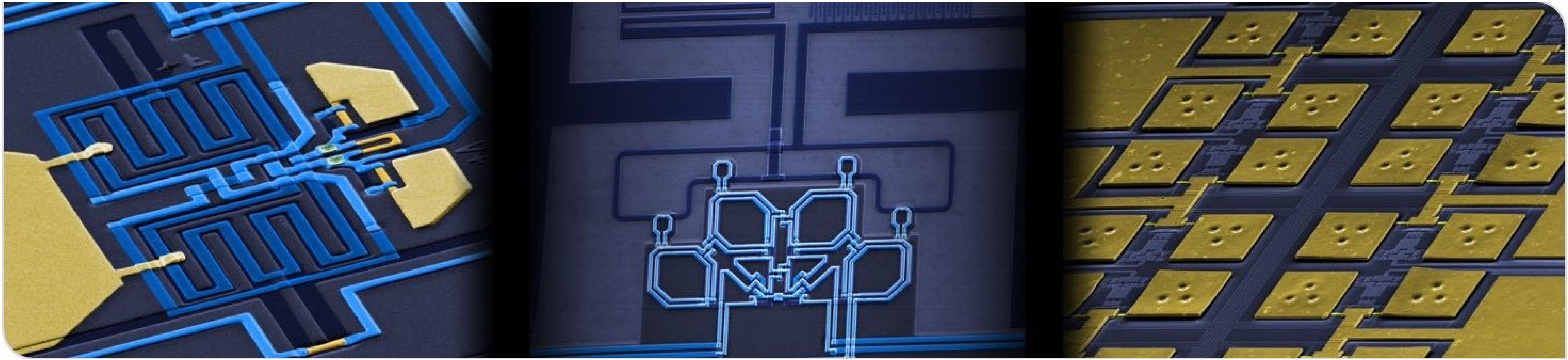
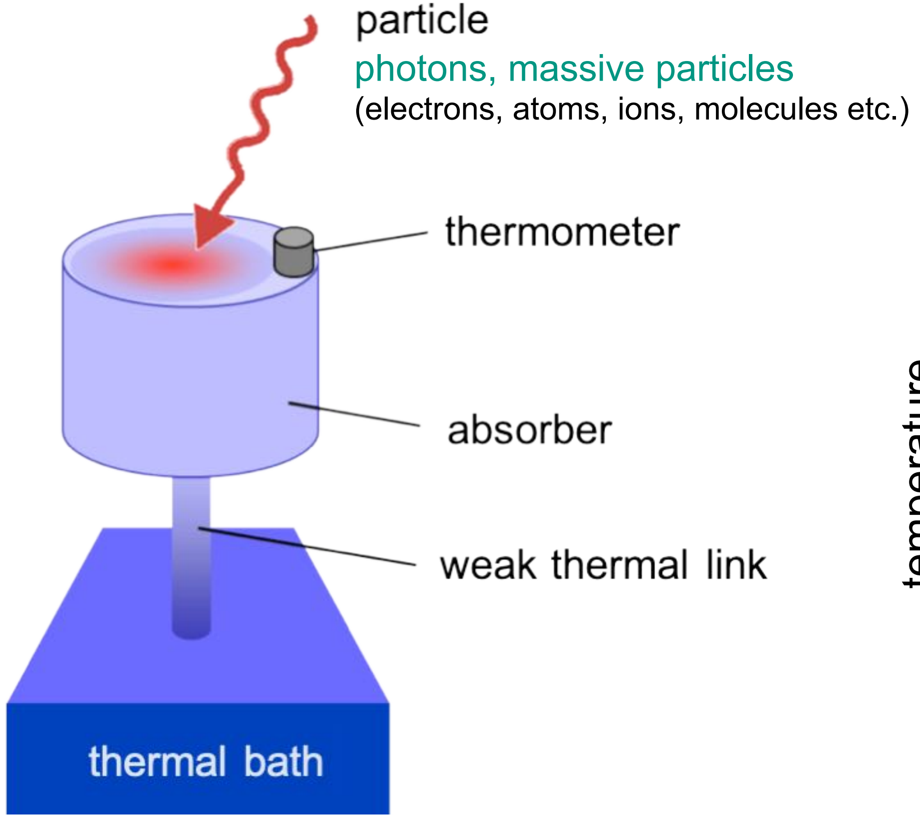
Superconducting microcalorimeters for particle and astroparticle physics experiments

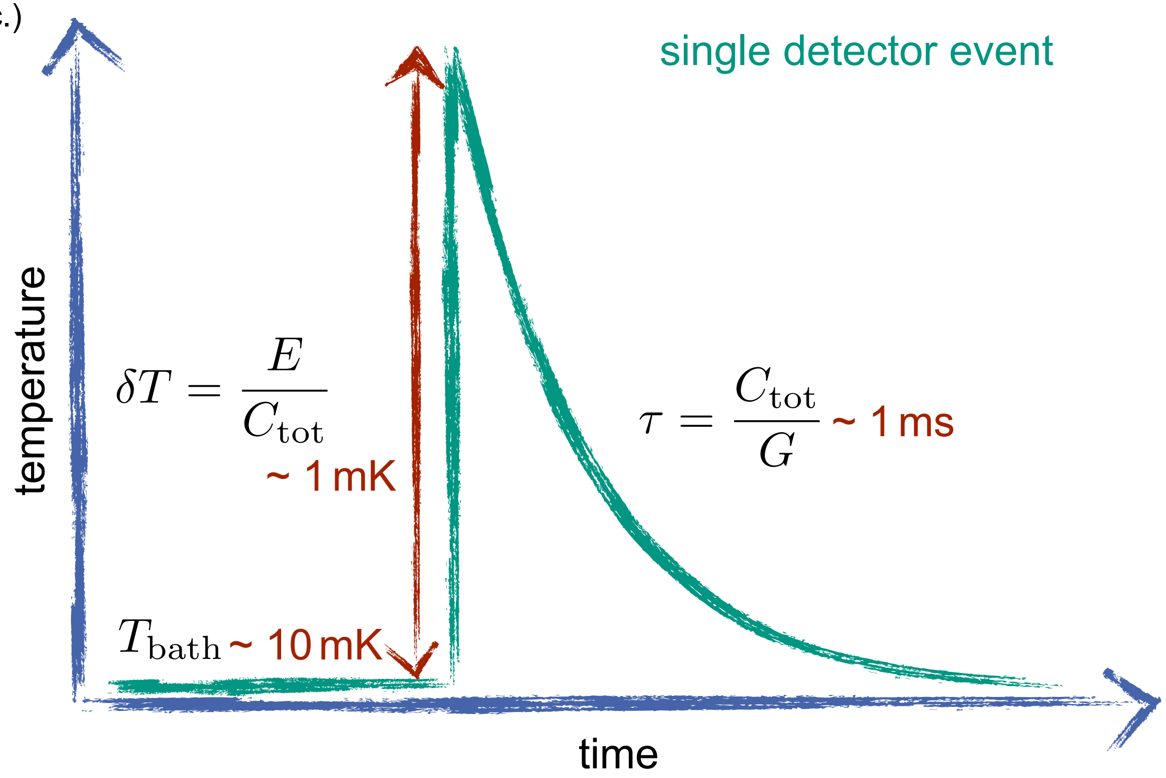
Sebastian Kempf

International Conference on Quantum Technologies for High-Energy Physics | CERN | January 22, 2025



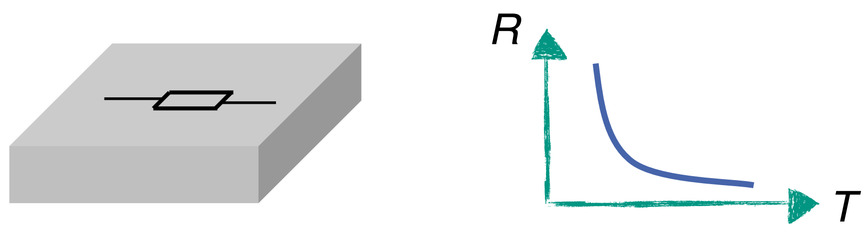
Superconducting microcalorimeters



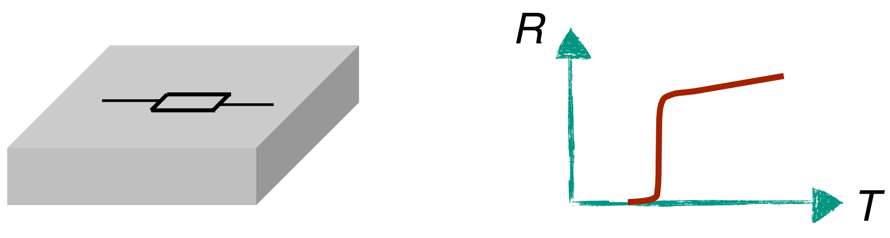


Temperature sensors

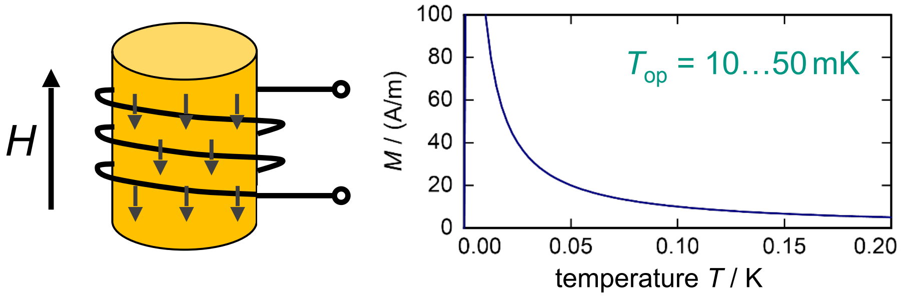
semiconductor thermistor



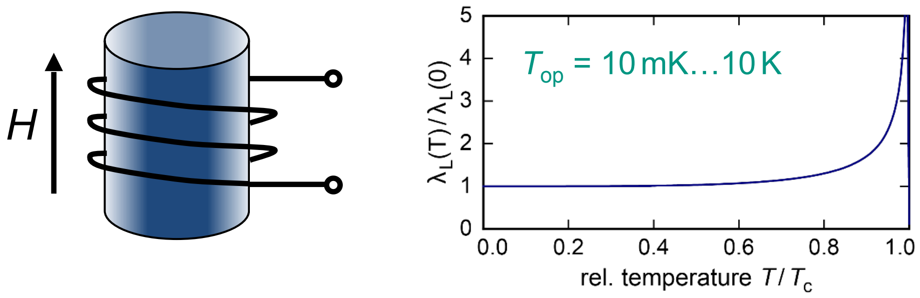
superconducting transition-edge sensor (TES)



metallic magnetic calorimeter (MMC)



magnetic penetration depth thermometer



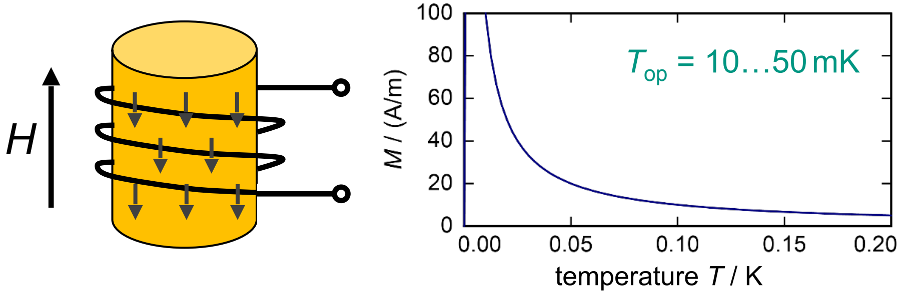
Temperature sensors

semiconductor thermistor

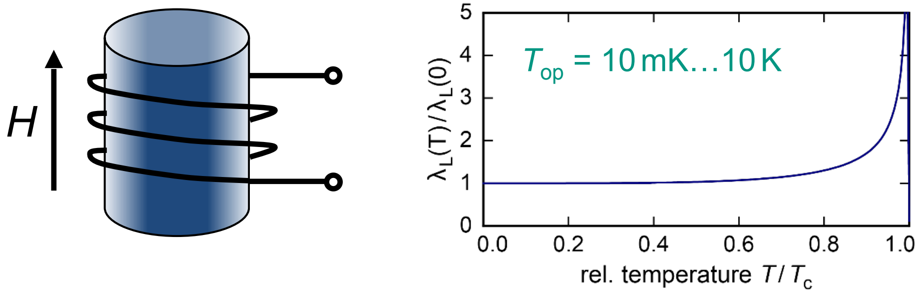
superconducting transition-edge sensor (TES)

magnetic microcalorimeters

metallic magnetic calorimeter (MMC)

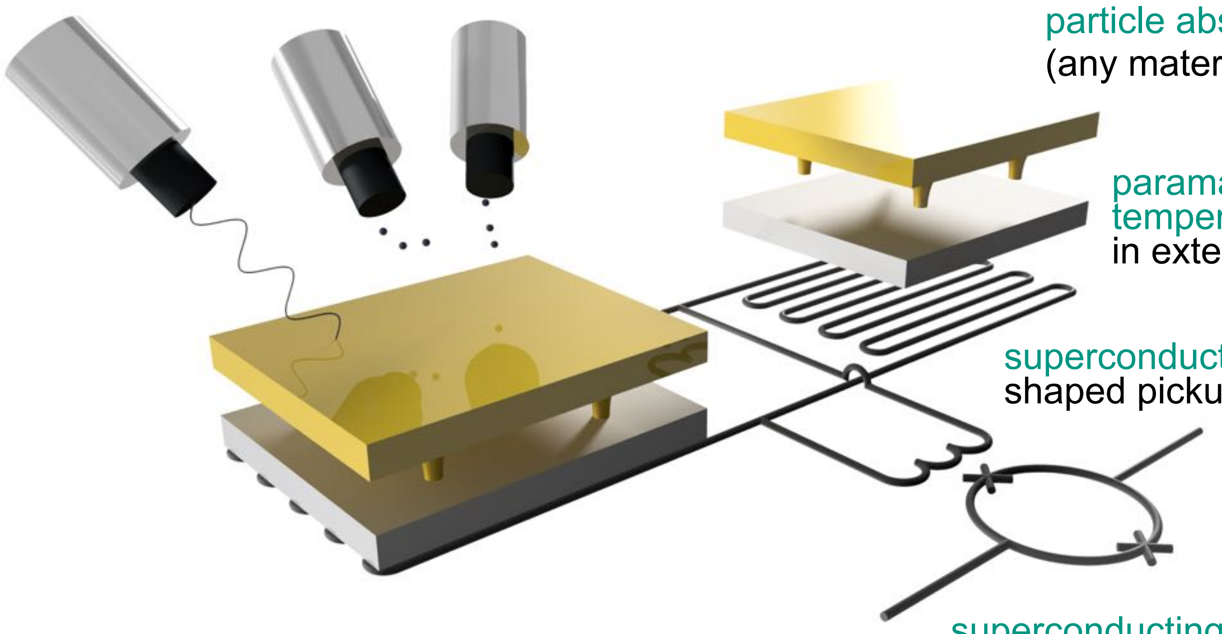


magnetic penetration depth thermometer

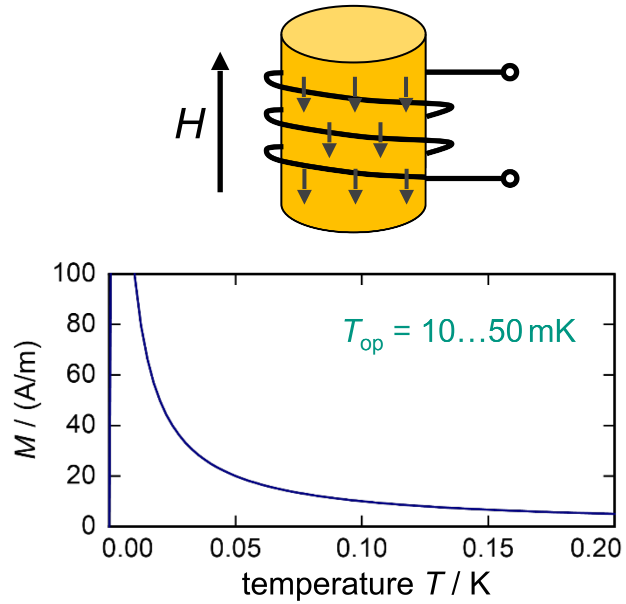


Metallic magnetic calorimeters (MMCs)

massive particles / photons / …



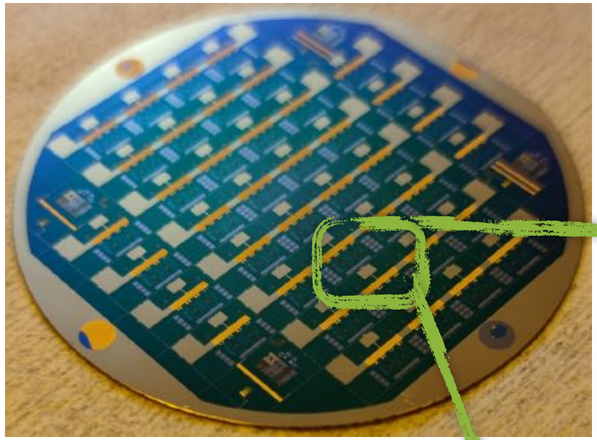
magnetization of a paramagnetic material



large variation of magnetization at mK temperature

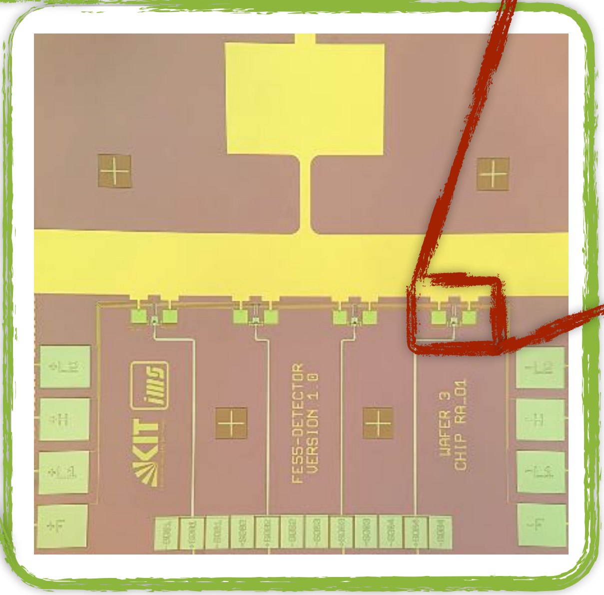
Example:
Metallic magnetic calorimeter for radionuclide metrology

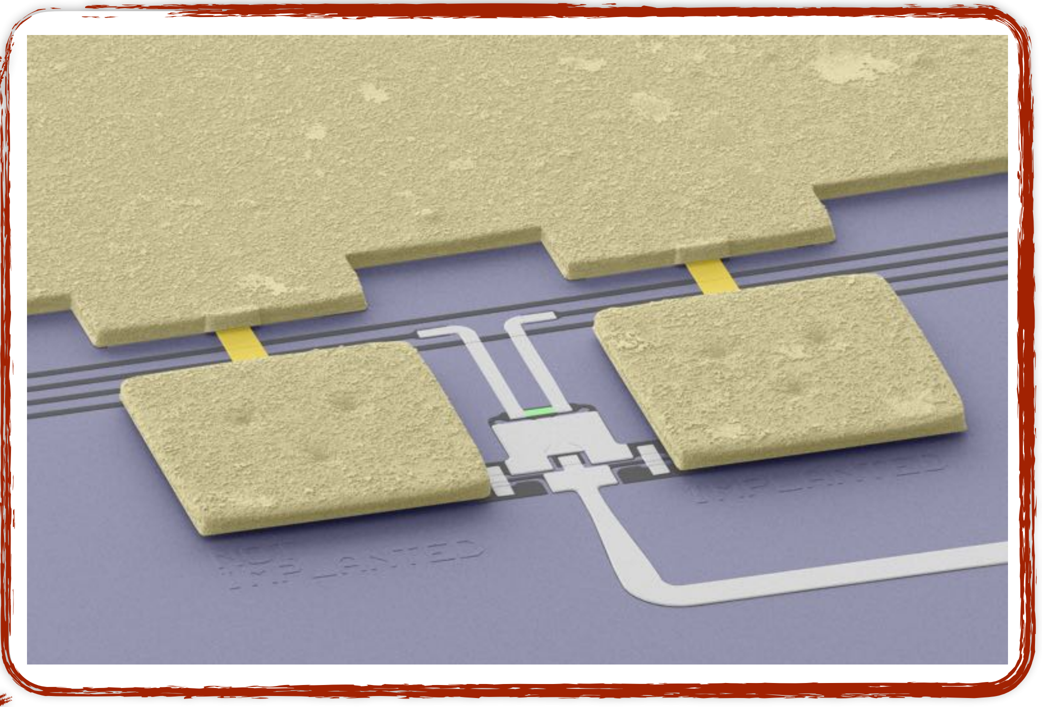
Magnetic microcalorimeter for measuring
EC spectrum of ion-implanted Fe-55 source



2 inch wafer

single detector chip

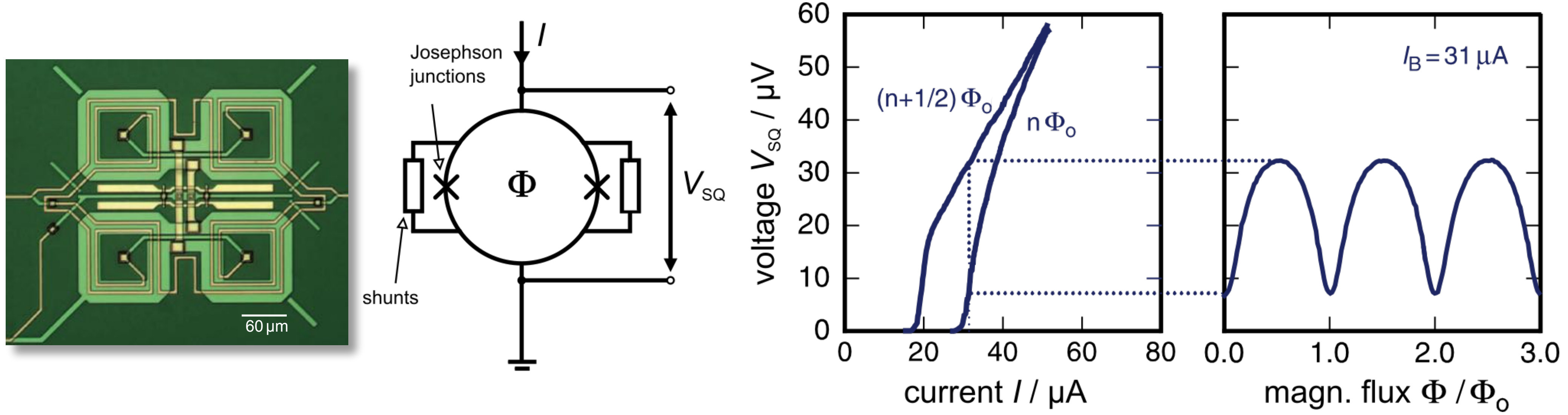




single detector
(before deposition of second absorber half)

SQUID-based detector readout

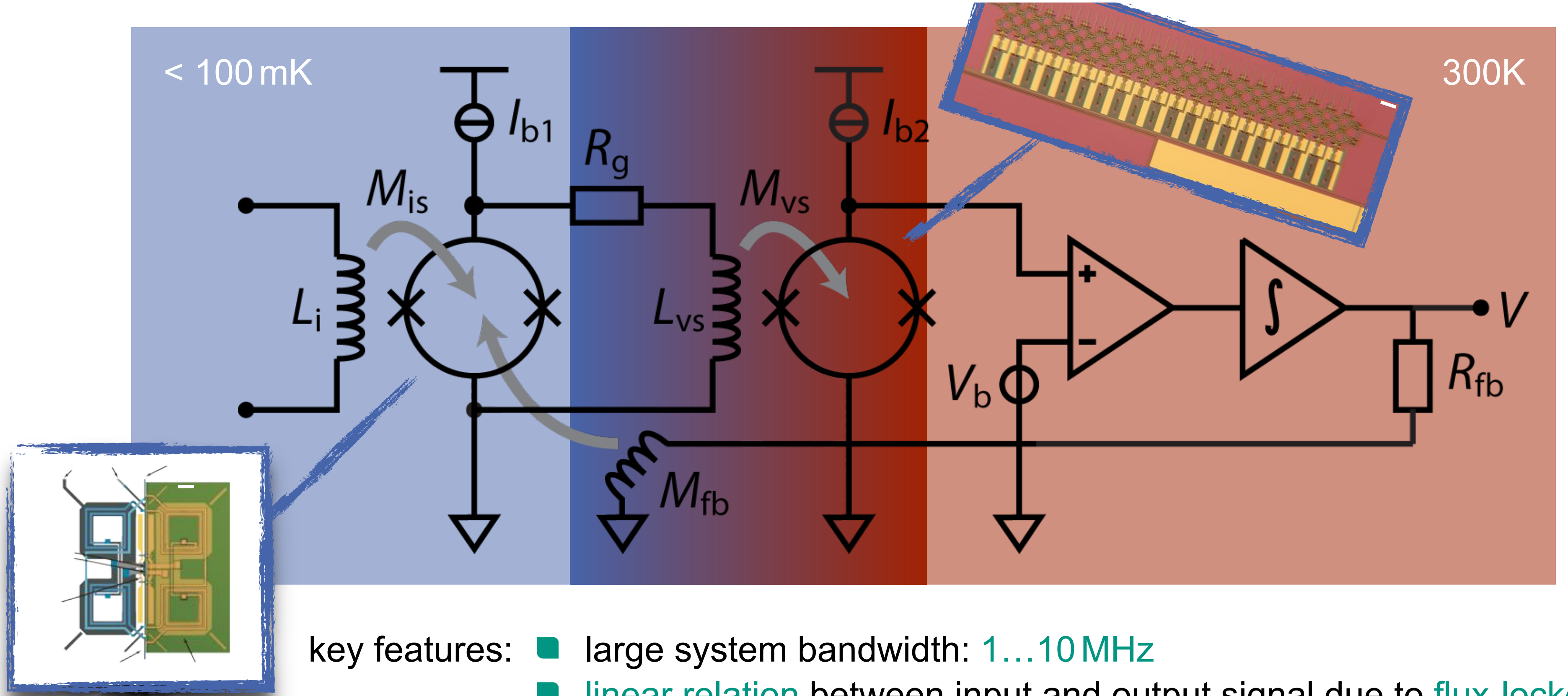
dc-SQUIDs = magnetic flux to voltage / current converters



- 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



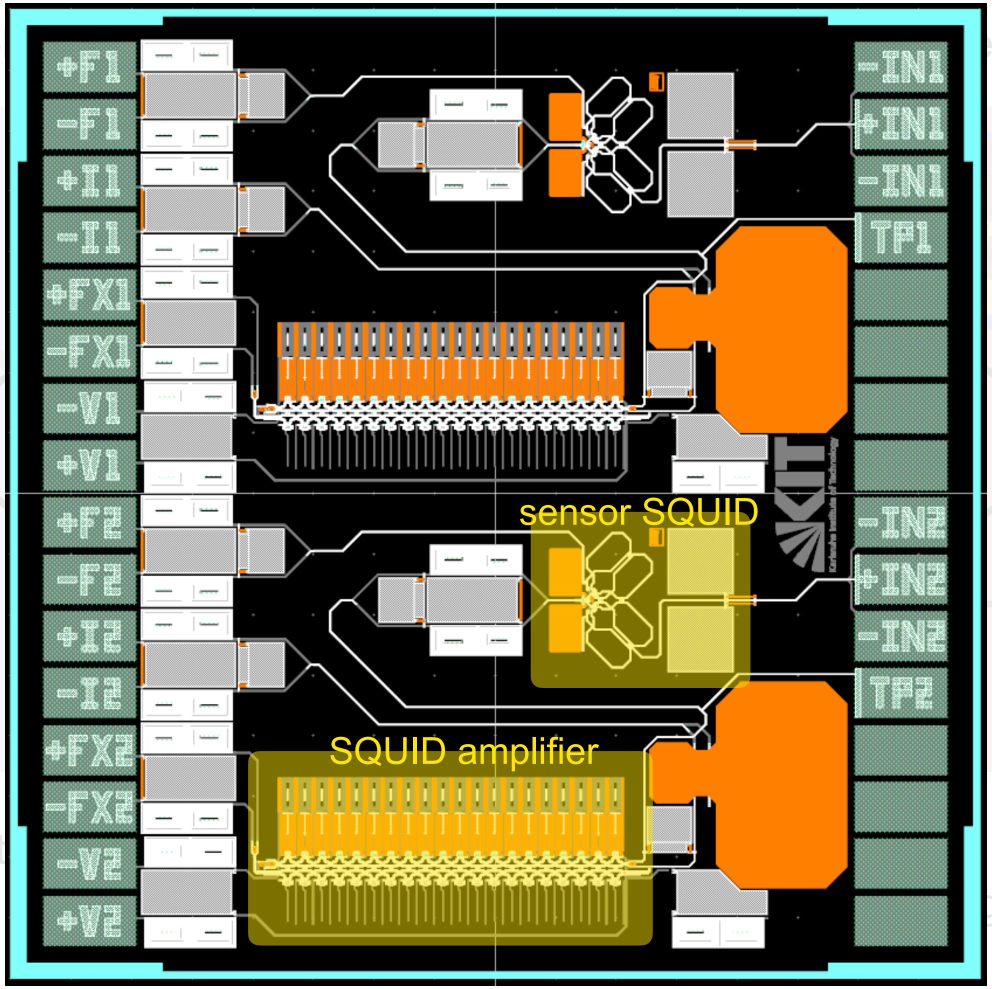
key features:
- large system bandwidth: 1…10 MHz
- linear relation between input and output signal due to flux-locked loop (FLL)
- impedance matched

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

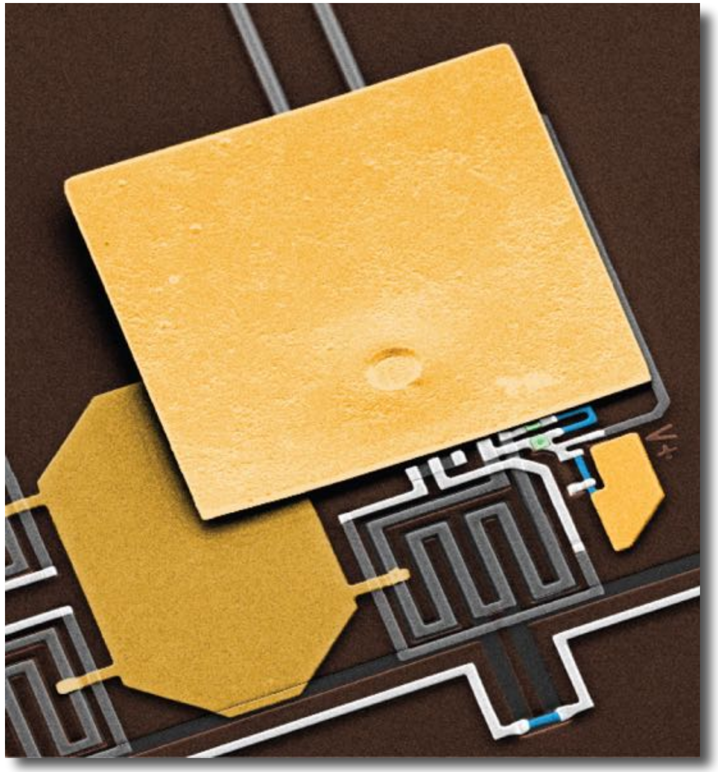


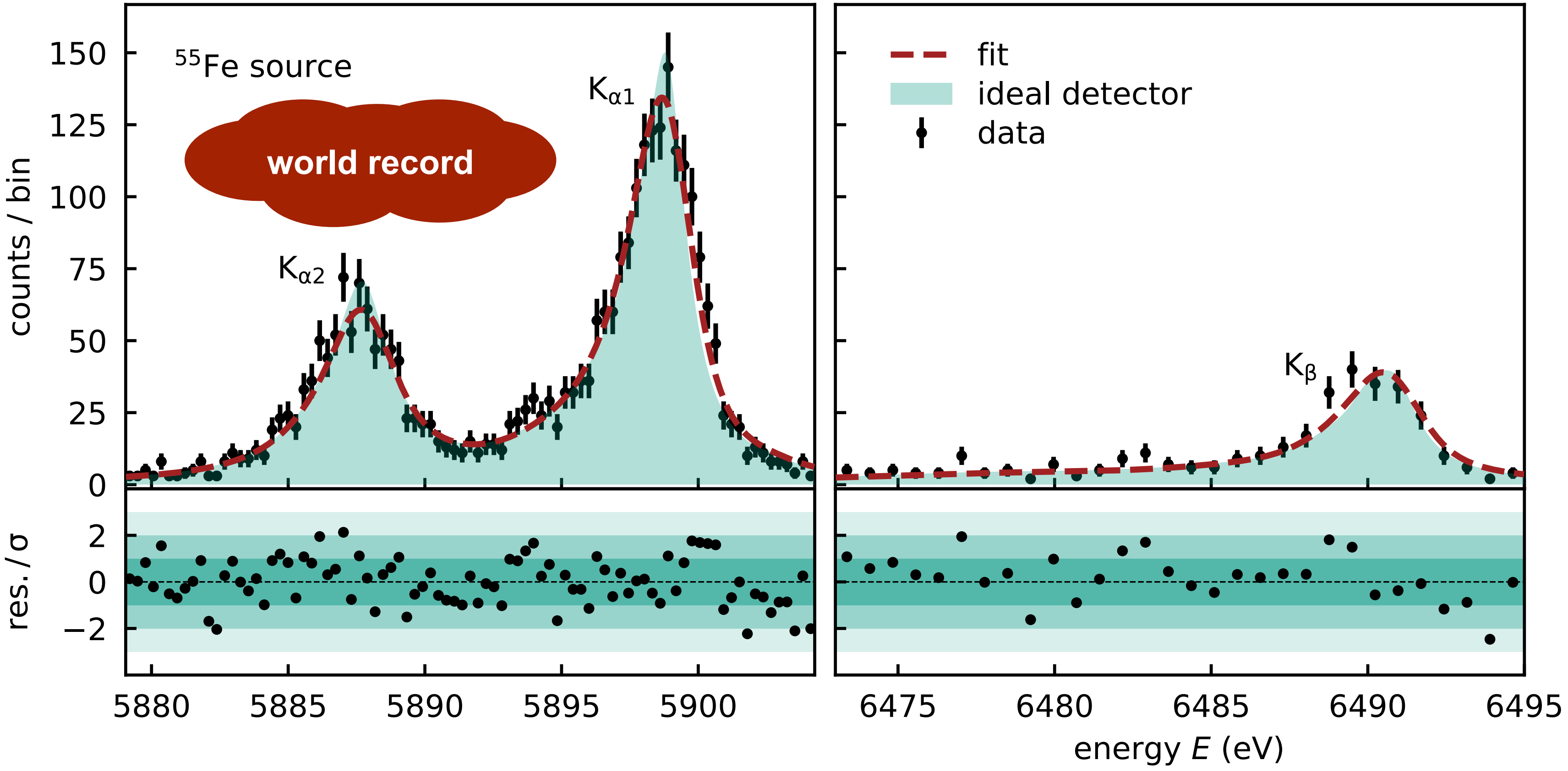
input ch #1

input ch #2

The present world-best X-ray photon detector

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

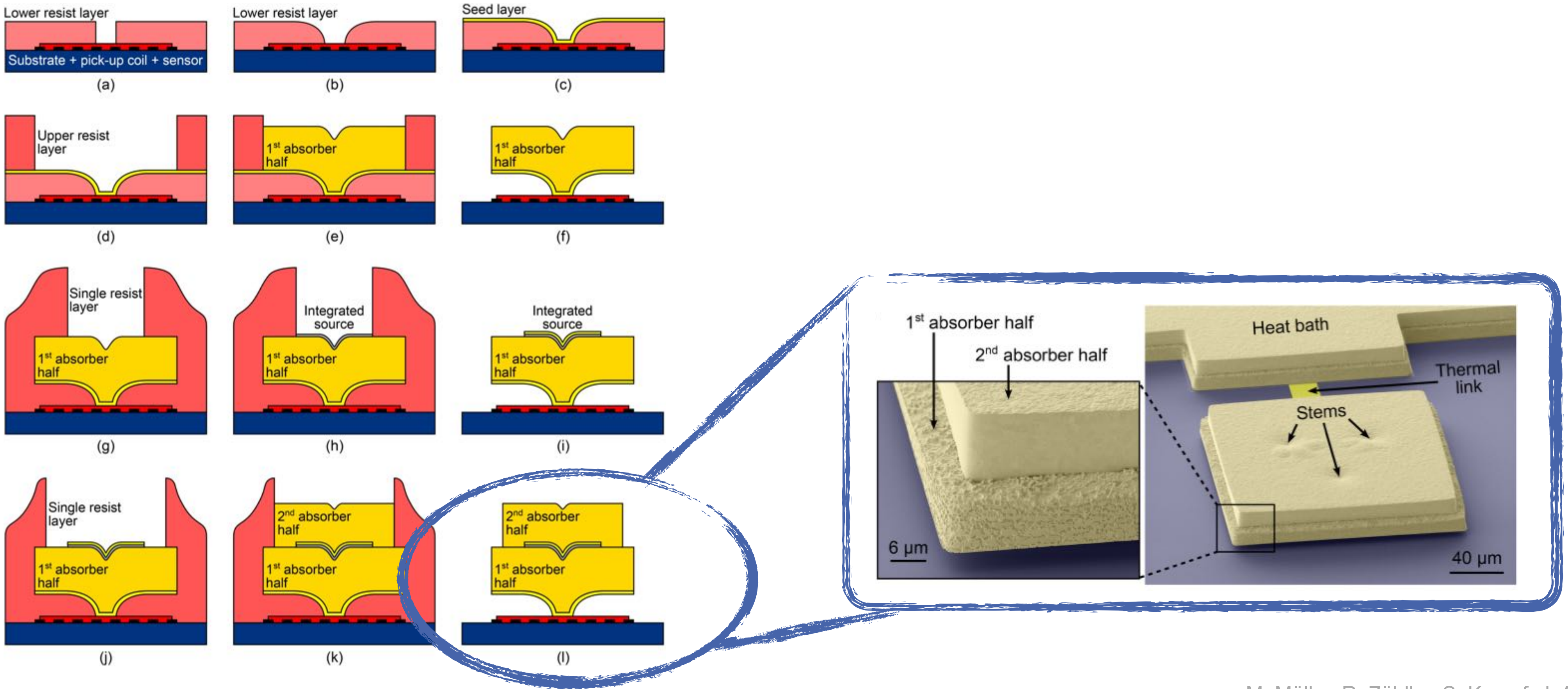




M. Krantz, …., S. Kempf, Appl. Phys. Lett. **124** (2024) 032601
F. Toschi, …., S. Kempf *et al.*, Phys. Rev. D **109** (2024) 043035

Fabrication process for particle absorbers…

…with varying thickness and/or embedded source



M. Müller, R. Zühlke, S. Kempf, J. Appl. Phys. **136** (2024) 204504

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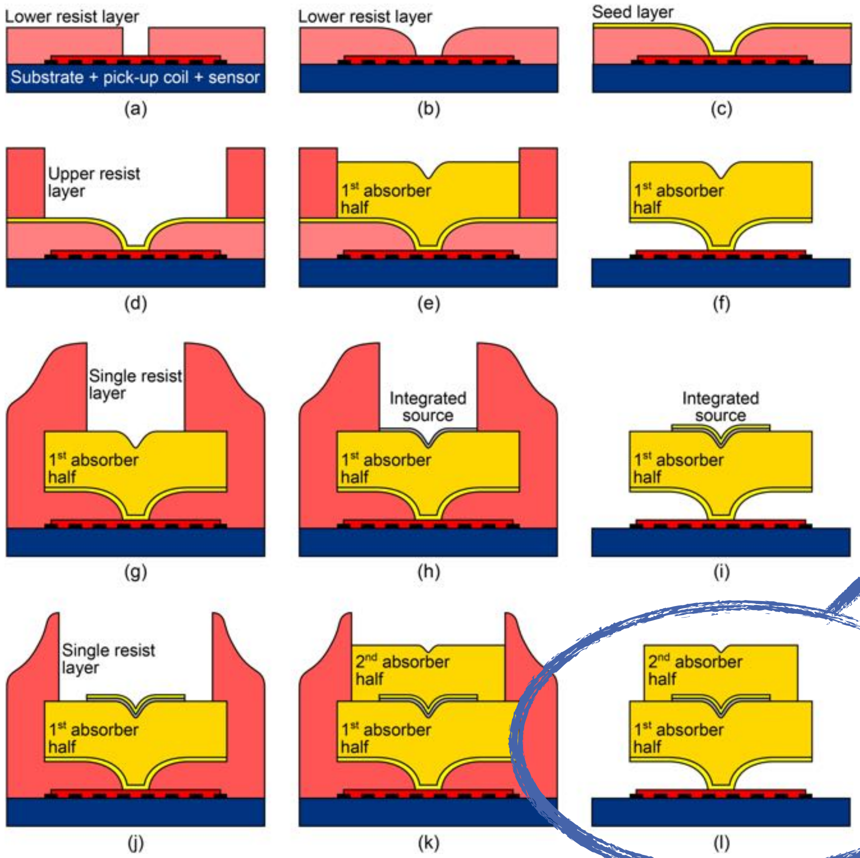
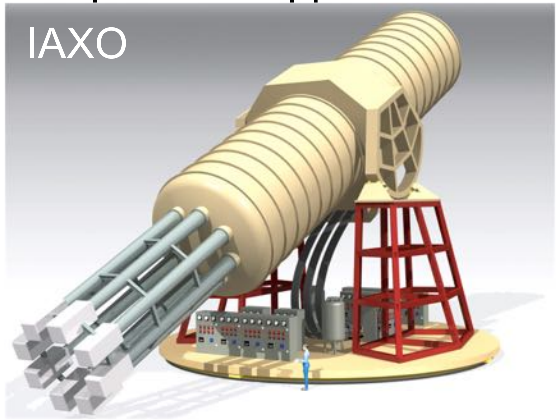
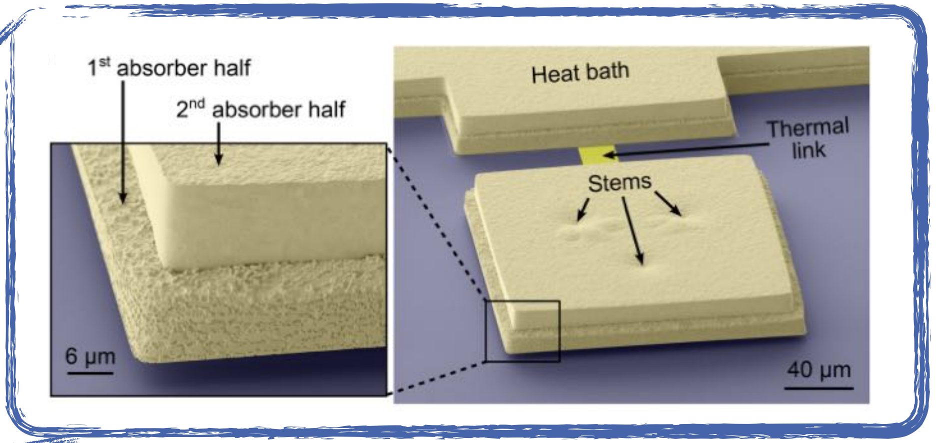


side view

varying absorber thickness
for multi-energy arrays

potential application

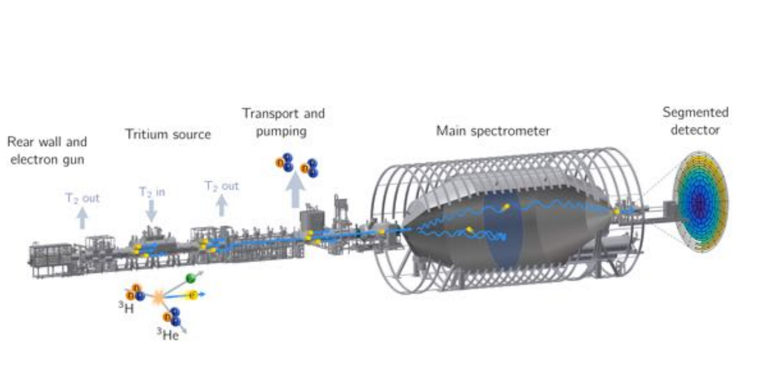




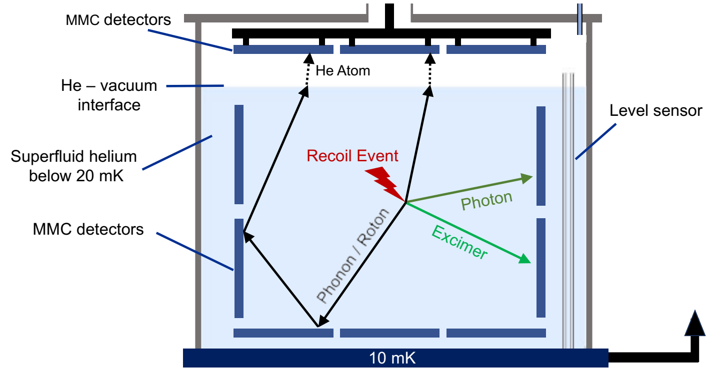
M. Müller, R. Zühlke, S. Kempf, J. Appl. Phys. **136** (2024) 204504

Applications we are working on…

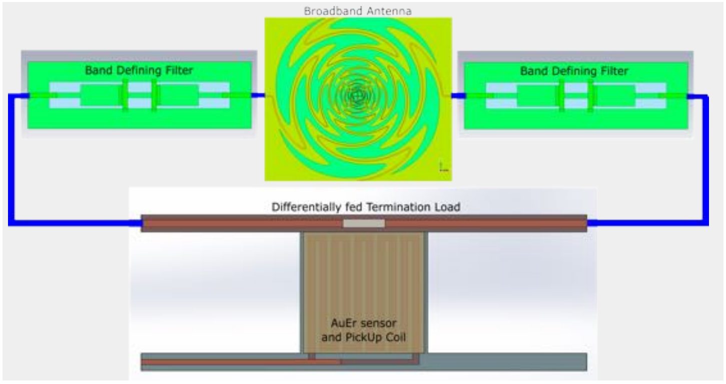
neutrino mass measurements



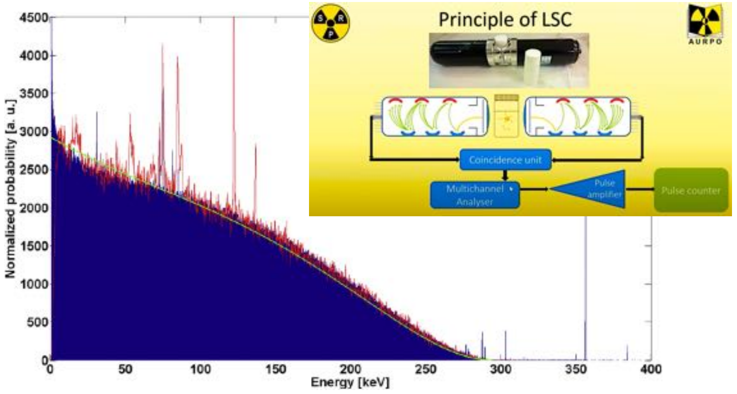
dark matter searches



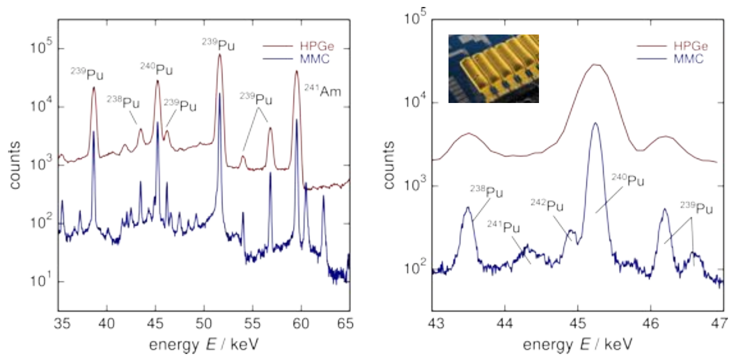
cosmic microwave background



radionuclide metrology



nuclear safeguards + forensics



XES at brilliant light sources

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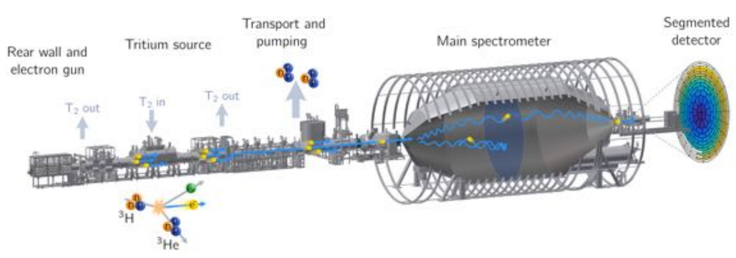

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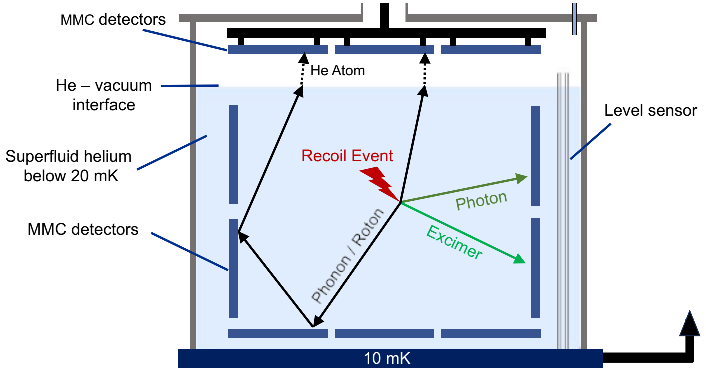

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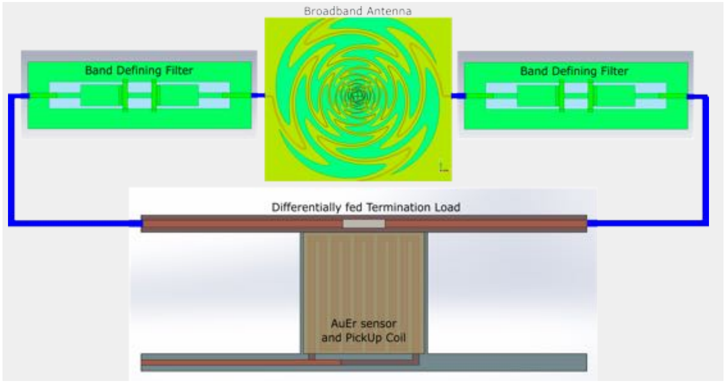

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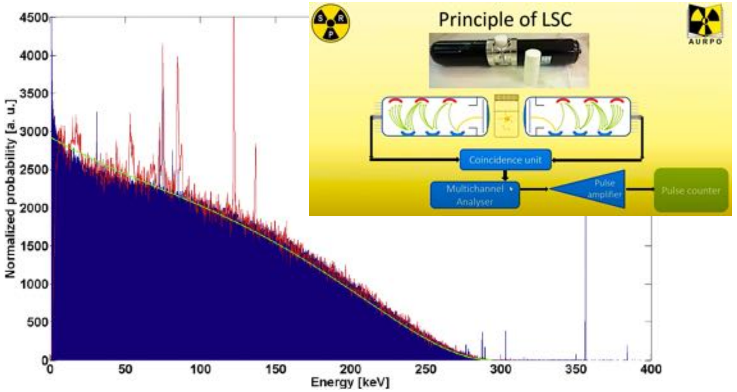

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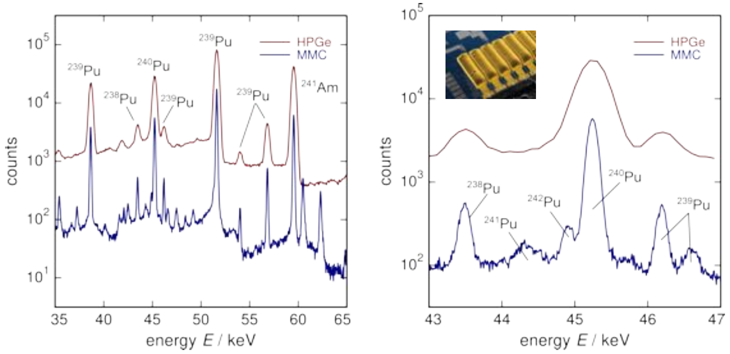
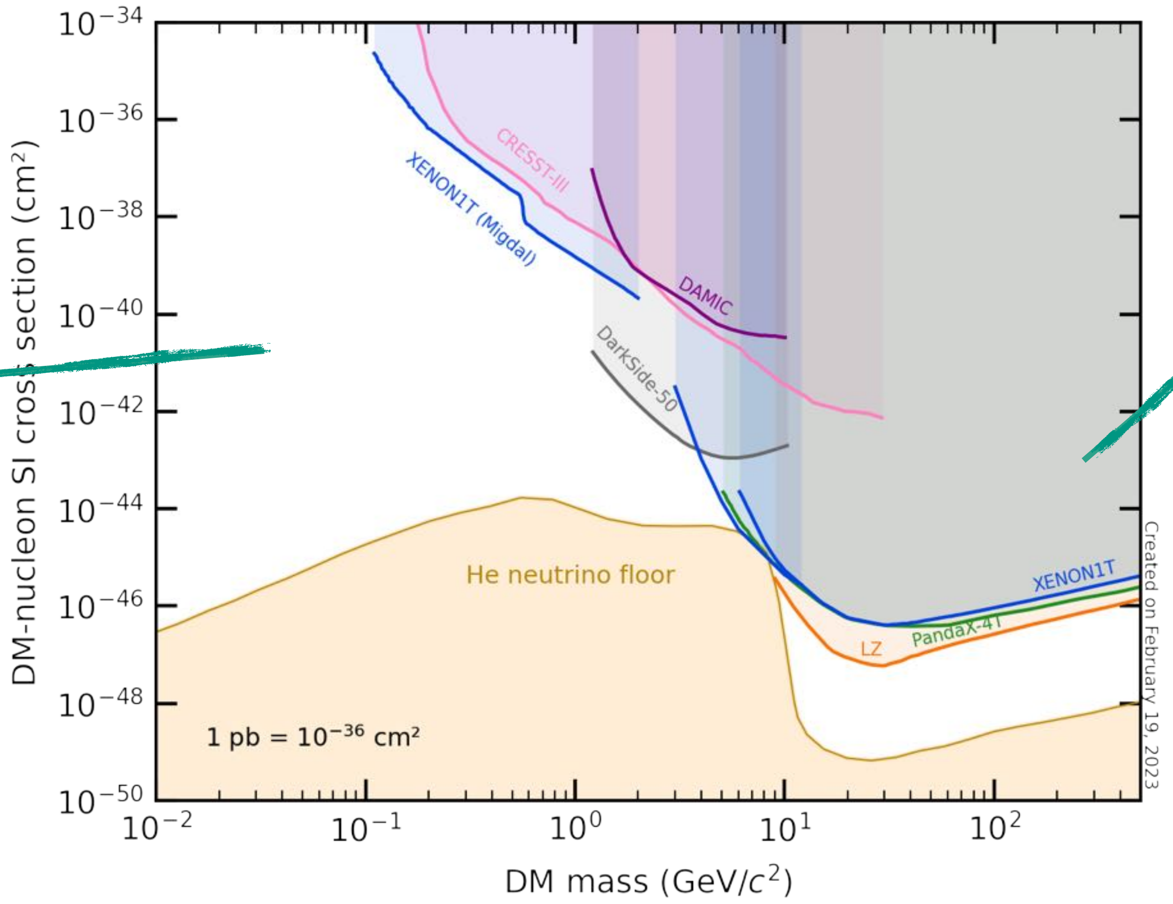


XES at brilliant light sources

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)

Current dark matter landscape

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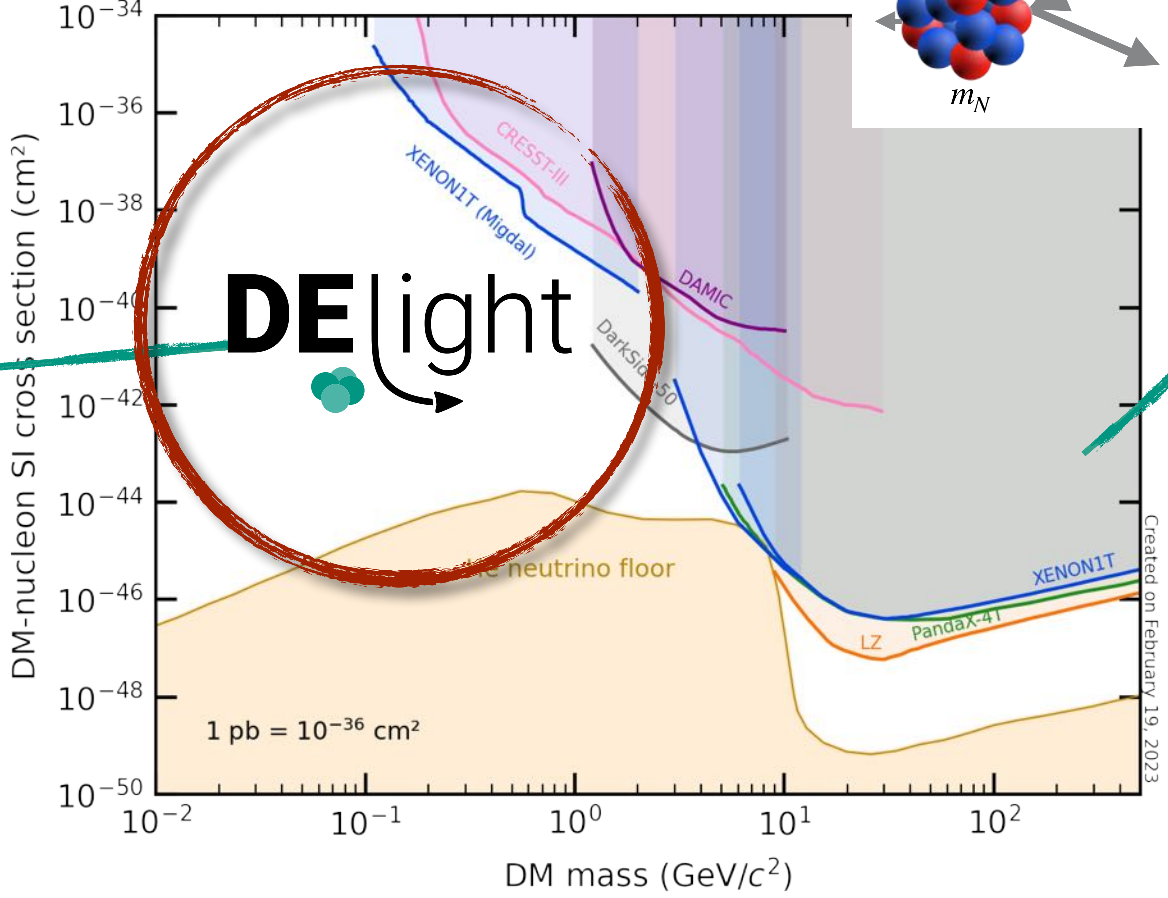

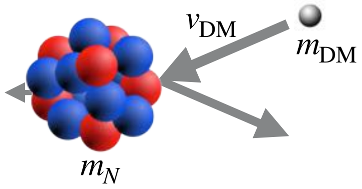

$$\Delta E = \frac{1}{2}\frac{\Delta p^2}{m_N} \lesssim \frac{2\, m_{DM}^2 v_{DM}^2}{m_N}$$

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

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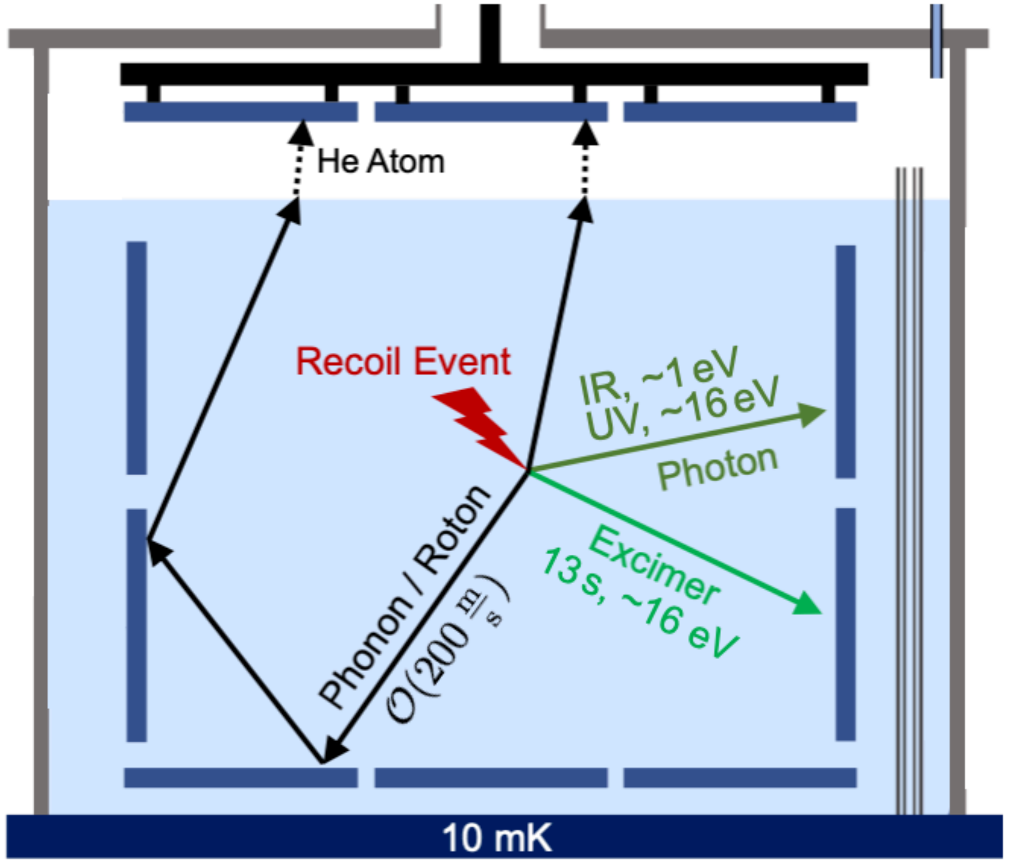
DELight - Direct Search Experiment for Light Dark Matter with superfluid Helium

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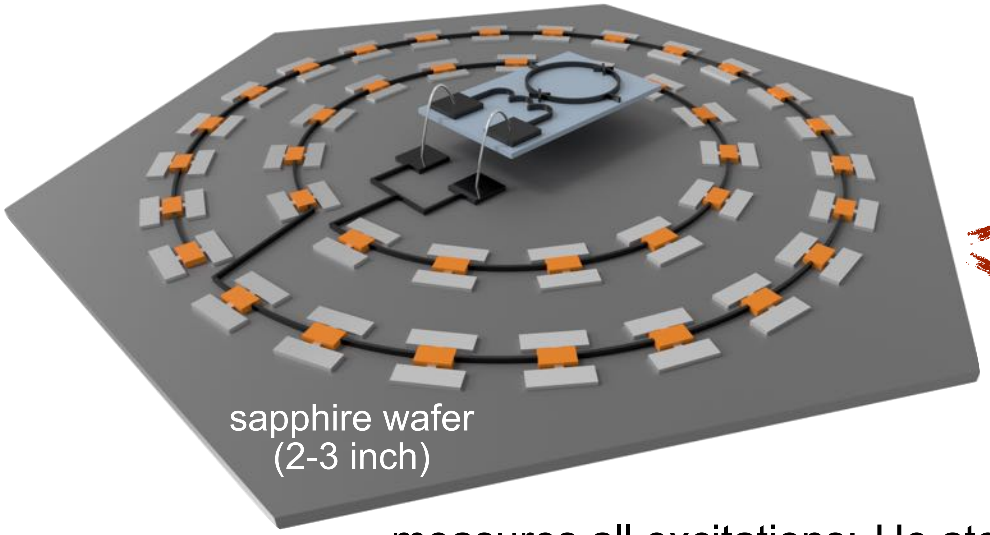
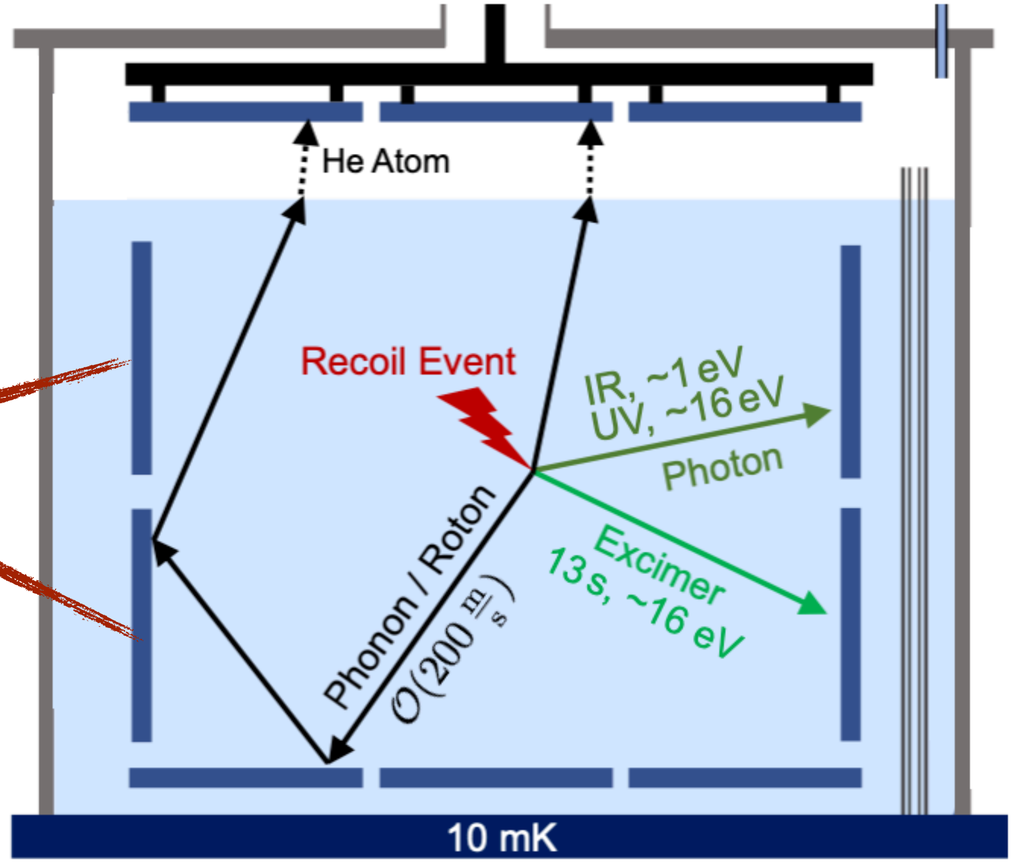
Large-area cryogenic microcalorimeter (LAMCALs)
(MMCs based on athermal phonon detection)





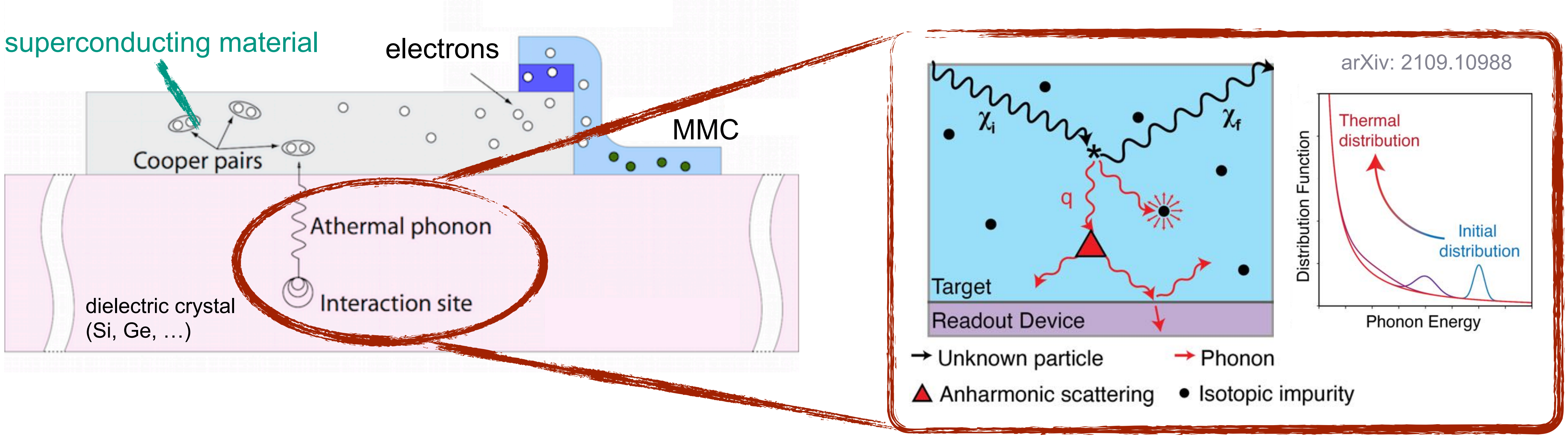
measures all excitations: He atoms
phonons
excimers

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

MMC-based athermal phonon detectors

Karlsruhe Institute of Technology

idea: measure athermal phonon population created by interacting particle

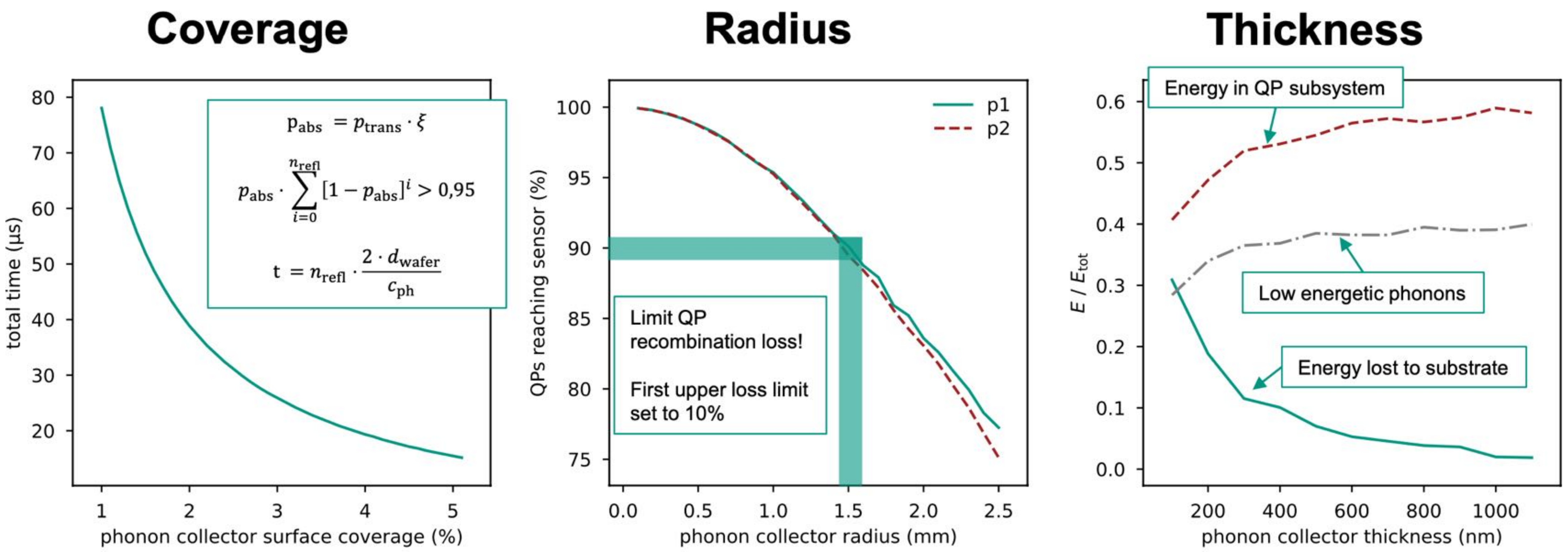


advantages:
- absorber heat capacity (to first order) irrelevant
- possibility for large absorber volumes

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

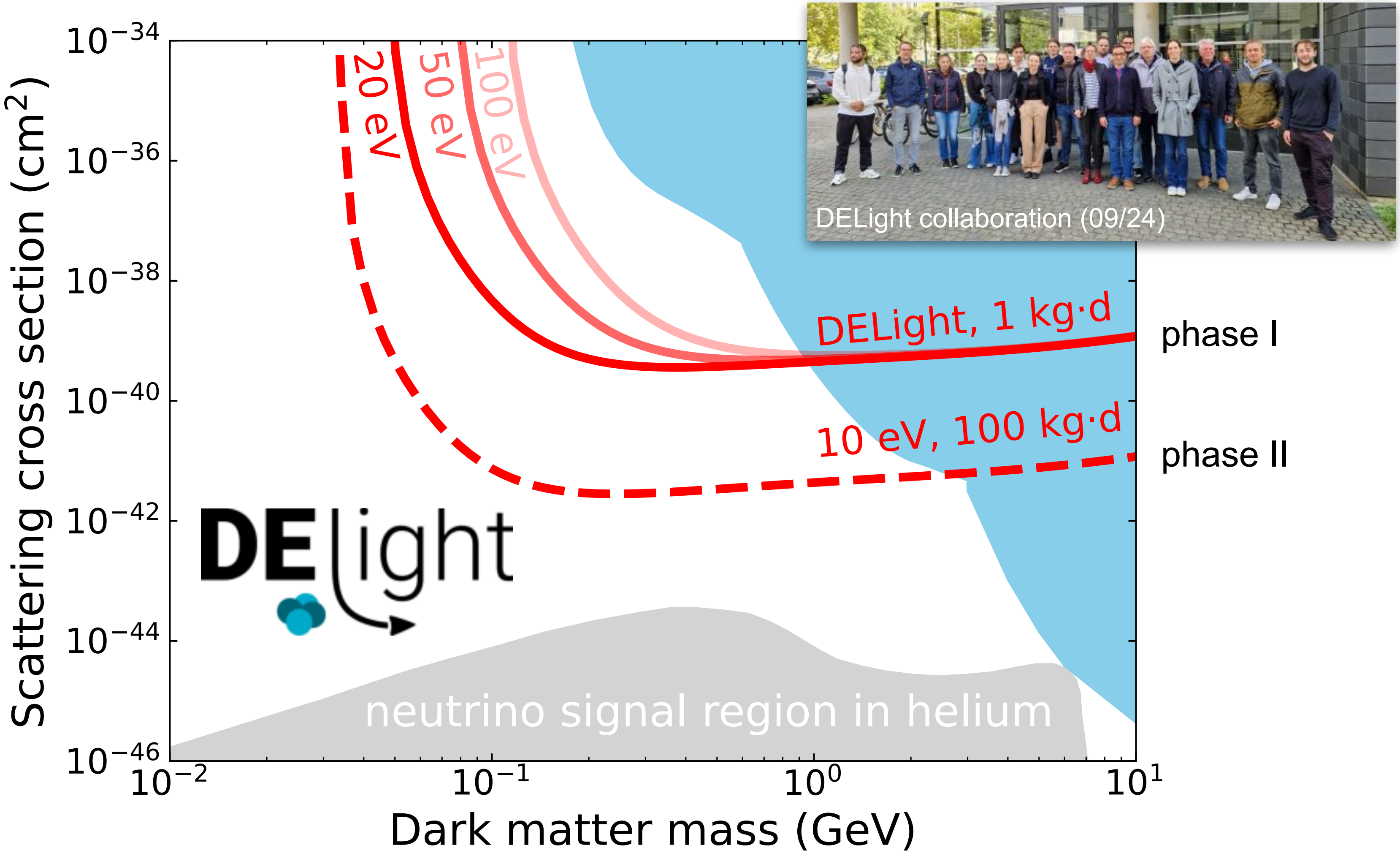
Ongoing R&D: LAMCAL optimization

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



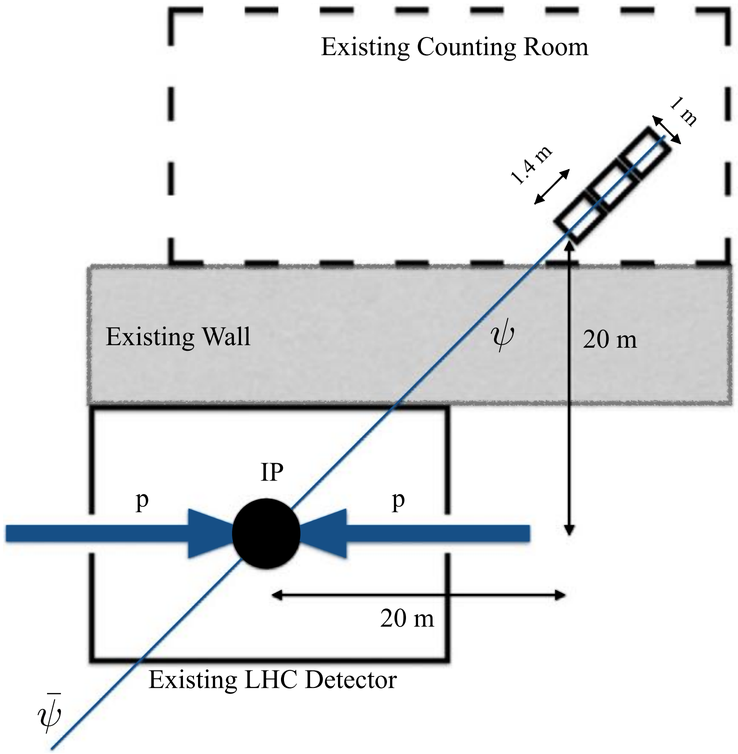
phonon collector distribution will set requirements for LAMCAL geometry

Sensitivity projection of DELight

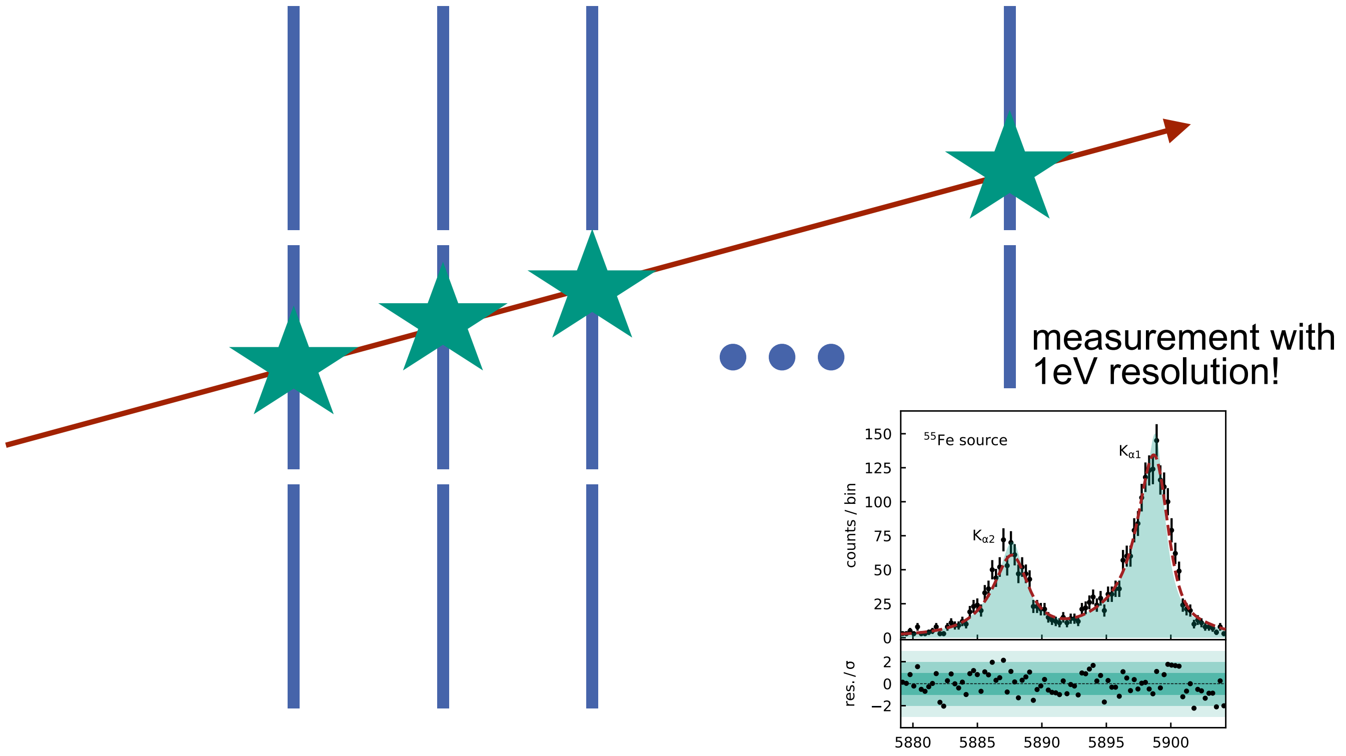


Search for hypothetical milli-charged particles

thickness of Si substrates can be precisely set by deep Si reactive ion etching (DRIE) → assumption: adjust thickness of Si substrate such that milli-charged particles deposit ~10 keV energy within absorber



A. Haas *et al.*, Phys. Lett. B **746** (2015) 117

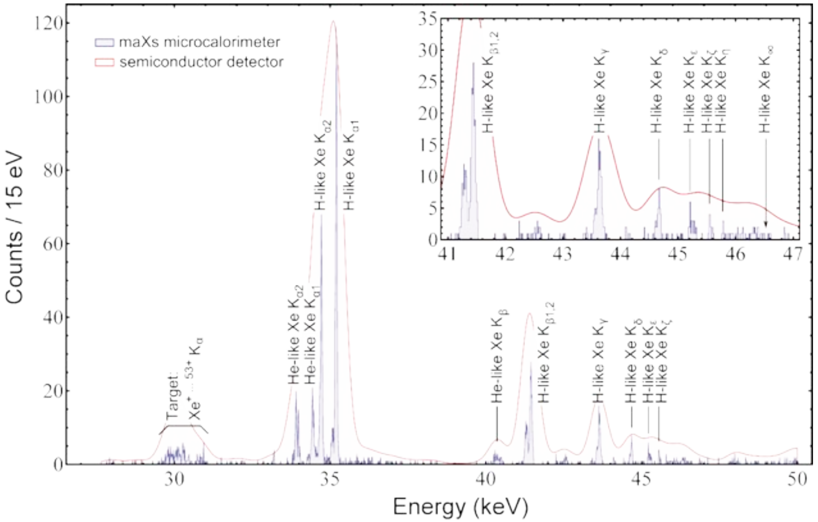


Research directions besides actual applications…

increasing pixel count

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

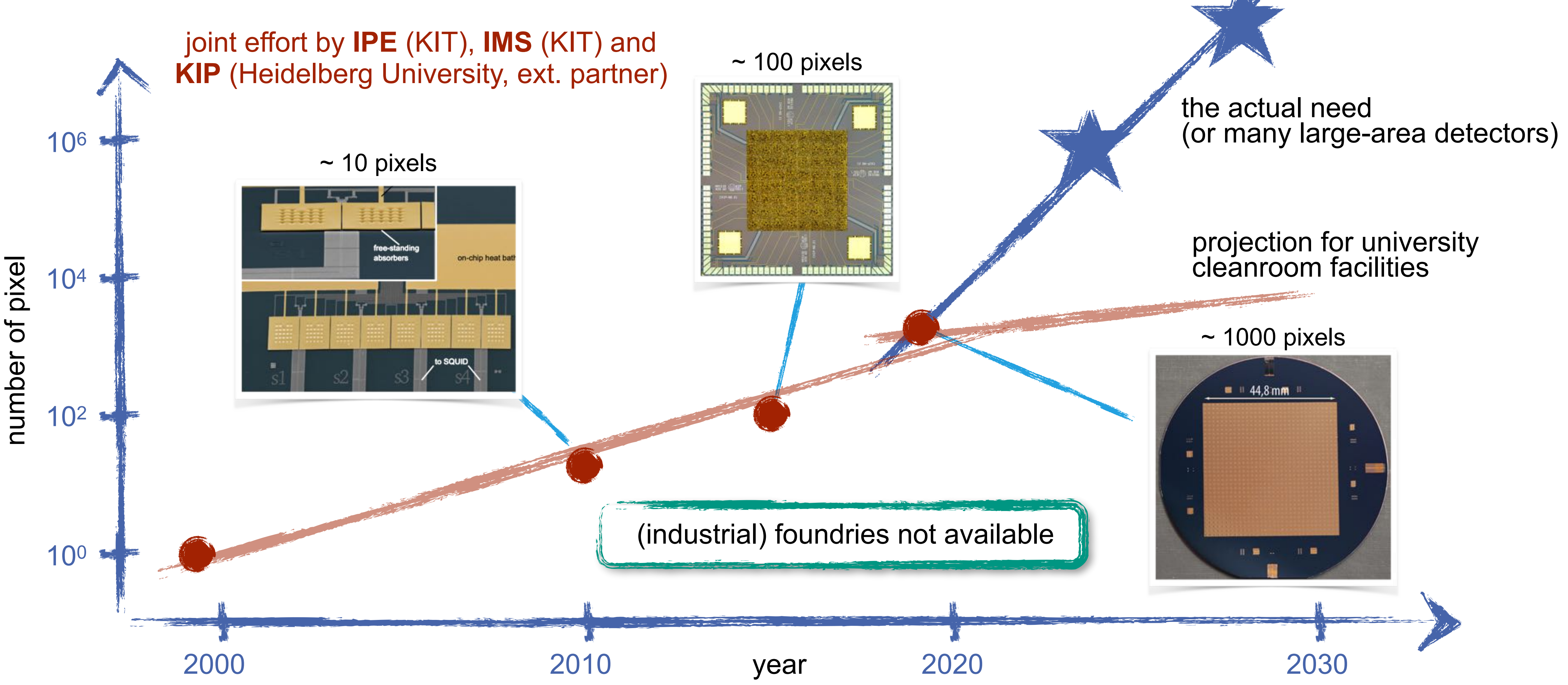
improving energy resolution



- 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)

Karlsruhe Institute of Technology



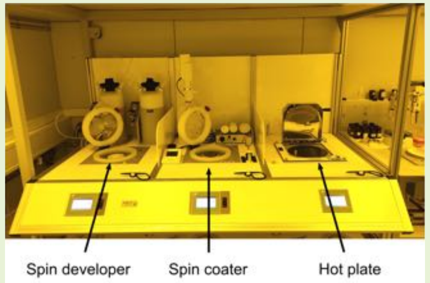
Present status of HSS technology portfolio

large-volume batch fabrication of superconducting sensors (SQUIDs, MMCs, MPTs, TESs, SNSPDs, Qubits, …)

Photolithography

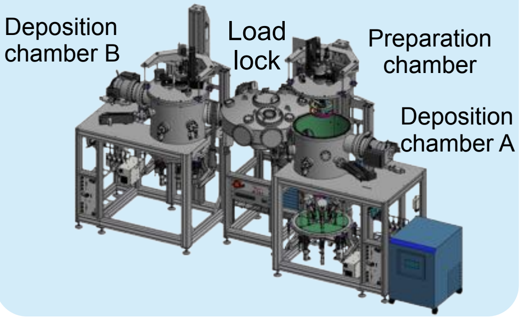
Maskless Aligner MLA 150

Resist Coating / Processing



Deposition systems

UHV Sputter Cluster



ICP-PECVD Cobra 100

Etching systems

ICP-RIE Cobra 100

ICP-RIE Cobra 100

Layer planarization

CMP POLI-400L
Post CMP Cleaner

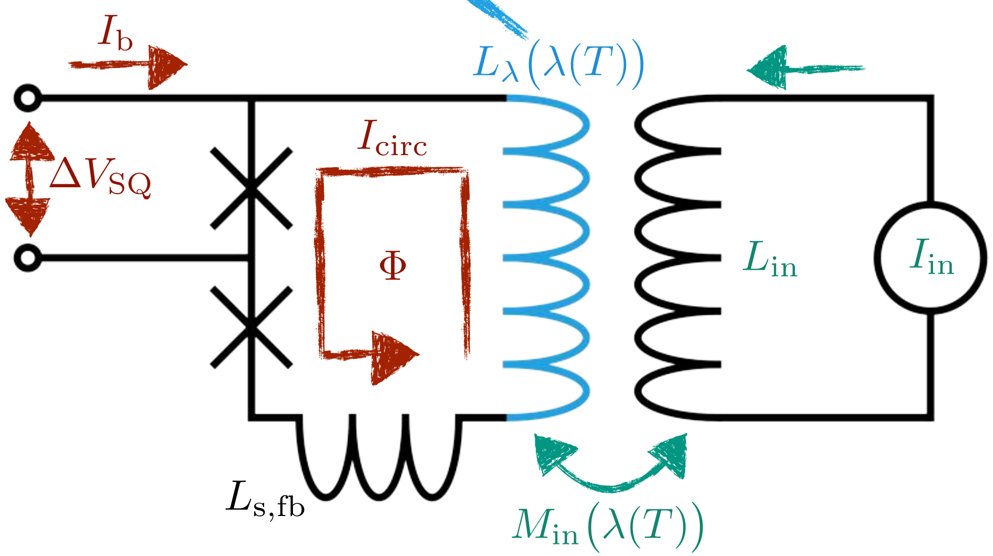
in operation

installation Q1/2025

ordered

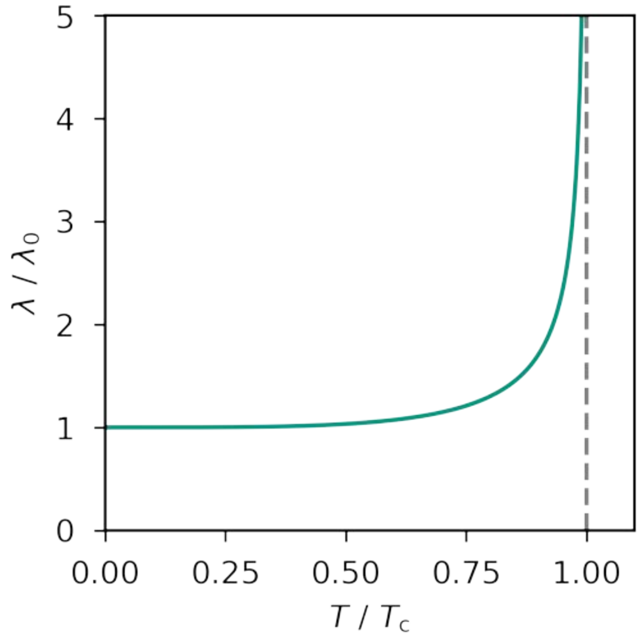
“Novel“ microcalorimeter concept: λ-SQUID

$$L_\lambda(\lambda(T)) = L_{\mathrm{geo}}(\lambda(T)) + L_{\mathrm{kin}}(\lambda(T))$$



$T_c \gg T_{bath}$

$T_{c,\lambda} \gtrapprox T_{bath}$



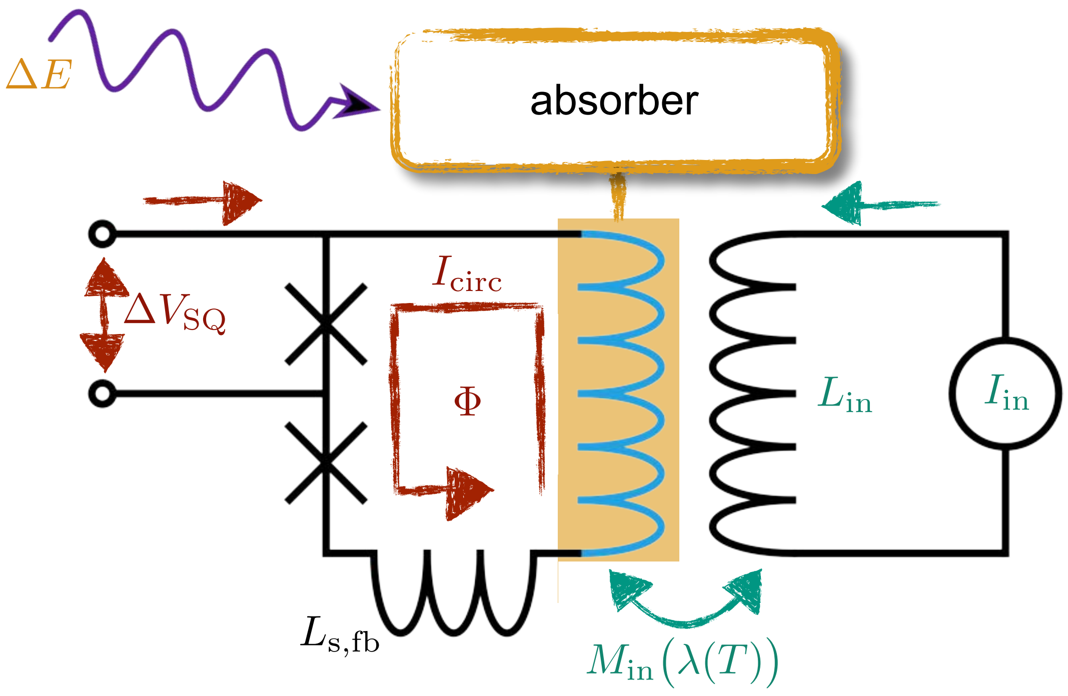
flux within SQUID loop

$$\Phi = \left[\Phi_{ext}(\lambda) + L_s(\lambda) I_{circ}(\Phi)\right]$$

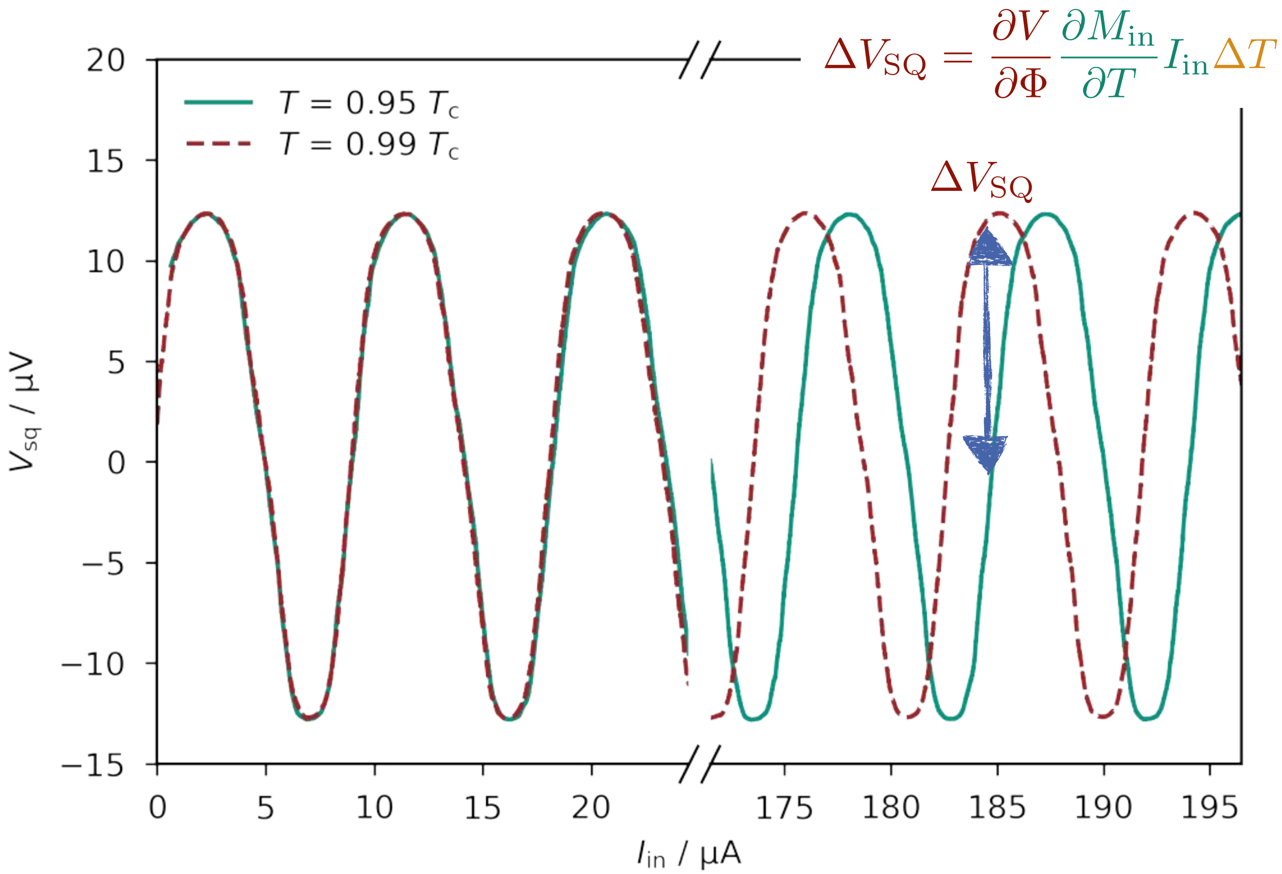
$\Phi_{ext}(\lambda) = M_{in}(\lambda) I_{in}$ $\quad L_s(\lambda) = L_{s,fb} + L_\lambda(\lambda)$

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

“Novel“ microcalorimeter concept: λ-SQUID



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



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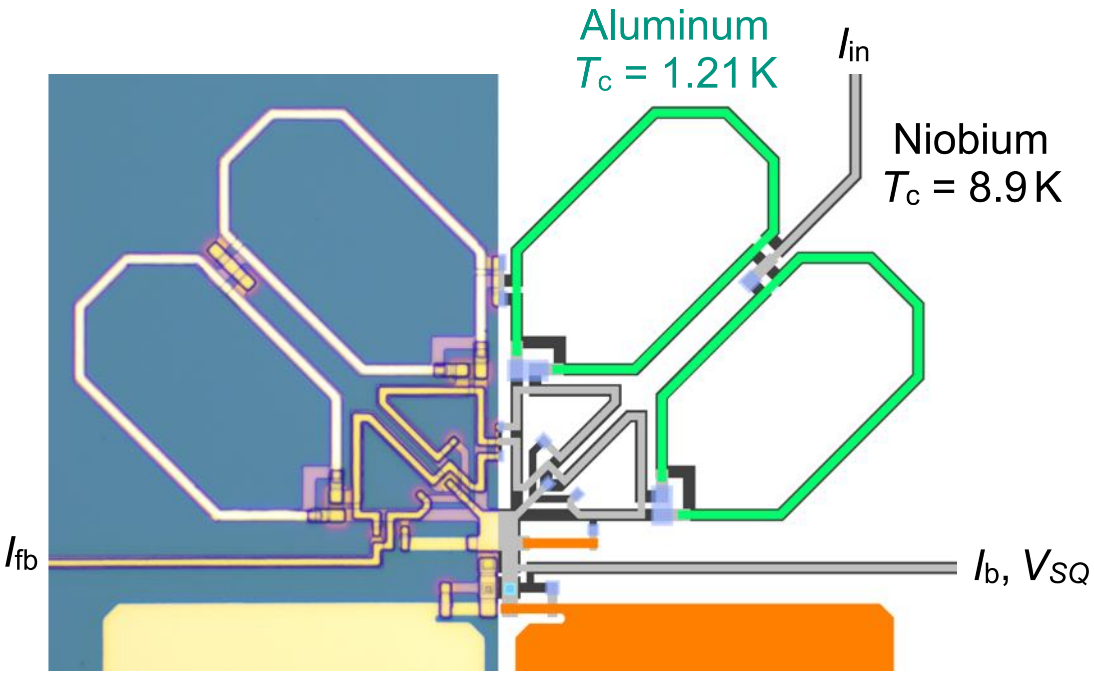
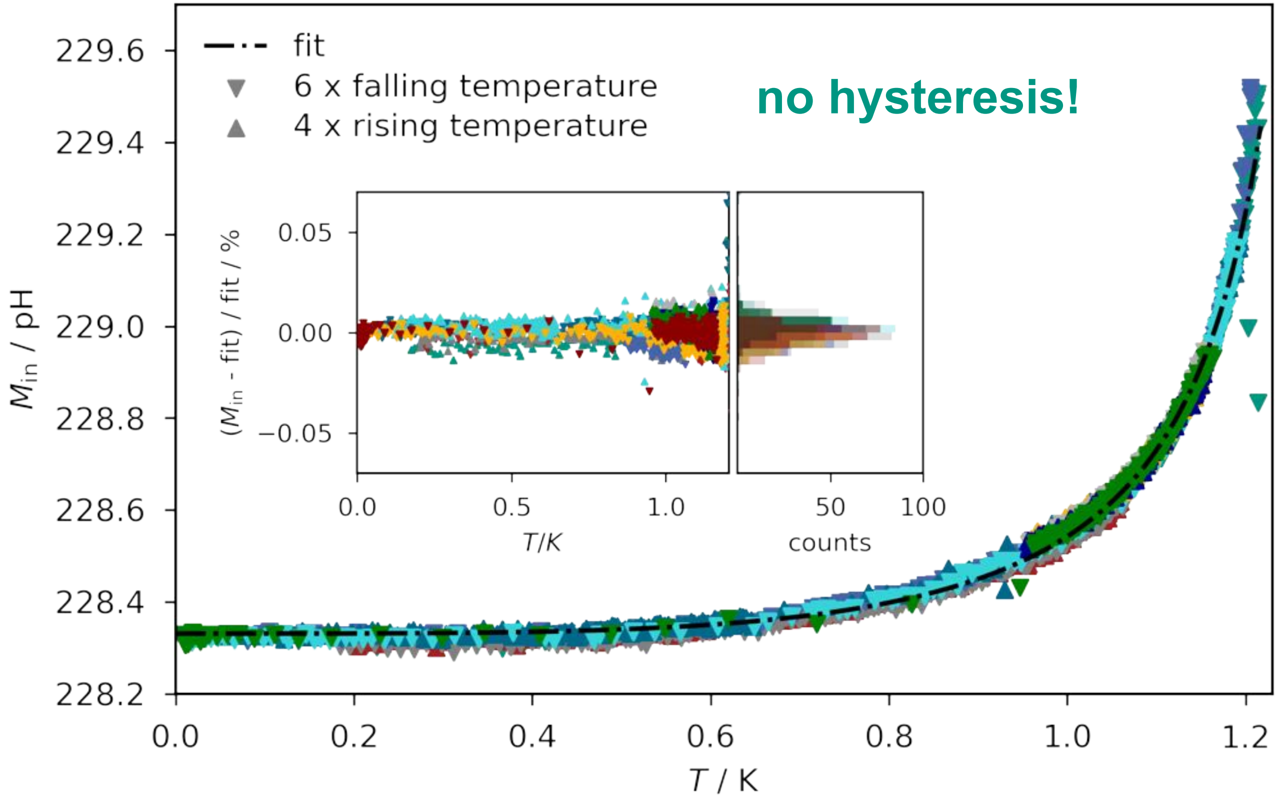
Temperature dependence of mutual inductance M_{in}

prototype device with Al-based λ-coil

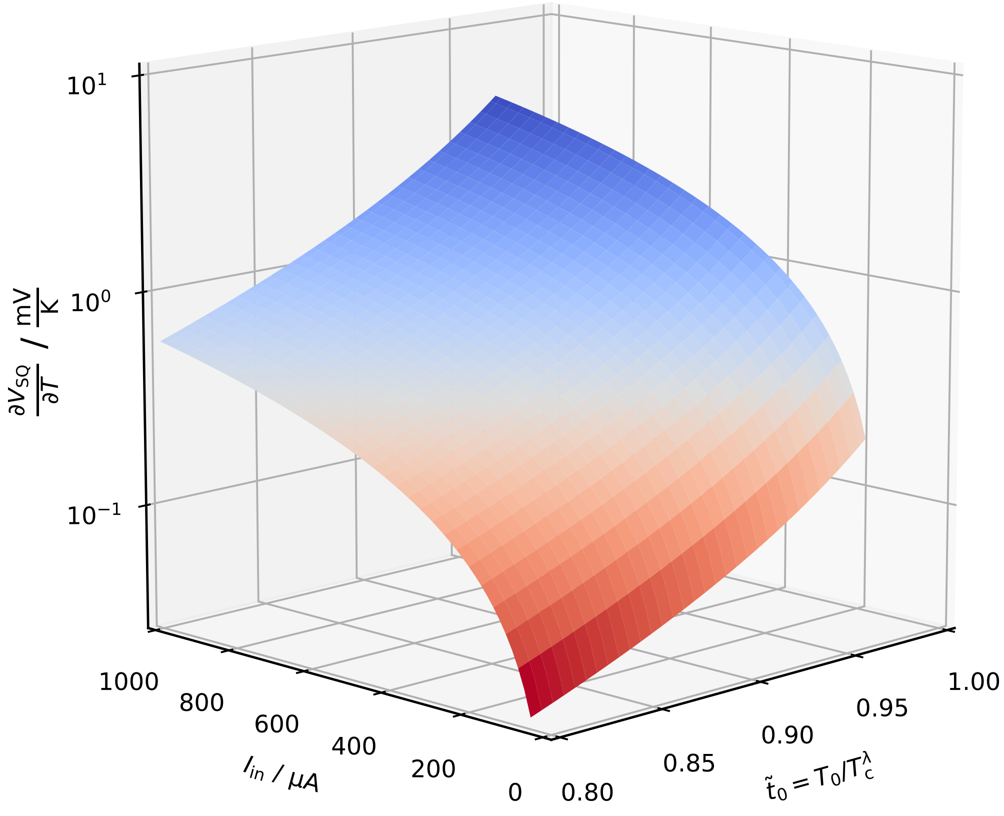


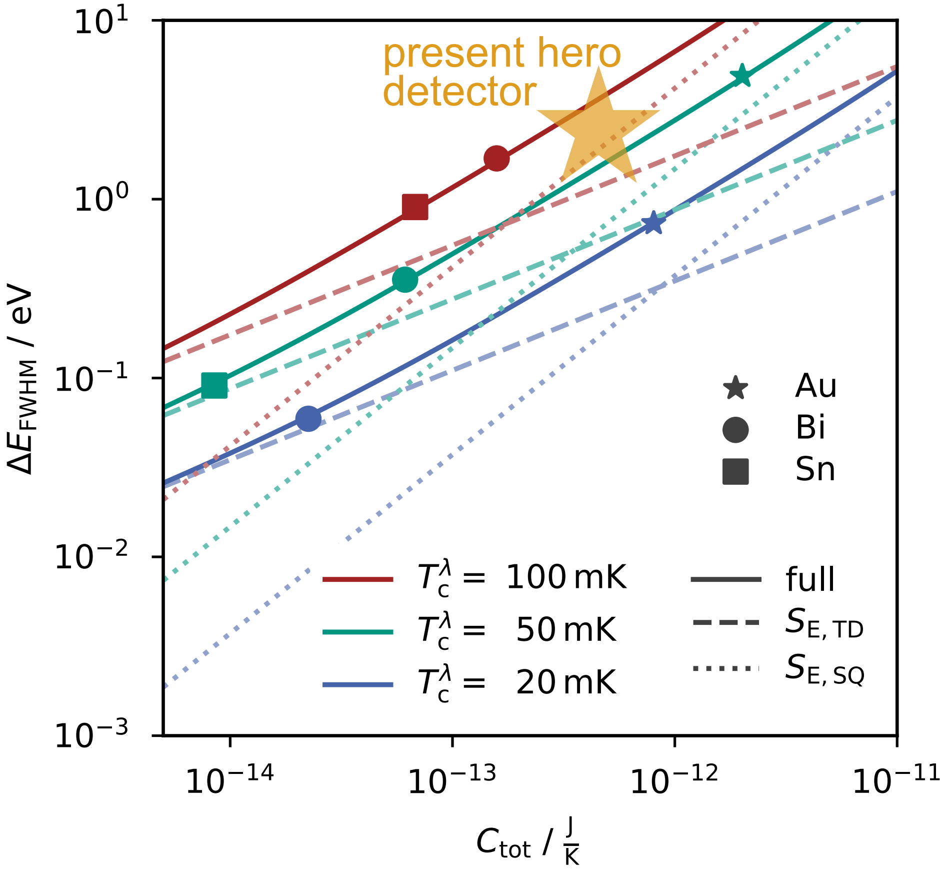


C. Schuster and S. Kempf, Appl. Phys. Lett. **123** (2023) 252603

Sensitivity study / performance estimate

prototype device with Al-based λ-coil





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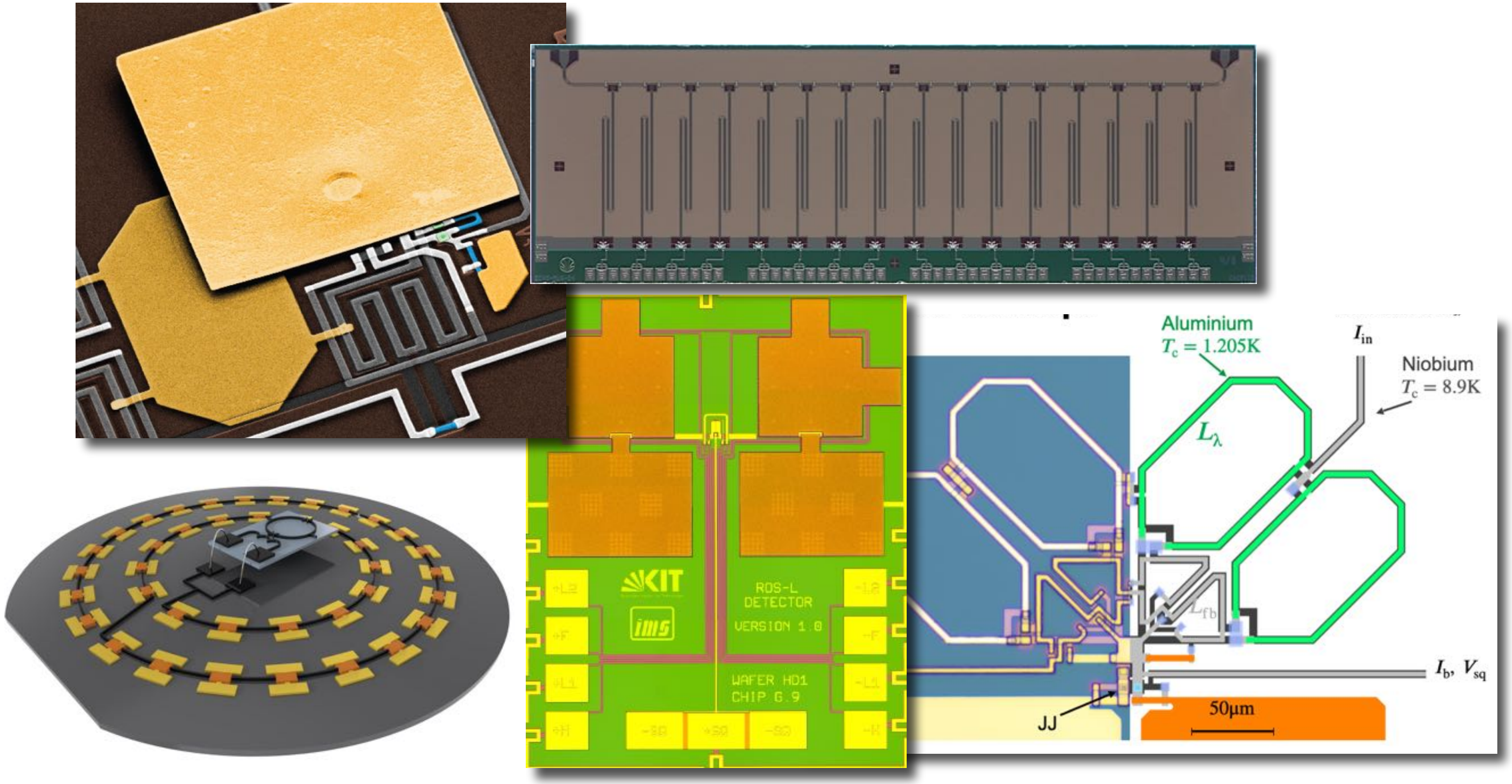
Summary, outlook, and acknowledgments

Karlsruhe Institute of Technology

superconducting quantum sensors are an incredible powerful tool for various applications



my present group

Prof. Sebastian Kempf

Dr. Fabienne Adam
Dr. Mathias Wegner
Dr. Stefan Wünsch

Nik Arldt
Juan Bonaparte
Jesus David Bonilla Neira
Juan Manuel Geria
Lena Hauswald
Michael Müller
Nahuel Müller
Martin Neidig
Constantin Schuster
Friedrich Wagner
Jodok Zeuner

Dr. Konstantin Ilin

Frank Ruhnau
Alexander Stassen
Daniel Hintermayer

Mario Bulic
Erik Frey
Konstantin Georgiev
Jessica Grochola
Mona Heinkelein
Nadine Heublein
Michaelis Ioannou
Gabriel Jülg
Saadia Khurram
Felix Kreft
Noah Rullmann
Dennis Walter

Thank you for your attention!