Direct Detection of Light Dark Matter with Polar Materials

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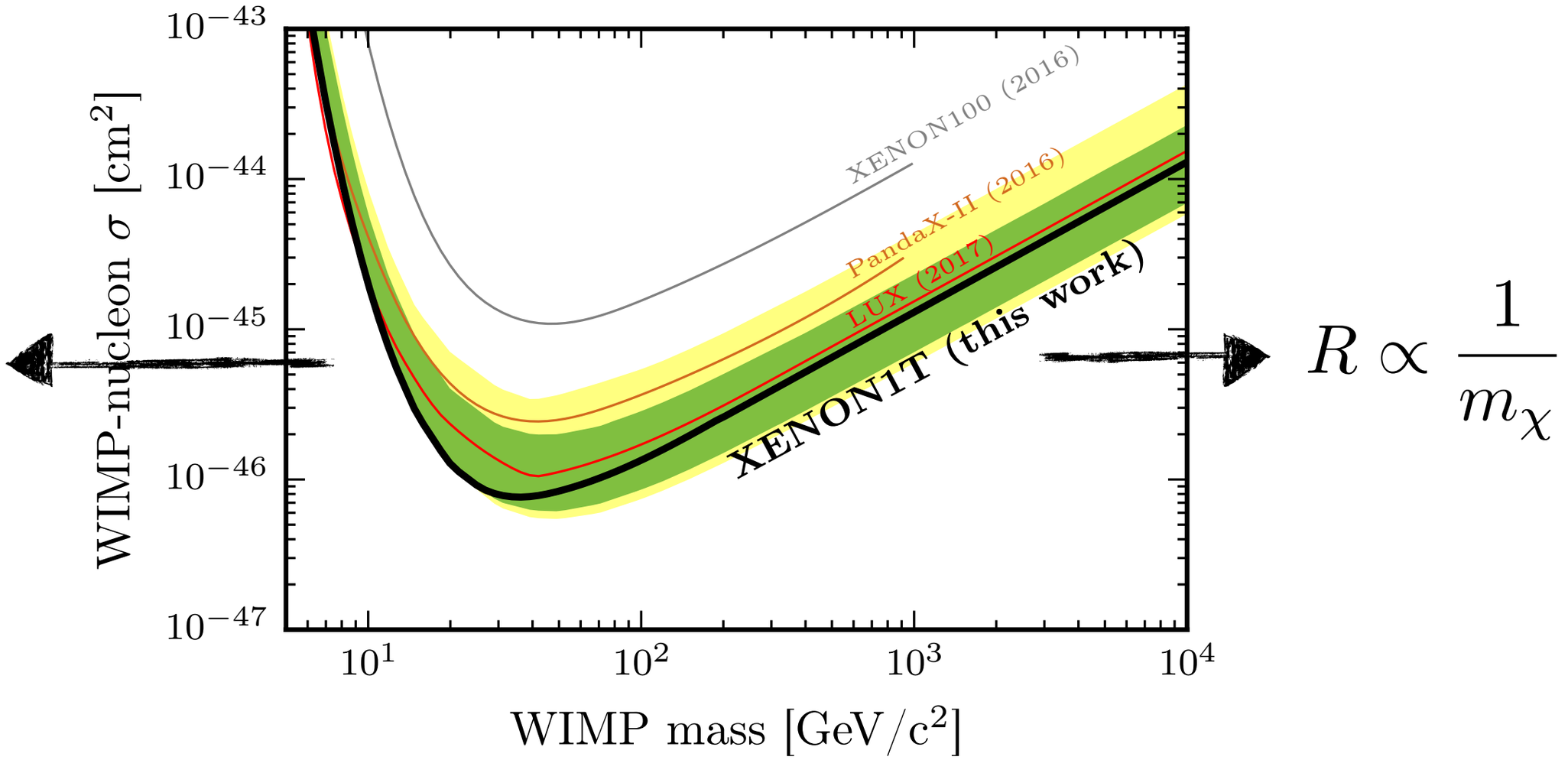
Aspen Winter 2018

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

Direct detection of WIMPs

Energy threshold

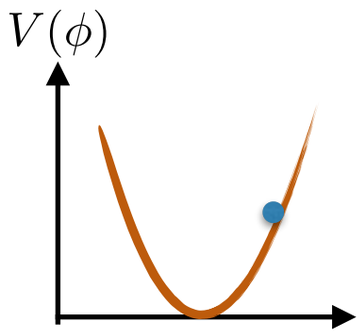


$$R \propto \frac{1}{m_\chi}$$

Typical threshold in experiment: ~keV nuclear recoil

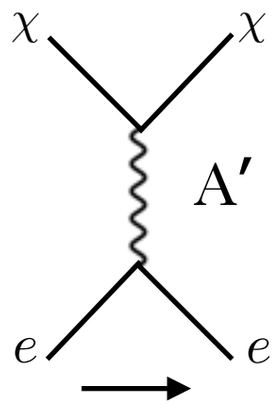
Sub-GeV DM detection

Bosonic DM



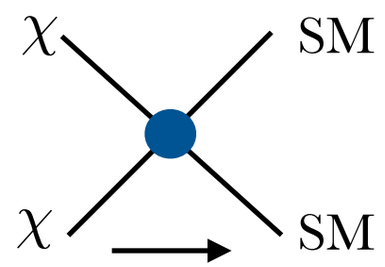
Absorption
Nonthermal DM

Light DM +
light mediators



Scattering
Thermal DM

WIMP

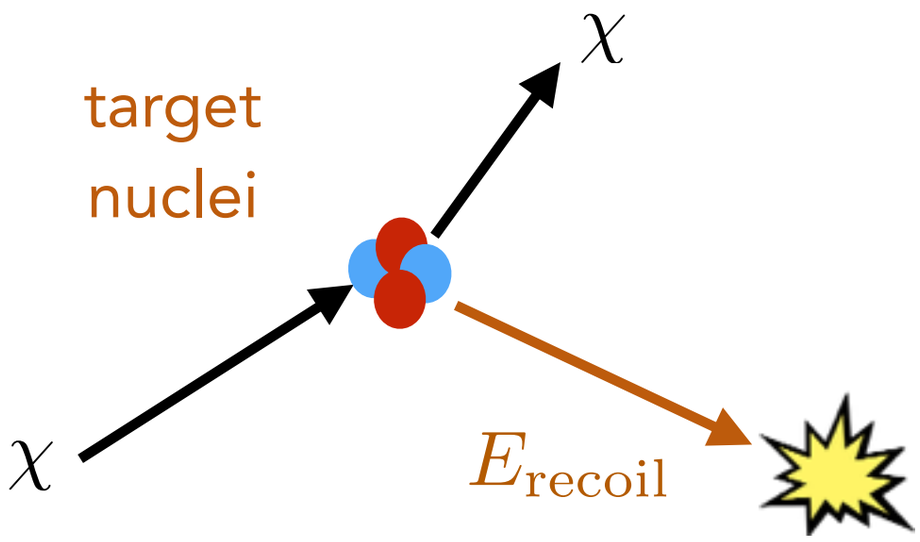


meV eV keV MeV GeV TeV

Dark matter mass

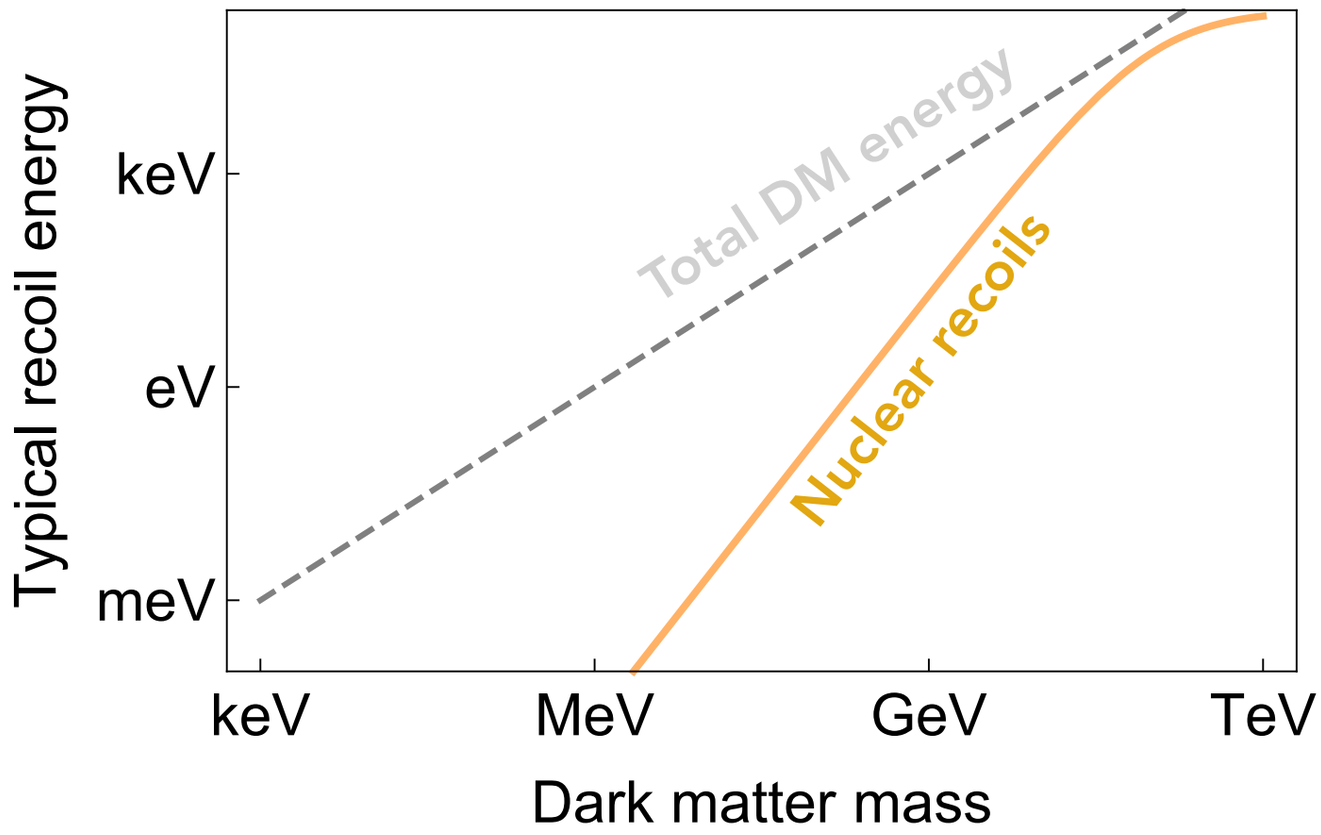
Many models, ideas for detection of light DM:
see also panel, other talks today

Direct detection of light DM



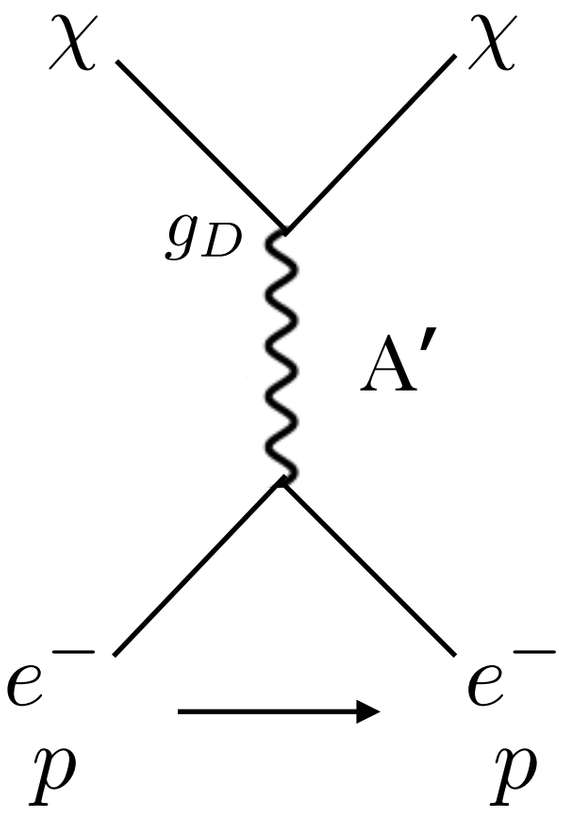
Heat, ionization, light
from recoiling nucleus

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



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

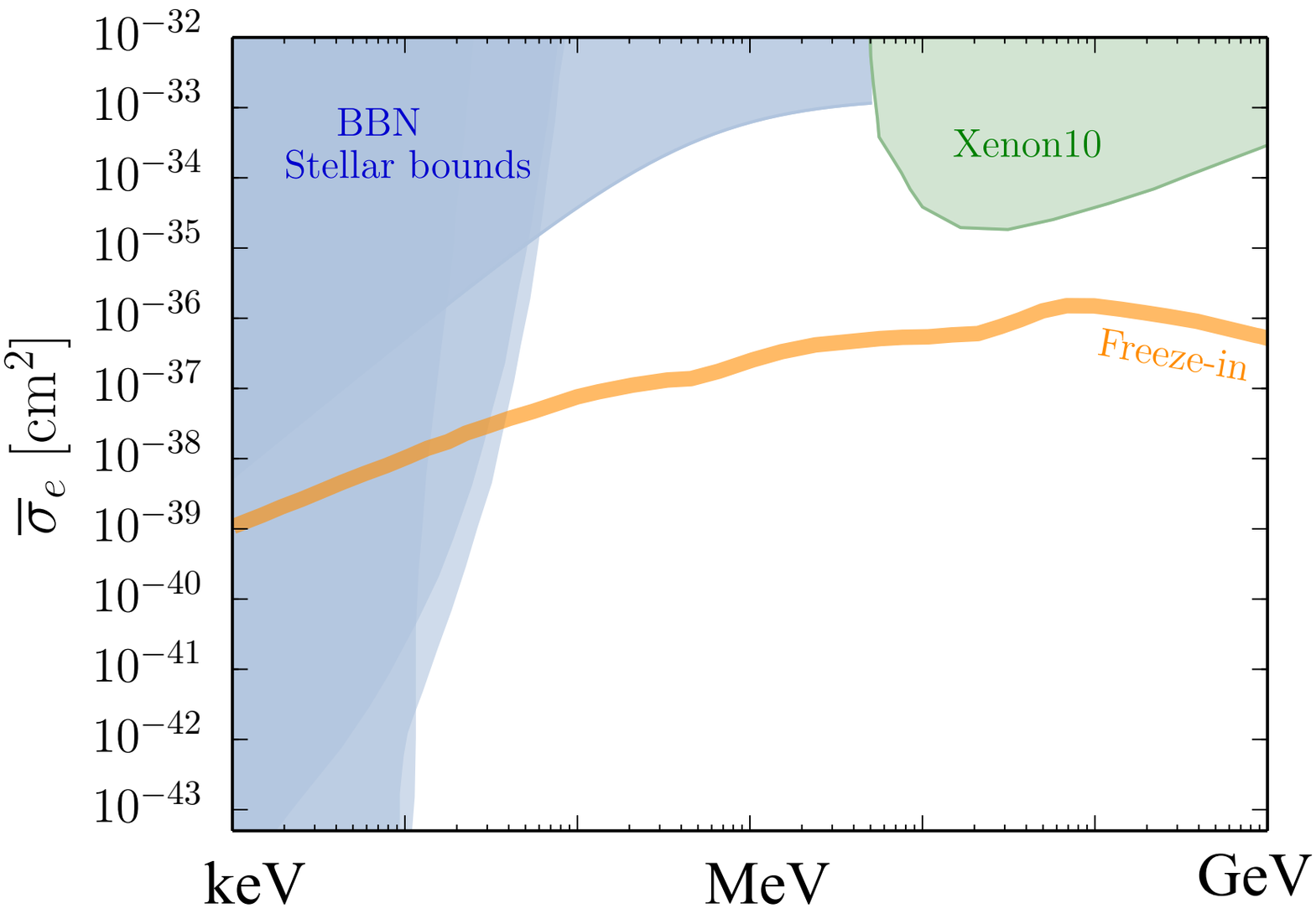
Dark photon mediator



Kinetically mixed
hidden photon A’

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

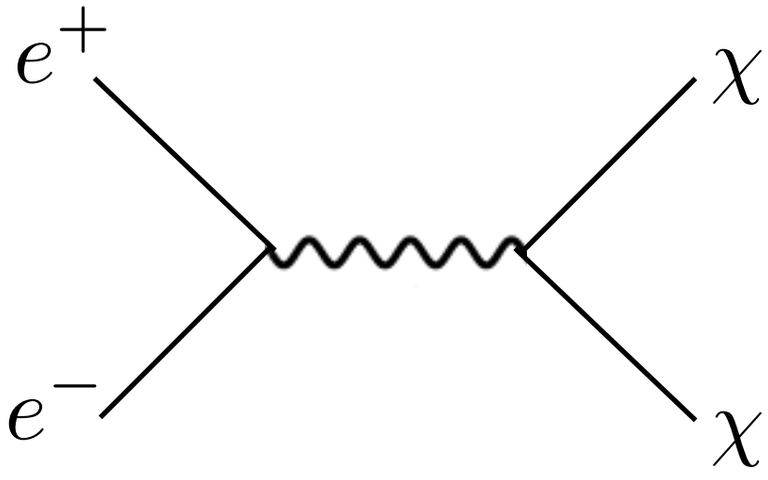
couples to electrons, nuclei



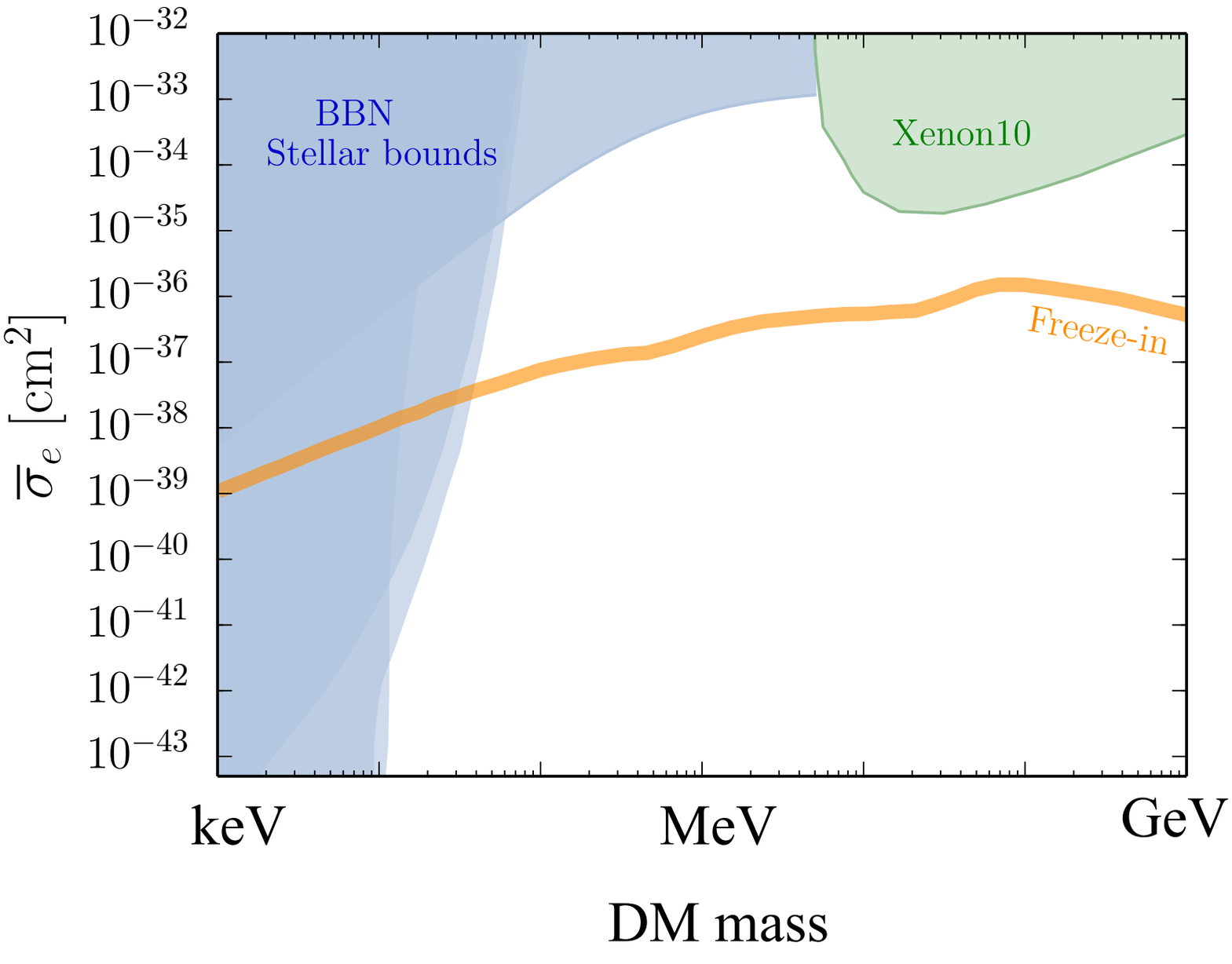
Essig Mardon Volansky 2011,
Essig Volansky Yu 2017
Vogel and Redondo 2014

Dark photon mediator

Freeze-in:



Out-of-equilibrium annihilations of SM



Essig Mardon Volansky 2011,
Essig Volansky Yu 2017
Vogel and Redondo 2014

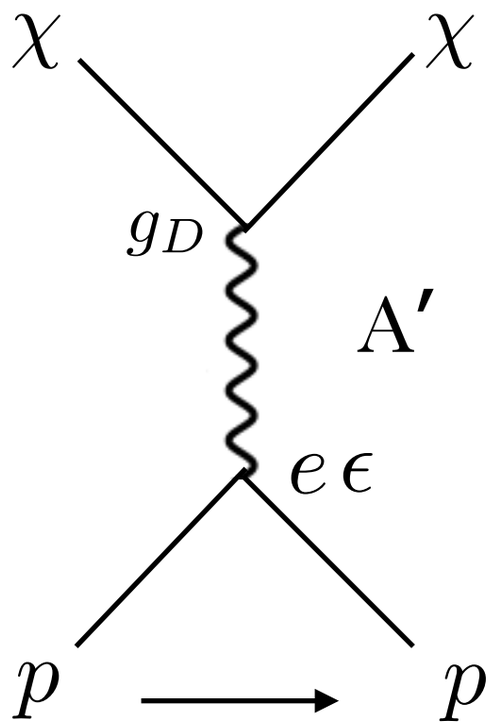
Phonon couplings

For low mass dark matter, the possible momentum transfer is

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

for m_χ = MeV

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



Dark photon

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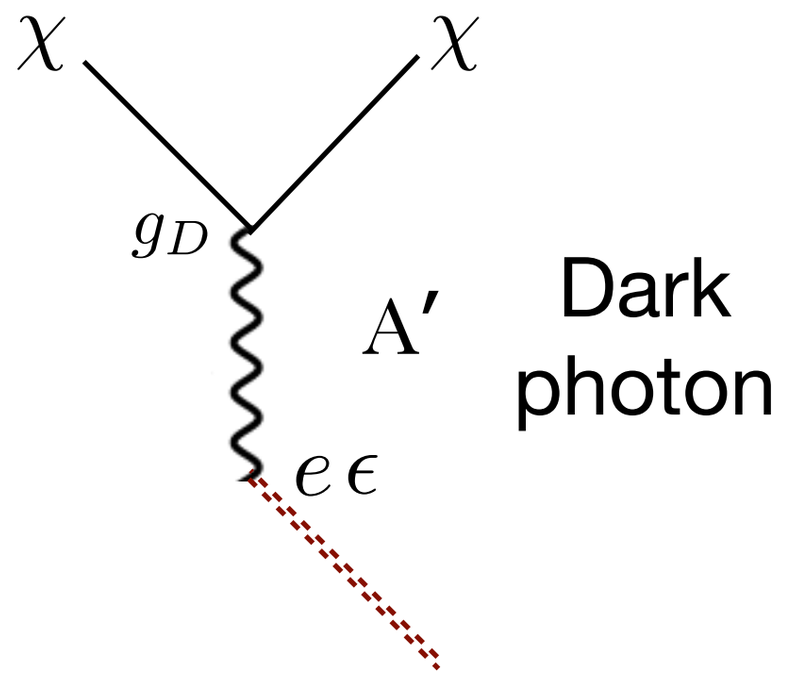

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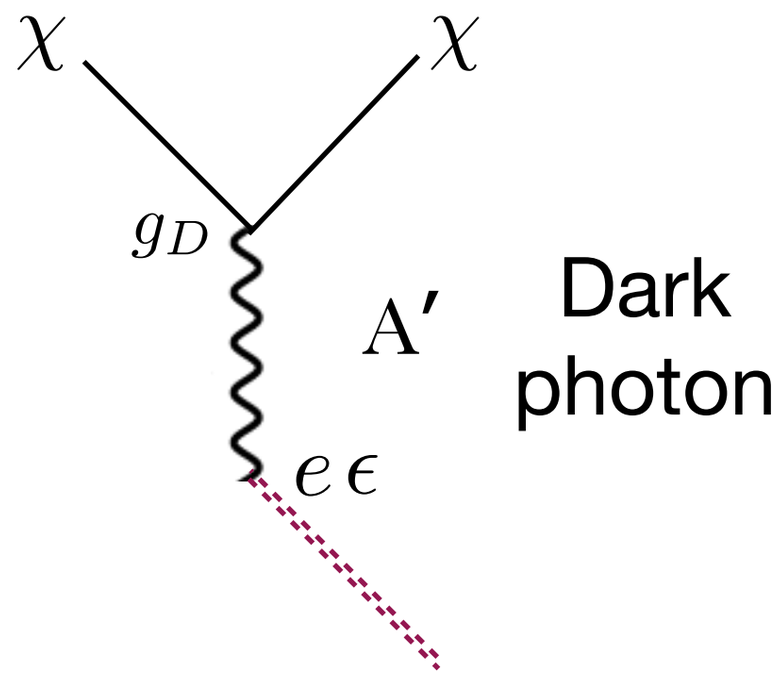
Polar materials

- What kind of phonons can be created by dark photon interactions?

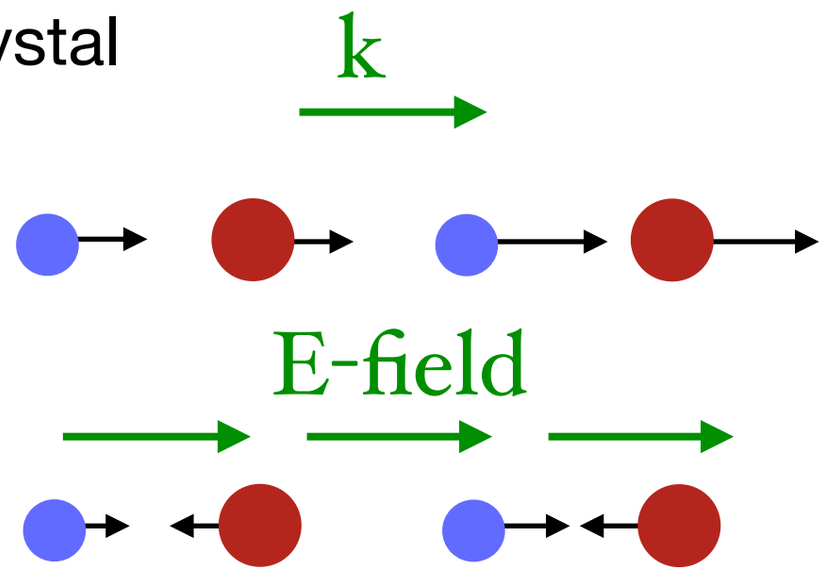
- At long wavelengths, material is neutral: very limited rate to produce acoustic phonons

- Long-wavelength <u>optical phonons in polar materials</u> generate a macroscopic E field (and therefore also E′ field)



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:

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

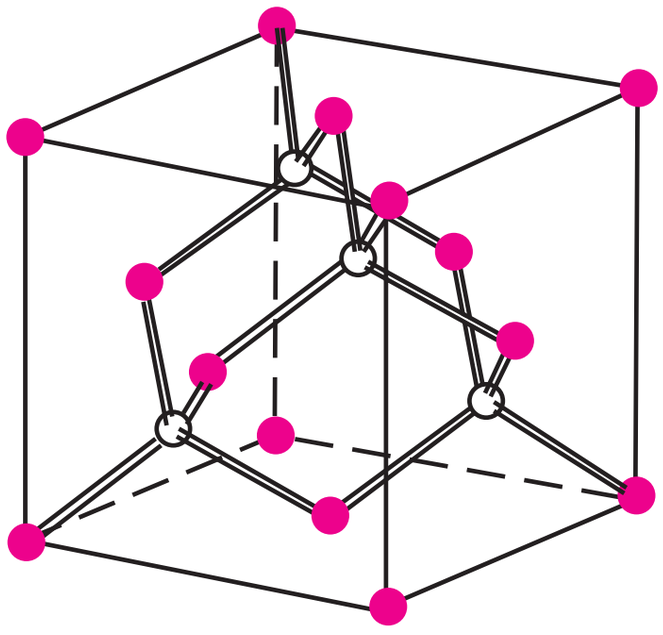
Dark photon field

Ion displacement (dipole)

Example: GaAs

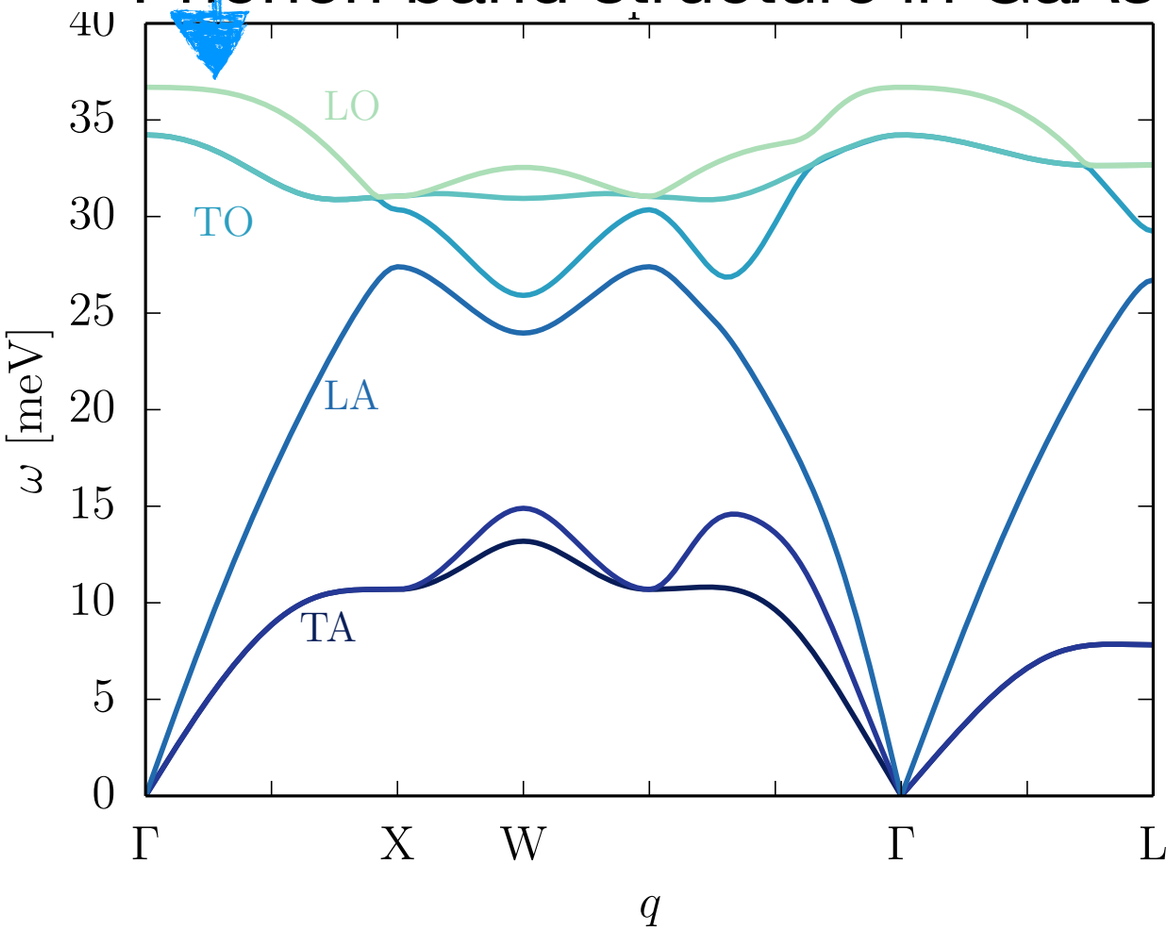
Gapped optical phonons

Crystal structure



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

Phonon band structure in GaAs



Path inside first Brillouin Zone

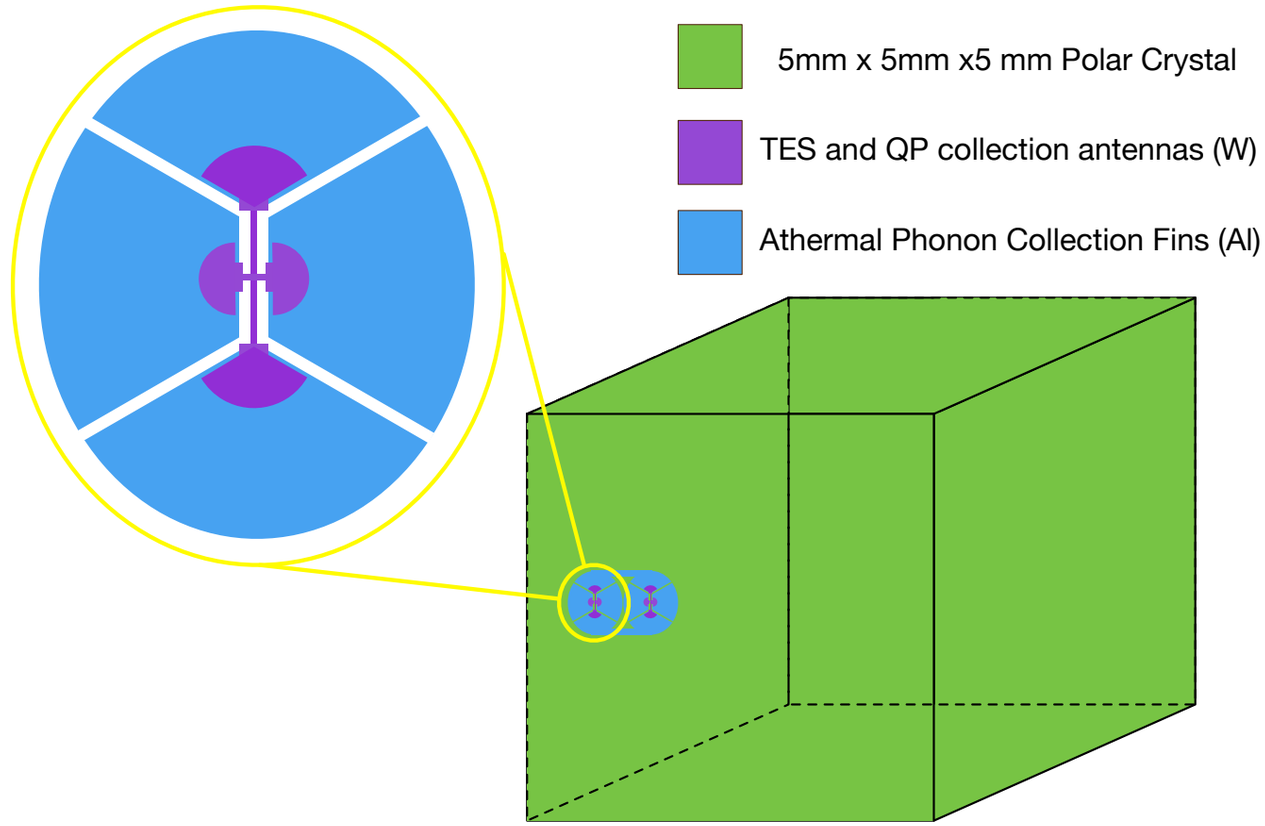
GaAs detector

Concept is similar to SuperCDMS:

DM scattering creates optical phonons;
These down-convert into (< meV) athermal phonons which are collected at surface.

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

TES with E_{th} ~ 30 meV



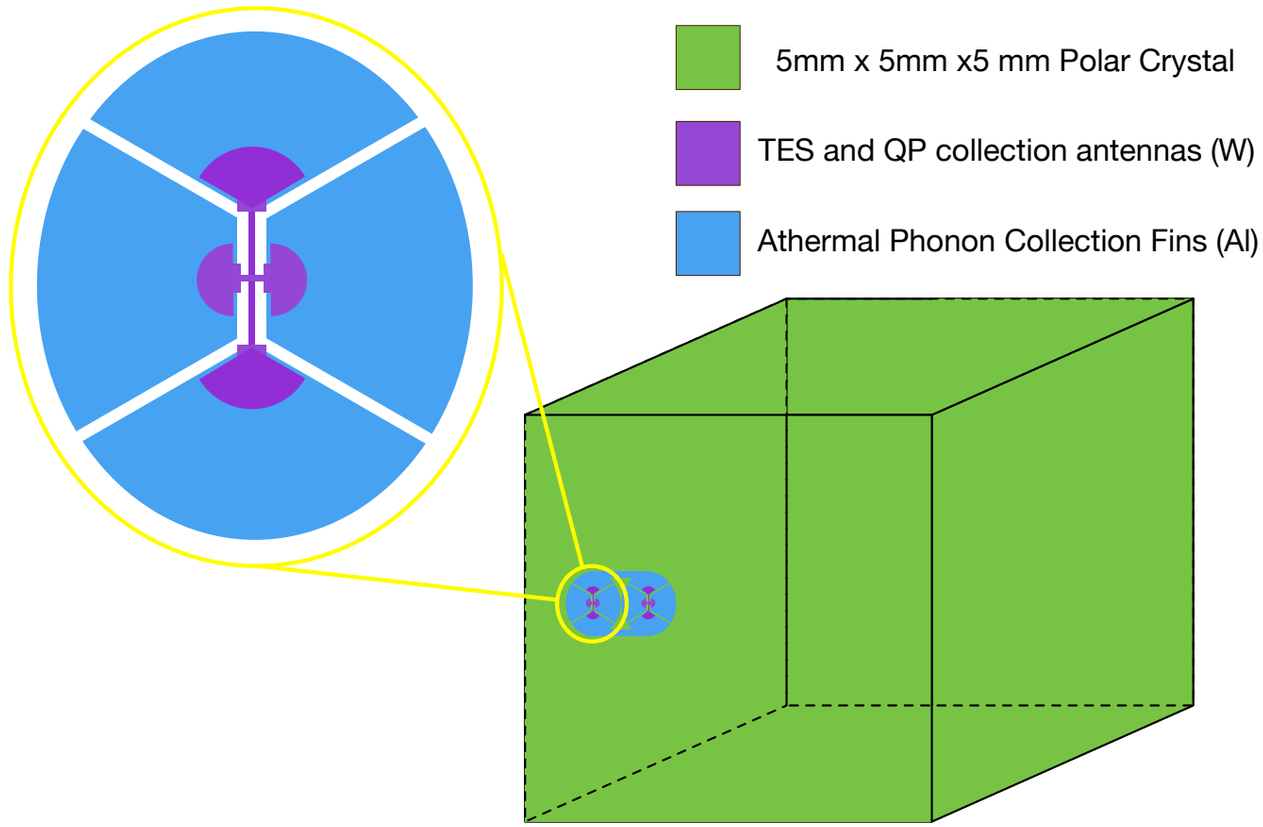
~0.6 gram of GaAs

GaAs detector

TES with ~55 meV resolution already demonstrated

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} ~ 30 meV



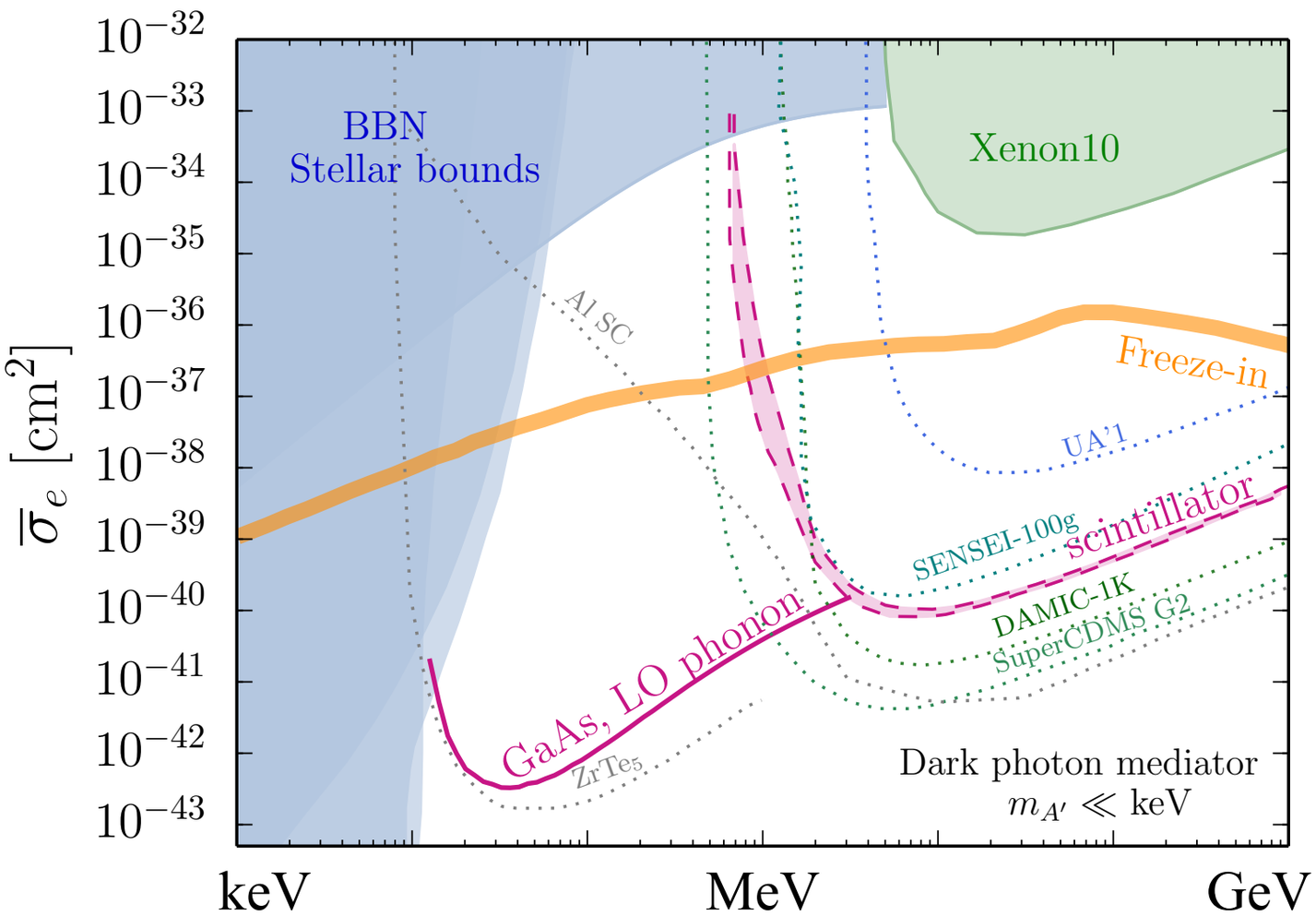
~0.6 gram of GaAs

Dark photon interactions

- DM sensitivity from optical phonon production in GaAs
- GaAs could cover the entire “freeze-in” region
- Can also be used as a scintillator for mX > MeV

Derenzo et al. 2016

DM scattering via ultralight dark photon mediator

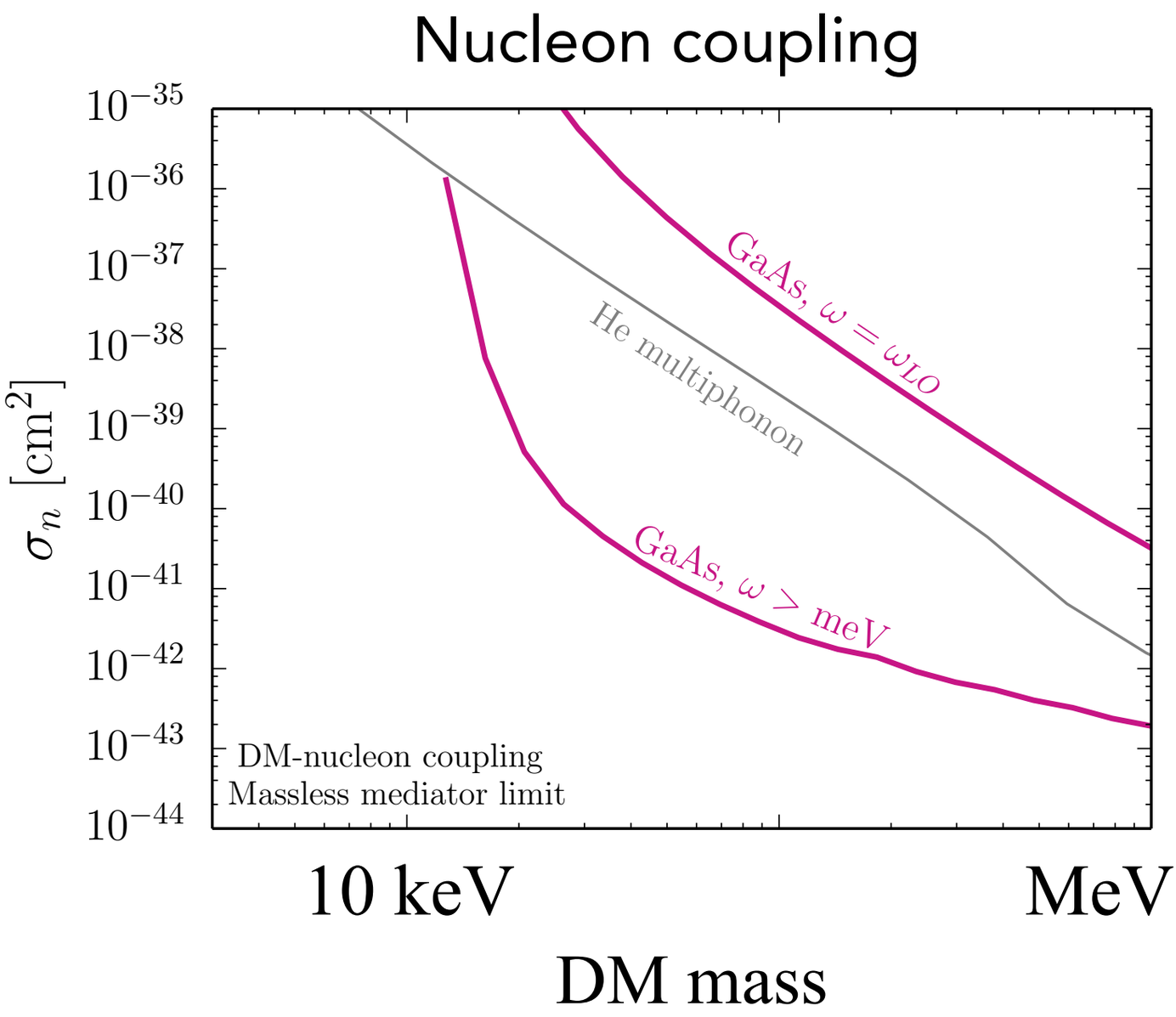


all projections assume kg-yr exposure

Cosmic Visions 2017;
Essig, Volansky, Yu 2017
Vogel and Redondo 2014

DM-nucleon scattering

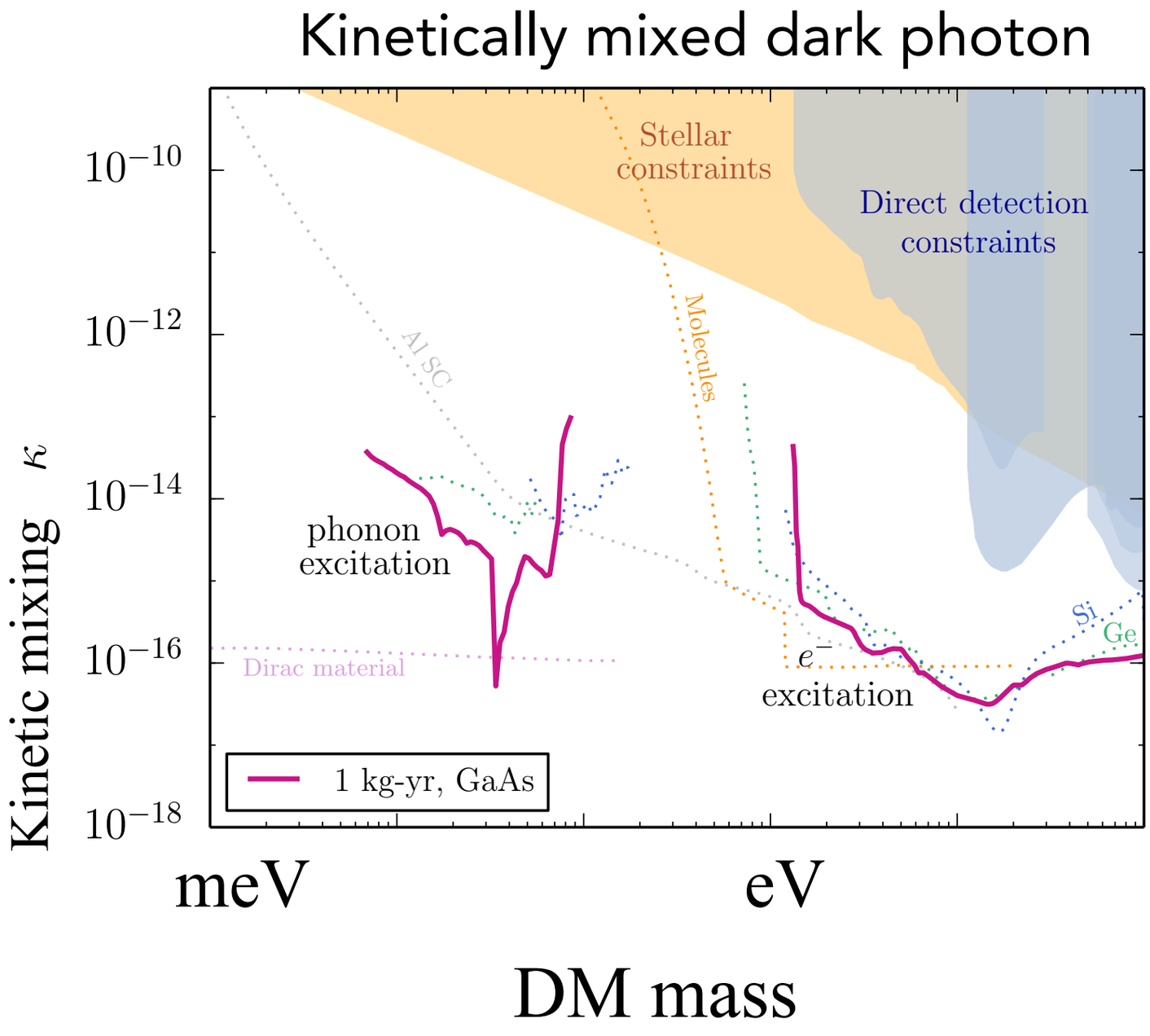
Single phonon production can be used for sub-MeV DM-nucleon scattering, competitive with multi-phonons in superfluid He



Knapen, TL, Zurek 2017

Dark matter absorption

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



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

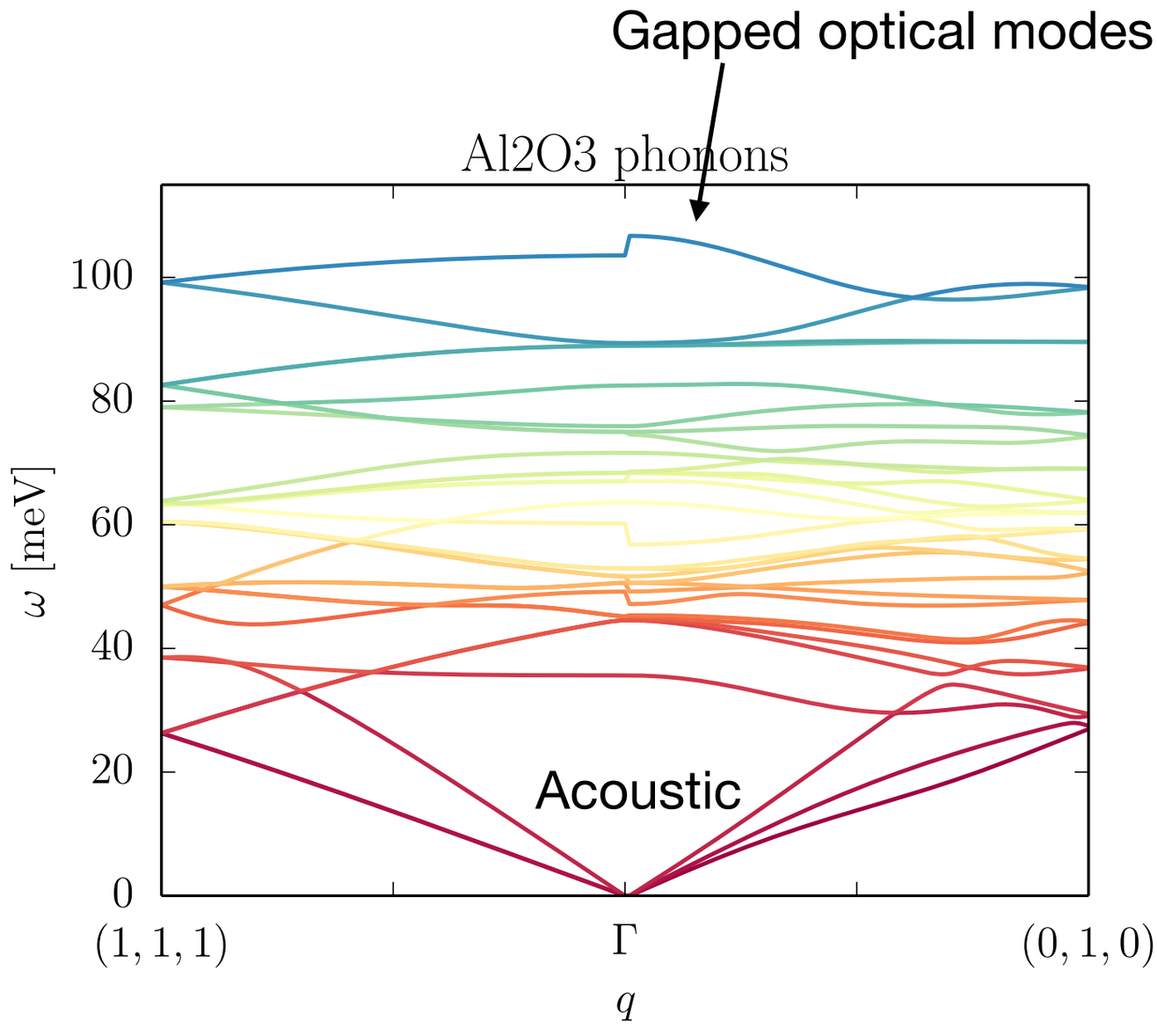
Even better: sapphire

- Good polarizability; similar reach as GaAs
- Possible fabrication of high purity crystals
- Optical modes with E=30-100 meV
- Good athermal phonon properties (high sound speed)

Colorful Al_2O_3 (Sapphire)

Sapphire phonons

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

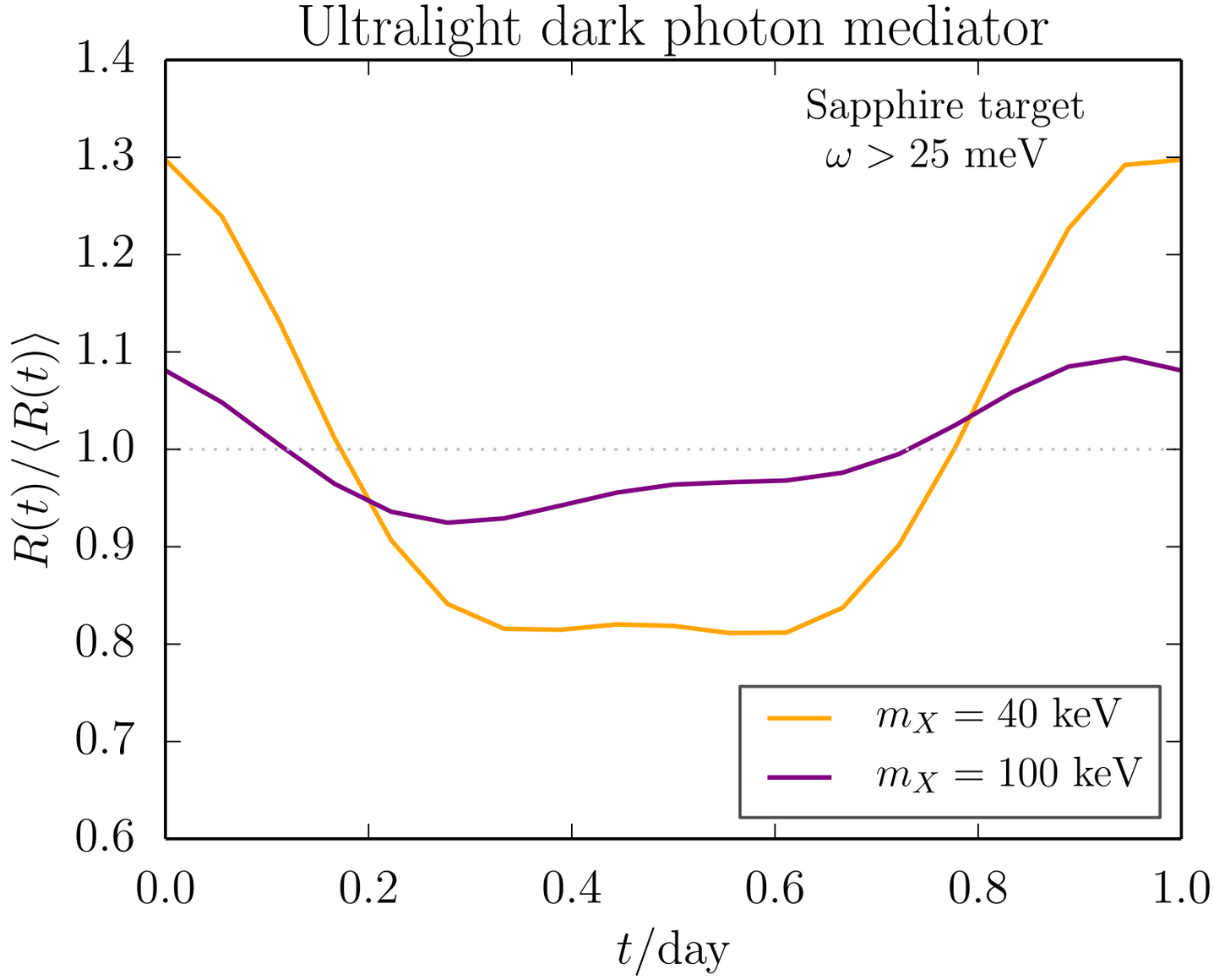


Phonon band structure in Al_2O_3 (Sapphire)

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.



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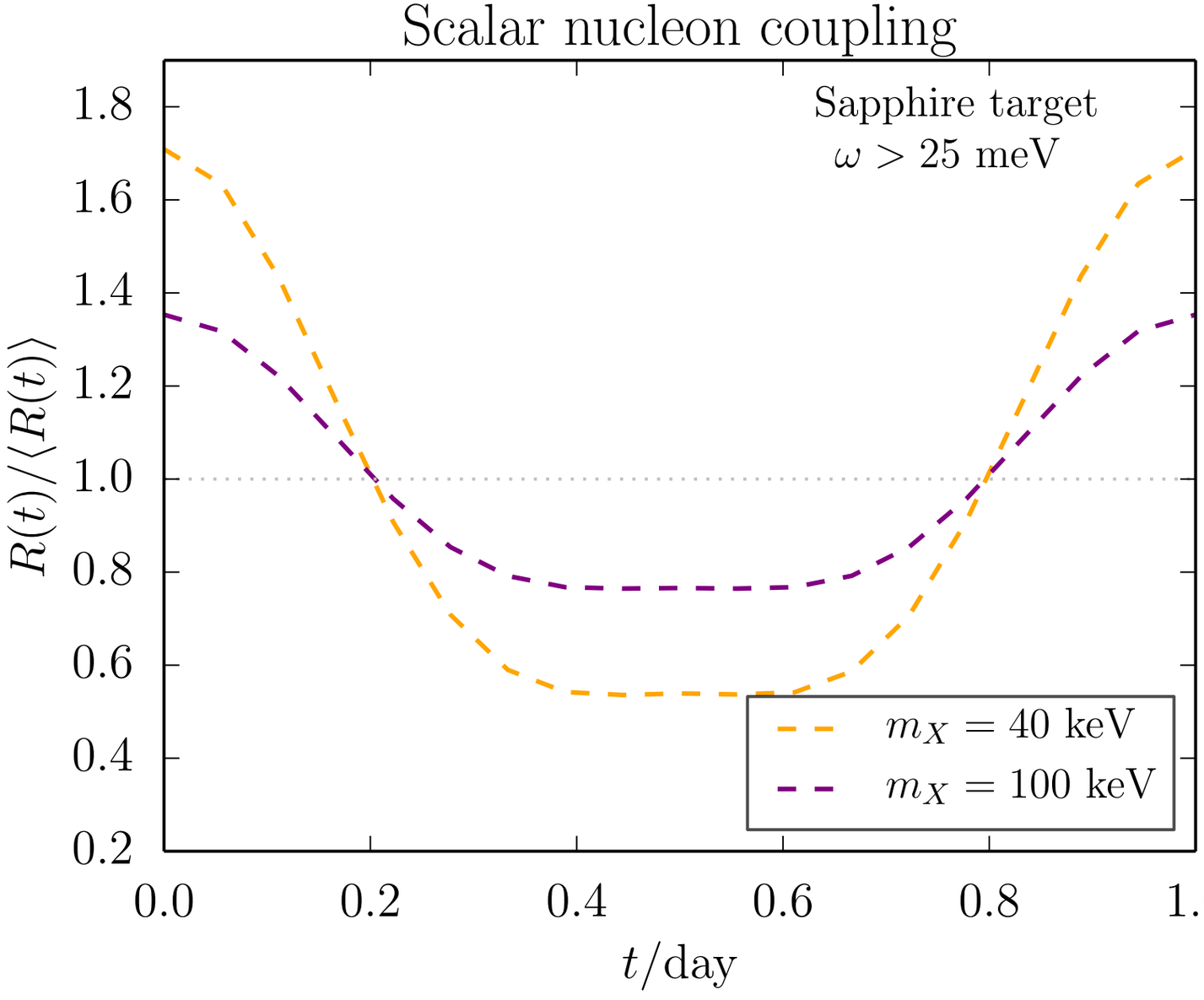
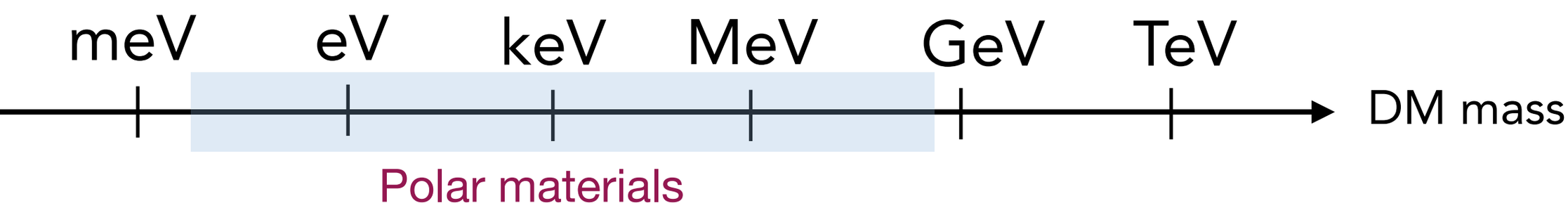


Conclusions

- Polar materials are excellent candidates for direct detection: ~1-10g target can already reach interesting DM candidates in meV-GeV range
- Directional detection also possible for sub-MeV DM!



Thanks!