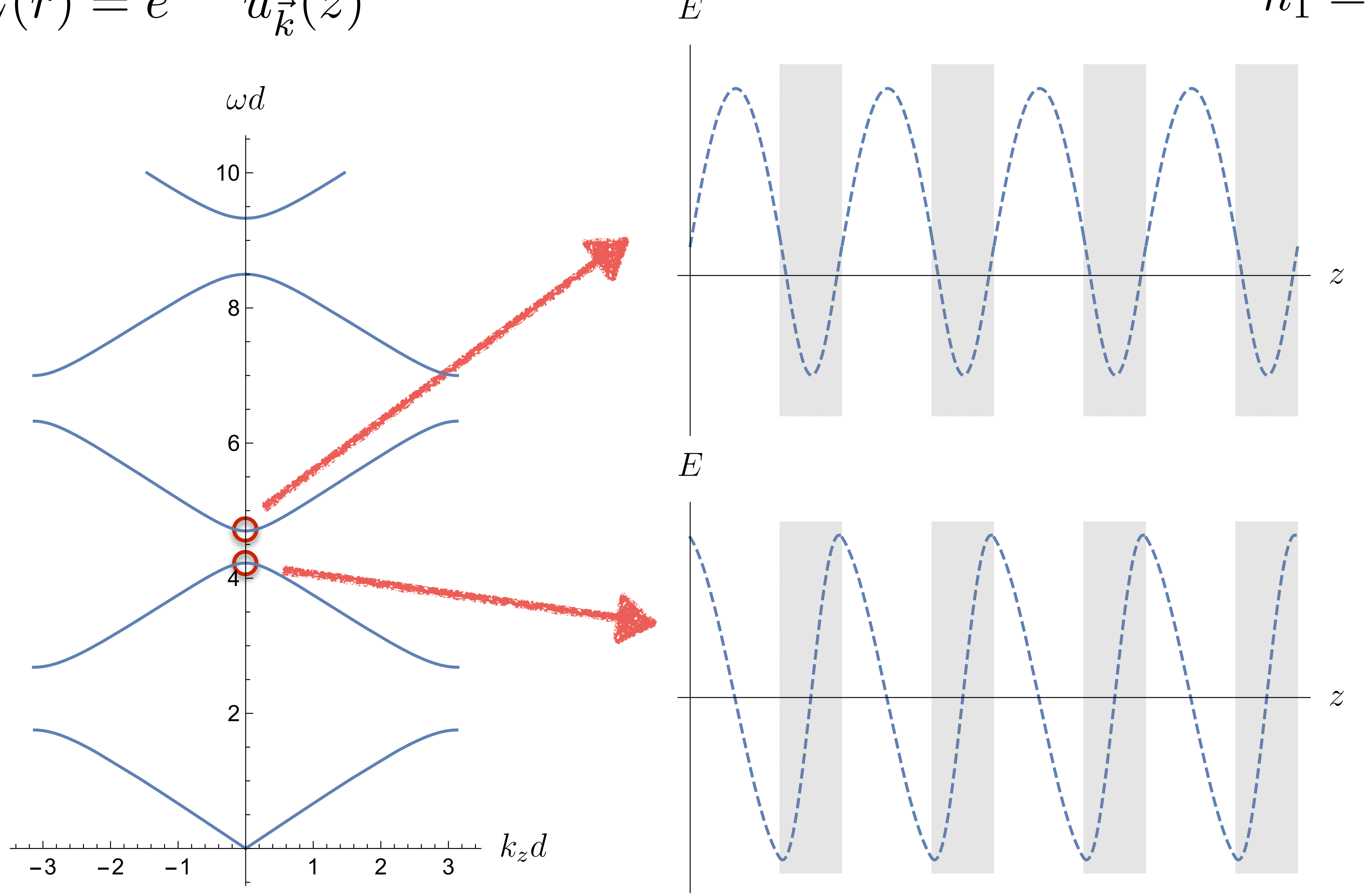


Photon modes

- In infinite periodic material, have photon Bloch modes

$$E(\vec{r}) = e^{i\vec{k}\cdot\vec{r}} u_{\vec{k}}(z)$$

$n_1 = 1, n_2 = 2$

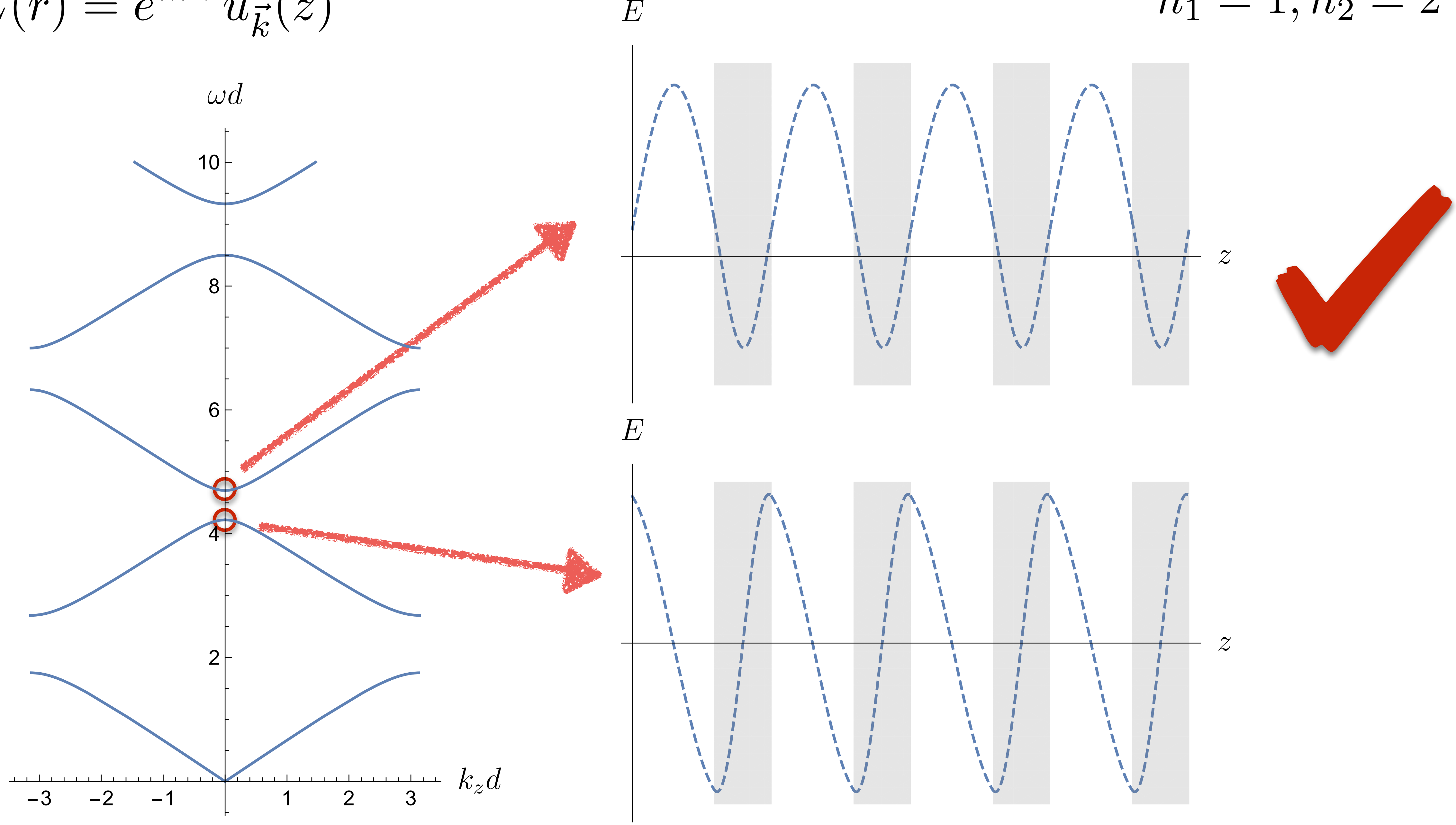


Photon modes

- In infinite periodic material, have photon Bloch modes

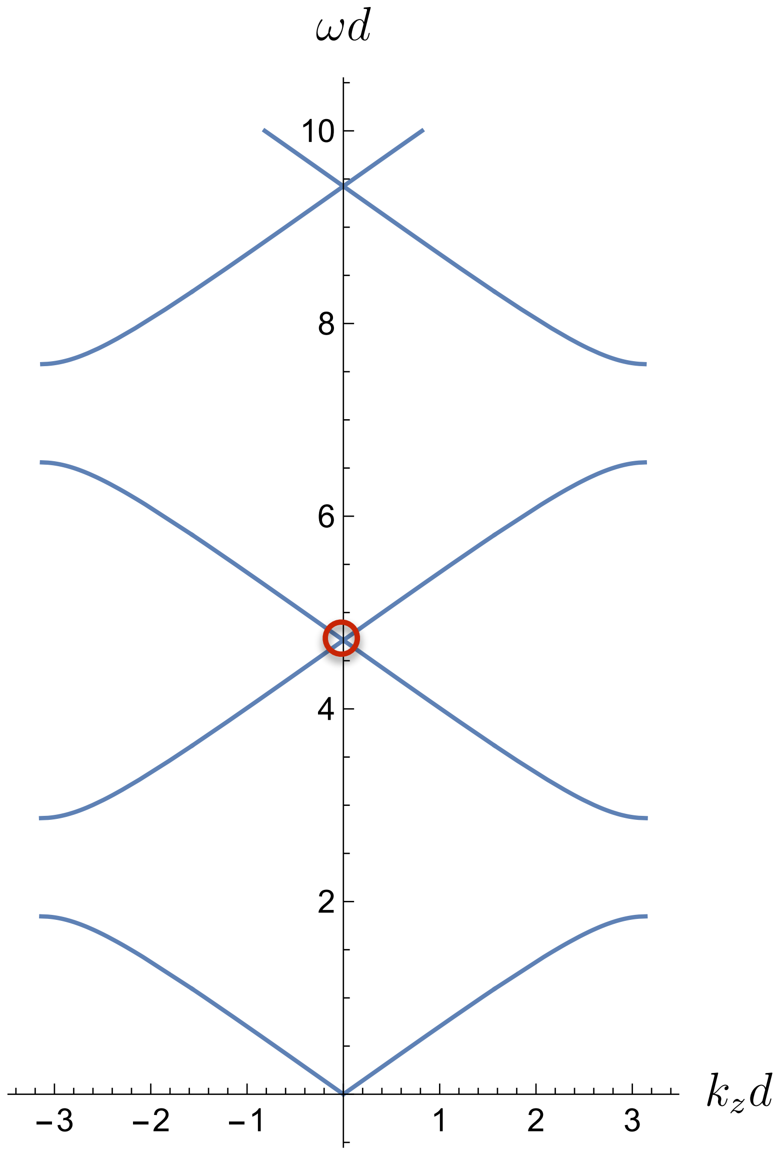
$$E(\vec{r}) = e^{i\vec{k}\cdot\vec{r}} u_{\vec{k}}(z)$$

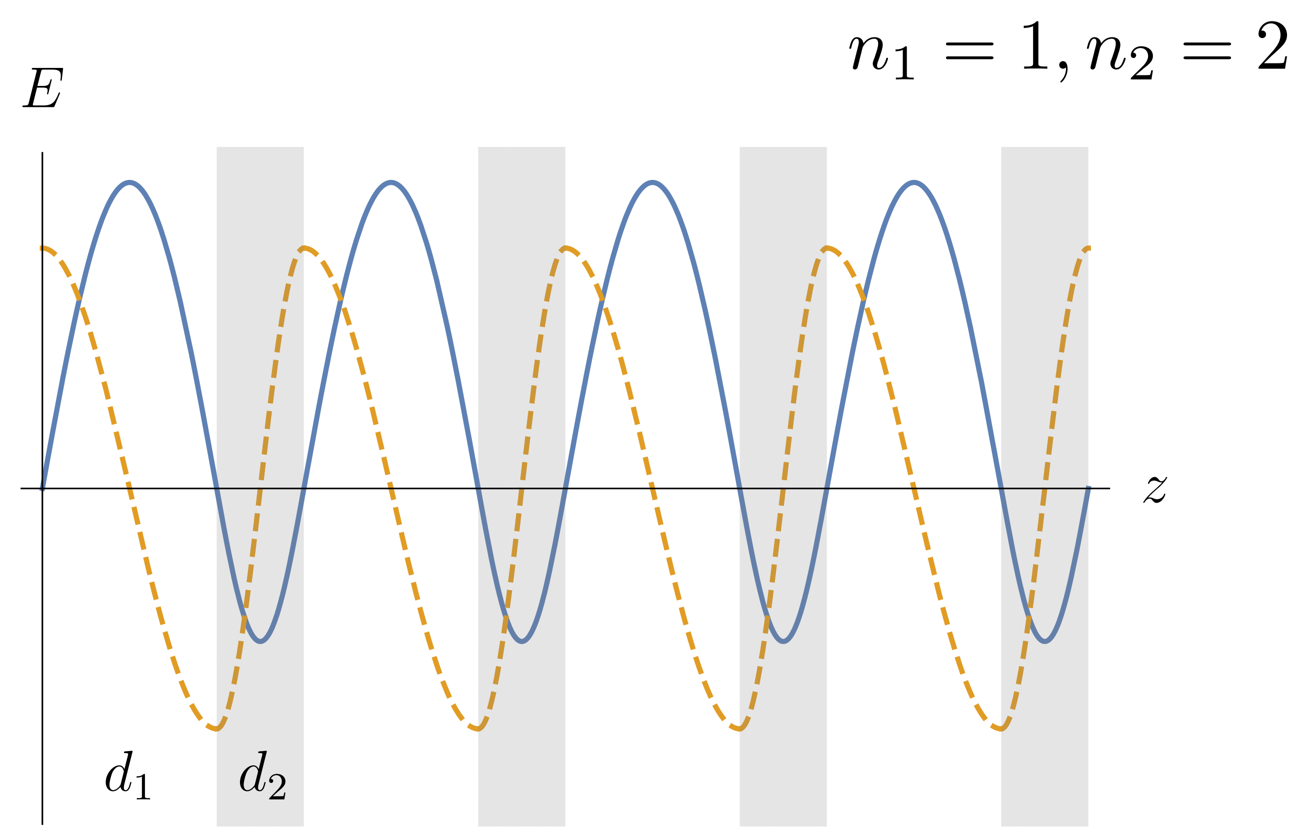
$n_1 = 1, n_2 = 2$



Half-wave stack

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



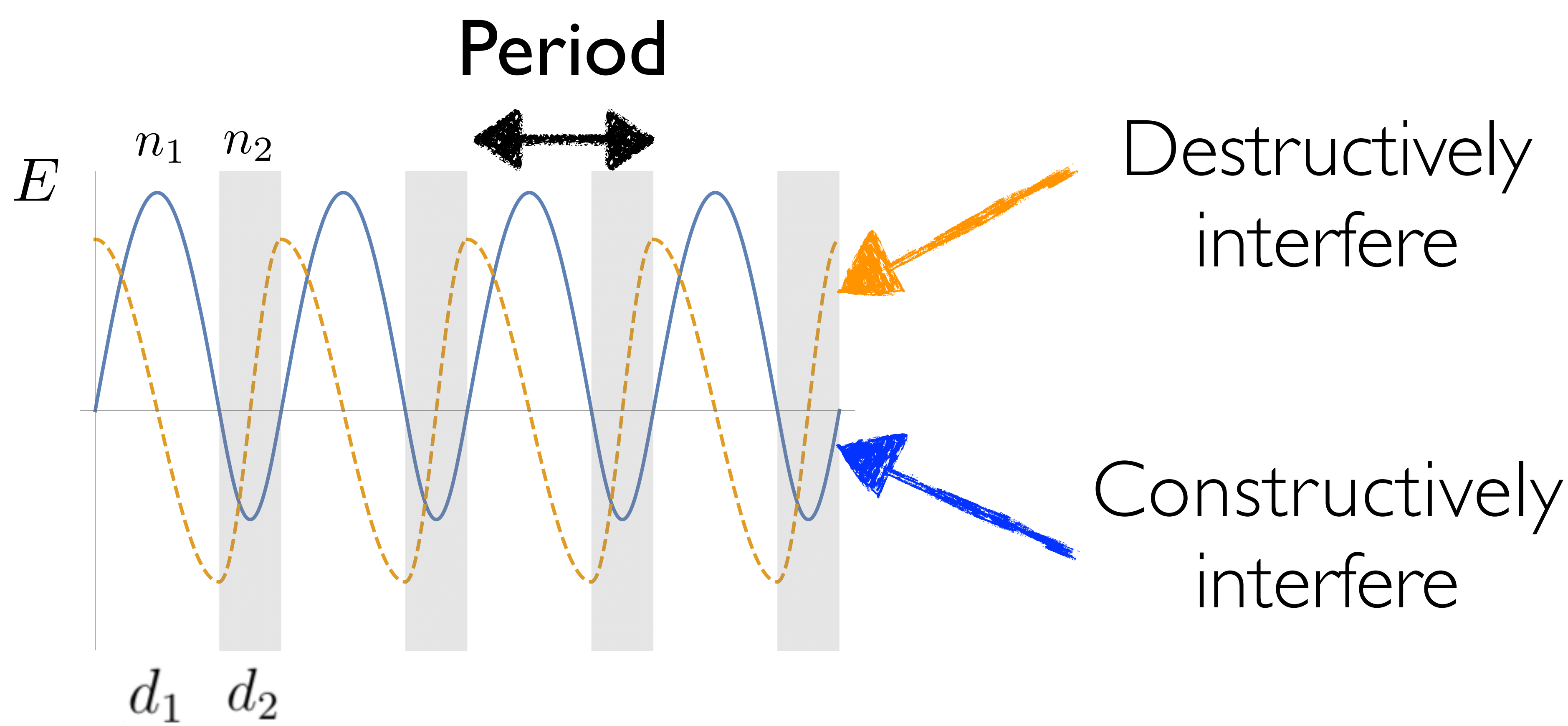


- Axion oscillations excite mode with non-zero $\int dV\, E$

Photon mode

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

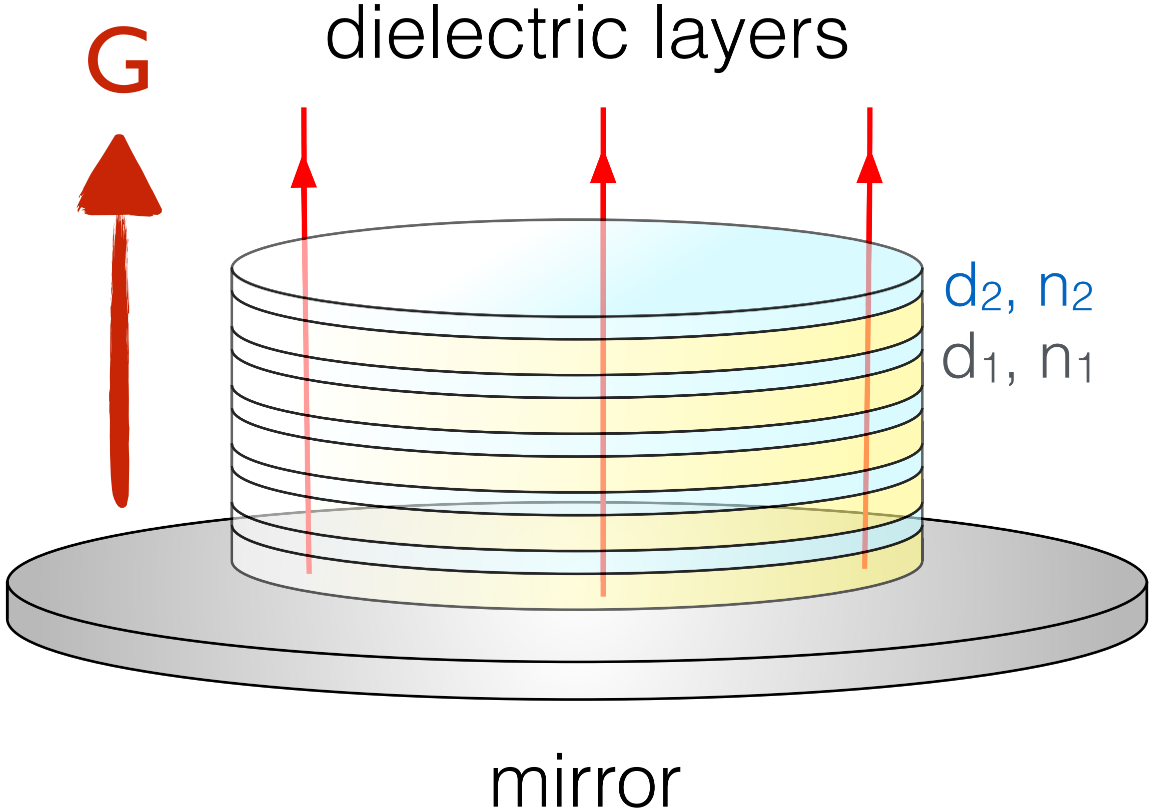
Very simple material pairs (Silicon & Silica)



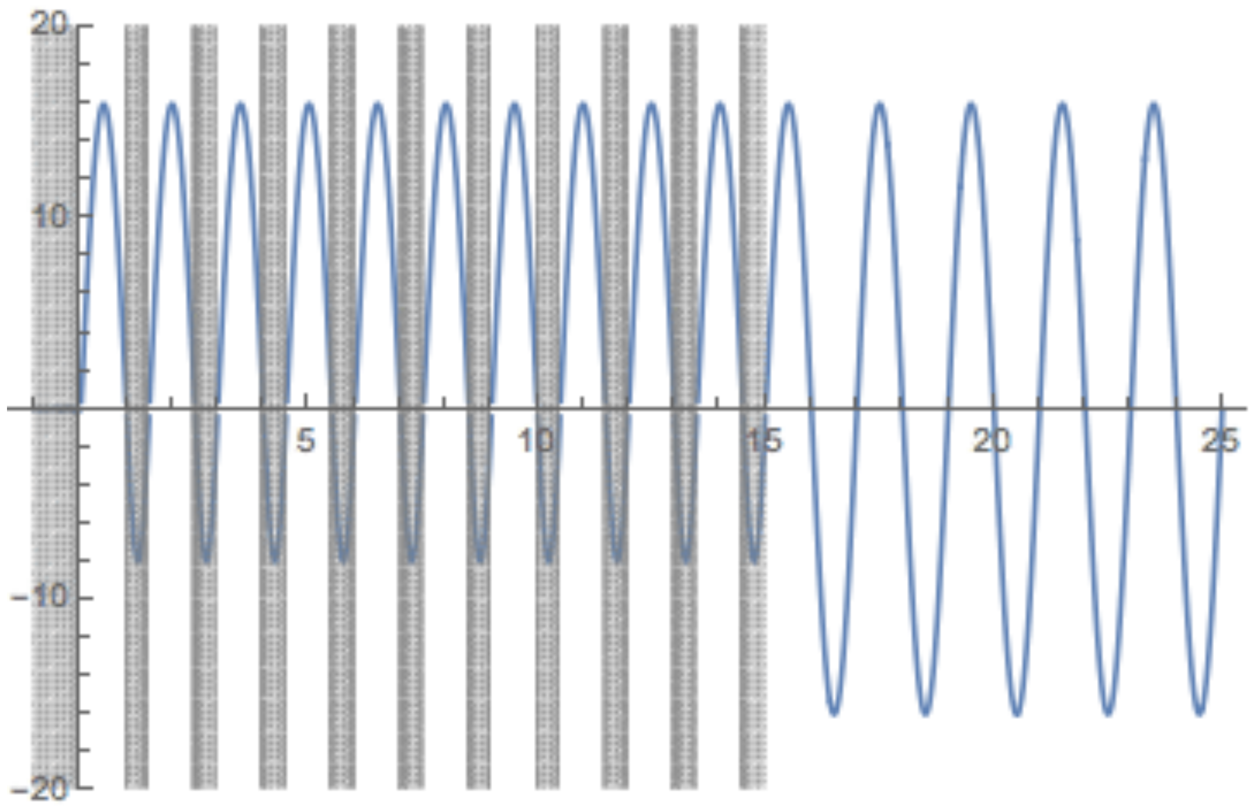
Experimental setup
&
Reach

Experimental setup

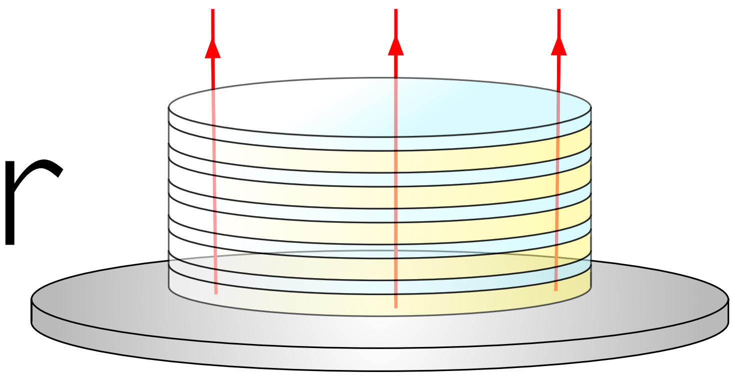
Time varying, spatially homogeneous dark matter sources photons in periodic structure



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



Converted power

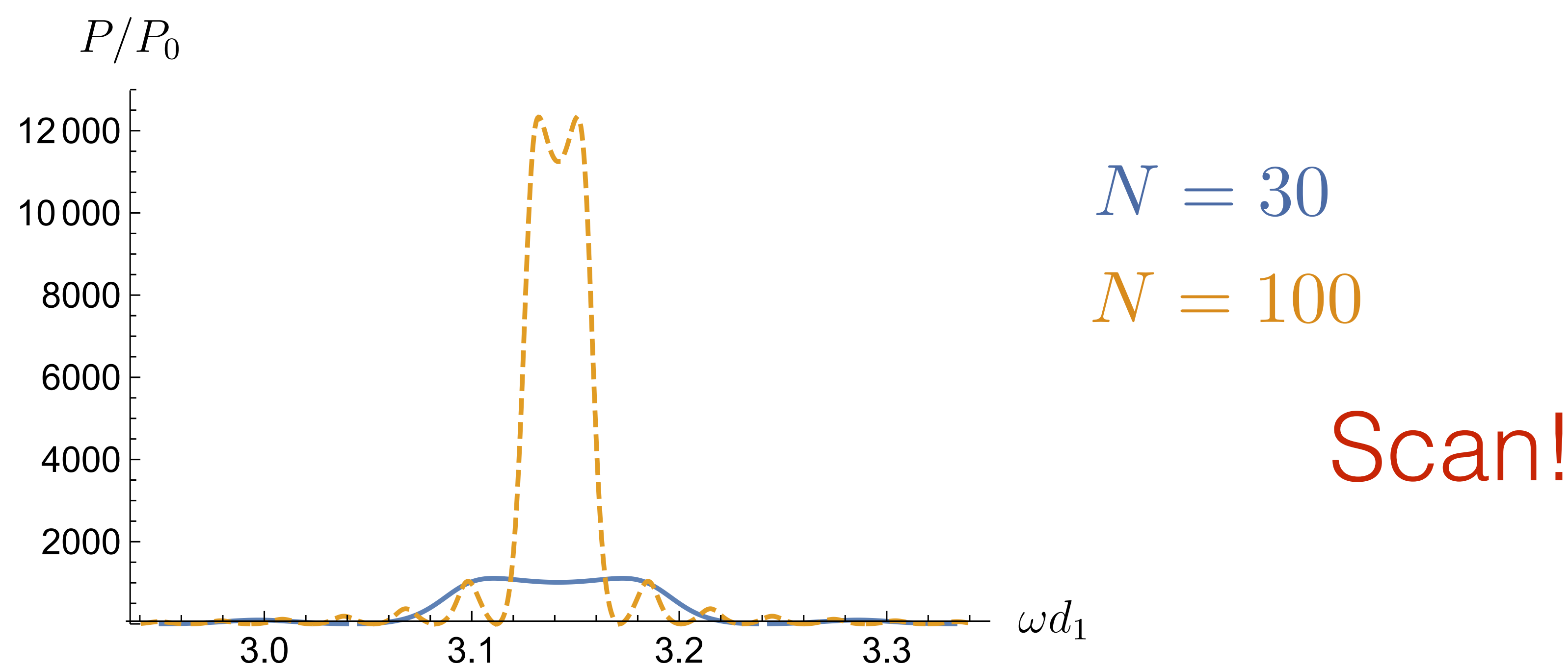


- For stack of N periods, with area A, converted power from DM at half-wave frequency is

$$\langle P_{\rm abs}\rangle = \kappa^2 \sin^2\theta \rho_{\rm DM} Q A N \left(\frac{1}{n_1}+\frac{1}{n_2}\right)\left(\frac{1}{n_2}-\frac{1}{n_1}\right)^2 ,$$

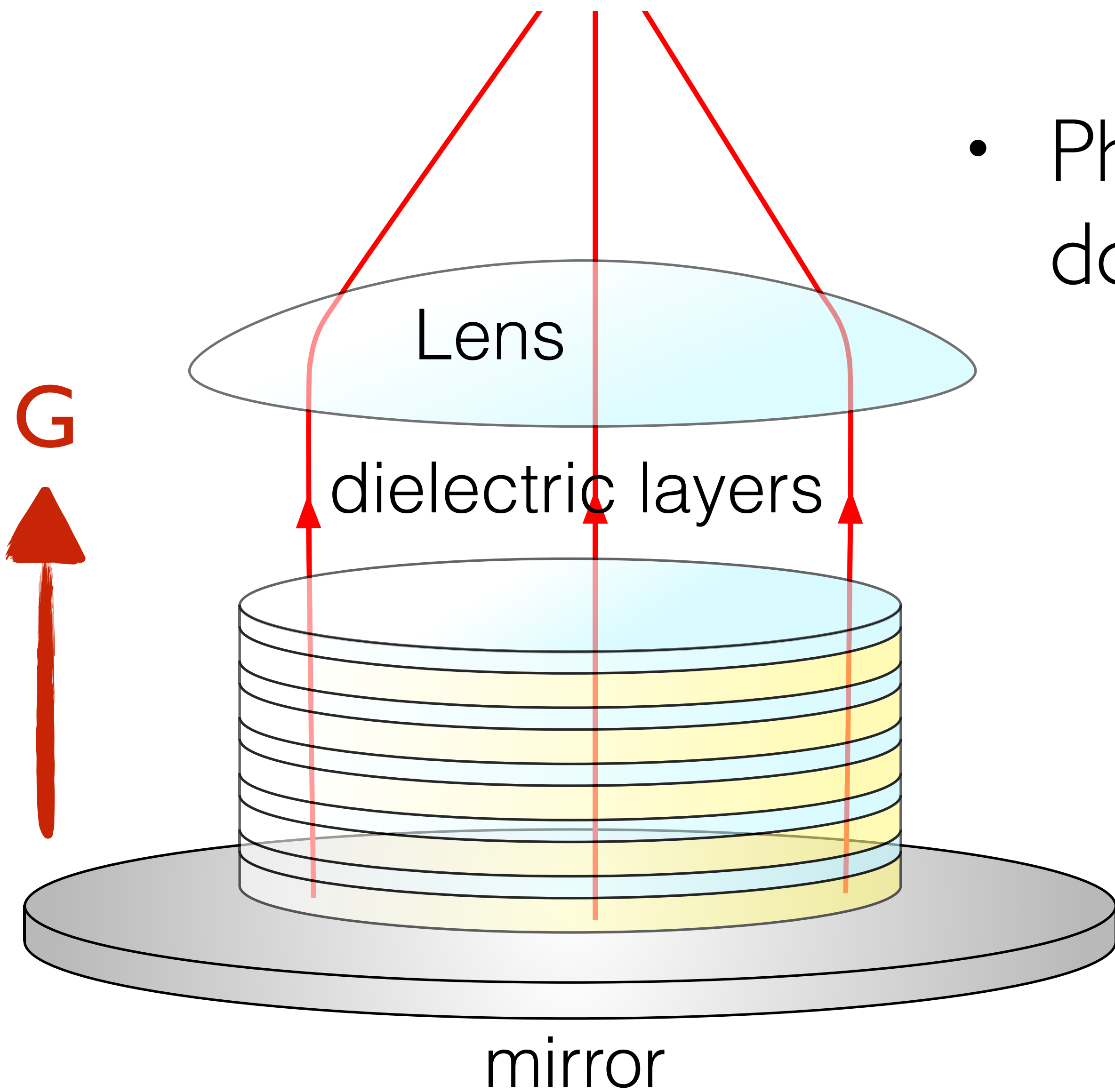
- For "open cavity", $Q \propto N$

- Frequency coverage:



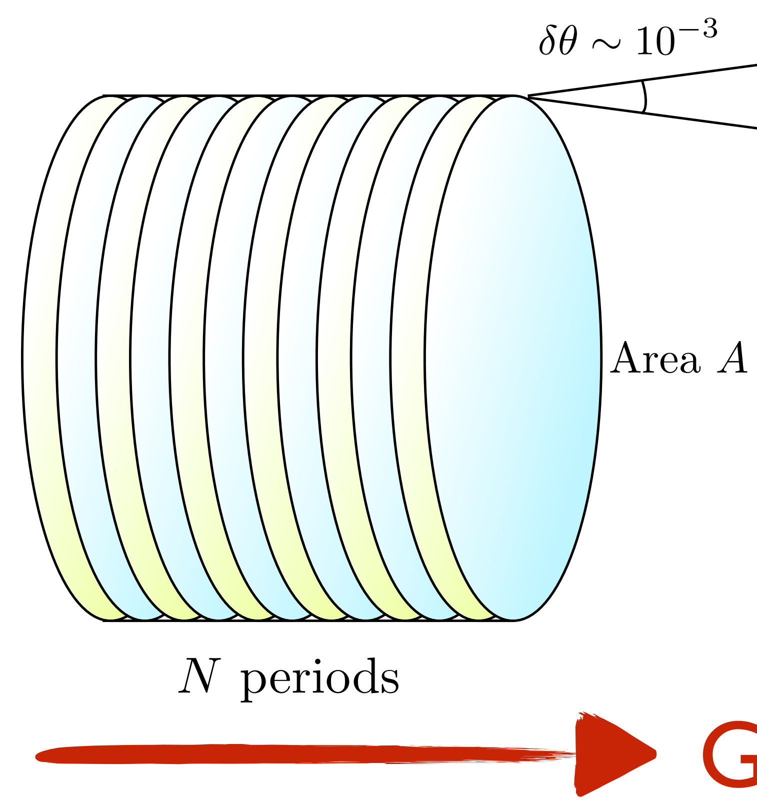
- Higher peak power compensated for by reduced bandwidth: frequency-averaged conversion power $\propto N$

Experimental setup



- Photons are emitted collimated to the surface
- Photons can be focussed down to area $\sim 10^{-6} A$

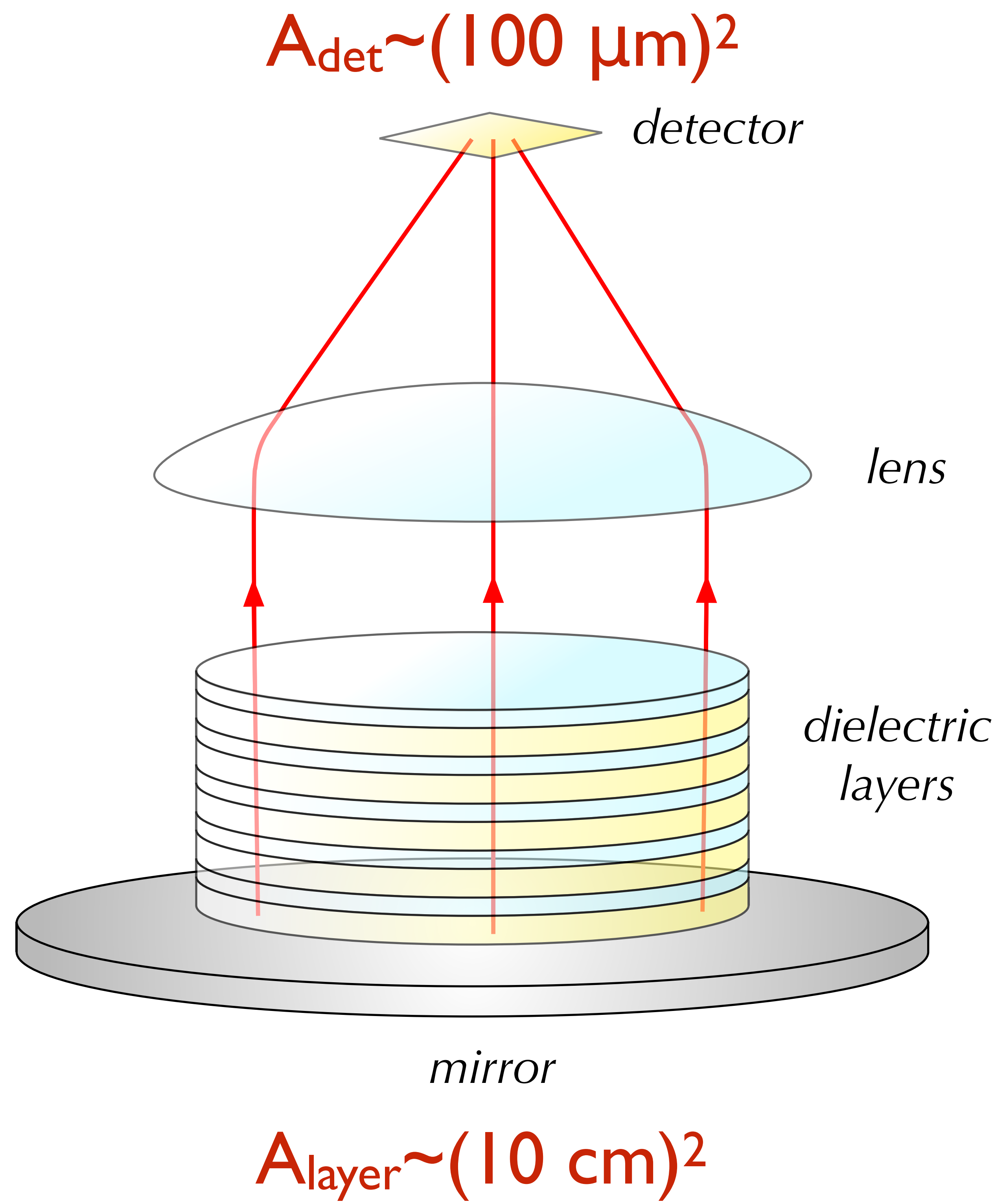
Background rejection



Experimental setup

- Signal photons can be focused into a sensitive photon detector

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



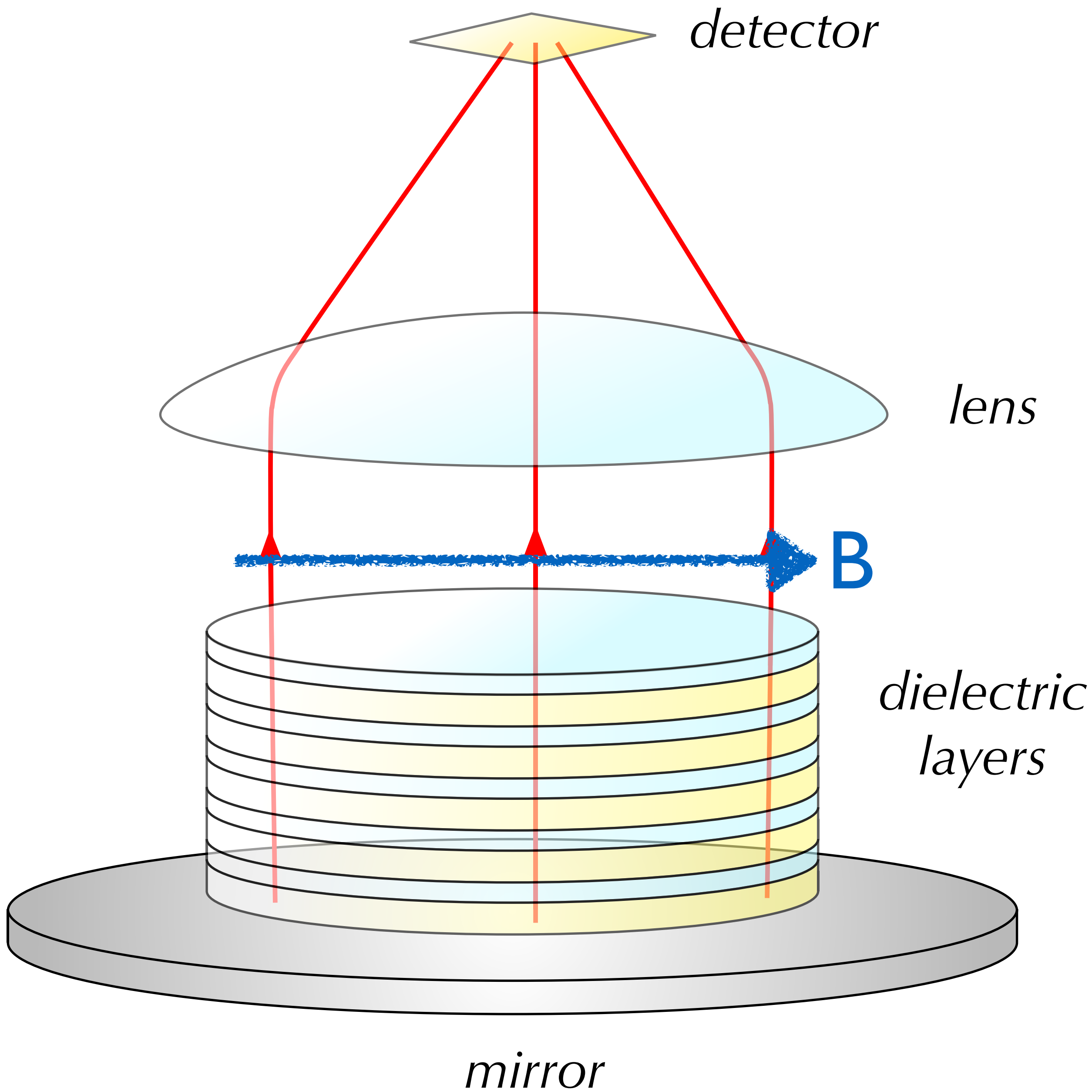
Experimental setup

- Signal photons can be focused into a sensitive photon detector

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

- A horizontal magnetic field is needed to look for axions

A_{det}~(100 μm)^2



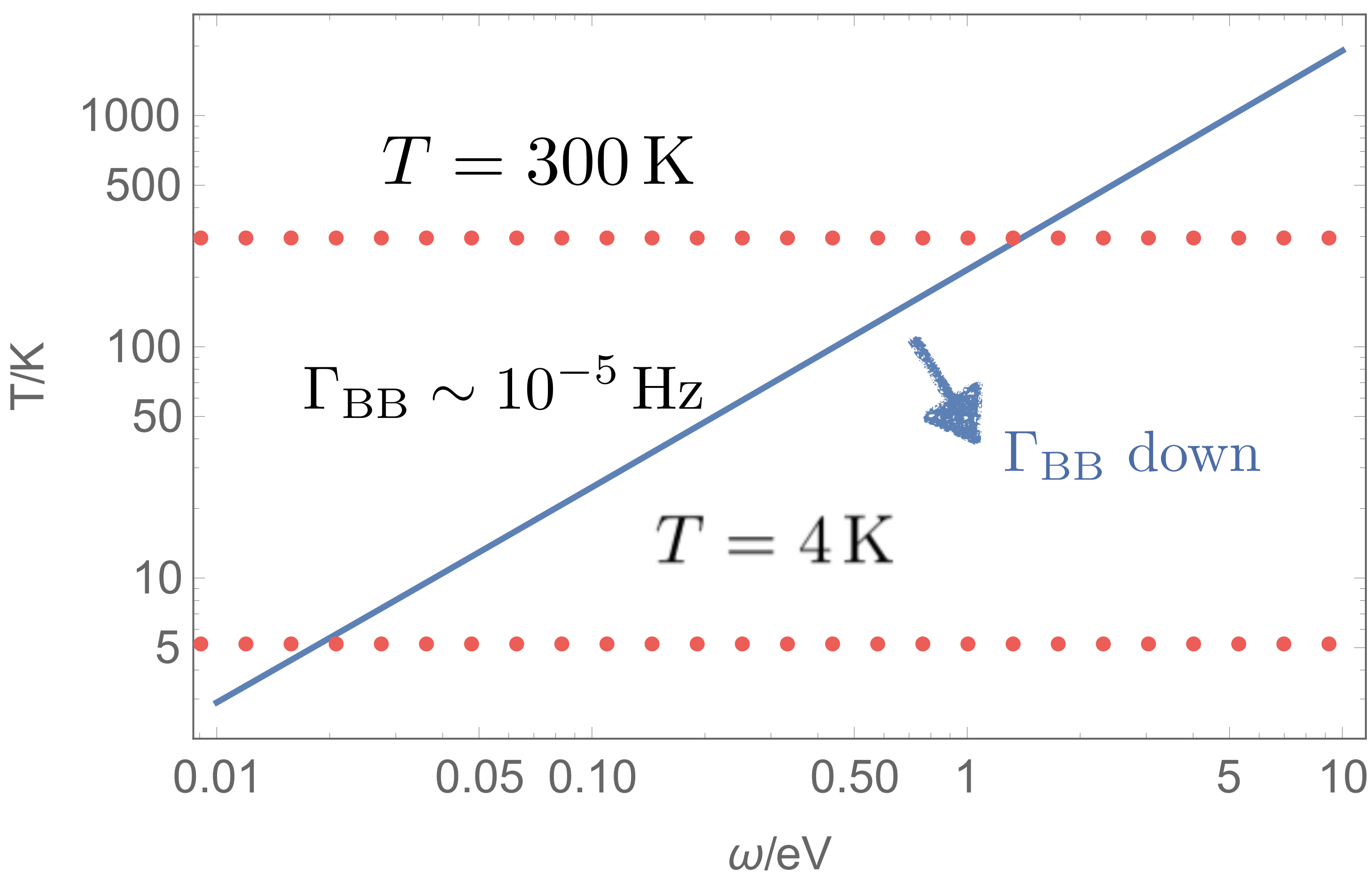
A_{layer}~(10 cm)^2

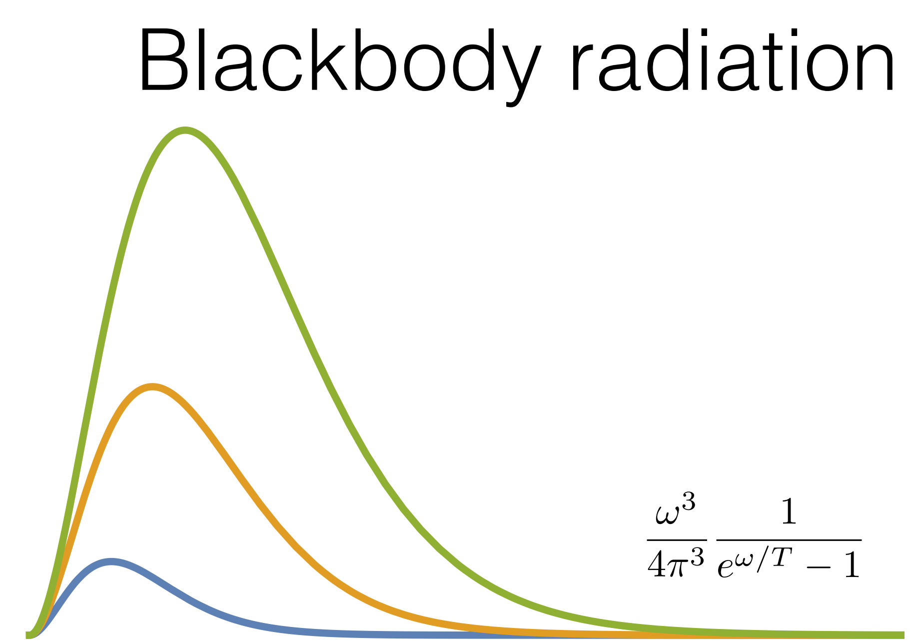
Background
(Not a detour)

Thermal backgrounds

- Blackbody photons: if detector's field of view ($A_{\rm det} = (100\,\mu{\rm m})^2$) is at temperature T , number of blackbody photons hitting detector is

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



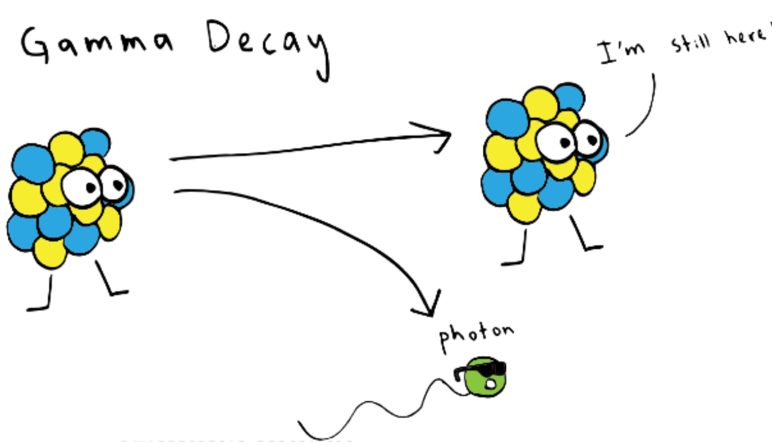


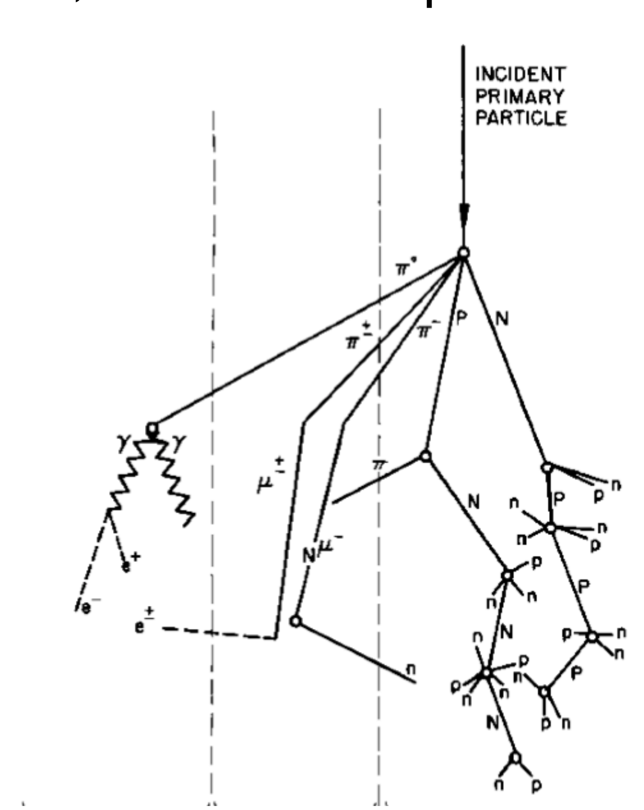
Radioactivity / cosmic rays

- Materials of target, shielding, detector etc will contain some radioactive isotopes; unpurified materials could result in $\sim 10/\mathrm{Target} * \mathrm{s}$ in random directions

- Cosmic ray muons: flux $\sim 1/(10\,\mathrm{cm}^2\,\mathrm{sec})$, each deposits energy $\sim 1 - 100\,\mathrm{keV}$ in target

Radioactivity





Cosmic ray

Radioactivity / cosmic rays

- Materials of target, shielding, detector etc will contain some radioactive isotopes; unpurified materials could result in $\sim 10/\mathrm{Target} * \mathrm{s}$ in random directions

- Cosmic ray muons: flux $\sim 1/(10\,\mathrm{cm}^2\,\mathrm{sec})$, each deposits energy $\sim 1 - 100\,\mathrm{keV}$ in target

- About **10^{-6}** of these background photon will end up in the detector ($\sim 10^{-5}\,\mathrm{Hz}$).

- All of these events much more energetic than signal photons, and usually leads to particle **showers** that can be vetoed

How to not see DM?

- Blackbody (Thermal)

$$T \lesssim \omega/40 \approx 300\,\mathrm{K}\left(\frac{\omega}{\mathrm{eV}}\right)$$

- Cosmic ray and Radioactivity
  - Background reduction by focusing
  - Active veto of particle shower
- Detector dark count
  - CCD: mHz
  - SCTJ, TES, MKIDs: O(1)/day

$$\Gamma \sim \mathcal{O}(10)/\mathrm{Target}$$

$$\Gamma_{\mathrm{det}} \simeq 10^{-6}\Gamma_{\mathrm{Target}} \sim 10^{-5}\,\mathrm{Hz}$$

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

↓

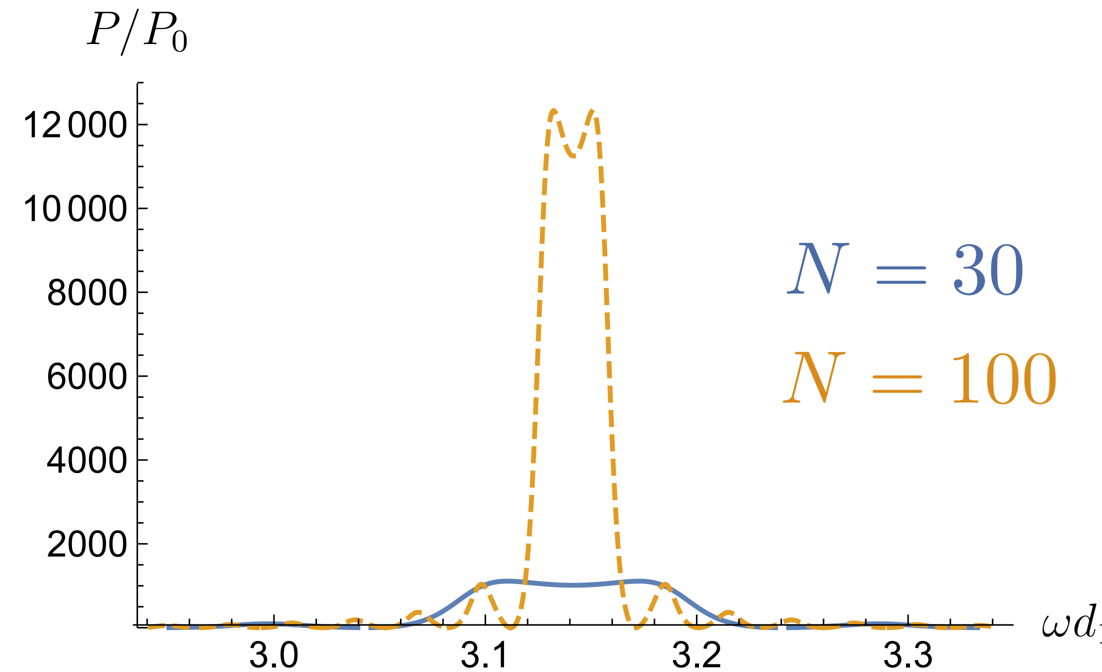
Running time/stack (weeks?)

Scanning

Taking advantage of the small background rate

- For half-wave stack, $P_{\rm abs} \propto N^2$ but bandwidth $\delta\omega/\omega \sim 1/N$ → $(P_{\rm total} \propto N)$

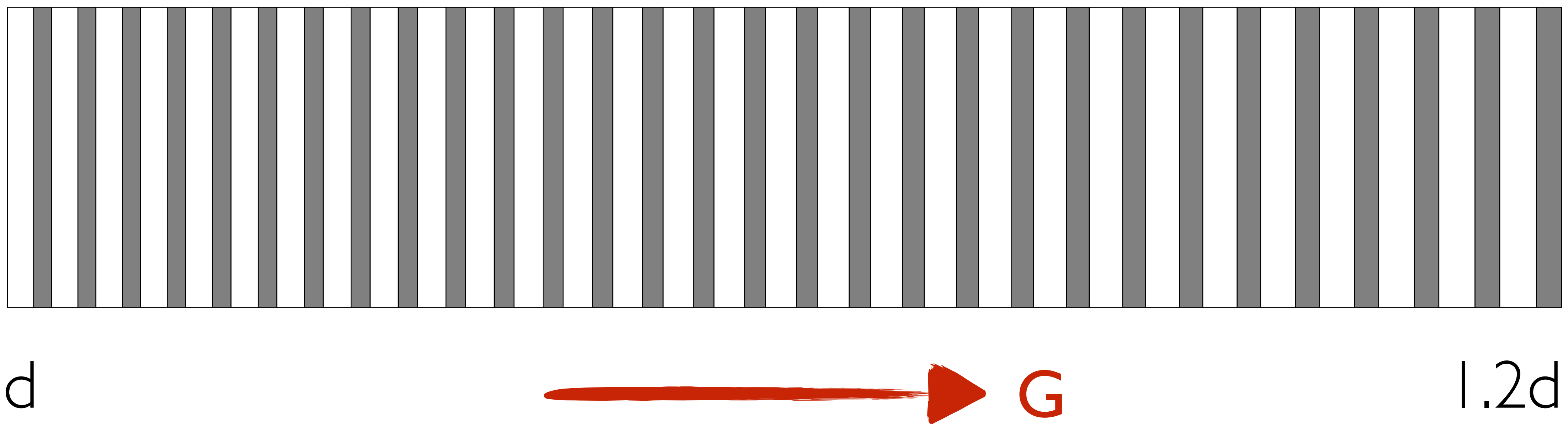
- Increasing conversion rate requires more layers, but this decreases the mass range covered by a given stack



How to get a wide coverage without sacrificing power?

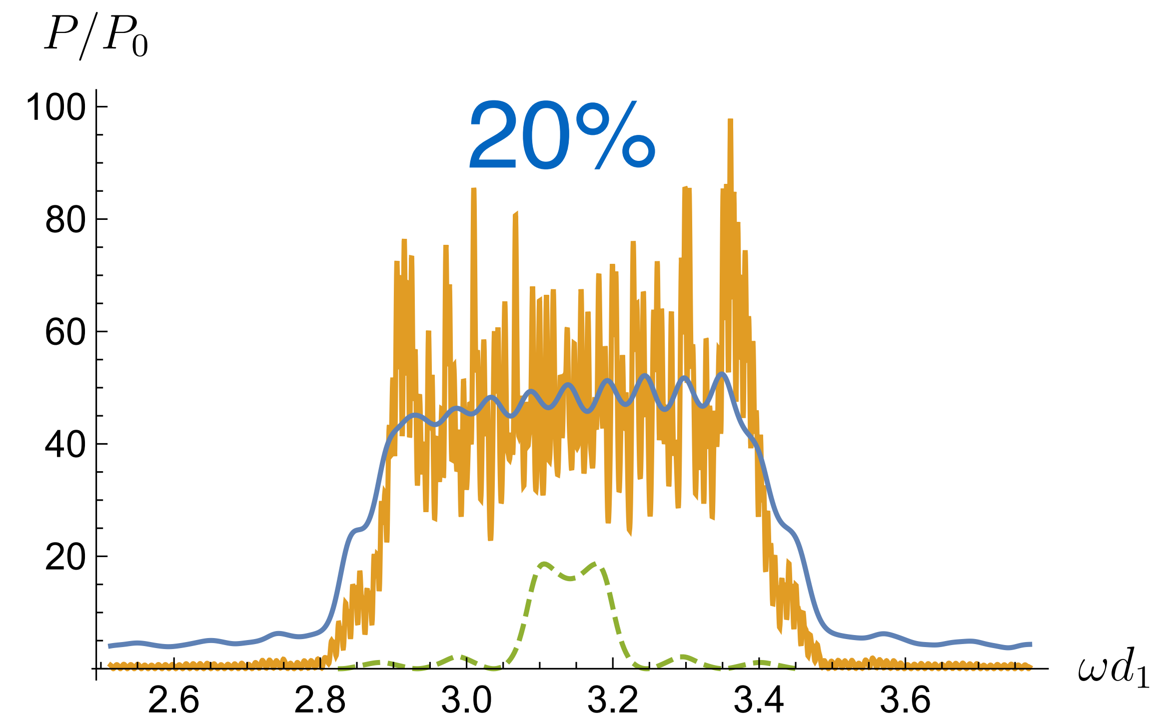
Chirped stack

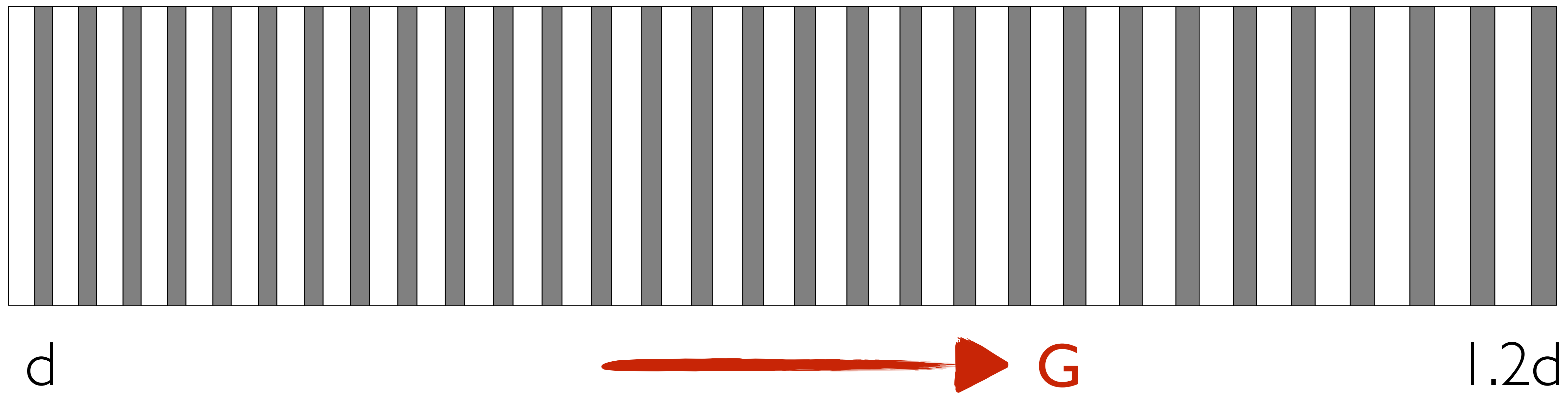
- Possibilities:
  - Combining stacks of different periodicities
  - **Chirped stack**

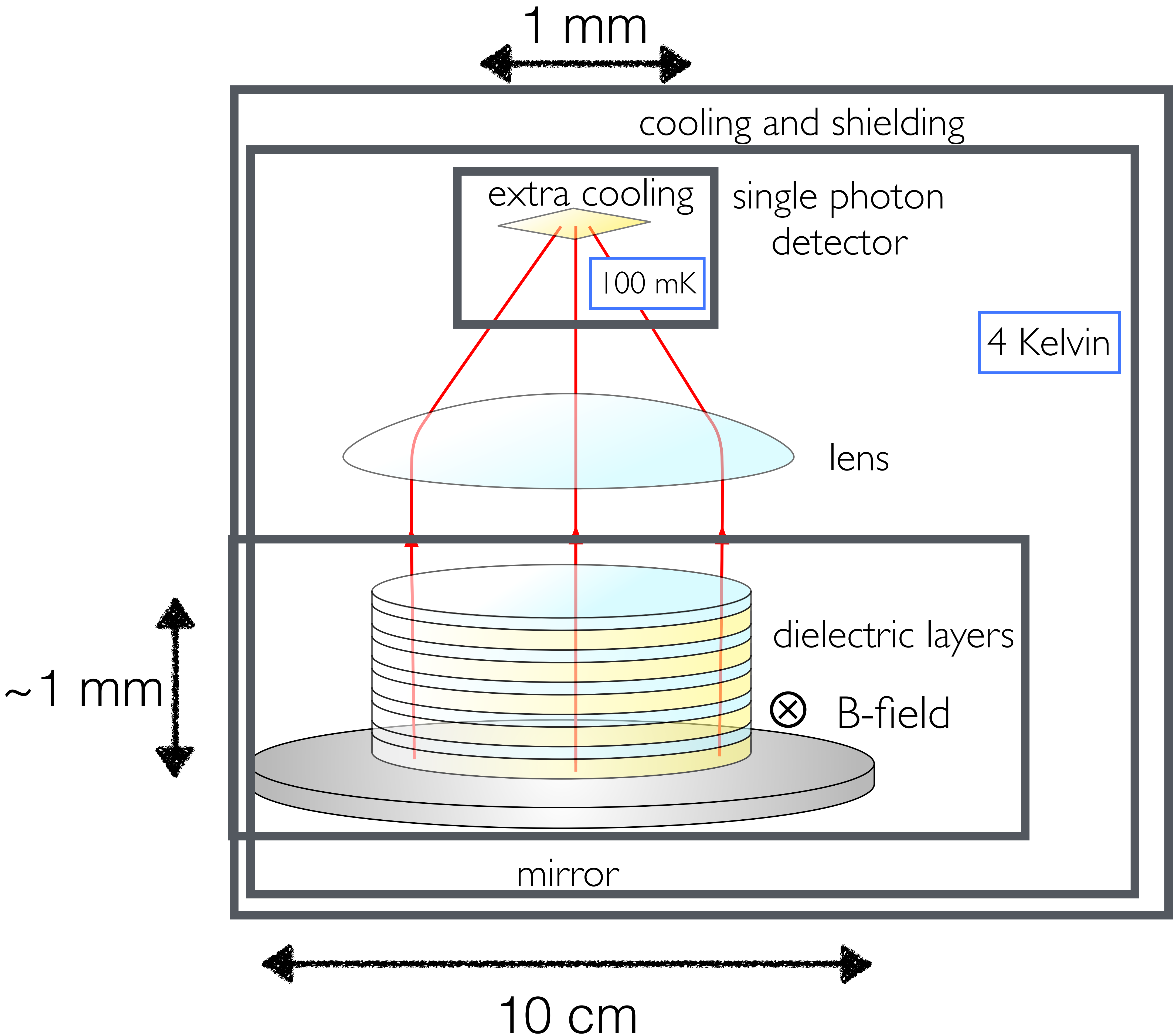


Chirped stack

- Possibilities:
  - Combining stacks of different periodicities
  - **Chirped stack**





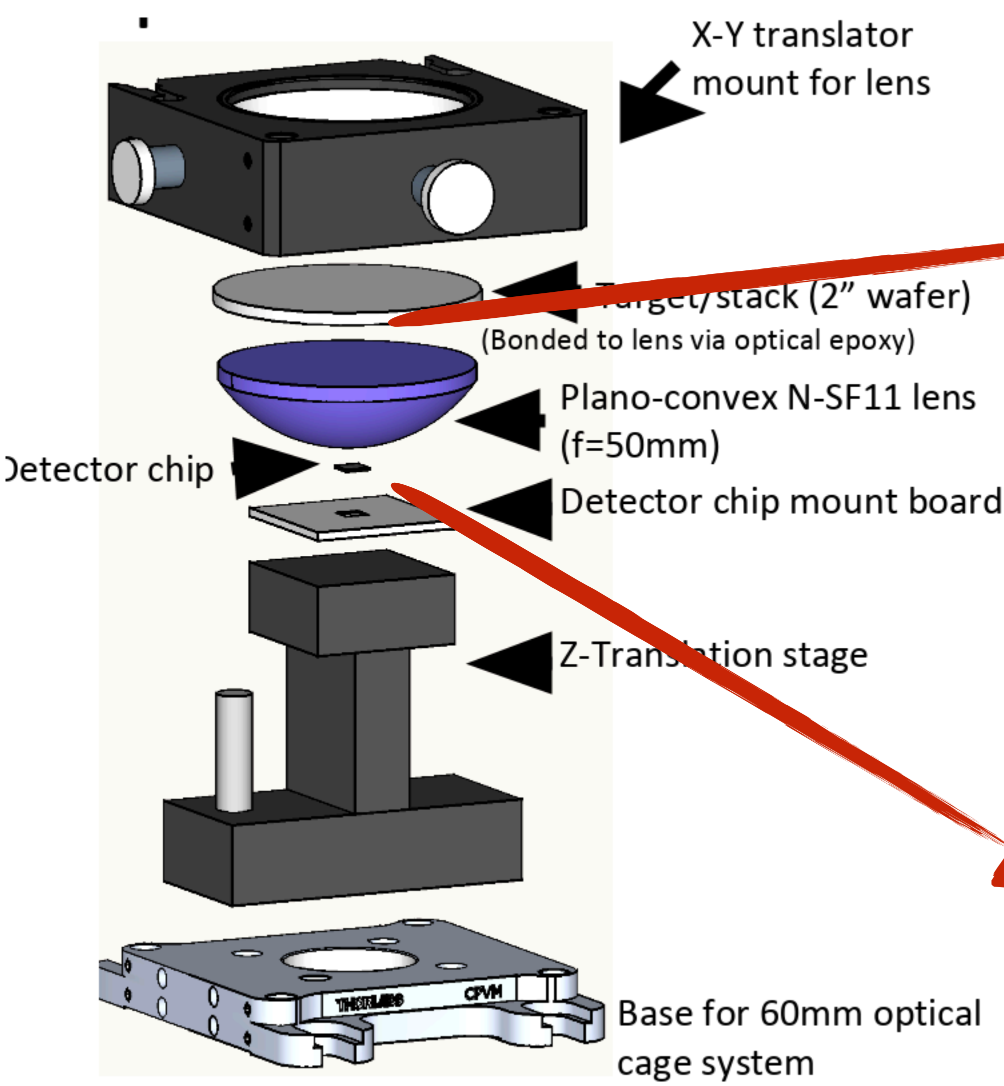


1 mm
cooling and shielding
extra cooling
single photon
detector
100 mK
4 Kelvin
lens
dielectric layers
B-field
~1 mm
mirror
10 cm

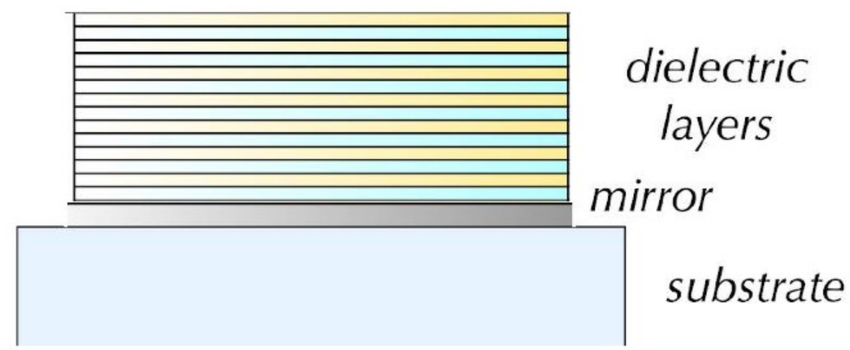
In progress

Prototype (MIT/NIST)

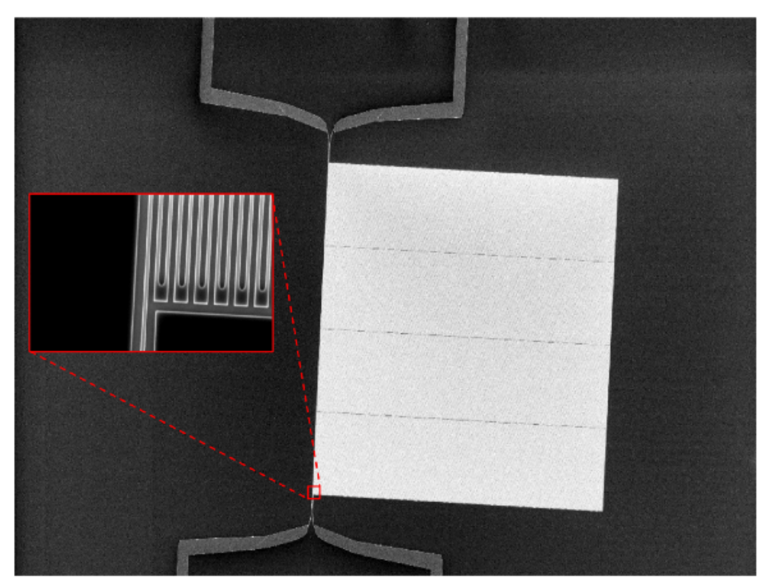
Experimental figure by Jeff Chiles

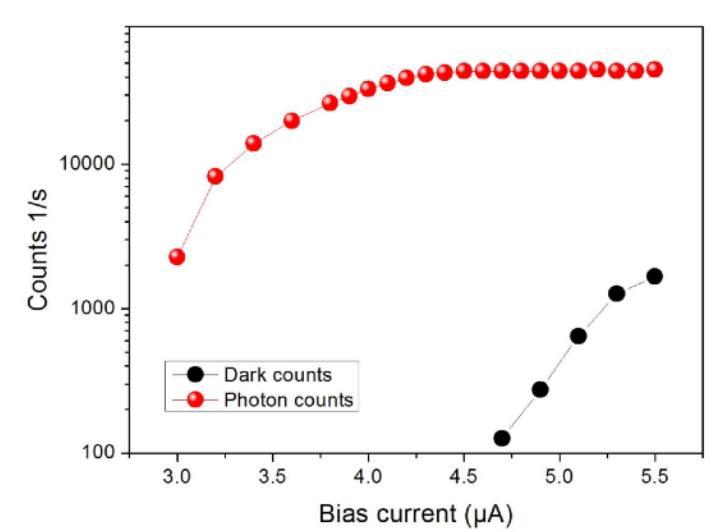


6 layers



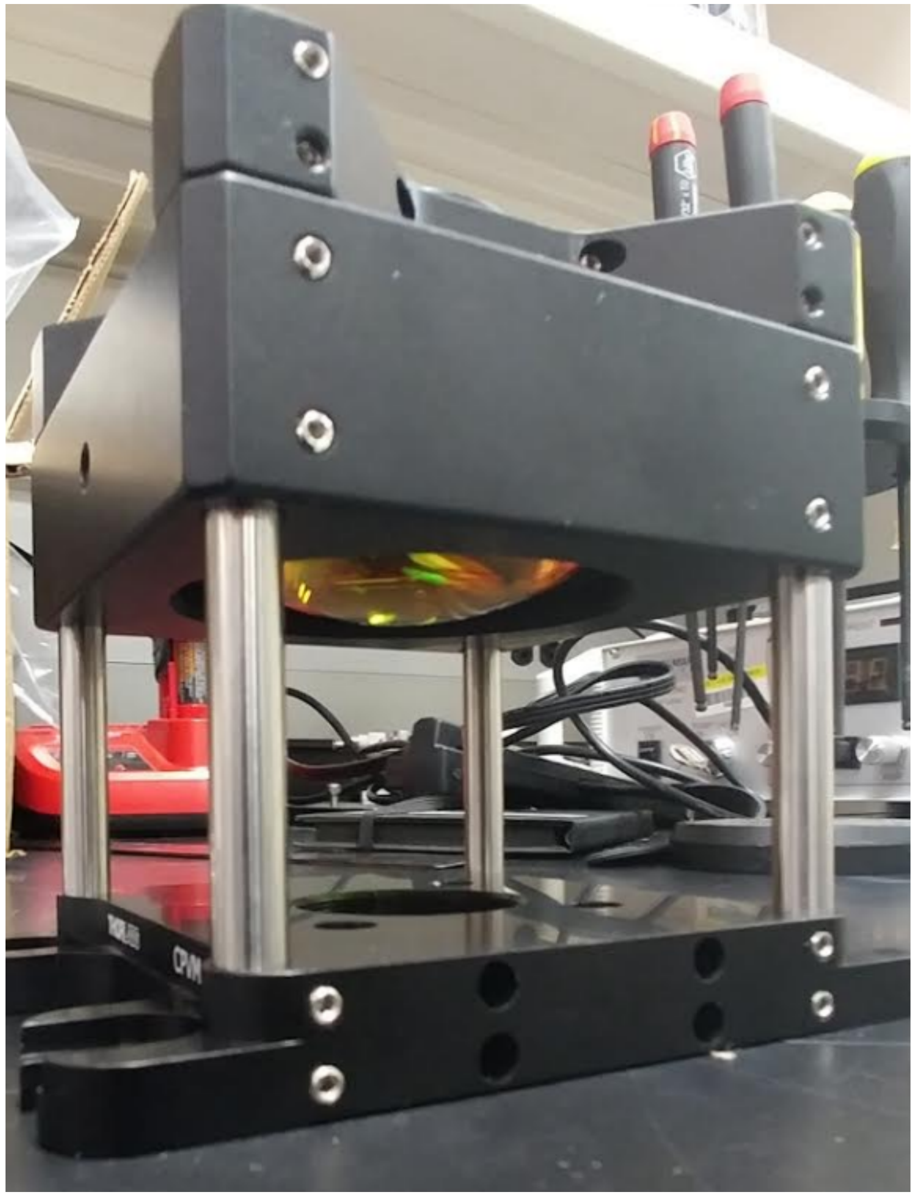
With Karl Berggren (MIT), Jeff Chiles and Saewoo Nam (NIST)



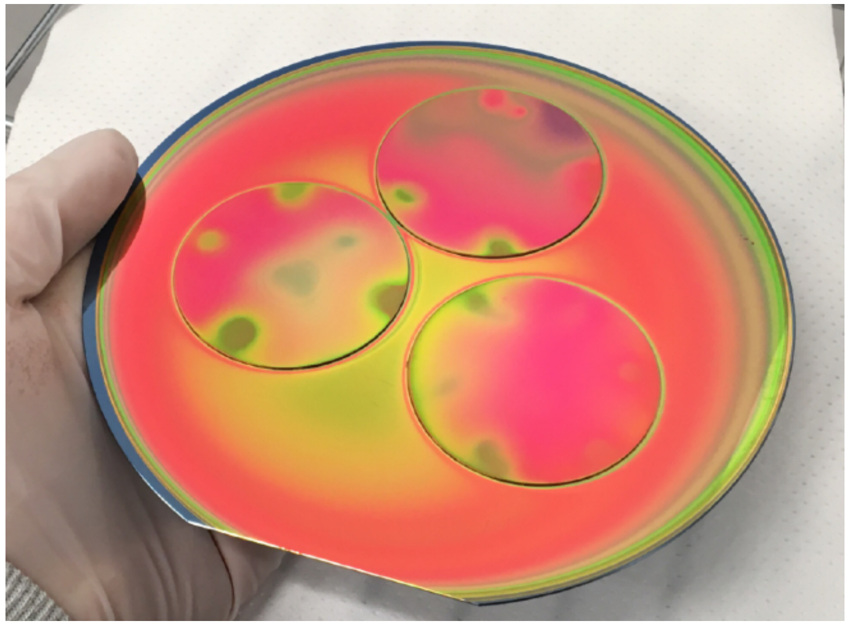


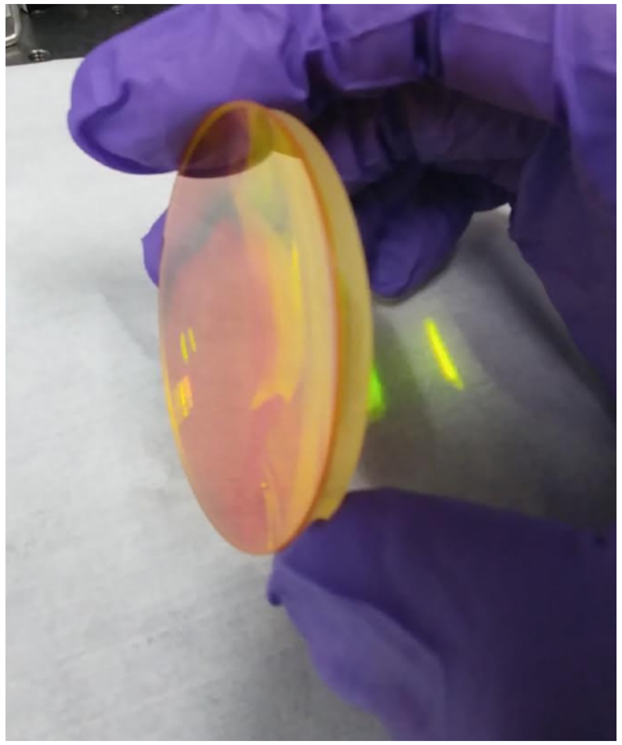
Prototype (MIT/NIST)

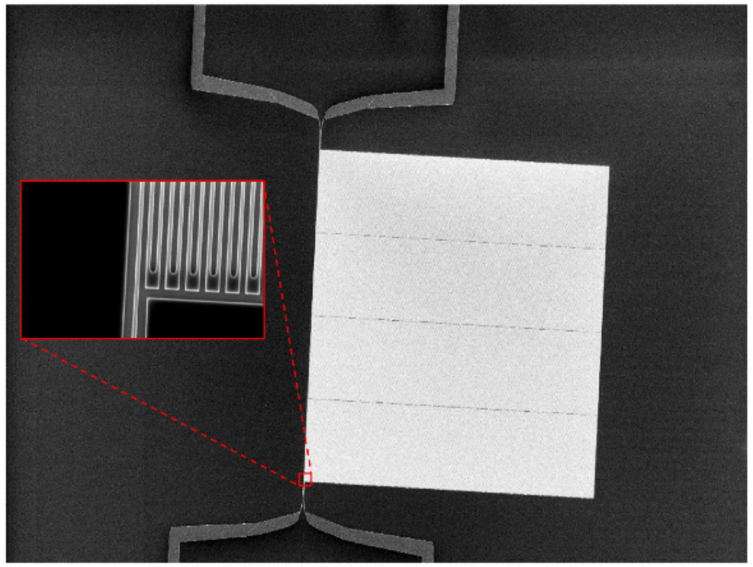
Experimental figure by Jeff Chiles

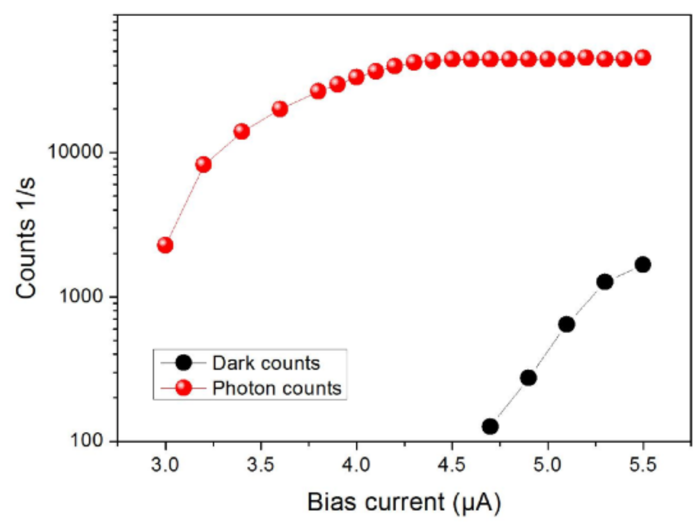


6 layers



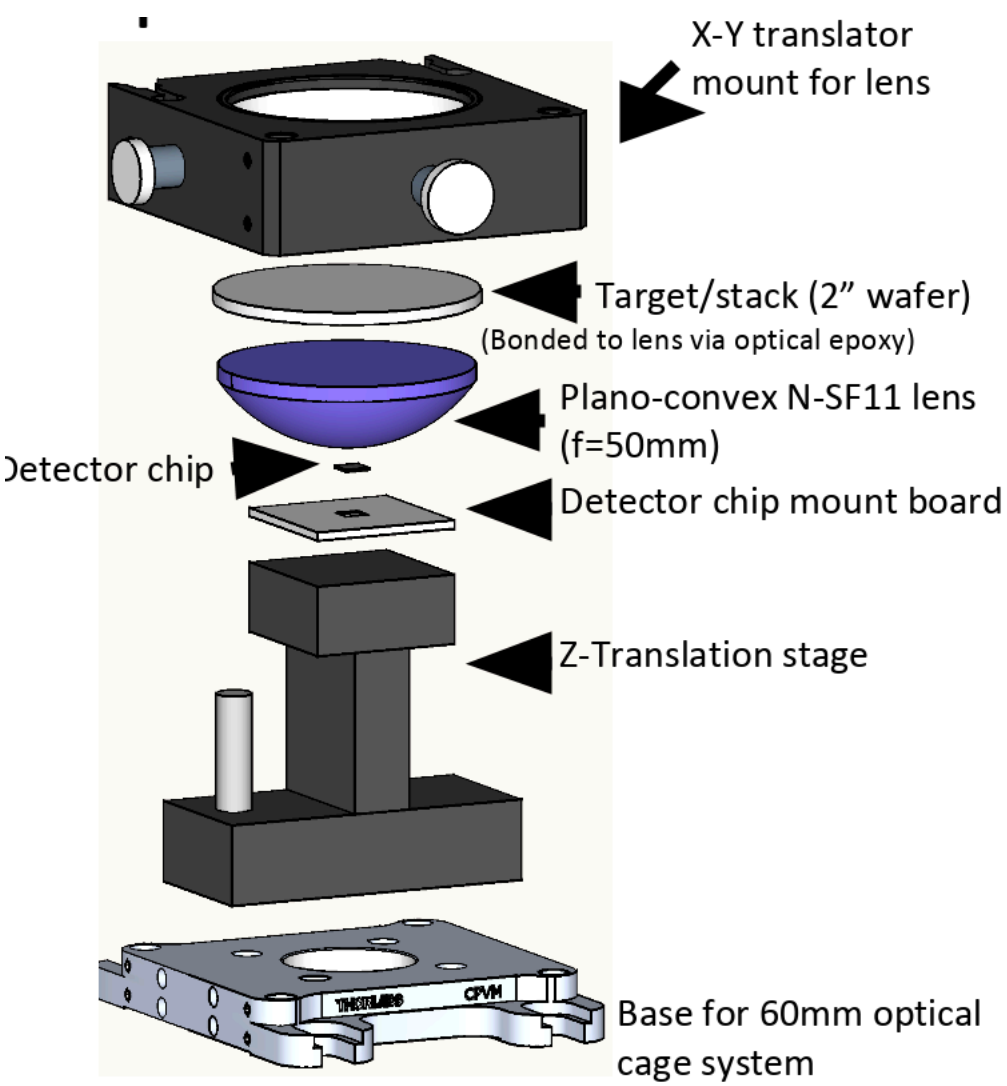


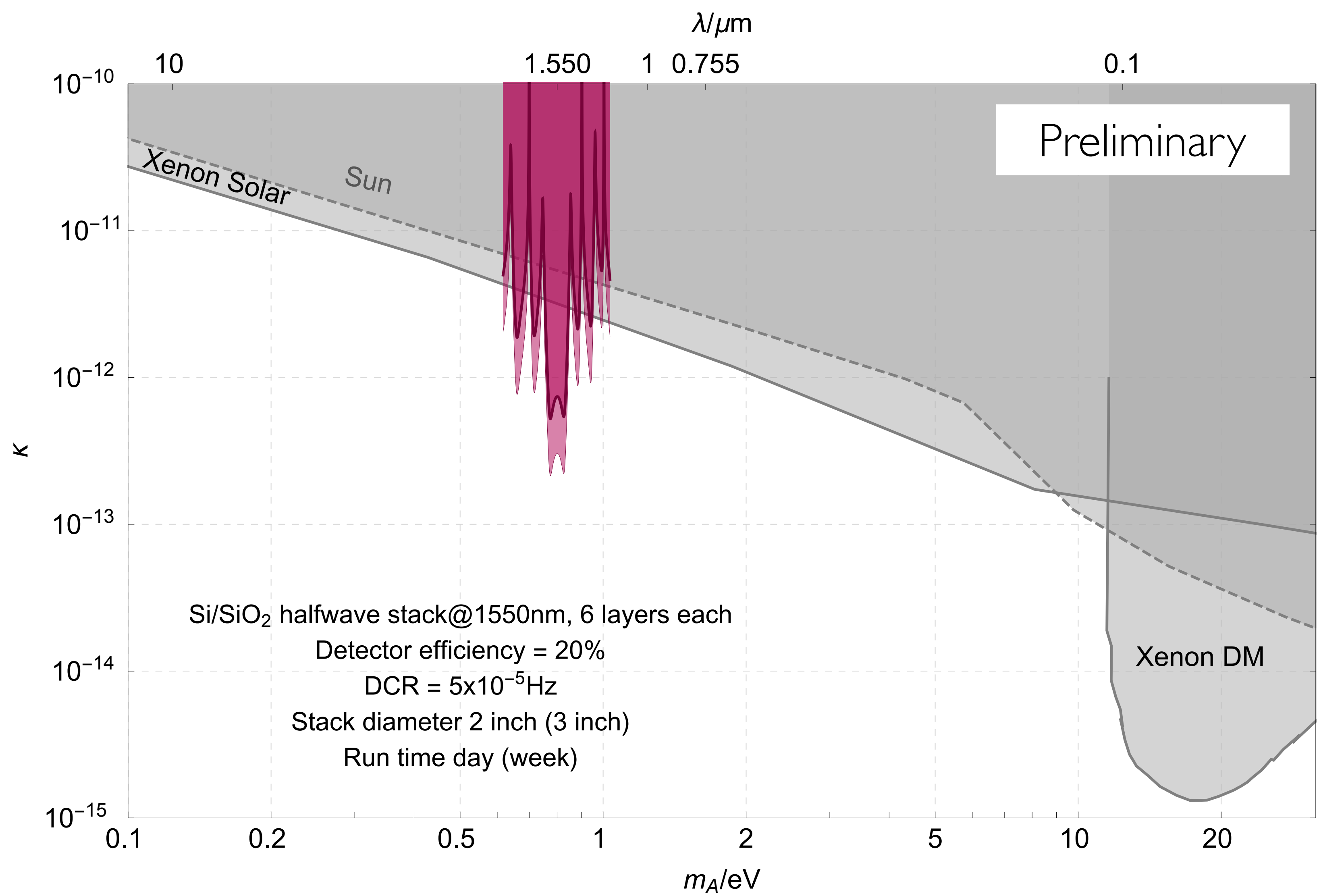




Prototype (MIT/NIST)

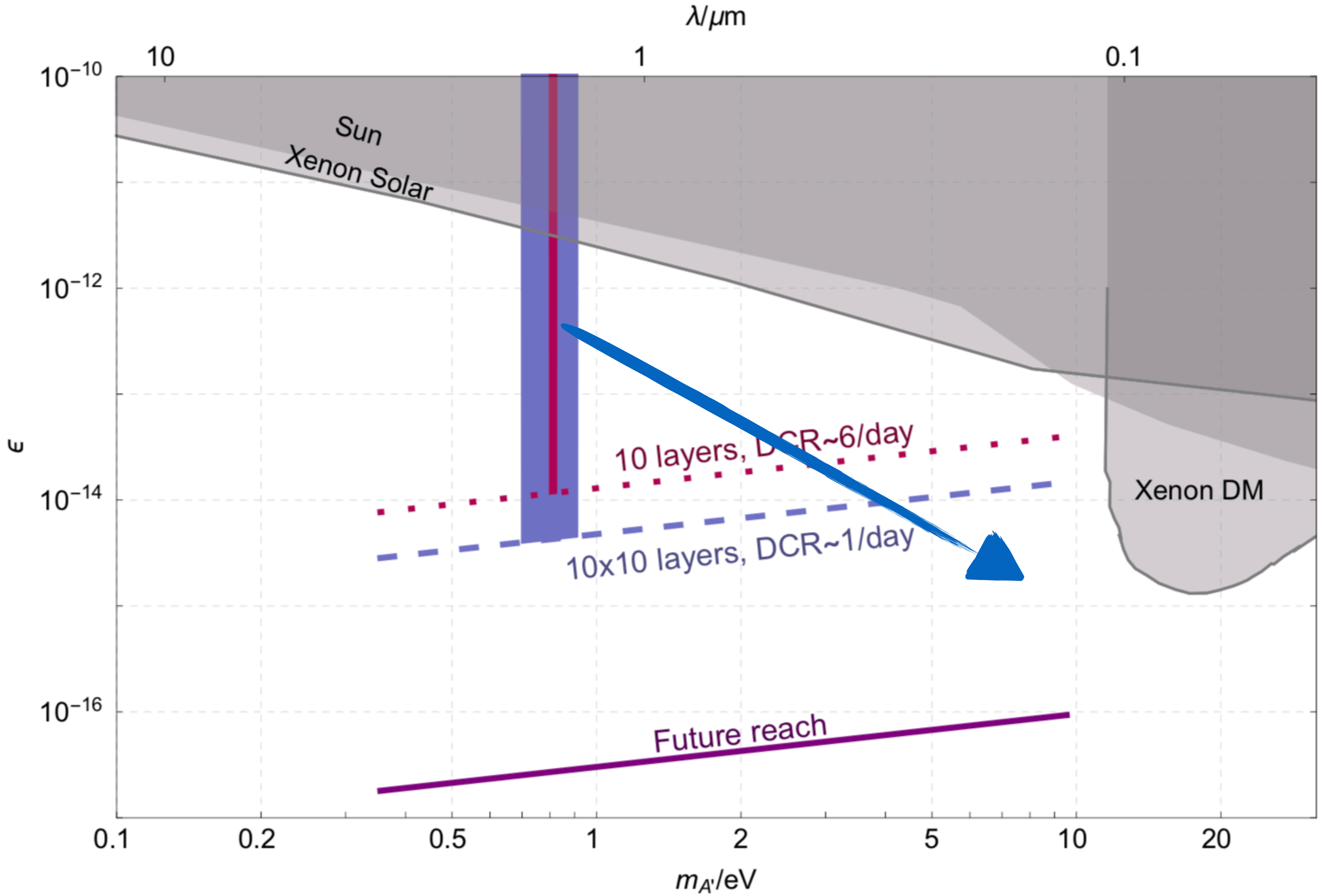
Experimental figure by Jeff Chiles



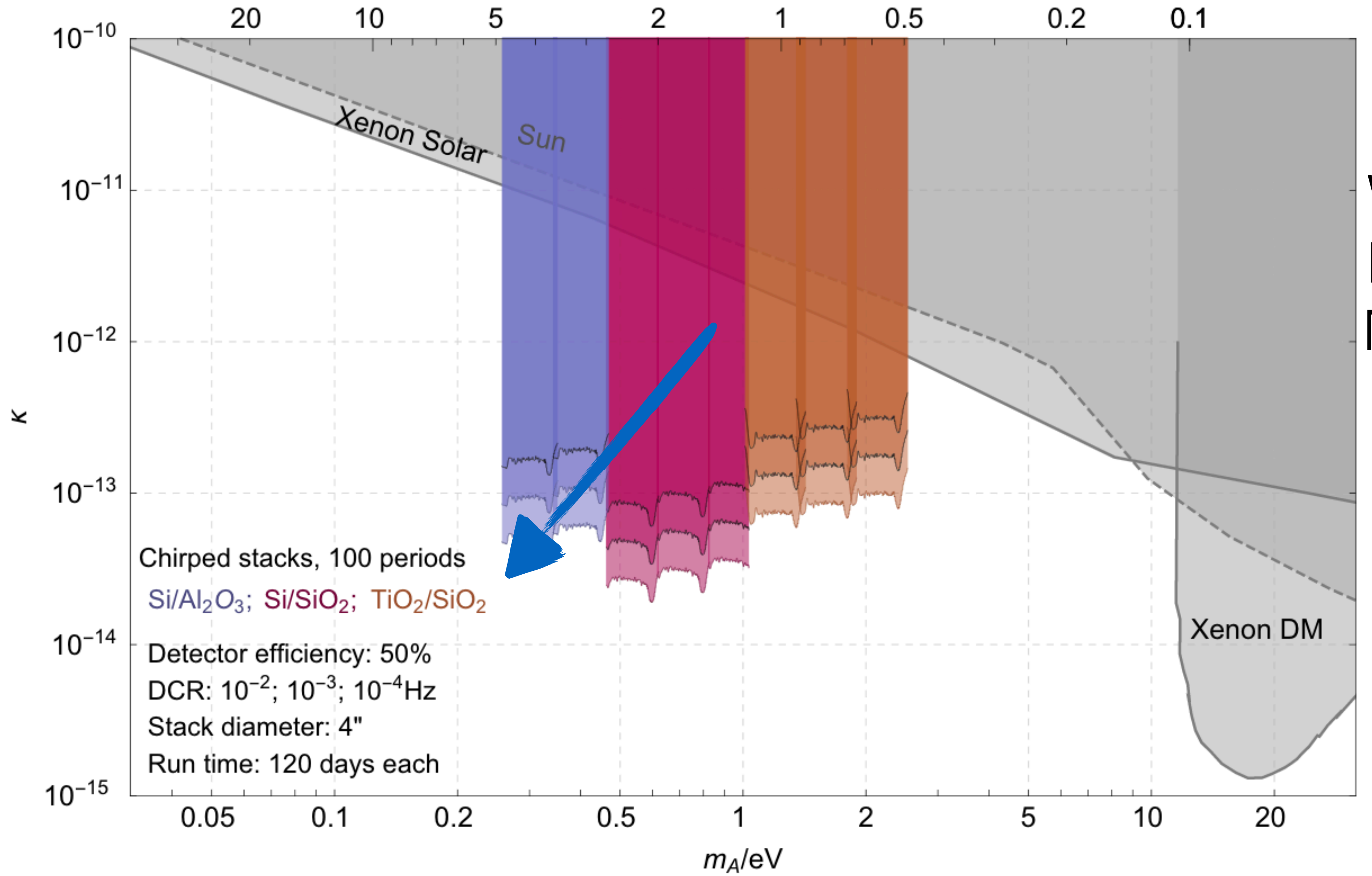


already can cut into new parameter space with one day of run time

Projection (MIT/NIST)

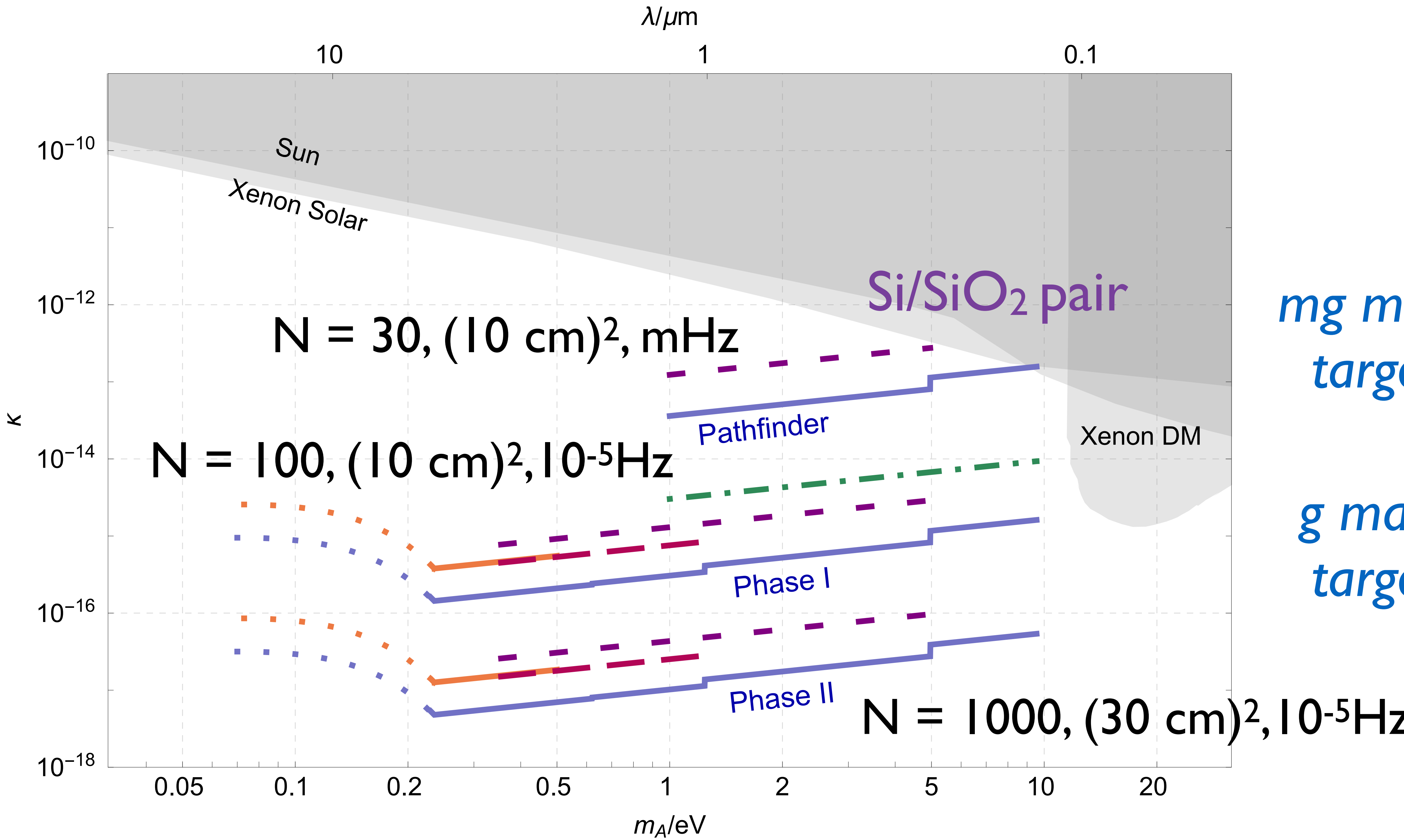


Projection (UCSB)



With Ben Mazin, Nathaniel Craig, Miguel Daal and David Weld (UCSB)

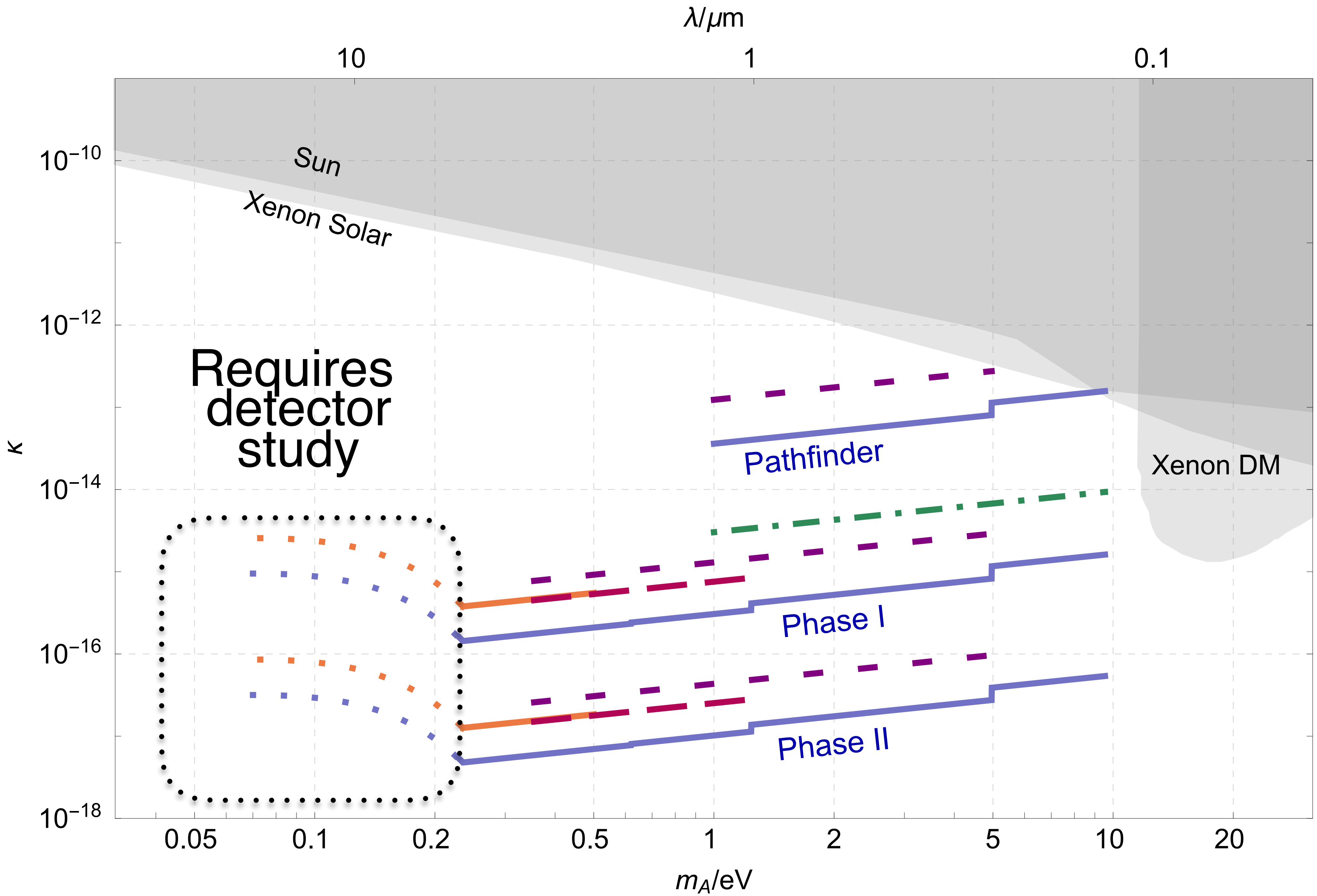
Dark Photon DM



mg mass target

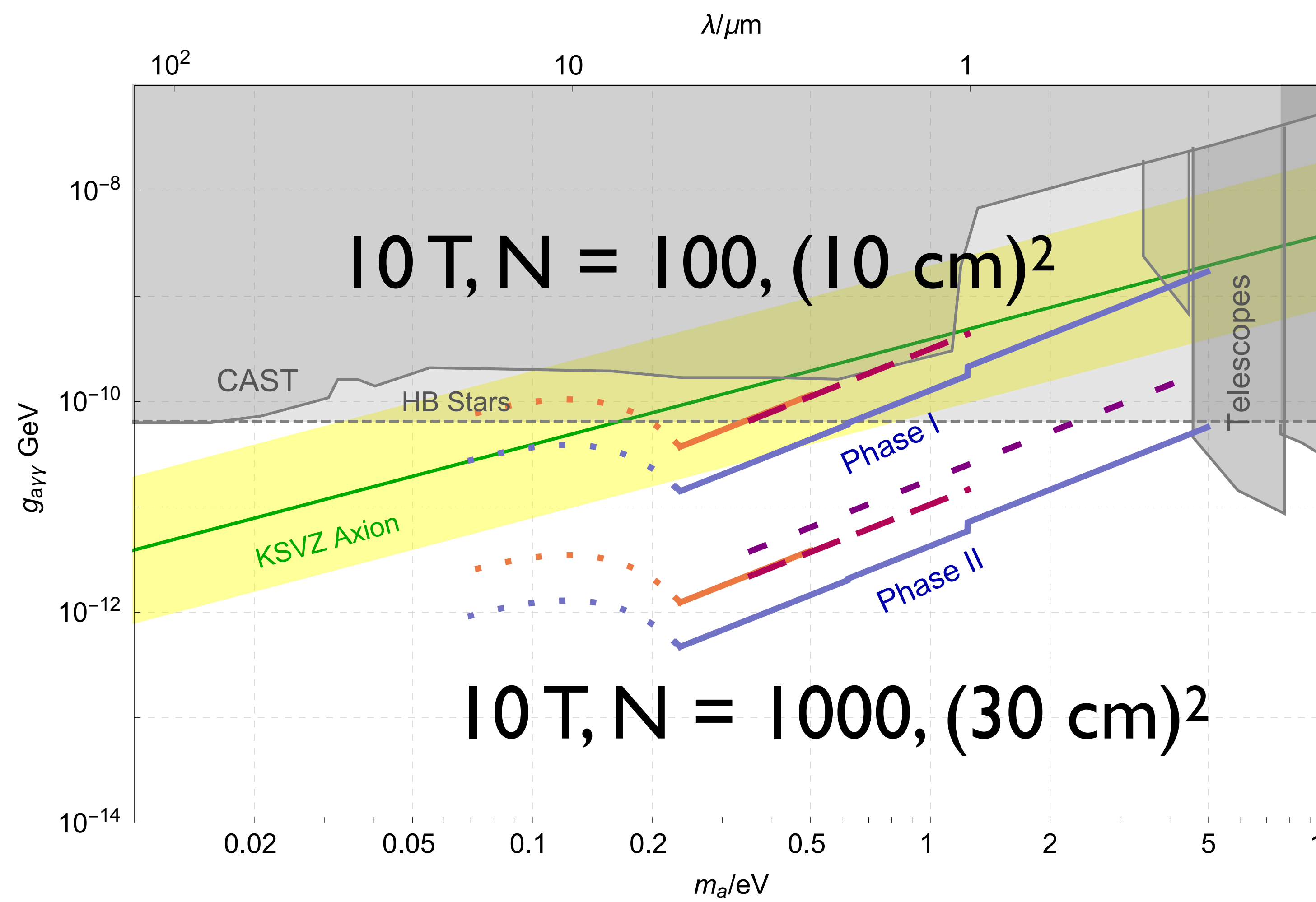
g mass target

Dark Photon DM



Axion DM

- 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

Dark matter axion: arXiv: 1711.10486 Co, Hall and Harigaya
arXiv: 1806.04677 Gorghetto, Hardy, Villadoro

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
- Improved axion and dark photon dark matter reach in the optical range
- Experimental design & set up underway

Thank you!

Light

Axion

Multilayer

Periodic

Optical

Scanning

Targets