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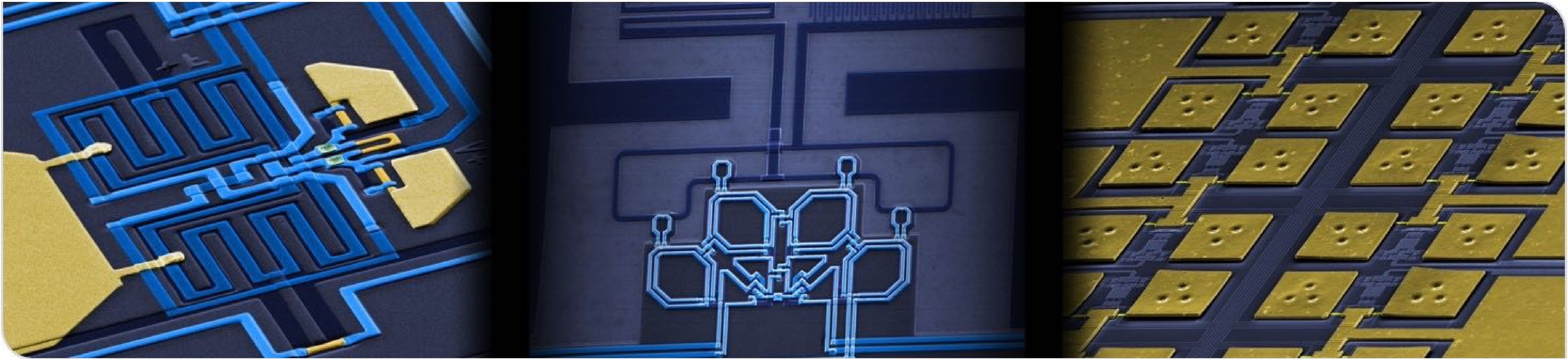
Superconducting Quantum Interference Devices (SQUIDs)

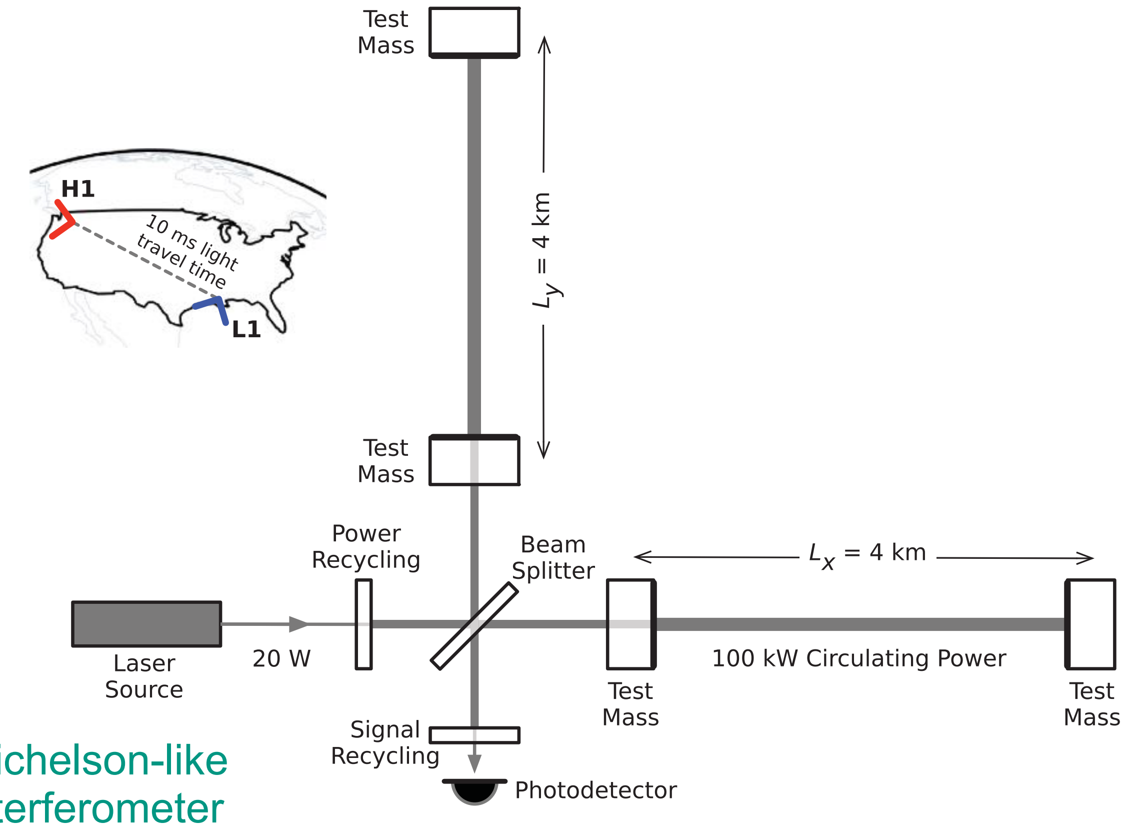
Sebastian Kempf

14th Terascale Detector Workshop 2022 | Virtual Workshop | February 23rd to February 25th, 2022

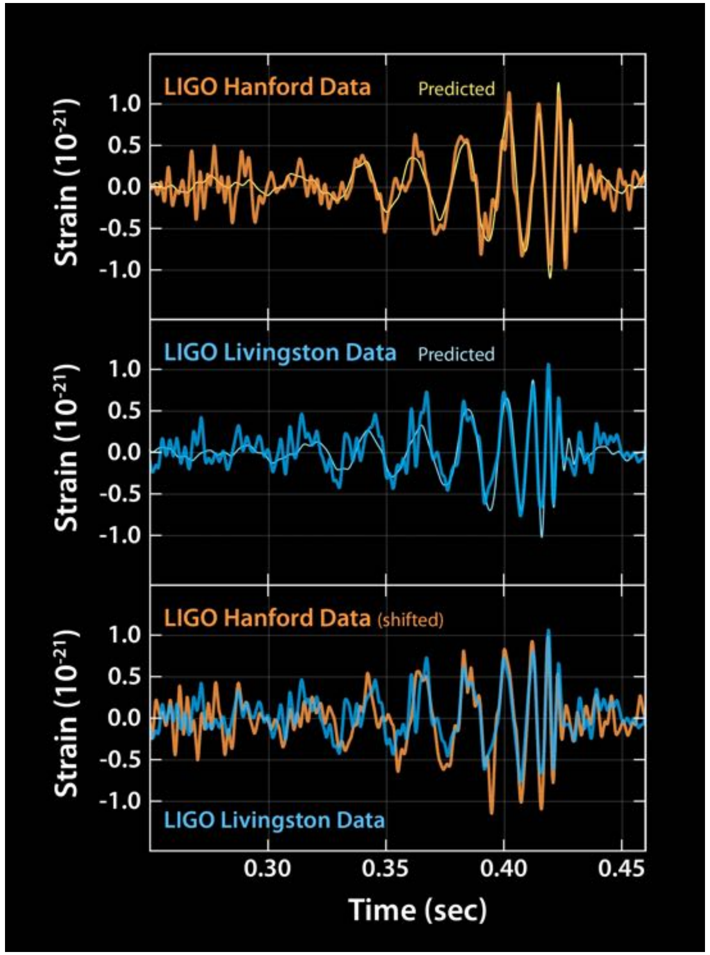


Optical interferometers

optical interferometers are among the most sensitive measuring devices, e.g. for gravitational wave detection



Michelson-like interferometer



B.P. Abbott *et al.*, Phys. Rev. Lett. **116** (2016) 061102

Optical interferometers

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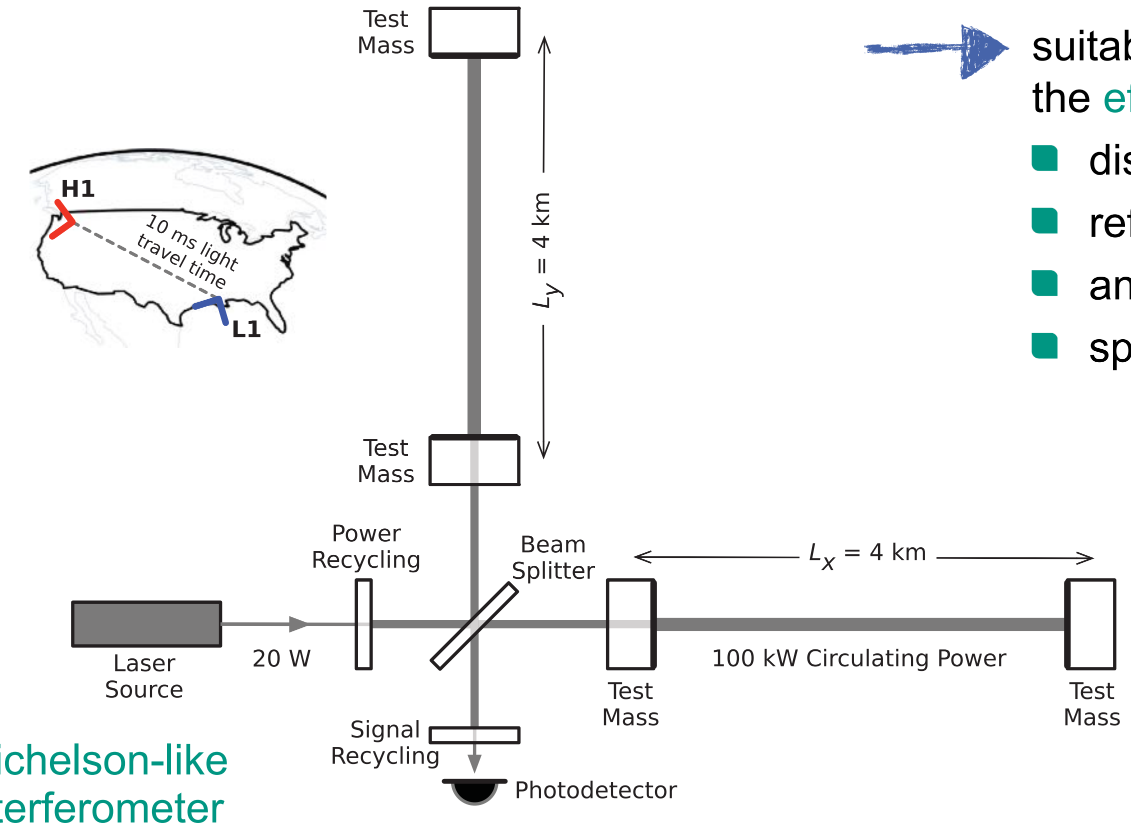


Michelson-like interferometer

suitable for any kind of physical quantity that influence the effective wavelength or phase of light

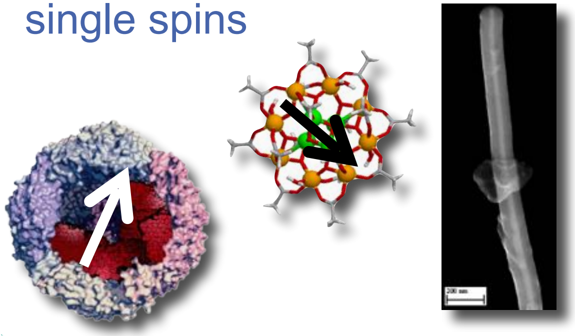
- displacement, length
- refractive index (humidity, temperature etc.)
- angular measurements
- spectroscopy

but: not very suited for electrical or magnetic measurements

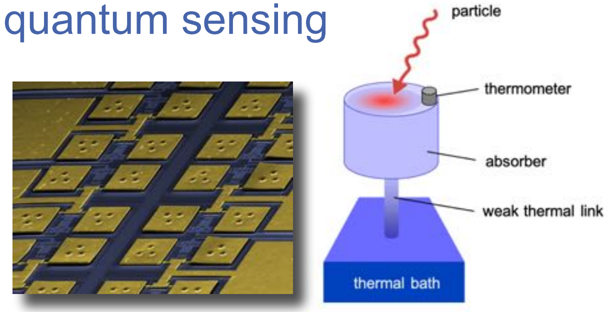
is there a similar measuring device for high-precision electrical or magnetic measurements?

Need for sensors with utmost sensitivity…

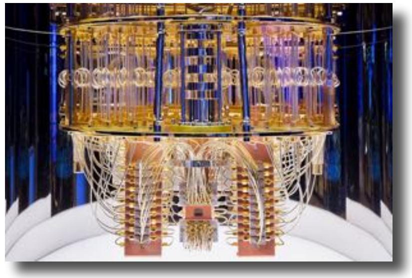
single spins



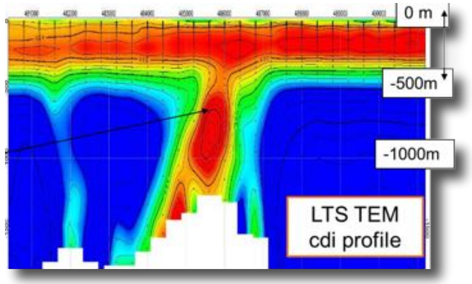
quantum sensing



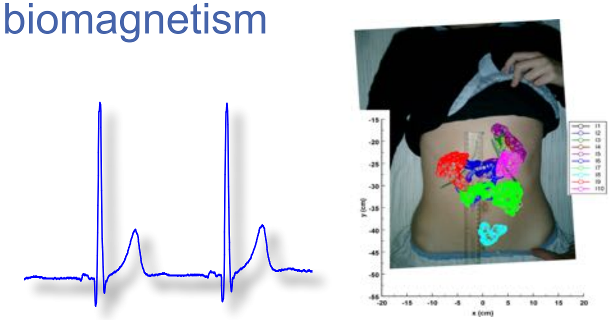
quantum computing



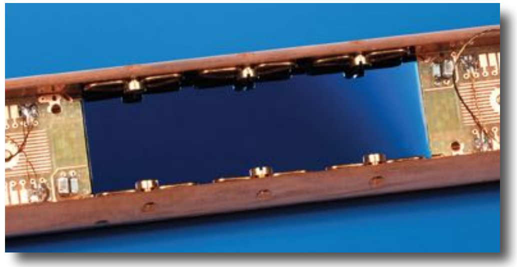
geophysics, mineral exploration



biomagnetism



metrology



…and many more…

Superconductivity in a nutshell

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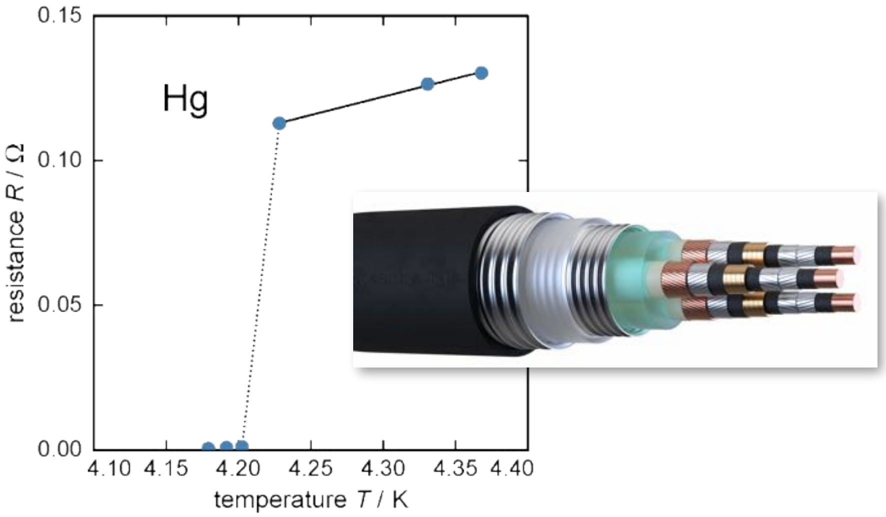
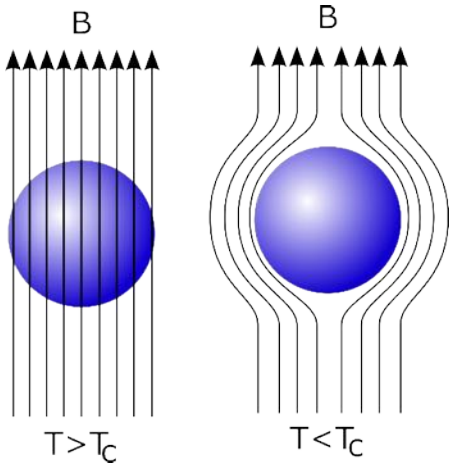
perfect conductor

H.K. Onnes, Leiden Commun. **124c** (1911)

superdiamagnet / ideal diamagnet

W. Meissner, R. Ochsenfeld, Naturwissenschaften **21** (1993)





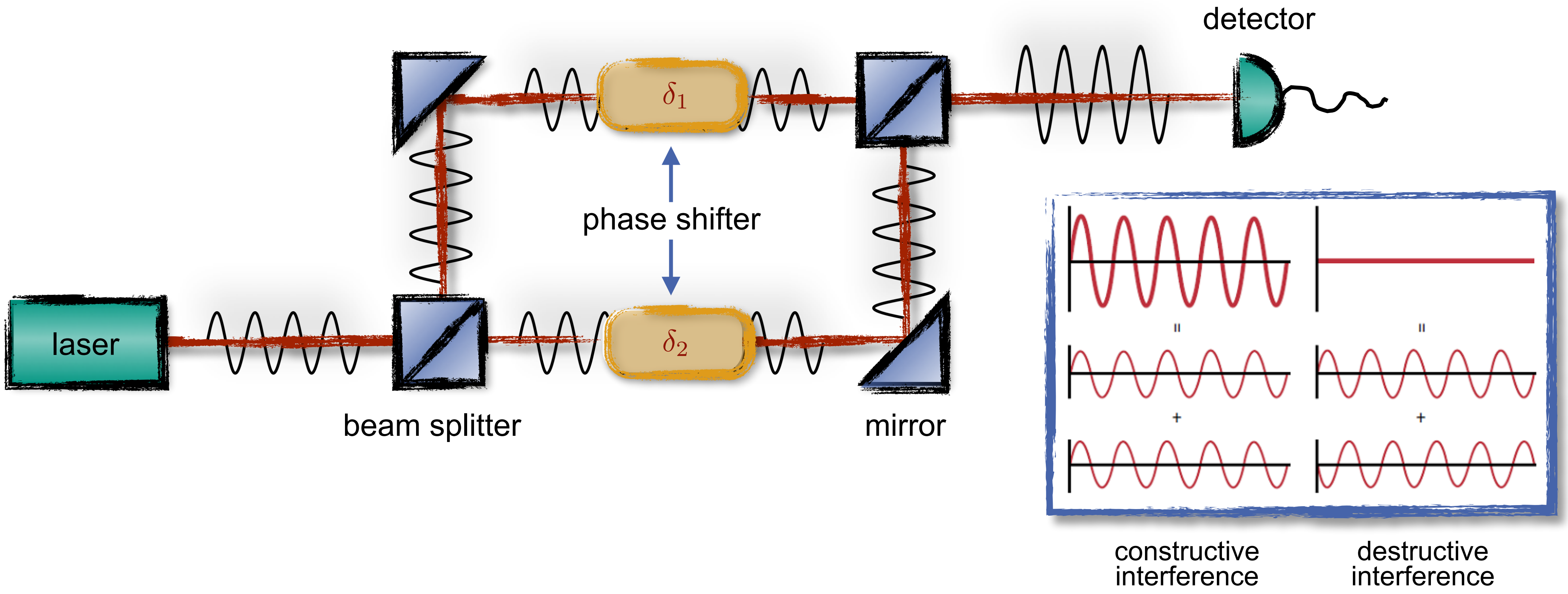
BCS-theory: superconductivity is governed by Cooper pairs being described by a macroscopic wavefunction

$$\Psi(\boldsymbol{r},t) = \Psi_0 e^{i\varphi(\boldsymbol{r},t)}$$

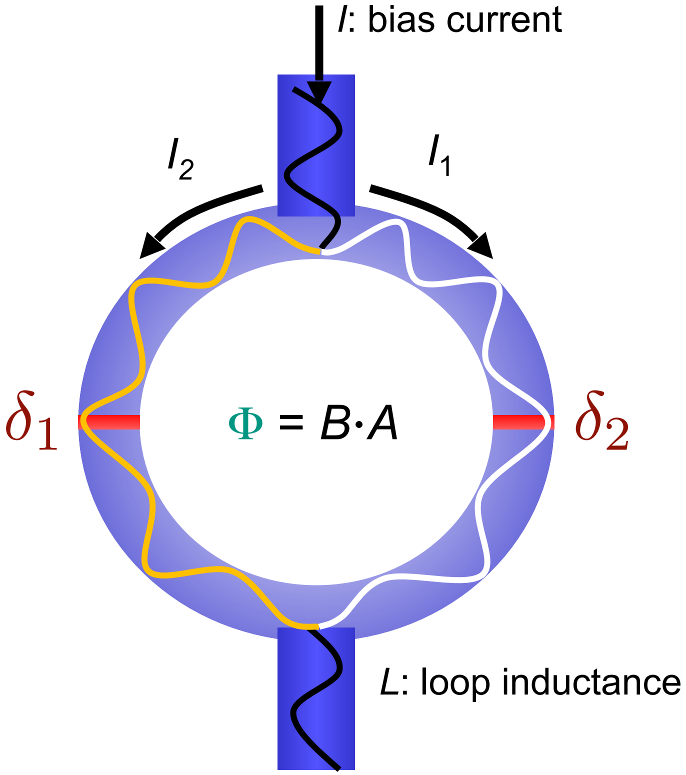
→ mathematically equivalent to plane wave!

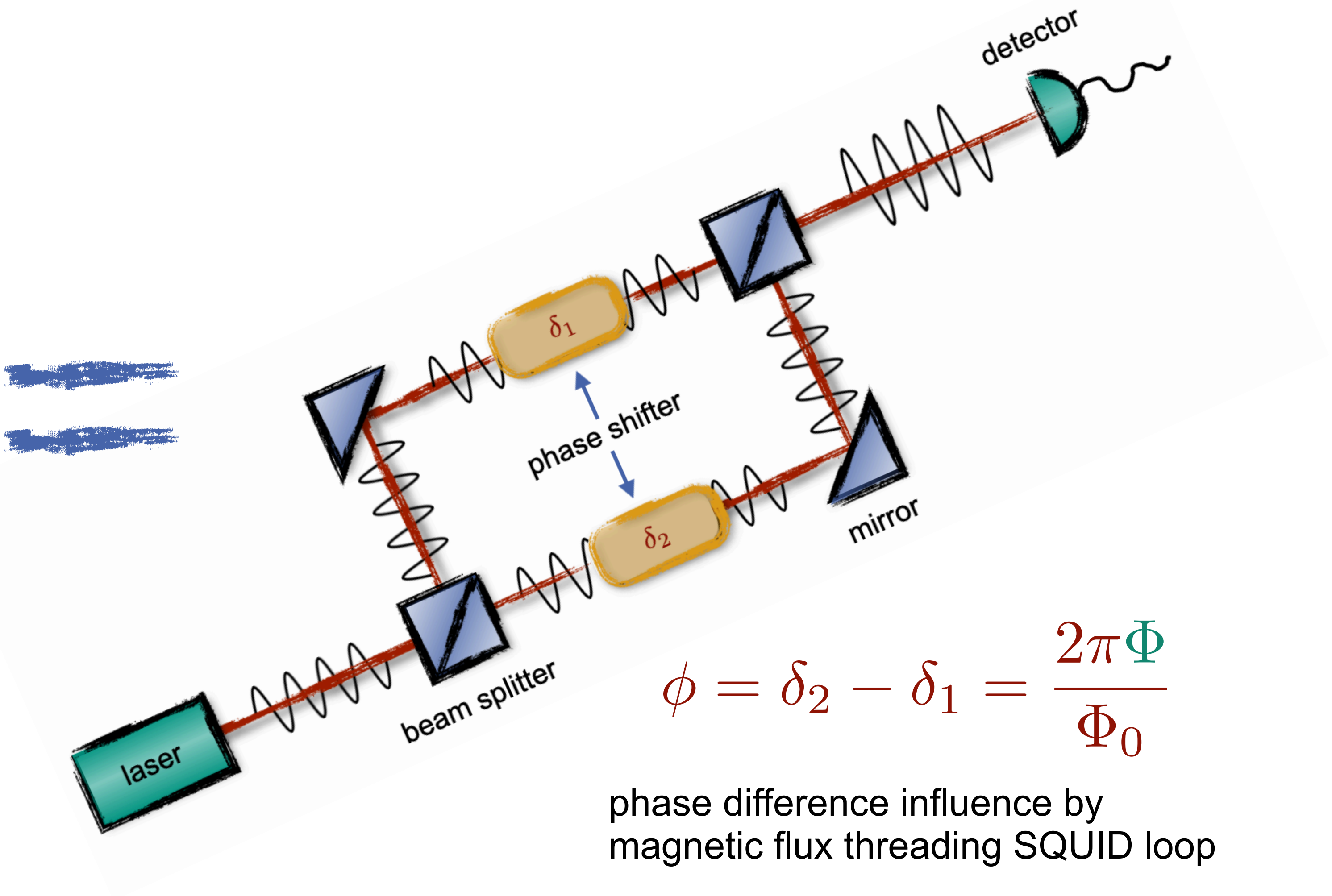
Mach-Zehnder-Interferometer

interference pattern depends on phase difference between both interferometer arms



Superconducting quantum interference devices



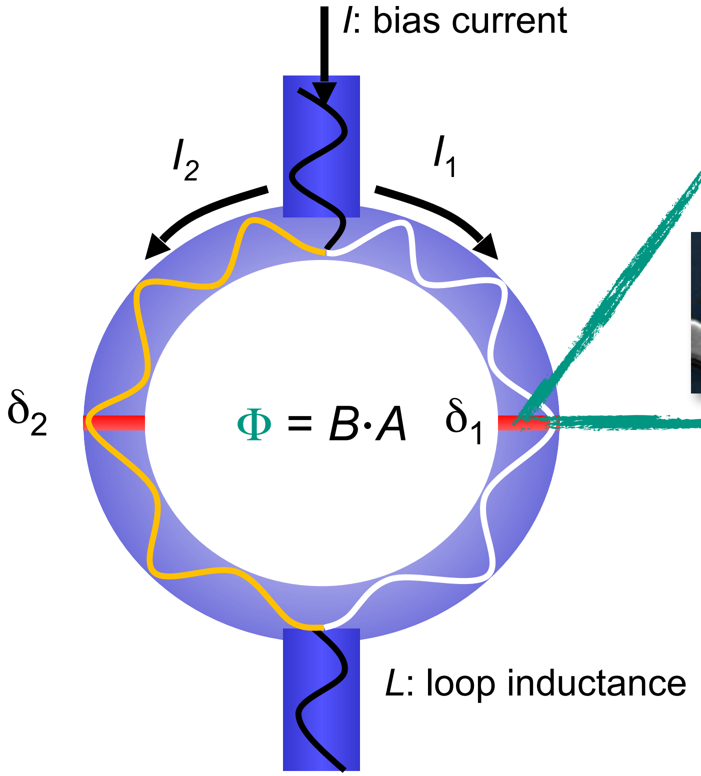


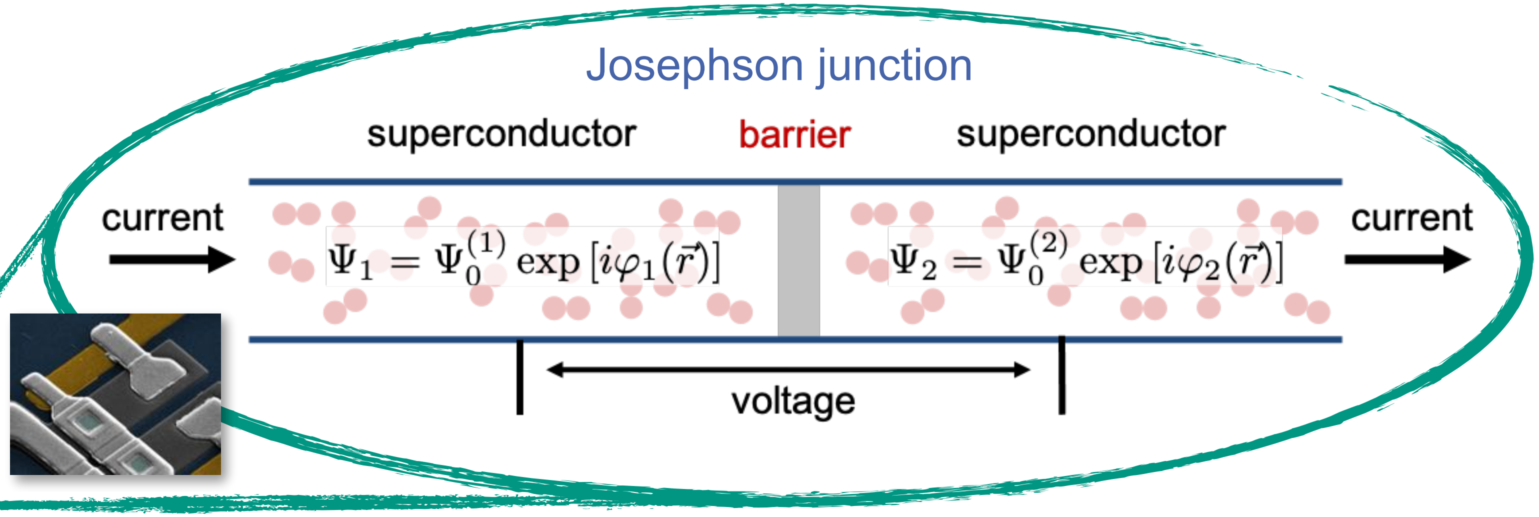
$$\phi = \delta_2 - \delta_1 = \frac{2\pi\Phi}{\Phi_0}$$

SQUID = quantum electromagnetic equivalent of an optical interferometer

phase difference influence by magnetic flux threading SQUID loop

Josephson tunnel junctions





Brian D. Josephson (1962):

critical current (geometry + material dependent)

first Josephson equation: $I_\mathrm{s} = I_\mathrm{c} \sin\varphi$

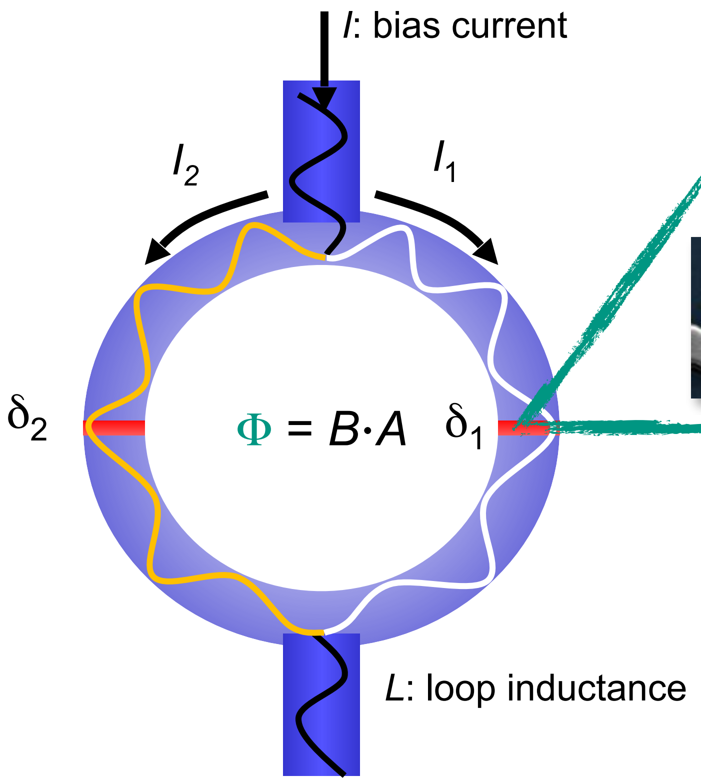
second Josephson equation: $\dot{\varphi} = \dfrac{d\varphi}{dt} = \dfrac{2e}{\hbar} V = \dfrac{2\pi}{\Phi_0} V$

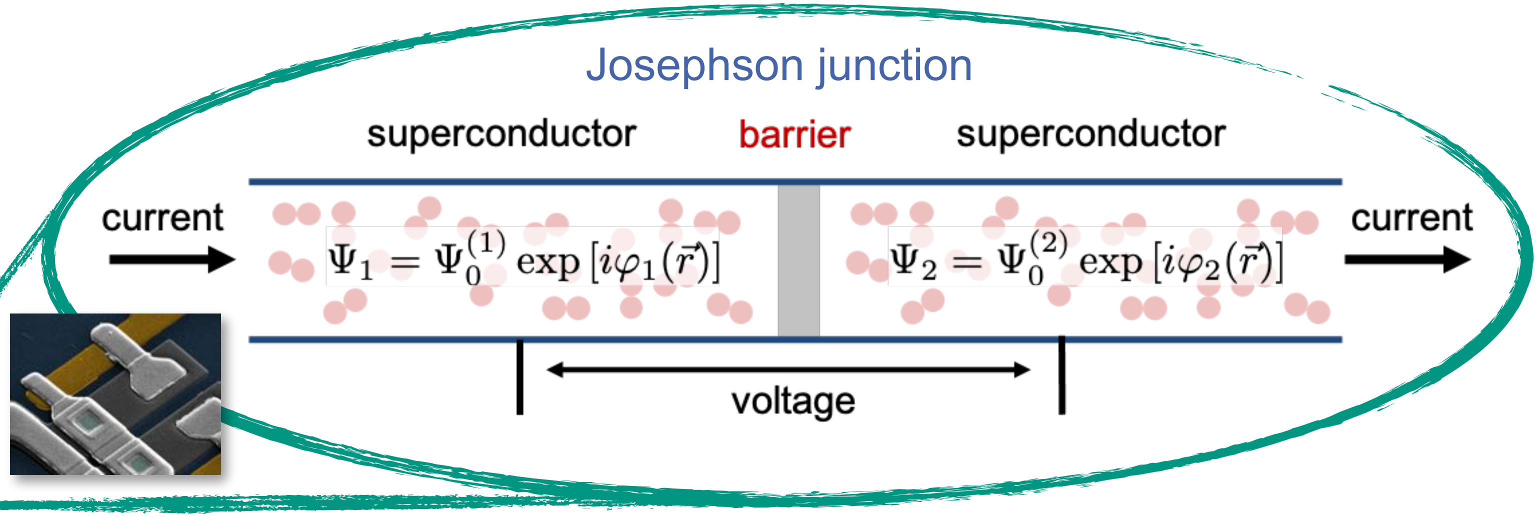
related to magnetic field

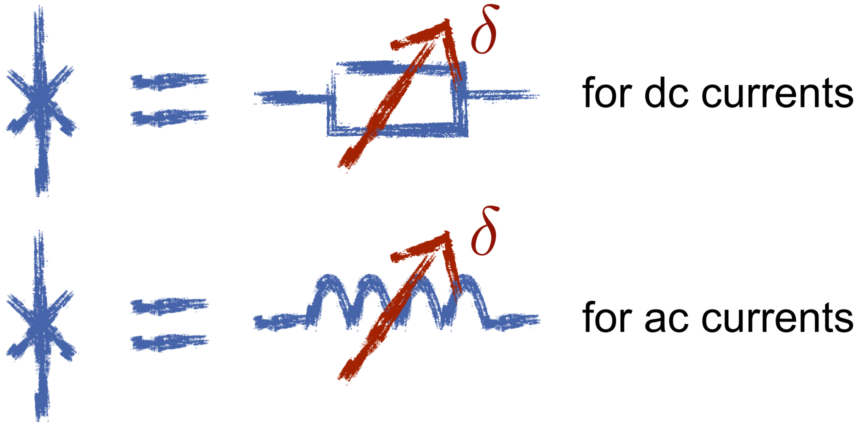
with $\varphi = \theta_2 - \theta_1 - \dfrac{2\pi}{\Phi_0} \displaystyle\int_{\mathrm{S1}}^{\mathrm{S2}} \boldsymbol{A}(\boldsymbol{r}, t) \cdot d\boldsymbol{l}$

SQUID = quantum electromagnetic equivalent of an optical interferometer

Josephson tunnel junctions



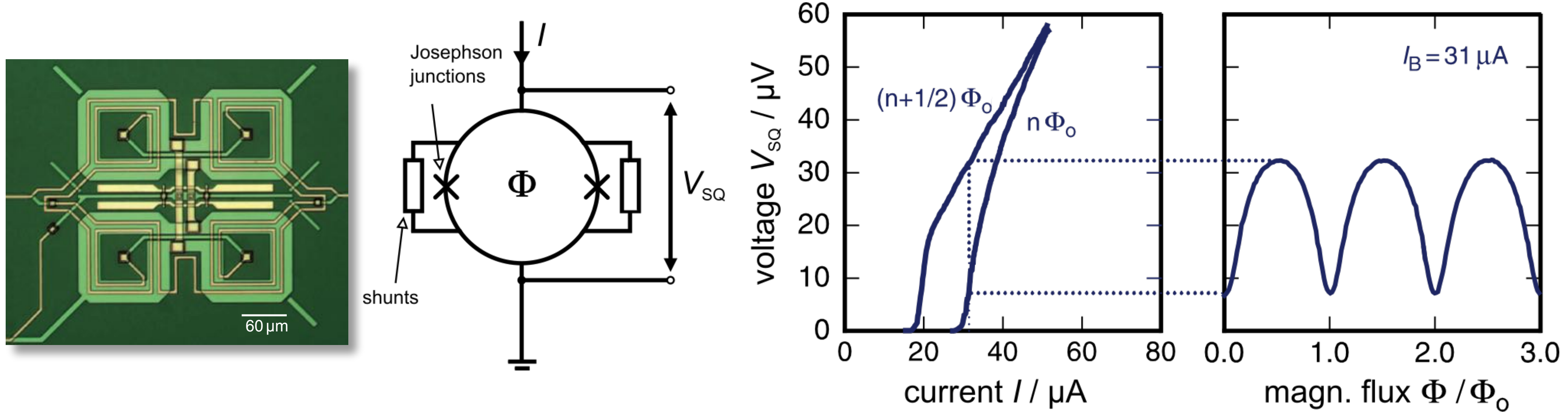




SQUID = quantum electromagnetic equivalent of an optical interferometer

SQUID-based detector readout

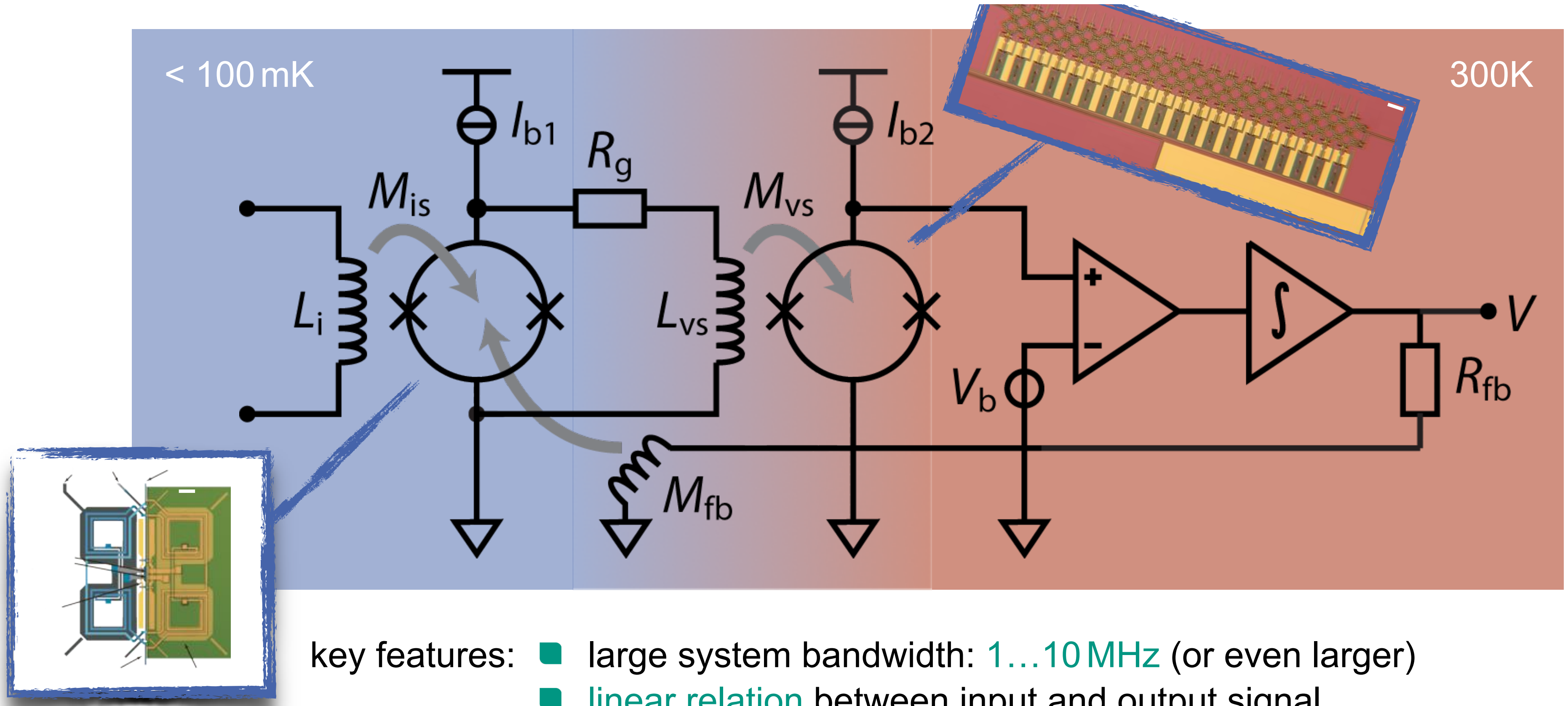
dc-SQUID = magnetic flux to voltage / current converter



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

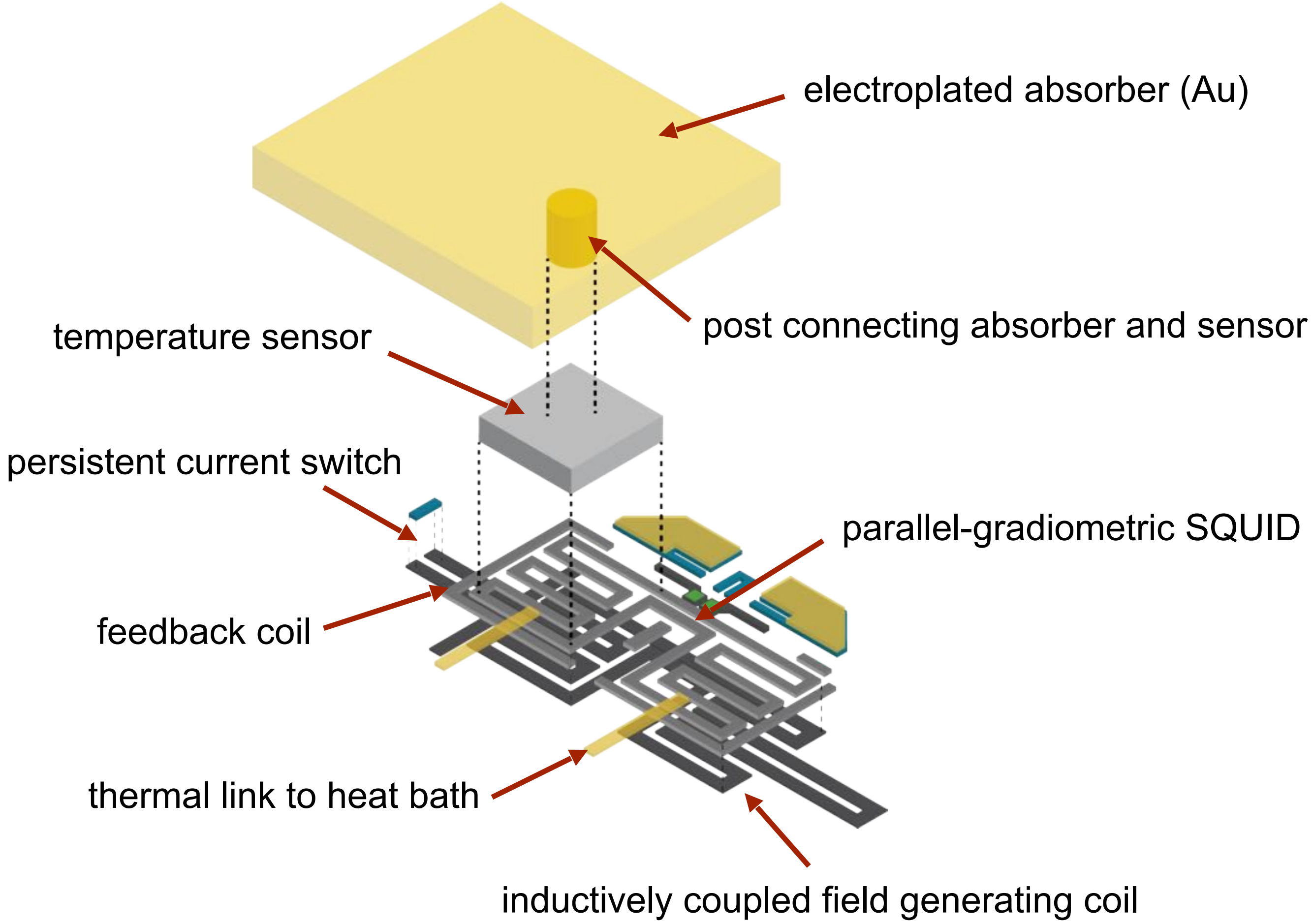
Two-stage SQUID setup with flux-locked loop

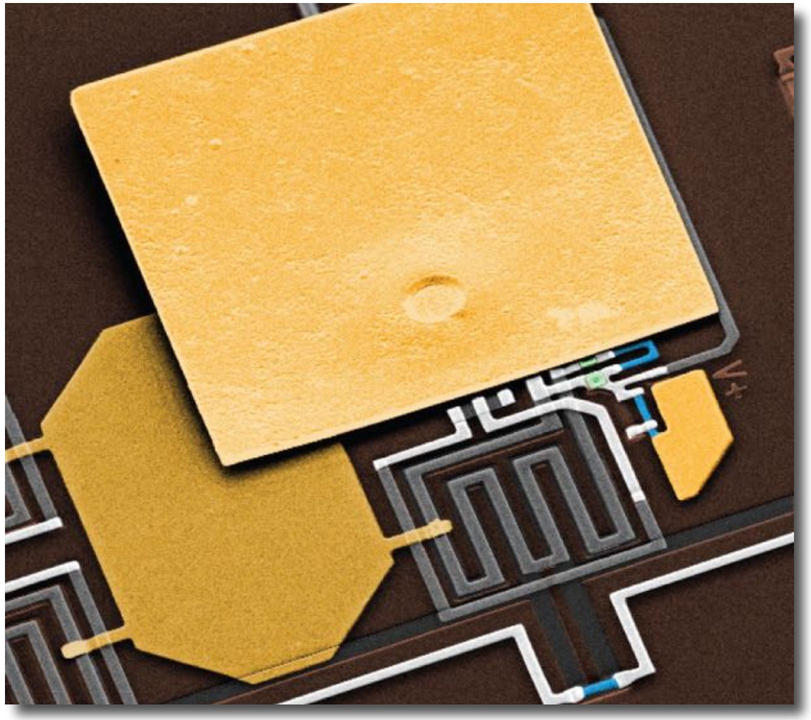
SQUID-based amplifier chain with ultrafast feedback electronics



key features:
- large system bandwidth: 1…10 MHz (or even larger)
- linear relation between input and output signal
- close to quantum-limited noise performance

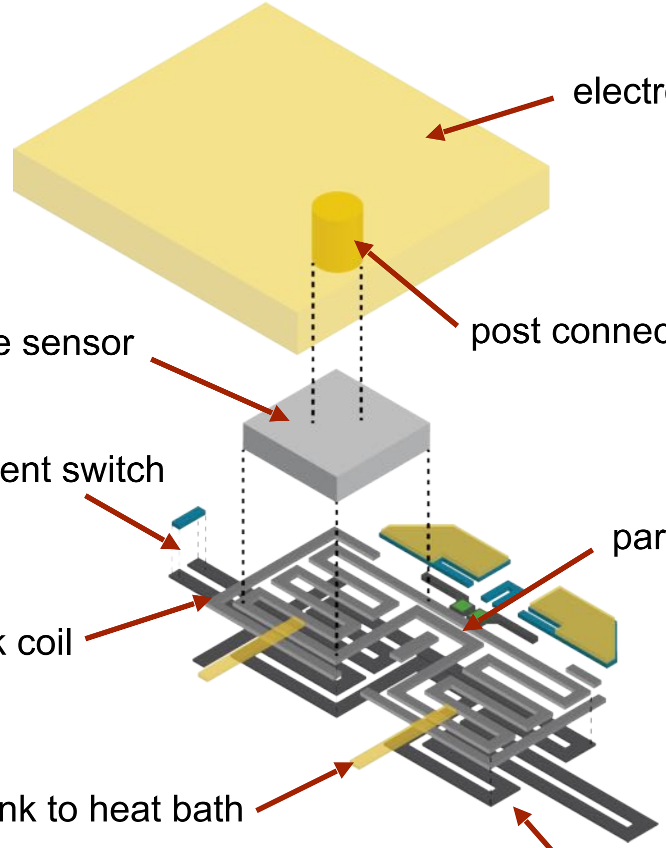
Integrated cryogenic microcalorimeters

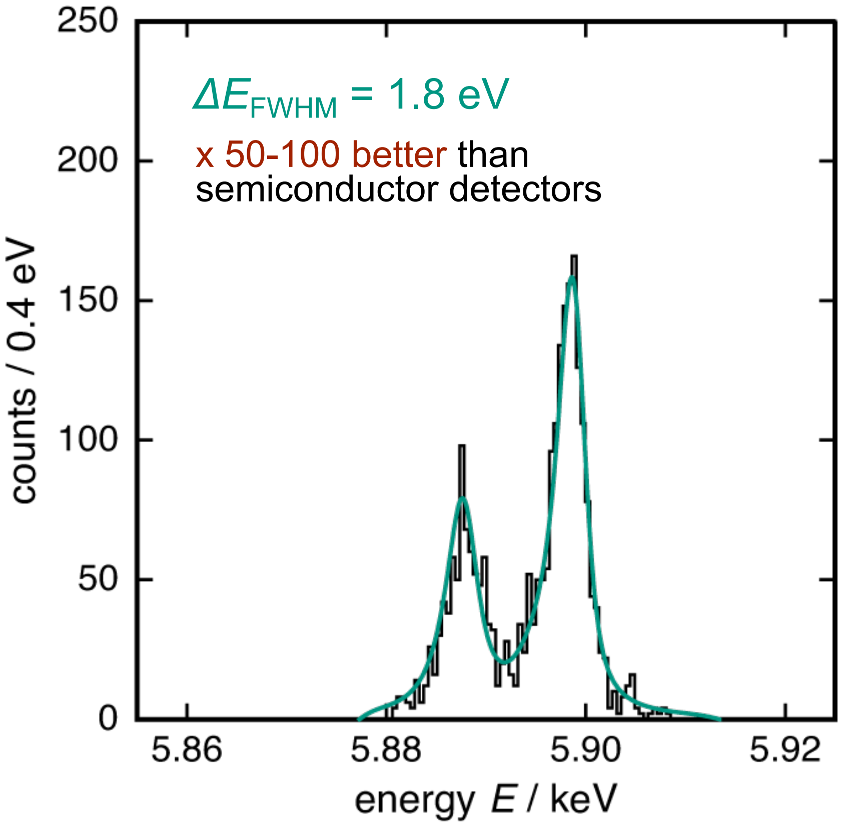




M. Krantz, SK *et al.*, IEEE Explore - ISEC 2019
M. Krantz, PhD thesis, Heidelberg University (2020)

Integrated cryogenic microcalorimeters





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

Pixels, pixels, pixels…

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(image) resolution

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

statistics

number of events determined
by number of pixels and measurement time

ECHo

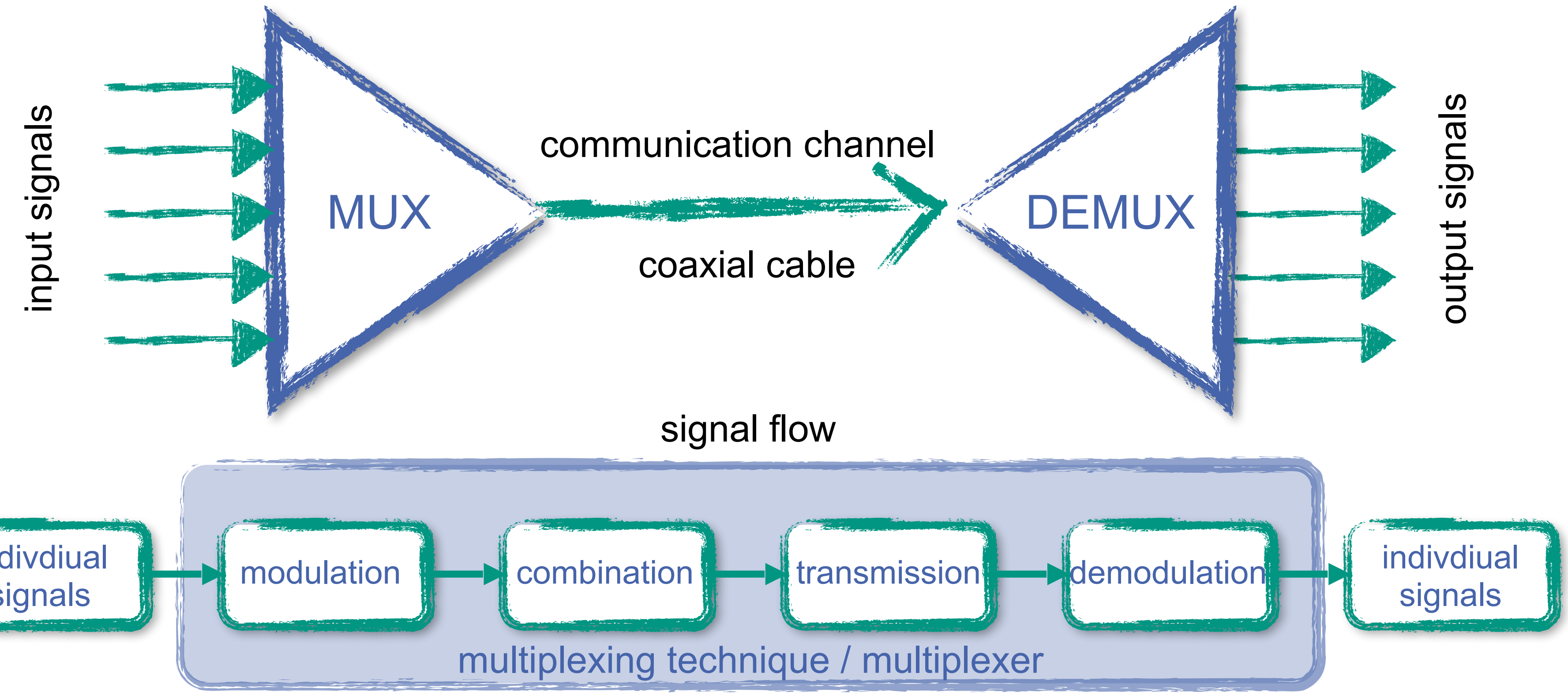
target: ~10^{14} Ho-163 decays

10 Bq/px → 1 detector for 3.2×10^5 yr

10 Bq/px → 10^5 detectors for 3.2 yr

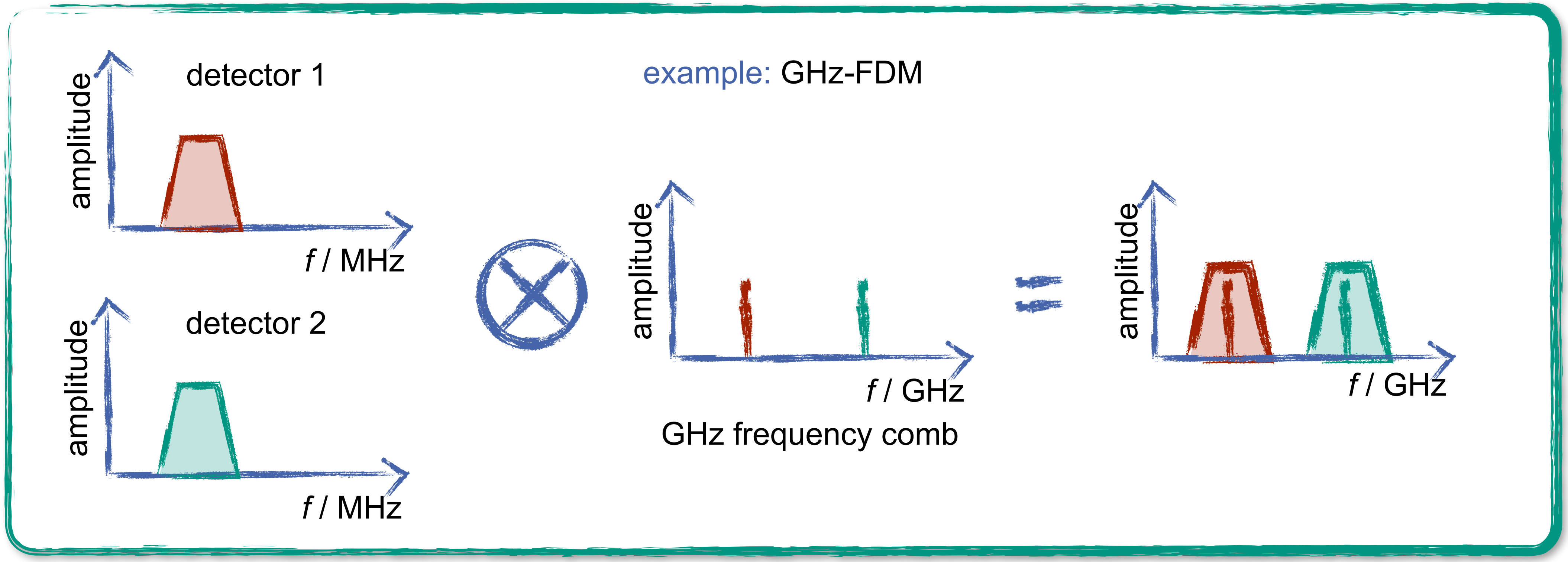
Cryogenic ’hard’ multiplexing

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



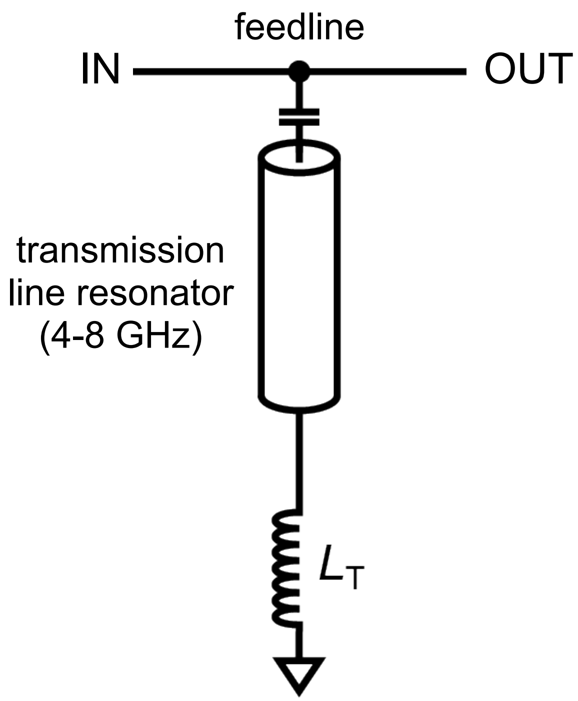
Frequency-division multiplexing (FDM)

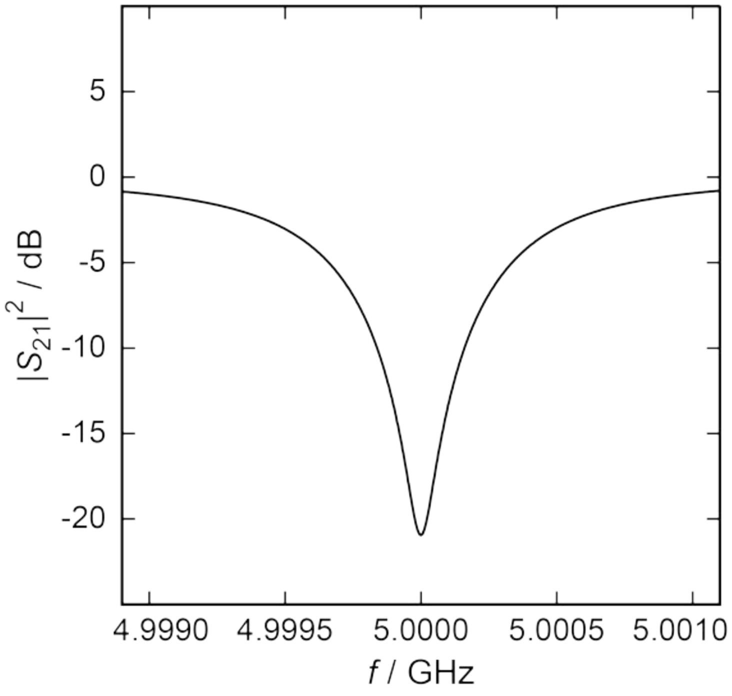
idea: detector signals are modulated on independent MHz / GHz carrier signals



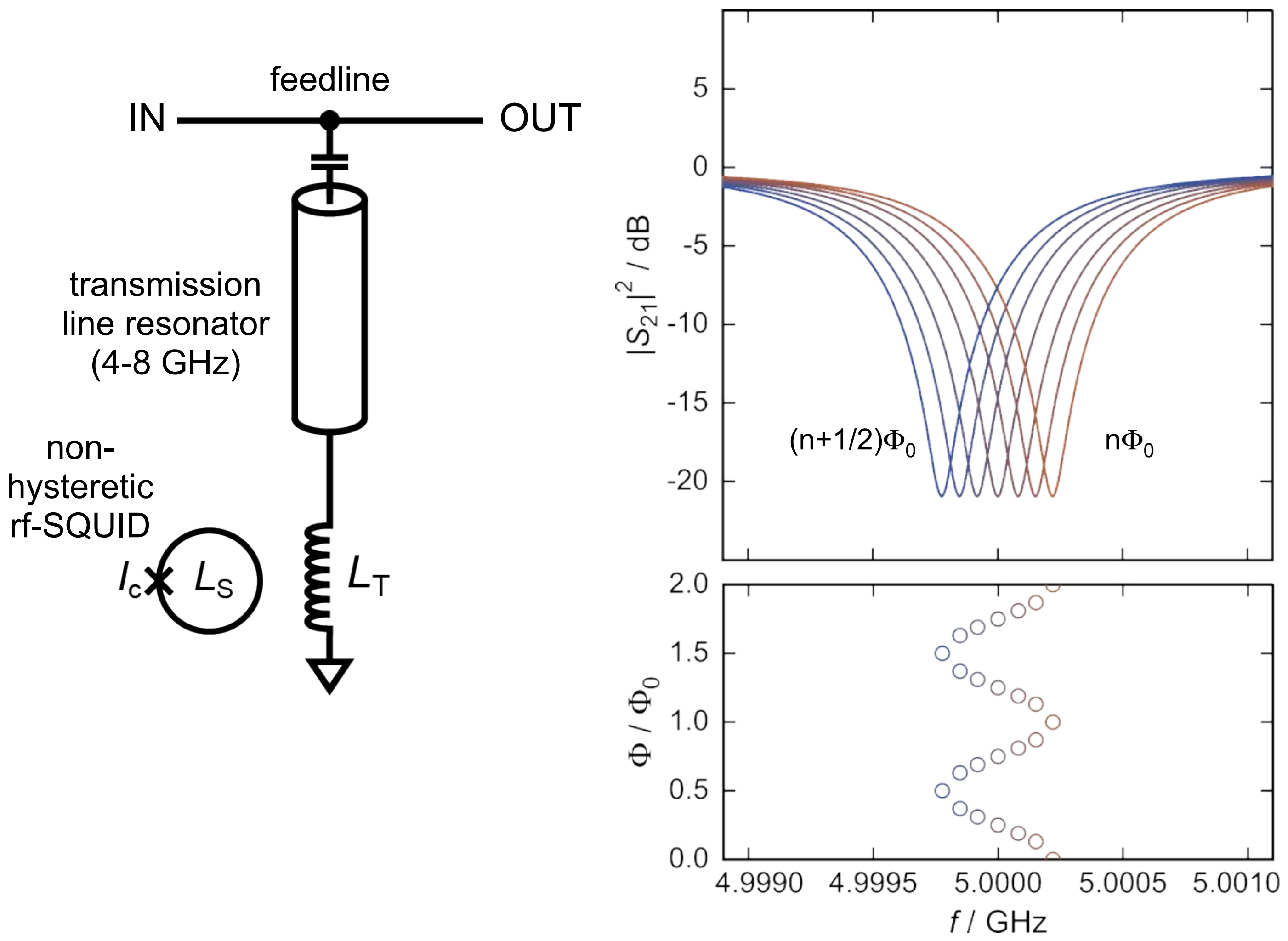
→ non-linear superconducting element required

Non-hysteretic rf-SQUIDs

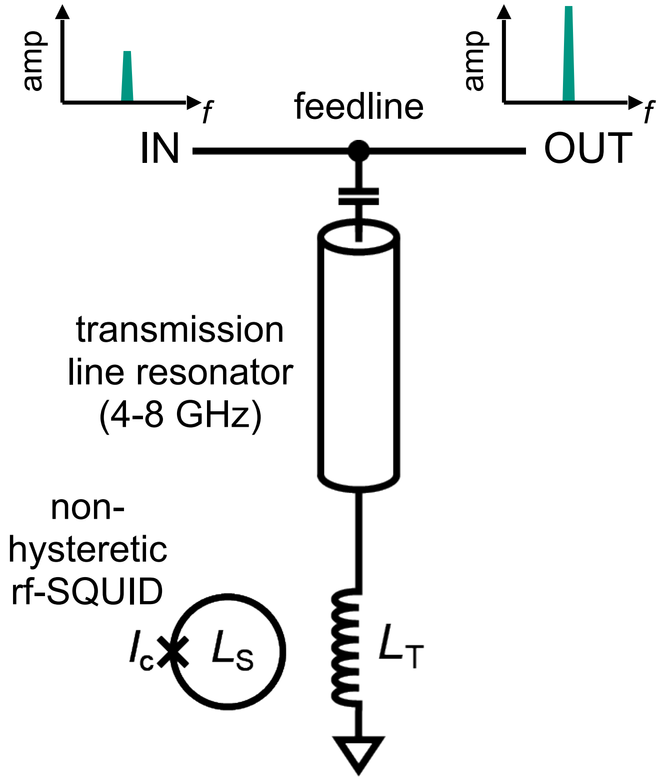


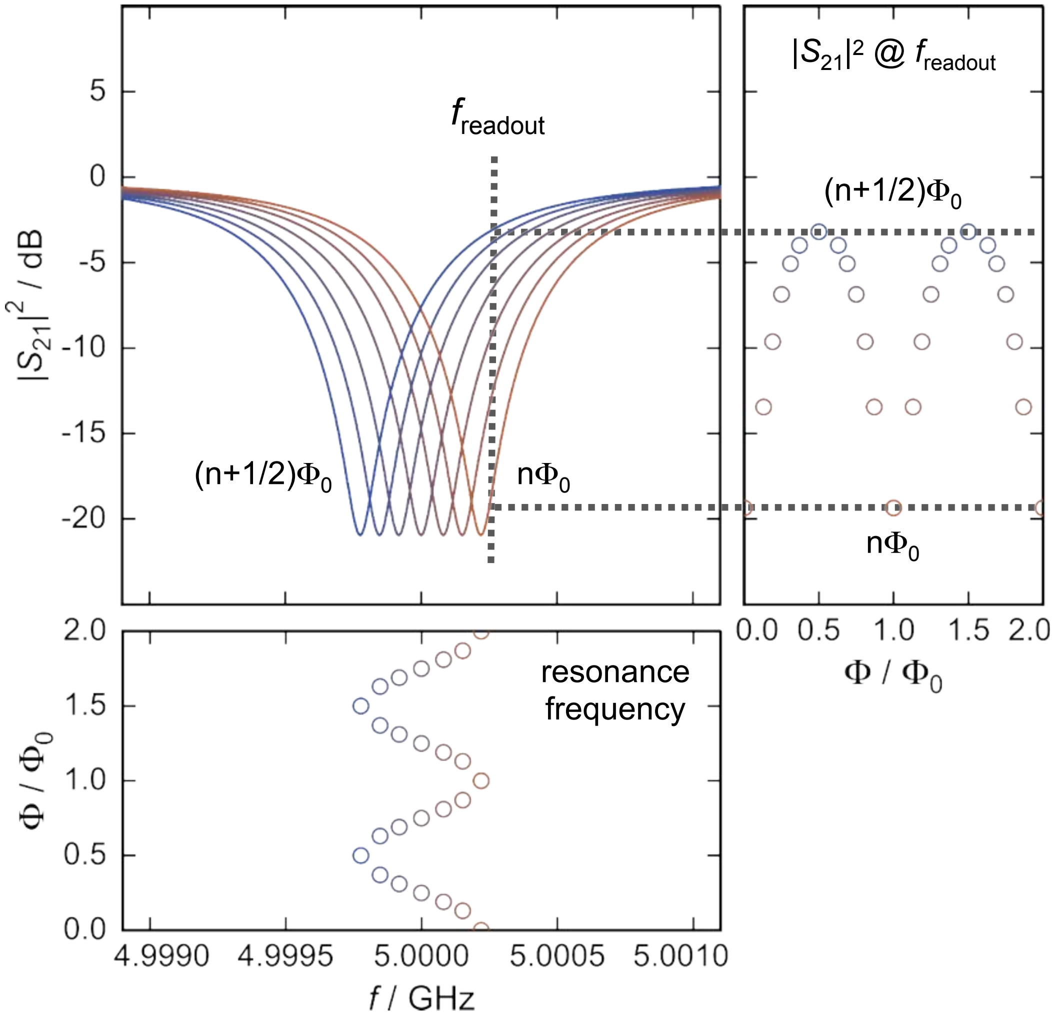


Non-hysteretic rf-SQUIDs



Non-hysteretic rf-SQUIDs





Microwave SQUID Multiplexing

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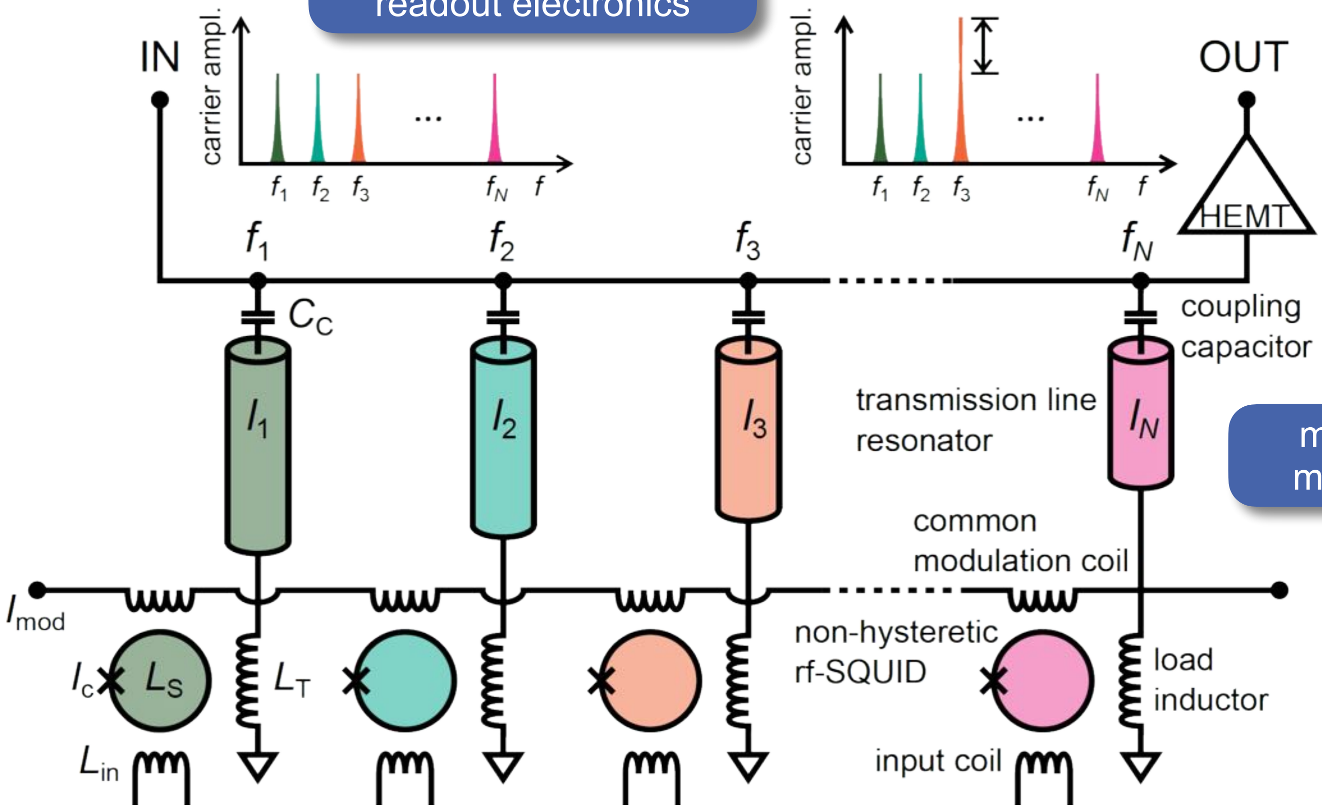
SDR-based readout electronics



microwave SQUID multiplexer (µMUX)

flux ramp modulation

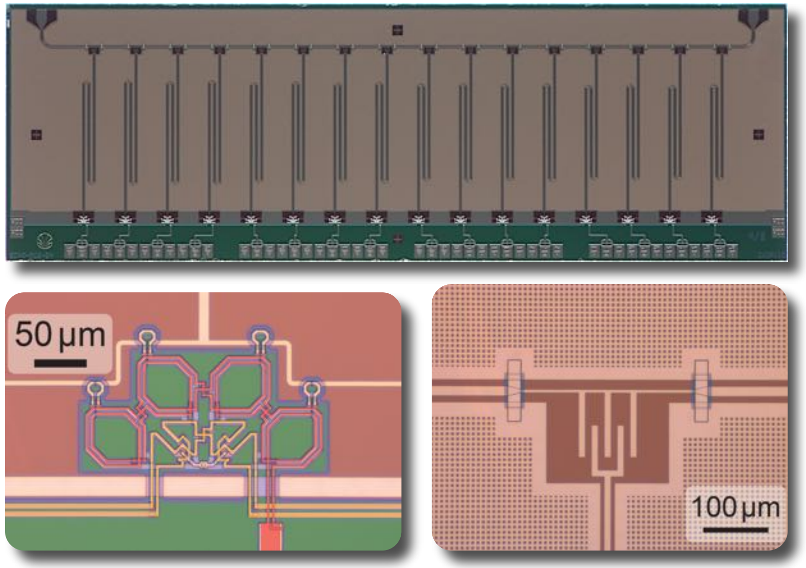
1 HEMT amplifier + 2 coaxes → ~1000 detectors

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

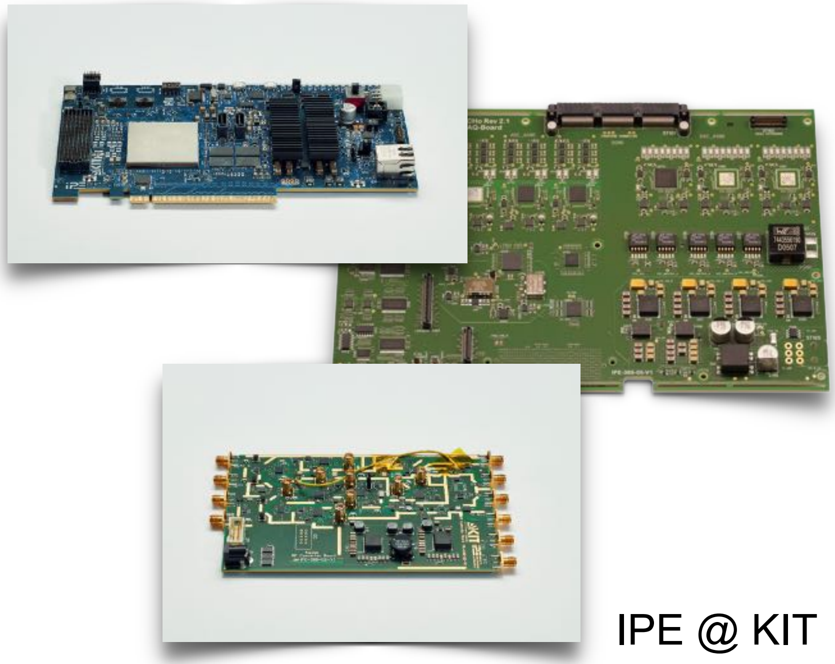
µMUX based readout system

quantum electronics

high-speed semiconductor electronics



IMS @ KIT

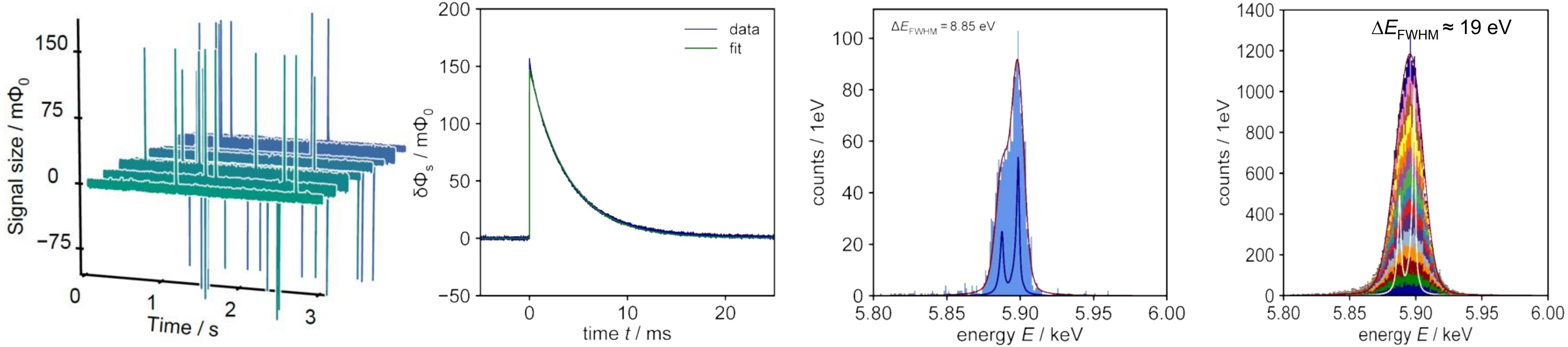


IPE @ KIT

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

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Thank you for your attention!

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