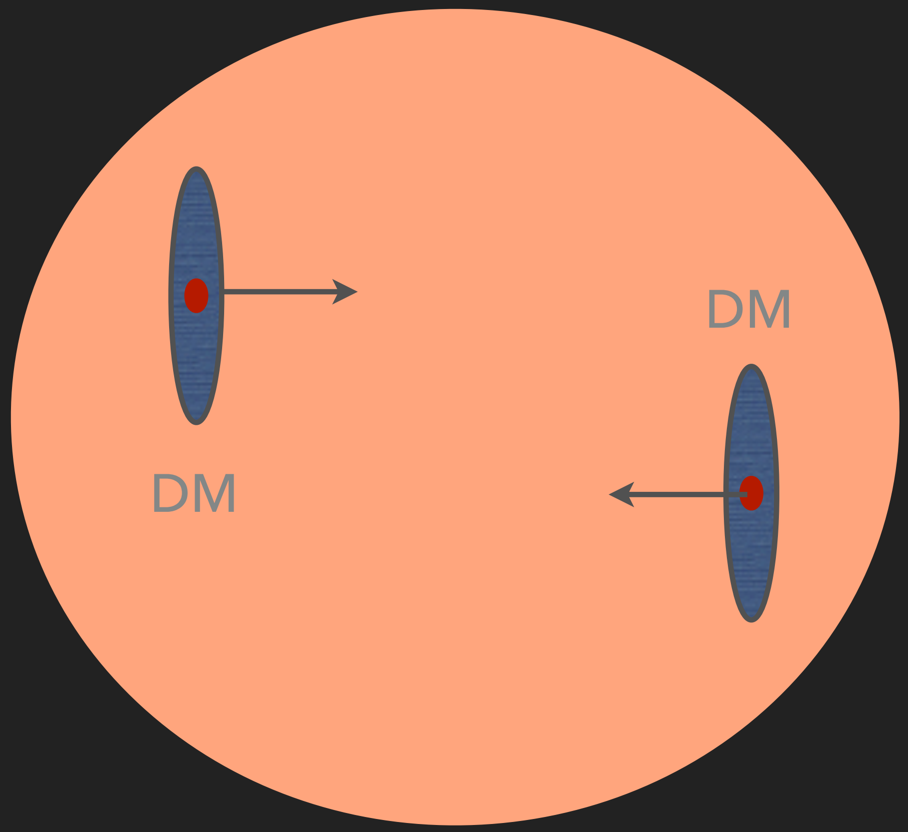
K. ZUREK

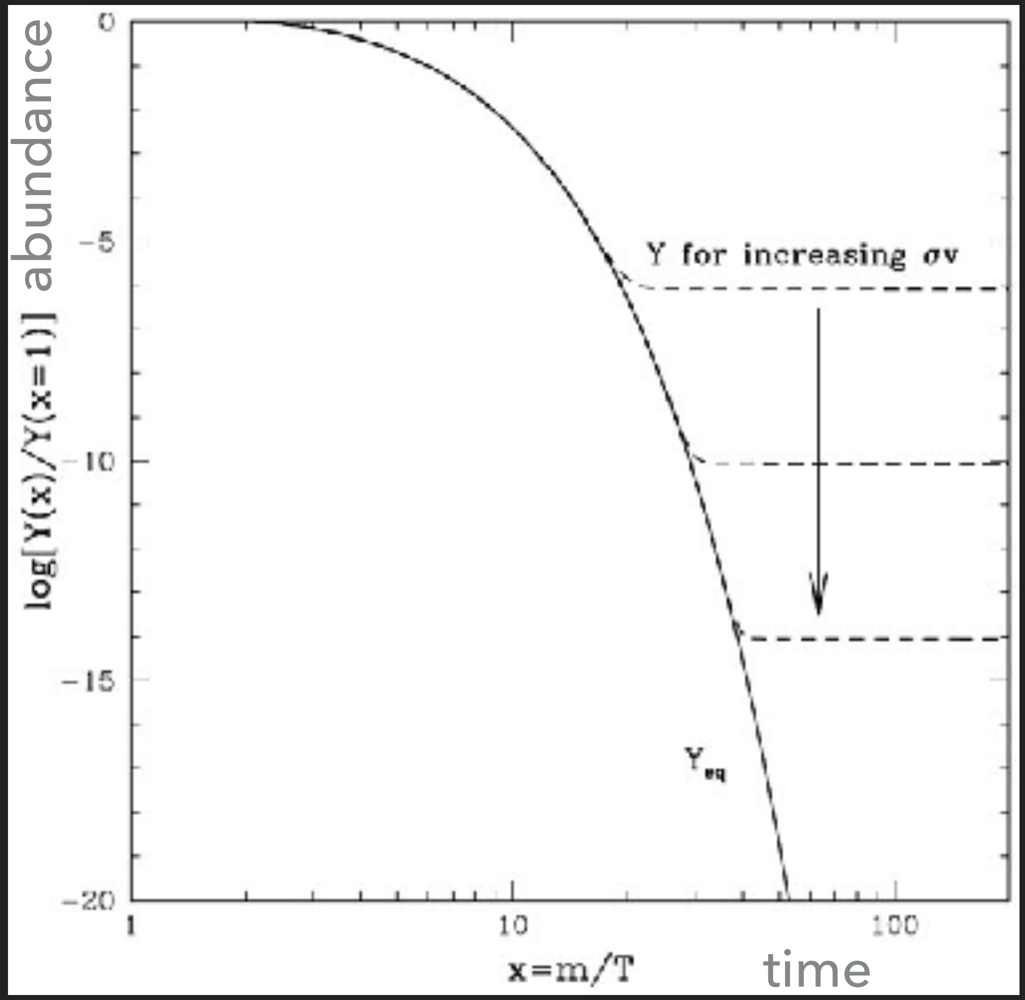
Leveraging the many faces (and phases) of matter

QUANTUM MATERIALS & DARK MATTER DETECTION

NEW IDEAS IN DARK MATTER THEORY

- Old paradigm: weak scale dark matter (with relic density fixed by freeze-out)





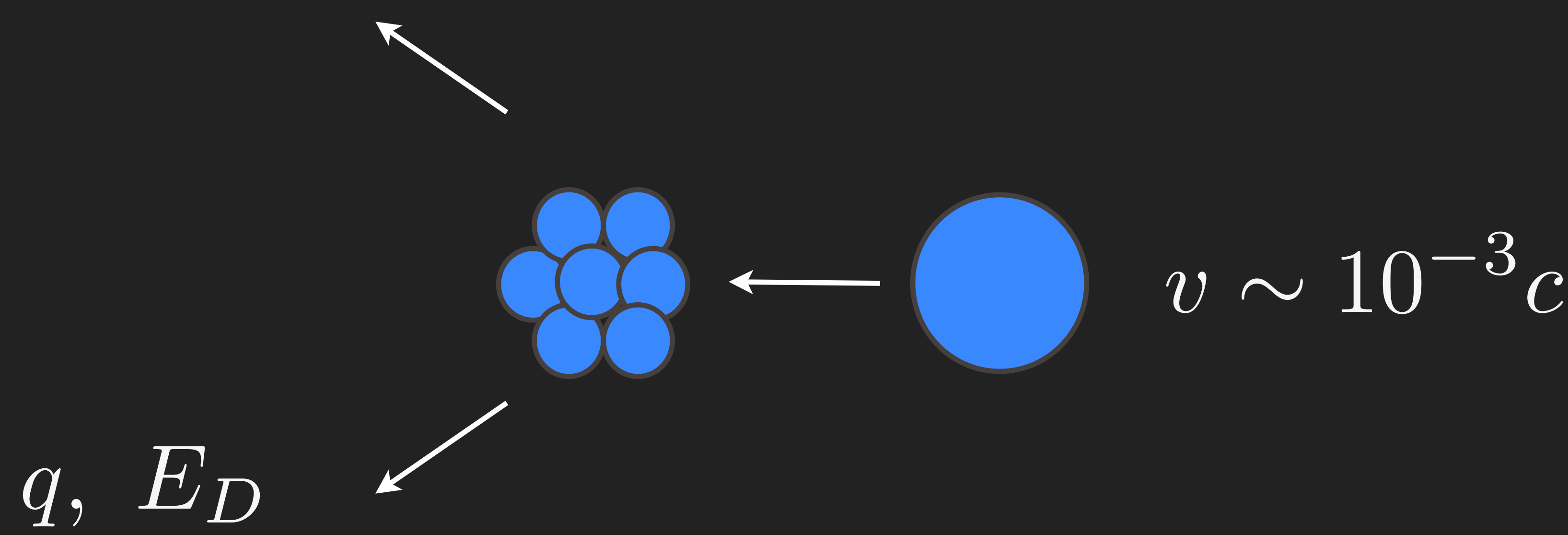
Kolb and Turner

$$n\langle\sigma v\rangle = H(T_{fo})$$

$$\implies \langle\sigma v\rangle \simeq \frac{1}{(20\ \mathrm{TeV})^2} \simeq \frac{g_{wk}^4}{4\pi(2\ \mathrm{TeV})^2}$$

DIRECT DETECTION GOLD STANDARD

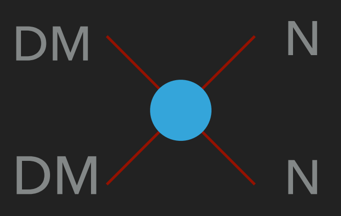
- Nuclear recoil experiments; basis of enormous progress in direct detection



$$\Longrightarrow \; 2\mu_N v = q_{\max} = \sqrt{2 m_N E_D} \qquad \mu_N \equiv \frac{m_N m_X}{m_X + m_N}$$

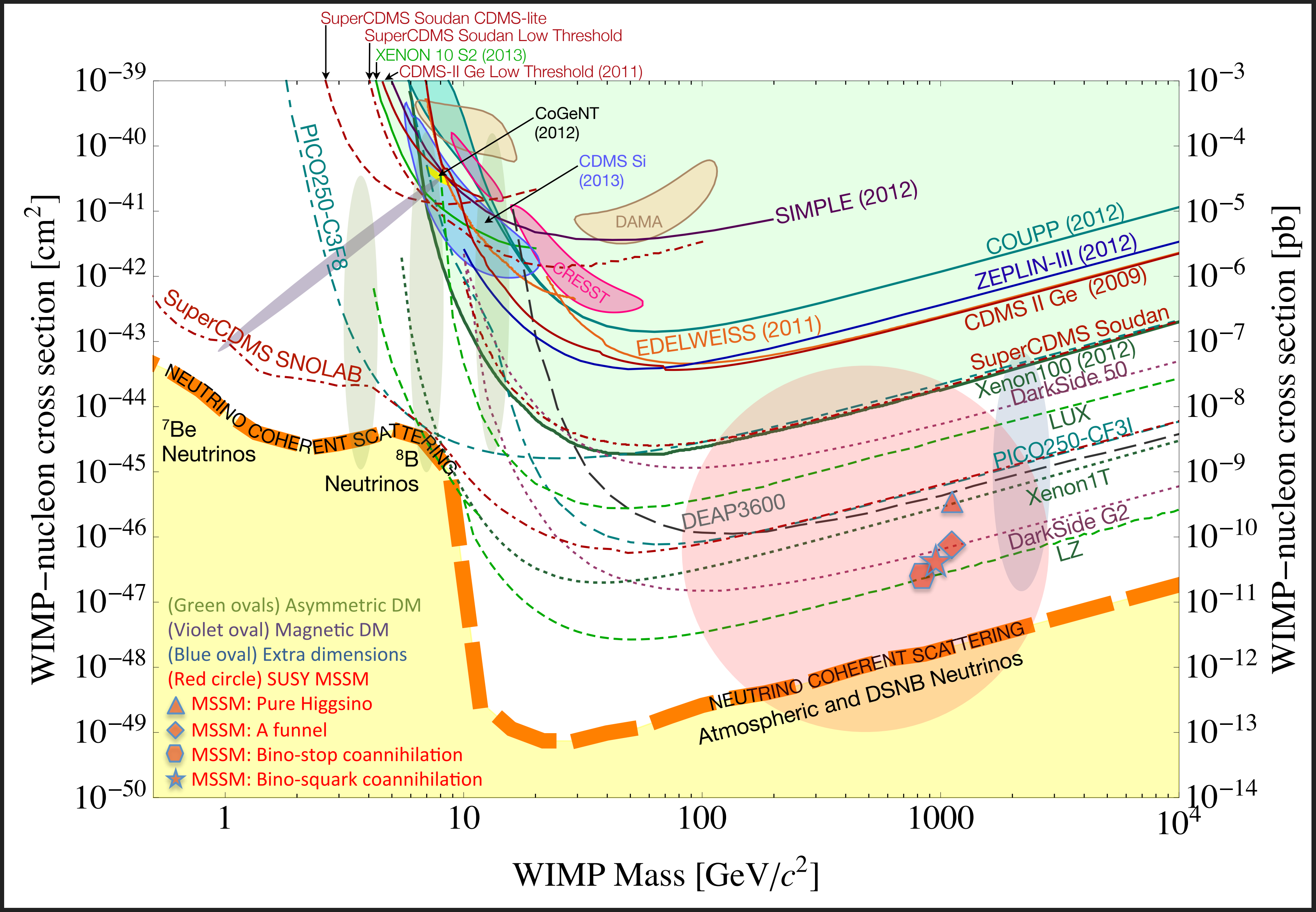
$v \sim 300 \text{ km/s} \sim 10^{-3} c \implies E_D \sim 100 \text{ keV}$ for 50 GeV target

WEAK SCALE PARADIGM: UNDER ASSAULT

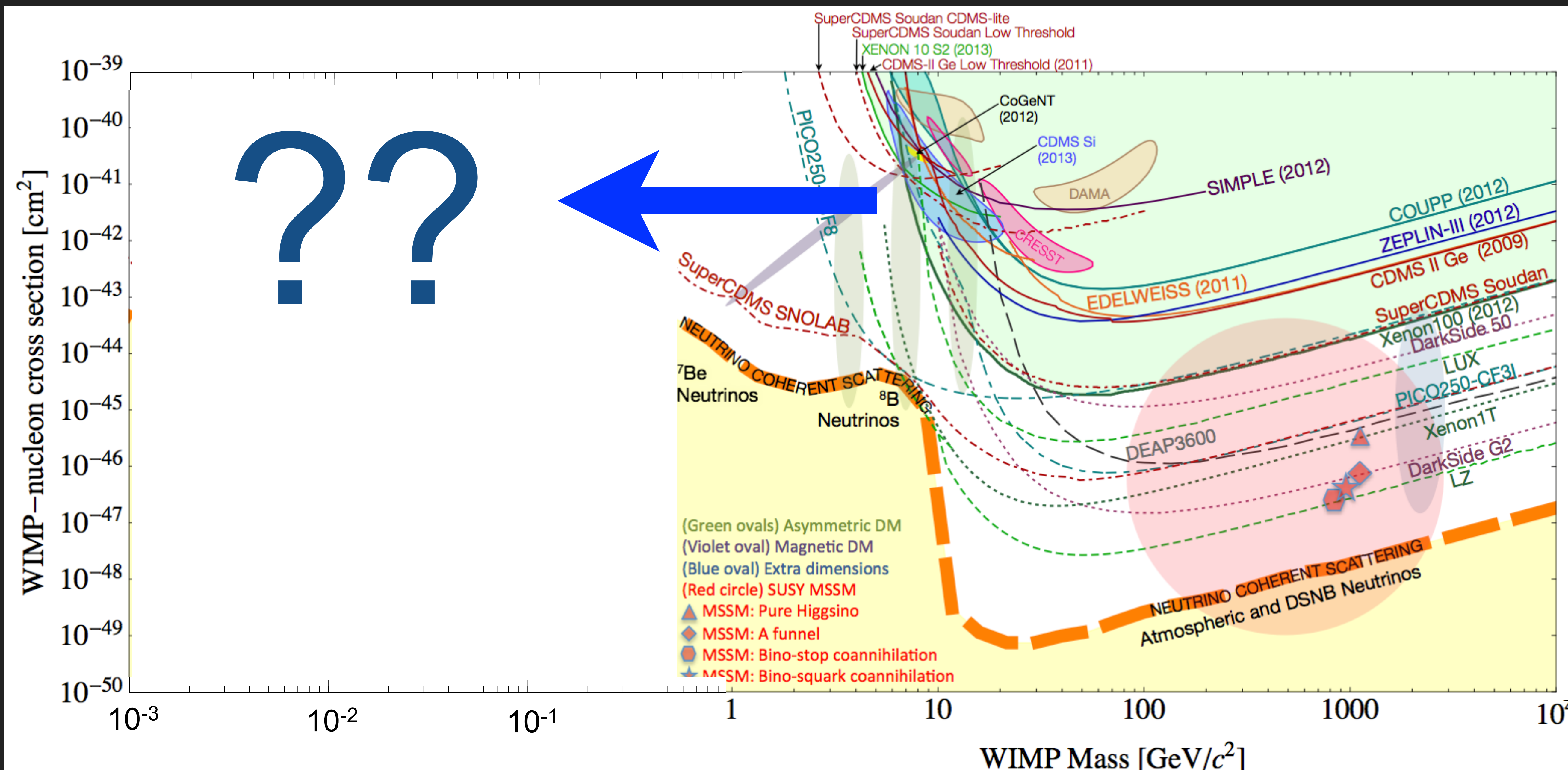


Z-boson interacting dark matter: ruled out

Higgs interacting dark matter: active target



DIRECT DETECTION GOLD STANDARD



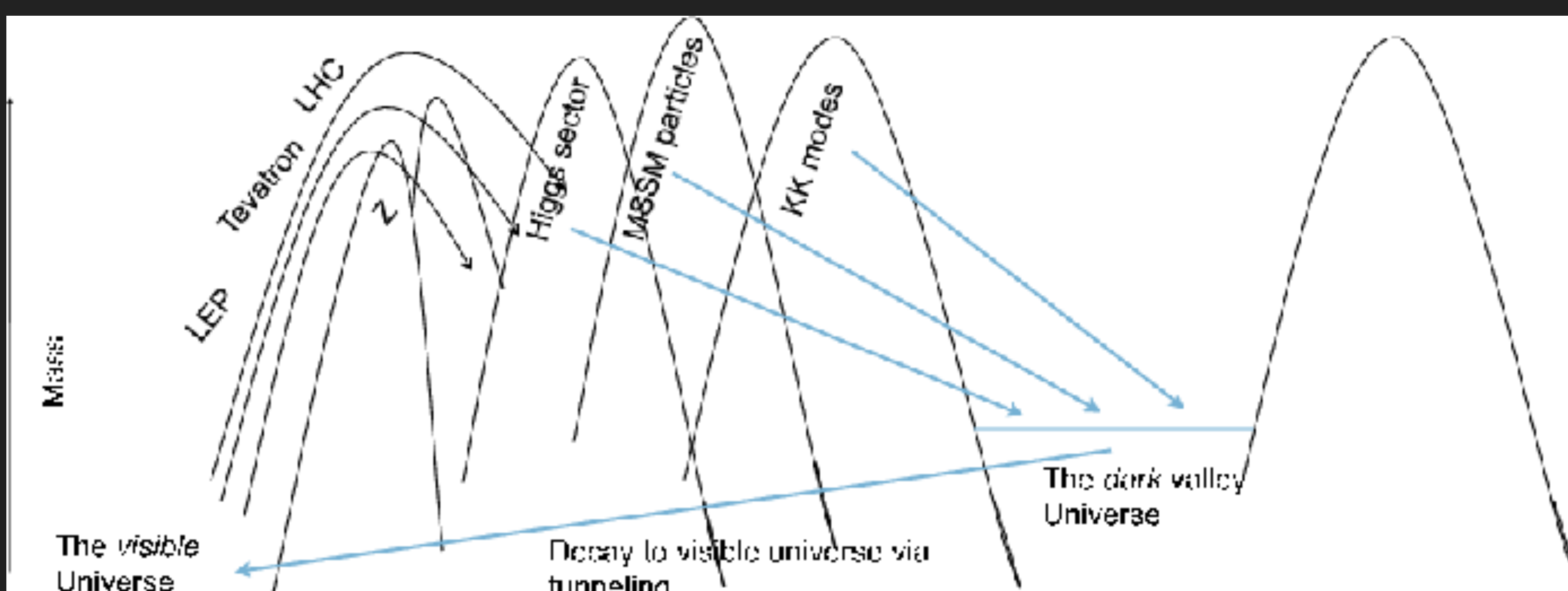
TOWARDS LIGHT DARK MATTER

Dark Matter May Reside in a Hidden Sector

Standard Model → Connector → Dark Matter

e.g. a stable dark pion

no weak force



$$\pi_v^+\pi_v^- \rightarrow \pi_v^0\pi_v^0$$

$$\pi_v^0 \rightarrow b\bar{b},\ \gamma\gamma$$

Hidden Sector / Valley Paradigm

NUCLEAR RECOILS

- Kinematic penalty when DM mass drops below nucleus mass

$$E_D = \frac{q^2}{2m_N} \qquad q_{\max} = 2m_X v$$

$$E_D \gtrsim \ \mathrm{eV} \leftrightarrow m_X = 300 \ \mathrm{MeV}$$

even though $E_{\mathrm{kin}} \gtrsim 300 \ \mathrm{eV}$

NEXT UP: ELECTRON

- More bang for the buck if DM lighter than 1 GeV

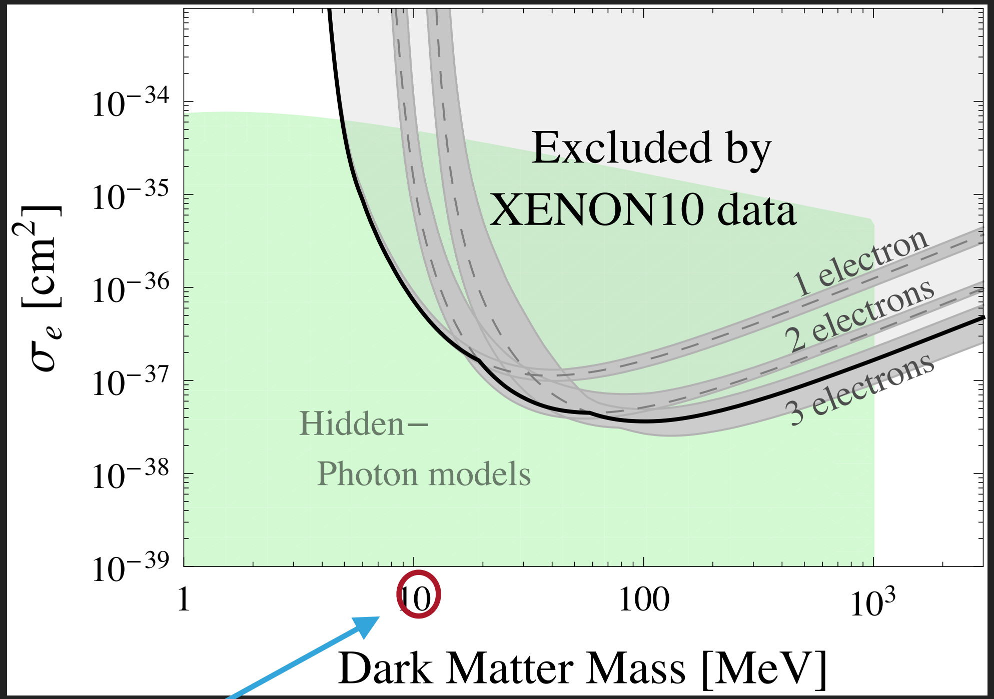
$$E_D = \frac{q^2}{2m_e} \qquad\qquad q_{\max} = 2m_X v$$

- Allows to extract all of DM kinetic energy for DM MeV and heavier

$$E_D \gtrsim \text{ eV} \leftrightarrow m_X = 1 \text{ MeV}$$

ELECTRONS IN MATERIALS

Sorensen, Essig, Manalaysay, Mardon, Volansky 1206.2644

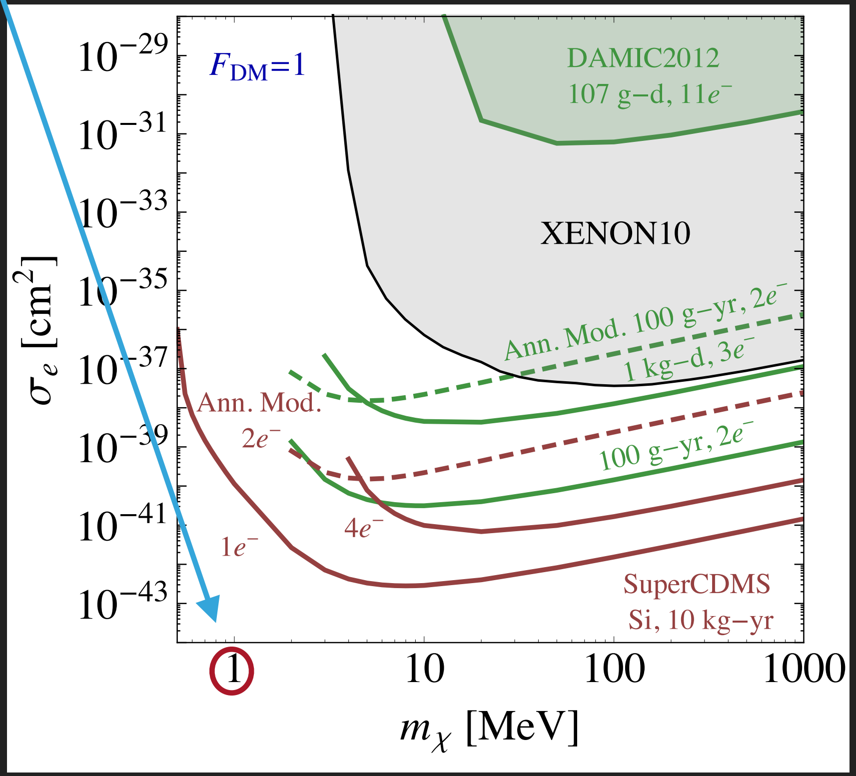


- In insulators, like xenon

  Ionize electron

Gap = DM Kinetic Energy

Essig et al 1509.01598



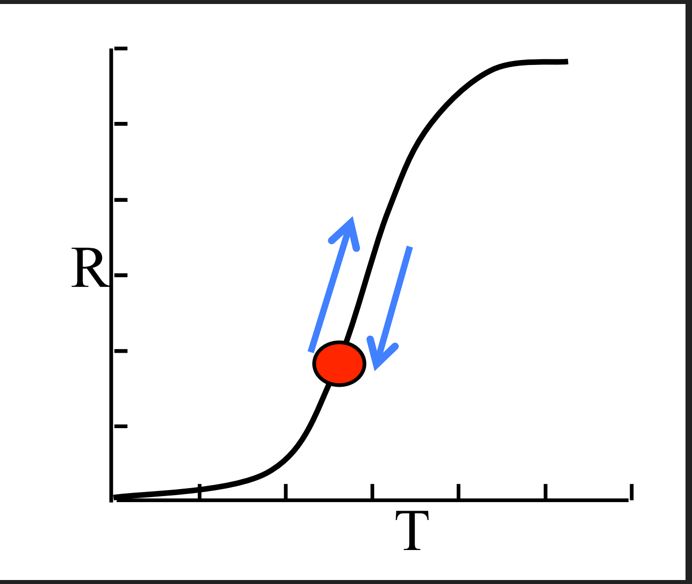
- In semi-conductors, like Ge, Si

  Excite electron to conduction band

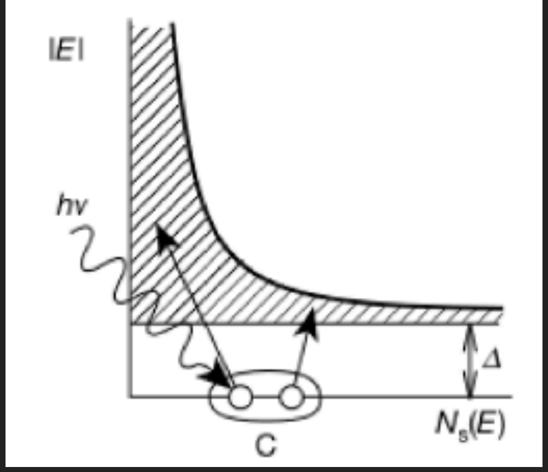
QUANTUM DEVICE R&D

- In addition to suitable target (quantum phases of matter), need quantum devices capable of measuring small energy deposits
- Superconducting devices that measure single quanta
- Single infrared or microwave photon detectors

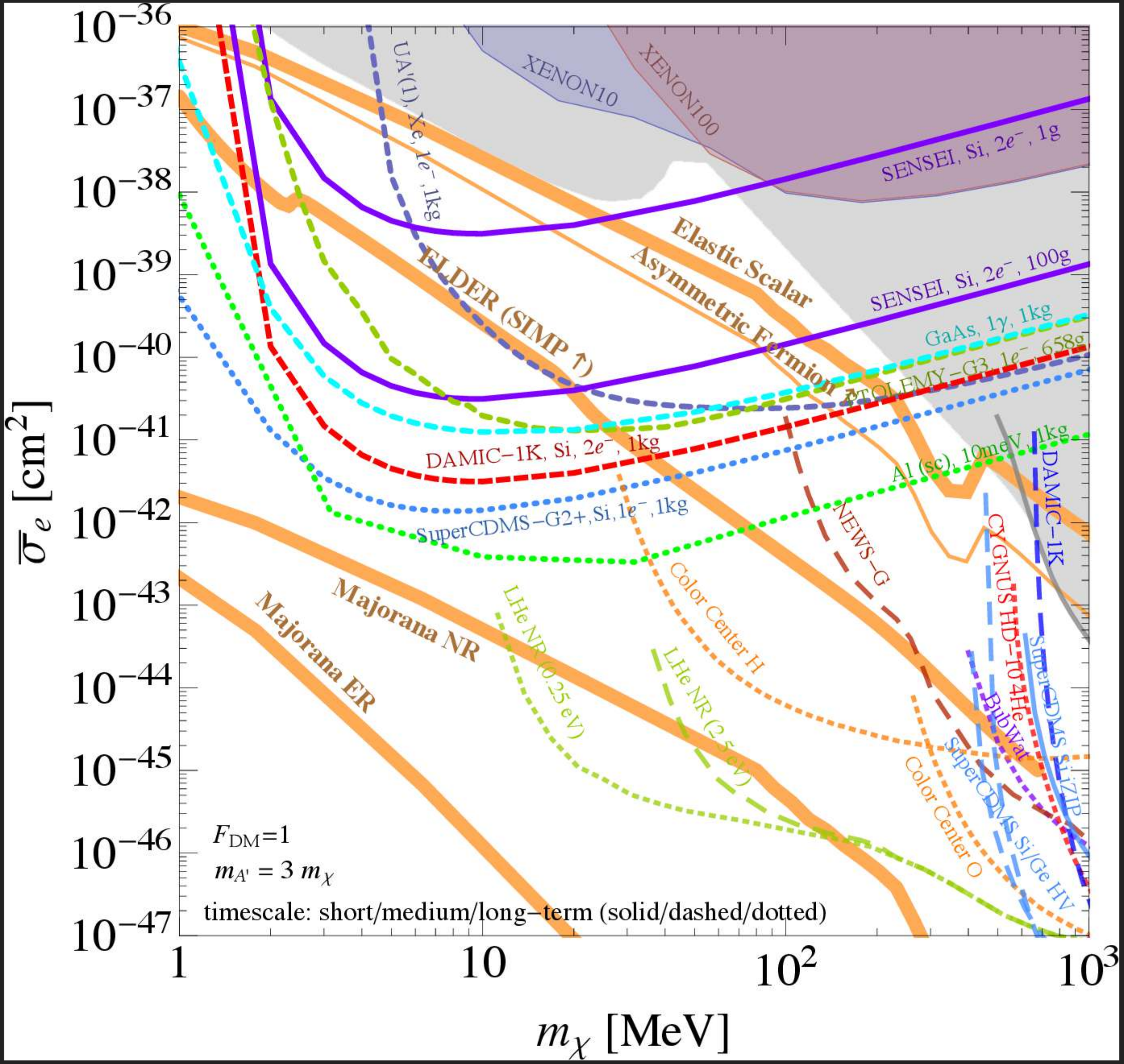
Transition Edge Sensor calorimeter



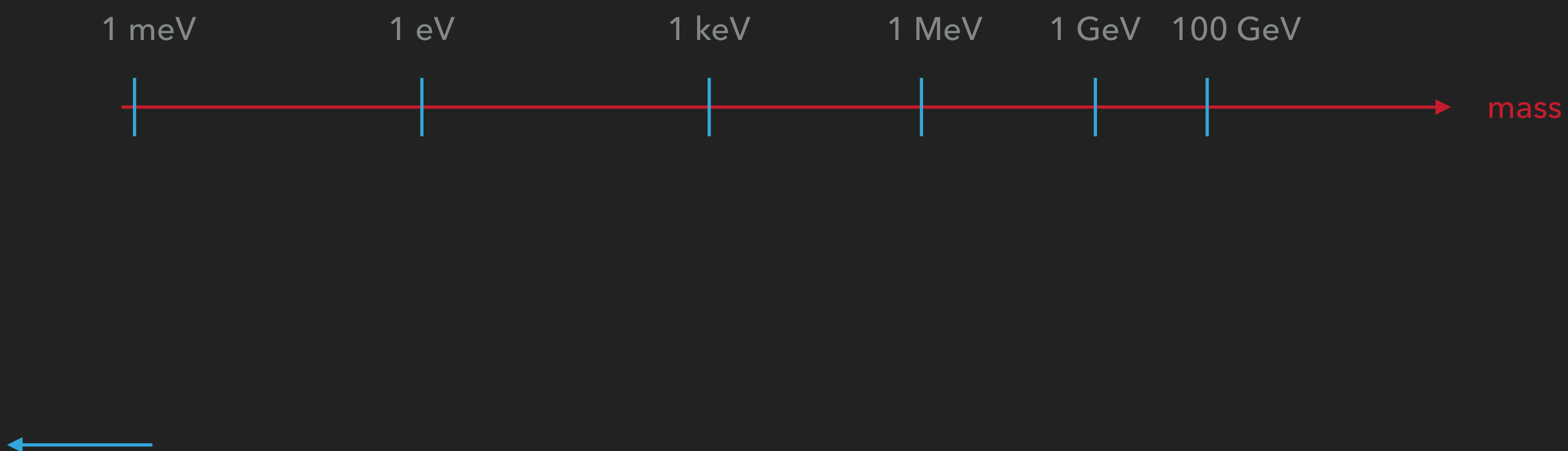
Microwave Kinetic Inductance Device



DEVELOPMENT OF NEW TECHNOLOGIES



DARK MATTER LANDSCAPE



QCD axion, “ultralight frontier”

DARK MATTER LANDSCAPE

Traditional WIMP

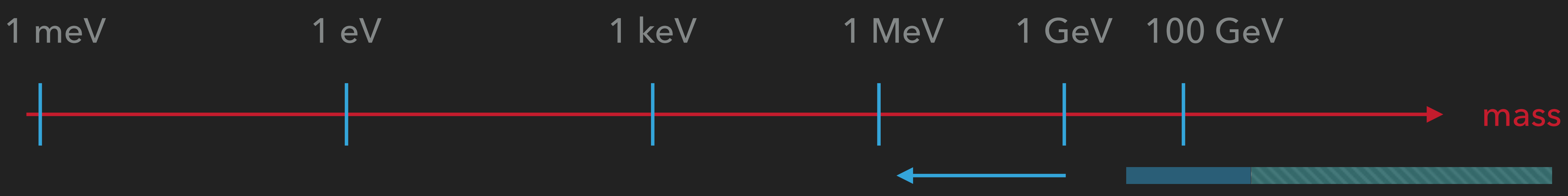
XENON1T

LZ

QCD axion, “ultralight frontier”

~keV energy resolution

DARK MATTER LANDSCAPE



Semiconductors

SuperCDMS

DAMIC, SENSEI

Graphene

~eV energy resolution

Traditional WIMP

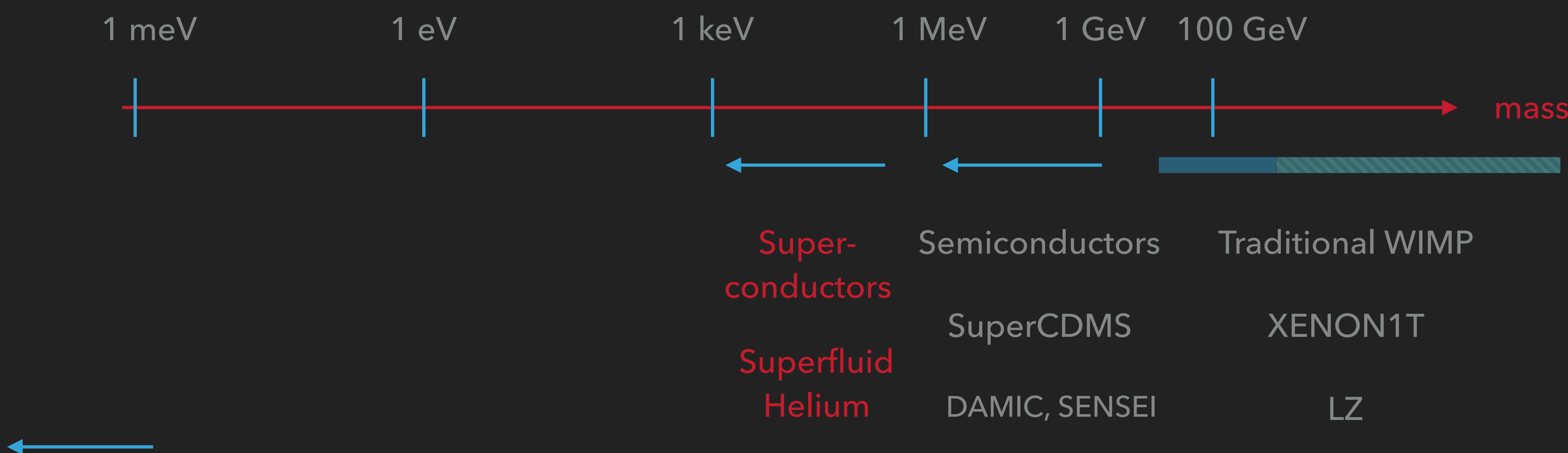
XENON1T

LZ

~keV energy resolution

QCD axion, “ultralight frontier”

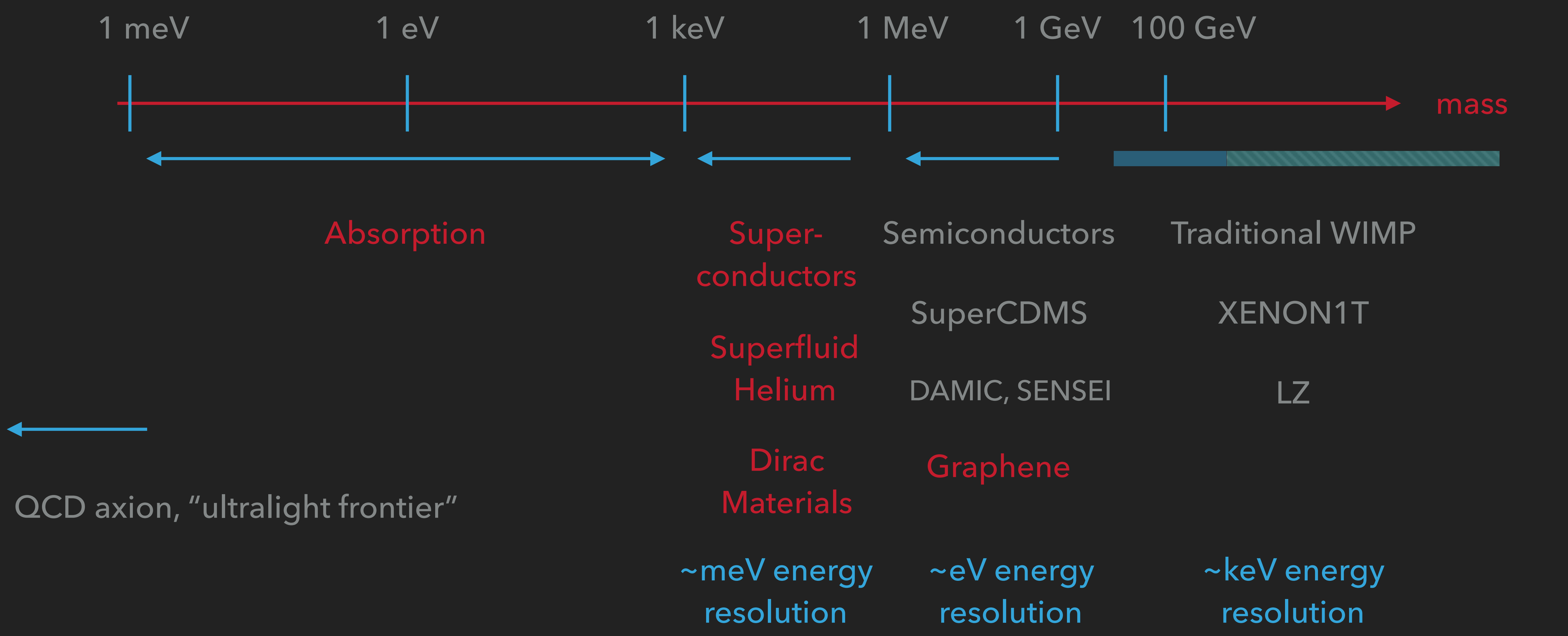
DARK MATTER LANDSCAPE



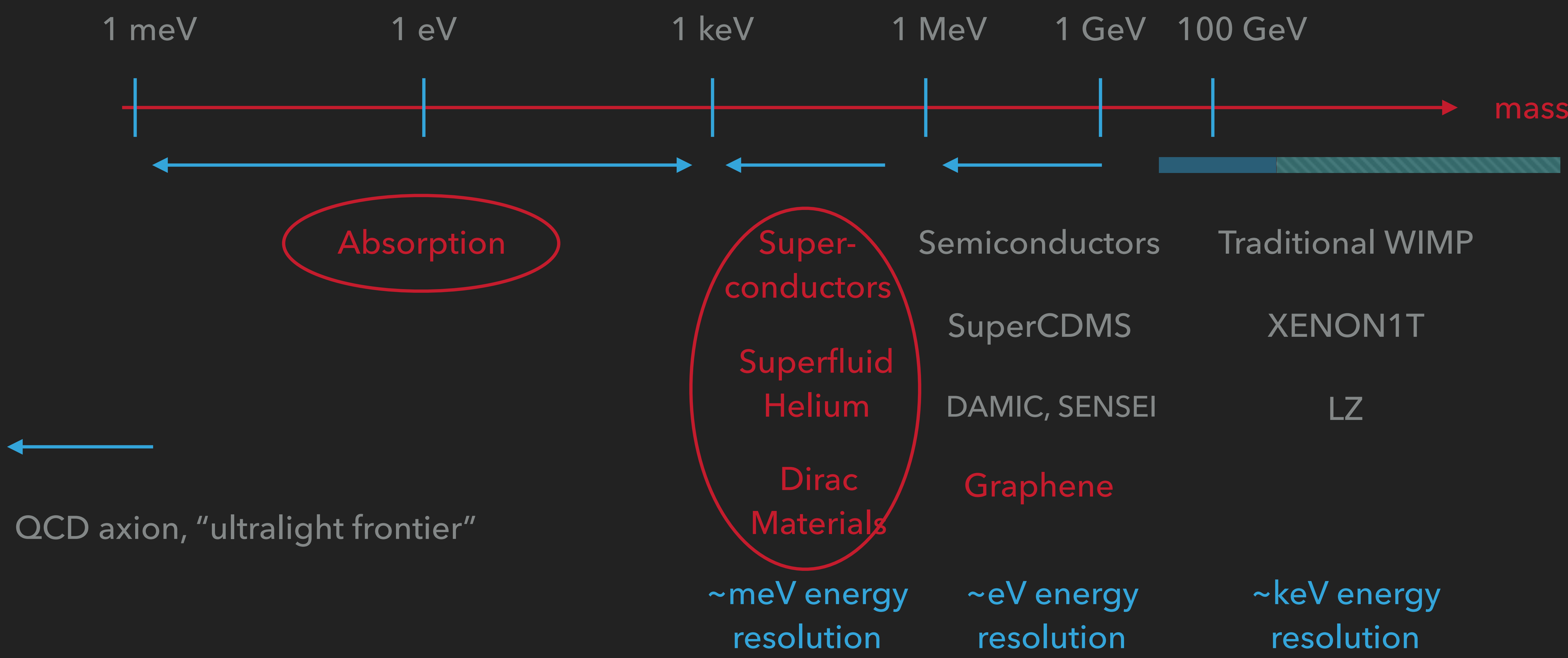
Super-conductors	Semiconductors	Traditional WIMP
	SuperCDMS	XENON1T
Superfluid Helium	DAMIC, SENSEI	LZ
Dirac Materials	Graphene	
~meV energy resolution	~eV energy resolution	~keV energy resolution

QCD axion, "ultralight frontier"

DARK MATTER LANDSCAPE

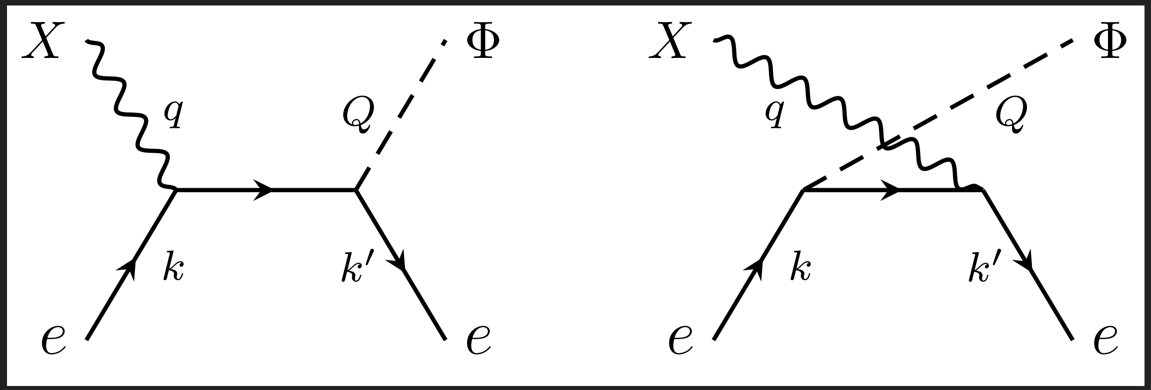


DARK MATTER LANDSCAPE



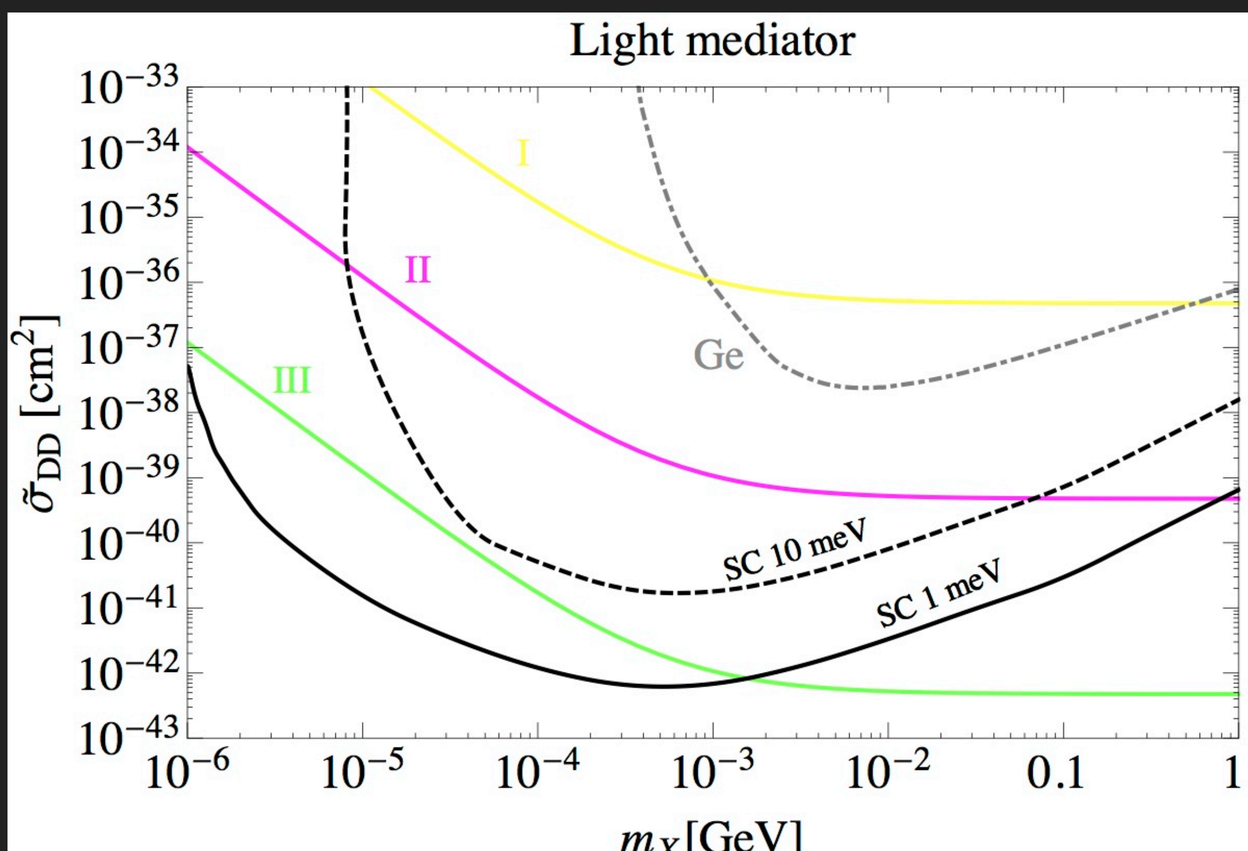
E.G. SUPERCONDUCTORS

- Free electrons succumb to collective dynamics
- Typical gap $\Delta \simeq 0.3\ \mathrm{meV}$
- Scattering and absorption modes
- Take advantage of collective modes! e.g. phonons to absorb DM particles



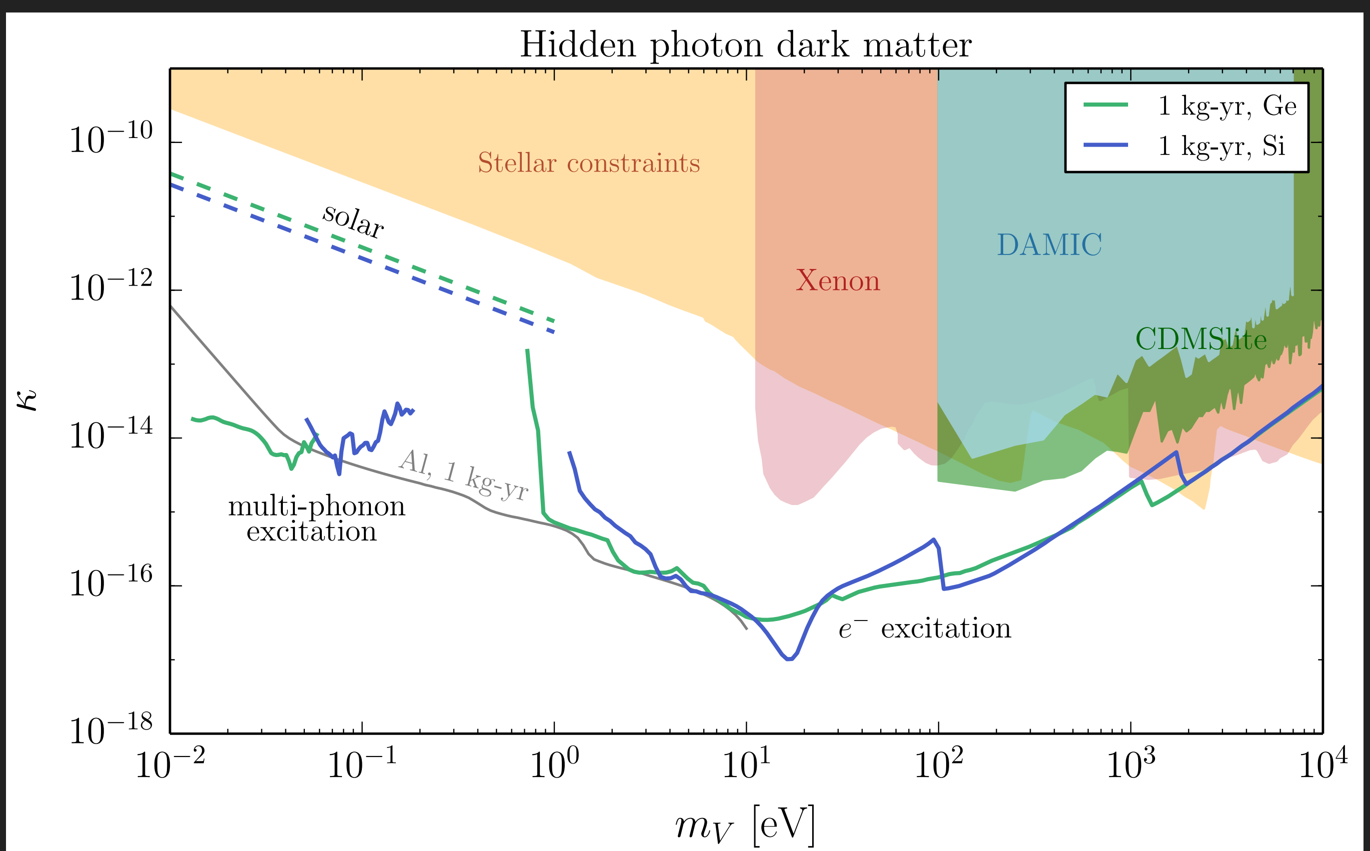
SCATTERING AND ABSORPTION REACH

Scattering



Hochberg, Pyle, Zhao, KZ 1512.04533

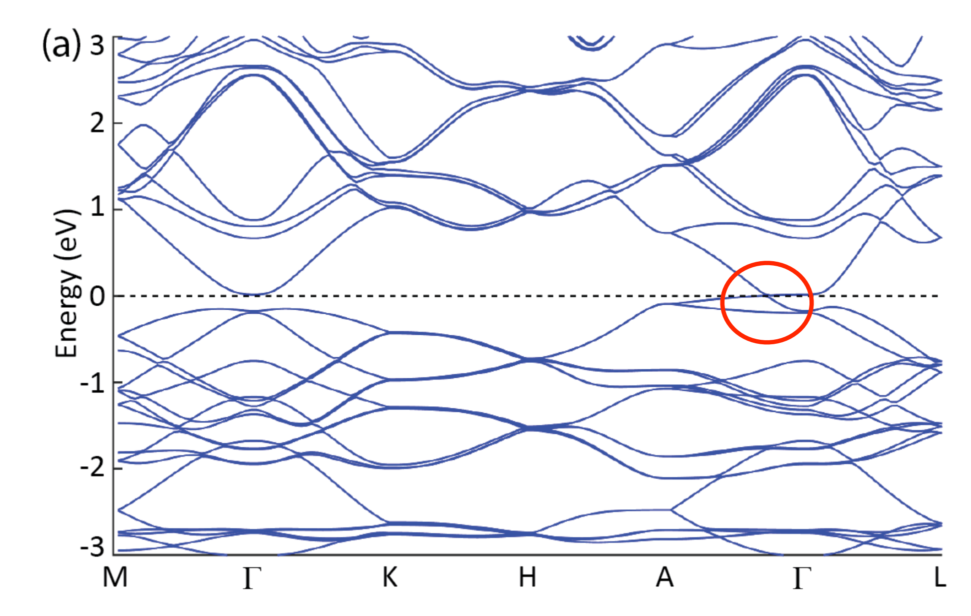
Absorption



Hochberg, Lin, KZ 1608.01994

WEYL OR DIRAC SEMI-METALS ~ 3D GRAPHENE

- Materials can be “quantum engineered”
- Correlation between electrons gives rise to a unique band structure
- Hamiltonian looks like free QED near Dirac point
- In QED, gauge invariance protects photon from obtaining a mass

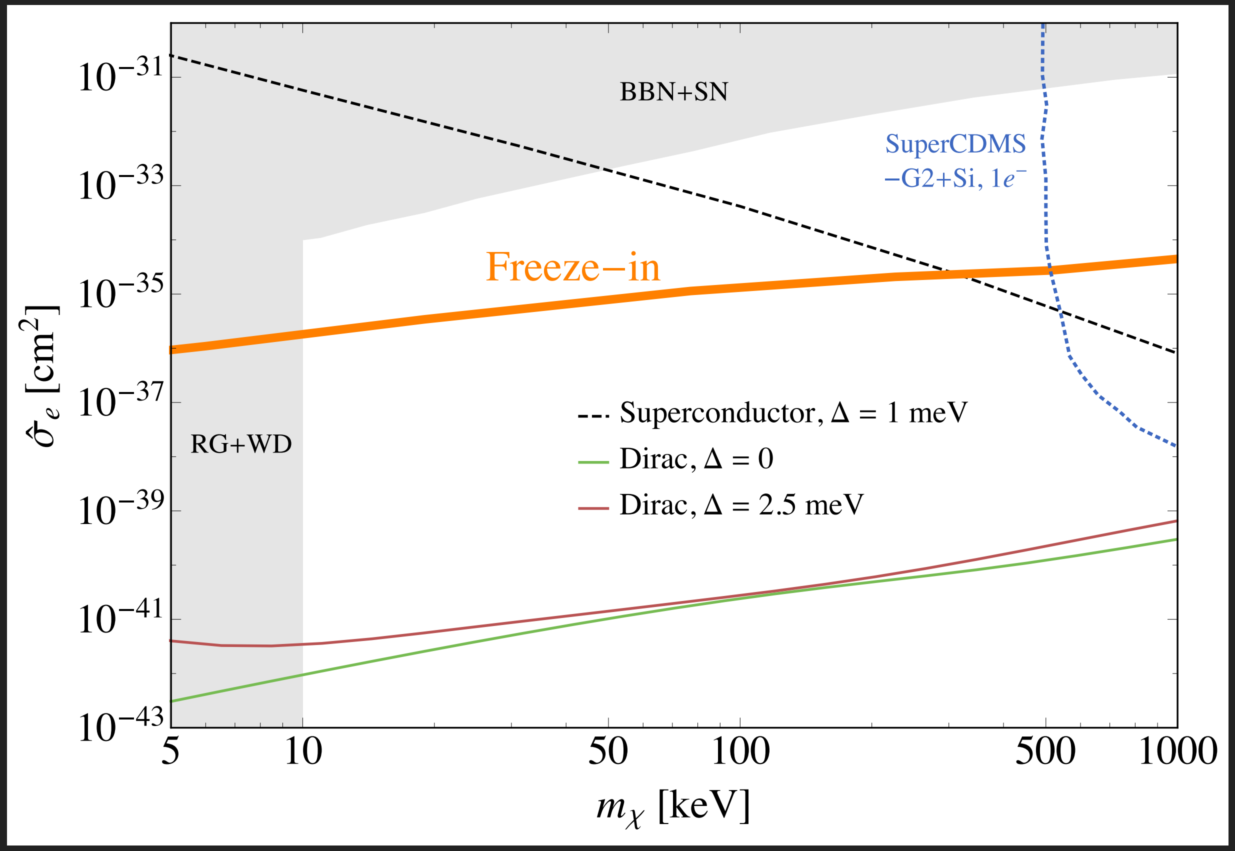


WEYL OR DIRAC SEMI-METALS ~ 3D GRAPHENE

- Optical response behaves exactly as electric charge renormalization in QED

$$\mathcal{L} \supset \varepsilon e \frac{q^2}{q^2 - \Pi_{T,L}} \tilde{A'}^{T,L}_{\mu} J^{\mu}_{\mathrm{EM}}$$

- Weaker Optical Response
- Stronger Sensitivity to Dark Photon



Yonit Hochberg,[1,2,*] Yonatan Kahn,[3,†] Mariangela Lisanti,[3,‡] Kathryn M. Zurek,[4,5,§] Adolfo Grushin,[6,7,¶] Roni Ilan,[8,**] Zhenfei Liu,[9] Sinead Griffin,[9] Sophie Weber,[9] and Jeffrey Neaton[9]

HELIUM

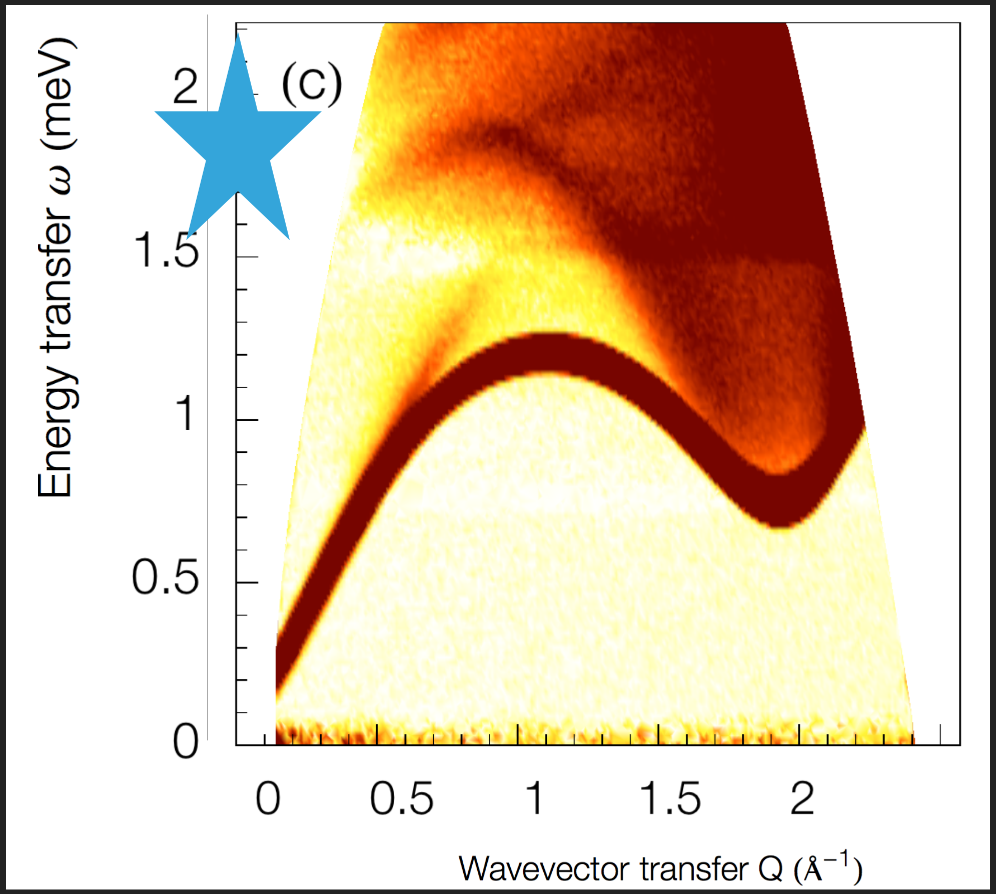
- Superfluids have been explored as a good light dark matter detector via nuclear recoils, McKinsey group 1605.00694
- To detect lighter DM, couple to phonon modes.
- Viable? At first glance – no

$$E_D \sim v_X q$$

vs $\qquad c_s \ll v_X$

$$E_D \sim c_s q$$

- Next glance -- yes!

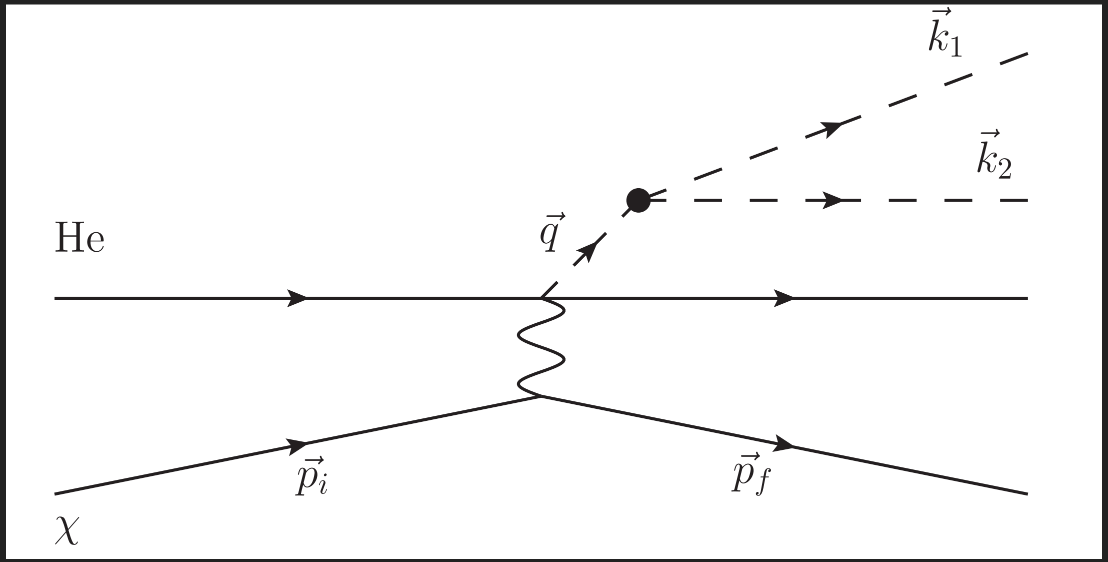


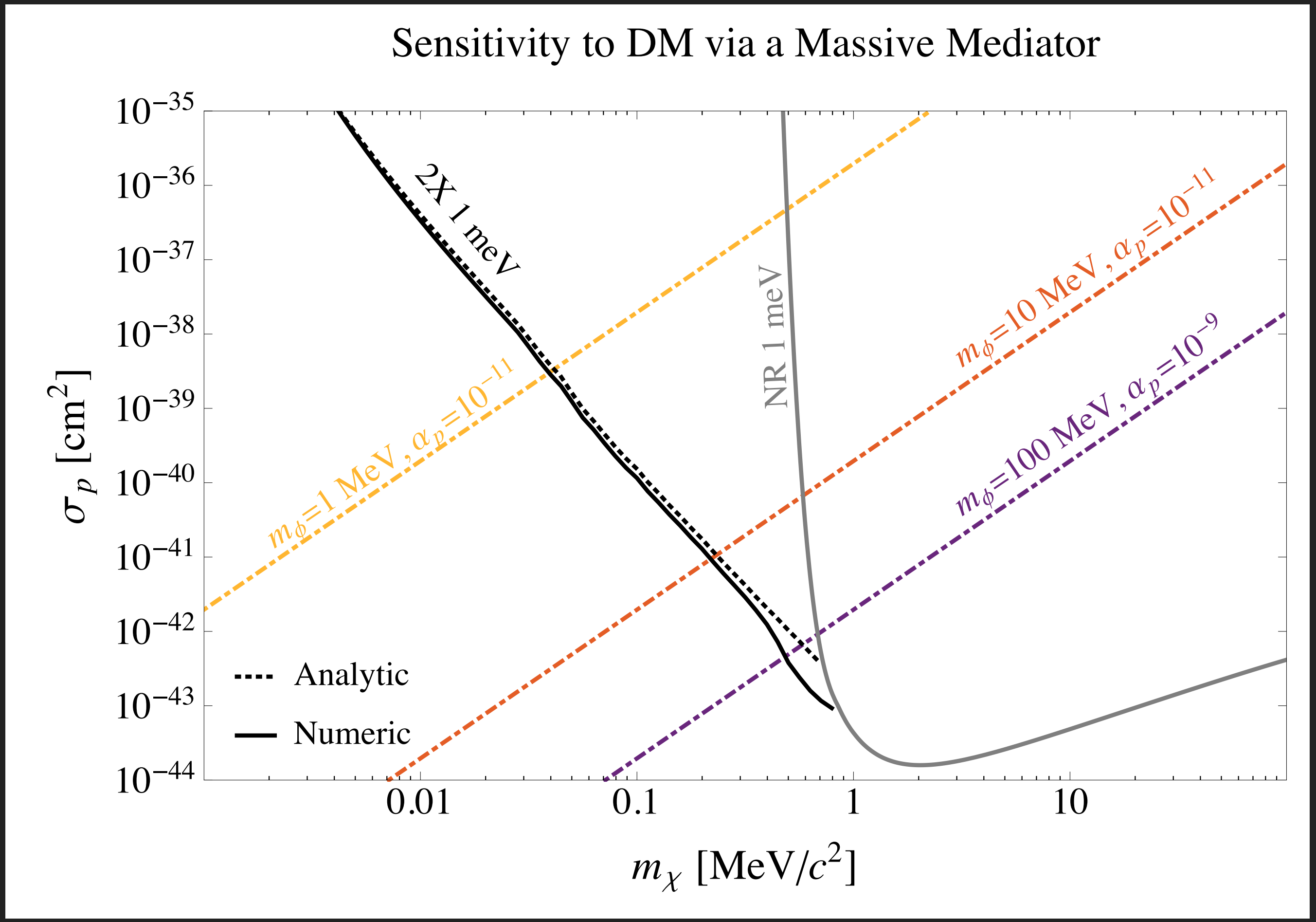
Beauvois et al 1605.02638

 Schutz, KZ 1604.08206, Knapen, Lin, KZ 1611.06228

MULTI-EXCITATIONS

- emit back-to-back excitations to bleed off energy while conserving momentum

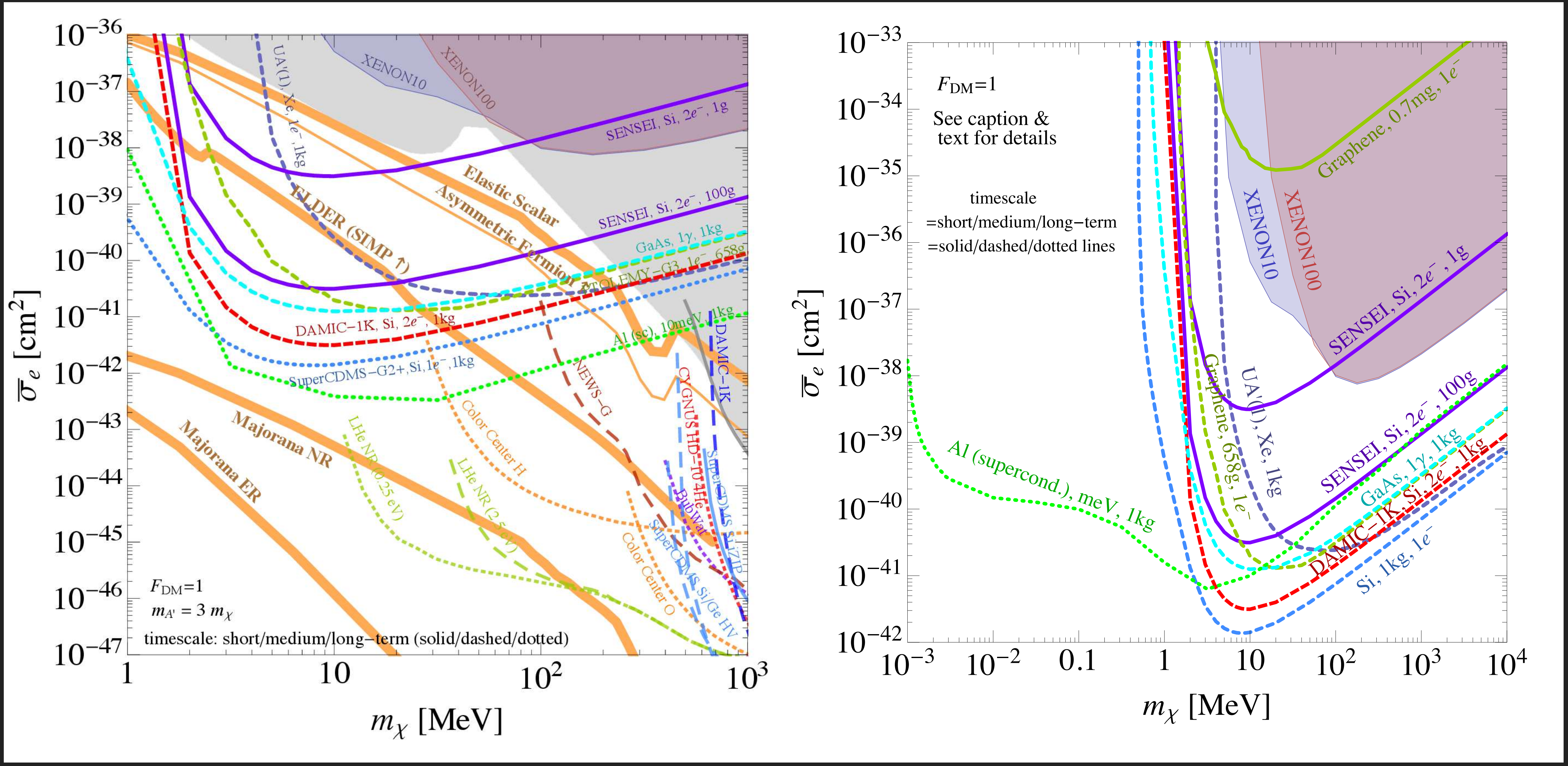




Great potential!

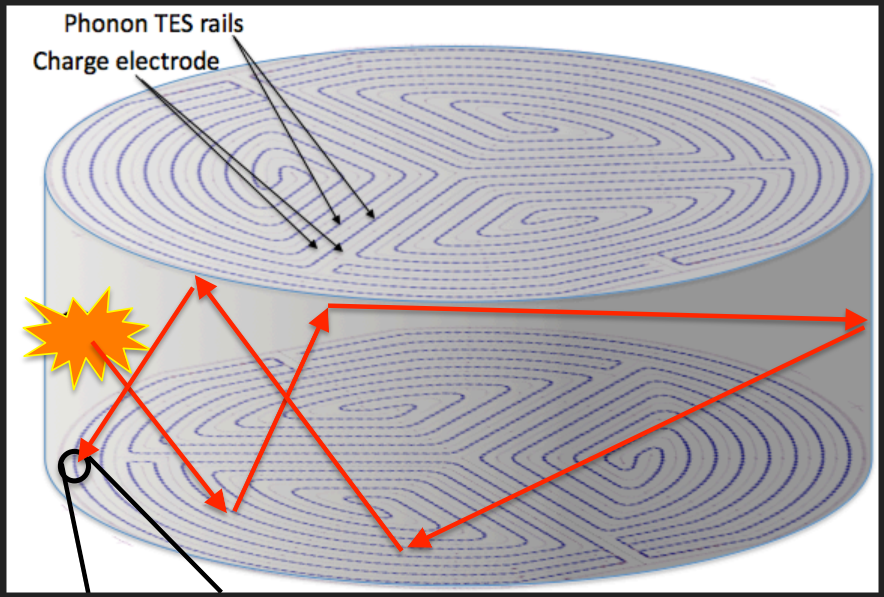
COMPLEMENTARITY

Cosmic Visions Whitepaper



ROAD FORWARD

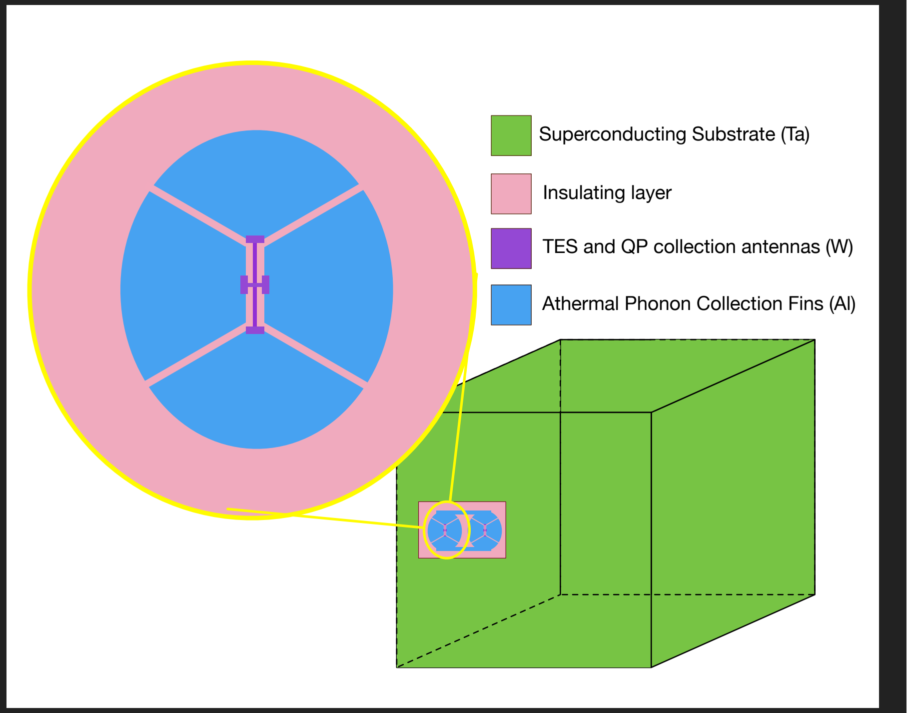
- Large part depends on better energy resolution sensors (TESs or KIDs); TESs or KIDs are portable to multiple targets



Semiconductors SuperCDMS

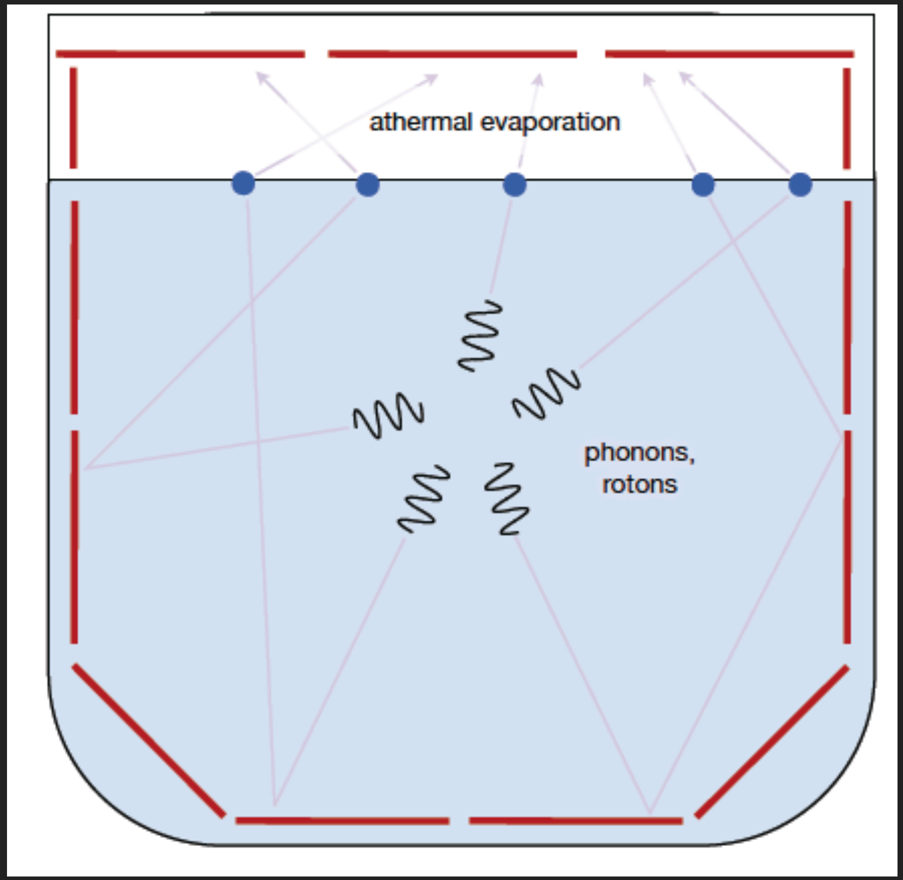
Current energy resolution: ~300 eV

Goal: ~1 eV



Superconductors

Goal: ~1 meV



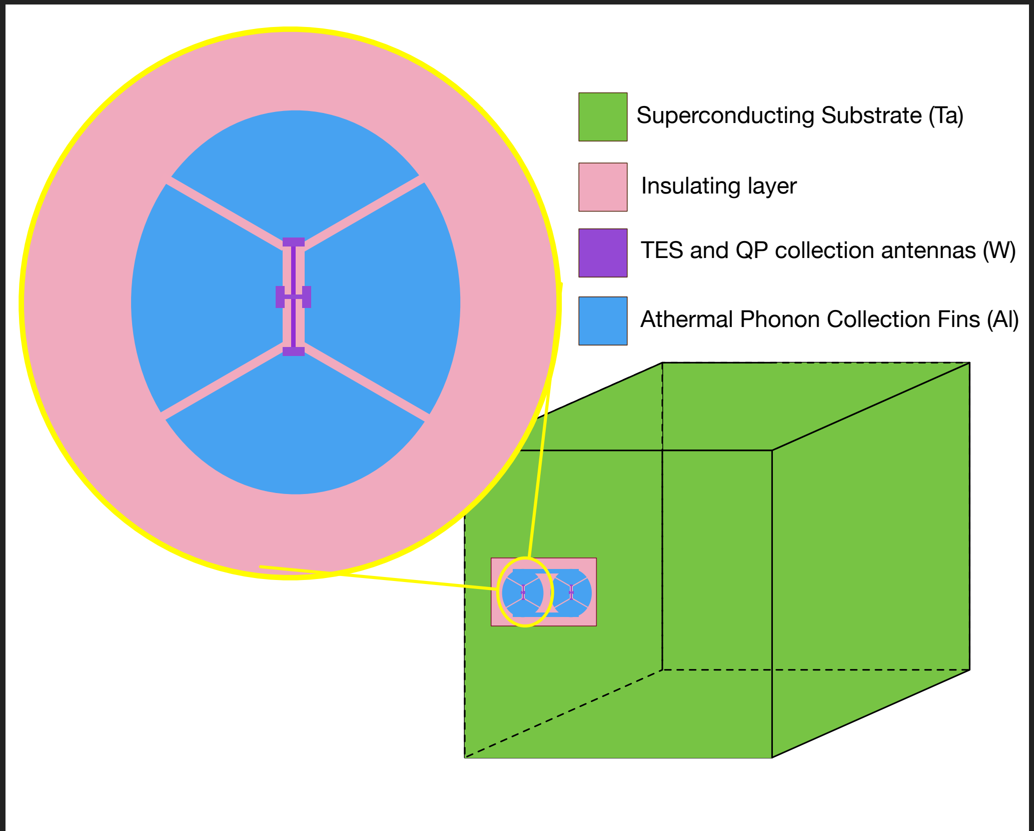
Superfluid Helium

Goal: ~1 meV

Hochberg, Pyle, Zhao, KZ 1512.04533

QUASIPARTICLE EXCITATION CONCENTRATION

Design by M. Pyle



Fundamental limitation: energy resolution of heat sensor (TES)

Current sensitivity:

TES	T_c [mK]	Volume [μm $\times$ μm $\times$ nm]	Bias Power [W]	Power Noise $\sqrt{S_{\mathrm{p,tot}}(0)}$ [W/$\sqrt{\mathrm{Hz}}$]	τ_{eff} [μs]	$\sigma_{\mathrm{E}}^{\mathrm{measured}}$ [meV]	$\sigma_{\mathrm{E}}^{\mathrm{scale}}$ [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

ROAD FORWARD

- New ideas for dark matter detection!
- Moving beyond nuclear recoils into phases of matter crucial to access broader areas of DM parameter space
- Target diversity essential. graphene, superconductors, semiconductors, helium, Dirac materials, ….
- Leverage progress is materials and condensed matter physics

ROAD FORWARD

- Realizing experimental program is 5-10+ years into future
- Explosion in Community Interest, US Cosmic Visions Whitepaper, University of Maryland, March 2017
- Nine orders of magnitude increased sensitivity in mass
- Long view necessary!