New low temperature and superconductivity technology challenges

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Sensor technologies for LTD

Dark Matter
ββ0ν
γ spect. / n spect.

Scint./Cherenkov light detectors

Coherent ν scatt.

Low *E* γ spect.

neutrino mass
X-ray spect.
α spect.

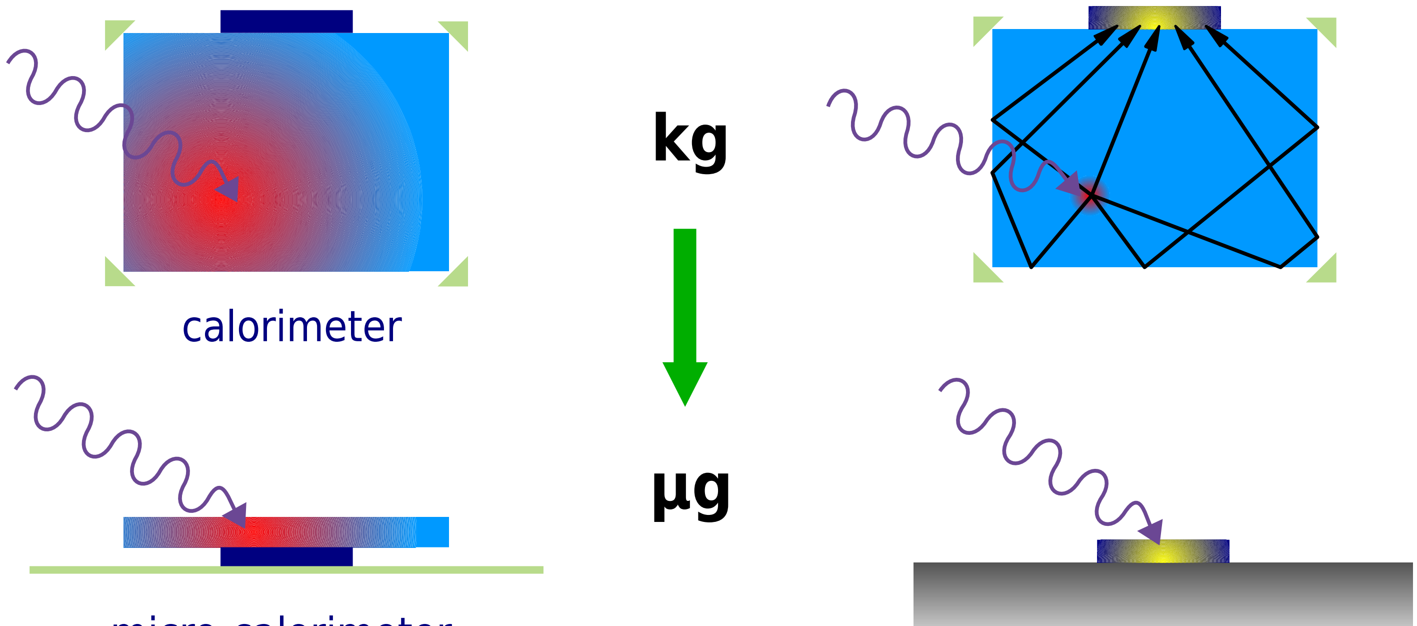
single photon

mm → THz bolometry/ radiometry

...

quasi-equilibrium LTD
thermal phonon sensors

out-of-equilibrium LTD
athermal phonon sensors



micro-calorimeter

$E \rightarrow \Delta T \approx E/C \rightarrow \Delta X(T)$

e.g: $R=R(T)$, $M=M(T)$

thermodinamic limit $\sigma_E^2 \approx k_B T^2 C$

Cooper pair breaking in S/C

$E \rightarrow \Delta n_{qp} \approx E/\Delta \rightarrow \Delta X(n_{qp})$

statistical limit $\sigma_E^2 \approx F E \Delta / \eta$

- high resolution ΔE / low E_{thres}
- fast τ_{rise} (→ BW)
- multiplexability → large number of channels
- material choice flexibility

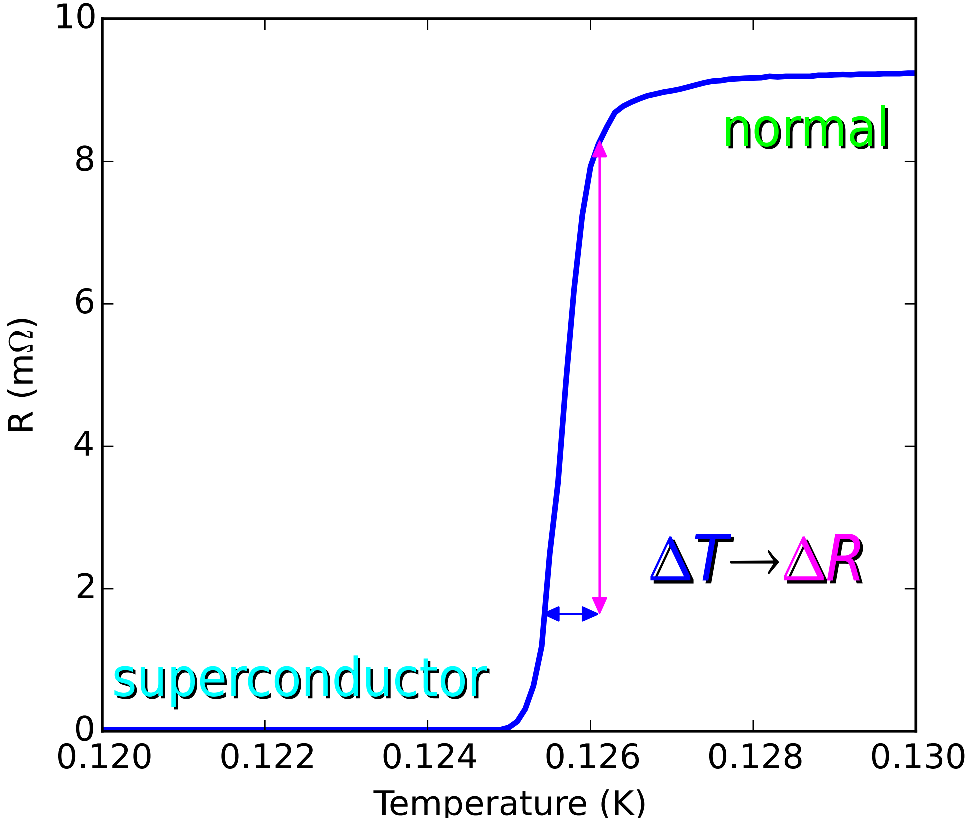
Outline

Low Temperature Detector (LTD) sensor technologies

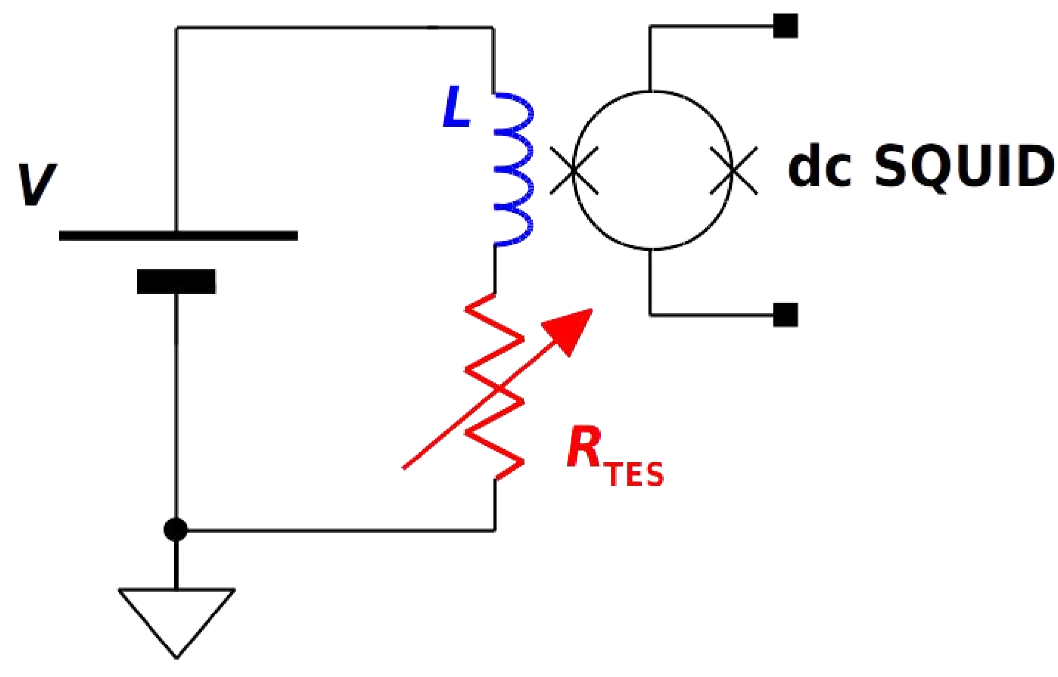
- Transition Edge Sensors (**TES**)
  - TES microcalorimeters
  - HOLMES TES
- Magnetic Metallic Calorimeters (**MMC**)
  - ECHo MMC
- Kinetic Inductance Detectors (**KID**)
  - KID for athermal phonon detection
  - CALDER KID
  - thermal KID
- KID microwave **multiplexing**
  - detector microwave multiplexing by upconversion

Superconducting transition edge sensors (TES)

- **superconductor thin films** used inside the phase transition at T_c
  - pure superconductors: Ir (T_c= 112 mK), W (T_c= 15 mK), ...
  - metal-superconductor bilayers ⇒ tunable T_c (20÷200 mK) : Mo/Cu, Ti/Au, Ir/Au, ...
- high sensitivity (A≈100) ⇒ **high energy resolution**
  - as **thermal sensors** → $\sigma_E^2 \approx \xi^2 k_B T^2 C$
  - also as **athermal sensors**
- high electron-phonon coupling ⇒ **high intrinsic speed**
- low impedance ⇒ SQUID read-out ⇒ **multiplexing for large arrays**

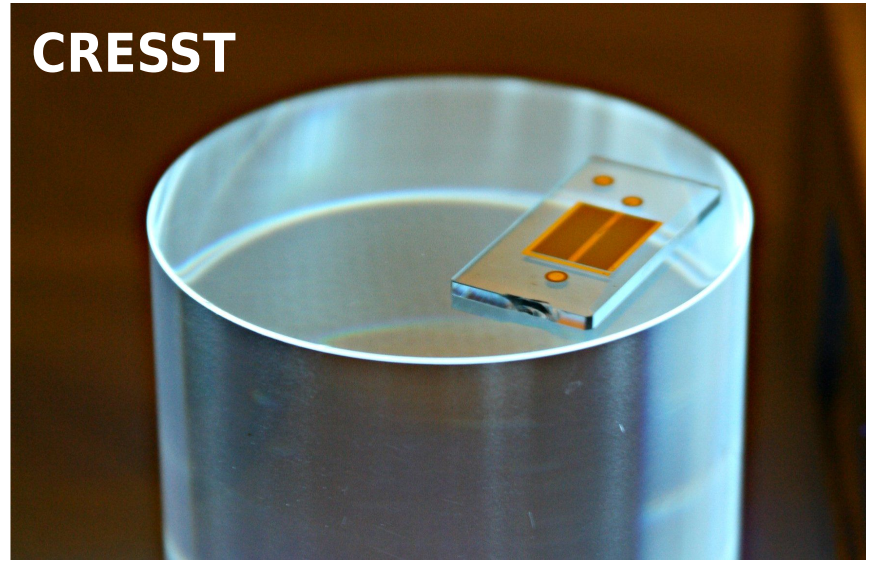


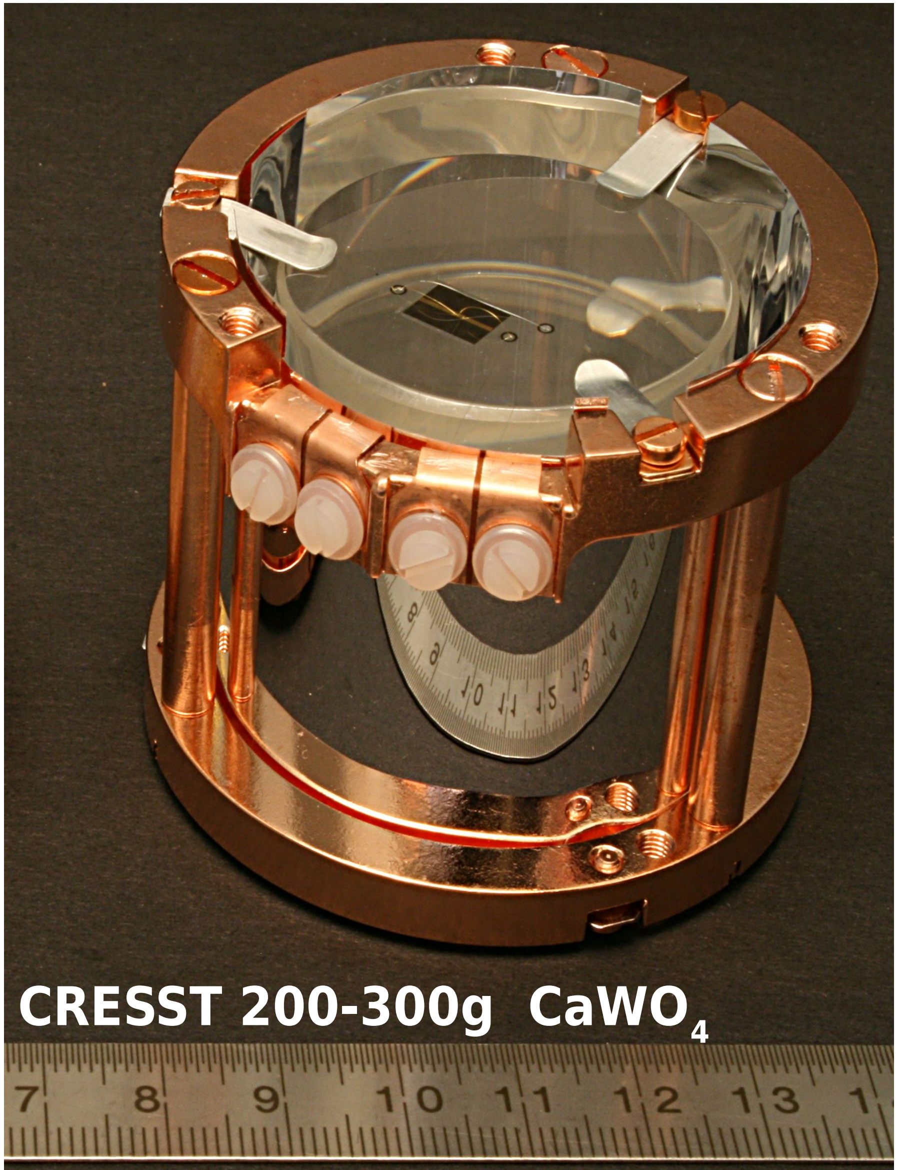
TES read-out: costant voltage bias

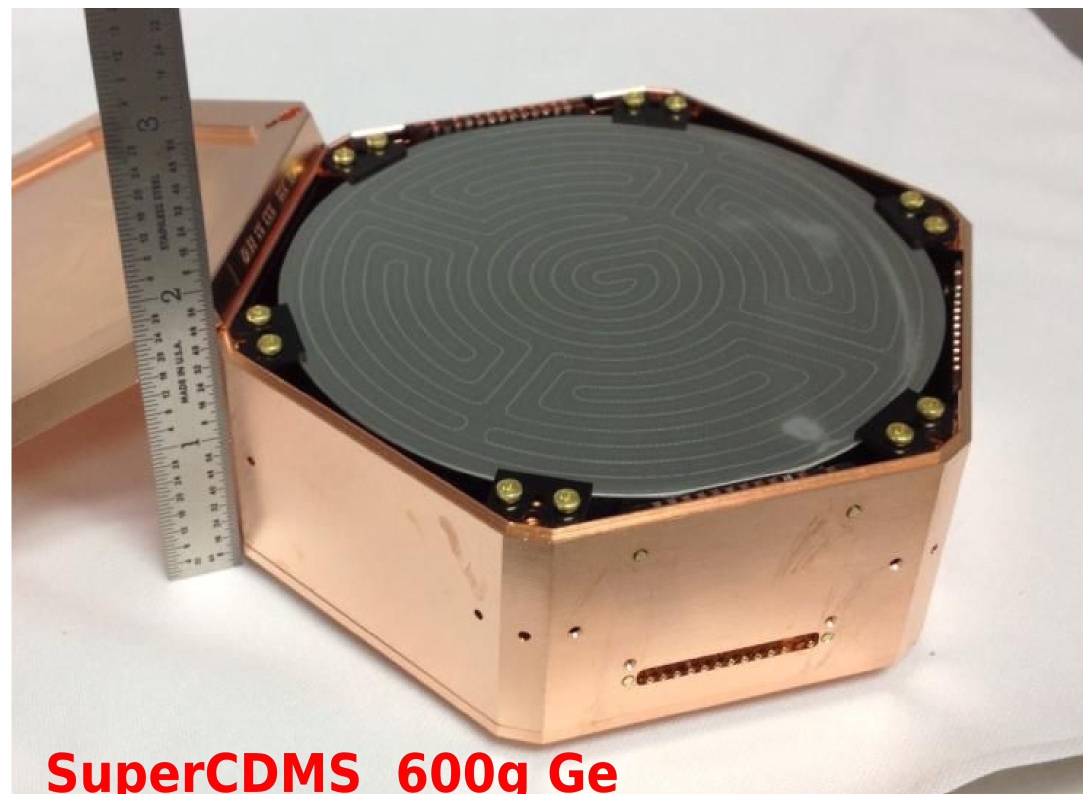


TES for massive LTDs: direct Dark Matter searches

- thin film deposition
- photolithographic patterning

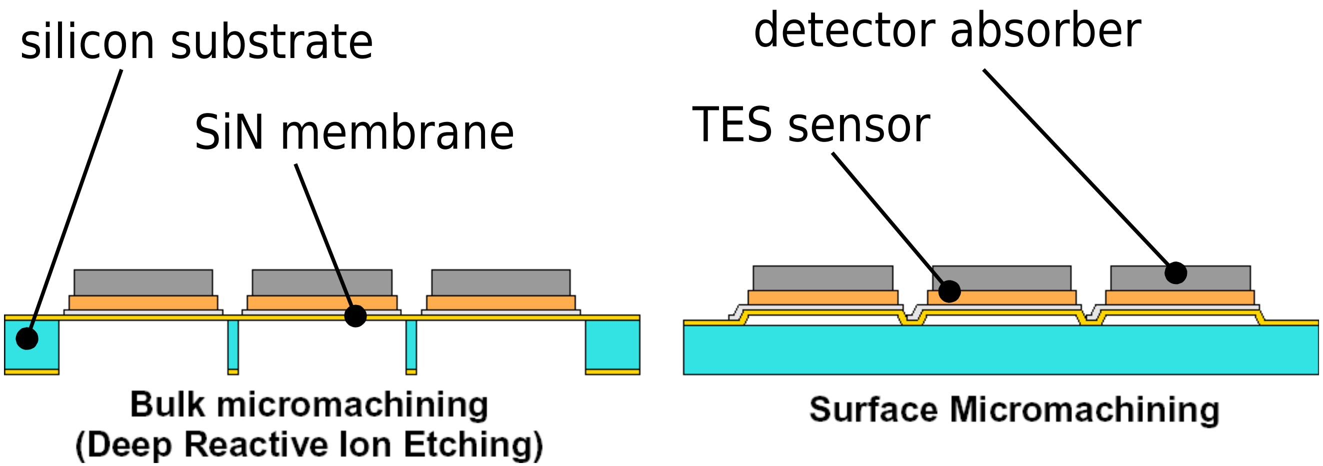


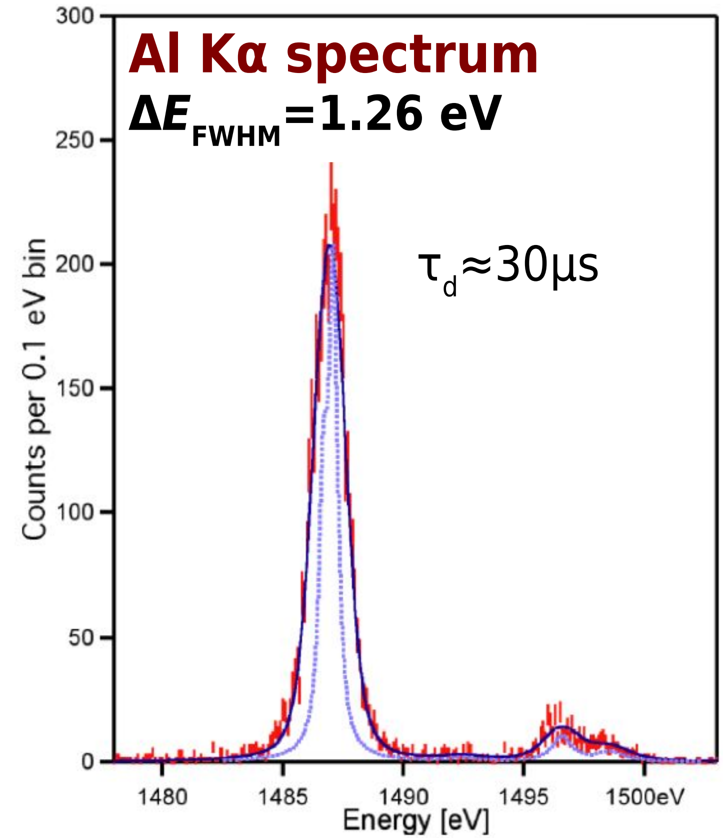


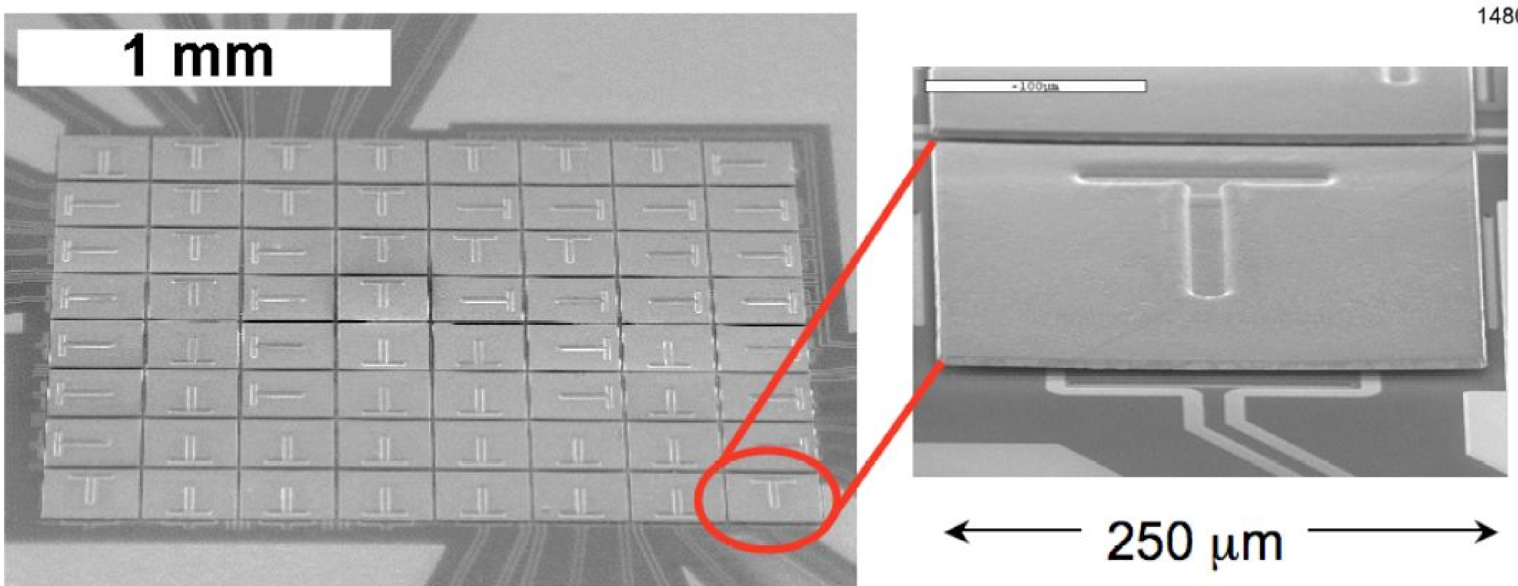


TES microcalorimeters / 1

- detectors for **α, β, low *E* γ, and X-ray** science
  - astrophysics, material science, nuclear physics, ...



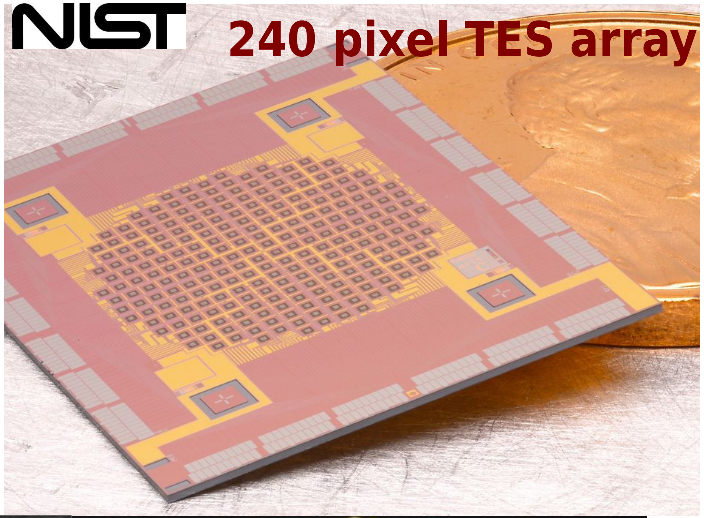


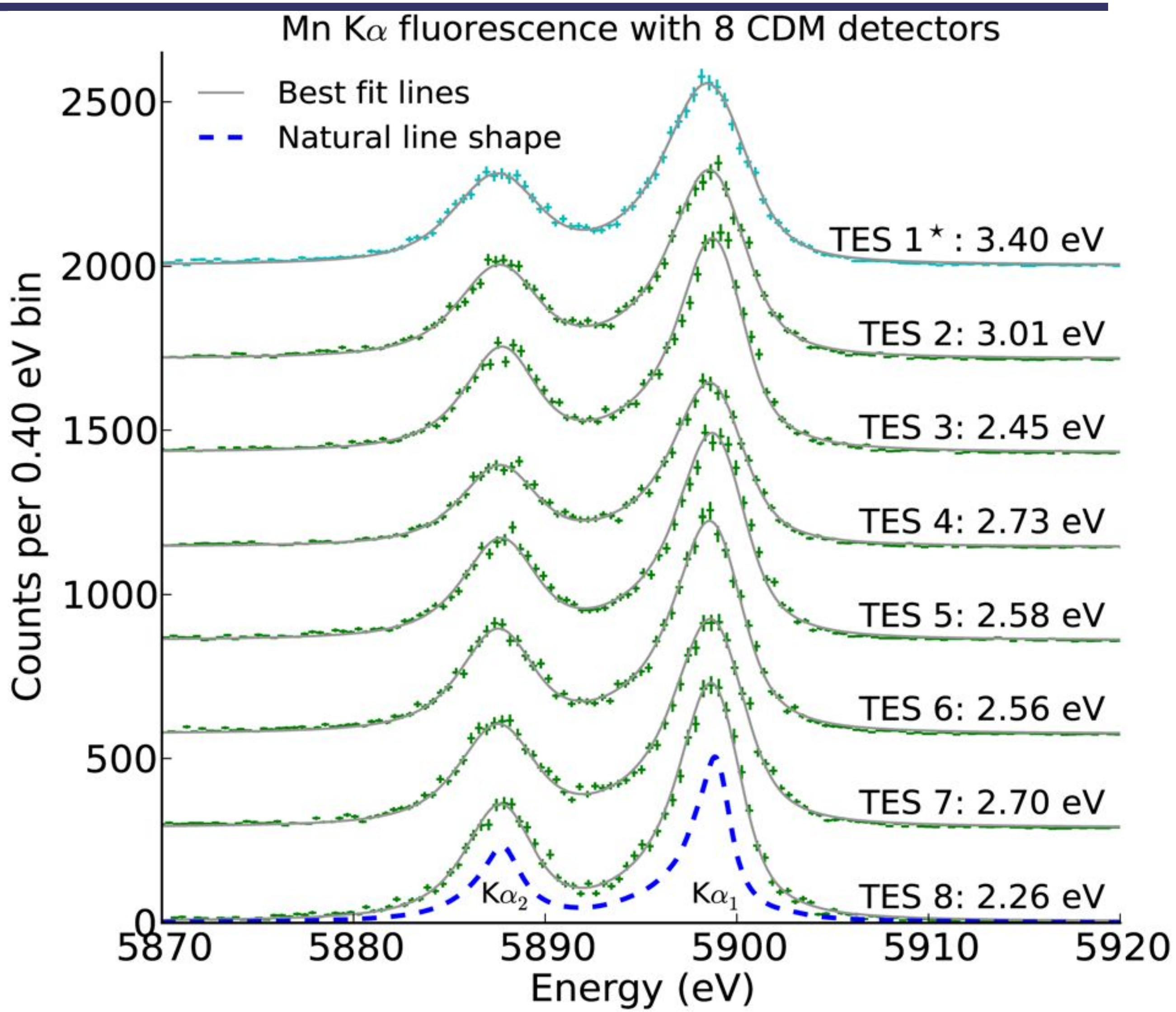


TES microcalorimeters / 2

X-ray spectroscopy

XES, EXAFS, XANES, RSXS ...
time resolved X-ray spectroscopy

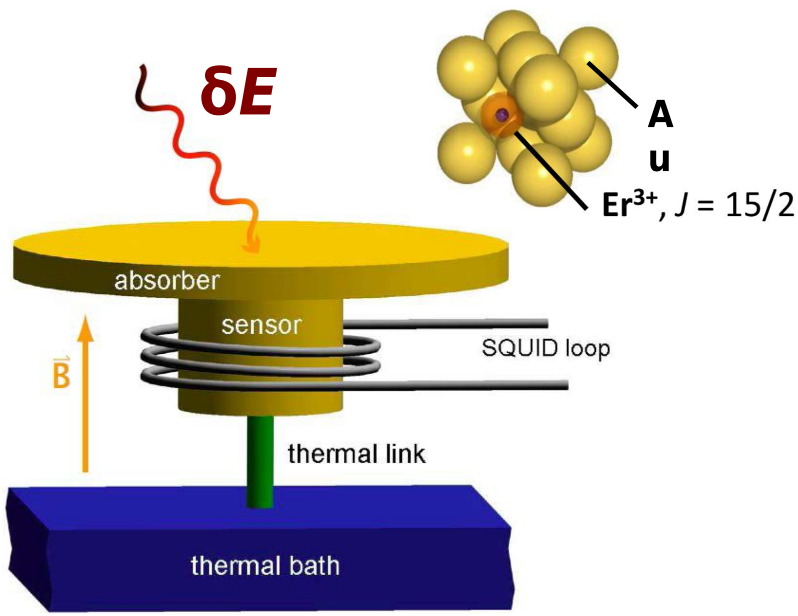




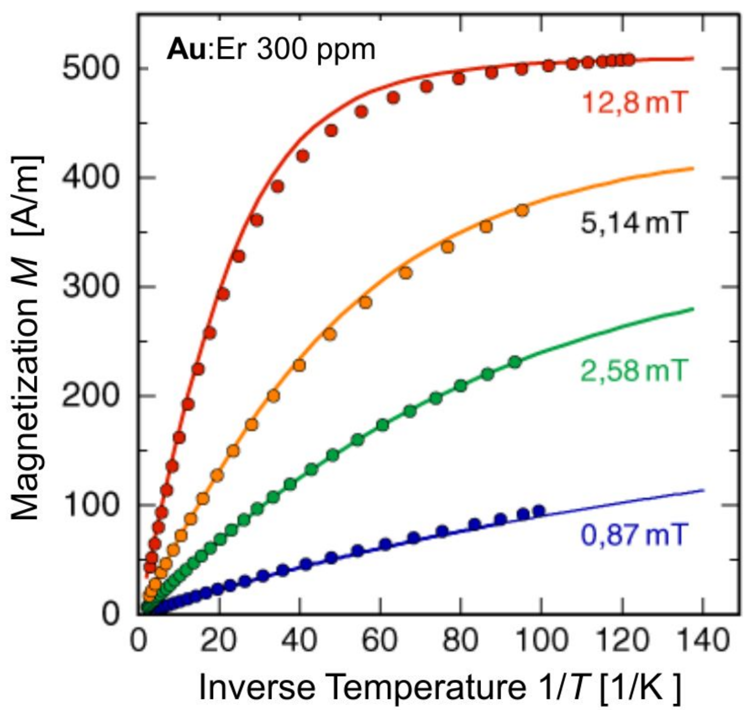
- 240 pixels, 23.4 mm^2 active area, 30% fill factor
- Code Division SQUID multiplexing
- $\Delta E \approx 2.5$ eV at 6 keV
- 80% Quantum Efficiency at 6 keV

J. Ullom et al. SUPERCONDUCTOR SCIENCE & TECHNOLOGY, 28 (2015) 084003

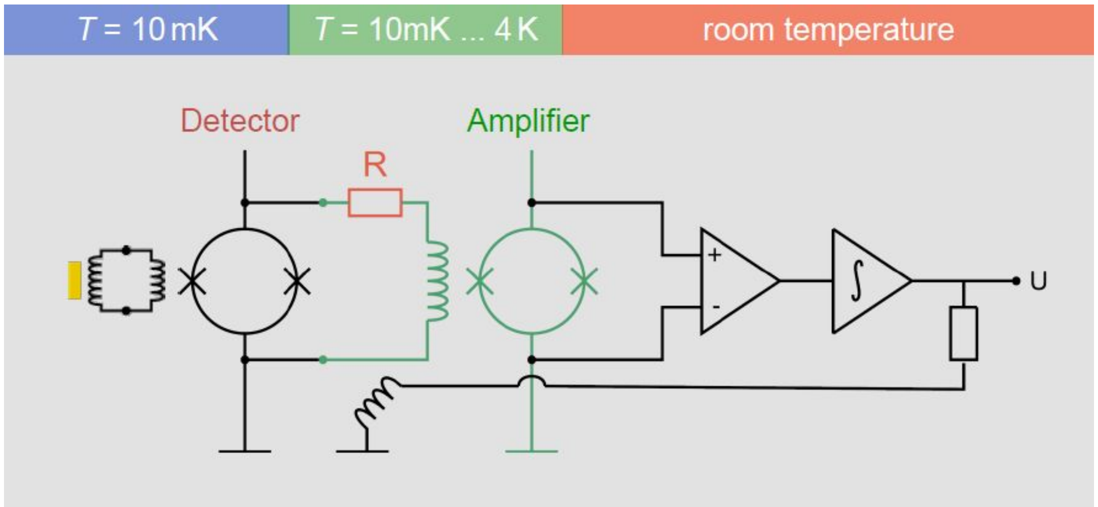
Metallic Magnetic Calorimeters (MMC)



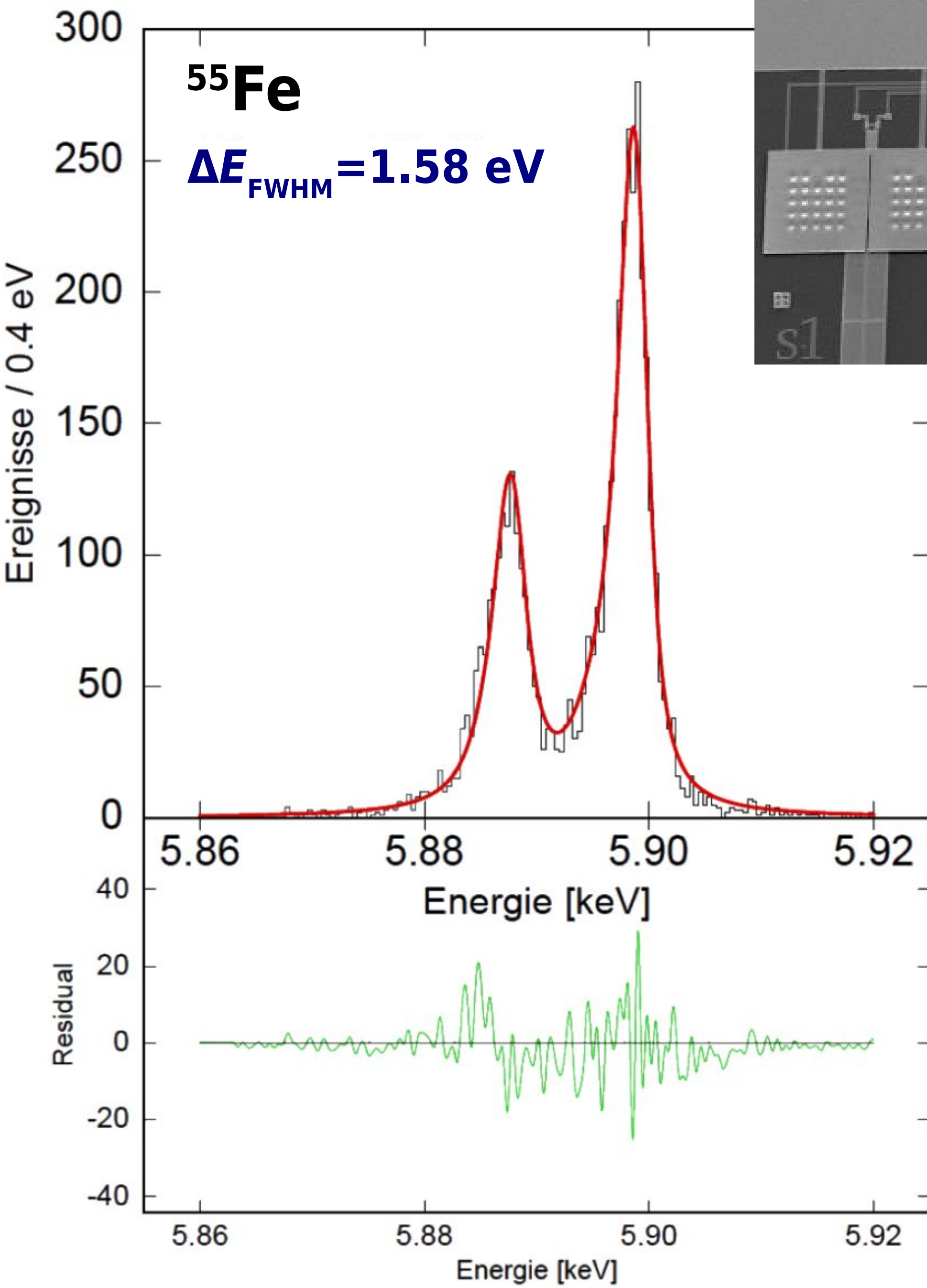
$\delta E \rightarrow \delta M \rightarrow \delta \Phi$

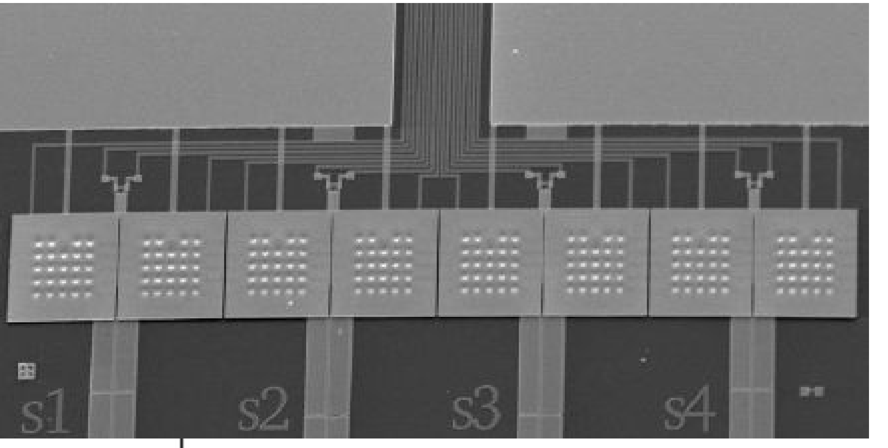


- paramagnetic temperature sensor
  - **Au:Er**, Ag:Er, PbTe:Er, Dy:W, W:Fe ...
- **dc-SQUID read-out**
  - high energy resolution with metallic absorbers
  - **fast rise time (≈100ns)**
- **high *C***
  - **massive absorbers**
  - high linearity
- no power dissipation in the sensor
- multiplexing by frequency up-conversion



MMC development at Heidelberg





AMORE/Lumineu (ββ0ν)

Electron capture end-point experiments

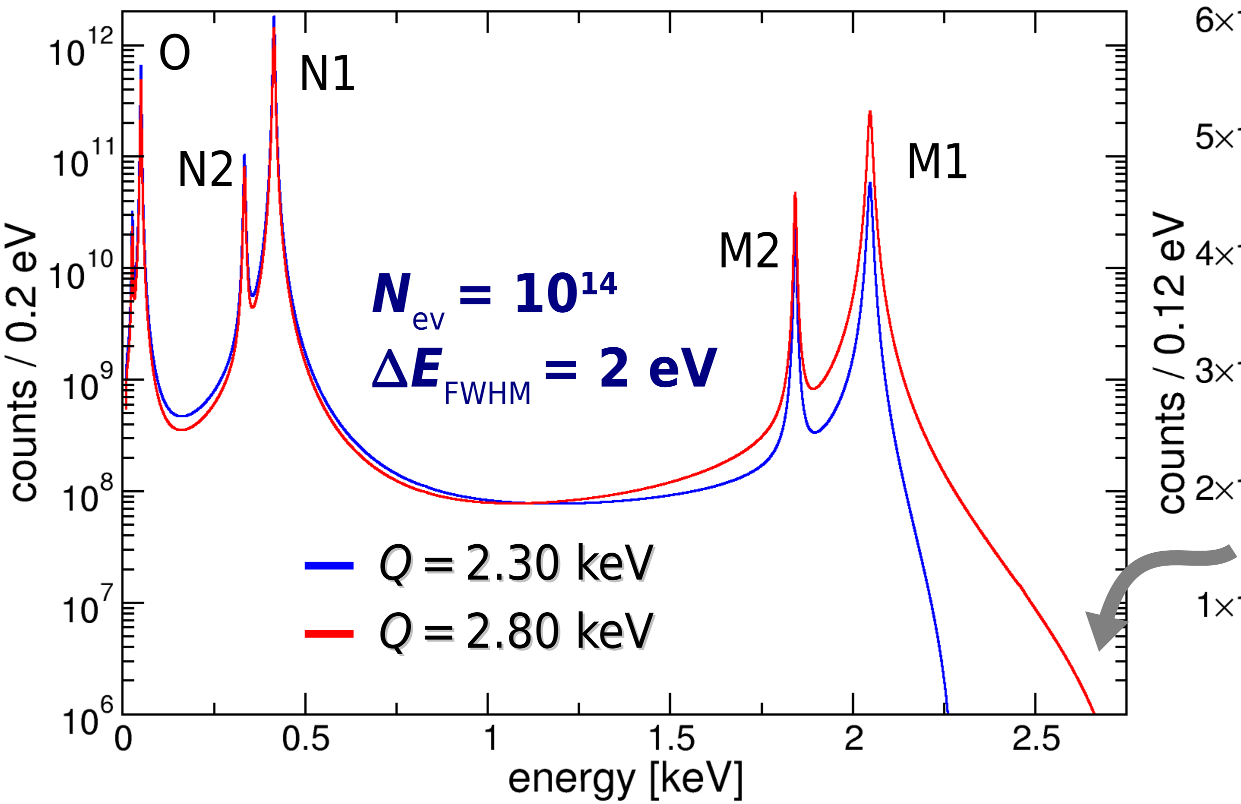
$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e$

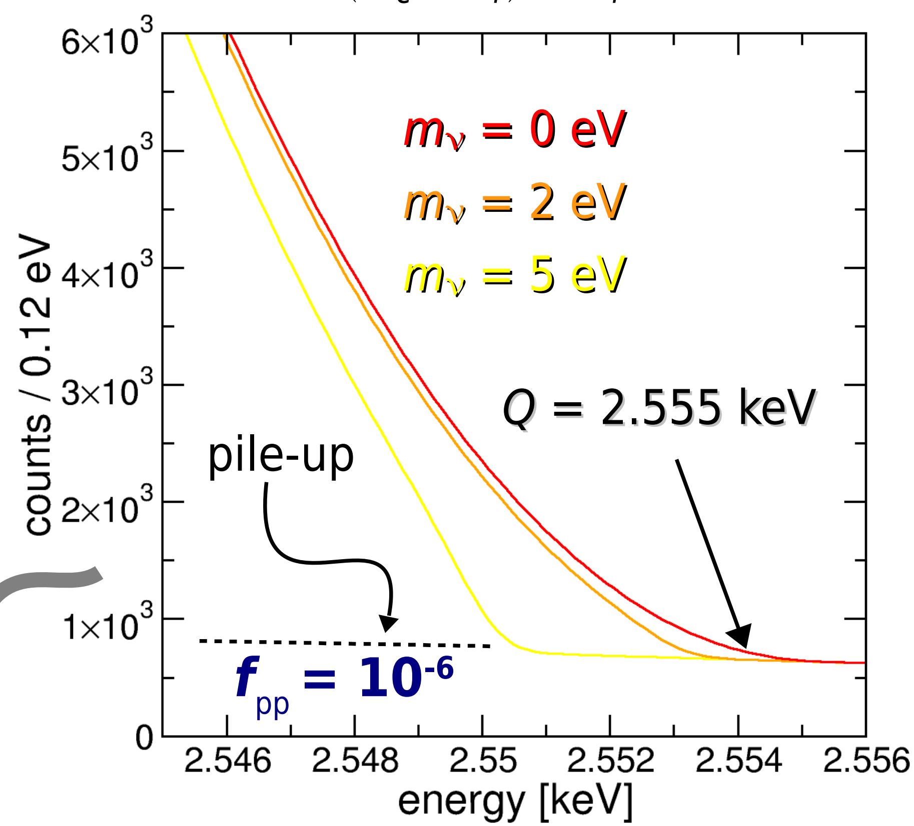
electron capture from shell ⩾ M1

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

- calorimetric measurement of Dy atomic de-excitations (mostly non-radiative)
- rate at end-point and ν mass sensitivity depend on Q
  - Past measurements: $Q = 2.3 \div 2.8$ keV. Recently measured **$Q = 2.83 \pm 0.04$ keV**
- $\tau_{1/2} \approx 4570$ years → few active nuclei are needed

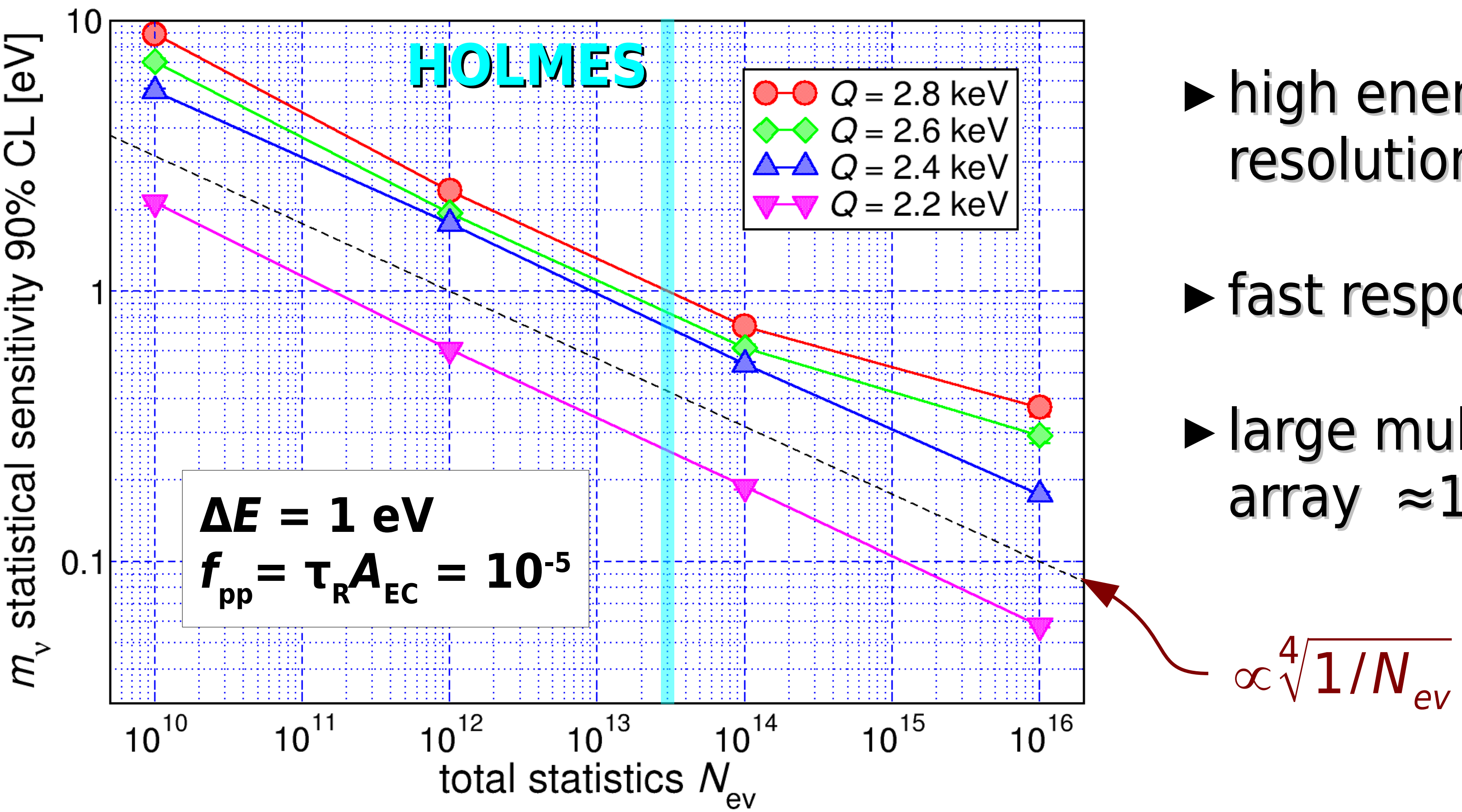
$$\frac{d\lambda_{EC}}{dE_c} = \frac{G_\beta^2}{4\pi^2}(Q-E_c)\sqrt{(Q-E_c)^2 - m_\nu^2} \times \sum_i n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi} \frac{1}{(E_c - E_i)^2 + \Gamma_i^2/4}$$





m_ν statistical sensitivity: Montecarlo simulations

- 2×10^{11} ^{163}Ho nuclei → 1 decay/s
- ^{163}Ho production: p.e. neutron irradiation of ^{162}Er enriched Er
- embed ^{163}Ho in thermal detectors for low energy X-rays spectroscopy

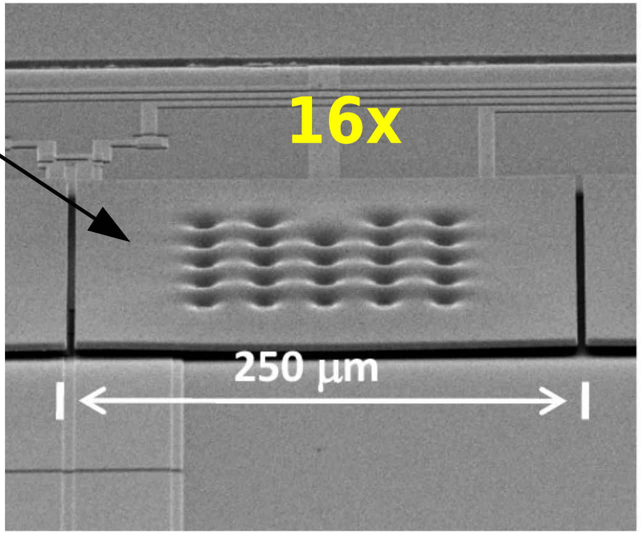


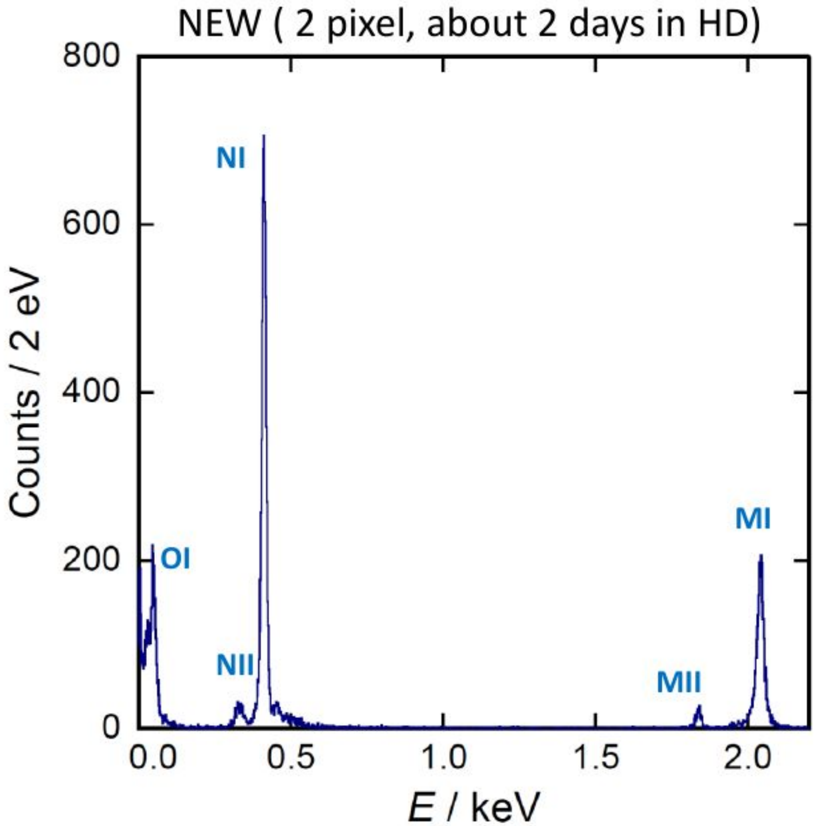
- ▸ high energy resolution ≈1eV
- ▸ fast response ≈1μs
- ▸ large multiplexable array ≈1000

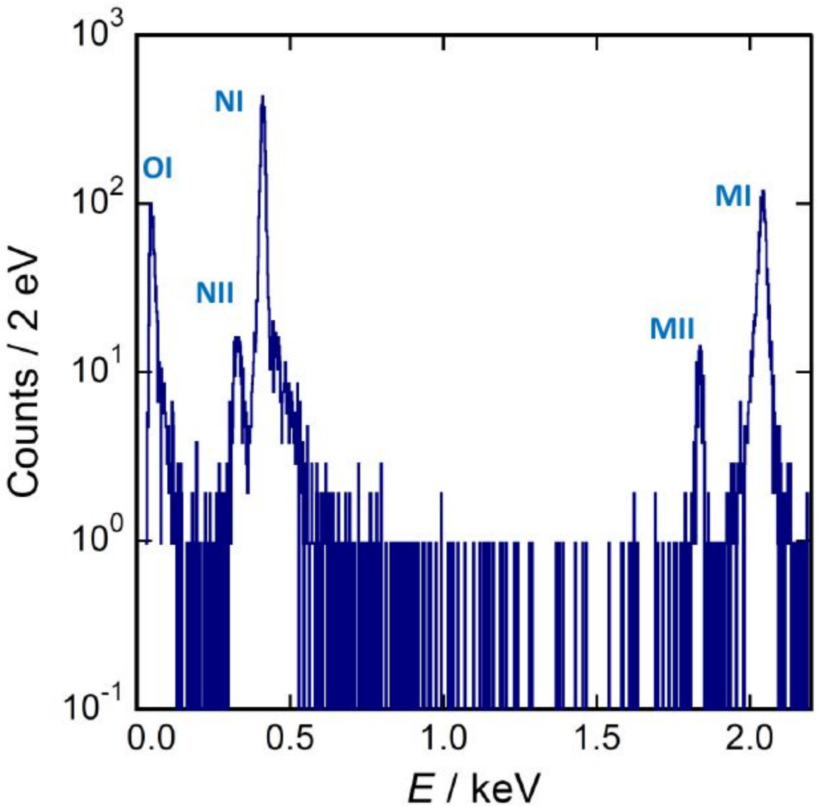
M. Galeazzi et al., arXiv:1202.4763v2
A. Nucciotti, Eur. Phys. J. C, (2014) 74:3161
B. Alpert et al., Eur. Phys. J. C, (2015) 75:112

ECHo MMC microcalorimeters

- 16x **MMC** with sandwiched **Au** absorber
- chemically purified **^{163}Ho**
- offline ^{163}Ho implantation at ISOLDE (CERN)
- $A(^{163}\text{Ho}) = 0.1$ Bq/pixel
- $\Delta E \approx 5$ eV
- $\tau_{rise} \approx 130$ ns
- **ECHo-1k**: 100 pixels, $A(^{163}\text{Ho}) = 10$ Bq/pixel



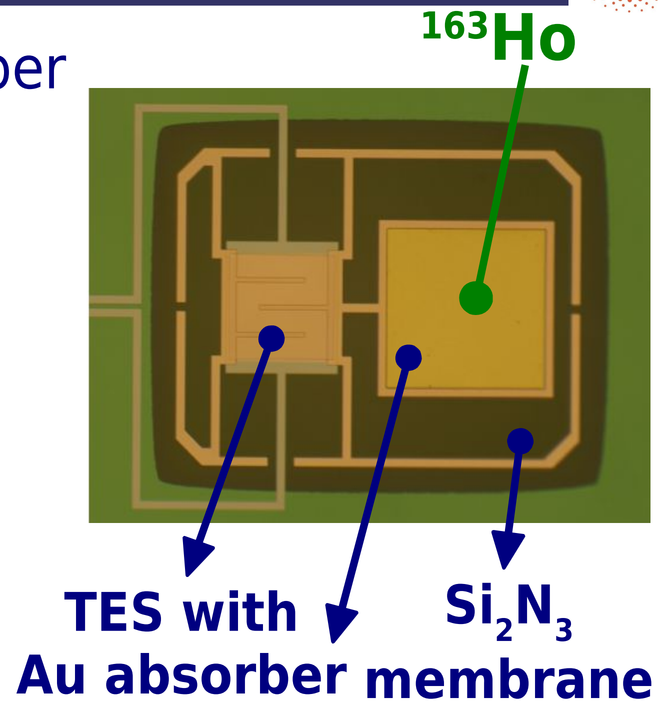


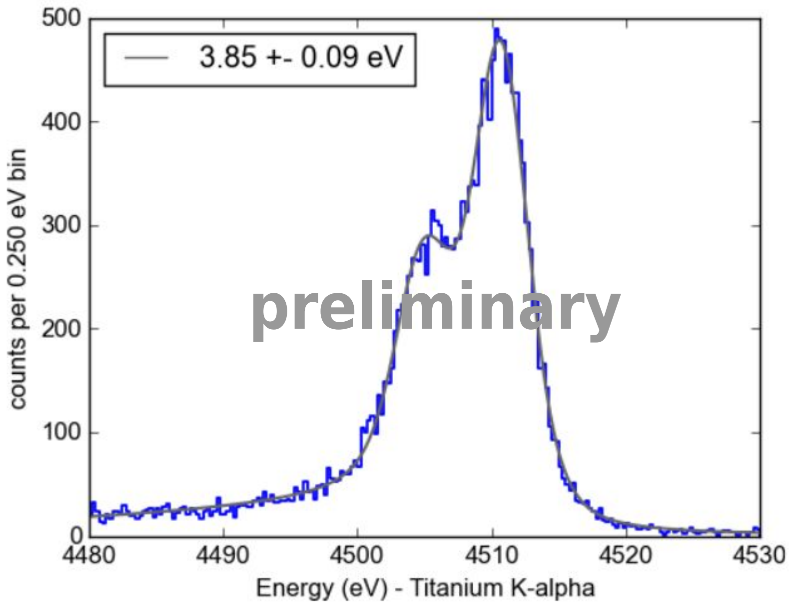


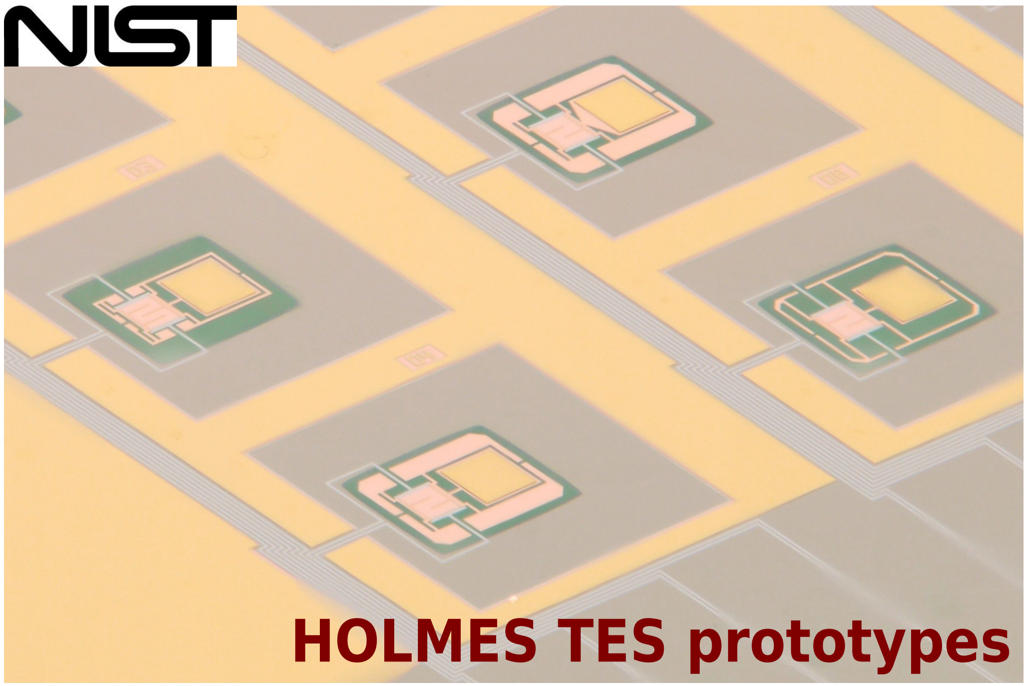
https://indico.cern.ch/event/437713/session/3/contribution/20
/attachments/1197979/1741935/Gastaldo_ECHo_ISOLDE_web.pdf

HOLMES TES microcalorimeters ERC AdG

- Transition Edge Sensors (TES) with Au (or Bi) absorber
  - ▹ **2 µm Au** total thickness for *full* electron and X absorption
- MoCu proximity TES → T_c≈100mK
- on Si_2N_3 membrane
- optimize design for speed and resolution
  - ▹ **specs @2.5keV :**
    - **ΔE_{FWHM} ≈ 1eV**
    - **τ_{rise} ≲ 5µs, τ_{decay} ≈ 100µs**
- from preliminary X-ray measurements:
  - ▹ **ΔE_{FWHM} ≈ 3 eV, τ_{rise} ≈ 5 µs, τ_{decay} ≈ 150 µs**

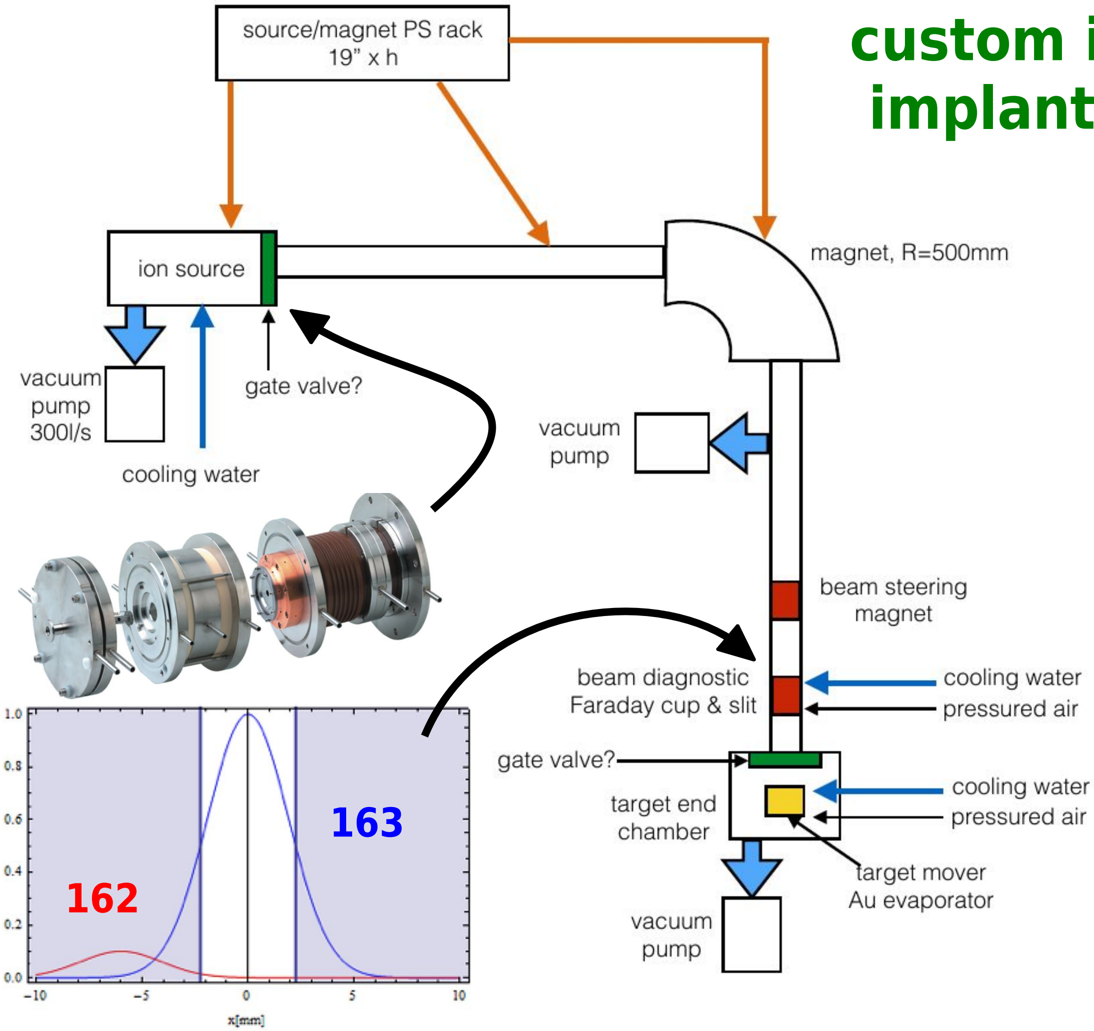


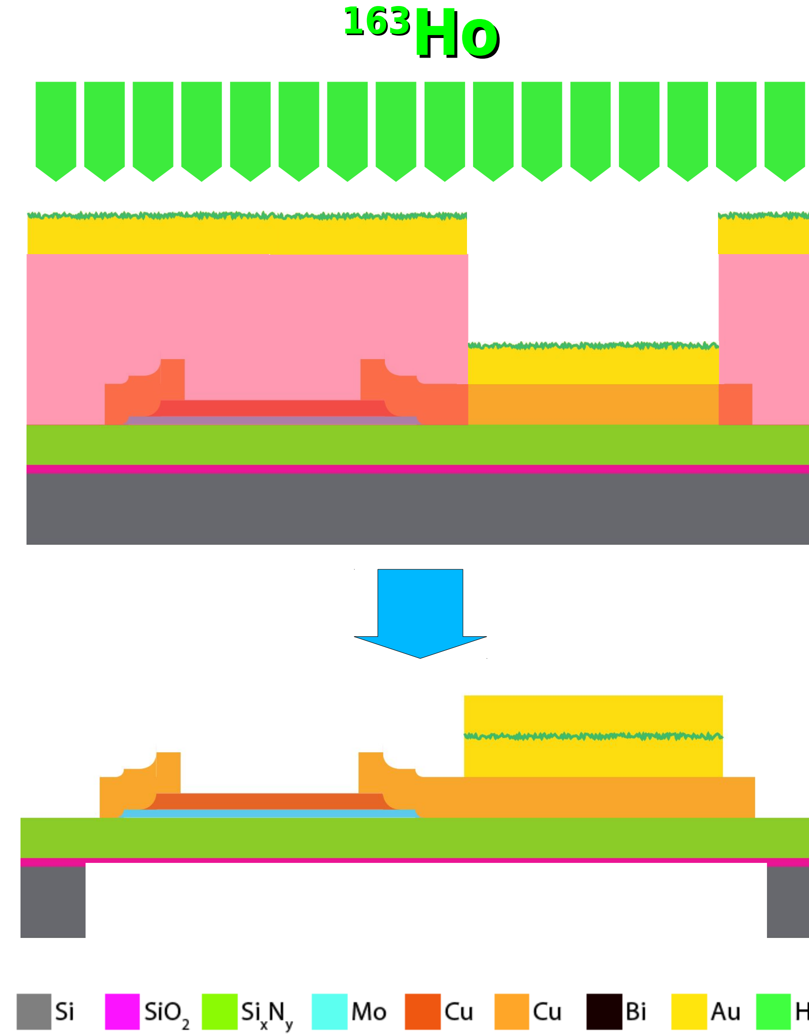




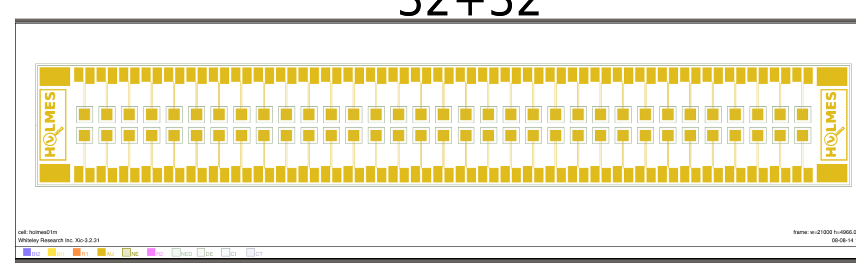
HOLMES detector array fabrication

custom ion implanter





32+32



- 2 µm thick Au encapsulating implanted ^{163}Ho
- TES fabricated at NIST, Boulder, CO, USA
- ^{163}Ho implantation at INFN Genova
- **HOLMES**: 1000 pixels, $A(^{163}\mathrm{Ho})$ = 300 Bq/pixel

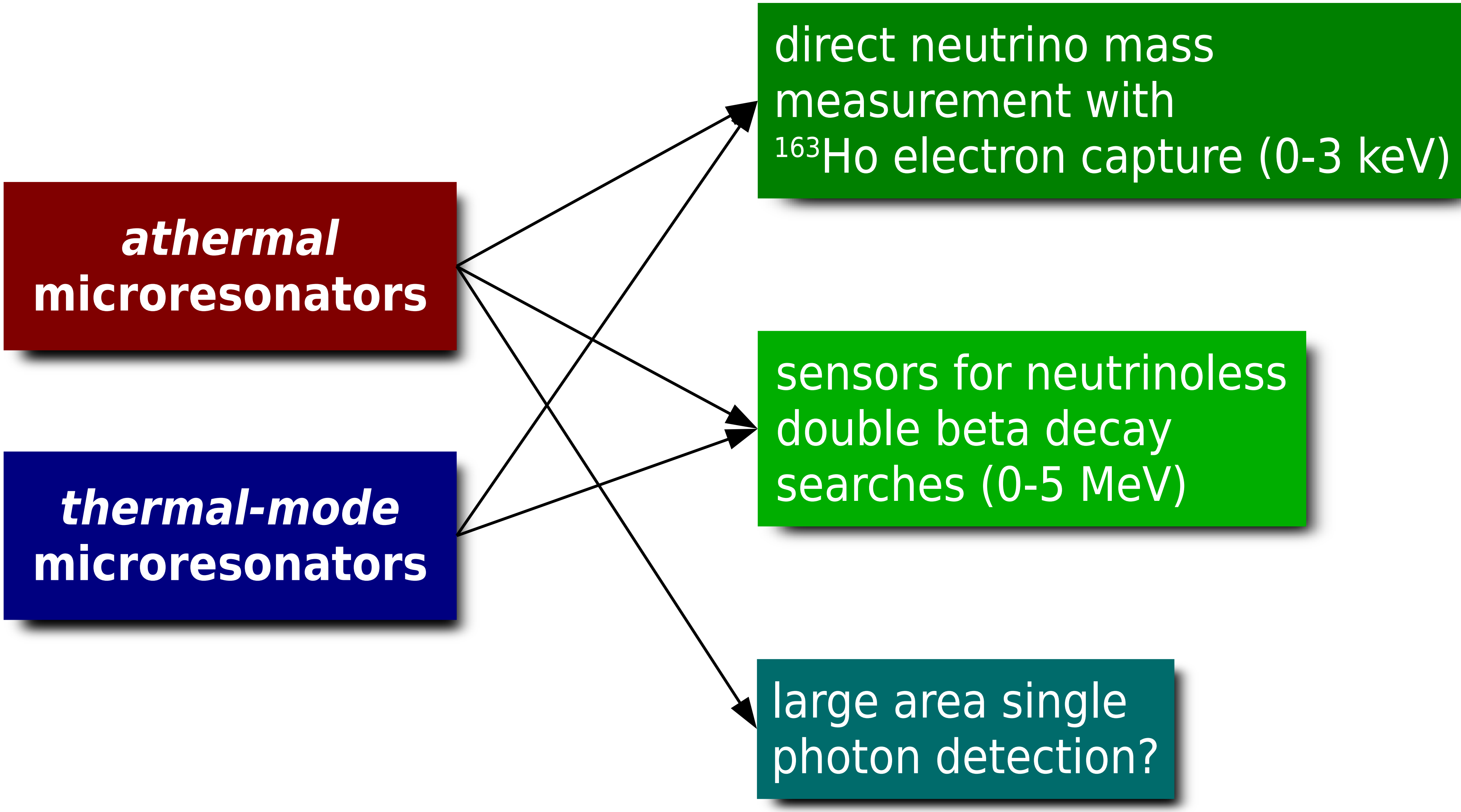
B. Alpert et al., Eur. Phys. J. C, (2015) 75:112

KID: an alternative to TES?

Development of microresonator detectors for neutrino physics

2011 – 2015 @ UniMiB

fondazione cariplo



KID principles: athermal mode

first developed as radiometers for mm astronomy

$E=h\nu > 2\Delta$ (≈meV)

pair breaking detector

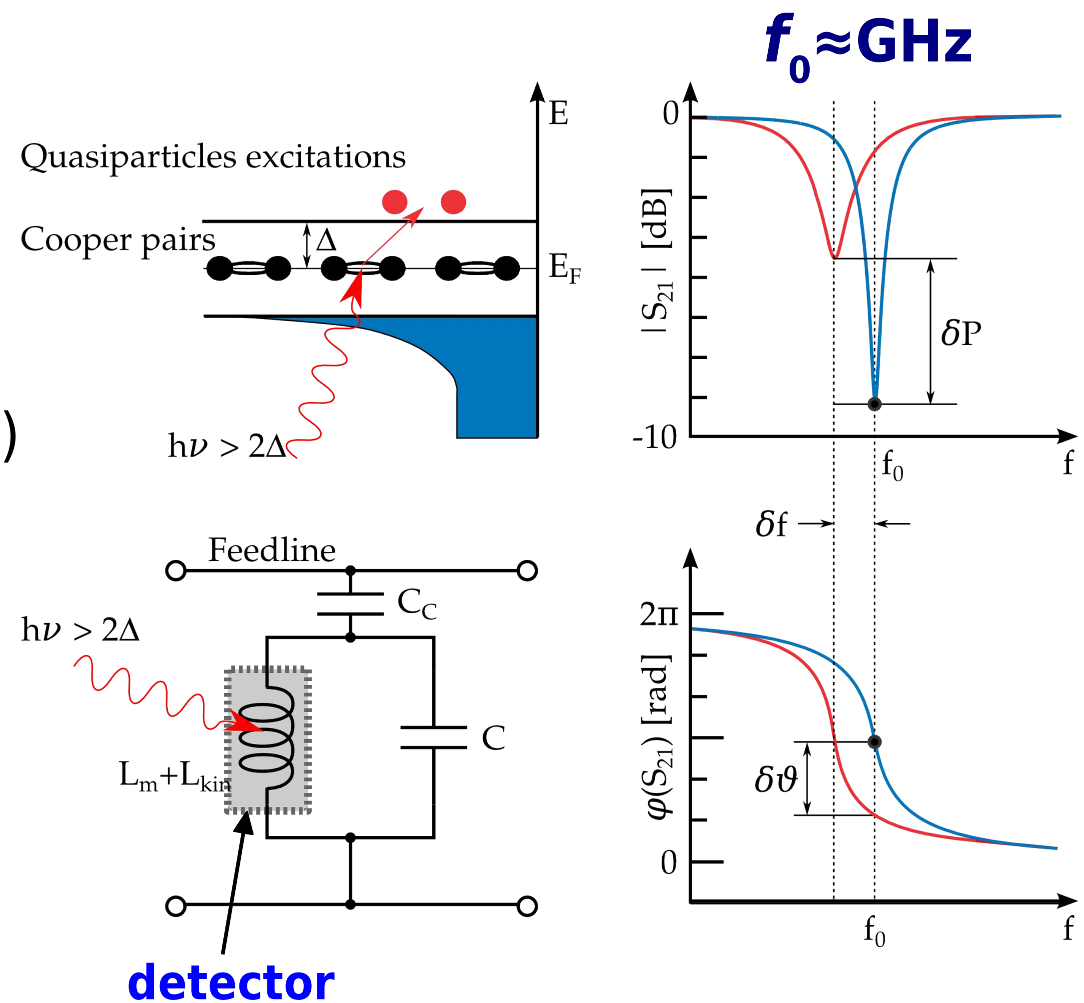
- Cooper pair breaking
- quasi-particle creation ($N_{qp} \approx \eta h\nu/\Delta$)
- increase qp density n_{qp}
- change in complex surface impedance $Z_s = R_s + i\omega L_s$

$$\frac{\delta f}{f_0} = -\frac{\alpha}{2}\frac{\delta L_s}{L_s} \qquad \delta Q^{-1} = \alpha \frac{\delta R_s}{\omega L_s}$$

α surface inductance L_s fraction in circuit inductance

relaxation time: qp recombination τ_{qp}

$f_0 \approx$ GHz

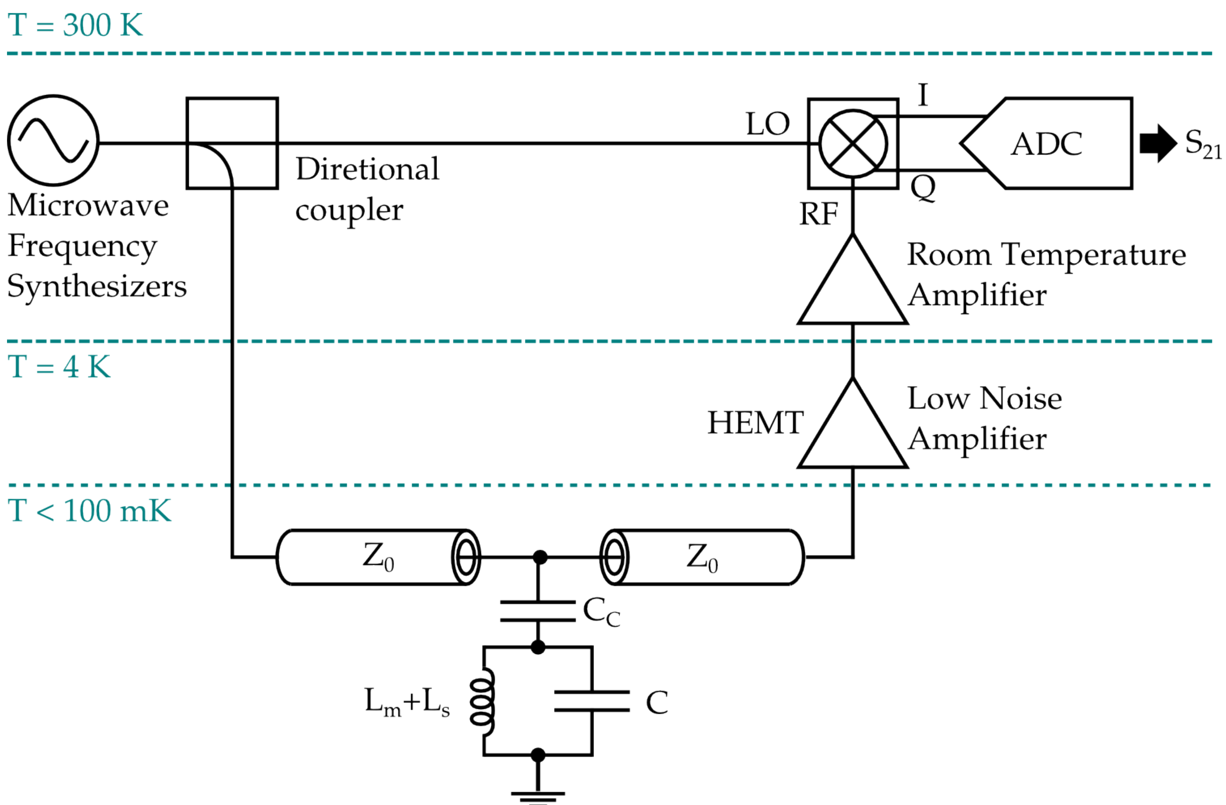


P. Day et al., Nature, 425 (2003) 817

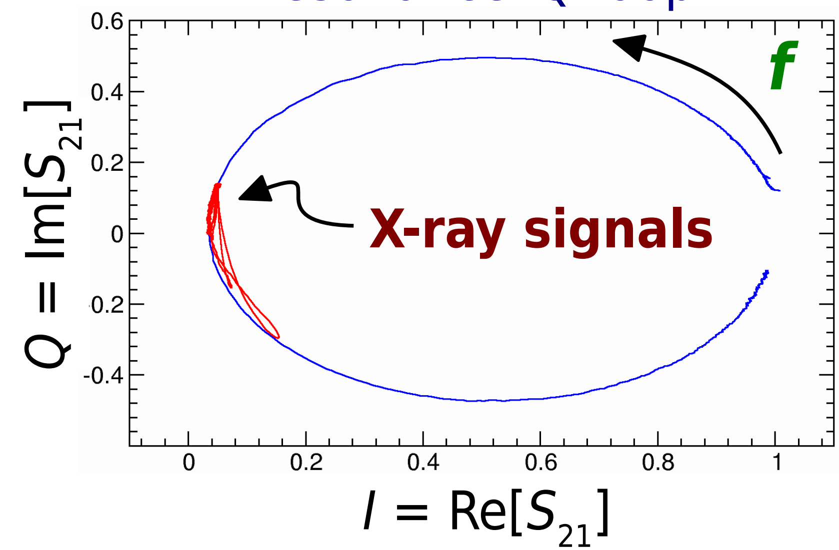
resolution limited by qp statistics $\sigma_E^2 \approx F E \Delta/\eta$

(order of 1eV for E = 6 keV)

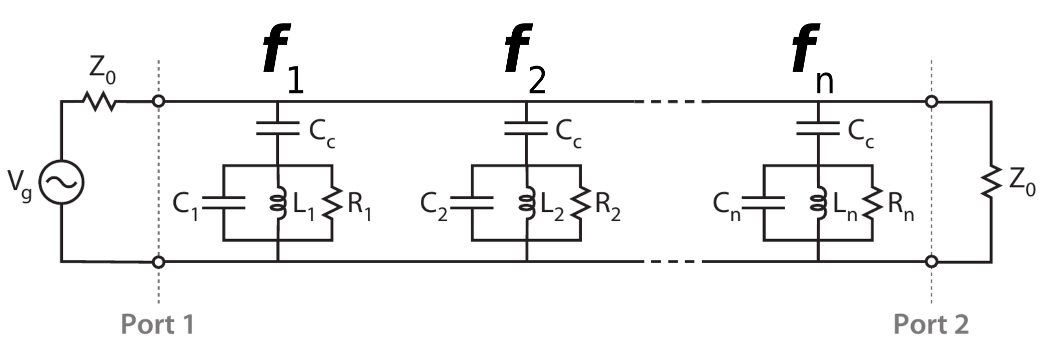
KID homodyne read-out

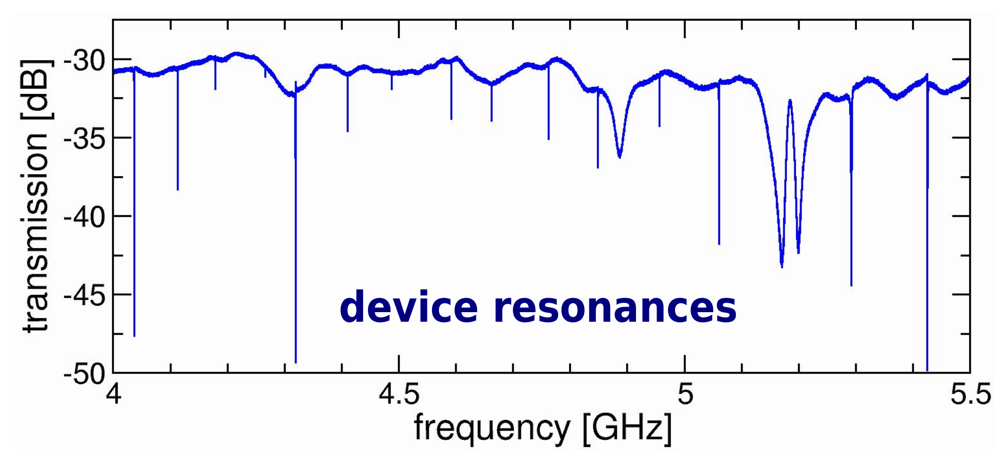


resonance *IQ* loop



microwave frequency multiplexing

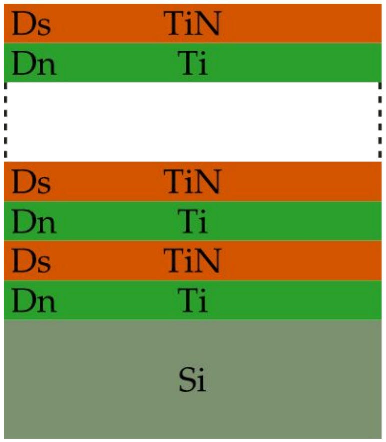




device ***i*** is read out tuning the RF carrier to f_i

Advanced materials for KIDs at FBK

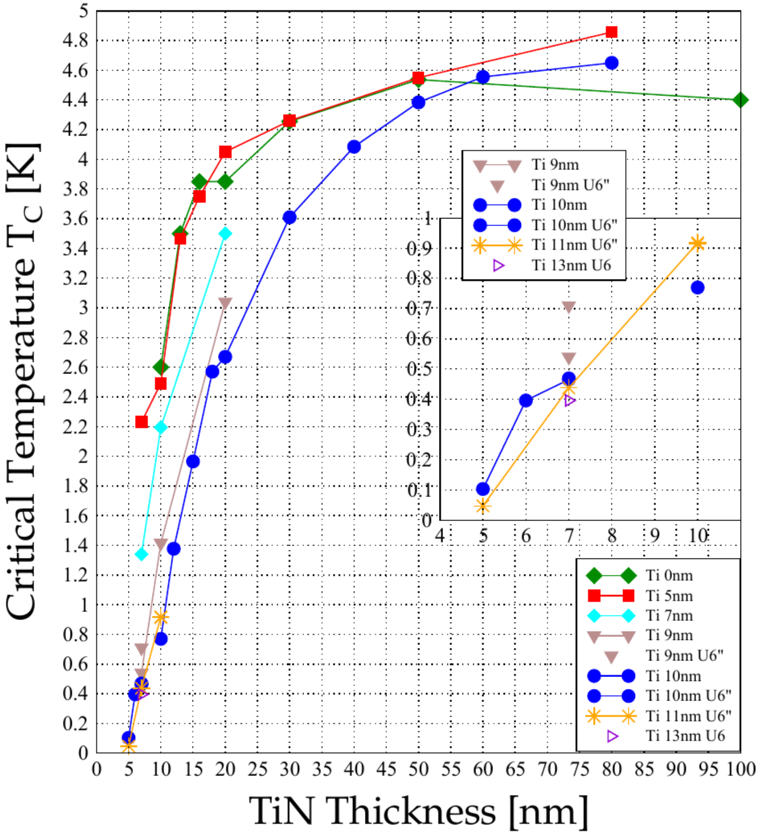
- **sub-stoichiometric TiN_x**
  - tunable T_c (0 → 4.5K) by adjusting x<1 → longer τ_{qp} for lower T_c
  - low losses → high Q_i devices
  - no surface oxide → low excess (TLS) noise
  - high surface inductance fraction α → large signals
  - hard to produce in a controlled way



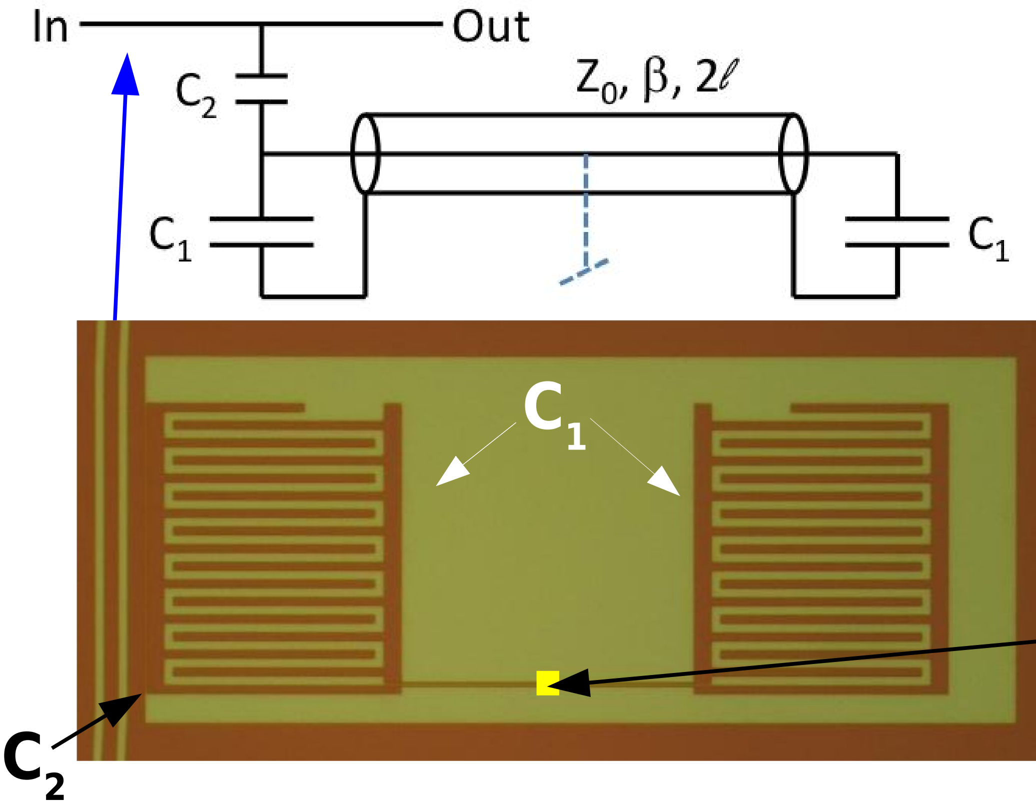
- **Ti/TiN sputtered multilayer (stoichiometric TiN)**
- proximity effect → T_c tuned by Ti and/or TiN thicknesses
  - good T_c control: tuning range **0.5 → 4.5K**
  - **high Q_i** and **high $\alpha = L_s/L_{tot}$**
  - good reproducibility and uniformity
  - **equivalent to sub-stoichiometric TiN_x**

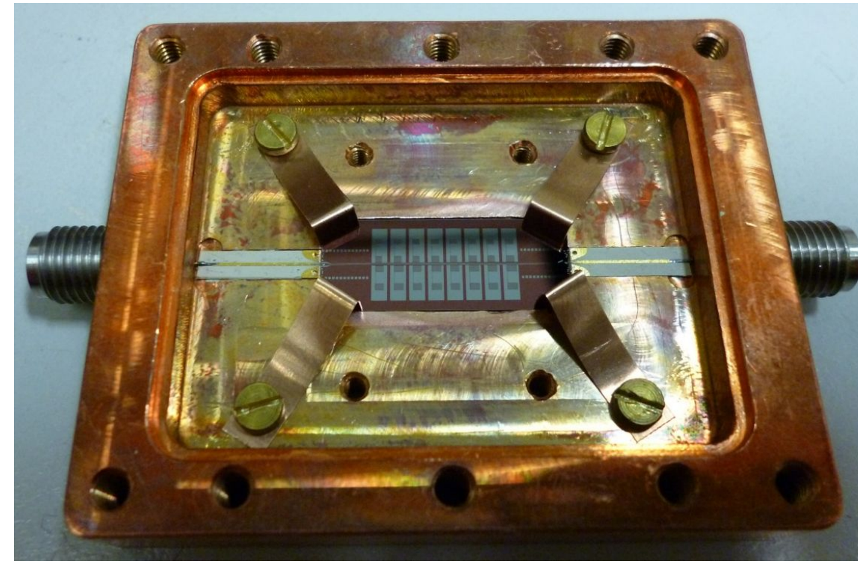
A. Giachero et al. J. Low Temp. Phys. 176 (2014) 155

T_C [K]	Δ [meV]	α	L_S [pH/sq]	Q_i
1.5	0.200 ± 0.004	0.26 ± 0.01	13.1	$< 10^5$
0.640	0.091 ± 0.001	0.95 ± 0.01	36.9	$< 10^4$

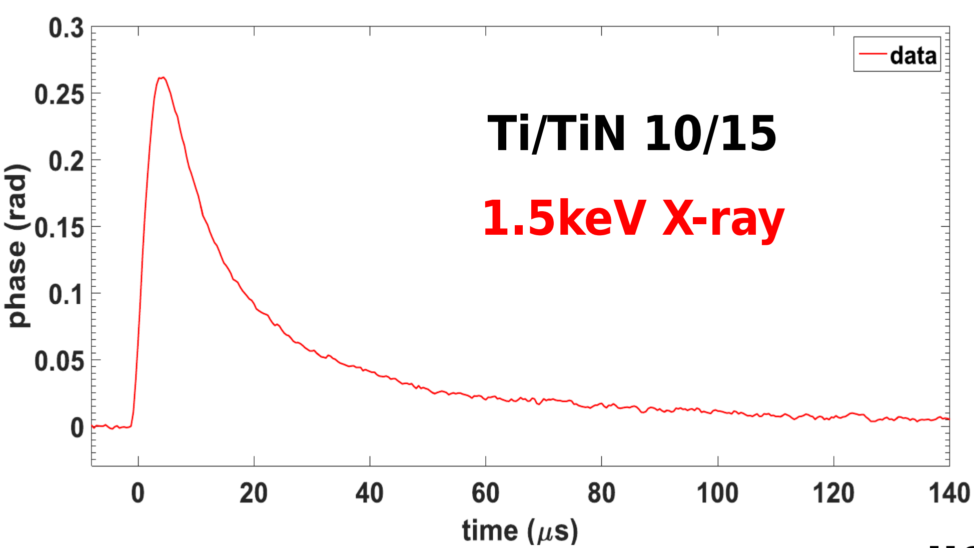


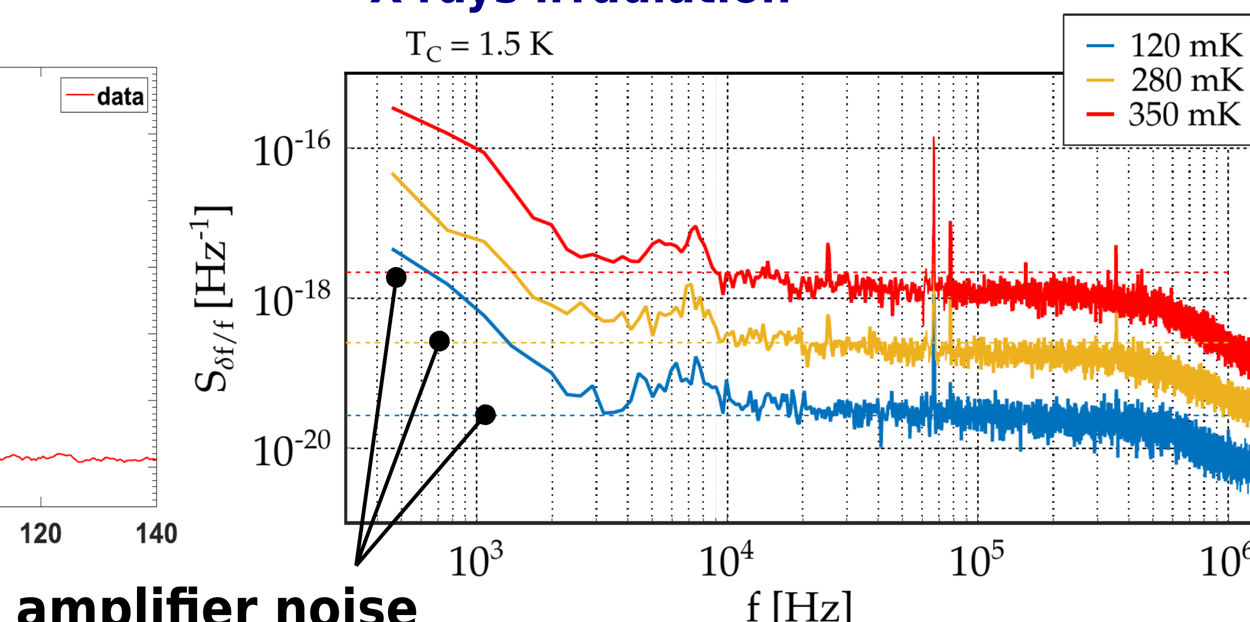
Microresonator X-ray characterization



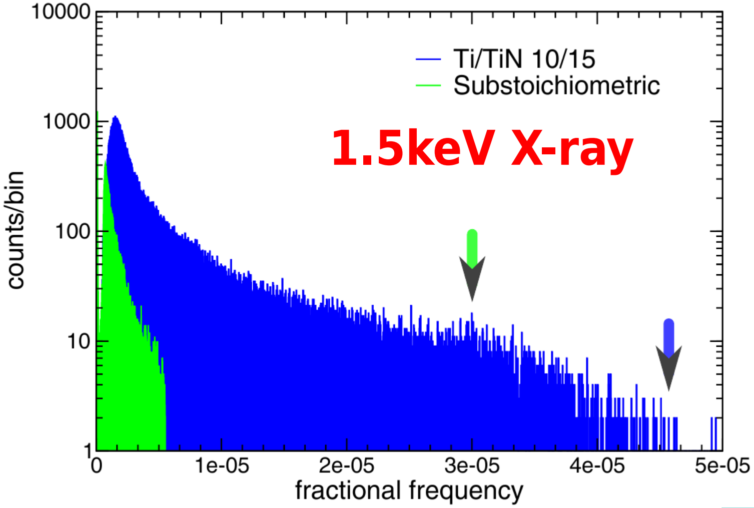


^{163}Ho implant
not yet implemented...
→ X-rays irradiation



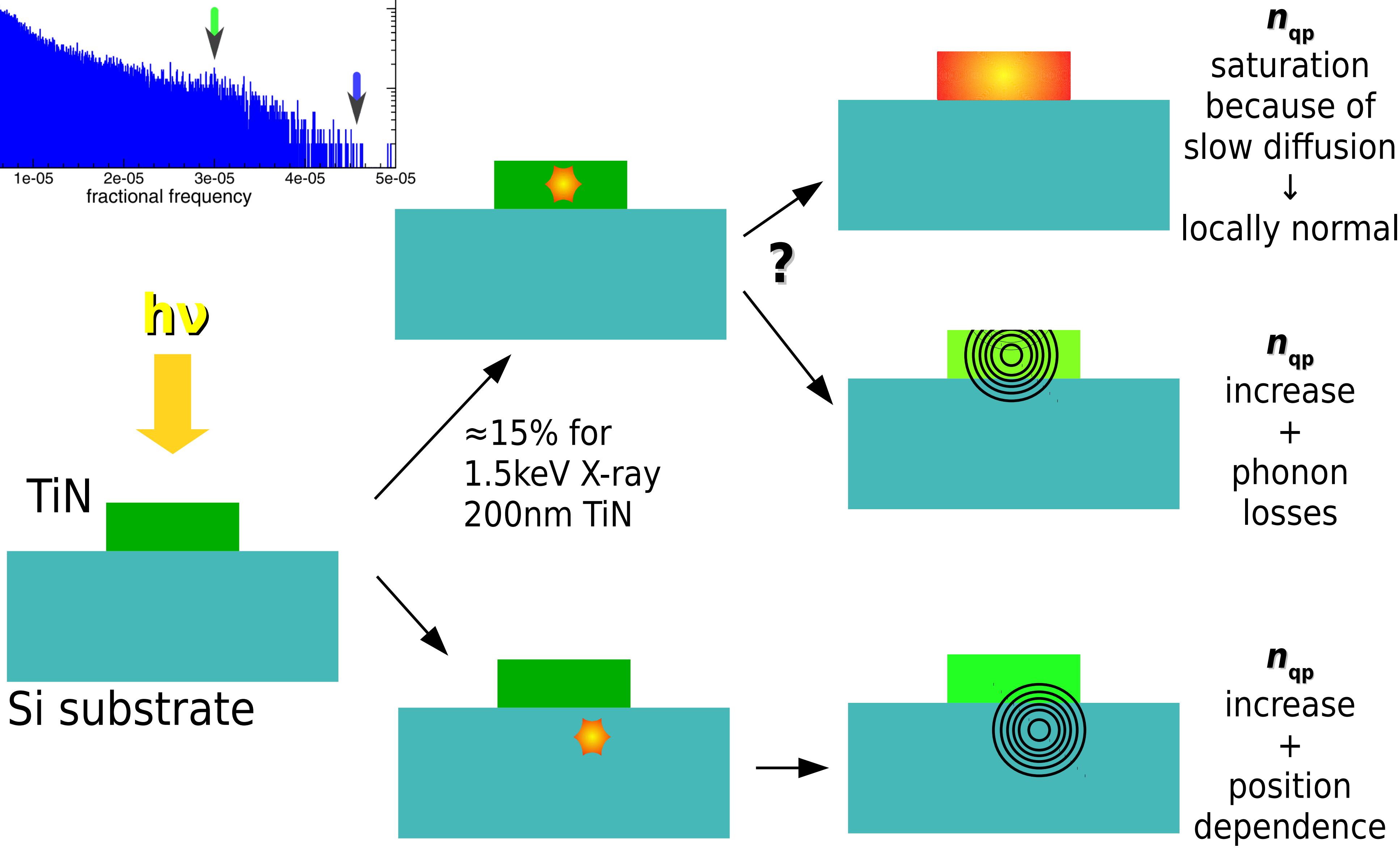


Microresonator X-ray response



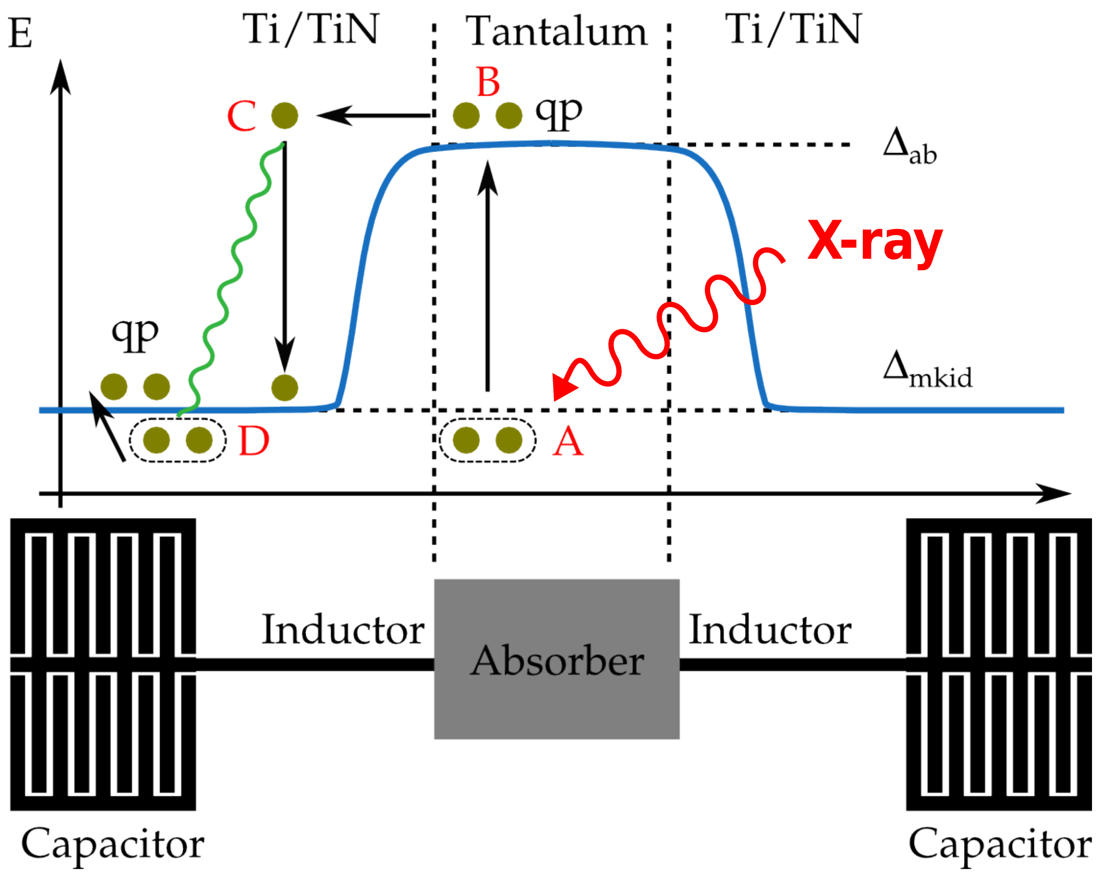
large (>1000) S/N but no resolving power!

HEMT noise dominated S/N

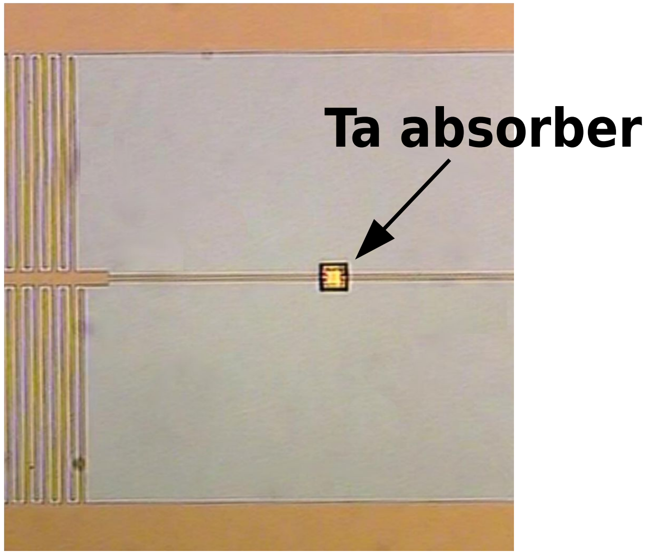


Microresonator detector improvements

- fast **qp diffusion** in Tantalum → no saturation
- **qp trapping** in TiN/Ti: Δ(Ta)>Δ(TiN/Ti)
- Tantalum: high Z → **high stopping power**
- Tantalum thickness: 200 / 500 nm

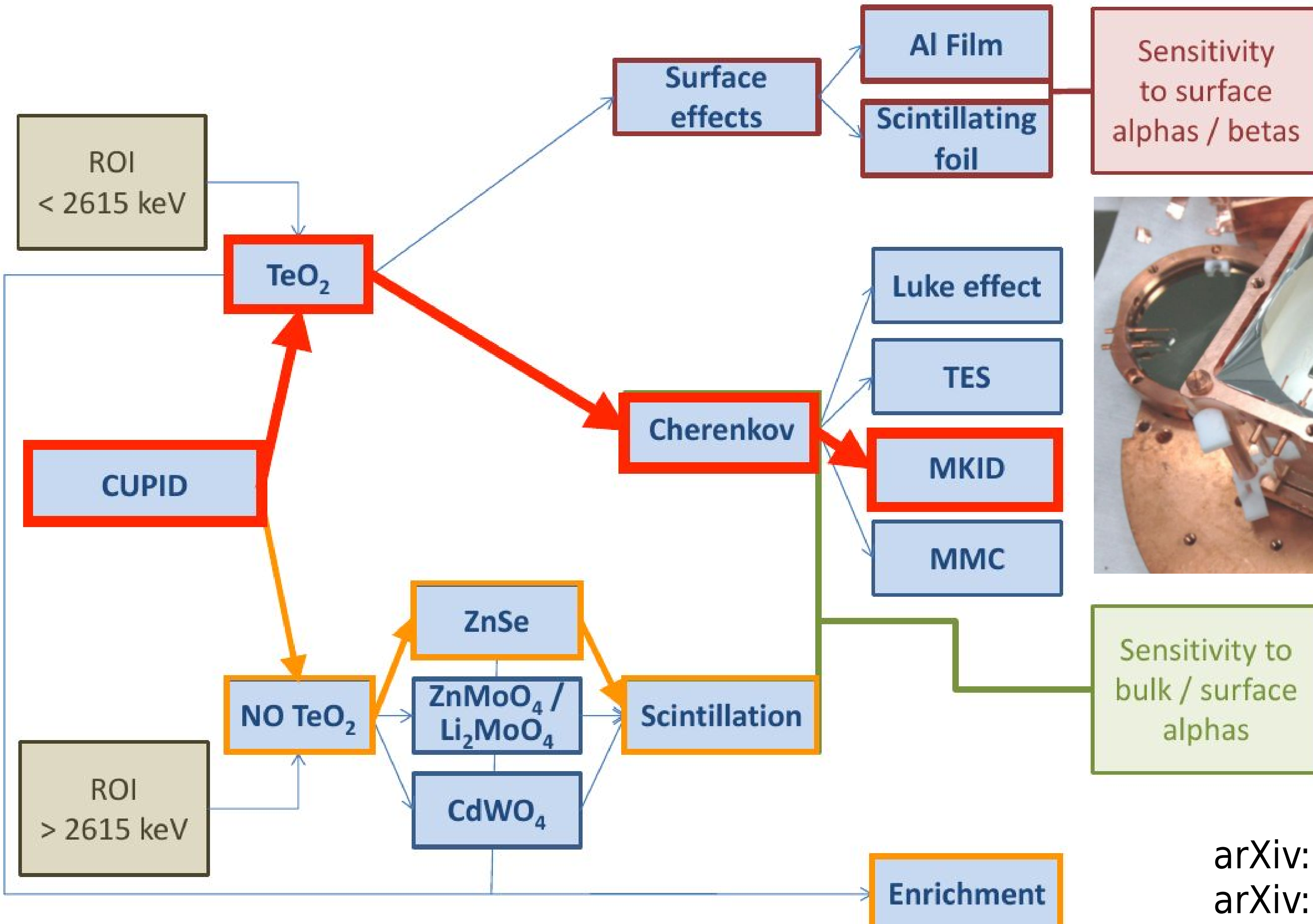


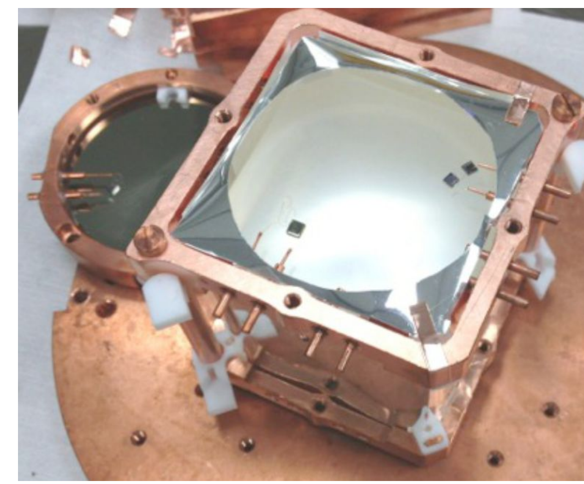
first prototype



Beyond CUORE: CUPID

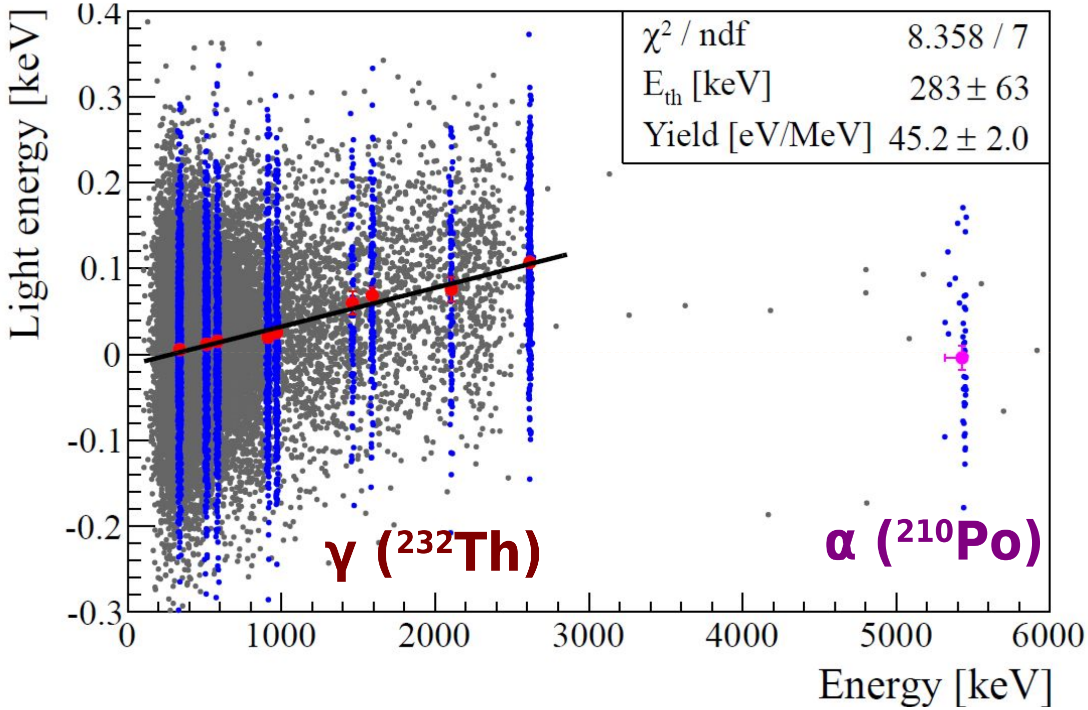
- Excluding **Inverted Hierarchy** → improve **CUORE** sensitivity by 5÷10
- CUORE upgrade with Particle ID (**CUPID**) → **reduce bkg from alphas**
  - ▹ **α/γ discrimination** with Cherenkov (T.Tabarelli de Fatis, EPJC65 (2010) 359)

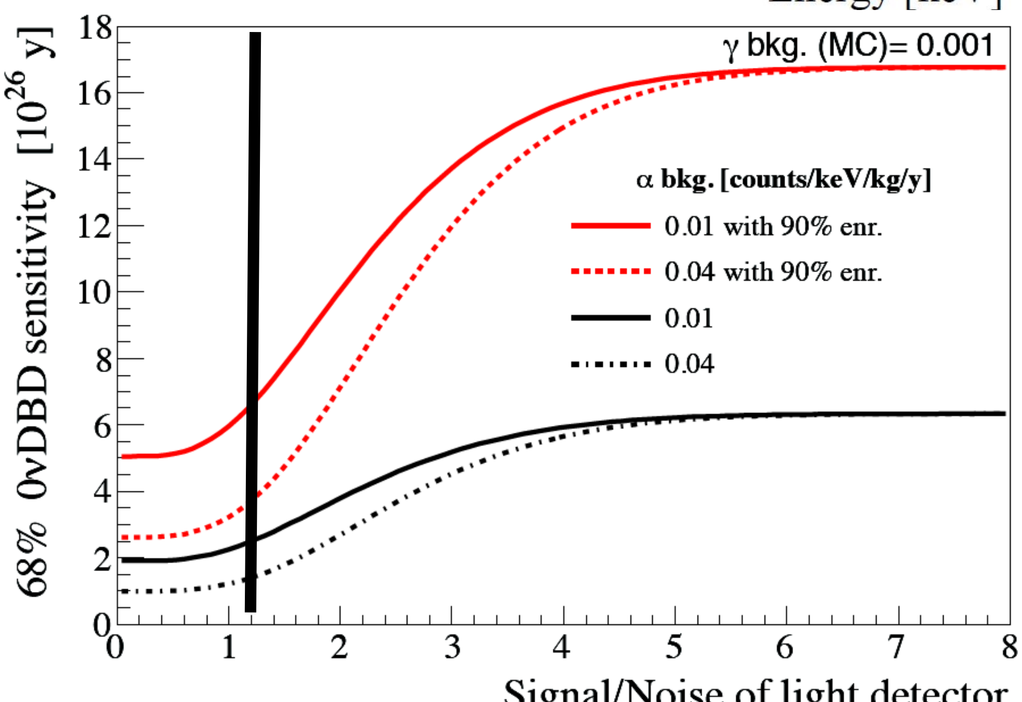




arXiv:1504.03599v1
arXiv:1504.03612v1

CUPID: TeO_2 with Cherenkov





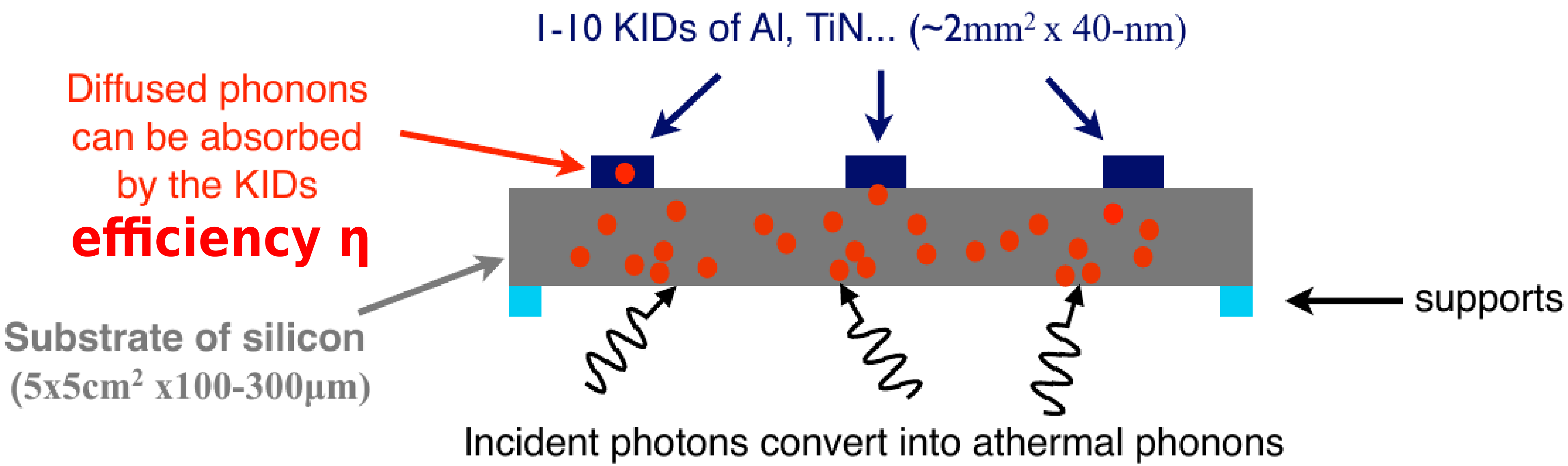
TeO_2 770g (CUORE size)

- **Detected light not sufficient for event by event discrimination**
  - LY≈45 eV/MeV
  - ≈100 eV for β/γ @ $Q_{\beta\beta}$ (S/N≈1.2)
- 10 times less than expected
- Montecarlo simulation
  - Cherenkov light is self absorbed
  - more sensitive light detectors
- **5 year sensitivity to ^{130}Te ββ-0ν**
  - CUORE + Cherenkov detection
  - with/without enrichment
  - γ bkg (10^{-3} c/keV/kg/y) dominates for S/N≥5

N. Casali et al., EPJ C75 (2015) 12
arXiv:1403.5528v1;

CALDER project ERC StG / FIRB

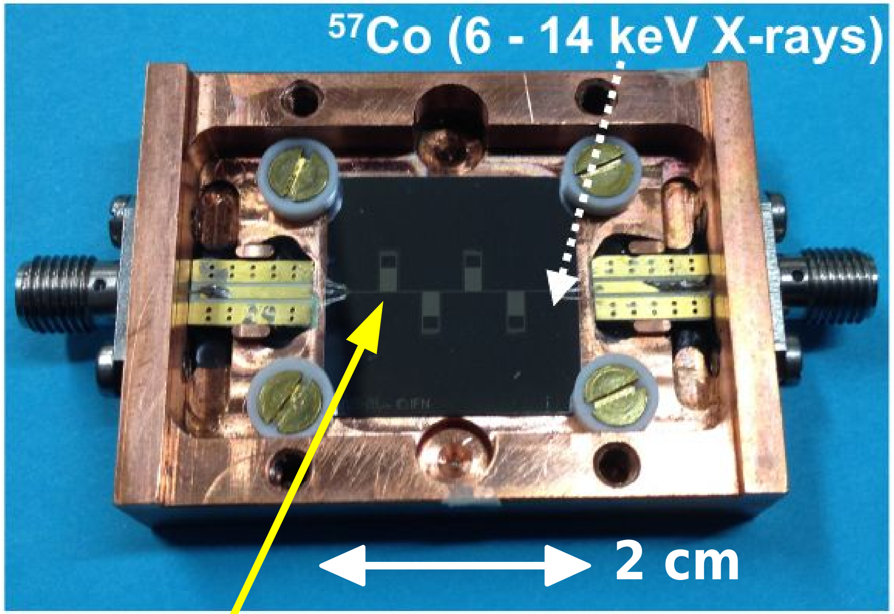
- **CALDER Target**
  - 50x50 mm^2 light detector
  - E_{thres} = 20 eV
  - T_{op} = 10 mK
- **Baseline detector design**
  - athermal phonon KID
  - Si substrate with up to 10 KID

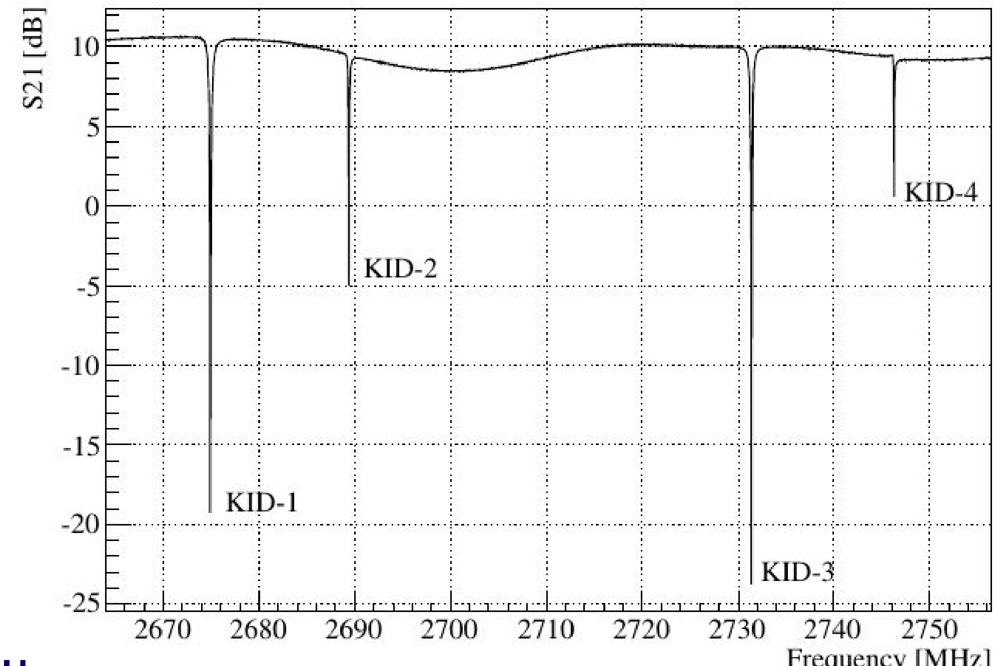


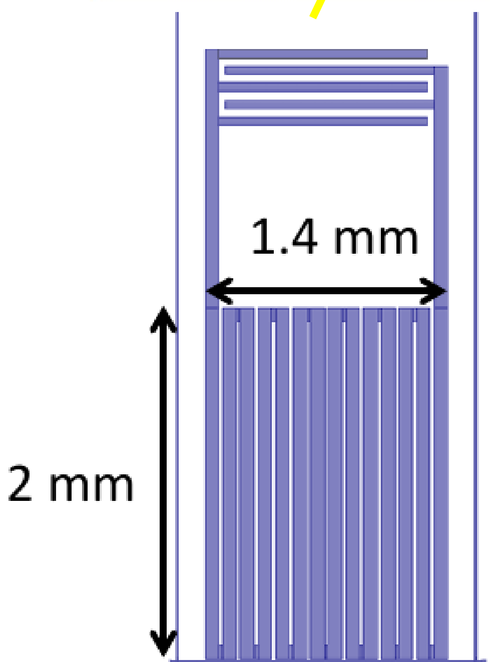
cherenkov photons

E. S. Battistelli et al. EPJ C 75 (2015) 353

CALDER prototype detectors

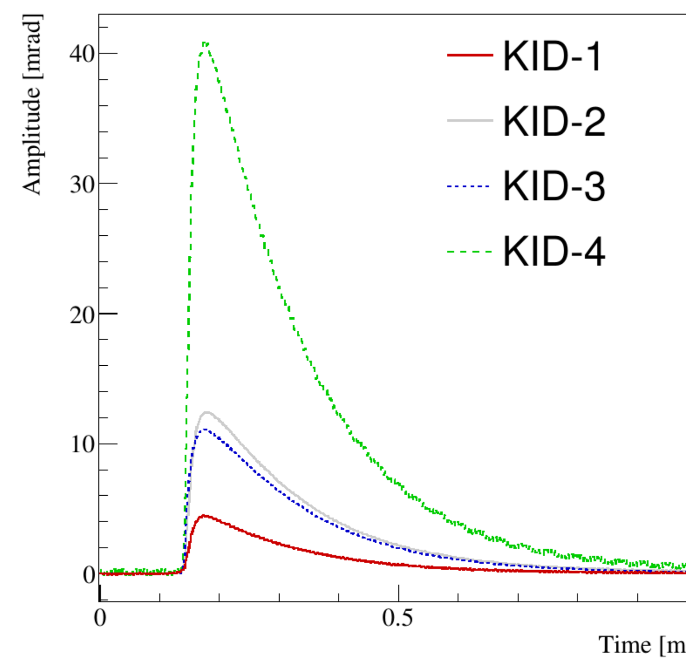






- 4x **Al KID** on Silicon
  - pair-breaking detectors
- **multiplexed** read-out
  - Software Defined Radio (NIXA)

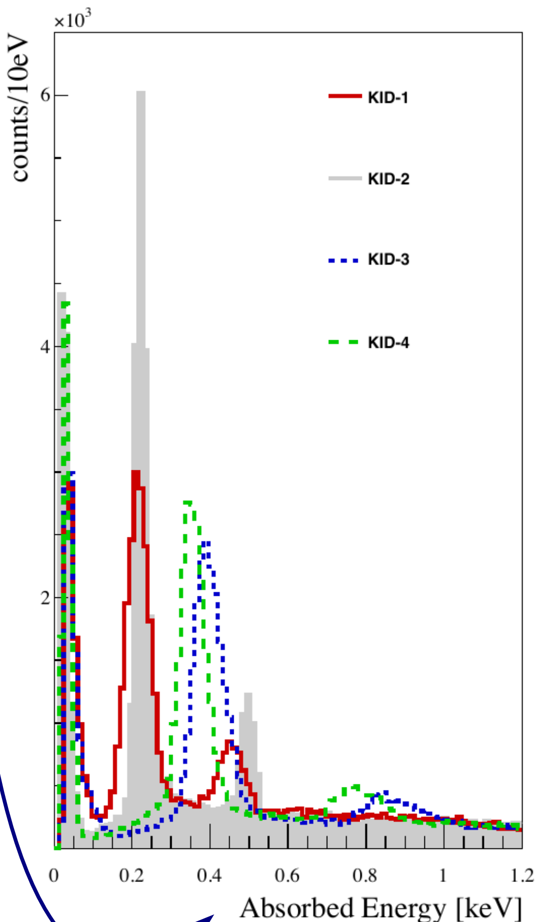
	f_0 [GHz]	Q [x10^3]
KID-1	2.675	6
KID-2	2.689	18
KID-3	2.731	8
KID-4	2.746	35

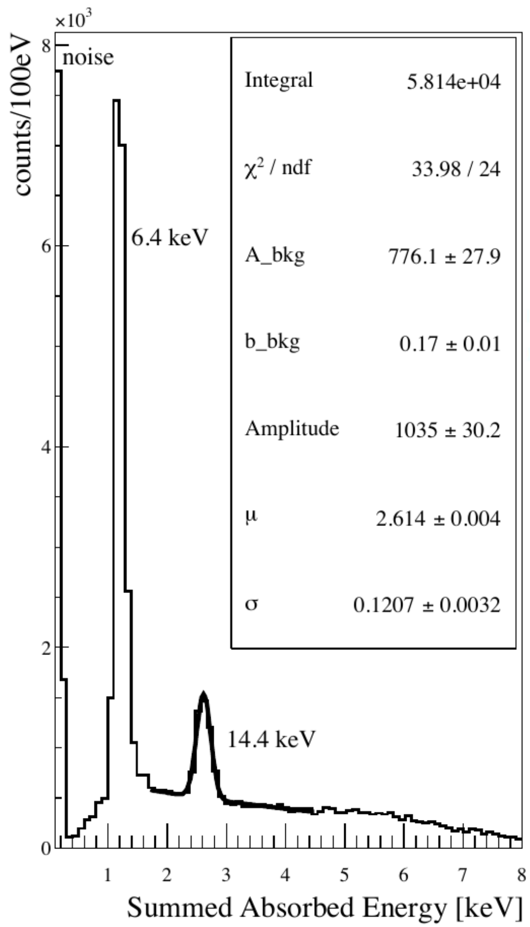


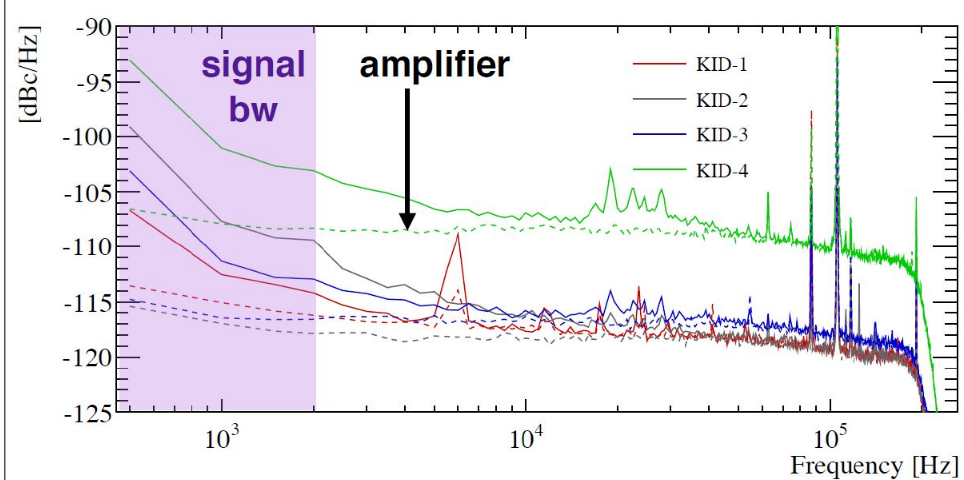
CALDER results

- KID response calibrated in energy
- summing up the energy absorbed by each KID
  - phonon collection efficiency **η = 18%**
  - baseline width **σ_E = 154 eV**
  - unknown **low *f* excess noise** dominates S/N

$$E = n_{qp}\Delta = \frac{\delta f_0/f_0}{p_0}\Delta$$





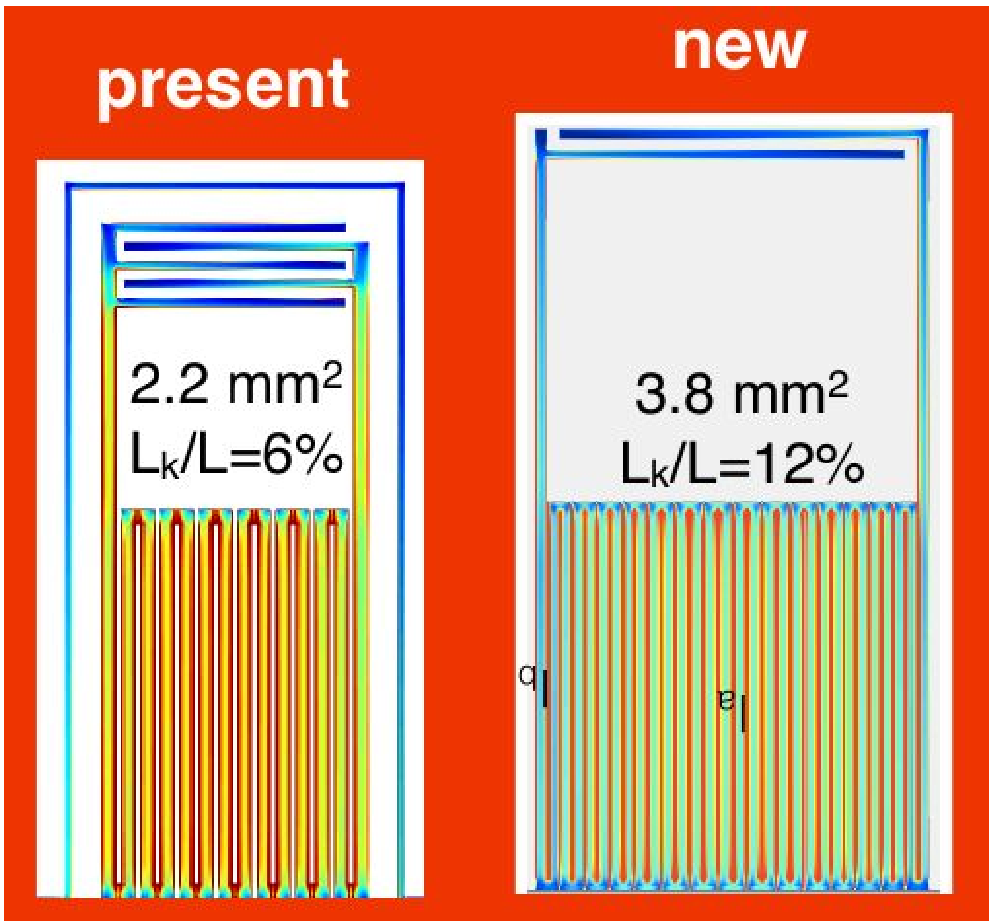


L. Cardani et al. Appl. Phys. Lett., 107 (2015) 093508

CALDER planned improvements

$$\Delta E \propto \frac{T_c}{\sqrt{Q \eta L_k / L_{tot}}}$$

- increase phonon collection efficiency **η** by design
- increase **$\alpha = L_k/L_{tot}$** by design
- increase **$\alpha = L_k/L_{tot}$** changing material
  - non stoichiometric **TiN_x**
  - **Ti/TiN** multilayers
- reduce ***1/f* excess noise**



	Al	TiN [non stoic.]	Ti+TiN [stoich]
T_c [K]	1.2	0.9	>0.4
L_k [pH/square]	0.5	3	30

Thermal-mode microresonators (KIDS_RD @CSN5)

Equivalence of temperature change and external pair breaking

- $h\nu$ absorption → $\Delta T \approx h\nu/C$
- increase qp density n_{qp}

$$n_{qp}(T) = 2 N_0 \sqrt{2\pi k T \Delta}\ e^{-\frac{\Delta}{kT}}$$

- change in complex surface impedance $Z_s = R_s + i\omega L_s$

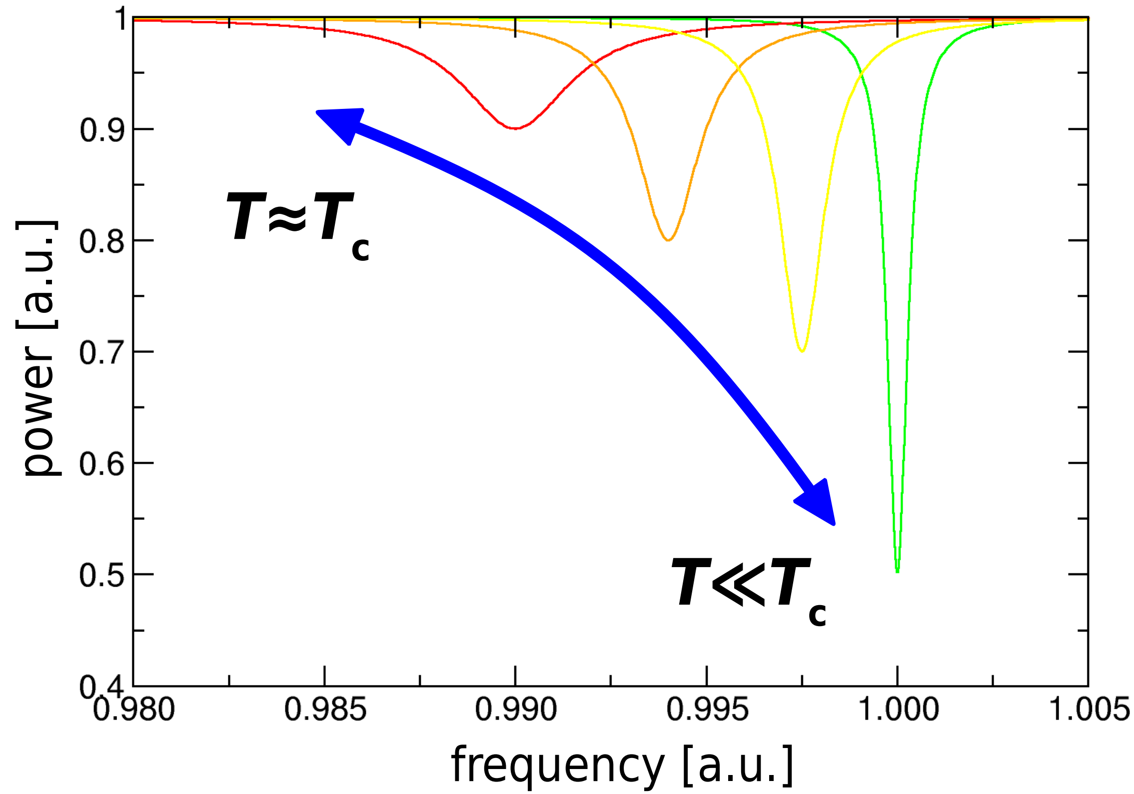
⬇

$$\frac{\delta f}{f_0} = -\frac{\alpha}{2}\frac{\delta L_s}{L_s} \qquad \delta Q^{-1} = \alpha \frac{\delta R_s}{\omega L_s}$$

α surface inductance L_s fraction in circuit inductance

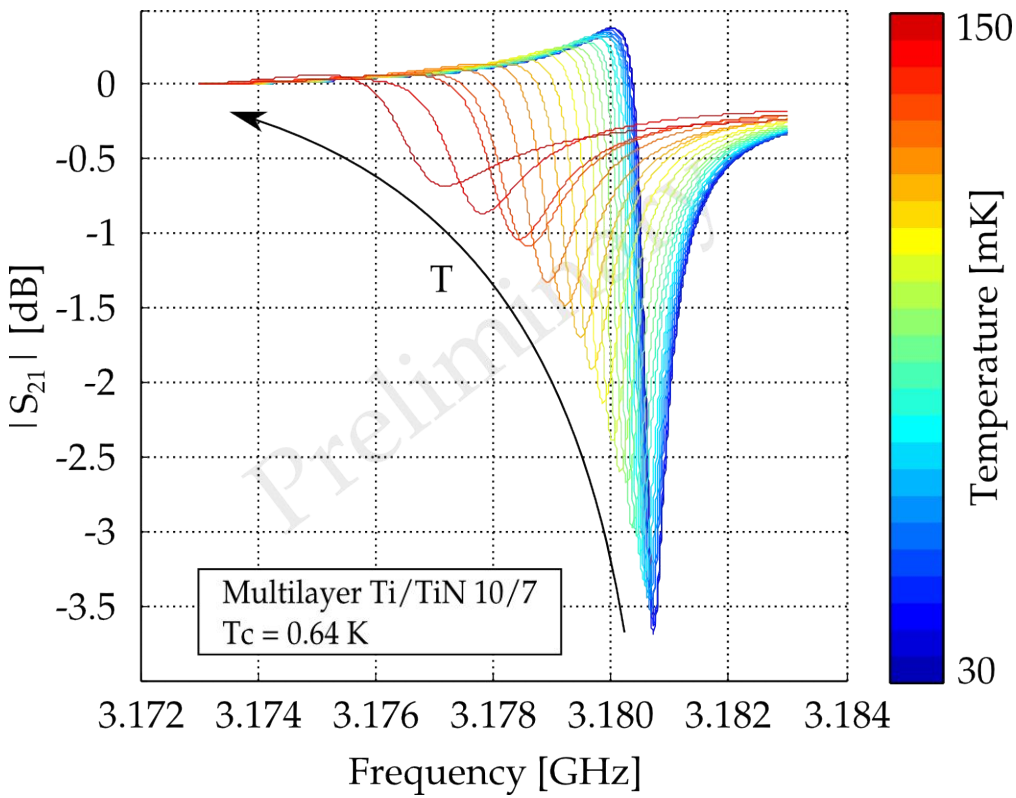
⬇

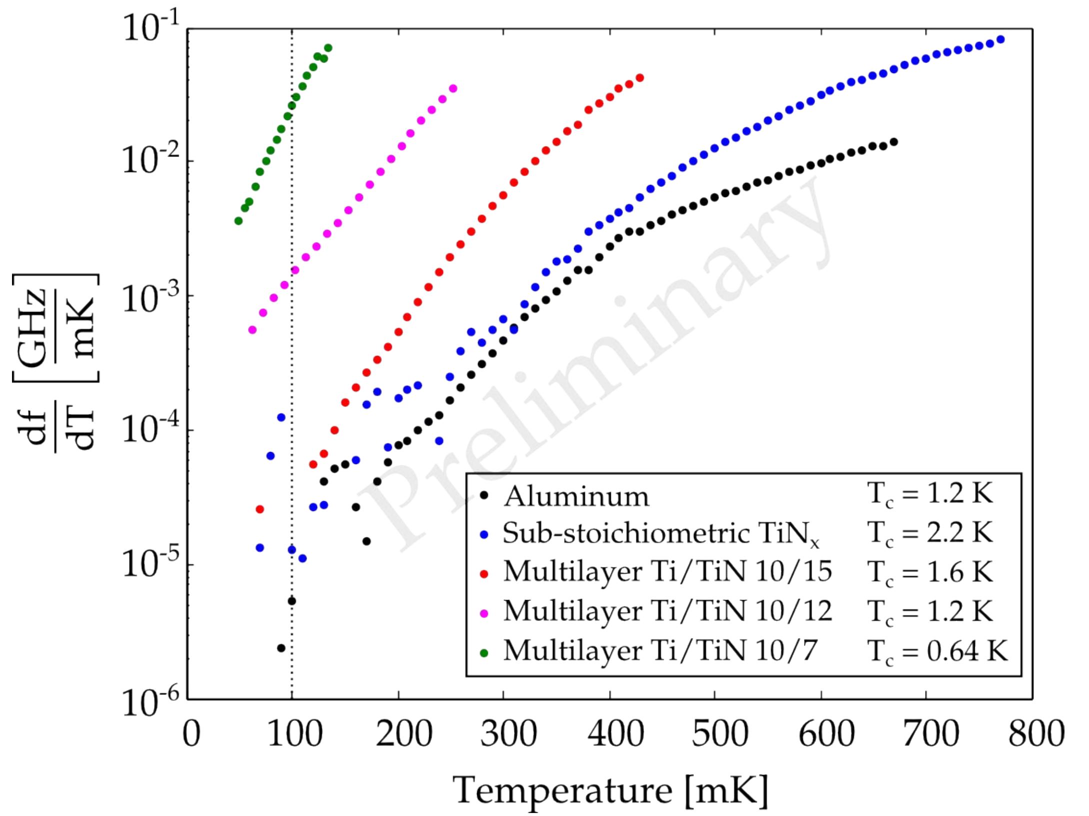
- relaxation time: thermal time constant $\tau = C/G$

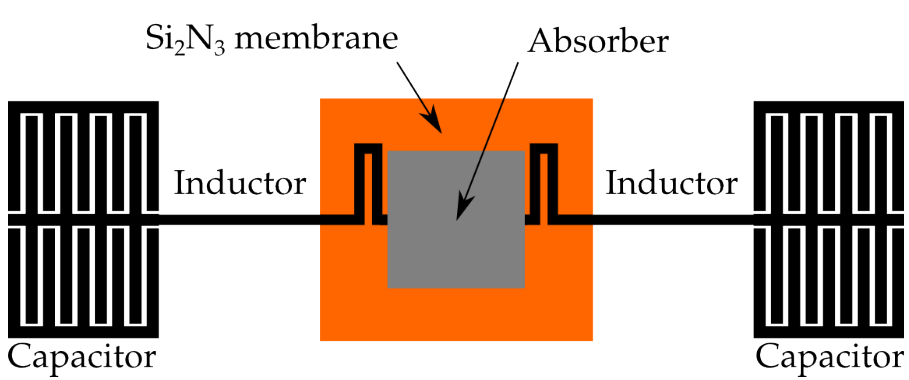


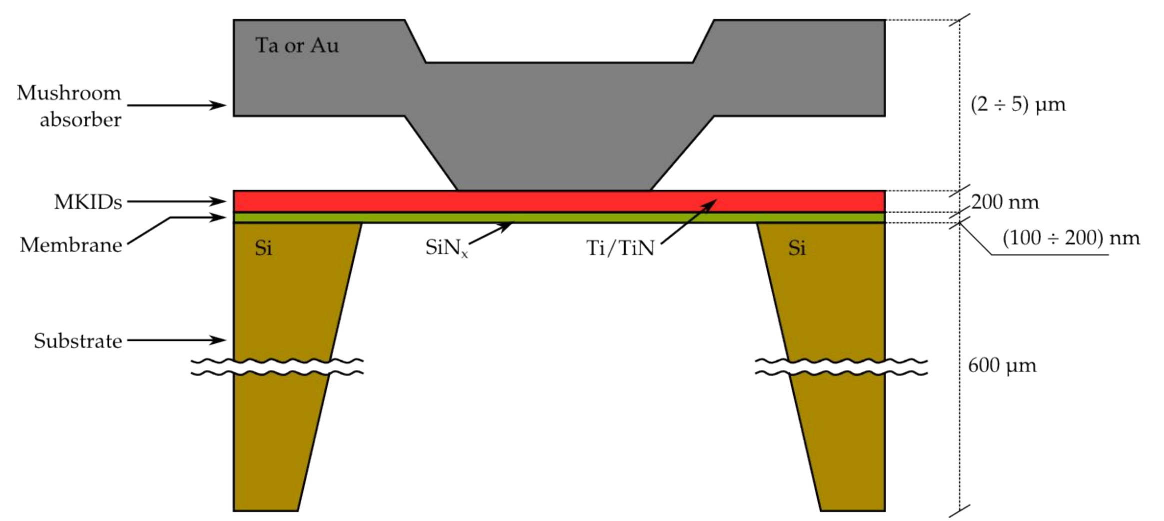
- **thermal KID** ↔ TES *replacement*
  - ▸ simpler micro-fabrication
  - ▸ simpler read-out (no SQUID)
  - ▸ easier high BW multiplexing
  - ▸ **ΔE ≈ thermodynamic limit**

Thermal-mode KID microcalorimeters

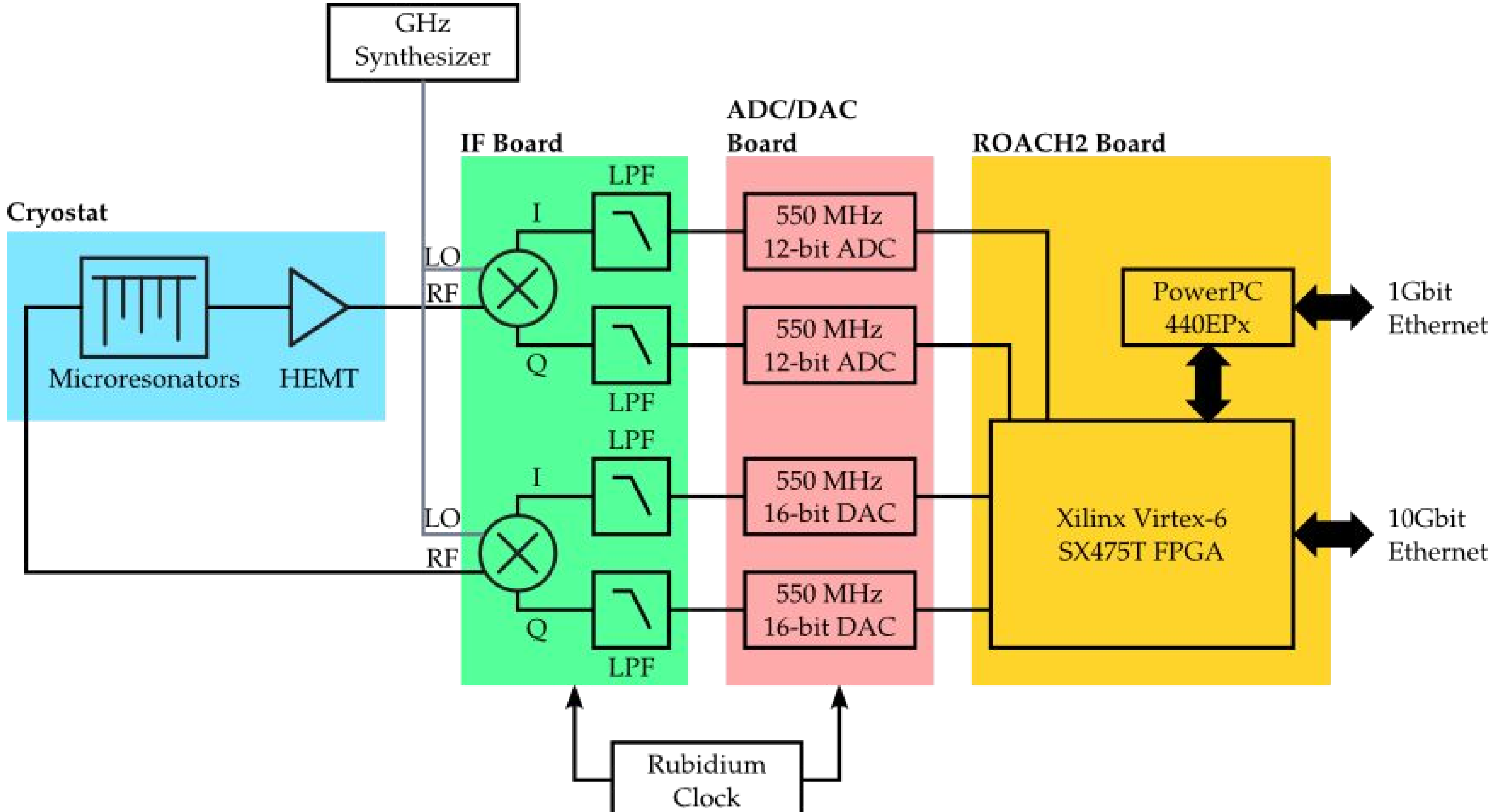








KIDS multiplexing: Software Defined Radio

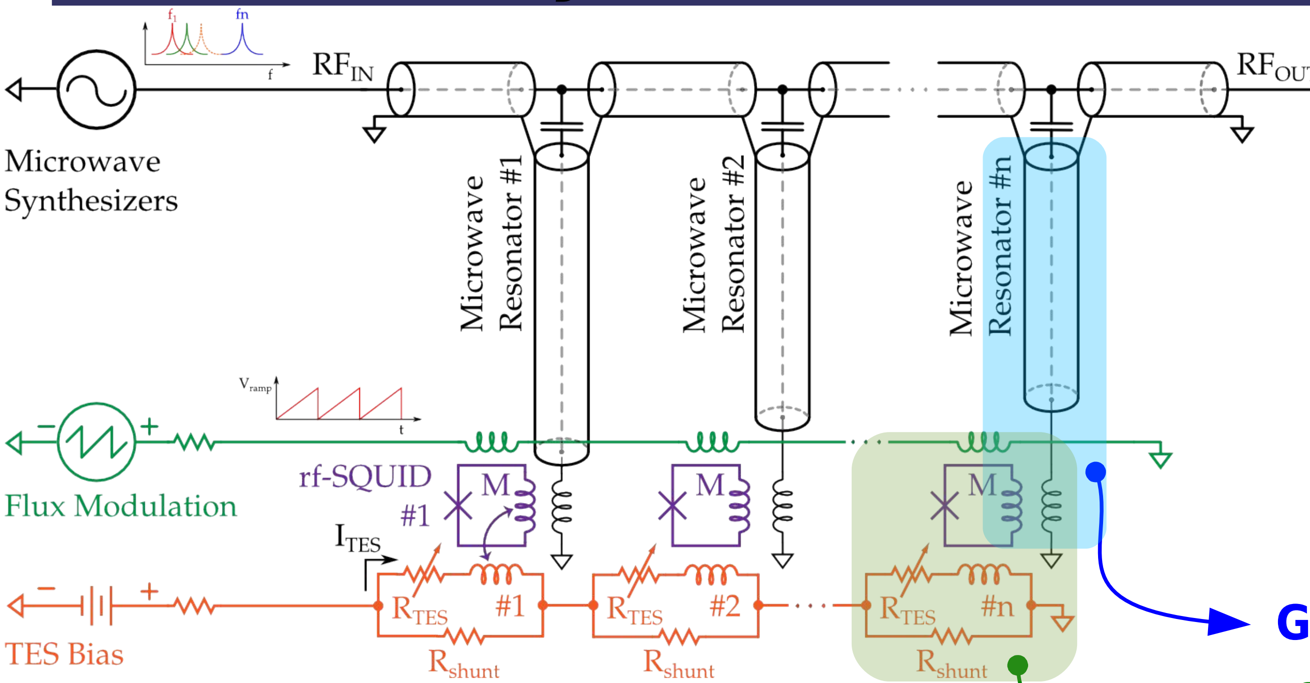


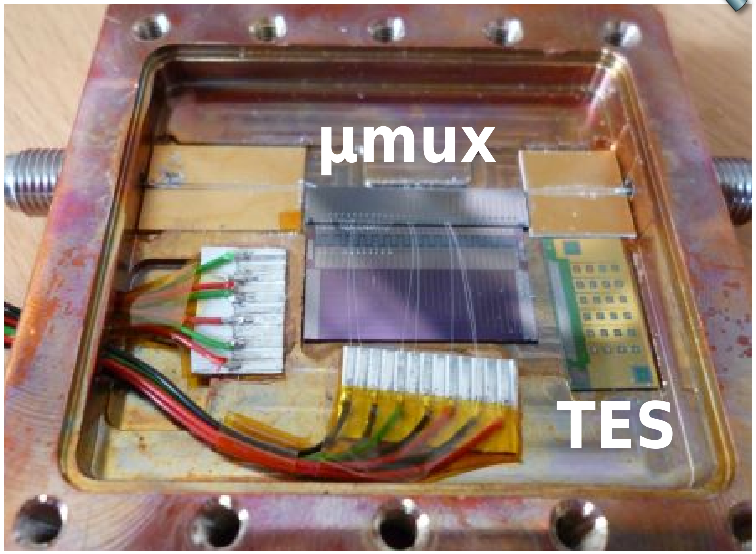
- **multiplexing factor N_{mux}**
- f_{BW} required bandwidth per channel **≈$1/\tau_{rise}$**

$$N_{mux} = \frac{f_{ADC}}{10 f_{BW}}$$

f_{ADC}= 550 MHz, f_{BW}**= 100 kHz → N_{mux}≈ 500**

HOLMES array read-out: rf-SQUID μwave mux

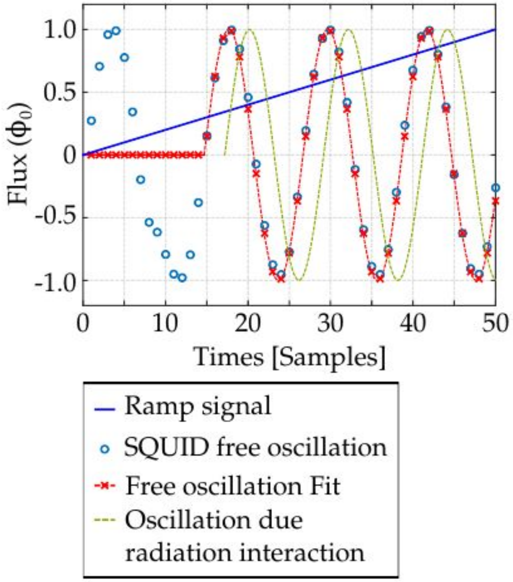


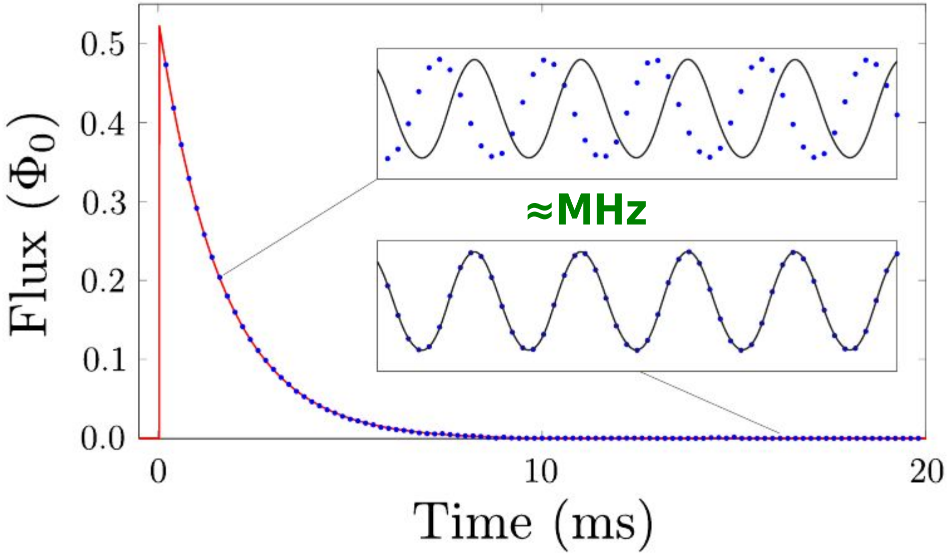


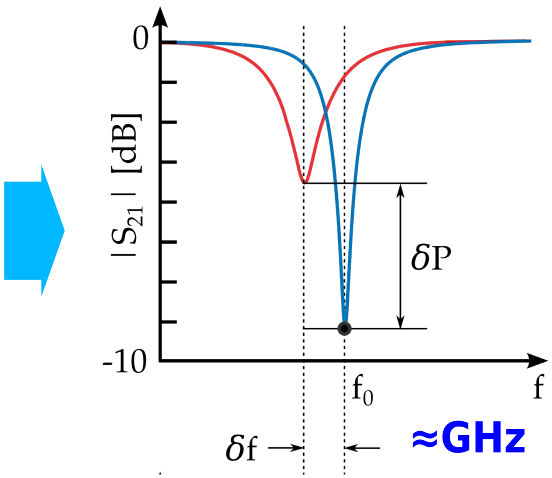
GHz LC resonator f_i

MHz flux ramp modulation f_{ramp} → f_{sampl}

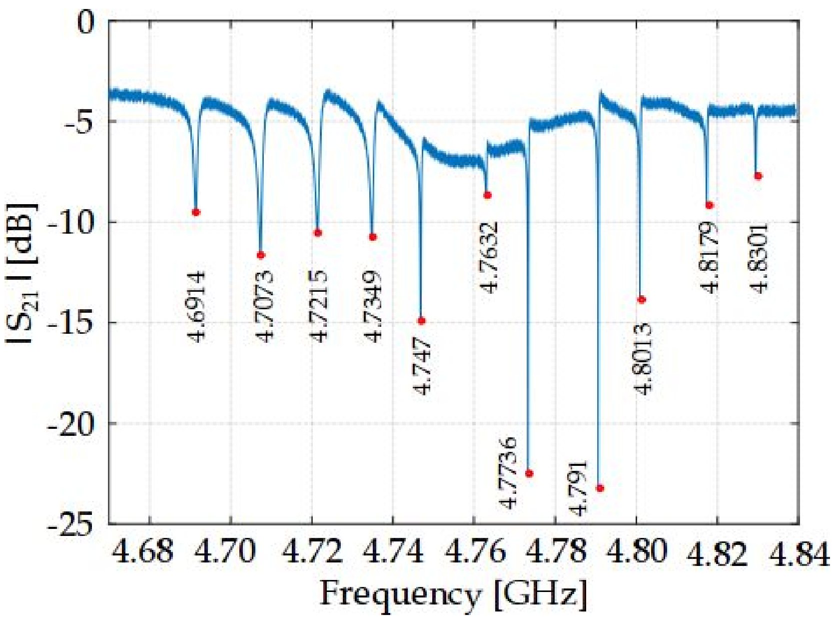
TES current signal frequency up-conversion + rf-SQUID response linearization

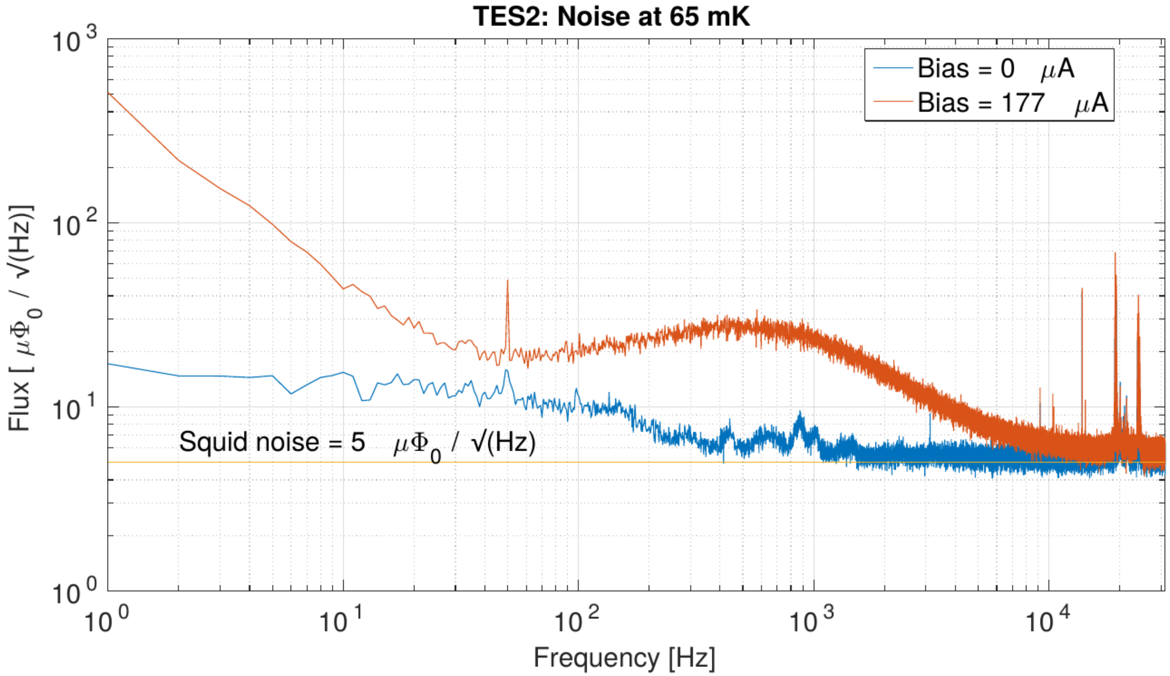


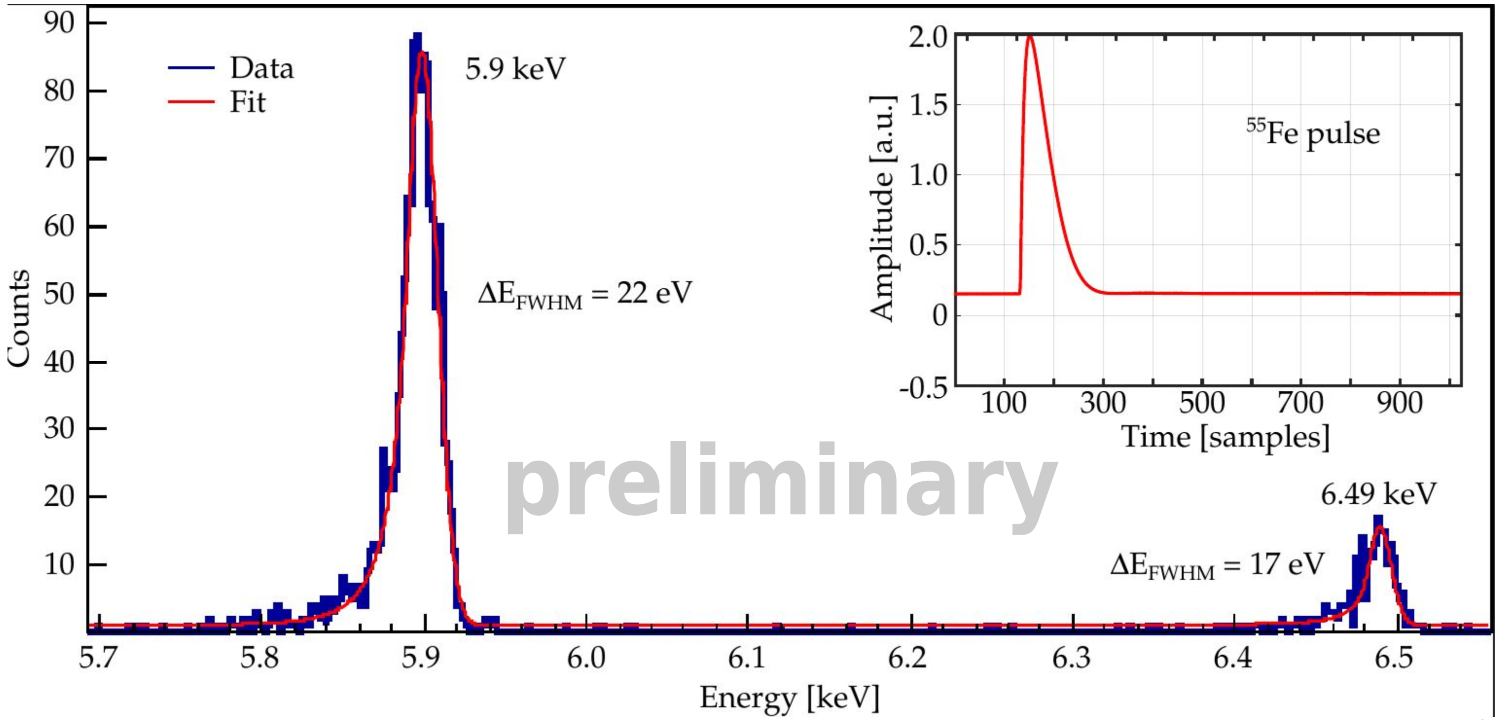




HOLMES TES µwave read-out testing

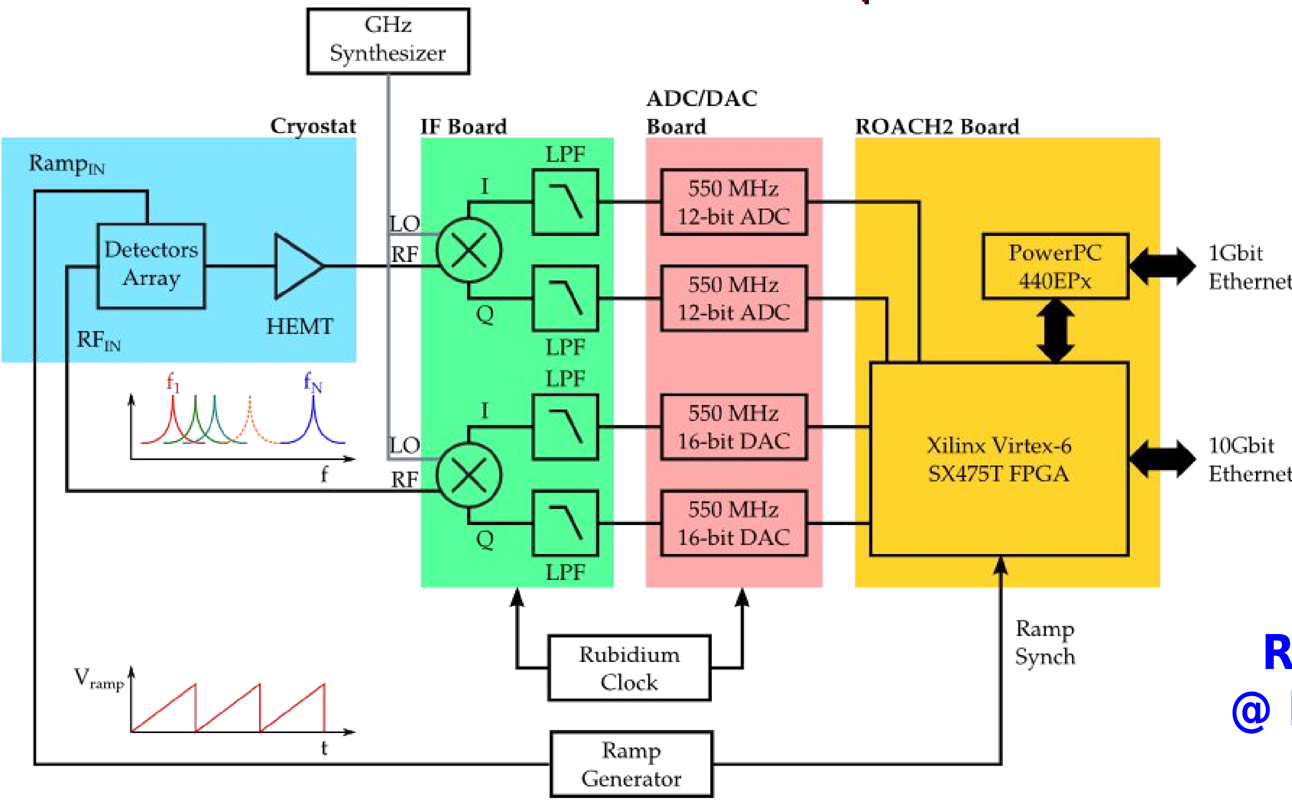


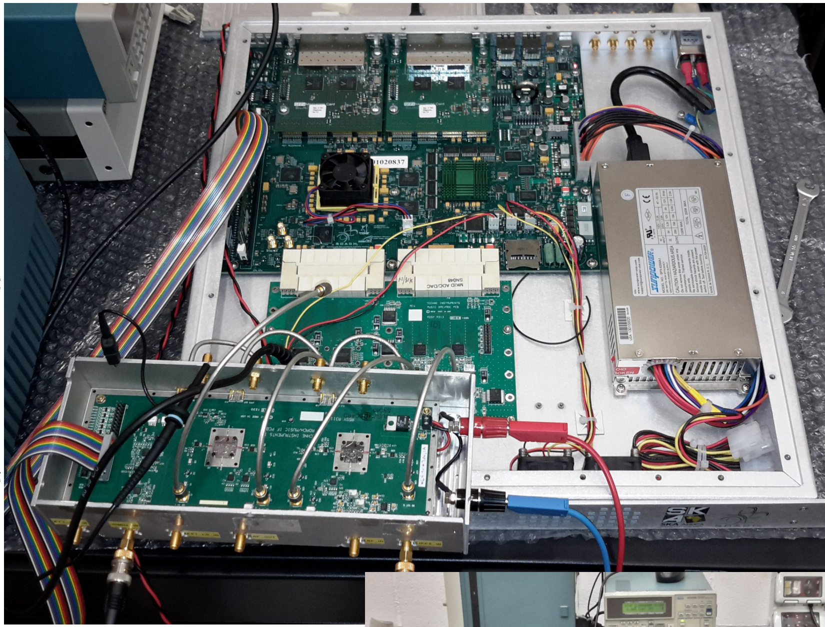




TES microwave multplexing (also for MMC)

Software Defined Radio + flux ramp modulation based on **ROACH2**





ROACH2 system @ Milano-Bicocca for HOLMES

- **multiplexing factor**
- f_{TES} required bandwidth per channel

$f_{TES} = n_{\Phi_0} f_{sampl}$ ($f_{sampl} = f_{ramp}$ from pile-up simulations)

$$N_{mux} = \frac{f_{ADC}}{10 f_{TES}}$$

$f_{sampl} = 0.5$MHz, $n_{\Phi_0} = 2 \rightarrow N_{mux} \approx 50$

Conclusions

Today LTD sensor technologies

are powerful and flexible tools for

cutting edge science applications

(largely incomplete review...)

There is room for further improvements

to make devices more *friendly* and flexible

Many more applications are possible

Backup slides ...

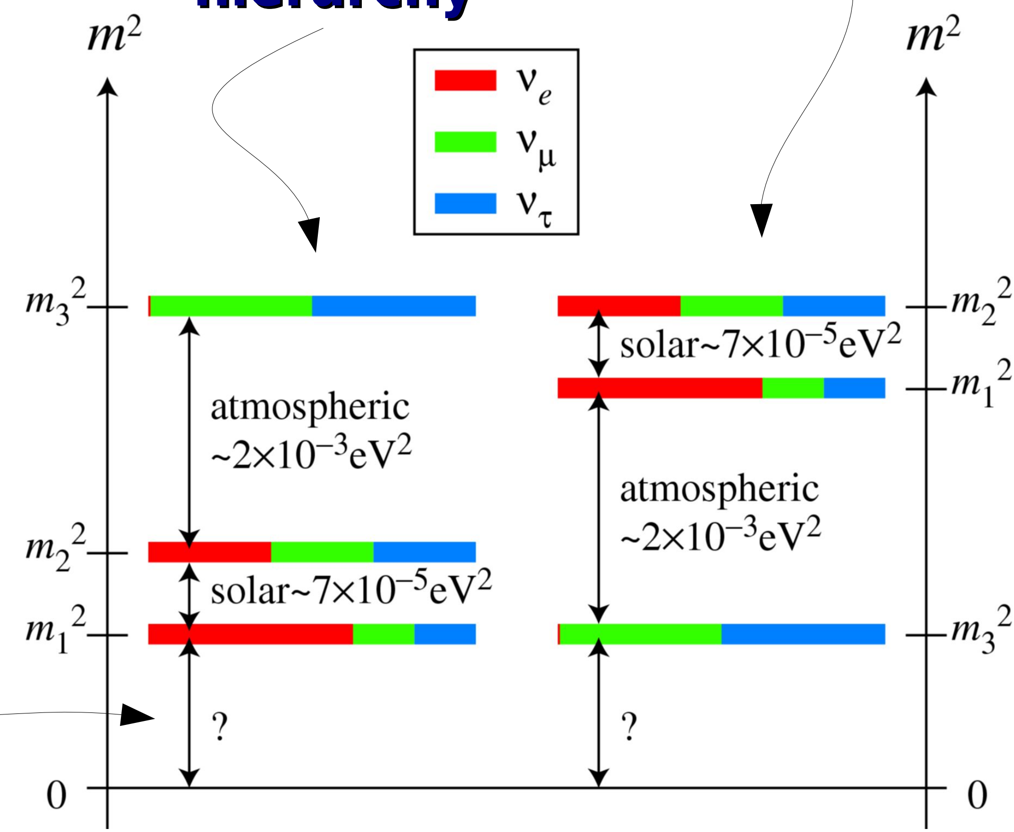
Neutrino open questions

- mass scale: i.e. mass of the lightest ν
- degenerate ($m_1 \approx m_2 \approx m_3$) or hierarchical masses
  - mass hierarchy: $m_1 < m_2 \ll m_3$ or $m_3 \ll m_1 \approx m_2$?
- $\nu = \bar{\nu}$? i.e. Dirac or Majorana particle?
- CP violation in the lepton sector

inverted hierarchy

normal hierarchy

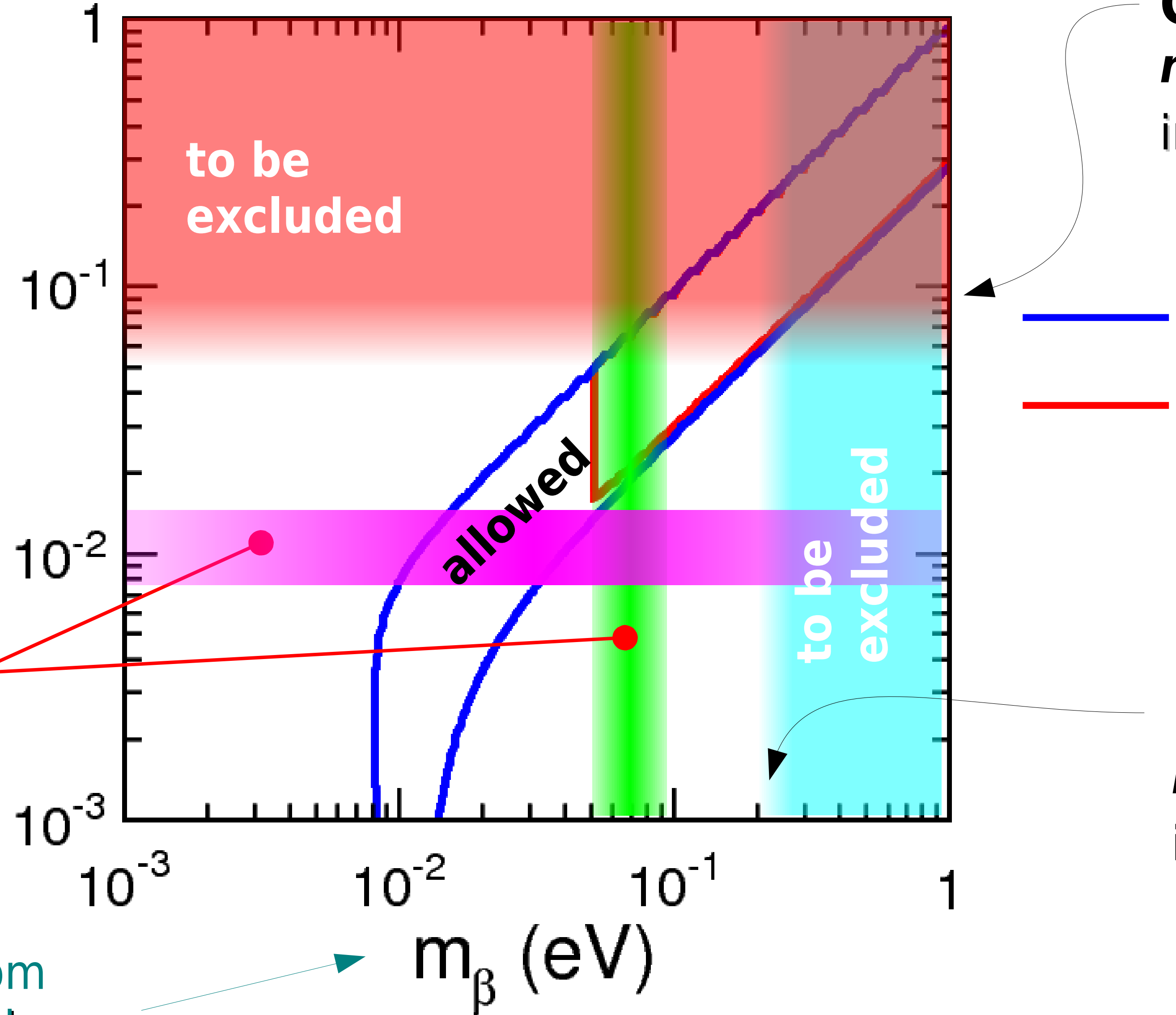
mass scale



The Challenge: absolute neutrino mass

expected for the next few years

from
Neutrinoless Double Beta decay



CUORE
$m_{\beta\beta} \lesssim 0.1$ eV
in 2016/2021

KATRIN
$m_{\nu} < 0.2$ eV
in 2016/2017

how to get to here?

from
Beta decay end-point

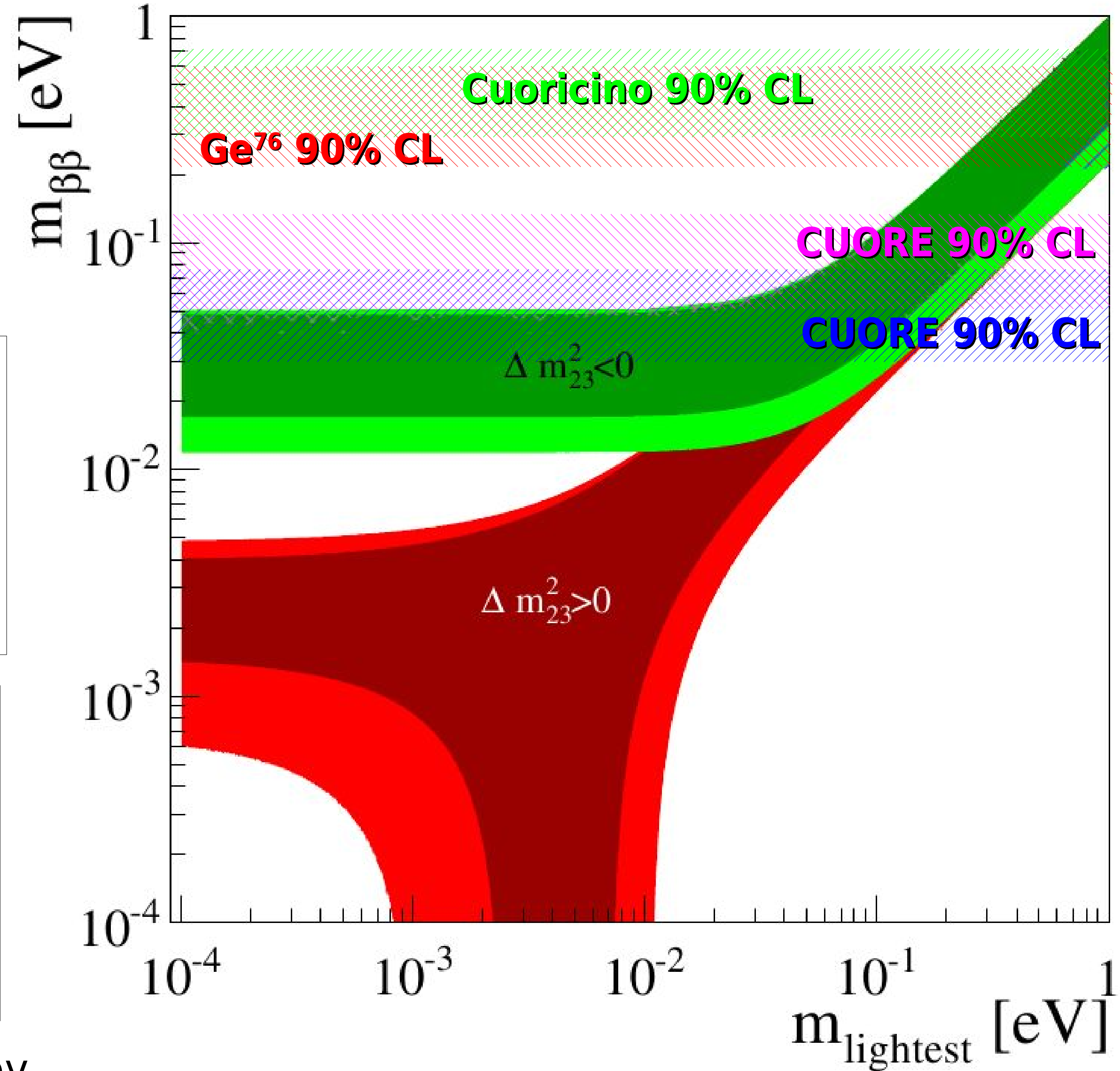
CUORE sensitivity potential

- sensitivity depends strongly on **background** level
- **NME uncertainties** broaden the sensitivity expectations *

90% CL sensitivity in 5 years

bkg [c/keV/kg/y]	*ΔE* [keV]	$\tau_{1/2}^{0\nu}$ [y]	$\langle m_\nu \rangle$ [meV]
0.01	5	1.0×10^{26}	50 ÷ 129
0.001	5	2.8×10^{26}	30 ÷ 77

Nuclear Matrix Elements from:
Poves et al., NPA 818 (2009) 139; Faessler et al., JoP G: Nucl. Part. Phys. 39 (2012) 124006; Fang et al. , PRC 83 (2011) 034320; Suhonen et al., JoP G: Nucl. Part. Phys. 39 (2012) 124005; Iachello et al., PRC 87 (2013) 014315; P.K. Rath et al., Phys. Rev. C82 064310 (2010); T. R. Rodriguez et al., Phys. Rev. Lett 105 252503 (2010)

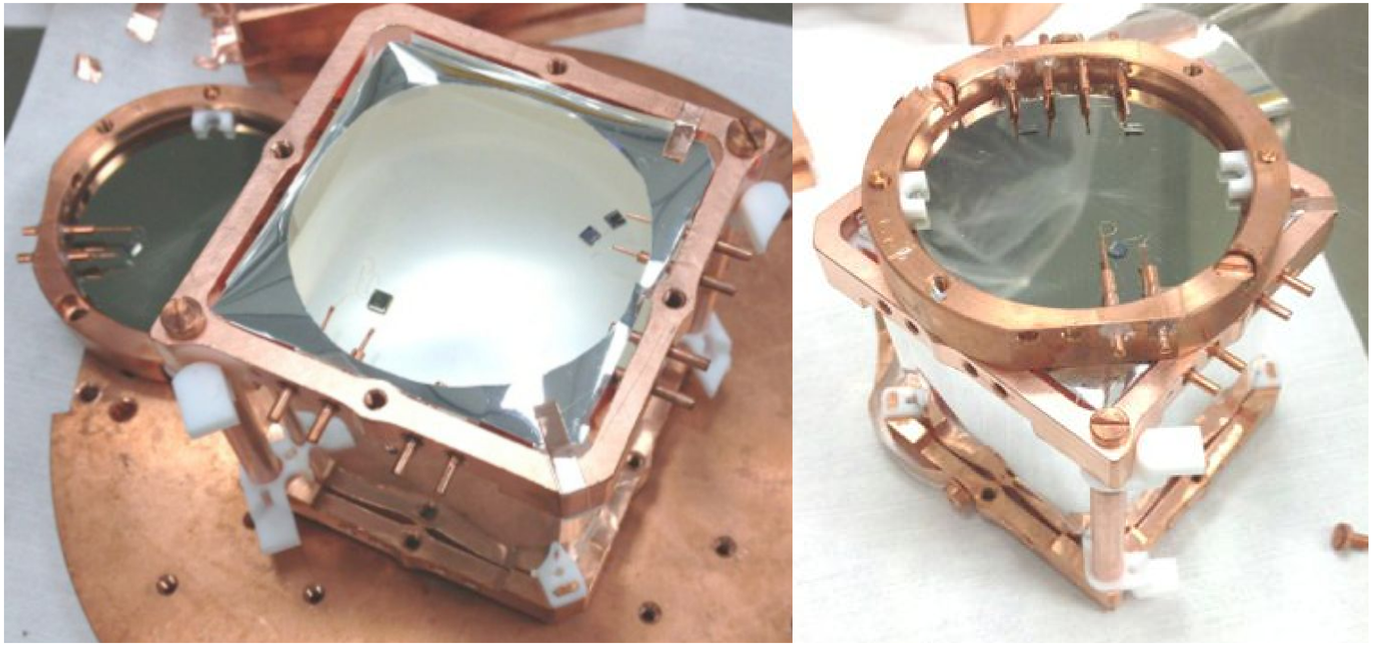


* **NME uncertainties** can be reduced by observing ββ-0ν in many different isotopes

F. Alessandria et al., *Sensitivity and Discovery Potential of CUORE to Neutrinoless Double-Beta Decay*, arXiv:1109.0494v3 [nucl-ex]

TeO_2 with Cherenkov

- TeO_2 does not scintillate, but MeV βs emit Cherenkov radiation
- threshold for Cherenkov light emission:
  - ▹ 50 keV for β/γ
  - ▹ 400 MeV for α
  - ▹ α/γ discrimination is possible (T.Tabarelli de Fatis, EPJC65 (2010) 359)
- Expected light emission: 140 eV/MeV
- Extremely challenging background discrimination

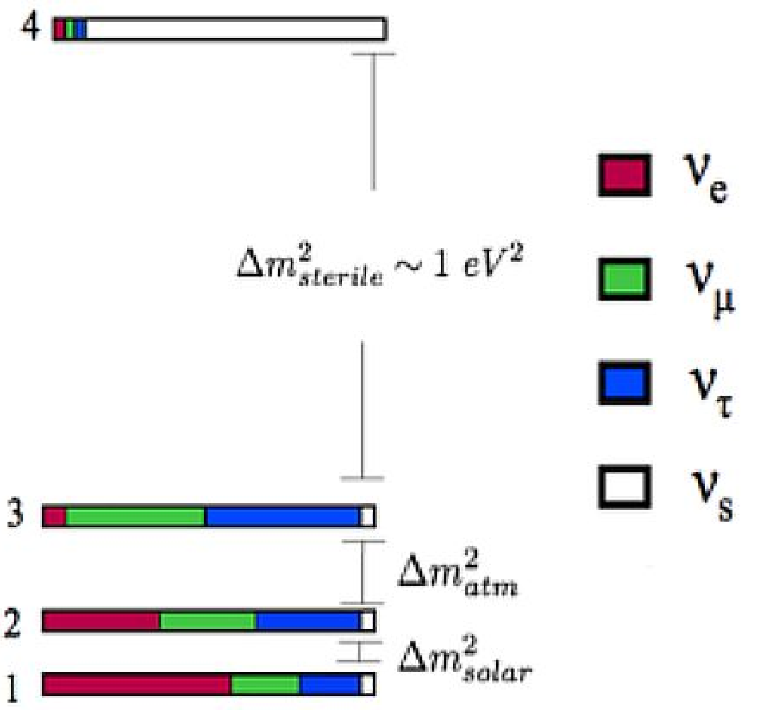


Anomalies and unobserved phenomenologies

- there are **anomalies** in data from
  - past reactor oscillation experiments (reanalyzed)
  - short baseline accelerator oscillation experiments (LSND, MiniBOONE)
  - solar experiment calibration with neutrino sources (GALLEX)
- call for 4th neutrino mass state **ν_4 → sterile neutrino**

$\Delta m^2 \approx 1$ eV and $\sin^2 2\theta \gtrsim 0.1$

normal hierarchy 3+1

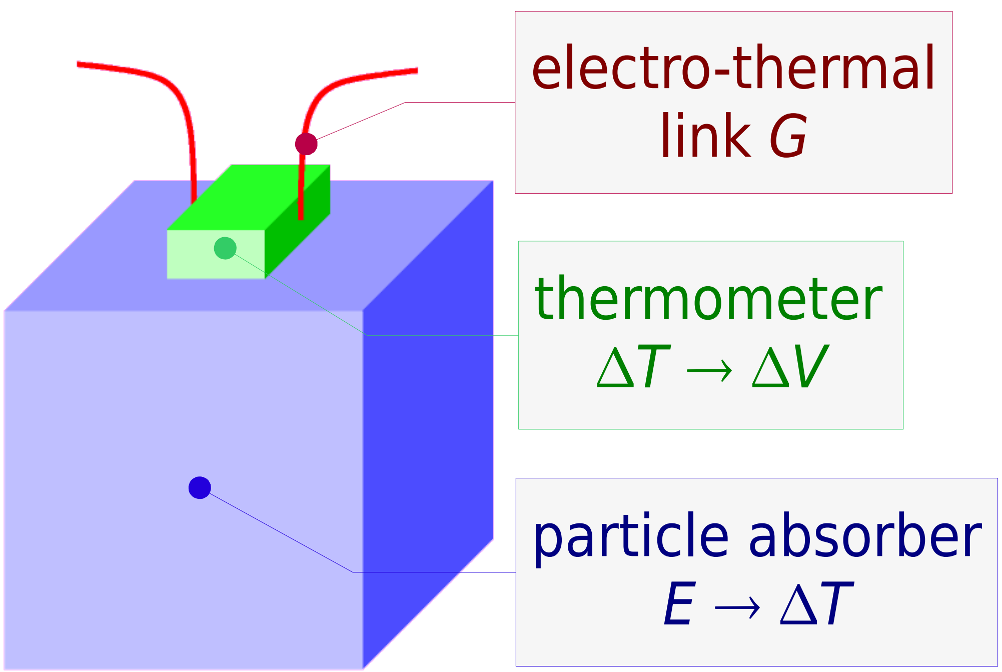


Anomalies and unobserved phenomenologies

- **Sterile (Right Handed) neutrinos** are a natural extension to the Standard Model to include the mass of active neutrinos (νMSM)
  - sterile neutrino in the keV mass range are perfect candidate as Warm Dark Matter (WDM) particles
- **Standard Model also predicts**:
  - coeherent neutrino scattering on nuclei → never observed!
  - cosmic neutrino background (CνB) → never observed!

→ neutrinos probe physics beyond Standard Model

Low temperature detectors as calorimeters



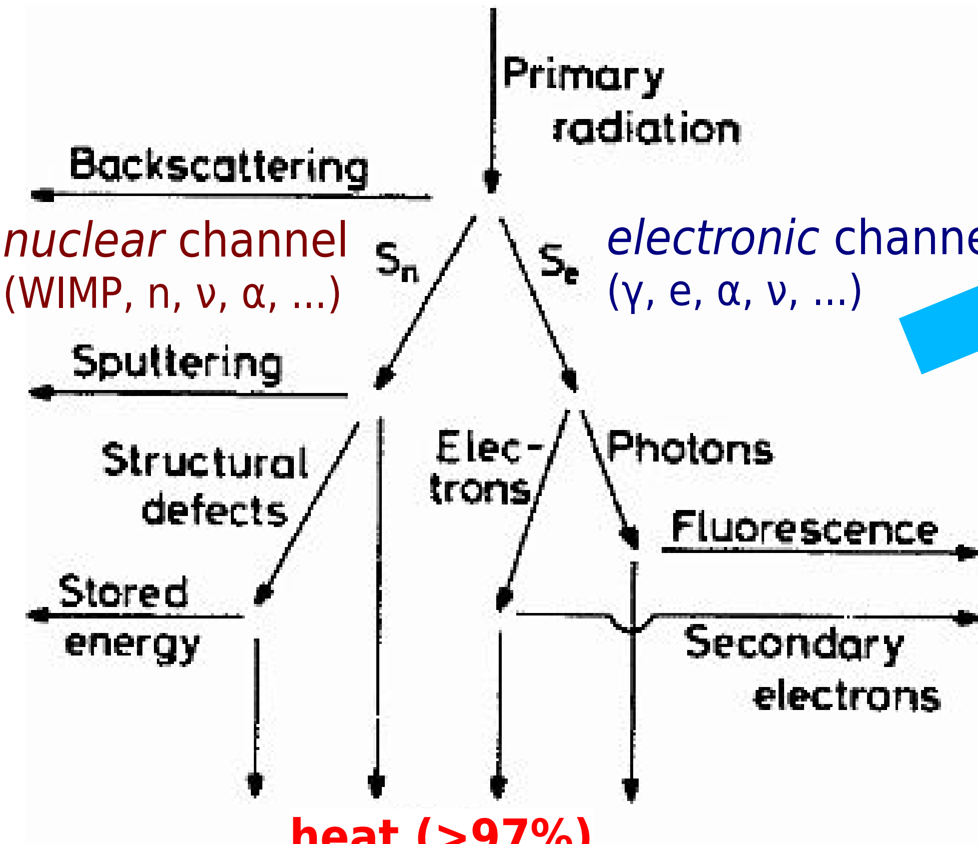
- (quasi-)equilibrium thermal detector
- complete energy *thermalization*
  - ▶ calorimetry
- $\Delta T = E/C$ (C thermal capacity)
  - ▶ low C
    - ▷ low T (i.e. $T \ll 1$K)
    - ▷ dielectrics, superconductors
- Pros and cons
  - ▲ high energy resolution
  - ▲ large choice of absorber materials
  - ▲ true calorimeters
  - ▼ only energy and time informations
  - ▼ slow time response

Particle interactions in LTD

directly ionizing: γ, e, α, …

indirectly ionizing: n, WIMP, ν, …

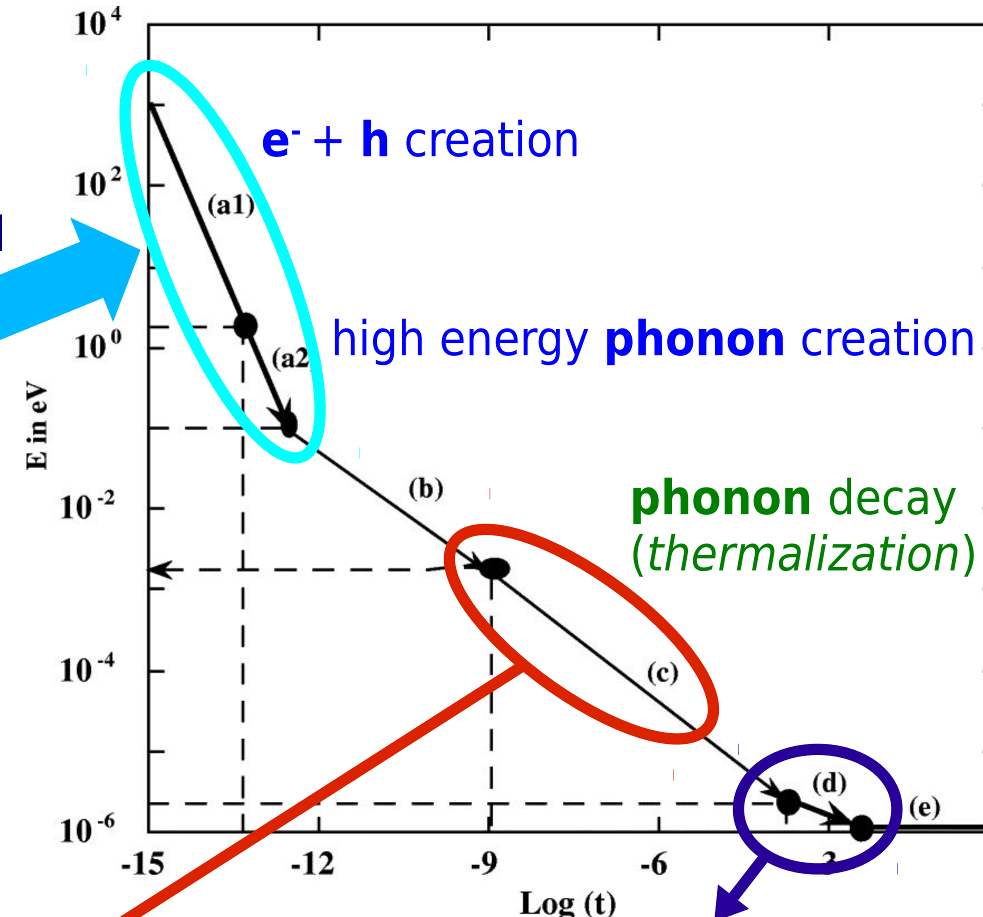
nuclear channel
(WIMP, n, ν, α, …)



electronic channel
(γ, e, α, ν, …)

heat (>97%)
i.e. phonons

timescale

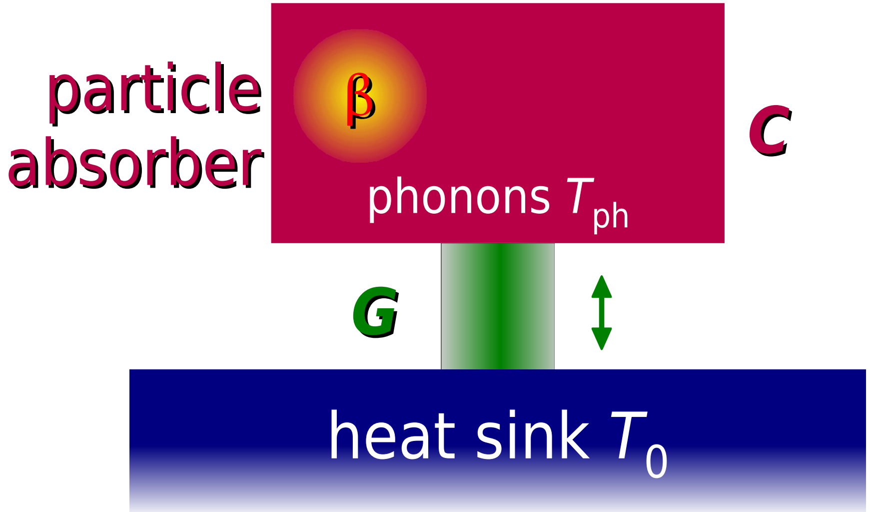


ballistic phonon propagation
→ **athermal** LTD signal

temperature rise/decay
→ **quasi-equilibrium** LTD signal

M. Chapellier, Nuclear Instruments and Methods in Physics Research A 520 (2004) 21–26

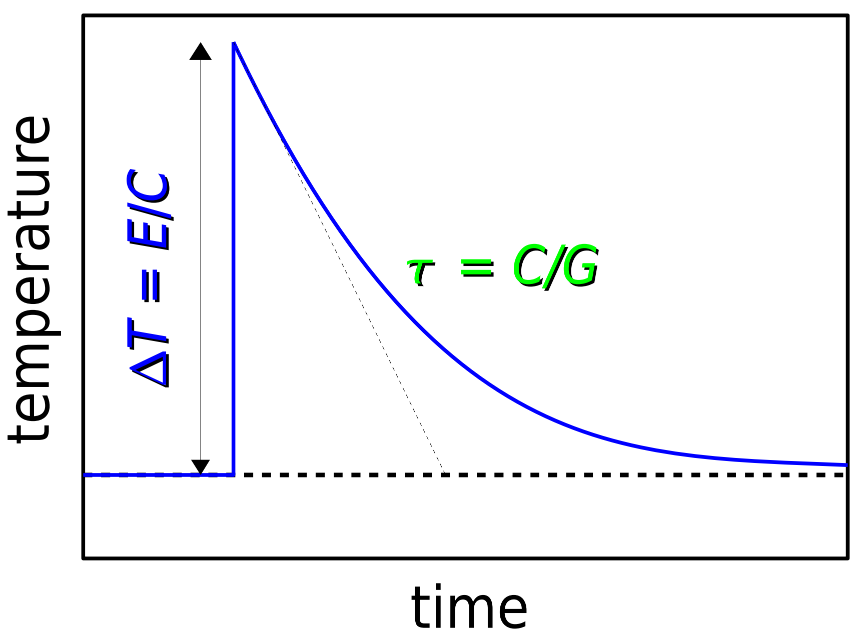
Low temperature detector principles



$$C(T_{ph})\frac{dT_{ph}}{dt}+G(T_{ph},T_0)=P(t)$$

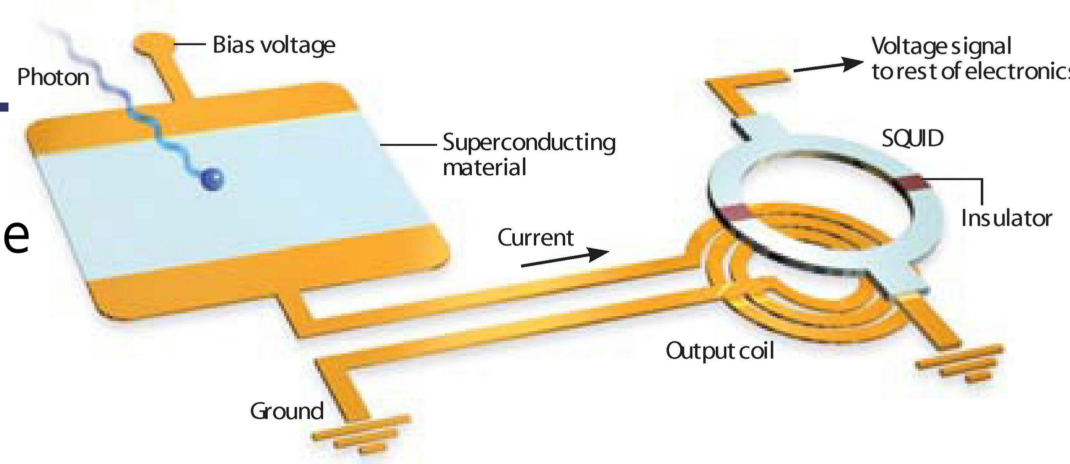
$$P(t)=\Delta E\delta(t) \rightarrow T_{ph}(t)=T_0+\frac{\Delta E}{C}e^{-t/\tau}$$

for $t>0$ and with $\tau=C/G$

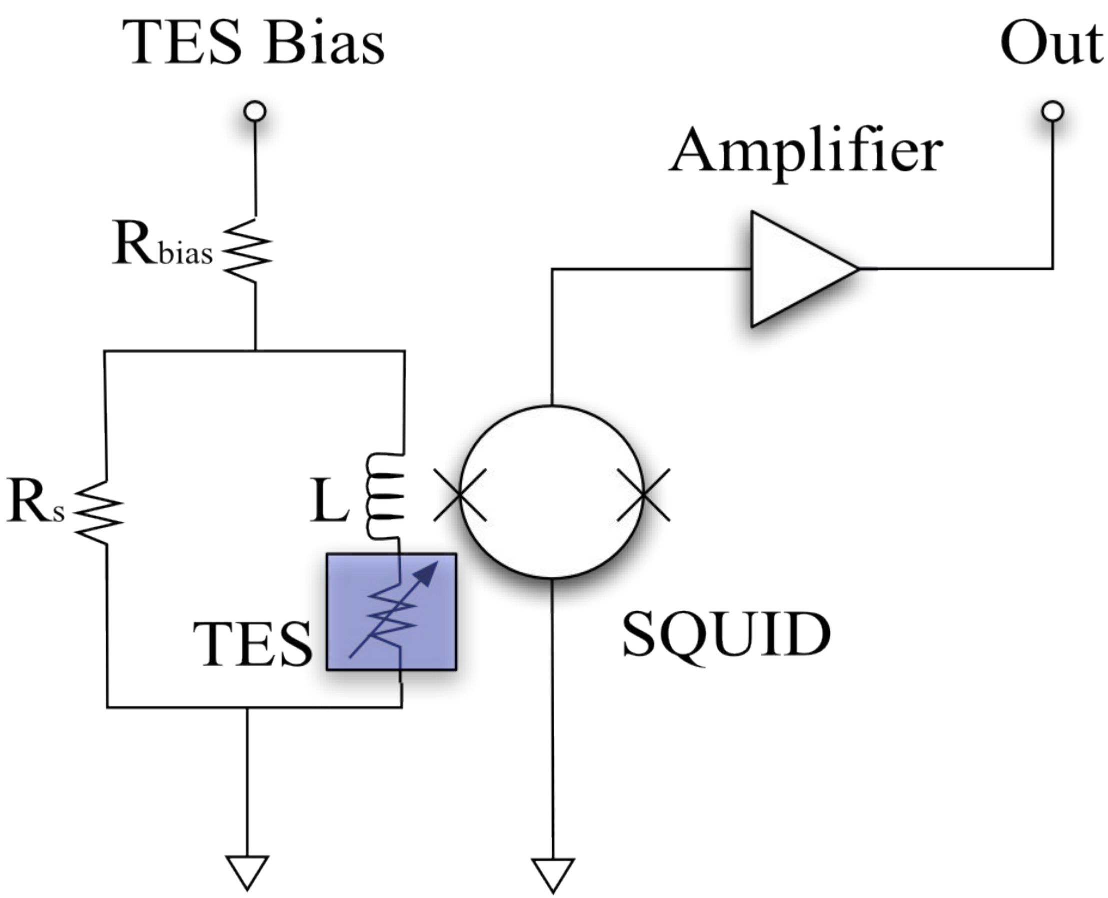


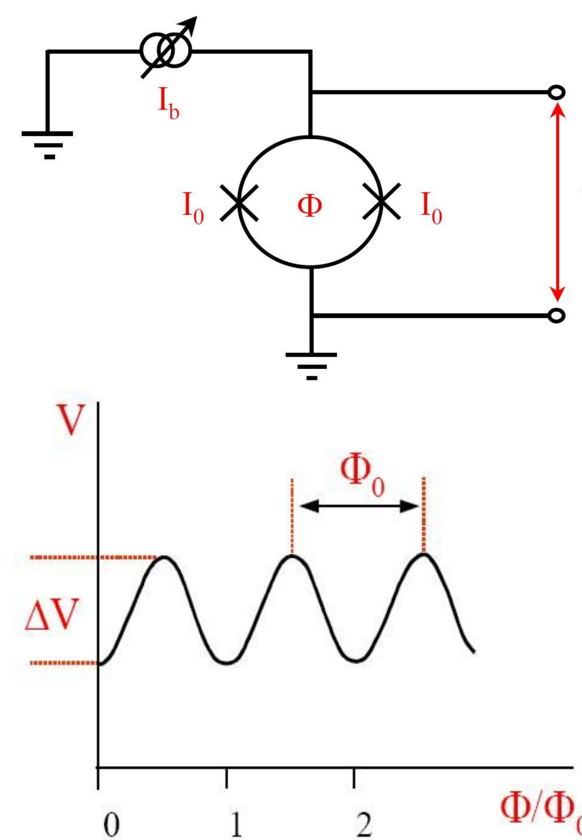
- **750 g of TeO_2 @ 10 mK**
  $C \sim T^3$ (Debye) $\Rightarrow$ $C \sim 2\times10^{-9}$ J/K
  1 MeV γ-ray $\Rightarrow$ **$\Delta T \sim 80\ \mu K$**
  $G \sim 4\times10^{-9}$ W/K $\Rightarrow$ **$\tau=C/G \sim 0.5$ s**
- **1 mg of Re @ 100 mK**
  $C \sim T^3$ (Debye) $\Rightarrow$ $C \sim 10^{-13}$ J/K
  6 keV X-ray $\Rightarrow$ **$\Delta T \sim 10$ mK**
  $G \sim 10^{-11}$ W/K $\Rightarrow$ **$\tau = C/G \sim 10$ ms**

TES read-out: SQUID

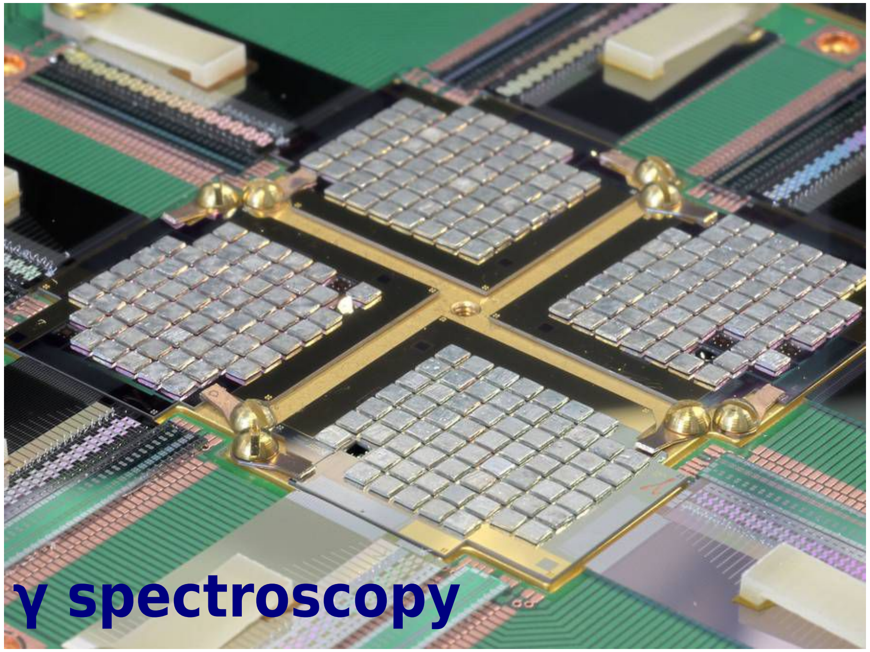


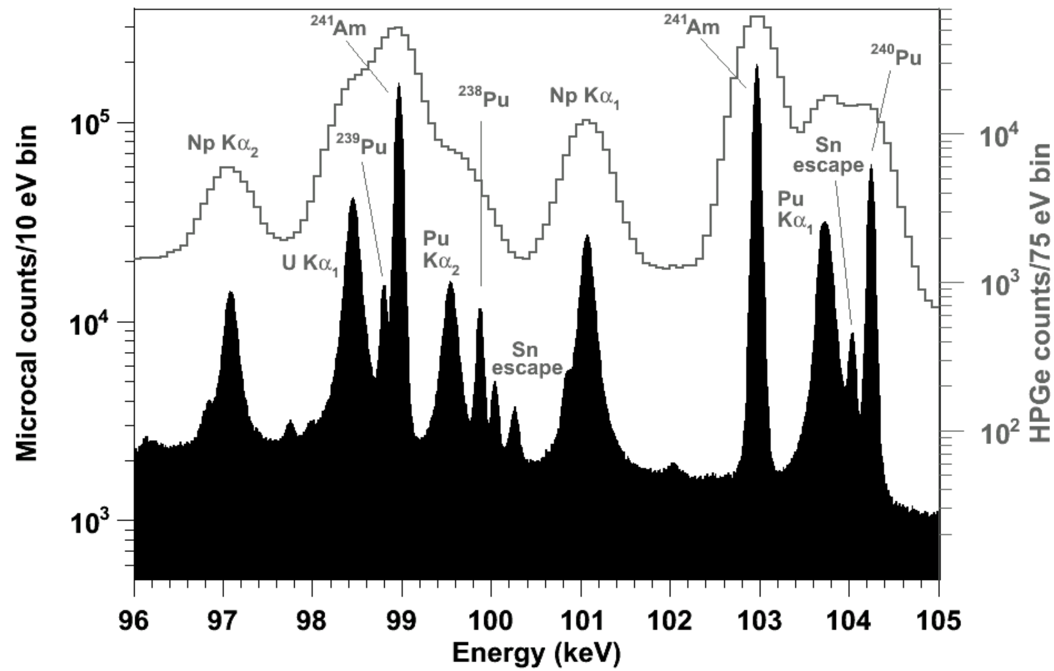
- low impedance suitable for multiplexable dc-SQUID magnetometers
- current amplifier configuration
  - ▷ $\Delta I \rightarrow \Delta \Phi \rightarrow \Delta V$
- feedback linearized response

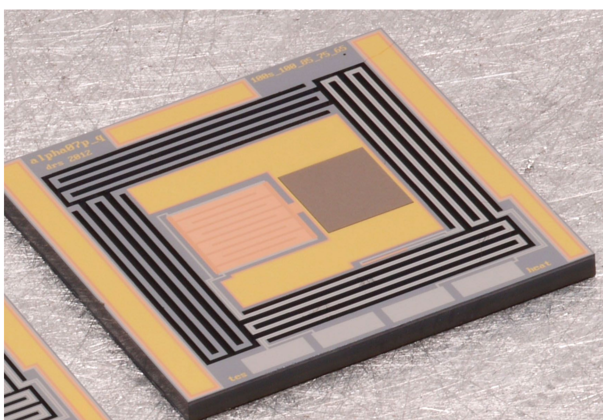


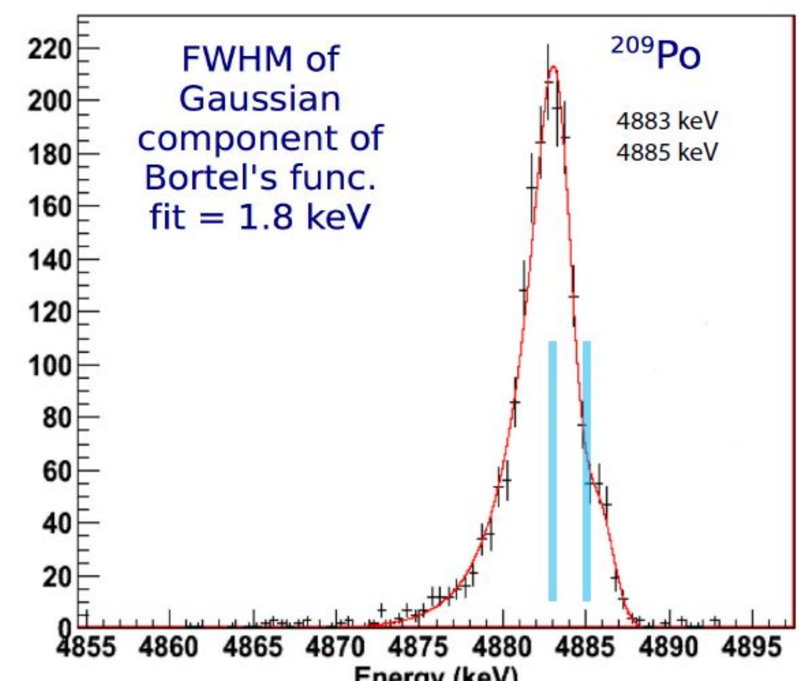


TES arrays for γ and α with Sn absorbers



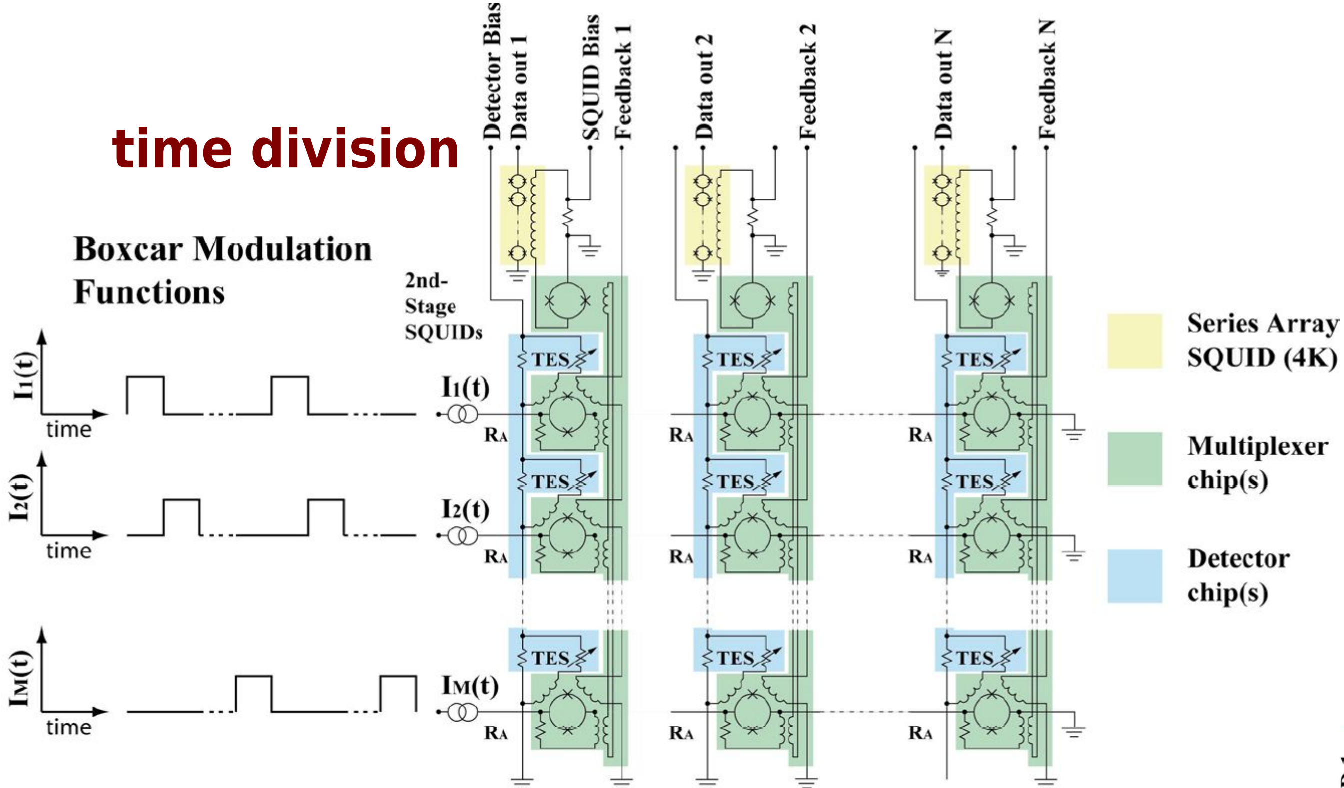






TES array multiplexing

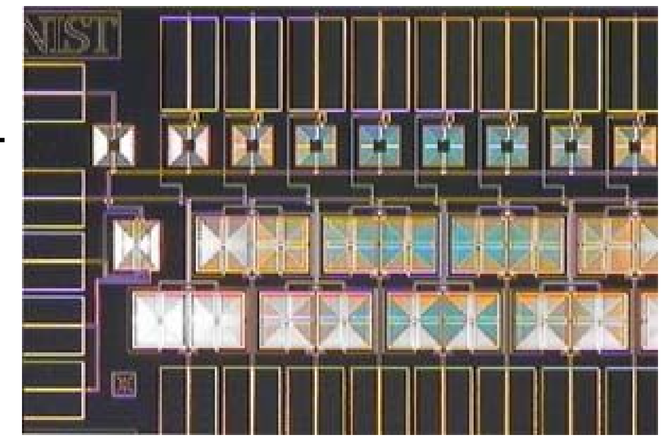
time division



32 channels in 1 column

32 addresses

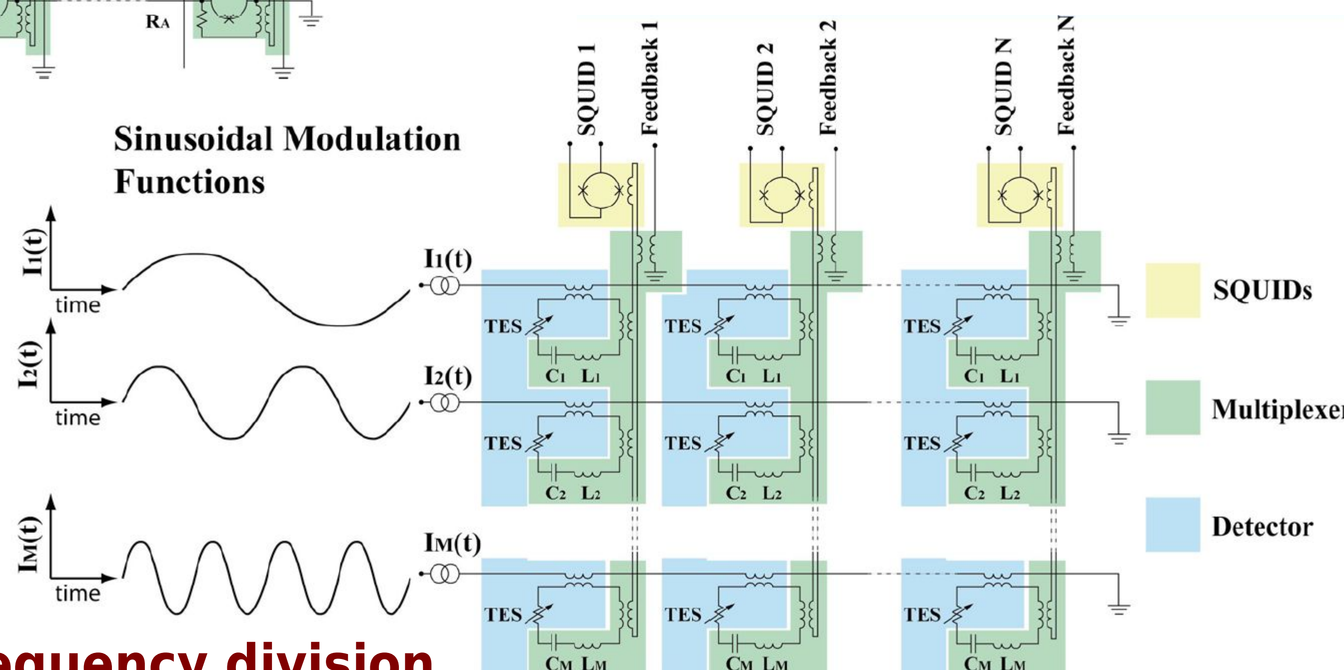
column outputs



...

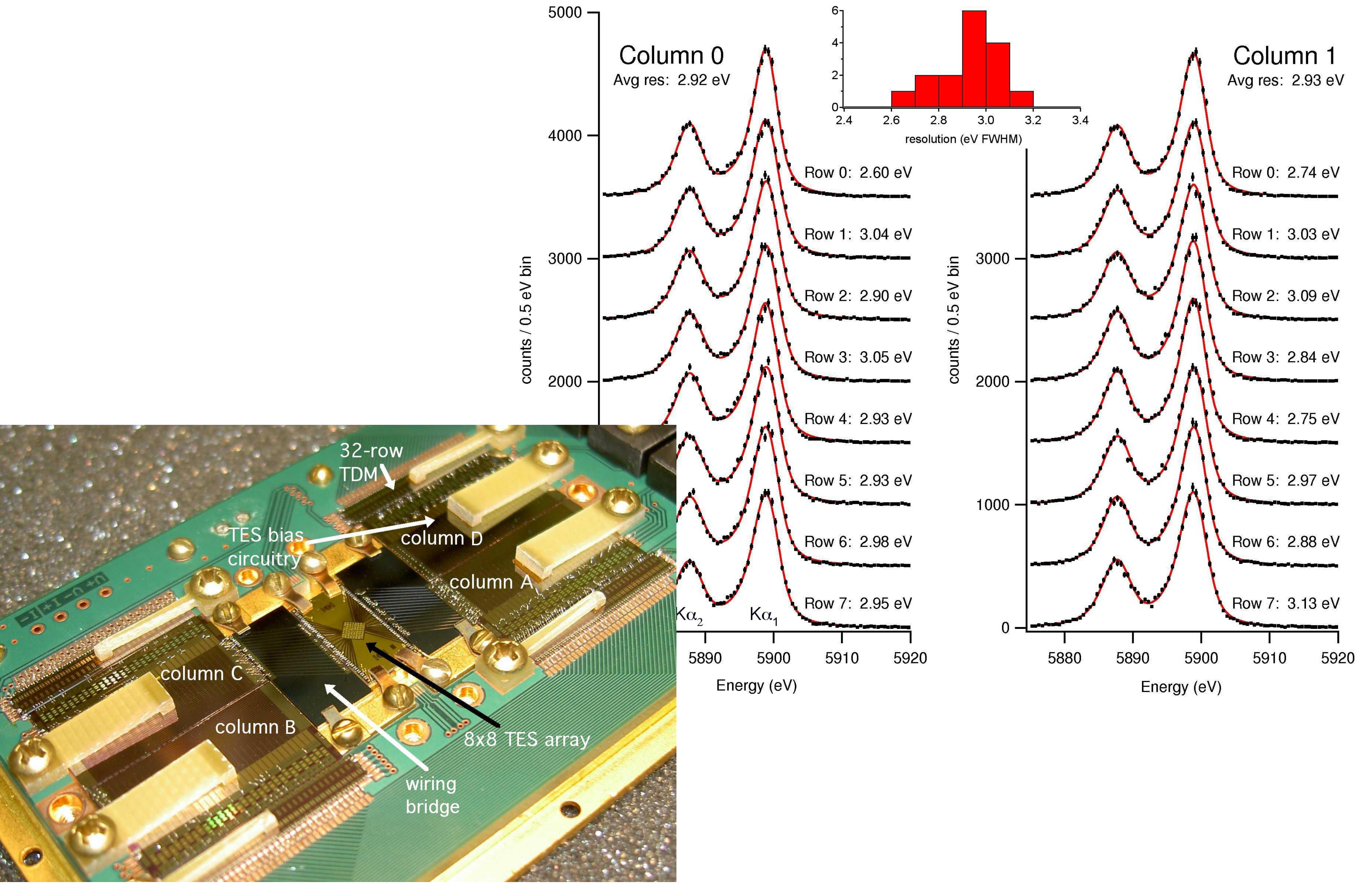
32 inputs

***NxN* array**
without *mux*
NxN readout channels
with *mux*
N addresses + *N* outputs

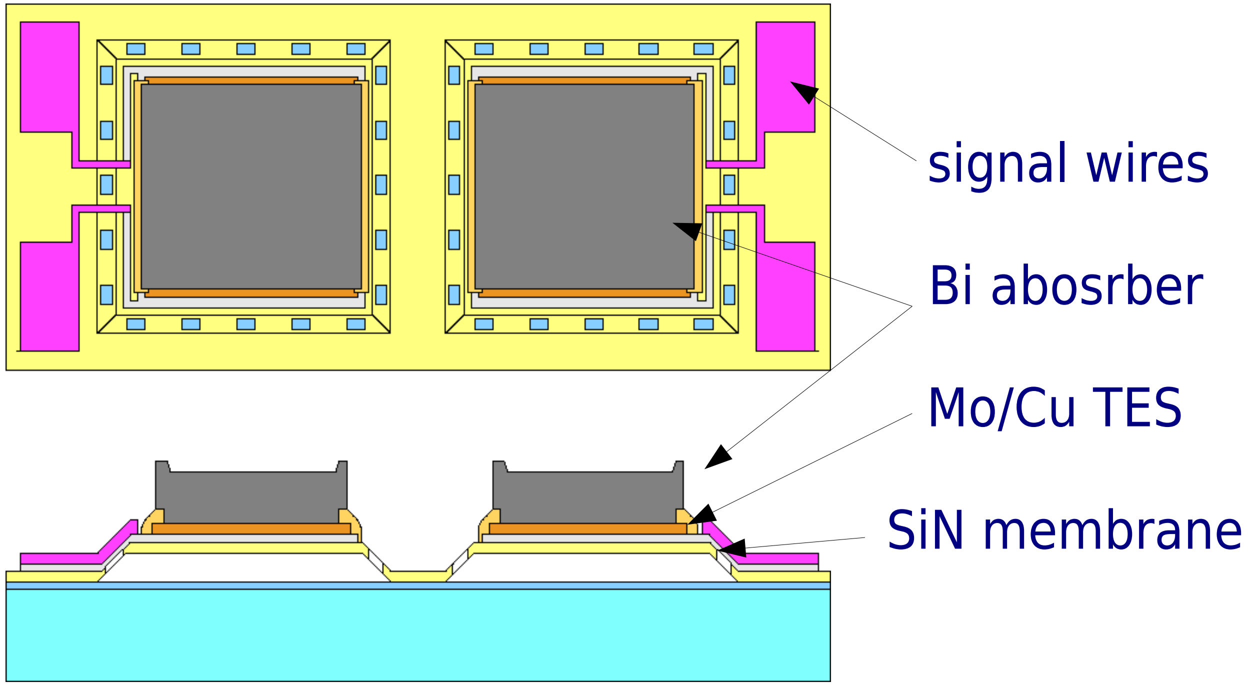


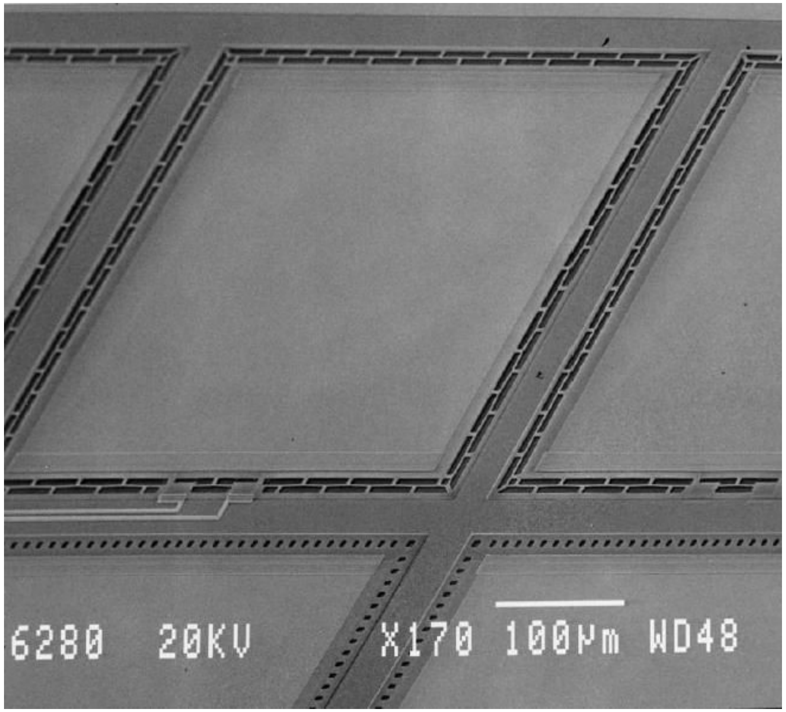
frequency division

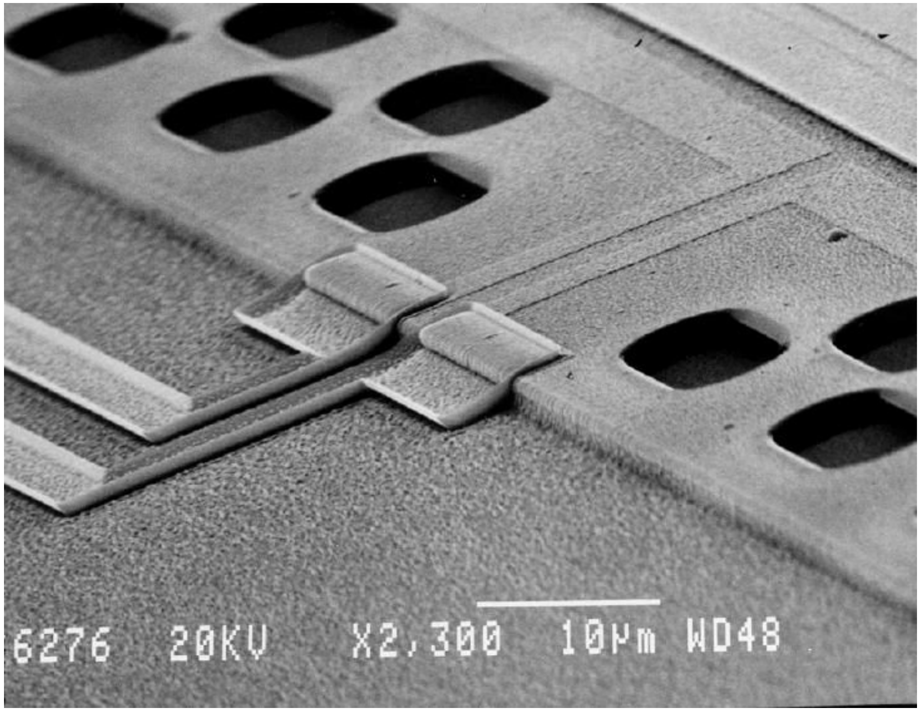
TDM array multiplexing



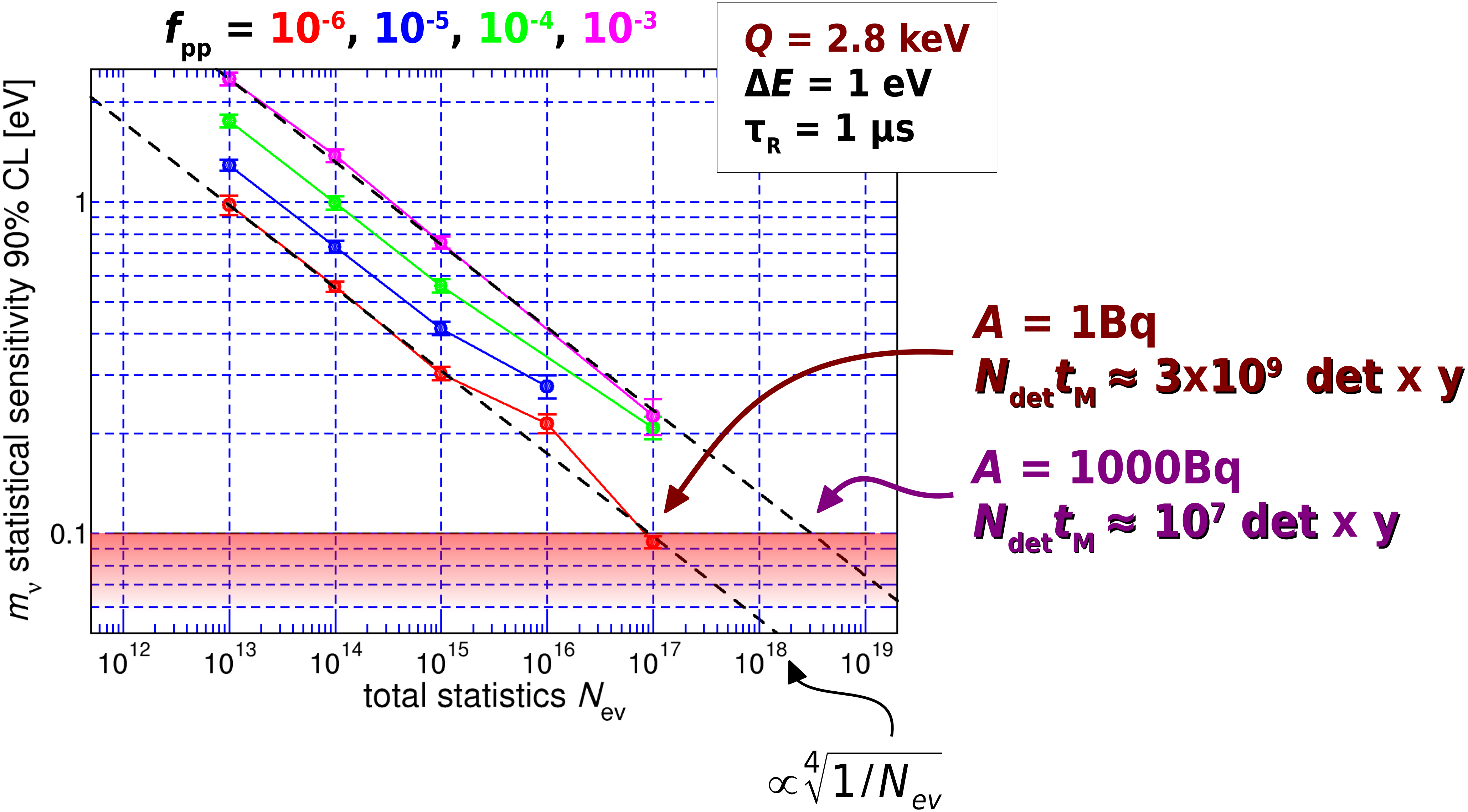
Micromachined TES arrays / 1







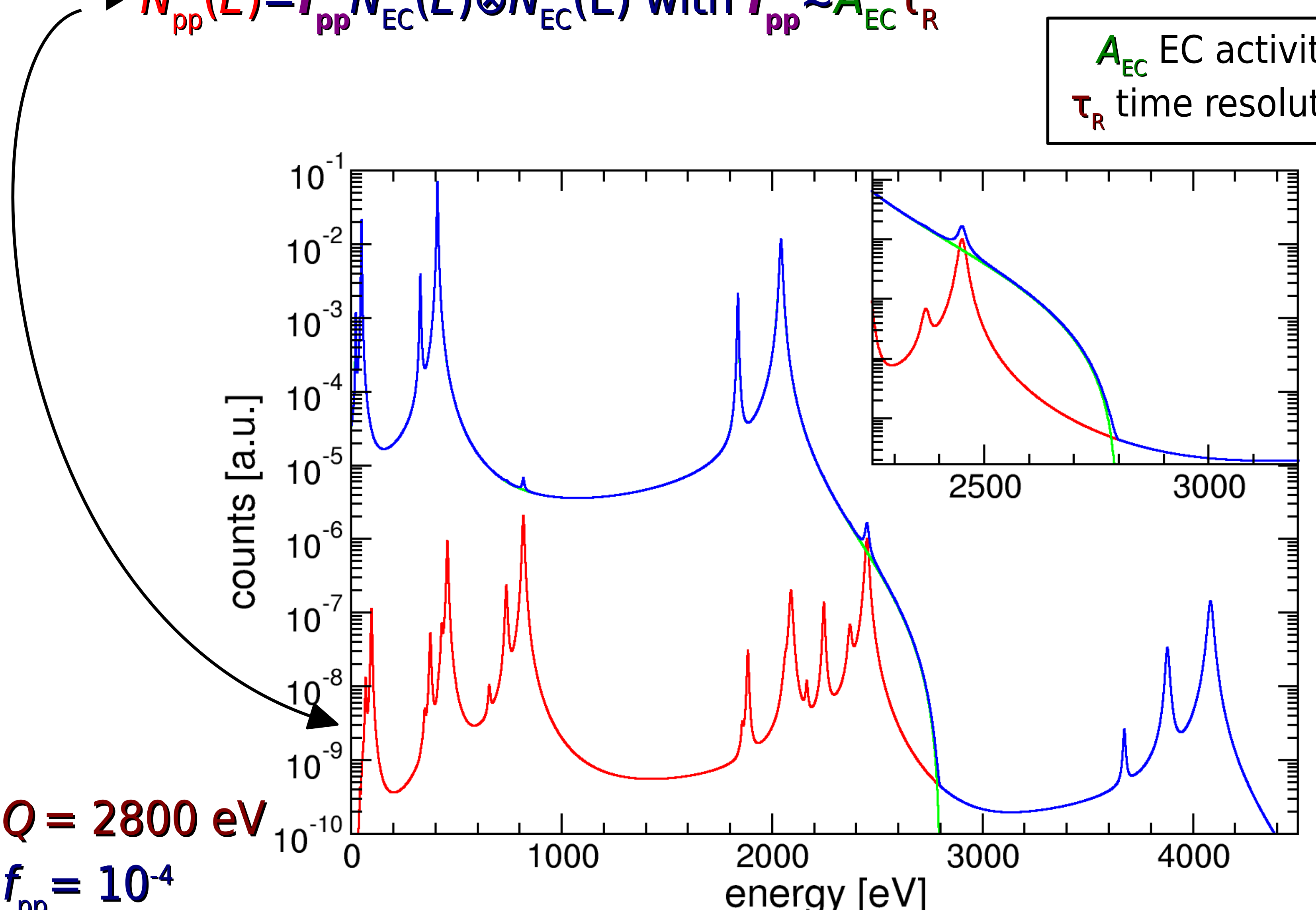
Statistical sensitivity: Montecarlo simulations / 2



Electron capture end-point experiment / 2

- no direct **calorimetric** measurement of Q (end-point) so far
- complex **pile-up spectrum**
  - $N_{pp}(E) = f_{pp} N_{EC}(E) \otimes N_{EC}(E)$ with $f_{pp} \approx A_{EC} \tau_R$

A_{EC} EC activity per detector
τ_R time resolution (≈rise time)

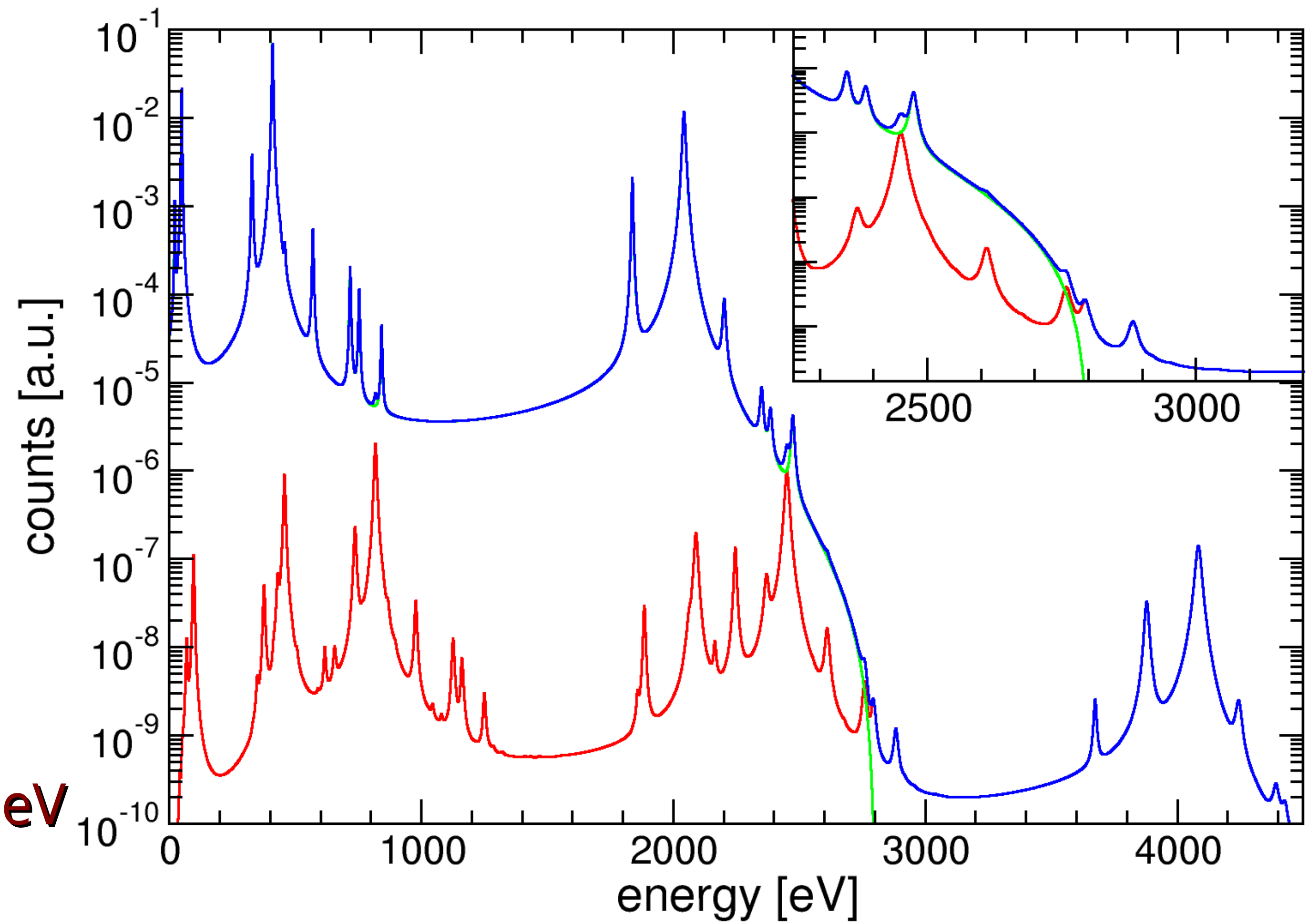


Q = 2800 eV
$f_{pp} = 10^{-4}$

Electron capture end-point experiment / 3

- shake-up/shake-off → **double hole excitations**
  - *n*-hole excitations possible but less probable
  - authors do not fully agree on energies and probabilities
- even more complex **pile-up spectrum**
  - it may be worth keeping **f_{pp} smaller than 10^{-4}**

A.De Rujula, arXiv:1305.4857
R.G.H.Robertson, arXiv:1411.2906
A.Faessler et al., PRC 91 (2015) 45505



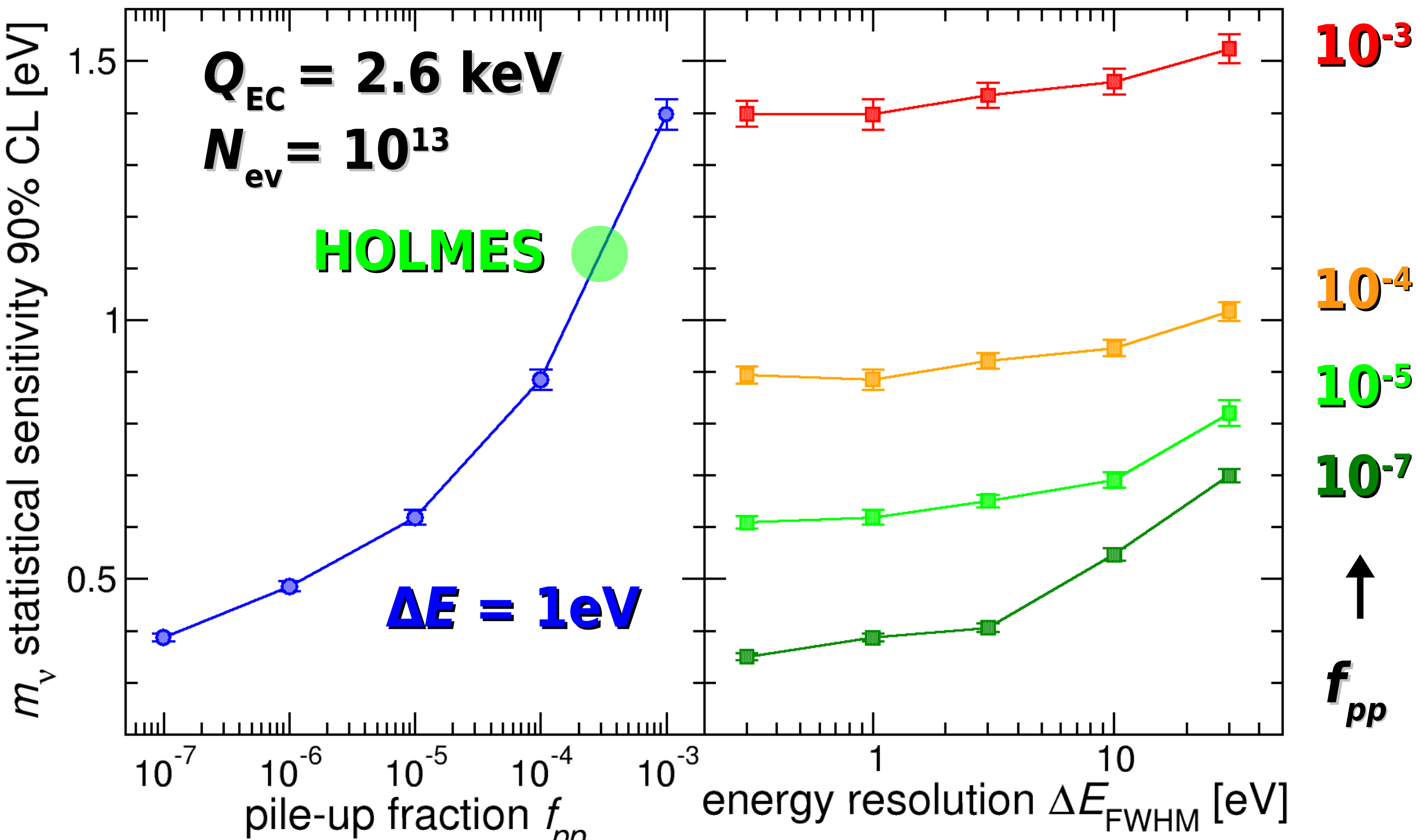
Q = 2800 eV
f_{pp} = 10^{-4}

HOLMES design: more MC simulations...

Statistical sensitivity $\Sigma(m_\nu)$ dependencies from MC simulations

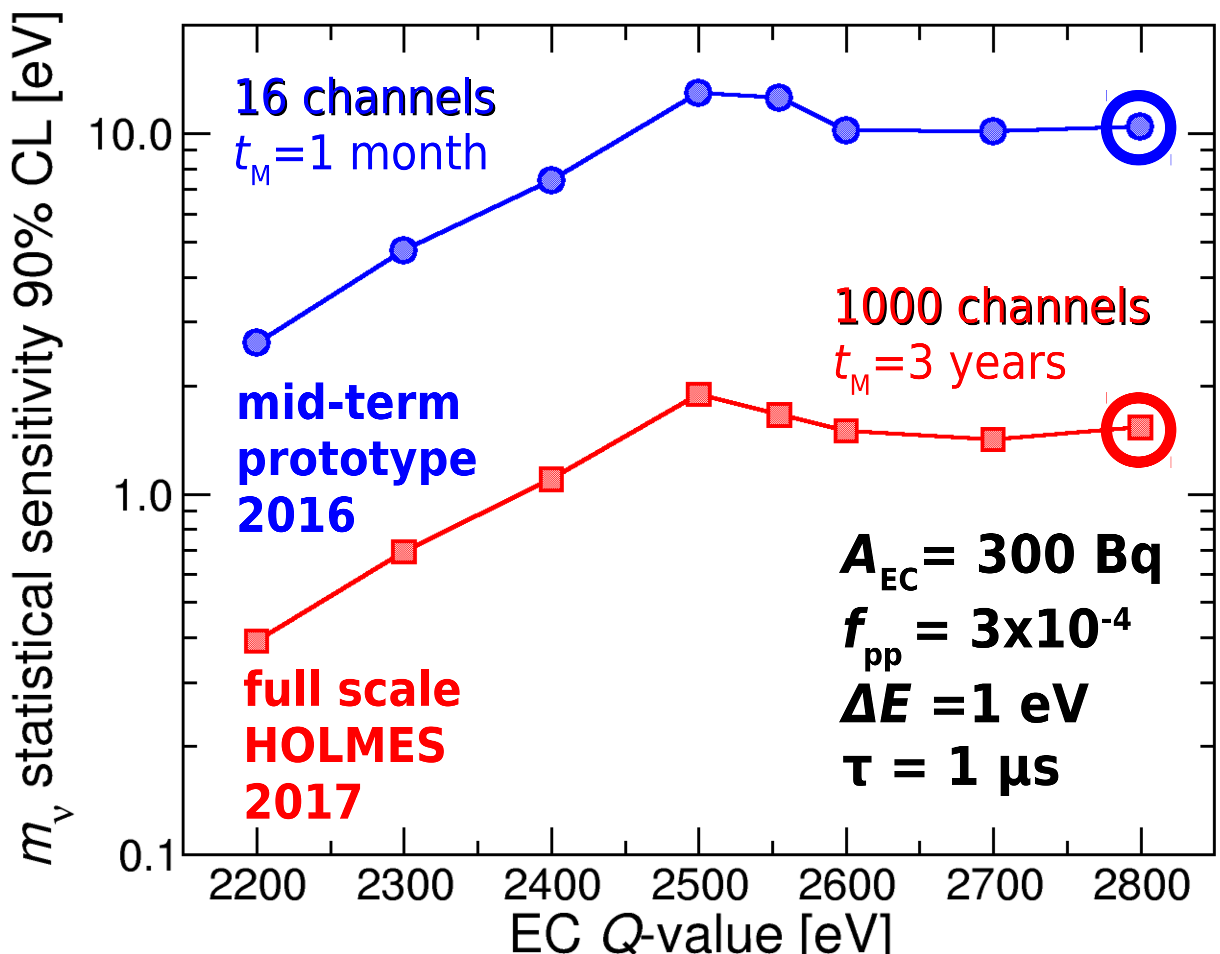
- strong on statistics $N_{ev}=A_{EC}N_{det}t_M$: $\Sigma(m_\nu) \propto N_{ev}^{1/4}$
- strong on rise time pile-up (probability $f_{pp} \approx A_{EC}\tau_R$)
- weak on energy resolution ΔE

t_M measuring time
N_{det} number of detectors
A_{EC} EC activity per detector
τ_R time resolution (≈rise time)



goal

- neutrino mass measurement: m_ν statistical sensitivity as low as 0.4 eV
- prove technique potential and scalability:
  - assess EC *Q*-value
  - assess systematic errors



baseline

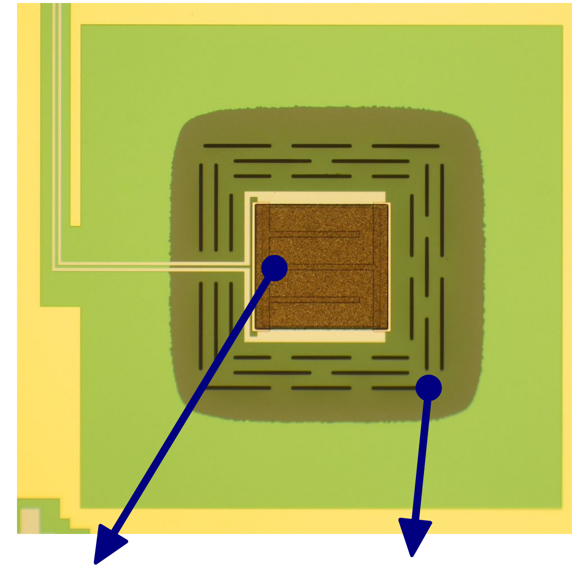
- TES with **implanted ^{163}Ho**
  - 6.5x10^{13} nuclei per pixel → 300 dec/sec
  - $\Delta E \approx$1eV and $\tau_R \approx$1μs
- 1000 channel array
  - 6.5x10^{16} ^{163}Ho nuclei → ≈18μg
  - 3x10^{13} events in 3 years

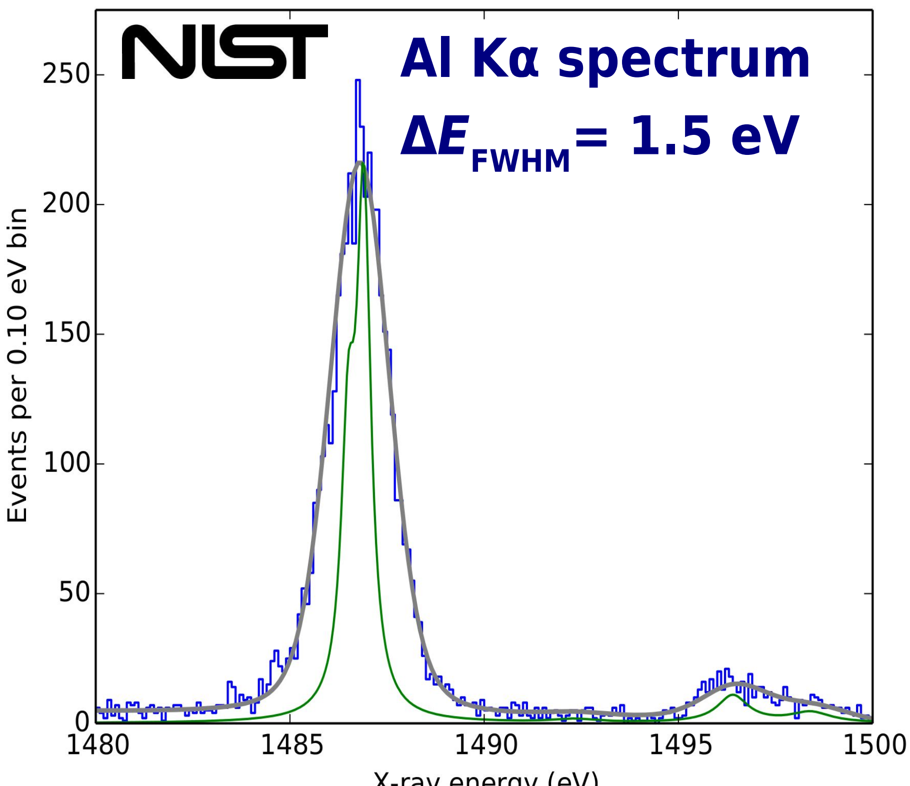
→ Project Started on February 1st 2014

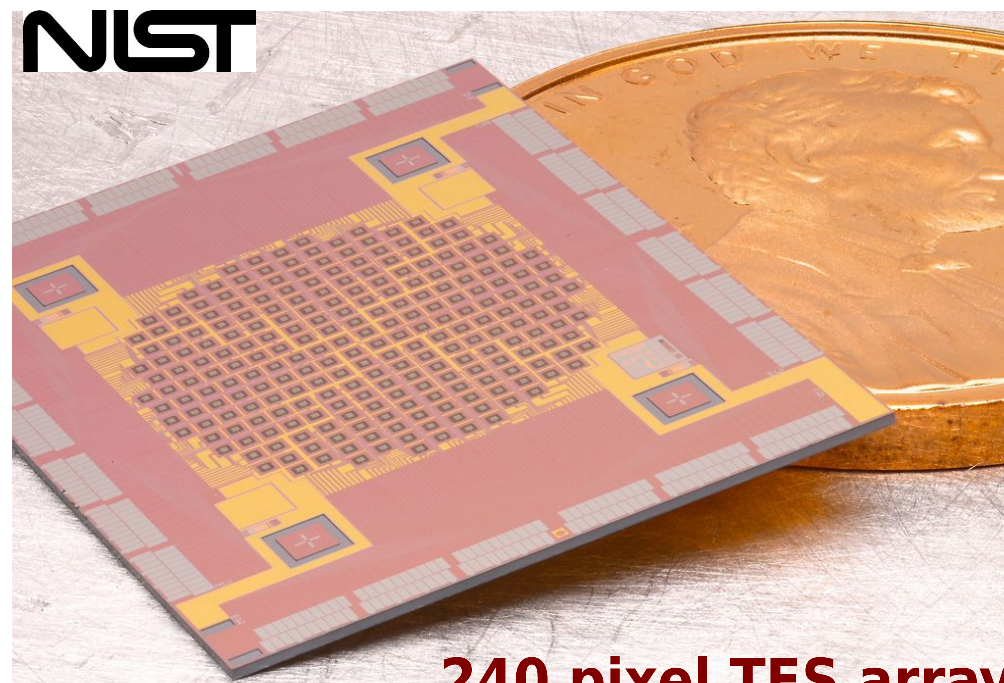
B. Alpert et al., Eur. Phys. J. C, (2015) 75:112
http://artico.mib.infn.it/holmes

HOLMES detectors

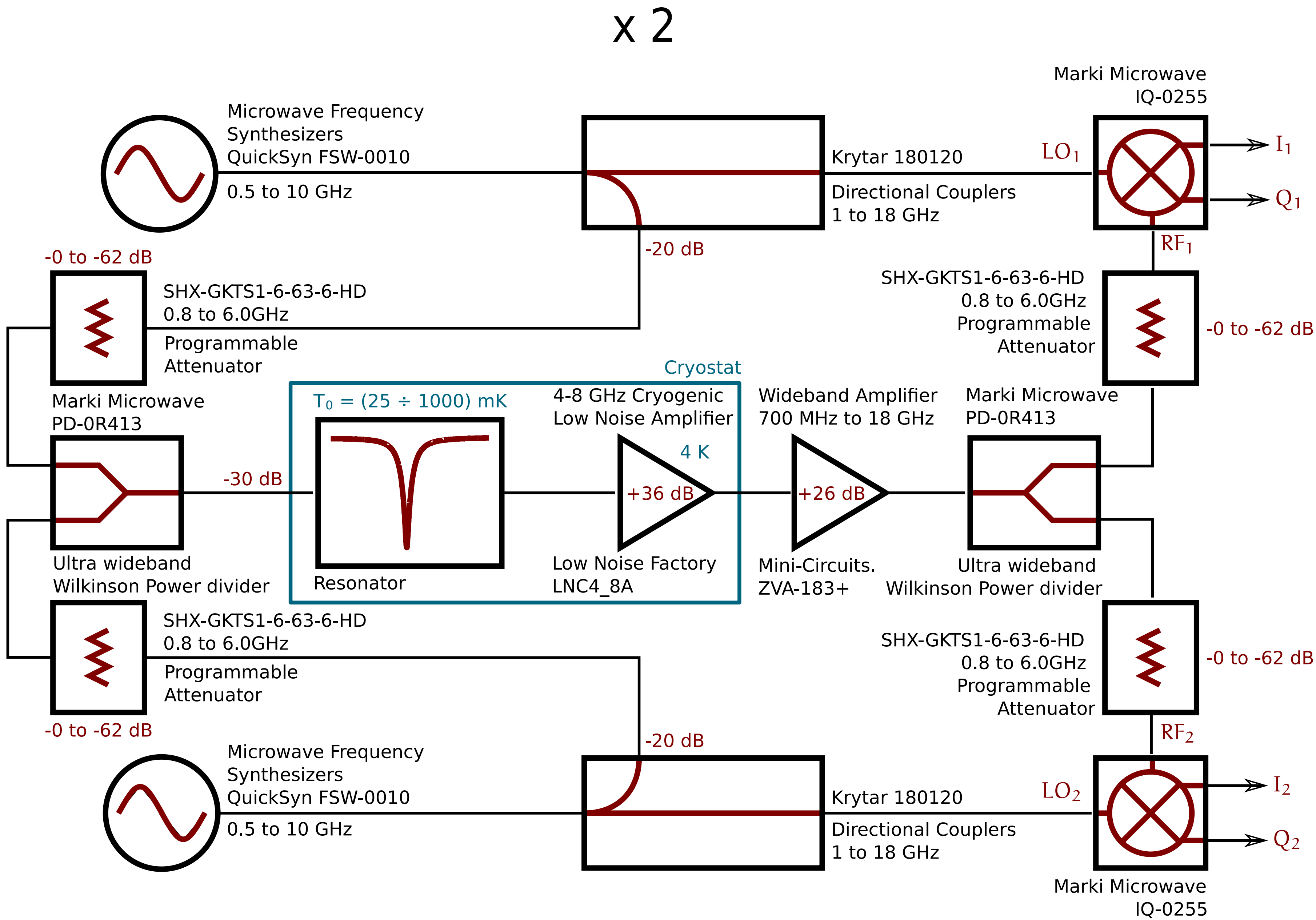
- Transition Edge Sensors (TES) with Au absorber
  - ▹ hot electron microcalorimeters with electro-thermal feedback
  - ▹ electrodeposited Au for full absorbtion
- MoAu or MoCu proximity TES → $T_c \approx 100$mK
- on Si_2N_3 membrane

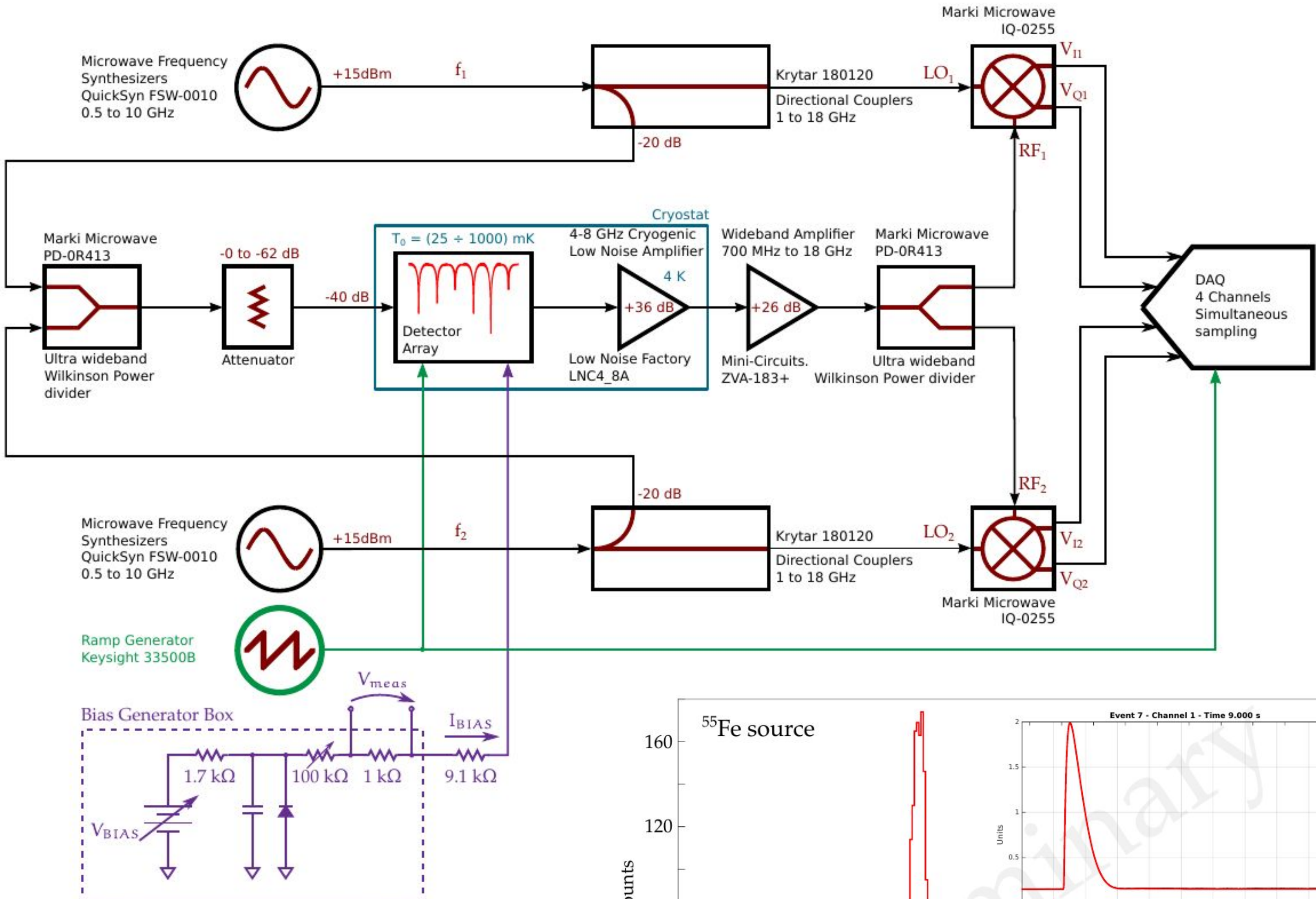




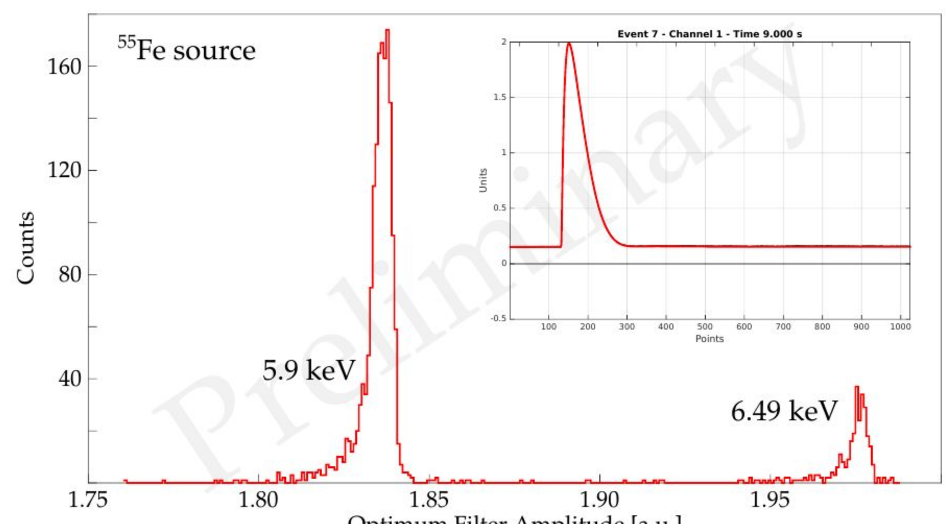


KIDS multiplexing





Microwave Frequency Synthesizers QuickSyn FSW-0010 0.5 to 10 GHz
+15dBm
f1
Krytar 180120
Directional Couplers 1 to 18 GHz
-20 dB
Marki Microwave IQ-0255
LO1
VI1
VQ1
RF1
Cryostat
Marki Microwave PD-0R413
-0 to -62 dB
T0 = (25 ÷ 1000) mK
4-8 GHz Cryogenic Low Noise Amplifier
Wideband Amplifier 700 MHz to 18 GHz
Marki Microwave PD-0R413
4 K
-40 dB
+36 dB
+26 dB
Detector Array
DAQ
4 Channels
Simultaneous sampling
Ultra wideband Wilkinson Power divider
Attenuator
Low Noise Factory LNC4_8A
Mini-Circuits. ZVA-183+
Ultra wideband Wilkinson Power divider
RF2
-20 dB
Microwave Frequency Synthesizers QuickSyn FSW-0010 0.5 to 10 GHz
+15dBm
f2
Krytar 180120
Directional Couplers 1 to 18 GHz
LO2
VI2
VQ2
Marki Microwave IQ-0255
Ramp Generator Keysight 33500B
Vmeas
Bias Generator Box
IBIAS
1.7 kΩ
100 kΩ
1 kΩ
9.1 kΩ
VBIAS



55Fe source
Event 7 - Channel 1 - Time 9.000 s
Units
Points
Preliminary
5.9 keV
6.49 keV
Counts
Optimum Filter Amplitude [a.u.]