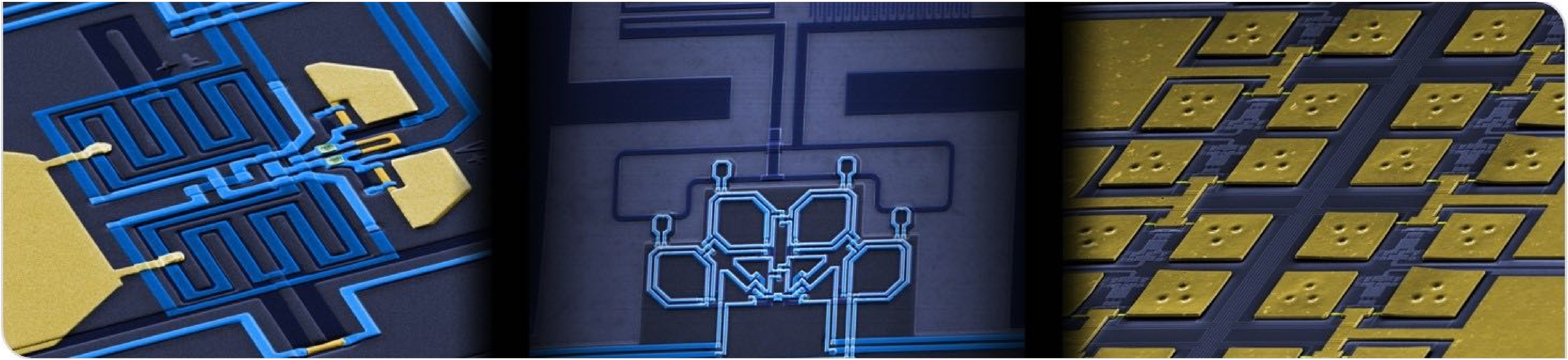
Karlsruhe Institute of Technology

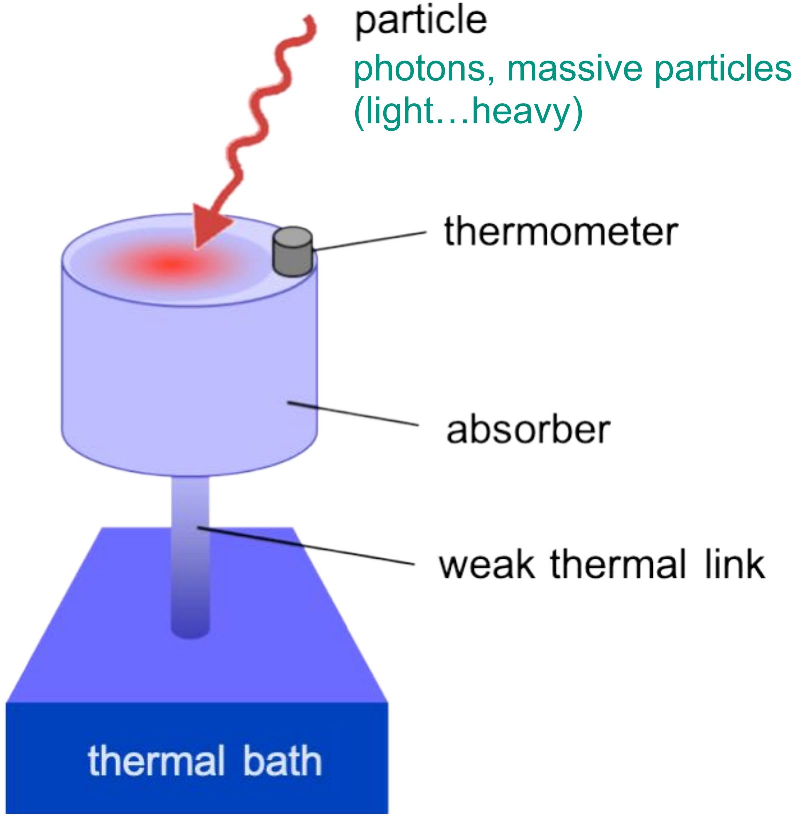
Superconducting quantum sensors
- enabling technology for next-generation physics experiments

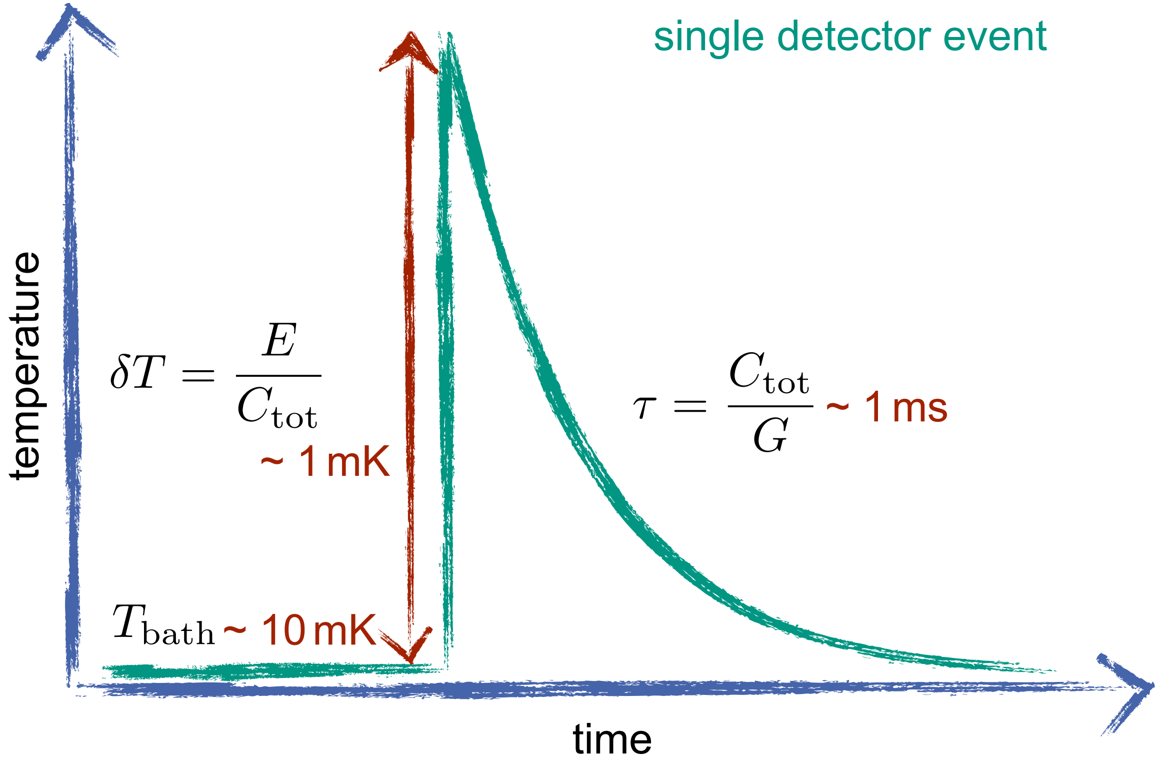
Sebastian Kempf

8th Annual MT Meeting | DESY Hamburg | September 26th-27th, 2022

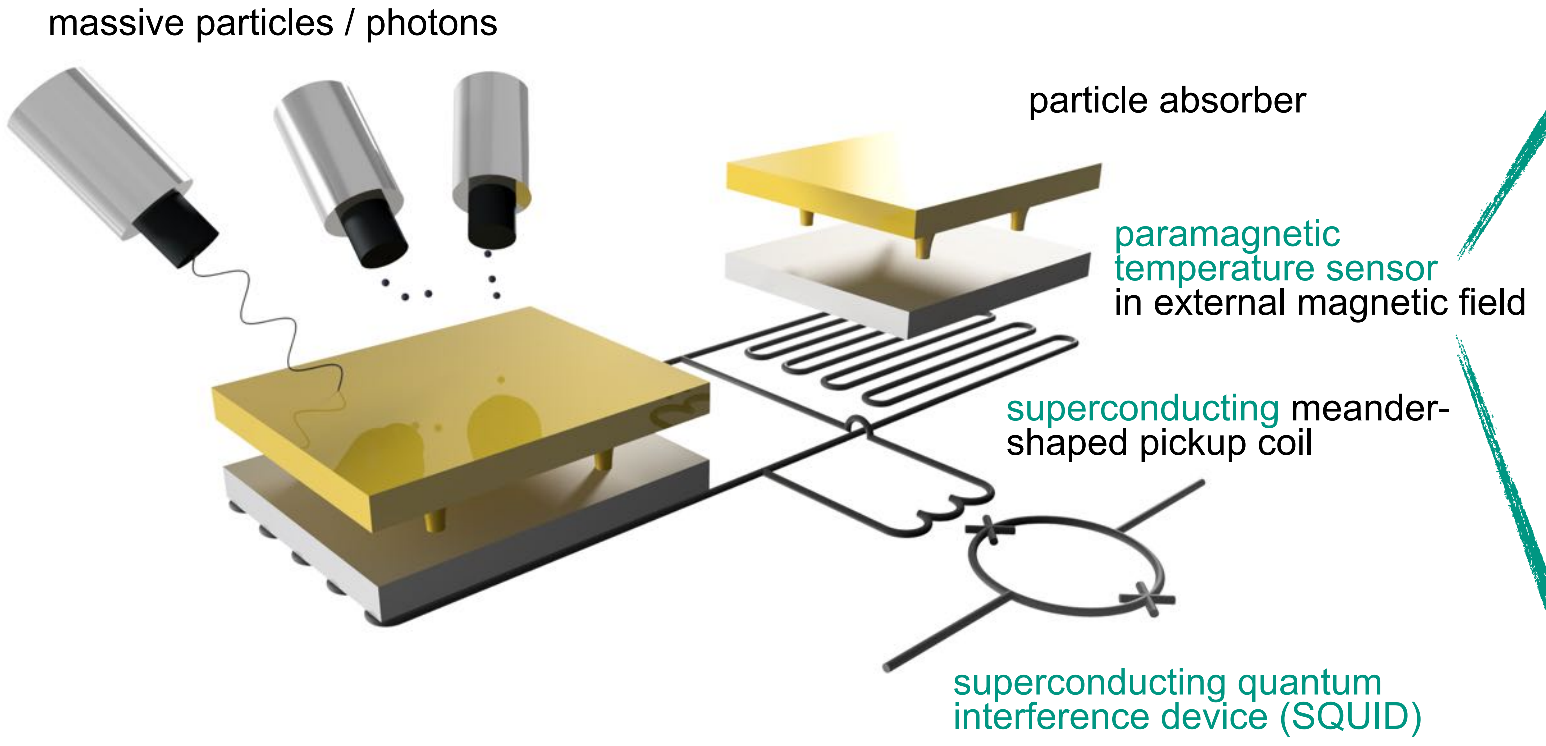


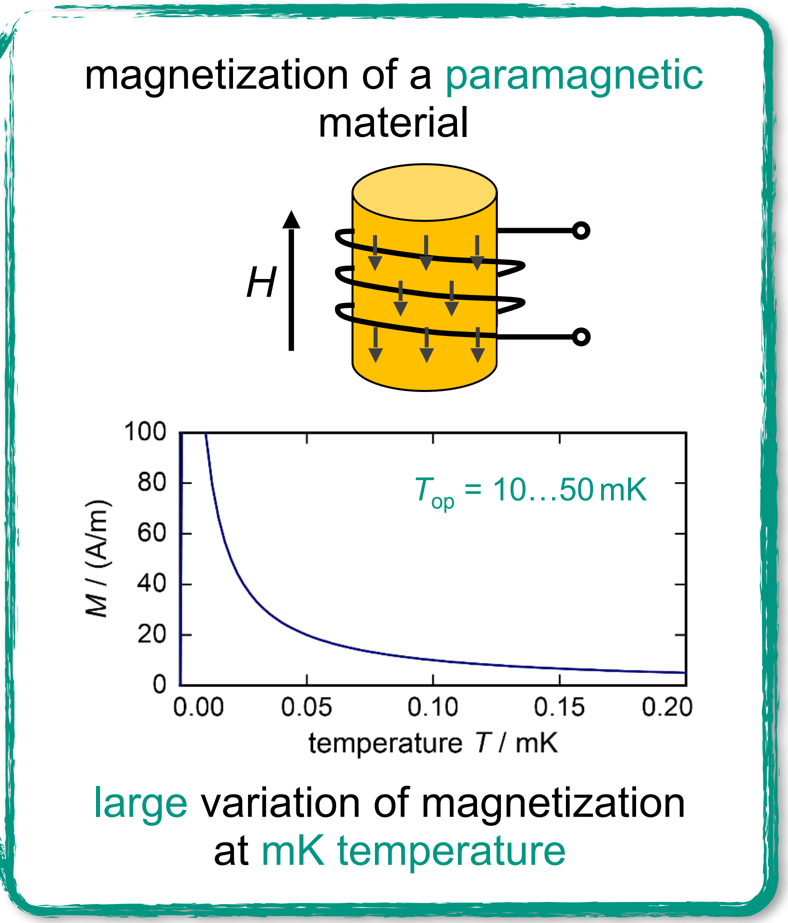
Cryogenic microcalorimeters





Magnetic microcalorimeters (MMCs)





fundamental (thermodynamic) limit on energy resolution

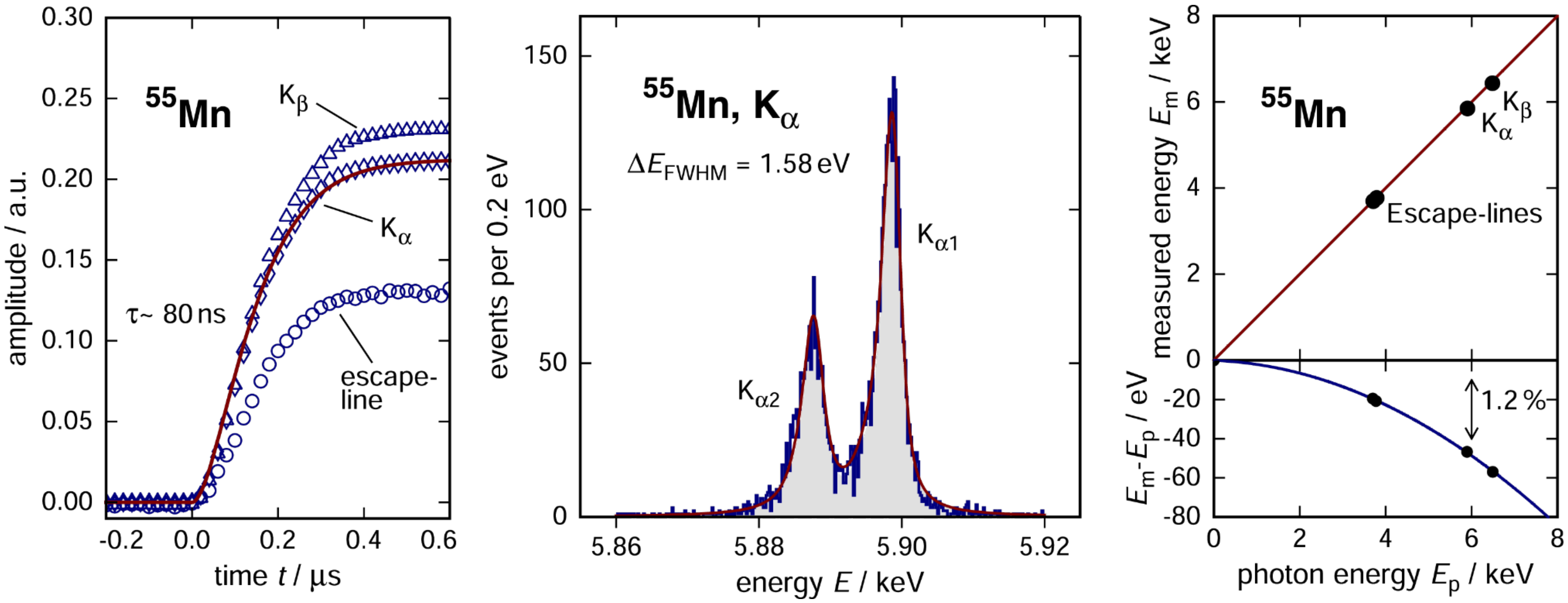
$$\Delta E_{\mathrm{FWHM}} \simeq 2.36\sqrt{4k_{\mathrm{B}}C_{\mathrm{abs}}T^2}\sqrt{2}\left(\frac{\tau_{\mathrm{rise}}}{\tau_{\mathrm{decay}}}\right)^{1/4}$$

Key features of magnetic microcalorimeters

fast signal rise time
$\tau_{rise} < 100\,ns$

excellent energy resolution
$\Delta E_{FWHM} = 1.6\,eV$ @ 6 keV

linear detector response
$NL = 1.2\%$ @ 6 keV



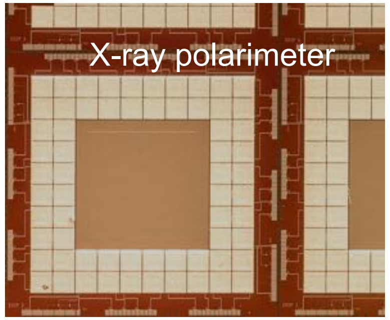
outstanding interplay between ultra-sensitive paramagnetic thermometer and near-quantum limited superconducting electronics device

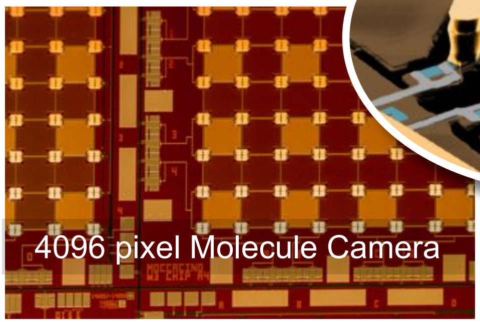
S. Kempf *et al.*, J. Low Temp. Phys. **193** (2018) 365

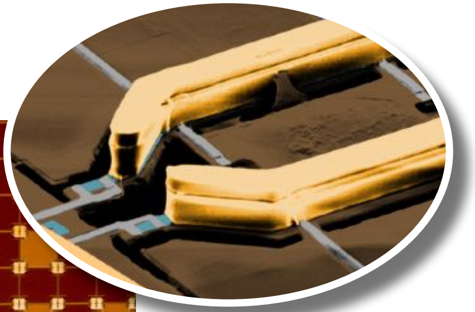
Micro- and nanofabrication

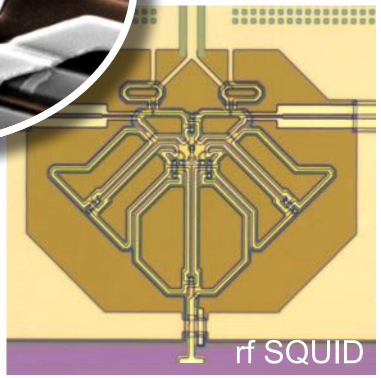

cleanroom @ IMS (KIT)

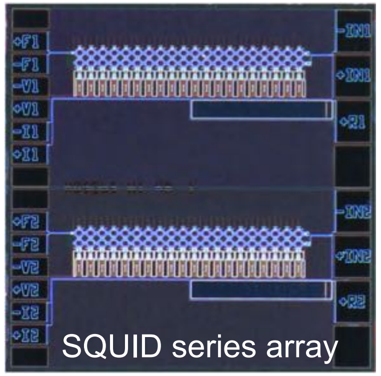
- standard UV-photolithography, EBL beneficial
- up to 18 (30) lithographic layers
- main process requirements:
  reliability, reproducibility, scalability

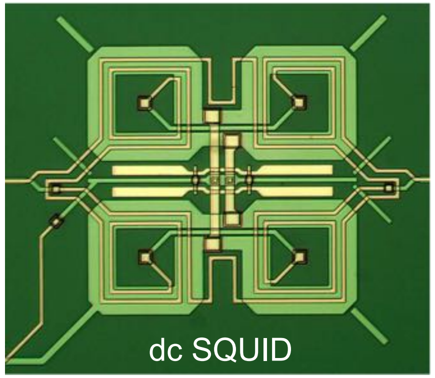

X-ray polarimeter

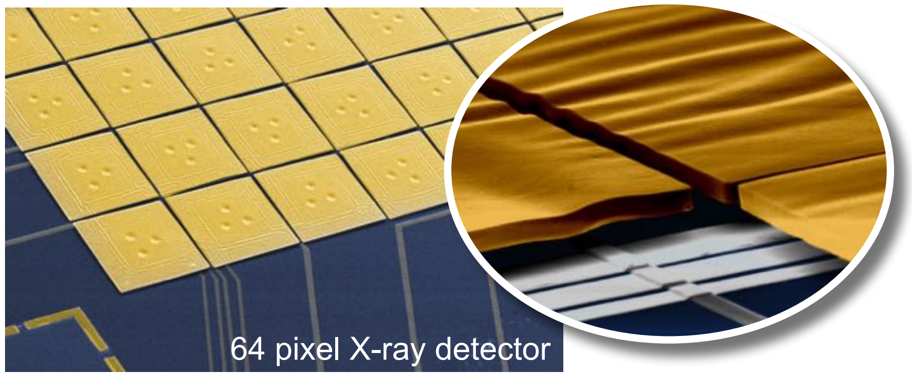

4096 pixel Molecule Camera




rf SQUID


SQUID series array

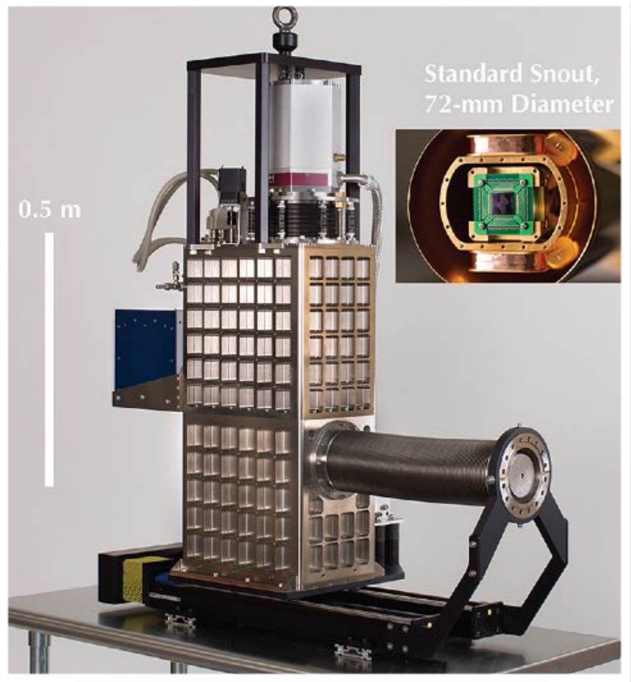

dc SQUID


64 pixel X-ray detector

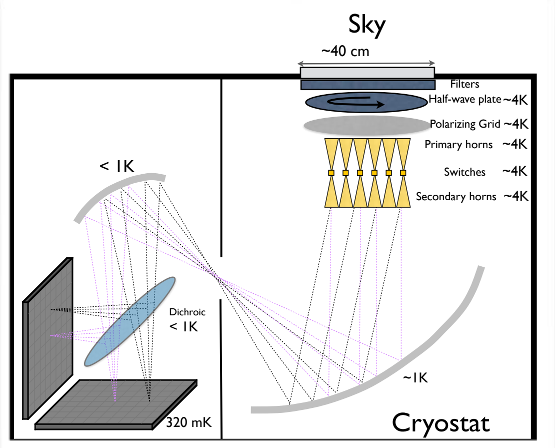
The goal: Large-scale cryogenic detector arrays

some examples:

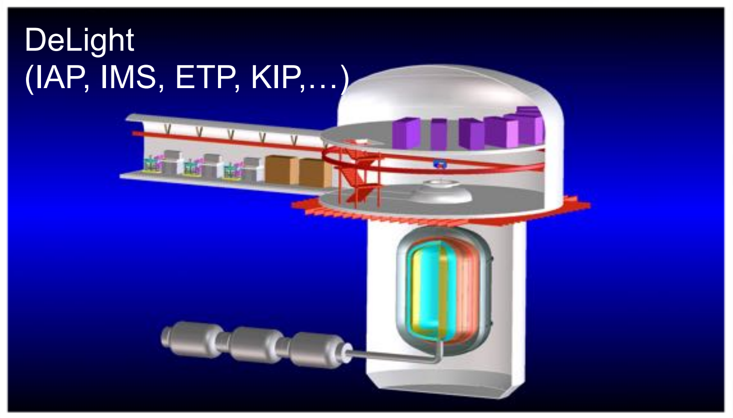
MPx to GPx X-ray cameras
e.g. for synchrotrons, FELs, …



B-mode polarization of CMB

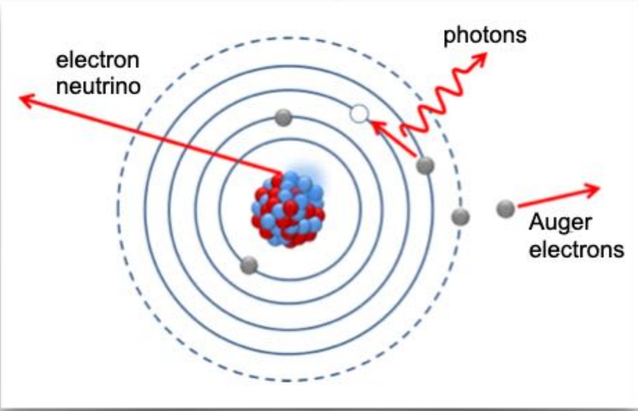


search for neutrino-less double beta decay (AMoRE)

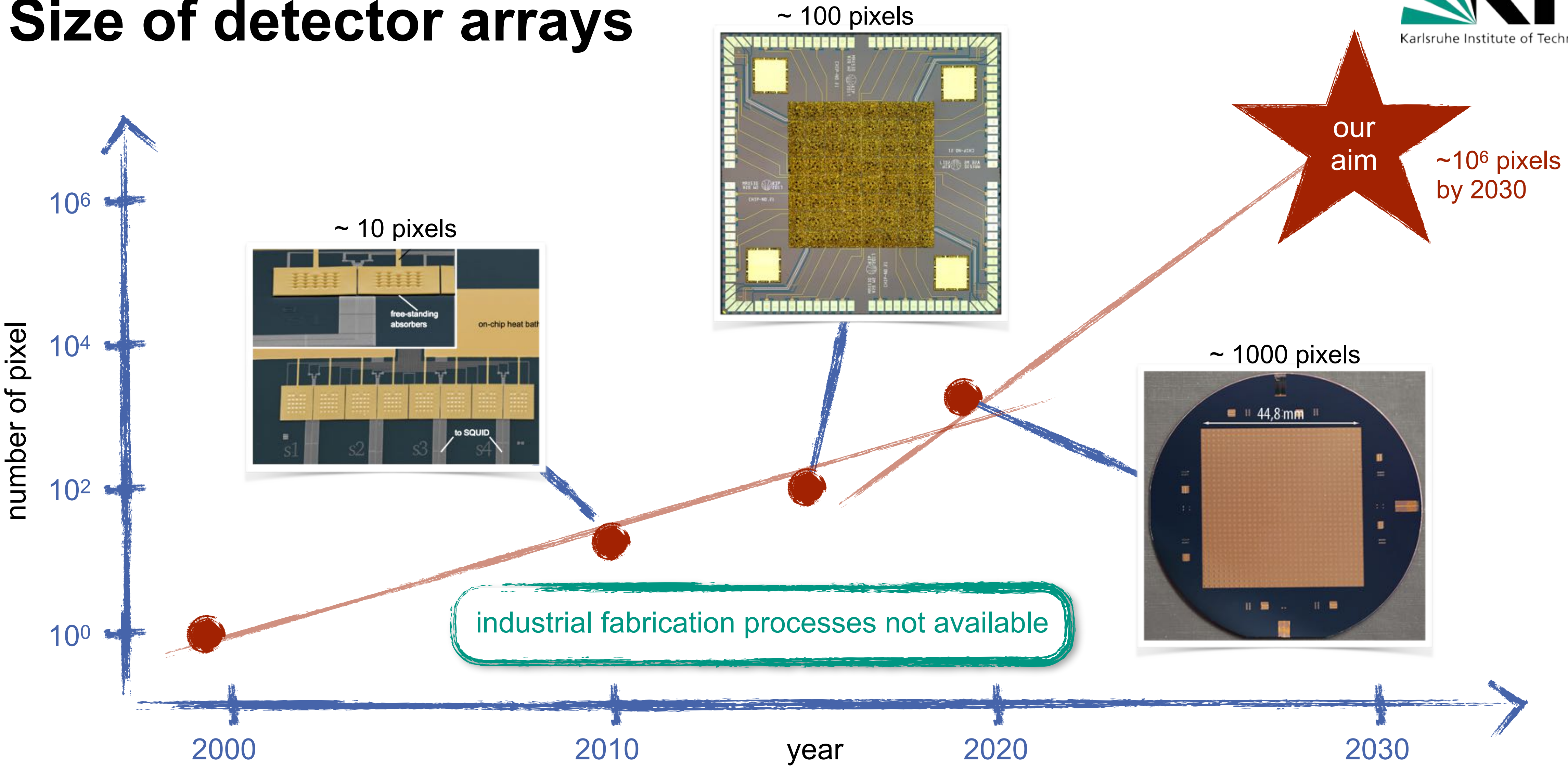


light dark matter searches
using superfluid helium

neutrino mass investigation
with sub-eV sensitivity

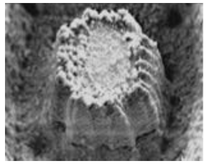
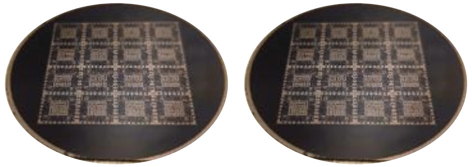
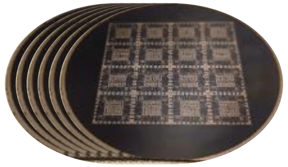
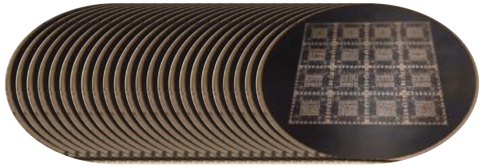


Size of detector arrays

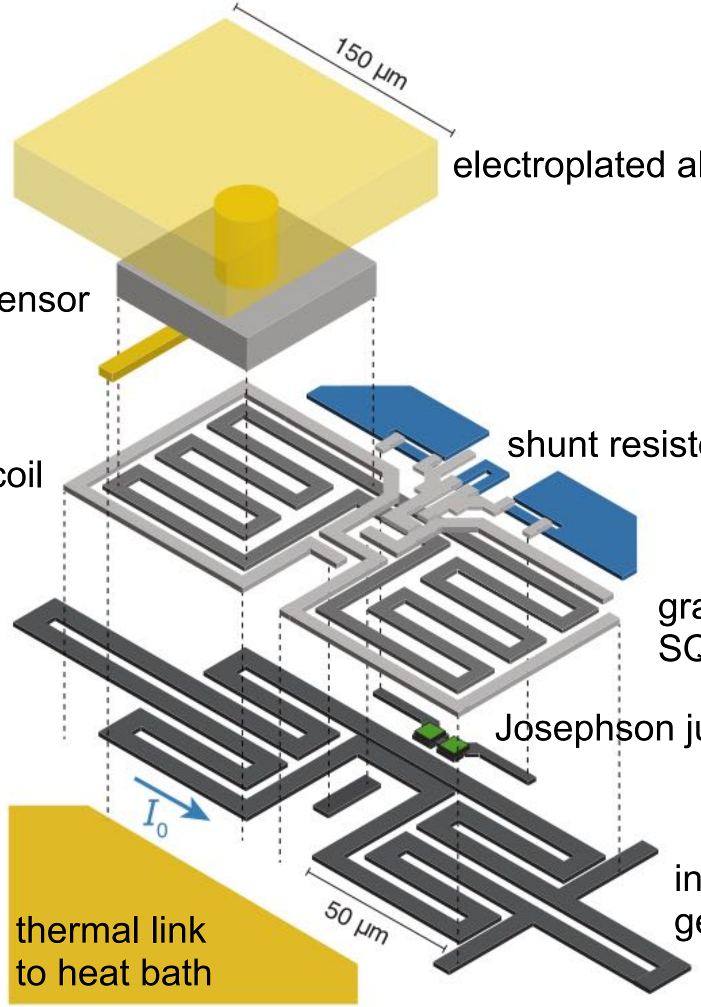


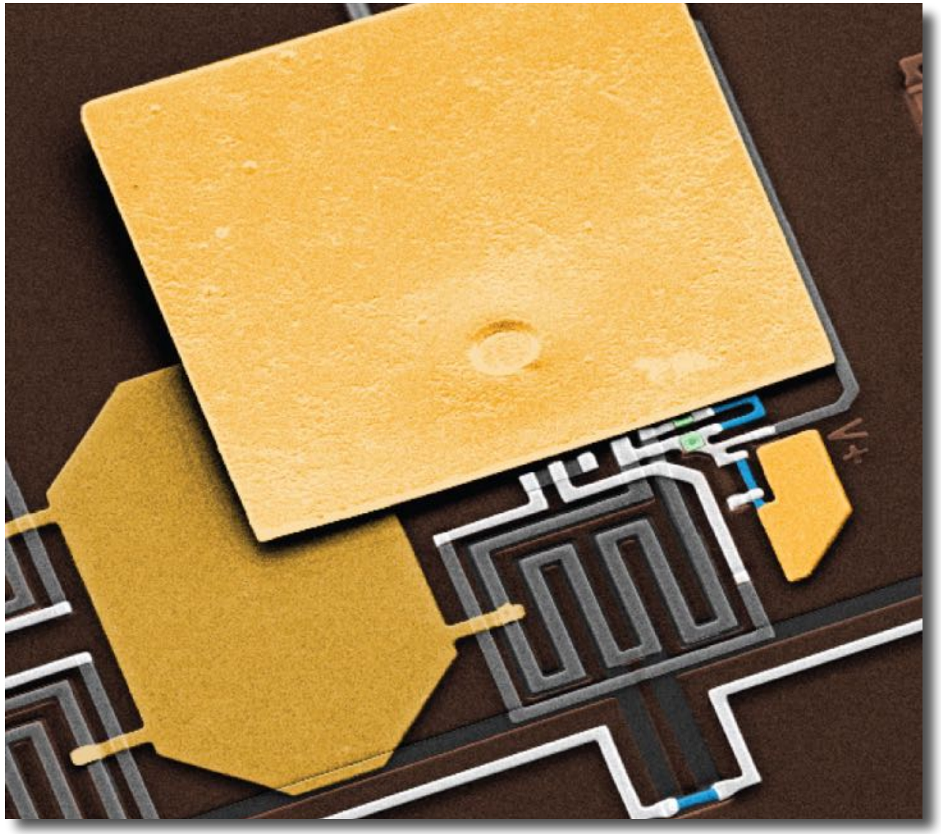
High-resolution superconducting sensors

large-scale infrastructure to foster forefront research activities

“handmade“	university cleanroom	HSS (short term)	HSS / DDL
single pixel fabrication	**2 / 3 inch** substrate **1 – 2 wafers** per month	**4 inch** substrate **10 wafers** per month	**4 / 6 inch** substrate **50 wafers** per month
			
2000	2010	2020	2030
1 pixel	100 pixels	100.000 pixels	1.000.000 pixels
single pixels	medium-sized detector arrays	large-scale experiments	ultra-large-scale experiments

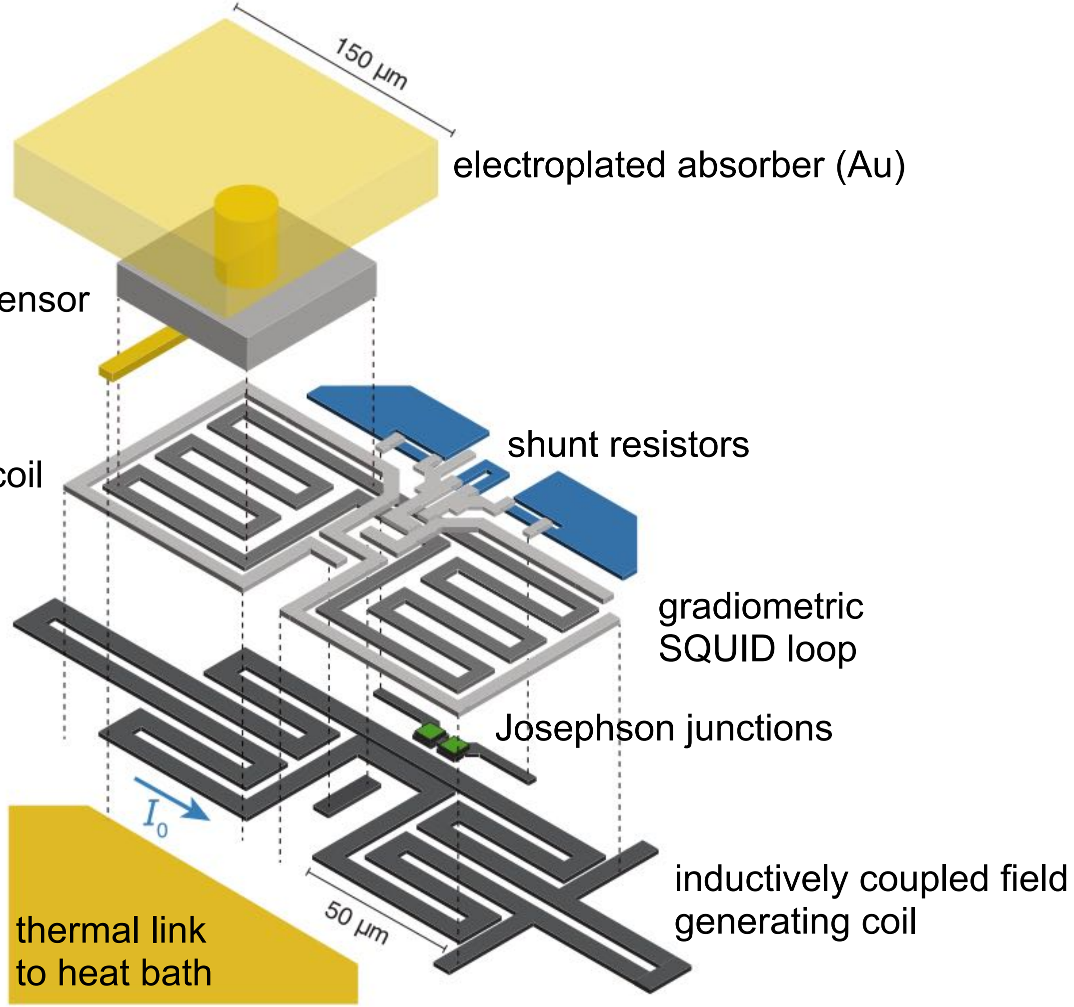
Towards sub-eV energy resolution at eV…10's of keV

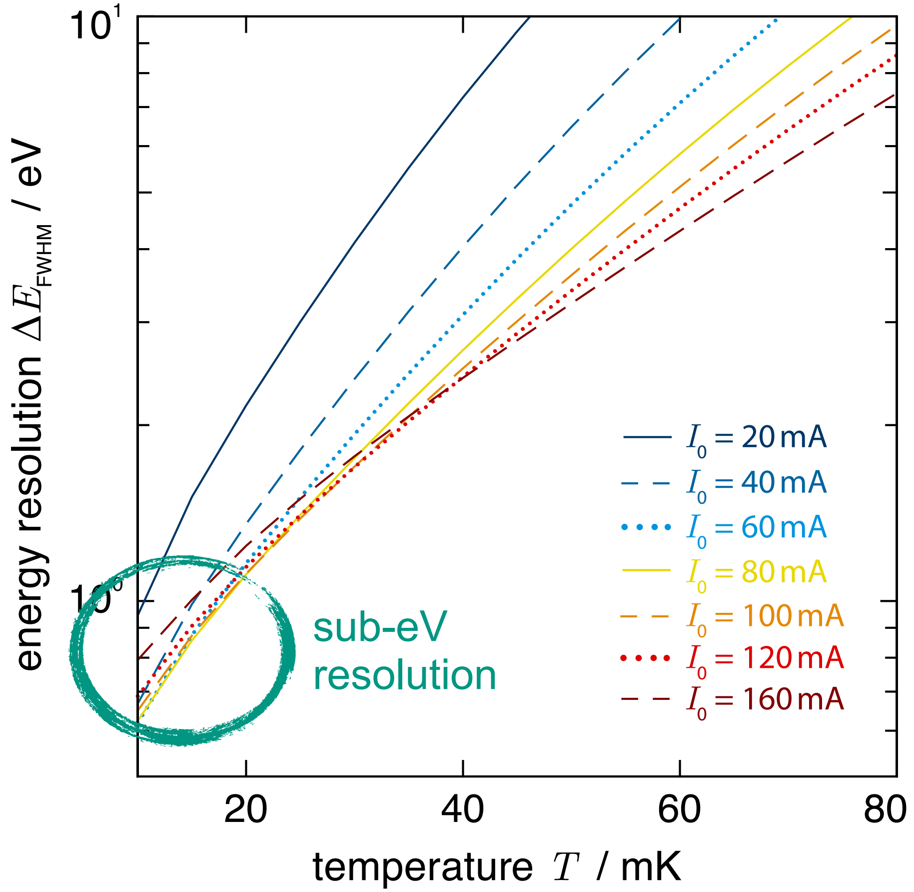




M. Krantz, *PhD thesis*, 2020 + in preparation

Towards sub-eV energy resolution at eV…10's of keV

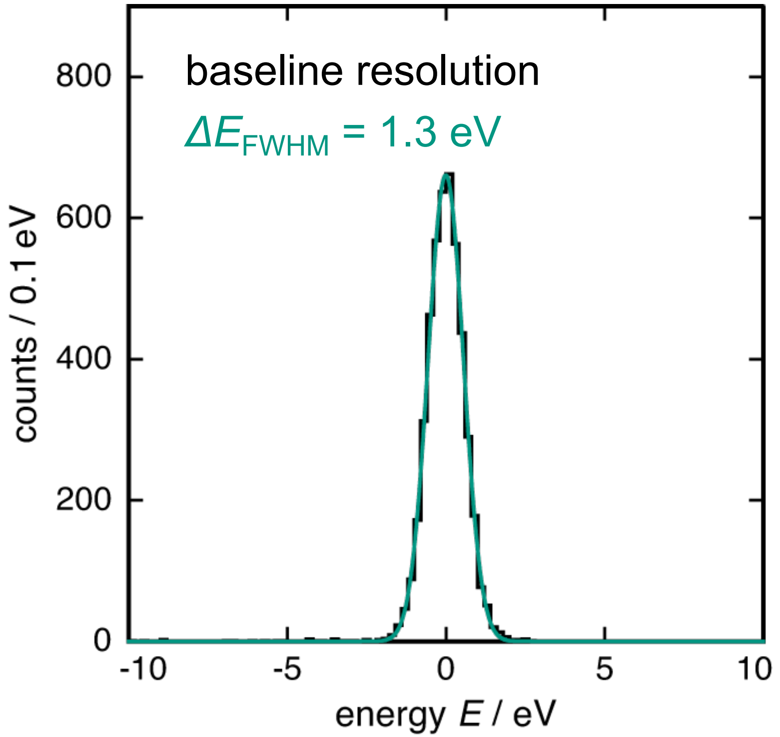




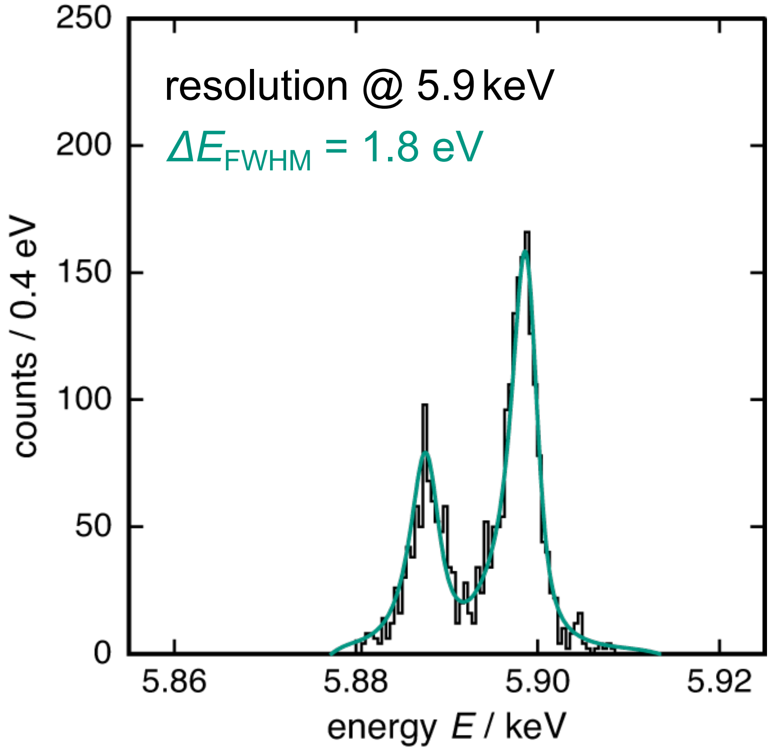
M. Krantz, *PhD thesis*, 2020 + in preparation

Towards sub-eV energy resolution at eV…10’s of keV

operation of HDMSQ in two-stage SQUID setup with home-made amplifier SQUID arrays



baseline resolution lowest ever reached with MMCs

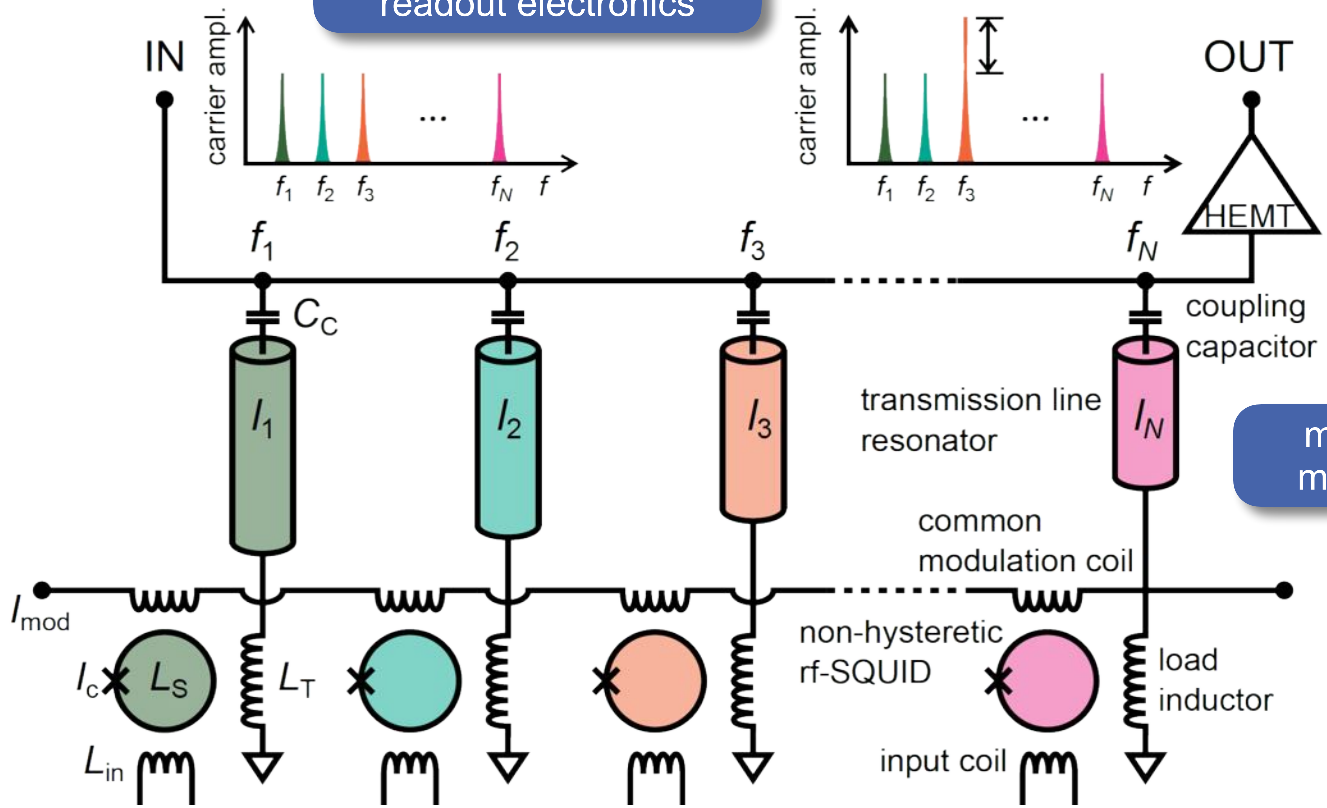


signal analysis not yet in good condition + T-stability

Microwave SQUID Multiplexing

Karlsruhe Institute of Technology

SDR-based readout electronics



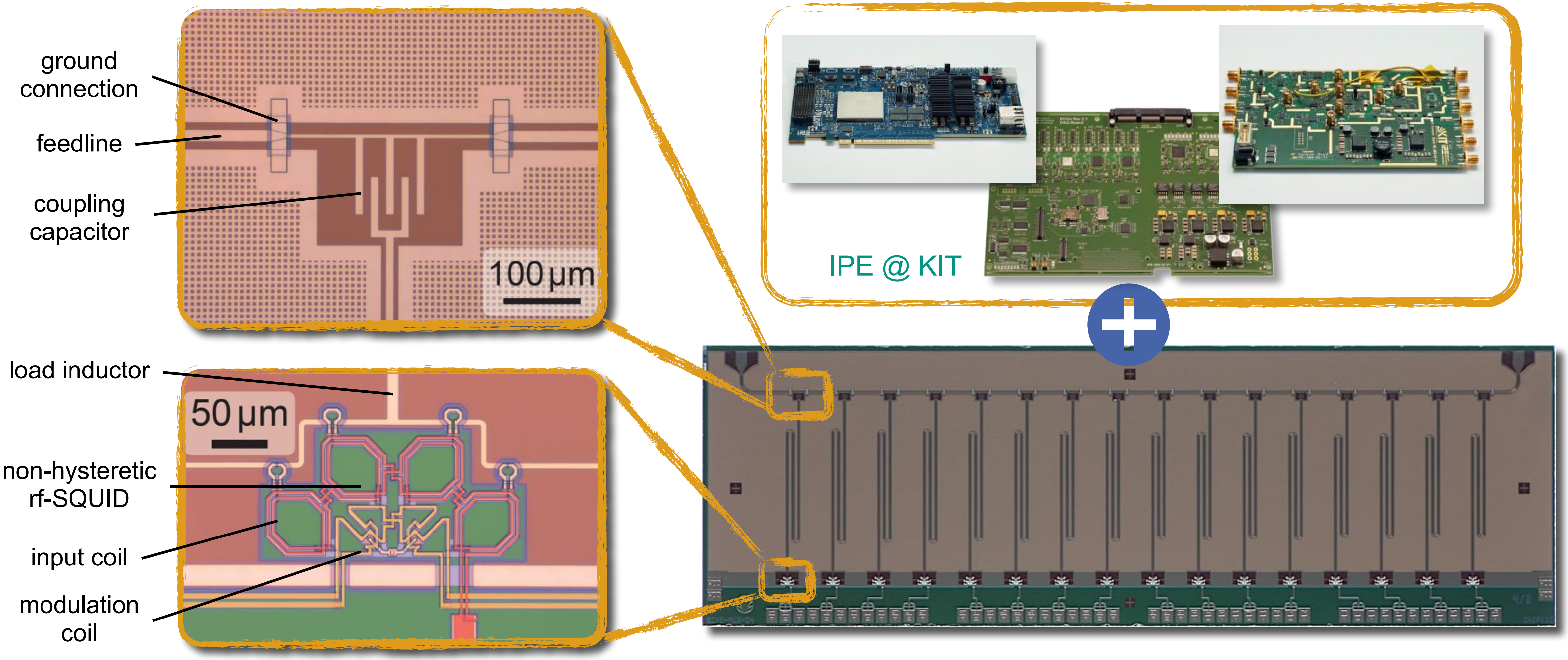
microwave SQUID multiplexer (μMUX)

flux ramp modulation

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
SK *et al.*, J. Low Temp. Phys. **175** (2014) 853
SK *et al.*, AIP Advances **7** (2017) 015007

ECHoMUX - µMUX for the ECHo experiment

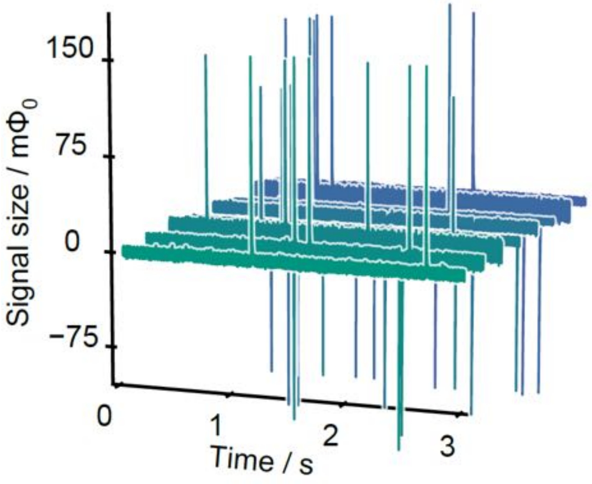


D. Richter, *PhD thesis*, 2021 + in preparation

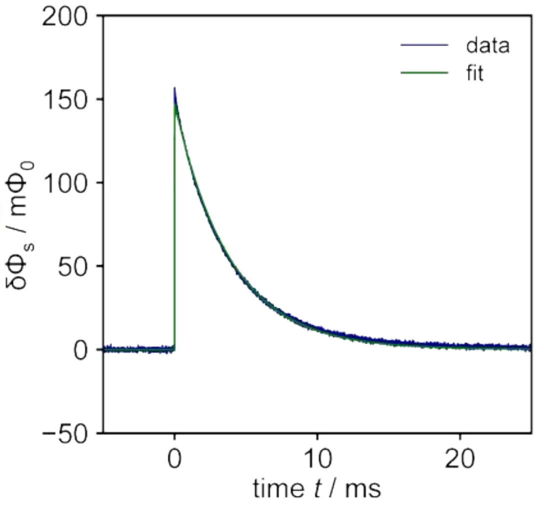
ECHoMUX - some results

64 pixel detector array connect to µMUX (latest generation); full online demodulation

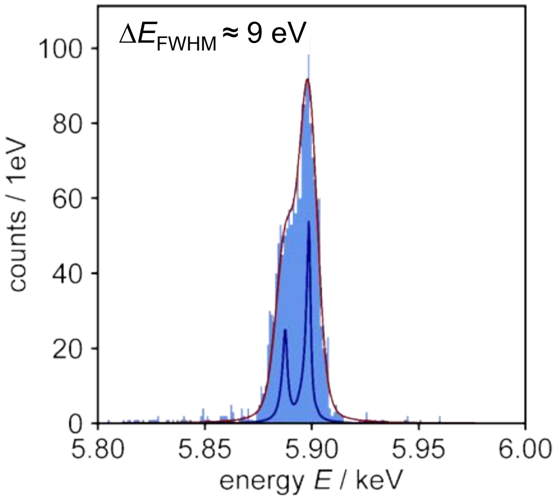
time traces of 16 detector pixels



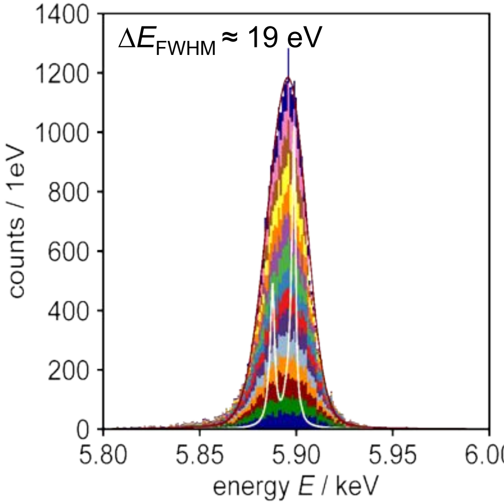
single raw data trace



'typical' spectrum



sum spectrum



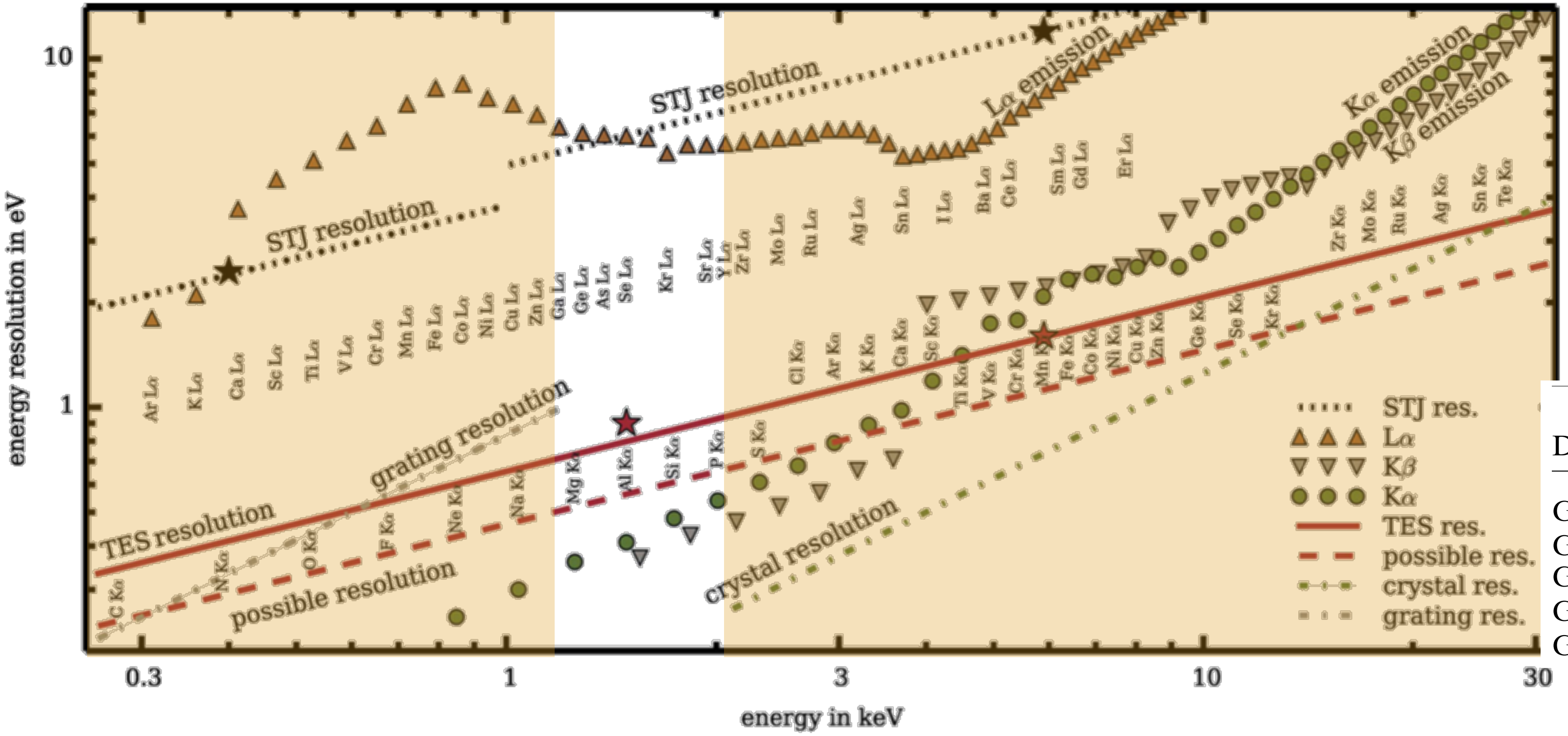
first truely multiplexing demonstration of magnetic microcalorimeters
some issues still to be resolved (ongoing)

D. Richter, *PhD thesis*, 2021 + in preparation

X-ray spectroscopy

X-ray spectroscopy is a versatile tool that can be used for a variety of applications, e.g. HERFD, RIXS, XES, …

gratings crystal spectrometers



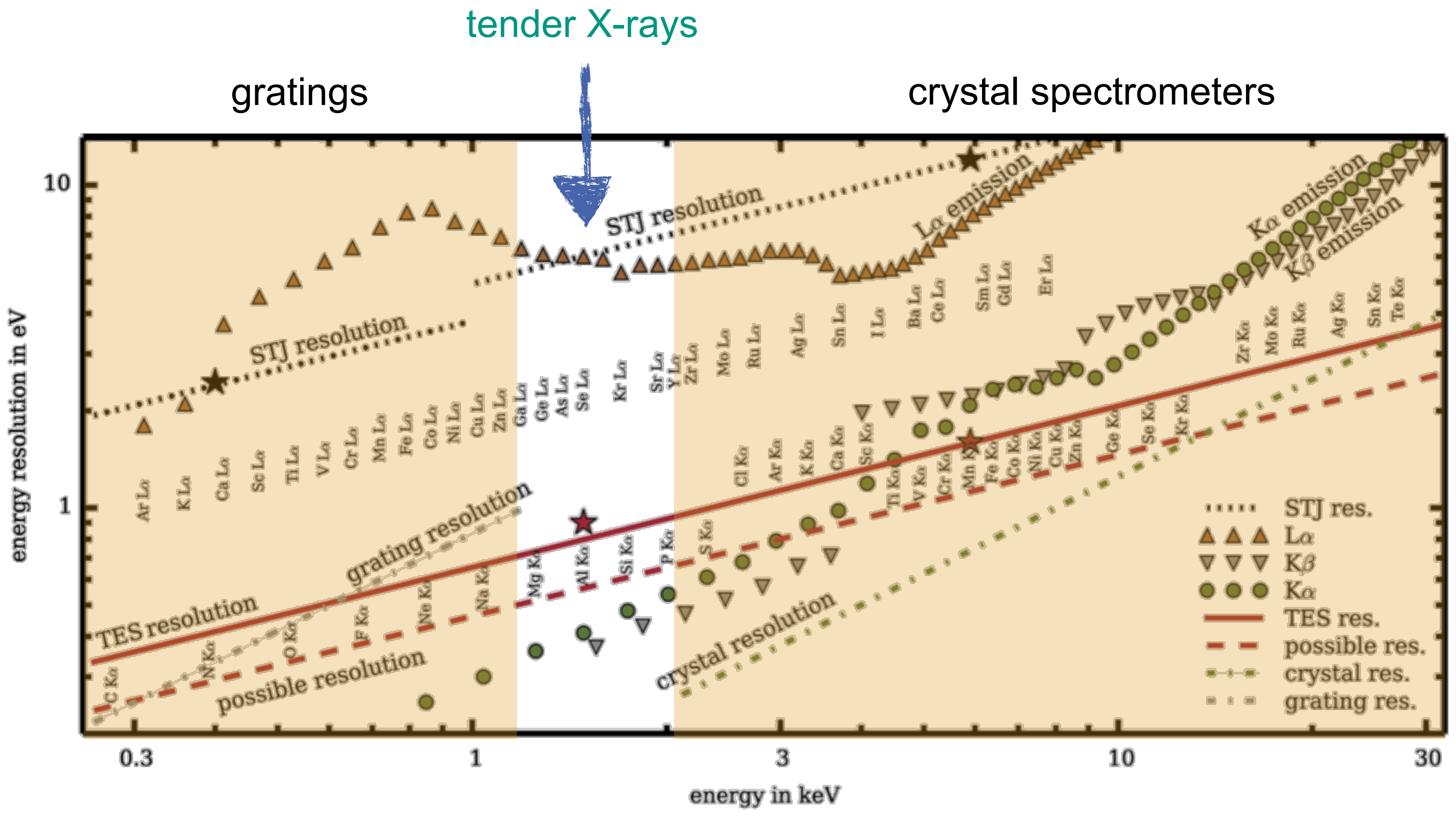
semiconductor vs.
grating spectrometer

Detector	Resolution ΔE_{FWHM} (eV)	Count rate (counts s^{-1})	Efficiency $\eta\Omega/4\pi$
Ge (typical)	130	3×10^5	0.1
Ge (best)	60	3×10^4	0.03
Grating (typical)	0.5	10^5	10^{-6}
Grating (best)	0.2	10^6	10^{-5}
Grating with optic	0.2	10^6	3×10^{-4}

count-rate / efficiency vs. resolution

J. Uhlig *et al.*, J. Synchrotron Rad. **22** (2015) 766-775

Tender X-rays



applications of tender X-rays
(as taken from NSLS-II website)

catalysis:
- materials (zeolites, thin films, nanomaterials)
- reaction mechanisms and intermediate species
- poisoning

energy materials:
- photovoltaic
- fuel cell
- battery and superconducting (nano) materials

environmental/earth science:
- biogeochemical and redox processes
- contaminant behavior and remediation

climate:
- terrestrial and marine C cycling
- carbonate mineralization
- geologic record of climate change

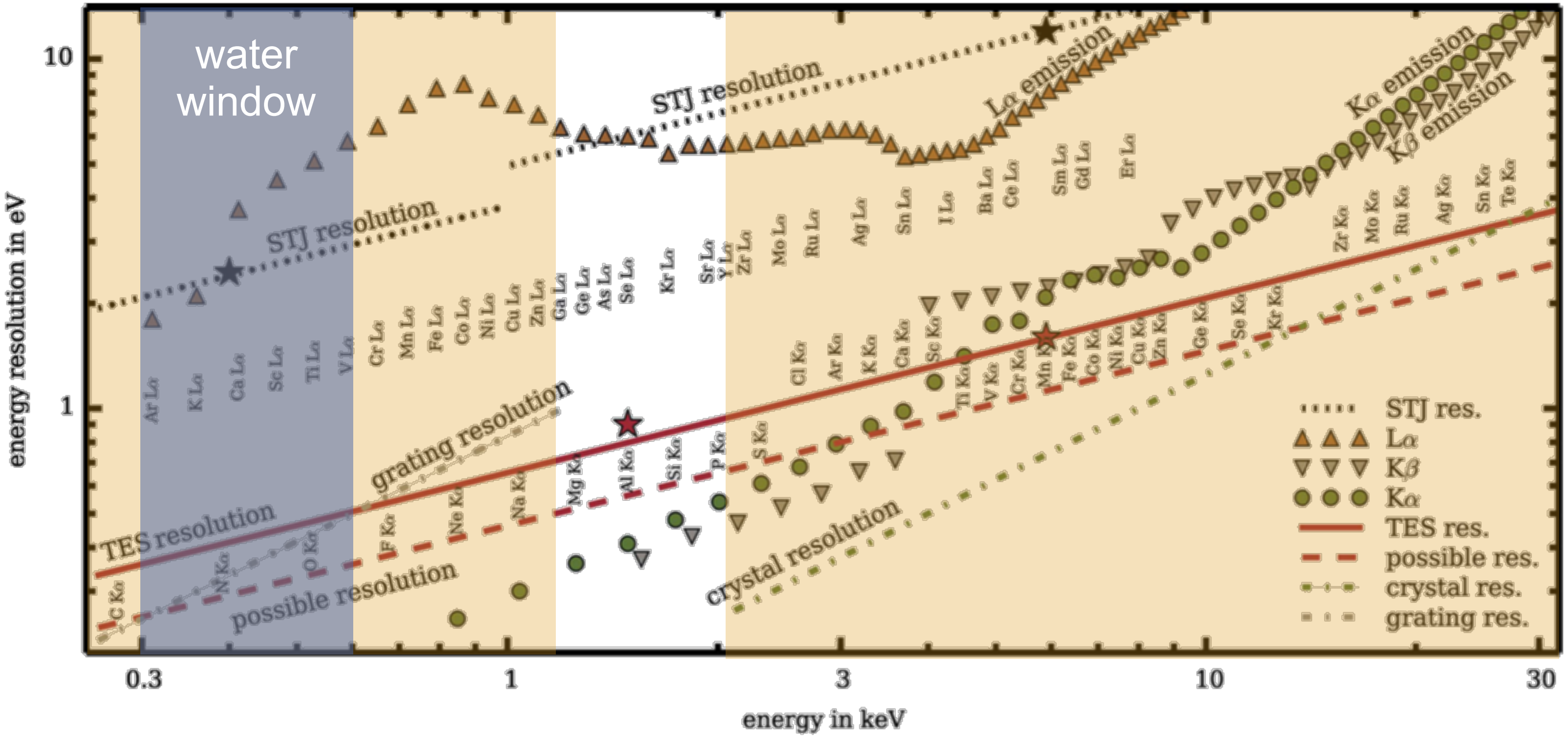
sustainability:
- nutrient (P, S, K, Ca, Mg, Fe) cycling
- transport and bioavailability
- biofuel/biomass productivity

J. Uhlig *et al.*, J. Synchrotron Rad. **22** (2015) 766-775

Water window

gratings

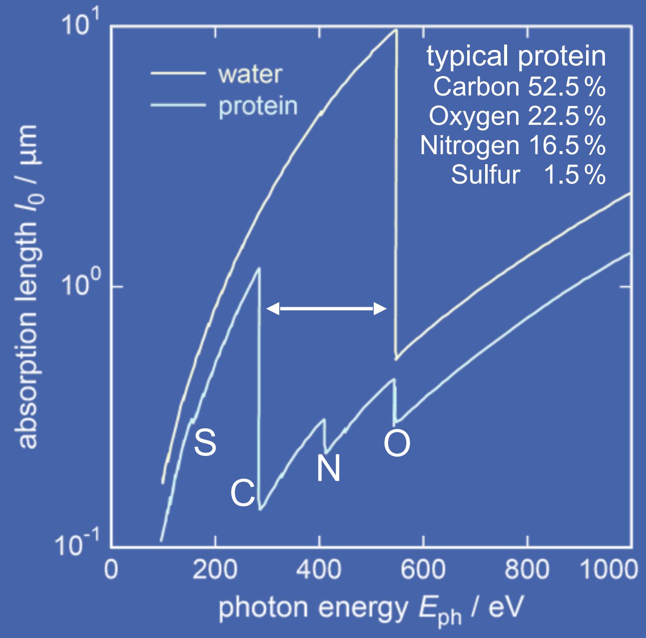
crystal spectrometers



resolution of conv. detectors sufficient, but quantum efficiency too low

water window

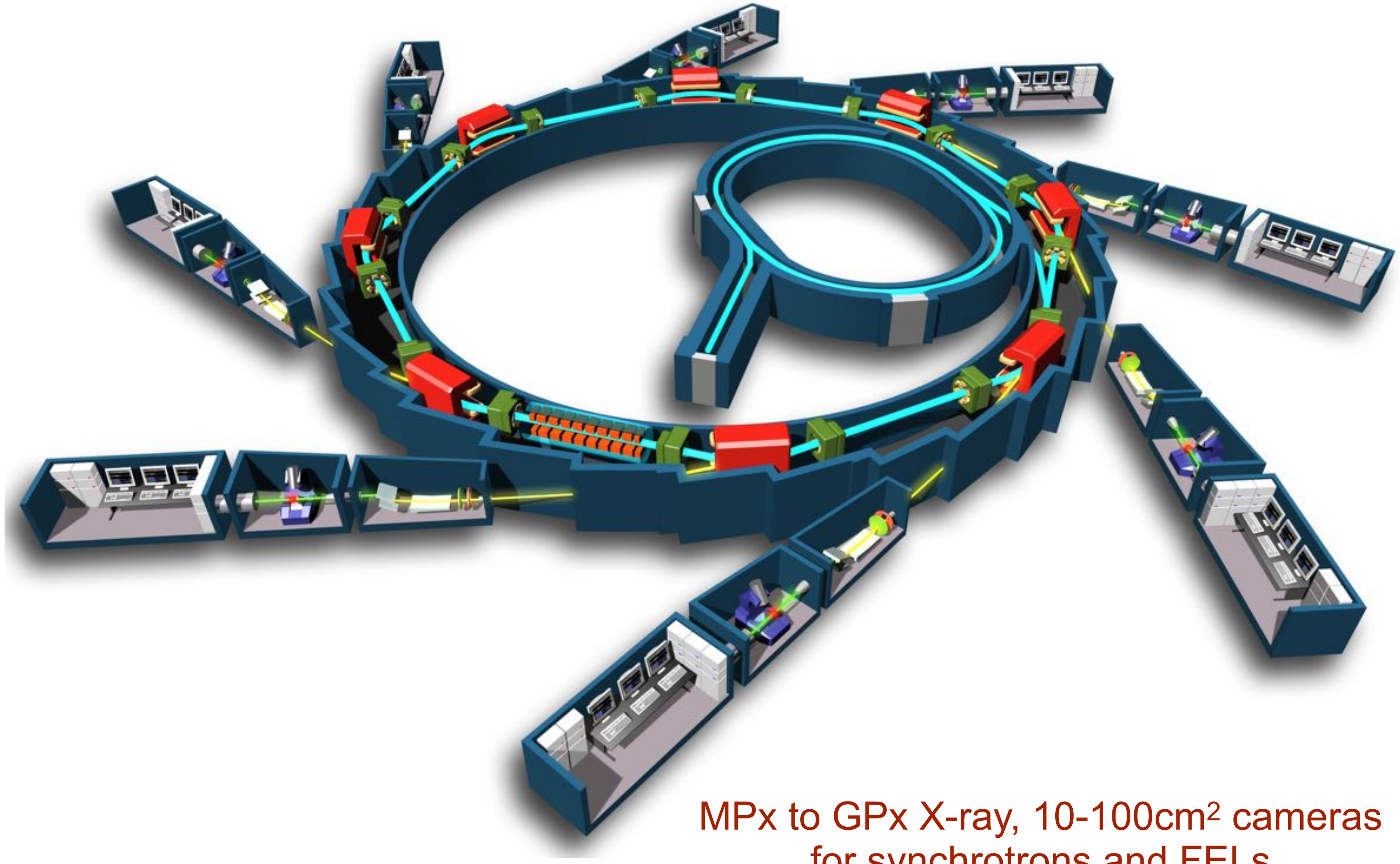
biomolecules (proteins, viruses, bacteria) are most studied in aqueous solution

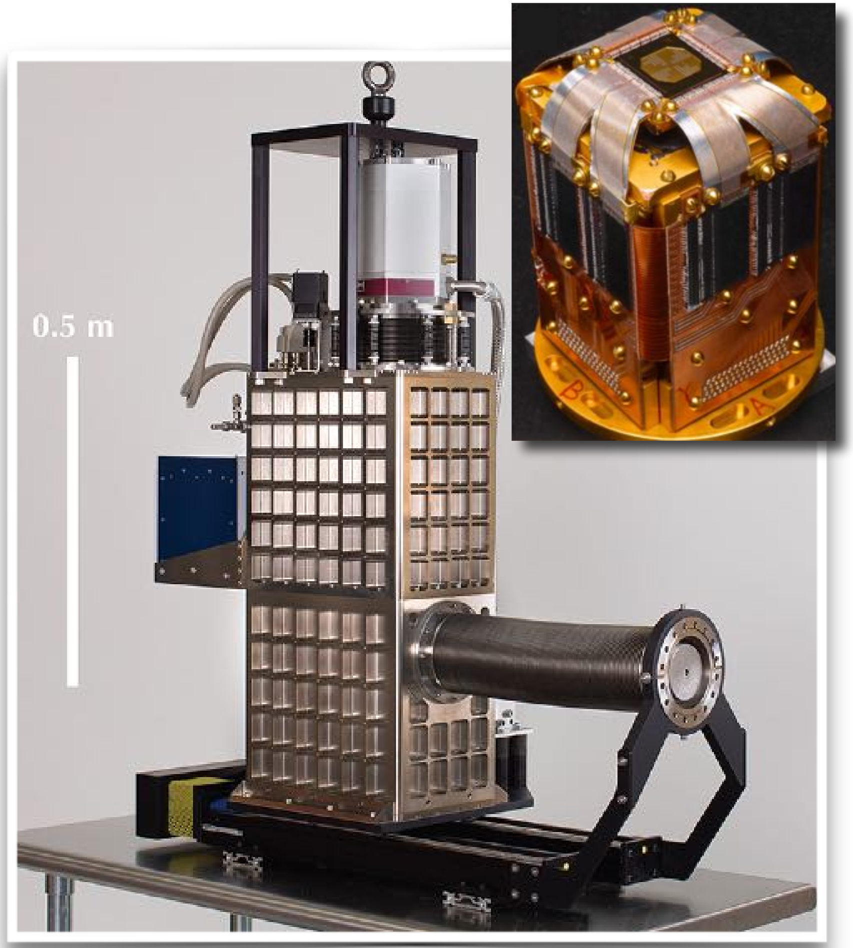


problem: radiation hardness

J. Uhlig *et al.*, J. Synchrotron Rad. **22** (2015) 766-775

Long-term goal - MMCs for photon sources

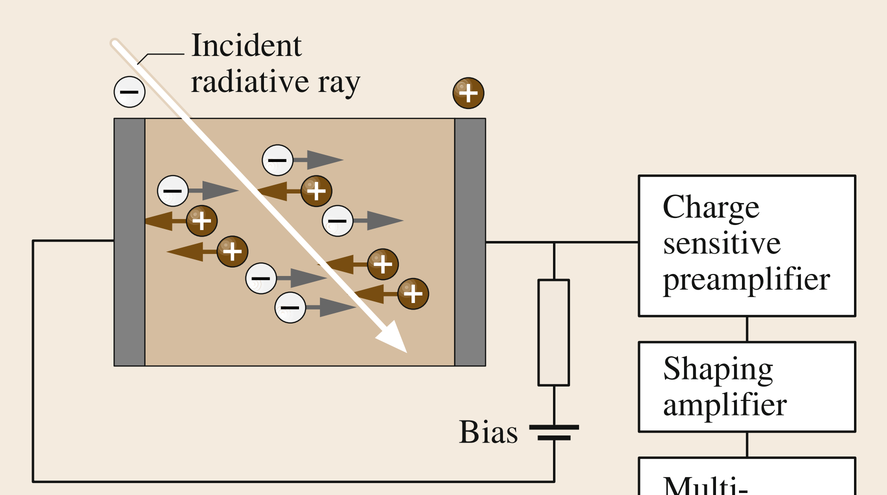




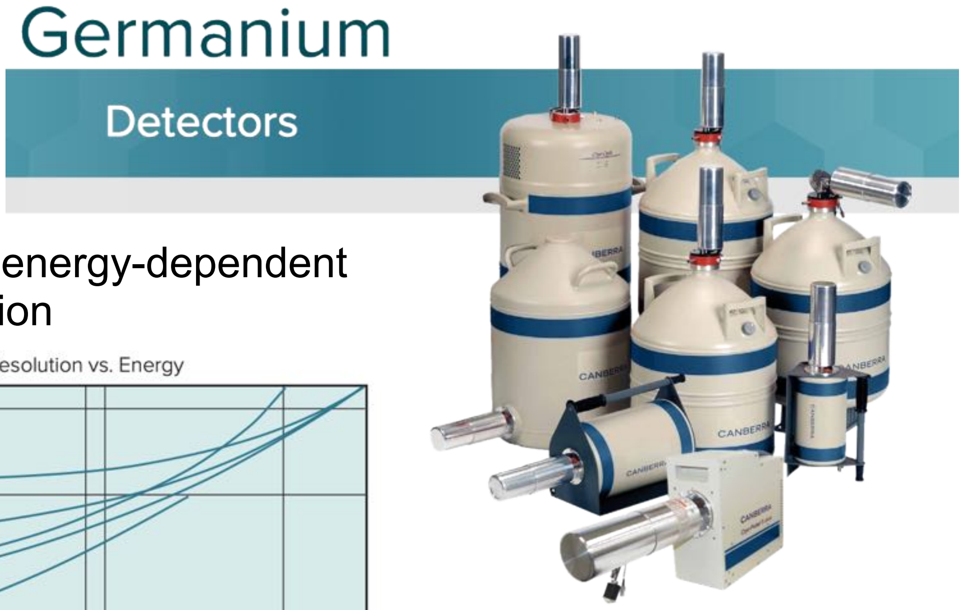
MPx to GPx X-ray, 10-100cm^2 cameras
for synchrotrons and FELs

Replacement of commercial X-ray systems

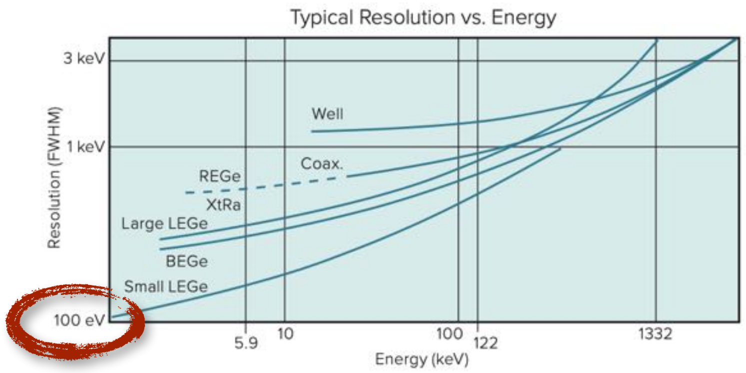
semiconductor detectors



charge pulse due to electron-hole-pairs created upon particle / photon absorption



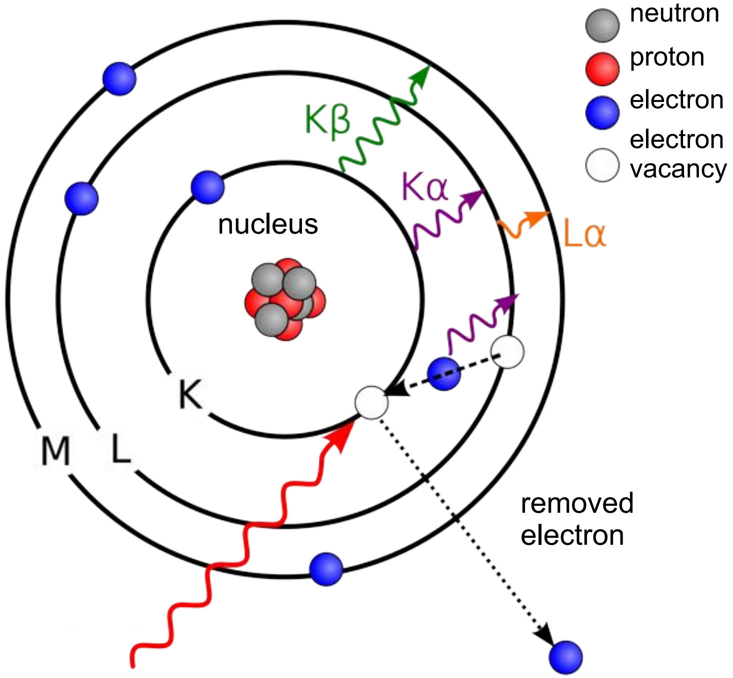
moderate and energy-dependent energy resolution

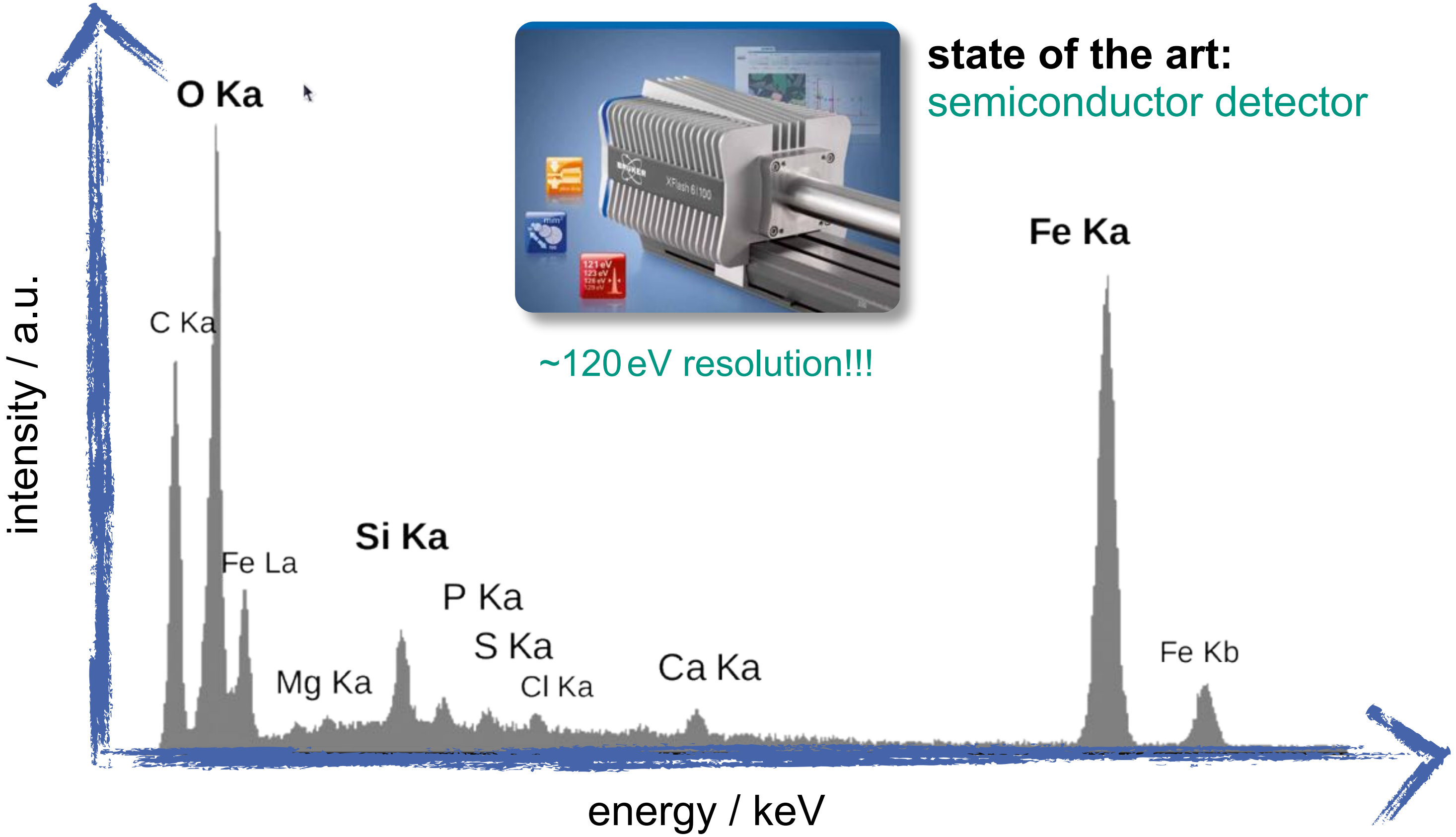


huge market for quantum sensors as replacement for semiconductor detectors due to significantly better resolution (about factor 100)

Energy-dispersive X-ray spectroscopy

X-ray fluorescence spectroscopy can be used for the identification / quantification of elements



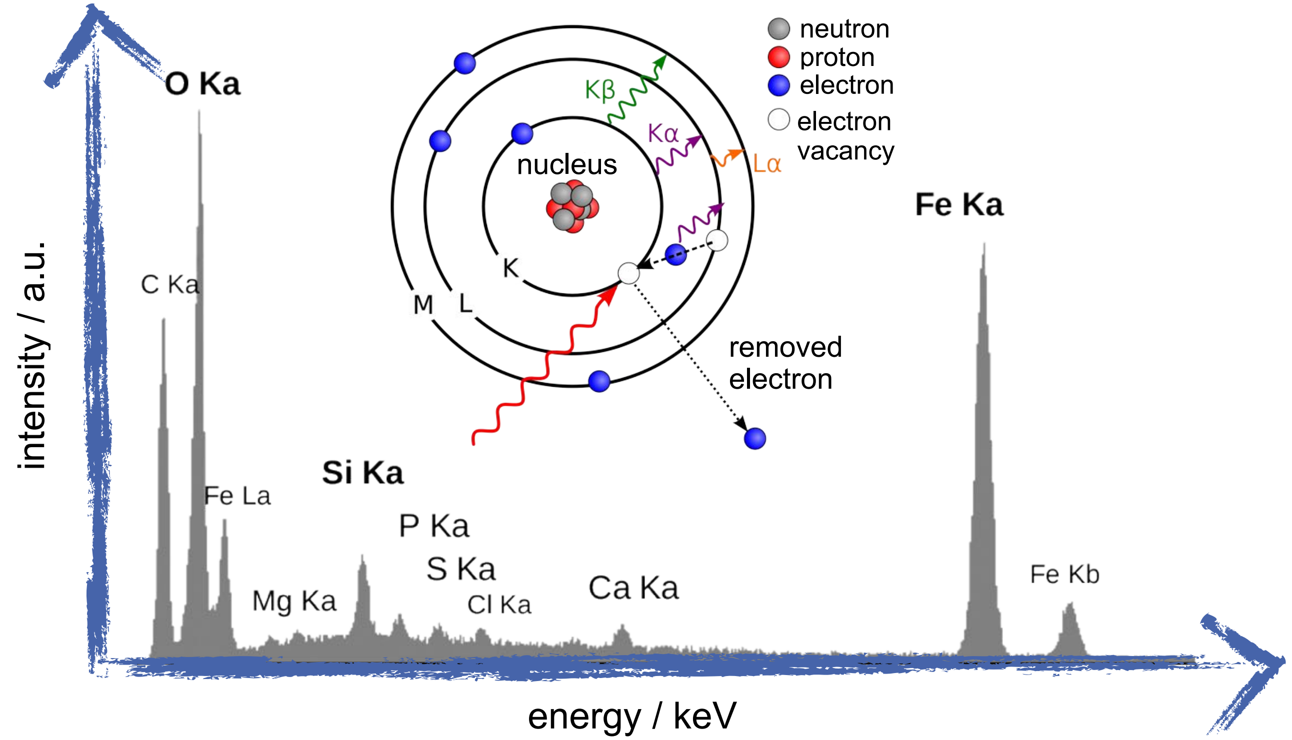


state of the art:
semiconductor detector

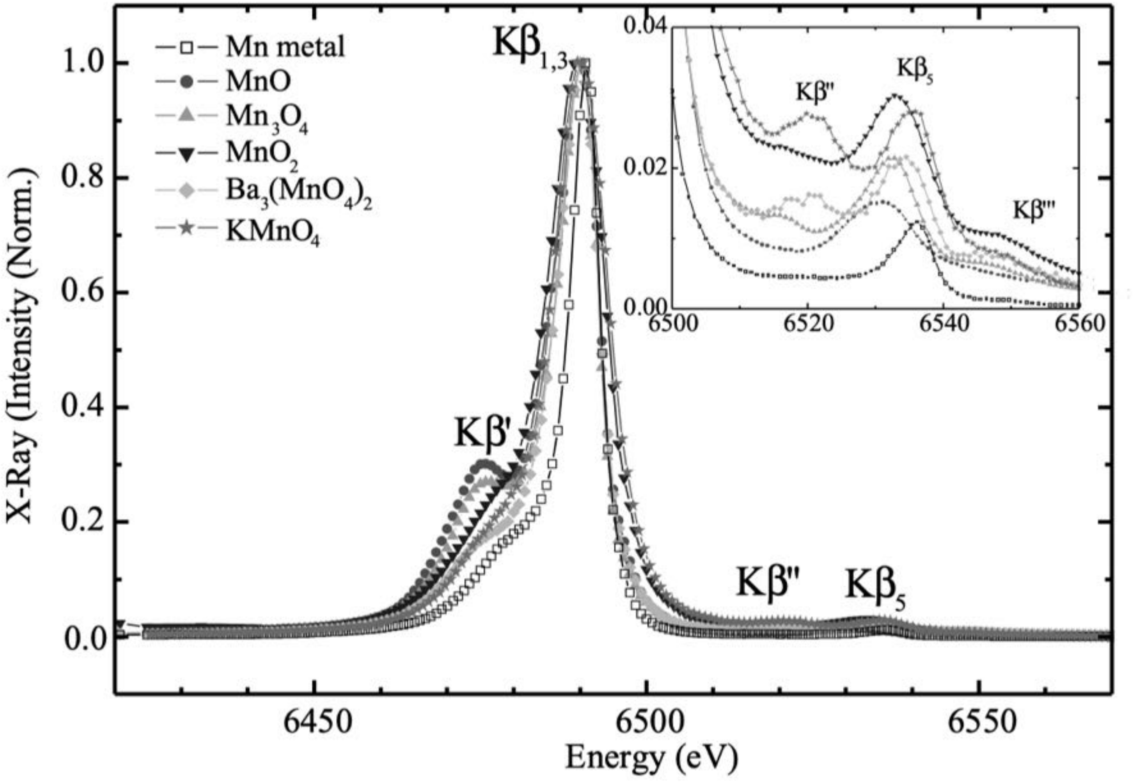
~120 eV resolution!!!

Energy-dispersive X-ray spectroscopy

X-ray fluorescence spectroscopy can be used for the identification / quantification of elements
…but it can also be used for identification of the chemical speciation



K. Sakurai *et al.*, Nucl. Instr. Meth. B **199** (2003) 391



identification of chemical speciation requires X-ray detectors with sub-5 eV (better: sub-1 eV) resolution

Energy-dispersive X-ray spectroscopy

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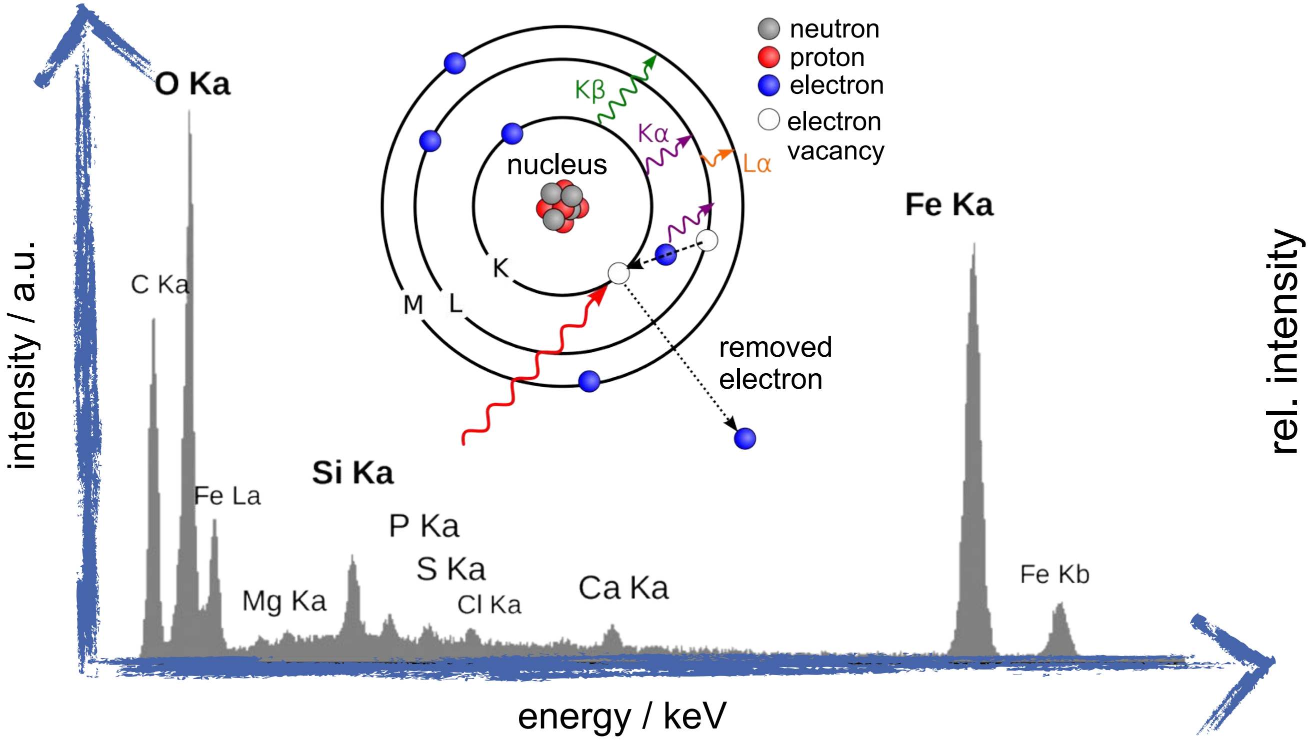
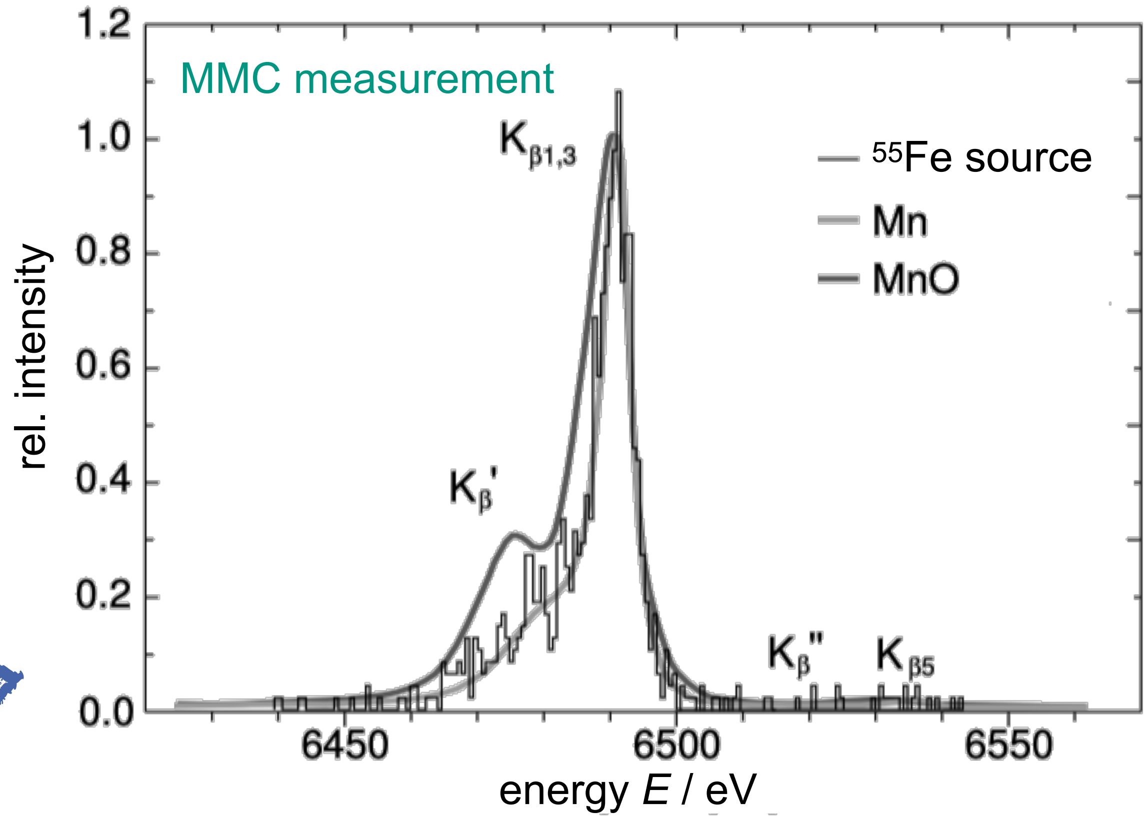
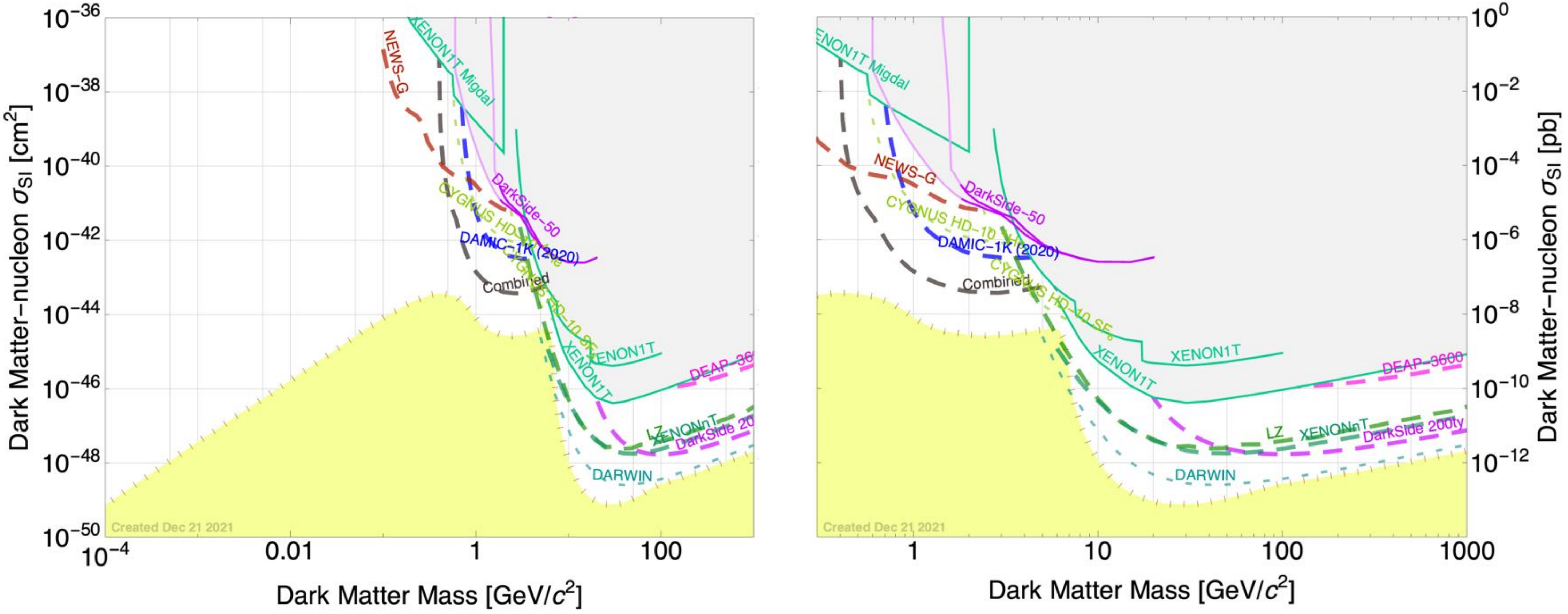




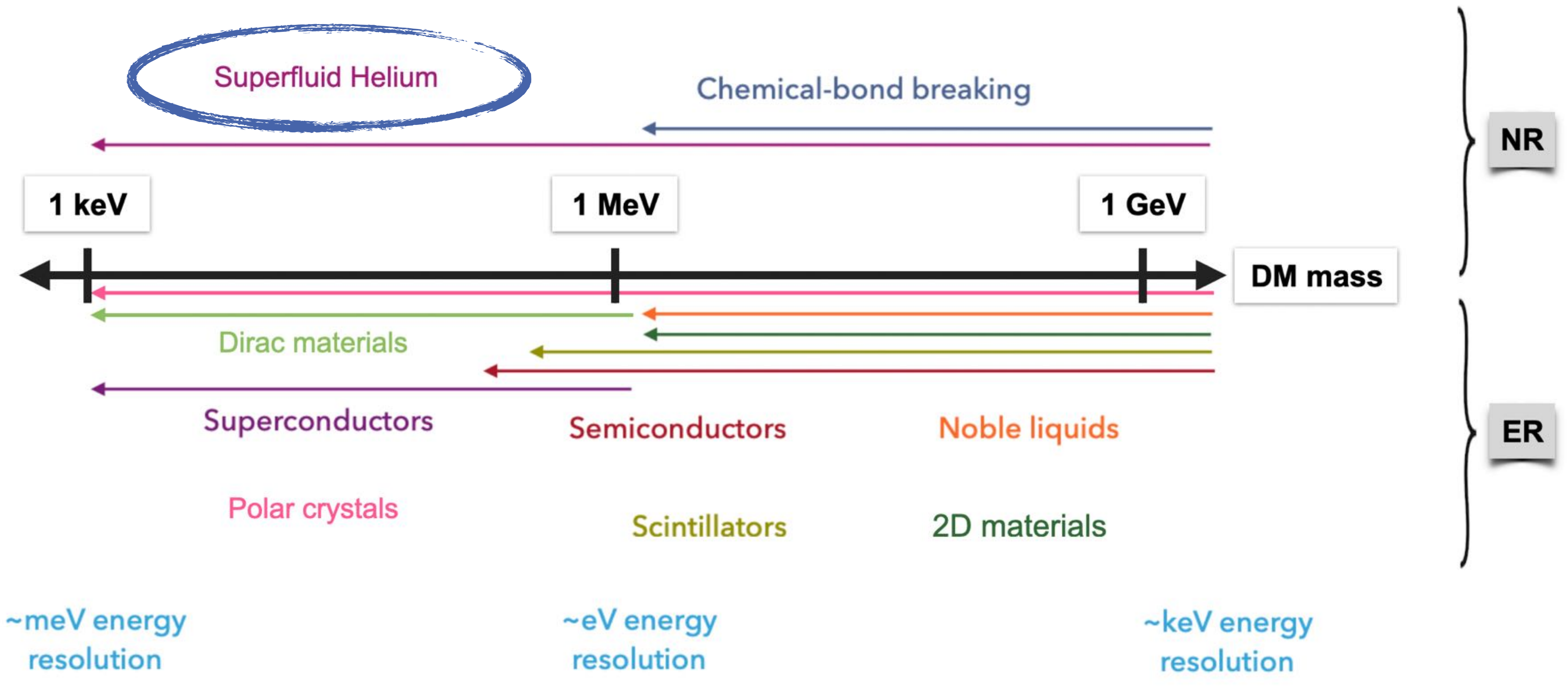
identification of chemical speciation requires X-ray detectors with sub-5 eV (better: sub-1 eV) resolution

Current direct WIMP search landscape

light dark matter

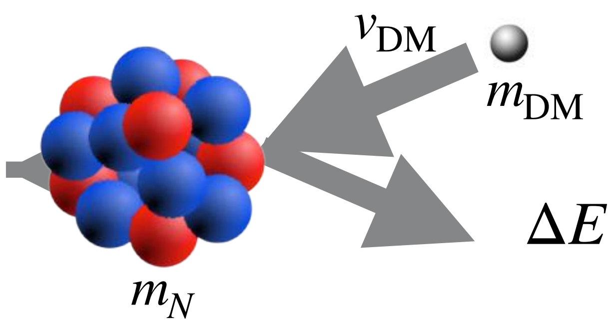


New avenues for light DM direct detection

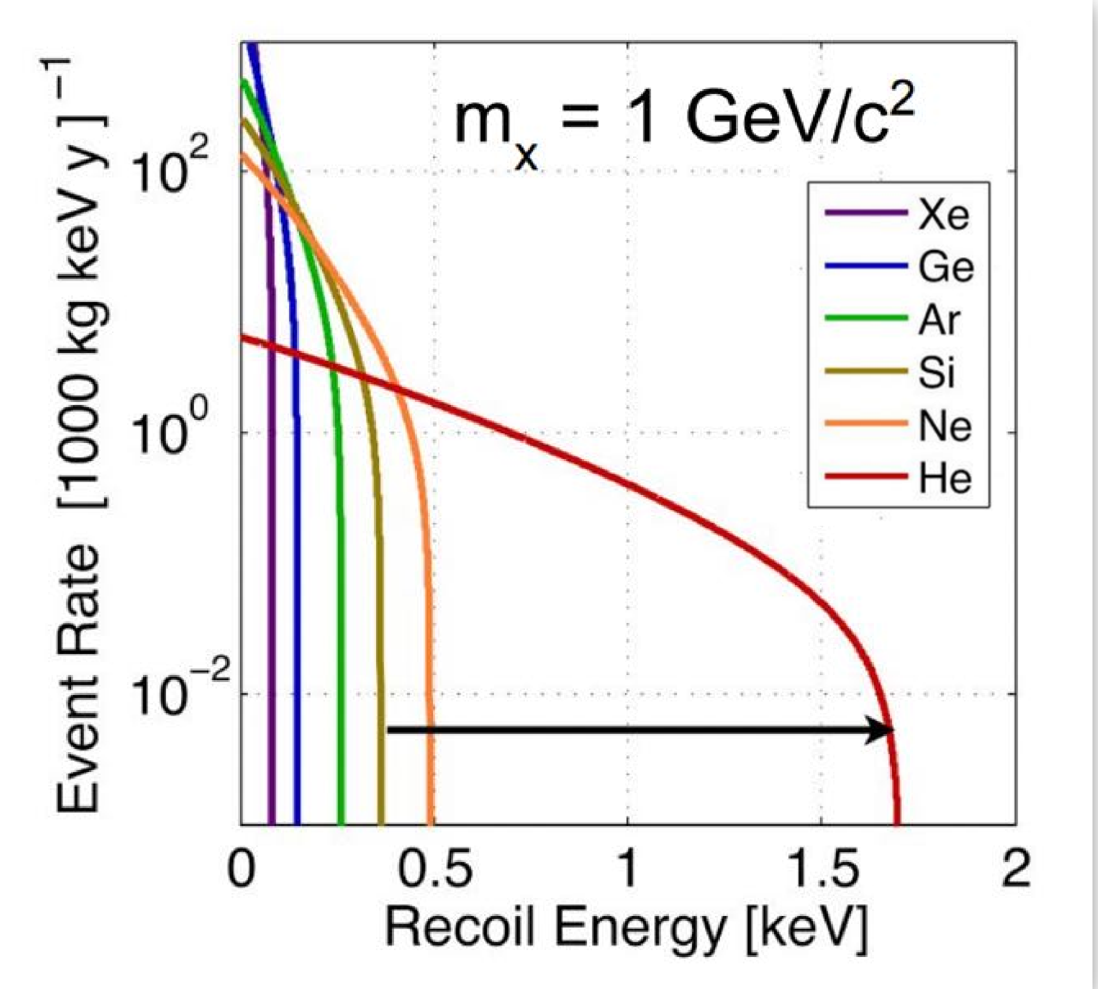


Why superfluid liquid helium?

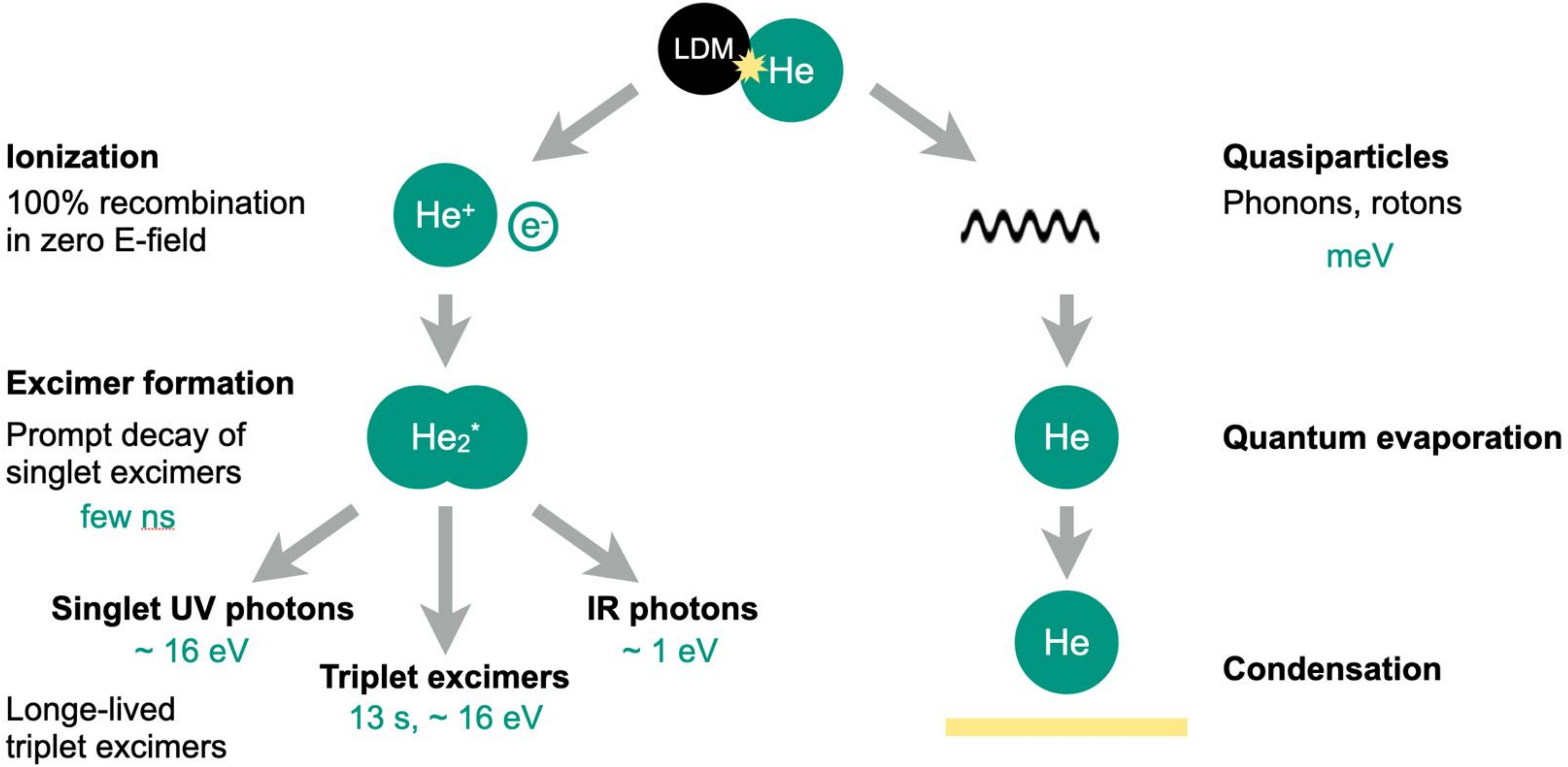
- very light
- cheap
- ultra-pure (no internal background)
- multiple signals (phonon & rotons, photons, excimers)
- NR / ER discrimination
- fiducialization possible
- easily scalable
- overall concept demonstrated



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



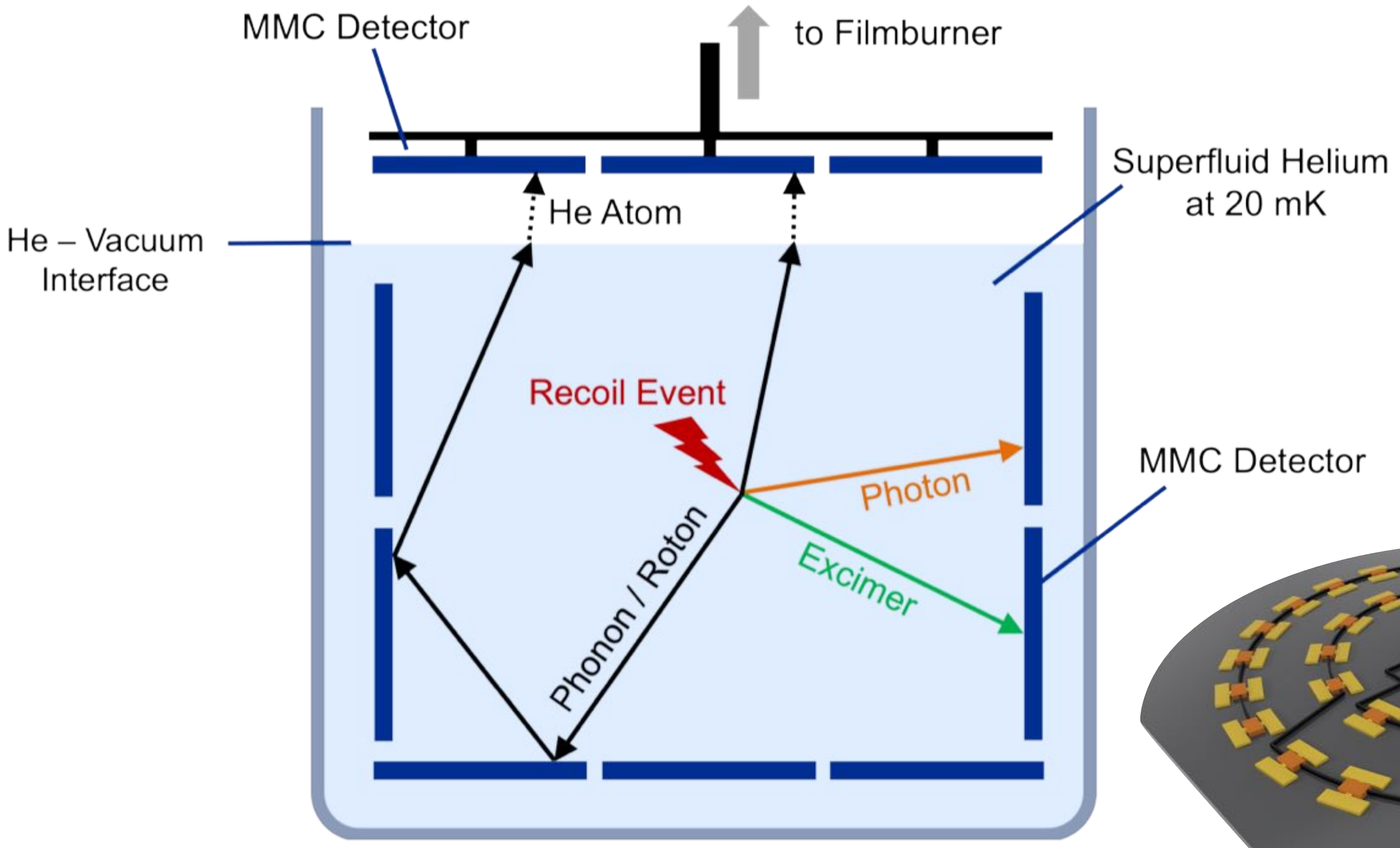
Multiple signals in superfluid ^4He



DELight: a Direct search Experiment for Light dark matter with superfluid helium

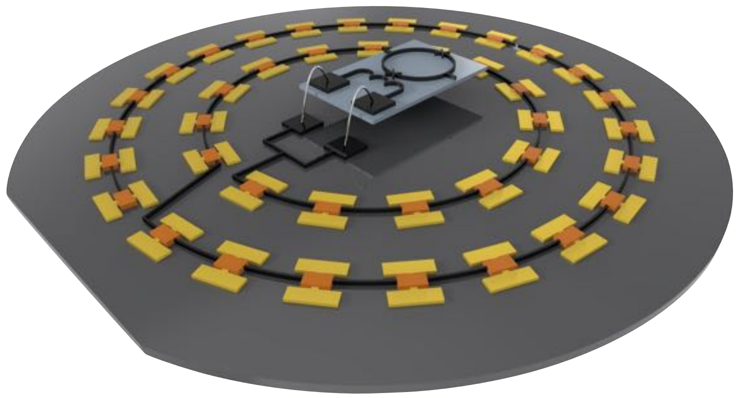
Belina von Krosigk, K. Eitel, C. Enss, T. Ferber, L. Gastaldo, F. Kahlhoefer, S. Kempf, M. Klute, S. Lindemann, M. Schumann, K. Valerius

DELight concept

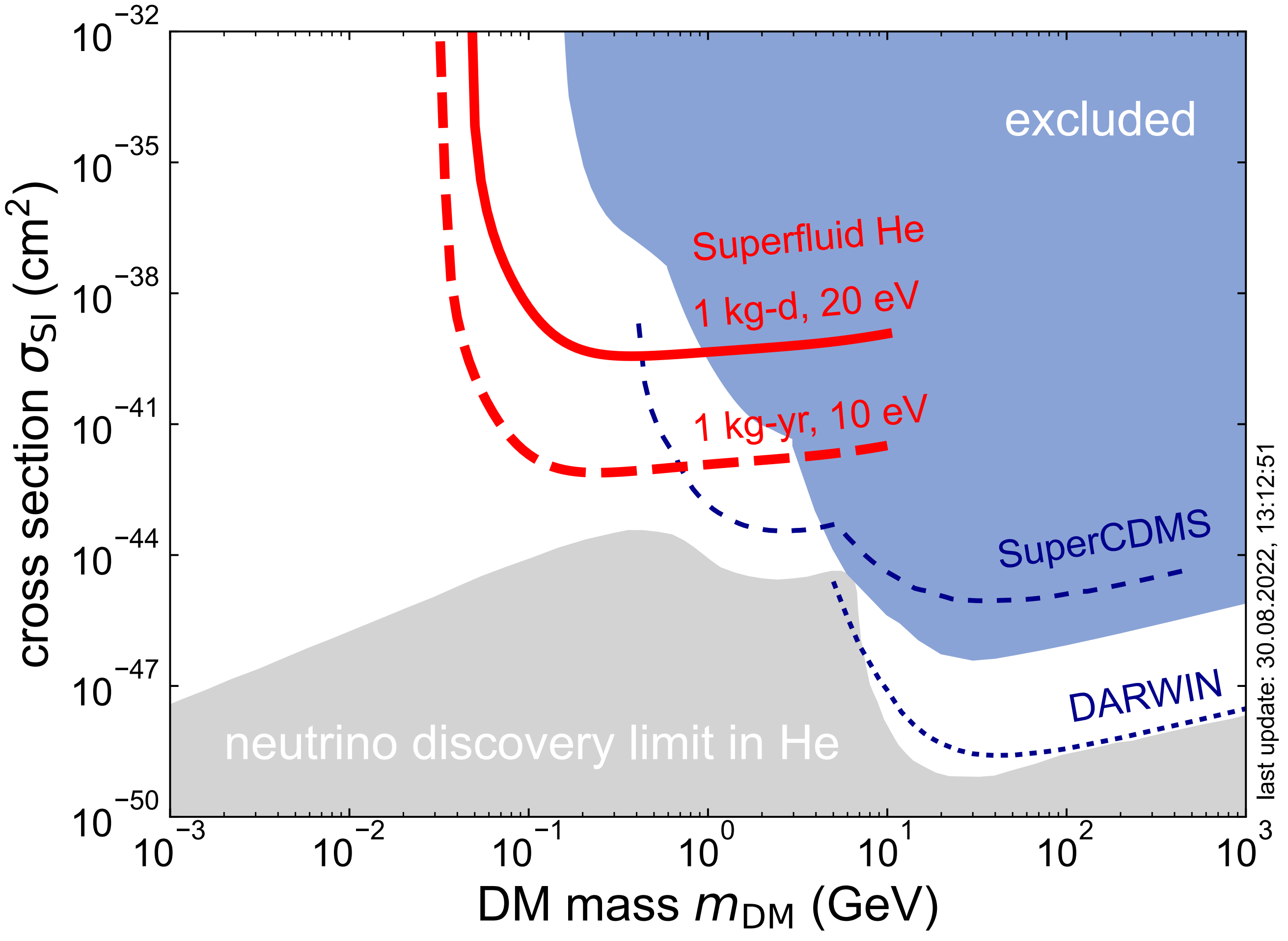


short-term plan:
- 10 L cell in shallow laboratory
- O(kg*d) exposure
- 20-30 eV threshold
- about 20 full-wafer detectors

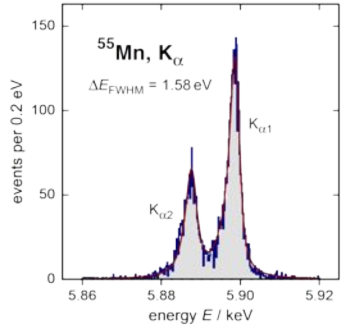
long range plan:
- up to 200 L cell
- O(kg*d) exposure
- < 10 eV threshold
- 10^3-10^4 (10^5) medium-sized detectors

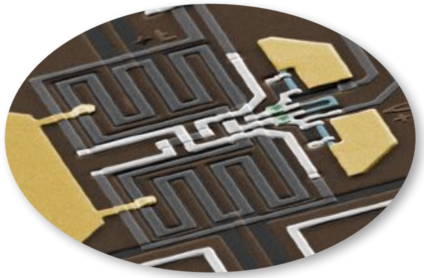


DELight concept



Summary and conclusion





magnetic microcalorimeters and SQUIDs

- flexible low-temperature detectors
- described by standard equilibrium thermodynamics
- wide range of applications

future detector systems

- large-scale detector arrays by using SQUID multiplexing
- realization of resolving powers > 10.000
- ultra-fast detectors

future applications

- X-ray spectroscopy at modern light sources, QIT, …
- muclear safeguards, medicine, …
- material analysis, EDS, EDX, …
- particle and astroparticle physics

Superconducting quantum sensors - enabling technology for next-generation physics experiments

Sebastian Kempf

8th Annual MT Meeting | DESY Hamburg | September 26th-27th, 2022

Thank you for your attention