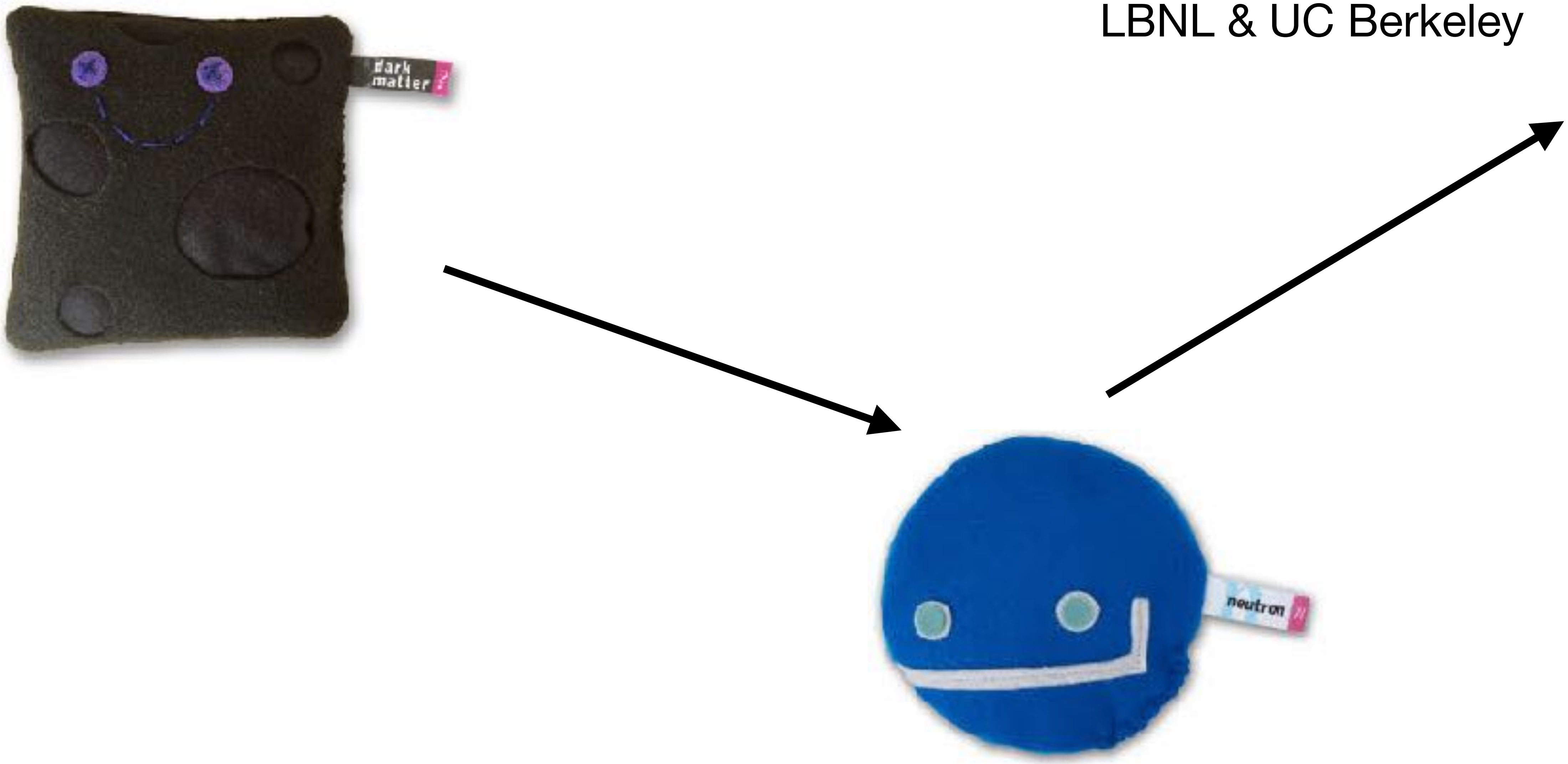
Detecting light dark matter with athermal phonons

(The "soft" frontier in dark matter direct detection)

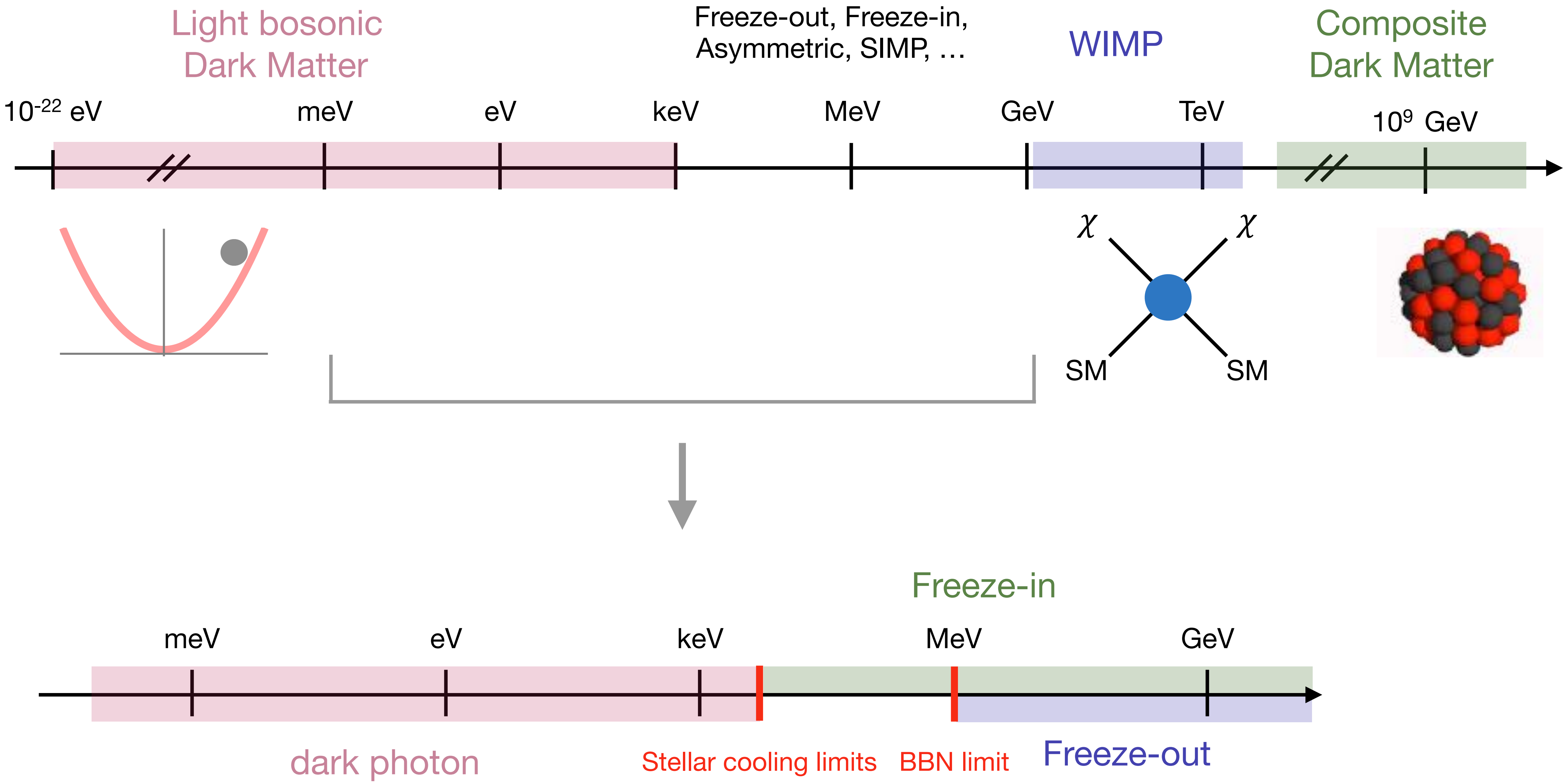
Simon Knapen
LBNL & UC Berkeley



@ KITP
04/10/2018

Work with Tongyan Lin, Kathryn Zurek, Sinead Griffin and Matt Pyle

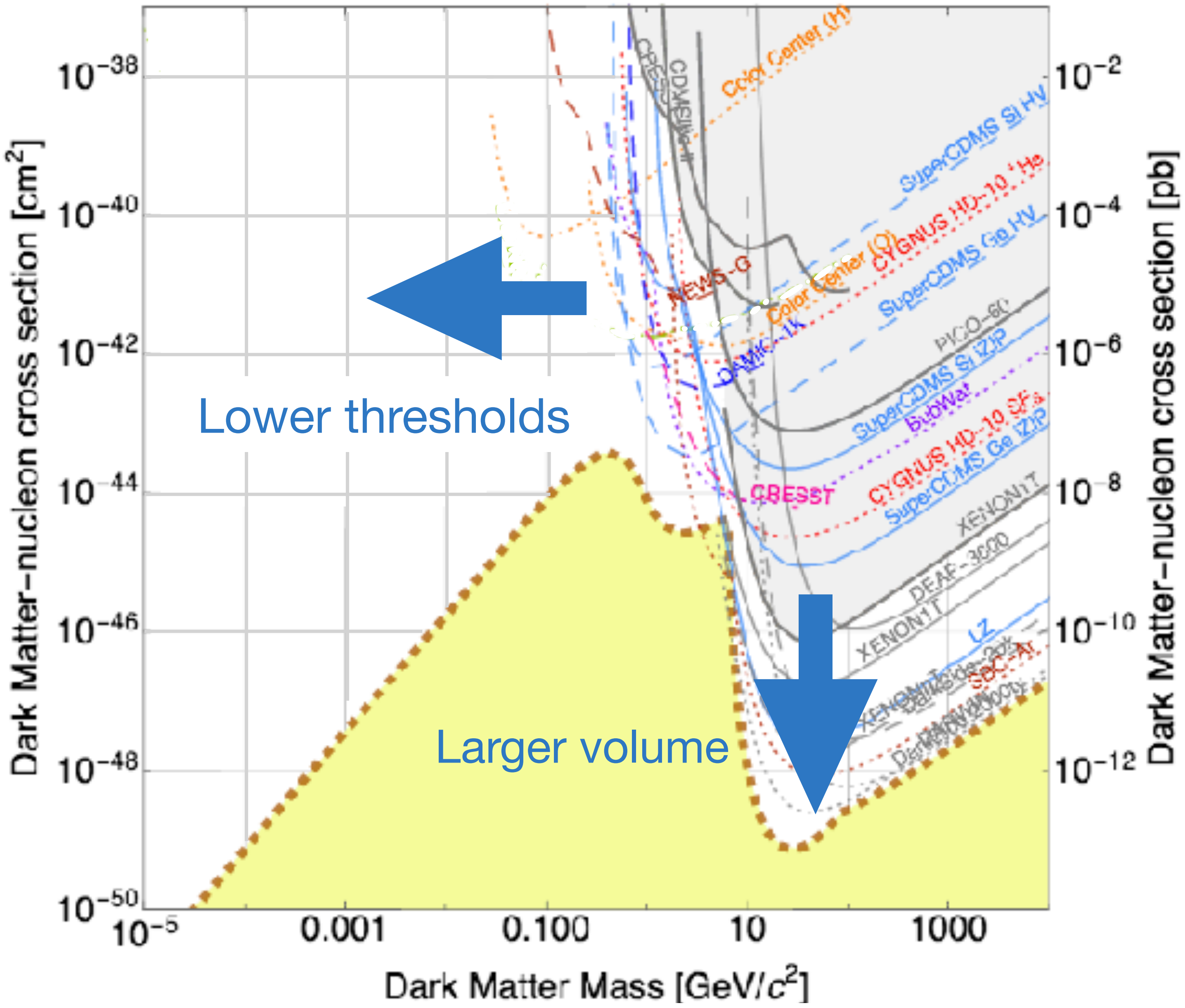
Models of Dark Matter



Freeze-out: Dark Matter drops out of equilibrium with Standard Model (e.g. WIMP’s)
Freeze-in: Dark Matter is never in equilibrium; Standard Model “leaks” into the dark sector

Dark matter direct detection

Cosmic visions report 2017: 1707.04591



What do we need?

Experiment:

1. Low target mass materials:

$$q < 2m_\chi v_\chi, \qquad v_\chi \approx 10^{-3}$$

$$E_R = \frac{q^2}{2m_N} < 10^{-6} \times \frac{m_\chi^2}{m_N}$$

2. Ultra-sensitive calorimeters with low dark counts

Theory:

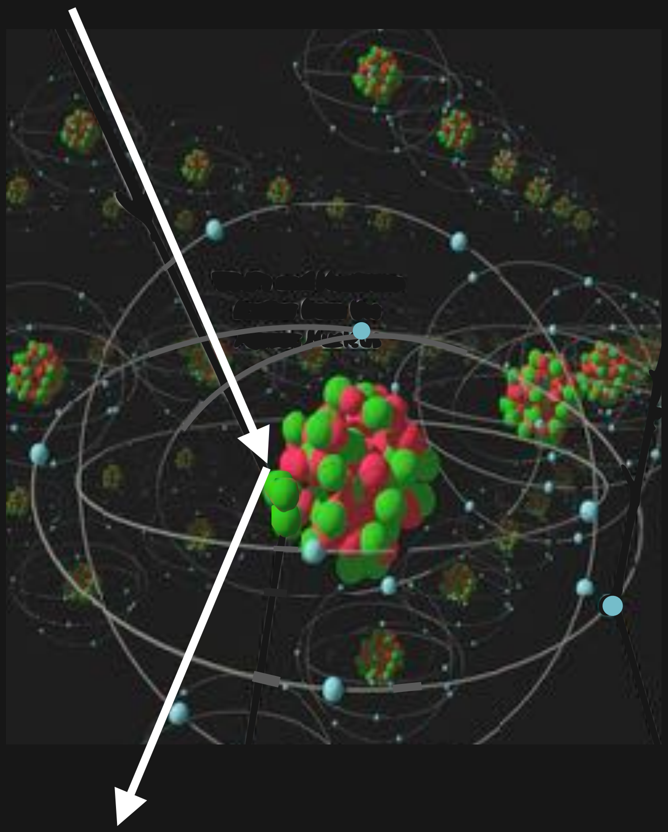
1. The mediator is important, independent set of constraints (effective theory breaks down, similar to LHC constraints on Dark Matter)

Y. Hochberg et. al.: 1512.04533
D. Green, S. Rajendran: 1701.08750
SK, T. Lin, K. Zurek: 1709.07882
…

This talk

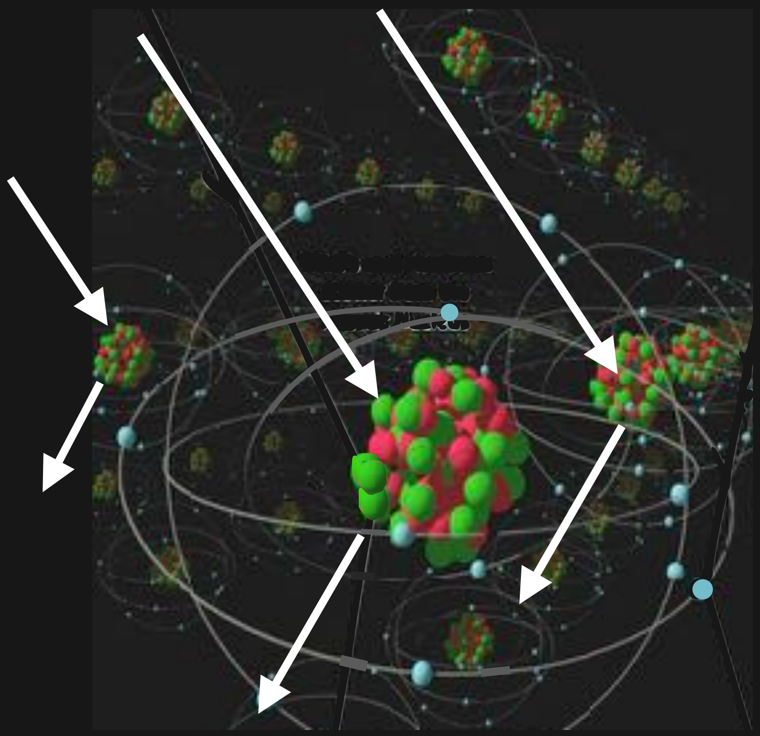
2. Beyond “billiard ball” scattering: structure effects are critical!

Structure effects



$m_\chi > 1$ MeV:

Recoil of nuclei/electrons



$m_\chi < 1$ MeV: $q \approx m_\chi v_\chi < \text{keV} \sim \text{nm}^{-1}$

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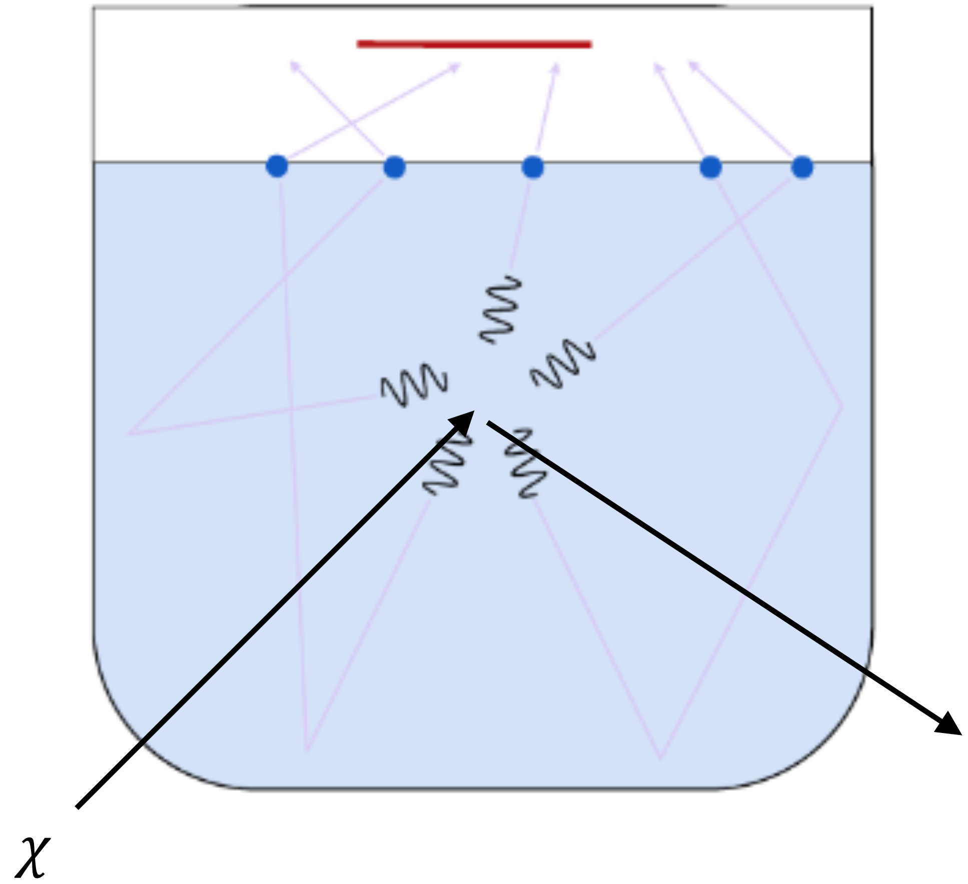
Scatter of collective excitations

(e.g. phonons)

Transition to different effective theory

Low threshold detectors

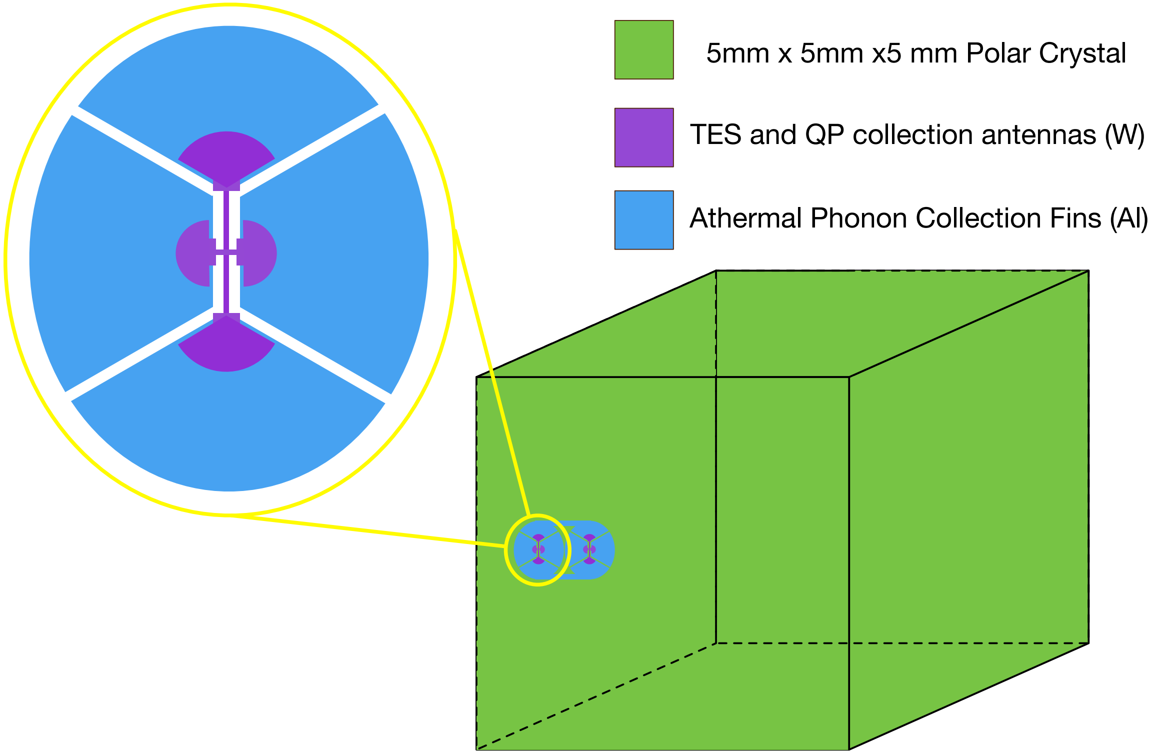
Superfluid helium detector



W. Guo, D. McKinsey: 1302.0534

Talk by D. McKinsey
(afternoon)

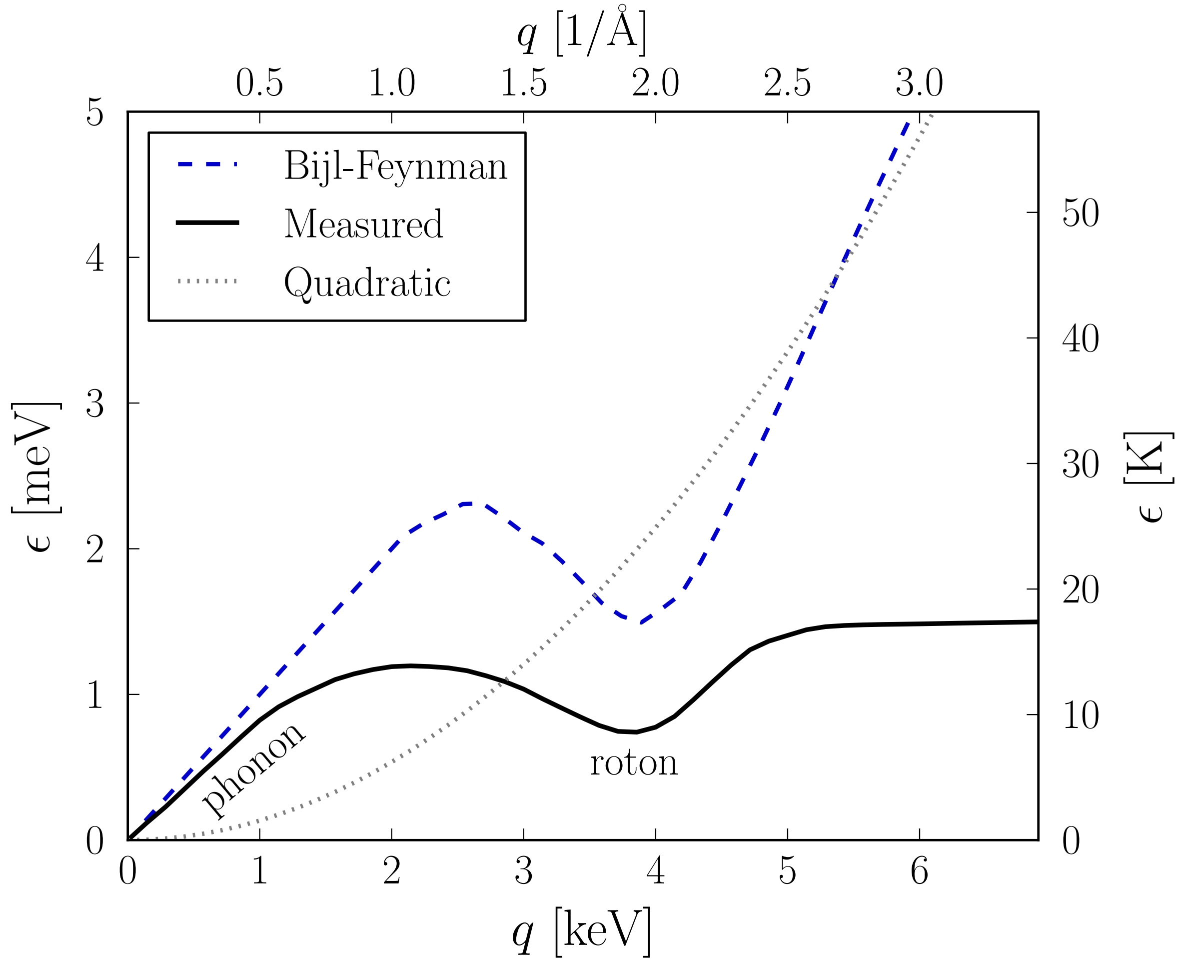
Polar material detector



SK, T. Lin, M. Pyle, K. Zurek: 1712.06598
See also: Y. Hochberg, M. Pyle, Y. Zhao, K. Zurek: 1512.04533

Talk by M. Pyle
(tomorrow)

Phonons & rotons in superfluid He



Issue: speed of Dark Matter >> speed of sound

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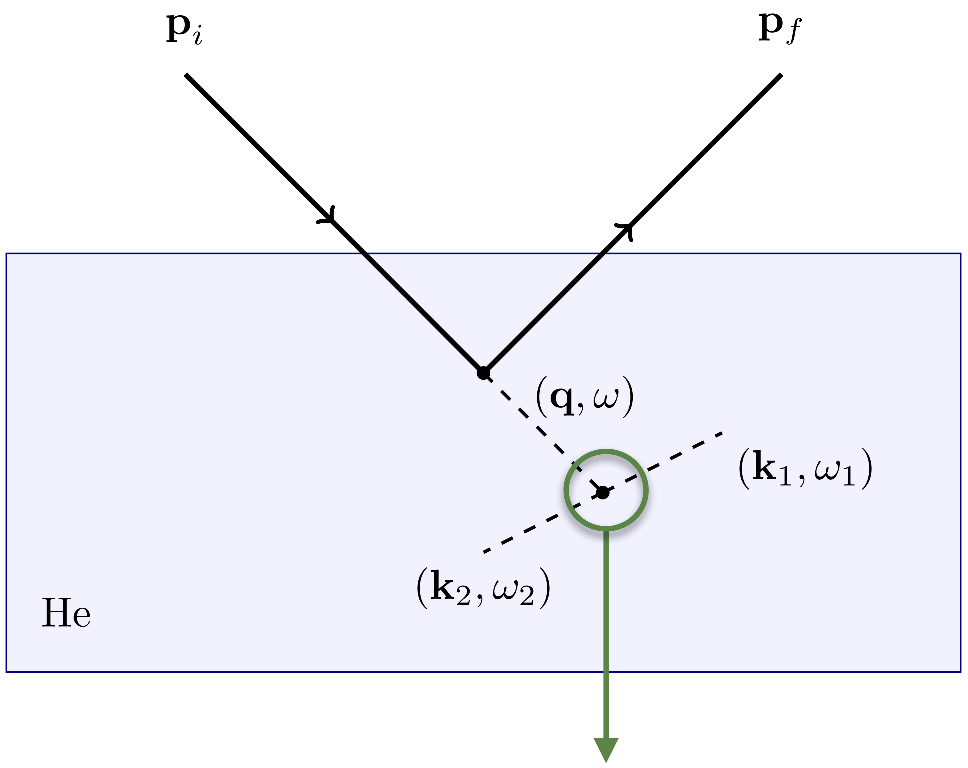
Cannot scatter against single, on shell excitation

Final state: two hard, back-to-back phonons



Calculate the 3-excitation matrix element

R. Feynman, 1954
H. W. Jackson, E. Feenberg, 1962
E. Feenberg, 1969
M. J. Stephen, 1969

K. Schultz, K. Zurek: 1604.08206
SK, T. Lin, K. Zurek: 1611.06228

Calculation

Step 1: Define orthogonal basis of states (ansatz + data input needed)

Step 2: Specify Hamiltonian description (Quantum hydrodynamics or microscopic formalism)

Step 3: Calculate the matrix element

Matrix element

$$\langle \mathbf{q}-\mathbf{k},\mathbf{k}|H-E_0|\mathbf{q}\rangle = \frac{\mathbf{q}\cdot(\mathbf{q}-\mathbf{k})S(\mathbf{k})+\mathbf{q}\cdot\mathbf{k}\,S(\mathbf{q}-\mathbf{k})-q^2S(\mathbf{k})S(\mathbf{q}-\mathbf{k})}{2m_{\rm He}\sqrt{N}\sqrt{S(\mathbf{q}-\mathbf{k})S(\mathbf{k})S(\mathbf{q})}}$$

Static structure function
(fixed from data)

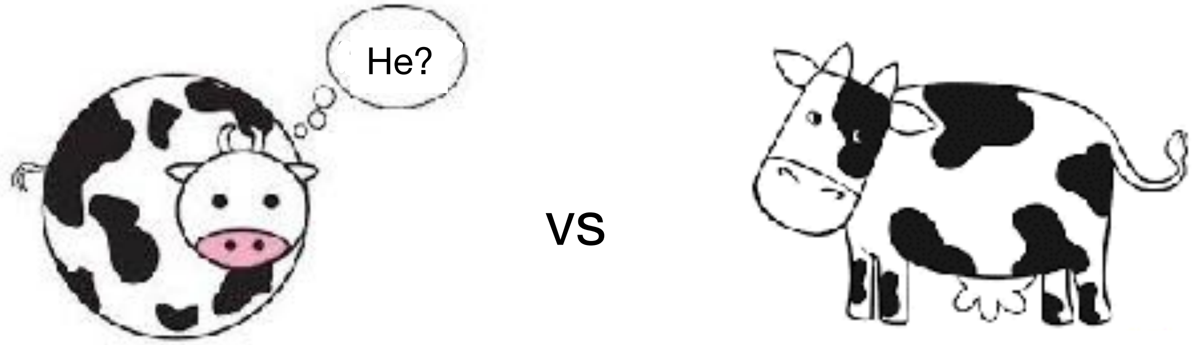
Expanding the rate in small q

$$\frac{d\sigma}{d\Omega d\omega} \approx \frac{\sigma_N}{64\pi^3}\frac{p_f}{p_i}\frac{\boxed{\mathbf{q}^4}}{n_0 c_s m_{\rm He}^2\omega^2}\sum_i \tilde{\mathbf{k}}_i^2\left(1-S(\tilde{\mathbf{k}}_i)\right)^2 \qquad \epsilon_0(\tilde{k}_i)=\omega/2$$

Power law reproduced in state-of-the-art simulation data

SK, T. Lin, K. Zurek: 1611.06228

A Modern Simulation



Combination of standard perturbation theory & dynamical multiparticle fluctuations theory

- More sophisticated ansatz for the potential
- Resummed self-energies

No resolution for low momentum transfer

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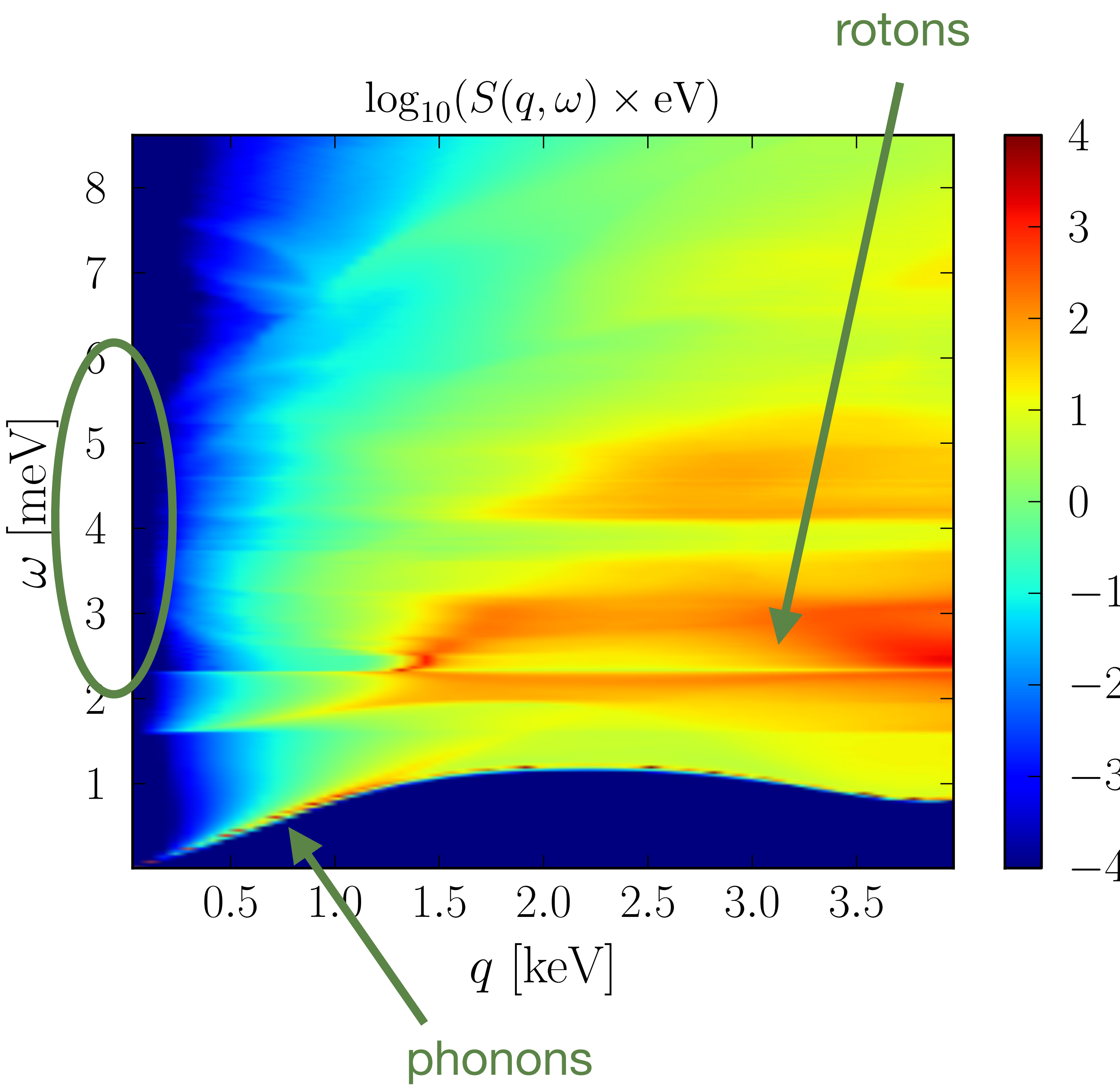
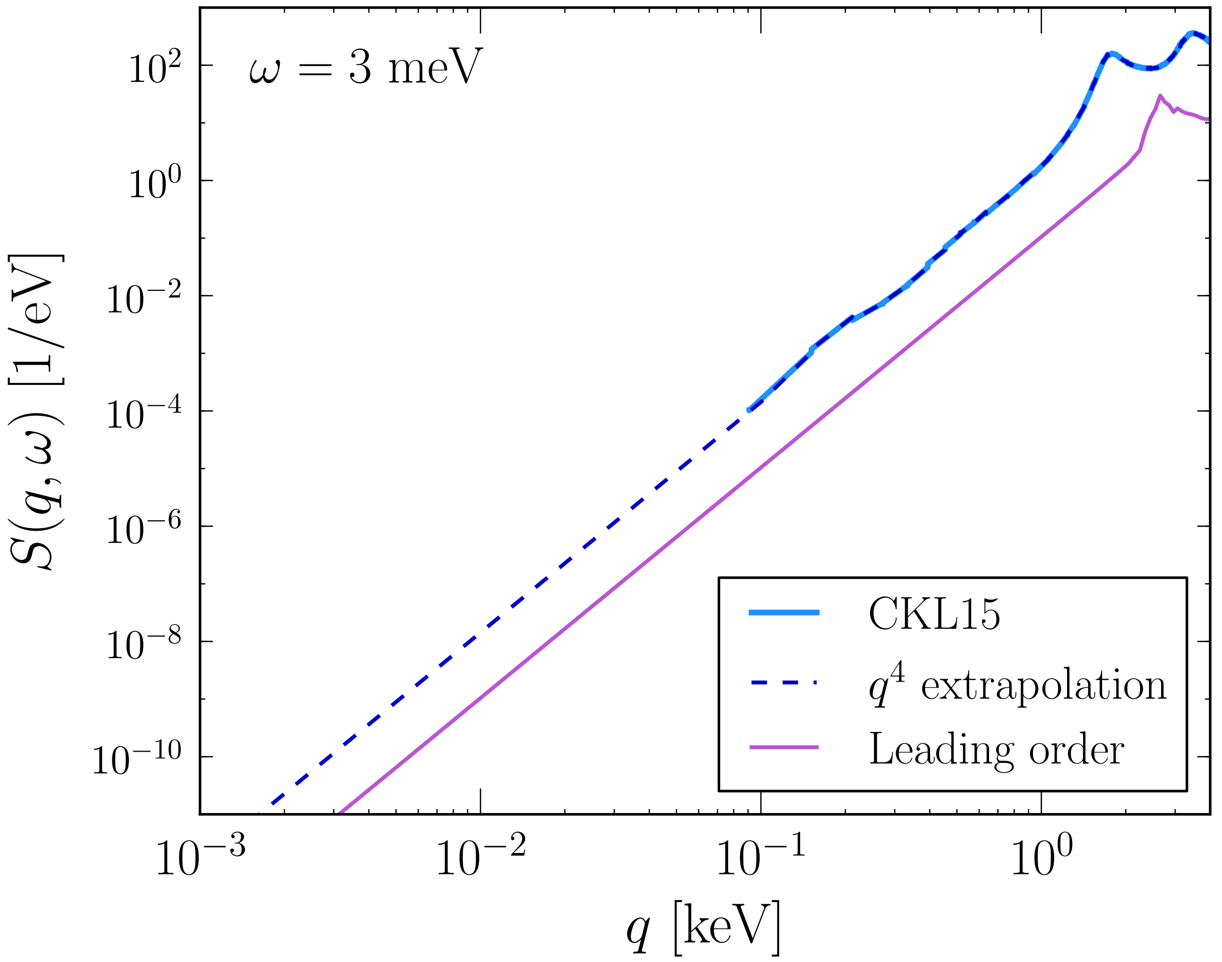
Use our analytic expressions to extrapolate



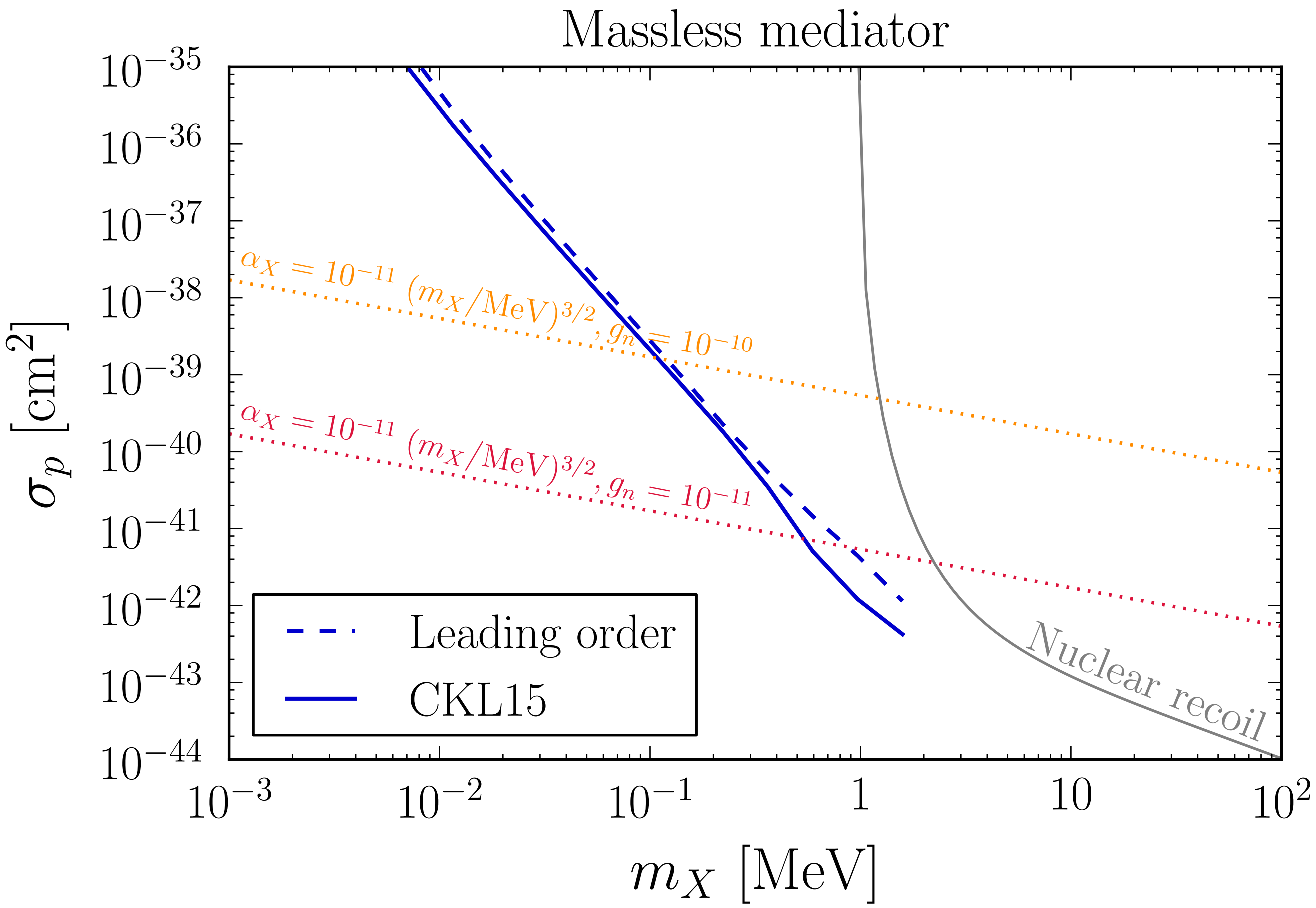
Campbell, Krotscheck and Lichtenegger (2015)

Comparison with simulation

q^4 scaling is reproduced in the simulation data



Reach agrees within a factor of ~ 2



kg x year exposure
1 meV threshold

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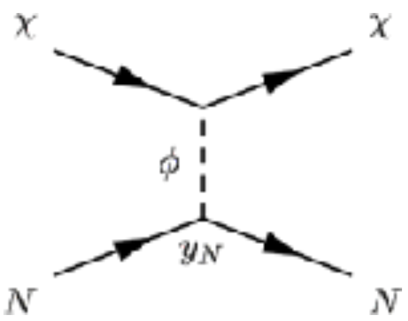
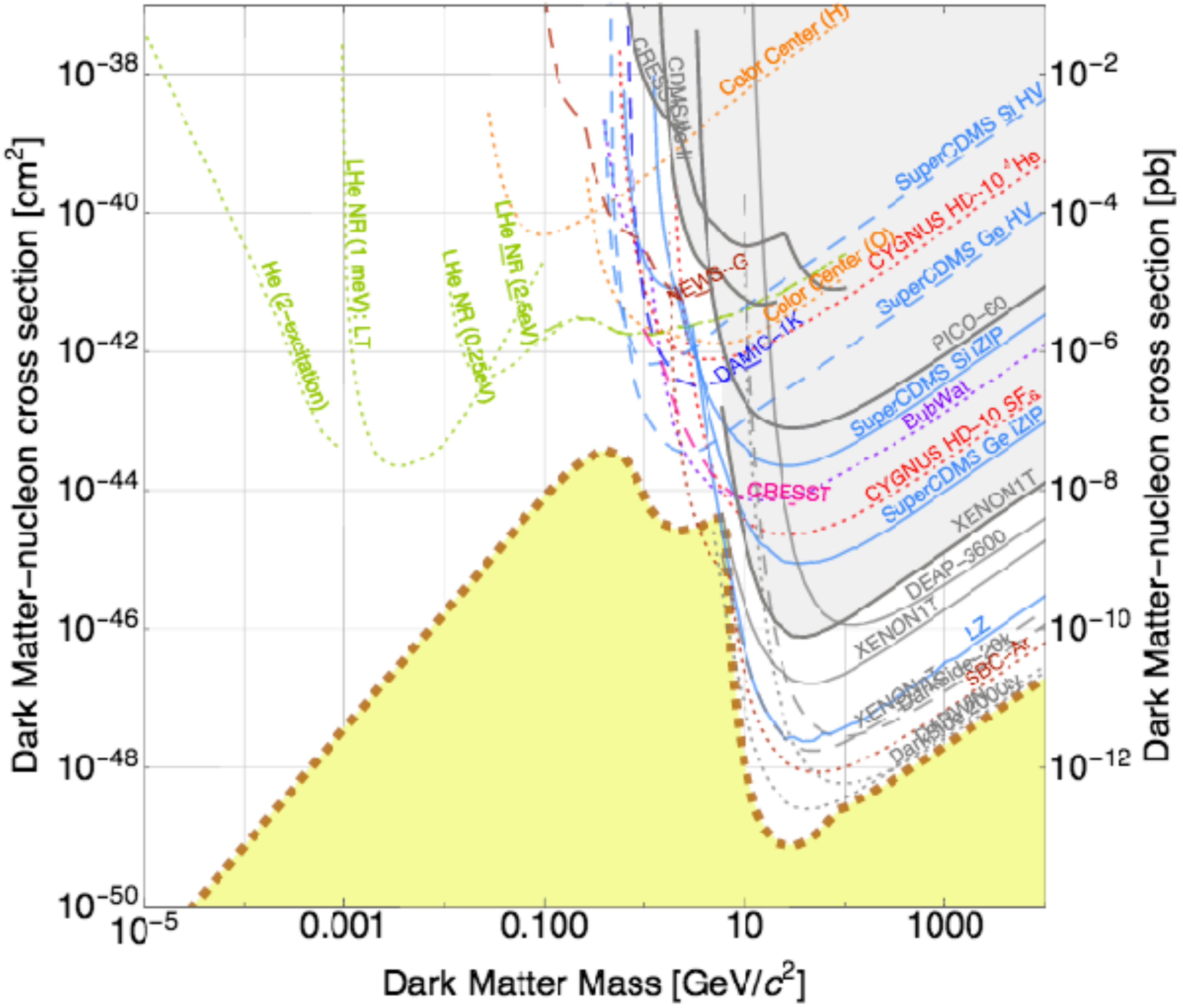
Reach



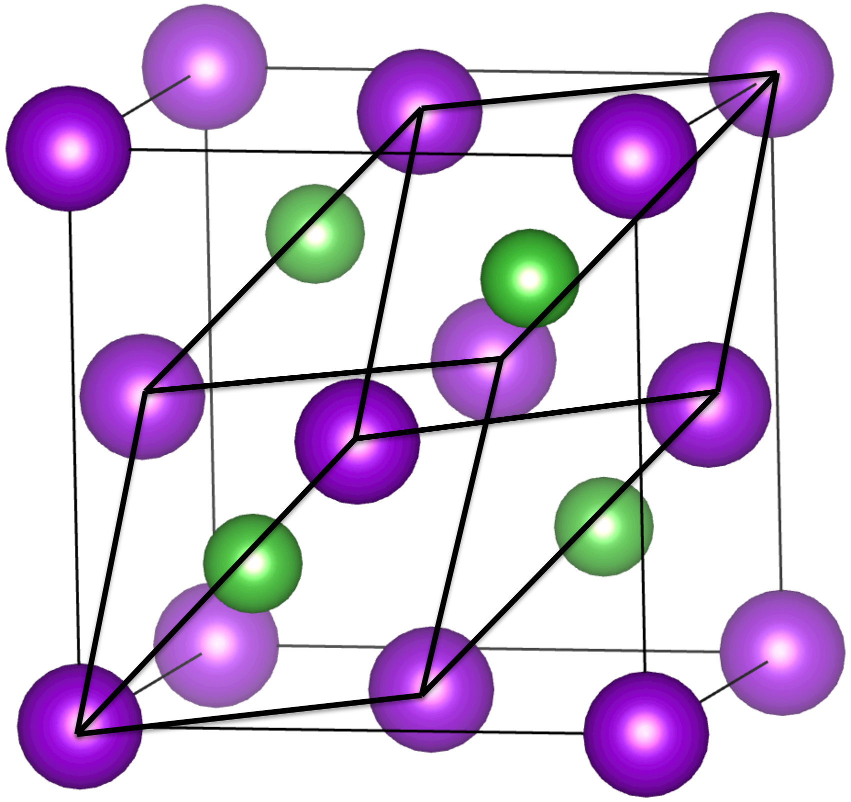


Superfluid helium is sensitive down to m$_{\chi}$ ~ 10 keV

Cosmic visions report 2017: 1707.04591

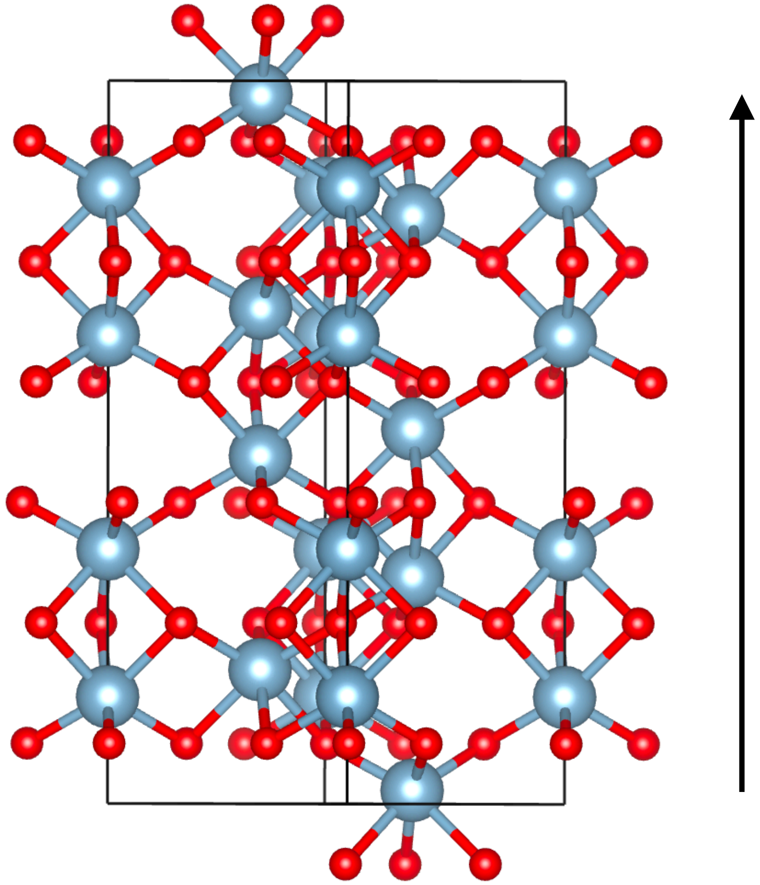
Polar materials

GaAs



2 atoms in primitive cell

Al_2O_3 (Sapphire)



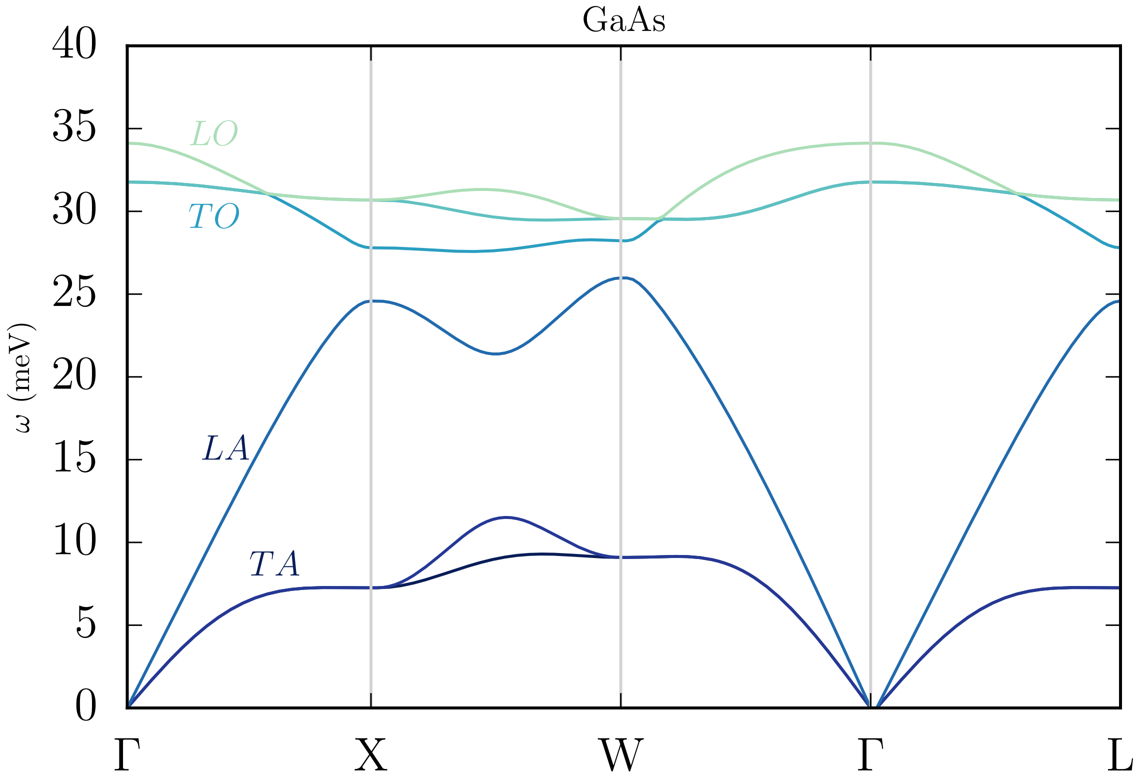
Primary crystal axis

10 atoms in primitive cell

At least two *different* atoms in the unit cell

Why polar materials?

1. Optical phonons for kinematic matching



3. Semi-conductors or insulators: screening is small

4. Crystal axis allows for directional detection (daily modulation!)

5. Readily available now

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Frölich Hamiltonian

H. Frölich, 1954
C. Verdi, F. Giustino, Phys. Rev. Lett. 115, 176401 (2015)

Electric dipole interacting with test charge: $H \sim i\,e \sum_{\mathbf{q}} \frac{\mathbf{q}\cdot\mathbf{P}}{|\mathbf{q}|^2} e^{i\mathbf{q}\cdot\mathbf{r}}$

Born effective charge tensor
for each atom

phonon eigenvectors
(atomic displacements)

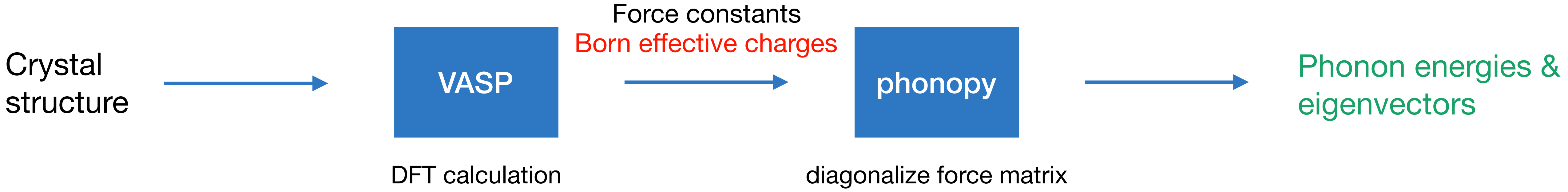
$$H = i\frac{\kappa e^2}{V}\sum_{j,\nu,\mathbf{q}}\sum_{\mathbf{G}\neq\mathbf{q}} \frac{1}{\sqrt{2Nm_j\omega_{\nu,\mathbf{q}}}} \frac{(\mathbf{q}+\mathbf{G})\cdot\mathbf{Z}_j\cdot\mathbf{e}_{j,\nu}(\mathbf{q})}{(\mathbf{q}+\mathbf{G})\cdot\epsilon_\infty\cdot(\mathbf{q}+\mathbf{G})} e^{i(\mathbf{q}+\mathbf{G})\cdot(\mathbf{r}+\boldsymbol{\tau}_j)}$$

Sum over:
atoms in unit cell
phonon modes
1st Brioullin zone
Reciprocal lattice

phonon energy

high frequency dielectric
tensor

Calculation overview:



Crystal structure

VASP

DFT calculation

Force constants
Born effective charges

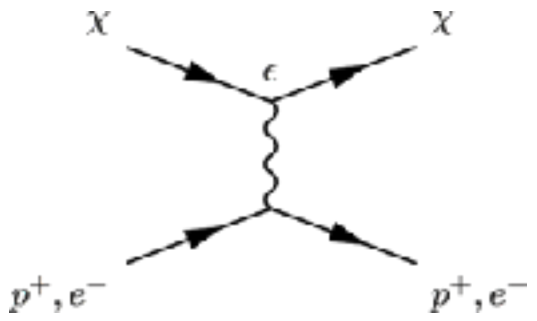
phonopy

diagonalize force matrix

Phonon energies & eigenvectors

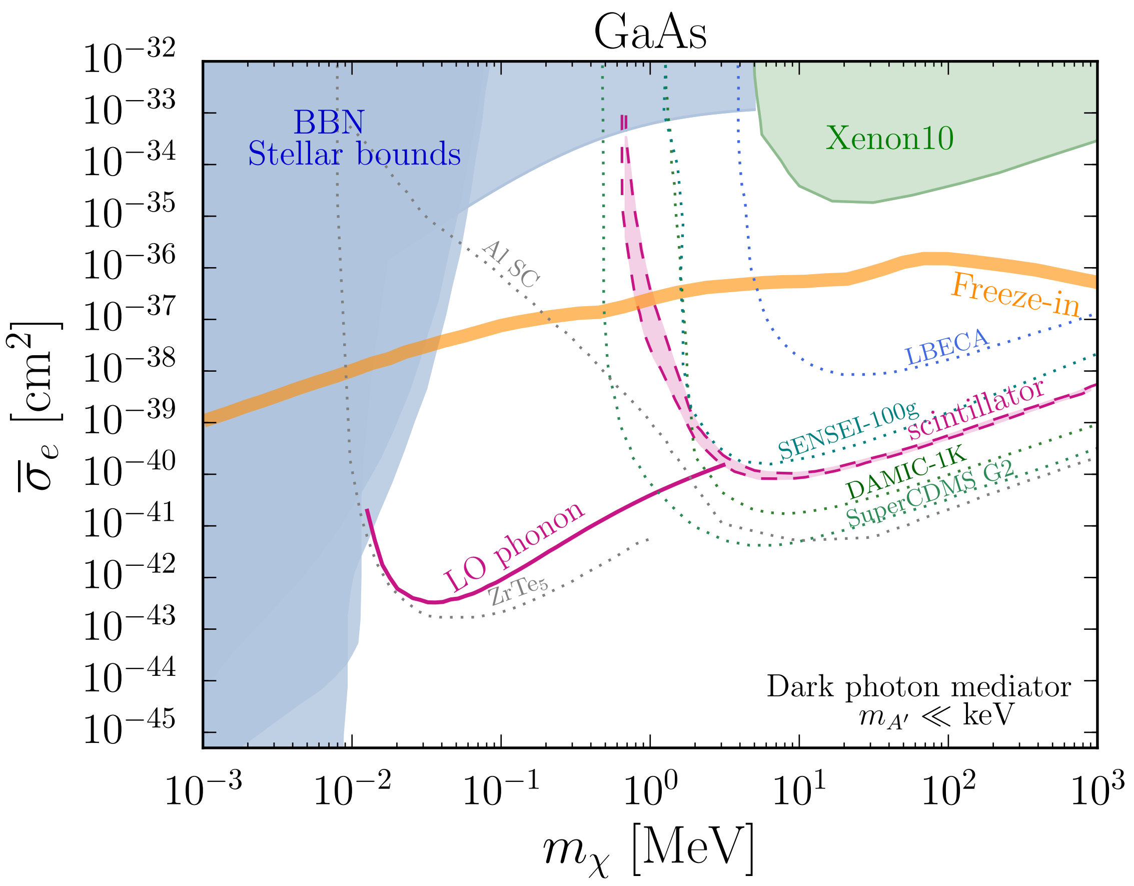
S. Griffin, SK, T. Lin, M. Pyle, K. Zurek: in preparation

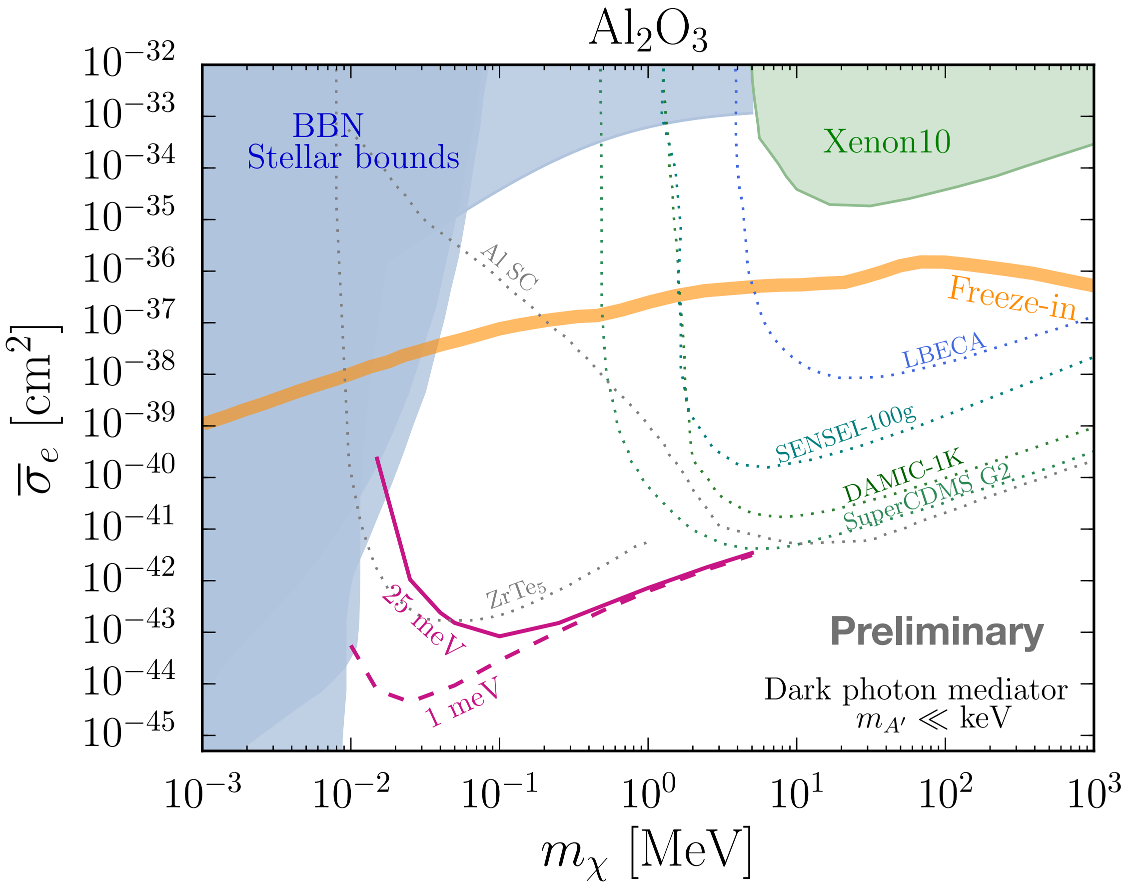
Reach



Both GaAs and Sapphire probe Dark Matter masses as low as 10 keV

(Reach comparable to Dirac materials)



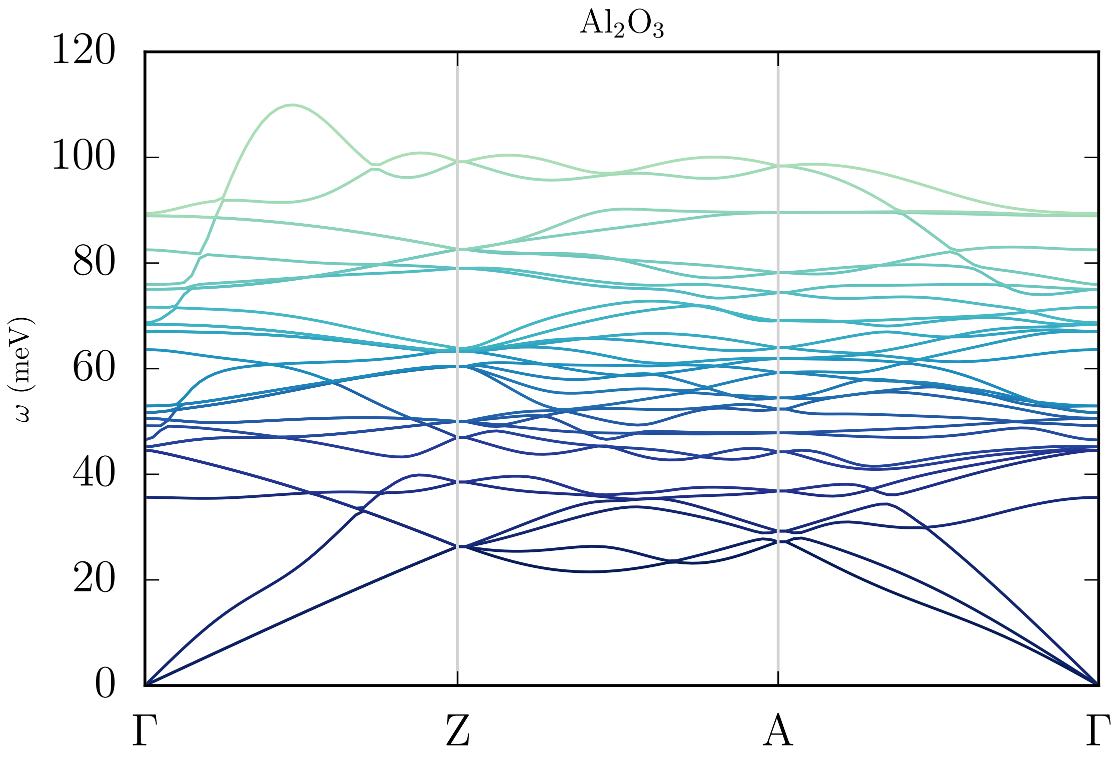


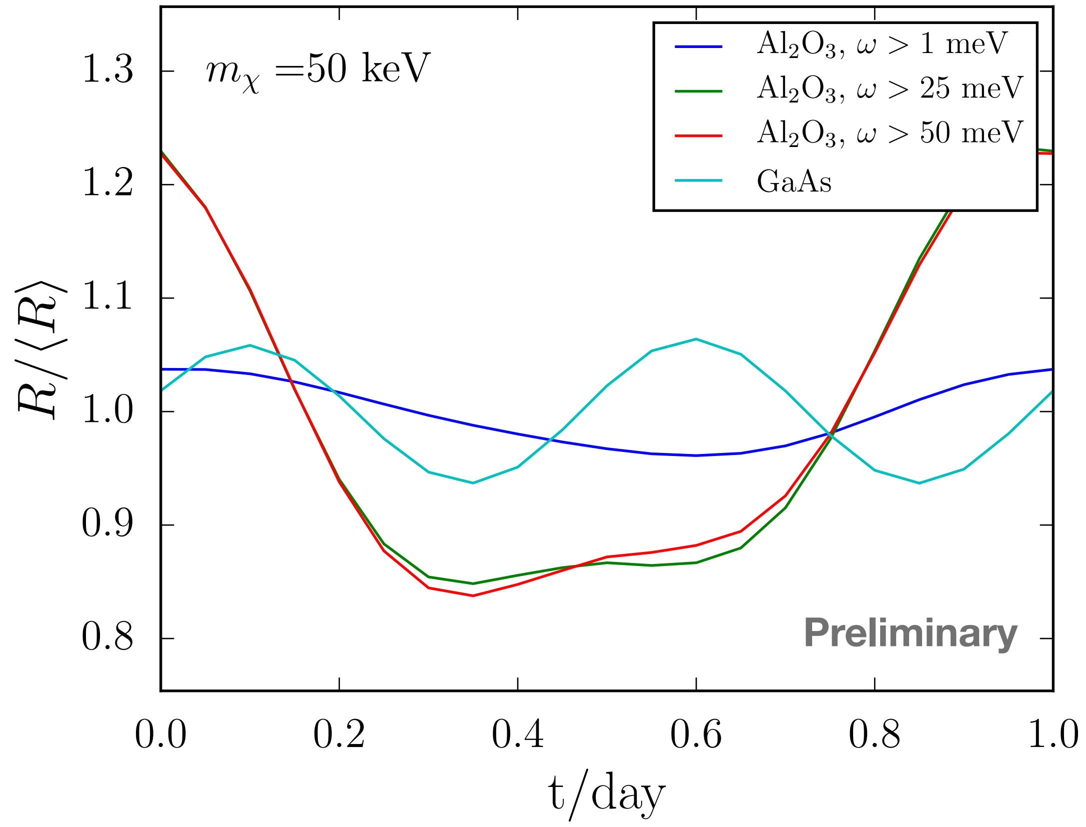
Probe the Freeze-in prediction with gram month exposure

SK, T. Lin, M. Pyle, K. Zurek: 1712.06598
S. Griffin, SK, T. Lin, M. Pyle, K. Zurek: in preparation

Daily modulation

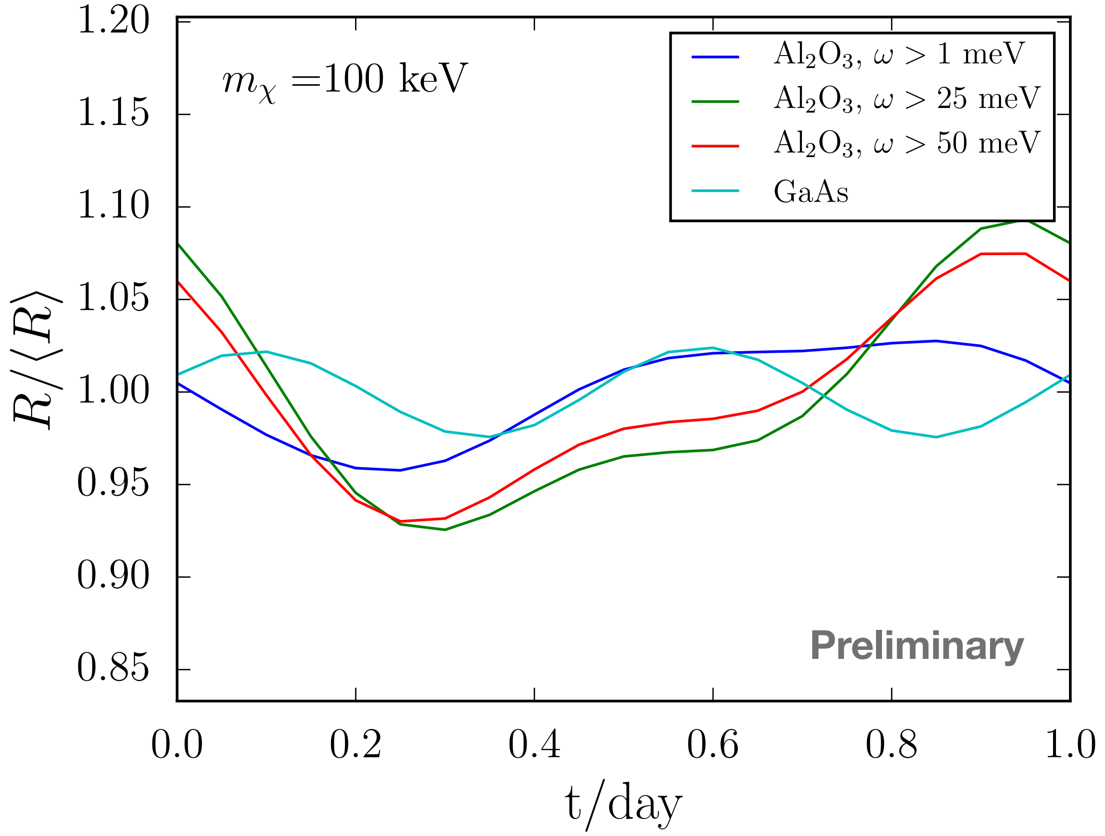
Sapphire band structure depends on direction





For Freeze-in dark matter

10^3 - 10^4 events with 1 kg year exposure



S. Griffin, SK, T. Lin, M. Pyle, K. Zurek: in preparation

Daily modulation

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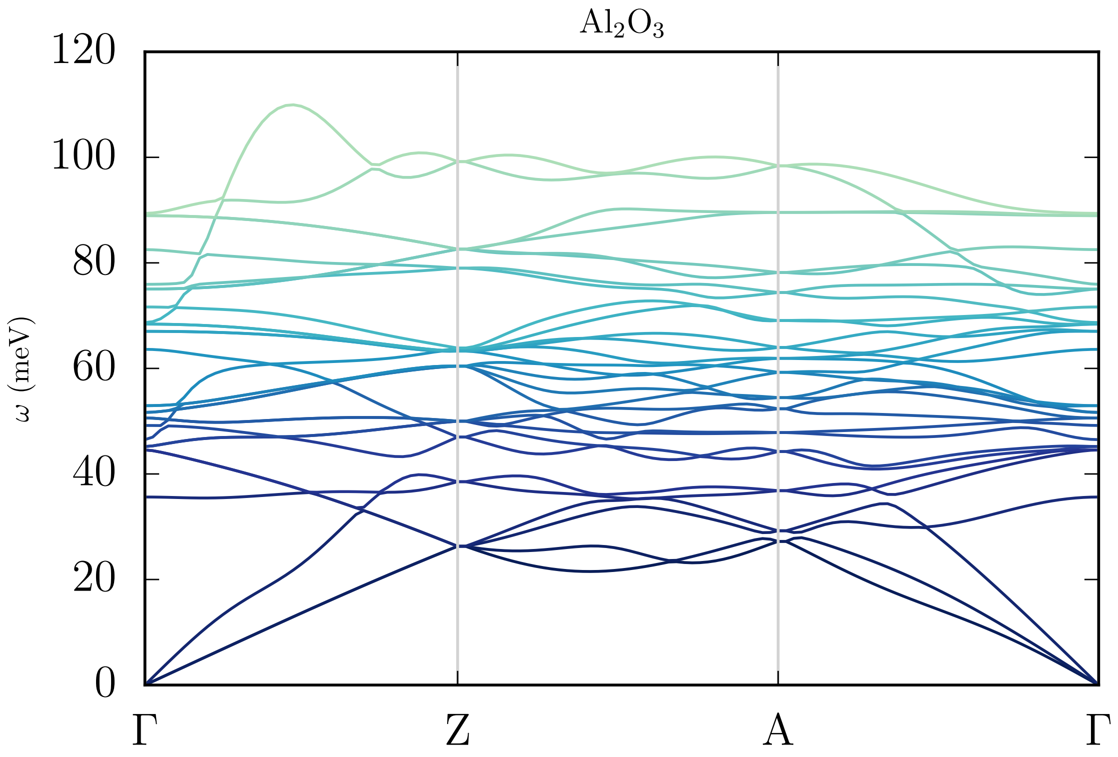
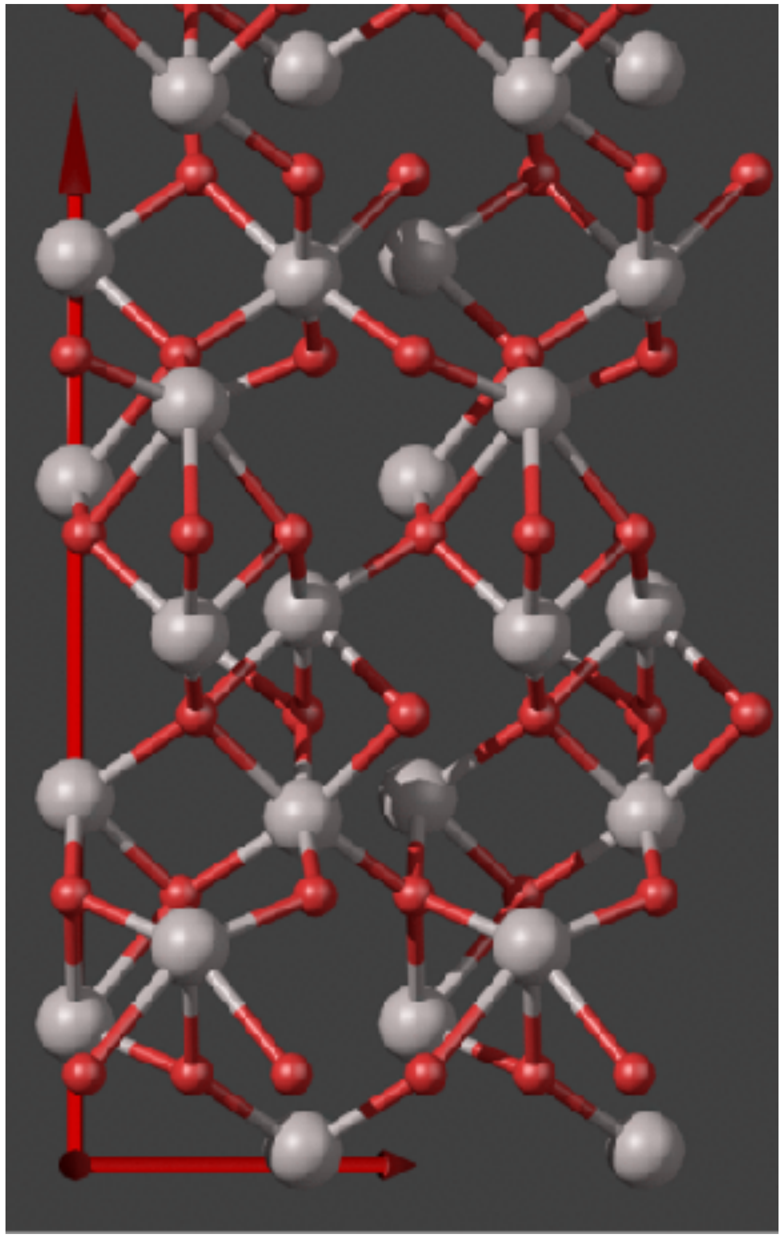


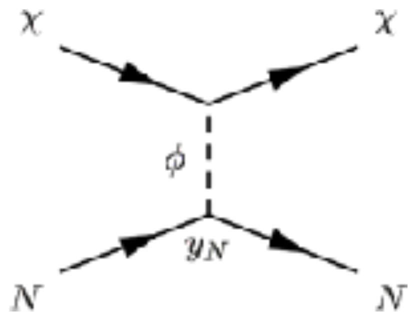
For Freeze-in dark matter
10^3 - 10^4 events with 1 kg year exposure

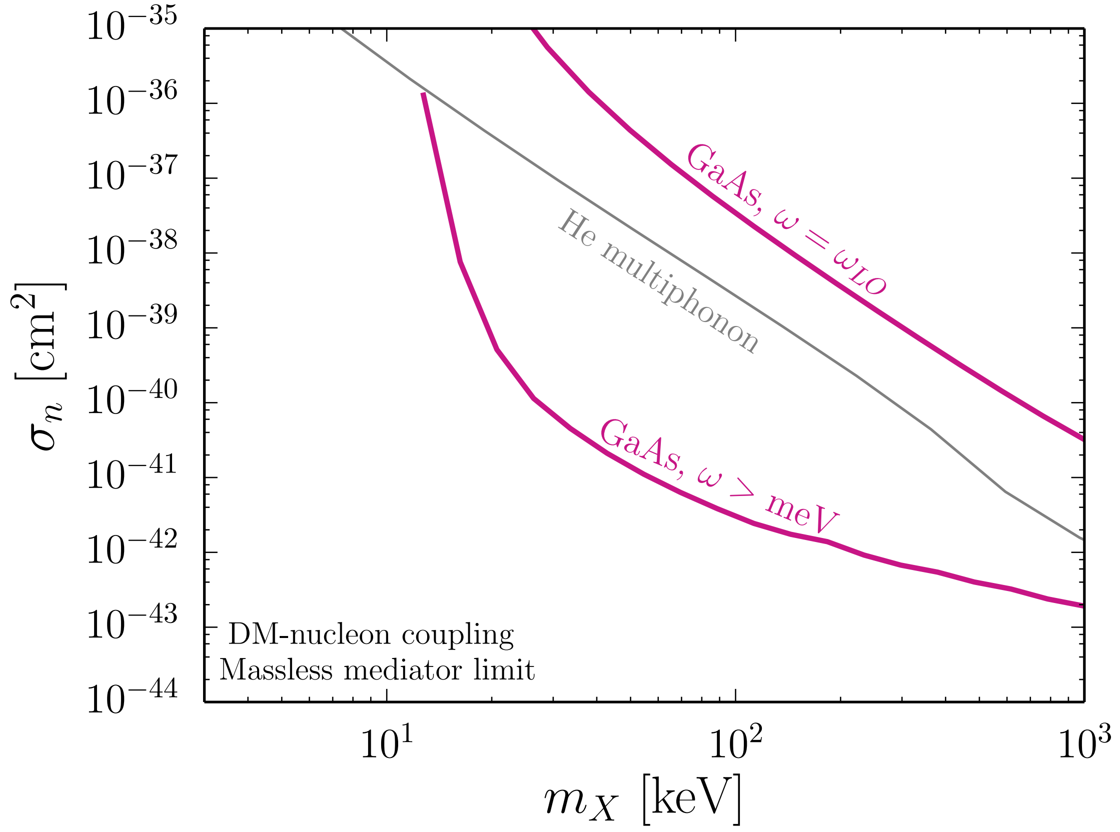


Modes with large oscillating dipole dominate

S. Griffin, SK, T. Lin, M. Pyle, K. Zurek: in preparation

Scalar mediator





phonon form factor:

$$|F_\nu(\mathbf{q})|^2 = \left| \sum_d \frac{\bar{b}_d}{\sqrt{m_d}} e^{-W_d(\mathbf{q})} \mathbf{q} \cdot \mathbf{e}_{\nu,d,\mathbf{q}} e^{-i\mathbf{q}\cdot\mathbf{r}_d} \right|^2$$

$$\Big\downarrow$$

$$|F_\nu(\mathbf{q})|^2 \approx \frac{\bar{b}_n^2}{2m_n} q^2 \left| \sqrt{A_{\mathrm{Ga}}} e^{i\mathbf{r}_{\mathrm{Ga}}\cdot\mathbf{q}} \pm \sqrt{A_{\mathrm{As}}} e^{i\mathbf{r}_{\mathrm{As}}\cdot\mathbf{q}} \right|^2$$

daily modulation!

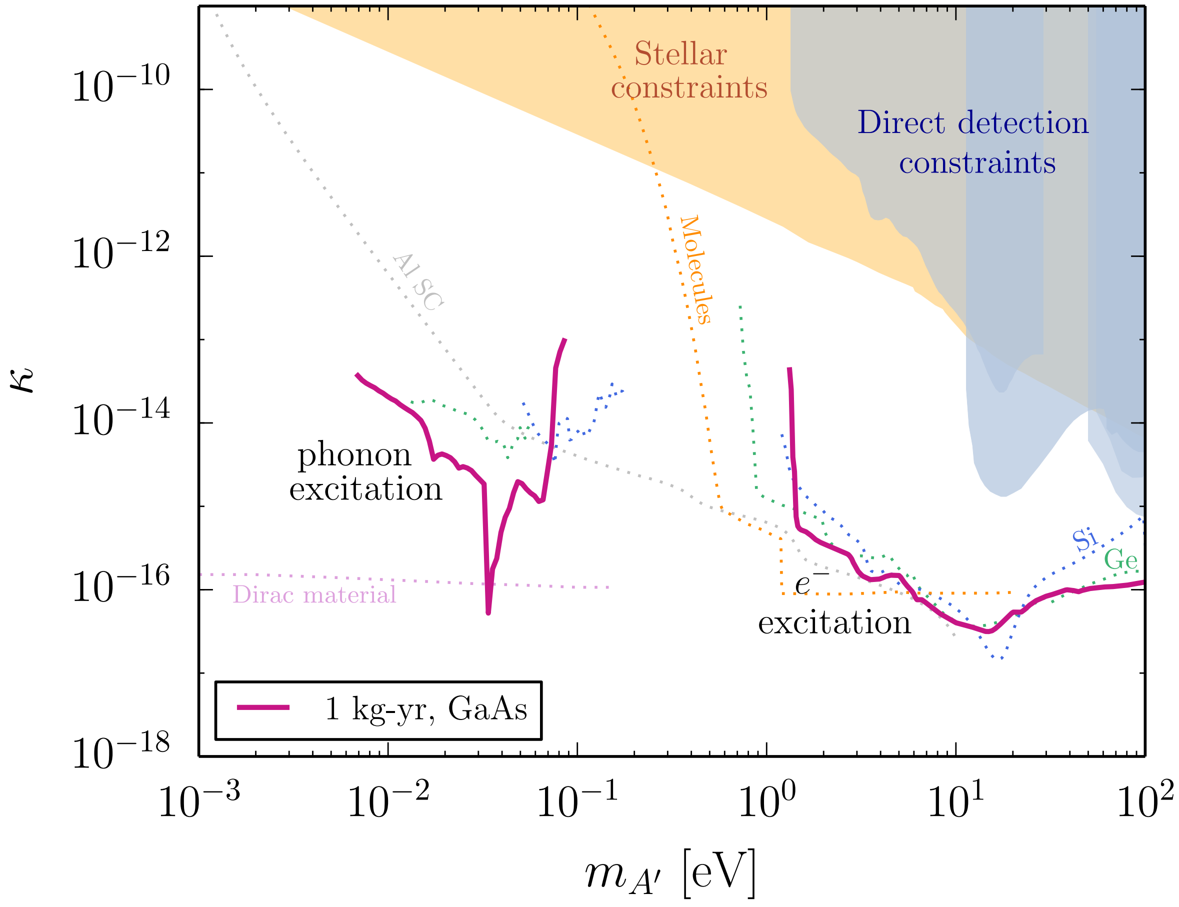
Destructive interference for the optical phonon mode

Expected to work better for crystals with larger mass hierarchies

SK, T. Lin, M. Pyle, K. Zurek: 1712.06598

Dark photon absorption

Dark photon dark matter: $\mathcal{L} \supset -\frac{\kappa}{2} F'_{\mu\nu} F^{\mu\nu}$



Absorption rate

$$R = \frac{1}{\rho} \frac{\rho_{\mathrm{DM}}}{m_{A'}} \kappa_{\mathrm{eff}}^2 \sigma_1 .$$

in medium kinetic mixing parameter

SM photon absorption rate

Extract from the complex index of refraction

(Sapphire still in progress)

SK, T. Lin, M. Pyle, K. Zurek: 1712.06598

Looking ahead

Experiment:

- See talks by Daniel & Matt today and tomorrow

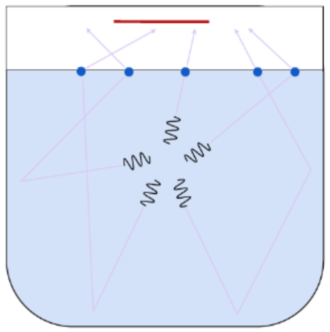
Theory:

- Complete the daily modulation analysis
- Absorption rate for sapphire
- Calculate neutrino and coherent photon backgrounds (expected to be small)
- Reach for other dark matter models

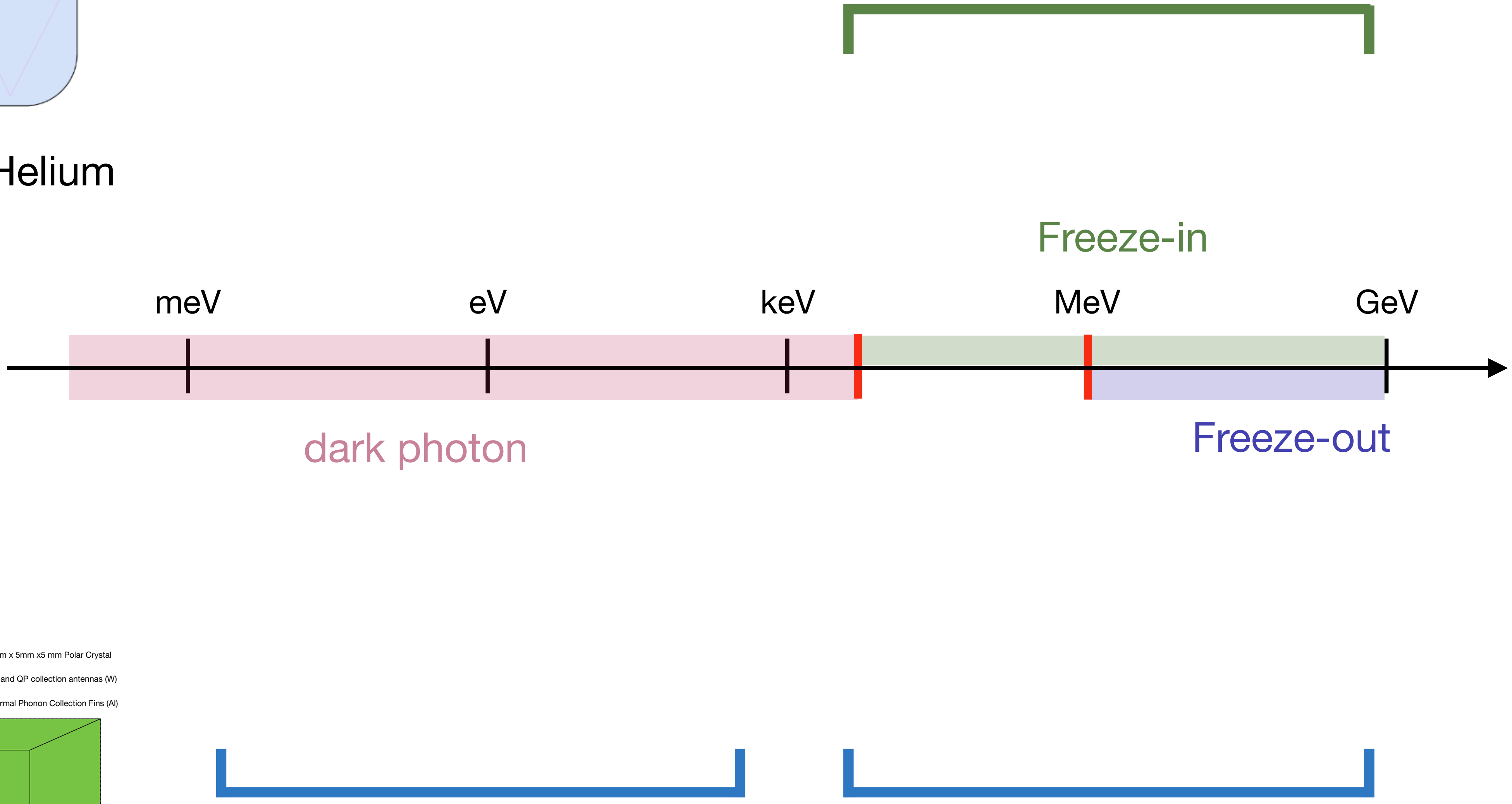
A. Cosuner, D. Grabowska, SK, K. Zurek: ongoing

Summary

Low threshold detectors can access a wide range of models and dark matter masses



Superfluid Helium



scalar mediator

Freeze-in

meV

eV

keV

MeV

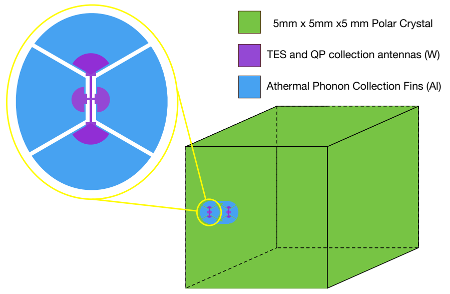
GeV

dark photon

Freeze-out

dark photon absorption

dark photon mediator
& scalar mediator



Polar materials → has daily modulation