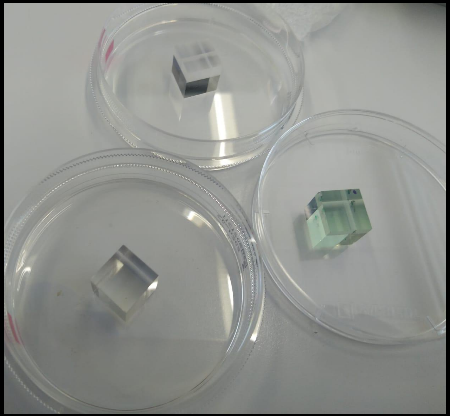
Passive particle detectors read out by light-sheet fluorescence microscopy



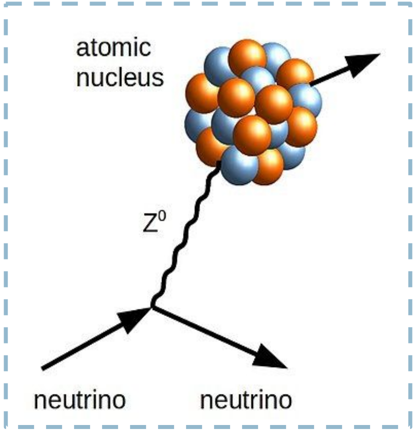
Gabriela R. Araujo
on behalf of the
PALEOCCENE collaboration

Seminar on Innovative Particle and Radiation Detectors

Siena, 28.09.2023

University of Zurich[UZH]

CEνNS detection: Low thresholds are required, especially for nuclear reactor neutrinos (νs)

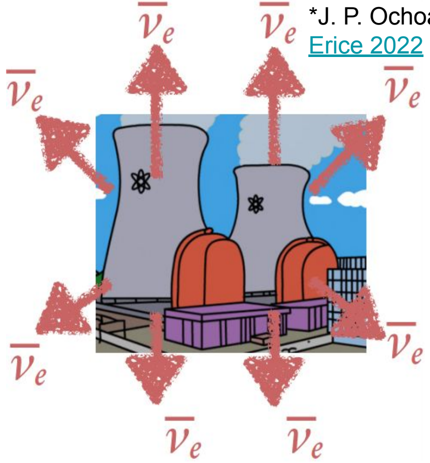


CEνNS: Coherent Elastic ν-Nucleus Scattering

CEνNS detection: “spotting a ghost”
First detection in 2017
using $E_\nu \lesssim$ 50 MeV
~ 5 keV thres.

CEνNS from reactor νs:

*J. P. Ochoa
Erice 2022

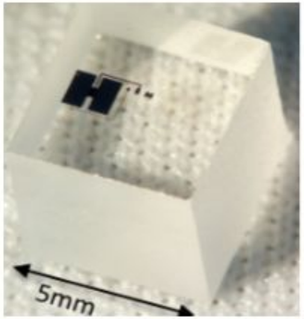


$E_\nu \lesssim$ 8 MeV*: Not yet detected:
E_{NR}~10-100 eV threshold!

*arxiv:1908.07113

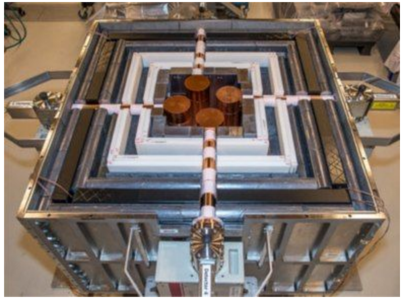
CEνNS detection:

Experiments designed to achieve low thresholds usually operate at cryogenic temperatures.



Nucleus experiment

T ~ mk



CONUS experiment

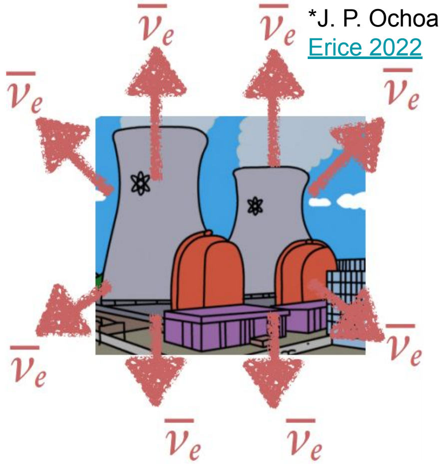
T ~ LN_2

Common detection mechanisms: collection of charge, prompt scintillation &/or phonons.

Lowest thresholds for phonon-based detectors operating at mK.

CEνNS from reactor νs:

*J. P. Ochoa Erice 2022

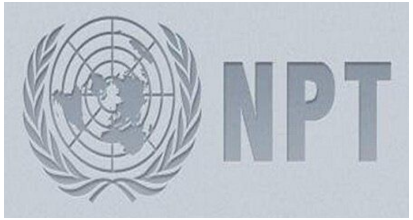


$E_\nu \lesssim$ 8 MeV*: Not yet detected: E_{NR}~10-100 eV threshold!

*arxiv:1908.07113

CEνNS detection for nuclear reactor monitoring purposes

Monitoring ν-flux from reactors allows for estimation of fissile material production and verification of non-proliferation agreements.



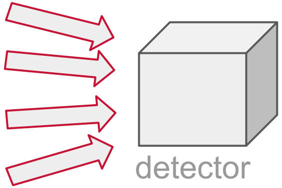
Nuclear non-proliferation Treaty

IAEA
International Atomic Energy Agency
Atoms for Peace and Development

~450 nuclear power reactors
>200 nuclear research reactors

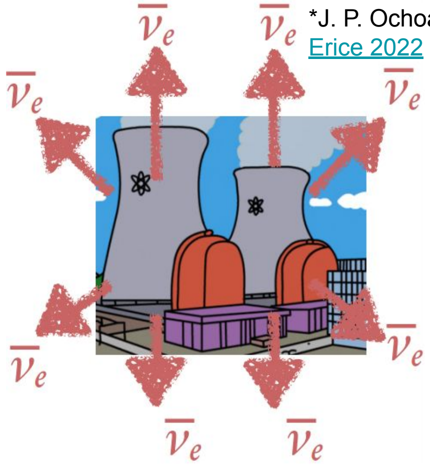
arxiv:1908.07113

ν-flux



CEνNS from reactor νs:

*J. P. Ochoa Erice 2022



$E_\nu \lesssim$ 8 MeV*: Not yet detected:
E_{NR}~10-100 eV threshold!

*arxiv:1908.07113

To monitor a large number of reactors, we need a simple & small detector

Detector wish list:

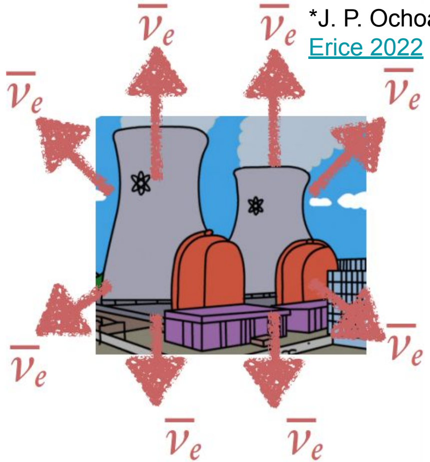
- Reasonably cheap
- Small: allows moderate distance to reactor / overburden
- Low threshold
- No cryogenics / HV / dedicated staff on-site

Passive crystals

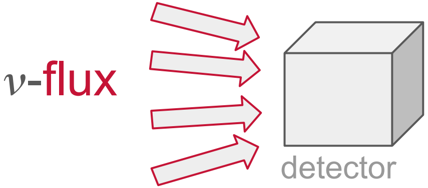
~450 nuclear power reactors
>200 nuclear research reactors

arxiv:1908.07113

CEνNS from reactor νs:



*J. P. Ochoa
Erice 2022



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CEνNS detection

The concept of a passive detector readout by microscopy

Detector wish list:

- Reasonably cheap
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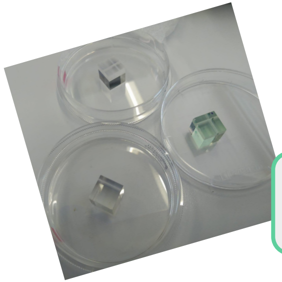
- Low threshold

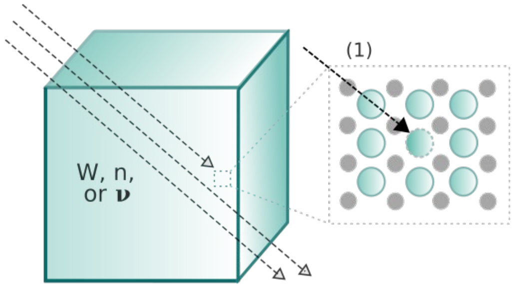


Passive crystals

Signal

- Long lived
- No / distinguishable response to ɣ rays

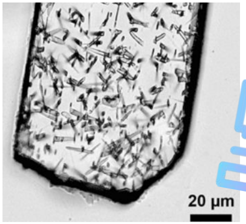
ν-induced defect/track



Readout

- Can be performed ex-situ or setup can be easily taken in-situ

Eg of microscopy track imaging: Etched fission tracks in apatite Thomson (2016)

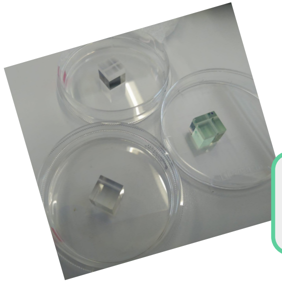


microscopy

The concept of a passive detector readout by microscopy

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
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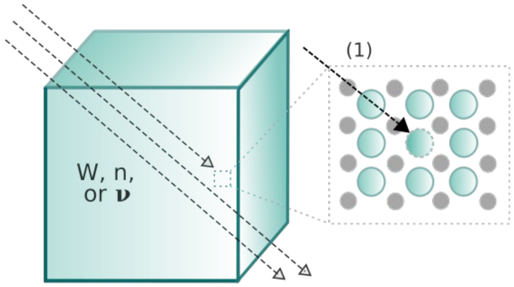


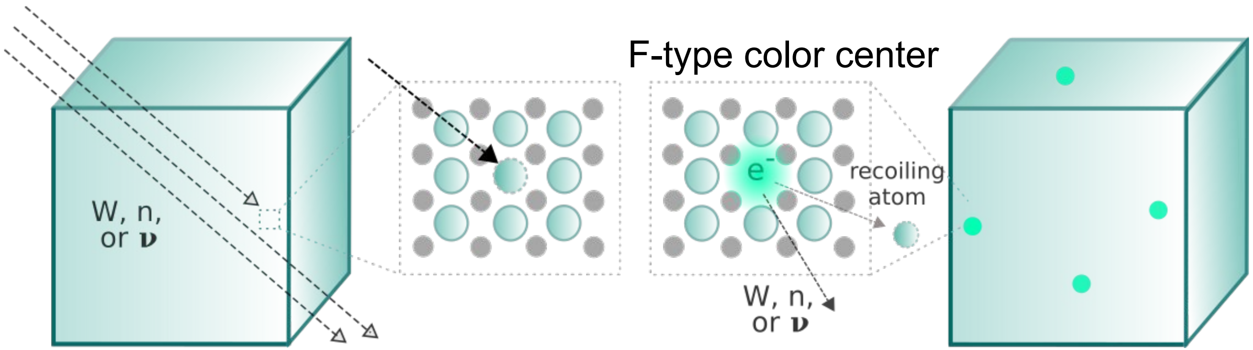
Readout

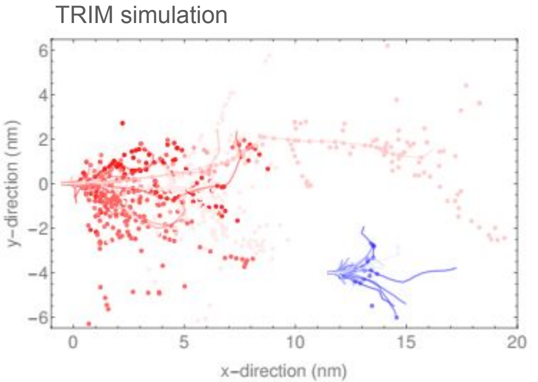
- Can be performed ex-situ or setup can be easily taken in-situ
- Identification of low -energy signals
- Reasonably Cheap
- Fast non-desctructive read-out of large volumes

microscopy

PALEOCCENE

Passive low-energy optical color center nuclear recoil





Vacancies (dots) and tracks (lines) induced in NaI by cosmic ray neutrons and CEνNS

Anion displacement has a low threshold*:

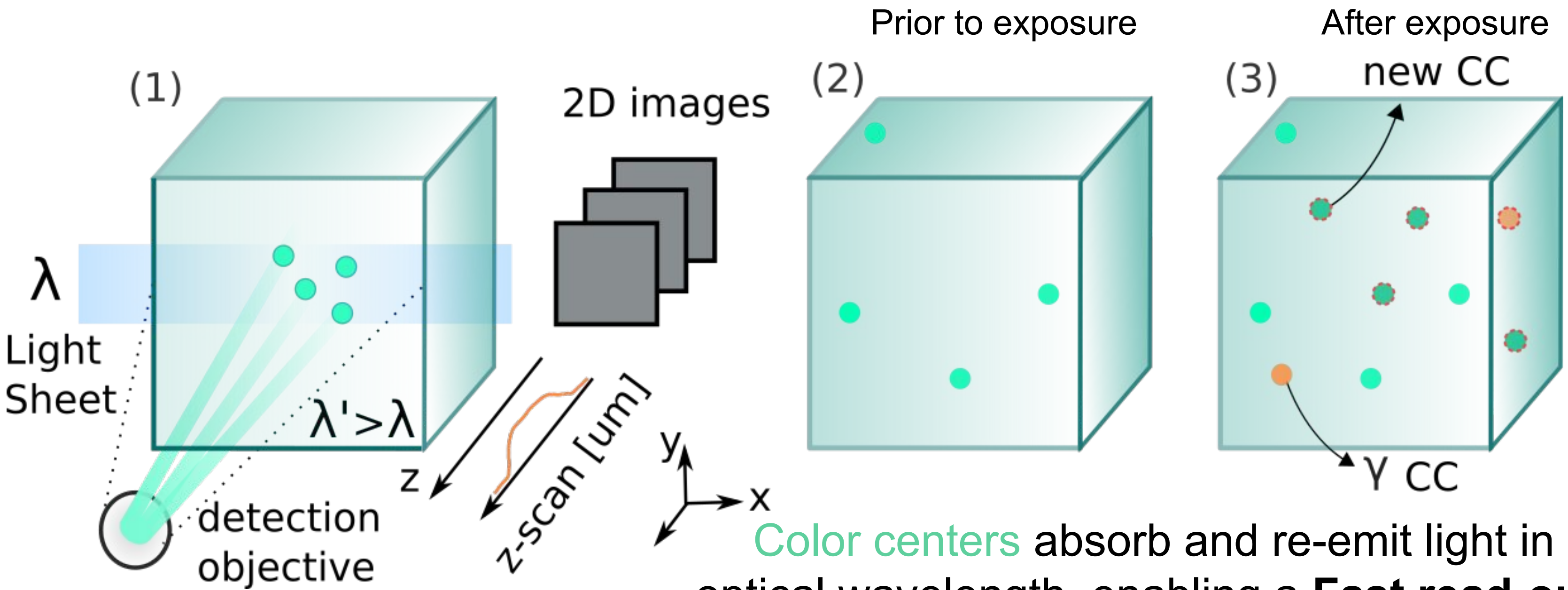
Sensitivity to rare low-energy events

(*)stopping power for most ions is around 20–100 eV/nm -> E recoiling nucleus ~20–200 eV

B. Cogswell, A. Goel, P. Huber

WP: 2203.05525

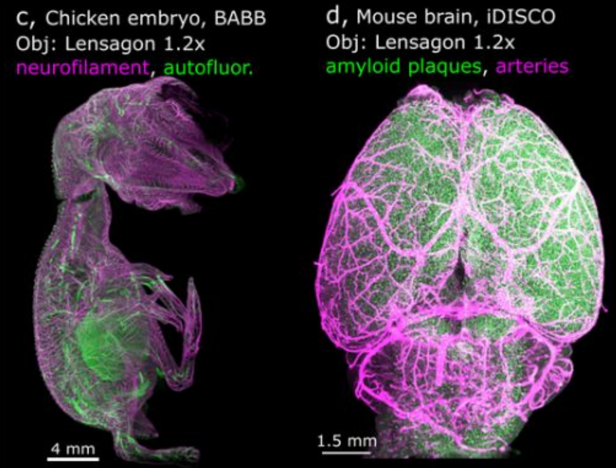
Read-out of color centers in passive detectors using light-sheet fluorescence microscopy

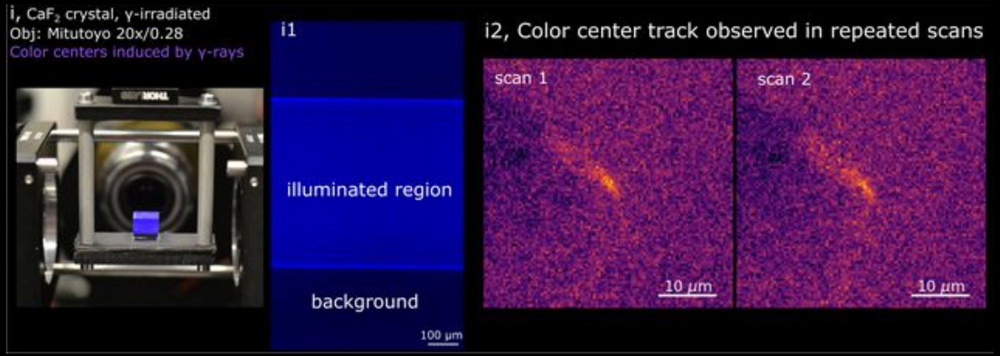


Color centers absorb and re-emit light in optical wavelength, enabling a **Fast read-out!**

mesoSPIM: “Large scale” light-sheet fluorescence microscopy

The mesoSPIM: the first setup to produce “volumetric images of centimeter-sized samples with near-isotropic resolution within minutes.” Nature methods (2019)

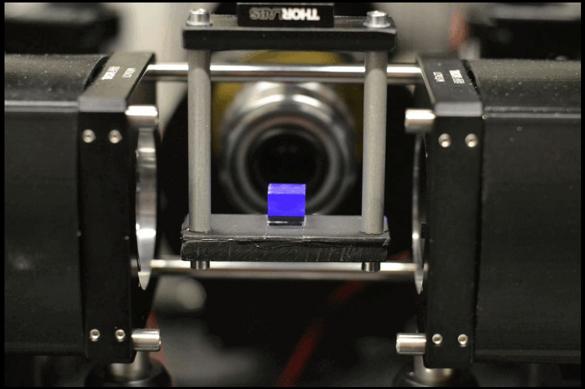




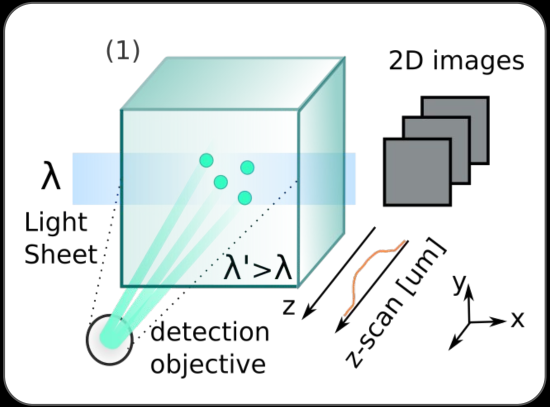
New (2023) benchtop version was optimized for color center imaging Vladimirov et. al (bioRxiv:2023.06.16.545256)

Large sCMOS camera (5056x2960 pixels, 4.25 µm pixel size), magnification up to 20x, 1.5 µm x-y resolution.

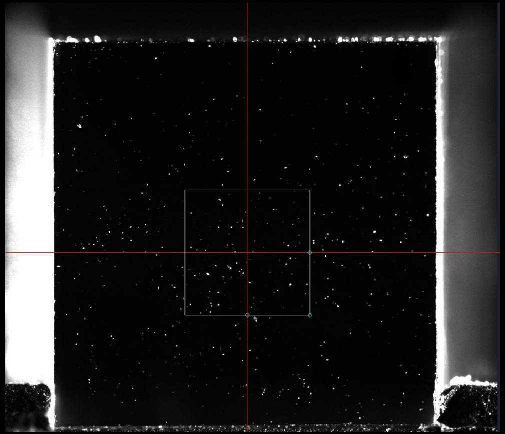
Testing the concept: Light-sheet microscopy of ɣ-ray induced color centers



Gamma- Irradiated CaF_2 (5 MRad dose)



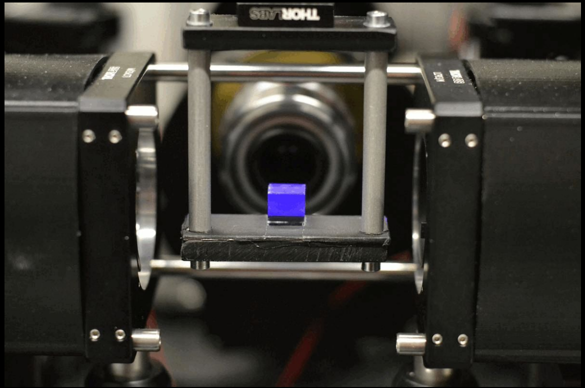
Scan speed at ~ 4 µm isotropic resolution: <10 min/cm^3



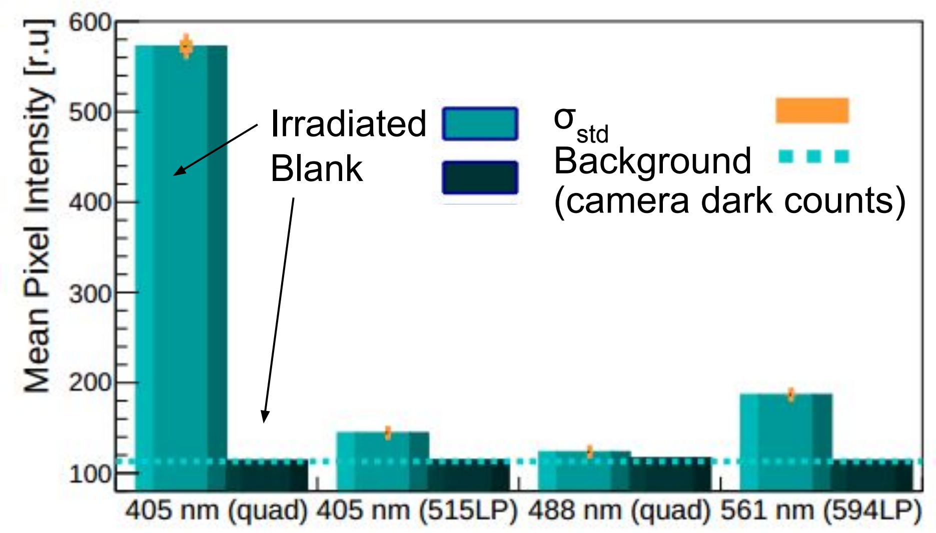
Microscopy image of the surface of a CaF_2 crystal

Large sCMOS camera (5056x2960 pixels, 4.25 µm pixel size), magnification up to 20x (1.5 µm x-y resolution).

Testing the concept: Fluorescence signal clearly above background measured with light-sheet microscopy



Gamma- Irradiated CaF_2 crystal fluorescing when the light sheet is on

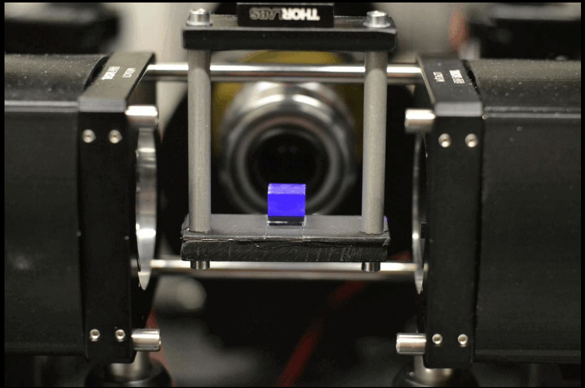


Exc. wavelength (and filter) vs. fluorescence intensity. Intensity is the highest in response to 405 nm excitation.

Crystal only became fluorescent after irradiation*.

*irradiated = 100 kRad dose

Testing the concept: Capabilities to measure color-center "tracks"



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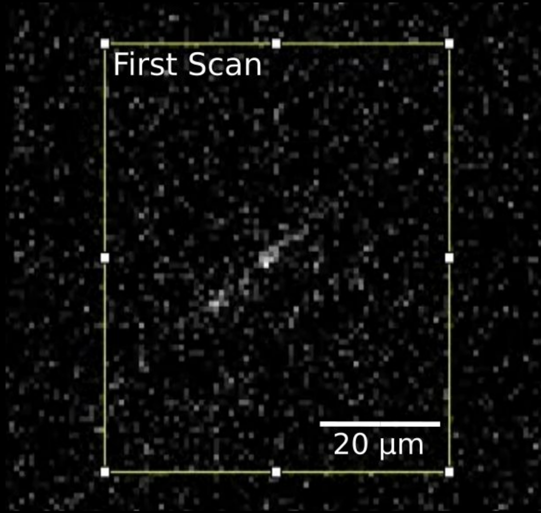
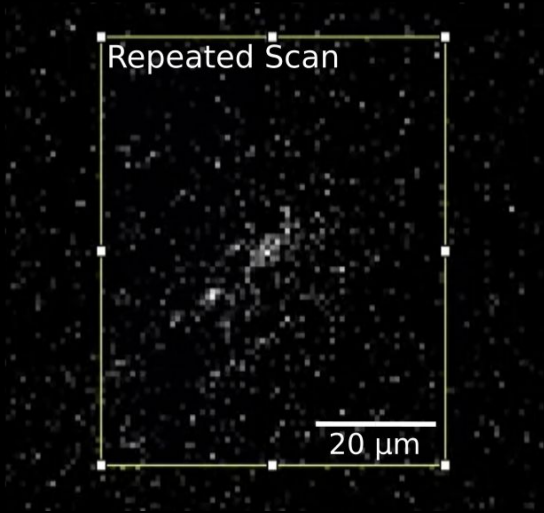


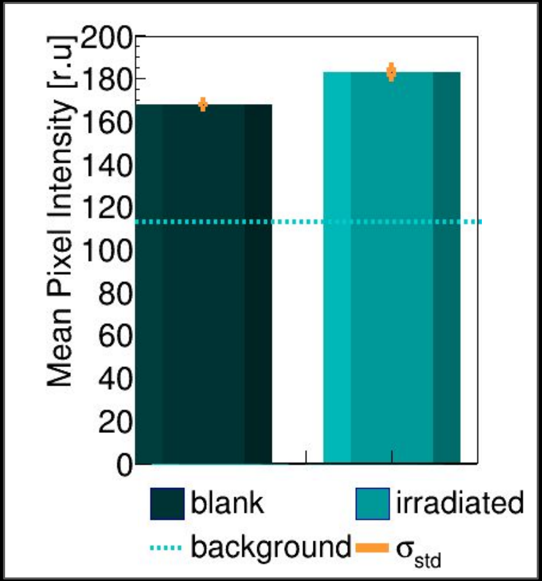
Mag. 10x



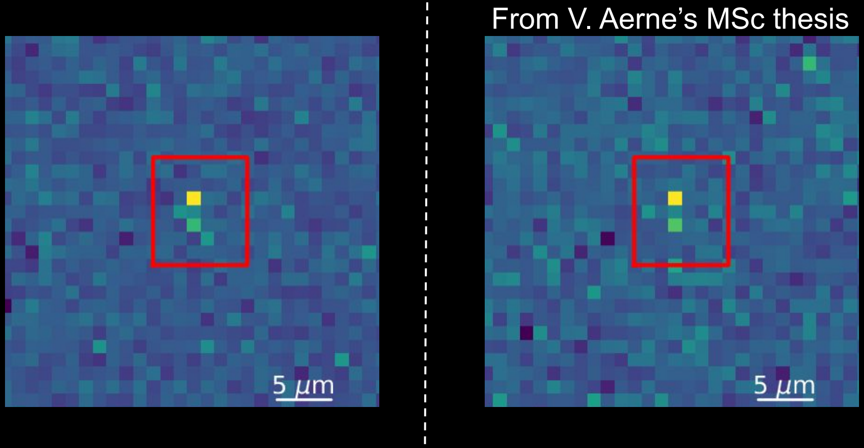
Mag. 10x

Track-like structures were identified and confirmed to exist in repeated scans of the same region (track origin is unknown).

Testing the concept: Fluorescence signal from neutron irradiated* samples



From V. Aerne's MSc thesis



Examples of bright pixels appearing at repeated scans imaged at 6x

No structures spanning several microns are expected. Analysis involves matching n≥1 pixels with intensity higher than a given threshold in repeated scans.

*AmBe source.

Preliminary results: irradiated crystal yields signal above the background, matching probability is larger than that expected from random matching and imaging artifacts.

Summary and next steps in the R&D of passive particle detectors read out by light-sheet fluorescence microscopy

- Demonstrated imaging of radiation-induced color centers with light-sheet microscopy
- Current tests focus on producing 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 impurities & color center formation; ion-induced tracks.

- Possible applications:
  - CEνNS detection, reactor monitoring
  - Dark matter (DM) detection
  - Neutron detector
  - Paleo detectors
  - Rock dating (geology)

- Literature:

PALEOCCENE: arXiv:2104.13926 , 2203.05525
Mineral detectors for νs & DM: arXiv:2301.07118
mesoSPIM: bioRxiv 2023.06.16.545256,