Superconducting Detectors for Super Light Dark Matter

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YH, Yue Zhao and Kathryn Zurek, PRL 116, 011301
YH, Matt Pyle, Yue Zhao and Kathryn Zurek, 1512.04533
and works in progress

Berkeley

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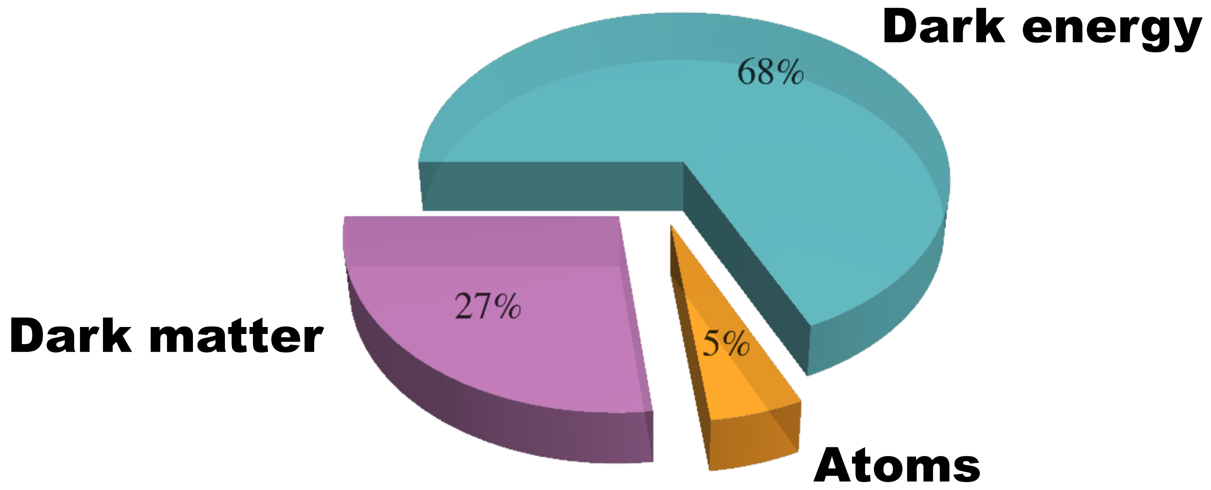
Outline

- 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.

Dark Matter Properties

- DM has 5 times the mass density of baryons
- Massive (m=?)
- Suppressed interactions with QED and QCD
- Doesn't very strongly self-interact

Dark Matter and Early Universe

Is possible to link DM with early universe cosmology

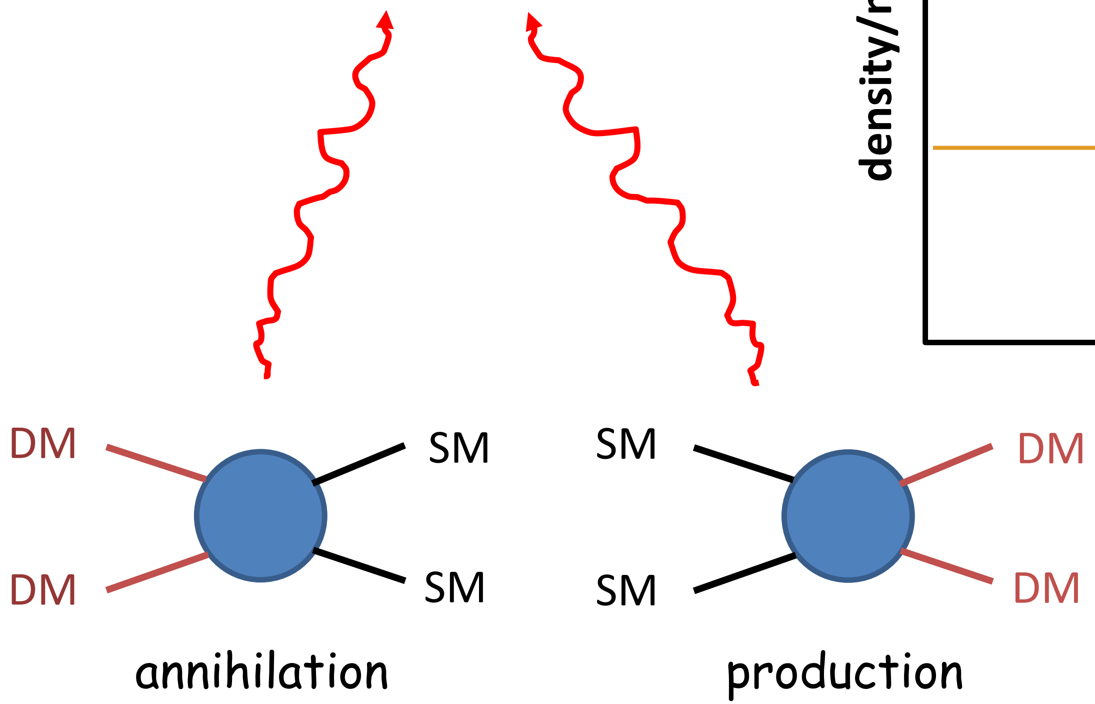
If new particle has 2 → 2 interactions with the SM, there will be a relic density left over

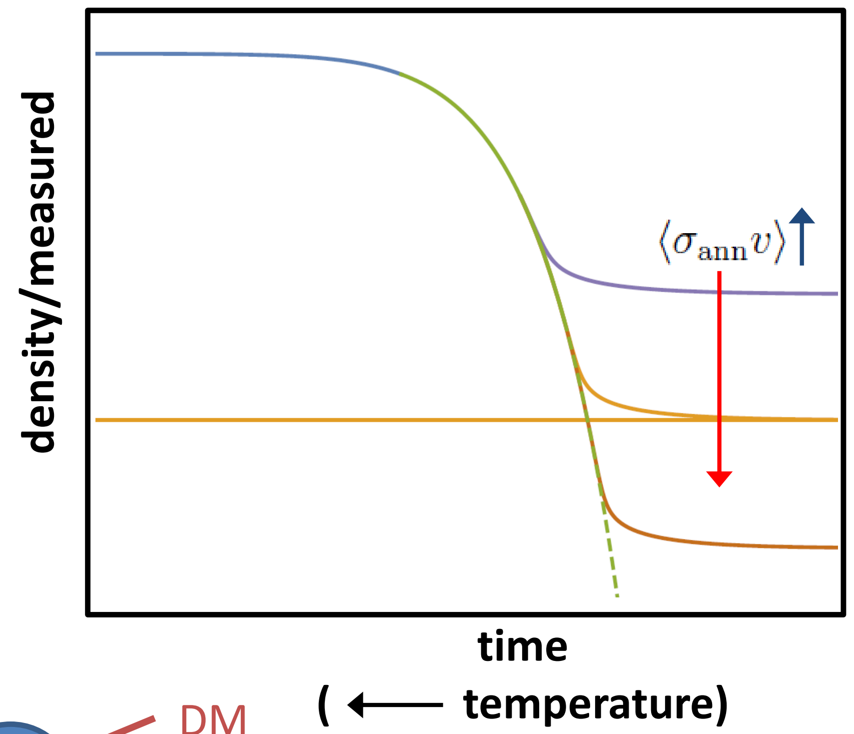
[Lee and Weinberg, PRL 39 (1977) 165–168]

Dark Matter Freeze Out

Boltzmann eq.:

$$\partial_t n + 3Hn = -(n^2 - n_{\rm eq}^2)\langle\sigma_{\rm ann} v\rangle$$





The WIMP Miracle

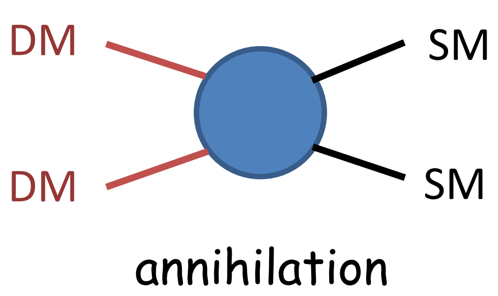
Correct thermal relic abundance:

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

$$m_{\rm DM}\ \sim\ \alpha \times 30\ \ {\rm TeV}$$

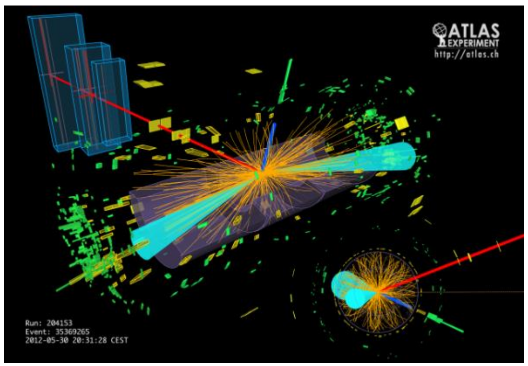
For weak coupling, weak scale emerges.

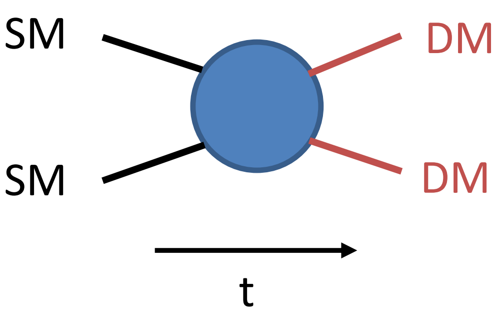
The dominant paradigm for ~35 years.



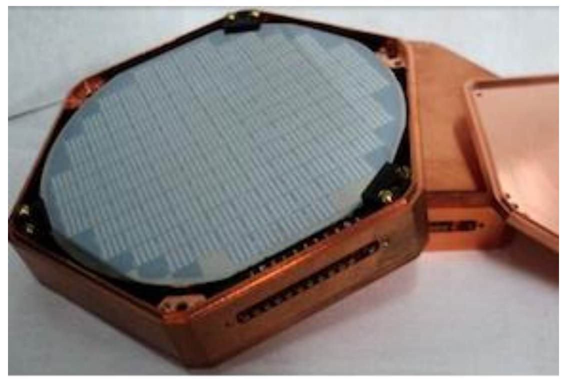
Searching for WIMPs

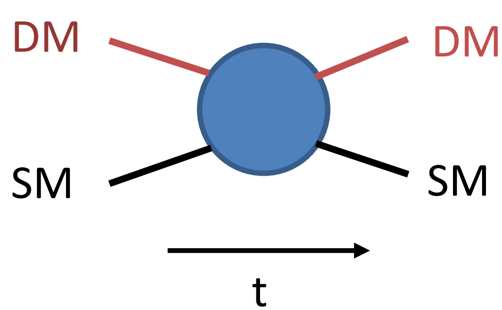
Direct production



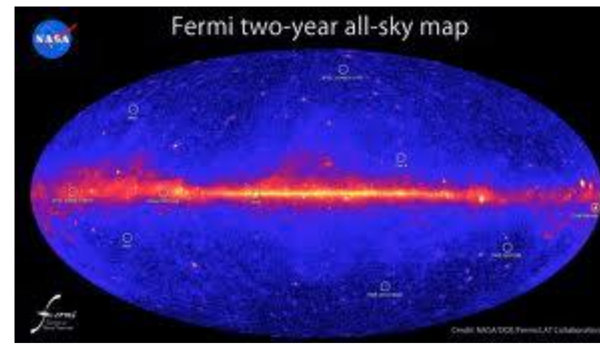


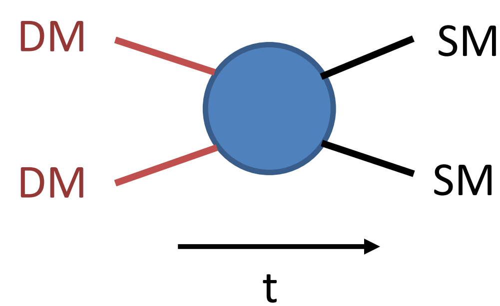
Direct detection





Indirect detection

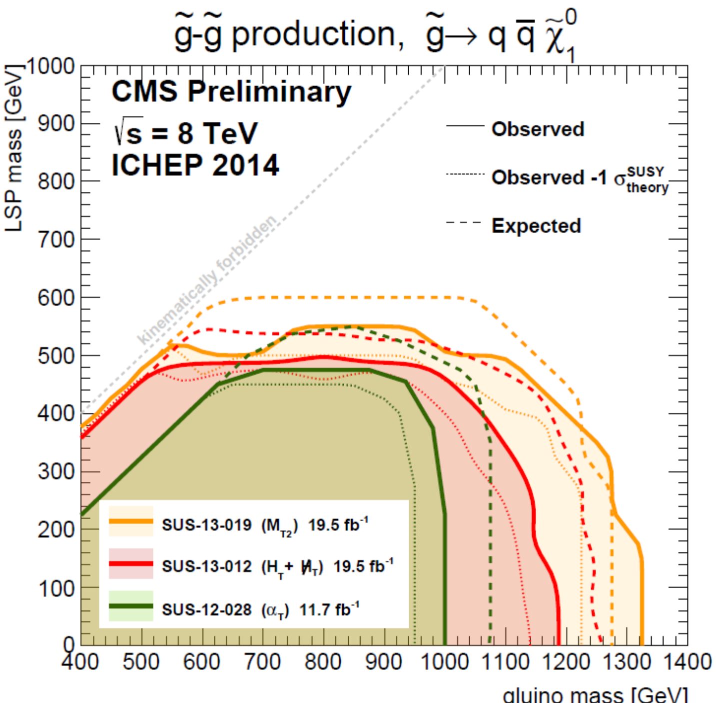




WIMPs current status

Direct production

LHC searches for EW-ino DM



Direct detection

LUX null results

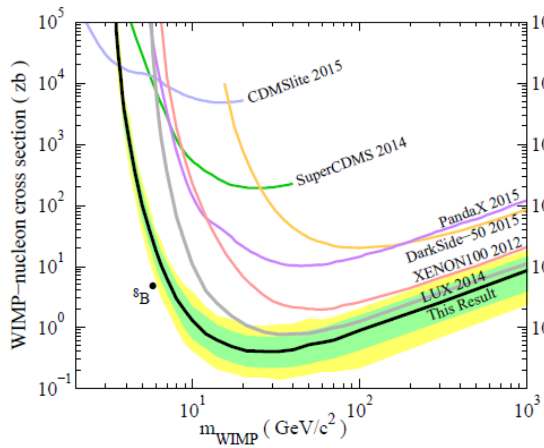
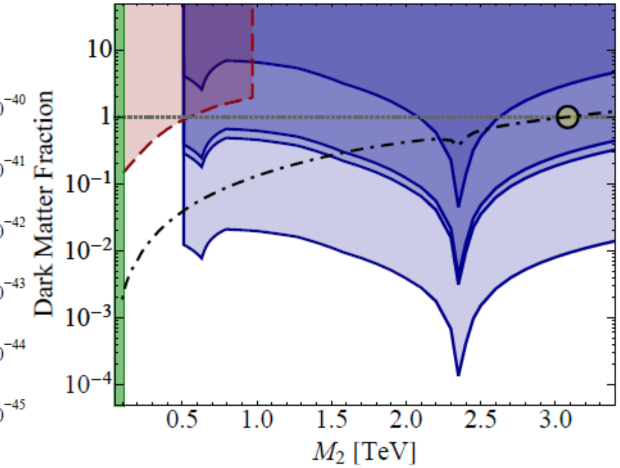


FIG. 3. Upper limits on the spin-independent elastic WIMP-nucleon cross section at 90% CL. Observed limit in black, with the 1- and 2-σ ranges of background-only trials shaded green and yellow. Also shown are limits from the first LUX analysis [6] (gray), SuperCDMS [35] (green), CDMSlite [36] (light blue), XENON100 [37] (red), DarkSide-50 [38] (orange), and PandaX [39] (purple). The expected spectrum of coherent neutrino-nucleus scattering by ^{8}B solar neutrinos can be fit by a WIMP model as in [40], plotted here as a black dot.

[LUX, 1512.03506]

Indirect detection



HESS pressing the thermal Wino

[Cohen, Lisanti, Pierce, Slatyer JCAP 1310, 061 (2013); Fan and Reece, JHEP 1310, 124 (2013)]

Been searching…
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…

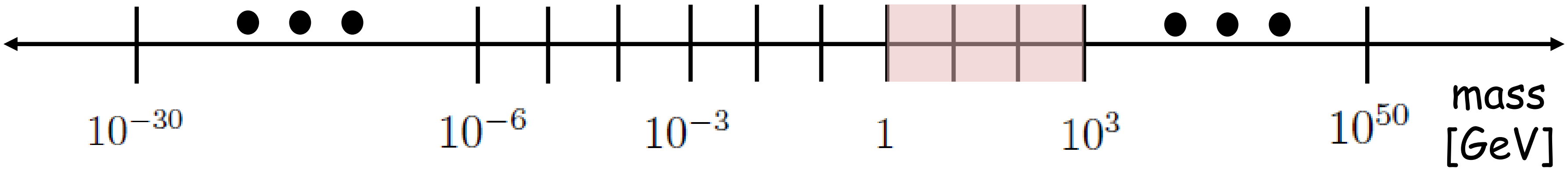
→

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

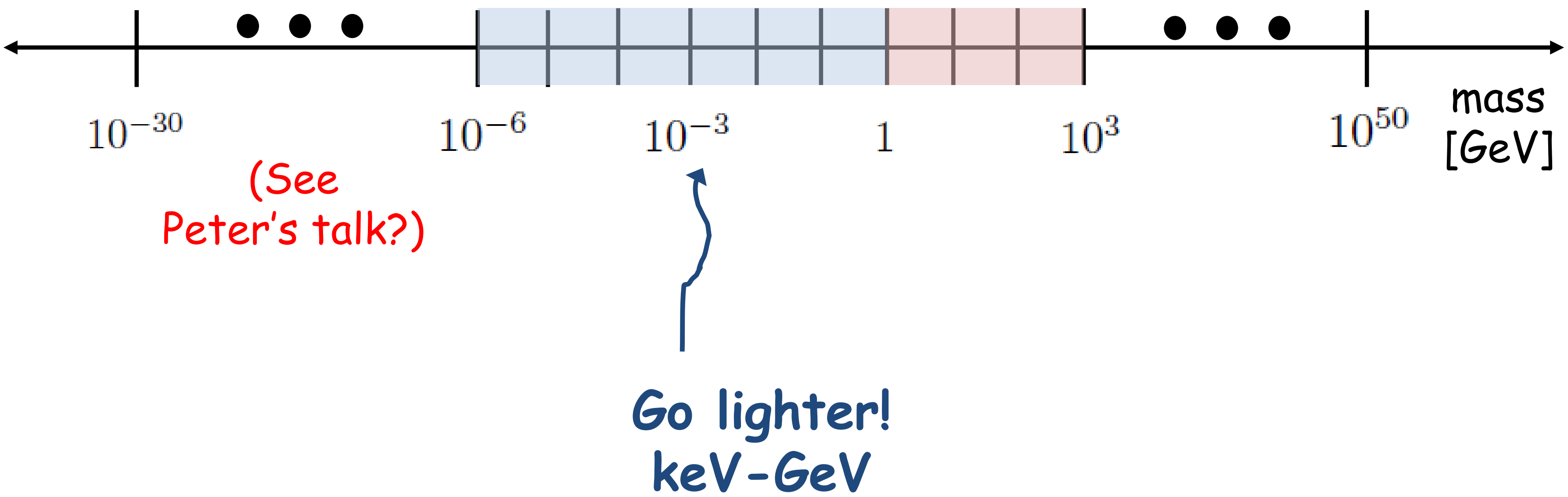
theoretically & experimentally

[Hitoshi]

Beyond the WIMP

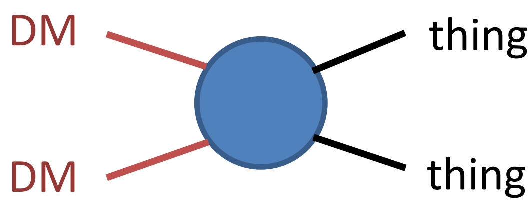


Beyond the WIMP



Theory: example #1

- **Weakly coupled 2→2:**



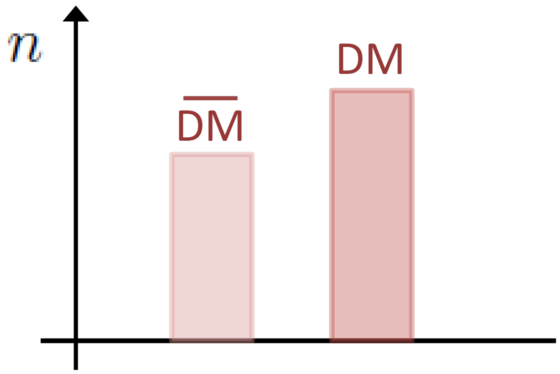
$$\langle \sigma v \rangle \sim \frac{\alpha^2}{m_{\rm DM}^2} \qquad \alpha \ll 1$$

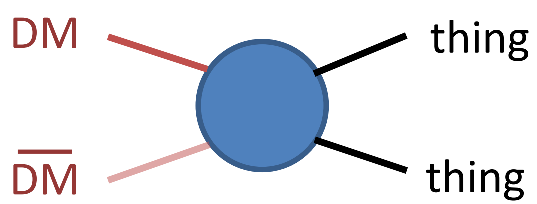
$$m_{\rm DM} \sim \alpha \times 30 \ \mathrm{TeV}$$

[Pospelov, Ritz, Voloshin 2007;
Feng, Kumar 2008]

Theory: example #2

- **<u>Asymmetric dark matter:</u>**



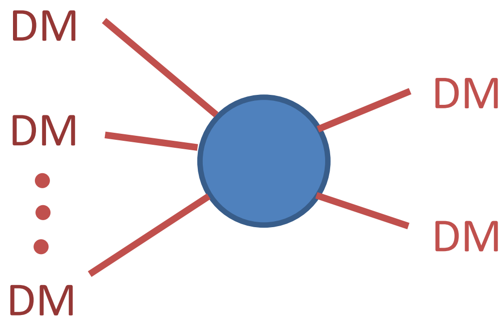


$$m_{\text{DM}} \sim 5\ \text{GeV} \left(\frac{n_B - n_{\overline{B}}}{n_{\text{DM}} - n_{\overline{\text{DM}}}} \right)$$

[Kaplan, Luty, Zurek, 2009]

Theory: example #3

- **SIMPs:** n→ 2 self-annihilations



$$m_{\rm DM} \sim \alpha \left(T_{\rm eq}^{n-1} M_{\rm Pl}\right)^{1/n}$$

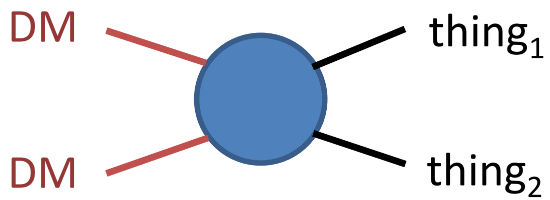
3→ 2 $\Longrightarrow$ $m_{\rm DM} \sim \alpha_{\rm eff} \times 100 \text{ MeV}$

[Carlson, Hall, Machacek, 1992;
YH, Kuflik, Volansky, Wacker, 2014]

(See also elastically decoupling dark matter (ELDERs)
[Kuflik, Perelstein, Rey-Le Lorier, Tsai, 2015])

Theory: example #4

- **Forbidden channels:**



$$2m_{\rm DM} < m_{\rm thing_1} + m_{\rm thing_2}$$

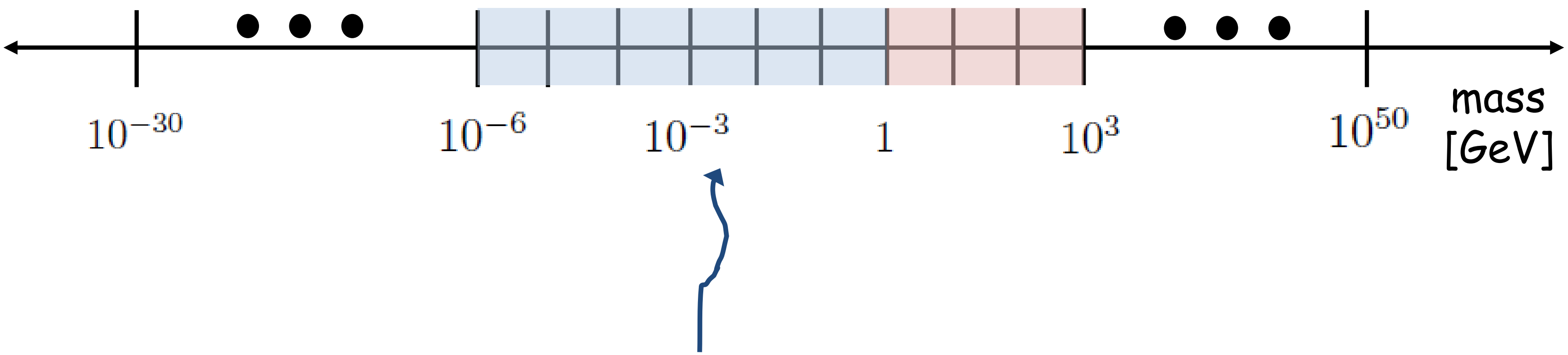
$$m_{\rm DM} \sim \alpha \times (30\ {\rm TeV}) \times e^{-x_F \Delta}$$

freezeout temp'

mass difference

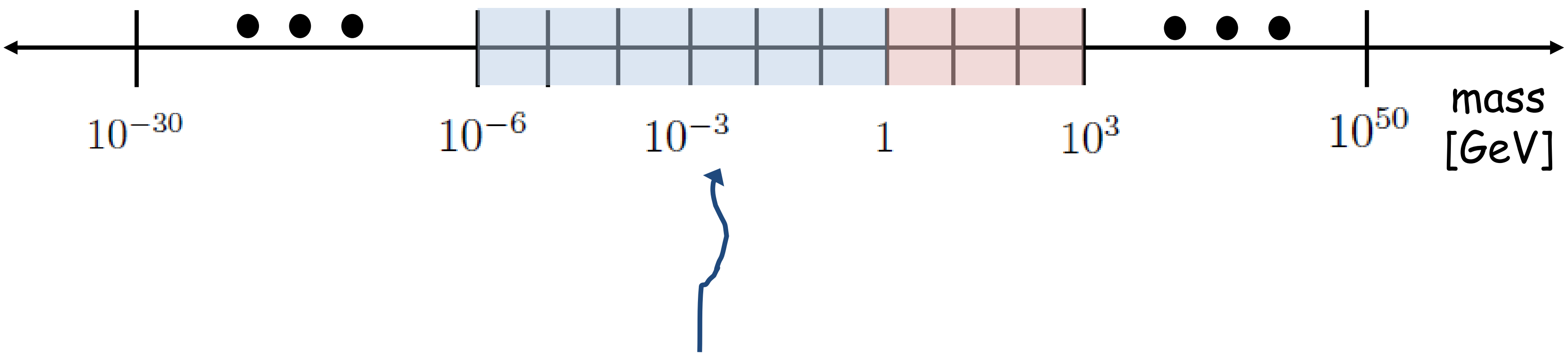
[Griest, Seckel, 1991;
D'Agnolo, Ruderman, 2015]

Beyond the WIMP



Theory:
Lots of activity in recent years

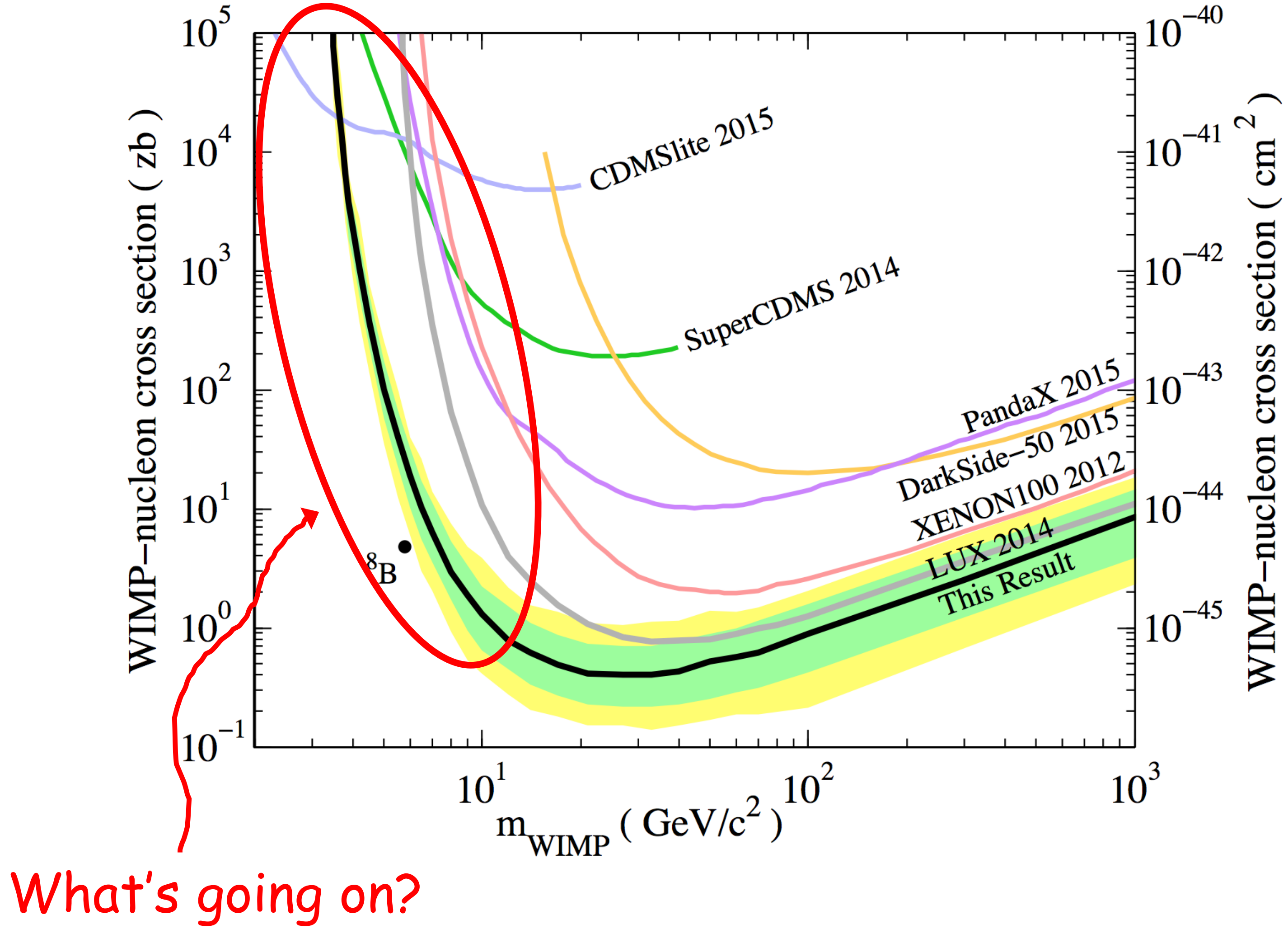
Beyond the WIMP



Experiment:
Focus on direct detection
of keV-GeV
dark matter

How?

Direct Detection



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);
Graham, Kaplan, Rajendran, Walters, PDU 1, 32 (2012)]

Direct Detection

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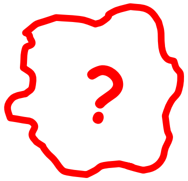
$m_{\rm DM} \sim {\rm MeV} \Rightarrow E_D \sim {\rm eV}$ → electron ionization, semiconductors

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



Direct Detection

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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

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

[**YH**, Zhao and Zurek, PRL 116, 011301
YH, Pyle, Zhao and Zurek 1512.04533]

Kinematics

Target at rest: $E_D \sim \frac{q^2}{2m_T}$

- Target = N: $q_{\max} \sim 2\mu_r v_{\rm DM} \sim 2m_{\rm DM}v_{\rm DM}$

  Even for $\sigma_E \sim {\rm eV}$, only $m_{\rm DM} \sim \mathcal{O}(100'{\rm s\ MeV})$ detectable

- Target = e: $m_{\rm DM} \sim {\rm keV}$ ⟹ $E_D \sim 10^{-6}\ {\rm eV}$

  $m_{\rm DM} \sim {\rm MeV}$ ⟹ $E_D \sim {\rm eV}$ [seminconductors]

Even $\sigma_E \sim {\rm meV}$ won't allow sensitivity to keV DM

Kinematics

Target w/ velocity: $$E_D \sim \left(\frac{\vec{q}^2}{2m_T} + \vec{q}\cdot\vec{v}_T\right) + \delta$$

- $m_{\rm DM} \gg m_T$: DM barely affected

  $$v_T \to v_T + 2v_{\rm DM}$$

  $$E_D^{\rm max} = \frac{1}{2}m_T\left[(v_T + 2v_{\rm DM})^2 - v_T^2\right]$$

- $m_{\rm DM} \ll m_T$: Target can fully stop the DM

  $$E_D^{\rm max} \sim \frac{1}{2}m_{\rm DM}v_{\rm DM}^2$$

  $\sigma_E \sim {\rm meV}$ for $m_{\rm DM} \sim {\rm keV}$!

Kinematics

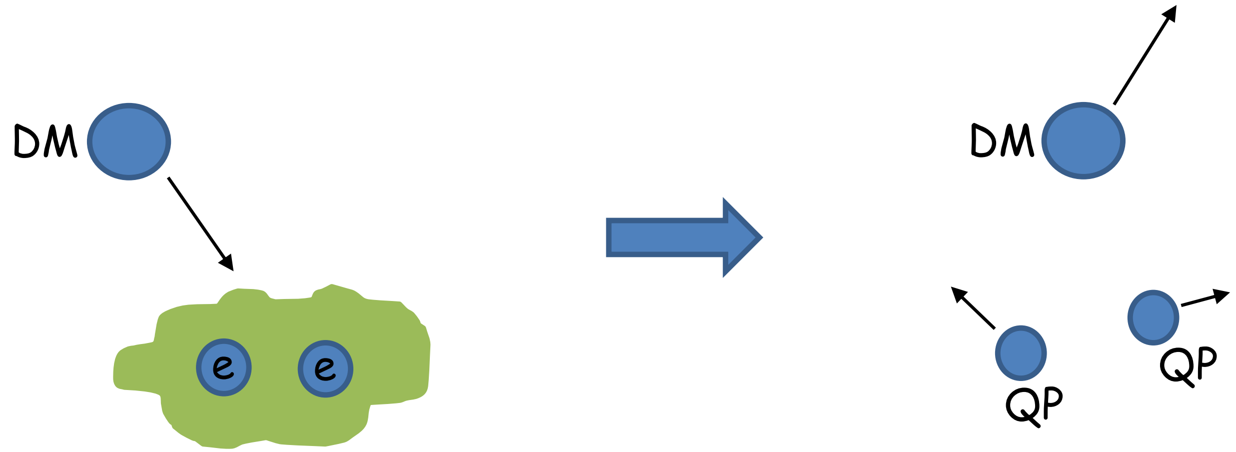
Target w/ velocity: $$E_D \sim \left(\frac{\vec{q}^2}{2m_T} + \vec{q}\cdot\vec{v}_T\right) + \delta$$

Fermi-degenerate materials
have velocity!

Focus on superconductor targets.

Superconductor Cheat Sheet

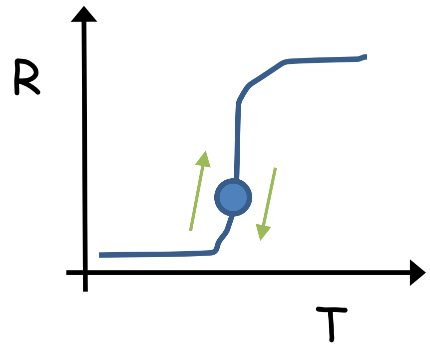
- Ground state of superconductor = Cooper pairs;
  Binding energy (gap) $\Delta \lesssim \mathrm{meV}$
- <u>The idea:</u>
  DM scatters with Cooper pairs, deposits enough energy, breaks Cooper pairs, creating quasiparticles → detect



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. ACT, SPT, 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

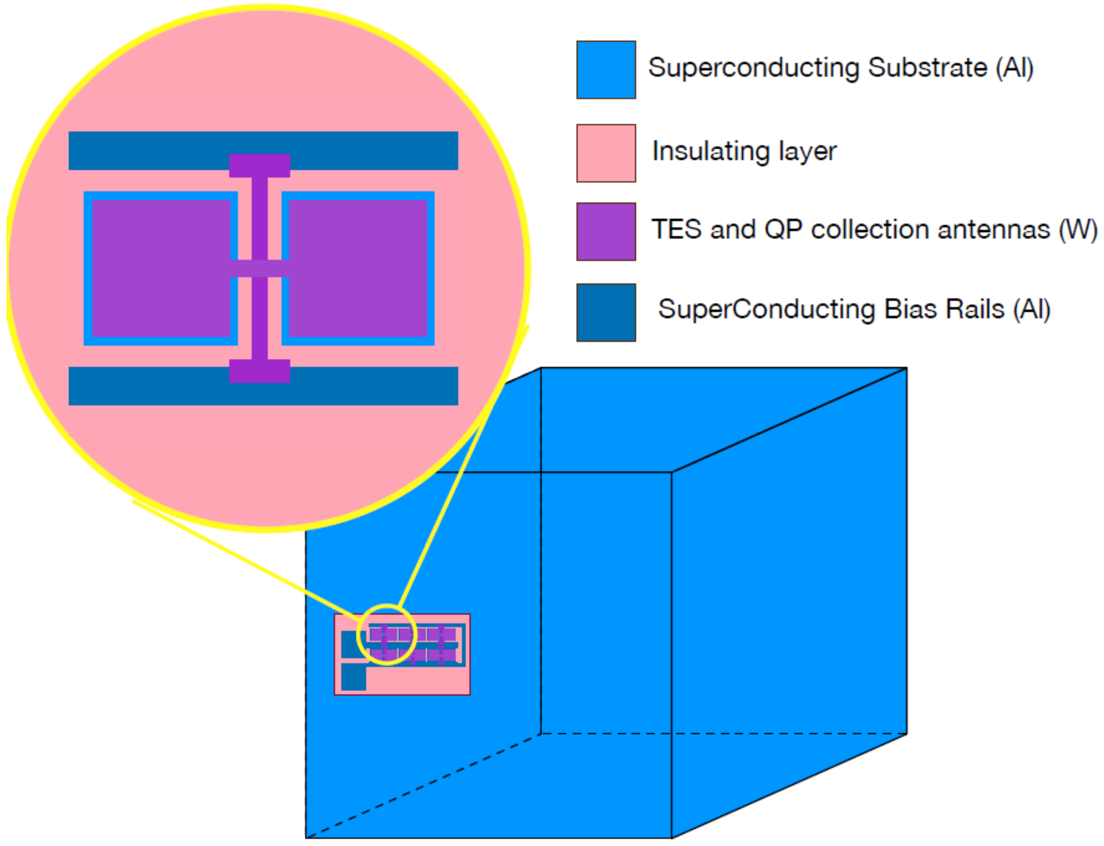
- Need to beat noise
- Energy resolution $\sigma_E \propto \sqrt{T^3 V}$ ⇒ **Reduce temperature and volume for O(meV) resolution**

Detector Concept

Basic device idea:
Large exposure but high energy resolution = excitation concentration

(E.g. SuperCDMS)

Absorber →
Collection fins→
TES

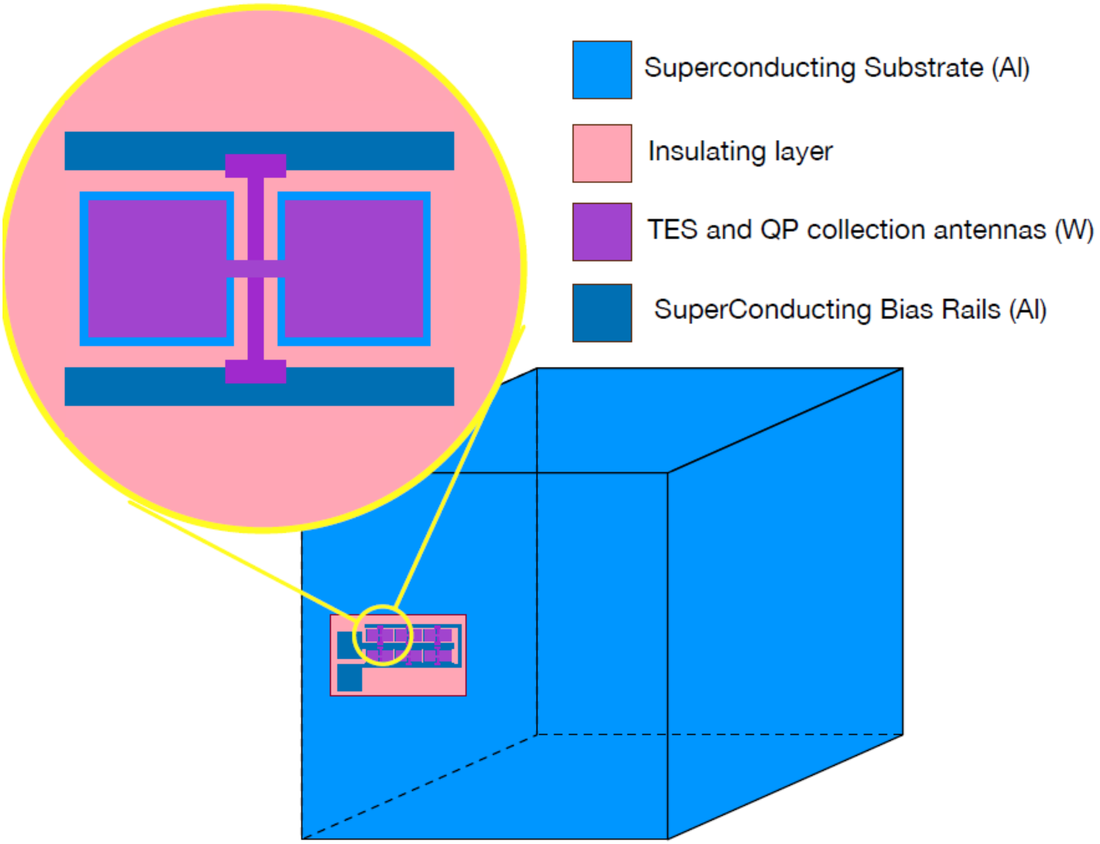


Design by Matt Pyle

Detector Concept

- Quasiparticle lifetime of order a milisecond

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

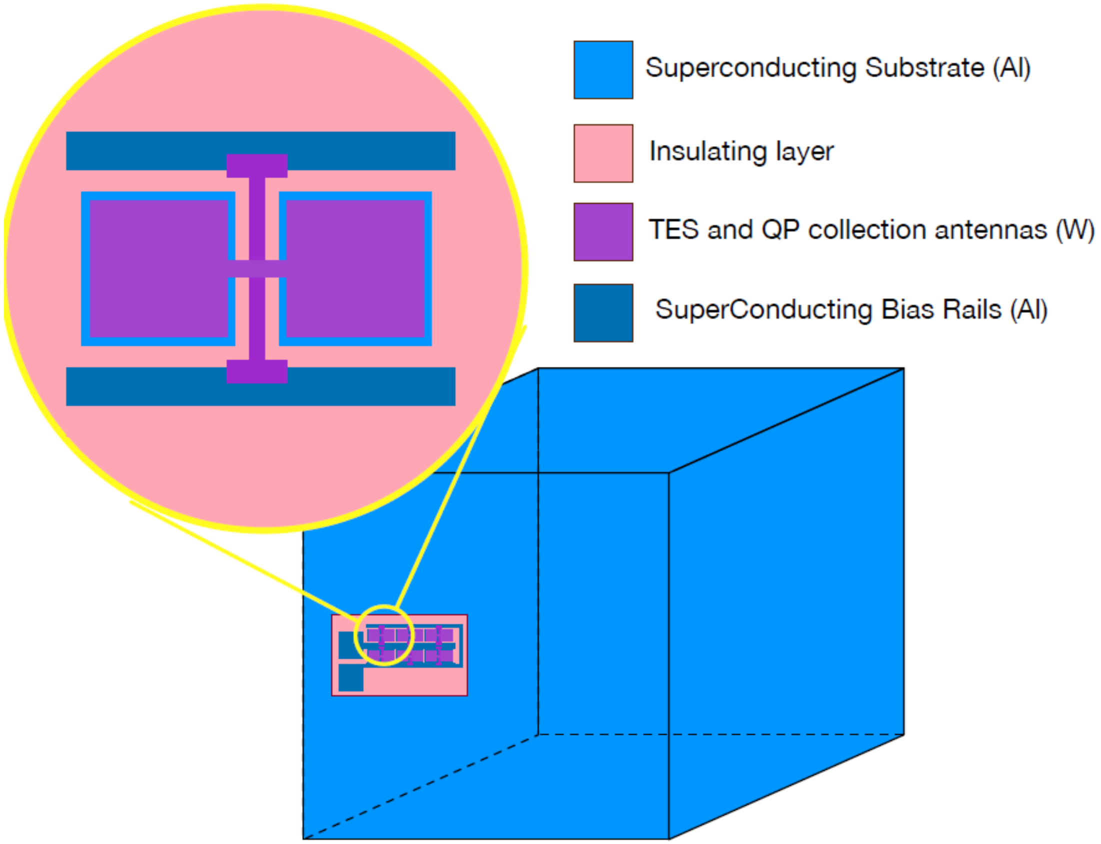


Design by Matt Pyle

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**

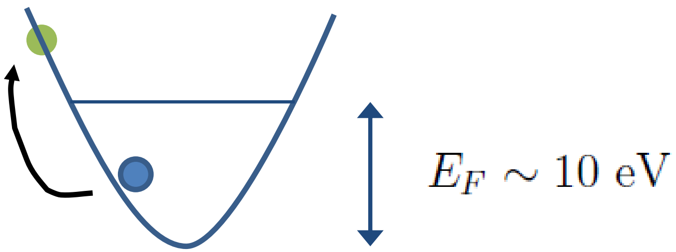


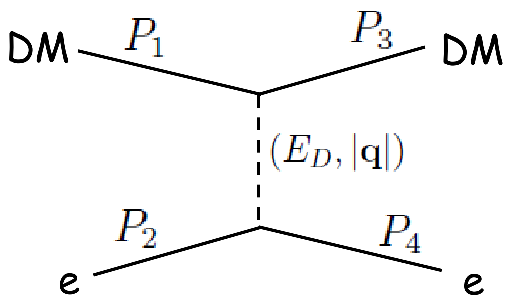
Design by Matt Pyle

Rates & Results

Rates

Scatter off electrons in Fermi-degenerate metal – Pauli blocking





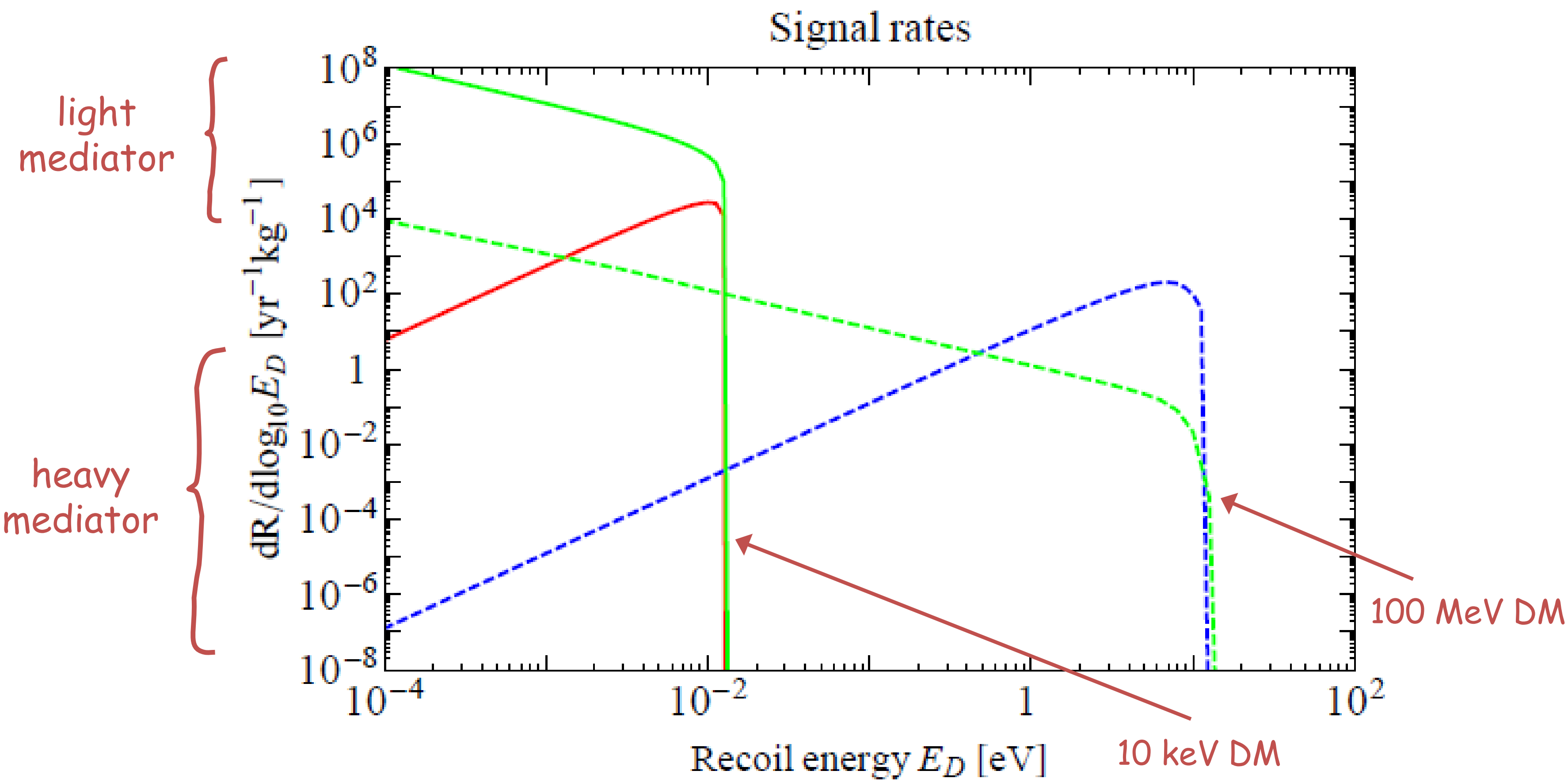
$$\langle n_e \sigma v_{\rm rel} \rangle = \int \frac{d^3 p_3}{(2\pi)^3} \frac{\langle |\mathcal{M}|^2 \rangle}{16 E_1 E_2 E_3 E_4} S(E_D, |\mathbf{q}|)$$

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

Fermi-Dirac distribution

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

Rates



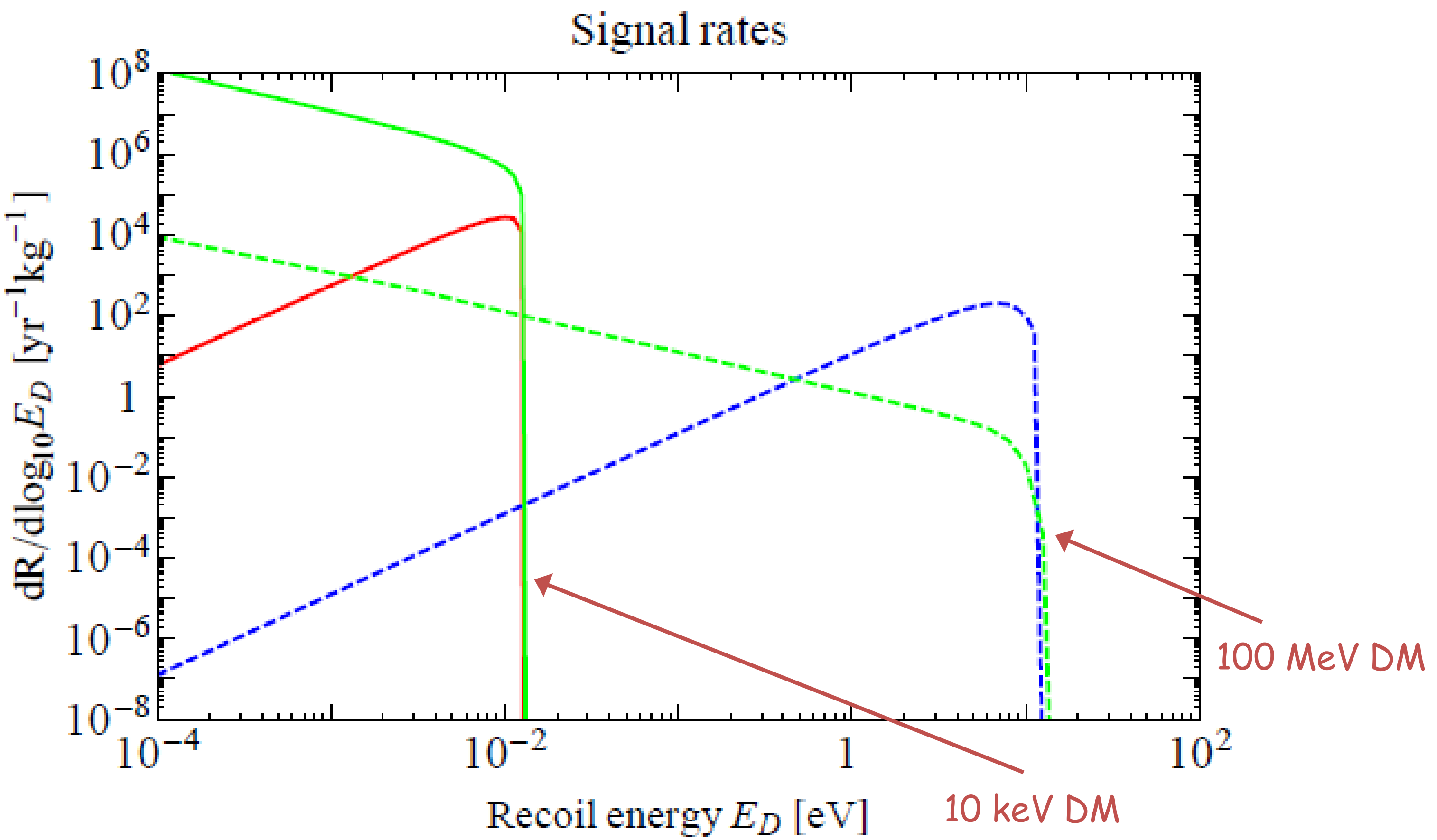
Signal rates
light mediator
heavy mediator
dR/dlog$_{10}E_D$ [yr^{-1}kg^{-1}]
10^8
10^6
10^4
10^2
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-4}
10^{-2}
1
10^2
Recoil energy E_D [eV]
100 MeV DM
10 keV DM

Rates

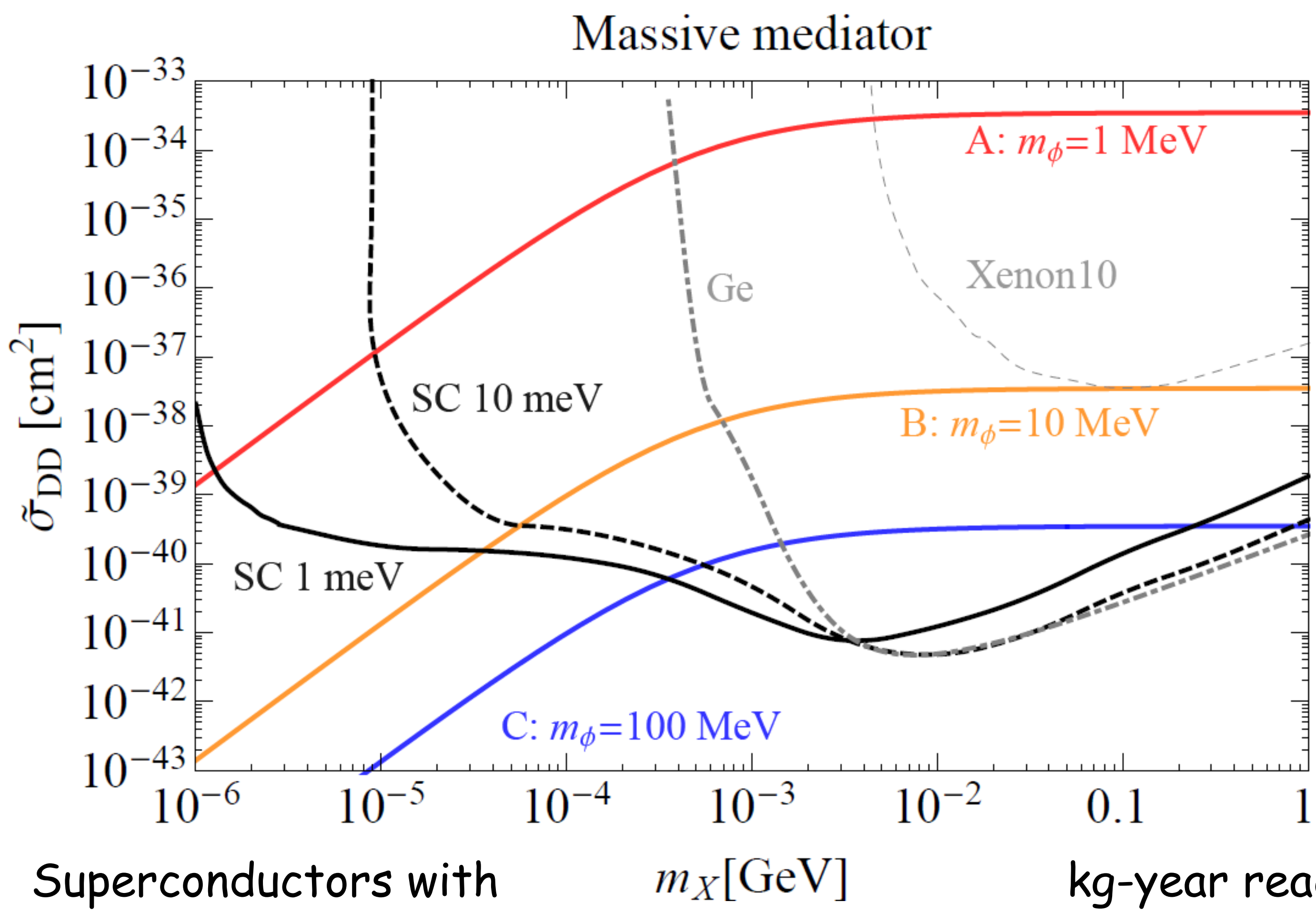
Low momentum dominates

$$\sigma = \frac{16\pi\alpha_e\alpha_X}{(m_\phi^2 - q^2)^2}\mu_{eX}^2$$

Pauli blocking dominates



Reach

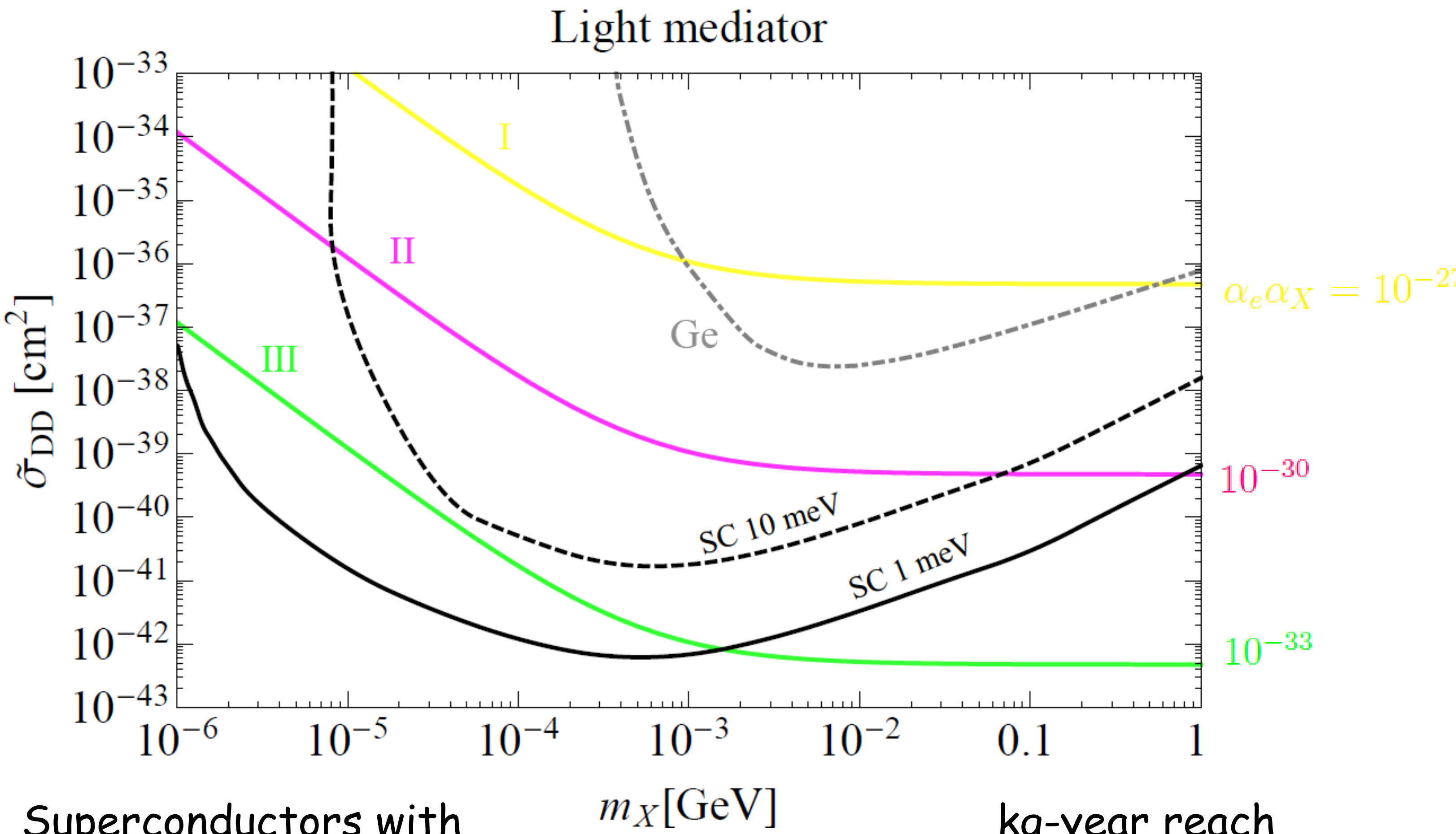


Superconductors with 1 meV or 10 meV threshold

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

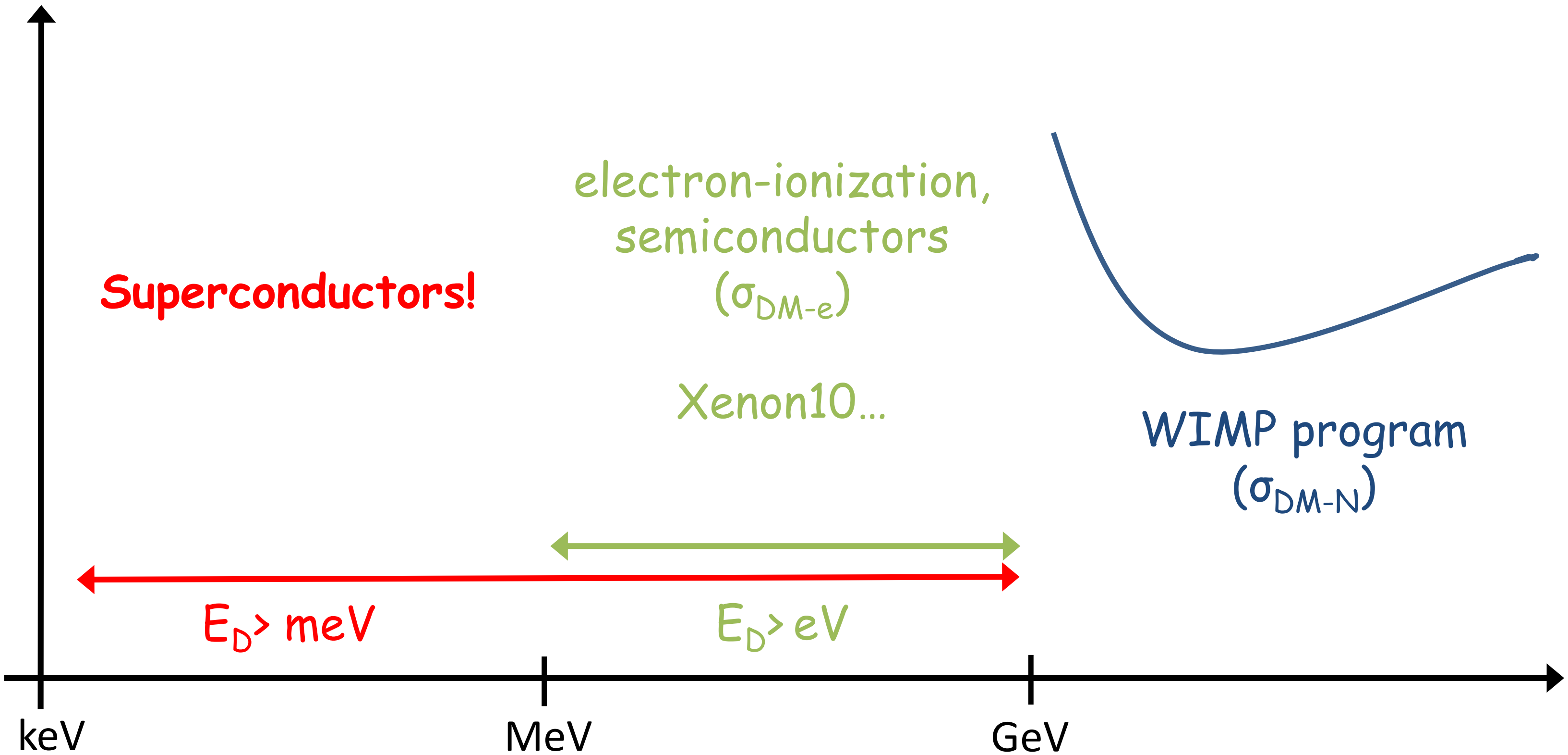
$$\tilde{\sigma}_{DD}^{\text{light}} = \frac{16\pi\alpha_e\alpha_X}{q_{\text{ref}}^4}\mu_{eX}^2$$

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

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 — works in progress
- Populate the models space

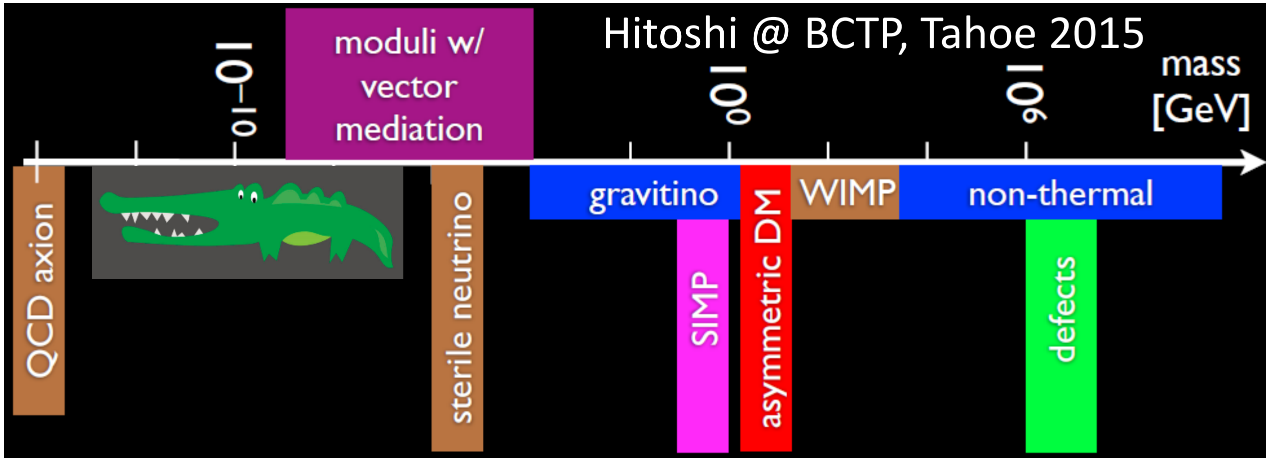
Prospects

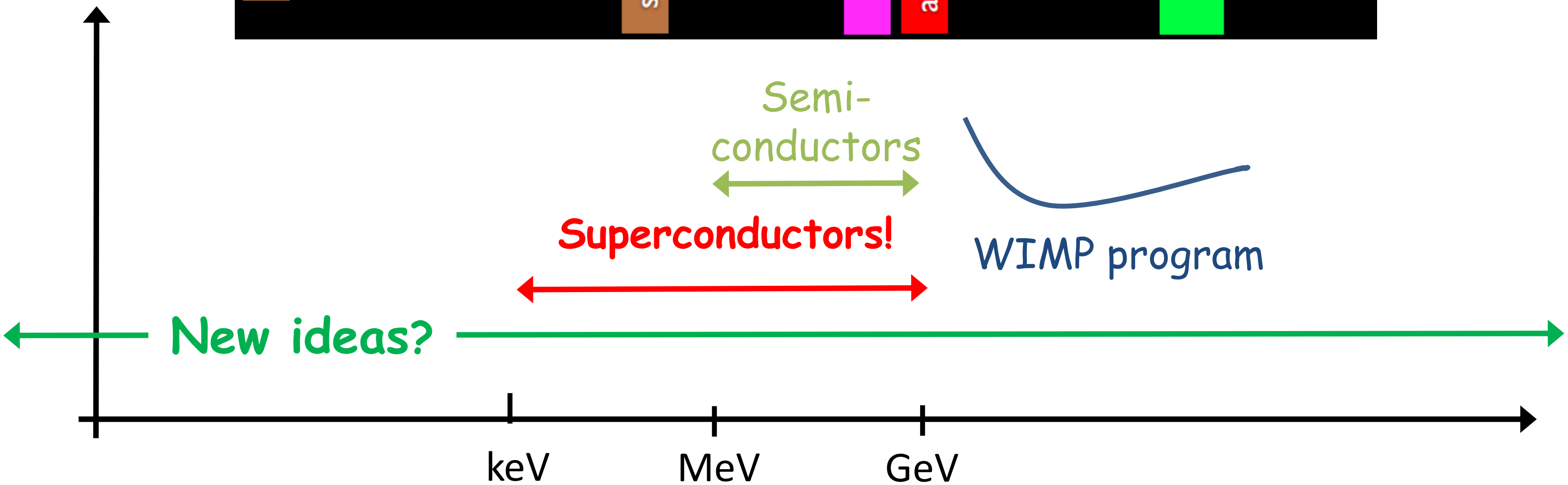


electron-ionization,
semiconductors
($\sigma_{DM\text{-}e}$)
Superconductors!
Xenon10…
WIMP program
($\sigma_{DM\text{-}N}$)
E_D> meV
E_D> eV
keV
MeV
GeV

Prospects

Model zoo





Experimental playground

“Make dark matter great again.”

Thanks!