The simulation framework of the DELight experiment

Francesco Toschi *on behalf of the DELight collaboration*

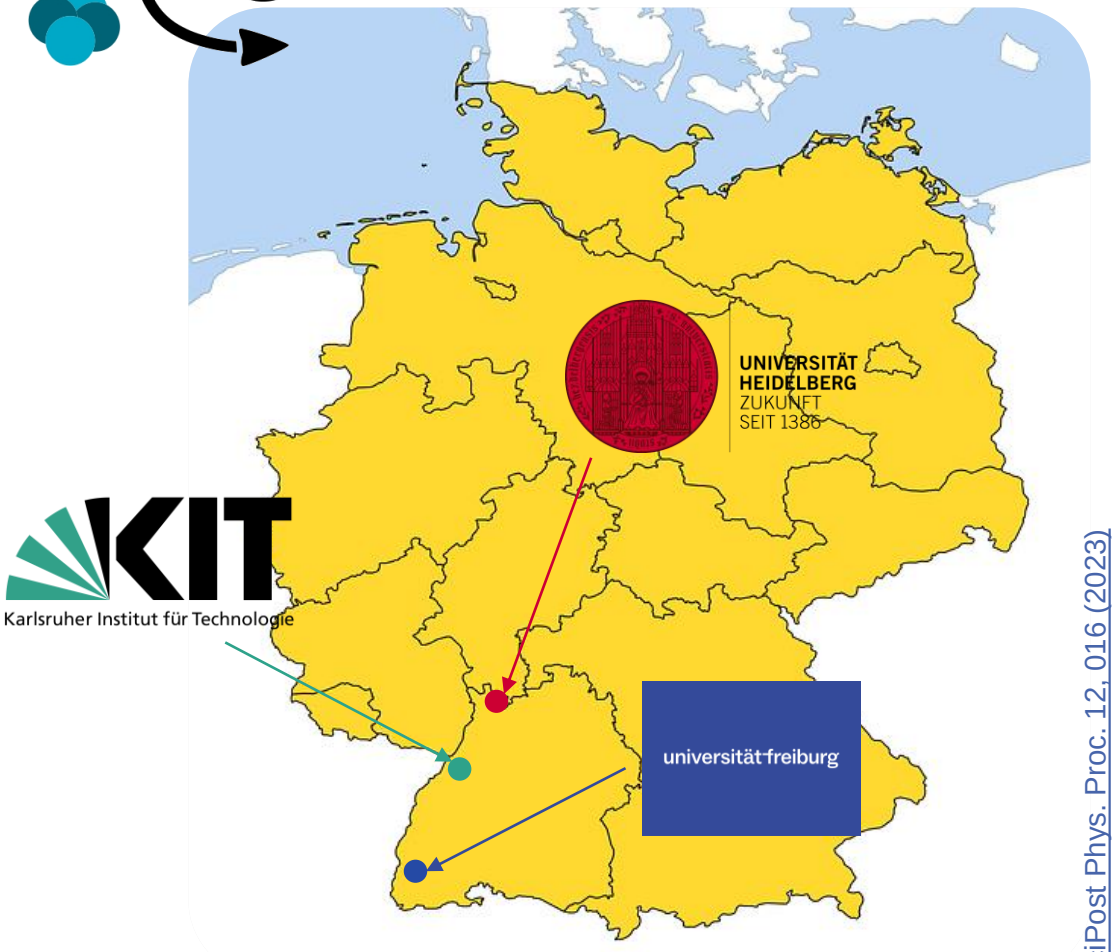
VIEWS24 – 26.04.2024, Vienna

The DELight collaboration

DELight

3 institutions from Baden-Württemberg

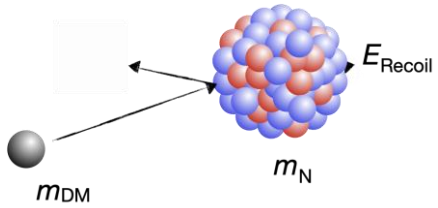
~20 scientists

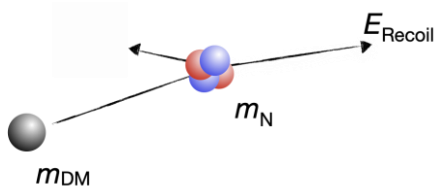


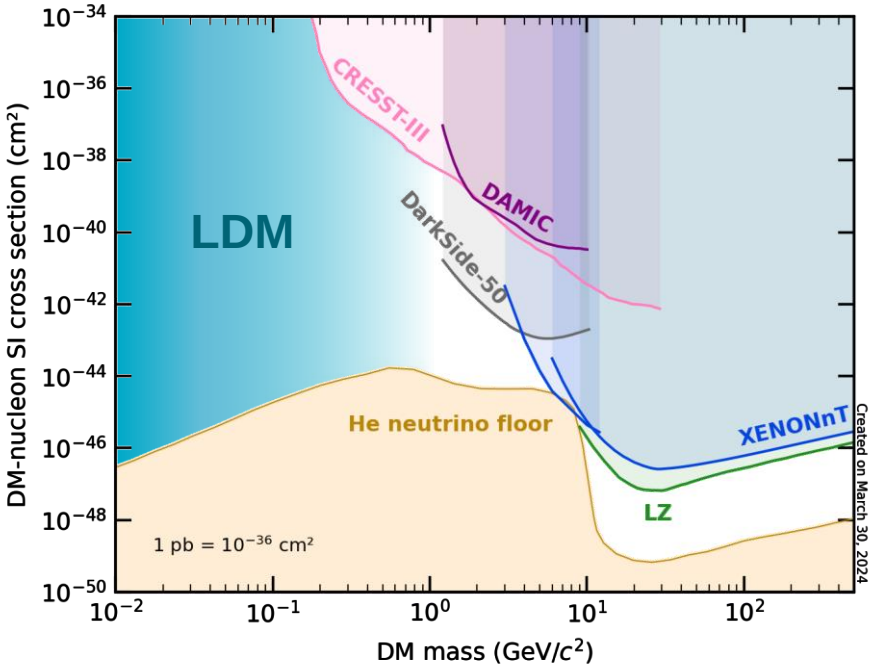
SciPost Phys. Proc. 12, 016 (2023)

Superfluid ^{4}He for LDM searches

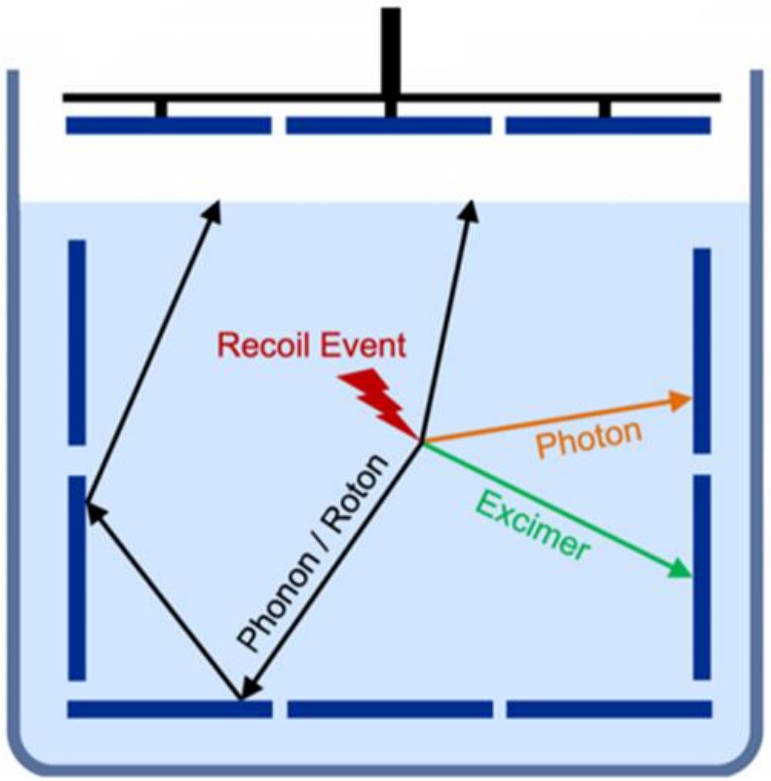
- Impurities freezing out (~20 mK)
- Multiple signal channels
  - ER/NR discrimination
  - Energy reconstruction
- Inexpensive material and scalable technology
- Light nuclei maximize recoil energy for LDM





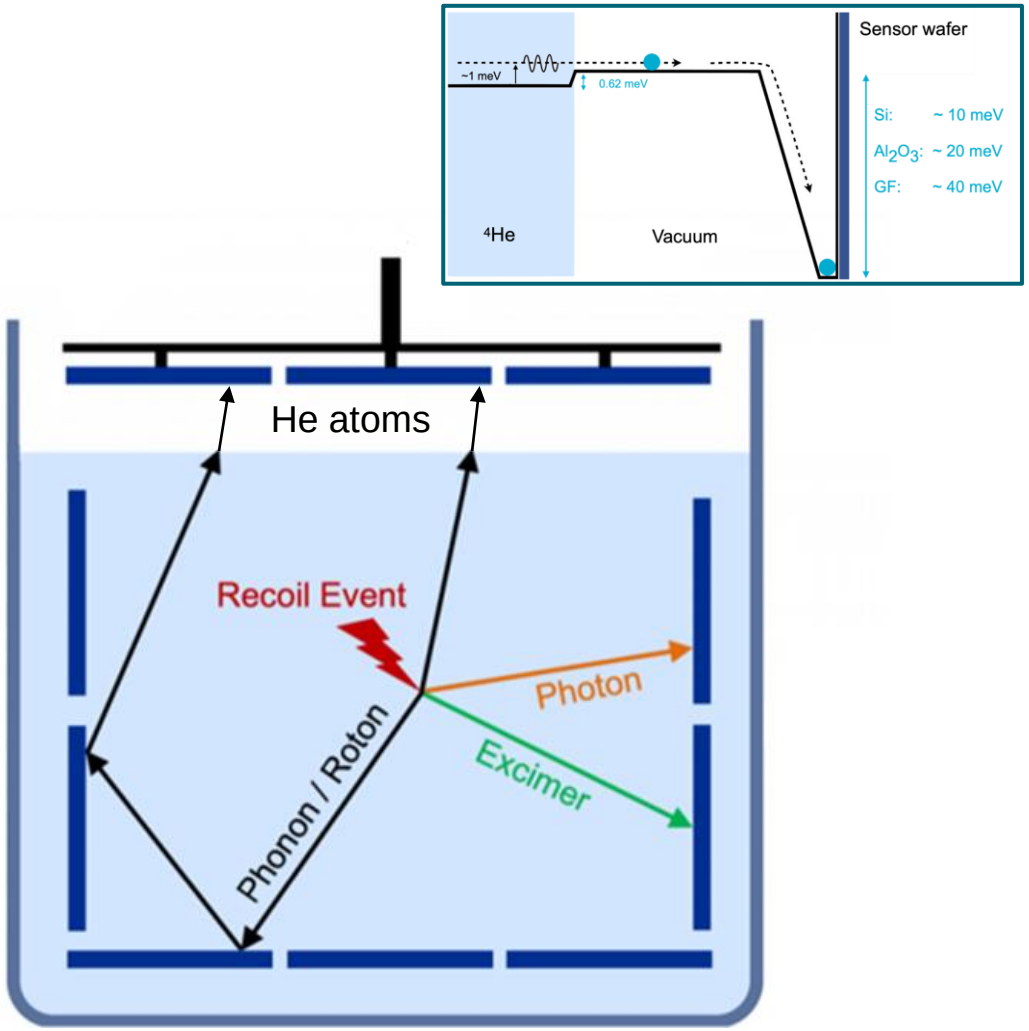


Working principle



- Prompt detection of UV and IR photons
- Ballistic triplet excimers
  - Lifetime ~13 s, speed ~2-4 m/s
  - Decay at interface with solid or vacuum
- Quasiparticles (phonons and rotons)
  - Ballistic propagation within He target
  - Reflection at interface with solid

Working principle



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- Quasiparticles (phonons and rotons)
  - Ballistic propagation within He target
  - Reflection at interface with solid
- Quantum evaporation
  - Noise-free gain $\gtrsim 10$ ($E_{He\text{-}He} < E_{He\text{-}MMC}$)
  - Sensors in vacuum must be film-free
    - **Film burner** (already tested by HERON)

R. Torii et al., Rev. Sci. Instrum., 63, 230, (1992)

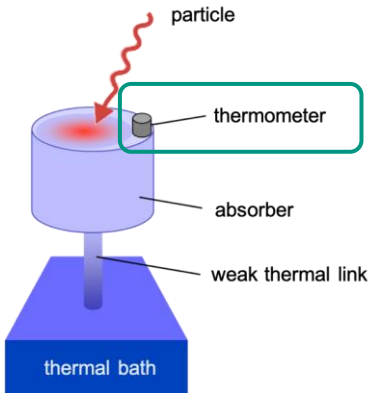
Magnetic microcalorimeters (MMC)

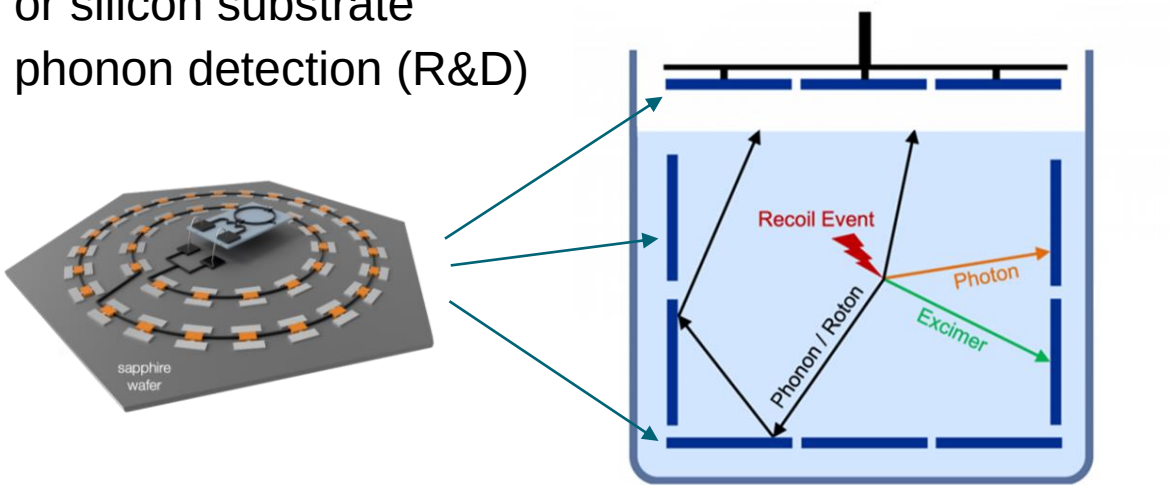
- Highly performant sensors
  - Best resolving power to date for x-rays

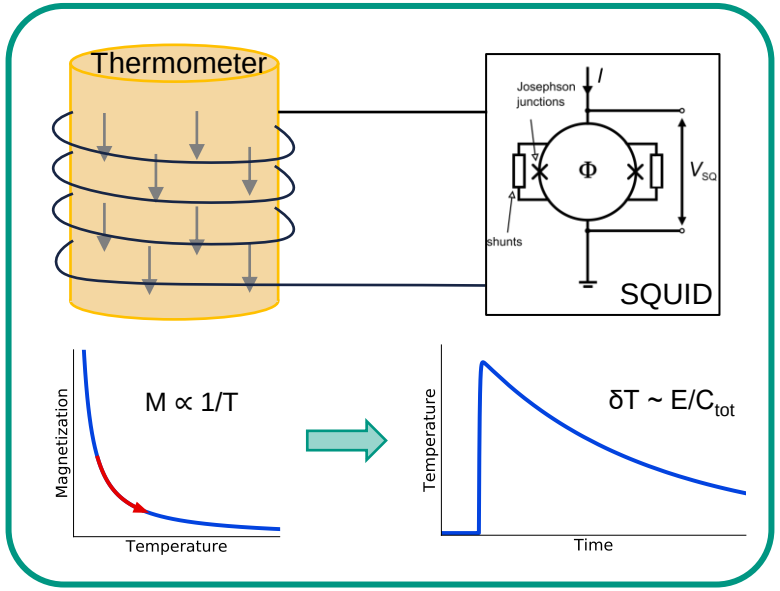
    $\Delta E_{FWHM} = 1.25(18)$ eV @ 5.9 keV (^{55}Fe source)

    Phys. Rev. D 109, 043035 (2024)
    Appl. Phys. Lett. 124, 032601 (2024)

- MMC-based wafer calorimeters for DELight
  - ΔE_{FWHM} = 5-6 eV ⇒ ~20 eV threshold
  - ~50 sensors with O(5 cm) diameter
  - Sapphire or silicon substrate
  - Athermal phonon detection (R&D)





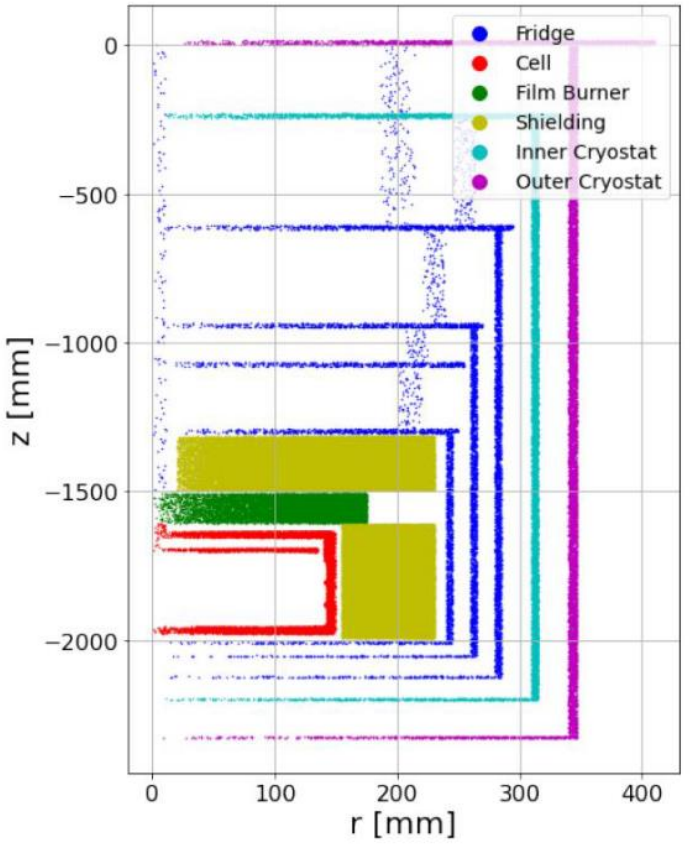


GEANT4 implementation

- Using GEANT4 v11.0.3 with multithread
- Simplified and flexible geometry for design studies
  - First shielding studies suggest an inner lead shielding
  - MMCs and Helium sensitive detectors
- Using suggested physics lists
  - *G4EmStandardPhysics_option4*
  - *G4HadronPhysicsQGSP_BERT_HP*
  - *…*
- SaG4n implemented for (α,n) reactions

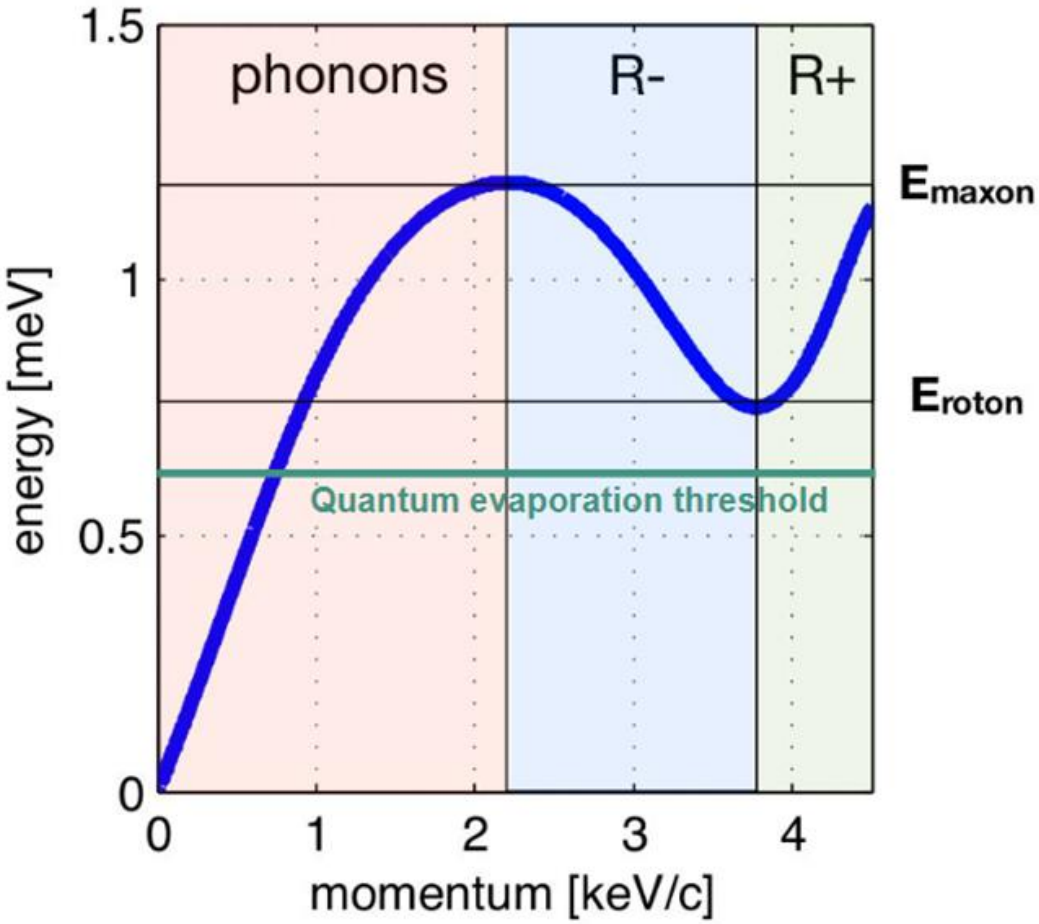
Nucl. Instrum. Methods Phys. Res. 960 (2020) 163659

Geantino view

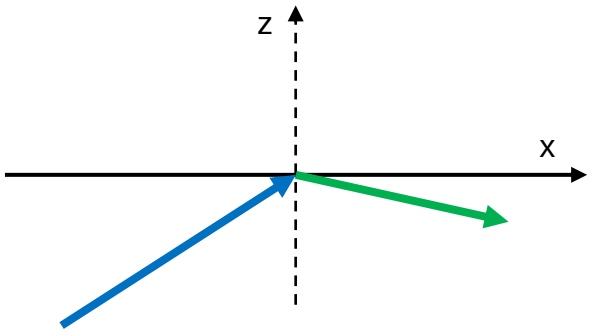


Quasiparticle propagation

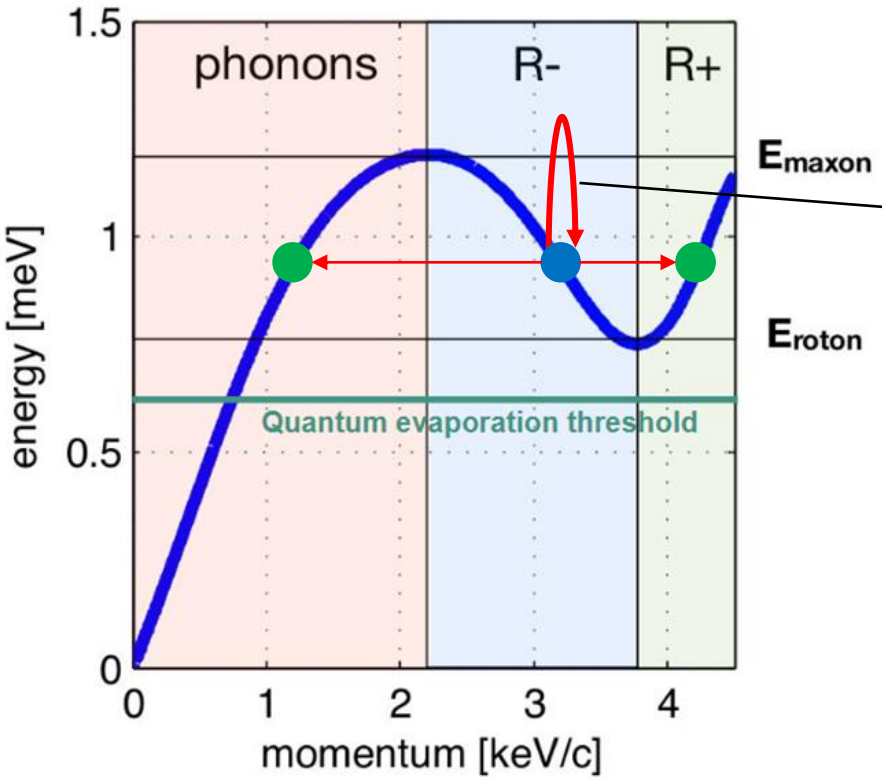
- Unique and characteristic dispersion relation
- G4CMP requires lattice structure information
  Nucl. Instrum. Methods A 1055 (2023) 168473
- Developed custom solution based on G4CMP
  - *G4VUserTrackInformation* storing momentum information
  - Phonons with energy below evaporation threshold are killed
  - „Acoustic“ surface implemented for reflection at surfaces

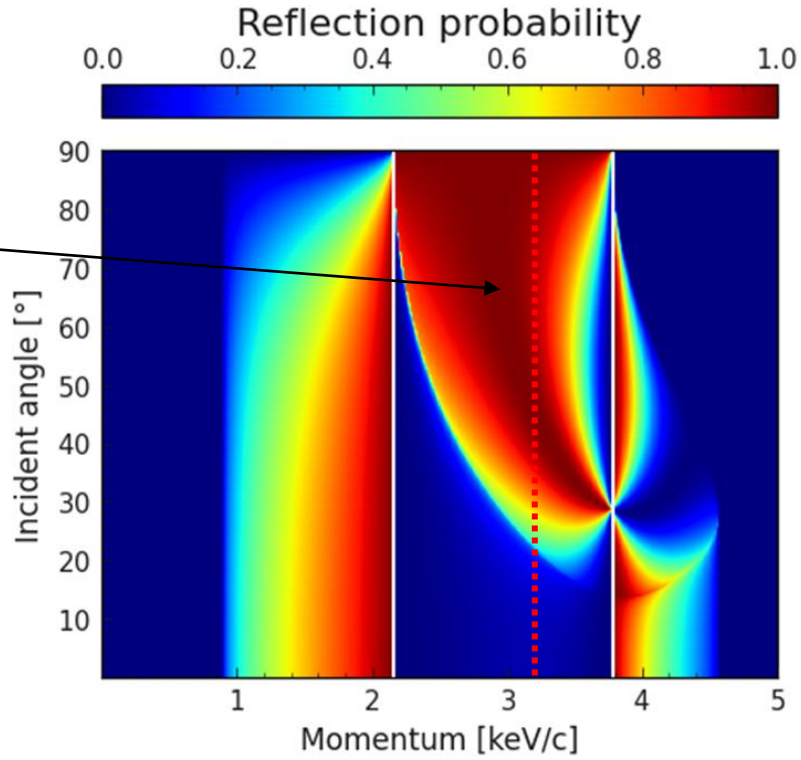


Quasiparticle propagation: reflection



$$\begin{cases} E^i = E^f \\ \vec{p}_{\parallel}^{\,i} = \vec{p}_{\parallel}^{\,f} \end{cases}$$

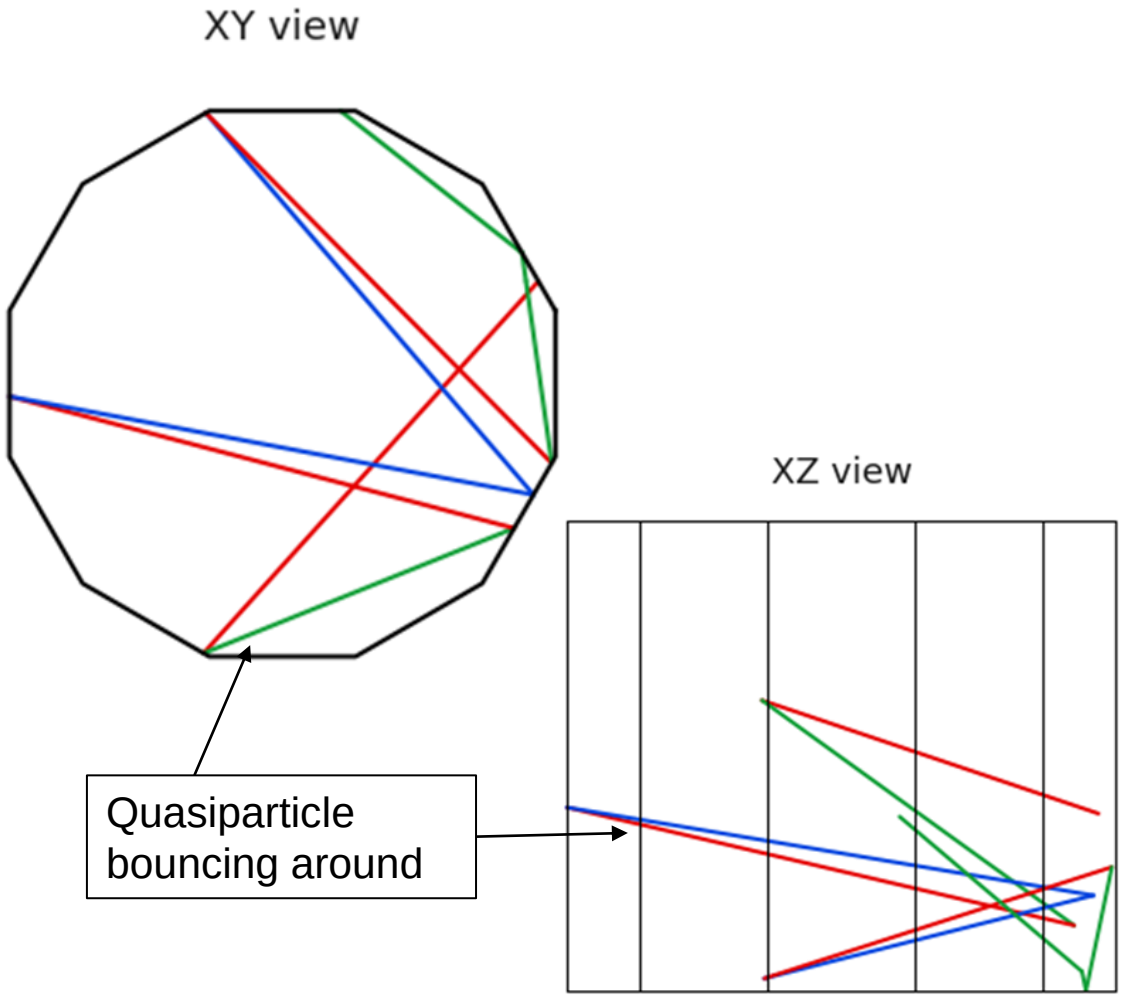


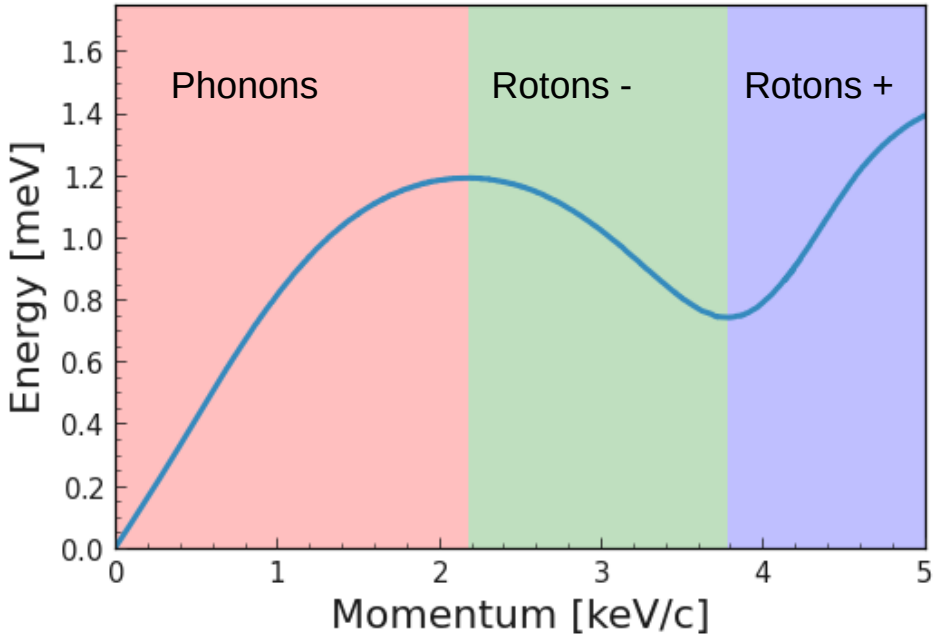


Reflection on copper

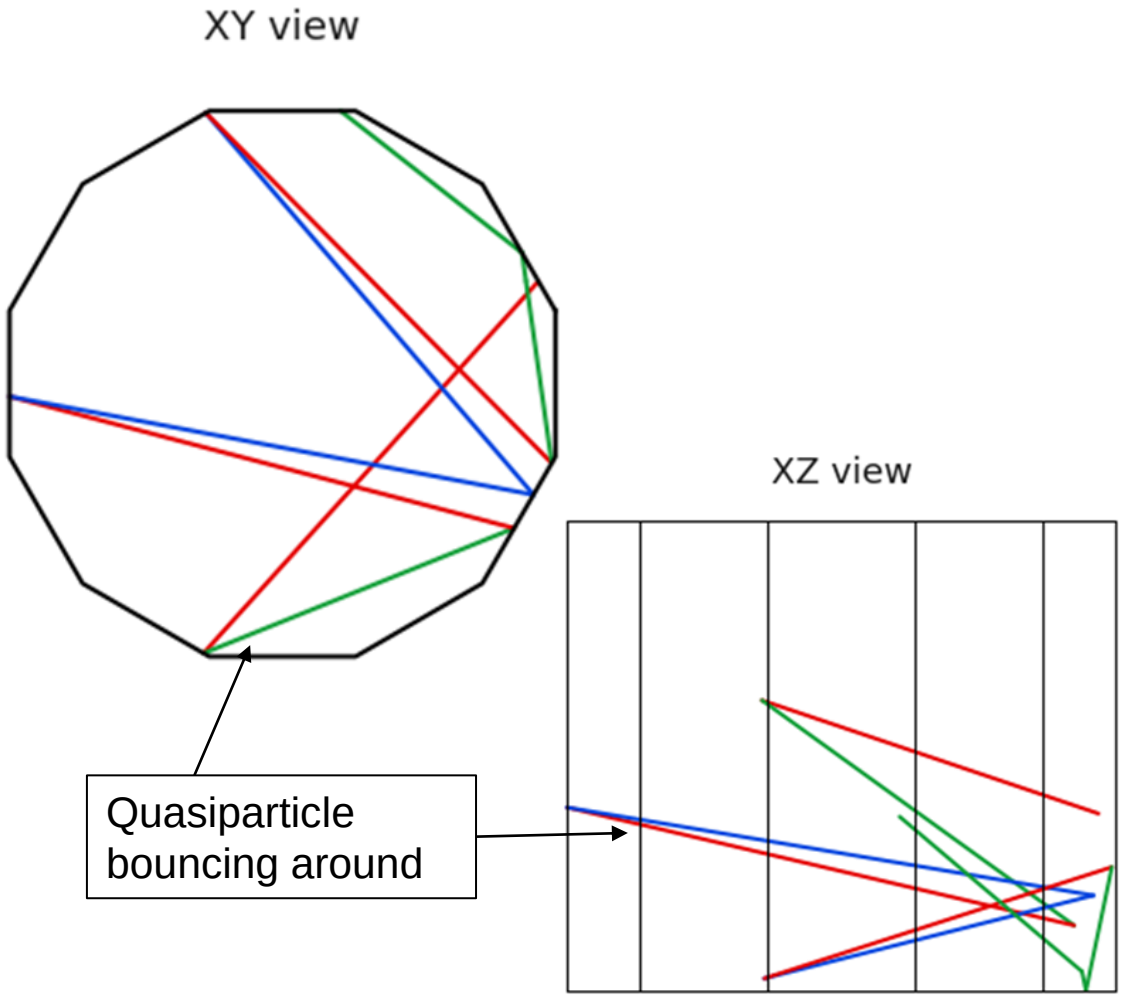
Phys. Rev. B 77, 174510

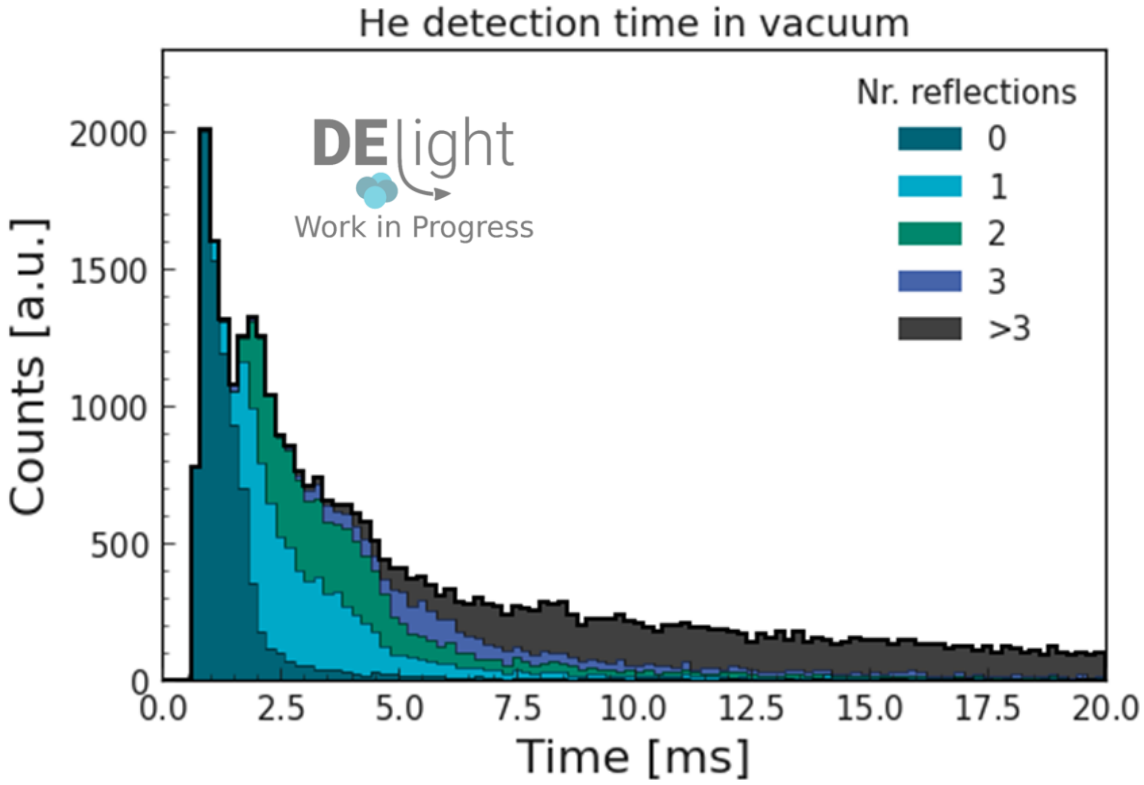
Quasiparticle propagation: reflection



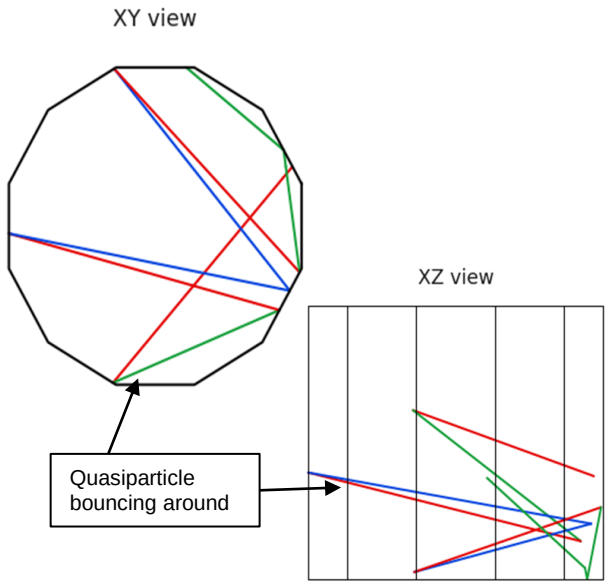


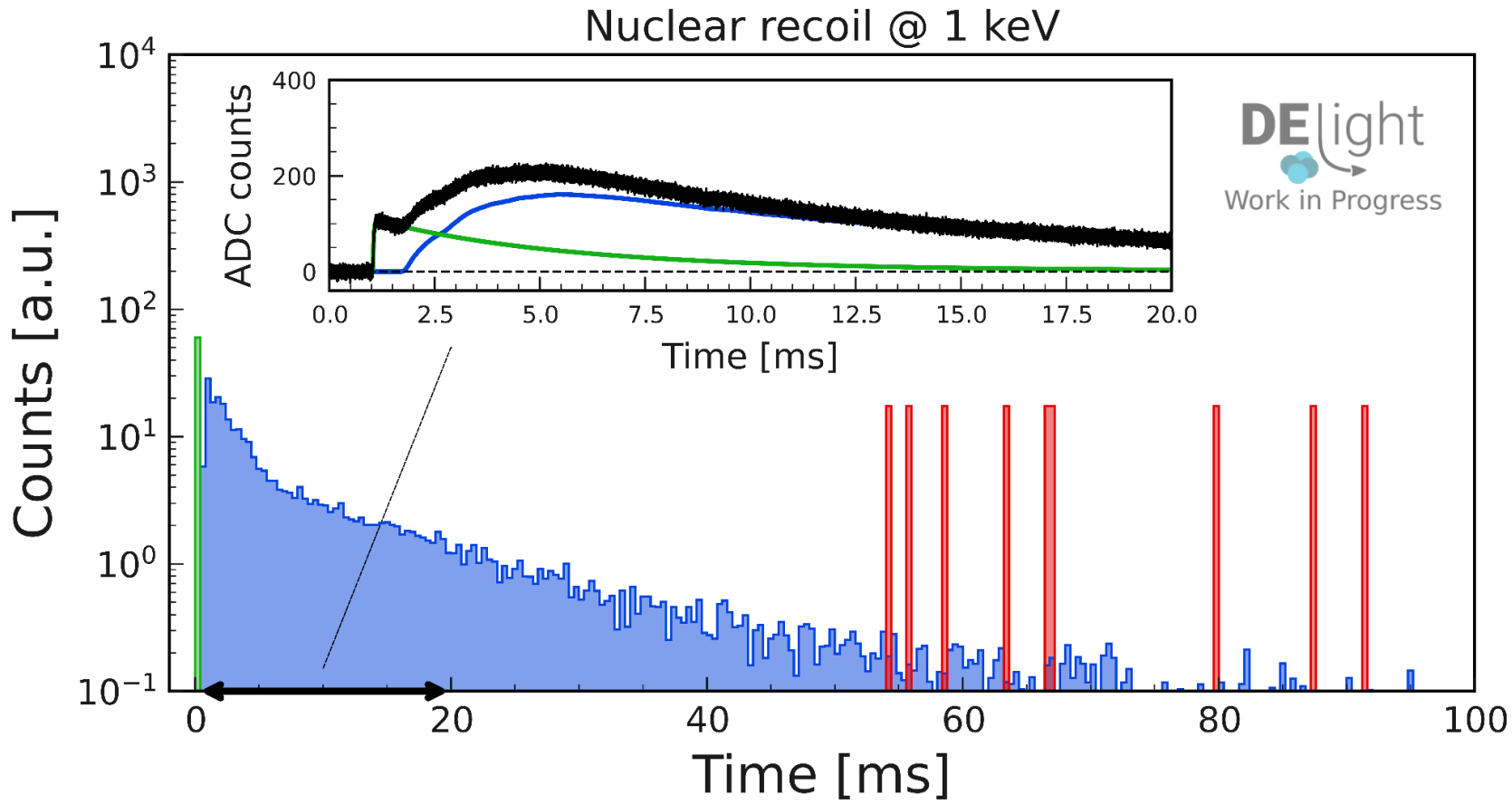
Quasiparticle propagation: reflection





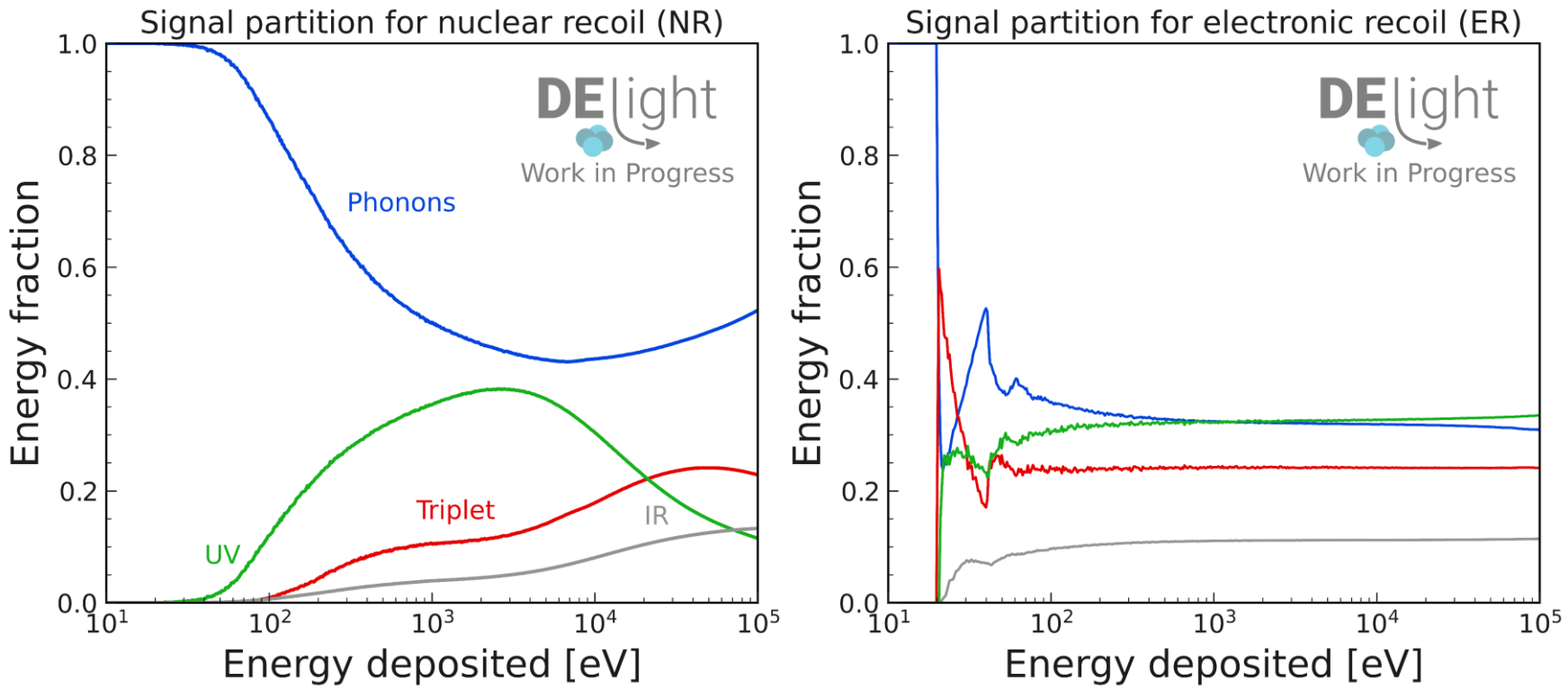
Quasiparticle propagation





Signal partitioning

- Derived from „interaction-by-interaction“ simulation using literature cross sections (e^--He, He-He)



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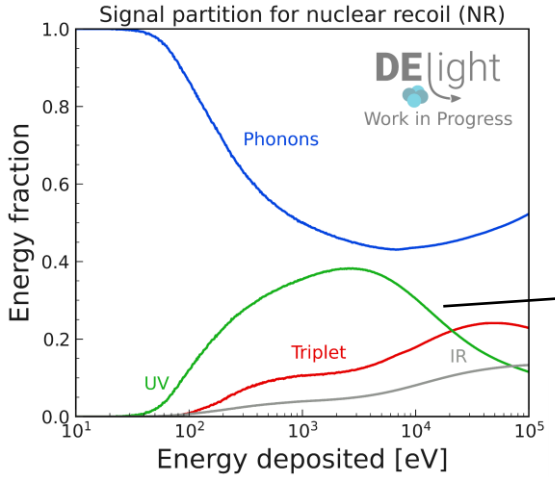
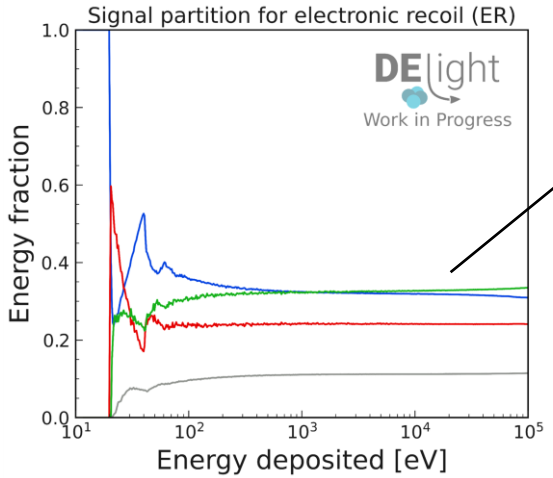
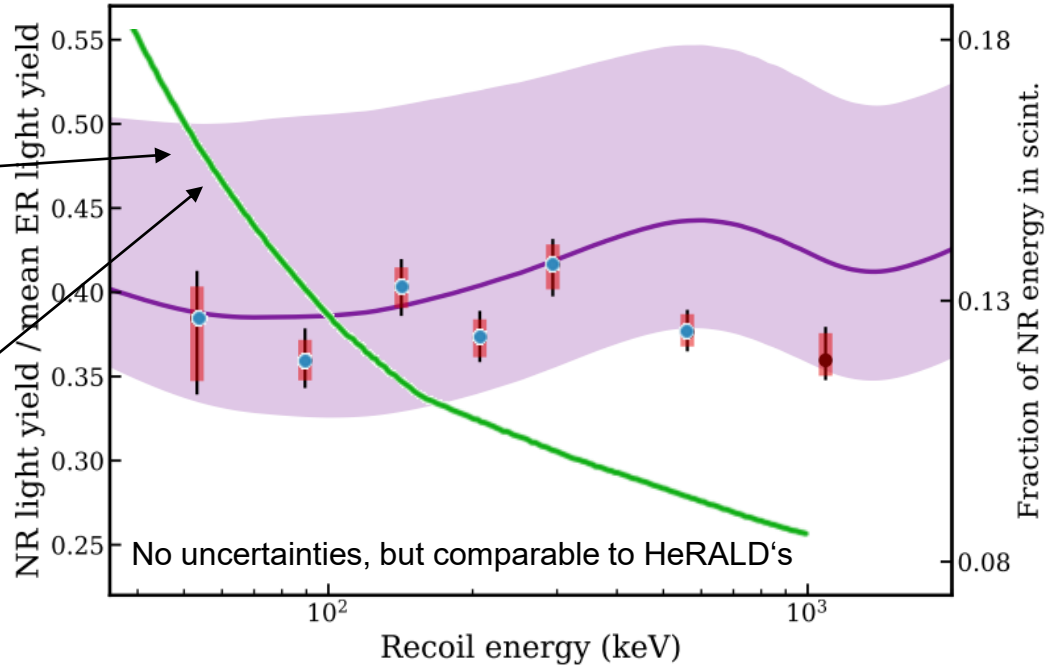


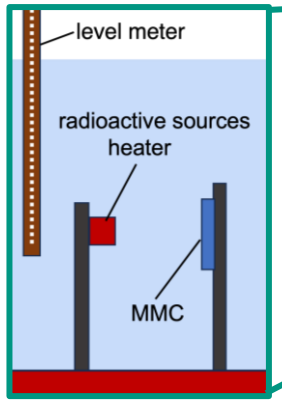


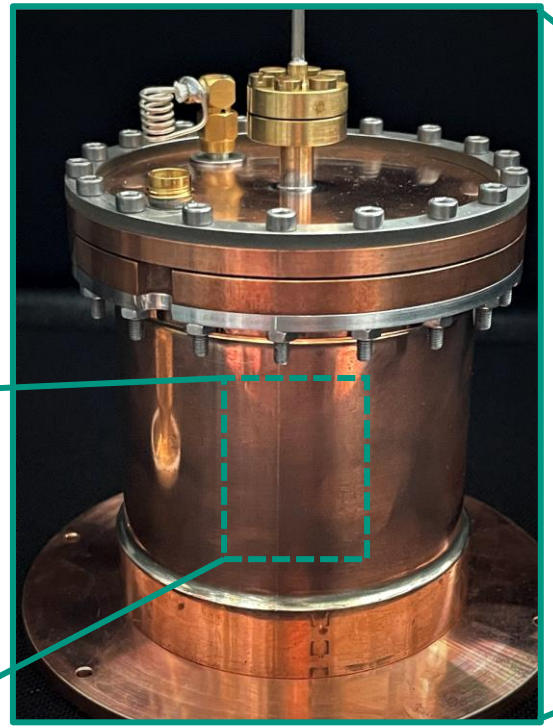


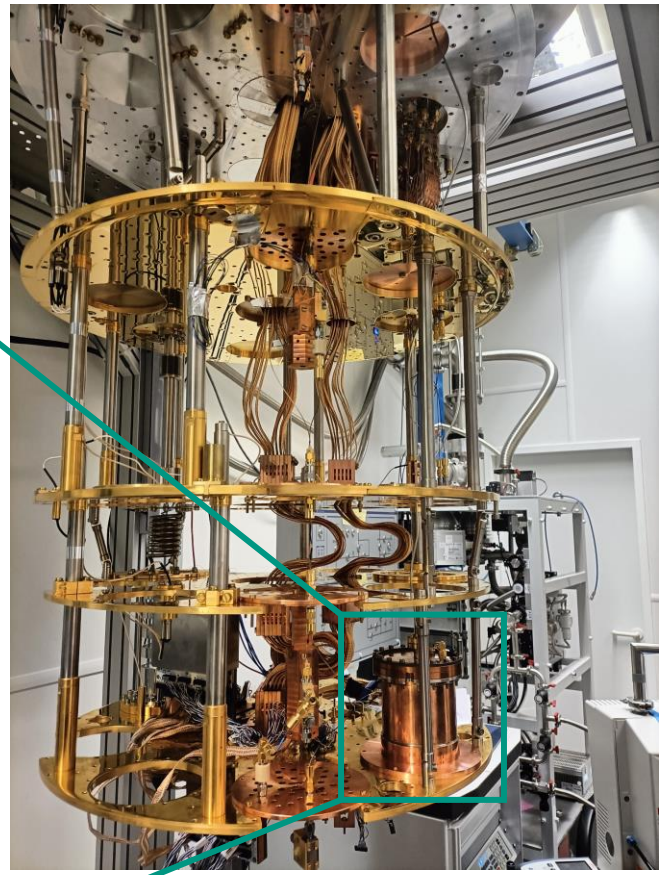
Helium cell @ Heidelberg University

- 280 mL test cell with capacitance level meter
- Operating in the ECHo experiment cryostat

- Planned/ongoing tests:
  - operation of MMC in superfluid helium,
  - direct quasiparticle measurement,
  - detection of UV photons and triplets,
  - and much more!

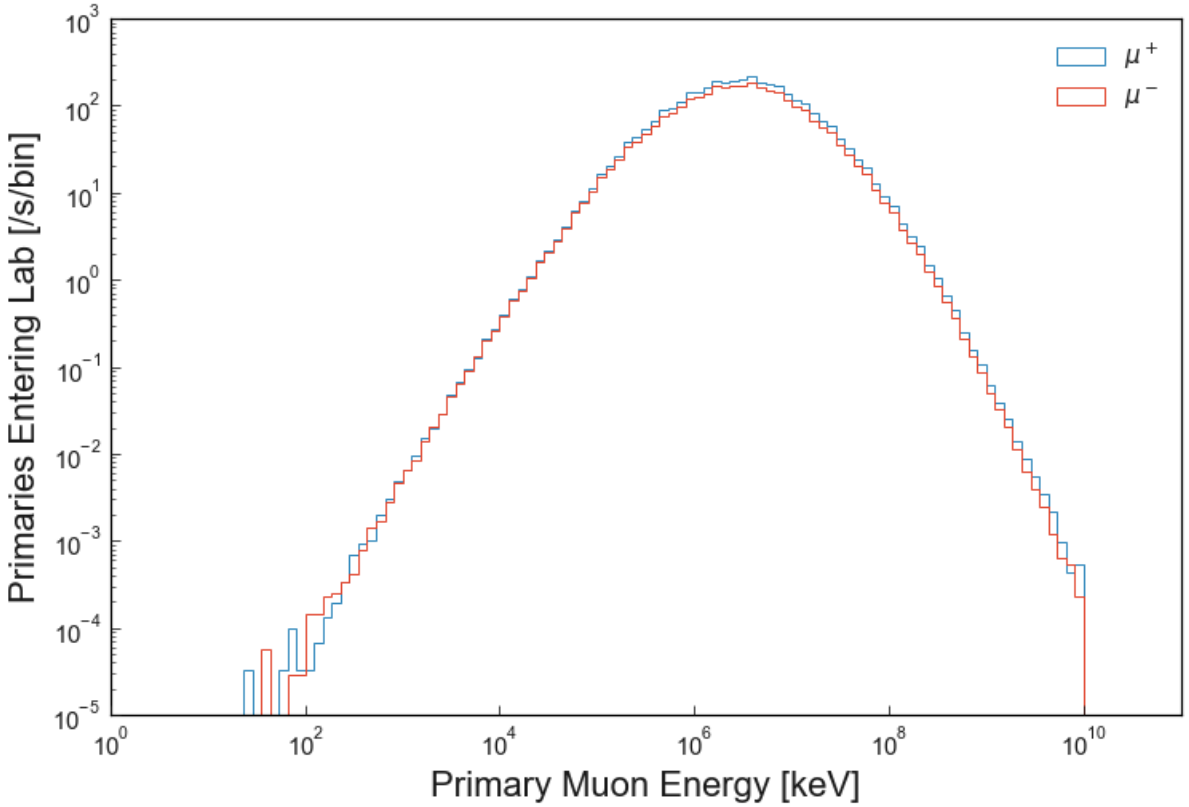






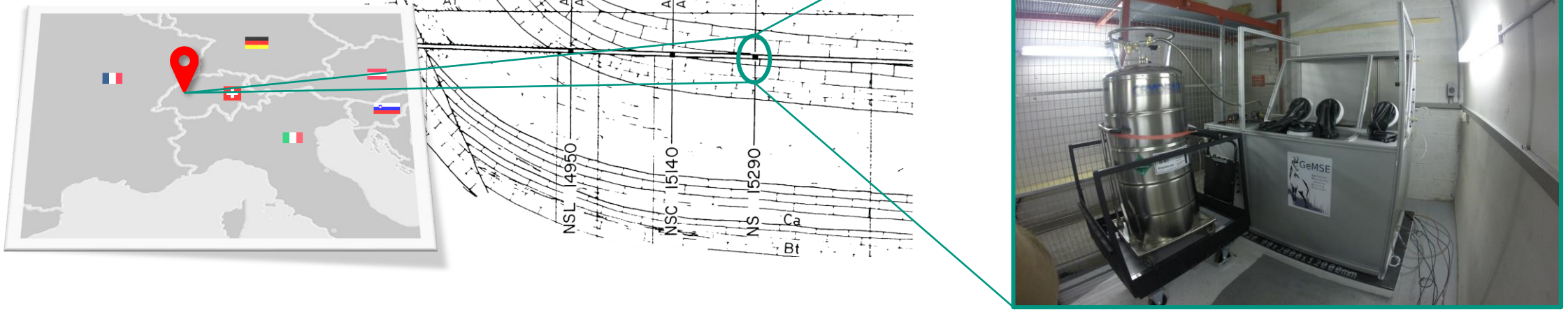
Cosmic muon simulations

- Primary muon spectrum from:
  - PARMA at low energies (< 10 GeV)
  - Modified Gassier at high energies
- PARMA code used also for other cosmics (neutron, protons, …) PLoS ONE 11(8): e0160390
- Simulations above- and underground ongoing



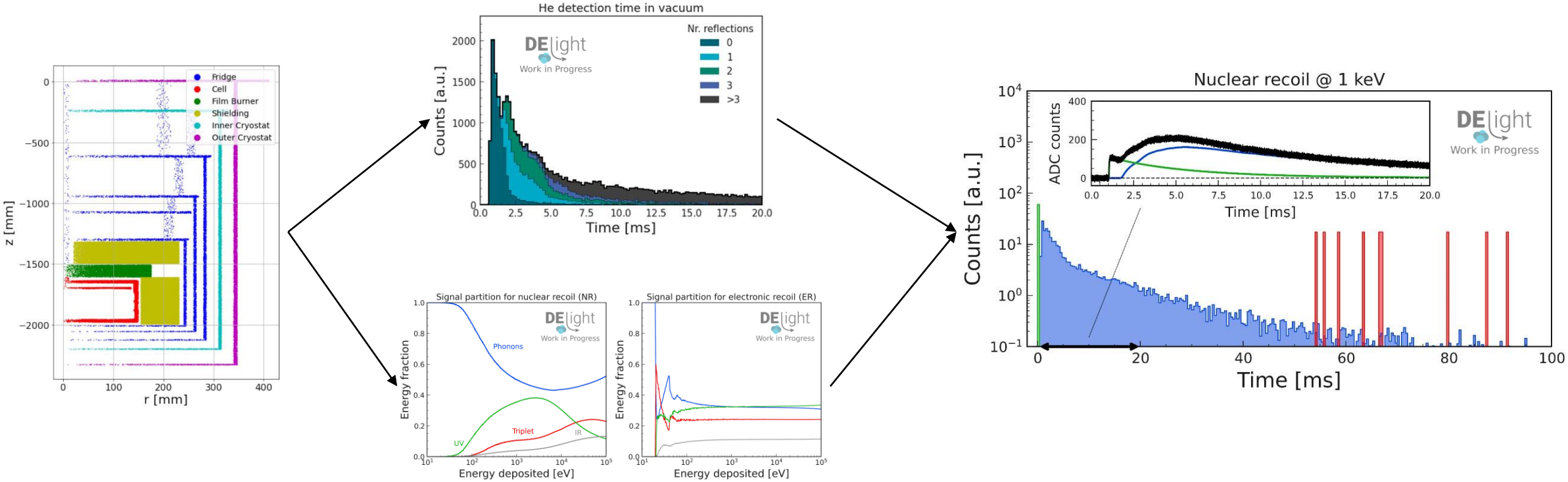
Vue-des-Alpes underground laboratory

- 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)



Conclusion

- First physics and detector models are implemented for DELight
- Starting taking first data for validation by the end of the year

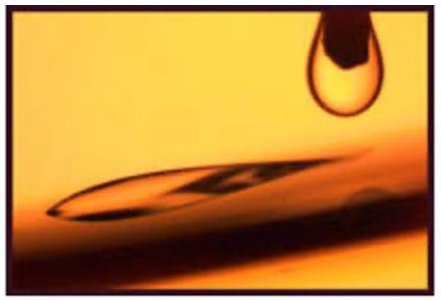


Backup slides

DELight detection principle

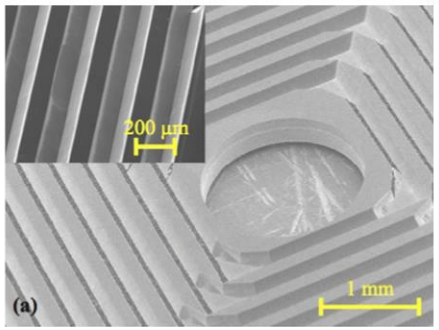
- Noise-free gain ≳10 in the MMC as binding energy He-He is smaller than He-absorber
- MMCs in vacuum need to be ^{4}He film-free → film burner (already tested by HERON)

Alternatives



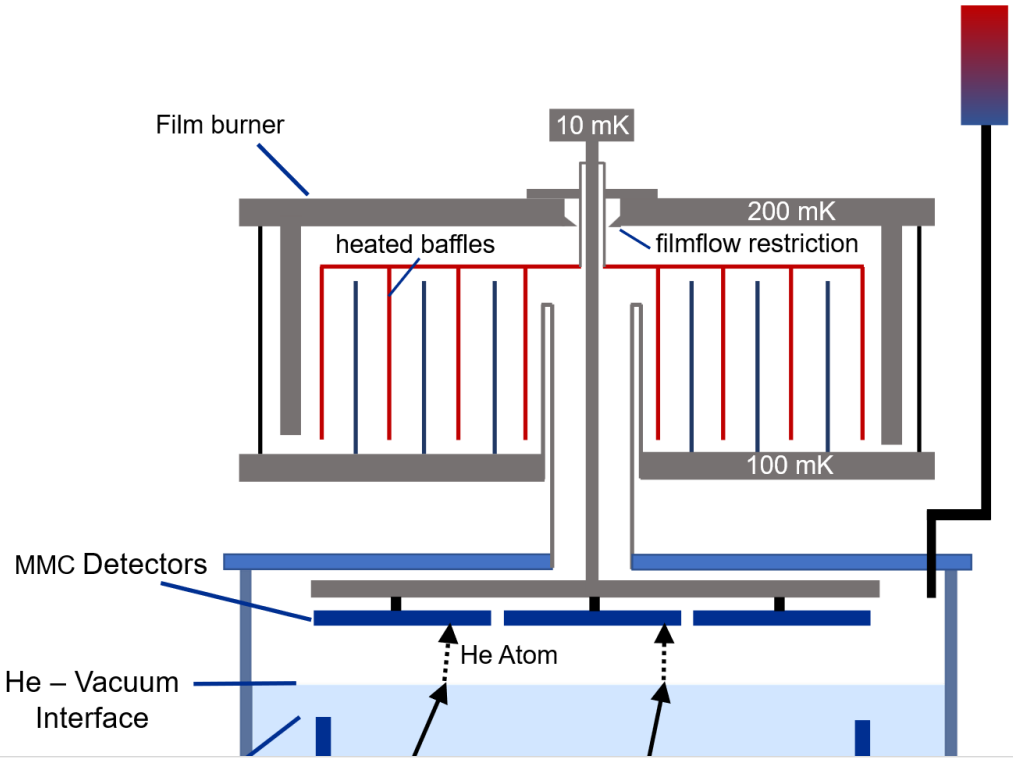
Cesium coat

successfully tested by HeRALD
arXiv:2307.11877



Knife-edge

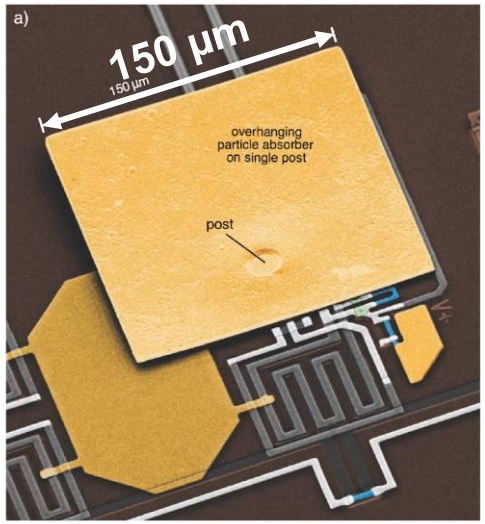
film-flow reduction of 30% (NASA)
J. Astr. Tel. Inst. Syst. 4(1), 011203

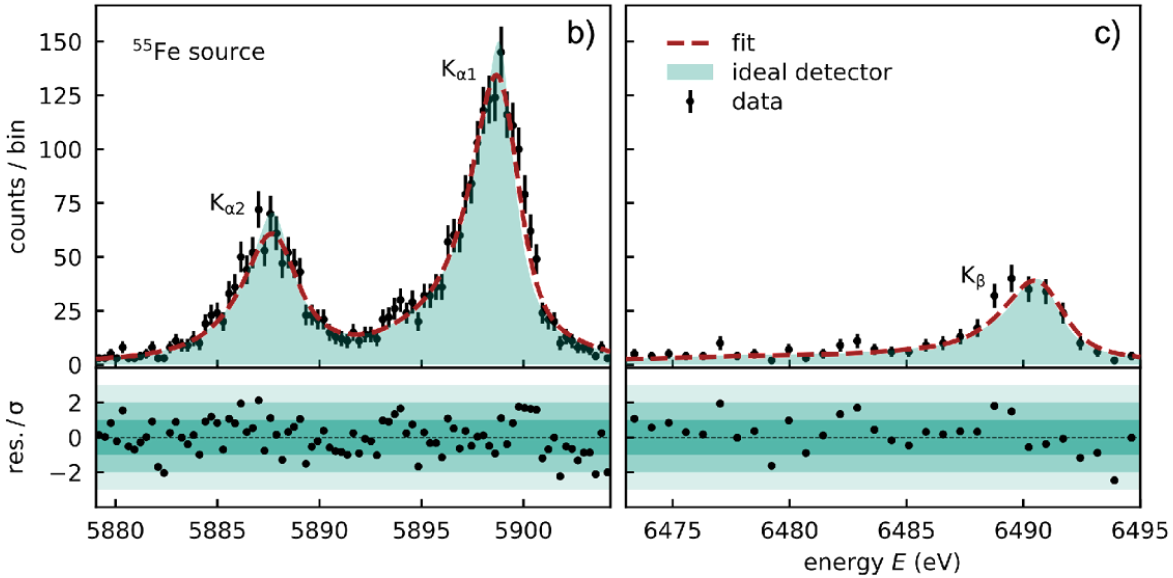


Magnetic microcalorimeters (MMC)

- Previous best MMC resolution: $\Delta E_{FWHM} = 1.58$ eV @ 5.9 keV (x-rays from ^{55}Fe) (1)
- Achieved best resolution to date with optimum-filter based analysis(2,3):
  - $\Delta E_{FWHM} =$ **1.25(18) eV** @ 5.9 keV;
  - amplitude fit to K_α data, validation reconstruction K_β.

X-rays MMC





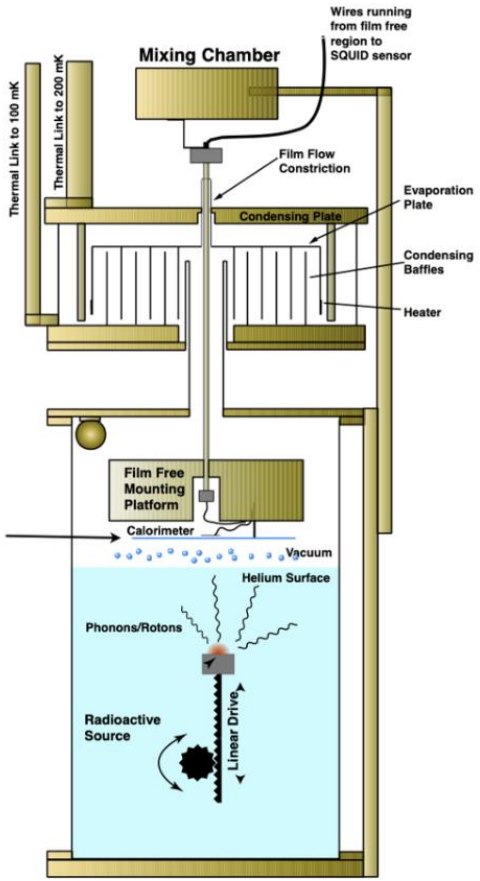
1 J. Low Temp. Phys. 193, 365-379 (2018)
2 Phys. Rev. D 109, 043035 (2024)
3 Appl. Phys. Lett. 124, 032601 (2024)

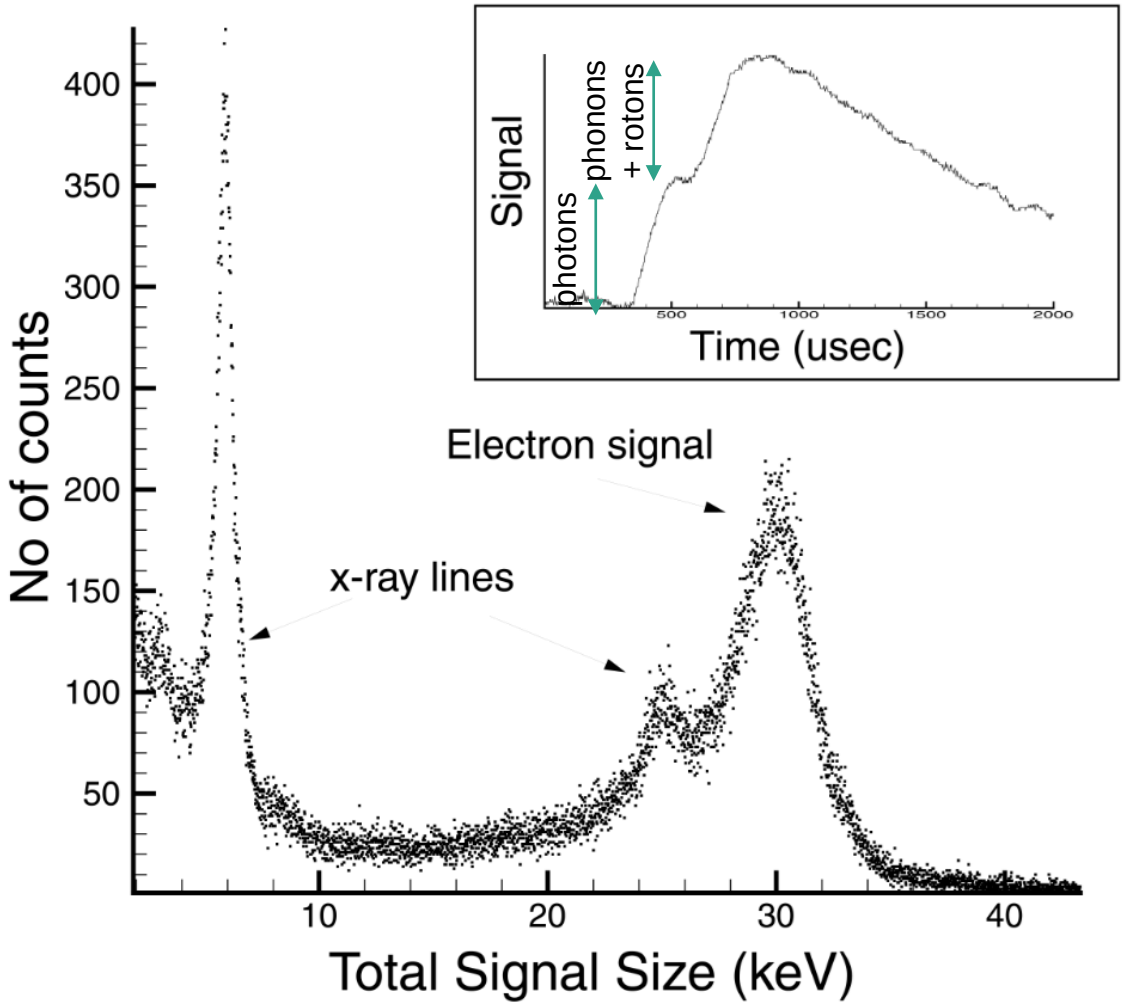
HERON

He film burner

wafer calorimeter

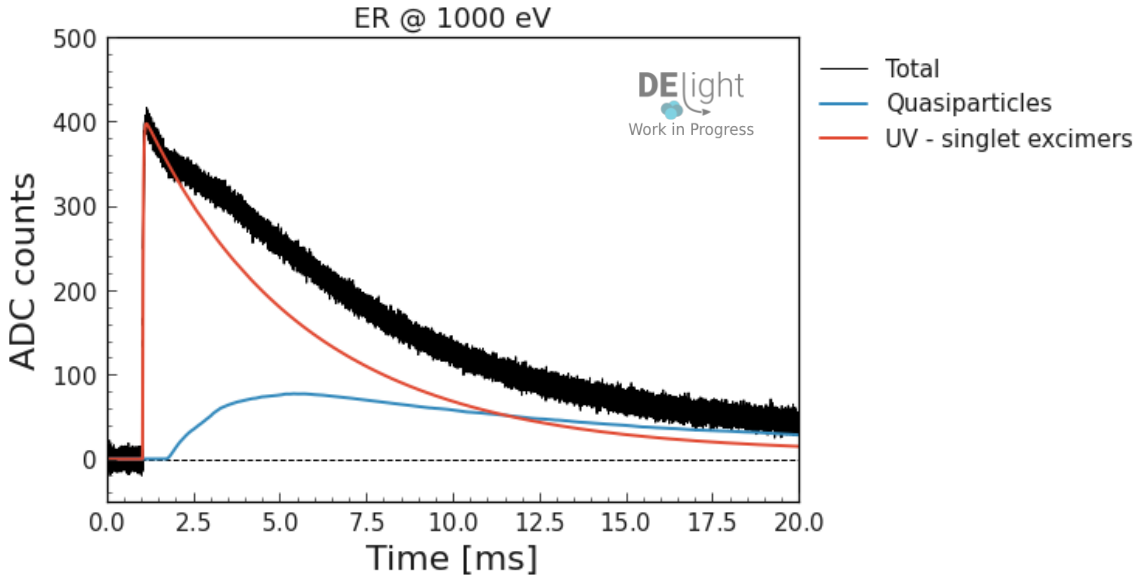
kg-scale
LHe mass

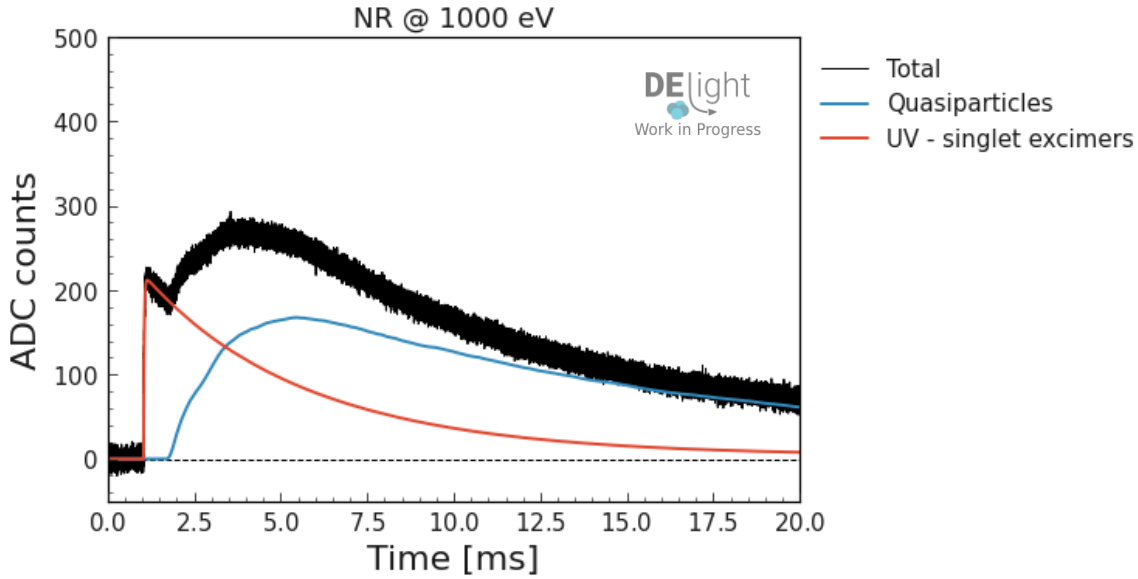




First waveform expectations

- First preliminary expectations using (x-ray) MMC response
  - MMC-based wafer calorimeters might likely have different time response





The future of DELight

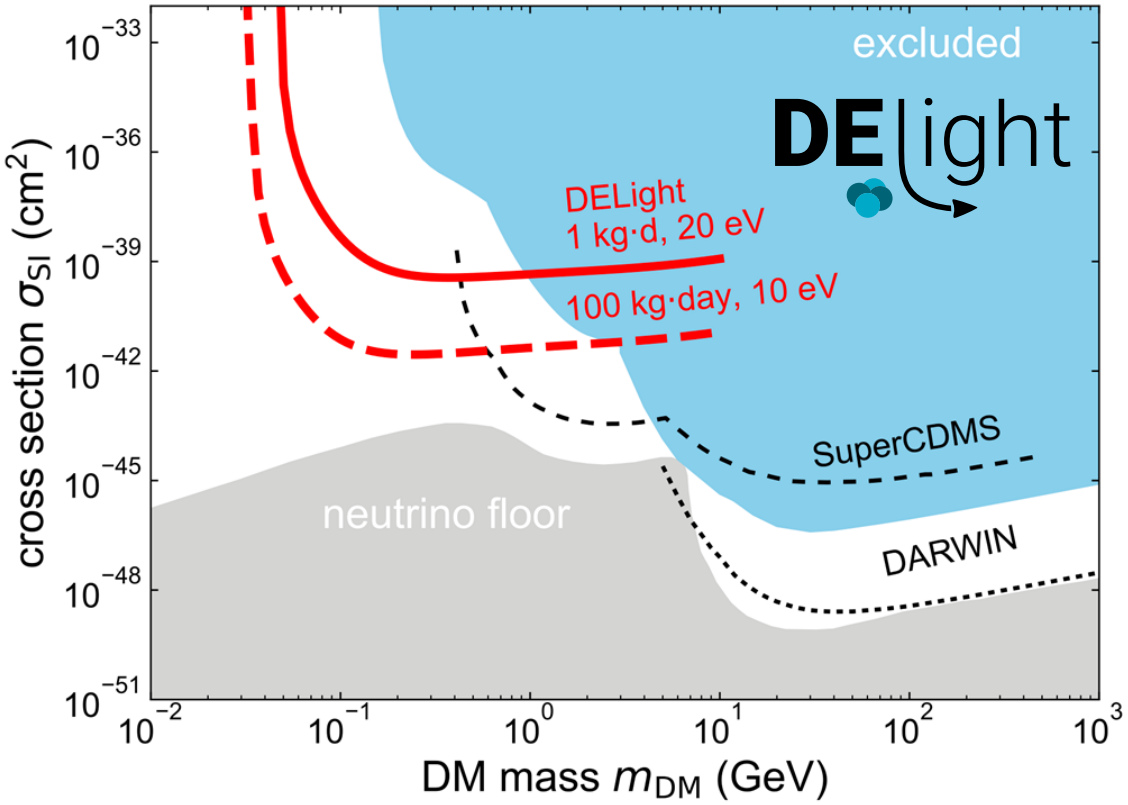
First phase

- Above ground and/or shallow lab (e.g., VdA)
- 10 L target volume (≳1 kg)
- Threshold of 20 eV
- Probing new physics with exposure of 1 kg·d

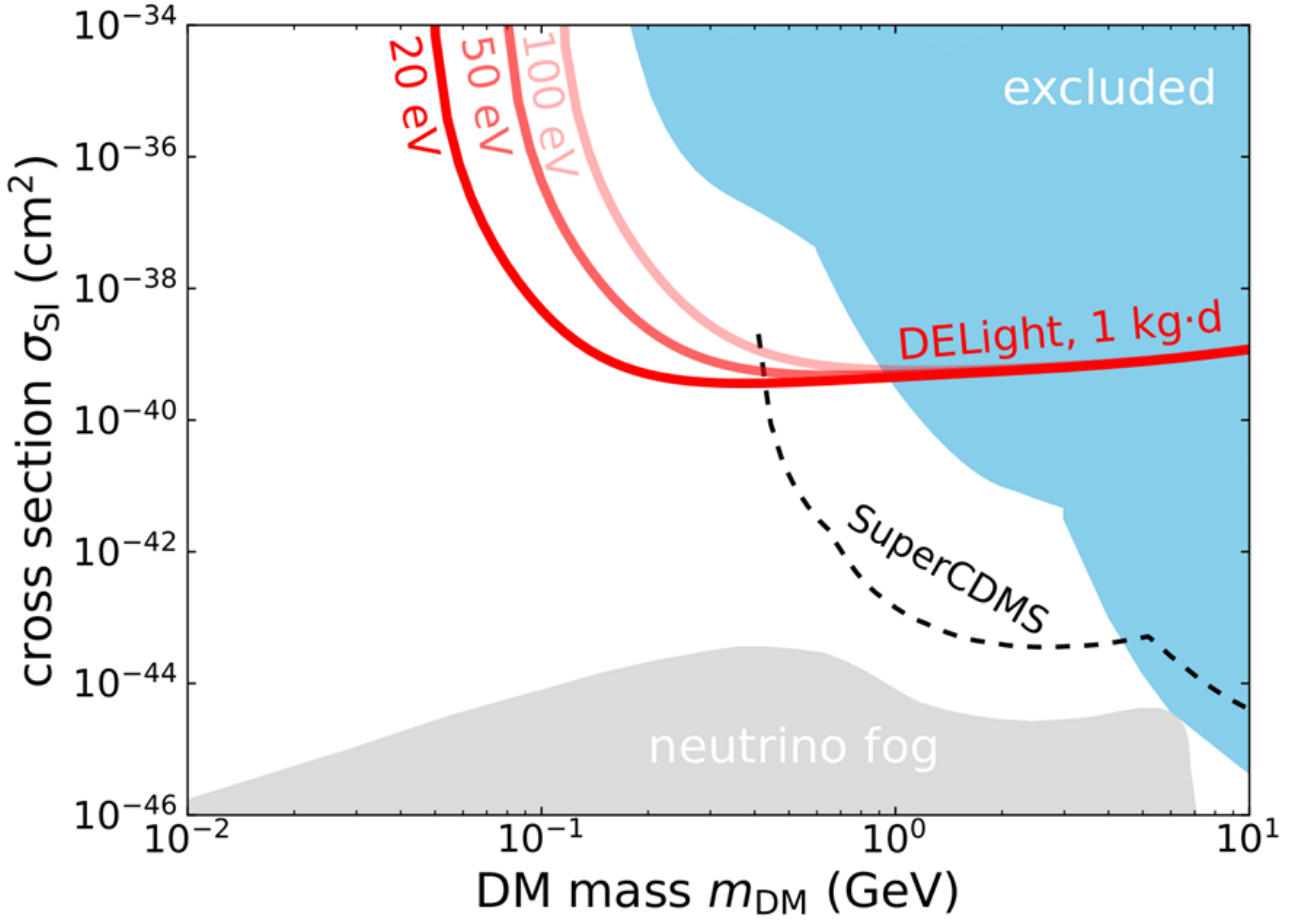
and beyond

- Underground lab
- Larger cell + long exposure
- Threshold <10 eV

Find out more and stay tuned!

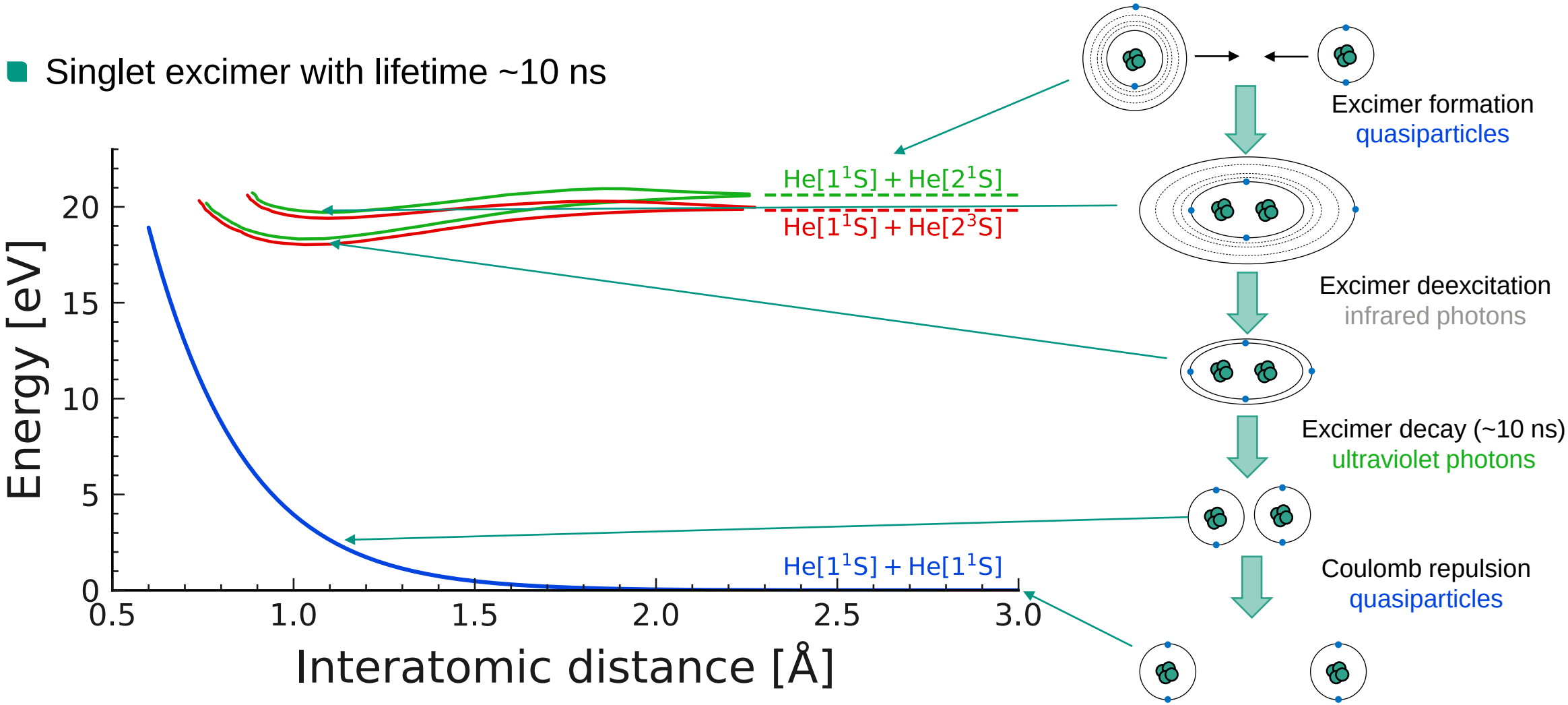


DELight phase-I: threshold impact



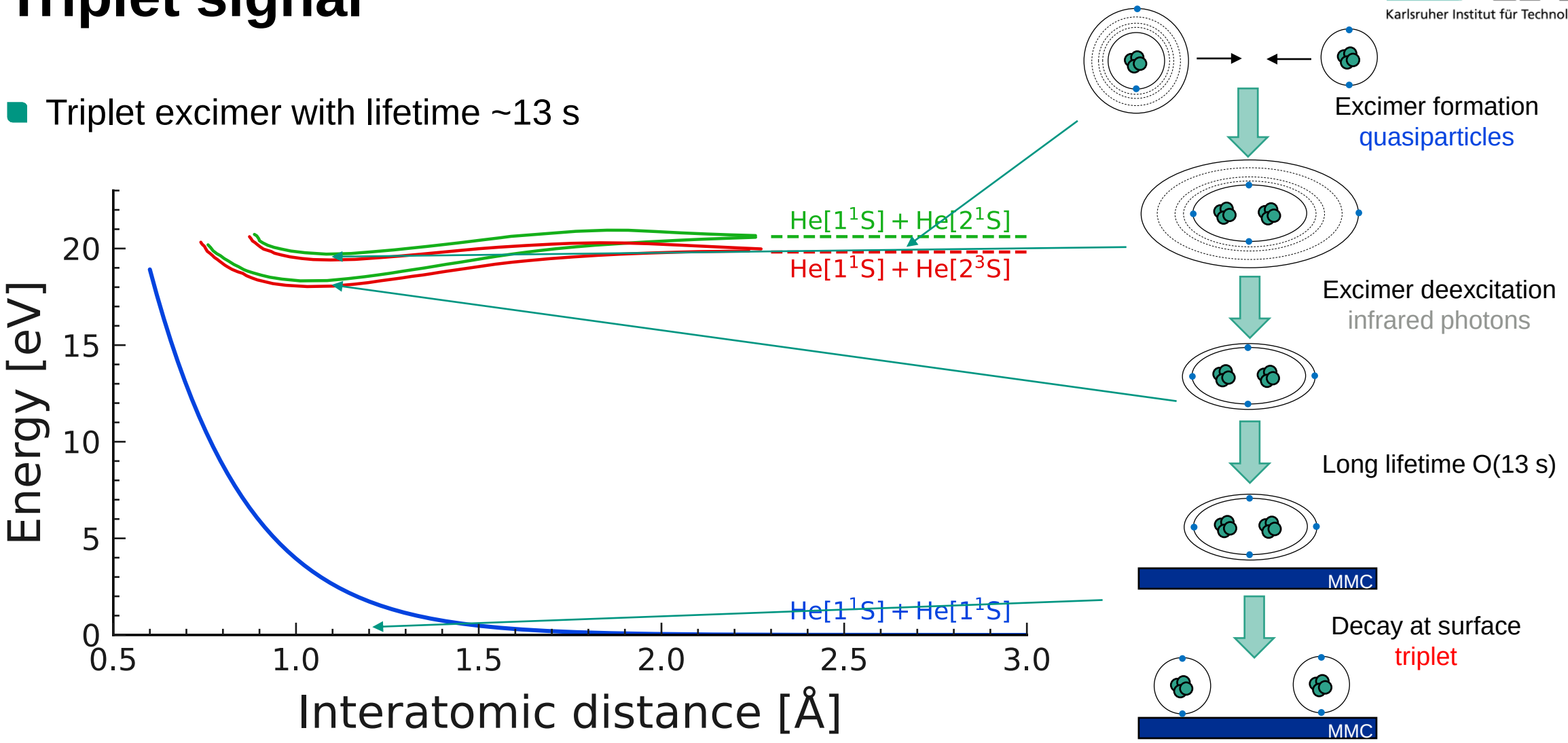
UV signal

- Singlet excimer with lifetime ~10 ns



Triplet signal

- Triplet excimer with lifetime ~13 s



From interactions to signal quanta (ER)