K. ZUREK

Leveraging the many faces (or, phases) of matter

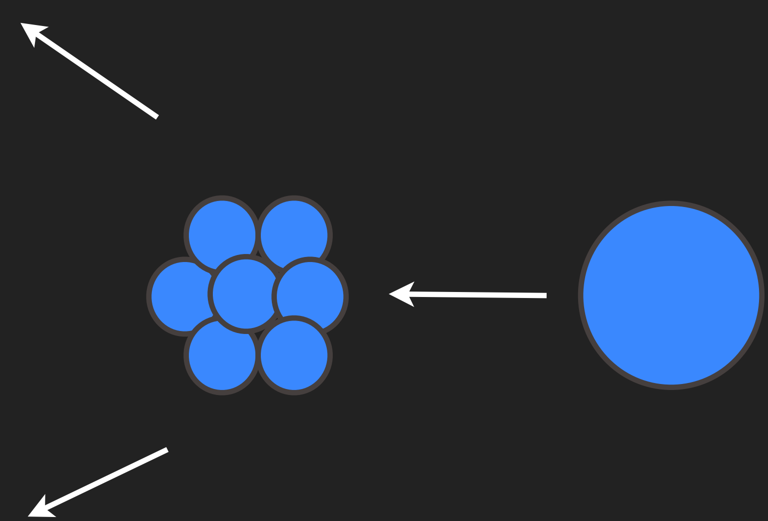
DIRECT DETECTION OF DARK MATTER

DIRECT DETECTION GOLD STANDARD

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

$$p_X^i = \begin{pmatrix} m_N \\ 0 \end{pmatrix}$$

$$p_X^f = \begin{pmatrix} \frac{{p_f^N}^2}{2m_N} + m_N \\ \vec{p}_f^N \end{pmatrix}$$



$$p_X^i = \begin{pmatrix} \frac{1}{2} m_X v^2 + m_X \\ m_X \vec{v} \end{pmatrix}$$

$$p_X^f = \begin{pmatrix} \frac{{p_f^X}^2}{2m_X} + m_X \\ \vec{p}_f^X \end{pmatrix}$$

$$E_i = E_f \qquad \vec{p}_i = \vec{p}_f$$

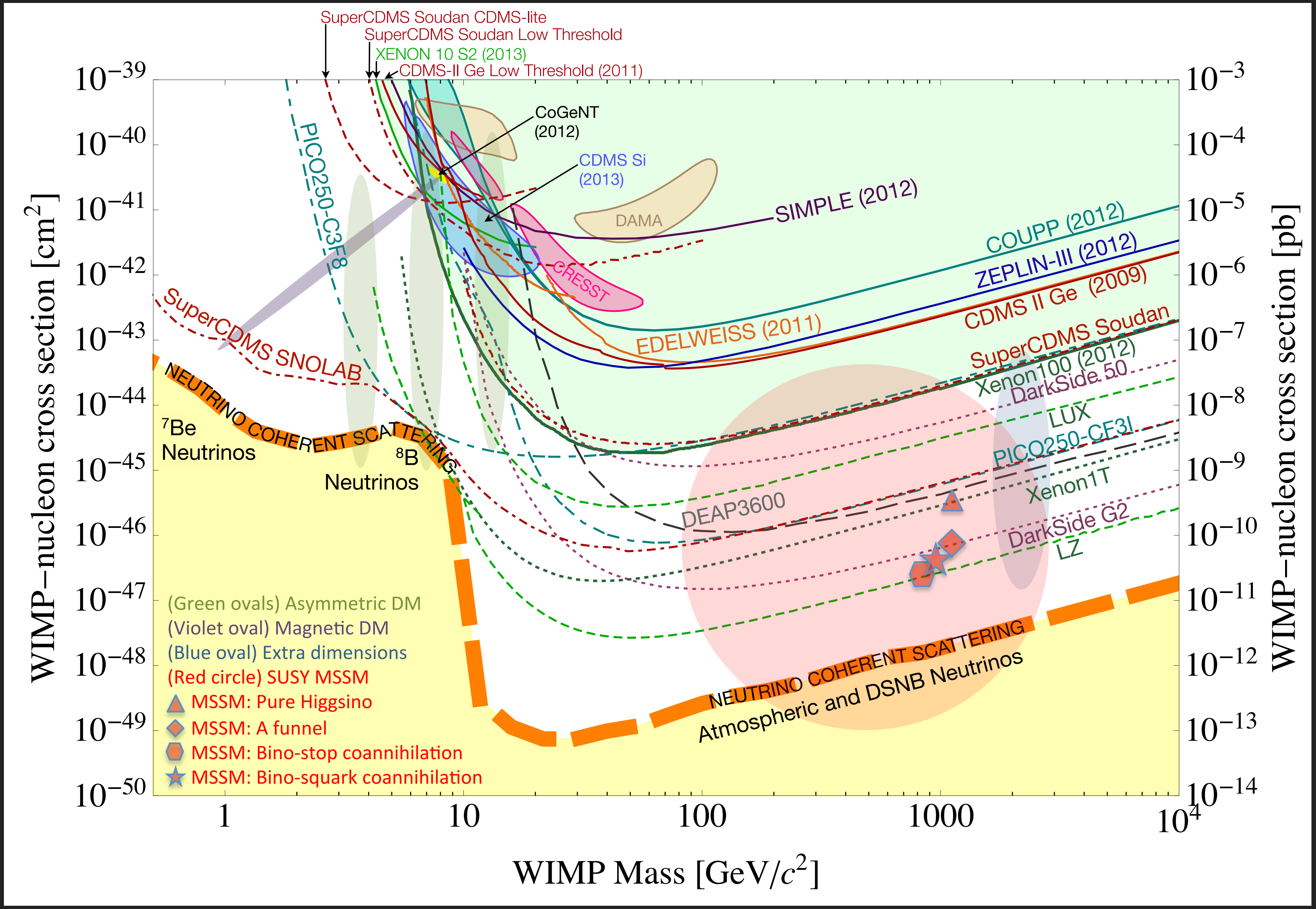
DIRECT DETECTION GOLD STANDARD

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

$$\implies 2\mu_N v = |\vec{p}_F^N| = \sqrt{2 m_N E_R} \qquad \mu_N \equiv \frac{m_N m_X}{m_X + m_N}$$

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

DIRECT DETECTION GOLD STANDARD



NUCLEAR RECOILS

- Kinematic penalty when DM mass drops below nucleus mass

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

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

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

NEXT UP: ELECTRON

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

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

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

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

ELECTRONS IN MATERIALS

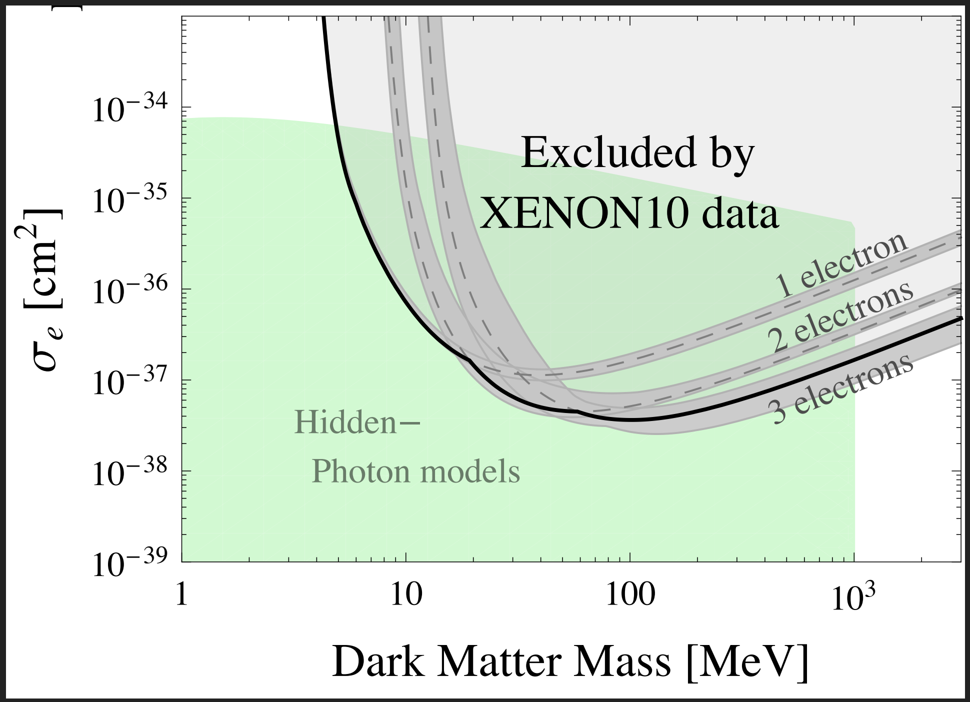
- In insulators, like xenon

Tightly bound; ionize for signal

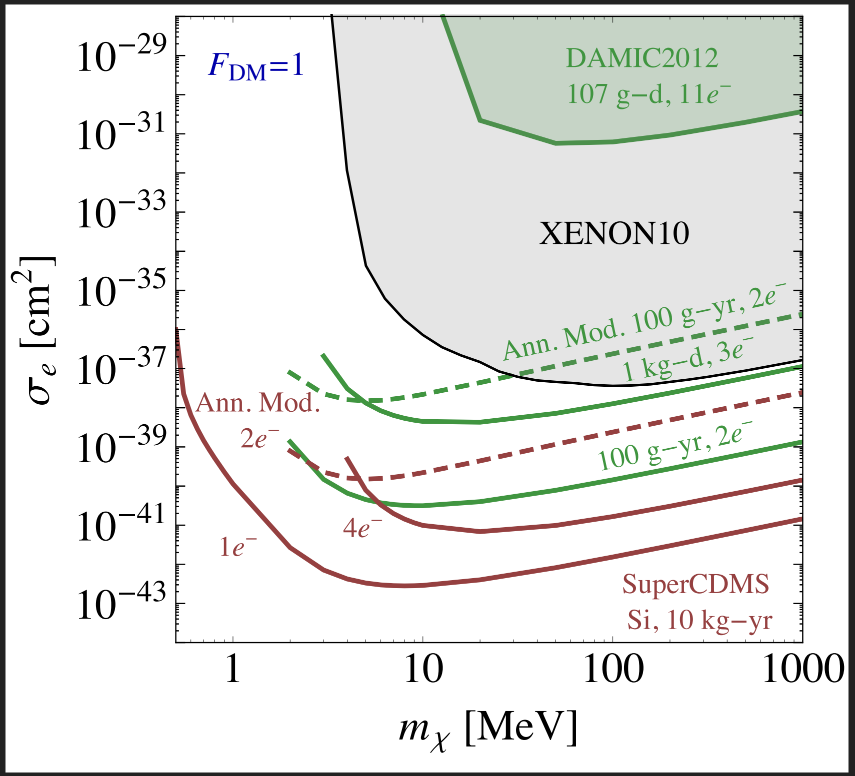
- In semi-conductors, like Ge, Si

Valence electrons become conducting; presence of collective modes

P. Sorensen et al 1206.2644



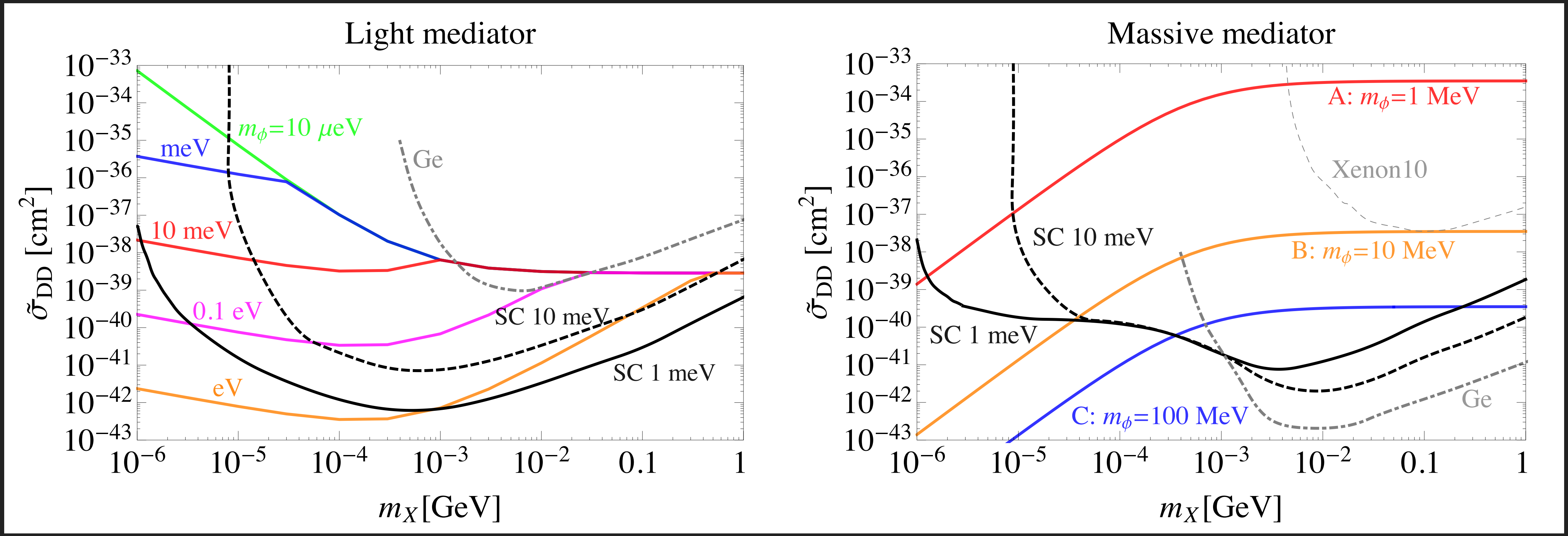
Essig et al 1509.01598



COOPER PAIRS

- Smaller gap
  - = more sensitivity to environmental noise
  - = more sensitivity to light dark matter

RATES AND CONSTRAINTS



Satisfy all astrophysical, cosmological, terrestrial constraints

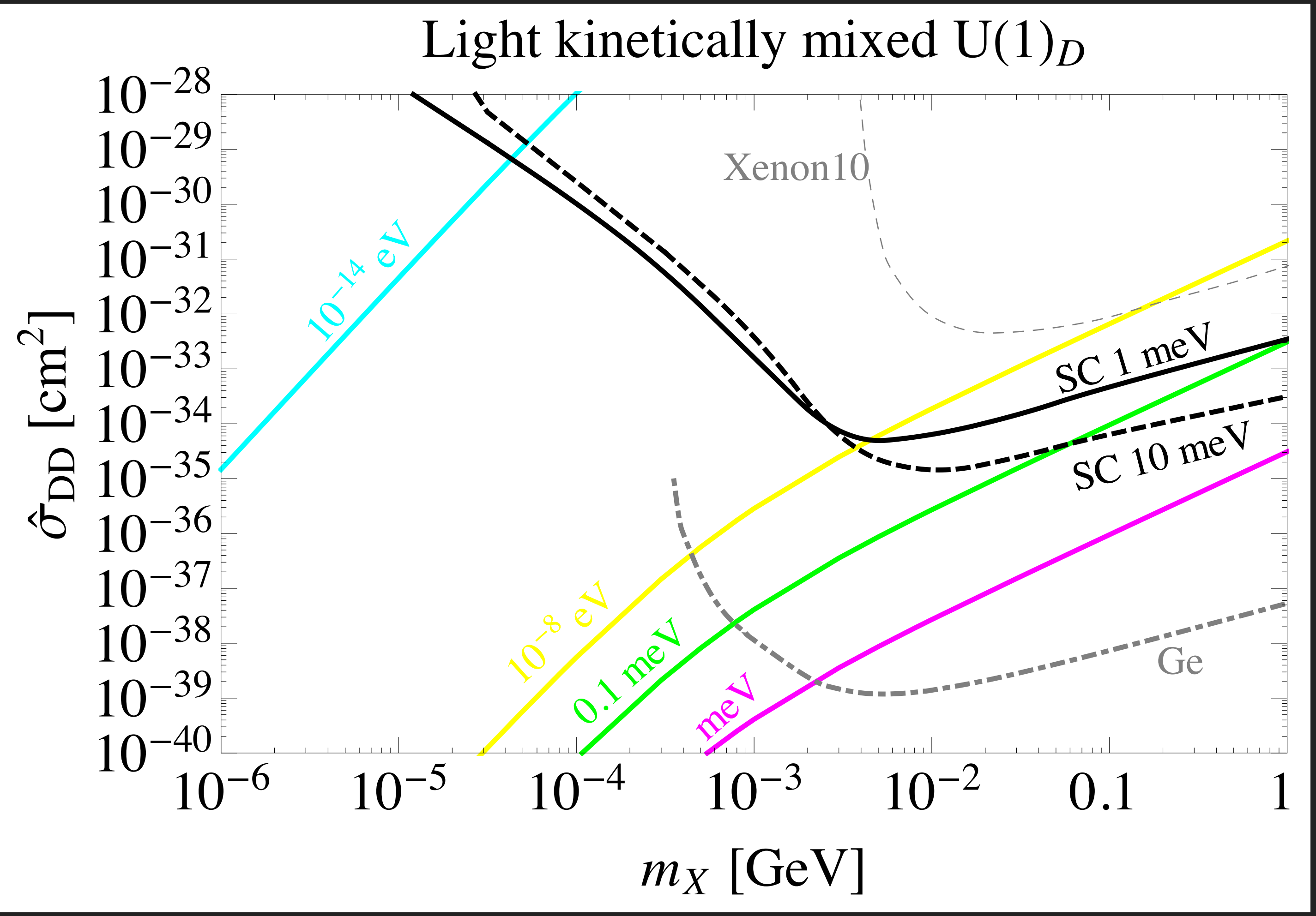
Medium effects on mediator not applied

Scalar DM + Scalar Mediators

OR

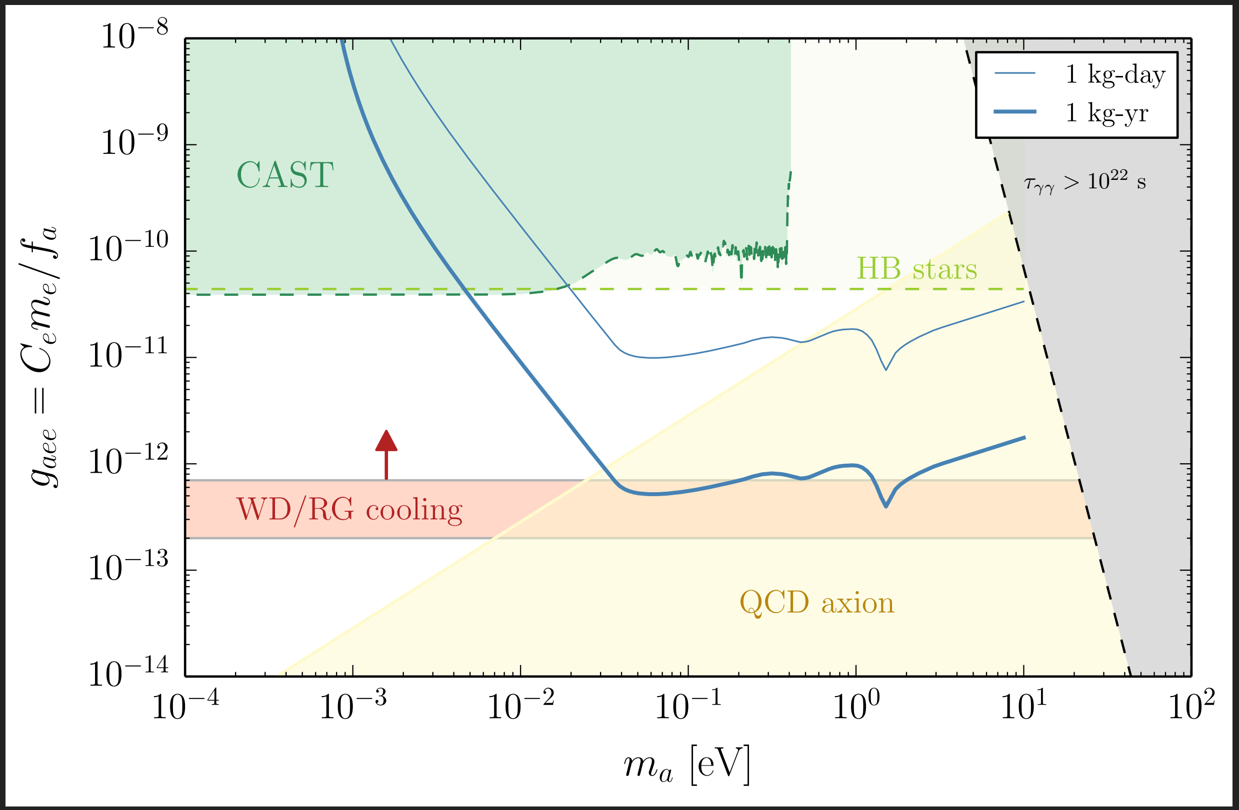
Lift BBN constraints

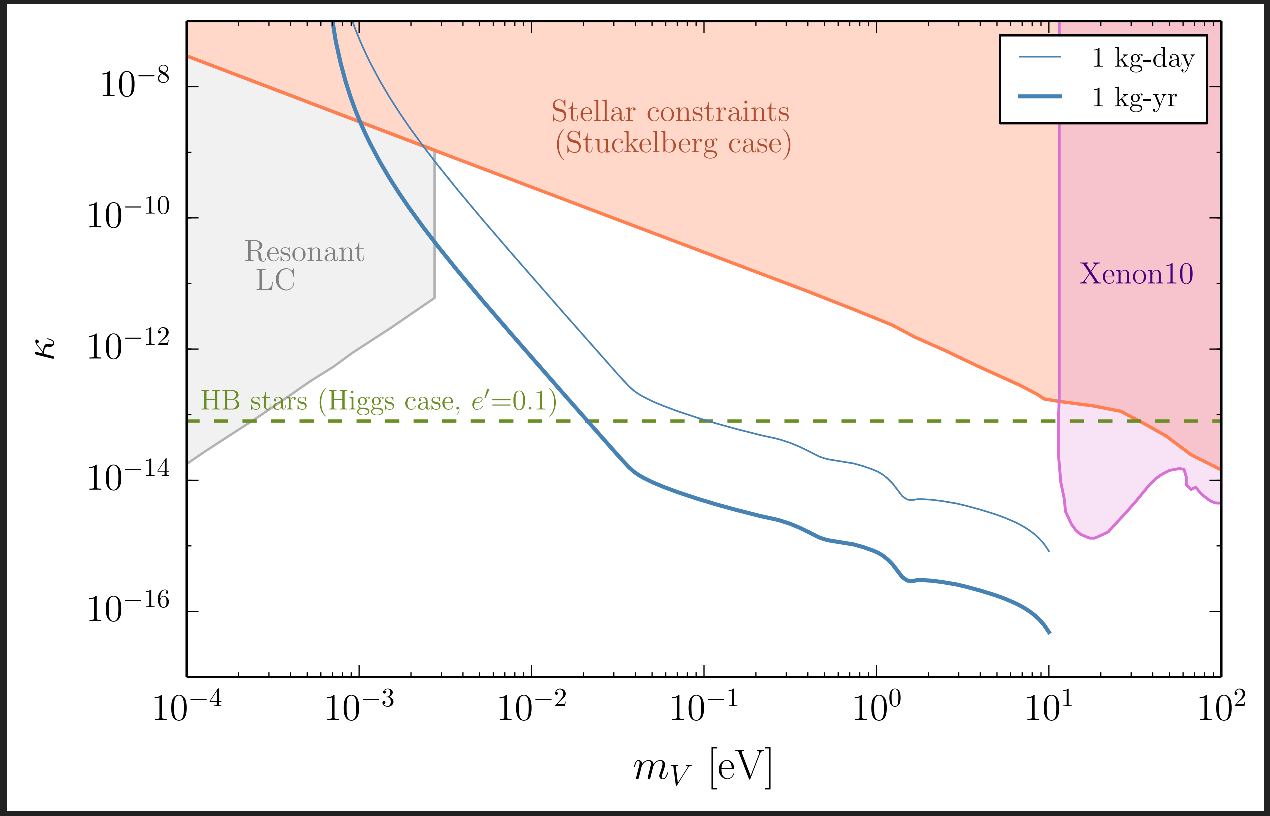
NEW REACH



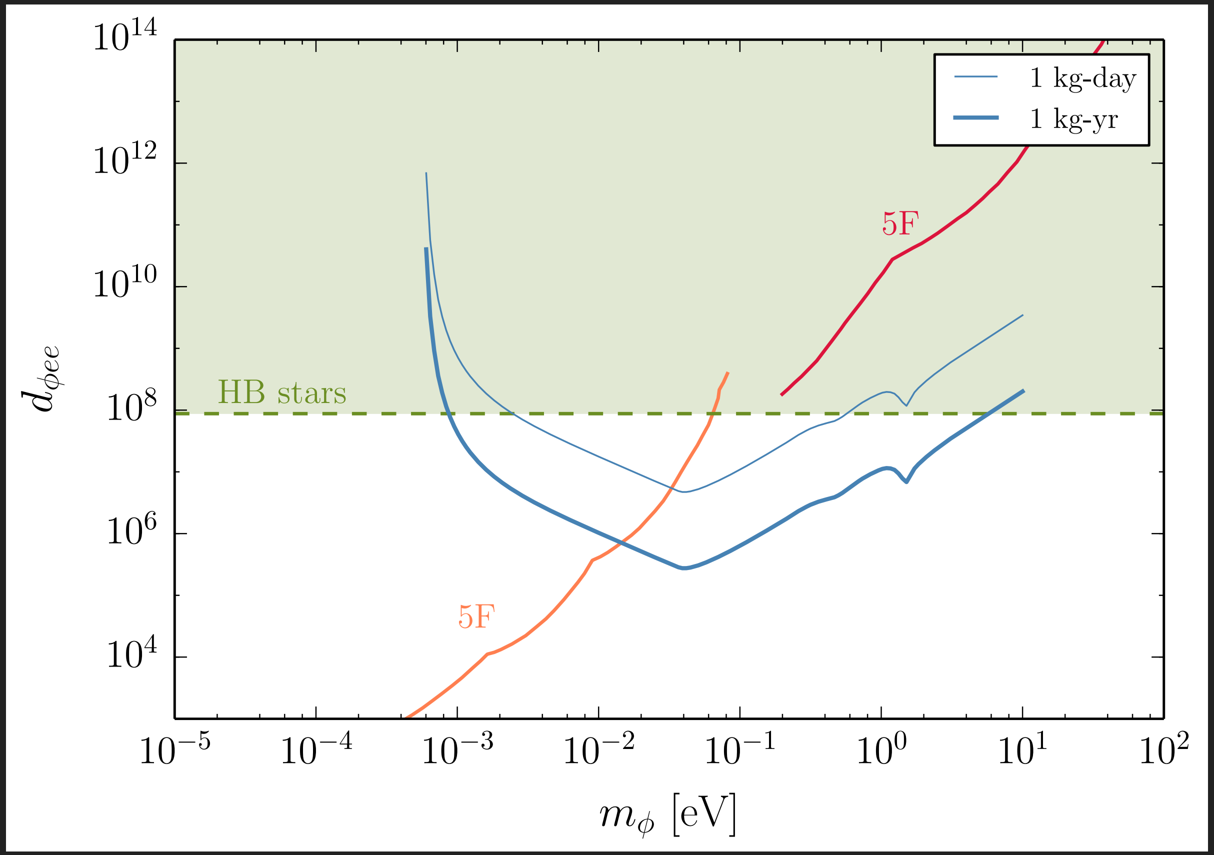
- Stay tuned for helium!

ABSORPTION





Still paying for metals being shiny

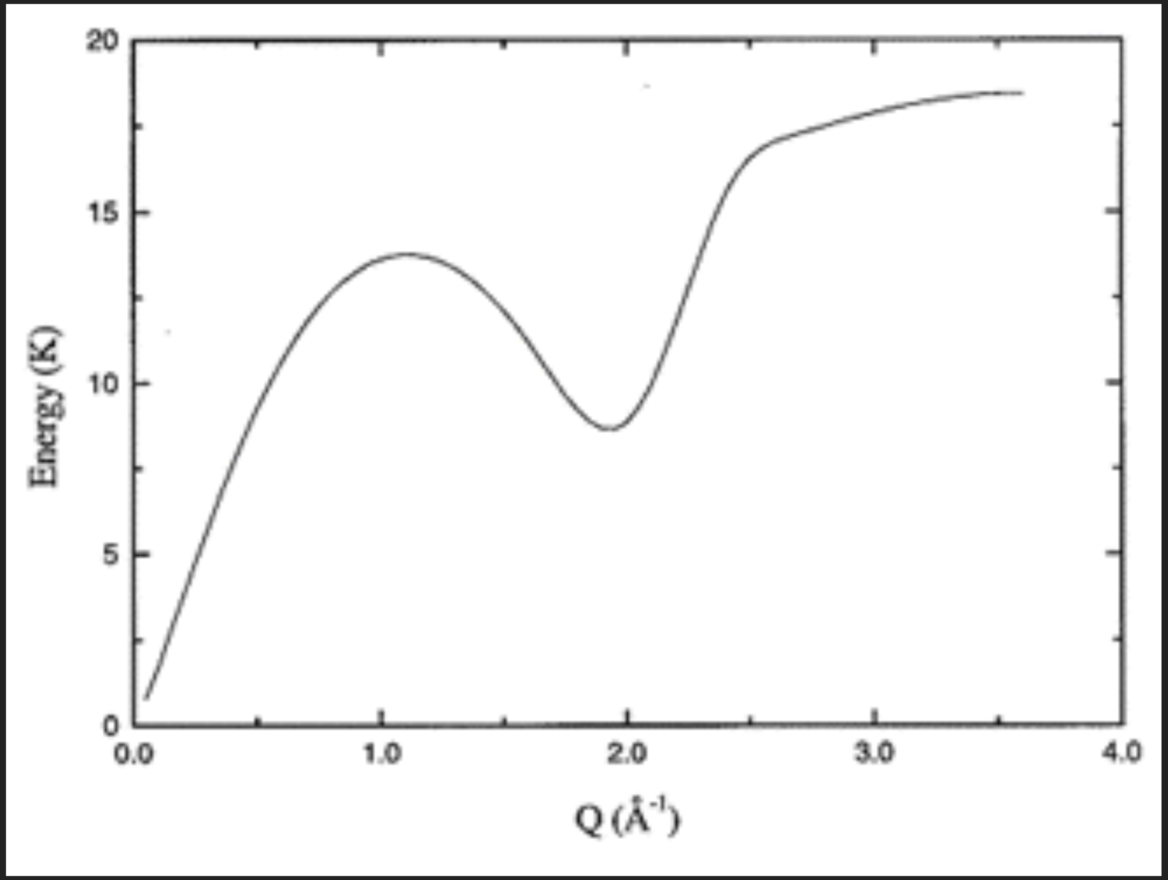


AN INSULATING SUPERFLUID

- Helium!
- Nuclear recoils, no.
- MeV DM deposits at most meV of energy
- However, displays collective behavior below 2.2K

$$E_D = \frac{q^2}{2m_T}$$

$$q_{\max} = 2m_X v$$



AN INSULATING SUPERFLUID

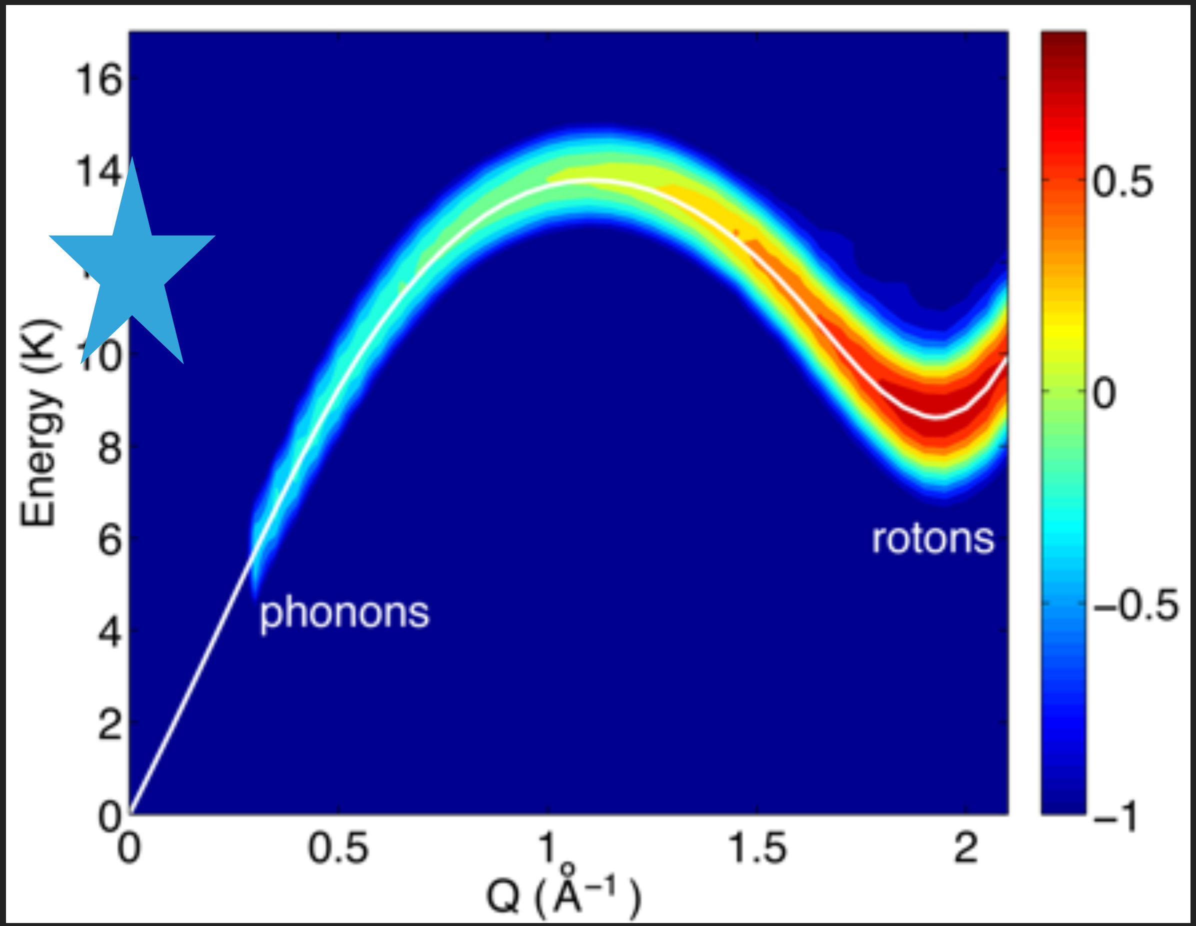
- Does this help us with DM detection?
- At first glance no -- collective modes simply have too low a speed of sound

$$E_D \sim v_X q$$

vs

$$E_D \sim c_s q$$

$$c_s \ll v_X$$

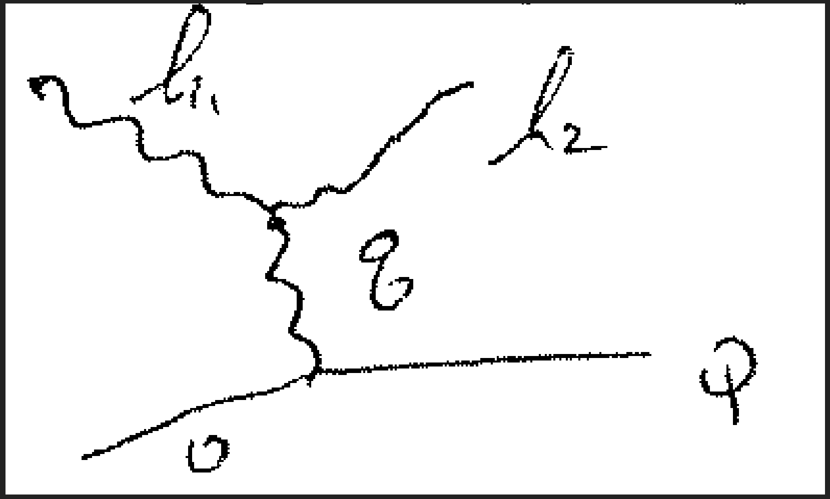


- Next glance -- yes!

ROTONS/PHONONS

- Calculated and observed for ultra-cold neutrons

$$\rho(\vec{r}) = \frac{\rho_0'}{m_{He}} + \frac{1}{m_{He}}\sqrt{\frac{\rho_0' \hbar}{2cV}} \sum_k \sqrt{k}\left(a_k e^{i\vec{k}\cdot\vec{r}} + a_k^\dagger e^{-i\vec{k}\cdot\vec{r}}\right) \quad (12)$$

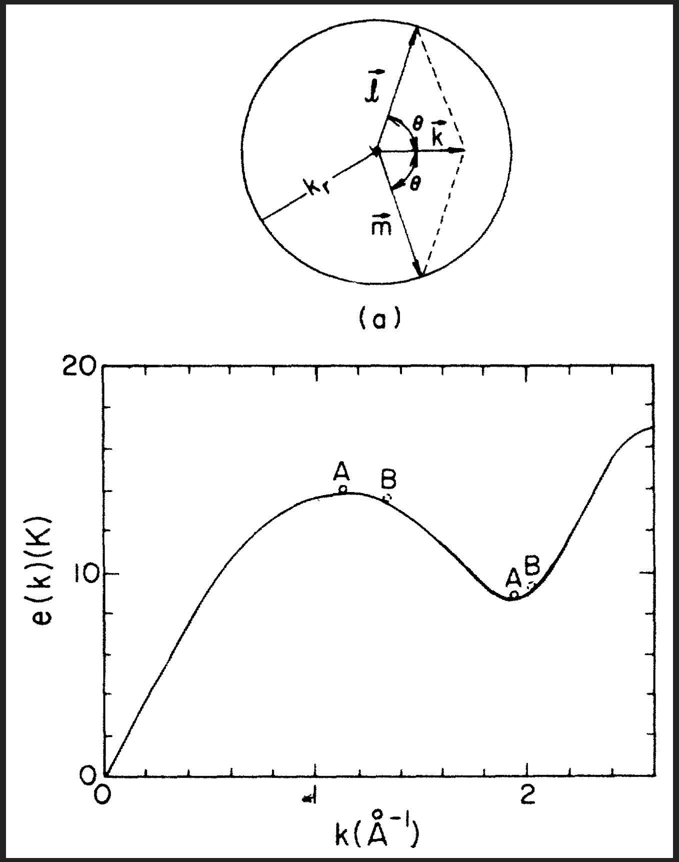


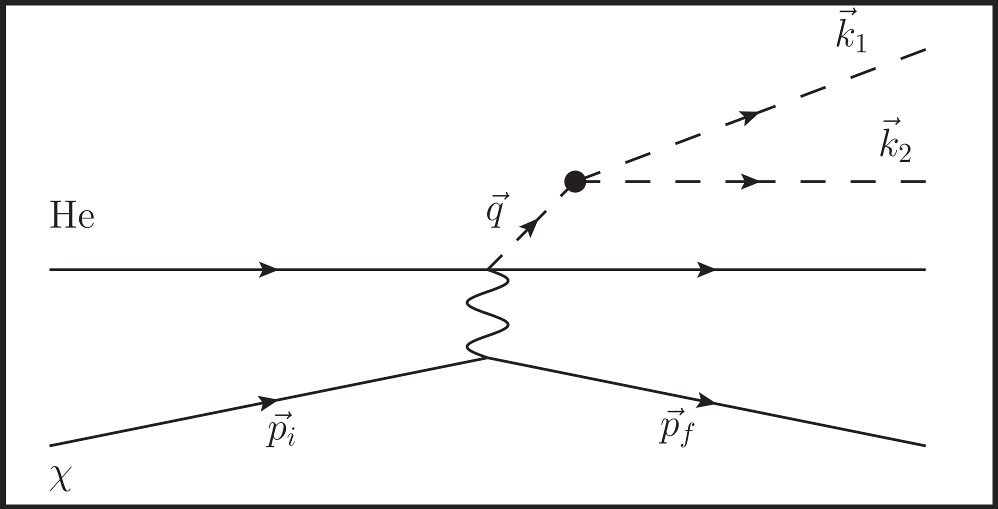
Internal note, R. Golub, 1977

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

MULTI-EXCITATIONS

- Free helium atom in the final state mediated by off-shell phonon
- momentum-energy balance equations modified





Manousakis and Pandharipande

HOW TO CALCULATE?

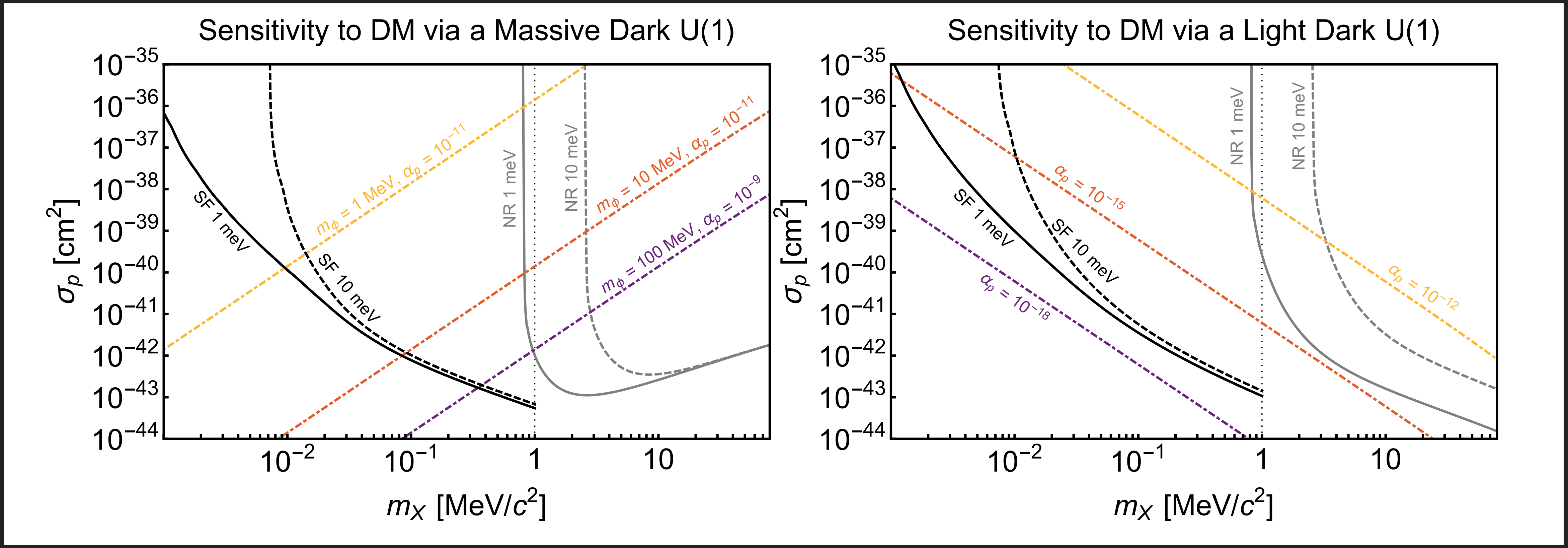
- Theory developed by Landau-Khalatnikov and Feynman-Cohen
- Quantize the fluid Hamiltonian, like SHO

$$H_0 = \frac{1}{2}\sum_k \left(\rho_0 v_{\vec{k}} v_{-\vec{k}} + \phi(k)\rho_{\vec{k}}\rho_{-\vec{k}}\right)$$

$$\rho_{\vec{k}} = m_{\text{He}}\sqrt{S(k)}(a_{\vec{k}} - a^\dagger_{-\vec{k}}) \qquad \omega_k = \rho_0 k^2 \phi(k)$$

$$\vec{v}_{\vec{k}} = -\frac{\vec{k}}{2m_{\text{He}}\sqrt{S(k)}}(a_{\vec{k}} + a^\dagger_{-\vec{k}}) \qquad m_{\text{He}}^2 S(k) = \langle \rho_k \rho_{-k} \rangle$$

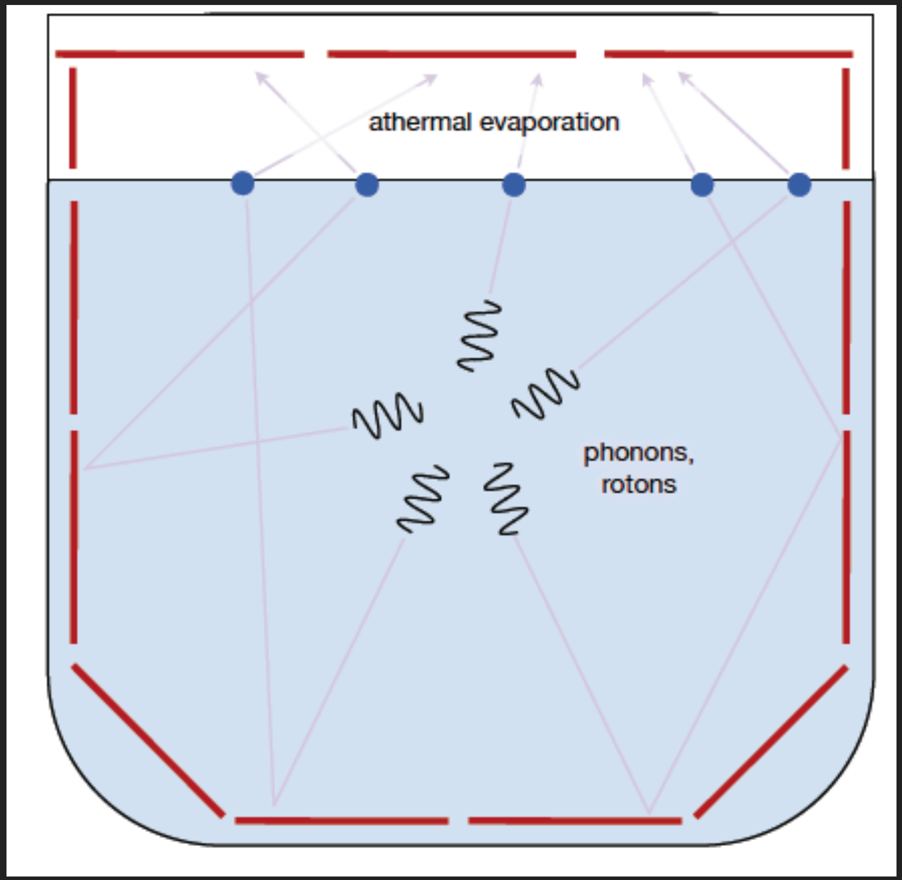
RESULTS

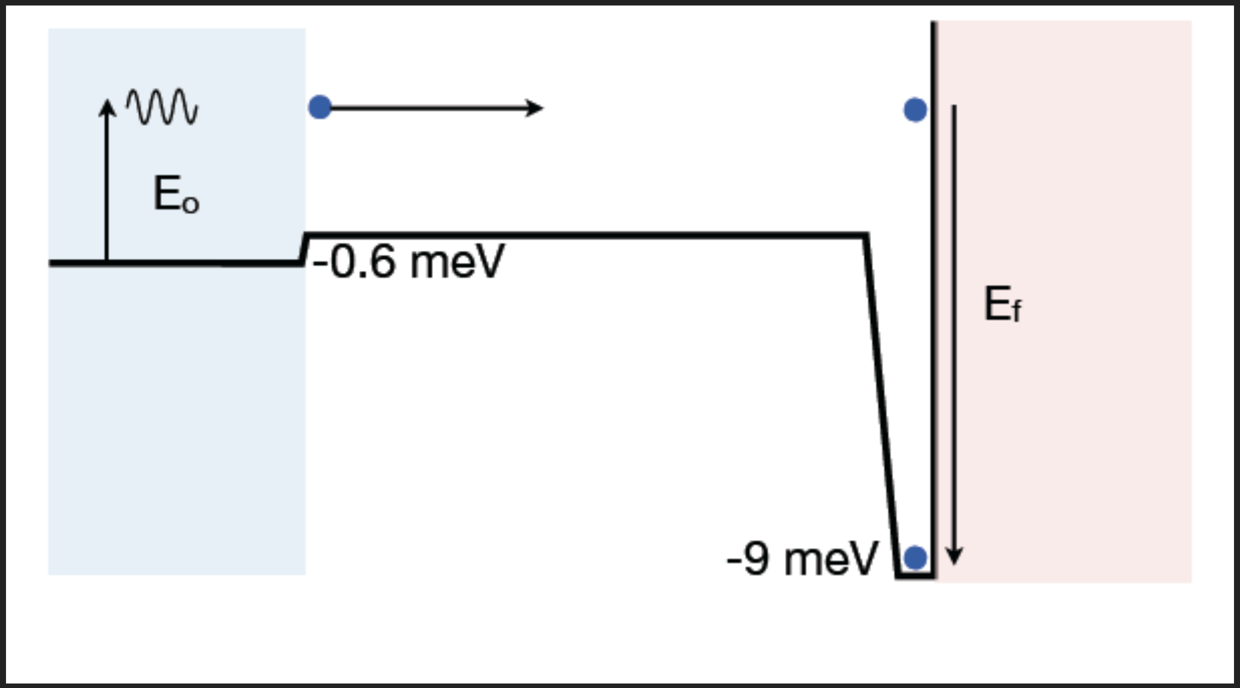


Great potential!

REALIZED IN EXPERIMENT

- Helium experiment under development in McKinsey group; modify to multi-excitation detector





Hertel, McKinsey

ROAD FORWARD