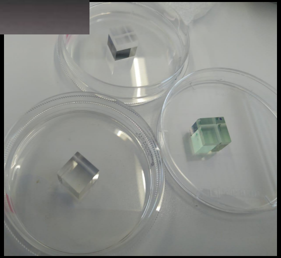
Microscopy of color centers: A new venue for neutrino and dark matter detection with passive crystals

Paleo Minerals



PALEOCCENE collaboration

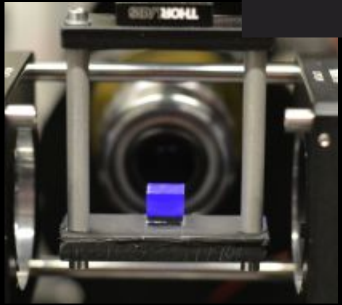
Gabriela R. Araujo

May 4th 2023

Particle Physics Colloquium at the

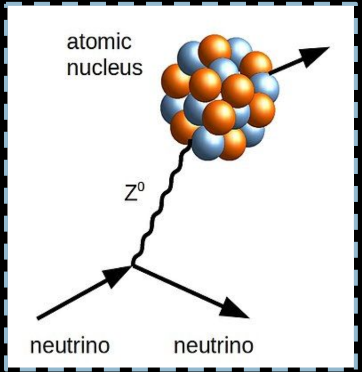
Karlsruher Institut für Technologie (KIT)

University of Zurich[UZH]



The mesoSPIM initiative

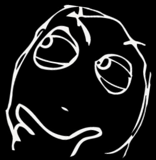
Microscopy of color centers: A new venue for neutrino and dark matter detection with passive crystals



CEνNS: Coherent Elastic ν-Nucleus Scattering

CEνNS detection described as “spotting a ghost”.
Coherent coll. Science (2017)

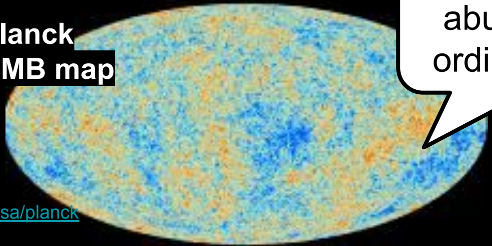
Why do we care about CEνNS?

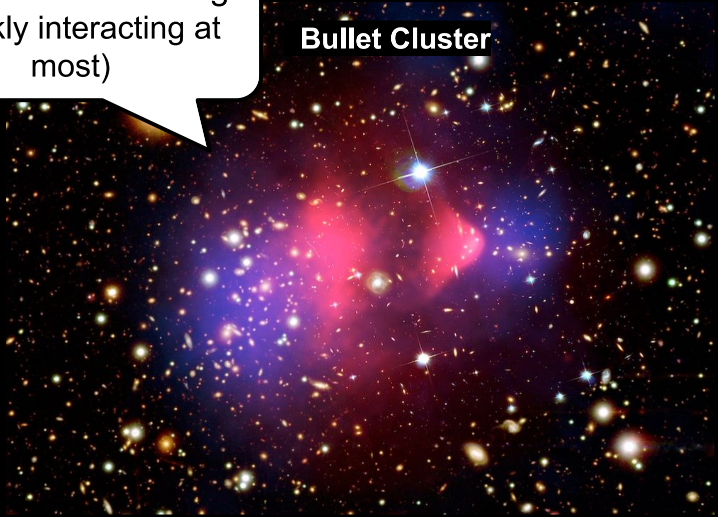


- Distribution of nucleons in nuclei
- Supernova νs
- Nuclear reactor (flux) monitoring

Microscopy of color centers: A new venue for neutrino and dark matter detection with passive crystals

We know dark Matter is…



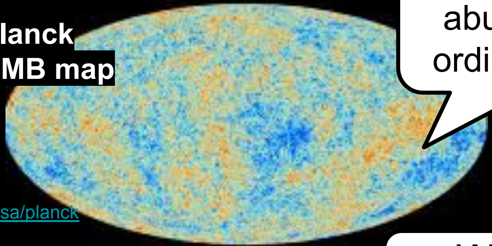


X-ray: NASA/CXC/CfA/ M. Markevitch; Optical and lensing map: NASA/STScI, Magellan/U.Arizona/D. Clowe; Lensing map: ESO WF

Microscopy of color centers: A new venue for neutrino and dark matter detection with passive crystals

We know dark Matter is…

Planck CMB map

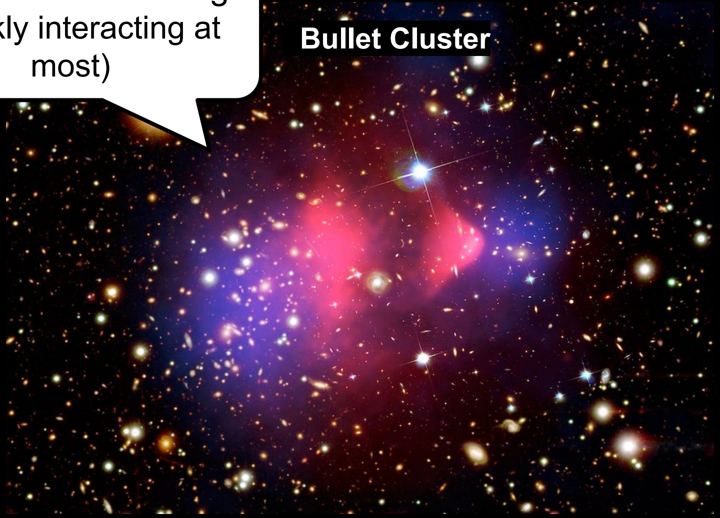


nasa/planck

5x more abundant than ordinary matter!

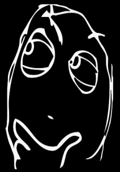
Not much interacting (weakly interacting at most)

Bullet Cluster



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

We **don't know what** dark matter is…



Maybe a WIMP*?

*weakly interacting massive particle

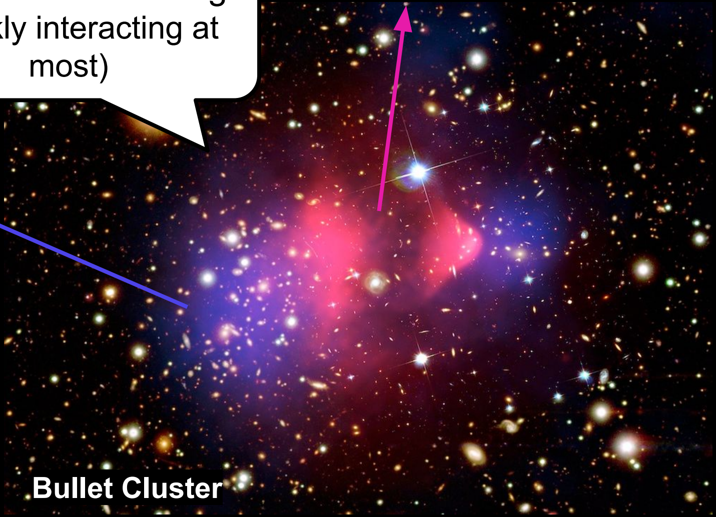
The physicist

Observations from the bullet cluster support the WIMP hypothesis**

Luminous gas: slowed down by interactions

Not much interacting (weakly interacting at most)

Non-luminous counterpart: most of the matter, not much interacting (gravitational interaction observed by the lensing)



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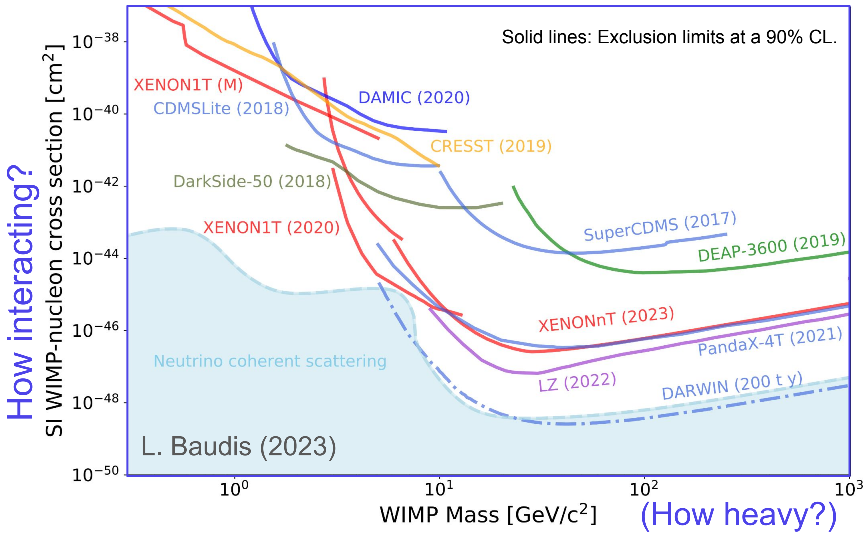
The physicist

Maybe a WIMP*?

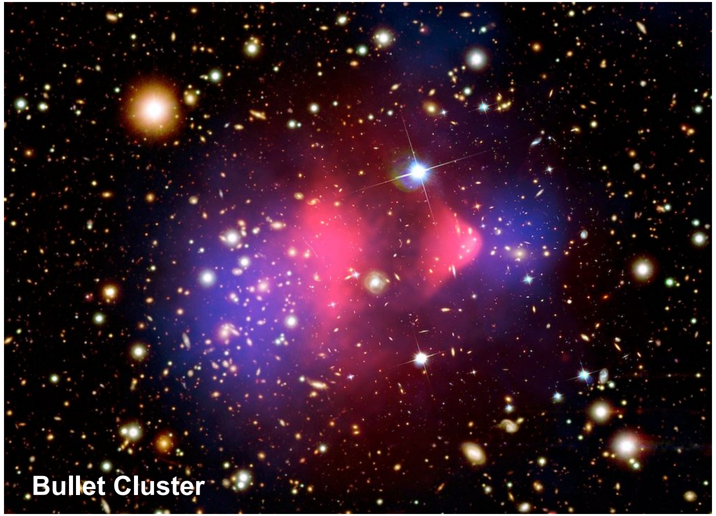
*weakly interacting massive particle

(**)This observation cannot be easily explained by other theories, such as the modified newtonian dynamics

WIMP Dark Matter: still some free parameter space to explore



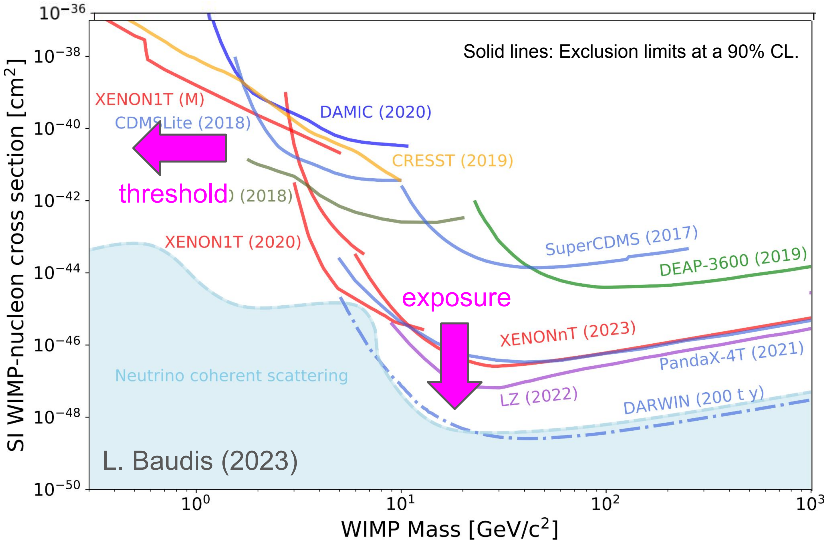
Experimental parameter space for the spin-independent interaction of WIMP with nucleons.



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

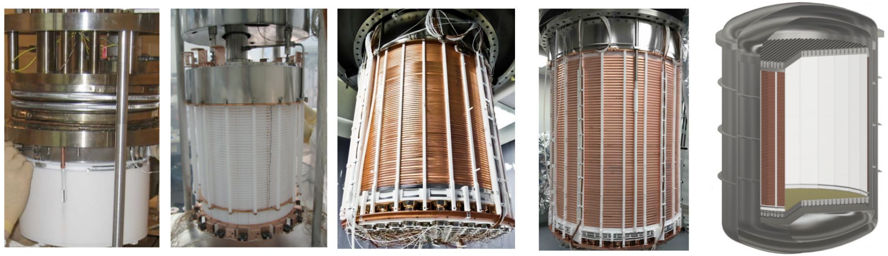
*weakly interacting massive particle

WIMP Dark Matter: pushing down the sensitivity by increasing exposure



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

XENON10 XENON100 XENON1T XENONnT DARWIN/XLZD



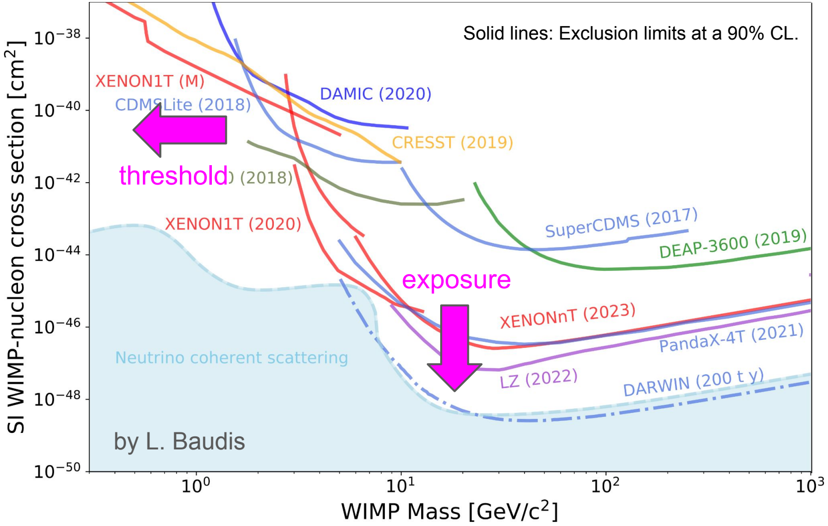
by L. Baudis

XENON10	XENON100	XENON1T	XENONnT	DARWIN/XLZD
2005-2007	2008-2016	2012-2018	**2020-2027**	2028—
15 kg	161 kg	3200 kg	8600 kg	50 tonnes
15 cm	30 cm	96 cm	150 cm	260 cm
~10^{-43} cm^2	~10^{-45} cm^2	~10^{-47} cm^2	~10^{-48} cm^2	~10^{-49} cm^2

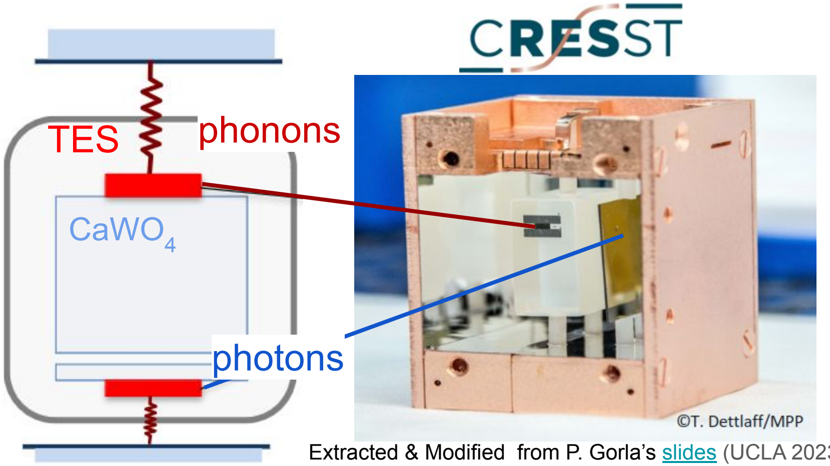
Exposure: Xenon experiments operating in underground labs increased from ~10kg to possibly 50000 kg with DARWIN/XLZD.

*weakly interacting massive particle

WIMP Dark Matter: pushing the sensitivity towards lower masses



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



Extracted & Modified from P. Gorla's slides (UCLA 2023)

Threshold (sub-keV E_{nr}): Cryogenic detectors at ~15 mK with transition edge sensors (TES). Energy depositions of ~keV correspond to temperature increase of ~uK (mOhm)

*weakly interacting massive particle

Low threshold & large "exposure" are keys to push sensitivity to WIMPs

Low threshold:

- Ability to measure low-energy nuclear recoils
- Access beyond "vanilla" medium-mass WIMP

Exposure:

- Increase target mass
- Increase measuring time

ps: We'll talk about backgrounds later….

Paleo detectors can achieve large “exposure” by having a large “measuring time”

Low threshold:

- Ability to measure low-energy nuclear recoils

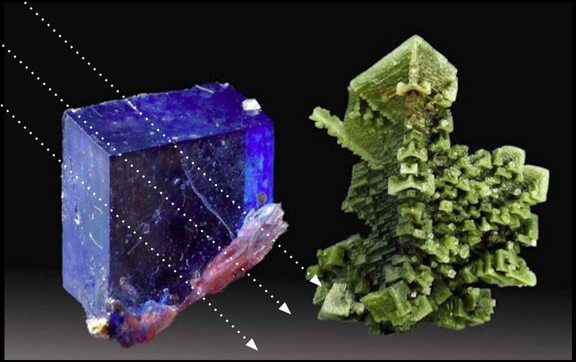
- Access beyond “vanilla” medium-mass WIMP

Exposure:

- Increase target mass
- Increase measuring time

“**Minerals Could Bear the Scars of Collisions With Dark Matter**“

geologyin.com



Paleo detectors: Ancient (Gyr old) minerals as passive DM detectors

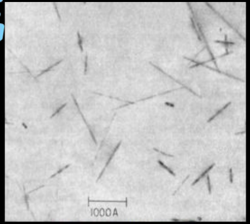
S. Baum et al, Phys. Lett. B (2020)

Microscopy of color centers: A new venue for neutrino and dark matter detection with passive crystals

Microscopy can be used to readout these “scars of collisions” (tracks)

Lattice damage
Ionization+dislocation of atoms

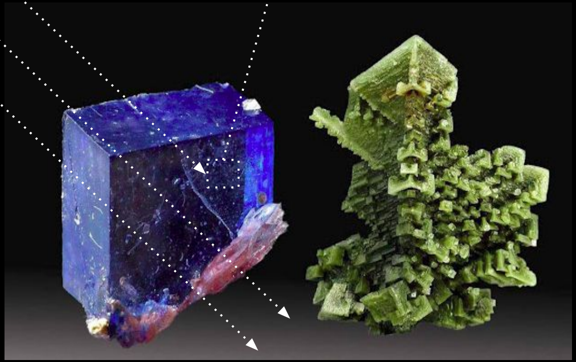
Eg from S. Baum (UCLA 2023): Fission tracks imaged in Mica with TEM



[Price&Walker ‘63]

Some rocks can preserve tracks for ~ Gyr time

“Minerals Could Bear the Scars of Collisions With Dark Matter“
geologyin.com



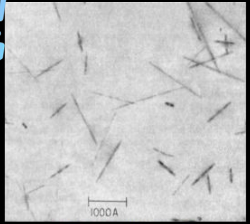
Paleo detectors: Ancient (Gyr old) minerals as passive DM detectors

S. Baum et al, Phys. Lett. B (2020)

Paleo detectors

Target: billion-year old minerals. Method: microscopy of tracks
Output: events per track size

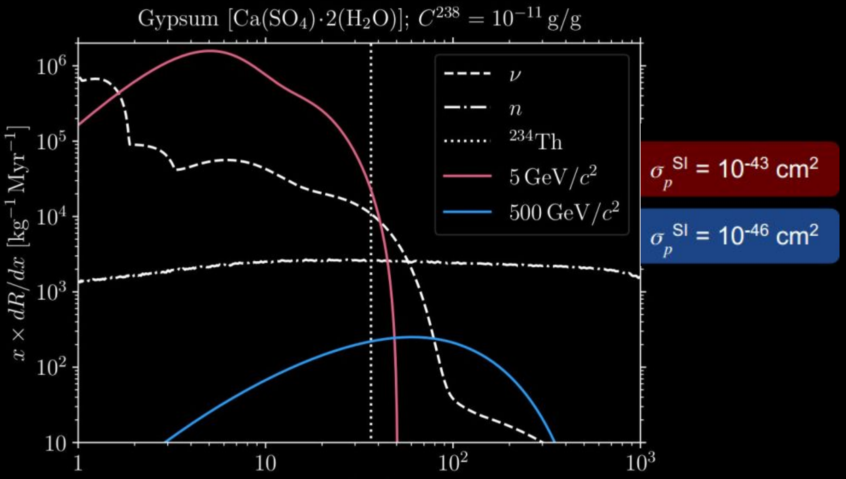
Image and count



[Price&Walker '63]

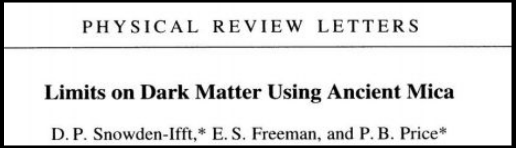
Eg from S. Baum (UCLA 2023): Fission tracks imaged in Mica with TEM

Build spectrum



S. Baum (UCLA 2023) x [nm]

First Paleo DM test in 1995:



PHYSICAL REVIEW LETTERS

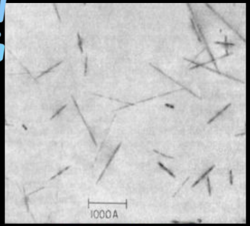
Limits on Dark Matter Using Ancient Mica

D. P. Snowden-Ifft,* E. S. Freeman, and P. B. Price*

Paleo detectors

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

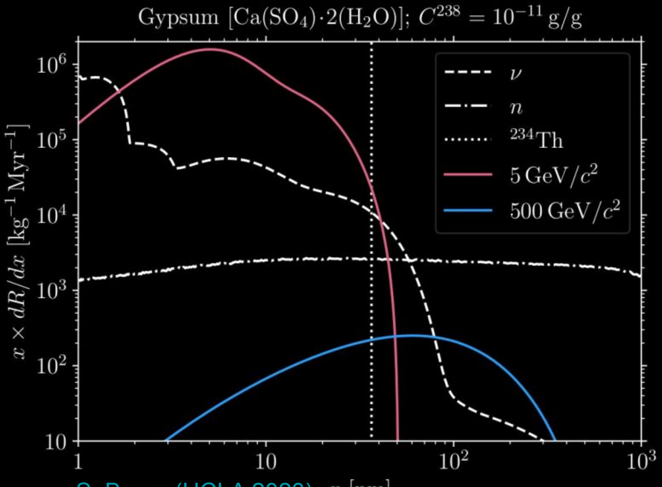
Image and count



[Price&Walker '63]

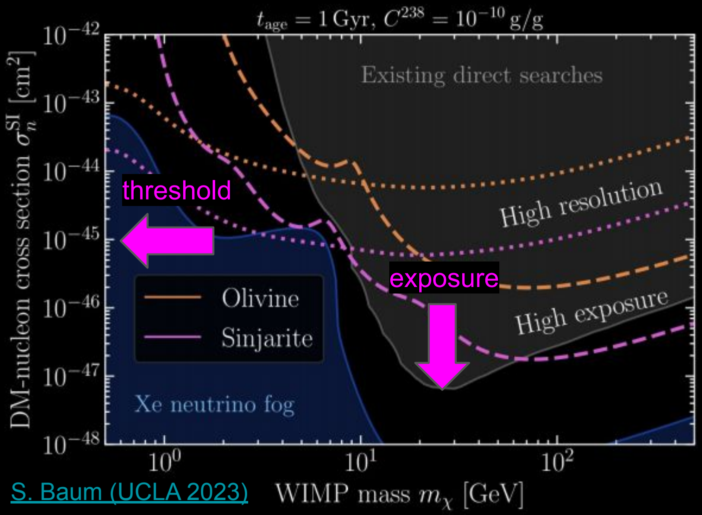
Eg from S. Baum (UCLA 2023): Fission tracks imaged in Mica with TEM

Build spectrum



S. Baum (UCLA 2023)

Projected sensitivity



S. Baum (UCLA 2023)

S. Baum et al, Phys. Lett. B (2020)

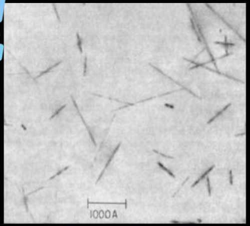
Microscopy technology has advanced: we should revisit this idea

… provided the readout of large samples at high resolution

Paleo detectors

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): Fission tracks imaged in Mica with TEM

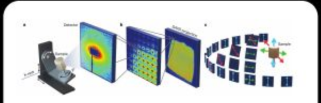
Sensitivity depends on the microscopy method

Exposure (throughput) : 0.01-100g * Gyr

Helium ion-beam microscopy

- 1 nm spatial resolution
- (10 mg) x (1 Gyr)

Small-angle X-ray scattering



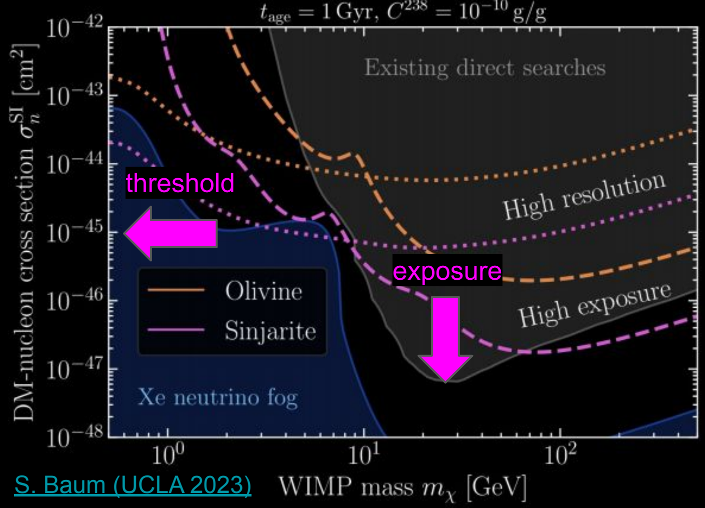
- 15 nm spatial resolution
- (100 g) x (1 Gyr)

1 nm: $E_R \gtrsim 20$ eV for epsomite

15 nm: $E_R \gtrsim 4$ keV

Threshold (resolution): ~nm level

Projected sensitivity

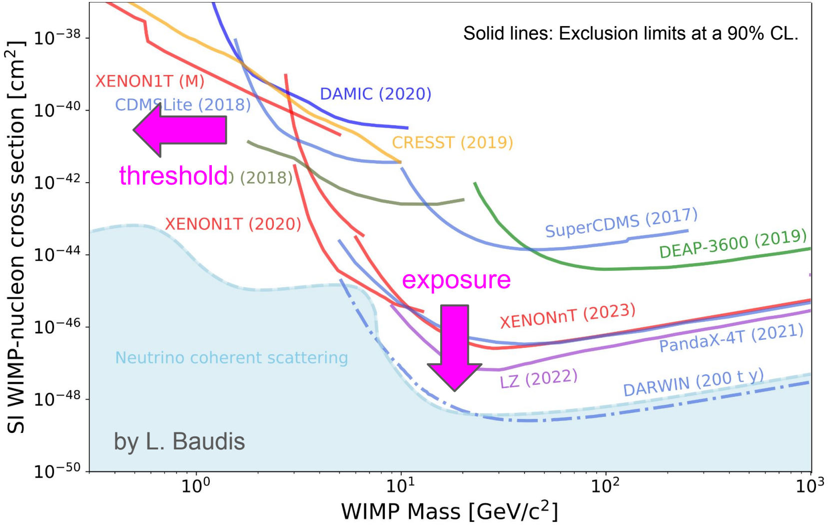


S. Baum (UCLA 2023)

… provided the readout of large samples at high resolution

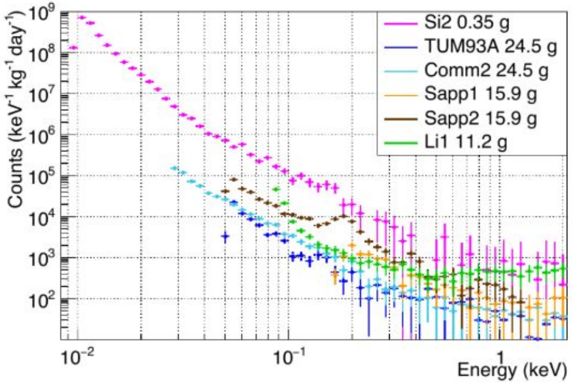
Back to the big picture:

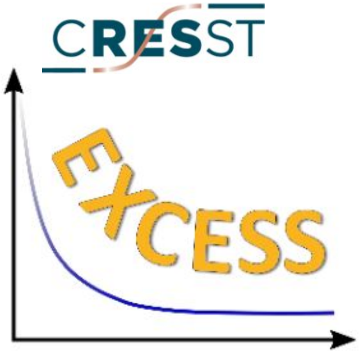
It has been hard to access the low-energy region: Excess observed in detectors designed for exploring this region



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

From F. Reindl's slides (UCLA 2023)

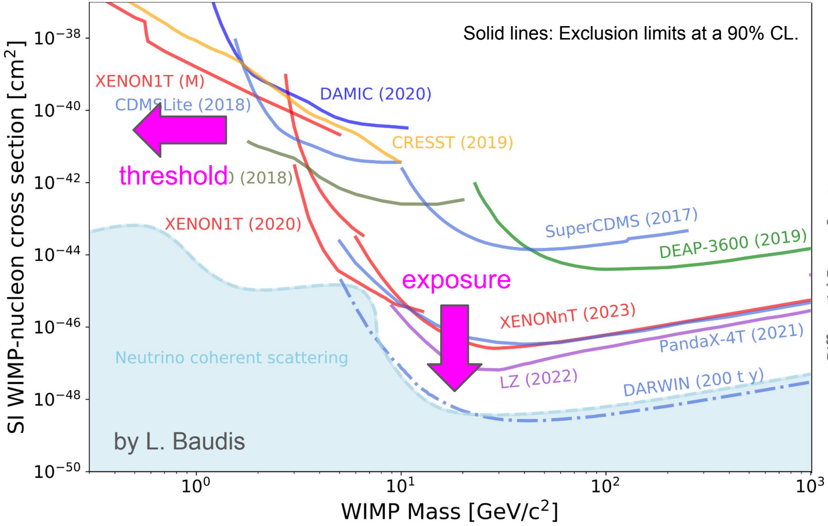




Excess of events observed in the low-energy region of several low-mass DM experiments, like CRESST*.

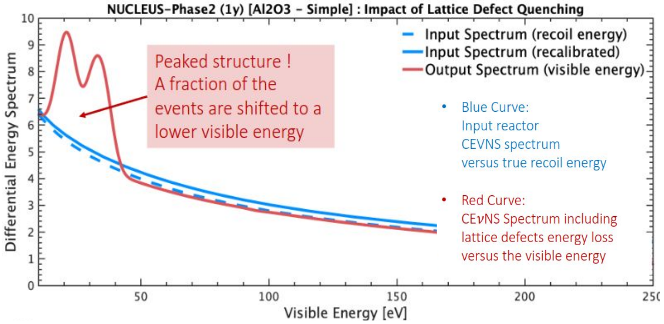
*Excess does not scale with mass and is observed in different technologies. Not all causes are so far fully understood.

Observed excess: Lattice defects could move events into low energy regions



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

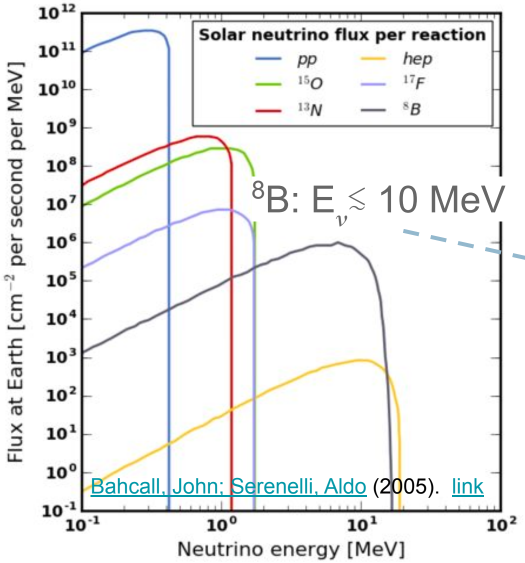
From T. Lassere's slides (Excess workshop 2022)

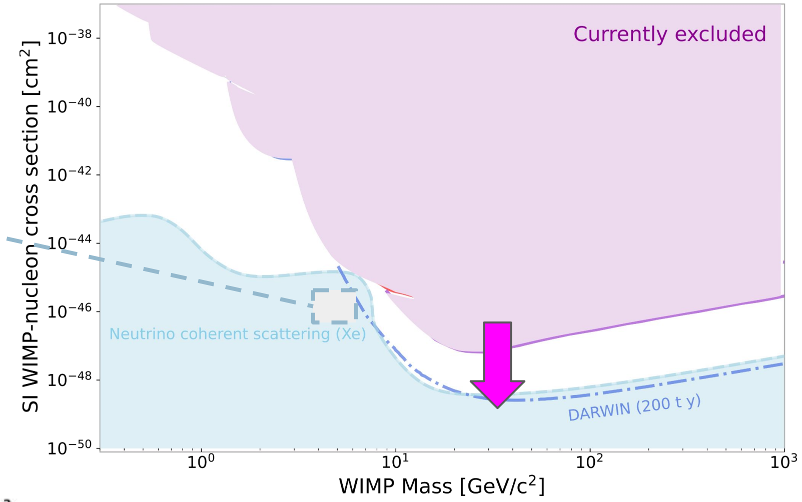


Study on how quenching due to lattice defects could move observed events to low-energy region in CEνNS detectors, like NUCLEUS.

Maybe "the excess" signature could become the signal?

Can we dig directly into the “neutrino fog” and detect their coherent scattering with nuclei?





“Neutrino fog” usually given for coherent elastic scattering from astrophysical neutrinos with target nuclei

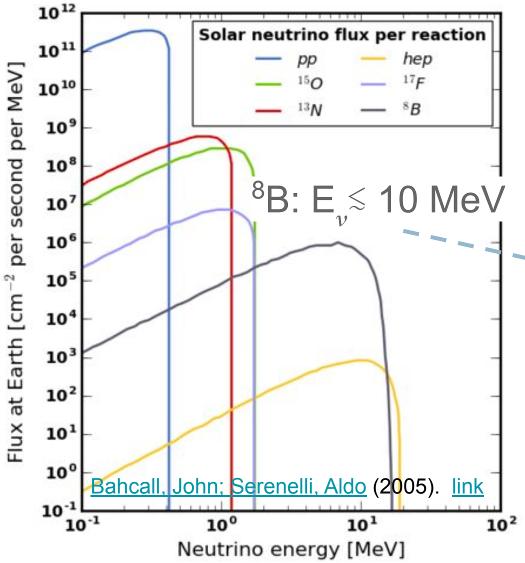
Exposure: hundreds of ton. yr

Future very large DM detectors will start exploring this region (eg. DARWIN/XLZD*)

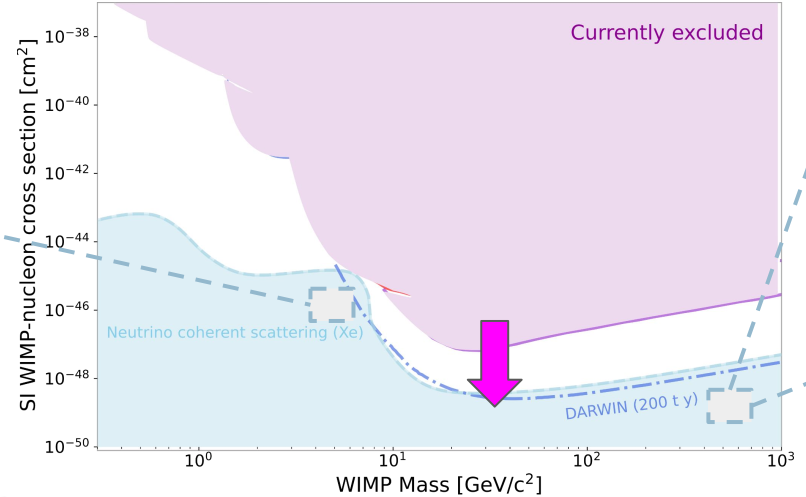
*arxiv:2203.02309

Back to neutrinos:

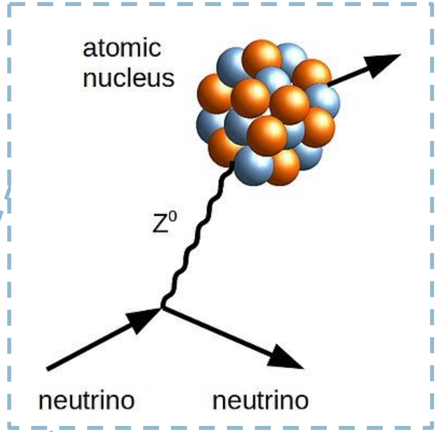
Can we dig directly into the “neutrino fog” and detect their coherent scattering with nuclei?



^{8}B: $E_\nu \lesssim 10$ MeV



“Neutrino fog” usually given for coherent elastic scattering from astrophysical neutrinos with target nuclei



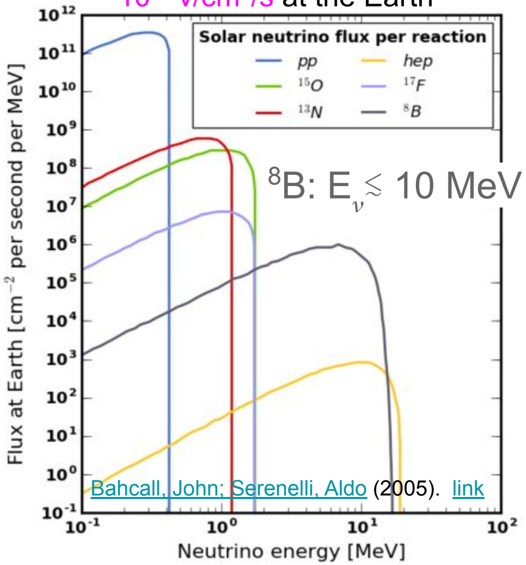
CEνNS: Coherent Elastic ν-Nucleus Scattering

Future very large DM detectors will start exploring this region (eg. DARWIN/XLZD*)

*arxiv:2203.02309

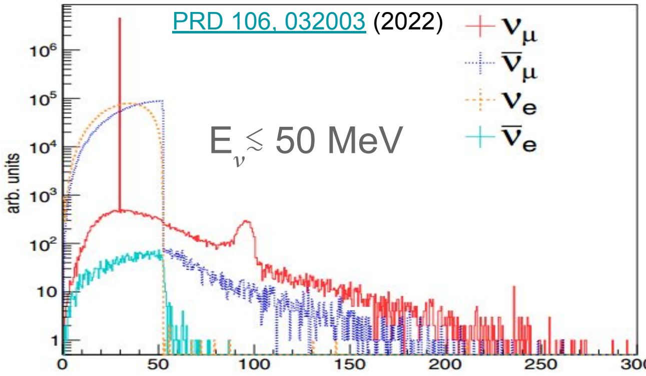
Increasing "exposure": Large flux of ~50 MeV neutrinos enables CEνNS detection

Solar νs: 10^{39} ν/s,
~10^{11} ν/cm^2/s at the Earth

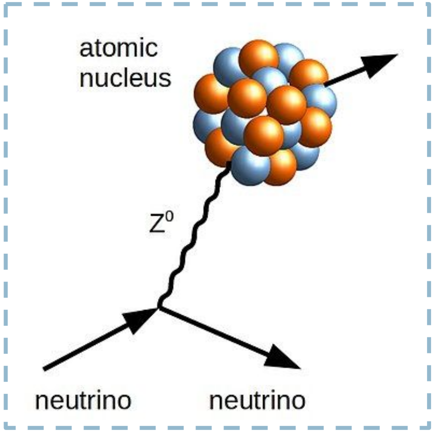


Bahcall, John; Serenelli, Aldo (2005). link

Spallation Neutron Source (SNS): 10^{15} ν/s
5×10^7 ν/cm^2/s at 20 m distance



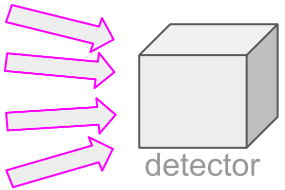
ν-flux from the SNS for the COHERENT experiment.



CEνNS: Coherent Elastic ν-Nucleus Scattering

~~exposure~~ → ν-flux

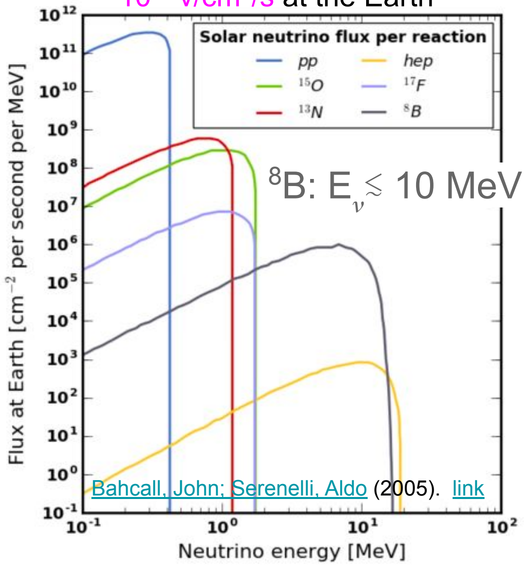
Keep low threshold



COHERENT SNS

CEνNS detection requires large flux & low threshold

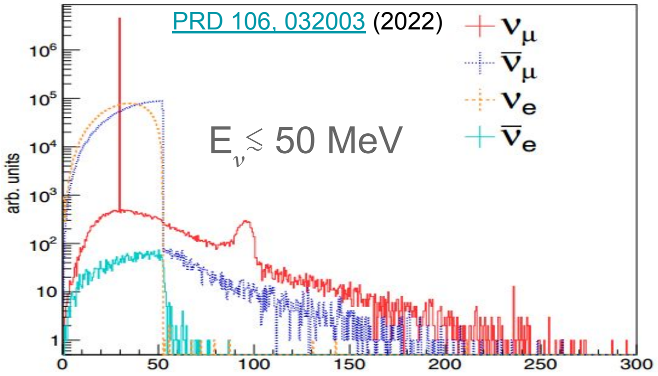
Solar νs: 10^{39} ν/s,
~10^{11} ν/cm²/s at the Earth



^{8}B: $E_\nu \lesssim$ 10 MeV

Bahcall, John; Serenelli, Aldo (2005). link

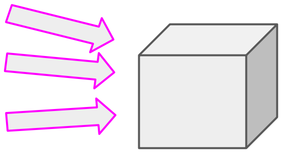
Spallation Neutron Source (SNS): 10^{15} ν/s
5×10^7 ν/cm²/s at 20 m distance



PRD 106, 032003 (2022)

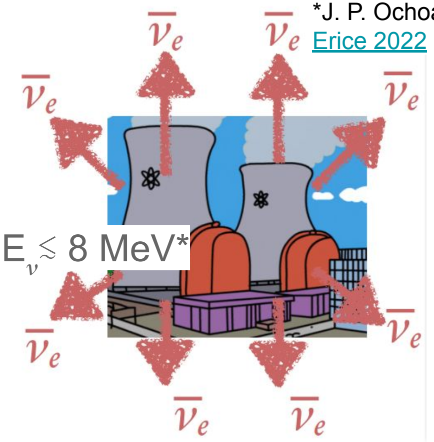
$E_\nu \lesssim$ 50 MeV

~~exposure~~ → ν-flux
Even lower threshold!



Reactor νs: ~10^{20} ν/GW*
~5×10^{12} ν/cm²/s at ~20m from a GW reactor

*J. P. Ochoa Erice 2022



$E_\nu \lesssim$ 8 MeV*

Not yet detected:
E_{NR}~10-100 eV threshold!
(<< than the value for IBD**)

*arxiv:1908.07113

**where a >1.8 MeV neutrino can produce >MeV signals from e^+e^- annihilation and neutron capture

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.

A treaty to “prevent the spread of nuclear weapons” and “further the goal of achieving nuclear disarmament “

NPT

Nuclear non-proliferation Treaty

IAEA

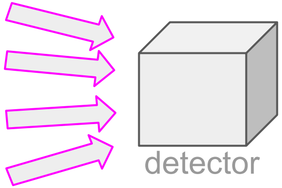
International Atomic Energy Agency

Atoms for Peace and Development

~450 nuclear power reactors
>200 nuclear research reactors

arxiv:1908.07113

ν-flux



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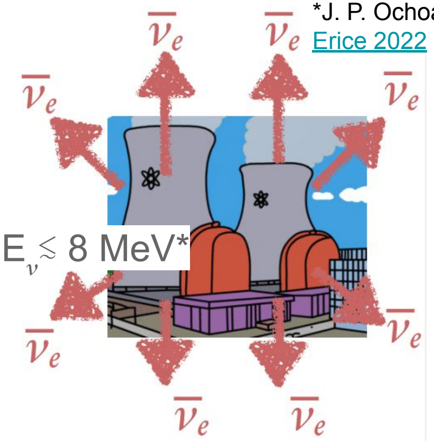
*J. P. Ochoa Erice 2022



Not yet detected:
E_{NR}~10-100 eV threshold!

*arxiv:1908.07113

CEνNS detection

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

Detector wish list:

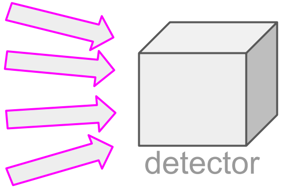
- Reasonably cheap
- Small: allows moderate distance to reactor / overburden
- No cryogenics / HV / dedicated staff on-site
- Low threshold

⇓

Passive crystals

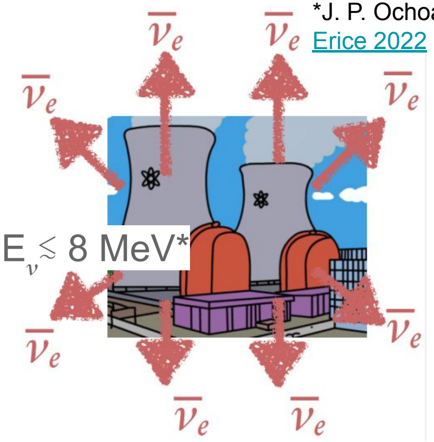
~450 nuclear power reactors
>200 nuclear research reactors

arxiv:1908.07113



Reactor νs: ~10^{20} ν/GW*
~5 x 10^{12} ν/cm²/s at ~20m from a GW reactor

*J. P. Ochoa Erice 2022



Not yet detected:
~10-100 eV threshold!
(<< than the value for IBD)

*arxiv:1908.07113

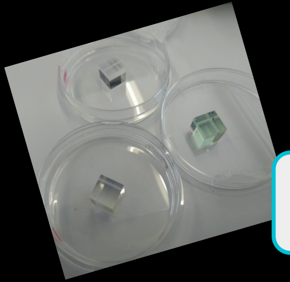
Microscopy of color centers: A new venue for neutrino and dark matter detection with passive crystals

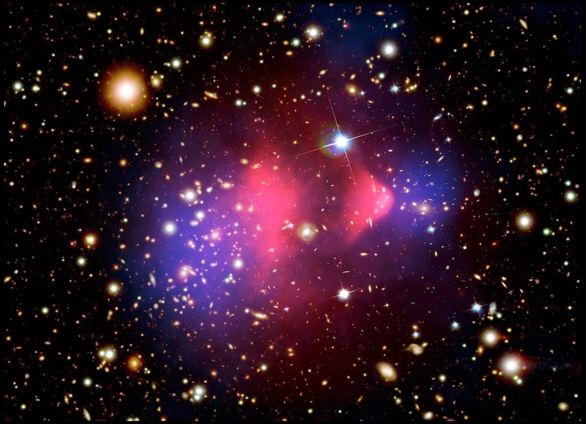
Requirements: **Detector**

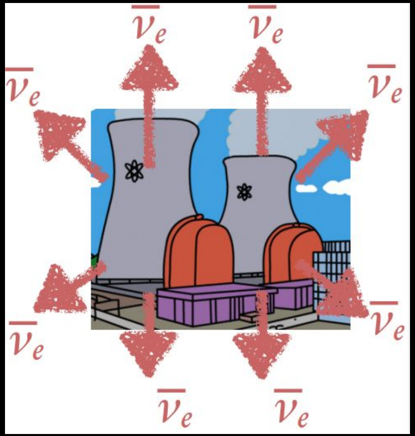
- Reasonably cheap
- Small: allows moderate distance to reactor / overburden
- No cryogenics / HV / dedicated staff on-site
- Low threshold

↓

Passive crystals







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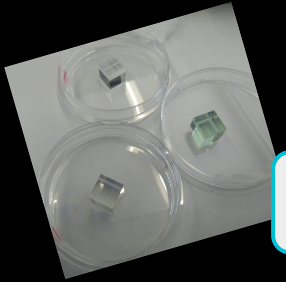
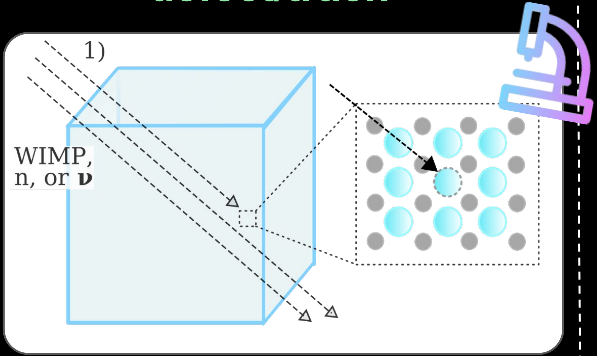


Passive crystals

Signal

- Long lived

WIMP, ν-induced defect/track



Readout

- Can be performed ex-situ or be easily taken in-situ
- Identification of low -energy signals
- Reasonably Cheap
- Fast scan/read-out of large quantities

microscopy

Microscopy of color centers: A new venue for neutrino and dark matter detection with passive crystals

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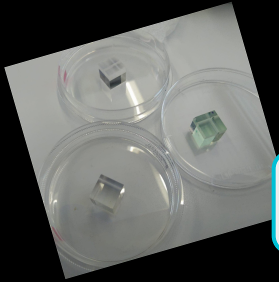

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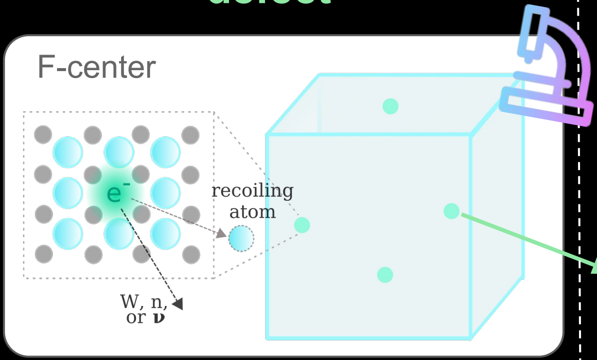

Readout

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- Reasonably Cheap
- Fast scan/read-out of large quantities

Quantum system that absorbs and re-emits light -> observable in optical wavelengths!

Microscopy of color centers: A new venue for neutrino and dark matter detection with passive crystals

Requirements:

Detector

- Reasonably cheap
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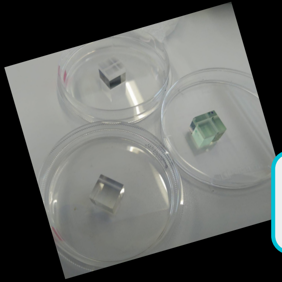
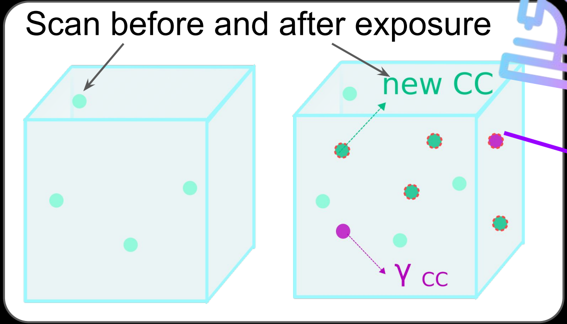


Passive crystals

Signal

- Long lived
- Tamper-proof
- Distinguishable from γ events

Color center (CC)



Readout

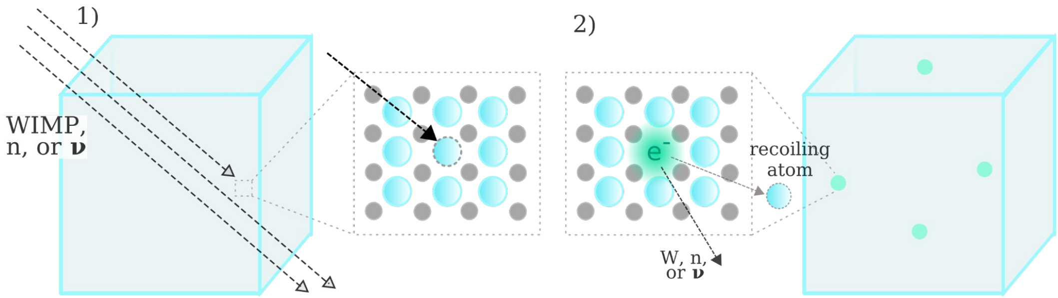
- Can be performed ex-situ or be easily taken in-situ
- Identification of low -energy signals
- Reasonably Cheap
- Fast scan/read-out of large quantities

Choose materials with no γ-induced CCs or with different γ-CC color

Y. Mossbacher et al (2019)

PALEOCCENE concept

Passive low-energy optical color center nuclear recoil

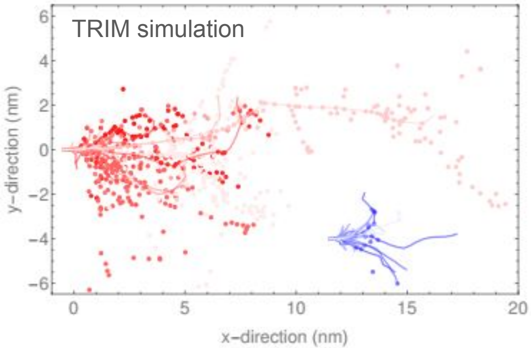


Anion displacement has a low threshold*:

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



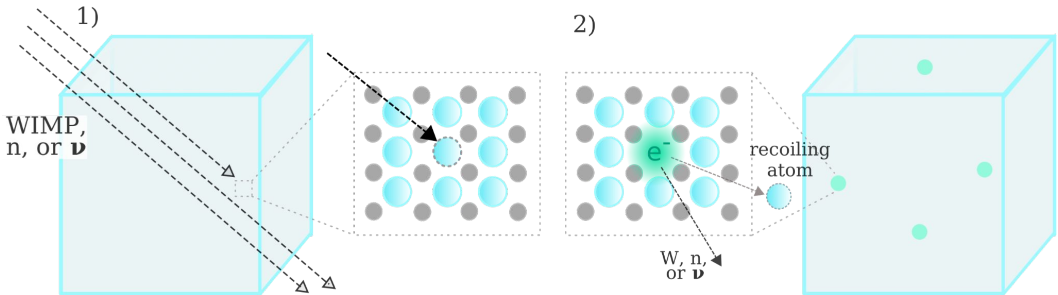
Vacancies (dots) and tracks (lines) induced in NaI by cosmic ray neutrons and CEνNS

First proposed by B. Cogswell, A. Goel, P. Huber.

Building upon R. Budnik et al arXiv:1705.03016

PALEOCCENE concept

Passive low-energy optical color center nuclear recoil



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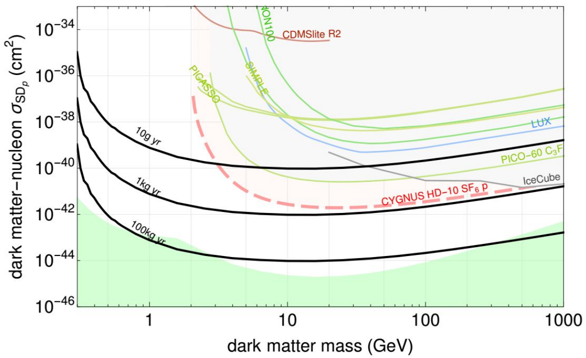


DM, spin-dependent (SD) sensitivity for LiF

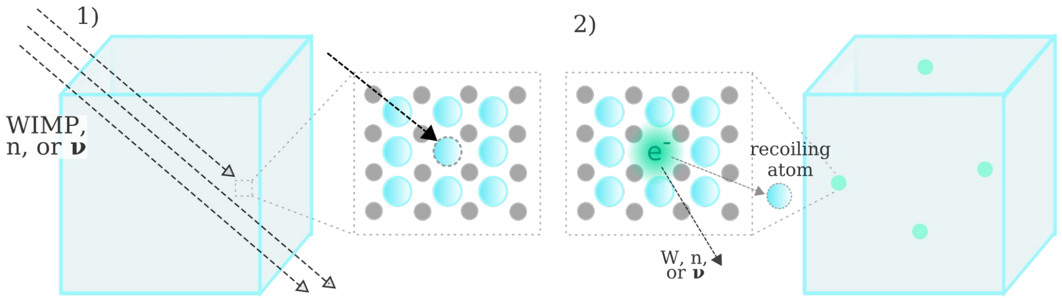
First proposed by B. Cogswell, A. Goel, P. Huber.

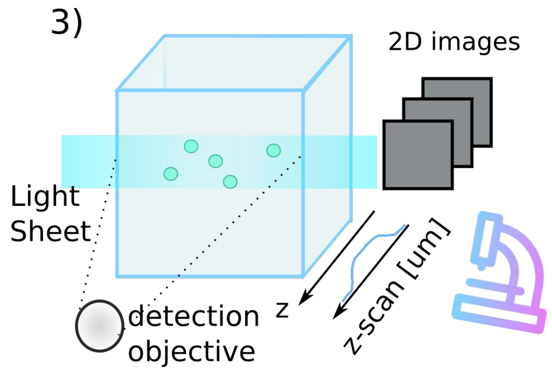
Building upon R. Budnik et al arXiv:1705.03016

SD coupling: target with net nuclear spins

PALEOCCENE concept

Passive low-energy optical color center nuclear recoil





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

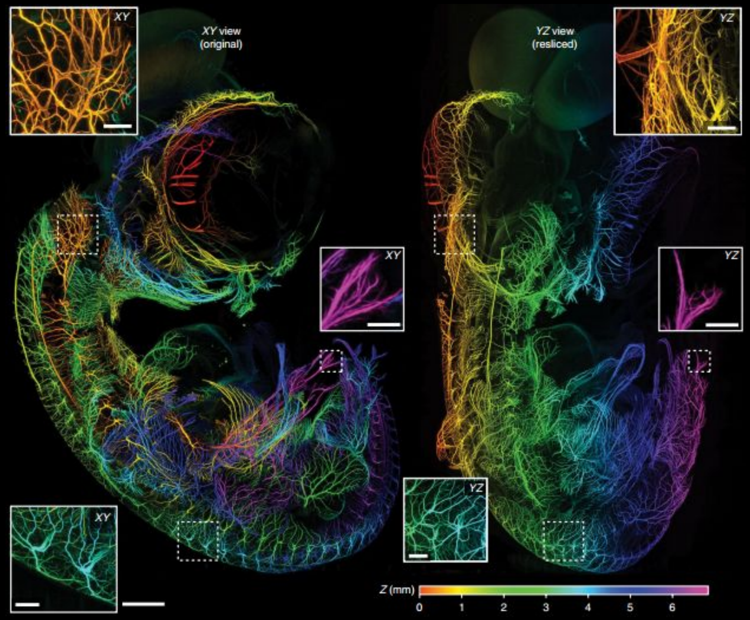
3D position reconstruction with ~1-6 um precision in xyz and speed of >20 cm^3/h

First proposed by B. Cogswell, A. Goel, P. Huber. More details in the collab. WP: (2203.05525)

Building upon R. Budnik et al (arXiv:1705.03016)

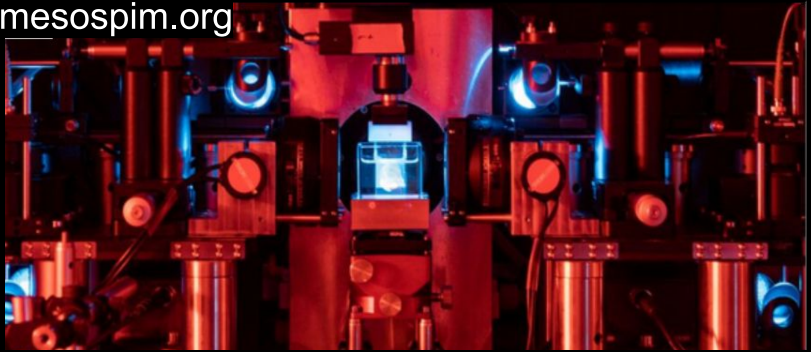
Large scale light-sheet microscopy with the mesoSPIM

Nature methods (2019)



The mesoSPIM: the first to produce "volumetric images of centimeter-sized samples with near-isotropic resolution within minutes."

mesospim.org



Main developers at: University of Zurich[UZH]

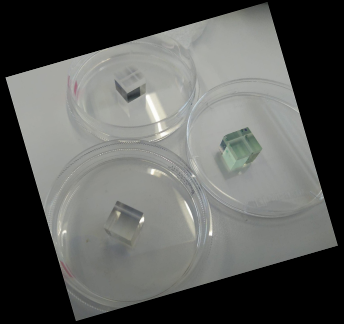
Center for Microscopy and Image Analysis

Testing the paleoccene concept with the mesoSPIM

R&D steps:

i) Select a crystal

- **Transparent** insulator
- Low threshold for forming vacancies
- (...)*
- Color centers (CC) at suitable wavelengths



CaF_2

*See B. K. Cogswell et al, Y. Mossbacher et al

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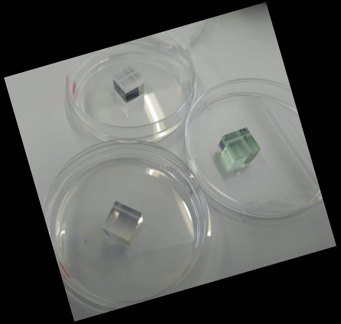
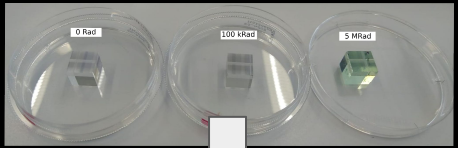


CaF_2

ii)“Fake a Signal”

- Low energy neutrons mimic DM, ν signals
- … but large irradiation dosage produces a more clear signal



Co-60 γ irradiation

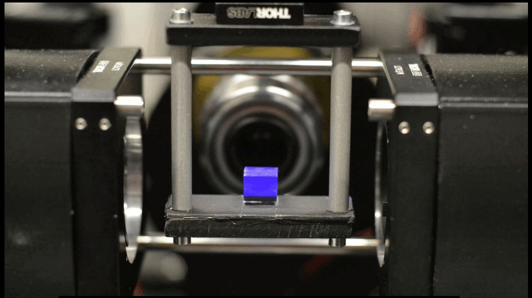
iii) Scan w. light-sheet

- Scan crystals before and after irradiation
- Use “blank” reference
- Understand color & distribution of CCs

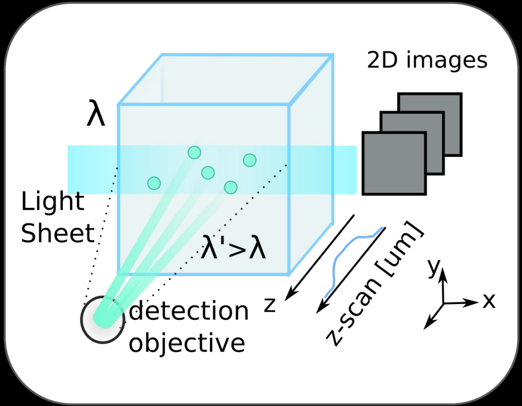
mesoSPIM

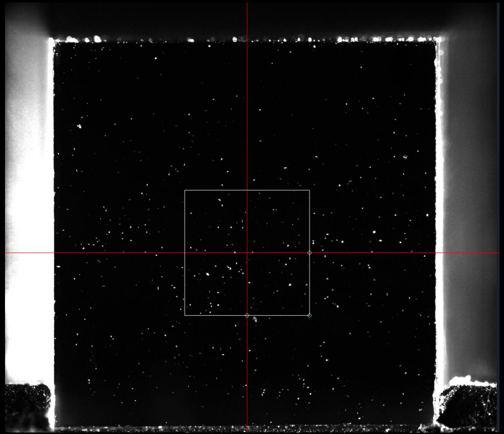
*See B. K. Cogswell et al, Y. Mossbacher et al

Light-sheet microscopy of crystals



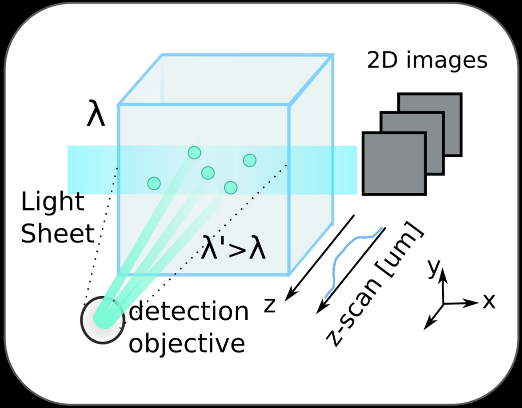
Irradiated crystal fluorescing when the light-sheet is on

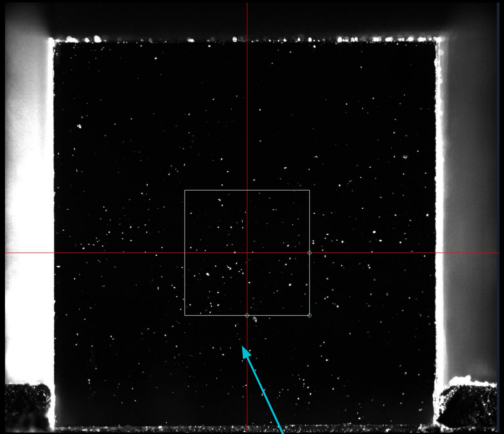


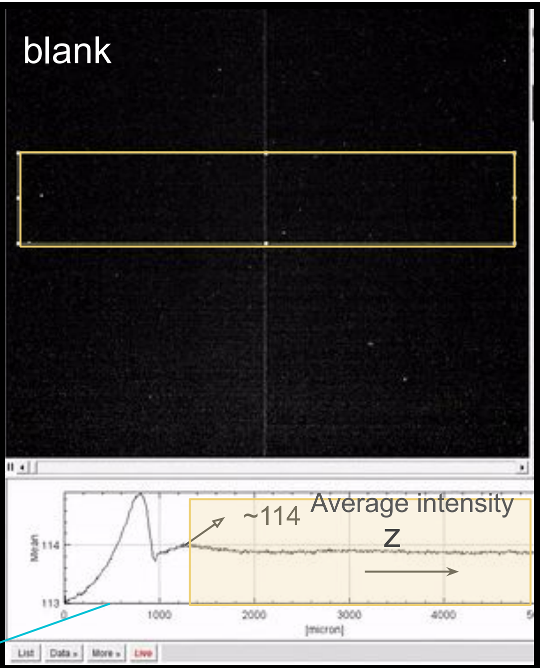


2D image of the surface

Blank samples: No clear signal above the background is observed

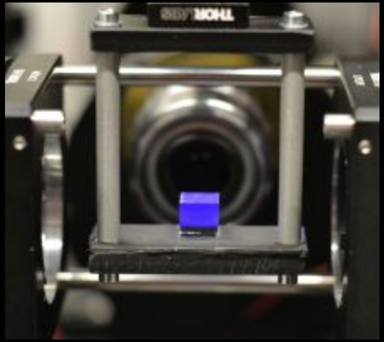


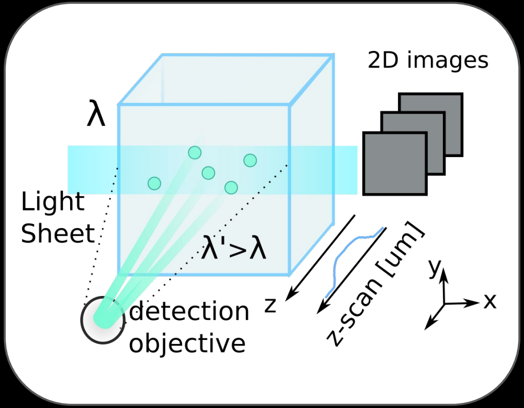


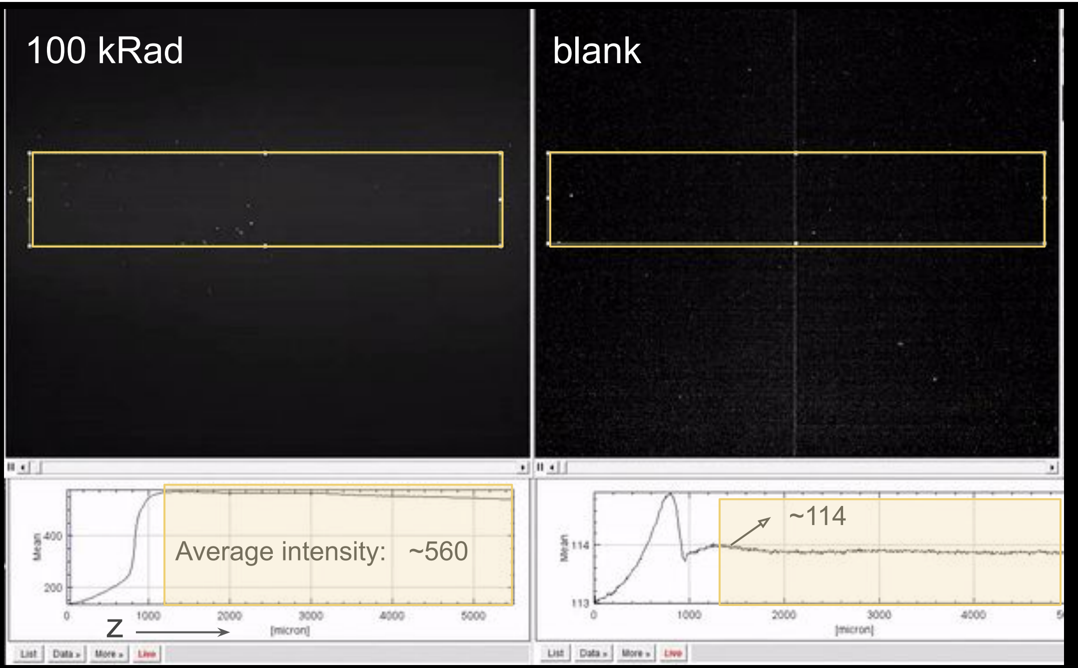


Blank sample only shows clear surface (dust) fluorescence

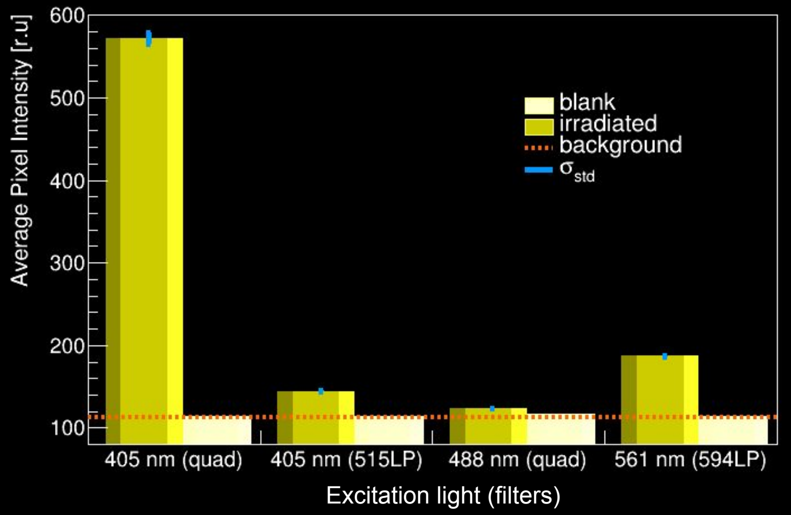
Irradiated sample yields clear fluorescence signal

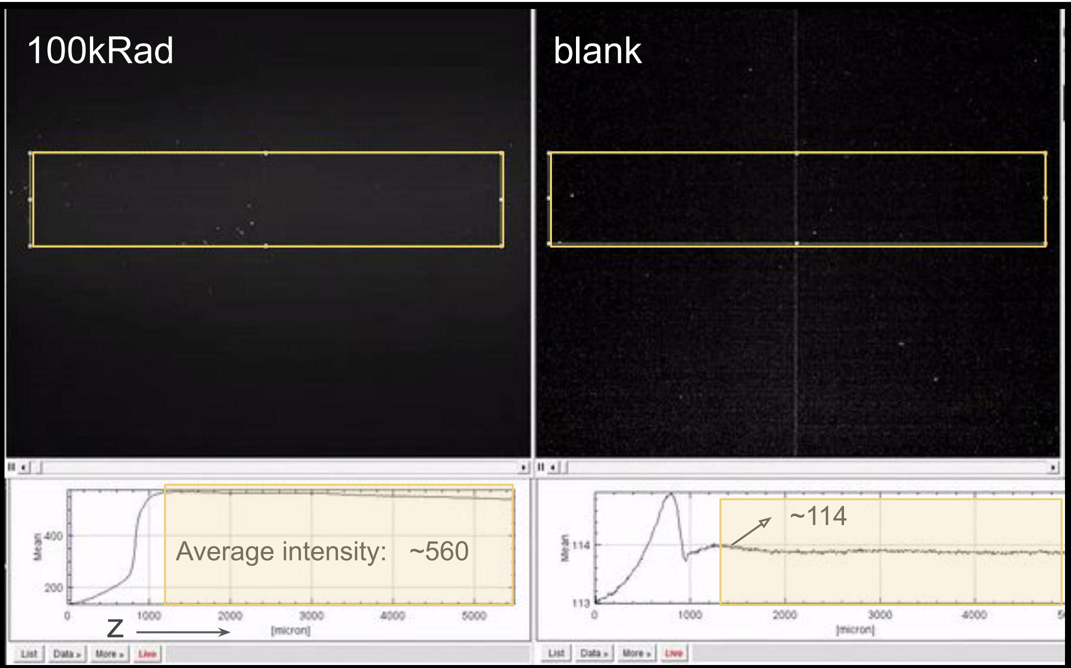






Comparing signal intensity and color





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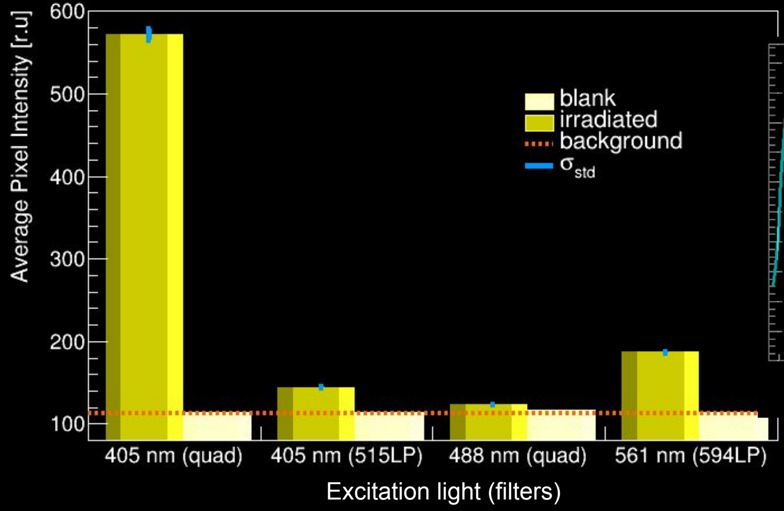
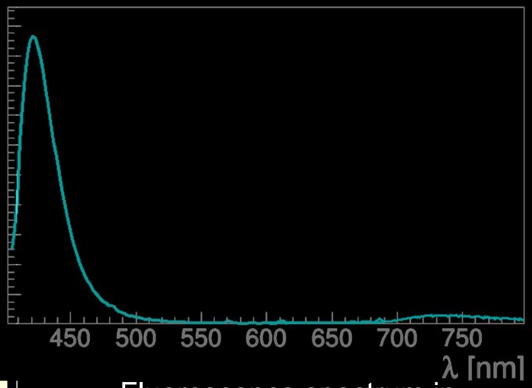
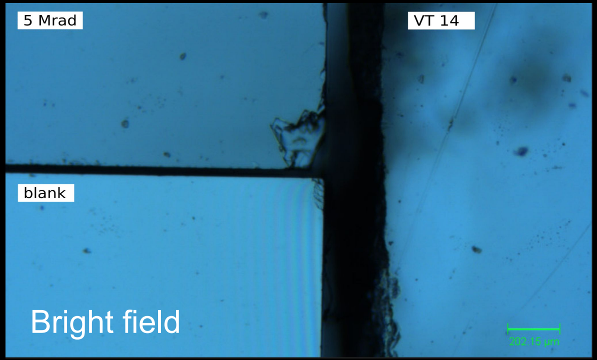
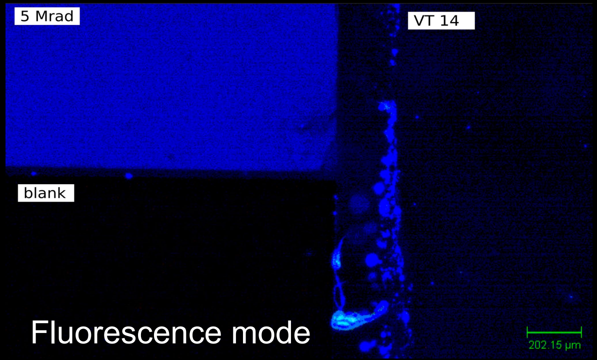


It shines blue!



Fluorescence spectrum in response to 400 nm light





*VT14: neutron irradiated sample (which also saw ɣ's)

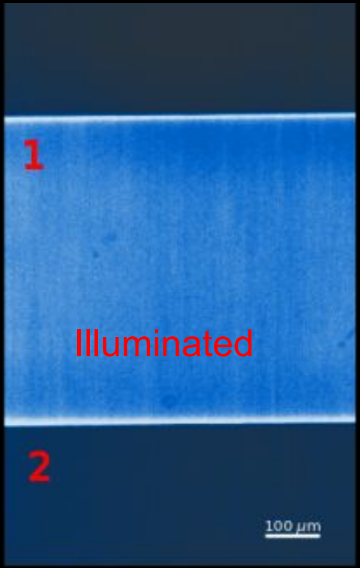
Upgrading the mesoSPIM for color center imaging

A new version of mesoSPIM will be soon released:

- Larger camera, smaller pixels
- Magnification up to 20x
- Smaller footprint & cost

Portable benchtop providing faster scans and larger resolution. Optimized for biological purposes but also for color center imaging for paleoccene

Upgraded mesoSPIM paper coming out soon!



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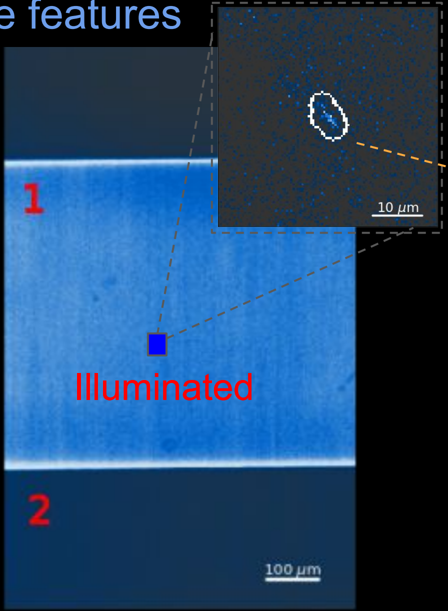
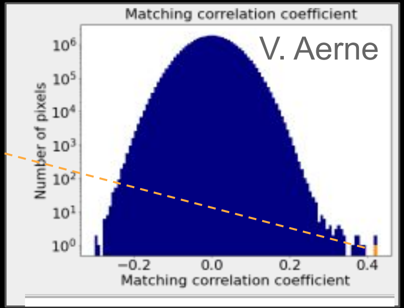
First scans with new mesoSPIM revealed track -like features



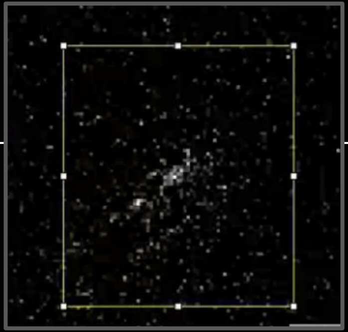


Pixel correlation in repeated scans

Portable benchtop providing faster scans and larger resolution. Optimized for biological purposes but also for color center imaging for paleoccene

Upgraded mesoSPIM paper coming out soon!

Track-like structure in repeated scans



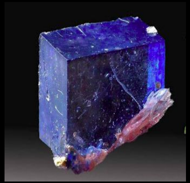
1)

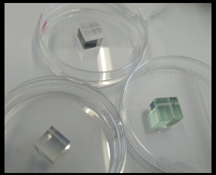
2)

Low threshold & large exposure are keys to push sensitivity to WIMPs and detect CEνNS from lower energy sources

Low threshold: Ability to measure low-energy nuclear recoils. Go beyond "vanilla" WIMP

Paleo	Paleoccene
high-resolution microscopy of small tracks	Colors centers induced at low energies.





composite DM

WIMP SD interaction

Exposure:

- Increase measuring time — Billion-year old rocks (DM sub-halo structure)
- Increase target mass — Scalable passive volume + readout
- Increase ν-flux (CEνNS) — reactor ν's, tamper-proof non-proliferation monitor

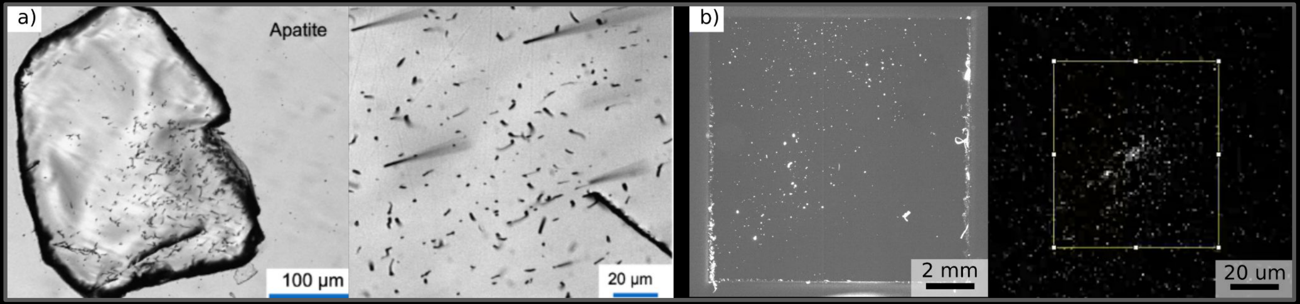
Background suppression:

- radio-pure minerals (below ppb level of ^{238}U)
- null or distinguishable response to EM background
- shielding against cosmic rays (deep underground rocks/lab)
- 3D-track reconstruction, vacancy number /track length, on/off reactor, vary targets + explore N^2 dependence

"Mineral Detection of Neutrinos and Dark Matter" 2301.07118

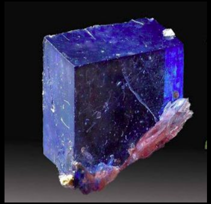
Next steps for LSM color center imaging

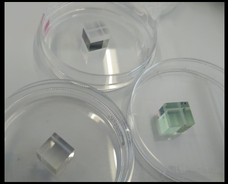
- Proton irradiation of crystals for full track imaging
- Pixel matching for neutron-induced color-centers
- Light-sheet (mesoSPIM) microscopy application in geology and paleo detectors.

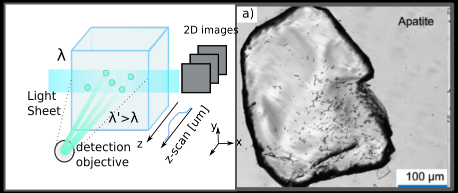


a) Fission track dating example b) mesoSPIM crystal scan (surface and track-feature in the bulk)

Can we also get the best out of both for DM detection?







	Paleo	Paleoccene	LSM of paleo transparent minerals?
i) Passive:	✓	✓	✓
ii) low energy:	✓ ~50eV (~1nm track)	✓ ~50eV (~1nm track)	✓
iii) optical:	✗ Helium-ion beam, SAXS microscopy	✓ Light sheet microscopy (LSM)	✓
iv) non-destructive readout:	✗ HIB requires layer ablation	✓	✓
v) large exposure:	✓ 10-10^5 tonne*yr (t~ Gyr, M: 0.01-100g limited by readout)	Scalable with LSM readout of >1kg/day/micr.	✓ >10^5 tonne*yr?

To be investigated!

Meet the Paleoccene team

Dr. B. Cogswell

Prof. P. Huber

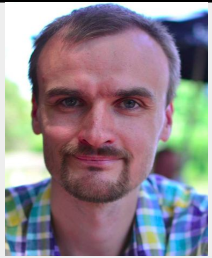
Theory (DM, ν, nuclear safeguards)

Prof. G. Khodaparast

Prof. B. Magill

spectroscopy

Prof. L. Baudis
DM detectors



Dr. N. Vladimirov
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developer

V. Aerne
mesoSPIM
data analysis

G. R. Araujo
mesoSPIM
widefield, spectr.

Dr. J. M .Melero
mesoSPIM
widefield

Igor Jovanovic
Nuclear
engineering/
radiology

Adam Hecht
Nuclear
engineering/
nonproliferation

& scientists/engineers in the fields of nuclear engineering, particle physics & optics
(not everyone's name is here)

2203.05525