Crystal defects as LDM detectors

Ranny Budnik

Y. Mosbacher, M. Weiss, N. Priel, H. Lansman (WIS)
A. Kreisel, I. Eliyahu (SNRC)
T. Volansky, O. Chechnovski, O. Slone (TAU)

Department of Particle Physics and Astrophysics
Weizmann Institute of Science

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The Color of Fancy Sapphire

Developing a novel light dark matter detector

All are Al_2O_3 >99.99%

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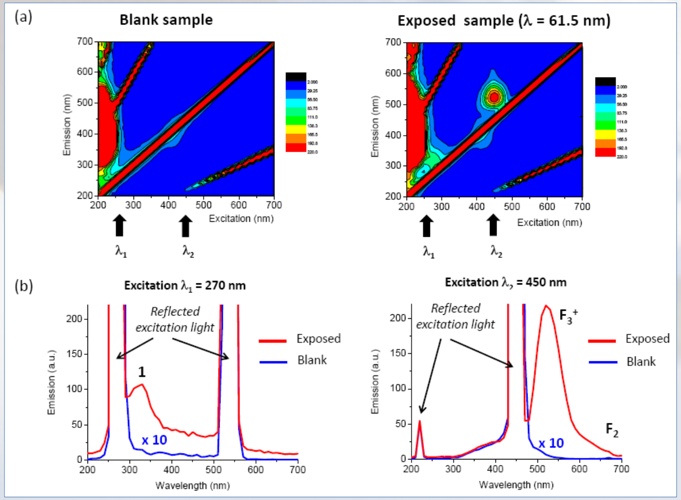
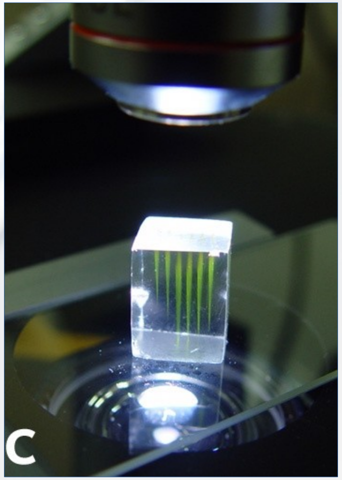
Color Centers

- It is known for many years that radiation damage gives color to transparent windows near e.g. nuclear power plants
- There are various mechanisms causing this effect, and the incident radiation can be gamma, neutron or charged particles
- Similar to the well-studied NV-center, however with a huge variety





Color Centers (LDM Fermilab)

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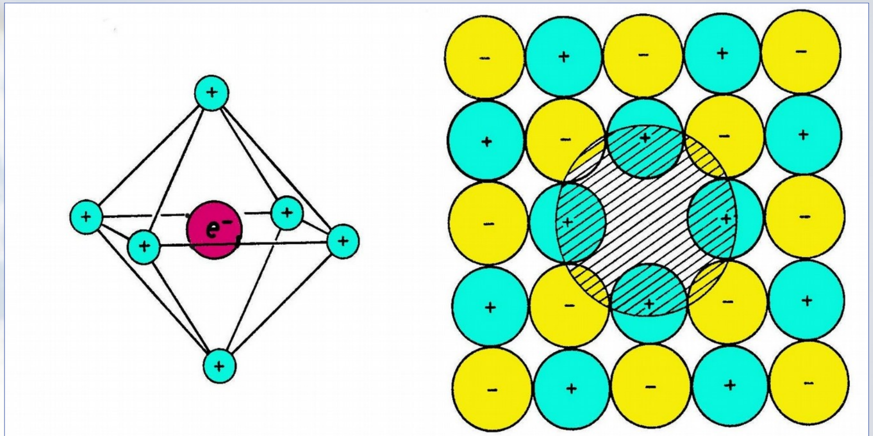
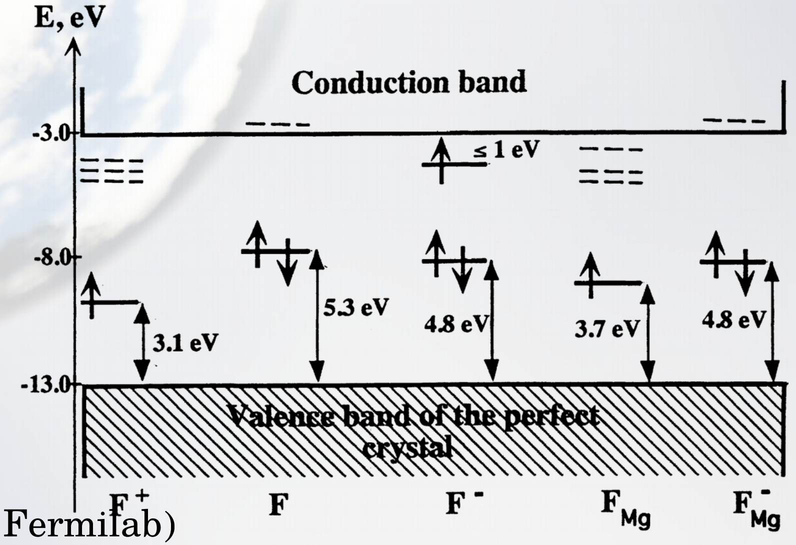
F-center in a nutshell

- 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



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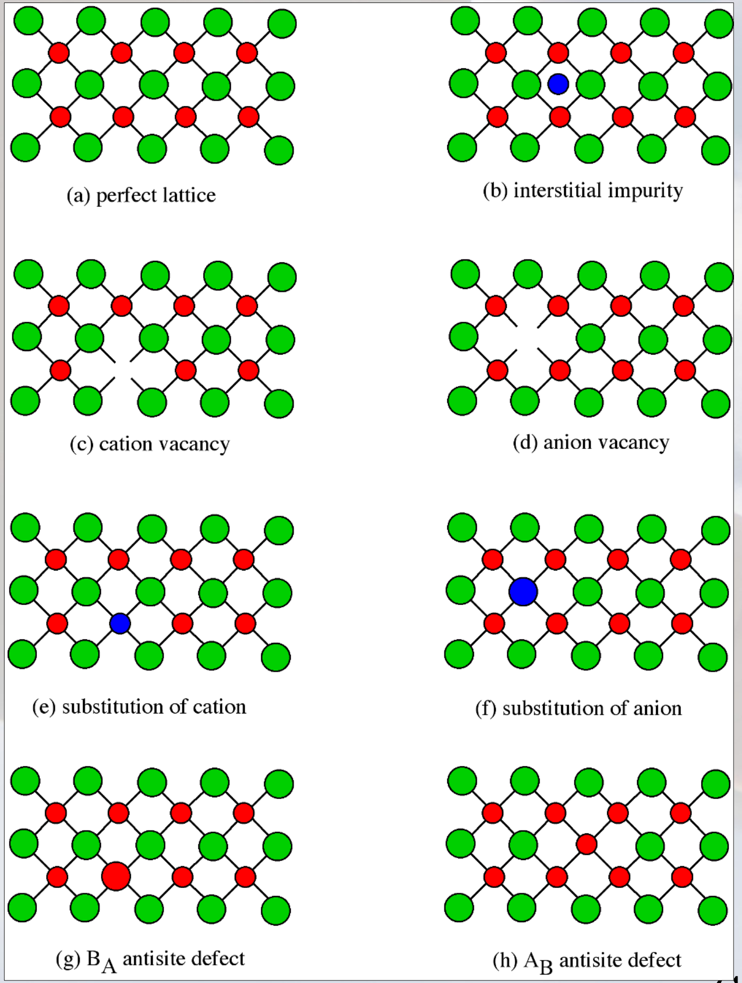
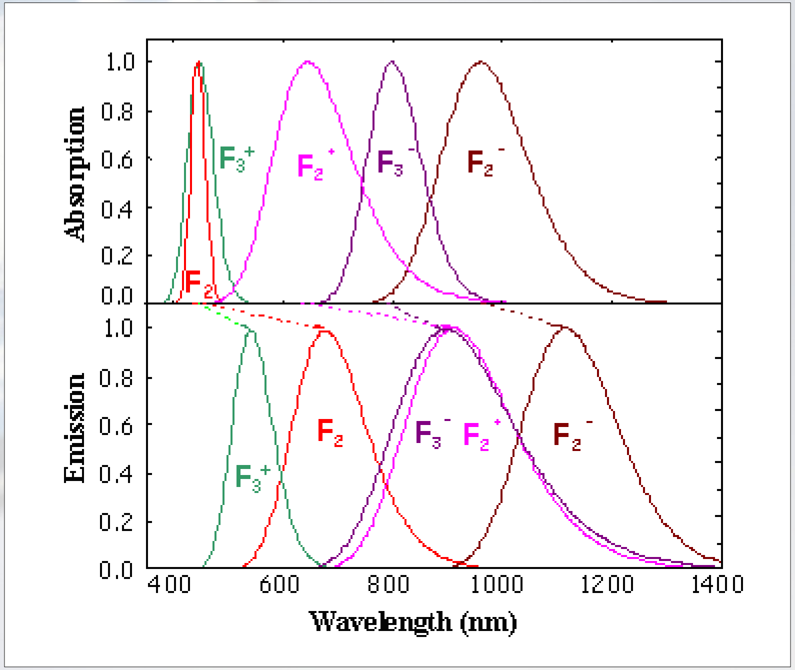
Known states of Ionic crystals

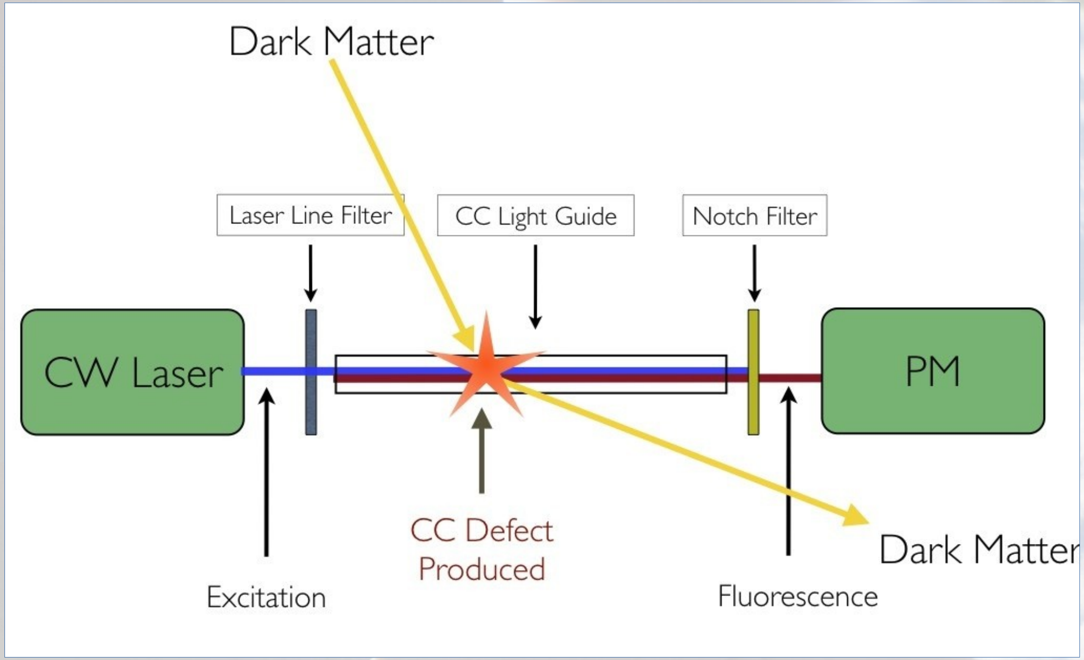


F-center

A vacancy filled by an electron can exhibit fluorescence.

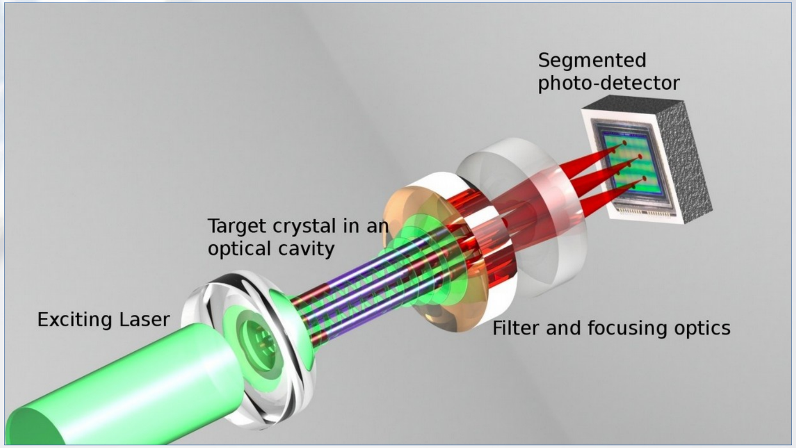


How can we use it?



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

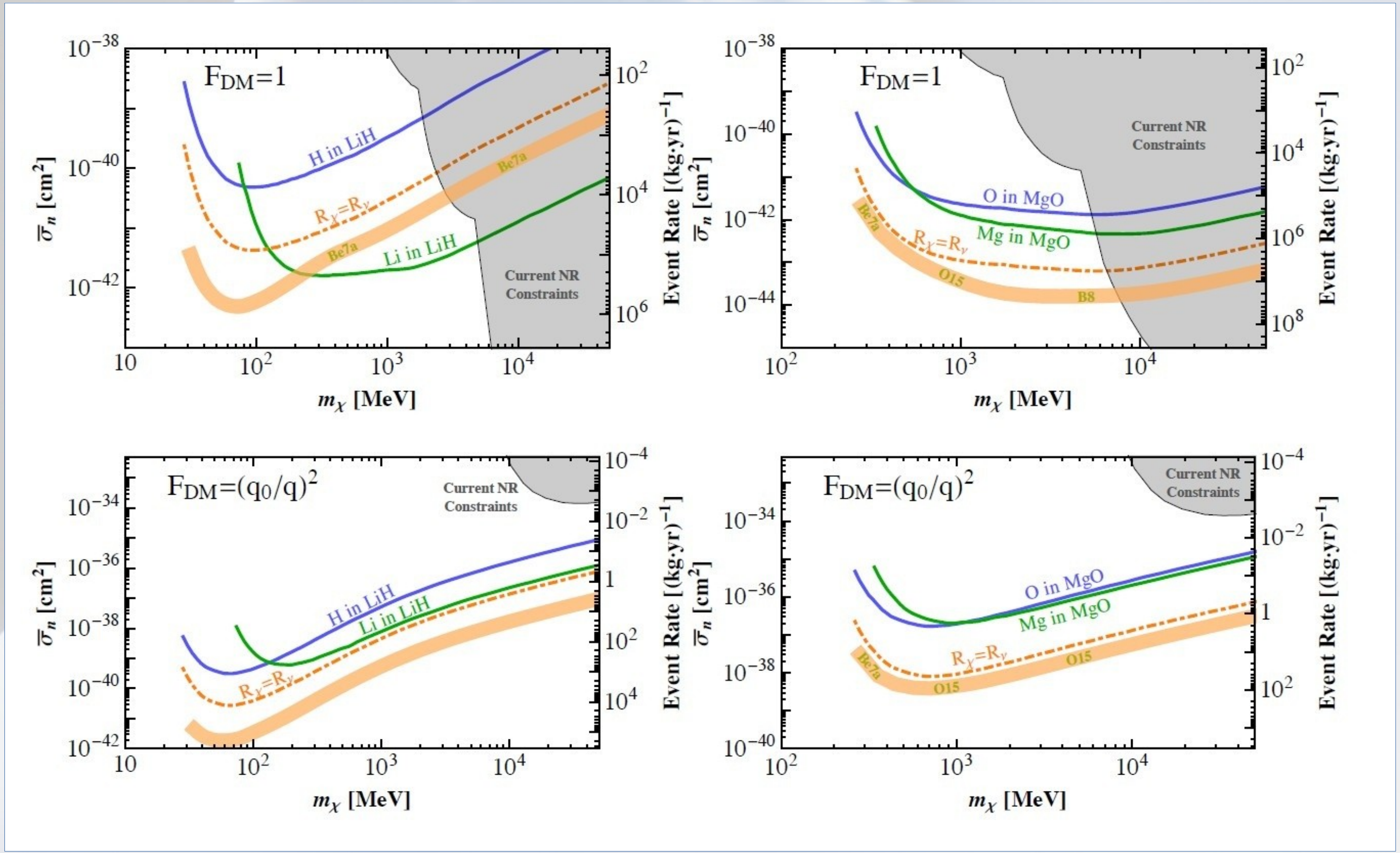
Fluorescence measurement can detect the creation of a single new defect in a bulk



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

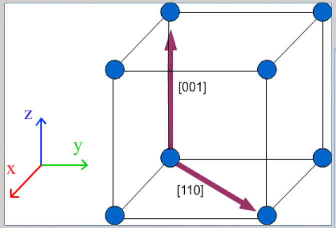
Physics reach

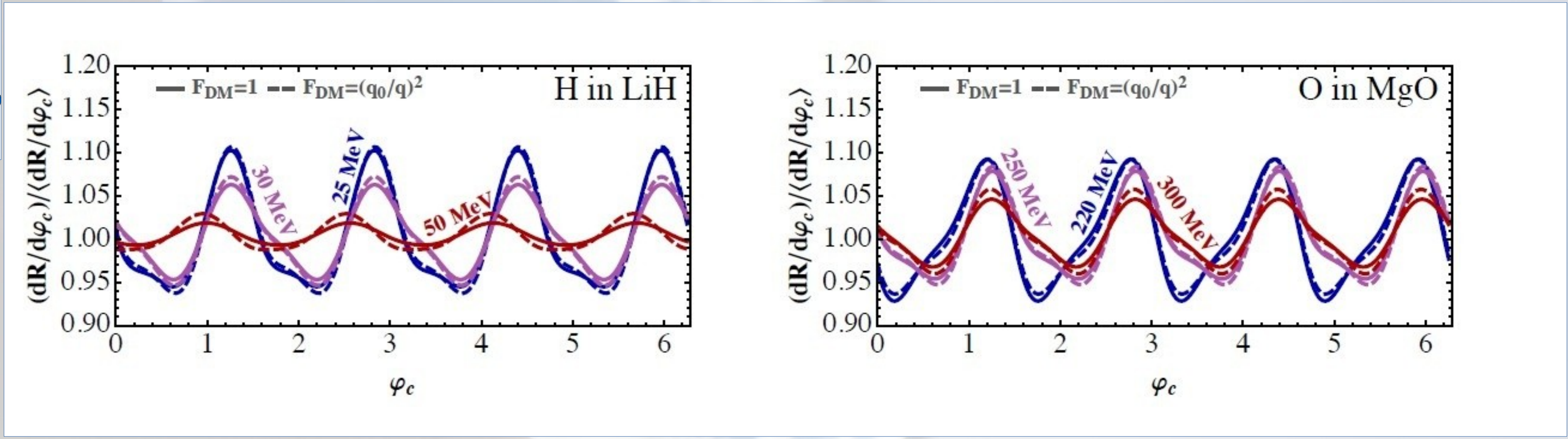
With 1 kg·yr



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

Modulation and directionality





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

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Color Centers (LDM Fermilab)

Color Centers – why is it hard?

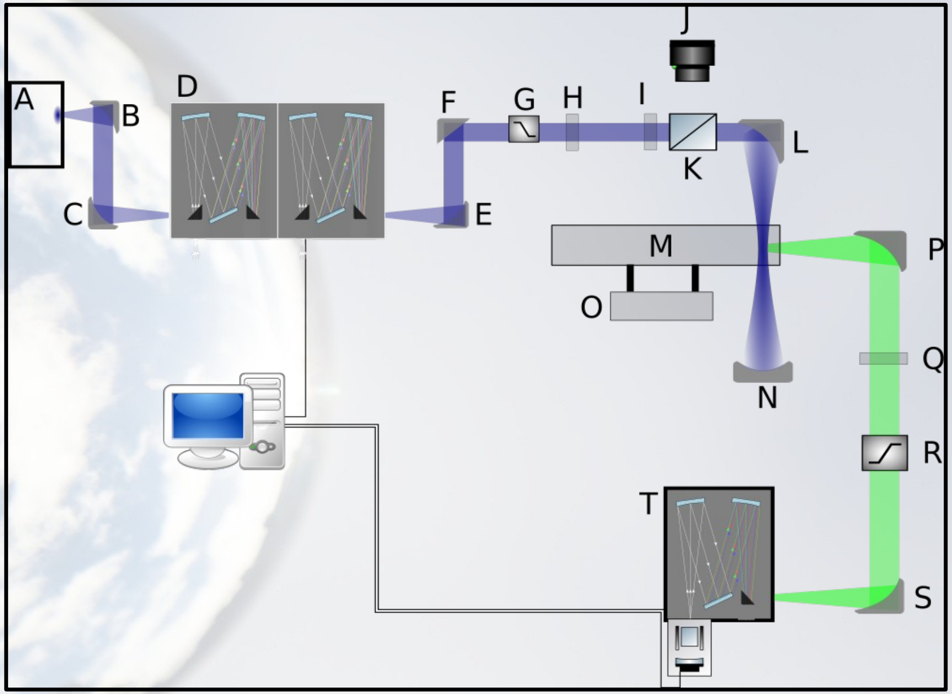
- “Needle in a haystack”:
  - Crystals and defects are too diverse for theoretical prediction
  - Backgrounds and contaminants at levels of 10^{-17} are required!
- Calibration and studies require O(keV) neutrons
- Auxiliary problems
  - Bleaching
  - Annealing
  - Background rejection

Game plan

- Scan all possible crystals and defects
- Find the ONE
- (or two, or more)
- Construct a dedicated optical setup for the study of the chosen CCs
- Proceed with R&D towards a full detector
- (and find DM)

An advanced optical setup

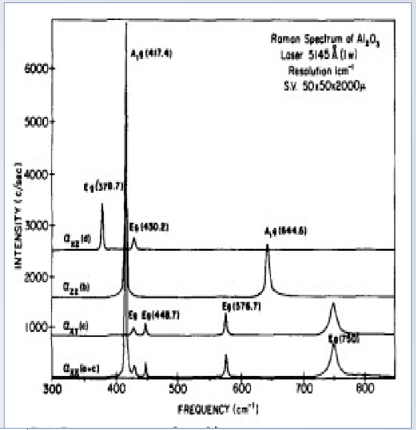
- Goal: Scan and find all signals produced in a macroscopic sample down to ~10^4 cm^{-3} active defects
- Broadband light source 200 nm – 800 nm
- High efficiencies, EM-CCD readout
- High repeatability, calibration
- Allows advanced analysis of the acquired data



Calibrating absolute sensitivity with Raman

- In Sapphire 2 modes are active in Raman scattering

$$A_{1g} = \begin{pmatrix} \alpha_{xx} & & \\ & \alpha_{xx} & \\ & & \alpha_{zz} \end{pmatrix} \; ; \; E_g = \begin{pmatrix} -\alpha_{xy} & \alpha_{xy} & \alpha_{xz} \\ \alpha_{xy} & -\alpha_{xy} & -\alpha_{xz} \\ \alpha_{xz} & -\alpha_{xz} & \end{pmatrix}$$



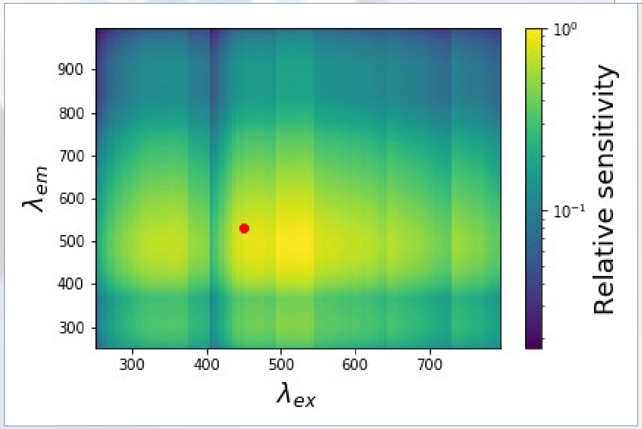
- The intensity of the scattering is

$$I_{ij}(\lambda) \propto |\langle e_i(\theta,\phi)| R(\lambda) |e_j(\theta,\phi)\rangle|^2$$

- The cross section is:

$$\left.\frac{d\sigma}{d\Omega}\right|_{\Delta q = 417.4\, cm^{-1}} = 1.59 \cdot 10^{-30}\, cm^2/\text{sr unit cell}$$

- The absolute and relative sensitivities are directly measured on the optical setup

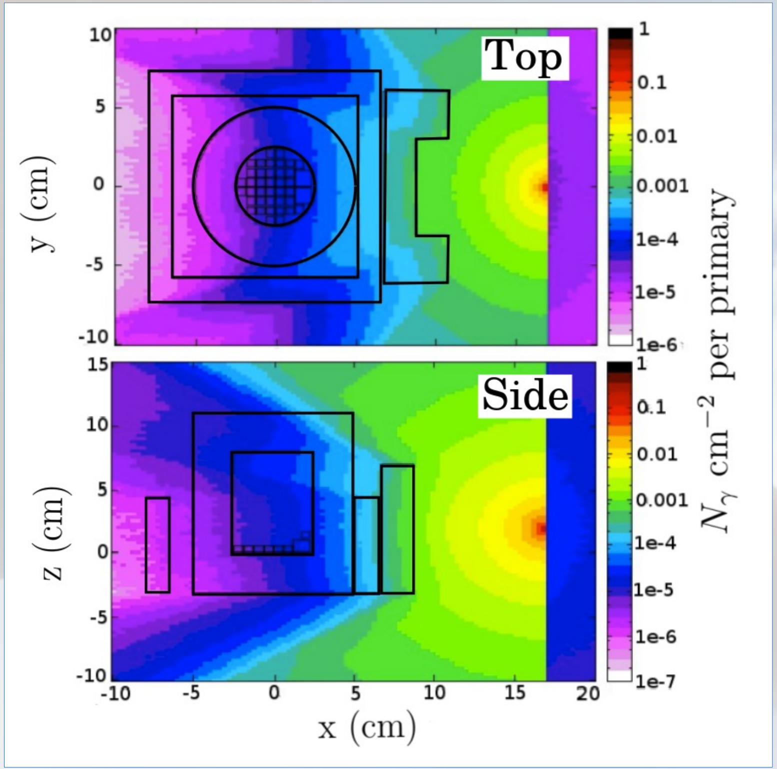


First measurements: ^{252}Cf and ^{60}Co

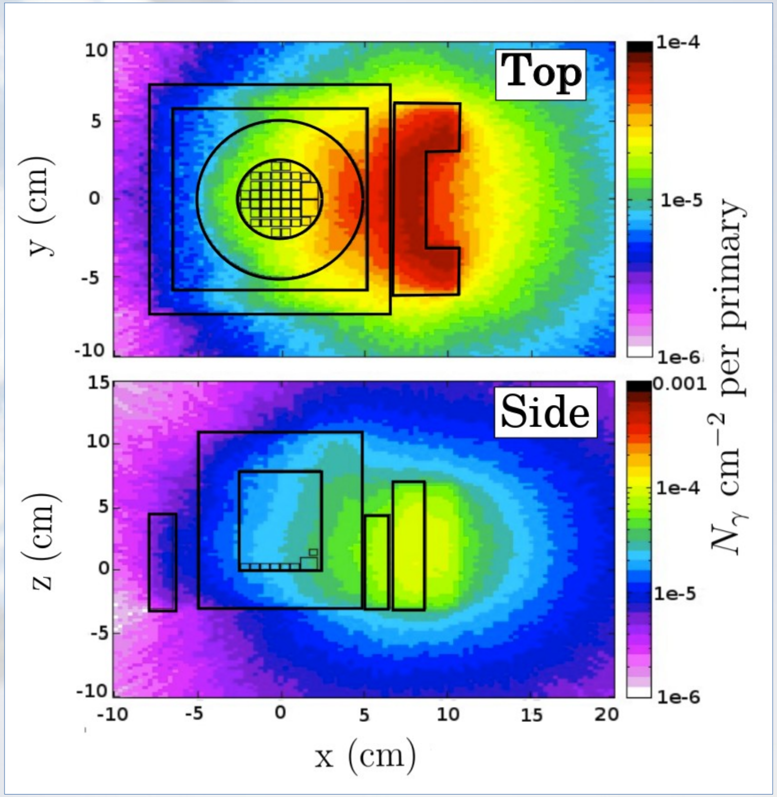
- Measurements of γ and (high E) neutrons
- Down to 10^4 cm^{-3} sensitivity @ (440,520) nm
- A first comprehensive comparison of γ vs. MeV neutrons CC production rates
- Analysis performed to identify centers produced by neutrons, γ and both
- ^{60}Co irradiations used to get the γ response

^{252}Cf setup

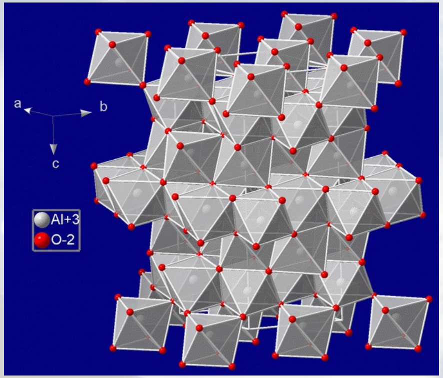
γ From Primary

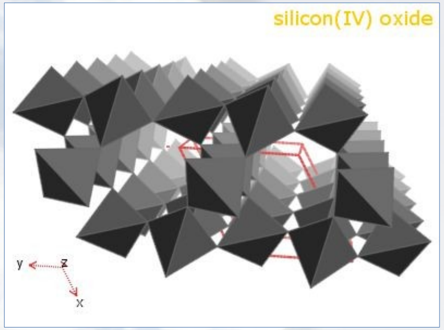


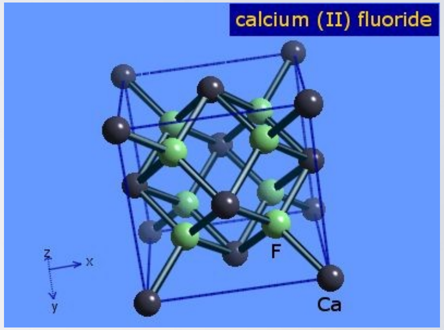
γ From Neutrons

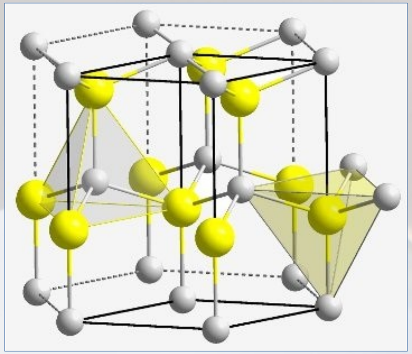


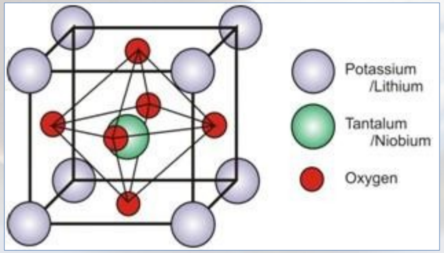
Many targets are being tested

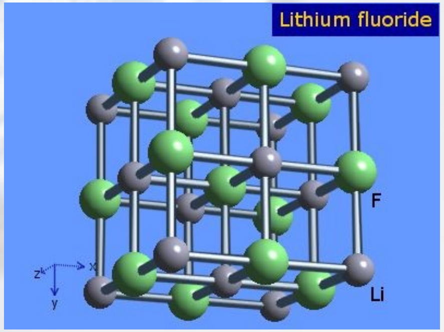


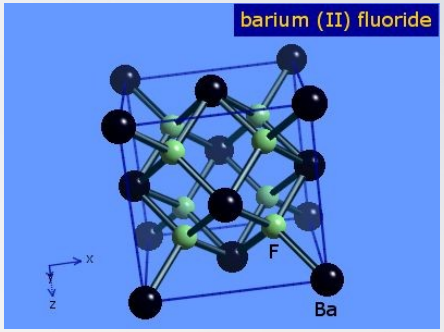






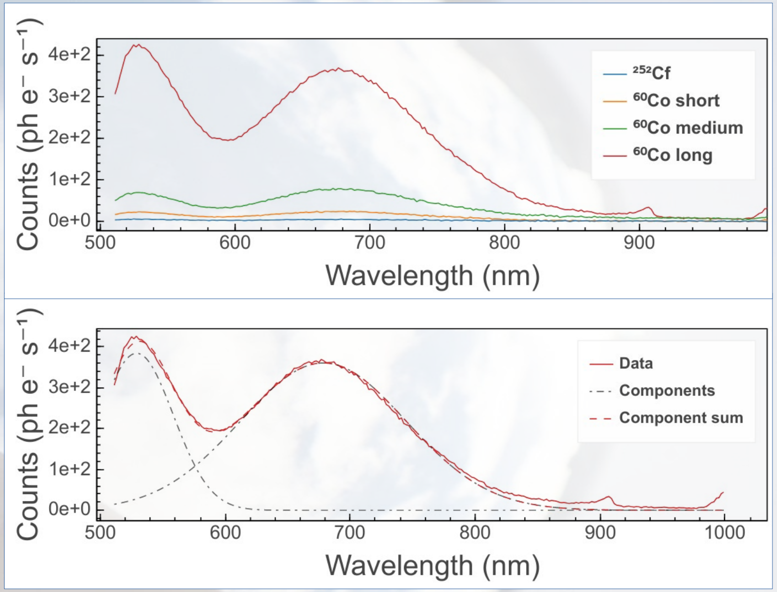


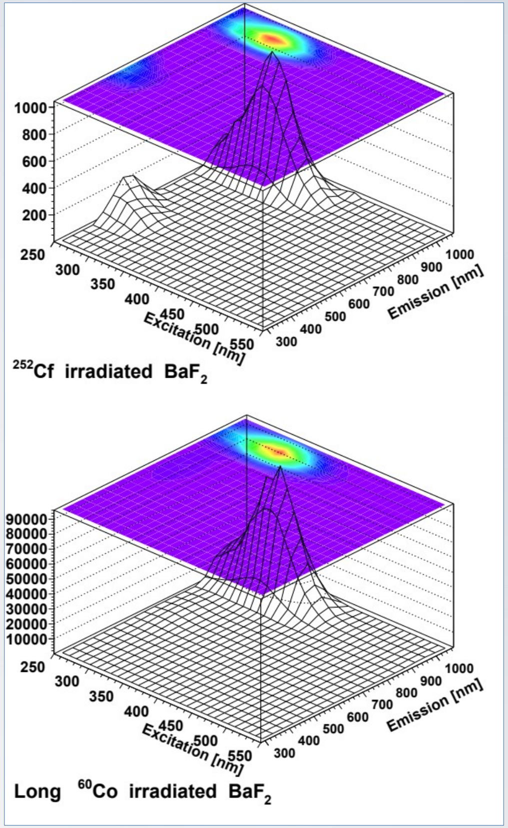




^{252}Cf and ^{60}Co results

- Each 2D scan is checked for all emissions
- Excess of Post-Pre searched for and decomposed
- Contribution on each peak assigned to γ, n
- Statistical significance found for each peak origin





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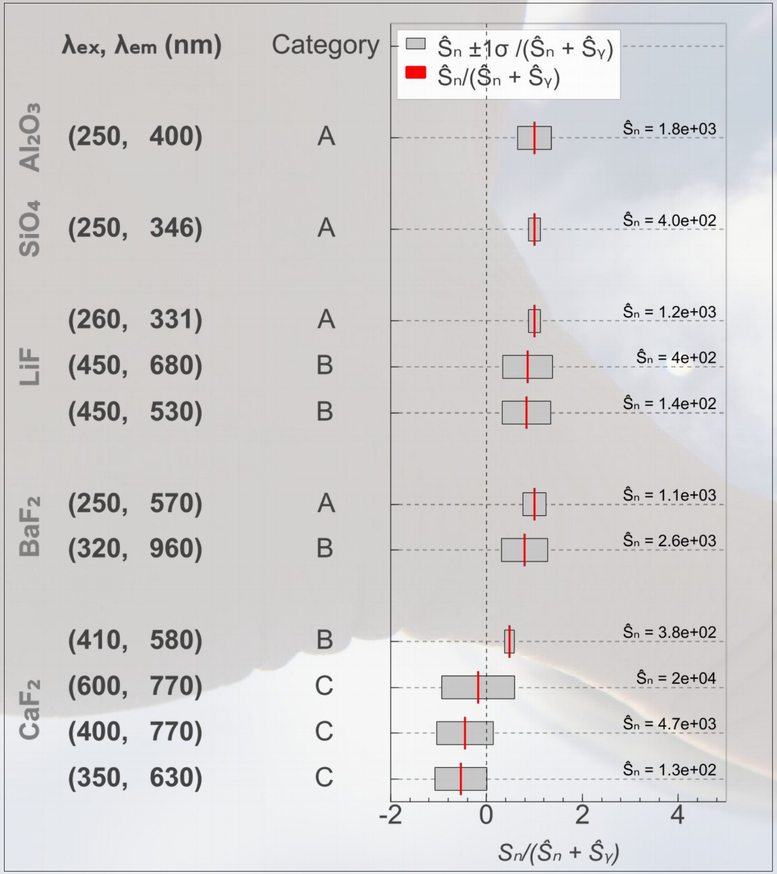
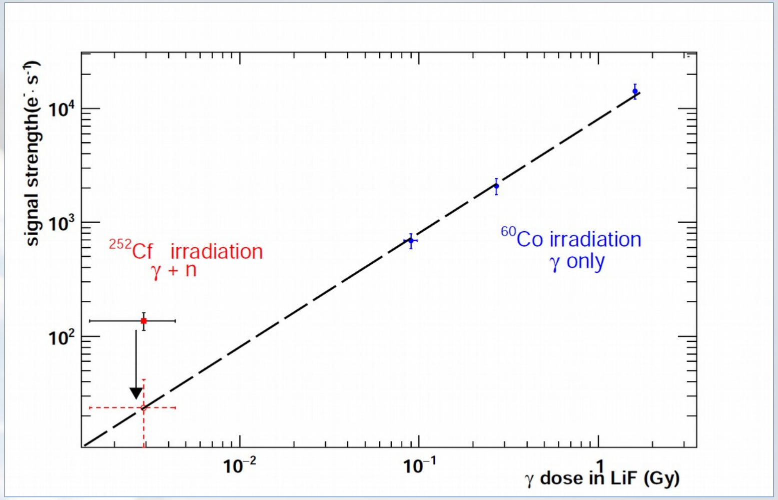
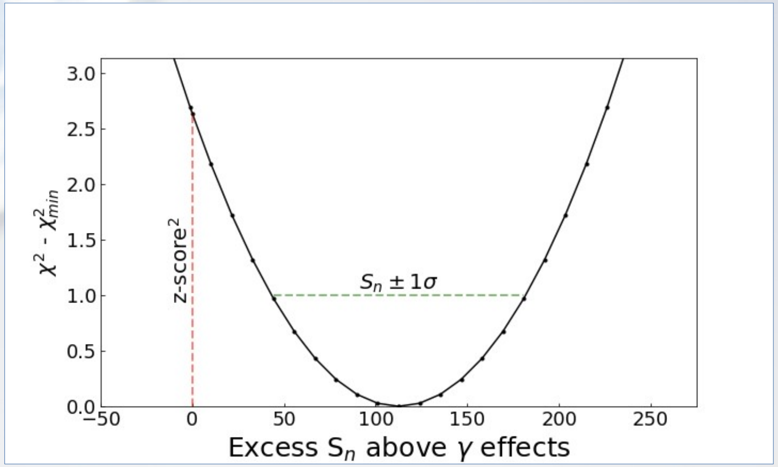
First measurements out



1902.10668

A: Neutrons
B: Both
C: γ



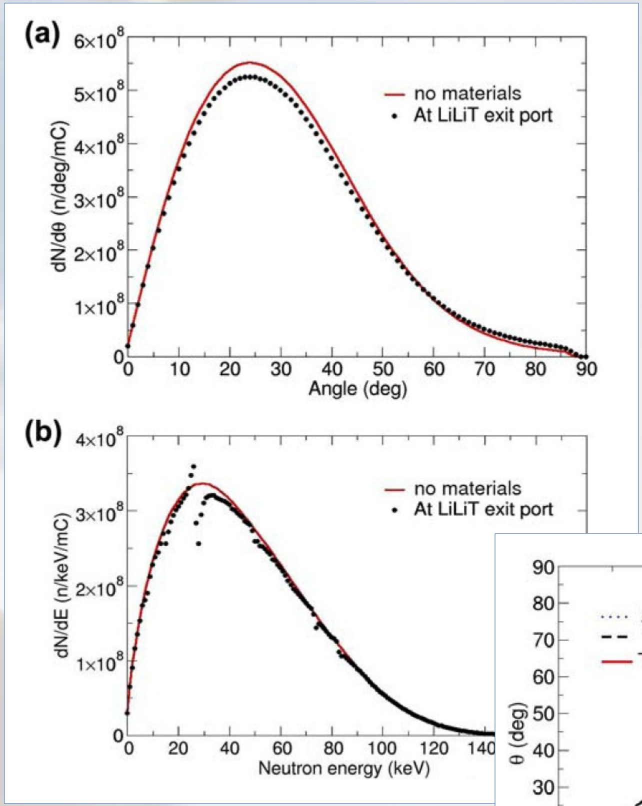


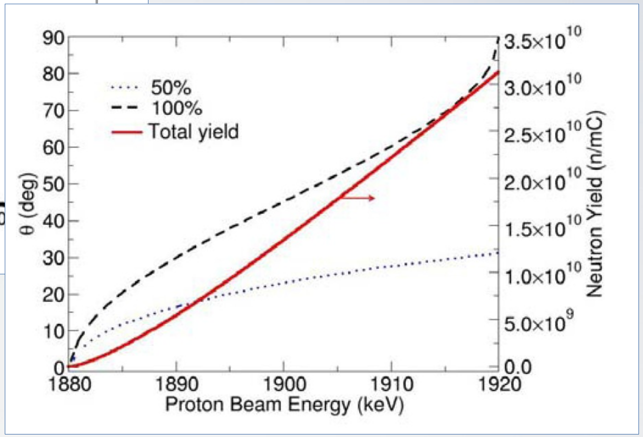
Getting the "Right" Neutrons

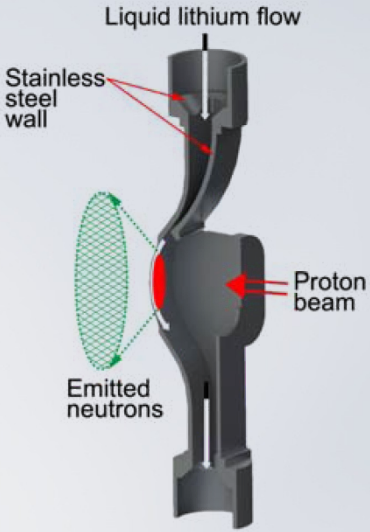
- Relevant energies of neutrons are keV scale
- An efficient way to produce MANY is by using Li(p,n) at high current, ~1.9 MeV proton beam
- A collaboration with SARAF on the project is ongoing
- Old results inconclusive, new irradiations just completed two weeks ago
- Analysis ongoing

LiLiT

- Employing $^{7}Li(p,n)$ at high currents
- Threshold at E_p=1.8804 MeV, fine tuning to get low E neutrons
- Liquid Lithim Target allows ~1mA CW, three orders of magnitude higher than solid targets
- The SARAF accelerator at SNRC with LiLiT target provides relevant energies at high fluxes (10^{12} n/s at the source)







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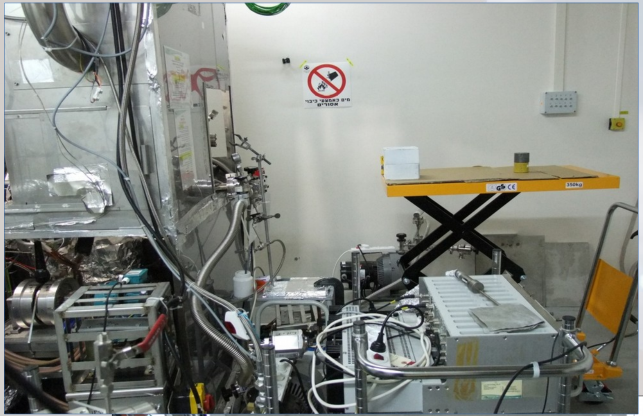
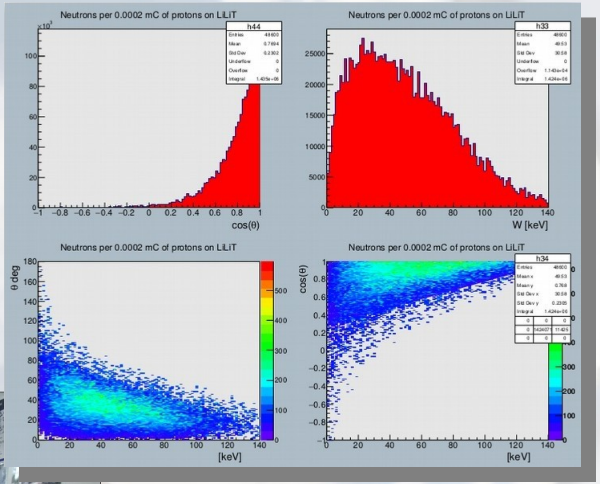
SARAF irradiations

Irradiation with 30 keV neutrons in the SARAF facility





- Accompanying γ radiation not trivial, several different measurements taken in order to account for various production mechanisms: Direct n, direct γ at different energies, thermal n, combinations
- Future studies will need a source during upgrade to SARAF II
- We have a gap in low-E neutrons starting in the fall

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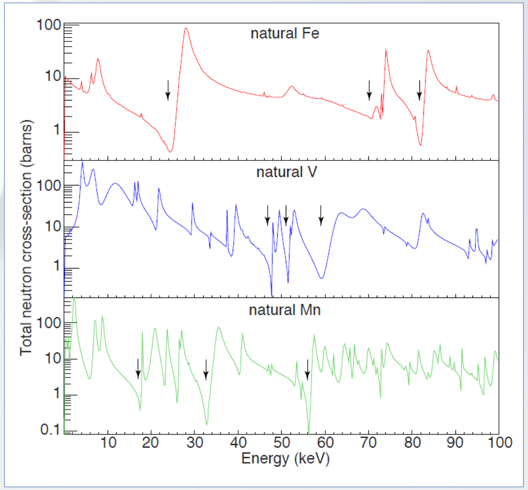
Down the road for Color Centers

- Irradiations with Liquid Lithium Target at the SARAF accelerator (~30 keV) ✔
- Optimizing optical system for specific “interesting” CCs
- Studies of response linearities, backgrounds, bleaching, annealing on “interesting” CCs
- Study of defect properties (with theoretical calcs)
- Search for new crystals
- …

A problem (for us) – availability of low E neutrons

- Starting fall 2019 SARAF goes down for a ~4 year upgrade
- Proton accelerators elsewhere have much lower fluxes (3 orders of magnitude), will need adjustments of the optical sensitivity, cleanliness etc.
- Ideas for low E neutrons:
  - Nuclear line filtering for 25 keV, 70 keV (1403.1285)
  - Nuclear filtering for 2 keV (Greenwood, Chrien 1976)
  - Both require high flux neutron sources



Time Line

- Strongly depends on finding a “golden” defect
- Once found, a dedicated setup optimized for it will be constructed and allow studies (1-2 y):
  - Production and annealing
  - Bleaching
  - Other responses, detector operation
- If successful, a demonstrator experiment can be built
  - Single scatter (above ground), backgrounds, operation
  - A full DM experiment can be proposed based on a successful demonstrator. Cost estimate ~1-2 M$ (equipment)

Quick Summary

- Color Centers: Lowering the threshold to make new windows viable
  - Preliminary results are promising for several crystals
  - Low E neutrons underway
  - Work is only in the Genesis mode
  - SARAF facility and other low energy neutron sources are extremely important, currently a bottleneck
- A search for successful candidates will continue. Once found, a candidate can advance to full DM mode in 3-5 years

Light Dark Matter:

Models @ Proposed Detectors

- MeV SUSY 0801.3686
- Gauge-mediated SUSY breaking 0803.4196
- Asymmetric Dark Matter 0901.4117
- FIMP Dark Matter 0911.1120
- SIMP Dark Matter 1402.5143;
- Elastically Decoupling Dark Matter 1512.04545
- Scalar Dark Matter hep-ph/0305261
- Abelian Hidden Sectors 0904.2567
- Cannibal Dark Matter 1602.04219
- And more…

- Graphene based 1606.08849
- SuperFluid He 1302.0534; 1604.08206
- TES readout
- He evaporation and field ionization 1706.00117
- CDMSlite 1509.02448
- Single photon scintillation 1607.01009
- TES readout
- CCDs (DAMIC, SENSEI) 1510.02126
- Superconducting Al cube 1512.04533
- 3D Dirac materials 1708.08929
- Semiconductor absorption 1608.01994
- Superconductor absorption 1604.06800
- Fermi-degenerate materials 1512.04533
- Chemical bond breaking/Color Centers *1705.03016; 1608.02940*
- And more…