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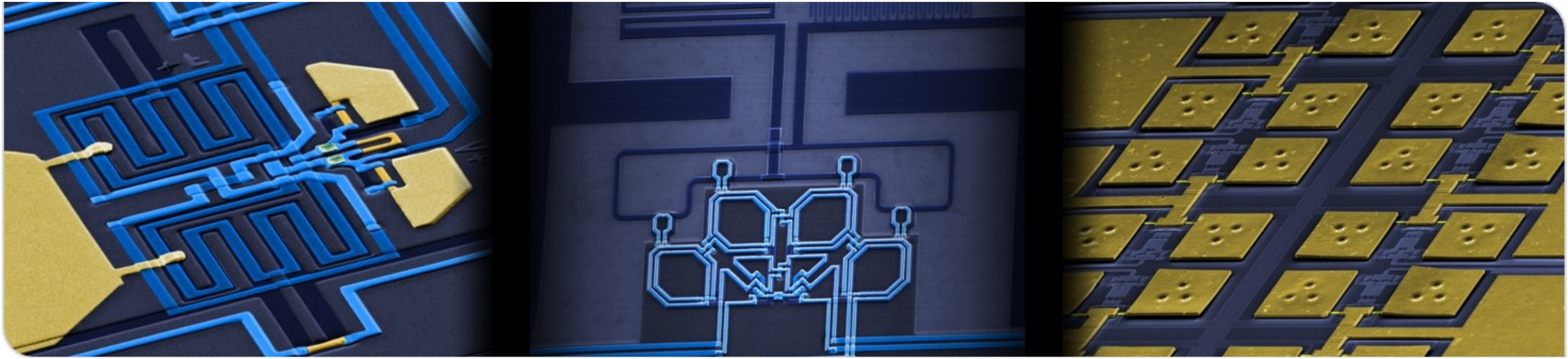
Multiplexed magnetic microcalorimeter arrays for astroparticle physics

Sebastian Kempf

HIRSAP Workshop 2021 | Hybrid Meeting KIT - Online | November 2nd, 2021



Outline

- magnetic microcalorimeters - basics and state-of-the-art
- application in neutrino physics: the ECHo experiment
- FRM-based dc-SQUID multiplexing
- microwave SQUID multiplexing
- hybrid microwave SQUID multiplexing
- conclusion and outlook

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- application in neutrino physics: the ECHo experiment
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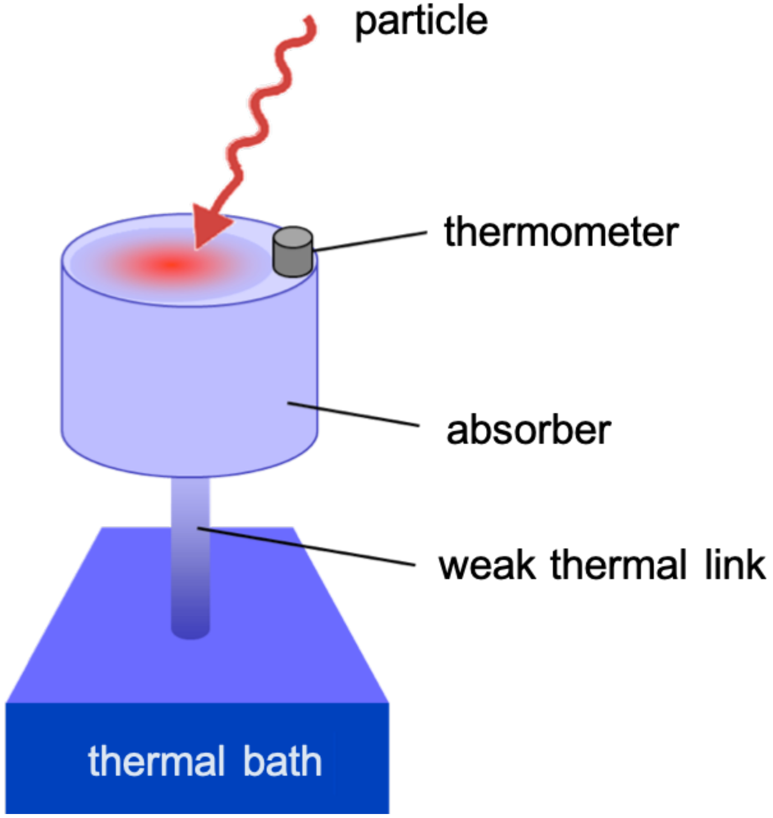
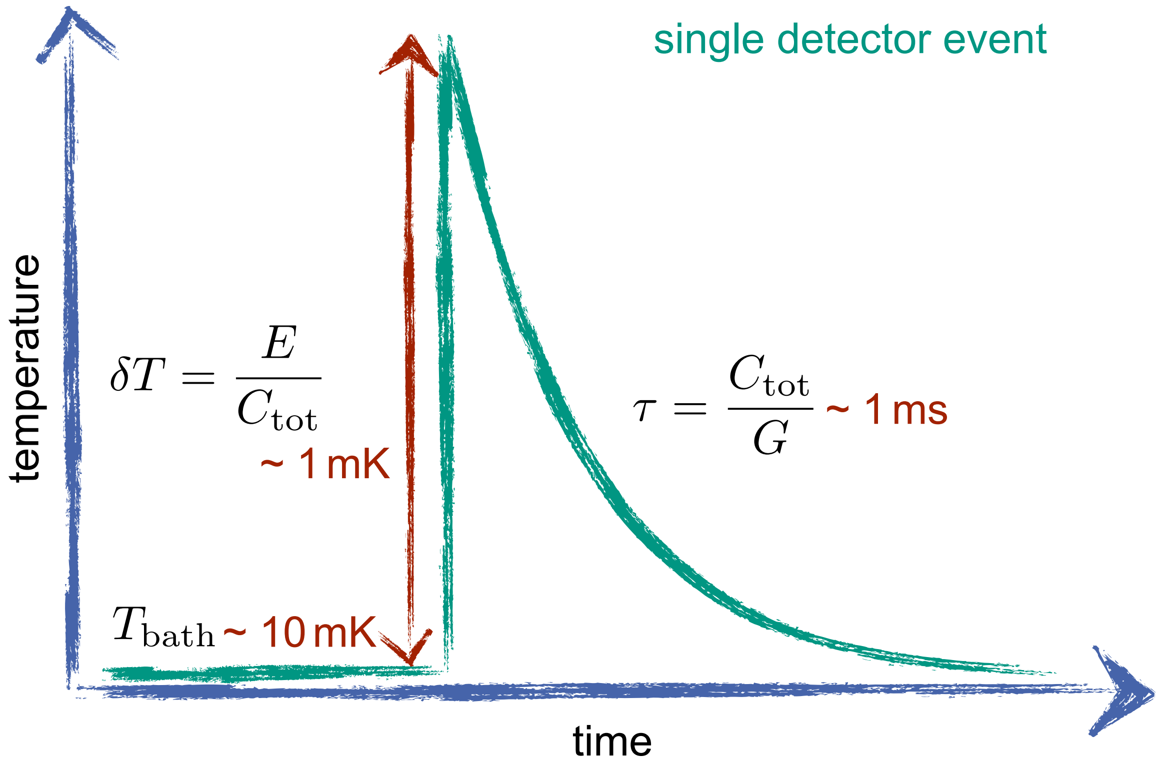
- hybrid microwave SQUID multiplexing
- conclusion and outlook

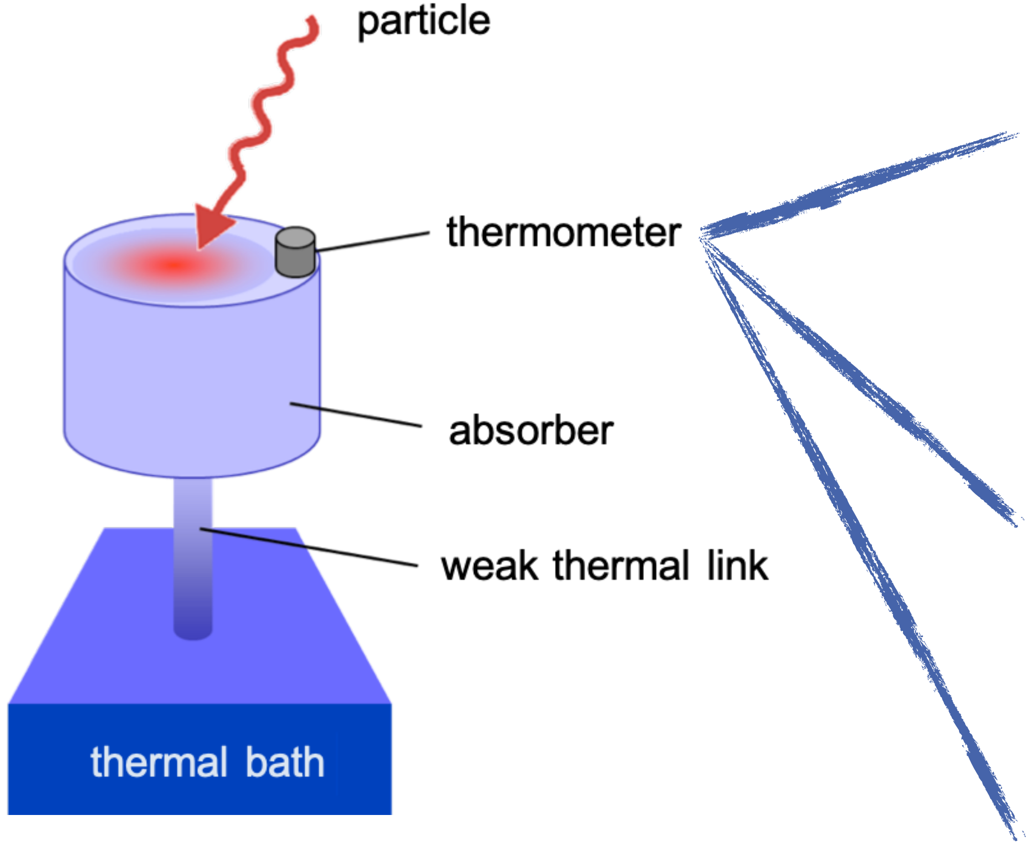
→ today: mostly focused on detector readout

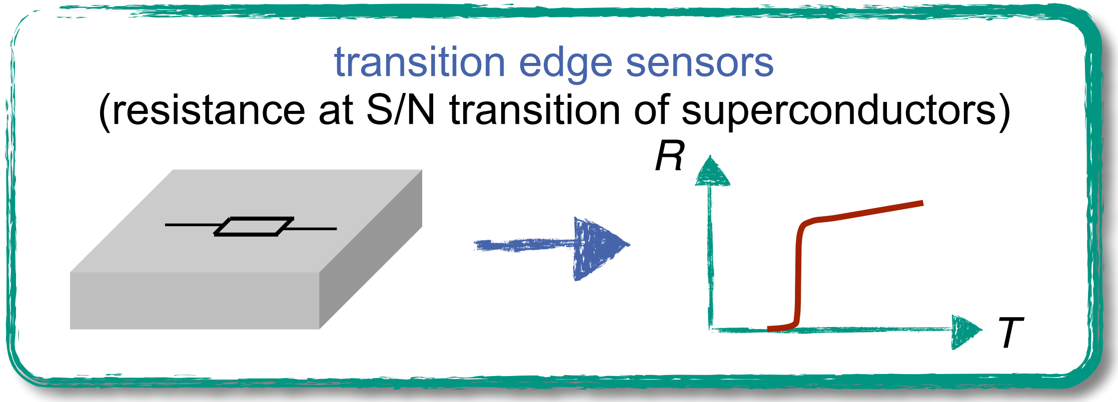
Cryogenic microcalorimeters

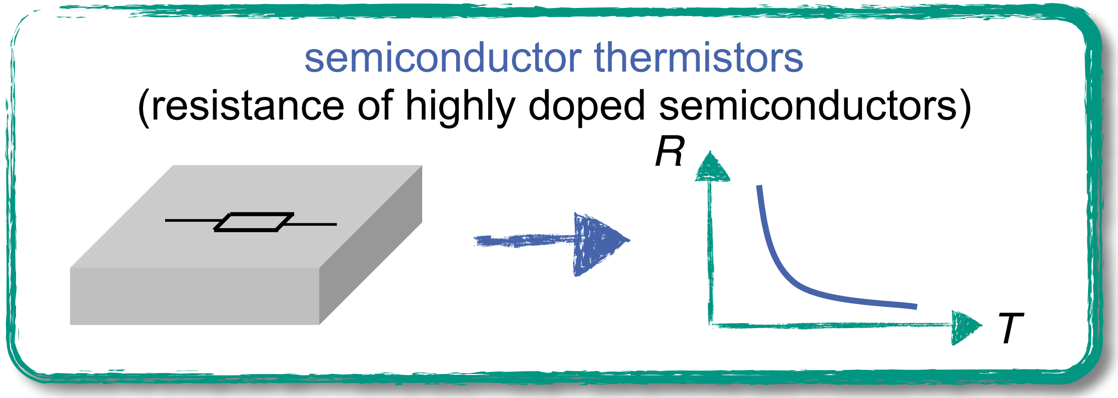




Cryogenic microcalorimeters



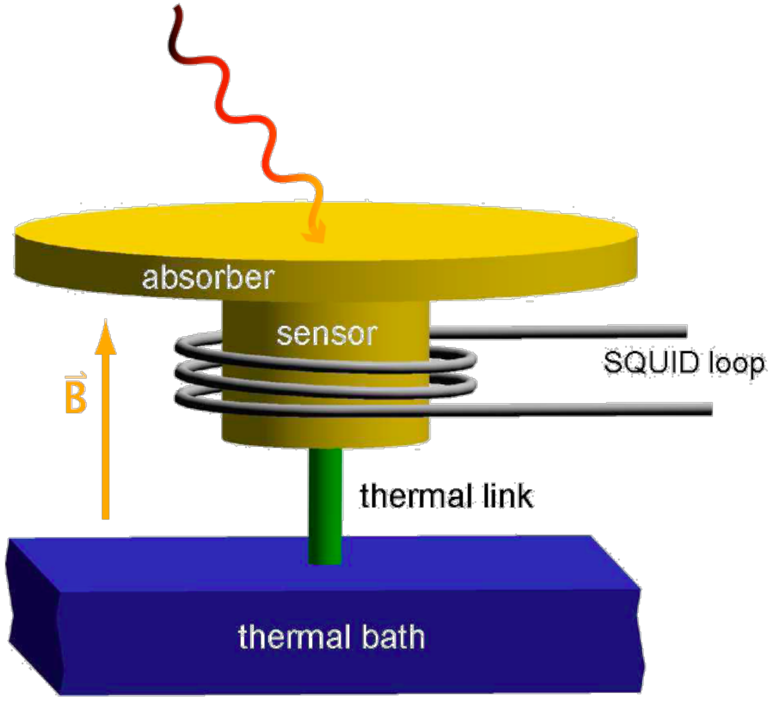




metallic magnetic calorimeters (MMCs)

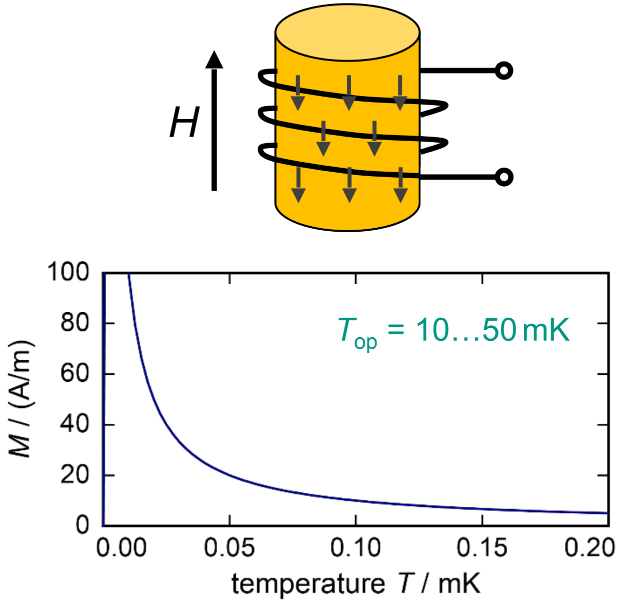
magnetic penetration depth thermometers (MPTs)

Magnetic microcalorimeters



metallic magnetic calorimeter

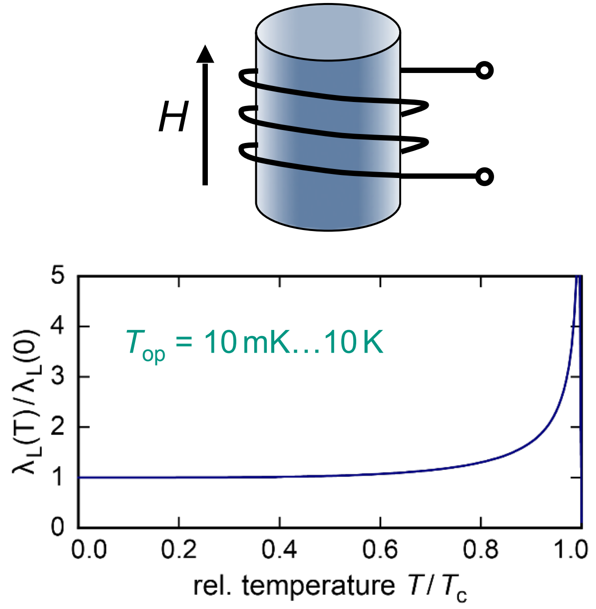
magnetization of a paramagnetic material



large variation of magnetization at mK temperature

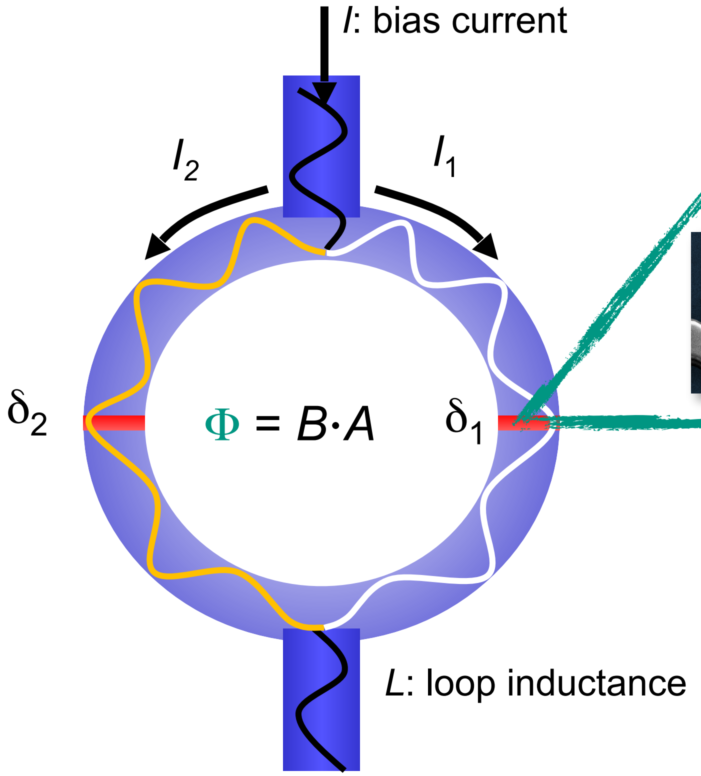
magnetic penetration depth thermometer

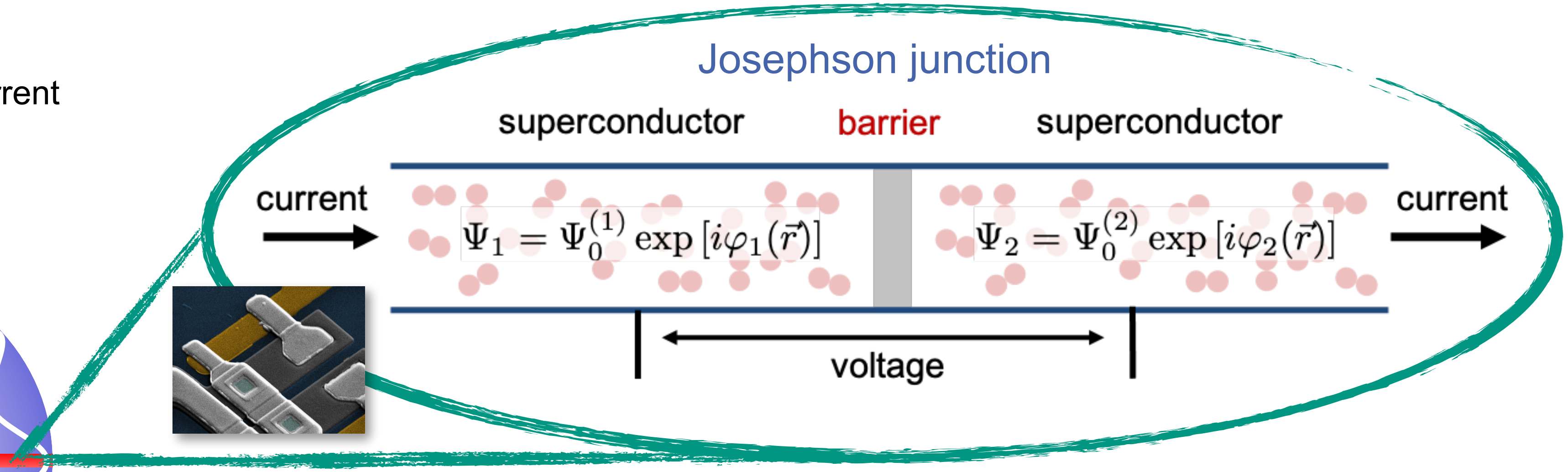
penetration depth of a superconducting material



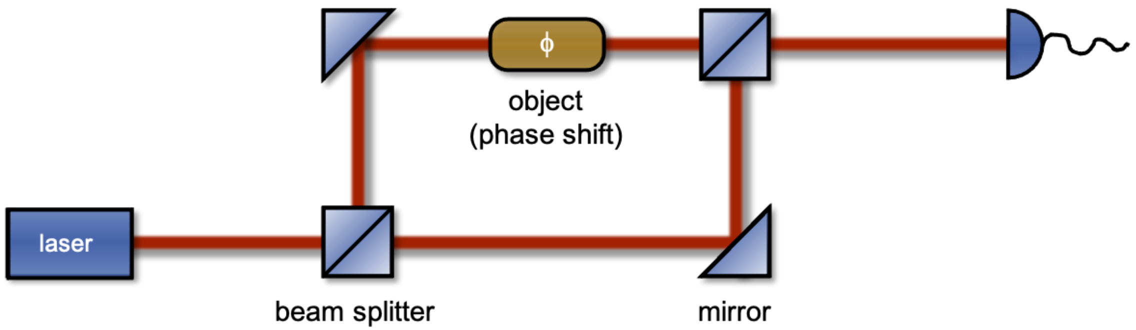
large variation of penetration depth at mK…K temperature

Superconducting quantum interference devices





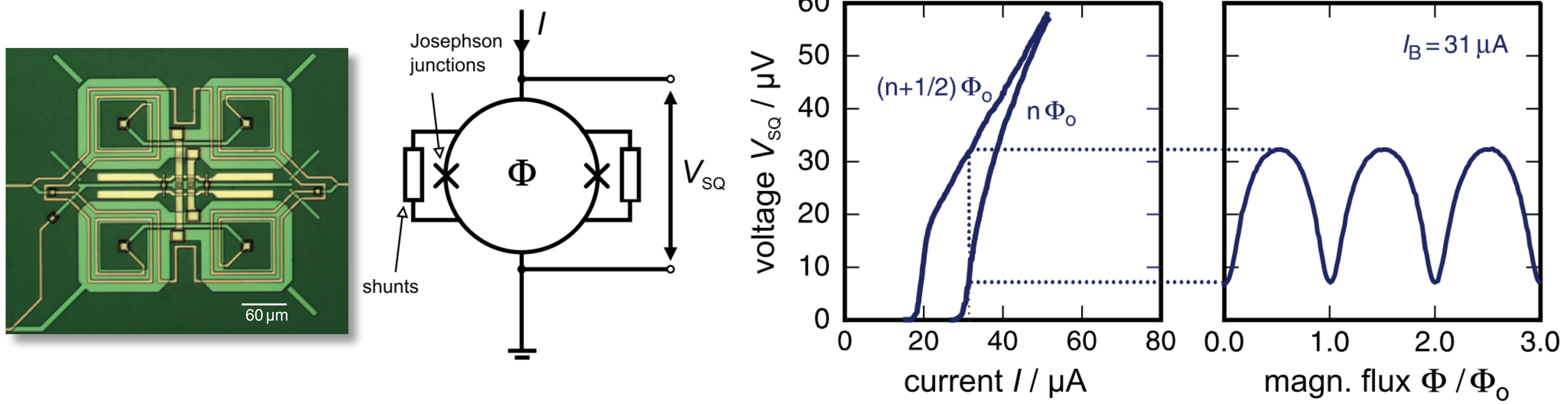
$$\phi = \delta_2 - \delta_1 = \frac{2\pi\Phi}{\Phi_0}$$



SQUID = quantum electromagnetic equivalent of an optical interferometer

SQUID-based detector readout

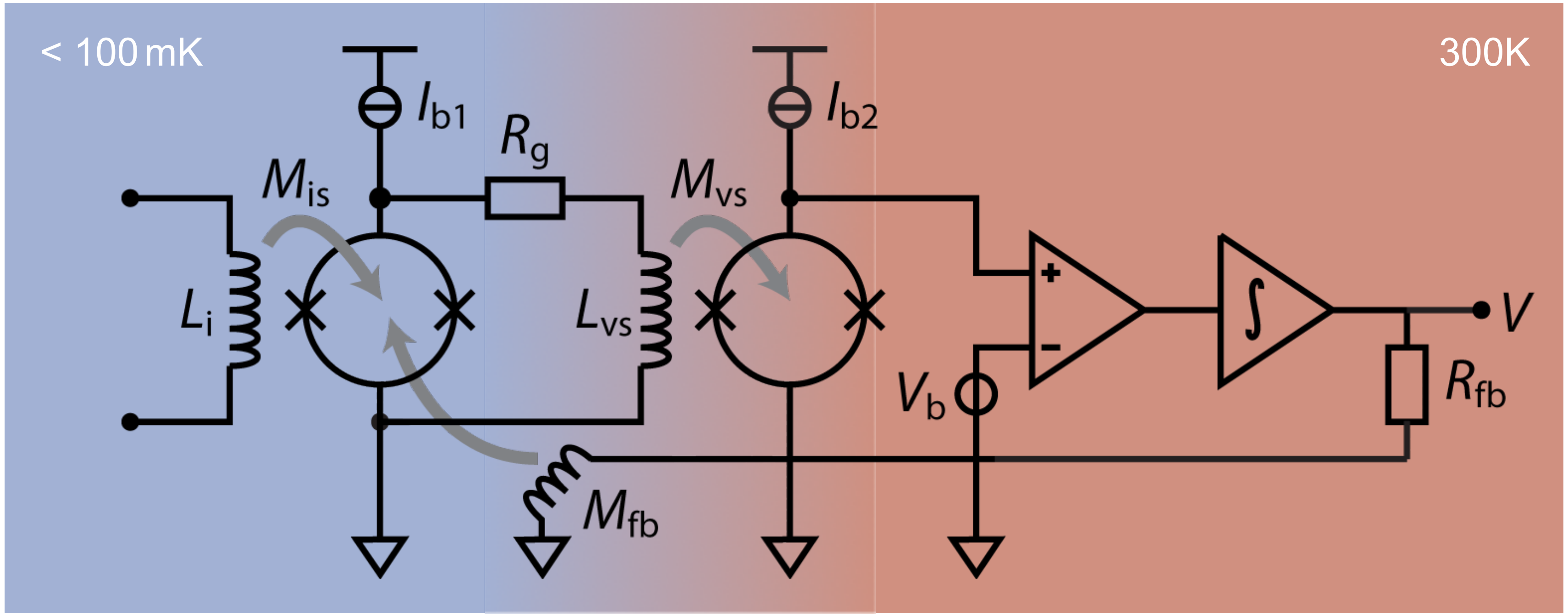
dc-SQUID = magnetic flux to voltage / current converter



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

Two-stage SQUID setup with flux-locked loop

cryogenic SQUID-based amplifier chain with ultrafast feedback electronics



key features:
- large system bandwidth: 1…10 MHz
- linear relation between input and output signal
- impedance matched

Alternative concept: Flux ramp modulation

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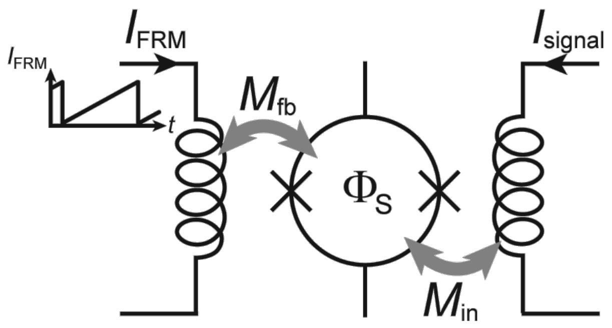
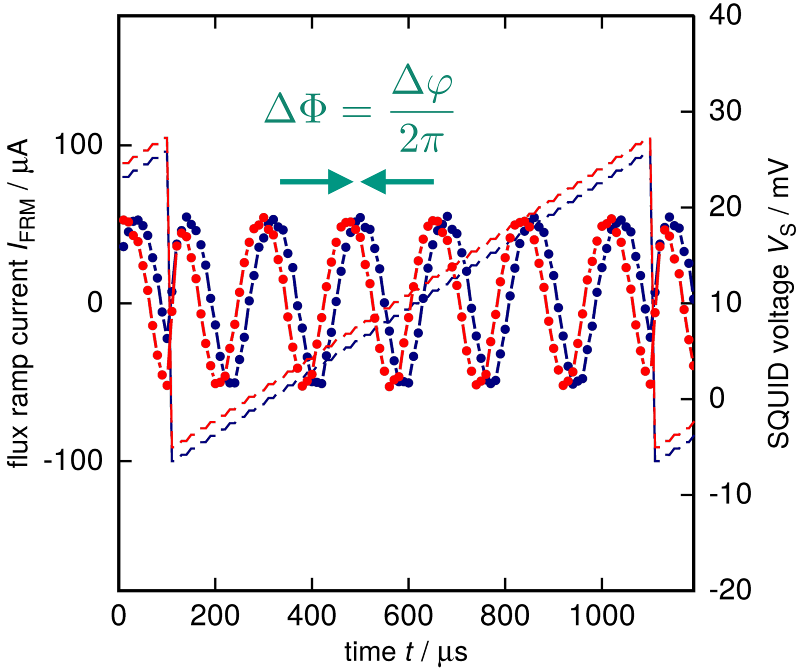
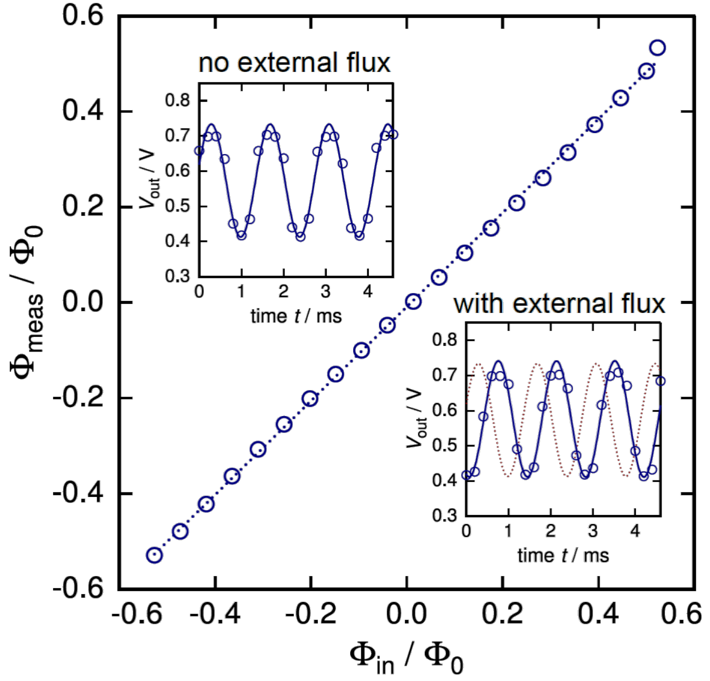
quasi-continuous SQUID characteristic measurement
by applying sawtooth-shaded current signal through modulation coil



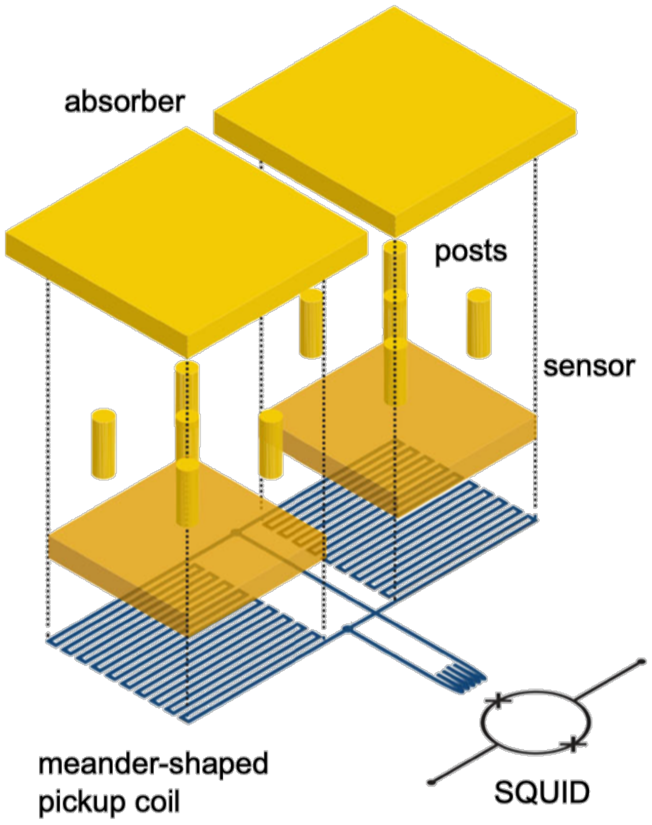


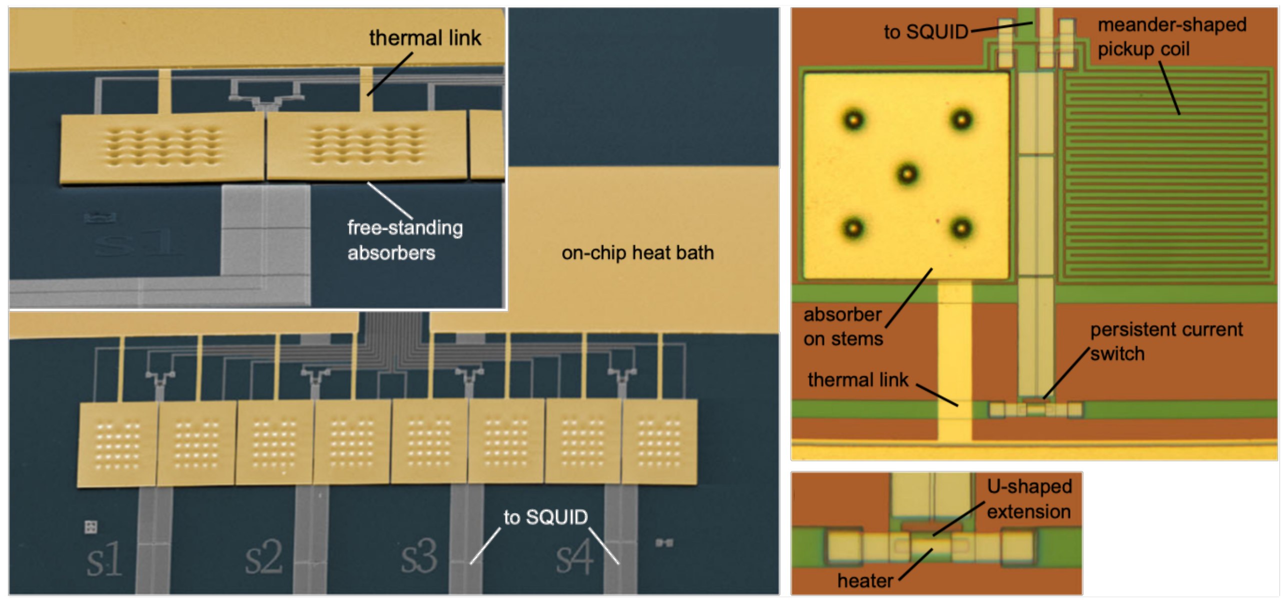


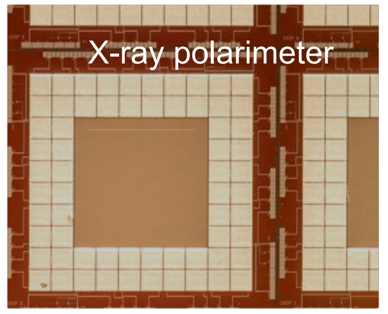
K. W. Lehnert *et al.*, IEEE Trans. Appl. Supercond., **17** (2007) 705
J. A. B. Mates *et al.*, Appl. Phys. Lett. **92** (2008) 023514
J. A. B. Mates *et al.*, J. Low Temp. Phys. **167** (2012) 707

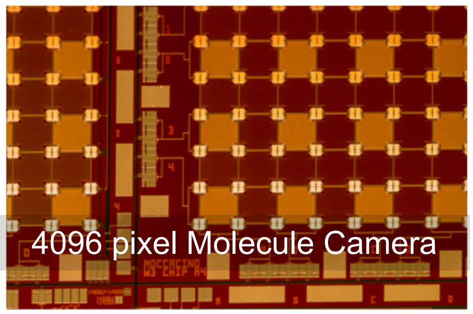
Transformer-coupled detectors

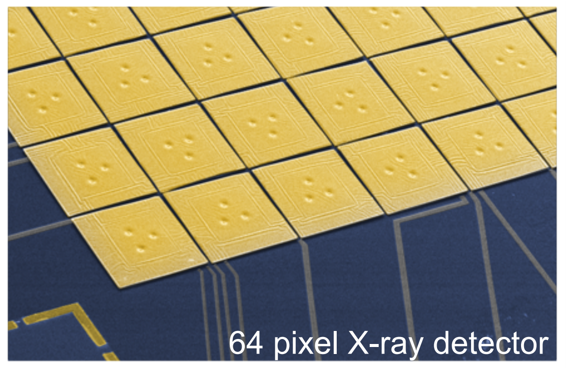
present workhorse:
transformer-coupled meander-shaped pickup coil



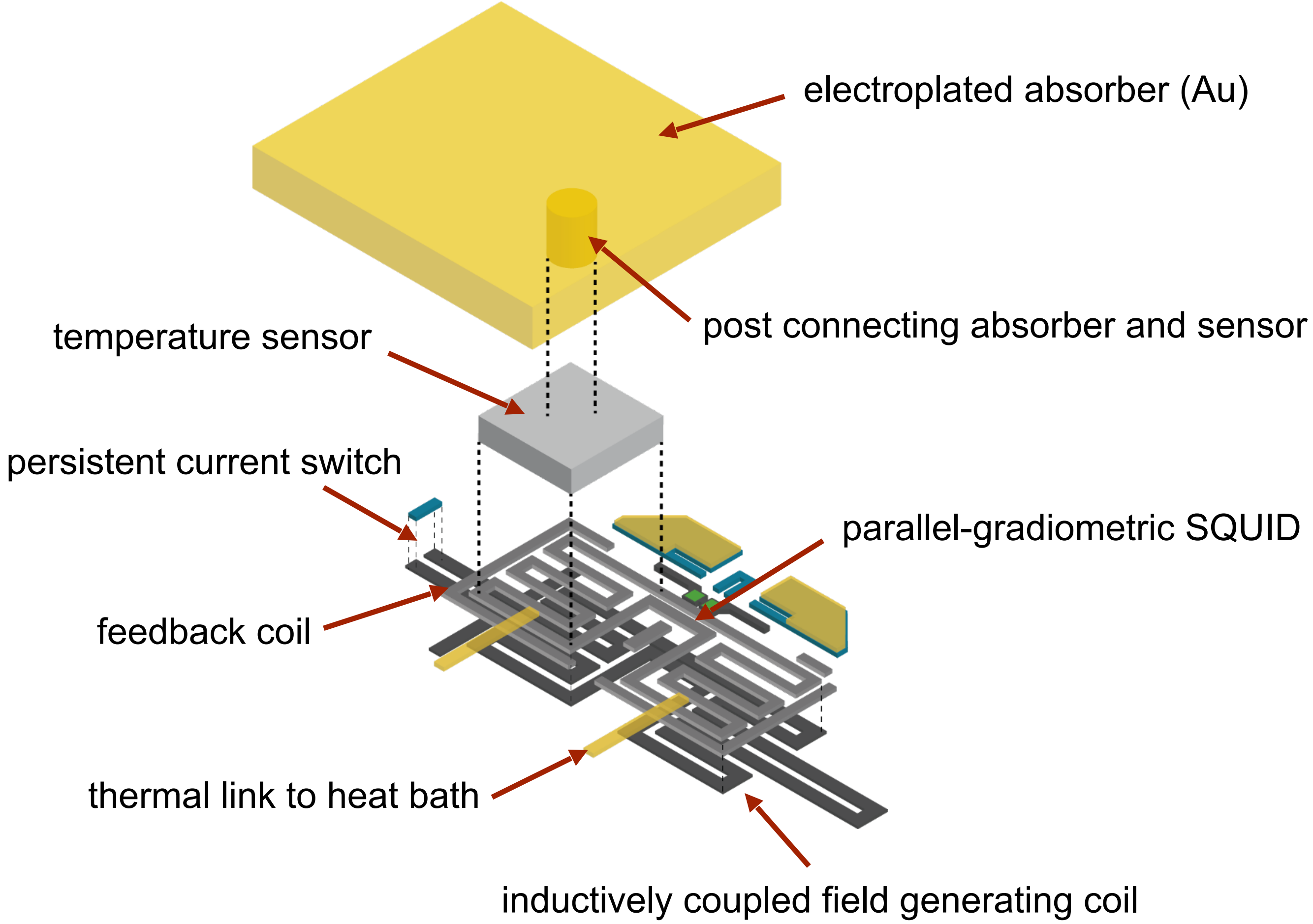


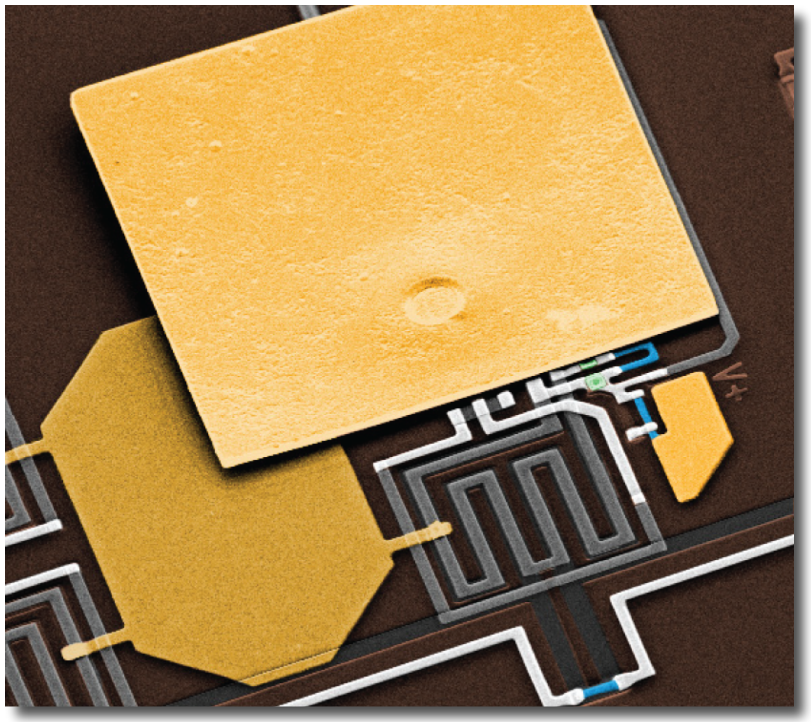






Integrated detectors





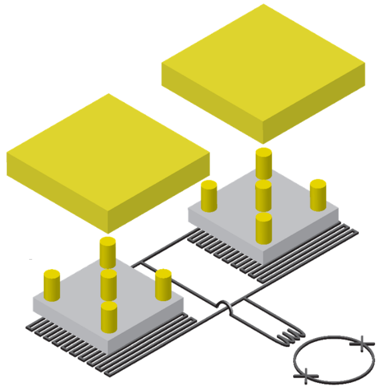
M. Krantz, SK *et al.*, IEEE Explore - ISEC 2019
M. Krantz, PhD thesis, Heidelberg University (2020)

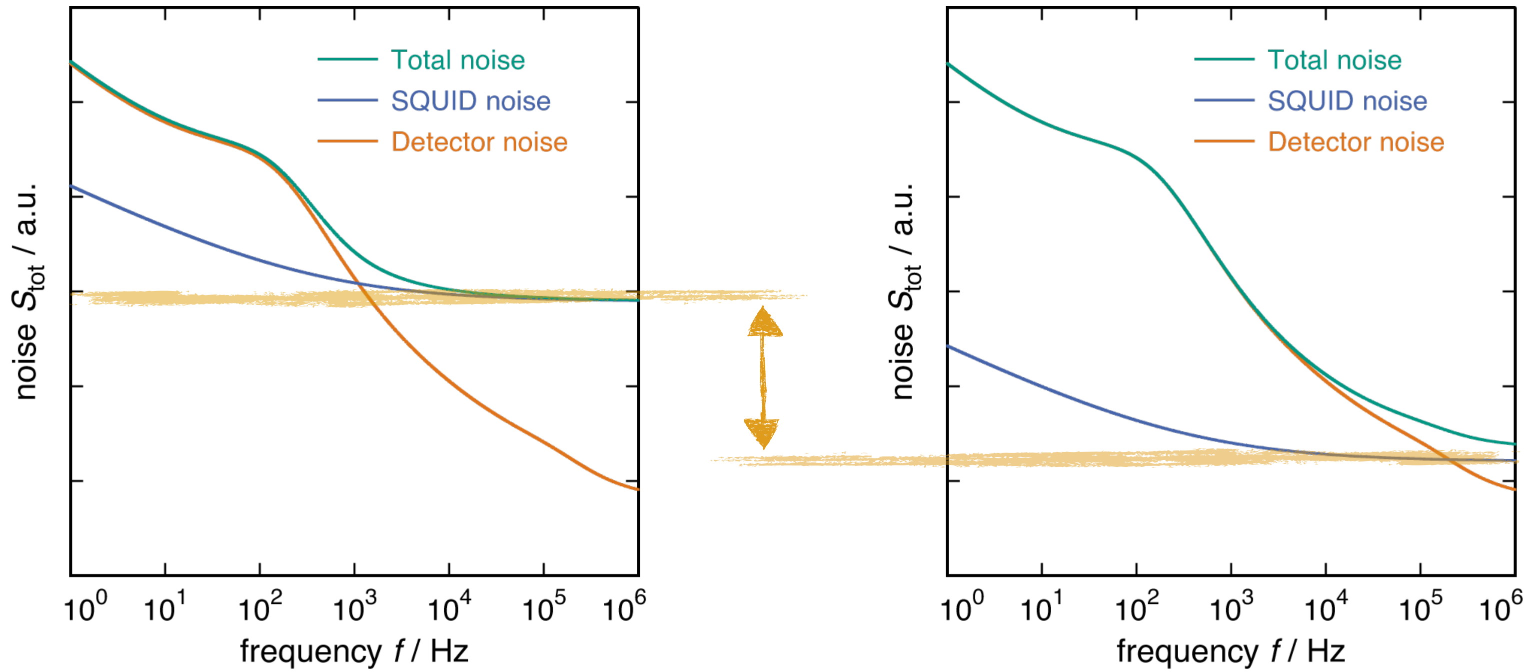
Integrated detectors

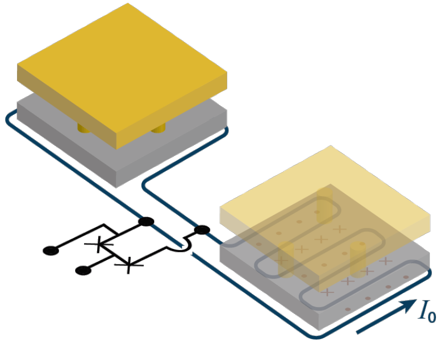
integrated detectors don’t suffer from transformer losses, but are affected by SQUID power dissipation

detector geometry with
superconducting flux transformer

direct detector readout
(SQUID integrated in pickup coil)

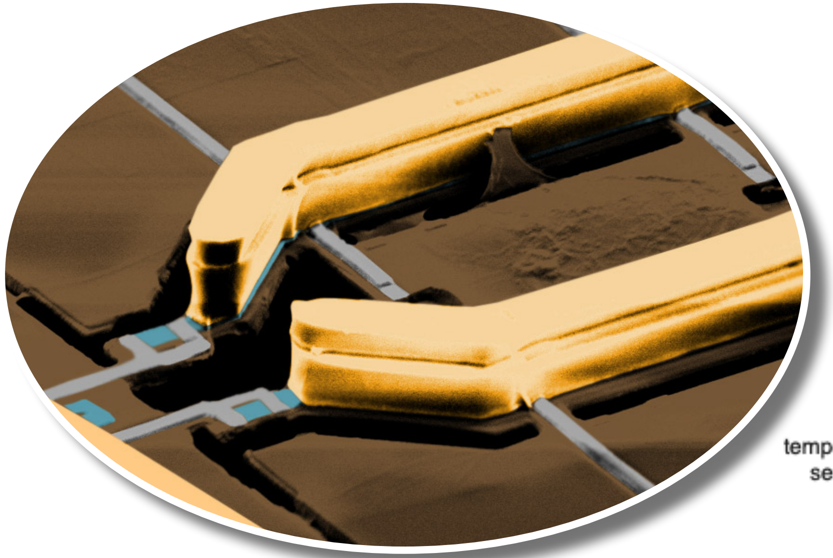




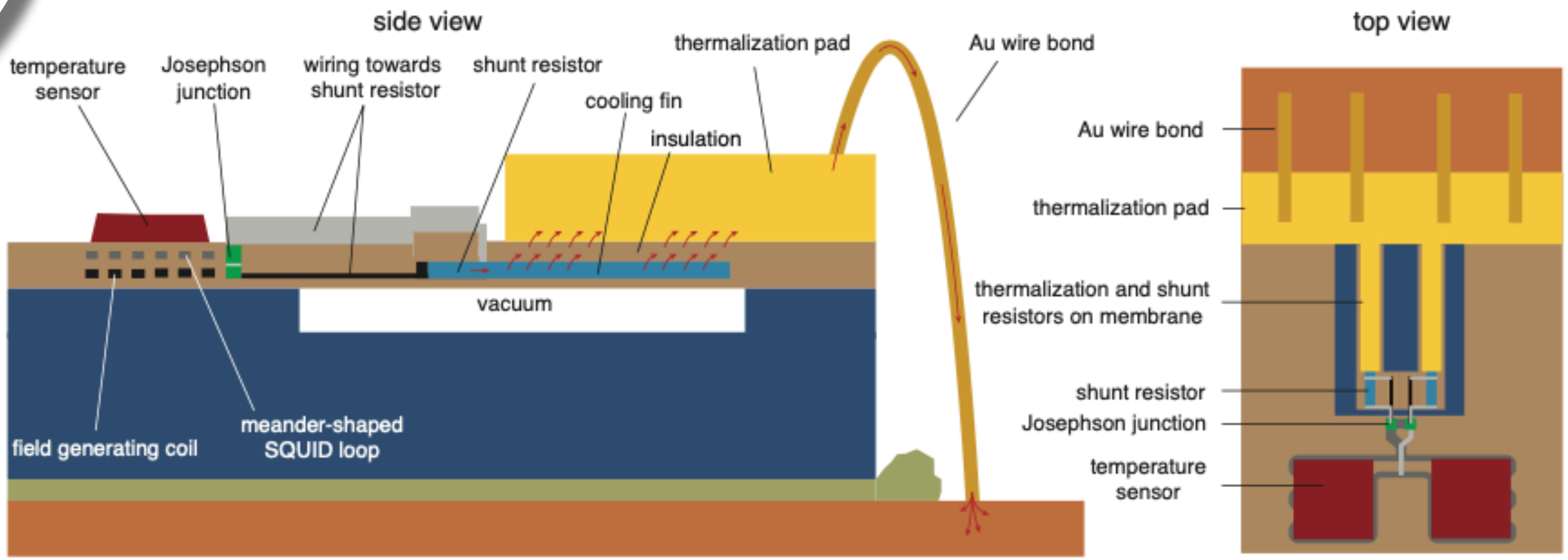


M. Krantz, PhD thesis, Heidelberg University (2020)
V. Zakosarenko *et al.*, Supercond. Sci. Technol. **16** (2005) 1404-1407
R. Stolz *et al.*, IEEE Trans. Appl. Supercond. 15 (2005) 773-776

Tackling power dissipation of integrated detectors



isolating SQUID shunts by placement on SiO2 membranes
(decoupling of SQUID and sensor)



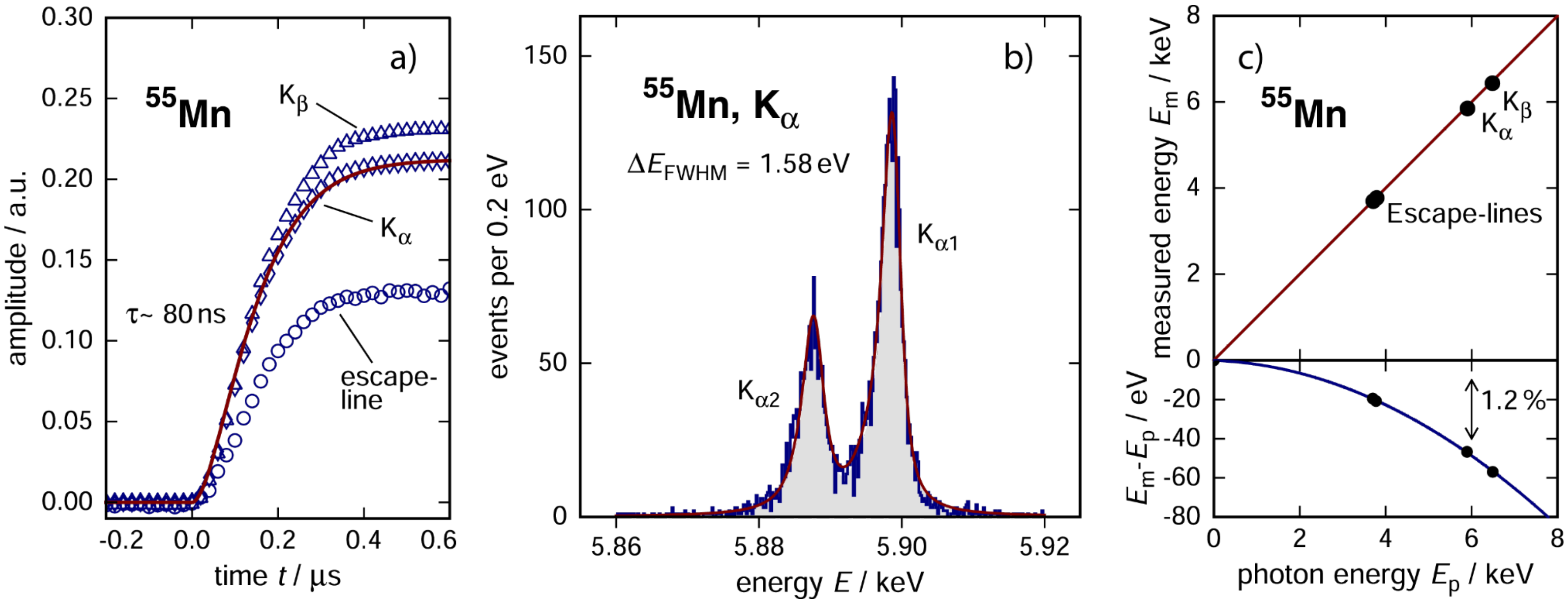
M. Krantz, PhD thesis, Heidelberg University (2020)

Key features of MMCs

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

MMC all around the world…

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atomic / molecular physics
- X-ray spectroscopy
- highly-charged ions
- molecular ion chemistry
- X-ray polarimetry

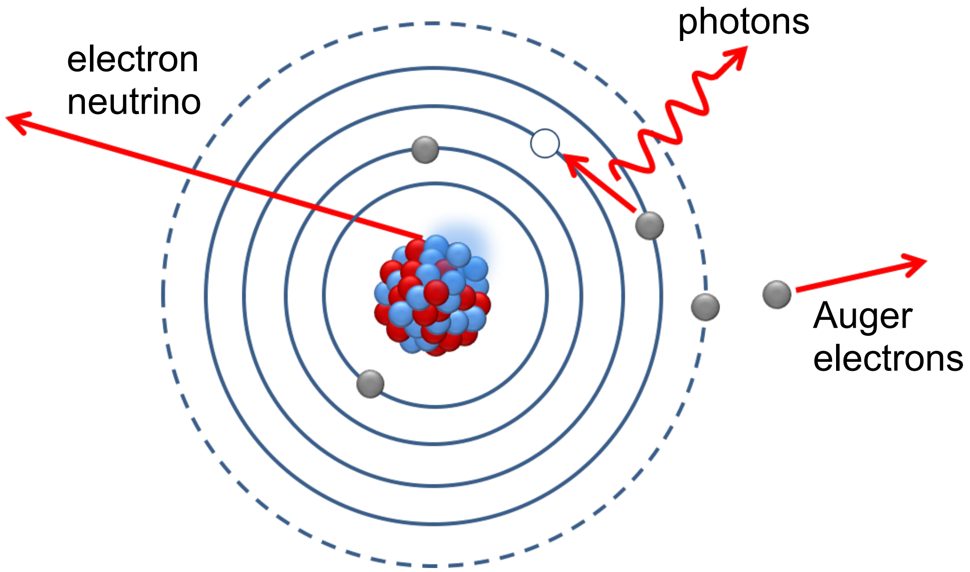
nuclear physics
- nuclear isomer state of ^{229}Th
- nuclear forensics
- nuclear safeguards
- gamma spectroscopy

radiation metrology
- α–, β–, and γ–spectroscopy
- Q-value measurements
- measurements of EC spectra

particle / astroparticle physics
- neutrino mass determination
- search for $0\nu\beta\beta$ decay
- dark matter searches (axions, sterile neutrinos)

Neutrino mass investigation using ^{163}Ho

Idea: Calorimetric measurement of the energy spectrum of the electron capture decay of ^{163}Ho



$$^{163}_{67}\mathrm{Ho} \rightarrow {}^{163}_{66}\mathrm{Dy}^* + \nu_e$$
$$\hookrightarrow {}^{163}_{66}\mathrm{Dy} + E_c$$

A. De Rujula, M. Lusignoli, Phys. Lett. B **118** (1982) 429

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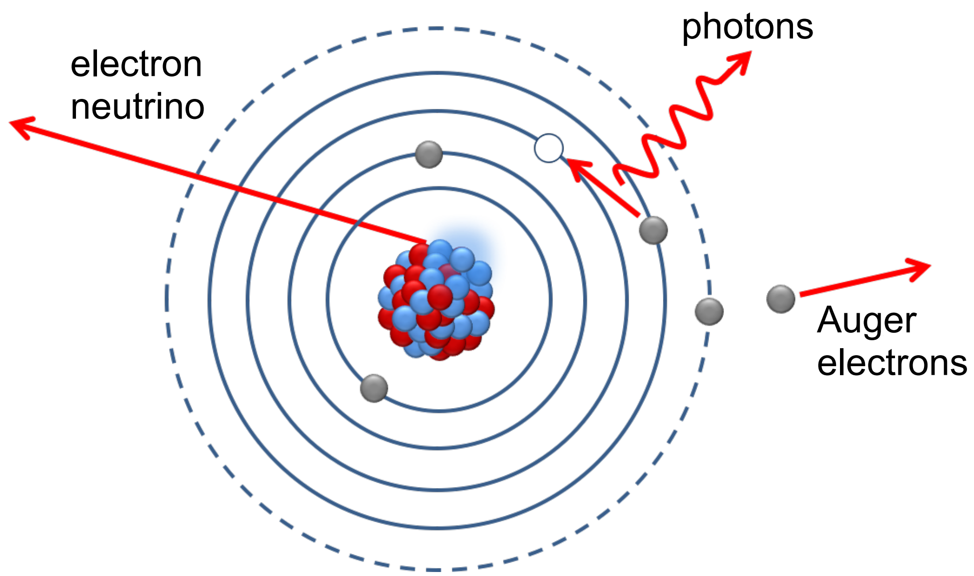

$$^{163}_{67}\text{Ho} \rightarrow {}^{163}_{66}\text{Dy}^{*} + \nu_{\text{e}}$$

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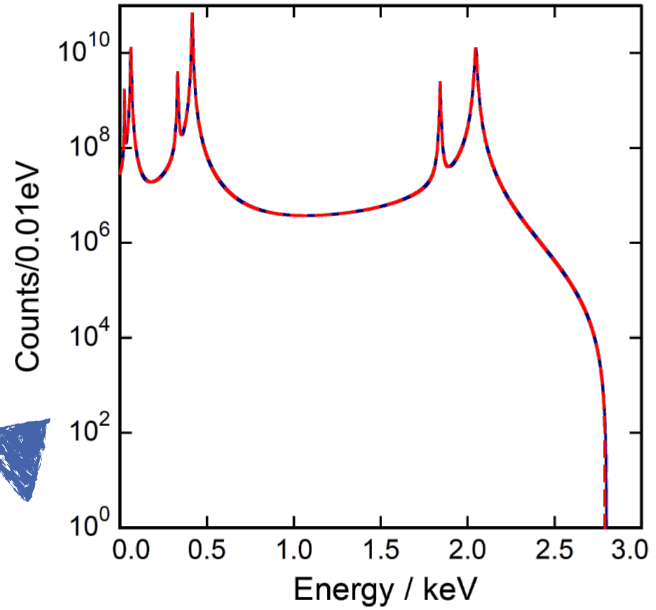

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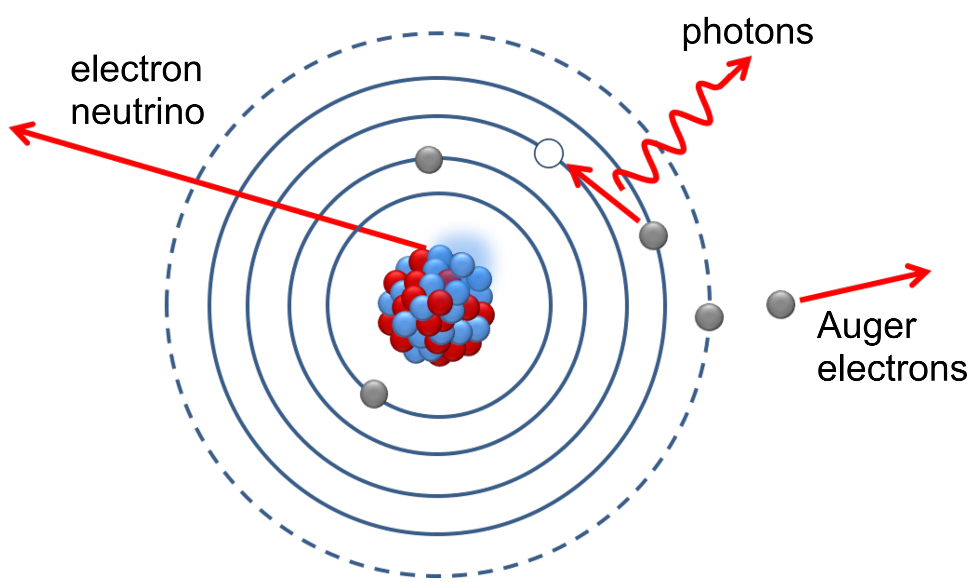

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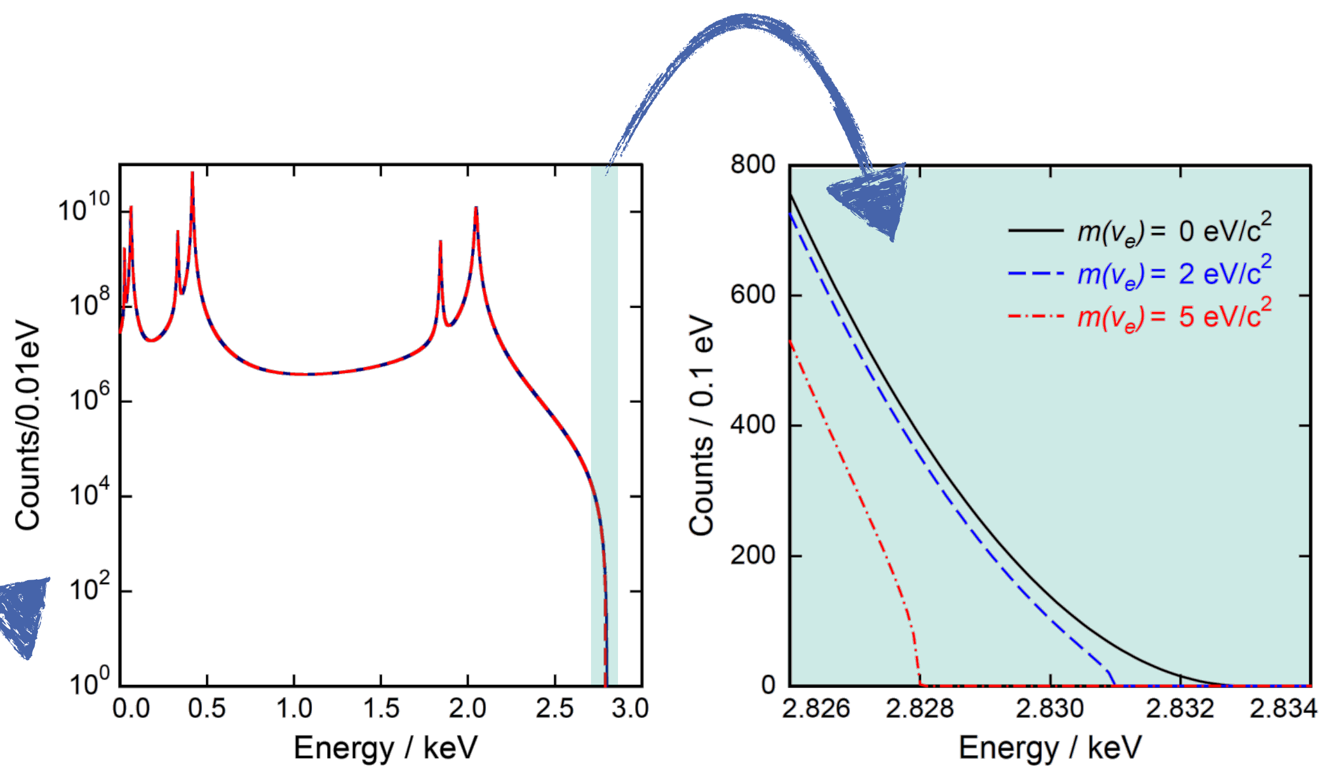
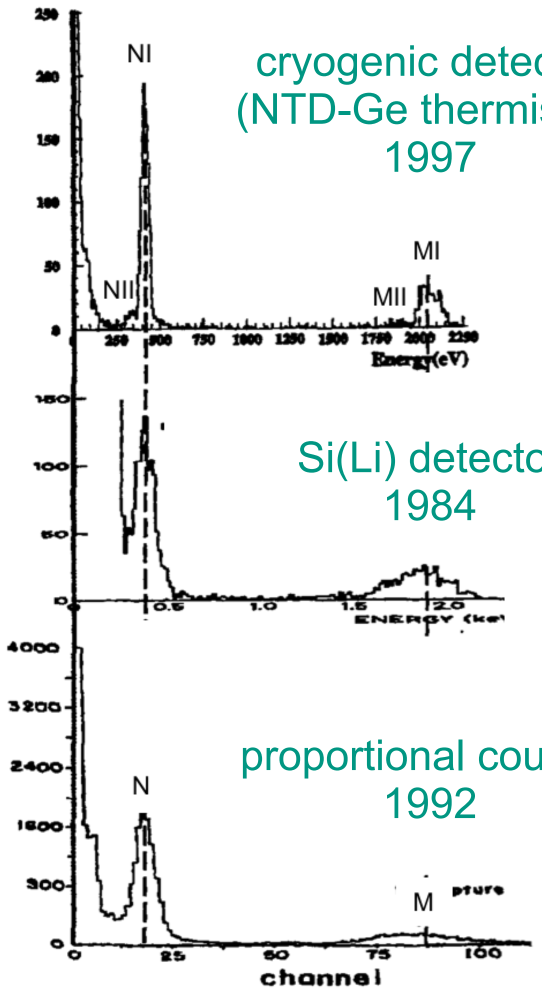


endpoint region of energy spectrum affected by finite electron neutrino mass

A. De Rujula, M. Lusignoli, Phys. Lett. B **118** (1982) 429

Previous and recent measurements



F. Gatti *et al.*, Physics Letters B **398** (1997) 415-419

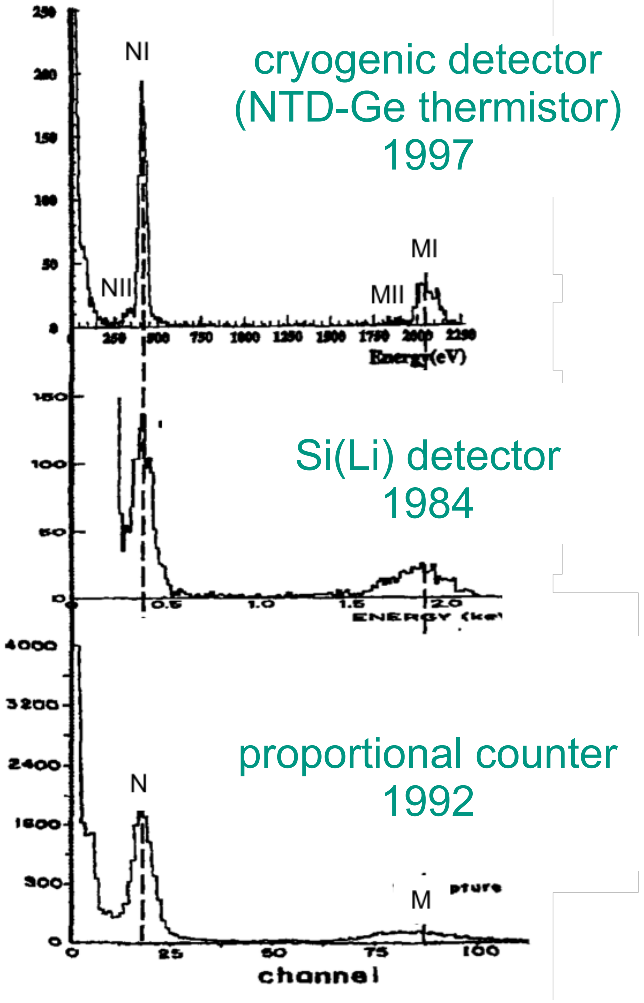
cryogenic detector
(NTD-Ge thermistor)
1997

Si(Li) detector
1984

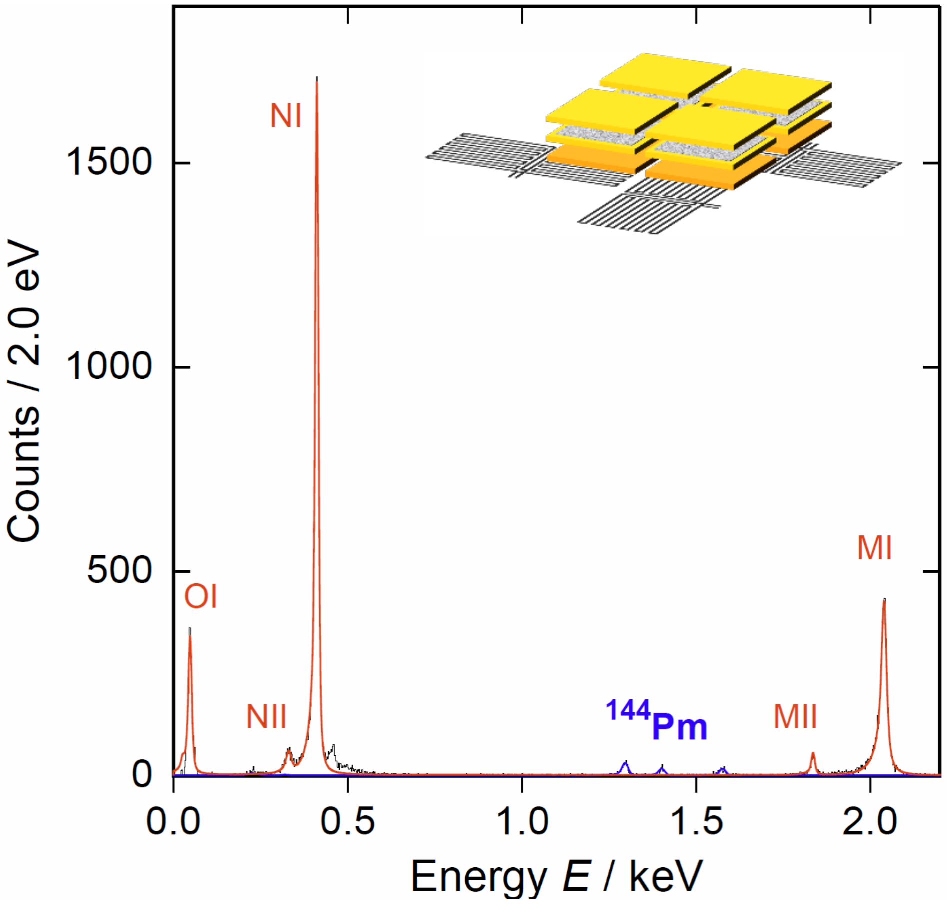
proportional counter
1992

Previous and recent measurements

F. Gatti *et al.*, Physics Letters B **398** (1997) 415-419



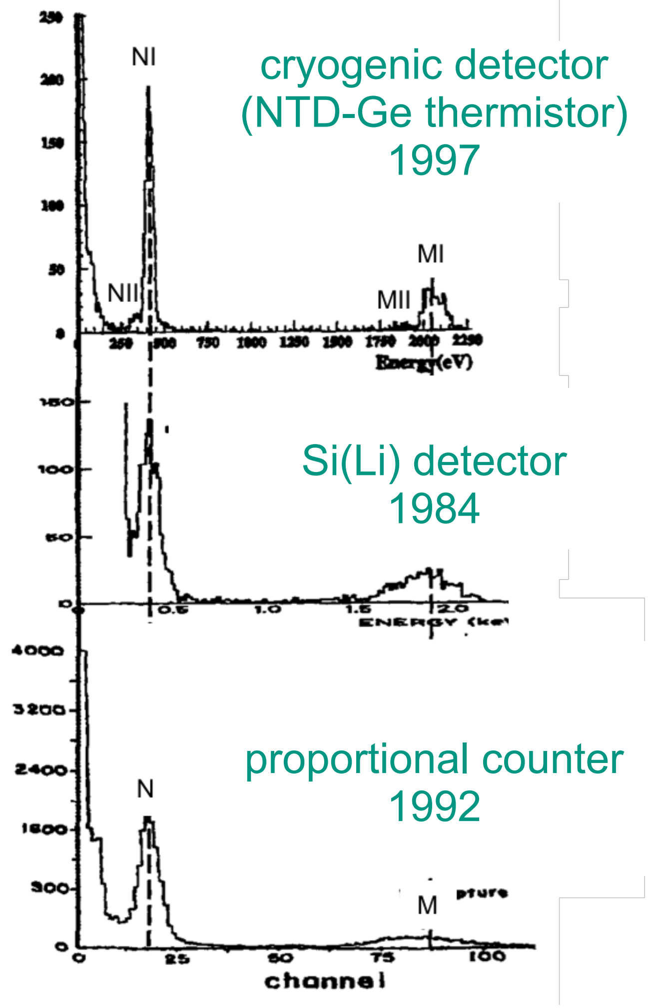
First MMC based measurement



L. Gastaldo *et al.*, Eur. Phys. J. Special Topics **226** (2017) 1623

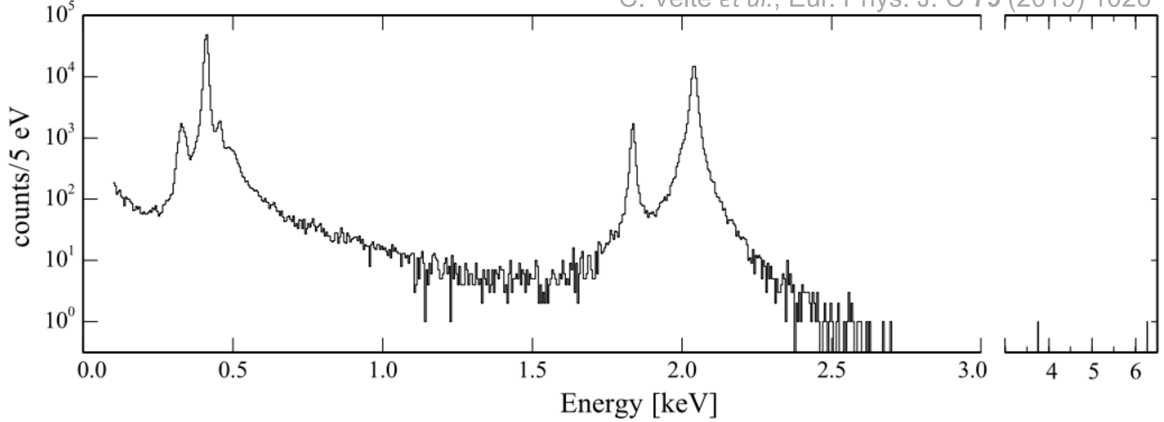
Previous and recent measurements

F. Gatti *et al.*, Physics Letters B **398** (1997) 415-419

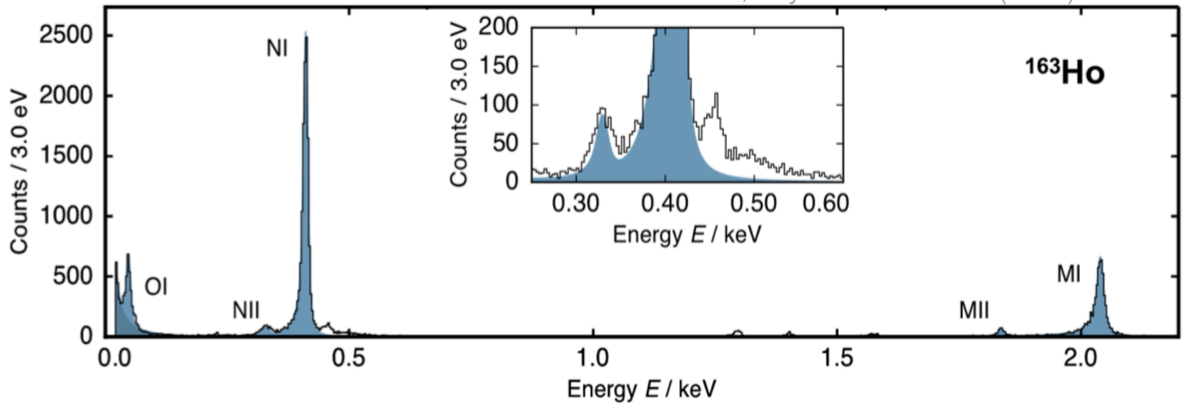


MMC based measurements

C. Velte *et al.*, Eur. Phys. J. C **79** (2019) 1026



P. Ranitzsch *et al.*, Phys. Rev. Lett. **119** (2017) 122501



Pixels, pixels, pixels…

(image) resolution

no. of pixels (for given area) determines picture resolution

100 × 75

140 × 105

500 × 375

Crab Nebula - NGC 1952

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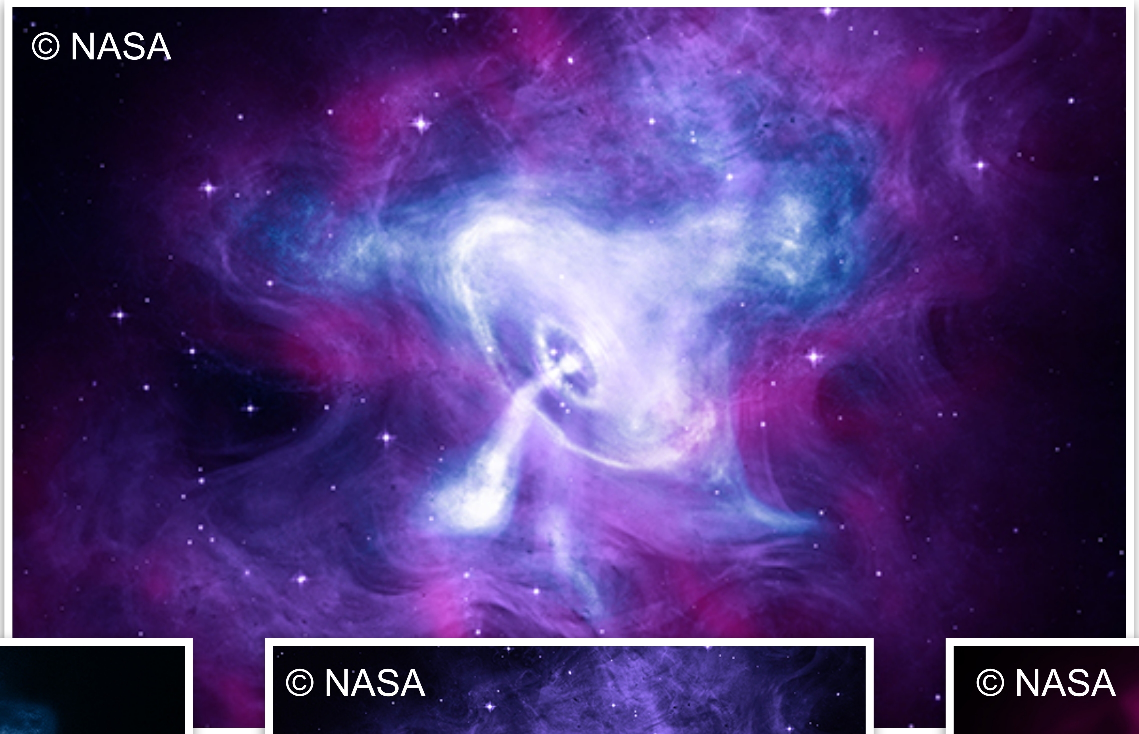
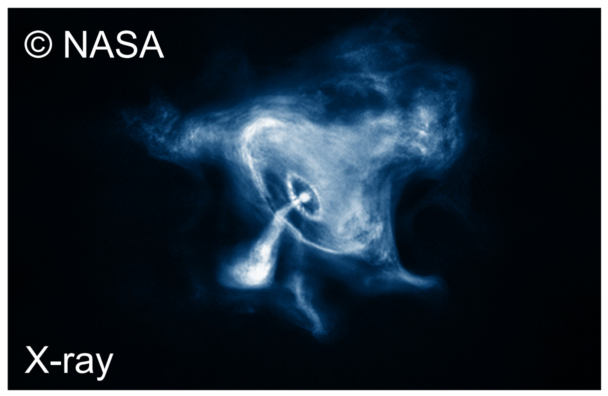
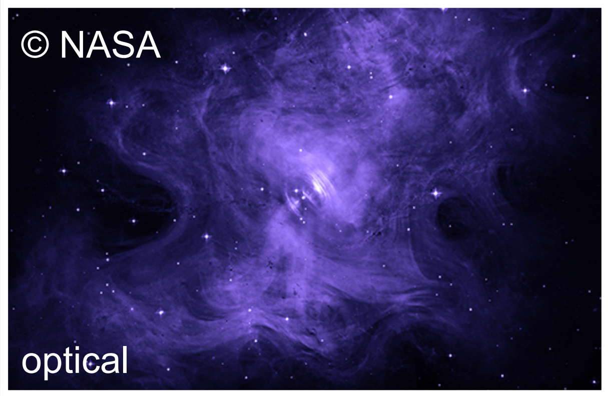
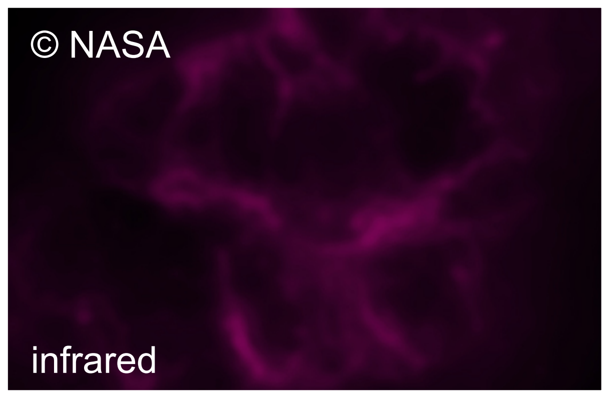


megapixel X-ray camera







Pixels, pixels, pixels…

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statistics

number of events determined by number of pixels and measurement time

example: ECHo-1M plans to measure ~10^{14} Ho-163 decays

ECHo

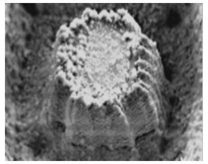
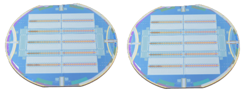
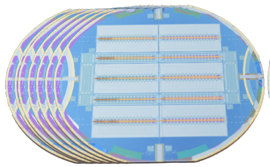
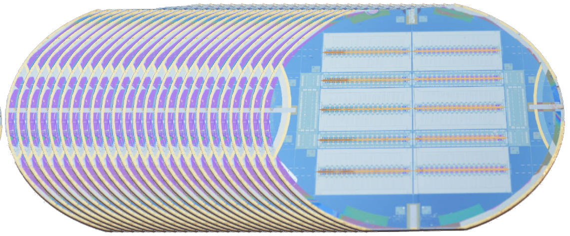
10 Bq/px → 1 detector for 3.2×10^5 yr

10 Bq/px → 10^5 detectors for 3.2 yr

L. Gastaldo *et al.*, Eur. Phys. J Special Topics **226** (2017) 1623 - 1694

High-resolution superconducting sensors (HSS)

HSS = large-scale production and development center for high-resolution superconducting sensors
(jointly operated by IPE, IMS and KIP)

“handmade“	university cleanroom	HSS (short term) @IMS	HSS (long term) @KCOP
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

Readout of large-scale detector arrays

simplest idea: multiply single-channel detector readout

- number of wires
- parasitic heat load
- costs
- complexity

→ scaling sets practical limit on array size (at least for cryogenic devices)

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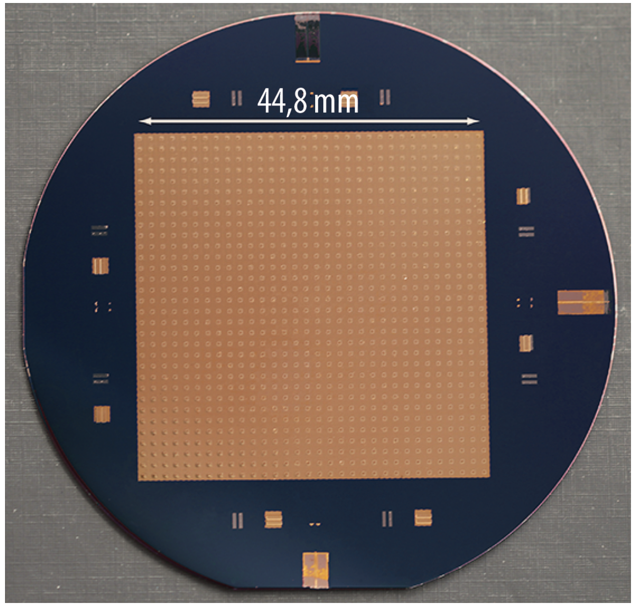
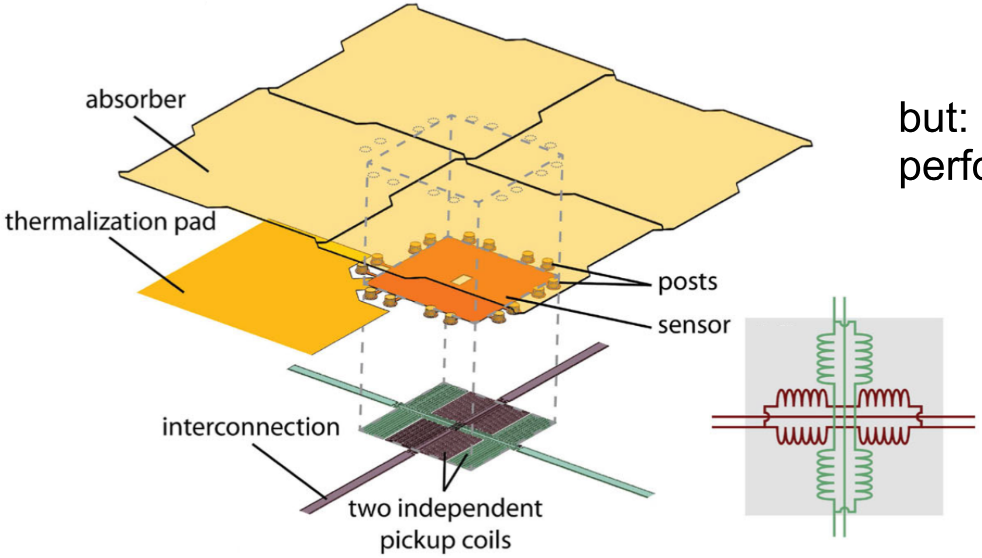
more sophisticated: readout scheme minimizing electronic channels ('soft' multiplexing)



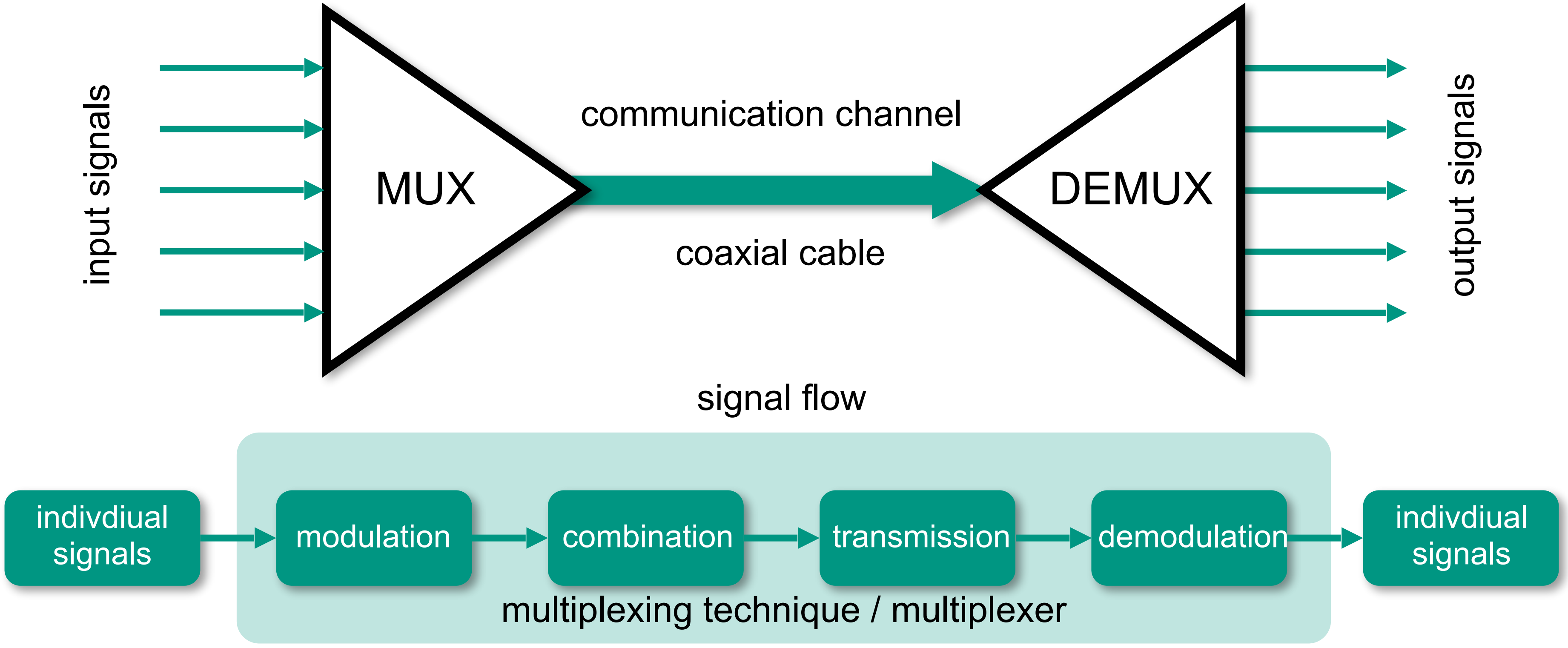


but: degradation of detector performance

L. Gamer *et al.*, J. Low Temp. Phys. **184** (2016) 839 - 844

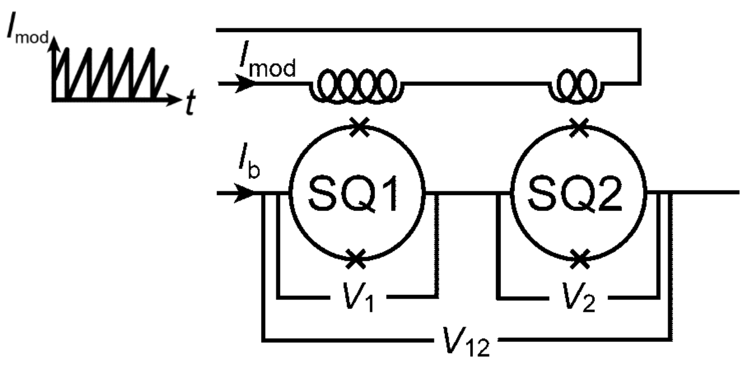
Cryogenic multiplexing

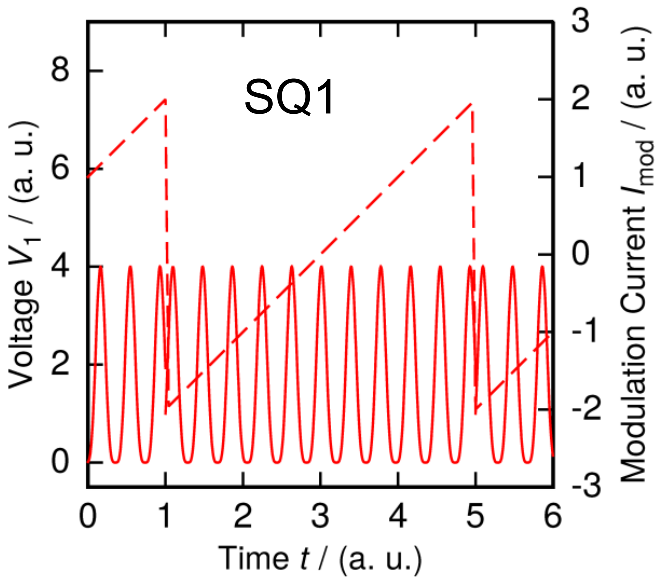
multiplexing (muxing)	method by which multiple signals are combined into one ‘physical’ channel to share a scarce resource.

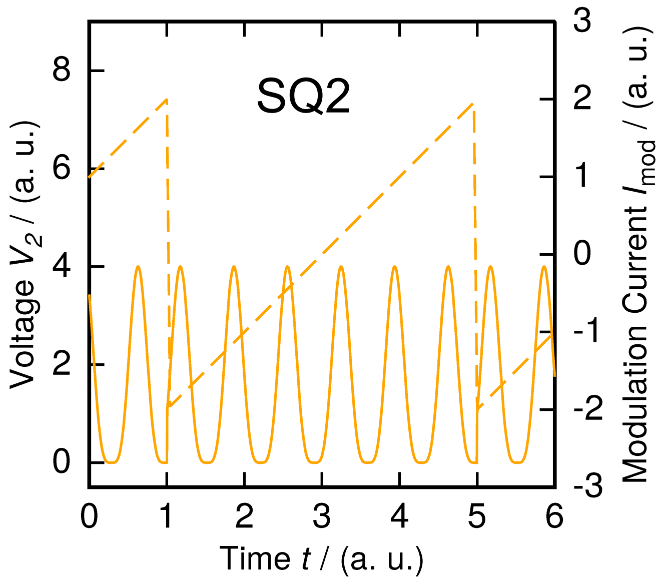


FRM based dc-SQUID multiplexer

idea: series connection of dc-SQUIDs simultaneously flux ramp modulated via common modulation coil coupled differently to each SQUID

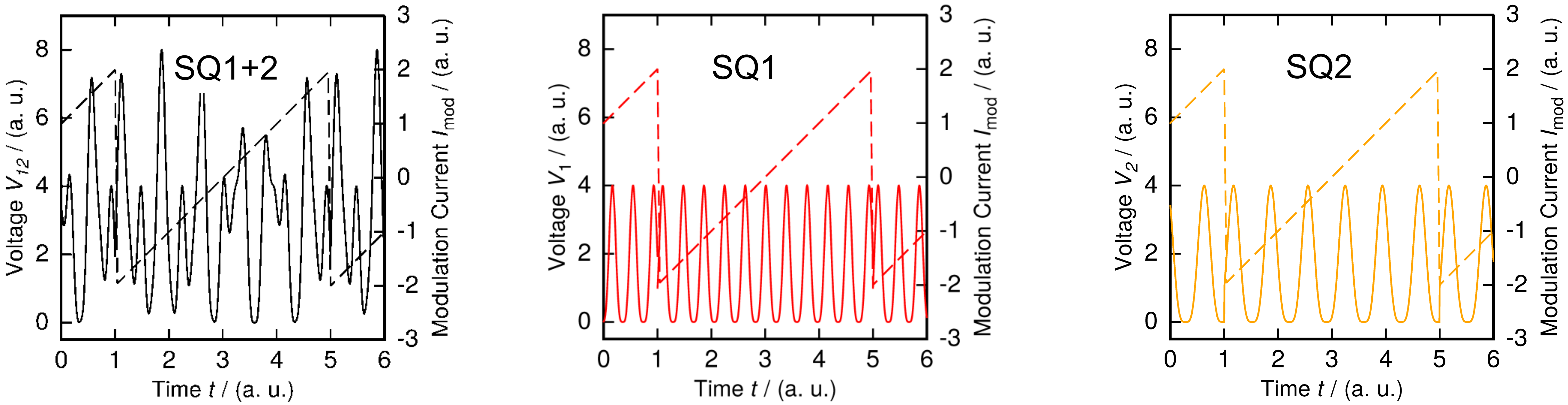






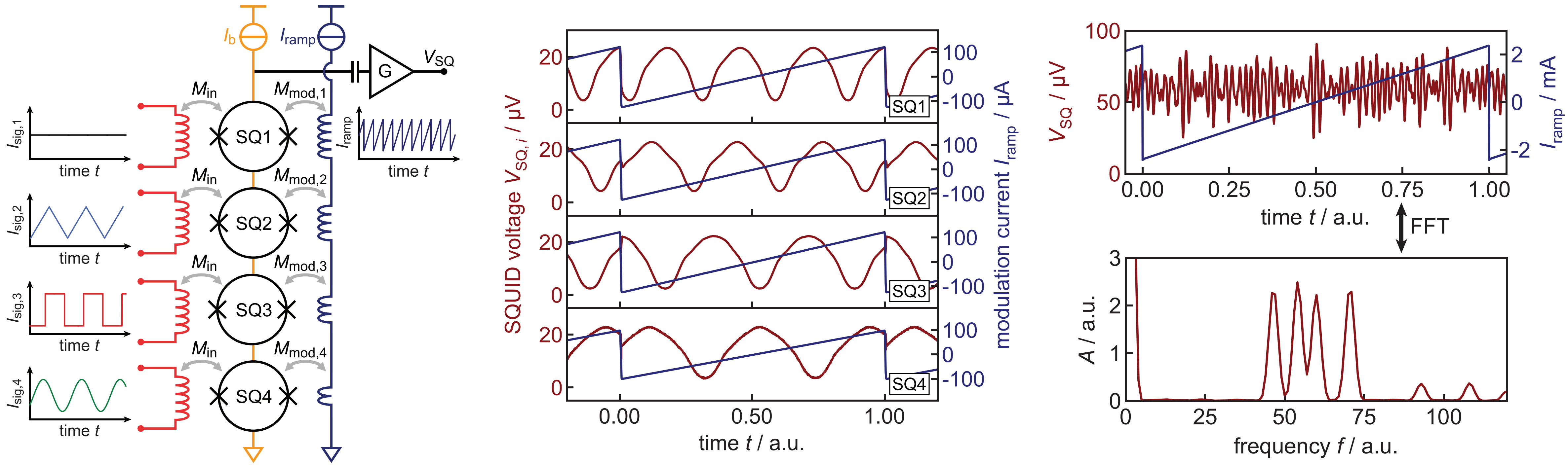
FRM based dc-SQUID multiplexer

idea: series connection of dc-SQUIDs simultaneously flux ramp modulated via common modulation coil coupled differently to each SQUID



FRM based dc-SQUID multiplexer

simplest possible prototype (proof-of-concept) with four individual readout channel



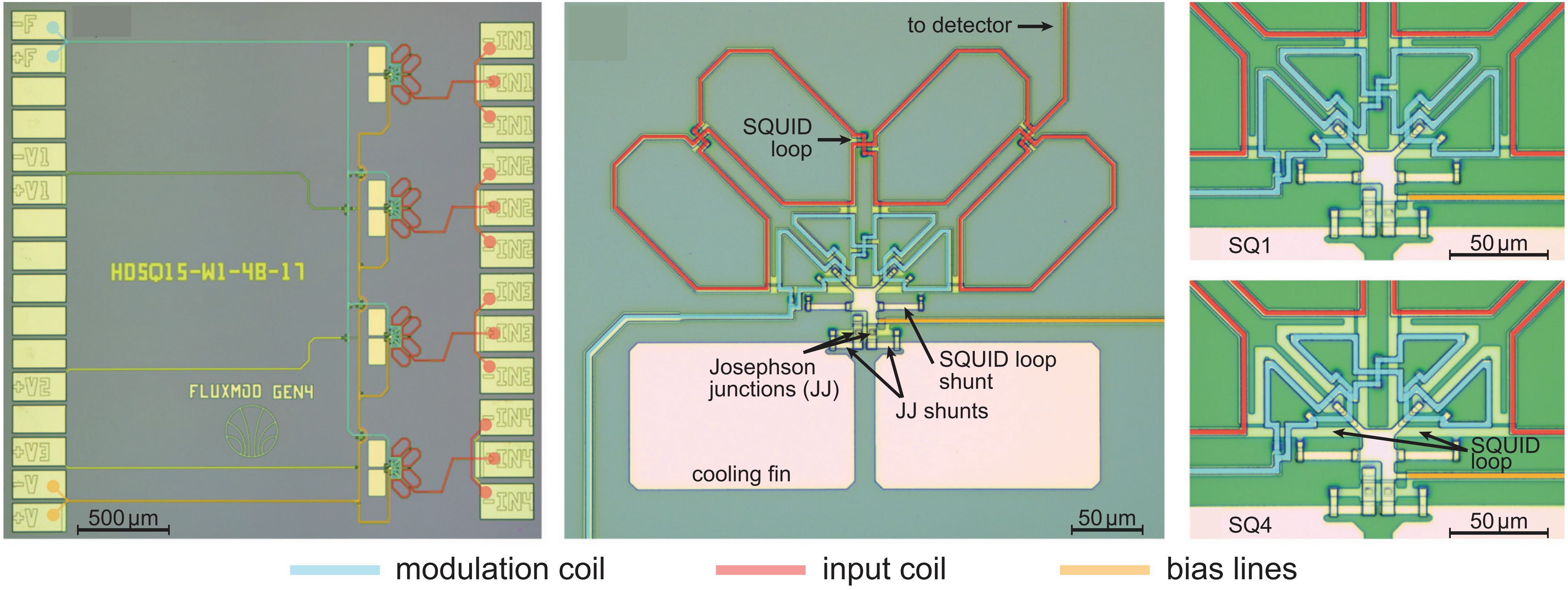
’simple’ realization of frequency-division multiplexing
suitable for reading out tens of individual detectors

D. Richter, SK *et al.*, Appl. Phys. Lett. **118** (2021) 122601

Prototype layout

Karlsruhe Institute of Technology

modulation coil coupling adjust by overlap between coil and SQUID loop



D. Richter, SK *et al.*, Appl. Phys. Lett. **118** (2021) 122601

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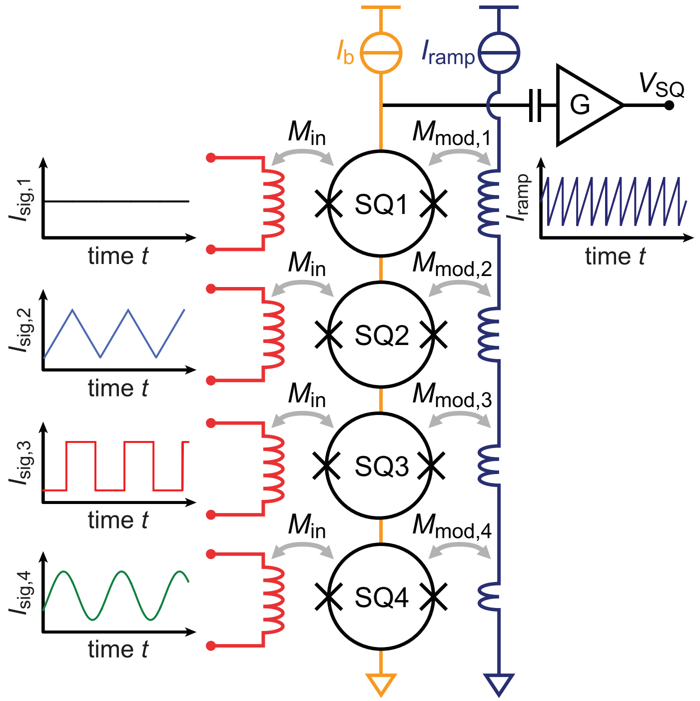
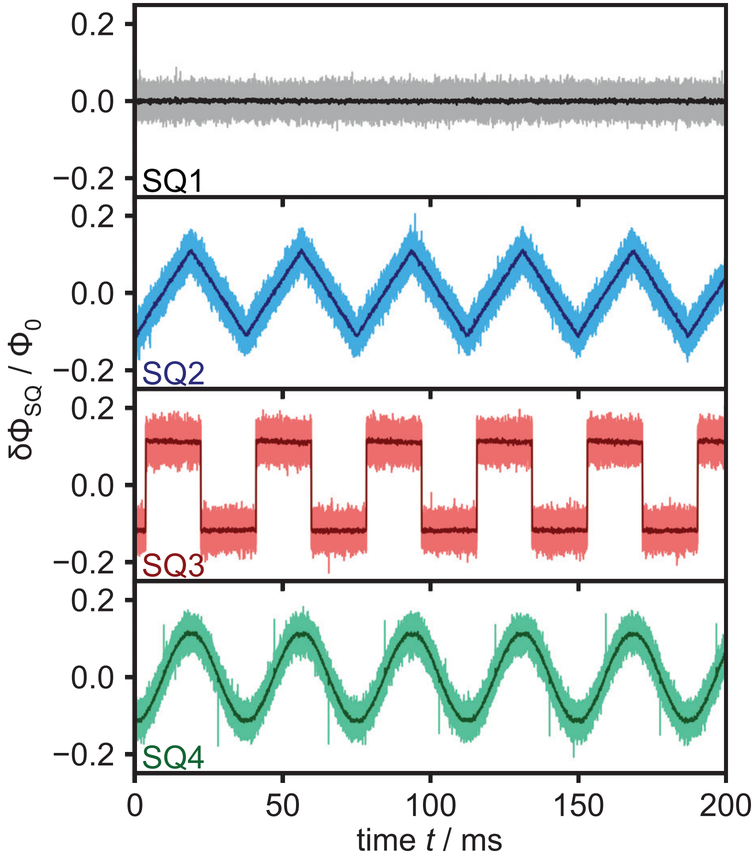


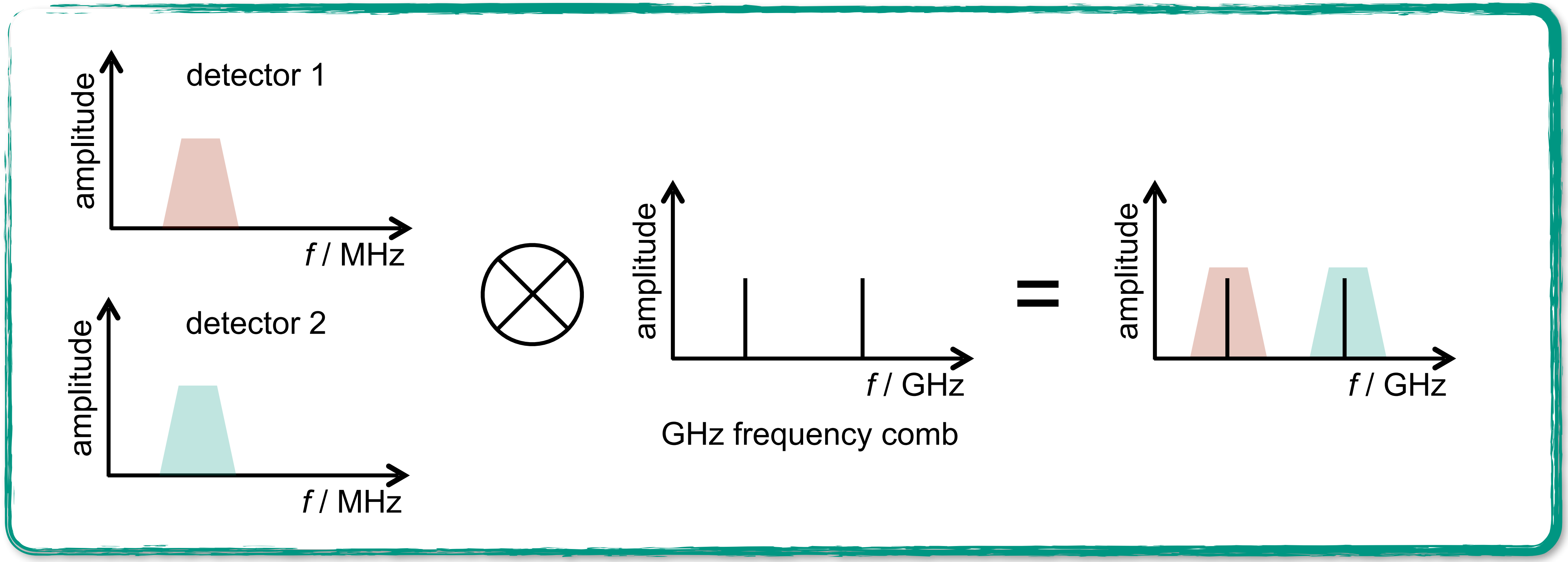


→ concept validated!

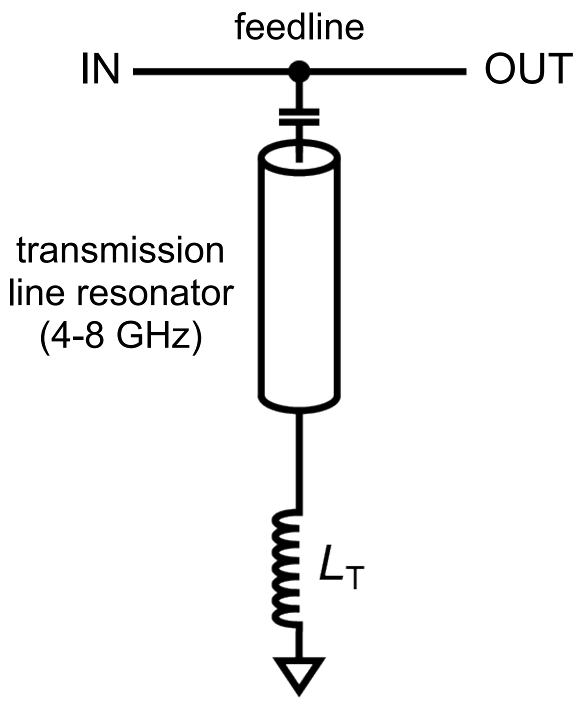
D. Richter, SK *et al.*, Appl. Phys. Lett. **118** (2021) 122601

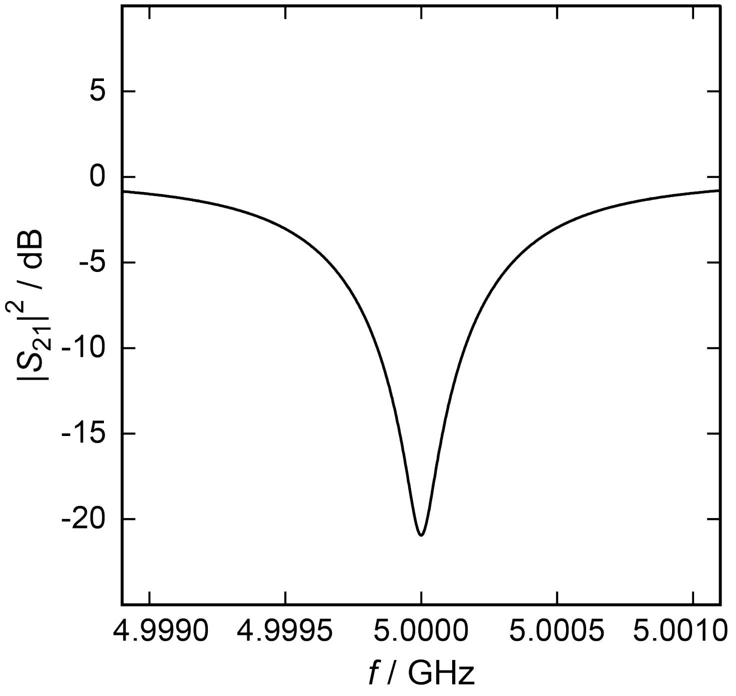
GHz frequency-division multiplexing (GHz-FDM)

idea: detector signals are modulated on independent GHz carrier signals



Non-hysteretic rf-SQUIDs





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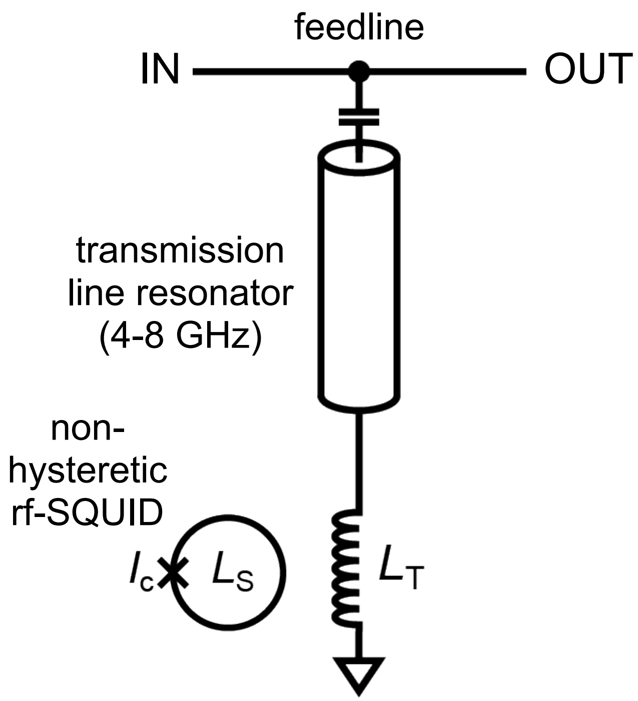

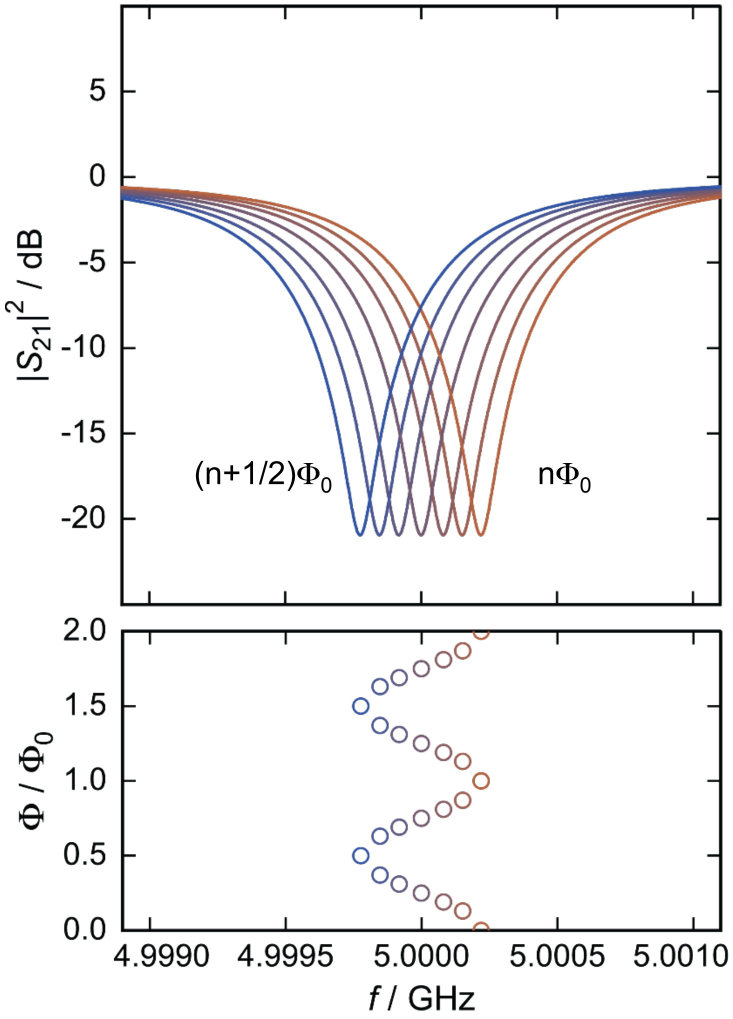

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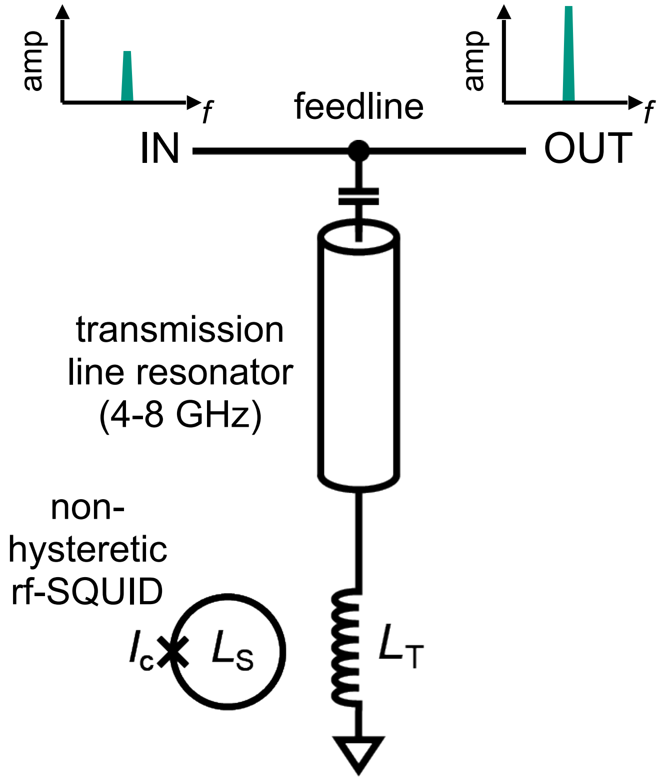
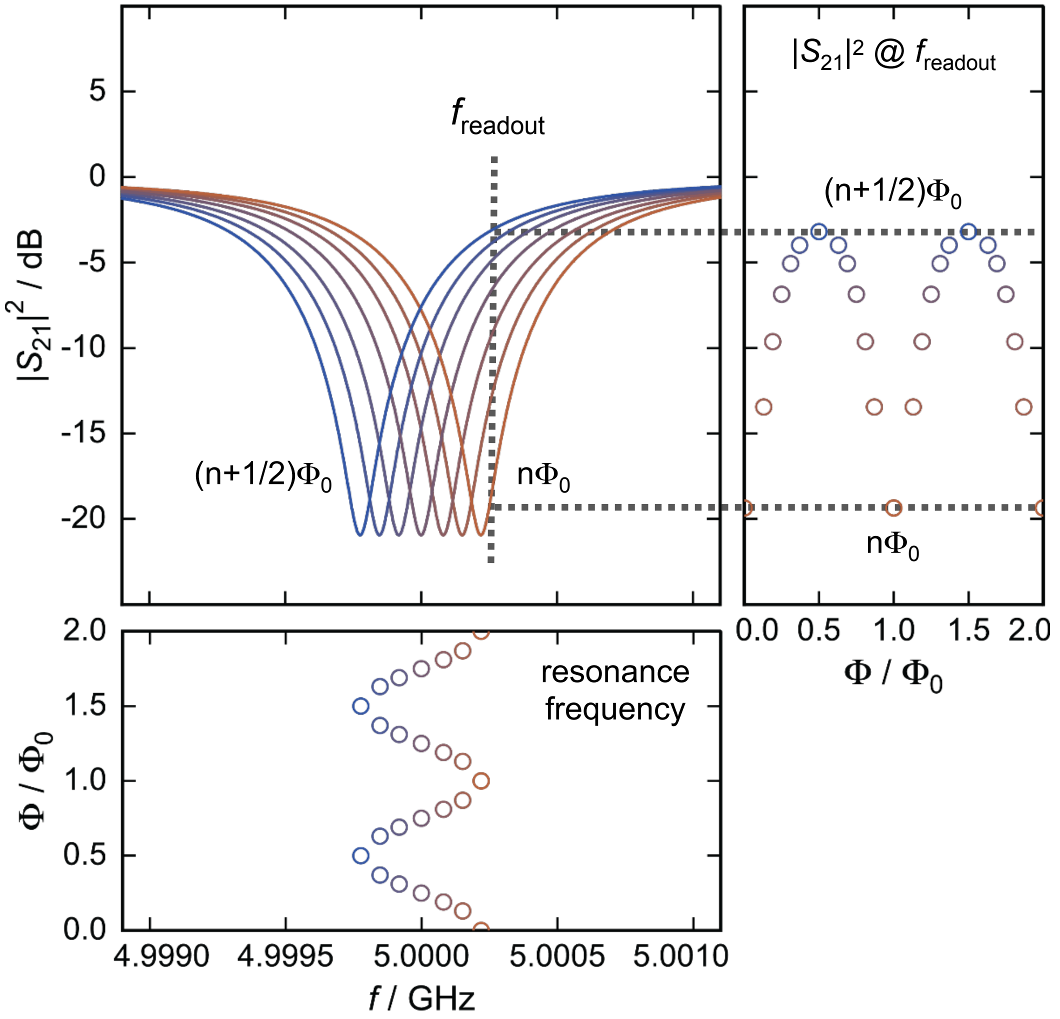
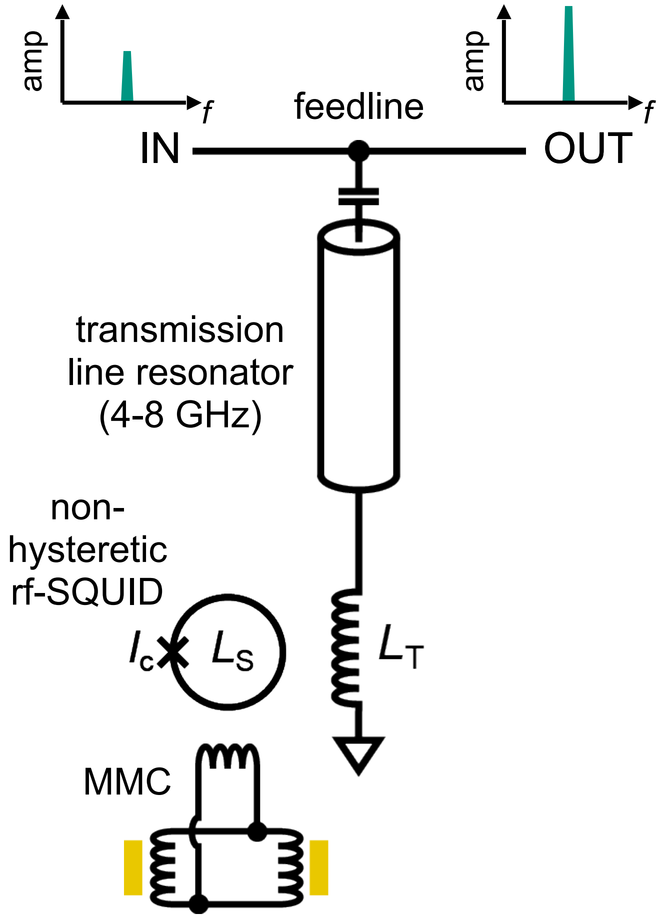
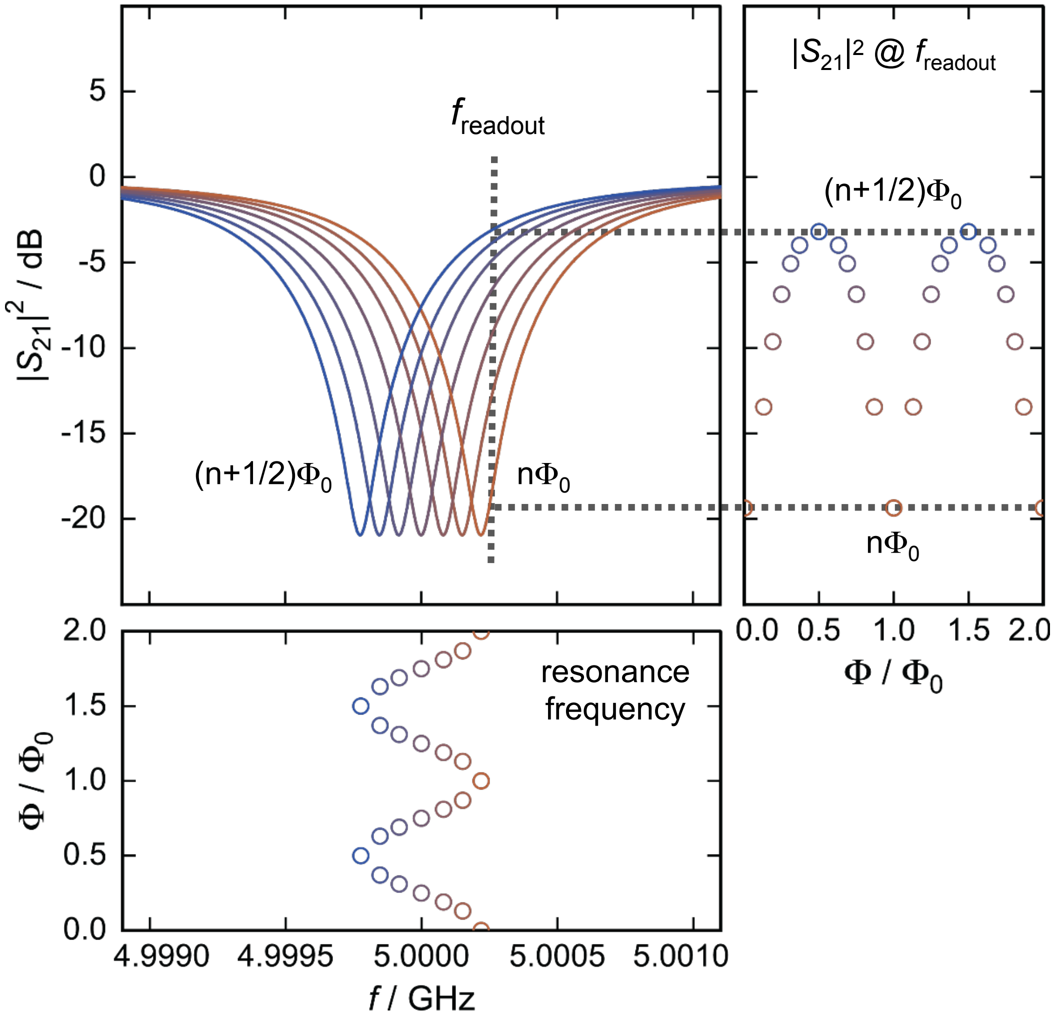


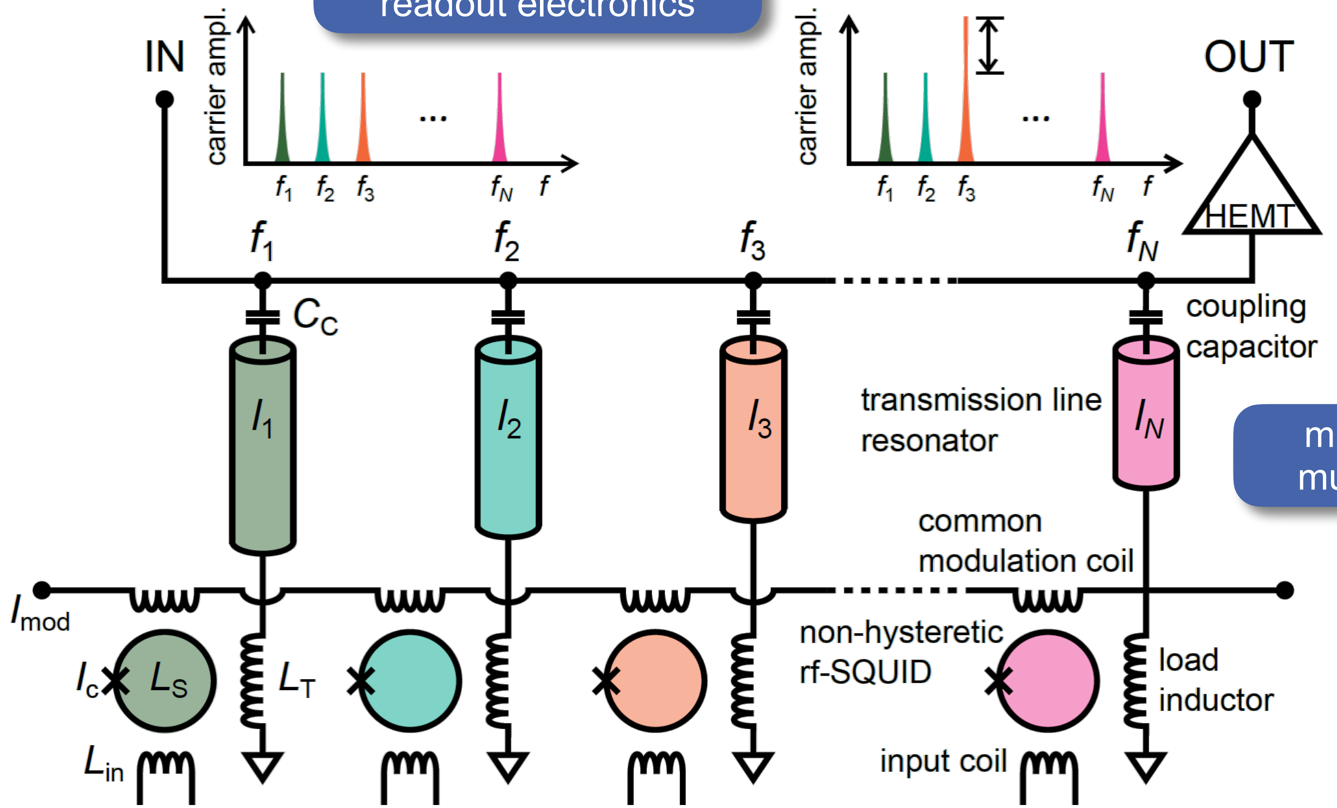


Non-hysteretic rf-SQUIDs





Microwave SQUID Multiplexing

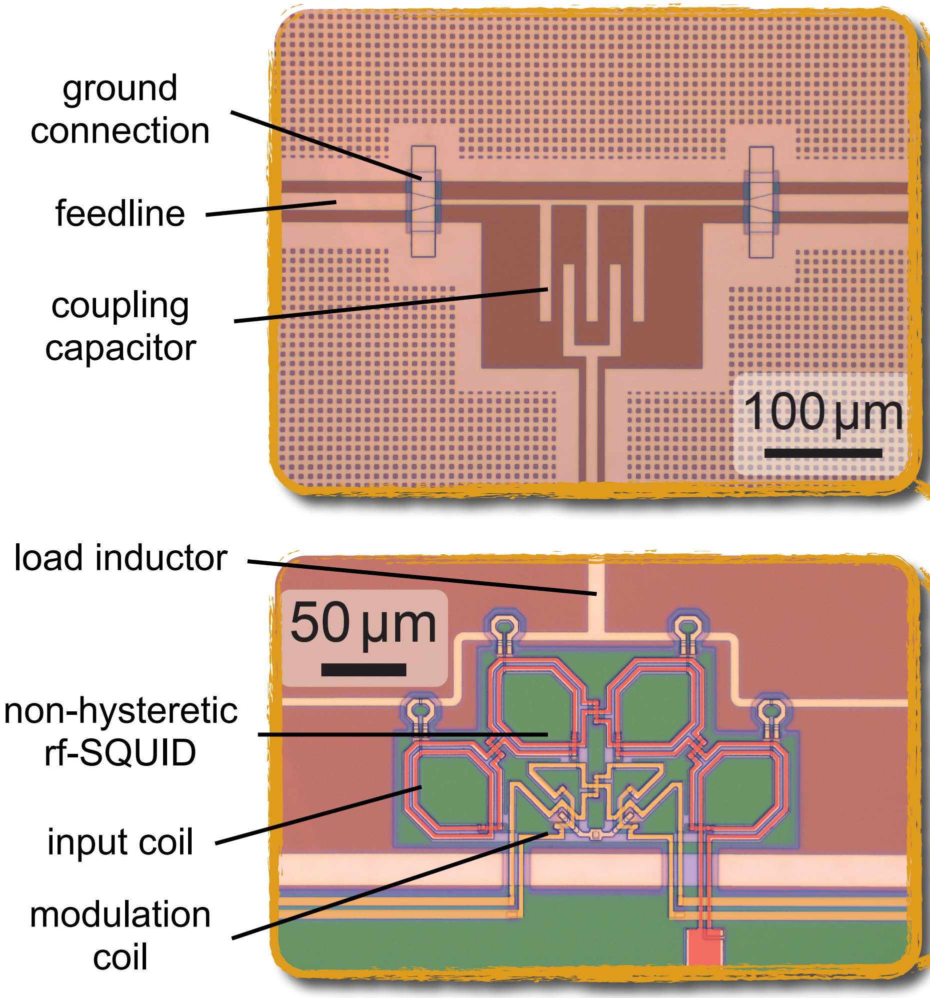


1 HEMT amplifier + 2 coaxes ⟶ ~1000 detectors

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

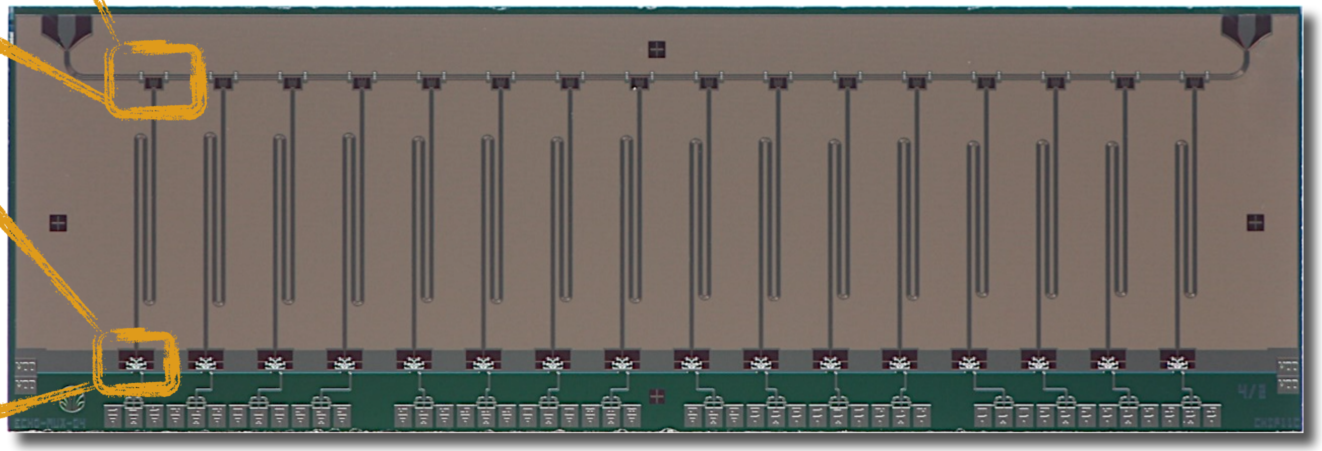
ECHoMUX - µMUX for the ECHo experiment

Karlsruhe Institute of Technology



16 channel MUX based on CPW resonators

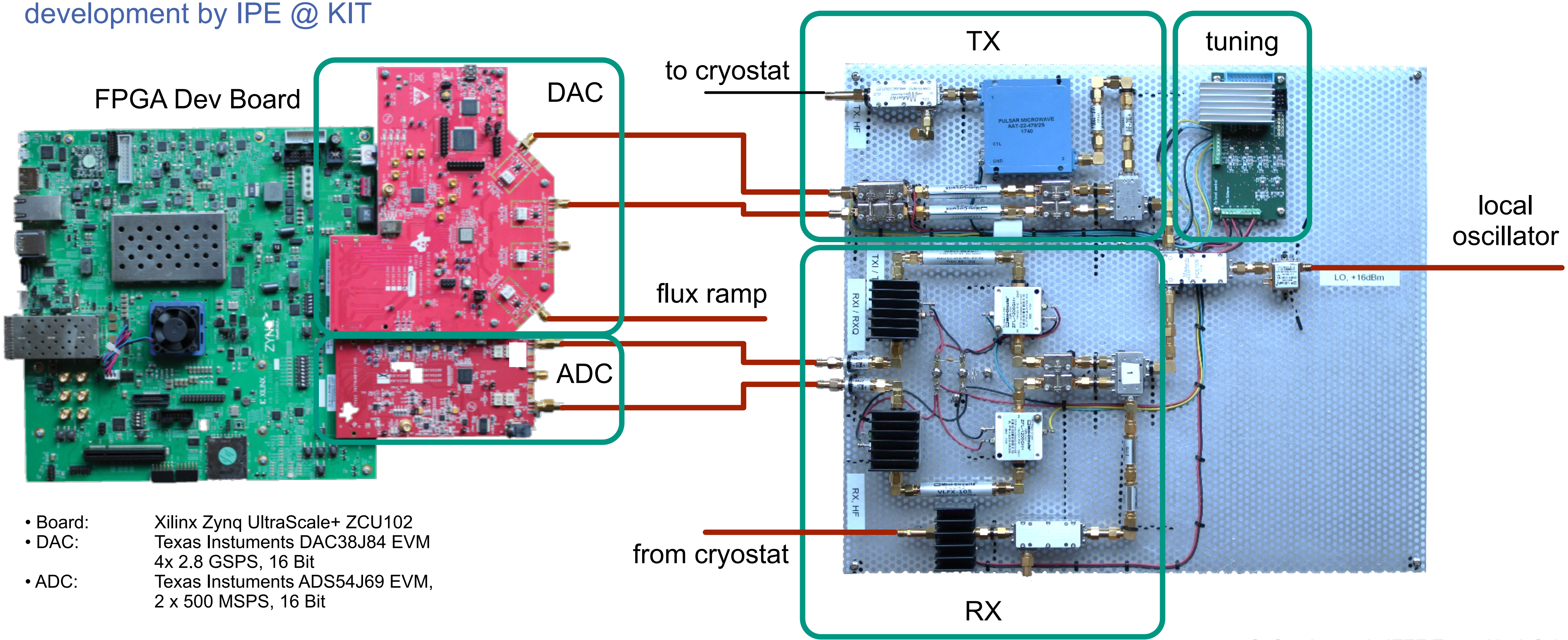
- frequency range ~ 4.5 GHz … 4.8 GHz
- resonator bandwidth ~ 1.0 MHz
- frequency shift Δf_r ~ 1.2 MHz
- frequency spacing ~ 20 MHz
- SQUID screening parameter β_L ~ 0.6
- input coil inductance L_{in} ~ 1.5 nH (impedance matched to MMC)



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

Readout electronics

development by IPE @ KIT



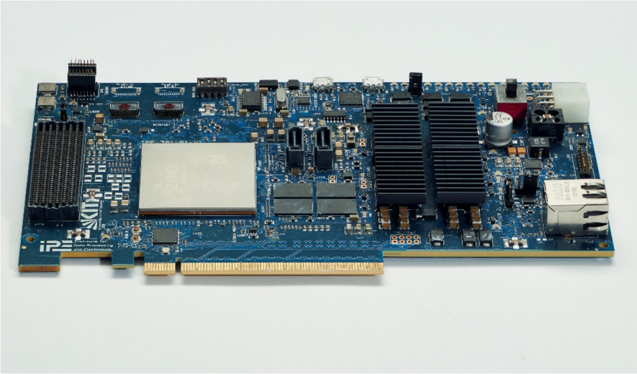
- Board: Xilinx Zynq UltraScale+ ZCU102
- DAC: Texas Instuments DAC38J84 EVM
  4x 2.8 GSPS, 16 Bit
- ADC: Texas Instuments ADS54J69 EVM,
  2 x 500 MSPS, 16 Bit

O. Sander *et al.*, *IEEE Trans. Nucl. Sci.* **66.7** (2019)
N. Karcher *et al.*, *J Low Temp Phys* **200,** 261–268 (2020)

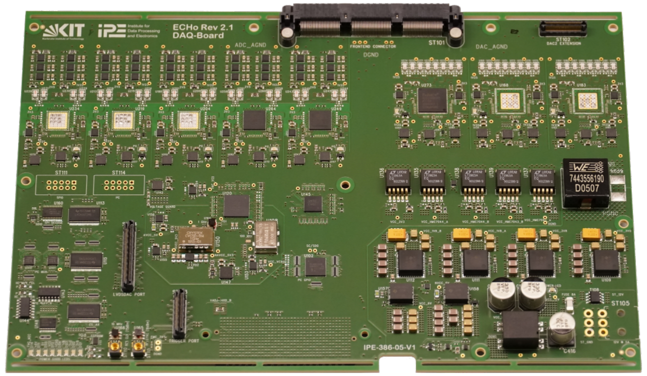
Readout electronics

development by IPE @ KIT

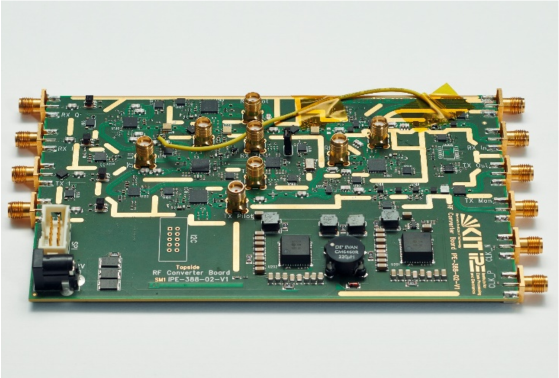
FPGA-Board



ADC/DAC-Board



mixing stage

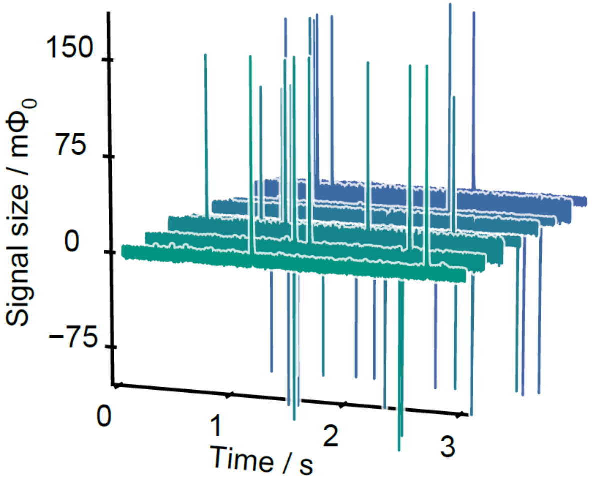


next generation: new readout electronics allows for 5 x 80 = 400 channel readout with optimal power

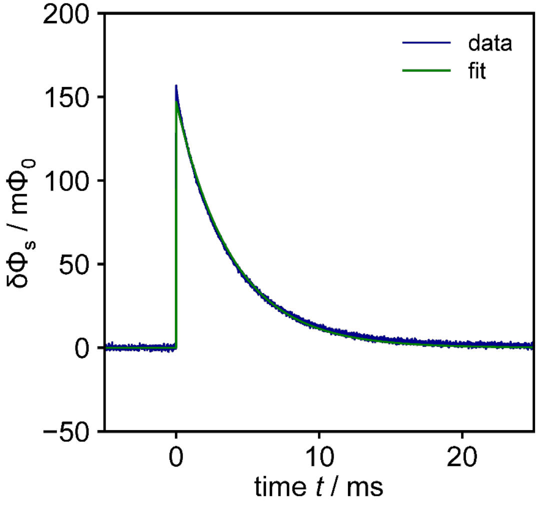
ECHoMUX - some results

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

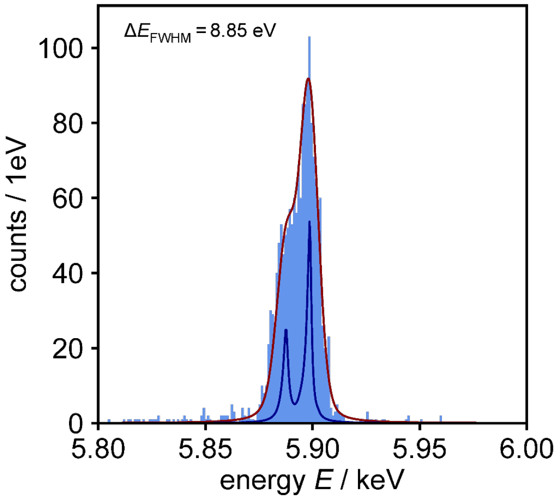
time traces of 16 detector pixels



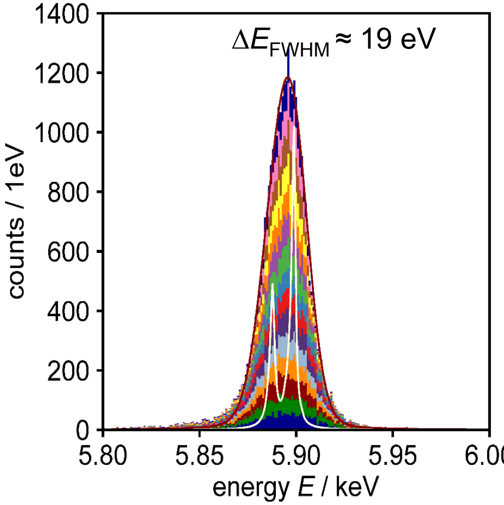
single raw data trace



'typical' spectrum



sum spectrum

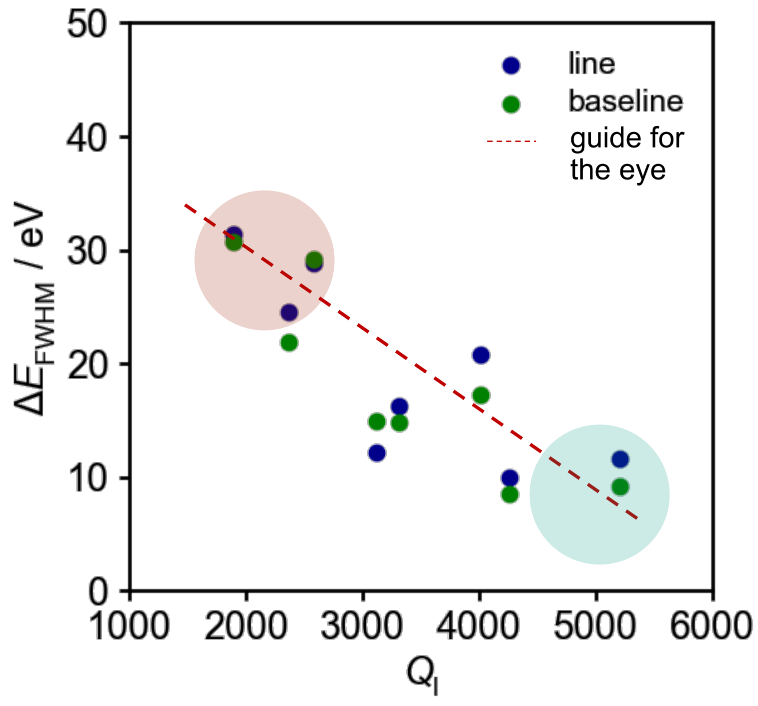


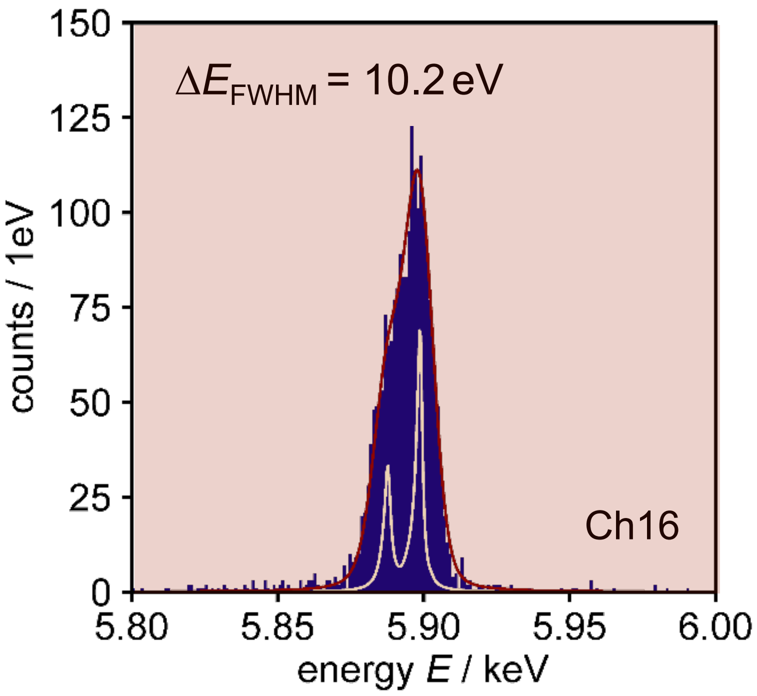
first truely multiplexing demonstration of magnetic microcalorimeters

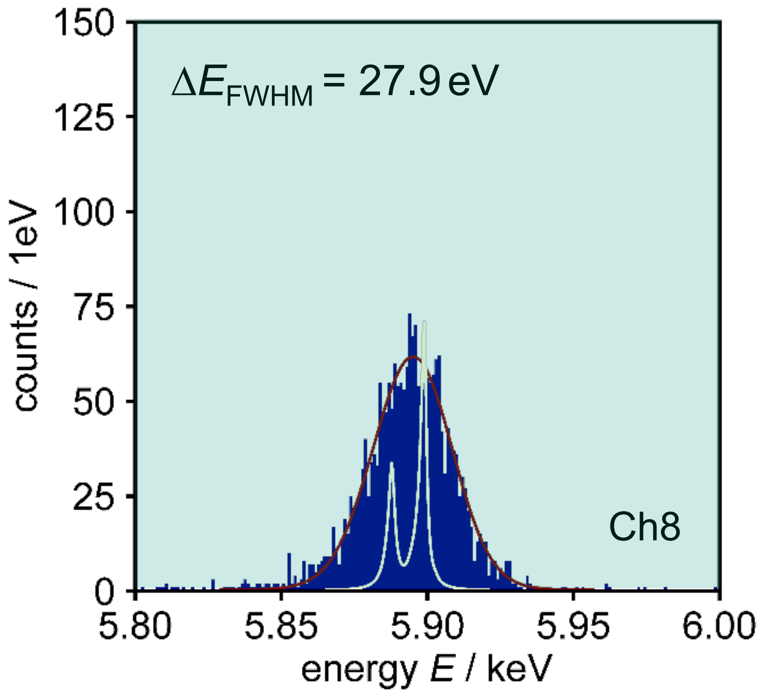
some issues still to be resolved (ongoing)

ECHoMUX - technology challenges

internal quality factor of Nb microwave resonators significantly affects achievable energy resolution







→ further optimization of fabrication technology

µMUX - theory challenges

readout noise is HEMT limited → $\sqrt{S_{\Phi,\mathrm{HEMT}}} \propto \frac{1}{\sqrt{P_{\mathrm{rf}}}}$ → use high readout power!

µMUX - theory challenges

Karlsruhe Institute of Technology

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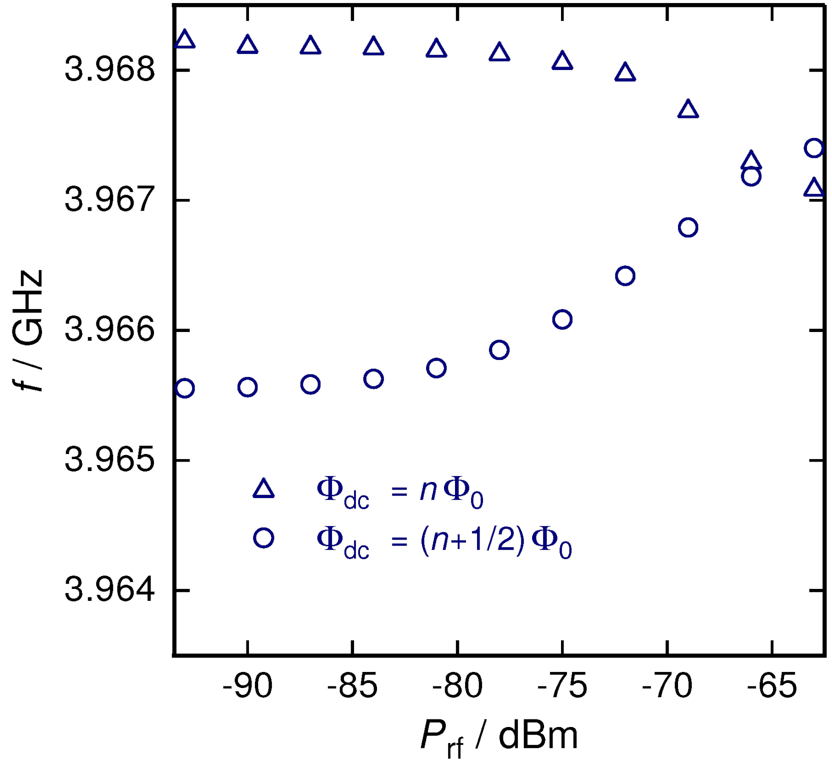

but: high P_{rf}… …reduces resonance frequency shift

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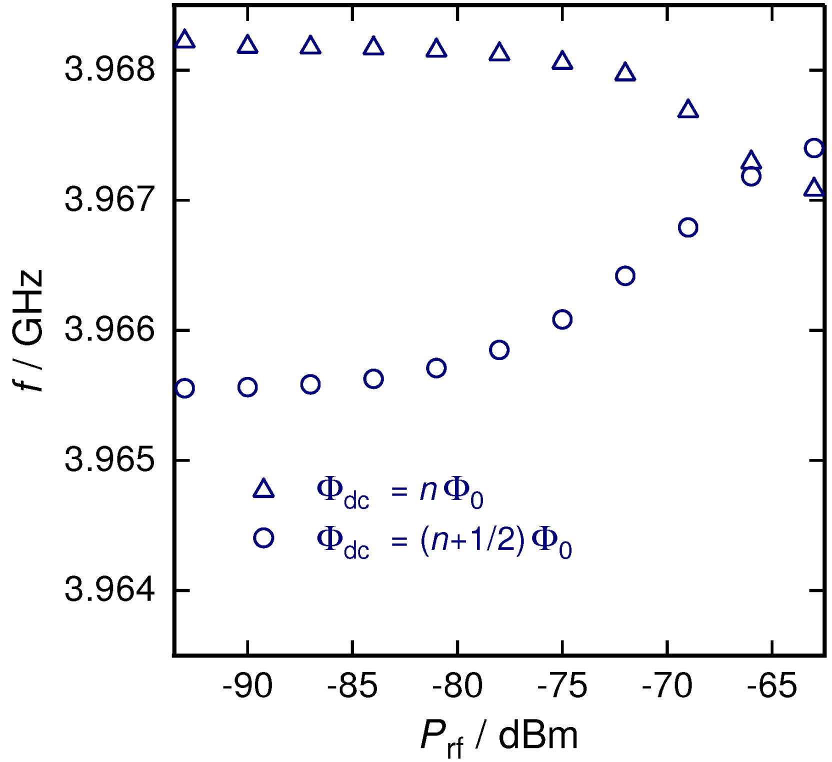

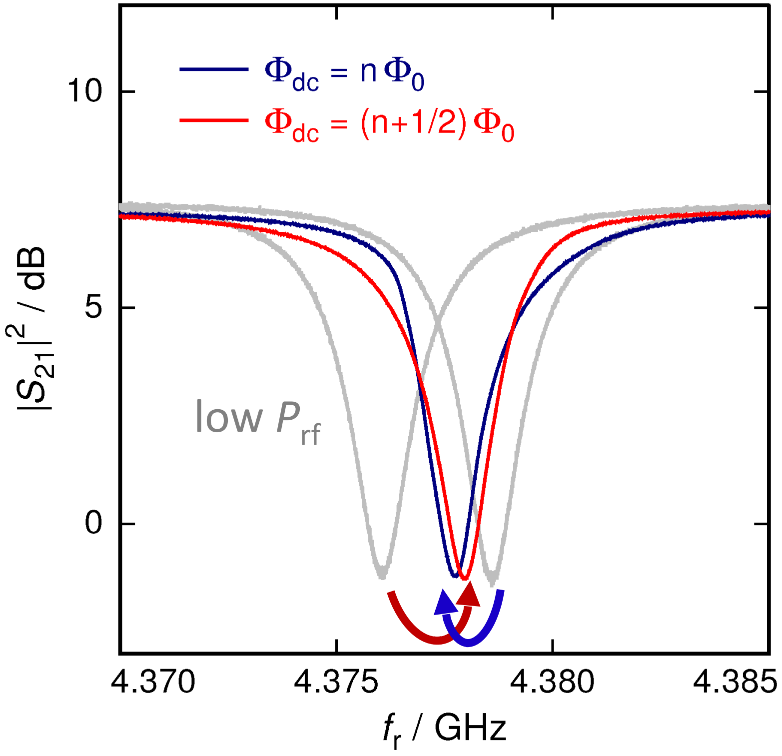

but: high P_{rf}… …reduces resonance frequency shift …and creates asymmetric resonance curves

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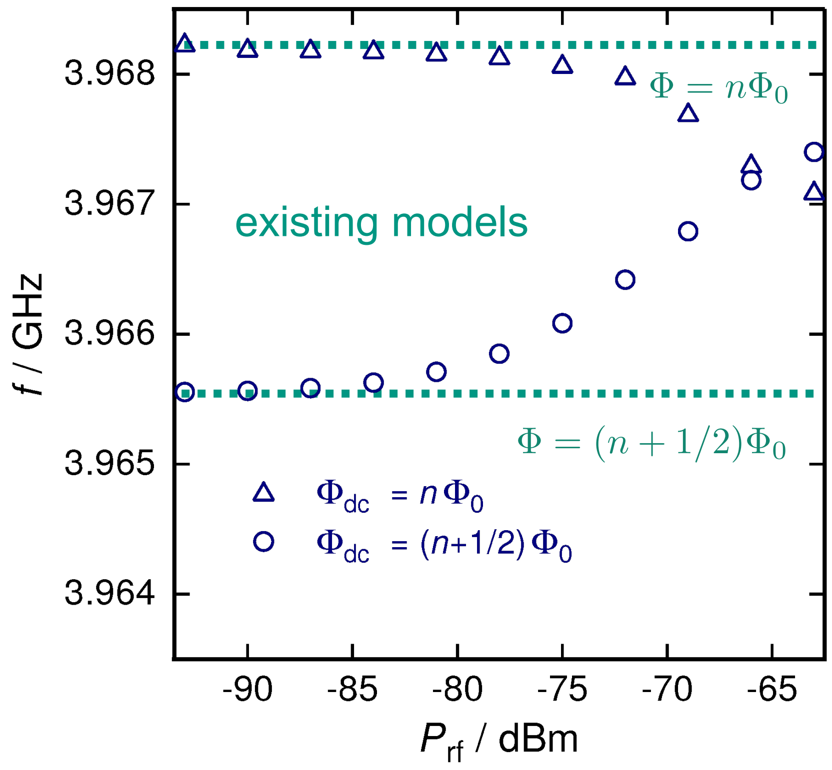

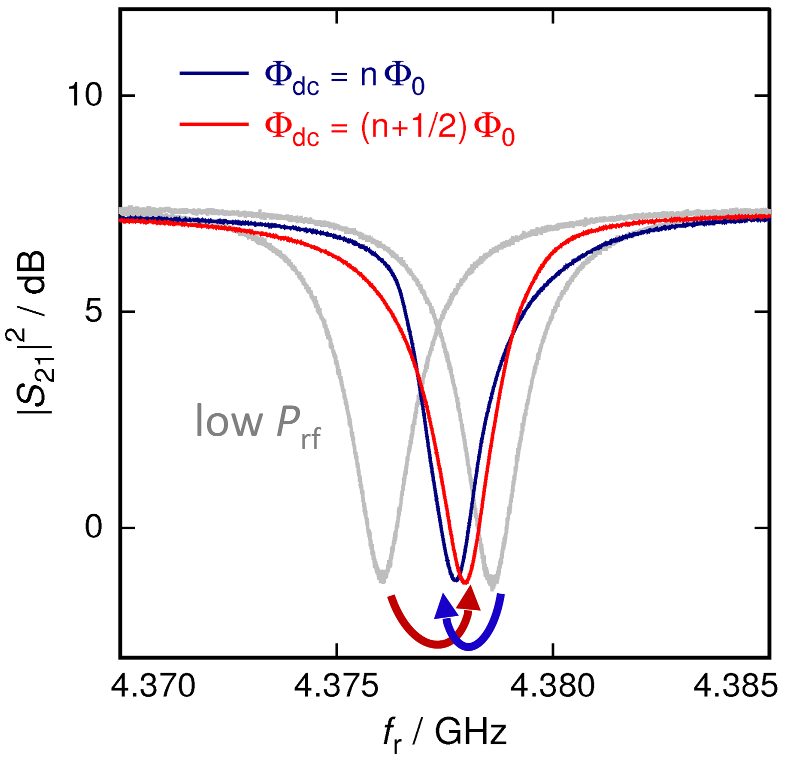

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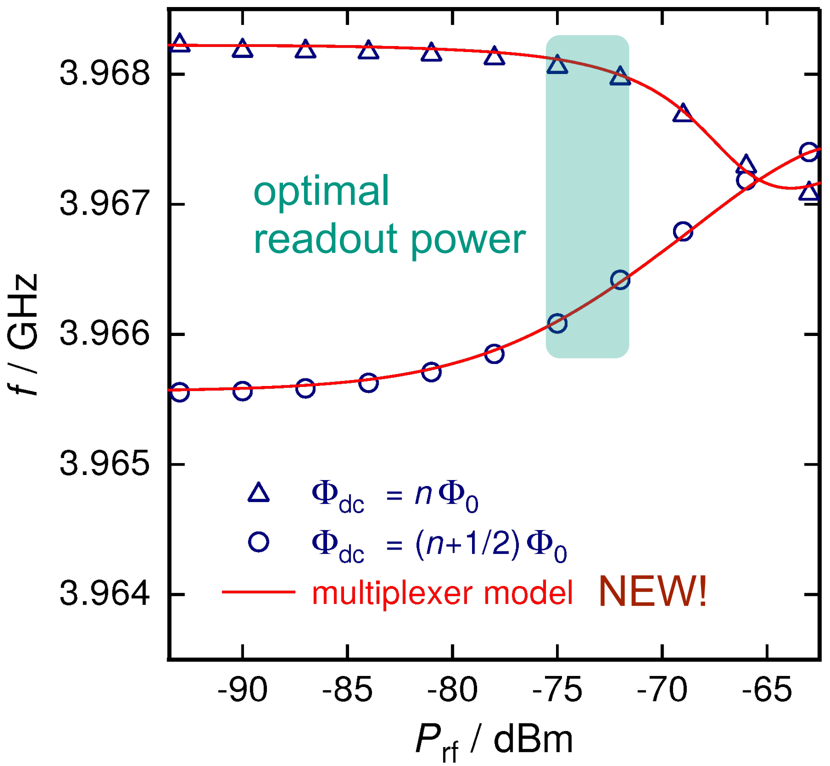
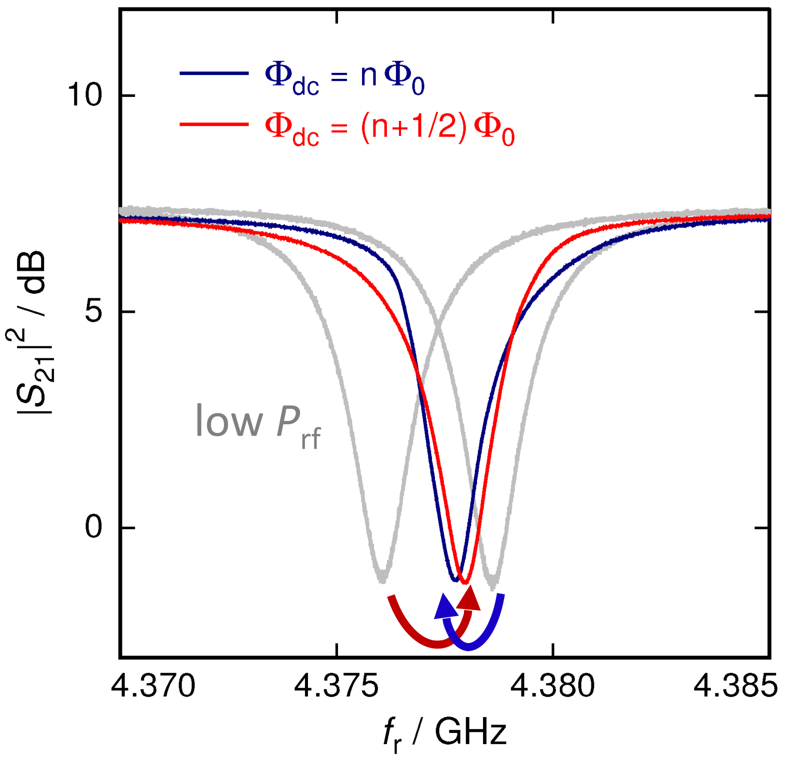
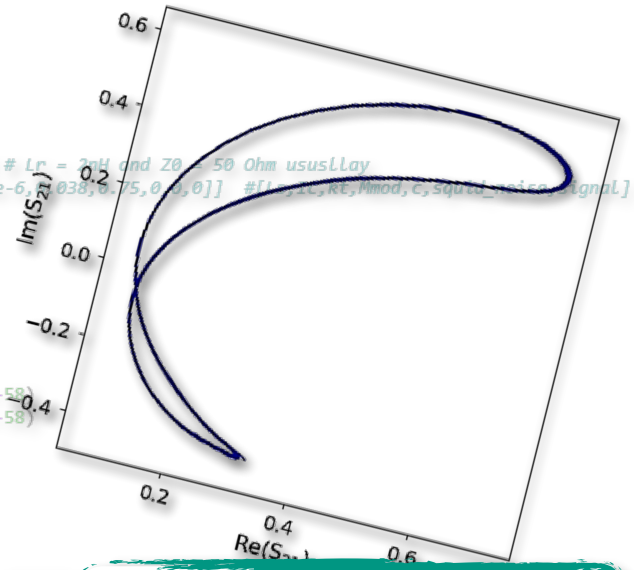


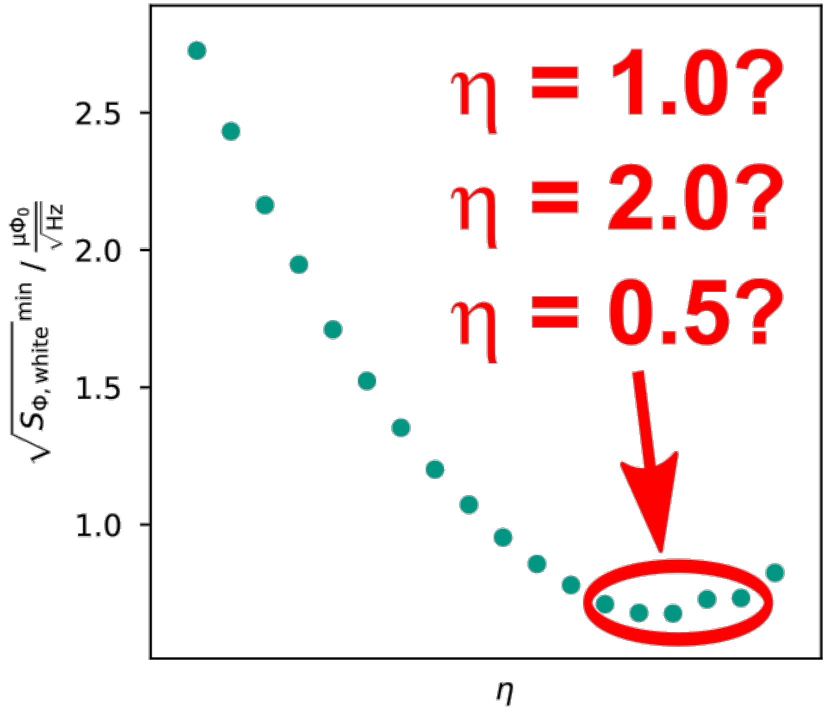


→ model too complex to perform empirical or analytical optimization

µMUX modeling



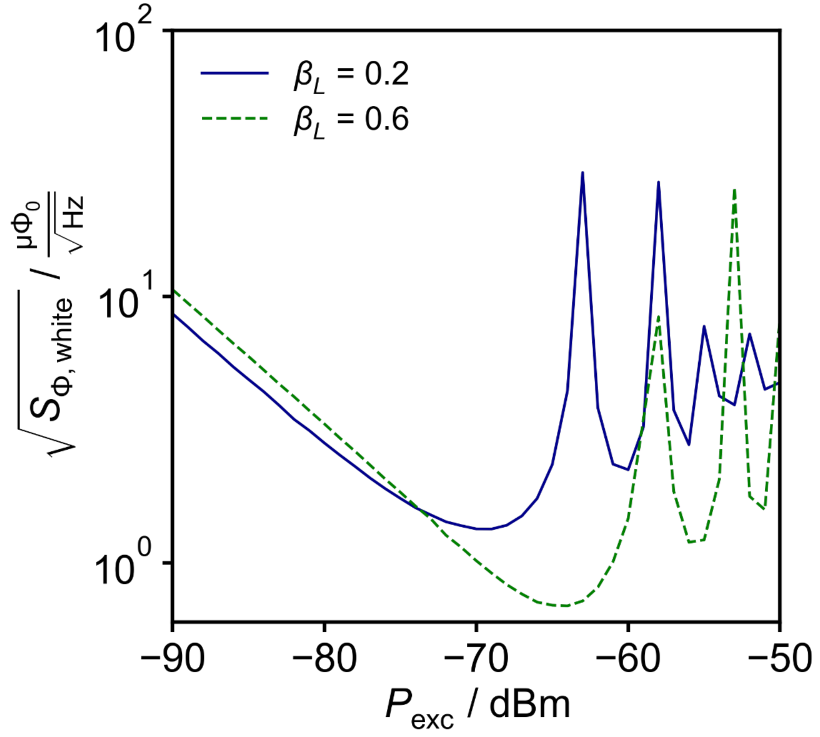
+ HEMT noise
+ SQUID noise
+ resonator noise
+ µMUX power dependence
+ resonator response time
+ flux ramp demodulation
+ readout parameters
+ resonator geometry



C. Schuster, SK *et al.*, submitted to J. Low. Temp. Phys. + *in preparation*

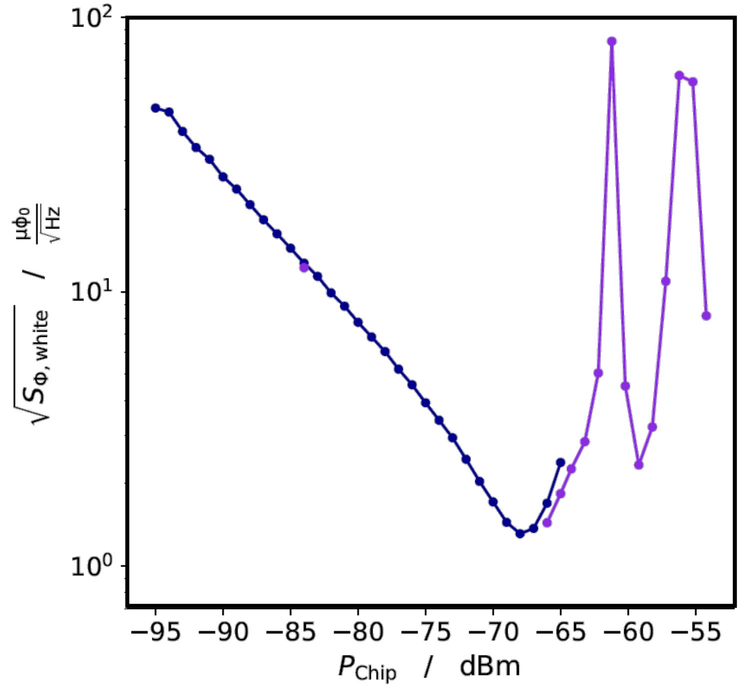
µMUX modeling

'empirical' optimization of a microwave SQUID multiplexer rather complex
due to the existence of various physical effects, noise sources, readout techniques etc.



simulation

experiment



simulation agree qualitatively very well with experiments, fine-tuning of simulation parameters ongoing
simulation based optimization in future feasible

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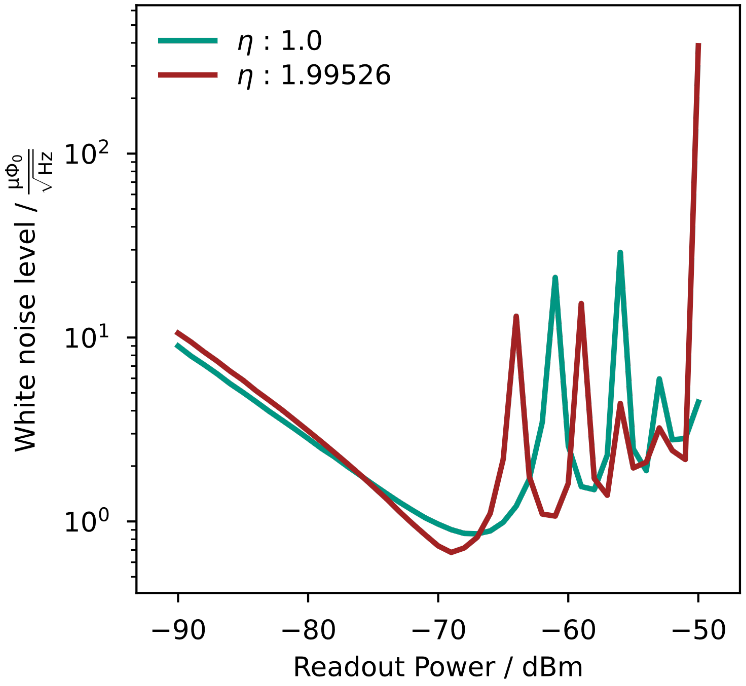

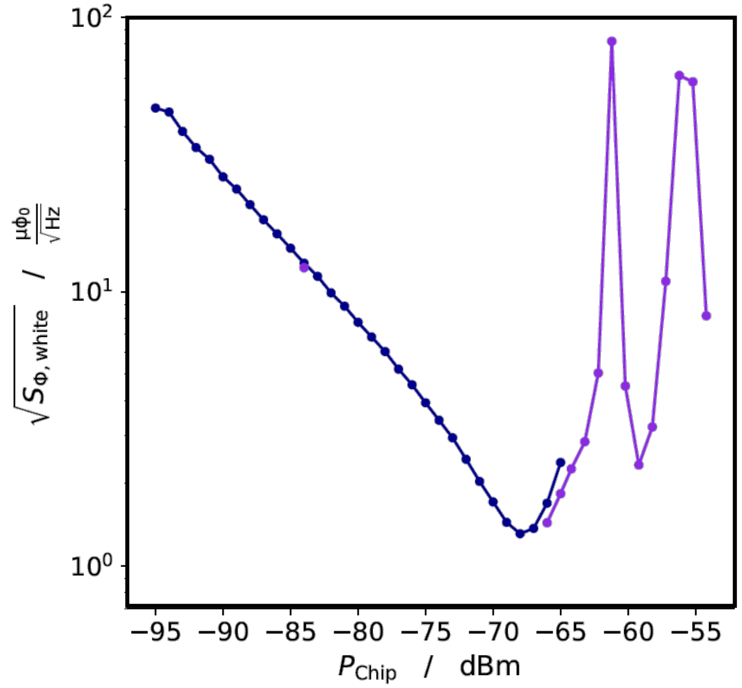

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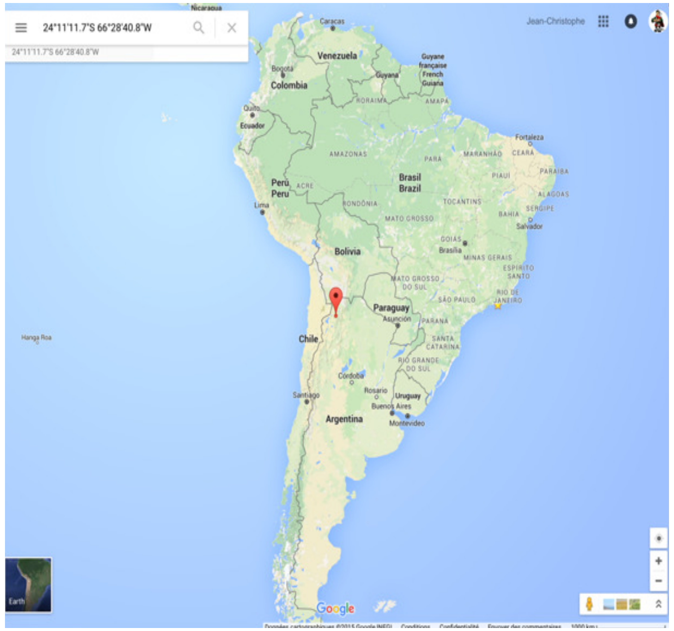
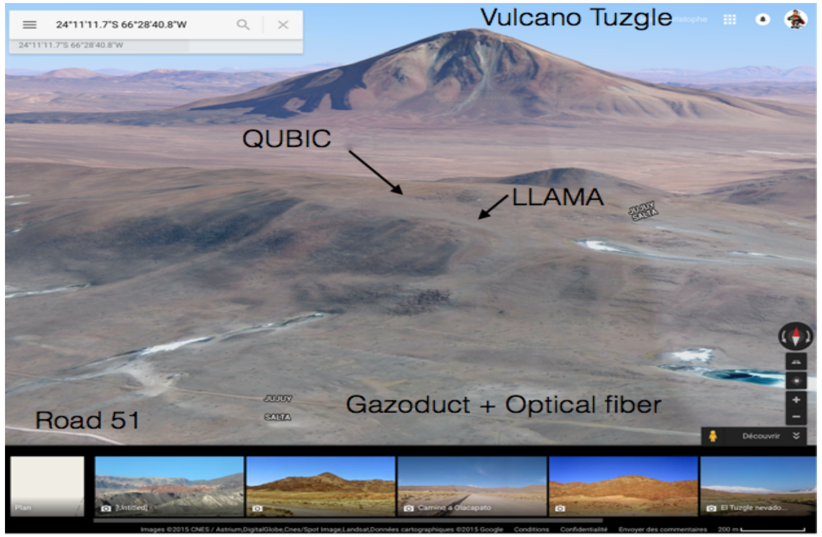
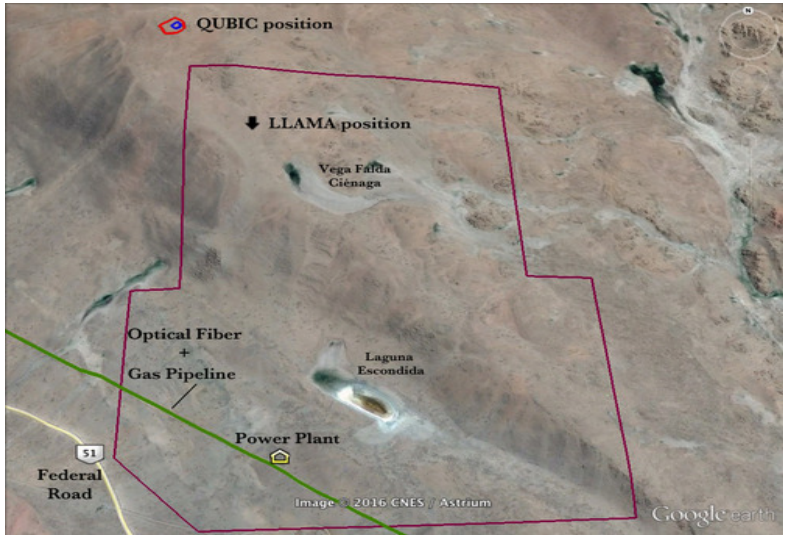
simulation based optimization in future feasible

MMCs for cosmology (LLAMA-QUBIC)

QUBIC and LLAMA plan to explore the inflation age of the universe by detecting and characterizing primordial B-modes of the cosmic microwave background polarization



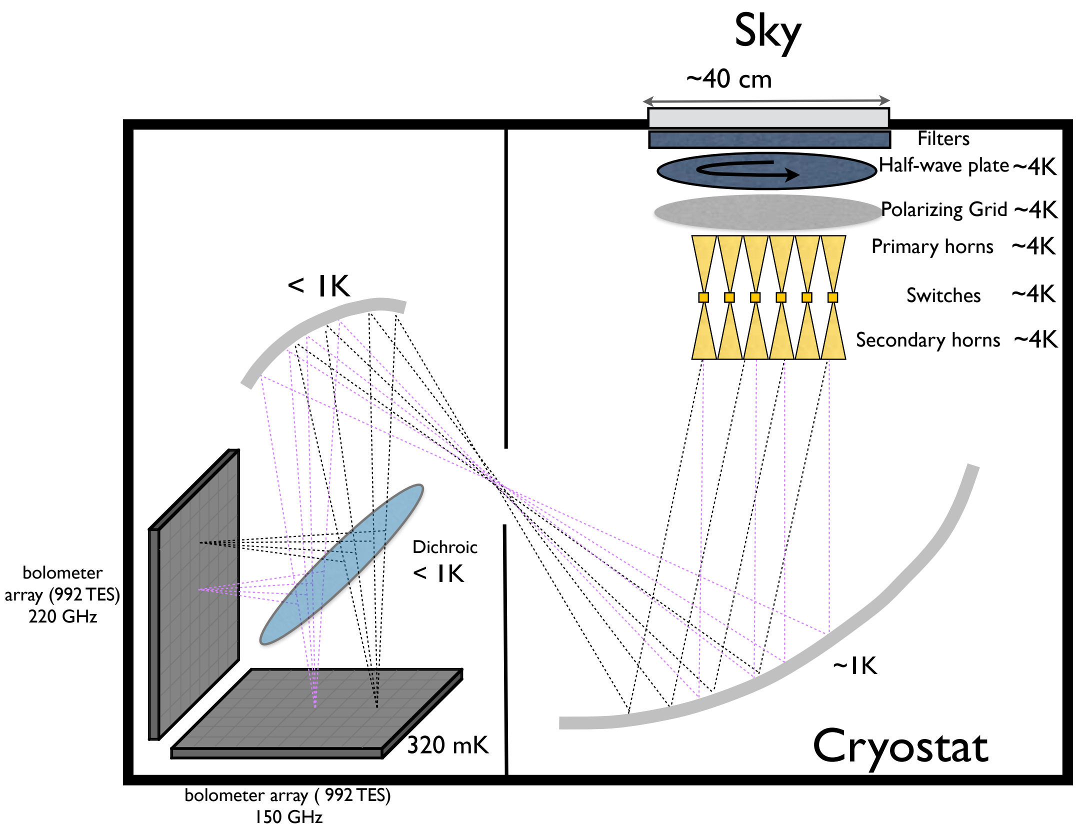


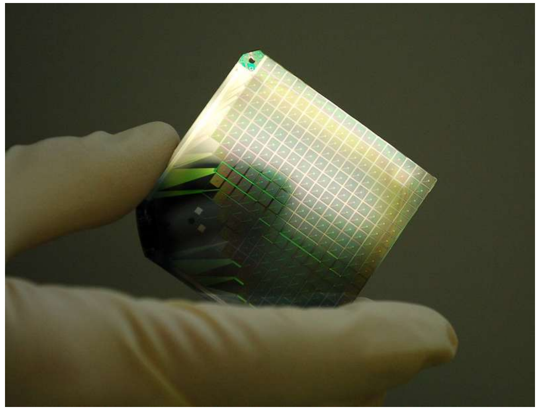


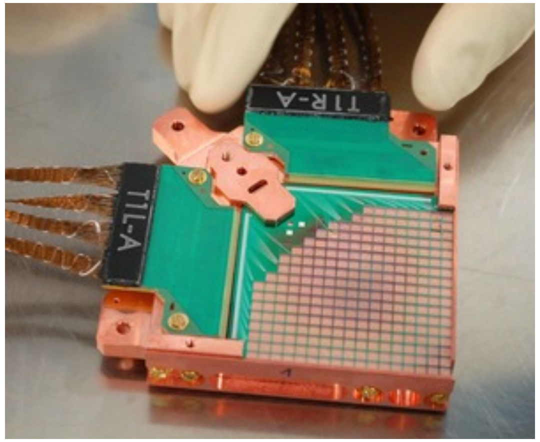
LLAMA → small-angular scale detection
QUBIC → large-angular scale detection

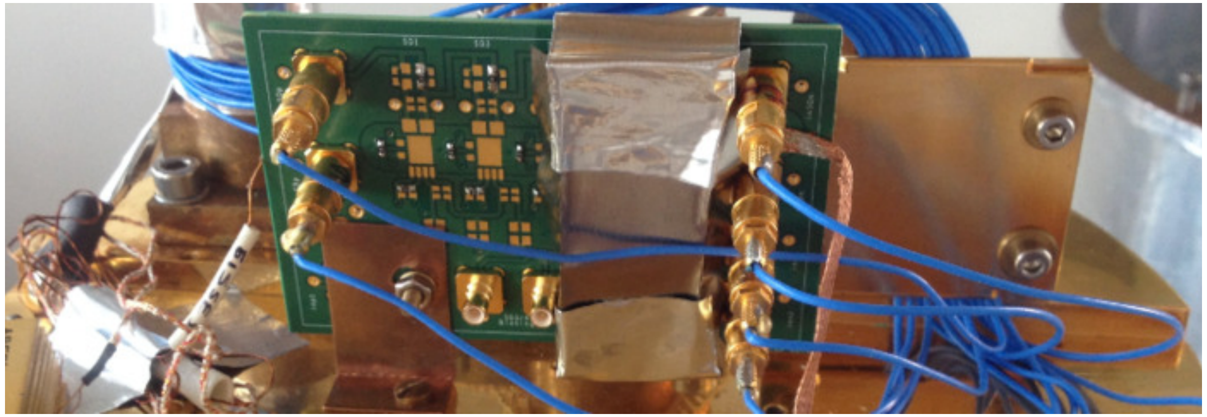
both experiments plan to use a cryogenic receiver!

QUBIC





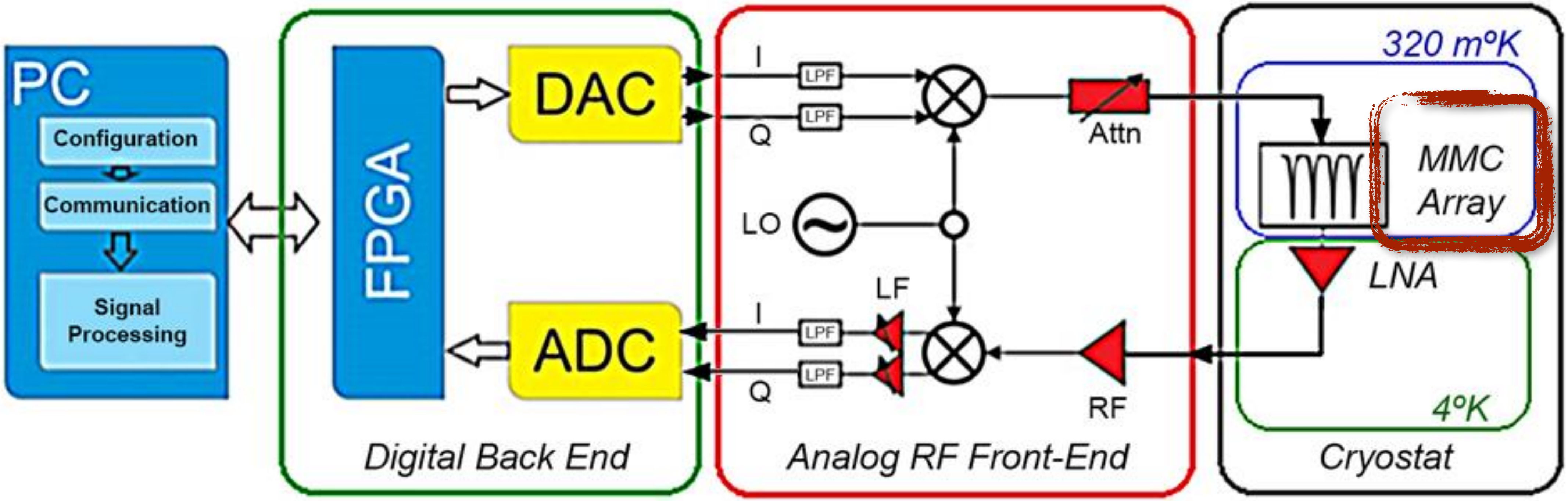




TES with SQUID readout and cryogenic SiGe ASICS

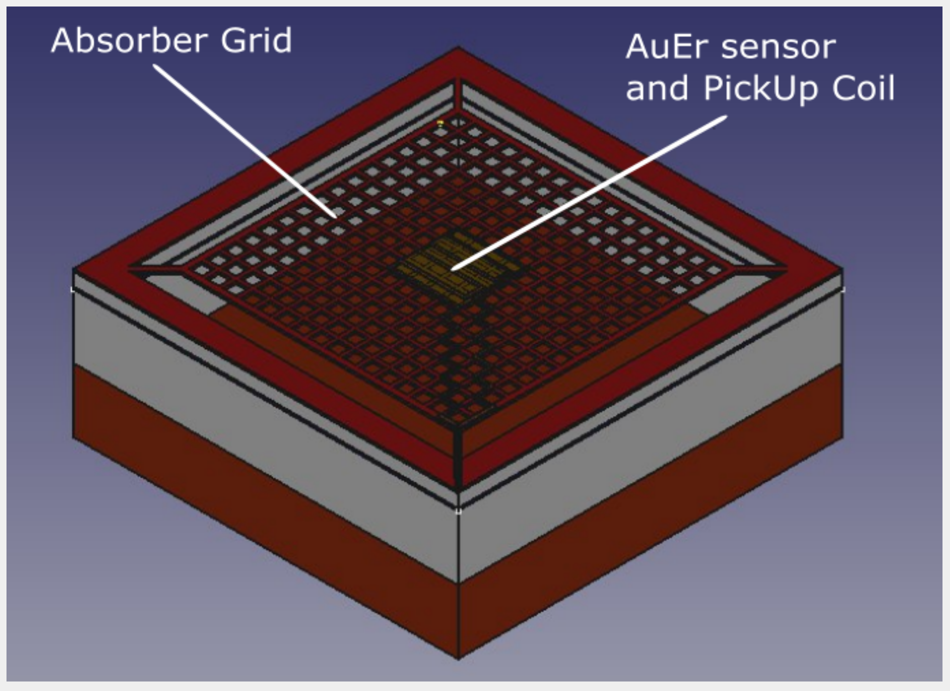
LLAMA

receiver technology for LLAMA not yet fixed; MMBs (magnetic microbolometers) are one of the possible option

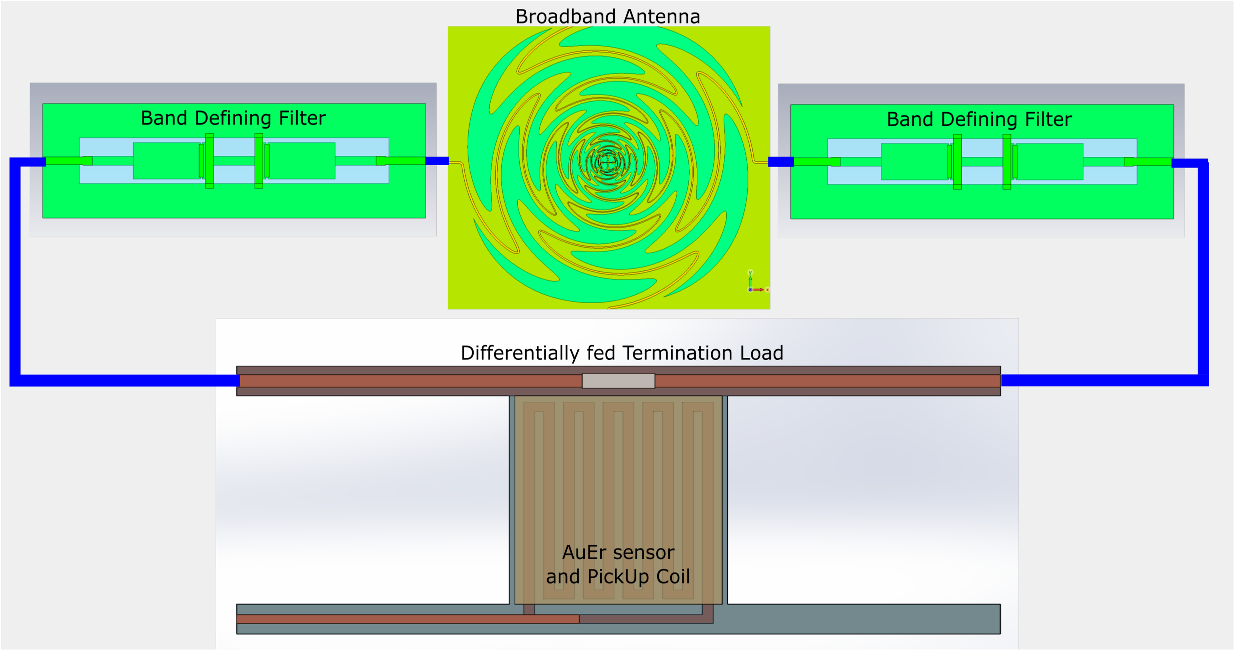


MMBs for LLAMA

absorber coupled detectors



antenna coupled detectors

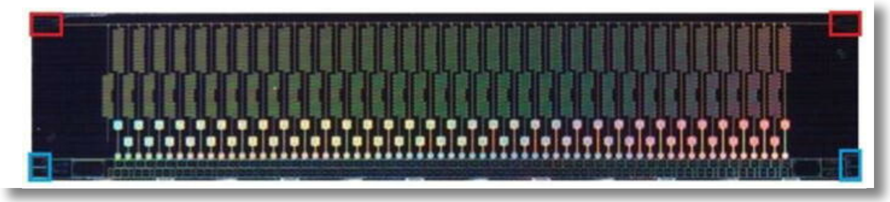


→ see talks of Juan Bonaparte and Juan Manuel Geria

µMUX applications

bolometric applications

e.g. Dober *et al.*, Appl. Phys. Lett. **118** (2021) 062601



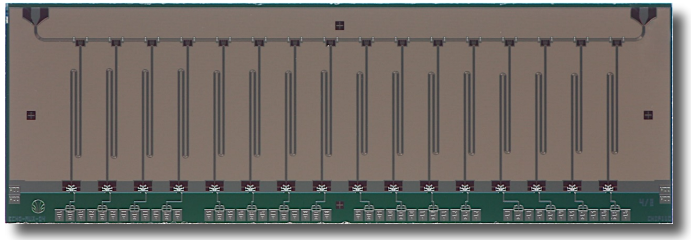
- small bandwidth per channel
  ~100 Hz to 1 kHz

  ↓ guard factor to minimize crosstalk

- (potential) frequency distance between resonators:
  ~1 kHz to 10 kHz

calorimetric applications

e.g. Richter *et al.*, in preparation



- large bandwidth per channel
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- frequency distance between resonators:
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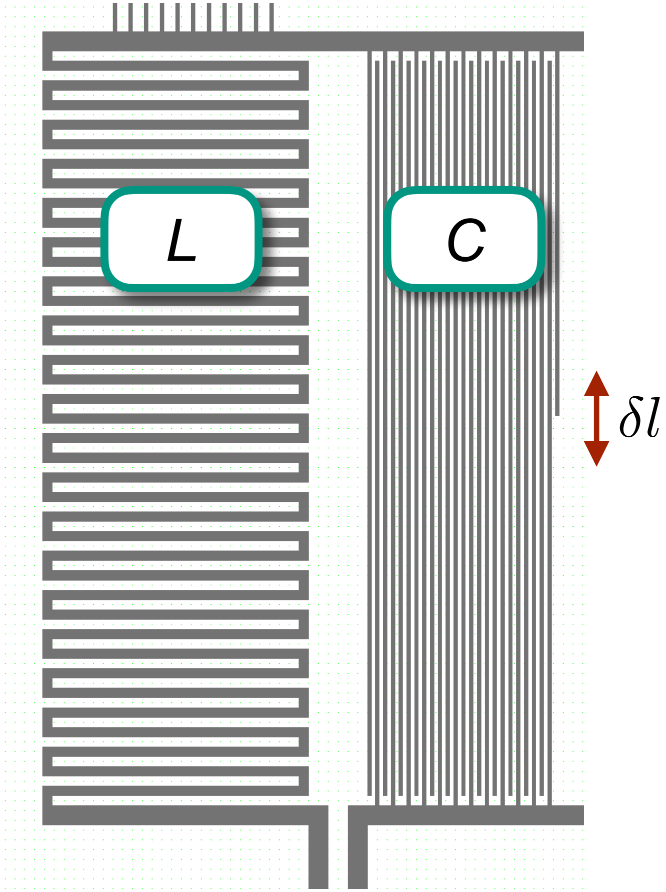
Fabrication tolerances

example: (semi-) lumped element resonator



calorimetric applications require a high fabrication accuracy (feasible with advanced fabrication methods, e.g. tile and trim)

$\delta l < 5\,\mu\mathrm{m}$ for $\delta f < 1\,\mathrm{MHz}$

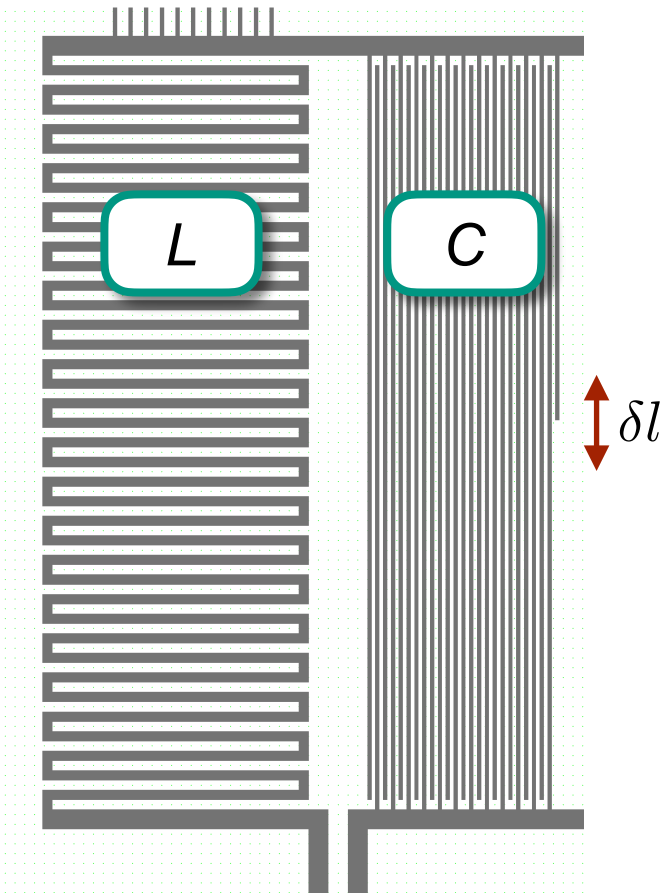
bolometric applications require a ultra high fabrication accuracy (not feasible with non-industrial fabrication methods)

$\delta l < 5\,\mathrm{nm}$ for $\delta f < 1\,\mathrm{kHz}$

Fabrication tolerances

Karlsruhe Institute of Technology

example: (semi-) lumped element resonator



bolometric applications require a ultra high fabrication accuracy (not feasible with non-industrial fabrication methods)

$\delta l < 5\,\mathrm{nm}$ for $\delta f < 1\,\mathrm{kHz}$

advancing fabrication methods ↔ **alternative readout concepts**

advancing fabrication methods:

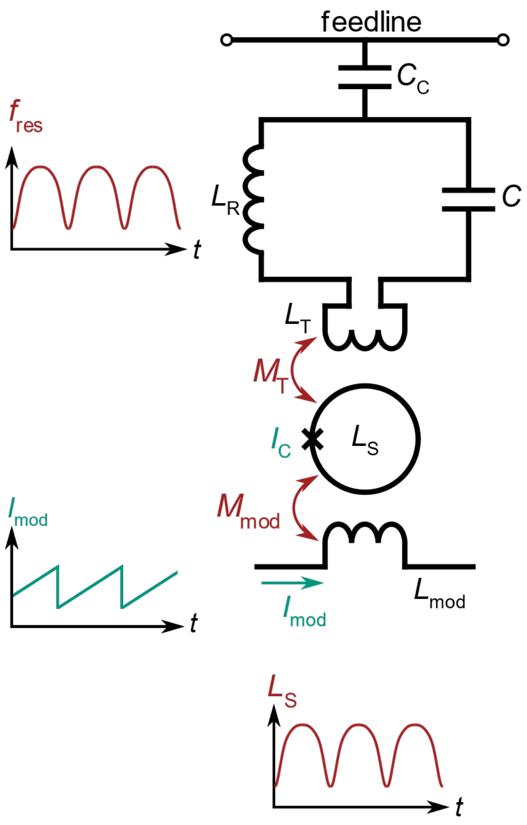
- UV/DUV stepper litho-graphy
- e-beam lithography
- FIB milling
- ….

alternative readout concepts:

- Hydra detectors
- hybrid multiplexing
- ….

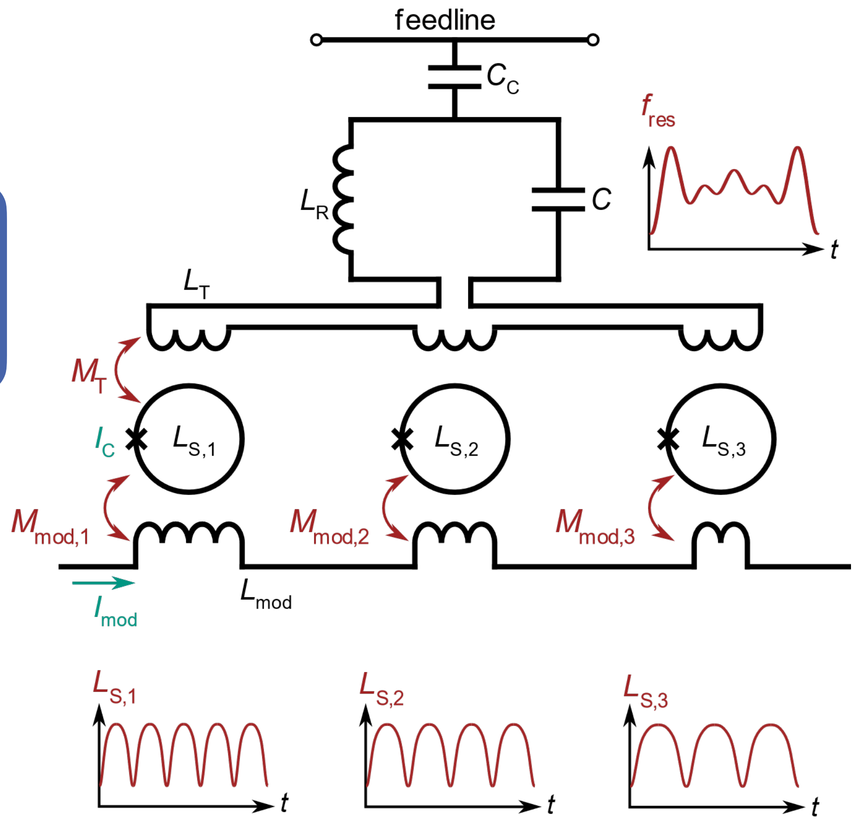
FRM-based hybrid µMUXing

‘conventional‘ µMUXing

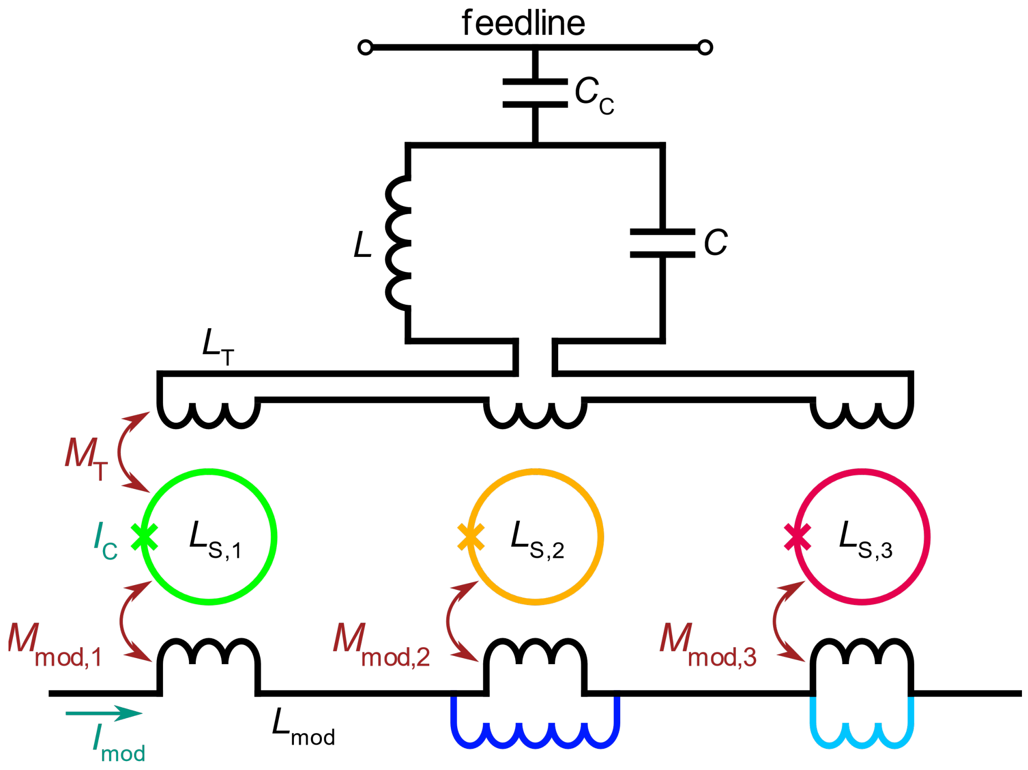


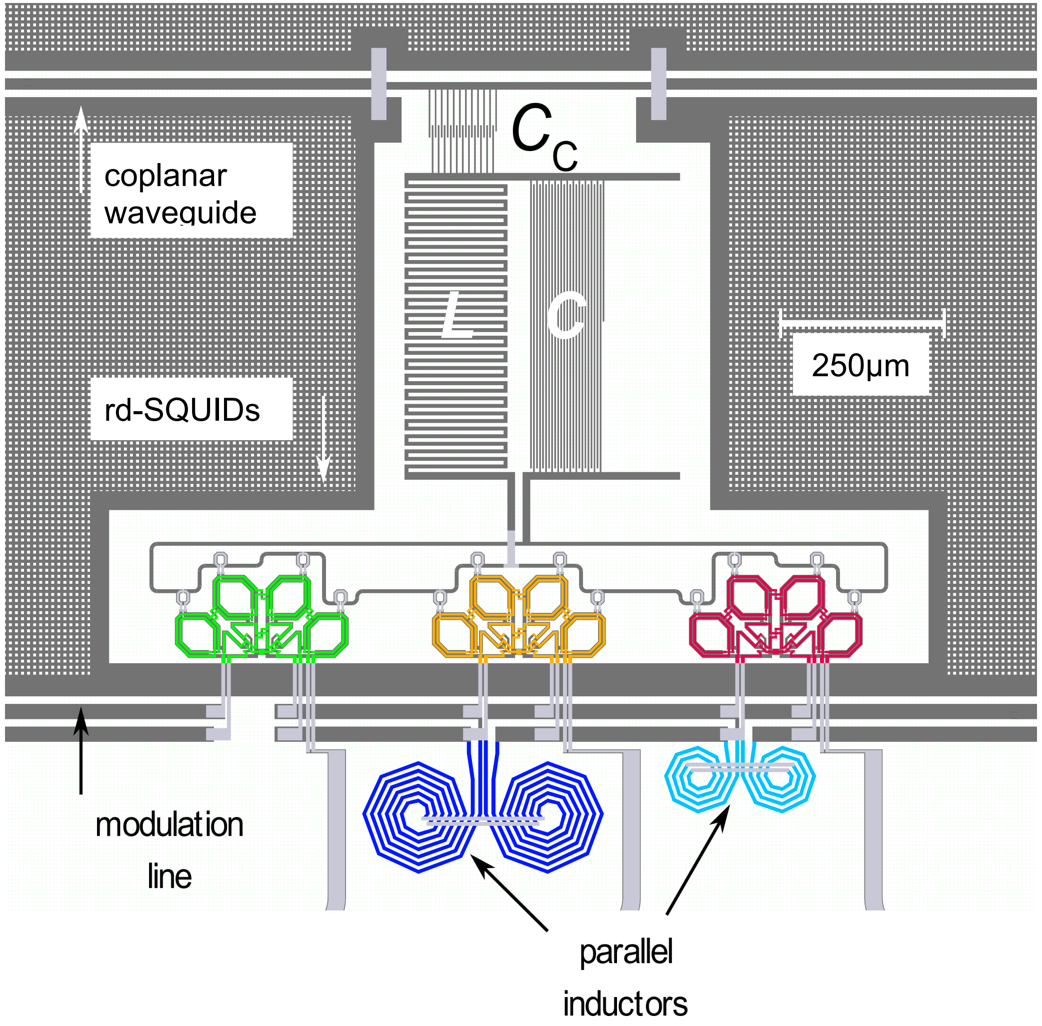
FRM-based hybrid µMUXing

- couple several independent SQUIDs to single resonator
- unique FRM-carrier frequency for each SQUID



Prototype: HyMUX

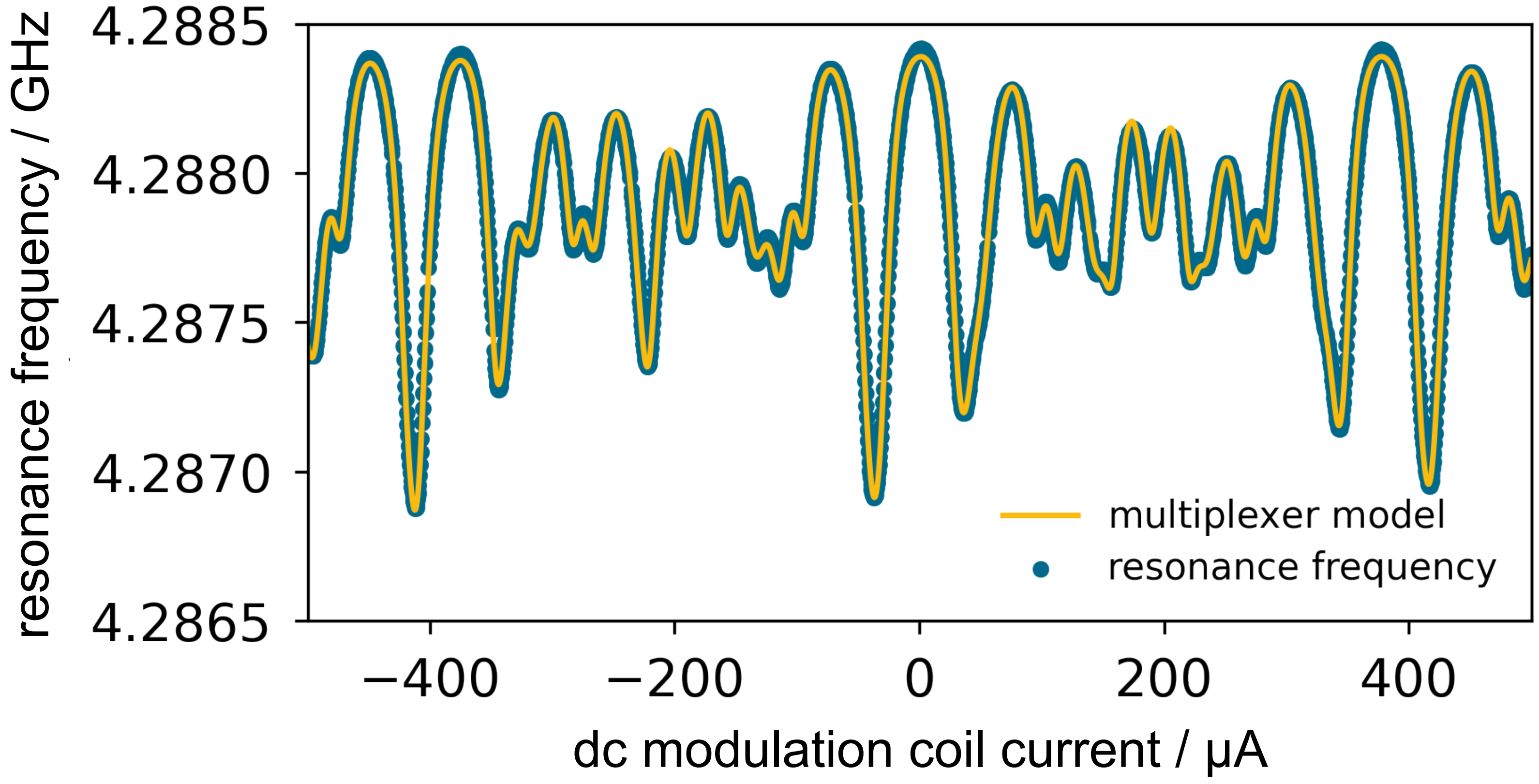




FRM carrier frequency adjusted by using parallel inductors

HyMUX - characterization

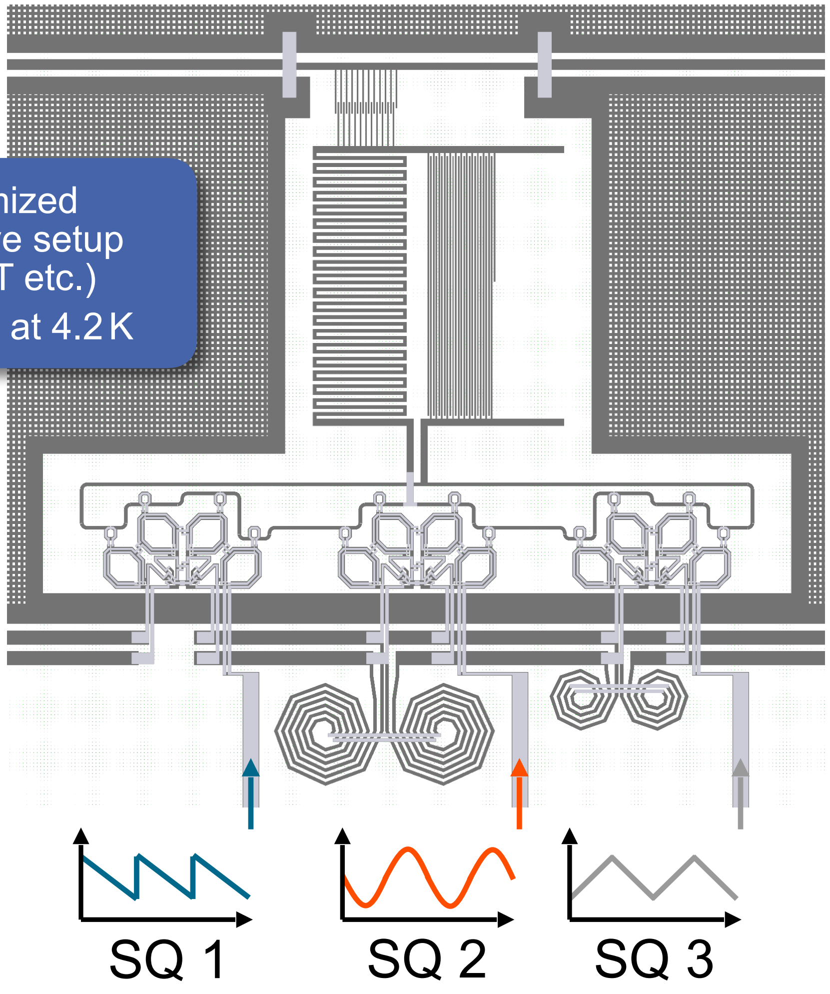
apply dc current through modulation coil and measure resonance frequency

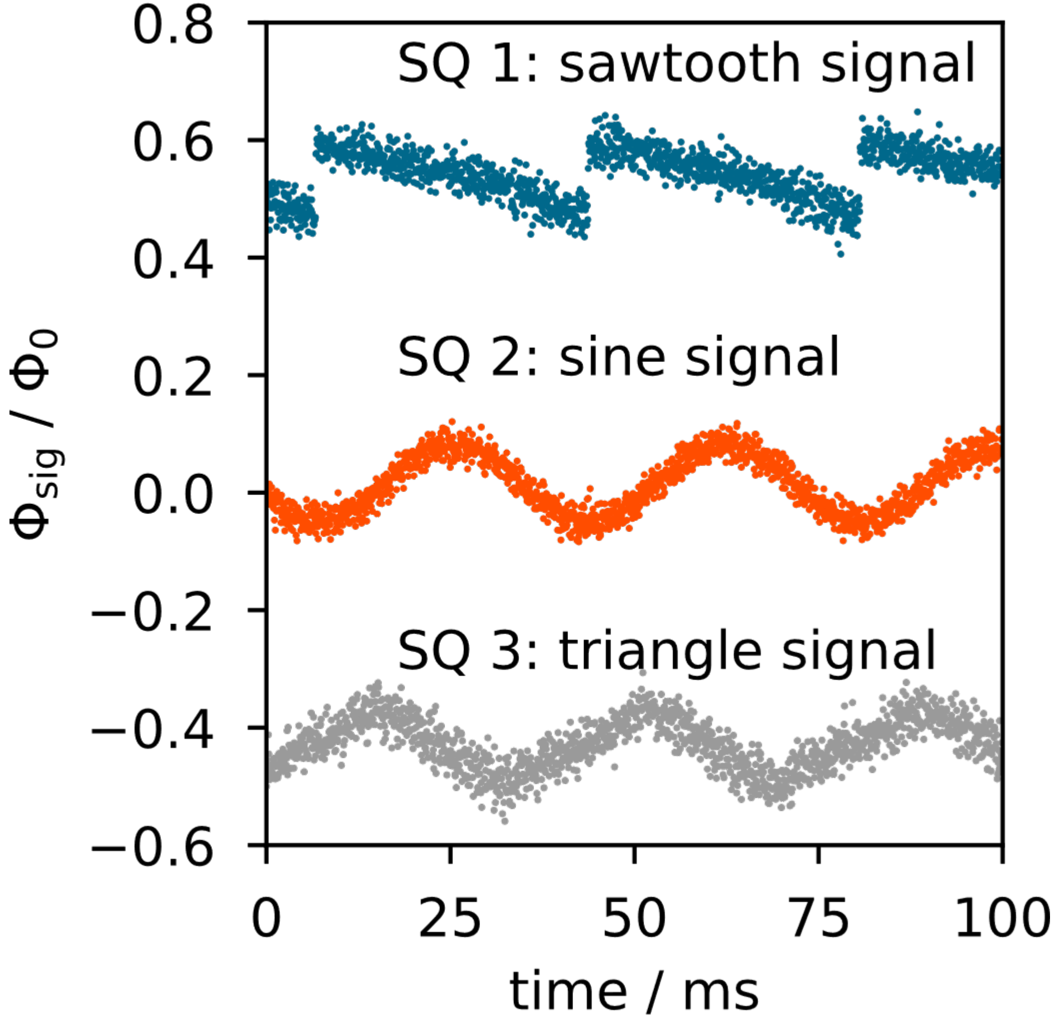


state-of-the-art multiplexer model predicts device characteristics very well

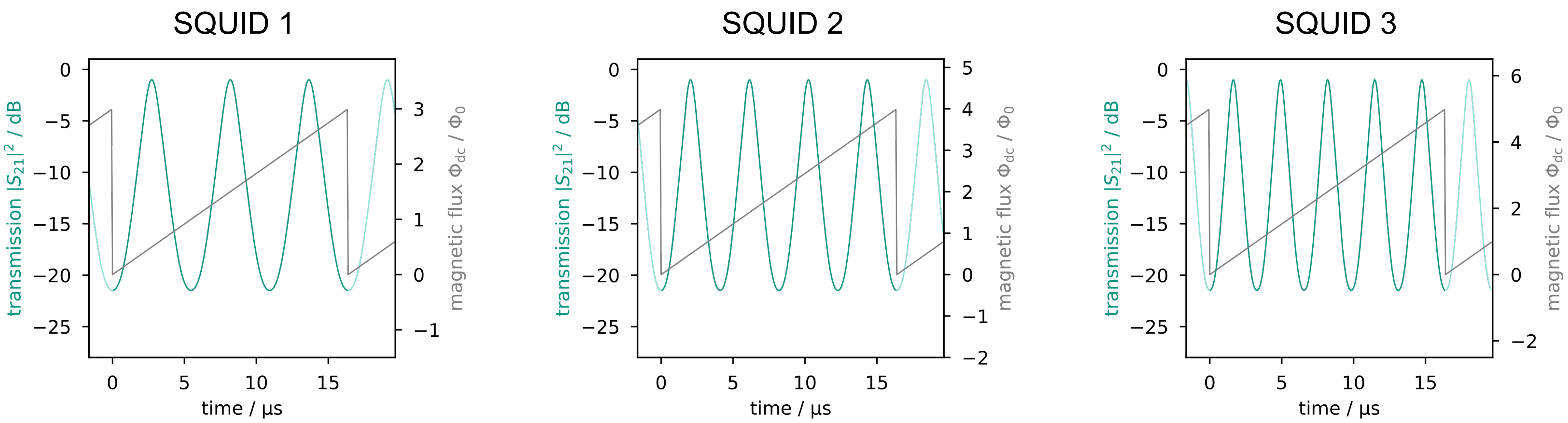
HyMUX - characterization

- non-optimized microwave setup (no HEMT etc.)
- operation at 4.2 K





HyMUX - the ultimate swiss army knife?



FRM carrier frequency

$$f_{\mathrm{mod}} = A_{\mathrm{mod}} f_{\mathrm{ramp}} = M_{\mathrm{mod}} I_{\mathrm{mod}} f_{\mathrm{ramp}}$$

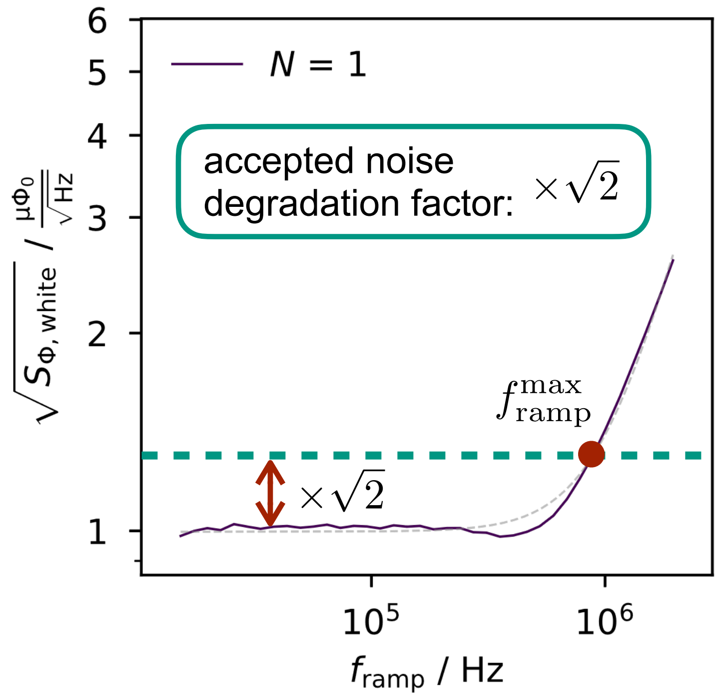
effective sampling rate
(set by detector)

- (modulation) frequencies of FRM-carrier must be unique
- modulation amplitudes must be integers
- modulation amplitudes must not be integer multiples of each other
- finite resonator response time limits highest FRM-carrier frequency

Monte carlo simulation

Monte-carlo simulation framework for µMUX modeling and optimization

µMUX simulation for calorimetric detectors ($\Delta f_{\mathrm{BW}} \simeq \Delta f_{\mathrm{res}}^{\max} \sim 1\,\mathrm{MHz}$)



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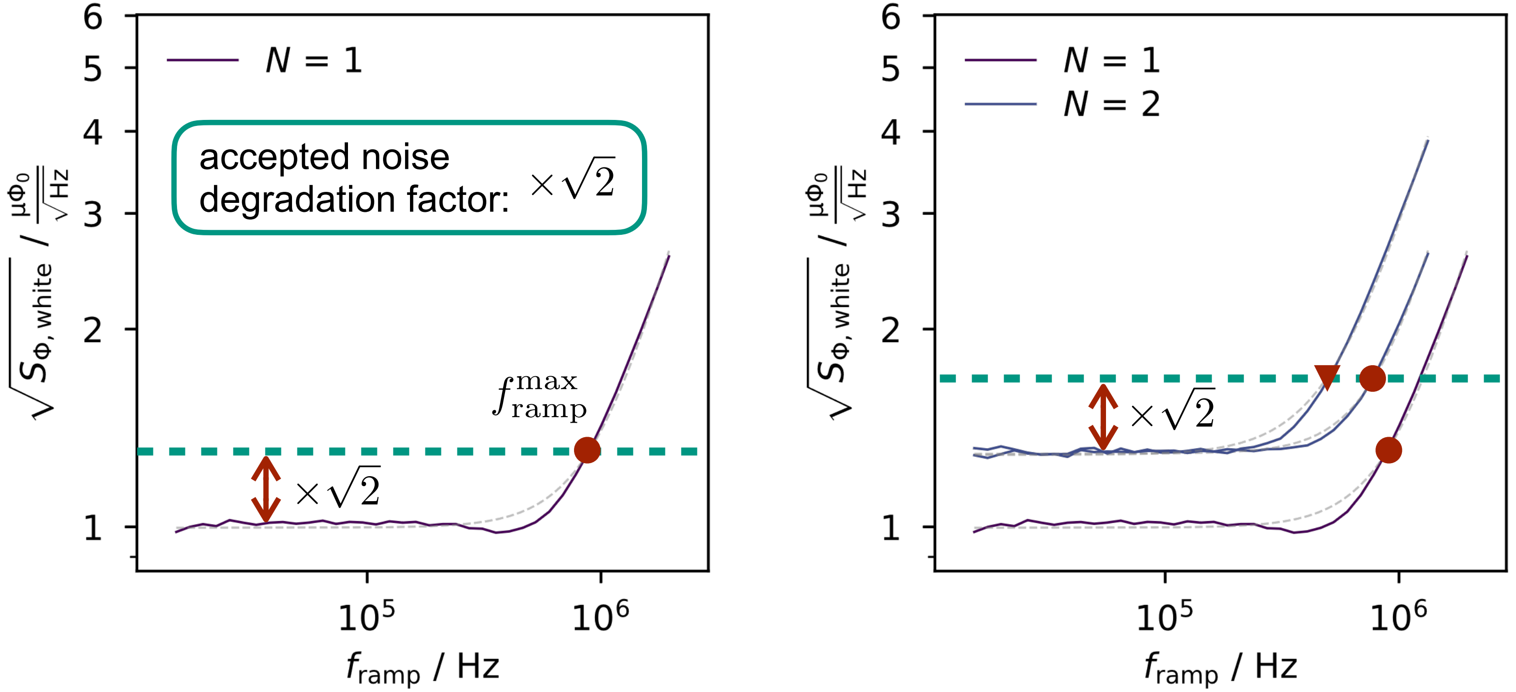

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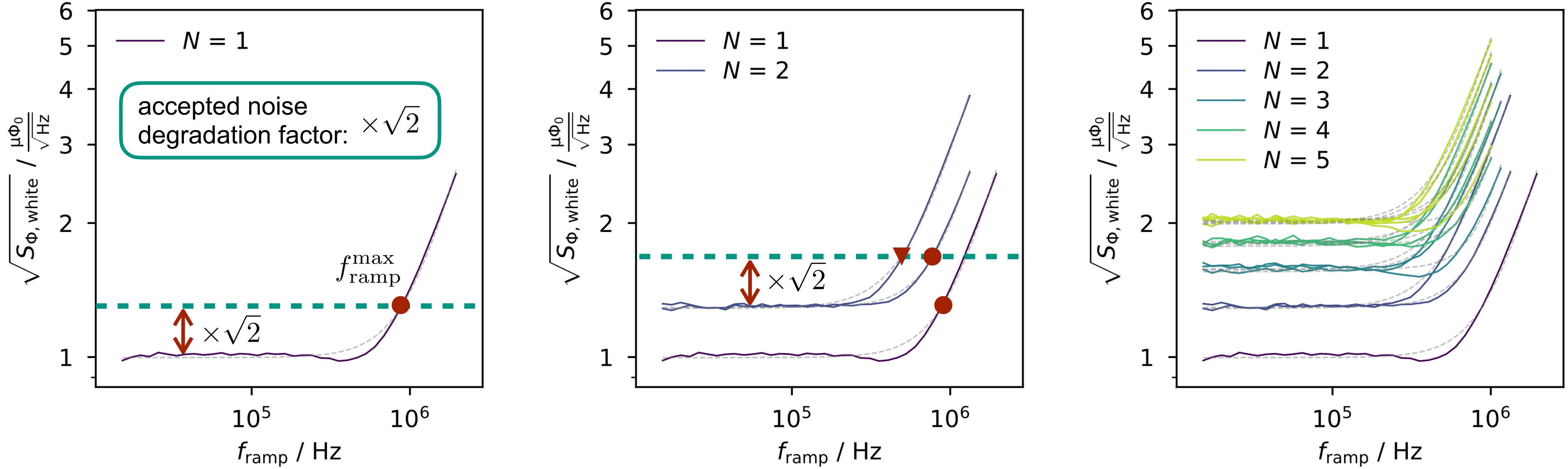

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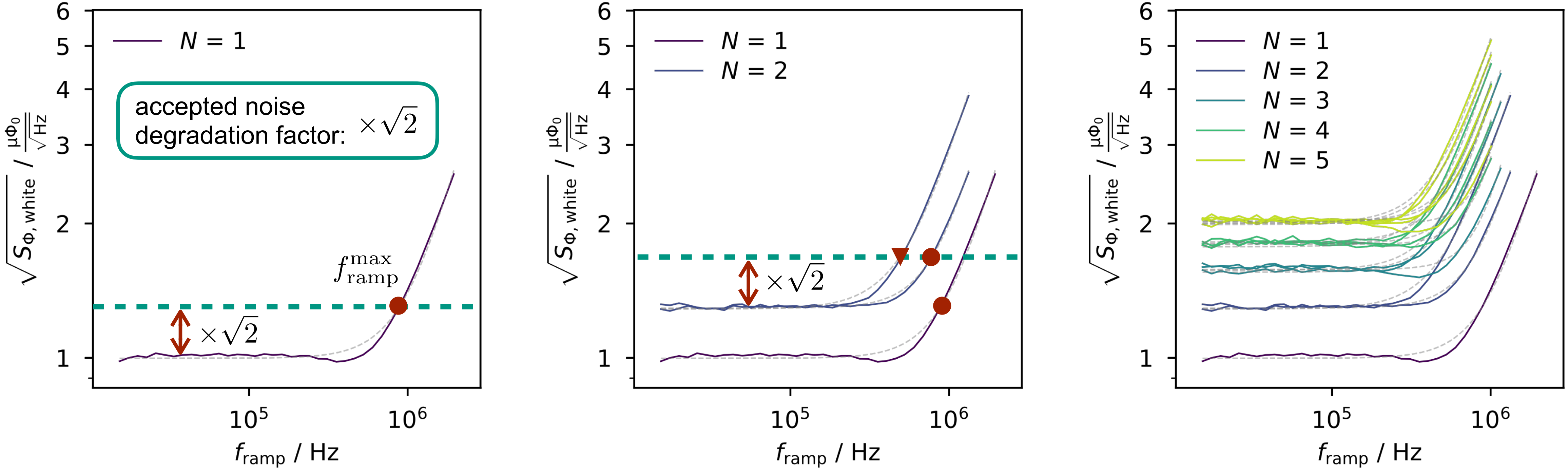

feasible technique for bolometers but likely not for calorimeters

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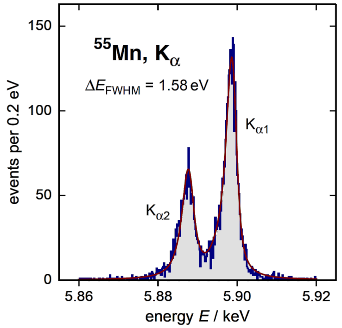
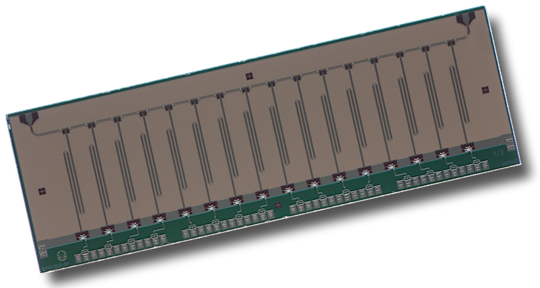
Summary and conclusion



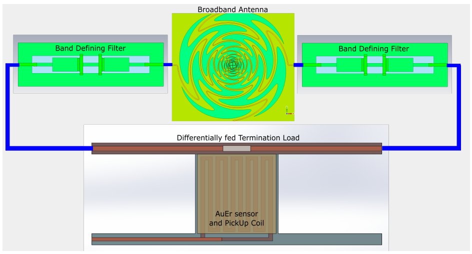
magnetic microcalorimeters and SQUIDs

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



multiplexed detector arrays

- FRM based dc-SQUID multiplexing for medium-sized arrays
- microwave SQUID multiplexing for large-scale arrays
- hybrid microwave SQUID multiplexing for bolometric arrays



future work

- multiplexer optimization and maturing
- fabrication technology
- bolometric arrays

DFG Deutsche Forschungsgemeinschaft German Research Foundation

Bundesministerium für Bildung und Forschung

cea cnrs GIF

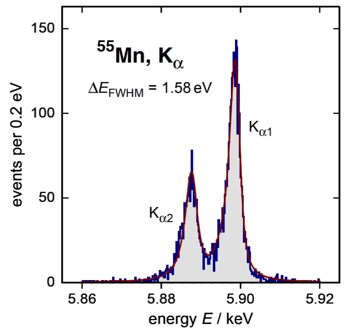
European Commission

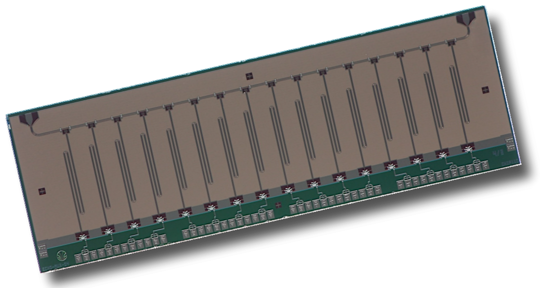
SEVENTH FRAMEWORK PROGRAMME

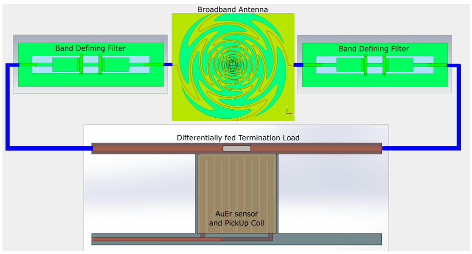
EMPIR EURAMET

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Summary and conclusion







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Thank you for your attention!

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Multiplexed magnetic microcalorimeter arrays for astroparticle physics

Sebastian Kempf

HIRSAP Workshop 2021 | Hybrid Meeting KIT - Online | November 2nd, 2021