DETECTING DM WITH SUPERCONDUCTORS

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SLAC Dark Forces workshop

Superconducting Detectors for Superlight Dark Matter
Phys.Rev.Lett. 116 (2016) no.1, 011301
Detecting Superlight Dark Matter with Fermi-Degenerate Materials
arXiv:1512.04533
with Yonit Hochberg , Matt Pyle, Kathryn M. Zurek

Existing experiments/proposals

DM-nucleus scattering:

Traditional (ton-scale) DD experiments: LUX, LZ, XENON100

Energy threshold $\sim$ few keV

DM mass > O(10) GeV

Super-CDMS:

Energy threshold $\sim$ 300 eV

DM mass > O(1) GeV

Existing experiments/proposals

DM-electron scattering:

Ionization of noble liquid:

Rouven Essig, Jeremy Mardon, Tomer Volansky, Phys.Rev. D85 (2012) 076007

DM mass > O(1) MeV

Single electron event in semi-conductor detector:

P. Graham, D. E. Kaplan, S. Rajendran, M. Walters, Physics of the Dark Universe 1 (2012) 32-49

R. Essig, M. Fernandez-Serra, J. Mardon, A. Soto, T Volansky, T. Yu, arXiv:1509.01598 [

DM mass > O(1) MeV

Energy threshold determined by binding energy/band gap ~ O(1) eV

Superconductor as detector

DM-electron scattering:

Superconductor has a much lower binding energy O(meV)

0.6 meV for Al ⟹ theoretical energy threshold for DM DD

may further probe lighter DM particles, DM mass > O(1) keV

The existence of SC gap is important:

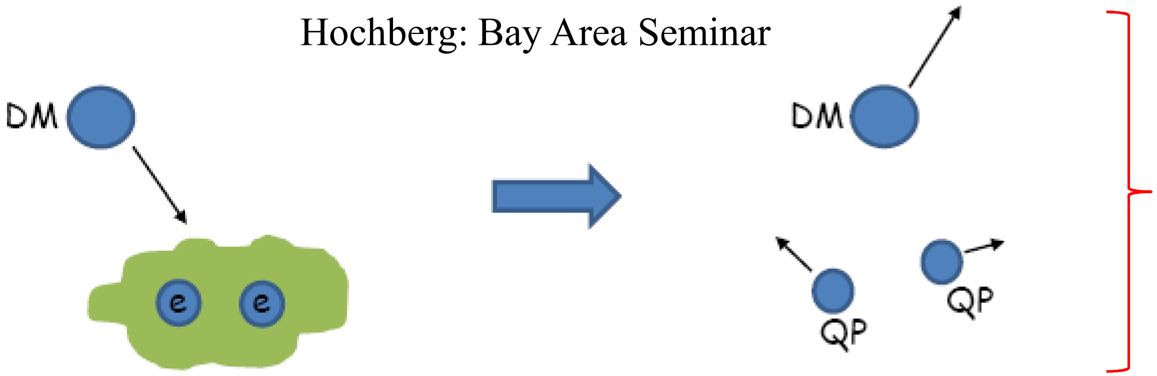
Athermal phonons and quasi-particles are long-lived due to the gap.

⟹ They can be collected before they thermalize.

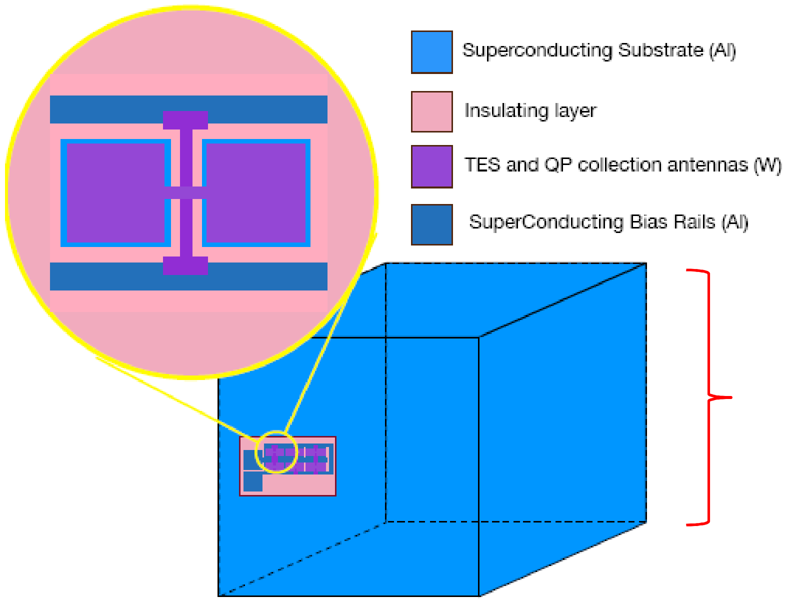
Thermal noise is efficiently suppressed in SC.

Superconductor as detector

Hochberg: Bay Area Seminar



60% quasi-particles
40% athermal phonons



5 mm

Superconductor as detector

Quasi-particle:

Group velocity: $10^{-3} \sim 10^{-2}$ c

Lifetime: 10 ms

⇨ bouncing ($10^{4} \sim 10^{5}$) in absorber (5 mm cubic Al) before recombine

Athermal phonon:

Group velocity: 10^{-5} c

Lifetime: 1 ms

bouncing ~ 1250 times (limited by surface down-conversion)

Superconductor as detector

Competition between large collection area v.s. energy resolution.

Assuming mainly from power noise:

$$\sigma_{\rm E} \propto \sqrt{V_{\rm TES}\, T_{c,\rm TES}^3}$$

For our particular choices of parameters, it can be as good as O(meV).

⟹ This is a numerical coincidence to the energy gap in Al.

We are not limited by SC gap yet, but close.

Energy resolution can be dominated by other sources of noise.

Although nothing prevents us reducing them in principle,

future R&D is definitely required.

DM-electron scattering in SC

When energy deposition is larger than Cooper pair binding energy, coherent factor of Cooper pair is unimportant.

⟹ approximately DM – free electron scattering

Electron Fermi velocity ~ 10^{-2} c >> DM escape velocity ~ 10^{-3}.

When DM mass >> electron mass

$$E_D^{\max} = \frac{1}{2} m_T [(v_{i,T} + 2v_X)^2 - v_{i,T}^2] \simeq 2 m_T v_{i,T} v_X$$

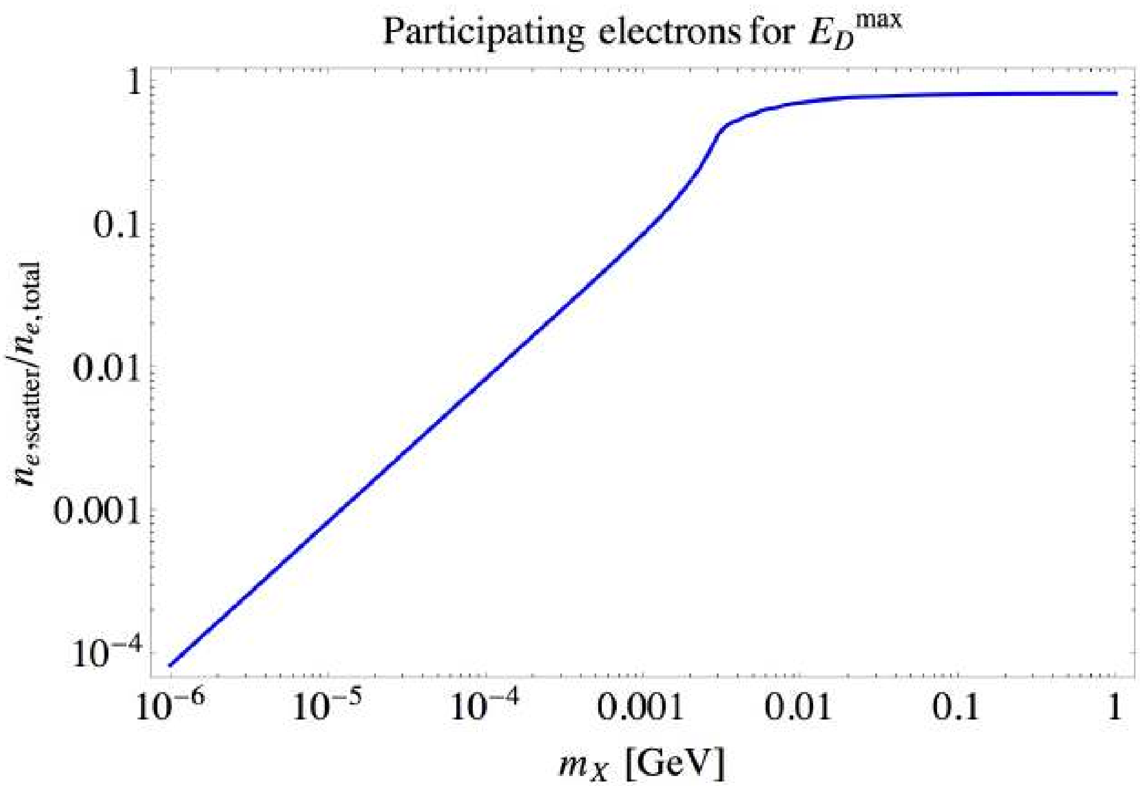
When DM mass << electron mass

DM can be fully stopped $E_D^{\max} = \frac{1}{2} m_X v_X^2$

DM-electron scattering in SC

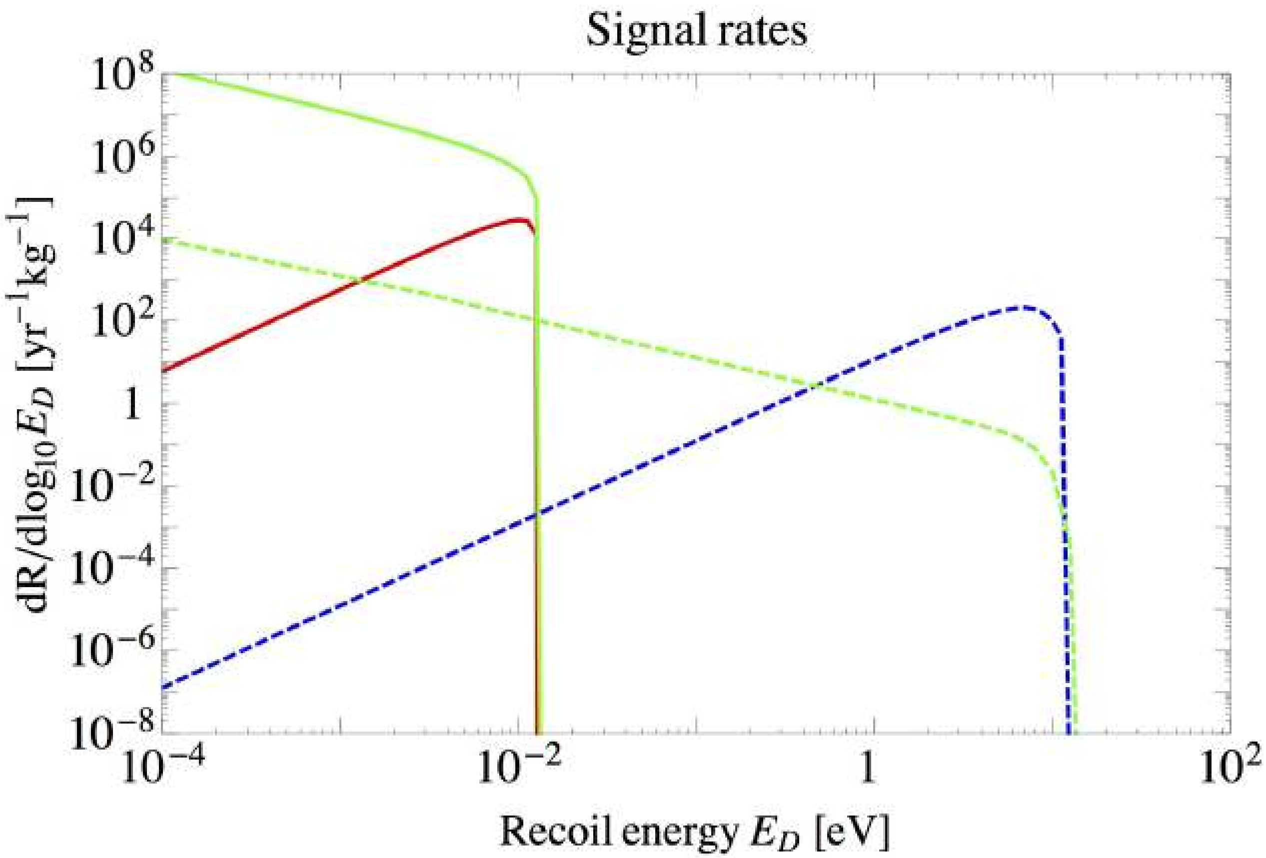
Pauli blocking in degenerate Fermi gas is important!

Suppression fraction $\sim E_D/E_F$



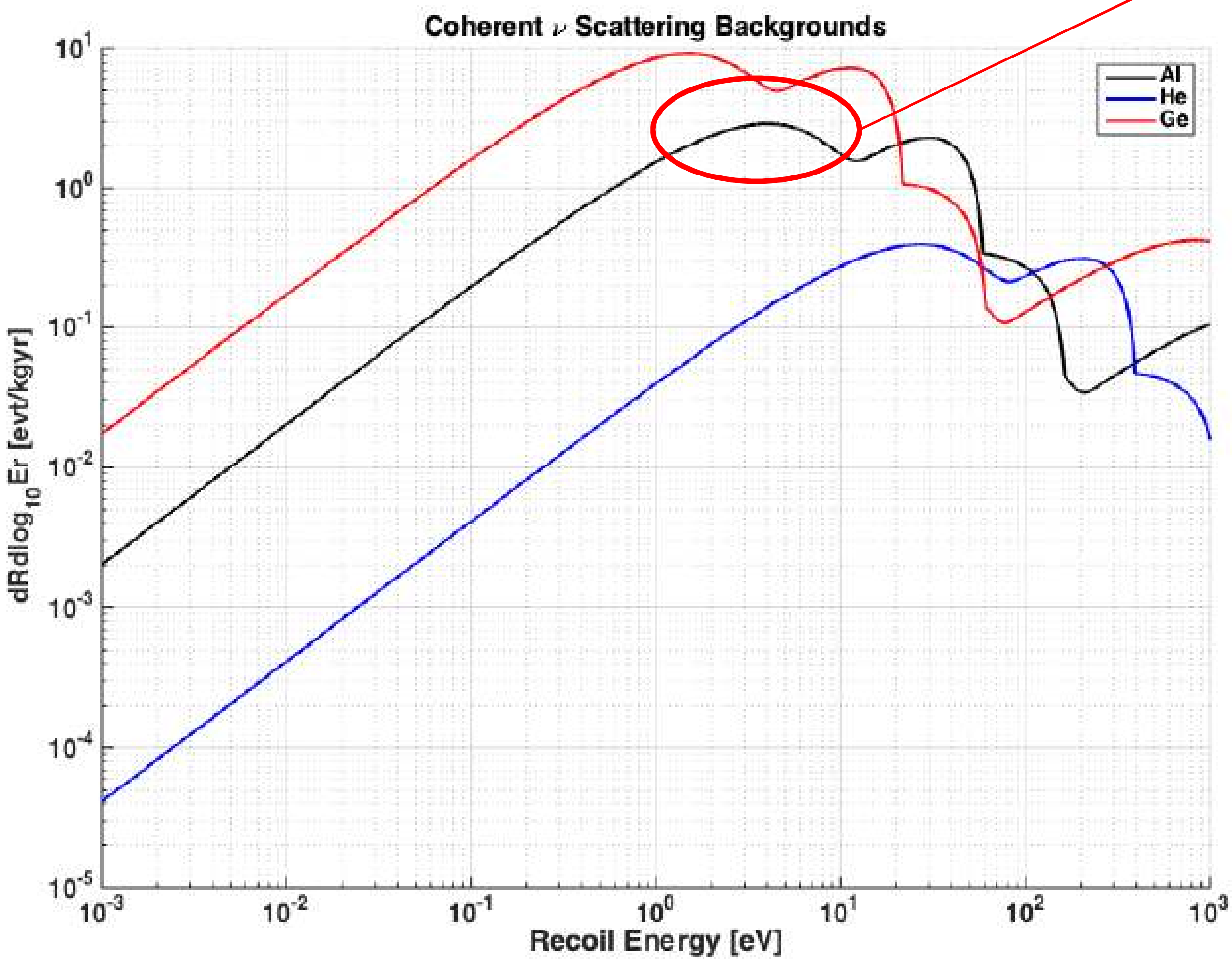
DM-electron scattering in SC

t-channel enhancement caused in light mediator scattering can be large when energy threshold is low.



Irreducible background:

From solar neutrino:



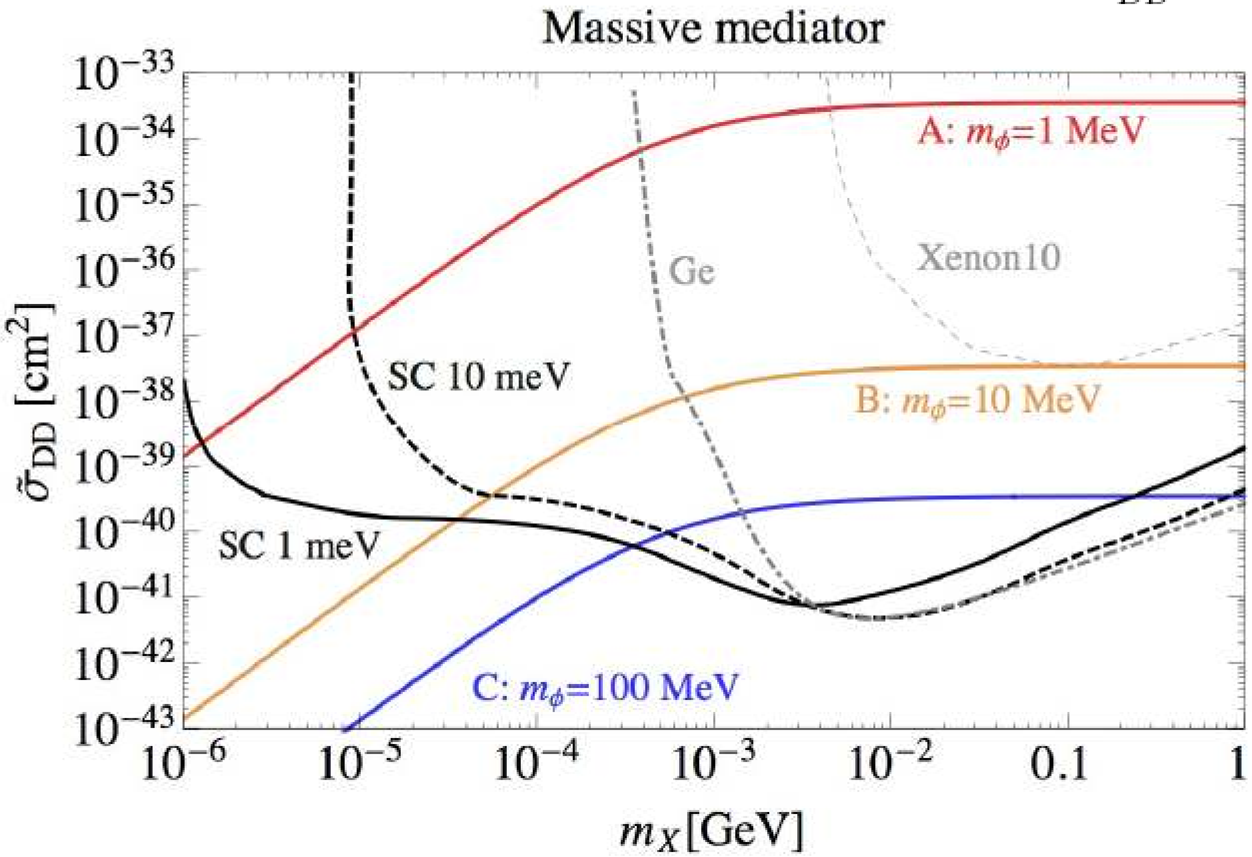
O(1) events/kg/year

pp neutrino is now relevant when energy threshold is low enough.

Radiative background is expected to be small, if 1/keV/day holds at low energy regime.

Non-kinetically mixed dark photon

$$\tilde{\sigma}_{\rm DD}^{\rm heavy} = \frac{16\pi\alpha_e\alpha_X}{m_\phi^4}\mu_{eX}^2$$



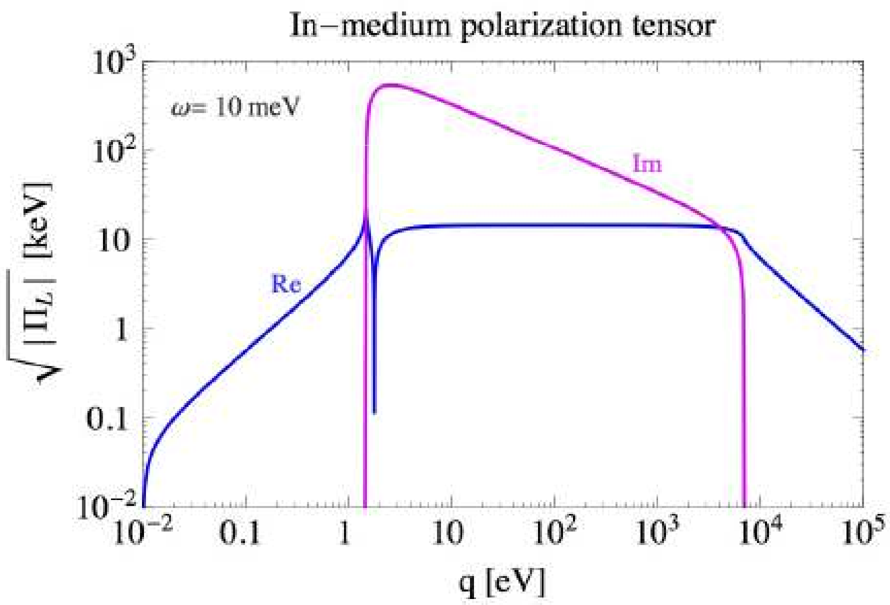
No medium induced suppression.

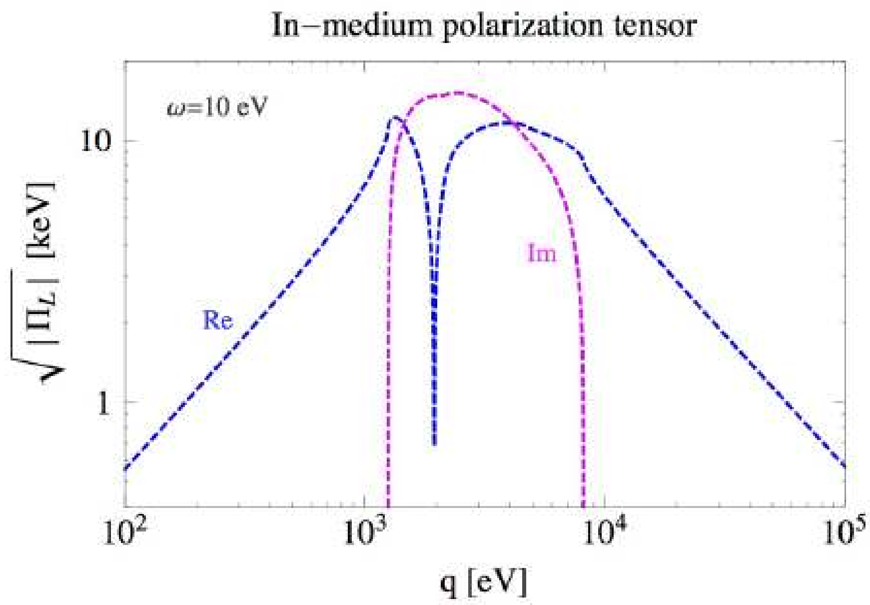
SC can do better than semi-conductor (Ge) for lighter DM.

Kinetically mixed dark photon

Dark photon receives large medium correlation in SC.

$$\epsilon_{\rm eff} = \epsilon \frac{q^2}{q^2 - \Pi_{T,L}}$$





Huge suppression to signal rate!

Effectively introducing a O(keV) “mass” (related to Thomas-Fermi screening length) to dark photon propagator.

Kinetically mixed dark photon