LiF as possible detection medium for Light Dark Matter

April 16th, 2026
MDνDM'26 Karlsruhe

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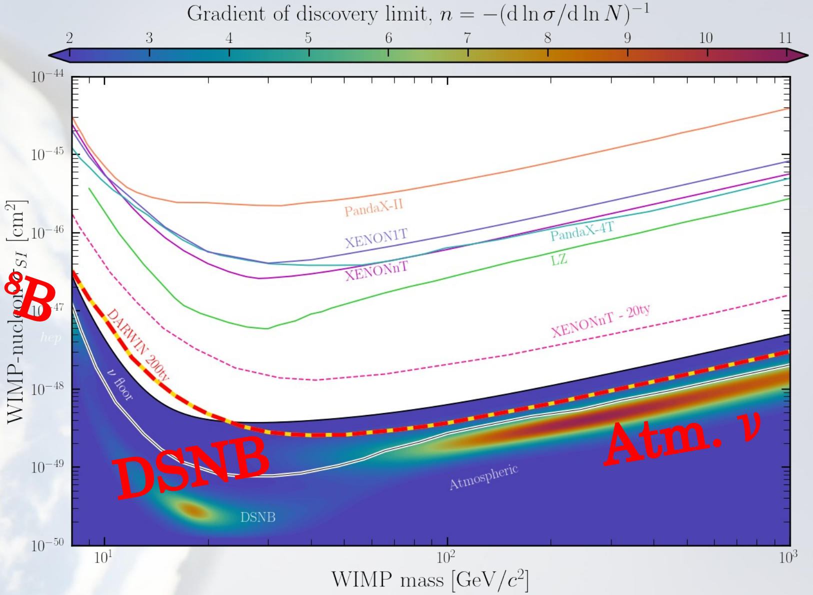
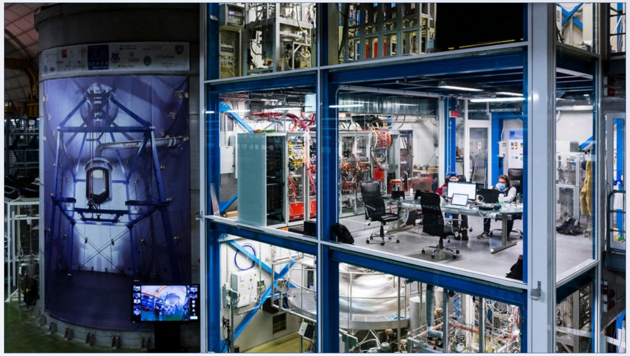
Some order

- Why CC are so interesting for Light Dark Matter?
- How can we do that?
- What we learned
- What we want to do onward

WIMPs

- We have been invested in WIMP searches for decades
- Progress: ~8 Orders of Magnitude in σ_{SI}!
- Next Gen is: 10 yr making, 10 yr data, $\mathcal{O}$ (500M$)
- Very motivated! But…





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The problem of “cost effectiveness” in BSM

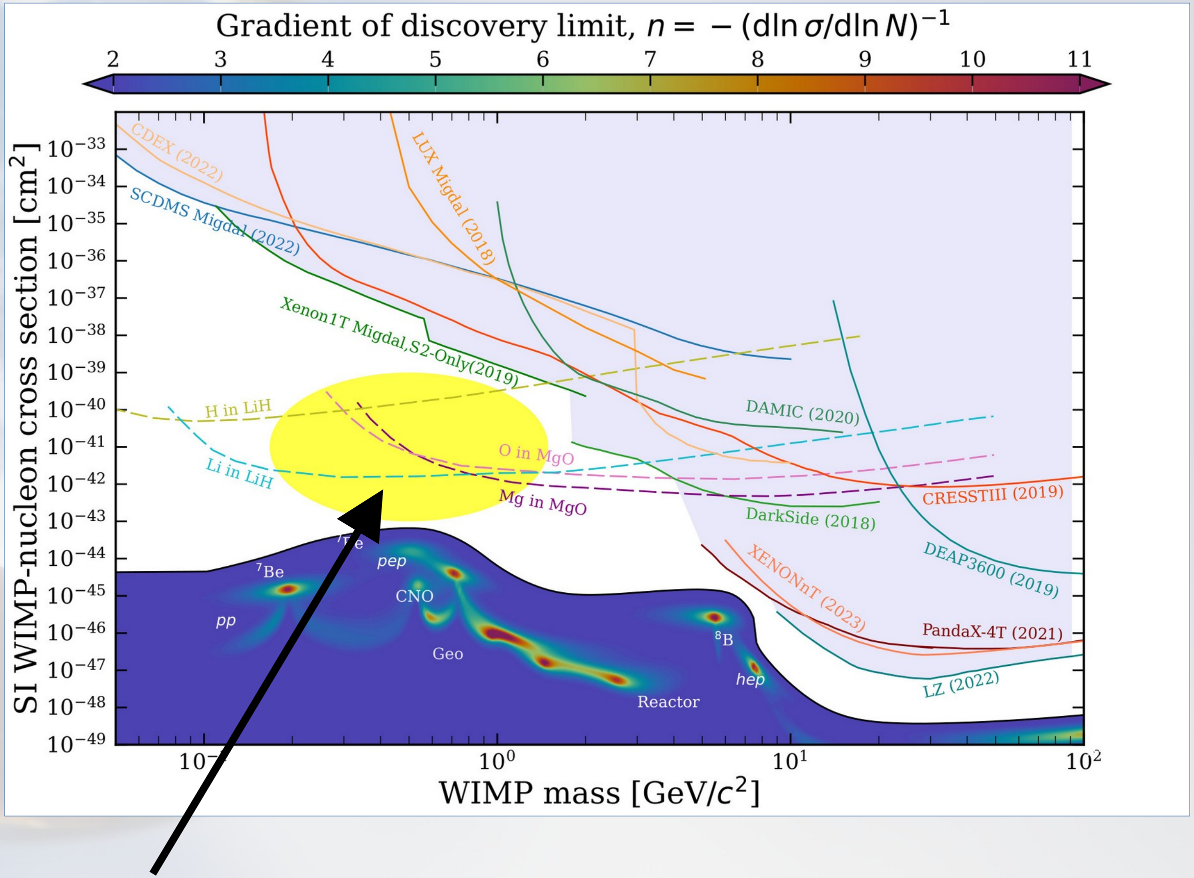
- We no longer have a “target” from theory
- We do believe that BSM is out there and can be discovered
- What should be our metric?
  - $\Delta m \times \Delta\sigma$?
  - No… tend to upper scale
- Like any scale-free problem, log is king:
  - $\mathbf{S_2 = \log_2(m_{max}/m_{min}) \times \log_2(\sigma_{max}/\sigma_{min})}$
  - A new “run” is worth if $\mathbf{S_2 > few}$
  - A new method/experiment is worth it if $\mathbf{S_2 \gg 10}$

The high-value goal: Light DM

Open a new window for Direct Detection of Light Dark Matter

Why is it **hard**?

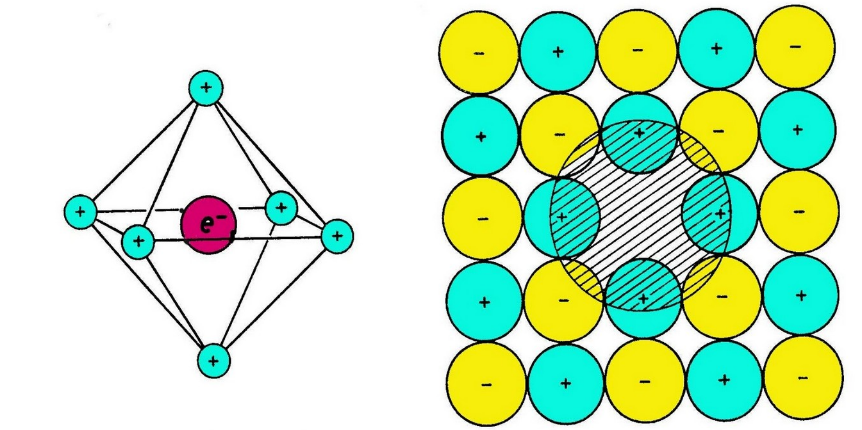
- Small number of quantas (eV range)
  - "Instrumental" backgrounds
  - Calibrating signal
  - Maturity of technologies



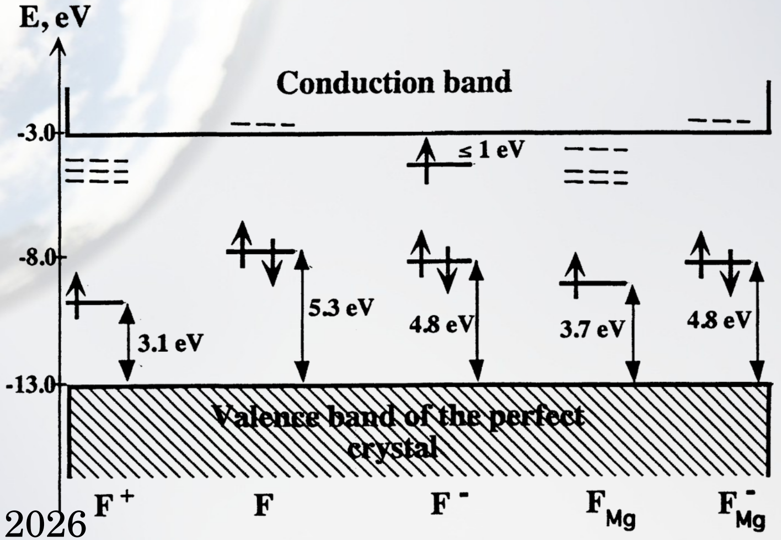
$E_R \sim m_\chi^2/m_N v^2 \ll$ keV

F-center in a nutshell

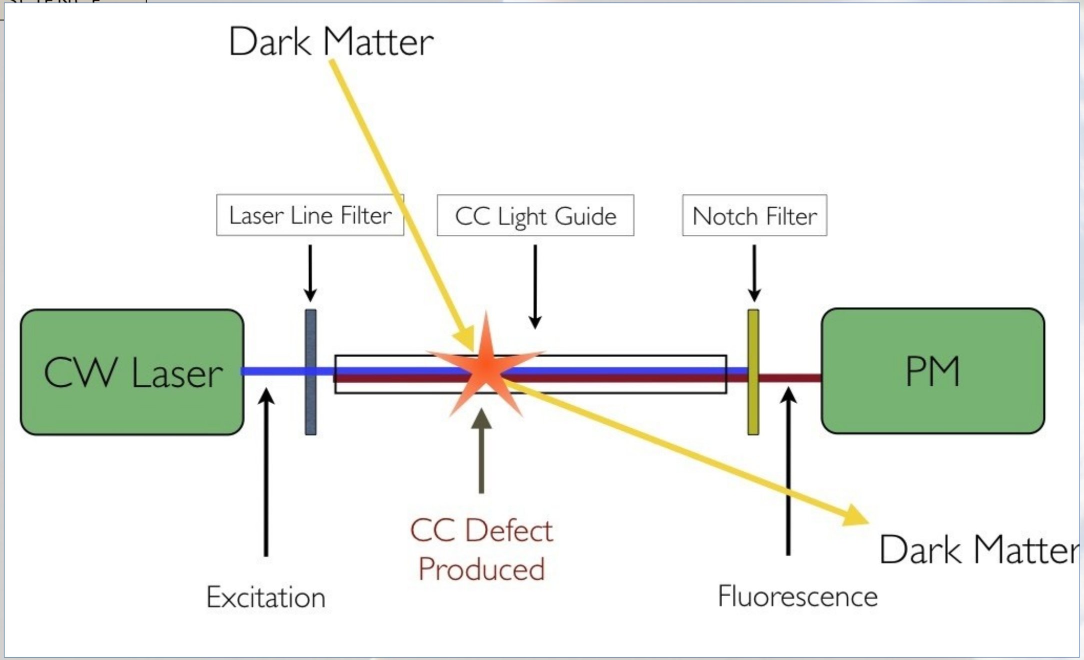
- Each type of defect has its own typical absorption and emission wavelengths
- By this mechanism a transparent medium becomes colored
- Elastic collision may produce displacement (gamma, electron, neutron and ions)



Atomic structure of the F center

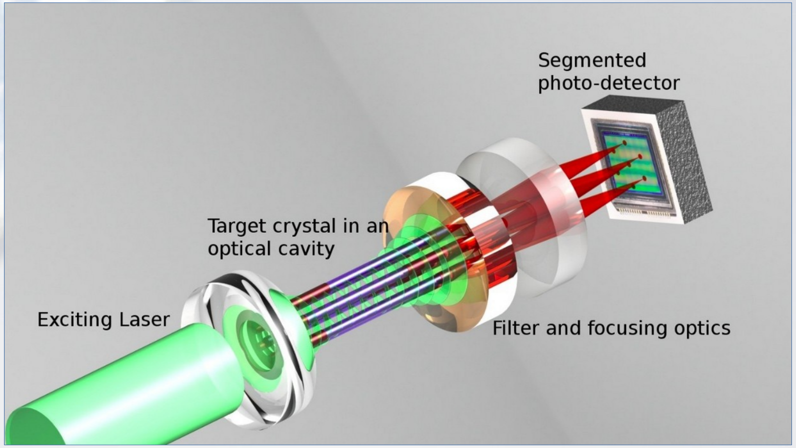


The idea - 2017



An array of single, pure crystals can be used as light-guides

Fluorescence measurement can detect the creation of a single new defect in a bulk

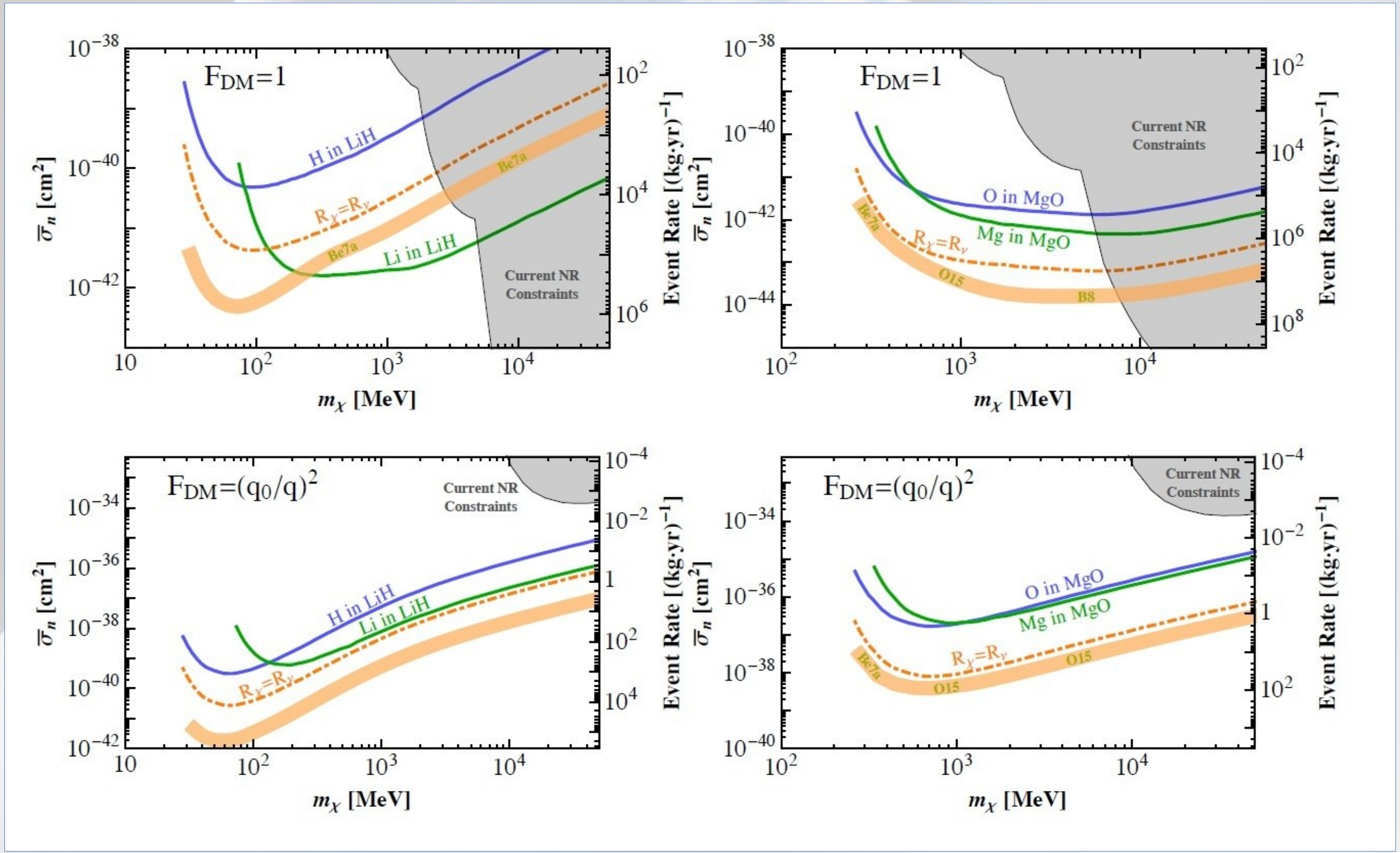


Realistic estimates show that such a setup can be able to distinguish a single new site in 10^5 existing per rod

RB, O. Cheshnovsky, O. Slone, T. Volansky 1705.03016

Physics reach (2017 ideas)

With 1 kg·yr



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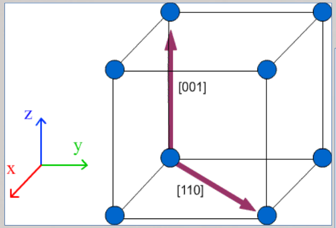
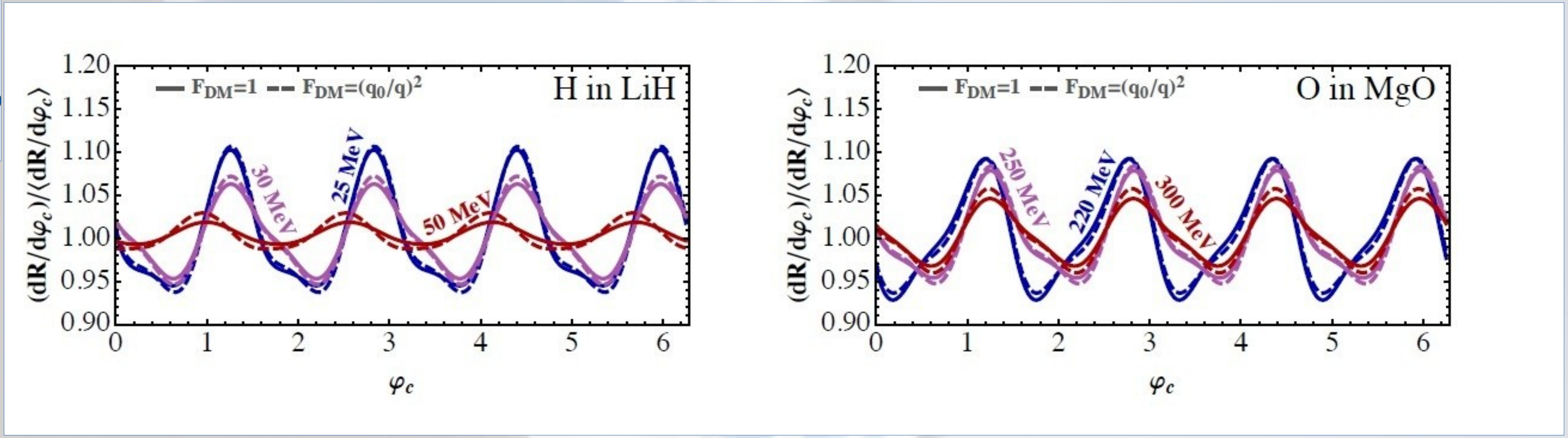
Modulation and directionality





- Hourly change of orientation relative to DM wind
- Modulated rate differs from solar direction (4 min/day), day/night, season
- **Strong especially near threshold**
- The smoking gun of Galactic origin

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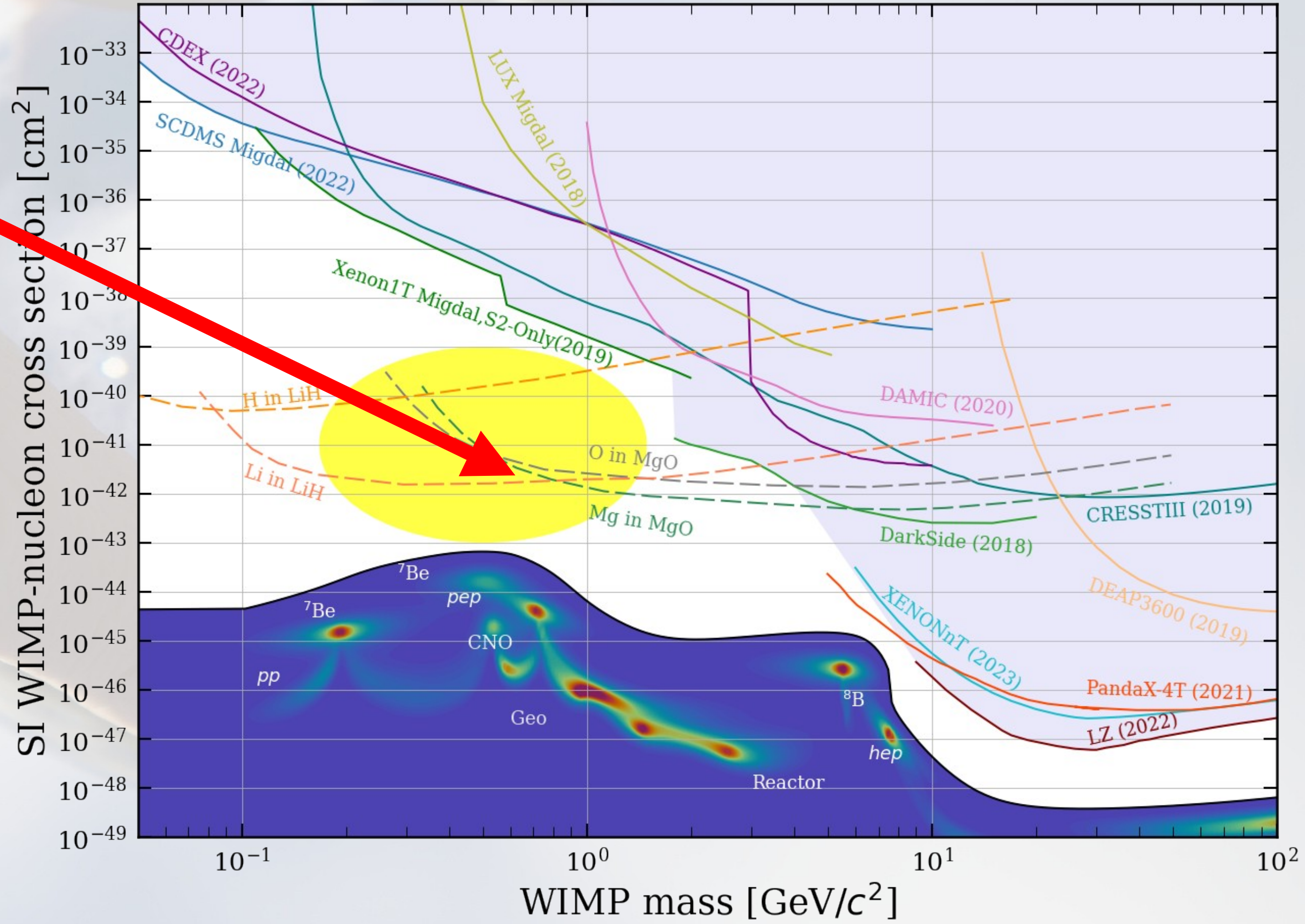
Physics Reach

"The Dream":

Finding single defects in a ~kg target



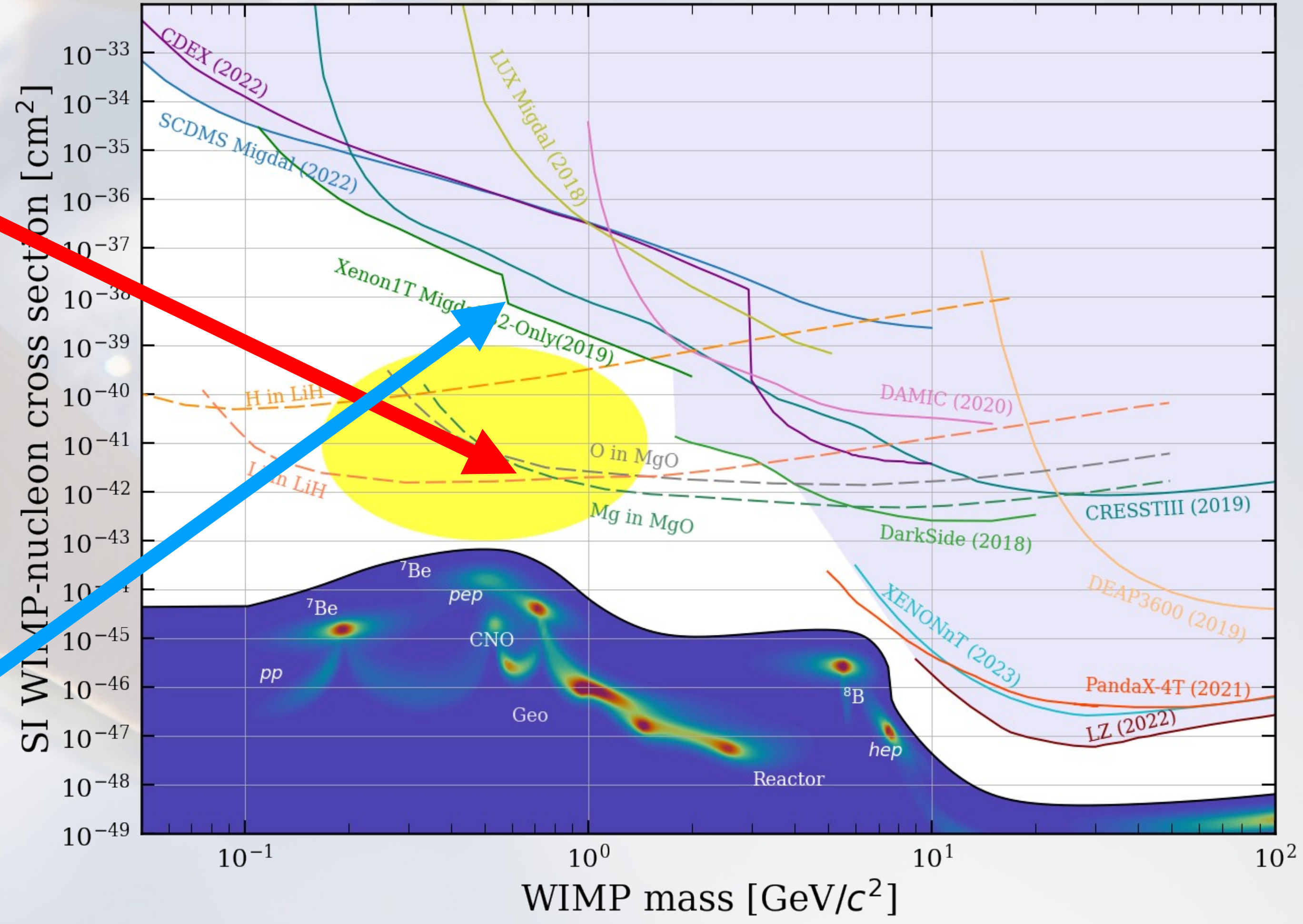
Physics Reach

"The Dream":

Finding **single** defects in a ~**kg** target

The reasonable near future:

Finding **100** defects in a ~**g** target



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Why Is This Hard?

The principal challenges — and why they matter

Needle in a Haystack^2

Find the Color Center that answers everything: computationally "impossible"

Detect 1 new site in 10^5 existing per rod. Single-event sensitivity requires exceptional optical stability.

Crystal Purity

Contaminants at 10^{-17} levels required. Any **impurity may create its own optically active defects**.

Calibration

O(keV) neutrons needed — non-trivial source geometry and flux characterization.

Background Discrimination

α, n, γ, β, ions all create color centers. Must attribute signal to DM specifically.
Instrumental backgrounds: optics, readout, thermal...

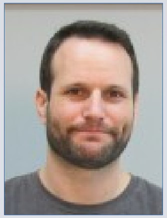
Bleaching

Laser illumination itself **destroys the signal**. Must characterize and manage carefully.

Three Annealing Processes

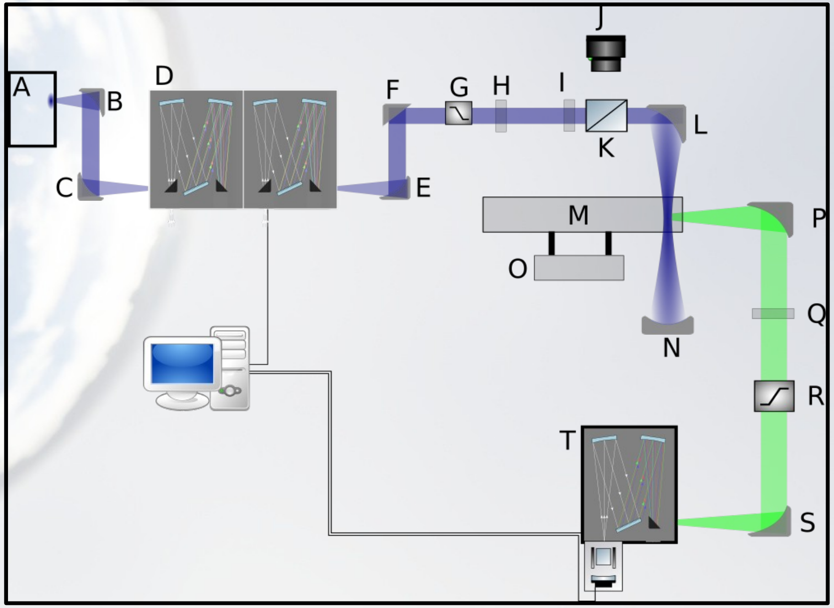
Optical bleaching ≠
thermal electron release ≠
true site healing.
Each different at different temperatures.

First actual step: 2019



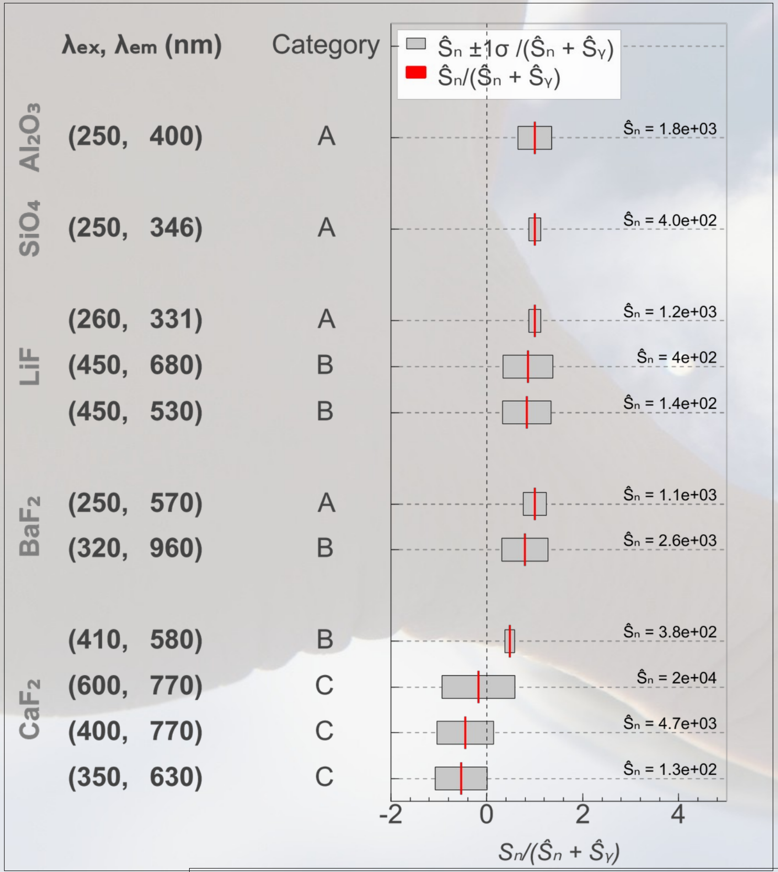
What we did

- **First systematic search for CC candidates for DM detection**
- Found 11 interesting color centers across 5 (**out of 10**) crystal materials: LiF, MgF_2, CaF_2, Al_2O_3, SiO_2
- Irradiation: ^{60}Co (γ) and ^{252}Cf (neutrons): low doses
- Purpose-built broadband optical system designed from scratch
- **→ Sensitivity down to 10^4 cm^{-3} defect density**
- **This paper provided the community with a "materials shortlist"**



Mosbacher et. al. :1902.10668

First measurements – “full scan”



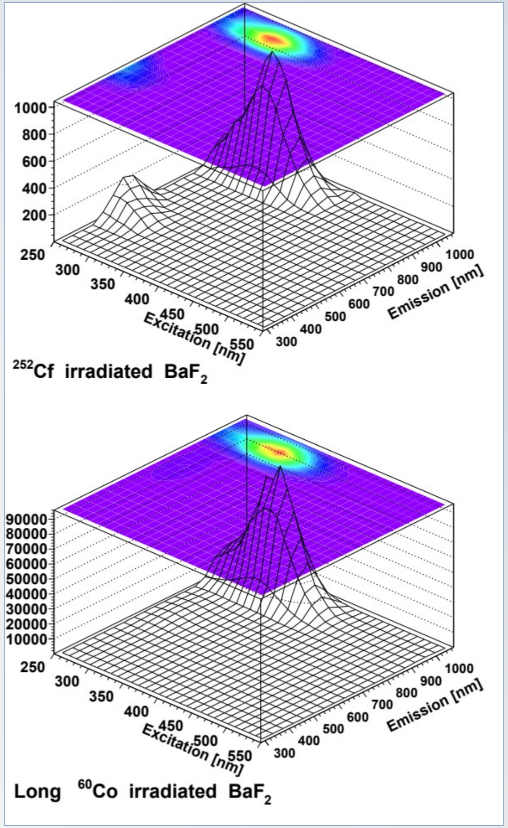
Mosbacher et. al. :1902.10668

- Measurements of gamma and (high E) neutrons
- Several “interesting” points identified
- More measurements with low E neutrons underway
- Down to **10^4 cm^{-3}** sensitivity

Category A: neutron-only → pure NR → ideal for DM

Category B: n + low-dose γ → needs discrimination

Category C: Only γ



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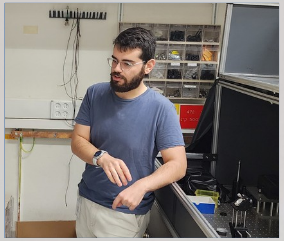
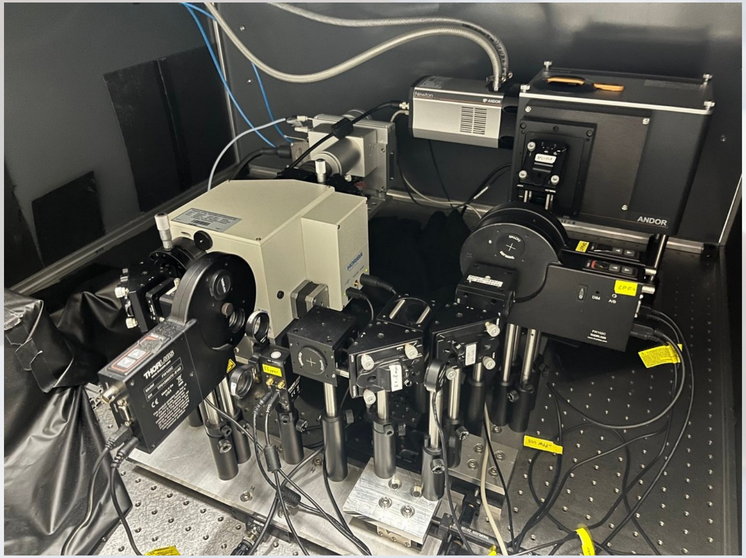
2023-2024 – A true candidate is showing up!

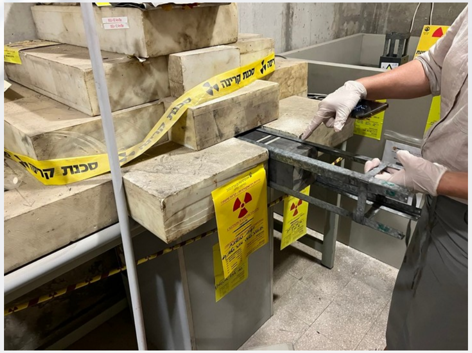


Improved stability and systematics on the optical system (3CS): Wide Band



Irradiation Sites: WIS ^{60}Co (~0.3mCi)

Irradiation Sites: BGU AmBe (~2Ci)

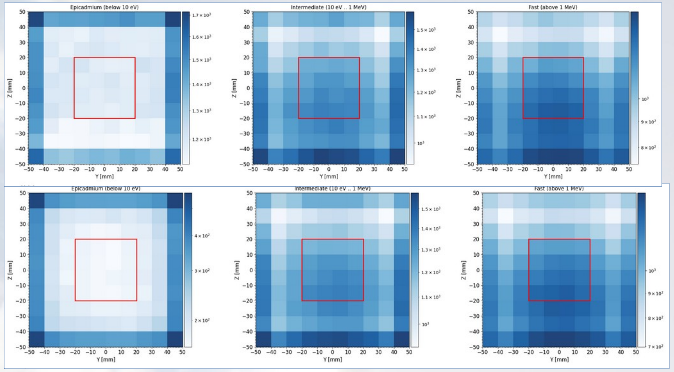


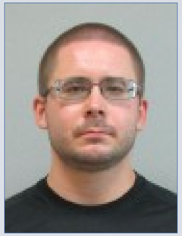
2023-2024 – A candidate!

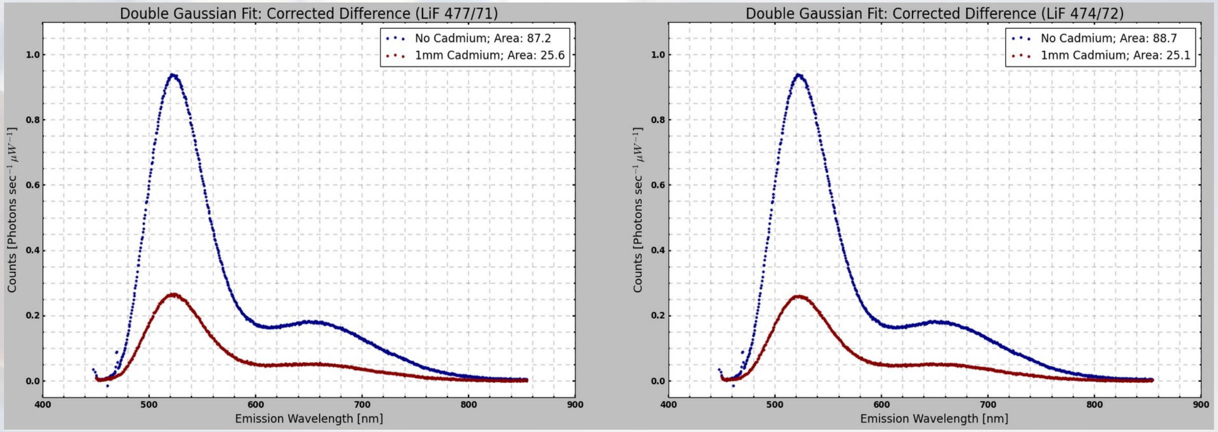
- LiF showed two "B-center" large excess.
- Known to be produced by thermal neutrons, we measured with Cd shield – expect factor 9 reduction
- Reduction is ~X3
- Ongoing improvement on sensitivity for cross-checks

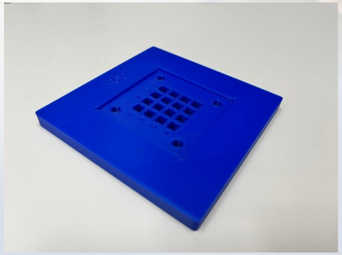
No Cadmium

1mm Cadmium





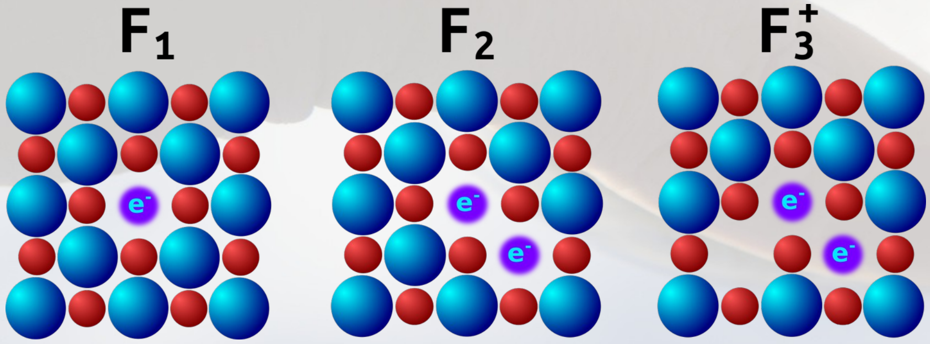


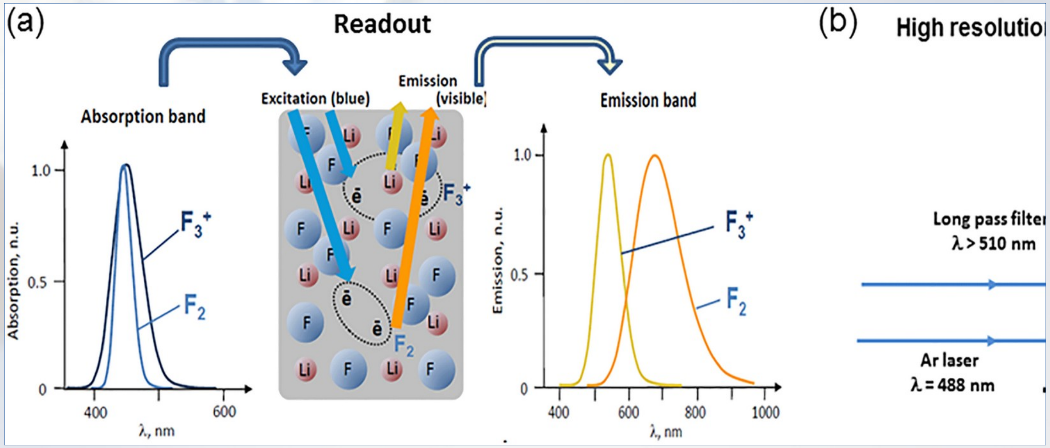


(γ contribution found to be negligible)

What is it then?

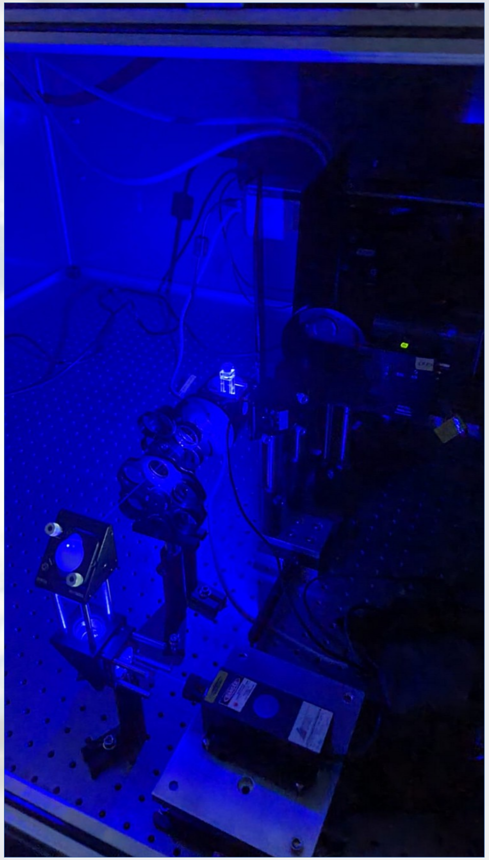
- Two centers are created: F_2 and F_3+
- Known to be created by n-capture
- Not the "simplest" F_1 – this one is in the deep UV (A-center) – for future studies
- Threshold estimated at 16 eV - 20 eV
- "Easy" spectroscopy





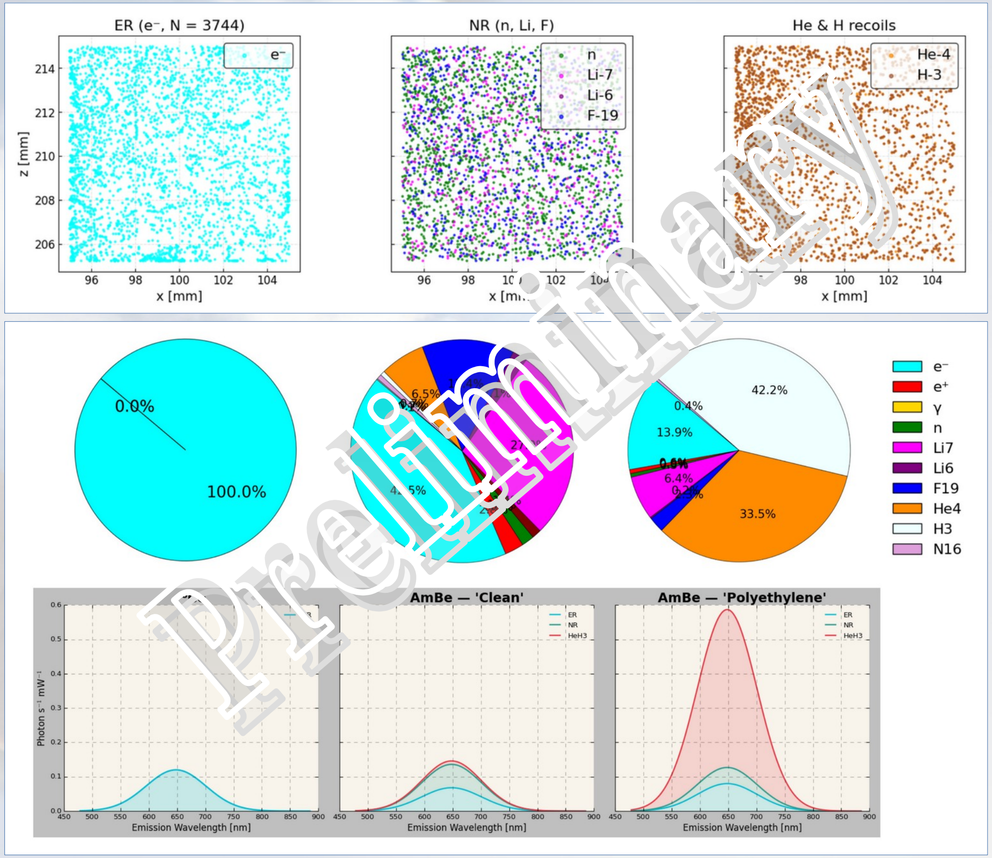
2024- Upgrading optics and deep studies

- New Lasers-based system
- Focus on LiF two centers, mostly F_2^+
- Larger, cleaner crystals with sensitivity for ~10^3 lower signals
- Goals:
  - Solidify the NR response
  - Study yields
  - Study Quantum properties
  - Study annealing
  - Study Bleaching



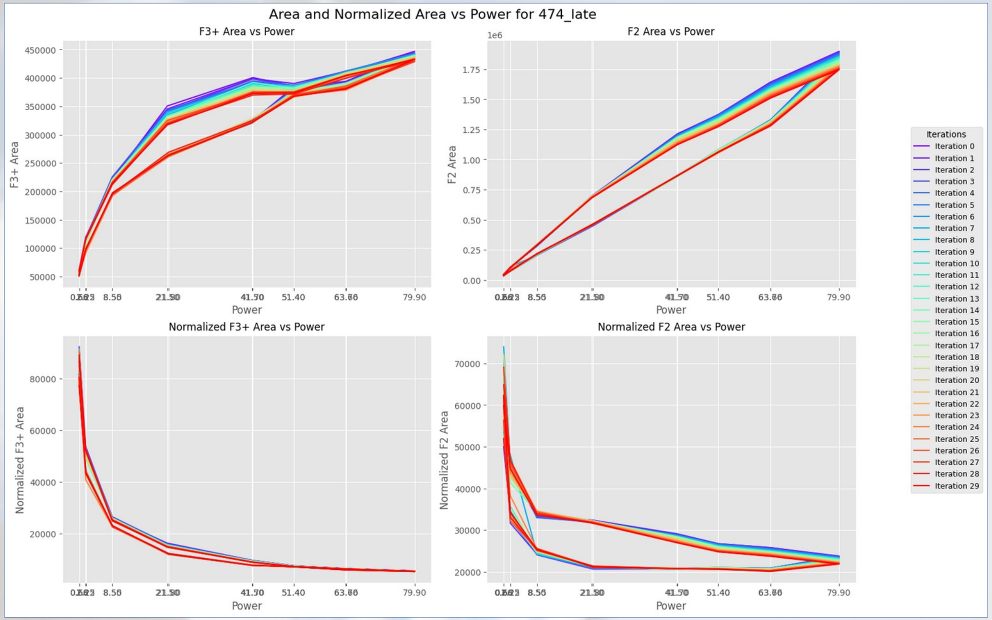
Yields: LiF works as an NR detector!

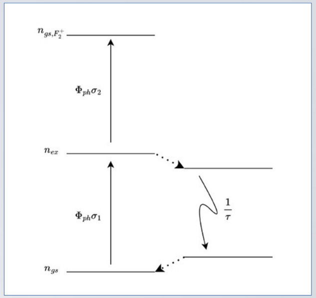
- Separating the contributions of 3 sources we found the yield of each in CC:
  - NR
  - ER
  - Fission
- Estimates are ~300 eV per active site created with NR
- Not yet testing lowest thresholds

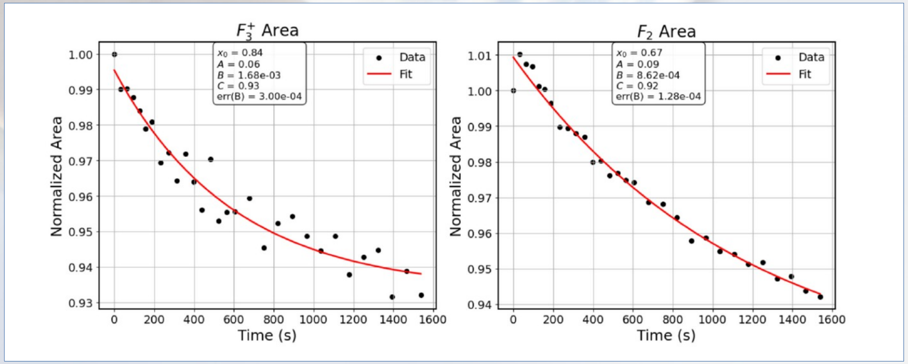


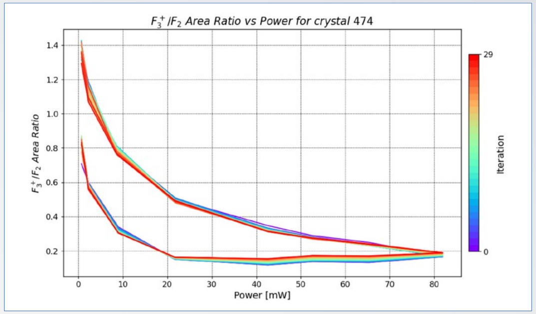
2025 – Quantum properties

- Studying temporal structure (>1 s resolution) with varying intensities
- Results are **non-linear** and **non-reversible***
- Bleaching:
  - F_2 shows "permanent" bleaching; to be tested as ionization to F_2^+
  - F_{3+} shows more resilience, recovers
- We use these to:
  - Establish **detector-like working points**
  - Study the **quantum structure** of the signal



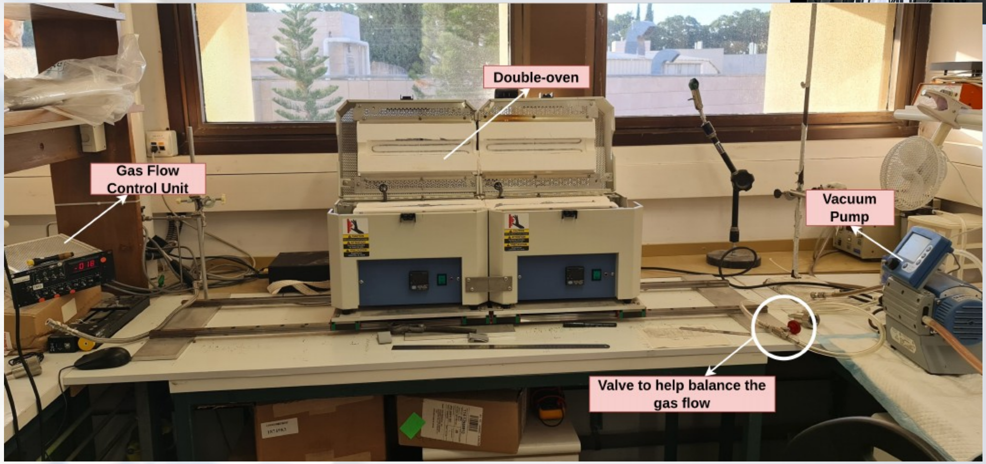


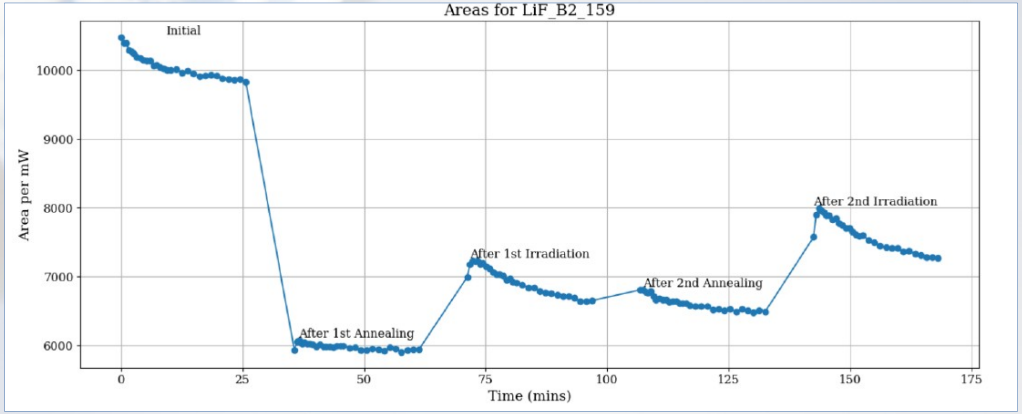




Annealing

- We tested several annealing protocols: **Temperatures, atmosphere, rate**
- **Cycling** through γ→ annealing→ γ→ …
- The requirements are minimization of output on signal channels repeatedly
- We have a **preliminary working point**; It will need updates with more sensitive devices





Comparing "All light" vs. "Imaging"

- Both systems have benefits, especially for the basic study
- In the long run, may combine in some way

- All light
  - Low threshold
  - No position *
  - No discrimination *
  - Higher exposure
  - sensitive to existing defects

- Imaging
  - Positioning
  - Discrimination
  - Track directionality
  - High threshold *
  - Slow readout *

Next for Color Centers

- Cross checks and high sensitivity LiF F_2
  - Aiming at a demonstration for in-situ detection
  - Study bleaching, annealing, purity, backgrounds, spectrum…
  - Theory – a huge gap, some growing interest is showing
- Testing LiF F_1 and other A-centers with a UV Laser
- Continue tests on other crystals

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Summary

- The range of DM masses below a few GeV is well motivated, however largely unexplored
- The challenges are significant, slowing progress for years
- New and old ideas combine to reach this space, relevant also for other low E physics such as CEνNS
- Color Centers in good-old LiF are under the microscope now!
- Stay tuned ...





The End

R. Budnik   April 2026