Superconducting Detectors for Super Light Dark Matter

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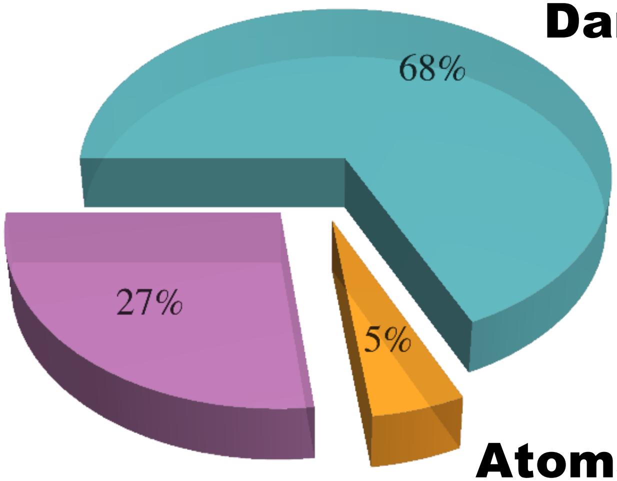
Outline

- Why?
- How?
- Rates & Results

Why?

The Universe is Dark



No suitable candidate within the Standard Model (SM).

Requires at least one new stable/extremely long lived particle to exist today.

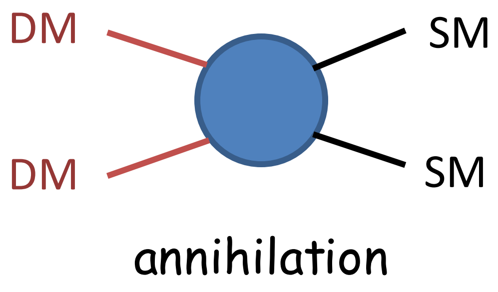
The WIMP Miracle

Correct thermal relic abundance:

$$\langle \sigma_{\rm ann} v \rangle \equiv \frac{\alpha^2}{m_{\rm DM}^2} \sim 3 \times 10^{-26}\ {\rm cm}^3/{\rm sec}$$

For weak coupling, weak scale emerges.

The dominant paradigm for ~35 years.



Been searching for WIMPs…
Dominant paradigm is being challenged.

Sociology

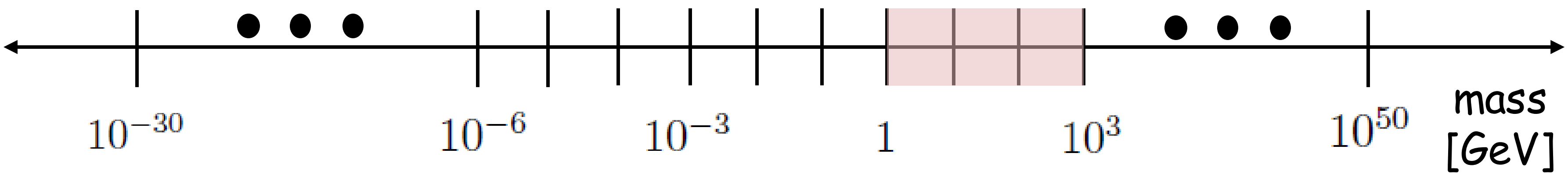
Dominant paradigm is being challenged.

- Big puzzles
- Great if a solution gives an option for dark matter candidate
- Big ideas: SUSY, extra dimensions…

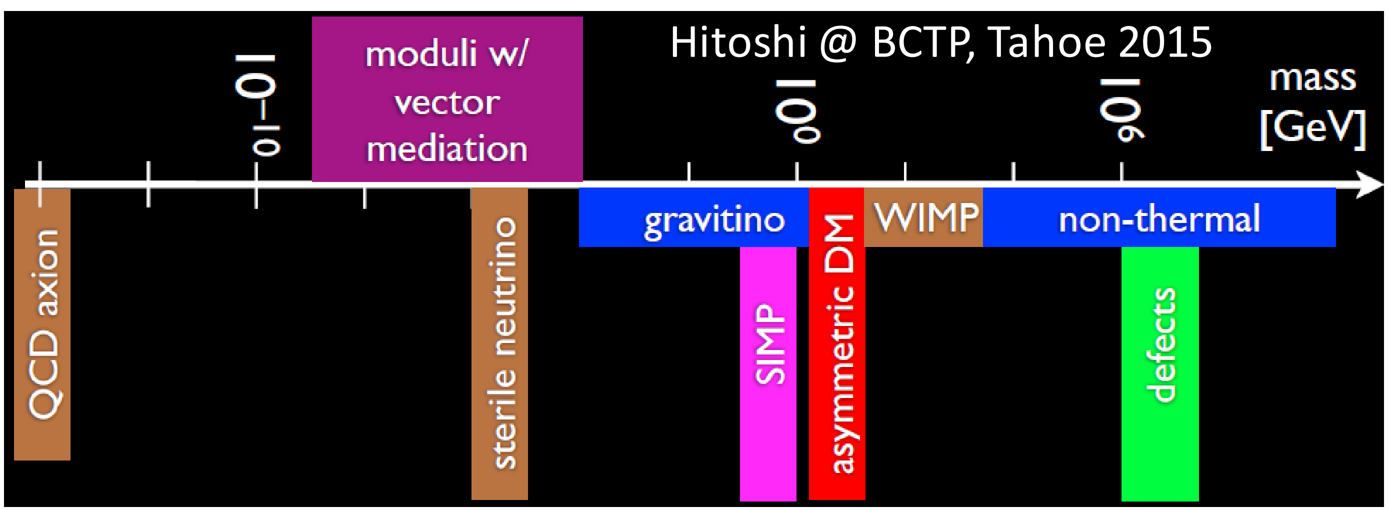
- Dark matter exists
- Explain on its own
- Perhaps decoupled from other puzzles
- Think outside the WIMP box

theoretically & experimentally

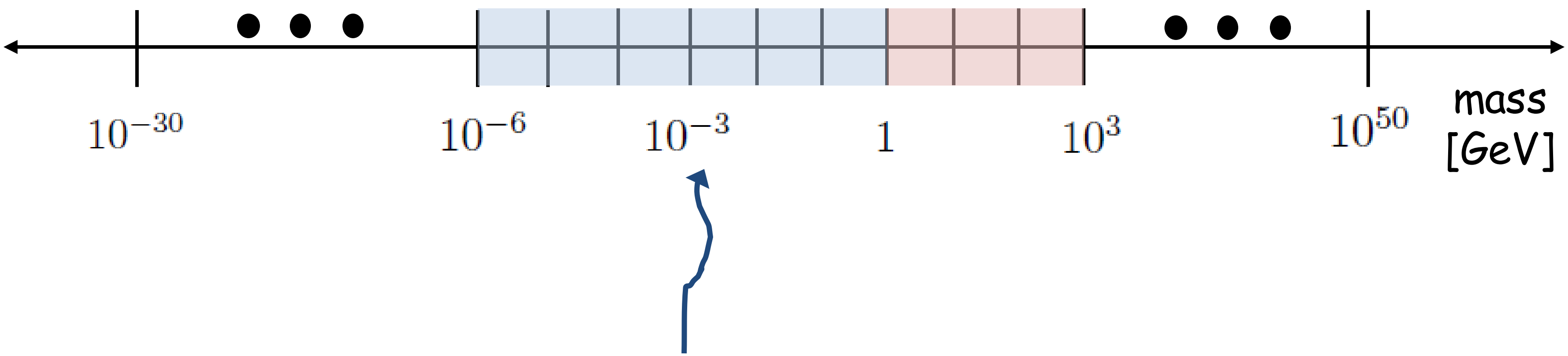
Beyond the WIMP



Model zoo



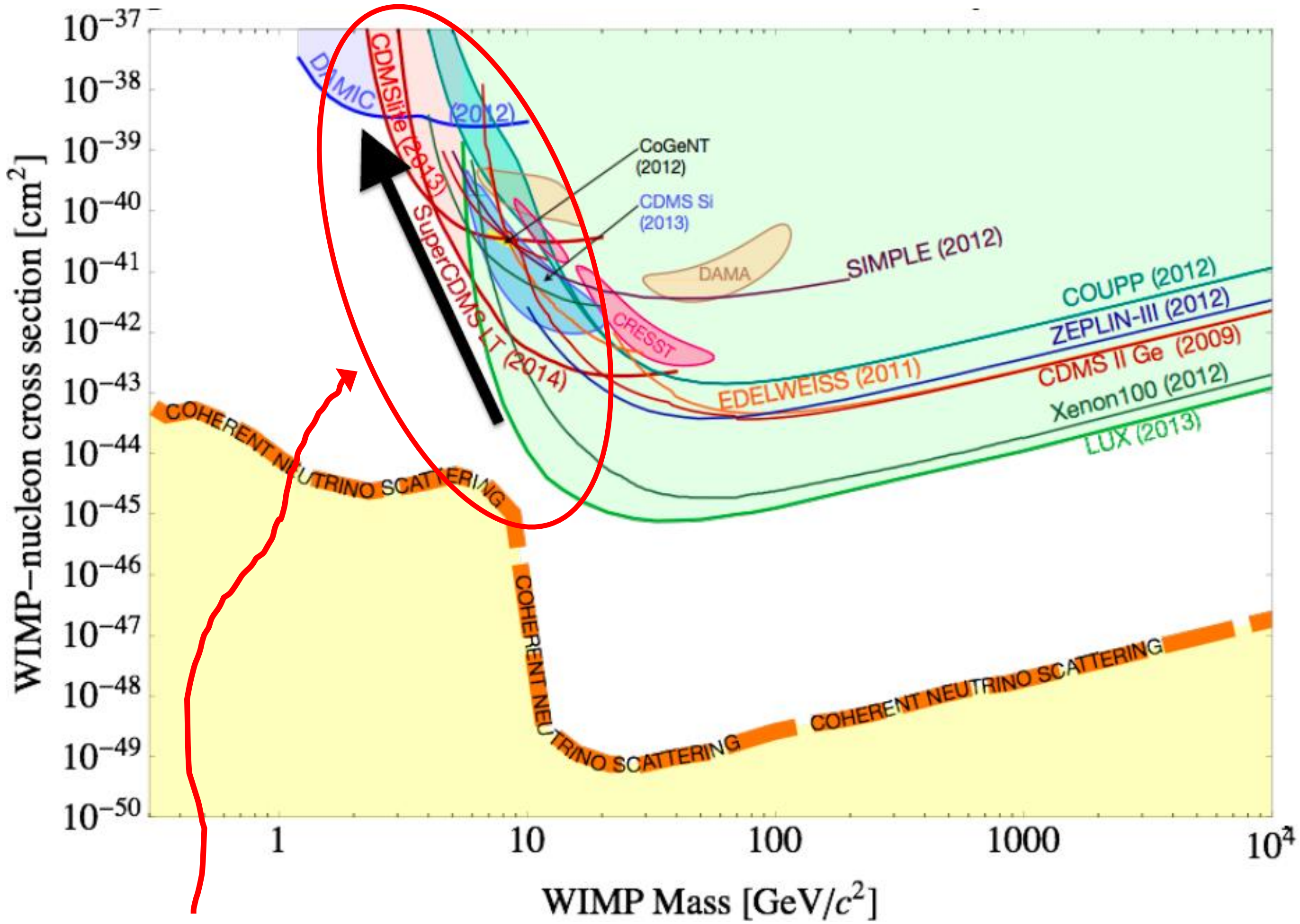
Beyond the WIMP



Focus on
direct detection
of keV-GeV
dark matter

How?

Direct Detection



What's going on?

Direct Detection

- Nuclear recoils: $E_{\rm NR} = \frac{q^2}{2m_N} = \frac{(m_{\rm DM} v)^2}{2m_N} \gtrsim E_{\rm th} \sim {\rm keV}$

- For sub-GeV dark matter, scatter off electrons!

Kinetic energy available: $E_D \sim \mu_r v^2$

$m_{\rm DM} \sim {\rm MeV} \Rightarrow E_D \sim {\rm eV}$ → electron ionization, semiconductors

[Essig, Mardon, Volansky, PRD 85, 076007 (2012)]

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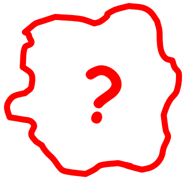
$m_{\rm DM} \sim {\rm keV} \Rightarrow E_D \sim {\rm meV}$ ⟹



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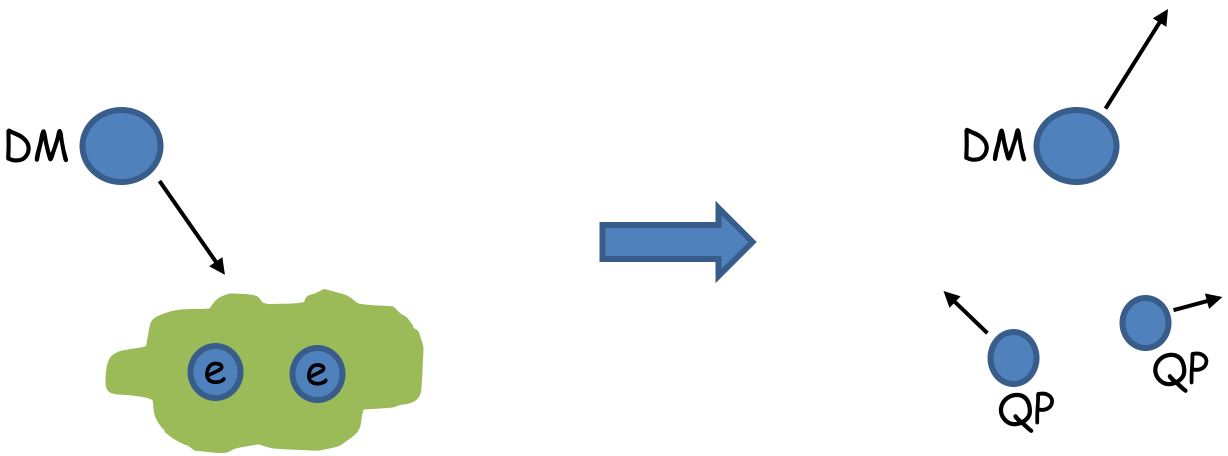
$m_{\rm DM} \sim \rm MeV \Rightarrow E_D \sim eV$ ➡ electron ionization, semiconductors

$m_{\rm DM} \sim \rm keV \Rightarrow E_D \sim meV$ ➡ **Superconductors!**

[YH, Zhao and Zurek, 1504.07237]

Superconductor Cheat Sheet

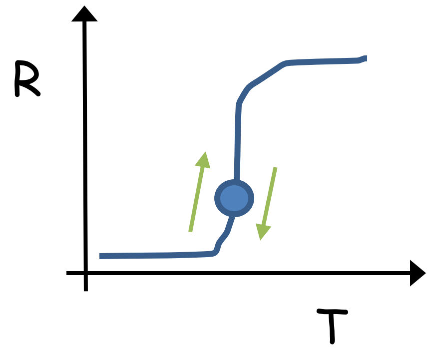
- Ground state of superconductor = Cooper pairs;
  Binding energy (gap) $\Delta \lesssim \mathrm{meV}$
- <u>The idea:</u>
  DM scatters with Cooper pairs, deposits enough energy, breaks Cooper pairs, creating quasiparticles → detect



Superconductor Cheat Sheet

- For energies exceeding the gap, scatter with free electrons in a Fermi-degenerate sea (“coherence factor” → 1)

- Ram an electron, create quasiparticles which random walk until collected by e.g. a Transition Edge Sensor (TES)



Heat calorimeter

TESs used to
detect microwaves and x-rays
in astro applications
(e.g. SPT, ACT, SuperCDMS)

Superconductor Cheat Sheet

- Current status? **Not there yet**

TES	T_c [mK]	Volume [μm $\times$ μm $\times$ nm]	Power Noise [W/$\sqrt{\text{Hz}}$]	σ_E^{now} [meV]	σ_E^{scale} [meV]
W [3]	125	$25 \times 25 \times 35$	2.72×10^{-18}	120	1.1
Ti [5]	50	$6 \times 0.4 \times 56$	2.97×10^{-20}	47	22
MoCu [6]	110.6	$100 \times 100 \times 200$	4.2×10^{-19}	295.4	0.3

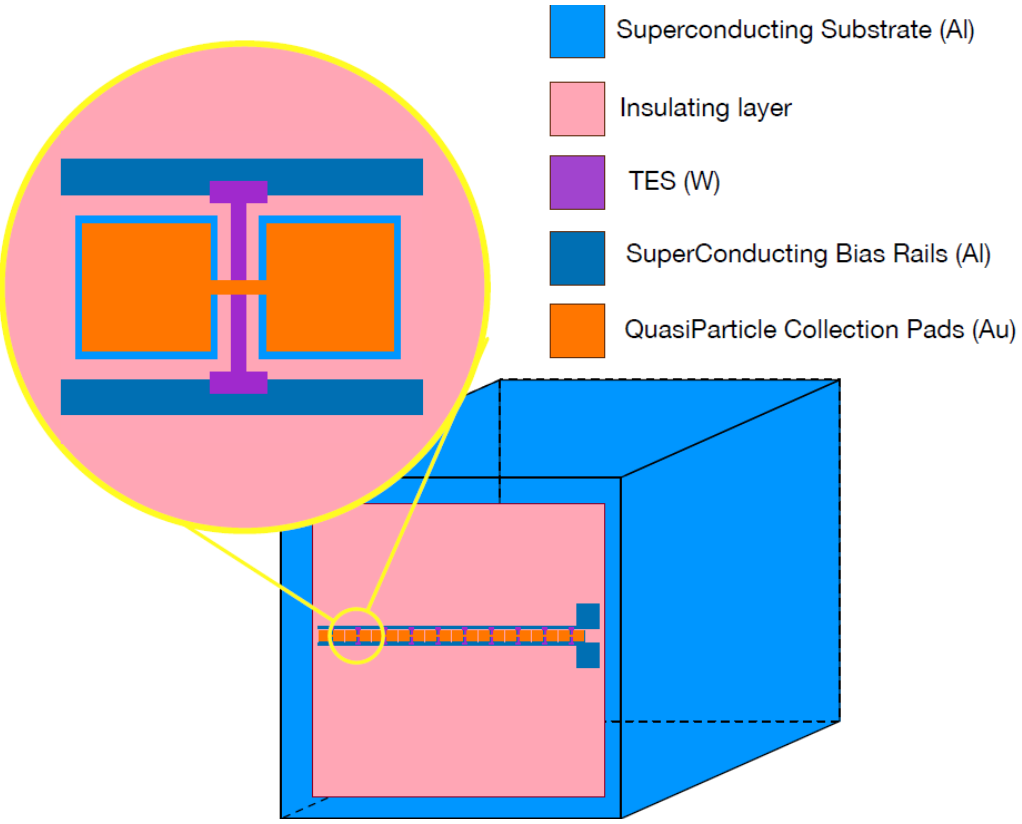
- Need to beat noise
- Energy resolution $\sigma_E \propto \sqrt{T^3 V}$ ⟹ **Reduce temperature and volume for O(meV) resolution**

Detector Concept

<u>Basic device idea:</u>
Large exposure but high energy resolution = excitation concentration

(E.g. SuperCDMS)

Absorber →
Collection fins→
TES

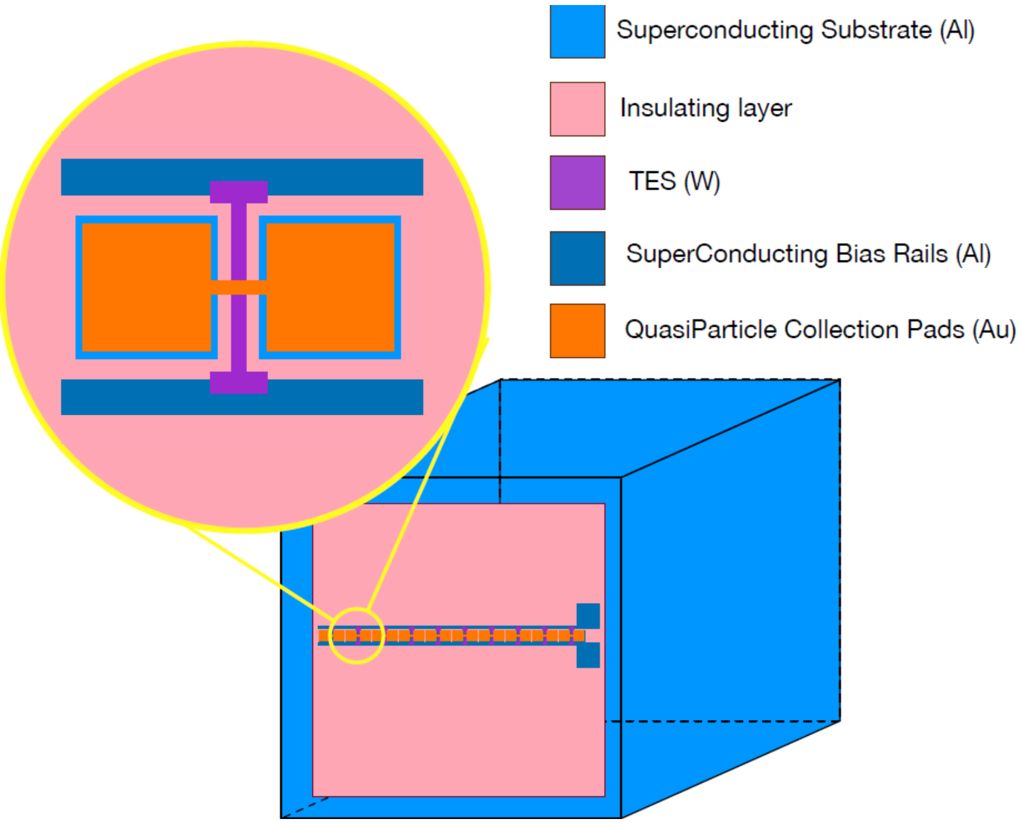


Design by Matt Pyle

Detector Concept

- Quasiparticle lifetime of order a milisecond

- With velocity $10^{-2}c$, plenty of time to random walk and get absorbed before recombine

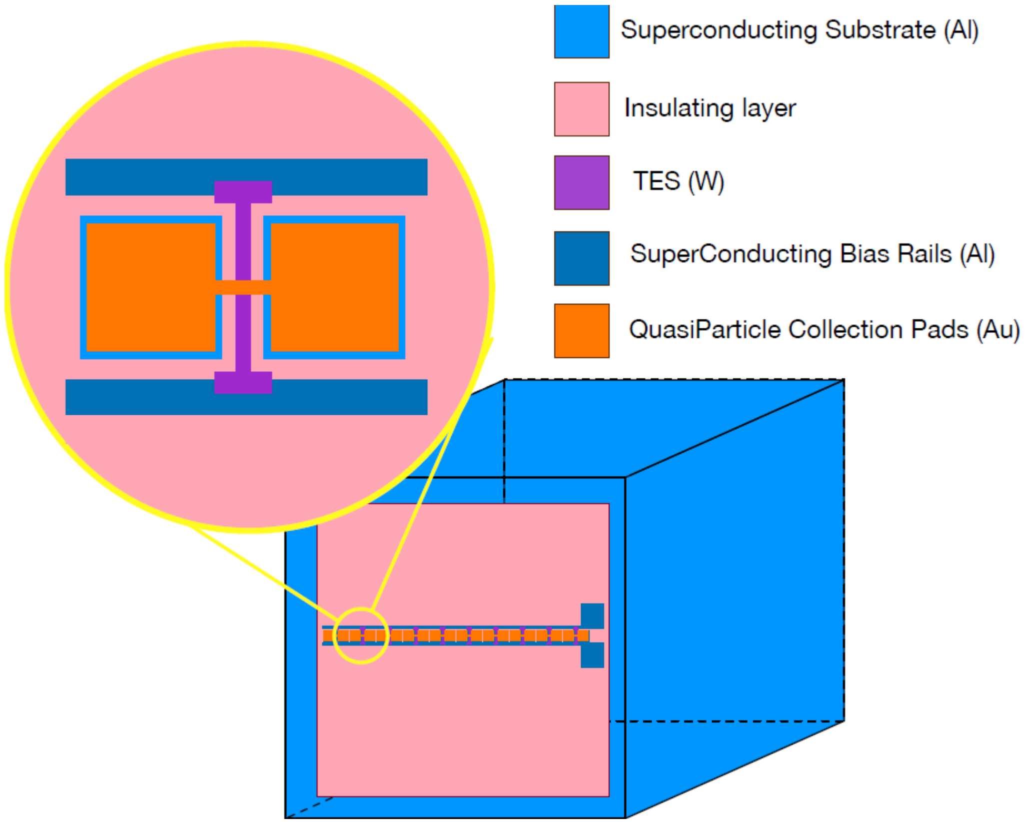


Design by Matt Pyle

Detector Concept

Comments:

- Low energy deposits: gapless absorber such as a metal
- But better: metal in superconducting phase so that the gap controls the thermal noise
- **Proof of concept**



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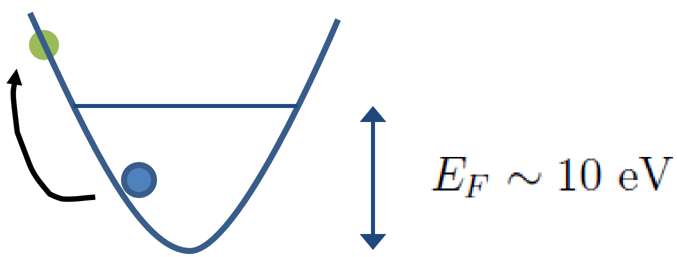
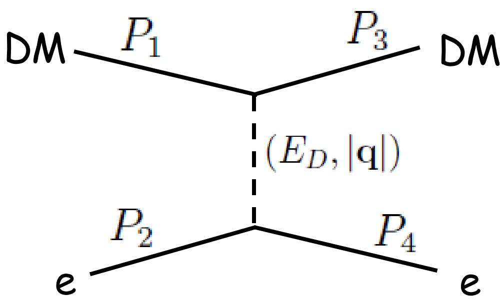
Rates & Results

Rates

Scatter off electrons in Fermi-degenerate metal – Pauli blocking





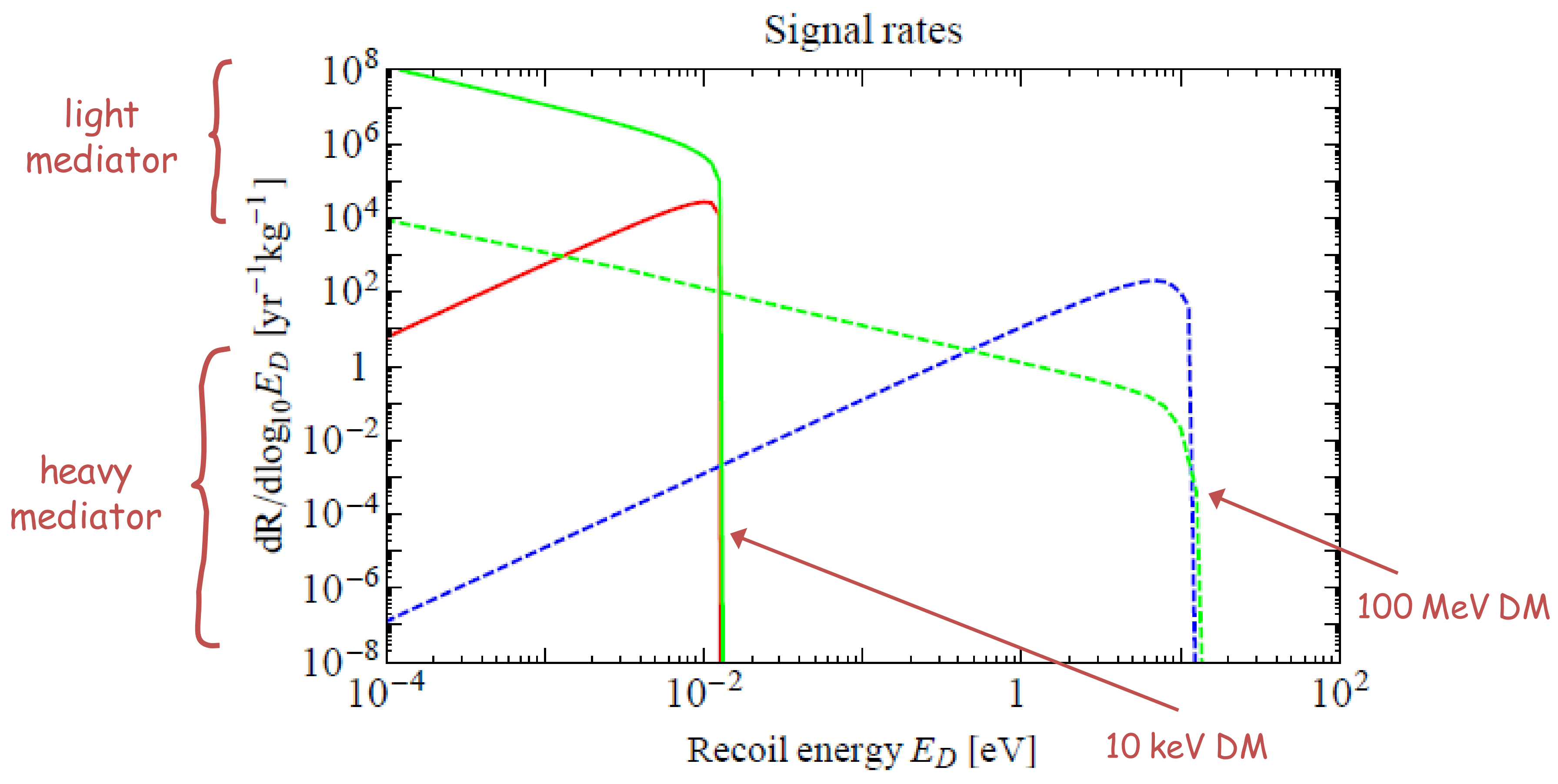
$$\langle n_e \sigma v_{\rm rel} \rangle = \int \frac{d^3 p_3}{(2\pi)^3} \frac{\langle |\mathcal{M}|^2 \rangle}{16 E_1 E_2 E_3 E_4} S(E_D, |\mathbf{q}|)$$

$$S(E_D, |\mathbf{q}|) = 2 \int \frac{d^3 p_2}{(2\pi)^3} \frac{d^3 p_4}{(2\pi)^3} (2\pi)^4 \delta^4(P_1 + P_2 - P_3 - P_4) \times f_2(E_2)(1 - f_4(E_4))$$

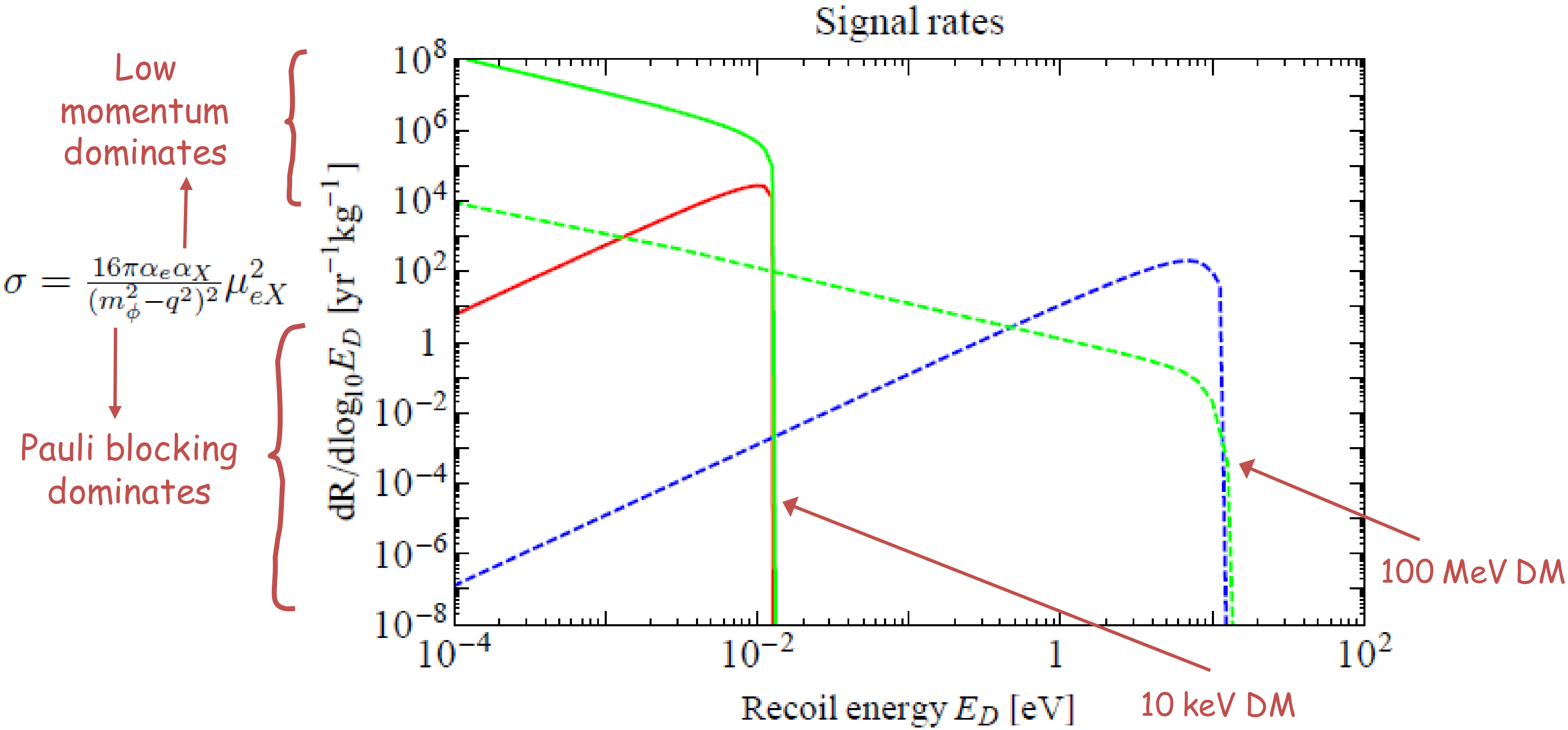
Fermi-Dirac distribution

Pauli blocking $\sim \frac{E_D}{E_F} \sim 10^{-4}$

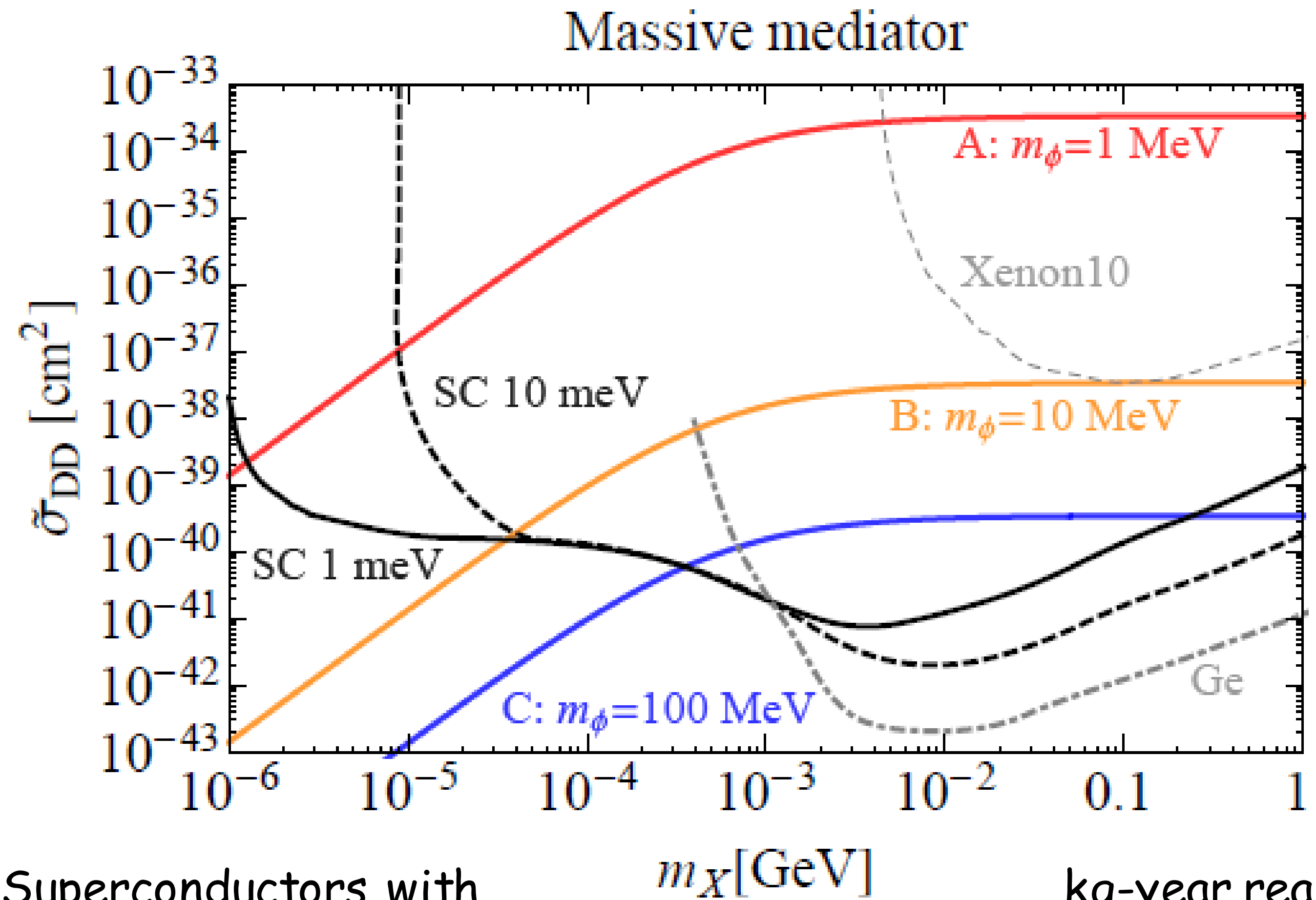
Rates


Signal rates
light mediator
heavy mediator
dR/dlog10ED [yr-1kg-1]
108
106
104
102
1
10-2
10-4
10-6
10-8
10-4
10-2
1
102
Recoil energy ED [eV]
100 MeV DM
10 keV DM

Rates


Low momentum dominates
$\sigma = \frac{16\pi\alpha_e\alpha_X}{(m_\phi^2-q^2)^2}\mu_{eX}^2$
Pauli blocking dominates
Signal rates
dR/dlog10ED [yr−1kg−1]
Recoil energy ED [eV]
10−4
10−2
1
102
108
106
104
102
1
10−2
10−4
10−6
10−8
100 MeV DM
10 keV DM

Reach

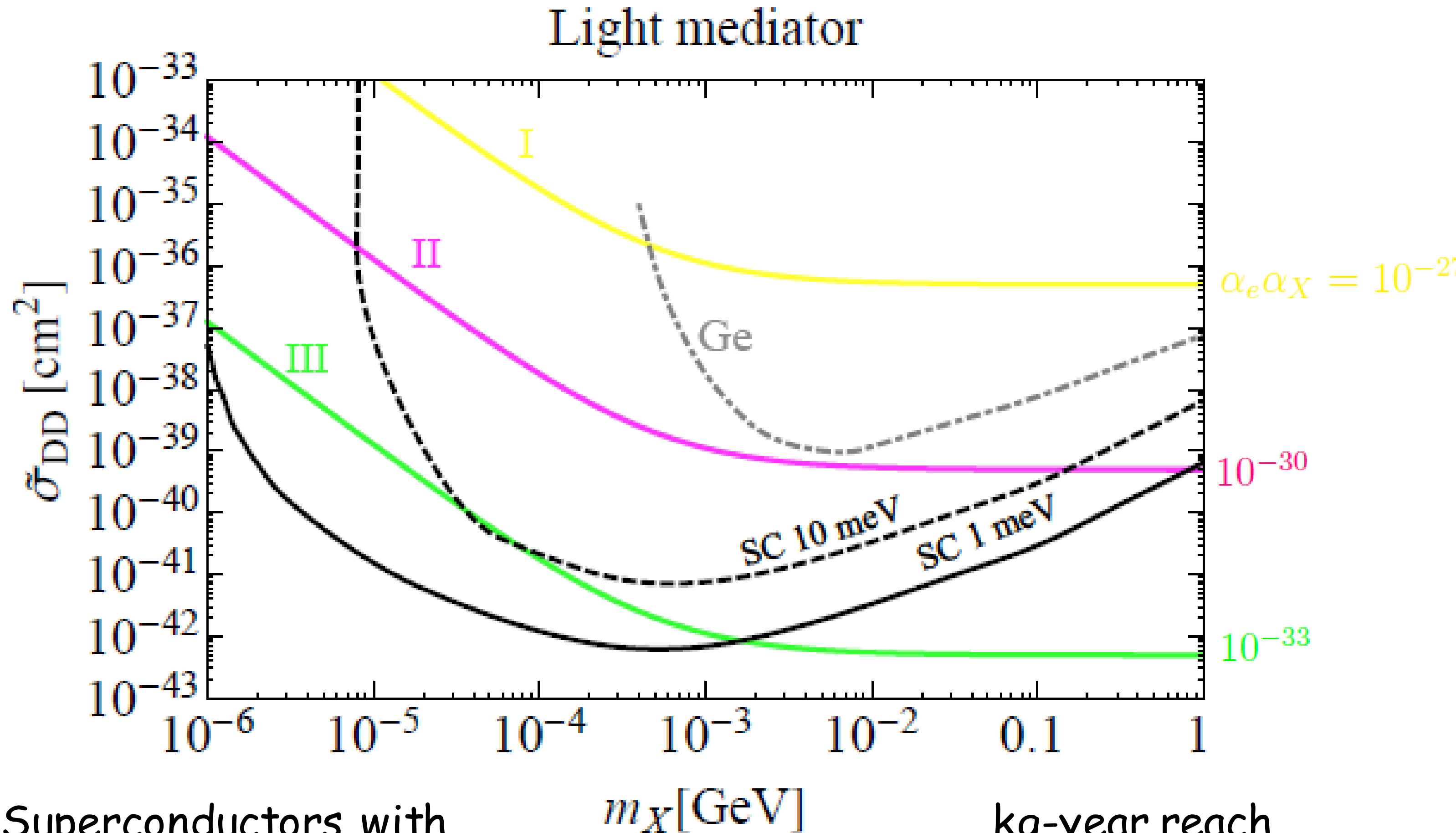


Superconductors with 1 meV or 10 meV threshold

kg-year reach

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

Reach



Superconductors with 1 meV or 10 meV threshold

kg-year reach

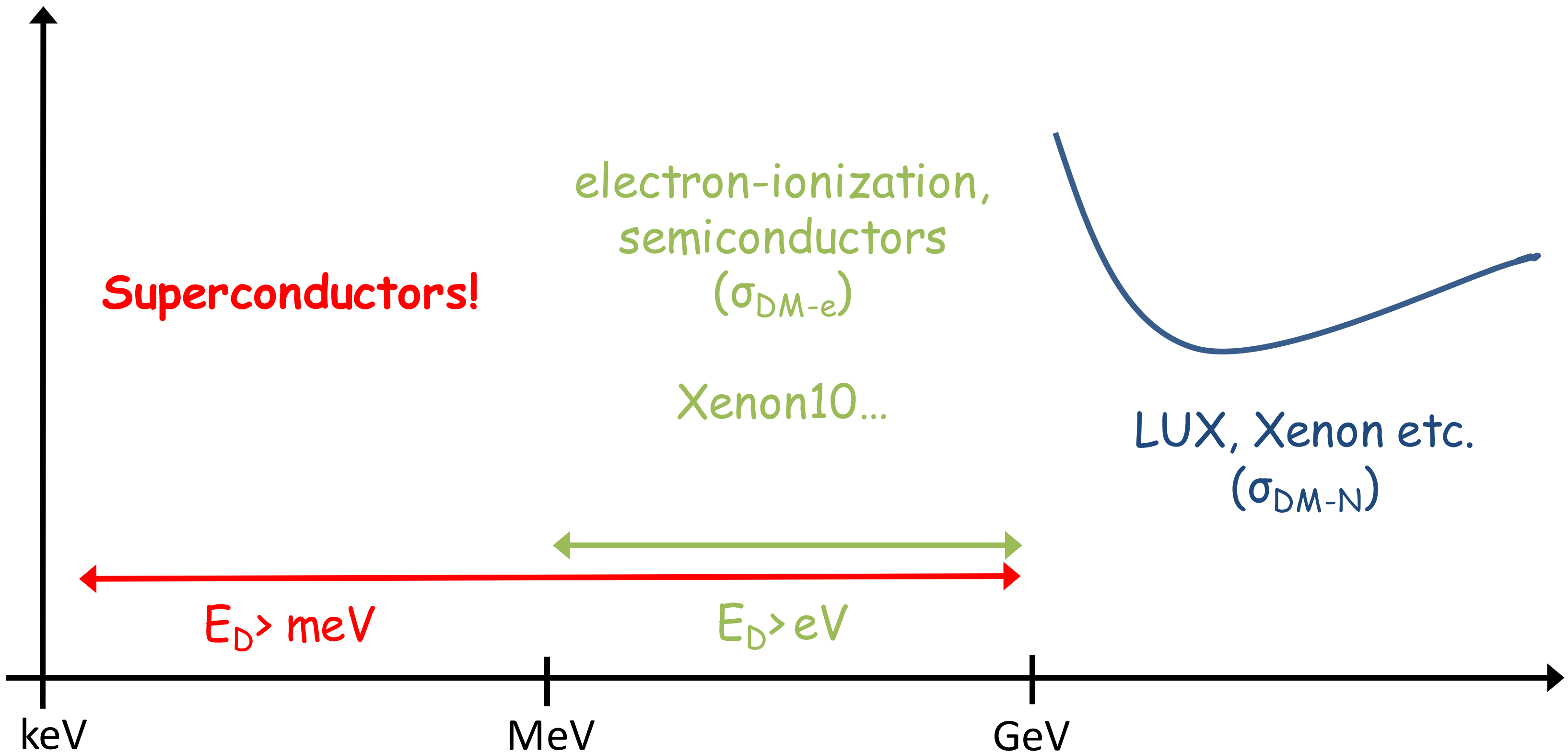
$$\tilde{\sigma}_{\rm DD}^{\rm light} = \frac{16\pi \alpha_e \alpha_X}{q_{\rm ref}^4} \mu_{eX}^2$$

$$q_{\rm ref} \equiv \mu_{eX} v_X$$

Summary

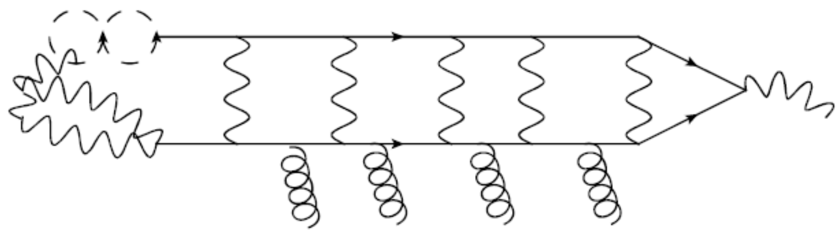
- Proposed new class of detectors using superconductors
- Sensitive to O(meV) energy deposits → keV dark matter
- R&D to lower noise such that O(meV) energies are detectable. (Port over everything being done now for semiconductors.)
- Other absorbers? Other calorimeters?
- Populate the models space

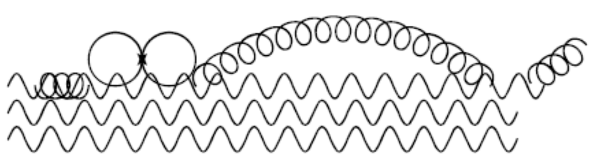
Prospects

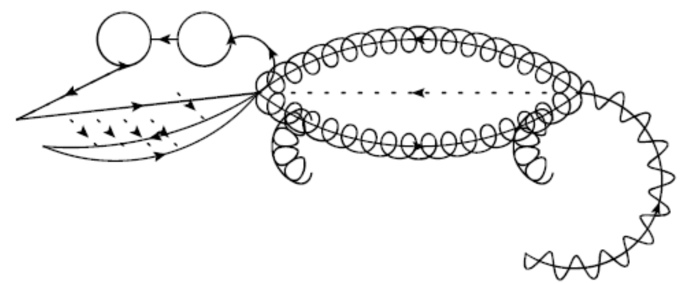


electron-ionization,
semiconductors
(σ_{DM-e})
Superconductors!
Xenon10…
LUX, Xenon etc.
(σ_{DM-N})
E_D> meV
E_D> eV
keV
MeV
GeV

Thanks!







Backup

Scalings

$$\mathrm{NEP} \propto \sqrt{T^2 G} \propto T^3$$

$$G \propto T^4$$

$$\tau \propto \frac{C}{G}$$

$$C \propto VT$$

$$\sigma_E \propto \mathrm{NEP}\sqrt{\tau} \propto \sqrt{T^3 V}$$