Detecting Ultralight Bosonic Dark Matter via Absorption in Superconductors

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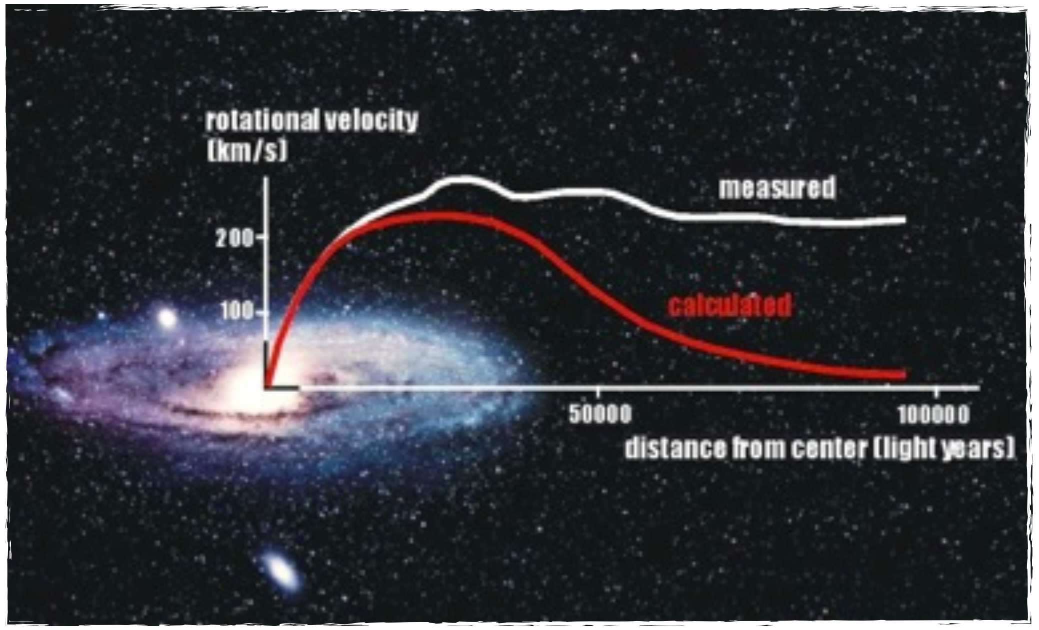
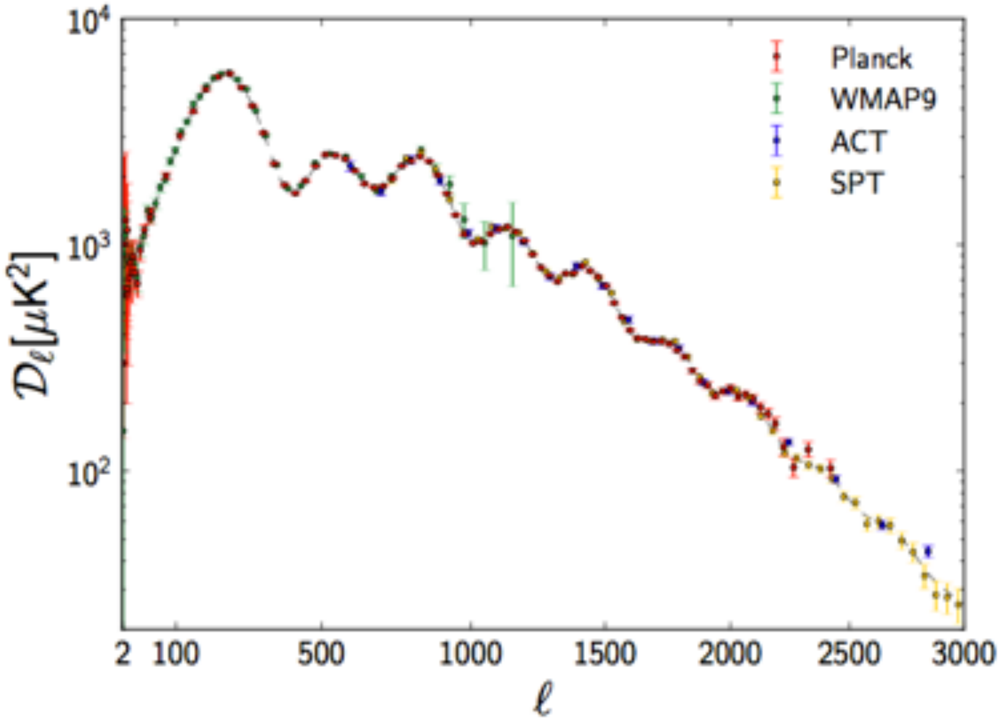
With Yonit Hochberg & Kathryn Zurek, 1604.06800

Mass scale of dark matter?





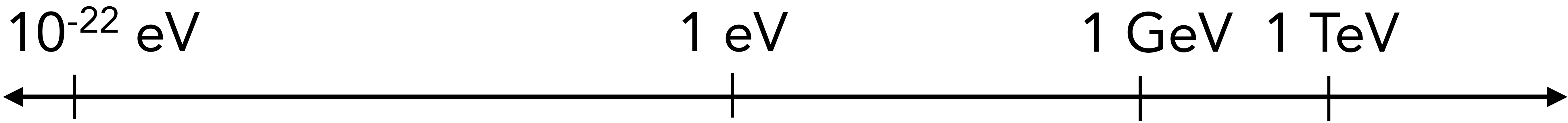
Local dark matter density:

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

Average dark matter density:

$$\Omega_c h^2 = 0.1199 \pm 0.0027$$

Mass scale of dark matter?



10^{-22} eV

1 eV

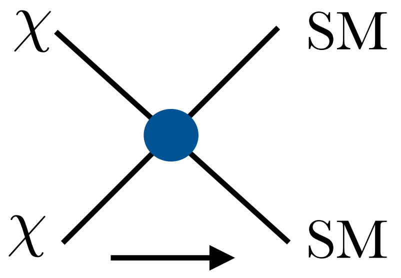
1 GeV

1 TeV

Bosonic dark matter

Low-threshold
(superconducting)
detectors!
[Today: meV to 10 eV]

WIMP



Nuclear recoil in
direct detection →
experiments

Ultralight bosonic dark matter

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

- Coherent field below m ~ eV

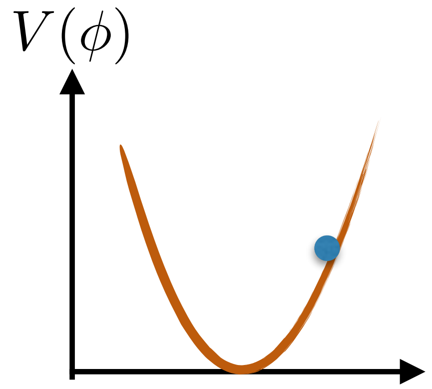
Local DM density: 0.4 GeV/cm^3 $\qquad \lambda_{\rm dB} \sim \frac{2\pi}{m_{\rm DM} v} \qquad v \sim 10^{-3}$

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

- Relic abundance through ``misalignment"

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

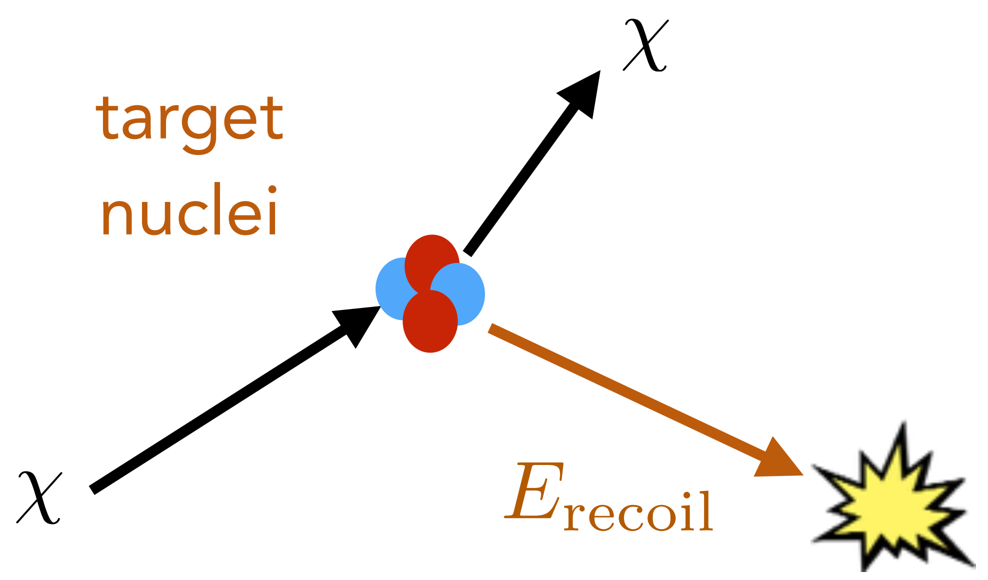
ϕ_0 — field amplitude today



Outline

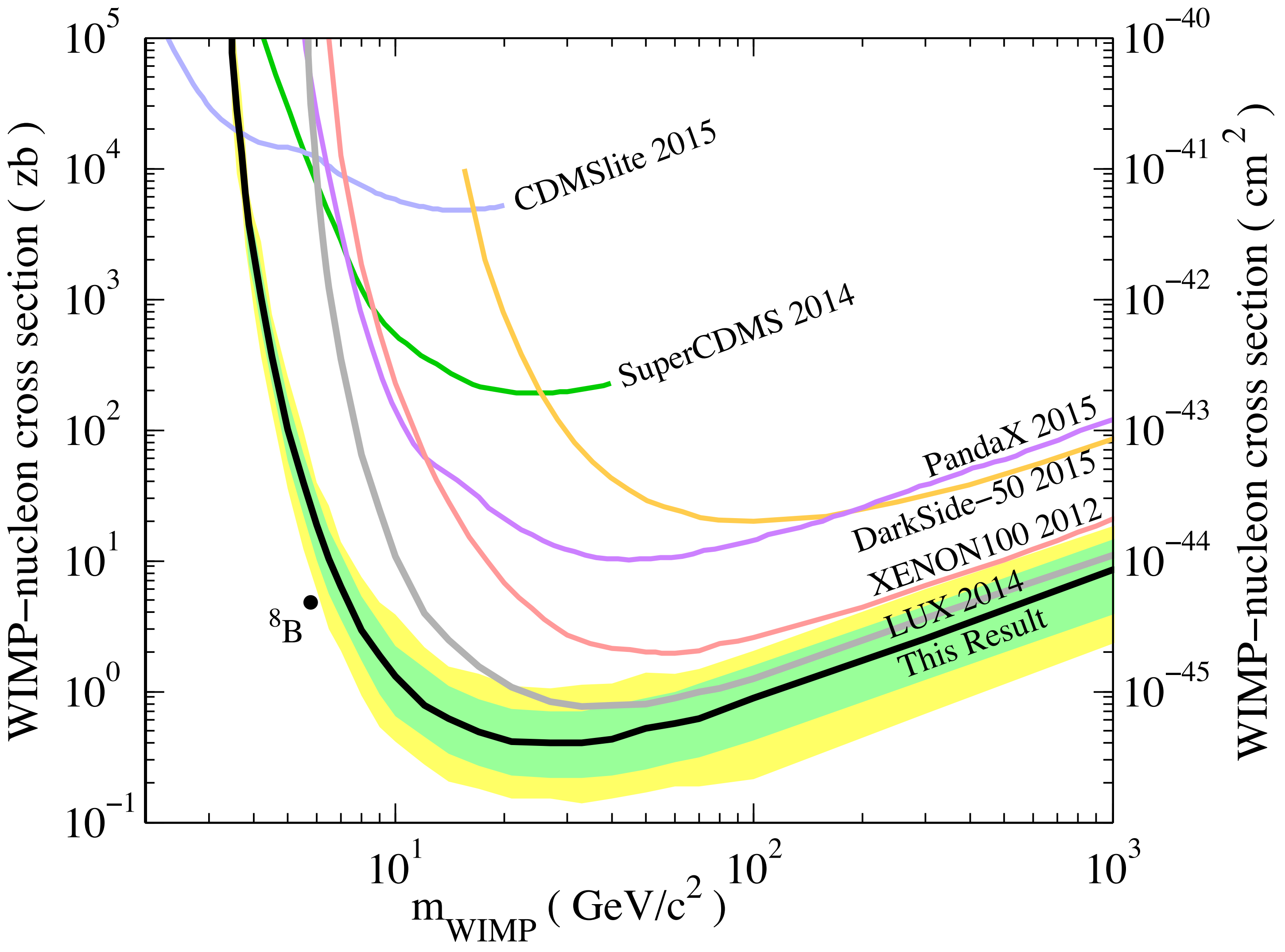
- Direct detection of light dark matter
- Detection with superconducting targets
- Absorption of light bosonic dark matter

Direct detection of WIMPs in the halo



Heat, ionization, charge from recoiling nucleus

Xe target - LUX 2015



- Energy deposited from WIMP in nuclear recoil:

$$E_R \sim \frac{\mu_{\chi N}^2 v^2}{m_N} \sim 1 - 100\,\mathrm{keV} \qquad v \sim 10^{-3}$$

Direct detection of light dark matter

- Below ~ 1 GeV, inefficient energy transfer to nuclei

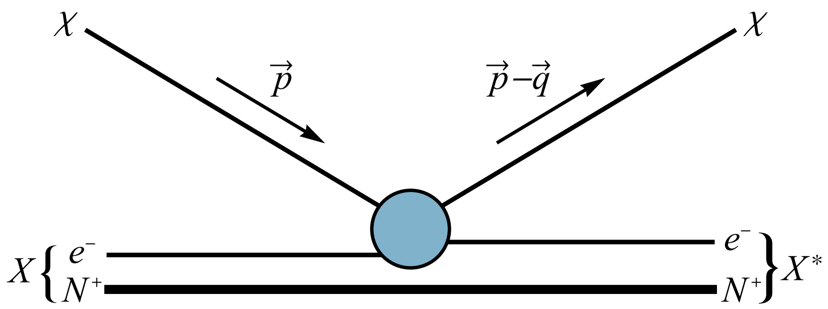
$$E_R \sim \frac{\mu_{\chi N}^2 v^2}{m_N} \sim \mathrm{eV} \times \left(\frac{m_\chi}{100\,\mathrm{MeV}}\right)^2 \left(\frac{10\,\mathrm{GeV}}{m_N}\right)$$

- Nuclear recoils below ~1 keV difficult to observe.

(But may be possible in superfluid helium!)

- Electron scattering is more efficient, can be observed to lower thresholds.

$$E_e \sim \mu_{\chi e} v^2 \sim \mathrm{eV} \left(\frac{m_\chi}{\mathrm{MeV}}\right)$$



Electron scattering

- Electron interactions already constrained with Xenon10, via DM ionization signal — $E_{th} \sim 14\,\mathrm{eV}$

[Essig, Volansky et al. 2012]

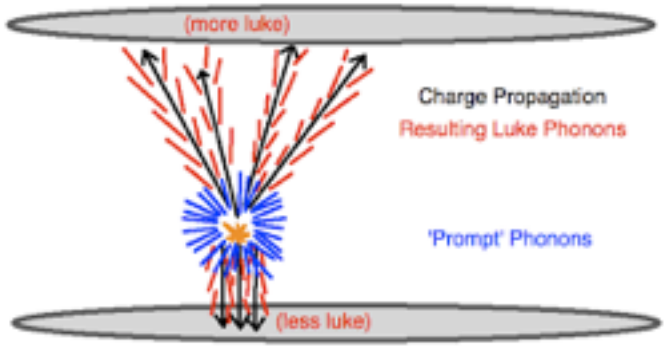
Going lower

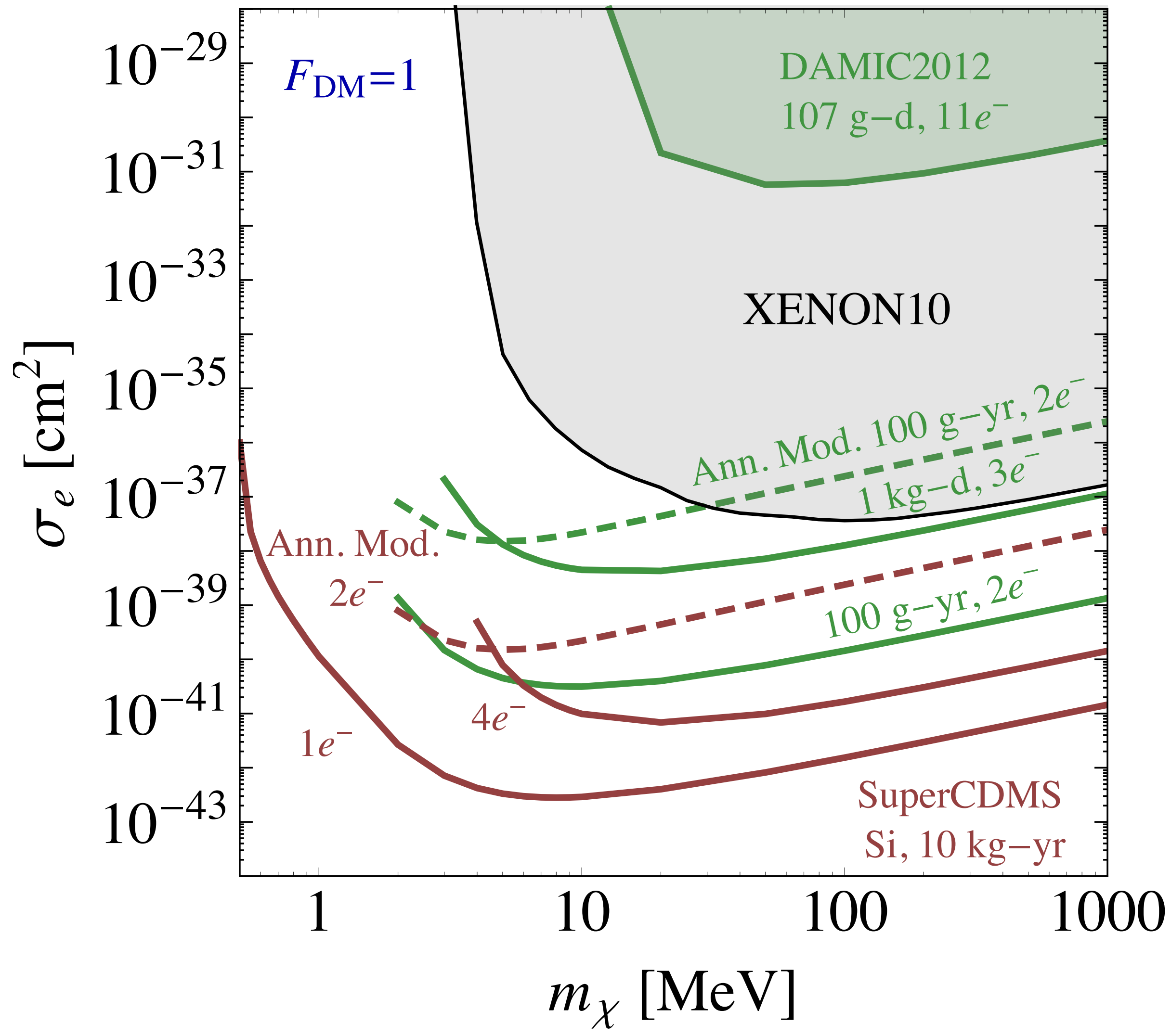
- Semiconductor targets have even smaller gap, ~ eV

— Ge, Si with SuperCDMS
— Si with DAMIC

- Access to ~ MeV mass for DM-electron scattering

CDMSlite/SuperCDMS

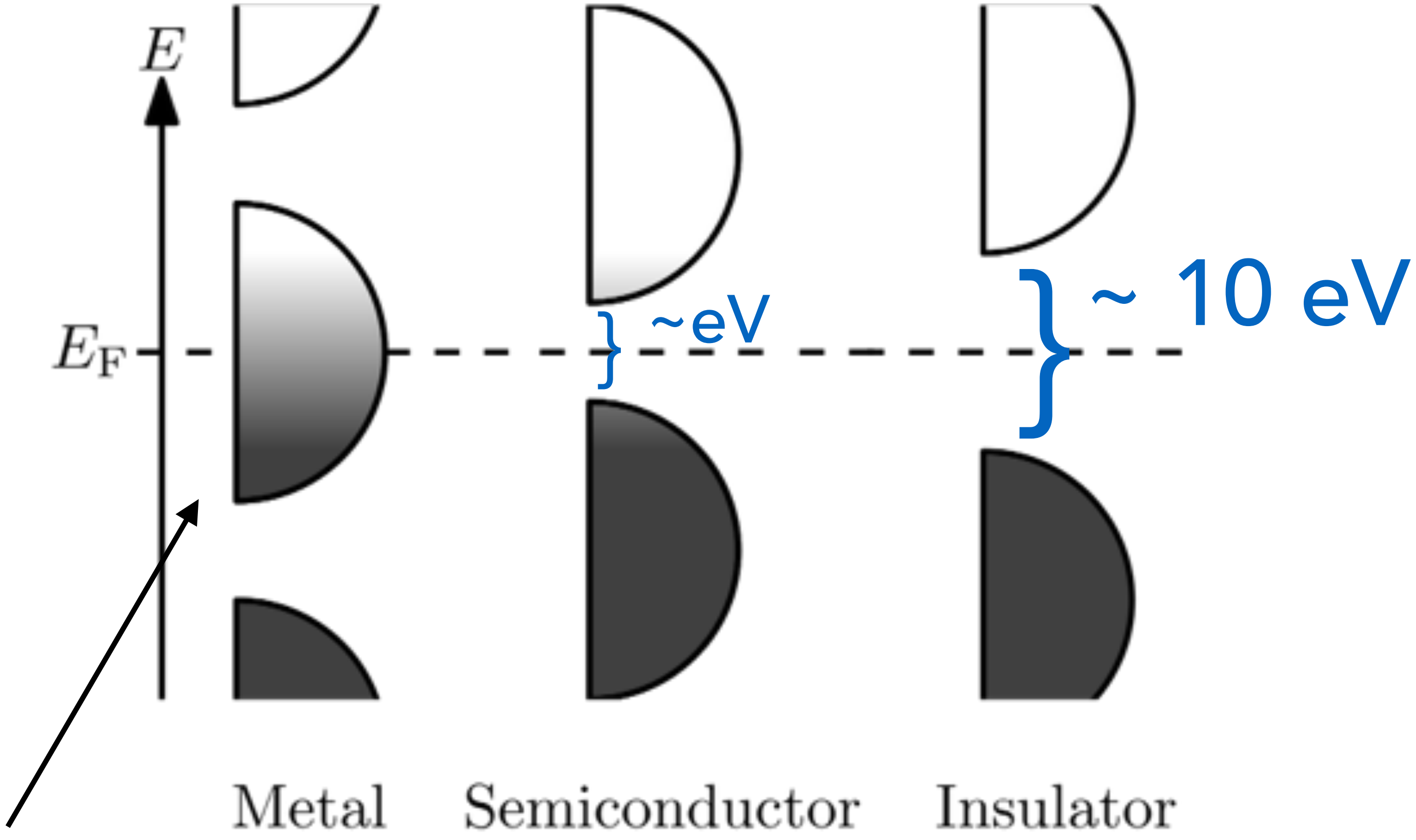




[Essig, Volansky et al. 2015]

Superconducting targets

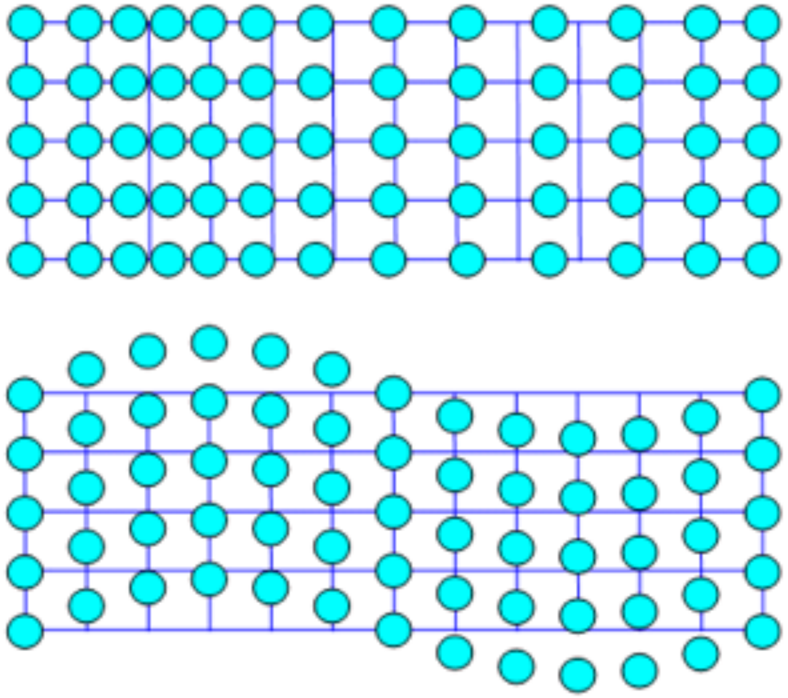
Band gaps



Gapless.
But excitations
in metals rapidly
thermalize!

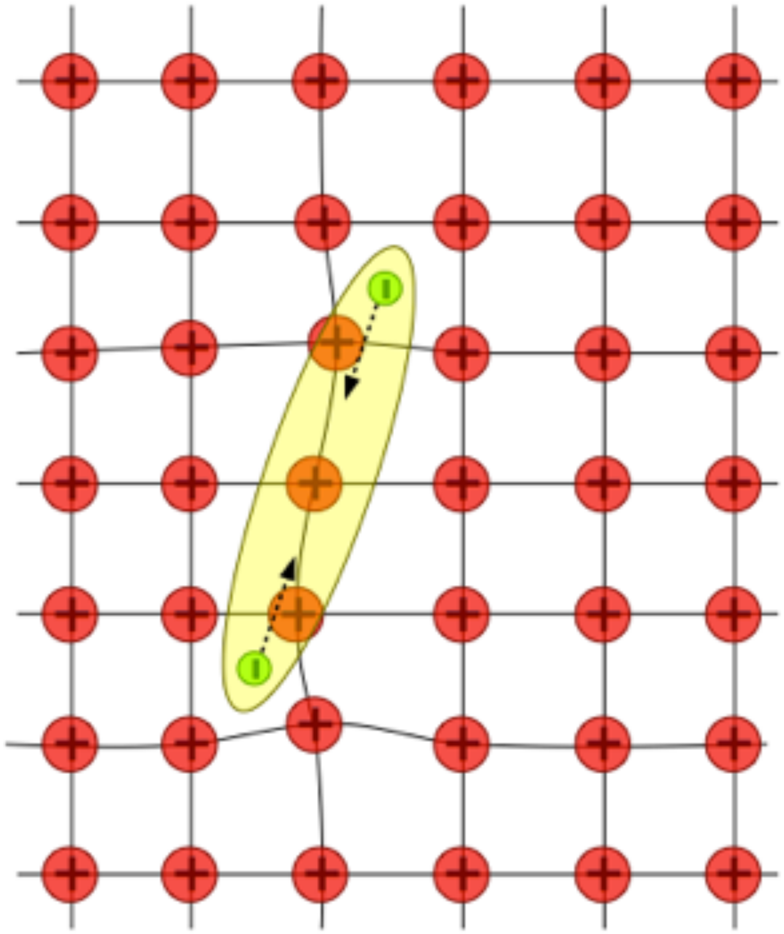
Phonons

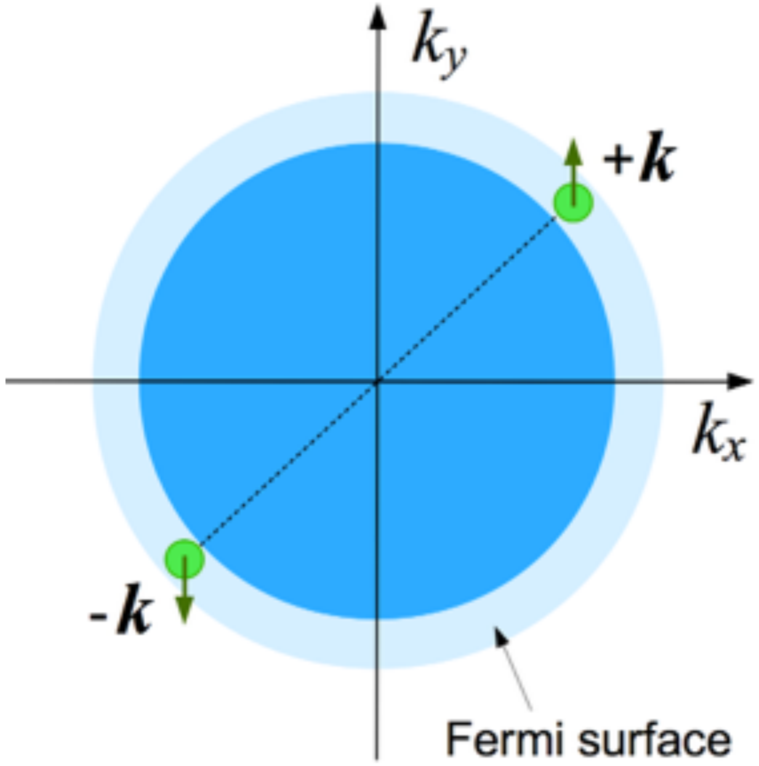
- Quantized lattice vibrations
- Electron-phonon interaction → thermalization, resistivity.
- (Later) also essential for absorption of very light DM
- Attractive force leading to superconducting phase



Cooper pairing

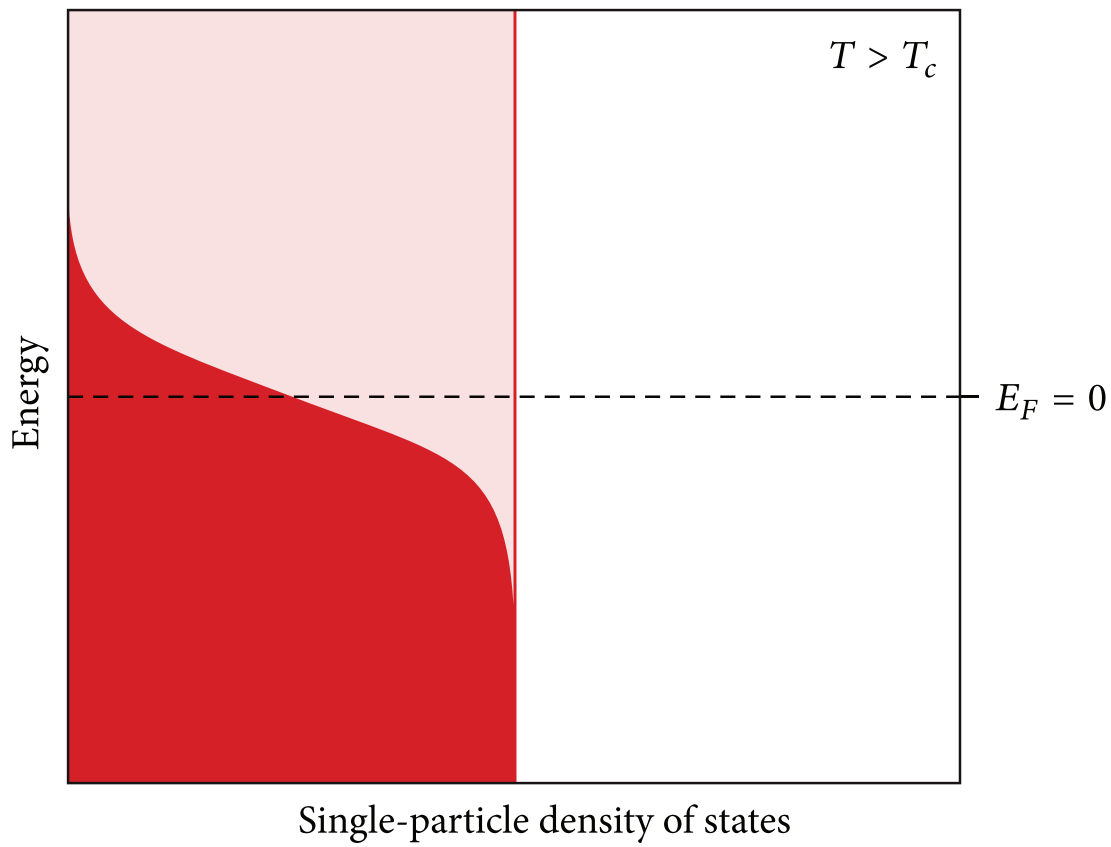
- Weak attractive force due to phonons:



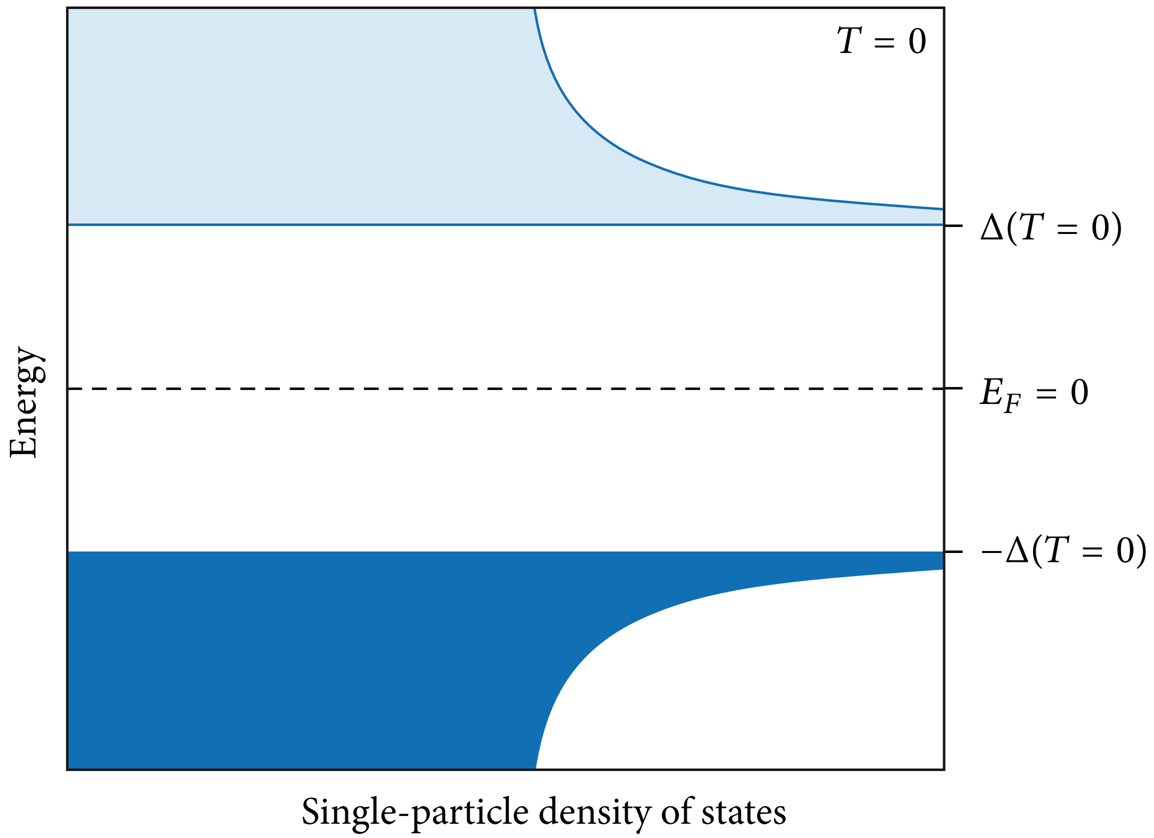


BCS superconductors

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



Metal



Superconductor

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

Why superconductors?

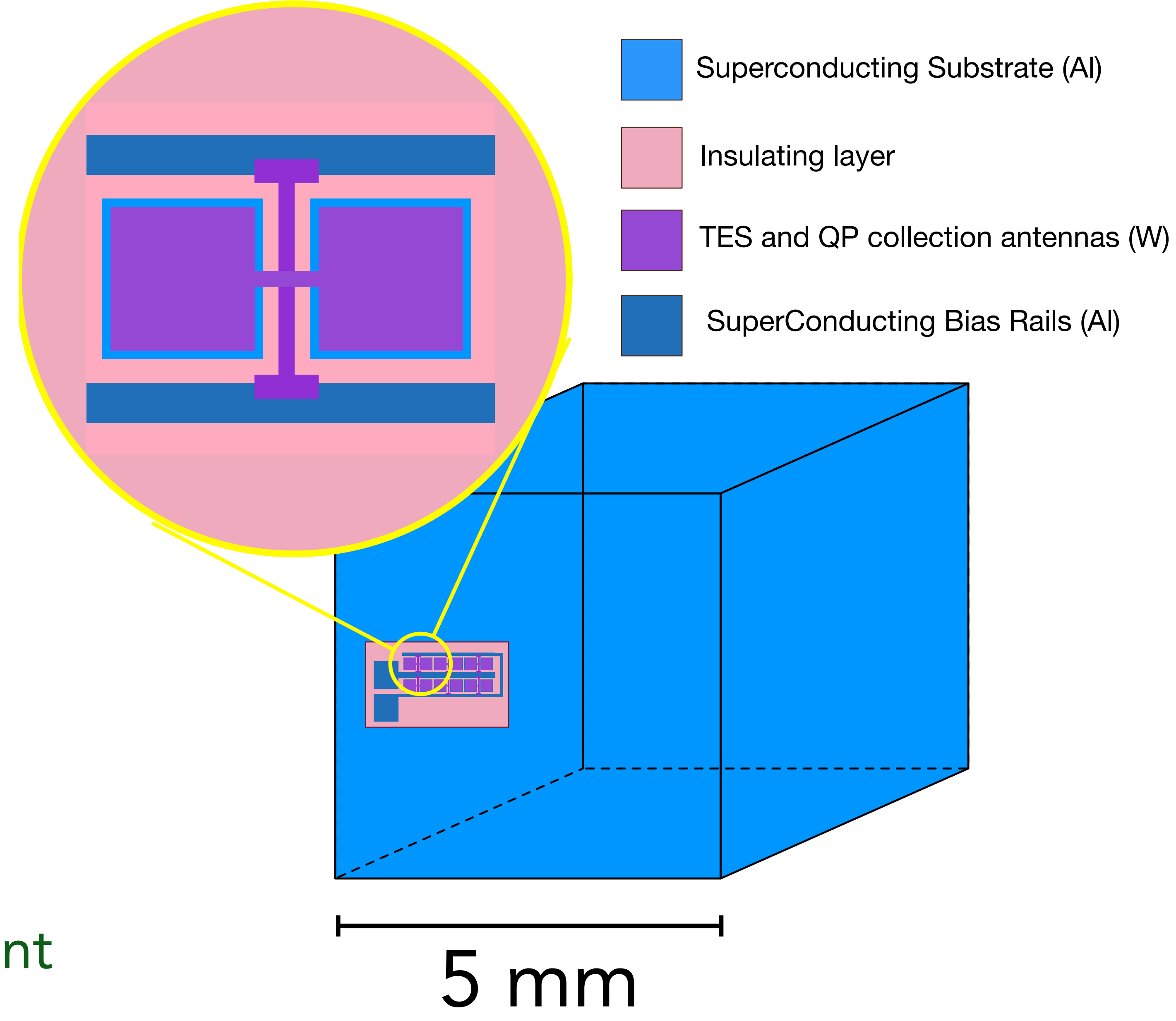
- Small band gap (< meV)
- Long-lived electron (quasiparticle) excitations
- Cooper pairs decoupled from thermal noise
- Large electron velocity ($v_F \sim 10^{-2}$) in metal can help to extract DM kinetic energy

Detection schematic

- Energy deposited from DM
- Excitations propagate and scatter with long lifetime
- Small collection fins for excitations
- Measurement by sensitive bolometer (TES)

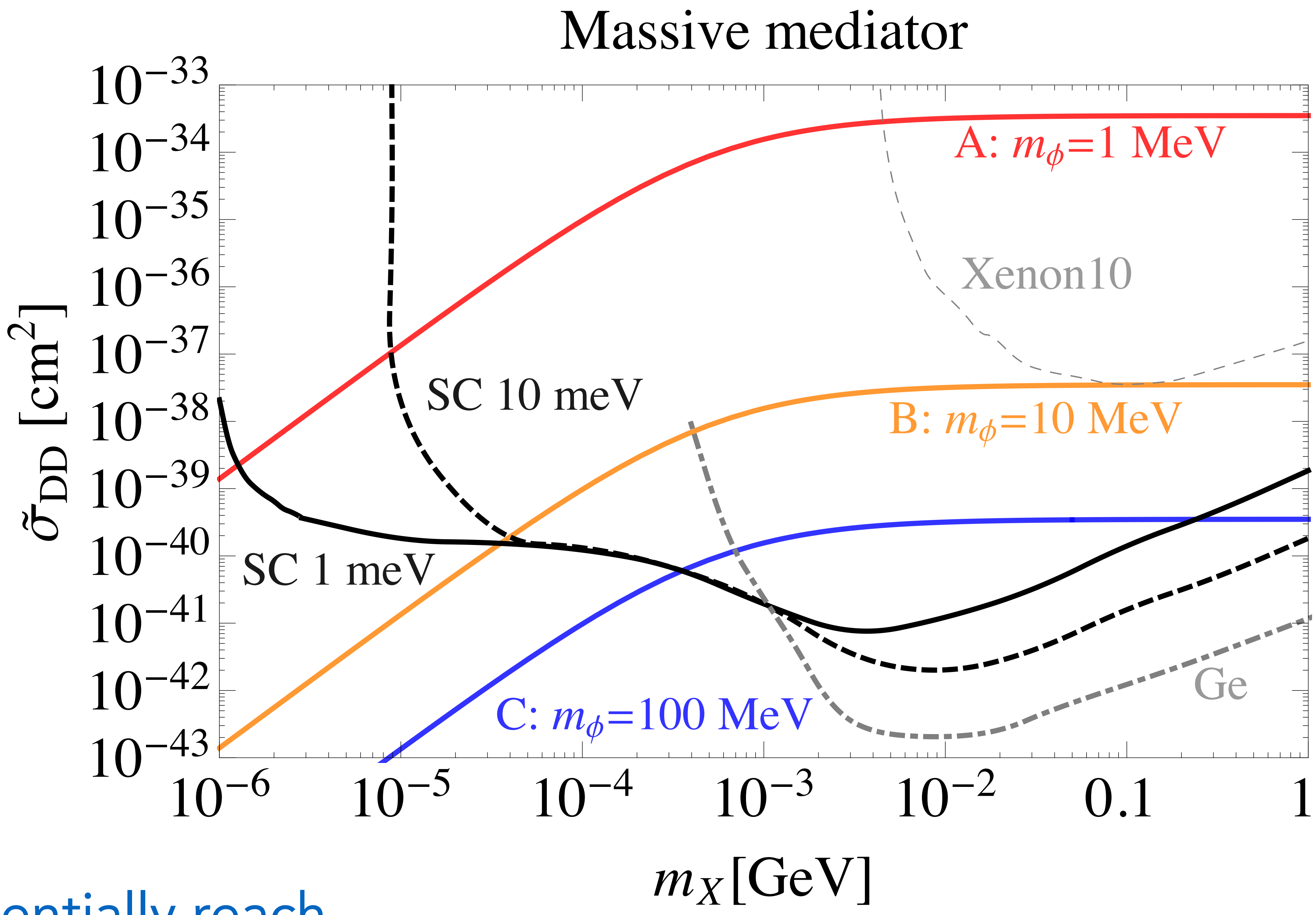
[Must improve substantially on current energy resolution~50-100 meV!]

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



Hochberg, Pyle, Zhao, and Zurek 2015

Reach for DM-electron scattering



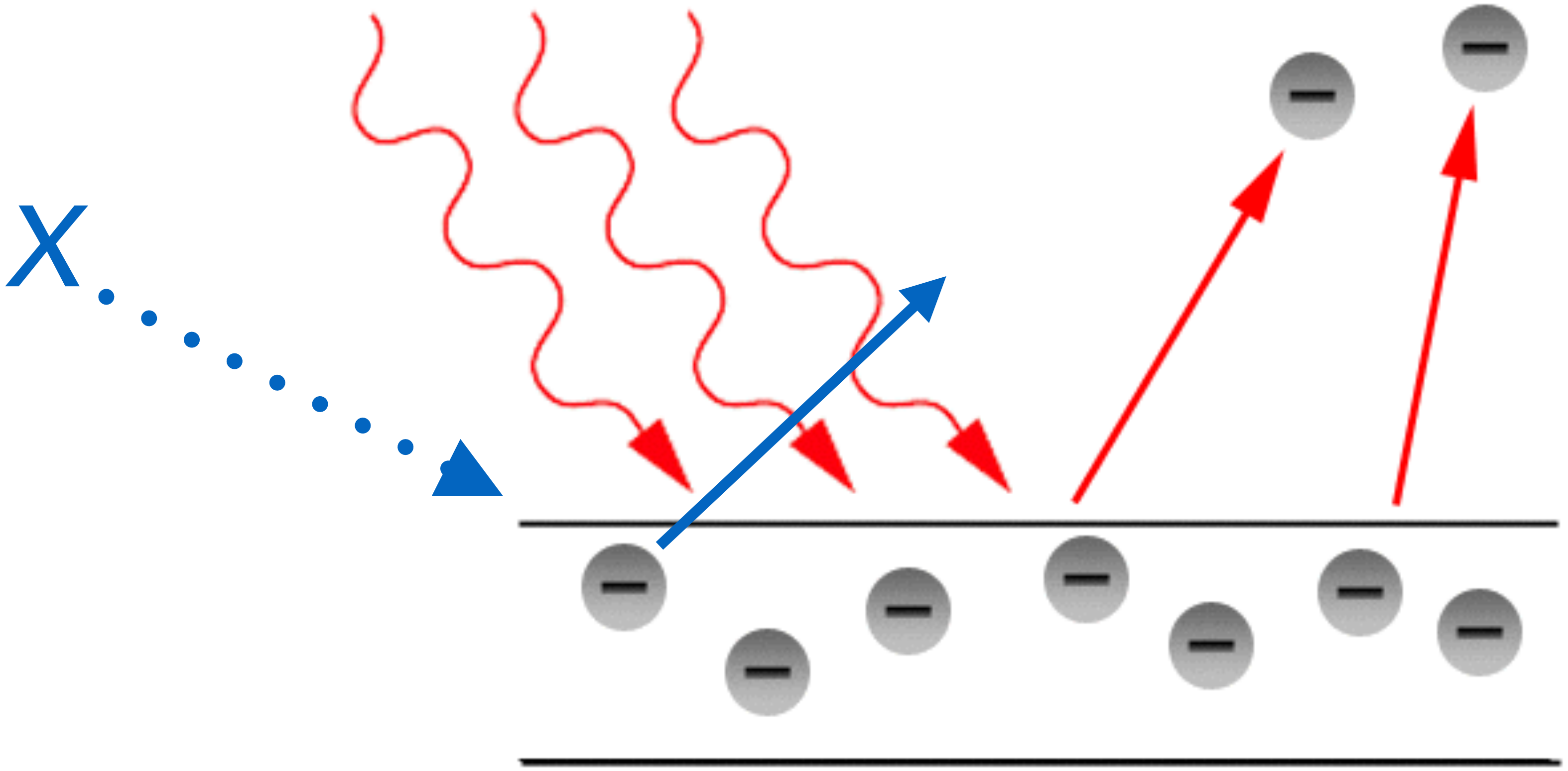
Potentially reach
“warm dark matter”
limit of keV

Hochberg, Pyle, Zhao, and Zurek 2015

Absorption of ultralight DM

Absorption

Photoelectric effect:



absorb all of the mass-energy of incoming dark matter, excite electrons

Absorption kinematics

Non-relativistic electron absorbing particle with energy $\omega \cong m$:

$$\frac{(\vec{k}_i + \vec{q})^2}{2m_e} = \frac{\vec{k}_i^2}{2m_e} + \omega$$

Typical $k_i \sim k_F$ = 3.5 keV in aluminum

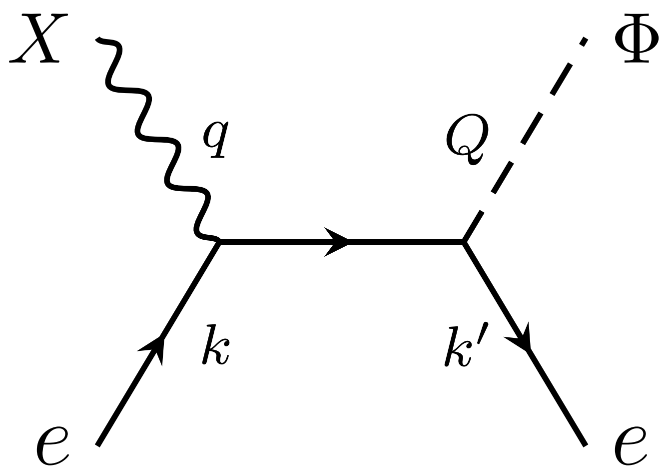
The required momentum transfer to the electron is:

$$|\vec{q}| \sim \omega \frac{m_e}{|\vec{k}_i|} \sim \frac{\omega}{v_F} \sim 100\ \omega$$

Not possible for cold dark matter, with $q \sim 10^{-3}\omega$

Phonon emission

The electron must recoil against the lattice:



Debye model for phonons:

Energy: $\Omega = c_s|\vec{Q}|$ ← Maximum value for |Q|, set by the lattice spacing

$$\Omega_{\mathrm{max}} = \omega_D \approx 0.036\,\mathrm{eV}$$

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.

Absorption rate

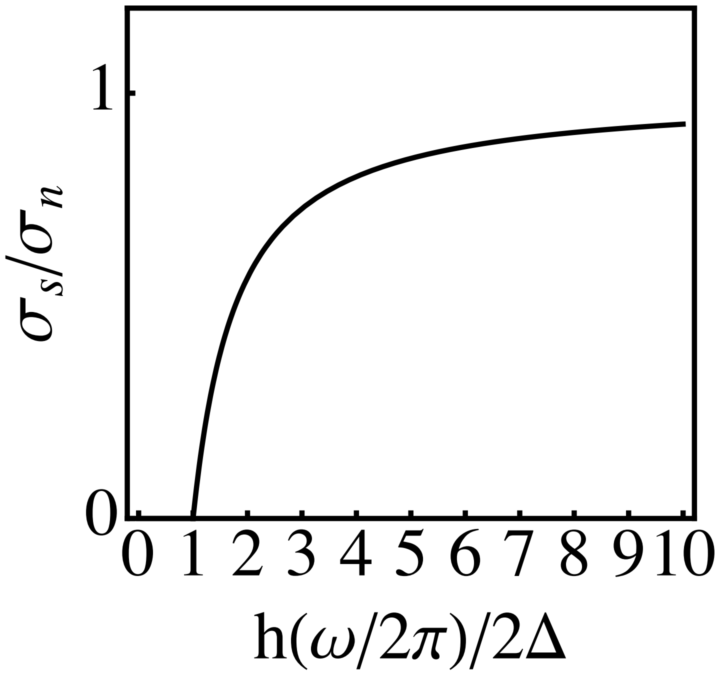
Rate per unit time per unit mass of the detector:

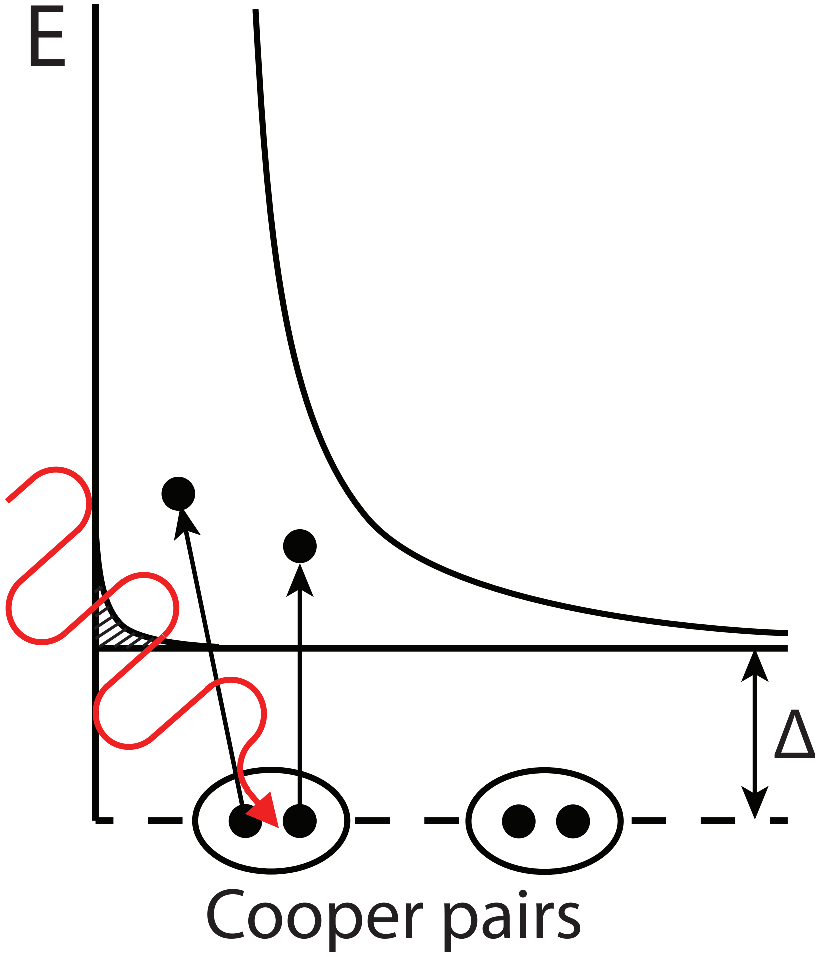
$$R = \frac{1}{\rho} \frac{\rho_X}{m_X} \langle n_e \sigma_{\text{abs}} v_{\text{rel}} \rangle$$

mono-energetic signal

- Compute rate near Fermi surface
- Use photon absorption rate for larger energy

At energies far above the gap Δ, the conductivity is just that of a metal:



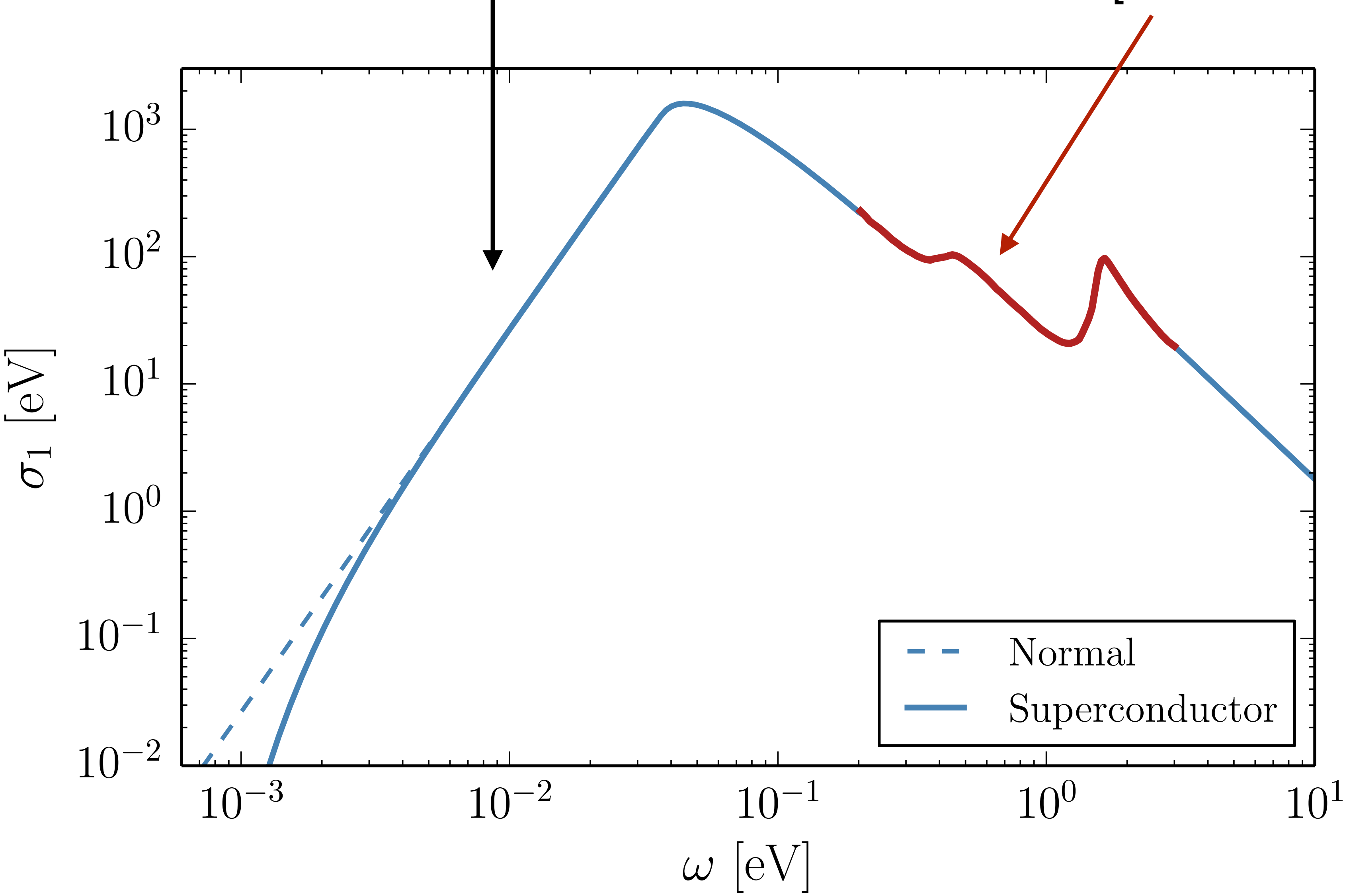


[Mattis-Bardeen theory]

Photon Absorption

Drude theory with $\tau(\omega)$

Match onto low-temp data [Benbow & Lynch 1975]



Photon absorption rate

Energy

We use this to get DM absorption rate.

Models

Hidden photon dark matter

Absorption rate

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

photon absorption

Kinetic mixing in vacuum

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

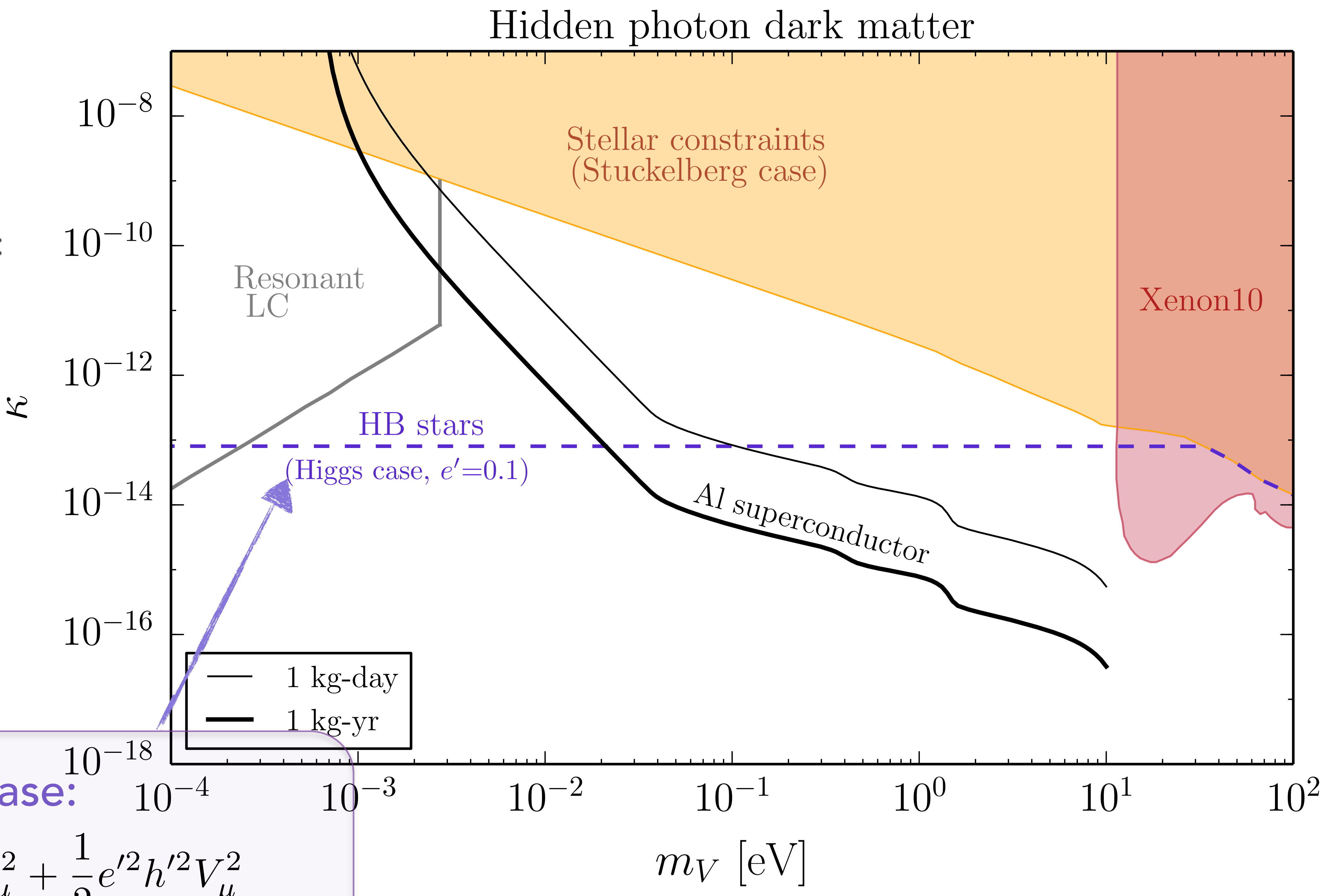
V-electron coupling from field redefinition:

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

For light vectors, large suppression of kinetic-mixing in metal:

$$\kappa^2_{\rm eff} \simeq \frac{\kappa^2 m_V^4}{\omega_p^4} \qquad \omega_p \approx 12.2\,{\rm eV}$$

Resonant LC:
Chaudhuri
et al. 2014



Higgs case:

$$e' m_V h' V_\mu^2 + \frac{1}{2} e'^2 h'^2 V_\mu^2$$

additional interactions

Stellar, Xenon100 constraints:
An, Pospelov, Pradler 2013, 2014

Pseudoscalar dark matter

- Coupling: $\mathcal{L} \supset \frac{g_{aee}}{2m_e}(\partial_\mu a)\bar{e}\gamma^\mu\gamma^5 e$

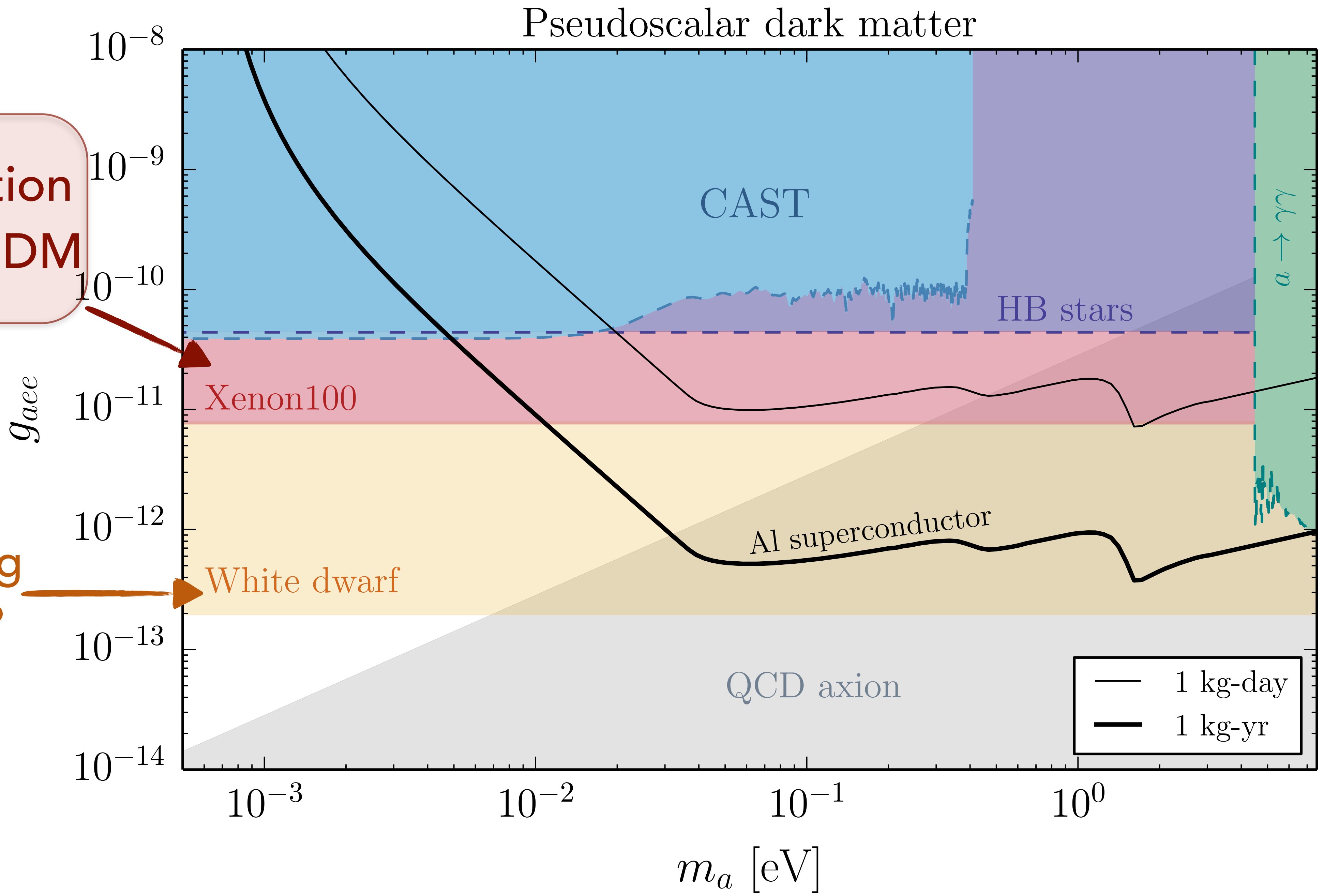
Absorption rate

$$R = \frac{1}{\rho}\frac{\rho_X}{m_X}\frac{3m_a^2}{4m_e^2}\frac{g_{aee}^2}{e^2}\sigma_1$$

photon absorption

Absorption of solar DM

Cooling hint??



Scalar dark matter

Coupling: $\mathcal{L} \supset d_{\phi ee}\sqrt{4\pi}\,\frac{m_e}{M_{pl}}\,\phi\bar{e}e$

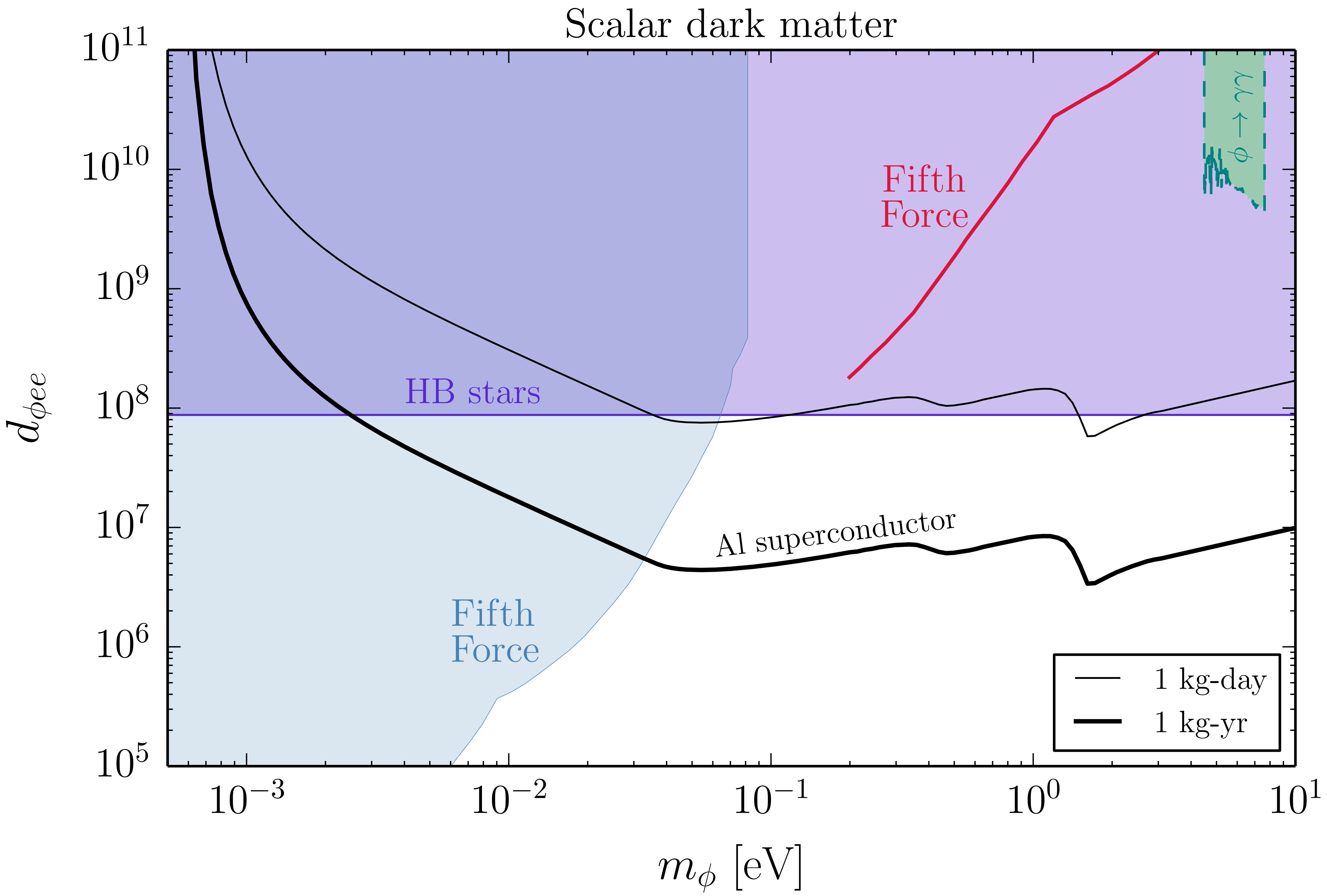
Absorption rate

photon absorption

$$R = \frac{1}{\rho}\,\frac{\rho_X}{m_X}\,\frac{3}{\alpha}\left(d_{\phi ee}\,\frac{m_e}{M_{pl}}\right)^2 \sigma_1 \times \begin{cases} \frac{5}{2}c_s^2 & , \quad \omega < \omega_D \\ \frac{5}{3}\,\frac{c_s^2\omega^2}{\omega_D^2}\,\frac{\left(1-\frac{3\omega_D}{4\omega}\right)}{\left(1-\frac{5\omega_D}{6\omega}\right)} & , \quad \omega > \omega_D \end{cases}$$

Different |Q| dependence: $|\mathcal{M}|^2 \approx \frac{3}{\alpha}\left(\frac{d_{\phi ee}m_e}{M_{pl}}\right)^2 \frac{\omega^2}{|\vec{Q}|^2}|\mathcal{M}_\gamma|^2$

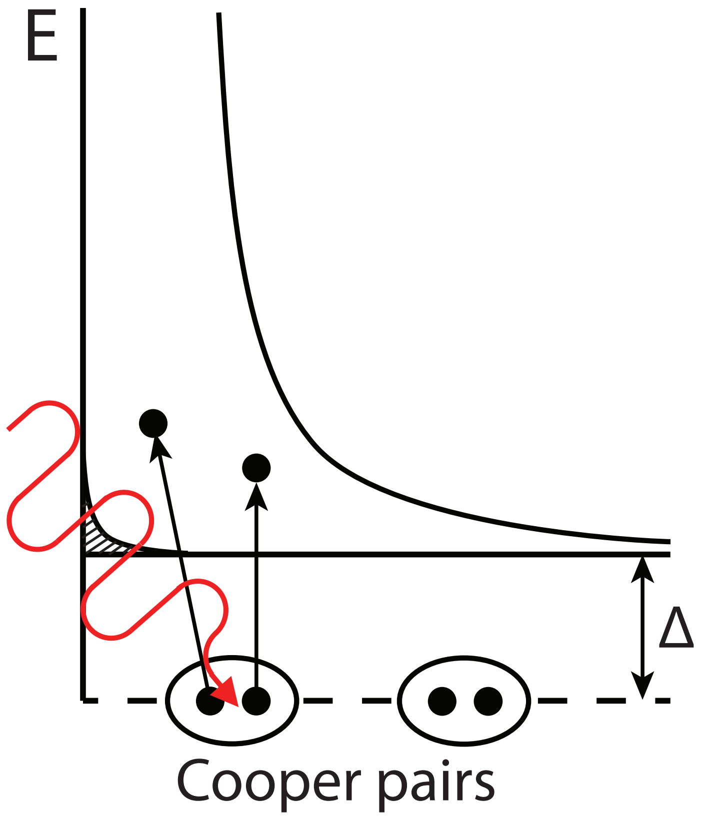
Scalar dark matter



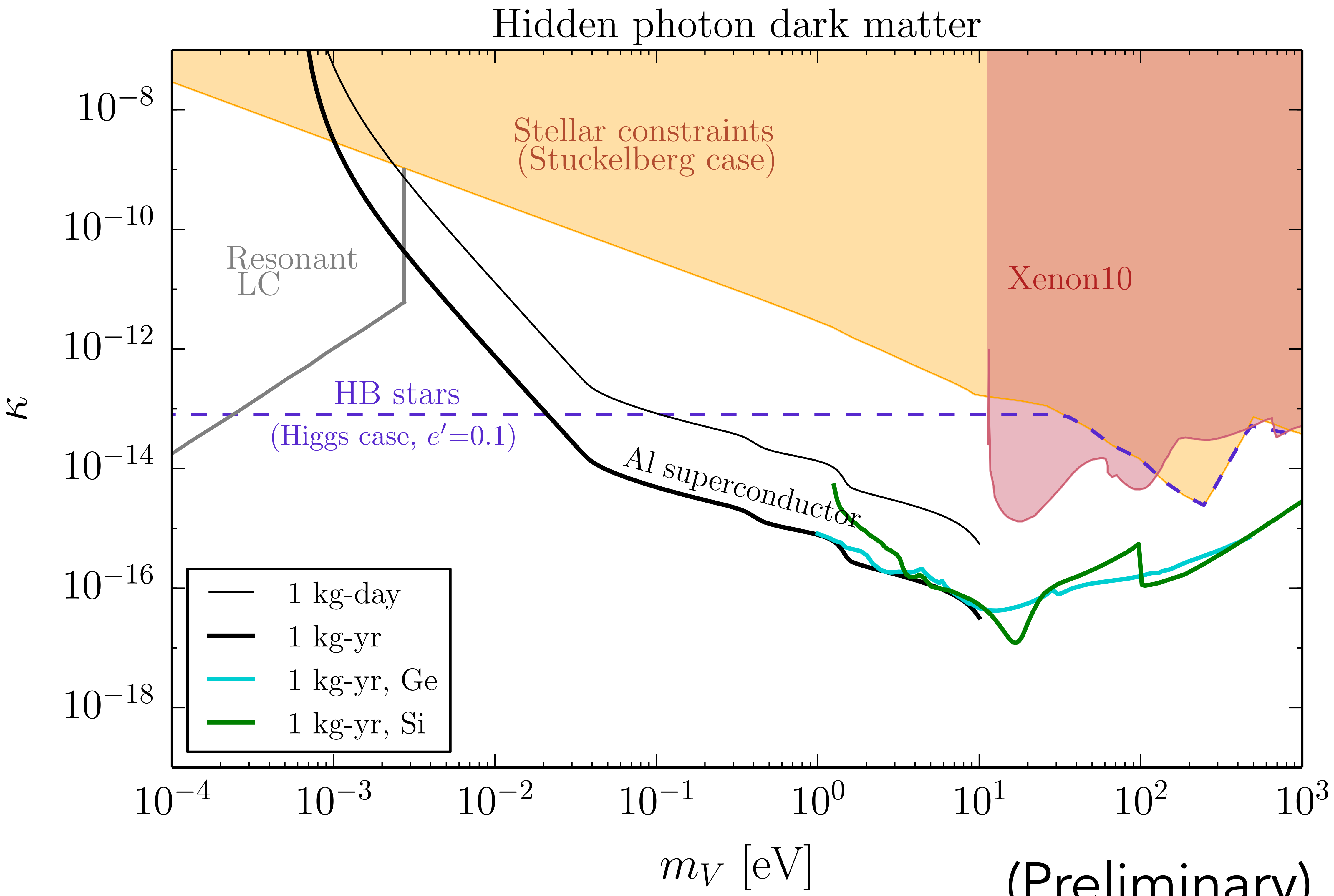
$$\mathcal{L} \supset d_{\phi ee}\sqrt{4\pi}\frac{m_e}{M_{pl}}\phi\bar{e}e$$

Conclusions

- New ideas for direct detection of (ultra)light DM
- Absorption of DM w/ meV to 10 eV mass
- Proposed superconducting detectors competitive with 1 kg-day to 1 kg-year
- Future work: semiconductor & other targets



Semiconductor reach



(Preliminary)