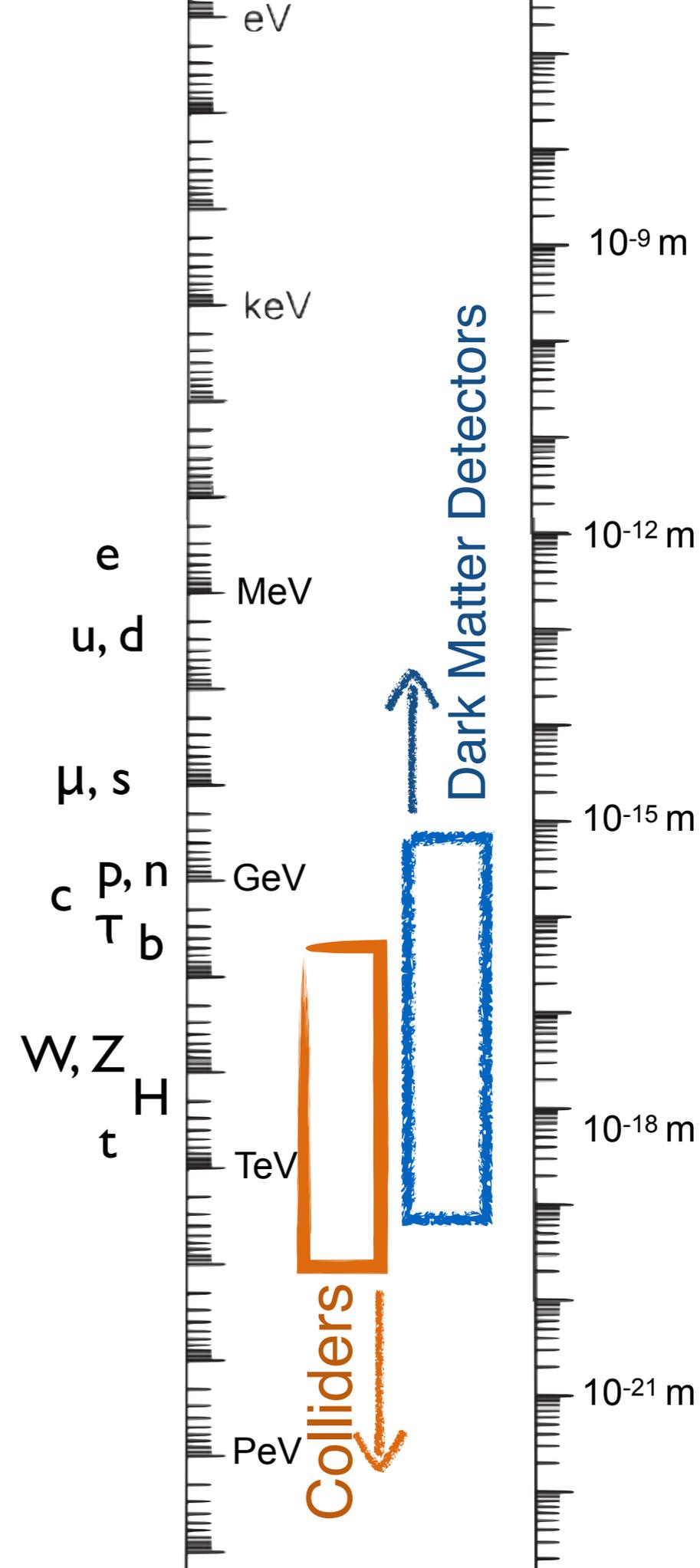


Precision Searches for Ultralight Dark Matter

Masha Baryakhtar (NYU)

Searching for New Physics

- Most of the Standard Model of particle physics lies within several orders of magnitude in mass
- Other scales must appear in a complete theory
 - Planck scale vs. TeV scale
 - Neutrino masses
 - Dark matter
 - Strong-CP problem
 - Cosmological constant...



Theorists Searching for New Physics

- Model-building and theoretical development
- Interpreting data
- Connecting theory to new signatures & observations
 - Well-motivated theories with wide-open parameter space
 - Progress relies on connections between theory and experiment & observation

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Adapted from K. Irwin

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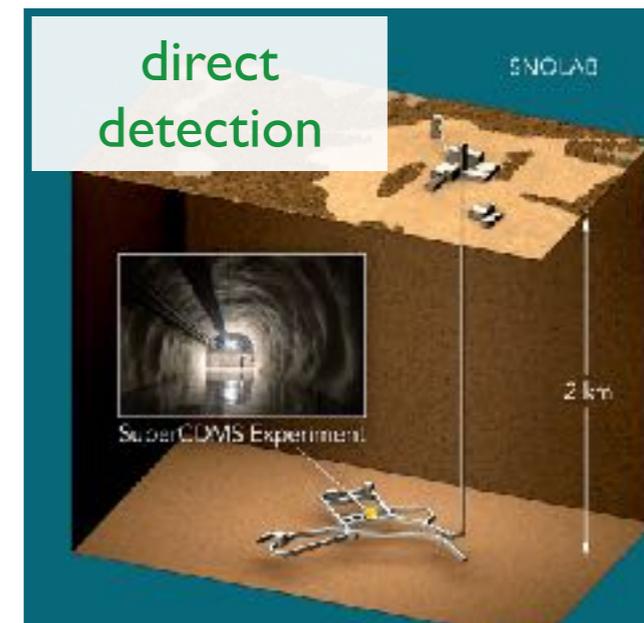
Krauss, Moody, Wilczek, Morris: *Calculations for Cosmic Axion Detection (1985)*

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Detectability of Certain Dark Matter Candidates (1984)



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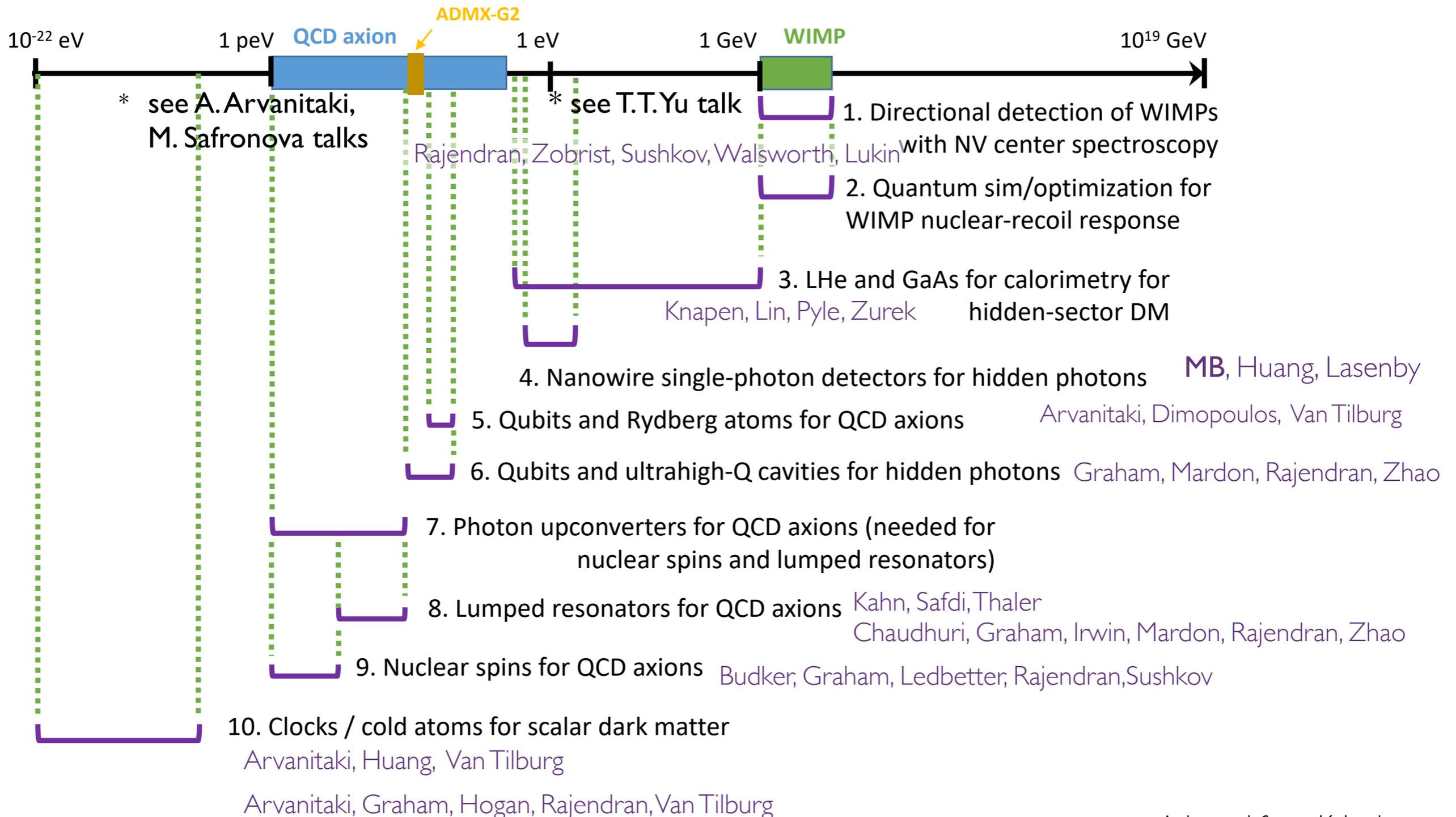


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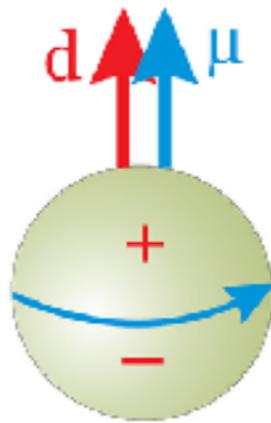
Theorists Searching for New Physics



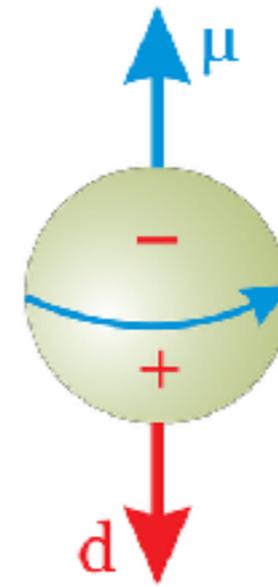
- Outstanding problems in the Standard Model motivate searches at low energies
- Dark matter, strong-CP problem, ...
 - QCD axion
 - Dilatons, moduli, dark photons, ...
 - Very weakly interacting
 - Long wavelength

The Strong-CP problem

- Theoretically expect significant CP violation in potential of strong interactions
- This would give the neutron an electric dipole moment



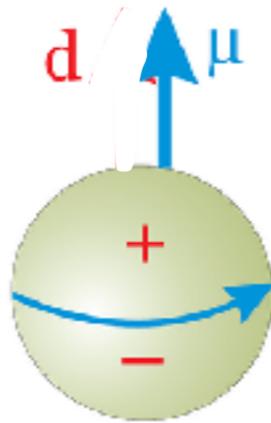
$$\mathbf{P}$$
$$\vec{\mu} \sim \vec{r} \times \vec{p}$$
$$\vec{d} \sim \vec{r}$$



$$\vec{\mu} \cdot \vec{d} \rightarrow -\vec{\mu} \cdot \vec{d}$$

The Strong-CP problem

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- Solve the problem by promoting the amount of CP violation to a dynamical field, the **axion**
- The axion has a potential which is **minimized** when the strong-CP problem is solved

Axions and New Ultralight Particles

- Axions are
 - Solutions to a theoretical puzzle of small numbers: the strong-CP problem:
approximately massless particle with mass and couplings fixed by a high scale f_a ,

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

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Dark photons
and axion like
particles

- Low-energy remnants of complex physics at high scales
- Automatically produced as dark matter in the early universe

Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell

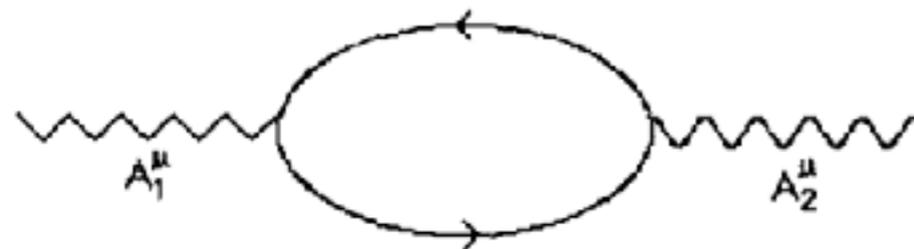
Nelson, Scholtz

Arias, Cadamuro, Goodsell, Jaeckel, Redondo, Ringwald
Graham, Mardon, Rajendran

Preskill, Wise, Wilczek

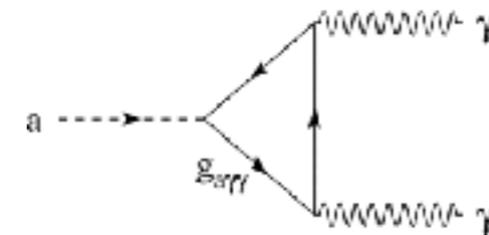
Searches for Axions and Dark Photons

- Wide parameter space of weakly coupled, light particles

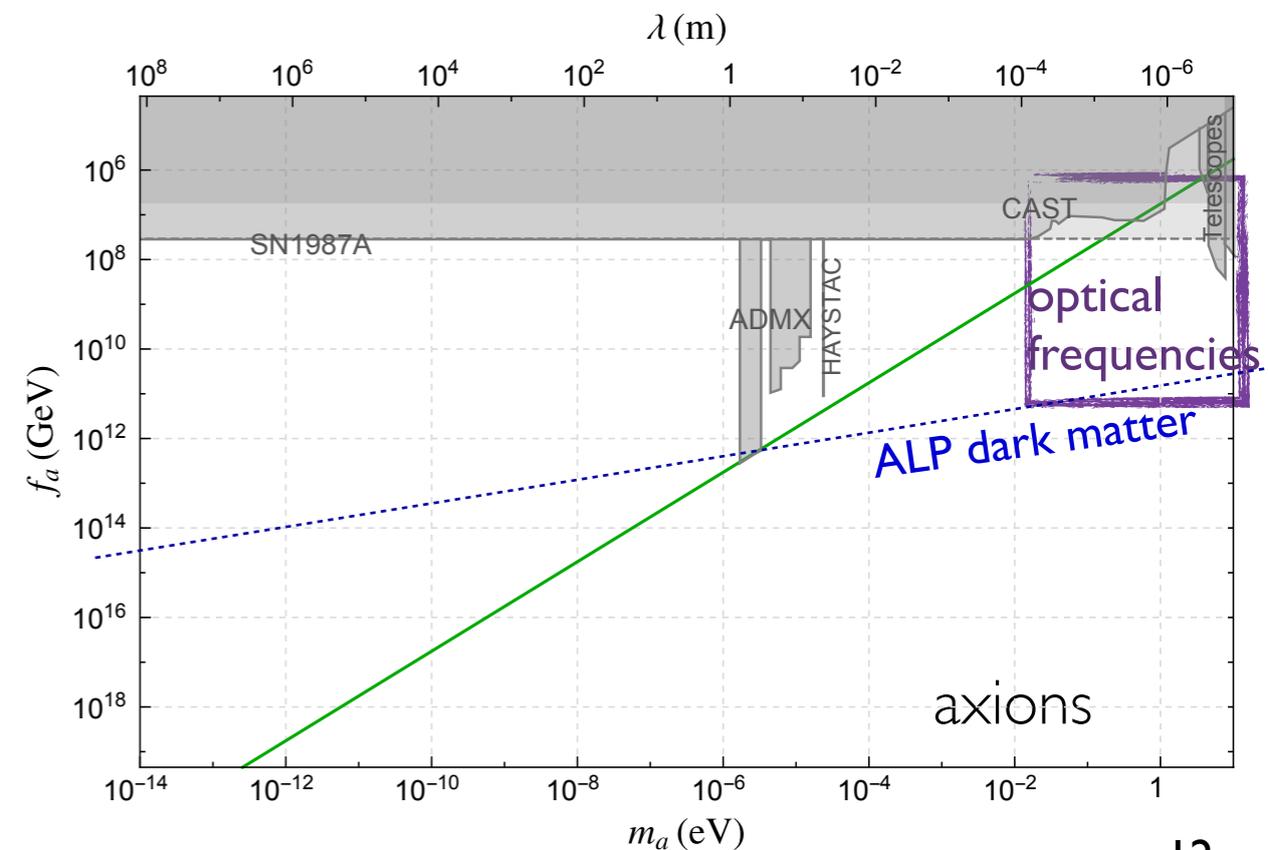
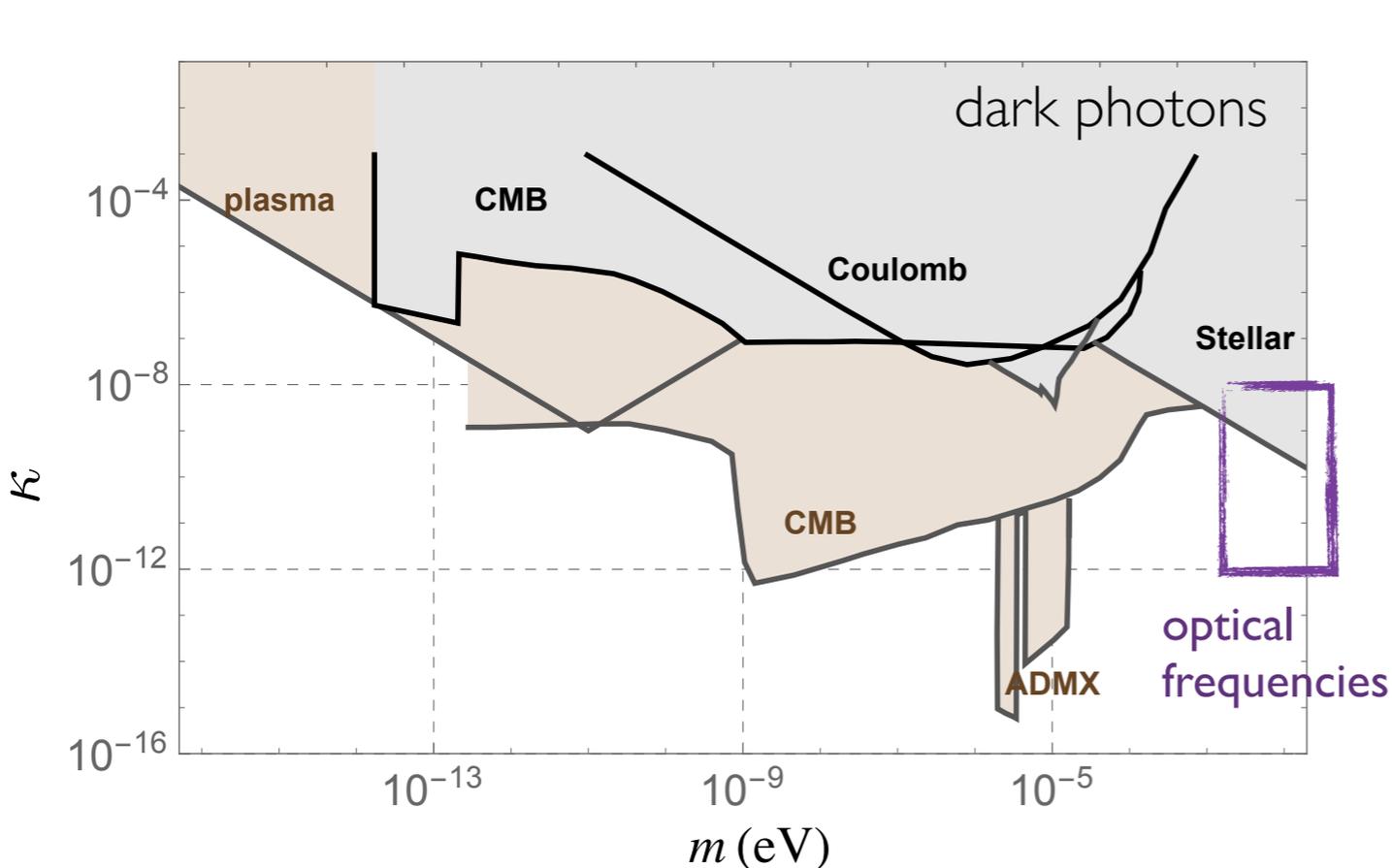


Holdom (1986)

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



Kim (1979); Shifman, Vainshtein, Zakharov (1980)
Dine, Fischler, Srednicki (1981); Zhitnitsky, (1980)

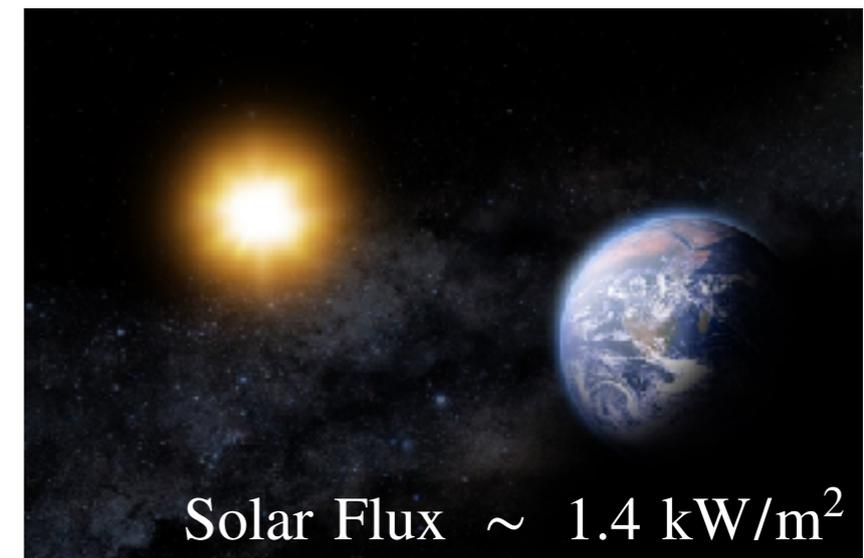


Seeing Dark Matter

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



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



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

Seeing Dark Matter

- For a given energy, **photons** have much more momentum than **dark matter**
- Even when *interactions* in the **dark matter** model allow one-to-one conversion to **photons**, *kinematics* do not

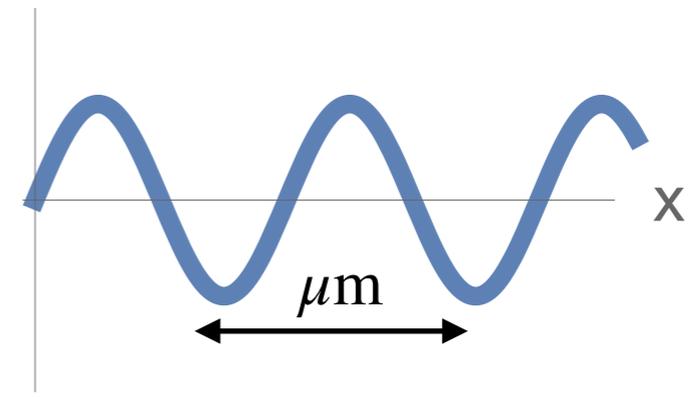
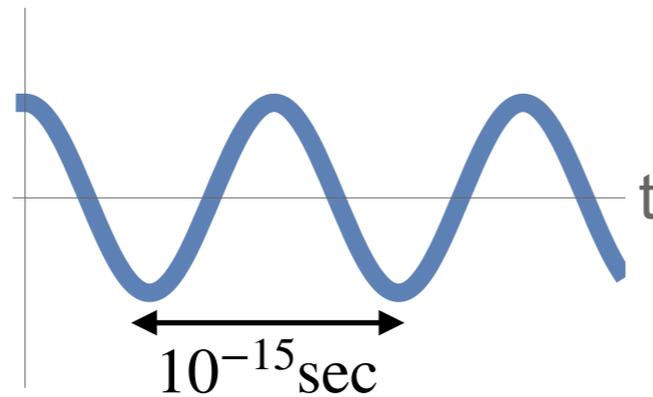
$$\omega_A = \omega_\gamma \Rightarrow k_\gamma \sim 0$$

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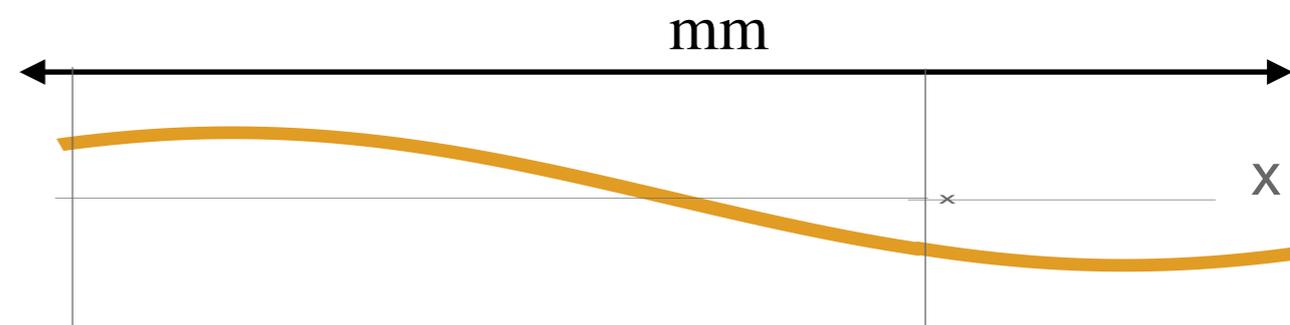
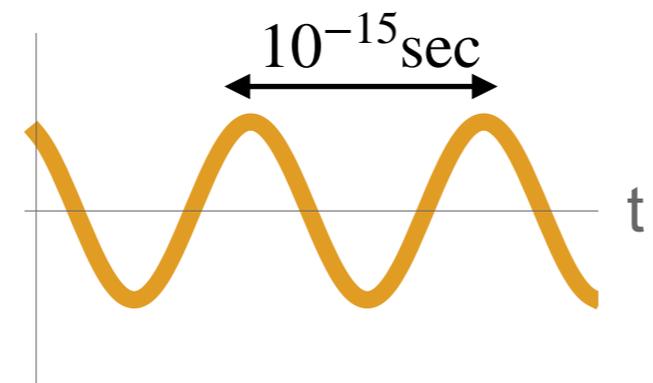
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photons



for an eV particle:

dark photon
dark matter



- Need systems which can efficiently absorb the momentum mismatch

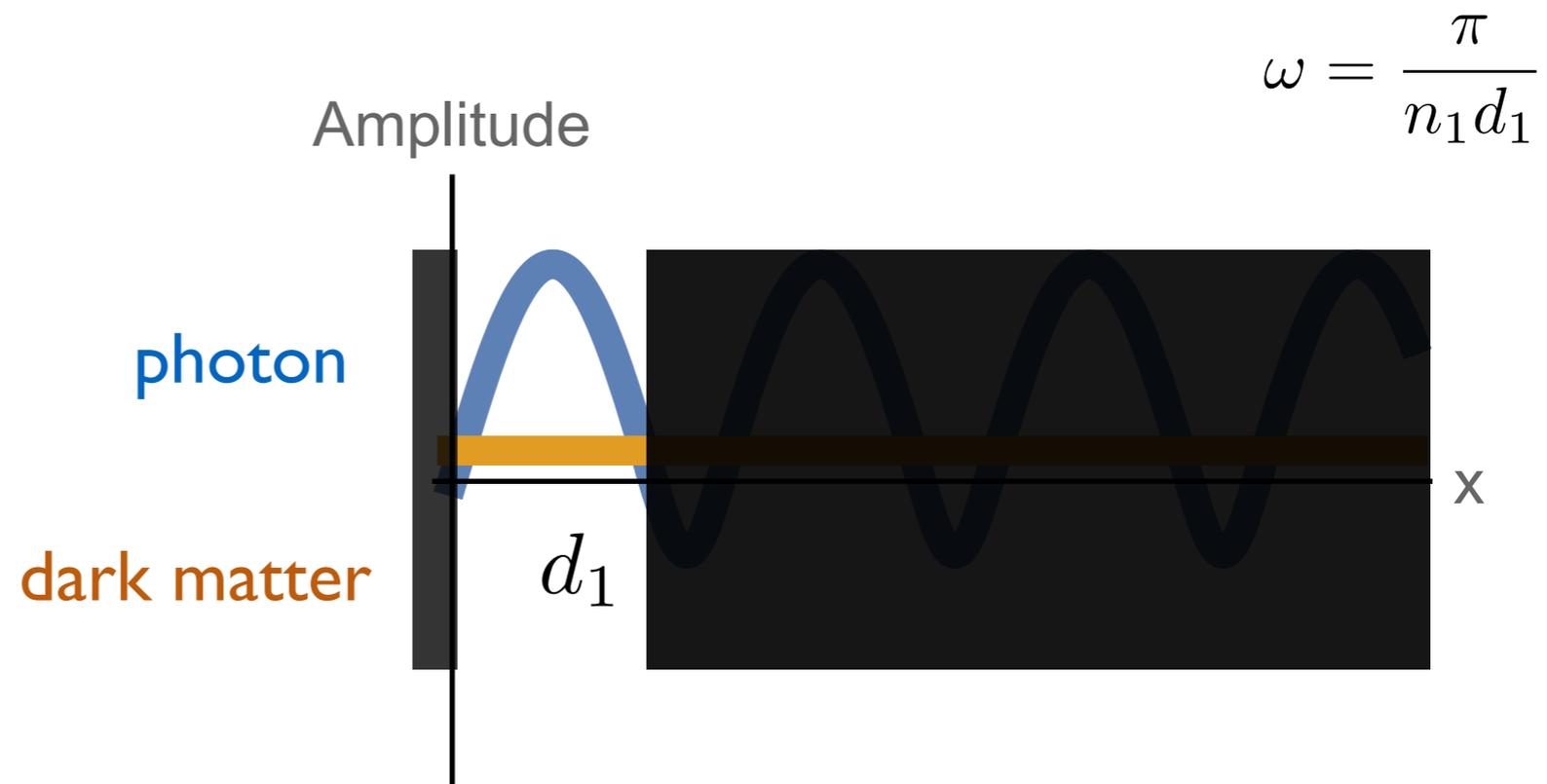
Converting Dark Matter to Light

- **Boundary conditions**

- Create 'gapped modes' for photons
- Standing waves have high energy, low momentum



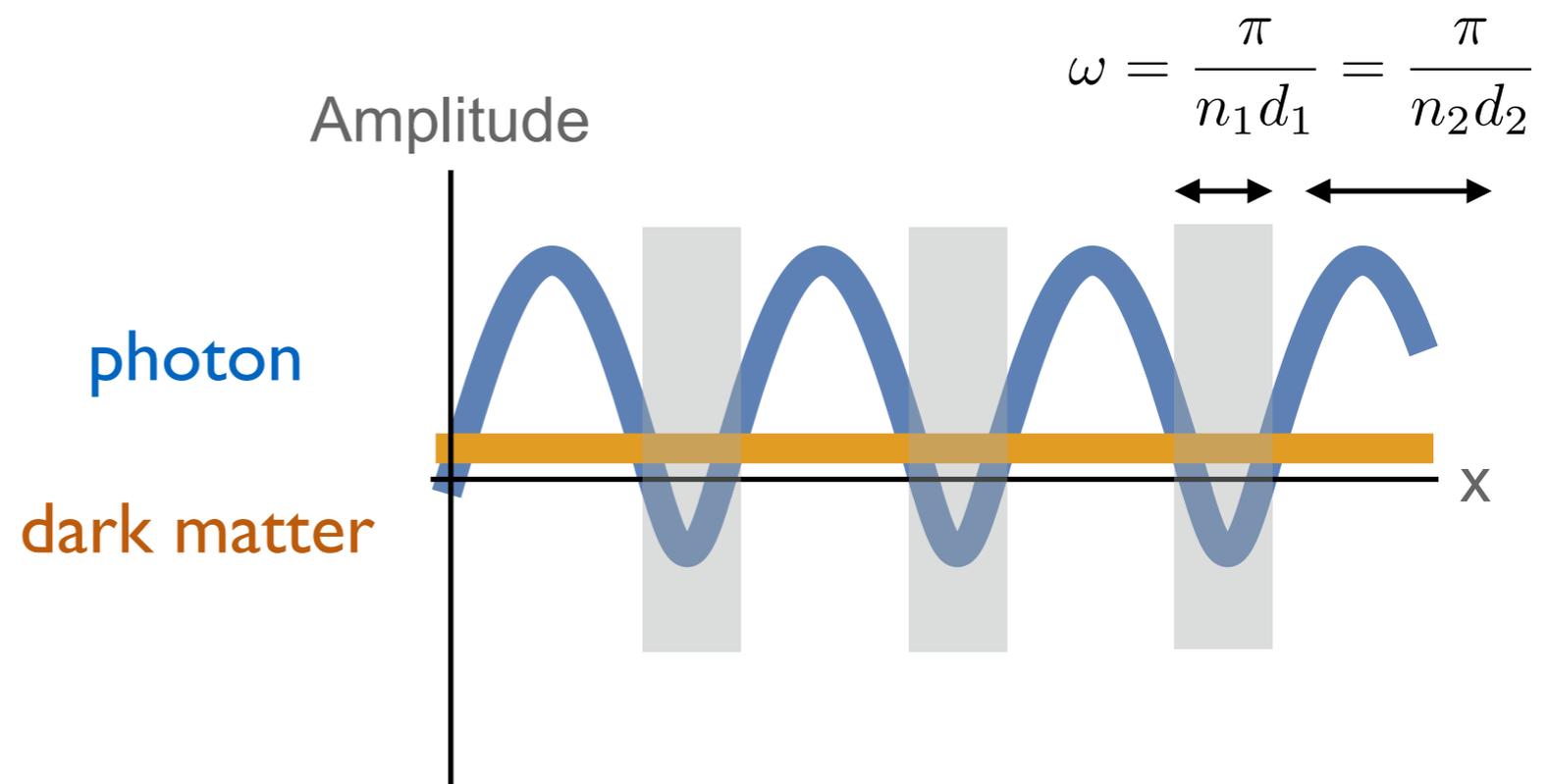
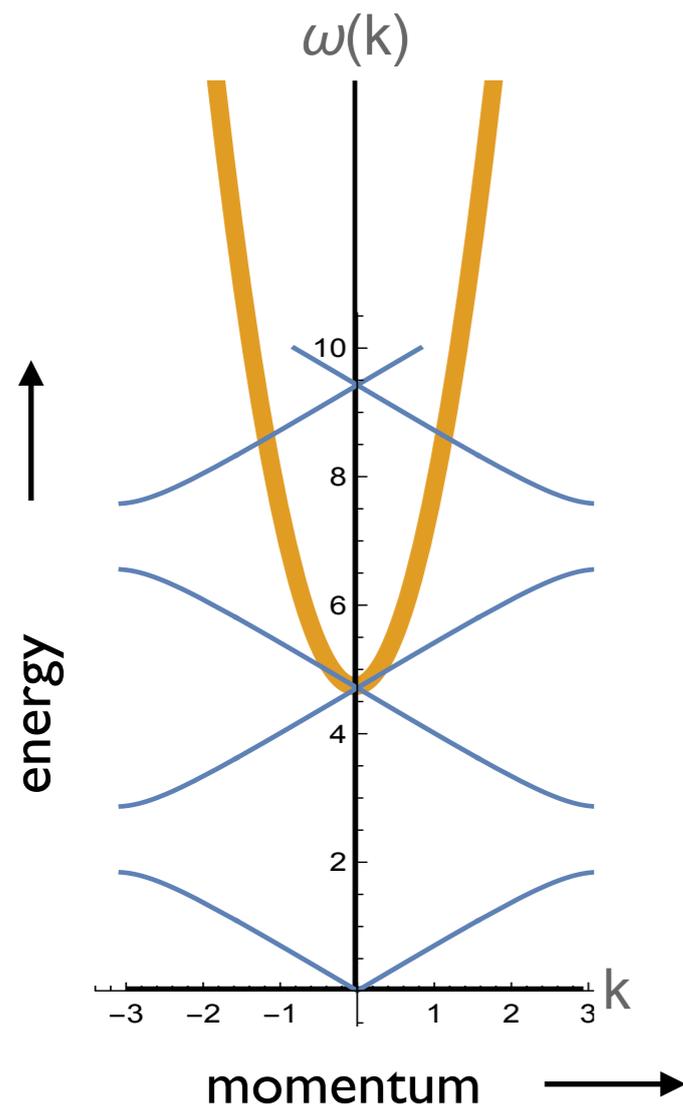
- ADMX: First axion DM experiment to reach motivated parameter space



Converting Dark Matter to Light

- **Photonic crystals:**

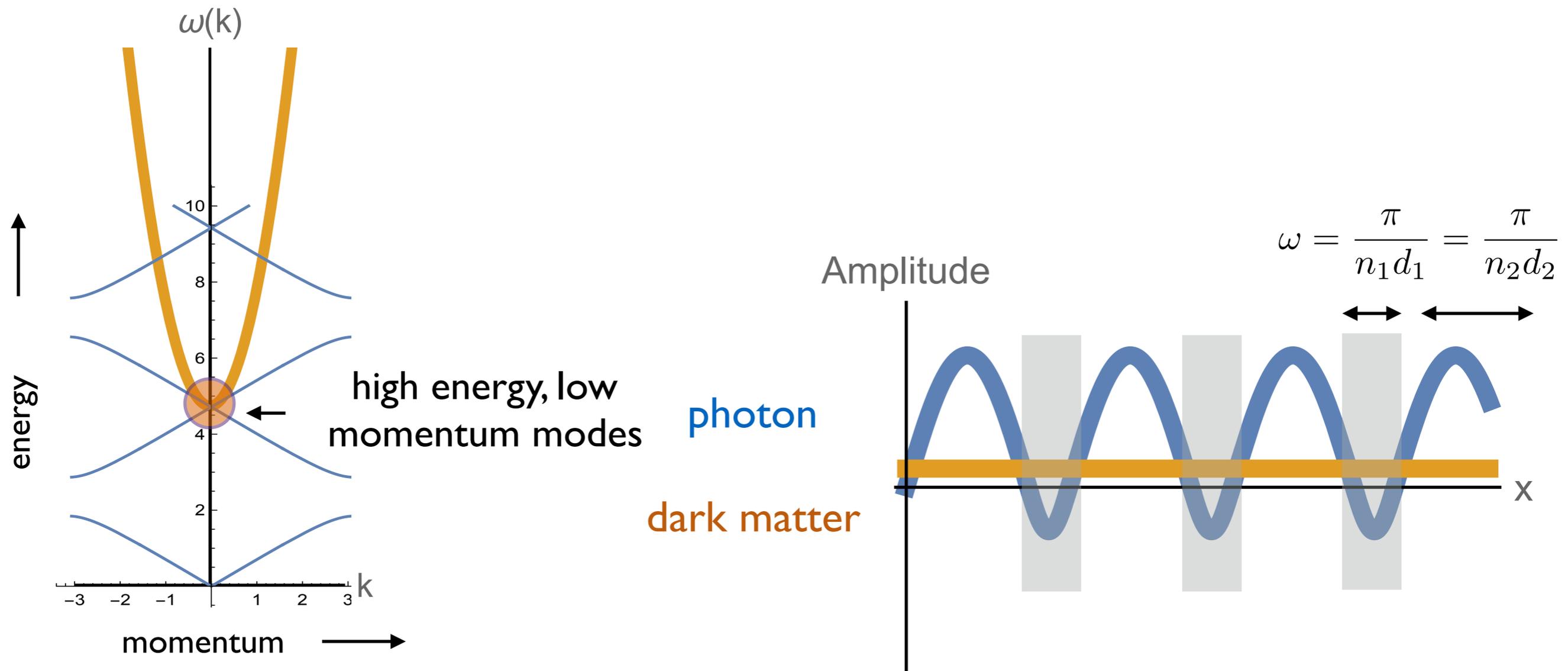
- Add periodicity in the medium in which photons propagate
- Periodic index of refraction changes free solutions of photon modes
- Efficient dark matter to photon conversion



Converting Dark Matter to Light

- **Photonic crystals:**

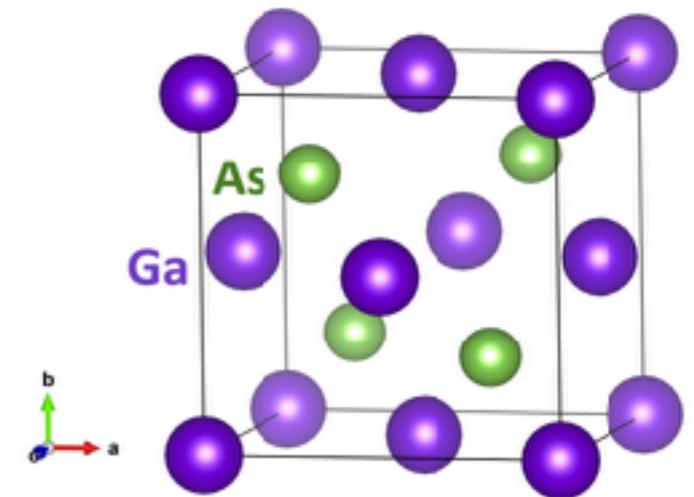
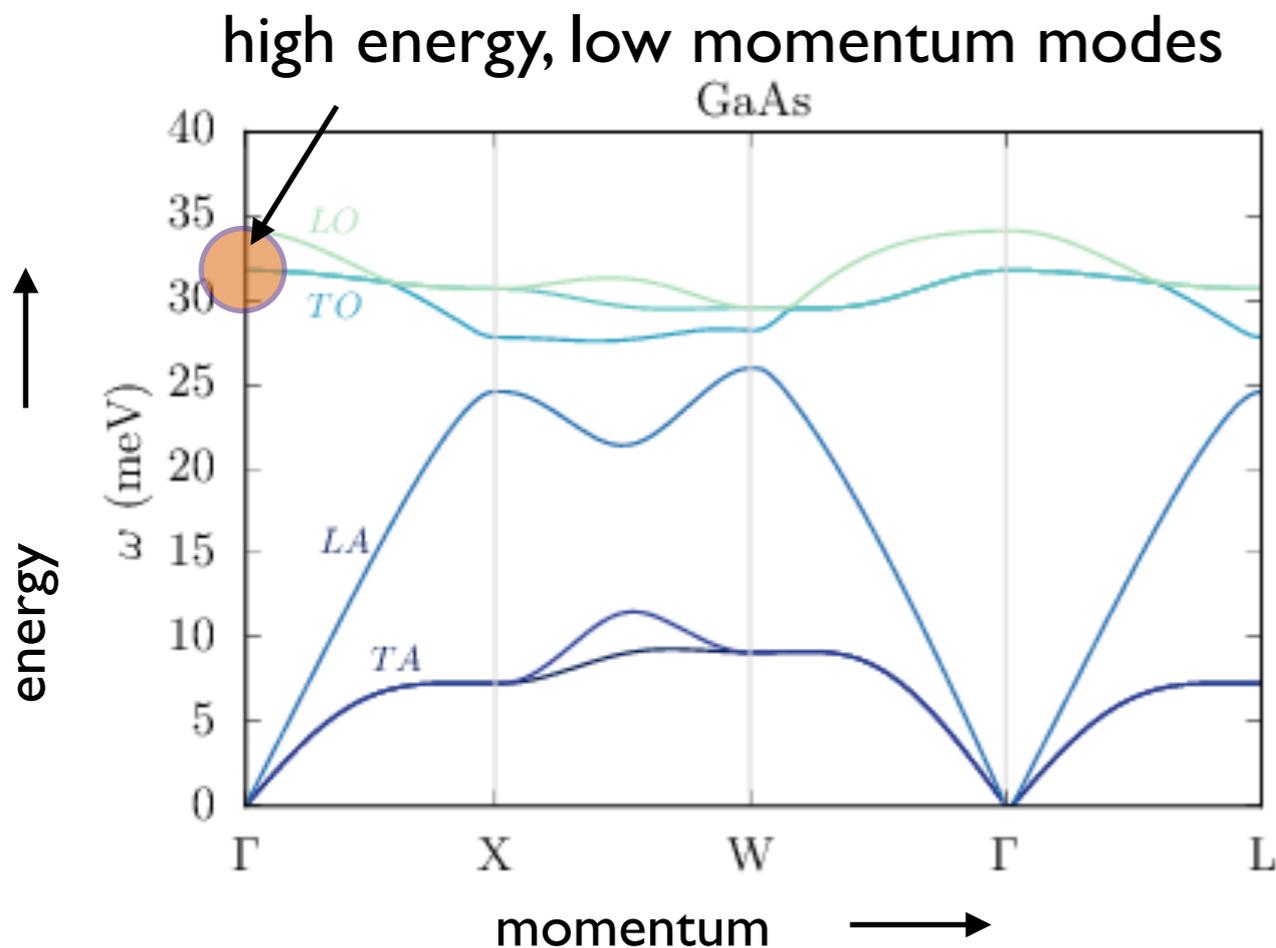
- Add periodicity in the medium in which photons propagate
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Converting Dark Matter to ~~Light~~ Sound

- **Crystals:**

- Specific periodic structures create 'optical' phonon modes with 'non-relativistic' dispersion
- Efficient dark matter to phonon conversion

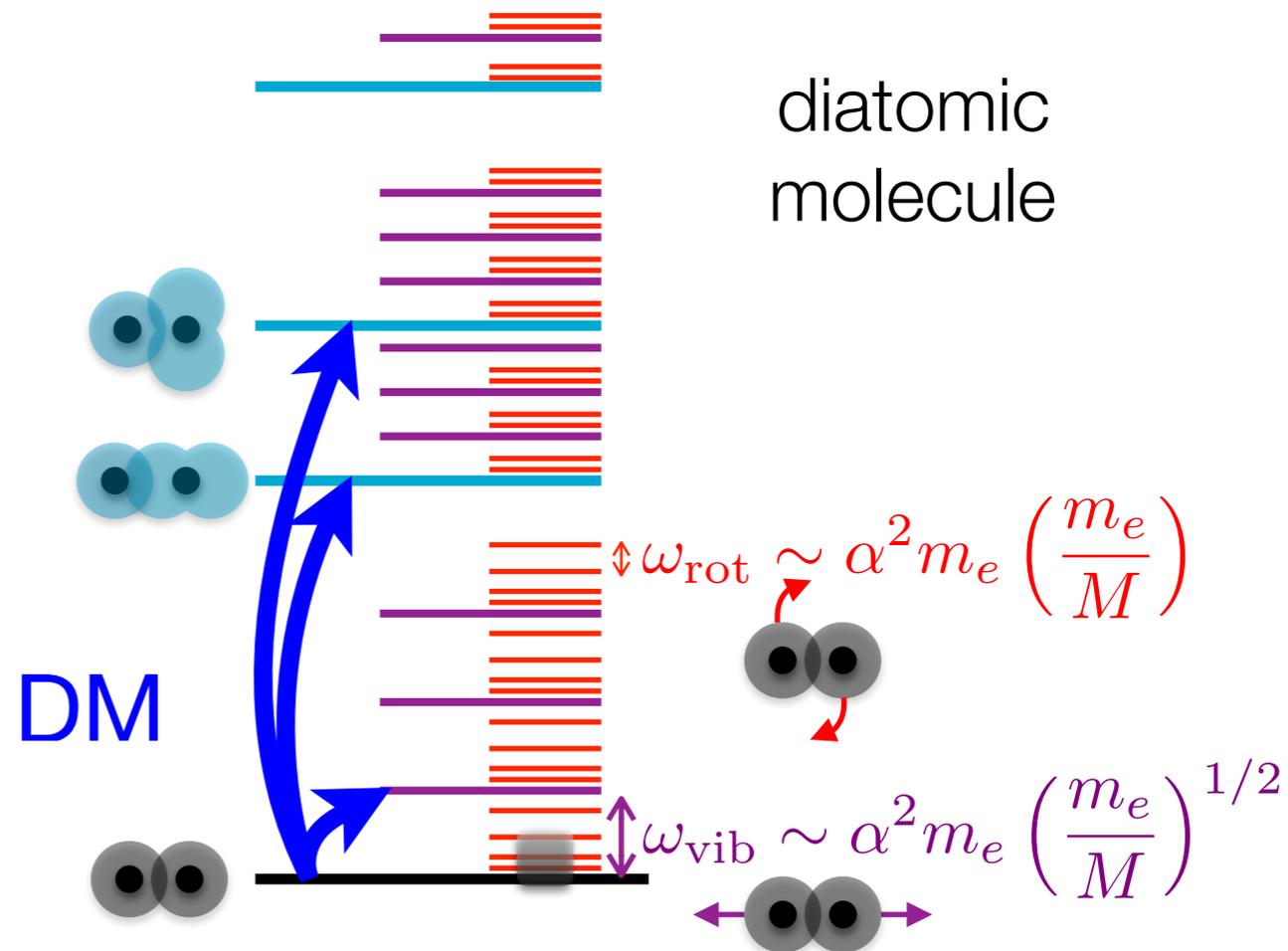
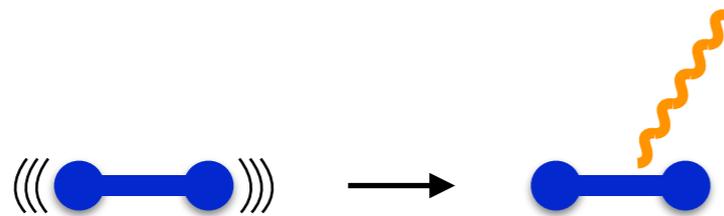
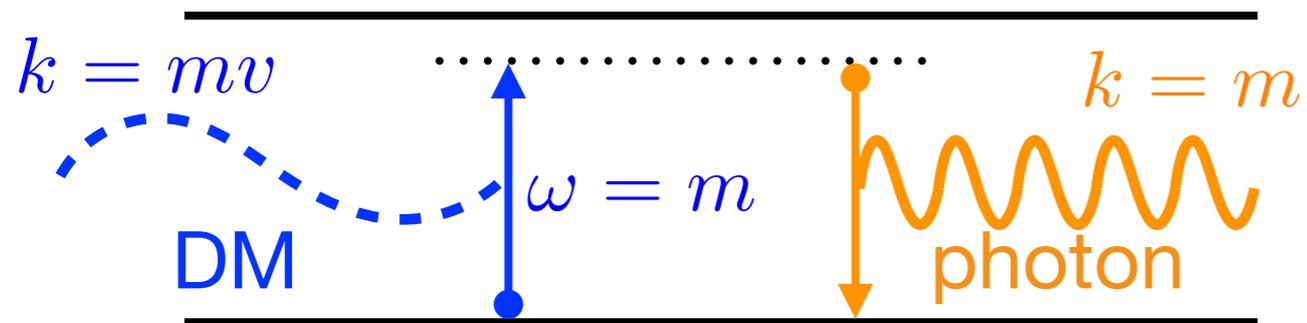


Griffin, Knapen, Lin, Zurek (2018)
see also talk by M. Pyle

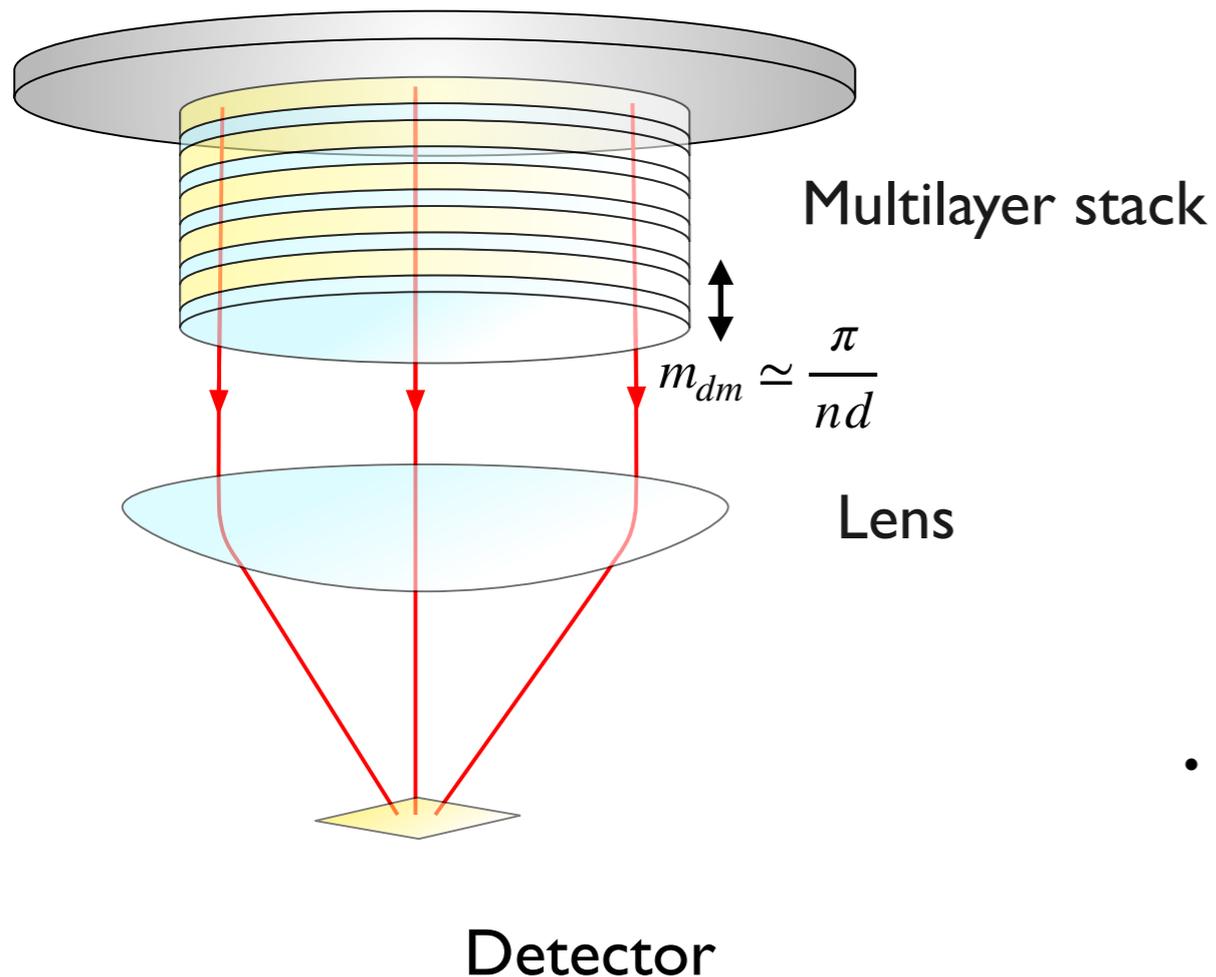
Converting Dark Matter to Light

- **Molecules**

- Energy splitting between states sets dark matter absorption, followed by photon reemission



Searches for dark matter with light



Dark photon dark matter converts to detectable single photons

- Outgoing photon energy sourced by dark matter:

$$\omega_\gamma \simeq m_{dm} + \mathcal{O}(10^{-6}m_{dm})$$

- Outgoing photon momentum sourced by periodicity:

$$k_\gamma \simeq \frac{\pi}{nd} + \mathcal{O}(10^{-3}m_{dm})$$

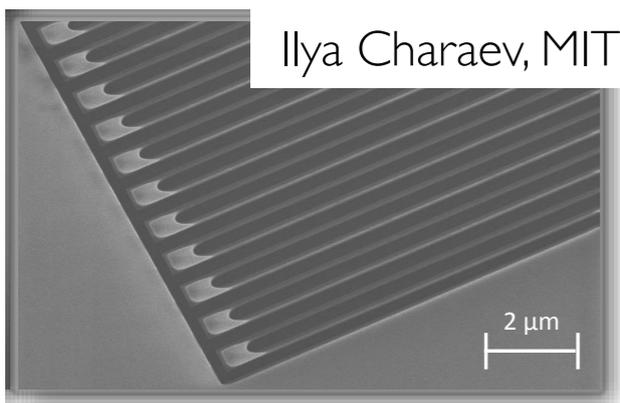
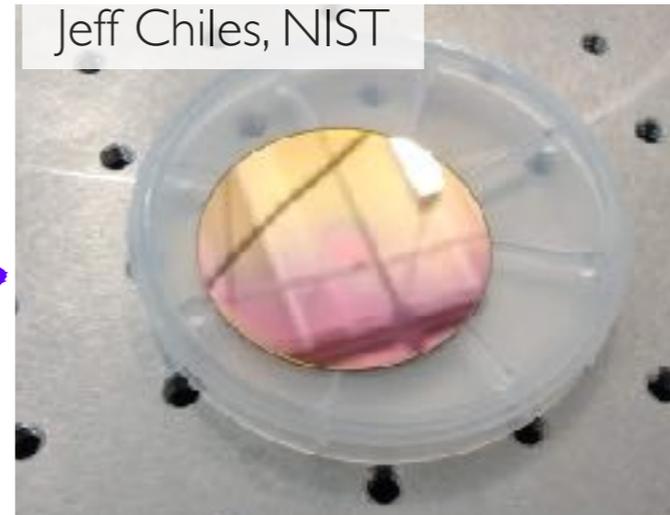
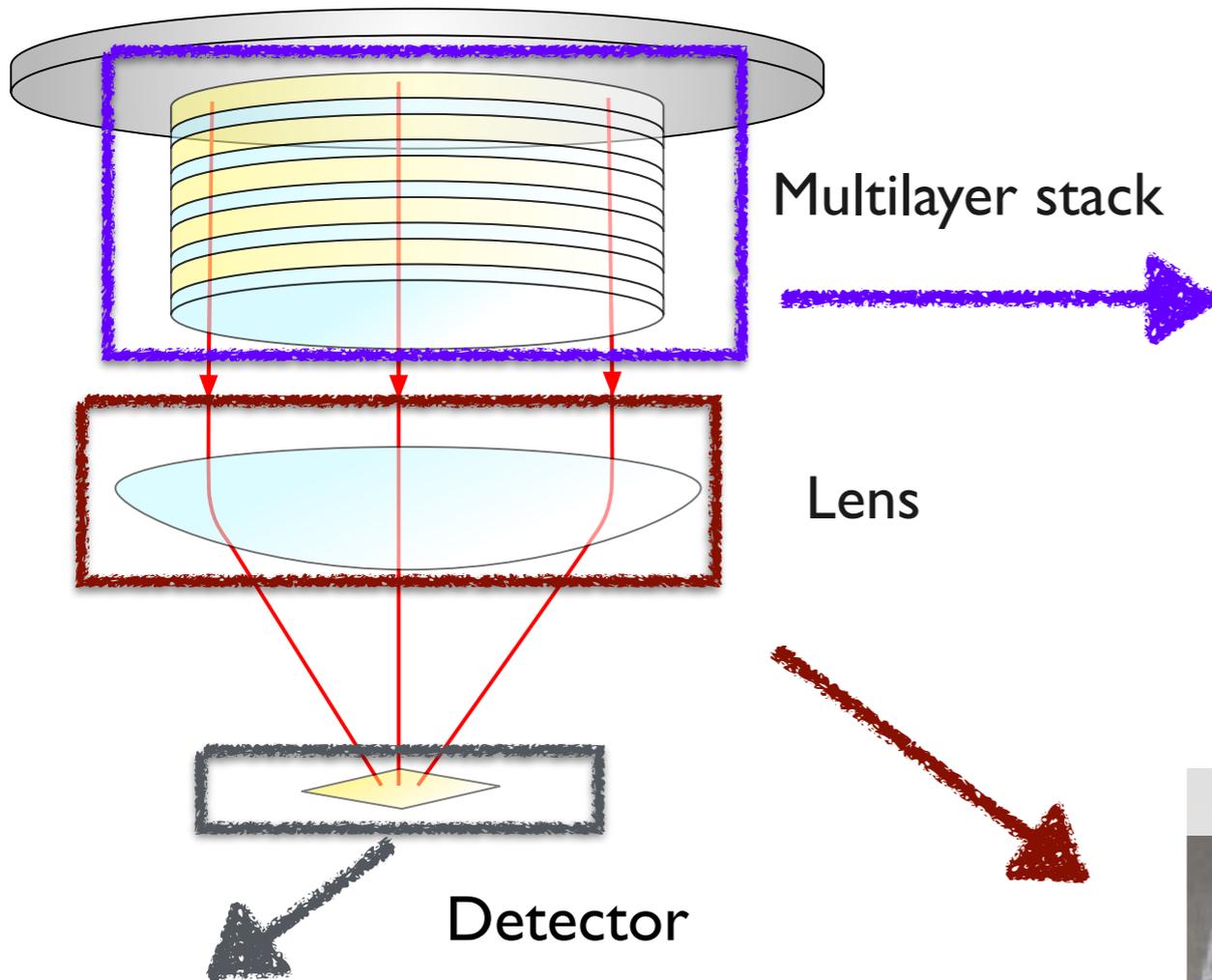
- Emission when DM mass matches periodicity:

$$m_{dm} \simeq \frac{\pi}{nd}$$

Dielectric 'lattice' corrects momentum mismatch between photon and dark matter

MB, J. Huang, R. Lasenby, PRD 2018

Nanowire Detection of Photons from the Dark Side



- High index of refraction contrast, more layers increase conversion
- e.g. **silicon** ($n_2=3.4$) and **silica** ($n_1=1.46$)

DOE QuantiSED grant, DE-SC0019129 (\$300,000 for two years)

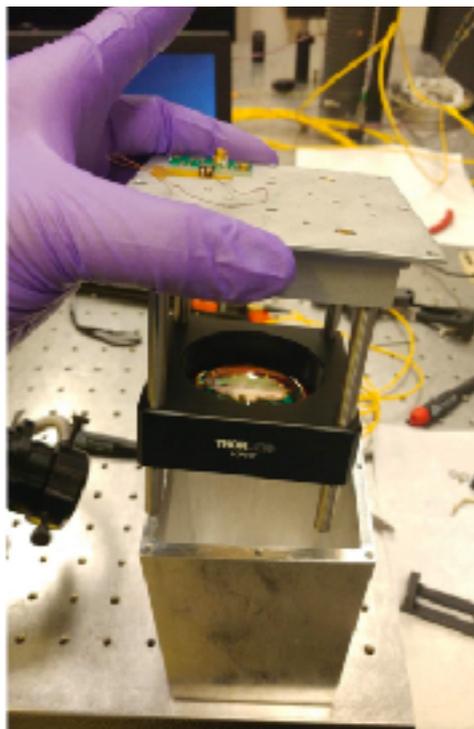
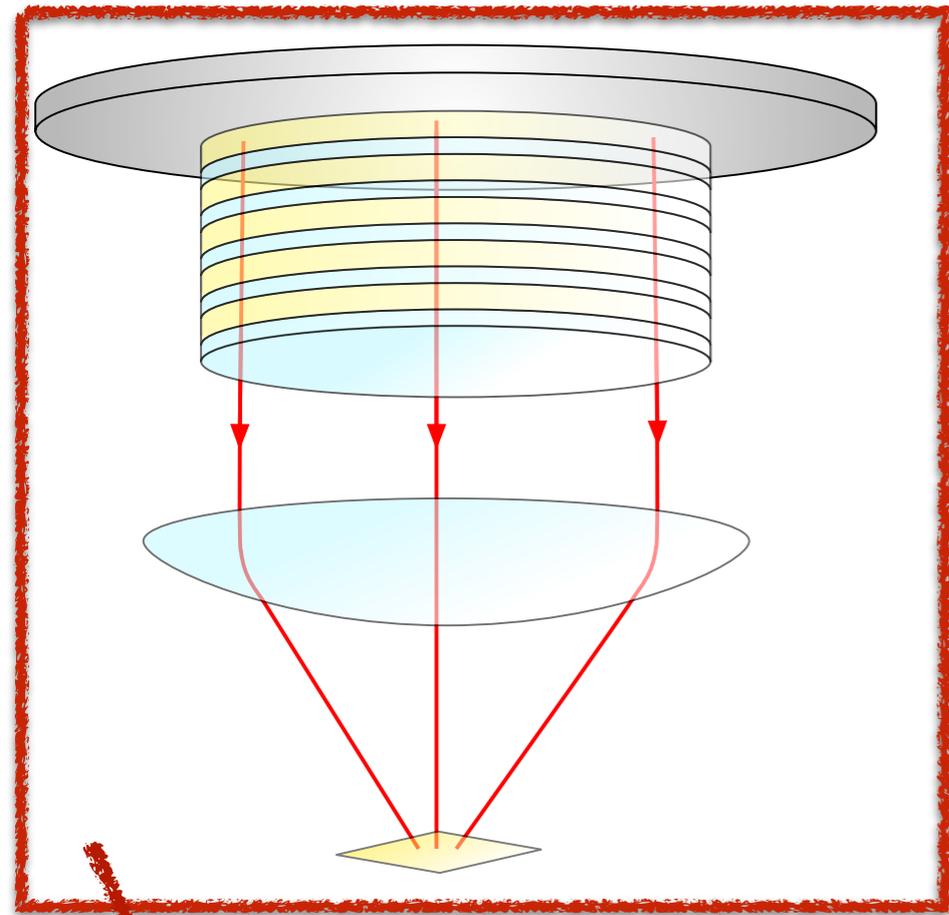
Bosonic Dark Matter Search Using Superconducting Nanowire Single-Photon Detectors.

(Exp) Berggren, Charaev; Chiles, Nam; (Th) Arvanitaki, **MB**, Huang, Lasenby, Van Tilburg.

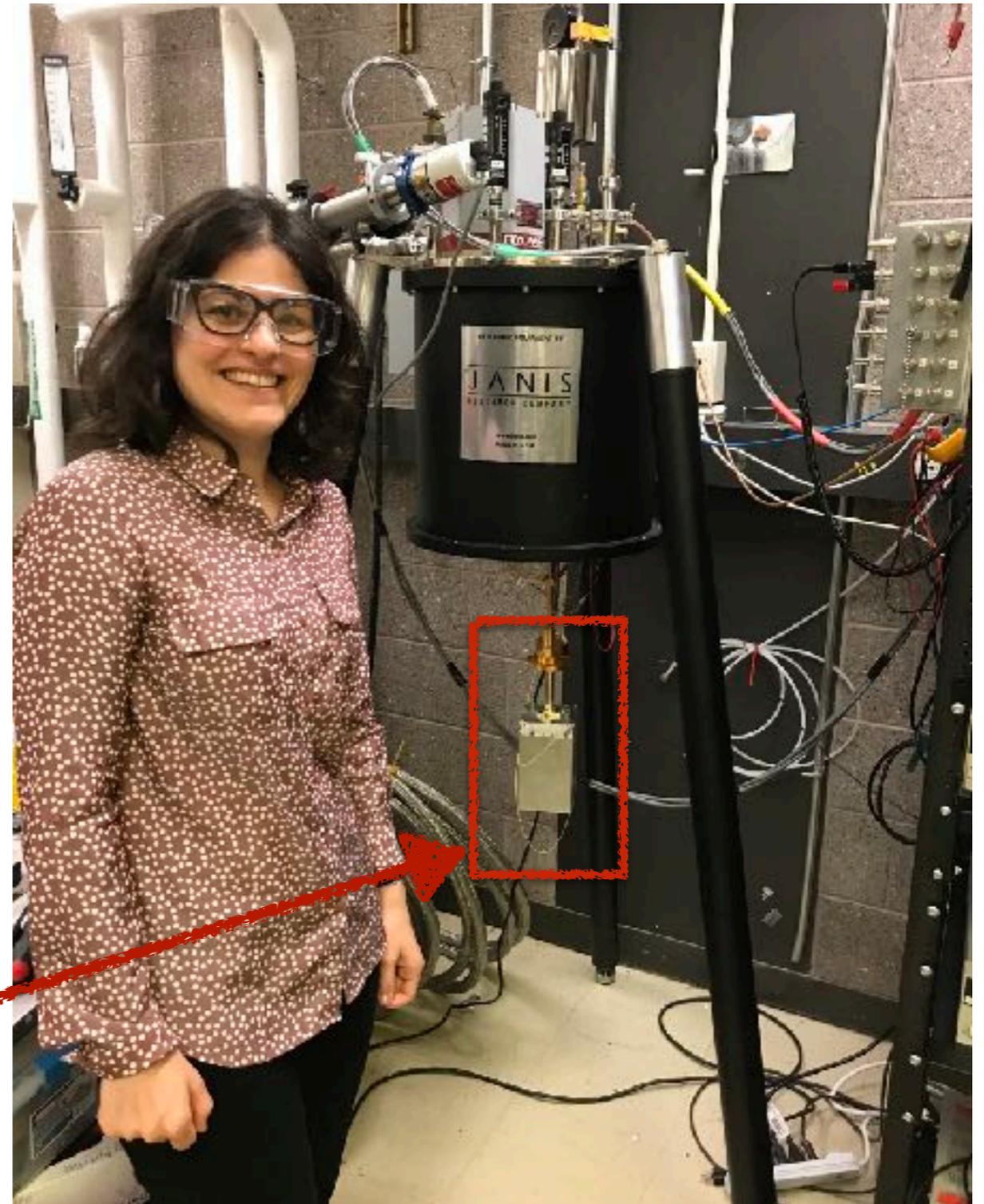
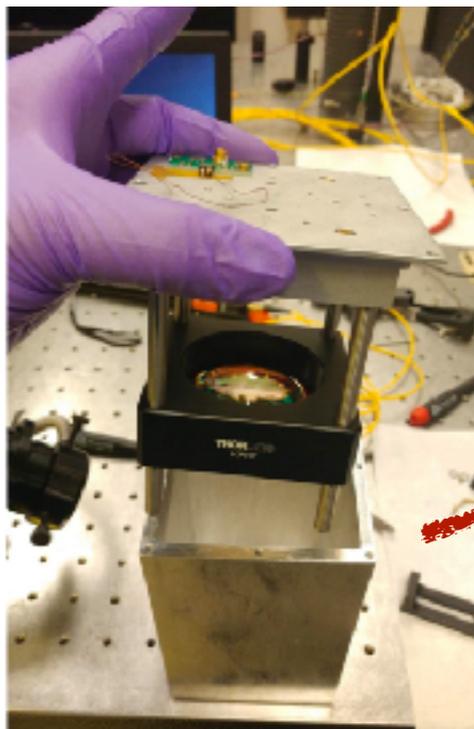
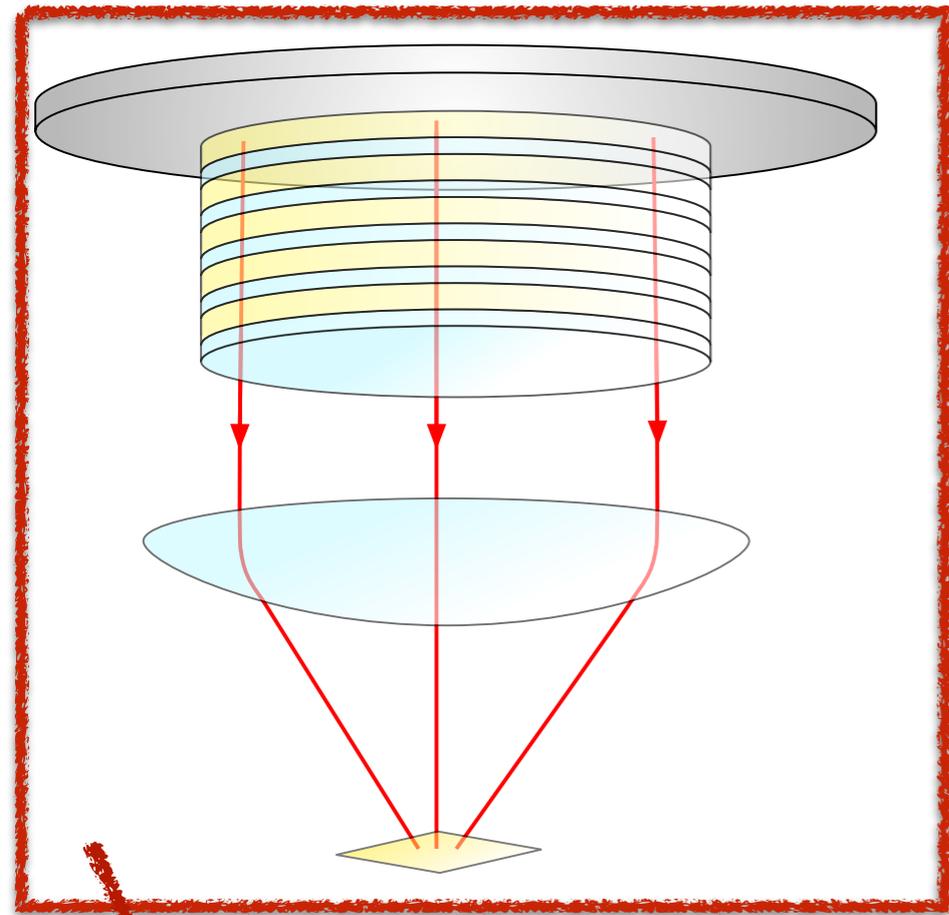
- Small area single photon detector with ultra low noise

- Signal photons perpendicular to stack: efficiently focused

Nanowire Detection of Photons from the Dark Side

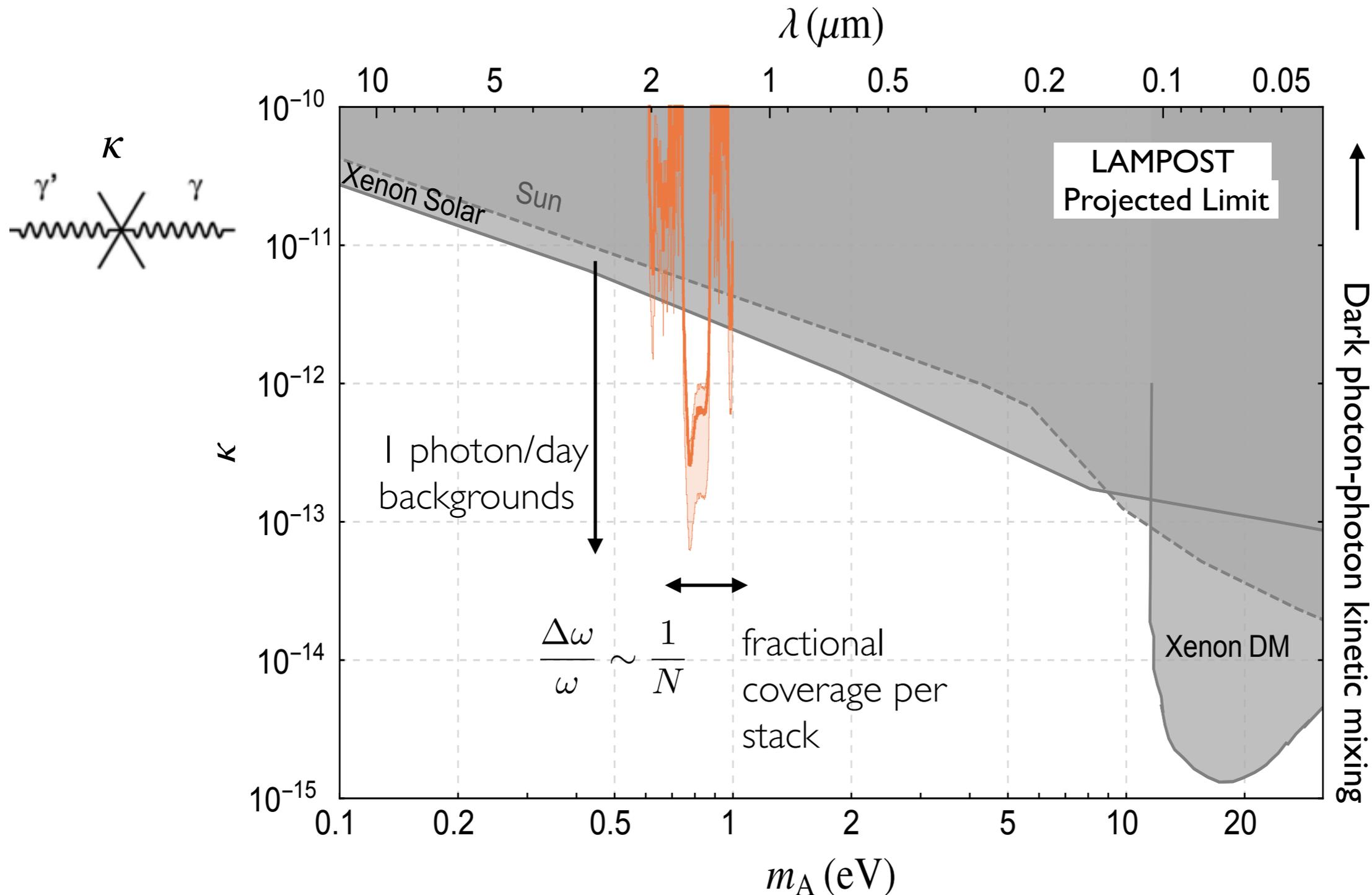


Nanowire Detection of Photons from the Dark Side



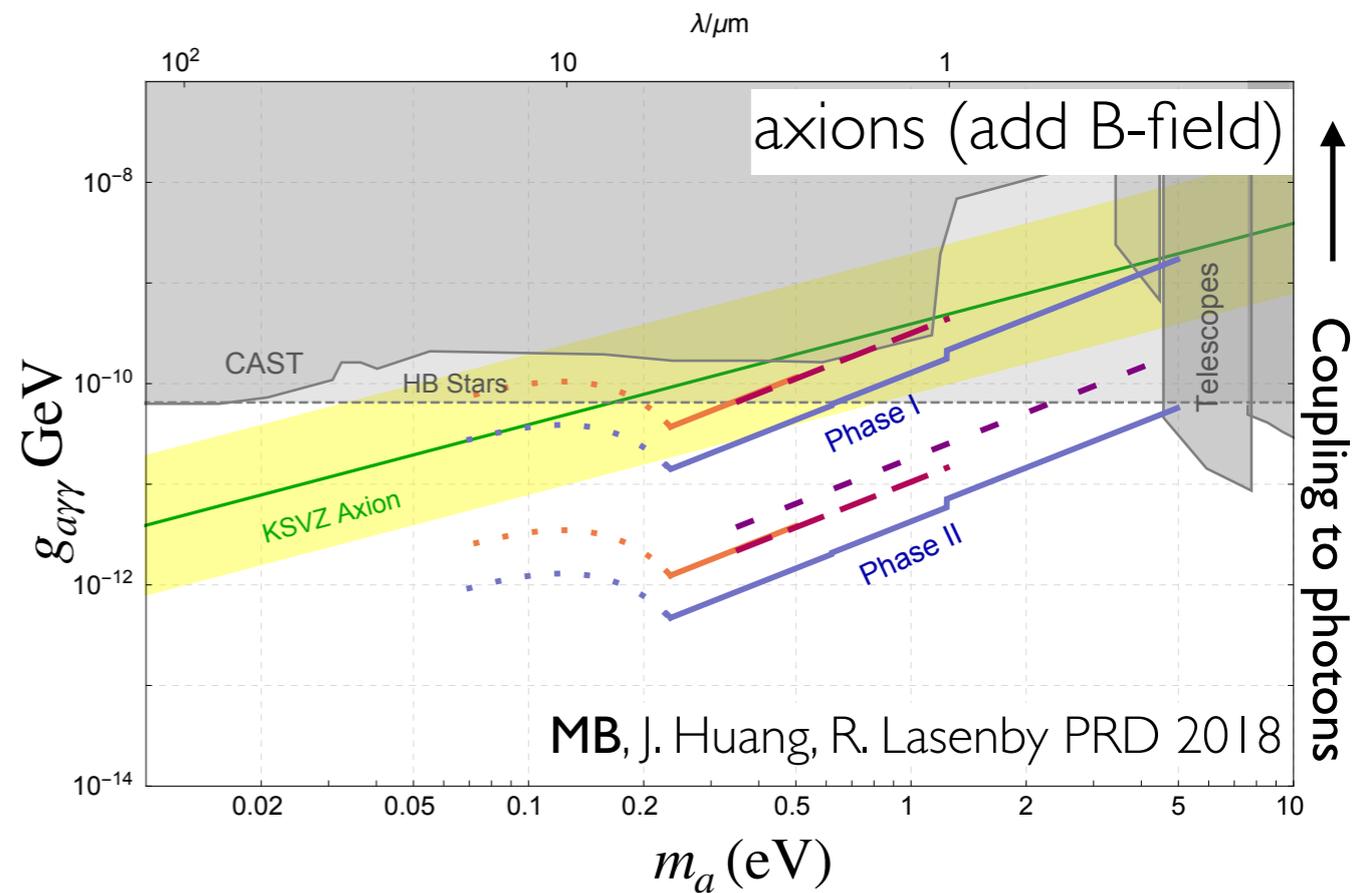
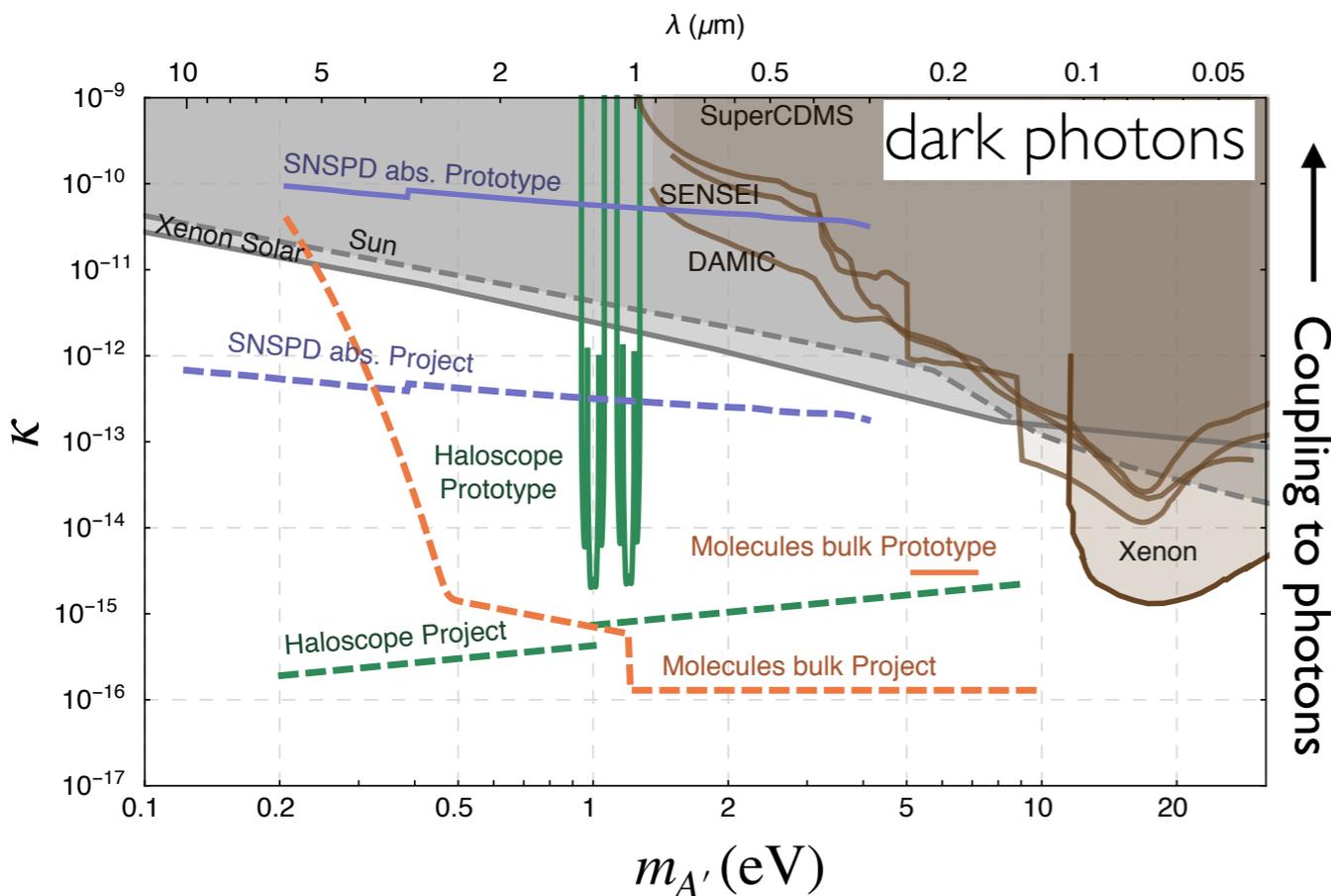
(Exp) Berggren, Charaev; Chiles, Nam;
(Th) Arvanitaki, **MB**, Huang, Lasenby, Van Tilburg. 24

Searches for dark matter with light



- Prototype can already cut into new parameter space with weeks of runtime
- Currently performing experimental checks
- Longer run time, other frequencies planned

Searches for dark matter with light



- Dielectric materials /crystal structures/ molecules can correct the dispersion mismatch in waves between a massless and massive particle of the same energy
- First steps underway, use well-established optics and detector technology; possible to reach very small couplings with larger setups
- Improve on parameter space by orders of magnitude, and perhaps see dark matter

