Absorption of light bosonic DM

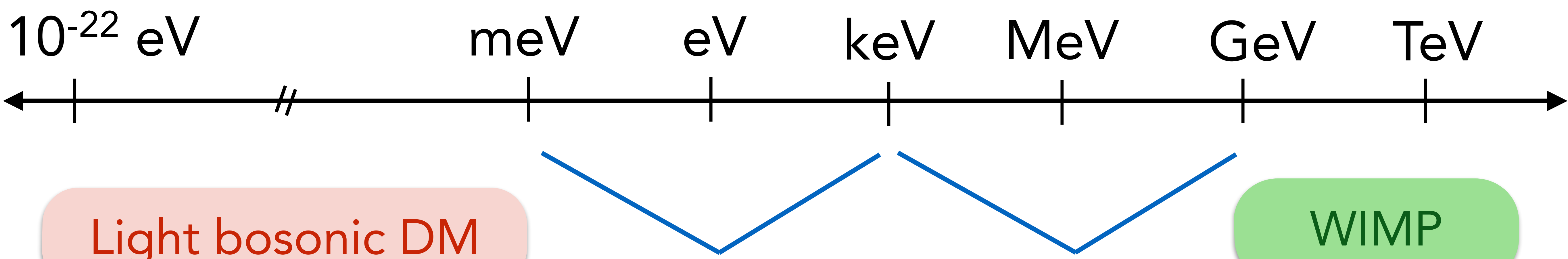
(in semiconductors, superconductors, superfluid helium...)

Tongyan Lin
UC Berkeley / LBL

LBL sub-eV workshop
December 9, 2016

Hochberg, TL, Zurek 1604.06800, 1608.01994
Knapen, TL, Zurek 1611.06228

Mass scale of dark matter

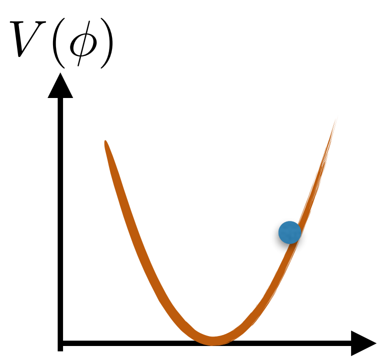


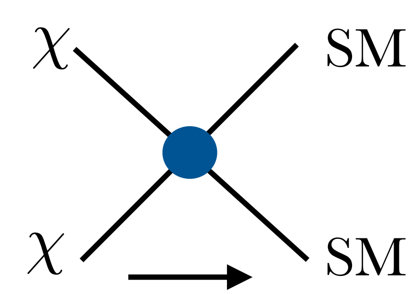
Light bosonic DM

Absorption, bosonic DM

Scattering, fermion DM

WIMP





meV-eV detectors

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

Nuclear recoil in direct detection

sub-keV bosonic dark matter

- Candidates:
  - Hidden photon
  - Pseudoscalar (axion)
  - Scalar

- Coherent field below *m* ~ eV

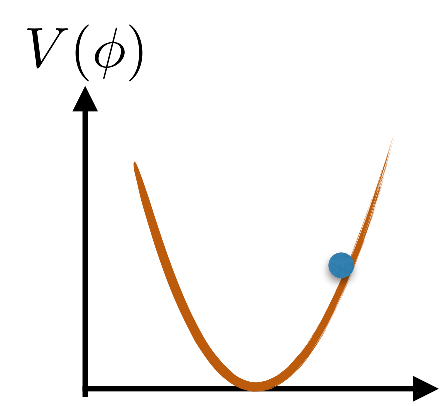
Local DM density: 0.4 GeV/cm^3 $\quad \lambda_{\rm dB} \sim \dfrac{2\pi}{m_{\rm DM} v} \quad v \sim 10^{-3}$

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

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

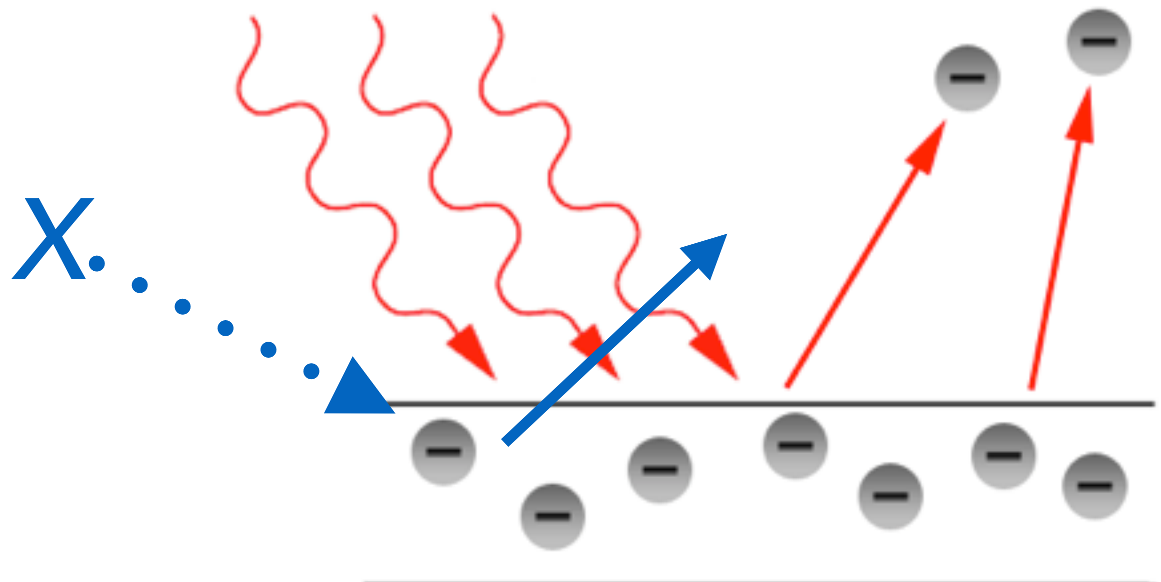
$$\rho_{\rm DM} = \frac{1}{2} m_{\rm DM}^2 \phi_0^2$$

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

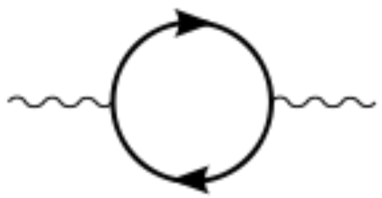
Relate the DM absorption rate to photon absorption rate:

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

(photon absorption, conductivity **σ**)

In-medium polarization tensor and conductivity are related:

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



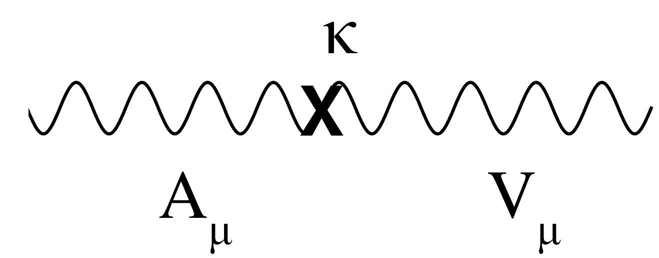
Real part gives effective mass, imaginary part gives absorption:

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

Hidden photon dark matter

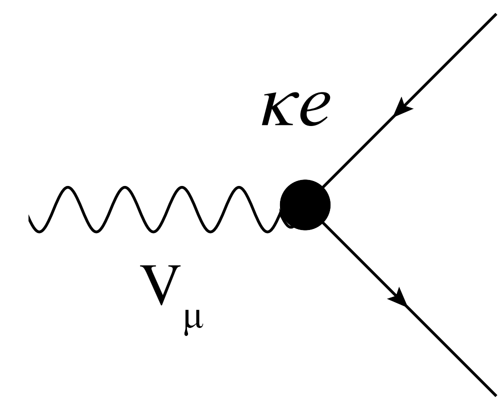
Kinetic mixing in vacuum:

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



Matter coupling:

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



Absorption rate of halo DM

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

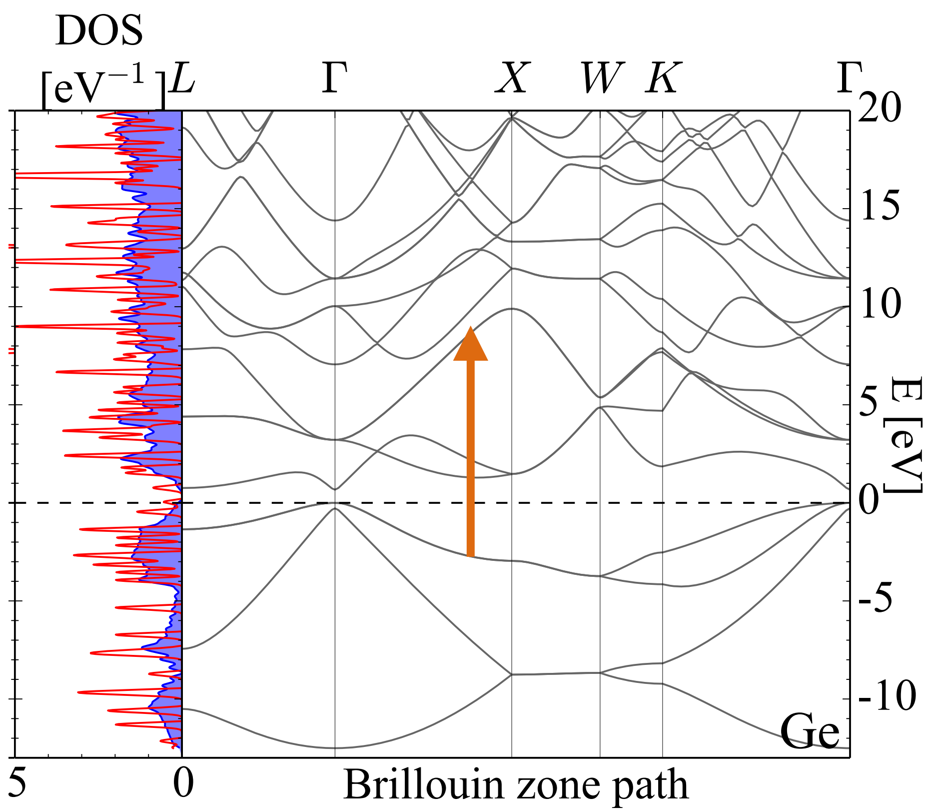
photon absorption

effective kinetic mixing in a material

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

Absorption in semiconductors and superconductors

Electron excitations in semiconductors



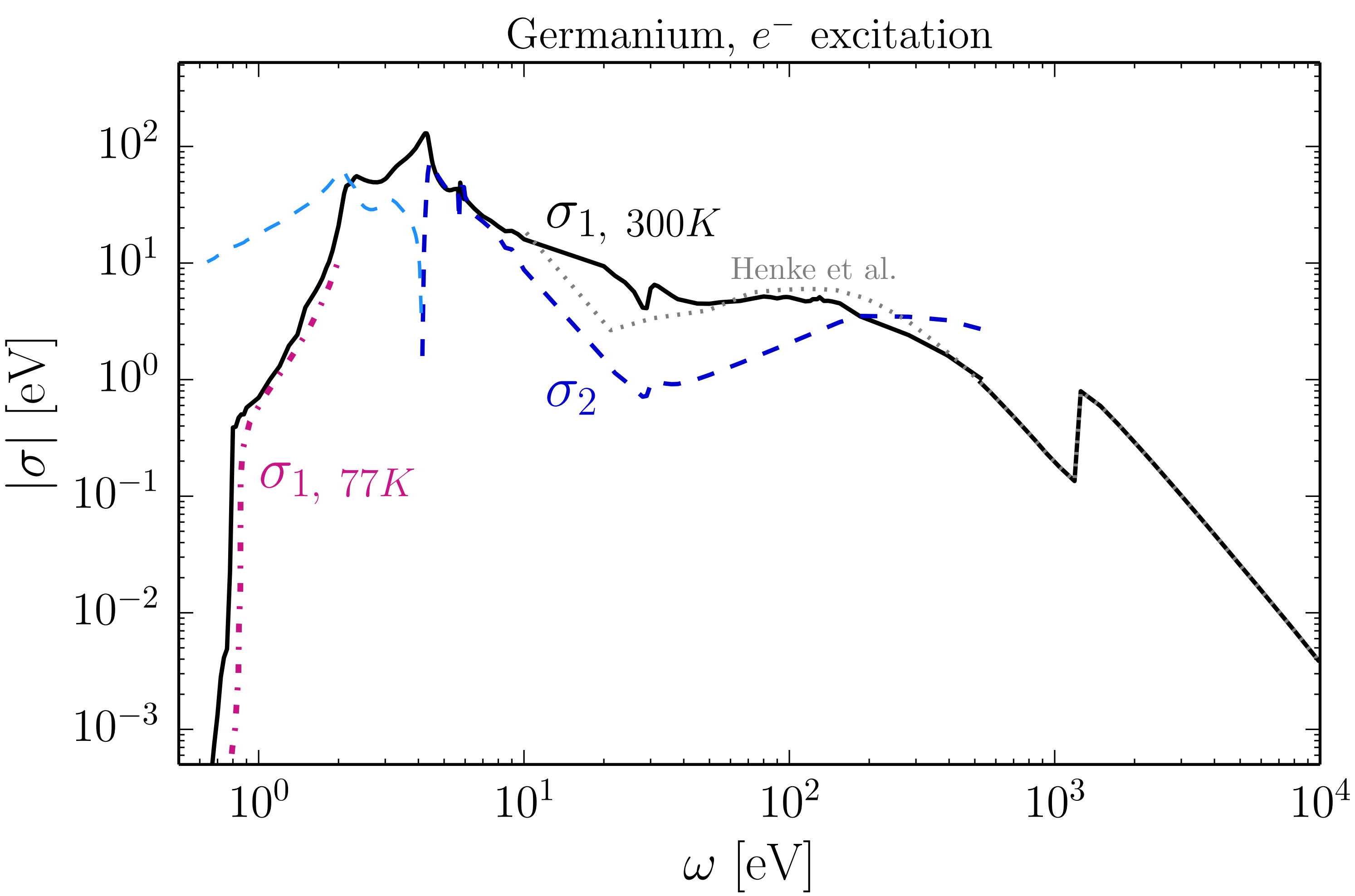
From Essig et al 2015

Band gap:

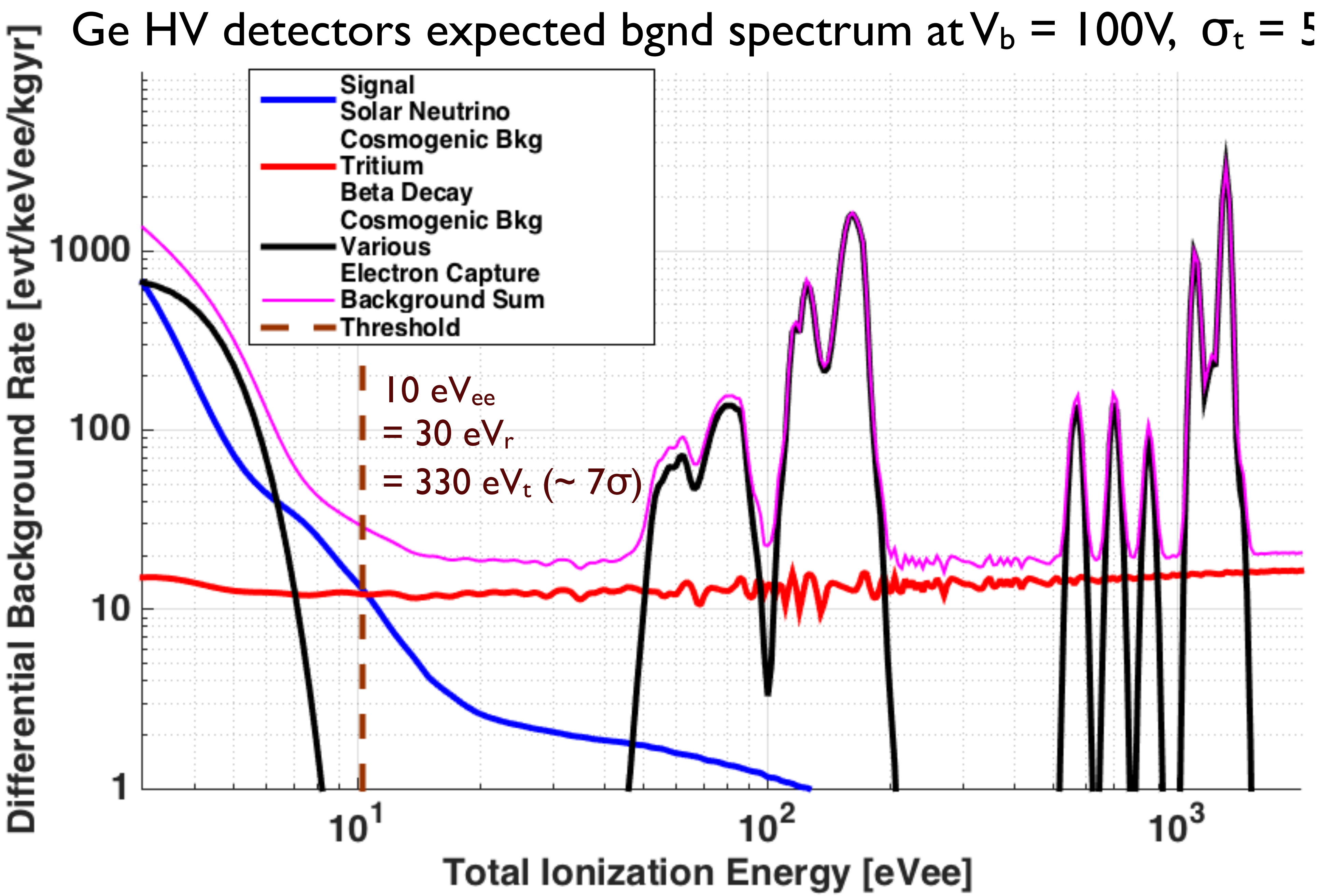
0.7 eV (Ge)

1.1 eV (Si)

Photon absorption data

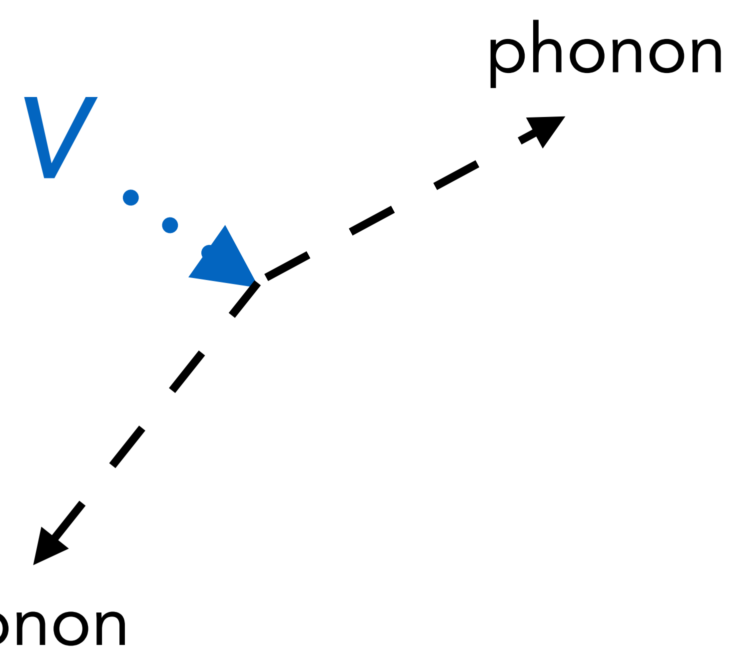


Backgrounds



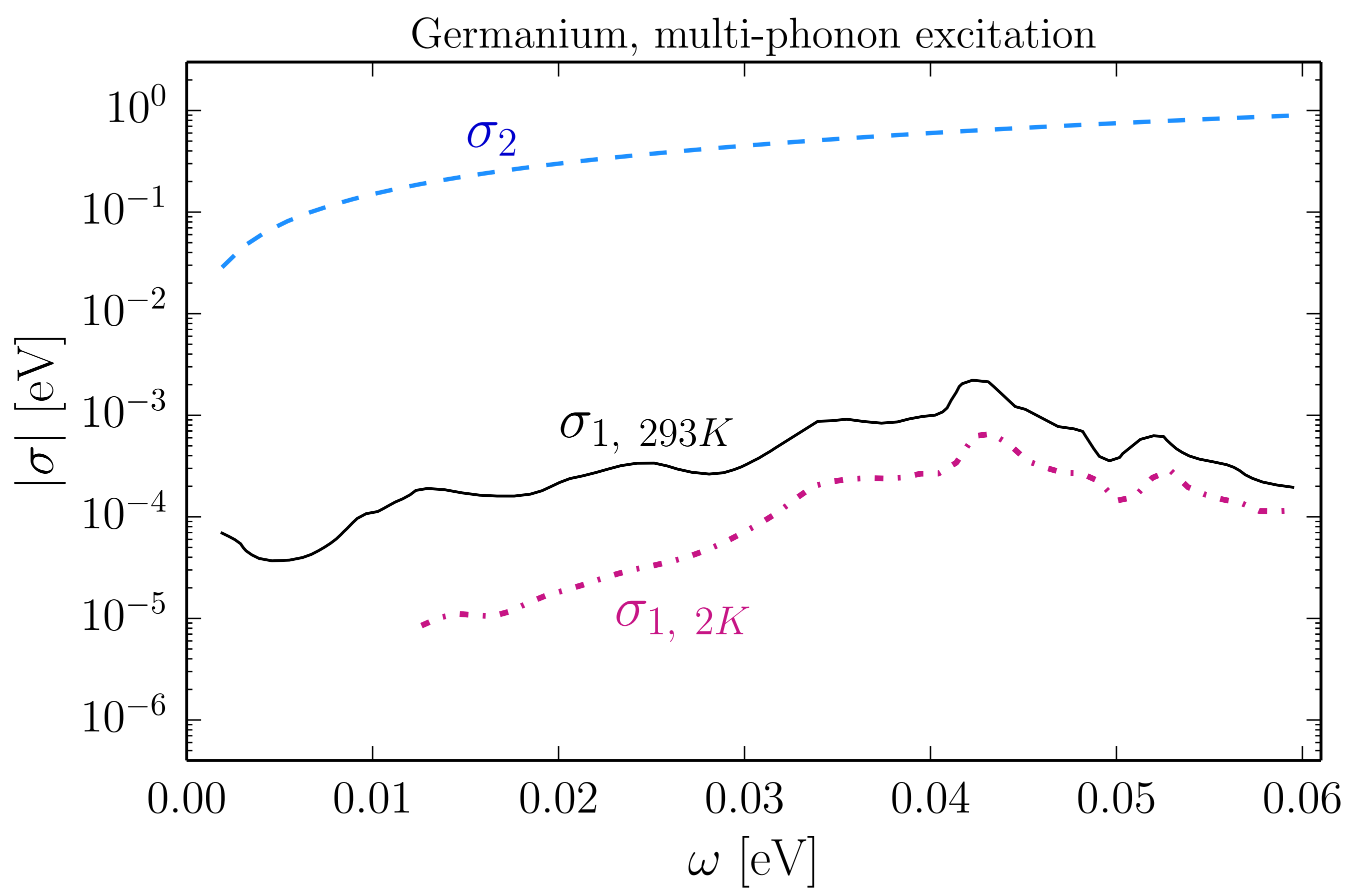
Slide: S. Golwala

Multi-phonon excitation



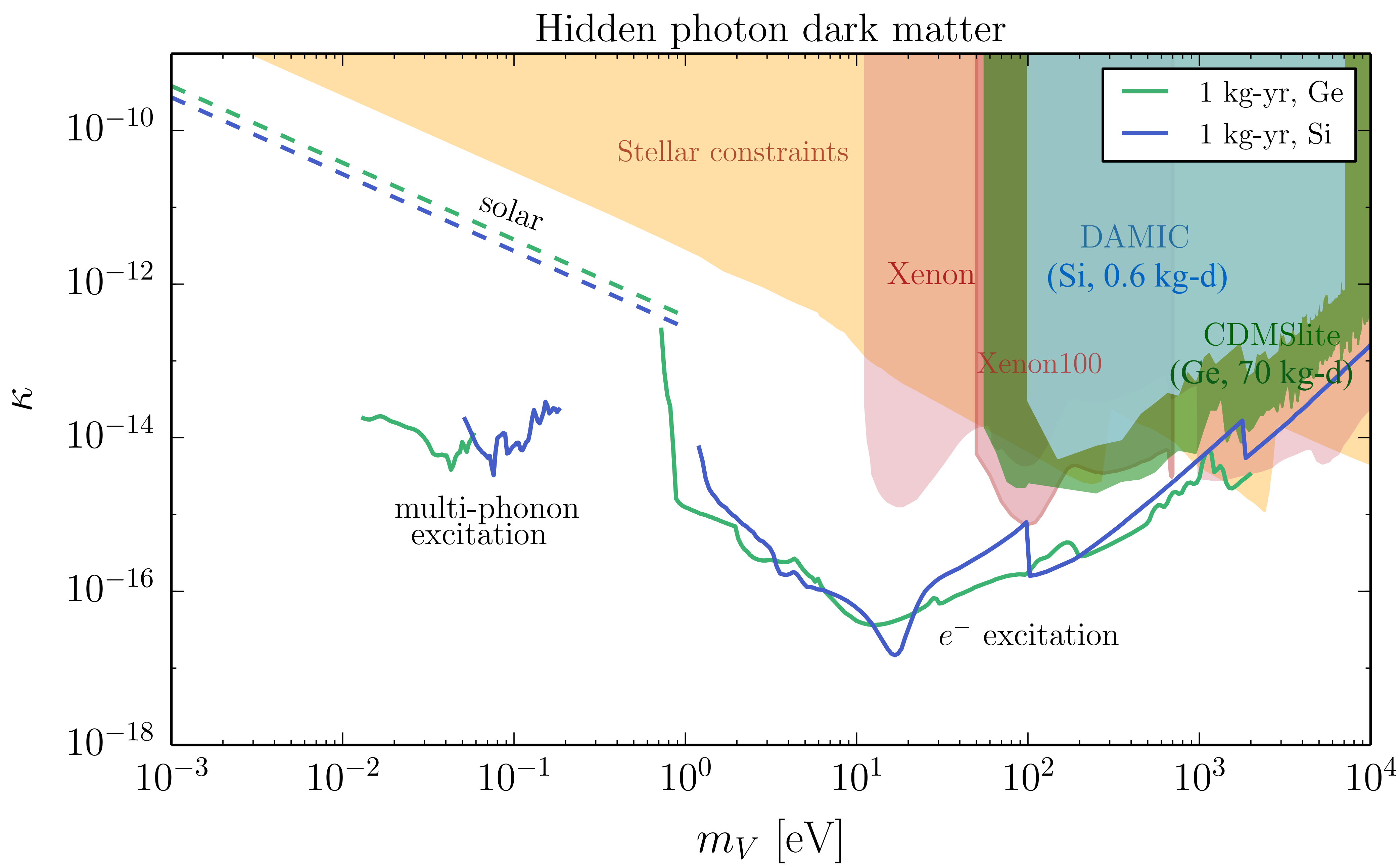
From second order dipole moment coupling of (hidden) photon with lattice

Photon absorption data



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

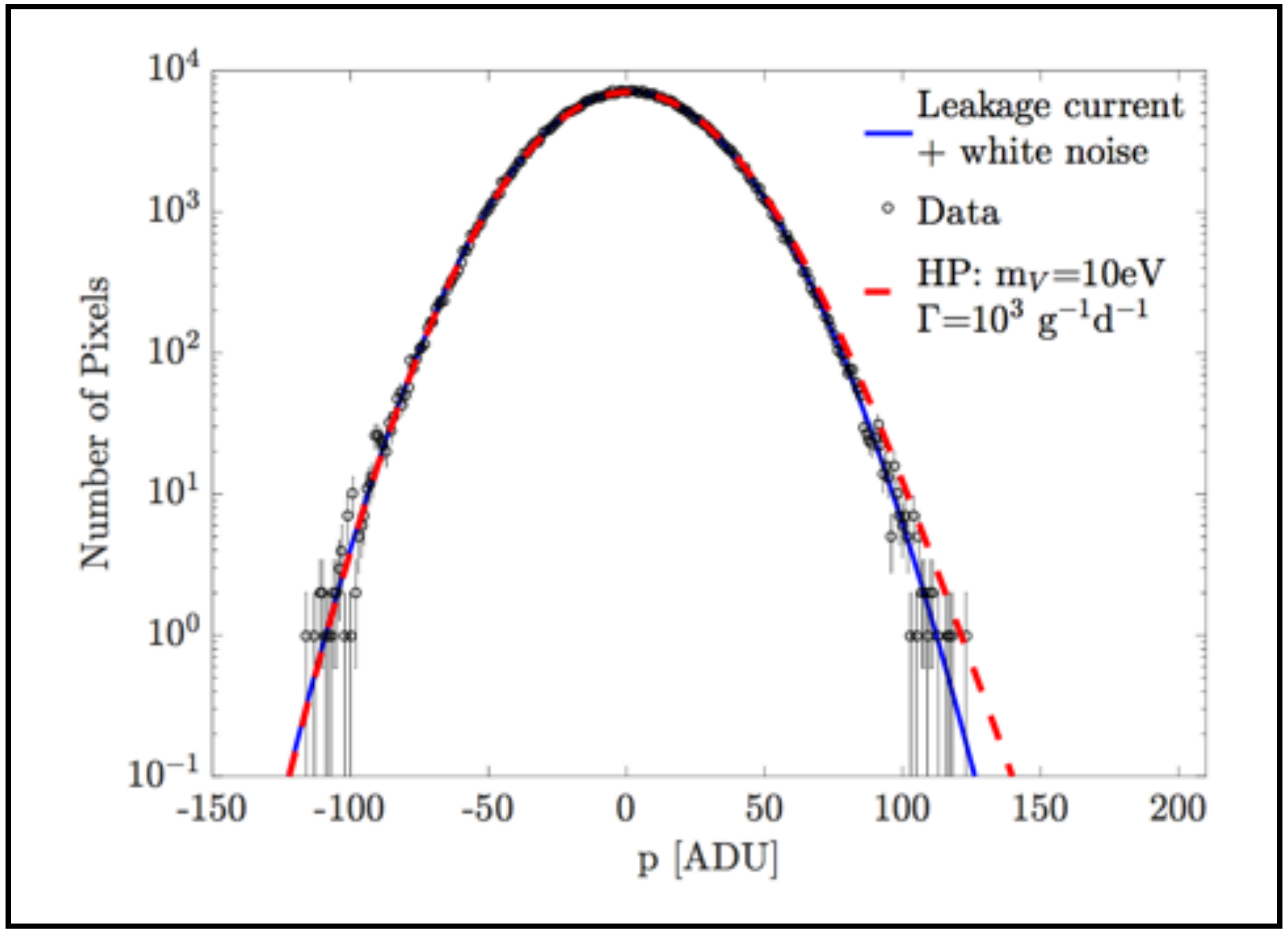
Hidden photon DM

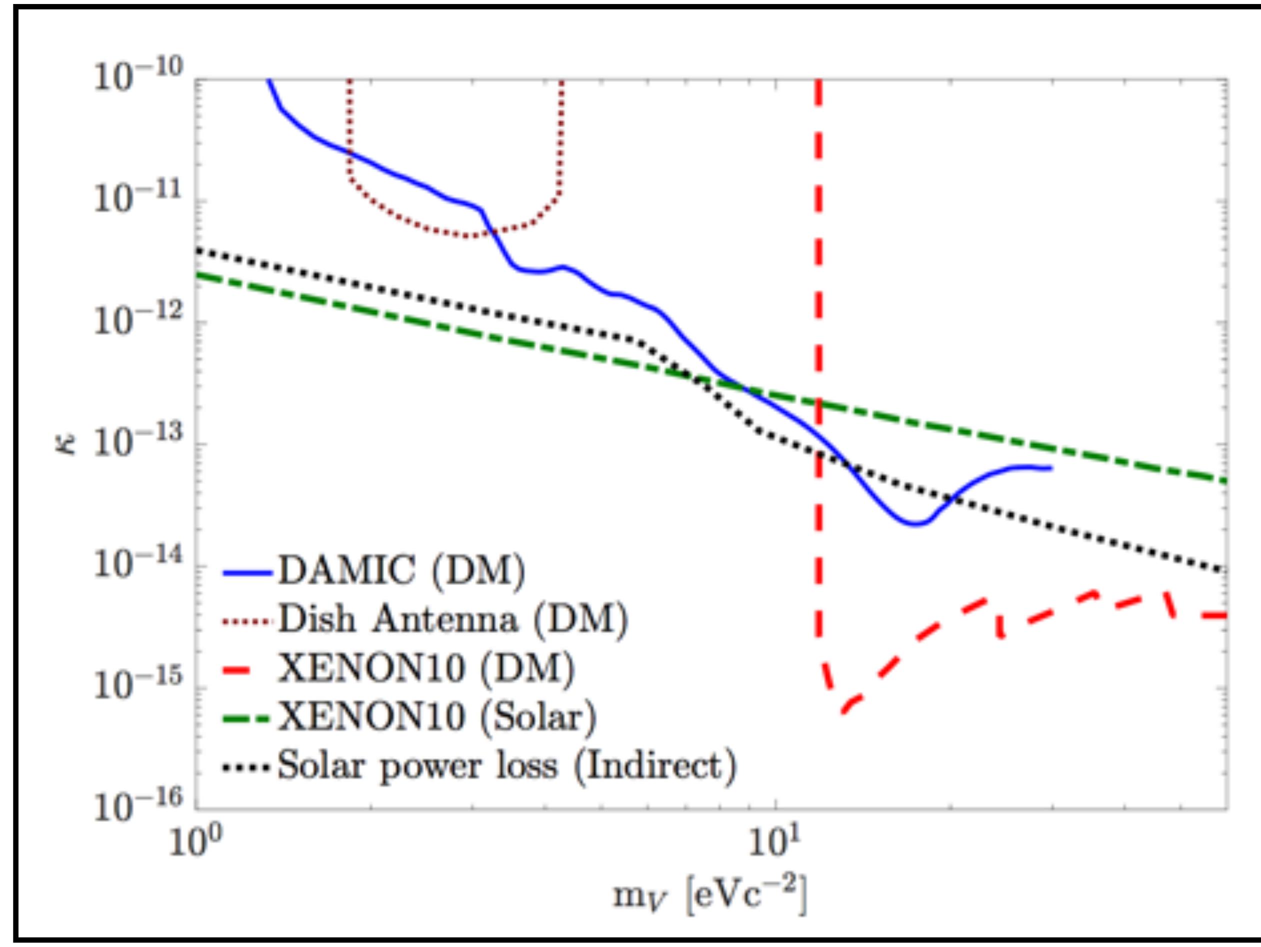


See also:
I. Bloch, Tien-Tien Yu, etc 2016
for similar study

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

First direct detection constraints on eV-scale hidden-photon dark matter with DAMIC at SNOLAB





DC : 4e-/mm^2/day ~ 0.0009 e-/pix/day ~ 7x10^{-22} A/cm^2

this dark current, by itself provides the best direct detection limits for low mass hidden-photon dark matter. We believe we have not reach the DC limit for the sensors yet.

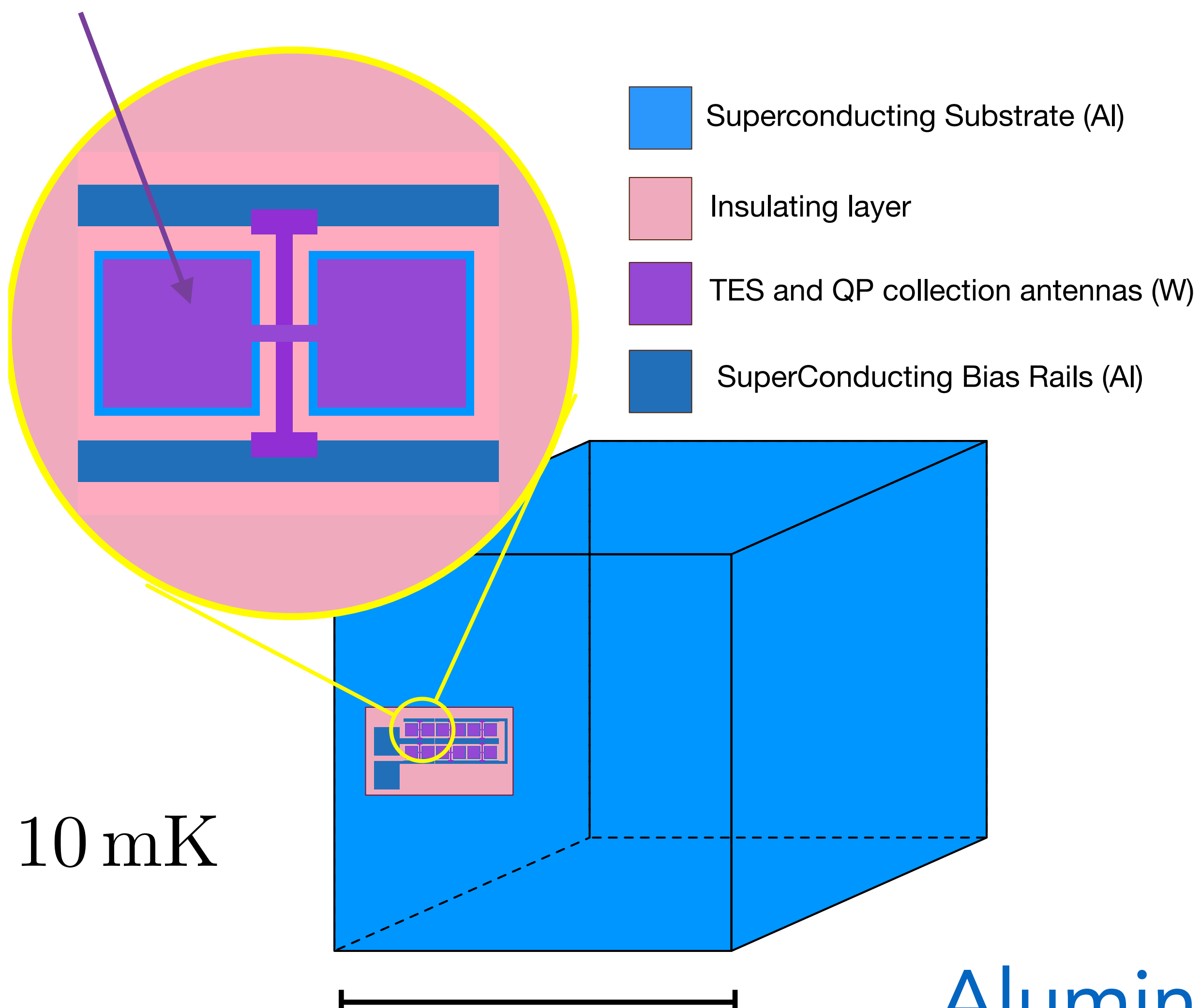
Theory prediction orders of magnitude lower

arXiv:1611.03066

Slide: J. Tiffenberg

Superconductor target

QP/phonon measurement with E_{th}~meV goal



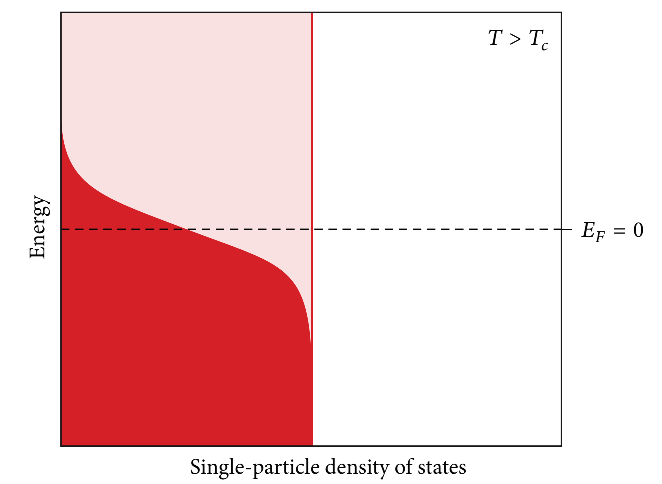
$T = 10\,\mathrm{mK}$

5 mm

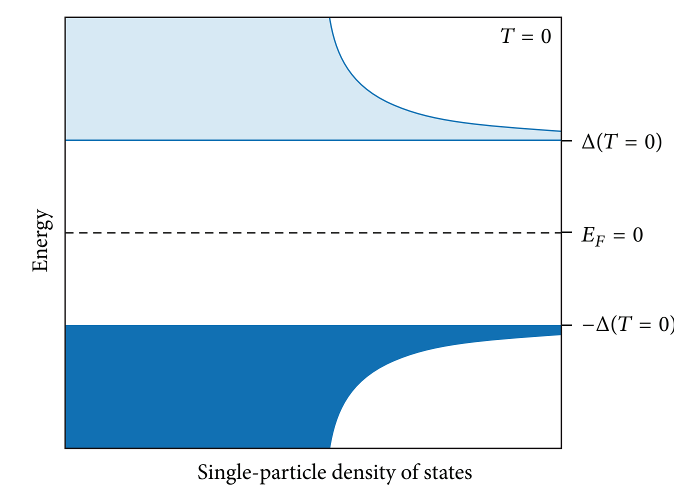
Aluminum

$T_c = 1.2\ K$

How we compute:



Metal

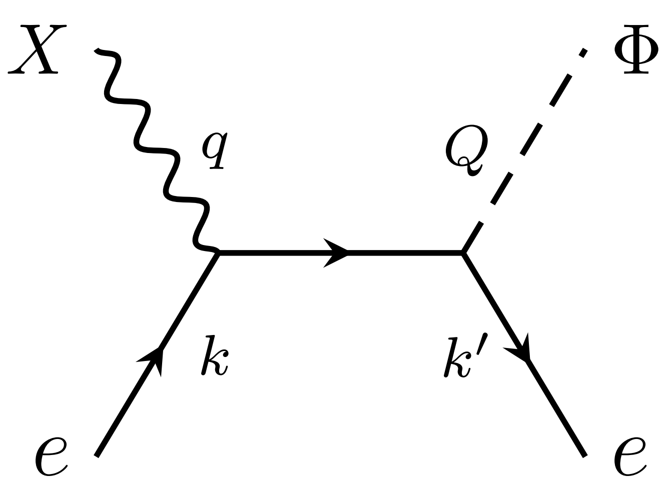


Superconductor

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

Absorption via phonon emission

Phonon energy:
$$\Omega = c_s|\vec{Q}|$$



Speed of sound in aluminum:
$$c_s \simeq 6320 \text{ m/s} \sim 2 \times 10^{-5}$$

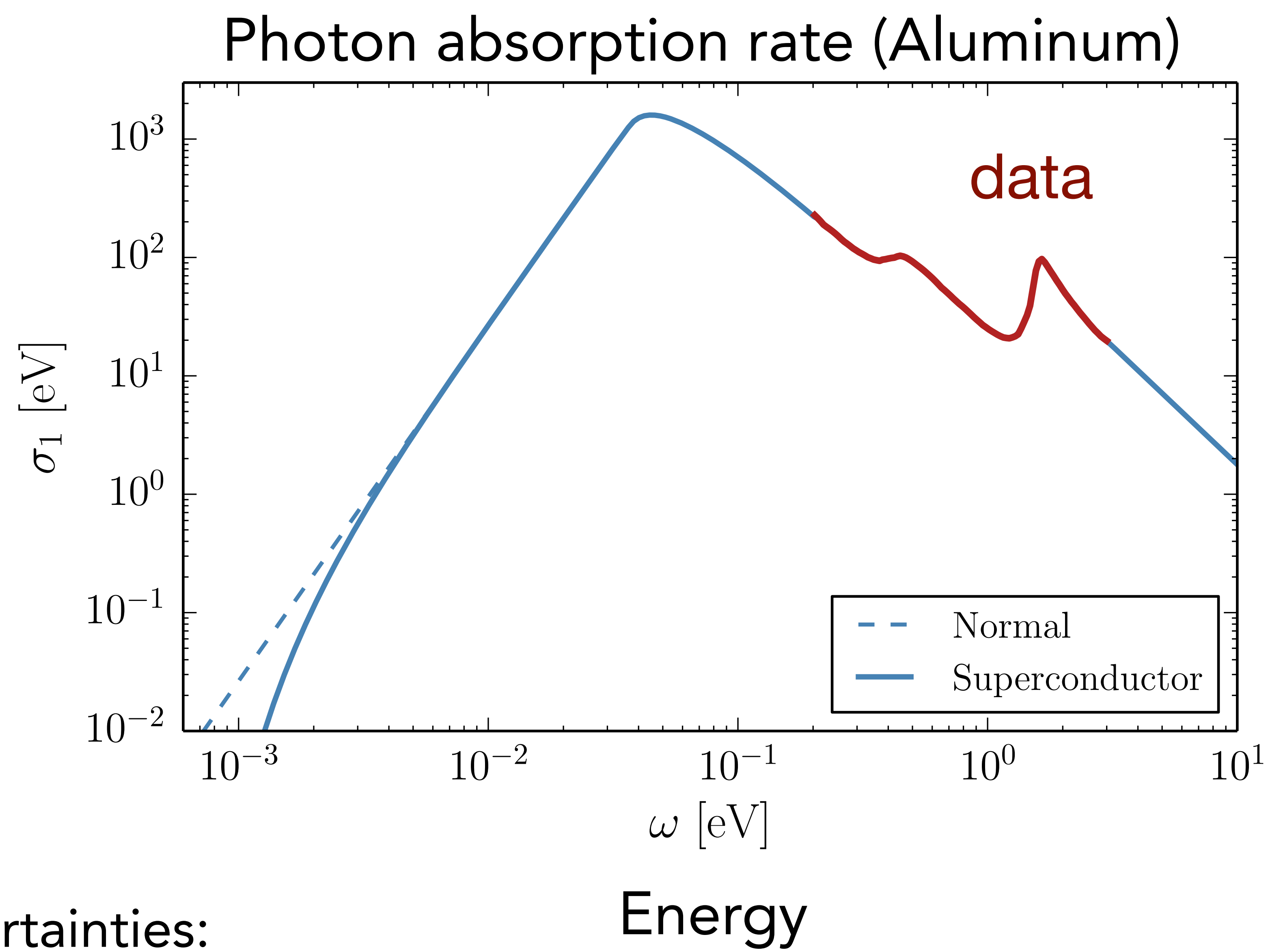
The phonon can carry large momentum, with small energy.

Time-scale for electron to emit photon (in Debye limit):

$$\frac{1}{\tau_\Phi} = \begin{cases} \frac{4}{5}\pi\lambda_{\rm tr}\omega_D\left(1 - \frac{5}{6}\frac{\omega_D}{\omega}\right) & , \ \omega \geq \omega_D \\ \frac{2}{15}\pi\lambda_{\rm tr}\frac{\omega^5}{\omega_D^4} & , \ \omega < \omega_D \end{cases}$$

Electron-phonon coupling is fixed by matching onto high-T resistivity of material.

Absorption via phonon emission



Theory uncertainties:

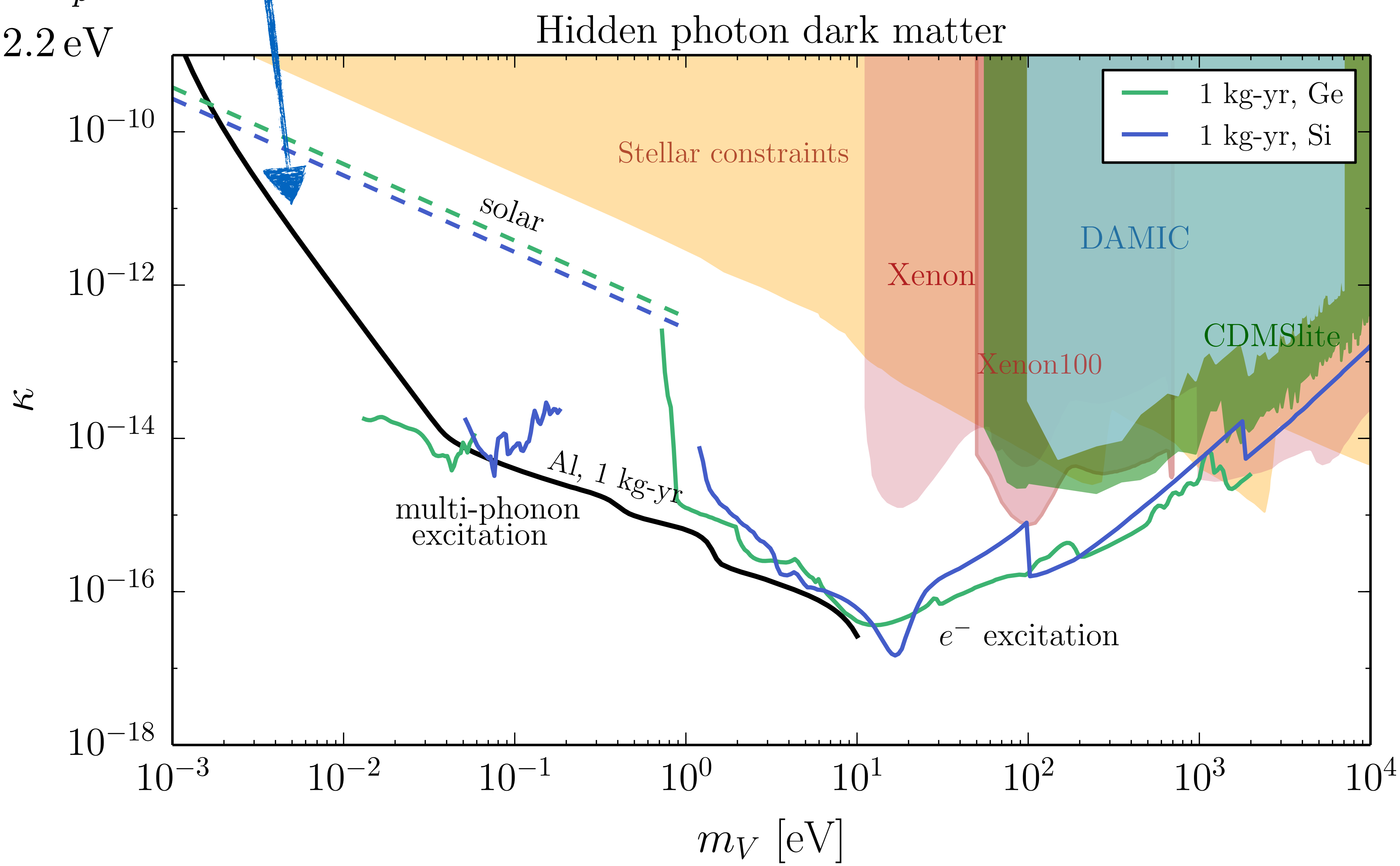
- phonon dispersion, coupling
- free electron approximation

Hidden photon DM

Suppression in absorption rate, reduced effective kinetic mixing

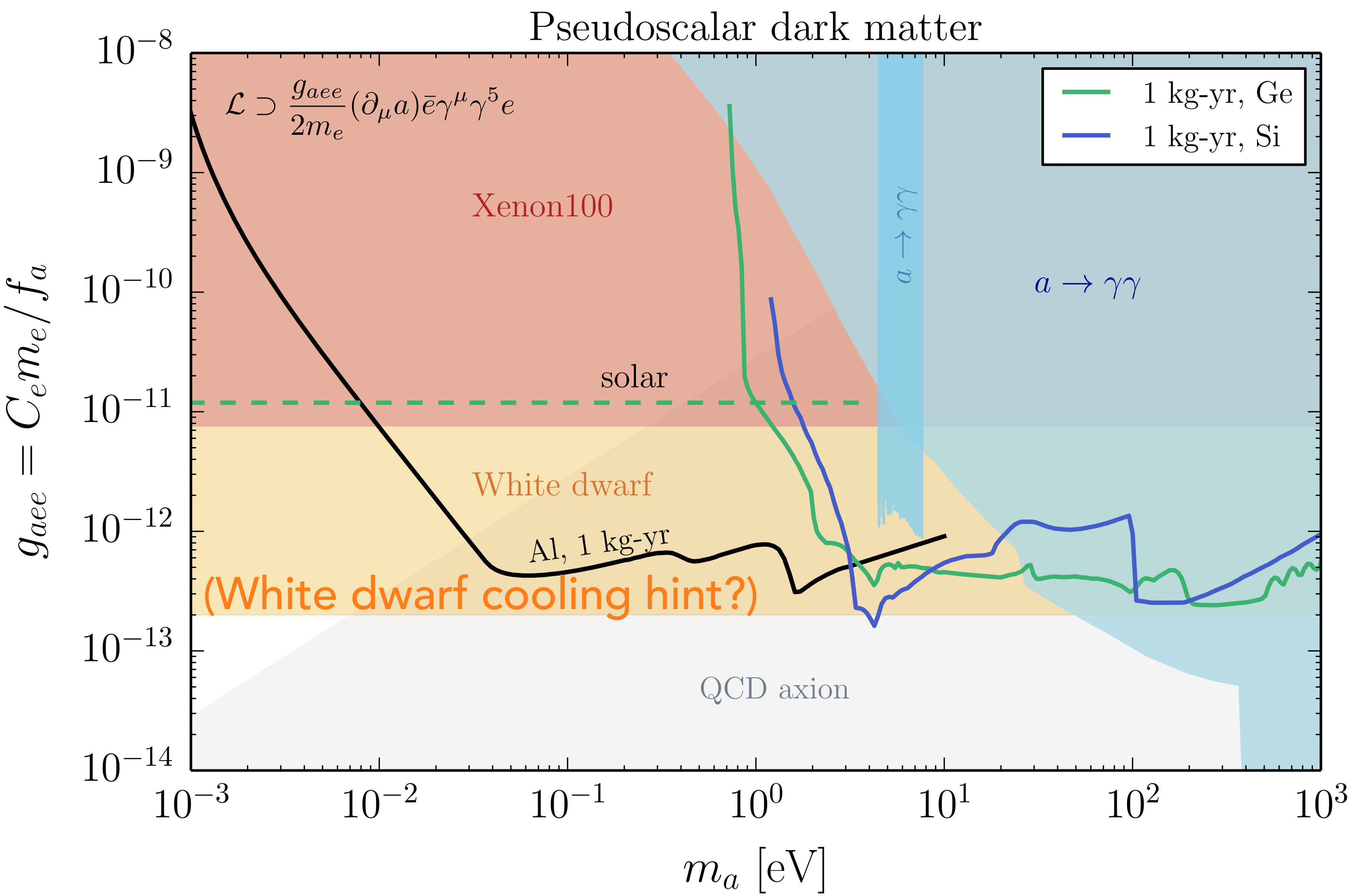
$$\kappa_{\rm eff}^2 \simeq \frac{\kappa^2 m_V^4}{\omega_p^4}$$

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

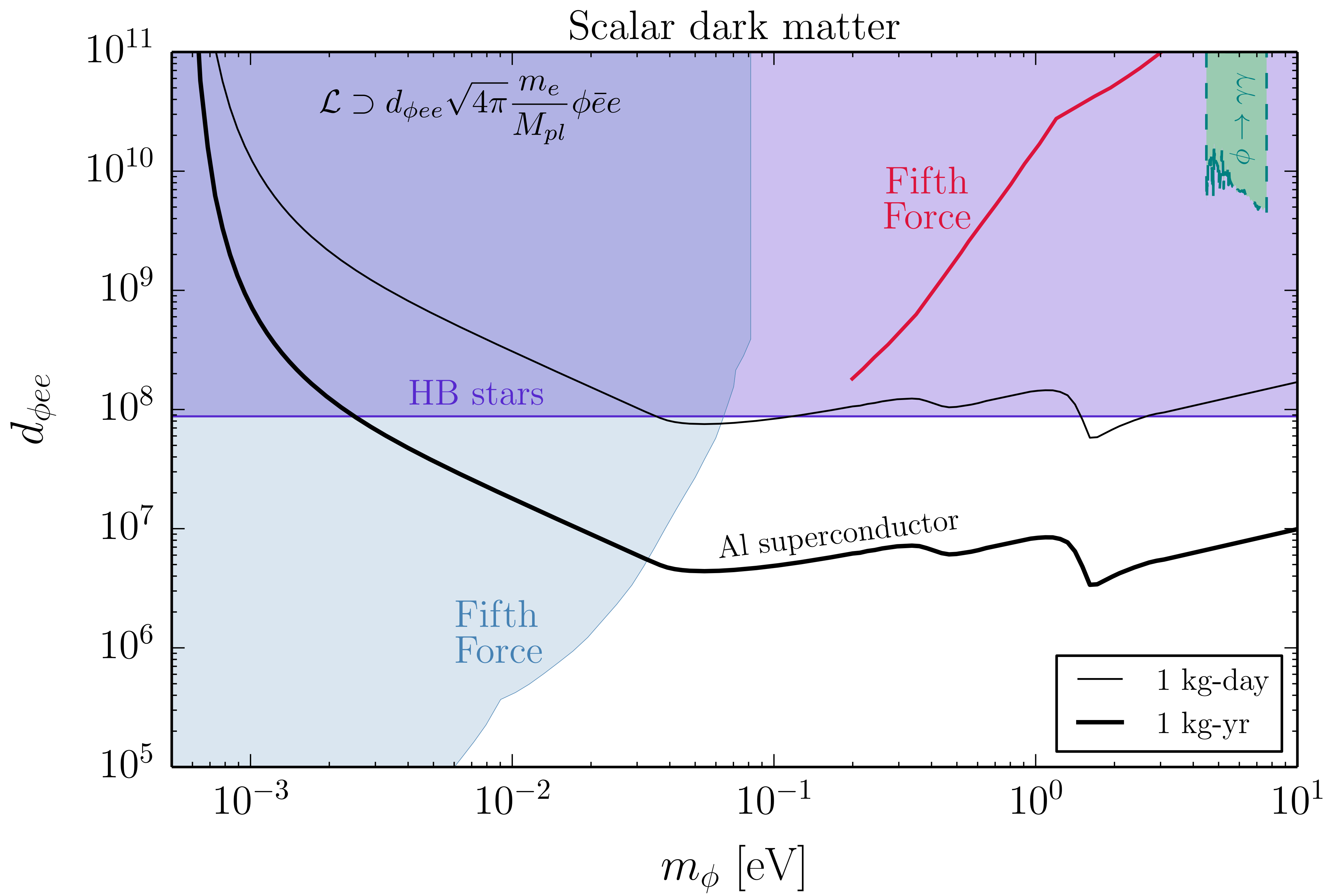


Stellar, Xenon10 constraints:
An, Pospelov, Pradler 2013, 2014
Redondo & Raffelt 2013

Pseudoscalar DM



Scalar DM

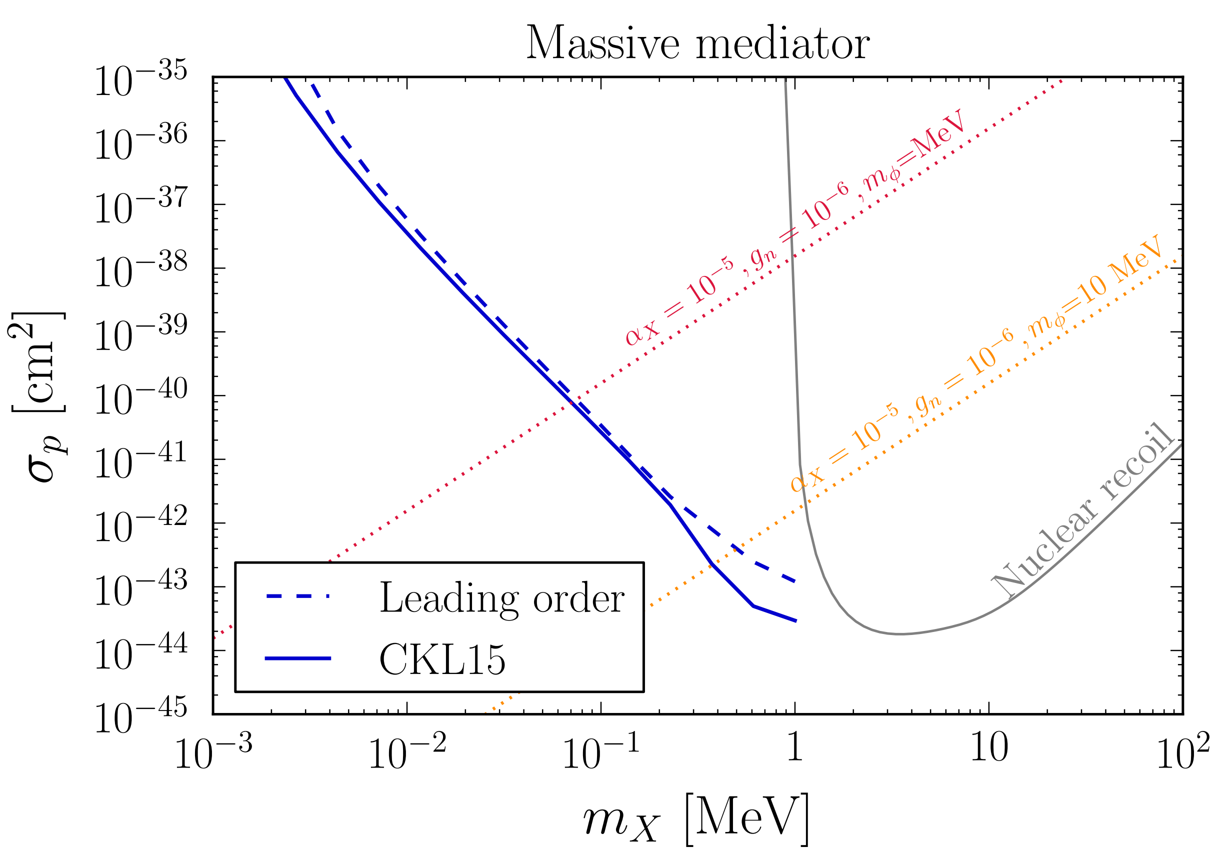


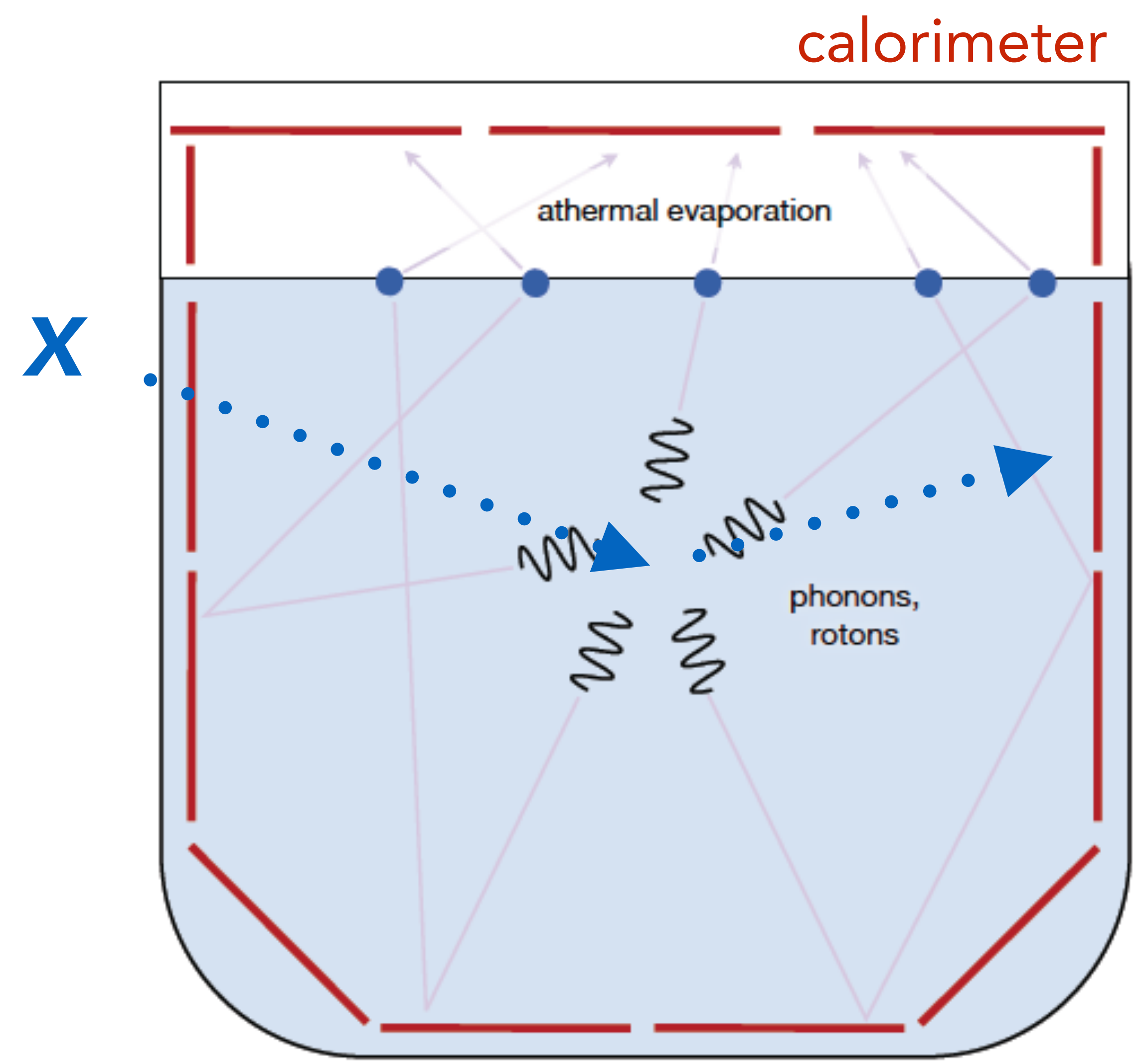
Scalar dark matter
$\mathcal{L} \supset d_{\phi ee}\sqrt{4\pi}\frac{m_e}{M_{pl}}\phi\bar{e}e$
Fifth Force
HB stars
Al superconductor
Fifth Force
$\phi \to \gamma\gamma$
1 kg-day
1 kg-yr
$d_{\phi ee}$
m_ϕ [eV]
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}

Absorption in superfluid helium

Superfluid helium

- Probe light DM scattering with phonon-roton excitations
- Evaporation/amplification down to ~0.6 meV





McKinsey, Hertel

Knapen, TL, Zurek 2016

Multiphonon excitations

Dynamic structure factor S(Q,ω)

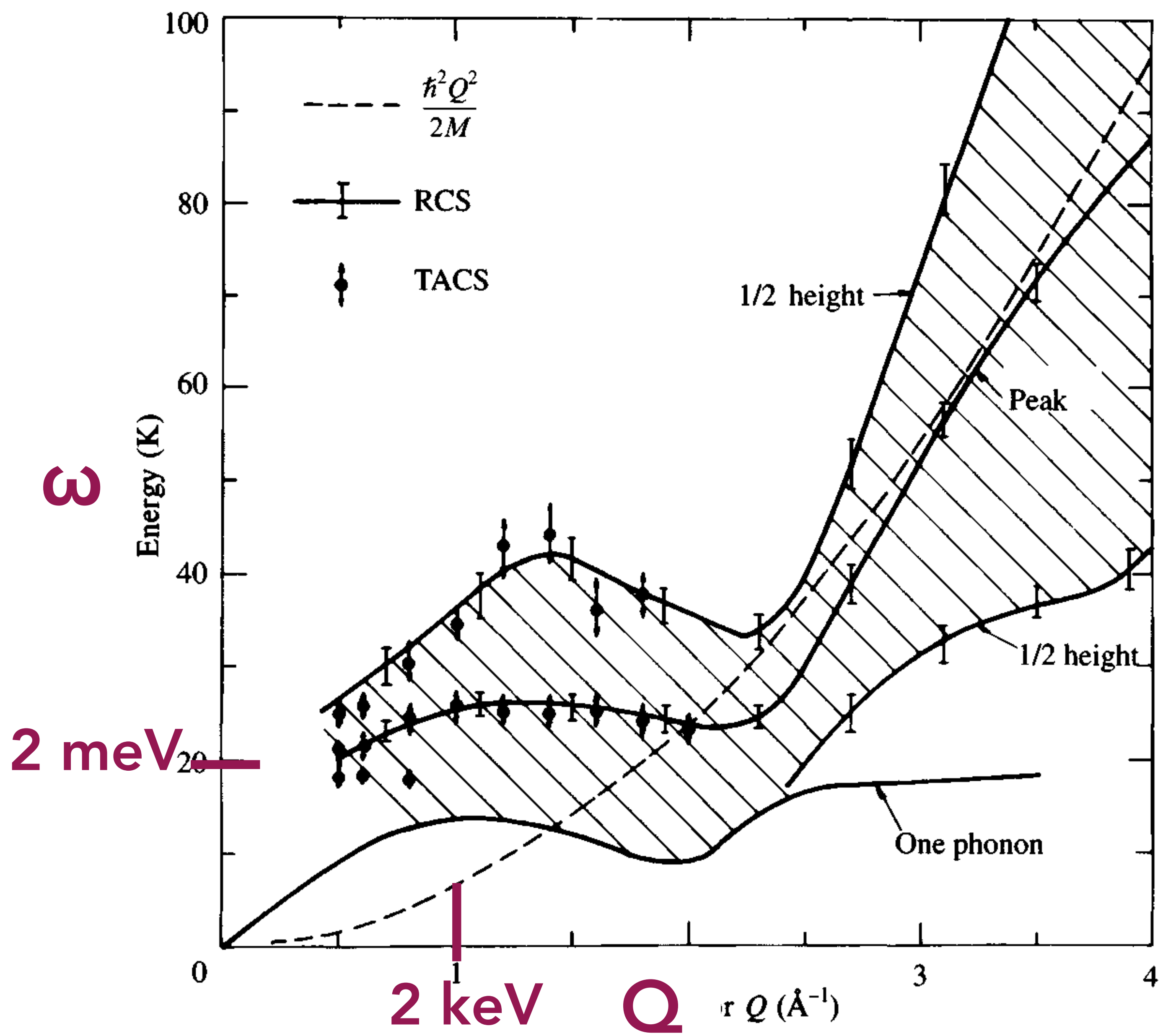
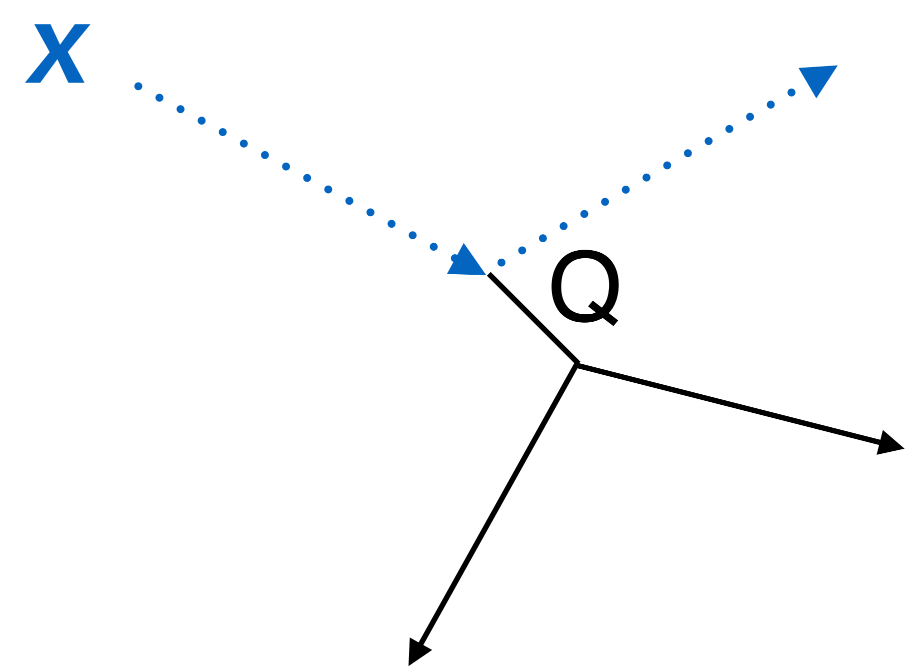


Fig. 1.6. The broad high-energy ...particle (or multiphonon) structure in $S(\mathbf{Q}, \omega)$ at intermediate Q at 1.1 K and SVP. The "peak" position and its width are indicated [Source: Cowley and Woods, 1971].

2-phonon excitation



Kinematics allows larger energy ω deposited, even for small Q

Schutz and Zurek 2016
Knapen, TL, Zurek 2016

Hidden photons in helium

Kinetic mixing: $\mathcal{L} \supset \frac{\kappa}{2} F^{\mu\nu} F'_{\mu\nu}$

At long wavelengths, the electric charge is screened and the hidden photon must couple to the atomic polarizability.

Leading operator for photon coupling in helium:

$$H_I = -\frac{1}{2}\int d^3r\, \mathbf{P}(\mathbf{r}) \cdot \mathbf{E}_\gamma(\mathbf{r}) \qquad \mathbf{P}(\mathbf{r}) = \alpha\, n(\mathbf{r})\, \mathbf{E}(\mathbf{r})$$

Fetter 1972

Leading operator for hidden photon coupling in helium:

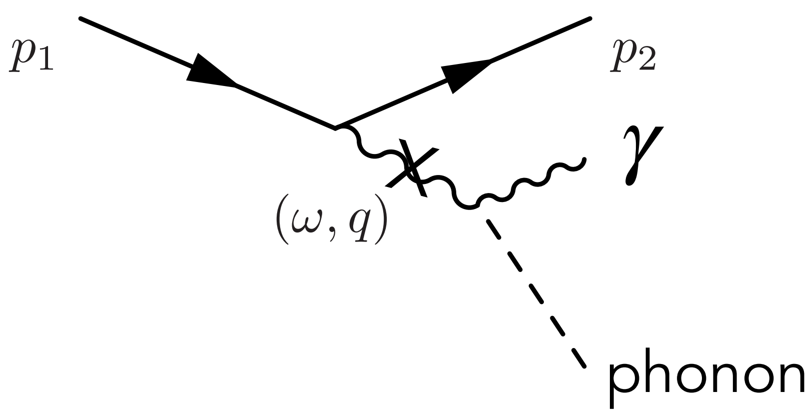
$$H_I = -\kappa\alpha \int d^3r\, n(\mathbf{r})\, \mathbf{E}(\mathbf{r}) \cdot \mathbf{E}'(\mathbf{r})$$

Atomic polarizability of He $\quad \alpha_{pol} \sim \frac{1}{(\alpha_{EM} m_e)^3} \approx 2 \times 10^{-25}\ \mathrm{cm}^3$

Hidden photons in helium

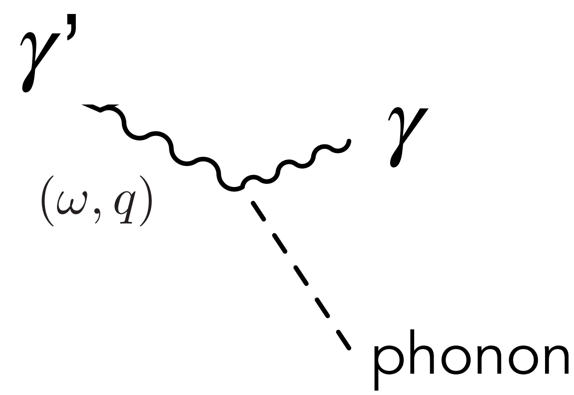
$$H_I = -\kappa\alpha \int d^3r\, n(\mathbf{r})\, \mathbf{E}(\mathbf{r}) \cdot \mathbf{E}'(\mathbf{r})$$

- Scattering via hidden photon



Reach $\kappa \sim 10^{-7}$ for $m_X = \mathrm{MeV}$

- Absorption of hidden photon



Reach $\kappa \sim 10^{-9}$ for $m_V = \mathrm{eV}$

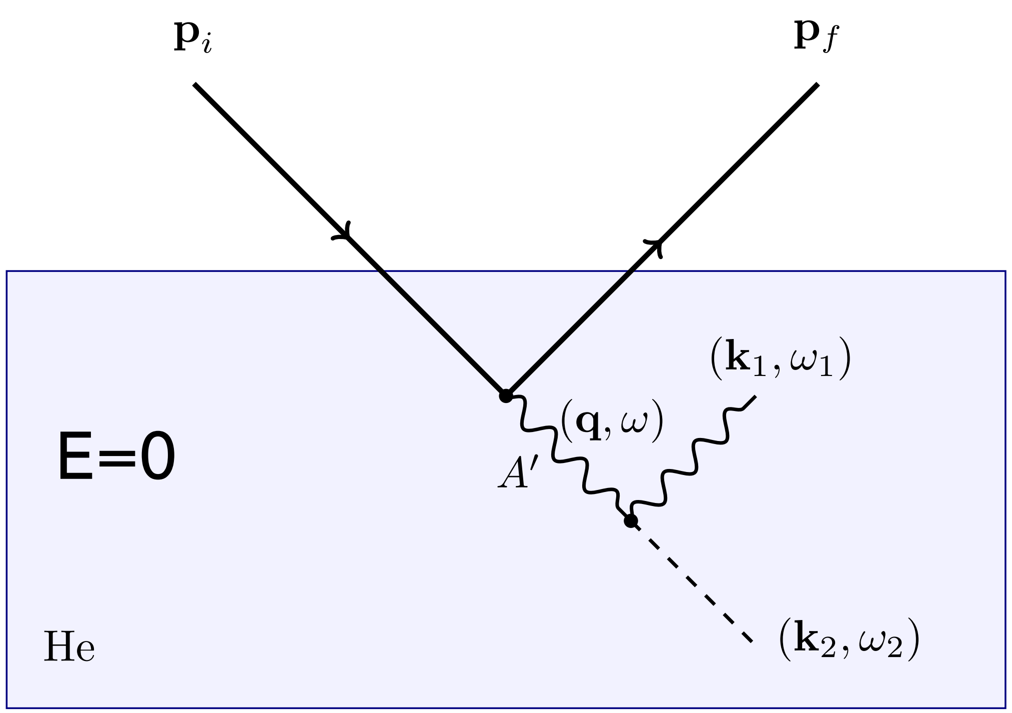
(Not competitive with existing stellar constraints)

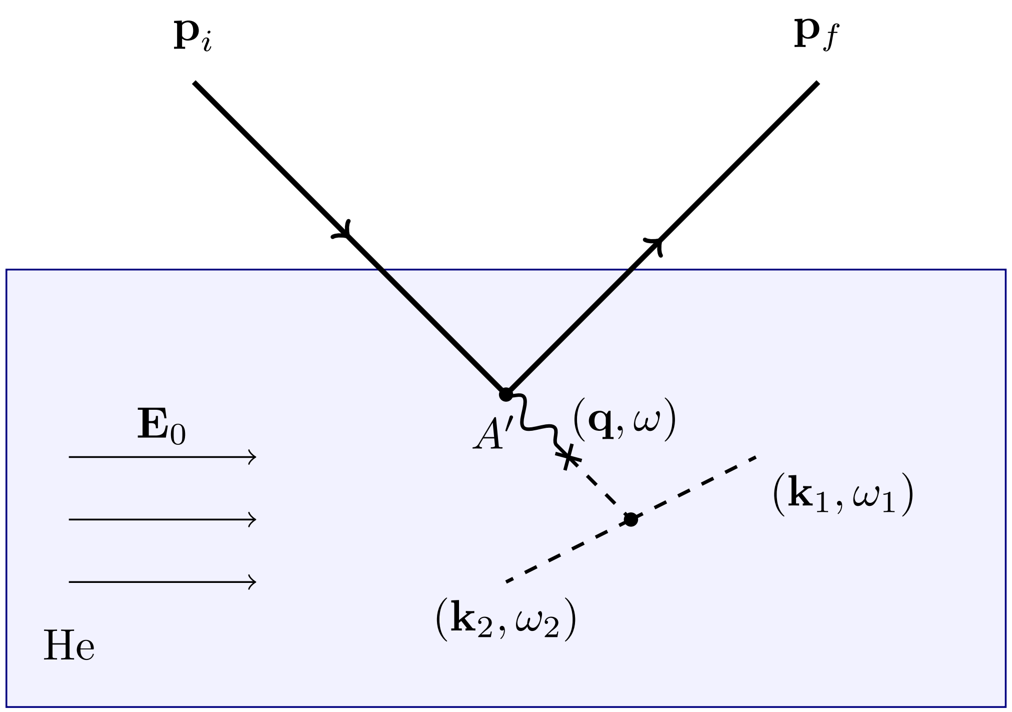
Helium is (very) transparent:

No in-medium suppression 😎

Coupling through polarizability small 😟

Applying an E field





- Consider applying E ~ 100 kV/cm (Ito et al. 2015)
- Energy threshold + kinematics now requires multi-phonon excitations again: this is highly suppressed for absorption of non relativistic bosons (small **q**). Again, sensitivity is not competitive.

Conclusions

- Semiconductors and superconductors: excellent prospects for DM absorption on electrons, despite in-medium effects

- Superfluid helium: great for nuclear recoils, difficult to probe hidden photon models

- Diversity of targets important