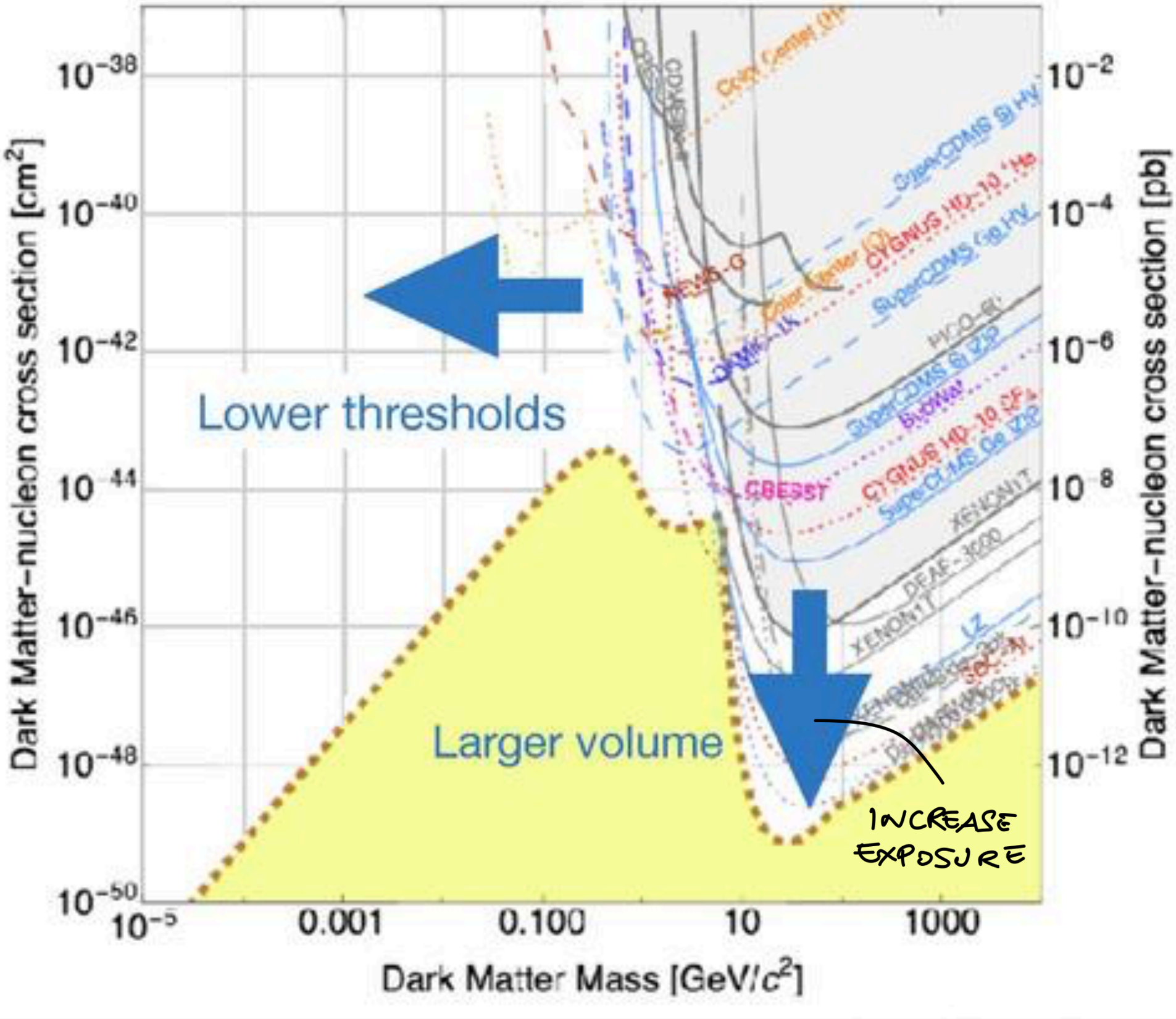
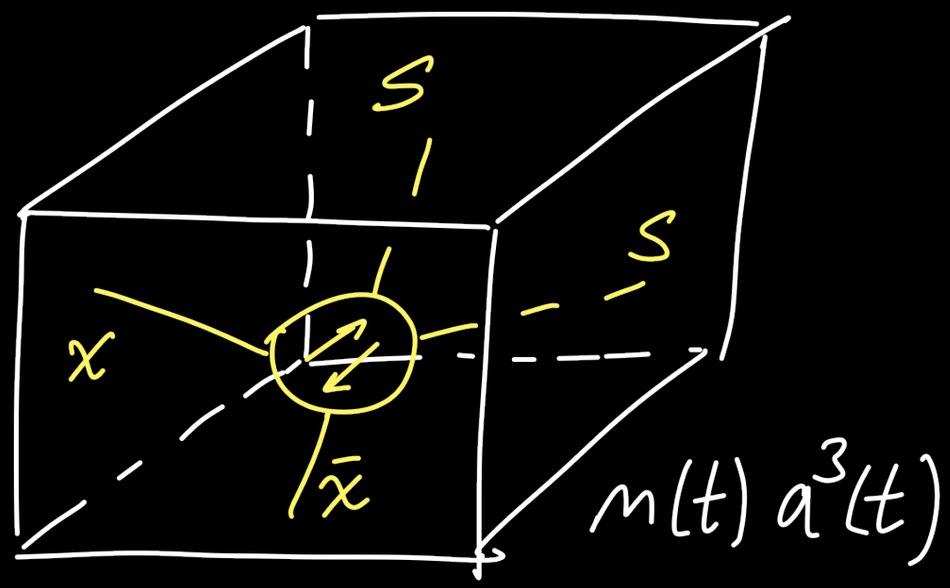
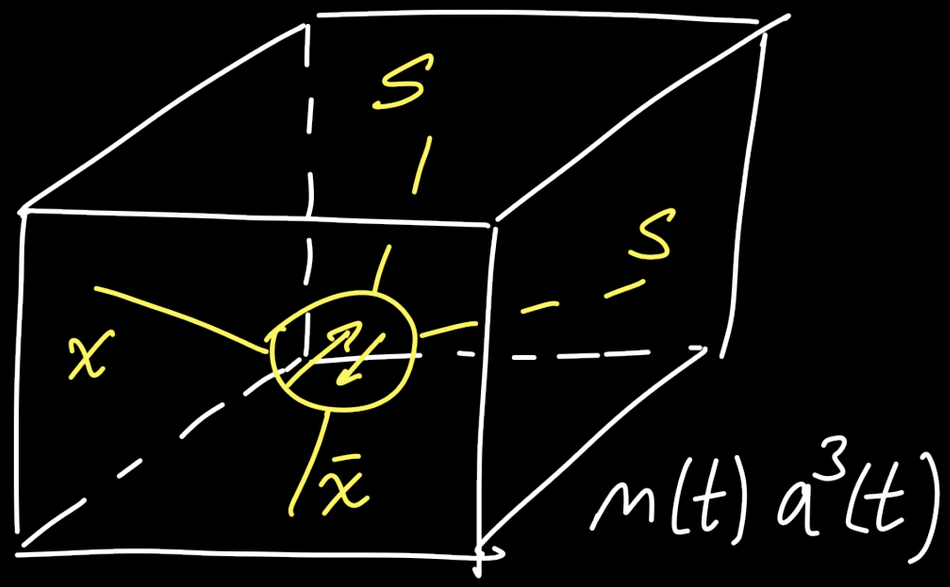
Light Dark Matter

AD Polosa

Cosmic visions report 2017: 1707.04591




S
S
x
z
x̄
m(t) a³(t)



$$\frac{d}{dt} n(t) a^3(t) = -\Big[n a^3 \cdot n \langle \sigma v \rangle_T - n_{EQ} a^3 \cdot n \langle \sigma v \rangle_T \Big]$$

$$\begin{cases} n(t_1) a(t_1) \neq 0 \\ \text{with } t_1 \to \infty \end{cases}$$

$$\rho_\chi(\text{today}) \cong 2 m_\chi \cdot 6 B^{-0.95} (k_B T_0)^3$$

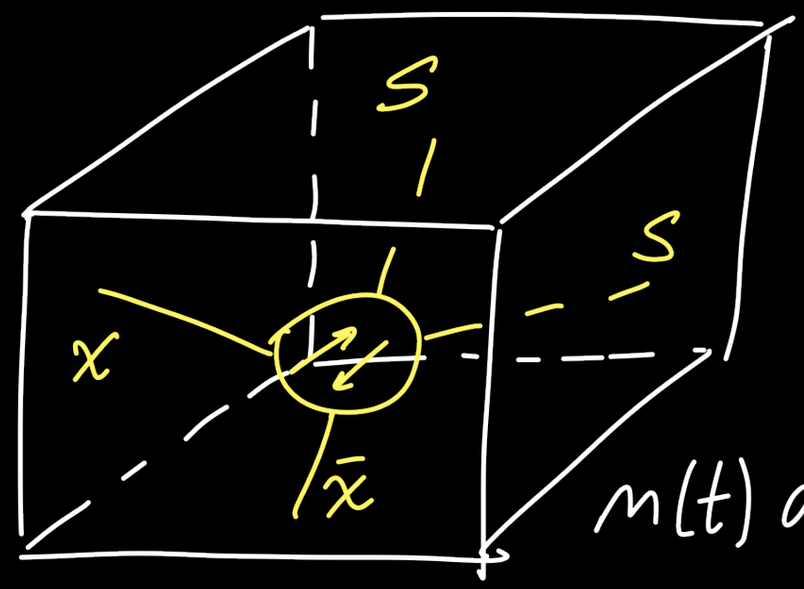
$$B = \sqrt{\frac{45}{4\pi^3 G_N N}} \langle \sigma v \rangle m_\chi$$

$$\Omega_\chi = \frac{8\pi G_N}{3 H_0^2} \rho_\chi \simeq \Omega_M$$

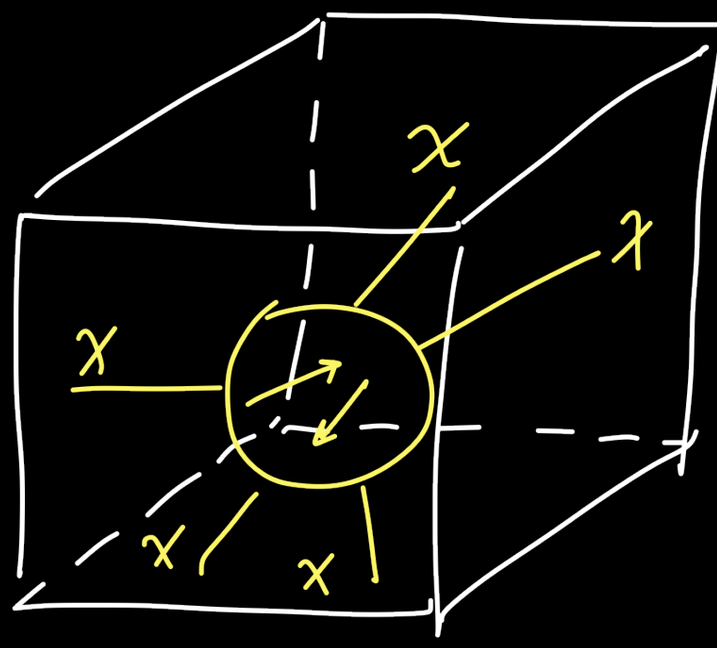
$$\langle \sigma v \rangle_T \simeq G_F^2 m_\chi^2 \frac{\mathcal{F}}{2\pi} \quad (\underline{\underline{\text{WIMP}}})$$

$$m_\chi \simeq 3.7 \left(\frac{\sqrt{N}}{\mathcal{F}}\right)^{1/2} (\Omega_m h^2)^{-1/2} \text{ GeV}$$

$m_\chi \simeq 10$ GeV with $\mathcal{F} = 1$



$m(t)\, a^3(t)$



SIMPs

Dark pions.

$$100 < m_\pi < 300\ \text{MeV}$$

[Murayama & al.]

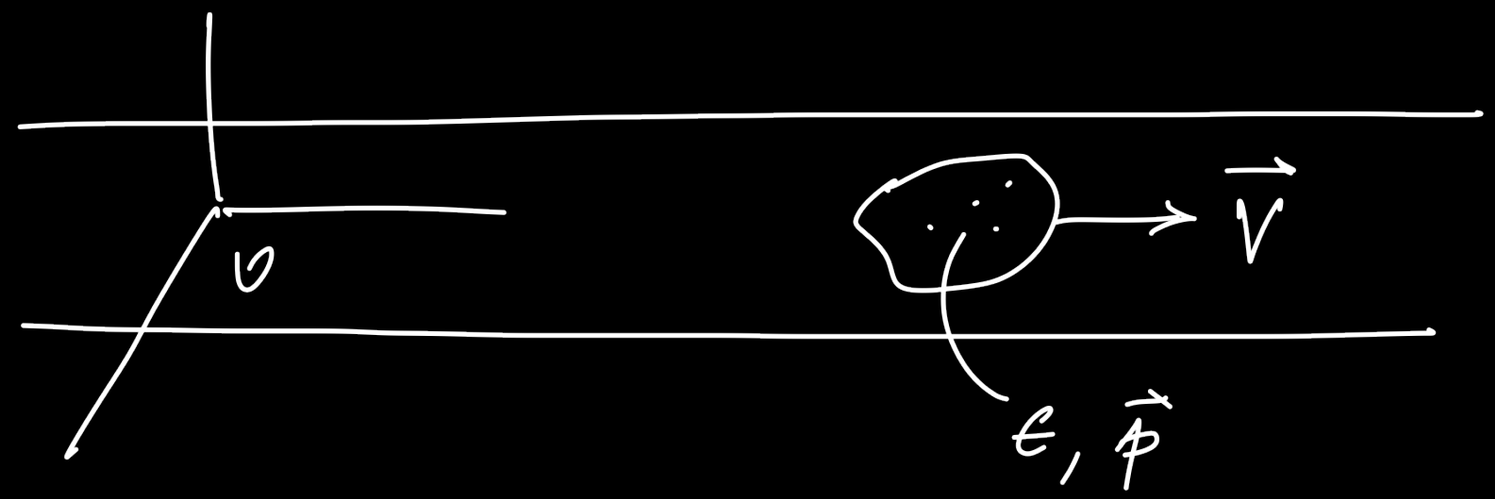
WIMPS : look for nuclear recoils

SIMPS : look for e^- recoils

CRYSTALS, GAS, LIQUIDS, SEMICONDUCTORS

SUPERCONDUCTORS ...

SUPERFLUIDS !



wrt O : $\Delta E = \epsilon + \vec{p} \cdot \vec{v}$

$\Delta E \overset{!}{<} 0$

$\epsilon - p \cdot v < 0$

$v > \frac{\epsilon}{p}$

If $v < \frac{\epsilon}{p}$ no excitations get produced

$$\boxed{v < \frac{\epsilon}{p}}$$

let

$$\epsilon = \frac{p^2}{2m^*}$$

$$V > \frac{\epsilon}{p} \Rightarrow V > \frac{p}{2m^*} > 0$$

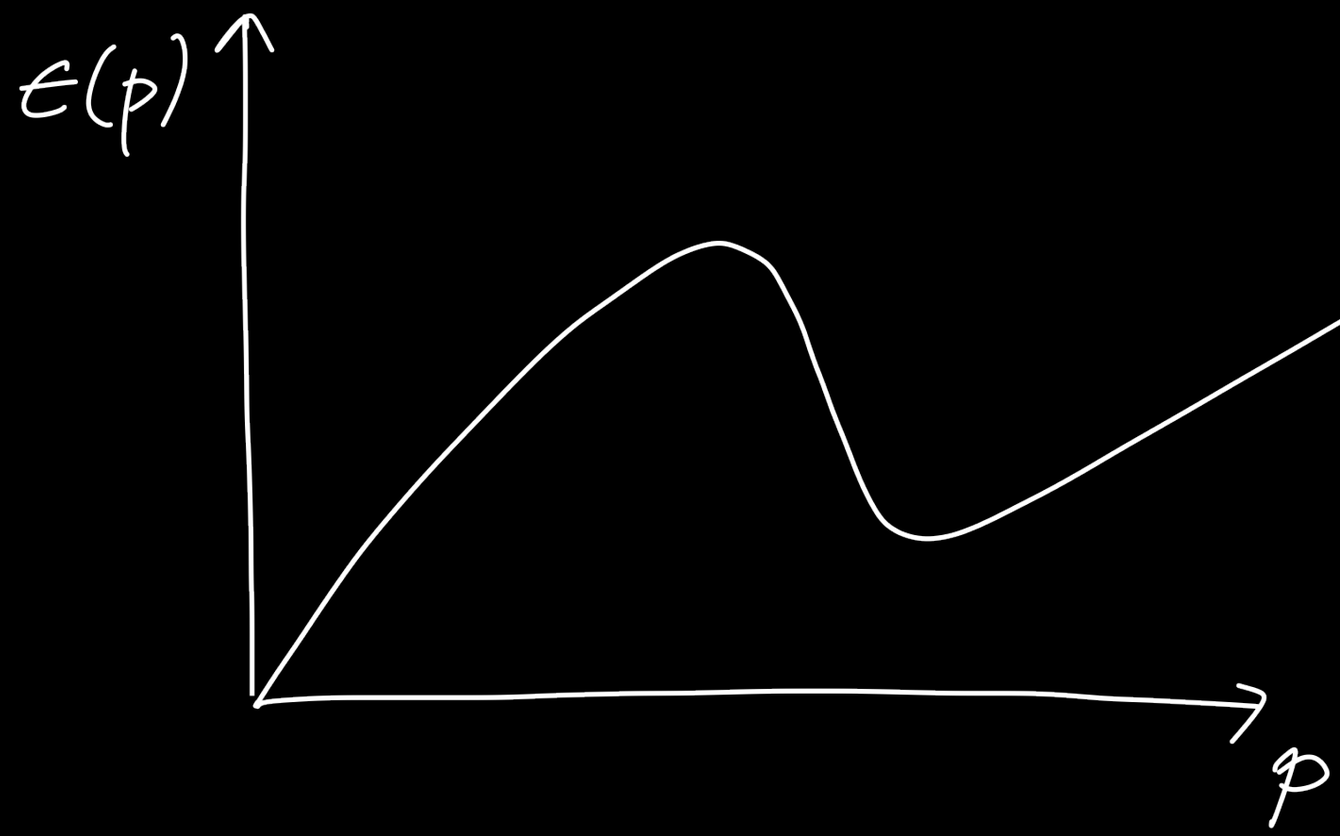
Superfluidity does not exist.

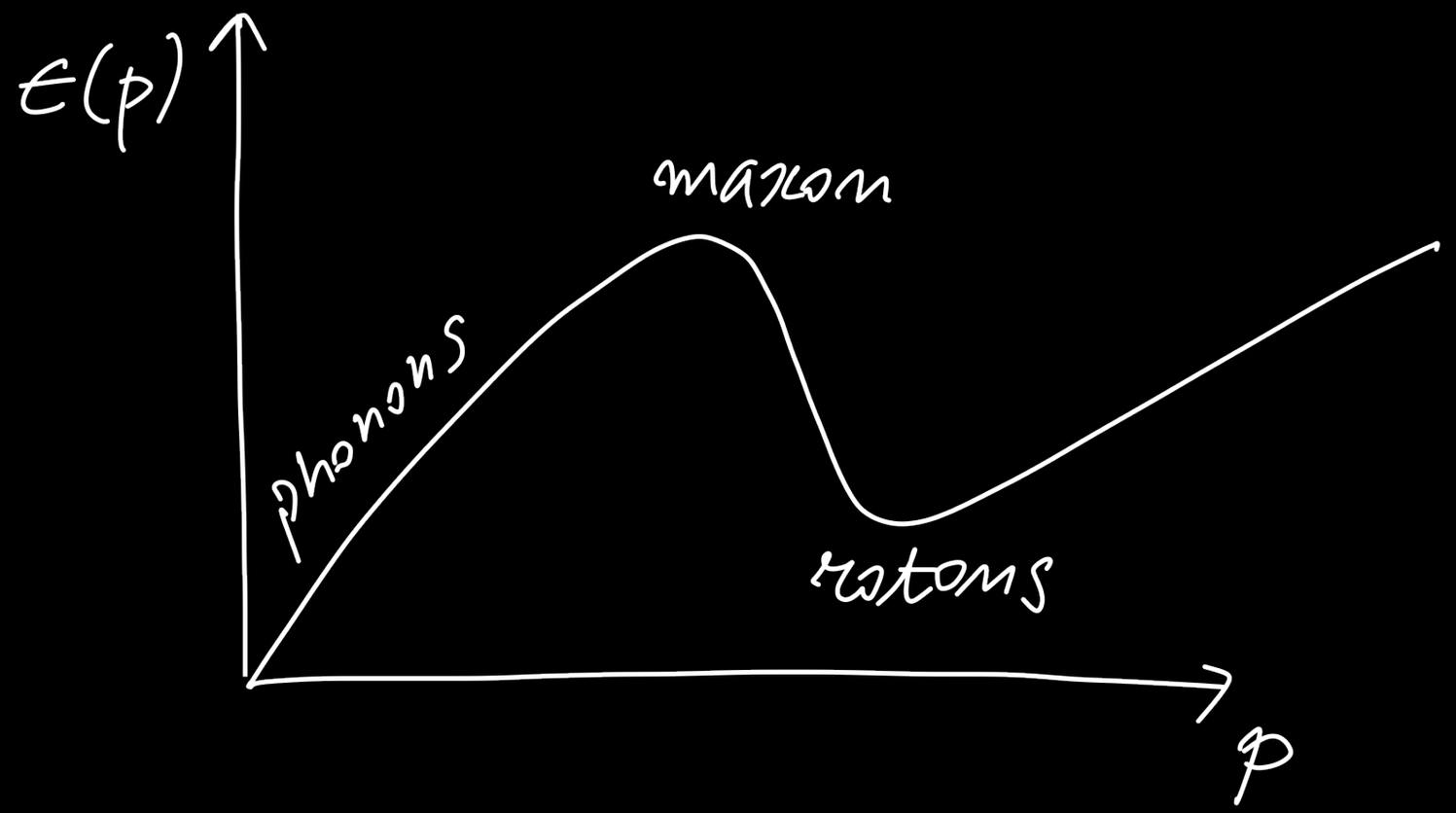
let

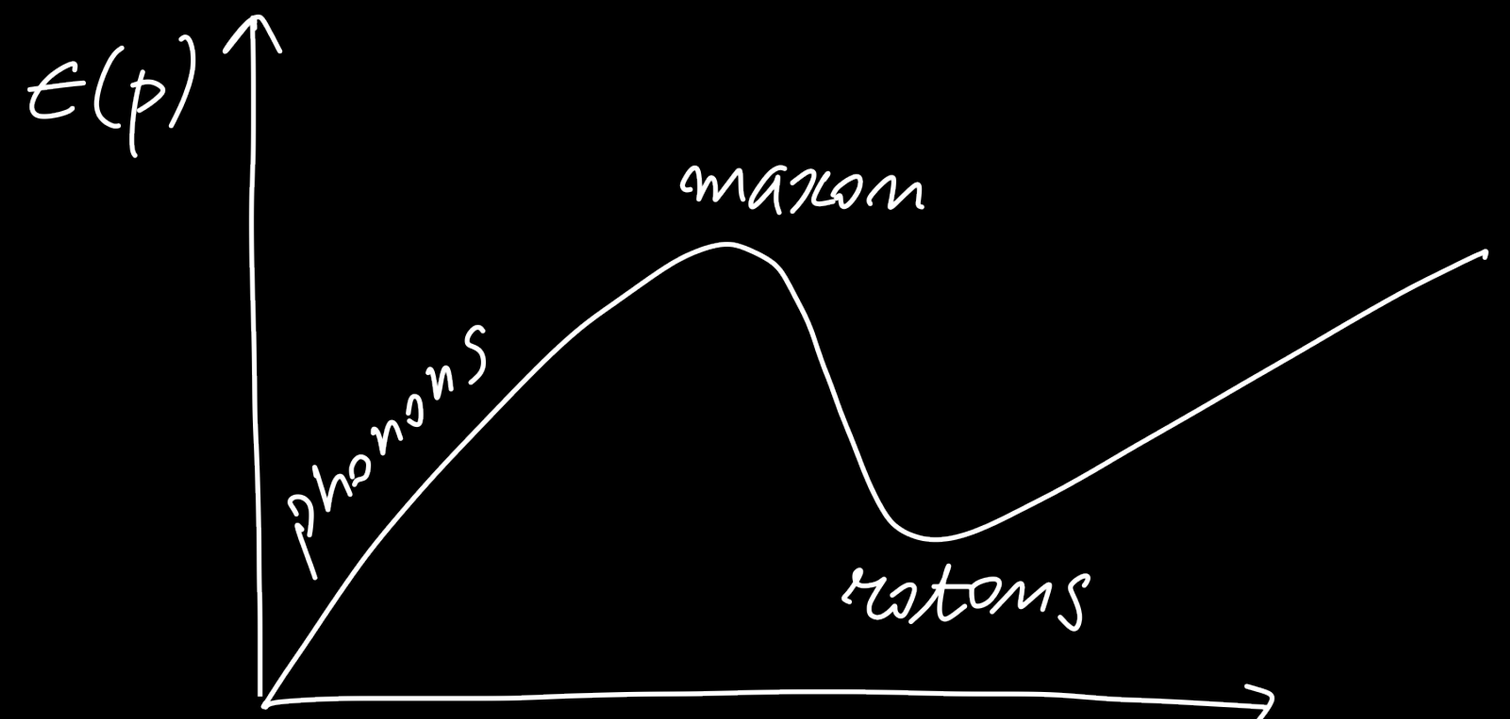
$$\epsilon = c_s p$$

We have superfluidity for

$$\epsilon < c_s$$


$\epsilon(p)$
p


$\epsilon(p)$
maxon
phonons
rotons
p

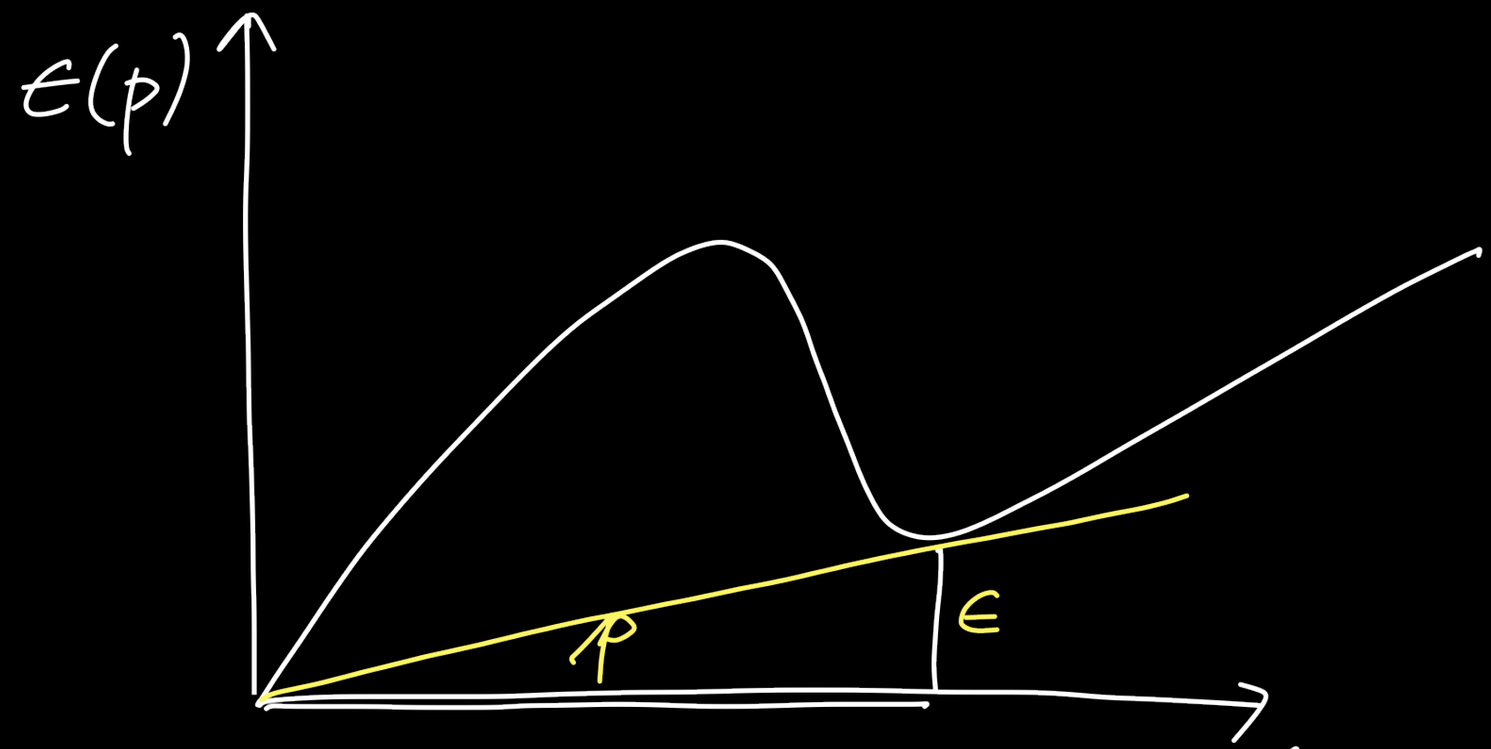


$$\epsilon(p) \simeq \Delta + \frac{1}{2m^*}(p - p_0)^2$$

$$\Delta \simeq 0.8\,meV$$

$$p_0 \simeq 3.94\,keV$$

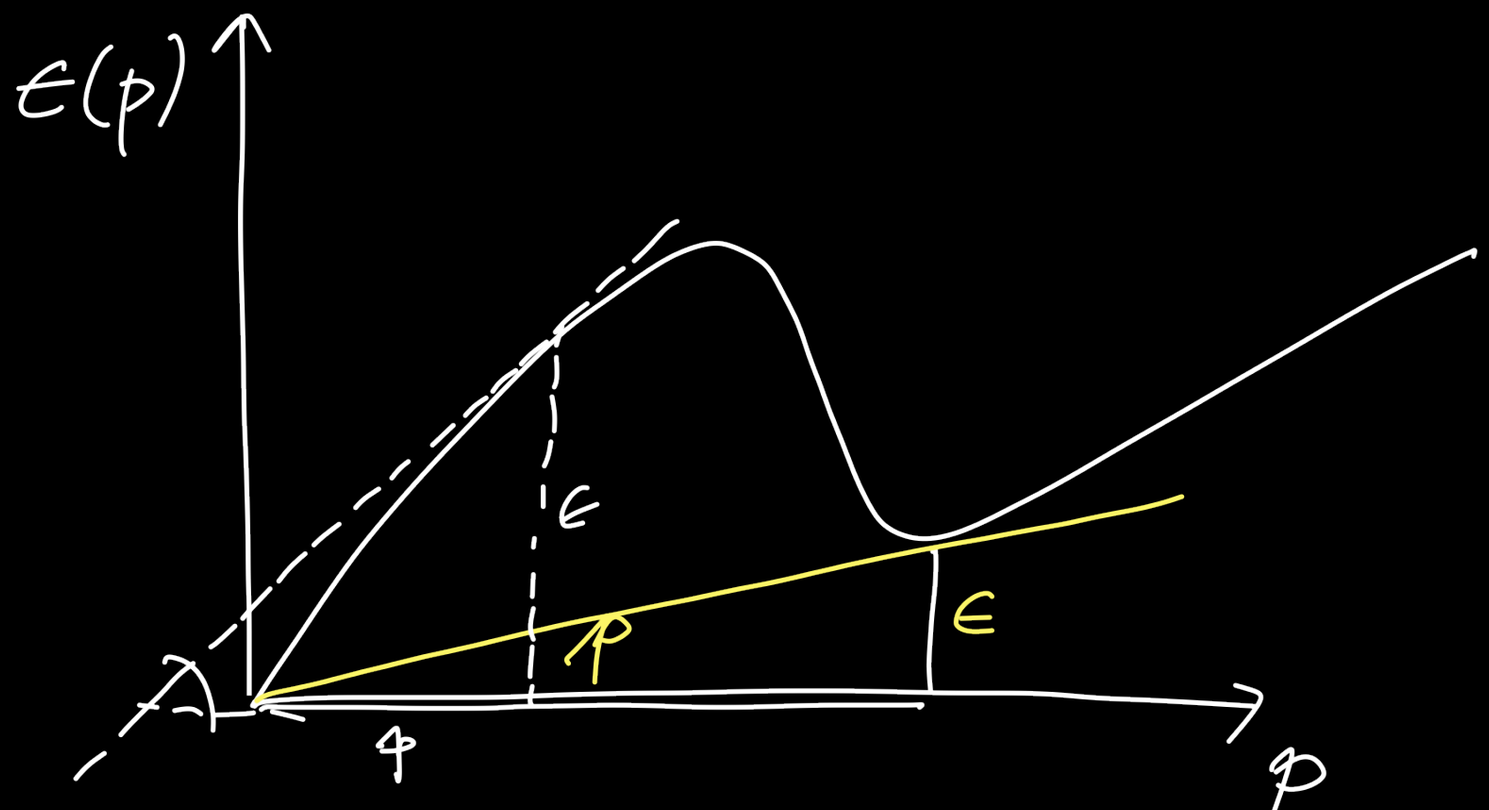
$$m^* \simeq 0.16\, m_{He^4}$$



$$V > \frac{\epsilon}{p} > \min \frac{\epsilon}{p}$$

The minimum is found for

$$\frac{\partial \epsilon}{\partial p} = \frac{\epsilon}{p}$$



$$V > \frac{\epsilon}{p} > \min \frac{\epsilon}{p}$$

The minimum is found for

$$\frac{\partial \epsilon}{\partial p} = \frac{\epsilon}{p}$$

For all other points on the left

$$\epsilon' > \epsilon / p$$

An excitation in the moving volume of liquid has velocity

$$v_g = \frac{\partial \epsilon}{\partial p} \quad \text{(direction opposite to } \vec{V}\text{)}$$

which in the O frame reads

$$v = V - \epsilon'$$

$$> V - \frac{\epsilon}{p}$$

$$> 0 \quad \text{— in the direction of } \vec{V}$$

but "lagging" behind.

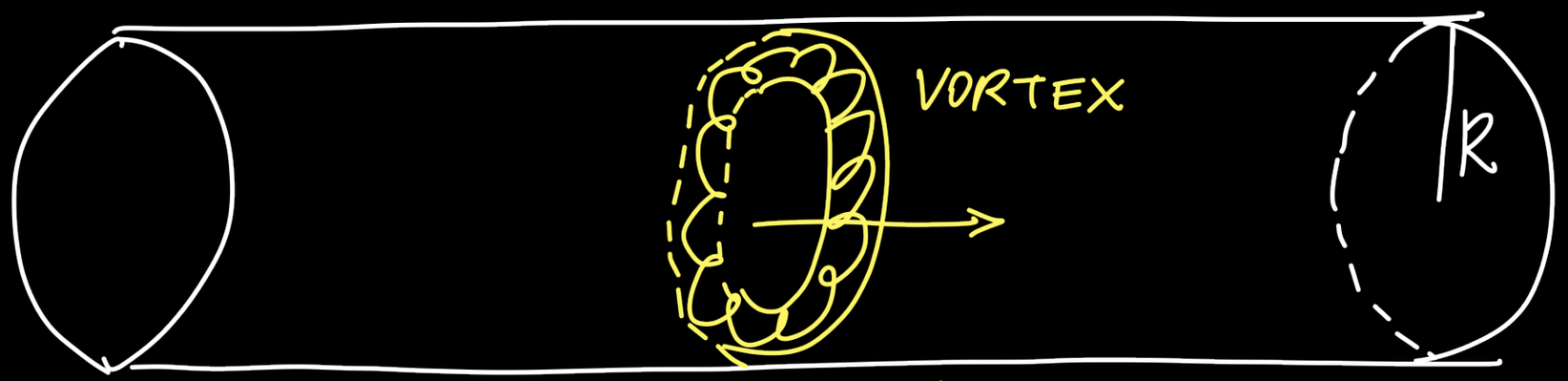
$$\in(\vec{p}) = \frac{p^2}{2m S'(\vec{p})}$$

$S'(\vec{p})$ is the Fourier component of the density correlation f.

$$\begin{cases} S(\vec{r}-\vec{r}') = \dfrac{\overline{\left(n(\vec{r})-\bar{n}\right)\left(n(\vec{r}')-\bar{n}\right)}}{\bar{n}} \\ n(\vec{r}) = \dfrac{1}{m}\rho(\vec{r}) \quad (\#\,\text{density}) \end{cases}$$

$$S(\vec{p}) = \frac{A}{2\pi\bar{n}} \int \sigma_{n\,He}(\omega)\, d\omega$$

slow neutron – Helium w/ energy transfer ω

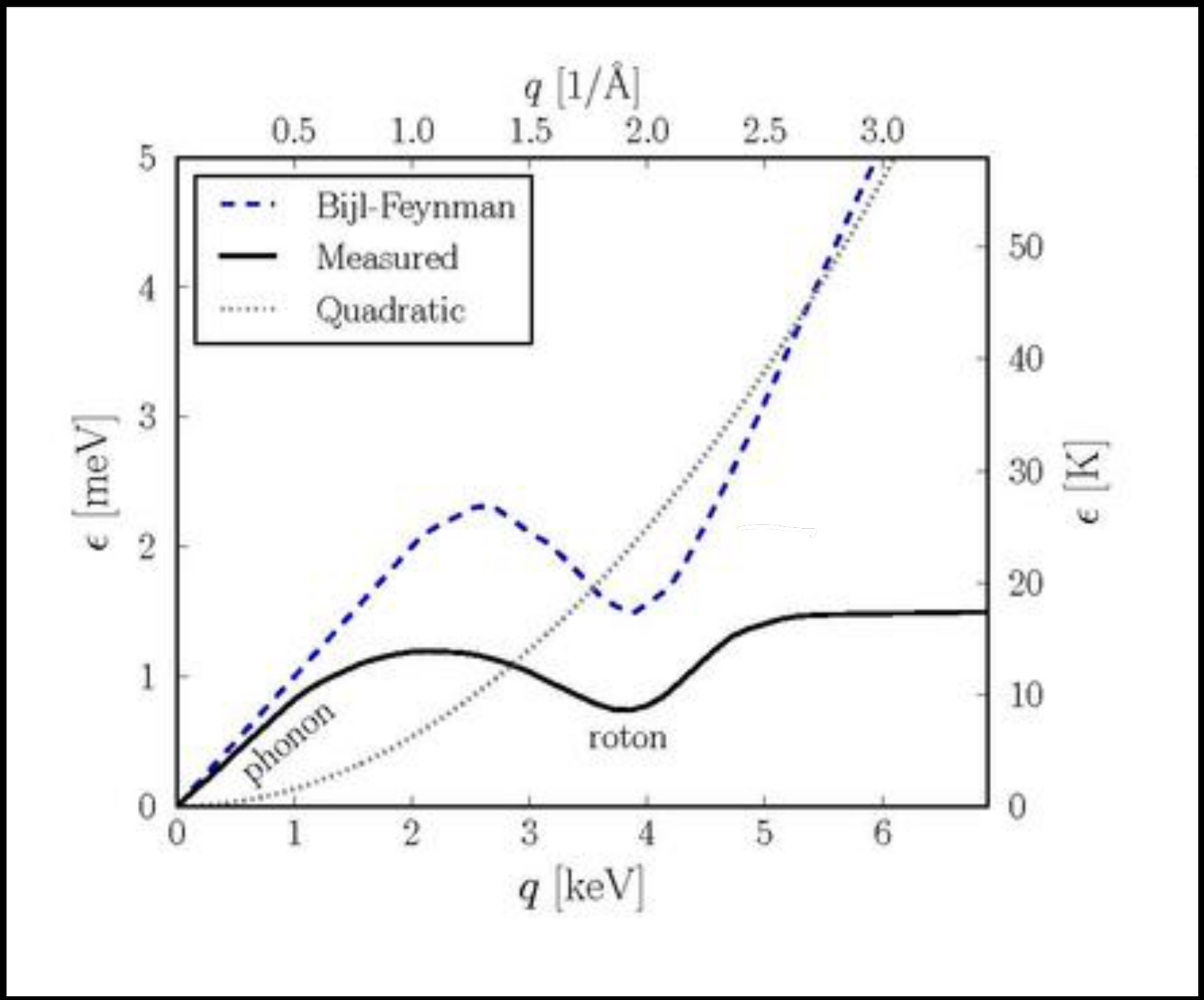


like smoke rings.

$$\frac{\mathcal{E}_V}{P_V} = a m c_s^2 \frac{\ln \frac{R}{a}}{\frac{R}{a}}$$

$<<$ $\frac{\epsilon}{p}$ of Photons & rotons

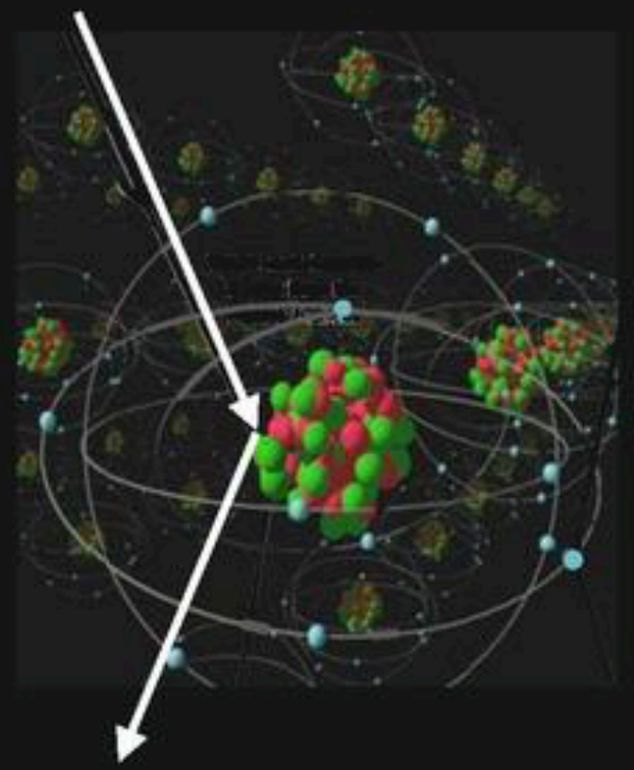
Probably the reason why the measured critical velocity is sensibly smaller than what expected from the (measured) spectrum of excitations.


q [1/Å]
0.5
1.0
1.5
2.0
2.5
3.0
Bijl-Feynman
Measured
Quadratic
ϵ [meV]
ϵ [K]
phonon
roton
q [keV]

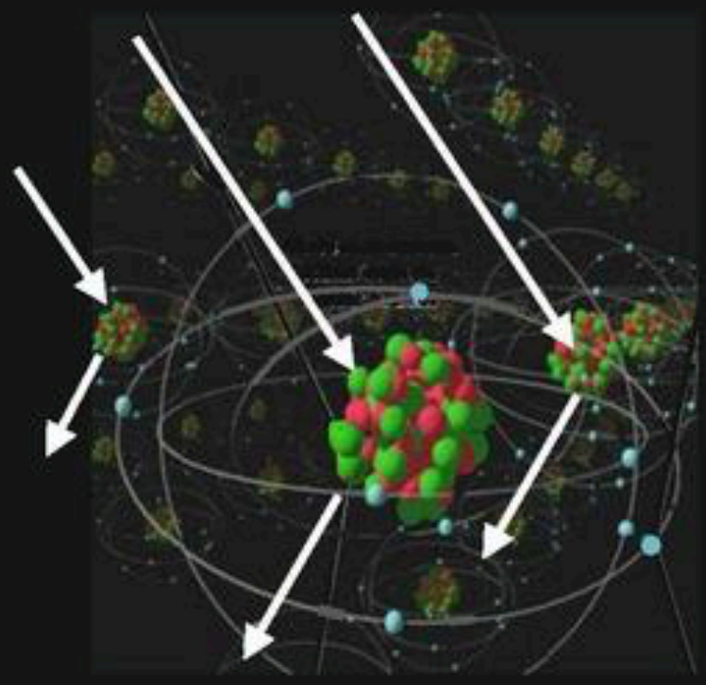
Structure effects

$m_\chi > 1$ MeV:

Recoil of nuclei/electrons



$m_\chi < 1$ MeV: $q \approx m_\chi v_\chi <$ keV ~ nm^{-1}

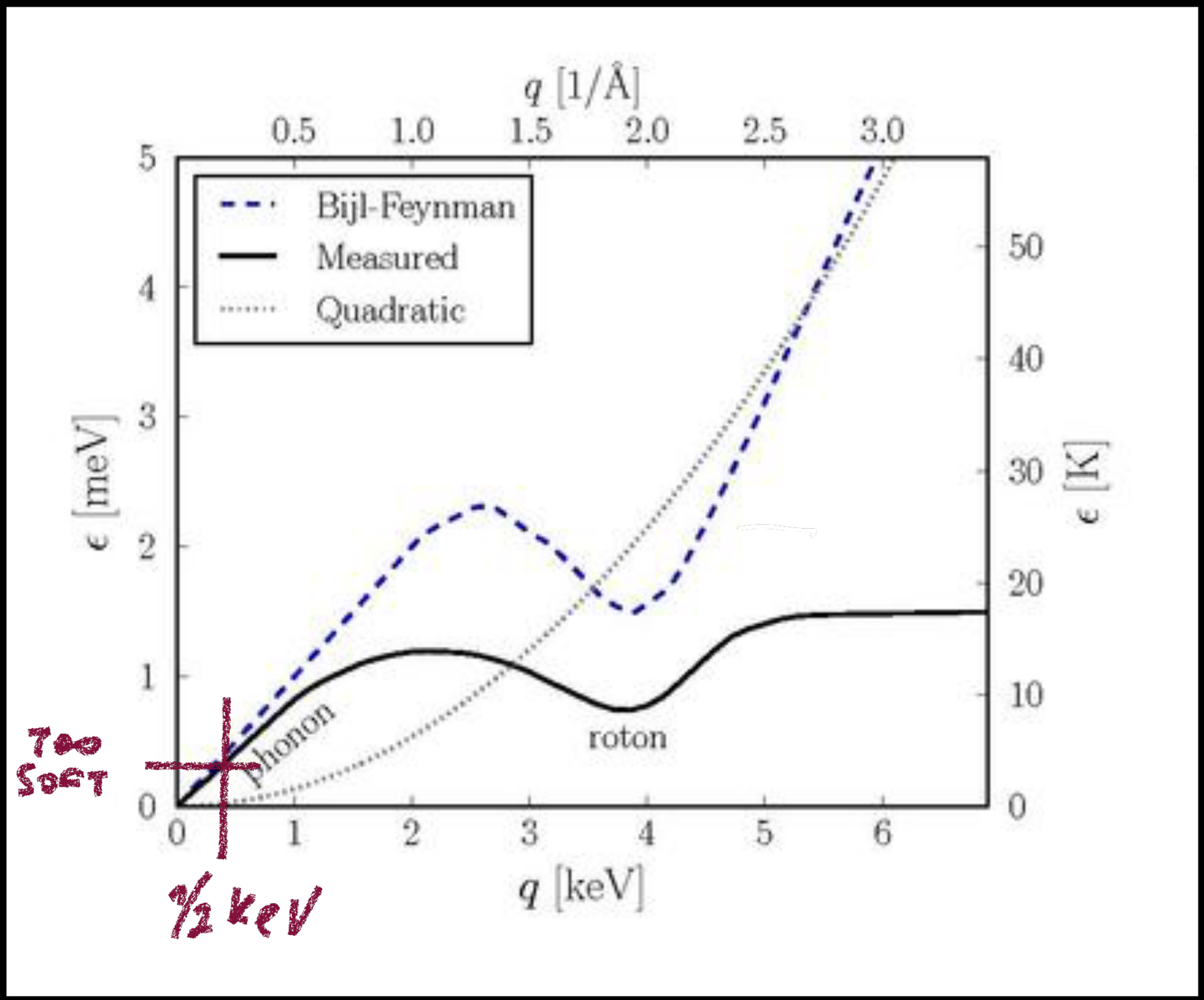


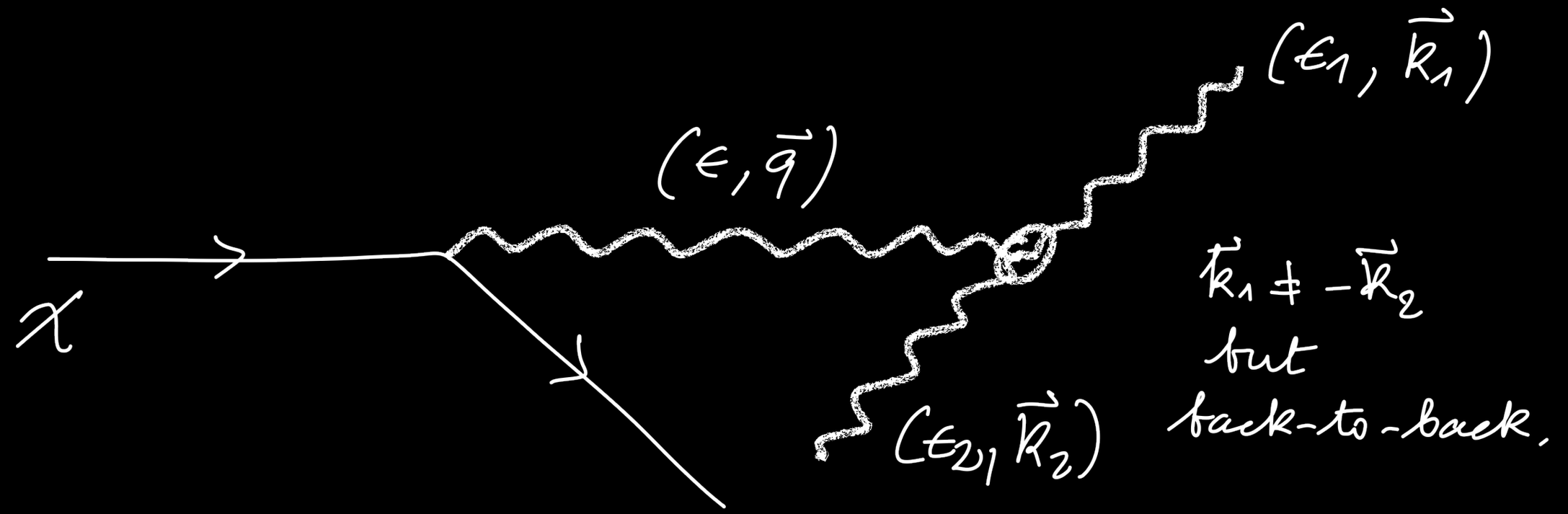
Scatter of collective excitations

(e.g. phonons)

Transition to different effective theory

from Knapen's talk — KITP — Apr 10, 2018


q [1/Å]
0.5
1.0
1.5
2.0
2.5
3.0
Bijl-Feynman
Measured
Quadratic
ϵ [meV]
ϵ [K]
phonon
roton
q [keV]
0
1
2
3
4
5
6
50
40
30
20
10
Too Soft
½ keV

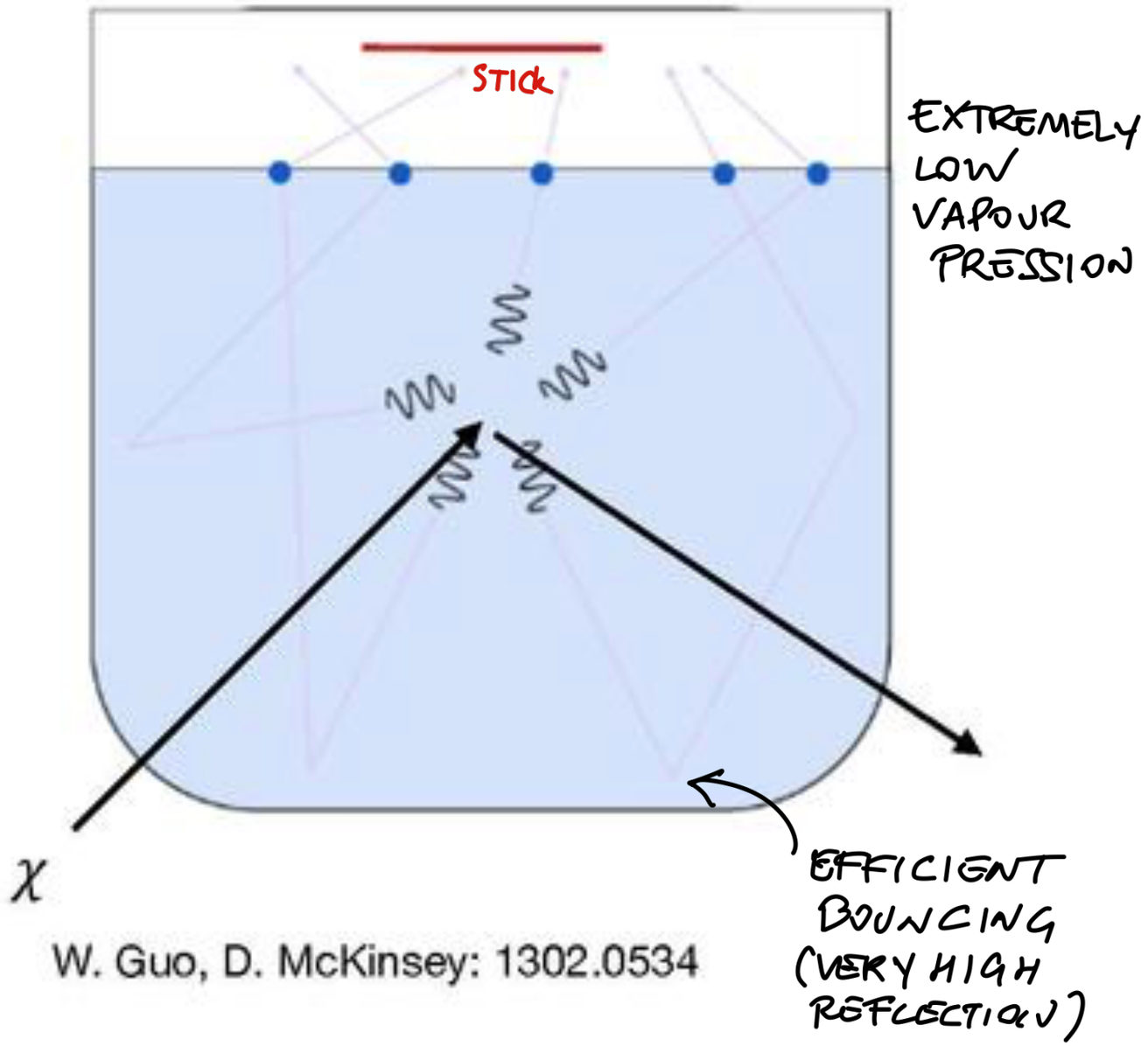


SHULTZ & ZUREK
1604.08206

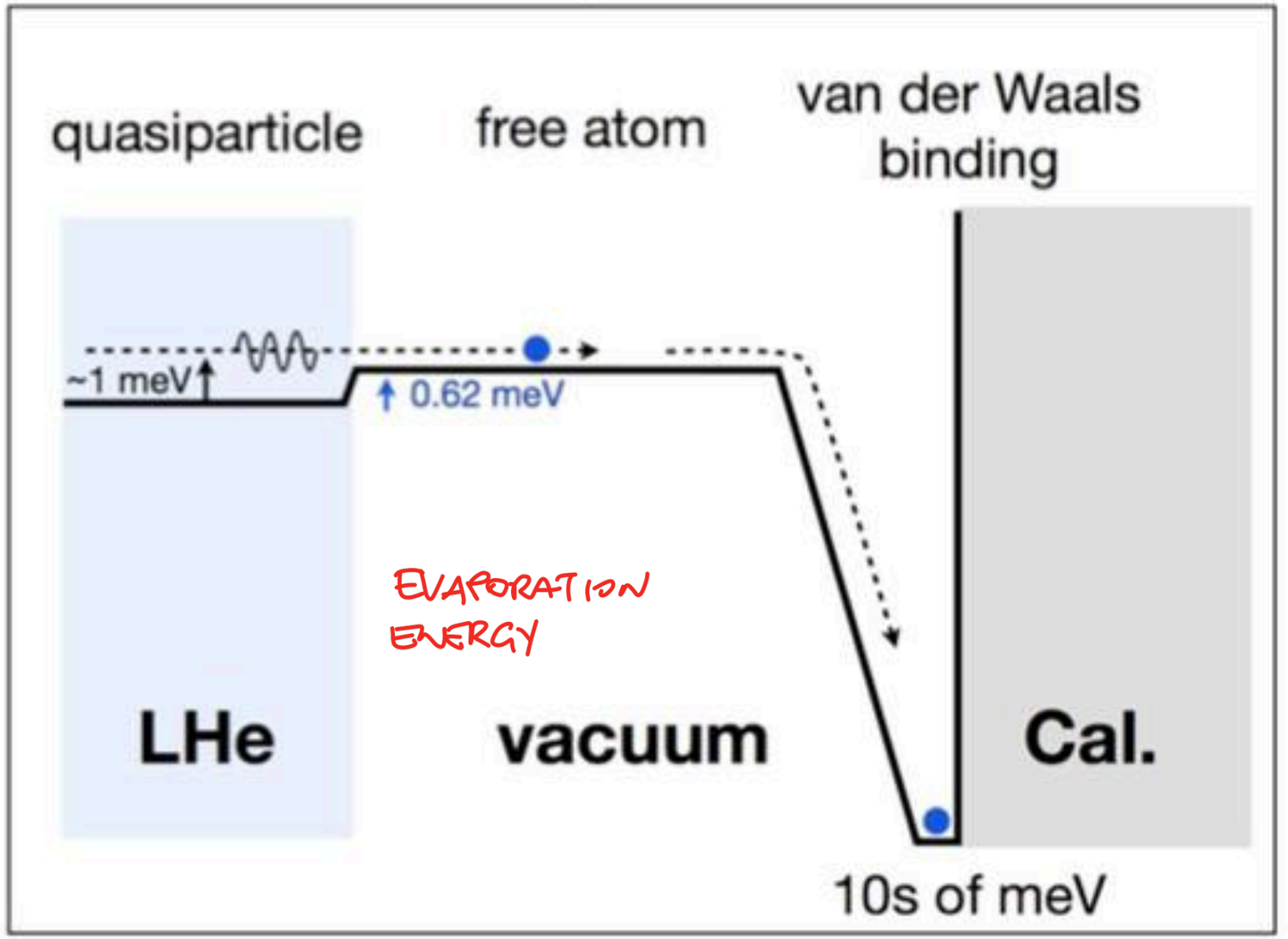
KNAPEN, LIN, ZUREK
1611.06228

Superfluid helium detector

POSSIBLE 100% DETECTION EFFICIENCY FOR PHONONS



W. Guo, D. McKinsey: 1302.0534



~10x signal energy enhancement!

QUASI PARTICLE W/ AT LEAST 0.62 meV → QUANTUM EVAPORATION OF AN He ATOM → STICK TO A CALOR. SURFACE

HELIUM STICKS MORE STRONGLY TO ANY SURFACE THAN IT DOES TO ITSELF.

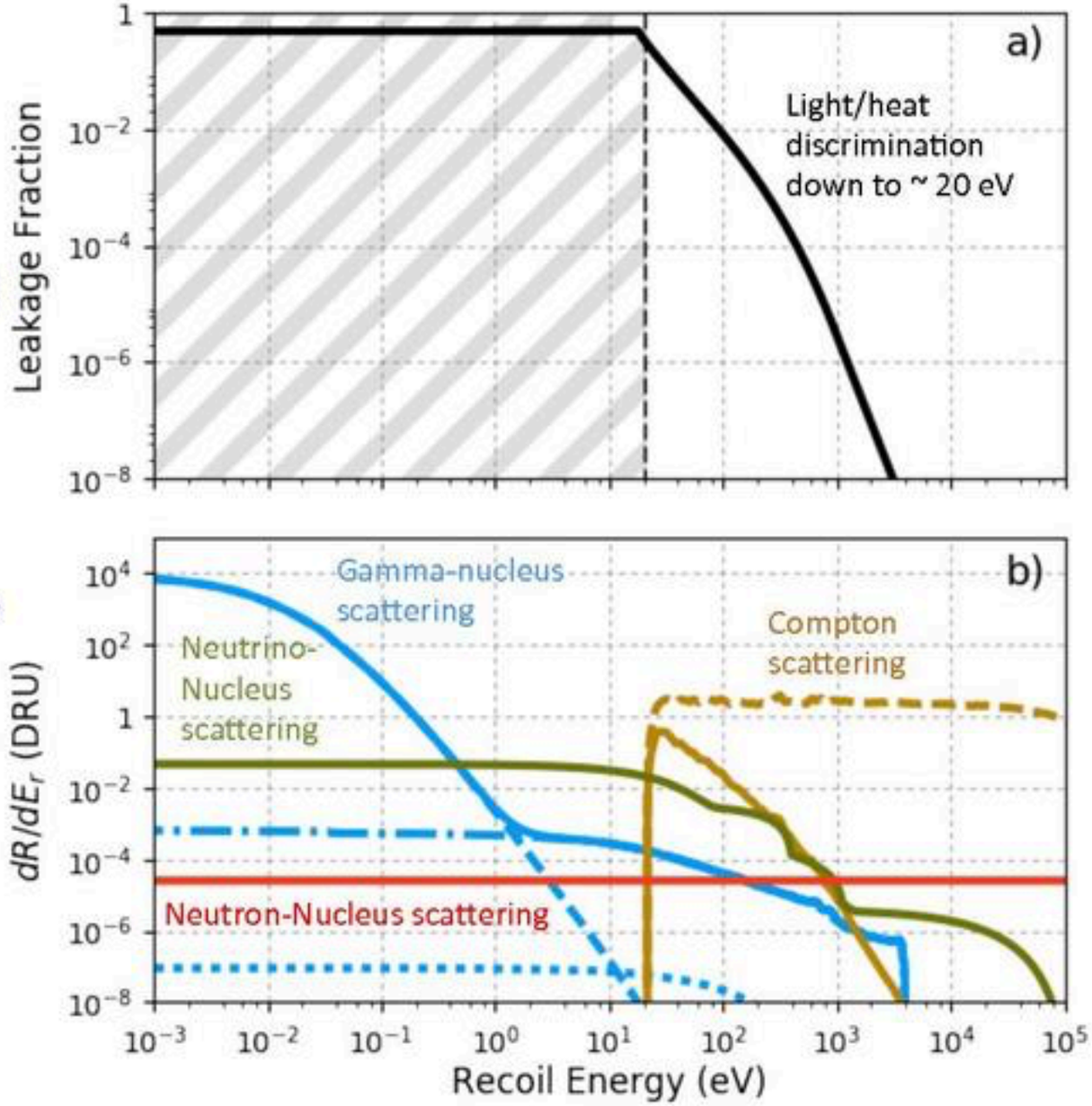
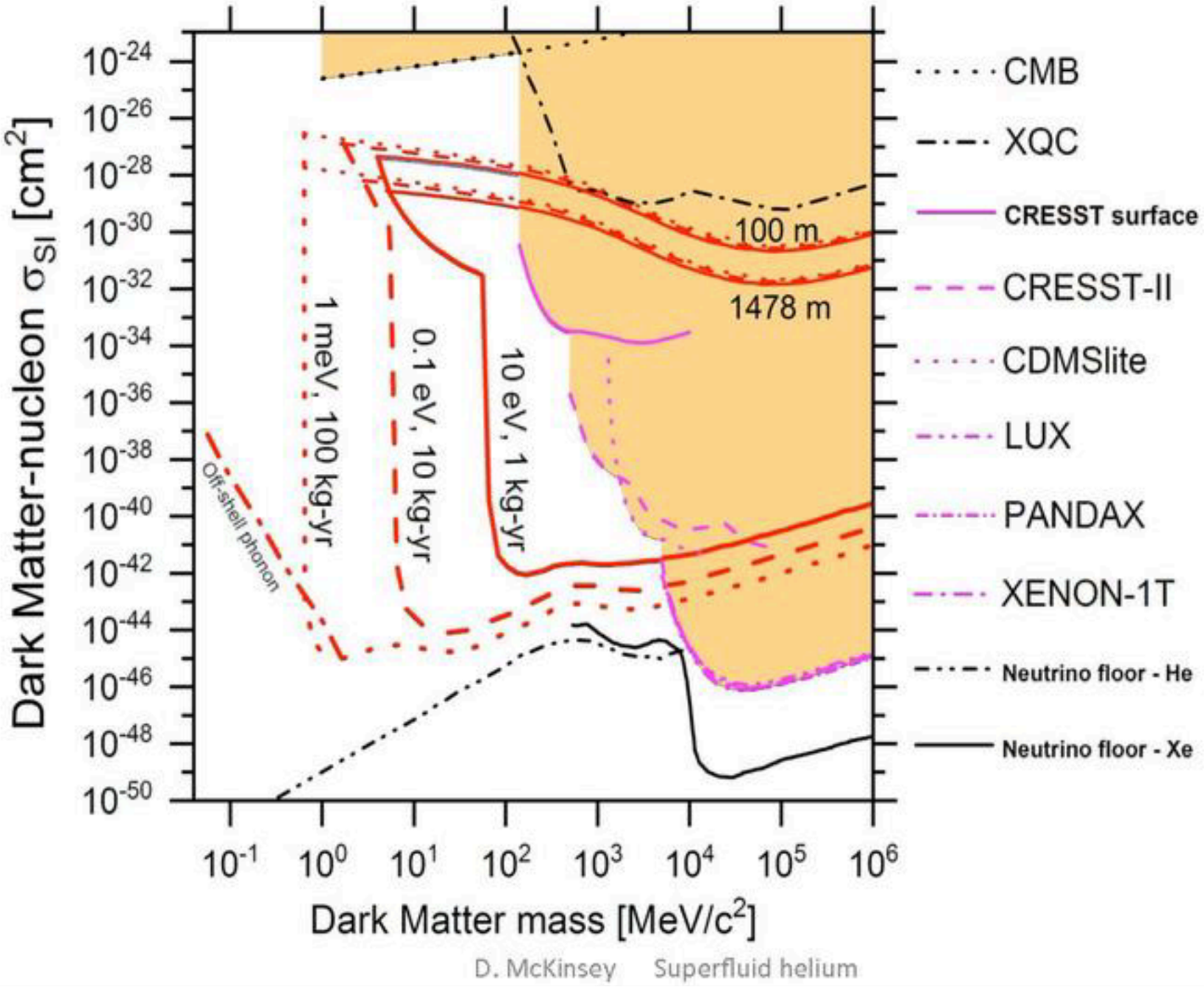
Expected Backgrounds

Backgrounds included:

- Neutrino nuclear coherent scattering
- Gamma-ray electron recoil backgrounds (similar to SuperCDMS)
- Note: Helium itself is naturally radiopure, and easily purified of contaminants
- Gamma-ray nuclear recoil backgrounds (see Robinson, PRD 95, 021301 (2017)

Arguments for low "detector" backgrounds:

- Low-mass calorimeter, easy to hold
- Target mass highly isolated from environment (superfluid: friction-free interfaces)



Projected Sensitivity – nuclear recoils