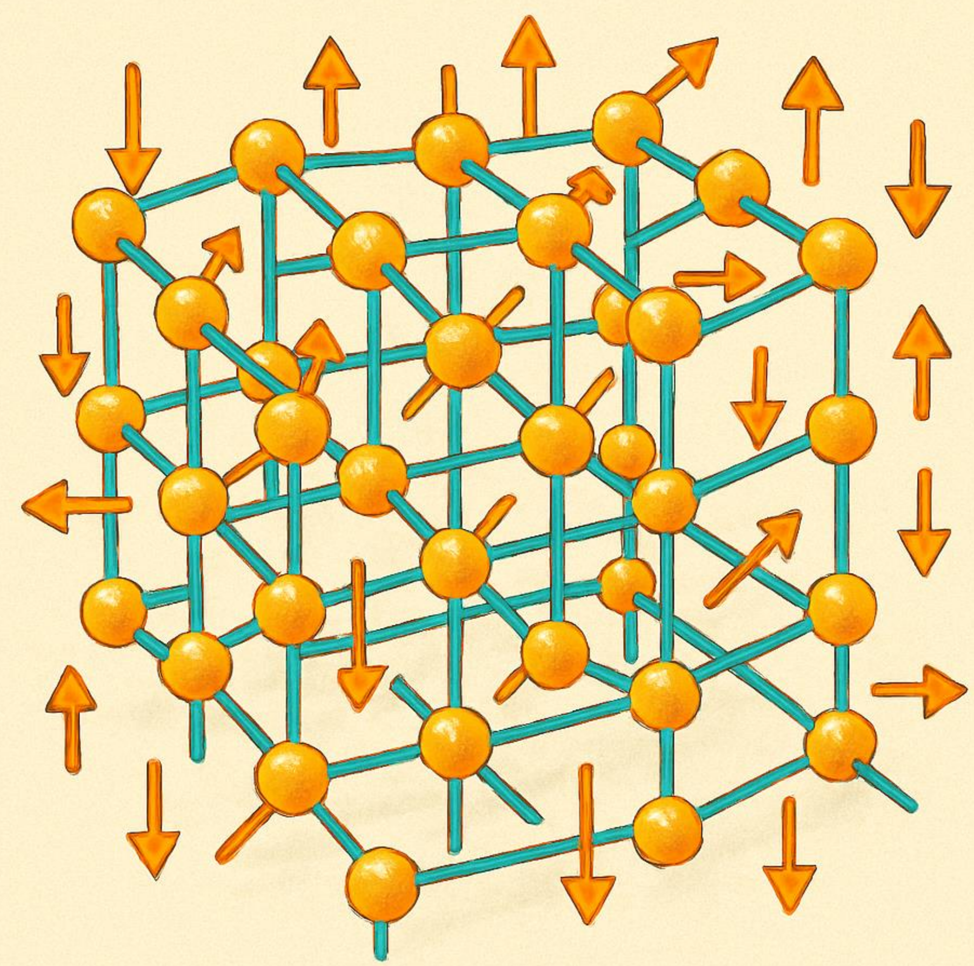
Searching for DM with Phonons through Dsr乇diOr



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Based on 2411.10542, with S. Knappen A. Madden, G. Marocco

Setting Expectations

- We will talk about ALP Dark Matter in the mass range $\mathcal{O}(1-100)\mathrm{meV}$.
- The ALP can excite phonons in crystals in a way that was previously missed.
- Realistic “projections” are “suboptimal”.
- However, this is an example of a more basic principle: **Disorder can allow phonon-based systems to have sensitivity to a broad range of DM masses.**

DM-Nucleon Interaction

So we start with $\mathcal{L} = g_n \partial^\mu a \bar{n} \gamma_\mu \gamma_5 n + (n \to p)$.

At leading order in the non-relativistic expansion,

"Axion Wind"

"Axioelectric Effect"

$$\delta H = g_{p,n} (\vec{\nabla} a) \cdot \vec{S} - \frac{g_{p,n}}{m_{p,n}} \dot{a} \vec{S} \cdot \vec{\nabla}$$

Rotates/Flips Spins

Rotates/Flips Spins & Couples to Spatial DOFs

Coarse Graining DOFs

First, from a **n**ucleon to a (no-zero spin) **N**ucleus:

$$\delta H \propto \frac{1}{m_{\mathrm{n}}} g_{\mathrm{n}} \mathbf{S}_{\mathrm{n}} \cdot \nabla_{\mathrm{n}} \rightarrow \lambda_{\mathrm{n-N}} \cdot \frac{1}{m_{\mathrm{N}}} \mathbf{J}_{\mathrm{N}} \cdot \nabla_{\mathrm{N}}$$

λ is a form factor that usually prefers small A.

As long as $m_a < \Delta E_{\mathrm{electrons}}$, we can use the Born-Oppenheimer approximation to take Nuclei to sites (basically atoms).

~~To finish the talk on time~~ For simplicity, let's say a crystal is just a set of sites located at $\mathbf{x}_\ell = \mathbf{u}_\ell + \ell$. $\ell = n_1 \mathbf{a}_1 + n_2 \mathbf{a}_2 + n_3 \mathbf{a}_3$ is the periodic location of the minima.

Fermi's Golden Rule

$$\Gamma = (2\pi)\sum_f |\langle i|\delta H(m_{\mathrm{DM}})|f\rangle|^2 \Delta(m_{\mathrm{DM}} - \omega_f + \omega_i)$$

$$\Delta(x) = \text{Lineshape} \sim \delta(x)$$

If no B fields: $\nabla_\ell = im[\mathbf{u}_\ell, H_0]$, so

$$\mathcal{M}_{\mathrm{axioelectric}} = \ldots = -2im_a(E_f - E_i) \cdot a_0 \sum_\ell \langle i|\lambda \mathbf{u}_\ell \cdot \mathbf{J}_\ell|f\rangle$$

But what "is" $\mathbf{u}_\ell$?

From Sites (Cells) to Phonons

We can index phonons (which are energy eigenmodes) by:

i. Their (c-number) momentum $\mathbf{k}$.

ii. Their integer "branch" ν (for one-site cells, there's 3 branches).

To a pretty good approximation, each site is sitting in a harmonic potential, and so

$$\mathbf{u}_\ell = \frac{1}{\sqrt{Nm}} \sum_{\nu,\mathbf{k}} \frac{1}{\sqrt{\omega_{\nu,\mathbf{k}}}} a_{\nu\mathbf{k}} \epsilon_{\nu\mathbf{k}} e^{i\mathbf{k}\ell} + \mathrm{h.c.}$$

$\ell, \mathbf{k}$-dependent phase

Deviation from VEV operator

Crystal mass

Annihilation operator

Polarization vector. Normalization is a bit non-trivial

Historical Context: Coherent Phonon Production

The matrix element for a fully polarized crystal in the initial and final states is

$$\mathcal{M} \propto \frac{1}{\sqrt{N_{\text{cells}}}} \langle i | \sum_{\ell} e^{i\mathbf{k}\ell} a_{\nu,\mathbf{k}} | f \rangle \to \delta_{\mathbf{k},0} \sqrt{N_{\text{cells}}}$$

So only modes with $\mathbf{k} = 0$ can be excited. There're very few of them! (it's actually $\mathbf{k} = \mathbf{k}_a$ if we had kept the ALP's momentum)

The rate is $\Gamma \propto N$, but is enhanced by the inverse phonon linewidth$1/\gamma$. $\gamma_{\nu,\mathbf{k}} \approx (0.1 - 10)\% \omega_{\nu,\mathbf{k}}$.

New: Incoherent Excitation Rate (Some of it)

If we allow $|i\rangle$ and $|f\rangle$ to have **one** spin (ℓ') that is different,

$$\frac{1}{\sqrt{N}}\sum_{\ell}\langle i|\mathbf{J}_{\ell}(\dots)|f\rangle \to \frac{1}{\sqrt{N}}\langle i|\left(J_{\ell',x}\hat{x}+J_{\ell',y}\hat{y}\right)(\dots)|f\rangle$$

Seemingly, we lose N^2… But: $\mathcal{O}(N)$ sites can change their spins, and…

$$|\mathcal{M}|^2 \propto \frac{N}{(\sqrt{N})^2}\sum_{f,\ell\,\mathrm{changed}}|\langle i|\mathbf{u}_{\ell}(\dots)|f\rangle|^2 \sim \sum_{f}\left|\sum_{\nu,\mathbf{k}}\langle i|a_{\nu,\mathbf{k}}(\dots)|f\rangle\right|^2$$

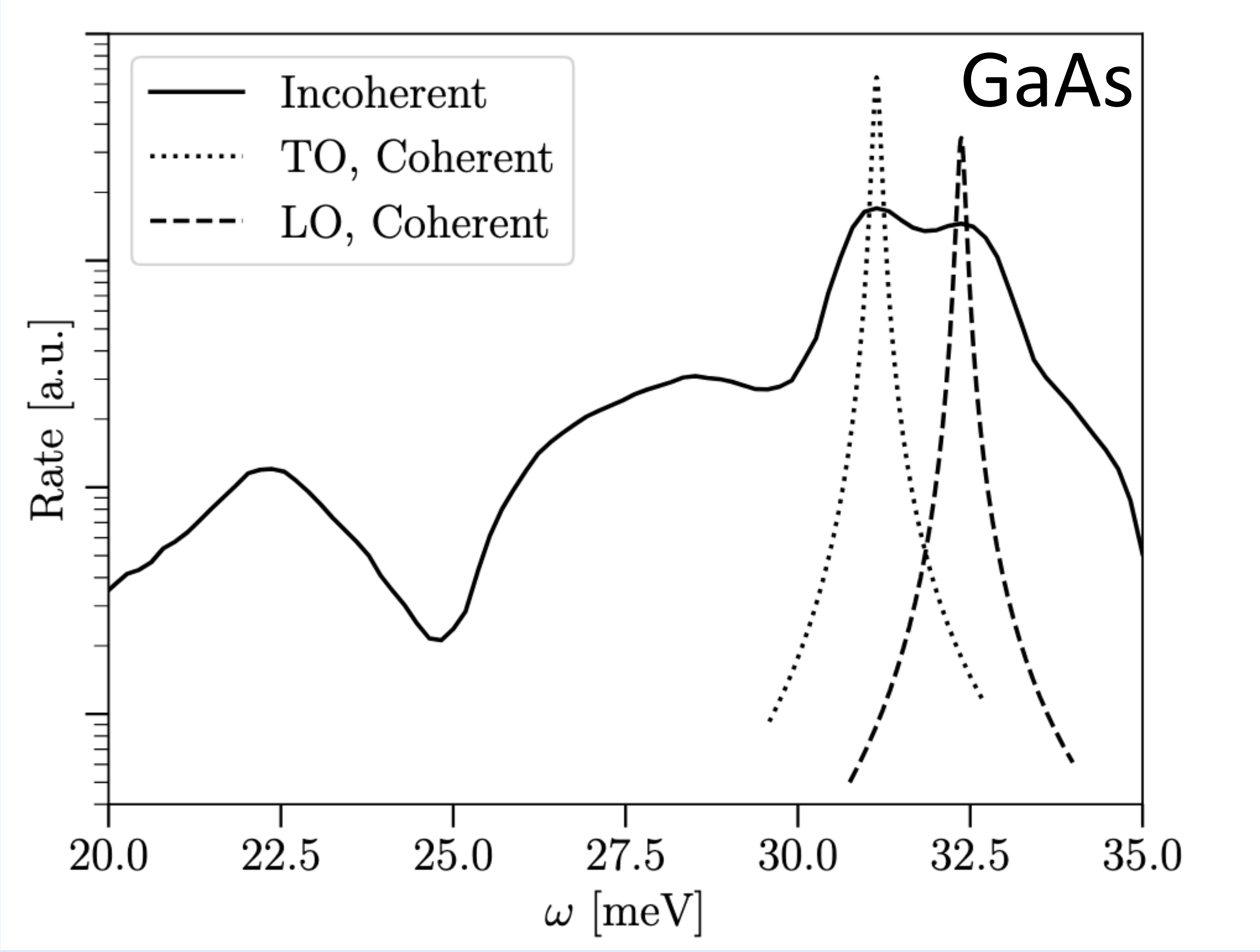
The number of k modes per unit energy scales with N!

Intuitively, this recovery makes sense: if we have twice as much crystal, the rate is twice as large.

Chaos All the Way!

At this point, there's no real reason to polarize the crystal!

The spin-changing incoherent rate is always there, but unpolarized crystals get a second spin preserving contribution of the same order, and if we compare coherent and incoherent rates:



Experimental Bonus: Much easier if we don't need nuclear polarization!
Theory Bonus: the coherent rate depends on several quantities that are very hard to directly compute/measure (e.g. the phonon linewidth).

The Excitation Rate per kg year (I added cells again)

$$R_{\text{incoherent}}(\omega) = \frac{2\pi m_a \rho_a}{m_{\text{cell}}} g_{p,n}^2 \sum_{j \in \text{cell}} \xi_j D_j(\omega)$$

Total mass of a cell.

$D_j(\omega) \equiv \frac{1}{3N} \sum_{\nu \mathbf{k}} |\epsilon_{j\nu\mathbf{k}}|^2 \Delta(\omega - \omega_{\nu\mathbf{k}})$ is the Phonon Density of States.

Normalized to 1. Measurable and computable (from/for SM stuff)!

The prefactor $\xi_j \equiv \frac{\lambda_j^2}{m_j} J_j(J_j + 1)$,prefers light nuclei.

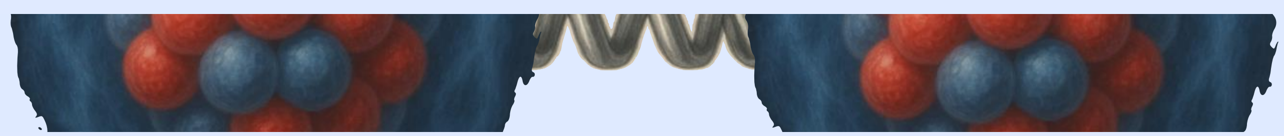
$$R_{\text{coherent}}(\omega_{\text{resonances}}) \sim \mathcal{O}(0-1) \frac{1}{\gamma D(\omega)} R_{\text{incoherent}} \sim \mathcal{O}(0-10) R_{\text{incoherent}}$$

Recovering Momentum Conservation

First things first: phonon momentum is internal, and hence "perpendicular" of Center of Mass momentum.

<u>A phonon:</u>

By focusing on phonons, we already "integrated out" the part that "has to be" conserved.



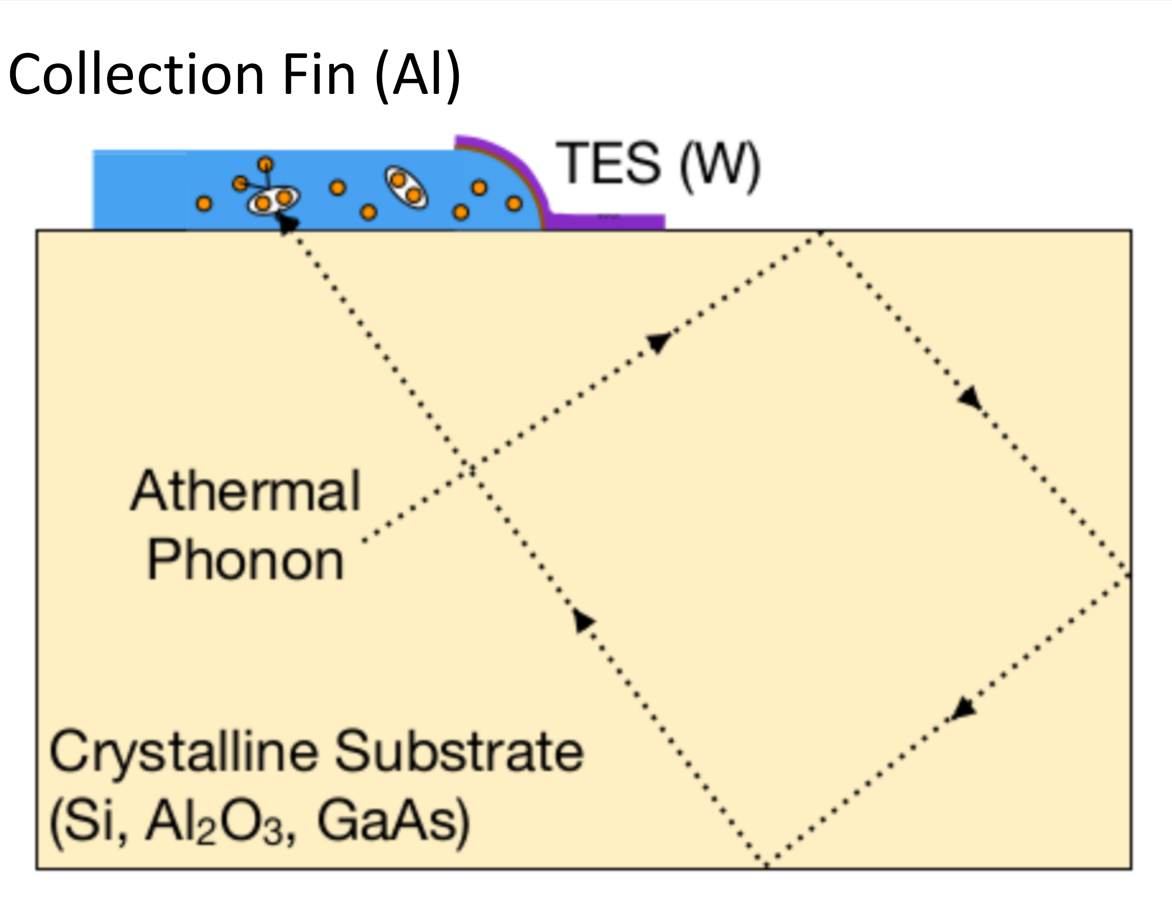
However, this is a cop-out. In the sites-based EFT, naively, momentum should be conserved if $k_a \to 0$.

However, since the potential depends on spins, in order to have no x dependence, they must be part of the Fock Space. The spin states carry momentum, but no energy. Thus momentum can be tracked again (presumably).

Experimental Implications and Future Directions

In the Real World

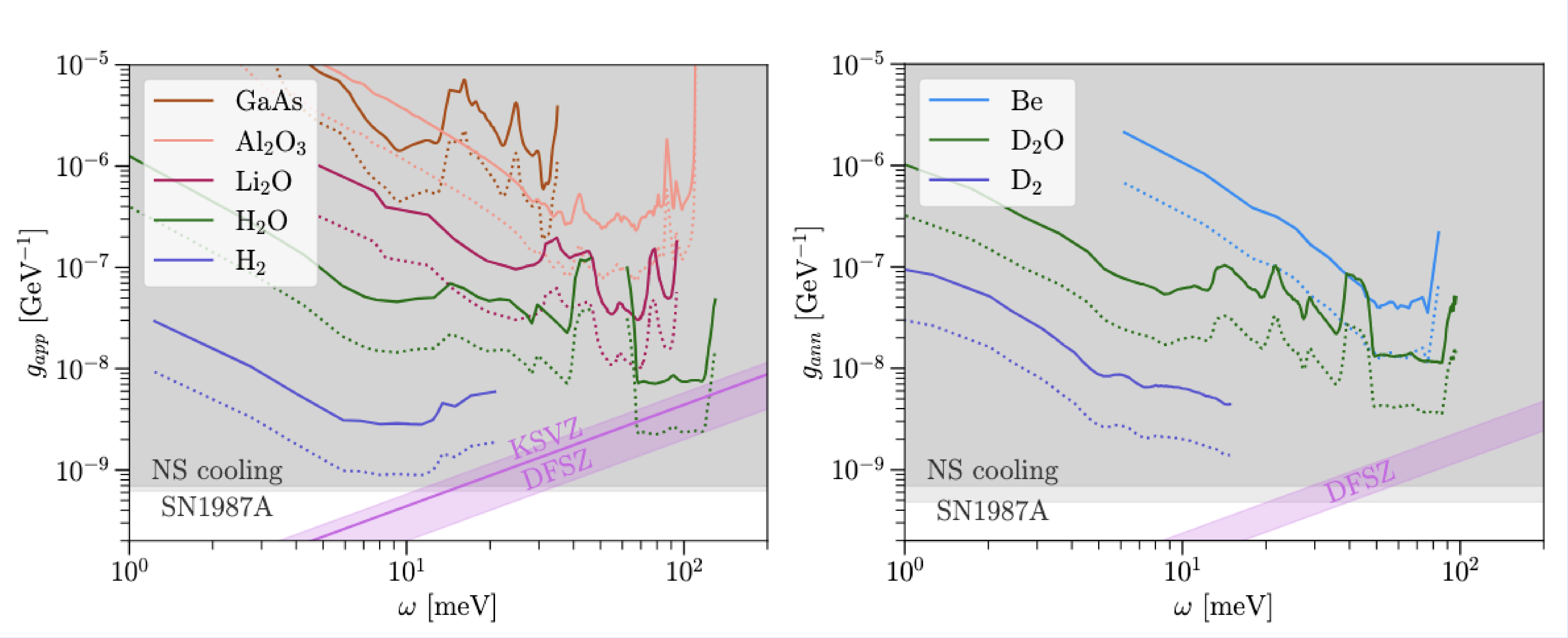
One collaboration pursuing low-energy phonon detection is the TESSERACT collaboration. (Apparently BREAD could also possibly do this).



Right now (2503.03683):

- Energy threshold is 1.5 eV.
- Near threshold event rate is O(event/gram/sec).
- Total mass is 0.2 grams.

Sensitivity (AKA ***<u>HIGHLY Optimistic</u>*** Projections)



Solid lines=3 events per kg year

Dotted lines=0.3 events per kg year

The QCD band's (~~and astro bounds'~~) edges shouldn't be taken too seriously.

Some Future Directions

- Since the axioelectric rate scales with $\omega^2/\omega_{\nu k}$, **higher energies** (multi-phonon excitations?) might enhance things. At some point electrons become important.(Migdal effect? Bloch` Functions!)

- Materials with nuclear-**spin** & **spatial**-DOFs **mixing**?(Superfluid ^{3}He?)

- We assumed no internal **magnetic fields**. What would they change for $g_{a-\mathrm{nuc}}$? Can they allow probing ALP-photon couplings?

- **Other BSM couplings**? (e.g. a static EDM+a magnetic field would excite phonons/shake a crystal). Open to more ideas!

We haven't looked too deeply into any of the above, except the last one, where we started looking at…

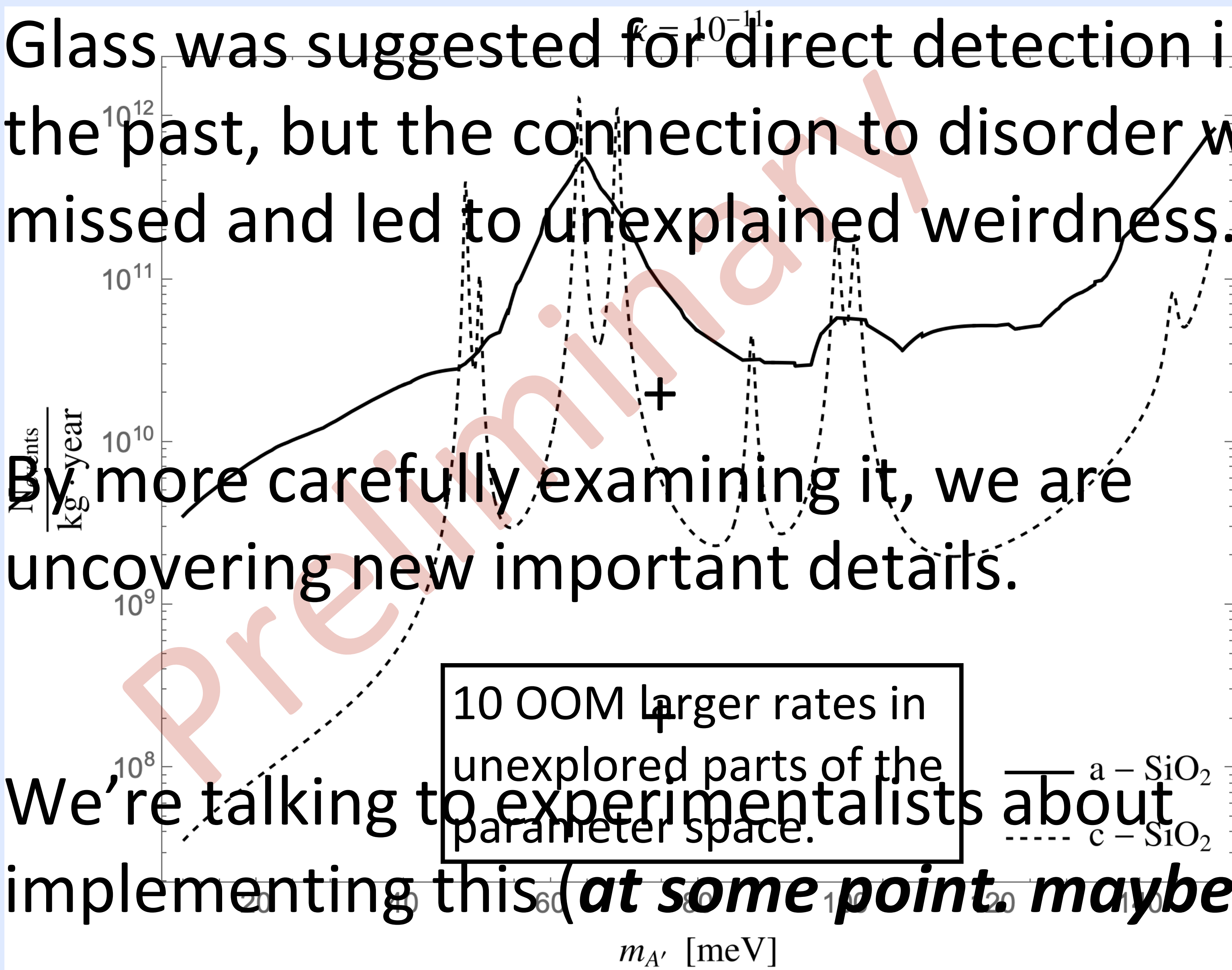
Inherently Disordered Materials

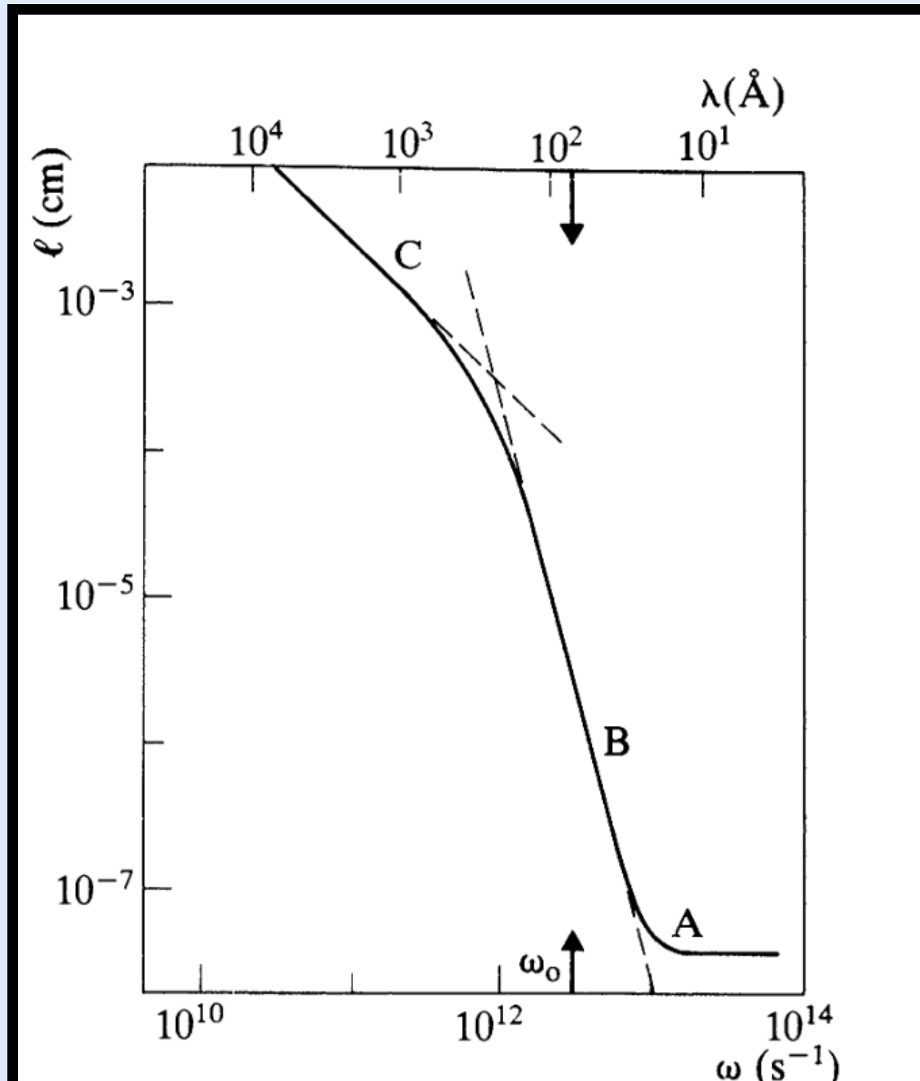
Materials with no internal order (e.g. glass) might have broadband sensitivity to a variety of DM models! In particular, for Dark Photons!

Glass was suggested for direct detection in the past, but the connection to disorder was missed and led to unexplained weirdness.

By more carefully examining it, we are uncovering new important details.

We're talking to experimentalists about implementing this (***at some point, maybe***).





Phonon mean free path for glass

Summary

- ALP Dark Matter can excite phonons in a crystal.
- By coupling to the disorder in spins, we can break momentum conservation in the phonon EFT.
- There are very few (none?) direct detection other ideas sensitive to g_{aNN} at this mass range.
- Even if it's not yet obvious how to measure the QCD axion with this, the concept is very interesting! Many future possibilities!

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From Nucleons To Nuclei

While we cast constraints on g_p, g_n, usually, they sit in a nucleus.

A nucleus has total angular momentum $\mathbf{J}$, so ignoring internal DOFs, we have an effective g_N, with: $\delta H = -\frac{m_a}{m_N} a g_N \mathbf{J} \cdot \mathbf{k}_N$.

$$g_N = \frac{\sum_{\text{neutrons}} S^z_{n_i}}{J} g_n + (n \to p) \equiv \lambda_n g_n + \lambda_p g_p$$

	nat. ab.	J	λ_p	λ_n
^{1}H	100%	1/2	1.00	0
^{2}D	0.01%	1	0.46	0.46
^{7}Li	92%	3/2	0.25	0
^{9}Be	100%	3/2	0	0.21
^{27}Al	100%	5/2	0.11	0.014
^{69}Ga	60%	3/2	0.07	0
^{71}Ga	40%	3/2	0.15	0
^{75}As	100%	3/2	−0.007	0