Roles of lattice defects in dark matter direct detection experiments

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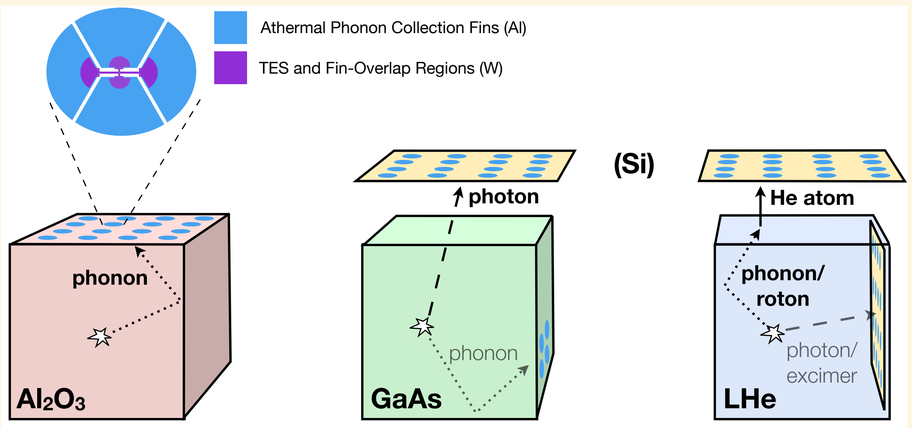
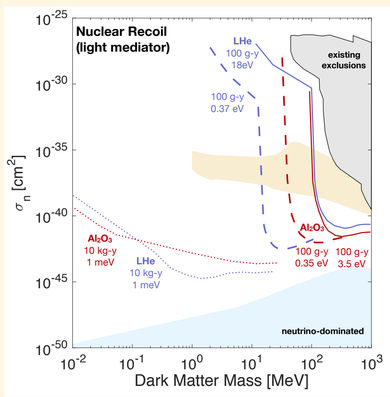
Work in progress

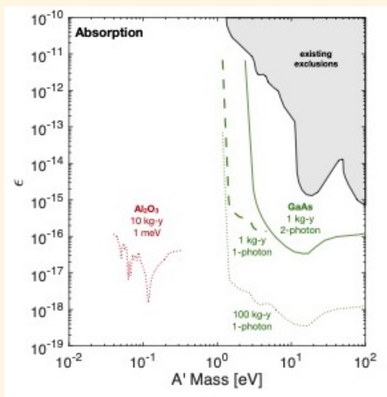
Low-energy phonon backgrounds!!

- Light DM search with phonons



- Ex) SPICE experiment @ TESSERACT project
- Targets $\sim \mathrm{MeV}$ (scattering) $\sim \mathrm{eV}$ (absorption) DM
- Looks for low-energy (1–$100\,\mathrm{meV}$) phonon signals



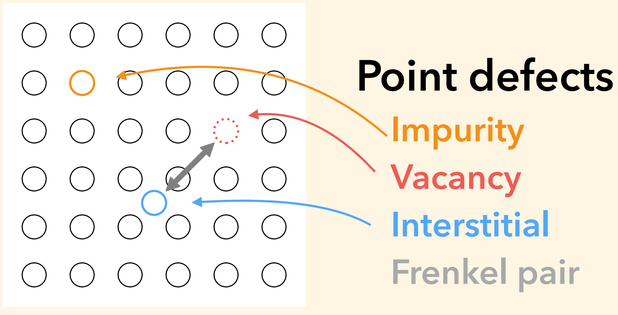


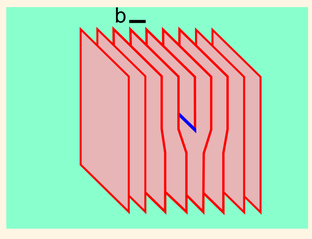
- Possible backgrounds
  - Dark current when $\vec{E} \neq 0$
  - Radioactive contaminants
    Berghaus, et al. '21
  - Stress-induced phonons
    Anthony-Petersen, et al. '22
  - Lattice defects
    Snowmass '21

✓ Consider the possible background events from the recombination/relaxation of lattice defects

Lattice defects?

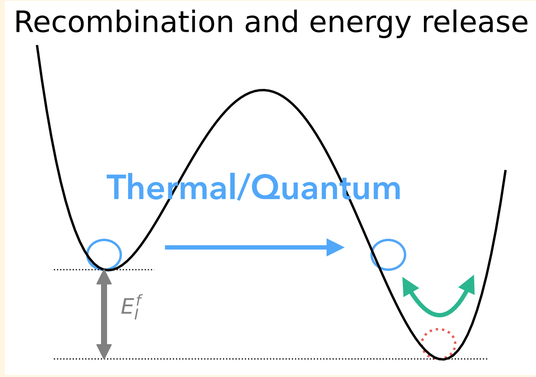
- **What are lattice defects?**





(Line defects etc.)

- **Why lattice (point) defects?**
- Intrinsic concentration
  - Thermal
  - Radiogenic
- Energy release from recombination
  - Mainly in terms of phonons



✓ Need to understand ``when'' and ``how often'' the recombination $\simeq$ phonon emission happens

Thermal defects = point defects

- **Evolution of point defect concentration**
- Equilibrium concentration

$$C_d^{\mathrm{eq}} = n_d N \exp\left(S_d^f - \frac{E_d^f}{T}\right) \qquad (d = I, V)$$

$n_d N$: # density of interstitial/vacancy sites

S_d^f, E_d^f : formation entropy/energy

- Transport (Boltzmann) equation

Cf) DM relic

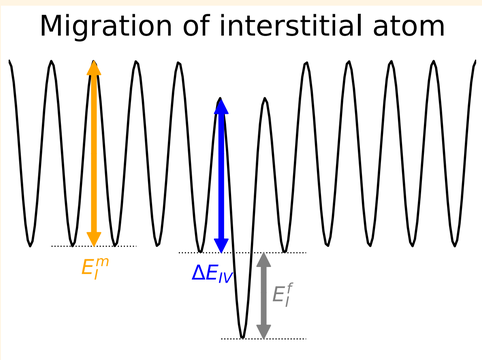
$$\frac{\partial C_I}{\partial t} = \frac{\partial C_V}{\partial t} = k_{IV}(C_I^{\mathrm{eq}} C_V^{\mathrm{eq}} - C_I C_V)$$

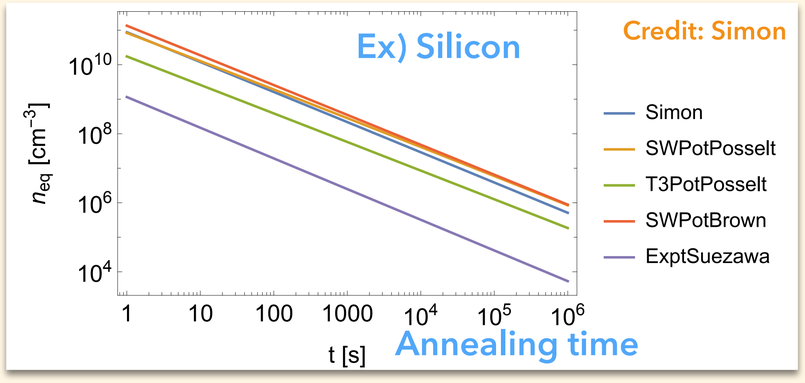
$$k_{IV} = 4\pi a_c (D_I + D_V)\, \exp\left(-\frac{\Delta E_{IV}}{T}\right)$$

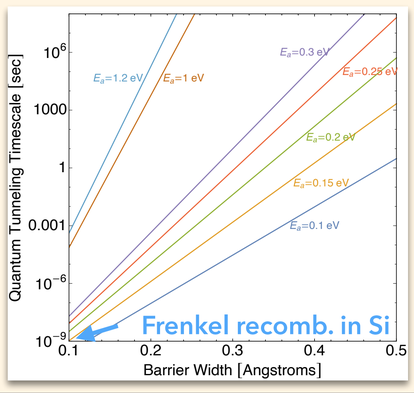
$D_d = D_d^{\mathrm{thermal}} \propto e^{-E_d^m/T} + D_d^{\mathrm{quantum}}$: diffusion coeff.

$a_c \sim 5\,\mathrm{\AA}$: recombination radius

- **Annealing with adiabatic cooling**
- Adiabatic = slow enough s.t. concentration does not ``freeze out''







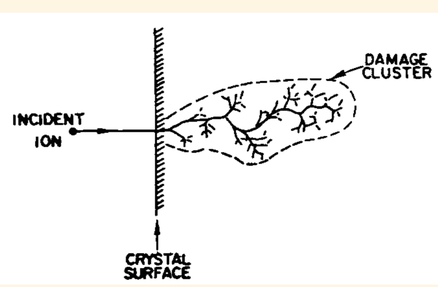
- **Resulting recombination rate under low $T \lesssim 400\,\mathrm{K}$**

$$R = 4\pi a_c (D_I + D_V) C^2 \sim 6 \times 10^{-6}\,\mathrm{s^{-1}cm^{-3}} \times \left(\frac{C}{10^8\,\mathrm{cm^{-3}}}\right)^2$$

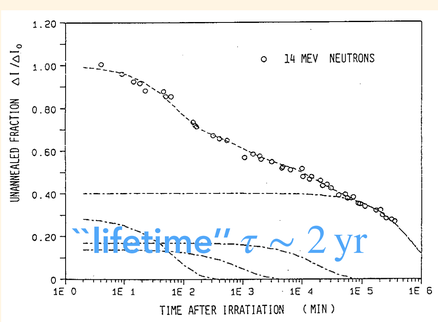
✓ ~ A few BGs per gram × month after annealing

Radiogenic defects = damage clusters

- Of great interest in terms of ion implantation
  Theoretical complexity vs. Many experiments



Gibbons '72



Lindstrom, et al. '89

- Extract damage cluster ``lifetime'' from experiments

- **Estimation of radiogenic recoil event rate**
  - w/ cosmic neutron when unshielded: $R_{\mathrm{rec}} \sim 50\,\mathrm{day}^{-1}$
  - w/ neutron from impurities of shield: $R_{\mathrm{rec}} \sim 0.1\,\mathrm{day}^{-1}$

Assuming DAMIC-like setup

- **Estimation of defect production rate $\simeq$ BG event rate**

Energy (keV)	N_{def}
Si 0.4	9 ± 1
2	35 ± 2
5	90 ± 3
5[a]	169 ± 4
10	196 ± 5

Nordlund, et al. '98

$$R = \int dE_{\mathrm{rec}} \frac{dR_{\mathrm{rec}}}{dE_{\mathrm{rec}}} N_{\mathrm{def}}(E_{\mathrm{rec}}) \sim \begin{cases} 5 \times 10^5\,\mathrm{day}^{-1} & (\text{cosmic}) \\ 70\,\mathrm{day}^{-1} & (\text{impurity}) \end{cases}$$

✓ Difficult to veto, careful setup required