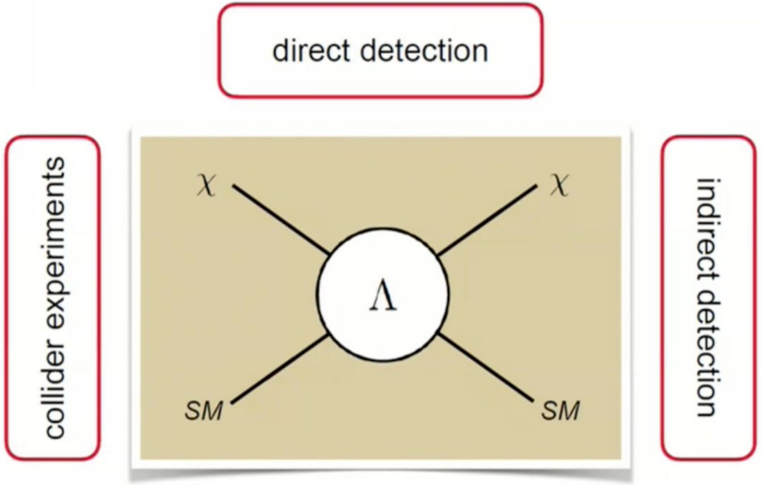
A short intro to DELight

dwong
Apr 18, 2025
16 pages, est. 18 mins

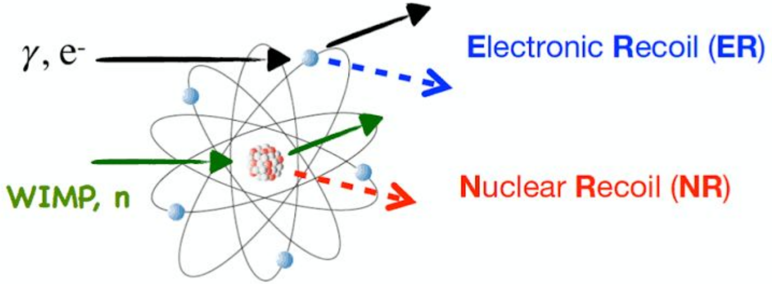
I. What is DELight?



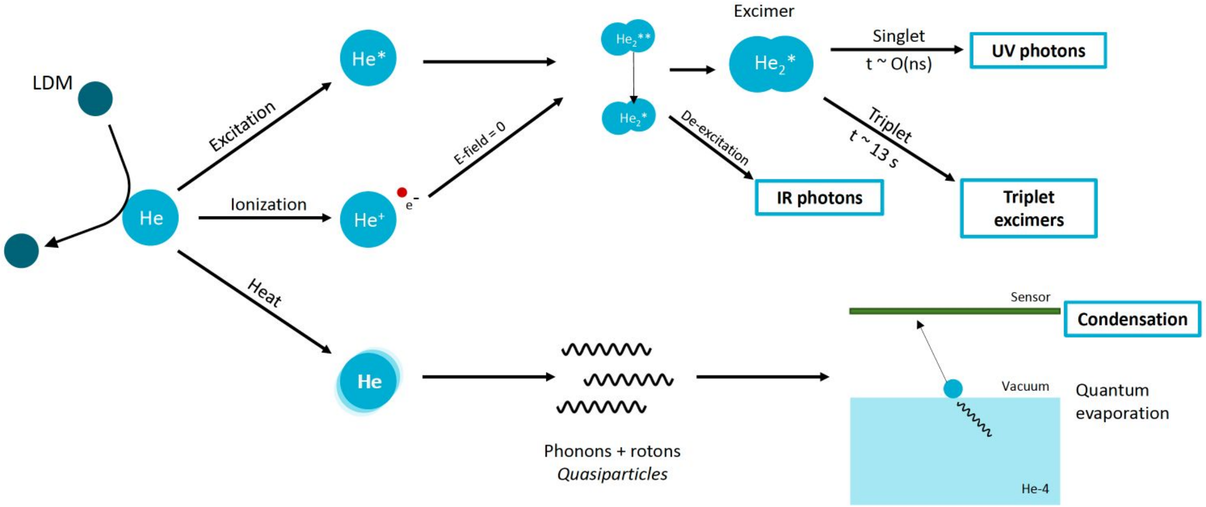
DELight is an upcoming direct detection dark matter experiment using a novel approach to probe the thus far uncharted low mass dark matter parameter space. We will search for interactions of dark matter in superfluid helium.

II. Novel_approach_0: What’s unique?

– Events and physics signature



Type of Recoil	Example Models	Scattering Type	Target	Energy Transfer
Electron Recoil (ER)	Dark photons, ALPs, millicharged particles	Inelastic	Electron	Excitation / ionization
Nuclear Recoil (NR)	Light WIMPs, Asymmetric DM	Elastic (mostly)	Nucleus	Kinetic energy to nucleus



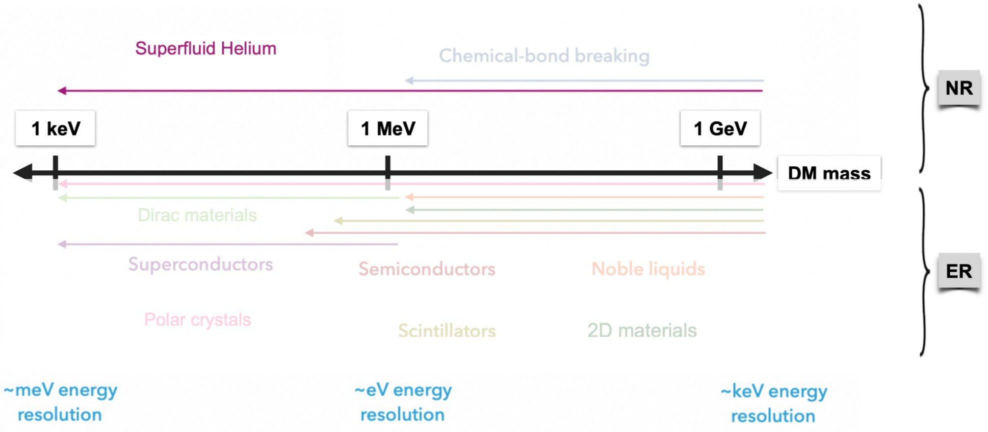
🎯Targets:

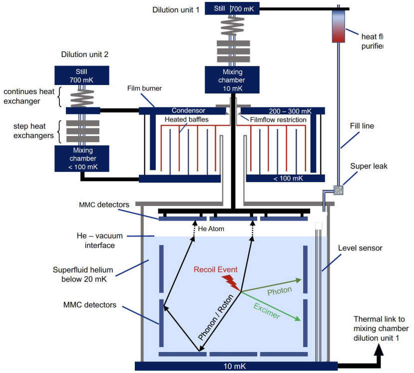
- Phonon
- Photon
- Roton(high P phonon)

LDM refers to the DM with energy ~ 1GeV

II. Novel_approach_1: What’s unique?

– Superfluid Helium as detection medium





$$E_R = \frac{1}{2}\frac{\Delta p^2}{m_N} \lesssim \frac{2\, m_{\rm DM}^2 v_{\rm DM}^2}{m_N}$$

Helium is very light compared to typical direct detection target elements like Xe, Ar, Ge and Si. Consequently, the energy transfer from the LDM particle to a target nucleus in a scattering event is more efficient and the resulting signals reach higher amplitudes naturally providing sensitivity to lower DM masses.

- Light nuclei maximize recoil energy for LDM
- Cheap
- Ultra-pure (Impurities freezing out)
- Multiple signals (phonon & rotons, photons,excimers)
- NR / ER discrimination
- Fiducialization possible
- Scalability
- Overall concept demonstrated

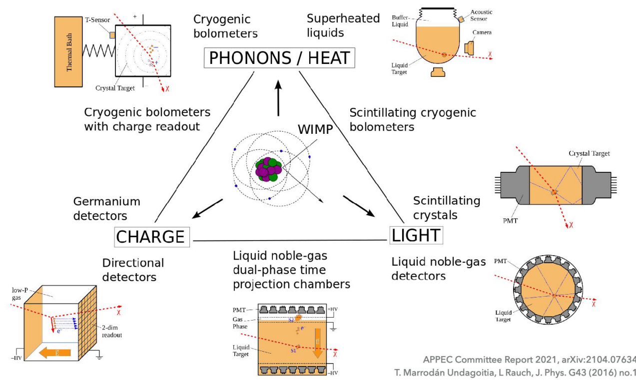
SuperCDMS: Cryogenic germanium (Ge) and silicon (Si) crystals

XENONnT: liquid Xenon

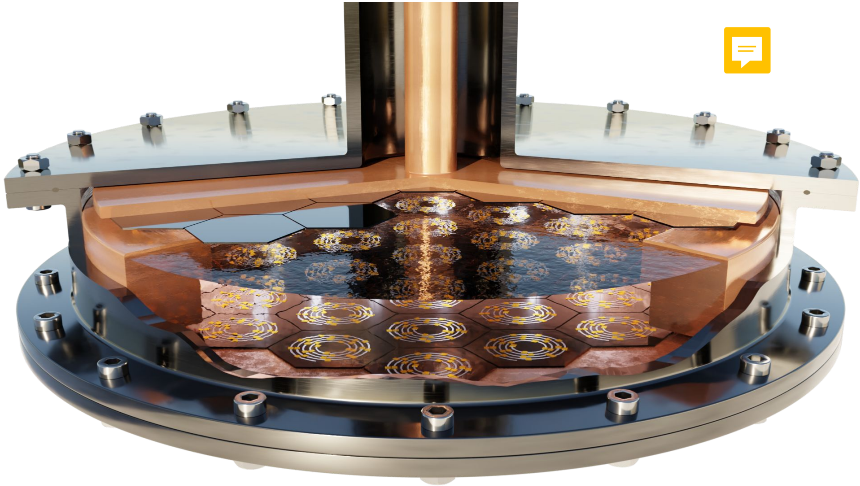
LUX-ZEPLIN: Liquid xenon

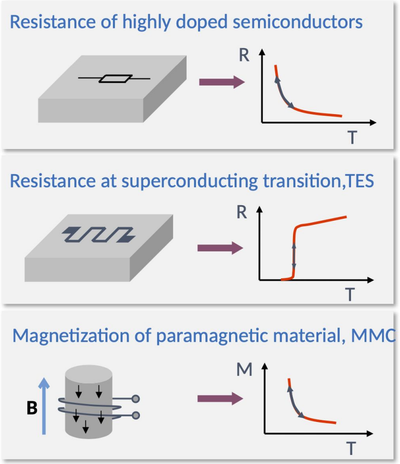
II. Novel_approach_2: What’s unique?

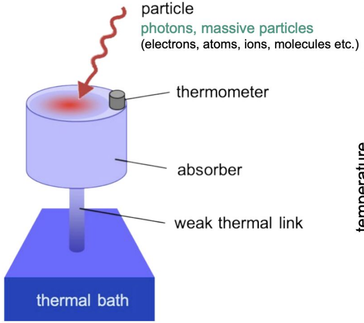
– MMC-LAMCAL vs TES-QET

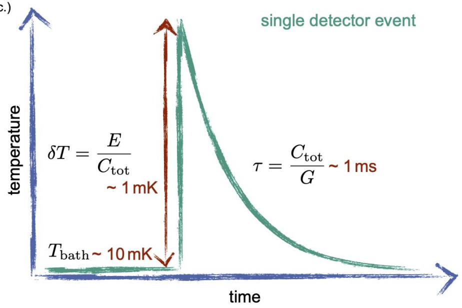


APPEC Committee Report 2021, arXiv:2104.07634 [hep-ex]
T. Marrodán Undagoitia, L Rauch, J. Phys. G43 (2016) no.1, 013001









Compare to TES, MMC has bigger variation vs temperature. From software point of view, we hold the world record of energy resolution: E_{FWHM} = 1.25 eV (please see energy calibration later pages)

III. Dive into the cell_0

– Dimension of the test cell

Sponsored by HEiKA

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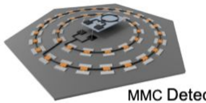
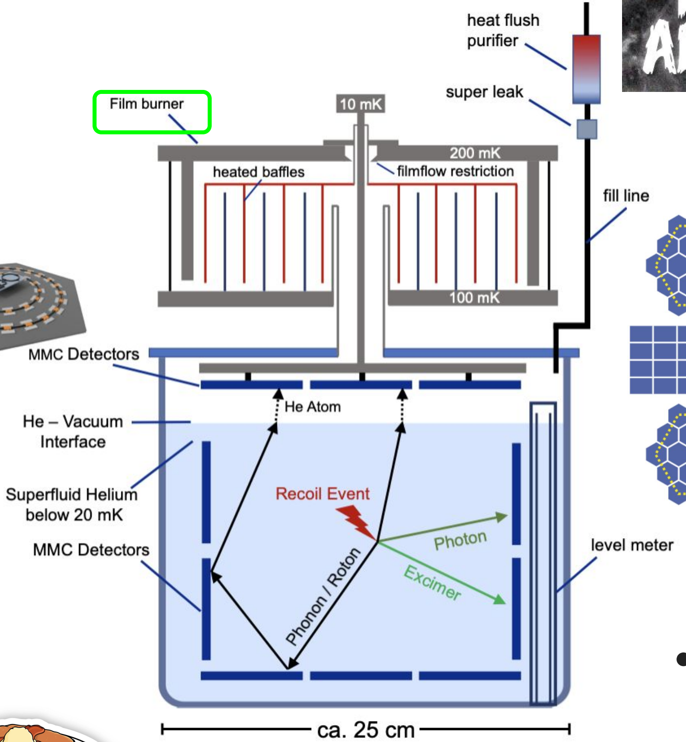
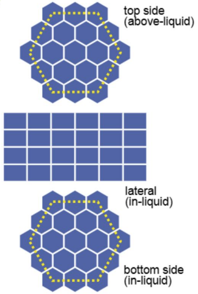
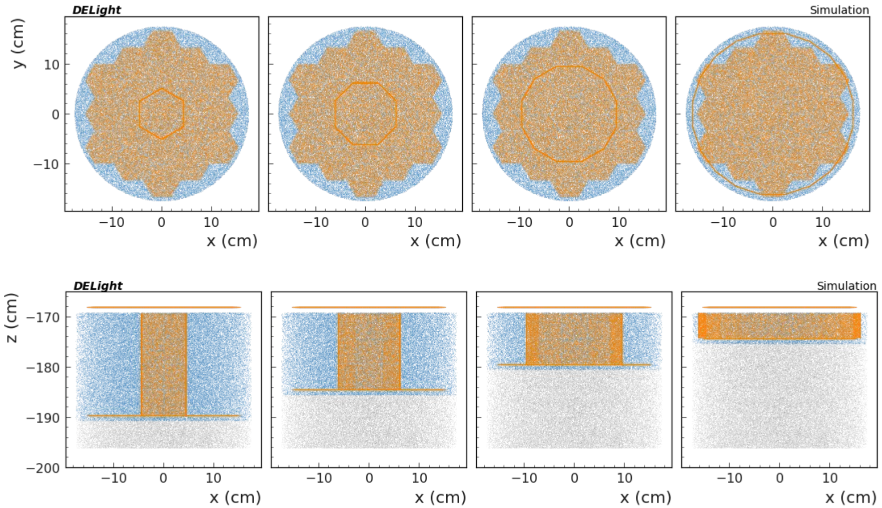
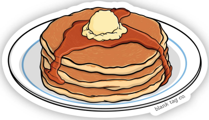








- Phase I: 10 L cell in shallow lab O(kg*d) exposure 20-30 eV threshold, with total 54 detector channels(45 submerged and 9 vacuum). Going to grow bigger for Phase II.
- MMCs in vacuum need to be 4He film-free → film burner (already tested by HERON)



III. Dive into the cell_1
– LAMCAL_0: MMC based Superconducting phonon collector

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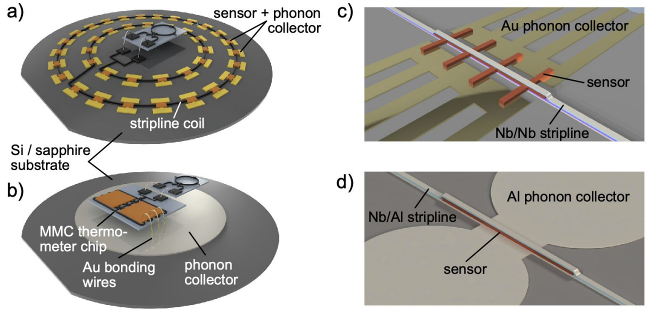
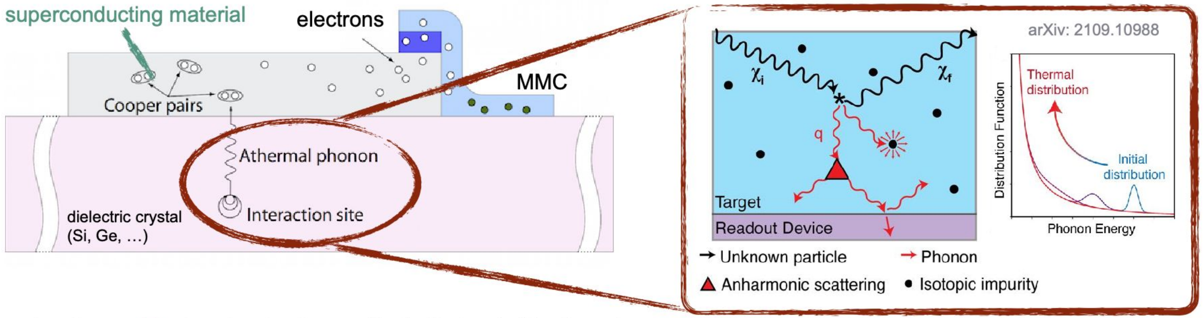
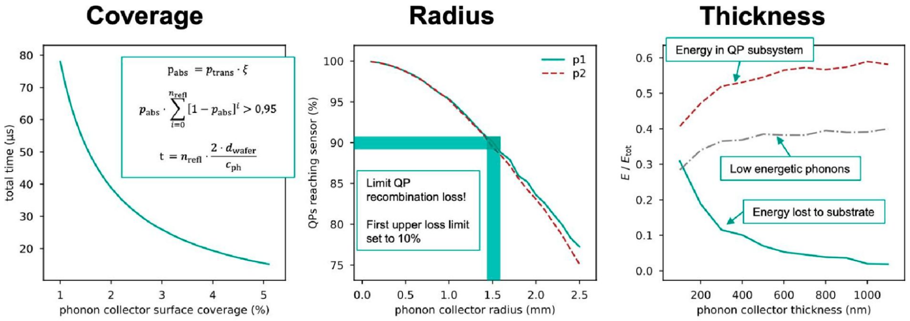




advantages:
- absorber heat capacity (to first order) irrelevant
- possibility for large absorber volumes

challenges:
- athermal phonon loss due to thermalization (phonon downconversion)
- quasiparticle losses due to recombination into Cooper pairs

usage of custom Monte Carlo simulation for optimzation of phonon collector geometry and distribution



phonon collector distribution will set requirements for LAMCAL geometry

While effective at preventing phonon back-emission, phonon collectors add significant heat capacity due to conduction electrons, degrading energy resolution—especially as surface coverage increases.

To address this, the DELight wafer calorimeters will instead be equipped with **superconducting phonon collectors**, which minimize heat capacity and preserve energy resolution.

III. Dive into the cell_2

– LAMCAL 1: dc-SQUID readout system

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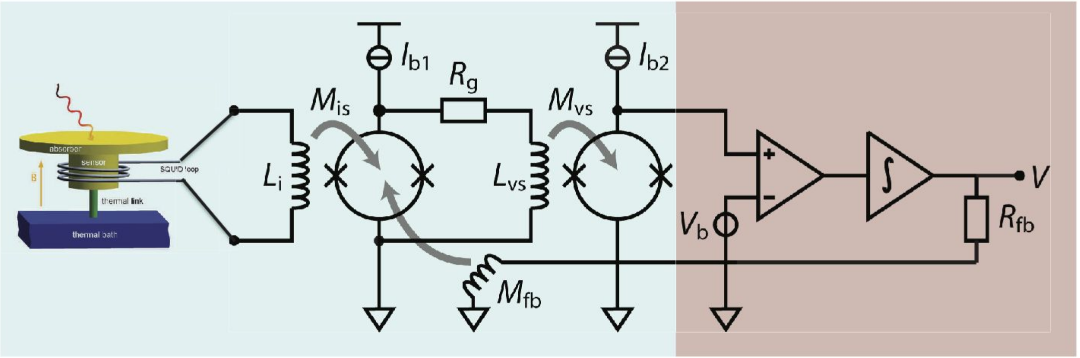
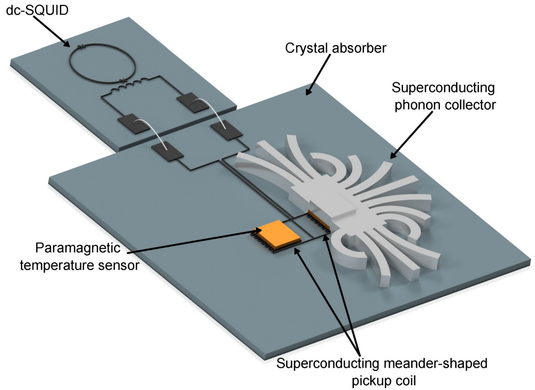
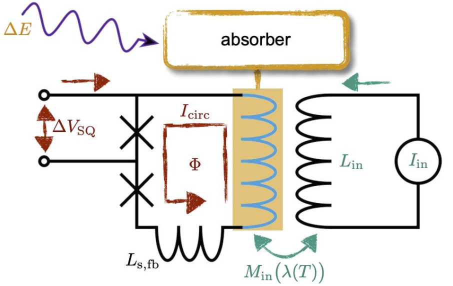
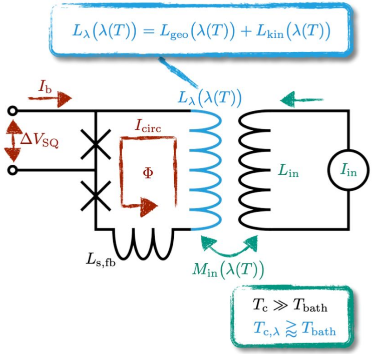
T ~ 30 mK T ~ 300 mK

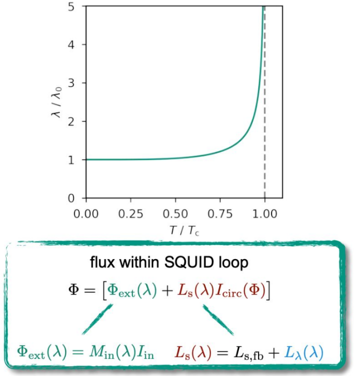






magnetic flux change within SQUID loop induced by change of M_{in}





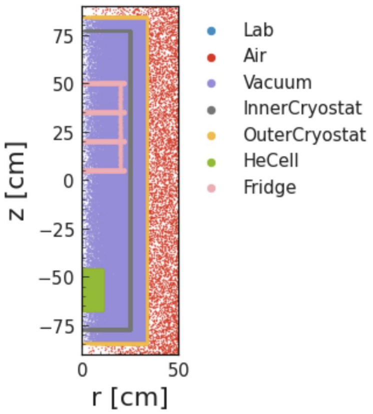
Large-area cryogenic microcalorimeter /LAMCAL: Single-channel MMCs or small-scale MMC arrays typically comprise two-stage dc-SQUIDs operated with a direct-coupled high-speed SQUID electronics with flux-locked loop (FLL) feedback

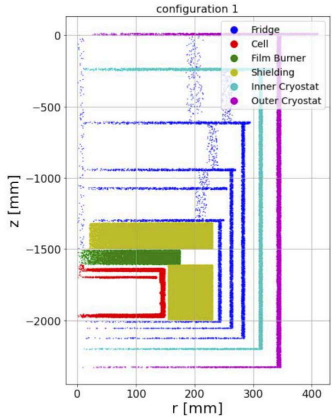
C. Schuster and S. Kempf, Appl. Phys. Lett. **123** (2023) 252603

III. Dive into the cell_3
– Low background environment

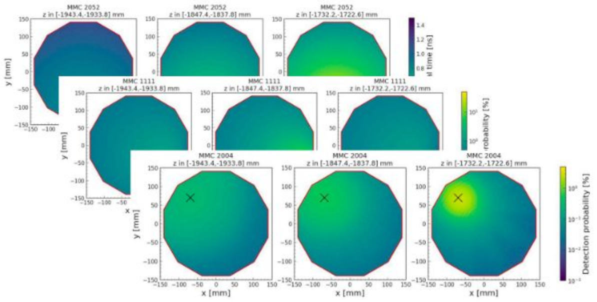
Vue-des-Alpes underground laboratory

Shallow underground lab close to Neuchâtel, Switzerland
Rock overburden of 620 m.w.e. ⇒ muon flux reduced by 1/2000
Gamma and radon background measurements
Operated by University of Freiburg (hosting GeMSE gamma spectrometer)

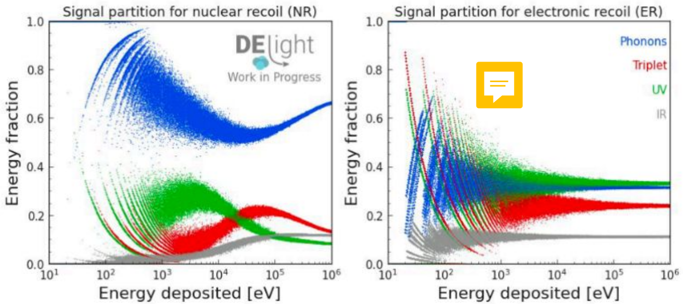




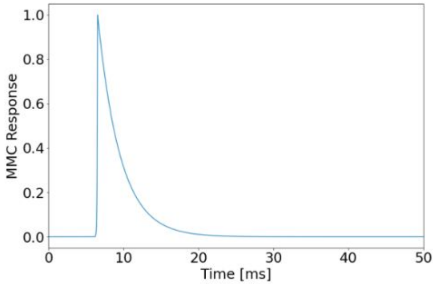
IV. Software: Simulation and Reconstruction_0
– GEANT4 implementation



Position

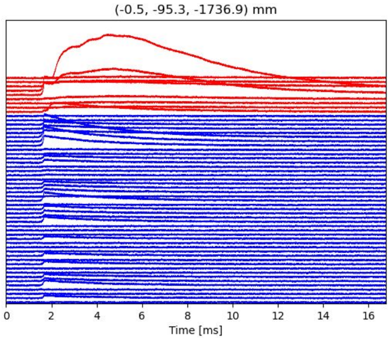


Recoil type signal partitioning



MMC response

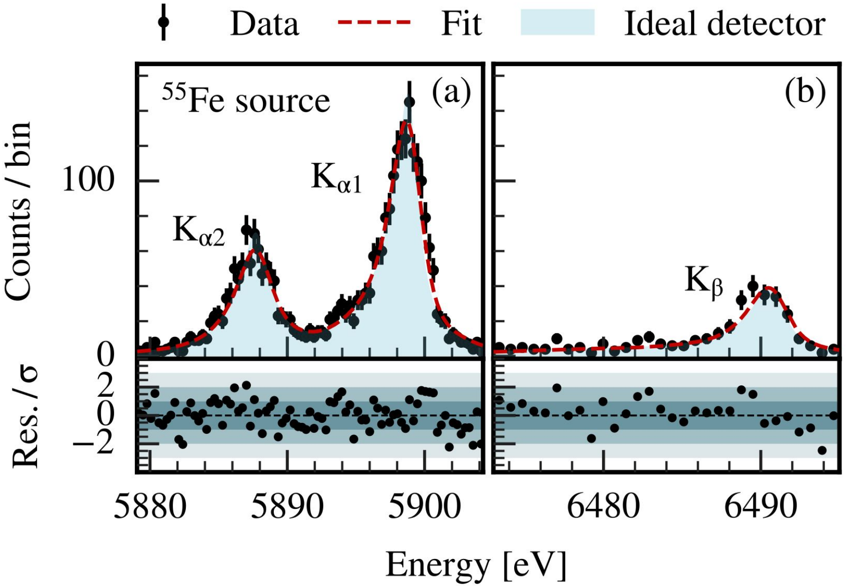
The **TraceSimulator** is configured using the geometry of the proposed test cell, taking into account inelastic DM-nucleus scattering interactions including secondary effects, such as the Migdal effect or Bremsstrahlung

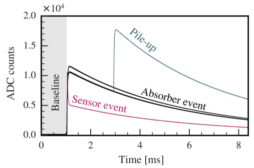


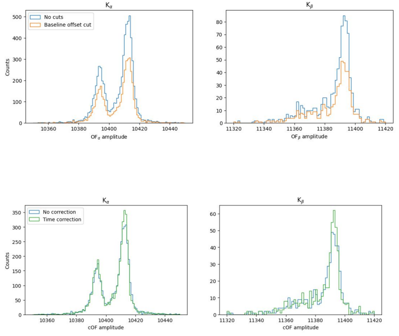
Diffusion model for generating simulation data at R&D stage(ICL)

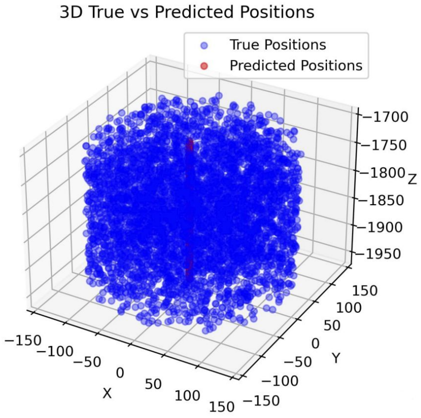
IV. Software: Simulation and Reconstruction_1

– Energy and position reconstruction









Position reconstruction(ICL):

Transformer-based position reconstruction, takes in waveform per channel and correlates it with other channels.

Currently able to reconstruct the z coordinate of the recoil event.

signal amplitude Time shift (template roll) template

$$\chi^2 = \int_{-\infty}^{\infty} \frac{|v(f) - Ae^{-i\omega t_0} s(f)|^2}{J(f)} df$$

Noise PSD

$$a = \frac{\sum_\nu S^*(\nu) A(\nu)/J(\nu)}{\sum_\nu |A(\nu)|^2/J(\nu)}$$

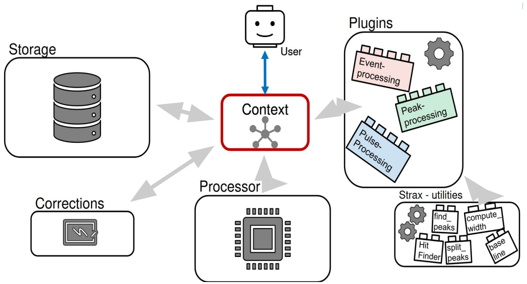
$$E = p_1 \cdot A_{\mathrm{cOF}}^2 + p_2 \cdot A_{\mathrm{cOF}}$$

$$\Delta E^{\mathrm{OF}}_{\mathrm{FWHM}} = 2\sqrt{2\ln 2}\left(\sum_\nu \frac{|A(\nu)|^2}{J(\nu)}\right)^{-0.5}$$

MMCs have achieved a world-leading energy resolution of ΔE_{FWHM} = 1.25 eV for 5.9 keV photons

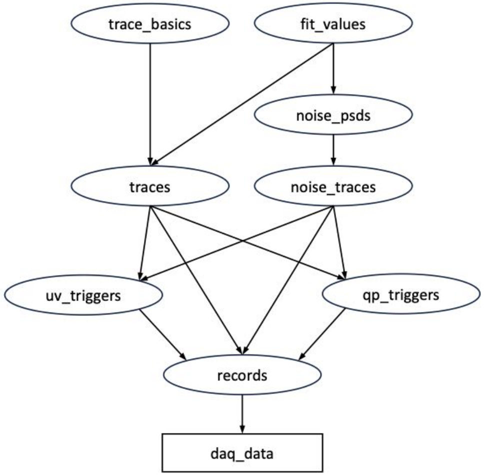
IV. Software: Simulation and Reconstruction_2

– **Software** OF trigger_0



Helix is a strax-based data processing software for DELight (superfluid Helium Dark Matter search experiment) and Magnetic Micro-Calorimeter (MMC) R&D projects.

Helix data structure



- basics, fit_values: fit results, integrals, baselines, etc
- noise_psds: noise Power Spectrum Densities for optimum filter
- traces: pieces of records containing events
- triggers: trigger locations with some trigger info
- records: digitized waveforms in strax format
- daq_data: DAQ output data files

IV. Software: Simulation and Reconstruction_3

– Software **OF** trigger_1

signal

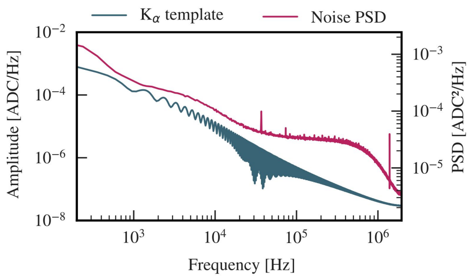
amplitude

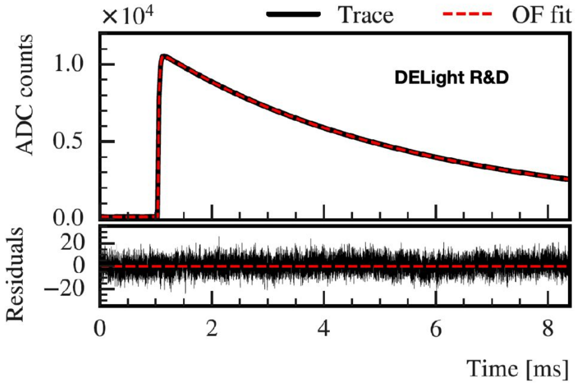
Time shift (template roll)

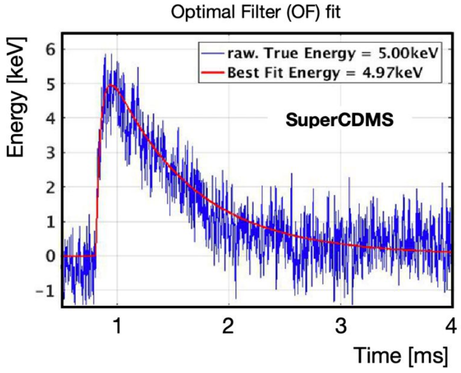
template

$$\chi^2 = \int_{-\infty}^{\infty} \frac{|v(f) - Ae^{-i\omega t_0} s(f)|^2}{J(f)} df$$

Noise PSD







E.1 Basic Optimal Filter

- Defines the filter that minimizes the chi-squared difference between a trace and a scaled template:

$$A = \frac{\int s^*(f)v(f)/J(f)\,df}{\int |s(f)|^2/J(f)\,df}$$

where $v(f)$ is the signal, $s(f)$ is the template, and $J(f)$ is the noise PSD.

E.2 Optimal Filter with Time Offset

- Extends the model to allow the signal to be time-shifted:

$$s(f) \to s(f, t_0) = e^{-i\omega t_0} s(f)$$

- The best-fit amplitude becomes a function of t_0, allowing peak-finding in time domain.

E.3 Two-Pulse Optimum Filter

- Generalizes to overlapping signals (pile-up):

$$v(f) \approx A_1 e^{-i\omega t_1} s(f) + A_2 e^{-i\omega t_2} s(f)$$

- Solves for both amplitudes with time separation accounted for.

E.4 Joint Channel Optimum Filter

- Multiple detector channels share templates but differ by scaling:

$$\chi^2 = \sum_i \int \frac{|v_i(f) - \sum_\alpha A_\alpha e^{-i\omega t_0} s_{i\alpha}(f)|^2}{J_i(f)} df$$

E.5 Joint Channel Correlated Optimum Filter

- Incorporates correlated noise via a cross-spectral density matrix $\Sigma_{ij}(f)$:

$$\chi^2 = \sum_{i,j} \int (v_i - \ldots)^* \Sigma_{ij}^{-1}(f)(v_j - \ldots)\, df$$

E.6 Optimal Filter Resolution

- Derives variance of amplitude estimates:

$$\sigma^2 = \left[\int s^*(f) J^{-1}(f) s(f)\, df\right]^{-1}$$

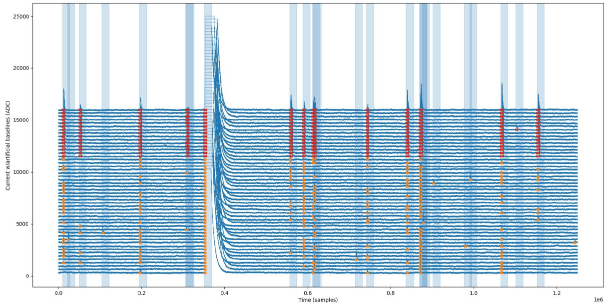
- Shows resolution improves with more channels and uncorrelated noise.

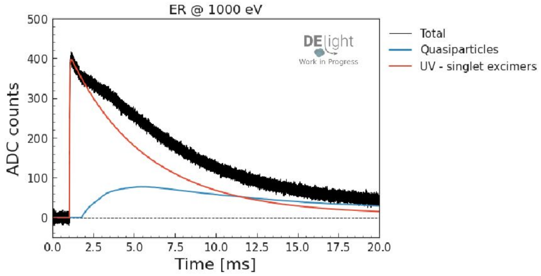
Expect to achieve moderate threshold of about 20 eV, as planned during phase-I of DELight, a DM-nucleon scattering cross section of < 1e-39 cm^2 at 200 MeV can be probed.

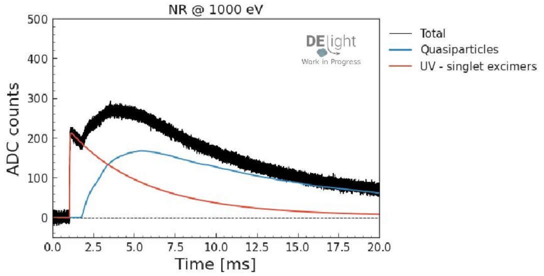
Kurinsky, Noah Alexander. "The Low-Mass Limit: Dark Matter Detectors with eV-Scale Energy Resolution." , Jan. 2018.

IV. Software: Simulation and Reconstruction_4

– Software OF **trigger**_2







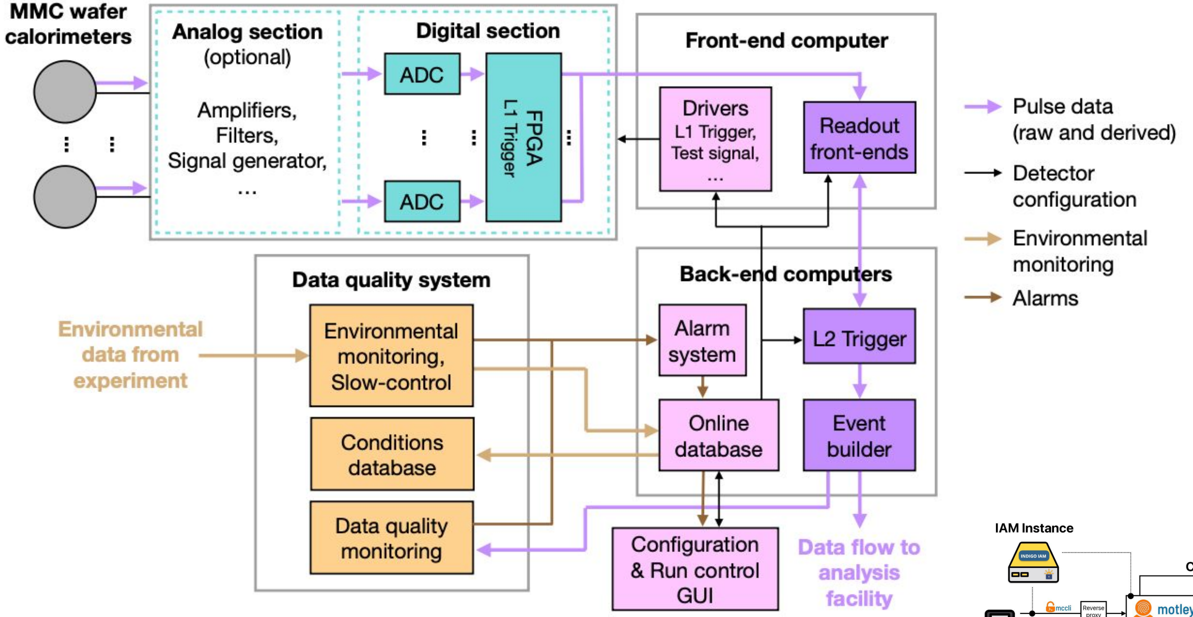
- Instead of a rolling approach, we implemented a sliding optimum filter (OF) trigger, which better suits our signal characteristics by focusing on the leading edge of the pulse and avoiding interference from the long quasiparticle tail.

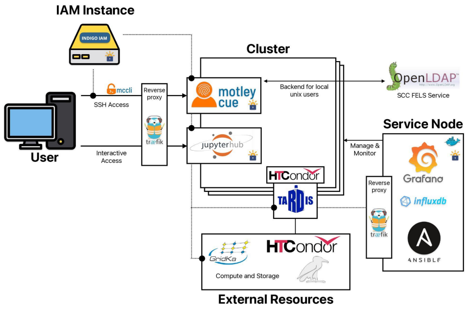
- At the R&D stage, we are developing a multi-template optimum filter trigger system, inspired by the SuperCDMS fast-slow template trigger, to enhance performance across a broader range of signal shapes.

A. Zaytsev. Light Dark Matter Searches and Modeling of Charge Propagation Effects in SuperCDMS Cryogenic Silicon R&D Detectors with eV-Scale Sensitivity. Karlsruhe Institute of Technology,2023.

V. Data acquisition and computing infrastructure

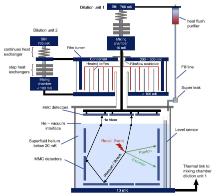
– FPGA based hardware trigger

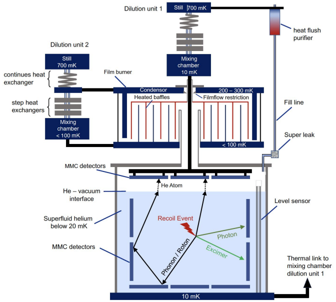


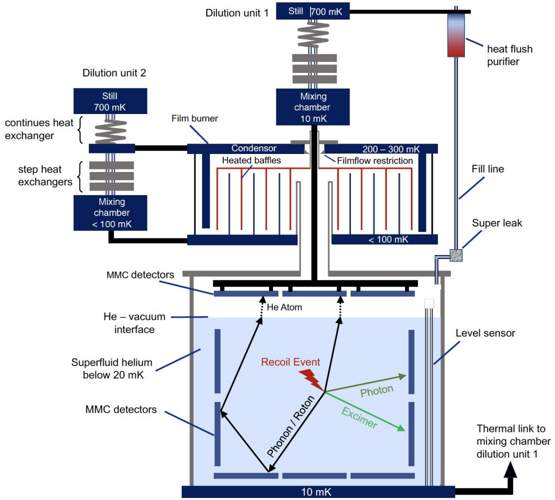


- ~~According to the proposal,~~ FPGA hardware trigger will be implemented at UHD.
- With Prof. MK's expertise in DAQ and Prof. TF's expertise in FPGA development, we are well-prepared to assist at any time.
- Inherit DARWIN cluster at KIT

DELight is growing bigger and stronger! Stay stunned!







Phase I -> Phase II -> Super DELight!