DELight: The Direct Search Experiment for Light Dark Matter

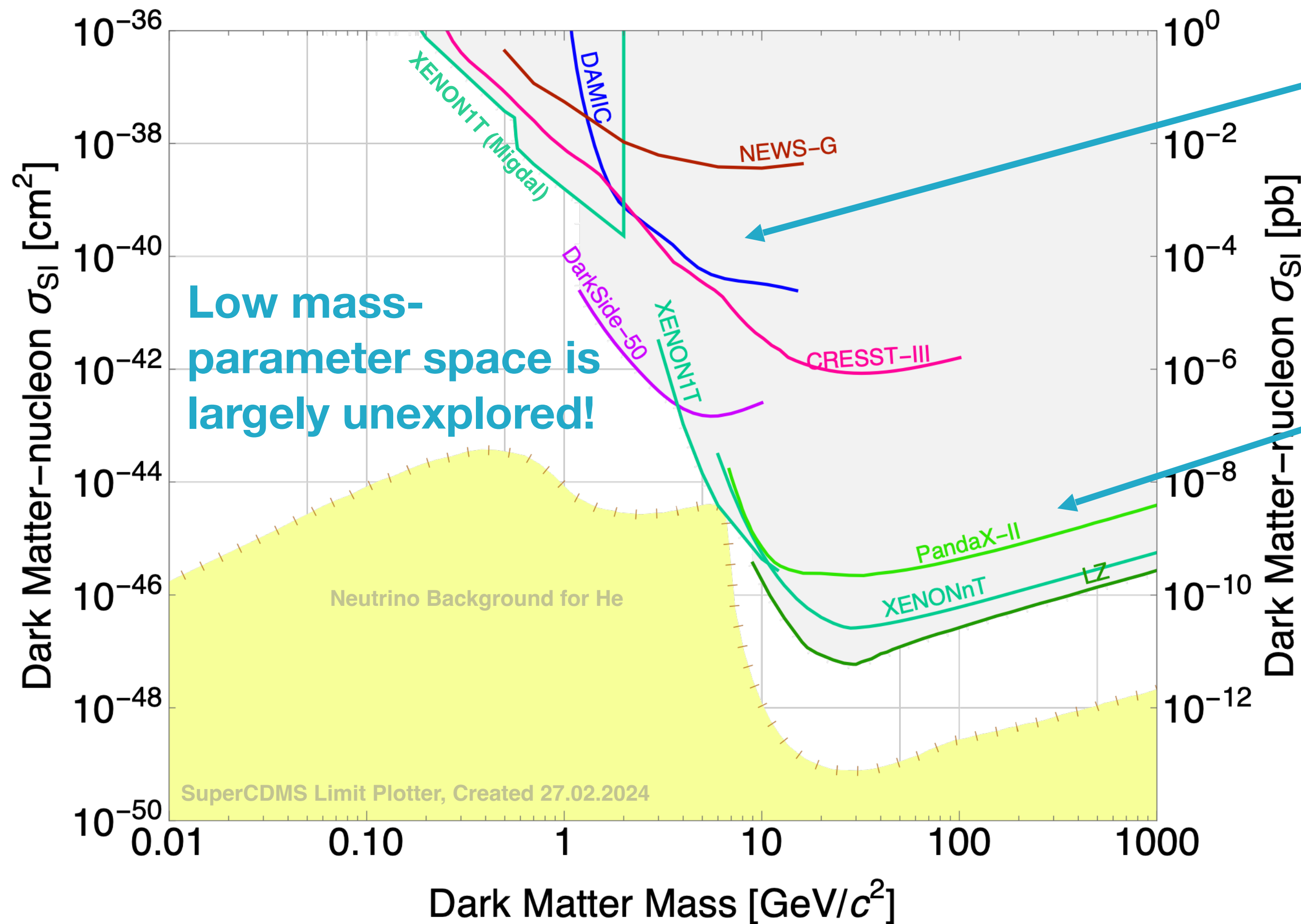Eleanor Fascione on behalf of the DELight Collaboration
INFN-LNF Workshop on The Low Energy Frontier of Particle Physics, 2025/02/11

The Current SI-DM Landscape and Push to Low Mass

Various experimental efforts to reach sensitivity to ~GeV/c^2 scale WIMPs

Heavy noble experiments constrain high-mass WIMP parameter space and push towards neutrino fog

1. J.I.Collar, Phys. Rev. D 98, 023005 (2018)
2. Arnaud et al., Astroparticle Physics 97, p.54--62 (2018)
3. Qiuhong Wang et al. (PandaX-II Collaboration) 2020 Chinese Phys. C 44 125001
4. Aalbers et al., Phys. Rev. Lett. 131, 041002 (2023)
5. Aprile et al., Phys. Rev. Lett. 131, 041003 (2023)
6. Aprile et al. Phys. Rev. Lett. 126, 091301 (2021)
7. Aprile et al., Phys. Rev. Lett. 123, 241803 (2019)
8. A. Aguilar-Arevalo et al., Phys. Rev. Lett. 125, 241803 (2020)
9. P. Agnes et al. (DarkSide), Phys. Rev. Lett. 130, 101001 (2023)
10. Abdelhameed, A. Physical Review D 100.10 (2019)

The DELight Collaboration

An upcoming light dark matter search using superfluid helium-4
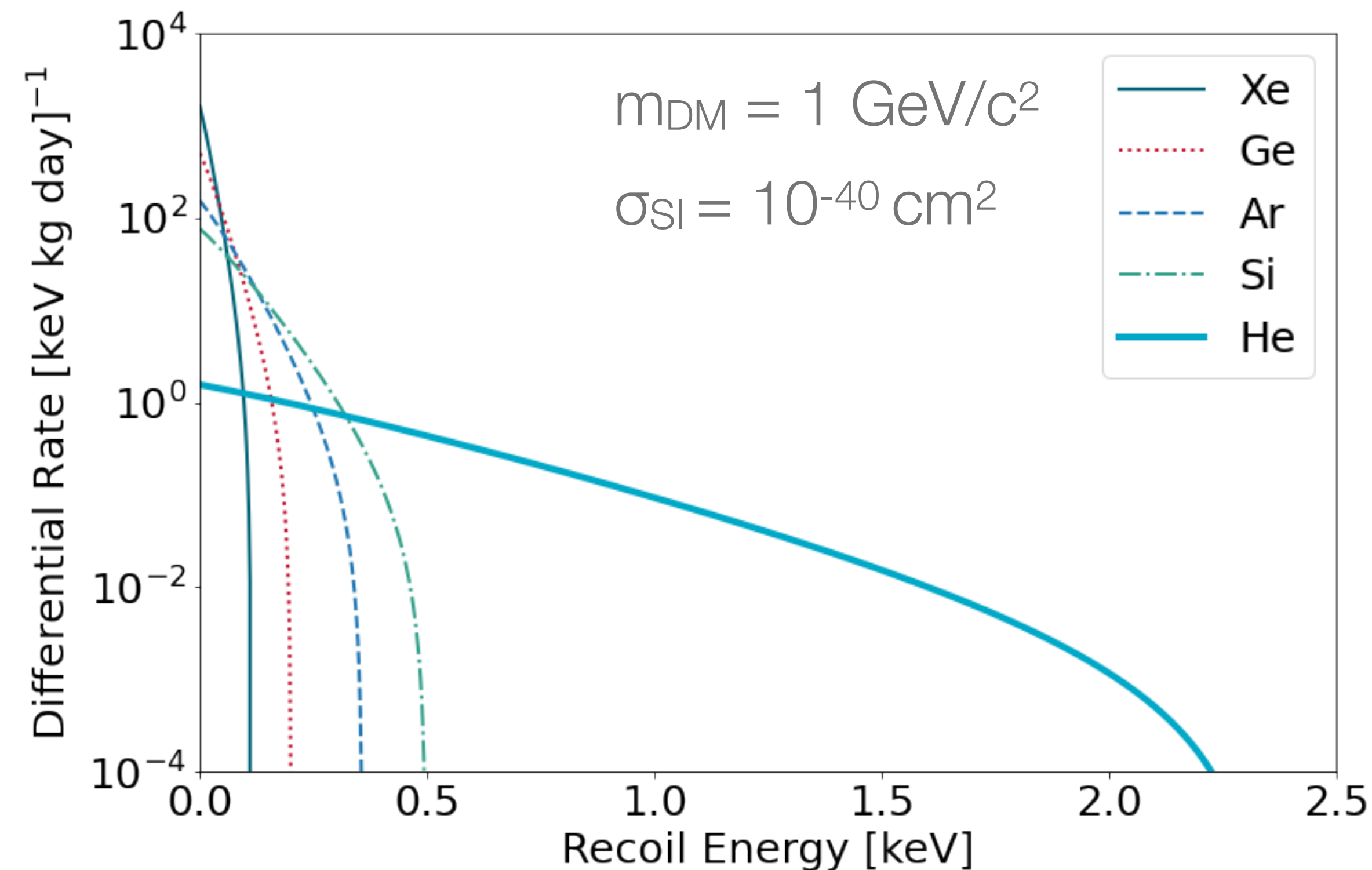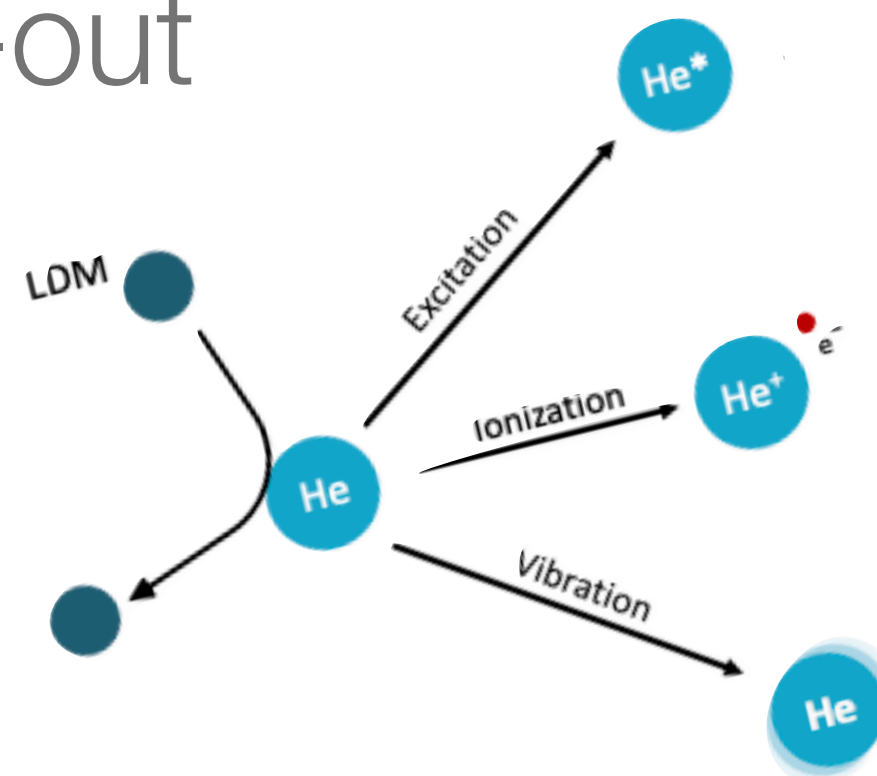
universität freiburg

KIT
Karlsruher Institut für Technologie

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

UNIVERSITÄT HEIDELBERG
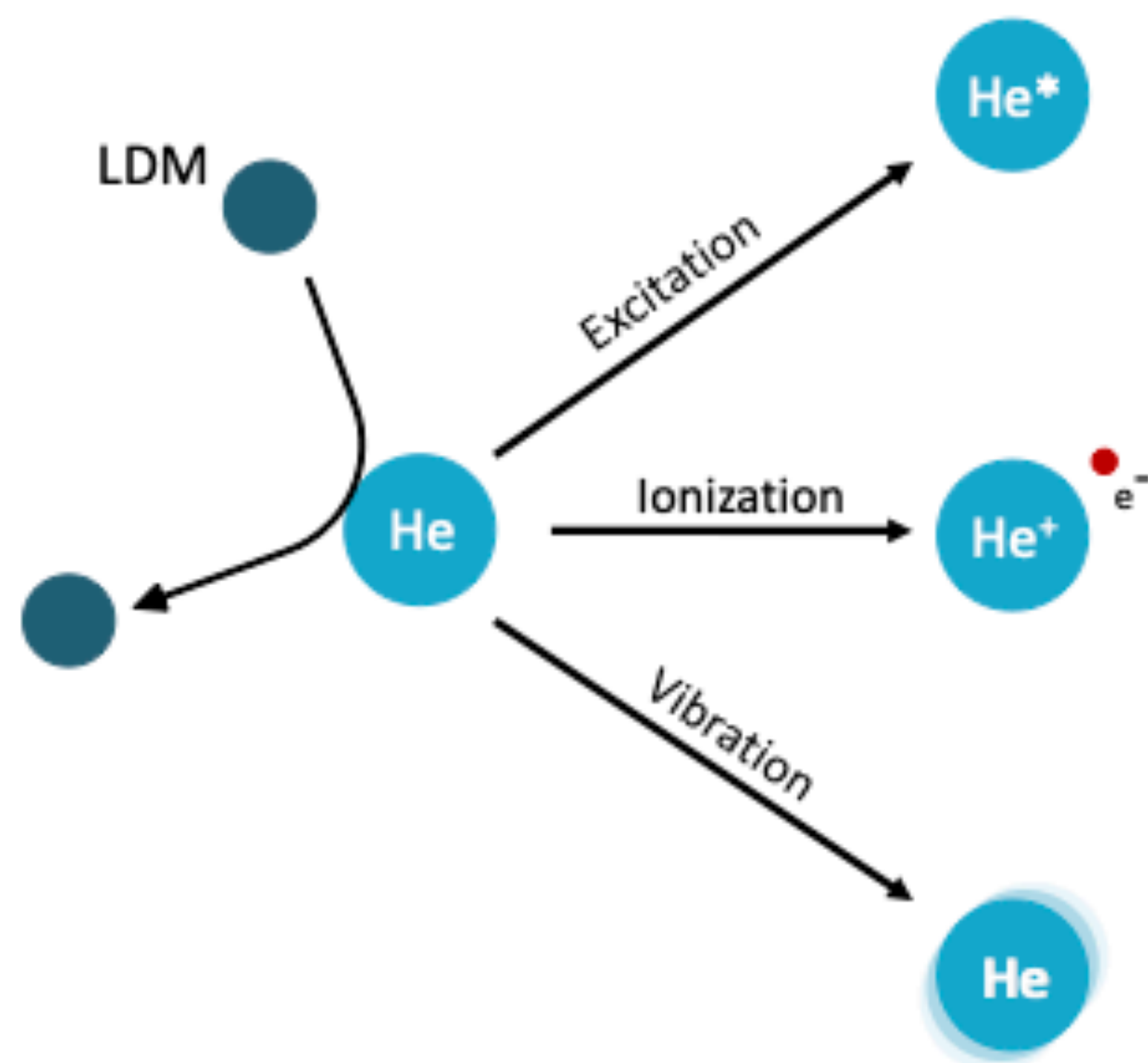ZUKUNFT SEIT 1386

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UHD

UFR

DElight

Superfluid Helium-4 Target

➡ Light nucleus ideal for LDM searches

➡ No intrinsic long-lived backgrounds

➡ Contaminants freeze-out

➡ Inexpensive

➡ Scalable

➡ Multiple signals: ER/NR discrimination

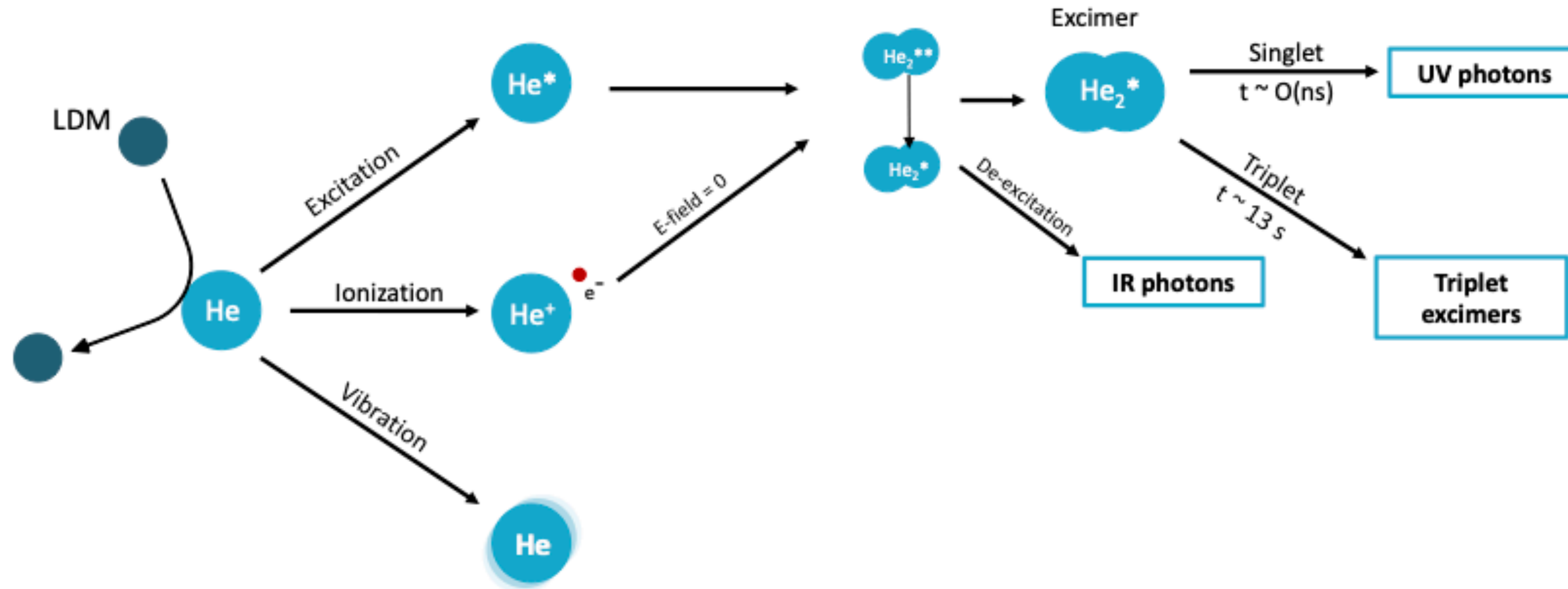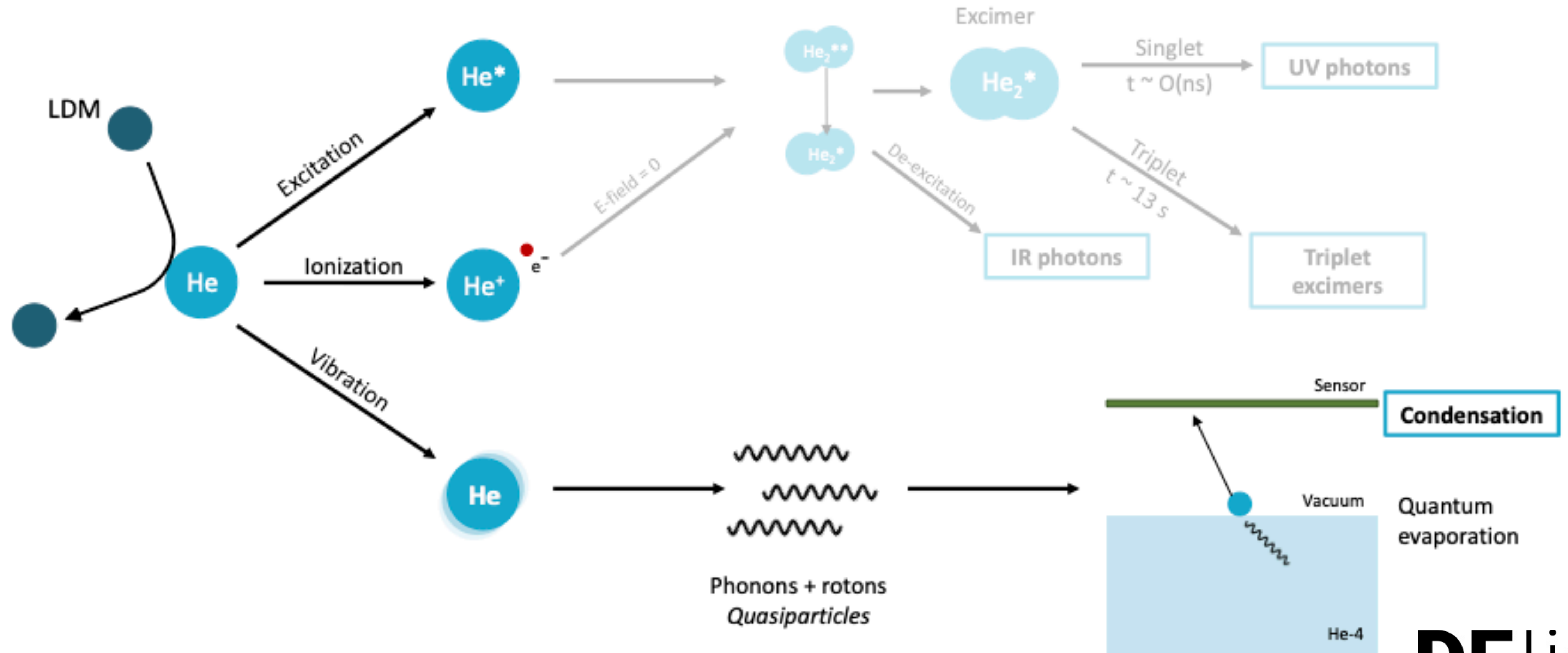$m_{DM} = 1$ GeV/c^2

$\sigma_{SI} = 10^{-40}$ cm^2
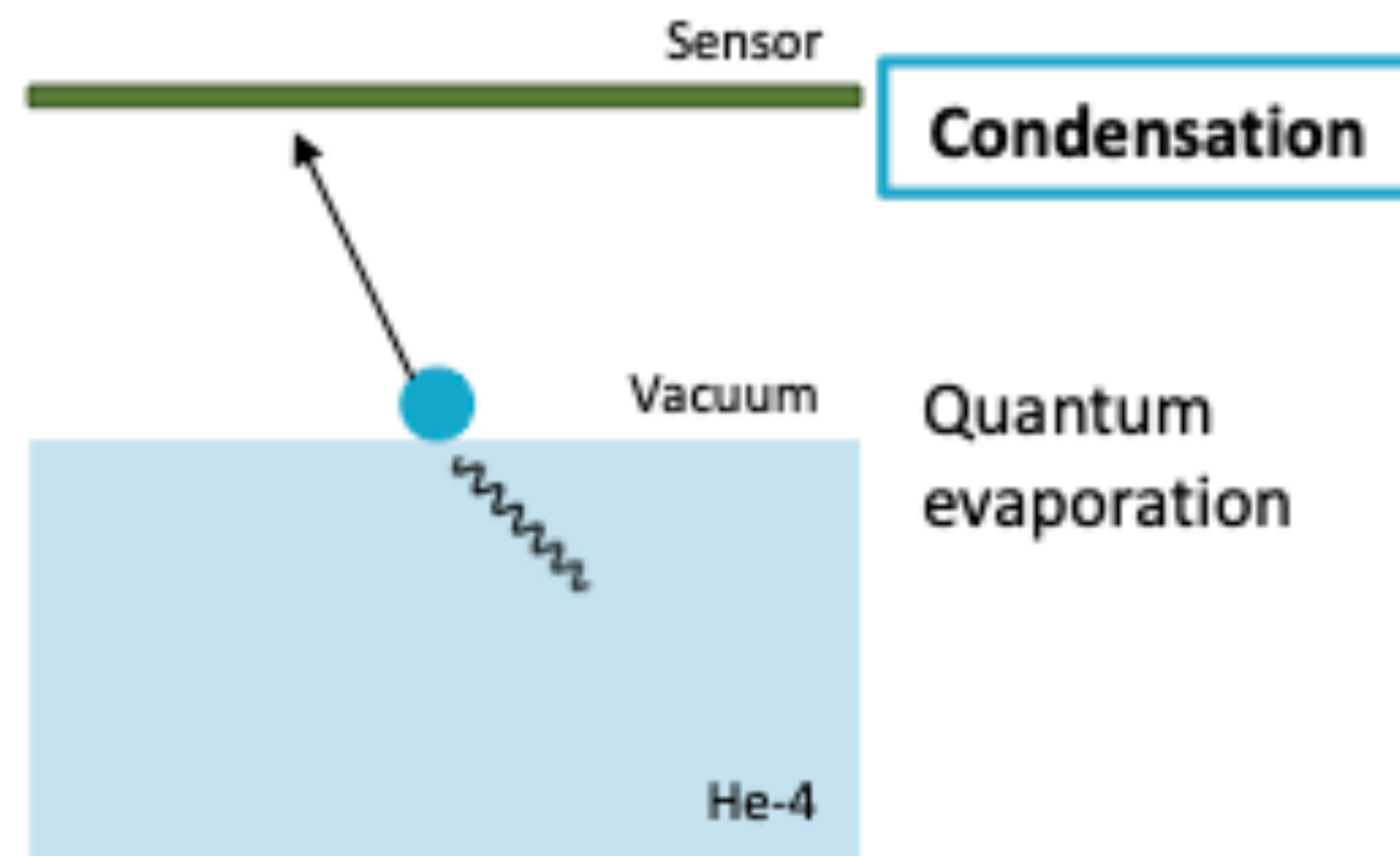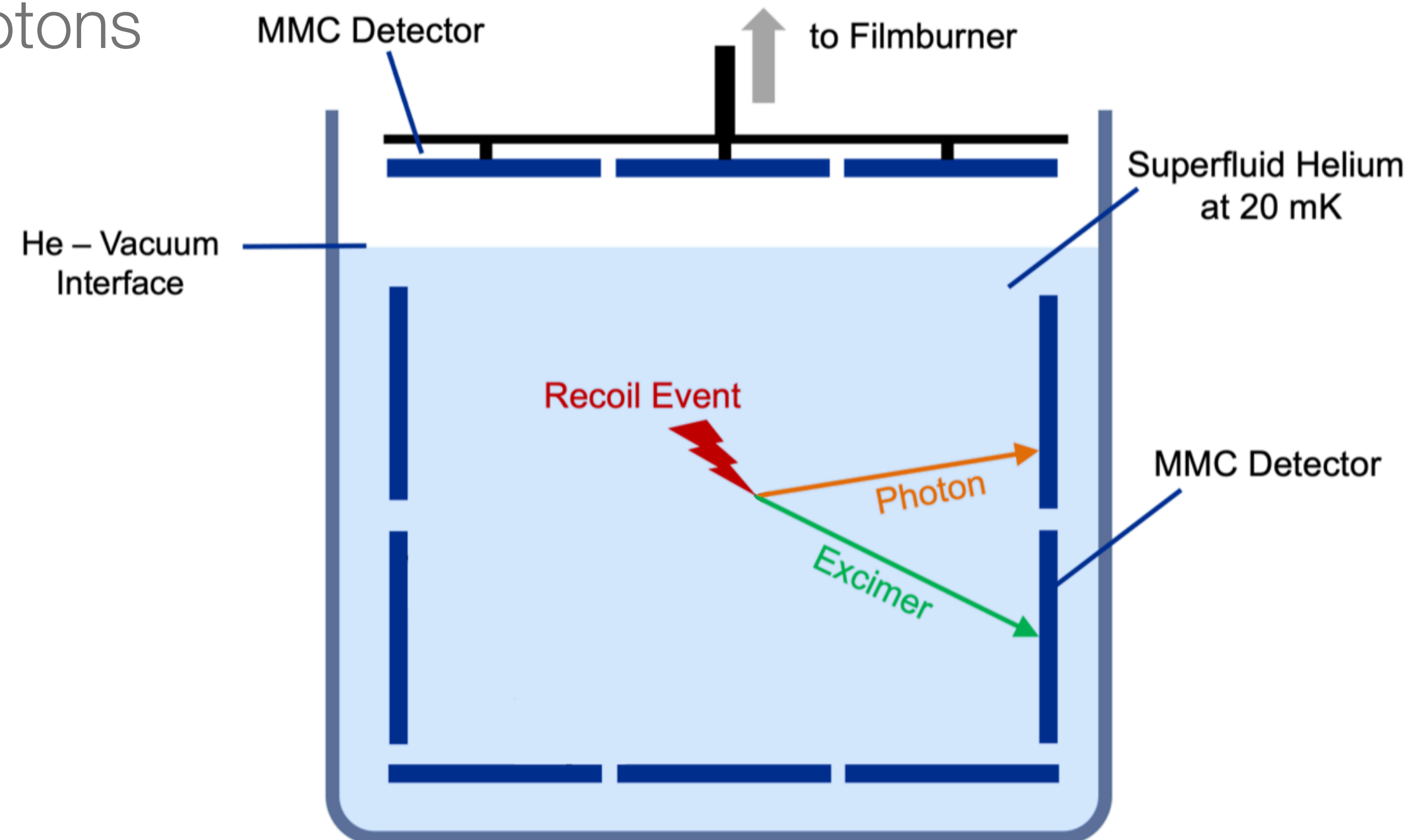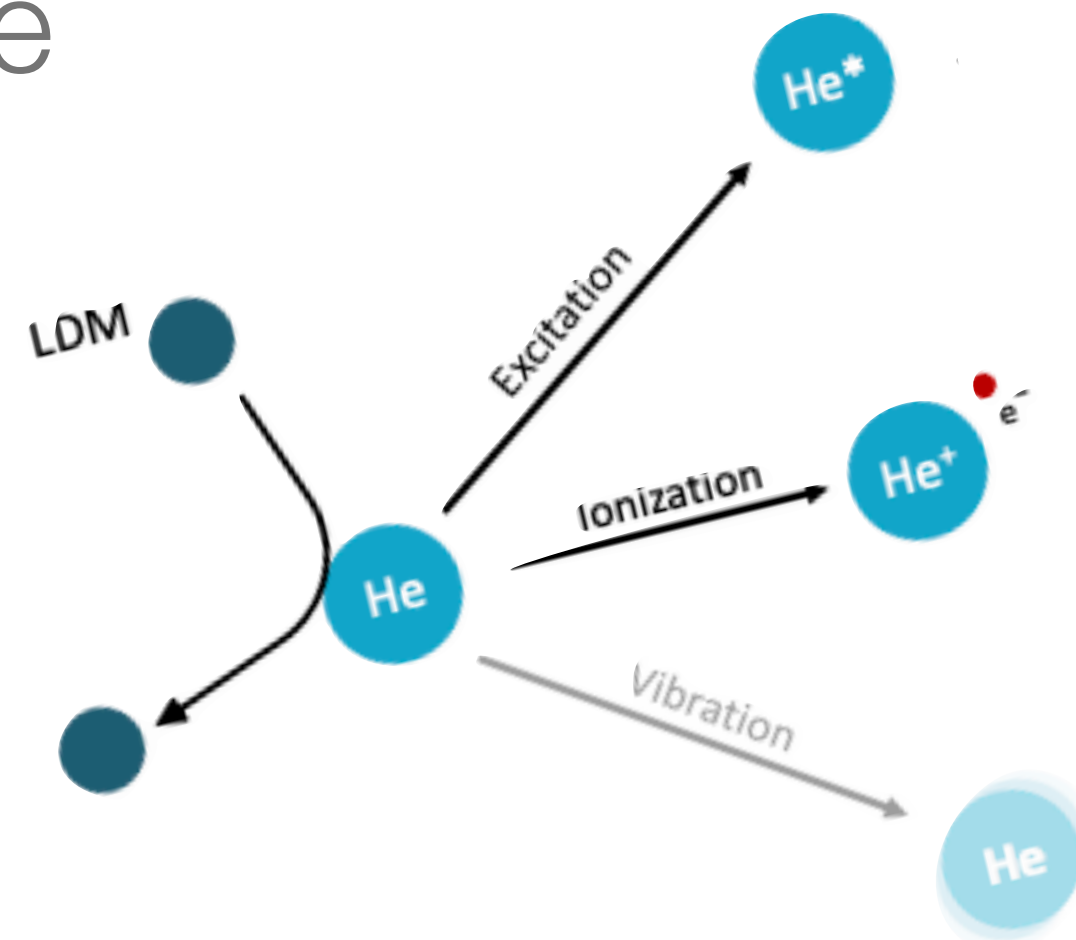
Signals in Superfluid He-4

Signals in Superfluid He-4

Signals in Superfluid He-4

➡ Collective long lived excitations in superfluid He

Condensation

Quantum evaporation

Quantum evaporation threshold
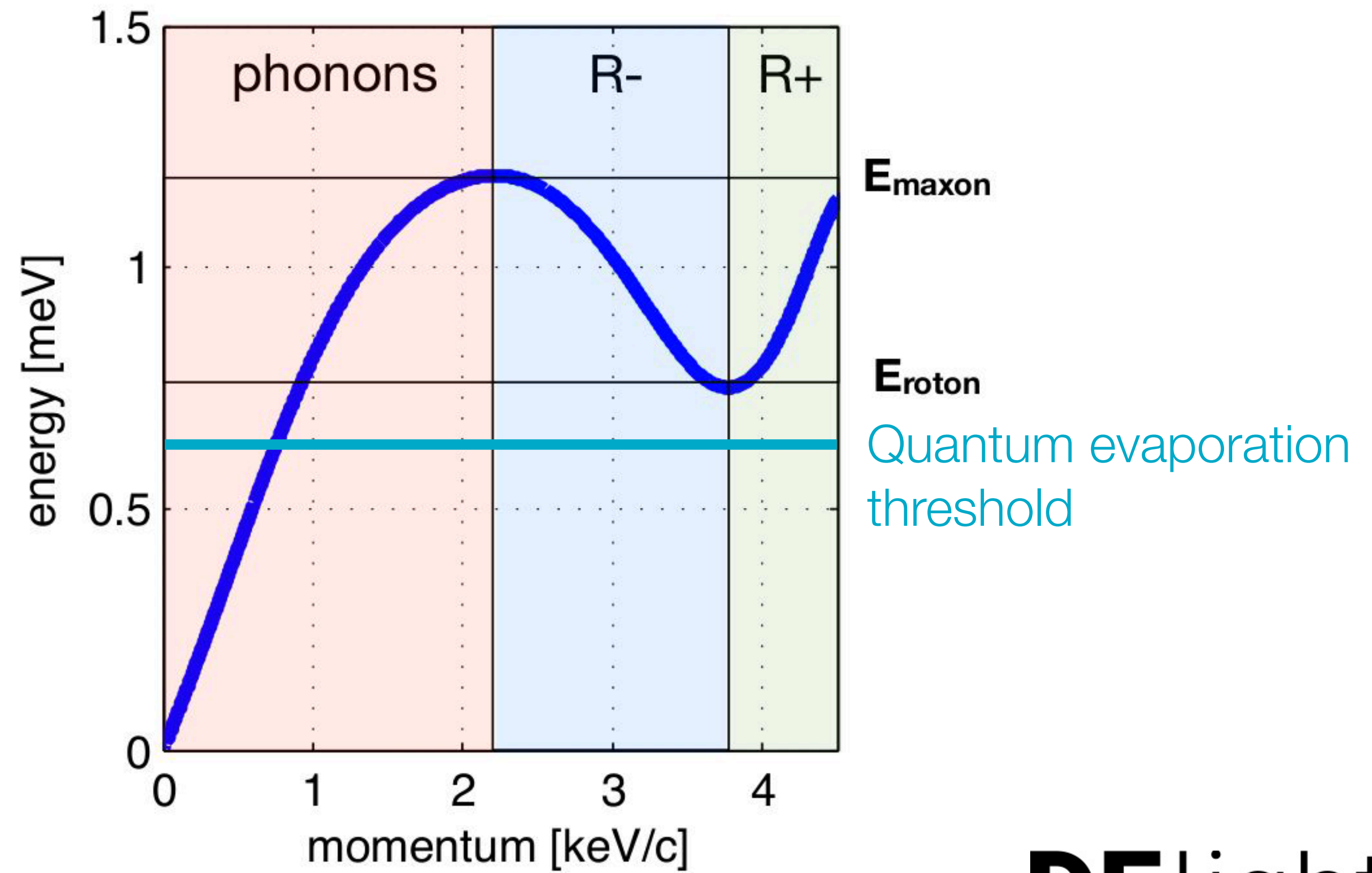
DELight Detector - Interactions in Superfluid Helium-4

➡ Prompt signal from UV and IR photons

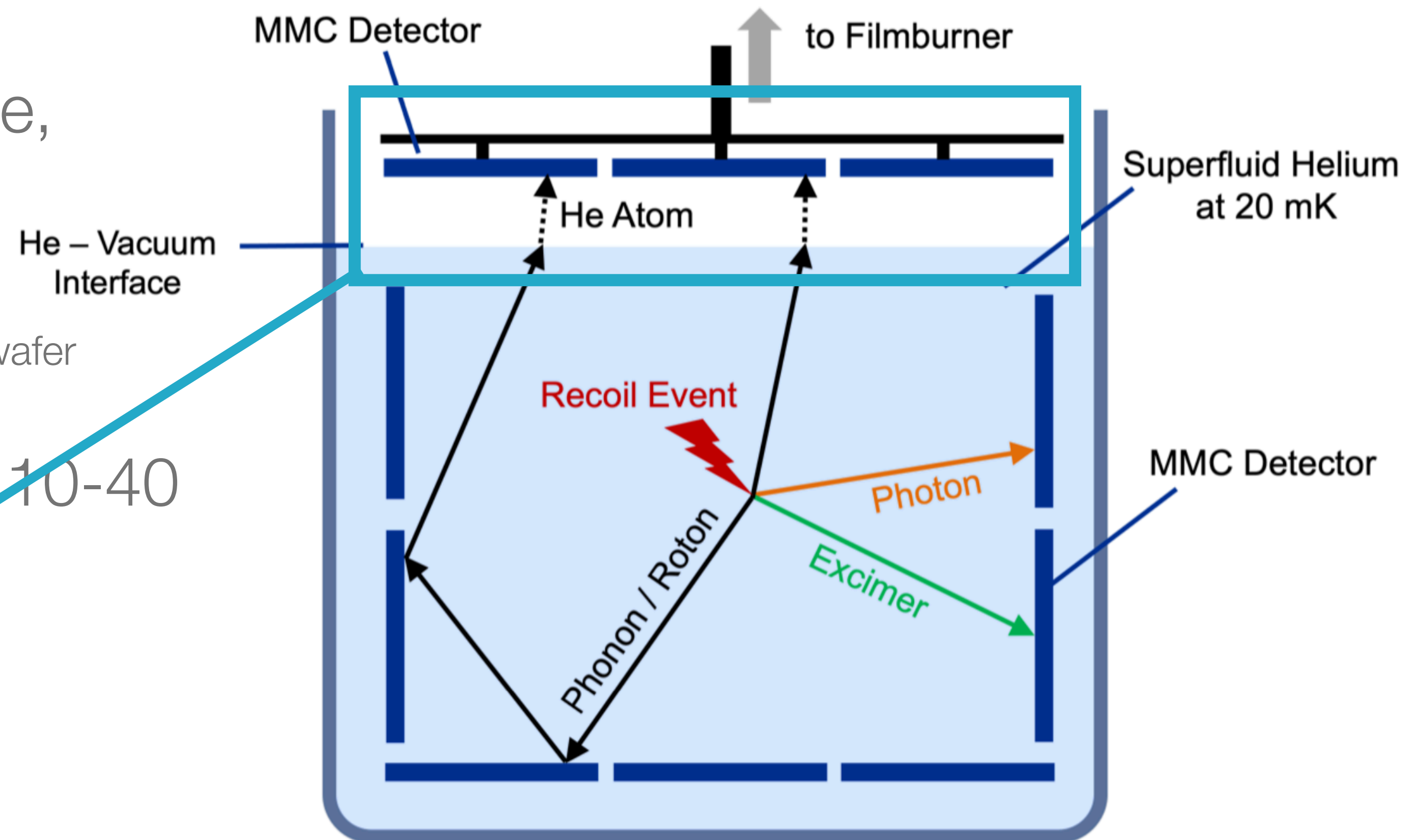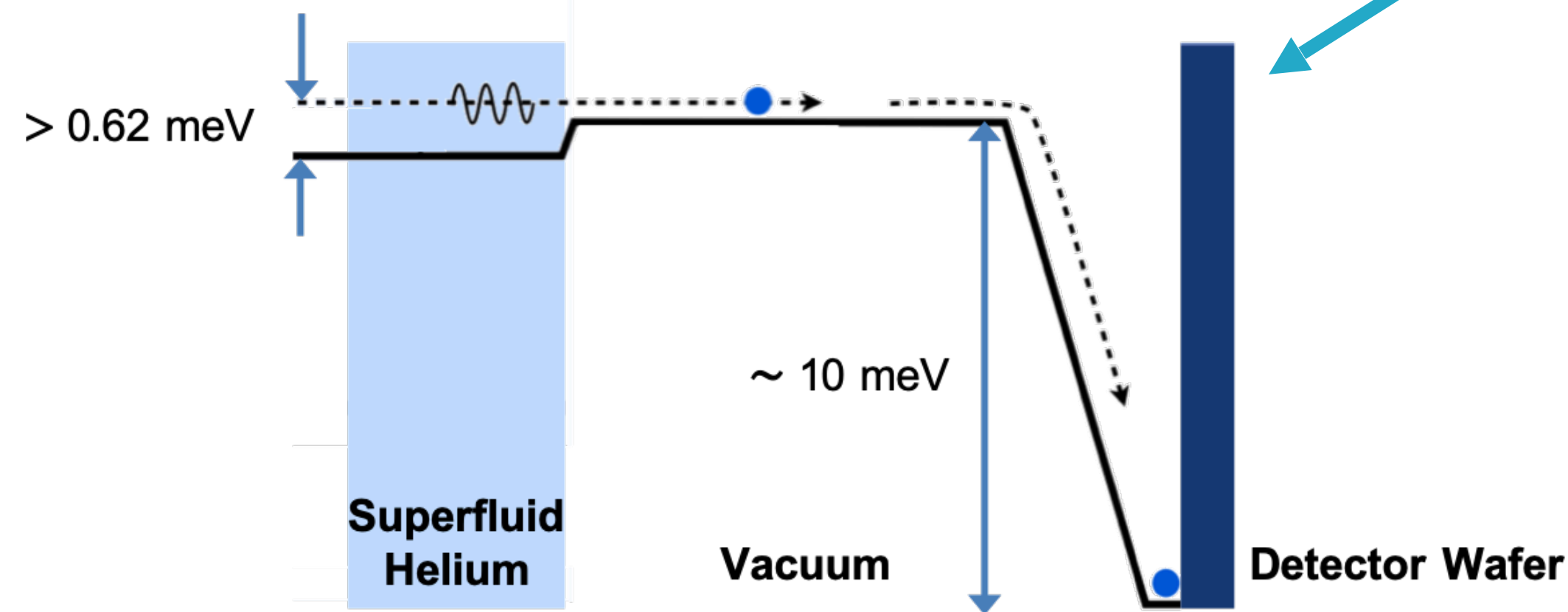➡ Triplet excimer

➡ Ballistic O(m/s) speed

➡ 13s lifetime

➡️Quasiparticles (phonon and rotons) propagate ballistically within the LHe, bouncing off of surfaces

Quasiparticle ➡️ Free He atom ➡️ He atom on wafer

Quantum evaporation   Condensation

➡️Noise free amplification of factor of 10-40

> 0.62 meV

~ 10 meV

Superfluid Helium   **Vacuum**   **Detector Wafer**

MMC Detector   to Filmburner

He Atom

He – Vacuum Interface

Superfluid Helium at 20 mK

Recoil Event

Photon

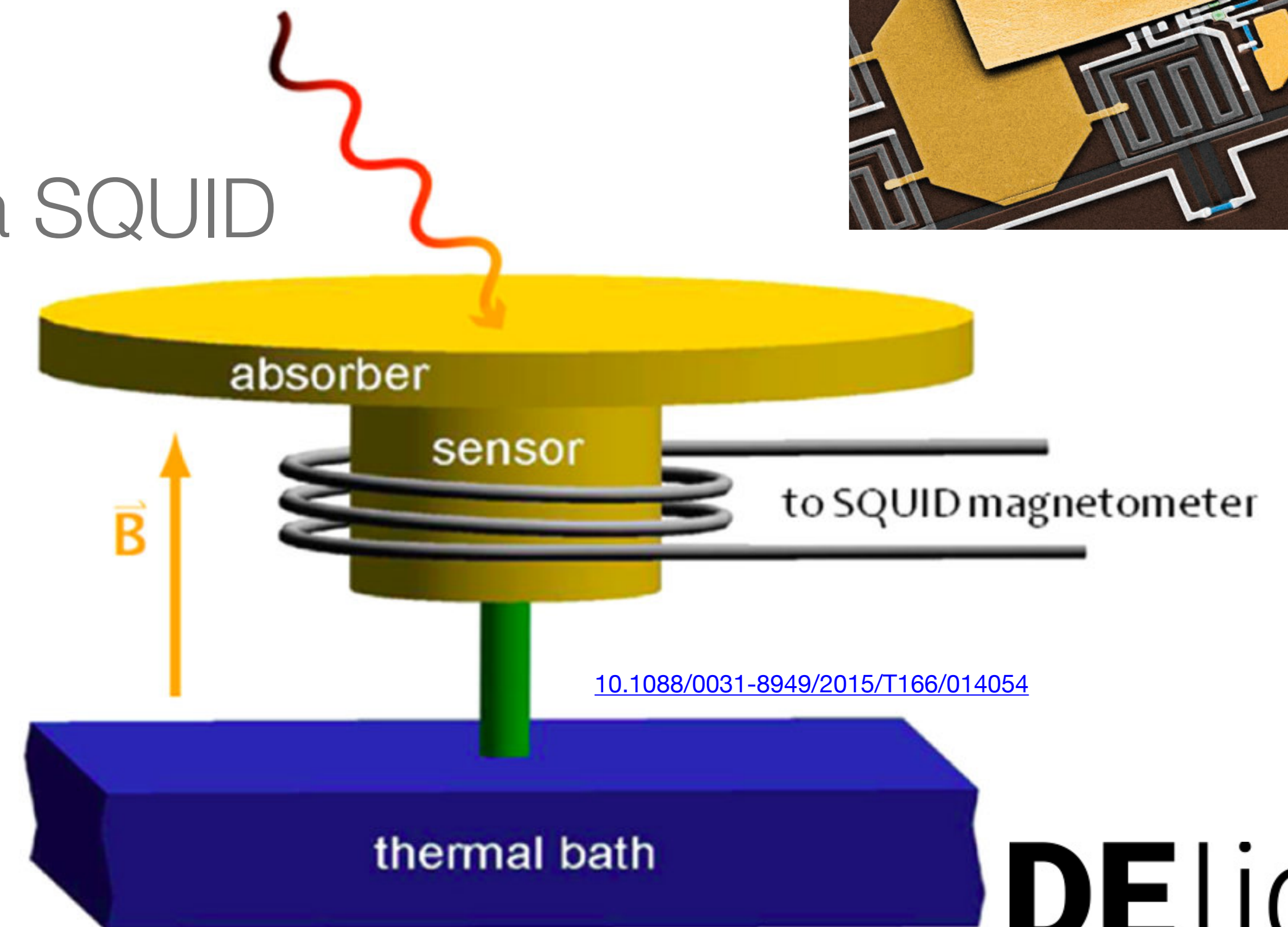Excimer

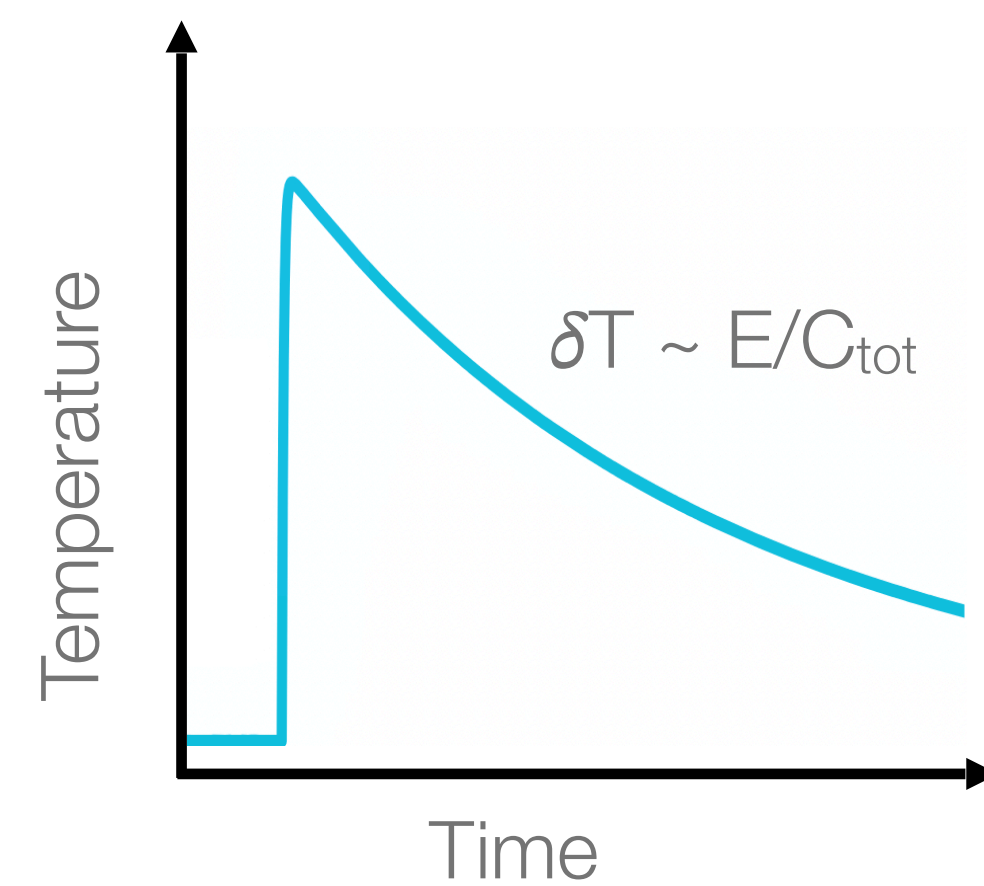Phonon / Roton

MMC Detector

DELight Detector - Film Burner
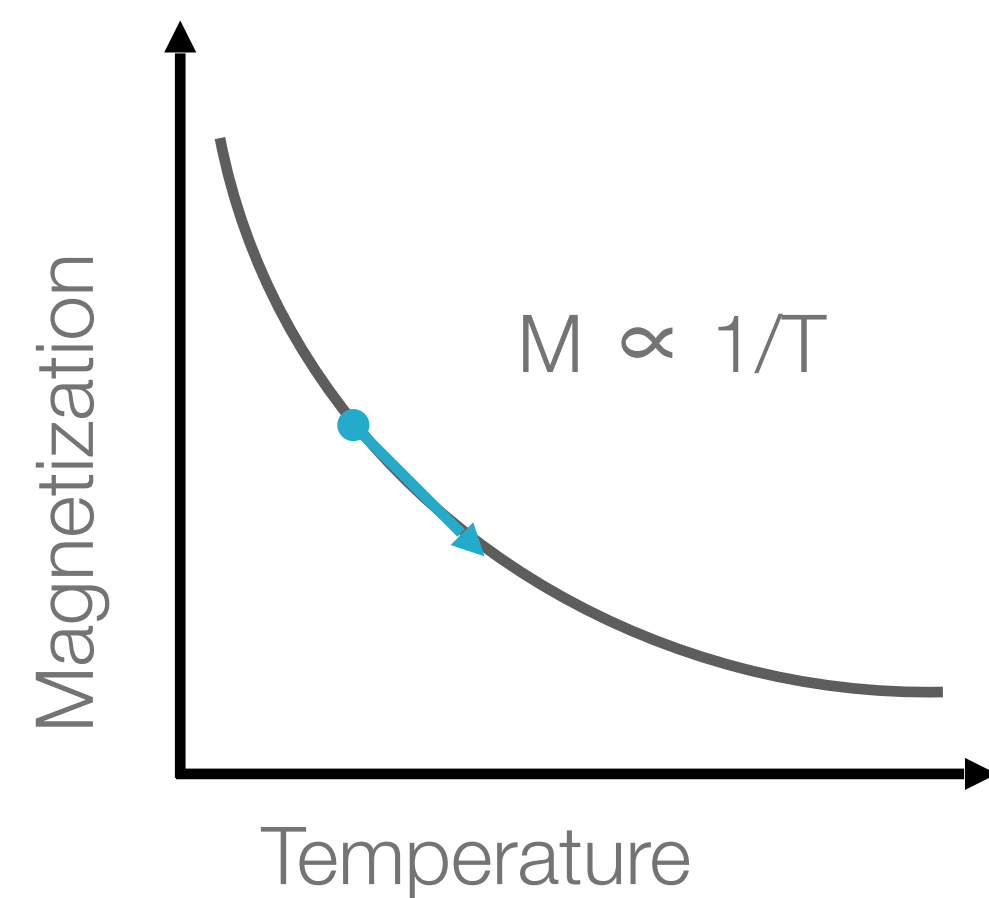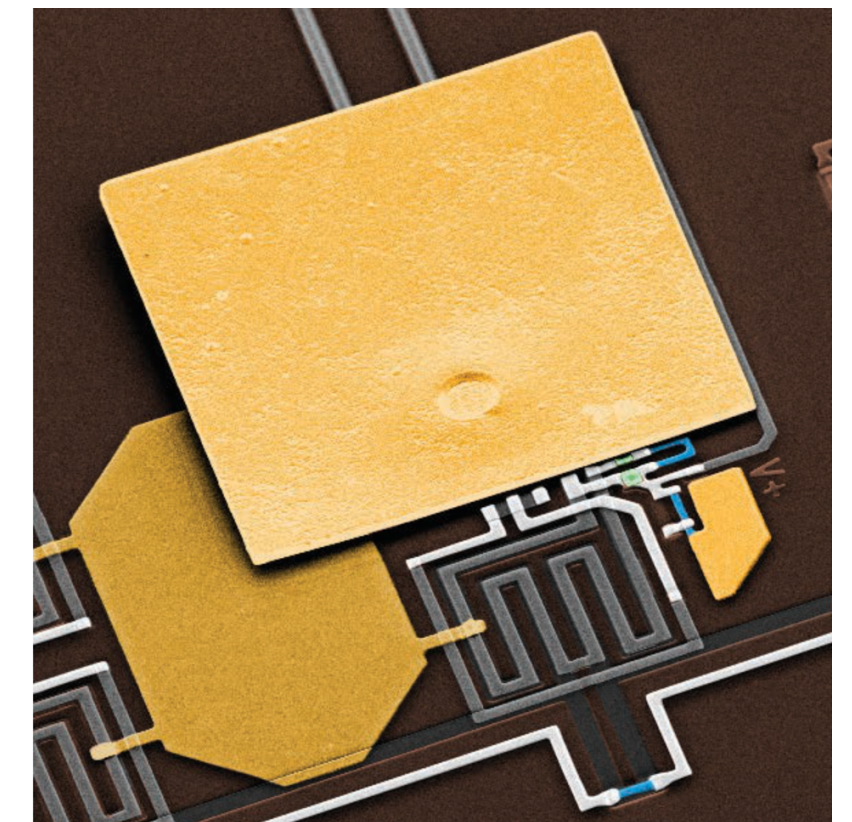
➡ Must keep sensors free of He film to maintain amplification factor
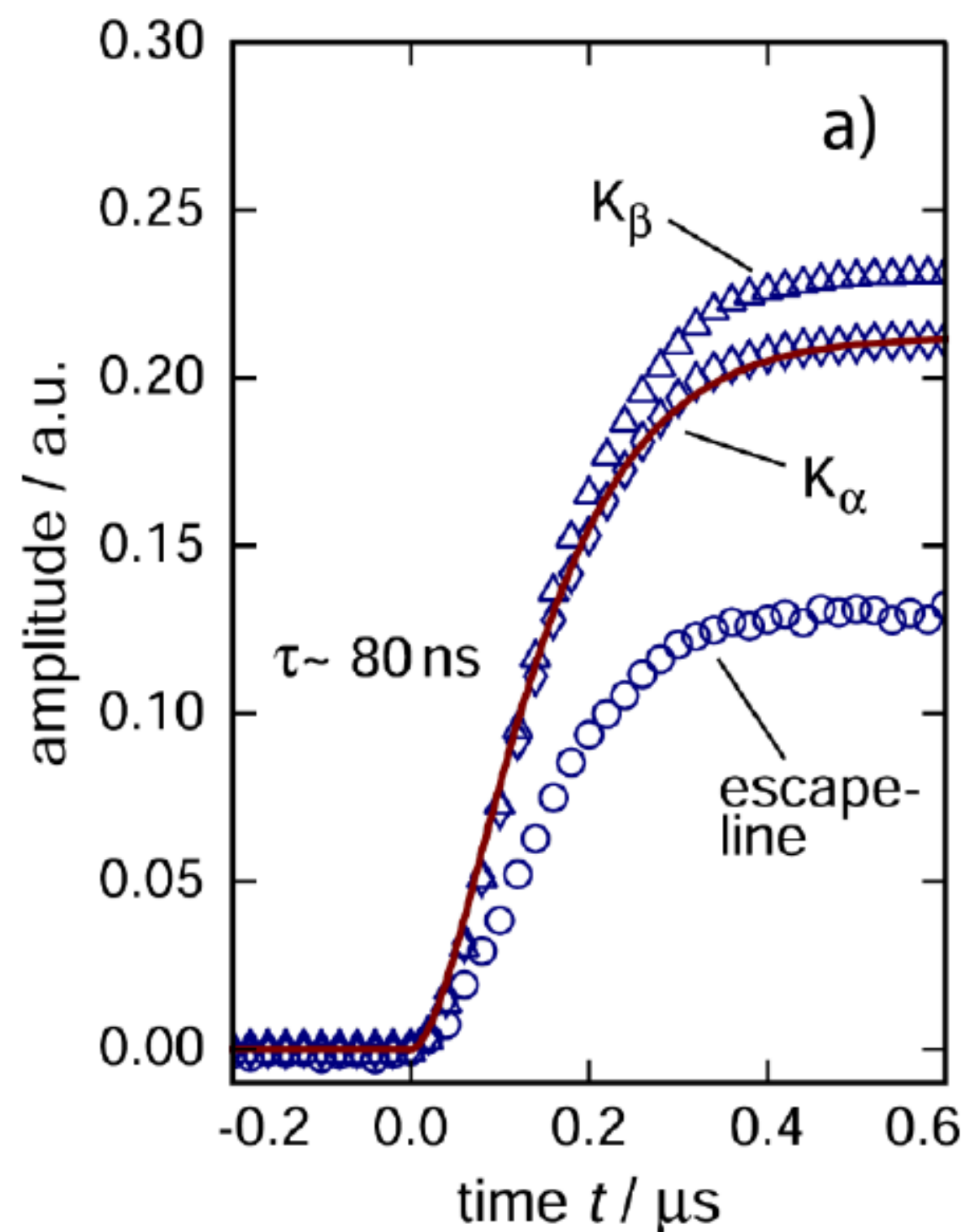
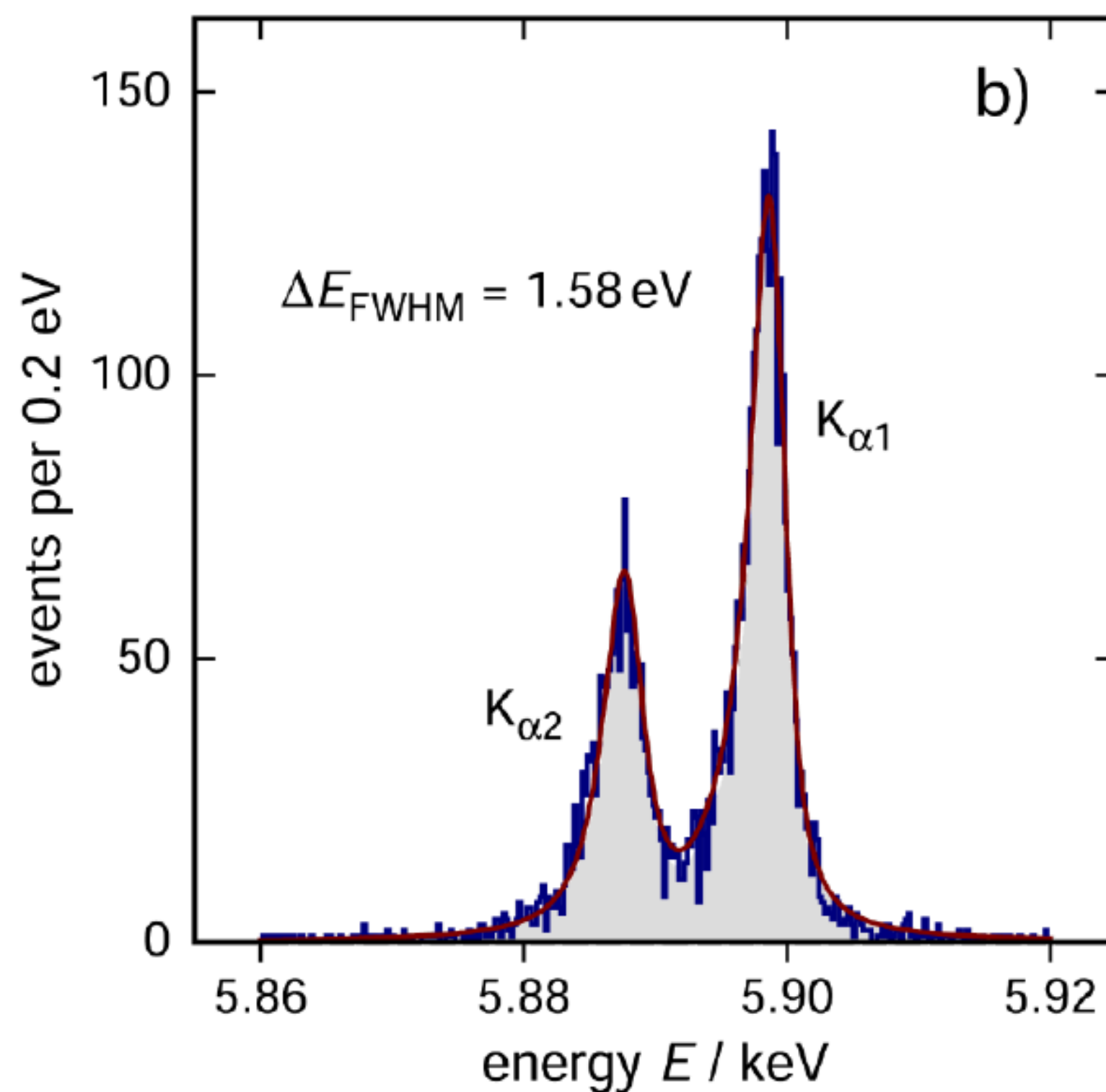➡ Implement a film burner
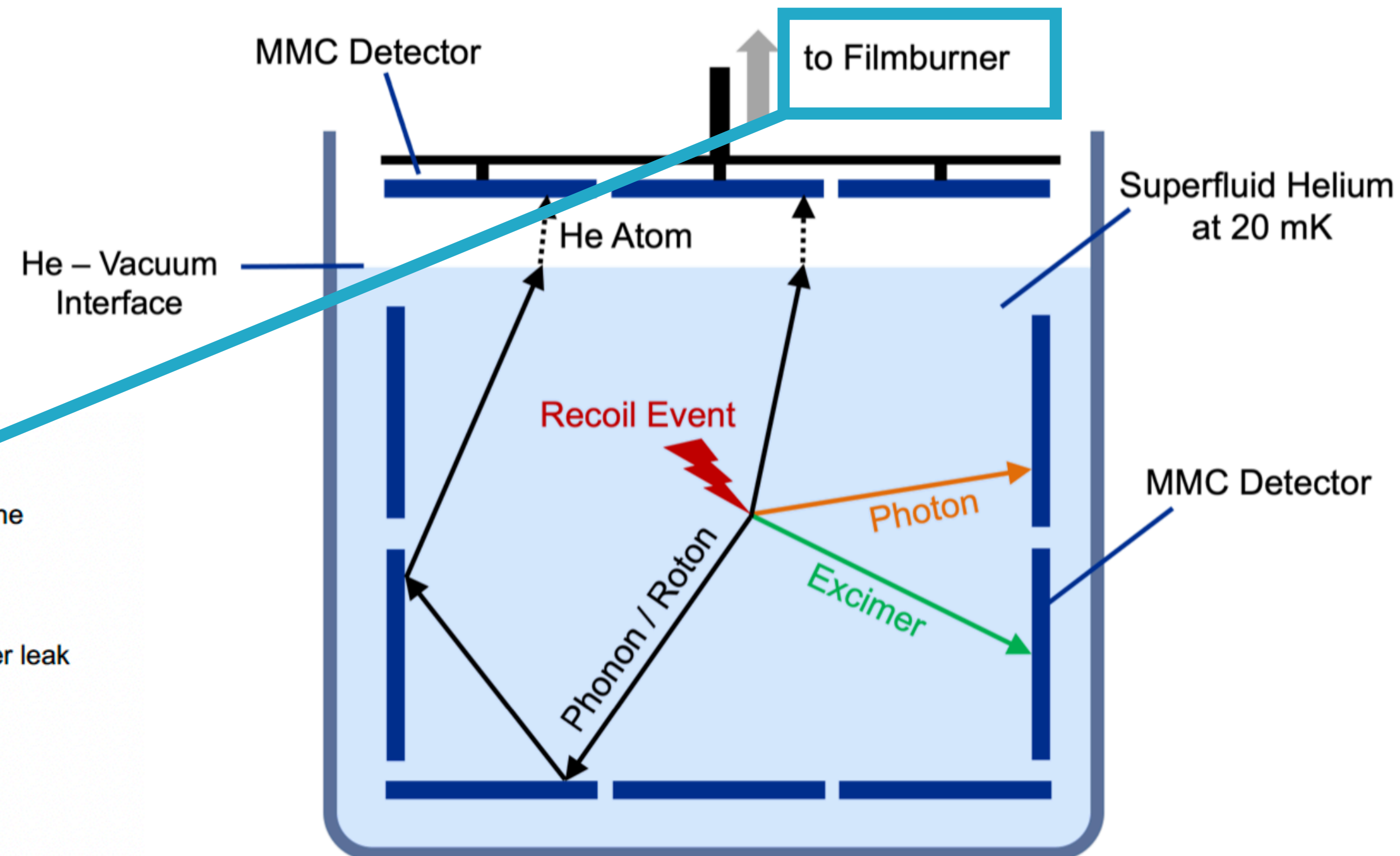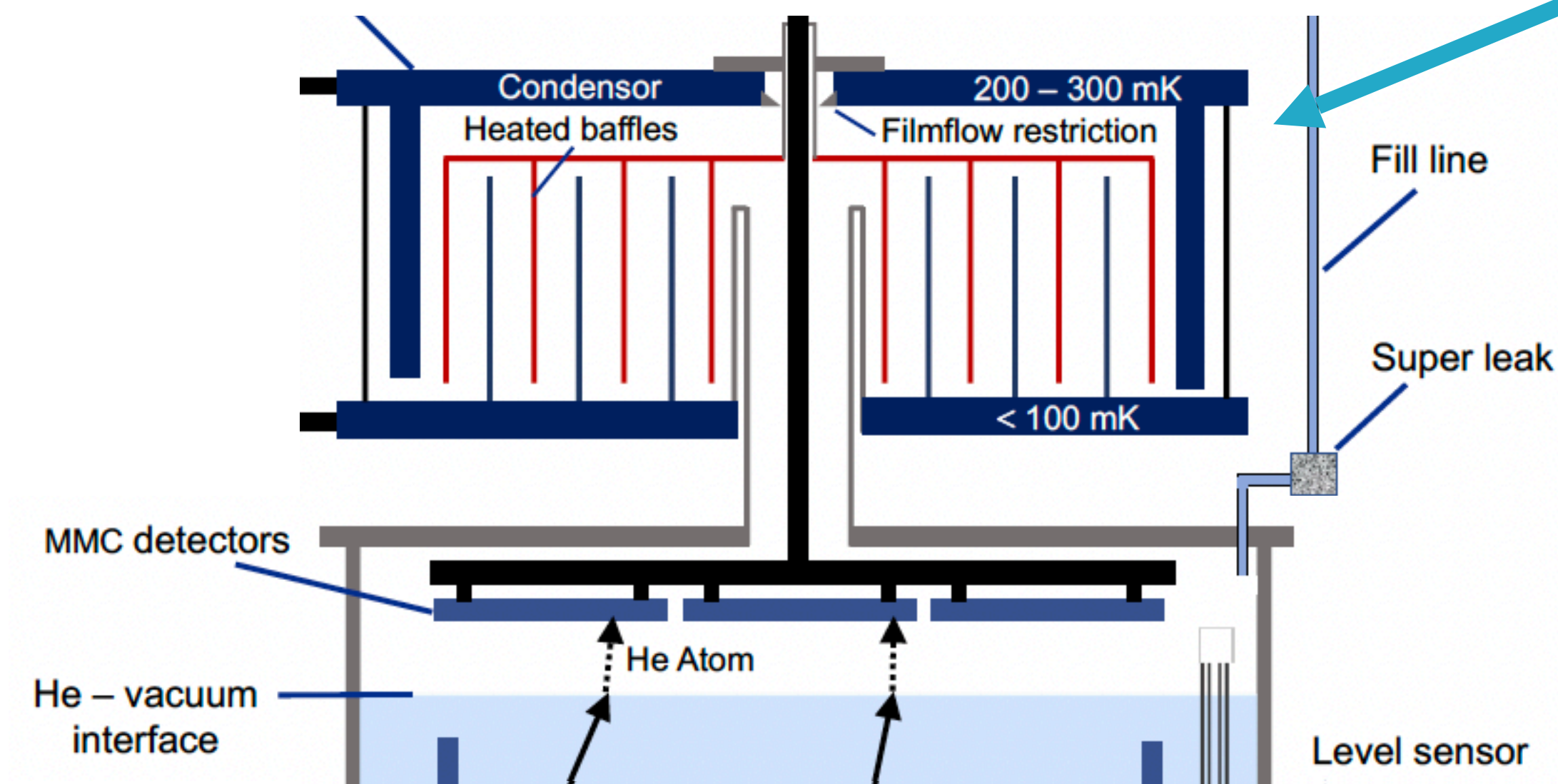
Magnetic MicroCalorimeters (MMCs)

➡ Energy deposition in absorber → increase in temperature δT and decrease in magnetization of the paramagnetic sensor $\delta M \propto \delta T$
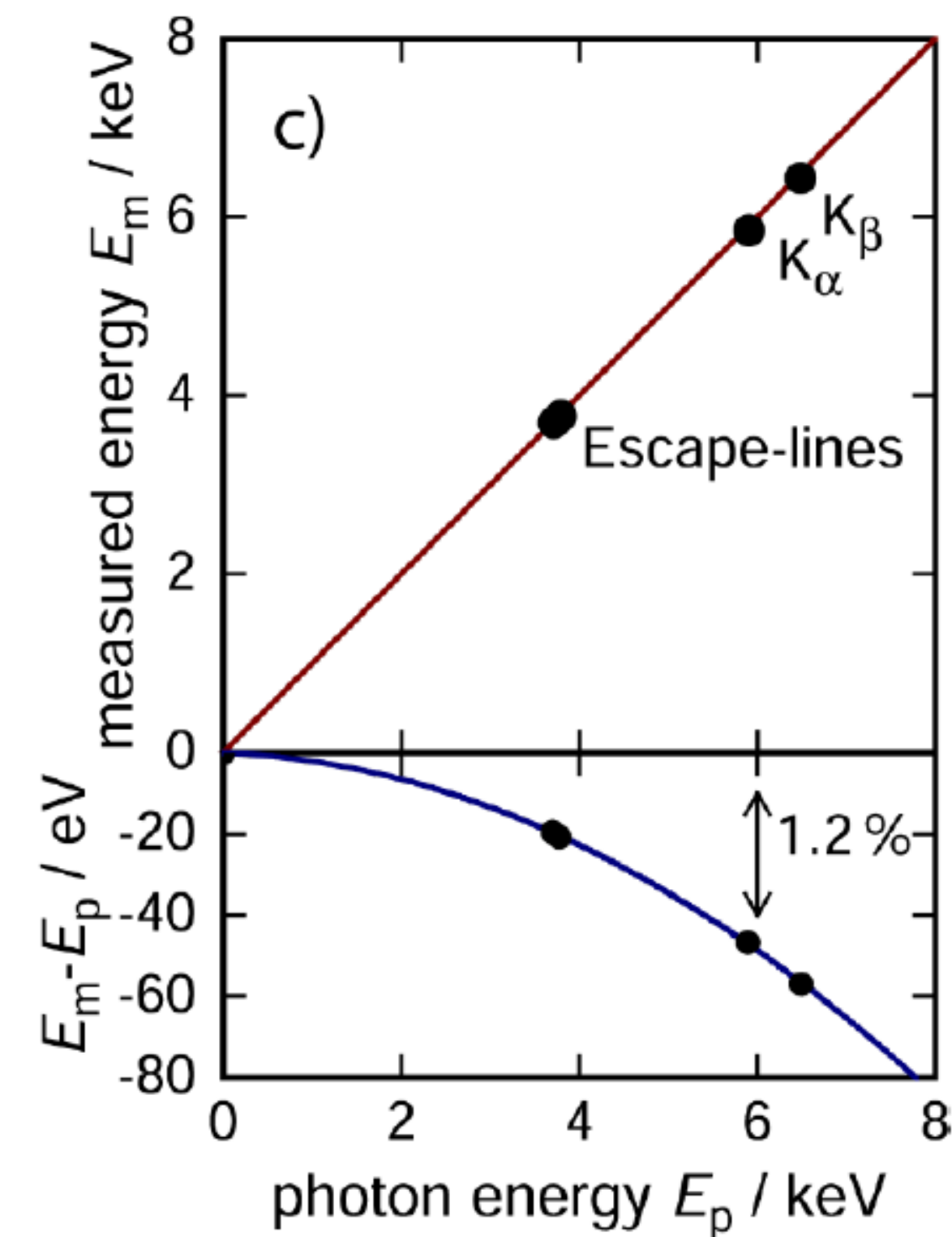
➡ Change in magnetization is read out by a SQUID

$M \propto 1/T$

Magnetization

Temperature

$\delta T \sim E/C_{tot}$

Temperature

Time

absorber

sensor

$\vec{B}$

to SQUID magnetometer

10.1088/0031-8949/2015/T166/014054

thermal bath

➡ Fast response

➡ Excellent energy resolution

➡ Linear response

S.Kempf et. al, *J Low Temp Phys* **193**, 365–379 (2018)

R&D - MMC Energy Resolution

➡ New MMCs achieved best resolution to date

➡ **ΔE_{FWHM} = 1.25 eV at 5.9keV**

   ➡ Optimal filter analysis of ^{55}Fe calibration peaks

   ➡ Amplitude fit to K_α data, calibration parameters validated by reconstructing K_β

➡ **Appl. Phys. Lett. 124, 032601 (2024)**

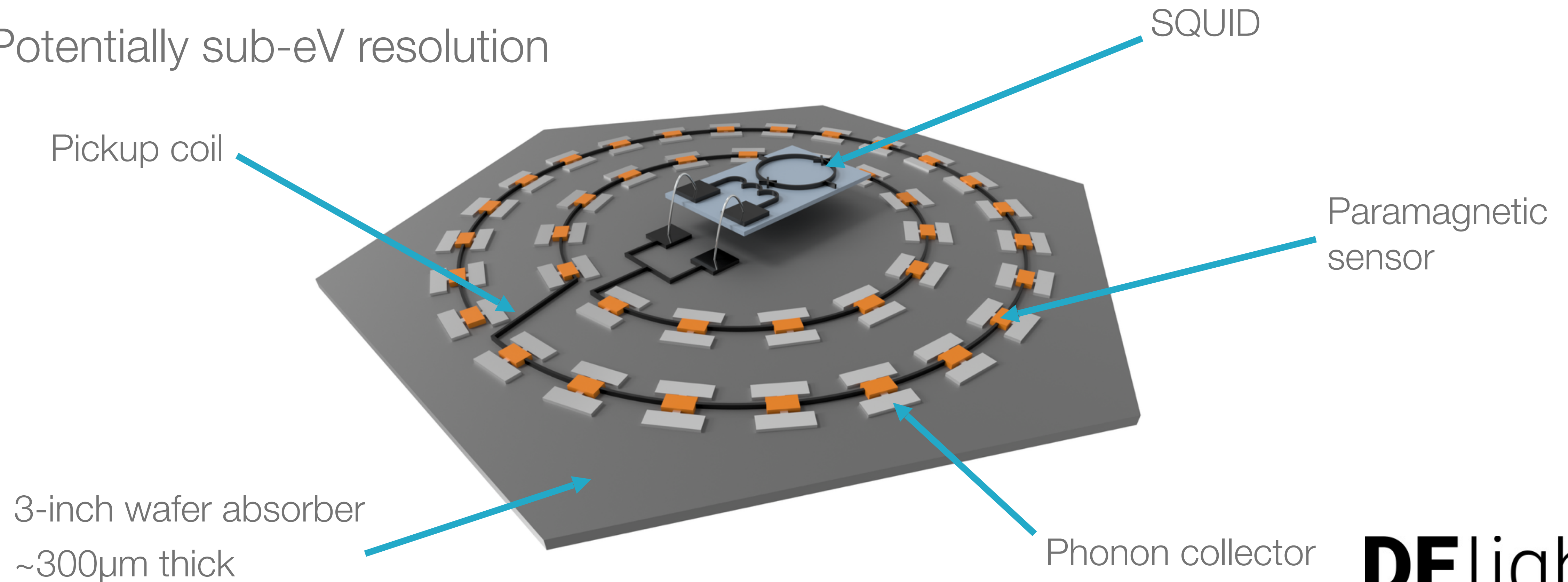Matthäus Krantz, Francesco Toschi, Benedikt Maier, Greta Heine, Christian Enss, Sebastian Kempf

➡ **Phys. Rev. D 109, 043035 (2024)**

Francesco Toschi, Benedikt Maier, Greta Heine, Torben Ferber, Sebastian Kempf, Markus Klute, and Belina von Krosigk
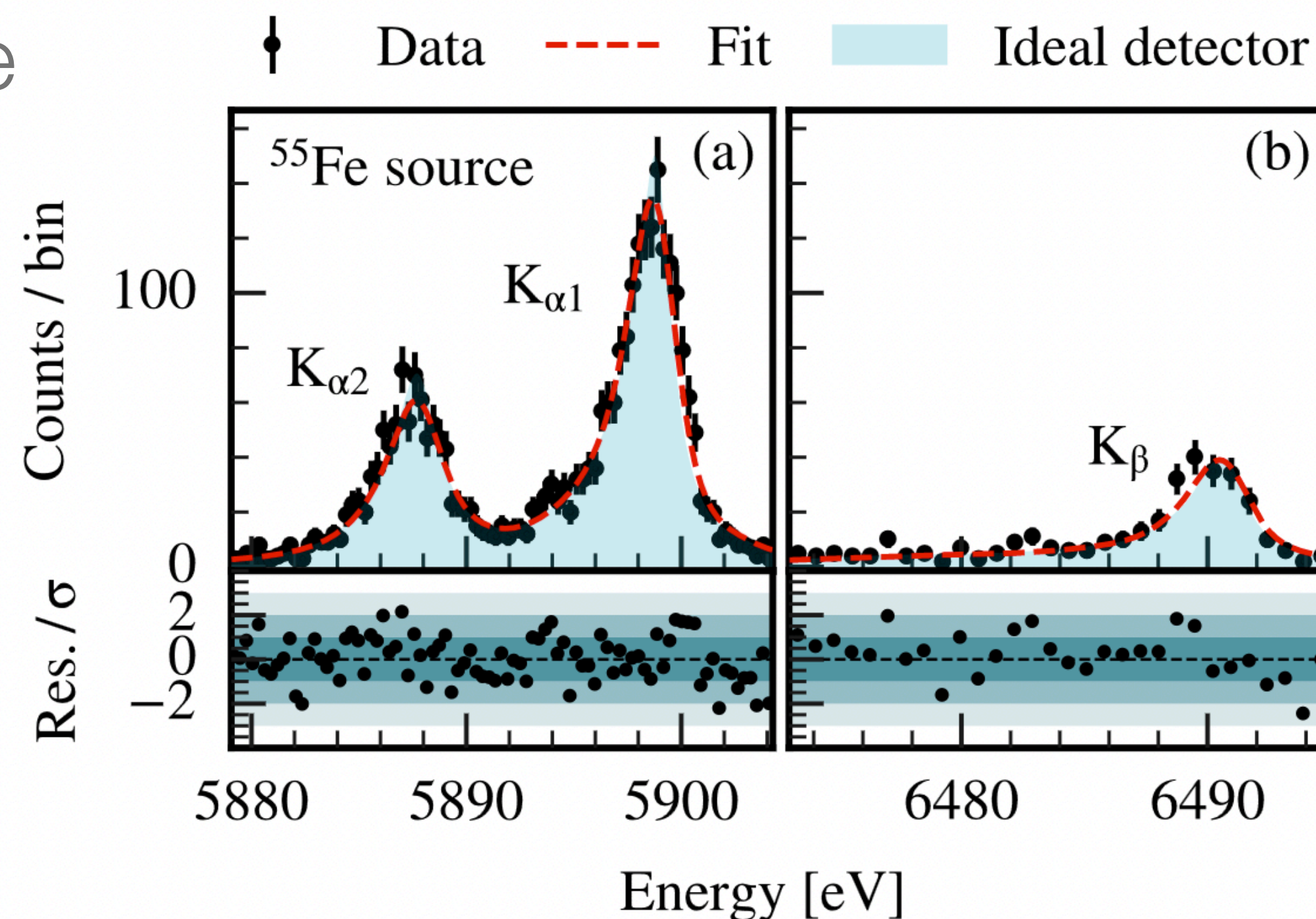
Possible DELight MMC Design

➡ Large area MMC for full surface coverage - silicon or sapphire wafer

➡ Potentially sub-eV resolution

SQUID

Pickup coil

Paramagnetic sensor

3-inch wafer absorber
~300μm thick

Phonon collector

Understanding Detector Response

➡ We have a target volume (superfluid He) instrumented with ~60 sensors (MMCs)… what now?

➡ Understand the partitioning of energy depositions into the different signal channels (UV/IR/triplet/quasiparticle)

➡ Understand what happens to these quanta → depends on detector geometry, MMC layout, etc.

Signal Formation in Superfluid Helium

➡ Developed a Monte Carlo-based approach to estimate signal partitioning

➡ **Signal partitioning in superfluid 4He: a Monte Carlo approach**, paper accepted by PRD, arXiv:2410.13684
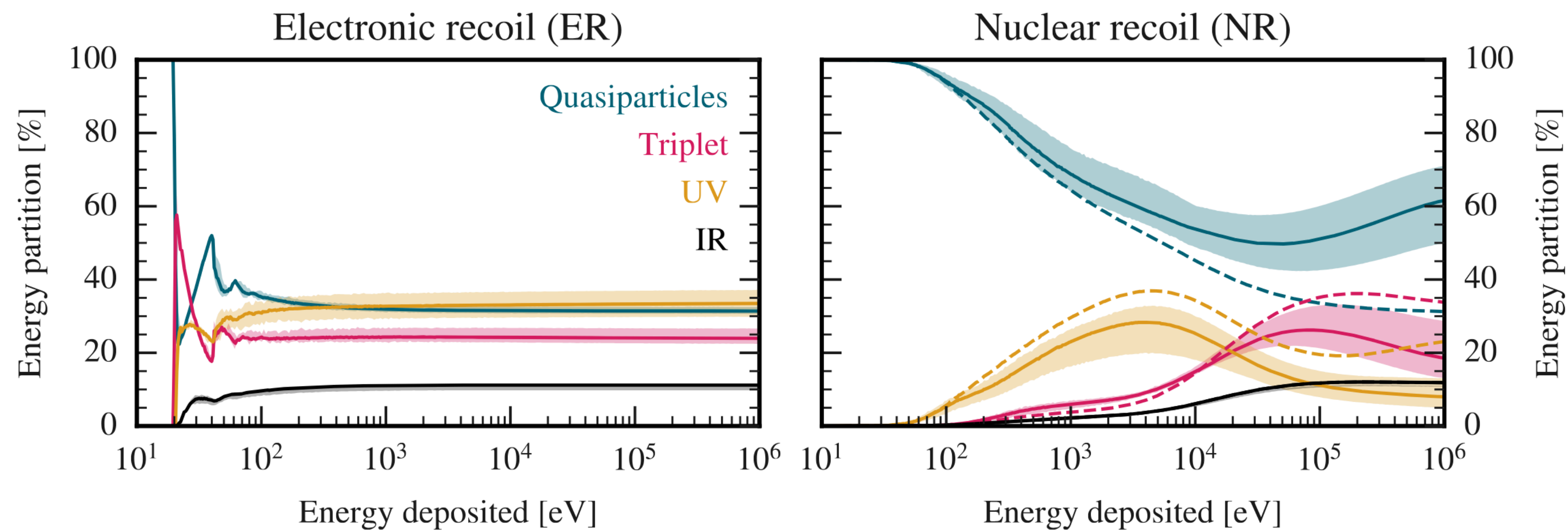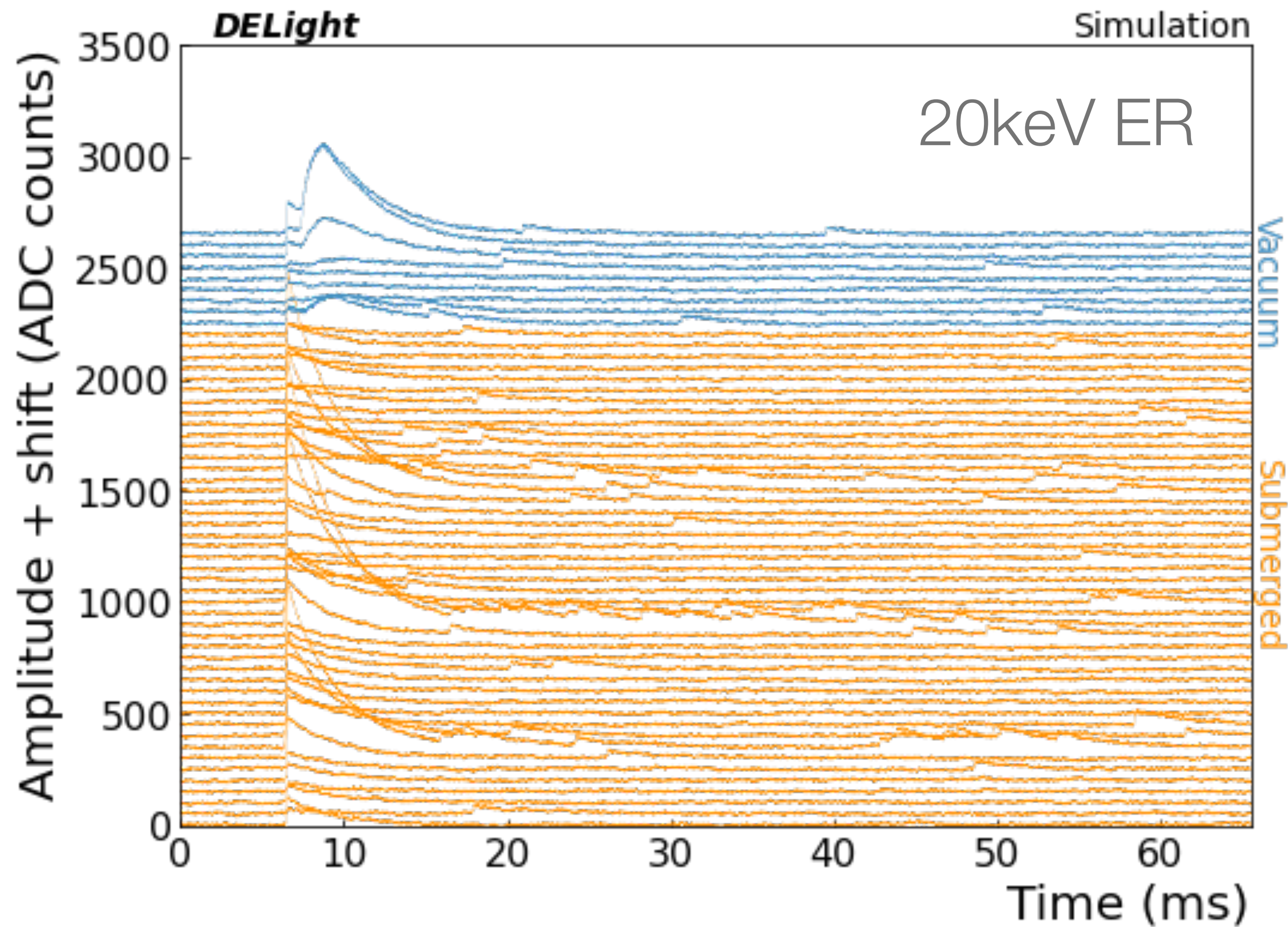
Simulating Signals in Superfluid Helium

➡ Implemented phonon physics in Geant4 - including quantum evaporation

➡ Produce detector geometry-dependent maps of quasiparticle/light/triplet collection efficiency and timing information

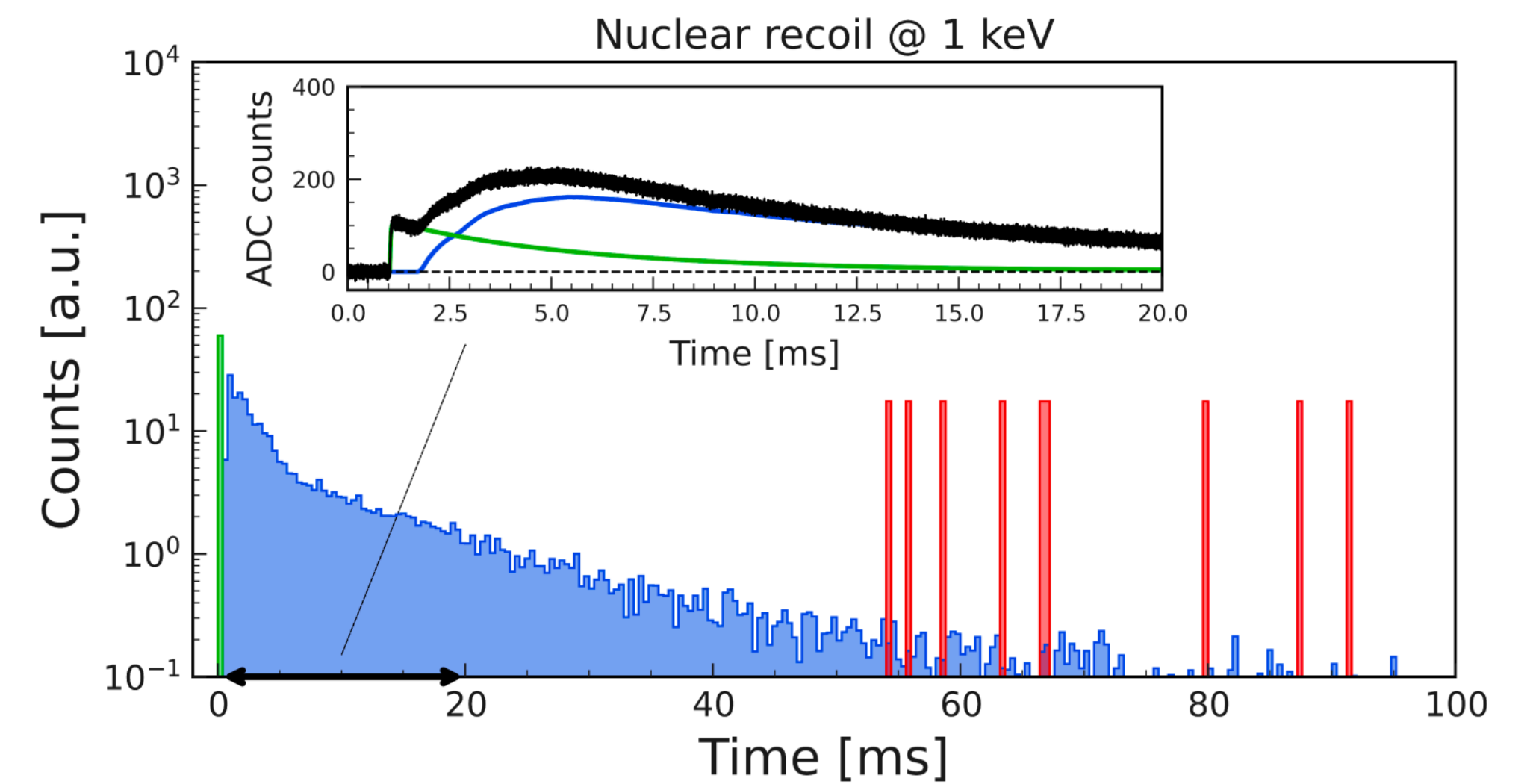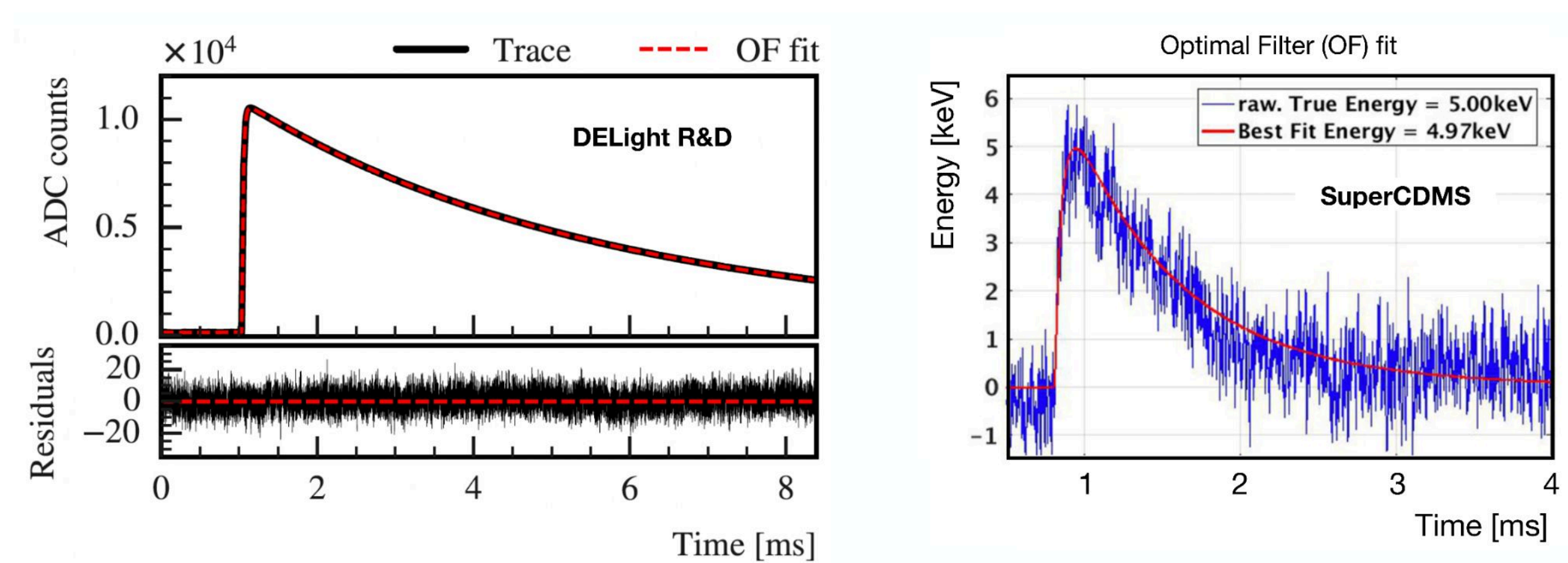   ➡ Depends on position of event within target volume
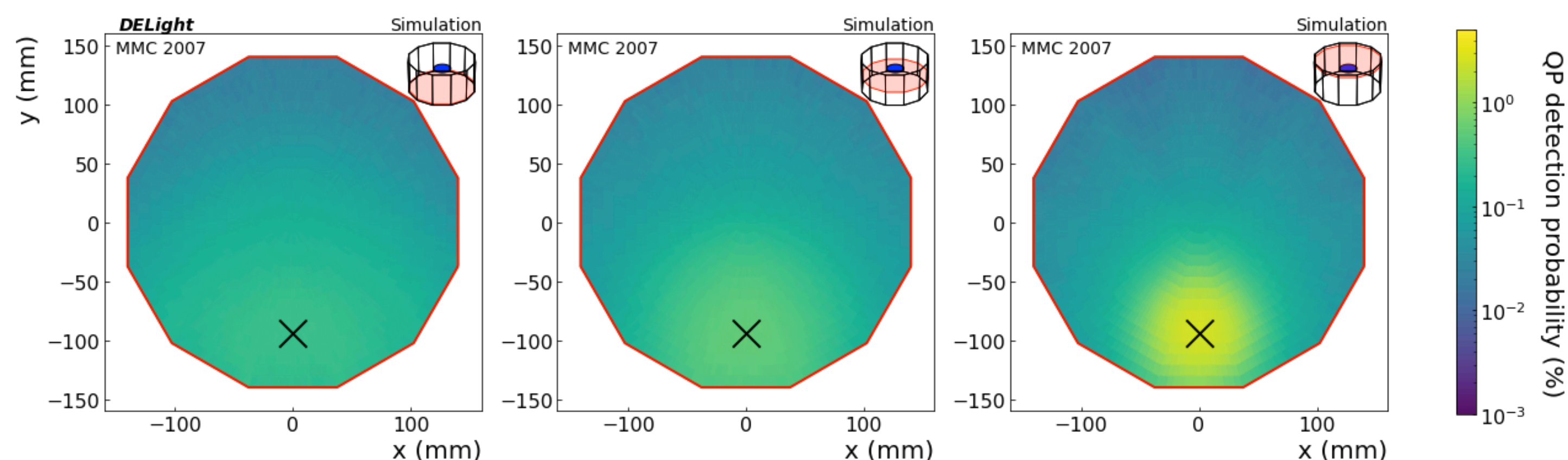
Waveform Simulation

➡ Using signal formation, timing information, and collection efficiency to simulate realistic waveforms
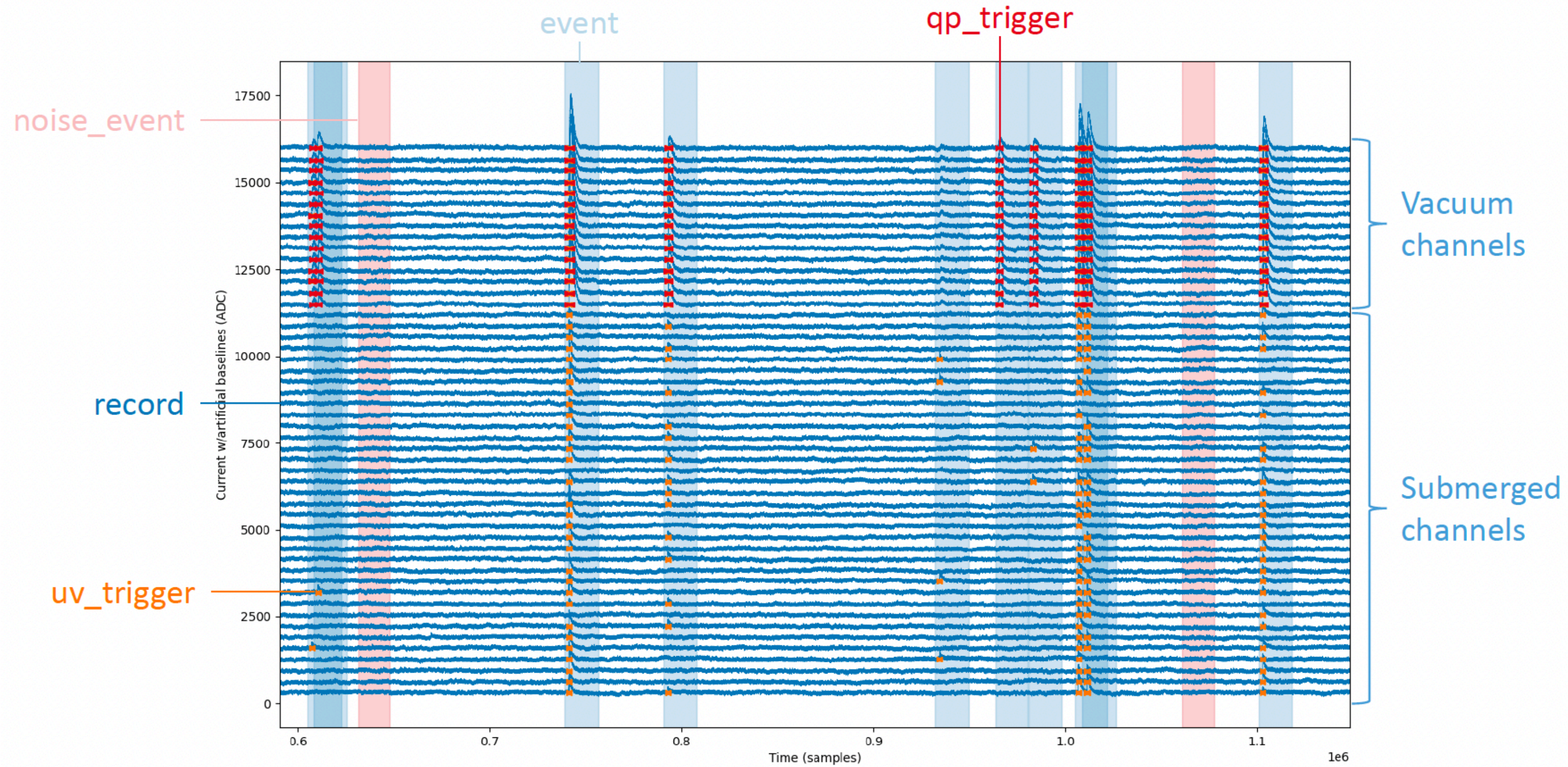
Event Reconstruction

➡ **helix**: a strax-based framework for data processing (strax: streaming analysis for xenon experiments)

➡ Optimal filter (OF) energy reconstruction

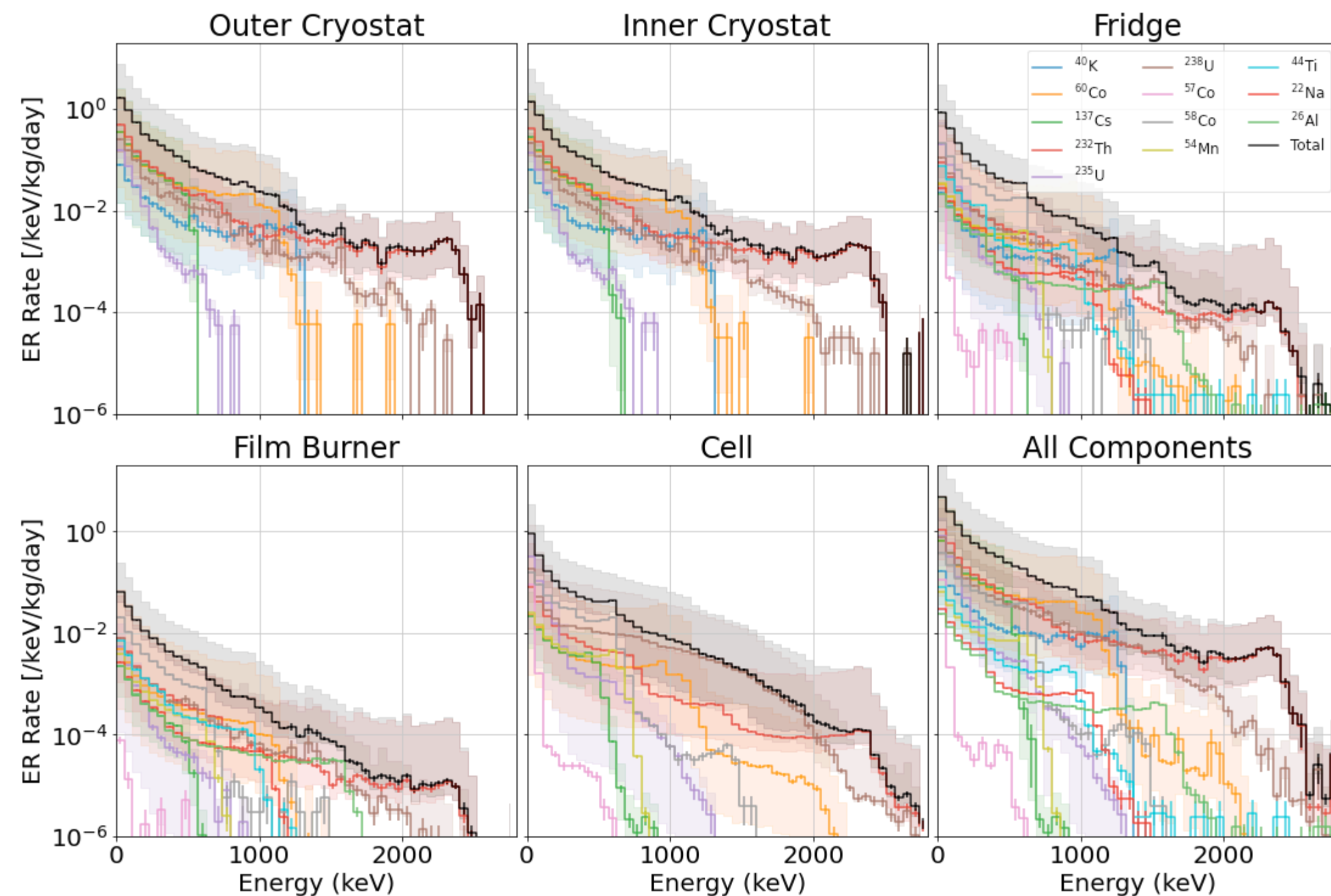➡ Energy and position reconstruction through machine learning

Helix Toy Data

R&D - Backgrounds and Simulations

➡ Geant4 model of preliminary DELight geometry implemented
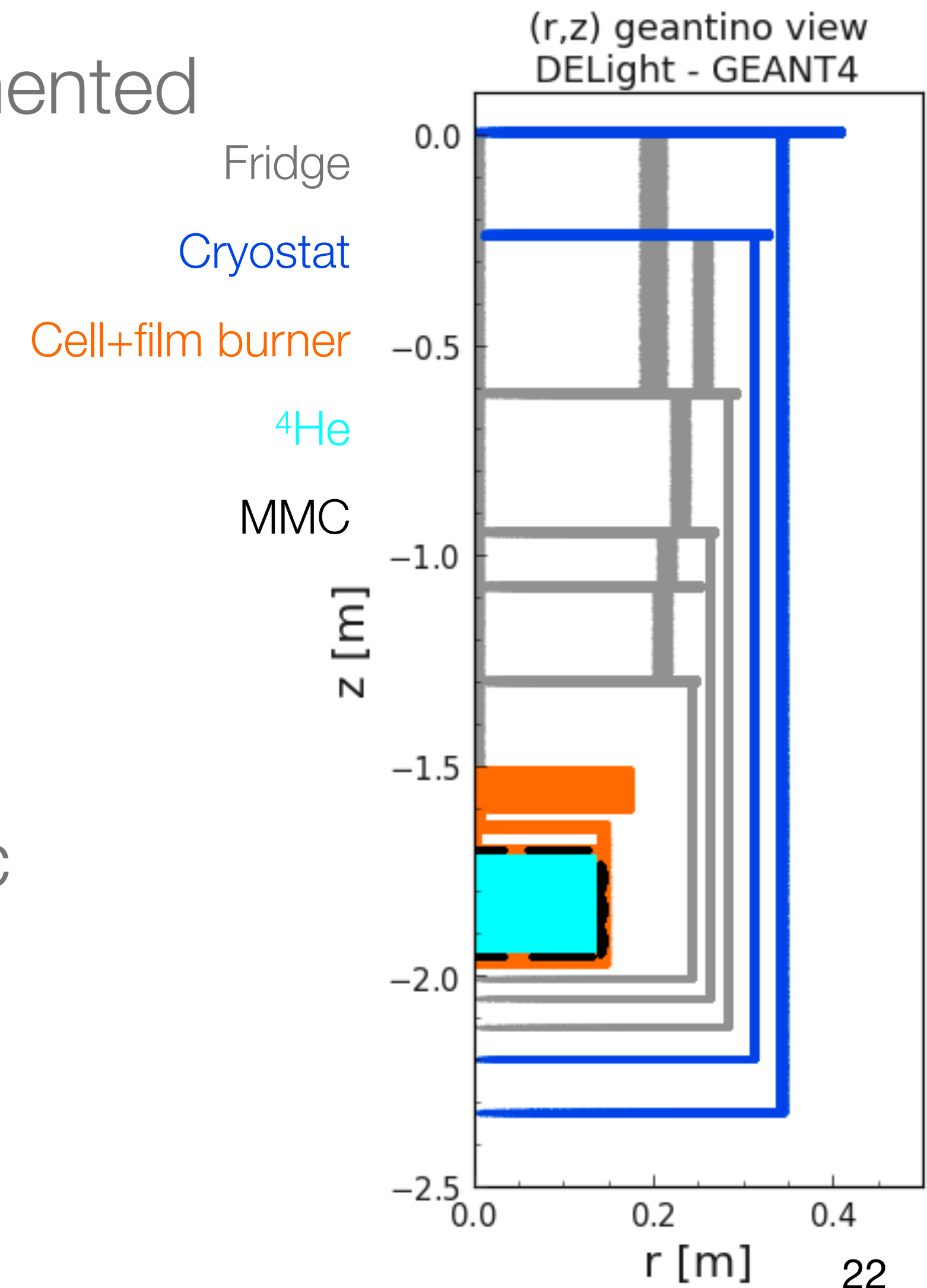
➡ Background model work is ongoing

➡ Radiogenics

➡ Cosmic

➡ Cosmogenic

➡ Etc.

(r,z) geantino view
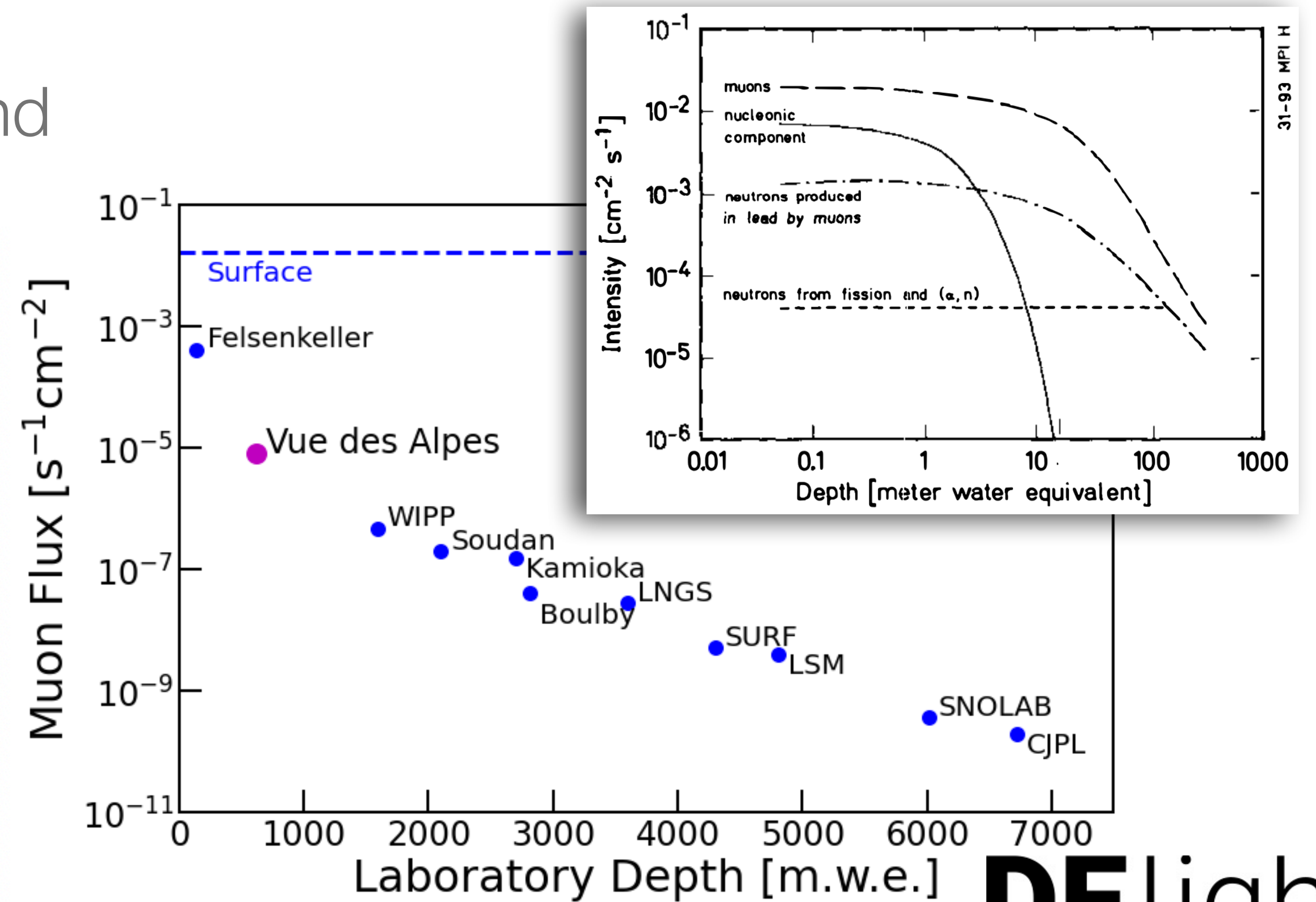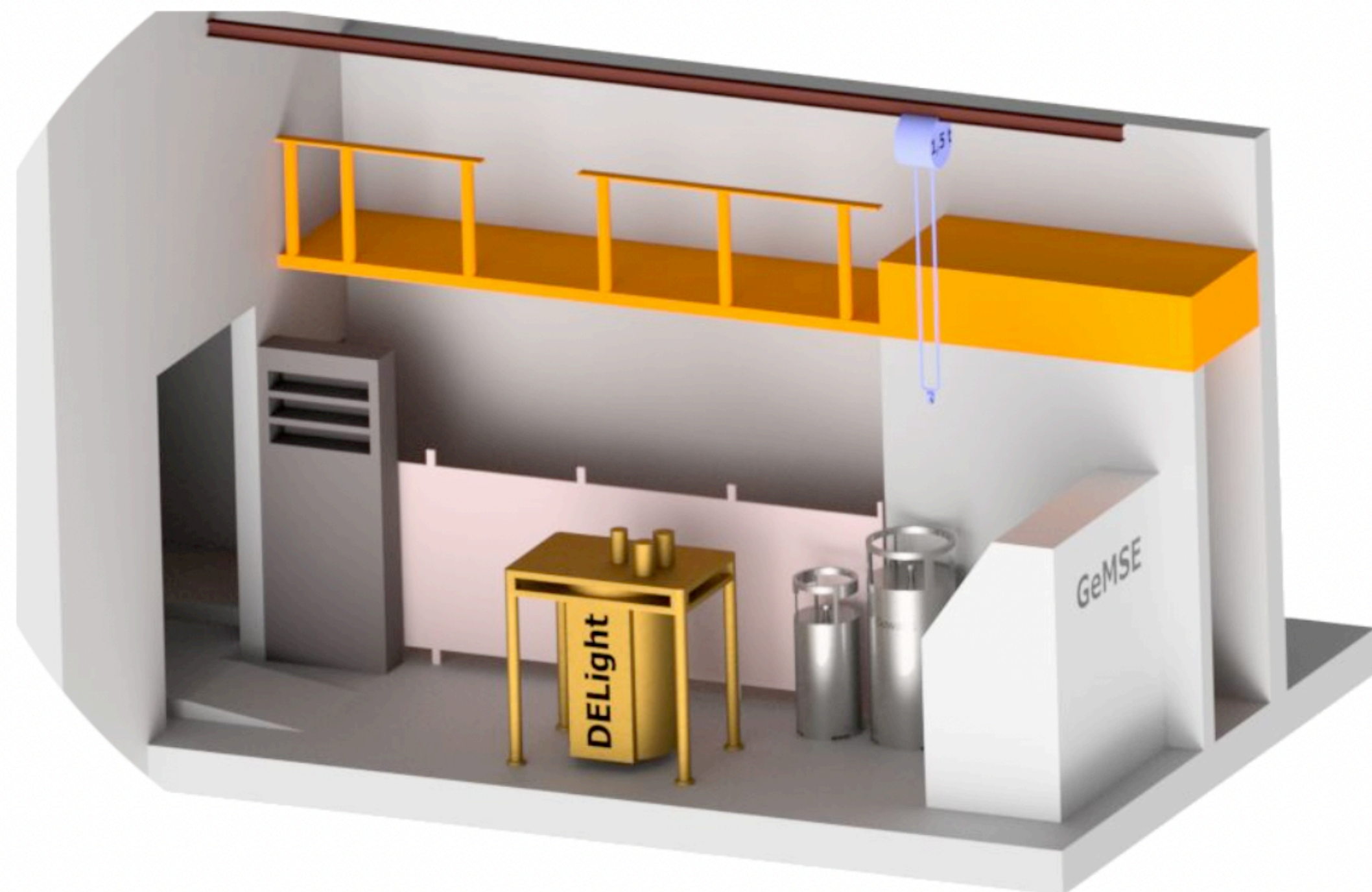DELight - GEANT4

Fridge

Cryostat

Cell+film burner

^{4}He

MMC

Vue-des-Alpes Underground Lab

➡ Significantly reduce cosmic background with 230m rock overburden (620m.w.e)
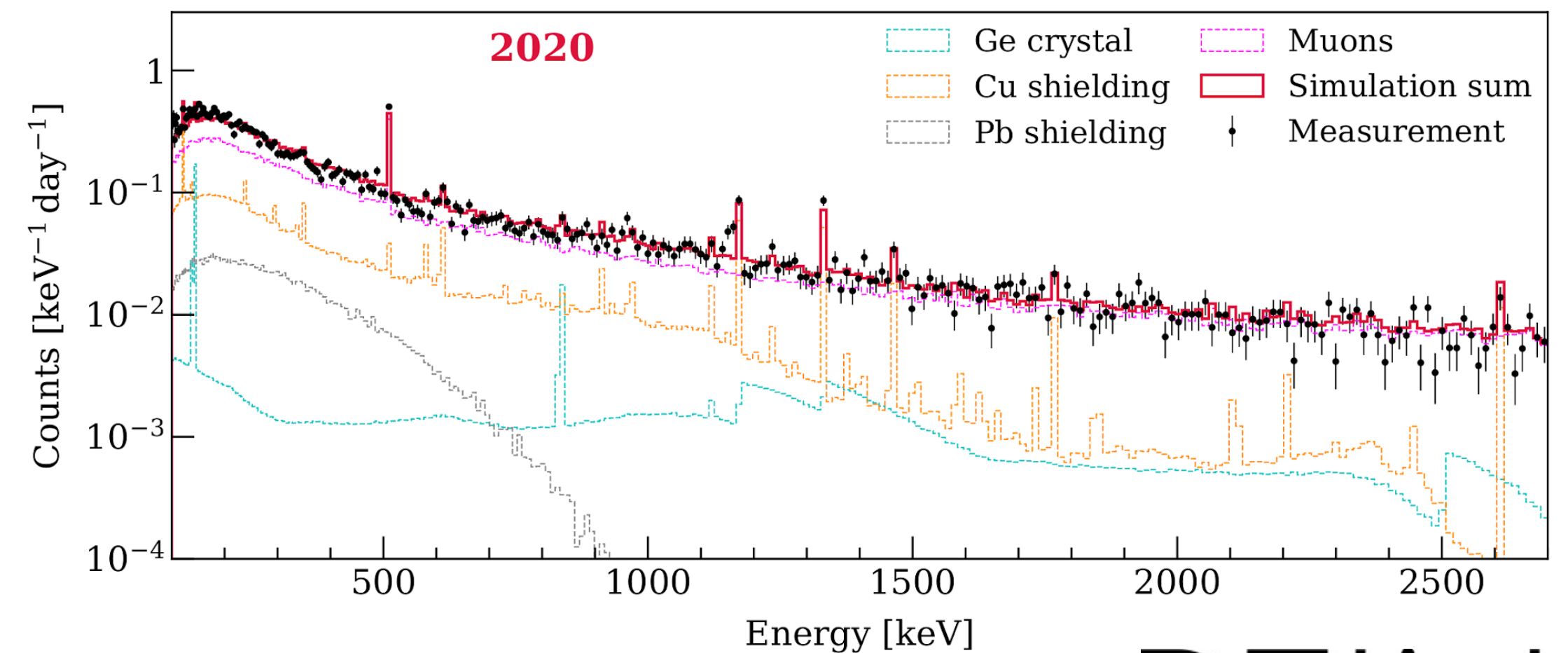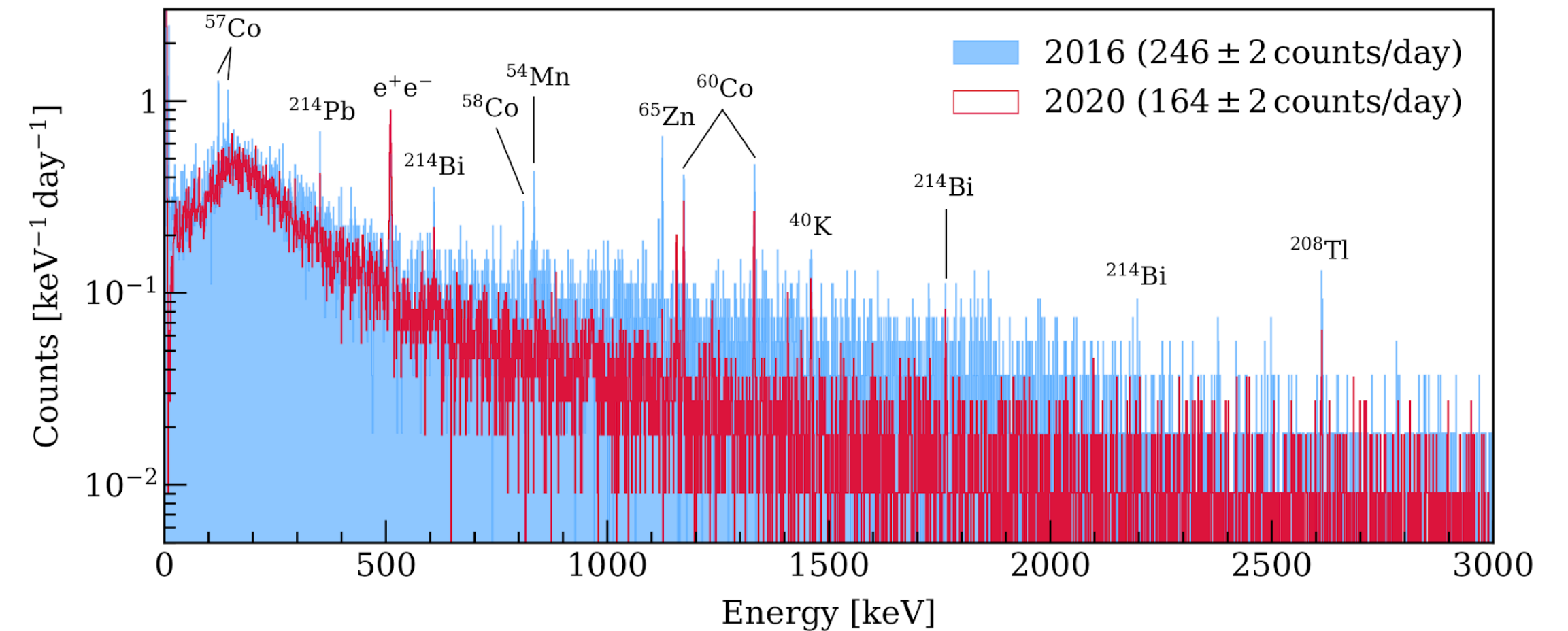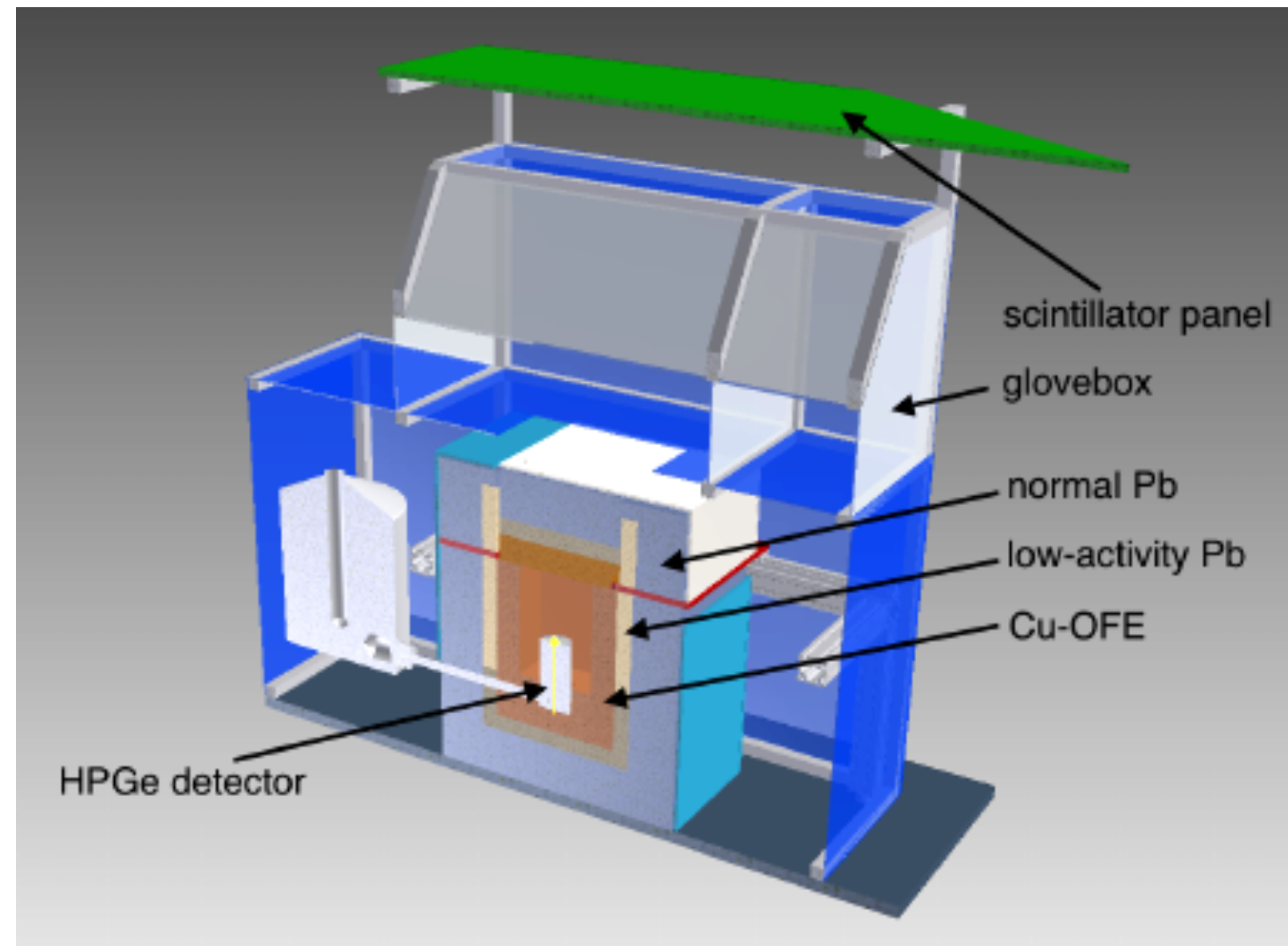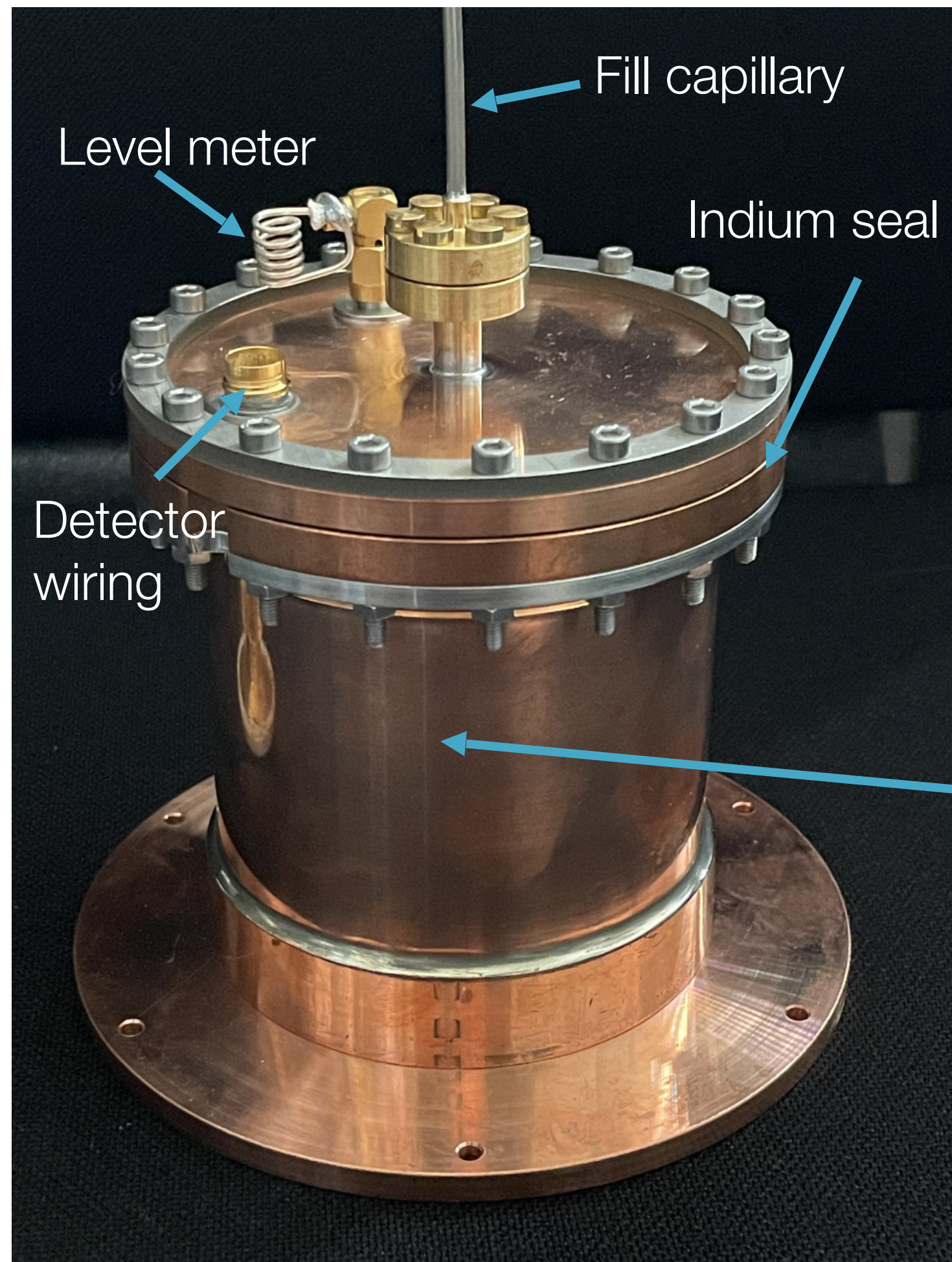
➡ Located in a road tunnel in Switzerland

GeMSE

➡ Low background HPGe crystal gamma spectrometer @ VdA

➡ Material selection campaign for experiment components
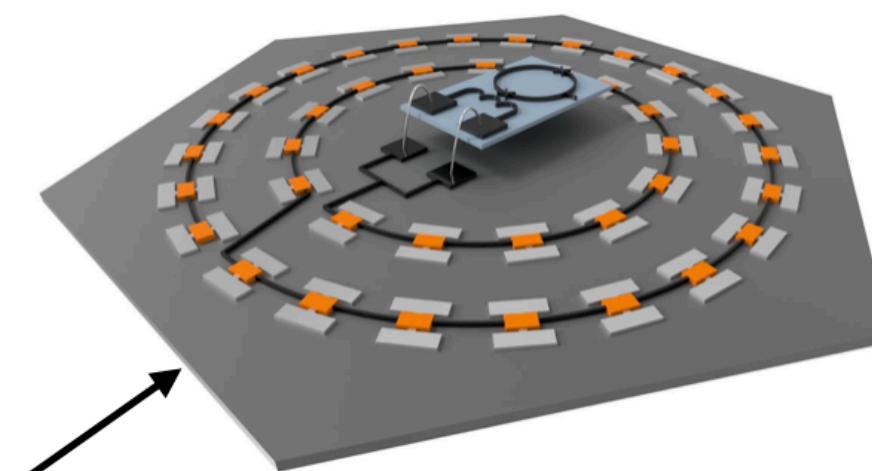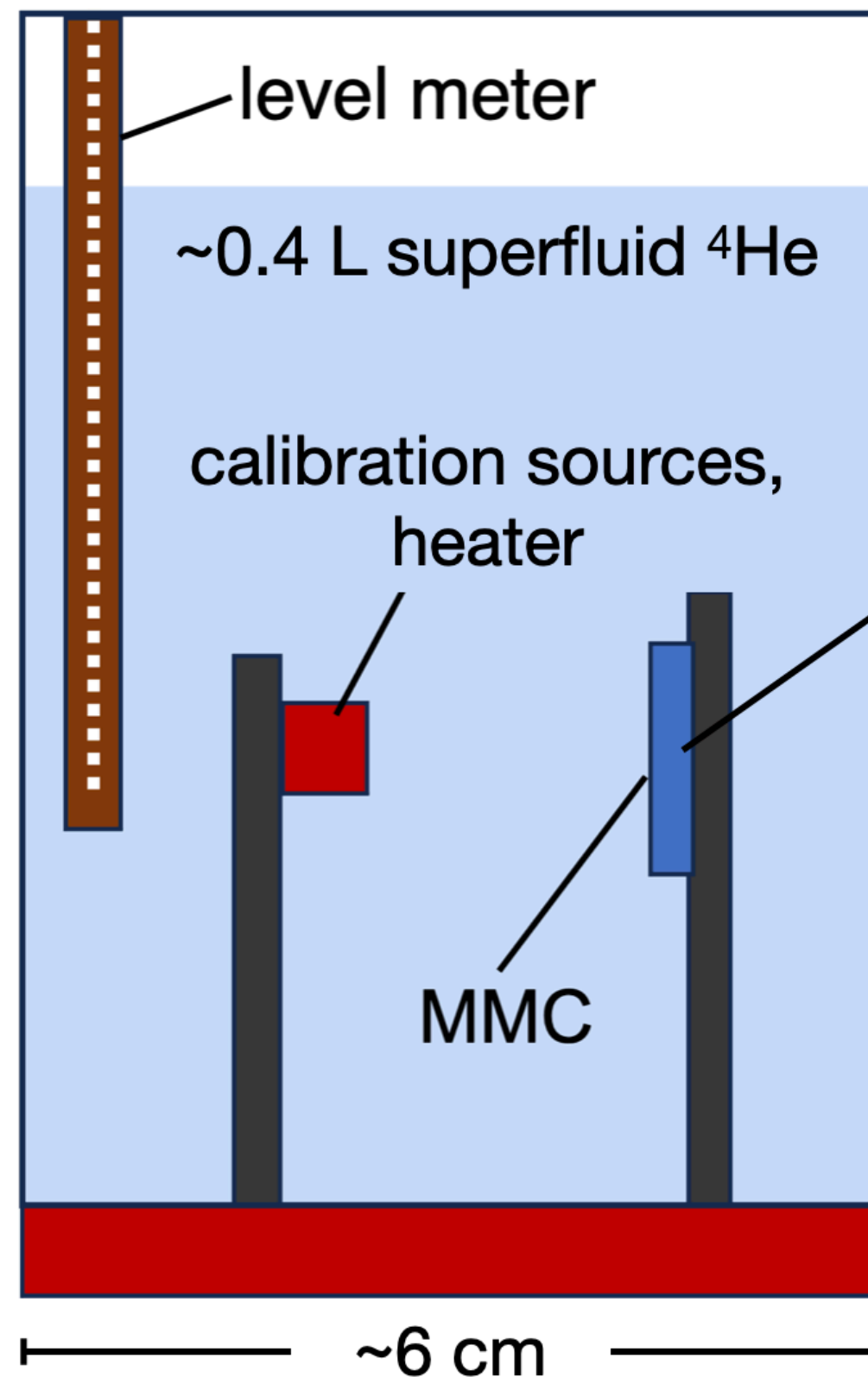

GeMSE HPGe spectrometer. JINST 17, P04005 (2022)

DELight Demonstrator

Fill capillary

Level meter

Indium seal

Detector wiring

level meter

~0.4 L superfluid ^{4}He

calibration sources, heater

MMC

~6 cm

➡ A small scale demonstrator for R&D

➡ MMC testing, athermal and thermal sensor characterization
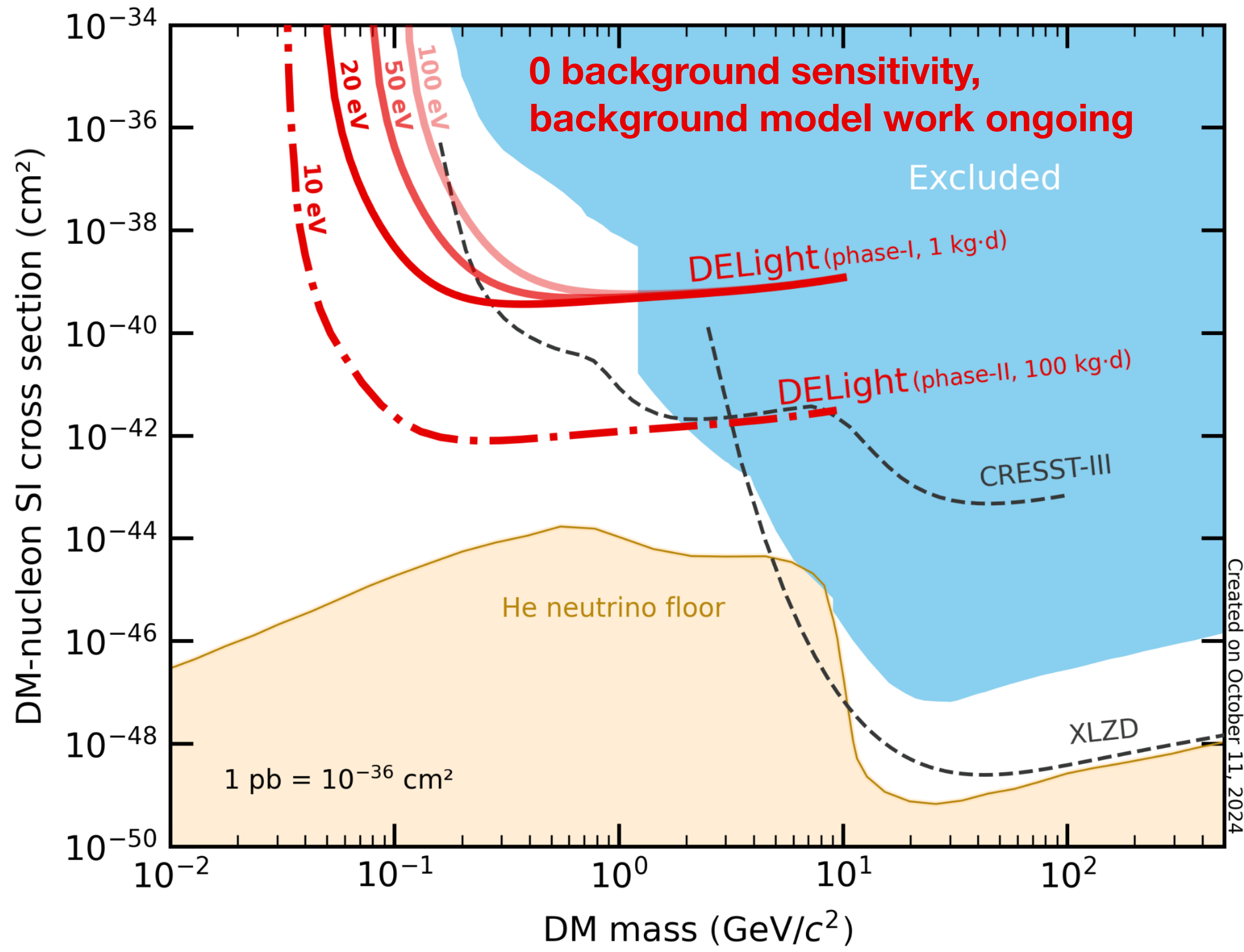
➡ Background modelling

➡ DAQ

➡ Event reconstruction

To Conclude: The DELight Forecast

- ➡ Phase-I
  - ➡ 10L target, 20 eV threshold, ~kg day exposure
  - ➡ Surface or shallow lab
- ➡ Phase-II
  - ➡ Lower threshold, ~100kg day exposure
  - ➡ Shallow lab
- ➡ Long range plan
  - ➡ Larger cell + O(kg·yr) exposure, <10eV threshold
  - ➡ Underground lab

Thank you