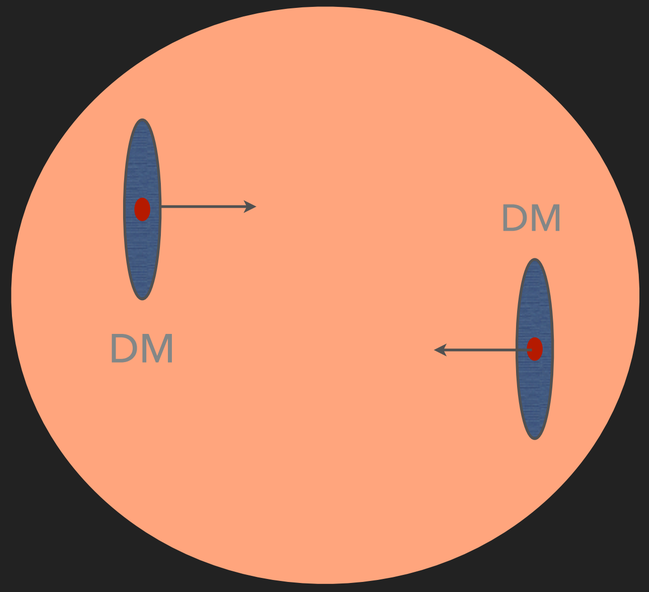
K. ZUREK

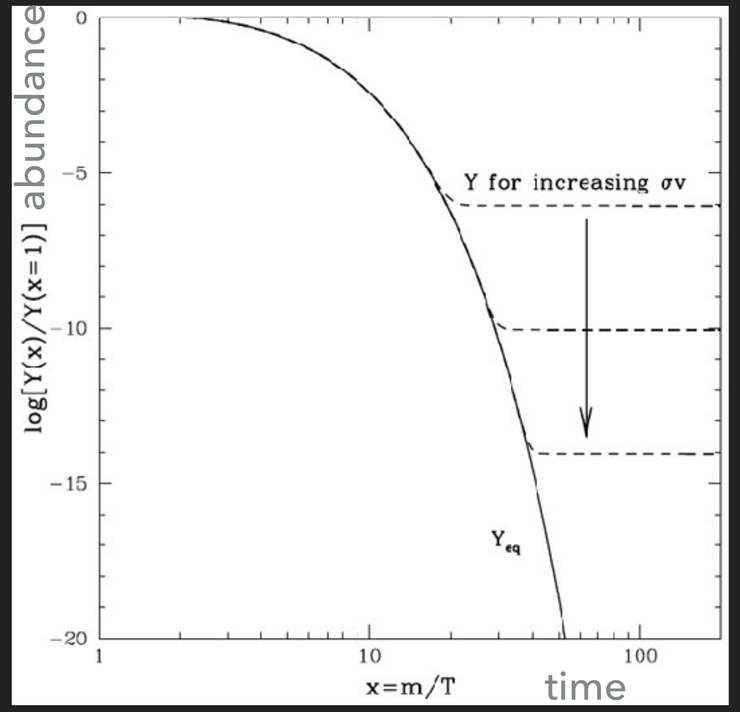
Leveraging the many faces (and phases) of matter

HIDDEN SECTOR DARK MATTER AND ITS (DIRECT) DETECTION

NEW DIRECTIONS IN DARK MATTER THEORY

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





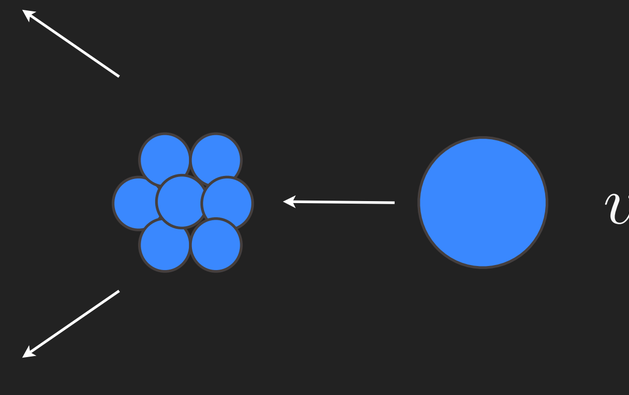
Kolb and Turner

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

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

DIRECT DETECTION GOLD STANDARD

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

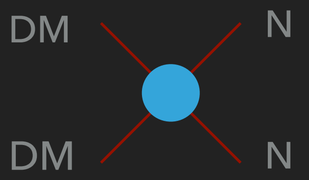


$$\implies 2\mu_N v = q_{\max} = \sqrt{2 m_N E_D} \qquad \mu_N \equiv \frac{m_N m_X}{m_X + m_N}$$

$$v \sim 300\ \mathrm{km/s} \sim 10^{-3}c \implies E_D \sim 100\ \mathrm{keV}$$

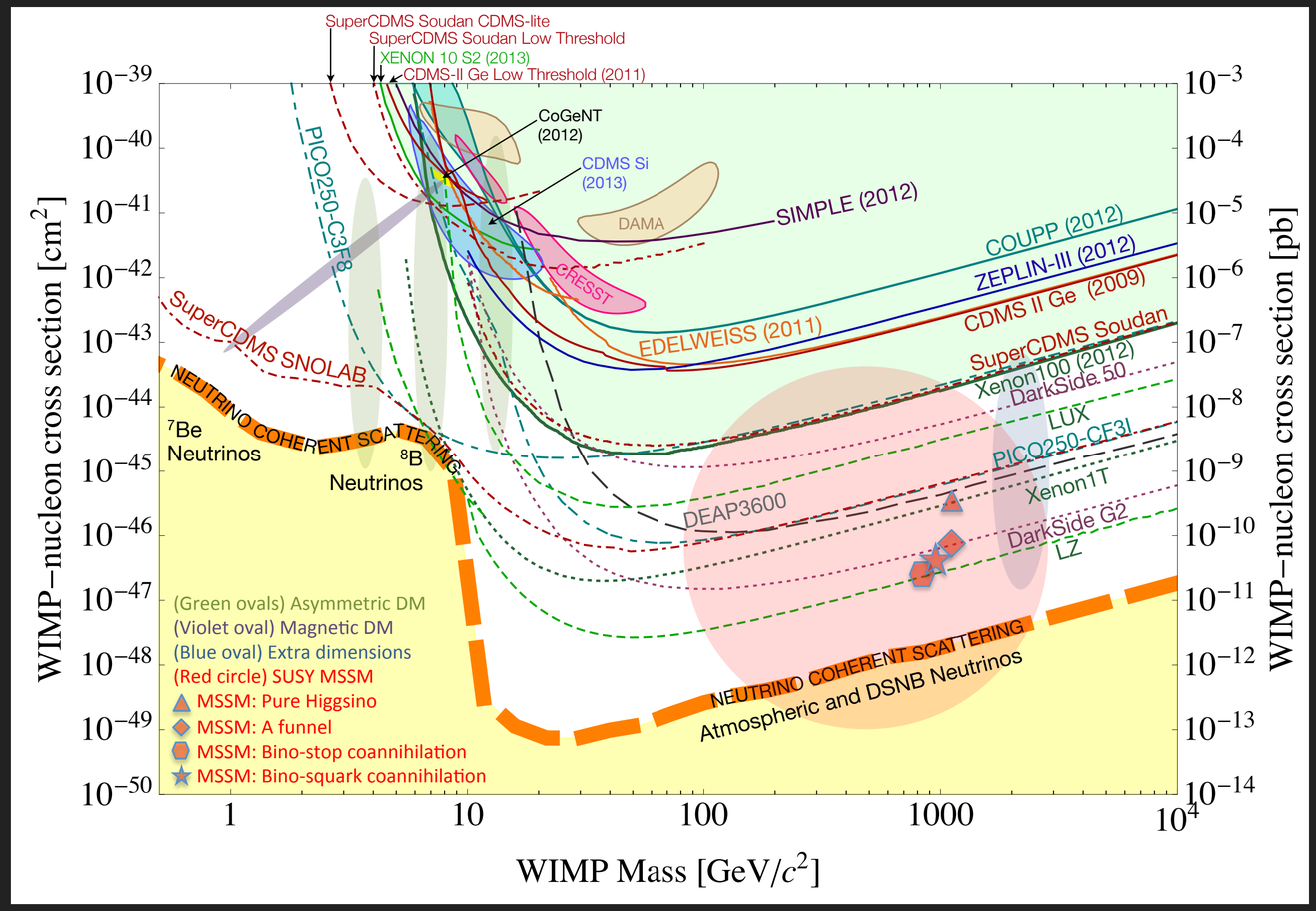
for 50 GeV target

WEAK SCALE PARADIGM: UNDER ASSAULT



Z-boson interacting dark matter: ruled out

Higgs interacting dark matter: active target



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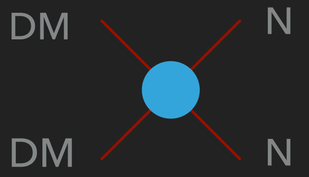

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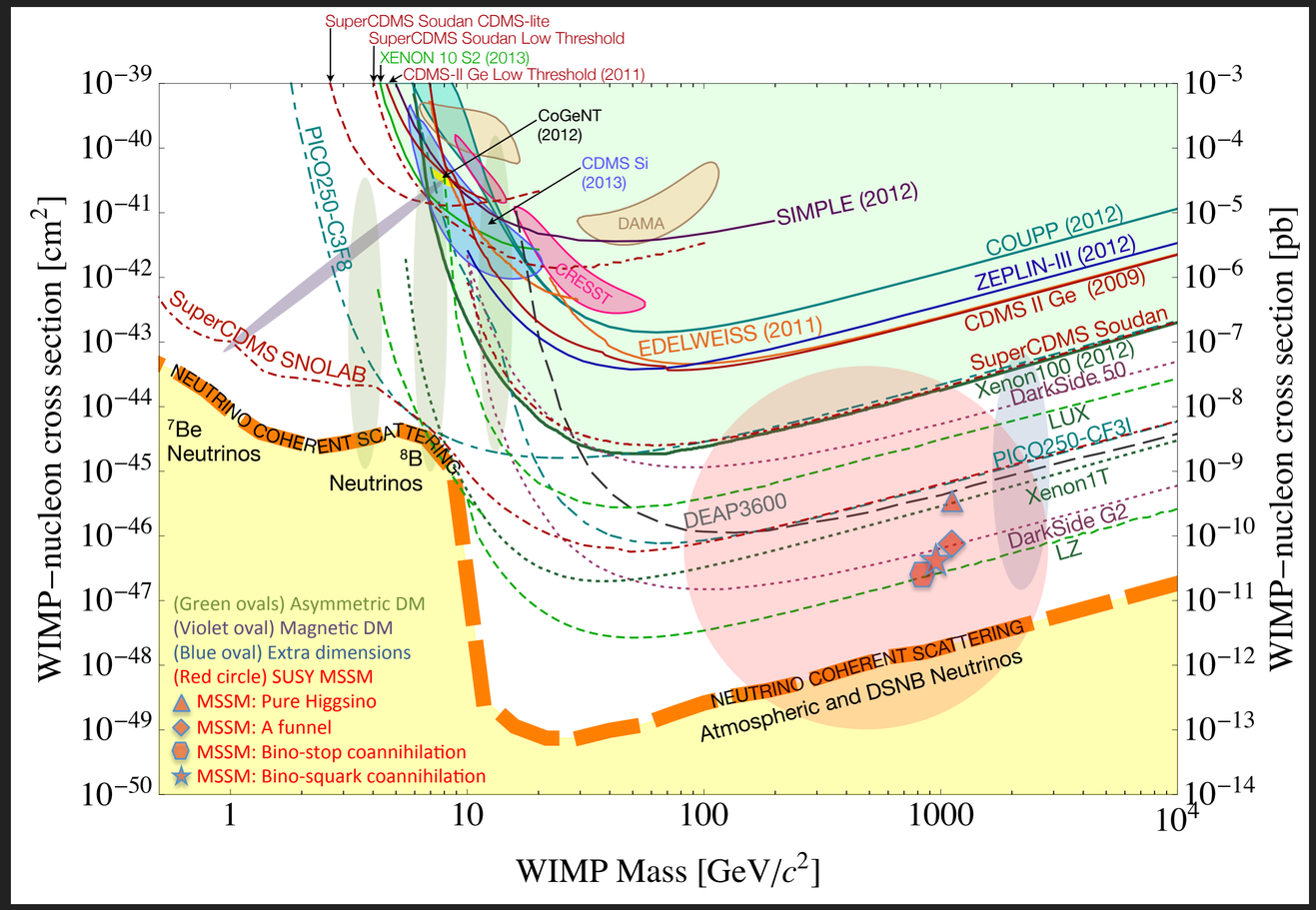
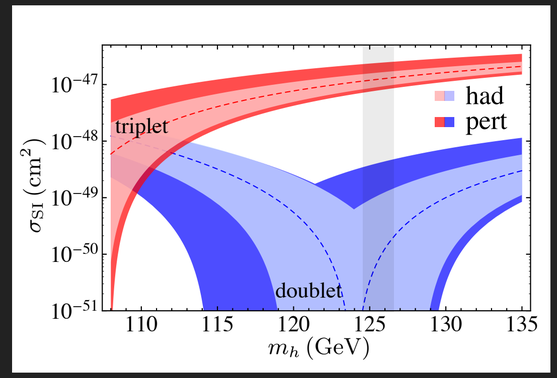
One-loop interacting DM

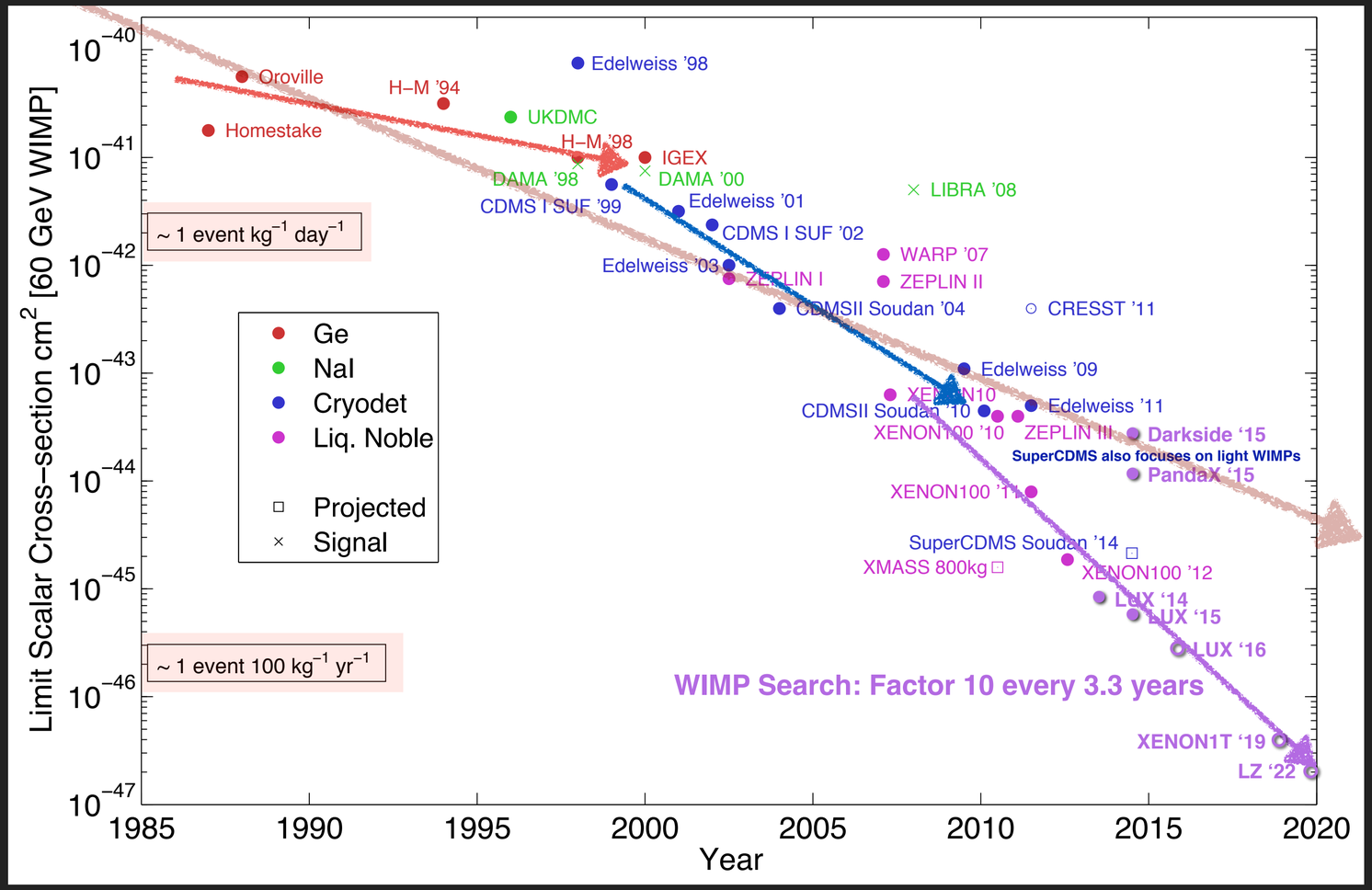


Hill and Solon



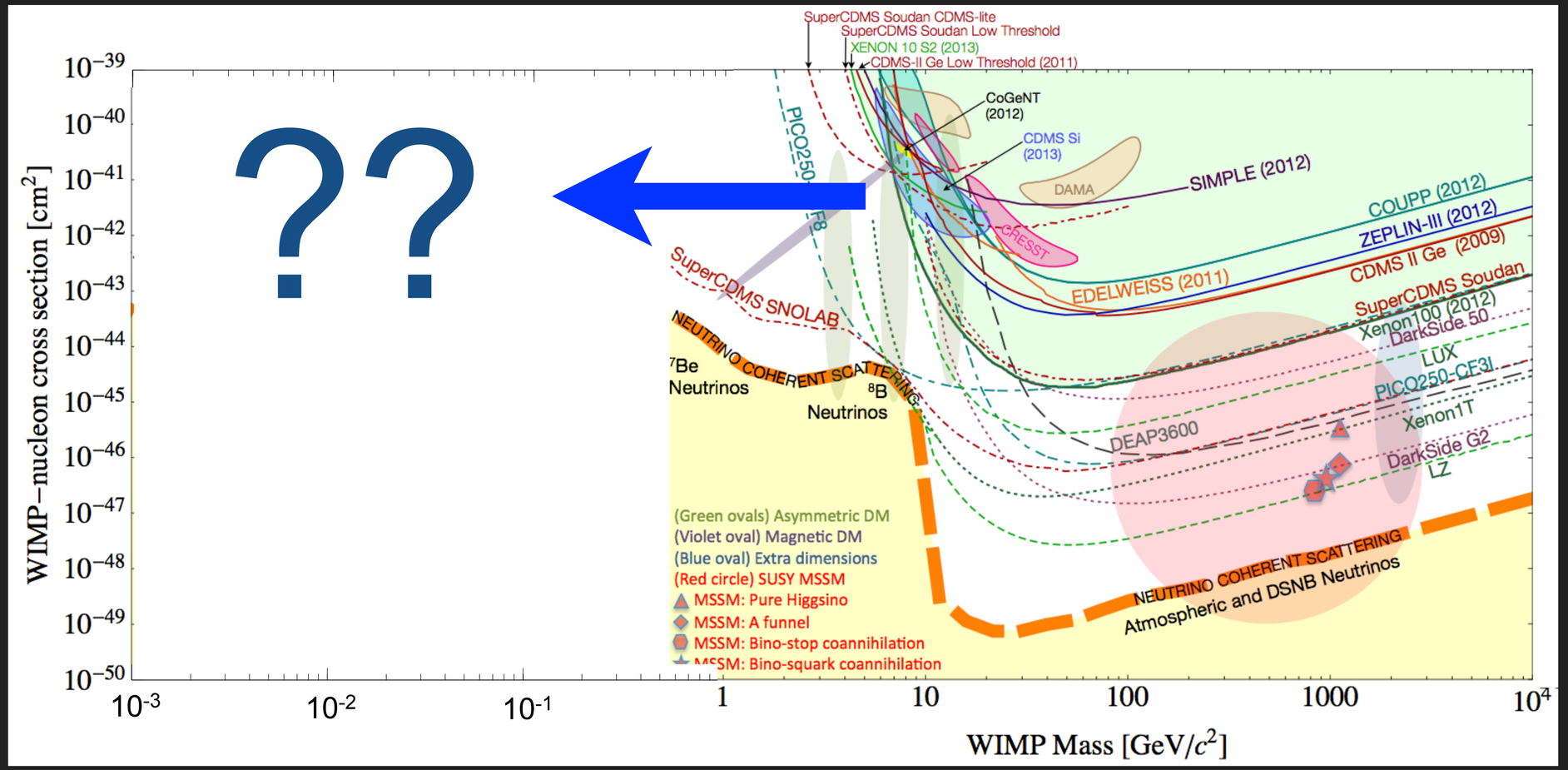
DARK MATTER MOORE'S LAW

Factor of 10 every 6.5 years



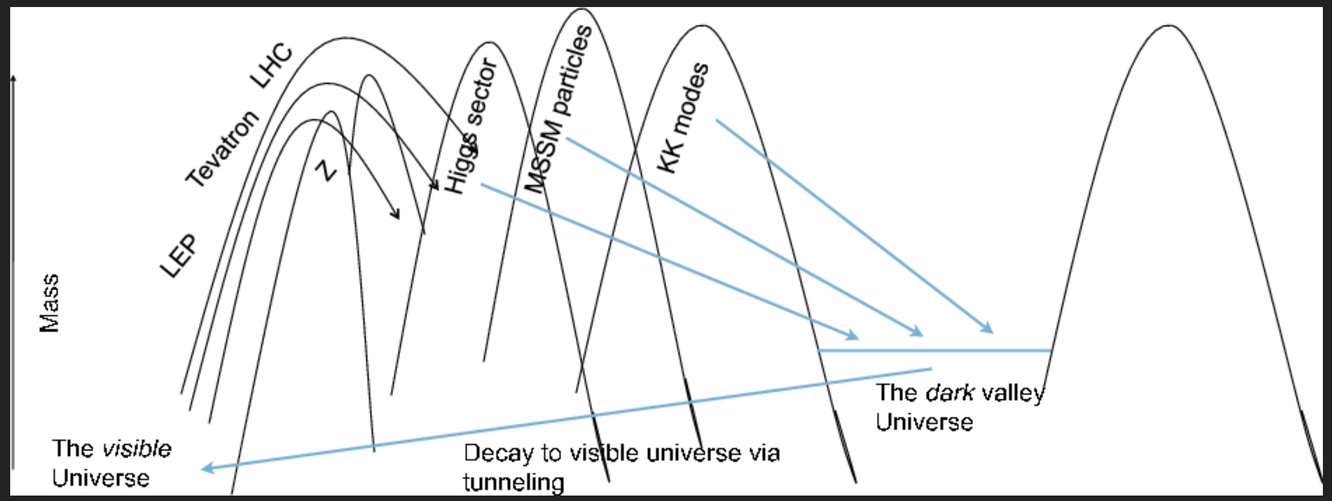
LUX Collaboration talk

DIRECT DETECTION GOLD STANDARD



TOWARDS LIGHT DARK MATTER

Dark Matter May Reside in a Hidden Sector



e.g. a dark pion

no weak force

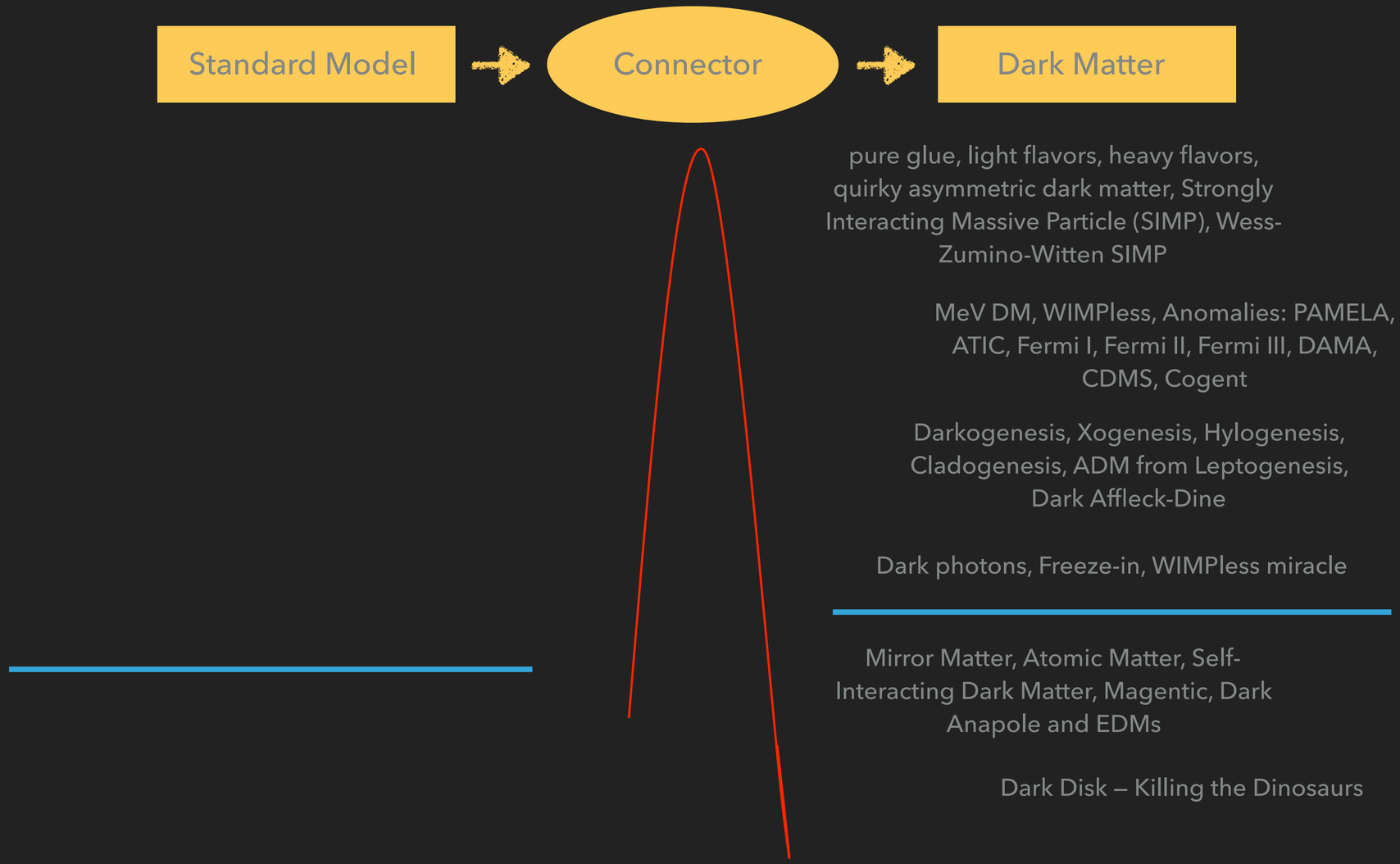
stable by accidental symmetry

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

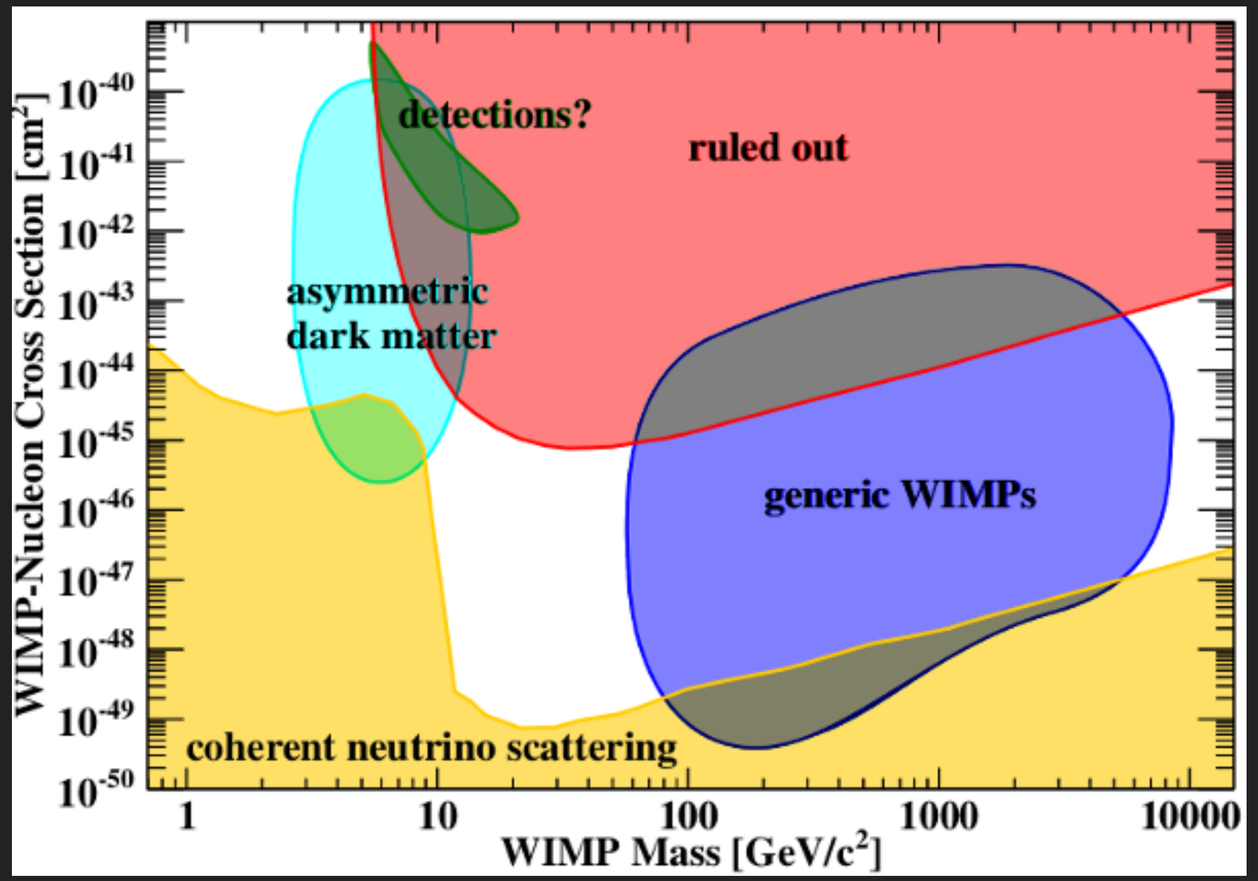
$$\pi_v^0 \rightarrow b\bar{b},\ \gamma\gamma$$

Hidden Valley Paradigm

BROAD RANGE OF MODELS



THEORY TARGETS

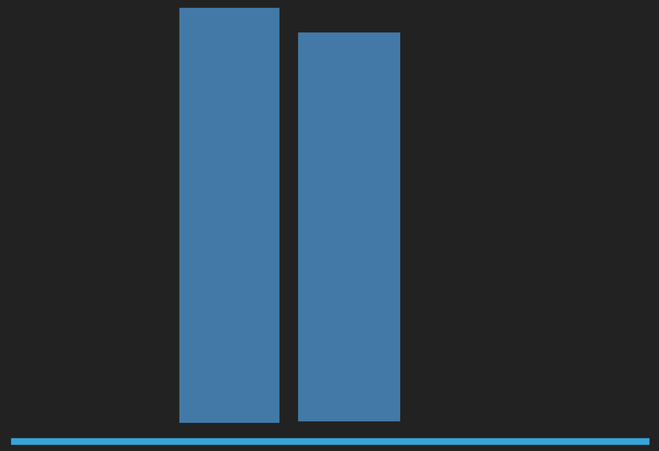


Physics Viewpoint, Raphael Lang

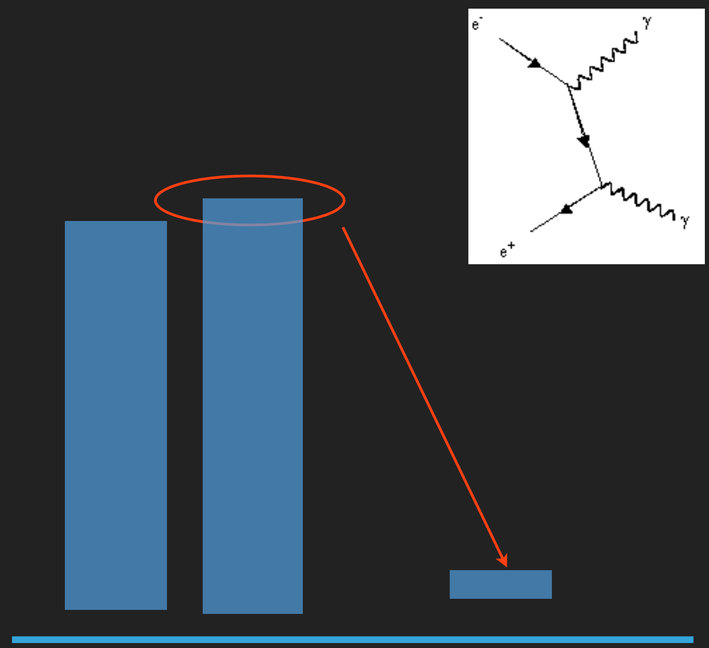
ASYMMETRIC DARK MATTER

$$\frac{X^n u^c d^c d^c}{M^n}$$

particle anti-particle



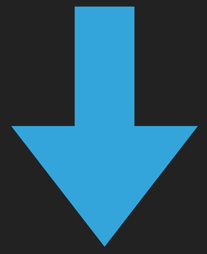
Dark Forces Arise Naturally



NUCLEAR RECOILS

- Kinematic penalty when DM mass drops below nucleus mass

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



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

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

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

Essig, Manalaysay, Mardon, Sorensen, Volansky, 1206.2644

- In insulators, like xenon

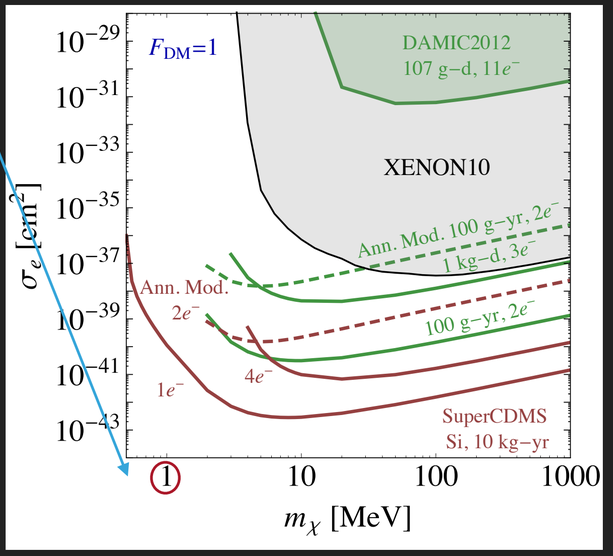
Ionize electron

Gap = DM Kinetic Energy

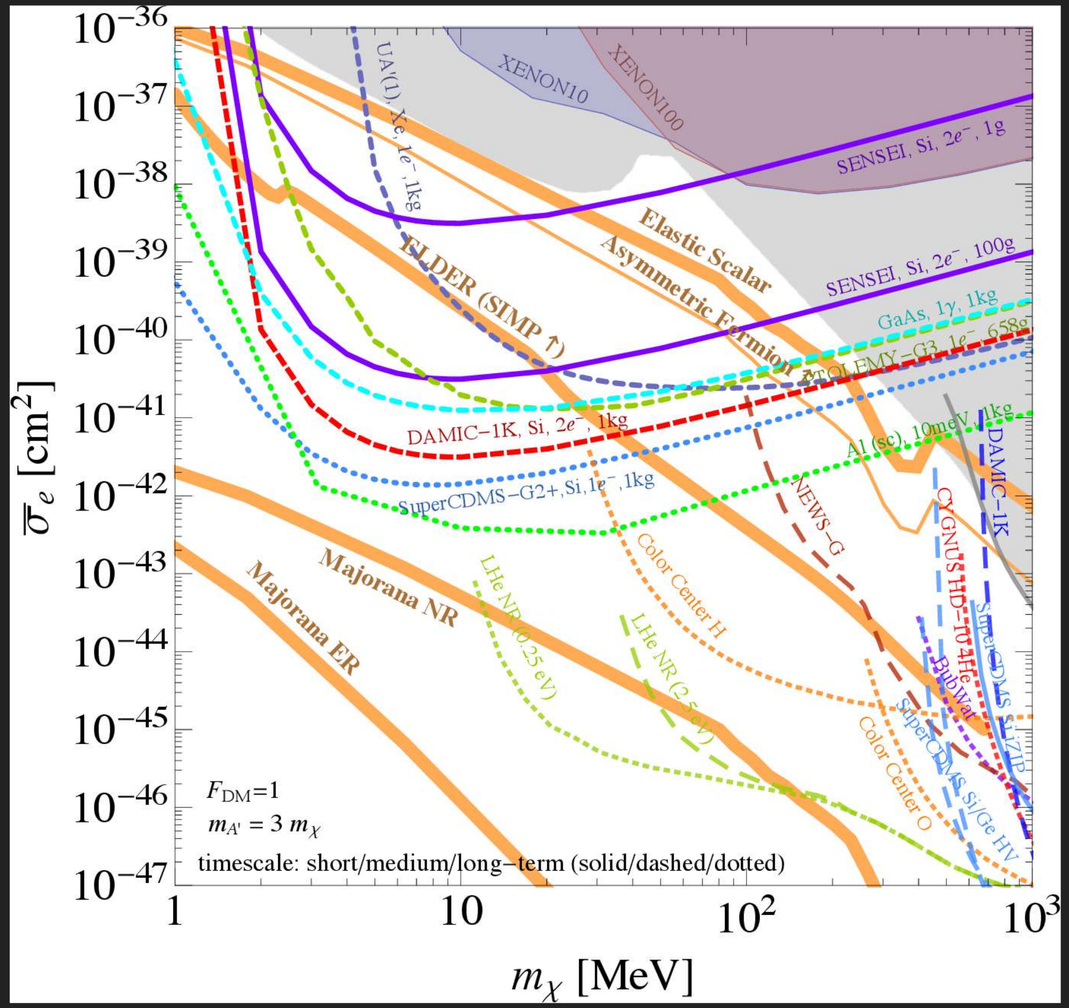
- In semi-conductors, like Ge, Si

Excite electron to conduction band

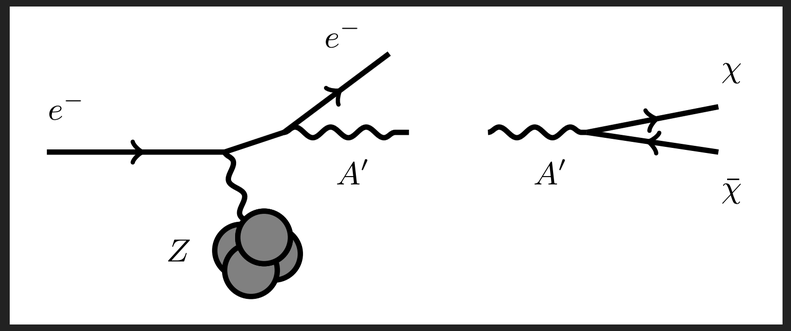
Essig, Fernandez-Serra, Soto, Volansky, Yu 1509.01598

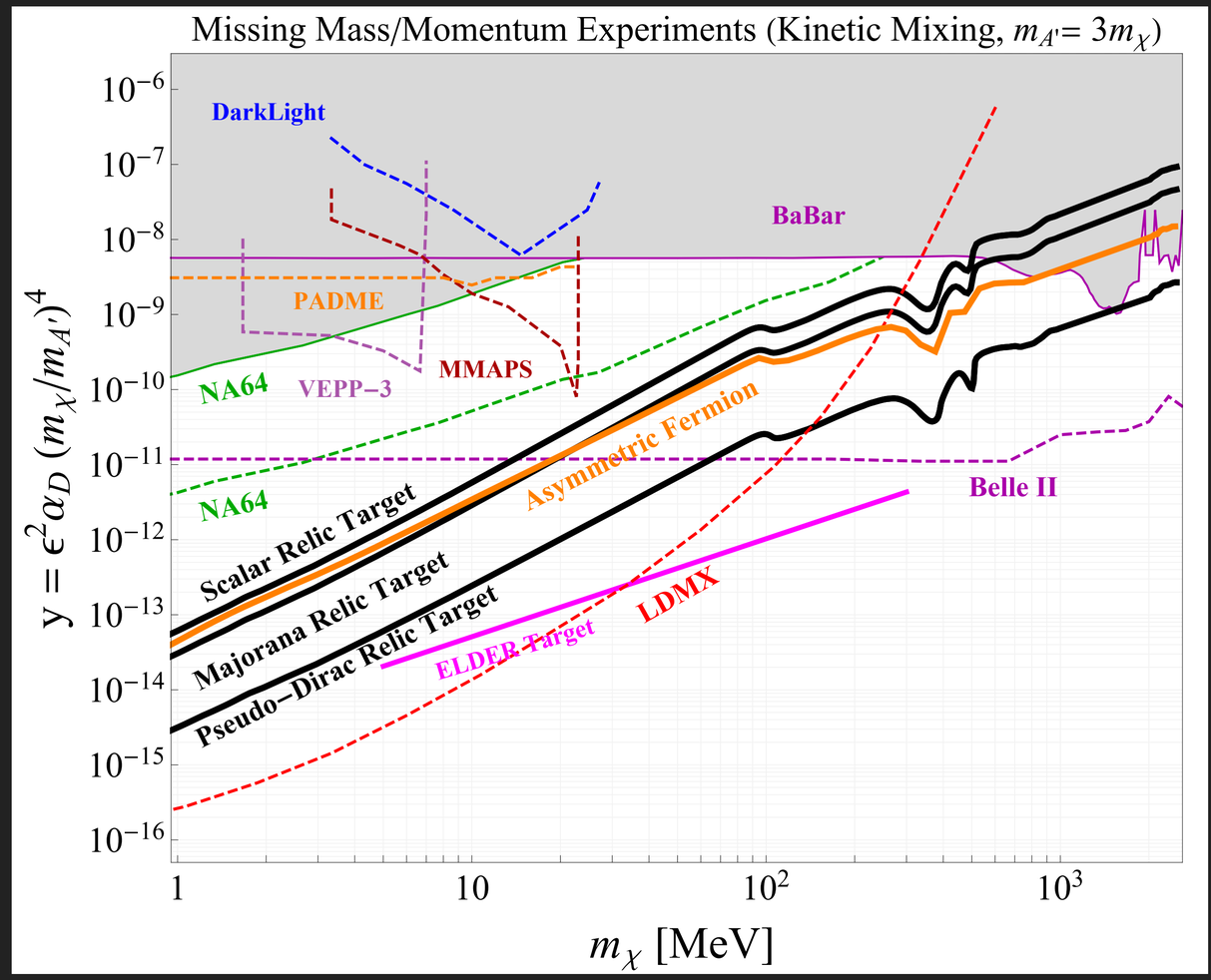


DEVELOPMENT OF NEW TECHNOLOGIES



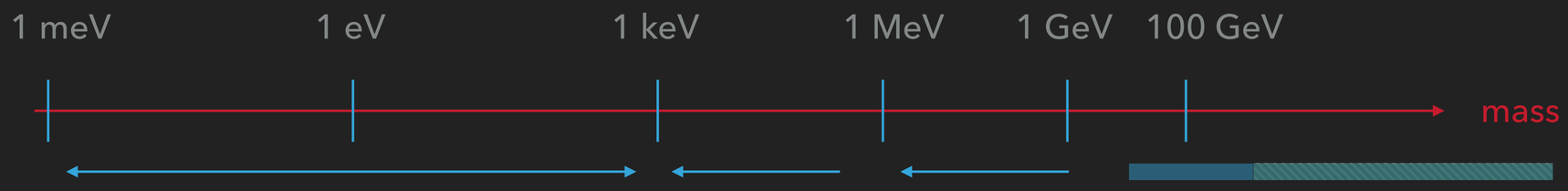
COMPLEMENTARITY WITH ACCELERATOR EXPERIMENTS





Izaguirre, Krnjaic, Schuster, Toro, 1411.1404

DARK MATTER LANDSCAPE



Absorption Coherent Mode Production

Super-conductors

Superfluid Helium

Semi-metals

Semiconductors

SuperCDMS

DAMIC, SENSEI

Graphene

Traditional WIMP

XENON1T

LZ

QCD axion, “ultralight frontier”

e.g. ADMX

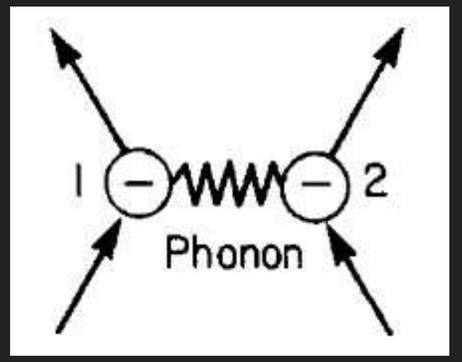
~meV energy resolution

~eV energy resolution

~keV energy resolution

E.G. SUPERCONDUCTORS

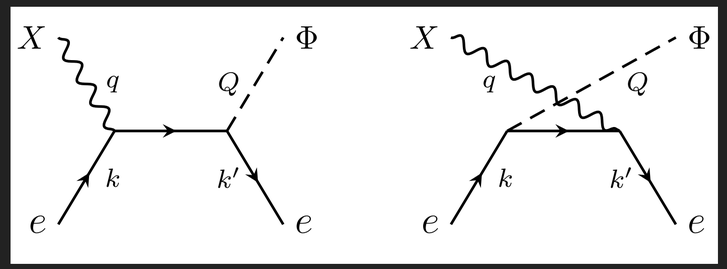
- Free electrons succumb to collective dynamics
- Typical gap $\Delta \simeq 0.3 \text{ meV}$



Hochberg, Zhao, KZ 1504.07237, Hochberg, Pyle, Zhao, KZ, 1512.04533

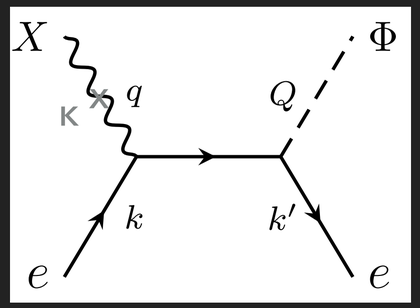
ABSORPTION — SUPERCONDUCTORS

- Can we absorb ultralight DM particles on electrons in a superconductor?
- Seems not – basic energy and momentum conservation
- Take advantage of collective modes! i.e. phonons

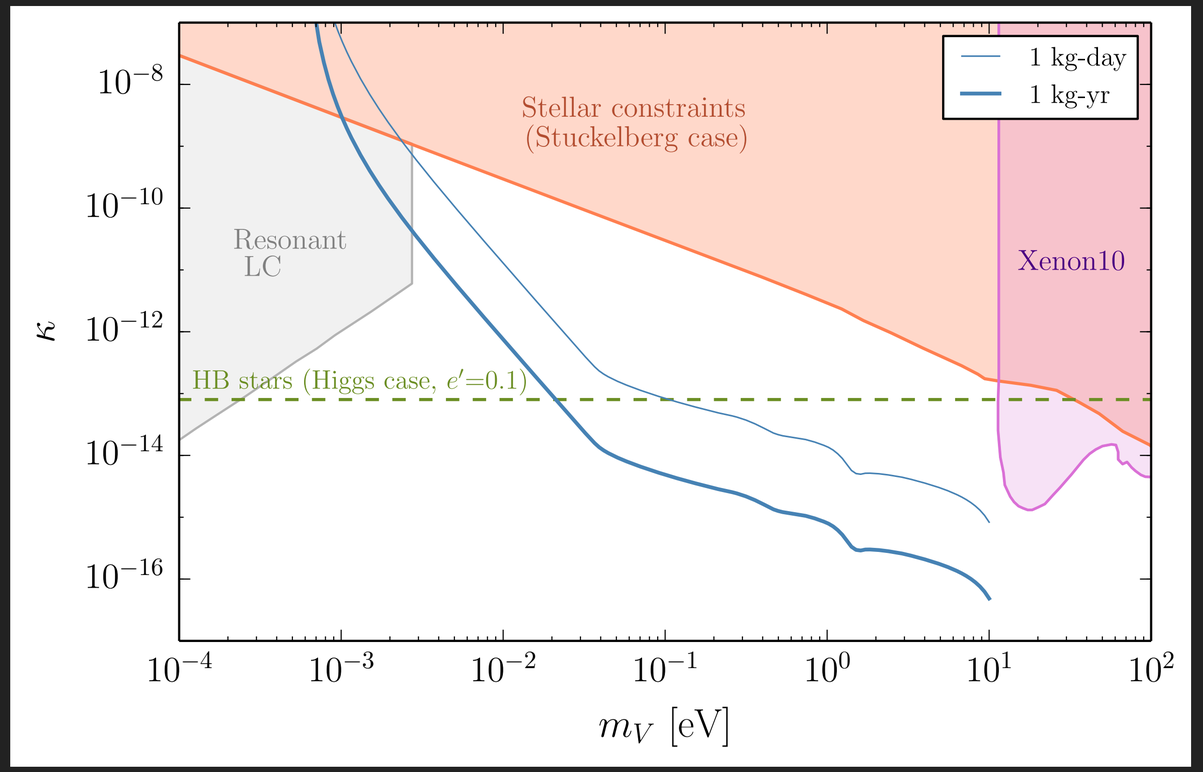


$$\mathcal{H} = \int d^3 y_{ph} \phi \bar{\psi} \psi = \frac{1}{\sqrt{V}} \sum_{\vec{k}} \sum_{\vec{k}'} \frac{C_{ph} |\vec{Q}|}{\sqrt{\rho}} \frac{1}{\sqrt{2E_Q}} (c_{\vec{Q}} + c^{\dagger}_{-\vec{Q}}) a_{\vec{k}'} a_{\vec{k}}$$

ABSORPTION — SUPERCONDUCTORS



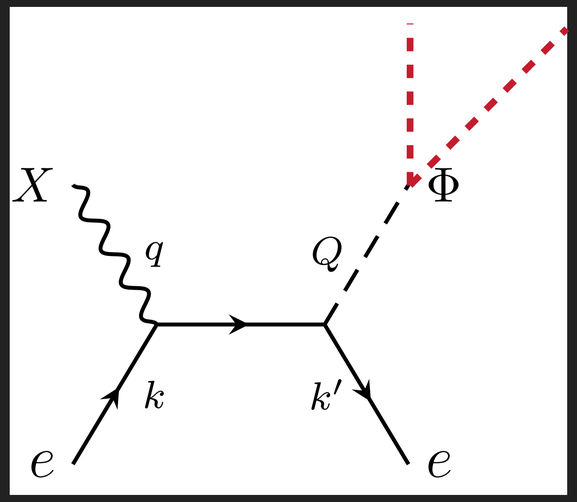
Dark Photon

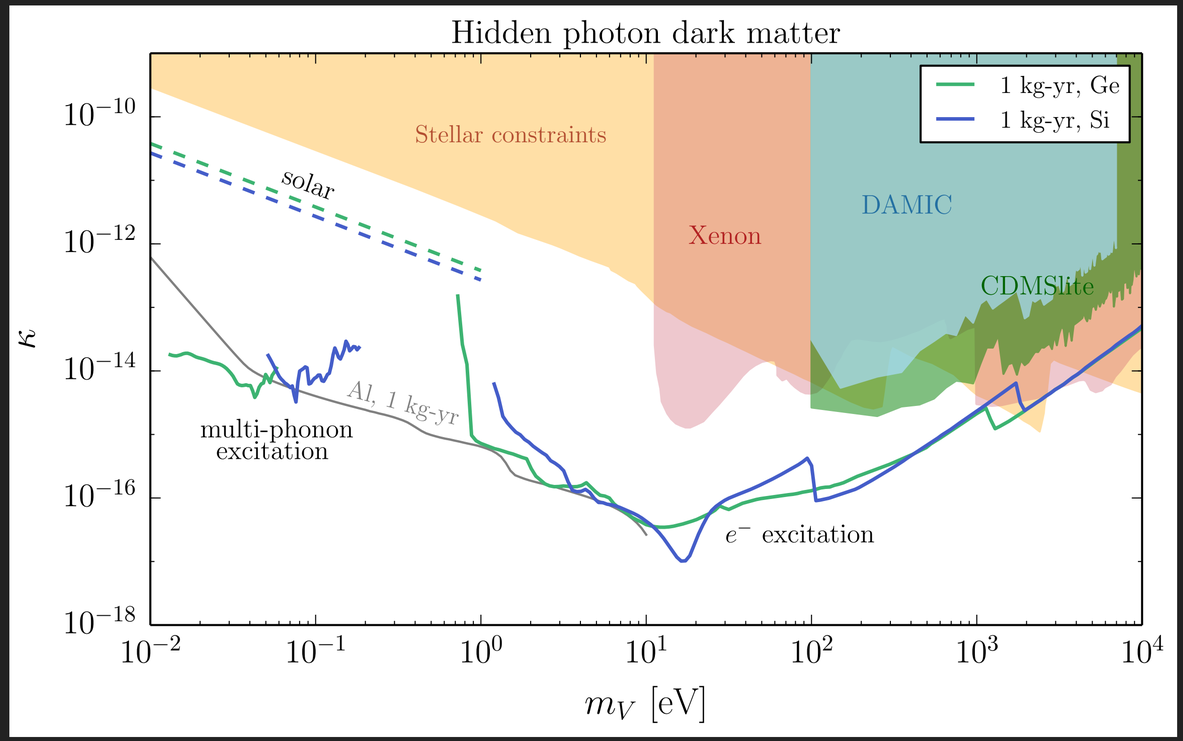


Hochberg, Lin, KZ 1604.06800

ABSORPTION — SEMICONDUCTORS

- Larger gap means sensitivity only to heavier particles … but, there is a new process!





Hochberg, Lin, KZ 1608.01994

HELIUM

- Superfluids are naturally insensitive to noise. A good light DM detector? In the context of ordinary nuclear recoils, yes, see e.g. McKinsey group, 1605.00694
- To detect lighter DM, couple to phonon modes.
- Viable? At first glance – no

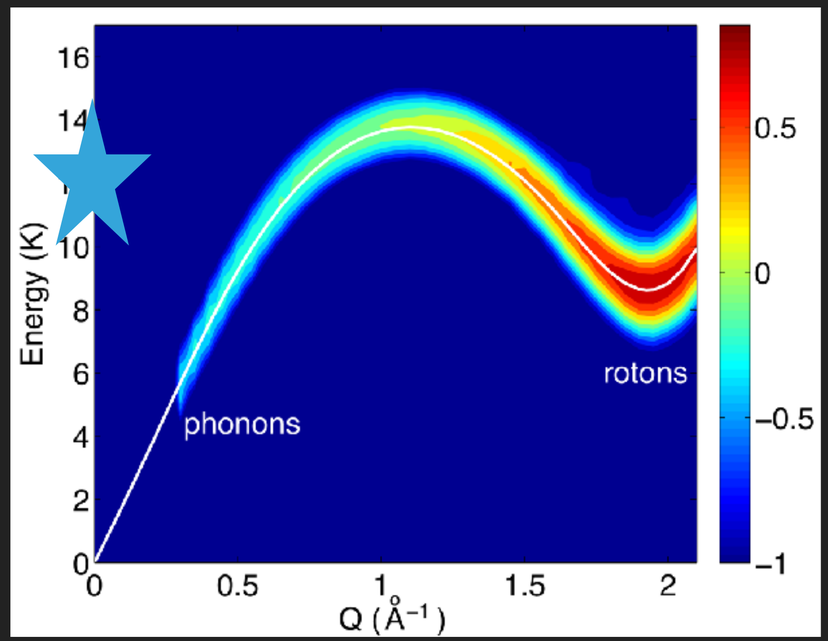
$$E_D \sim v_X q$$

vs

$$c_s \ll v_X$$

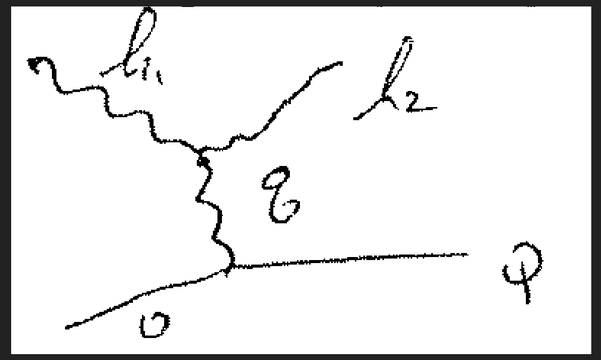
$$E_D \sim c_s q$$

- Next glance -- yes!



HELIUM

Internal note, R. Golub, 1977



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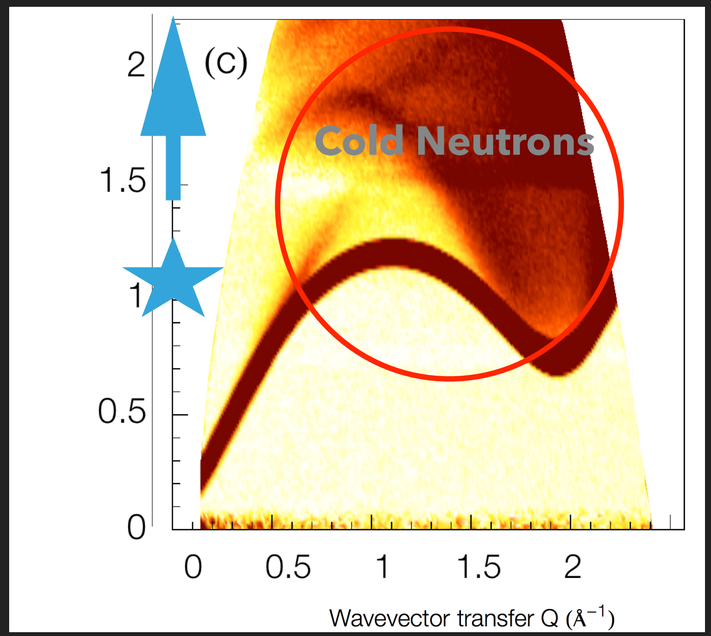
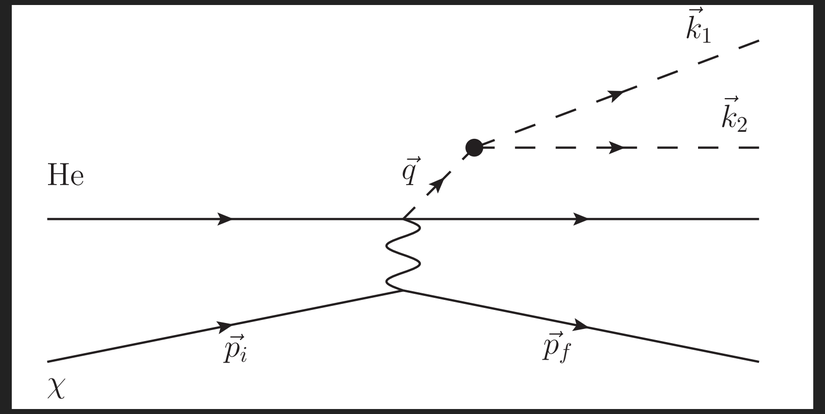


Beauvois et al 1605.02638

HELIUM

Schutz, KZ 1604.08206



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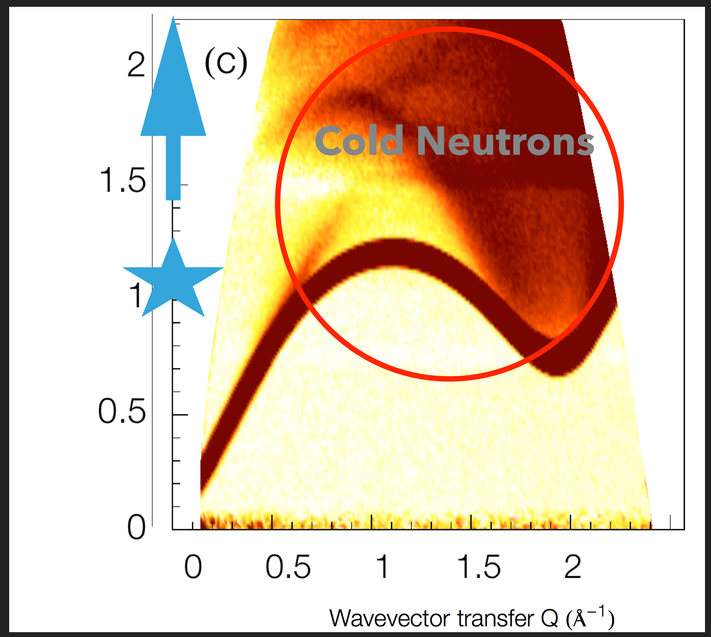
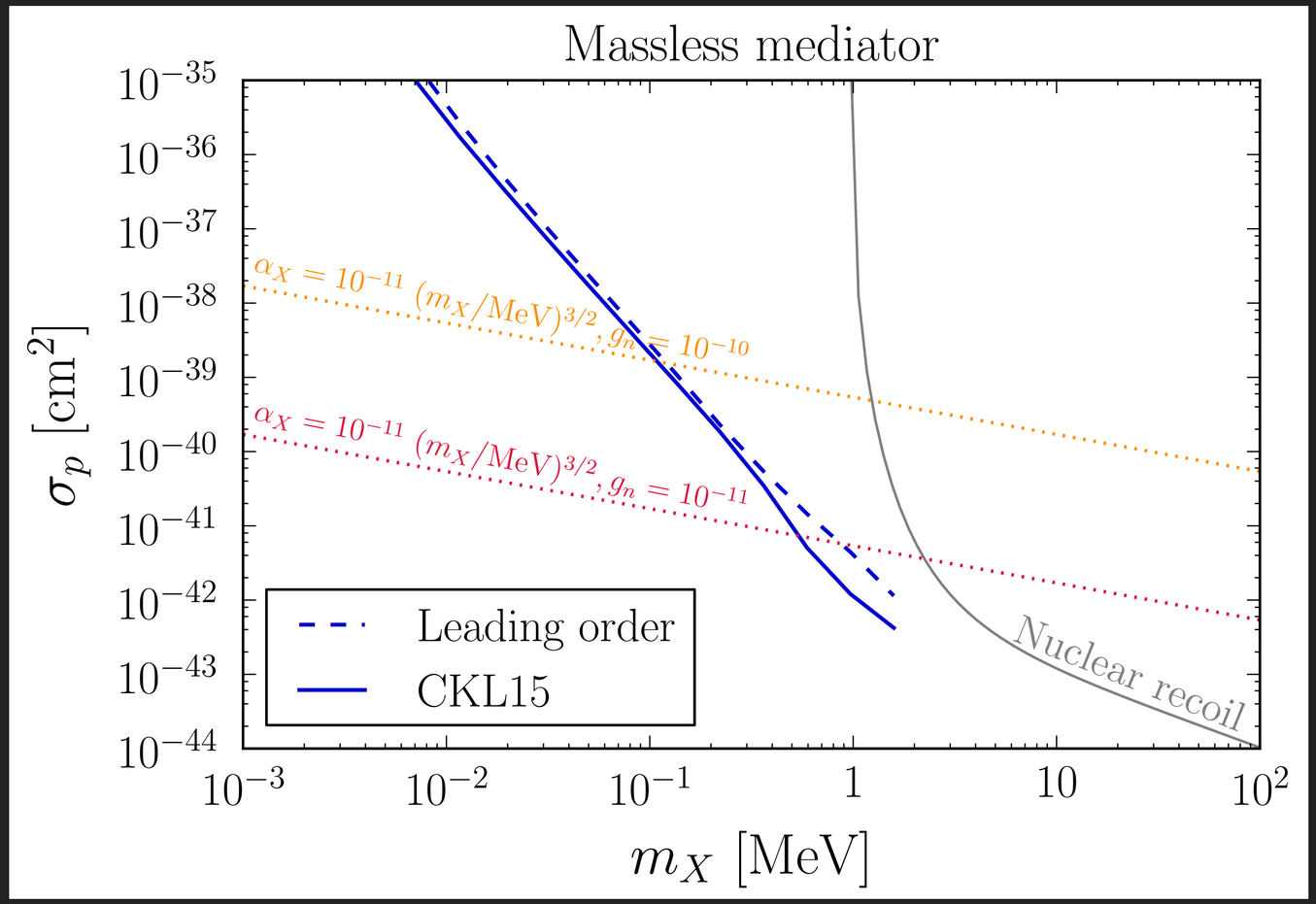


Beauvois et al 1605.02638

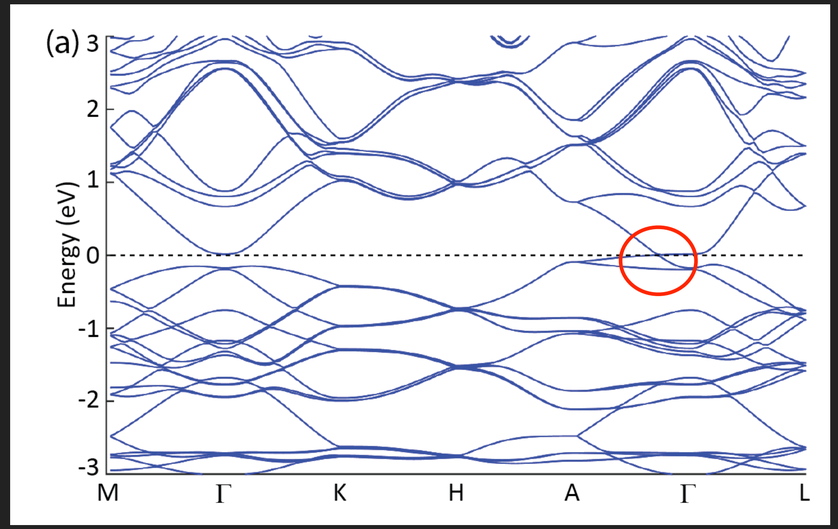
REACH

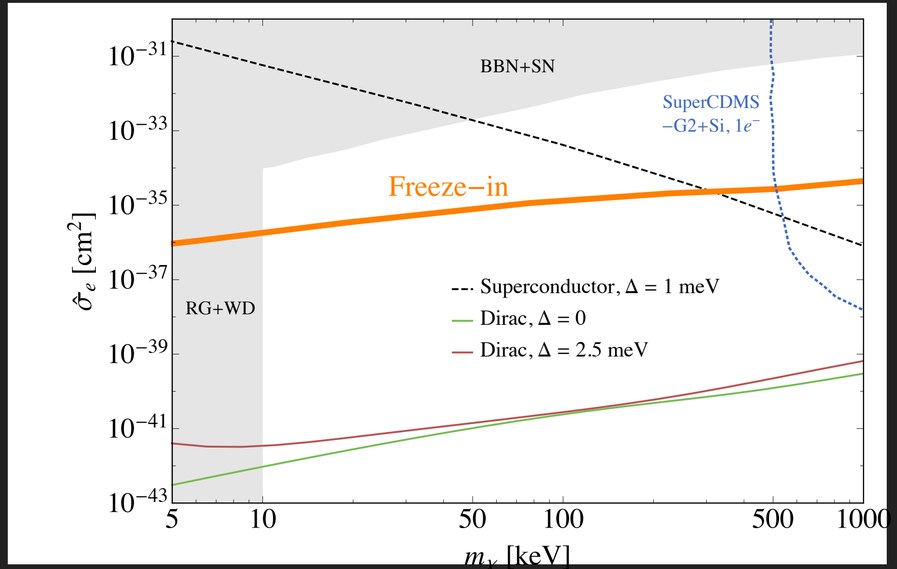


Lin, Knapen, KZ 1611.06228

WEYL OR DIRAC SEMI-METALS ~ 3D GRAPHENE

- Correlation between electrons gives rise to a unique band structure
- Materials can be “quantum engineered”
- Hamiltonian looks like free QED near Dirac point

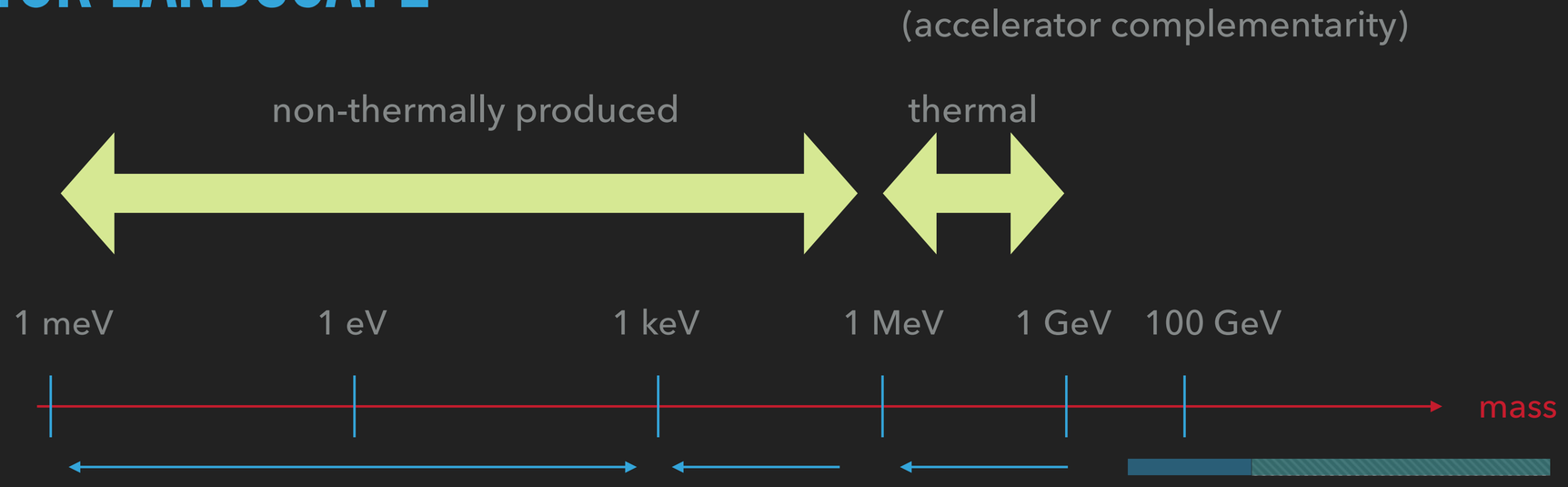




Yonit Hochberg,[1,2,*] Yonatan Kahn,[3,†] Mariangela Lisanti,[3,‡] Kathryn M. Zurek,[4,5,§] Adolfo Grushin,[6,7,¶] Roni Ilan,[8,**] Zhenfei Liu,[9] Sinead Griffin,[9] Sophie Weber,[9] and Jeffrey Neaton[9]

to appear

HIDDEN SECTOR LANDSCAPE



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~meV energy resolution

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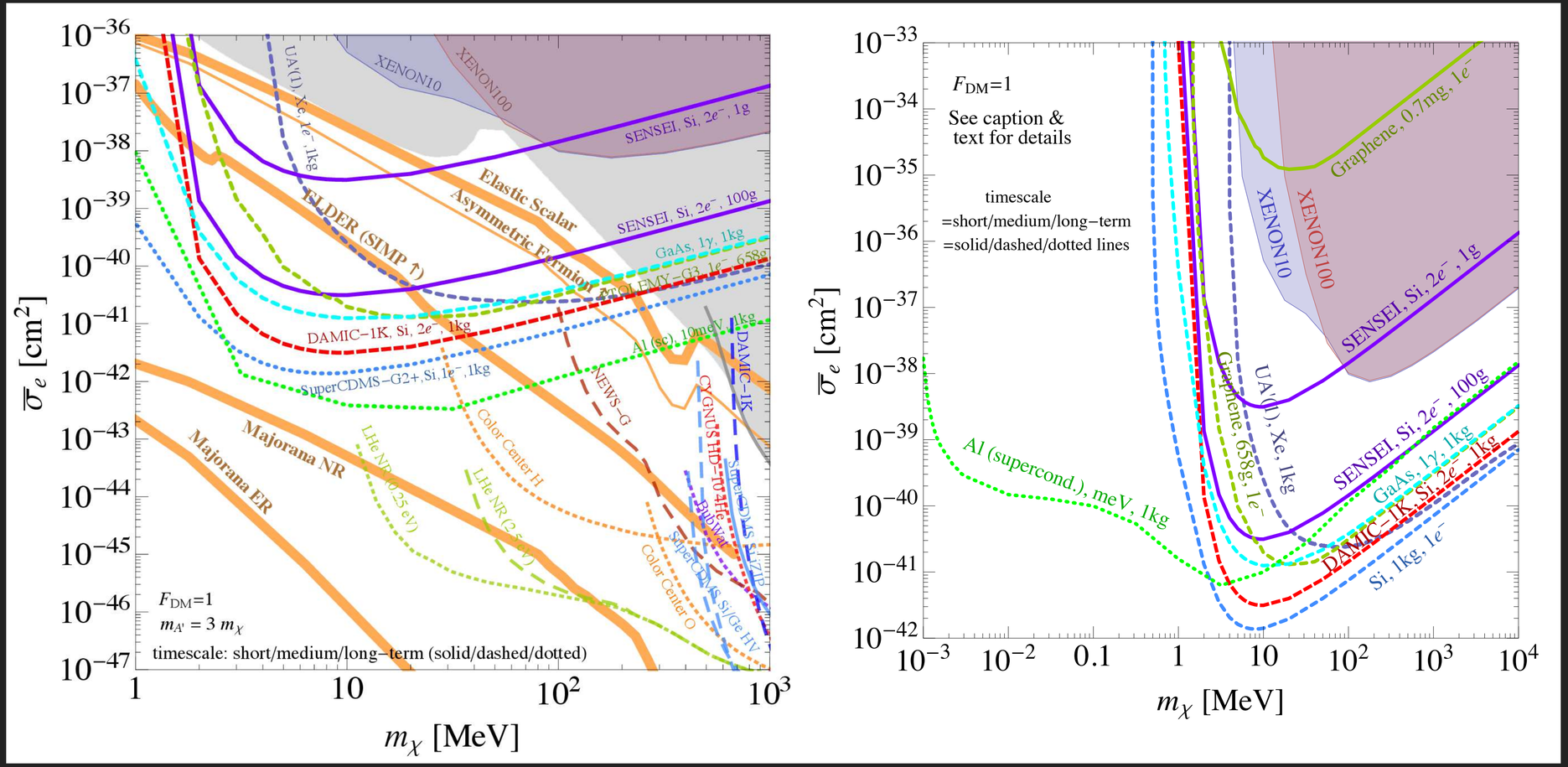
~keV energy resolution

COMPLEMENTARITY

Cosmic Visions Whitepaper



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, semi-metal ….
- 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
- Twelve orders of magnitude increased sensitivity in mass
- Long view necessary!