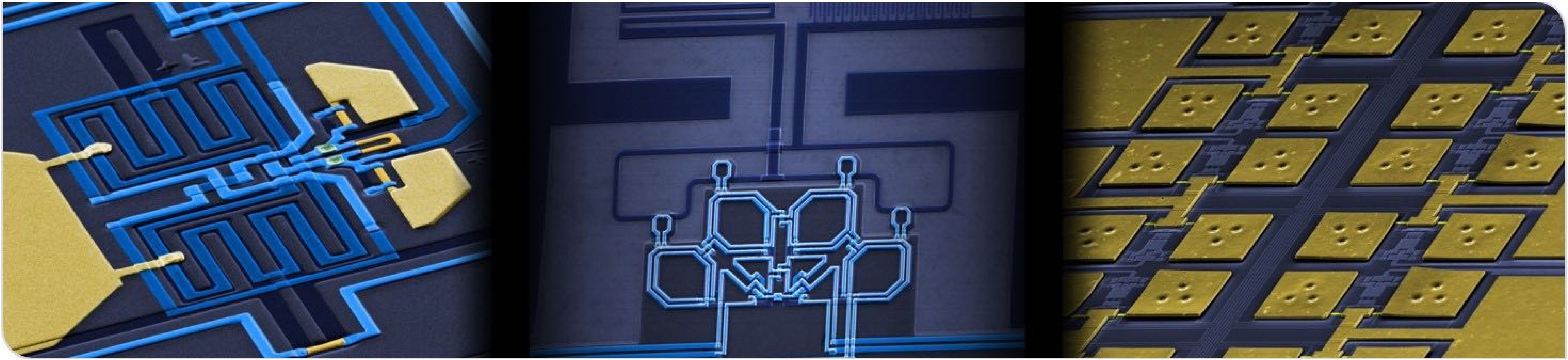
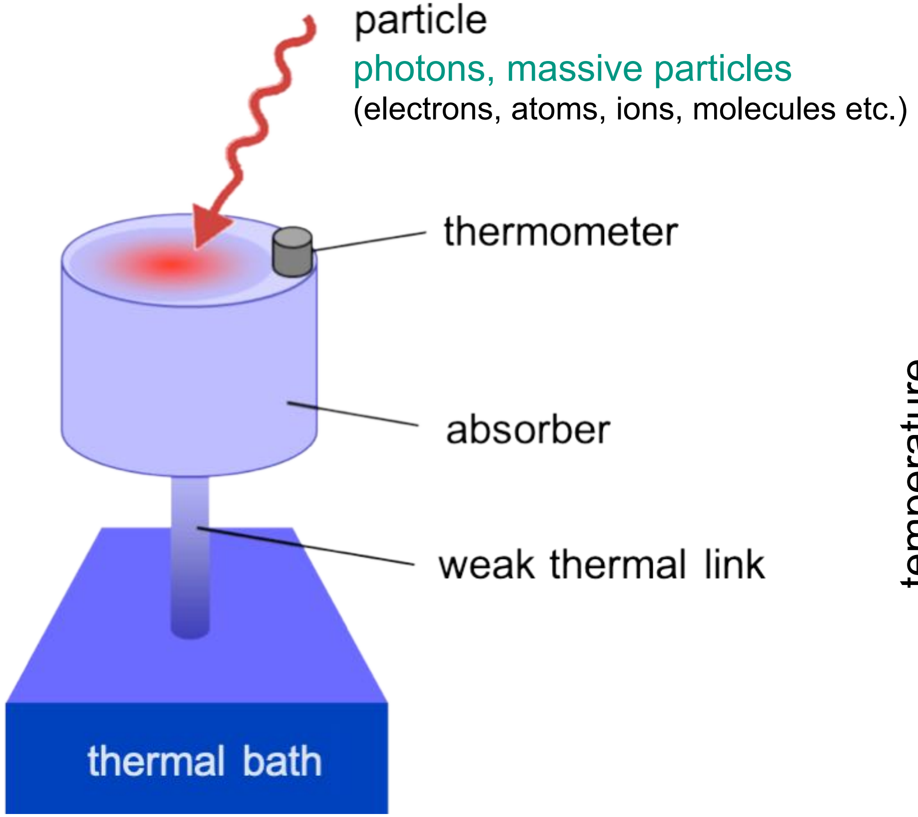
Magnetic microcalorimeters: Cryogenic quantum sensors for demanding applications

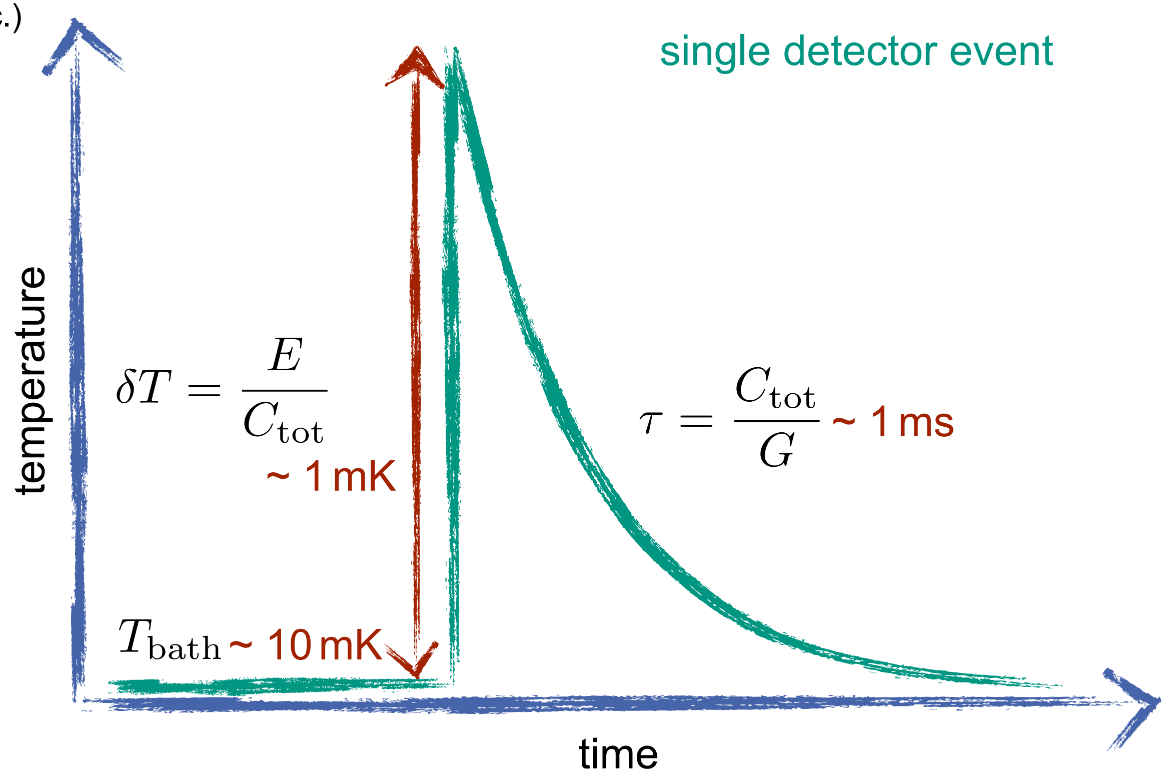
Sebastian Kempf

2nd Workshop on Silicon Sensors for Radiation Detection and Quantum Applications | Lake Starnberg | May 14, 2025



Cryogenic microcalorimeters

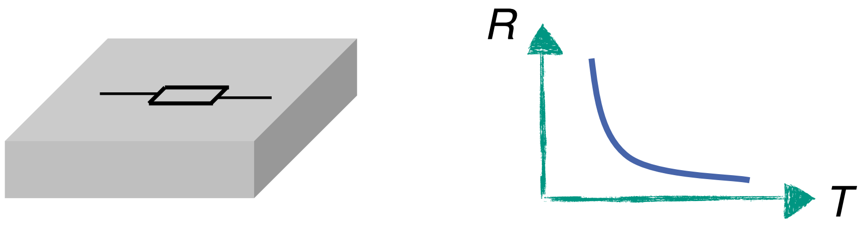




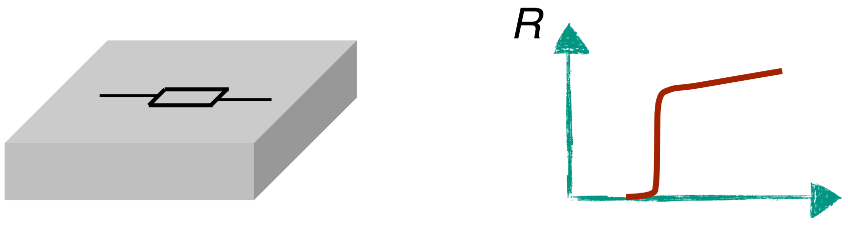
no surface dead layer,
thermal detector, i.e. not limited by (Fano) statistics or excitation energy

Temperature sensors

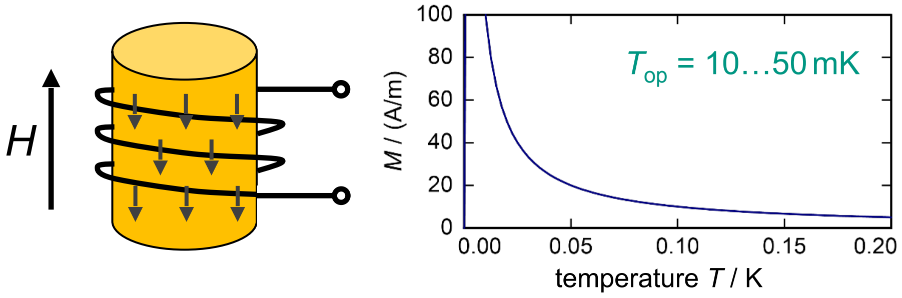
semiconductor thermistor



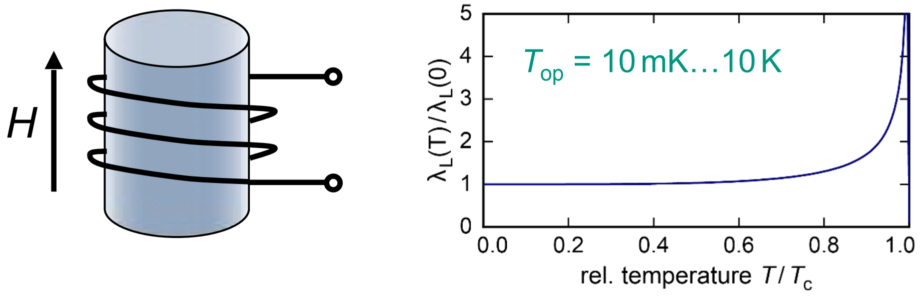
superconducting transition-edge sensor (TES)



metallic magnetic calorimeter (MMC)



magnetic penetration depth thermometer (MPT)
λ-SQUID (new)



Temperature sensors

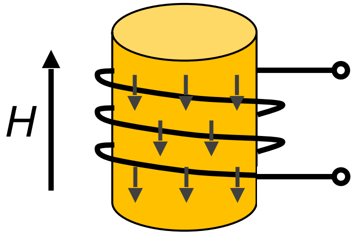
Karlsruhe Institute of Technology

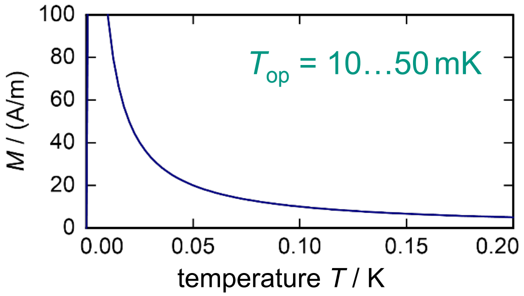
semiconductor thermistor

superconducting transition-edge sensor (TES)

magnetic microcalorimeters

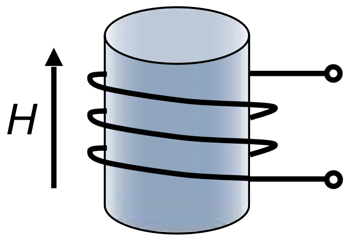
metallic magnetic calorimeter (MMC)

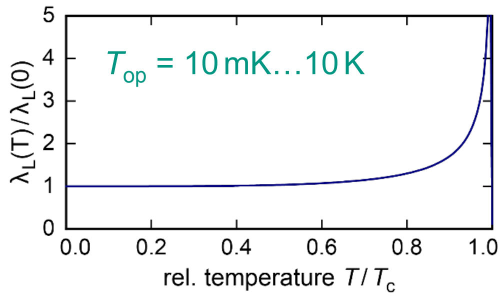




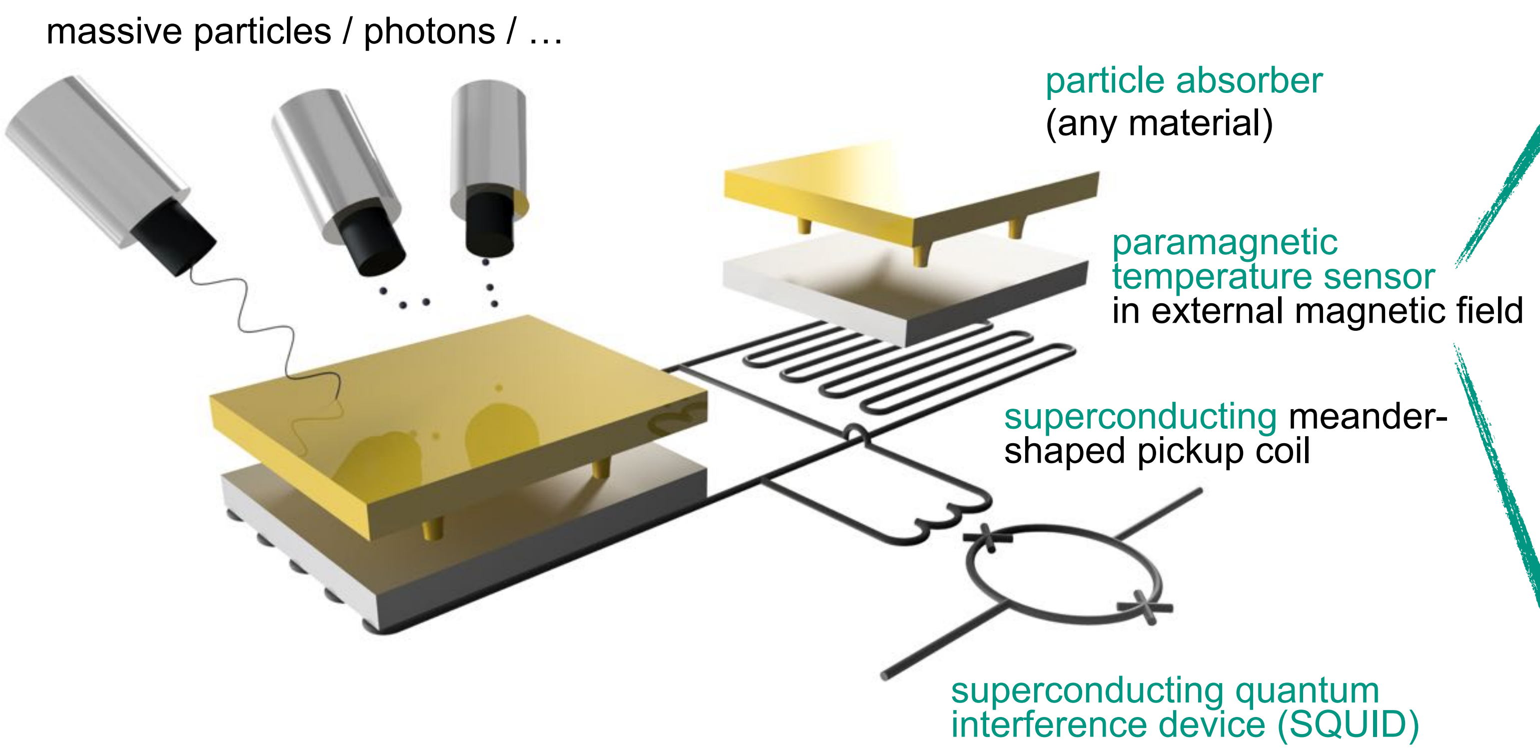
magnetic penetration depth thermometer (MPT)

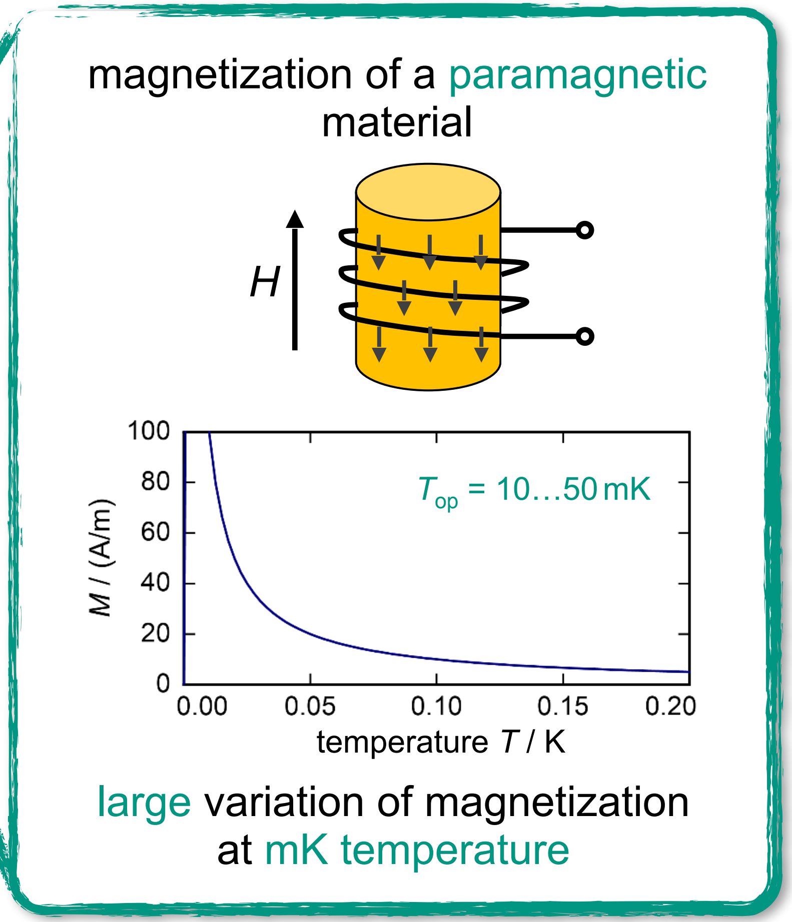
λ-SQUID (new)





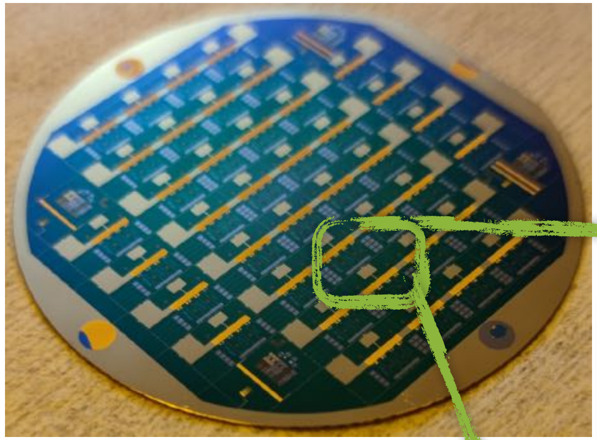
Metallic magnetic calorimeters (MMCs)





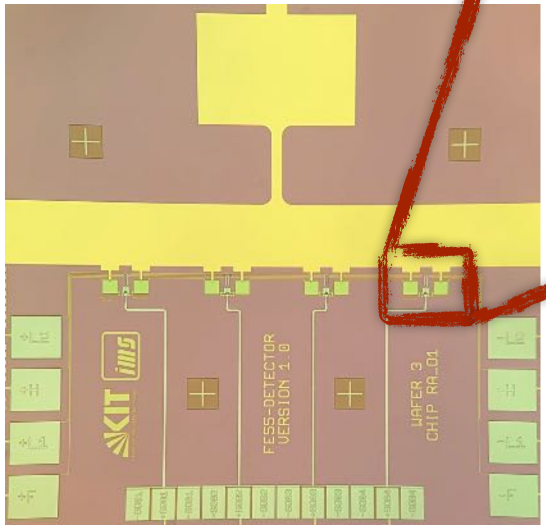
Example:
Metallic magnetic calorimeter for radionuclide metrology

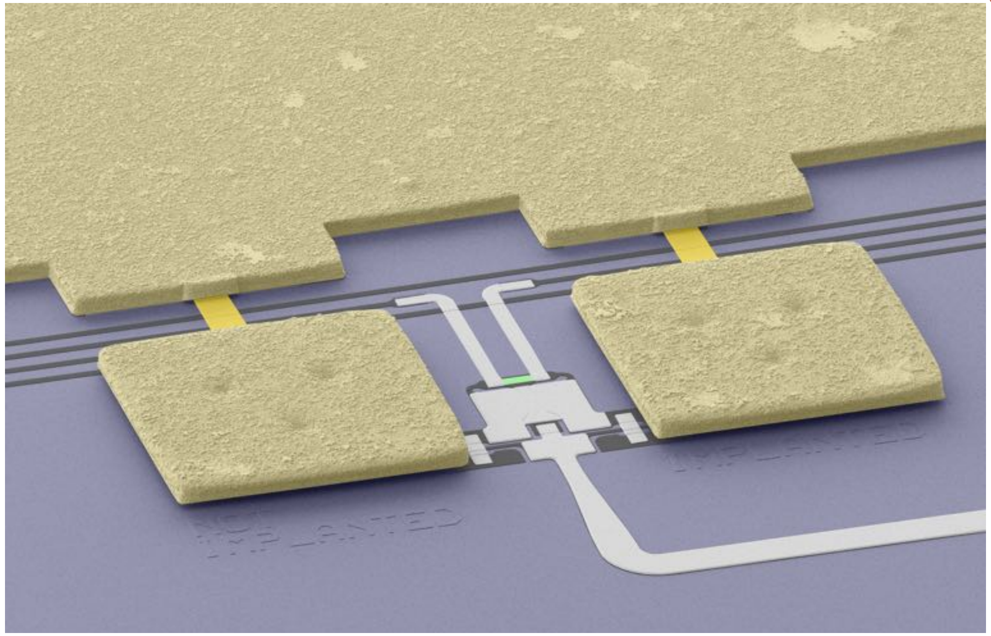
Magnetic microcalorimeter for measuring
EC spectrum of ion-implanted Fe-55 source



2 inch wafer

single detector chip



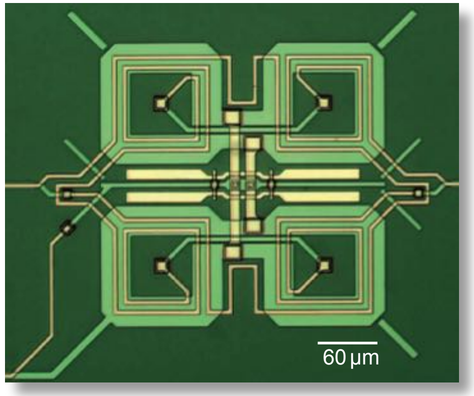


single detector
(before deposition of second absorber half)

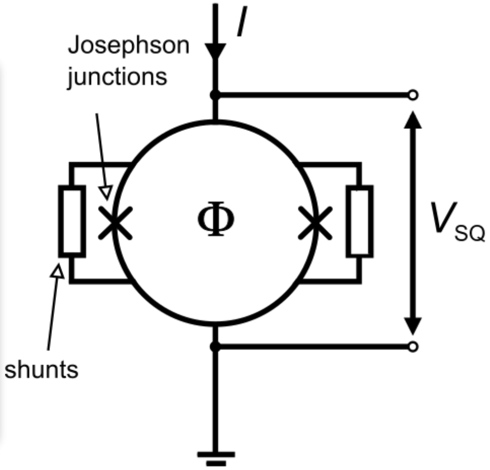
detectors are application-specific customized

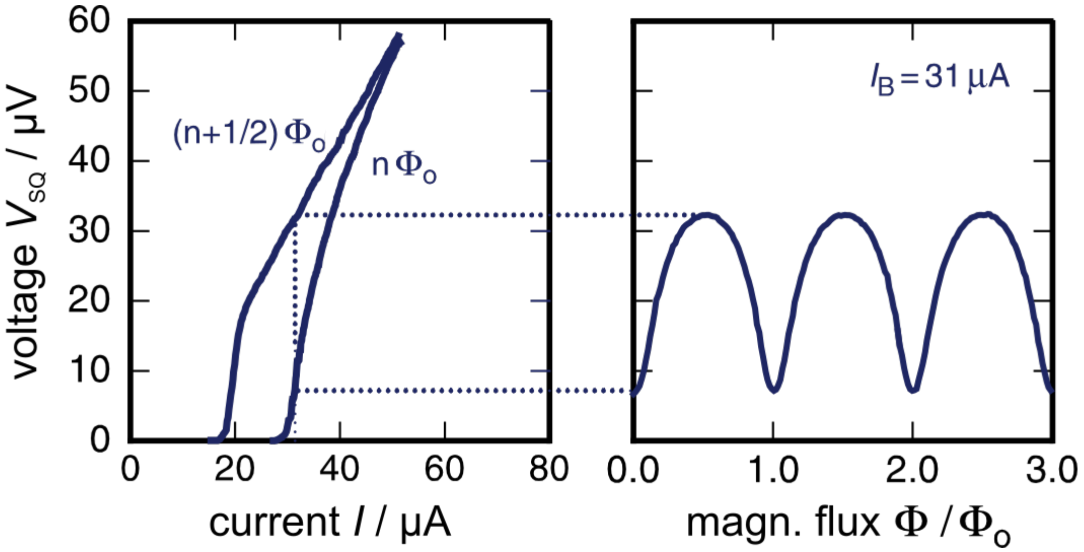
SQUID-based detector readout

dc-SQUIDs = magnetic flux to voltage / current converters



example:
current-sensor dc-SQUID (KIT)

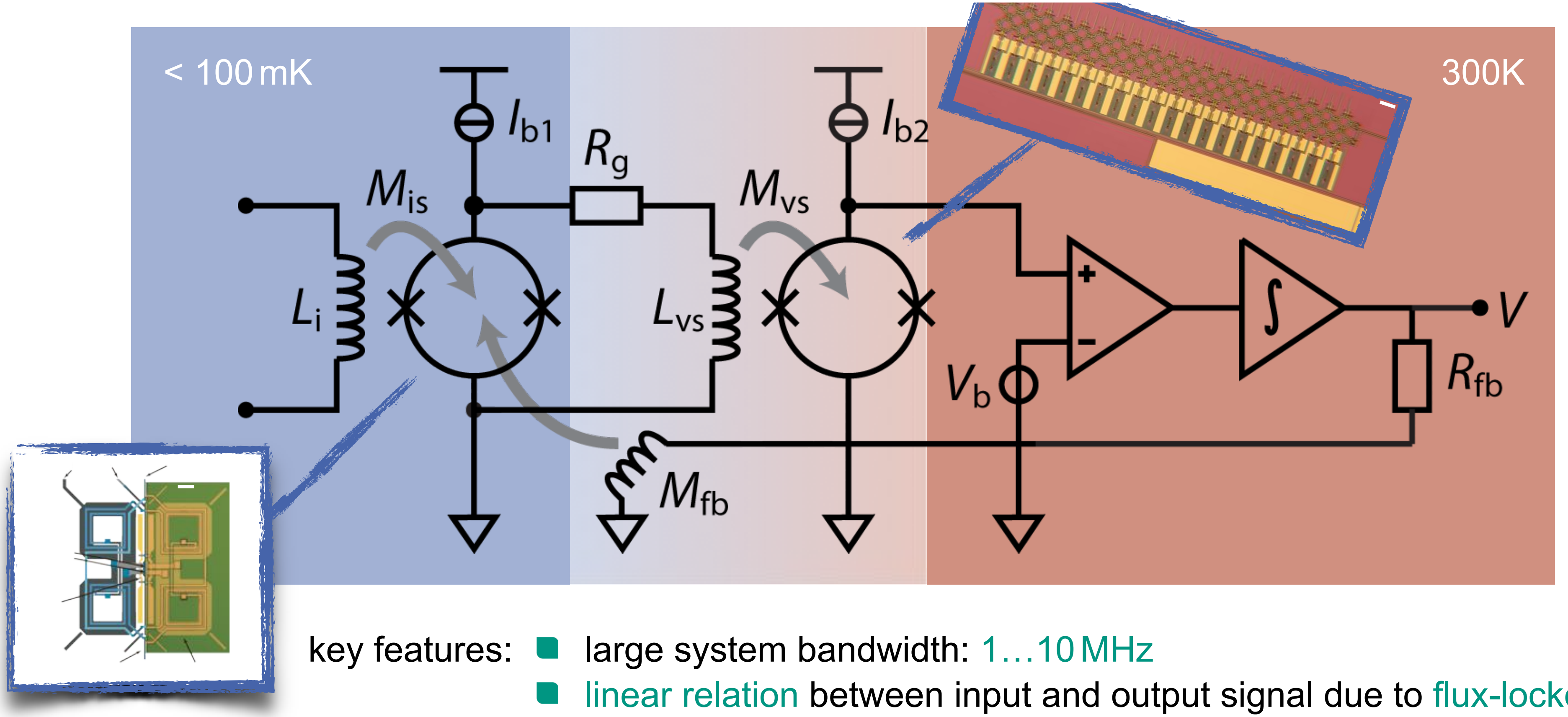




- compatibility with mK operation temperatures
- low power dissipation: P_{diss} ~10 pW…1 nW
- near quantum-limited noise performance: ε ~1 h possible

In-house development of multi-stage dc-SQUIDs

SQUID-based amplifier chain with ultrafast FLL feedback electronics



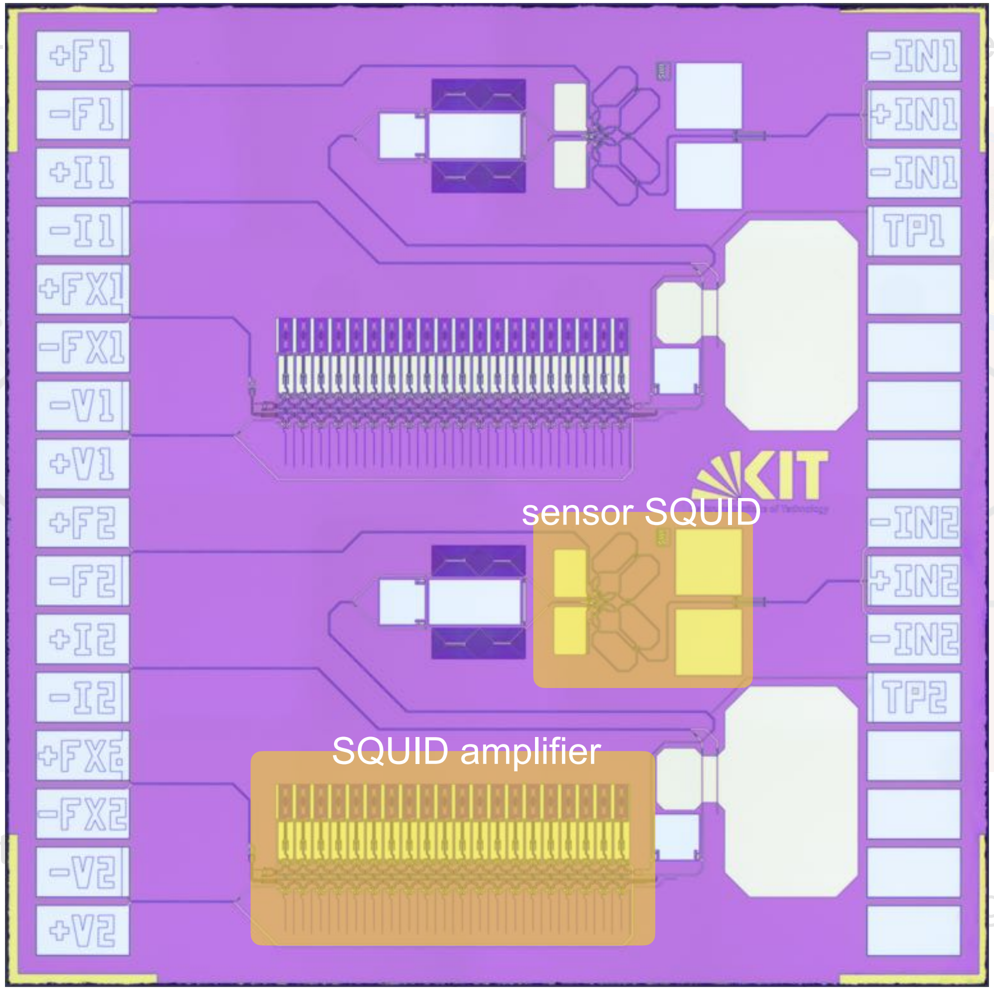
key features:
- large system bandwidth: 1…10 MHz
- linear relation between input and output signal due to flux-locked loop (FLL)
- impedance matched

In-house development of multi-stage dc-SQUIDs

example:
2 channel, two-stage dc-SQUID

SQUID bias / readout ch #1

SQUID bias / readout ch #2



input ch #1

input ch #2

In-house development of multi-stage dc-SQUIDs

example:
2 channel, two-stage dc-SQUID

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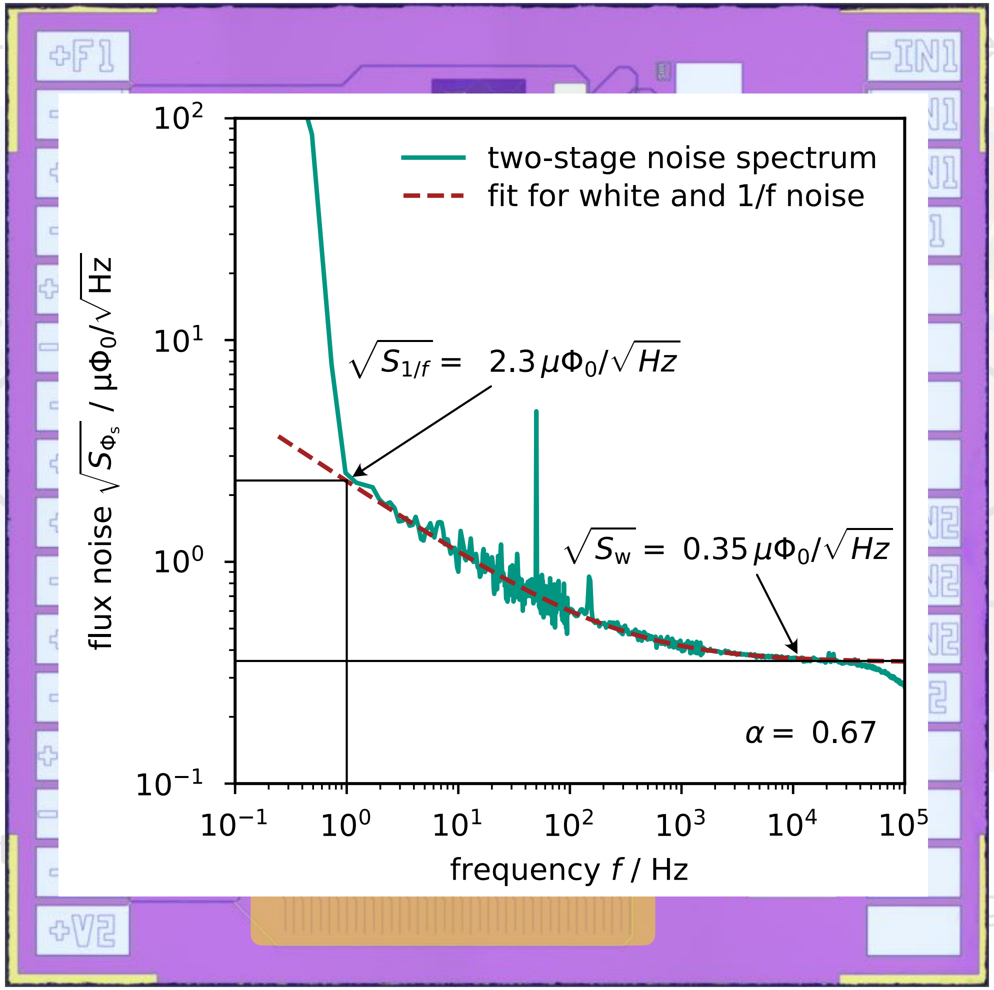
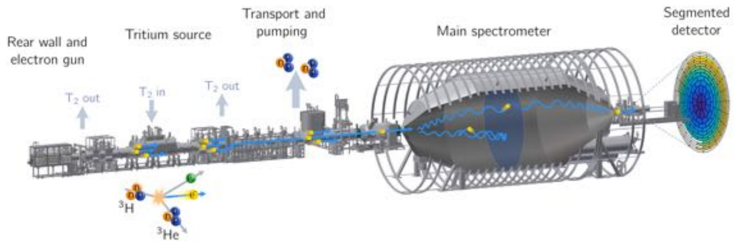


input ch #1

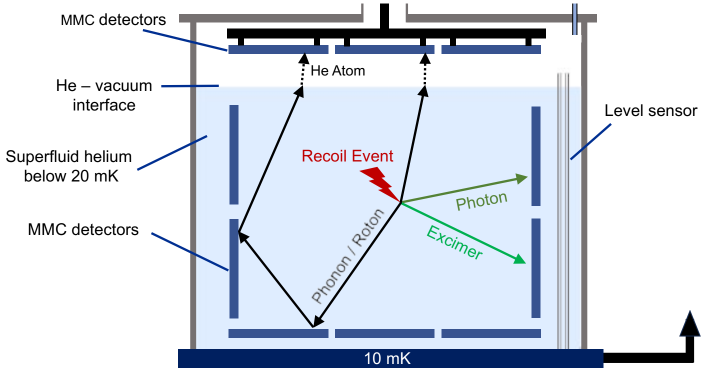
input ch #2

Applications we are working on…

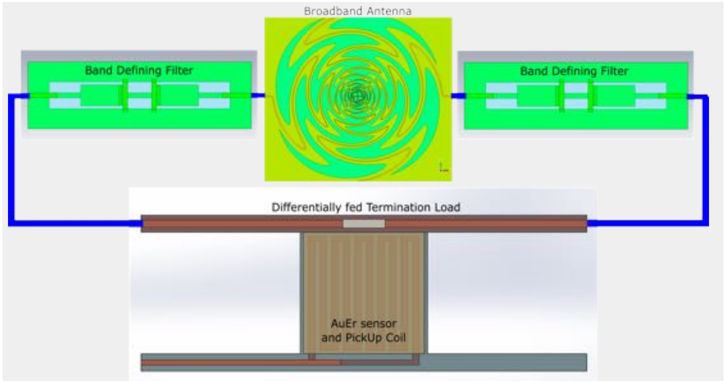
neutrino mass measurements



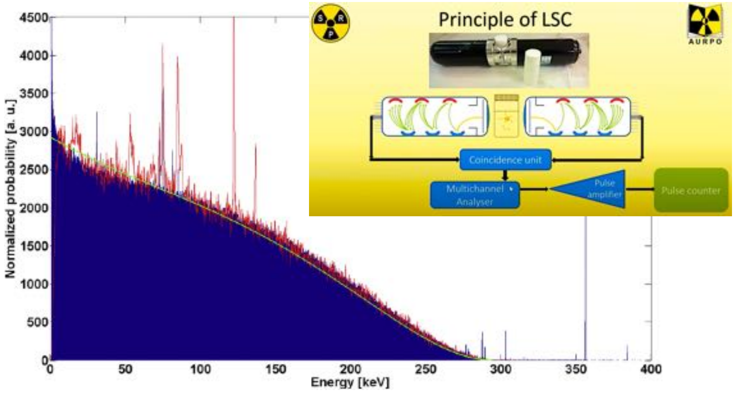
dark matter searches



cosmic microwave background



radionuclide metrology

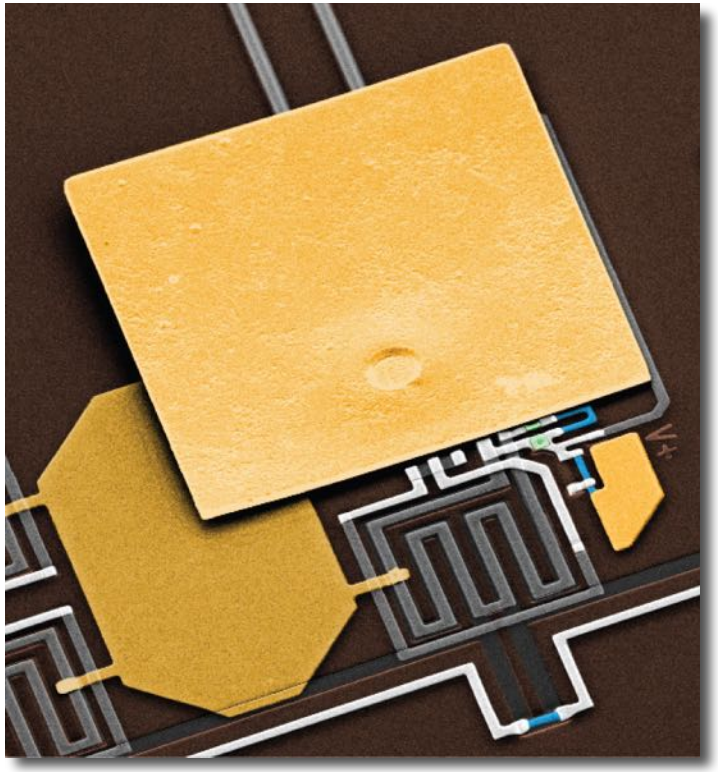


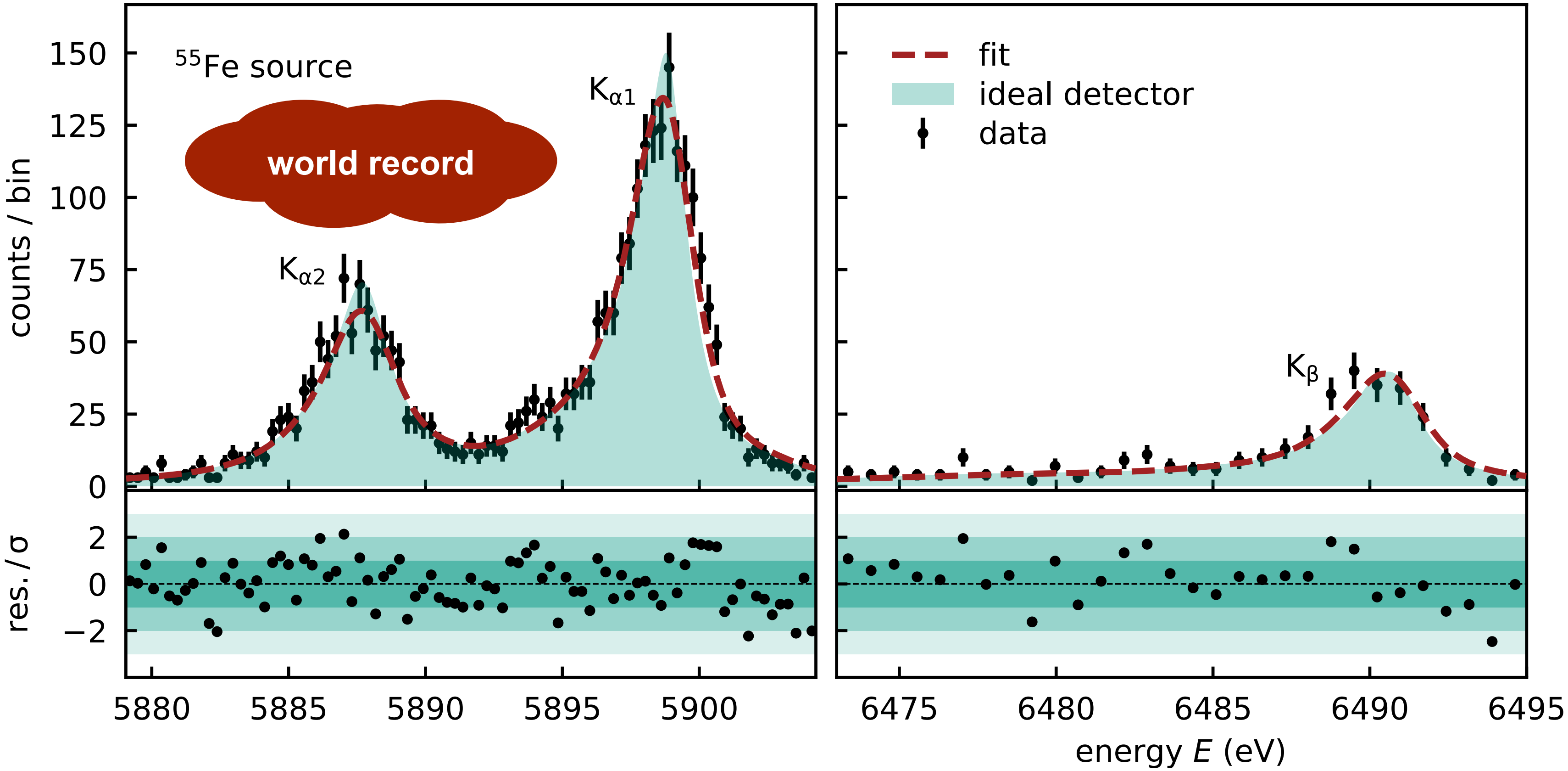
XES at brilliant light sources

and many, many more…

MMC with integrated SQUID readout for soft and tender X-ray spectroscopy

$\Delta E_{\mathrm{FWHM}} = 1.25(18)\,\mathrm{eV}$



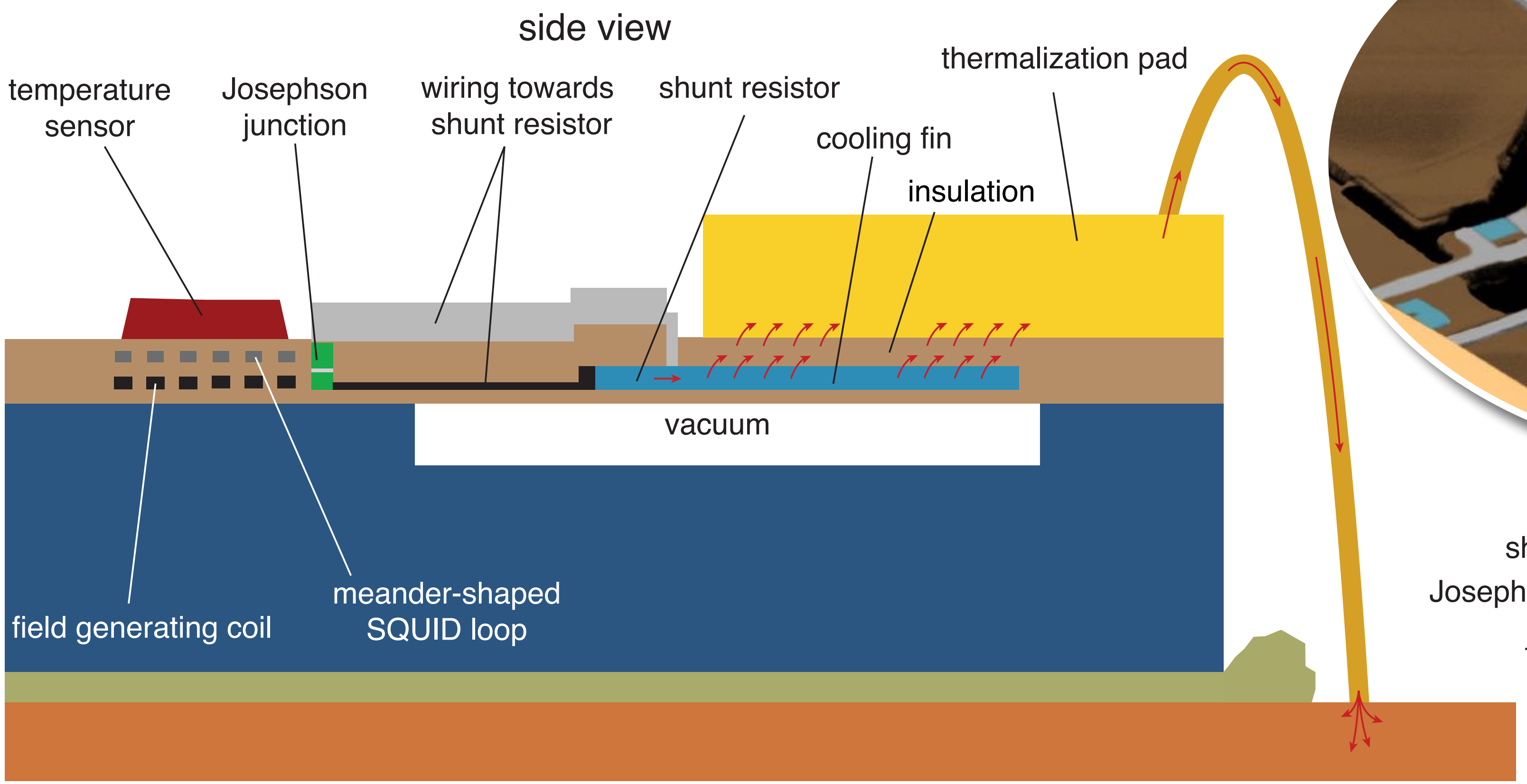


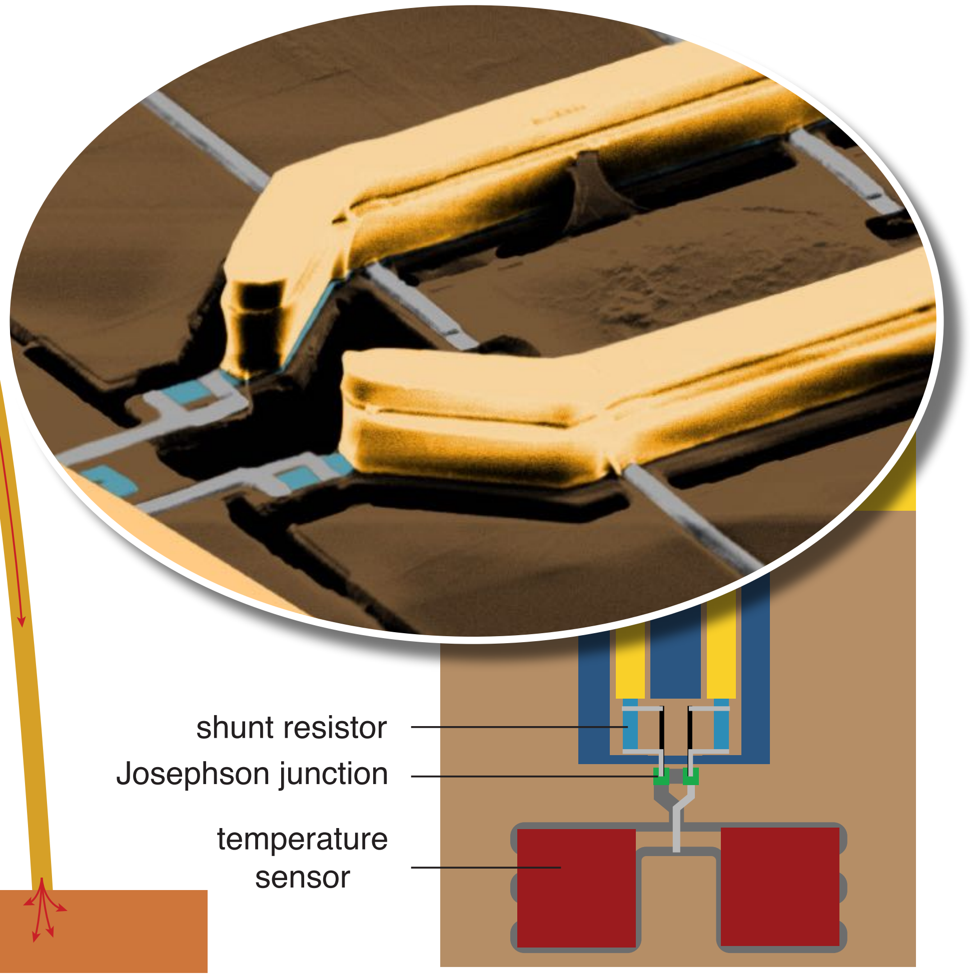
M. Krantz, …., S. Kempf, Appl. Phys. Lett. **124** (2024) 032601
F. Toschi, …., S. Kempf *et al.*, Phys. Rev. D **109** (2024) 043035

Challenging detector fabrication

Karlsruhe Institute of Technology

thermal isolation of shunt resistors required membrane fabrication



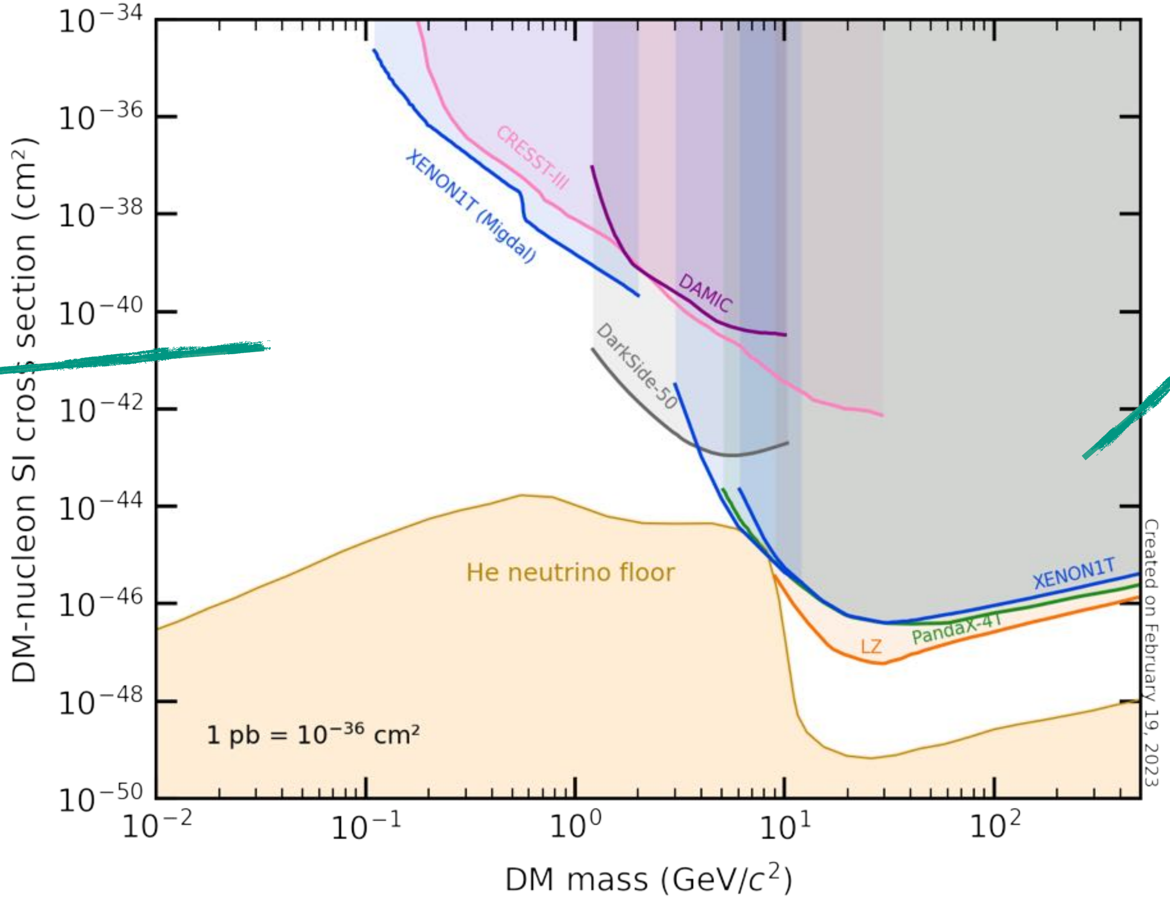


works fine, but technologically very demanding!

M. Krantz, …., S. Kempf, Appl. Phys. Lett. **124** (2024) 032601

Current dark matter landscape

Phase space for Light Dark Matter (LDM) mostly unexplored



Noble liquid dual-phase TPC constrain phase space for large WIMP

arxiv:2207.03764

arXiv:2207.11966

Phys. Rev. Lett. **121**, 111302 (2018)

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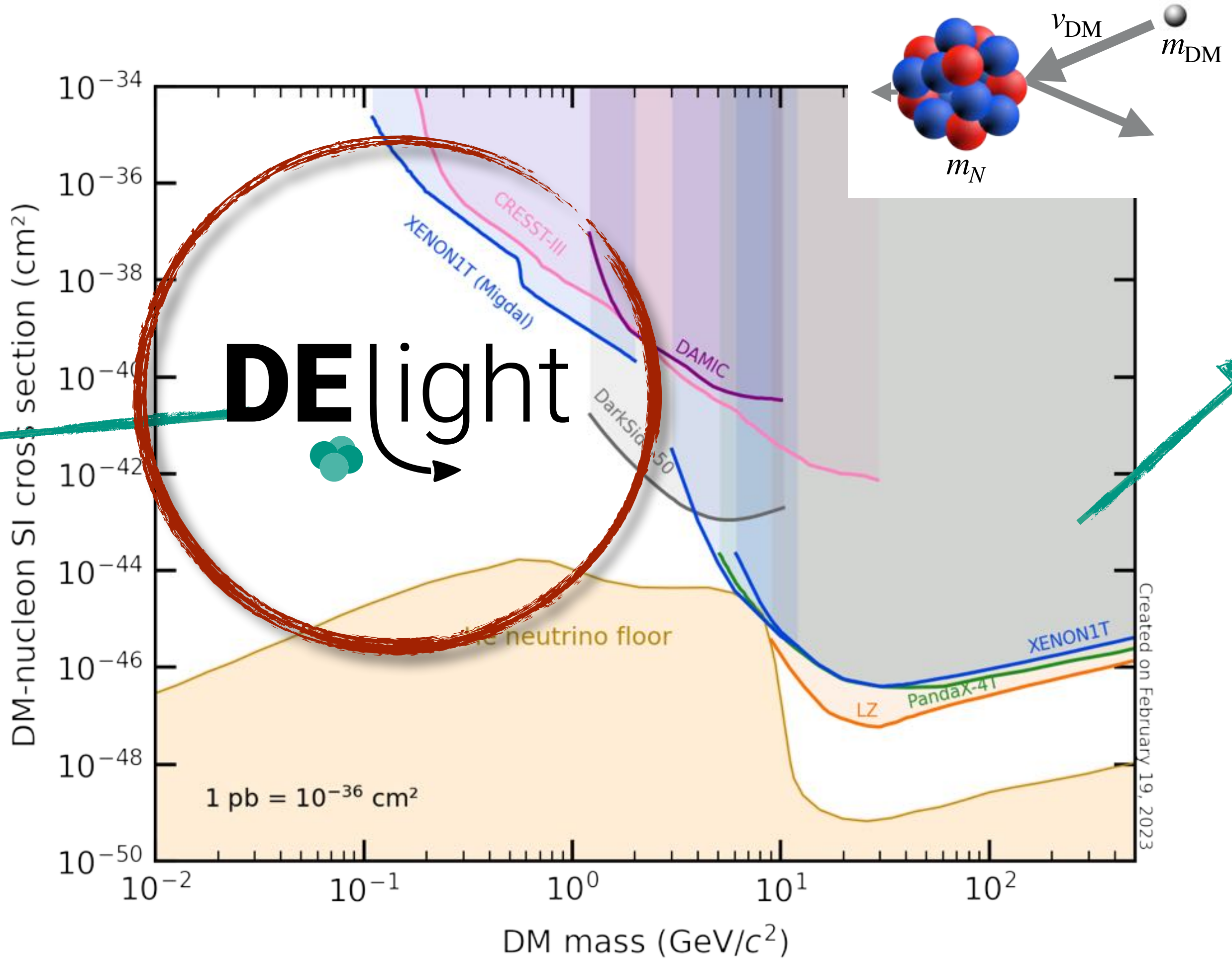

$$\Delta E = \frac{1}{2}\frac{\Delta p^2}{m_N} \lesssim \frac{2\, m_{DM}^2 v_{DM}^2}{m_N}$$

Noble liquid dual-phase TPC constrain phase space for large WIMP

arxiv:2207.03764

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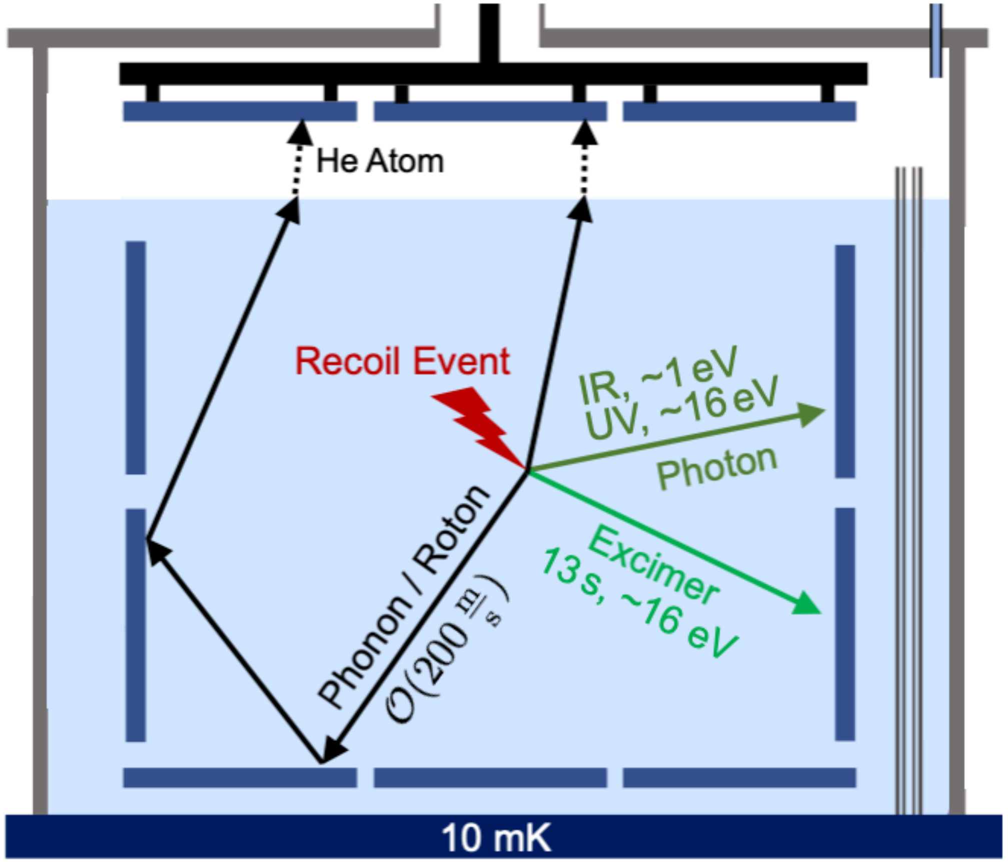
Phys. Rev. Lett. **121**, 111302 (2018)

DELight - Direct Search Experiment for Light Dark Matter with superfluid Helium

→ joint initiative by KIT, Heidelberg University, and University of Freiburg



DELight - Direct Search Experiment for Light Dark Matter with superfluid Helium

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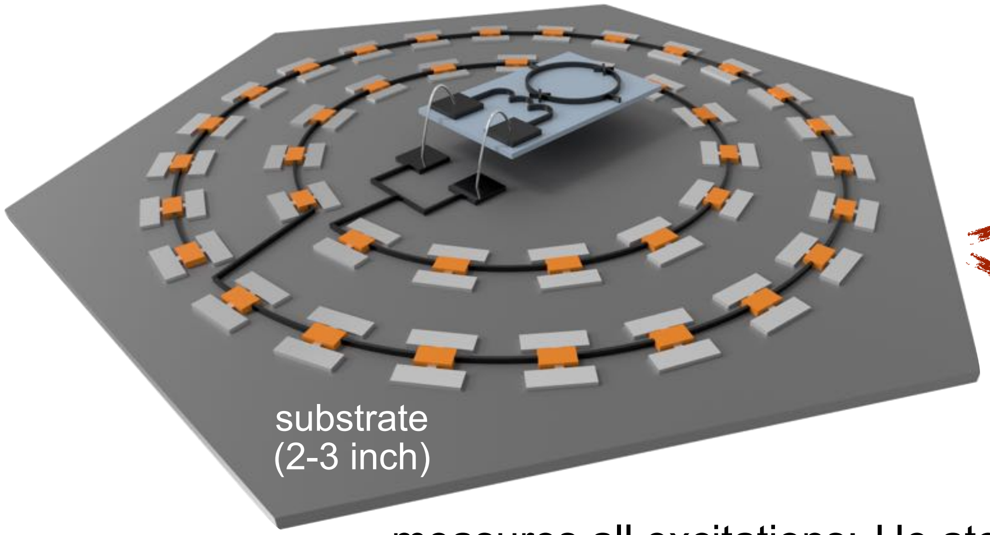
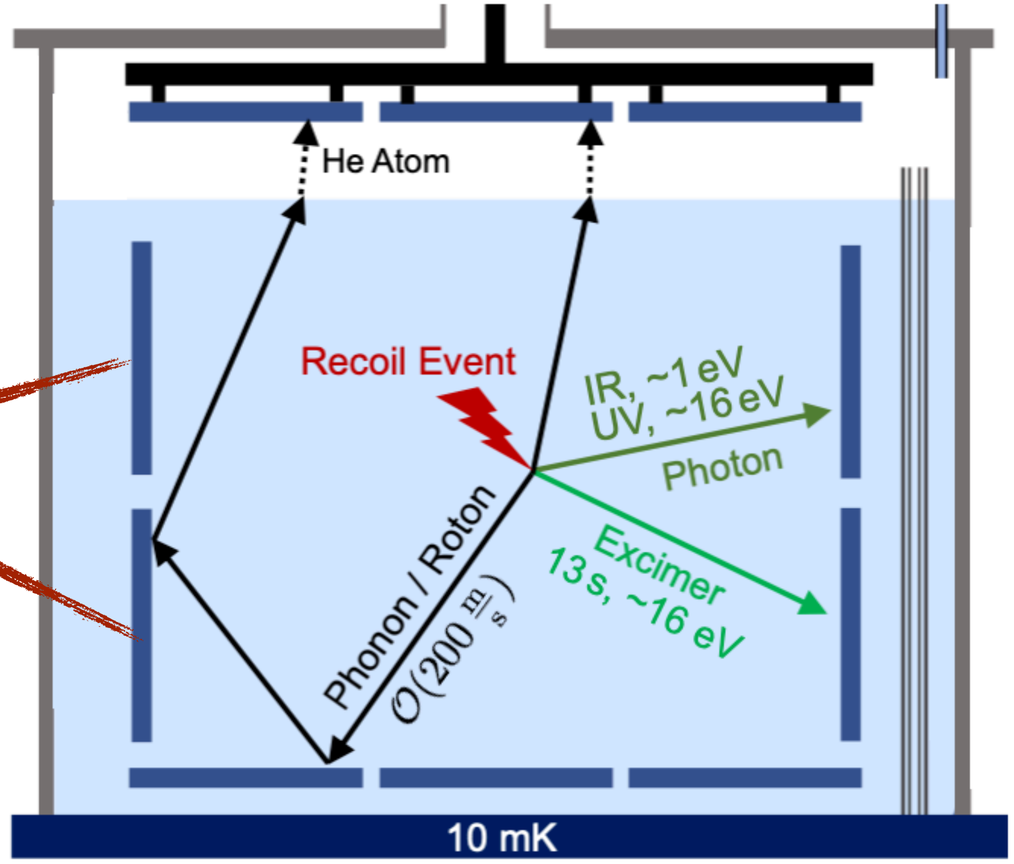
Large-area cryogenic microcalorimeter (LAMCALs)
(MMCs based on athermal phonon detection)

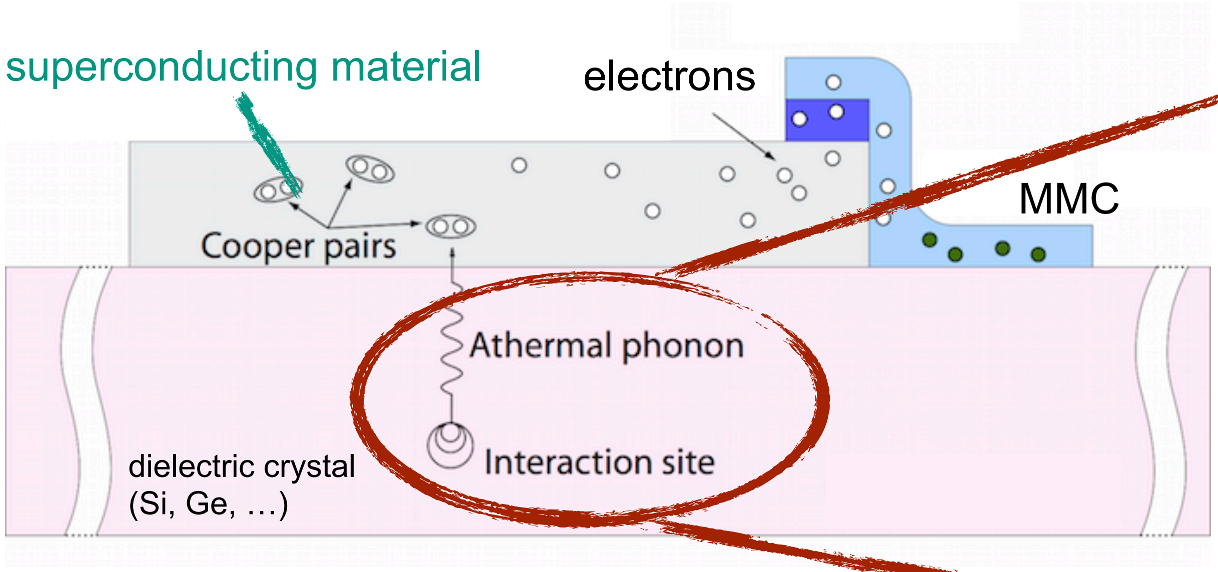


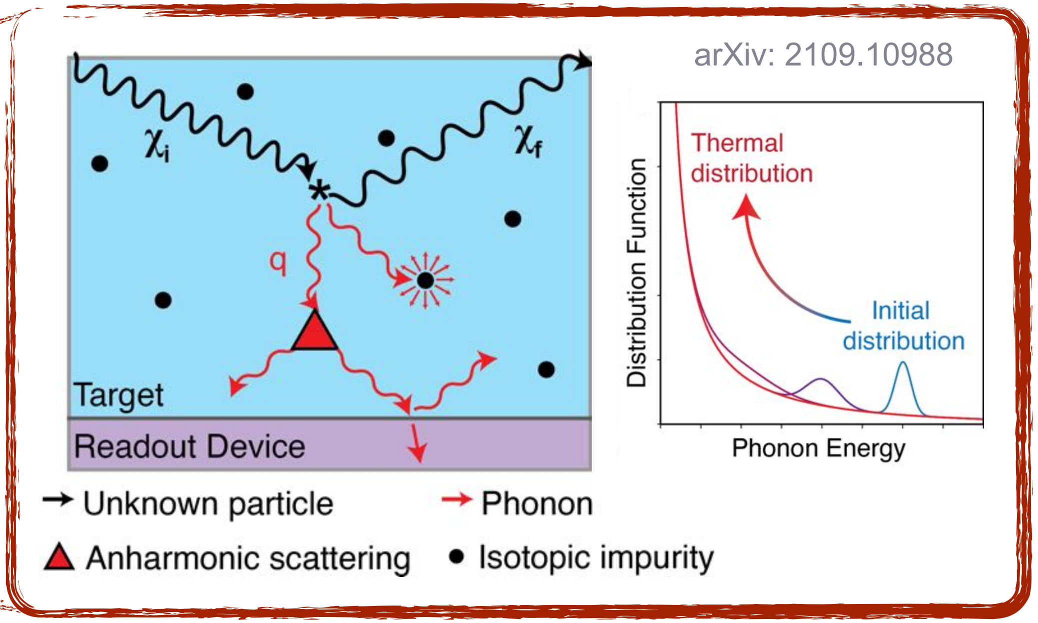
measures all excitations: He atoms
phonons
excimers



MMC-based athermal phonon detectors

idea: measure athermal phonon population created by interacting particle





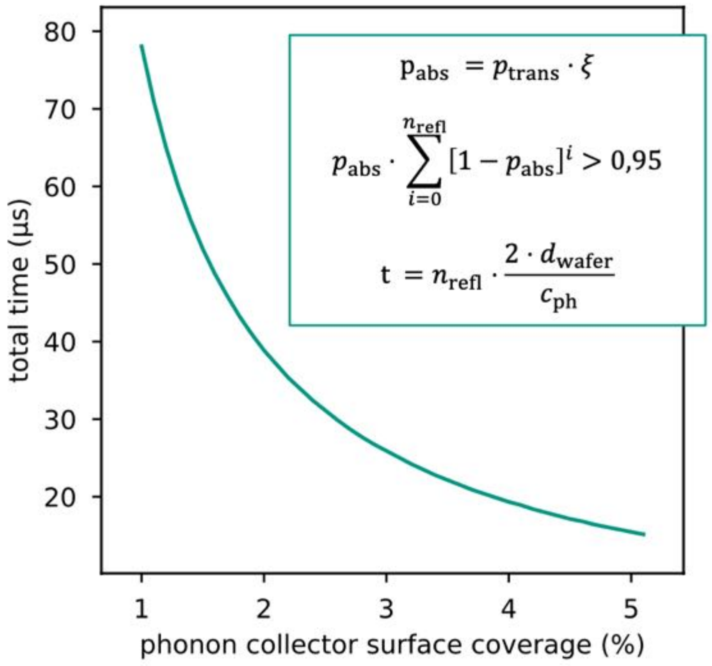
advantages:
- absorber heat capacity (to first order) irrelevant
- possibility for large absorber volumes / areas

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

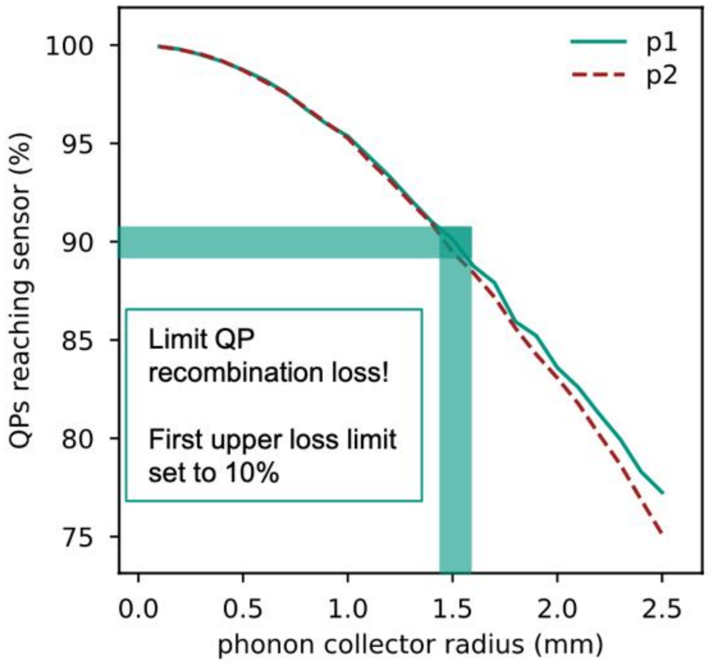
Ongoing R&D: LAMCAL optimization

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

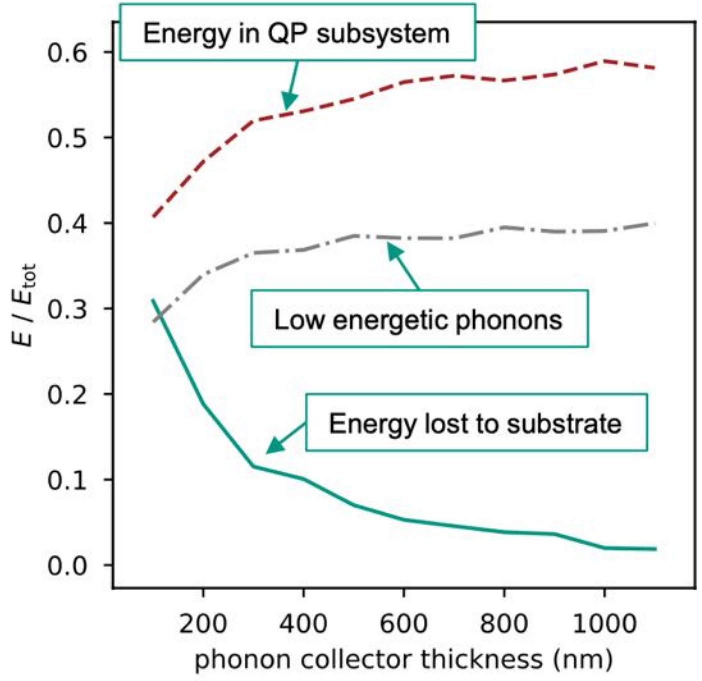
Coverage



Radius



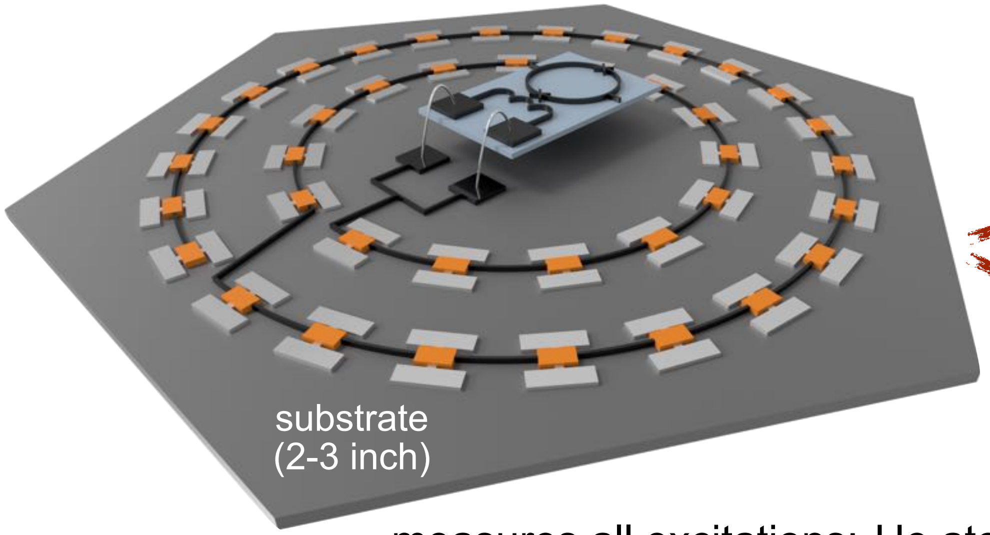
Thickness



phonon collector distribution will set requirements for LAMCAL geometry

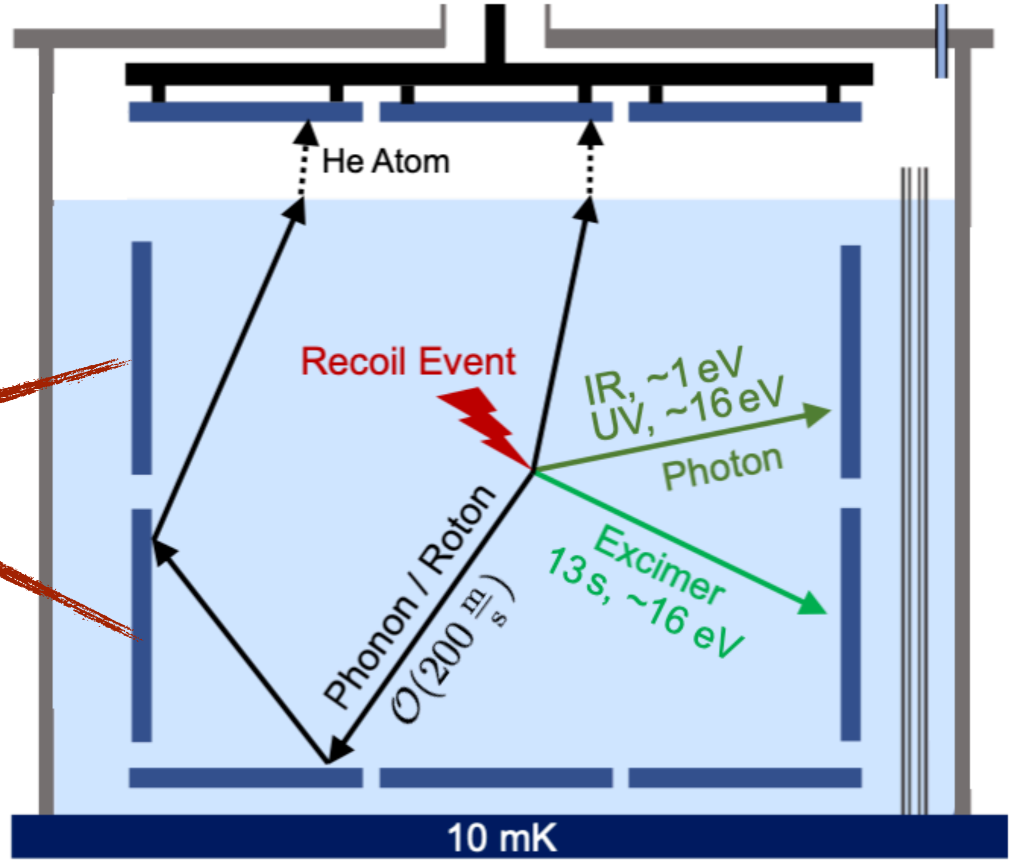
Expected LAMCAL performance

Large-area cryogenic microcalorimeter (LAMCALs)
(MMCs based on athermal phonon detection)

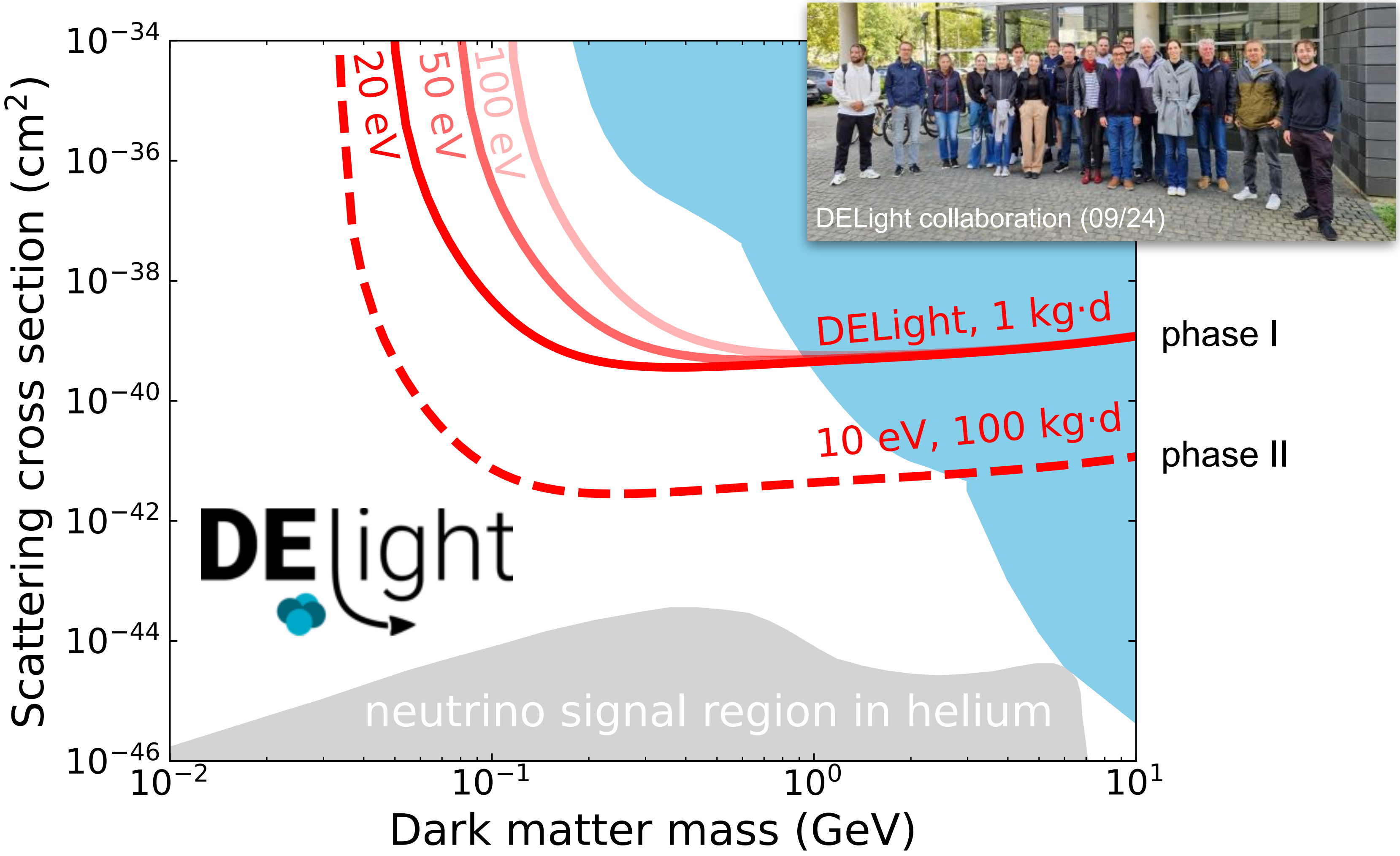


measures all excitations: He atoms
phonons
excimers

$\Delta E_{\mathrm{FWHM}} \sim 1\,\mathrm{eV}$



Sensitivity projection of DELight



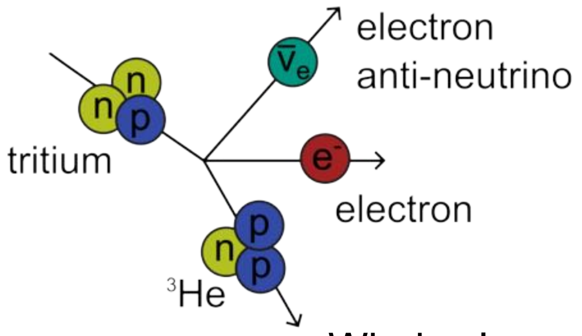
DELight collaboration (09/24)

phase I

phase II

A next-generation neutrino mass measurements

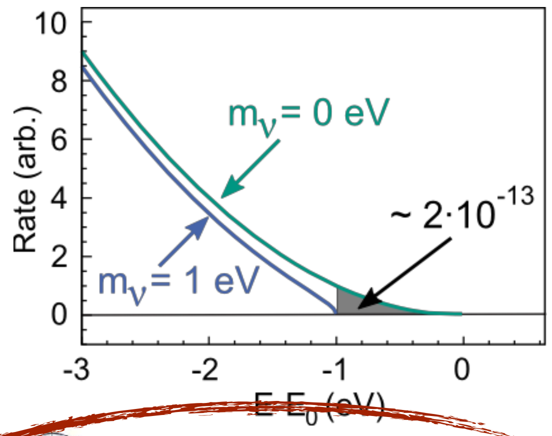
Measurement of tritium β^- decay to determine the electron anti-neutrino mass

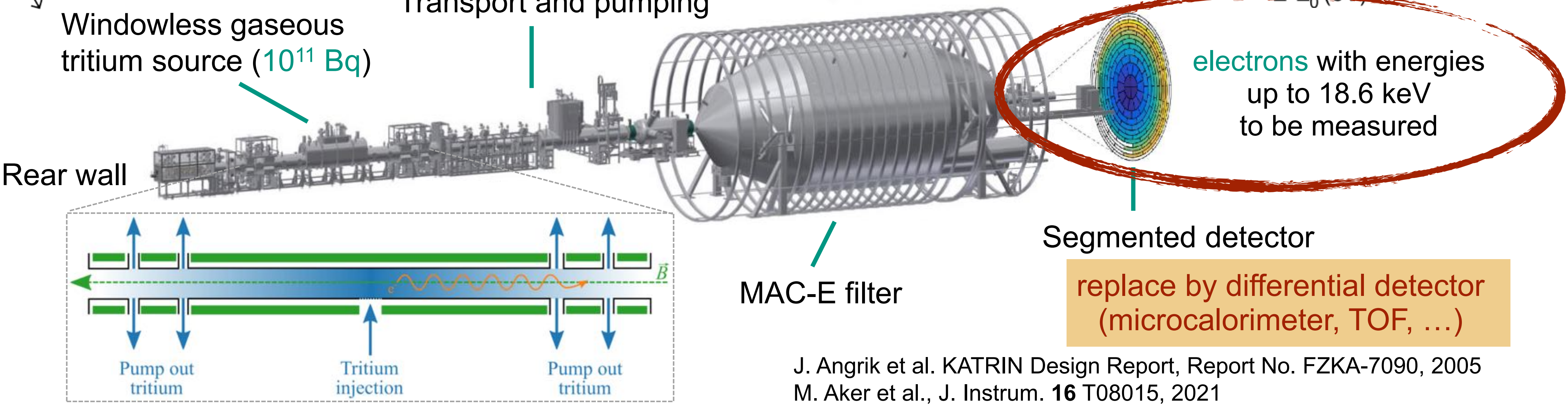


Only the endpoint region of the spectrum is measured

→ High statistics and high resolution required

replace by atomic tritium source (ATS)



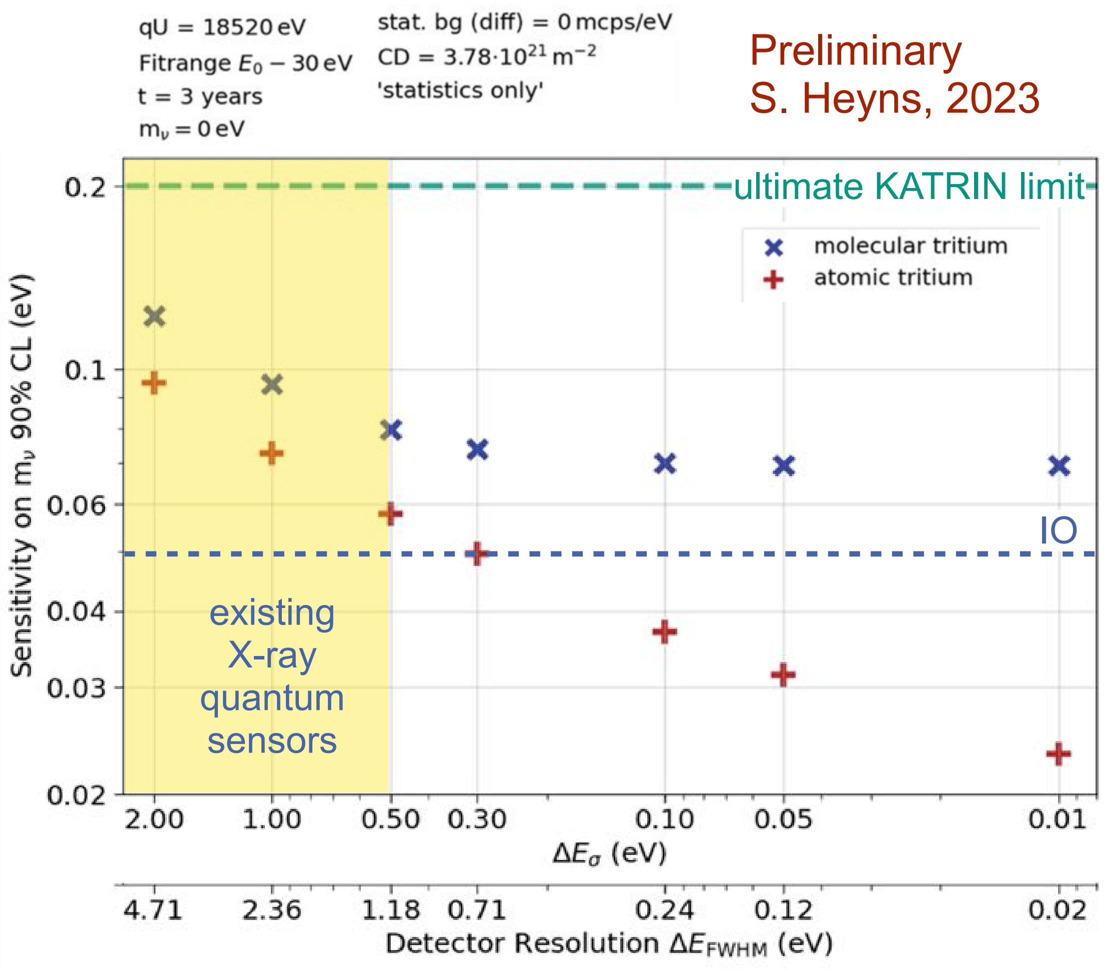


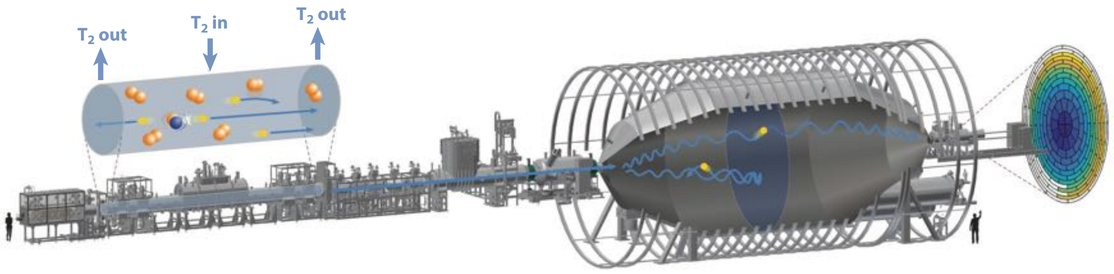
replace by differential detector (microcalorimeter, TOF, …)

J. Angrik et al. KATRIN Design Report, Report No. FZKA-7090, 2005
M. Aker et al., J. Instrum. **16** T08015, 2021

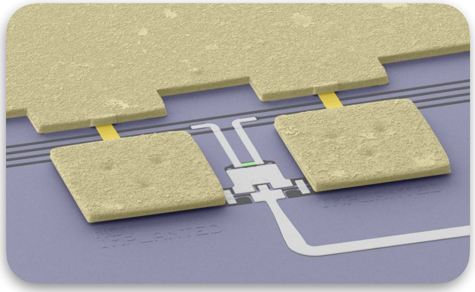
Sensitivity studies

Karlsruhe Institute of Technology





+

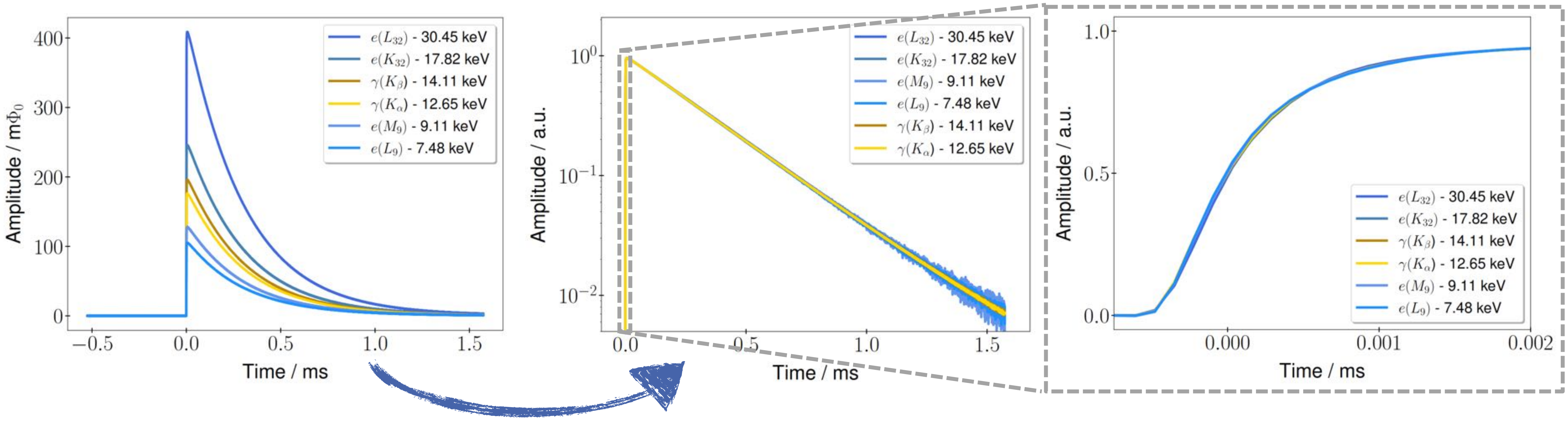


challenges:

- sub-eV energy resolution
- interaction of electrons with particle absorbers
- cryogenic microcalorimeters are not ‚made‘ to work in magnetic background fields
- the smaller the magnetic background field, the larger the sensitive area of the detector
- cryogenic detector (mK) coupled to a warm (RT) spectrometer
- …

Detector response for electrons and photons

spectroscopy of ^{83}Rb/^{83m}Kr source emissions



amplitude normalization

→ MMCs show same response for electrons and photons

N. Kovac, F. Adam *et al.*, arXiv: 2502.05975

Detector response for electrons and photons

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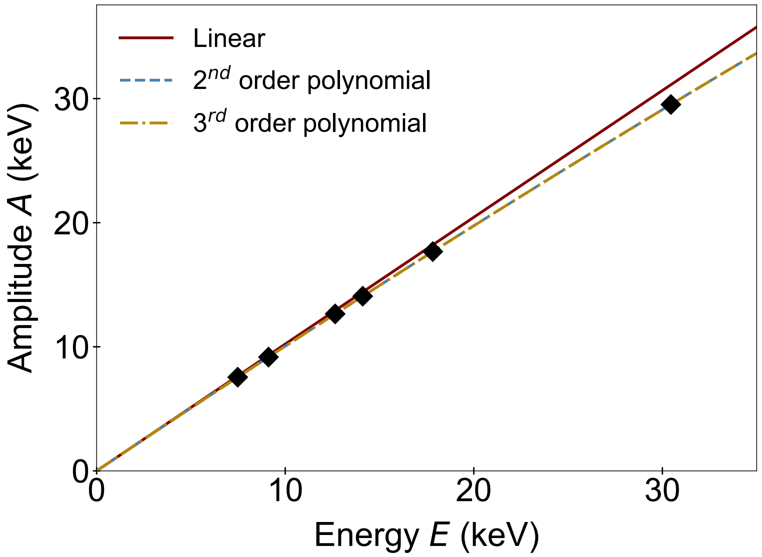
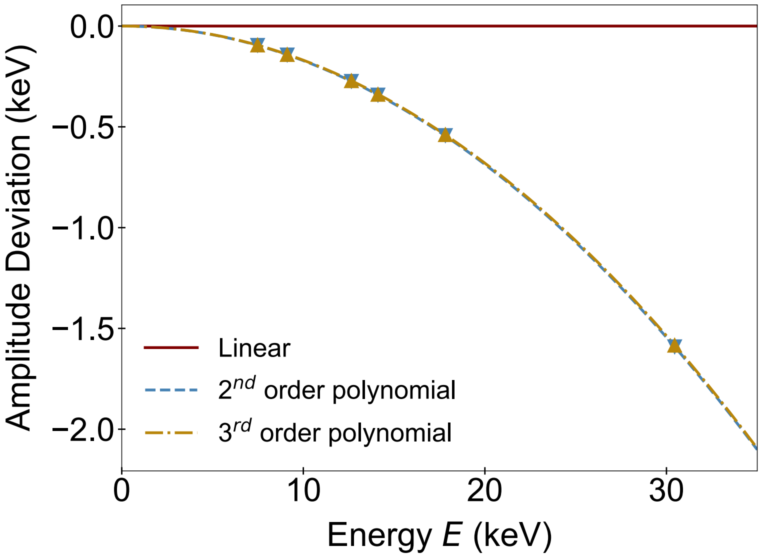
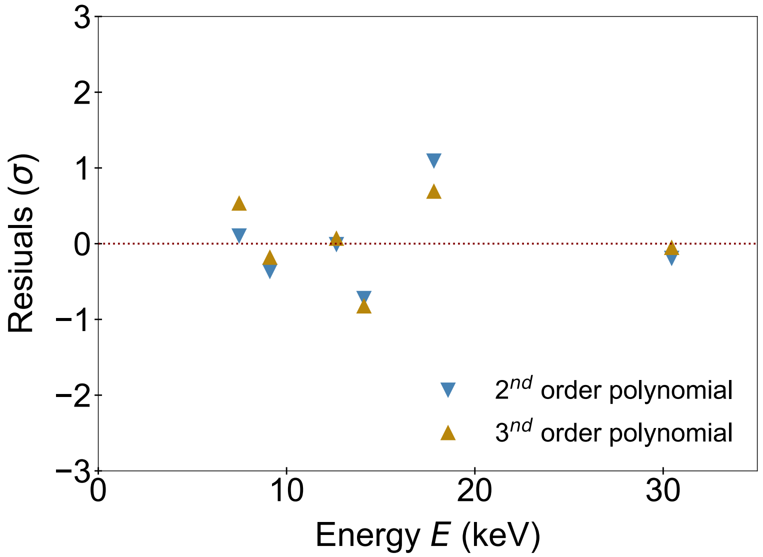




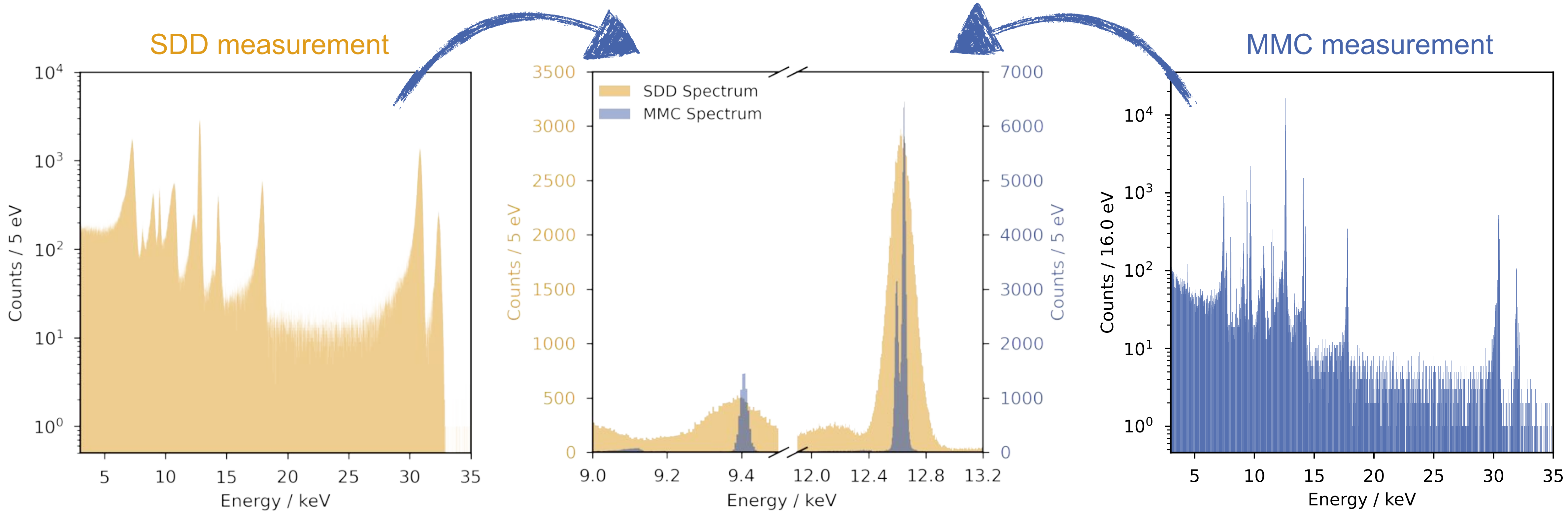


No significant energy losses due to backscattering, dead layer etc.

N. Kovac, F. Adam *et al.*, arXiv: 2502.05975

Silicon drift detectors vs. MMCs

spectroscopy of $^{83}Rb/^{83m}Kr$ source emissions



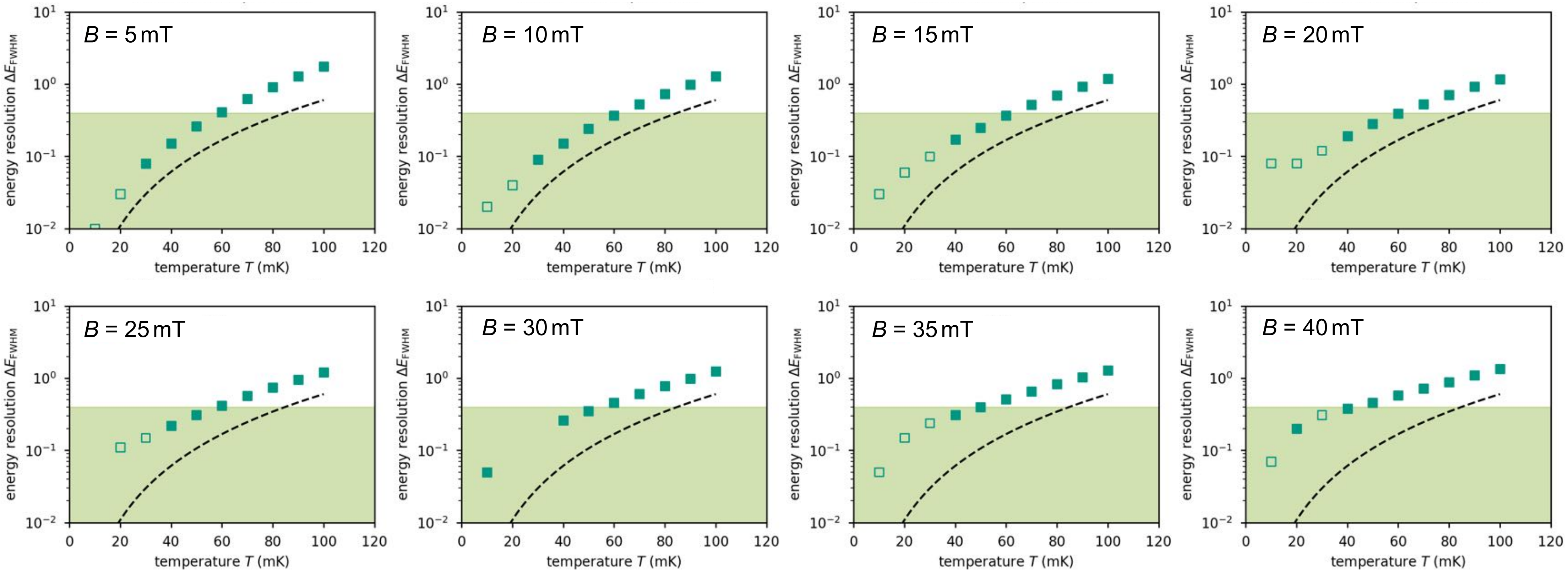
MMCs outperform conventional semiconductor detectors

N. Kovac, F. Adam *et al.*, in preparation

What about the magnetic background field?

example: silicon absorber with $V_{\mathrm{abs}} = 2\,\mathrm{mm} \times 2\,\mathrm{mm} \times 20\,\mu\mathrm{m}$

very preliminary results



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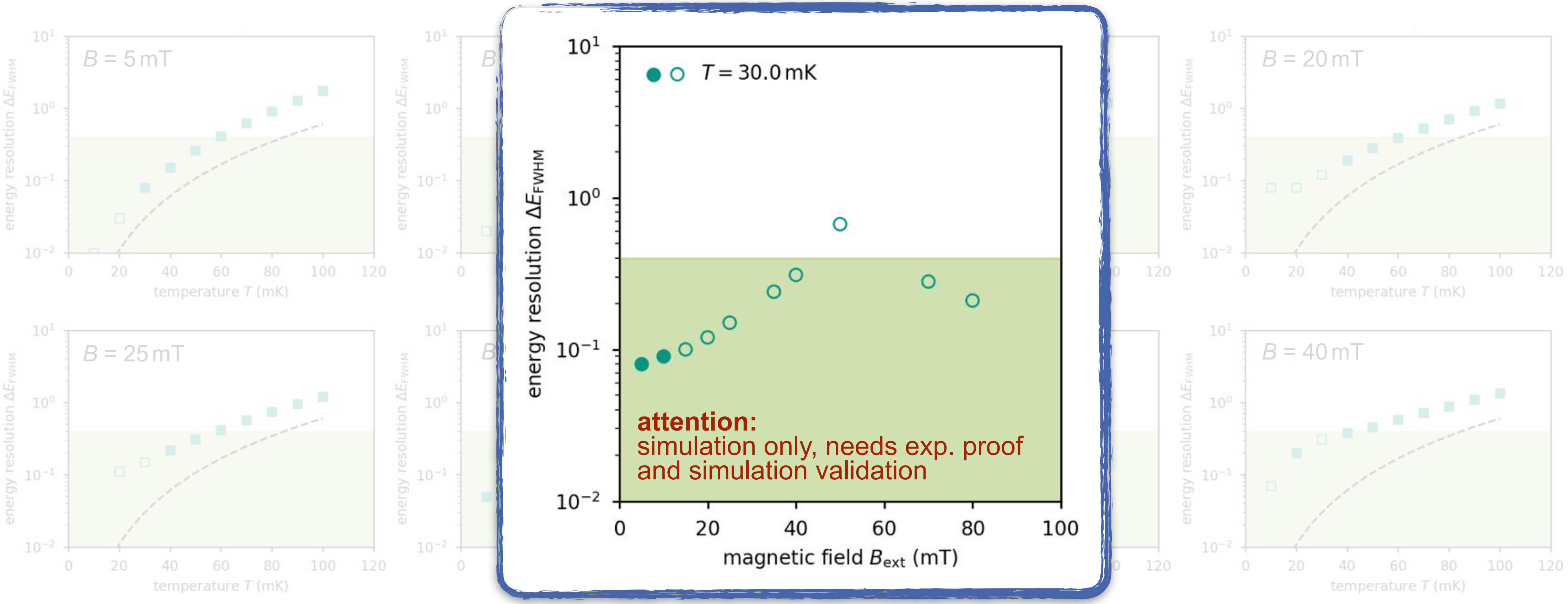
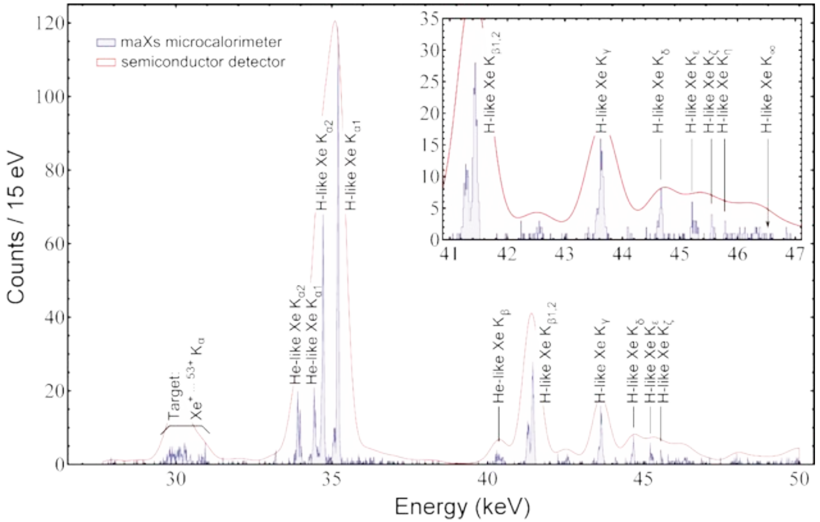


Research directions besides applications…

increasing pixel count

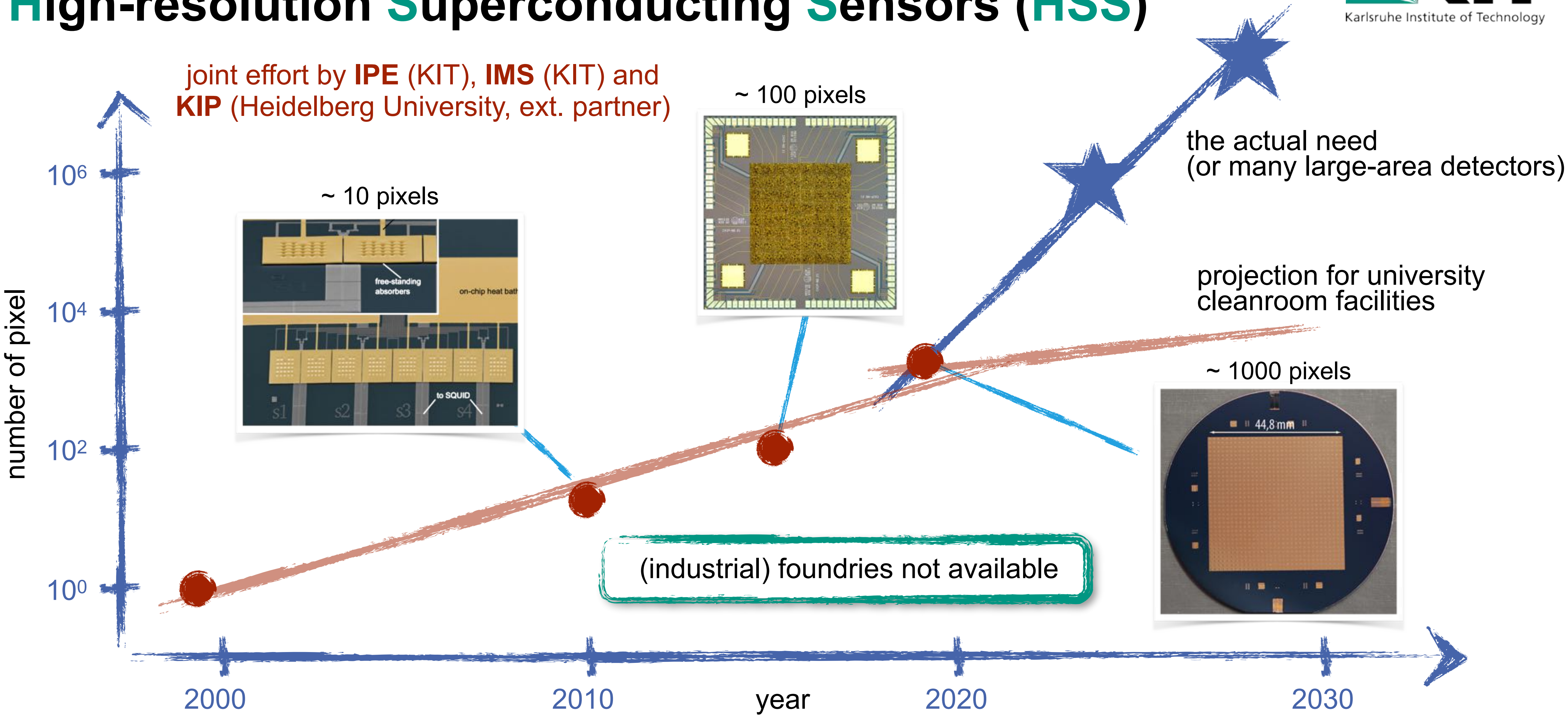
- SQUID multiplexing
- readout electronics
- large-volume batch fabrication

improving energy resolution



- novel sensor concepts („going beyond MMCs + TES“)
- improving gain and stability of existing detectors
- fighting against parasitic noise sources

Competence Center for
High-resolution Superconducting Sensors (HSS)



Competence Center for High-resolution Superconducting Sensors (HSS)

Karlsruhe Institute of Technology

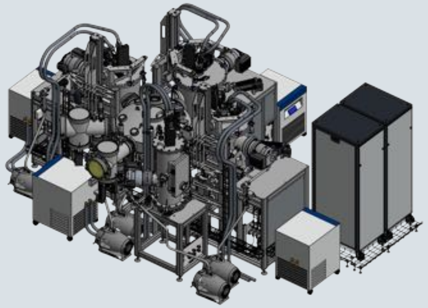
- strategic HGF investment
- addresses the ever-increasing need for large-scale / large-volume QS arrays
- three pillars of HSS:
  - QS development
  - QS prototype and batch fabrication
  - QS application
- allows to compete with internationally renowned facilities, e.g. MIT-LL, NASA/GSFC, NIST, …
- continuous equipment extensions and technology (r)evolutions to enable next generation QS development

HSS
SUPERCONDUCTING SENSORS

Photolithography

photoresist processing, direct laser lithography

UHV material deposition cluster



magnetron sputtering, e-beam evaporation, in-situ oxidation, ion-based substrate cleaning

ICP-PECVD **3 x ICP-RIE**

TEOS + silane based insulator deposition

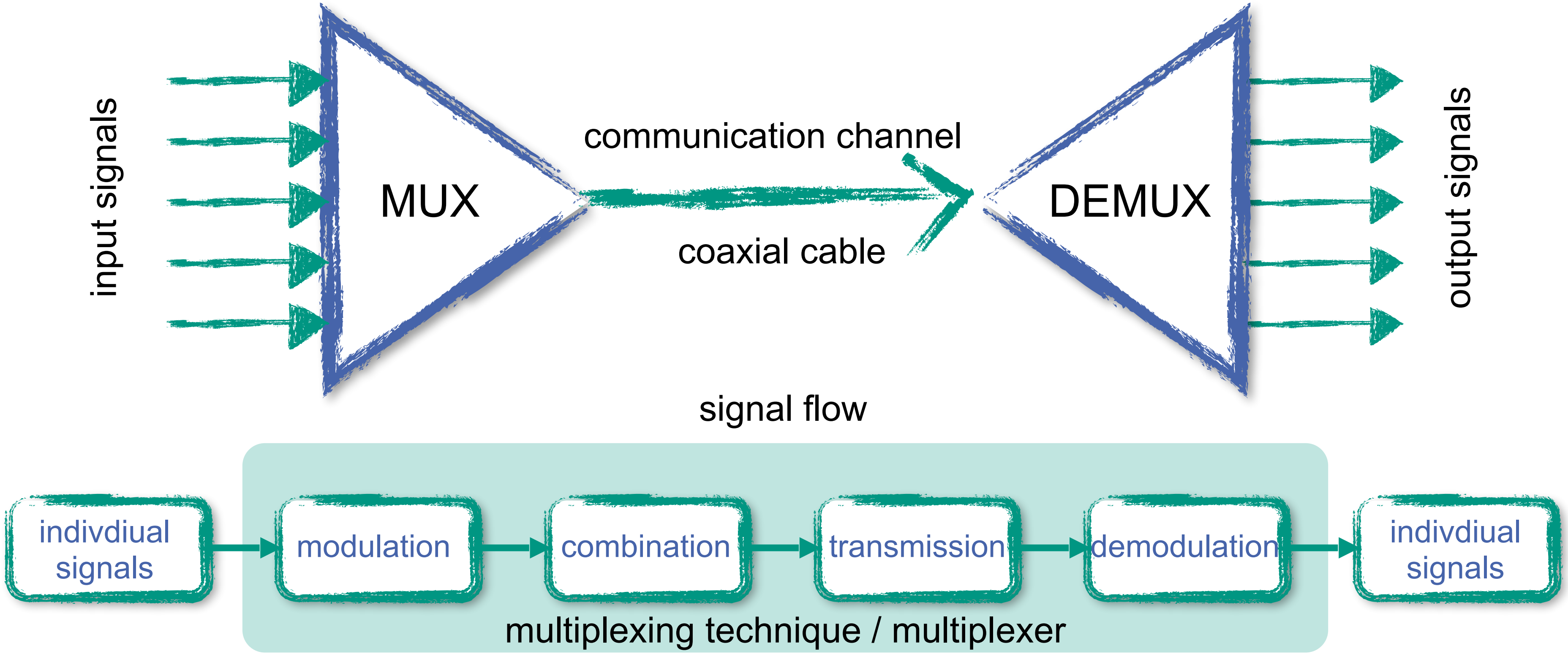
F- and Cl-based RIE of metals, dielectrics, and Si

CMP technology

Wafer polishing for multi-layer supercond. structures

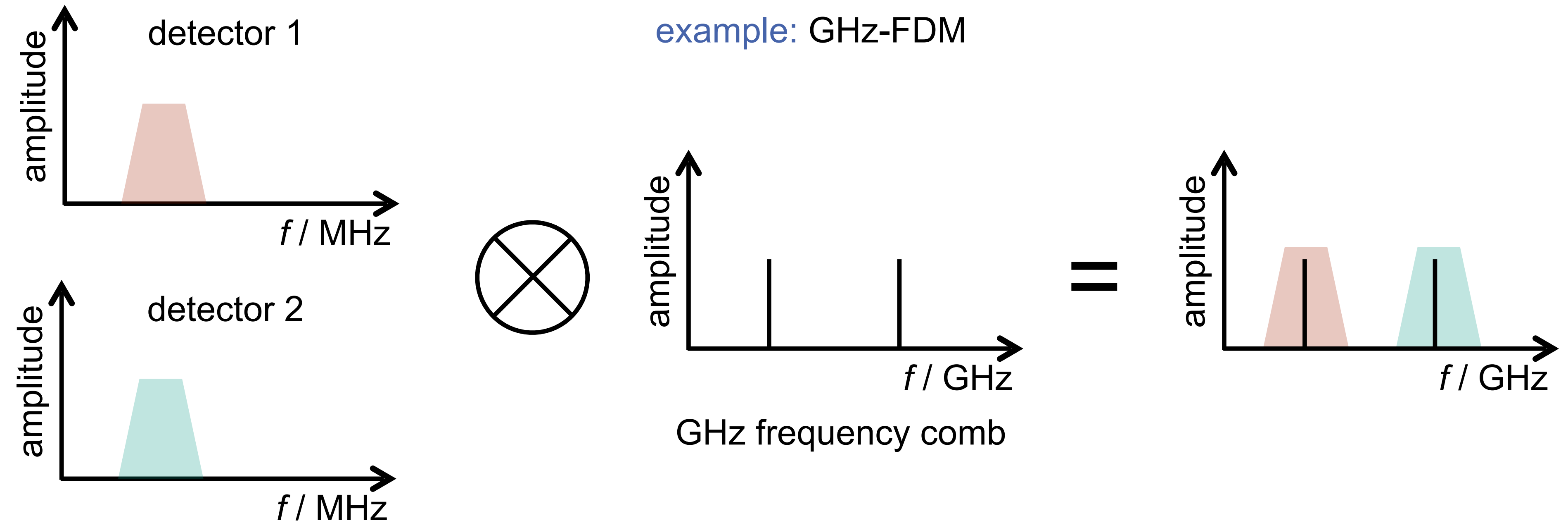
Cryogenic multiplexing

multiplexing (muxing)	method by which multiple signals are combined into one ‘physical’ channel to share a scarce resource.



Frequency-division multiplexing (FDM)

idea: detector signals are modulated on independent MHz / GHz carrier signals



Microwave SQUID Multiplexing

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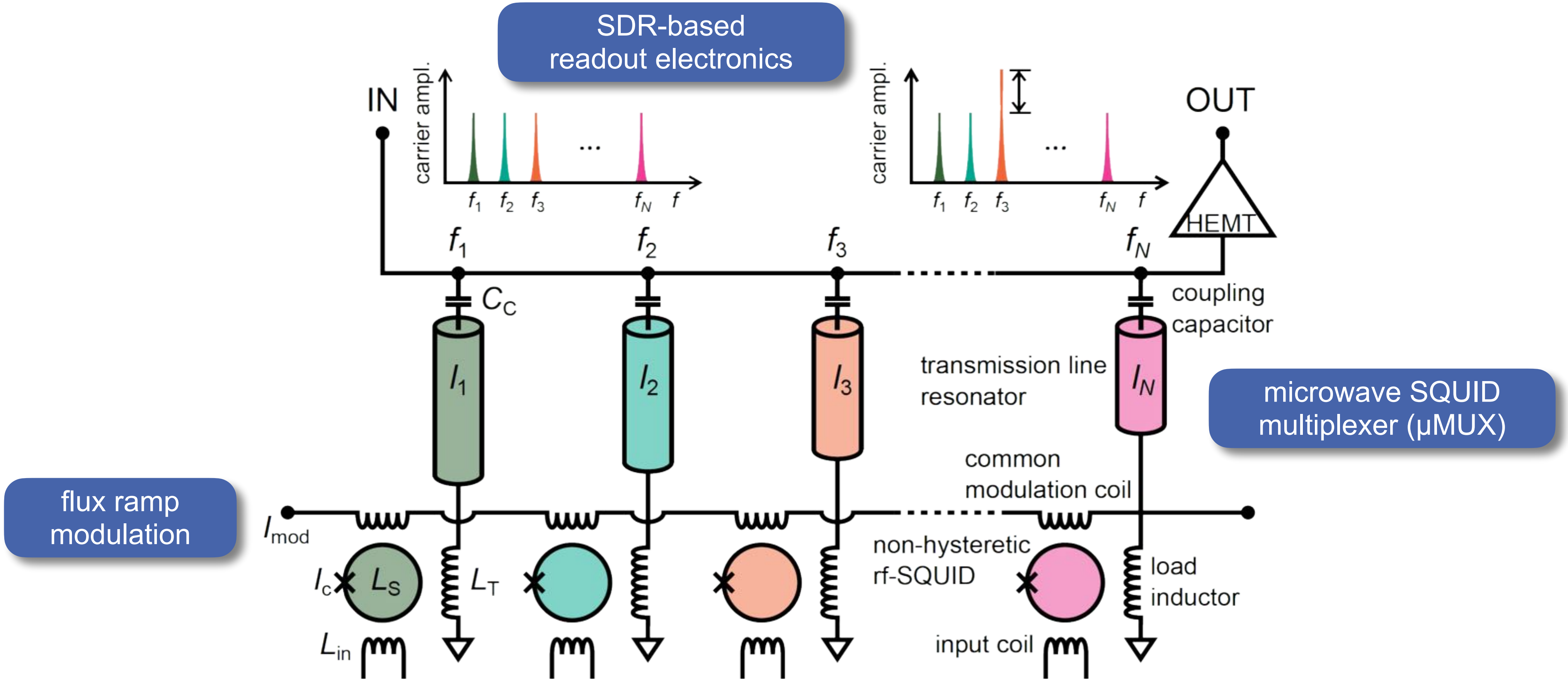
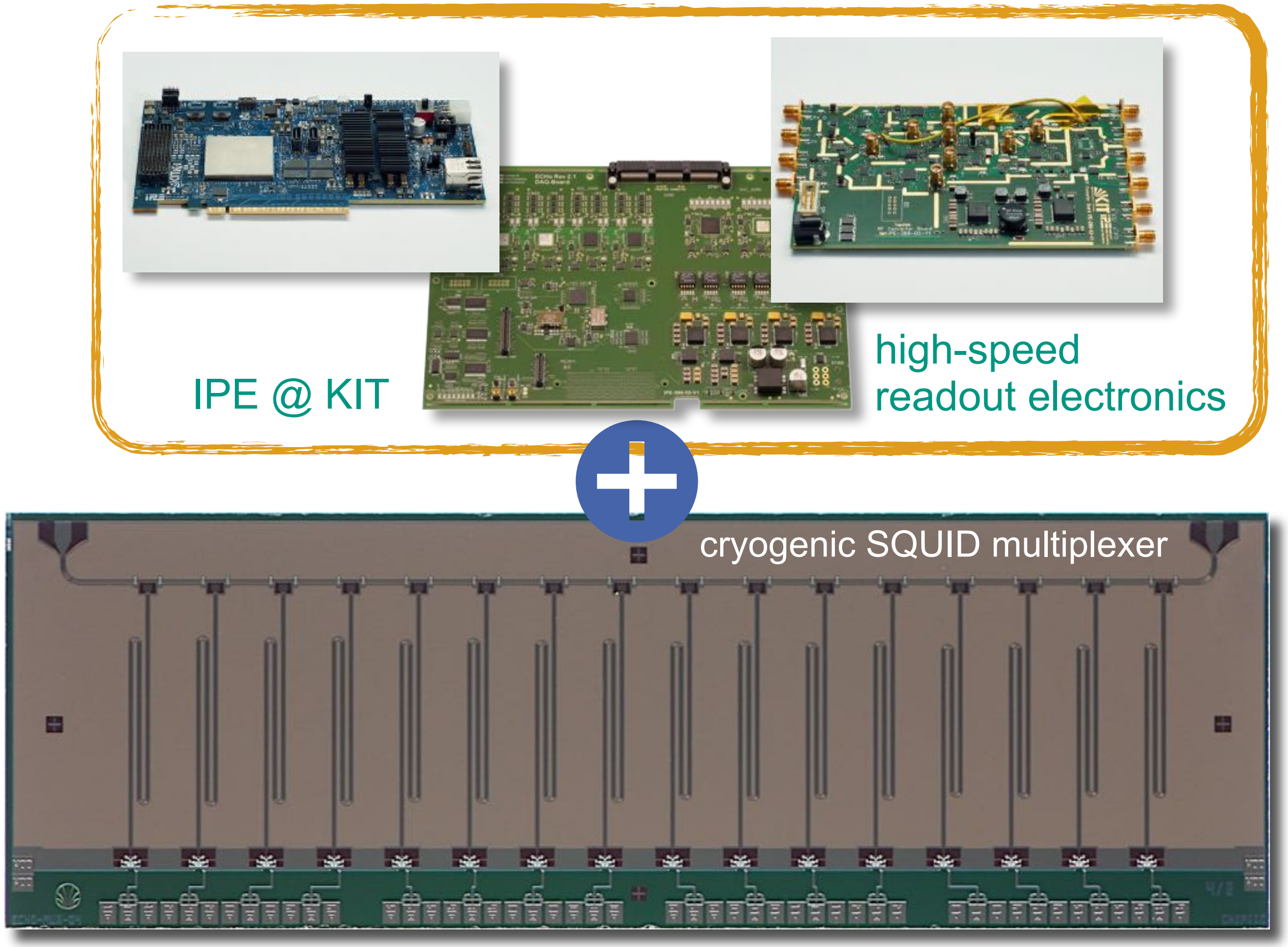
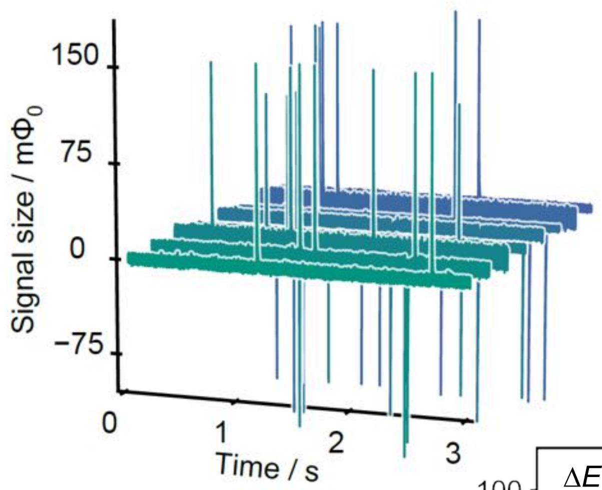


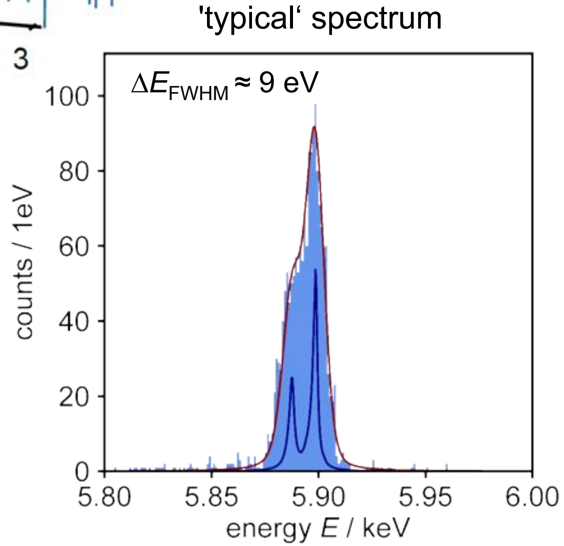
1 HEMT amplifier + 2 coaxes → ~1000 detectors

Irwin *et al.*, Appl. Phys. Lett. **85** (2004) 2107
Mates *et al.*, Appl. Phys. Lett. **92** (2008) 023514
S. Kempf *et al.*, J. Low Temp. Phys. **175** (2014) 853
S. Kempf *et al.*, AIP Advances **7** (2017) 015007

Cryogenic SQUID multiplexing







D. Richter, …, S. Kempf, IEEE Trans. Appl. Supercond. **33** (2023) 2500705

Summary, outlook, and acknowledgments

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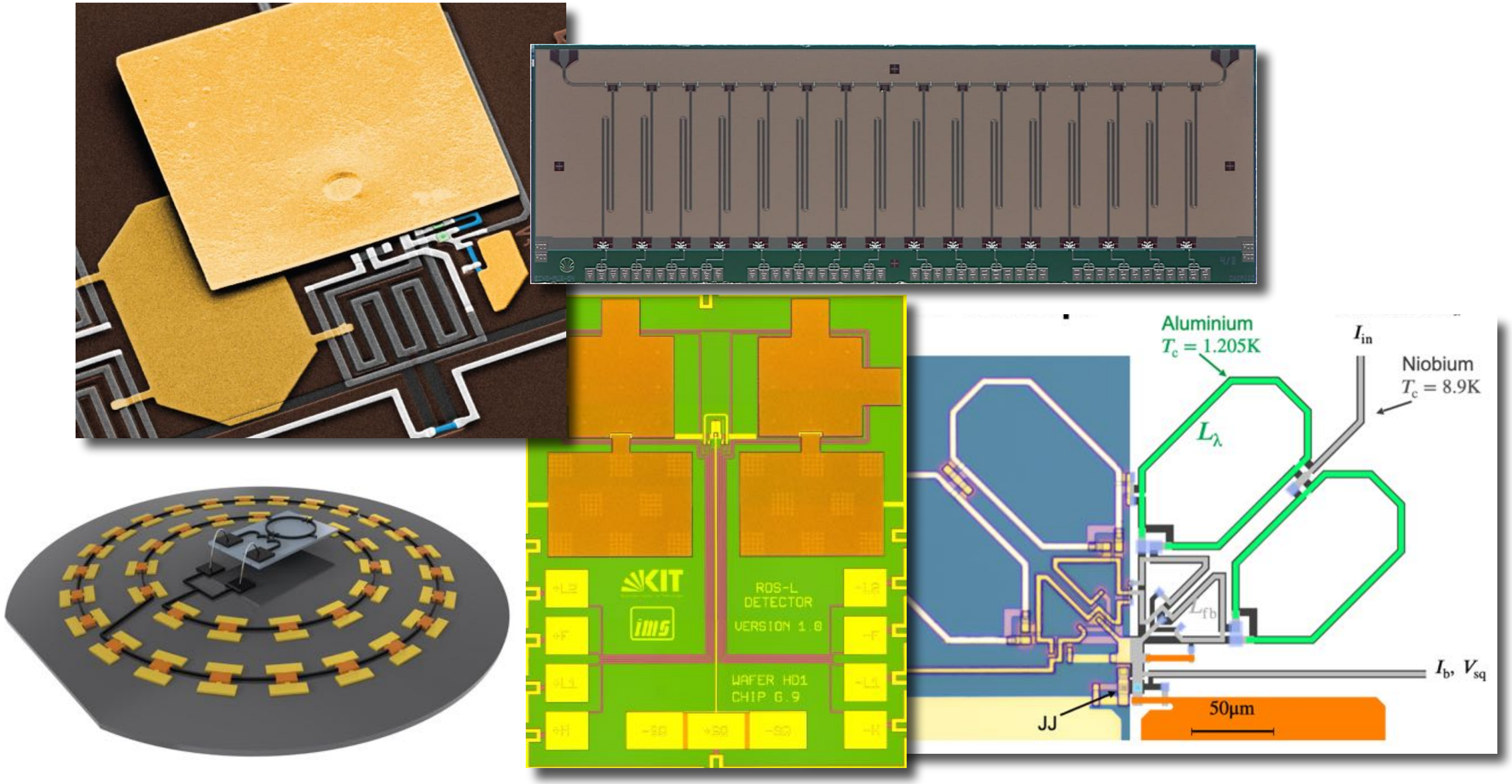
magnetic microcalorimeters are an incredible powerful tool
for various applications



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+ many, many talented and highly motivated Bachelor and Master students

Thank you for your attention!