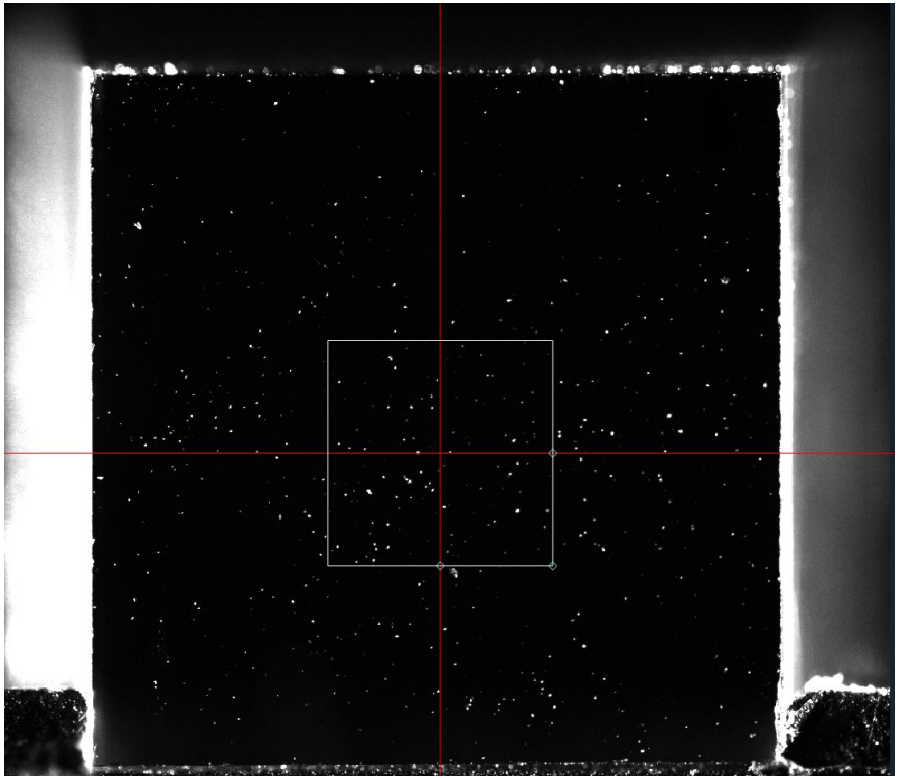
READ-OUT OF COLOR CENTERS WITH LIGHT-SHEET FLUORESCENCE MICROSCOPY



MINERAL DETECTION OF NEUTRINOS AND DARK MATTER WORKSHOP
VIRGINIA TECH EXECUTIVE BRIEFING CENTER - JAN 11 2023

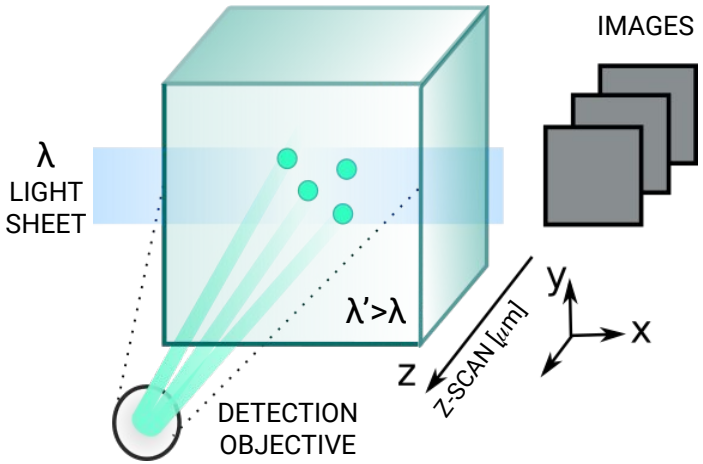
GABRIELA R. ARAUJO

University of Zurich[UZH]

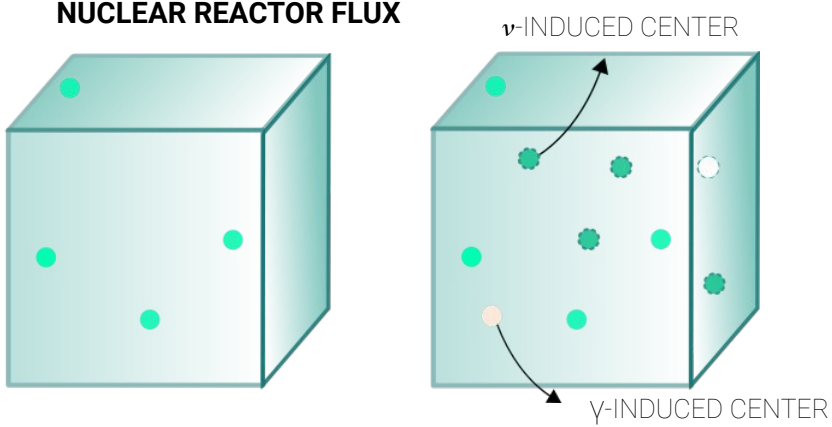
PALEOCCENE

THE PALEOCCENE CONCEPT

READ-OUT OF COLOR CENTERS IN PASSIVE DETECTORS USING LIGHT-SHEET FLUORESCENCE MICROSCOPY



NUMBER OF CENTERS CAN BE USED TO ESTIMATE NUCLEAR REACTOR FLUX



PRIOR TO EXPOSURE TO REACTOR νS

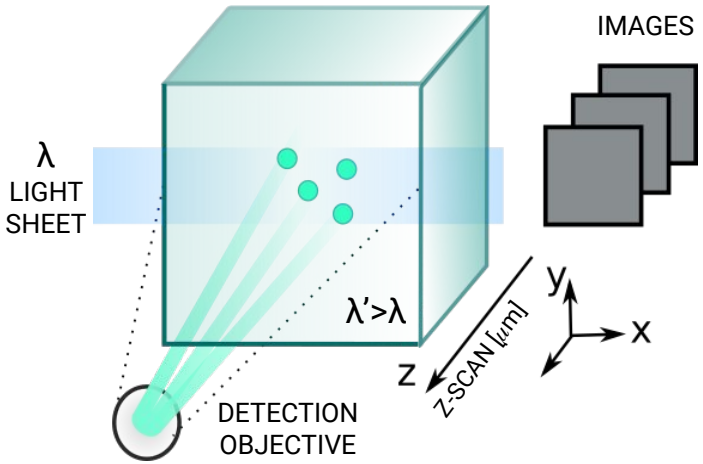
AFTER EXPOSURE

COLOR CENTERS ABSORB AND RE-EMIT LIGHT IN OPTICAL WAVELENGTHS, ENABLING A FAST READ-OUT.

PALEOCCENE: B. Cogswell, A. Goel, P. Huber

TESTING THE PALEOCCENE CONCEPT

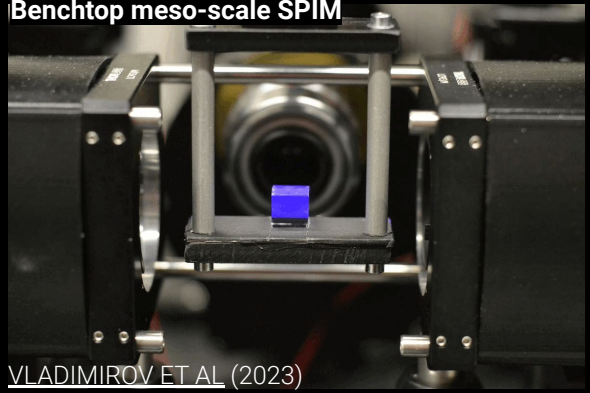
READOUT OF COLOR CENTERS WITH THE MESOSPIM



SPIM: Selective Plane Imaging Microscopy
Scan speed at ~ 4 μm XYZ resolution: <10min/cm^3

STATE-OF-THE-ART LIGHT-SHEET MICROSCOPE THAT IMAGES CENTIMETER -SIZED SAMPLES WITHIN MINUTES. NAT. METH. (2019)

Benchtop meso-scale SPIM



VLADIMIROV ET AL (2023)

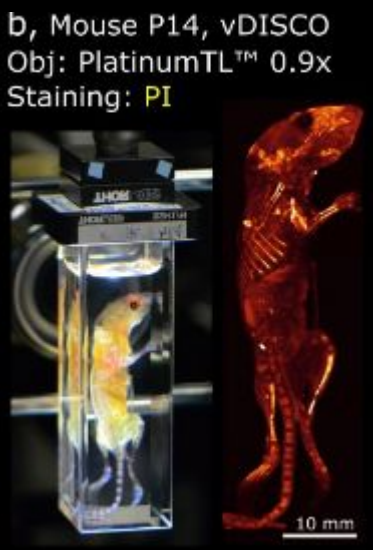
THE MESOSPIM

A “LARGE SCALE” LIGHT-SHEET FLUORESCENCE MICROSCOPY

FROM **WHOLE-BODY RAT SCANS** TO **COLOR CENTER IMAGING IN** CUBIC-CM SIZED **CRYSTALS:** New (2023) benchtop version was optimized for color center imaging*, with pixel sizes down to 0.21 µm compared to ~1 µm in previous version.

This new version has: sample holder for crystal imaging, larger sCMOS camera (5056x2960 pixels, 4.25 µm pixel size), magnification up to 20x (1.5 µm x-y resolution), smaller footprint and cost.

File sizes for a full crystal scan and ~4 µm isotropic resolution: ~30 Gb.

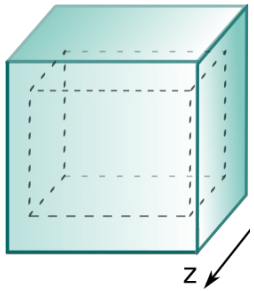


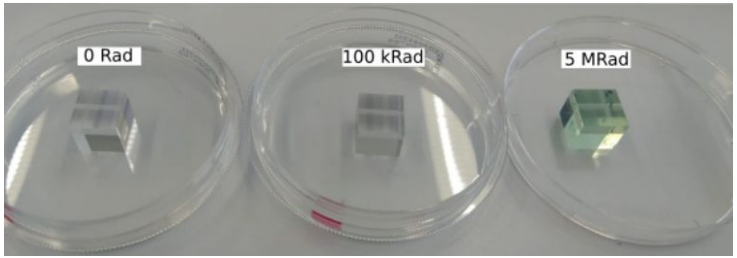
*VLADIMIROV ET AL (2023)

IMAGING TRANSPARENT CRYSTALS WITH THE MESOSPIM

SAMPLES: BLANK, IRRADIATED WITH γ-RAYS, OR NEUTRONS

1 cm^3 **CaF_2 transparent crystals** (all sides polished) were **irradiated** with γ-rays or neutrons and imaged in comparison to a **blank**.





γ-RAY DOSES: 100 kRad, 5 MRad
(~10^{13}-10^{14} ph/cm^2 from a ~1 MeV source ^{60}Co source)

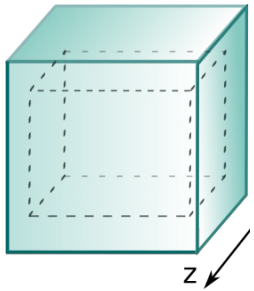
NEUTRON DOSES: neutron flux of ~10^8 n/cm^2

CRYSTAL VENDORS: Crystran, or United Crystals

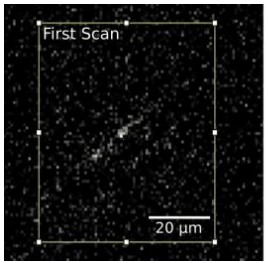
IMAGING TRANSPARENT CRYSTALS WITH THE MESOSPIM

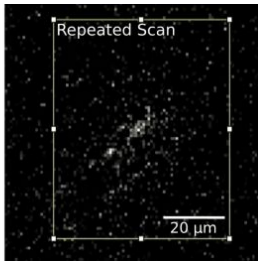
METHODS & ANALYSIS

CaF_2 transparent crystals (all sides polished, 1 cm^3) were **irradiated** with γ-rays or neutrons and imaged in comparison to a **blank** crystal.

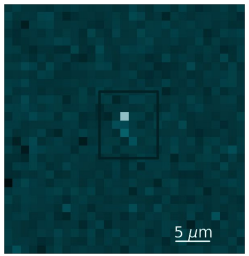


(1)





(2)



(3)

1. **ESTIMATING BULK FLUORESCENCE:** average fluorescence intensity within fiducialized volume.

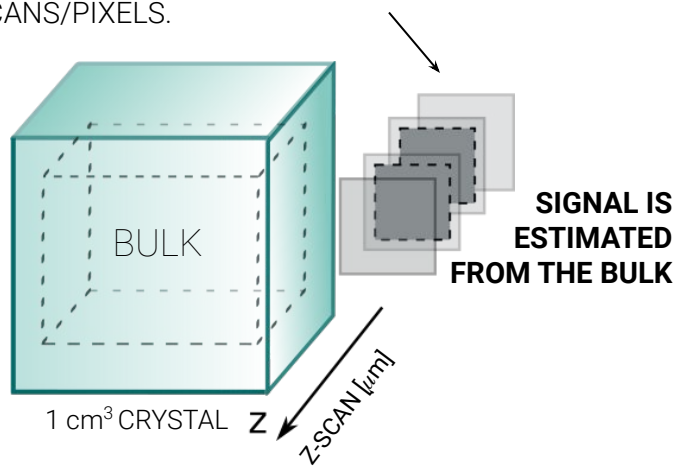
2. **FLUORESCENT TRACK-LIKE & POINT-LIKE STRUCTURES:** Find pixel clusters & match repeated scans

3. **ESTIMATING SINGLE COLOR CENTER FLUORESCENCE:** matching of high-intensity pixels at 1-pixel level and comparison to random matches.

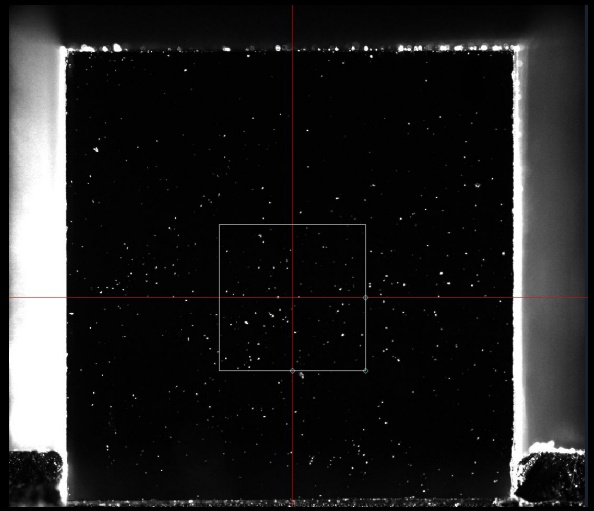
BULK FLUORESCENCE FROM γ-IRRADIATED CRYSTALS

ESTIMATING THE FLUORESCENCE SIGNAL FROM COLOR CENTERS

- SURFACE BACKGROUND IS AVOIDED BY DISCARDING SURFACE SCANS/PIXELS.



- CAMERA DARK COUNTS NOISE IS ESTIMATED IN DARK

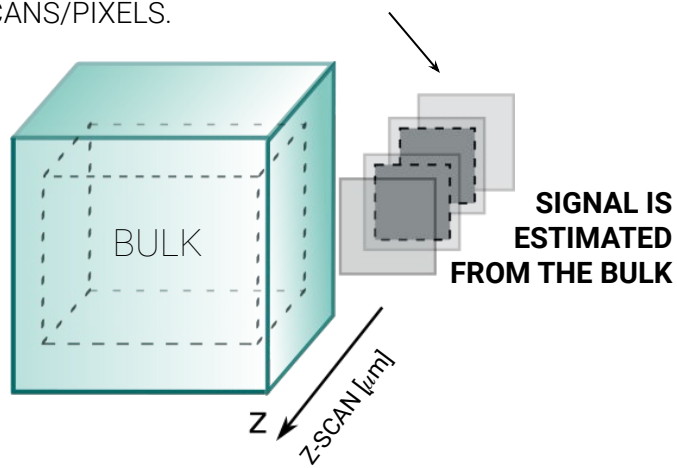


SURFACE OILS, DUST, & POLISH ARE FLUORESCENT **BACKGROUND**

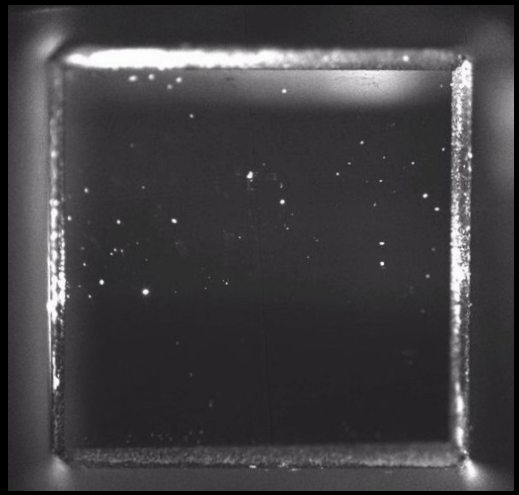
BULK FLUORESCENCE FROM γ-IRRADIATED CRYSTALS

ESTIMATING THE FLUORESCENCE SIGNAL FROM IRRADIATED CRYSTALS

- SURFACE BACKGROUND IS AVOIDED BY DISCARDING SURFACE SCANS/PIXELS.



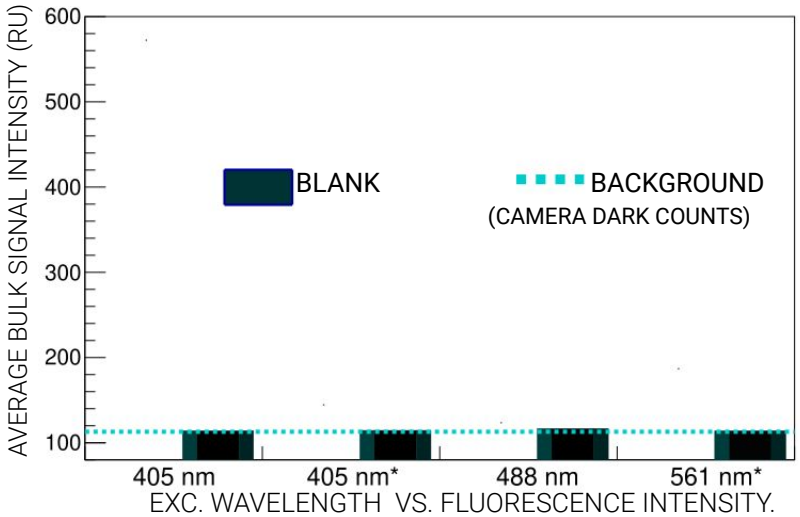
- CAMERA DARK COUNTS NOISE IS ESTIMATED IN DARK
- **BLANK VS IRRADIATED CRYSTALS ARE COMPARED**

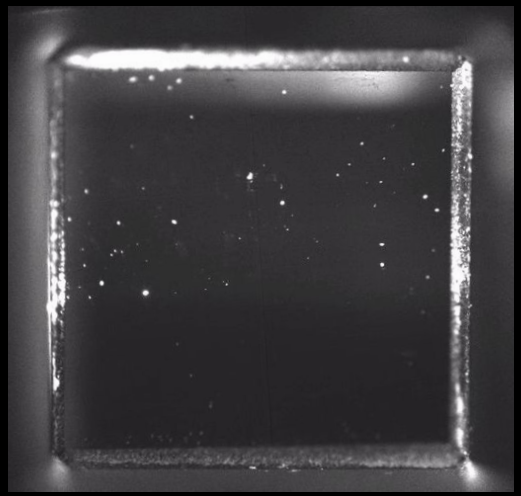


BLANK CaF_2 CRYSTALS YIELDED **NO** BULK **SIGNAL**

BULK FLUORESCENCE FROM γ-IRRADIATED CRYSTALS

ESTIMATING COLOR CENTER FLUORESCENCE SIGNAL



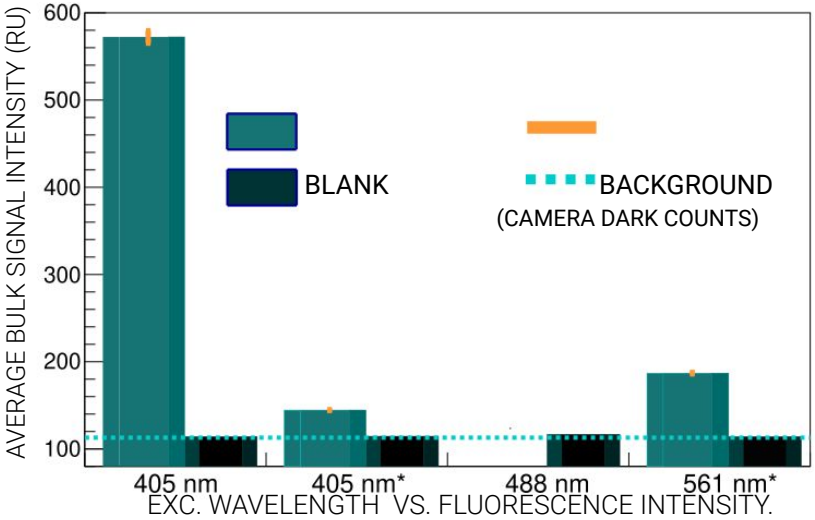


BLANK CaF_2 CRYSTALS YIELDED **NO** BULK **SIGNAL**

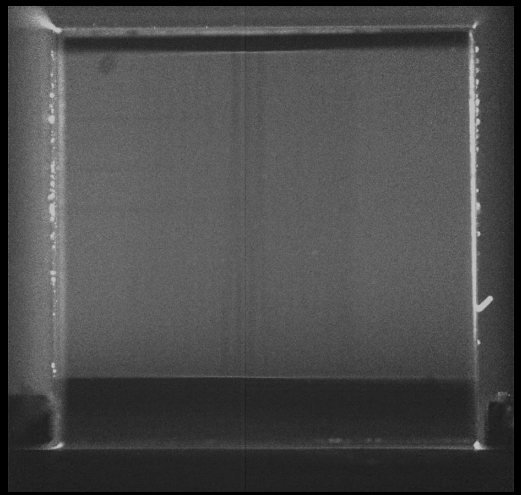
(*)MEASUREMENT WITH LONG-PASS FILTER

BULK FLUORESCENCE FROM γ-IRRADIATED CRYSTALS

COLOR CENTER FLUORESCENCE SIGNAL BLANK VS IRRADIATED



INTENSITY IS THE HIGHEST IN RESPONSE TO 405 nm EXCITATION. *100 kRad dose from ^{60}Co source.

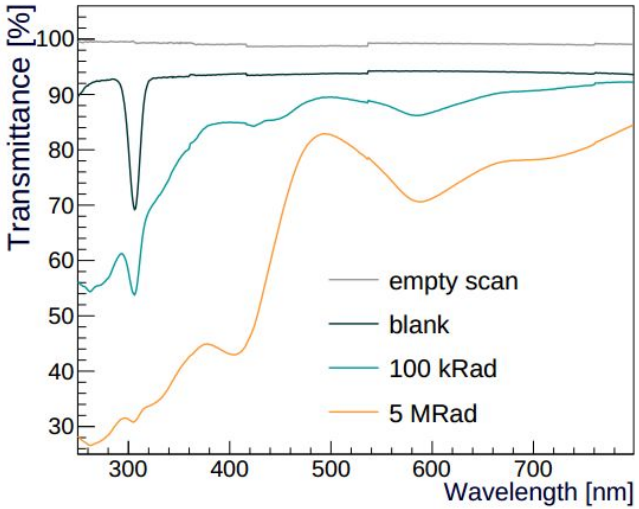


CRYSTAL IS **FLUORESCENT** AFTER **IRRADIATION***

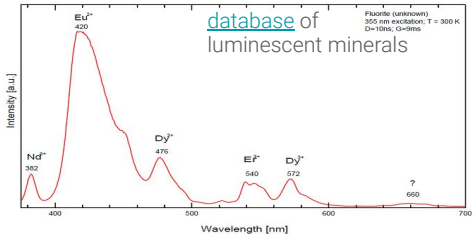
BULK FLUORESCENCE FROM γ-IRRADIATED CRYSTALS

MEASUREMENTS OF ABSORPTION

CRYSTAL BECOMES LESS TRANSPARENT AFTER IRRADIATION & RE-EMITS LIGHT IN BLUE.

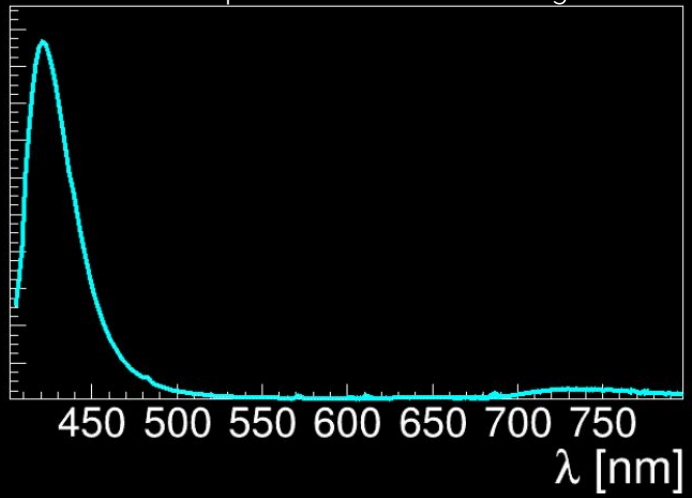


Absorption and emission spectra seemed to match literature values from fluorescing crystals containing rare-earth elements.



& EMISSION SPECTRA

Fluorescence spectra from the irradiated crystal measured in response to 400 ± 10 nm light



BULK FLUORESCENCE FROM γ-IRRADIATED CRYSTALS

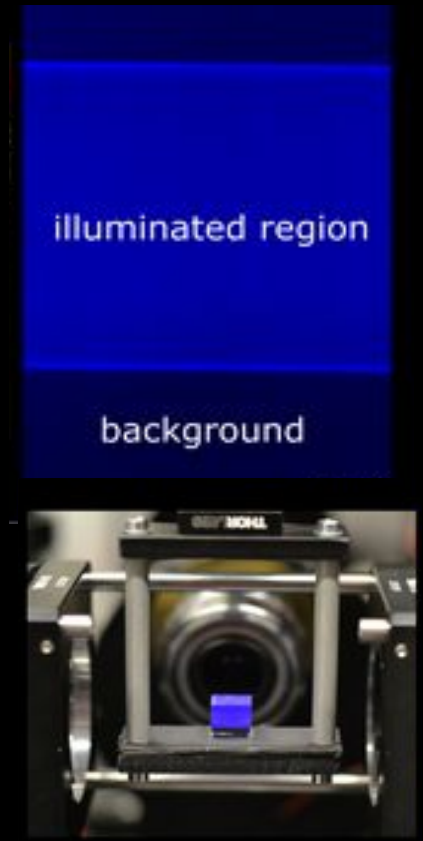
COLOR CENTERS INDUCED BY IONIZATION

THE IONIZATION OF TRACE AMOUNTS OF RARE-EARTH ELEMENTS (REE)* BY γ-RAYS IS LIKELY THE CAUSE OF THE STRONG FLUORESCENCE OBSERVED IN THE γ-RAY IRRADIATED SAMPLES.

Element	Crystals	
	Unit (ppb)	Unit (ppb)
	VT14	100K
La	80	1400
Ce	6875	3020
Pr	45	330
Nd	530	1430
Sm	205	315
Eu	85	85

Table: concentration of REEs measured from two CaF_2 crystals that displayed high intensity of fluorescence after irradiation with neutrons (VT14) and γ-rays. (100kRad).

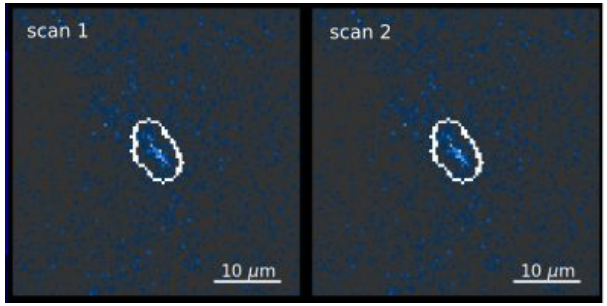
*Normally found in their stable trivalent state (such as Sm3+, Eu3+ occupying the place of Ca ions, with charge compensated by interstitial F− ions), these ions can transition to fluorescing divalent states (Sm2+, Eu2+) upon acquiring an electron.



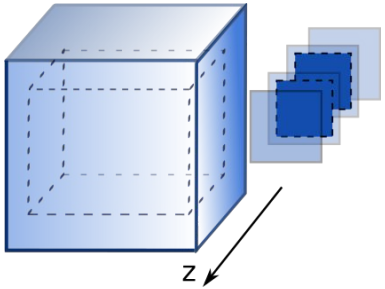
300 ppb of Eu is enough to yield >1 impurity / μm^3 and explain the homogeneous blue fluorescence observed in the 100 kRad irradiated crystal.

IMAGING COLOR CENTER STRUCTURES OR SINGLE COLOR CENTERS

DATA ANALYSIS METHODS



Example of track-like structure found by a clustering algorithm and also observed in a repeated scan. (10x magnific., 0.4 μm pixel size).



These structures may span a few z-planes but hot pixels span many more z-planes.

1. **BULK FLUORESCENCE:** average fluorescence intensity within fiducialized volume.

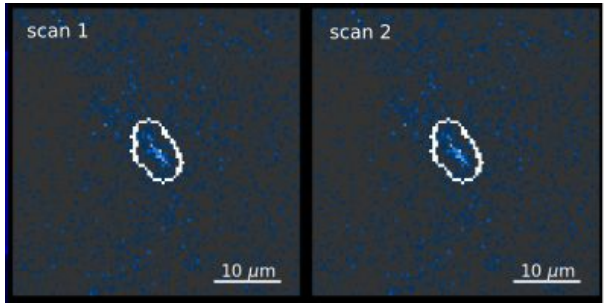
2. **FLUORESCENT TRACK-LIKE & POINT-LIKE STRUCTURES:** Find pixel clusters & match repeated scans

3. **ESTIMATING SINGLE COLOR CENTER FLUORESCENCE:** matching of high-intensity pixels at 1-pixel level and comparison to random matches.

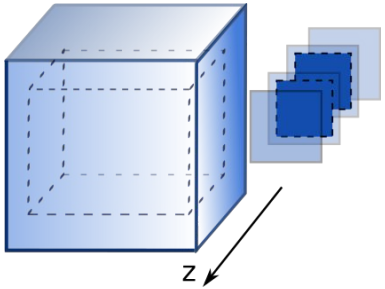
IMAGING COLOR CENTER STRUCTURES OR SINGLE COLOR CENTERS

DATA ANALYSIS METHODS

TO CONFIDENTLY IMAGE SMALL STRUCTURES/SINGLE COLOR CENTERS SEVERAL BACKGROUND SOURCES NEED TO BE ESTIMATED &/OR EXCLUDED FROM THE DATA.



Example of track-like structure found by a clustering algorithm and also observed in a repeated scan. (10x magnific., 0.4 μm pixel size).



These structures may span a few z-planes but hot pixels span many more z-planes.

Datasets are very large (several Gb). **Analysis is computationally intensive** (exclusion of background sources at pixel level while finding track-like or point-like structures and matching them in repeated scans).
-> Development of Analysis Methods (V. Aerne, MSc Thesis, UZH 2023)

& BACKGROUND SOURCES

EXTERNAL SOURCES:
STRAY LIGHT & FILTER LEAKAGE:
Estimated with blank measurement.

CAMERA SHOT NOISE:
estimated by data taking with laser off.

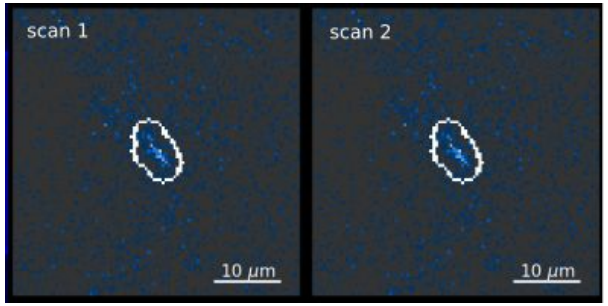
HOT PIXELS & LENS FLUORESCENCE:
Exclusion of fluorescent spots that appear in the same xy position across several z-planes.

SAMPLE SOURCES:
TRACE IMPURITIES FLUORESCENT UPON IONIZATION & FLUORESCENT SURFACE OILS, DUST, POLISH:
Avoided/excluded by fiducialization, comparison between neutron and γ-irradiated samples.

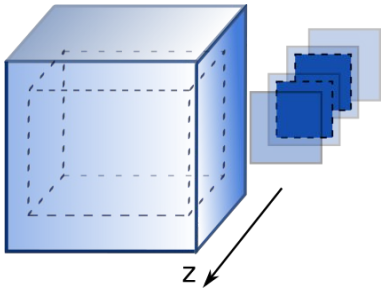
Further checks: Repeat scan and search for xyz matches. Estimate random matching.

ANALYSIS METHODS FOR IMAGING COLOR CENTERS WITH THE MESOSPIM

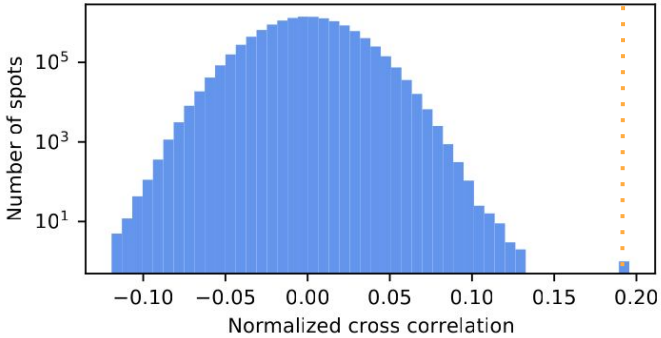
FiNDING TRACK-LIKE (LARGE) FLUORESCENT STRUCTURES



Example of track-like structure found by a clustering algorithm and also observed in a repeated scan. 10x magnific., 0.4 μm pixel size (ps).



These structures may span a few z-planes but hot pixels span many more z-planes.



Only the same spot shows high correlation in the repeated scan.
-> The structure is a real fluorescent feature in the crystal.

Work of MSc. Student V. Aerne

ANALYSIS METHODS:

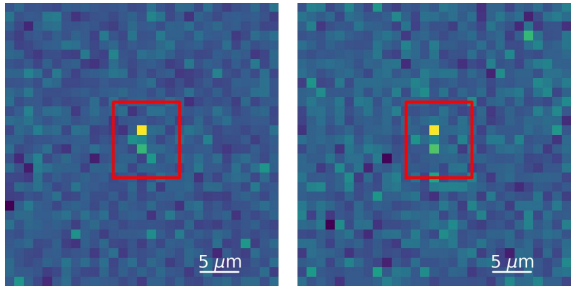
1) Automatic fiducialization of the data
2) Algorithm to find dense color center structures
   - Connects high-intensity pixels
   - Selects structures that exceed a certain threshold.
3) Structure matching
   - Compare structures to repeated scans
   - Quantify similarity

Origin of the structure is unknown. They were first identified by eye, but a couple more were found by this analysis method.

ANALYSIS METHODS FOR IMAGING COLOR CENTERS WITH THE MESOSPIM

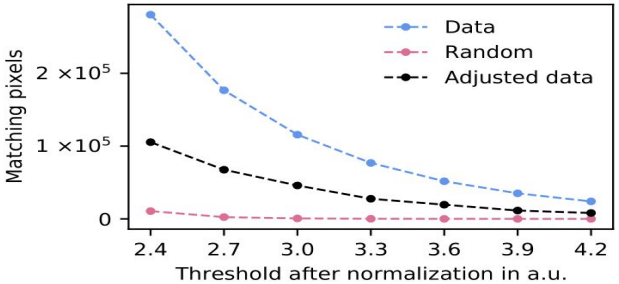
SIGNAL INDUCED BY NEUTRONS: FINDING POINT-LIKE STRUCTURES

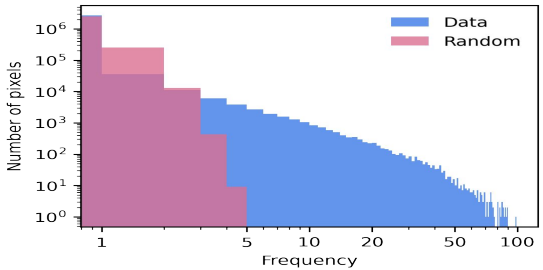
Work of MSc. Student V. Aerne



Example of bright pixels appearing at repeated scans imaged at 6x, 1μm ps. Only a few structures are observed in the data (but this data was taken at lower resolution and the structures are expected to be small).

-> use a different analysis method





Excess of matches in data of neutron irradiated crystal is observed in comparison to random matching estimation. **Bulk fluorescence** measurements **also show excess** in comparison to blank.

ANALYSIS METHOD:

1) Automatic fiducialization of the data
2) ~~Algorithm to find dense color center structures~~ Find high intensity pixels.
3) Pixel matching
   - Find number of matching pixels
   - Exclude defective pixels
   - Compare to random matching

Still to investigate: Sample variability, intensity of neighboring pixels using high magnification scans (20x), level of signal excess for γ-irradiated crystals.

SUMMARY

& OUTLOOK

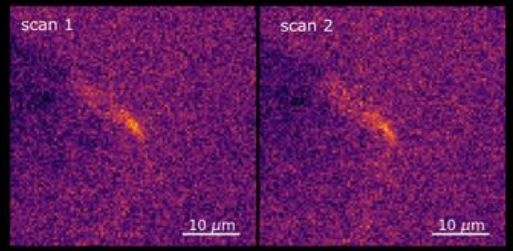
Demonstrated imaging of radiation-induced color centers with light-sheet microscopy;

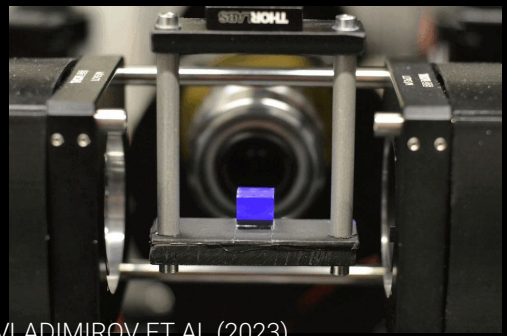
Current tests focus on the production of neutron induced color centers and identification of single color centers in this data;

Future tests will focus on:

- different materials (LiF, Al_2O_3, …);
- relation between fluorescence istensity and neutron dose;
- imaging large ion-induced (or Li $(n,\alpha)^3H$) tracks.

Applications of imaging color centers with the mesoSPIM beyond PALEOCCENE (CEνNS & DM detection): Paleo detectors neutron detectors, Rock dating (geology)





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PALEOCCENE: 2104.13926, 2203.05525

mesoSPIM: bioRxiv 2023.06.16.545256

PALEOCCENE TEAM AT UZH:

University of Zurich[UZH]


Prof. L. Baudis


Dr. N. Vladimirov


V. Aerne


G. R. Araujo


Dr. J. M .Melero

BACK UP SLIDES