Direct Detection of Light Dark Matter with Optical Phonons

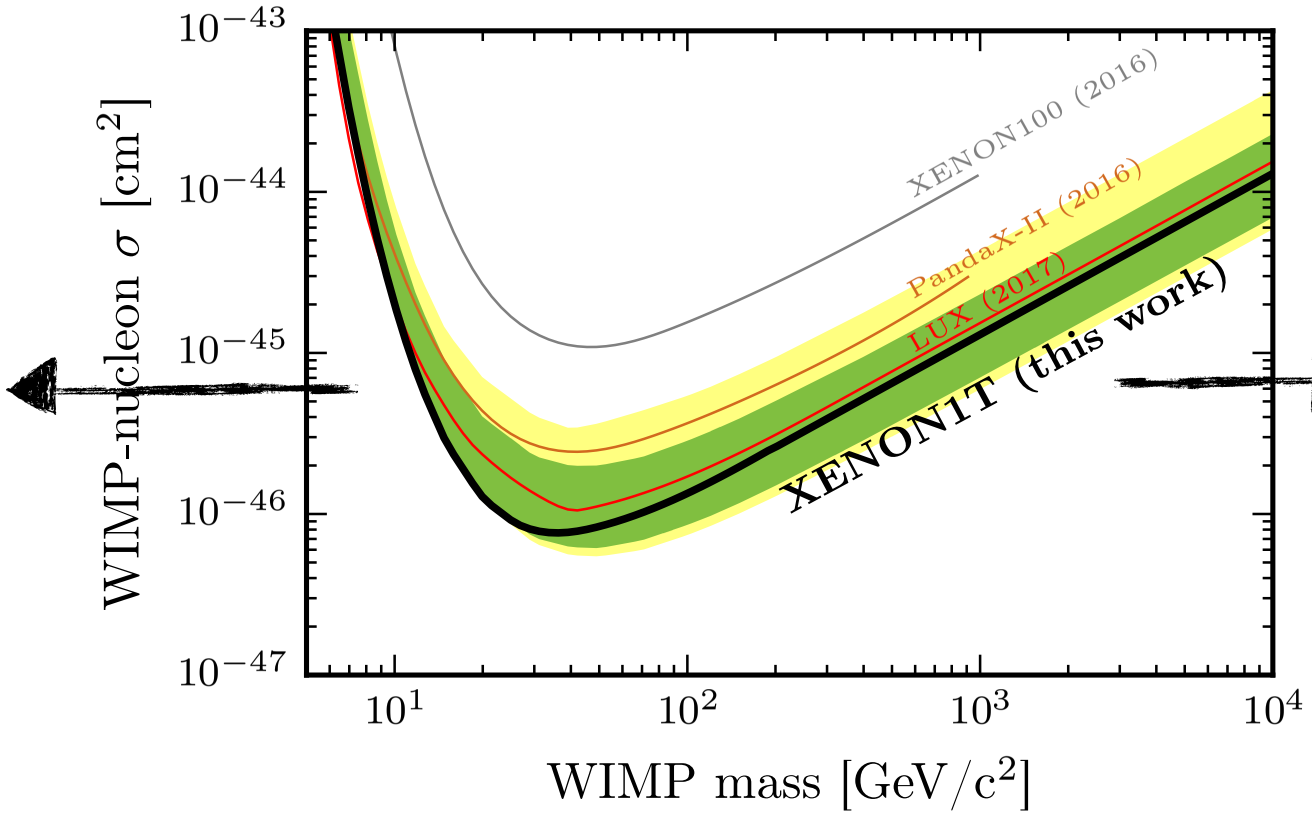
Tongyan Lin
UCSD

April 30, 2018, KITP

Based on 1712.06598 Knapen, TL, Pyle, Zurek
and work in progress with authors + S. Griffin

Direct detection of WIMPs

Energy threshold

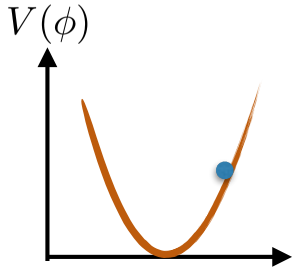


$$R \propto \frac{1}{m_\chi}$$

Typical threshold in experiment: ~keV nuclear recoil

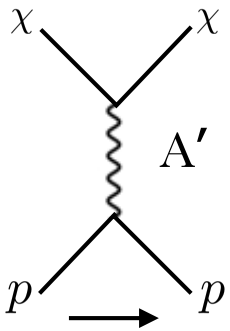
Direct detection of light DM

Bosonic DM



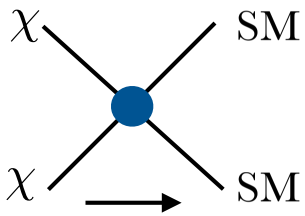
Absorption
Nonthermal DM

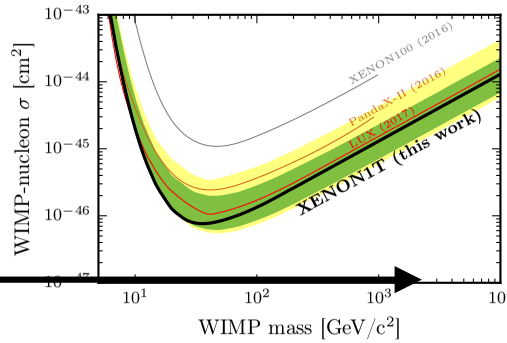
Dark sectors with light mediators



Scattering
Thermal DM

WIMP

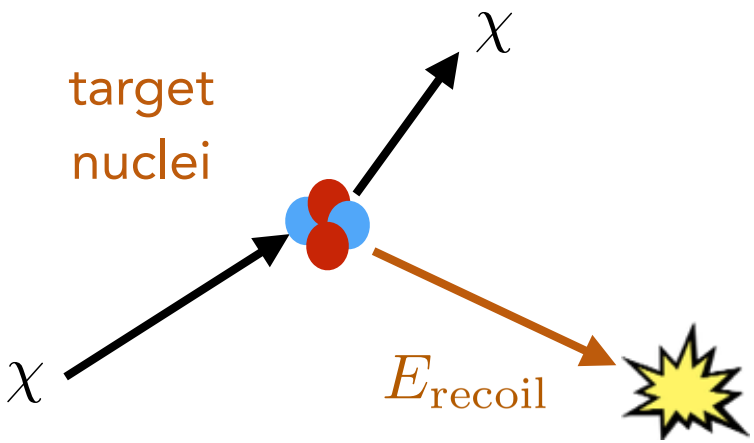




meV eV keV MeV GeV TeV

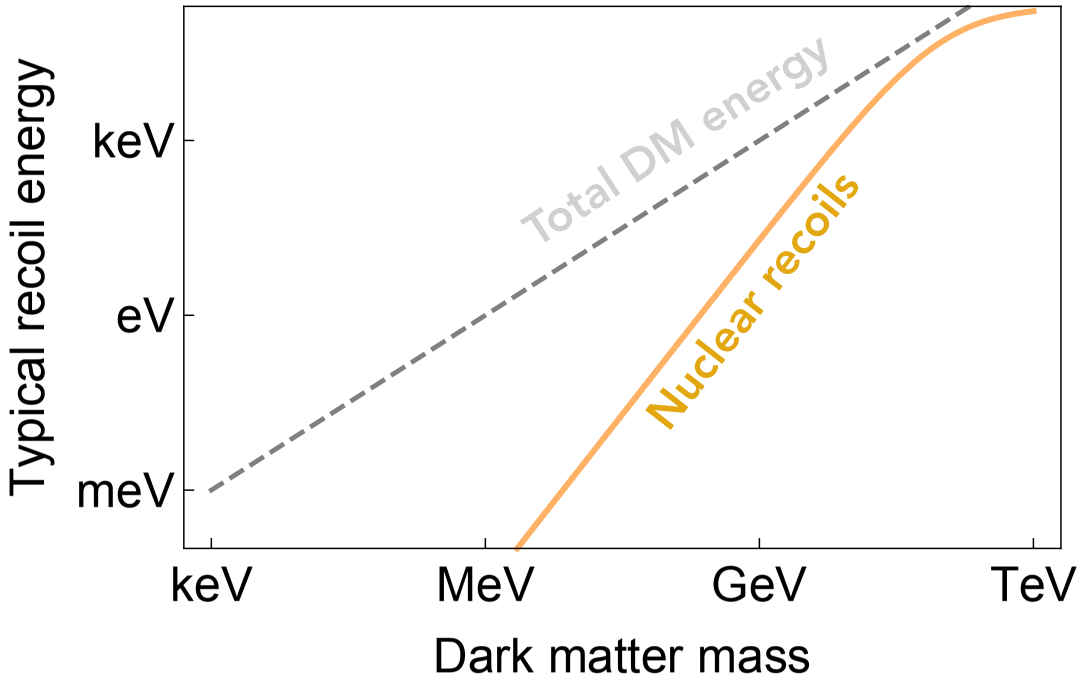
Dark matter mass

Direct detection of light DM



Heat, ionization, light
from recoiling nucleus

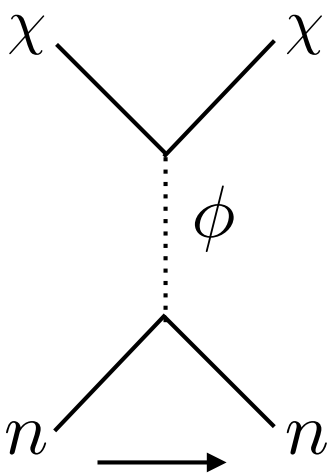
$$E_R \sim \frac{\mu_{\chi N}^2 v^2}{m_N} \sim 1 - 100\,\mathrm{keV}$$



Goal: access total DM energy, obtain sensitivity to ~**meV** recoils for keV DM scattering.

DM-nucleus interactions

DM-nucleon scattering



For low mass dark matter, the possible momentum transfer is

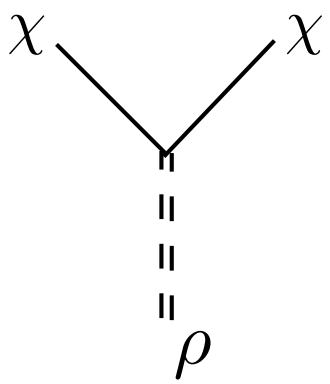
$$Q \sim m_\chi v \sim 1/\text{Angstrom}$$

for m_χ = MeV

At these scales, DM no longer scatters off of single atoms — the relevant degree of freedom is a phonon

DM-phonon interactions

DM-phonon scattering



Quasiparticle

For low mass dark matter, the possible momentum transfer is

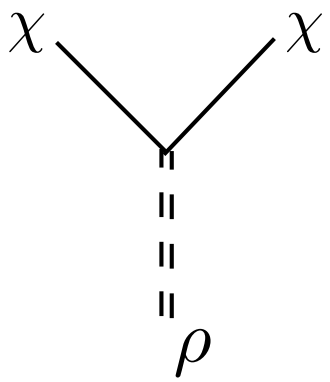
$$Q \sim m_\chi v \sim 1/\text{Angstrom}$$

for m_χ = MeV

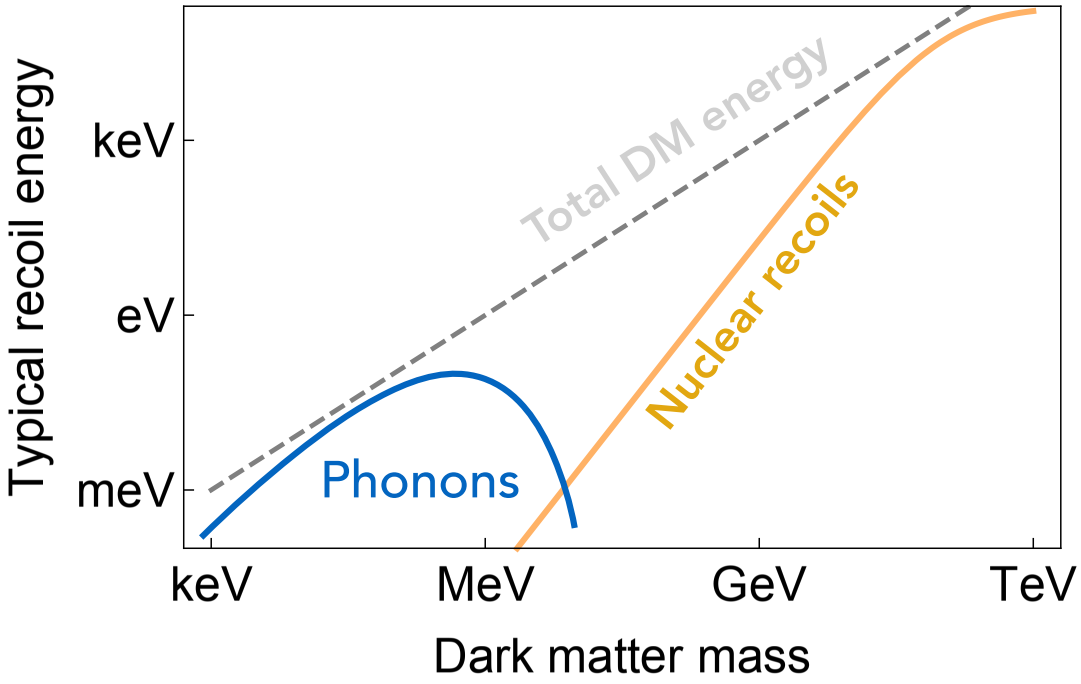
At these scales, DM no longer scatters off of single atoms — the relevant degree of freedom is a phonon

DM-phonon interactions

DM-phonon scattering



Quasiparticle

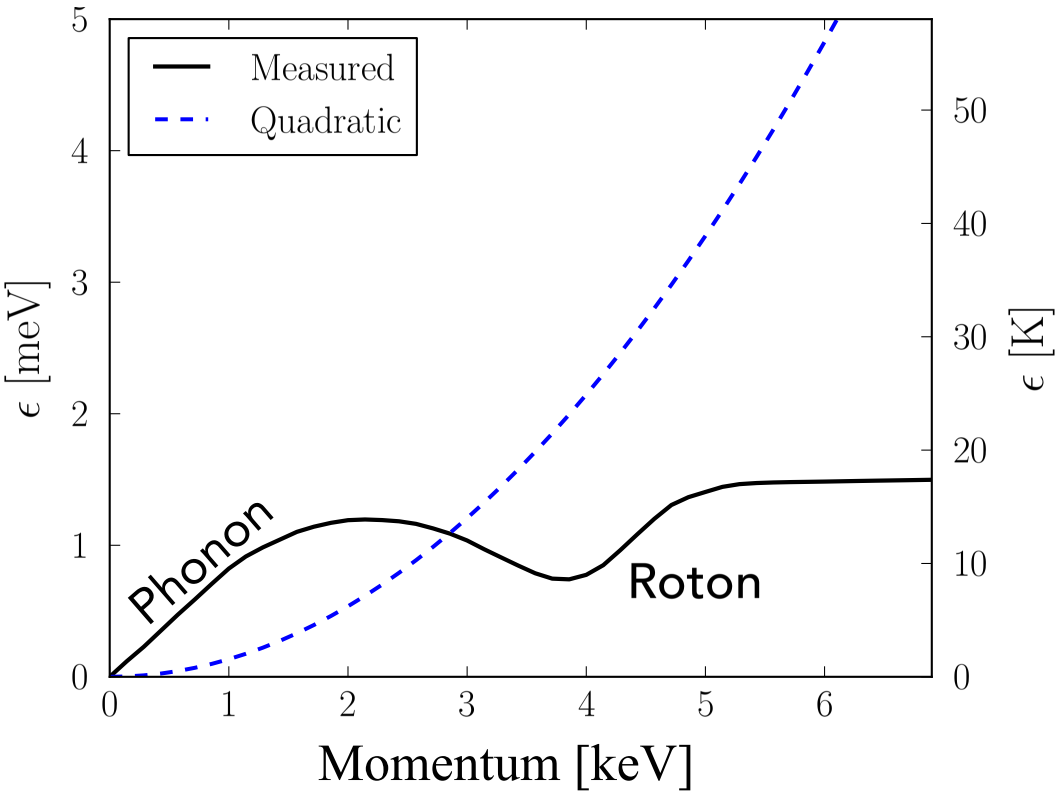


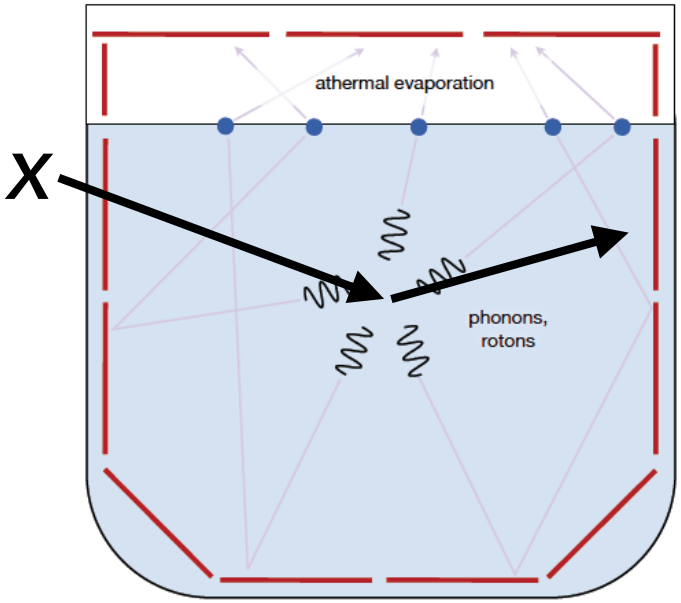
DM scattering into **single** or **few** phonons has different kinematics

Superfluid helium

Long-lived quasiparticle excitations

Possible ~meV thresholds





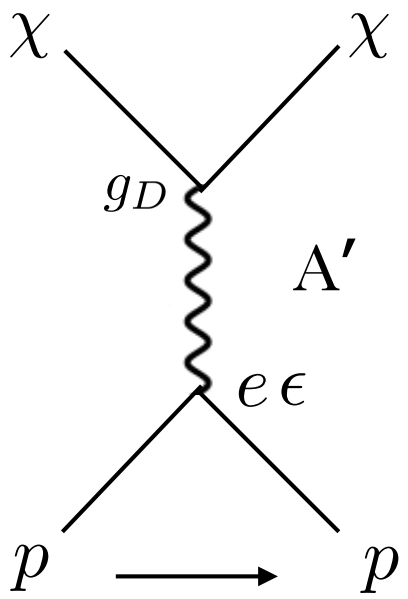
See Dan McKinsey's talk

Schutz and Zurek 2016

Knapen, **TL**, Zurek 2016

Polar materials

- What kind of phonons can be created by dark photon interactions?
- At long wavelengths, material is neutral: very limited rate to produce acoustic phonons
- Long-wavelength optical phonons in polar materials generate a macroscopic E field (and therefore also E′ field)



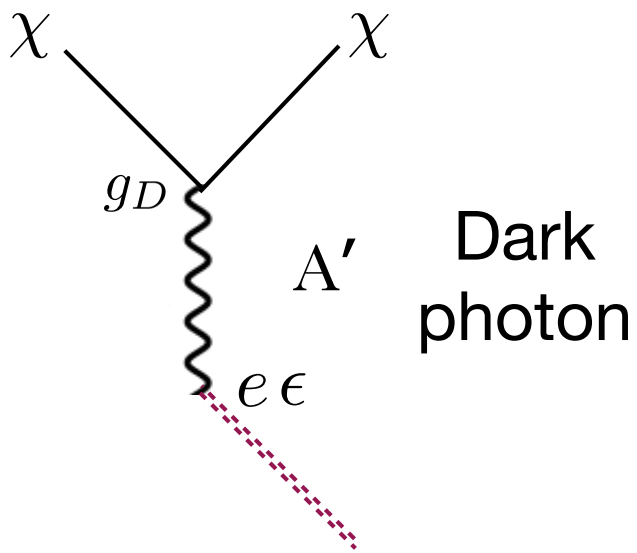
Dark photon

Kinetically mixed dark photon A'

$$\epsilon e A'_\mu J^\mu_{\rm EM}$$

Polar materials

- What kind of phonons can be created by dark photon interactions?
- At long wavelengths, material is neutral: very limited rate to produce acoustic phonons
- Long-wavelength <u>optical phonons in polar materials</u> generate a macroscopic E field (and therefore also E′ field)

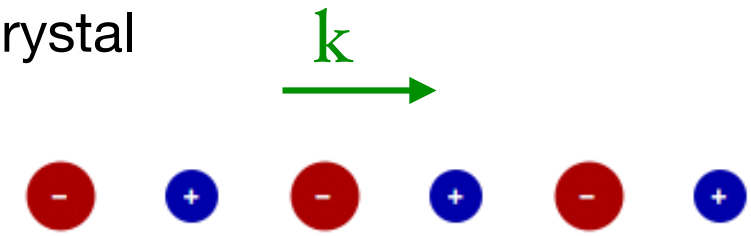


Optical phonon

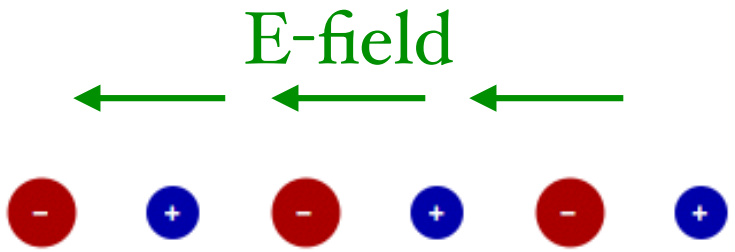
Polar materials

= Oppositely charged ions in crystal

Longitudinal acoustic (LA)



Longitudinal optical (LO)



LO phonons ~ coherently oscillating dipoles

Dark photon interaction with
LO phonon is dipole interaction:

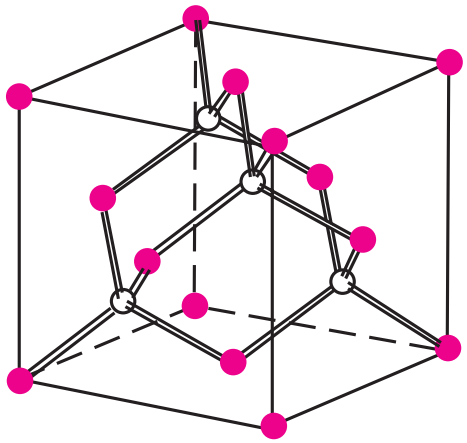
$$H \propto \kappa Q\, \mathbf{E}' \cdot \mathbf{u}$$

Dark photon field

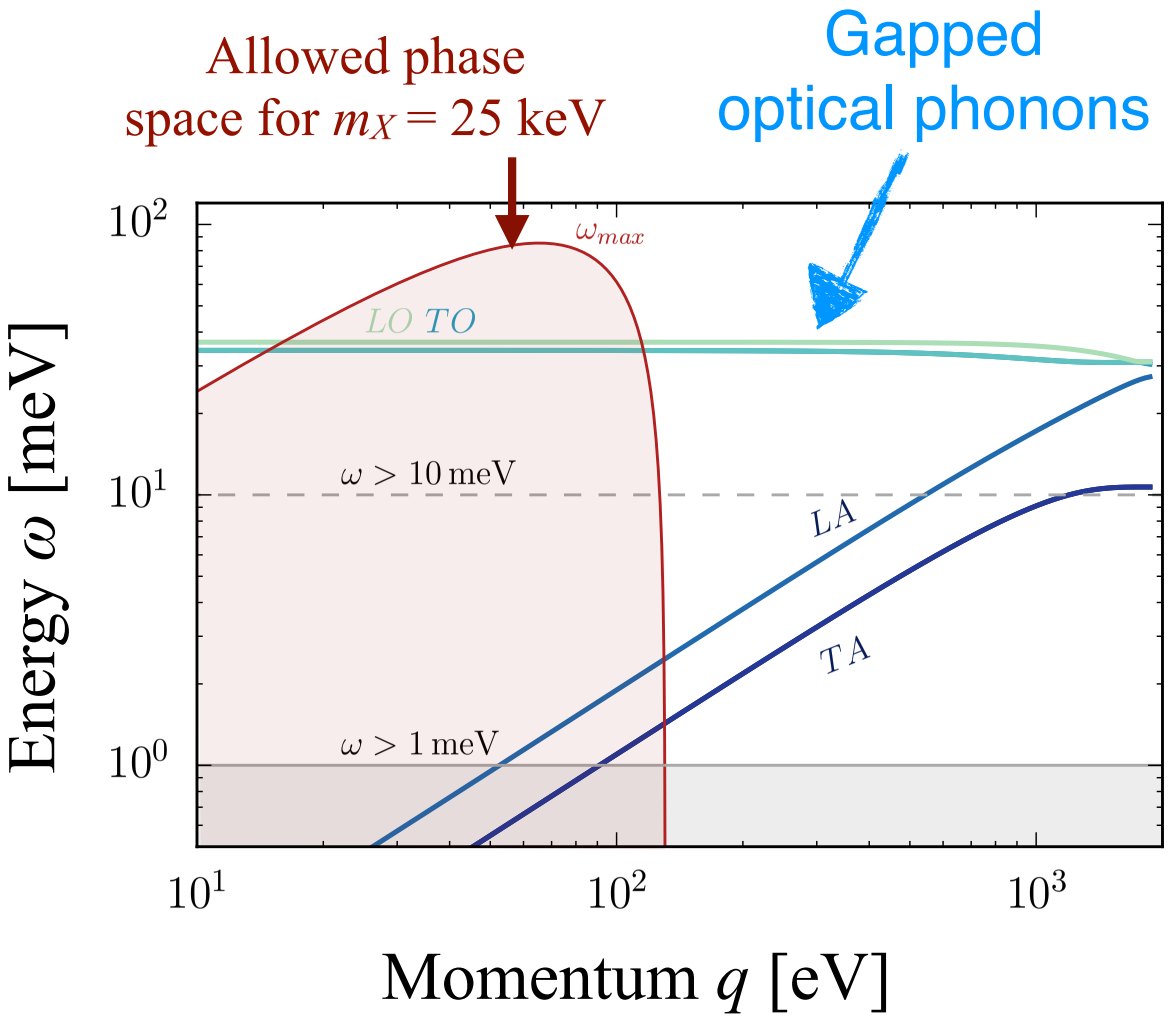
Ion displacement (dipole)

Example: GaAs

Crystal structure



- Ga, +2.1 effective charge
- As, -2.1 effective charge



Phonon band structure in GaAs

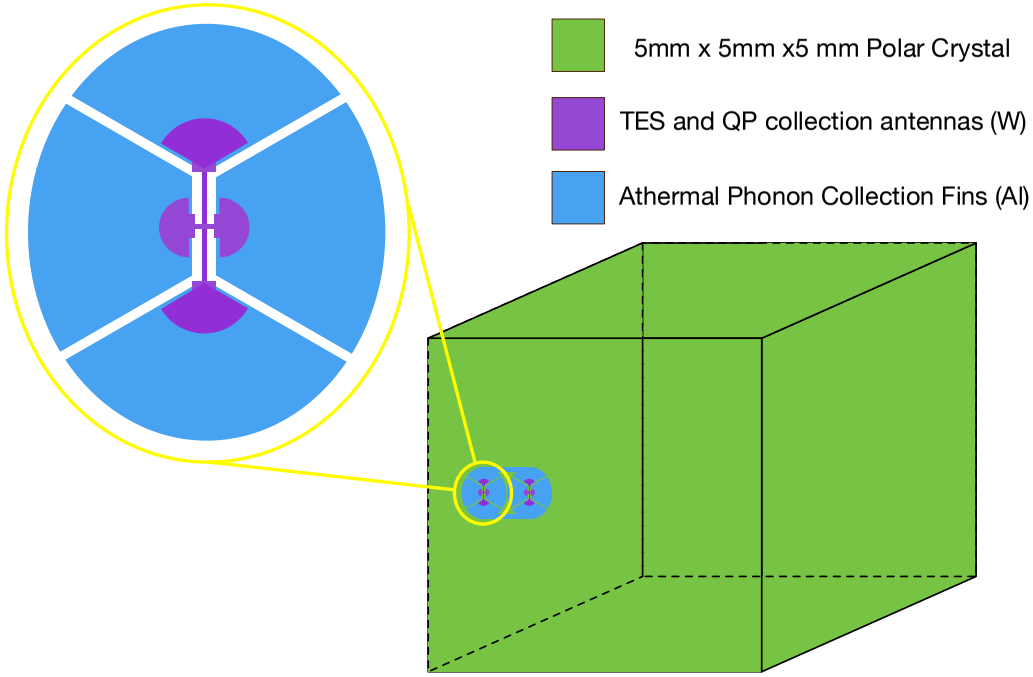
GaAs detector

Concept is similar to SuperCDMS:

DM scattering creates **single** optical phonon. These down convert into sub-meV athermal phonons which are collected at surface.

Instrument ~% of surface to collect deposited energy with O(1) efficiency

TES with E_{th} ~ 10 meV



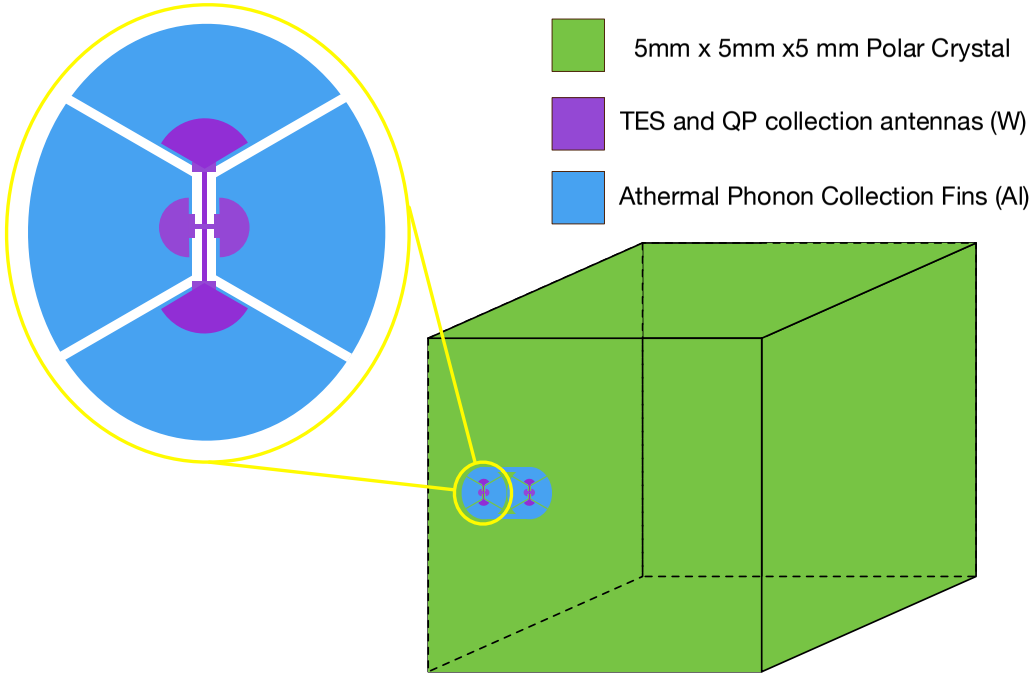
~gram of GaAs

GaAs detector

TES with ~72 meV resolution already demonstrated on test chips

Radiogenic backgrounds are at much higher energy; here dominant backgrounds are solar neutrinos and coherent photon scattering, < 1 event/kg-yr.

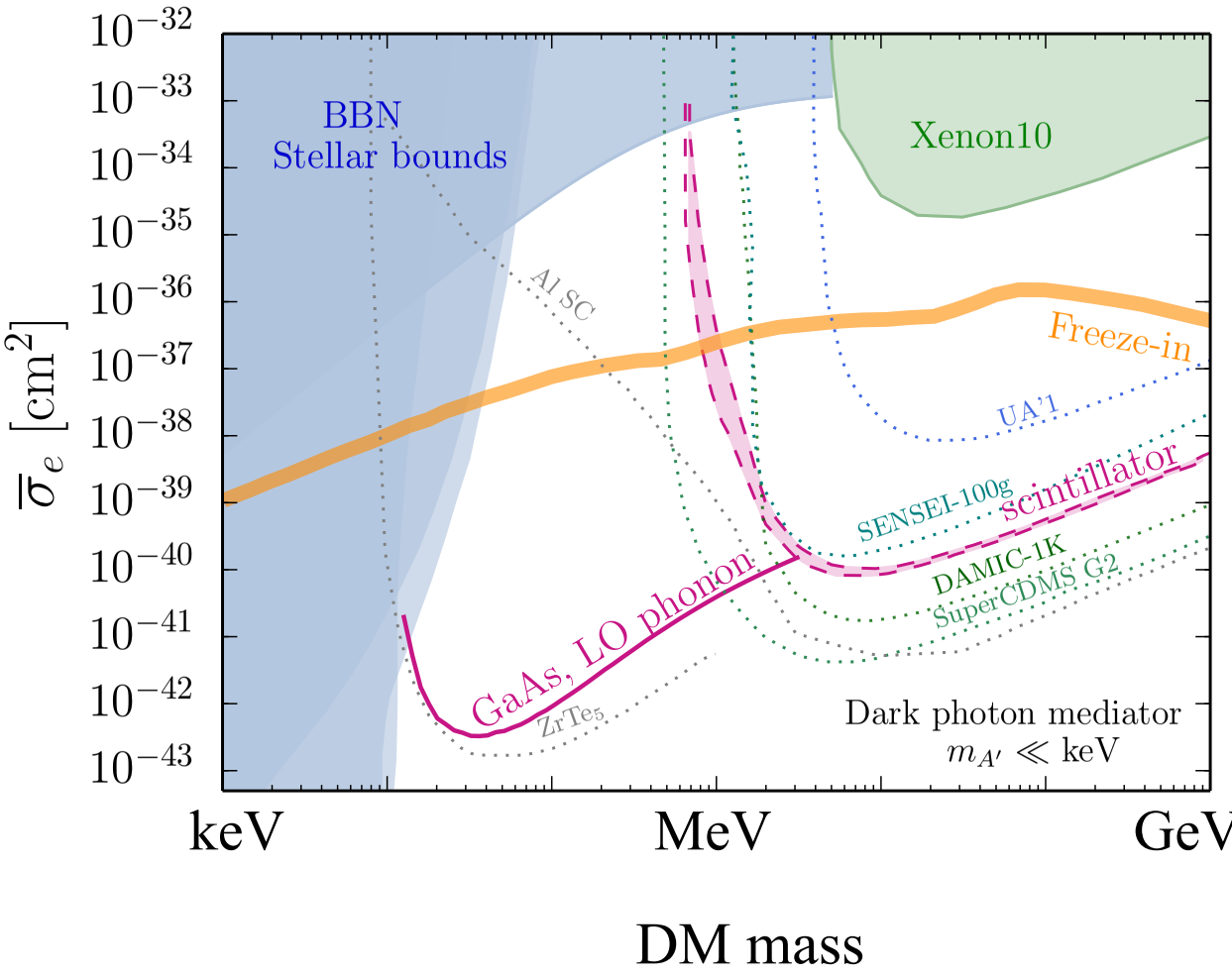
TES with E_{th} ~ 10 meV



~gram of GaAs

Dark photon interactions

- DM sensitivity from optical phonon production in GaAs
- GaAs could cover the entire “freeze-in” region even with ~10 gram-month exposure
- Pure GaAs crystals readily available now

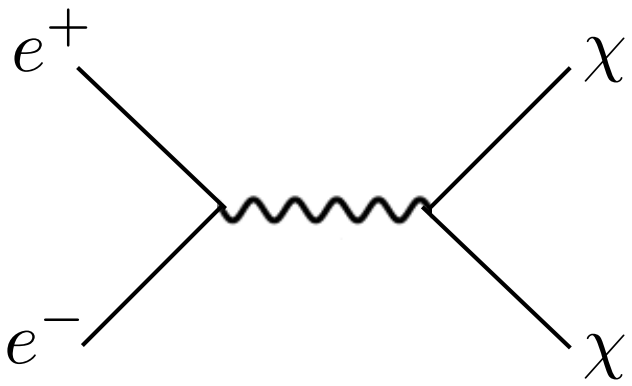


all projections assume kg-yr exposure

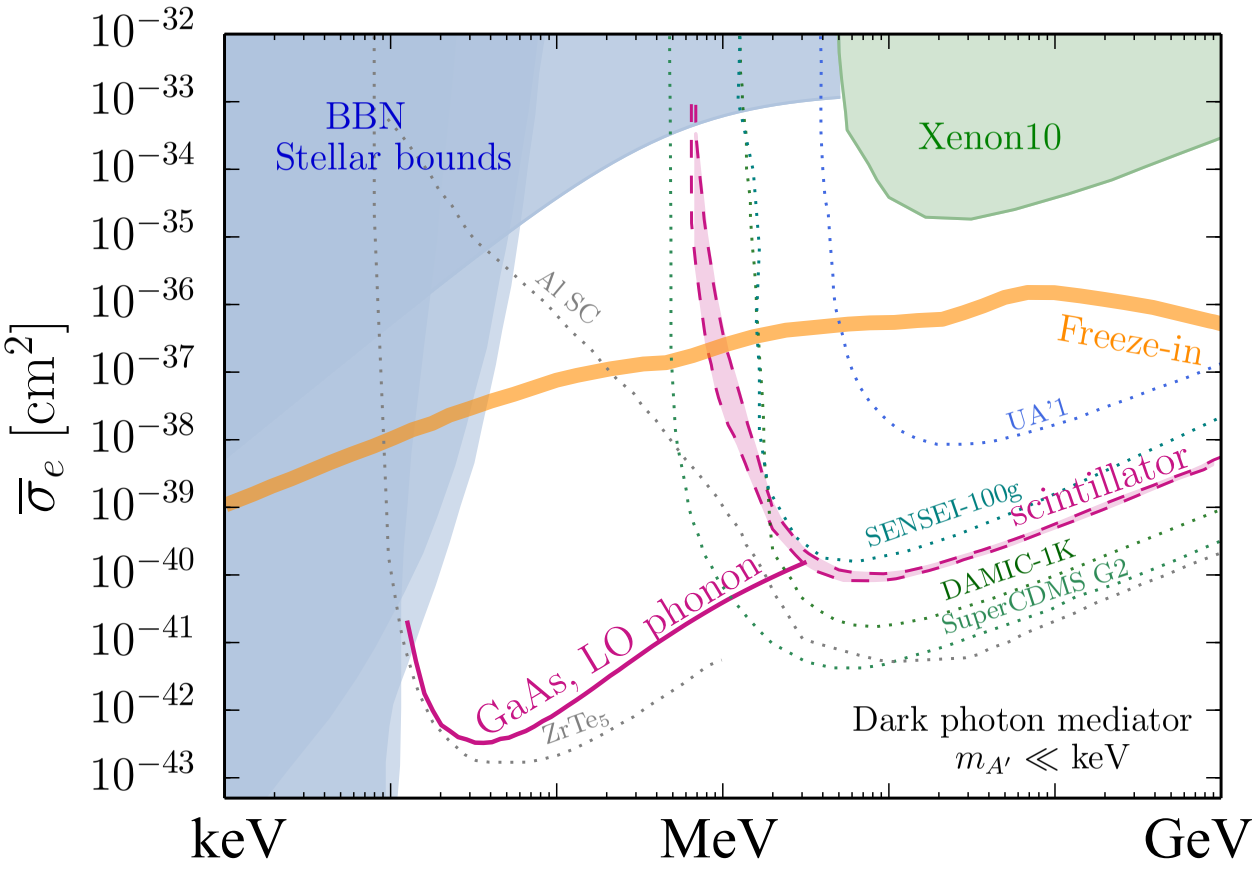
Cosmic Visions 2017;
Essig, Volansky, Yu 2017
Vogel and Redondo 2014
Derenzo et al. 2016

Dark photon interactions

Freeze-in:



Out-of-equilibrium annihilations of SM

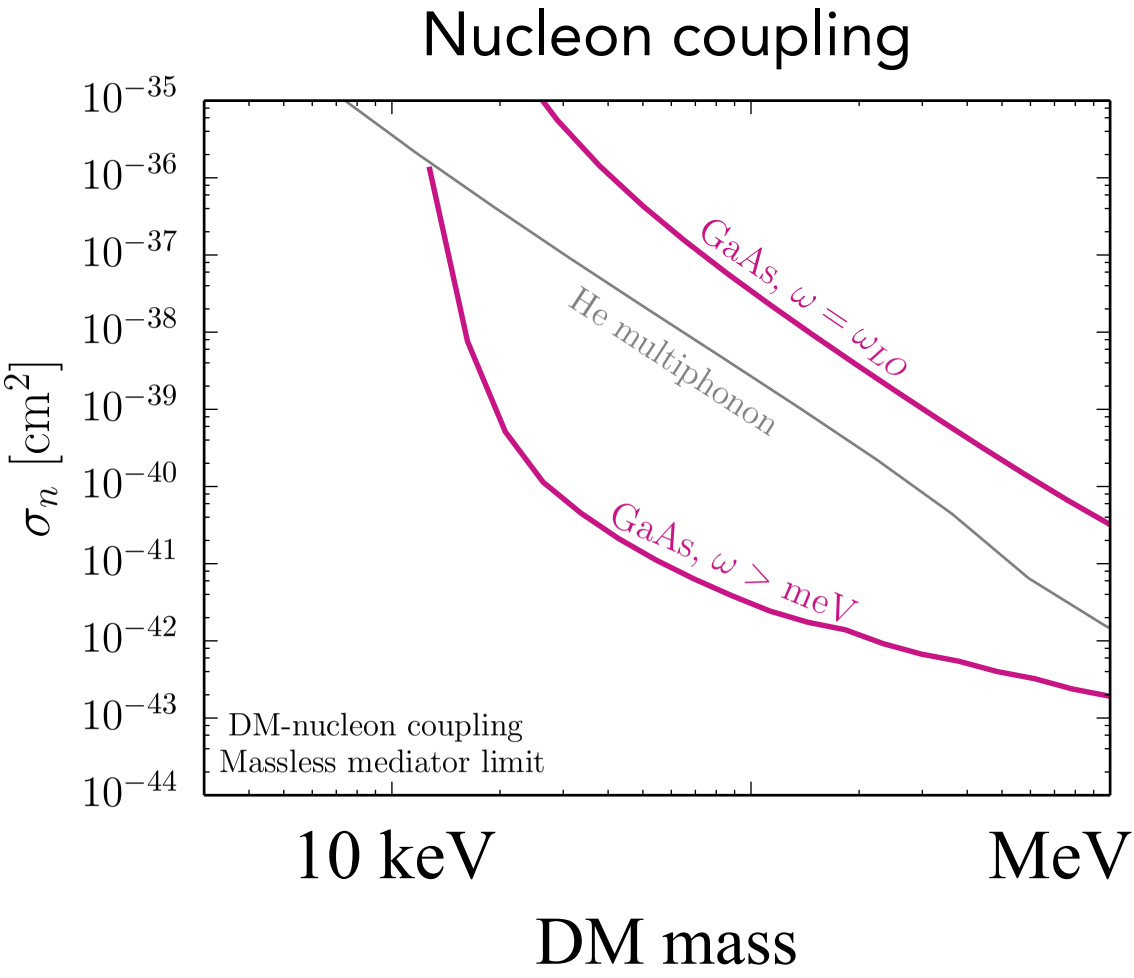


all projections assume kg-yr exposure

Cosmic Visions 2017;
Essig, Volansky, Yu 2017
Vogel and Redondo 2014
Derenzo et al. 2016

DM-nucleon scattering

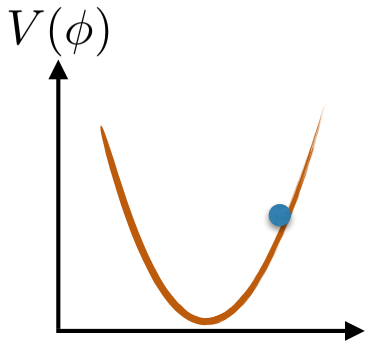
Single phonon production can be used for sub-MeV DM-nucleon scattering, competitive with multi-phonons in superfluid He



Knapen, TL, Zurek 2017

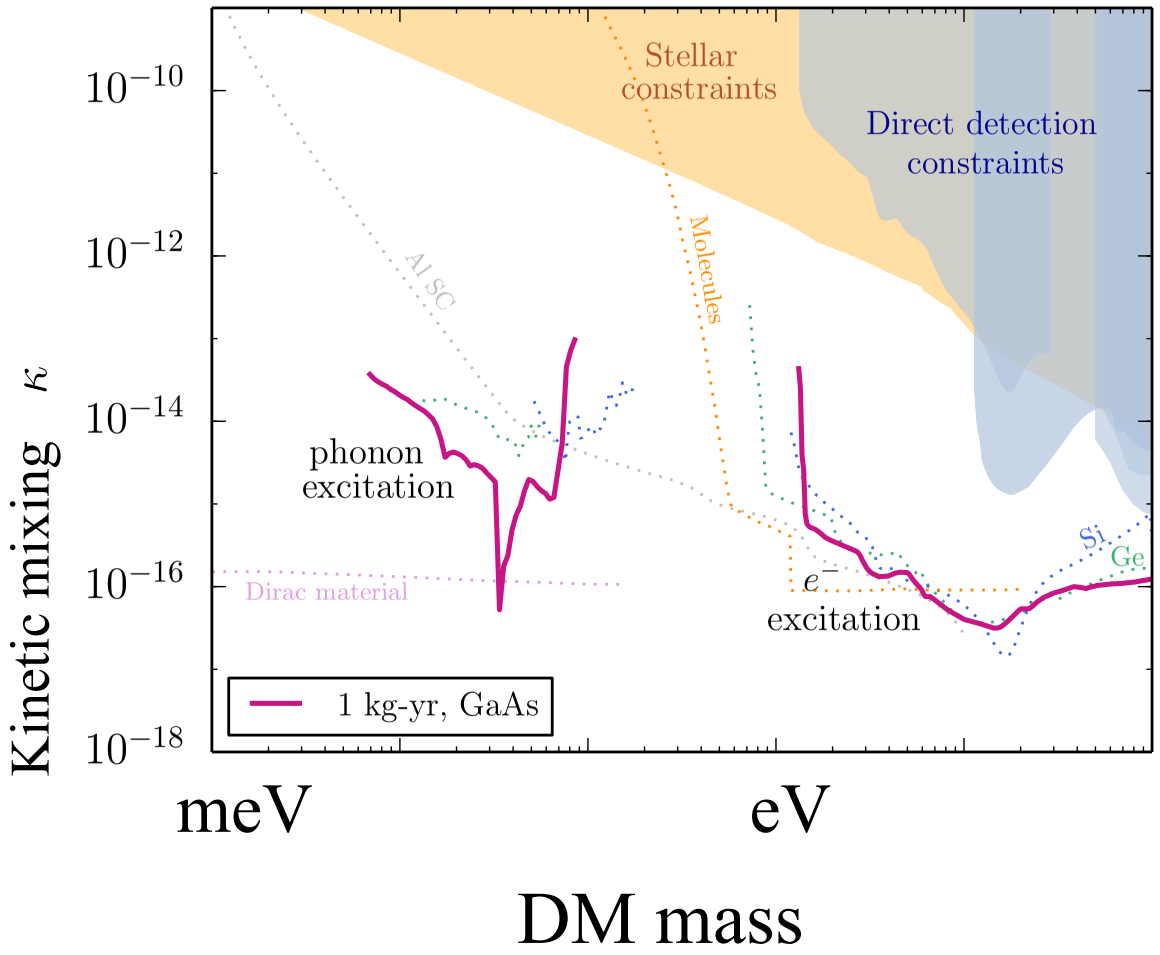
Dark matter absorption

sub-keV bosonic



- Dark photon is all of the dark matter
- Mono-energetic absorption signal

Kinetically mixed dark photon

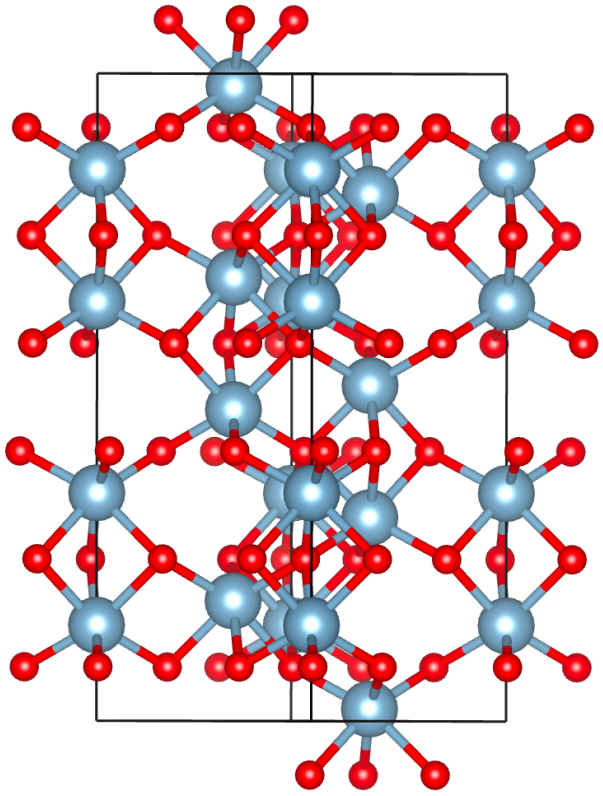


Hochberg, TL, Zurek 2016+2017
DAMIC: Chavarria et al. 2017
An, Pospelov, Pradler 2013, 2014

Even better: sapphire

Similar advantages as GaAs:

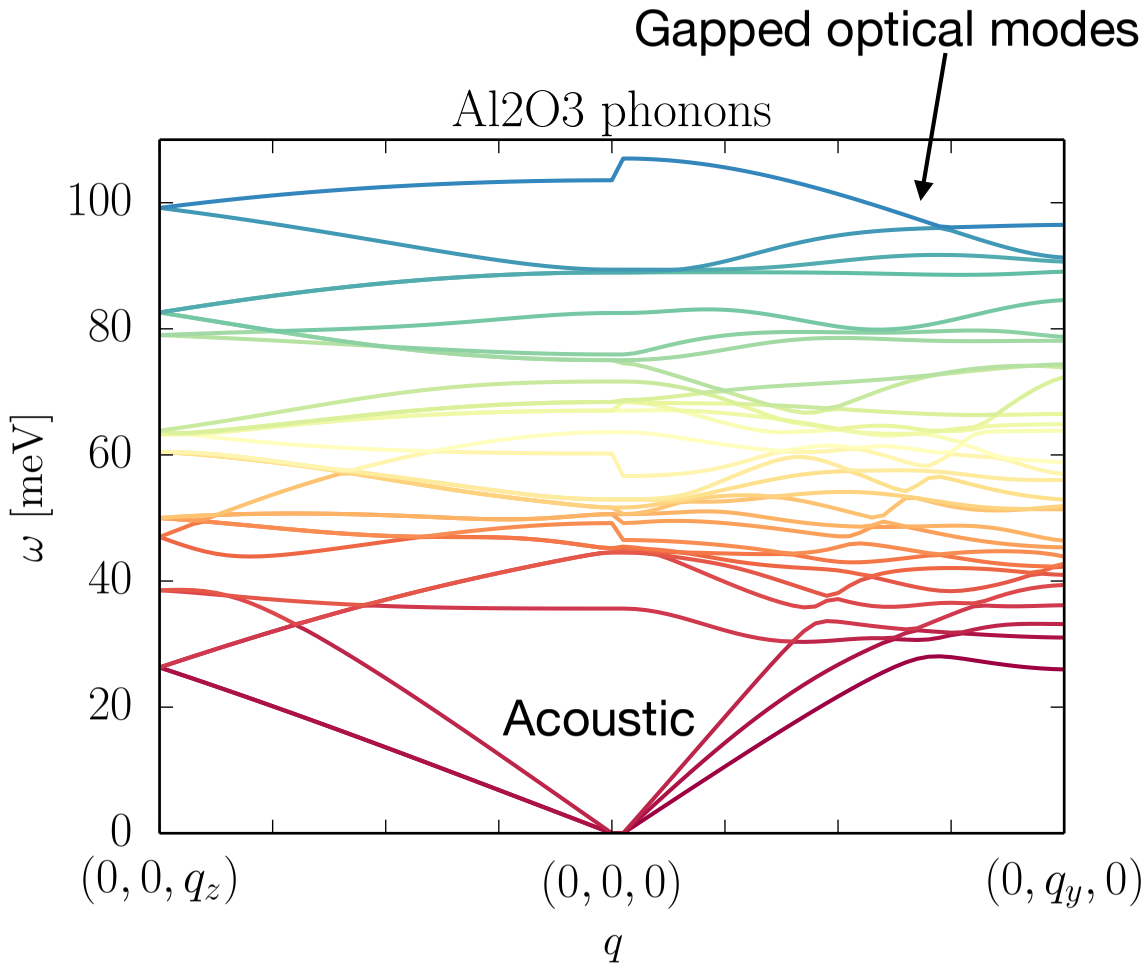
- Optical phonons allow coupling to dark photons
- Optical modes are gapped, with energies 30-100 meV — better for light DM scattering
- Sensitive to different DM models
- Possible fabrication of high purity crystals, good athermal phonon properties



Al_2O_3 (Sapphire)

Sapphire phonons

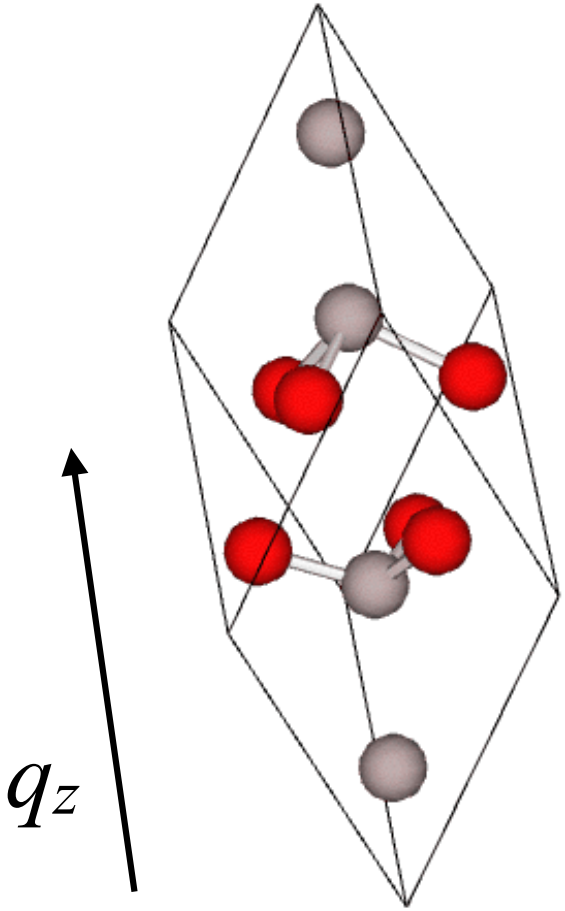
- Many more “high energy” optical phonon modes
- Potential for **directional detection** with q-dependent phonon couplings and energies.

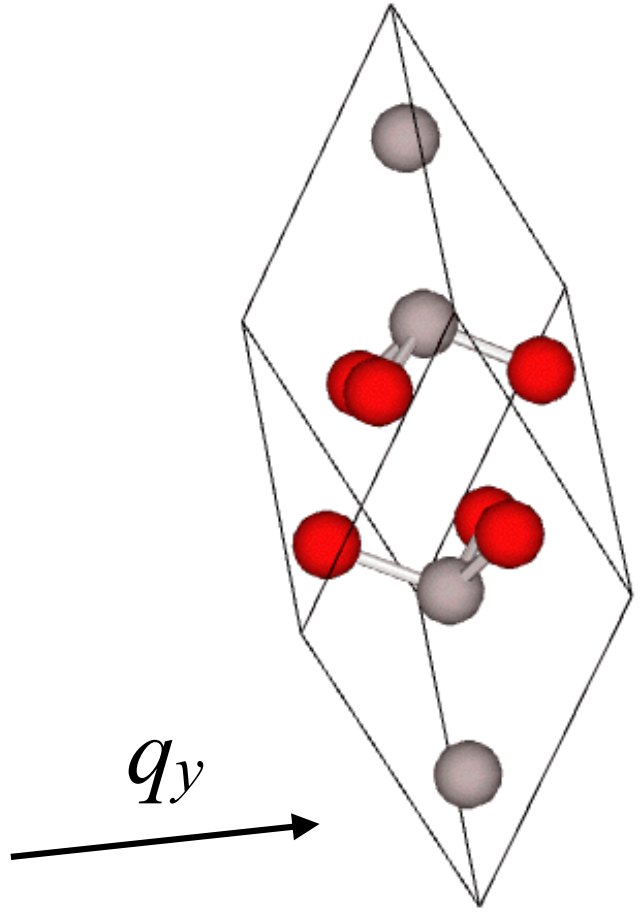


Phonon band structure in Al_2O_3 (Sapphire)

Sapphire phonons

Size of dipole and energy of optical phonon varies with phonon propagation direction



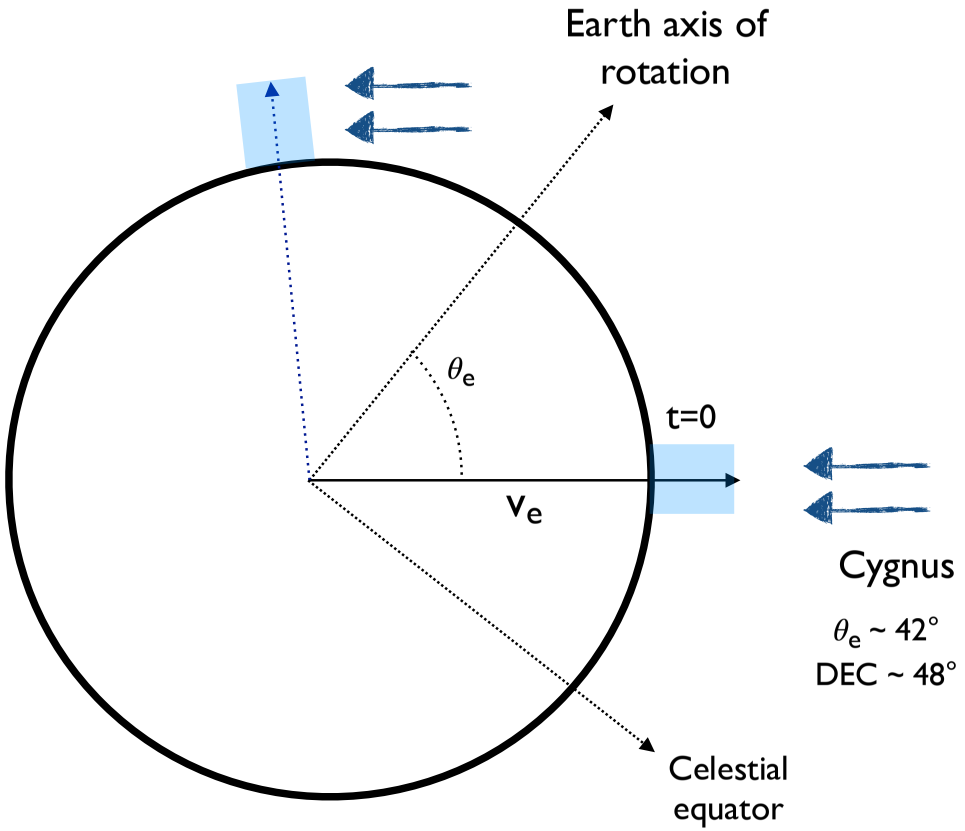


Animations made with
H. Miranda's phonon webtool

Daily modulation

Direction-dependent phonon modes in sapphire (Al_2O_3) lead to daily modulation as the Earth rotates

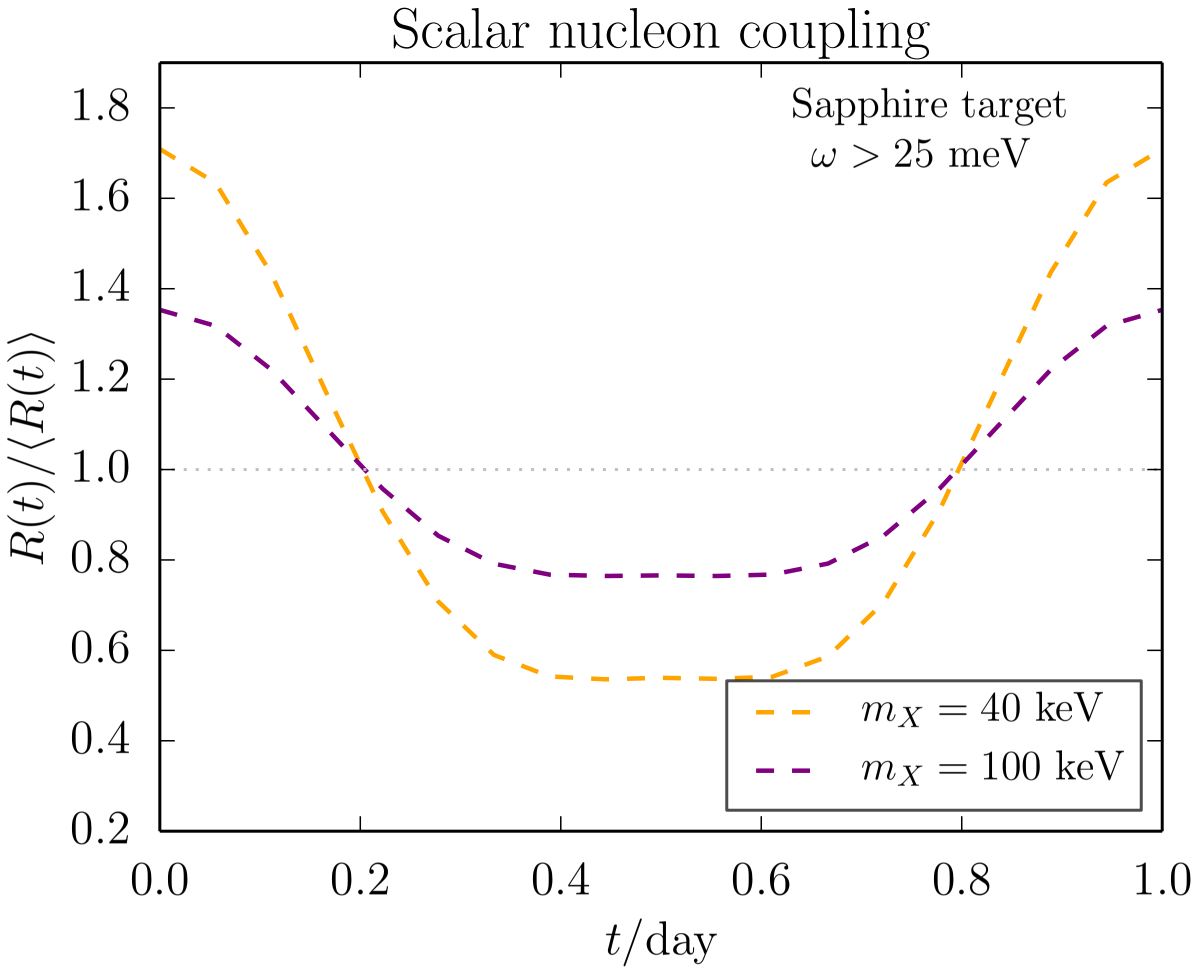
In phase with sidereal day, not solar day — could be distinguished from terrestrial backgrounds.



Daily modulation

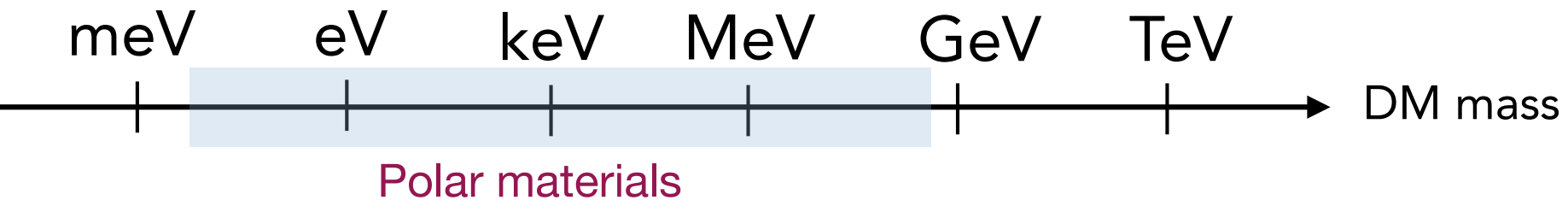
Direction-dependent phonon modes in sapphire (Al_2O_3) lead to daily modulation as the Earth rotates

In phase with sidereal day, not solar day — could be distinguished from terrestrial backgrounds.



Conclusions

- Only scratched the surface in low mass DM detection; ~gram-scale targets can reach new parameter space
- Polar materials are promising target for sub-MeV DM scattering and absorption into *optical phonons*. Directional detection may be possible as well.
- Interesting times for direct detection of low mass DM!



Thanks!