Exploring the low mass frontier in dark matter direct detection

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KICP Particle Cosmo Workshop
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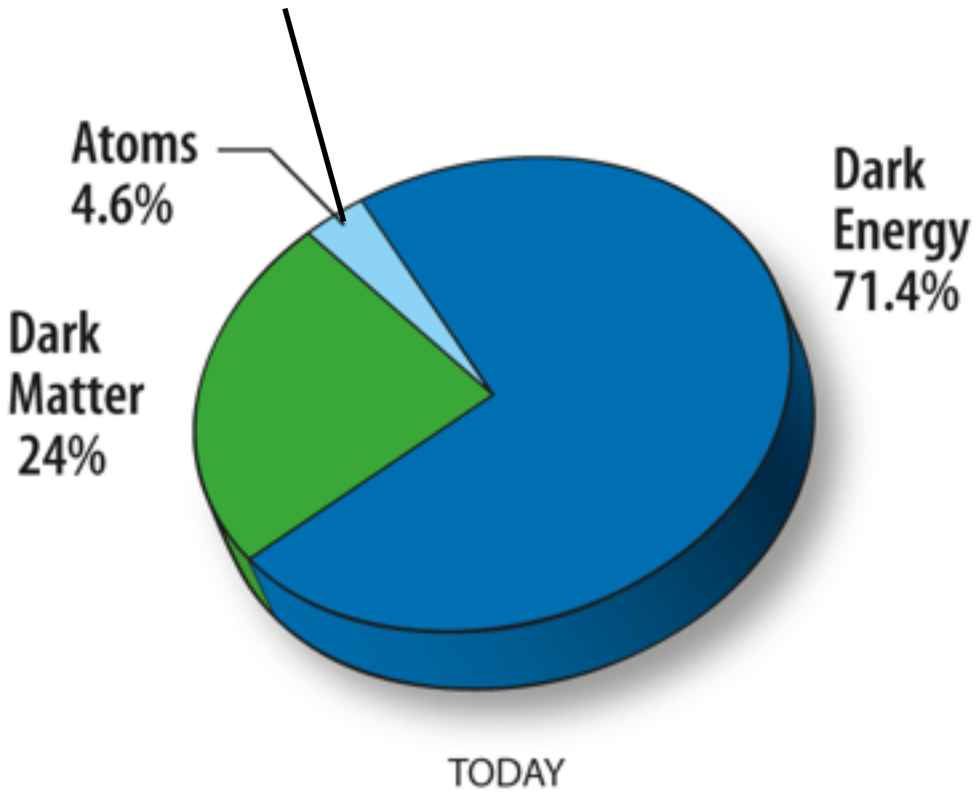
Outline

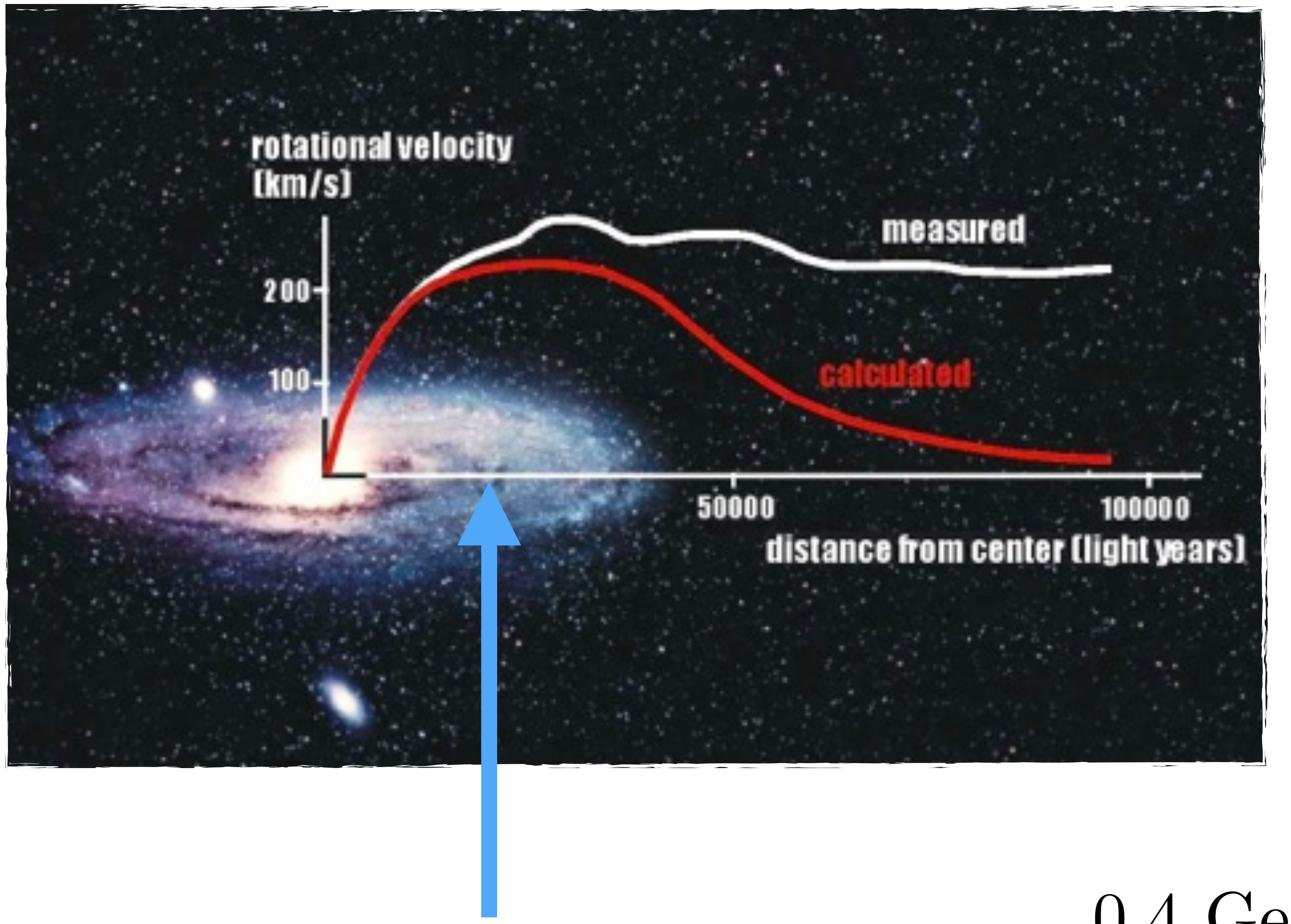
1. Why light dark matter?
2. Direct detection of light dark matter
3. Low-threshold targets for M=meV-MeV

   a. absorption in semi/super-conductors
   b. scattering in liquid helium

Dark matter puzzles

Standard Model





Solar neighborhood: $\rho_\chi \approx \frac{0.4\ \mathrm{GeV}}{\mathrm{cm}^3}$

Some new particle physics is needed

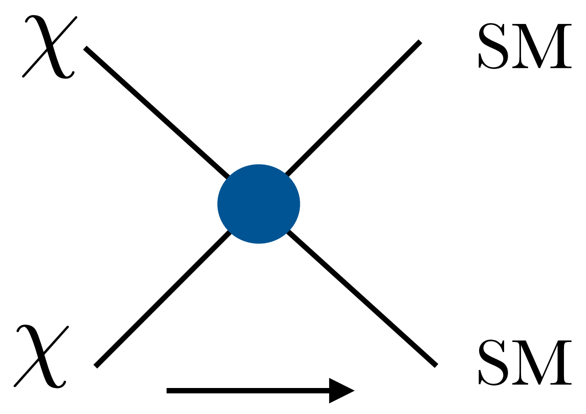
Directions

- Standard Model has other unresolved questions -
  use as a guide for dark matter.

- Look more broadly for a dark sector. Generically, this would be as rich as the Standard Model.

WIMP dark matter

WIMP (Weakly Interacting Massive Particle)



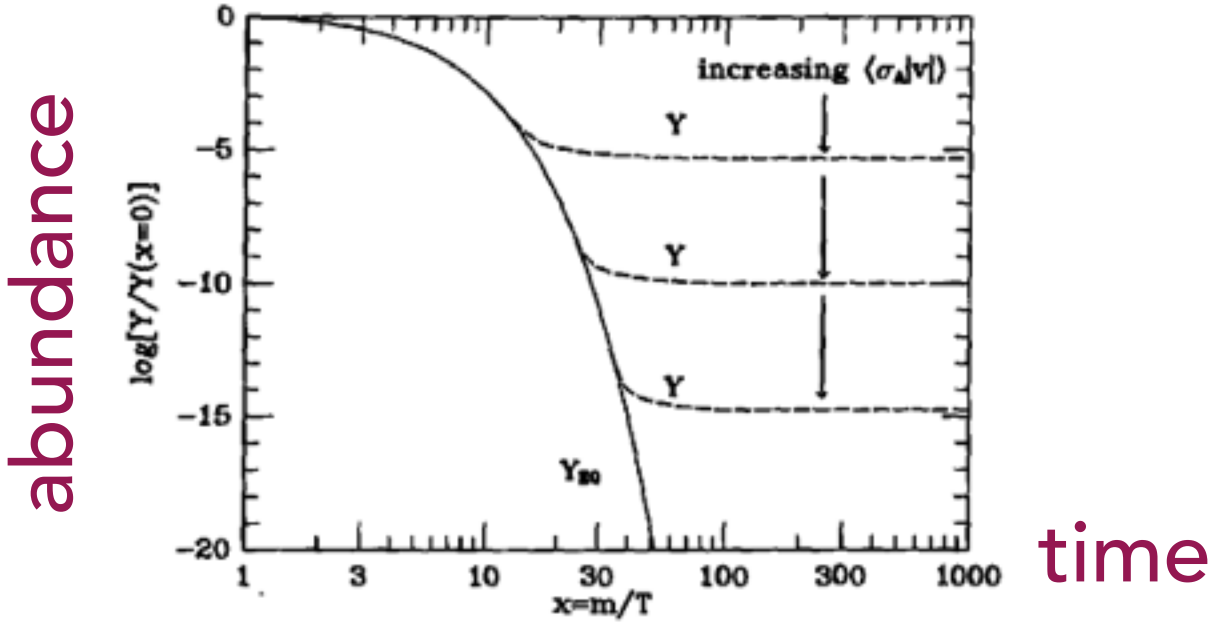


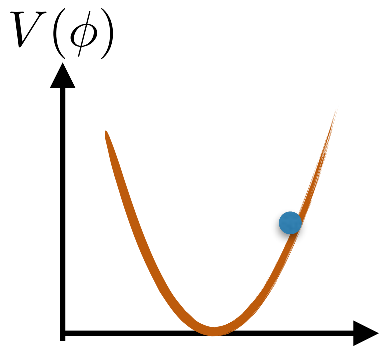
Fig. 5.1: The freeze out of a massive particle species. The dashed line is the actual abundance, and the solid line is the equilibrium abundance. Kolb & Turner

Relic abundance of dark matter today set by weak-scale interactions in the early universe

M = 10 GeV - 10 TeV ?

Mass scale of dark matter?

Light bosonic DM



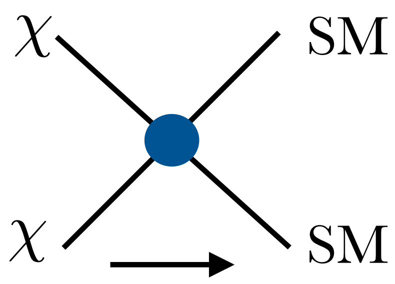
coherent light boson searches
(e.g. ADMX, CASPEr)

Many recent theory ideas

+

Many proposals for **detection**

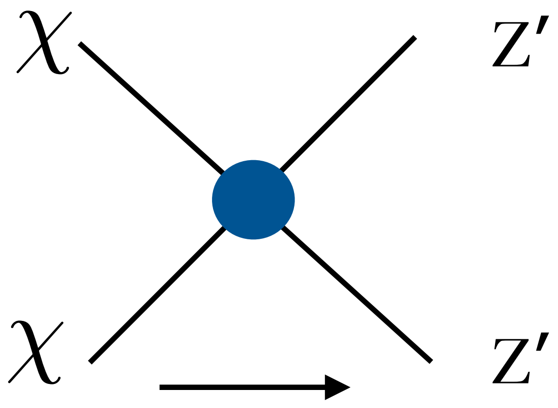
WIMP



Nuclear recoil in direct detection

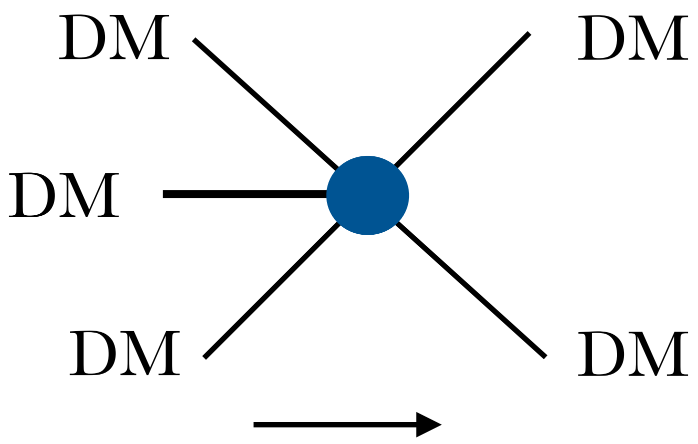
sub-GeV dark matter

light mediators



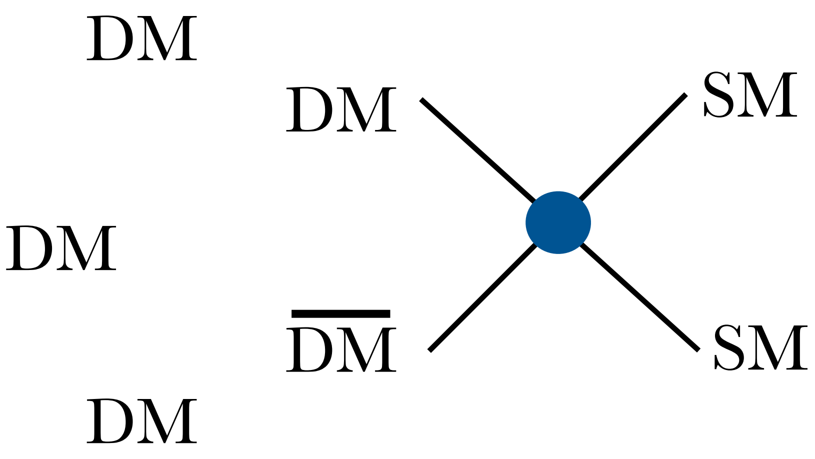
e.g. Fayet, Pospelov et al. 2007

3 to 2 annihilation, SIMPs



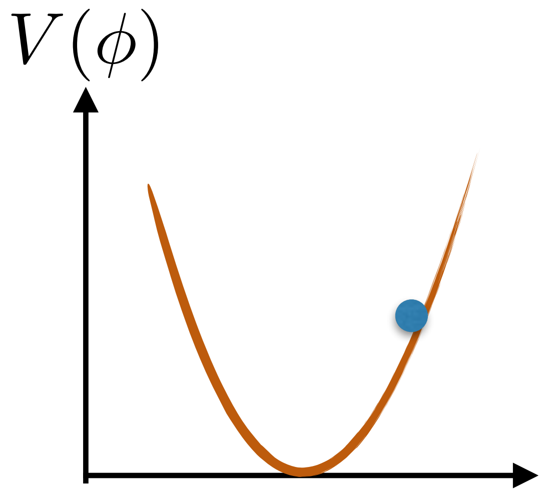
Hochberg et al. 2014, 2015

asymmetric



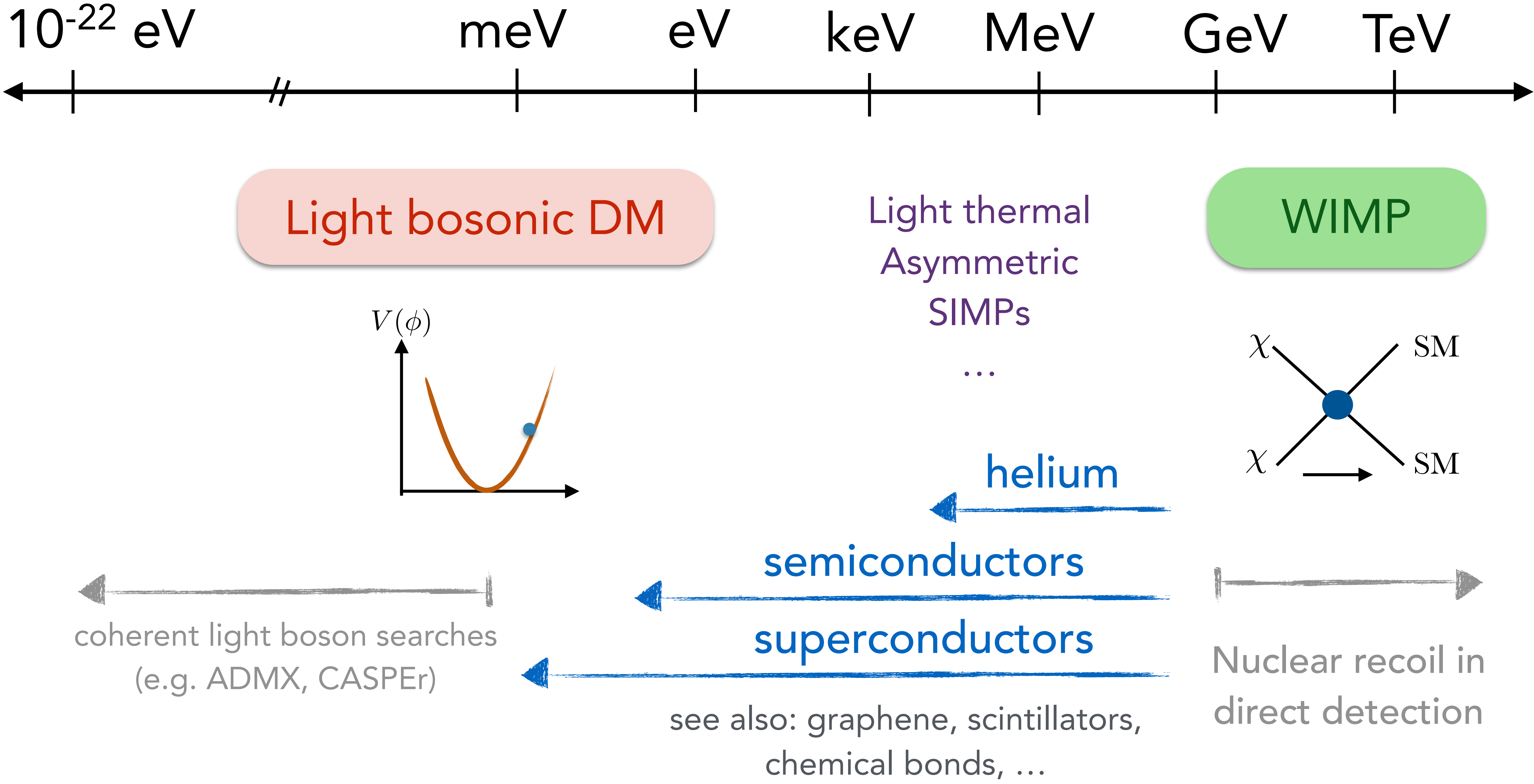
e.g. Nussinov, Barr, Kaplan et al.

sub-keV non-thermal



e.g. Pospelov et al. 2008, Arias et al. 2012

Mass scale of dark matter?



Light bosonic DM

Light thermal
Asymmetric
SIMPs
…

WIMP

helium

semiconductors

superconductors

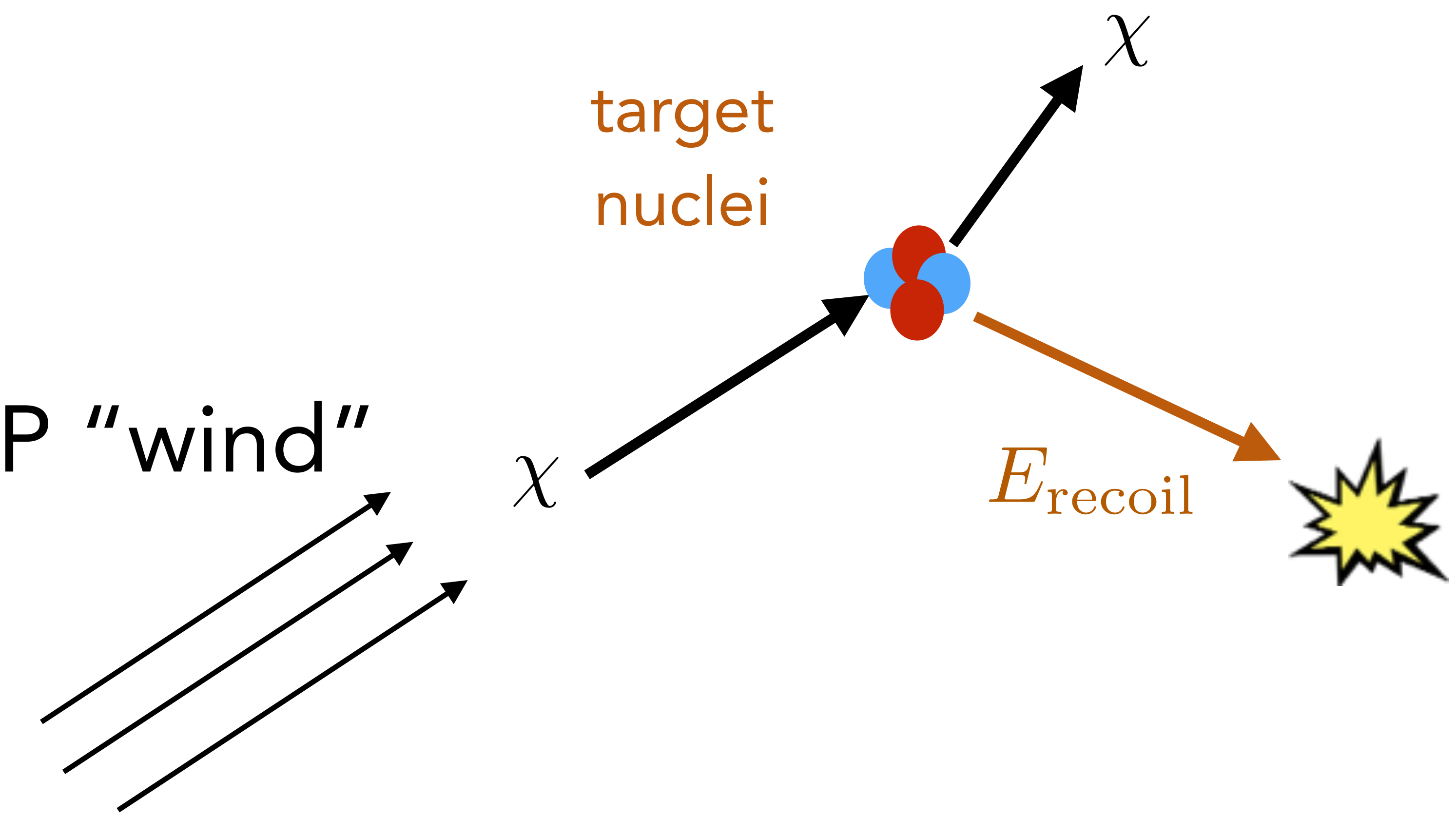
coherent light boson searches
(e.g. ADMX, CASPEr)

Nuclear recoil in
direct detection

see also: graphene, scintillators,
chemical bonds, …

2. Direct detection of light dark matter

Direct detection of WIMPs



target nuclei

χ

WIMP "wind"

χ

E_{recoil}

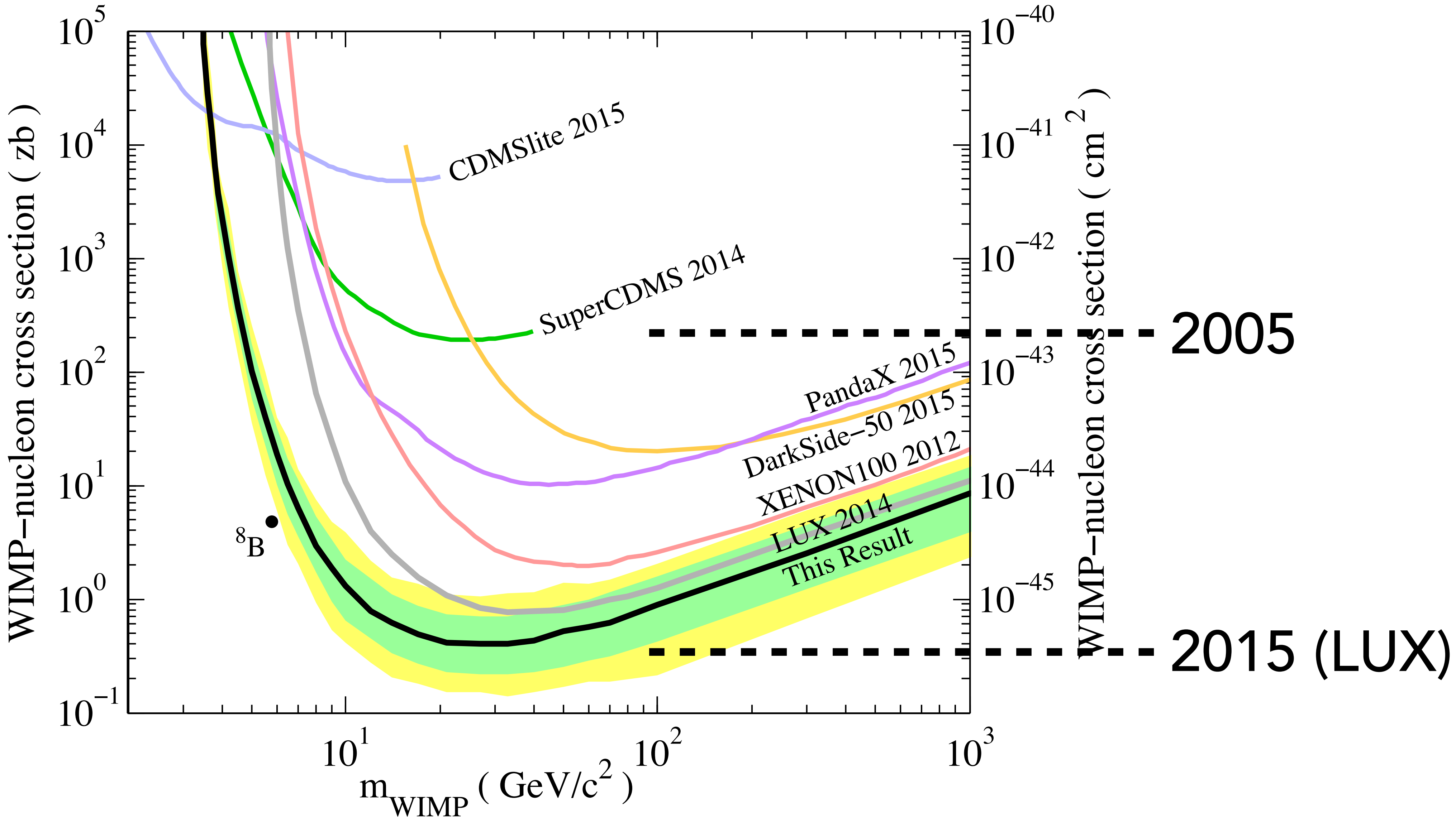
Heat (phonons),
ionization, scintillation
from recoiling nucleus

Energy deposited from WIMP in nuclear recoil:

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

Typical dark matter velocity $v \sim 10^{-3}$

Direct detection of WIMPs

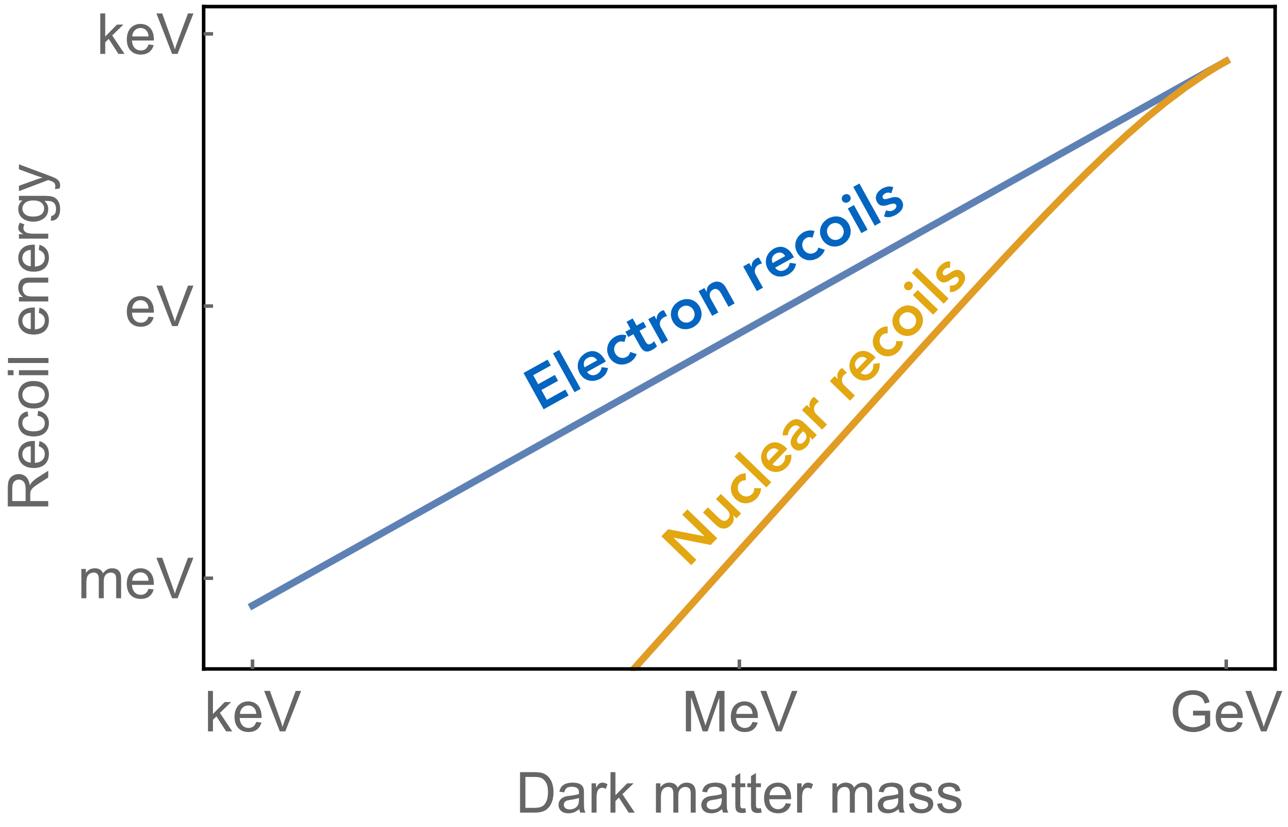


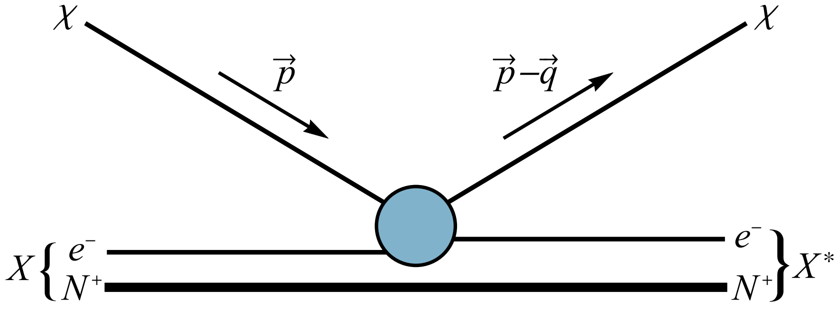
2005

2015 (LUX)

Typical threshold in experiment: > 1 keV recoil energy

Detecting light dark matter





Look for electron recoils

- Below ~ 1 GeV, inefficient energy transfer to nuclei.
- Idea applied in: Xenon, semiconductors…

Essig, Mardon, Volansky 2011
Essig et al. 2012, Graham et al. 2012

Electron recoils

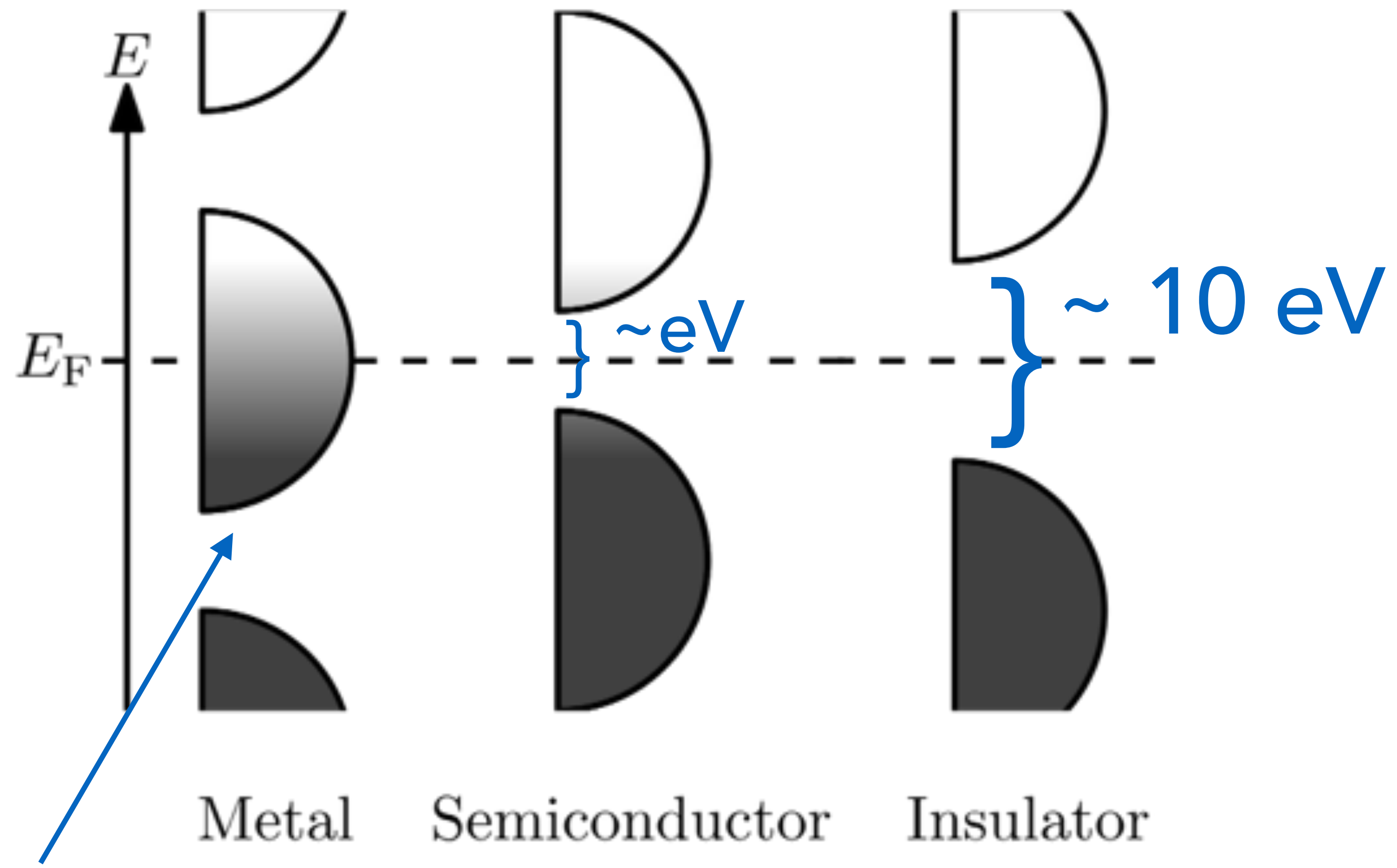
- Electron interactions already constrained with Xenon10 low-threshold analysis, search for DM ionization signal

$$E_{th} \sim 12 \text{ eV}$$

Essig et al. 2012

Electron recoils

Electronic band structure



~ meV gap in superconductor

Al

Ge, Si

(Xe)

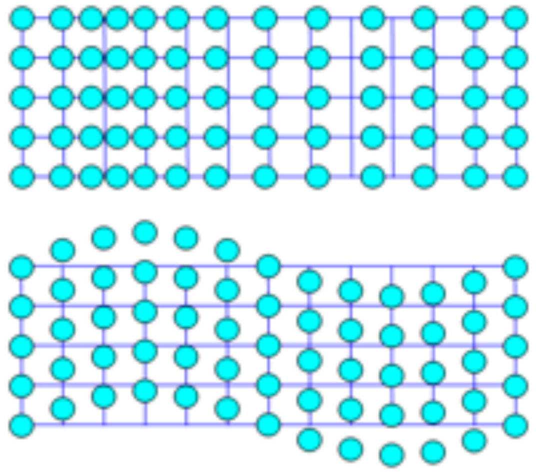
Gapless excitations

Long wavelength acoustic phonons have linear dispersion:

speed of sound

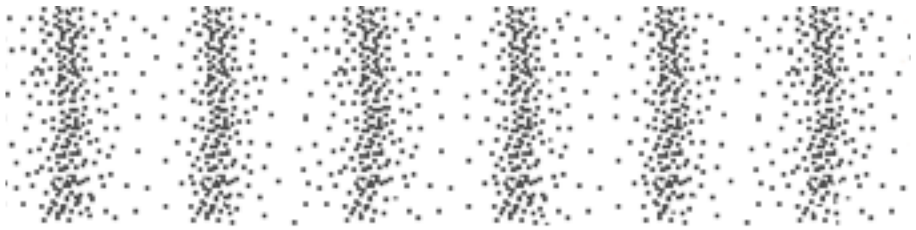
$$\Omega = c_s|\vec{Q}|$$

- Lattice vibrations in a solid



$c_s \sim 10^{-5}$ in aluminum

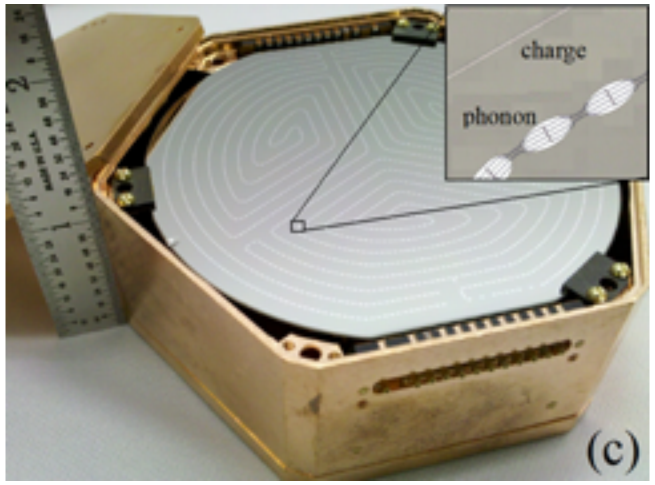
- Density perturbations in a liquid



$c_s \sim 10^{-6}$ in helium

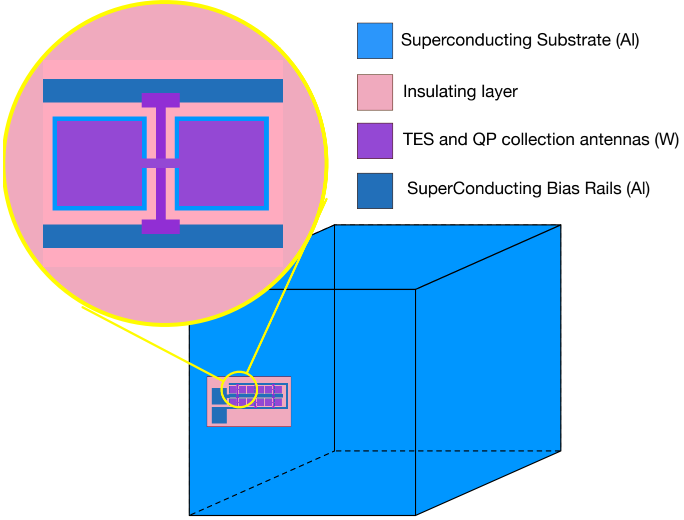
Low-threshold targets

Semiconductors



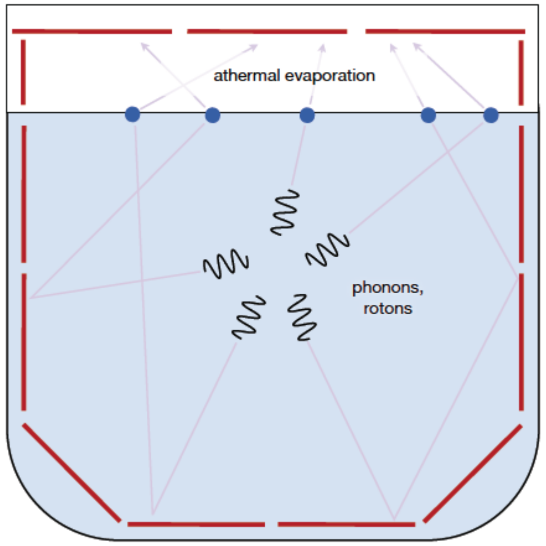
- **E_{th} ~ eV, electron+phonon**
- Reach MeV DM (scattering)
- Used in DAMIC, SuperCDMS, …

Superconductors



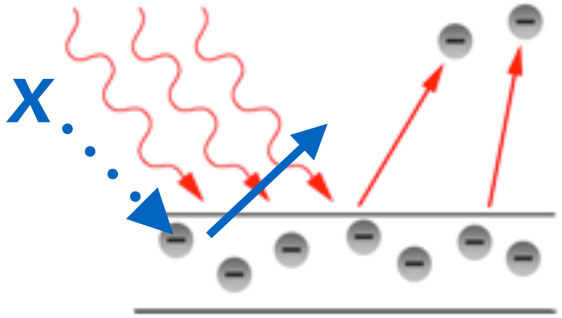
- **E_{th} ~ meV, electron+phonon**
- Reach keV DM (scattering)

Helium



- **E_{th} ~ meV, phonons**
- Reach keV DM (scattering)

3a. Absorption of light bosonic dark matter



with:

Yonit Hochberg

Kathryn Zurek

1604.06800, 1608.01994

sub-keV bosonic dark matter

- Candidates:
  - Hidden photon
  - Pseudoscalar (axion)
  - Scalar
- Coherent field below *m* ~ eV

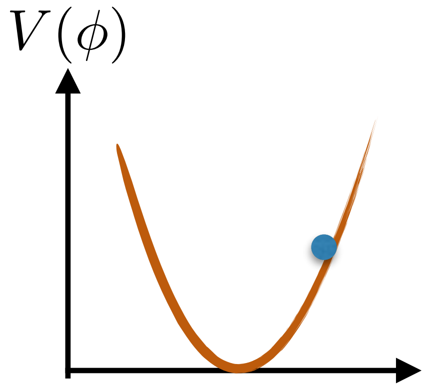
Local DM density: 0.4 GeV/cm^3 $\lambda_{\rm dB} \sim \frac{2\pi}{m_{\rm DM} v}$ $v \sim 10^{-3}$

Occupation number is high: $\frac{\rho_{\rm DM}}{m_{\rm DM}} \gg \lambda_{\rm dB}^{-3}$

- Non-thermal relic abundance, e.g. ``misalignment”

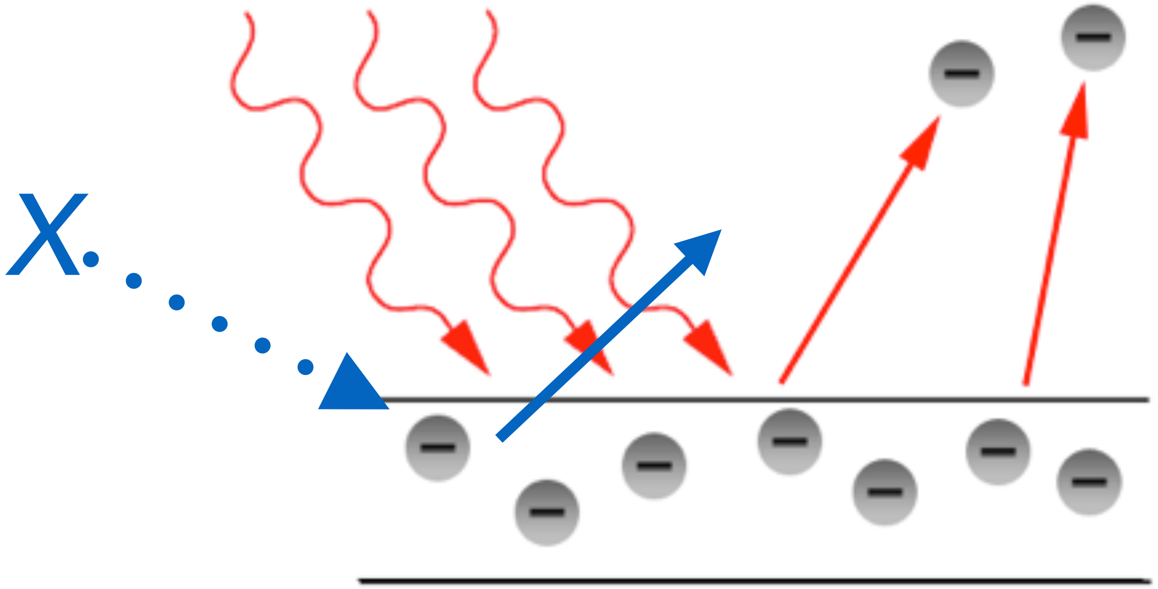
$$\rho_{\rm DM} = \frac{1}{2} m_{\rm DM}^2 \phi_0^2$$

ϕ_0 — field amplitude today



Absorption

Photoelectric effect:



absorb all of the energy of incoming dark matter

Absorption from halo

- mono-energetic
- doesn't require coherent field

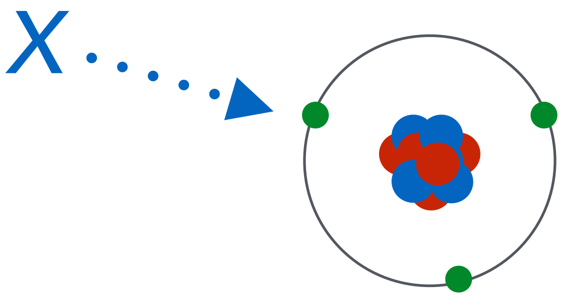
Solar emission

- ~keV energies
- ``axio-electric" effect

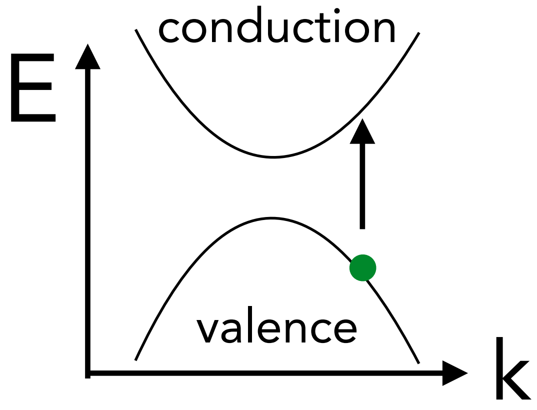
Dimopoulos, Starkman, Lynn 1986
Pospelov, Ritz, Voloshin 2008

DM absorption in materials

Typical electron in material has k ~ keV.
Need momentum transfer q ~ 100 m_X in absorption.



- **Atomic ionization**
  - Ex: Xenon, ionization energy = 12 eV



- **Absorption on a crystal/solid**
  - Rely on band structure
  - Phonon emission

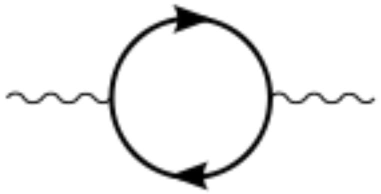
Relate the DM absorption rate to **photon** absorption rate:

$$\langle n_e \sigma_{\rm abs} v \rangle_{\rm DM} \propto \langle n_e \sigma_{\rm abs} v \rangle_\gamma = \sigma_1 \longleftarrow$$

(photon absorption,
conductivity **σ**)

Conductivity

- Polarization tensor in medium:



$$\Pi^{\mu\nu} = e^2 \langle J^{\mu\dagger}_{\rm EM}, J^{\nu}_{\rm EM} \rangle \qquad \Pi^{\mu\nu}(\vec{q},\omega) = \Pi(\omega) \sum_{i=1,2} \epsilon^{T\mu}_i \epsilon^{T*\nu}_i + \Pi(\omega)\epsilon^{L\mu}\epsilon^{L\nu}$$

- Related to optical conductivity

$$\vec{J} = \hat{\sigma}\vec{E} \qquad \Pi(\omega) \approx -i\hat{\sigma}\omega$$

↑
Conductivity

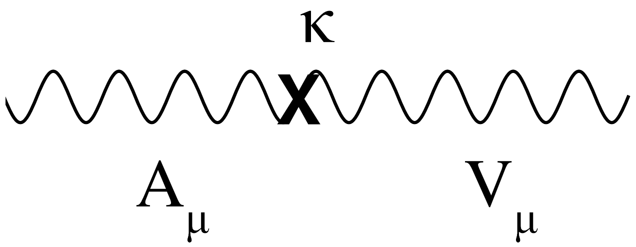
Real part gives effective mass , imaginary part gives absorption:

$$\text{Re } \Pi(\omega) \approx \omega_p^2 = \sigma_2 \omega \qquad -\frac{\text{Im } \Pi(\omega)}{\omega} = \sigma_1 = \langle n_e \sigma_{\rm abs} v \rangle_\gamma$$

Hidden photon dark matter

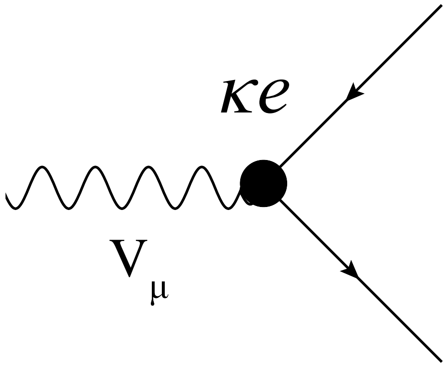
Kinetic mixing in vacuum:

$$\mathcal{L} \supset -\frac{\kappa}{2} F_{\mu\nu} V^{\mu\nu}$$



Matter coupling:

$$A_\mu \to A_\mu - \kappa V_\mu \longrightarrow \kappa e V_\mu J^\mu_{\rm EM}$$



Absorption rate of halo DM

$$\boxed{R = \frac{1}{\rho} \frac{\rho_{\rm DM}}{m_{\rm DM}} \kappa^2_{\rm eff} \sigma_1}$$

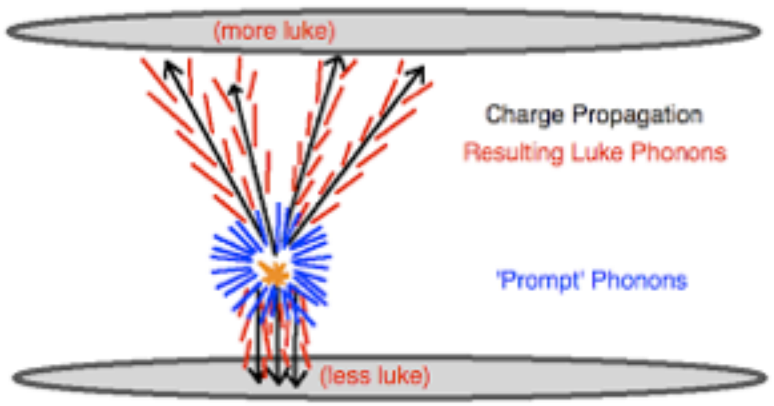
photon absorption (conductivity **σ**)

effective kinetic mixing in a material

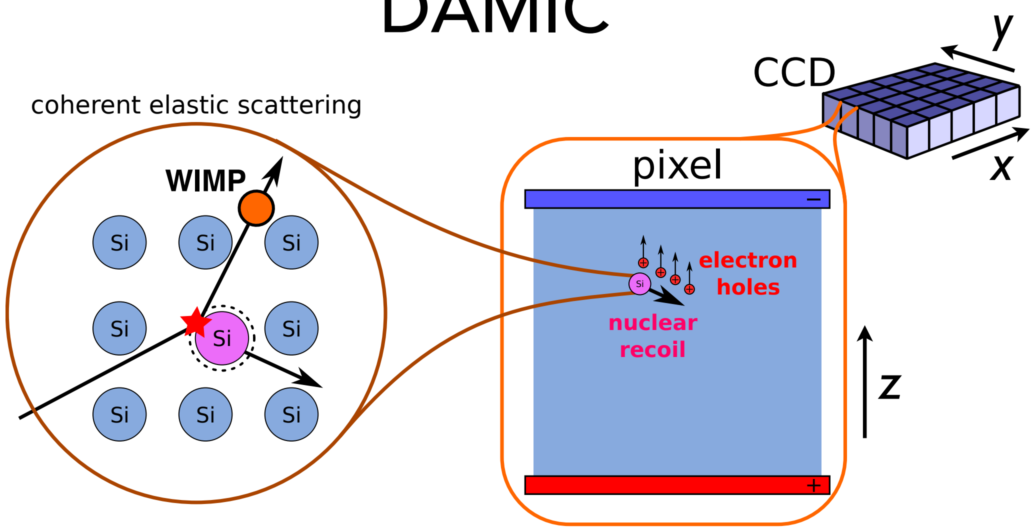
$$\kappa^2_{\rm eff} = \frac{\kappa^2 m_V^4}{\left[m_V^2 - {\rm Re}\,\Pi(\omega)\right]^2 + \left[{\rm Im}\,\Pi(\omega)\right]^2}$$

Semiconductor targets

SuperCDMS



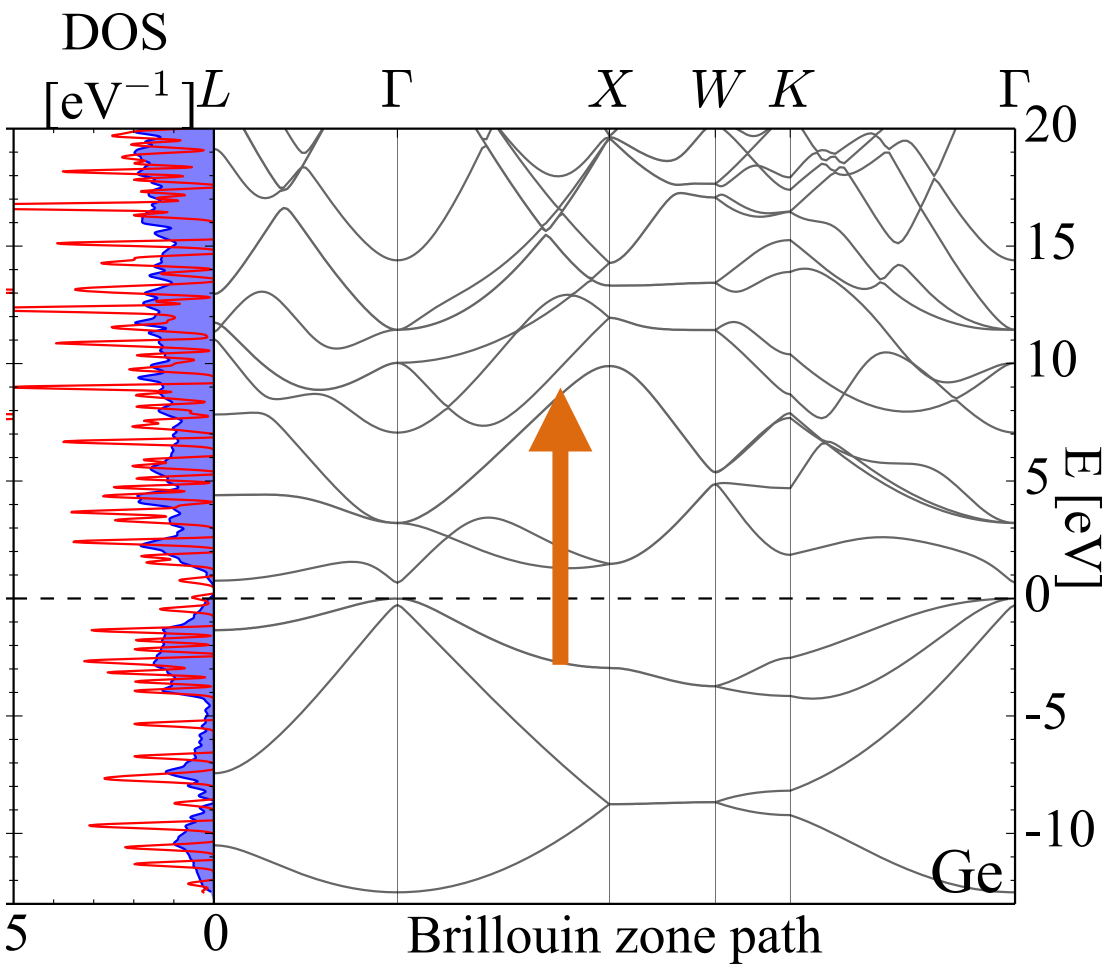
DAMIC



(b) WIMP detection in a CCD

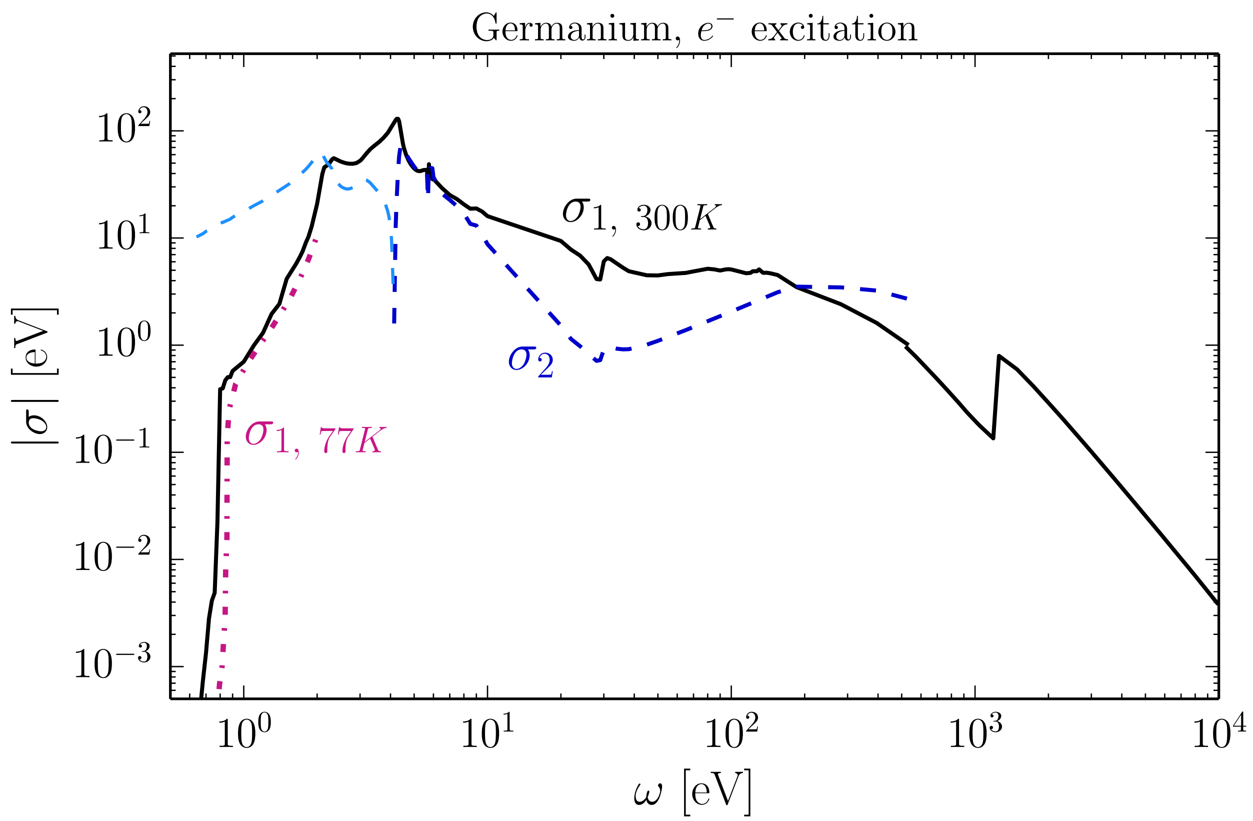
- Existing experiments already use Germanium, Silicon targets.
- Current E_{th}~50 eV electron recoil.
- E_{th}~eV could be reached in the near future.

Electron excitations



From Essig et al. 2015

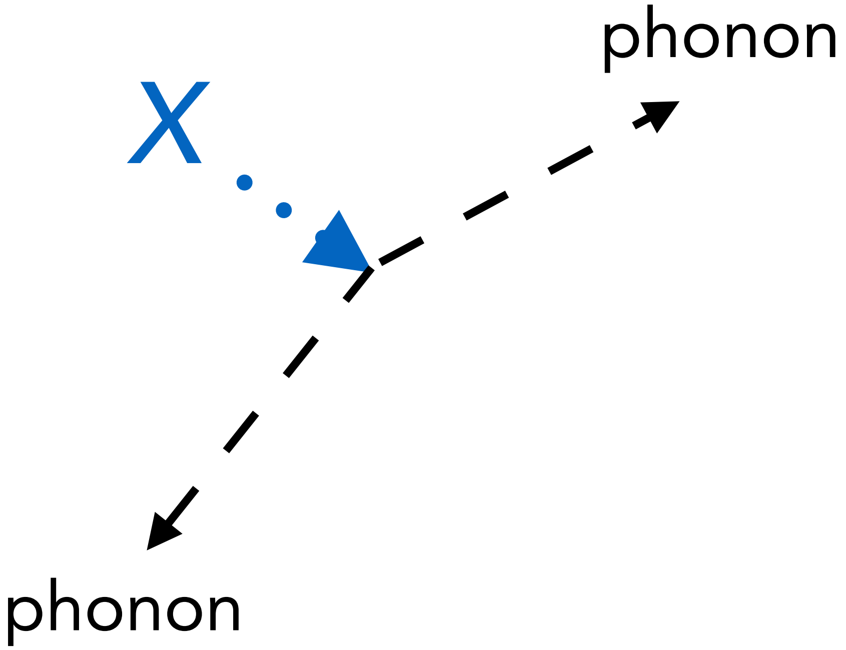
Photon absorption data



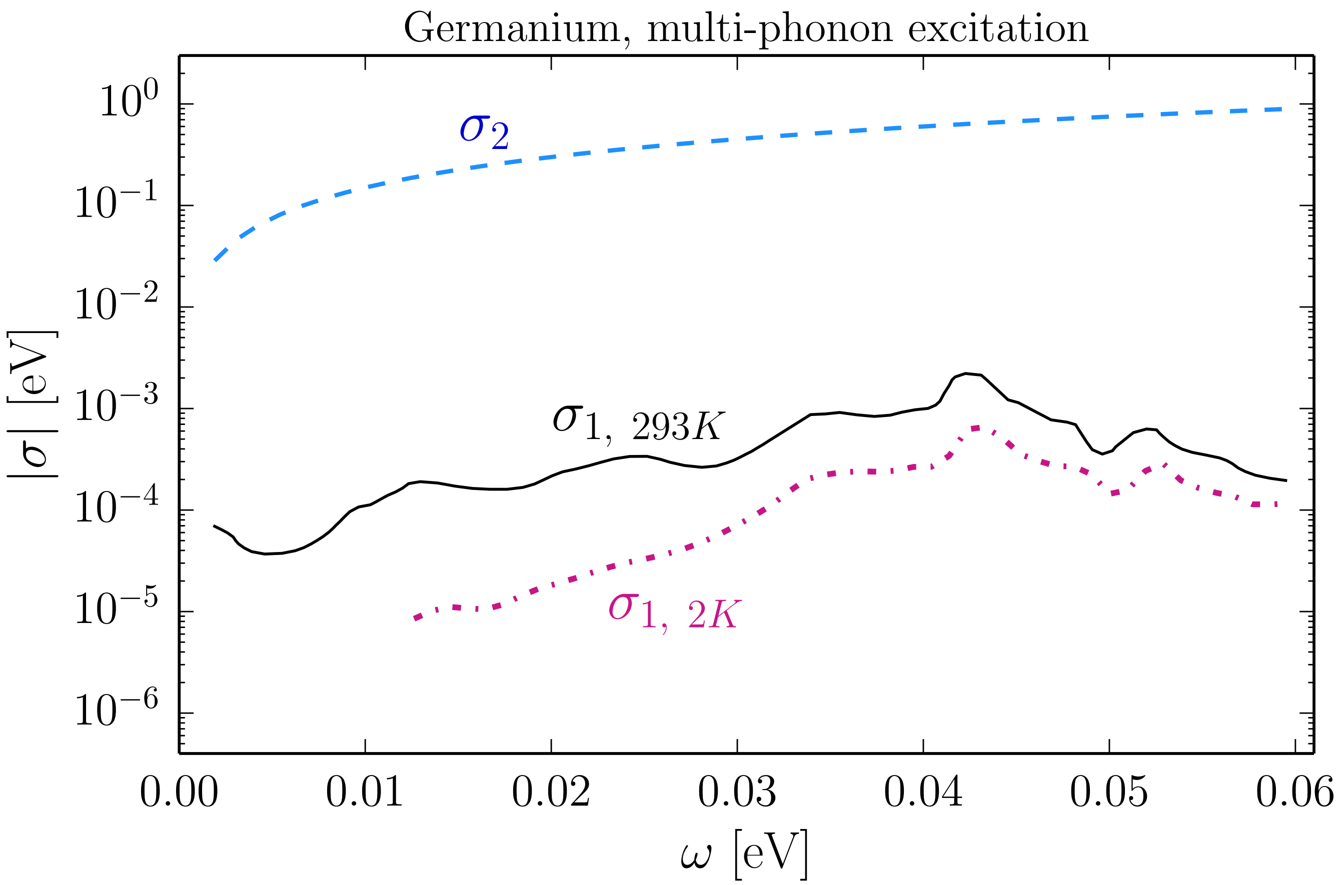
Optical absorption dominated by direct transitions

Band gap: 0.7 eV (germanium), 1.1 eV (silicon)

Multi-phonon excitation

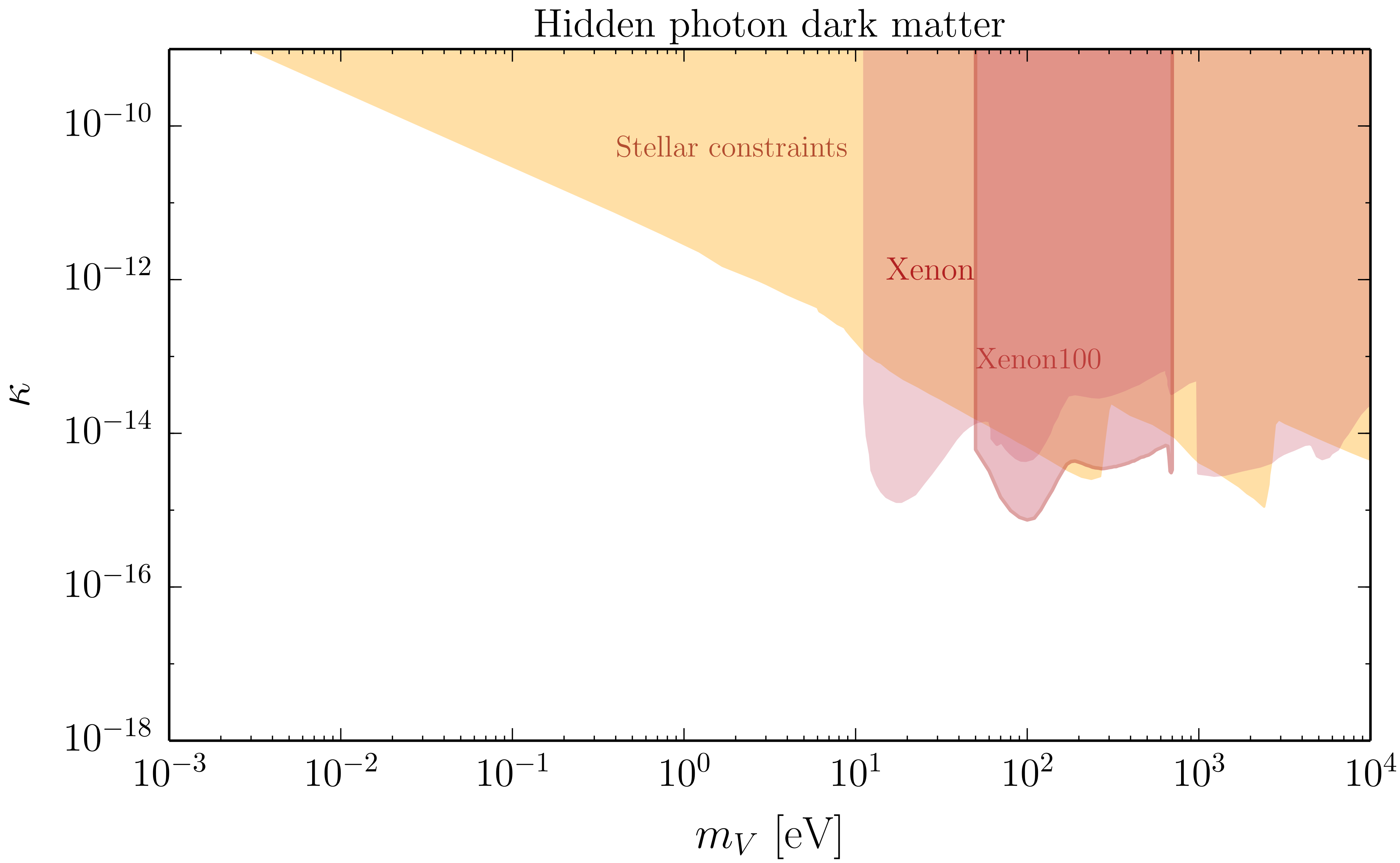


Photon absorption data



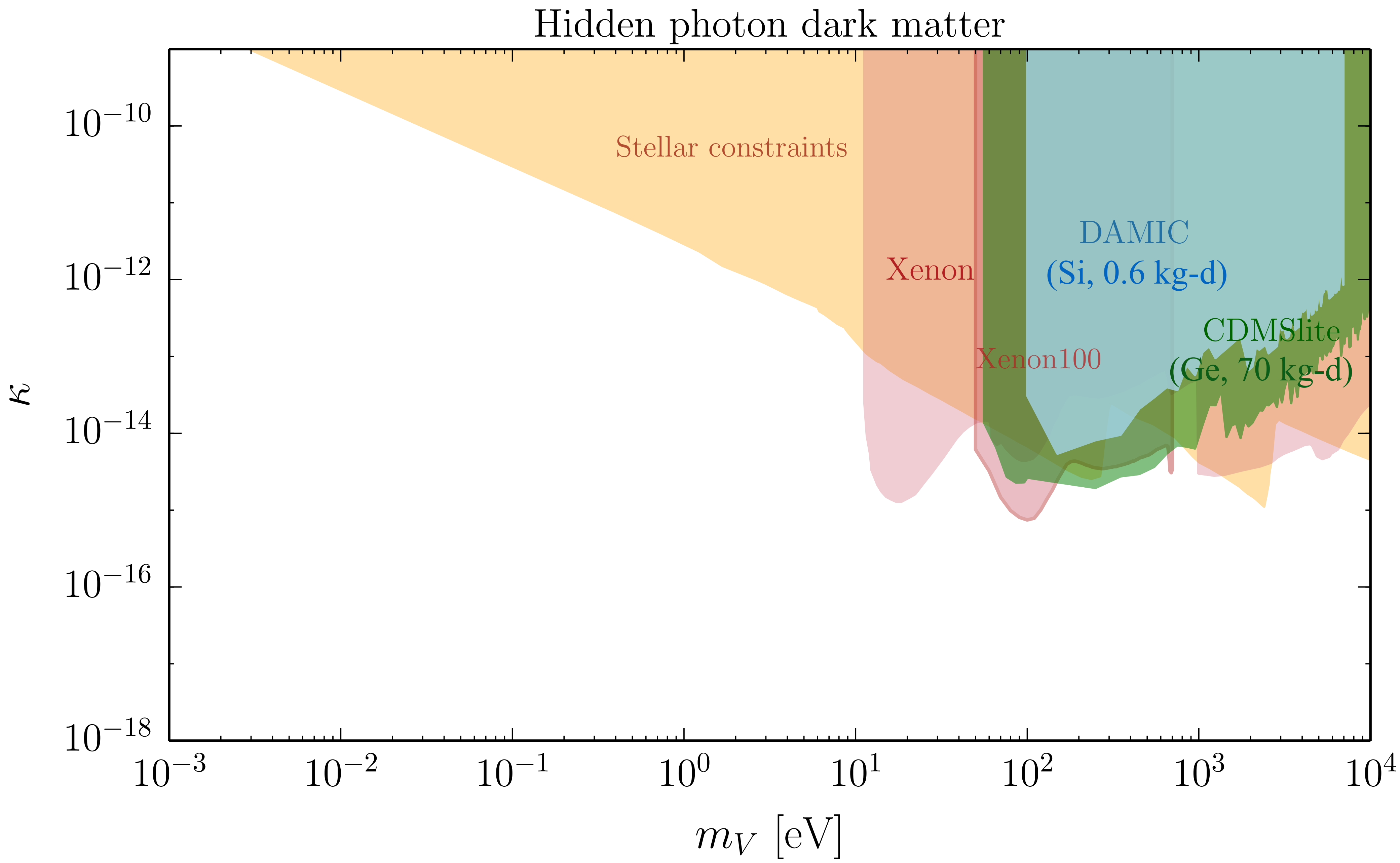
Optical absorption below the band gap is allowed if (multiple) phonons are excited instead!

Hidden photon DM



Stellar, Xenon10 constraints:
An, Pospelov, Pradler 2013, 2014
Redondo & Raffelt 2013

Hidden photon DM



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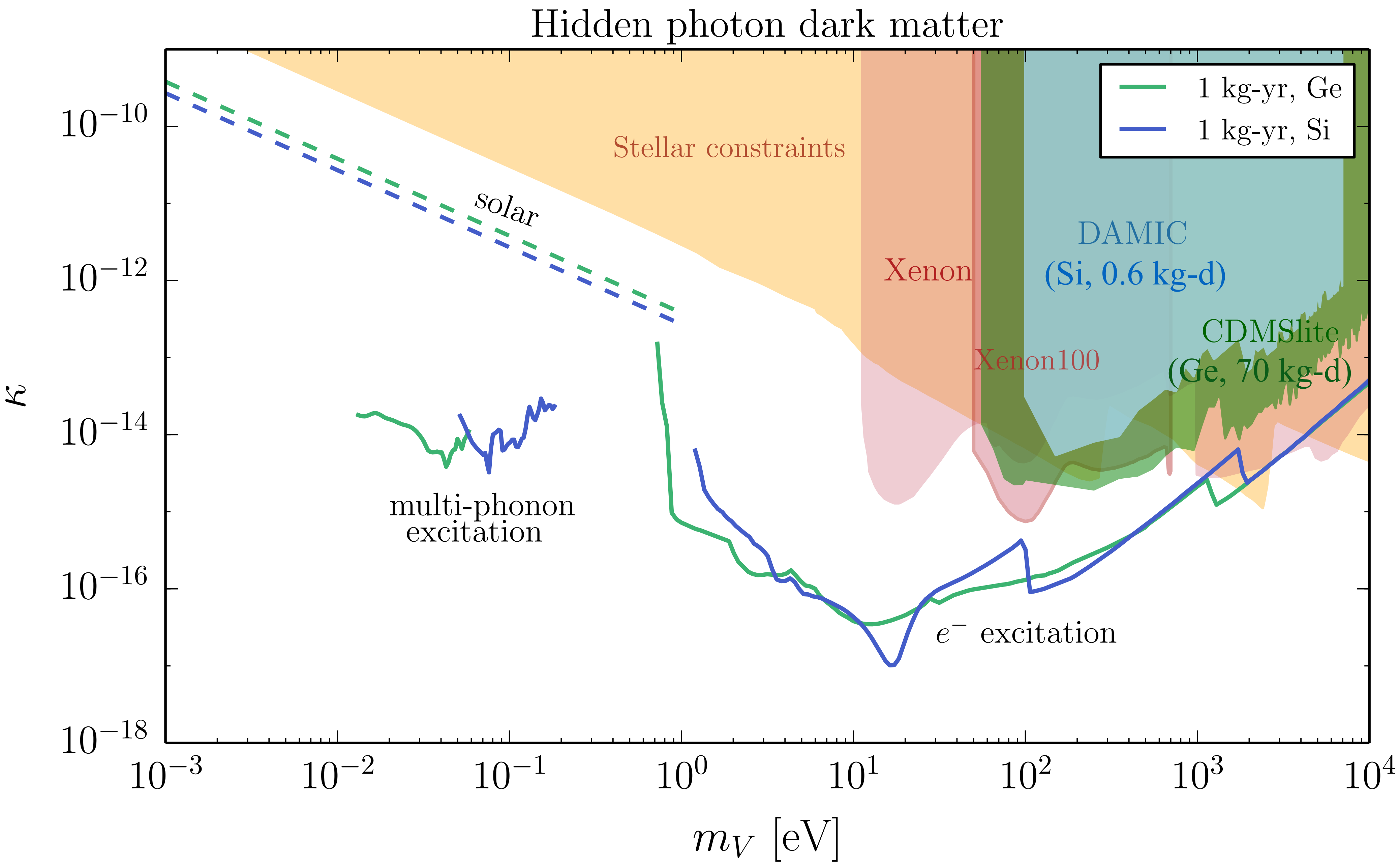


See also:
I. Bloch, Tien-Tien Yu, etc 2016
for similar study

Stellar, Xenon10 constraints:
An, Pospelov, Pradler 2013, 2014
Redondo & Raffelt 2013

Superconductor target

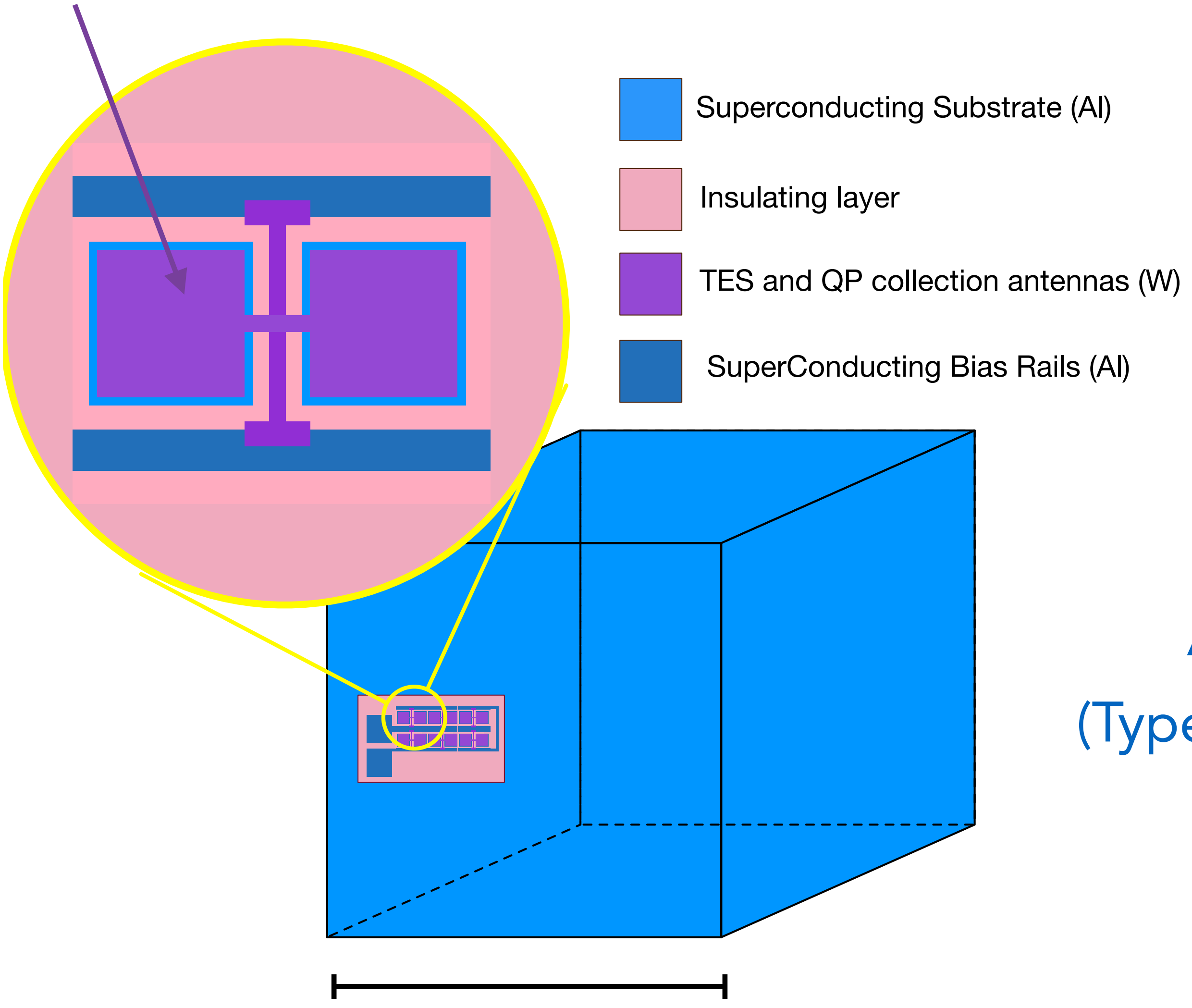
Measurement
by sensitive
bolometer (TES)

$$T = 10\,\mathrm{mK}$$

E_{th} ~ meV goal

- Must improve substantially on current energy resolution ~50-100 meV

- Noise is going to be an issue, backgrounds at low energies unknown.



5 mm

Aluminum

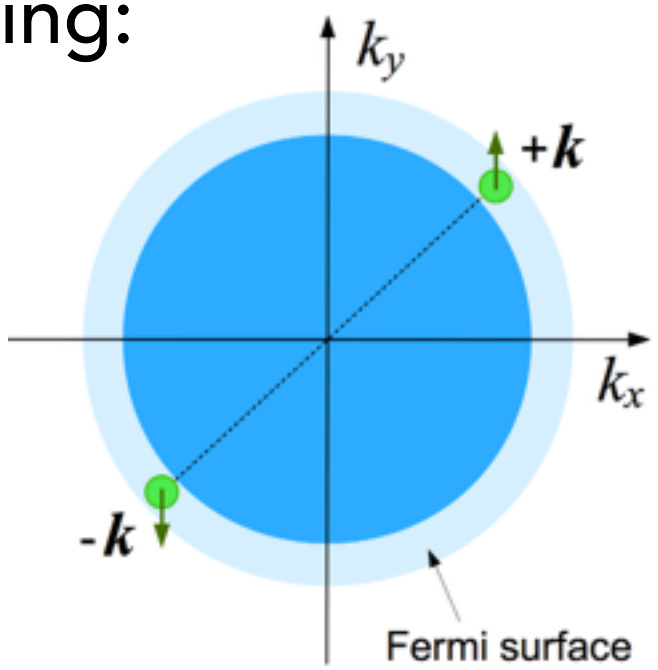
(Type I superconductor)

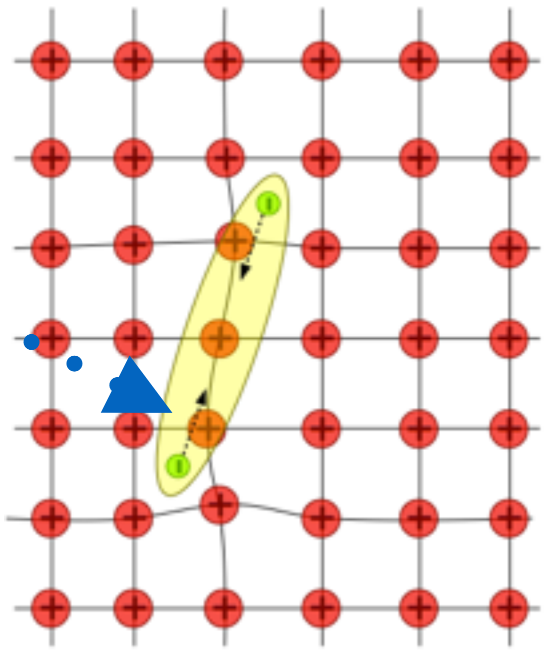
$$T_c = 1.2\ K$$

Hochberg, Zhao, and Zurek 2015
Hochberg, Pyle, Zhao, and Zurek 2015

Why superconductors?

Cooper pairing:



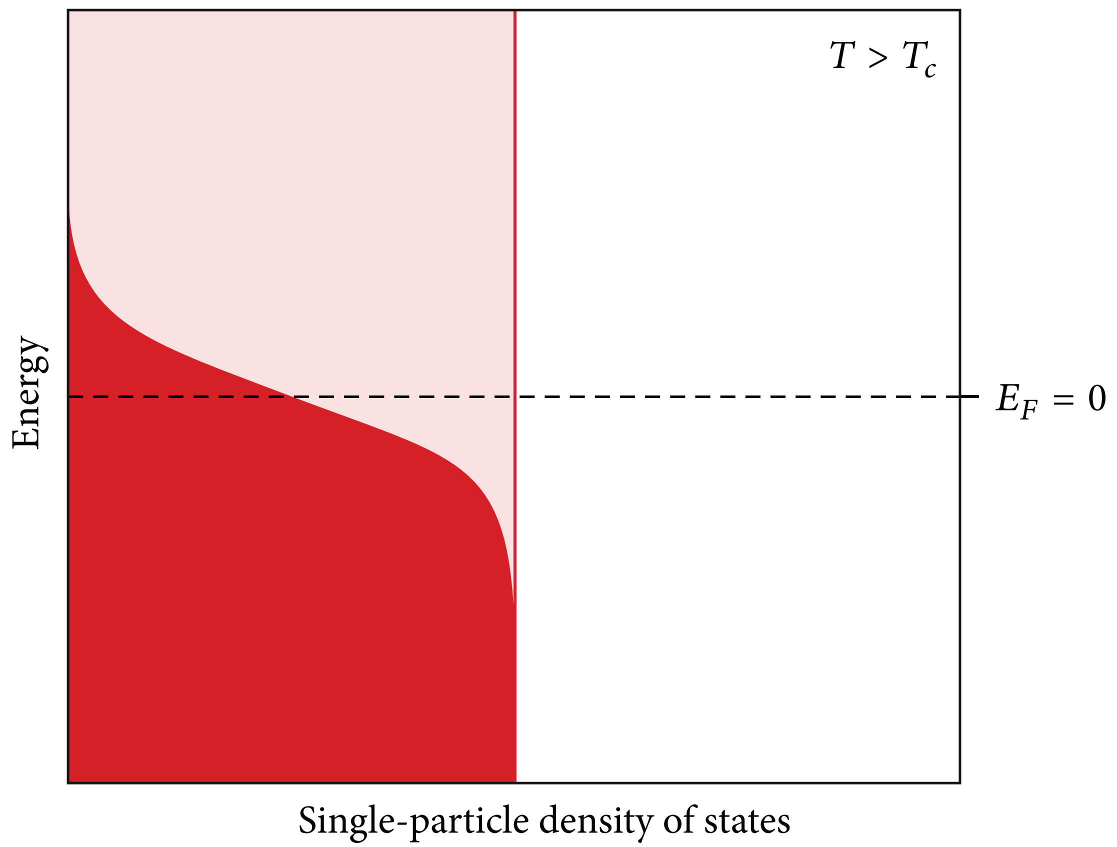


$$\Delta = \frac{3}{2}T_c \approx 0.3\,\mathrm{meV}$$

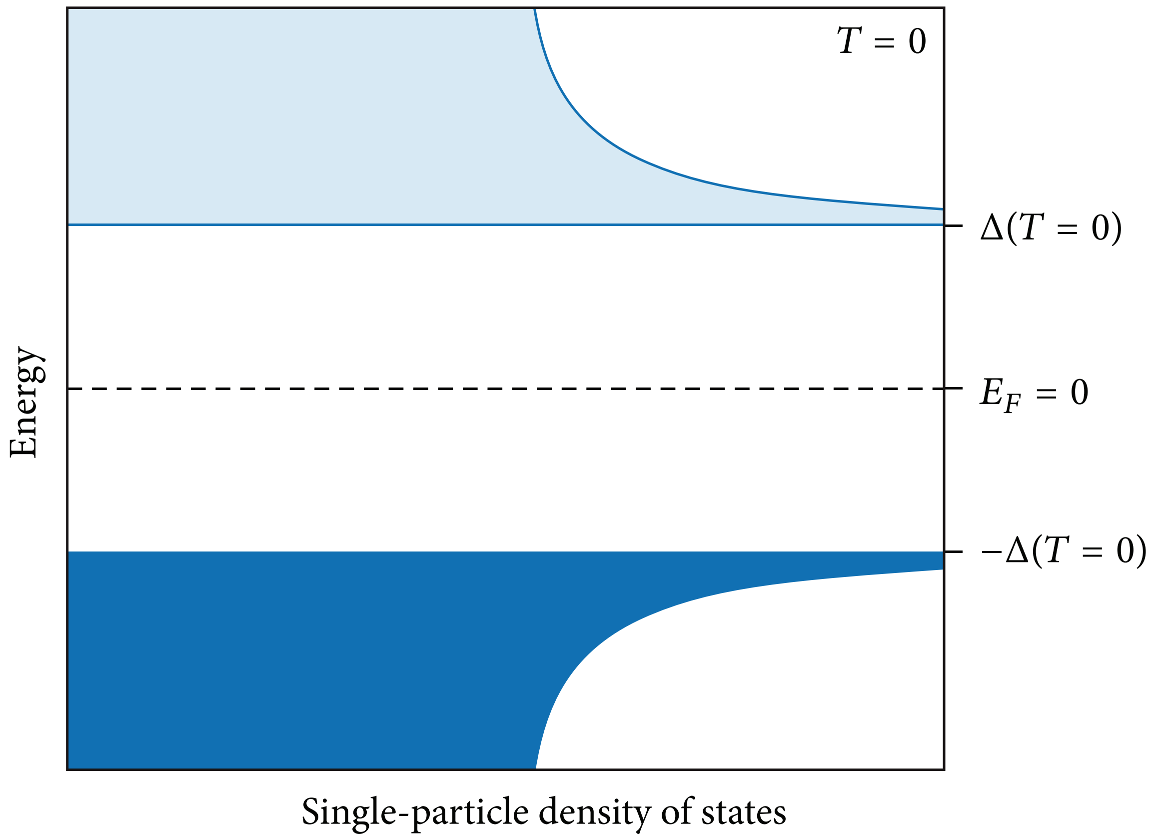
- Small band gap (< meV)
- Long-lived quasiparticle (electron) excitations
- Cooper pairs decoupled from thermal noise

Superconductors

$\Delta = \frac{3}{2} T_c \approx 0.3\,\mathrm{meV}$ in aluminum



Metal



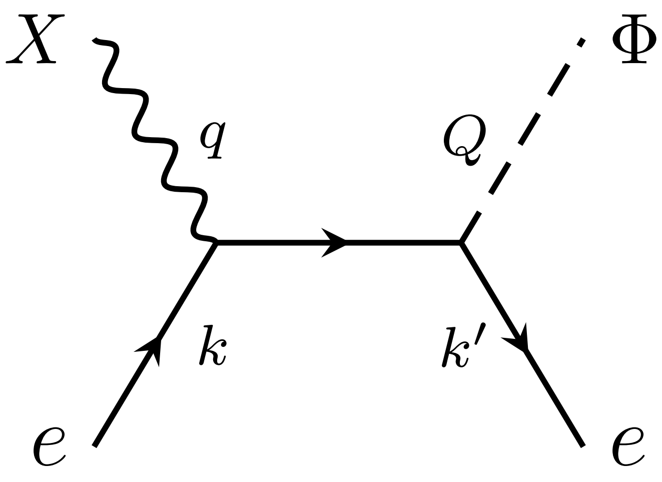
Superconductor

Because of gap, excitations (broken Cooper pairs) take a long time to recombine!

Absorption via phonon emission

Phonon energy:

$$\Omega = c_s|\vec{Q}|$$

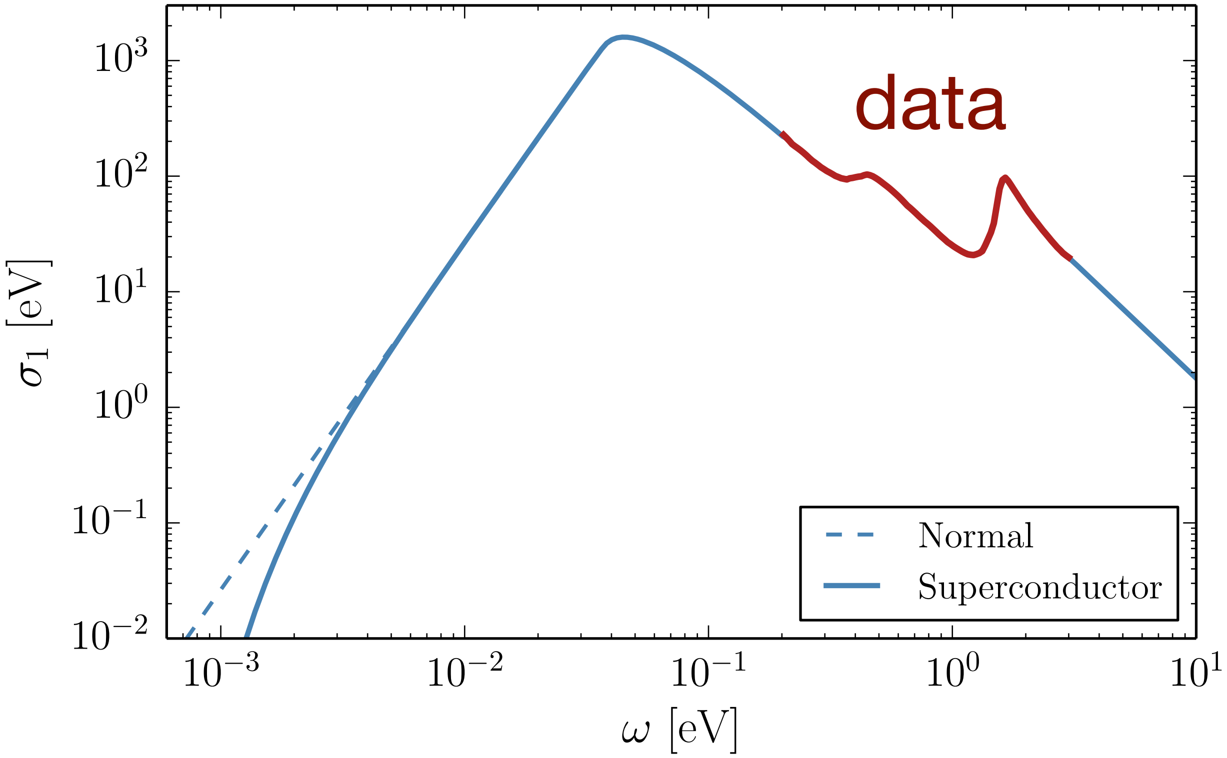


Speed of sound in aluminum:

$$c_s \simeq 6320\ \mathrm{m/s} \sim 2 \times 10^{-5}$$

The phonon can carry large momentum, with small energy.

Photon absorption rate



Energy

Theory uncertainties:

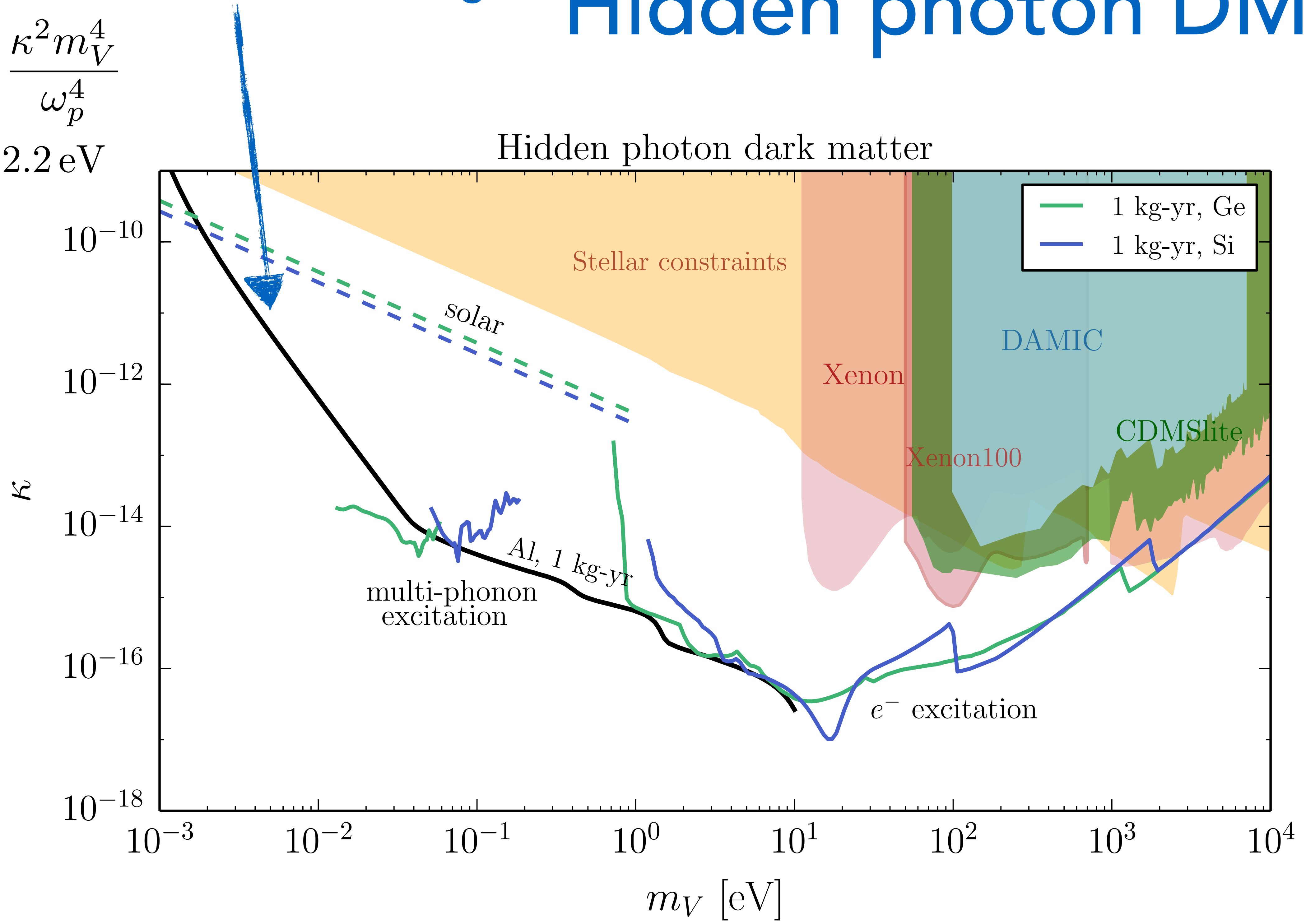
- phonon dispersion, coupling
- impurities

Suppression in absorption rate, reduced effective kinetic mixing

Hidden photon DM

$$\kappa_{\rm eff}^2 \simeq \frac{\kappa^2 m_V^4}{\omega_p^4}$$

$$\omega_p \approx 12.2\,{\rm eV}$$



Stellar, Xenon10 constraints:
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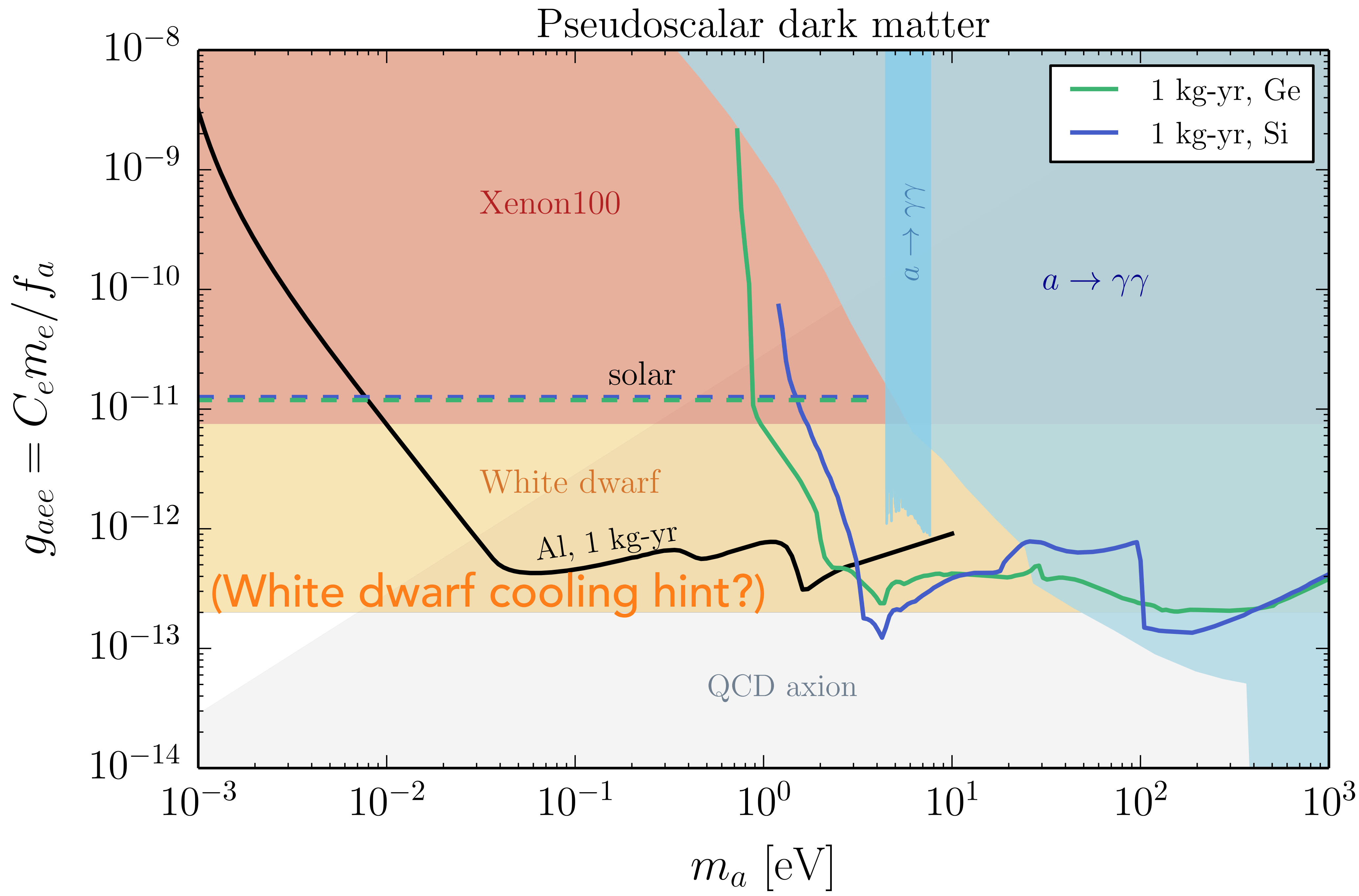
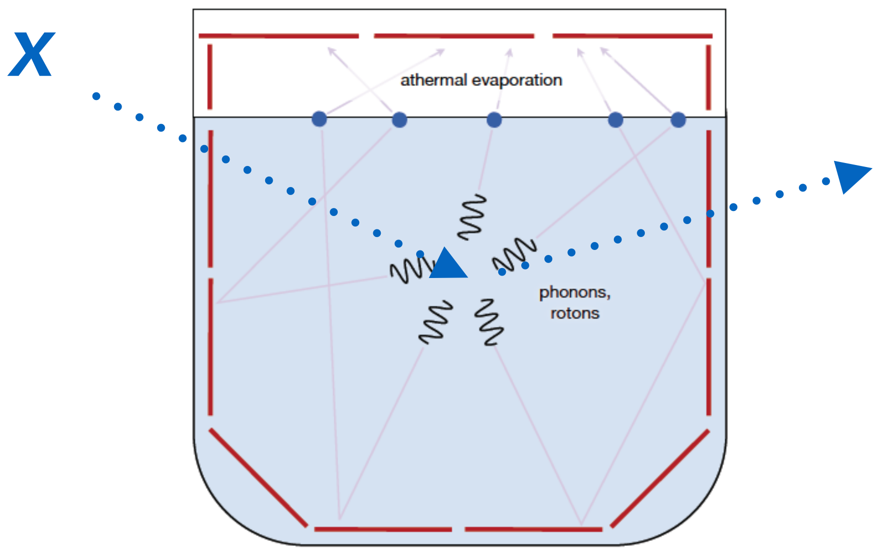
Redondo & Raffelt 2013

Pseudoscalar DM



(White dwarf cooling hint?)

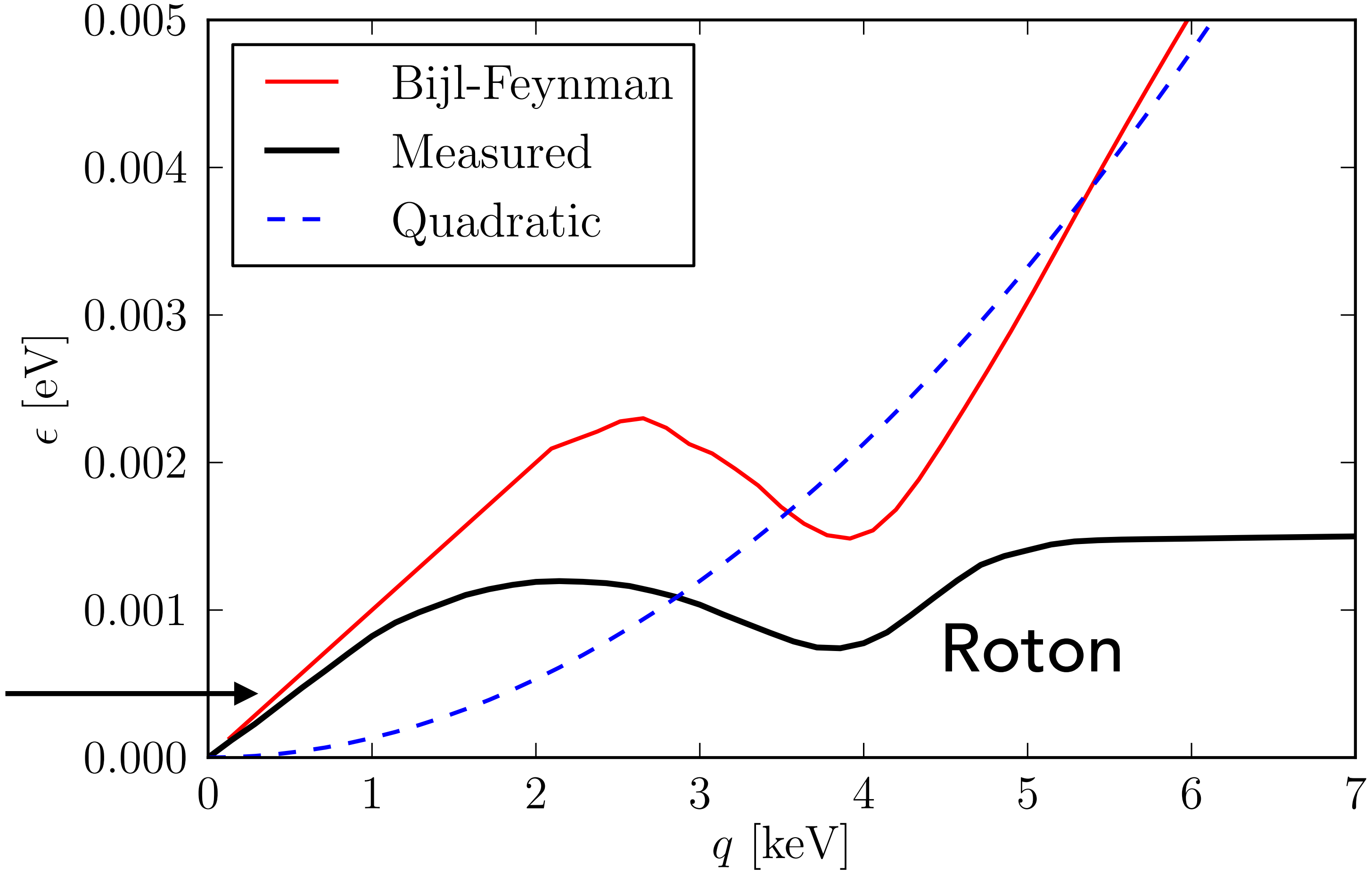
3b. DM scattering in superfluid He



in progress, with:
Simon Knapen
Eckhard Krotscheck
Kathryn Zurek

Why superfluid Helium?

- Long-lived quasiparticle excitations
- Potential detection of meV energy depositions

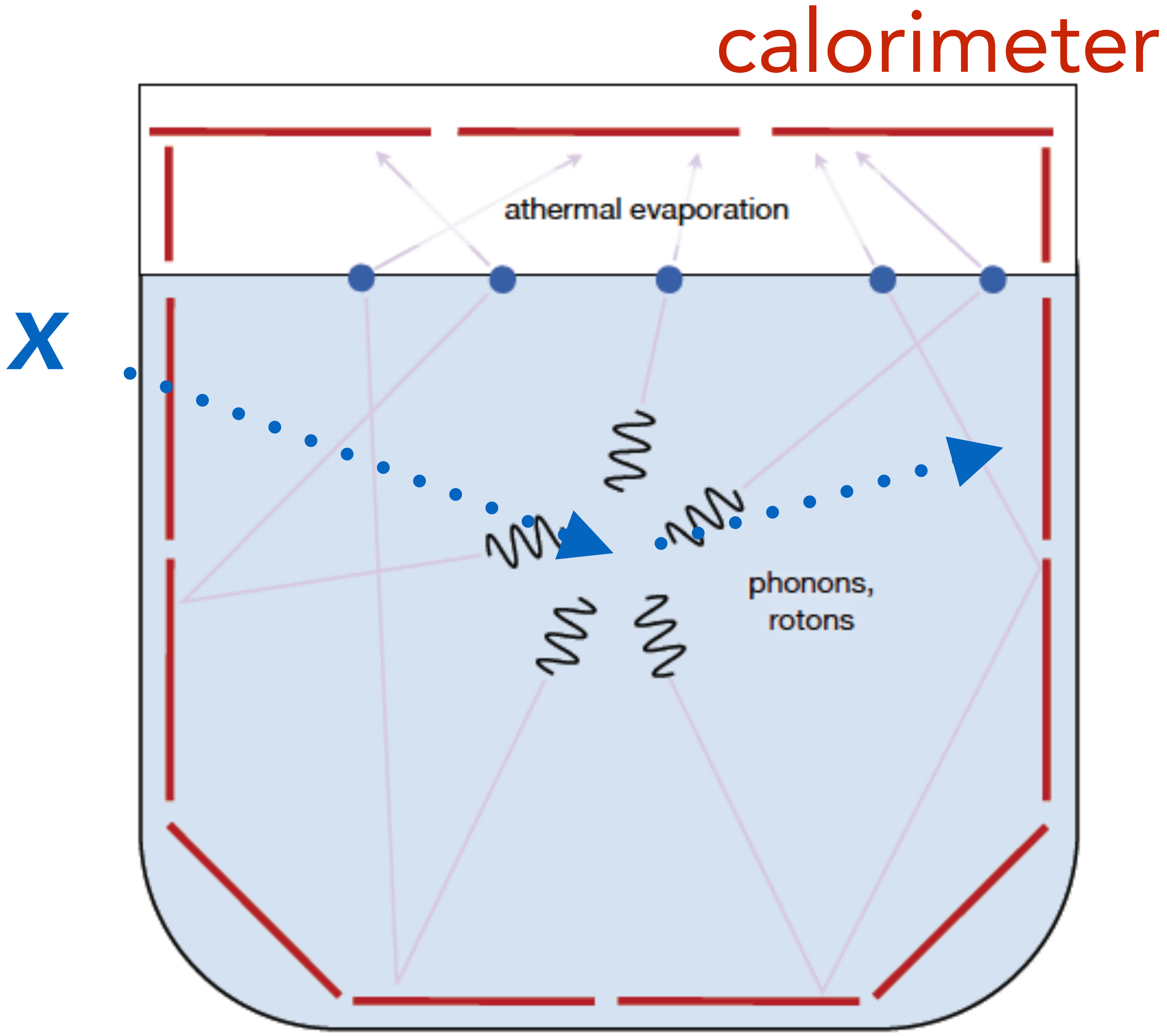


Phonon

Roton

Detector concept

- Operation at 10-100 mK
- Evaporation and amplification x10-40 down to 0.6 meV!
- Measure scintillation at energies ≳ 100 eV
- Superfluid helium used for ultracold neutrons, etc.
- Easy to obtain and purify



D. McKinsey, S. Hertel

Scattering in Helium

- Neutron scattering:

$$\frac{d^2\sigma}{d\omega d\Omega} \equiv \frac{\sigma^n}{4\pi}\frac{k_f}{k_i}S(Q,\omega)$$

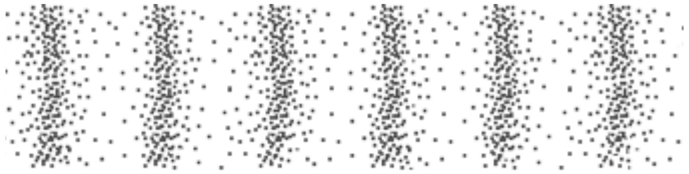
Dynamic structure factor:

$$S(\mathbf{Q},\omega) = \frac{1}{n_0}\sum_F |\langle F|n_{\mathbf{Q}}|I\rangle|^2\delta(E_F - E_I - \omega)$$

response of the fluid to a **density** perturbation with momentum transfer Q, energy ω

Density operator:

$$\hat{n}_{\mathbf{k}} = \frac{1}{\sqrt{N}}\sum_i e^{i\mathbf{k}\cdot\mathbf{r_i}}$$



- Apply directly to dark matter scattering

$$\frac{d^2\sigma}{d\omega d\Omega} \equiv \frac{\boxed{\sigma^n}}{4\pi}\frac{k_f}{k_i}S(Q,\omega)$$

Multiphonon excitations

Dynamic structure factor S(Q,ω)

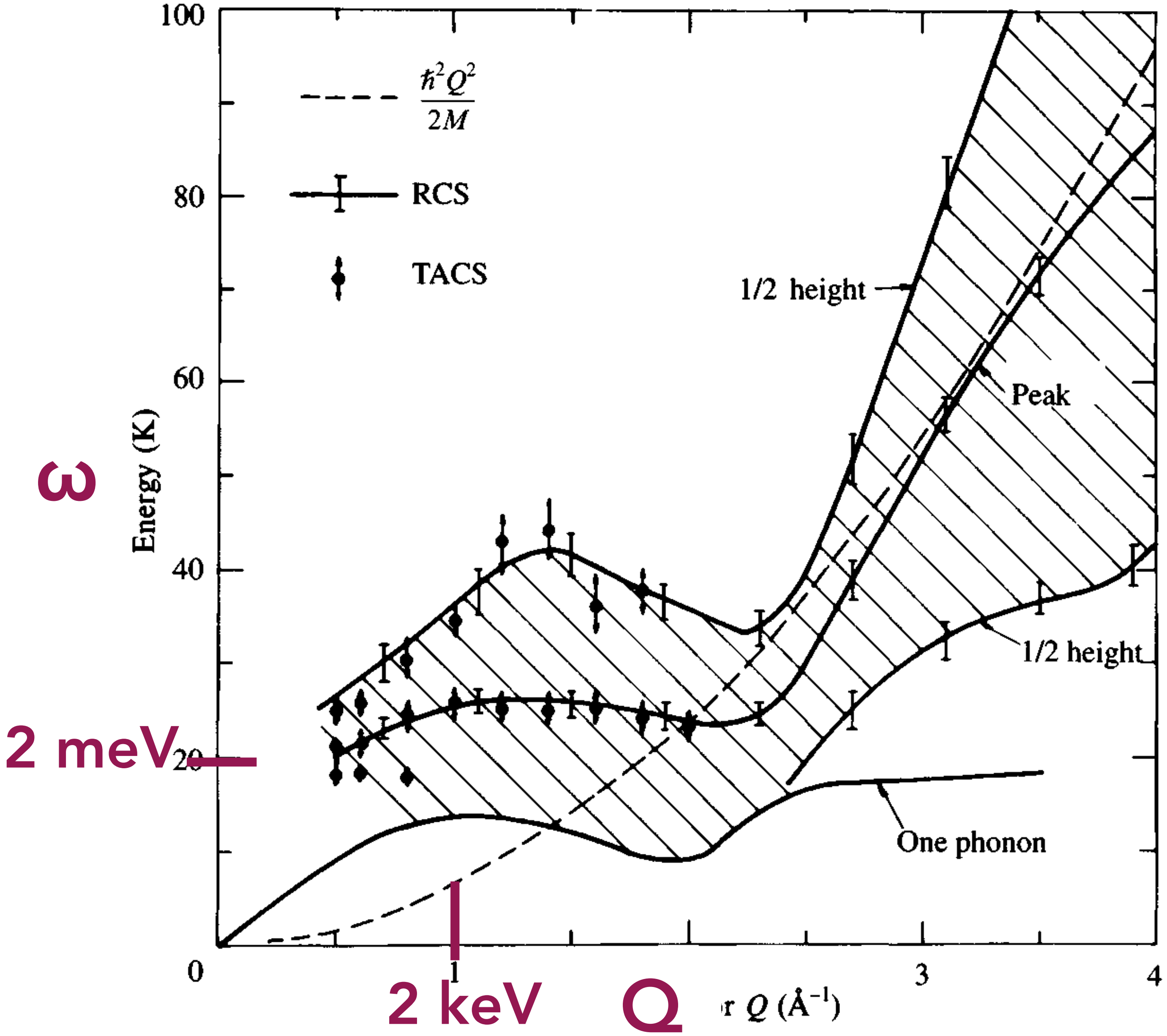
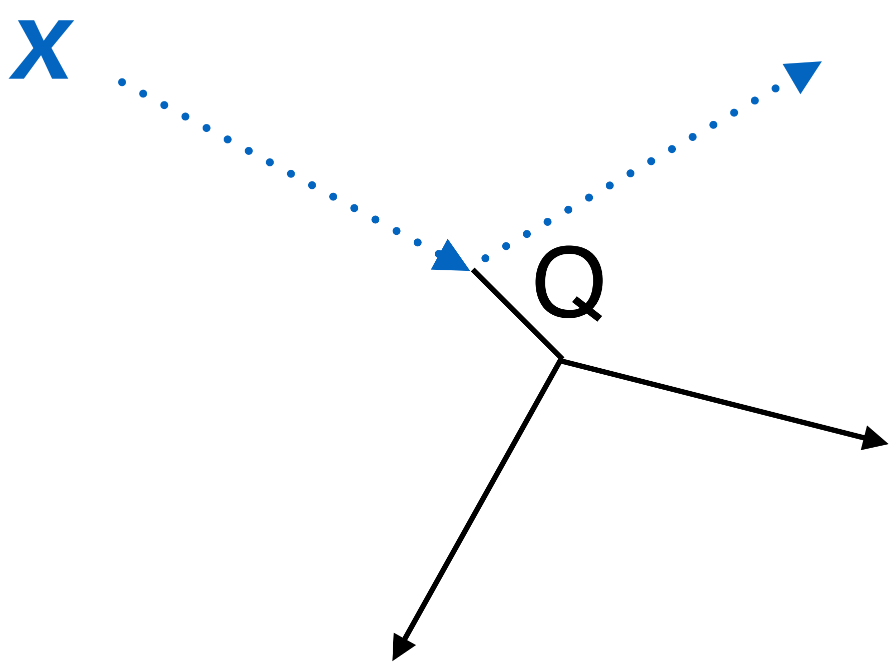


Fig. 1.6. The broad high-energy ……particle (or multiphonon) structure in $S(\mathbf{Q},\omega)$ at intermediate Q at 1.1 K and SVP. The "peak" position and its width are indicated [Source: Cowley and Woods, 1971].

2-phonon excitation

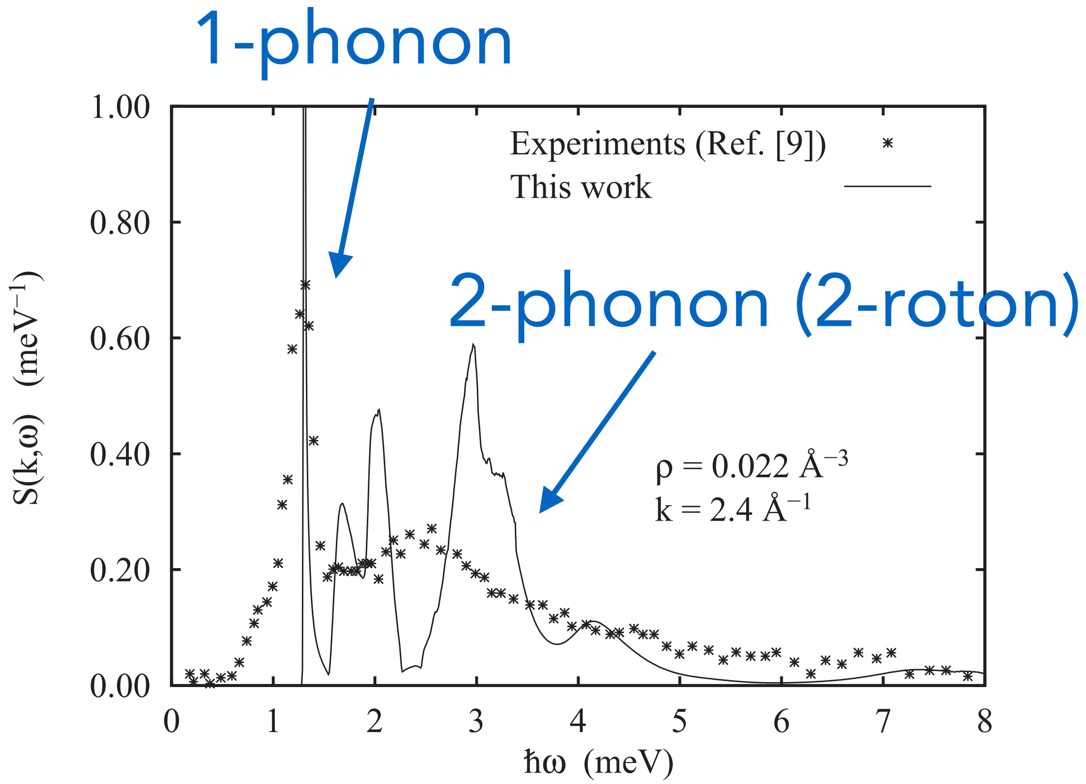


Kinematics allows larger energy ω deposited, even for small Q

Schutz and Zurek 2016

Theory vs. experiment

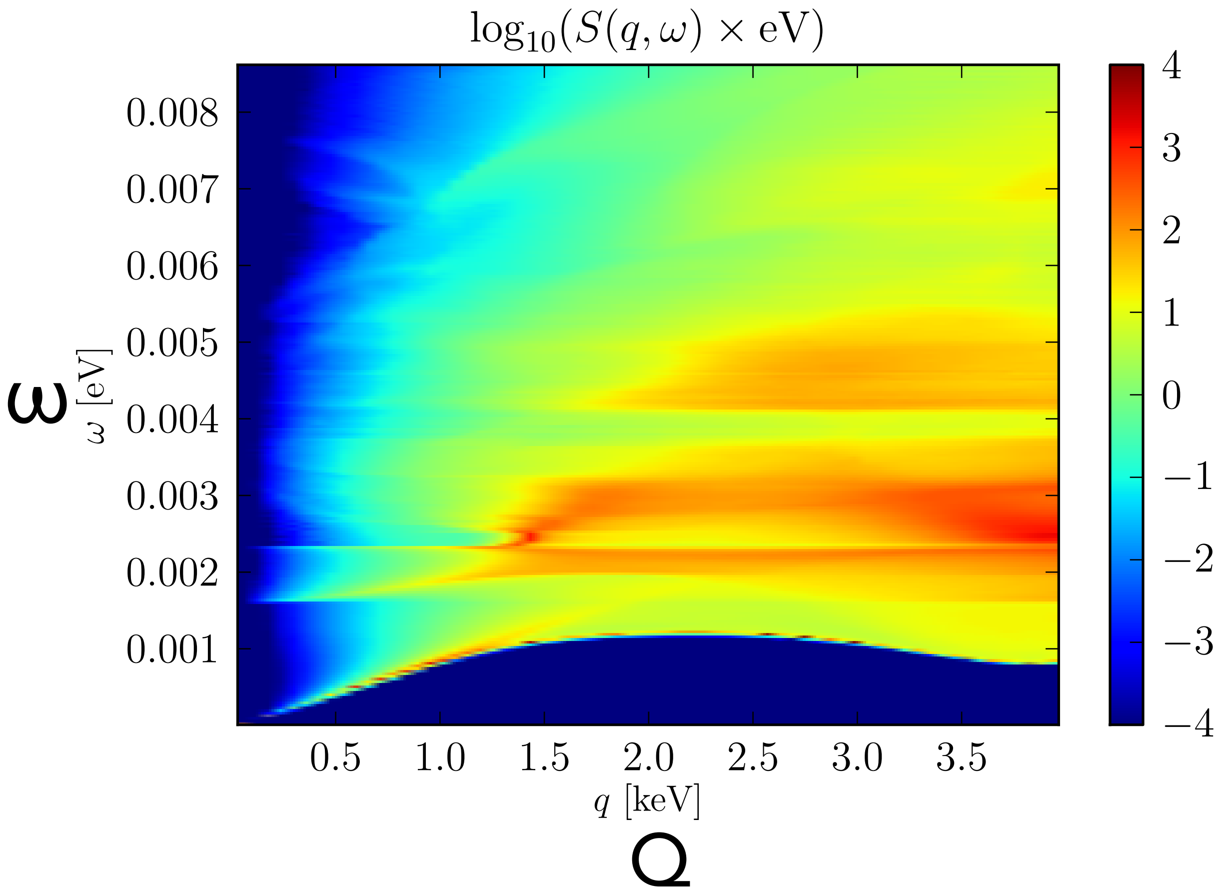
Dynamic structure factor S(Q,ω)



1-phonon

2-phonon (2-roton)

FIG. 21. The figure shows a comparison between our $S(k,\hbar\omega)$ (solid line) and the experimental one [9] (stars) at a momentum transfer of $k = 2.4$ Å^{-1}. The experimental values have been normalized to satisfy the m_0 sum rule.

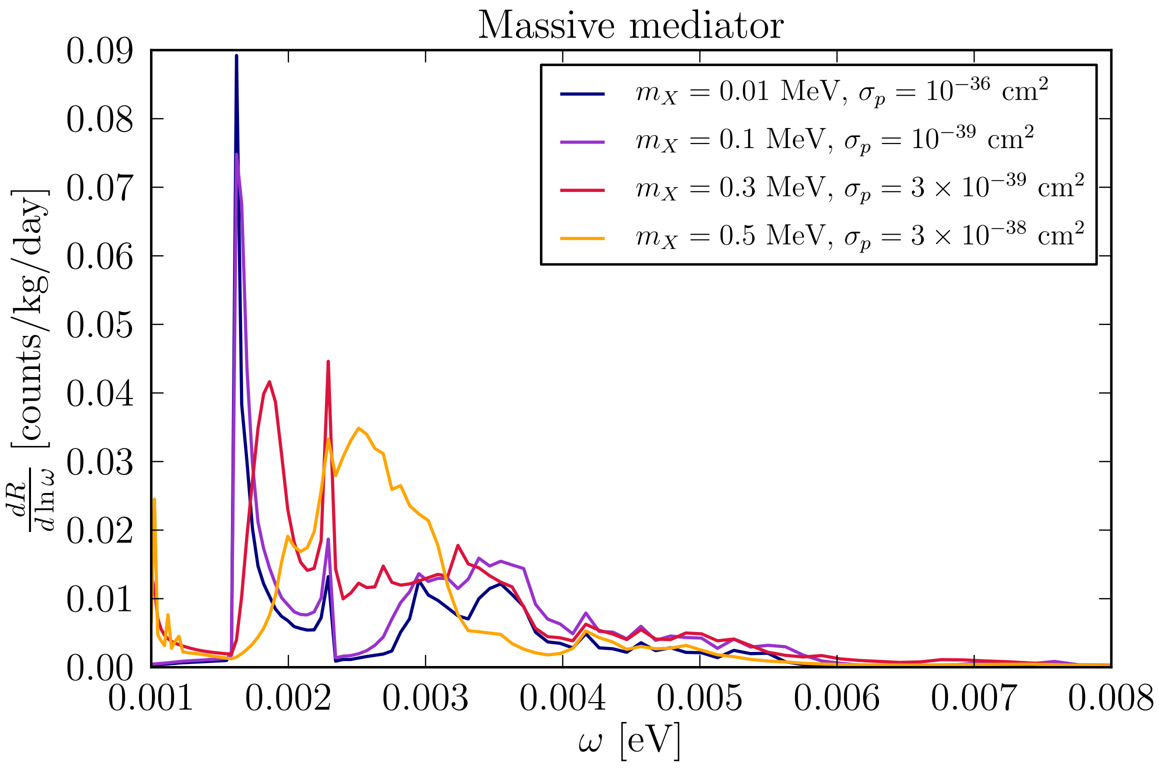


Theory

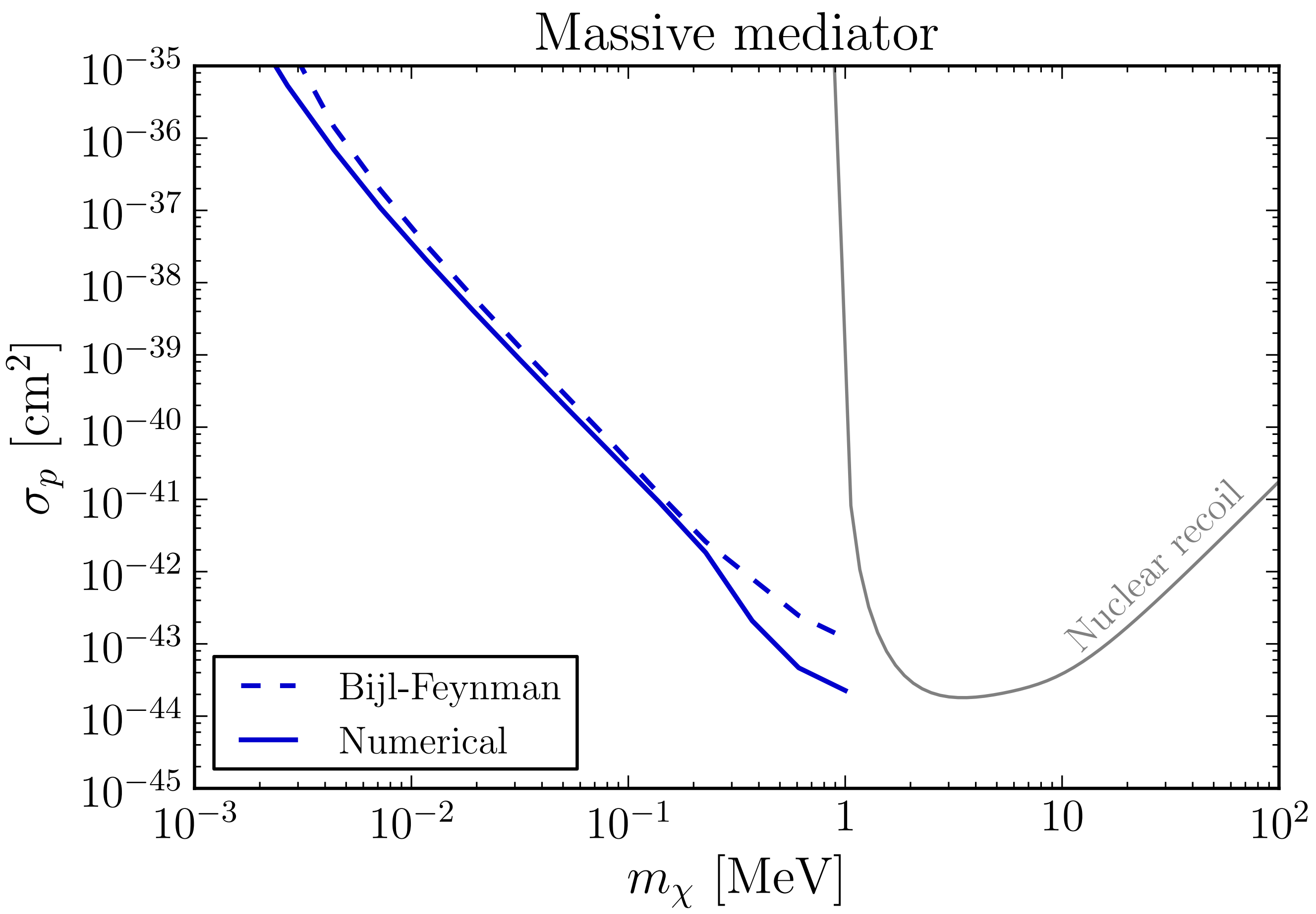
Campbell et al. 2015

Sensitivity to light DM

Two-phonon scattering rate



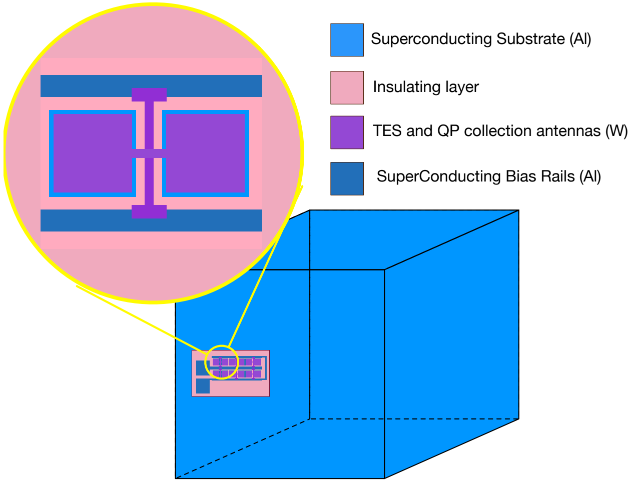
Dominant scattering into two rotons

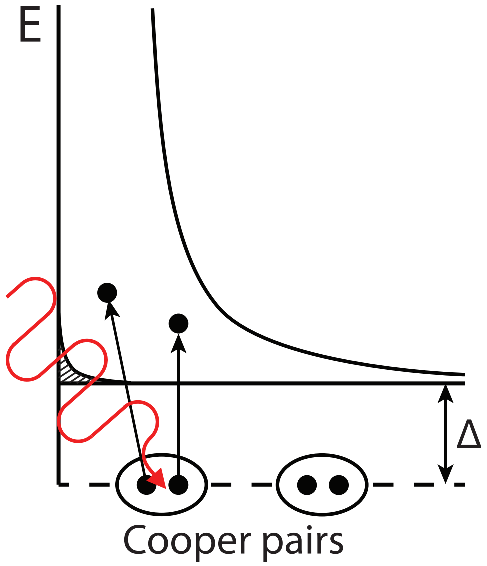


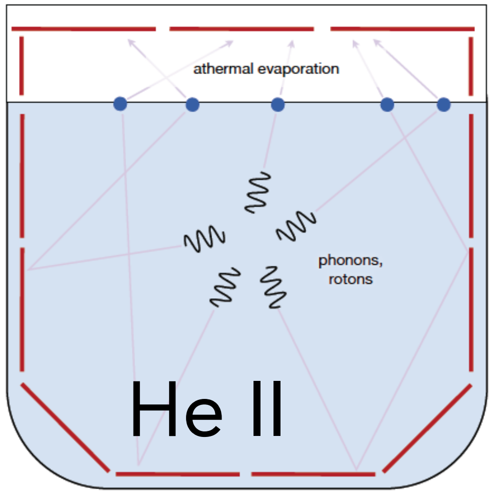
Extends reach to lower mass DM!
(~10 meV resolution)

Conclusions

- Current direct detection experiments focus on WIMP dark matter at or above 1 GeV
- New ideas (for models and detection) explore many orders of magnitude in mass!







Absorption of bosonic DM down to meV

Scattering of < MeV DM