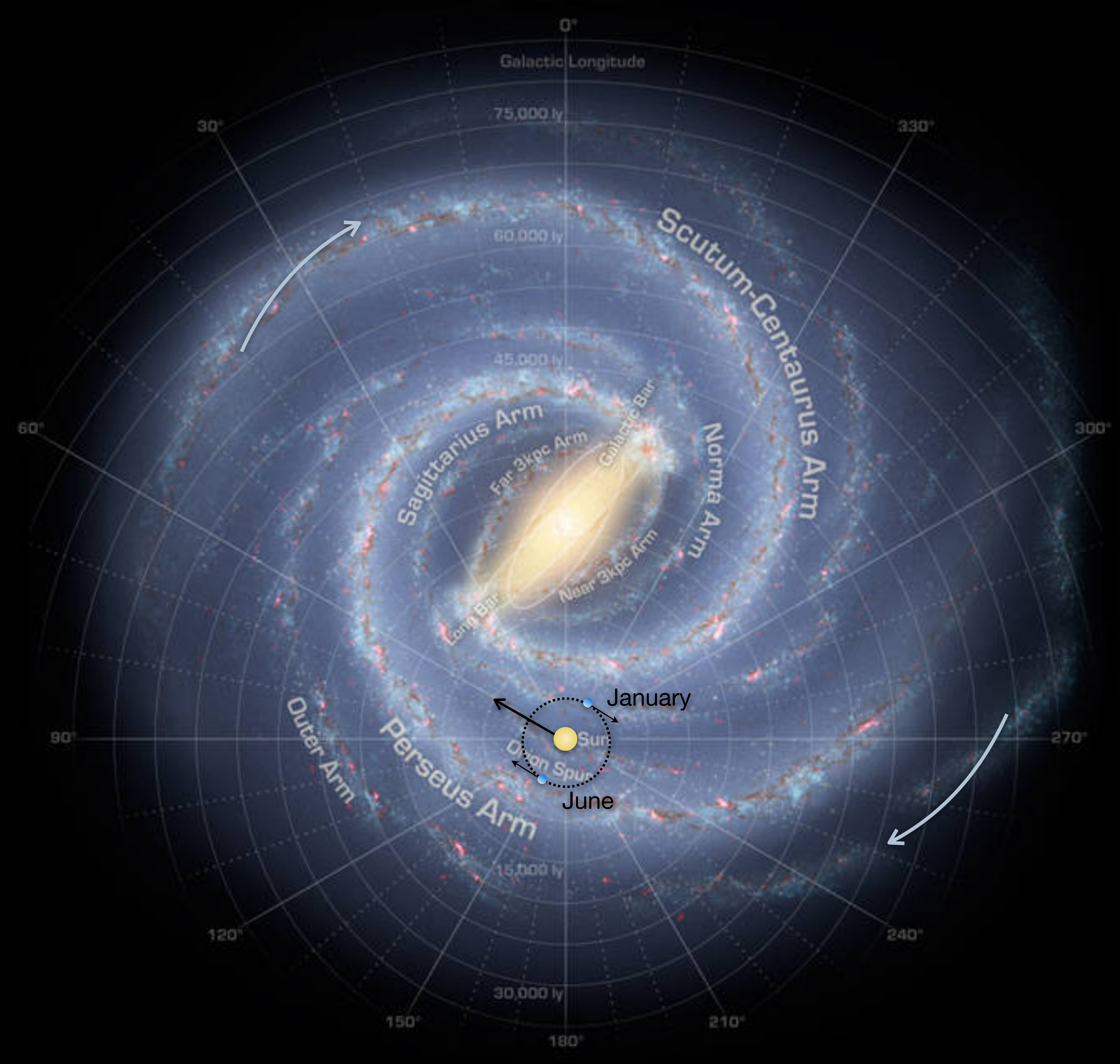
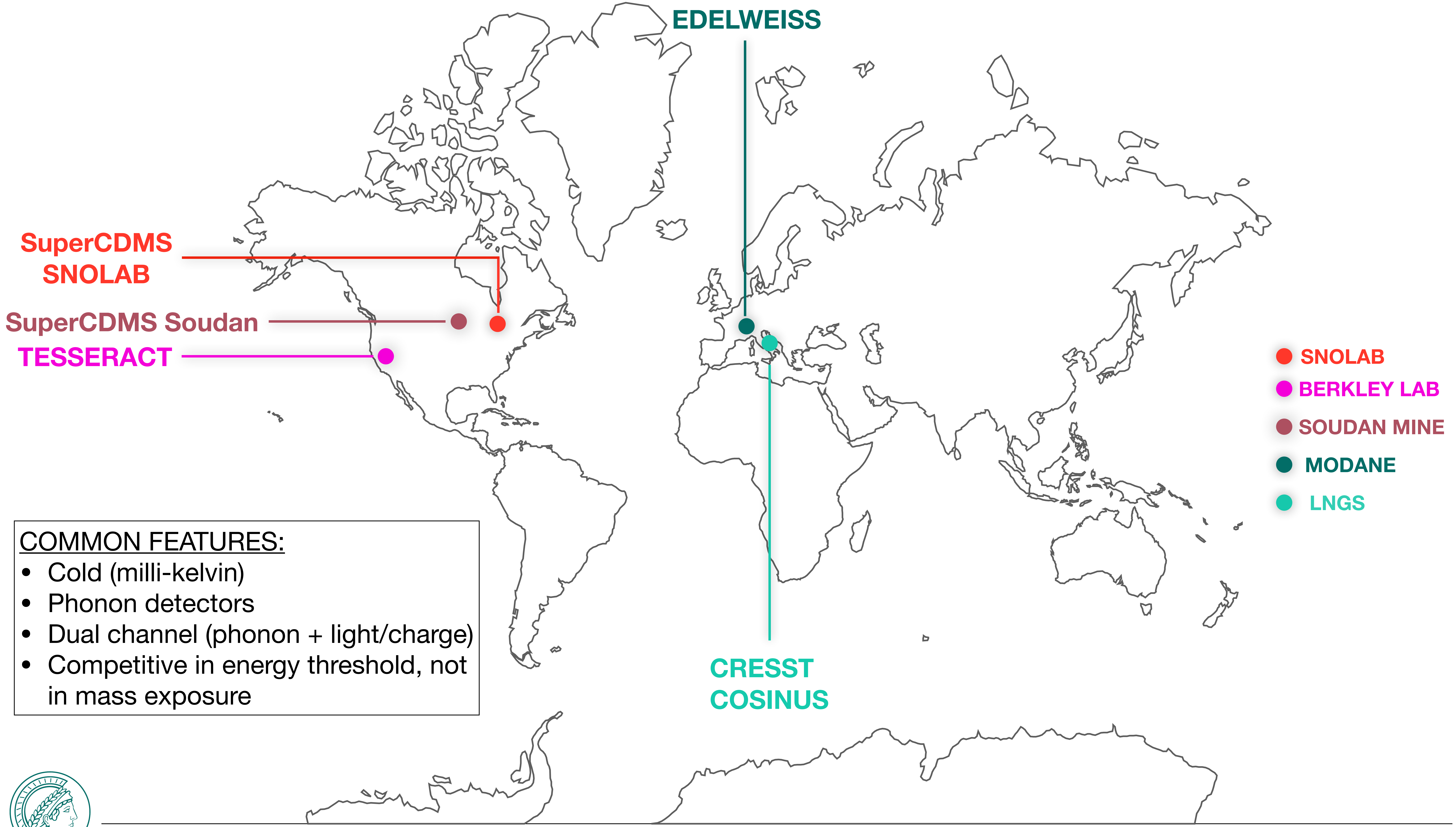
Dark matter direct search using cryogenic detectors

Vanessa Zema

MAX-PLANCK-INSTITUT
FÜR PHYSIK



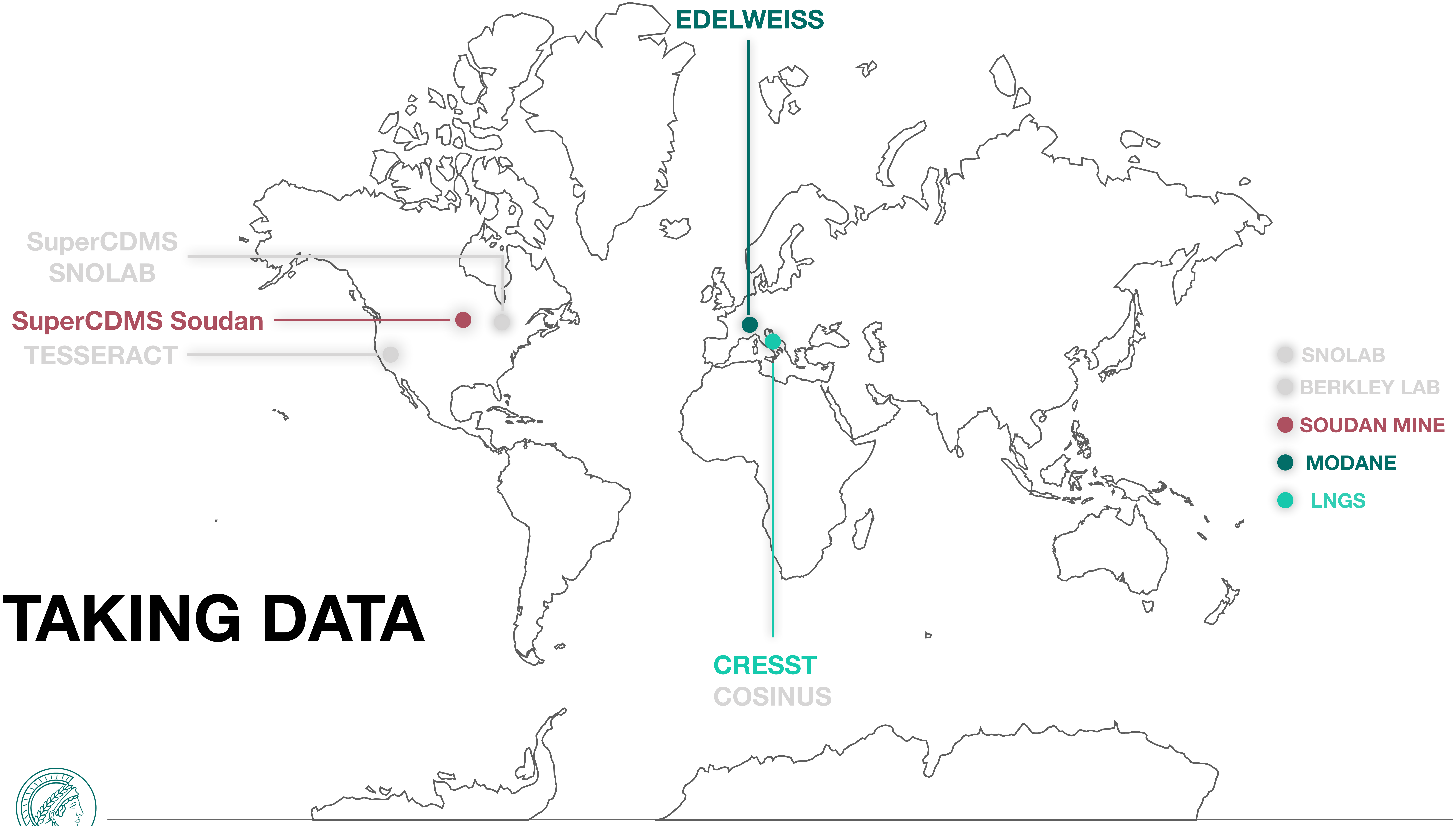
0°
Galactic Longitude
75,000 ly
30°
330°
60,000 ly
Scutum-Centaurus Arm
45,000 ly
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
60°
300°
Near 3kpc Arm
Long Bar
January
90°
Sun
270°
Outer Arm
Perseus Arm
June
15,000 ly
120°
240°
30,000 ly
150°
210°
180°



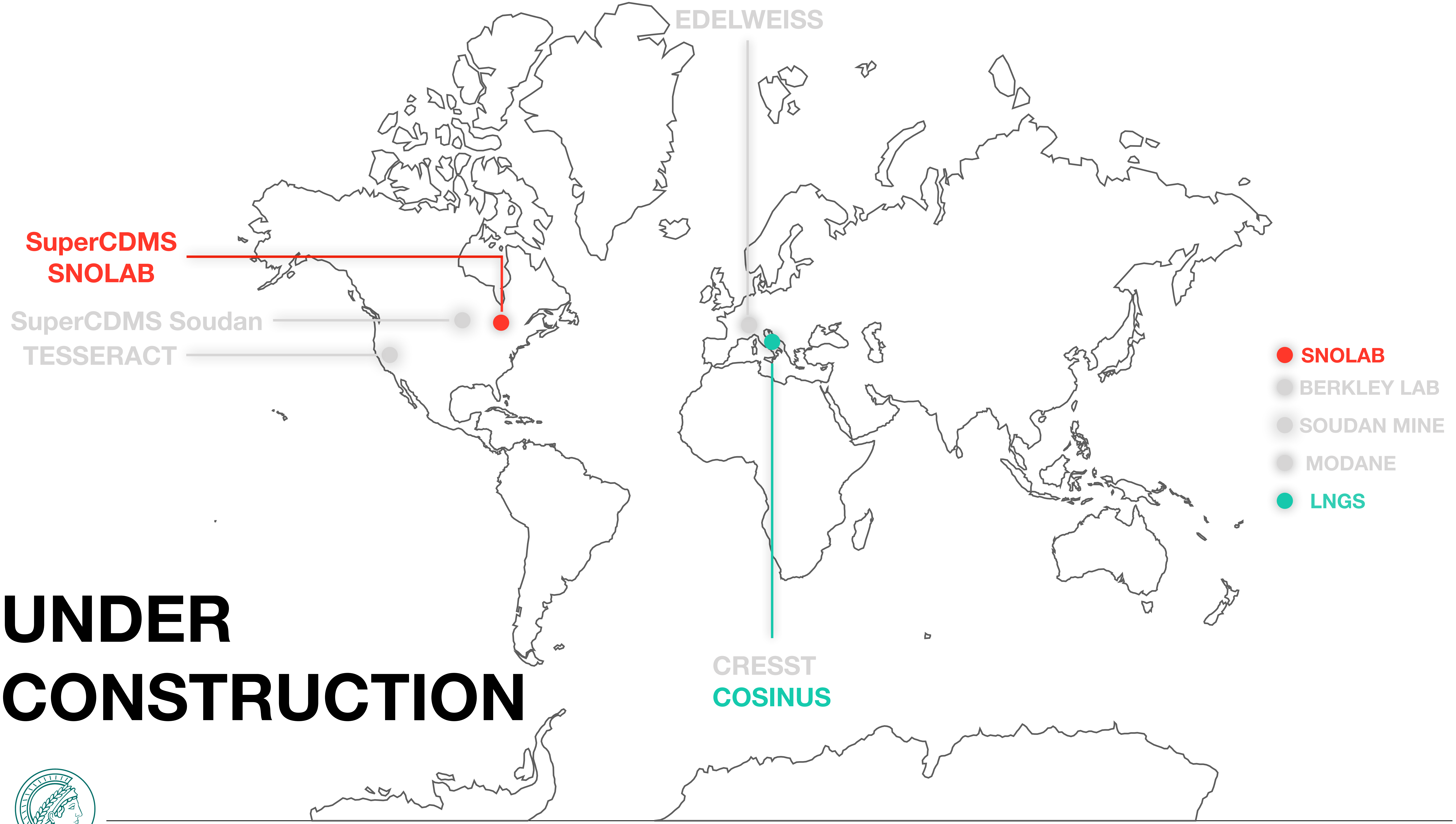
COMMON FEATURES:

- Cold (milli-kelvin)
- Phonon detectors
- Dual channel (phonon + light/charge)
- Competitive in energy threshold, not in mass exposure

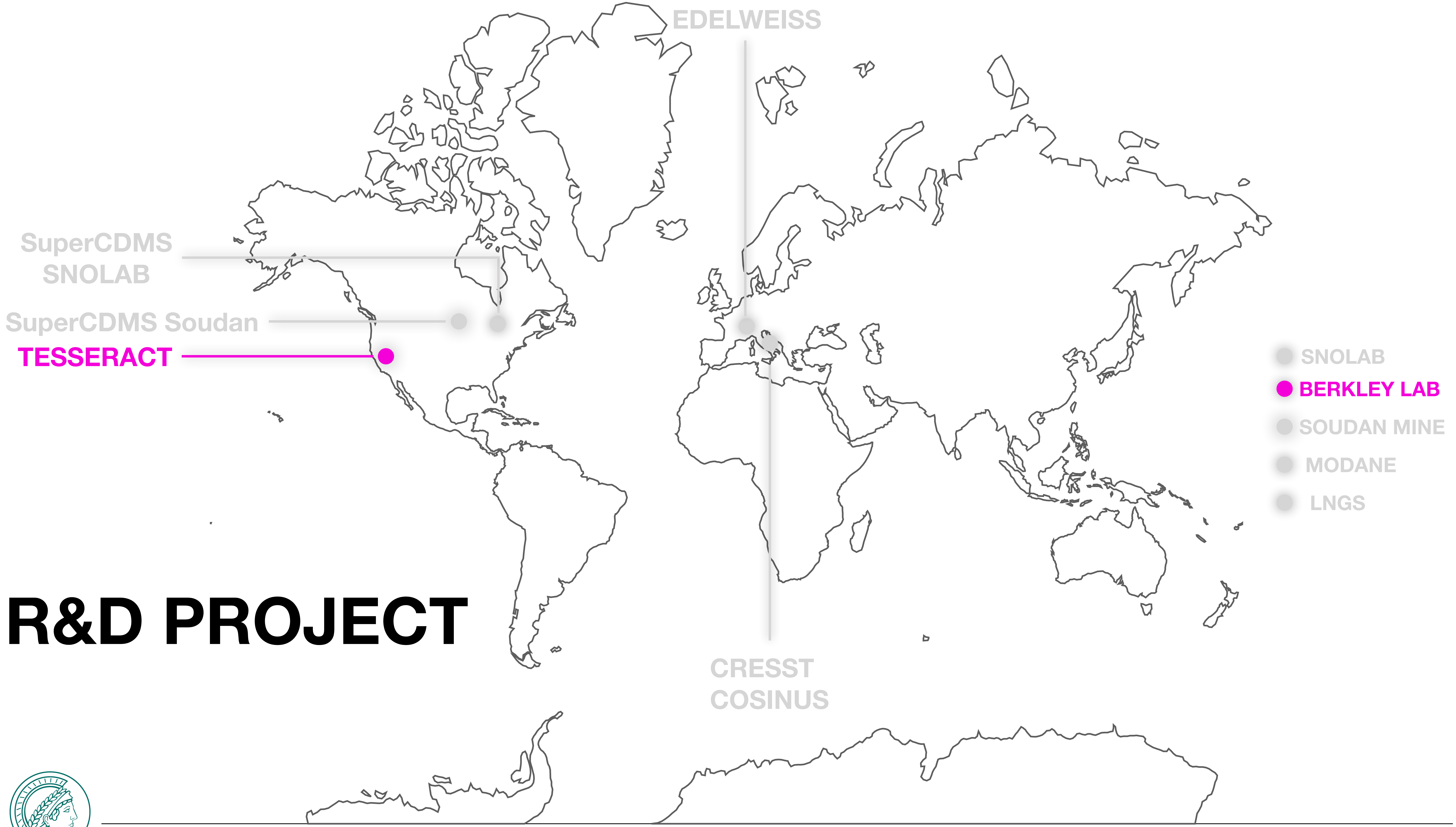
TAKING DATA



EDELWEISS
SuperCDMS
SNOLAB
SuperCDMS Soudan
TESSERACT
CRESST
COSINUS
SNOLAB
BERKLEY LAB
SOUDAN MINE
MODANE
LNGS



UNDER CONSTRUCTION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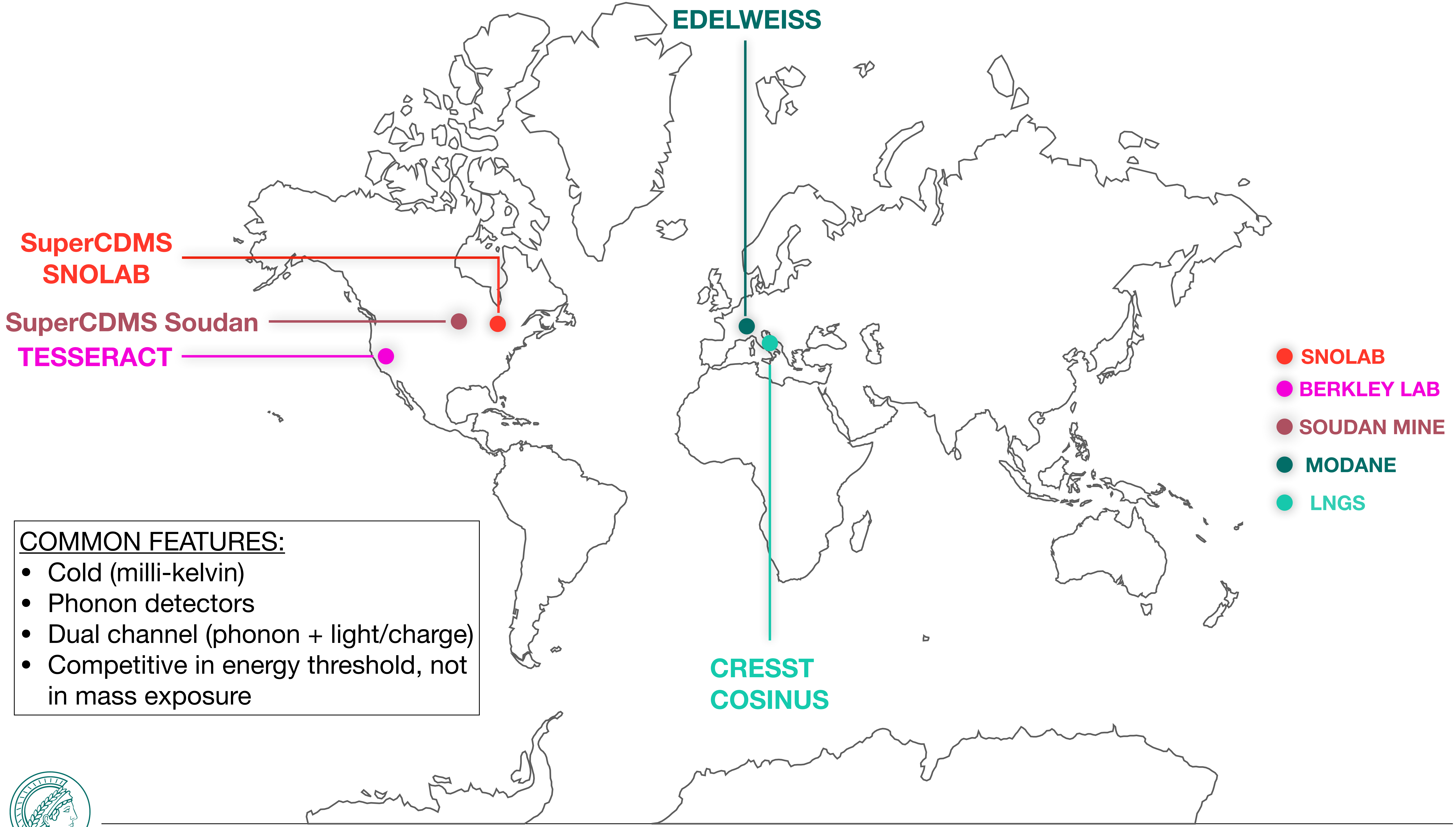
R&D PROJECT



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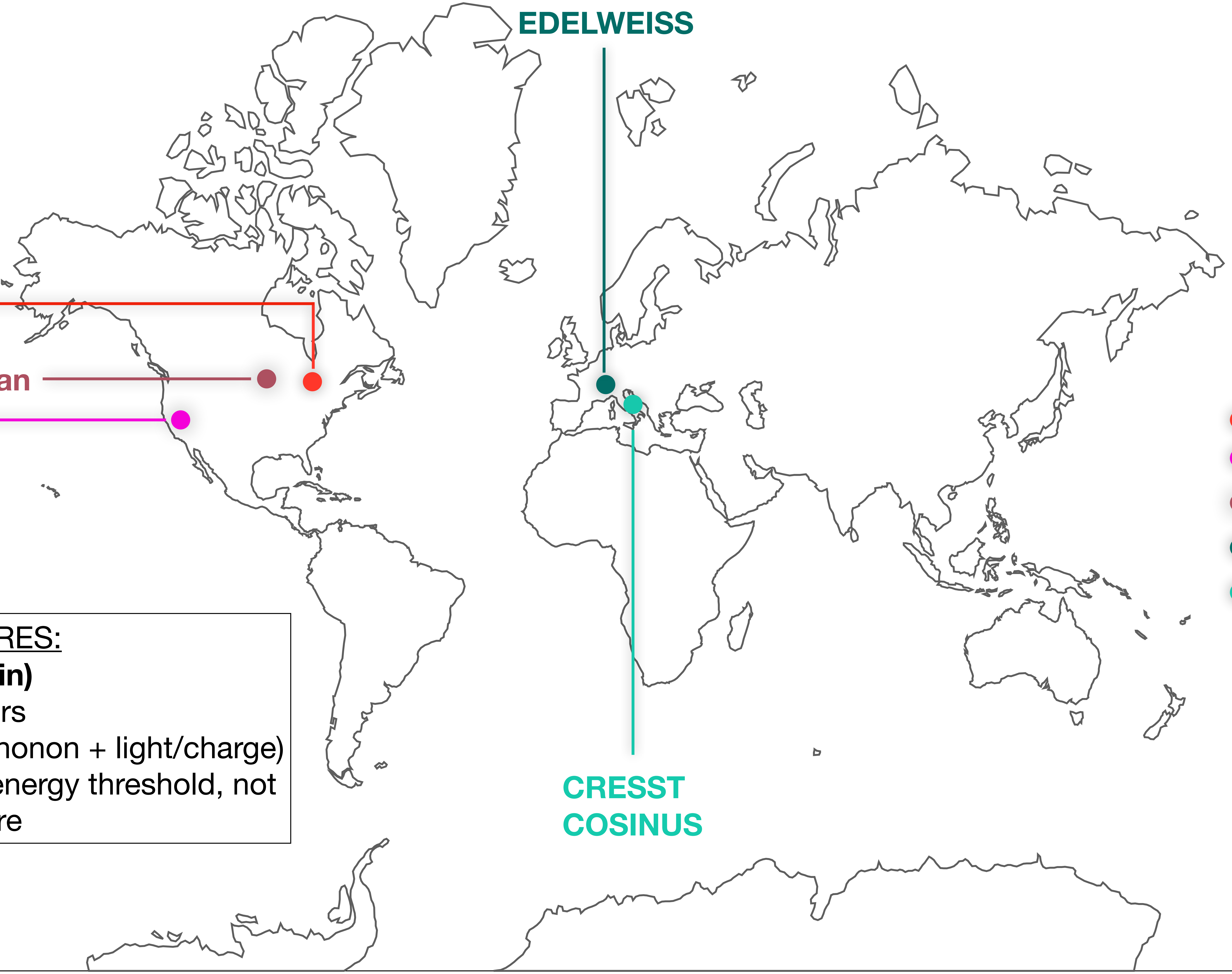

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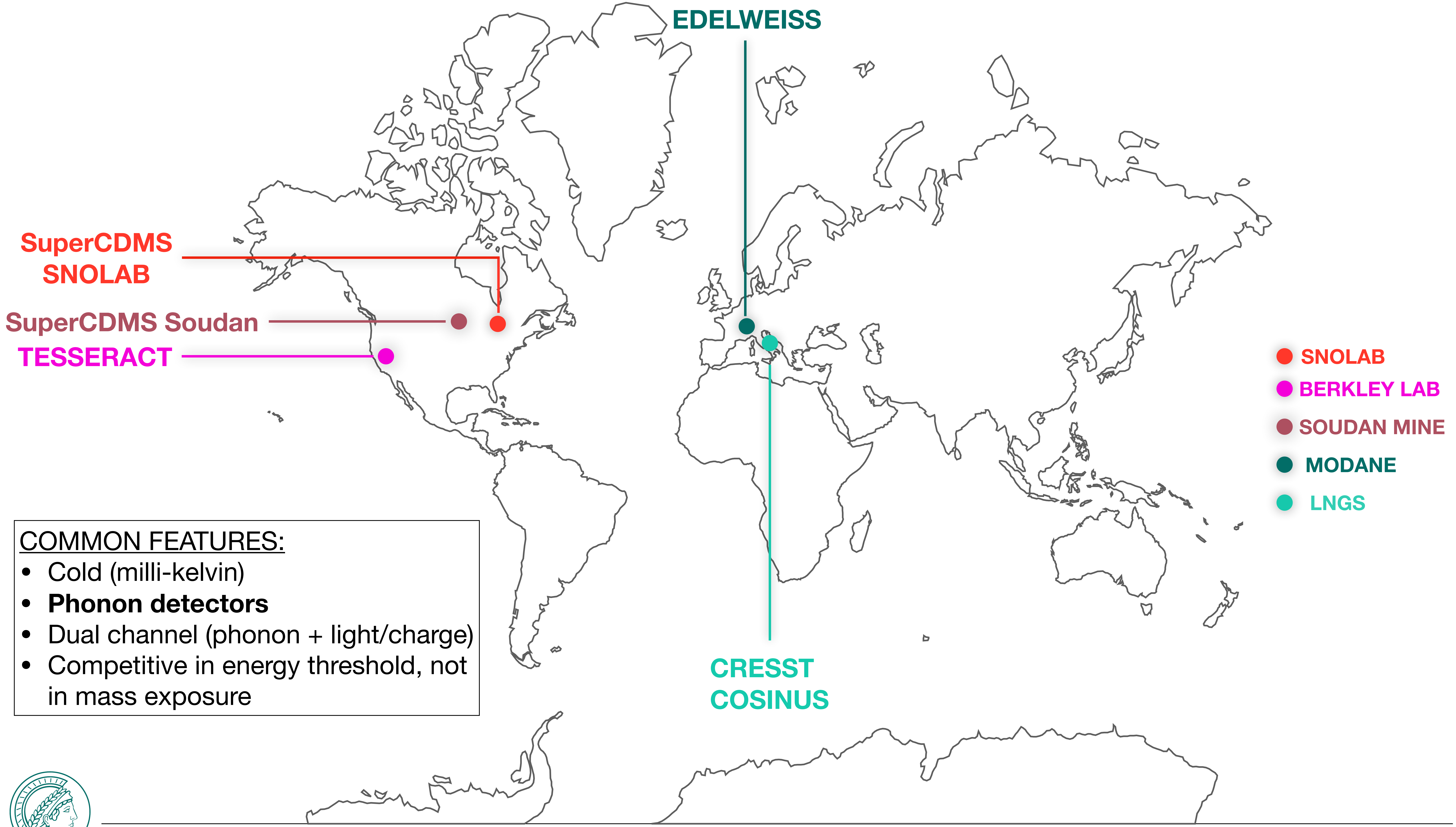

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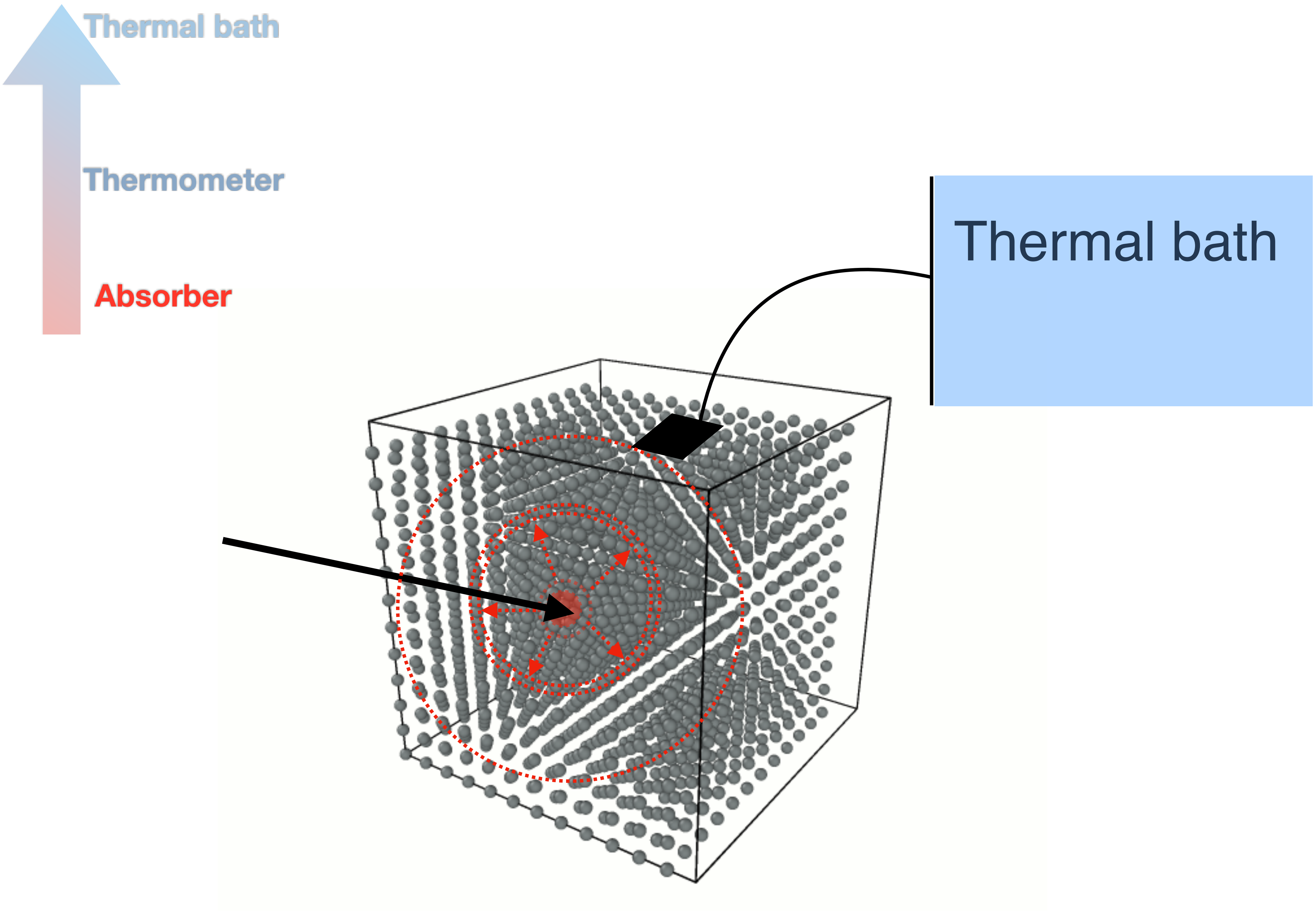
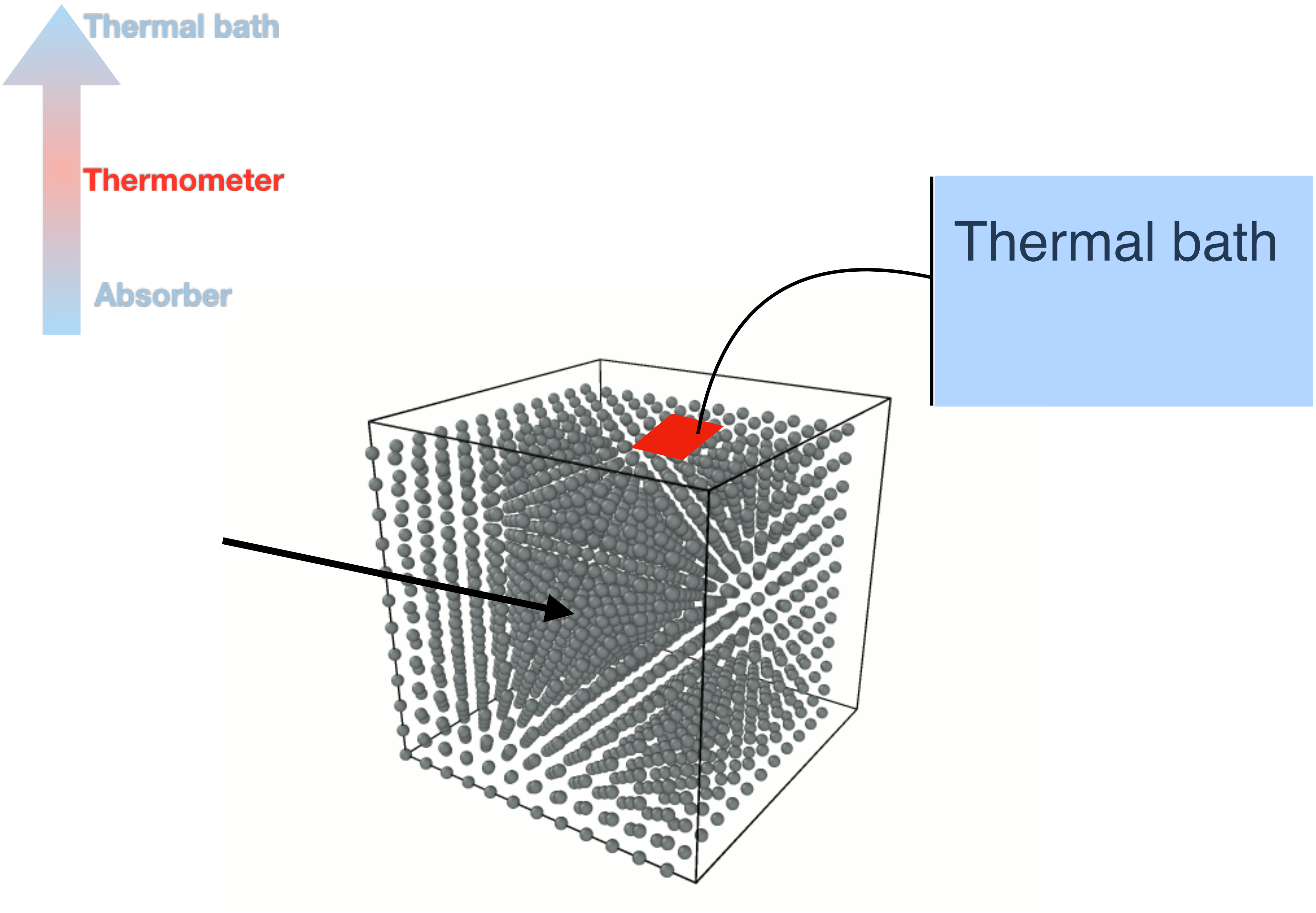
PHONON DETECTOR



ADVANTAGE: MOST OF THE ENERGY IS CONVERTED INTO COLLECTIVE EXCITATIONS called PHONONS

PHONON DETECTOR



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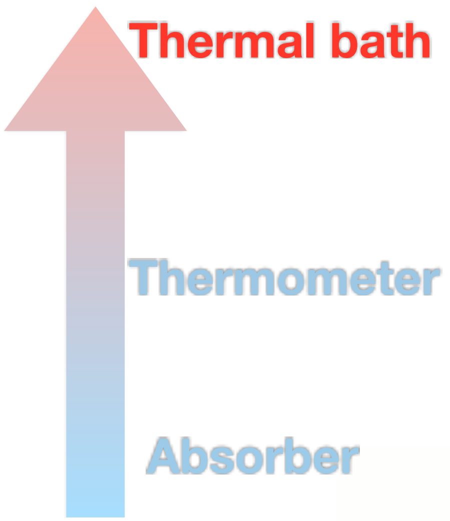
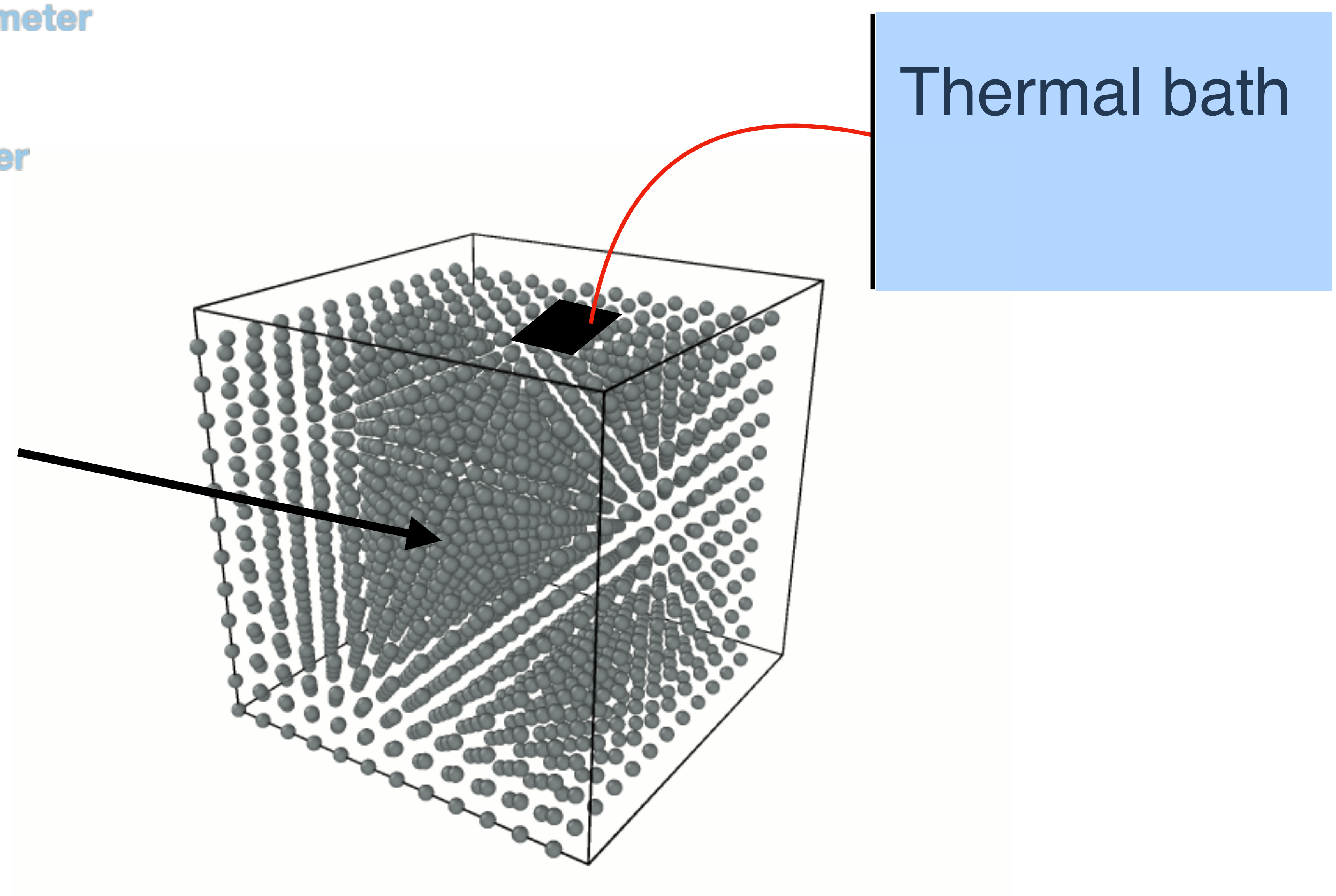
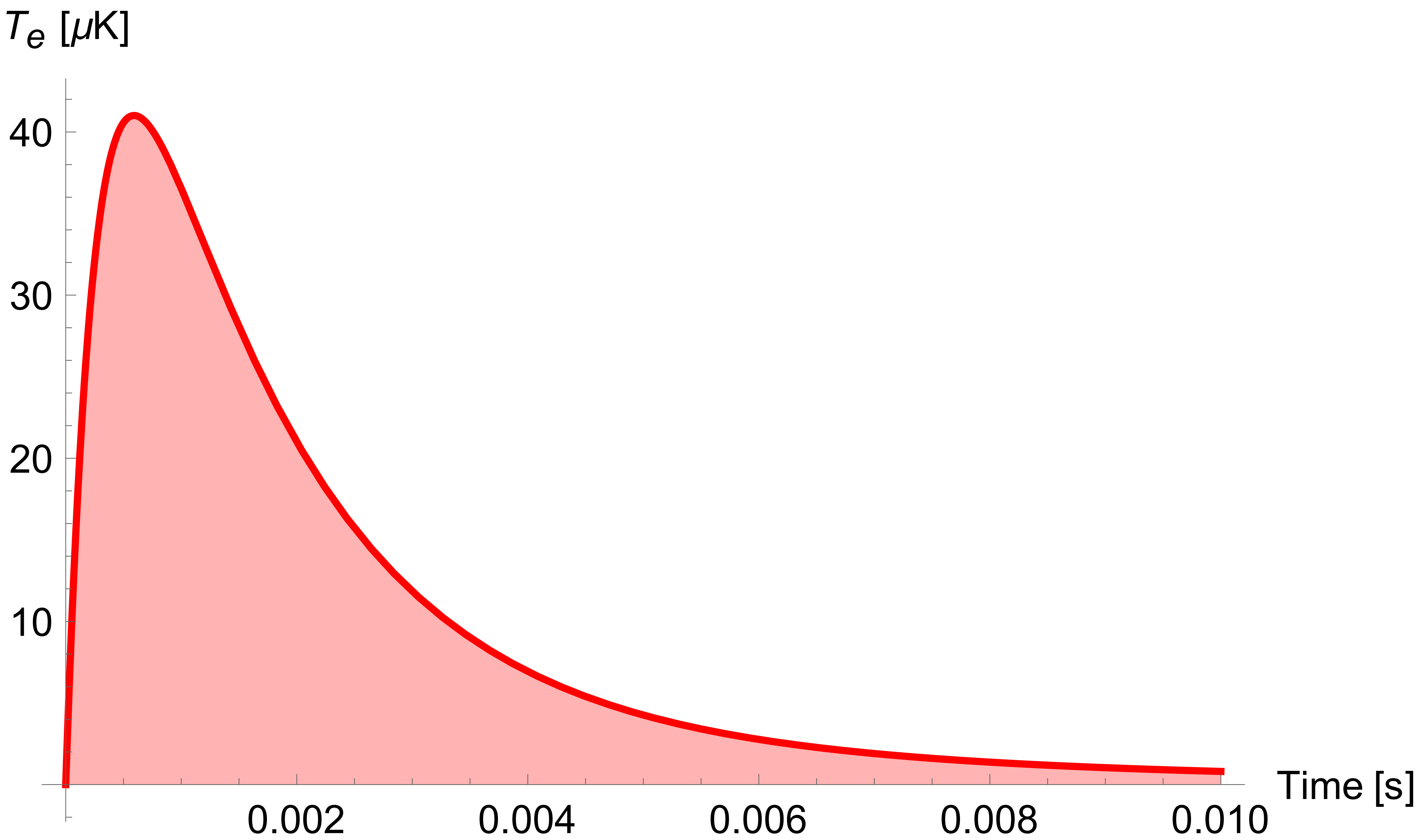
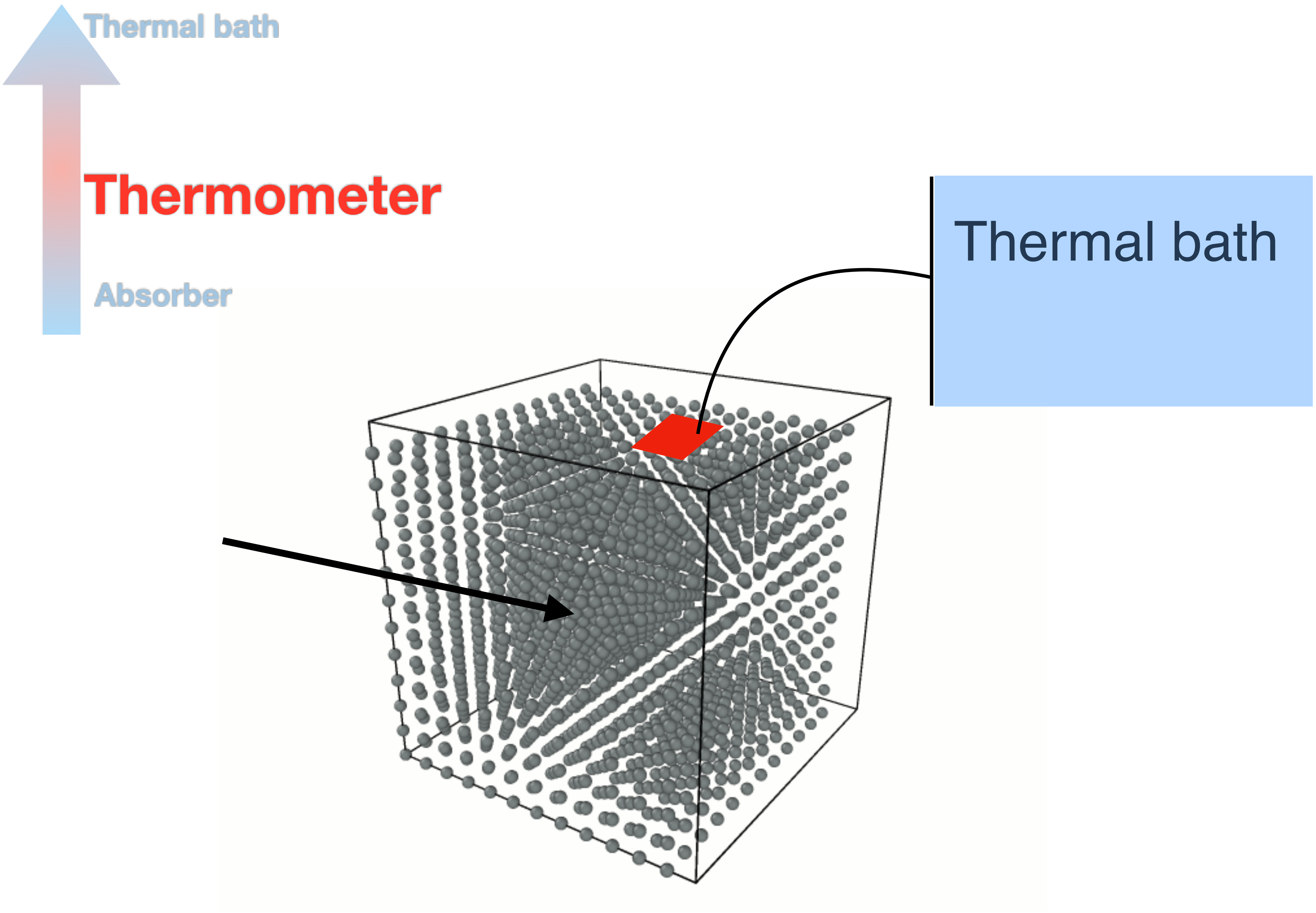






<u>ADVANTAGE</u>: MOST OF THE ENERGY IS CONVERTED INTO COLLECTIVE EXCITATIONS called PHONONS

TEMPERATURE SENSORS



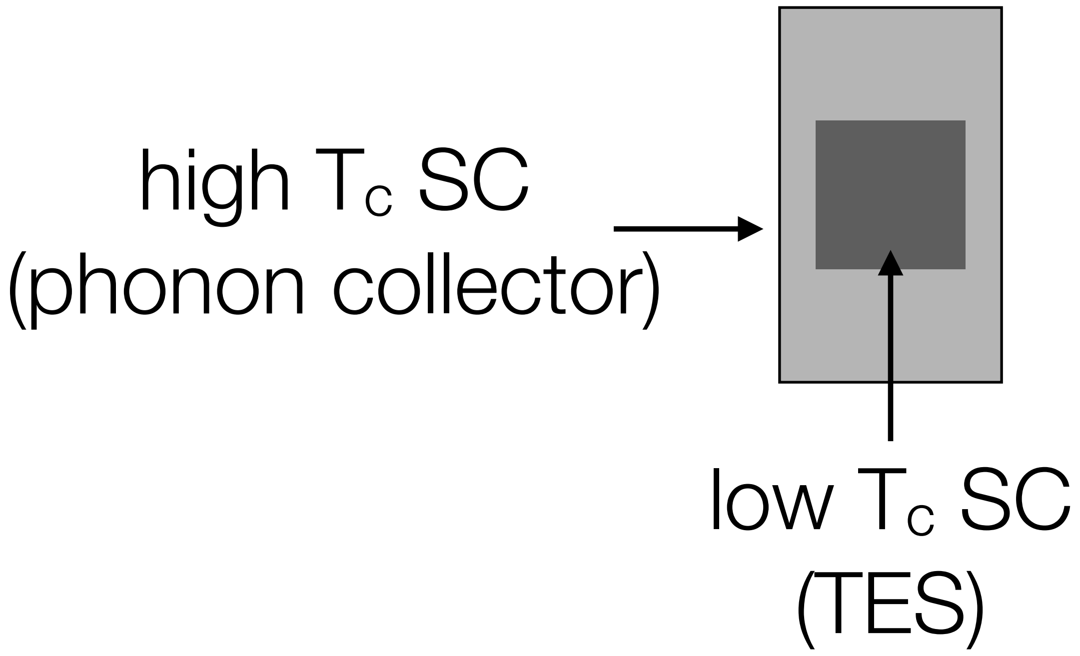
- **NTD**: **N**eutron **T**ransmutation **D**oped germanium/silicon thermistor

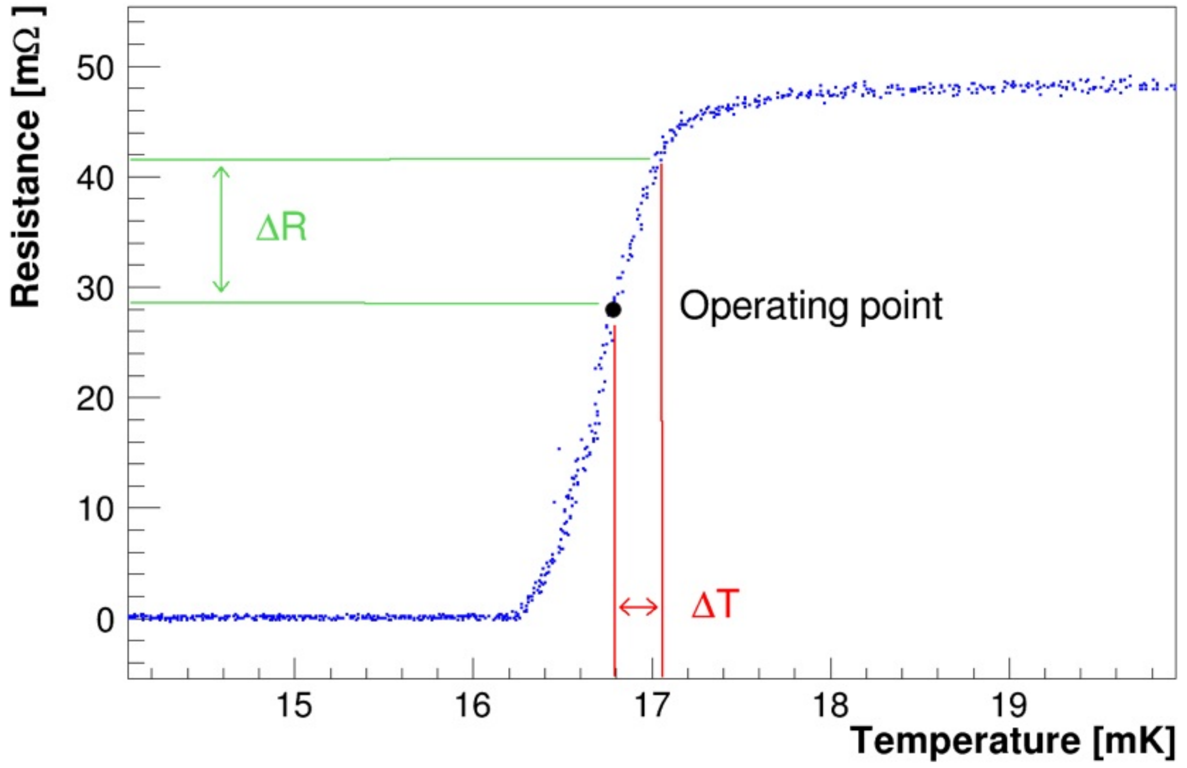
Thin wafer of germanium or silicon doped using a thermal neutron flux, up to a concentration corresponding to the $R(T)$ law:

$$R(T) = R_0 \; exp \left(\frac{T_0}{T} \right)^{\gamma}$$

- **TES**: **T**ransition **E**dge **S**ensor

Superconducting (SC) thin film operated in between the superconducting and the normal conducting phase





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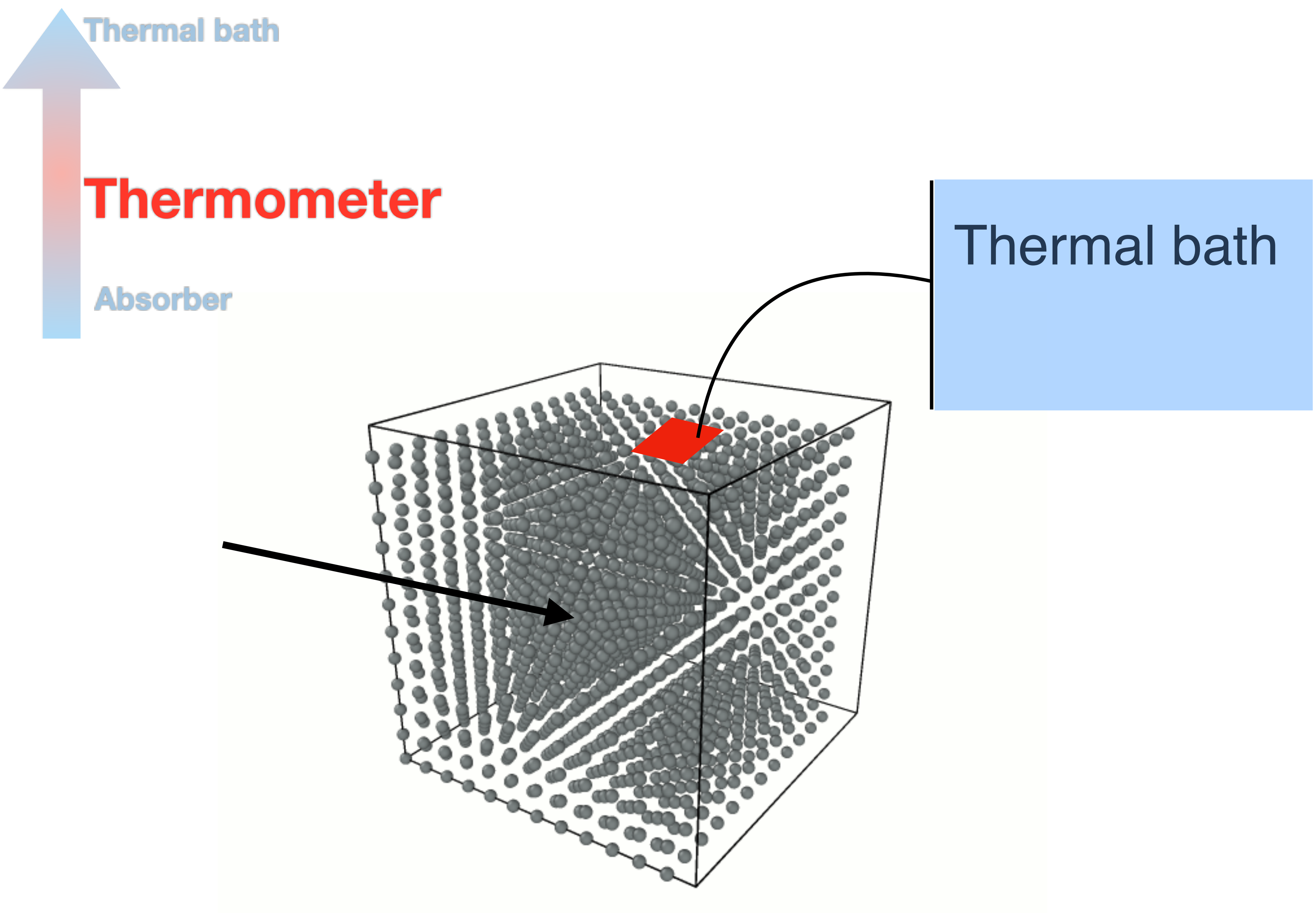
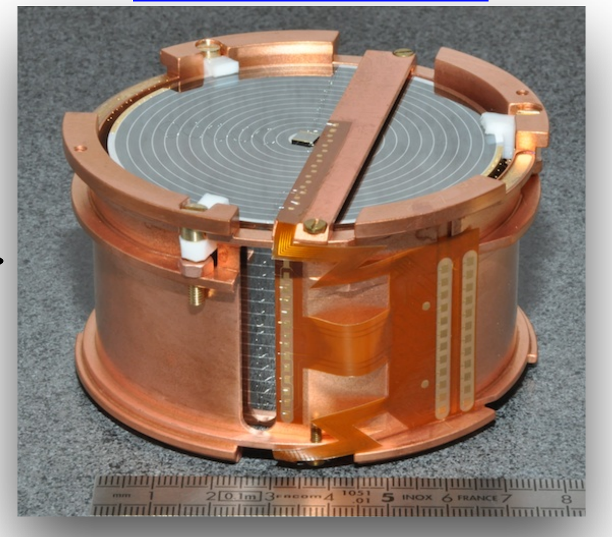


- **NTD**: **N**eutron **T**ransmutation **D**oped germanium/silicon thermistor
  - EDELWEISS

arXiv:1706.01070v1



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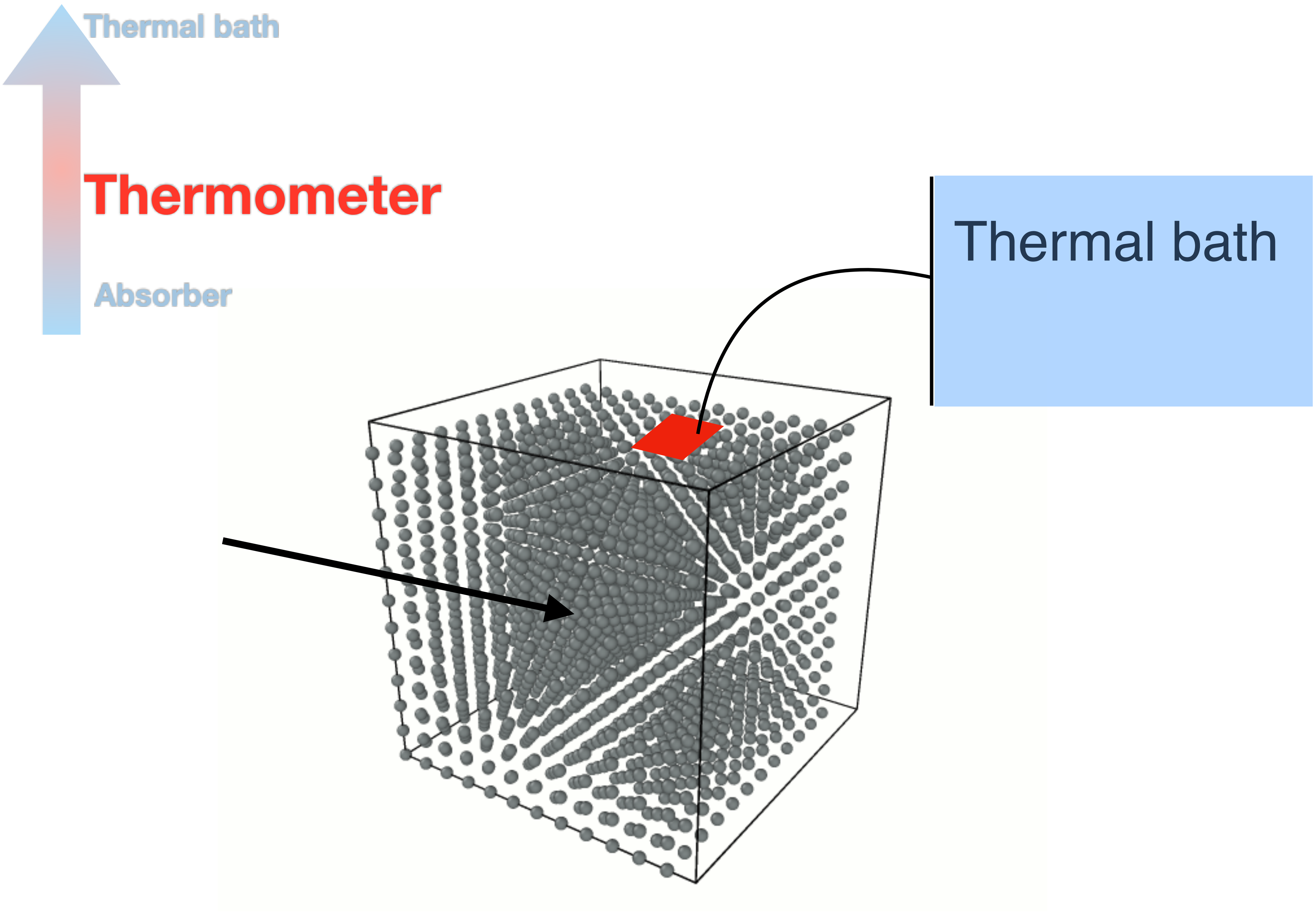
TEMPERATURE SENSORS



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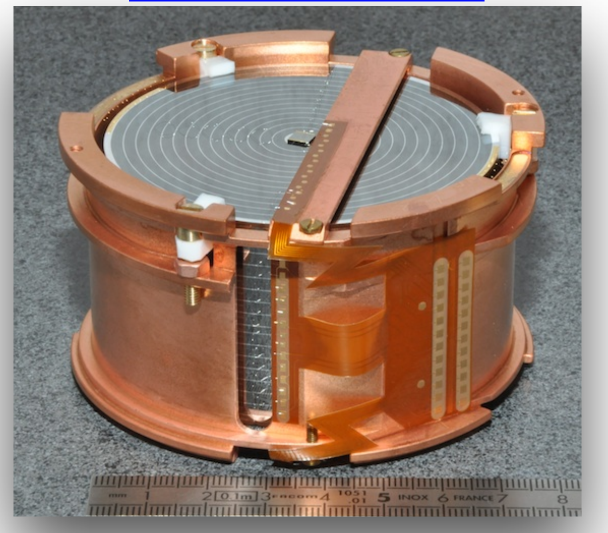

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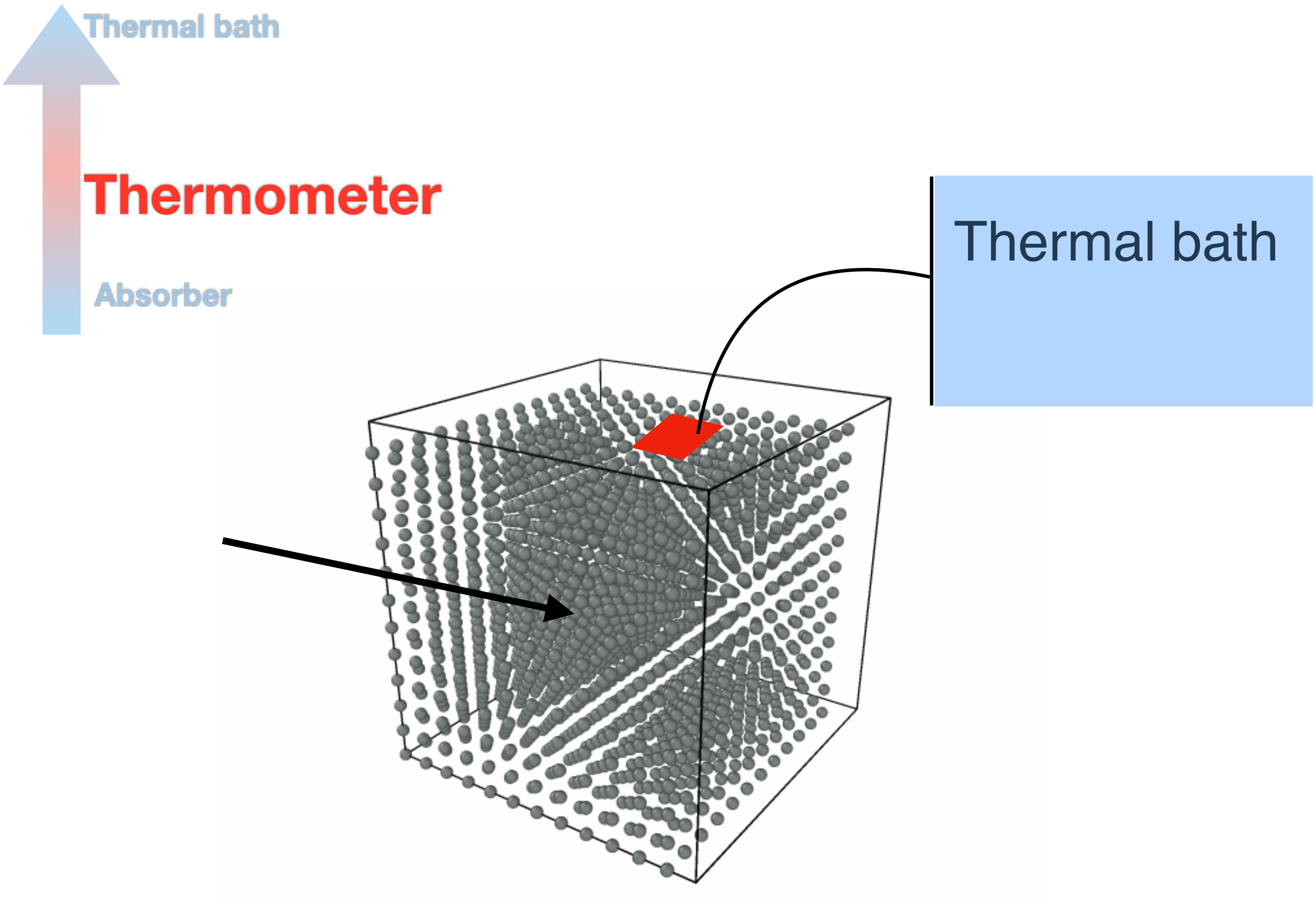

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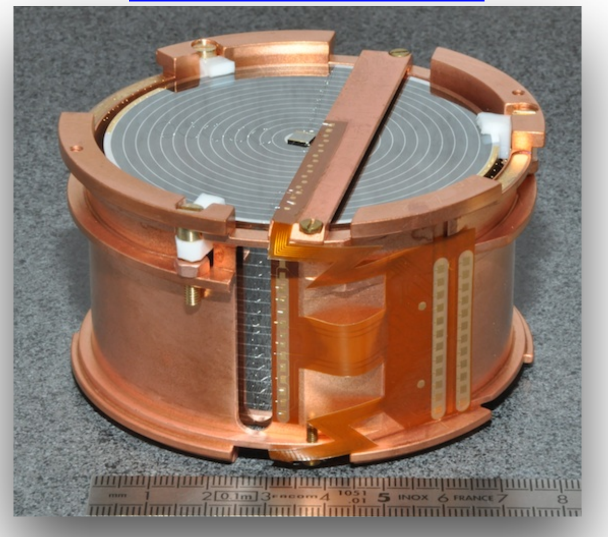

- **TES**: **T**ransition **E**dge **S**ensor
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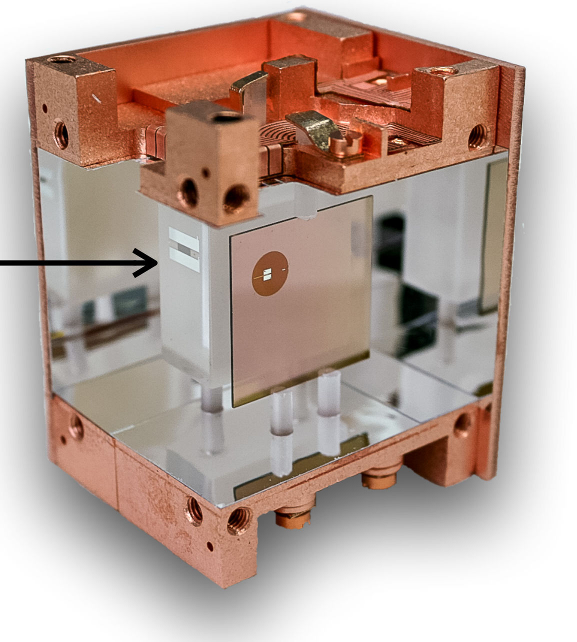
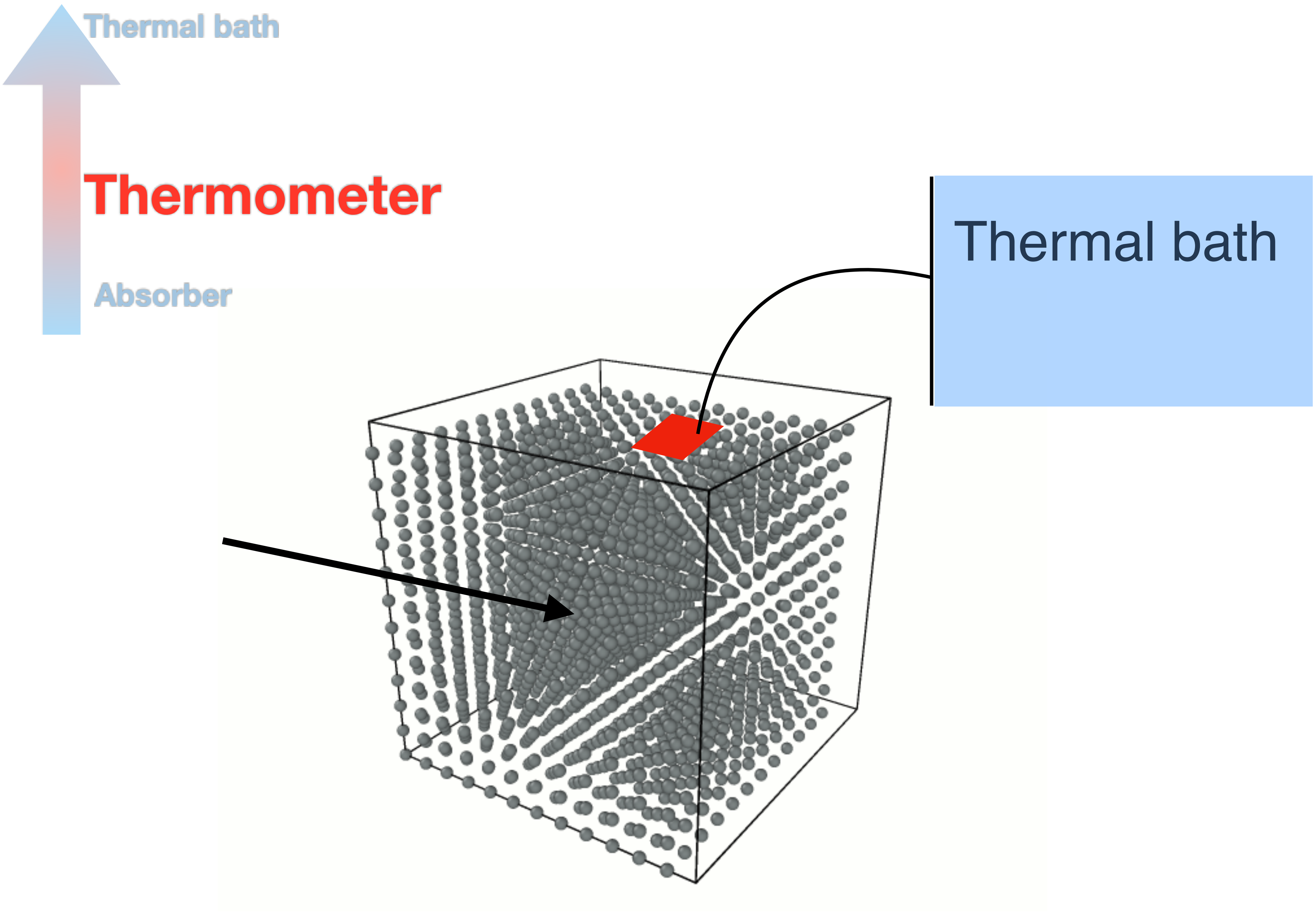
C. STRANDHAGEN | IDM 2022



TEMPERATURE SENSORS



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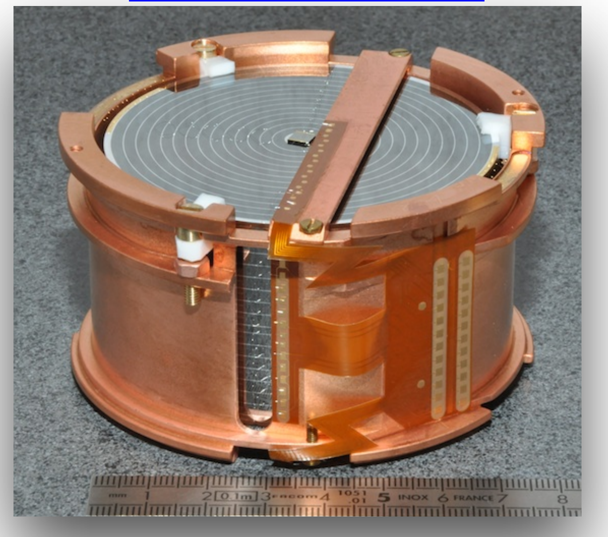

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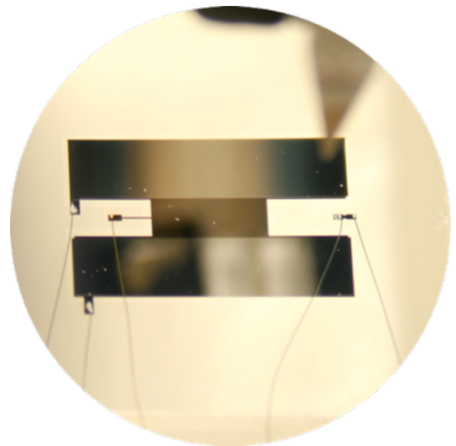
1 H-shaped W/Al-TES



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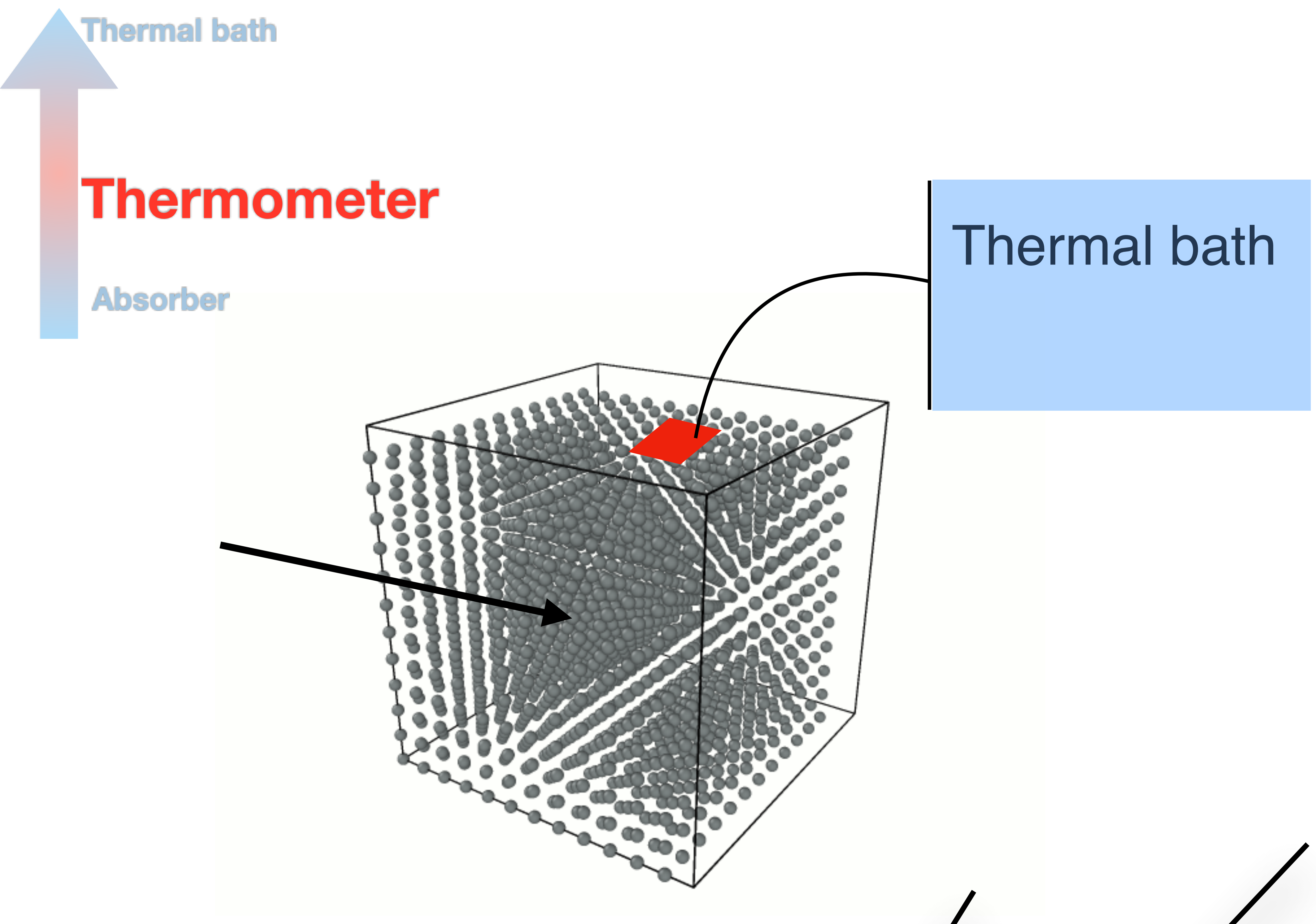

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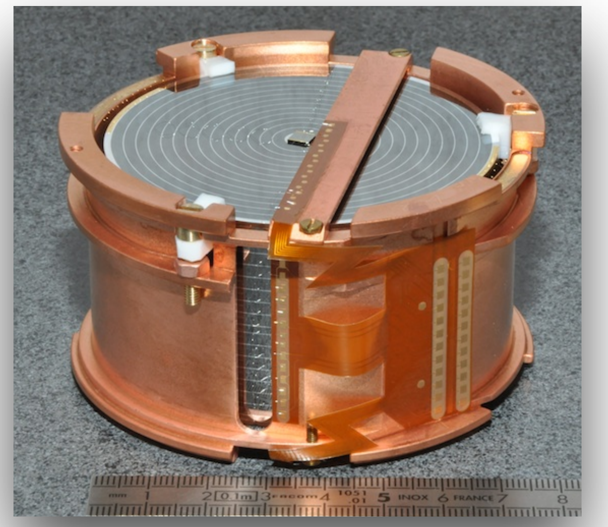

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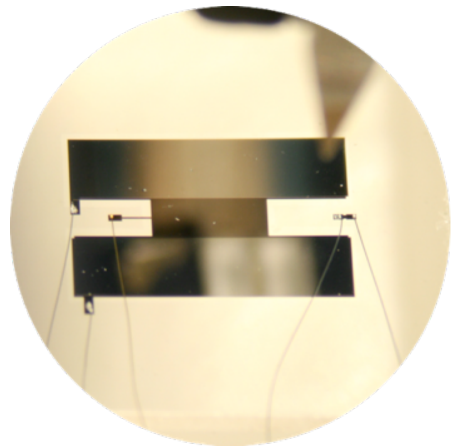
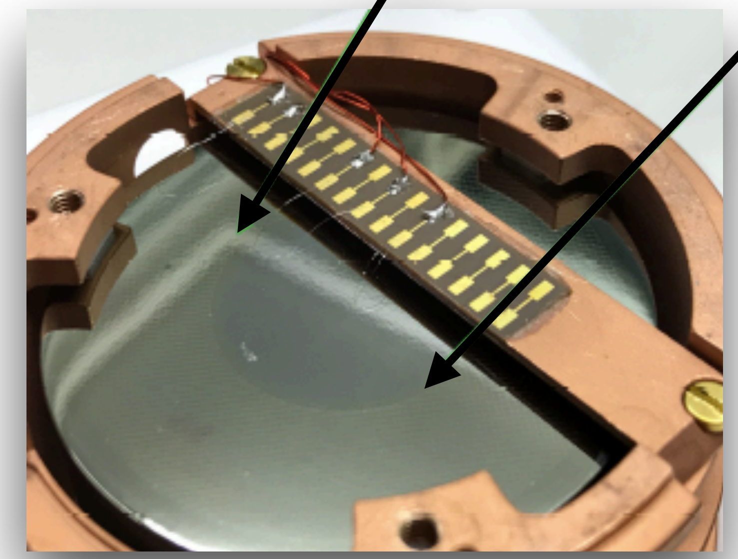
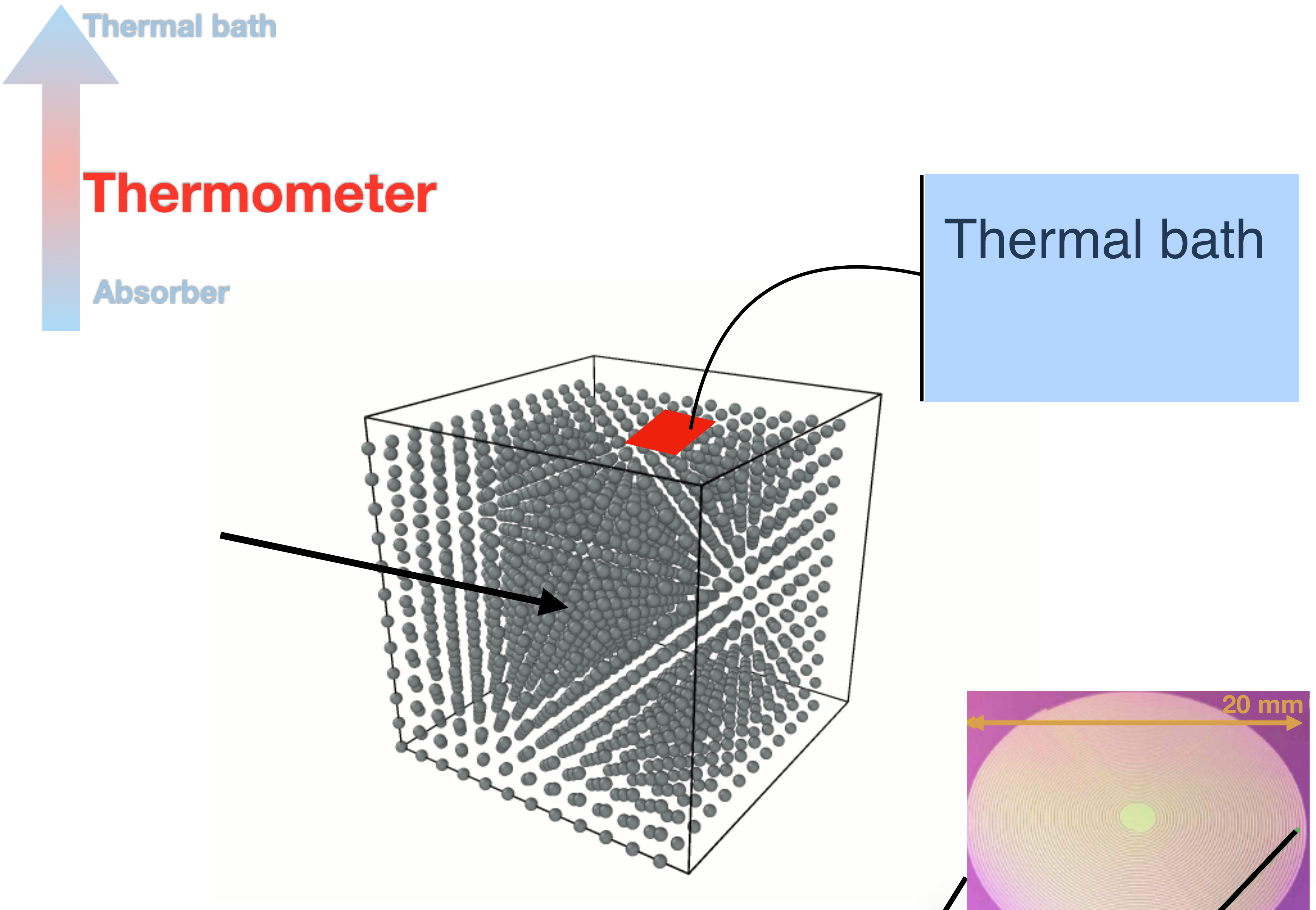




arXiv:2203.03993

TEMPERATURE SENSORS



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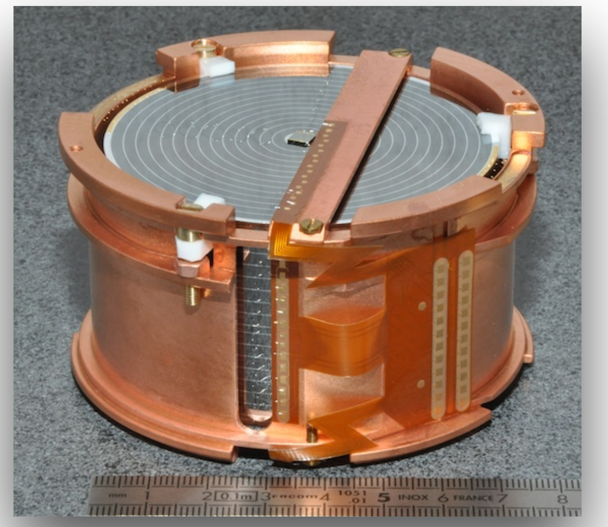

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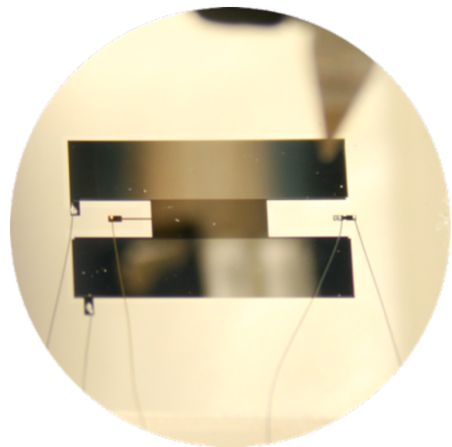

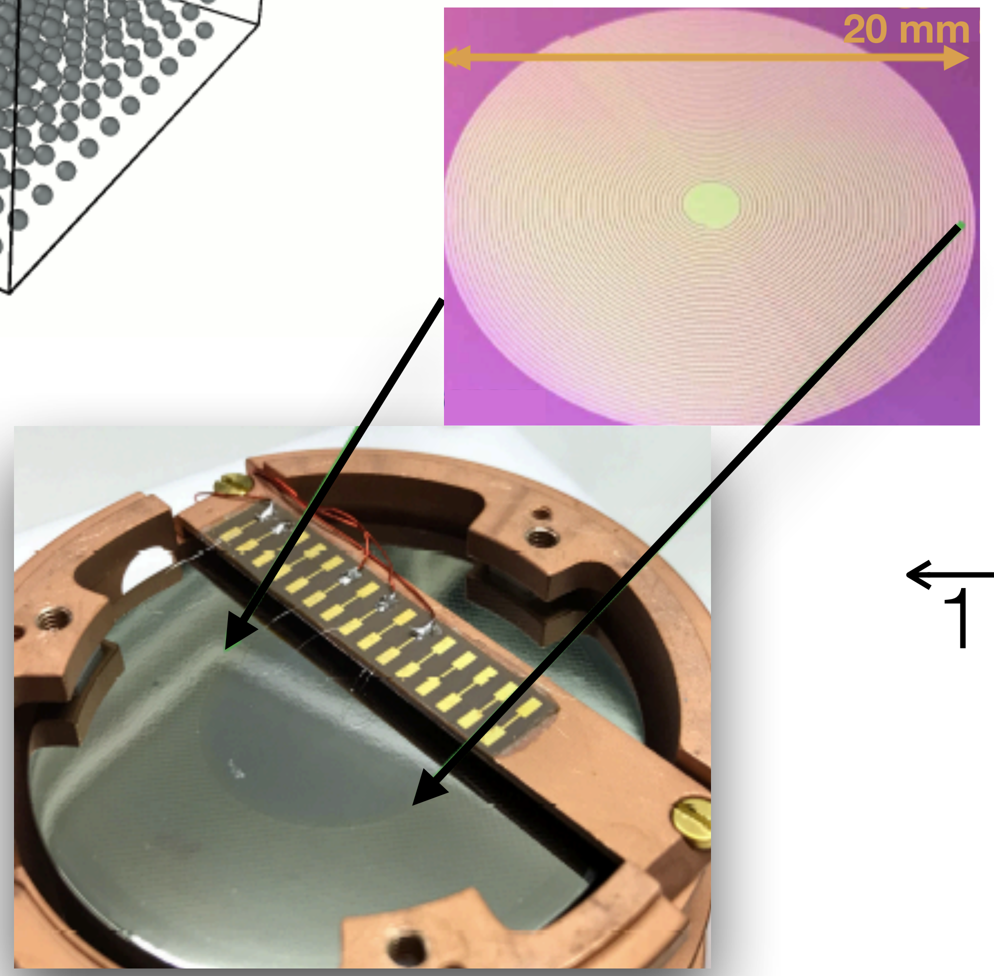

arXiv:2203.03993

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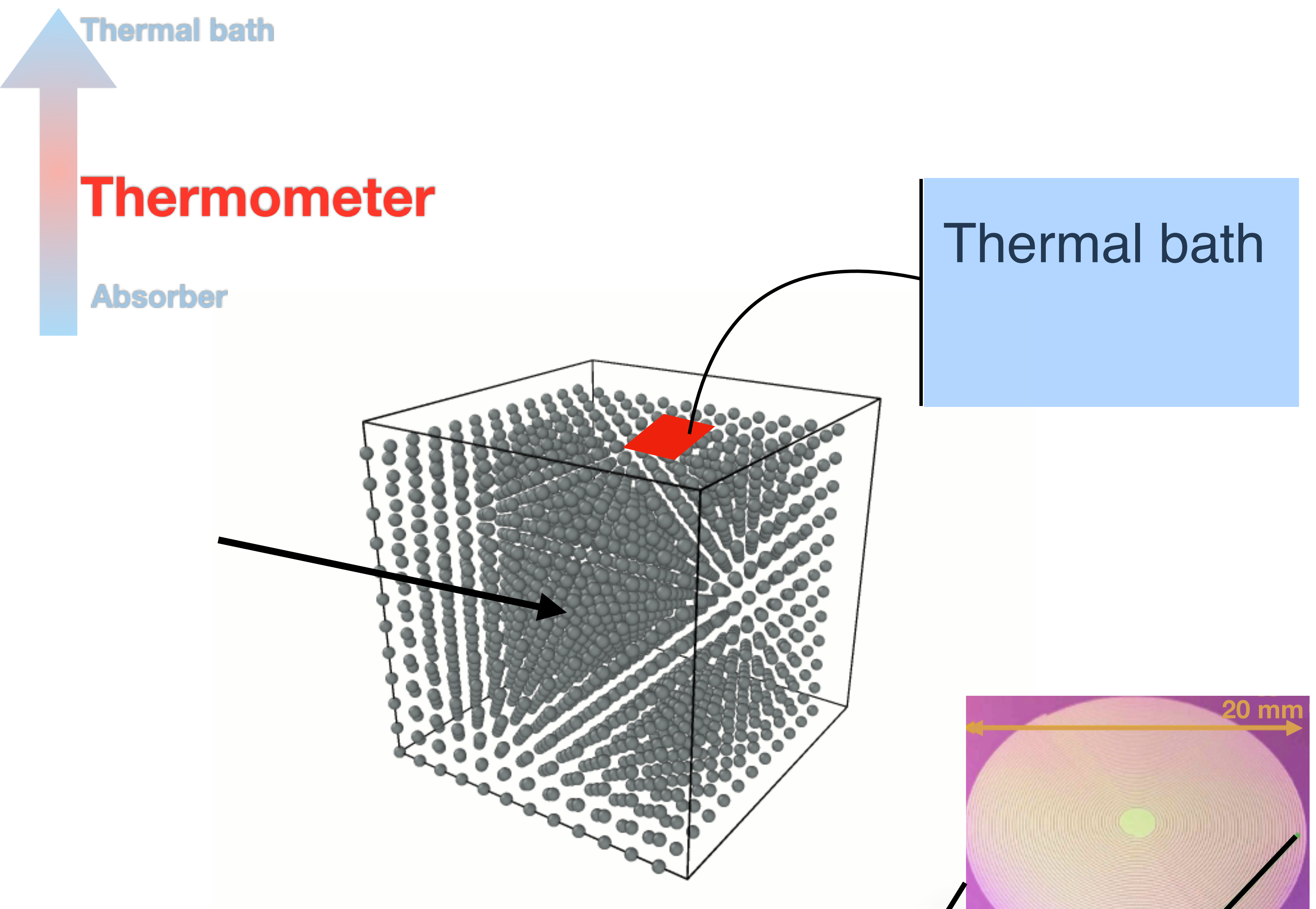

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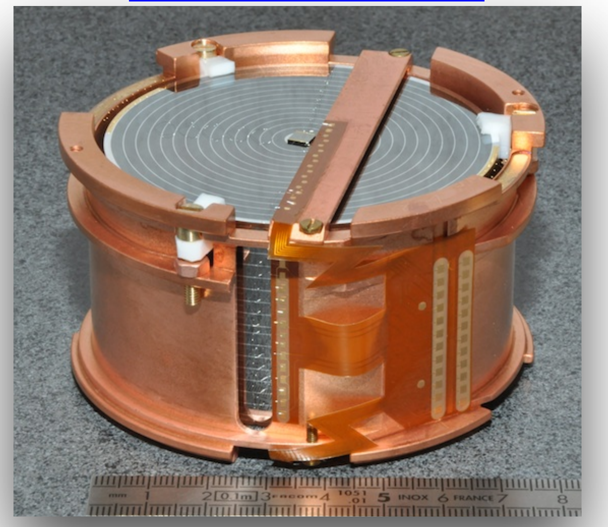

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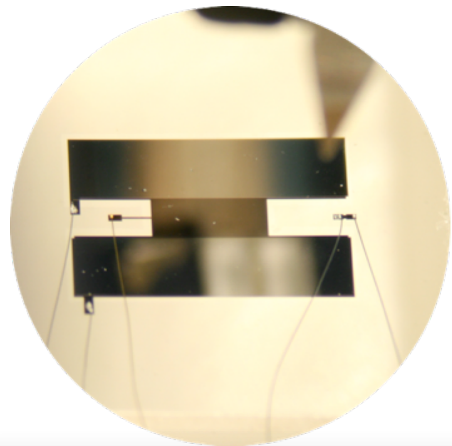

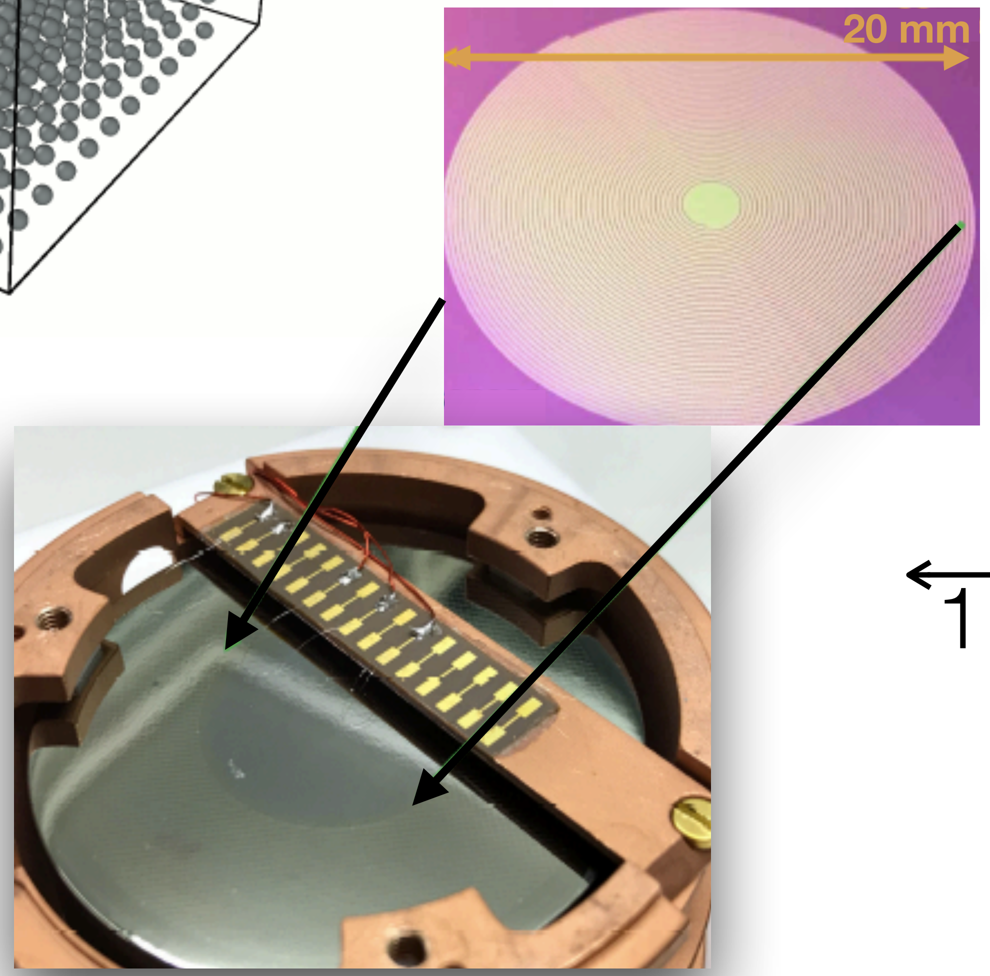

arXiv:2203.03993

Appl. Phys. Lett. 118, 022601 (2021)

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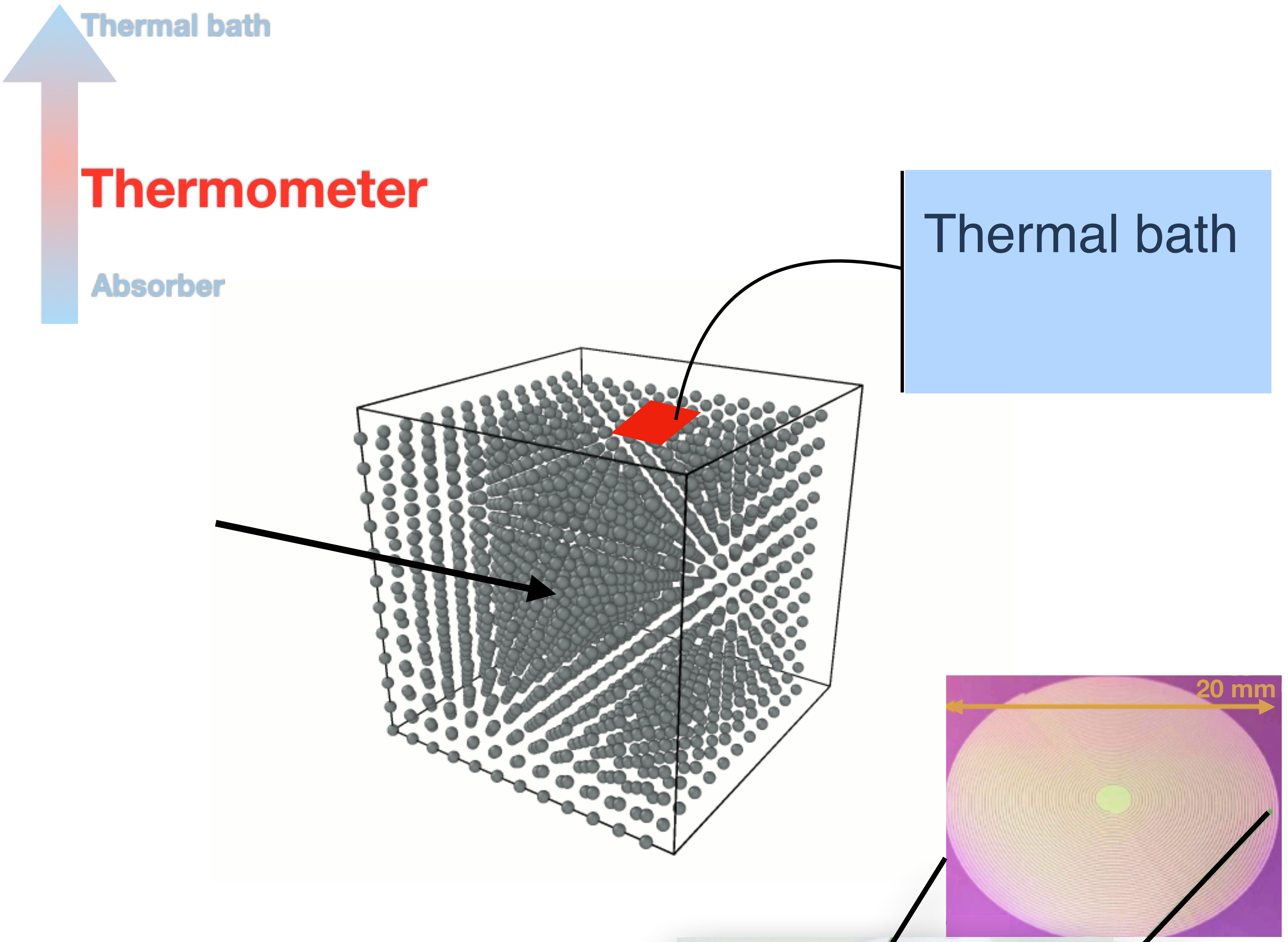

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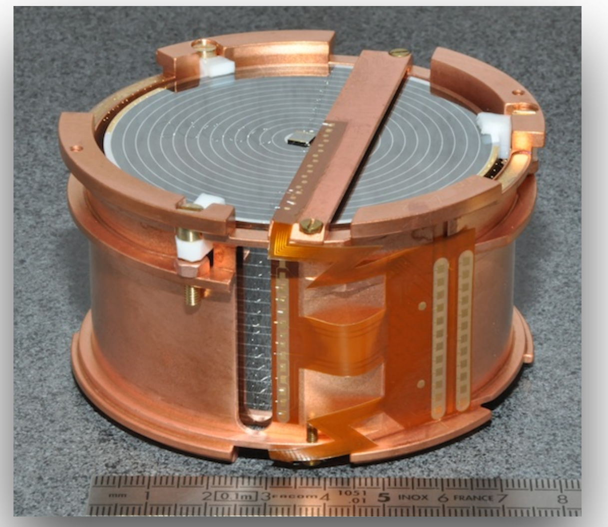

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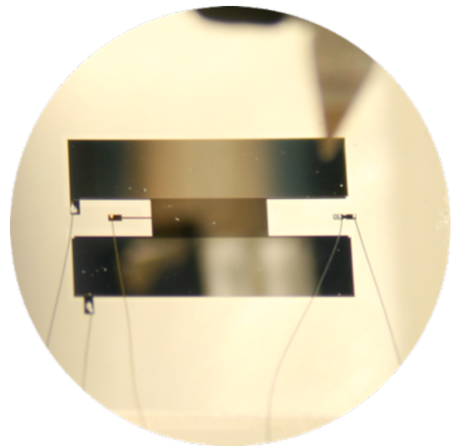

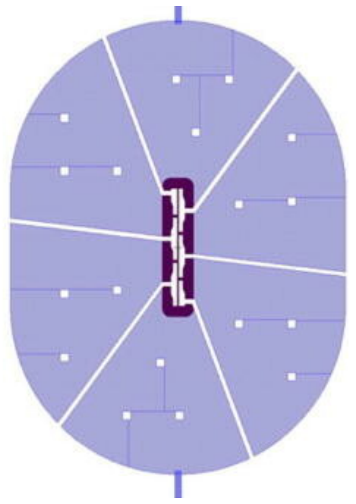

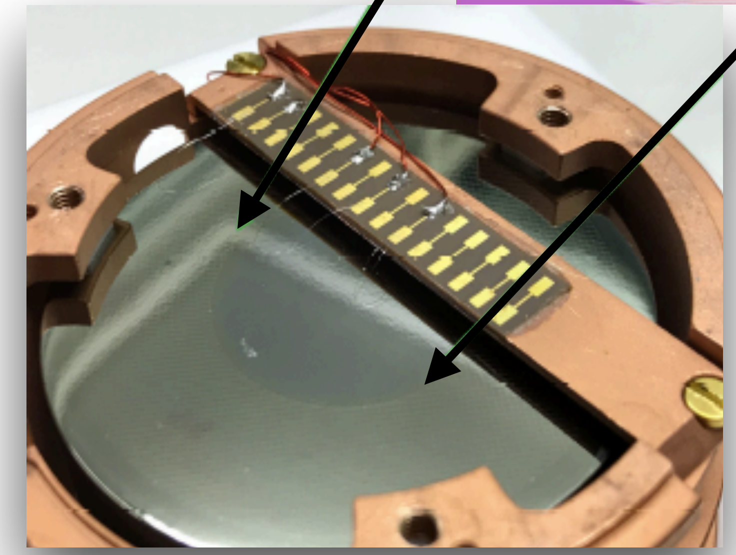

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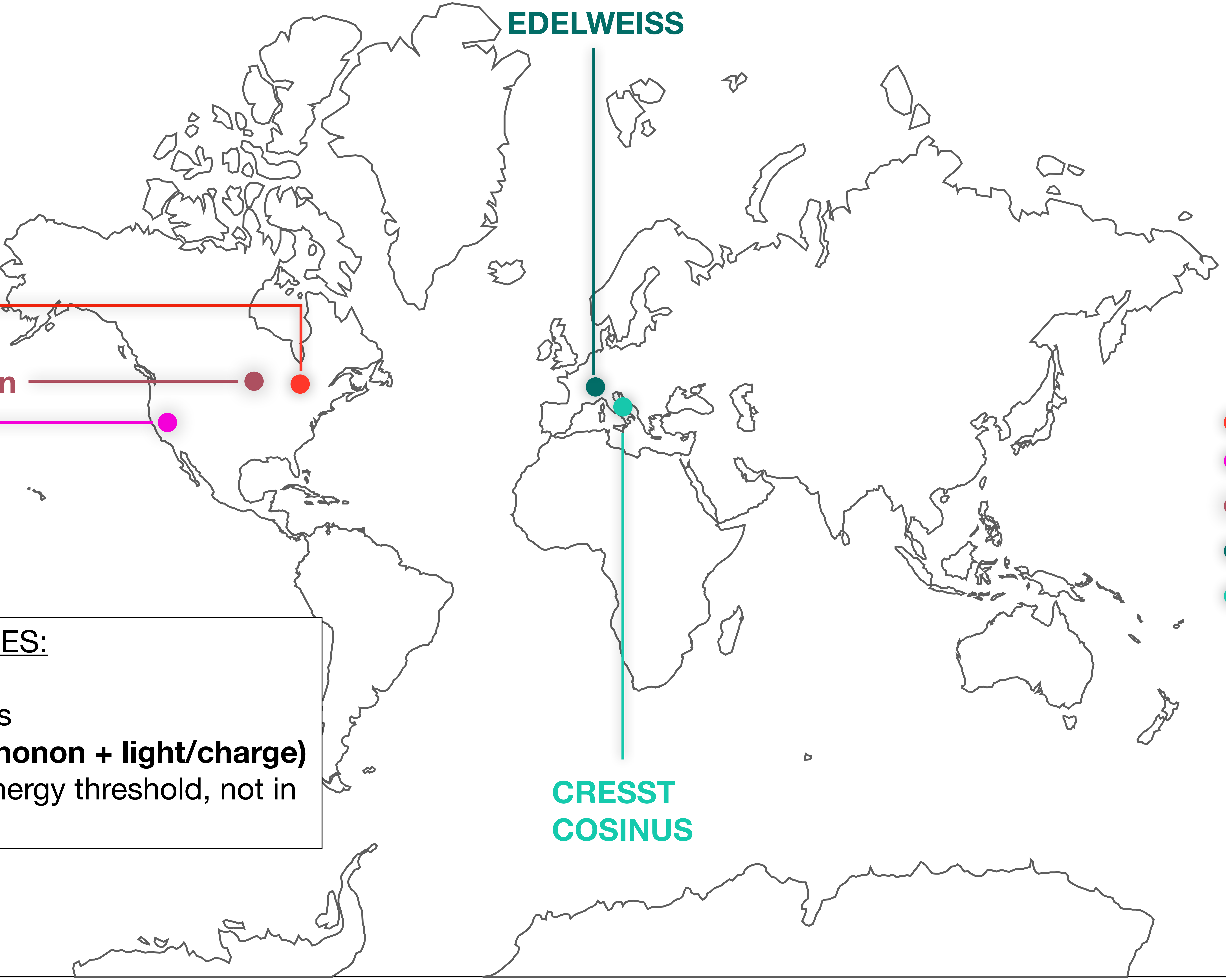

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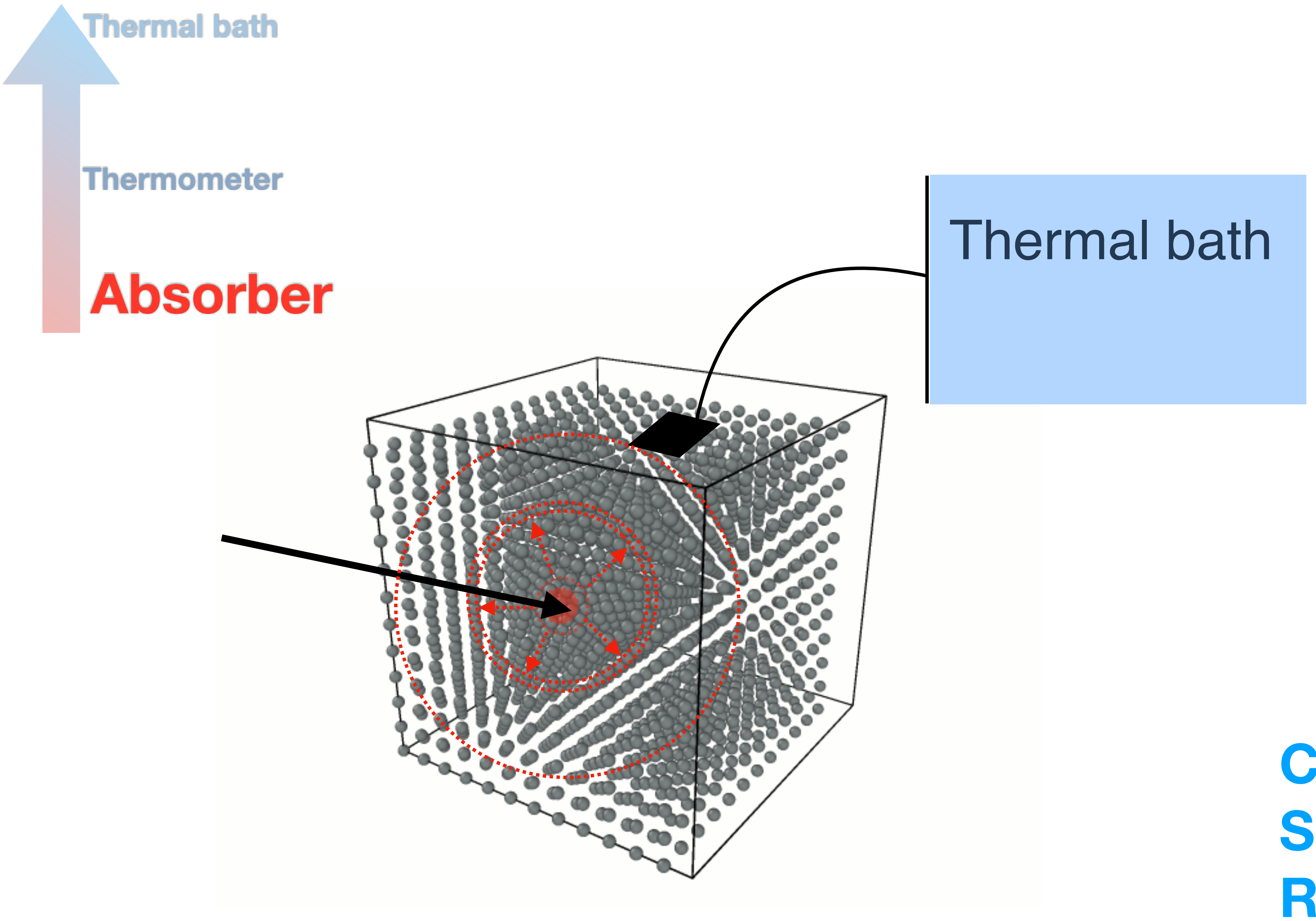
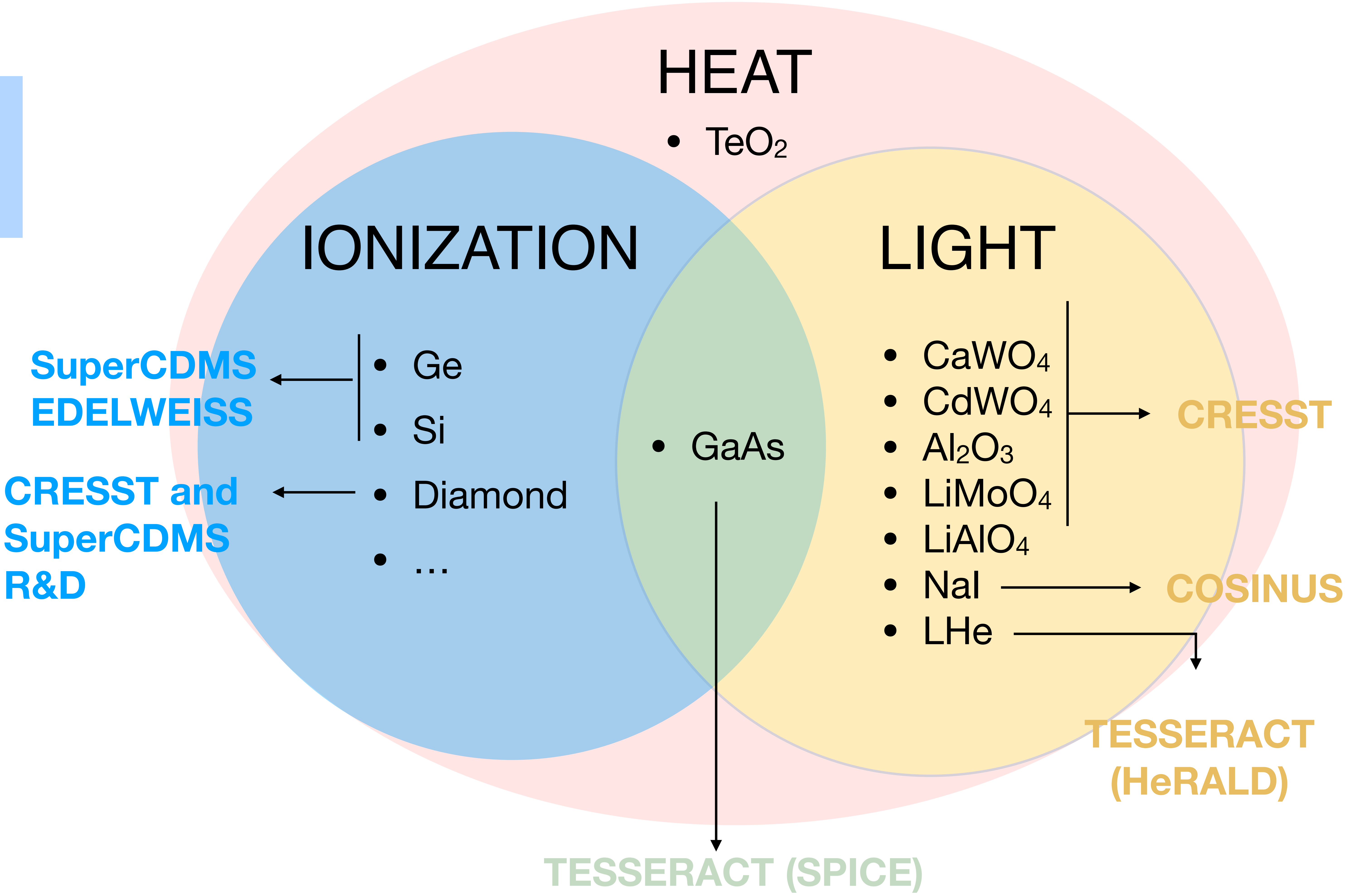
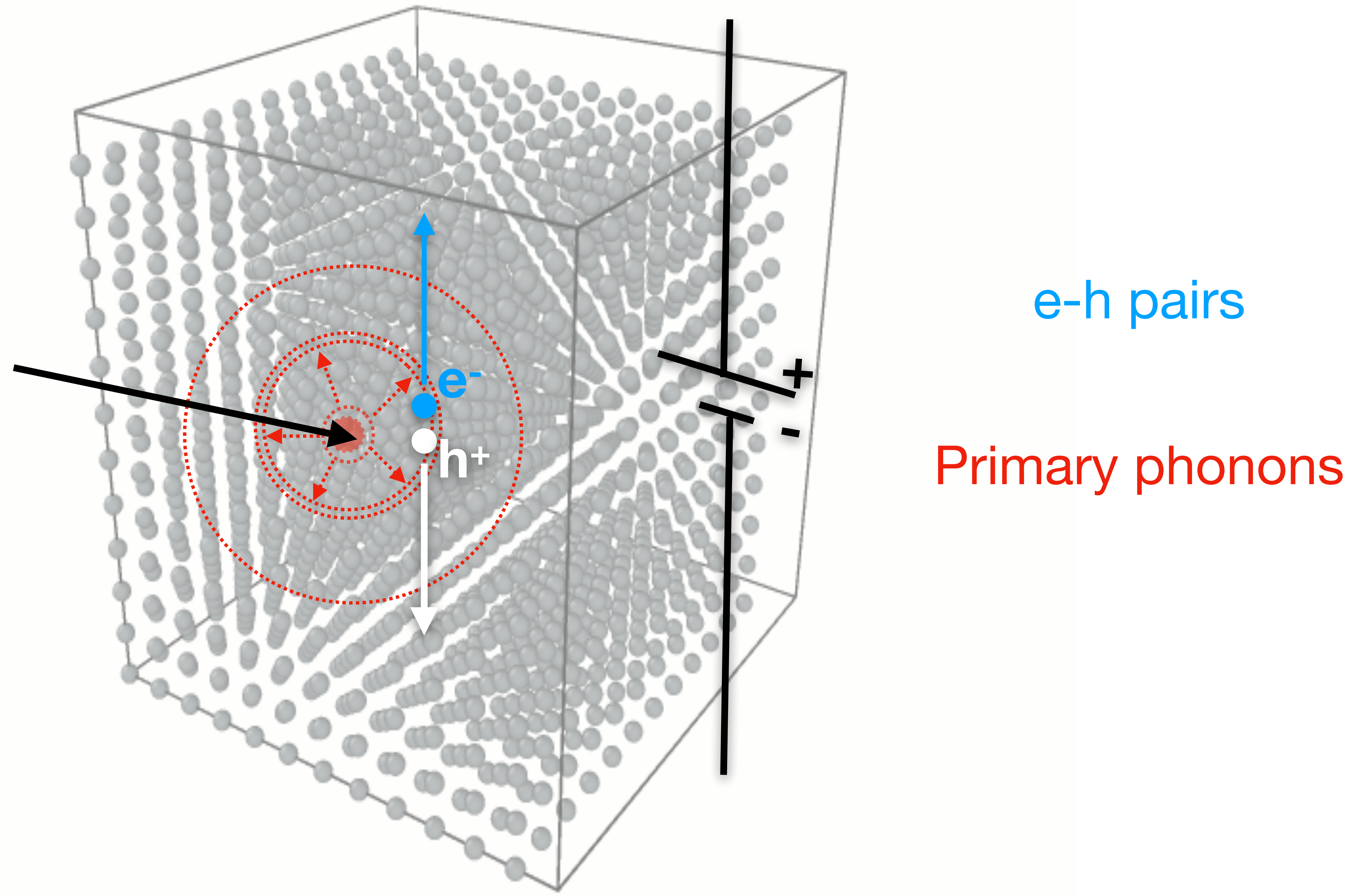
SEMICONDUCTORS OR SCINTILLATORS





DUAL CHANNEL

PHONON+IONIZATION

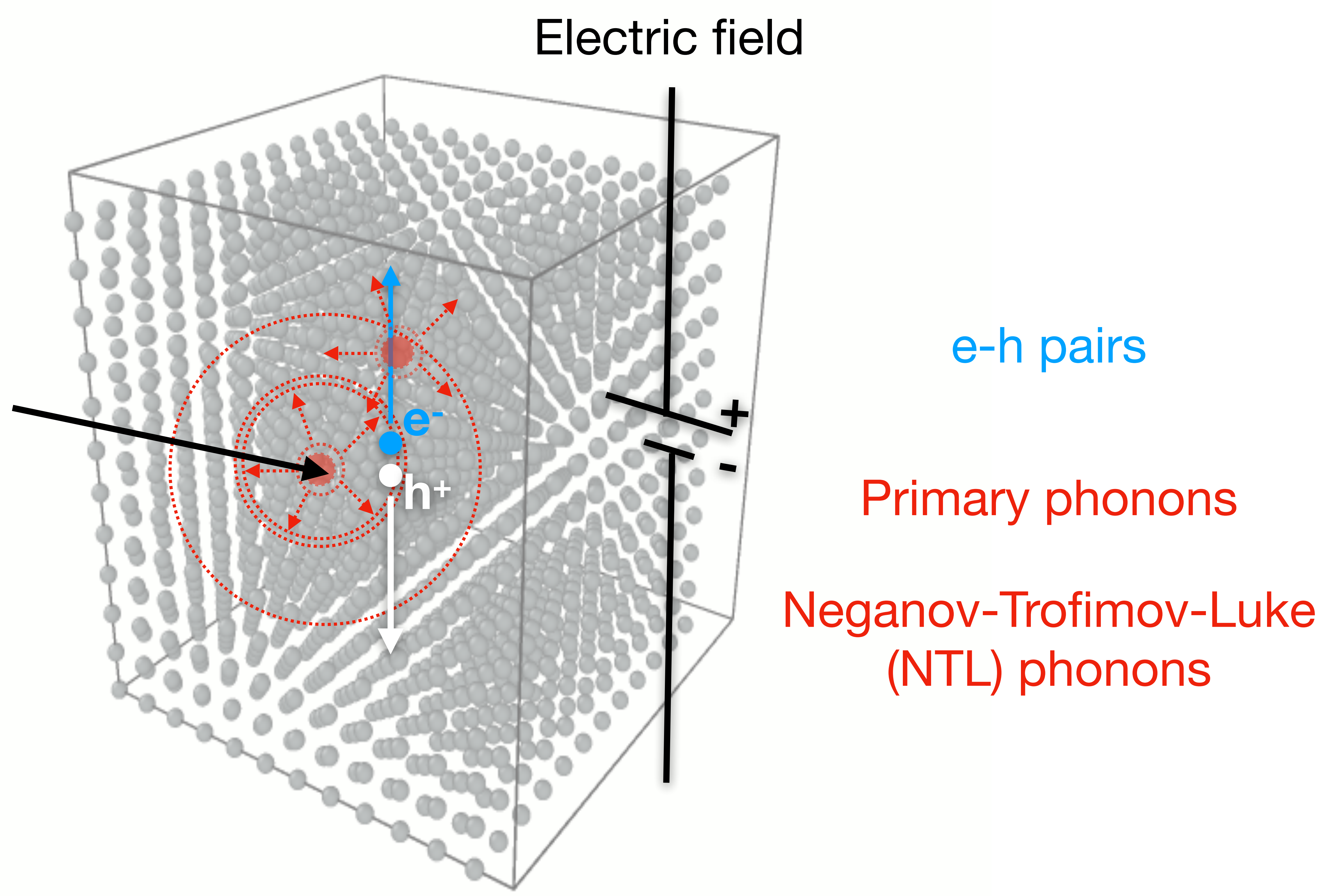


- Channel 1: phonon measured with temperature sensor -> Enhanced
- Channel 2: charge measured with electrodes placed on both surfaces

PHONON+SCINTILLATION

DUAL CHANNEL

PHONON+IONIZATION



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PHONON+SCINTILLATION

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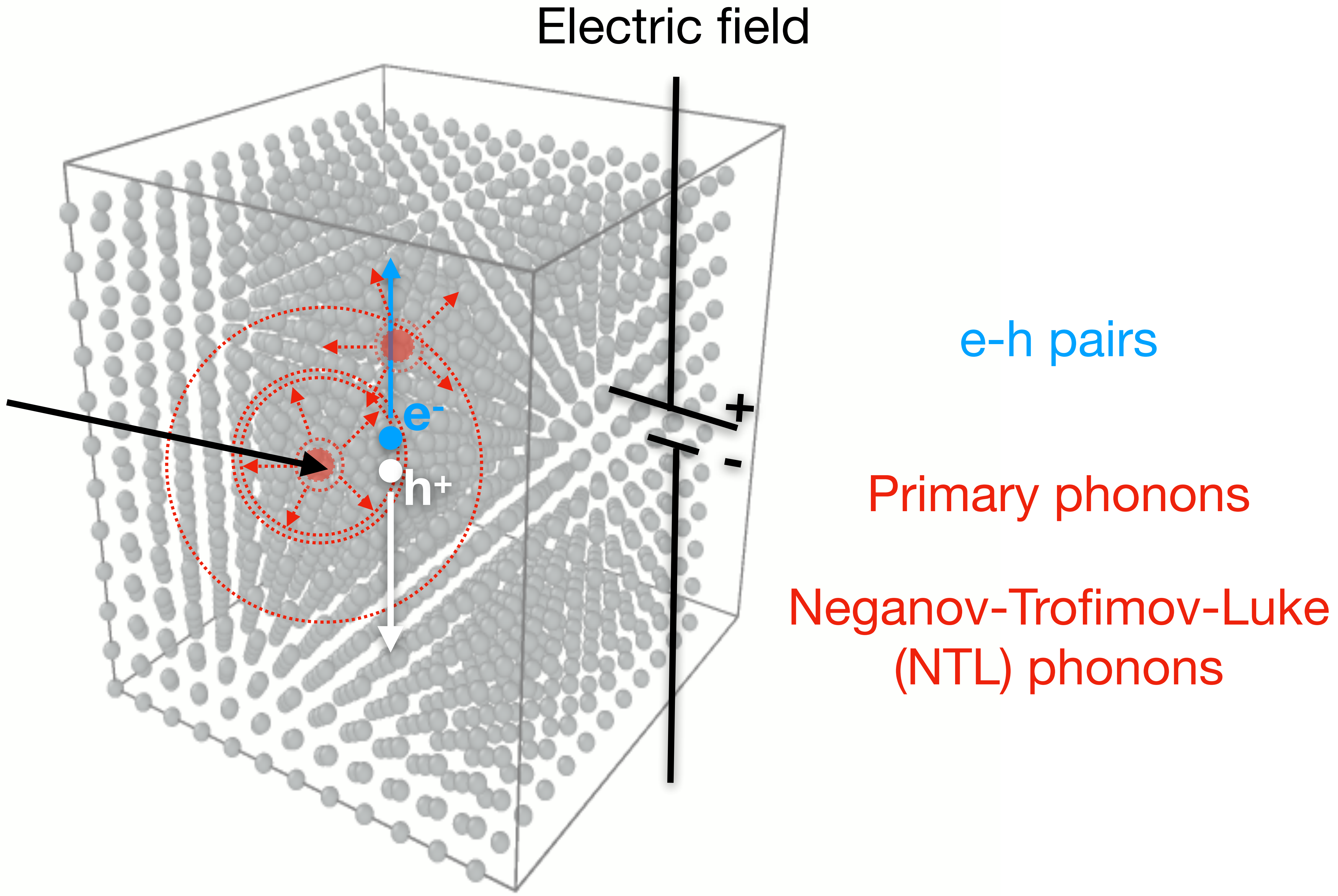

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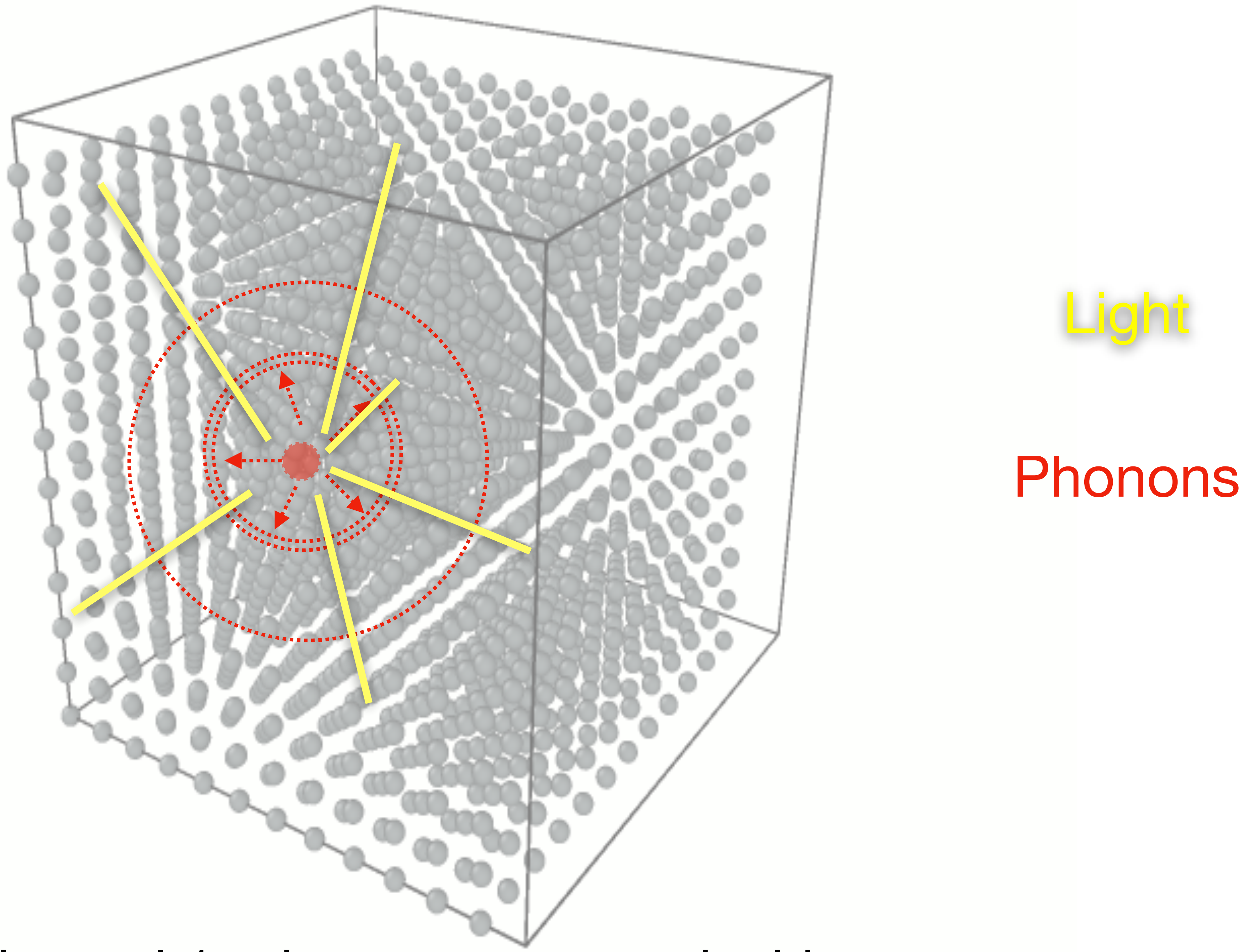
PHONON+SCINTILLATION

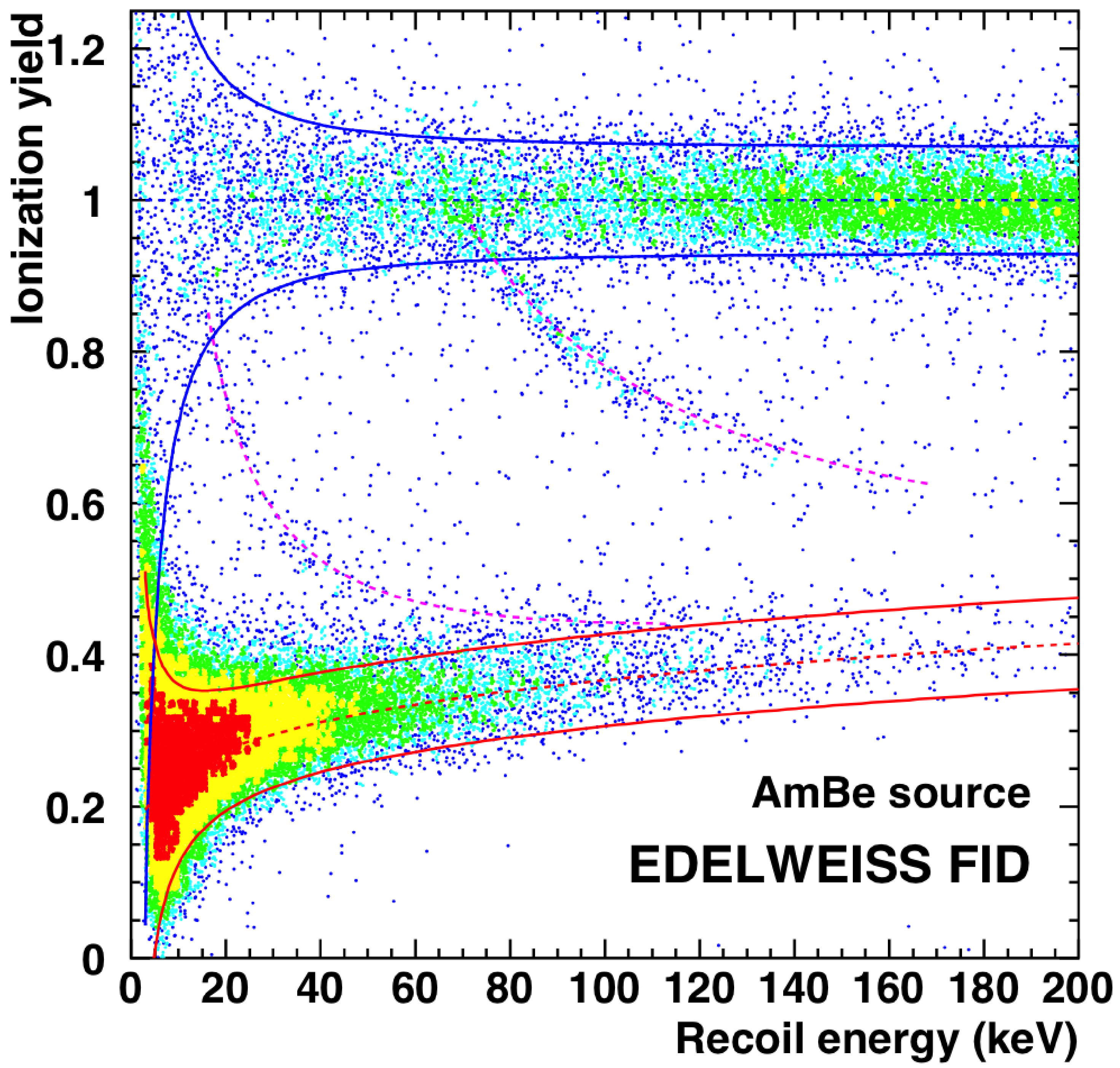


- Channel 1: phonon measured with temperature sensor
- Channel 2: light collected by another absorber (wafer or beaker shaped) and measured with a temperature sensor

PARTICLE DISCRIMINATION

PHONON+IONIZATION

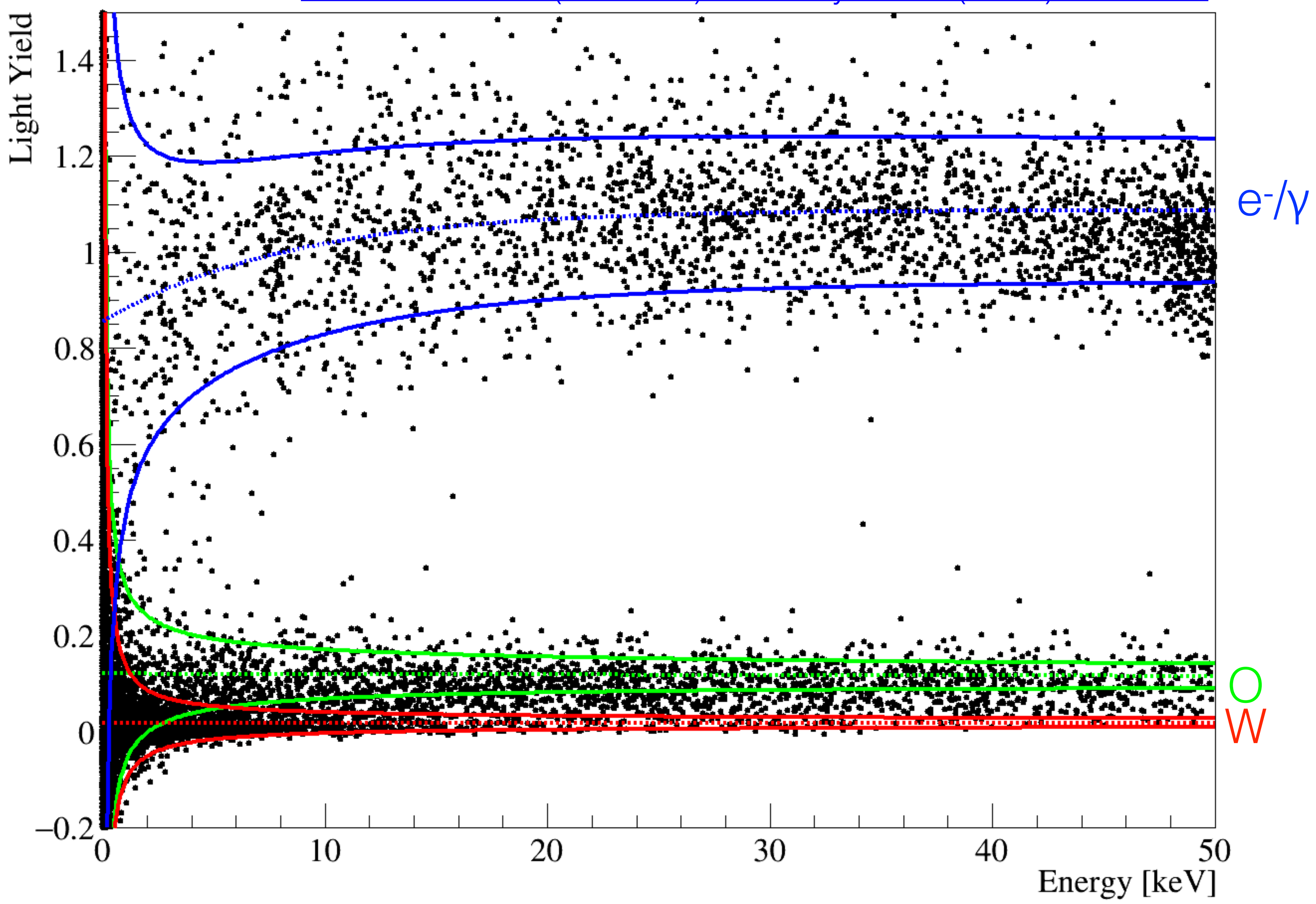
JINST 12 (2017) 08, P08010



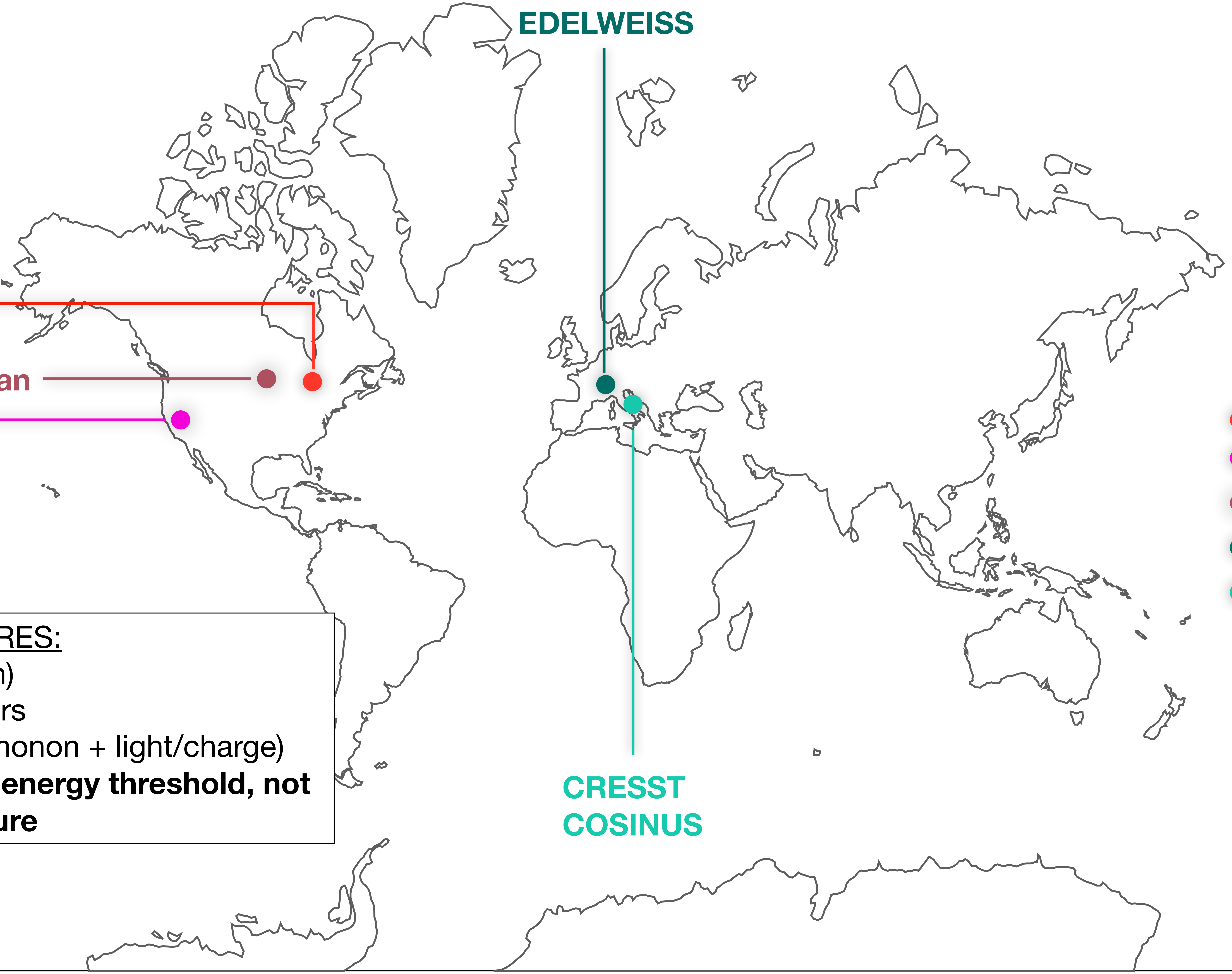
$$\text{Ionization Yield} = \frac{\text{Charge energy}}{\text{Phonon energy}}$$

PHONON+SCINTILLATION

R. Strauss. et al (CRESST) Eur. Phys. J. C (2014) 74: 2957.



$$\text{Light Yield} = \frac{\text{Light energy}}{\text{Phonon energy}}$$



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LOW ENERGY THRESHOLDS

SUPERCDMS

arXiv:2203.08463

	iZIP		HV	
	Ge	Si	Ge	Si
Number of detectors	10	2	8	4
Total exposure [kg·yr]	45	3.9	36	7.8
Phonon resolution [eV]	33	19	34	13
Ionization resolution [eV_{ee}]	160	180	–	–
Voltage Bias ($V_+ - V_-$) [V]	6	8	100	100

Phys.Rev.Lett. 127 (2021) 061801
- CPD: Cryo PhotoDetector
- Heat only (single channel)
- 45.6 cm^2 Si wafer, 1 mm thick

$\sigma_E = 3.86 \pm 0.04$ eV

Phys.Rev.Lett. 121 (2018) 051301
- HVeV: High Voltage eV-resolution
- 0.93 g Si absorber
- Double channel
- Limits on DM-electron scattering
- Limits on dark photon interactions

0.1 e-h pairs charge resolution

EDELWEISS

Phys.Rev. D 99 (2019) 082003
- sub-GeV search program
- 33.4 g Ge read out with NTD
- Heat only (single channel)

$\sigma_E = 17.7$ eV

arXiv:2203.03993
- 200 g Ge read out with TES
- Double channel

$\sigma_E \simeq 130$ eV

Phys.Rev. Lett 125 (2020) 141301
- sub-MeV search program
- 33.4 g Ge read out with electrods
- Double channel

0.53 e-h pairs charge resolution

CRESST

Phys. Rev. D 100 (2019) 102002
- 23.6 g $CaWO_4$ read out with TES
- Double channel

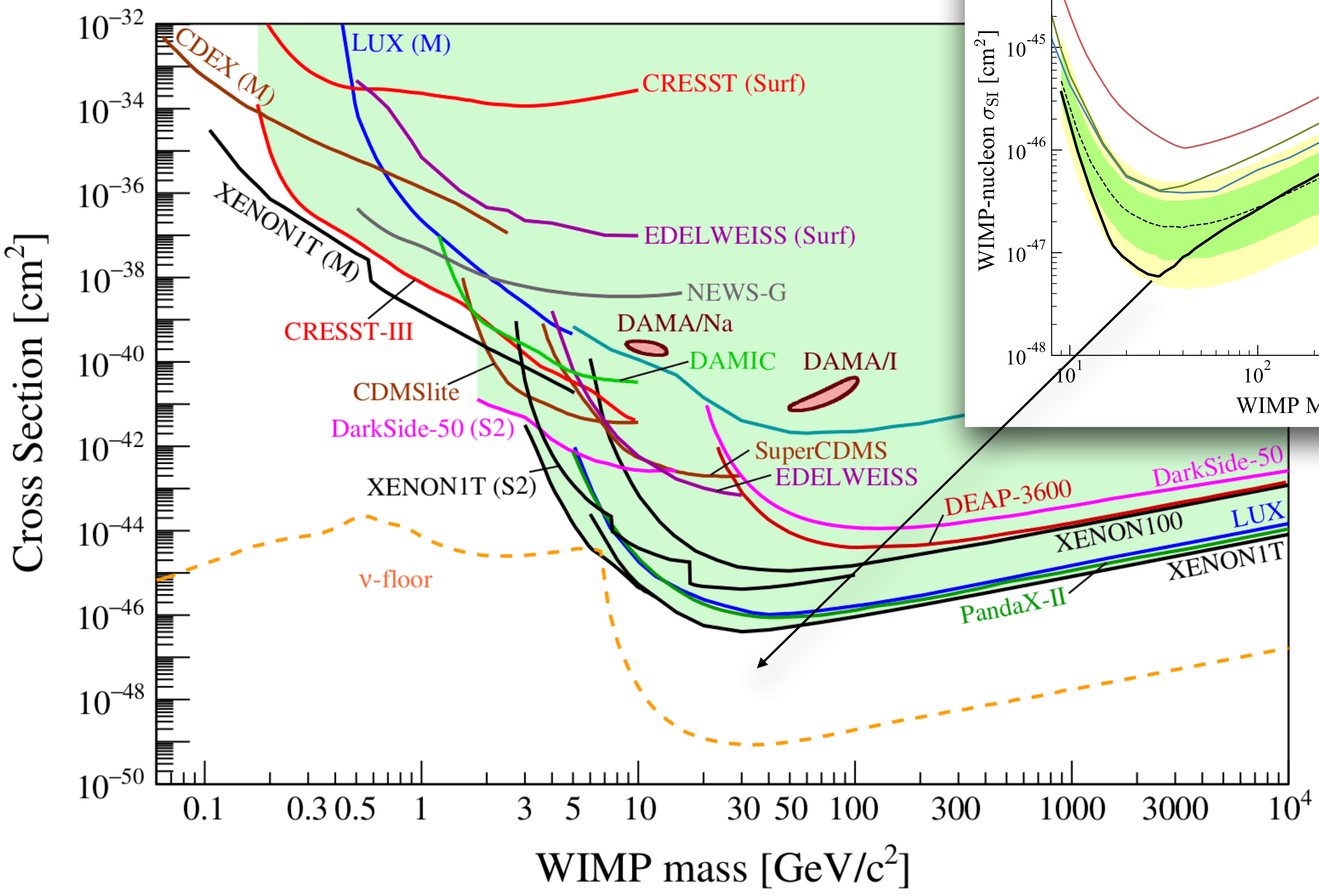
$\sigma_E = 4.6$ eV

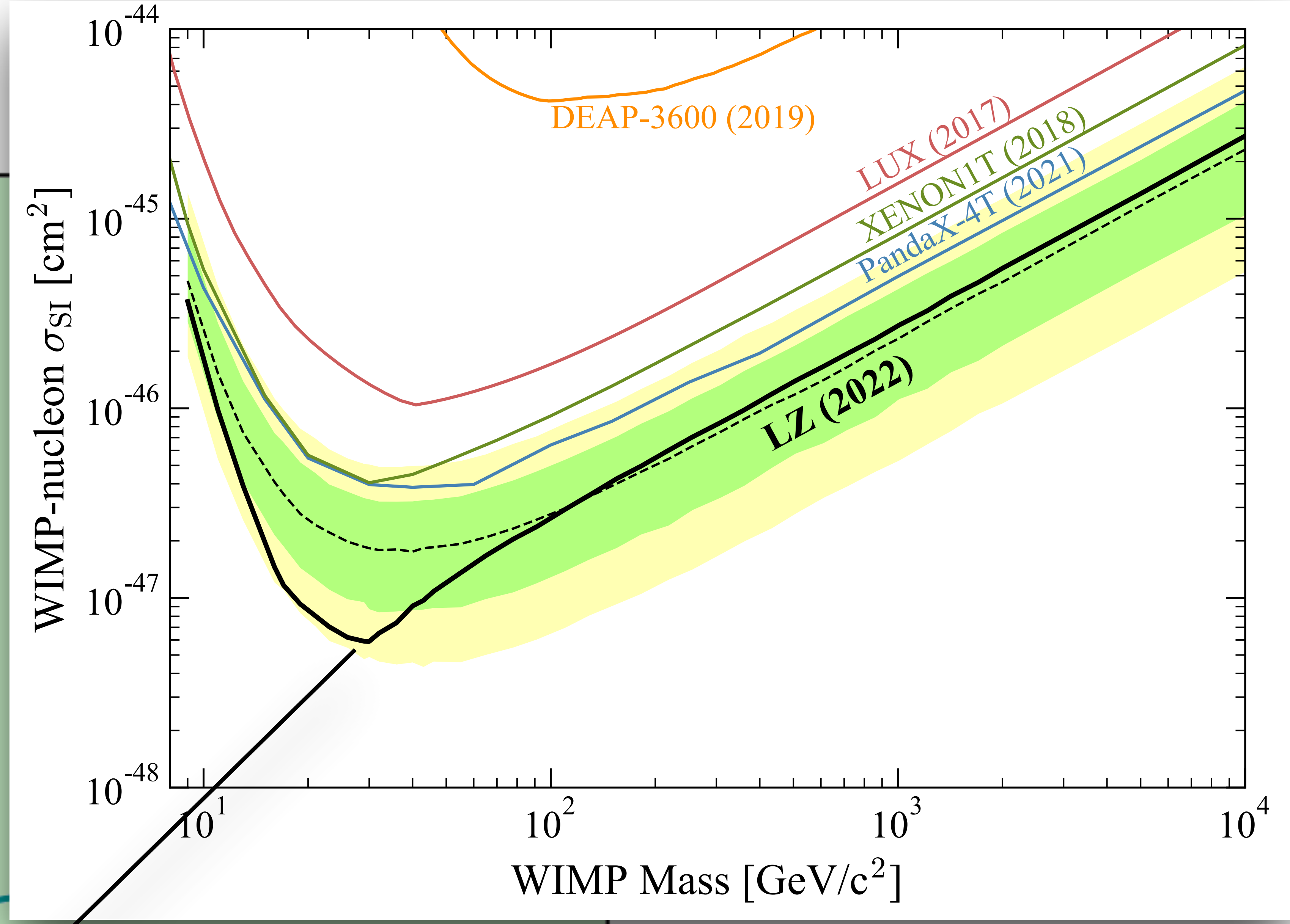
C. Strandhagen | IDM TALK (publication in preparation)
- 0.35 g Si-wafer read out with TES
- Heat only (not scintillating)

$\sigma_E = 1.36$ eV

SENSITIVITY CURVES

https://arxiv.org/pdf/2207.03764.pdf

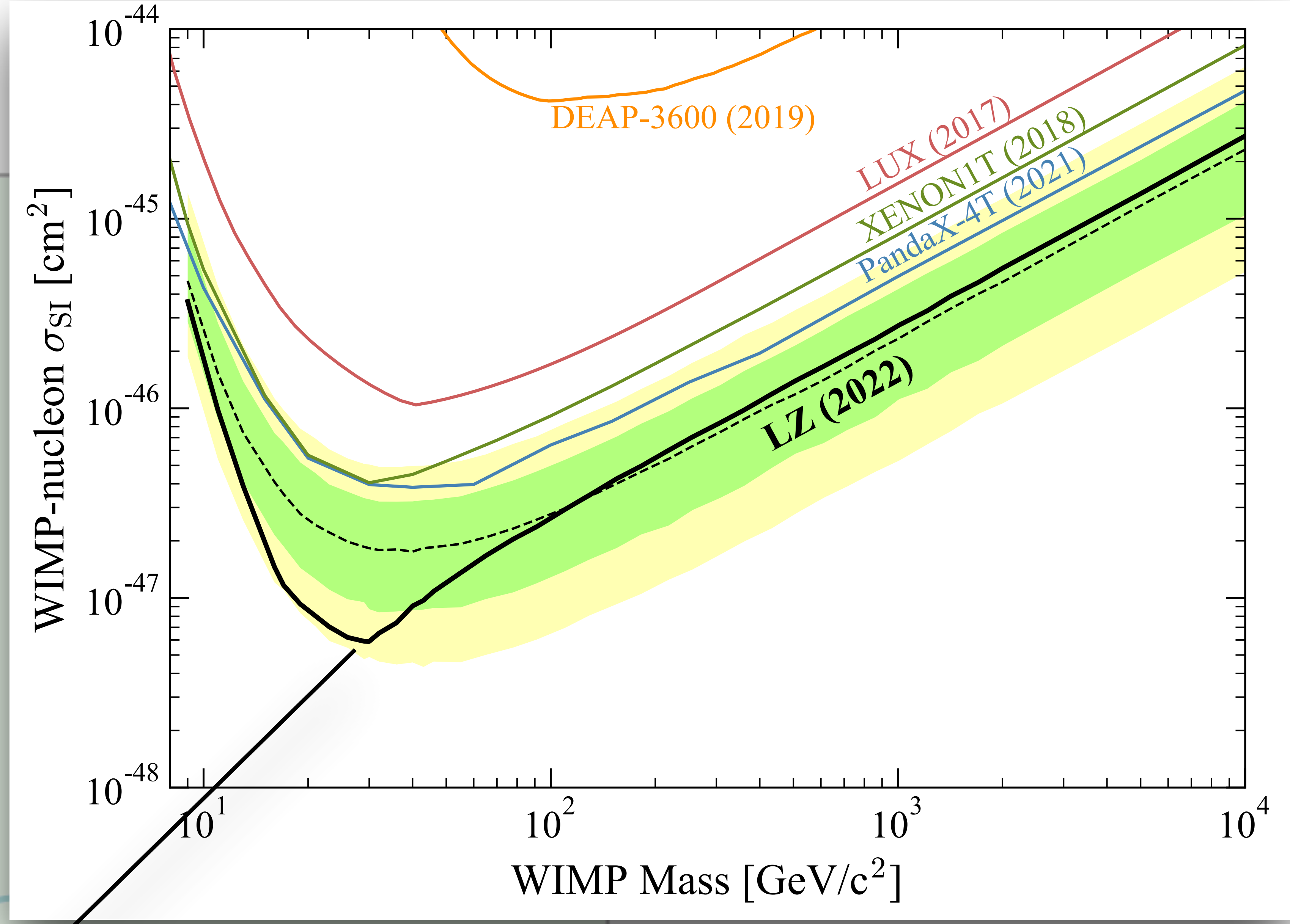


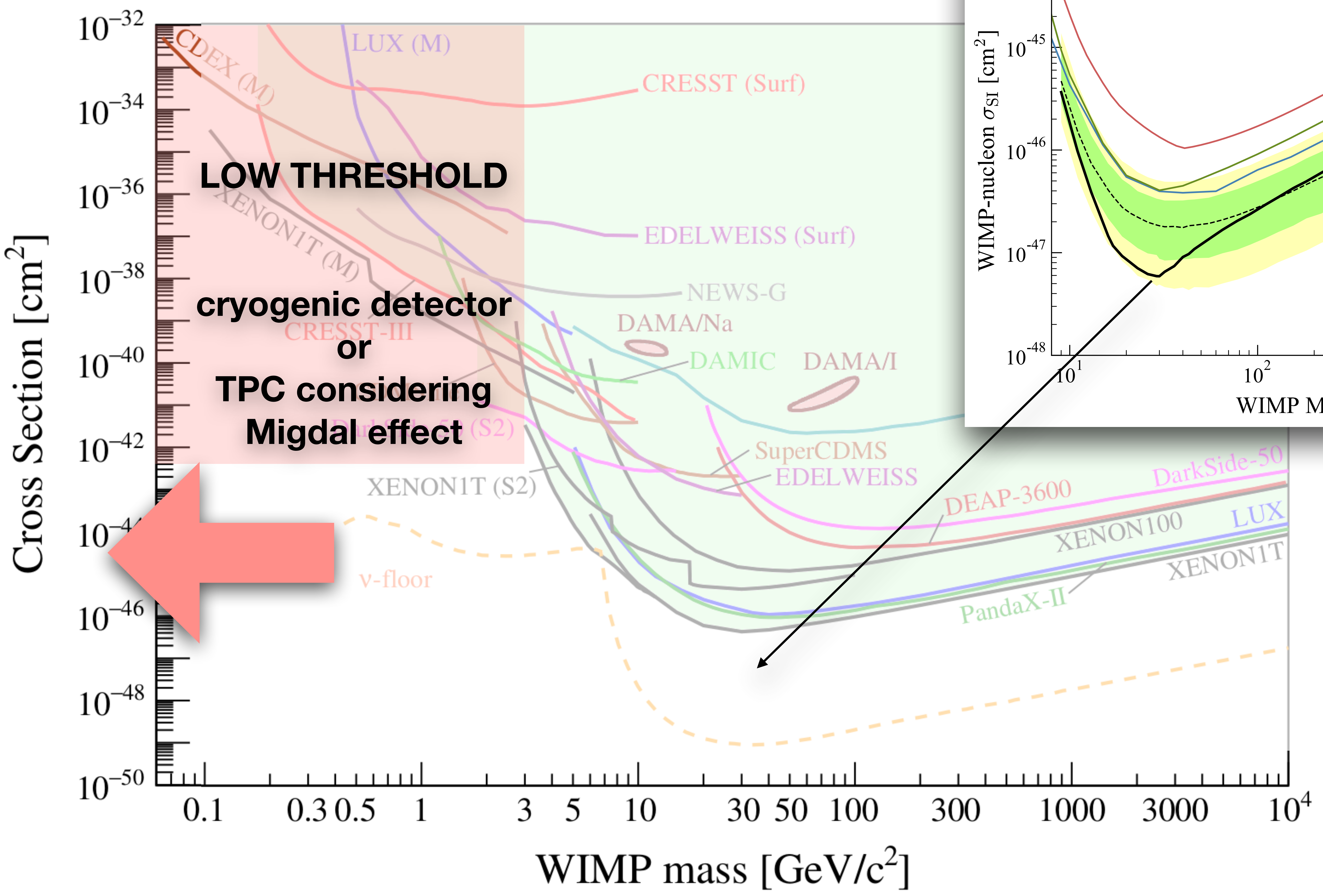


Direct Detection of Dark Matter – APPEC Committee Report - arXiv:2104.07634

SENSITIVITY CURVES

https://arxiv.org/pdf/2207.03764.pdf





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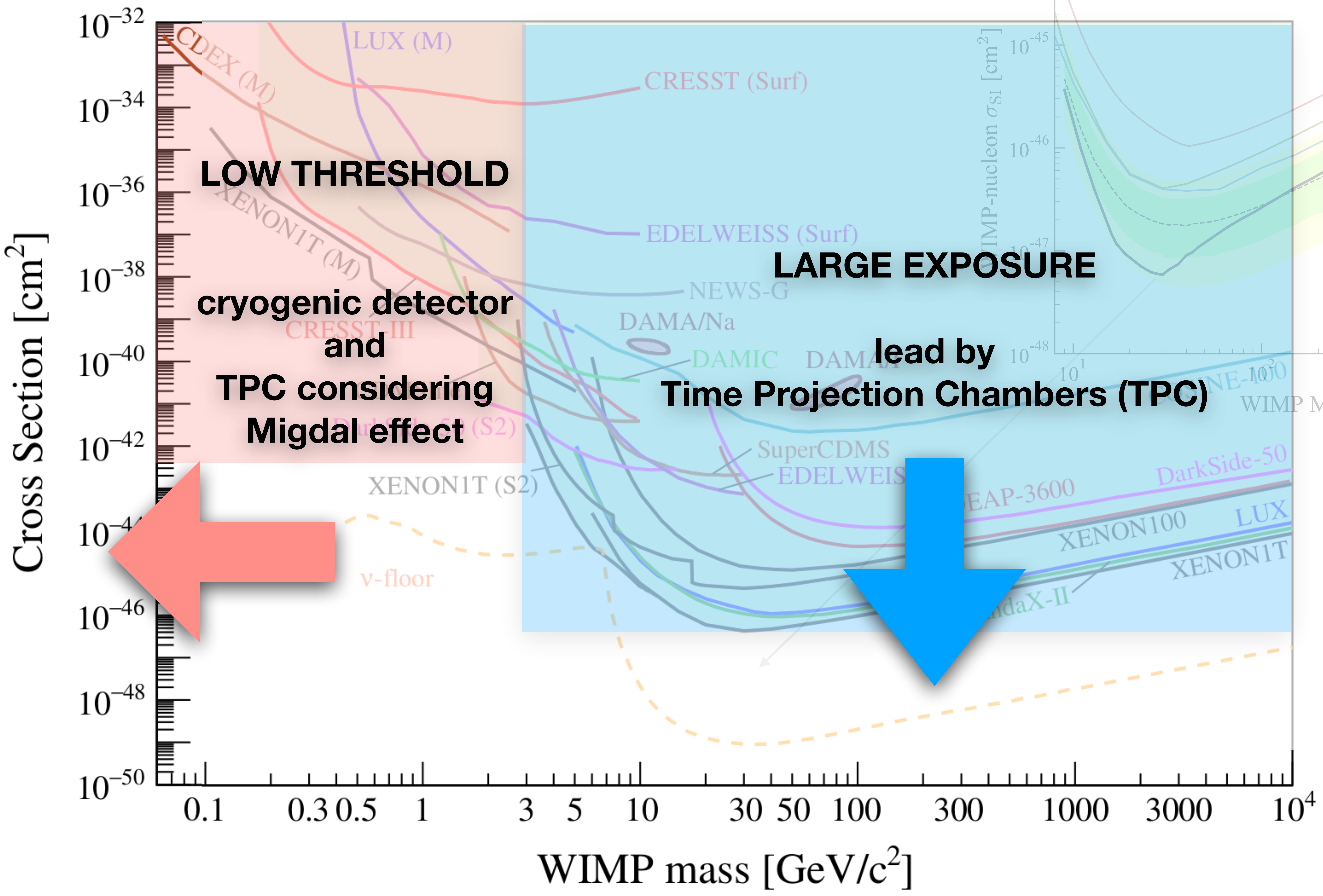
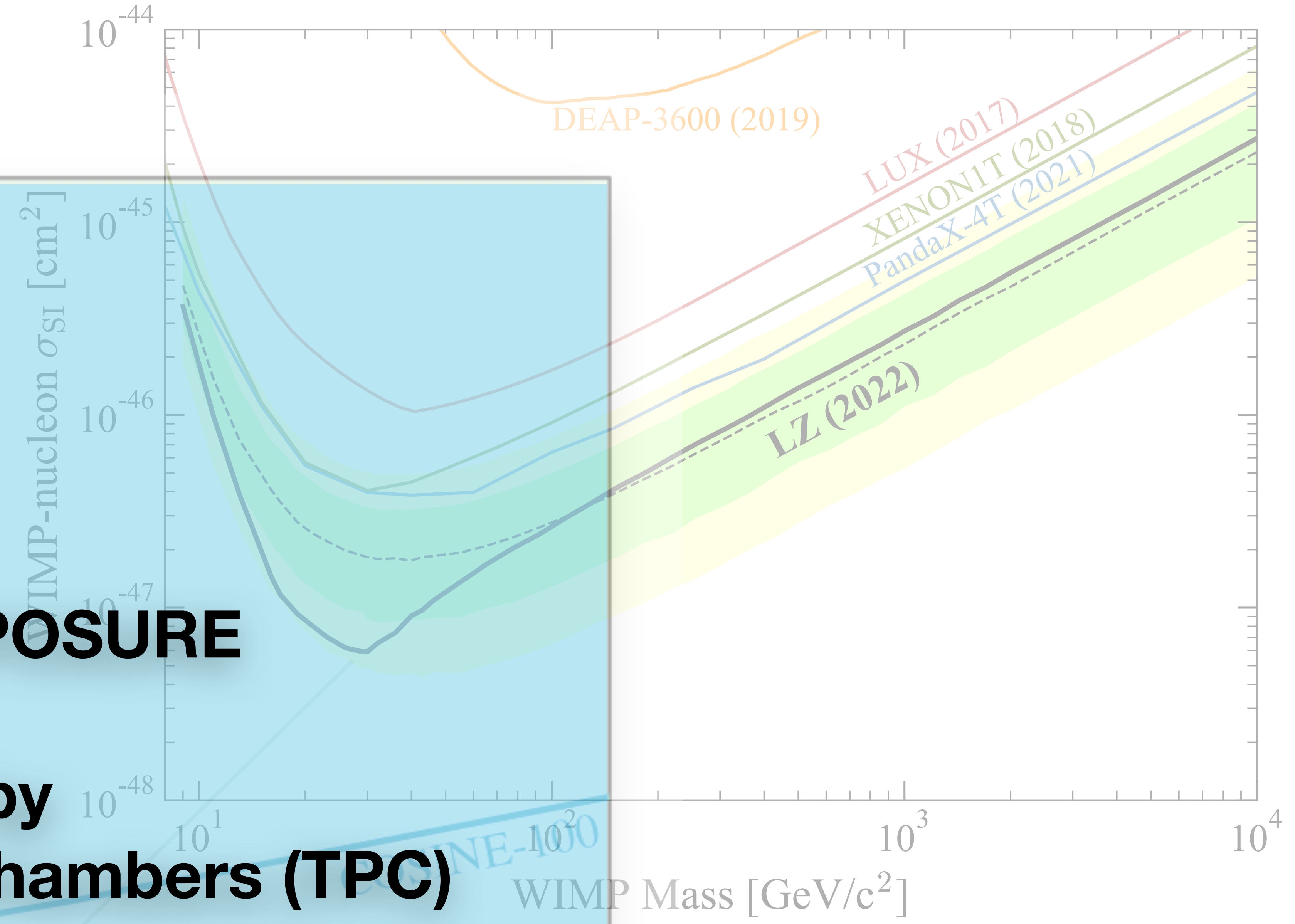
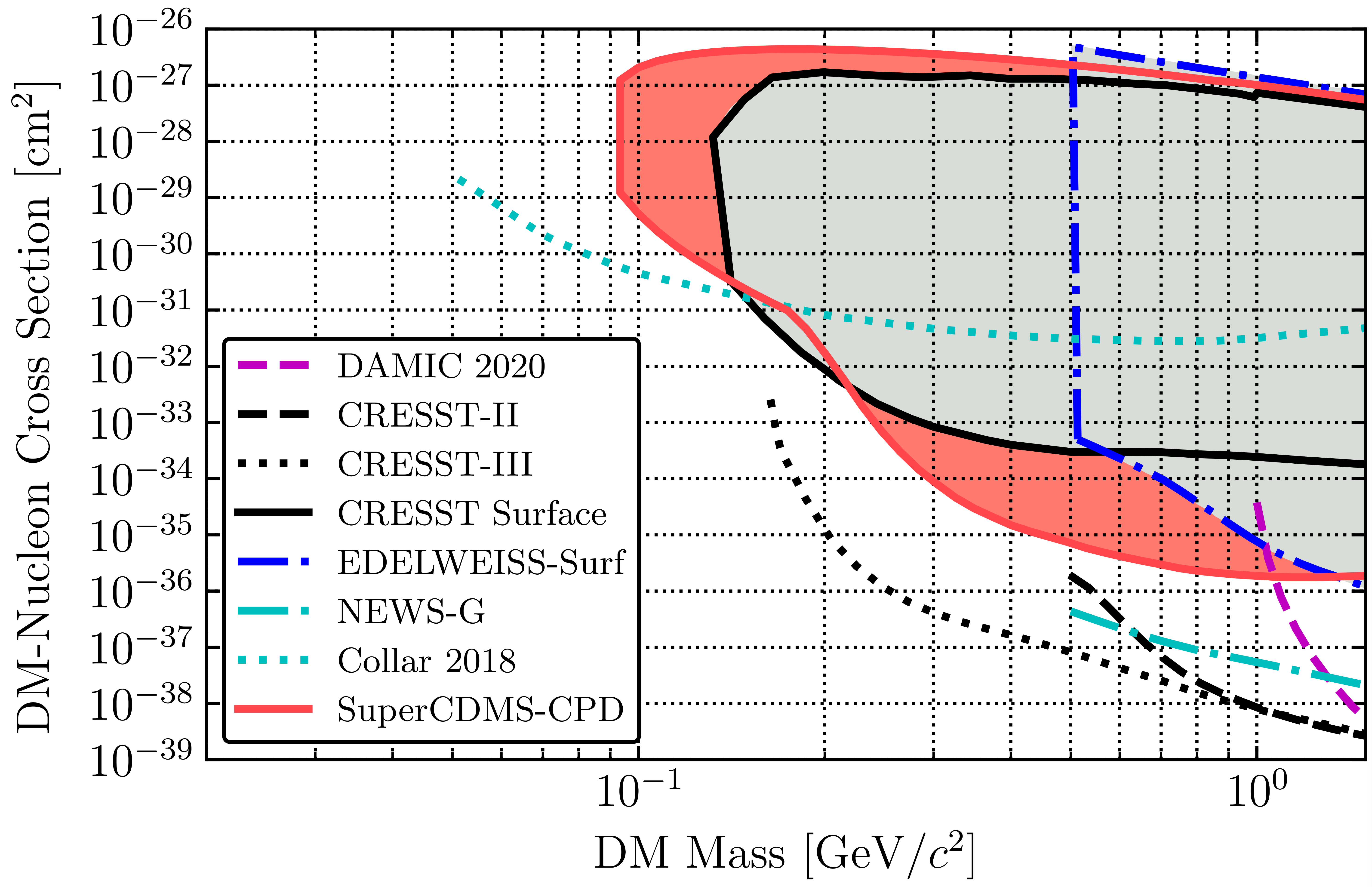




Direct Detection of Dark Matter – APPEC Committee Report - arXiv:2104.07634

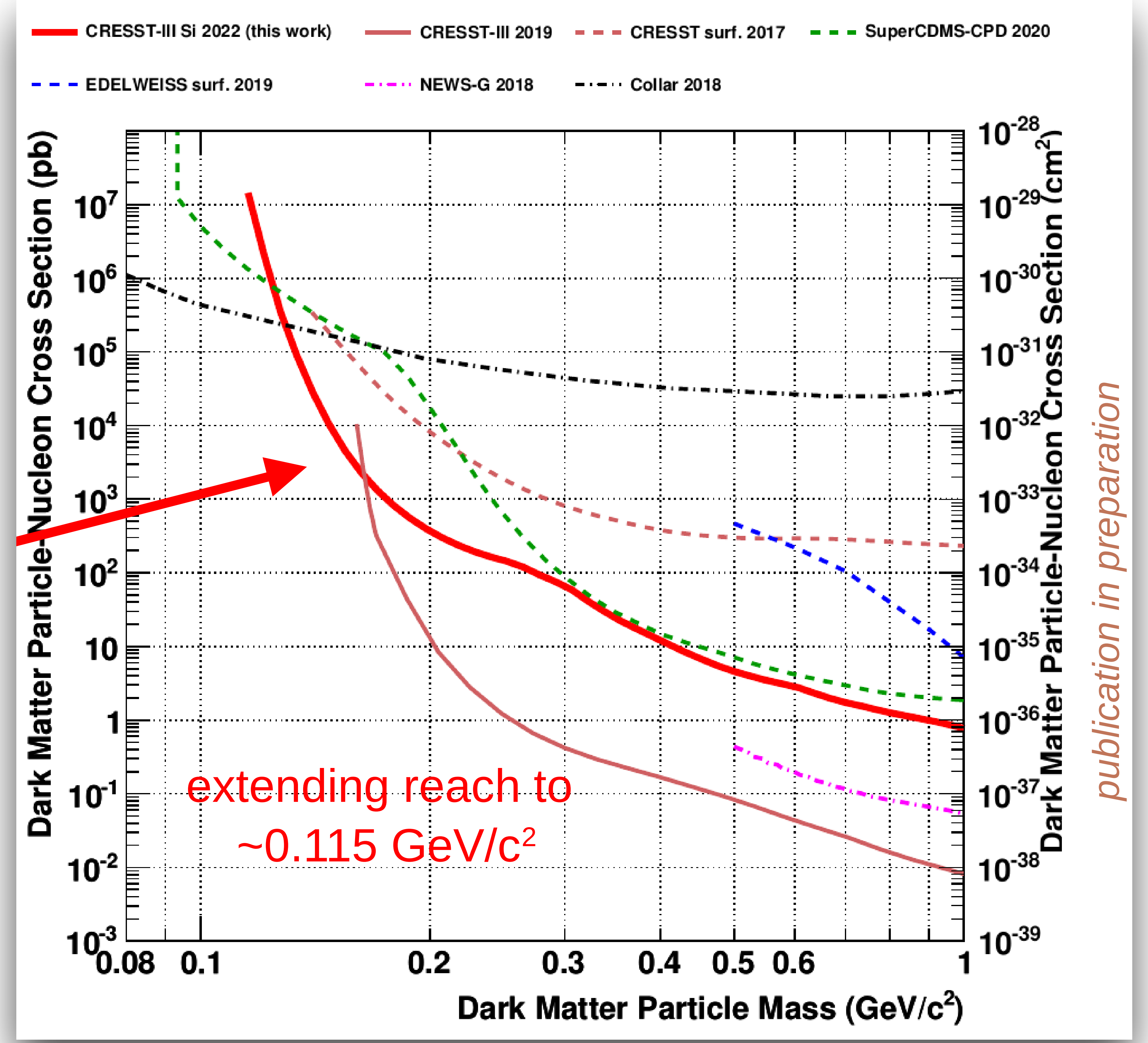
SENSITIVITY CURVES

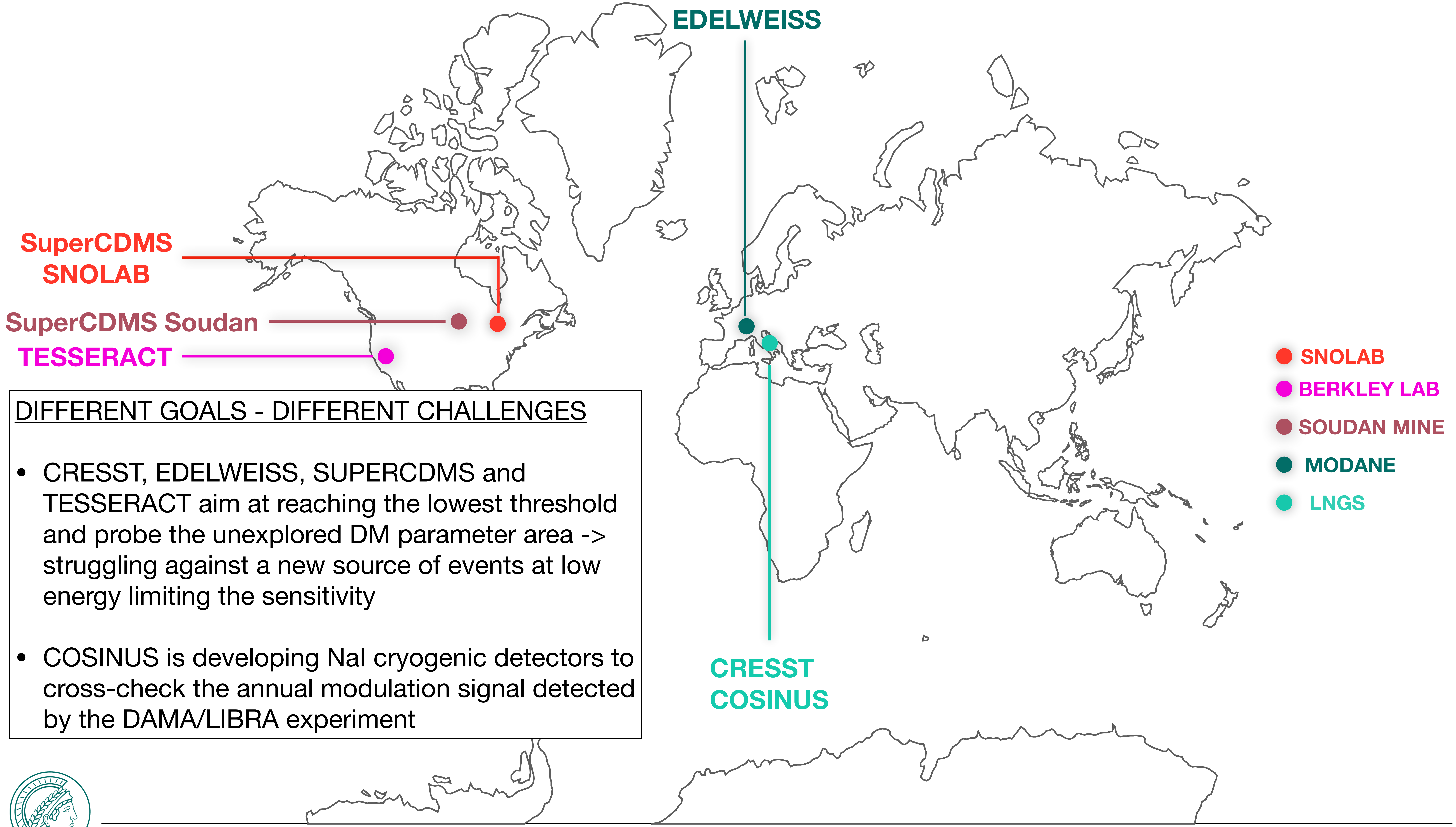
Phys.Rev.Lett. 127 (2021) 061801



C. Strandhagen | IDM TALK

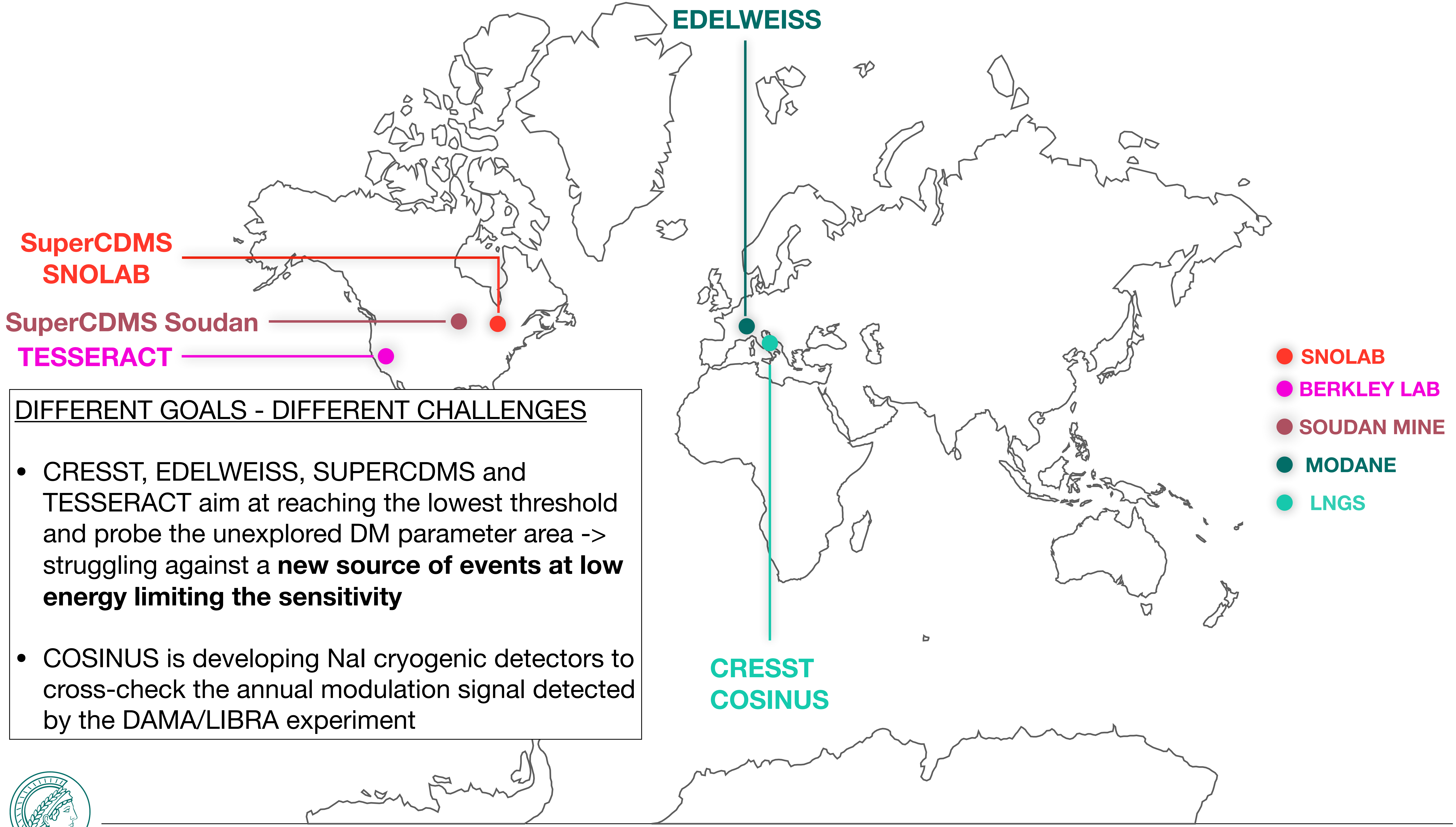
(publication in preparation)





DIFFERENT GOALS - DIFFERENT CHALLENGES

- CRESST, EDELWEISS, SUPERCDMS and TESSERACT aim at reaching the lowest threshold and probe the unexplored DM parameter area -> struggling against a new source of events at low energy limiting the sensitivity
- COSINUS is developing NaI cryogenic detectors to cross-check the annual modulation signal detected by the DAMA/LIBRA experiment



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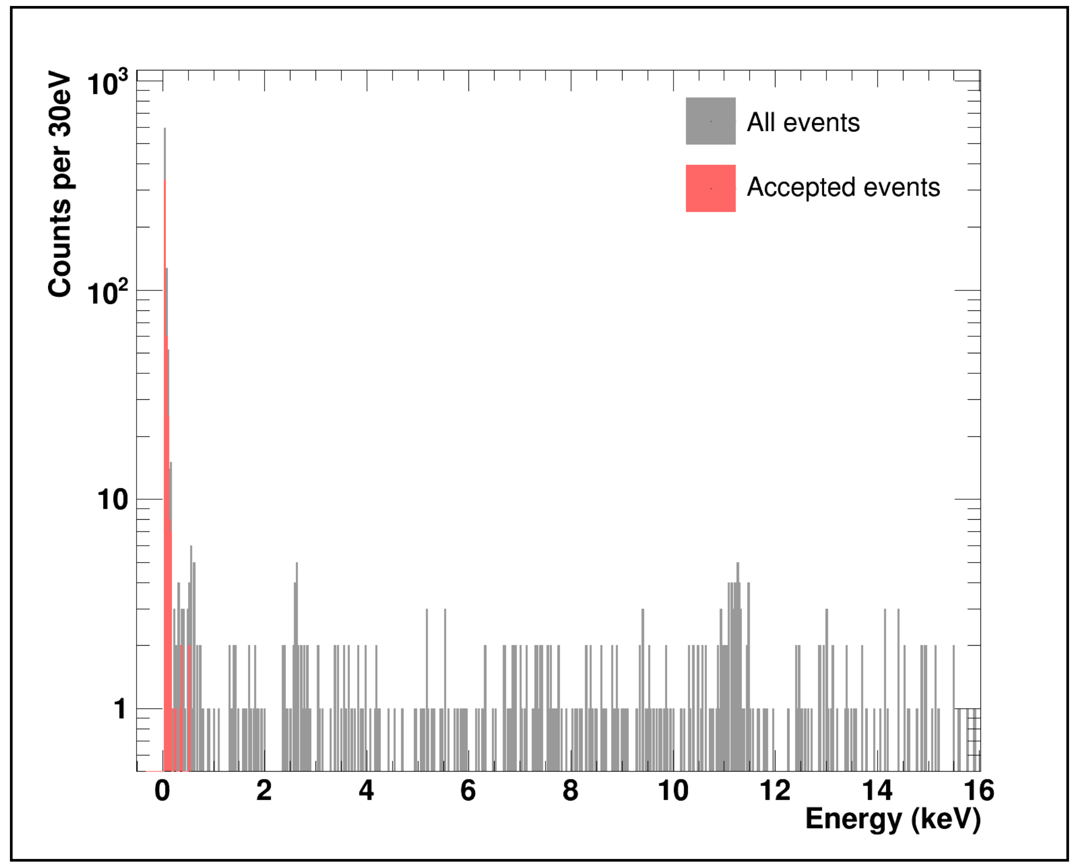
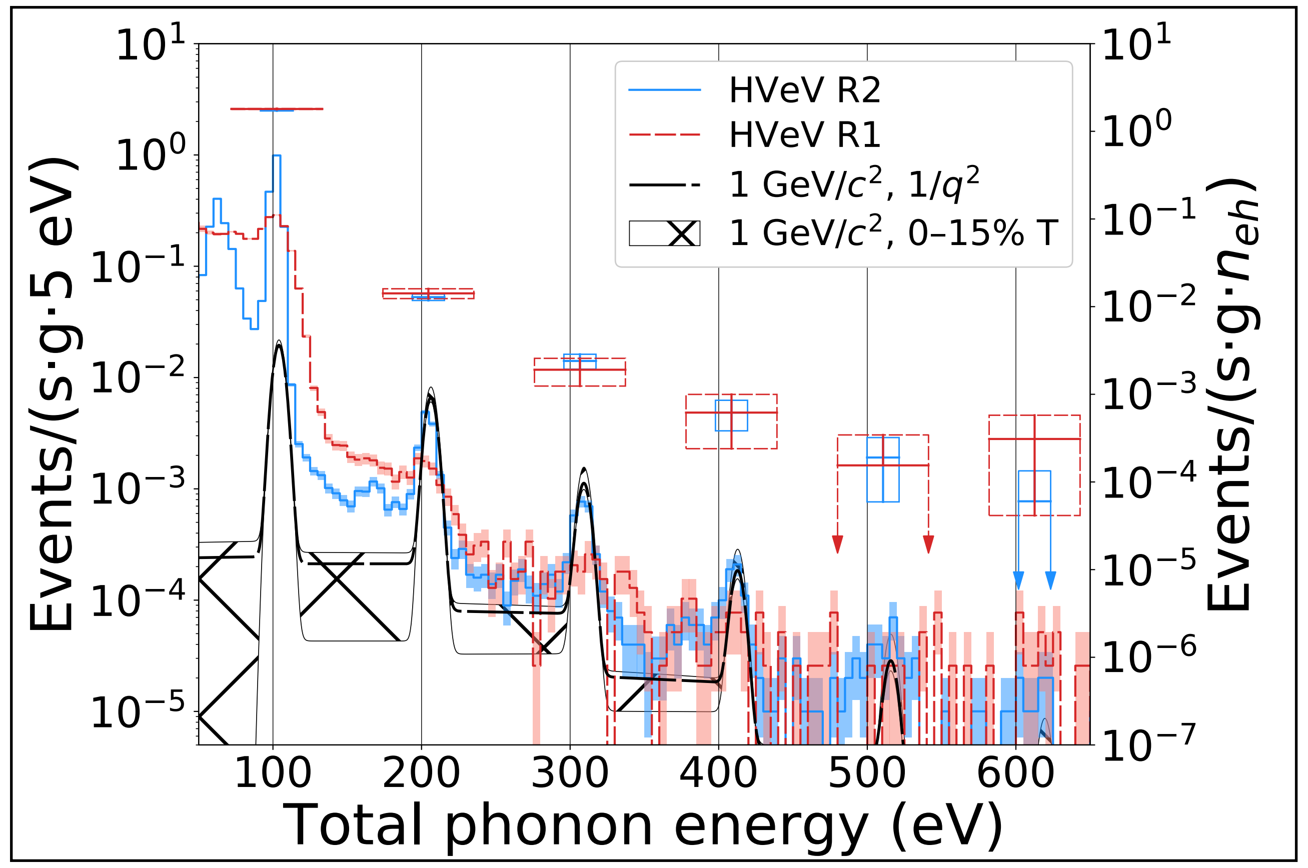
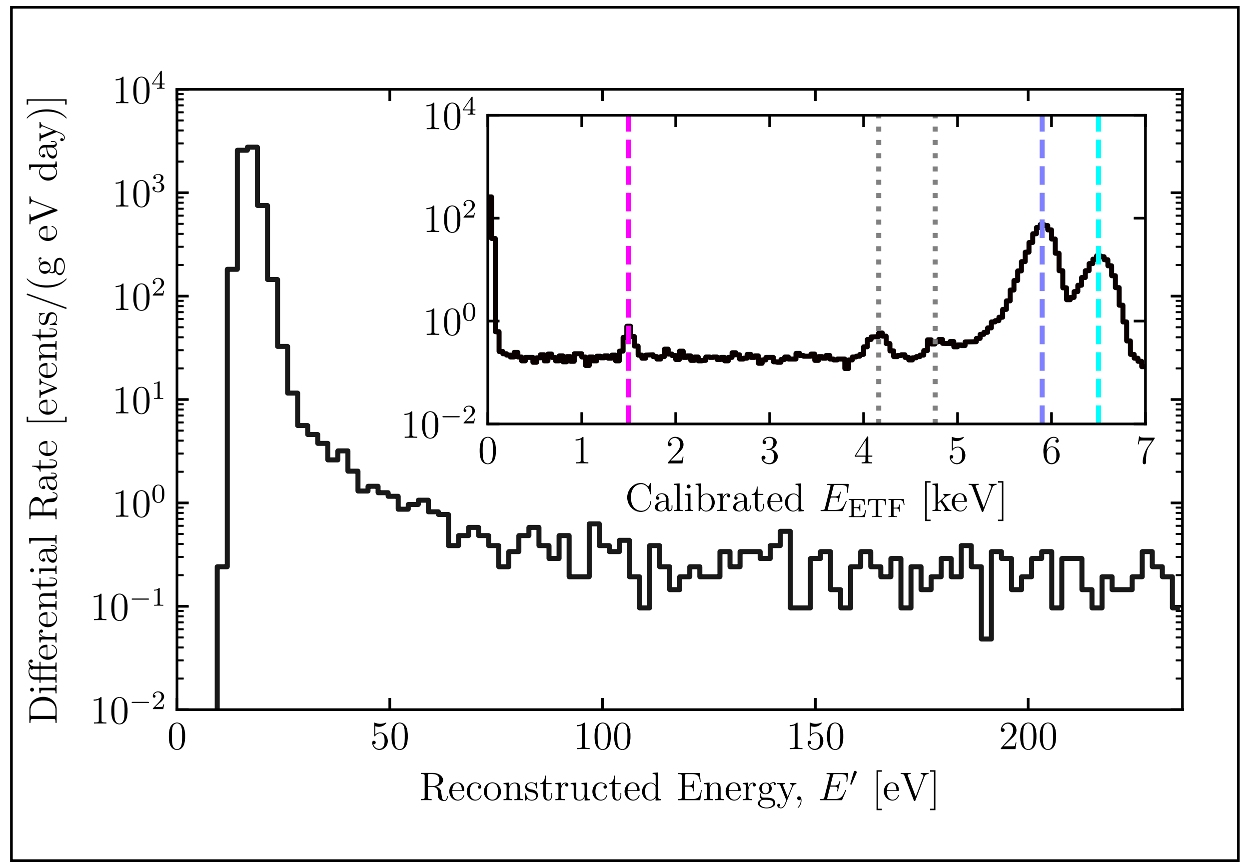
LOW ENERGY EXCESS



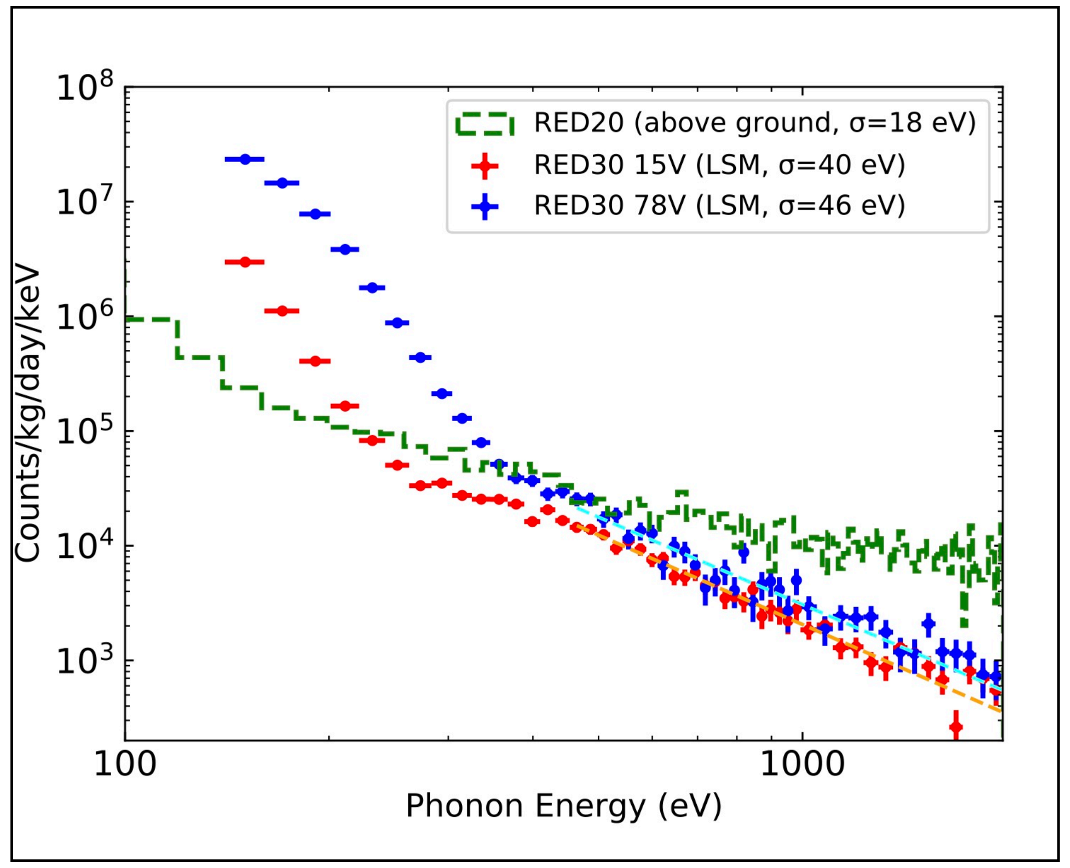
CRESST-III



SUPERCDMS - HVeV



SUPERCDMS - CPD



EDELWEISS

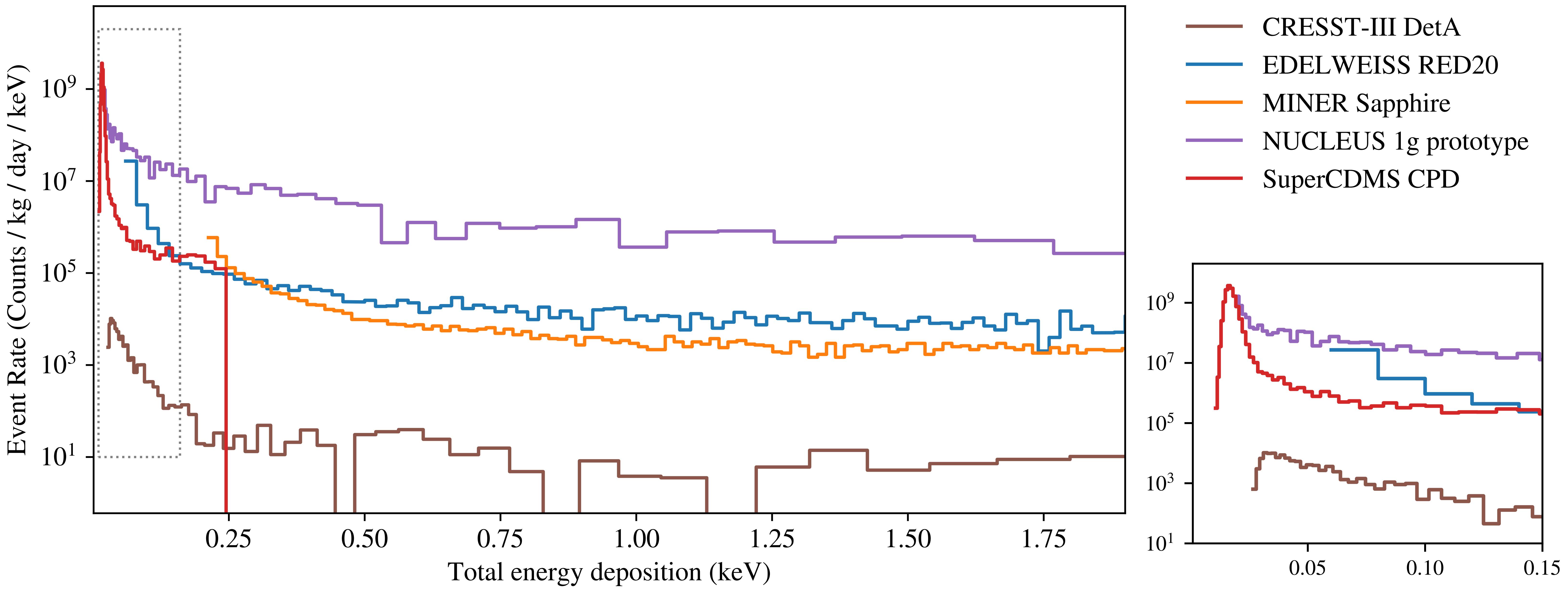
arXiv:2202.05097

LOW ENERGY EXCESS

Cryogenic detectors are observing an excess of events below about 200 eV, which limits the sensitivity

- Exponentially decaying
- Different rates in different detectors
- Different origins are possibile
- A solution is needed for the future of this technique

https://github.com/fewagner/excess



LOW ENERGY EXCESS: WORKSHOP

Cryogenic detectors are observing an excess of events below about 200 eV, which limits the sensitivity

A remarkable worldwide effort has been undertaken to understand the origin of these events

arXiv:2202.05097

EXCESS22@IDM

EXCESS

EXCESS22@IDM

16 July 2022 · Vienna · https://indico.cern.ch/event/1117540

Participant List
46 participants

Organizers:
Alexander Fuss
Felix Wagner
Florian Reindl
Margarita Kaznacheeva

Welcome	*Felix Wagner*	*Technical University Vienna*	09:00 - 09:15
Review on Low-Energy Excess Signals Observed in Cryogenic Rare Event Search Experiments	*Jules GASCON*	*Technical University Vienna*	09:15 - 09:45
Review on Excess Signals Observed in CCD Detectors	*Daniel Baxter*	*Technical University Vienna*	09:45 - 10:15
Coffee break		*Technical University Vienna*	10:15 - 10:45
Ionization efficiency at sub-keV energies for crystals and noble liquids	*Youssef Sarkis Mobarak et al.*	*Technical University Vienna*	10:45 - 11:10
Background discrimination for low quanta events with NEWS-G	*Francisco Andres Vazquez de Sola*	*Technical University Vienna*	11:10 - 11:35
Low-energy event excess in SuperCDMS HVeV detectors	*Dr Valentina Novati*	*Technical University Vienna*	11:35 - 12:00
Latest results on the low energy excess in CRESST-III	*Dominik Raphael Fuchs*	*Technical University Vienna*	13:30 - 13:55
Heat-only background in the EDELWEISS detectors with NbSi TES sensor	*Dr Hugues LATTAUD*	*Technical University Vienna*	13:55 - 14:20
Stress Induced Background in Cryogenic Crystal Calorimeters	*Daniel Mckinsey*	*Technical University Vienna*	14:20 - 14:45
Low energy excess in MAGNETO R&D Data	*Geon-Bo Kim*	*Technical University Vienna*	14:45 - 14:50
Dark matter detectors and understanding of glasses	*sergey pereverzev*	*Technical University Vienna*	14:50 - 15:15
Coffee break		*Technical University Vienna*	15:15 - 15:40
Energy loss due to defect creation in solid state detectors	*Matti Heikinheimo*	*Technical University Vienna*	15:40 - 16:05
Impact of crystal lattice defect quenching on coherent neutrino scattering experiments	*thierry lasserre*	*Technical University Vienna*	16:05 - 16:30

https://indico.cern.ch/event/1117540/timetable/#20220716.detailed

14

EXCESS22@IDM REPORT

EXCESS

IDM 2022 — 14th International Conference on Identification of Dark Matter — 18-22 July 2022, Vienna, Austria

The EXCESS initiative: towards understanding the observed rates in sub-keV direct searches - Latest News

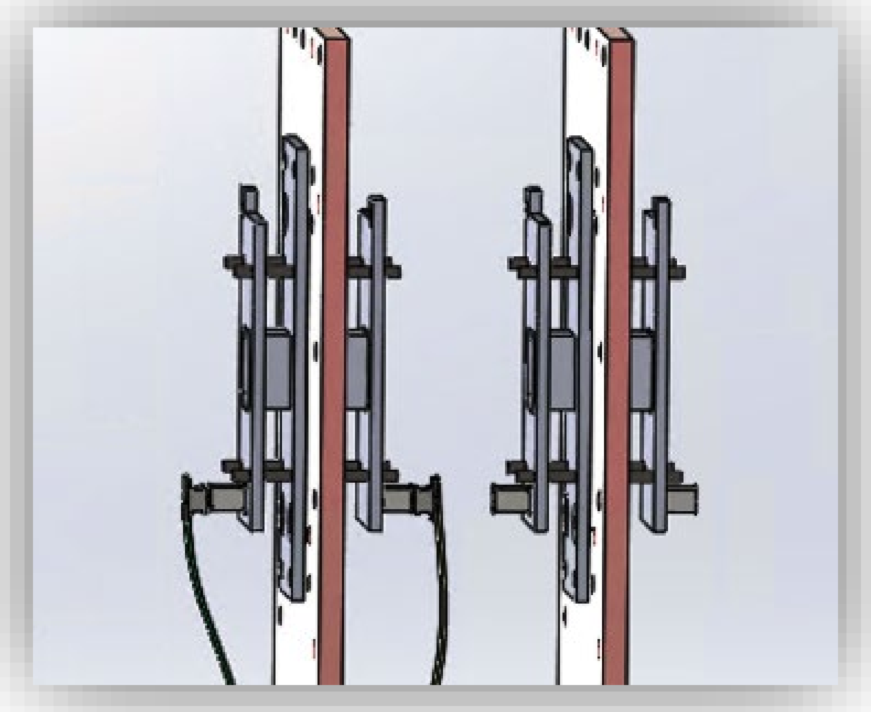
Belina von Krosigk[1], Margarita Kaznacheeva[2]
belina.krosigk@kit.edu, margarita.kaznacheeva@tum.de

On behalf of the EXCESS22@IDM organizers:
A. Fuss[3,4], M. Kaznacheeva[2], F. Reindl[3,4], F. Wagner[3]

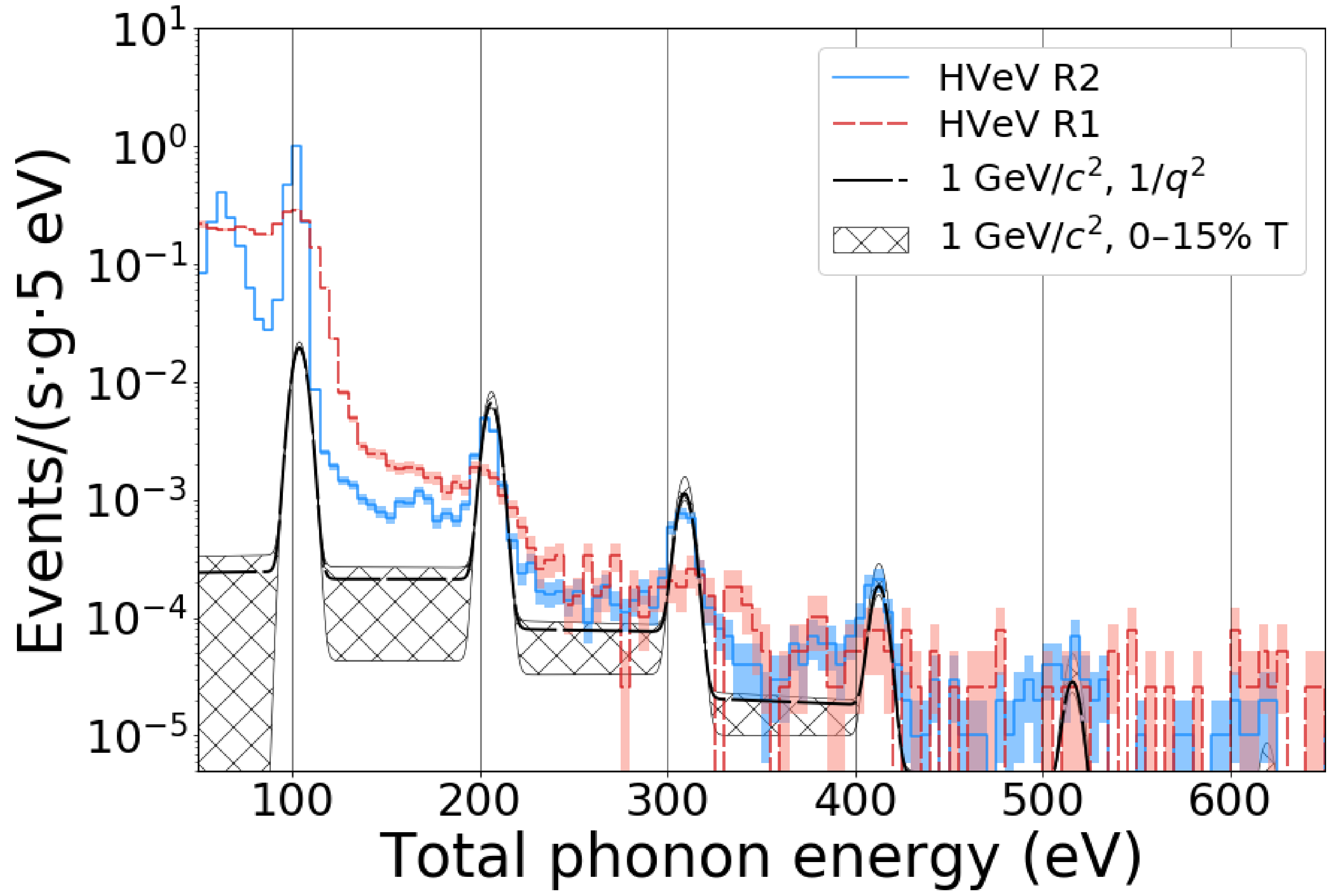
[1] Karlsruhe Institute of Technology,[2] Technical University of Munich, [3] Institute of High Energy Physics of the Austrian Academy of Sciences,[4] Institute of Atomic and Subatomic Physics, Vienna University of Technology

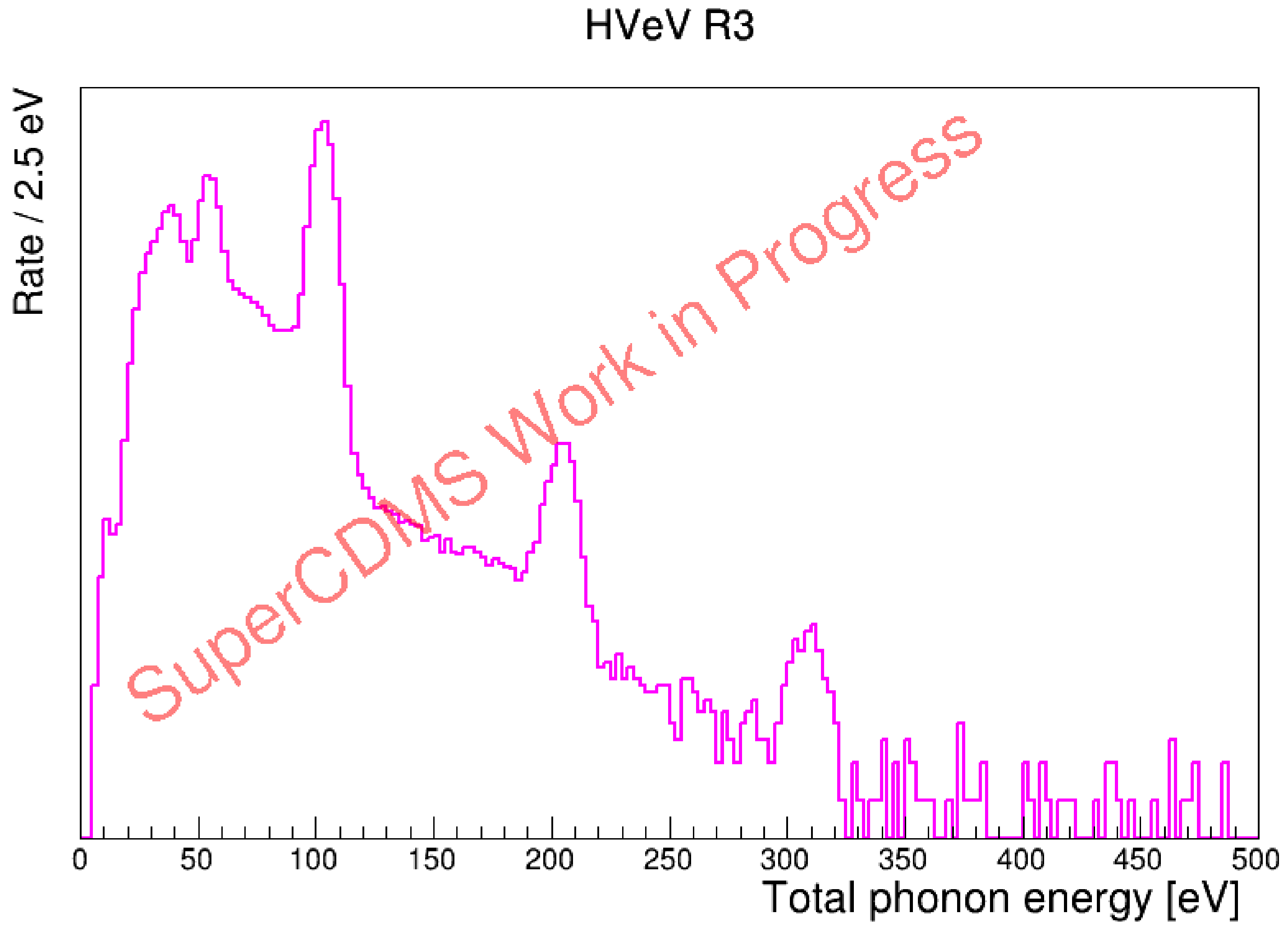
LOW ENERGY EXCESS: NEWS

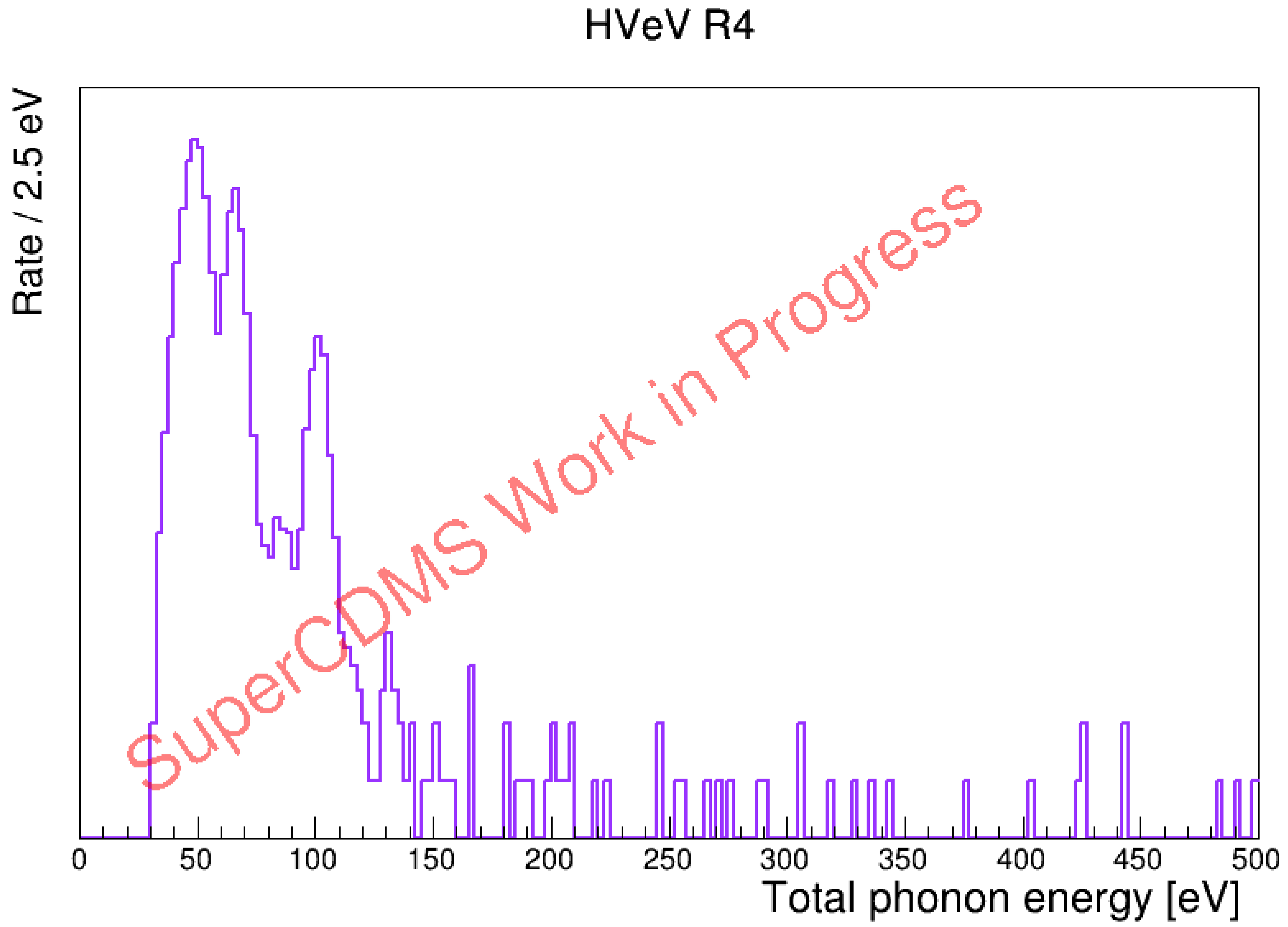
V. NOVATI for the SuperCDMS collaboration



- By doing coincidence measurements, SuperCDMS identified some events in the excess as originated by SiO_2 in the detector holder.
- Events removed by coincidence cut



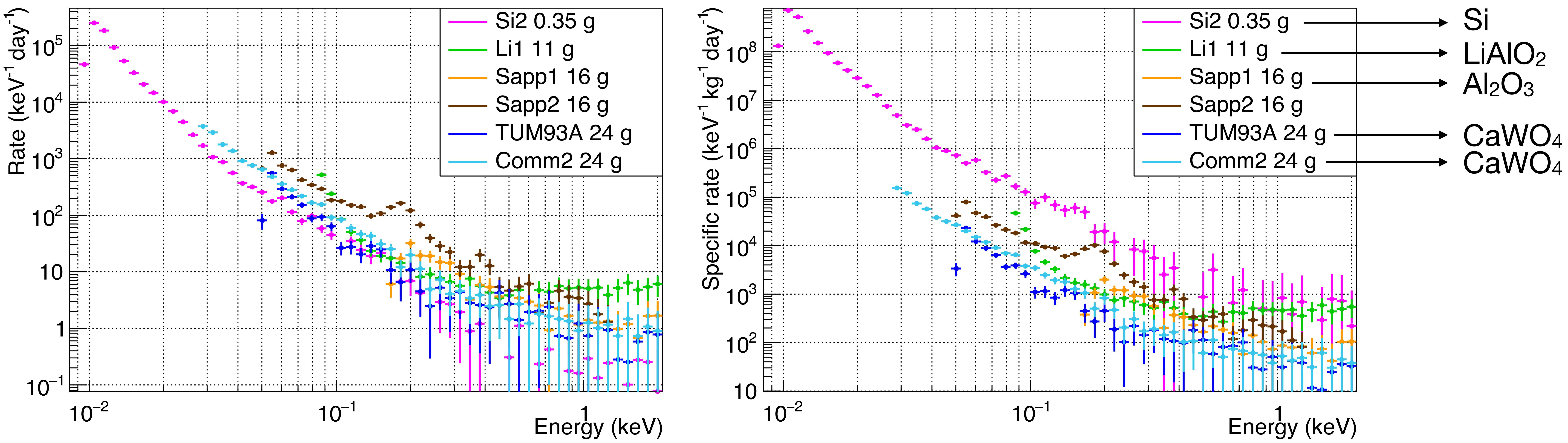




LOW ENERGY EXCESS: NEWS

EXCESS22@IDM

D. FUCHS for the CRESST collaboration



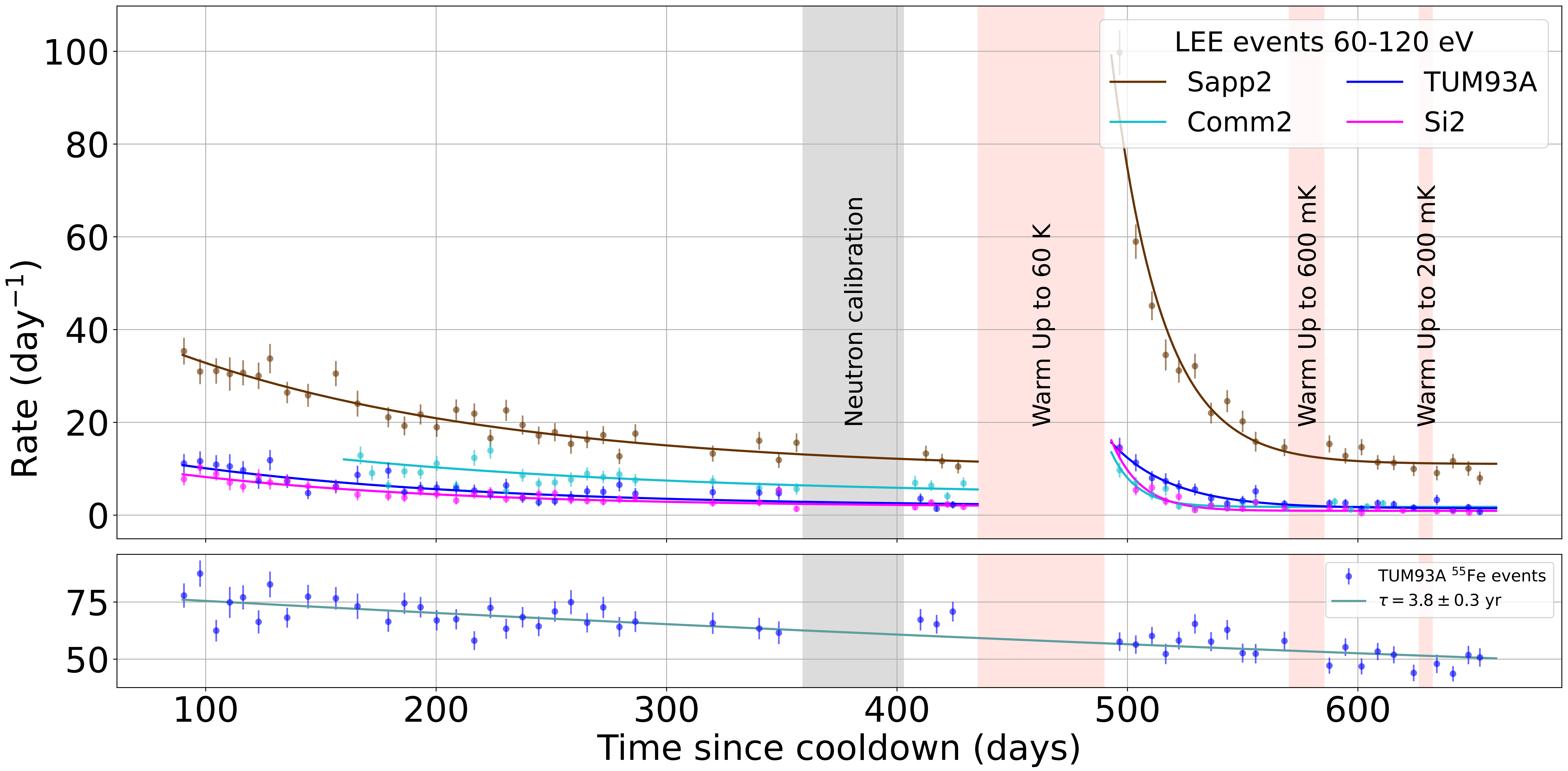
By comparing the low energy excess in different materials CRESST showed that:

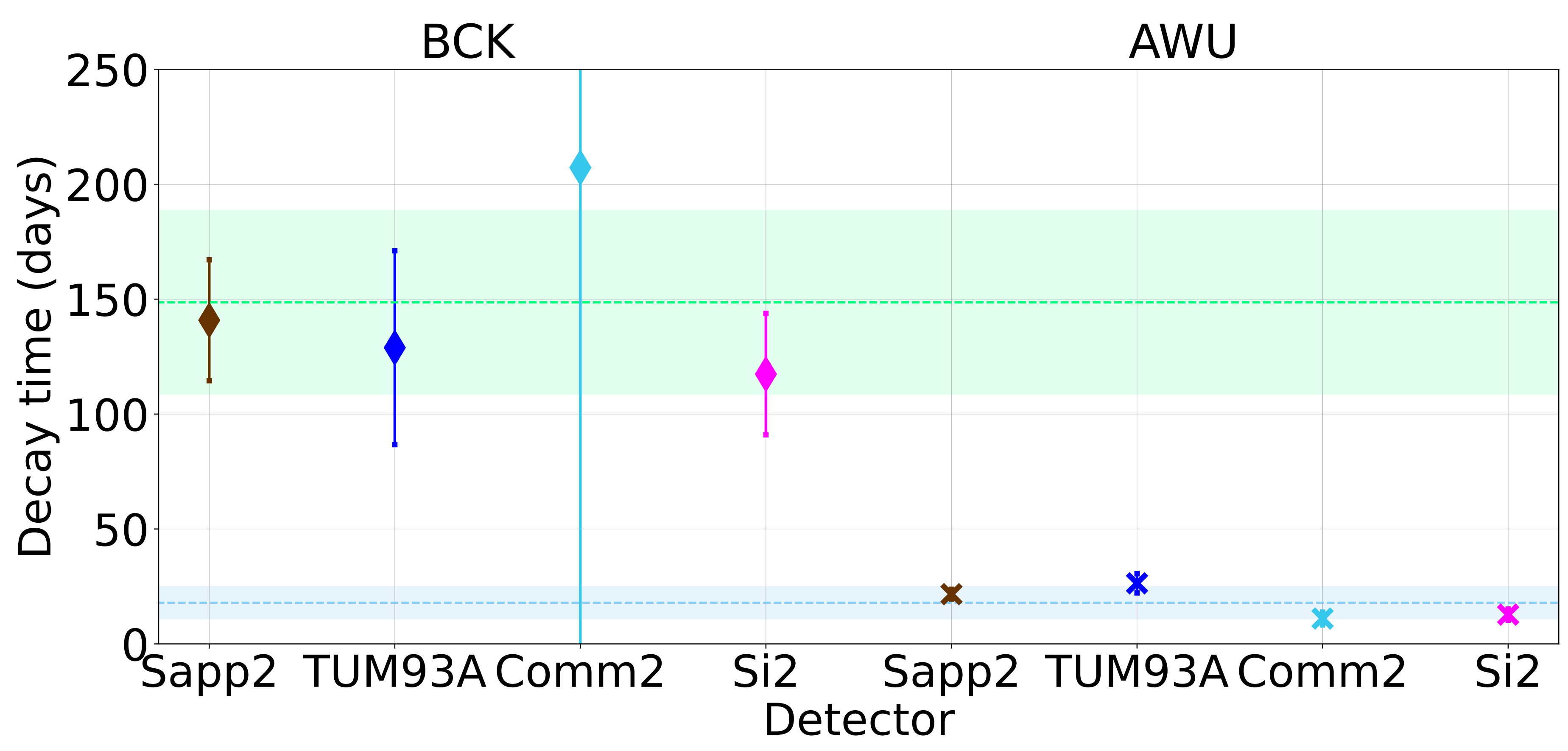
1. the excess is present in all detectors
2. the rate does not scale with the mass
3. hypotheses of dark matter and external radioactive background are disfavoured

LOW ENERGY EXCESS: NEWS

EXCESS22@IDM

D. FUCHS for the CRESST collaboration





Observations:

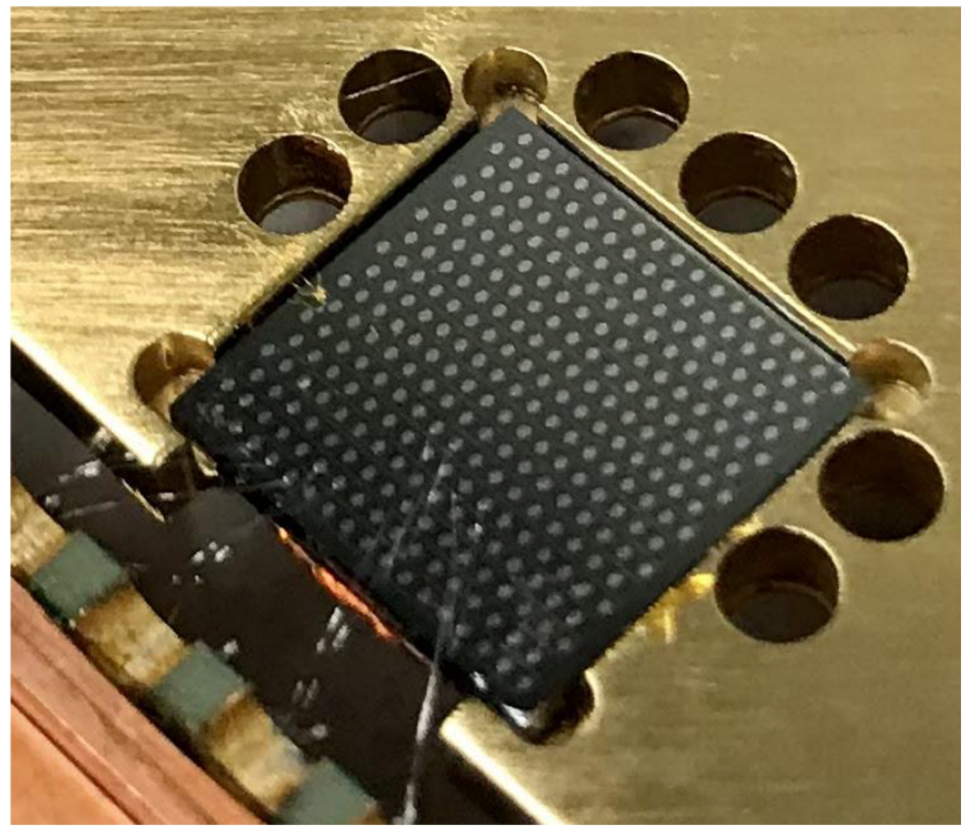
1. Neutron calibration did not affect the LEE
2. The warm up to 60 K affects the LEE with a large increase in the rate
3. The warm up to 600 mK and 200 mk did not affect the rate
4. The time constant estimated from an exponential fit of the after warm up (AWU) data is smaller than the one of the background (BCK) data before warm up.

LOW ENERGY EXCESS: NEWS

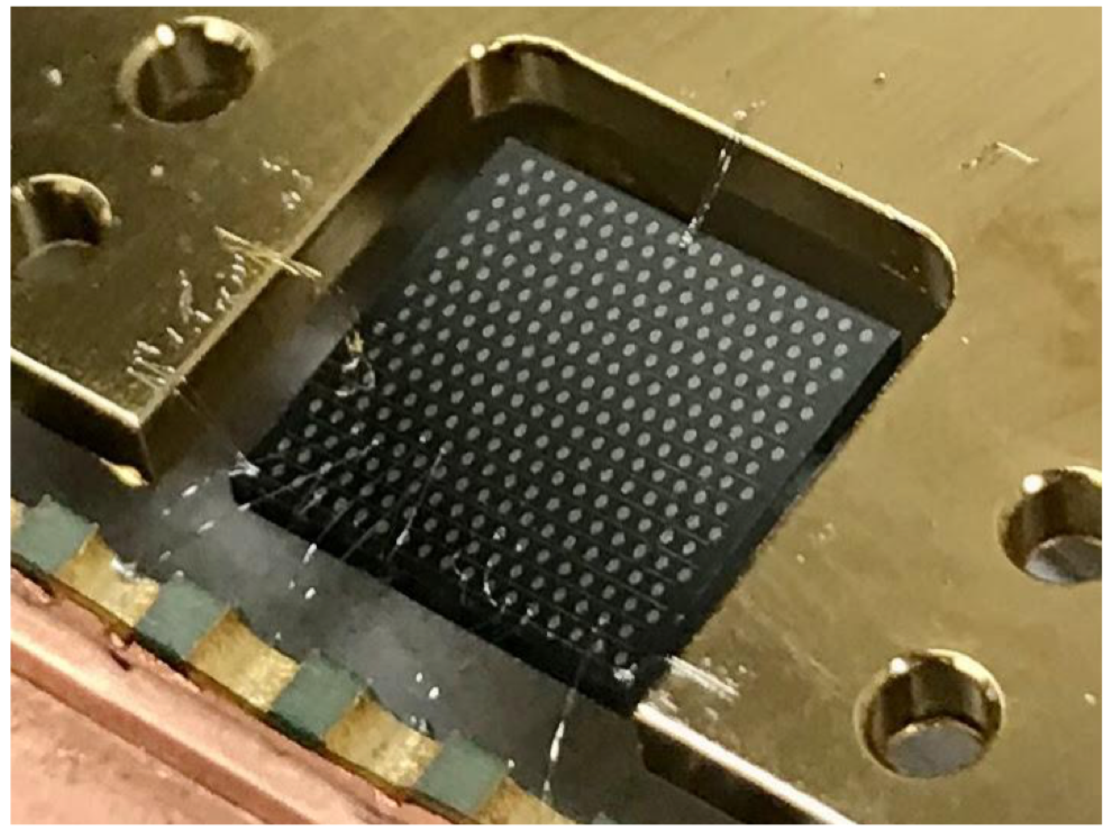
EXCESS22@IDM

D. McKinsey for the HeRALD/SPICE (TESSERACT) Collaborations

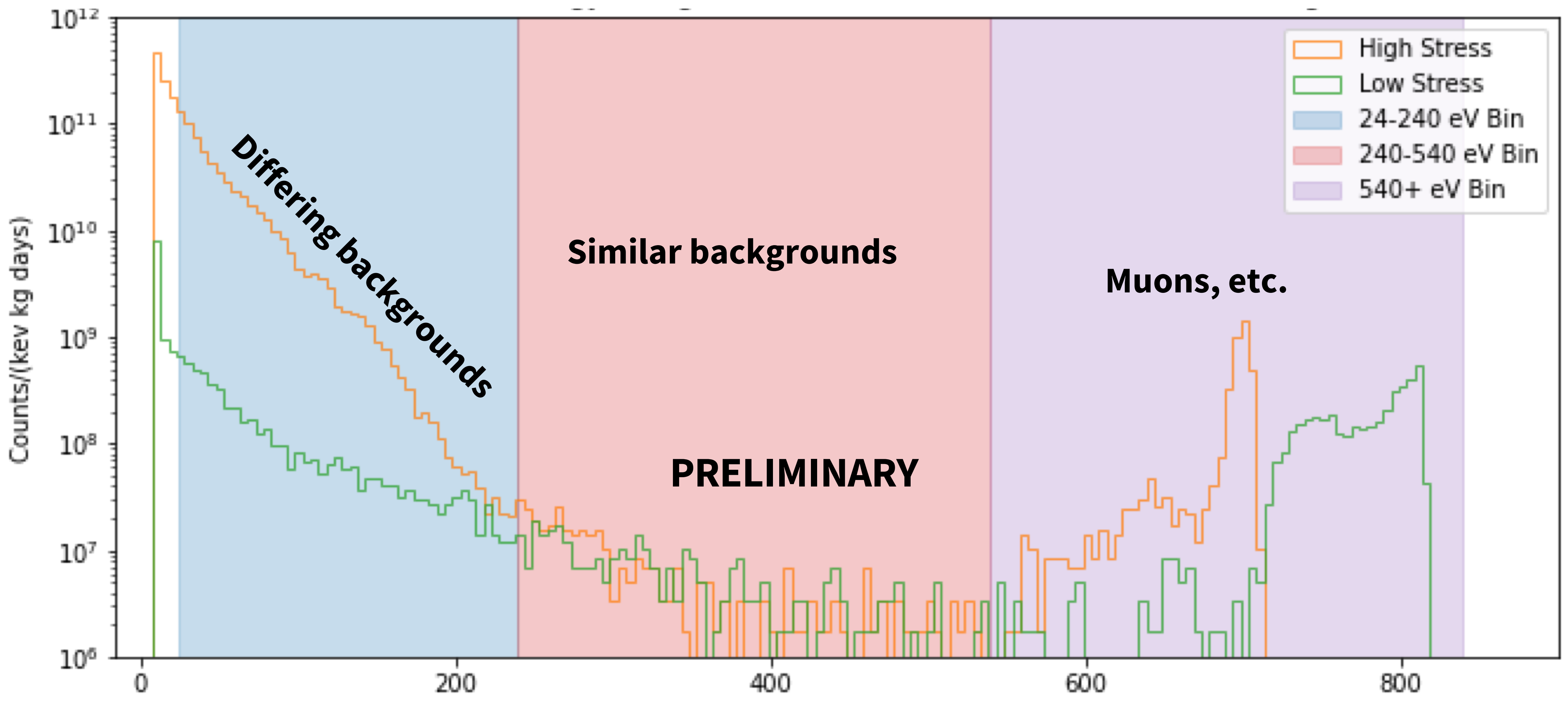
- Two tests with 1 cm^2 and 1mm thick Si were performed: once the wafer was hold glued to the holder (high stress) and once suspended by wire bonds.
- The result shows that an increase in the low energy excess is obtained in the "high stress" case. The excess is still present in the low stress case.



High stress



Low stress



LOW ENERGY EXCESS: NEWS

EXCESS22@IDM

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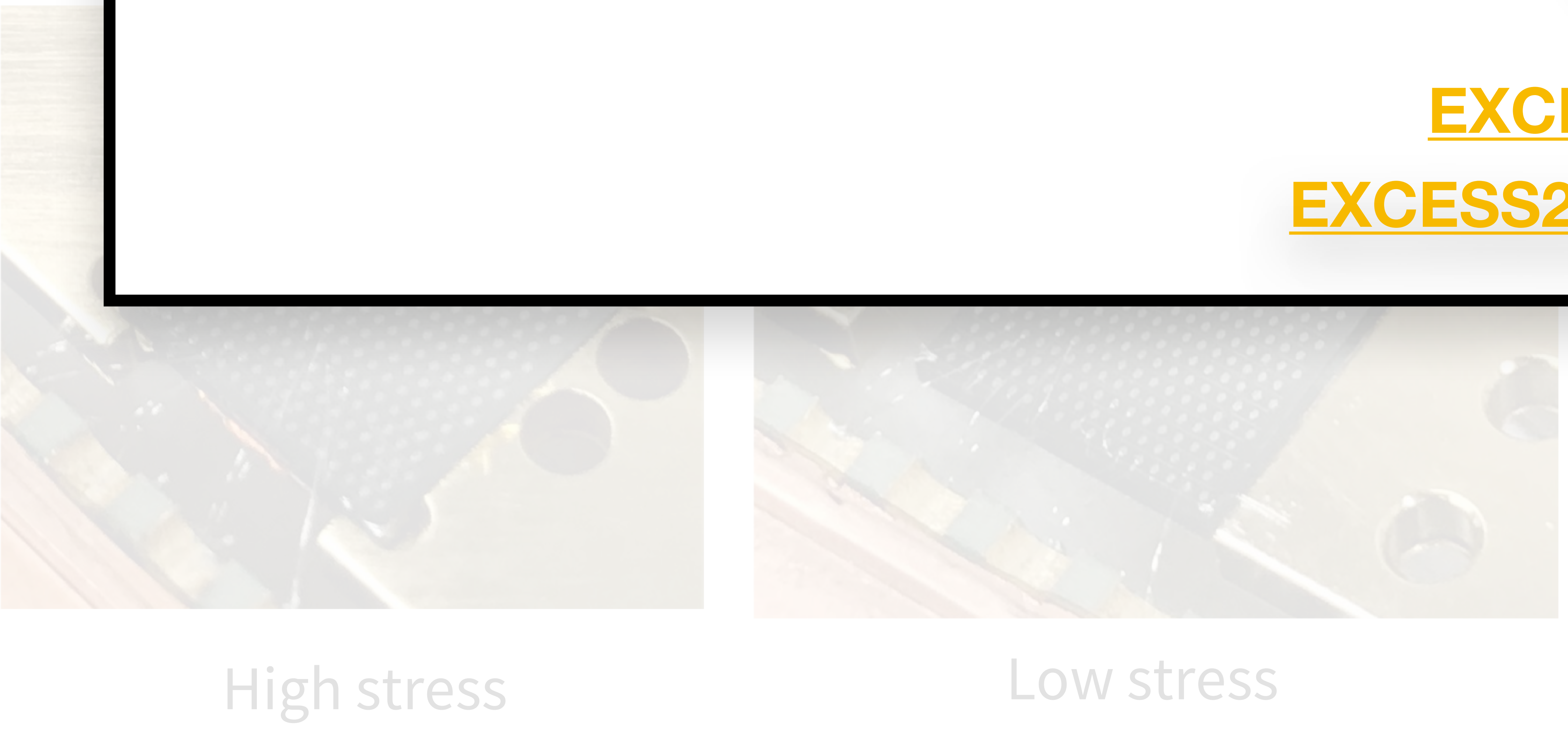
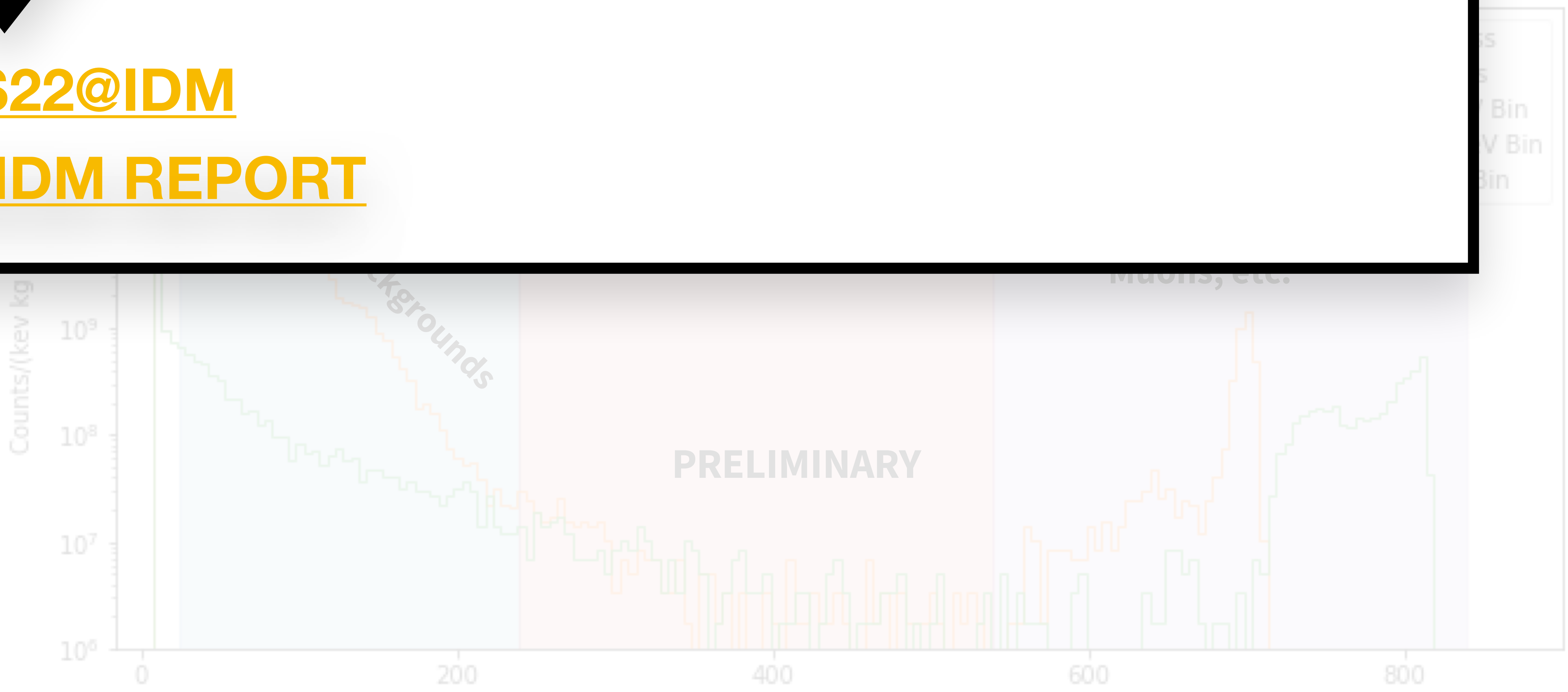
- Th… st…

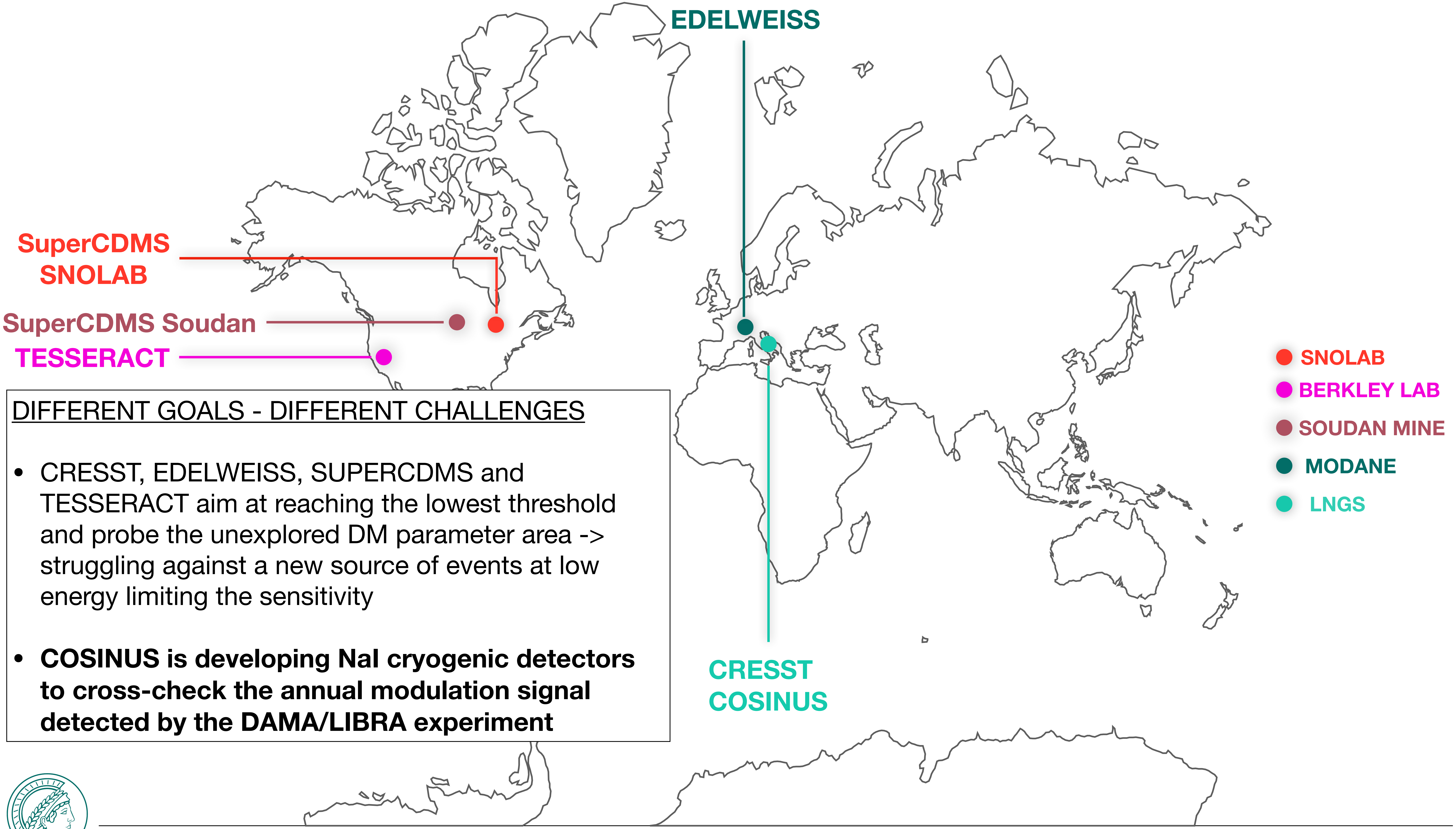
THIS IS AN EXTRACT OF THE FINDINGS DISCUSSED AT THE EXCESS WORKSHOP.
FOR THE FULL OVERVIEW GO HERE:

EXCESS22@IDM

EXCESS22@IDM REPORT





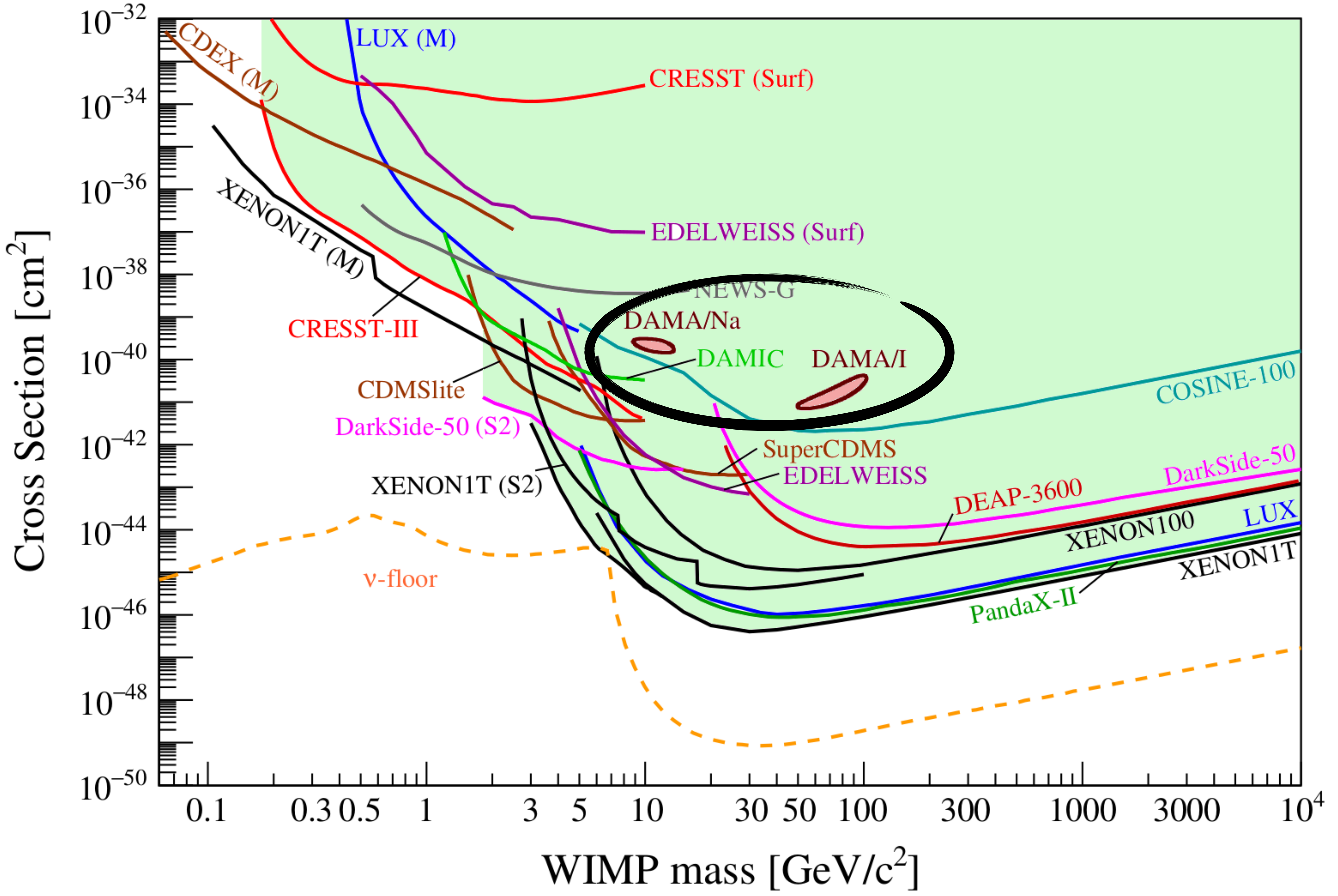


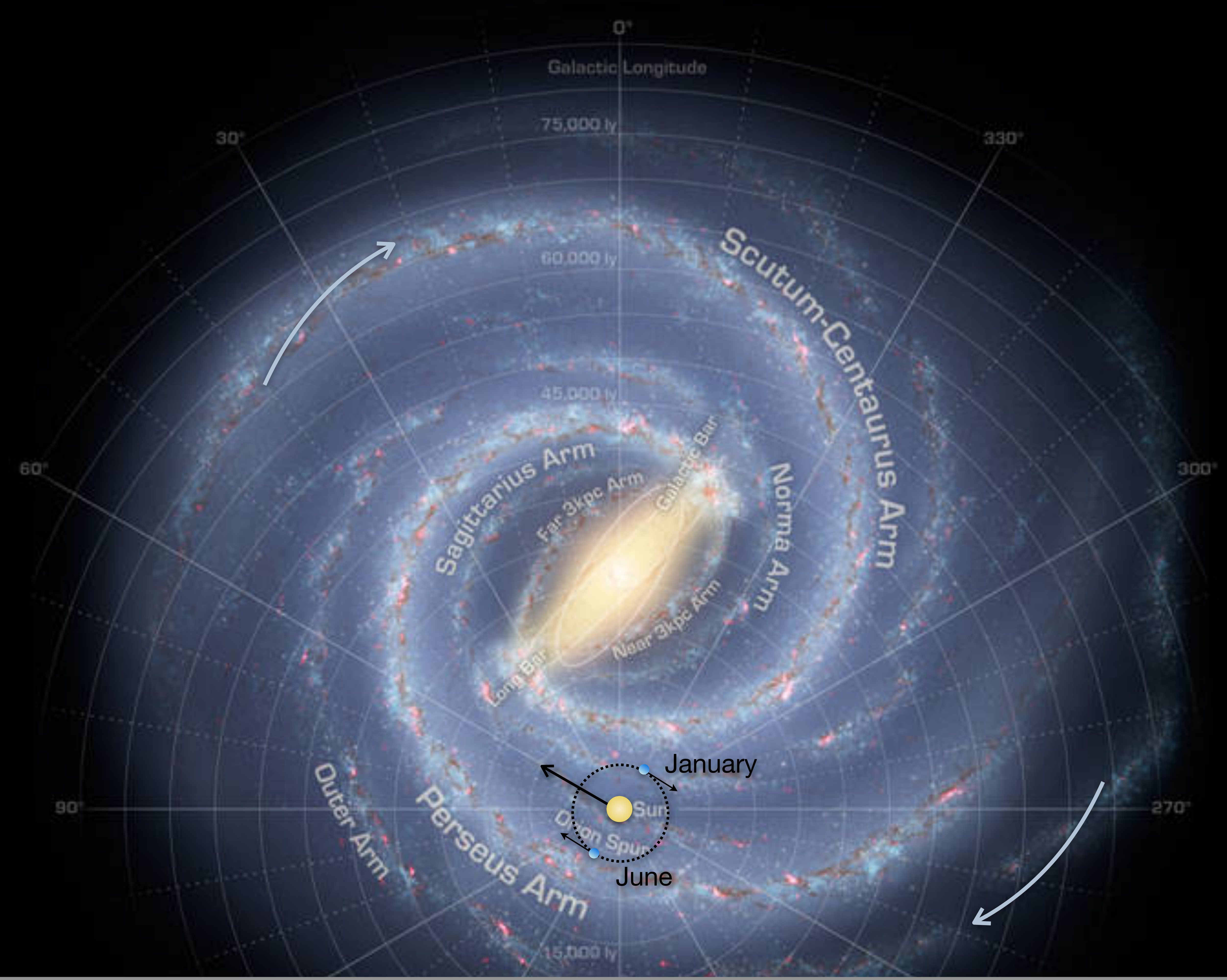
DIFFERENT GOALS - DIFFERENT CHALLENGES

- CRESST, EDELWEISS, SUPERCDMS and TESSERACT aim at reaching the lowest threshold and probe the unexplored DM parameter area -> struggling against a new source of events at low energy limiting the sensitivity
- **COSINUS is developing NaI cryogenic detectors to cross-check the annual modulation signal detected by the DAMA/LIBRA experiment**

COSINUS

CROSS-CHECK OF THE DAMA/LIBRA'S RESULT

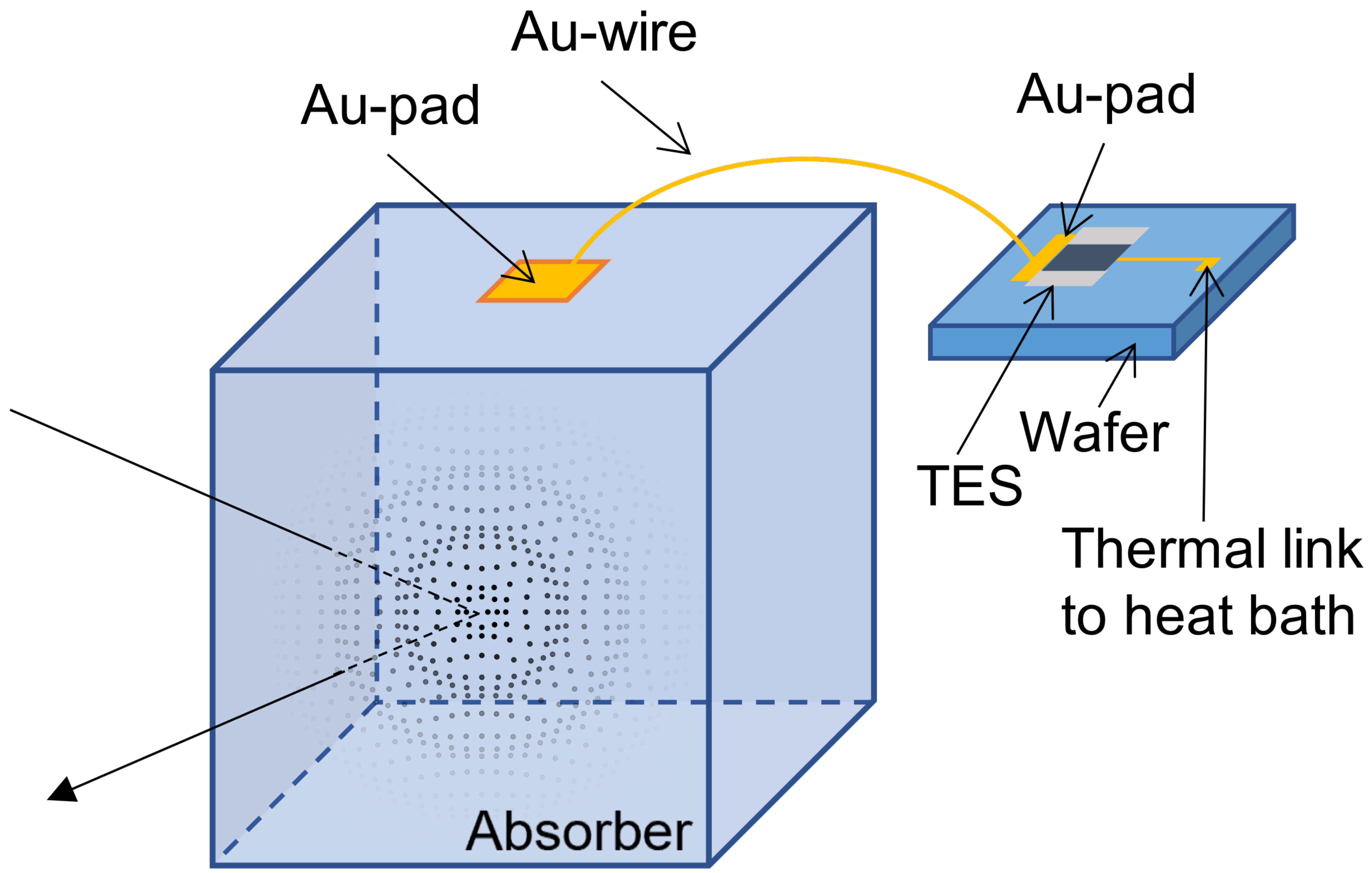




DAMA/LIBRA is detecting an annually modulating signal compatible with the expectations for dark matter but which has not been observed by any other experiment so far

COSINUS

CROSS-CHECK OF THE DAMA/LIBRA'S RESULT



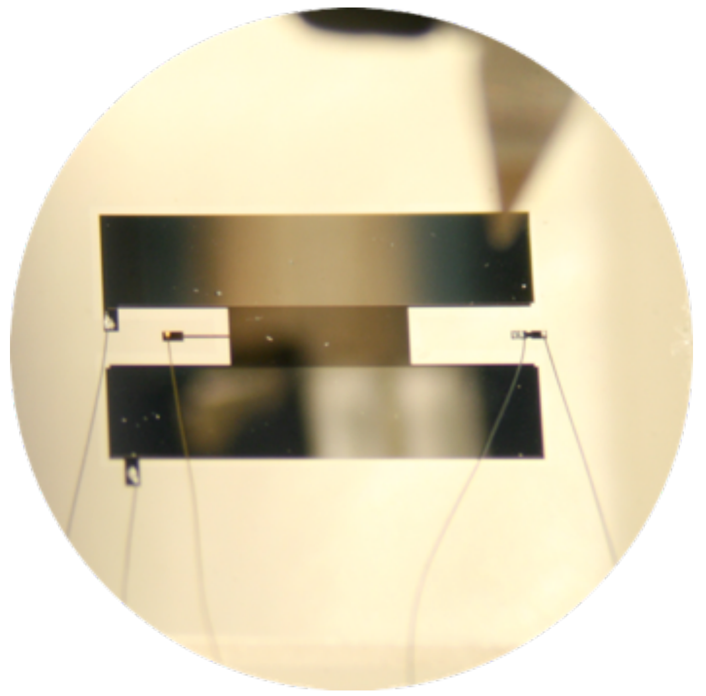
arXiv:2111.00349v1

COSINUS employs NaI absorbers, to use the same target material as DAMA/LIBRA

NaI is hygroscopic and has a low melting point. It does not survive any TES fabrication process

Thus COSINUS implemented a "remoTES", where the sensor is fabricated on a separate wafer and connected to the absorber through a gold bonding wire and a gold pad

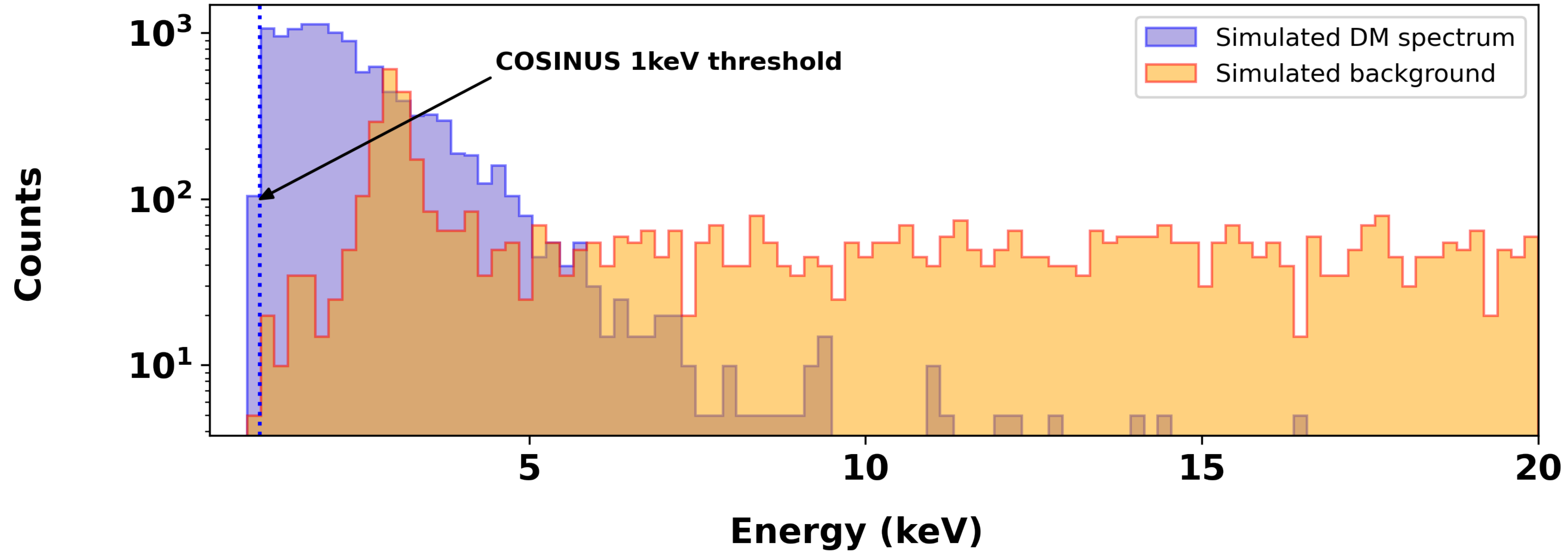
COSINUS uses the Transition Edge Sensors developed by CRESST

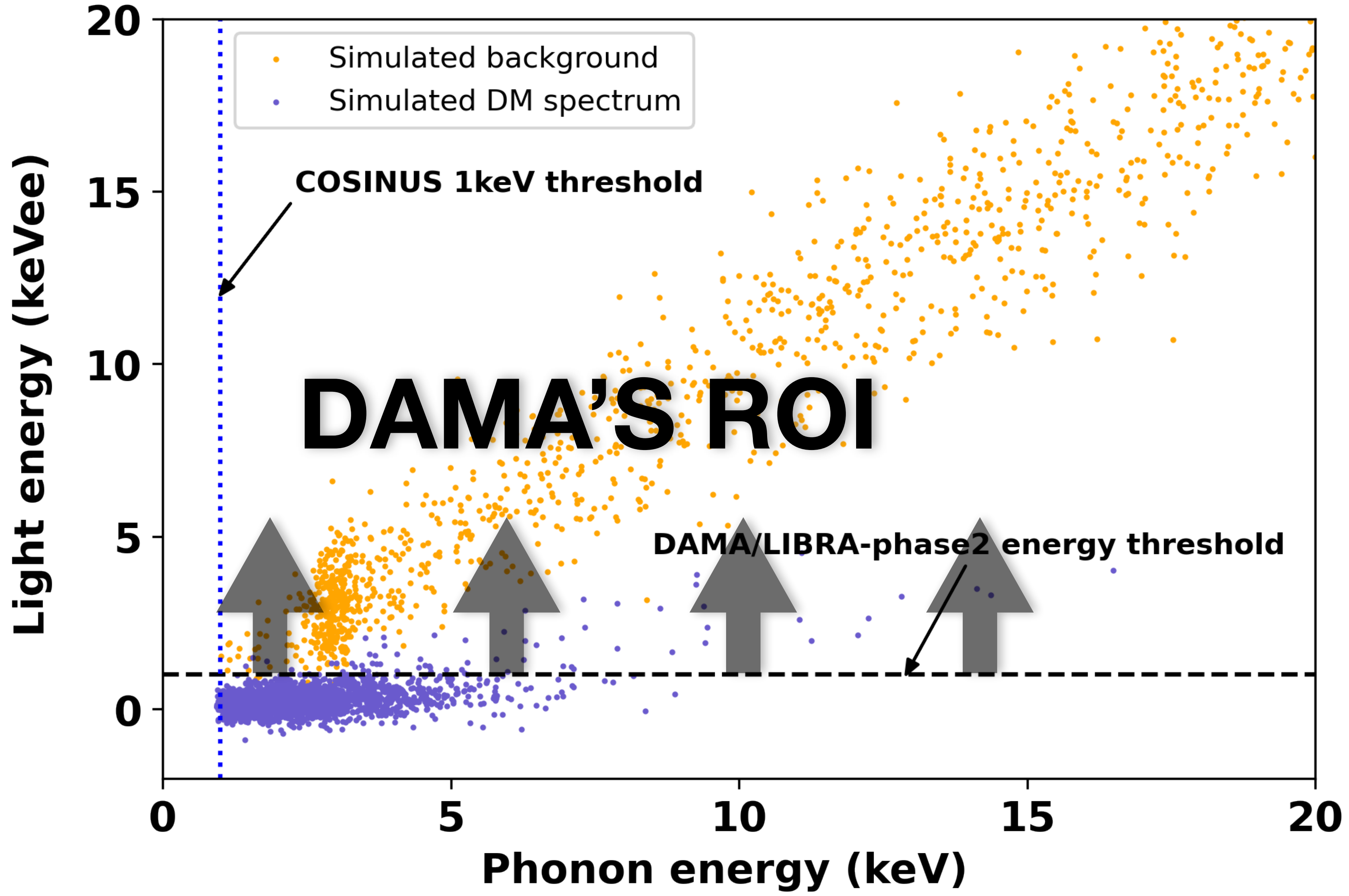


COSINUS

THE ADVANTAGES ARE LOW THRESHOLD AND PARTICLE DISCRIMINATION

K. SCHÄFFNER | IDM 2022





SIMULATED DATA
(100 kg day gross exposure):

- 20 ppb of ^{40}K + 1 cpd/(keV kg)
- Baseline resolution for NaI 0.2 keV
- efficiency between 20-50% at 1-2 keV and at 50% above 2keV
- Energy in light: 4%
- QF for Na ~ 0.3, QF for I ~ 0.09
- σ^{SI}= 2 x 10^{-4} pb (m_{DM}=10 GeV/c^2)

Eur. Phys. J. C 76, 441 (2016)

COSINUS

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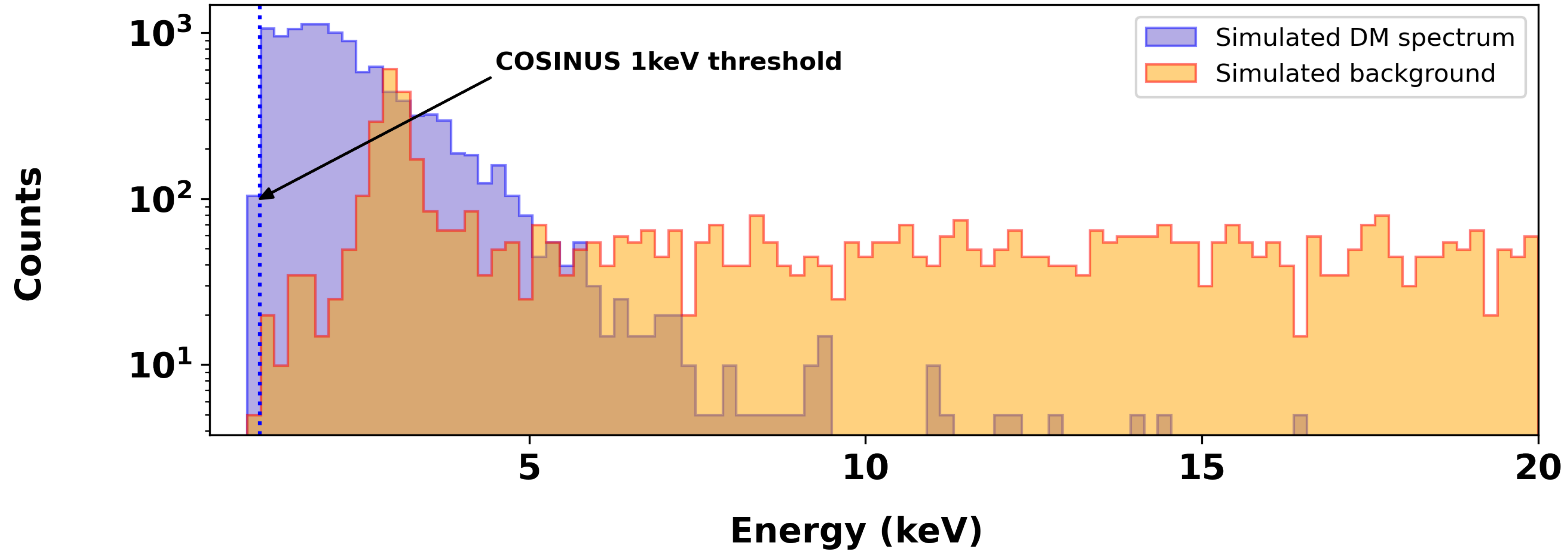
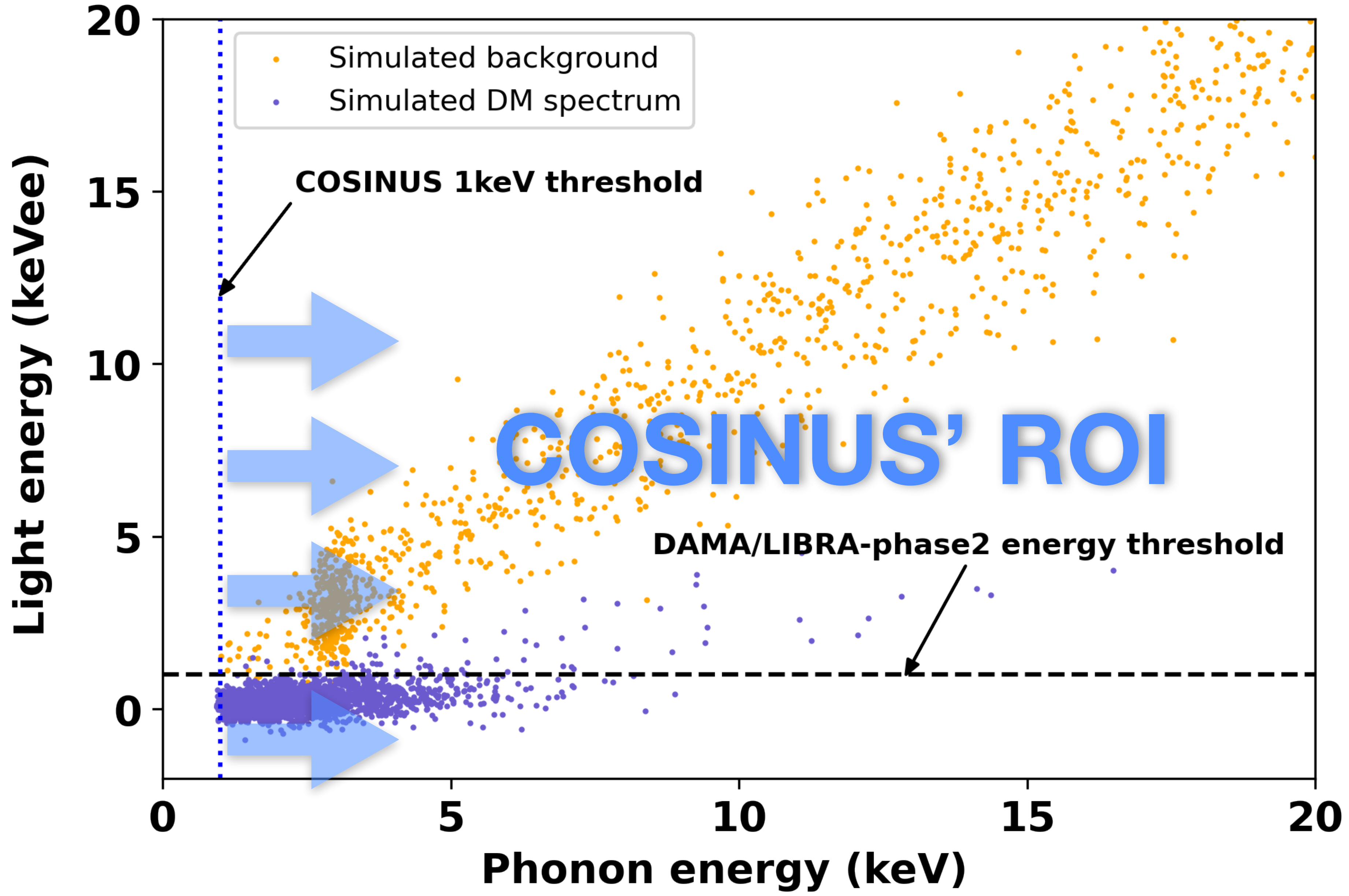
K. SCHÄFFNER | IDM 2022





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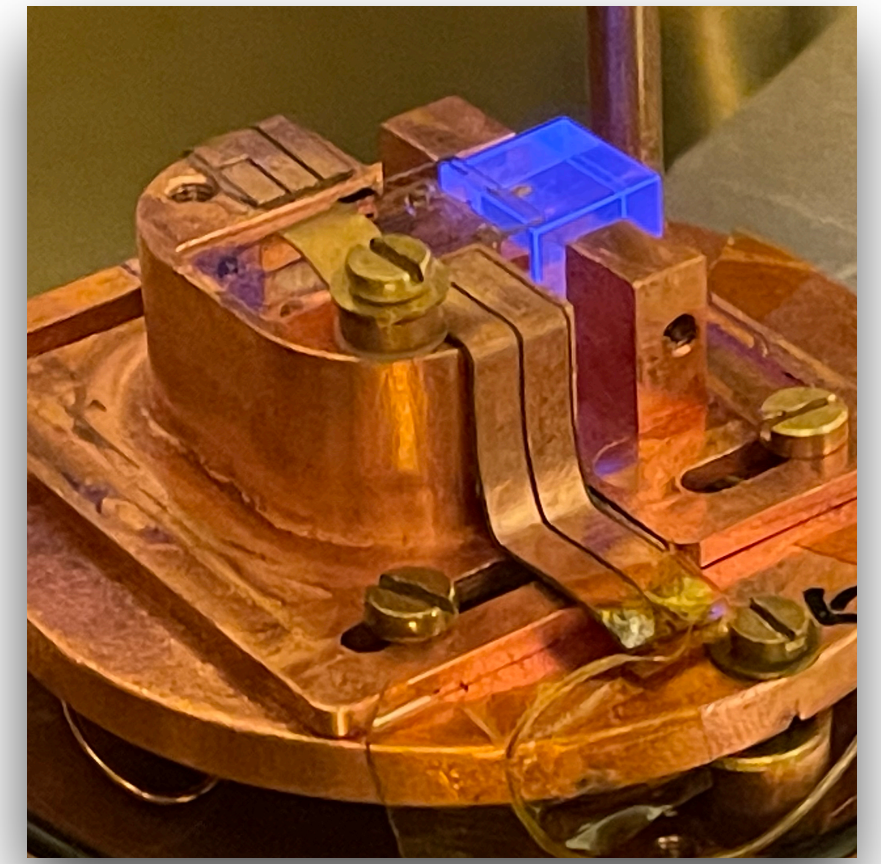
COSINUS

THE ADVANTAGES ARE LOW THRESHOLD AND PARTICLE DISCRIMINATION

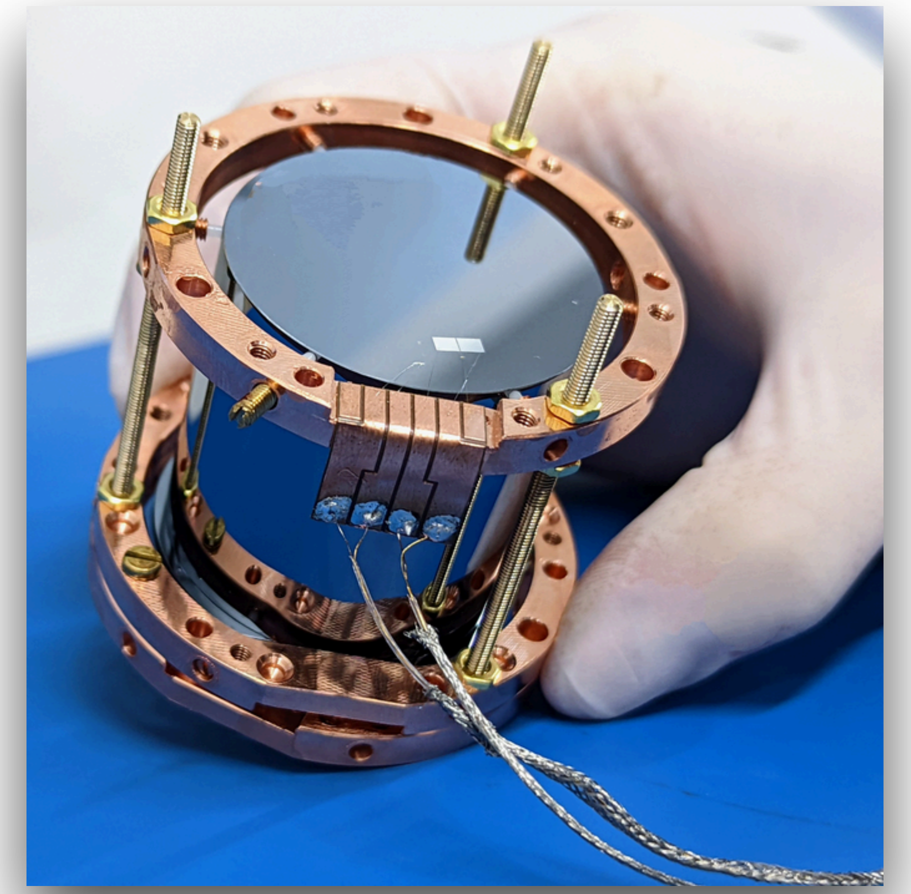
K. SCHÄFFNER | IDM 2022

PHONON+SCINTILLATION



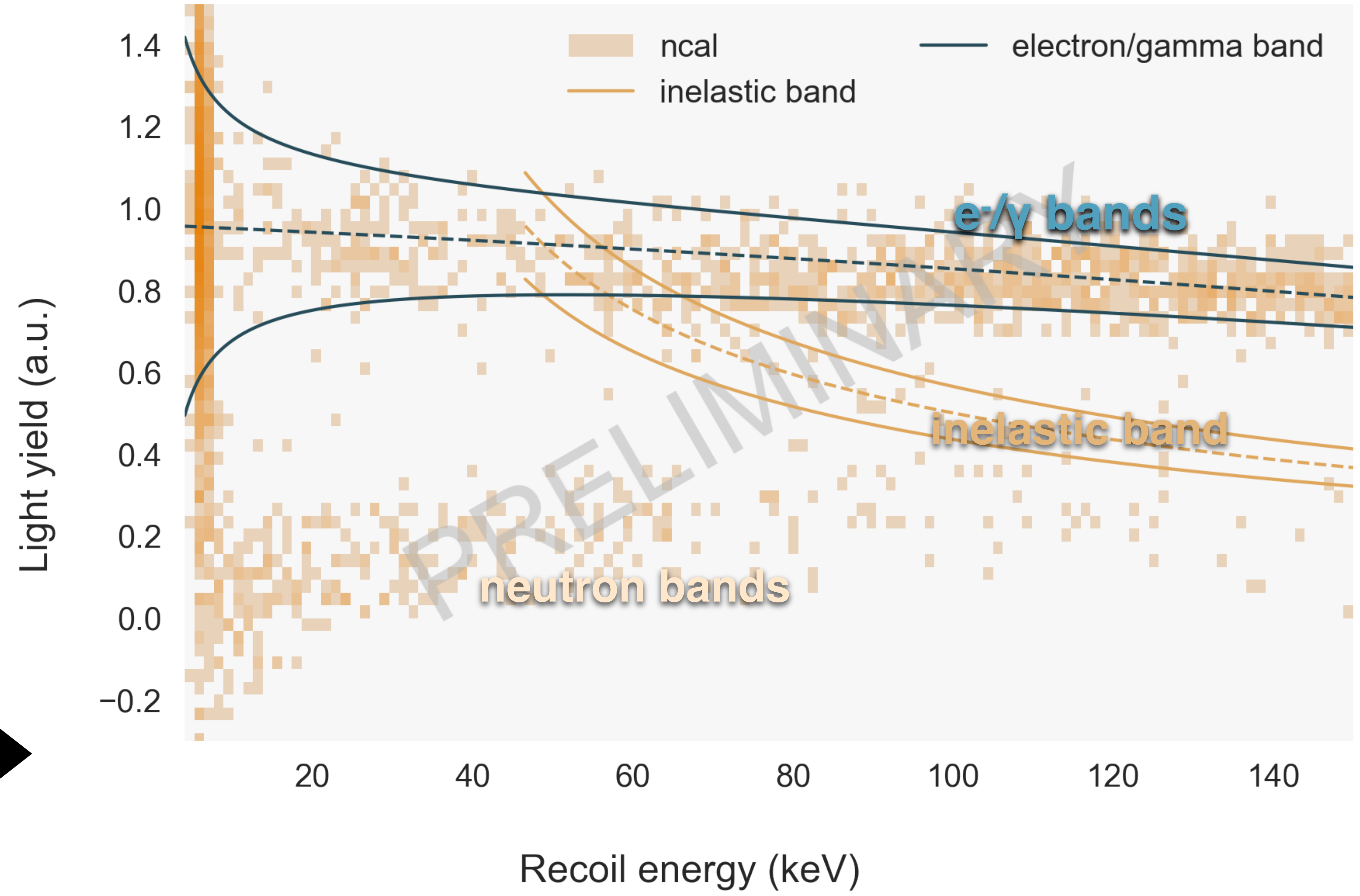
NaI-remoTES
- NaI grown by SICCAS
- 5-6 ppb of ^{nat}K achieved
- 1 cm^3
- Gold pad glued with epoxy
- Gold pad size 4 mm^2
- W-TES of sapphire wafer

0.39 keV baseline resolution



Silicon beaker
- 4 cm diameter and height
- 1 mm thickness
- 15 g
- W-TES evaporated on the surface
- 20 eV baseline resolution

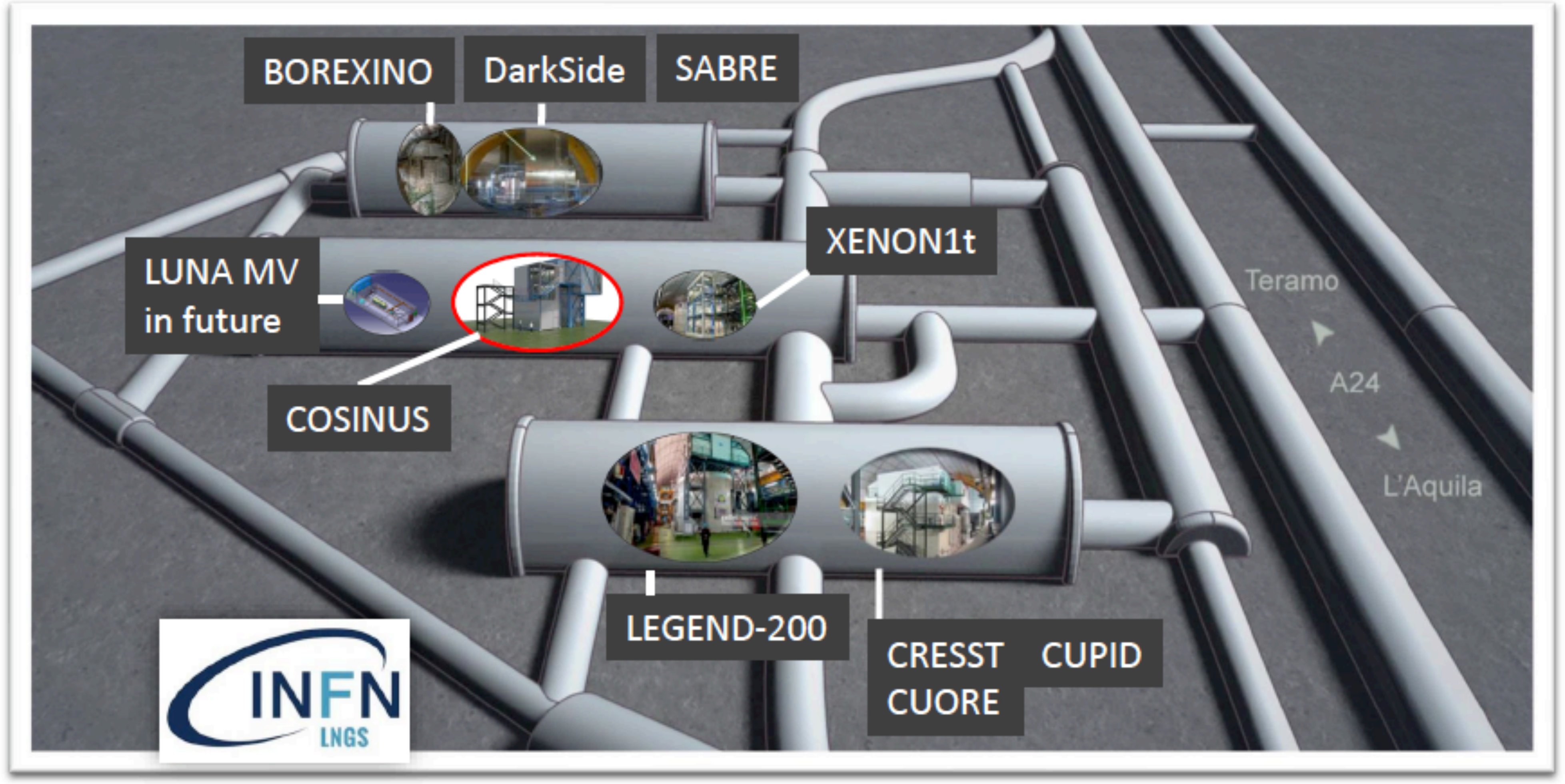
best performance:
10.2 eV baseline resolution

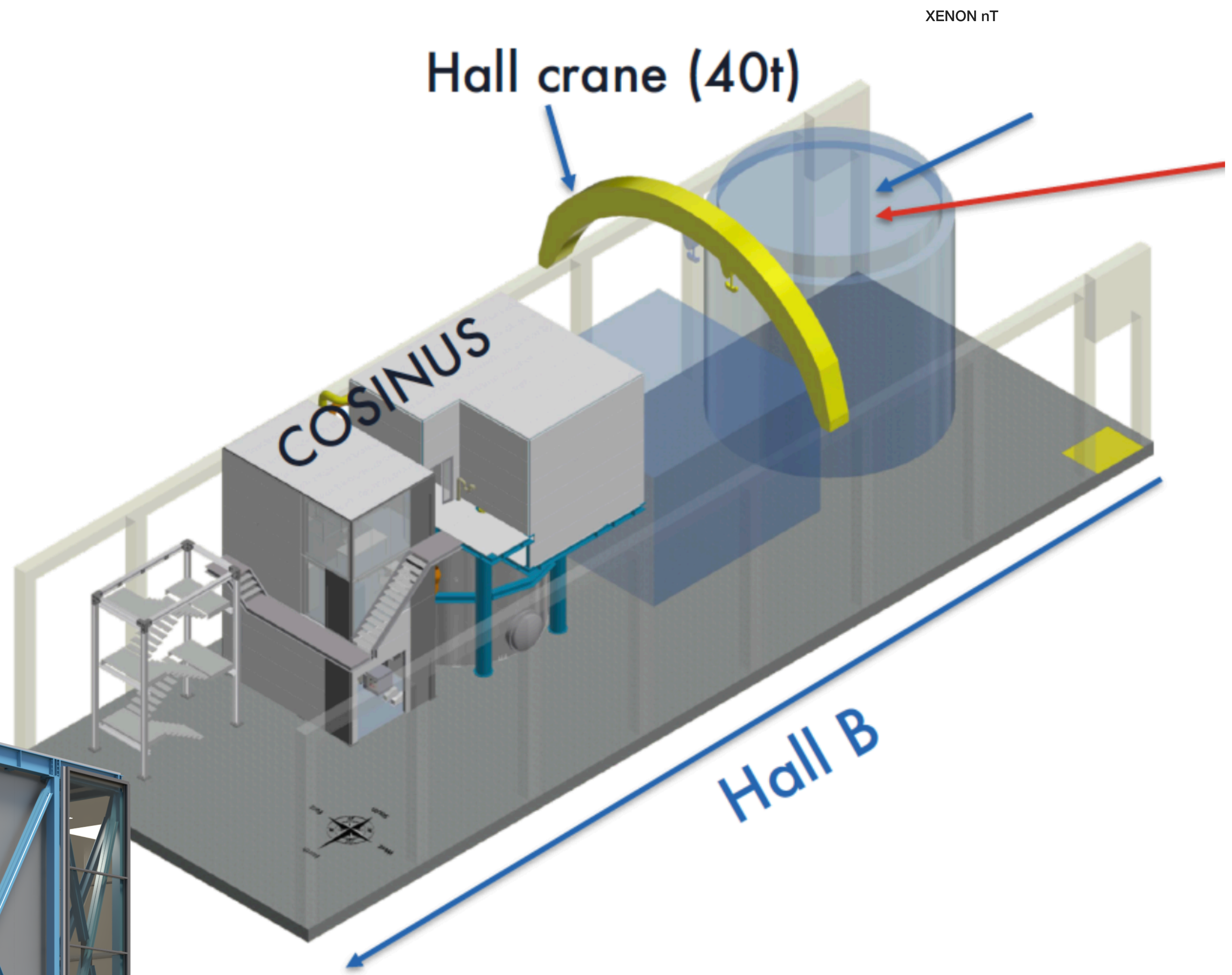


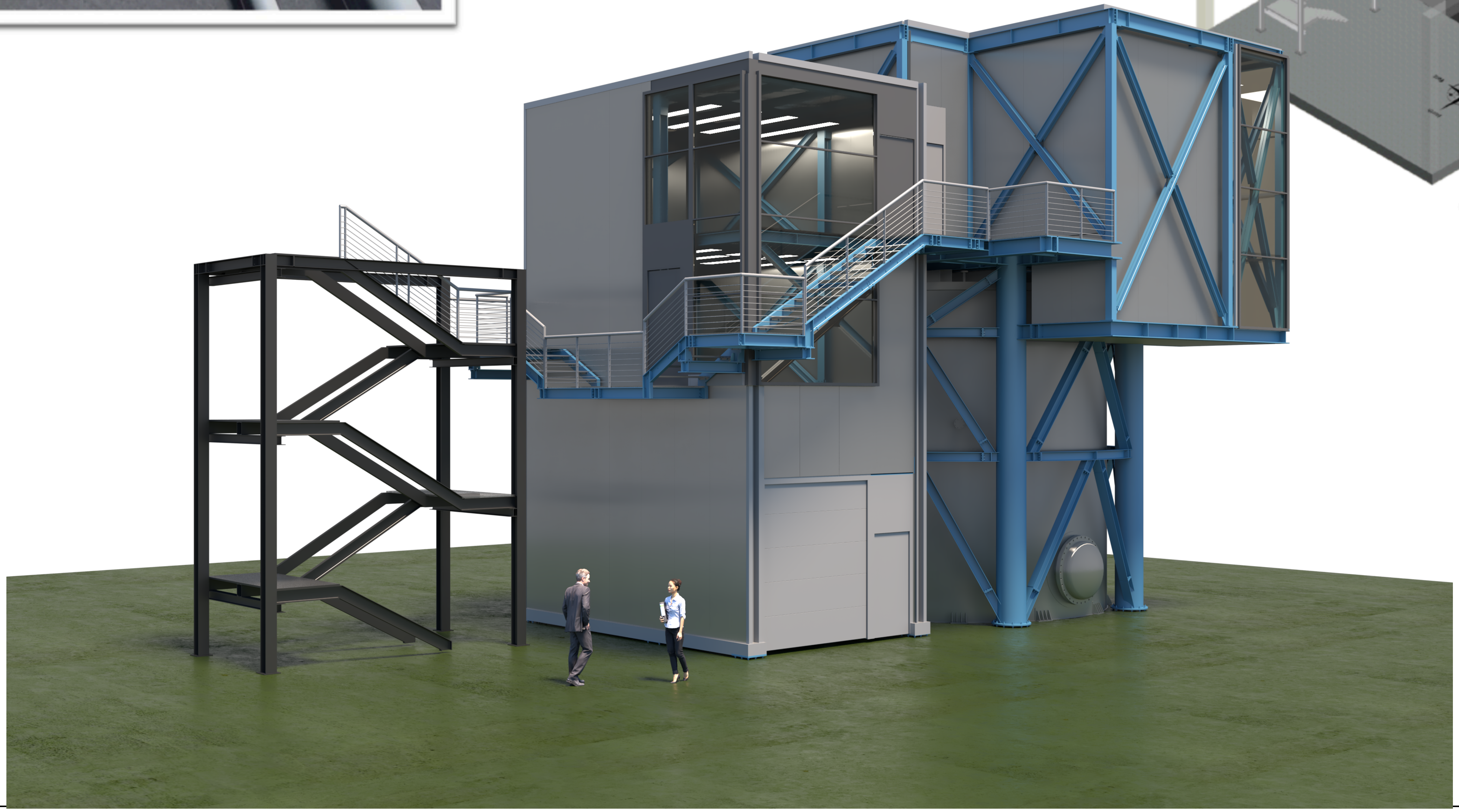
JUNE 2022 : underground measurement at CRESST test facility at LNGS

Particle discrimination demonstrated for the first time in NaI

COSINUS LOCATION







COSINUS

STATUS OF THE FACILITY CONSTRUCTION

Planned to be completed by 2023

OCTOBER 2021

WATER TANK

JANUARY 2022

DRY WELL

JUNE 2022

CLEAN ROOM

AUGUST 2022

SERVICE BUILDING

COSINUS

STATUS OF THE FACILITY CONSTRUCTION

STAY TUNED!

Planned to be completed by 2023

OCTOBER 2021

WATER TANK

JANUARY 2022

DRY WELL

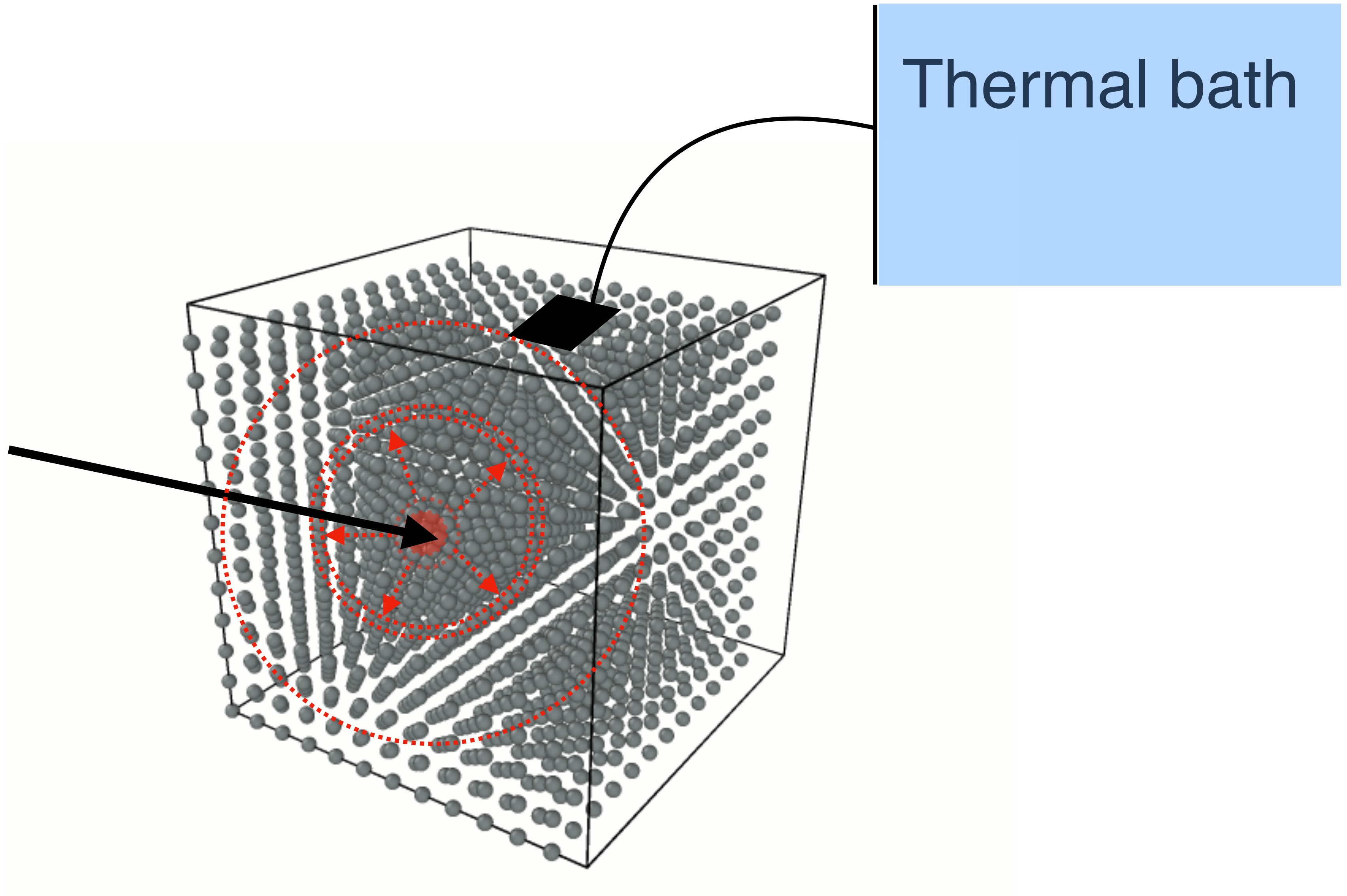
JUNE 2022

CLEAN ROOM

AUGUST 2022

SERVICE BUILDING

CRYOGENIC DETECTORS



- LOW ENERGY THRESHOLD
- DUAL CHANNEL BACKGROUND REJECTION
- LIMITS FOR DARK MATTER - NUCLEI INTERACTIONS
- LIMITS FOR DARK MATTER - ELECTRON INTERACTIONS
- SHARED EFFORT TO EXPLAIN LOW ENERGY EXCESS
- VERSATILE
- INVOLVED IN ANNUAL MODULATION SEARCHES
- WORKING PRINCIPLE UNDERSTOOD, BUT A LOT TO STILL DISCOVER…

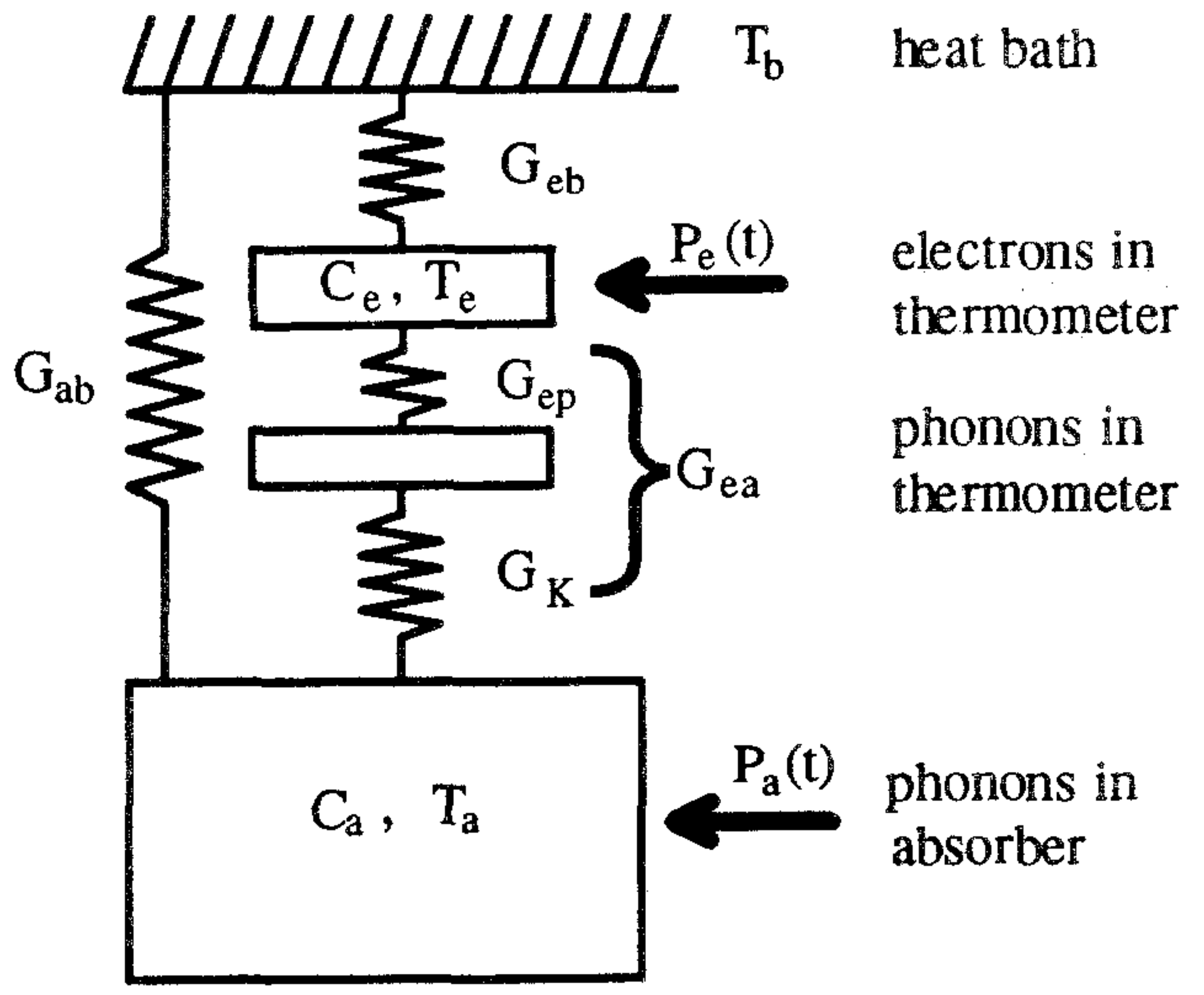
THANK YOU

BACKUP

ATHERMAL AND THERMAL PHONONS

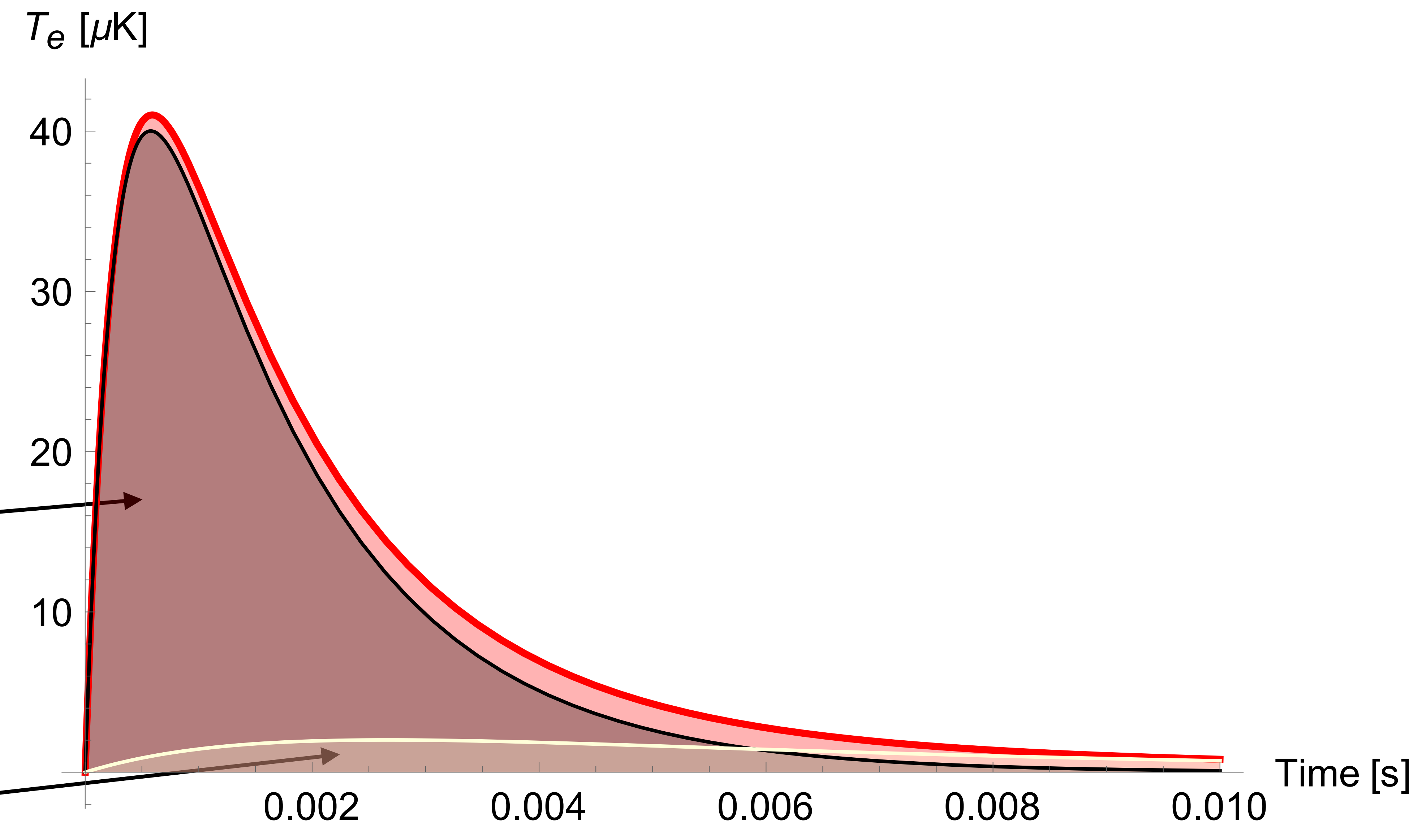
A general model for TES-based cryogenic detectors was published in 1995 by F. Pröbst et al.

J. Low Temp. Phys. 100,69 (1995))



$$\begin{cases} C_e \frac{dT_e}{dt} + G_{ea}(T_e - T_a) + G_{eb}(T_e - T_b) & = P_e(t) \\ C_a \frac{dT_a}{dt} + G_{ea}(T_a - T_e) + G_{ab}(T_a - T_b) & = P_a(t) \end{cases}$$

$$\begin{cases} \dot{\mathbf{x}}(t) & = \mathbf{A}\,\mathbf{x} + \mathbf{f}(t) \\ \mathbf{x}(t=0) & = \begin{pmatrix} T_b \\ T_b \end{pmatrix} \end{cases}$$



$$\Delta T_e(t) = \theta(t)[\underbrace{A_n\,(e^{-t/\tau_n} - e^{-t/\tau_{in}})}_{Non-thermal} + \underbrace{A_t\,(e^{-t/\tau_t} - e^{-t/\tau_n})}_{Thermal}]$$

SuperCDMS HISTORY

CDMS
Stanford Underground Facility
BLIP (Ge, NTD) detectors
ZIP (Si, TES) detectors
completed
- *Phys. Rev. D 66* (2002) *122003* (BLIP)
- *Phys.Rev. D 68* (2003) *082002* (ZIP)

>1996

CDMS-II
Soudan Underground Lab.
ZIP detectors (Ge, Si, TES)

completed
- *NIMA Volume 444, Issues 1–2 (2000), Pages 308-311*
- *Applied Physics Letters **100**, 232601 (2012)*

> 2005

SuperCDMS Soudan
Soudan Underground Lab.
iZIP, CDMSlite, HV, HVeV, CPD

ongoing
- *J Low Temp Phys* (2014) *176:959–965* (iZIP)
- *Phys.Rev.D* 97 (2018) 2, 022002 (CDMSlite)
- PRL 121, 051301 (2018) (HVeV)
- *Appl.Phys.Lett.* 118 (2021) 2, 022601 (CPD)

> 2009

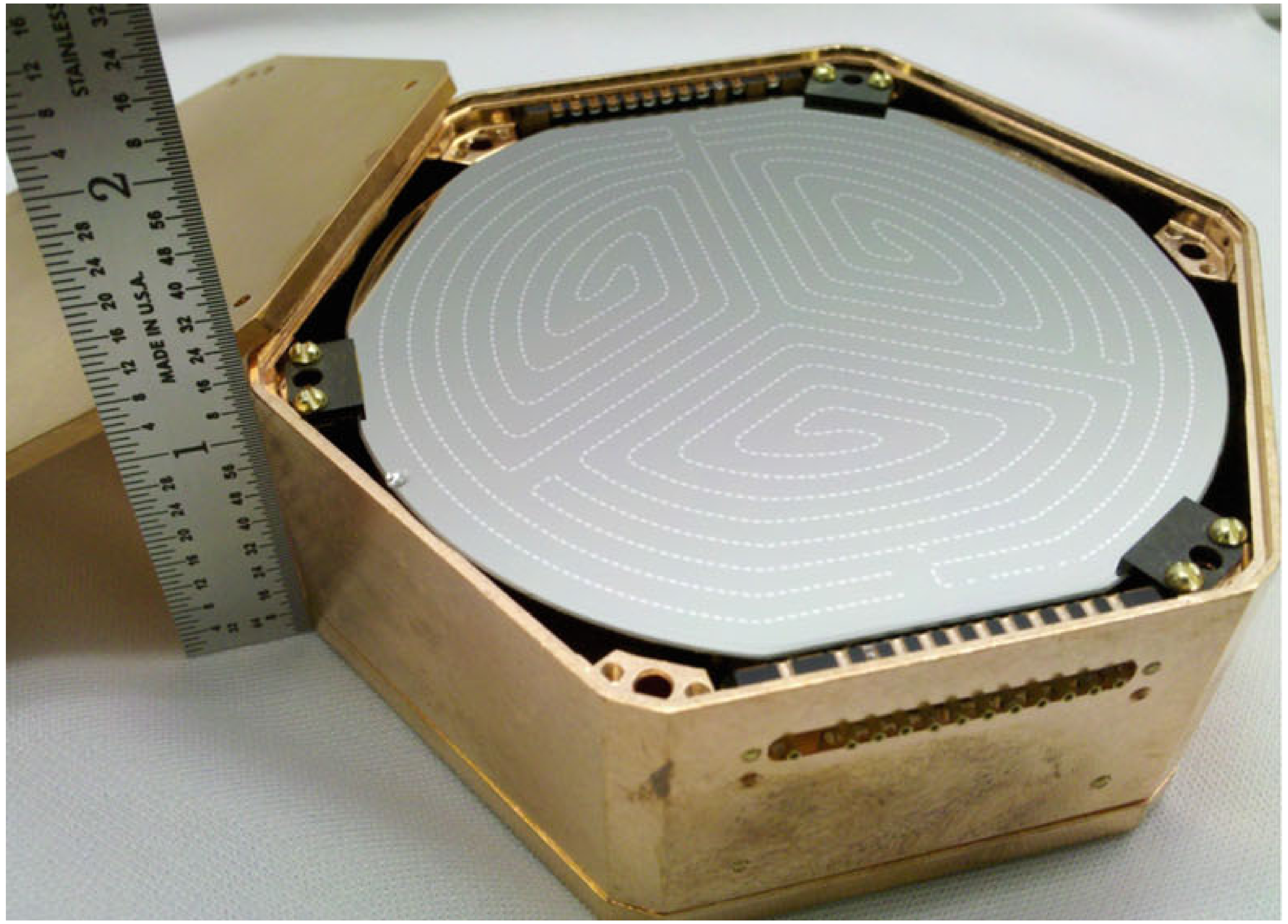
SuperCDMS SNOLAB
SNOLAB

under construction

today

- BLIP: Berkley Large Ionization-and-Phonon-mediated detector
- ZIP: Z-sensitive Ionization-and-Phonon-mediated detector
- iZIP: interleaved ZIP (a ZIP detector where the electrodes are interleaved with the phonon detector)
- CDMSlite: Cryogenic Dark Matter Search low ionization threshold experiment (high voltage, 50–80 V)
- HV: High Voltage (high voltage, ~100 V, not different from CDMSlite)
- HVeV: High Voltage eV resolution (a gram-scale ZIP high-voltage prototype with eV-scale resolution, 140 V)
- CPD: Cryogenic PhotoDetector (45.6 cm^2 area instrumented with QETs, of a 1mm thick Si-detector, $\sigma_E \simeq 3.9\ eV$)

SuperCDMS Soudan (iZIP)



Location: Soudan Underground Laboratory

Absorber: Ge - 15 cylinders, 0.62 kg each

Thermometer: TES in a QET configuration

Base temperature: 50 mK

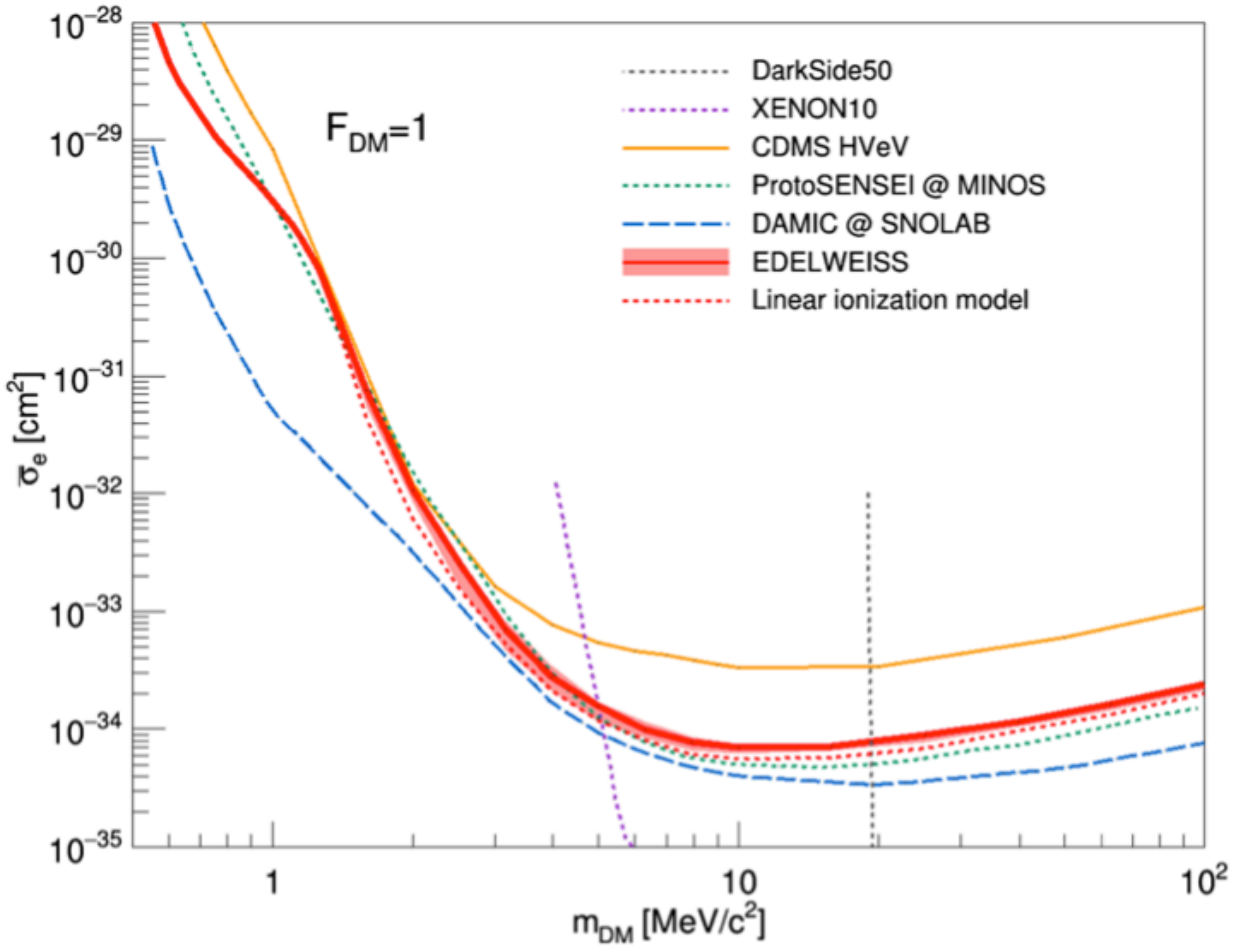
Dual channel: ionisation and phonons

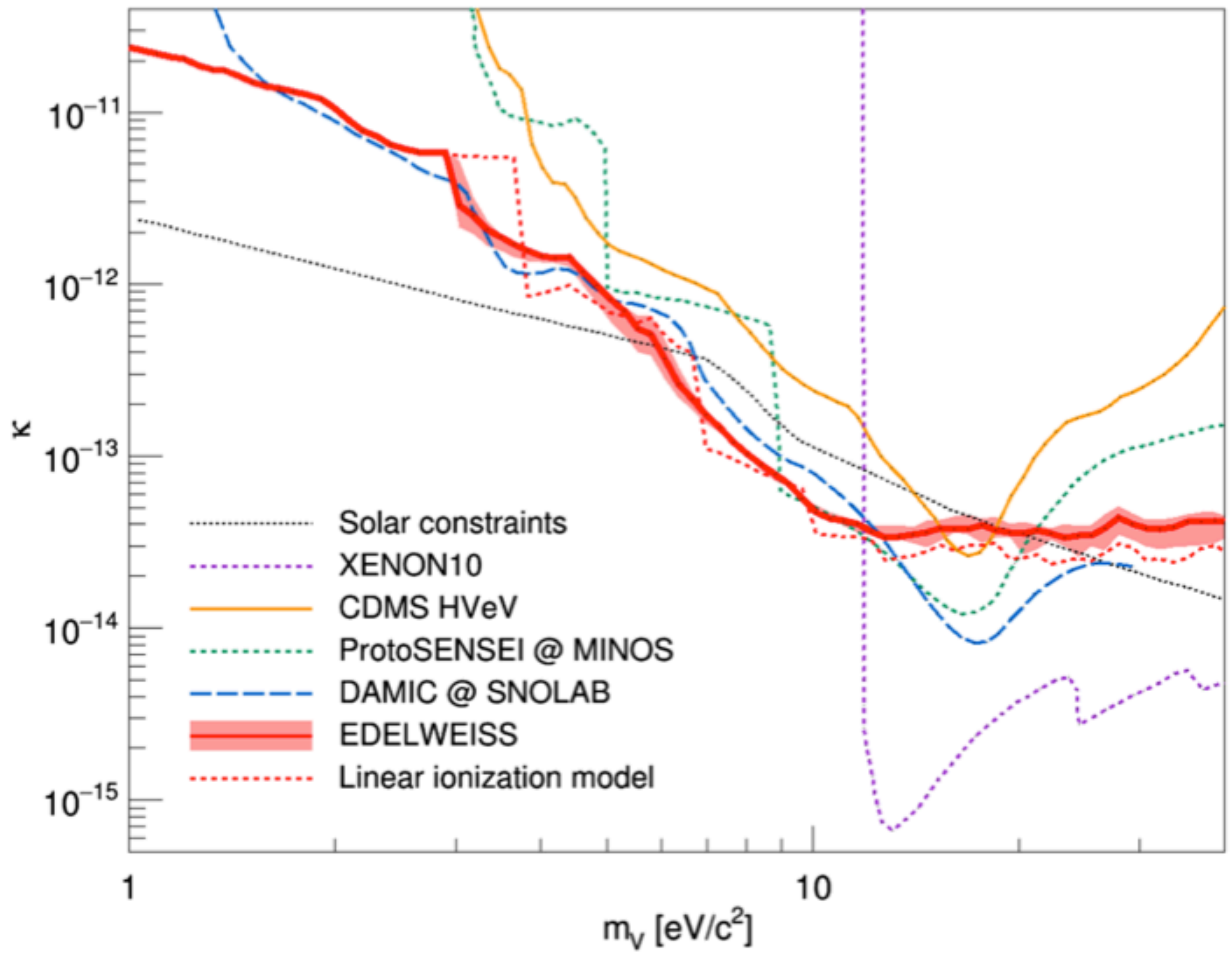
More details: interleaved z-sensitive ionisation and phonon detectors (iZIPs) measure ionization and athermal phonons from particle interactions with sensors (TESs) on both sides of the Ge crystal

Pulse shape from primary phonon absorption depends on position Luke-Neganov phonons enhance the position dependence, as they are emitted as electron-hole drifts near the surface and have frequencies of 0.3 and 0.7 Hz. Potential for pulse shape discrimination at the low energies where the ionisation signal is not produced anymore.

Anderson, A. Phonon-Based Position Determination in SuperCDMS iZIP Detectors. *J Low Temp Phys* **176**, 959–965 (2014). https://doi.org/10.1007/s10909-013-1015-2

SENSITIVITY CURVES





Phys.Rev. Lett 125 (2020) 141301

COSINUS TIME SCHEDULE