
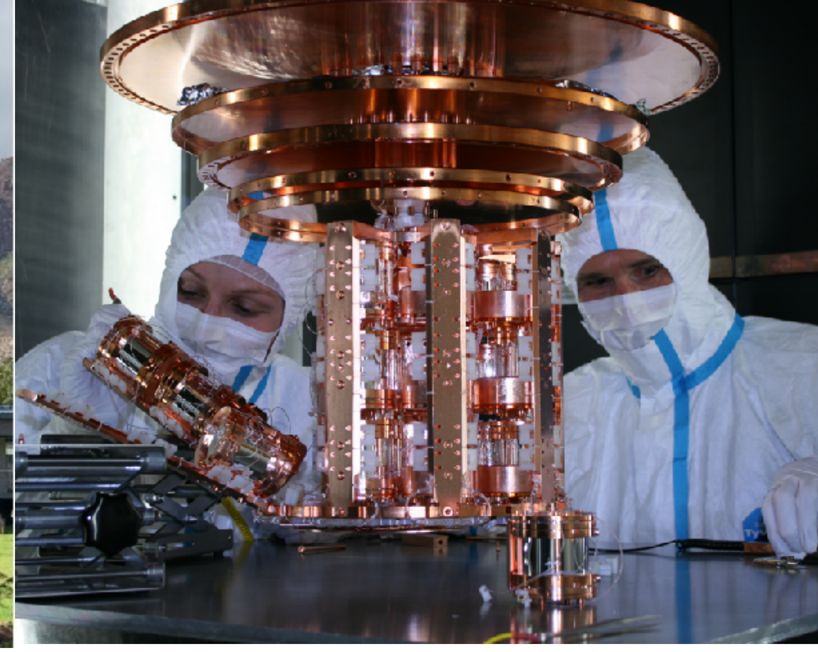


Dark Matter Searches with the Cryogenic Experiments **CRESST** and **COSINUS**

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(https://cresst-experiment.org/)(https://cosinus.it/)

COSINUS

CRESST

HEPHY
INSTITUT FÜR HOCHENERGIEPHYSIK

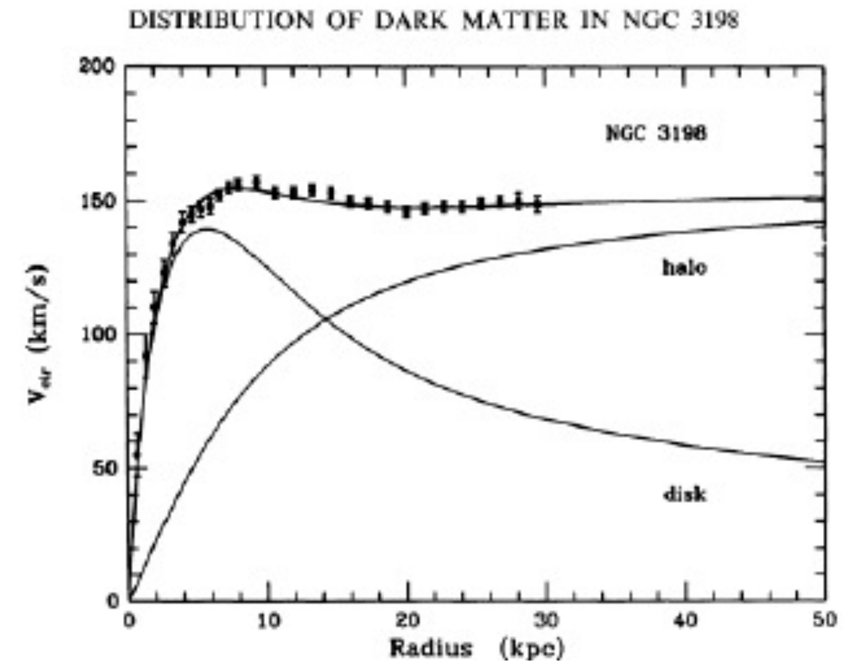
ÖAW
ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

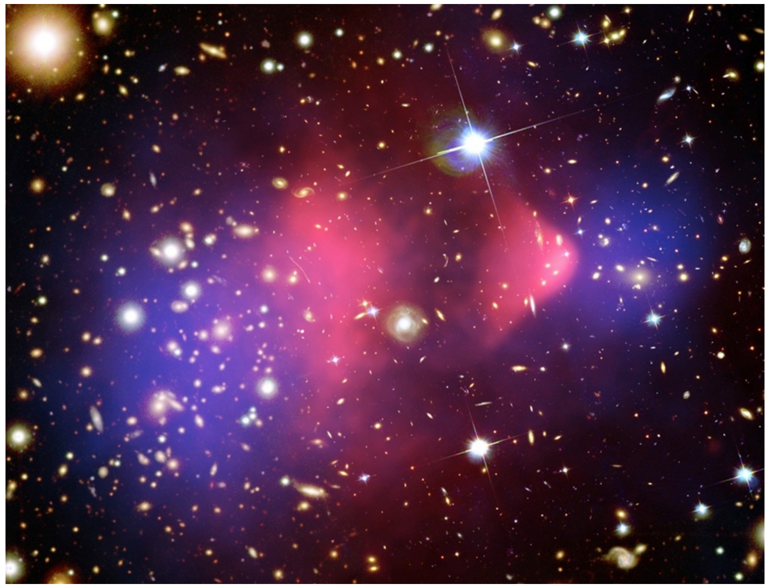
TU WIEN
TECHNISCHE UNIVERSITÄT WIEN

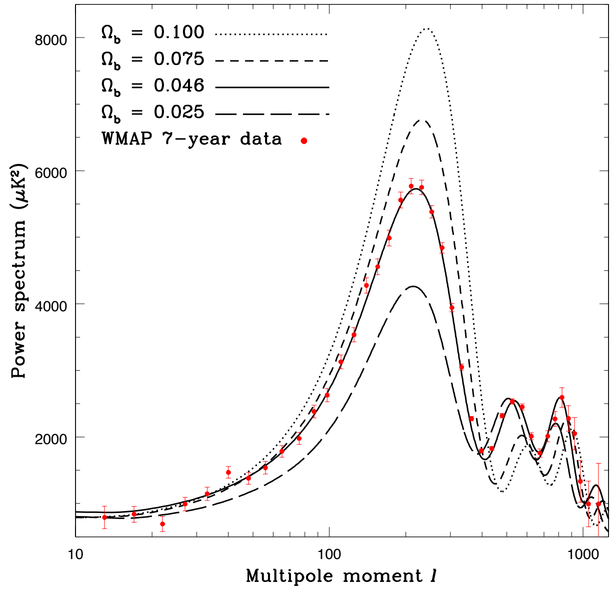
Evidence for Dark Matter

- **Rotation curves of galaxies**
  - Arms of spiral galaxies rotate faster than anticipated
- **Gravitational lensing**
  - Light of distant galaxies is bent by gravitational potential
- **Temperature fluctuations of microwave background**
  - Acoustic oscillations depend on dark matter density
- **Bullet cluster**
  - Collision-less penetration of two massive galaxies
- **Structure formation**
  - Observed present-day structure requires Dark Matter

Several observations on astrophysical scales can not be explained with particles or forces from the Standard Model of Particle Physics



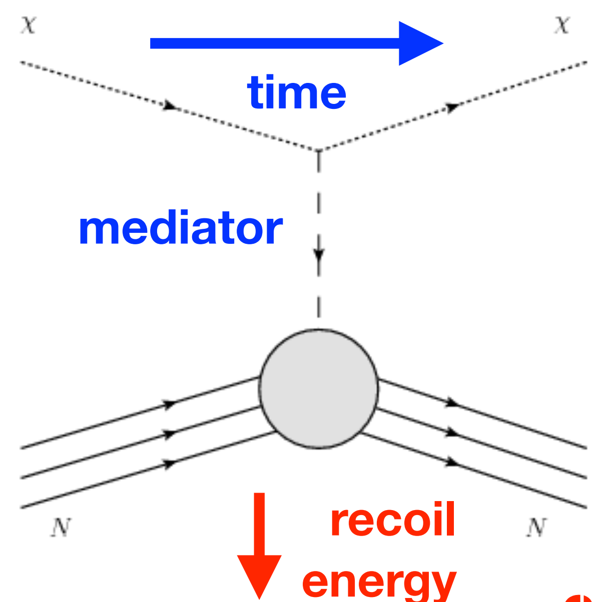


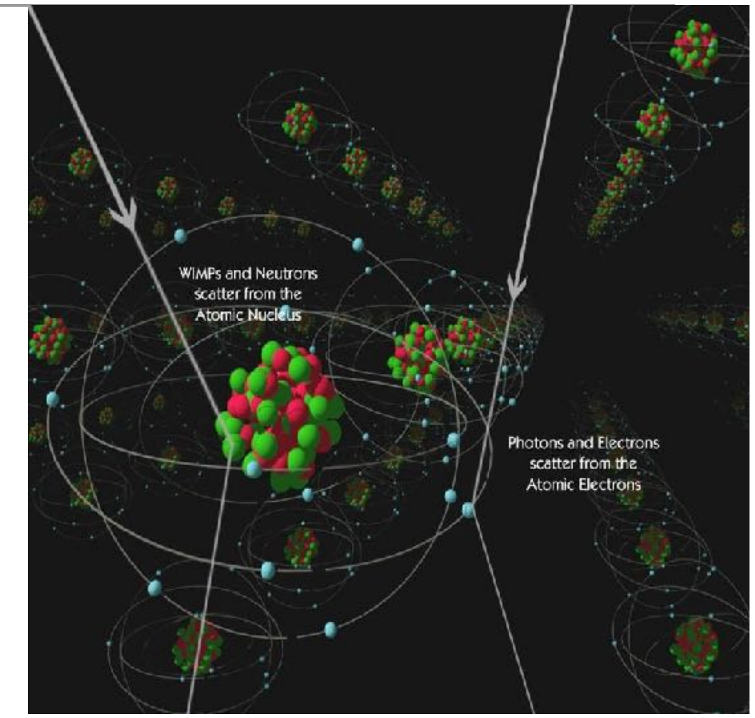


Direct Detection of Dark Matter - Basic Principle

- Weakly interacting massive particles scatter elastically with baryonic matter

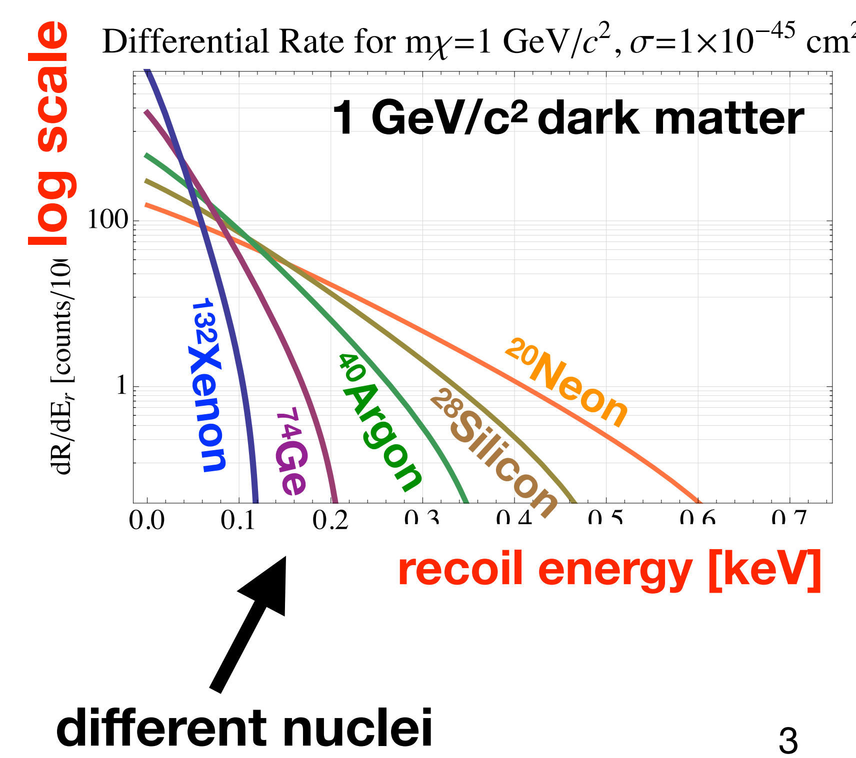
  1. **Recoil** of nucleus leads to
  2. Deposition of **energy** followed by
  3. Measurement of deposited energy
  4. With at least one **readout channel**





- Exact interaction rate (=cross section) and amount of deposited energy (=mass of dark matter particle) are unknown

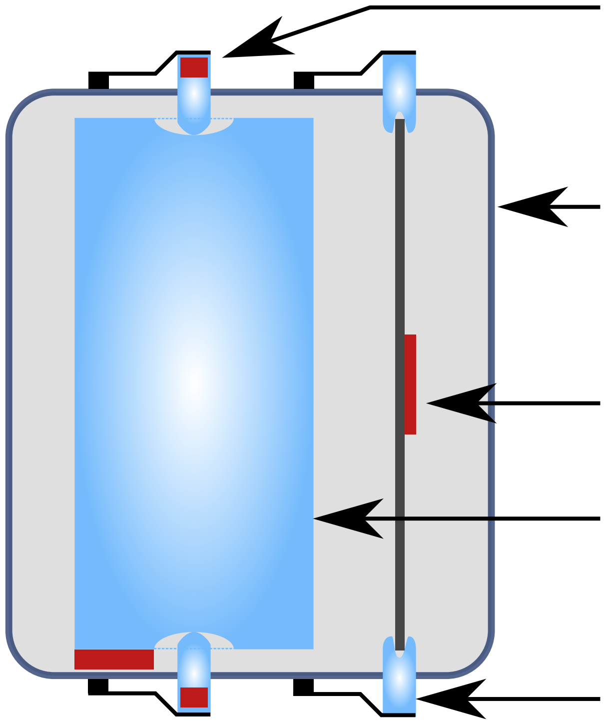
- **Low mass dark matter requires sensitivity to low energy deposition ~ 10 eV**



Scintillating Calorimeters - Detection Principle I

Simultaneous read-out of two signals

- **Phonon channel:**
particle independent measurement of deposited energy
(= nuclear recoil energy)



- **(Scintillation) light:**
different response for signal and background events for background rejection ("quenching")

Scintillating Calorimeters - Detection Principle II

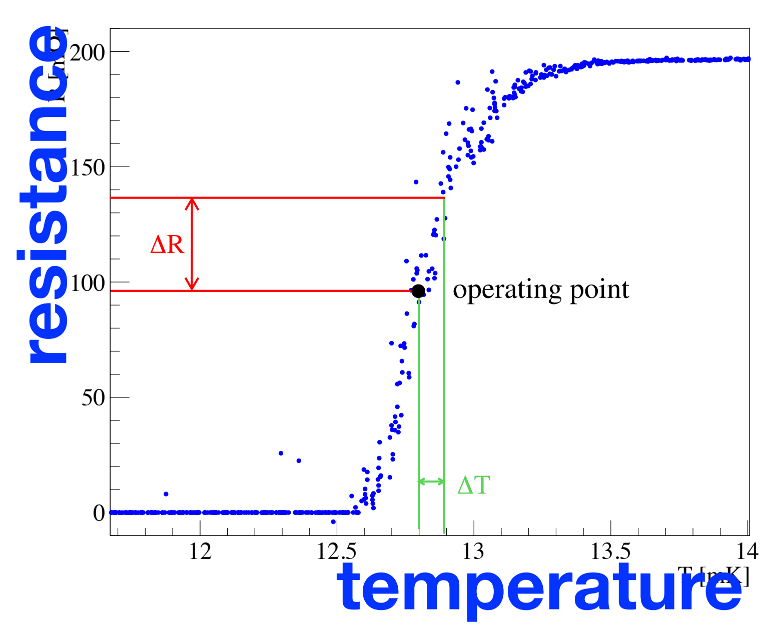
- Experiment operated at **cryogenic** temperature (~15 mK)
- Nuclear recoil will deposit energy in the crystal leading to a **temperature rise** proportional to energy

$$\Delta T \propto \frac{\Delta Q}{c \cdot m}$$

$$c \propto (T/\theta_D)^3$$

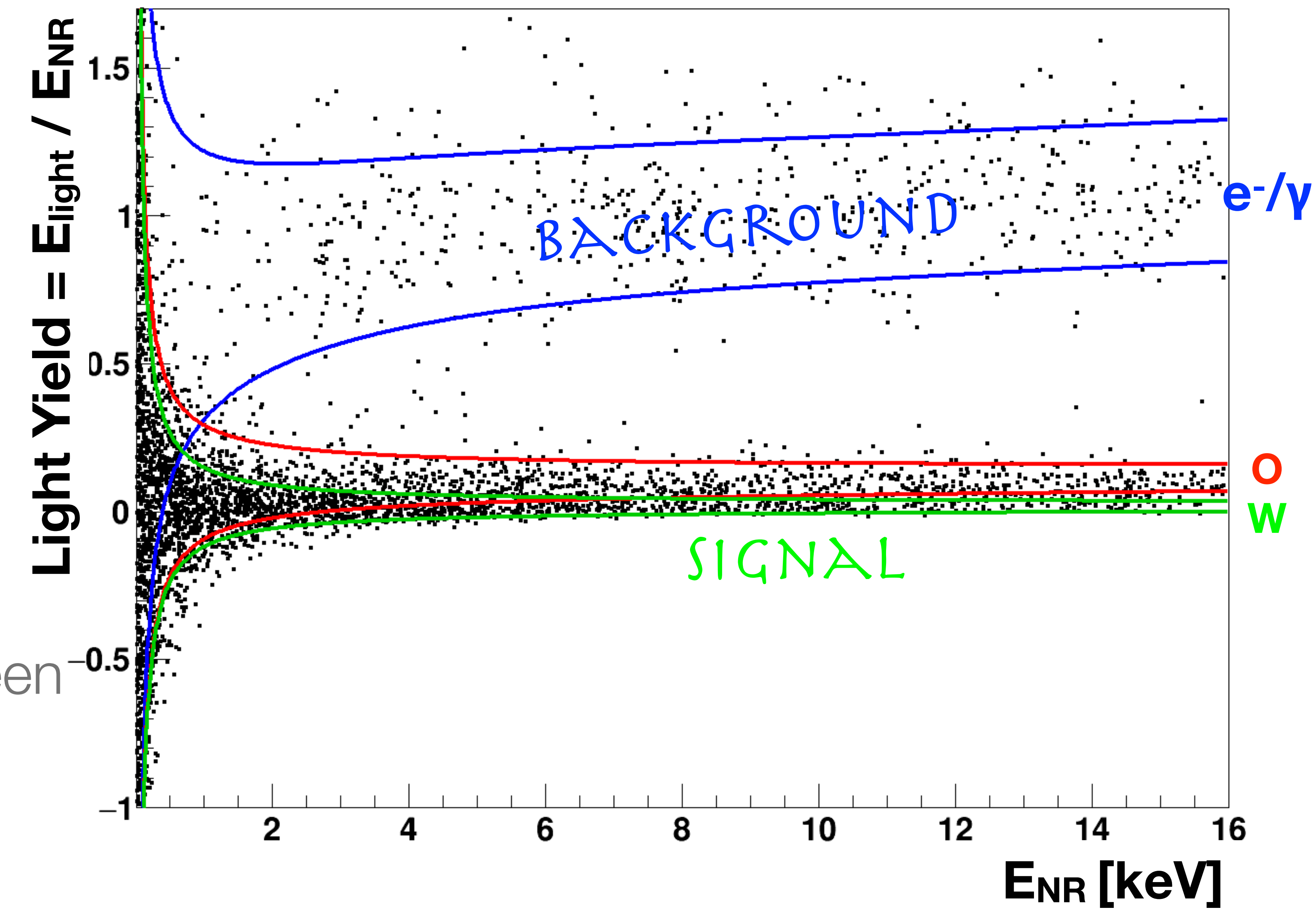
Θ_D:Debye temperature

- Detection of small energy depositions requires very **small heat capacity c**
- Detection of temperature rise with superconductor operated at the phase transition from **normal to superconducting**



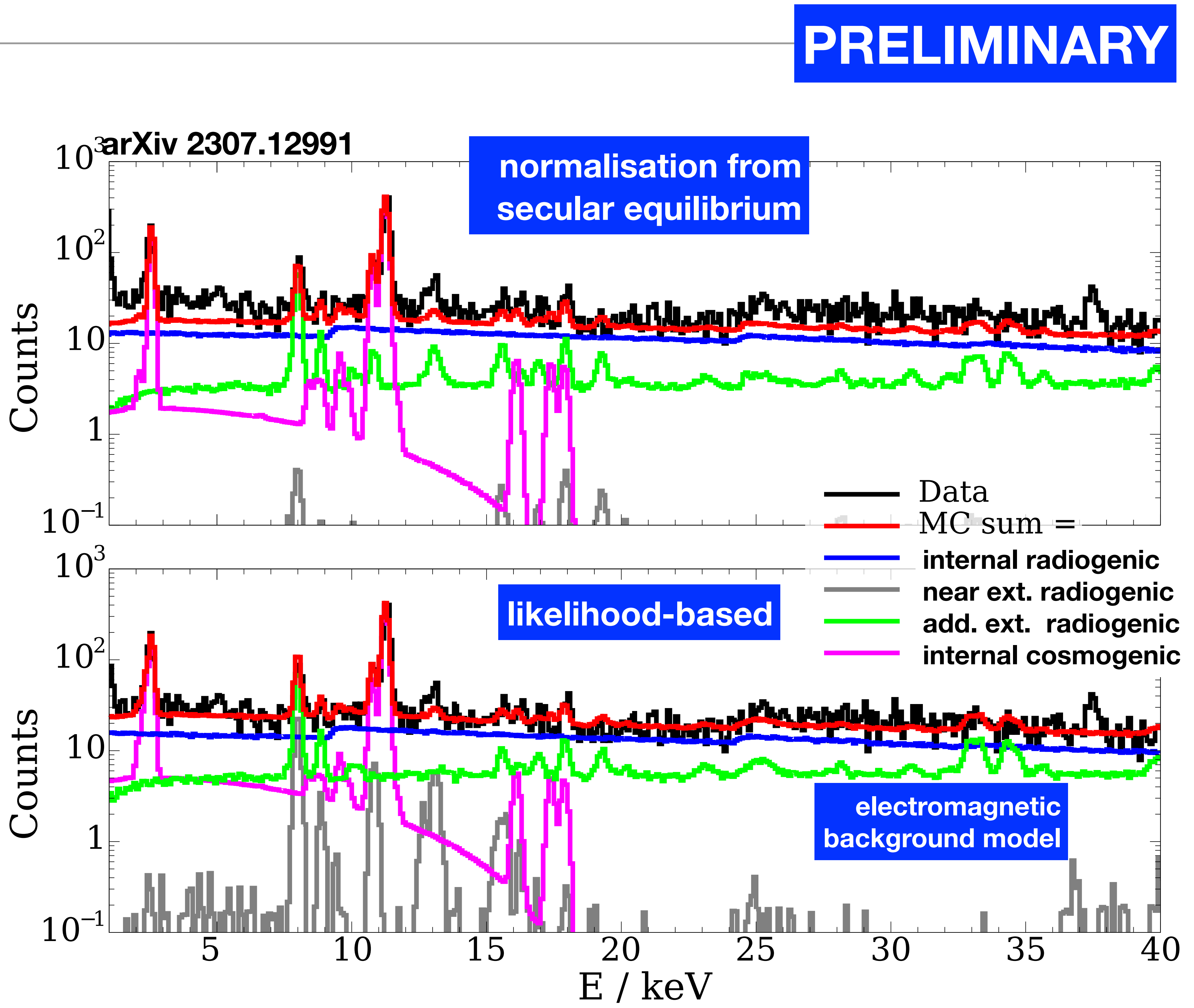
Signal-Background Separation

- Simultaneous readout of light and phonon channel allows background reduction
- Less scintillation light for nuclear recoils ("quenching")
  - Clear separation between signal and background at large E_{NR}
  - **Significant overlap of bands at low energies (= low mass dark matter)**

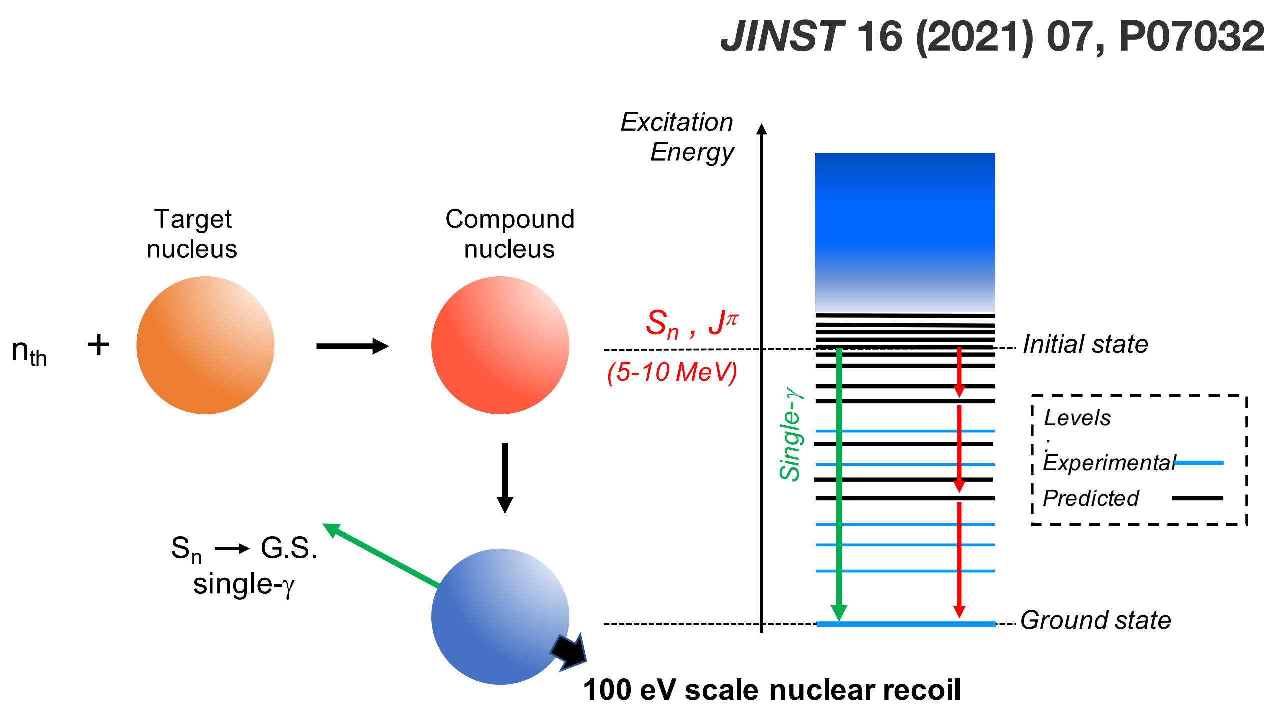


Background Simulation for CRESST

- **Geant4 based simulation of background contribution and composition**
- **Simulation reproduces ~80% of the observed events in the region of interest [1 keV, 40 keV]**



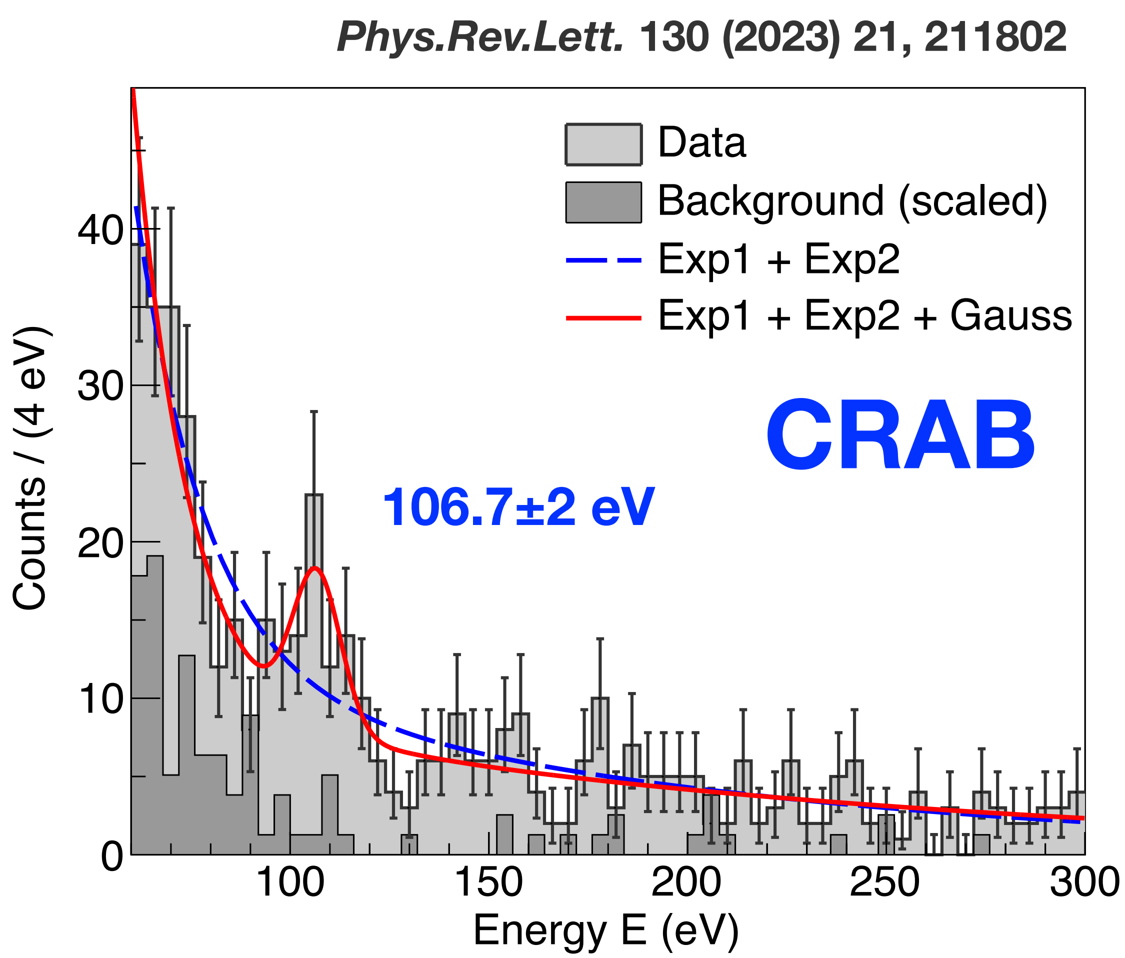
Energy Calibration using Neutron Capture Events

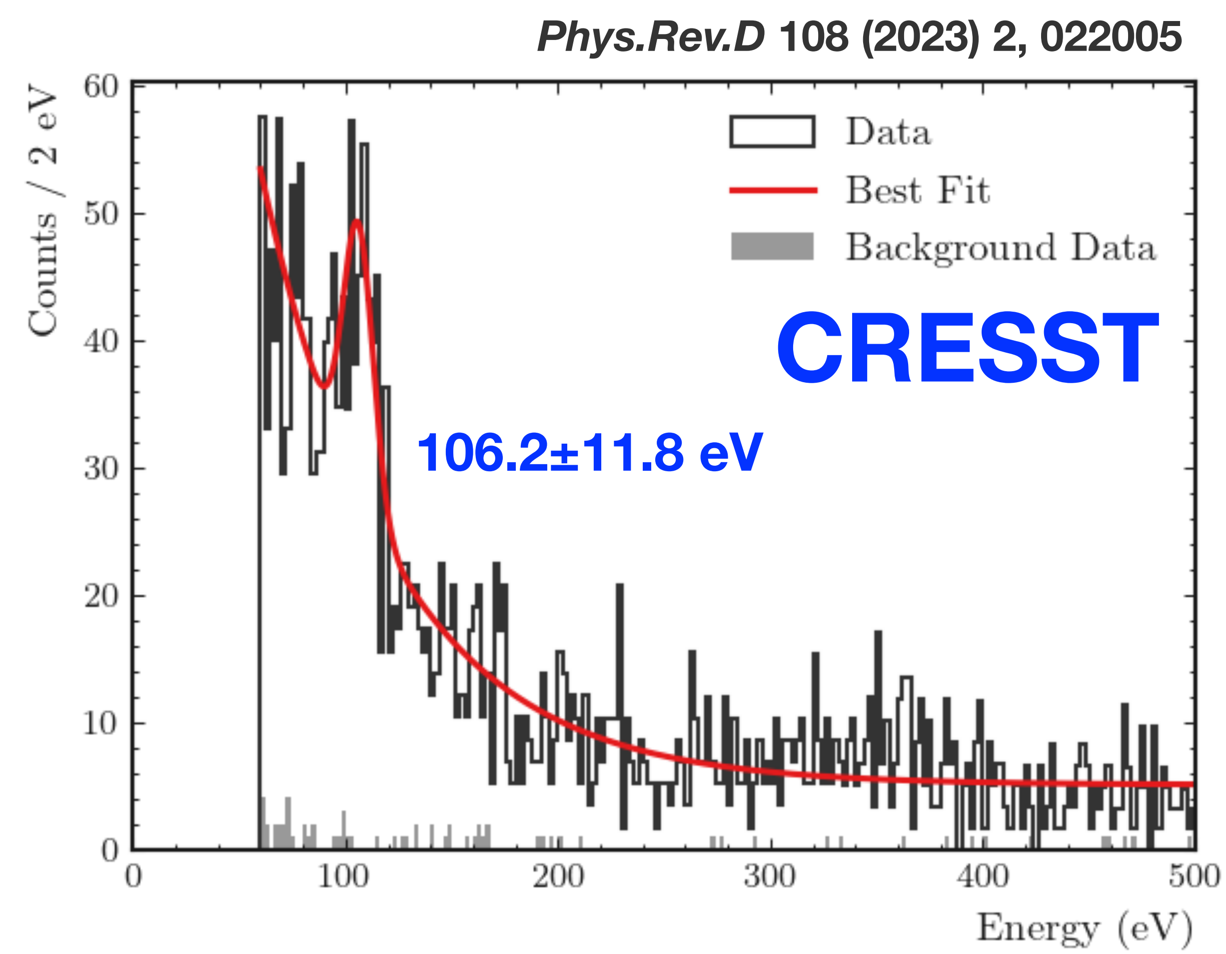


- Several tungsten isotopes have a high cross-section $\mathcal{O}$(20 b) for **neutron-capture**
- Subsequent **γ-emission** with energy transfer to the nucleus → **nuclear recoil**
- γ escapes undetected
- neutron capture of ^{182}**W** (27%) produces a recoil energy of **112.4 eV**

- **Energy calibration performed with keV X-ray sources** (e.g. ^{55}Fe@5.9 keV and 6,5 keV) and **extrapolated** towards lower energies
- **Calibration in $\mathcal{O}$(100 eV)** energy region is of great interest

Energy Calibration using Neutron Capture Events





- Irradiation with **neutron source** (^{252}Cf, AmBe)
- **Significant recoil peak** of ^{182}W neutron capture with subsequent γ-emission
- Dedicated experiment with neutrons from a reactor in preparation **CRAB**

Results from the CRESST Experiment

The CRESST Collaboration

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

TECHNISCHE UNIVERSITÄT MÜNCHEN

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

INFN LNGS

HEPHY INSTITUT FÜR HOCHENERGIEPHYSIK

TU WIEN

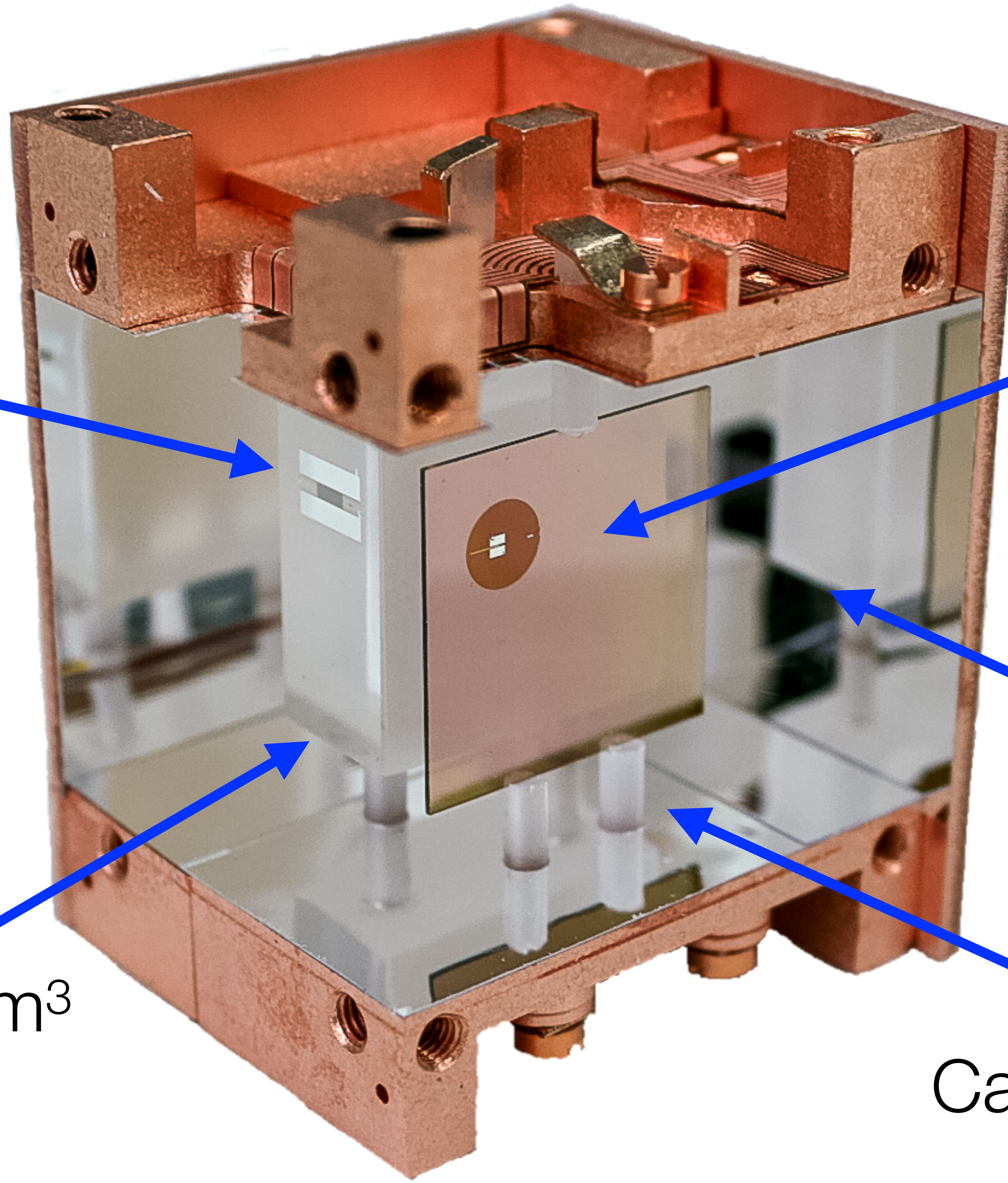
UNIVERSITY OF OXFORD

UNIVERSITAS COMENIANA BRATISLAVENSIS MCMXIX

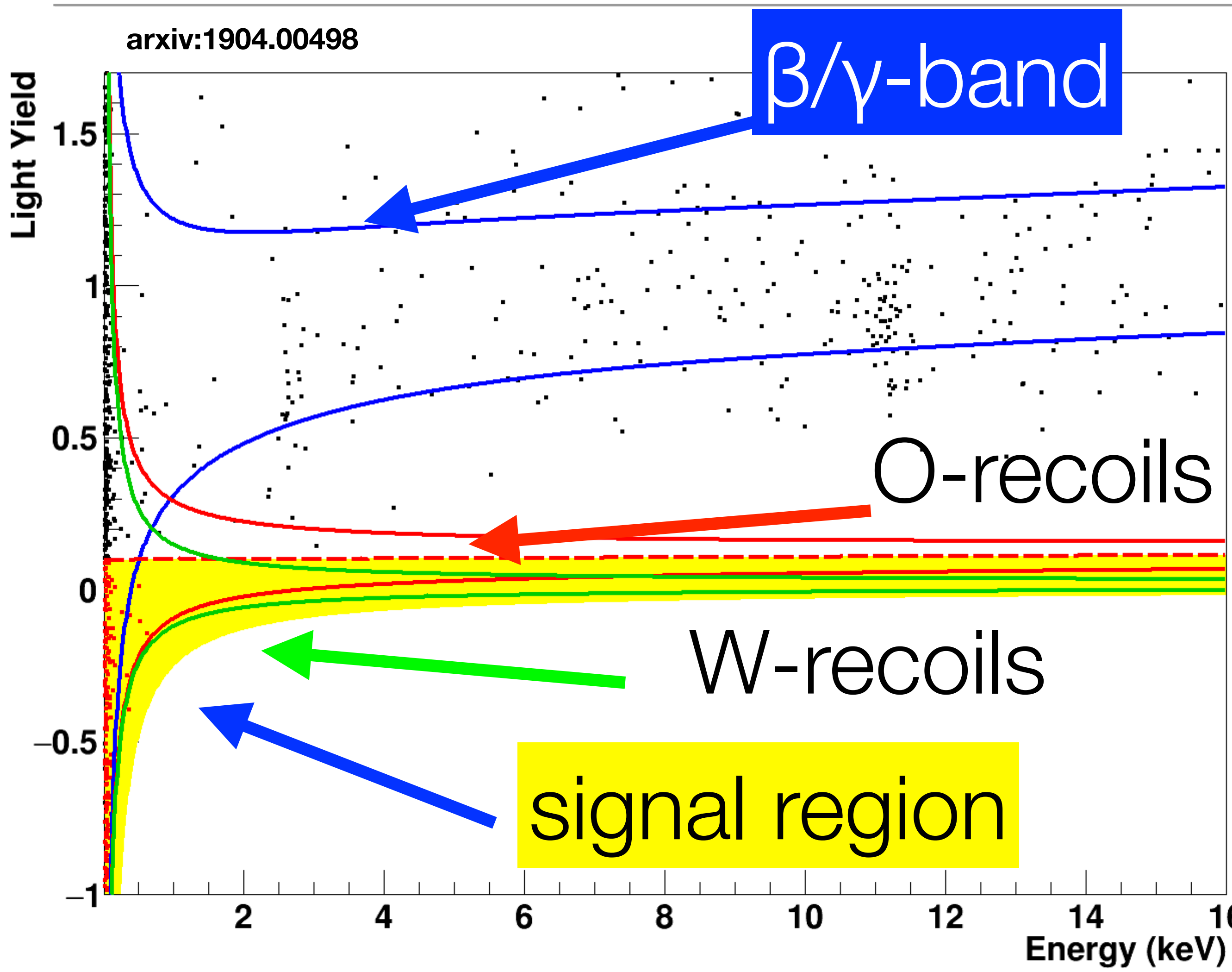
UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

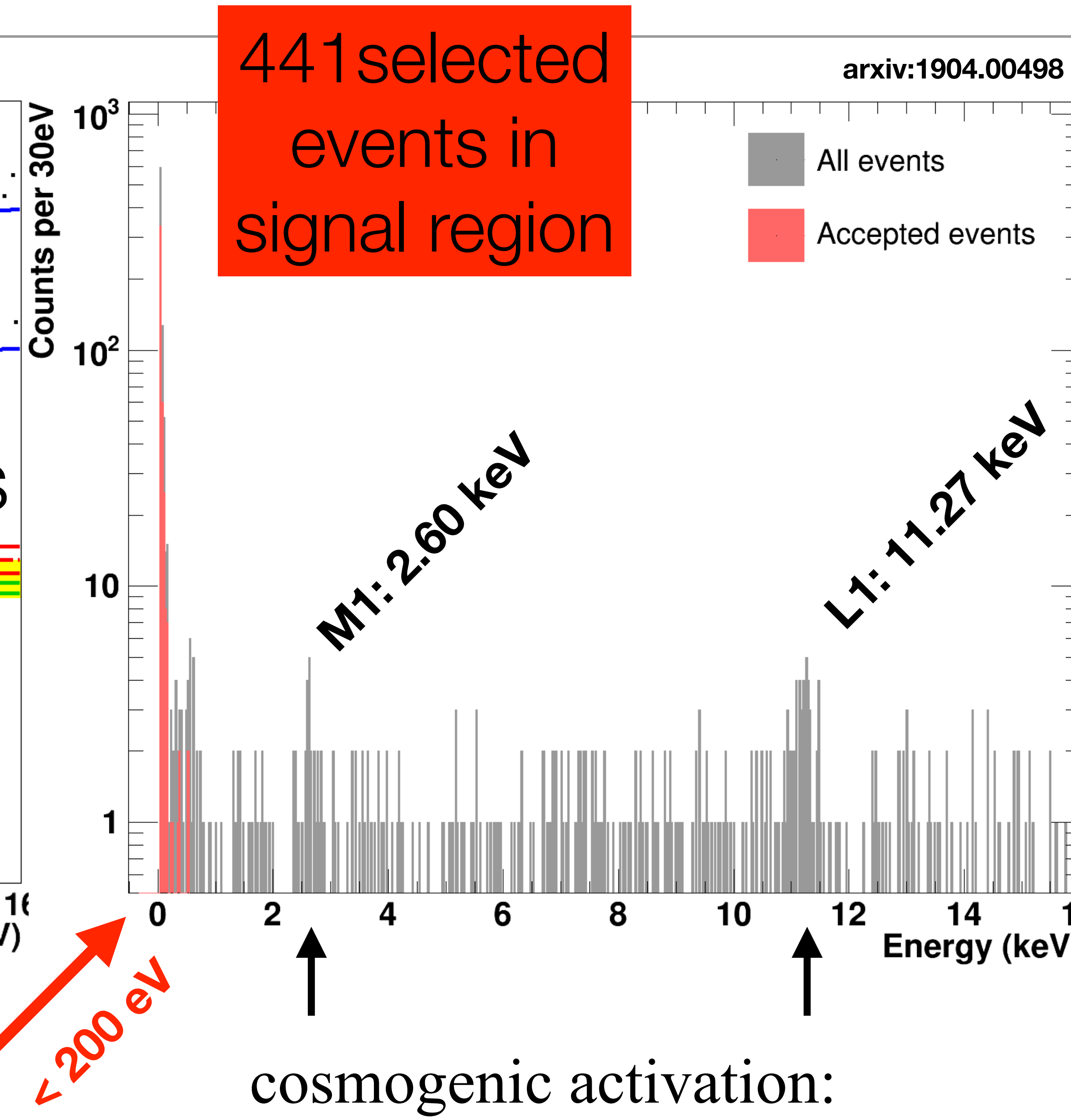
about 60 scientists from
9 institutions and 5 countries

CRESST III - Detector Module



CRESST III - Selected Data



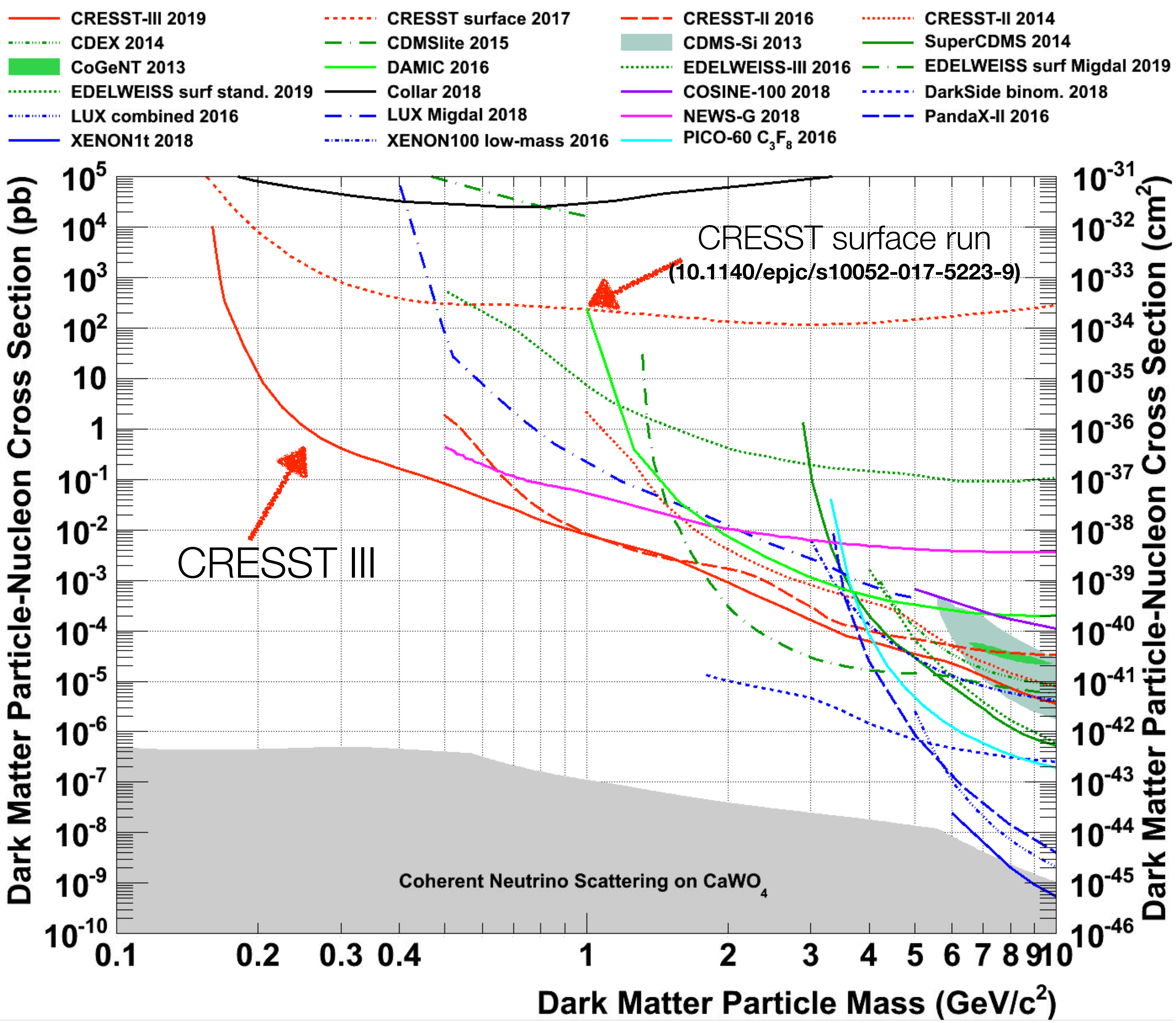


cosmogenic activation:

$$^{182}\mathrm{W} + \mathrm{p} \rightarrow {}^{179}\mathrm{Ta} + \alpha, \quad {}^{179}\mathrm{Ta} \xrightarrow{\mathrm{EC}} {}^{179}\mathrm{Hf} + \gamma.$$

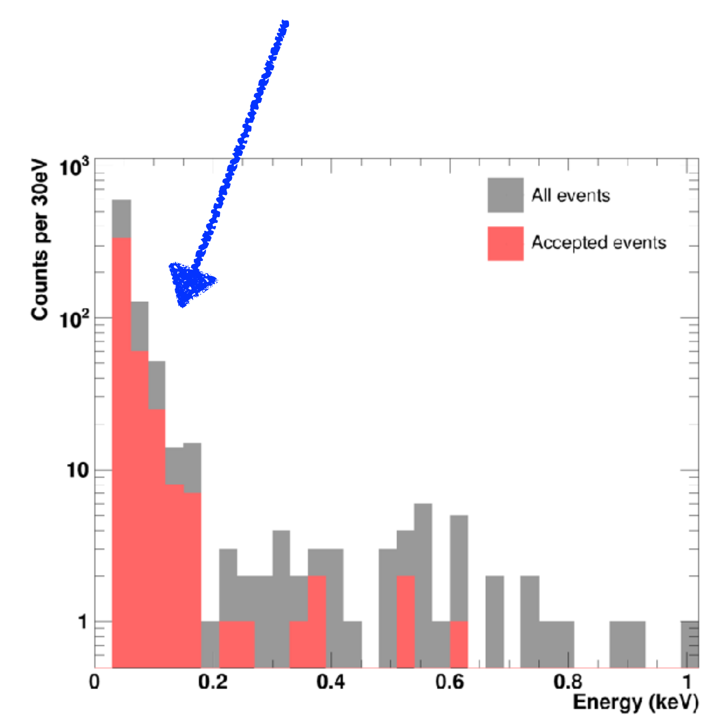
- number of events exponentially increasing for low energies

Limit on Spin-independent Dark Matter



Phys. Rev. D 100, 102002 (2019)

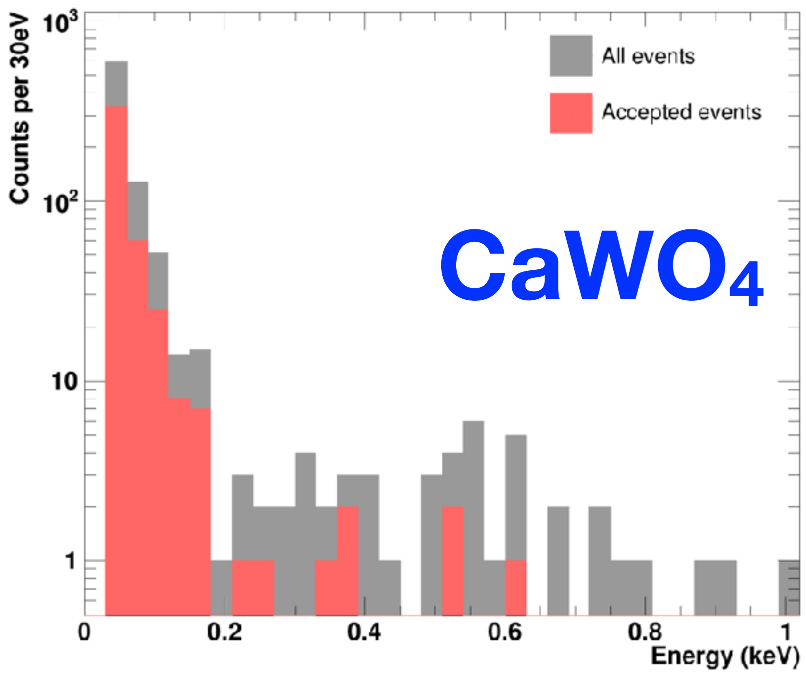
- extend sensitivity down to 160 MeV/c^2
- **unexpected rise of event rate below 200 eV**



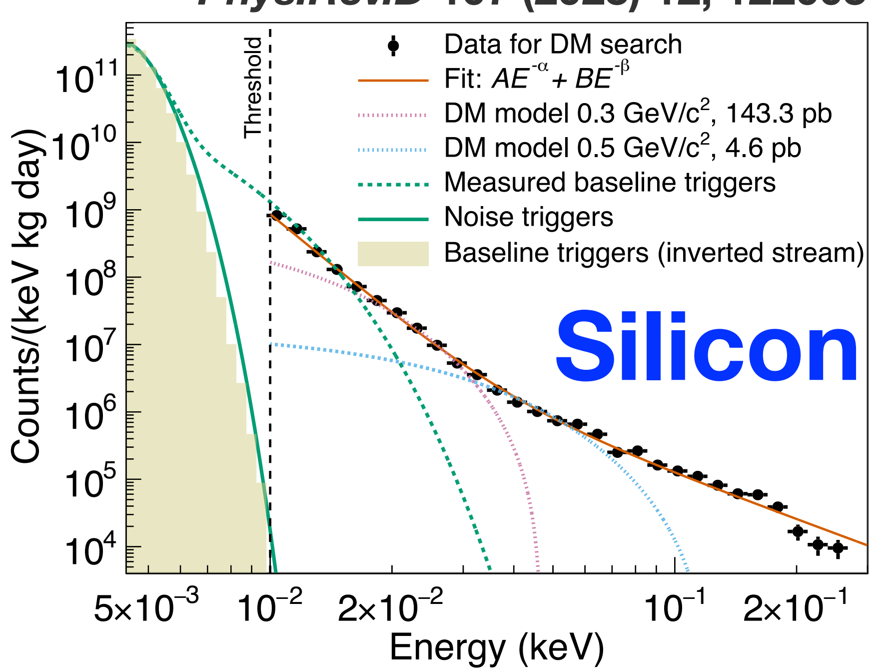
Rising background towards low Energies -
the low Energy Excess (LEE)

Low Energy Excess - the Observation

Phys.Rev.D 100 (2019) 10, 102002



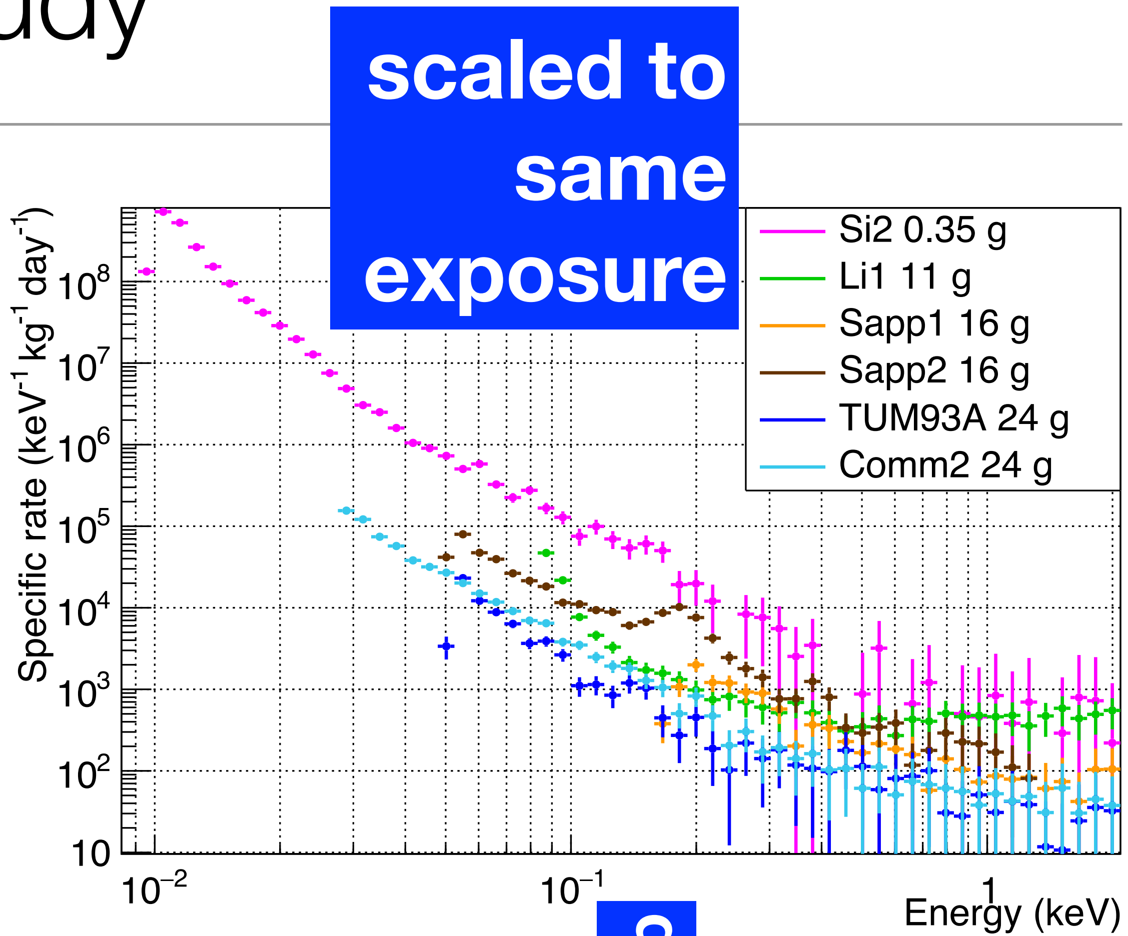
Phys.Rev.D 107 (2023) 12, 122003

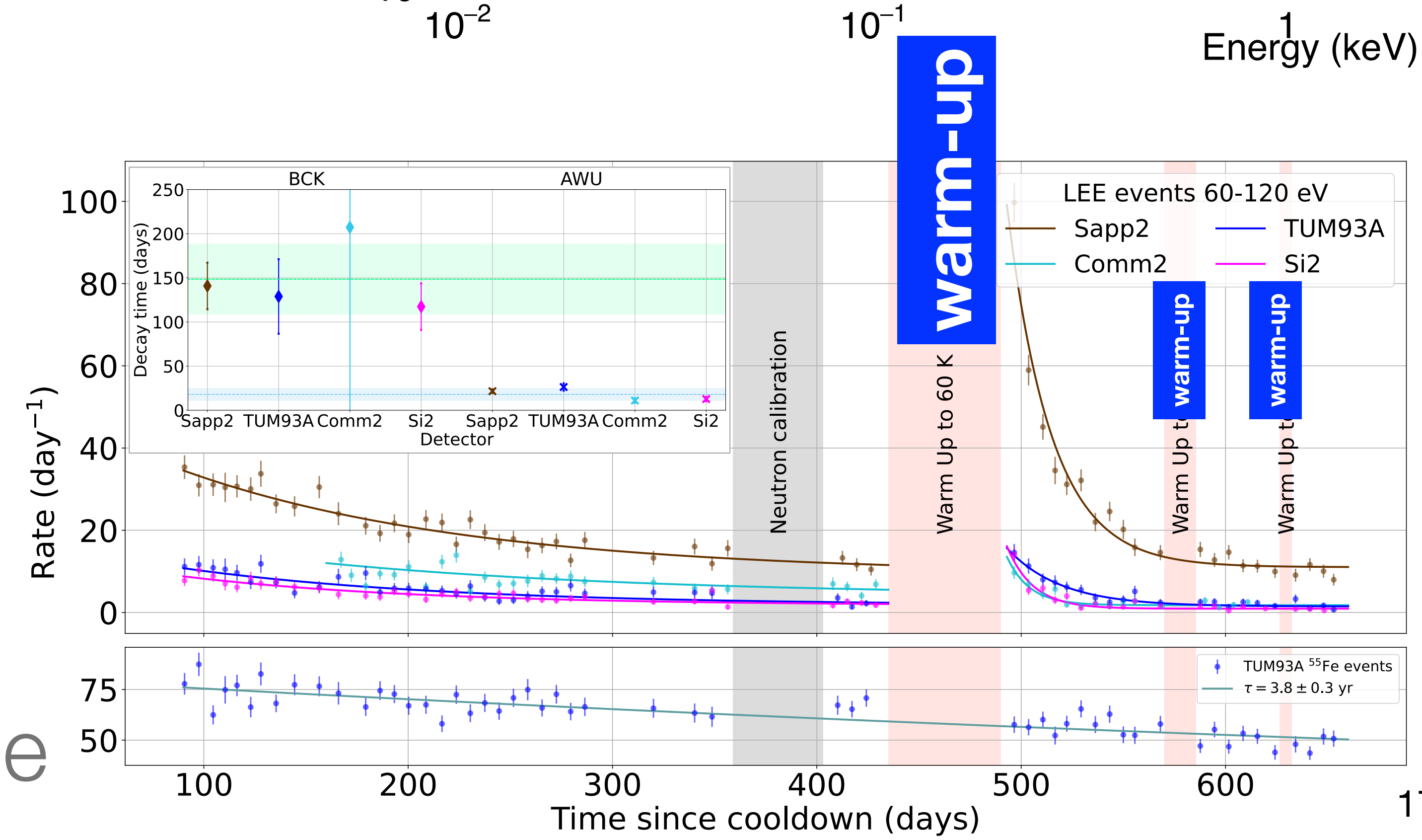


- The non-observation of a potential dark matter signal in the “classical” WIMP region led to an opening **toward lower energy regions**
- Starting from ~200 eV nuclear recoil observation of **unexpected exponential crowing background**
- Similar observations by **different experiments**
- Unexplained origin of background **limits searches** in the **sub-GeV mass region**

Low Energy Excess - the Study

- Joint workshop serious among low-energy experiments aka **EXCESS-Workshop**
- **dark matte**r, **radioactivity** and **scintillation light** can be excluded as origin
- **more investigations** are currently ongoing
- **5th workshop** foreseen July 6th, 2024, INFN / La Sapienza, Rome



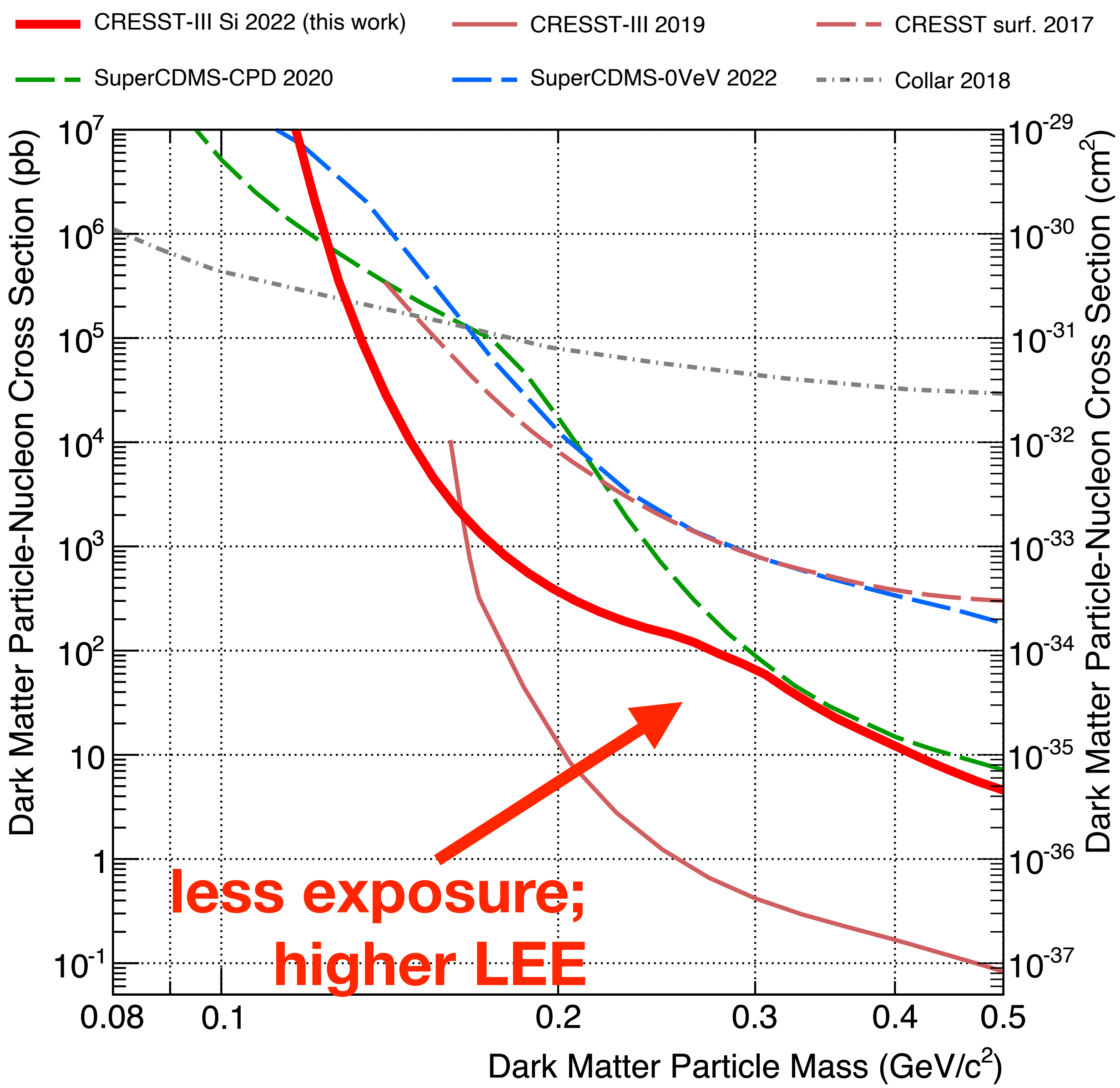


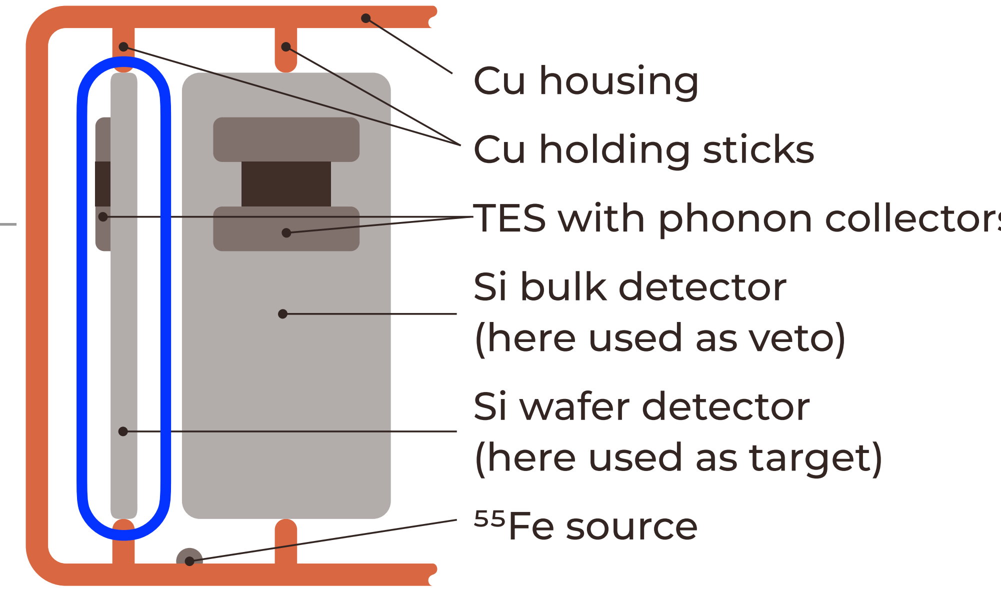
SciPost Phys.Proc. 9 (2022) 001

SciPost Phys.Proc. 12 (2023) 013

Dark Matter Search using Silicon

Phys.Rev.D 107 (2023) 12, 122003



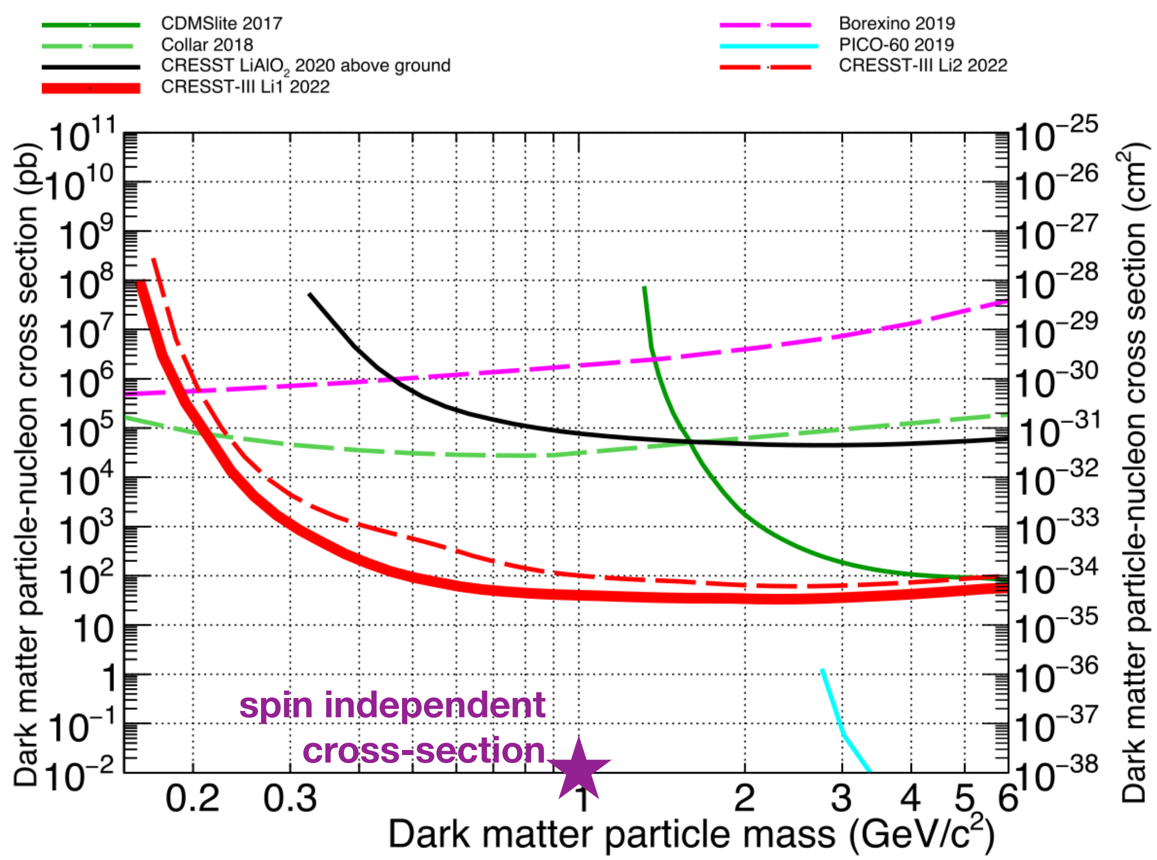


- Wafer-like silicon detector with 0.35 g used as absorber
- **E_{thr} = (10±0.2) eV**
- Improved sensitivity for dark matter masses below 160 MeV/c^2

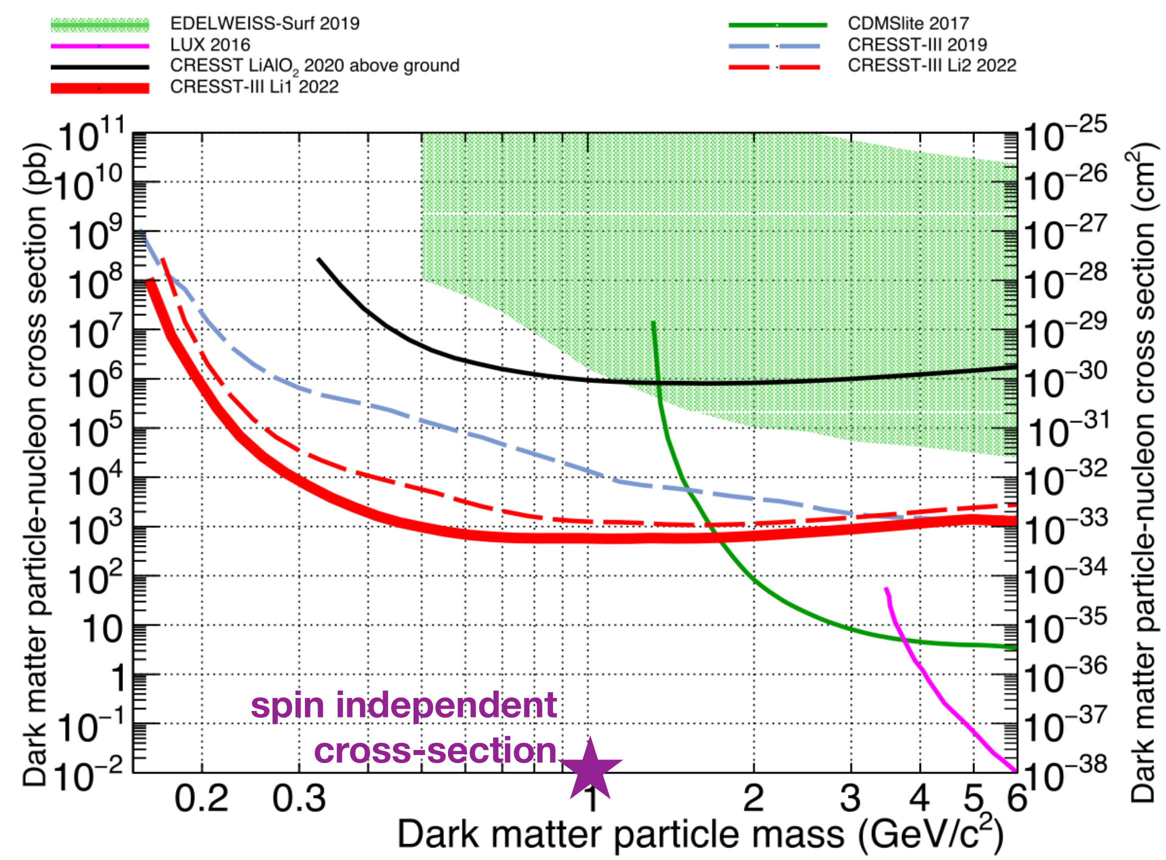
Spin-dependent Dark Matter search using LiAlO$_2$

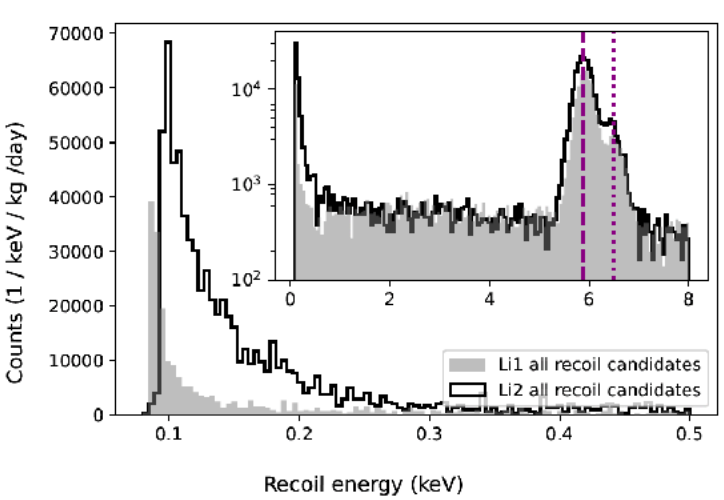
$^{6/7}$Li ^{27}Al

Proton



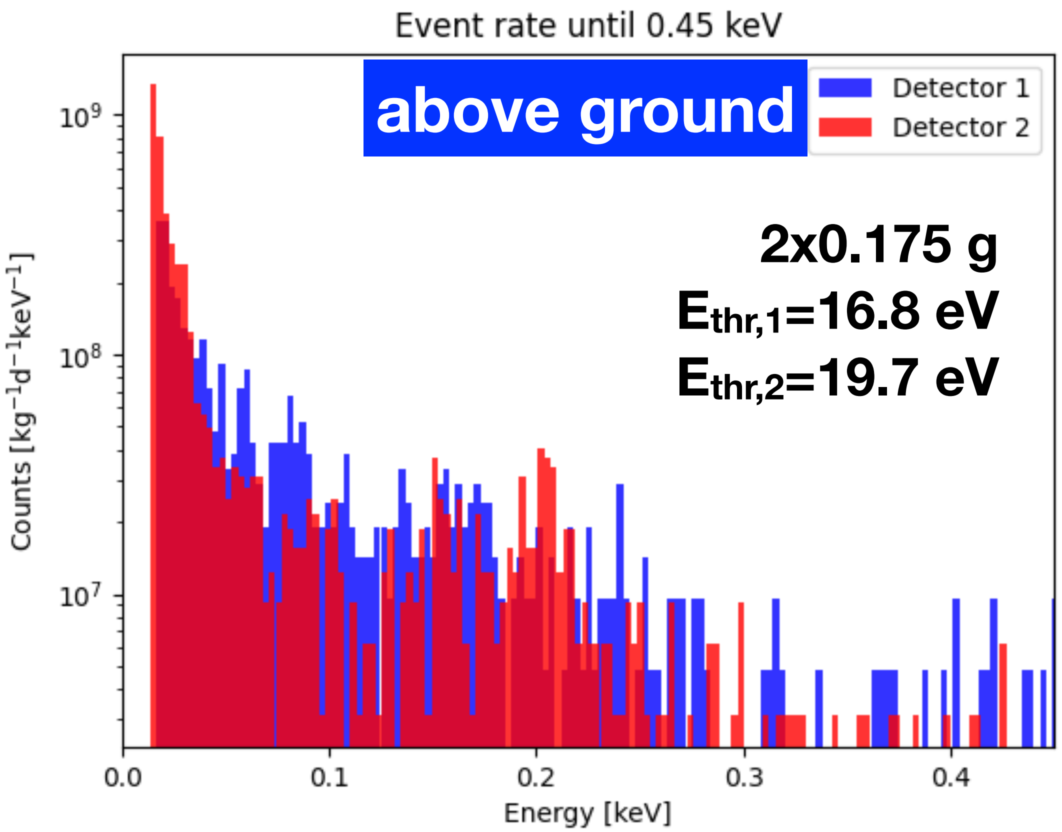
Neutron

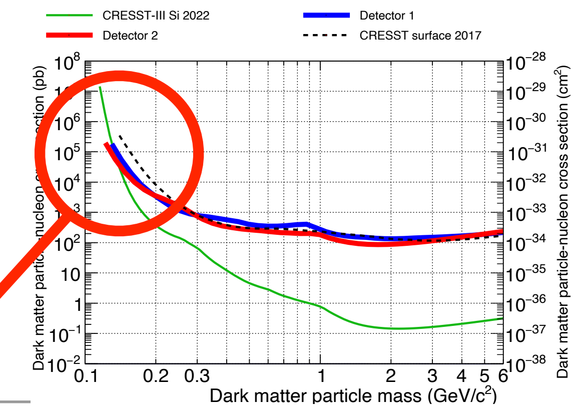


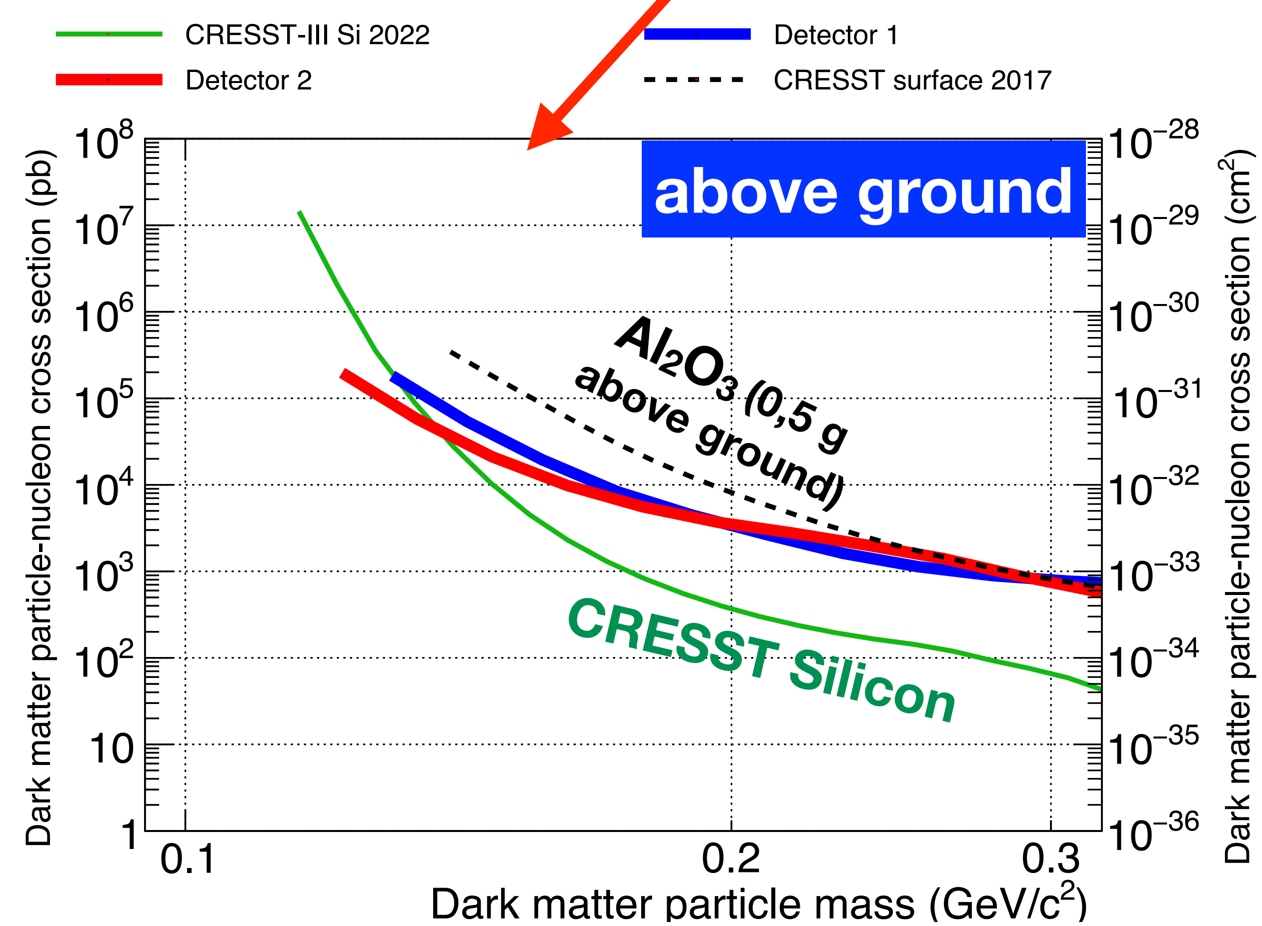


- Lithium and Aluminum have **unpaired proton / neutron** leading to an effective spin coupling to dark matter
- LiAlO$_2$ crystals 10.5 g each and E_{thr} ~ 90 eV

Dark Matter Searches with Diamond







- Diamond offers **access to even lower dark** matter masses
- Successful above-ground **proof-of-principle** measurement
- Next steps: enlarge detector mass and exposure and further improve TES design

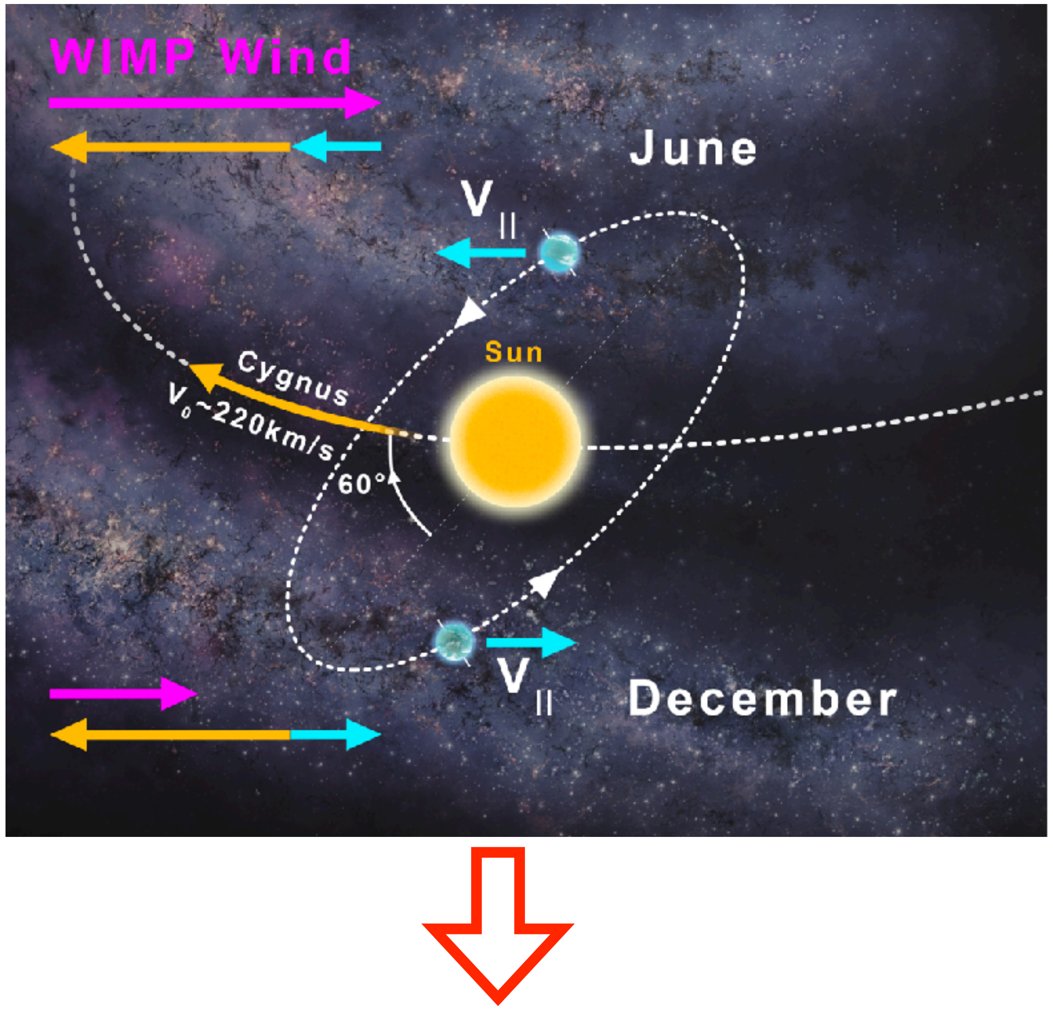
COSINUS

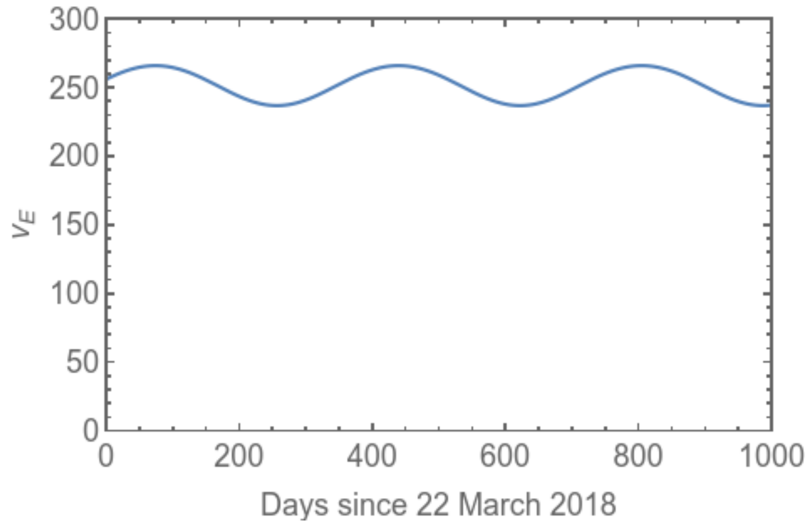
Cryogenic Observatory for Signals seen in Next Generation Underground Searches

Dark Matter Searches by Annual Modulation

- small interaction rate of dark matter expected
- excellent knowledge of background required to identify dark matter signal
- movement of earth in dark matter wind leads to **annual modulation of dark matter signal**
  - size of **modulation amplitude** can reach **up to 7%**

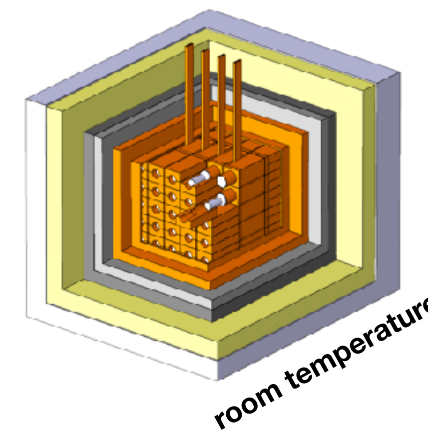
J.Phys.G 47 (2020) 9, 094002



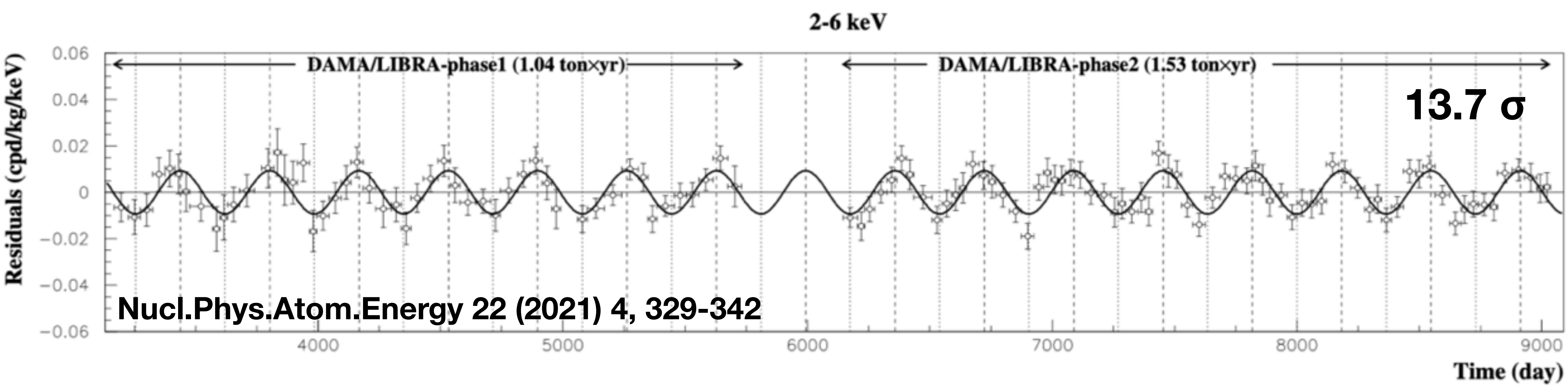


Annual Modulation of Dark Matter Interaction Rate

- **DAMA/LIBRA** experiment searches for dark matter via annual modulation of signal rate



- operation of radiopure NaI(Tl)-crystals and **detection of scintillation light from dark matter - nucleus scattering**
- **residual signal** shows clear sign for an **annual modulation** of interaction rate in the energy region of **2-6 keVee (now E_{thr}=0.75 keVee)**



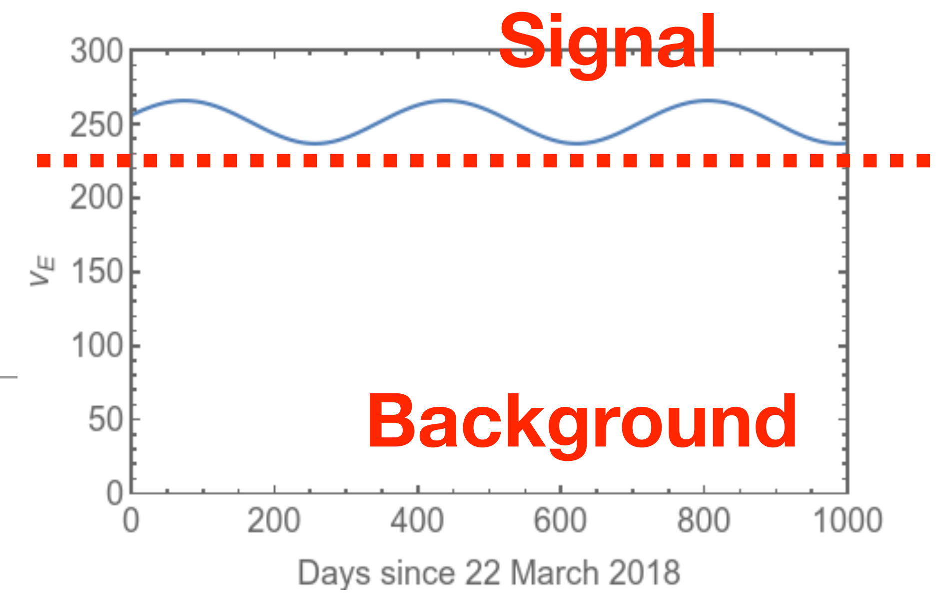
The COSINUS Experiment

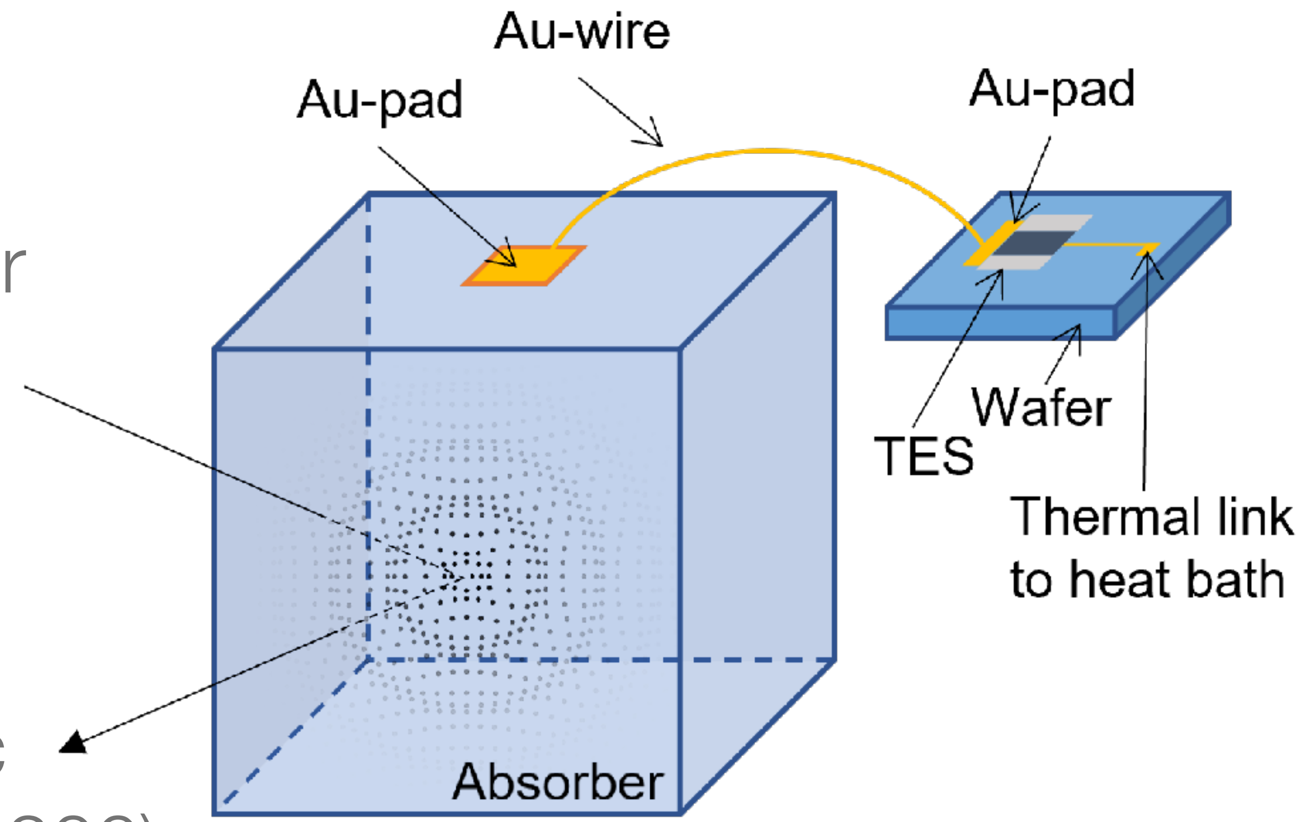
- Apply **cryogenic detector** technology pioneered by CRESST to **NaI crystals**

➡ Gain **new information** on the underlying process

- **Challenges:** Operation of NaI-crystals as cryogenic detector
  - **hygroscopic, soft, low melting point…**

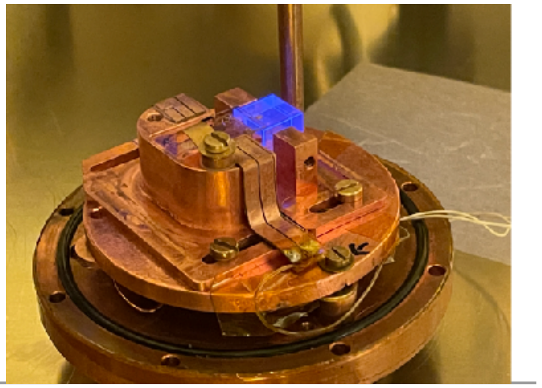
➡ operation as **remoTES** cryogenic calorimeter (M.Pyle et al. 1503.01200)



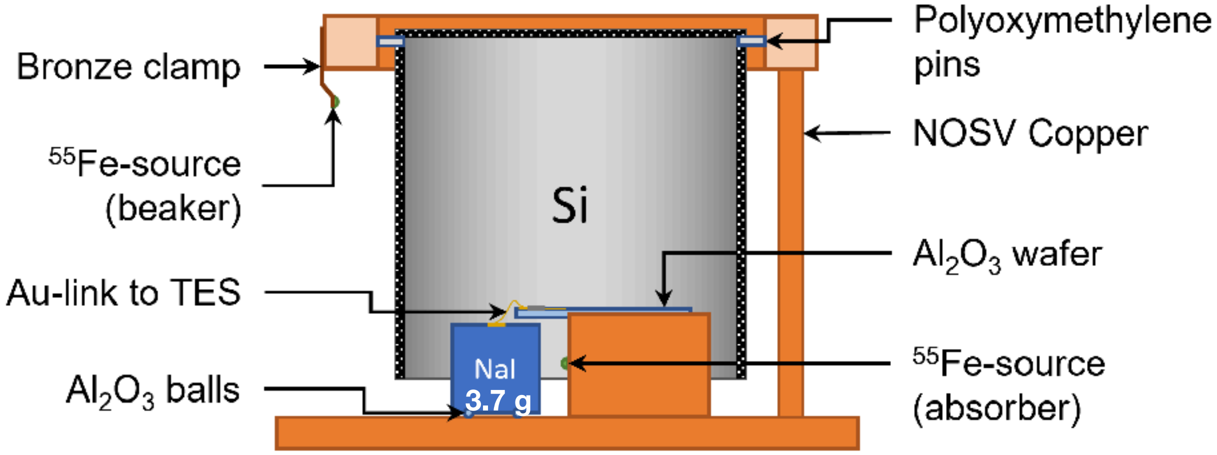


Nucl.Instrum.Meth.A **1045 (2023) 167532**

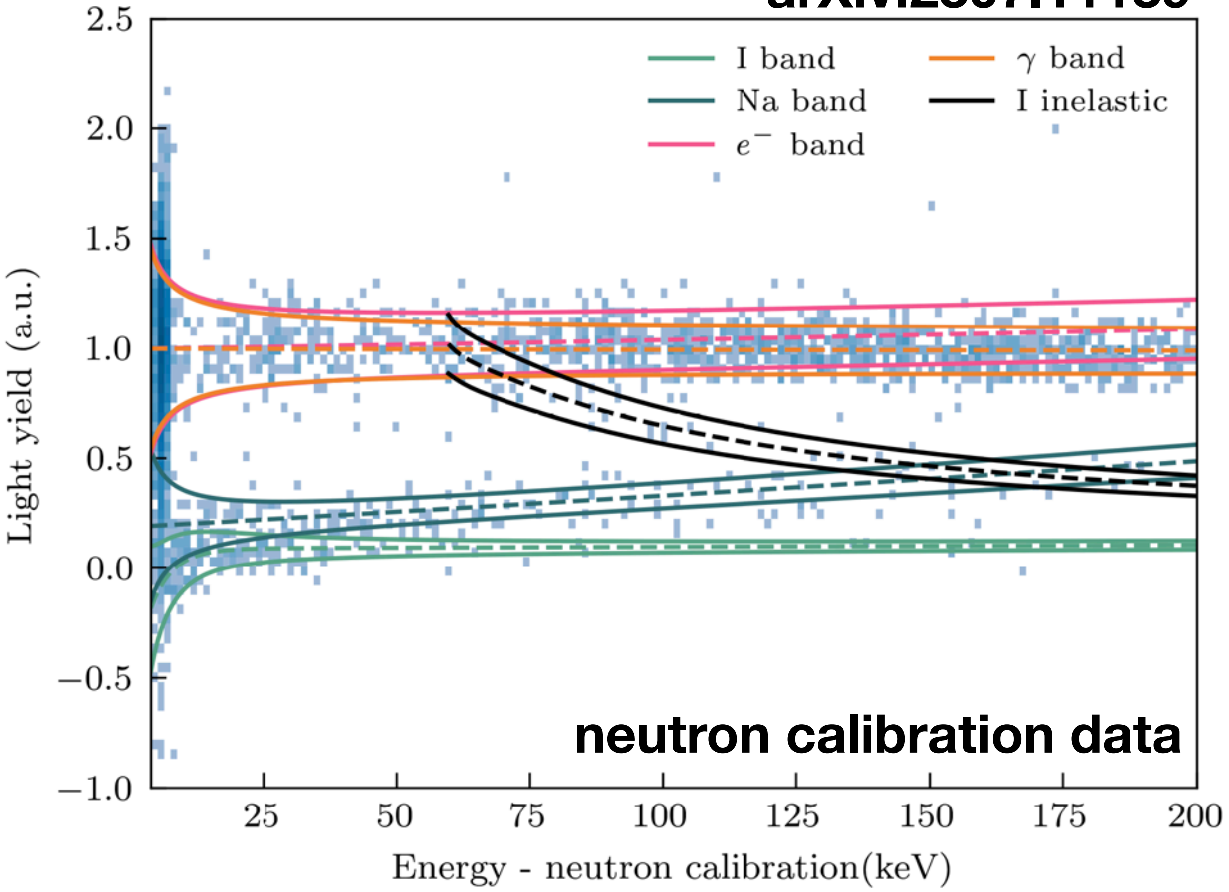
COSINUS Detector Prototype Module



- **First underground measurement** of a cryogenic operated NaI crystal



arXiv:2307.11139

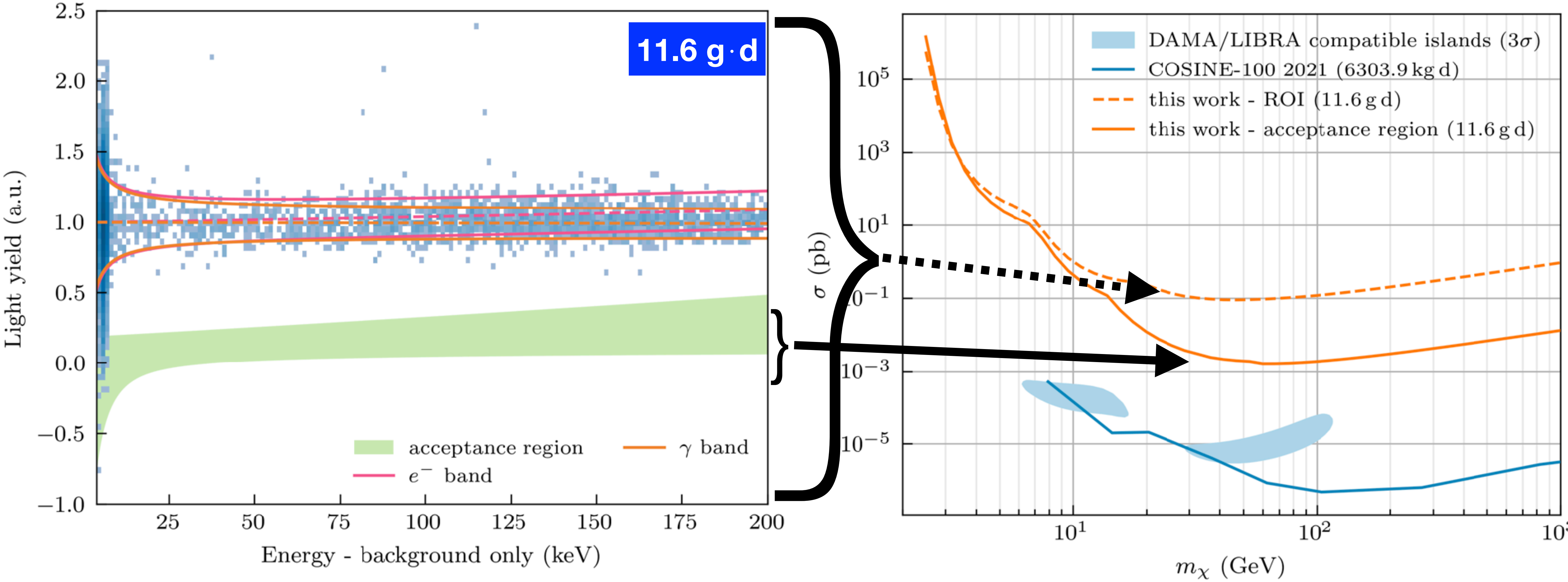


- NaI crystal from SICAS with **high intrinsic radiopurity** (6-22 ppb of 40K - design goal)
- **E_{thr}=2.66±0.04 keV** (Final design goal 1 keV)
- **event-by-event particle discrimination** for NaI demonstrated for the first time
- **σ_{NaI}=(0.441±0.011) keV** σ_{beaker}=(0.998±0.052) keVee (for NaI-remoTES scintillation light)

First Underground Dark Matter Limit

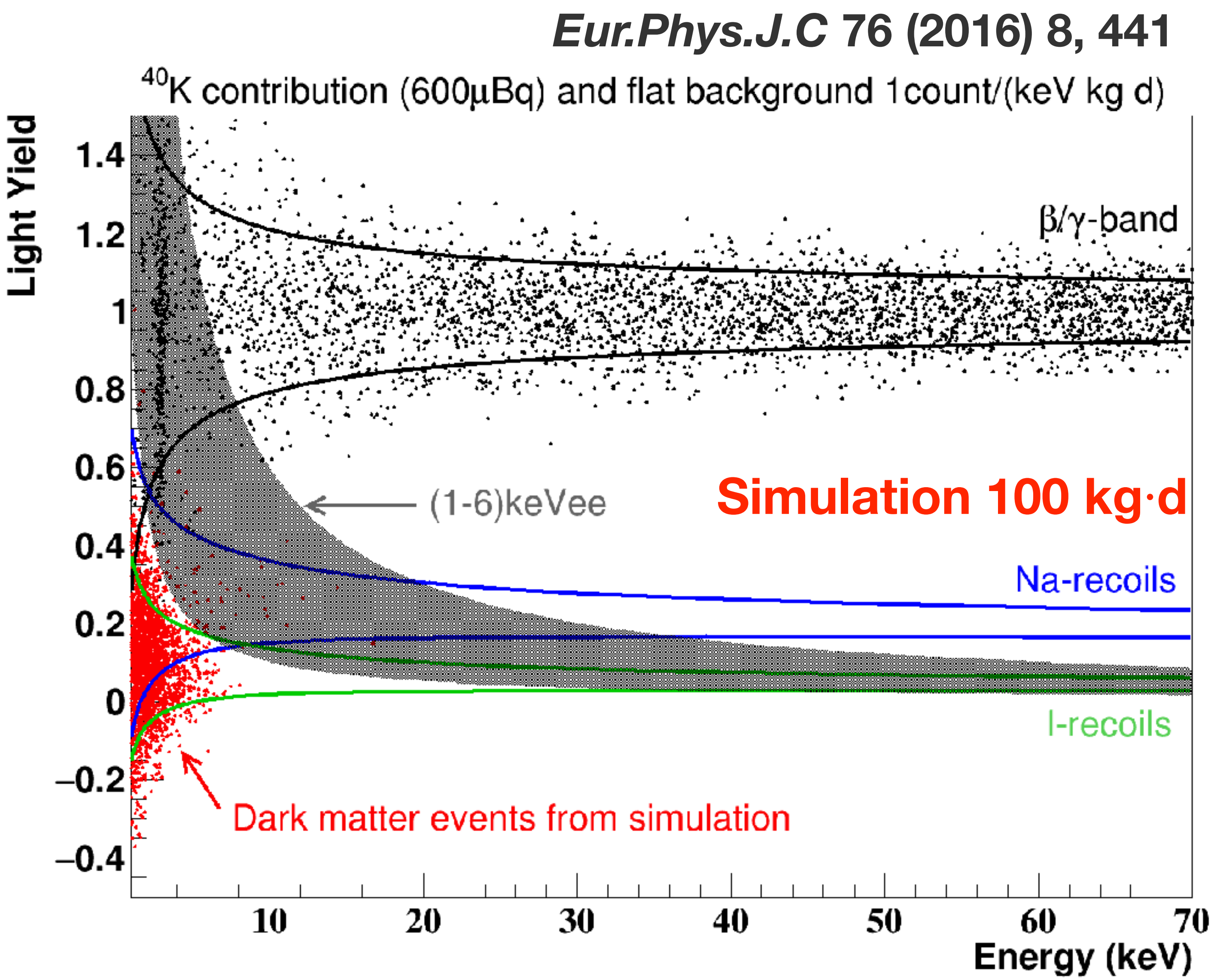
arXiv:2307.11139

arXiv:2307.11139



- First dark matter limit with cryogenic operated NaI crystal clearly shows power-of-event by event discrimination

COSINUS - next Steps



- Event-by-event discrimination allows separation between signal and background events

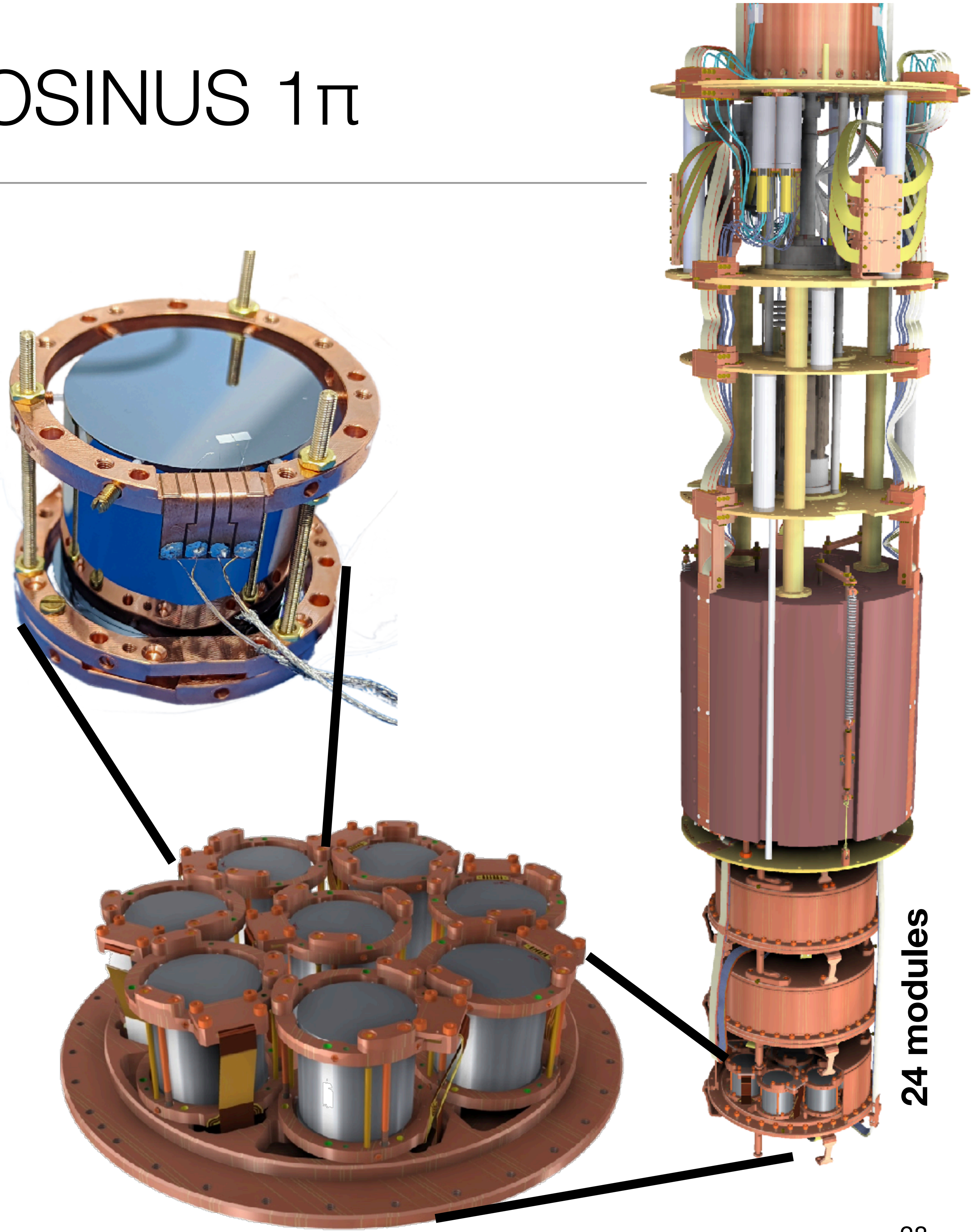
COSINUS Strategy - COSINUS 1π

Exposure 100 kg·d ~ 1y

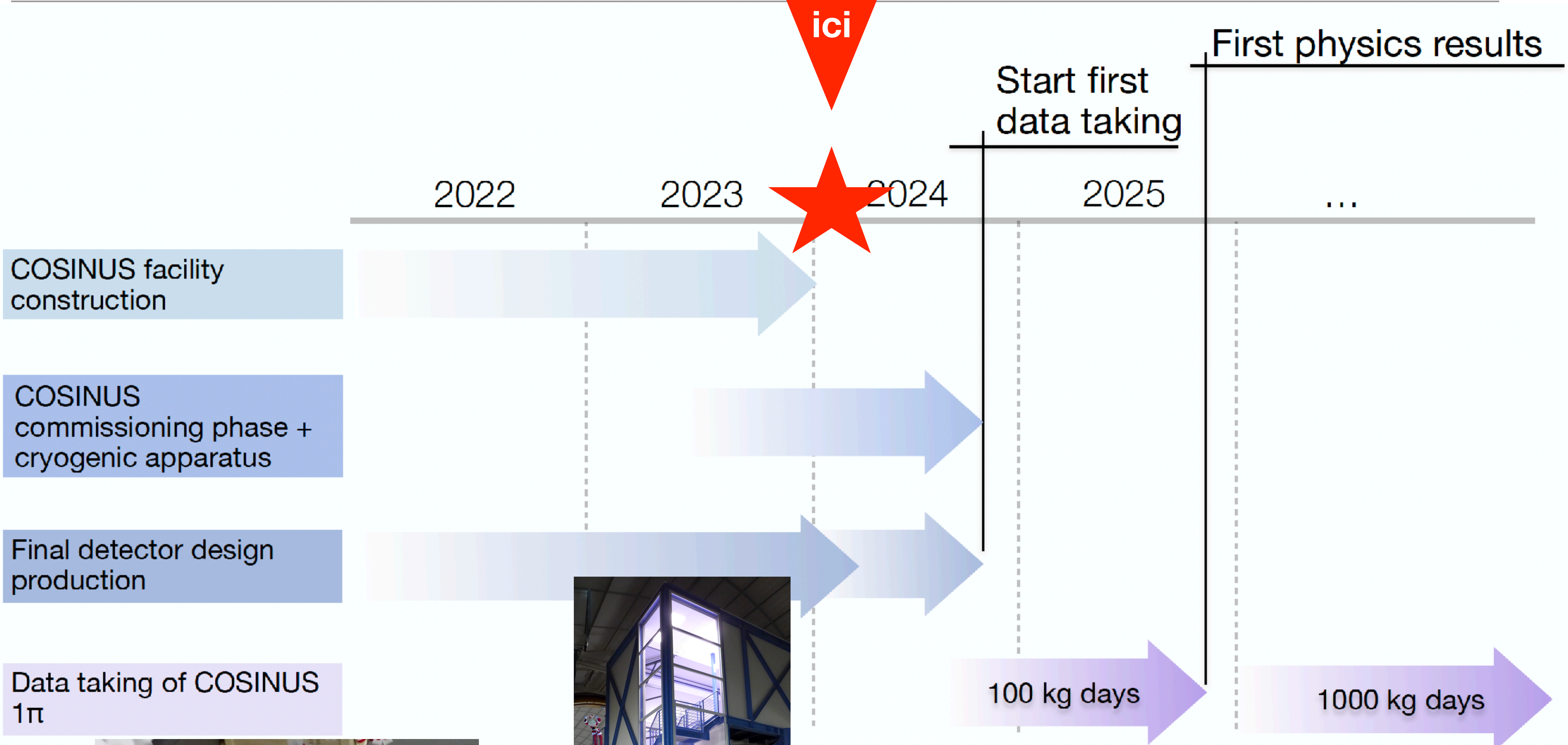
- **8 modules à 34g** x **365** days ~ 100 kg·d
- exclusion of any falling recoil spectra with **m_X> 6 GeV/c²**

Exposure 1000 kg·d ~ 3y

- **24 modules à 34g** x (**3.3x365**) days ~ 100 kg·d
- exclusion of any arbitrary recoil spectra with **any m_X**



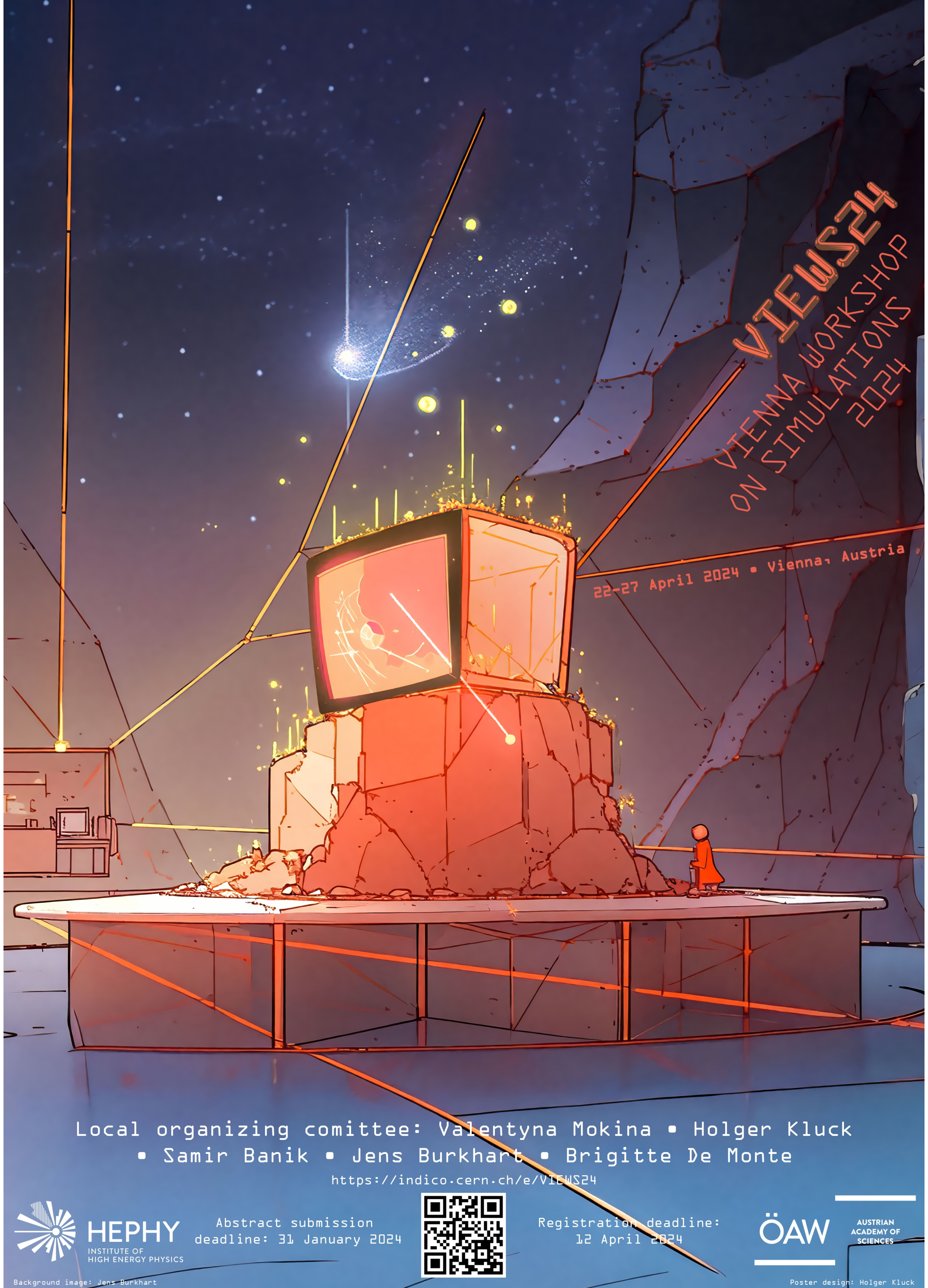
Strategy - Timeline



Data taking will start this year

Summary

- Cryogenic detectors make significant contribution to dark matter searches in the sub-GeV dark matter mass region
- Technology allows easy operation of different absorber material
  - multiple nuclei in a single crystal ($CaWO_4$, $LiAlO_2$,…)
  - first cryogenic operation of NaI will provide unique information for understanding DAMA/LIBRA
- Current sensitivity to low-mass dark matter is limited by exponentially rising background below ~200 eV
  - origin of background studied in a community-wide effort
  - significant progress achieved; however, no full understanding yet



Vienna Workshop on Simulation 2024

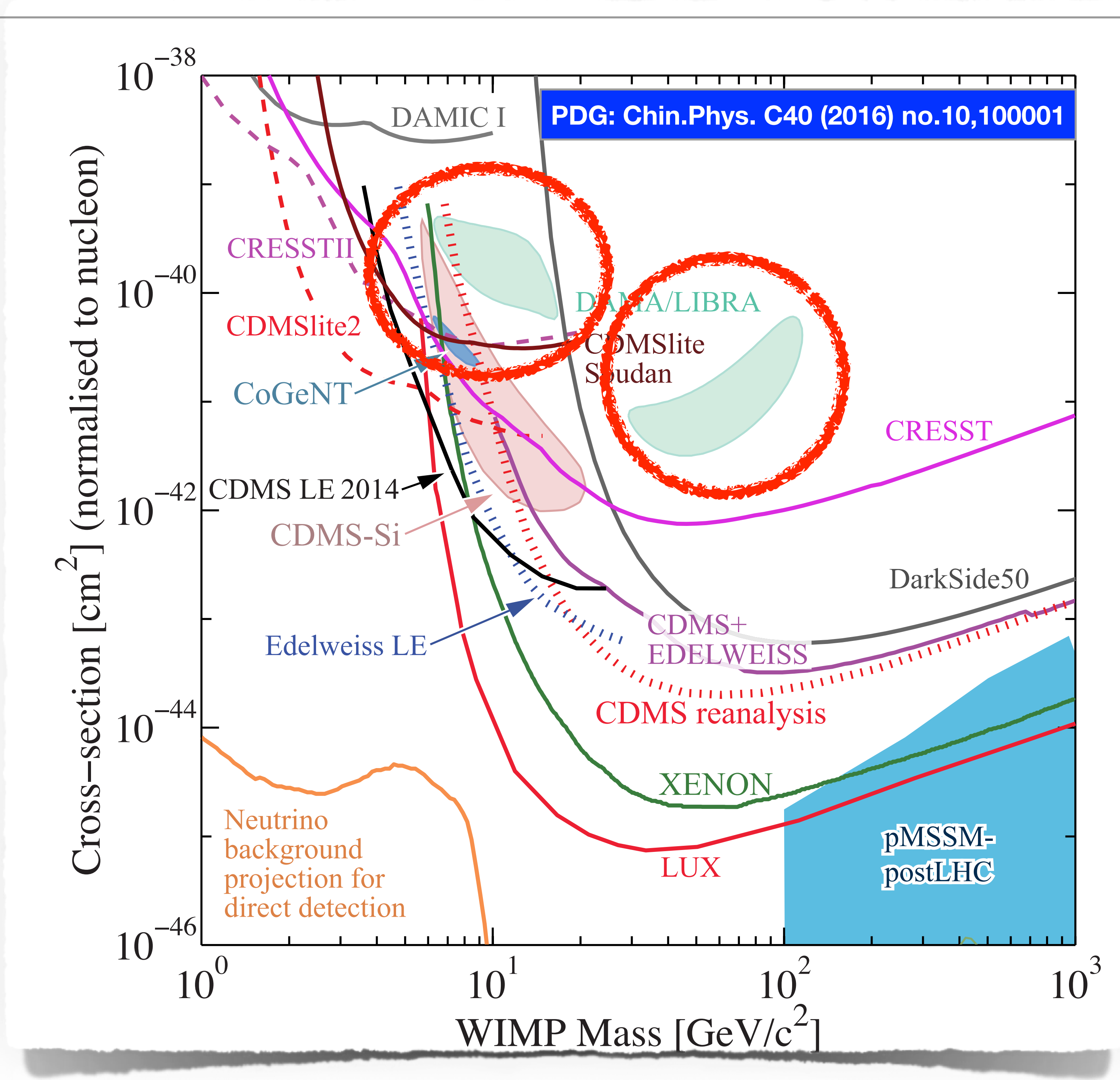
22nd-27th April 2024

https://indico.cern.ch/event/1275551/

Additional Information

DAMA/LIBRA Measurement - Interpretation of Annual Modulation as Dark Matter

valid for standard assumptions only



$m_\chi \approx$ 50 GeV ; $\sigma_{\chi n} \approx 7 \cdot 10^{-6}$ pb

$m_\chi \approx$ 6-10 GeV ; $\sigma_{\chi n} \approx 10^{-3}$ pb

- **interpretation** of annual modulation as **dark matter** scattering
- standard astrophysical assumptions for WIMP density and velocity
- **preferred mass and cross-section area excluded by other dark matter experiments**

Spin-dependent Dark Matter search using $LiAlO_2$

- Interaction of dark matter with the net Spin of the nuclei
- Nuclei Spin determined by single unpaired proton or neutron

n/p spin matrix elements

$$\frac{dR}{dE_R} = \frac{2\rho_0}{m_\chi}\sigma^{SD}_{p/n}\sum_{i,T} f_{i,T}\left(\frac{J_{i,T}+1}{3J_{i,T}}\right)\left(\frac{\langle S_{p/n,i,T}\rangle^2}{\mu^2_{p/n}}\right)\eta(v_{min})$$

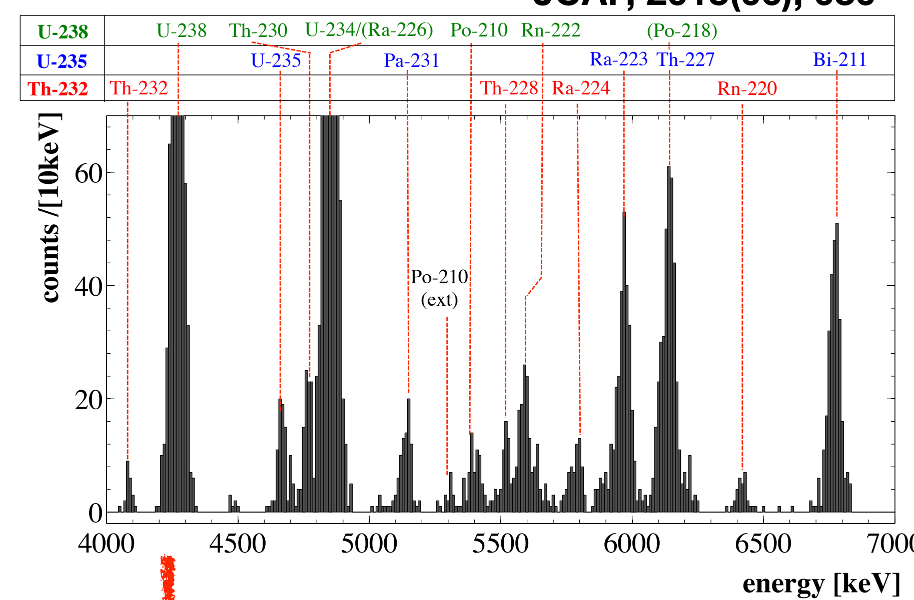
nuclear angular momentum

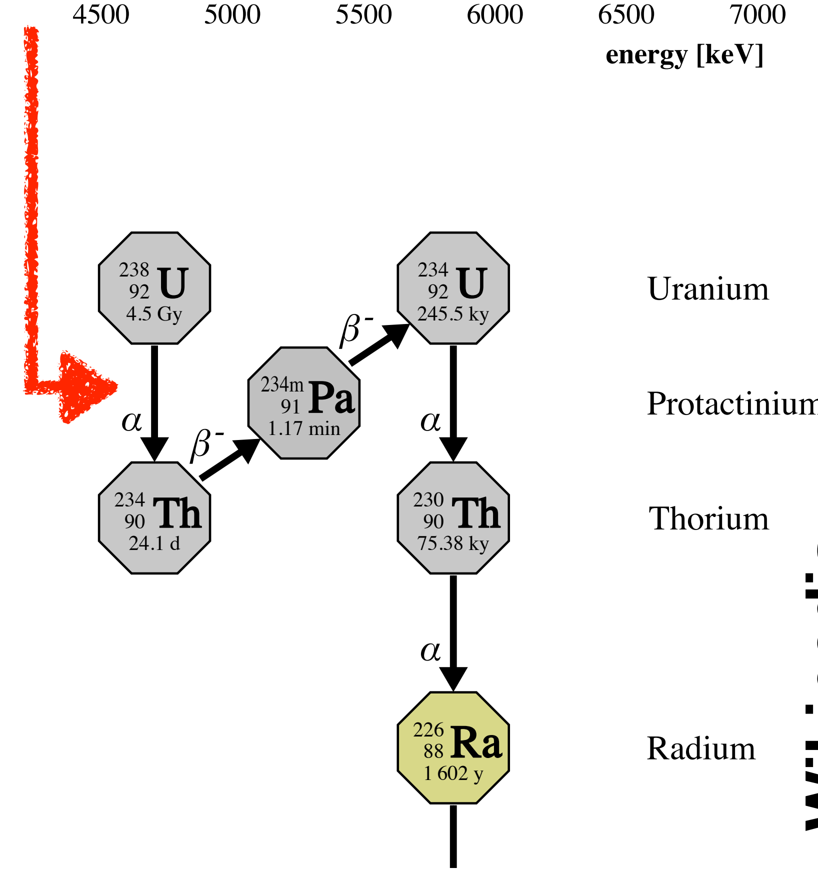
- lower sensitivity since spin-dependent cross-section scales with A^2 due to coherent scattering

Background simulation for CRESST - method I

- Geant4 based simulation to estimate intrinsic background
- use α-activity as input:
    - identification of decay / isotope
    - measured activity reflects size of contamination
- determine energy spectrum of isotope decay and scale it accordingly to the measured activity

JCAP, 2015(06), 030

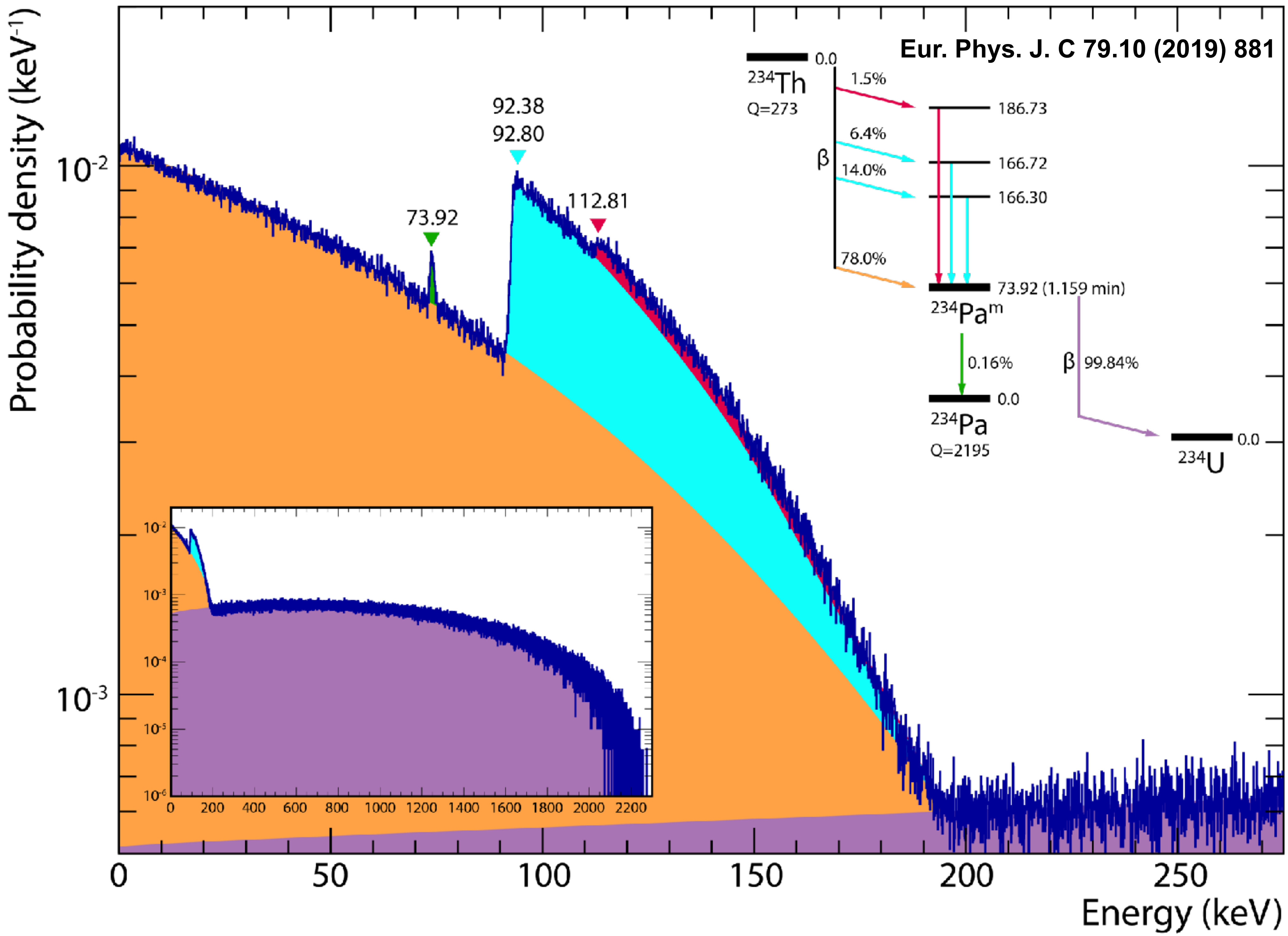




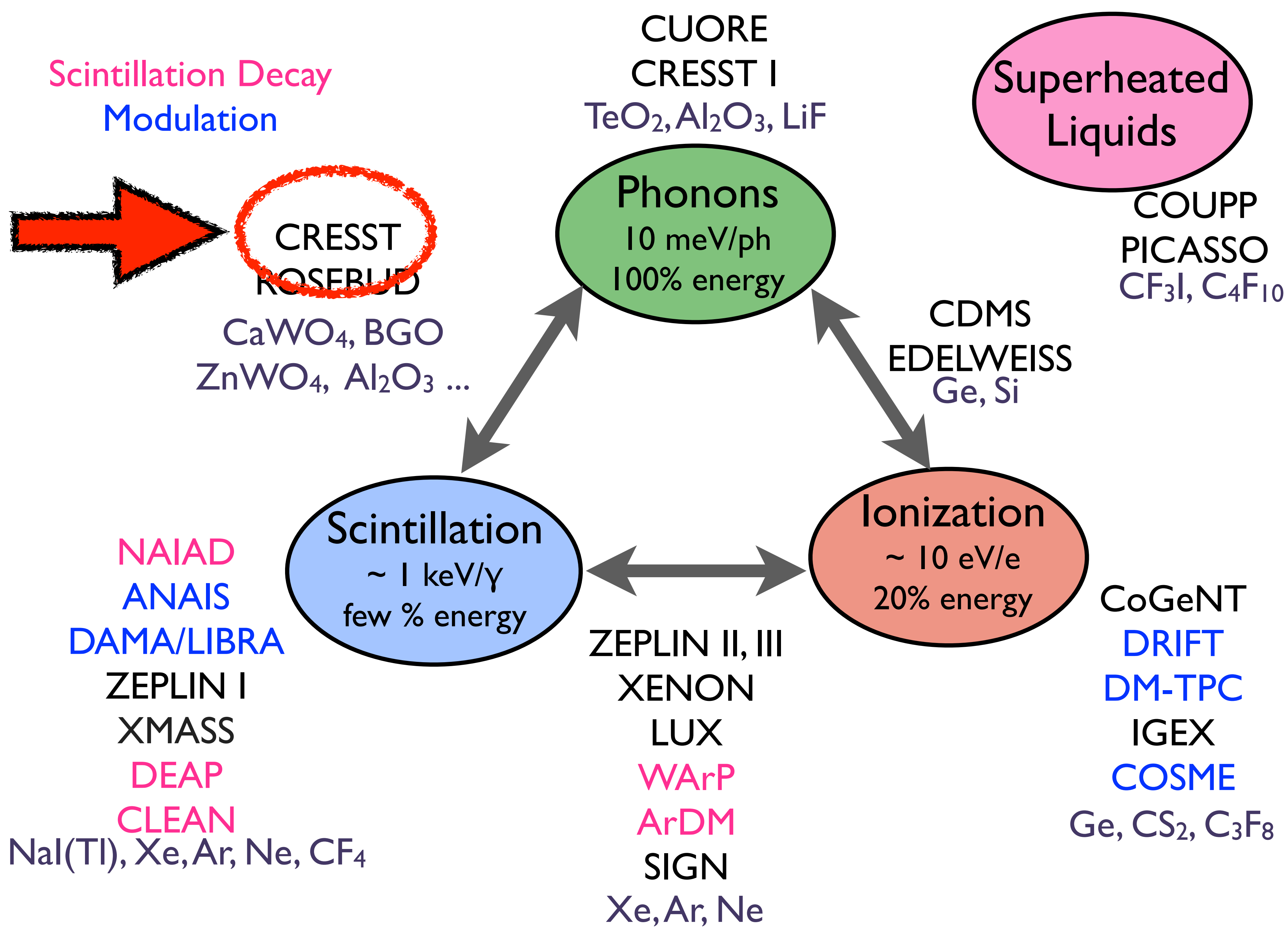
Wikipedia

Background simulation for CRESST - method II

energy spectrum of simulated ^{234}Th decay with Geant4



Measurement of Recoil Energy deposited by Scattering

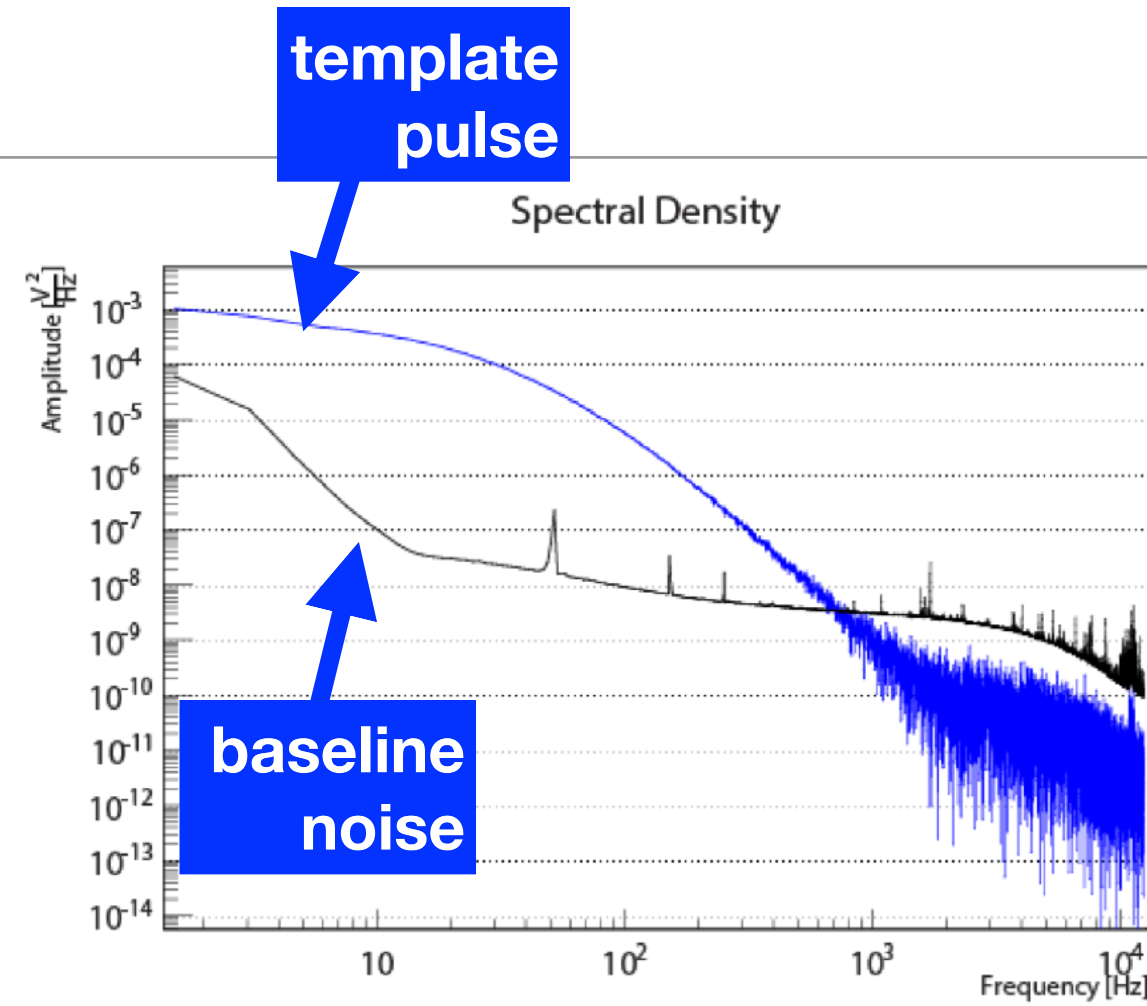


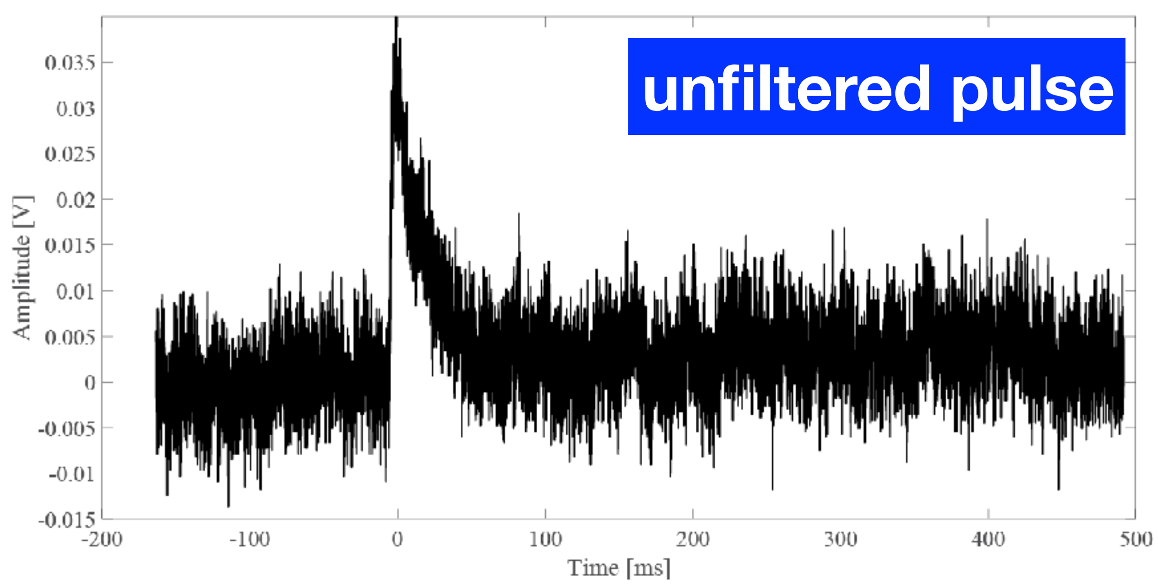
Properties	**NaI(pure)**	**CsI(pure)**	**$CdWO_4$**	**$CaWO_4$**
Density [g/cm^3]	3.67	4.51	7.9	6.12
Melting point [°C]	661	894	1598	1650
Structure	CsCl	CsCl	Wolframite	Scheelite
λ_{max} at 300 K [nm]	~300	~315	~475	420-425
Hygroscopic	yes	slightly	no	no
Θ_D [K]	169	125	-	335
Photons per keV at 3.4 K	19.5 ±1.0	58.9±5.6	-	-
Mean energy of emitted photon [eV]	3.3	3.9	-	3.14

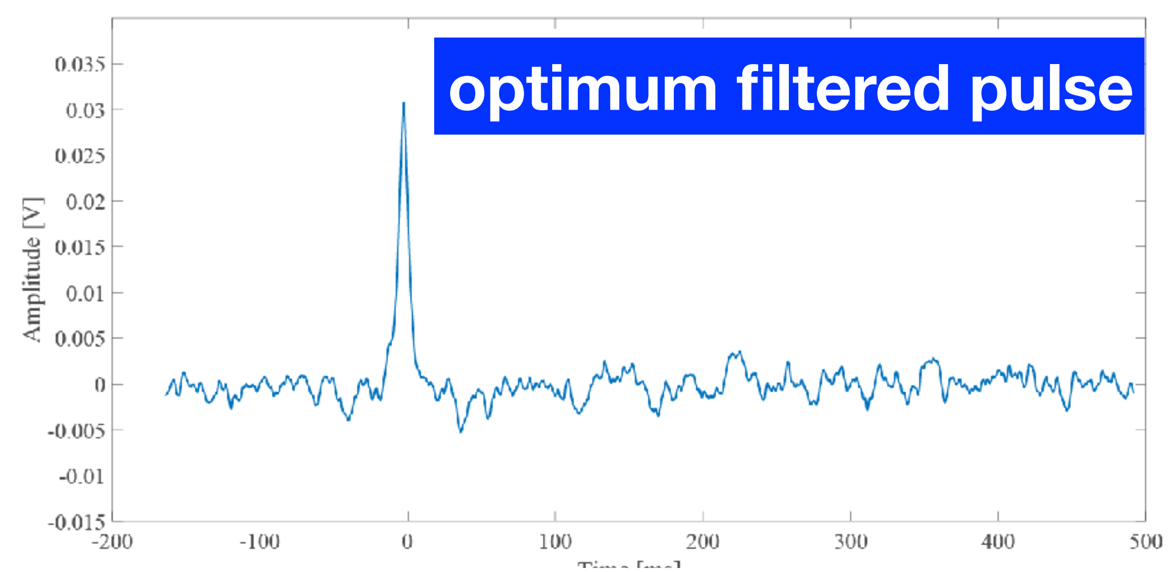
10.1016/j.nima.2019.06.030

CRESST-III optimum filter

- implementation of the Gatti-Manfredi filter
- optimum filter maximizes signal-to-noise ratio
- typical improvement about factor 2-3
- new DAQ for CRESST-III with continuous data sampling
- threshold set after optimum filter

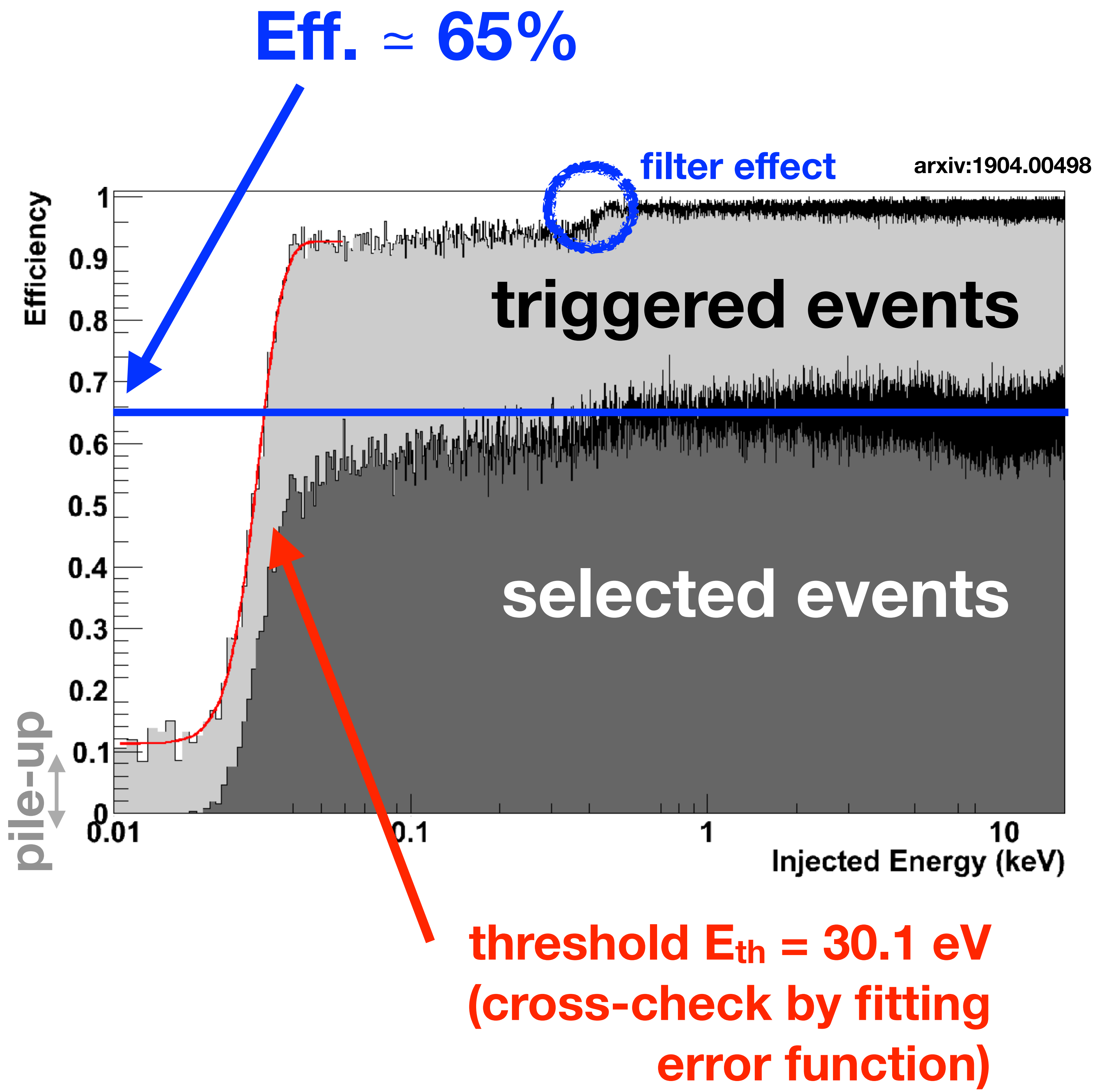






Selection efficiency

- data taking period: 5/2016-02/2018
- 20% of data as non-blind training set randomly selected
- size of selected data set (after cuts): 3.64 kg·d
- efficiency (energy dependence not taken into account) ~65%



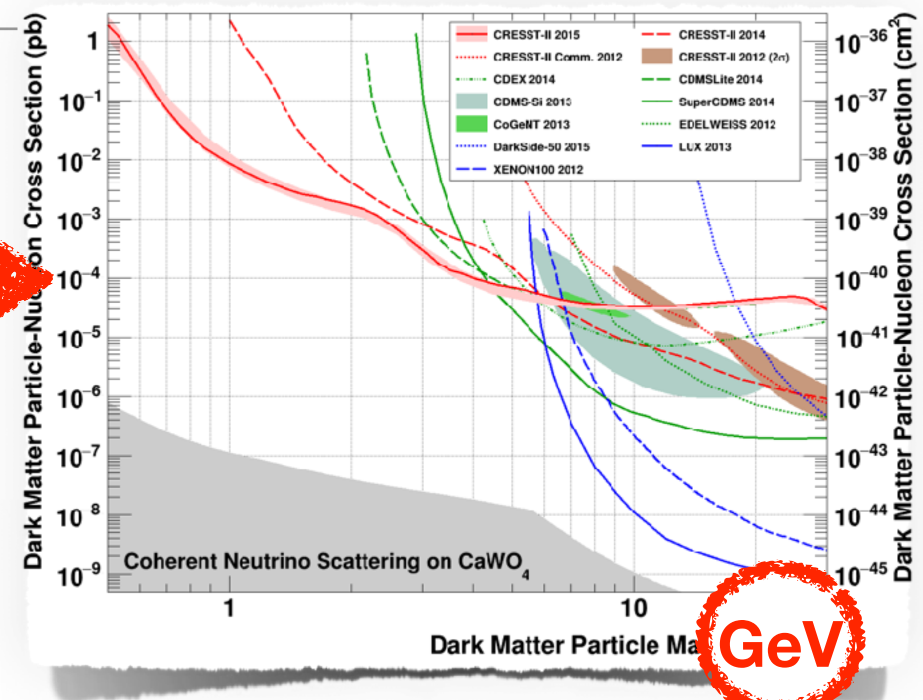
DANAE

Physics of the Dark Sector

- new forces / new mediators relax the theoretical lower bound on dark matter masses
  → **sub-GeV dark matter**
- dark matter searches based on dark matter nucleon **elastic scattering**
- energy deposition from recoil:
  $E_{NR} \simeq 2\mu_{X,N}^2 \cdot v_X^2/m_N$
  → for 100 MeV $m_X \sim$ 1 eV E_{NR}*

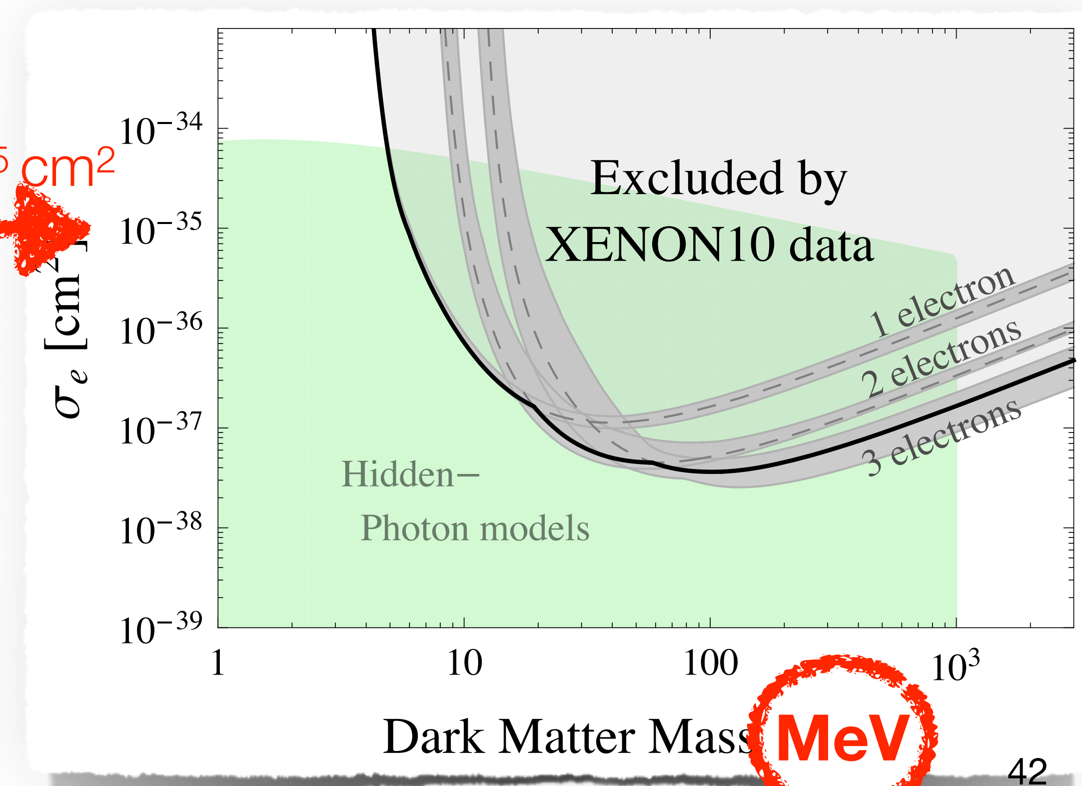
arXiv:1509.01515

10^{-40} cm^2



arXiv:1206.2644

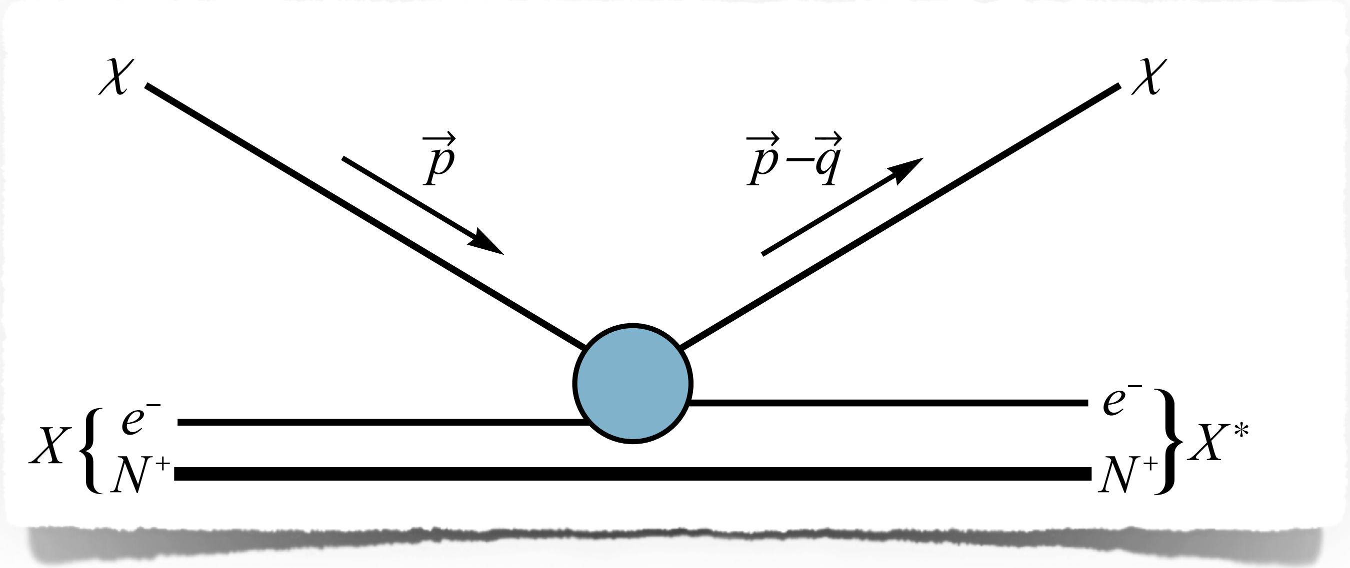
10^{-35} cm^2



* for silicon

Detection techniques for light Dark Matter

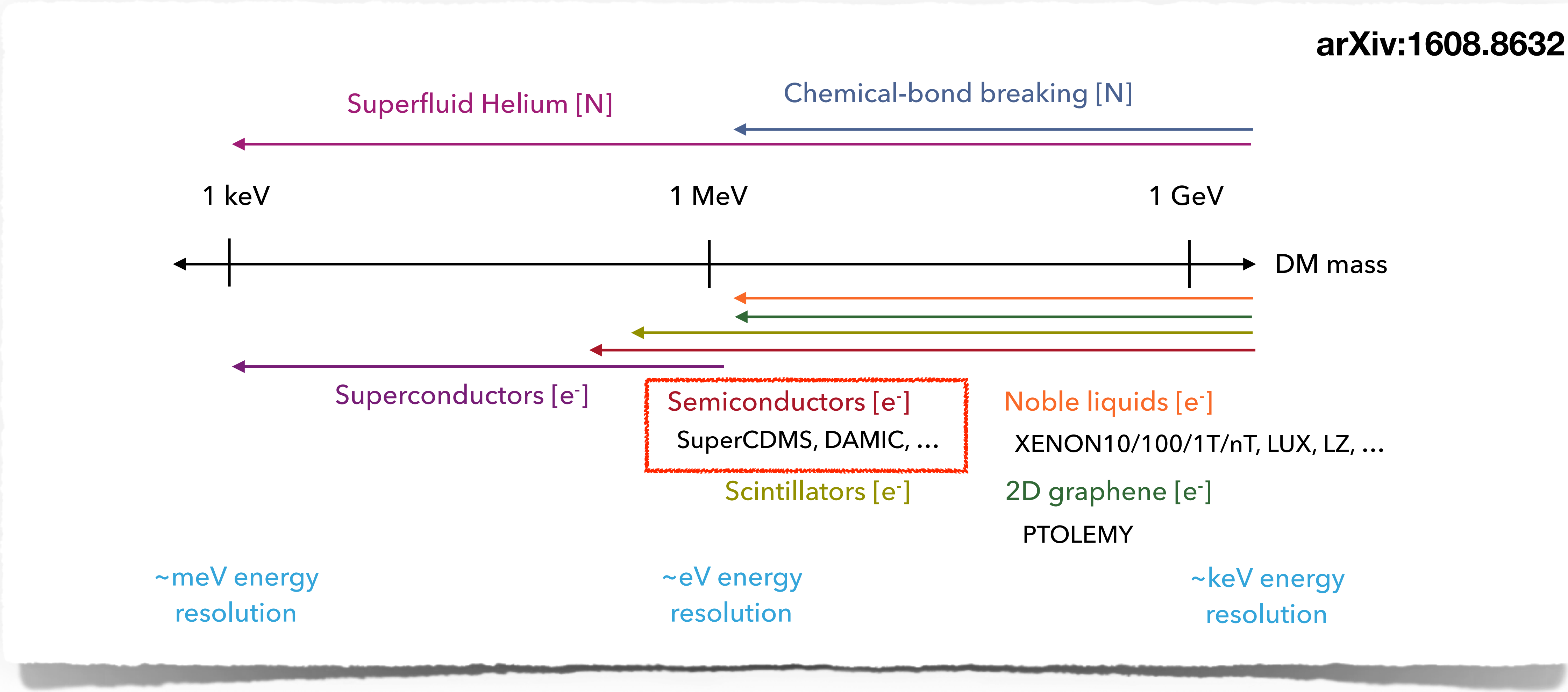
- dark matter detection using ionisation signal from **Dark Matter-electron** scattering



- inelastic nature of scattering and increased energy transfer possible due to lightness of electron

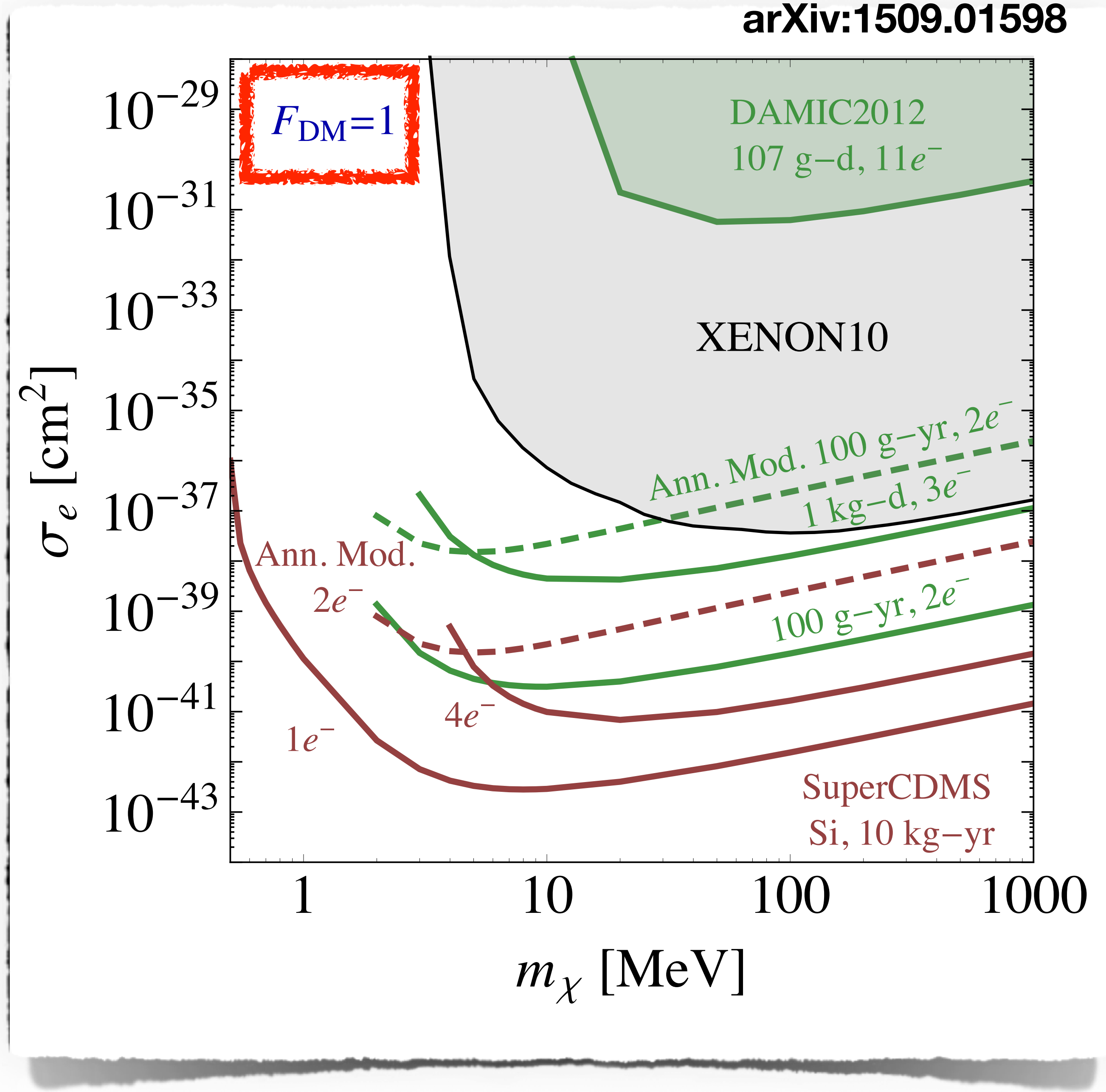
- detection of small ionisation signals allow to probe Dark Matter particles down to ~ 1 MeV

Detection techniques for light Dark Matter



- band gap of silicon ~ eV order of magnitude smaller compared to Xe
- expected reach for Dark Matter $m_X \gtrsim 250$ keV · (ΔE_B/1eV)
- sensitivity depends crucially on detector specific backgrounds (e.g. “dark counts”)

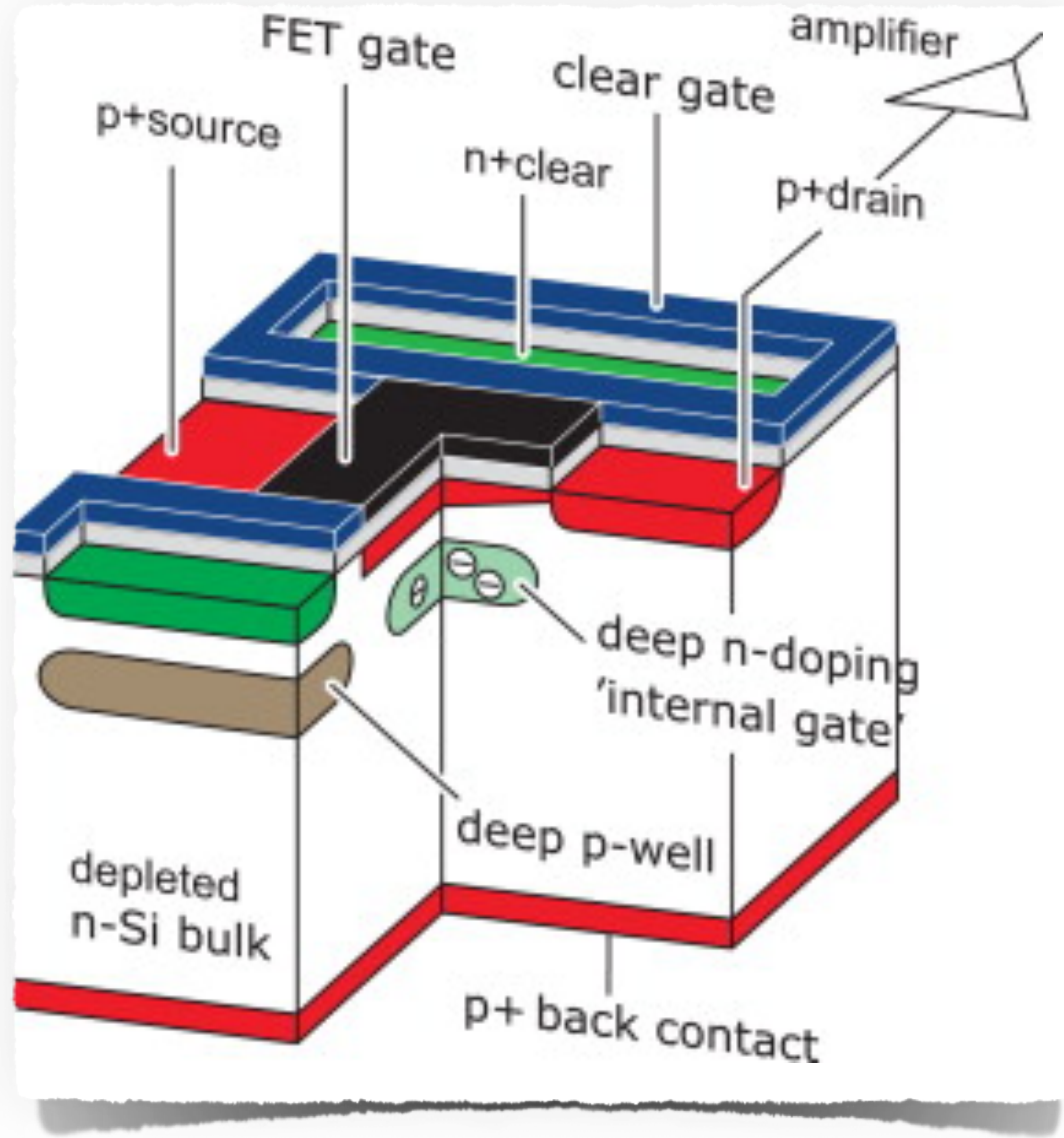
Detection techniques for light Dark Matter



- Dark Matter scatters on bound electrons in dense media
  - relation between energy deposition and momentum transfer differs to nuclear scattering
  - parametrised with a momentum dependent form factor F_{DM}
- **detection of single electrons with low noise**

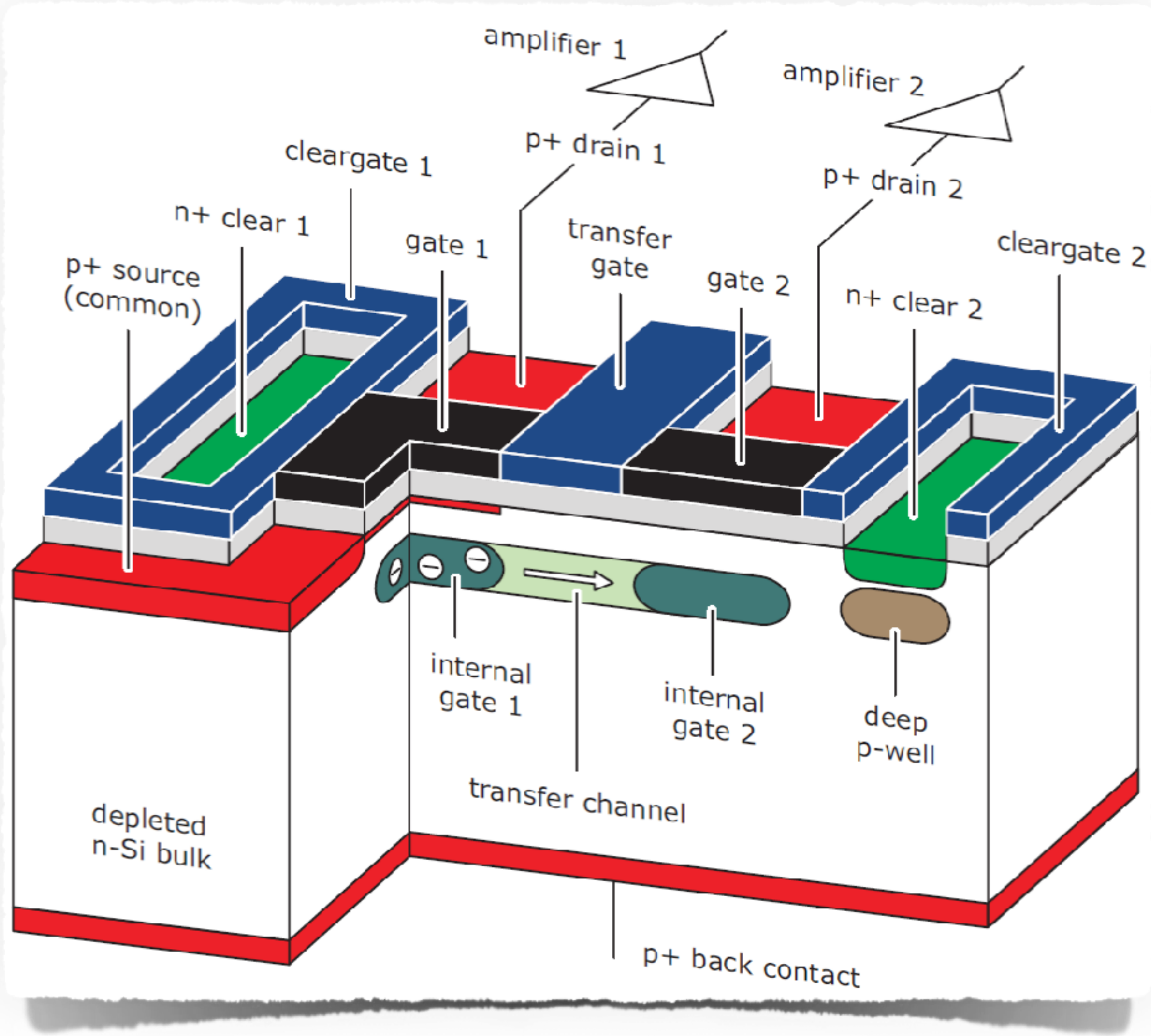
DEPFET detector as sub-GeV Dark Matter detector

- DEPFET: depleted field effect detector
  - charge collection in an internal gate
  - collected charge modulates current in FET
- known and applied detector concept, e.g. for Belle II
  - focus previously on energy measurement and spatial resolution
- **noise performance limited by 1/f noise**



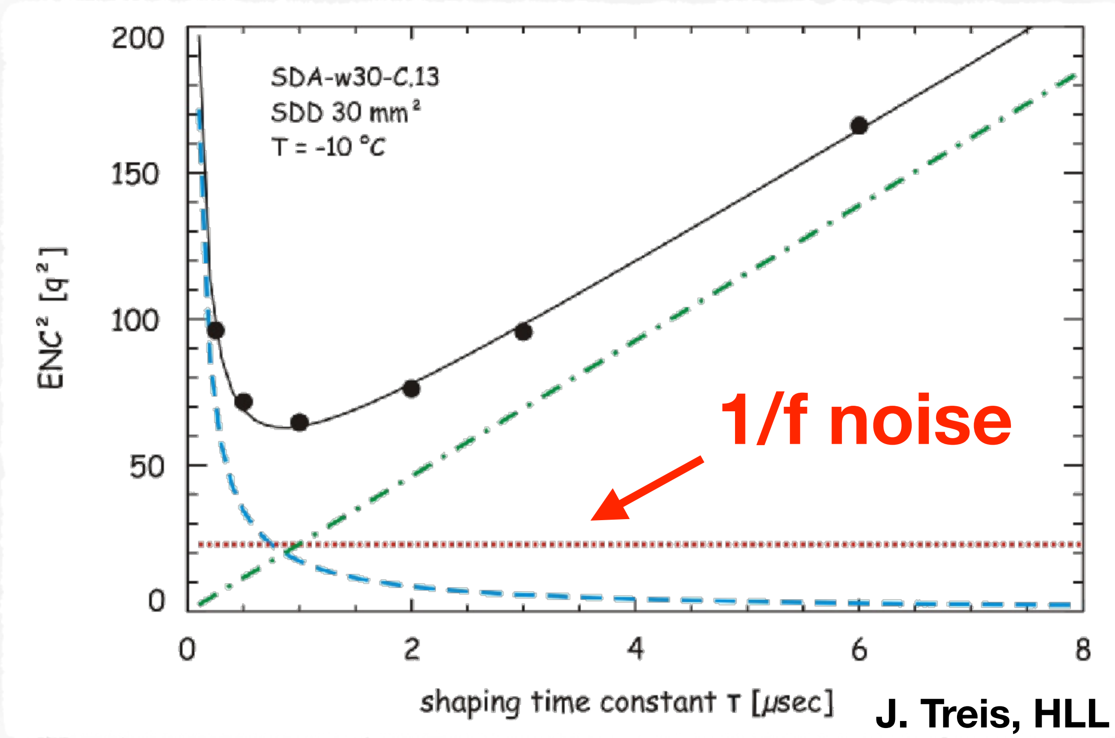
DEPFET detector as sub-GeV Dark Matter detector

- 1/f noise limit can be further reduced by using repetitive non-destructive readout (RNDR)
- charge transfer between sub-pixels in a “super-pixel” allow statistically independent measurements
- **effective noise can be reduced to $\sigma_{eff} \approx \sigma/\sqrt{N}$**

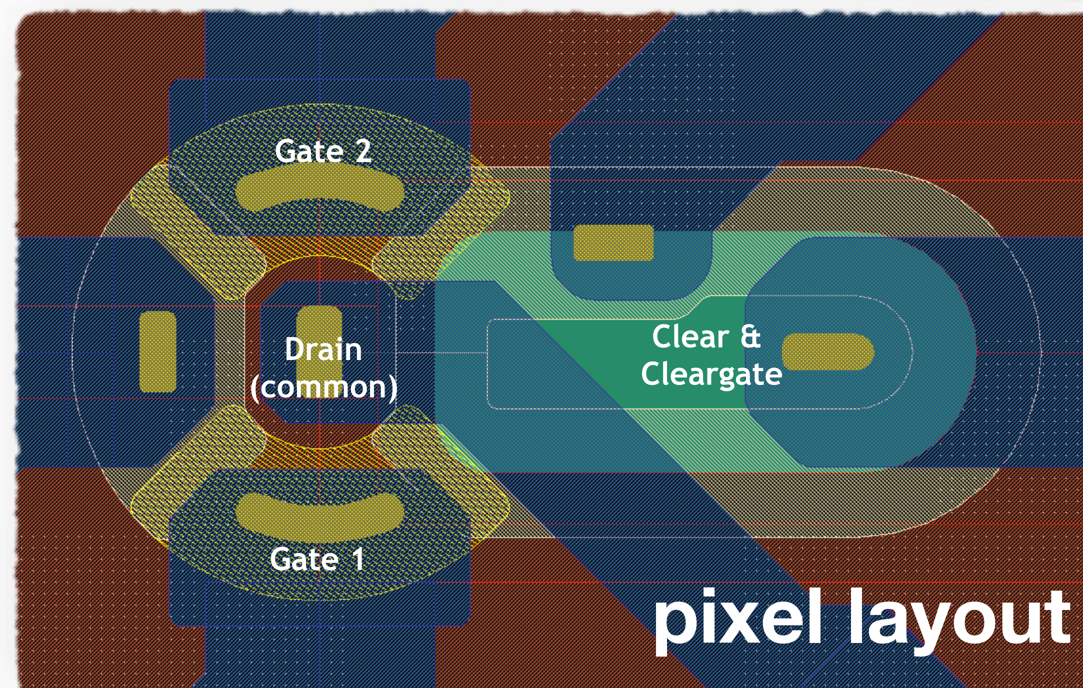


DEPFET-RNDR Prototypes

- proof-of-principle for DEPFET-RNDR demonstrated (Wölfel et al., NIMA 566 (2006) 536)
- DEPFET-RNDR prototype sensors are available
- 450 µm thickness, in principle up to 850 (1000?) µm possible
- “target mass” about 13 g / module

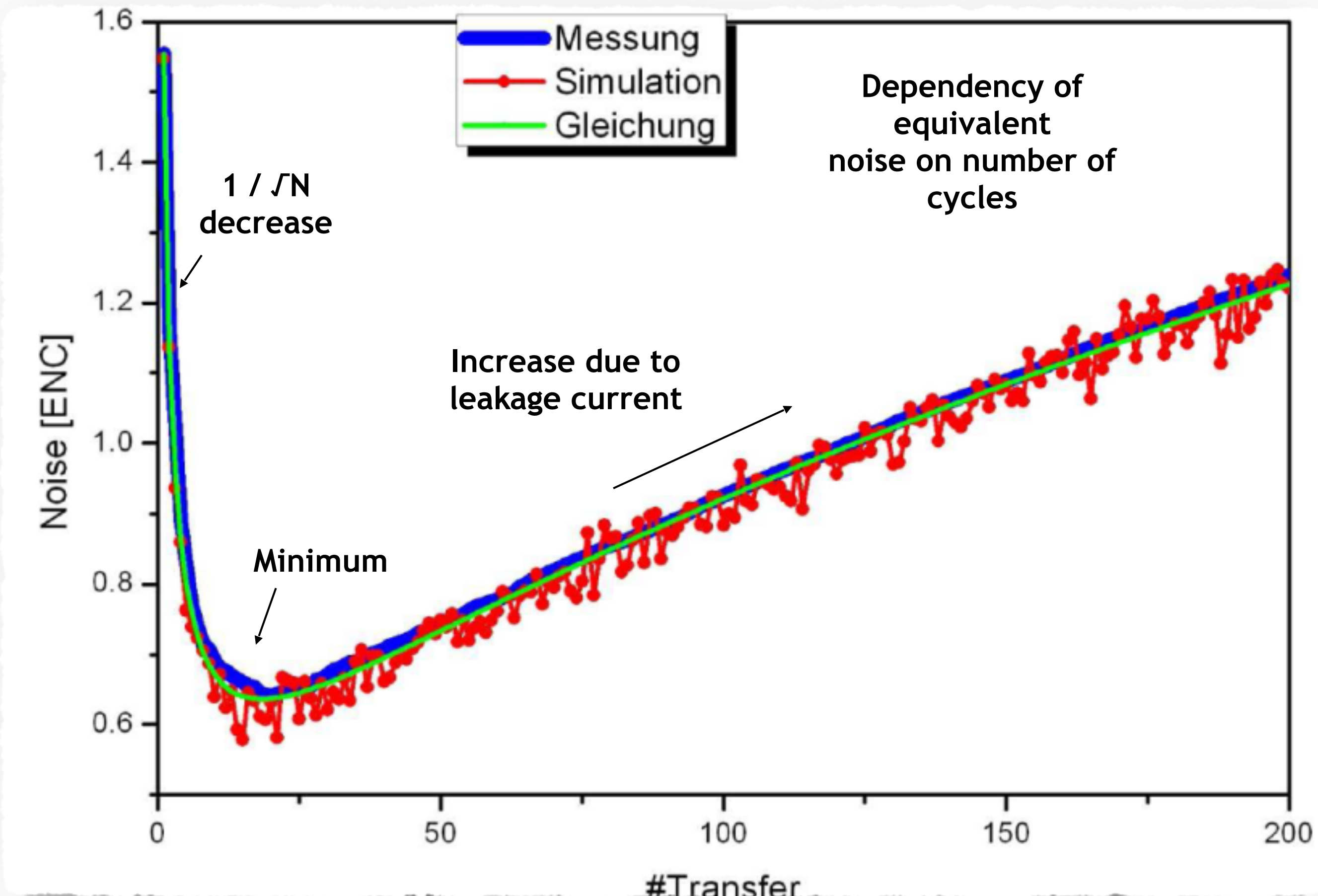


J. Treis, HLL

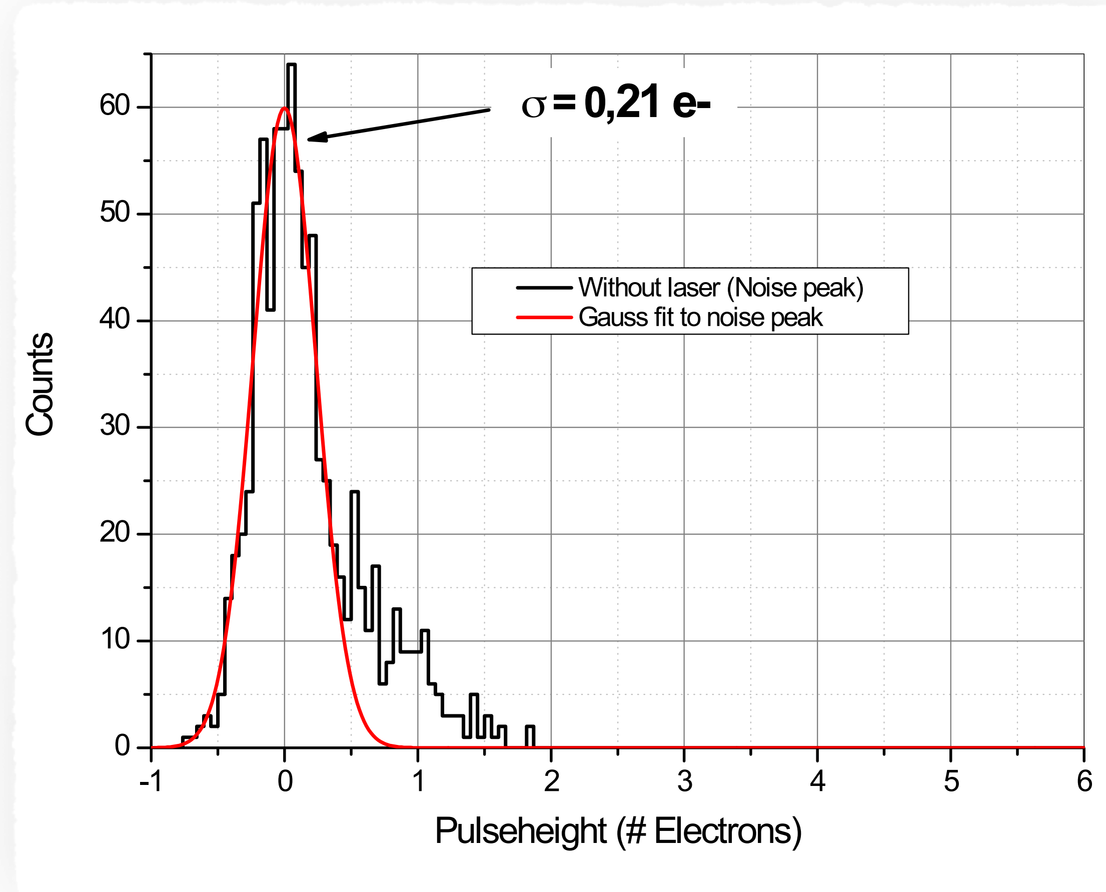


Measured Performance for DEPFET-RNDR

J. Treis, HLL



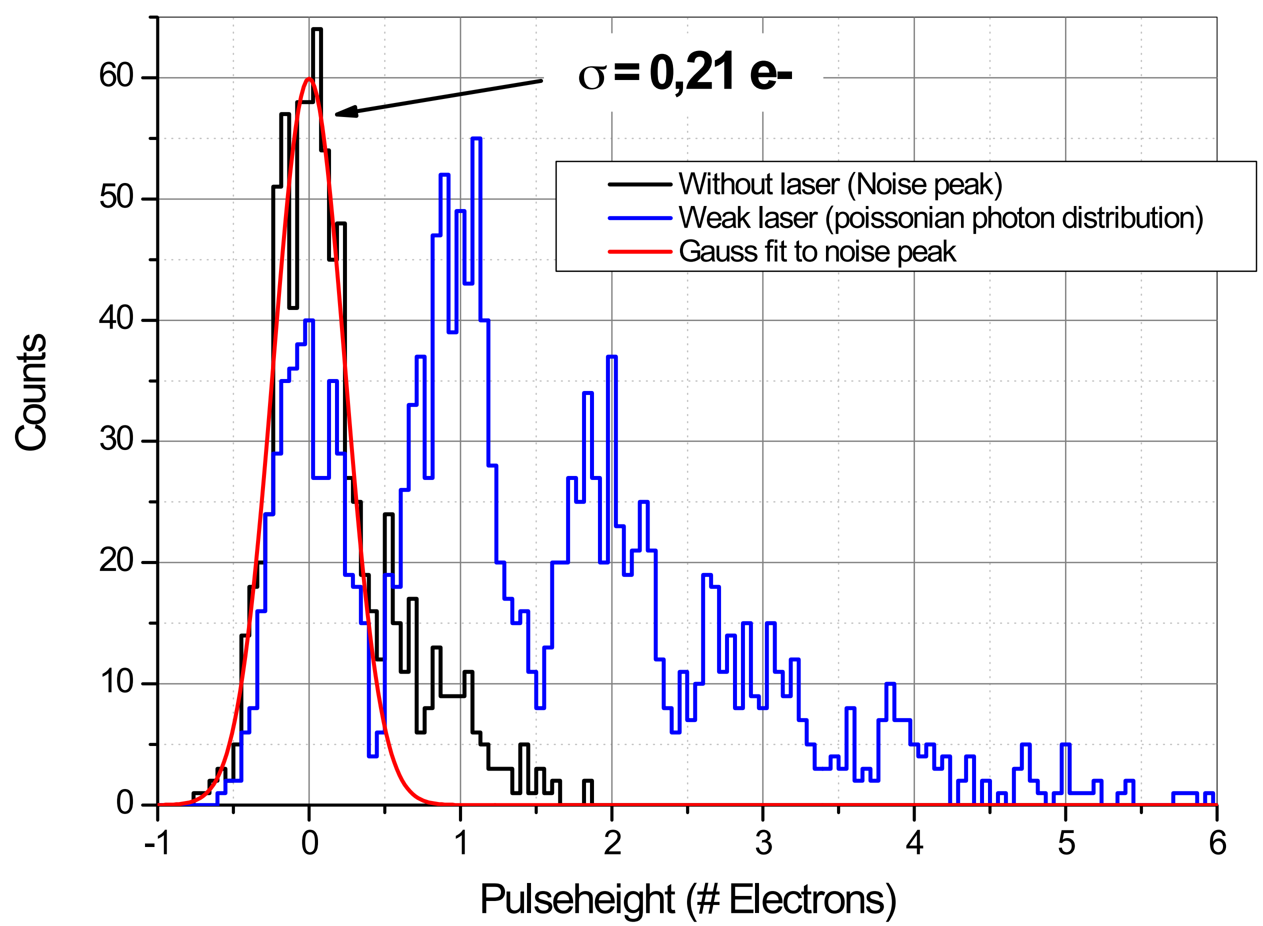
J. Treis, HLL



- noise performance as a function of readout cycles measured and reproduced by simulation
- **noise performance of σ=0,21 e^- achieved**

Measured Performance of DEPFET-RNDR

J. Treis, HLL



- measurement of single electrons with 5σ separation possible
- discrimination of number of electrons possible
- gated operation (switch off charge collection during readout) under investigation
    - reduction of noise increase with #transfers due to leakage currents