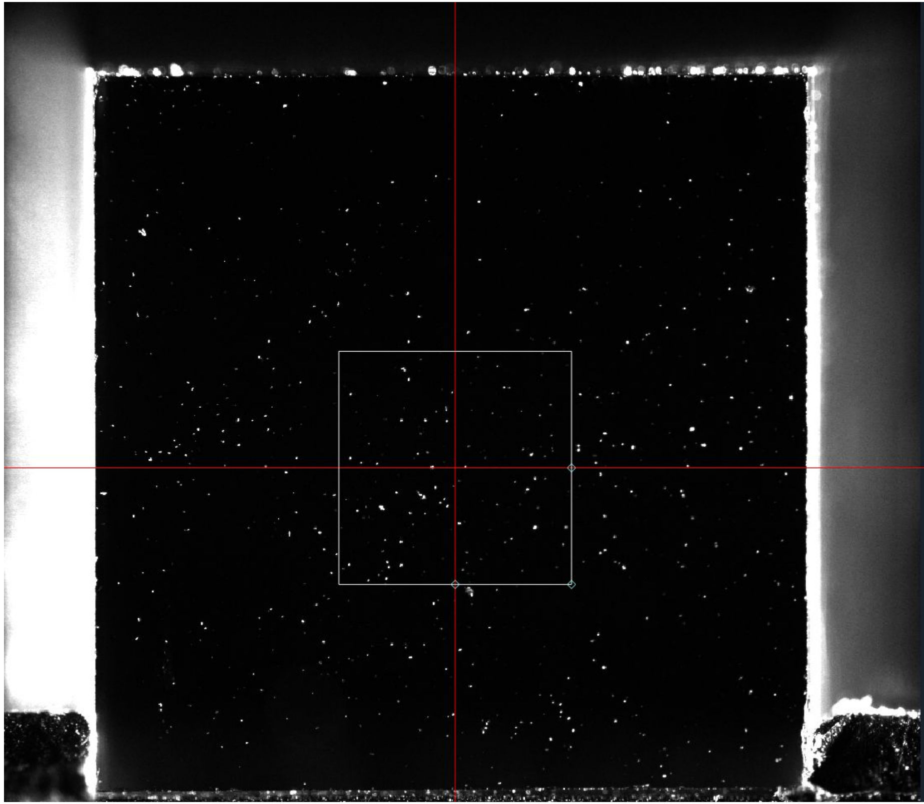
NOVEL NEUTRINO AND DARK MATTER DETECTORS READ OUT BY LIGHT-SHEET FLUORESCENCE MICROSCOPY



THE DARK SIDE OF THE UNIVERSE 2024.
CORFU SUMMER INSTITUTE, SEP 10 2024

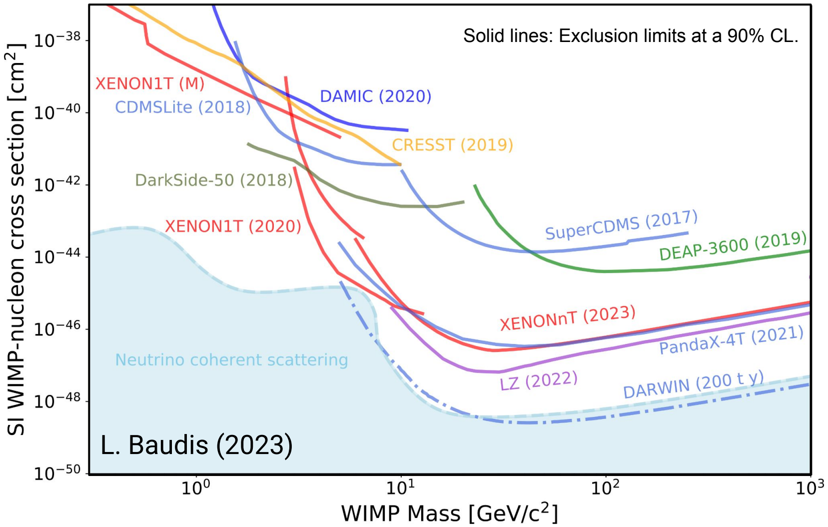
GABRIELA R. ARAUJO

University of Zurich UZH

PALEOCCENE

SEARCHING FOR WIMP DARK MATTER

STILL SOME FREE PARAMETER SPACE TO EXPLORE

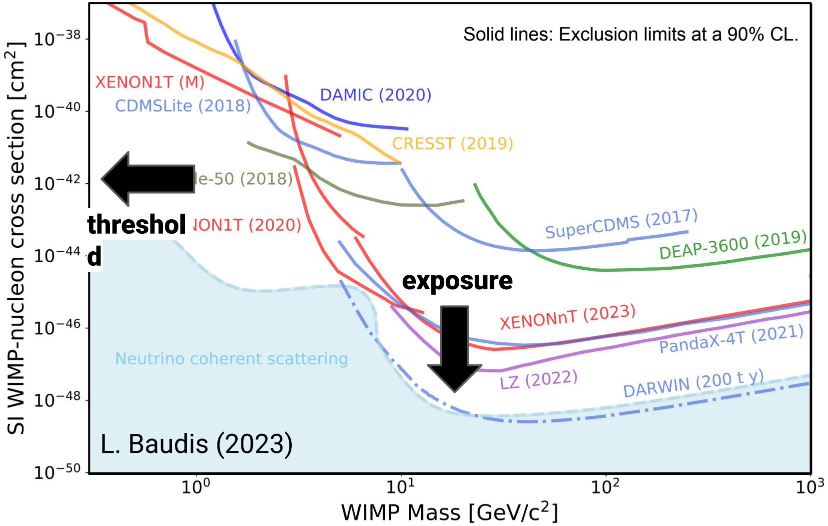


Experimental parameter space for the spin-independent interaction of WIMP* with nucleons.

*weakly interacting massive particle

X-ray: NASA/CXC/CfA/ M. Markevitch; Optical and lensing map: NASA/STScI, Magellan/U.Arizona/D. Clowe; Lensing map: ESO WF

PUSHING THE SENSITIVITY BY INCREASING EXPOSURE & LOWERING THE DETECTION THRESHOLD#



Experimental parameter space for the spin-independent interaction of WIMP with nucleons.

LOWERING THRESHOLD: Detectors at ~15 mK collect phonons with transition edge sensors (TES). Energy depositions of ~keV correspond to temperature increase of ~uK (mOhm)

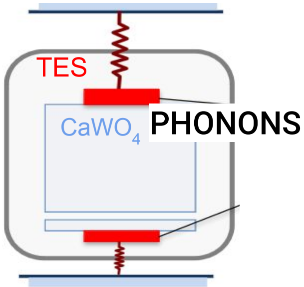


FIGURE: CRESST Example, from P. Gorla's slides (UCLA DM 2023)

INCREASING EXPOSURE: Xenon experiments increased from ~**10kg to possibly 50000 kg** with DARWIN/XLZD.

FIGURES: XENON10 & XENONnT, from E. Aprile et al

15 kg
161 kg
3200 kg
8600 kg
50000kg
XENON10
XENON100
XENON1T
XENONnT
XLZD

---

*weakly interacting massive particle. (#) and suppressing background.

SEARCHING FOR WIMP DARK MATTER

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.

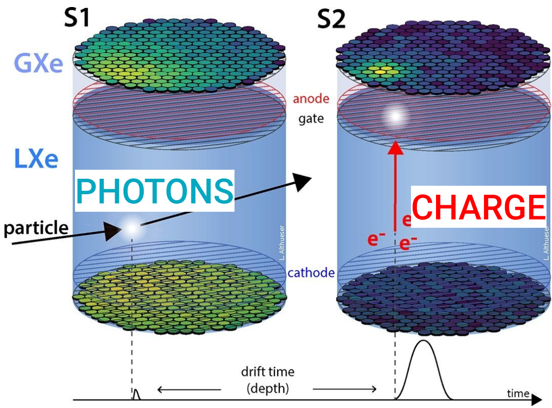


FIGURE: XENON COLLABORATION

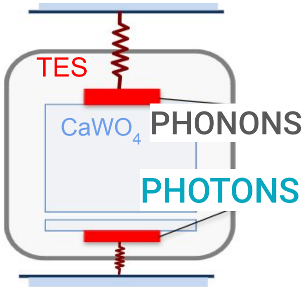


FIGURE: CRESST Example, from P. Gorla's slides (UCLA DM 2023)

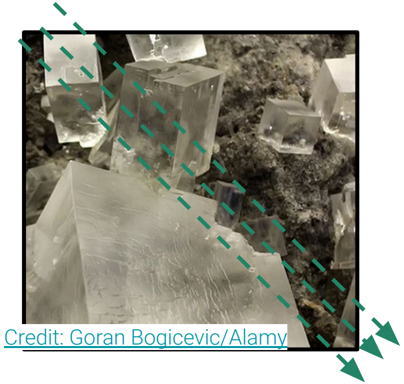
SEARCHING FOR WIMP DARK MATTER

RECENTLY, PASSIVE DETECTORS THAT INTEGRATE SIGNALS OVER TIME HAVE ALSO BEEN PROPOSED

EXAMPLE: **PALEODETECTORS**

"MINERALS COULD BEAR THE SCARS OF COLLISIONS WITH DARK MATTER"
geologyin.com

LARGE EXPOSURE ACHIEVED BY LARGE INTEGRATION TIME



Credit: Goran Bogicevic/Alamy

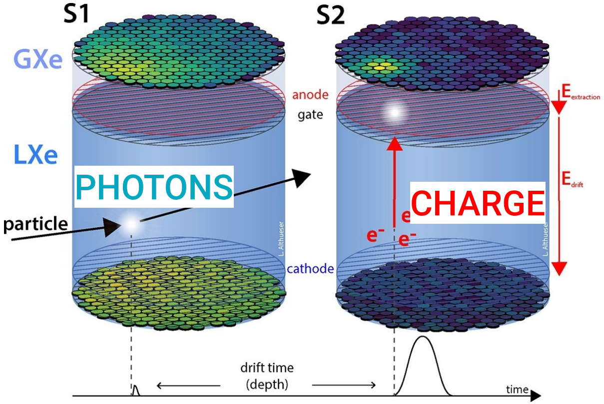


FIGURE: XENON COLLABORATION

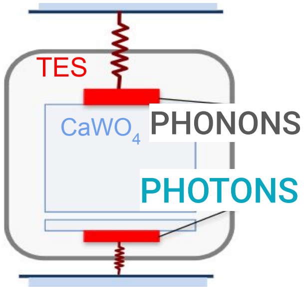
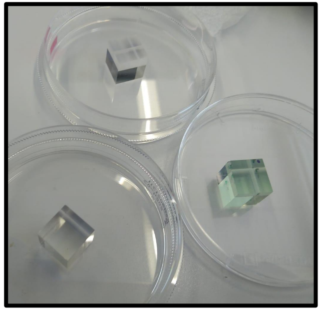
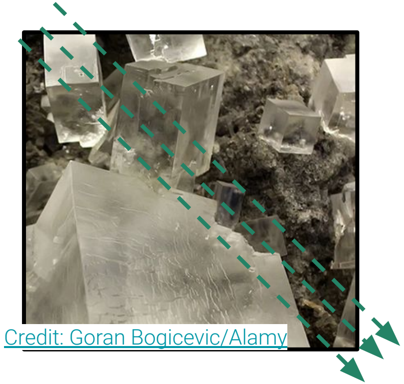


FIGURE: CRESST Example, from P. Gorla's slides (UCLA DM 2023)

SEARCHING FOR WIMP DARK MATTER

A NEW DETECTION CHANNEL AT LOW ENERGIES: READOUT OF COLOR CENTERS





Credit: Goran Bogicevic/Alamy

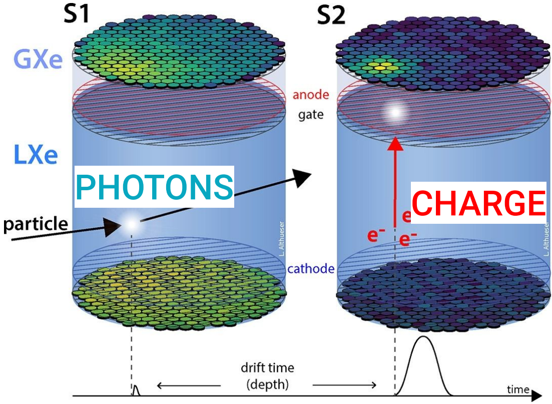


FIGURE: XENON COLLABORATION

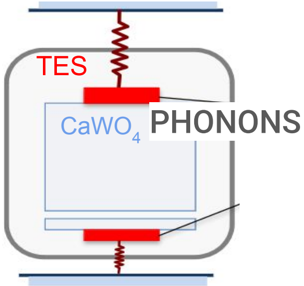


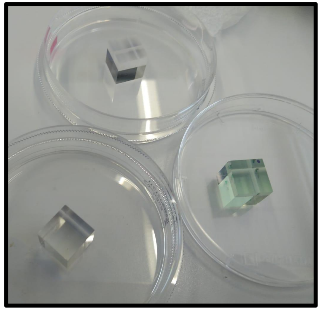
FIGURE: CRESST Example, from P. Gorla's slides (UCLA DM 2023)

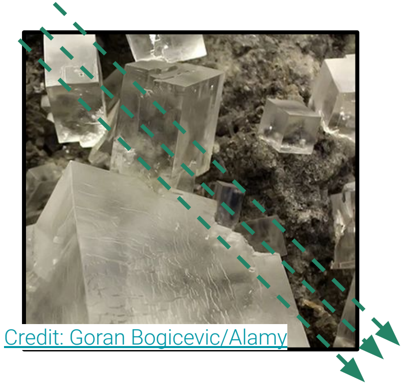
TRANSPARENT CRYSTALS MAY OFFER A NEW DETECTION CHANNEL: READOUT OF CRYSTALLINE DEFECTS INDUCED BY NUCLEAR RECOILS. FOCUS HERE: **COLOR CENTER DEFECTS***

(*) R. Budnik, et al (2018), B. Cogswell, A. Goel, P. Huber (2021)

SEARCHING FOR WIMP DARK MATTER

COLOR-CENTER BASED DETECTORS COULD REACH LOW DETECTION THRESHOLDS.





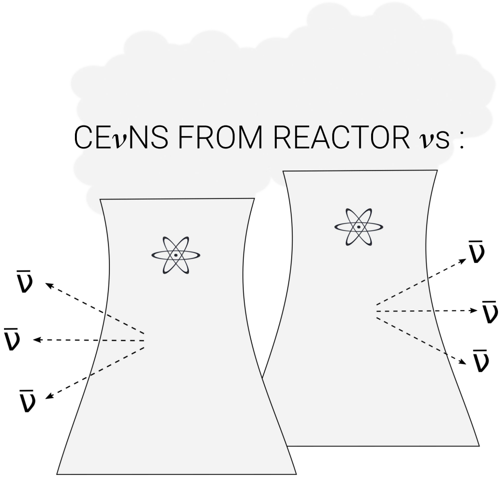
Credit: Goran Bogicevic/Alamy

TRANSPARENT CRYSTALS MAY OFFER A NEW DETECTION CHANNEL: READOUT OF CRYSTALLINE DEFECTS INDUCED BY NUCLEAR RECOILS. FOCUS HERE: **COLOR CENTER DEFECTS***, ENABLING LOW-ENERGY THRESHOLDS.

AT LOW THRESHOLDS:

ACCESS BEYOND “VANILLA” MEDIUM-MASS WIMP**.**

ABILITY TO MEASURE LOW-ENERGY NUCLEAR RECOILS = ABILITY TO MEASURE CEνNS: COHERENT ELASTIC ν-NUCLEUS SCATTERING USING **SMALL (<KG) DETECTORS**



CEνNS FROM REACTOR νs :

NOT YET DETECTED

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

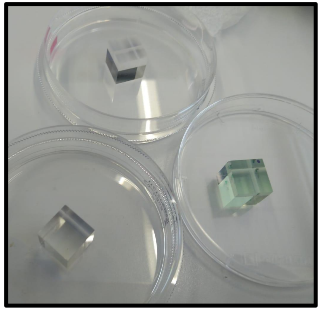
FLUX MANY ORDERS OF MAGNITUDE HIGHER THAN BORON-8 SOLAR NEUTRINOS.

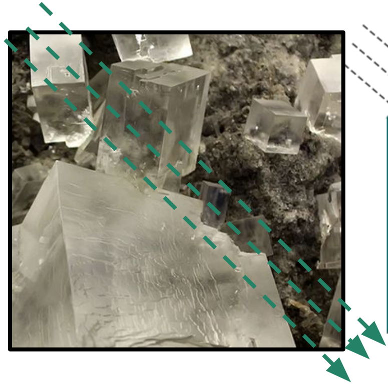
(*) R. Budnik, et al (2018), B. Cogswell, A. Goel, P. Huber (2021)

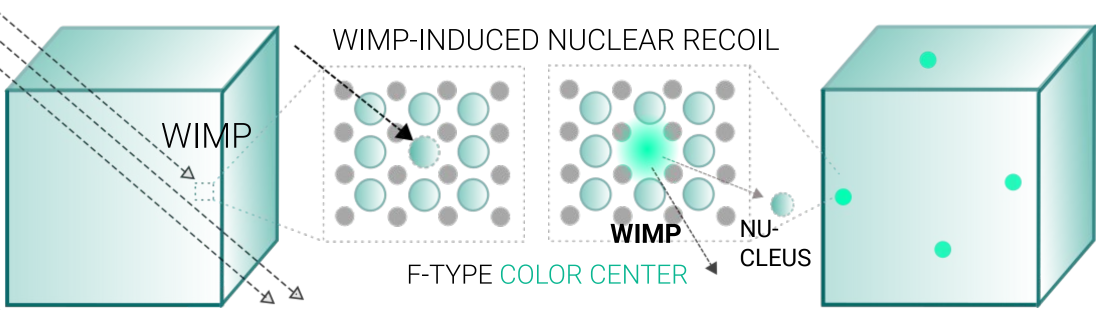
THE PALEOCCENE CONCEPT

PASSIVE DETECTION OF COLOR CENTERS RESULTING FROM LOW-ENERGY NUCLEAR RECOILS INDUCED BY DARK MATTER AND NEUTRINOS

B. Cogswell, A. Goel, P. Huber. [PRA 16 (2021)]





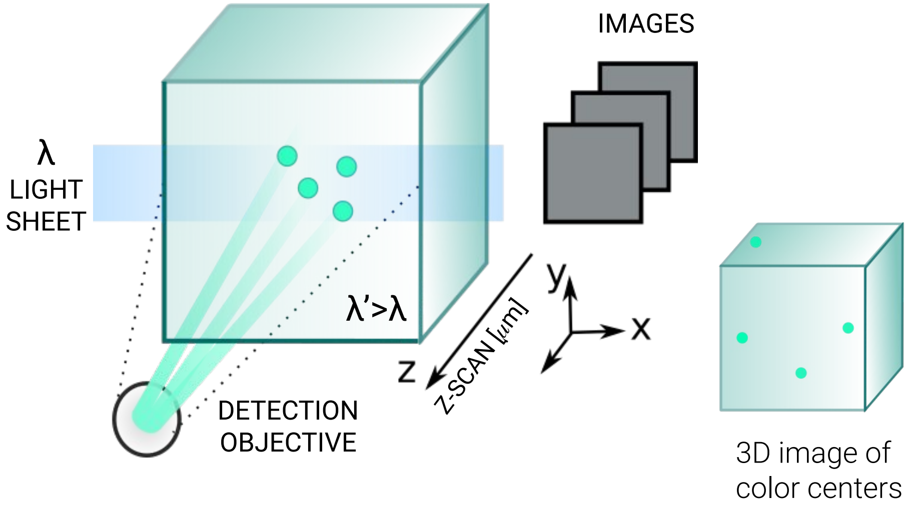


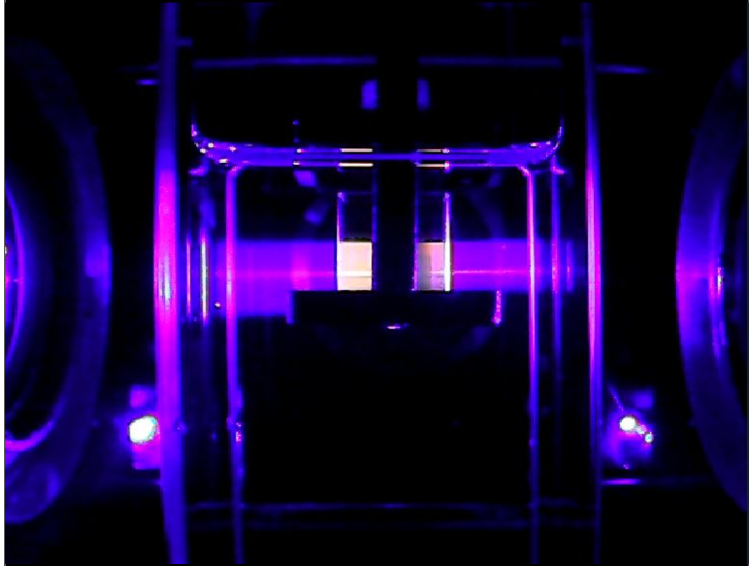
ANION DISPLACEMENT HAS A **LOW THRESHOLD***: SENSITIVITY TO LOW-ENERGY NUCLEAR RECOILS INDUCED BY WIMPs OR NEUTRINOS.

(*)STOPPING POWER FOR MOST IONS IS AROUND 20–100 eV/nm. ENERGY OF RECOILING NUCLEUS ~20–200 eV. DESPITE THE **nm-SIZE OF DISLOCATIONS**, THESE SIGNALS CAN BE OBSERVED IN **OPTICAL WAVELENGTHS (~500 nm)**.

THE PALEOCCENE CONCEPT

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

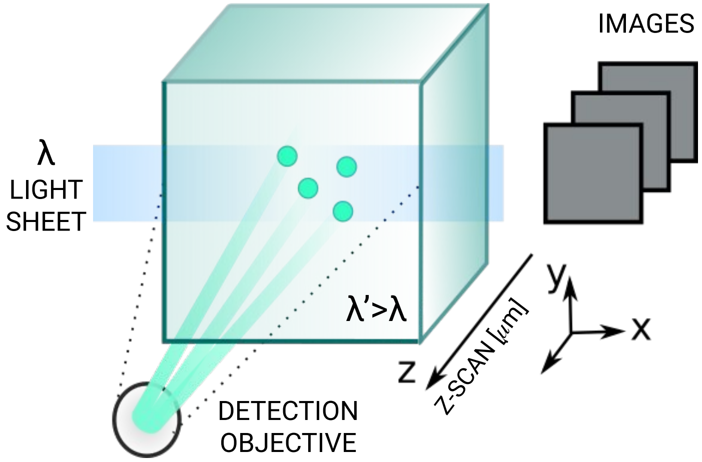




COLOR CENTERS ABSORB AND RE-EMIT LIGHT IN OPTICAL WAVELENGTHS, ENABLING A FAST READ-OUT.

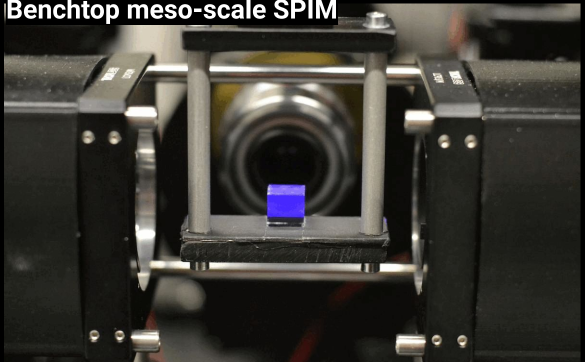
TESTING THE PALEOCCENE CONCEPT

READOUT OF COLOR CENTERS 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.

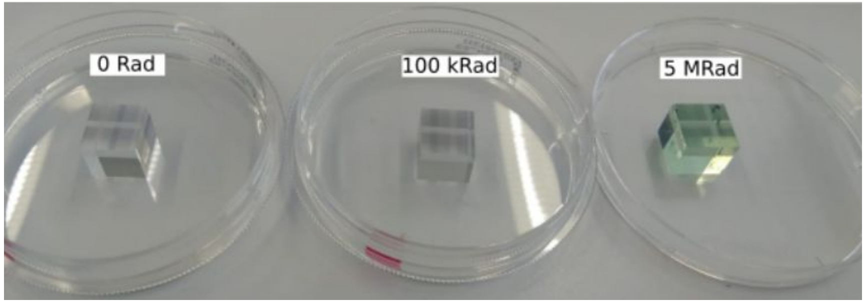


VLADIMIROV ET AL, Nature Communications (2024)

TESTING THE PALEOCCENE CONCEPT

READOUT OF COLOR CENTERS WITH THE MESOSPIM

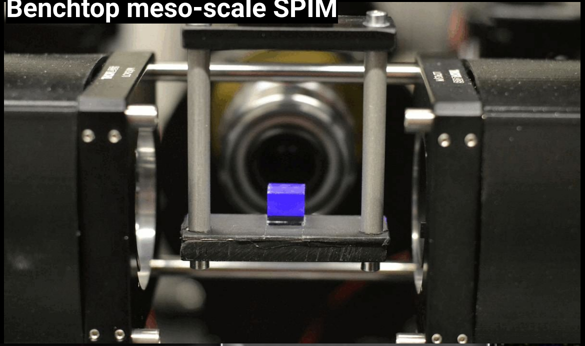
CaF$_2$, LiF and Sapphire transparent crystals were **irradiated** and imaged in comparison to a **blank**.

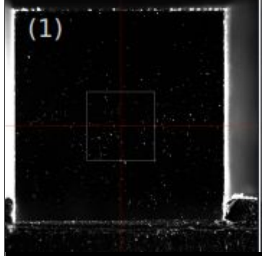


γ-RAY DOSES: from 100 Rad to 5 MRad* (*~10^{10}-10^{14} ph/cm^2 from a ~1 MeV ^{60}Co source)
NEUTRON DOSES: ~10^8 n/cm^2 (100mCi AmBe source, shielded by lead)
ALPHA DOSES: ~10^6 alphas/cm^2 (30 Bq Am-241 source)

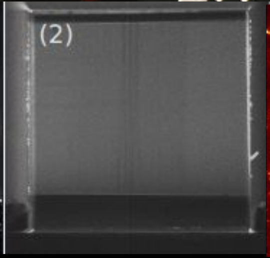
STATE-OF-THE-ART LIGHT-SHEET FLUORESCENCE MICROSCOPE (**LSFM**) THAT IMAGES CENTIMETER -SIZED SAMPLES WITHIN MINUTES.

Benchtop meso-scale SPIM

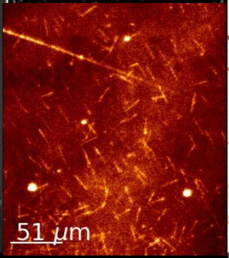




BLANK



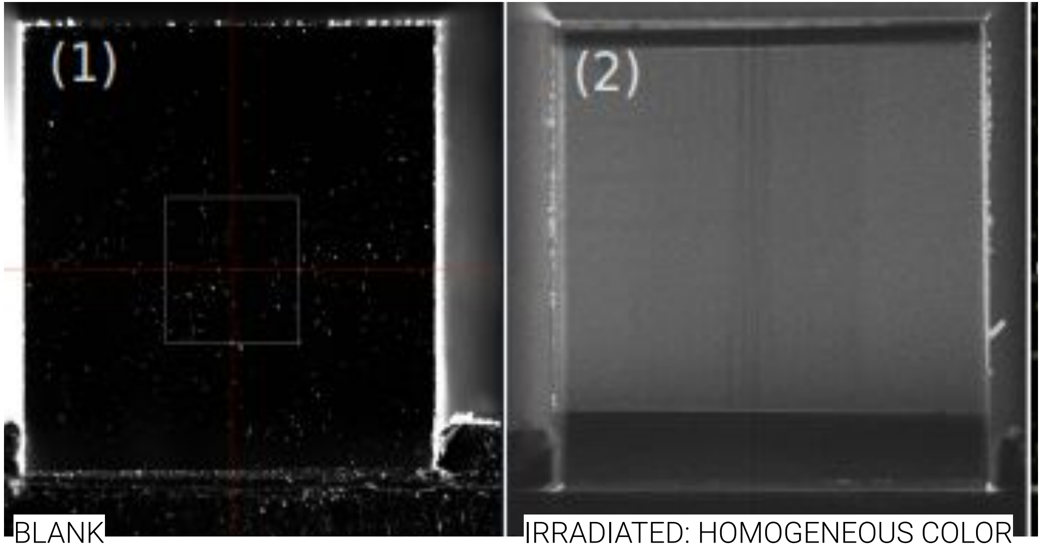
HOMOGENEOUS COLOR CENTER FLUORESCENCE



COLOR CENTER TRACKS

TESTING THE PALEOCCENE CONCEPT: IMAGING GAMMA-IRRADIATED SAMPLES

COLOR CENTERS INDUCED BY GAMMA IRRADIATION ARE VISIBLE AND UNIFORMLY DISTRIBUTED

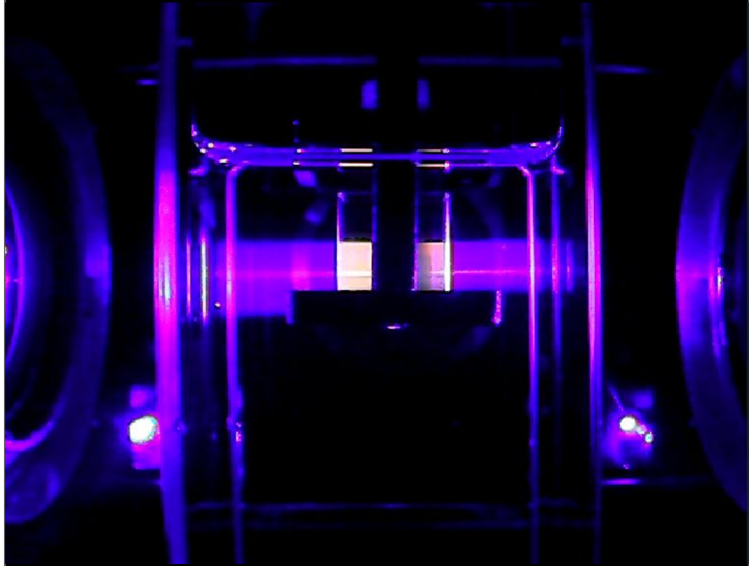


BLANK

IRRADIATED: HOMOGENEOUS COLOR CENTER FLUORESCENCE

Gamma-ray irradiation of LiF and CaF_2 crystals produced clear uniform fluorescence of the entire crystals.

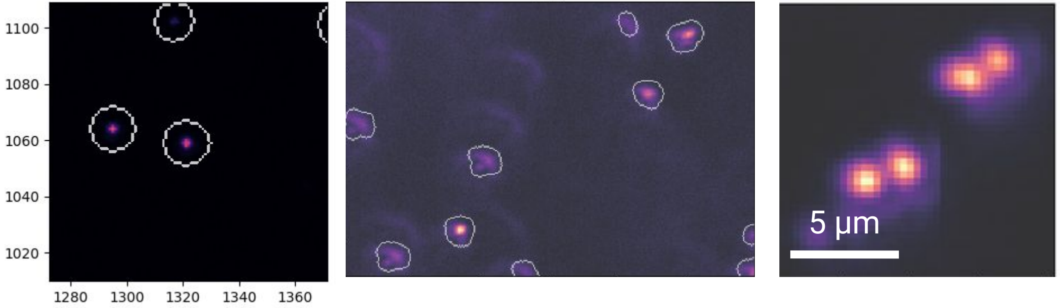
BUT **CAN LIGHT-SHEET MICROSCOPY IMAGE SINGLE COLOR CENTERS OR SMALL TRACKS?**



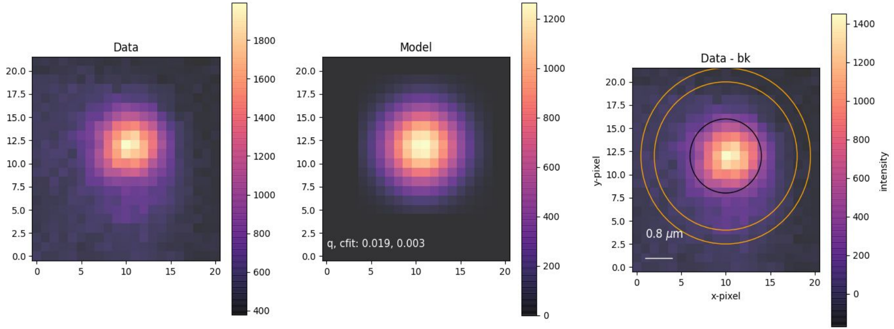
TESTING THE PALEOCCENE CONCEPT: CHARACTERIZING THE MICROSCOPE’S RESPONSE

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

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



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.**

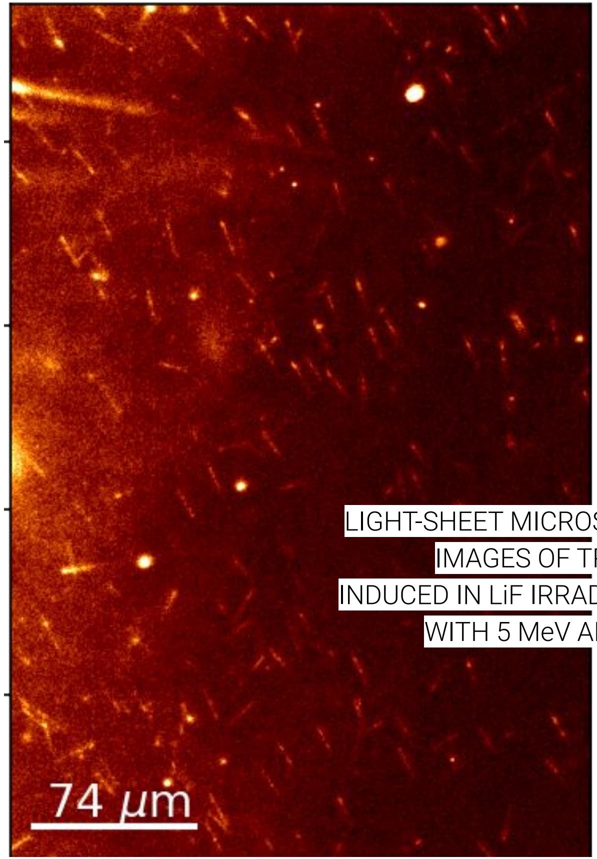


Examples of fitting and modelling of the point spread function.

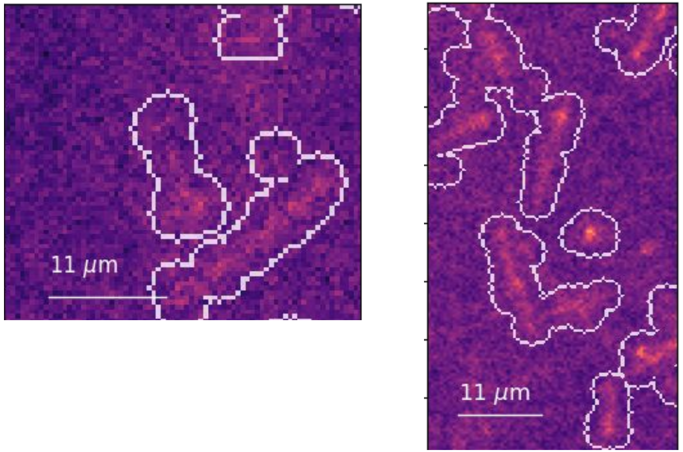
NEUTRINOS AND DARK MATTER MAY CREATE SMALL CLUSTERS OF COLOR CENTERS IN CRYSTALS: **QUANTUM DOTS AND NANO-FLUORESCENT BEADS IN A TRANSPARENT TARGET SERVE AS CALIBRATION REFERENCES.**

TESTING THE PALEOCCENE CONCEPT: IMAGING ALPHA-IRRADIATED SAMPLES

ALPHA TRACKS WERE CLEARLY VISIBLE, THEIR SIZE AND BRIGHTNESS PROFILE AGREE WITH THEORY.

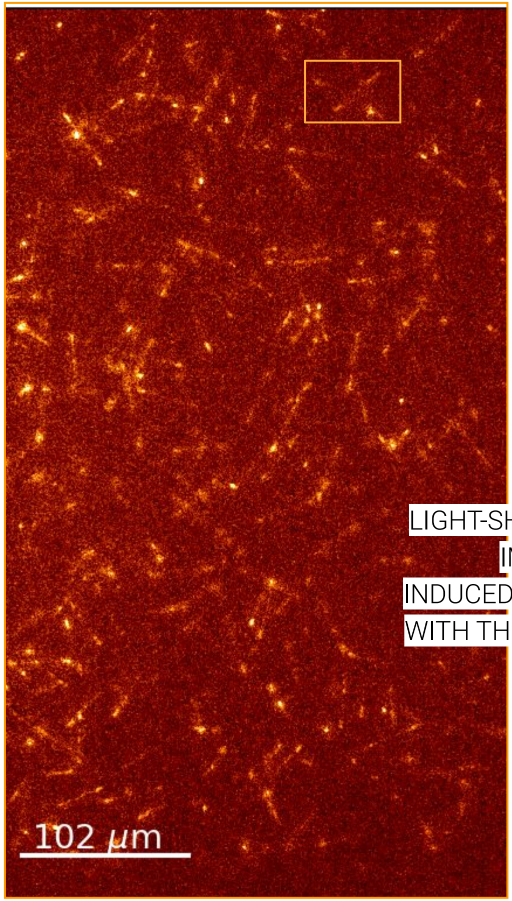


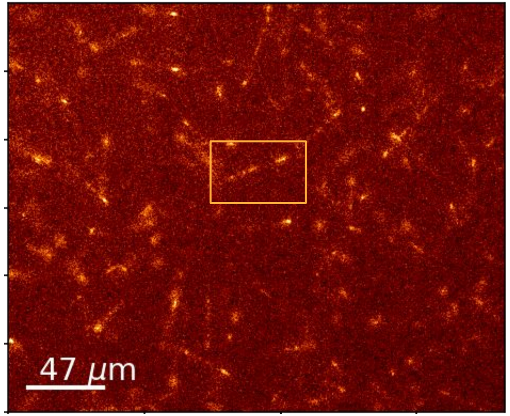
LIGHT-SHEET MICROSCOPY IMAGES OF TRACKS INDUCED IN LiF IRRADIATED WITH 5 MeV ALPHAS



We are still optimizing the algorithm to identify and measure track sizes.
So far, the **average track size is ~ 20 um** (as expected from 5 MeV alphas)

IRRADIATION OF LiF WITH THERMAL NEUTRONS PRODUCE CLEAR Li-6 FISSION TRACKS





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

$^{6}\mathrm{Li} + \mathrm{n} -> \mathbf{{}^{3}H} + \mathbf{{}^{4}He}$

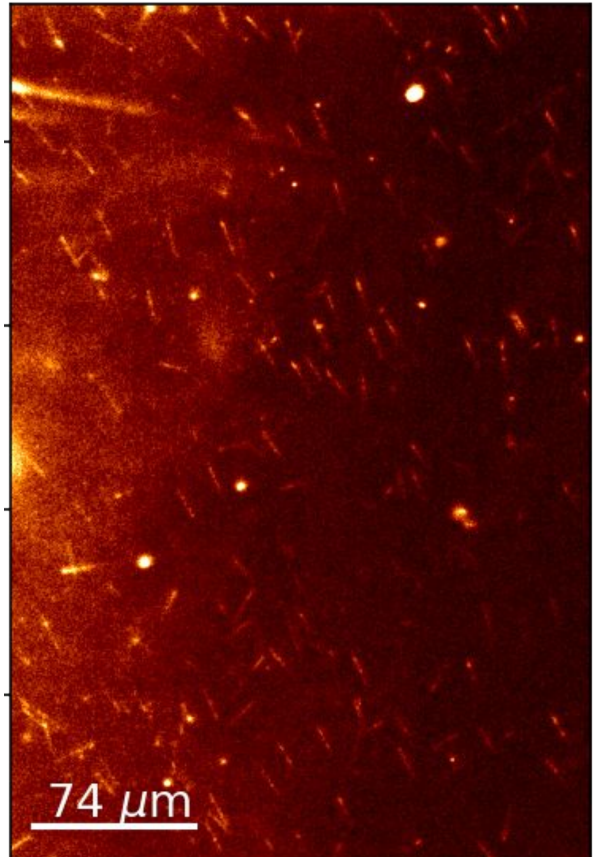
LIGHT-SHEET MICROSCOPY IMAGES OF TRACKS INDUCED IN LiF IRRADIATED WITH THERMAL NEUTRONS

IMAGING AT ~ **1 mm INSIDE THE CRYSTAL**! (USUALLY NOT POSSIBLE WITH OTHER MICROSCOPY TECHNIQUES)

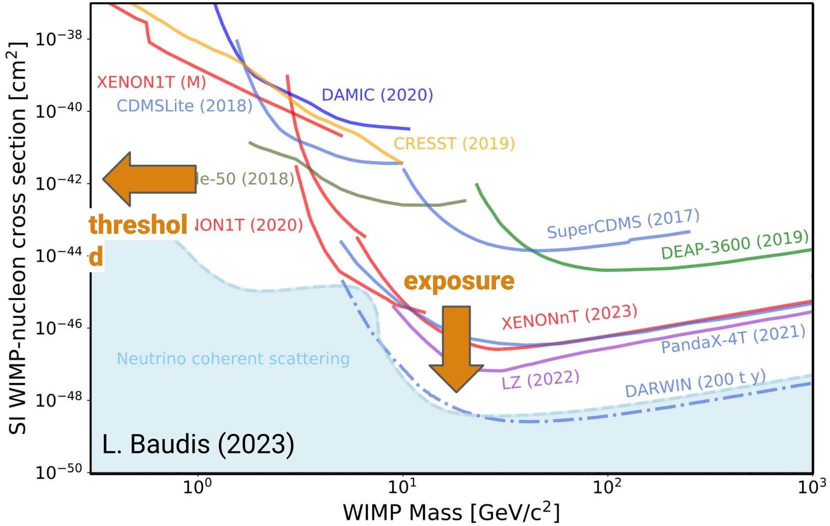
Still to improve: Clear 3D imaging and 3D identification of tracks

SUMMARY & CONCLUSIONS

PALEOCCENE IS A PROMISING CONCEPT FOR THE DETECTION OF νS & DARK MATTER.



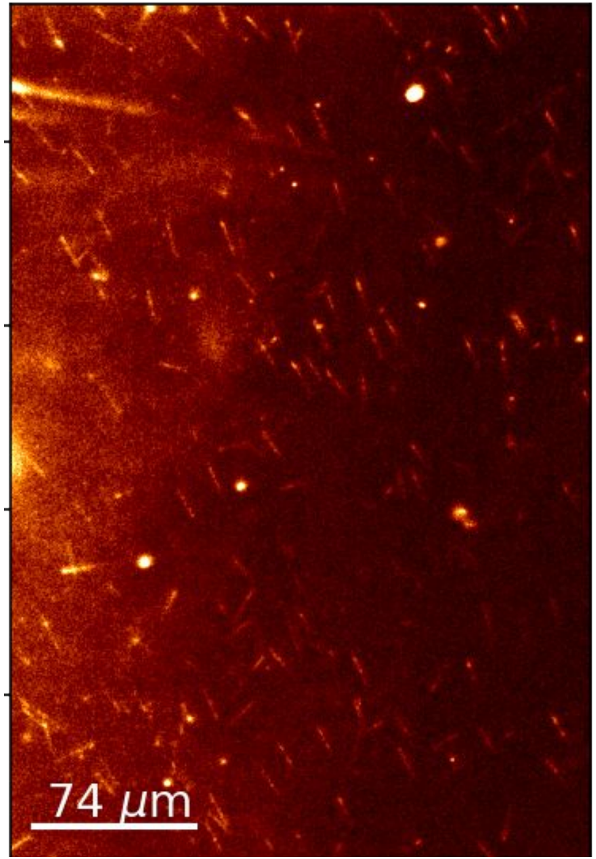
COLOR CENTERS PROVIDE **LOW-THRESHOLD** WHILE OLD ROCKS (PALEO DETECTORS) MAY PROVIDE **LARGE EXPOSURE.**



ADDITIONALLY, THIS TECHNOLOGY COULD ENABLE THE FIRST CEνNS DETECTION FROM NUCLEAR REACTOR NEUTRINOS (ν).

TESTING THE CONCEPT: FIRST MEASUREMENTS OF COLOR CENTERS AND TRACKS WITH LIGHT-SHEET MICROSCOPY WERE SUCCESSFUL SO FAR!

PALEOCCENE IS A PROMISING CONCEPT FOR THE DETECTION OF νS & DARK MATTER



COLOR CENTERS PROVIDE **LOW-THRESHOLD** WHILE OLD ROCKS (PALEO DETECTORS) MAY PROVIDE **LARGE EXPOSURE.**

PALEOCCENE FAST PATH FORWARD

THE PALLEOCCENE COLLABORATION:

NEUROSCIENTISTS, MICROSCOPY DEVELOPERS, PARTICLE PHYSICISTS, NUCLEAR ENGINEERS, GEOLOGISTS, SOLID STATE PHYSICISTS

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!

ADDITIONALLY, THIS TECHNOLOGY COULD ENABLE THE FIRST CEνNS DETECTION FROM NUCLEAR REACTOR NEUTRINOS (ν).

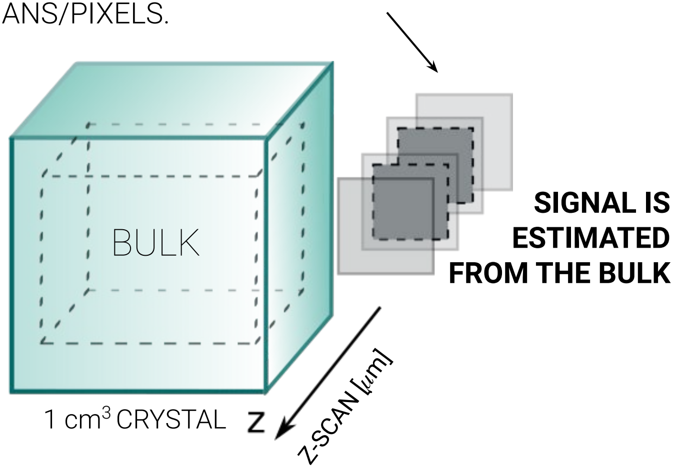
TESTING THE CONCEPT: FIRST MEASUREMENTS OF COLOR CENTERS AND TRACKS WITH LIGHT-SHEET MICROSCOPY WERE SUCCESSFUL SO FAR!

BACK UP SLIDES

TESTING THE PALEOCCENE CONCEPT

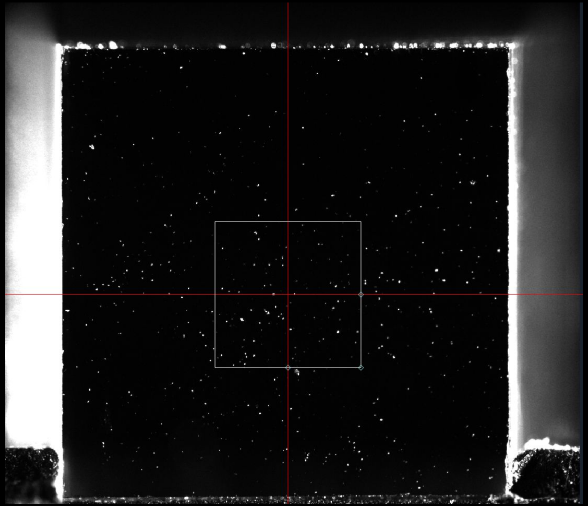
ESTIMATING THE FLUORESCENCE SIGNAL FROM COLOR CENTERS

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



SIGNAL IS ESTIMATED FROM THE BULK

- ☐ CAMERA DARK COUNTS NOISE IS ESTIMATED IN DARK

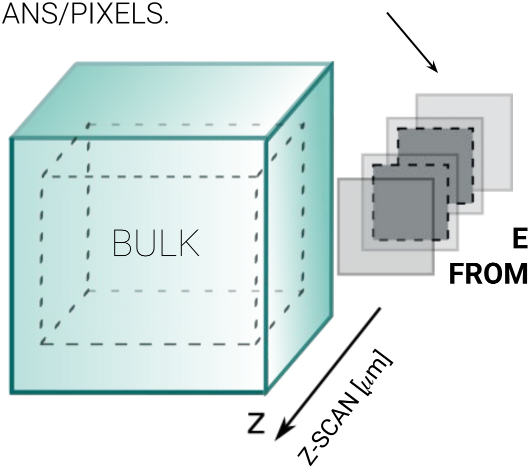


SURFACE IMPURITIES & SCRATCHES ARE FLUORESCENT **BACKGROUND**

TESTING THE PALEOCCENE CONCEPT

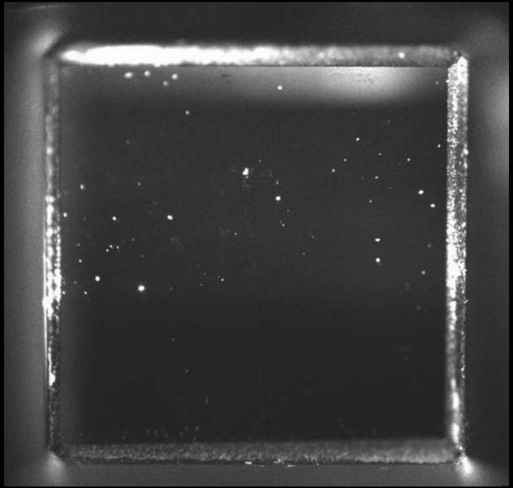
ESTIMATING THE FLUORESCENCE SIGNAL FROM IRRADIATED CRYSTALS

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



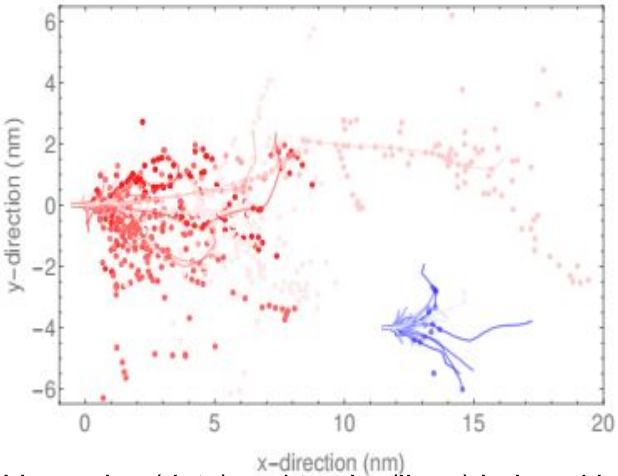
SIGNAL IS ESTIMATED FROM THE BULK

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

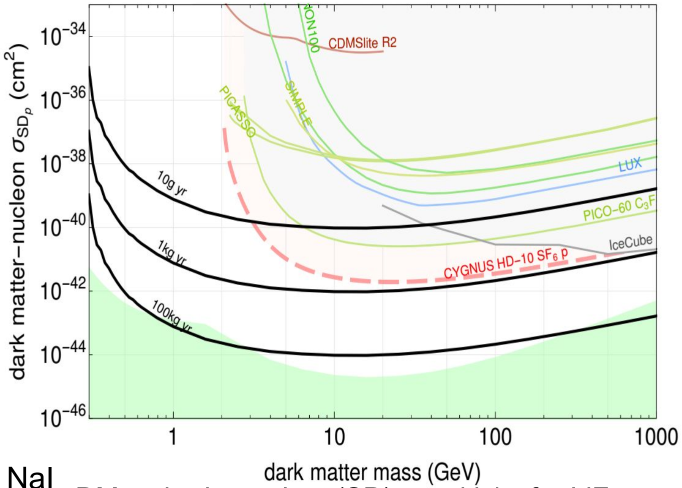


BLANK CaF_2 CRYSTALS YIELDED **NO** BULK **SIGNAL**

SENSITIVITY & SPECTRAL SHAPE



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



DM, spin-dependent (SD) sensitivity for LiF

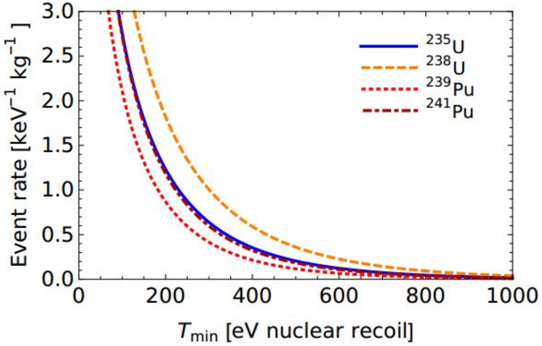
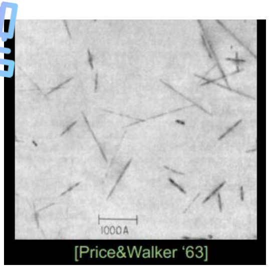


FIG. 1. Shown is the nuclear recoil spectrum on germanium in arbitrary units for neutrinos stemming from fission of ^{235}U, ^{239}Pu, ^{238}U, and ^{241}Pu, respectively.

B. Cogswell, A. Goel, P. Huber. PRA 16 (2021)
Bowen, Huber (2020) https://arxiv.org/pdf/2005.10907

Target: billion-year old minerals. Method: microscopy of tracks
Output: events per track size → Competitive sensitivity to WIMPs

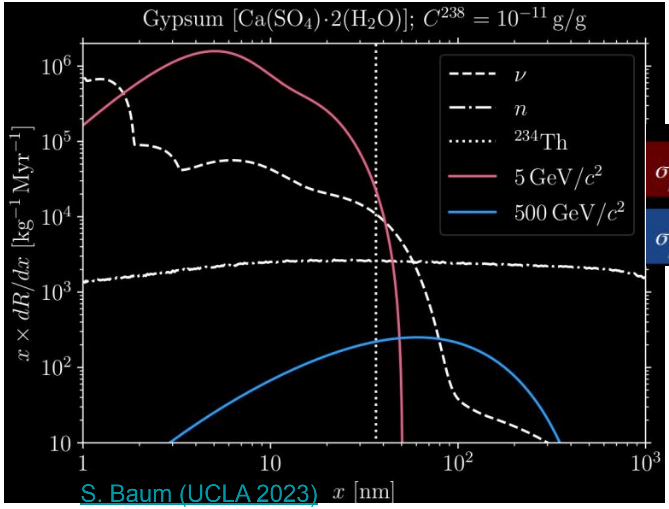
Image and count



[Price&Walker '63]

Eg from S. Baum (UCLA 2023)

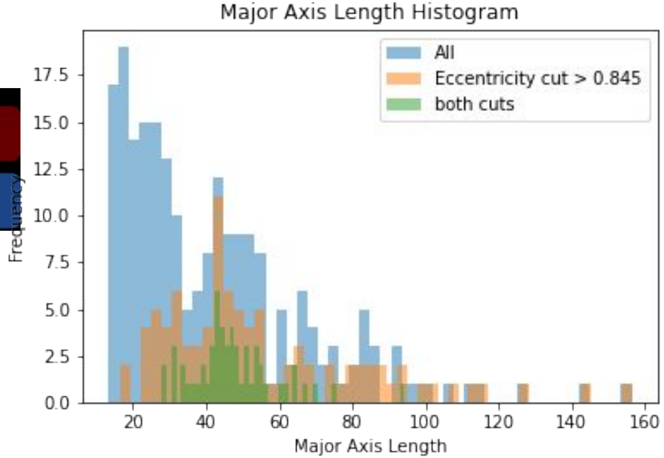
Build spectrum



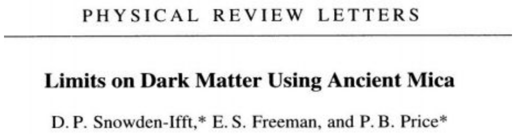
S. Baum (UCLA 2023)

$\sigma_p^{SI} = 10^{-43}$ cm^2

$\sigma_p^{SI} = 10^{-46}$ cm^2



First Paleo DM test in 1995:



PHYSICAL REVIEW LETTERS

Limits on Dark Matter Using Ancient Mica

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