PALEOCCENE: COMPACT & PASSIVE NEUTRINO DETECTORS ENABLED BY FLUORESCENCE MICROSCOPY OF COLOR CENTERS

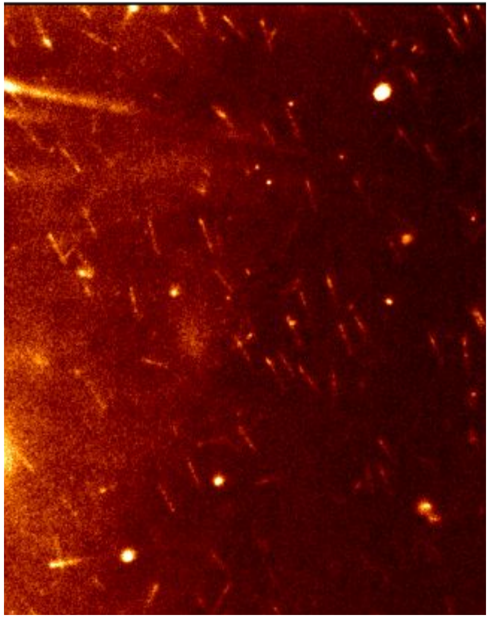
APPLIED ANTINEUTRINO PHYSICS WORKSHOP 2024

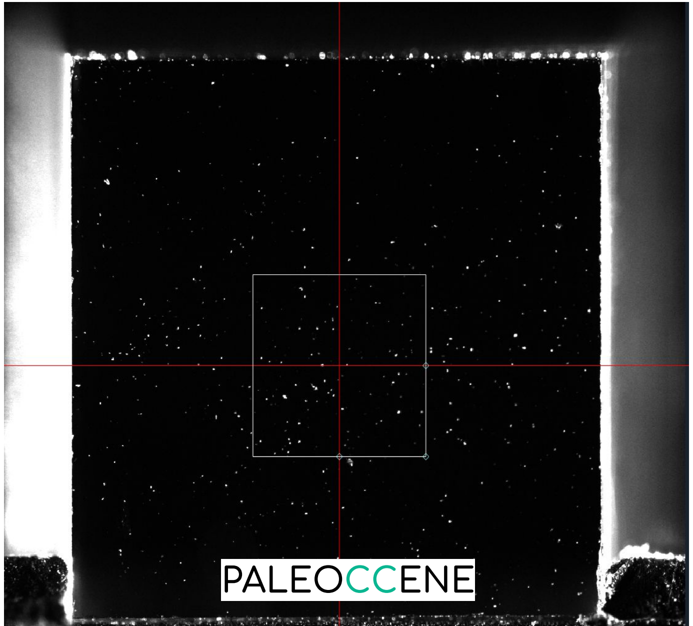
RWTH AACHEN, OCT 29 2024

GABRIELA R. ARAUJO

ON BEHALF OF PALEOCCENE

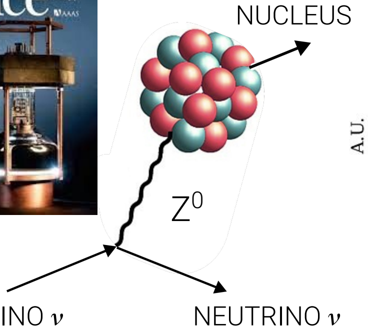
University of Zurich[UZH]

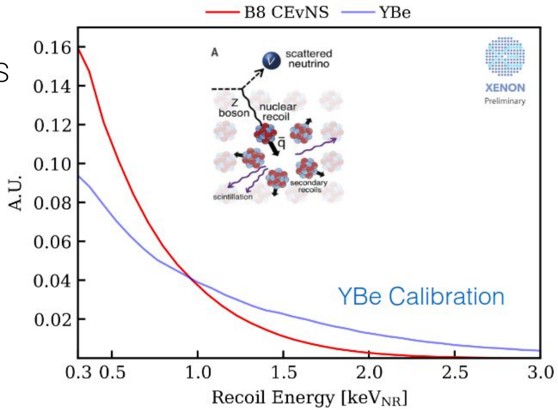




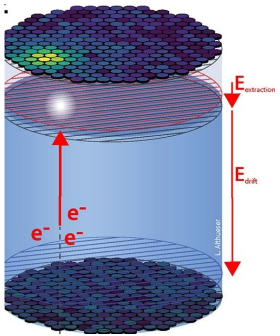
SEARCHING FOR RARE NUCLEAR RECOILS*

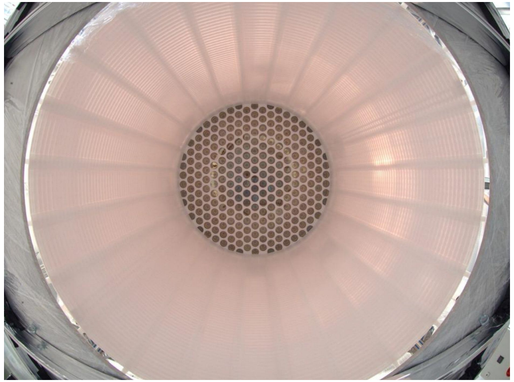
STATE-OF-THE ART EXPERIMENTS ARE SEEING THE FIRST "LOW-ENERGY"** CEνNS EVENTS





FIGURES: XENON COLLABORATION





1[ST] CEνNS DETECTION @ SNS:
$E_\nu \lesssim$ 50 MeV, ~5 KeV threshold

1[ST] DETECTION OF CEνNS FROM SOLAR (^{8}B) NEUTRINOS:
(**)$E_\nu \lesssim$ 10 MeV, ~1 KeV threshold
BY THE XENON DARK MATTER EXPERIMENT. arxiv:2408.02877

CEνNS: COHERENT ELASTIC ν-NUCLEUS SCATTERING
*Either from weakly interacting massive particles (WIMPs, dark matter candidate) or CEνNS

SEARCHING FOR RARE NUCLEAR RECOILS*

TRADITIONAL DETECTION TECHNIQUES ARE BASED ON THE COLLECTION OF PROMPT SCINTILLATION PHOTONS, CHARGE…

EXAMPLES: SEMICONDUCTORS, TIME PROJECTION CHAMBERS, ETC

FIGURES: XENON COLLABORATION

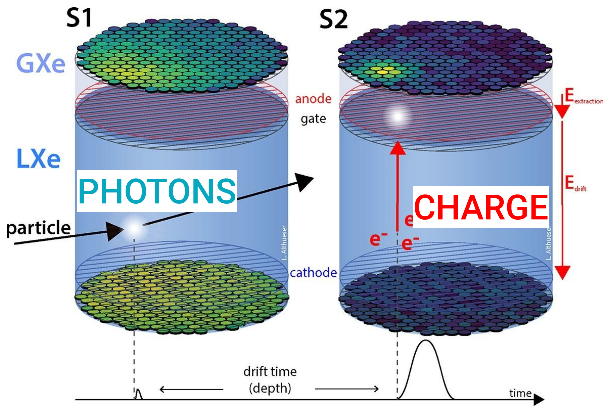
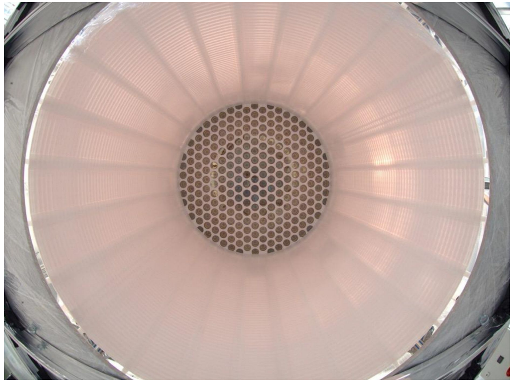


FIGURE: XENON COLLABORATION



arxiv:2408.02877

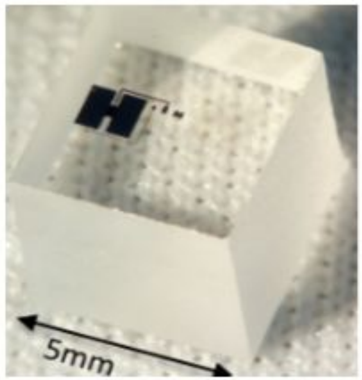
*Either from weakly interacting massive particles (WIMPs, dark matter candidate) or CEνNS

SEARCHING FOR RARE NUCLEAR RECOILS*

TRADITIONAL DETECTION TECHNIQUES ARE BASED ON THE COLLECTION OF PROMPT SCINTILLATION PHOTONS, CHARGE, AND/OR PHONONS*.

EXAMPLES: TIME PROJECTION CHAMBERS AND BOLOMETERS. IN BOTH CASES, SIGNALS ARE PROMPLY READ OUT.

FIGURE: Example of detector from the Nucleus experiment, from Johannes Rothe slides



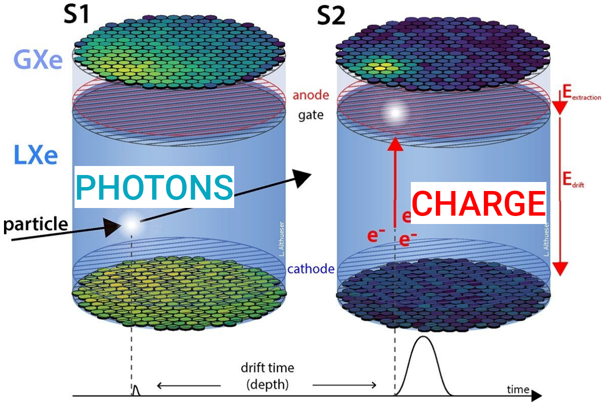


FIGURE: XENON COLLABORATION

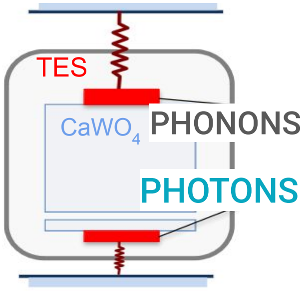


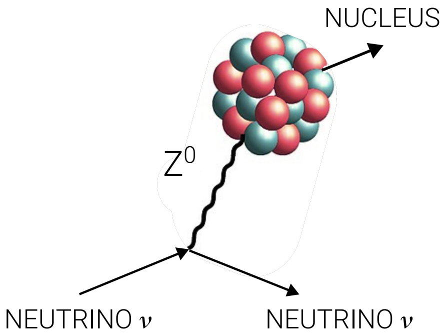
FIGURE: Example of phonon detector from P. Gorla's slides (2023)

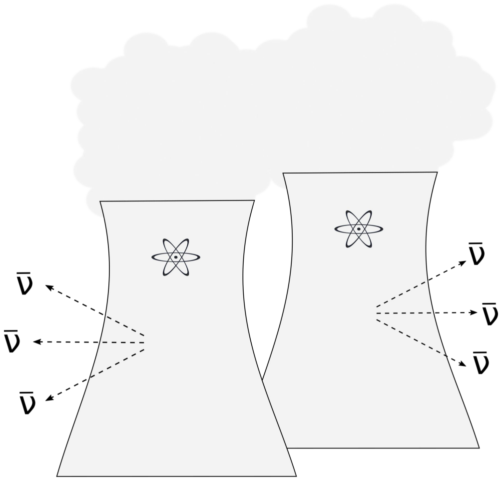
THIS REQUIRES ON-SITE INSTRUMENTATIONS. DETECTORS HAVE A LARGE FOOTPRINT (& COST)

*Either from weakly interacting massive particles (WIMPs, dark matter candidate) or

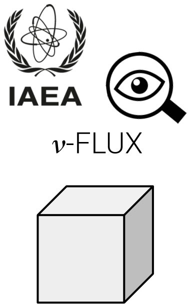
NEW DETECTION TECHNIQUE: PALEOCCENE

PALEOCCENE AIMS TO DEVELOP COMPACT PASSIVE DETECTORS THAT ENABLE MONITORING OF A LARGE NUMBER OF DETECTORS





CEνNS FROM REACTOR νs :
~450 nuclear power reactors
>200 research reactors.
Bernstail et al arxiv:1908.07113



NUCLEAR SAFEGUARD

1ST CEνNS DETECTION:
$E_\nu \lesssim$ 50 MeV, ~5 KeV threshold

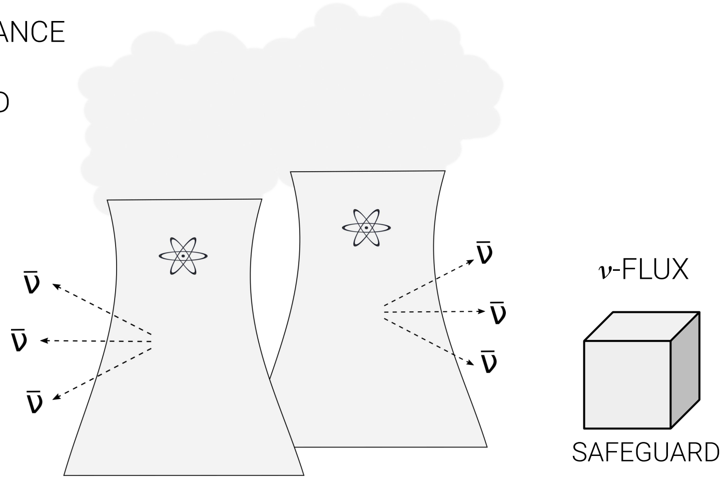
REACTOR CEνNS
$E_\nu \lesssim$ **8 MeV.** E_{NR}~10-100 eV threshold

TWO MAIN CHALLENGES: DETECTORS HAVE TO BE COMPACT & STILL ACHIEVE THE NECESSARY **LOW THRESHOLDS**.

TO MONITOR A LARGE NUMBER OF REACTORS, WE MAY NEED A PASSIVE DETECTOR

DETECTOR WISH LIST:

- ❑ **LOW THRESHOLD**
- ❑ **SMALL**: ALLOWS MODERATE DISTANCE TO REACTOR / OVERBURDEN
- ❑ NO CRYOGENICS / HV / DEDICATED STAFF ON-SITE
- ❑ REASONABLY **CHEAP**



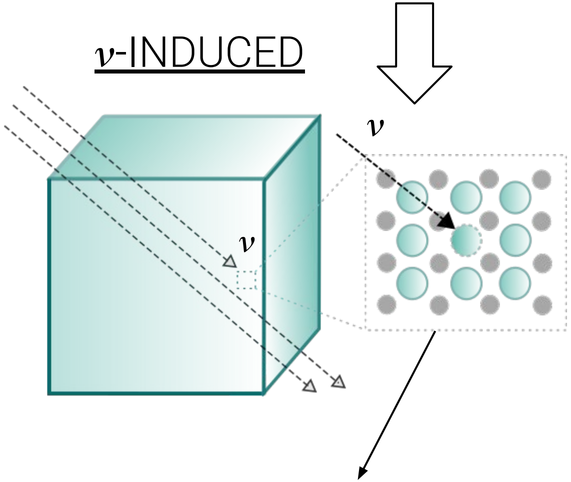
PALEOCCENE: THE CONCEPT OF A PASSIVE DETECTOR THAT RECORDS CRYSTALLINE DEFECTS INDUCED BY CEνNS

DETECTOR WISH LIST:

- ❑ REASONABLY **CHEAP**
- ❑ **SMALL**: ALLOWS MODERATE DISTANCE TO REACTOR / OVERBURDEN
- ❑ NO CRYOGENICS / HV / DEDICATED STAFF ON-SITE
- ❑ **LOW THRESHOLD**

SIGNAL:

- ❑ LONG LIVED
- ❑ NO OR DISTINGUISHABLE RESPONSE TO γ-RAYS



CRYSTALLINE DEFECTS INDUCED BY NUCLEAR RECOILS.

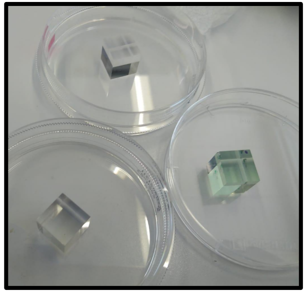
FOCUS HERE: **COLOR CENTER DEFECTS***

(*) R. Budnik, et al (2018)

PALEOCCENE: THE CONCEPT OF A PASSIVE DETECTOR THAT RECORDS COLOR CENTERS INDUCED BY CEνNS IN TRANSPARENT CRYSTALS

DETECTOR WISH LIST:

- ❑ REASONABLY **CHEAP**
- ❑ **SMALL**: ALLOWS MODERATE DISTANCE TO REACTOR / OVERBURDEN
- ❑ NO CRYOGENICS / HV / DEDICATED STAFF ON-SITE
- ❑ **LOW THRESHOLD**

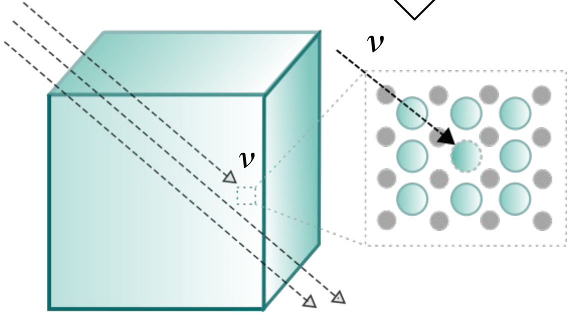


PASSIVE CRYSTALS

SIGNAL:

- ❑ LONG LIVED
- ❑ NO OR DISTINGUISHABLE RESPONSE TO γ-RAYS

ν-INDUCED



READOUT

- ❑ **FAST NON-DESTRUCTIVE** READ-OUT OF LARGE VOLUMES
- ❑ IDENTIFICATION OF **LOW -ENERGY** SIGNALS
- ❑ CAN BE PERFORMED EX-SITU OR WITH A SETUP THAT CAN BE EASILY TRANSPORTED

CHALLENGE:
FAST X LOW-ENERGY

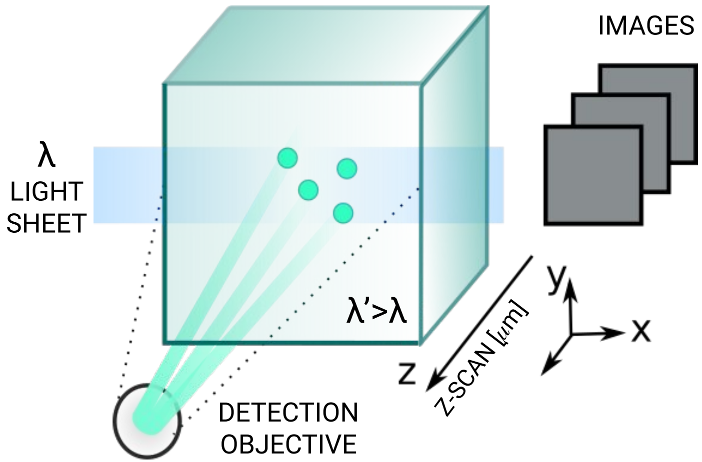
PASSIVE TRANSPARENT CRYSTALS OFFER A UNIQUE DETECTION CHANNEL: READOUT OF CRYSTALLINE DEFECTS INDUCED BY NUCLEAR RECOILS.

FOCUS HERE: **COLOR CENTER DEFECTS***

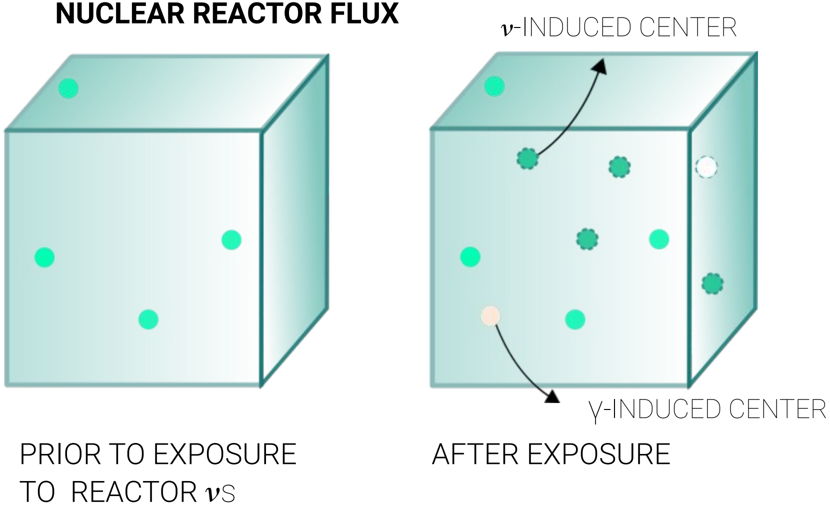
(*) R. Budnik, et al (2018)

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

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



NUMBER OF CENTERS CAN BE USED TO ESTIMATE NUCLEAR REACTOR FLUX

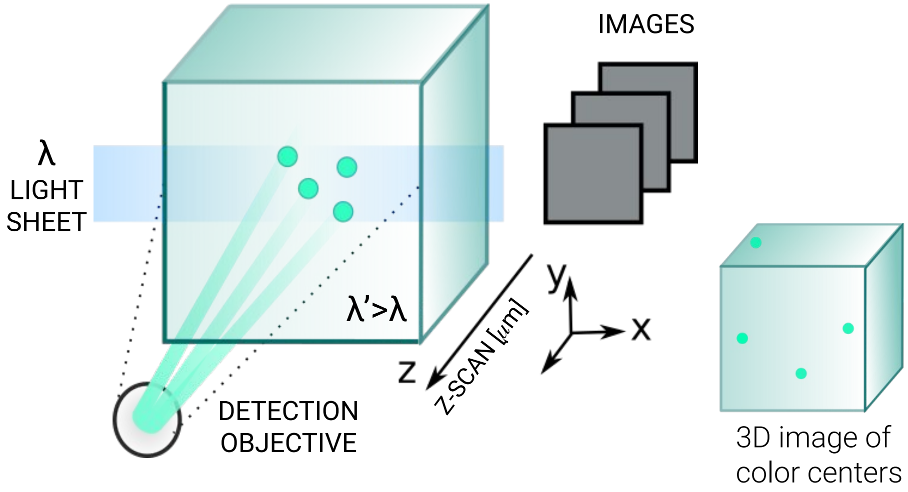


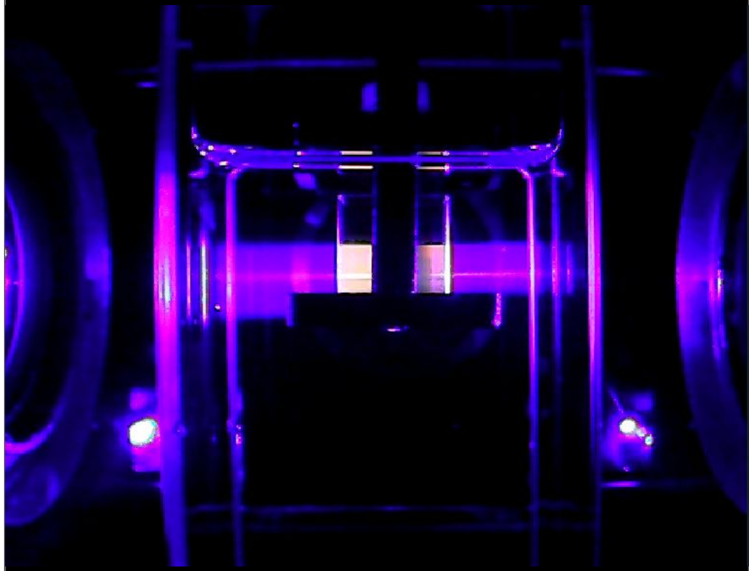
COLOR CENTERS ABSORB AND RE-EMIT LIGHT IN OPTICAL WAVELENGTHS, ENABLING A FAST READ-OUT.

PALEOCCENE: B. Cogswell, A. Goel, P. Huber, WHITE PAPER: 2203.05525

THE PALEOCCENE CONCEPT

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





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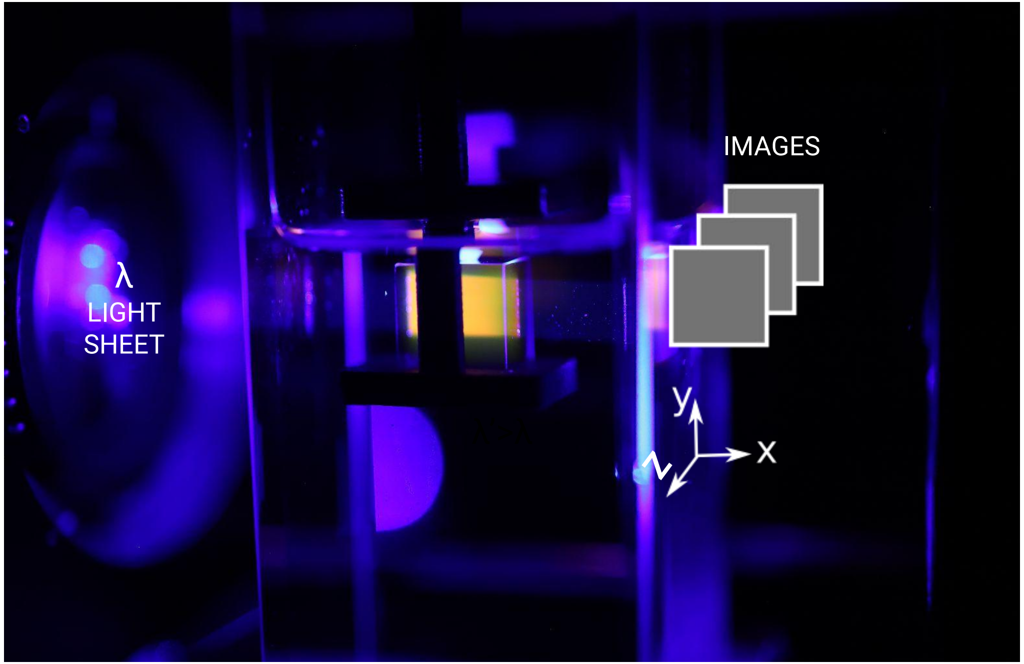

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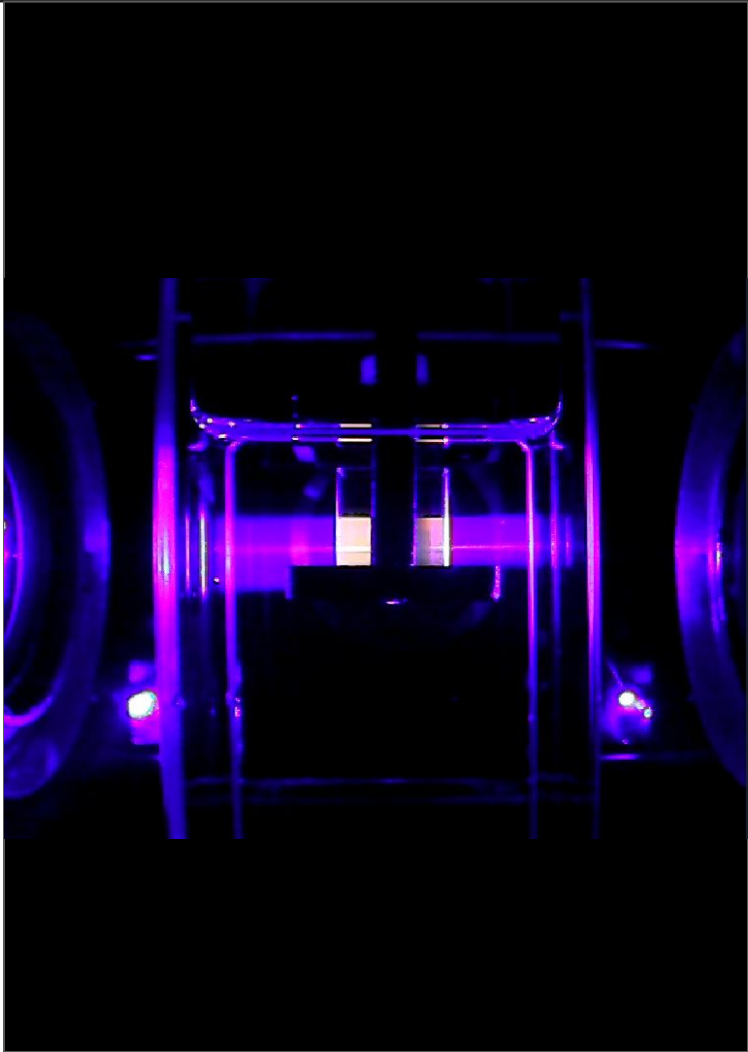
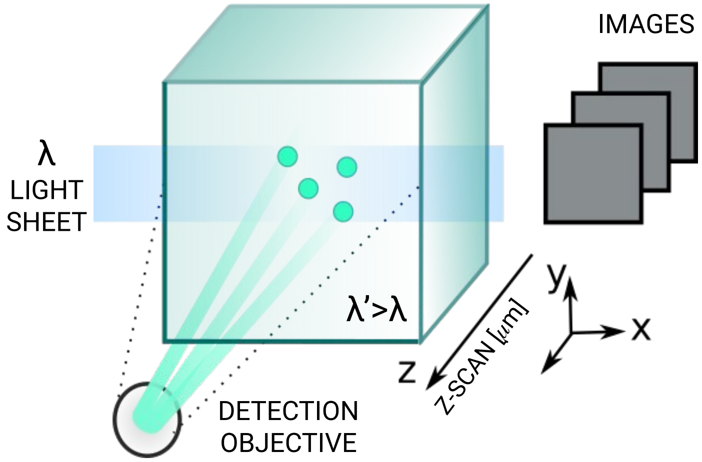


TESTING THE PALEOCCENE CONCEPT

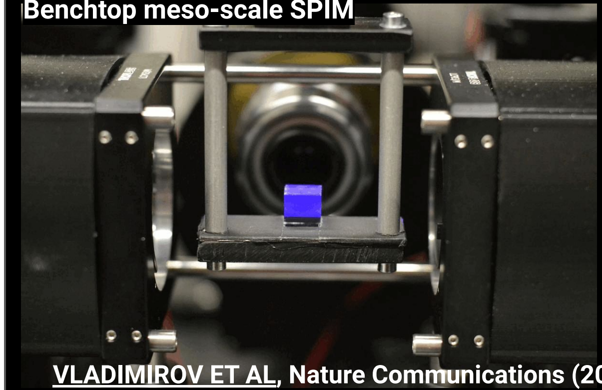
READ-OUT OF COLOR CENTERS IN CRYSTALS WITH THE MESOSPIM



Scan speed at ~ 4 μm XYZ resolution: <10min/cm^3

STATE-OF-THE-ART LIGHT-SHEET FLUORESCENCE MICROSCOPE THAT IMAGES CENTIMETER -SIZED SAMPLES WITHIN MINUTES.

Benchtop meso-scale SPIM



VLADIMIROV ET AL, Nature Communications (2024)

University of Zurich[UZH]

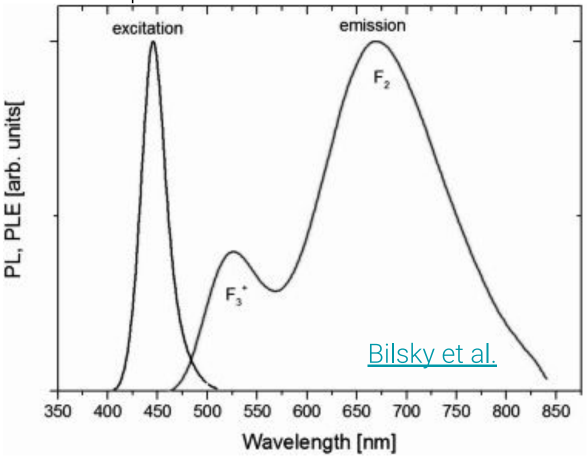
TESTING THE READOUT OF COLOR CENTERS WITH LIGHT-SHEET MICROSCOPY

TO TEST THE IMAGING METHOD, WE NEED:

1.TO SELECT CRYSTALS, UNDERSTAND THEIR FLUORESCENCE SPECTRA AND RESPONSE TO RADIATION

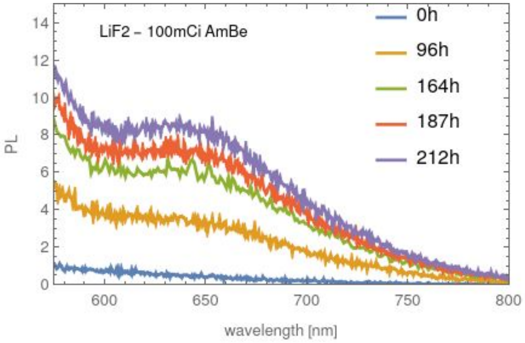
CRYSTALS STUDIED SO FAR: CaF_2, LiF and Sapphire transparent crystals

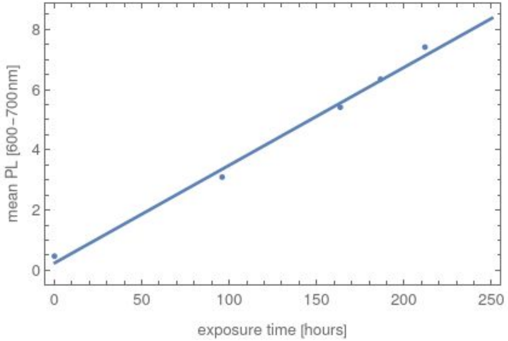
Absorption and emission of LiF

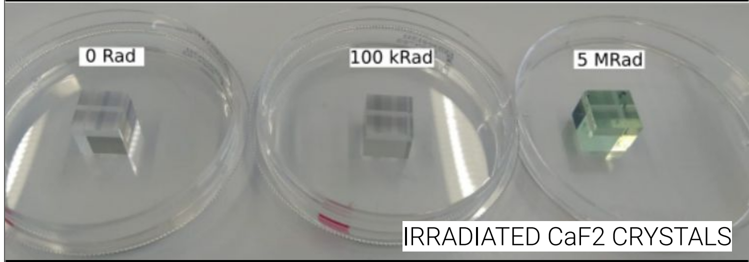


Bilsky et al.

Neutron irradiation response of LiF

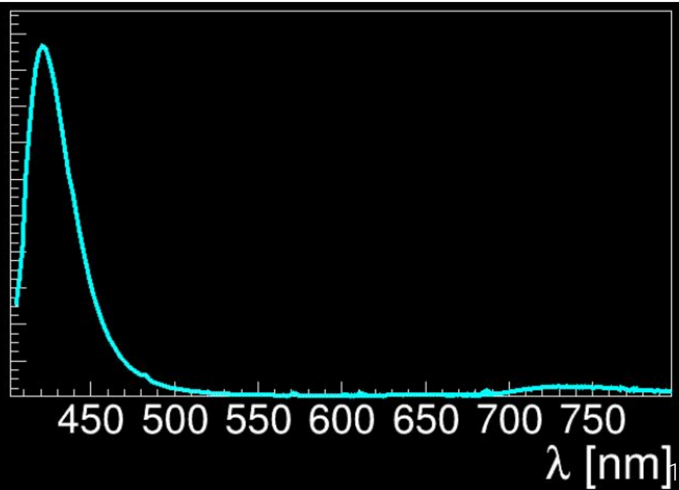






IRRADIATED CaF2 CRYSTALS

EMISSION FLUORESCENCE SPECTRUM OF IRRADIATED CaF2



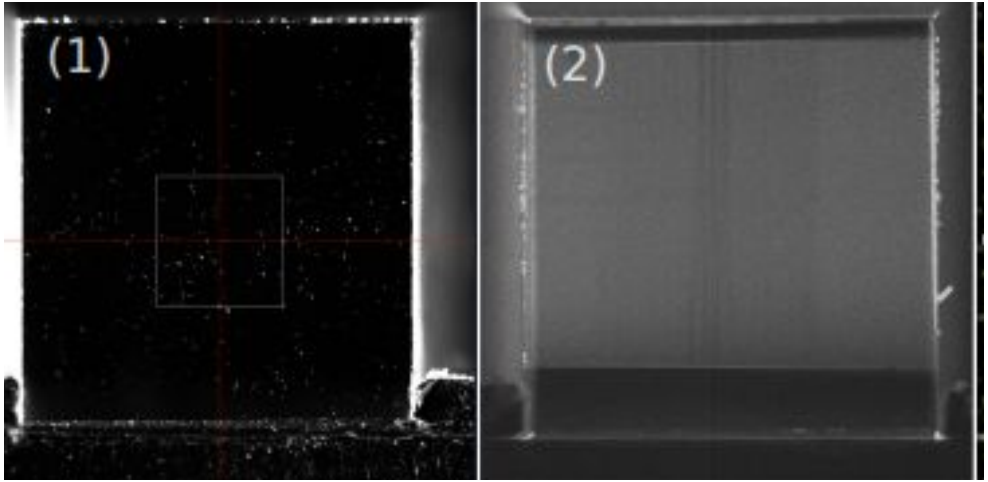
VIRGINIA TECH

Spectrometry & irradiation mostly done by P. Huber and collaborators @VTech

TESTING THE READOUT OF COLOR CENTERS WITH LIGHT-SHEET MICROSCOPY

TO TEST THE IMAGING METHOD, WE NEED:

1.TO SELECT CRYSTALS, UNDERSTAND THEIR FLUORESCENCE SPECTRA AND RESPONSE TO RADIATION



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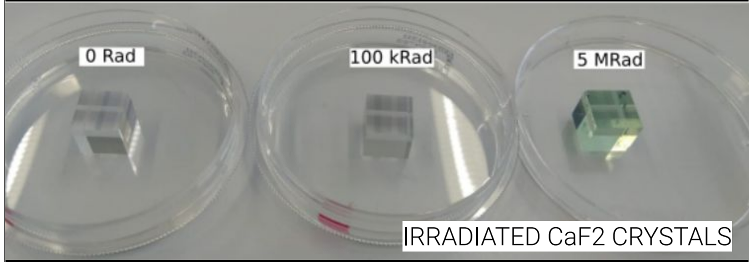
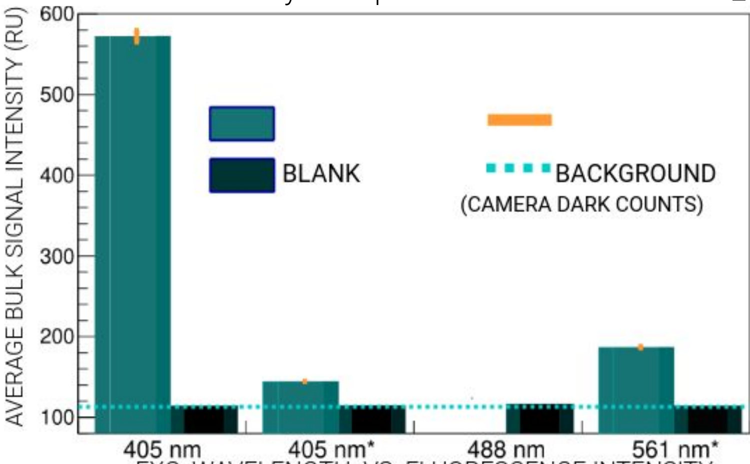
HOMOGENEOUS COLOR CENTER FLUORESCENCE

WE CAN QUANTIFY THE DISTRIBUTION AND INTENSITY OF FLUORESCENT FEATURES USING THE MICROSCOPE



IRRADIATED CaF2 CRYSTALS

Fluorescence intensity in response to various excitations



EXC. WAVELENGTH VS. FLUORESCENCE INTENSITY.

TESTING THE READOUT OF COLOR CENTERS WITH LIGHT-SHEET MICROSCOPY

TO TEST THE IMAGING METHOD, WE NEED:

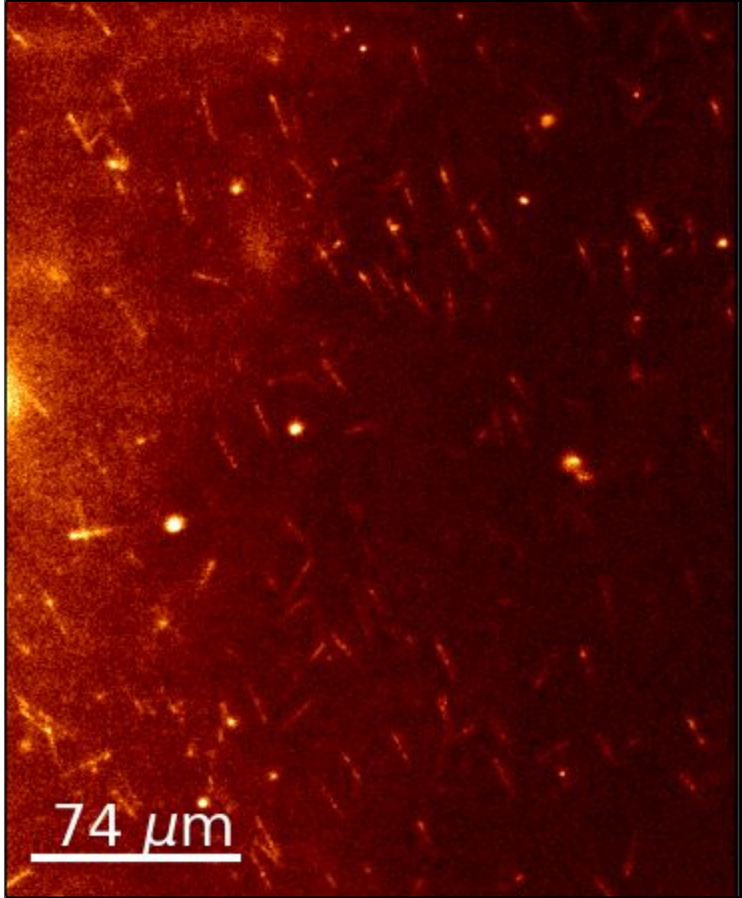
2.TO PRODUCE RESOLVABLE TRACKS IN THE CRYSTAL

GAMMA-RAYS: PRODUCE HOMOGENEOUS FLUORESCENCE OF THE BULK*
NEUTRONS: PRODUCE TRACKS IN THE BULK
ALPHAS: PRODUCE TRACKS ON THE SURFACE

γ-RAY DOSES: from 100 Rad to 5 MRad: ~10^{10}-10^{14} ph/cm^2 from a ~1 MeV ^{60}Co source
NEUTRON DOSES: ~10^8 n/cm^2 (100mCi AmBe source, shielded by lead)
ALPHA DOSES: ~10^6 alphas/cm^2 (30 Bq Am-241 source)

VIRGINIA TECH

Spectrometry & irradiation mostly done by P. Huber and collaborators @VTech

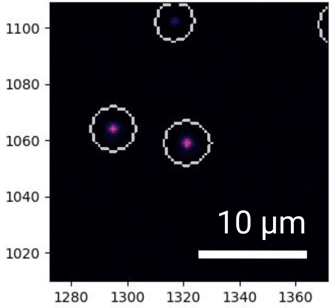


TESTING THE READOUT OF COLOR CENTERS WITH LIGHT-SHEET MICROSCOPY

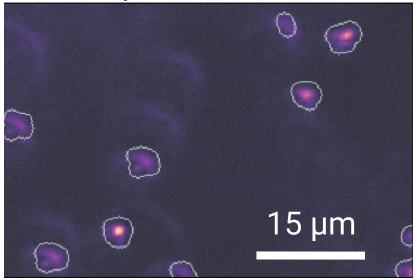
TO TEST THE IMAGING METHOD, WE NEED:

3.UNDERSTAND THE MICROSCOPES' RESPONSE

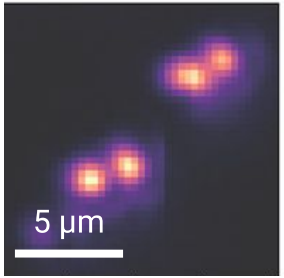
Fluorescent beads, 5x



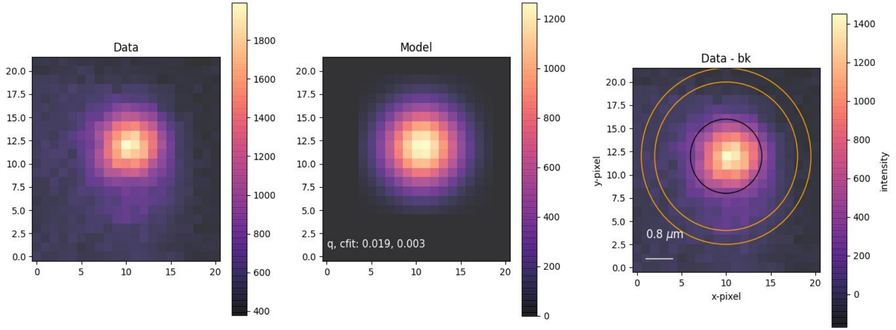
Fluorescent beads, 20x. Structures identified by the software are out outlined.



Quantum dots



Reference data is used to to understand the point spread function of the microscope, check stage reproducibility and **optimize algorithms used to identify structures & tracks.**



Examples of fitting and modelling of the point spread function.

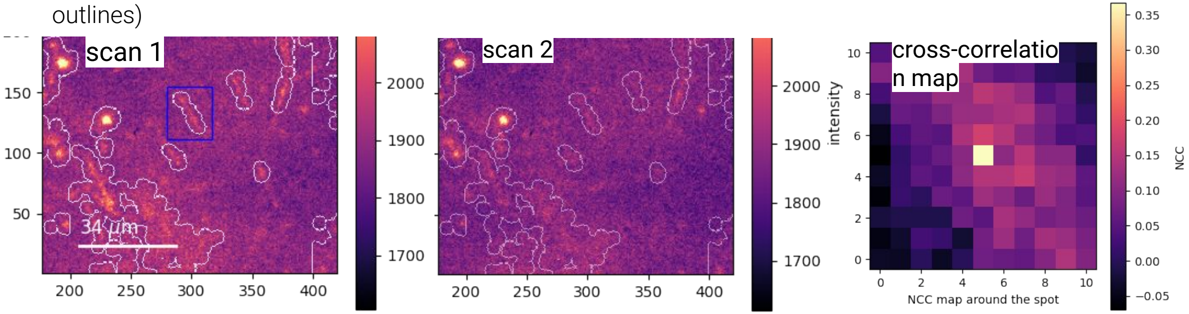
MIMICKING SMALL STRUCTURES / SIGNALS: FLUORESCENT BEADS & QUANTUM DOTS AS CALIBRATION REFERENCES

TESTING THE READOUT OF COLOR CENTERS WITH LIGHT-SHEET MICROSCOPY

TO TEST THE IMAGING METHOD, WE NEED:

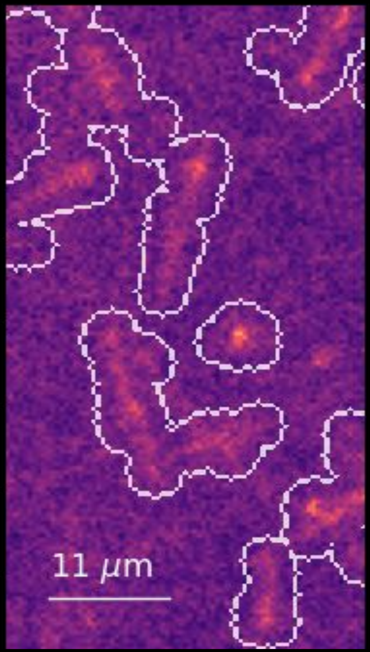
4.AUTOMATIZED DATA ANALYSIS / TRACK FINDING

Step 1: A threshold-based algorithm finds tracks and mark them with a mask (shown here by the white outlines)



Step 2: A further check is performed by matching the track candidates to a repeated scan

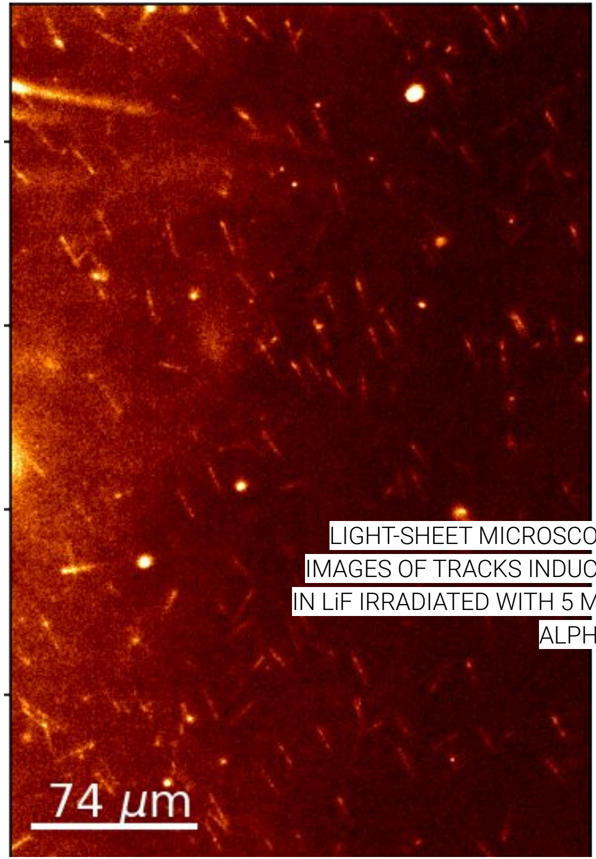
Matched track: maximum is at ~the same xyz map position but nowhere else.



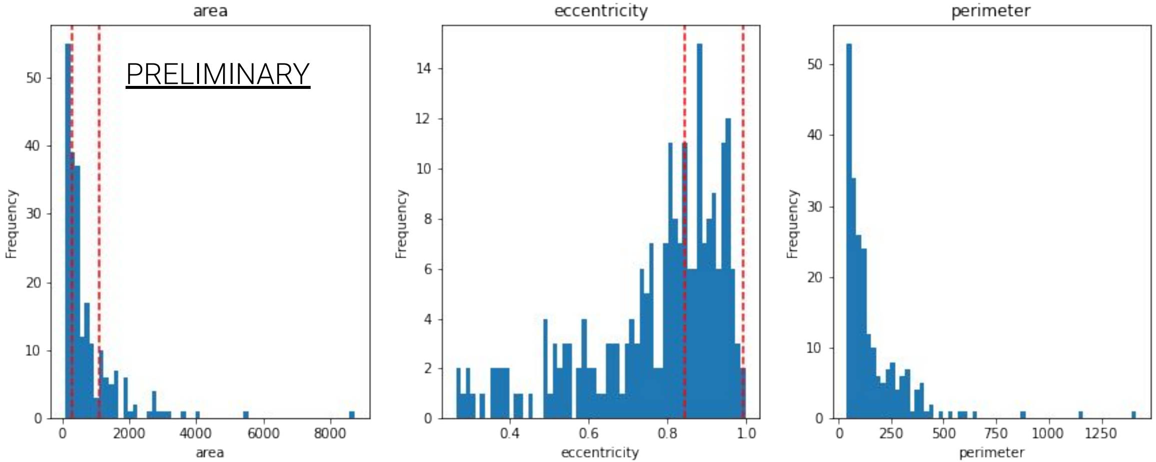
SURFACE ALPHA TRACKS

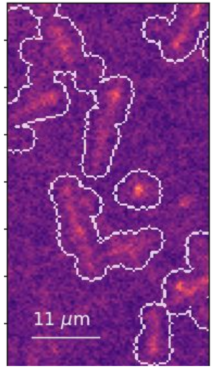
IMAGING RESULTS:

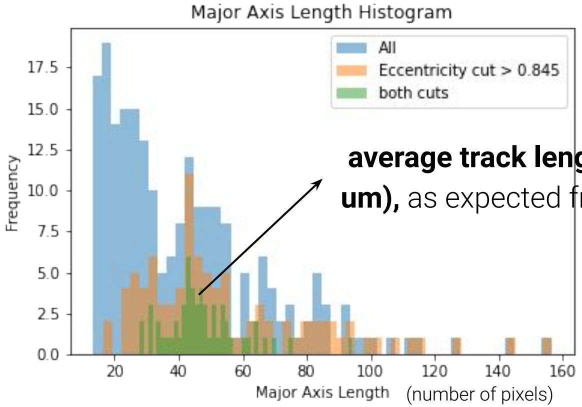
PRELIMINARY SPECTRUM OF TRACK SIZES: RESULTS AGREE WITH EXPECTED VALUE



LIGHT-SHEET MICROSCOPY IMAGES OF TRACKS INDUCED IN LiF IRRADIATED WITH 5 MeV ALPHAS



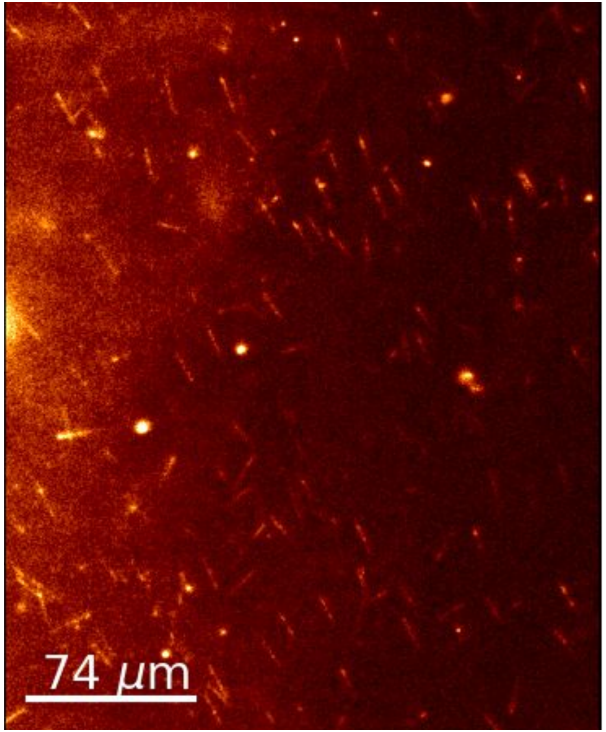


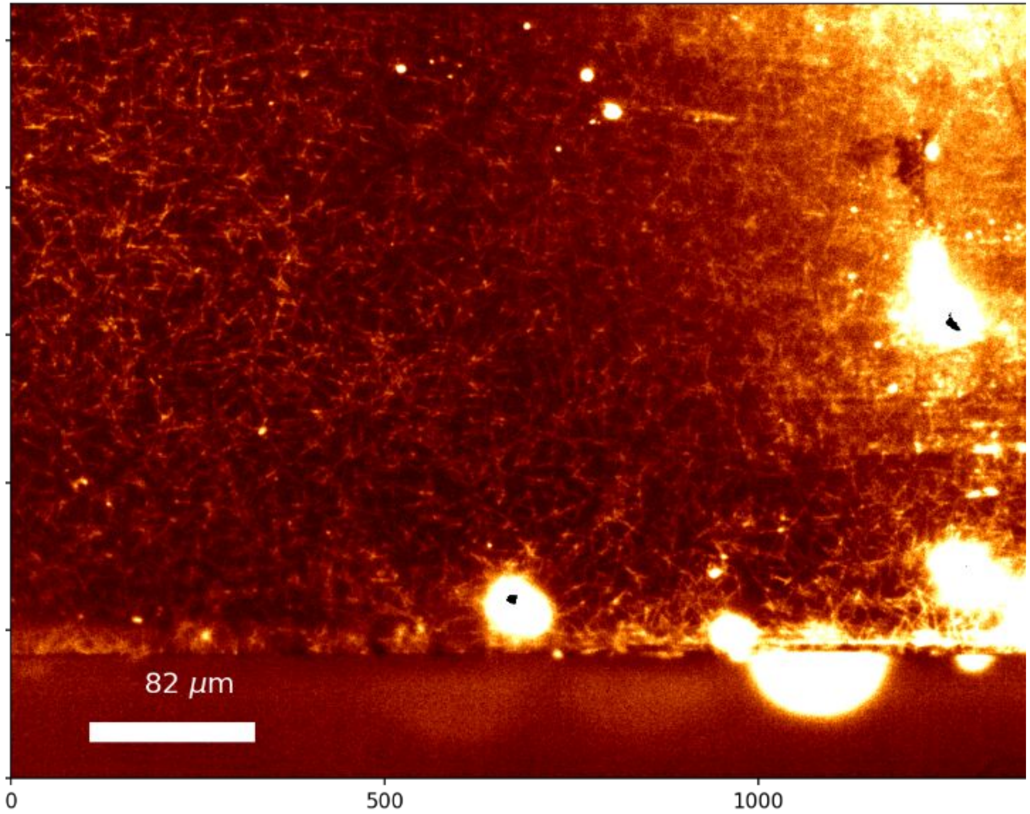


average track length is ~ 45 pixels (20 um), as expected from 5 MeV alphas in LiF

IMAGING RESULTS:

LIGHT-SHEET FLUORESCENCE IMAGES OF ALPHA TRACKS IN LiF

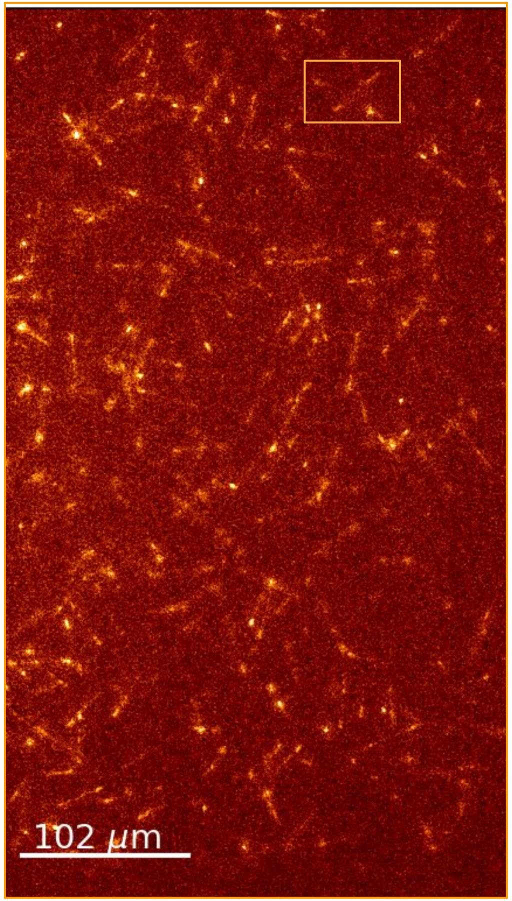


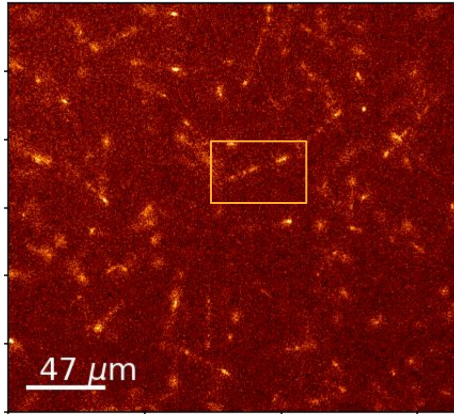


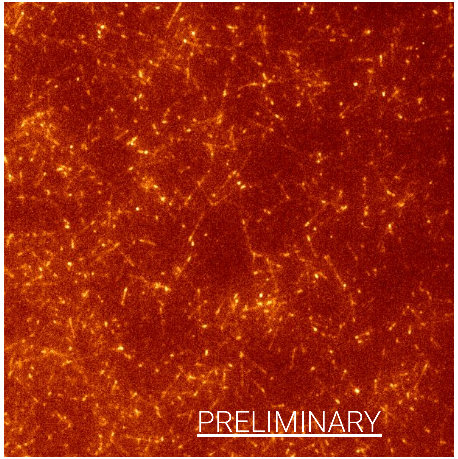
Parts of the crystal centered at the source are very dense with tracks, but some other parts are less populated

IMAGING RESULTS:

IRRADIATION OF LiF WITH THERMAL NEUTRONS PRODUCE ^{6}Li FISSION TRACKS







TRITIUM + ALPHA: some tracks show sizes according to expected. Tritium track (~**33 um**) and alpha track (**~ 6um**).

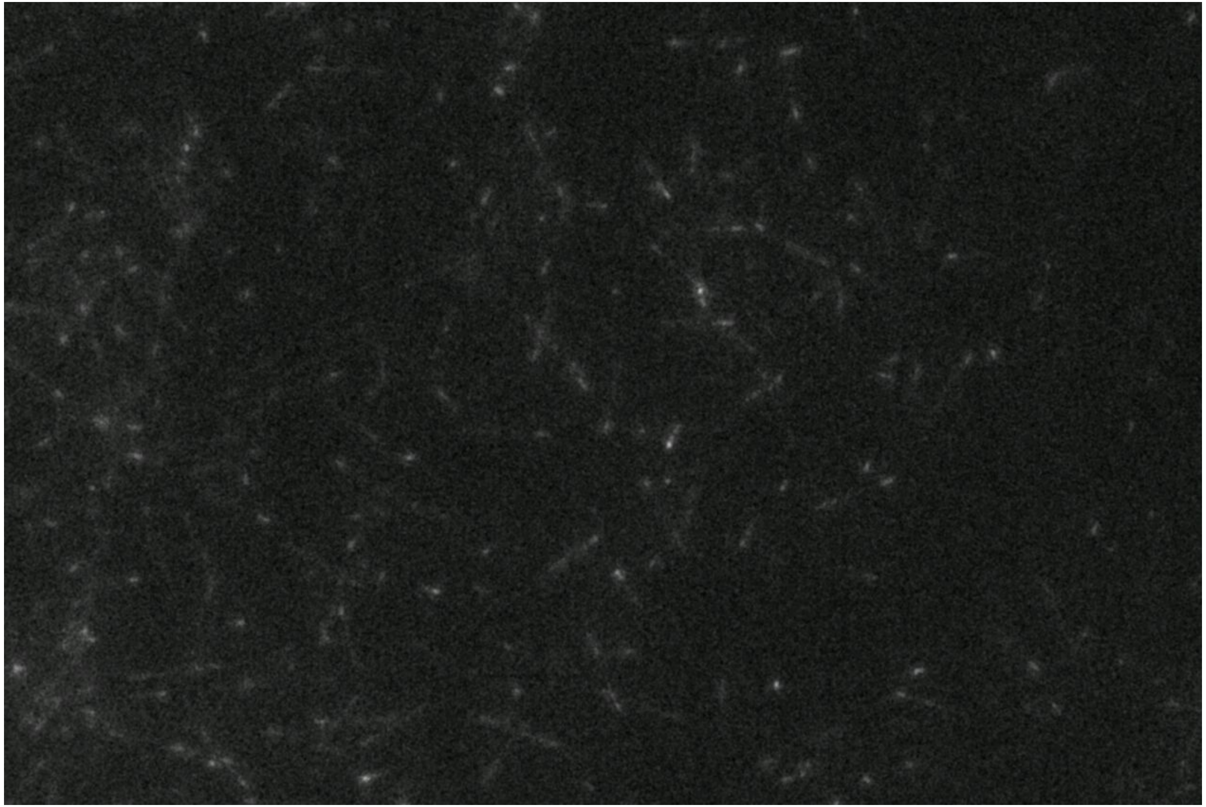
$^{6}Li + n \rightarrow$ $\mathbf{^{3}H + {^{4}He}}$

IMAGING AT at **millimeters INSIDE THE CRYSTAL**! (USUALLY NOT POSSIBLE WITH OTHER MICROSCOPY TECHNIQUES)

IRRADIATION OF LiF WITH FAST NEUTRONS PRODUCE SHORT (A FEW MICRONS) TRACKS AND SOME AMOUNT OF FISSION TRACKS CAUSED BY SLOWER NEUTRONS

IMAGING RESULTS:

IRRADIATION OF LiF WITH THERMAL NEUTRONS PRODUCE ^{6}Li FISSION TRACKS



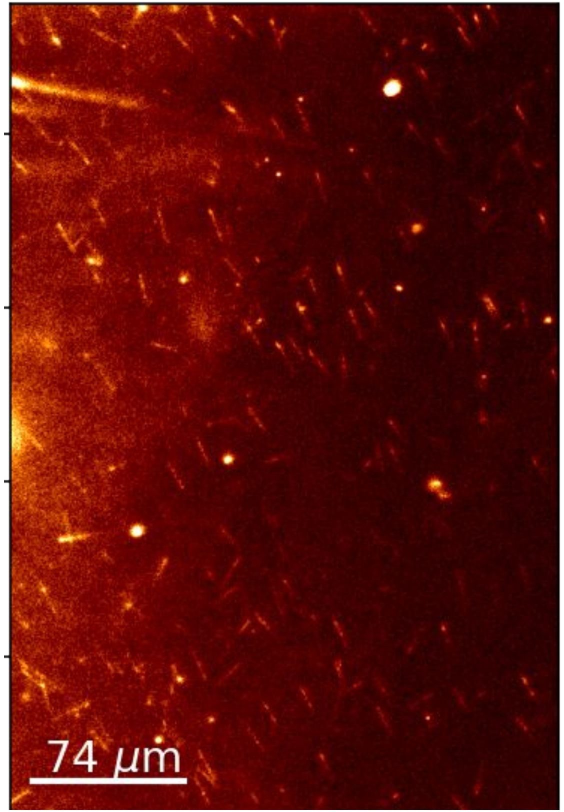
TRITIUM + ALPHA: some tracks show sizes according to expected. Tritium track (~**33 um**) and alpha track (**~ 6um**).

$^6Li + n \rightarrow \mathbf{^3H + {}^4He}$

IMAGING AT at **millimeters INSIDE THE CRYSTAL**! (USUALLY NOT POSSIBLE WITH OTHER MICROSCOPY TECHNIQUES)

SUMMARY & CONCLUSIONS:

PALEOCCENE IS A PROMISING CONCEPT OF SAFEGUARDS (& CEνNS DETECTORS*): WE SUCCESSFULLY PERFORMED THE FIRST LIGHT-SHEET IMAGING OF PARTICLE-INDUCED TRACKS



- We understand the fluorescence response of LiF to gamma & neutron irradiation
- We obtained 3D imaging of tracks from fast neutrons, alphas and fission tracks
- We understand fairly well the microscope's response
- We tested / optimized a software for automatic data processing and track identification

(*) & neutron detector
Stay tuned for upcoming results!

PALEOCCENE FAST PATH FORWARD

CONCEPT PROPOSED BY COGSWELL et. al. (12. 2021)

- PALEOCCENE WHITE PAPER (2022)
- MINERAL DETECTION OF νS & DM Phys. Dark Univ. (2023)
- NEW MESOSPIM Nat. Comm. (2024)
- MINERAL DETECTION OF νS & DM. Proceedings (2024)
- RESULTS PRESENTED HERE TO BE PUBLISHED SOON!