מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

Coloring crystals with Dark Matter

WARNING
May contain optimism!

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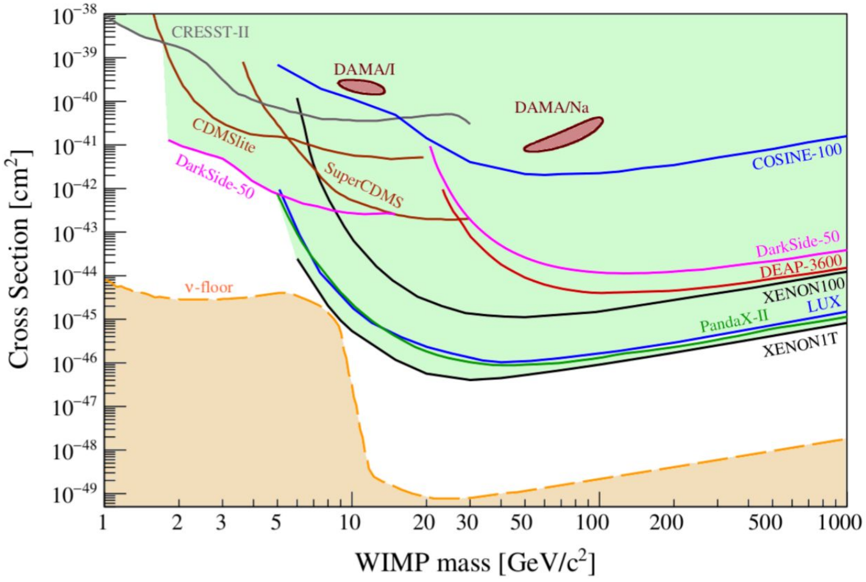
Crystal defects: friend or foe?

The state of Direct Detection Searches

1903.03026



Low energy thresholds are needed. But with great sensitivity comes great background...

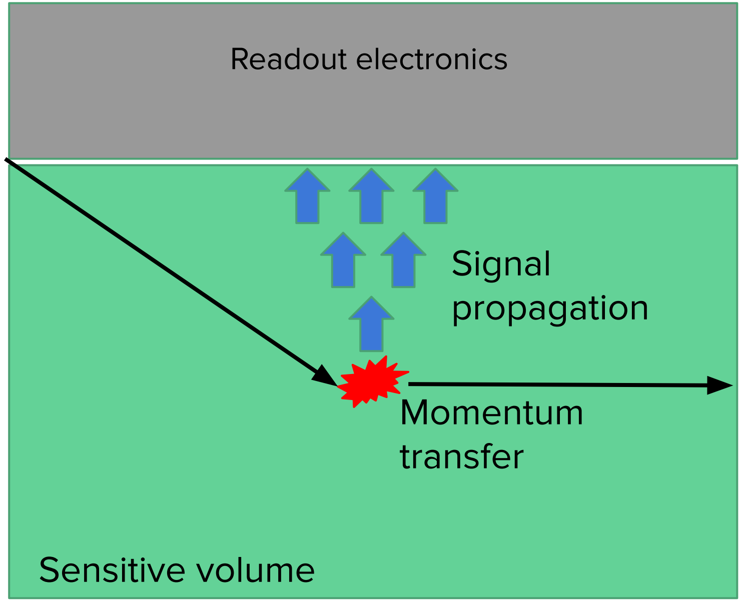
Low rates of low energy recoils pose a difficult detection challenge.

Both low thresholds and large exposures are needed.

Some context for theorists

A typical detection process

1. Interaction with dark matter excites a DoF in the detector.
2. The signal is propagated through secondary DoFs to reach readout electronics.
3. Amplification and digitization.



The signal path

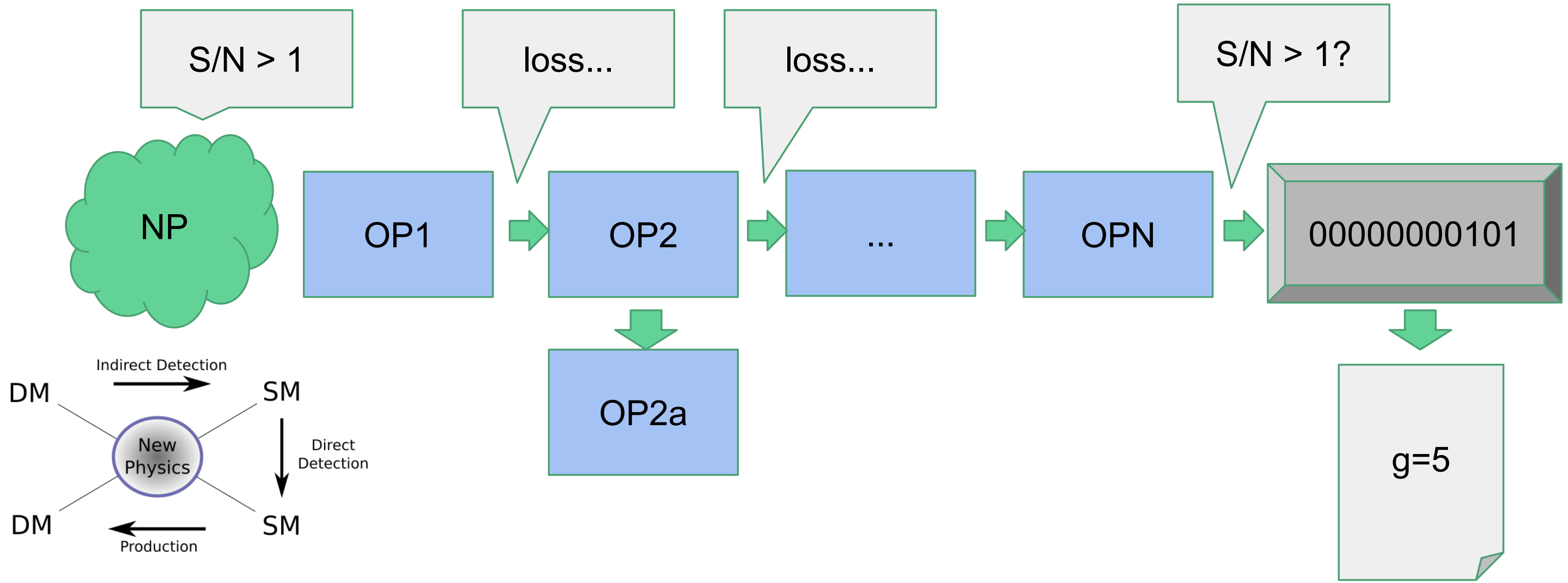


Table top experiments

“Collaboration” experiments

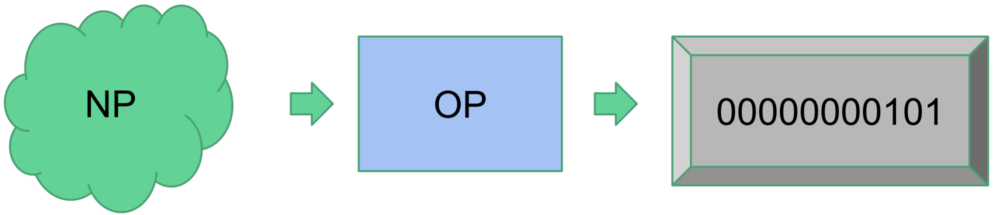
The low threshold challenge

- MeV scale masses require eV scale detection thresholds, increasing background.
- Small cross sections require large quantities of sensitive mass.

Options

1. Build a large number of small detectors - Expensive and readout noise limited.
2. Build a small number of large detectors - Need to extract a small signal from deep inside the sensitive mass and also reject large amounts of background.

Rejecting Electronic Recoil (ER) backgrounds always an issue.



Fifty shades of Sapphire*

Small defects in crystals can have a large effect on optical properties.

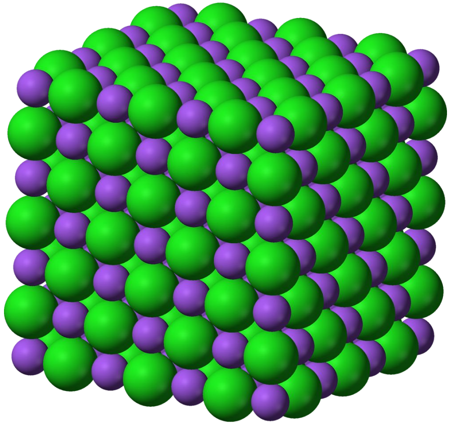
*99.99% AlO_2

Crystal defects as a detection mechanism
The best of both worlds?

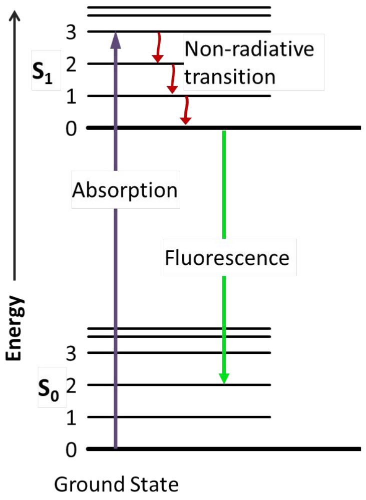
Crystal defects can have threshold energies of O(10) eV and are stable at room temperature. They can be created by nuclear recoils, and often alter the optical properties of the host crystal.

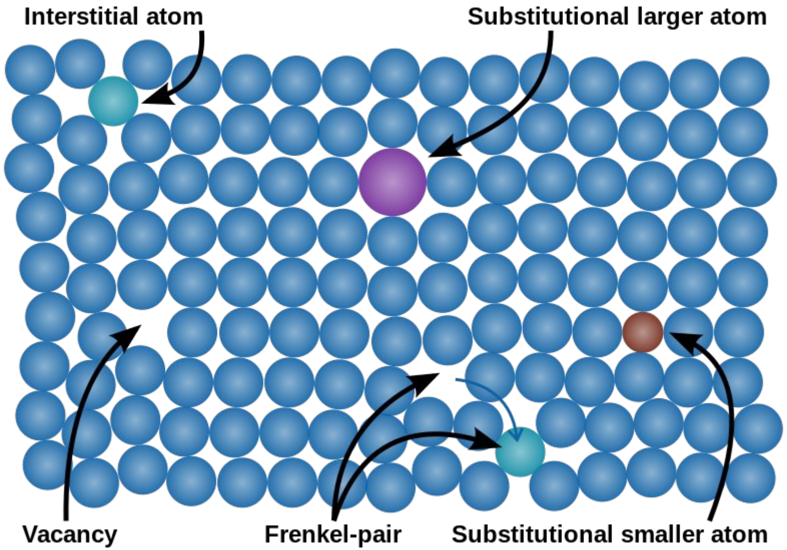
Great!

But is a single defect in a bulk crystal detectable?



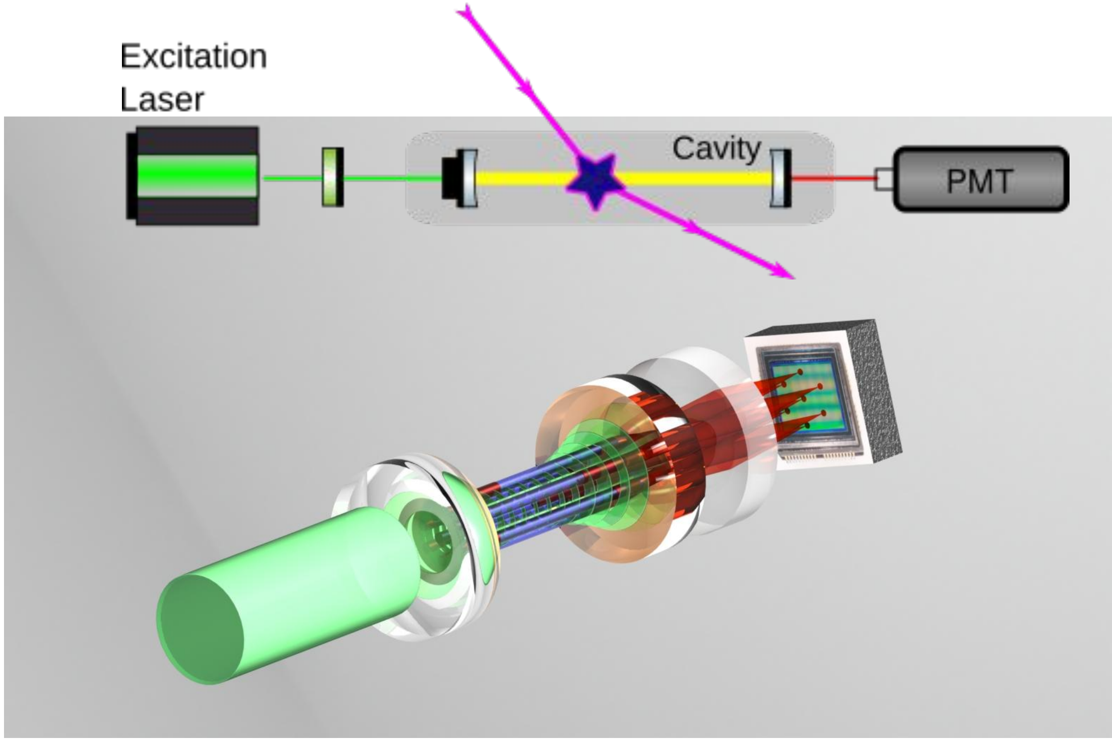
Fluorescent defects in transparent crystals





Many fluorescent defects are measurable at the single defect level.

The detector - an artists depiction



Advantages and challenges

Advantages

- Color Center are long lived and not destroyed by measurement, minimizing readout noise.
- Optical photons have very large mean free paths in many materials, allowing for large volume detectors.
- Fluorescence photons are easily separated from excitation photons, increases sensitivity to small number of color centers.
- Large mass to readout-device ratio. Many single crystals are commercially available in kgs of mass.

Challenges

- Very difficult to study defect creation and annihilation mechanisms.
- Hard to say ahead of time which crystals will be best, theory is limited. Most of the crystals being studied will not be useful.
- Existing color centers are difficult to remove.
- Can have low production efficiency at low recoil energies.

Could this possibly work?

The total signal extracted from a single "event" can be limited by the bleaching probability of the color center, intensity of excitation light, the time resolution needed and the extraction efficiency.
For a given number of photons, N_{ph} detected from each color center, and a given number of preexisting color centers for a crystal; Detecting the creation of a single color center with Nσ confidence requires:

$$\frac{s}{\sqrt{b}} > N_\sigma \qquad \frac{N_{ph}}{\sqrt{N_{ph} N_{cc}}} > N_\sigma$$

$$\Rightarrow \quad \frac{N_{ph}}{N_\sigma^2} > N_{cc}$$

Scientific reach

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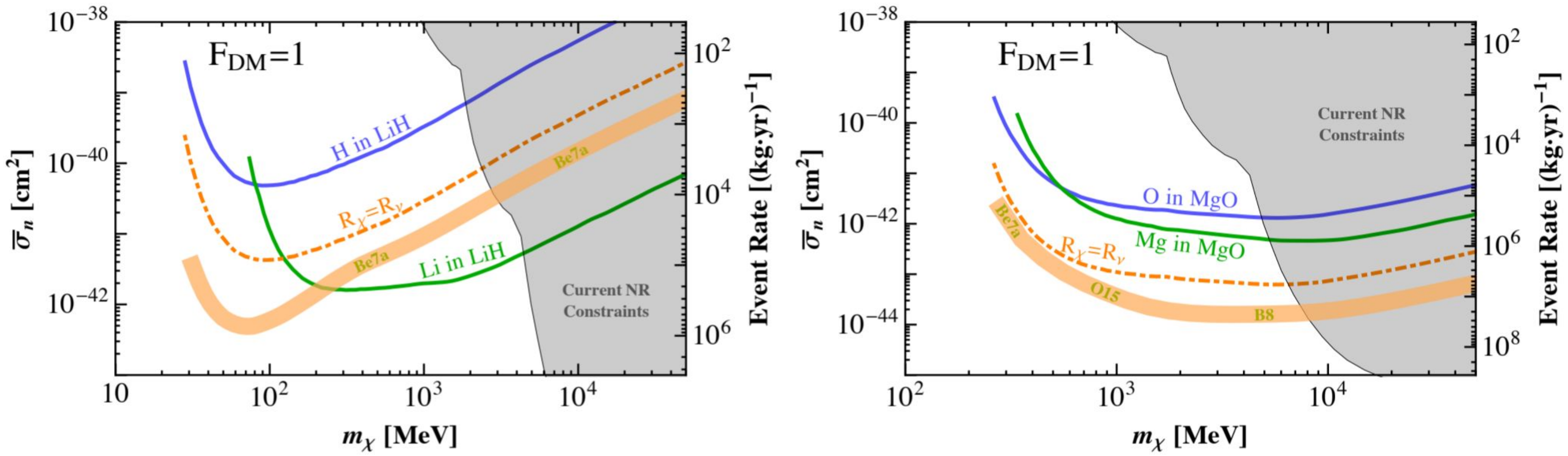

Scientific reach

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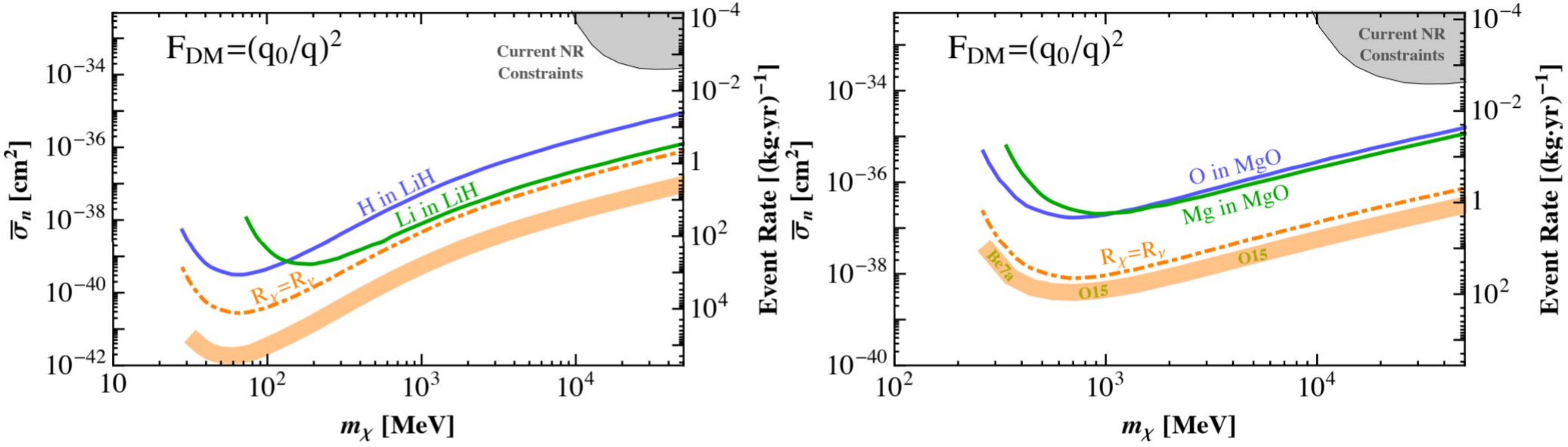

Daily modulation

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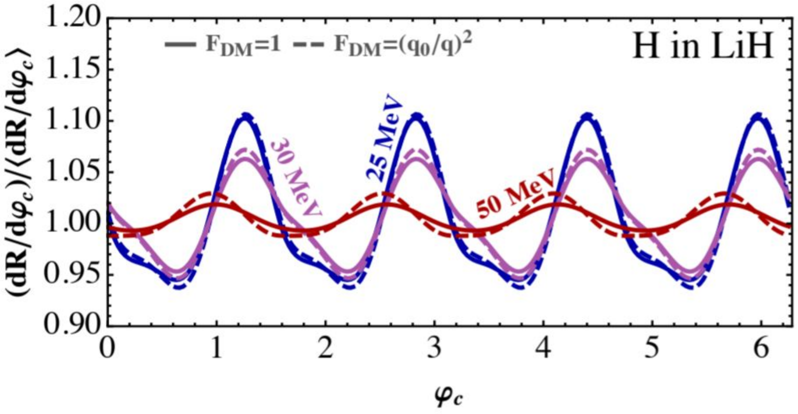
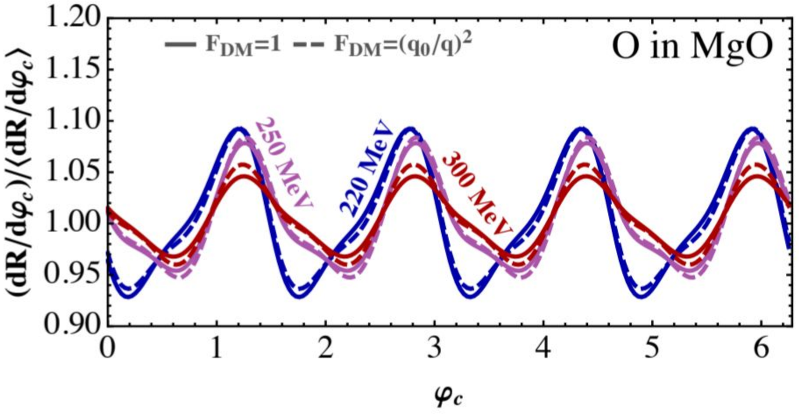




What are we looking for

- Fluorescent Color Centers.
- Detectable at O(1) defect resolution.
- Created by low energy nuclear recoils with a reasonable efficiency.

So youre telling me there may be a crystal (field) that has some excitation (particle) that can solve all our problems, but there is a huge parameter space to search in and it may not even exist?

Sounds familiar...

Strategy

Methodically scan the parameter space, starting with the low hanging fruit.

Invest resources only on most promising parts.

1. Investigate as many mass-produced transparent crystals as we can get our hands on.
2. Focused research on most promising crystal candidates.
3. Build small scale prototype detector with best crystal.
4. If it works, build full scale detector and detect Dark Matter.

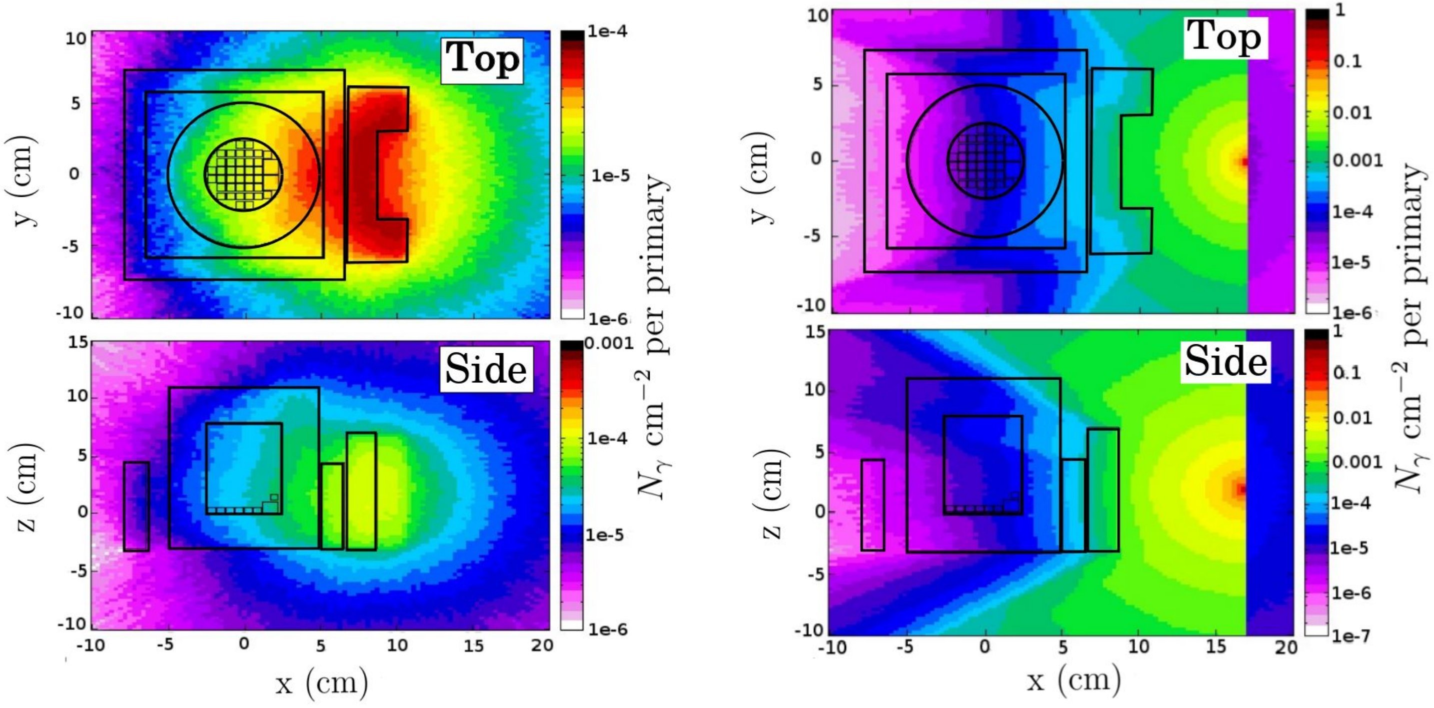
First filter: response to nuclear recoils

- ^{252}Cf source providing roughly 5e4 n/cm^2/s and 5e3 γ/cm^2/s (3 mGy).
- ^{60}Co source providing 90, 270 and 1600 mGy.

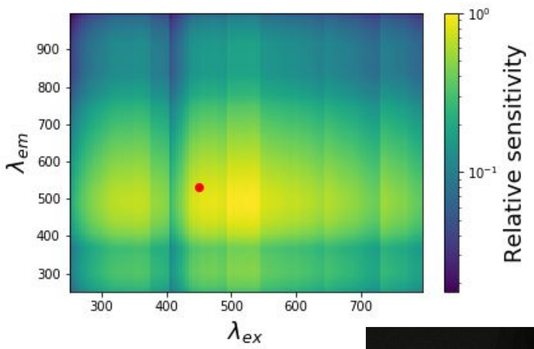
  Average neutron energy of 2.13 MeV - not representative of MeV scale DM.

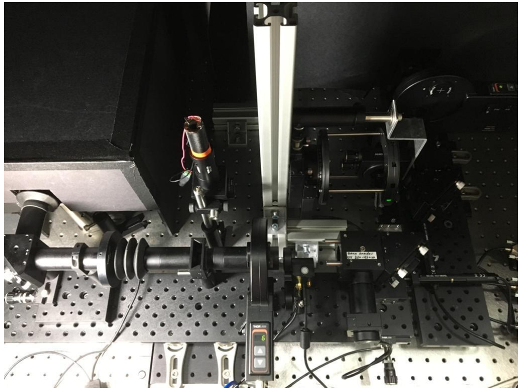
Likelihood ratio rejection of null hypothesis (signal only comes from gammas) in favor of alternative hypothesis (some of the signal comes from gammas) at a significance of 1 sigma considered “interesting”.

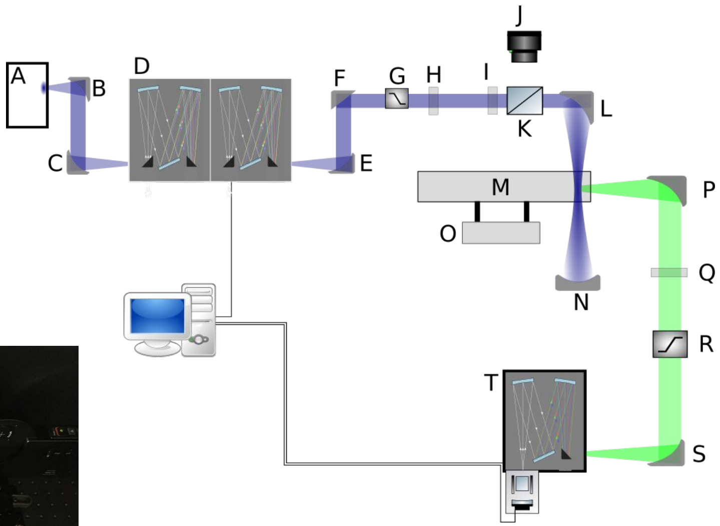
Experimental setup - irradiation campaign



Experimental setup - fluorescence



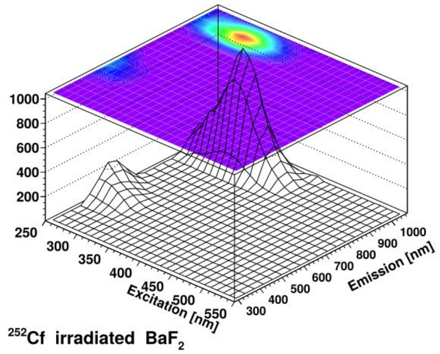


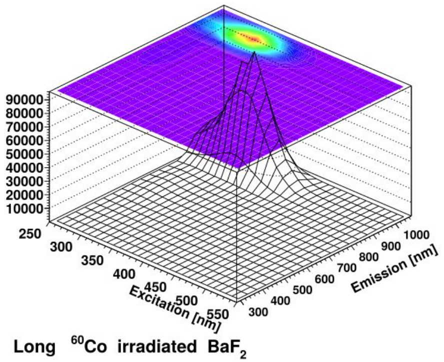


What does an “interesting” signal look like?

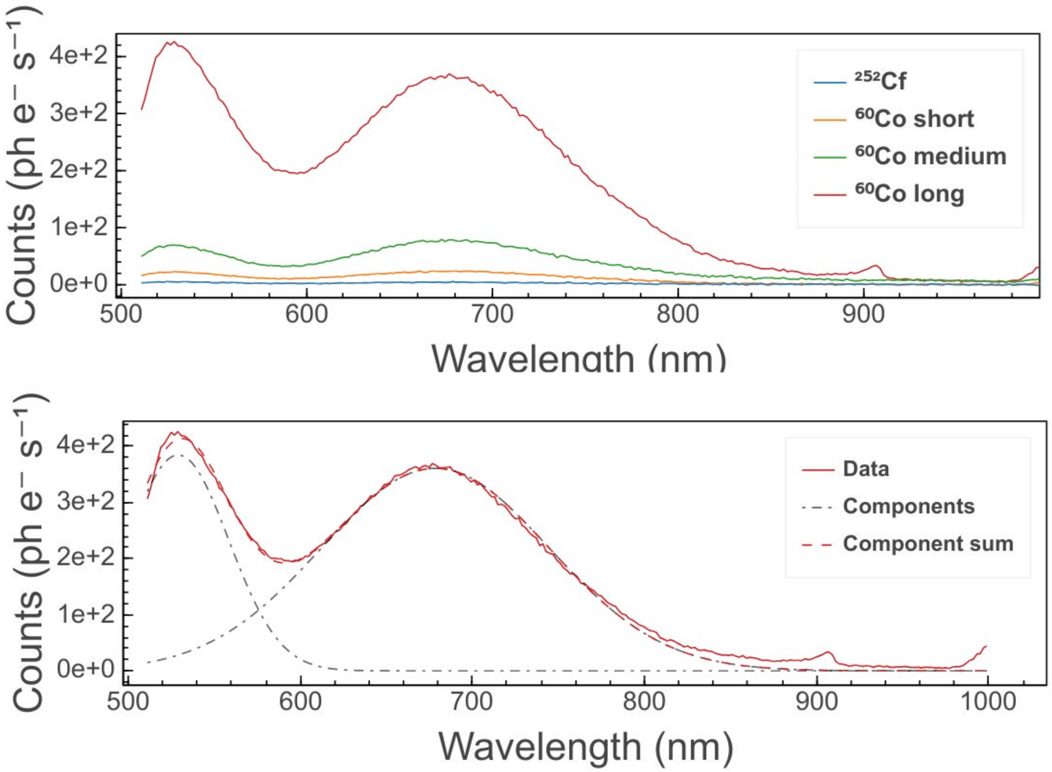
The signal with 500nm emission wavelength increases after neutron irradiation but not after gamma irradiation.

Such signals need to be further investigated.

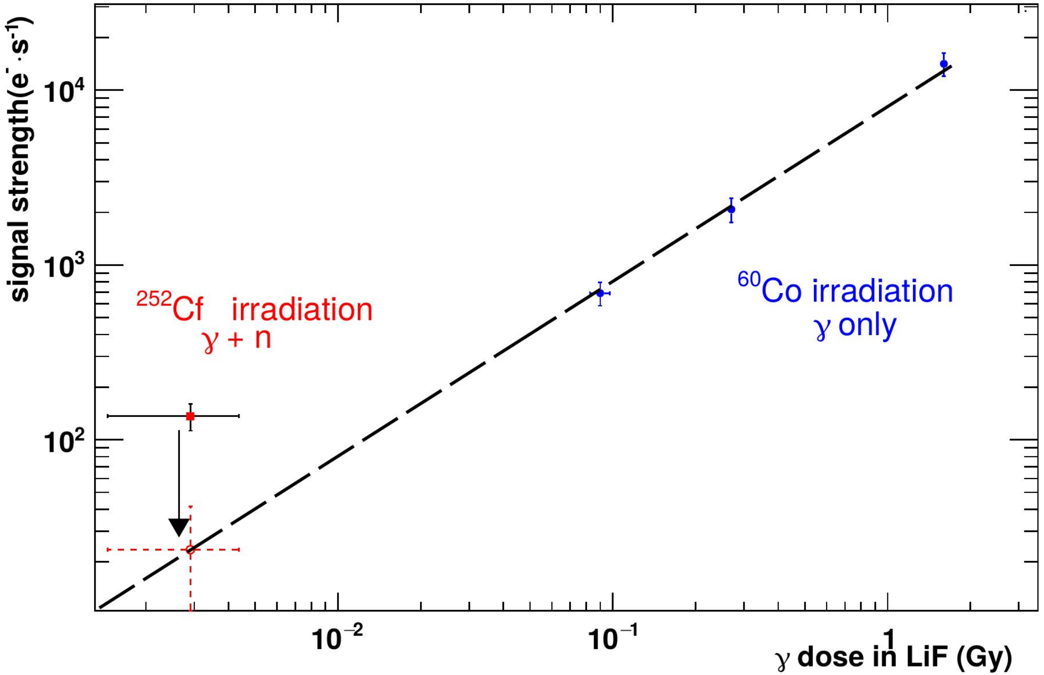




Fluorescent spectra decomposition



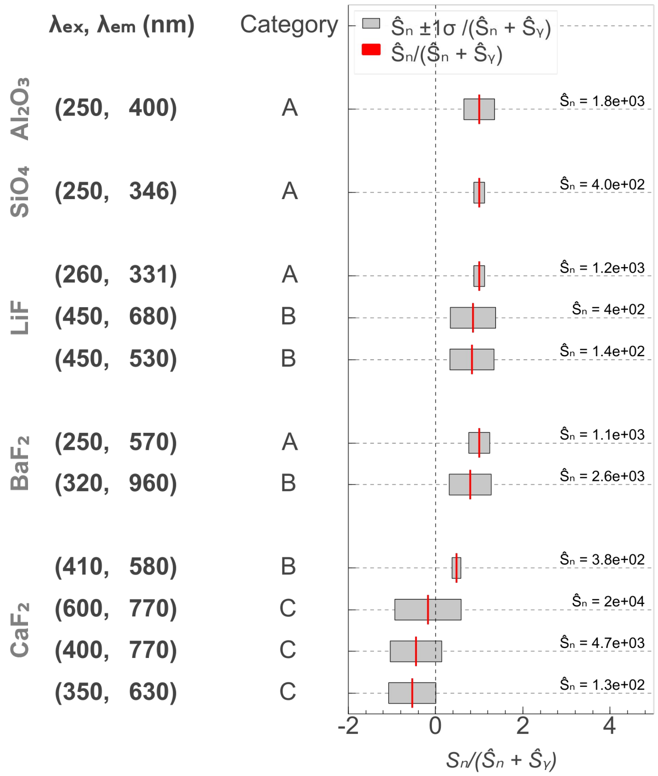
Fit to null and alternative hypotheses



Preliminary results arXiv [1902.10668](https://arxiv.org/abs/1902.10668)

Categories

A. Increased signal from neutron irradiation but not from gammas.
B. Increased signal in all irradiations with contribution from neutrons at more than 1 sigma significance.
C. Increased signal in all irradiations but no measured contribution from neutrons.



The path forward

- Analysis of irradiation with 40keV neutrons.
- Careful study of the effect of low energy neutrons in promising crystals.
- Test the maximum annealing of promising color centers.
- Develop theoretical model for specific color center production.
- Build prototype detector for best color center found.
- Detect MeV scale dark matter.

Take home message

- Direct detection of DM requires large exposures.
- Low mass wimp-like DM deposits very small amounts of energy in detectors.
- Small energy depositions in large masses are challenging to reliably extract in the readout stage.
- Readout of fluorescence can offer single-defect sensitivity in large volumes.
- Efforts to find a suitable crystal defect for DM is ongoing.

Thank You.

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