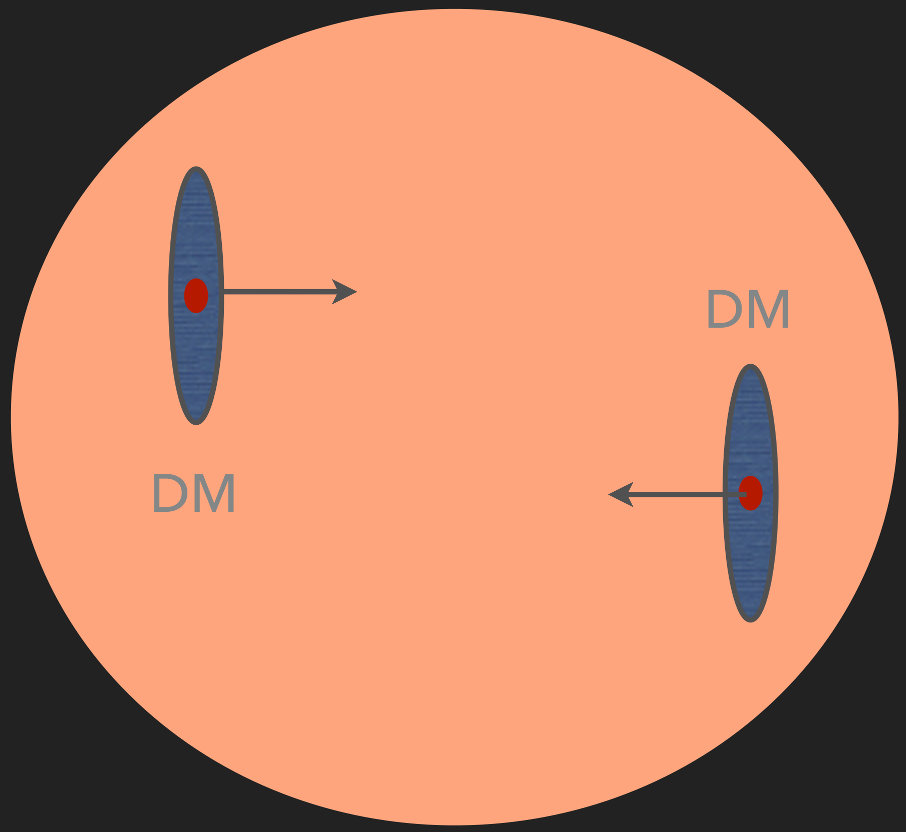
K. ZUREK

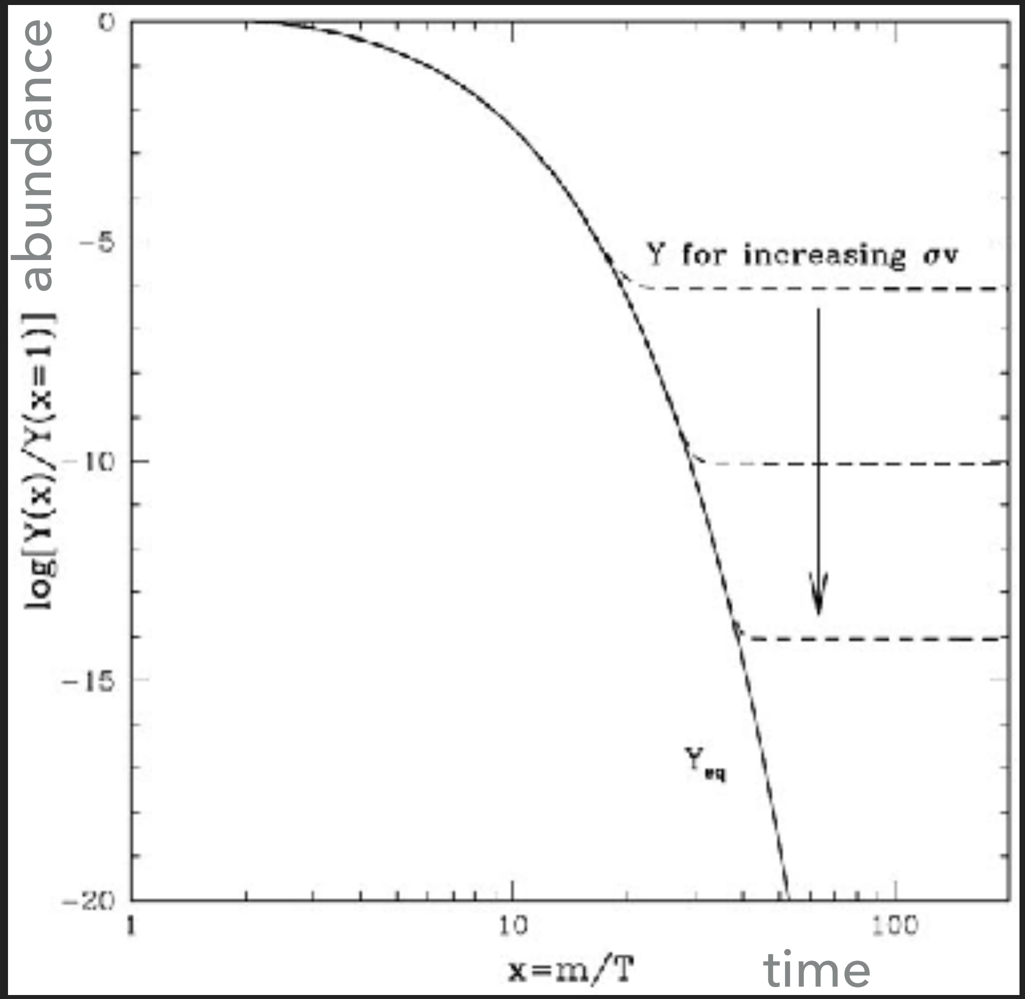
Leveraging the many faces (and phases) of matter

QUANTUM MATERIALS & DARK MATTER DETECTION

NEW DIRECTIONS IN DARK MATTER THEORY

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





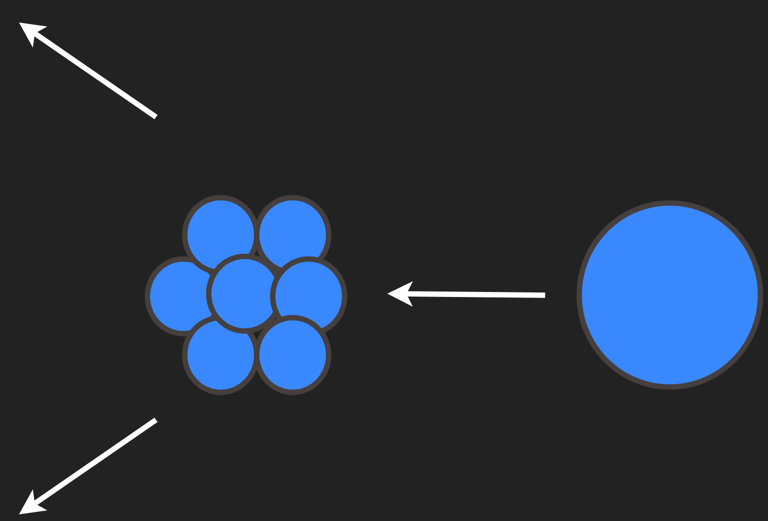
Kolb and Turner

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

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

DIRECT DETECTION GOLD STANDARD

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



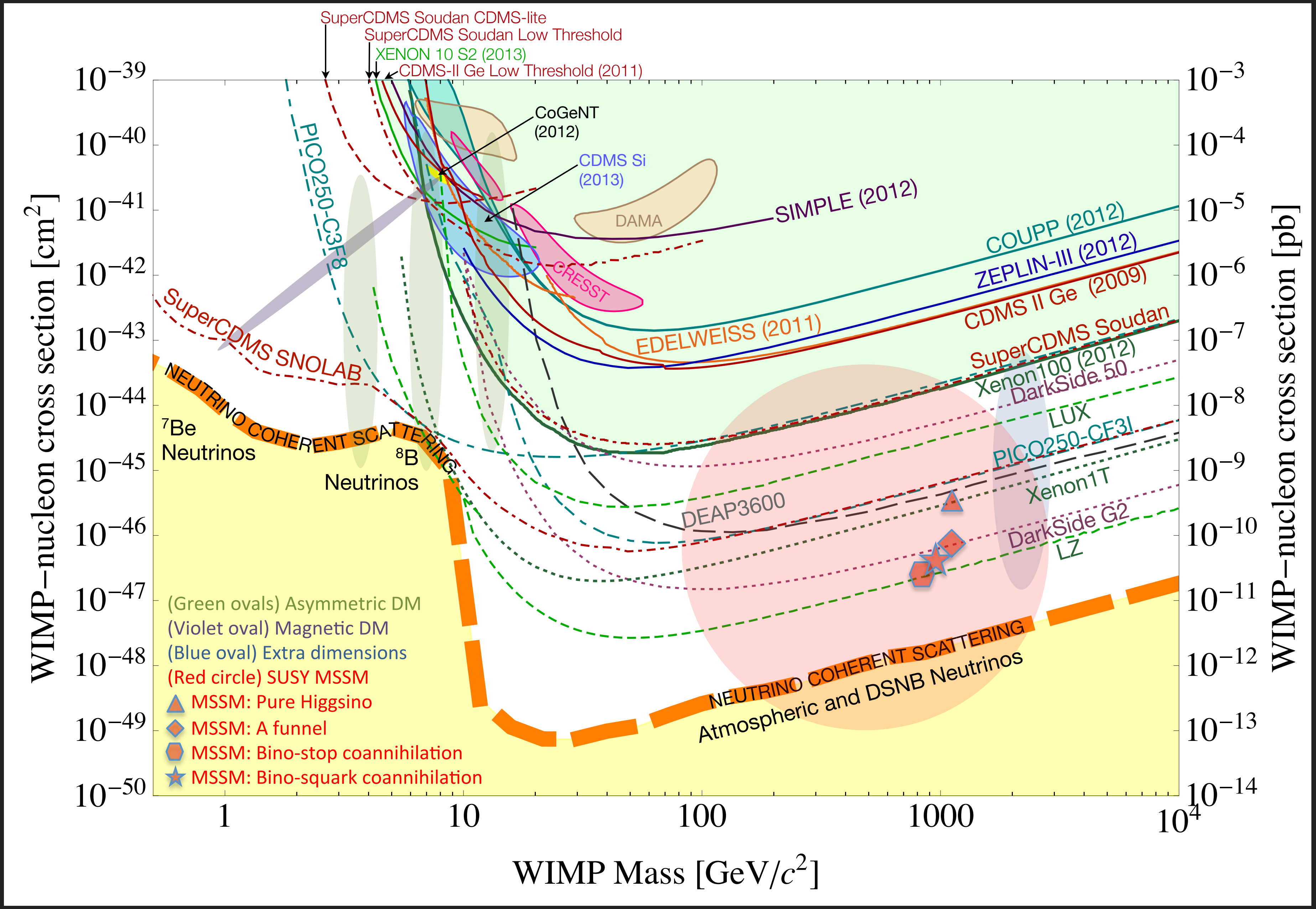
$$v \sim 10^{-3} c$$

$$q, \;\; E_D$$

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

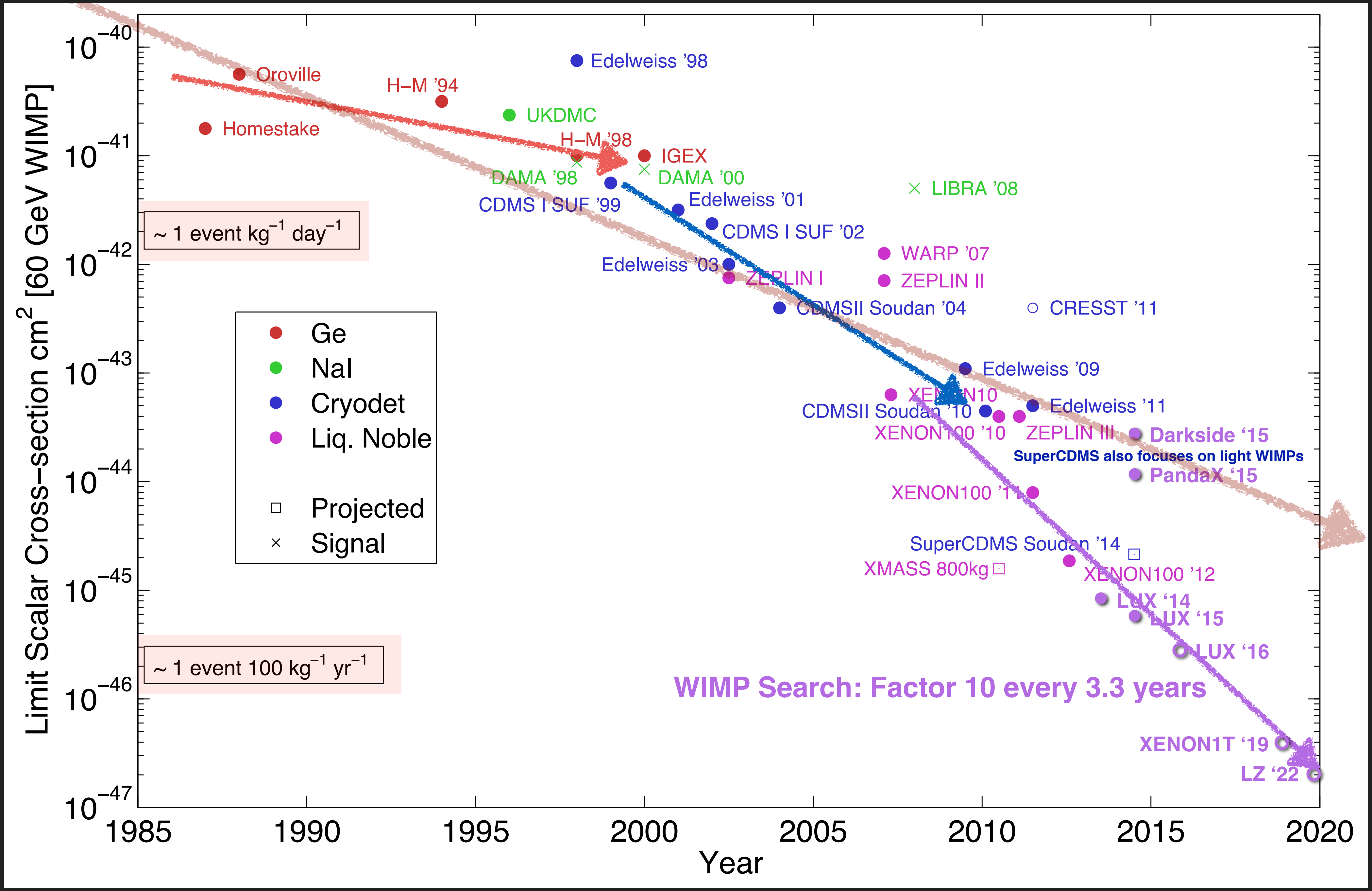
$v \sim 300 \text{ km/s} \sim 10^{-3} c \implies E_D \sim 100 \text{ keV}$ for 50 GeV target

DARK MATTER AND CLASSICAL BILLIARD BALLS

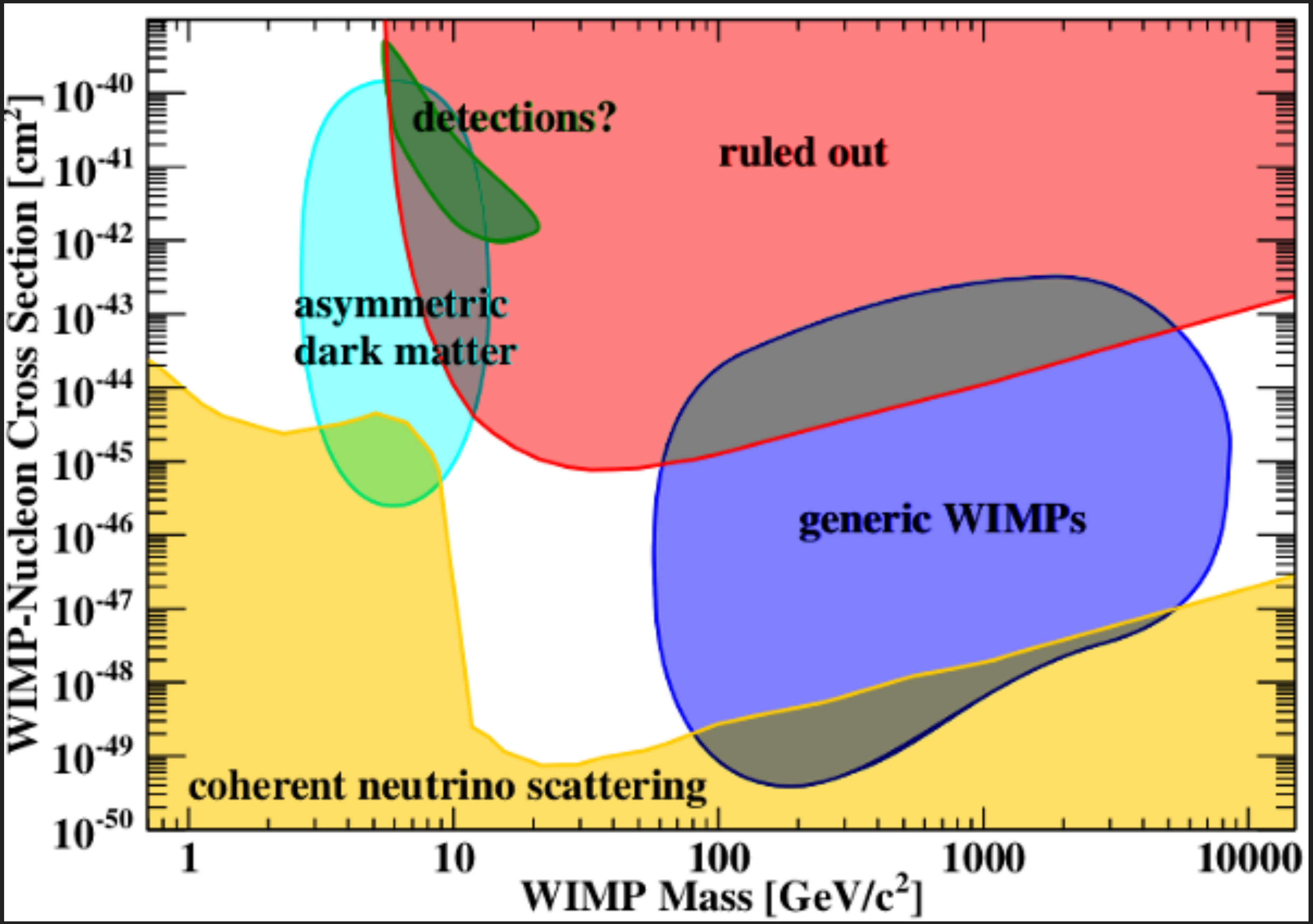


DARK MATTER MOORE'S LAW

Factor of 10 every 6.5 years

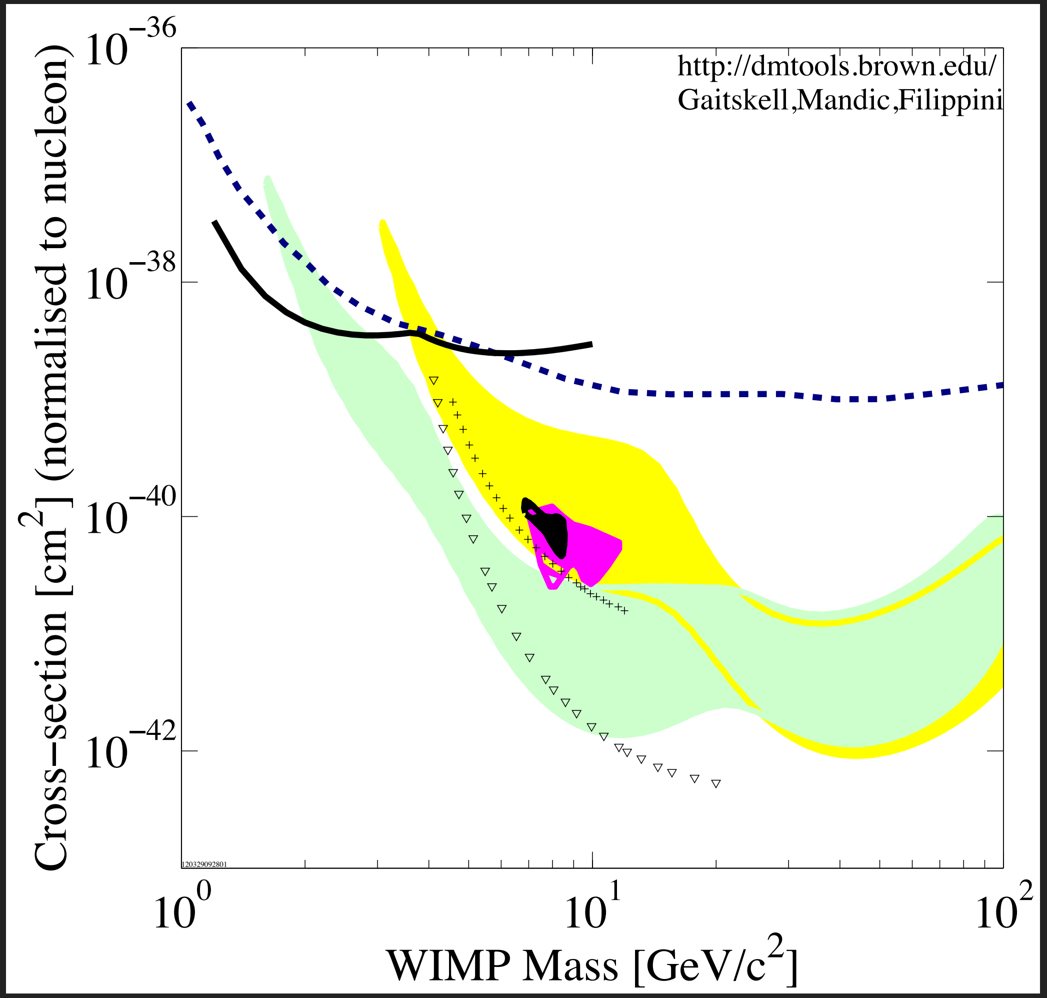


THEORY TARGETS



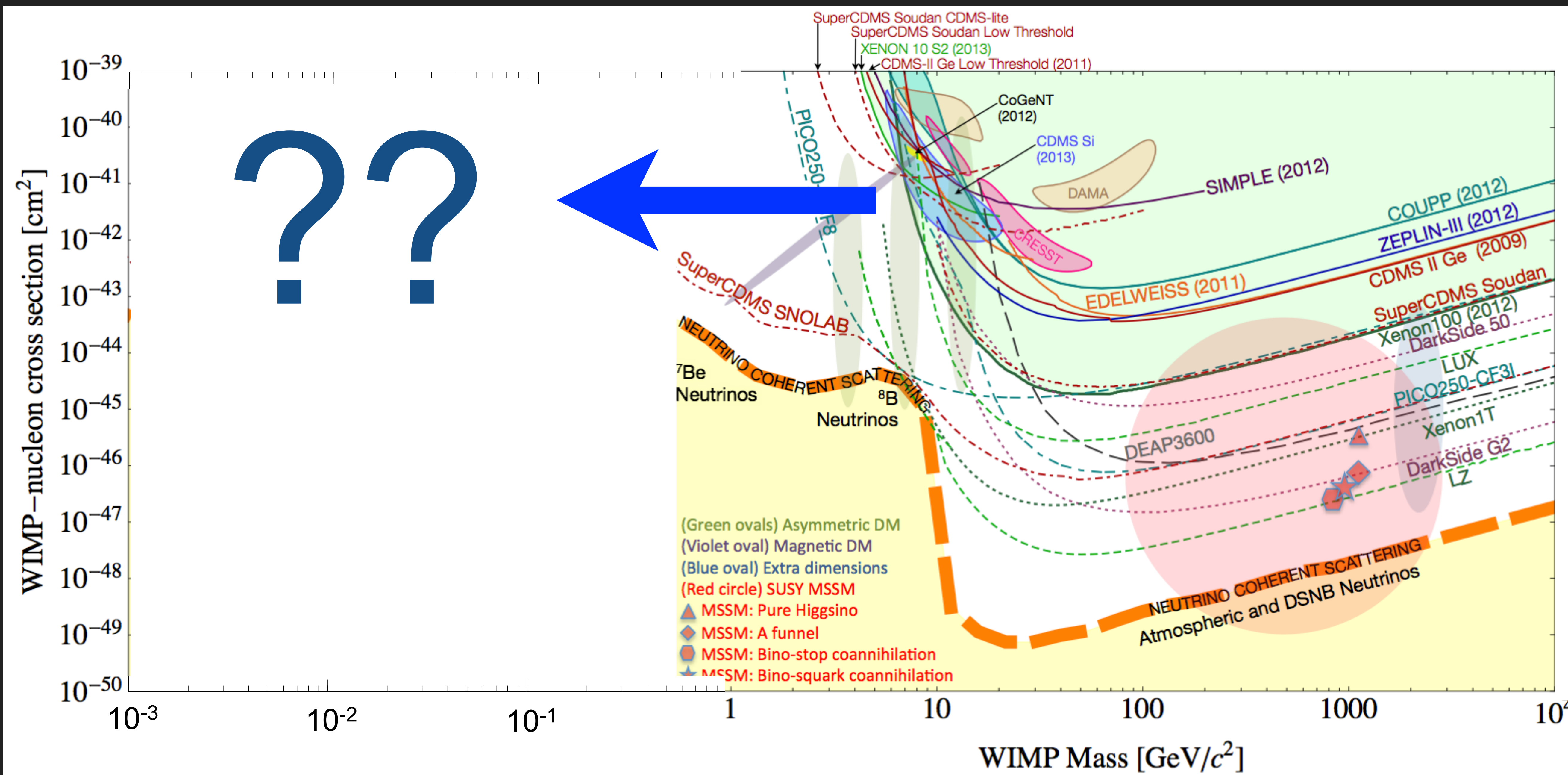
EARLY EFFORT : DAMIC CCD AT FNAL

- Detecting DM Whispers dependent on dark counts and read-out noise
- 40 eV threshold, nuclear recoils



DAMIC collaboration, 1105.5191

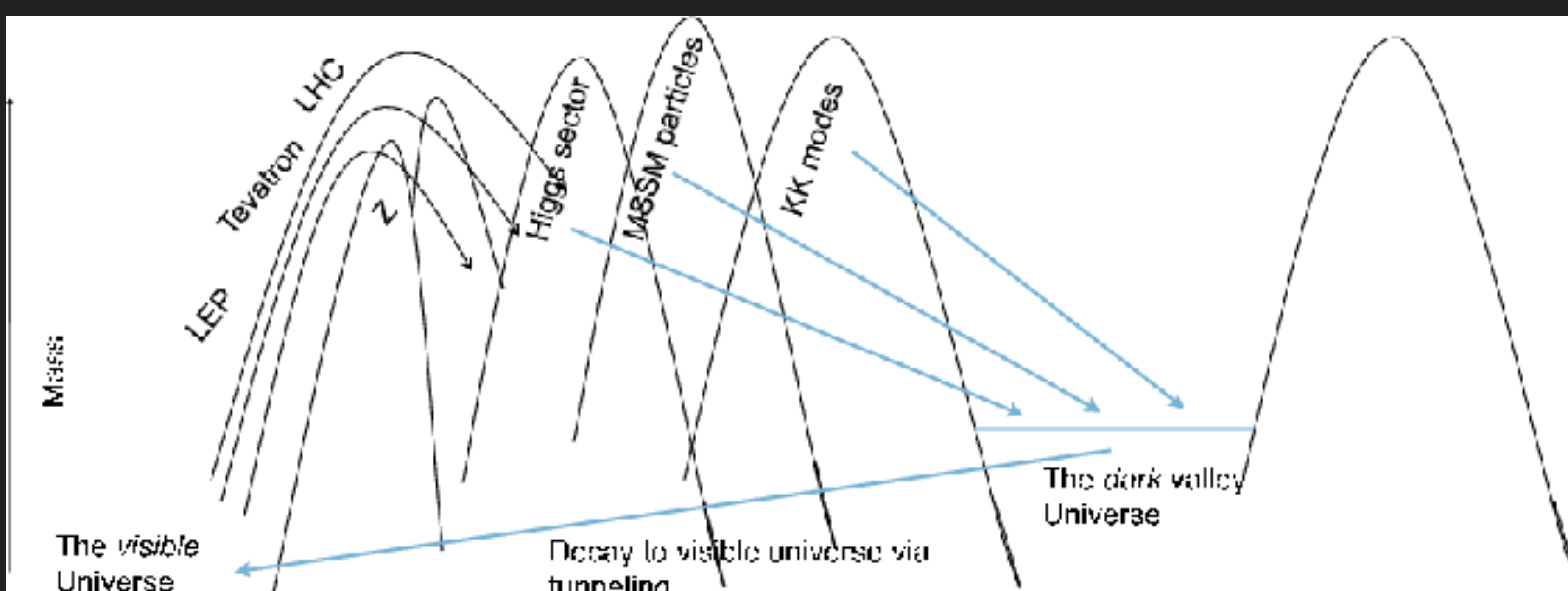
DIRECT DETECTION GOLD STANDARD



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

$$\pi_v^+\pi_v^- \to \pi_v^0\pi_v^0$$

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

NUCLEAR RECOILS

- Kinematic penalty when DM mass drops below nucleus mass

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

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

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

NEXT UP: ELECTRON

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

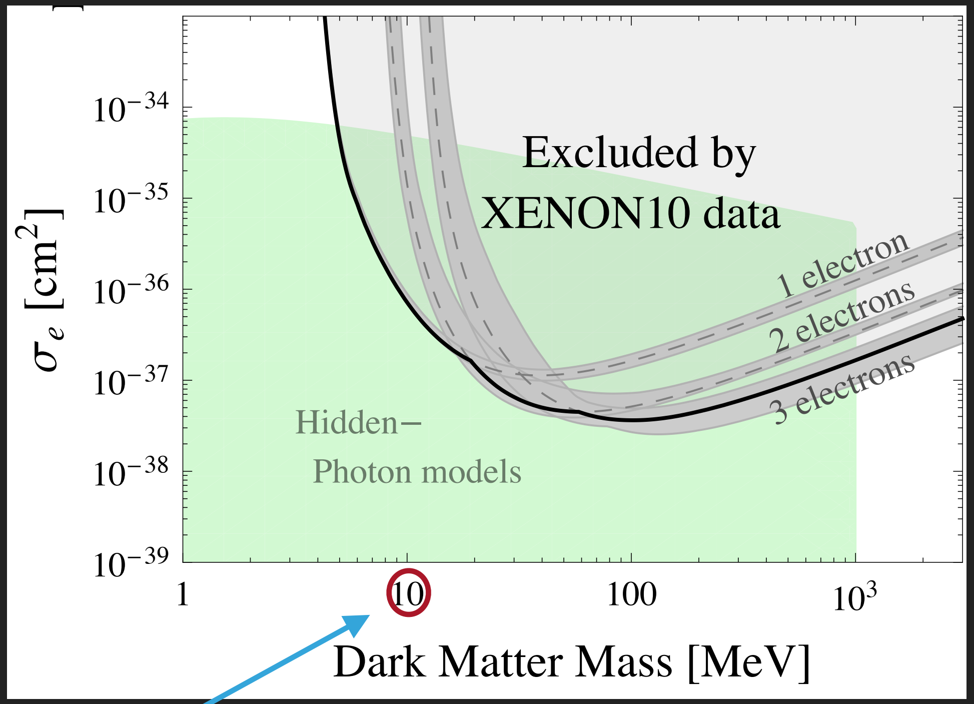
$$E_D = \frac{q^2}{2m_e} \qquad q_{\max} = 2m_X v$$

- 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

P. Sorensen et al 1206.2644

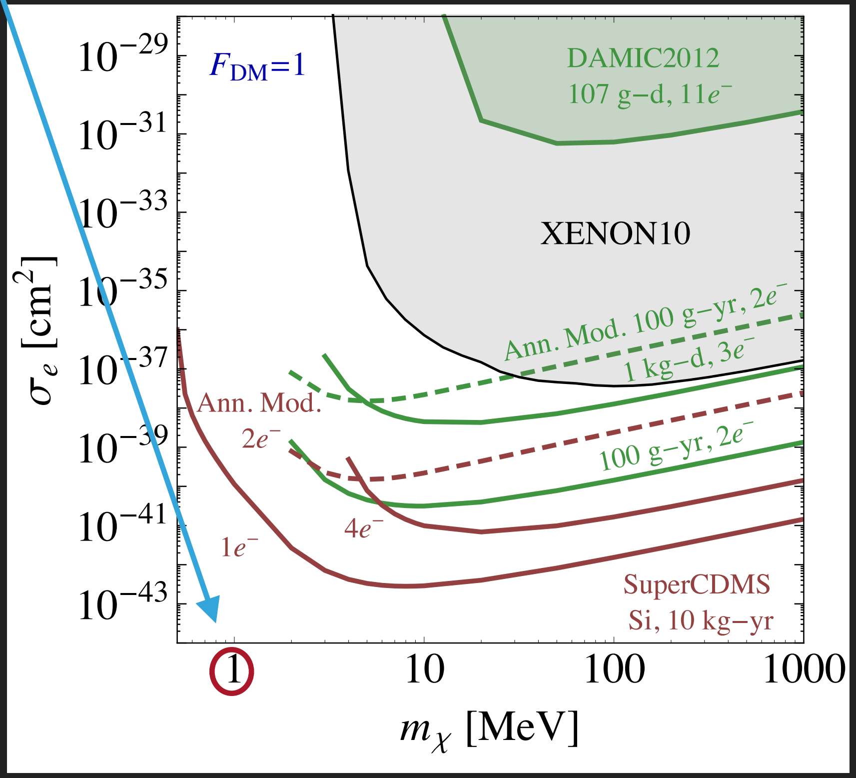


- In insulators, like xenon

  Ionize electron

Gap = DM Kinetic Energy

Essig et al 1509.01598



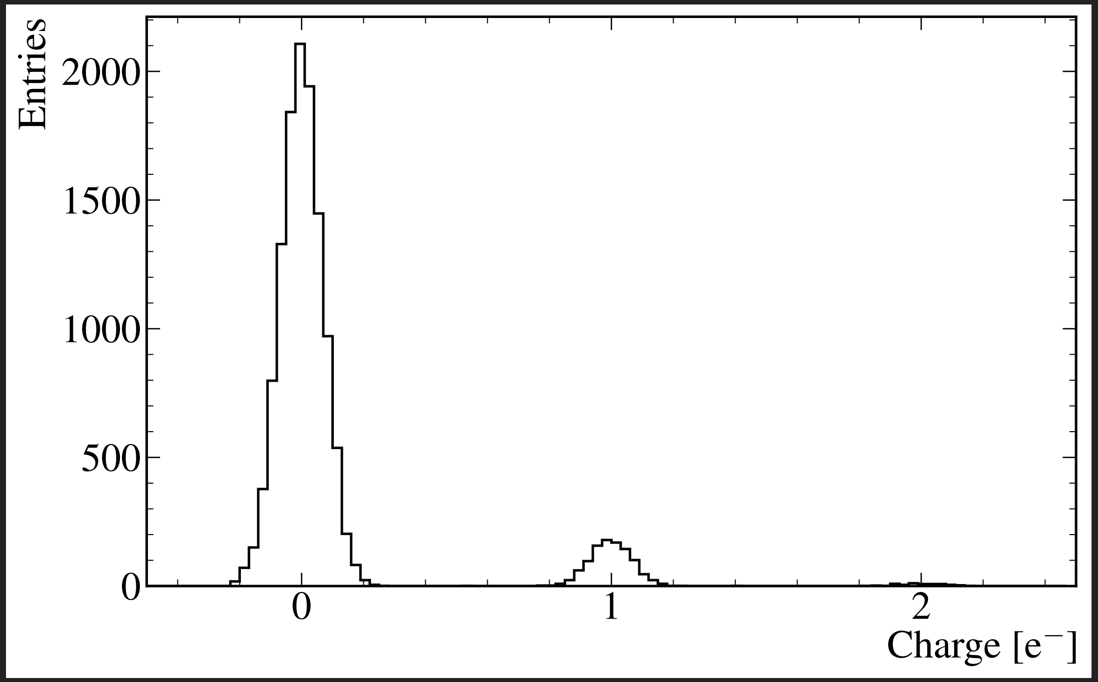
- In semi-conductors, like Ge, Si

  Excite electron to conduction band

SENSEI AND SKIPPER CCD'S

- DAMIC utilized sensitivity to charge to place constraints on DM
- Fundamentally limited by noise
- More noise = less sensitivity to DM Whispers
- Improved Read-out

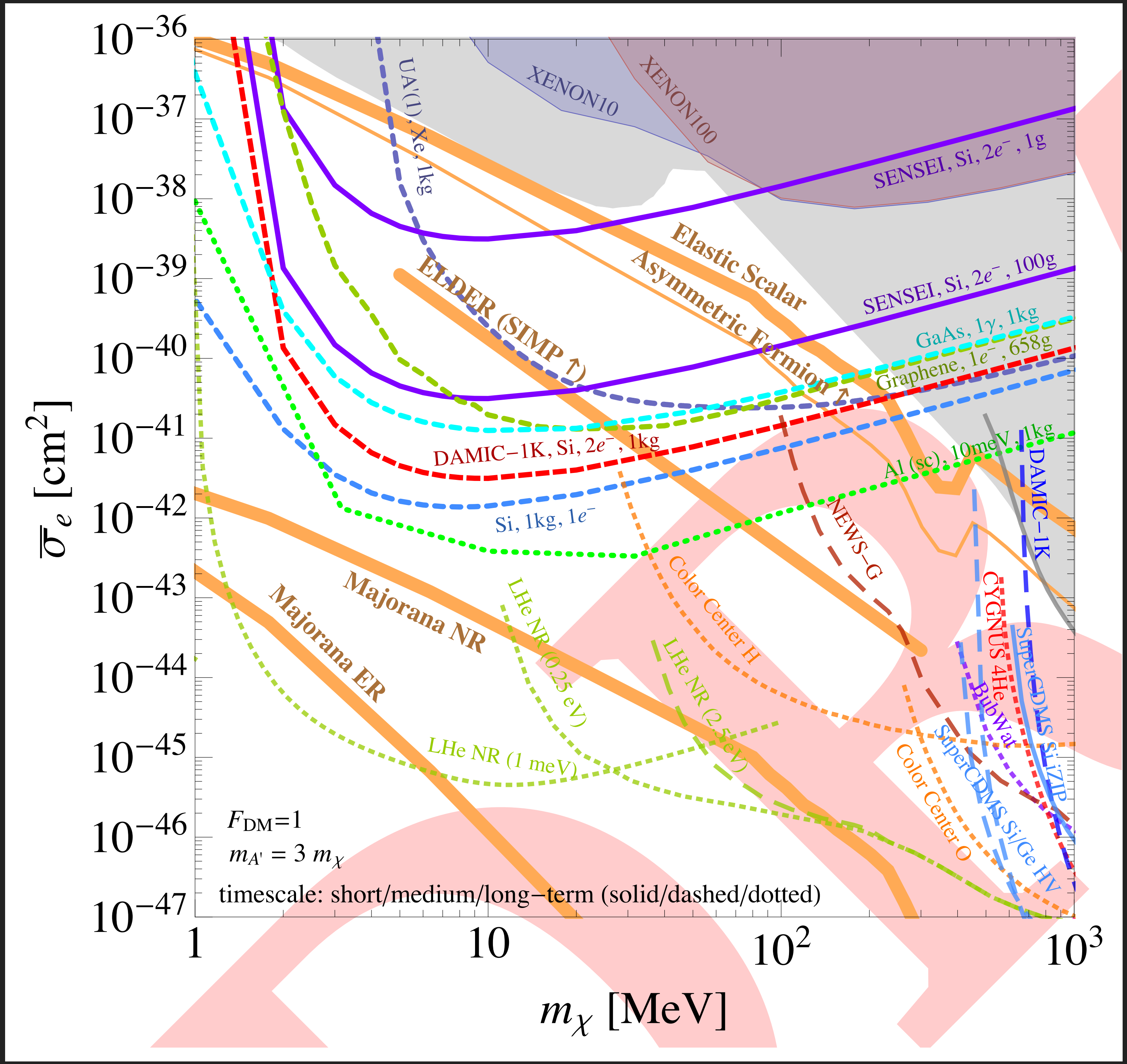
LDRD led by Javier Tiffenberg



SENSEI, 1706.00028

RMS = 0.068 e/pix

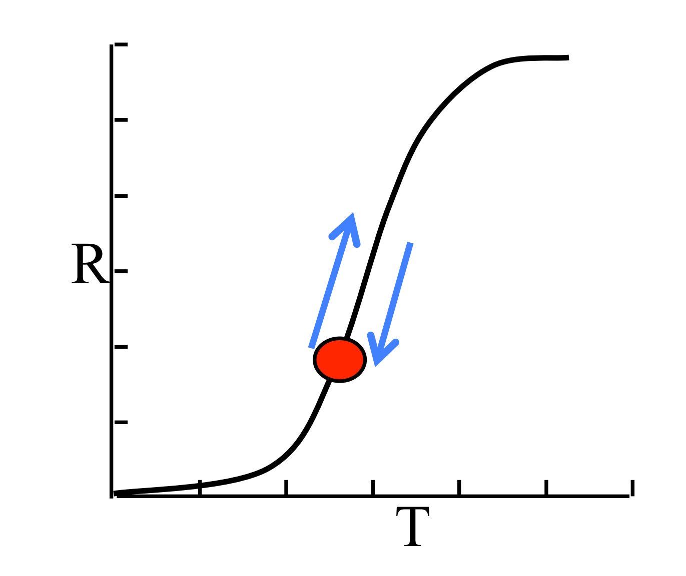
SENSEI AND SKIPPER CCD'S



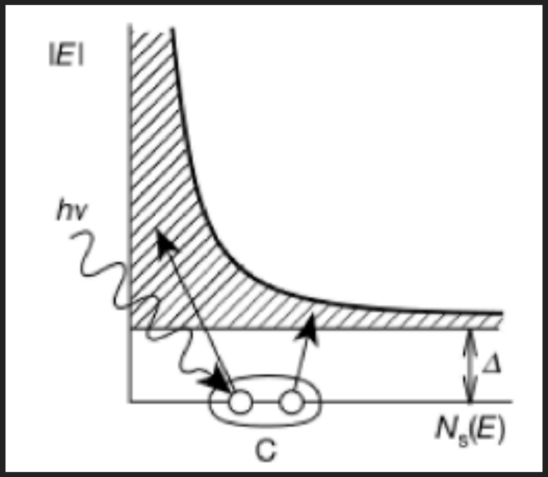
QUANTUM DEVICE R&D

- 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, e.g. Aaron Chou LDRD

Transition Edge Sensor calorimeter

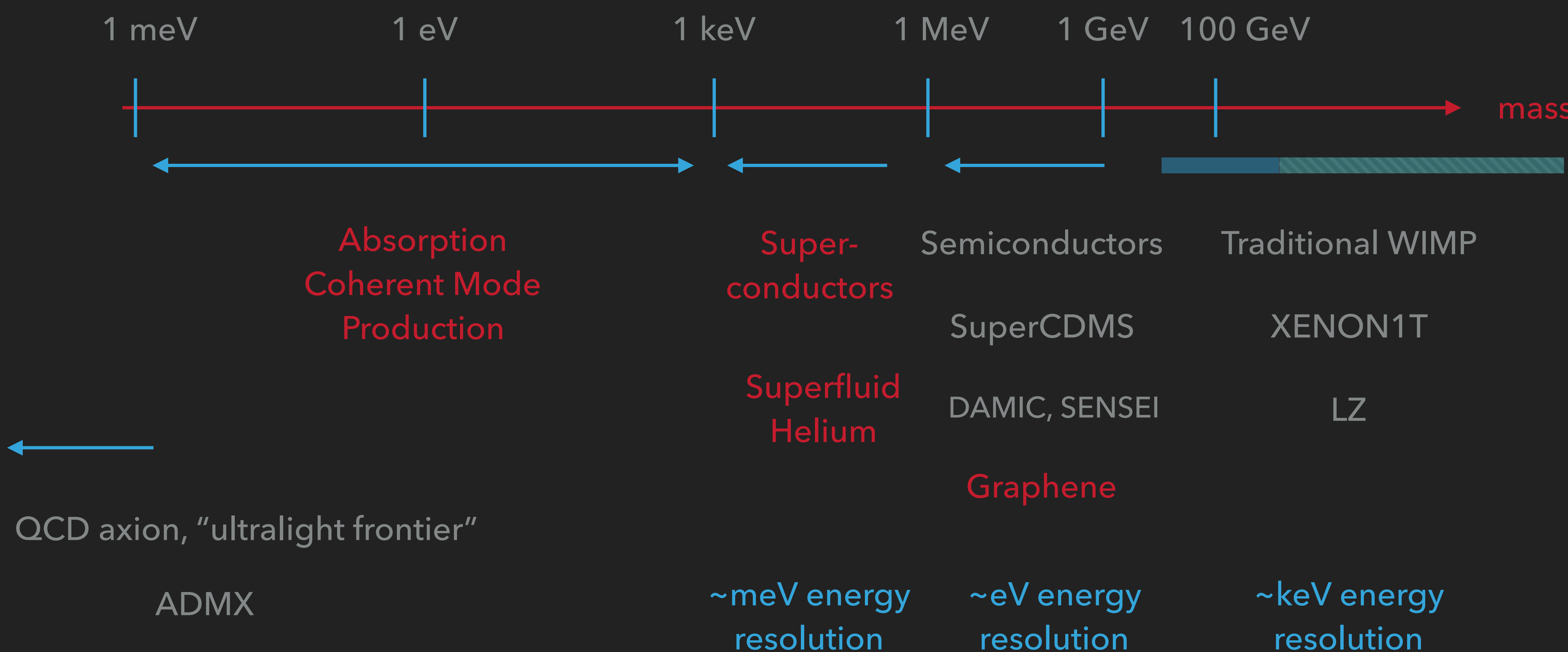


Microwave Kinetic Inductance Device



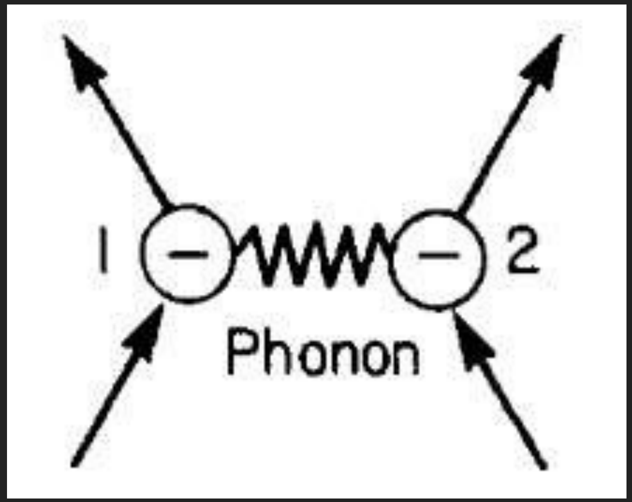
See W. Wester talk

DARK MATTER LANDSCAPE



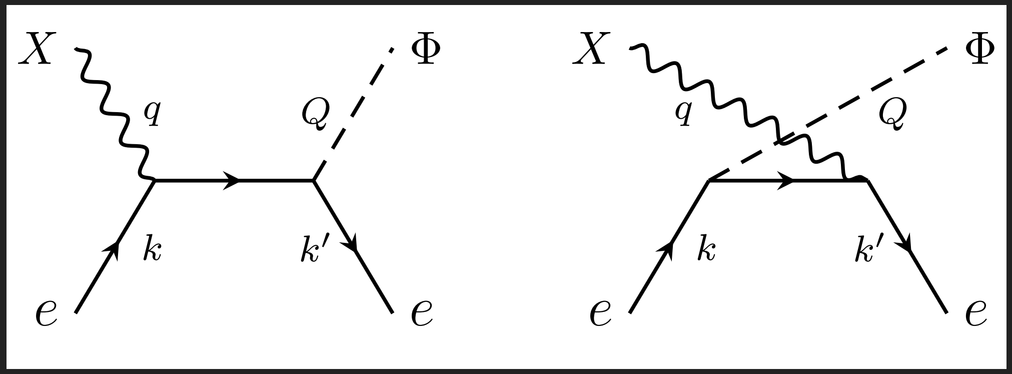
E.G. SUPERCONDUCTORS

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



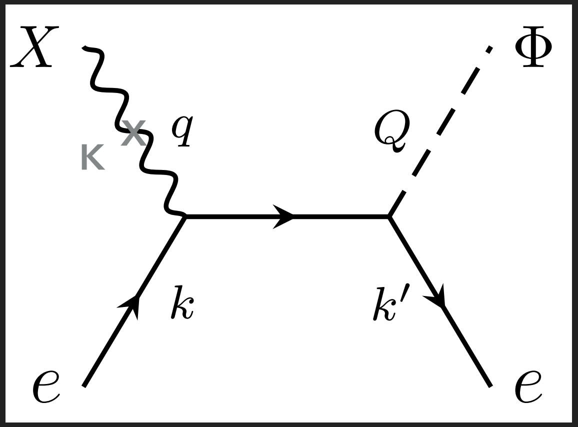
ABSORPTION — SUPERCONDUCTORS

- 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

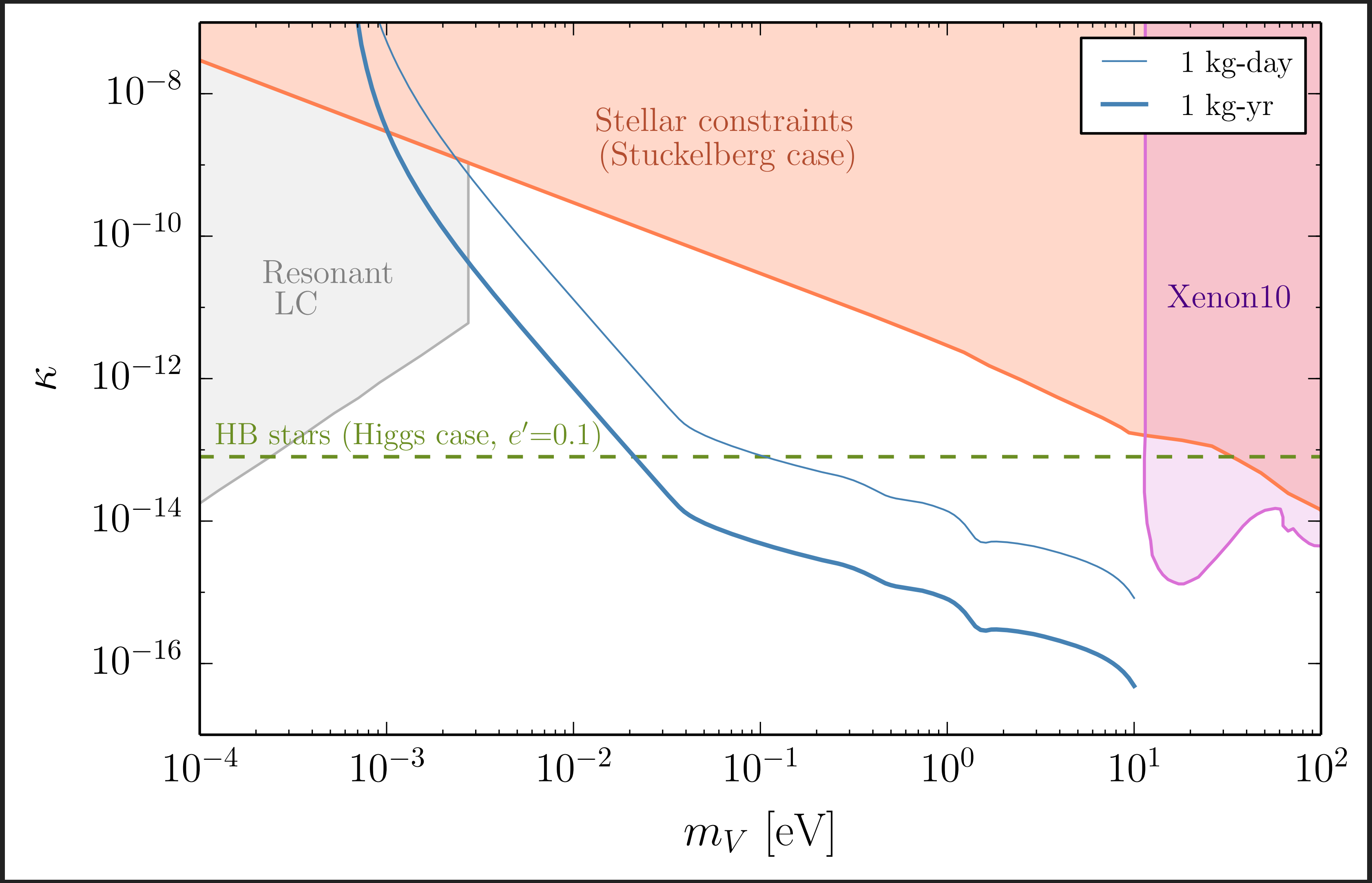


$$\mathcal{H} = \int d^3 y_{ph} \phi \bar{\psi} \psi = \frac{1}{\sqrt{V}} \sum_{\vec{k}} \sum_{\vec{k}'} \frac{C_{ph} |\vec{Q}|}{\sqrt{\rho}} \frac{1}{\sqrt{2E_Q}} (c_{\vec{Q}} + c^{\dagger}_{-\vec{Q}}) a_{\vec{k}'} a_{\vec{k}}$$

ABSORPTION — SUPERCONDUCTORS



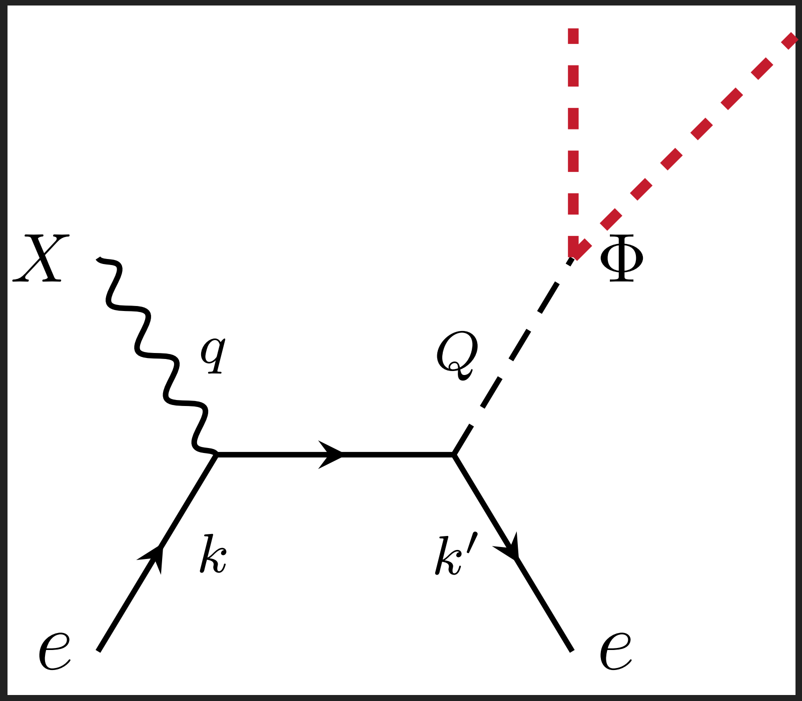
Dark Photon

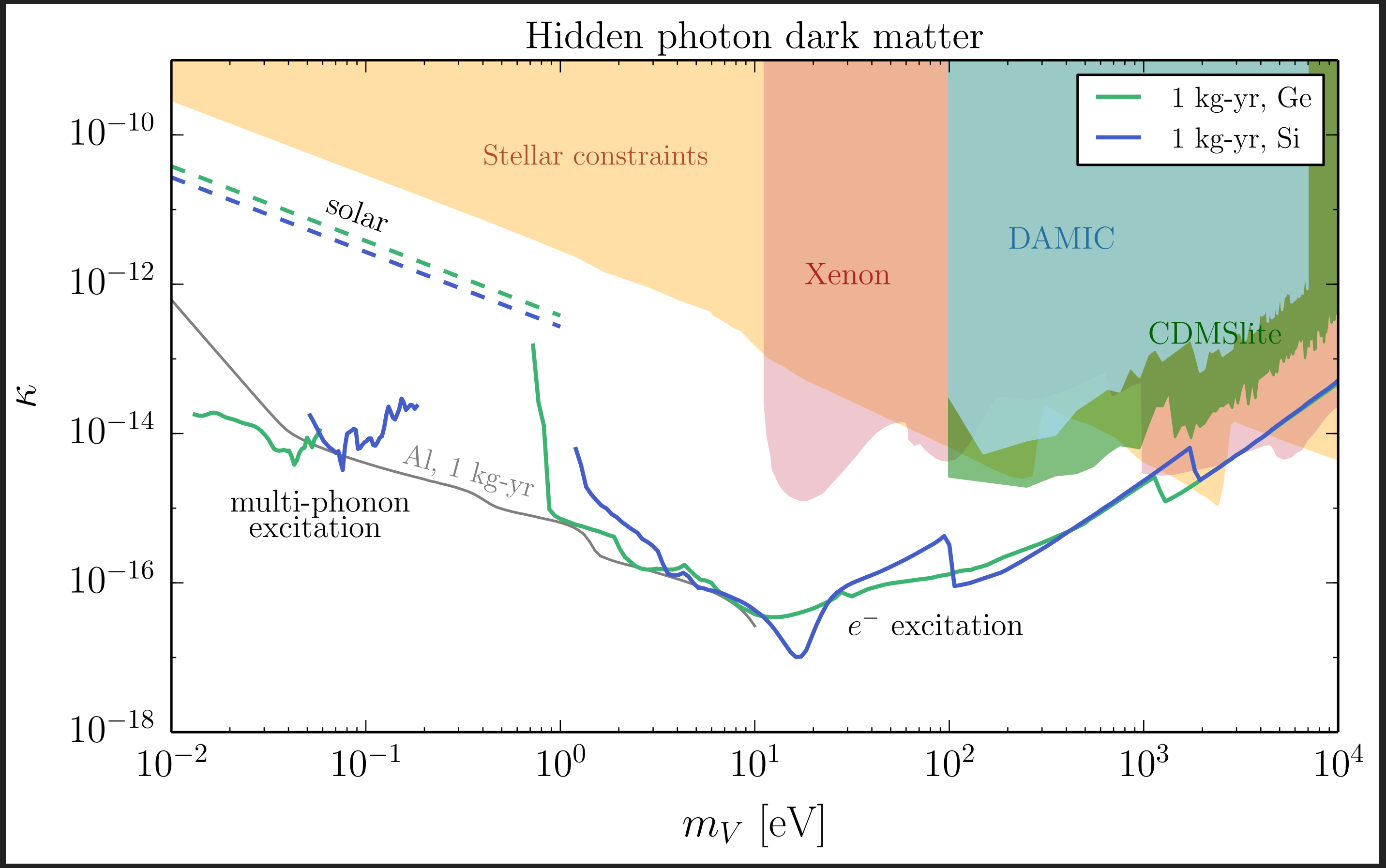


Hochberg, Lin, KZ 1604.06800

ABSORPTION — SEMICONDUCTORS

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





Hochberg, Lin, KZ 1608.01994

HELIUM

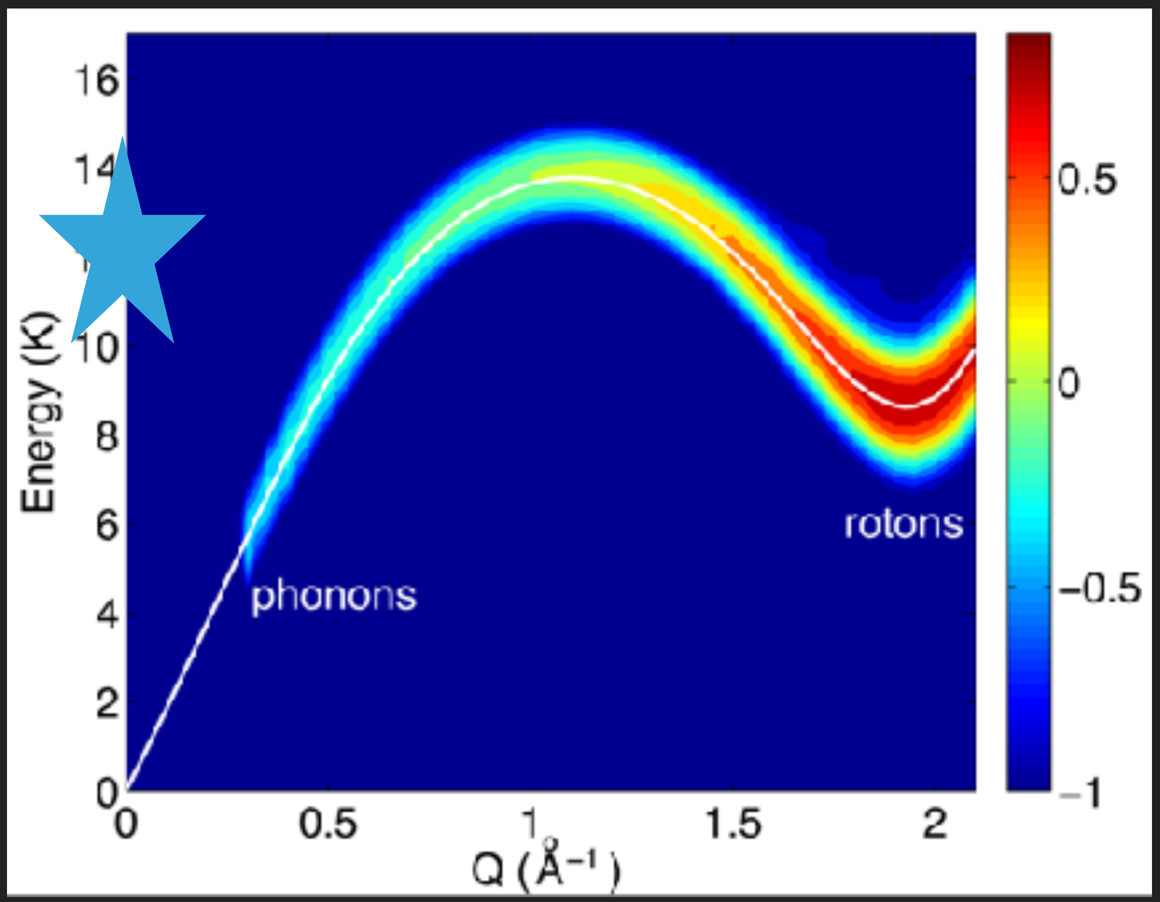
- Superfluids are naturally insensitive to noise. A good light DM detector? In the context of ordinary nuclear recoils, yes, see e.g. 1605.00694
- To detect lighter DM, couple to phonon modes.
- Viable? At first glance – no

$$E_D \sim v_X q$$

vs

$$E_D \sim c_s q$$

$$c_s \ll v_X$$



- Next glance -- yes!

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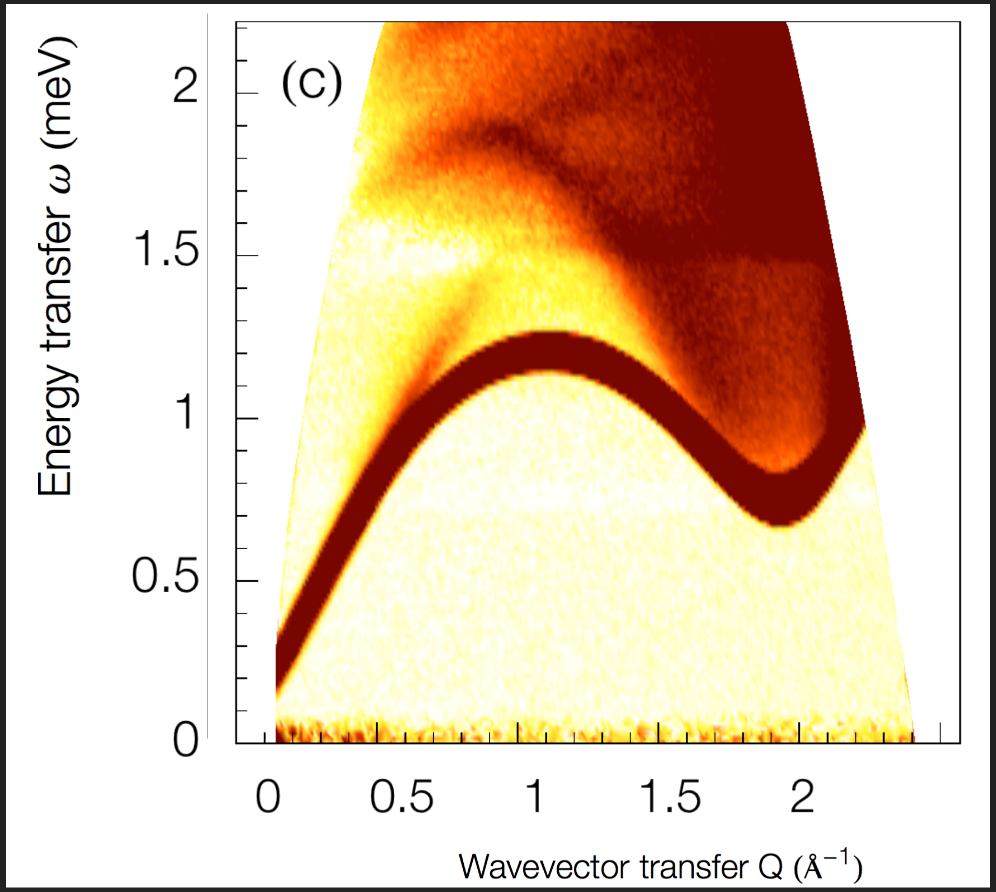
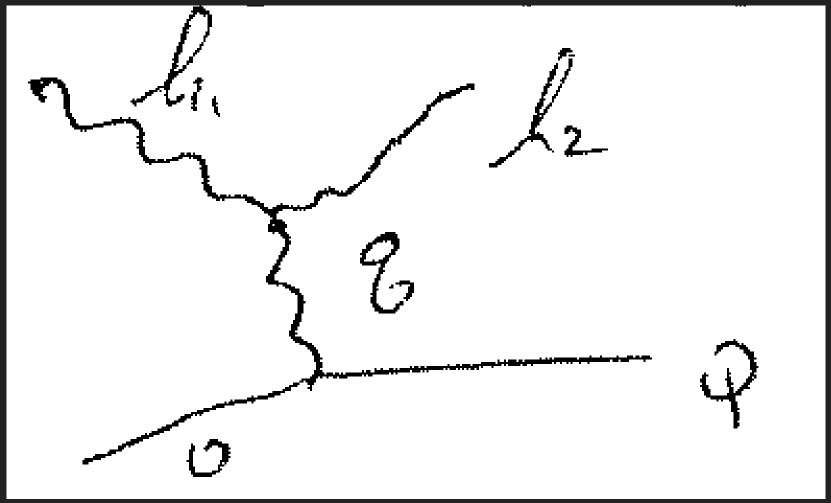


Beauvois et al 1605.02638

MULTI-EXCITATIONS

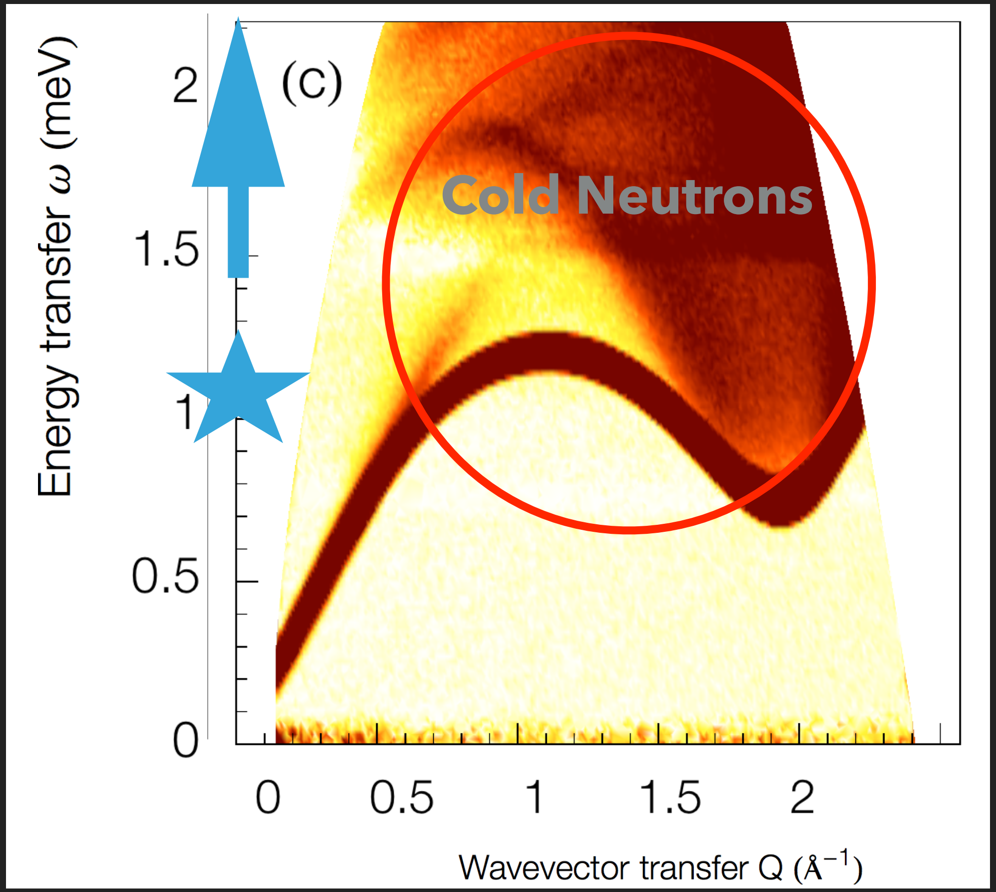
Internal note, R. Golub, 1977



- Calculated and observed for cold neutrons

$$V_3 = \int d^3r \left[\frac{\vec{v}\cdot\rho'\vec{v}}{2} + \frac{1}{3!}\frac{d}{d\rho}\left(\frac{c^2}{\rho}\right)(\rho')^3 \right]$$

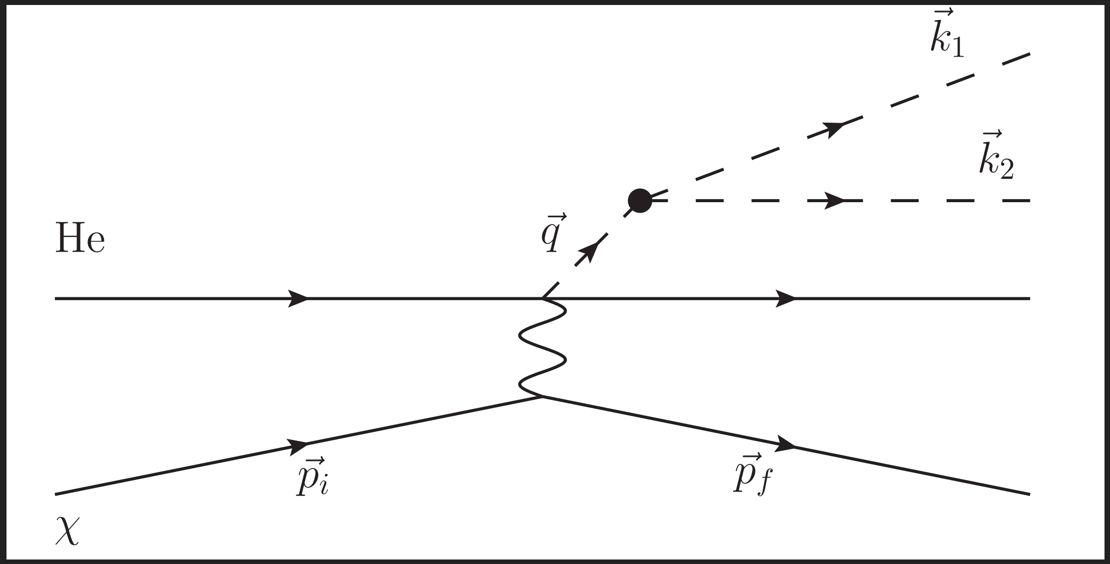
- However, this is in a very different kinematic regime
- No existing calculations in regime of interest



Beauvois et al 1605.02638

MULTI-EXCITATIONS

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

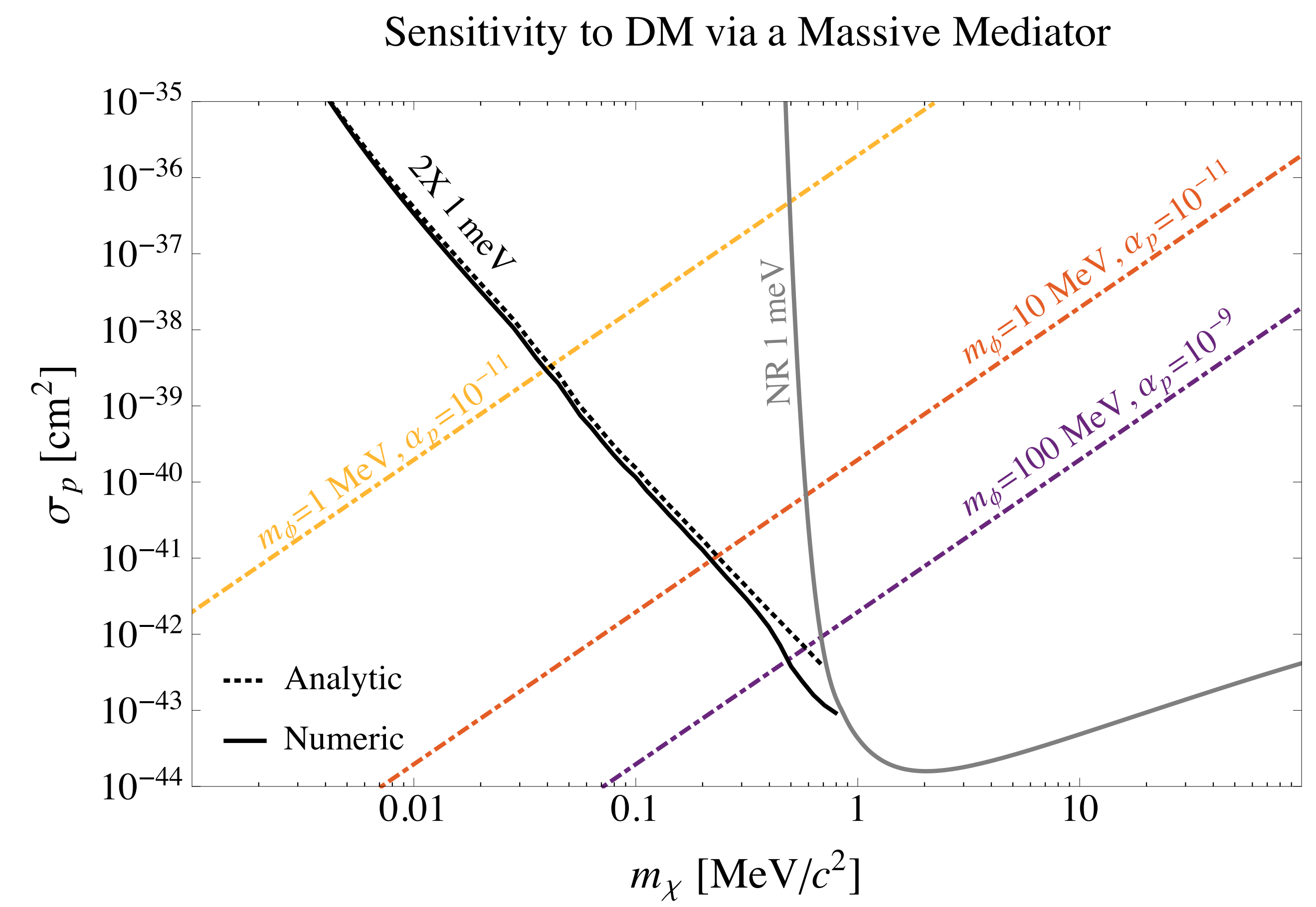


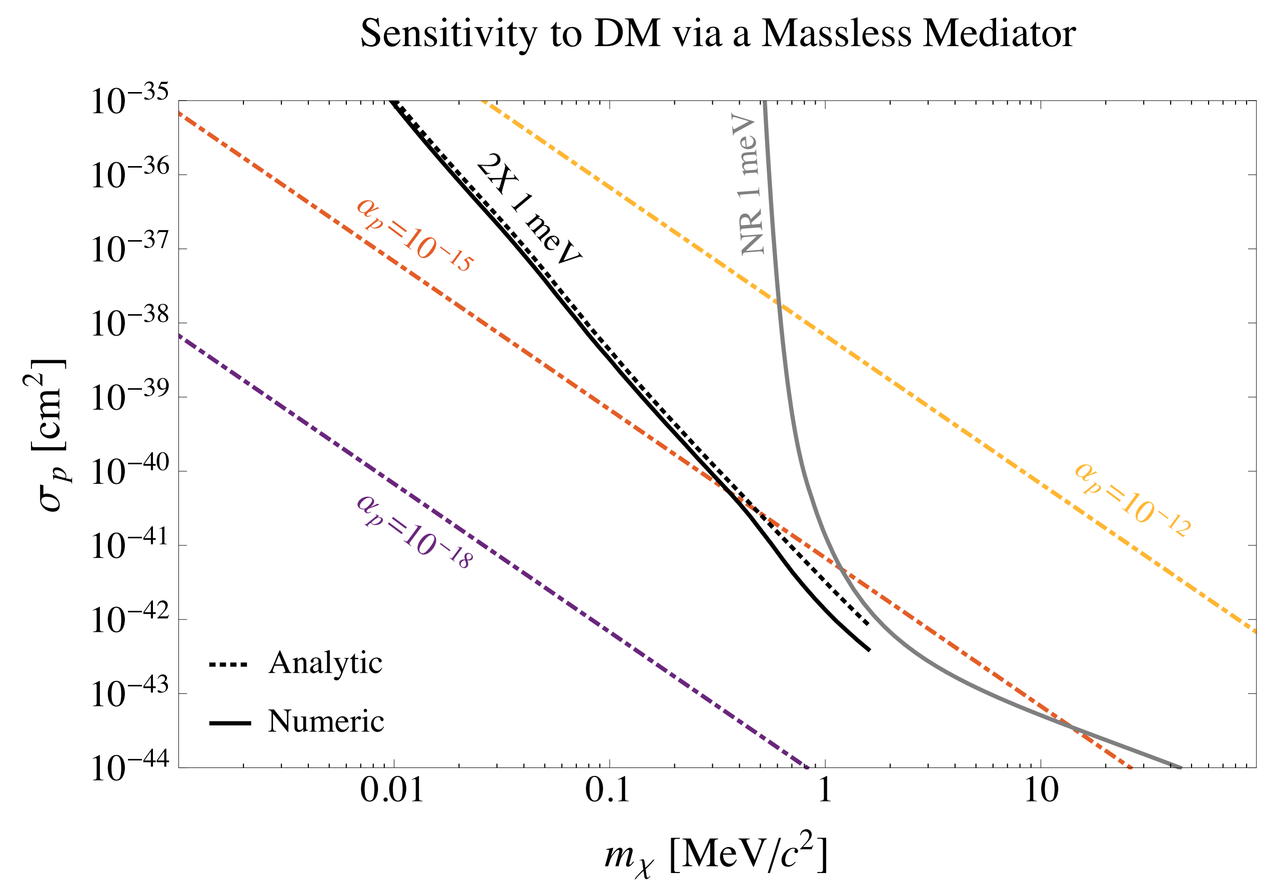
Schutz, KZ 1604.08206

- Quantize the fluid Hamiltonian, like SHO

$$H_0 = \frac{1}{2}\sum_k \left(\rho_0 v_{\vec{k}} v_{-\vec{k}} + \phi(k)\rho_{\vec{k}}\rho_{-\vec{k}}\right) \qquad m_{\rm He}^2 S(k) = \langle \rho_k \rho_{-k} \rangle$$

RESULTS

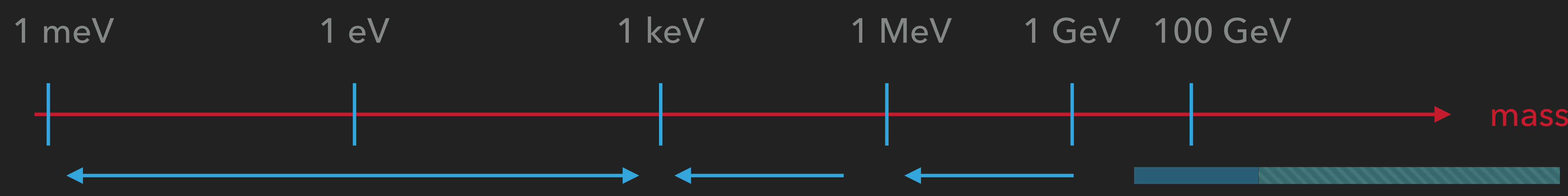




Schutz, KZ 1604.08206

Great potential!

DARK MATTER LANDSCAPE



Absorption
Coherent Mode
Production

Super-
conductors

Superfluid
Helium

Semiconductors

SuperCDMS

DAMIC, SENSEI

Graphene

Traditional WIMP

XENON1T

LZ

QCD axion, “ultralight frontier”

ADMX

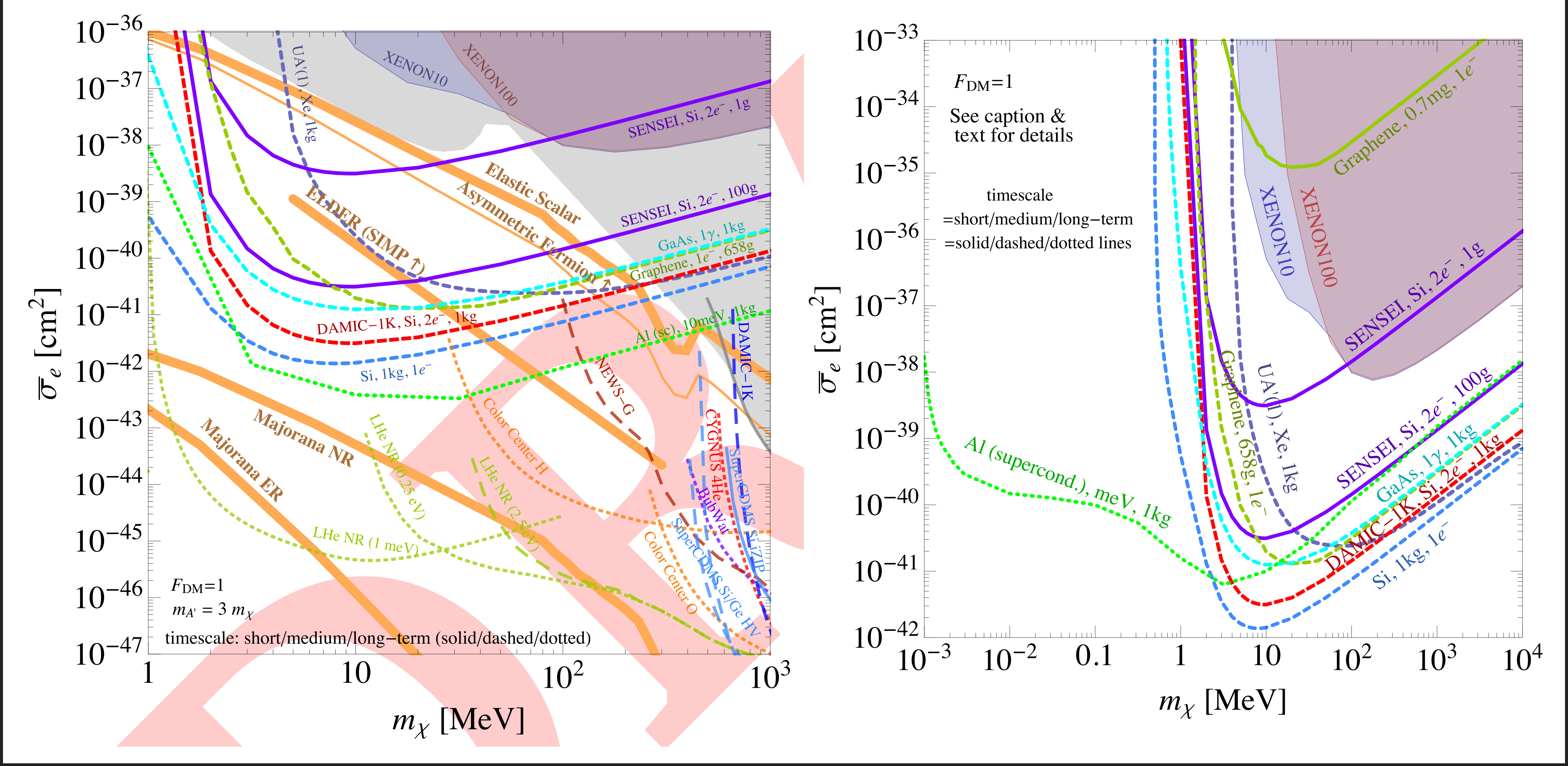
~meV energy
resolution

~eV energy
resolution

~keV energy
resolution

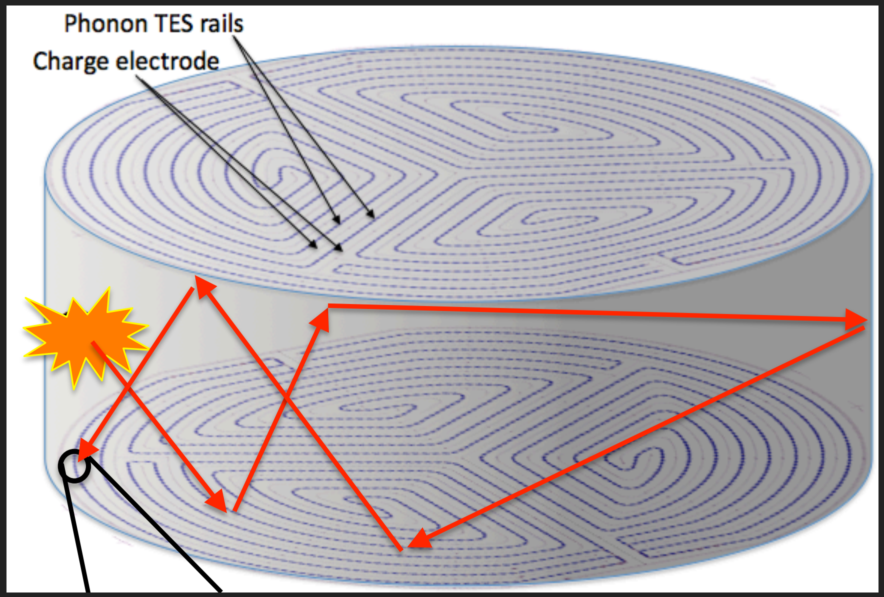
COMPLEMENTARITY

Cosmic Visions Whitepaper



ROAD FORWARD

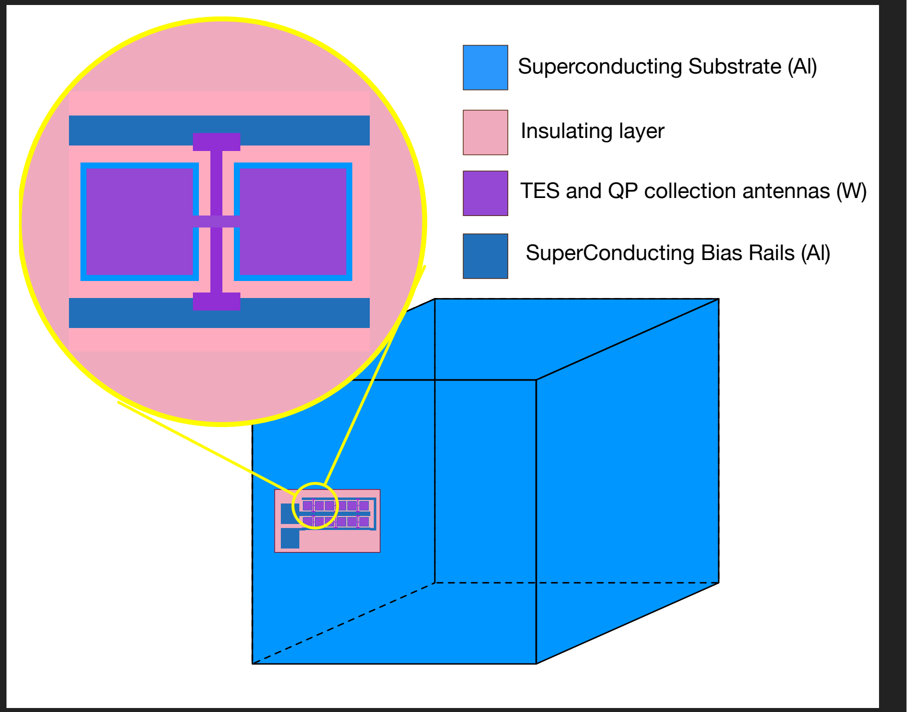
- Large part depends on better energy resolution sensors (TESs or KIDs); TESs or KIDs are portable to multiple targets



Semiconductors SuperCDMS

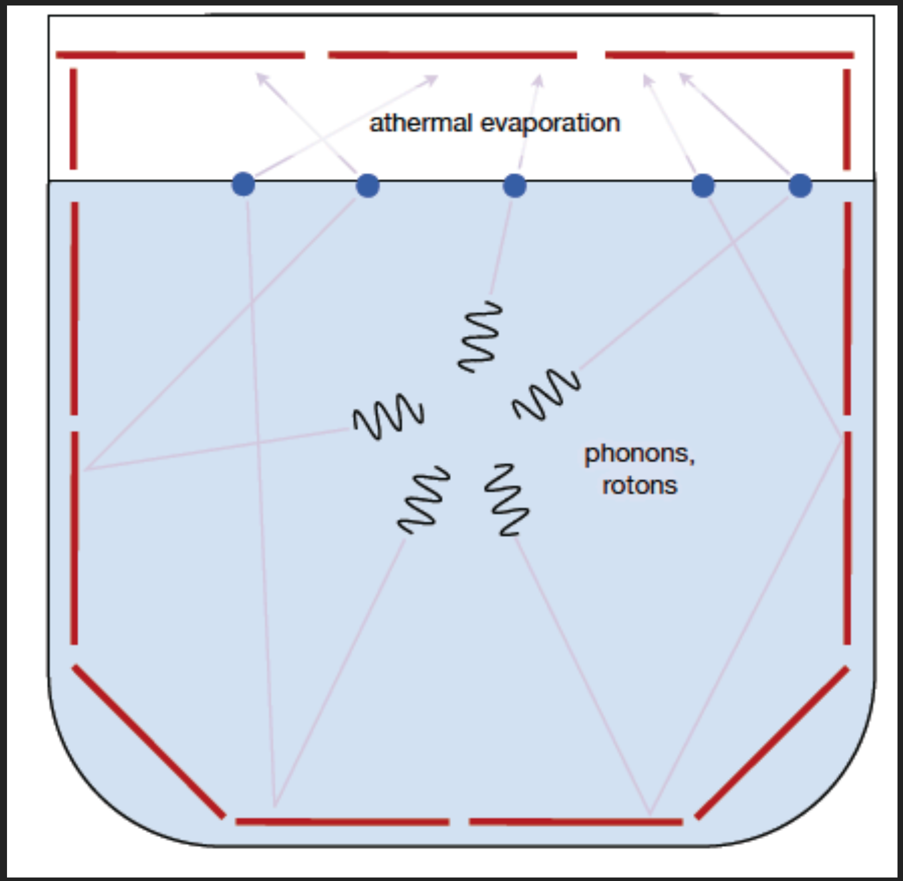
Current energy resolution: ~300 eV

Goal: ~1 eV



Superconductors

Goal: ~1 meV



Superfluid Helium

Goal: ~1 meV

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 ….. Weyl semi-metal
- Leverage progress is materials and condensed matter physics
- Realizing experimental program is 5-10+ years into future
- Nine orders of magnitude increased sensitivity in mass
- Long view necessary!