Detecting DM with Superconductors

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JHEP 1608 (2016) 057
Yonit Hochberg , Matt Pyle, Y.Z., Kathryn M. Zurek

Phys.Rev. D94 (2016) no.1, 015019
Yonit Hochberg, Tongyan Lin, Kathryn M. Zurek

Existing experiments/proposals

DM-nucleus scattering:

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

Energy threshold ~ few keV

DM mass > O(10) GeV

Super-CDMS:

Energy threshold ~ 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 $\Longrightarrow$ theoretical energy threshold for DM DD

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

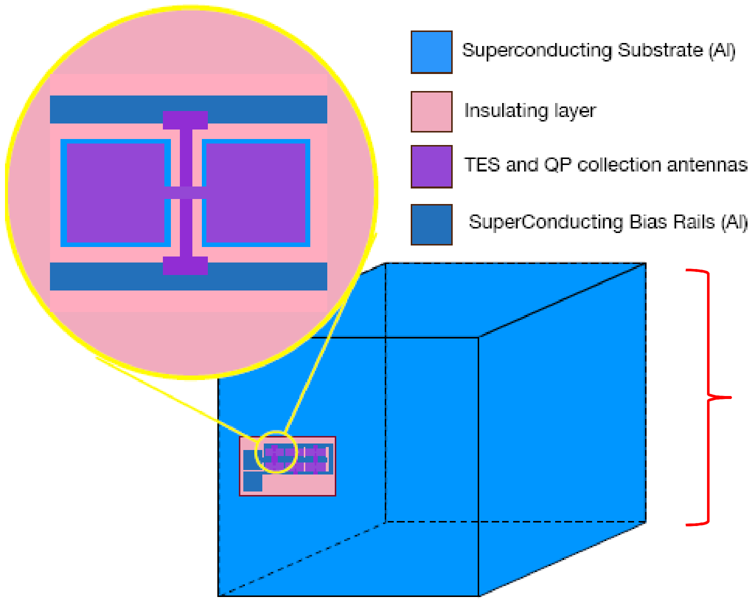
The existence of SC gap is important:

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

$\Longrightarrow$ They can be collected before they thermalize.

Superconductor as detector

60% quasi-particles
40% athermal phonons



O(1) cm

Superconductor as detector

Quasi-particle:

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

Lifetime: 10 ms

⇨ bouncing ($10^{4} \sim 10^{5}$) in absorber (~ cm 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.

Superconductor as detector

TES	T_c [mK]	Volume [μm $\times$ μm $\times$ nm]	Bias Power [W]	Power Noise $\sqrt{S_{p,tot}(0)}$ [W/$\sqrt{Hz}$]	τ_{eff} [μs]	$\sigma_E^{measured}$ [meV]	σ_E^{scale} [meV]
W [47]	125	$25 \times 25 \times 35$	2.1×10^{-13}	5×10^{-18}	15	120	1.1
Ti [48]	50	$6 \times 0.4 \times 56$	5.8×10^{-17}	2.97×10^{-20}		47	22
	100		2.6×10^{-15}	4.2×10^{-19}		47	7.8
MoCu [49]	110.6	$100 \times 100 \times 200$	8.9×10^{-15}	4.2×10^{-19}	12700	295.4	0.3

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

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

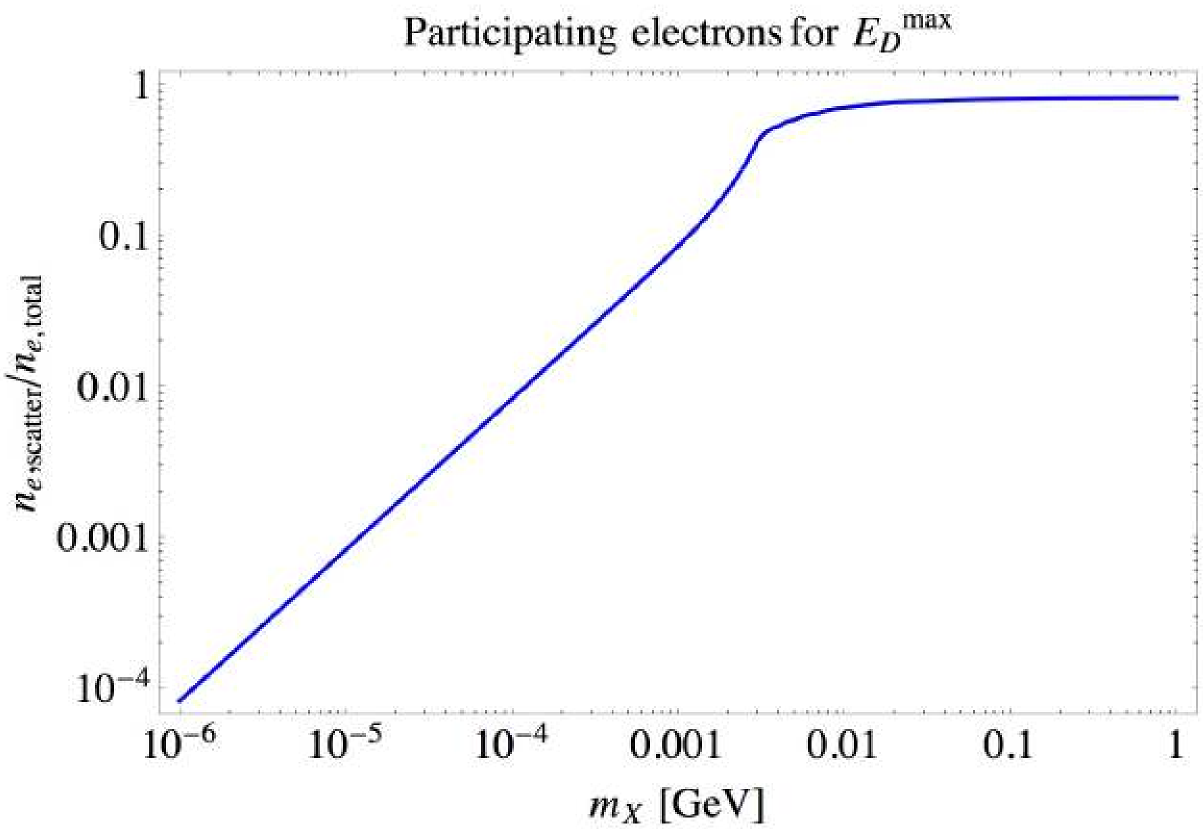
When DM mass << electron mass

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

DM-electron scattering in SC

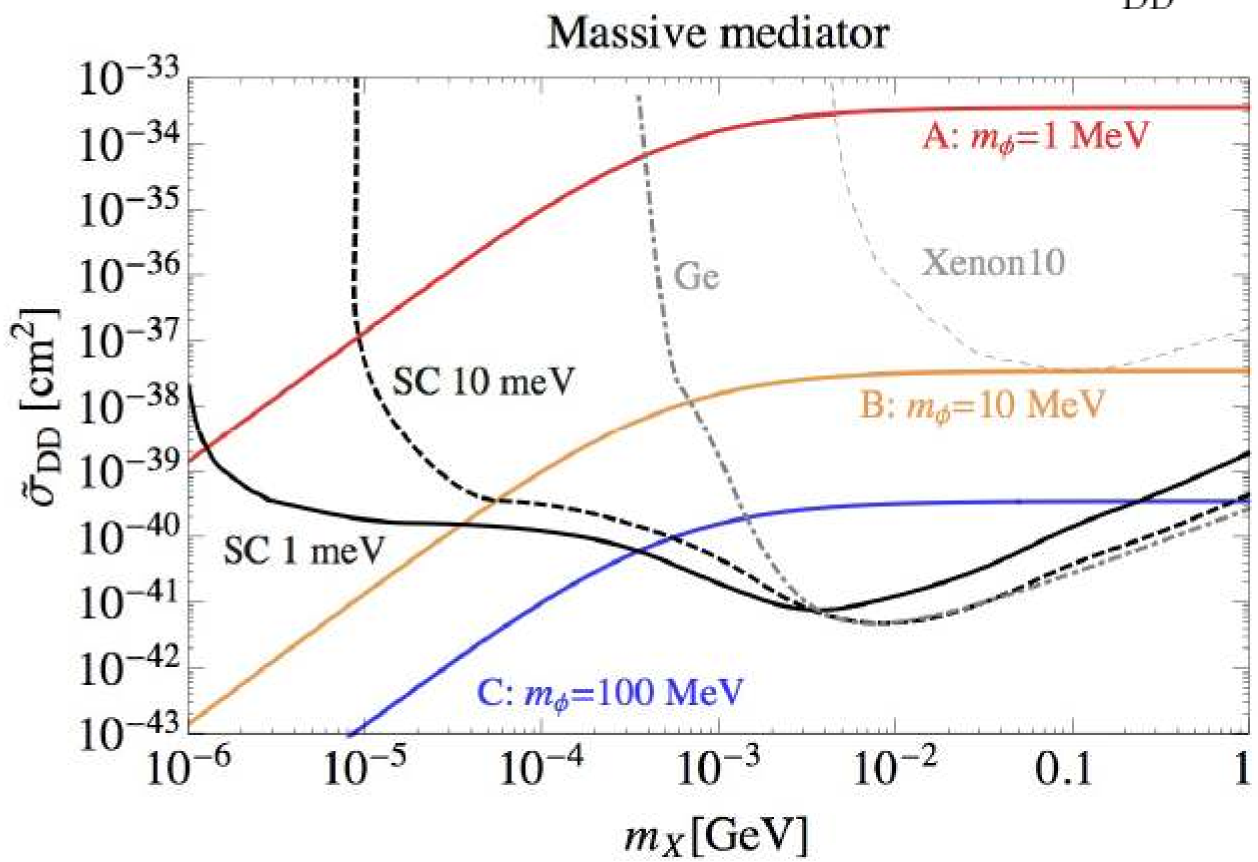
Pauli blocking in degenerate Fermi gas is important!

Suppression fraction $\sim \; E_D/E_F$



Non-kinetically mixed dark photon

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



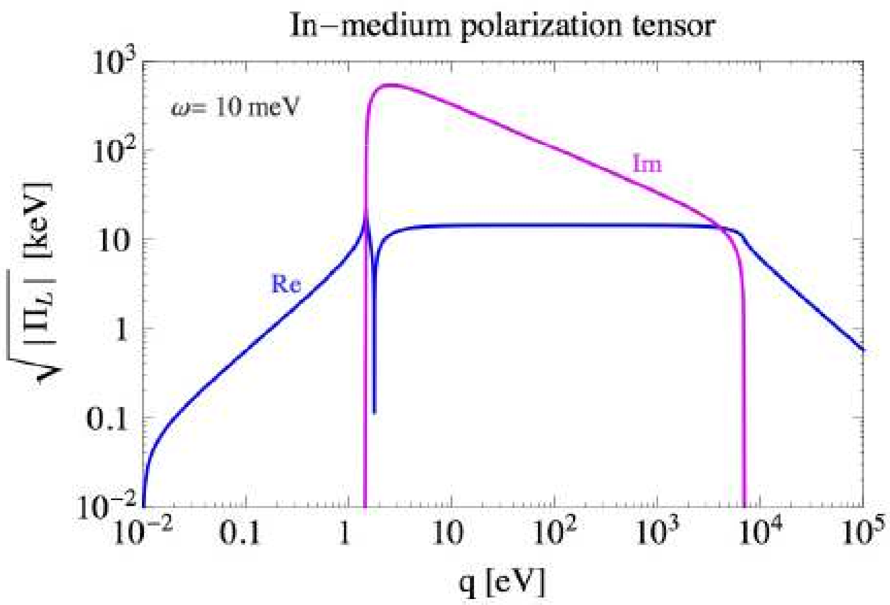
DM self-interaction, terrestrial experiments, stellar cooling

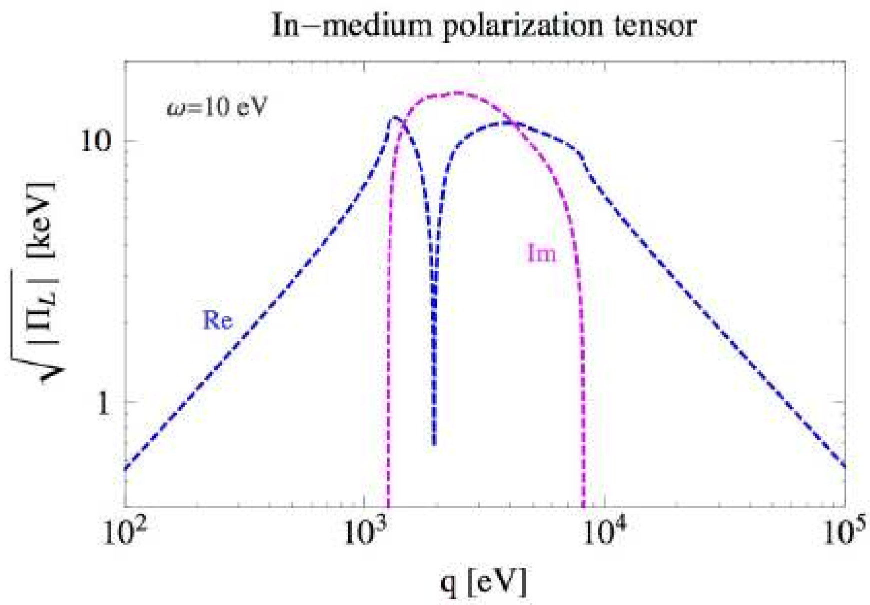
BBN (may be avoided through late phase transition etc.)

Kinetically mixed dark photon

Dark photon receives large medium correlation in SC.

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

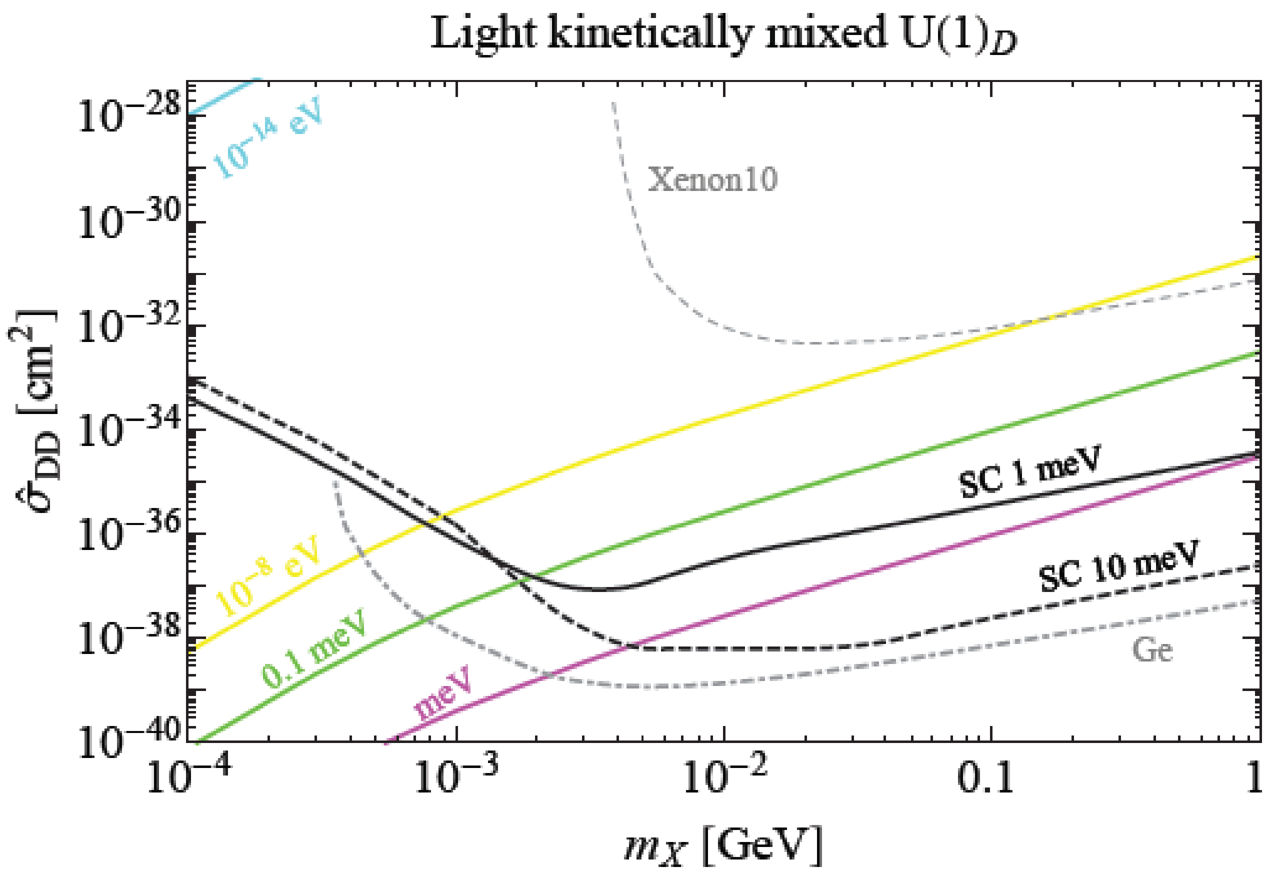




Huge suppression to signal rate!

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

Kinetically mixed dark photon



DM self-interaction, terrestrial experiments, stellar cooling

BBN (may be avoided through late phase transition etc.)

Dark matter absorption

Absorption rate of hidden photon DM

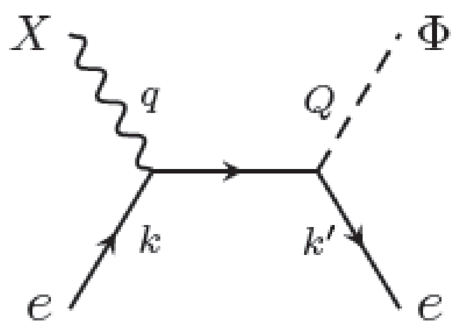
photon absorption

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

effective kinetic mixing in a material

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

For sub-eV DM in superconductors:



Phonon energy:

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

Speed of sound in aluminum:

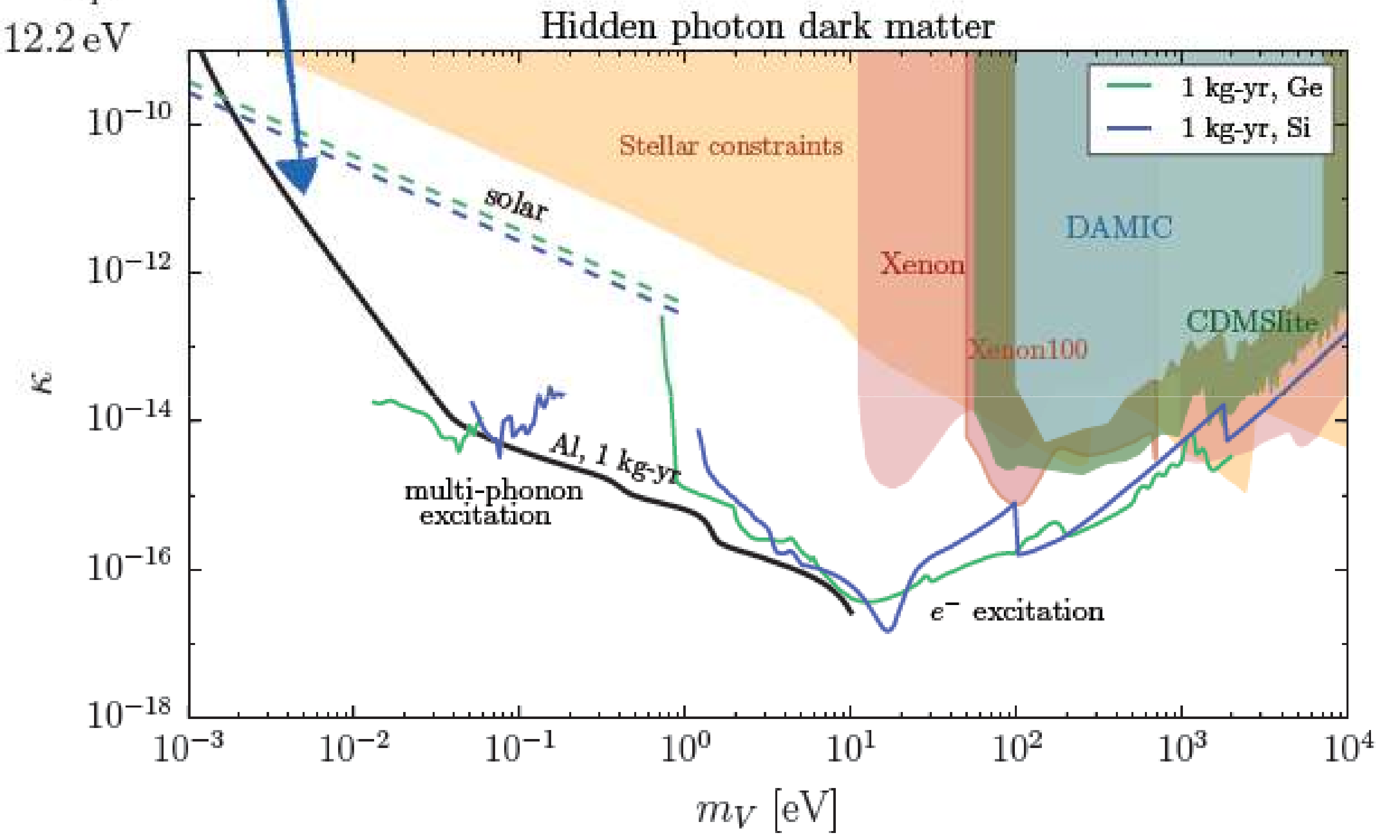
$$c_s \simeq 6320\ {\rm m/s} \sim 2\times10^{-5}$$

Hidden photon DM

Reduced effective kinetic mixing

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

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



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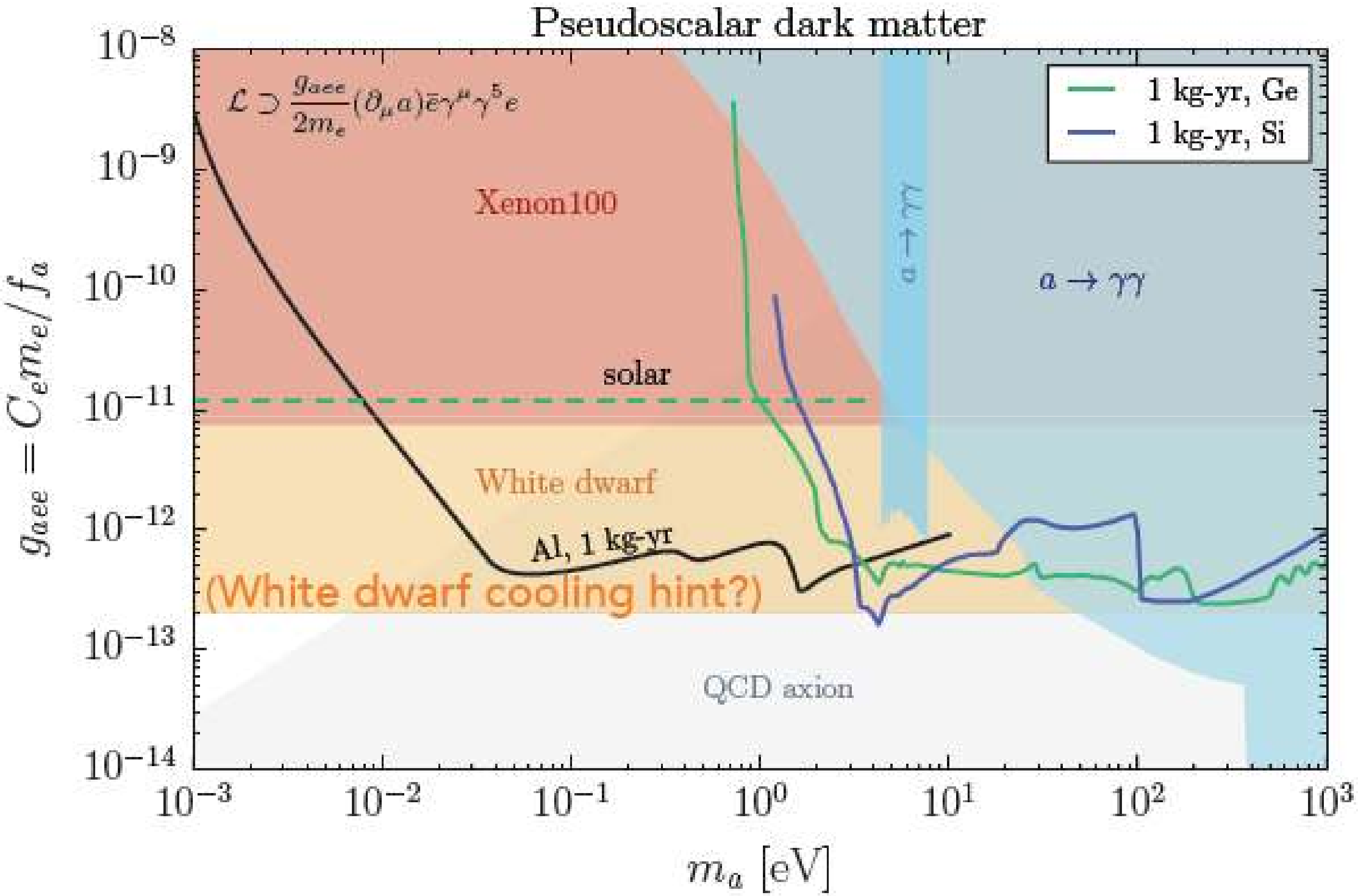
Pseudoscalar DM



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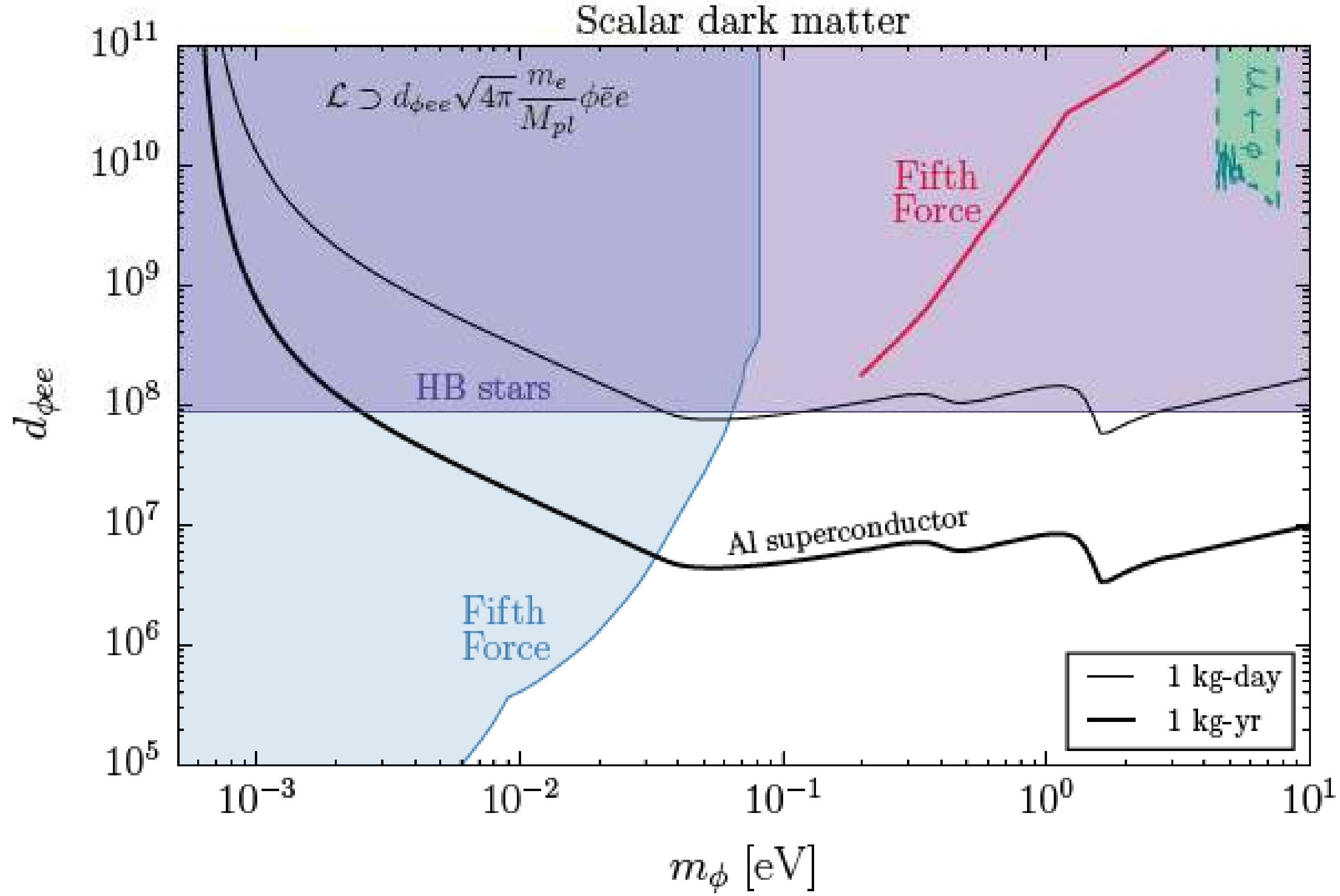
Scalar DM



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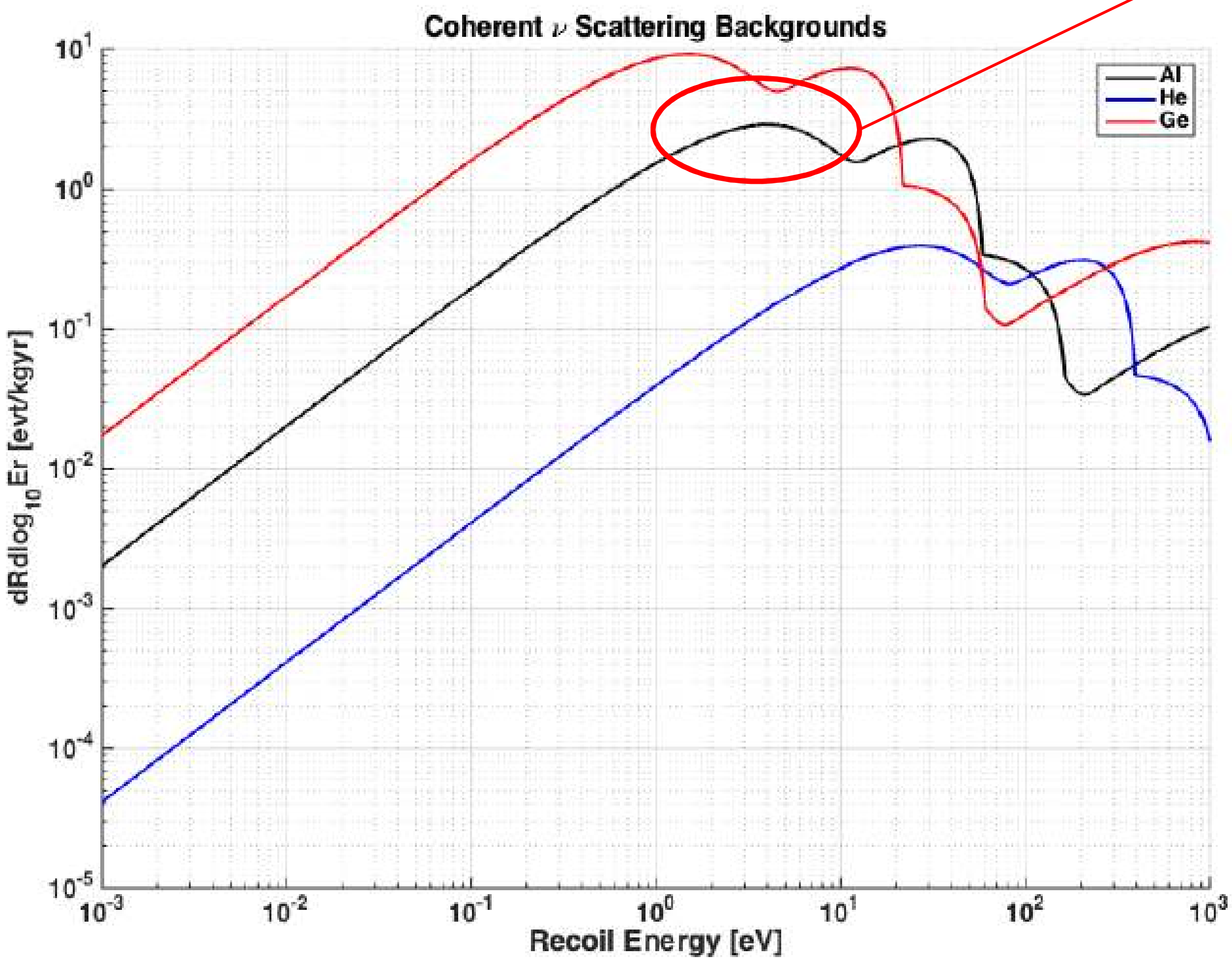
Irreducible background:

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.

DM-electron scattering in SC

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