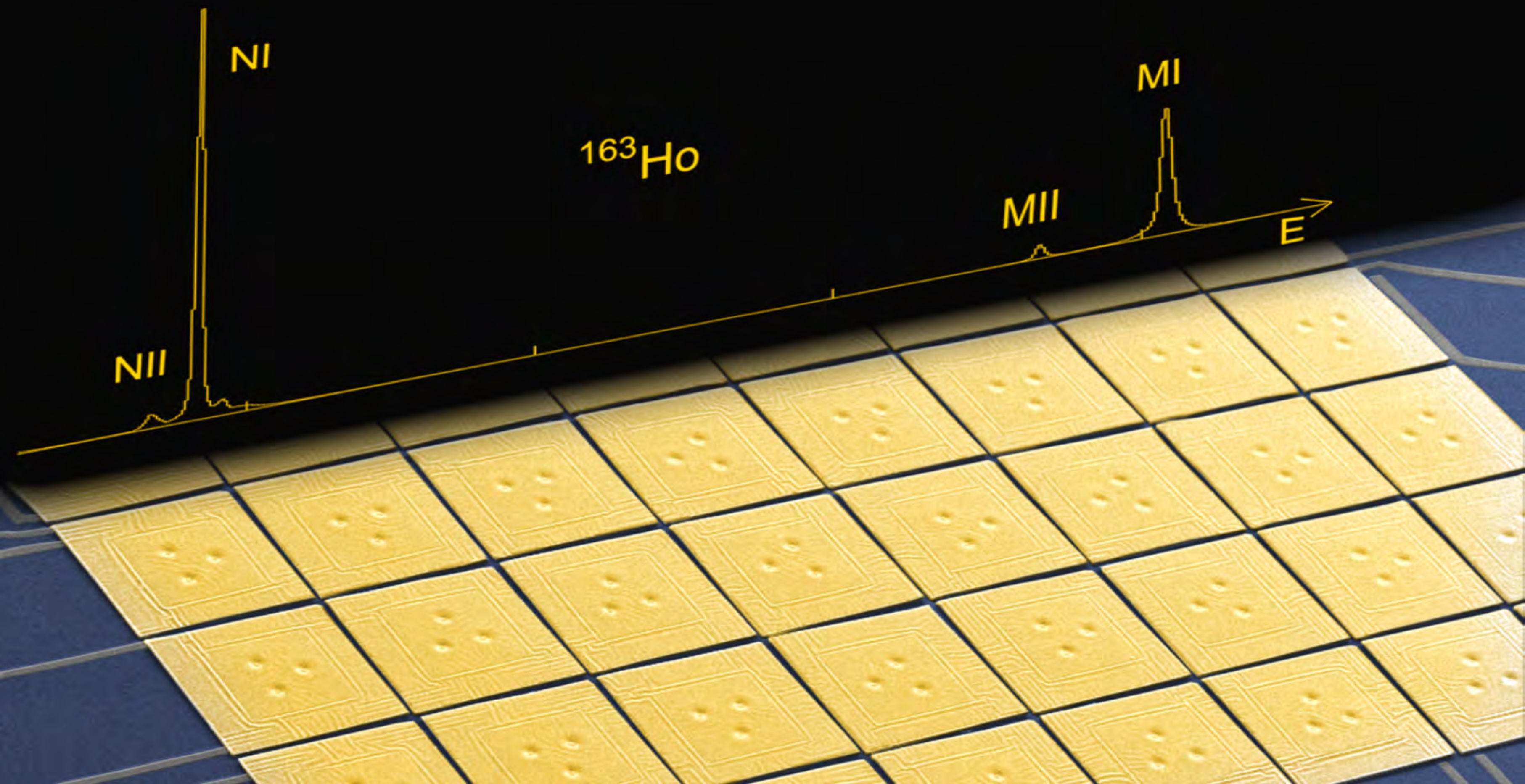
Christian Enss, Heidelberg University
for the ECHo Collaboration

The Electron Capture in ^{163}Ho Experiment
ECHo



Direct Neutrino Mass Determination

current best limits

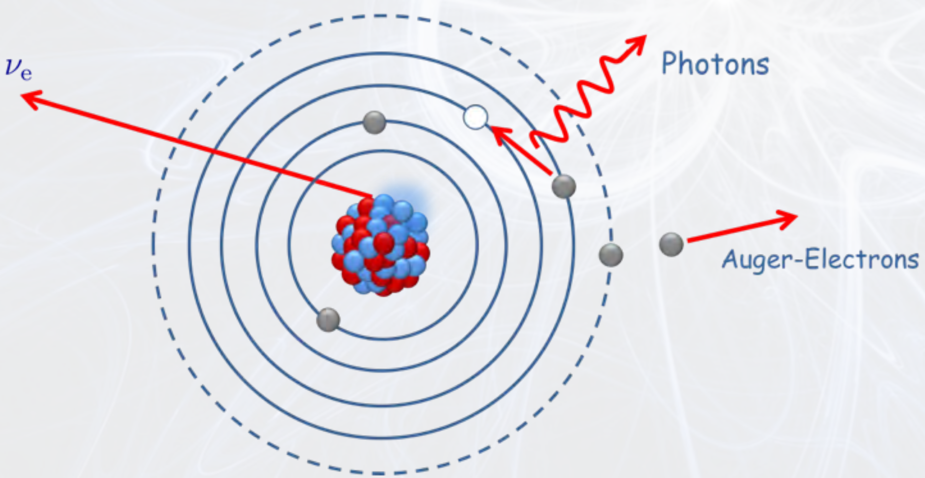
$m(\overline{\nu}_e)$	$\leq$	1.1 eV/c^2	beta decay	Tritium	M. Aker *et al.*, PRL **123**, 221802 (2019)
$m(\nu_e)$	$\leq$	150 eV/c^2	beta capture	Holmium	C. Velte *et al.*, EPJC **79**, 1026 (2019)

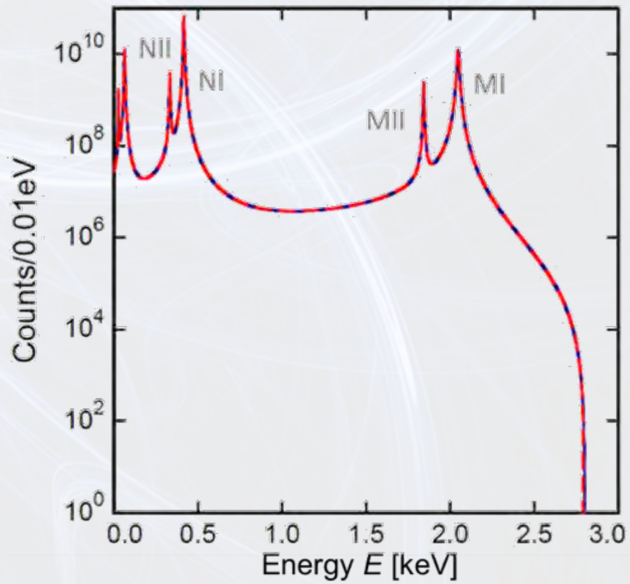
the case of ^{163}Ho

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

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

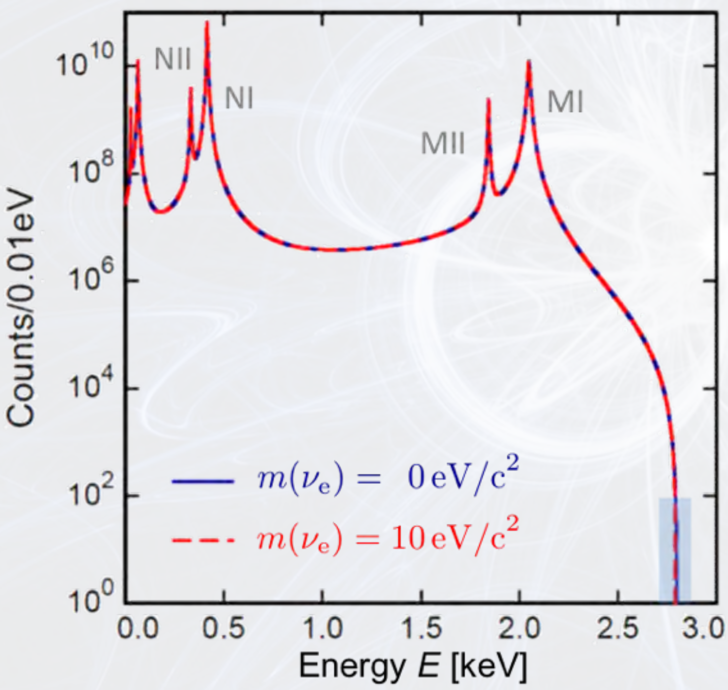
$$\hookrightarrow {}^{163}_{66}\mathrm{Dy} + E_C$$

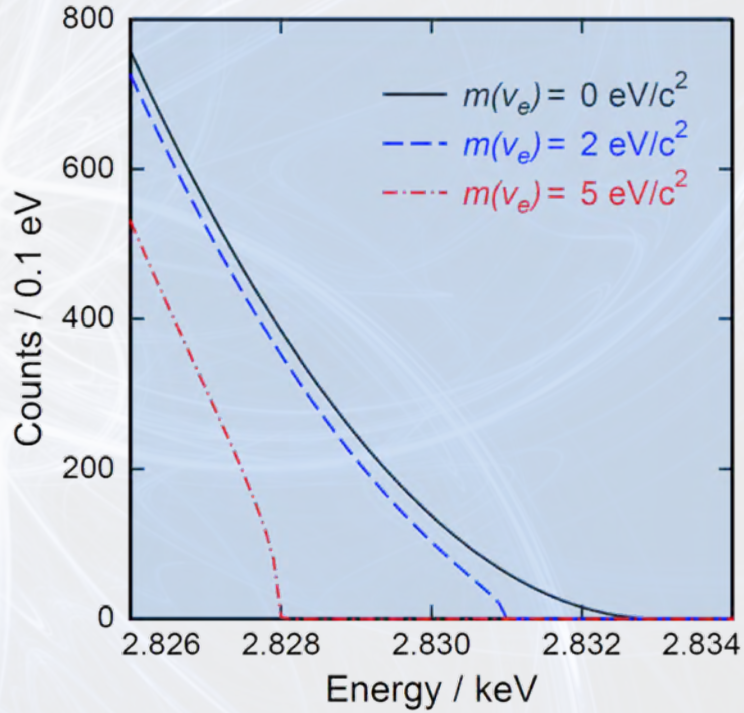




Electron Capture: The Case of ^{163}Ho

$$\frac{\mathrm{d}N}{\mathrm{d}E_\mathrm{C}} = A\,(Q_\mathrm{EC}-E_\mathrm{C})^2\sqrt{1-\frac{m_\nu^2}{(Q_\mathrm{EC}-E_\mathrm{C})^2}}\sum_j C_j n_j B_j \phi_j^2(0)\frac{\Gamma_j/2\pi}{(E_\mathrm{C}-E_j)^2+\Gamma_j^2/4}$$

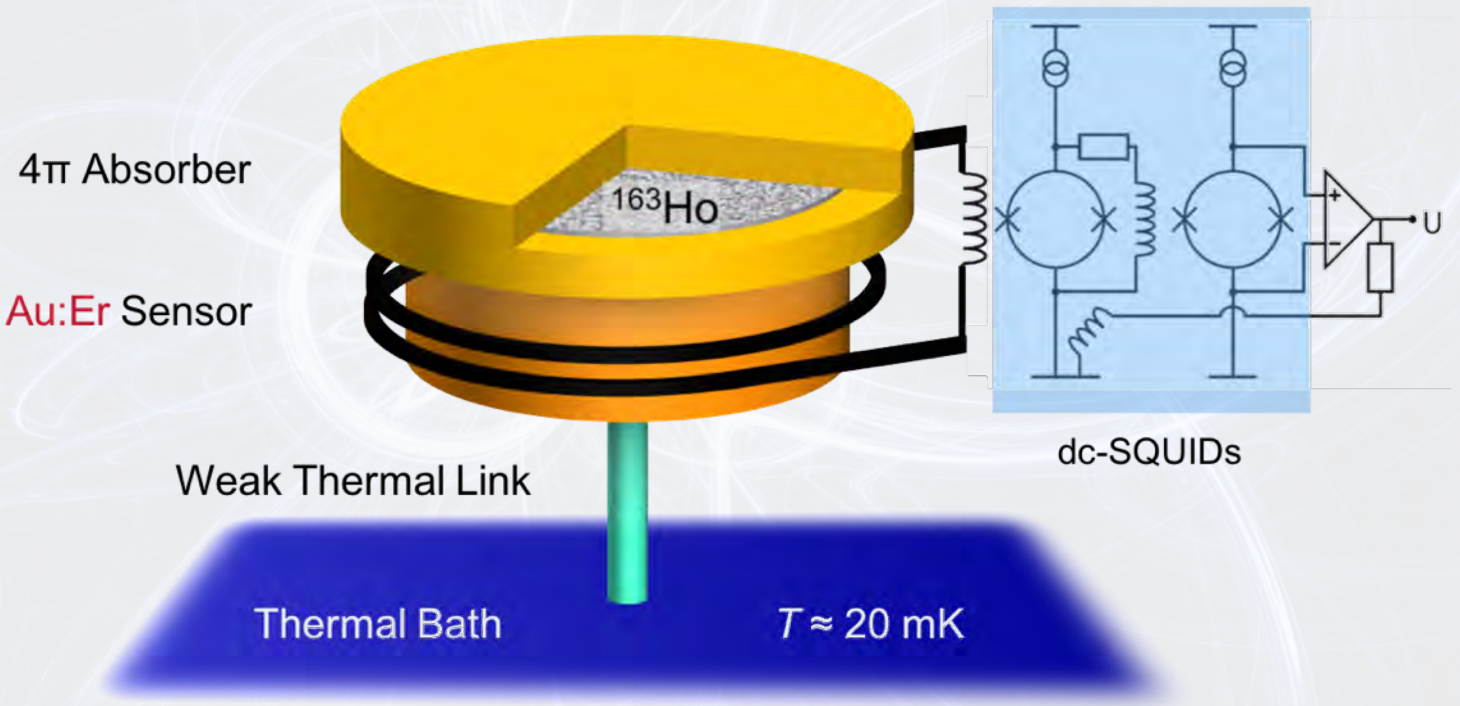




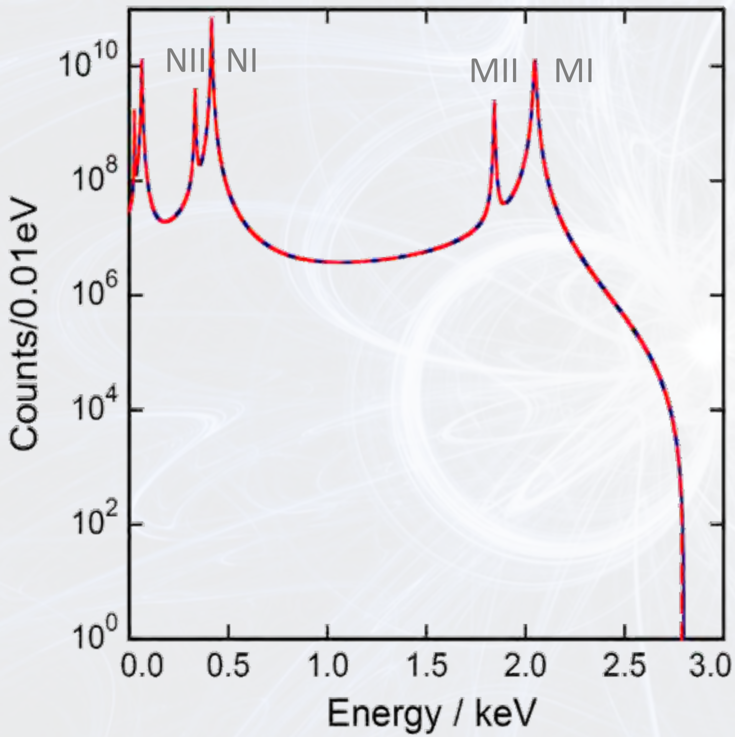
Low Q_{EC} = (2.833 $\pm$ 0.030^{stat} $\pm$ 0.015^{sys}) keV
(2.858 $\pm$ 0.010^{stat} $\pm$ 0.050^{sys}) keV

S. Eliseev *et al.*, PRL **115**, 062501 (2015)
P. Ranitzsch *et al.*, PRL **119**, 122501 (2017)

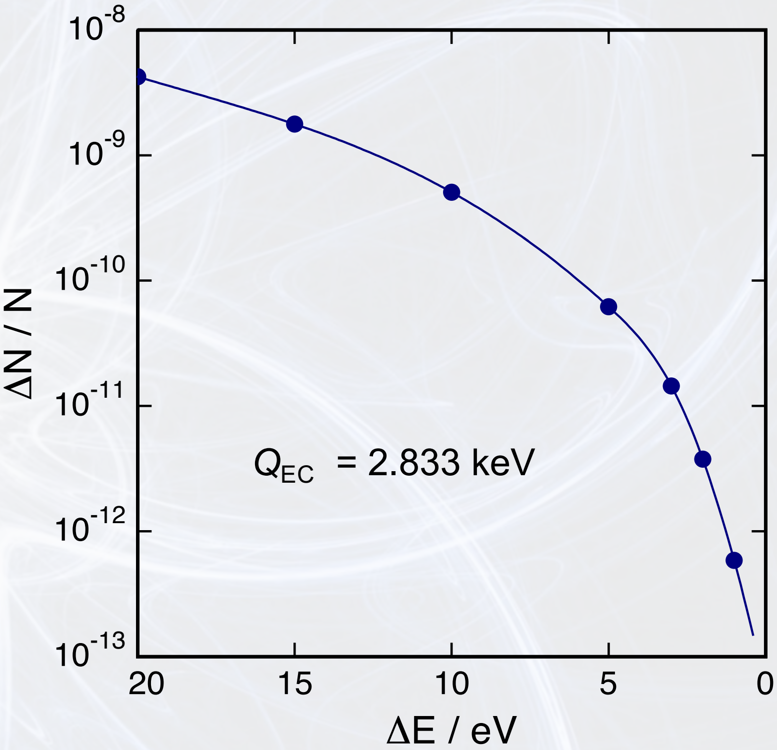
Embedding ^{163}Ho in the absorber of an MMC



Requirements for ECHo: Total Number of Counts



fraction of counts in endpoint region

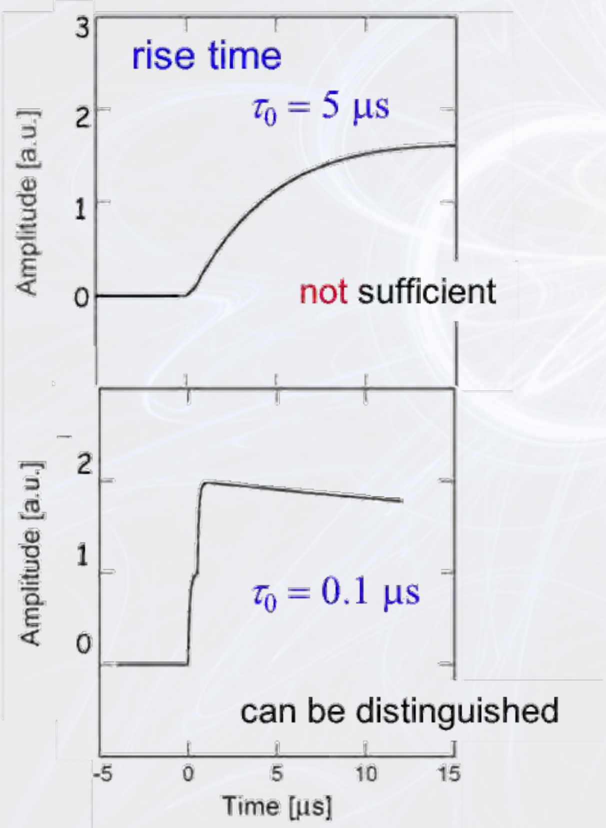


in last 1 eV interval only 6×10^{-13} counts

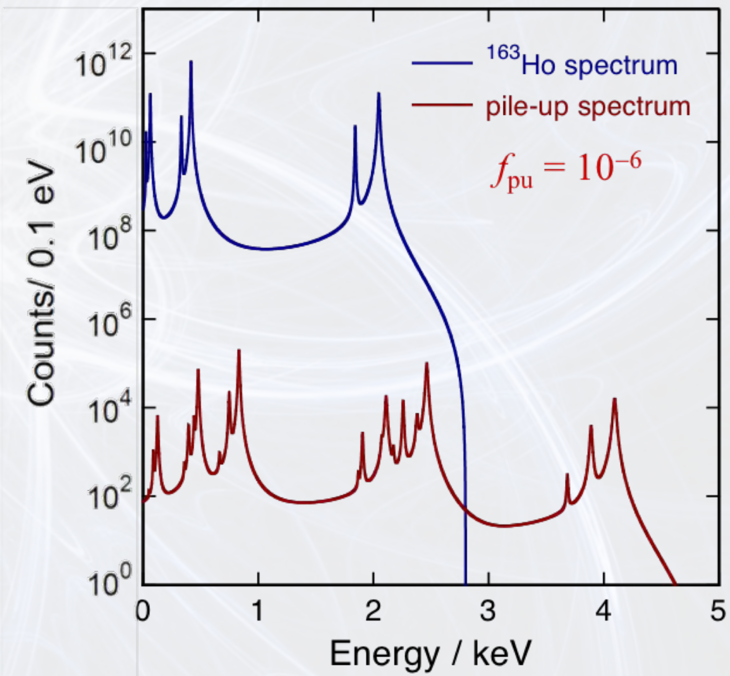
more than 10^{14} total number of counts needed unresolved pile-up fraction: $f_{pu} = A_p \cdot \tau_0$

activity per pixel — signal rise time

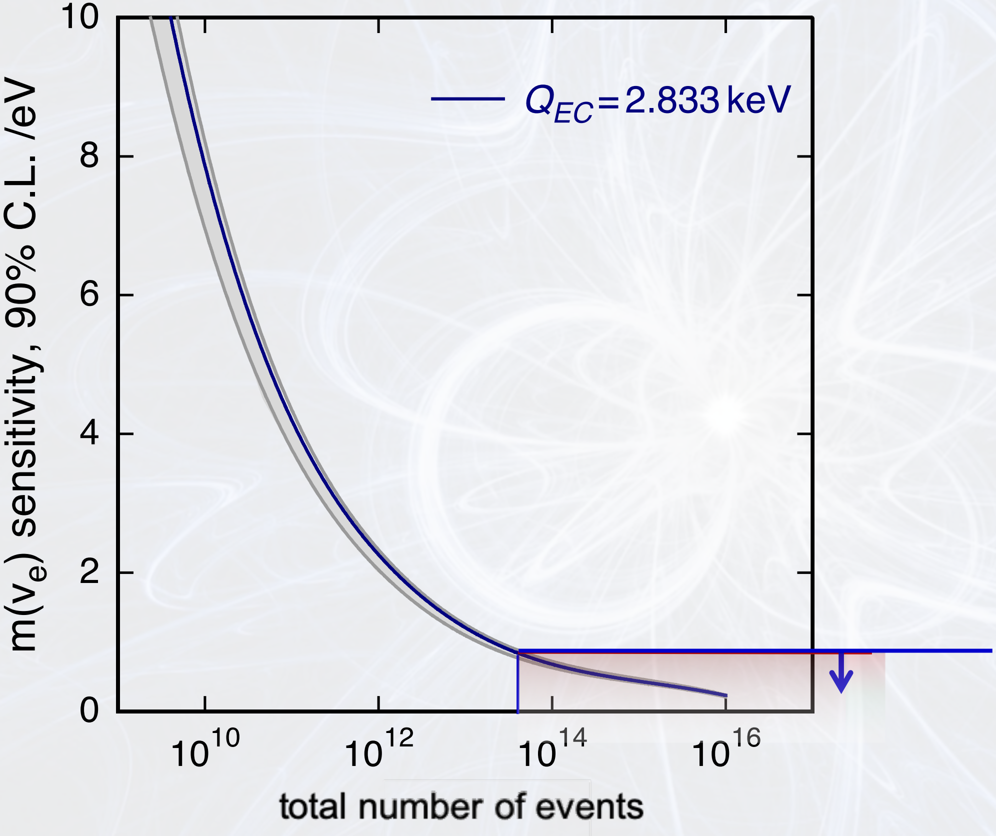
two events 0.5 μs apart



pile-up spectrum



Sensitivity for $\Delta E_{FWHM} = 3$ eV and $f_{pu} = 10^{-5}$



ECHo-100k

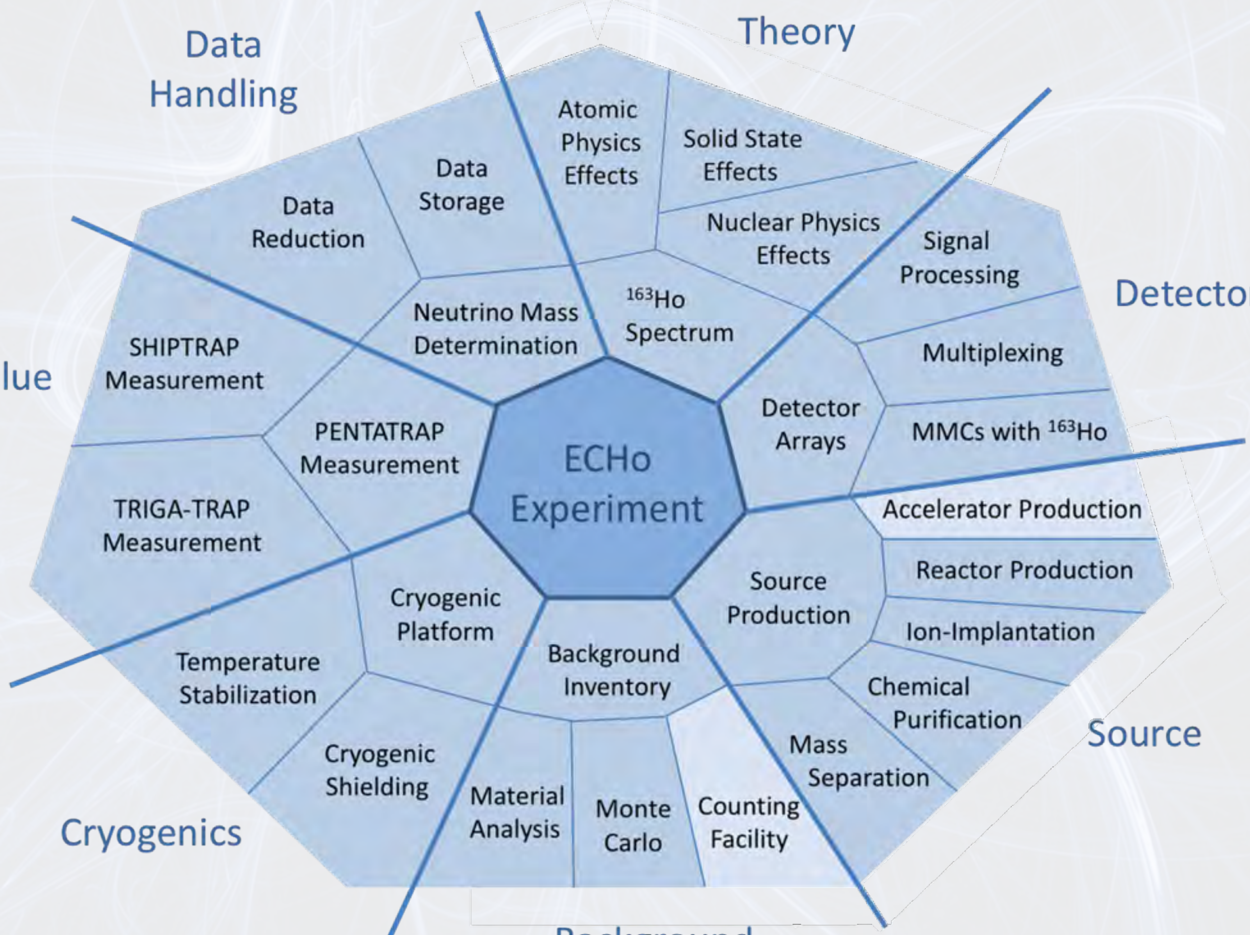
50 × 200 pixel × 10 Bq

36 months → 3×10^{13} events

↓

sub 2 eV resolution

Overview of ECHo



ECHo Collaboration

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Funded by the Germany Research Foundation DFG

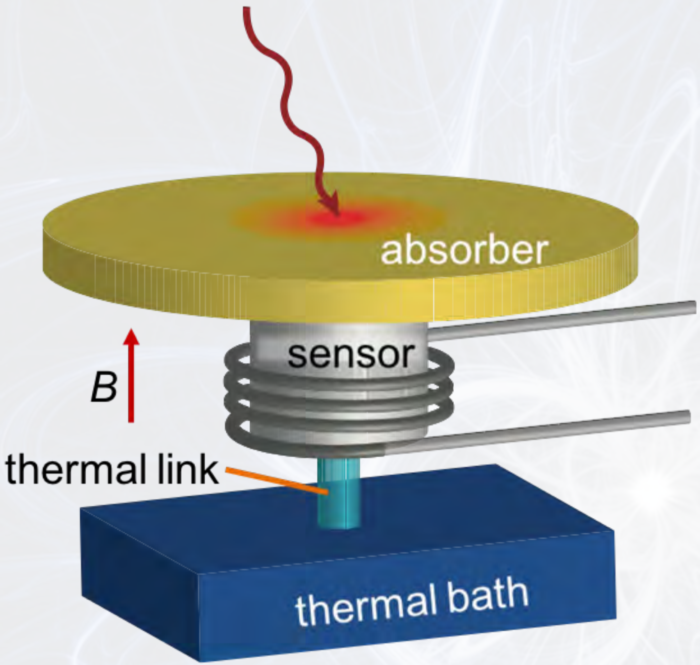
FOR 2202

ECHo

DFG Deutsche Forschungsgemeinschaft

The Electron Capture in ^{163}Ho experiment - ECHo
L. Gastaldo *et al.*, Eur. Phys. J Special Topics. **226** (2017) 1623-1694

Metallic Magnetic Calorimeters (MMCs)



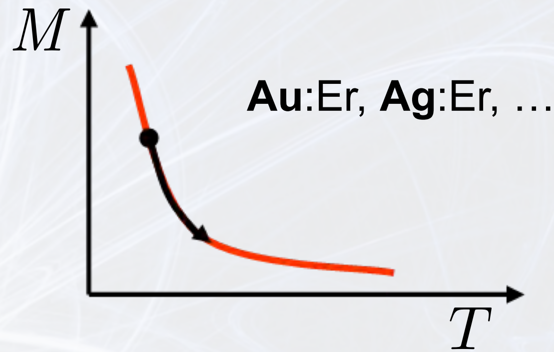
$$\Delta T \propto \Delta M \propto \Delta \phi \propto \Delta U$$

main difference to resistive calorimeters:

no dissipation in the sensor

no galvanic contact to the sensor

paramagnetic sensor:



signal size:

$$\delta M = \frac{\partial M}{\partial T} \delta T = \frac{\partial M}{\partial T} \frac{E}{C_{\mathrm{tot}}}$$

energy resolution:

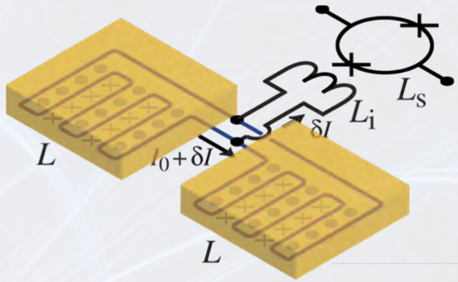
$$\Delta E_{\mathrm{FWHM}} \simeq 2{,}36 \sqrt{4 k_{\mathrm{B}} C_{\mathrm{Abs}} T^2} \sqrt{2} \left(\frac{\tau_0}{\tau_1} \right)^{1/4}$$

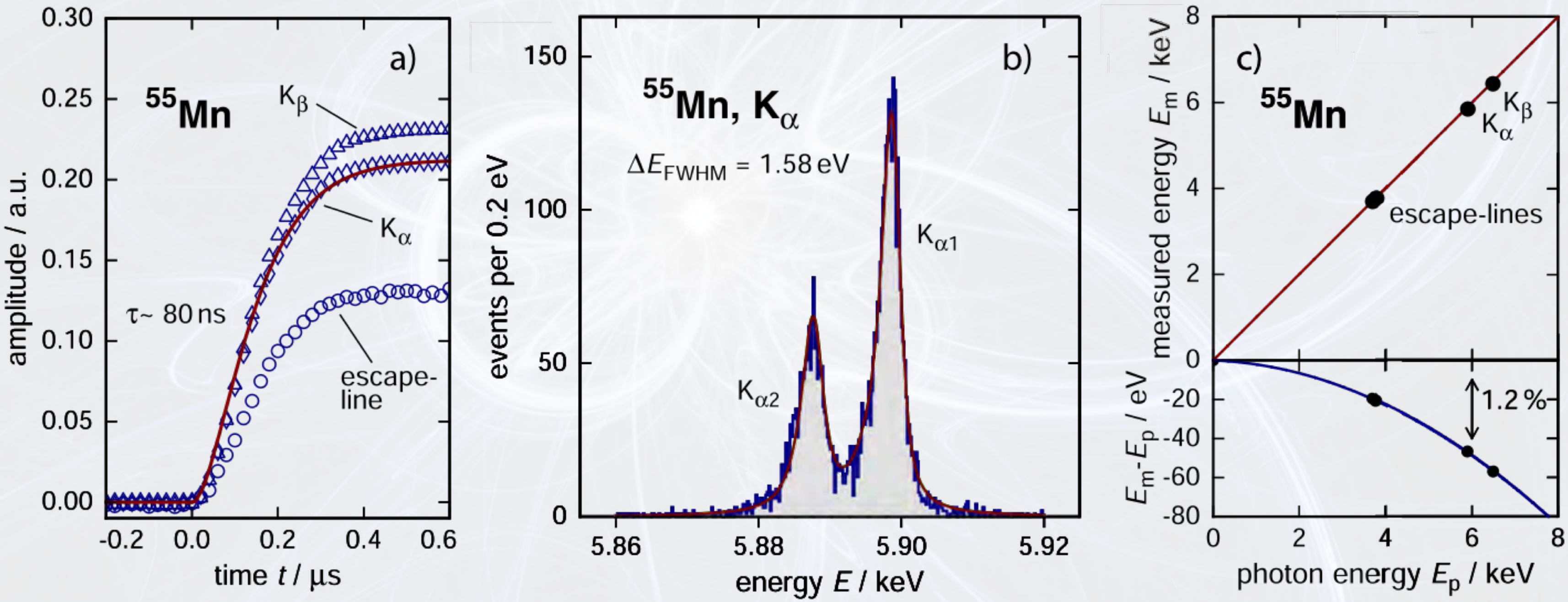
A. Fleischmann, Adv. Solid State Phys. **41**, 577 (2001)

MMC Performance at 6 keV

250 µm × 250 µm Gold, 5 µm thick

98% Quantum Efficiency @ 6 keV





record speed **record resolving power** **record linearity**

S. Kempf, A. Fleischmann, L. Gastaldo, C.E., J. Low Temp. Phys. **193,** 365 (2018)

Production and Purification of ^{163}Ho

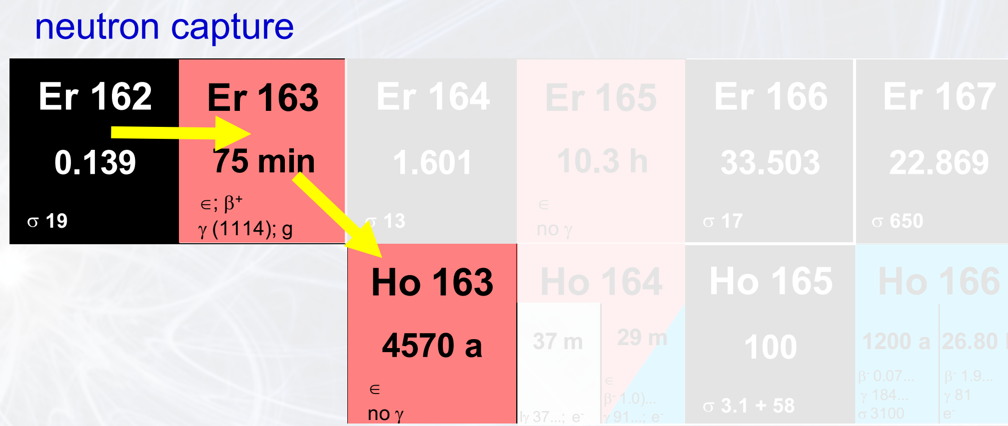
requirement: for 10^6 Bq more than 10^{17} atoms

reactor production: (n,γ)-reaction on ^{162}Er

high cross-section (19 b)

but radioactive contaminants

purification needed



- ► separate Er from all lighter lanthanides before irradiation
- ► perform neutron irradiation of enriched ^{162}Er
- ► separate Ho from all heavier lanthanides after irradiaton
- ► mass separate ^{163}Ho to remove ^{166m}Ho

J.W. Engle *et al.*, Nucl. Instrum. Meth. B **311**, (2013) 131

Production and Purification of ^{163}Ho

Thermal neutron flux

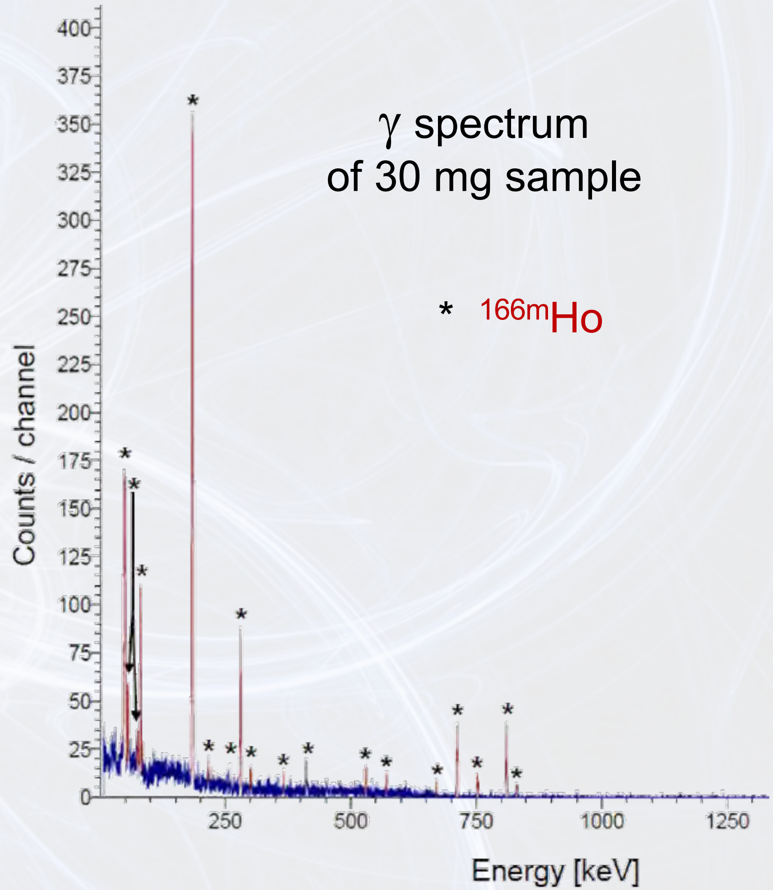
1.3×10^{15} cm^{-2}s^{-1}

NEUTRONS FOR SCIENCE

two irradiations at ILL:

30 mg for 55 days → 1.6×10^{18} ^{163}Ho atoms

7 mg for 7 days → 1.4×10^{16} ^{163}Ho atoms

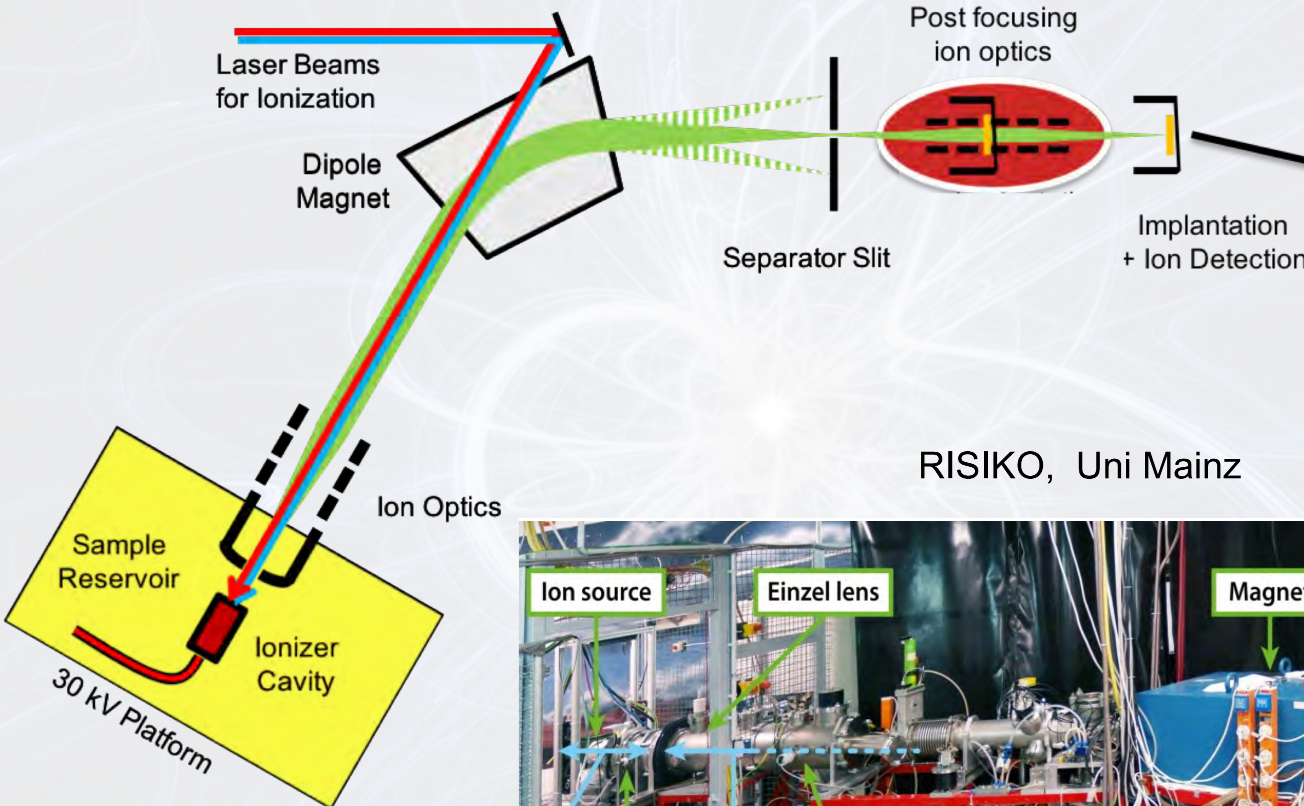


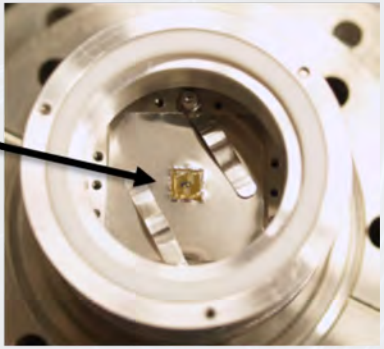
→ excellent chemical separation
… just ^{166m}Ho remaining

H. Dorrer, *et al.*, Radiochim. Acta **106** (2018)

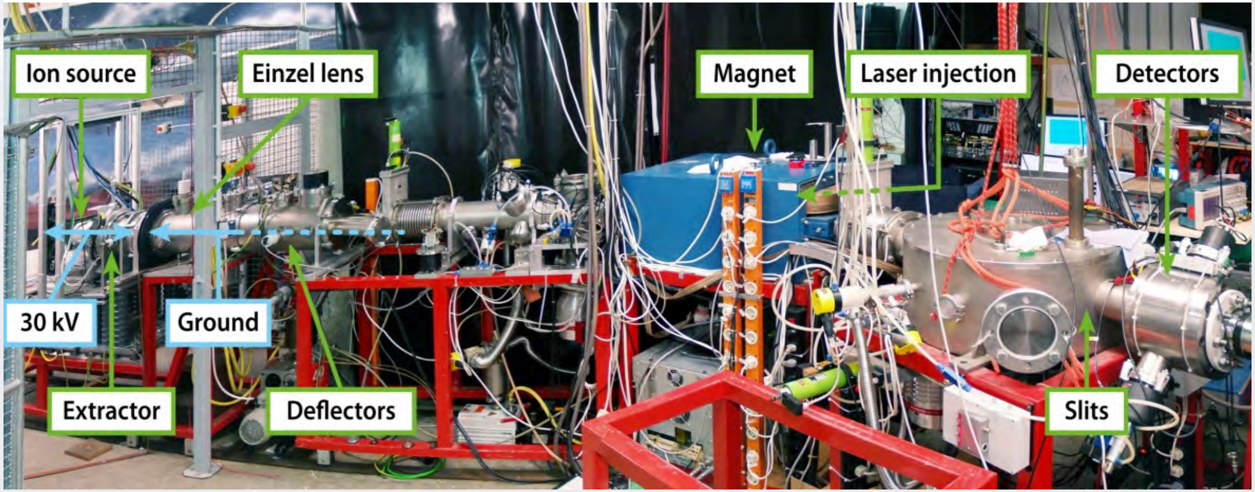
Mass Separation and Implantation

ISOLDE, CERN and RISIKO, Uni Mainz



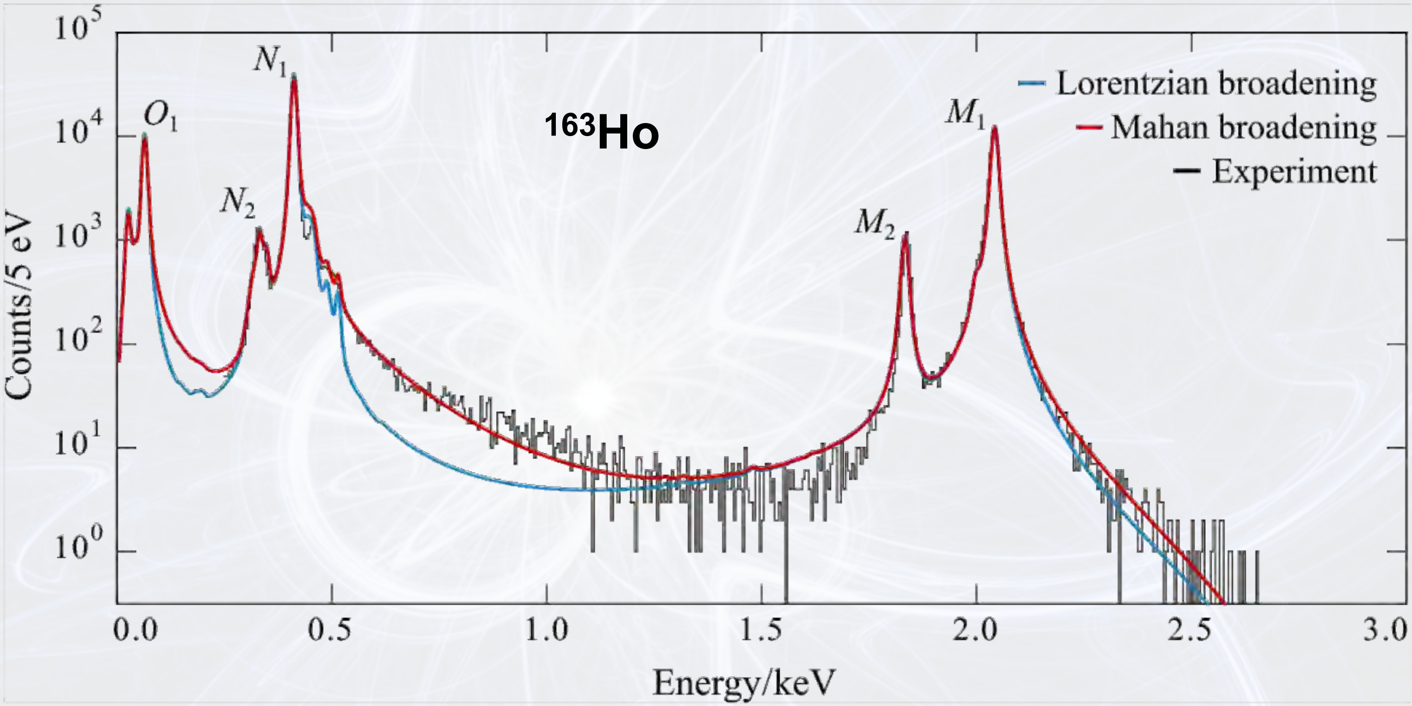


RISIKO, Uni Mainz



Modane Data and Theoretical Spectrum

4 MMC pixels (A ≈ 0.2 Bq), 4 days → 275,000 counts



Q-value: Q_{EC} = (2838 ± 14) eV

New limit on neutrino mass $m(\nu_e) < 150$ eV (95% C.L.)

Background $b < 1.6 \times 10^{-4}$ events/pixel/day (95% C.L.)

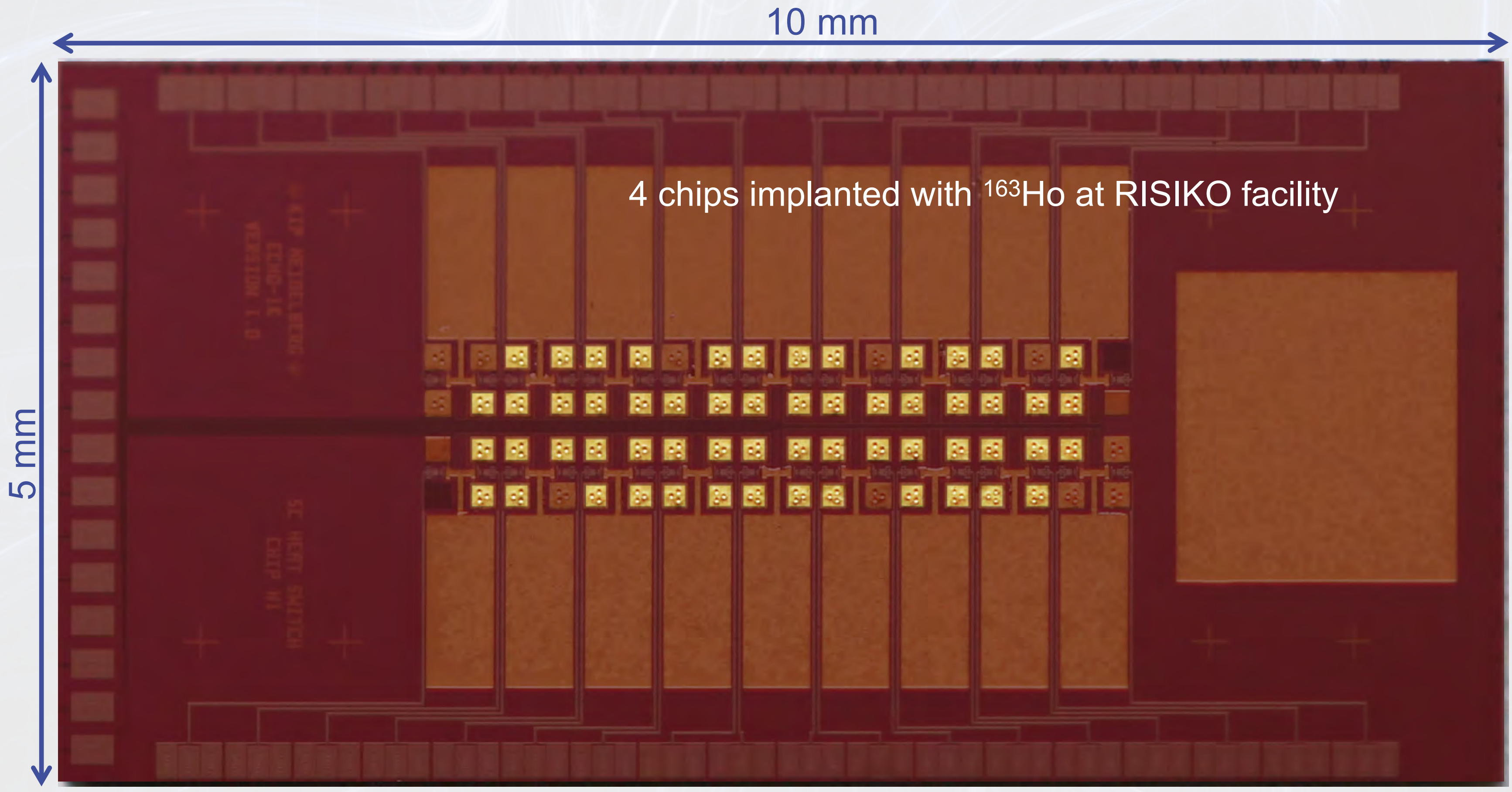
M. Brass et al, Phys. Rev. C **97**, 054620 (2018)

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

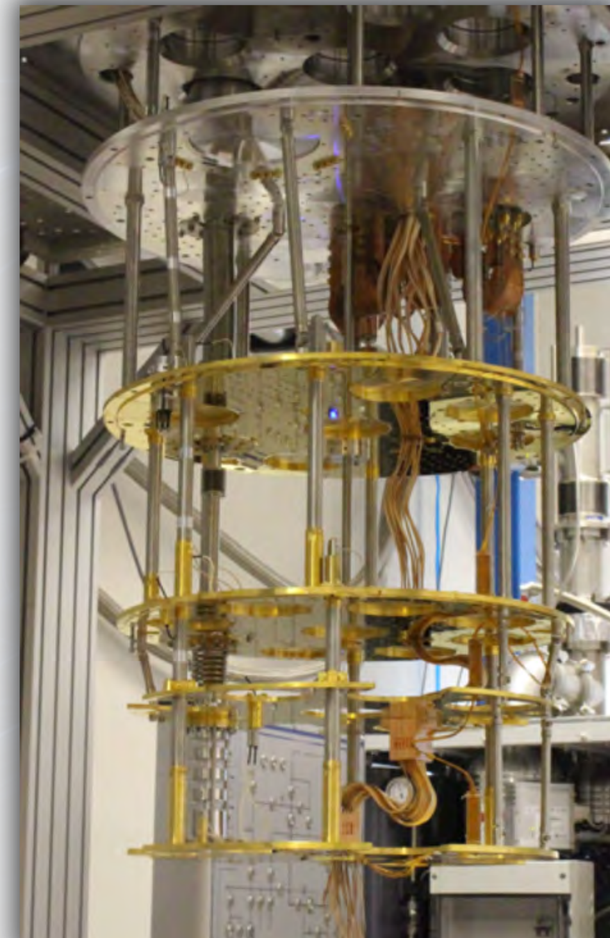
Current Work Horse: ECHo-1k Detector Chip

ECHo-1k array: 64 pixels to be loaded with ^{163}Ho

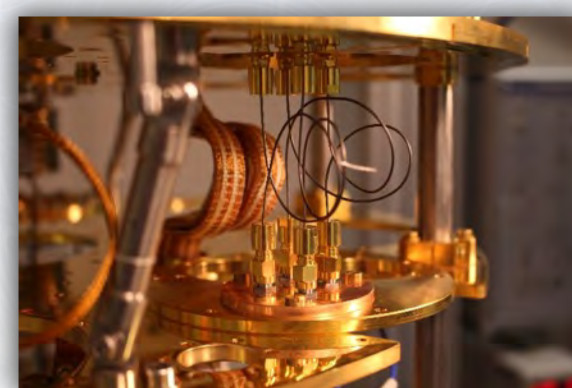
+ 4 detectors for diagnostics



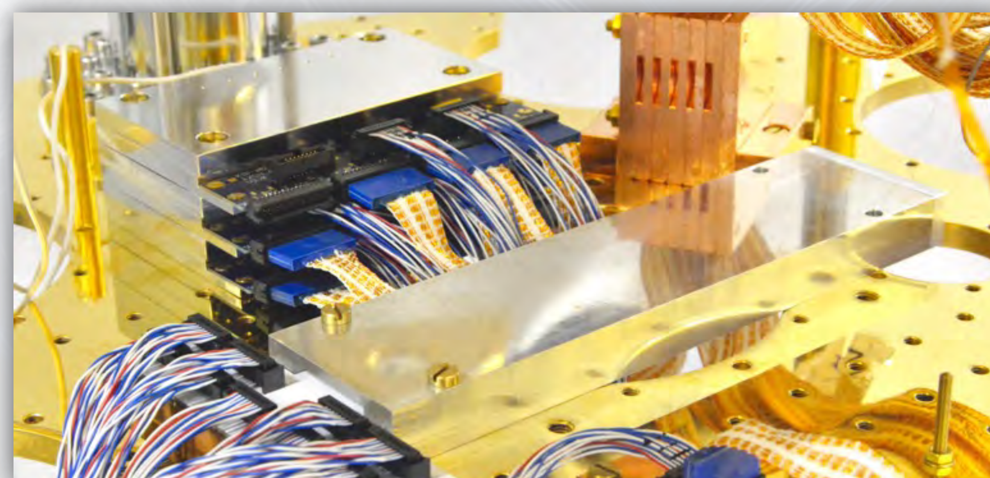
Cryogenic Platform For ECHo



installation of two cryogenic microwave setups



dc wiring and SQUID array installation

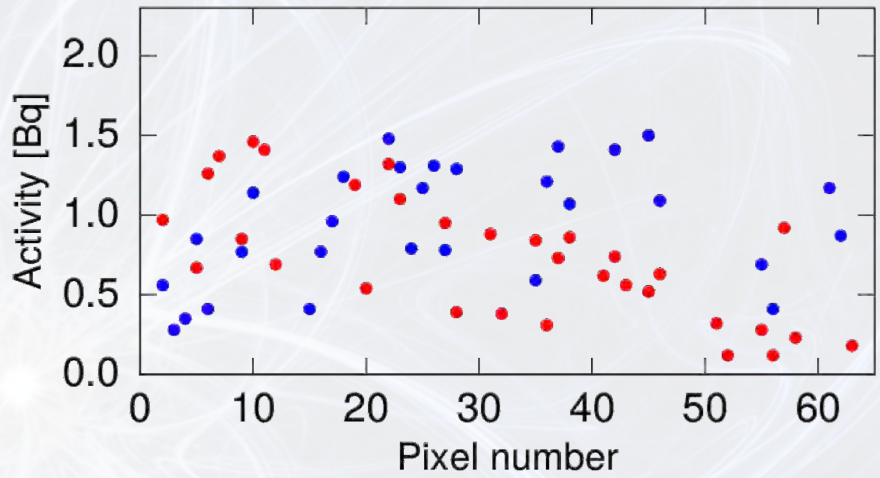


ultra-high sensitivity and ultra-fast *T*-stabilization system

On-going ECHo-1K Run

Set-up 1
Ho in Au 28 pixels
average activity = 0.94 Bq
total activity of 28.1 Bq

Set-up 2
Ho in Ag 35 pixels
average activity = 0.71 Bq
total activity of 25.9 Bq



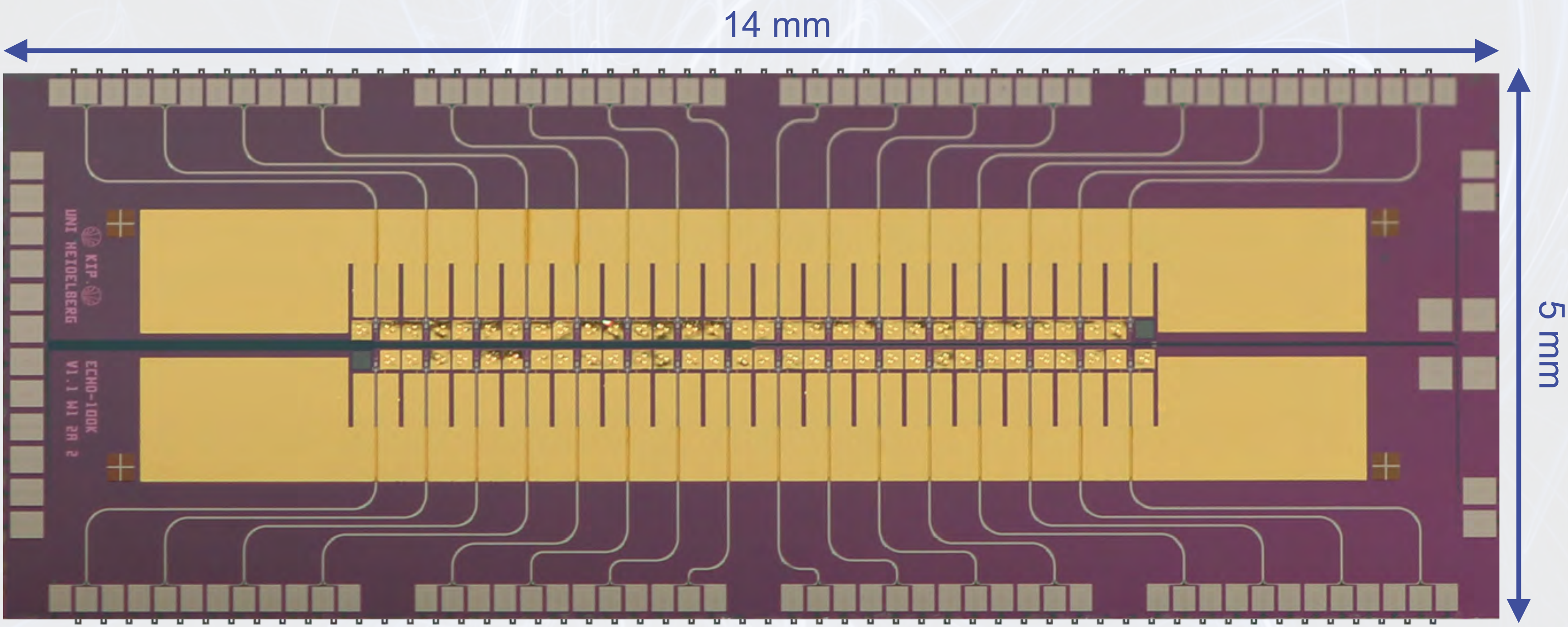
22 days of continuous acquisition to reach 10^8 events

Limit on m_ν: < 20 eV/c^2

Detector set-up

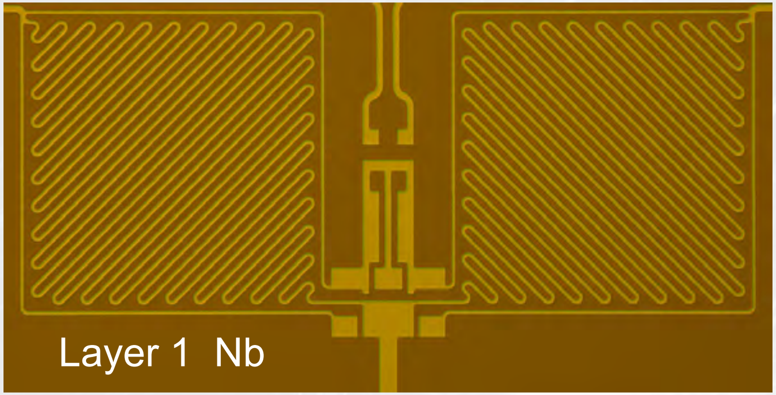
ECHo-100k Chip

30 gradiometric channels → 60 MMC pixels + 2 channels for temperature monitoring

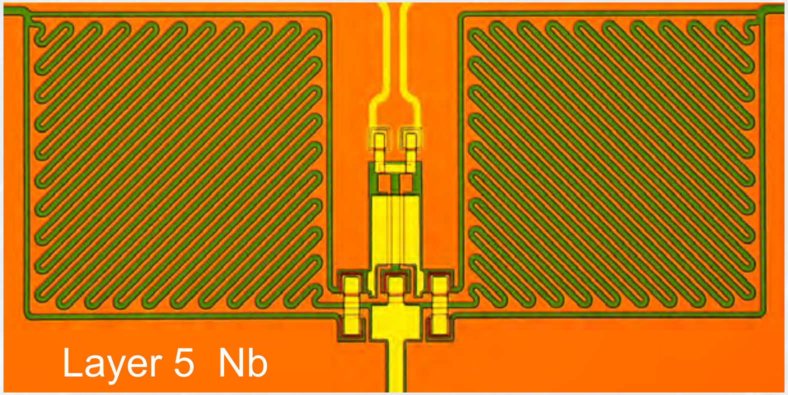


- optimized for higher implantation efficiency
- optimized for better energy resolution
- designed for coupling to multiplexer and parallel readout

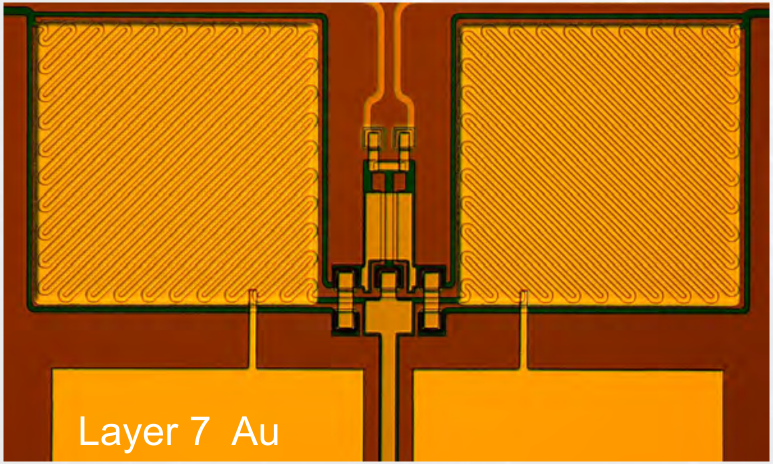
ECHo-100k Chip



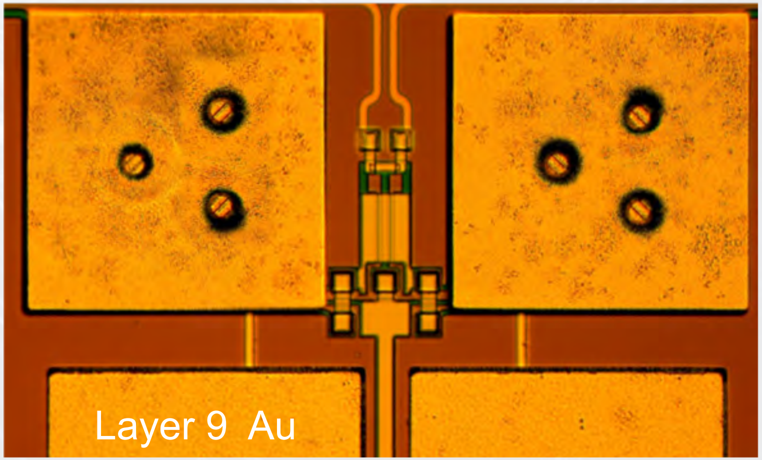
superconducting meander



superconducting switch and bridges

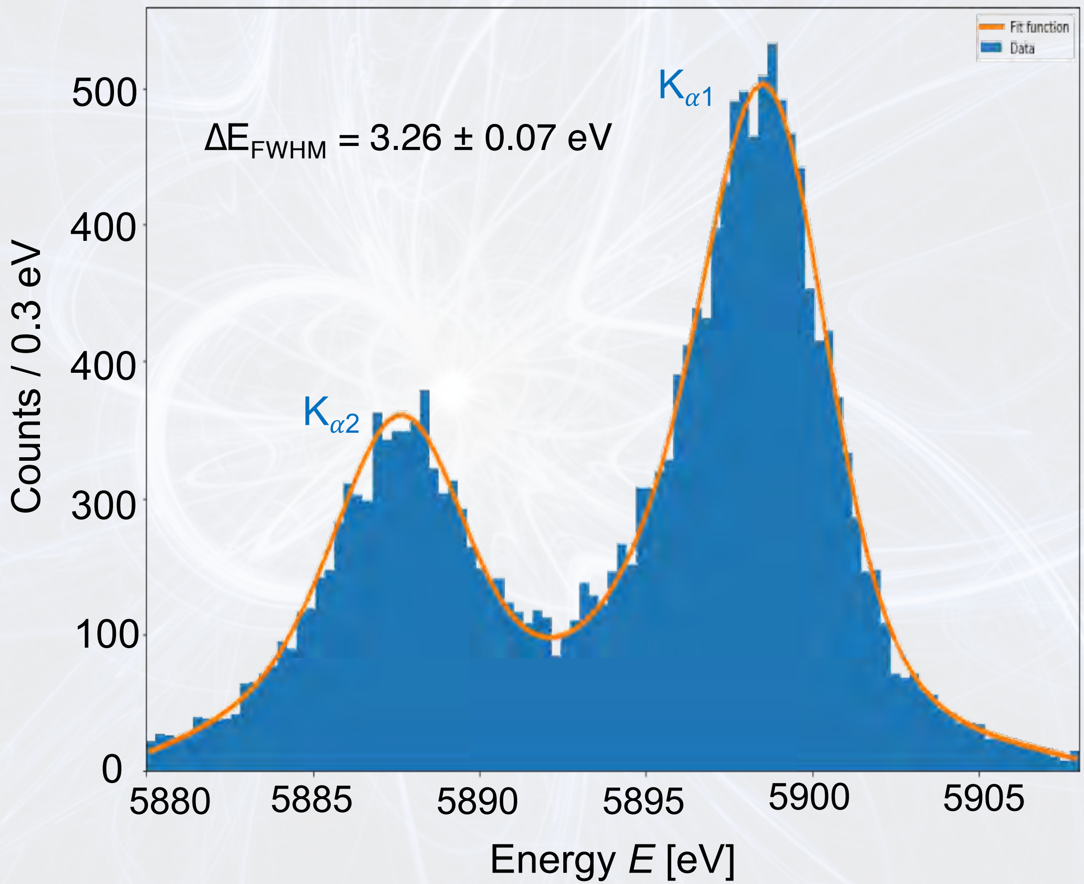


thermalization pads



absorbers

ECHo-100k Characterisation



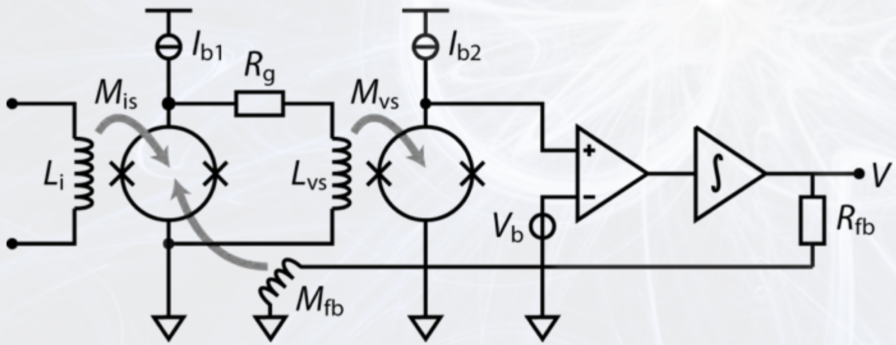
Requirements for ECHo: Scalability

ECHo-1k: ~ 50 detectors → ECHo-100k: > 5.000 detectors → ...

how to read out a large number of detectors ?

single channel readout:

10 wires, 2 SQUIDs, 1 electronics



number of wires
parasitic heat load
costs
complexity
} $\sim N$

multiplexed readout:

~ 1000 detectors per readout cannel

possible schemes: FDM, CDM, TDM, …

↓

readout techology of ECHo

↓

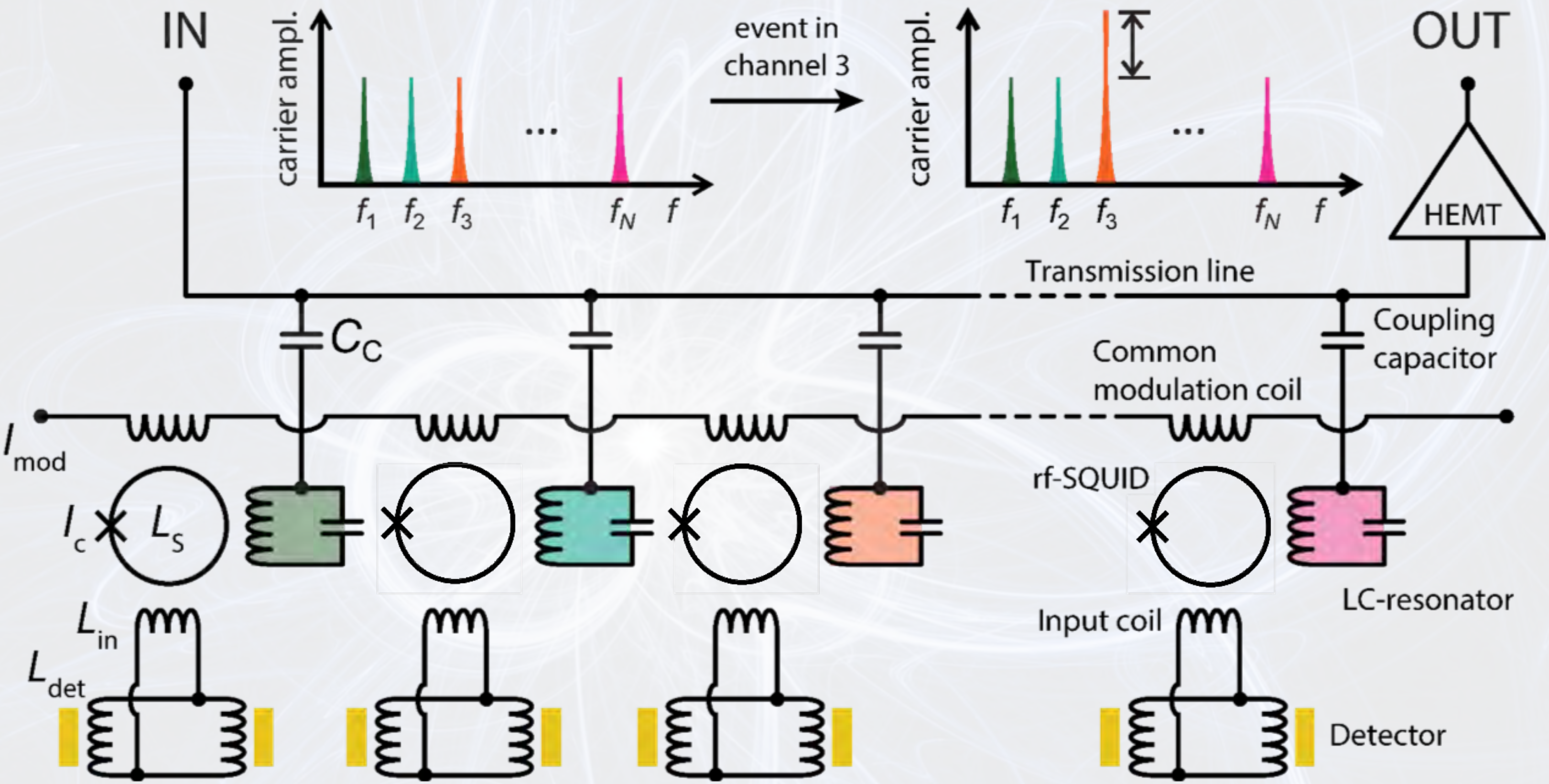
scalability

Frequency Division Multiplexing

idea: detector signal is modulated on a GHz carrier

- different carrier frequencies
- non-linear element for mixing

Microwave SQUID Multiplexer (µMUX)

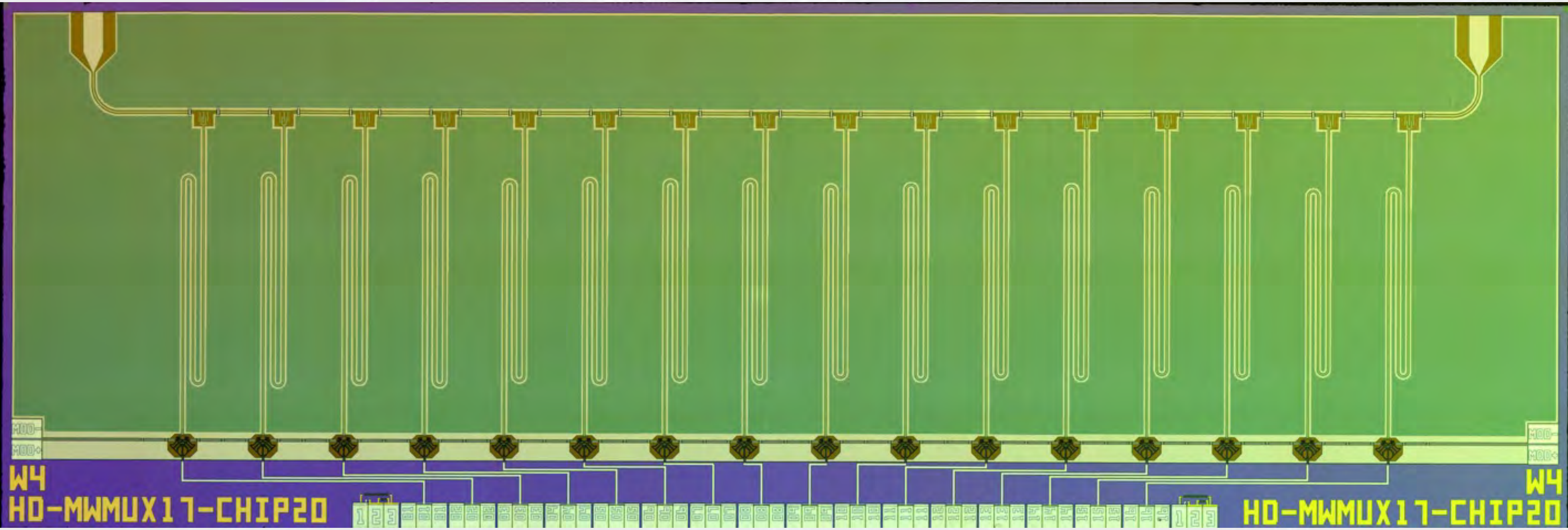


array readout using only one HEMT amplifier and two coaxes

K. Irwin and K. Lehnert, Appl. Phys. Lett. **85**, 2107-9 (2004)
J.A.B. Mates *et al*., Appl. Phys. Lett. **92**, 023514 (2008)
S. Kempf, L. Gastaldo, A. Fleischmann, C.E., J. Low. Temp. Phys. **175,** 850 (2014)
M. Wegner, *et al*., J. Low. Temp. Phys. **193,** 462 (2018)

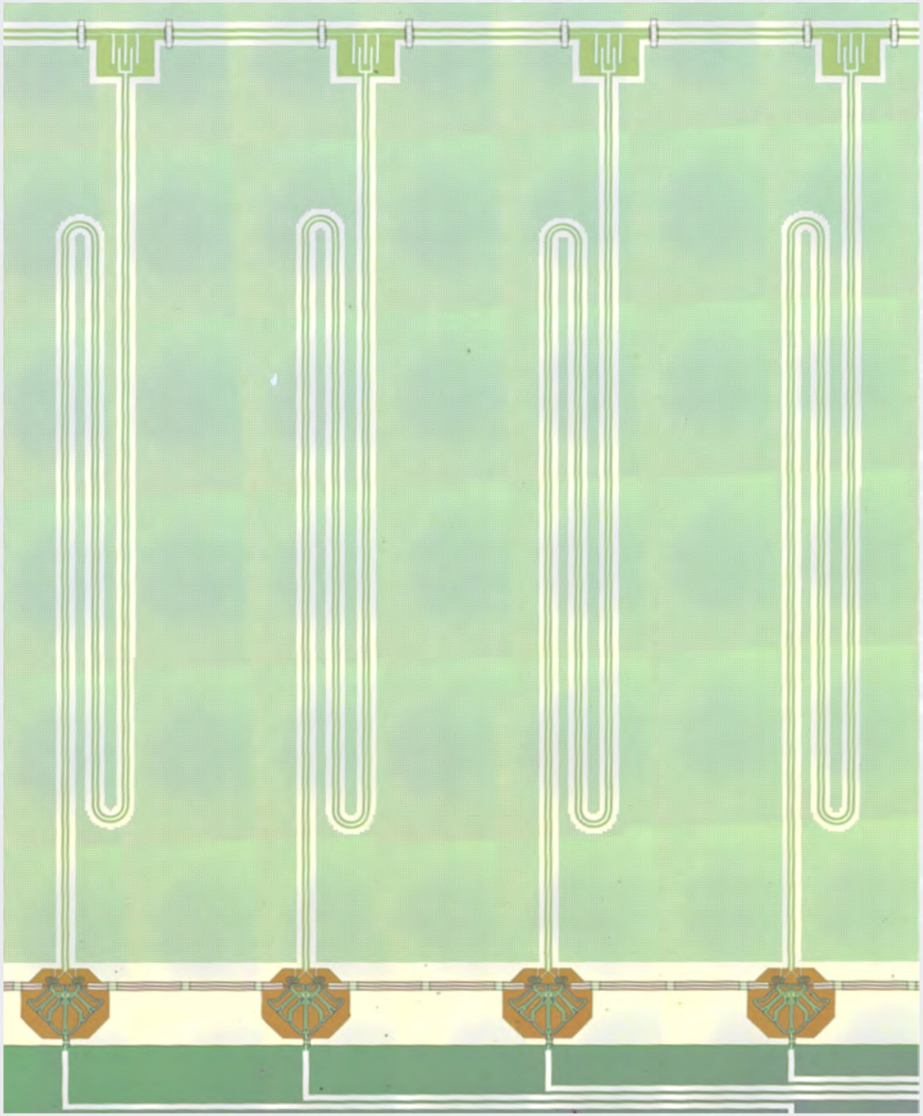
2nd Generation Multiplexer µMUX02

- optimized rf-SQUID design
- Josephson-Contacts with high qualitiy factor
- optimized resonators
- first tests with SDR-System

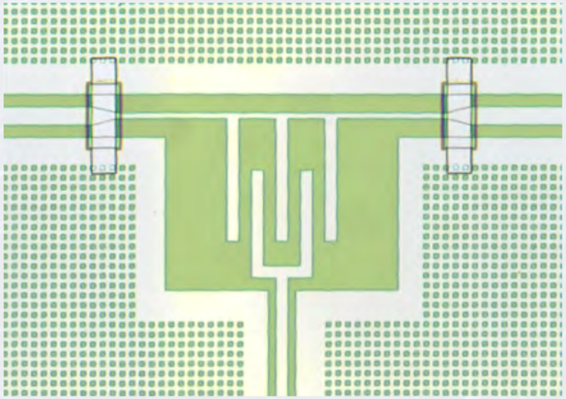


S. Kempf, *et. al.*, to be published

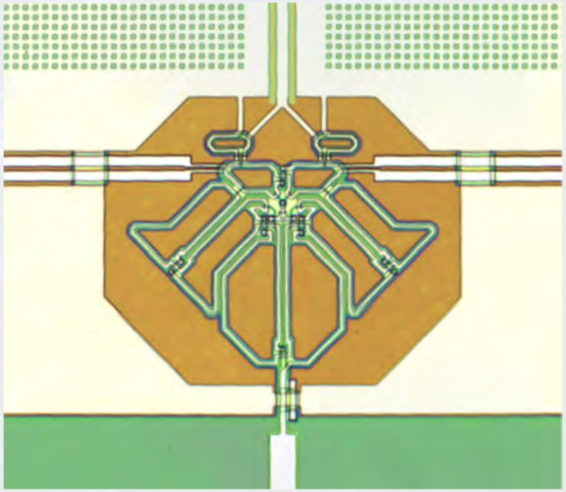
2nd Generation Multiplexer µMUX02



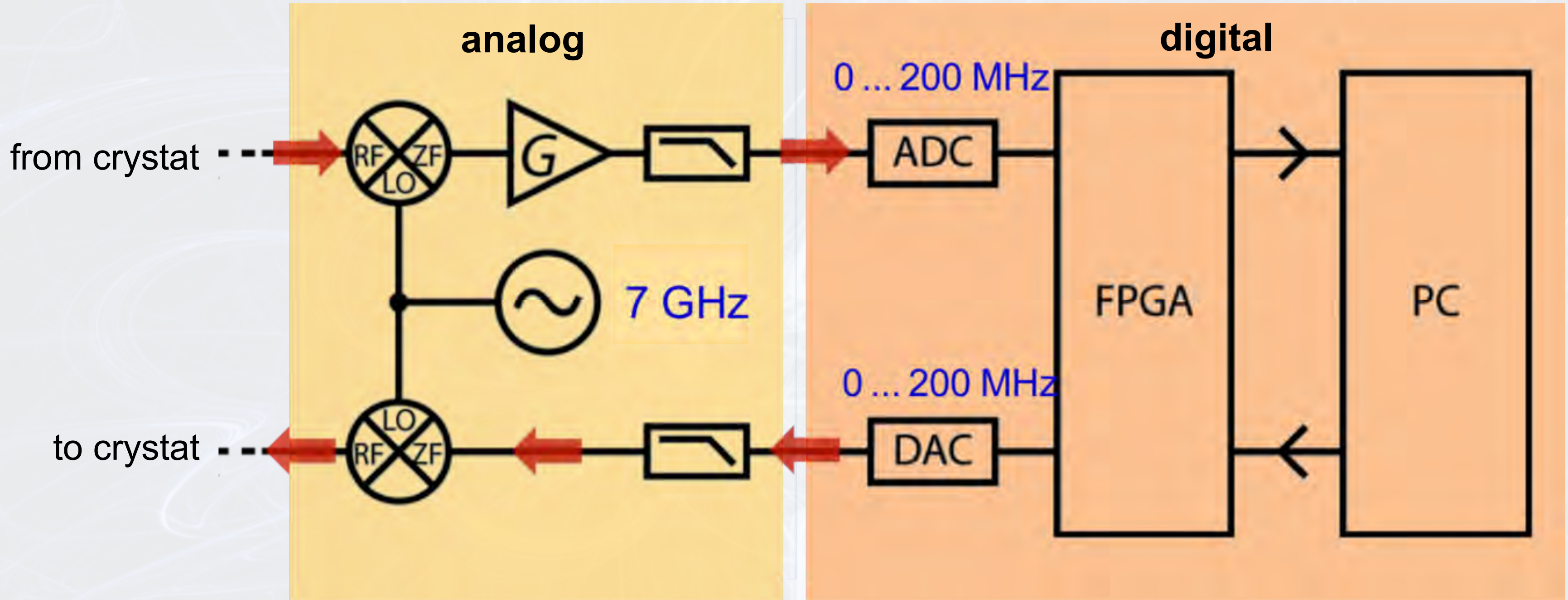
new coupling design



new rf SQUID design



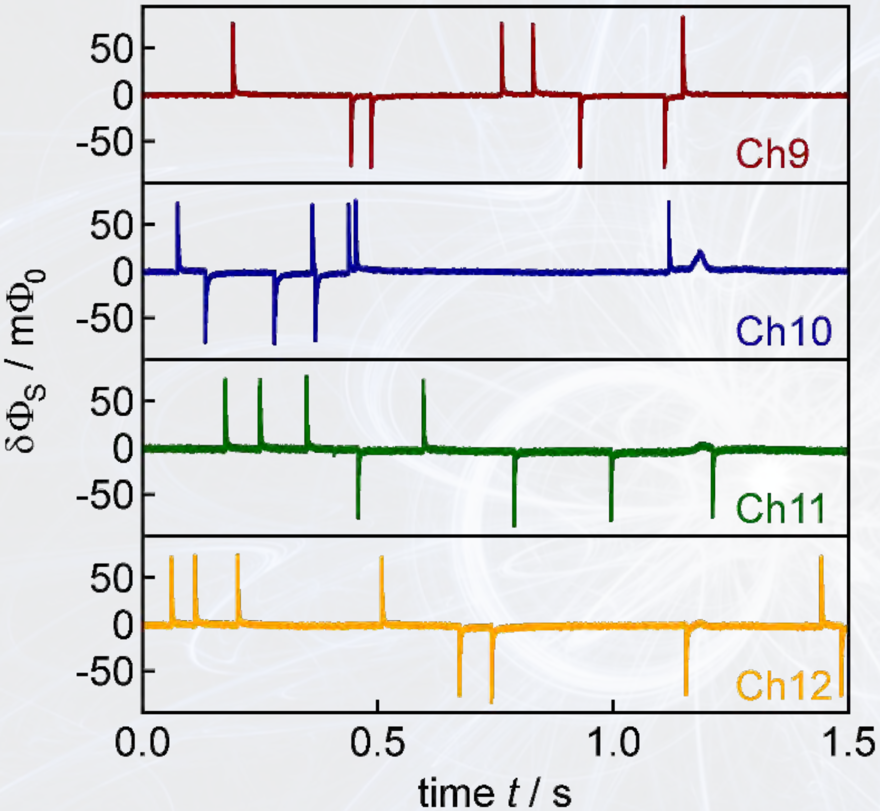
S. Kempf, *et. al.*, to be published



Joint development with
M. Weber, O. Sander, (KIT)
J. Becker (KIT)

O. Sander *et al.*, IEEE Trans. Nucl. Sci. **66**, 7 (2019)

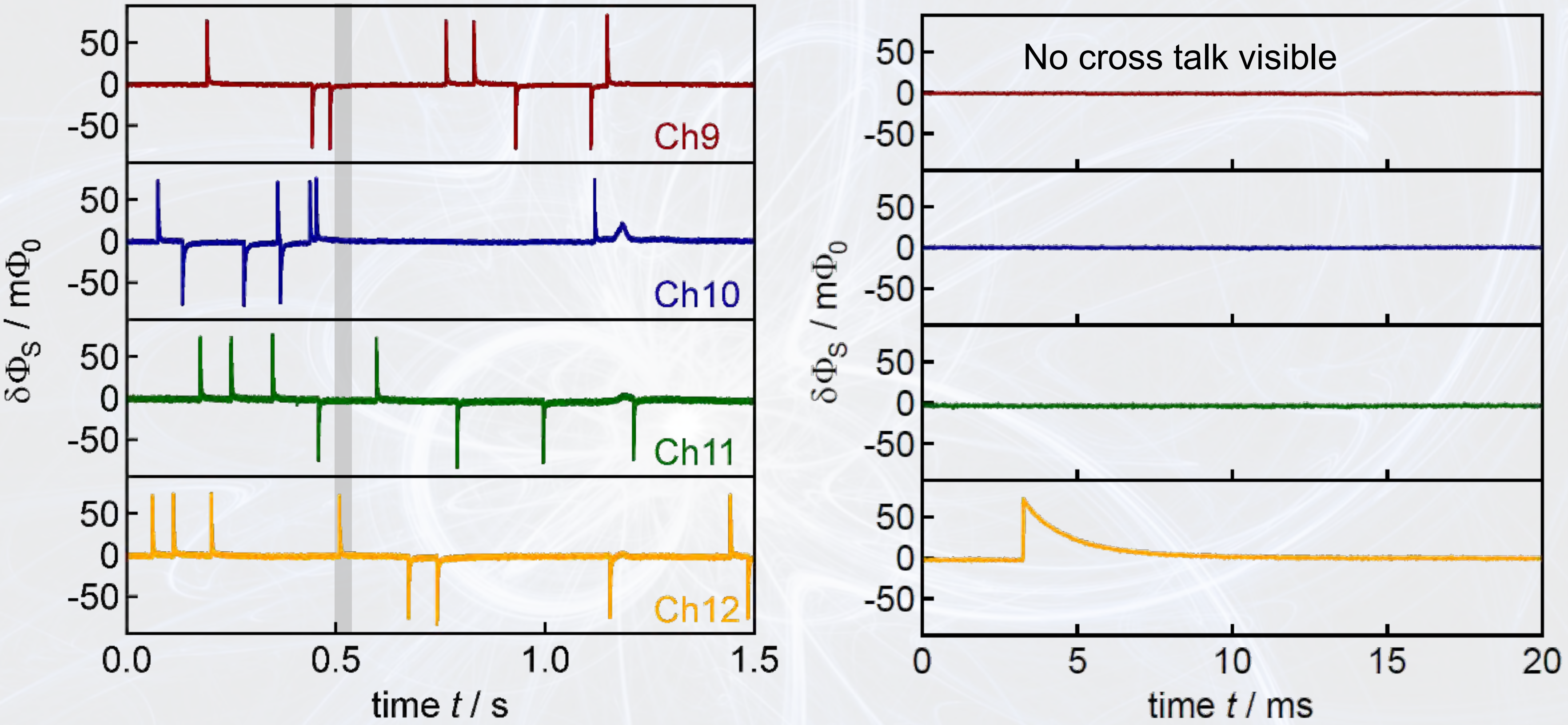
First Test of µMUX02 with SDR



► parallel readout of 8 Pixels

N. Karcher *et al.*, JLTP (2020)

First Test of µMUX02 with SDR

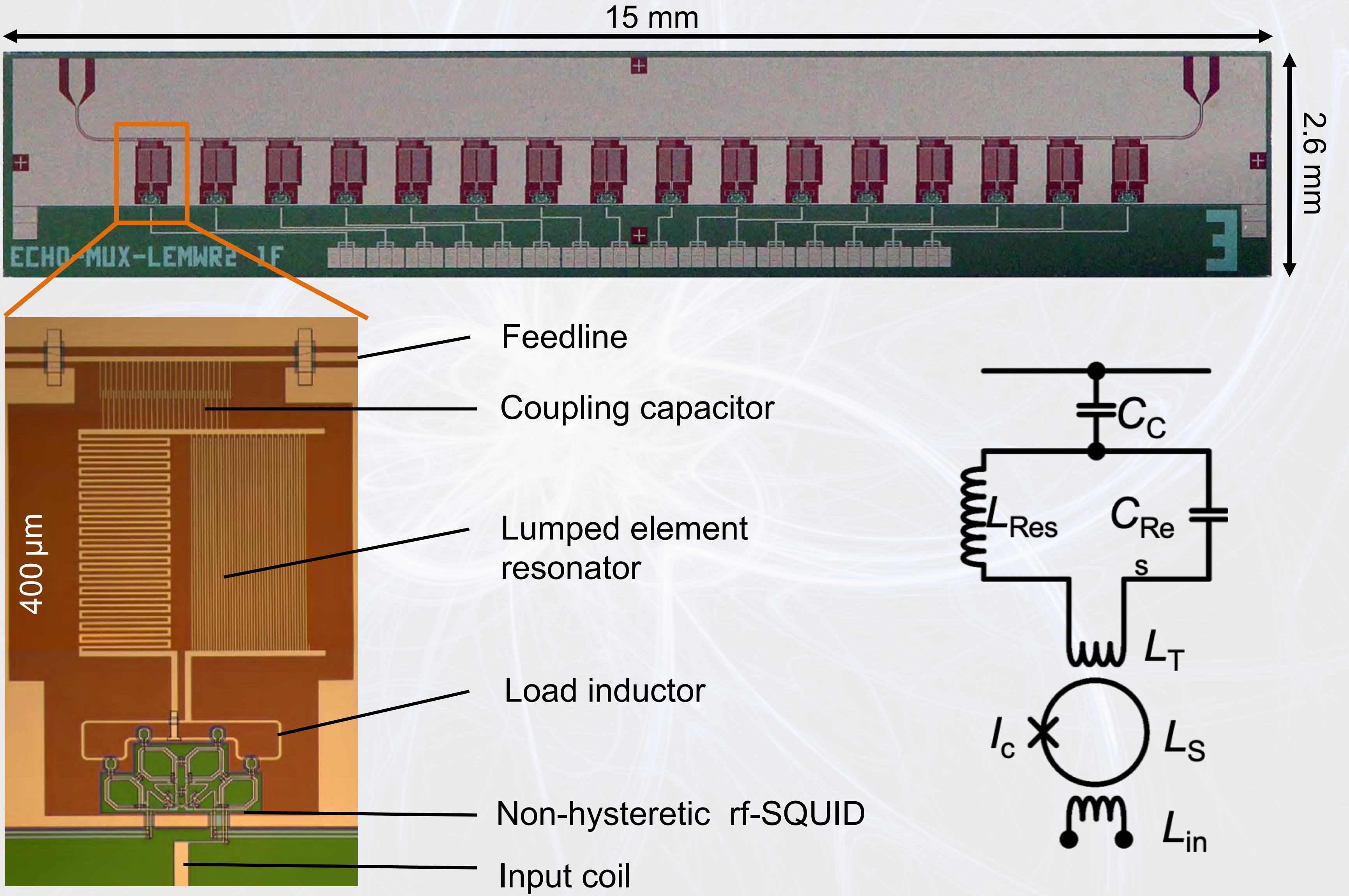


► parallel readout of 8 Pixels

► no visible cross talk

N. Karcher *et al.*, JLTP (2020)

µMUX03 LEMUX Design

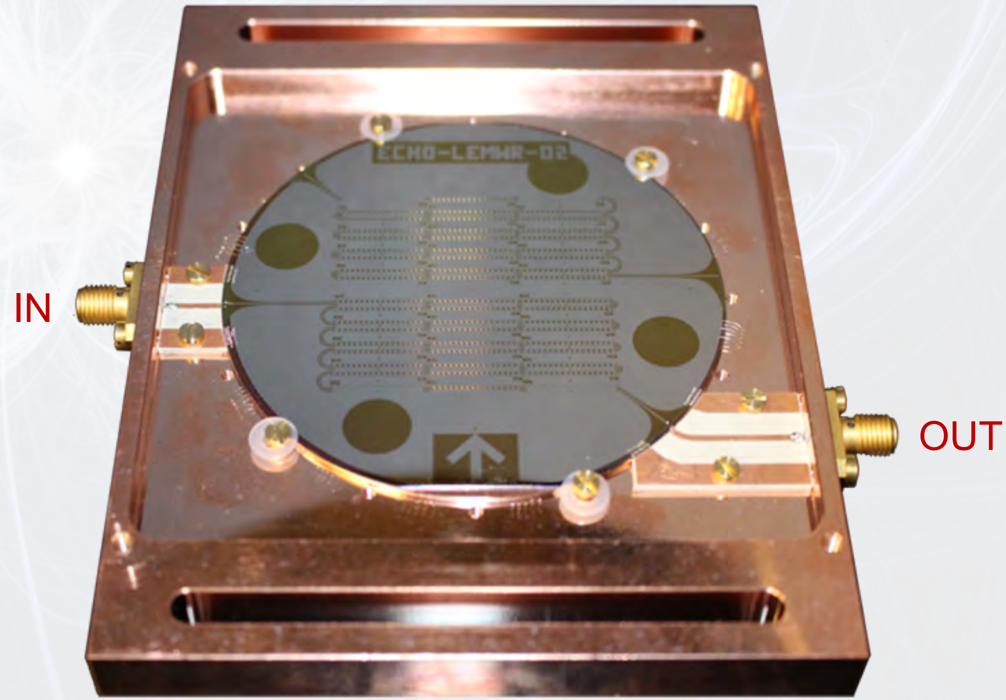


µMUX03 LEMUX Module

ECHo-100k: 12,000 MMC pixels → 400 channels, 15 MUX devices

Resonance frequency spacing: 10 MHz

System bandwidth: 4 – 8 GHz



Conclusions

ECHo is well underway … so far no show stoppers discovered

A new limit is expected this year

ECHo-100k is being prepared and will be commissioned 2020

Thank you!