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Metallic Magnetic Calorimeters for Astroparticle Physics Applications

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CENTER FOR UNDERGROUND PHYSICS

ibs 기초과학연구원 Institute for Basic Science

Outline

1. Introduction
   - LTD,   Sensor technologies
   - MMC

2. MMC applications in
   - Neutrinoless double beta decay
   - Neutrino mass
   - keV sterile neutrinos

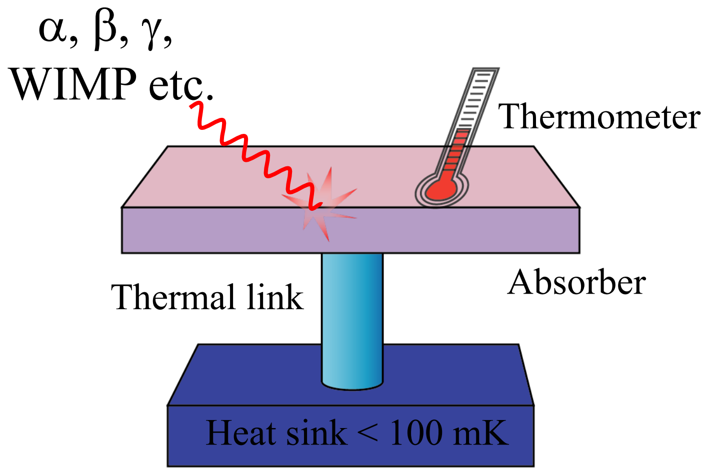
Introduction to

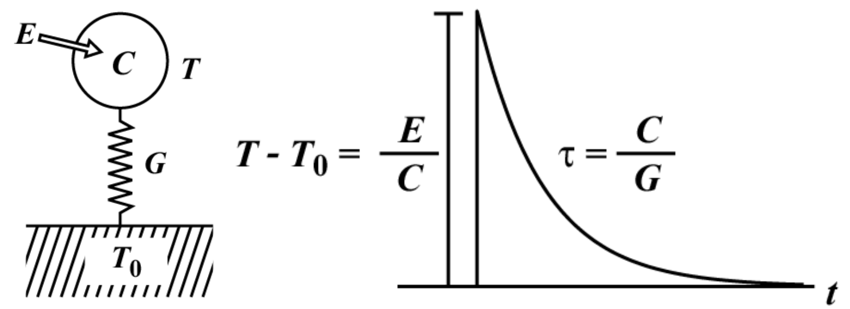
Low-Temperature Detectors

for particle detection

Equilibrium thermal detectors at Low Temp.

Energy absorption → Heat (Temperature)





Measurement of the energy ***E*** of individual particles as a temperature rise $\Delta T = E/C$

Temperature pulse with decay time $\tau = C/G$

Very low temperature(10–100 mK)

- Small ***C*** → Large ΔT
- Low noise

Sensor technology

Choice of detector sensors (superconducting detectors)

- **Thermistors (doped Ge, Si)**
- **TES (Transition Edge Sensor)**
- **MMC (Metallic Magnetic Calorimeter)**

➔ Currently used as sensors for equilibrium thermal detectors

- **STJ (Superconducting Tunneling Junction)**
- **KID (Kinetic Inductance device)**
- **etc.**

➔ Have great potentials useds for equilibrium thermal detectors

Semiconductor-based detectors

PD APD SiPM
CCD CMOS
High Purity Ge detectors

- Convenient (fabrication & electronics)
- Room temperature operable
- Sizable (big & small)
- Affordable (not extraordinary)

- Limited resolution for low energy radiation
- Limited threshold (dark current)

Signal and noise in semiconductor detectors

Signal ~ N

- For Si, $E_{gap} = 1.2$ eV
- Number of e-h created

$$N = E_0/\varepsilon, \quad \neq E_0/E_{gap}$$

- For Si, $\varepsilon \sim 3.7$ eV
  measures only 30% of energy (E_0)
- The rest (phonons)
  → heat generation

Noise ~ δN

- the generation of e-h pairs is not statistically independent

$$\delta N \neq \sqrt{N}$$

- Fano factor, $f \sim 0.115$ for Si

$$\delta N = \sqrt{f \cdot N}$$

- $$\frac{\delta E}{E_0}(\mathrm{FWHM}) = \frac{2.35\sqrt{f\varepsilon E_0}}{E_0} \approx \frac{120\ \mathrm{eV}}{6000\ \mathrm{eV}}$$

Intrinsic resolution of thermal detectors

"A naïve concept in thermodynamic energy fluctuations"

- **Thermal Energy** of a detector with heat capacity C at temperature T:

  $\sim CT$

- **Average energy** per carrier (phonons, electrons, etc) : $\sim k_B T$

  $k_B T = 1.38\times10^{-23}$ J $= 8.6\times10^{-5}$ eV (at 1 Kelvin)

- **Number of carriers** $N \sim CT / k_B T$

- **Statistical thermal noise due to thermal energy fluctuation**

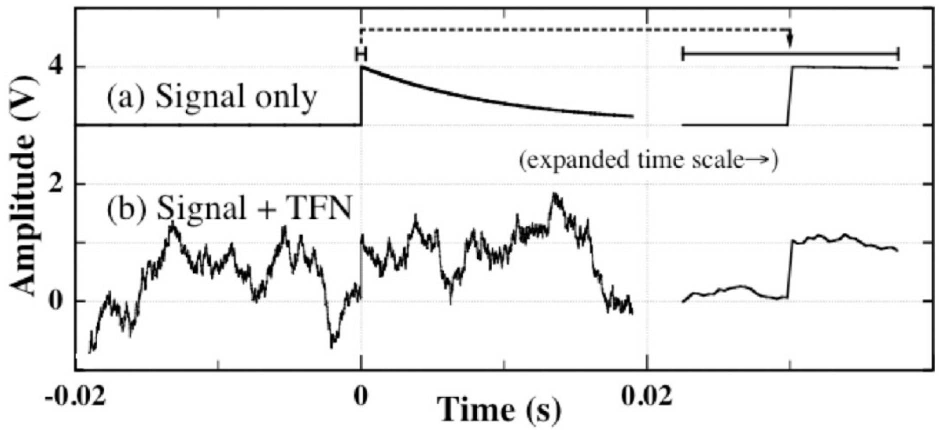
$$(\Delta E)_{\mathrm{FWHM}} \sim 2.35 \cdot k_B T (N)^{1/2} = 2.35 \cdot (k_B T^2 C)^{1/2}$$

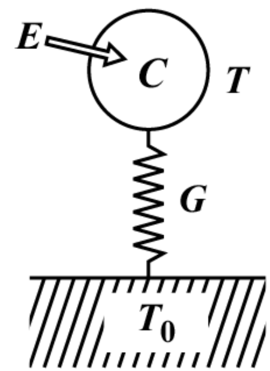
~ 2.5 eV with 0.2 pJ/K at 100 mK

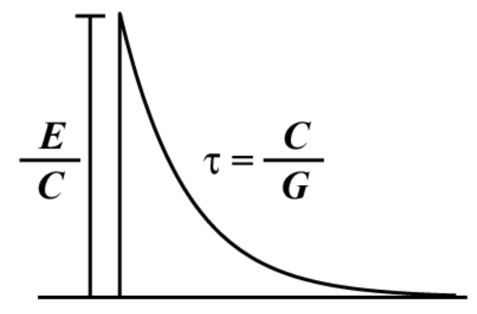
~ 400 eV with 1 kg $CaMoO_4$ at 20 mK

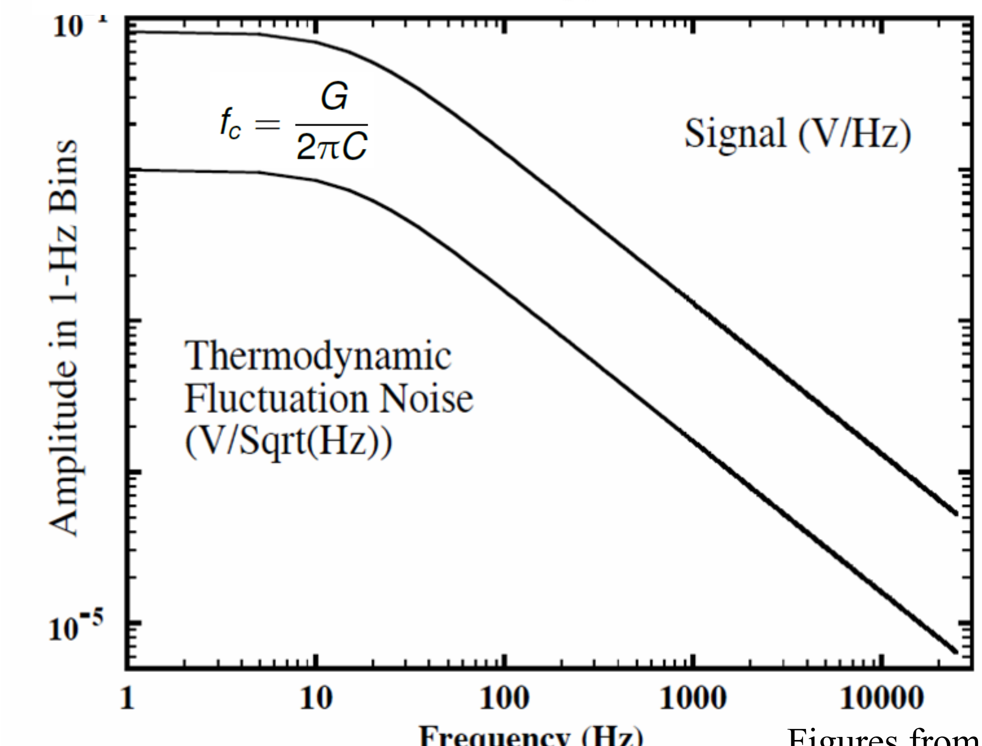
Energy resolution in TFN

(Thermodynamic Fluctuation Noise)









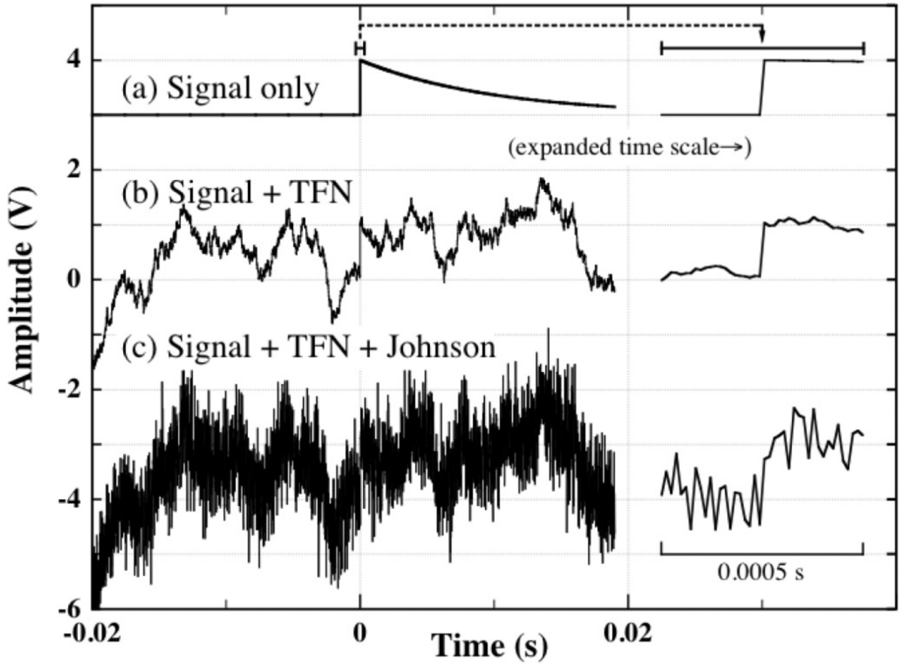
$$\Delta E = \left(\frac{2\pi f_c}{\Delta f}\right)^{\frac{1}{2}} \sqrt{k_B T^2 C}$$

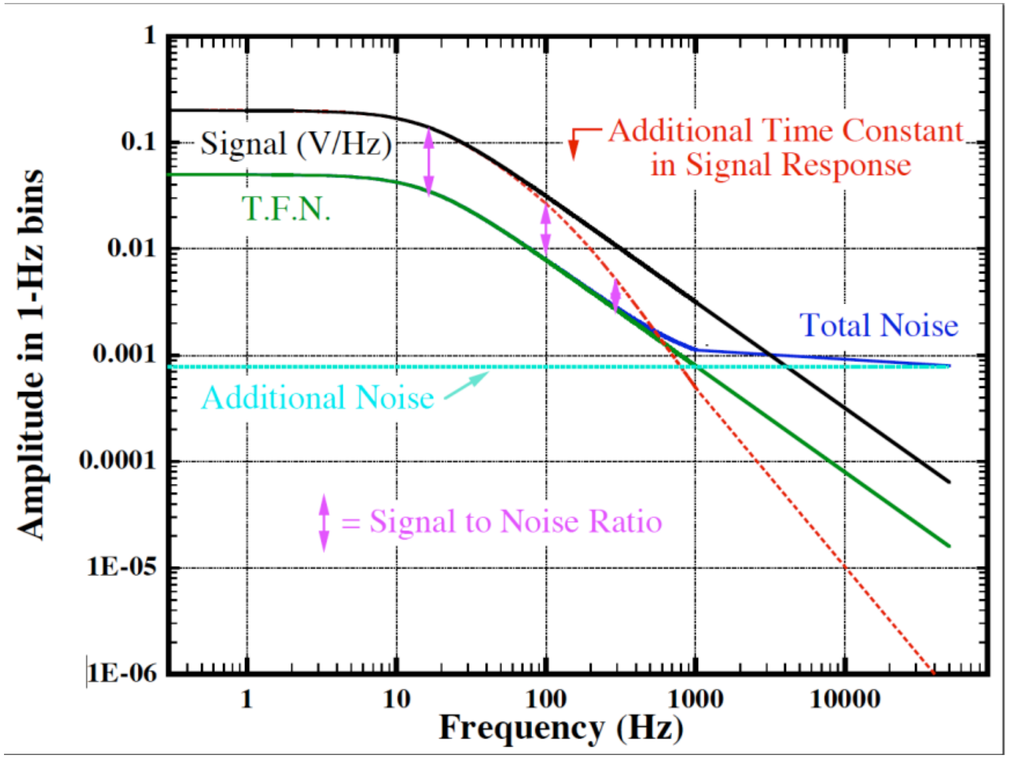
"Still naïve"

Figures from D. McCammon, Topics of Appl. Phys. 99 1 (2005)

Energy resolution in real

"Signal response-time and thermometer (amp etc.) noise play rolls too"





Figures from D. McCammon, Topics of Appl. Phys. 99 1 (2005)

One should design for **larger and faster signals** at given noise conditions.

Best ΔE achieved with LTDs

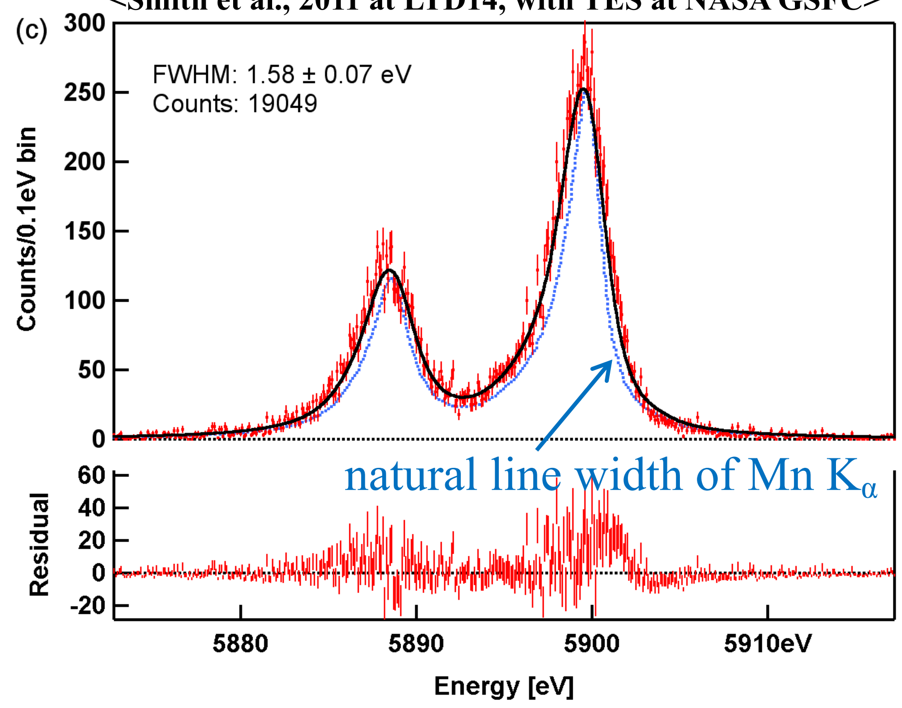
(measured with TFN & thermometer noise)

Measured energy resolution of 6 keV x-rays from ^{55}Fe source

detector resolution

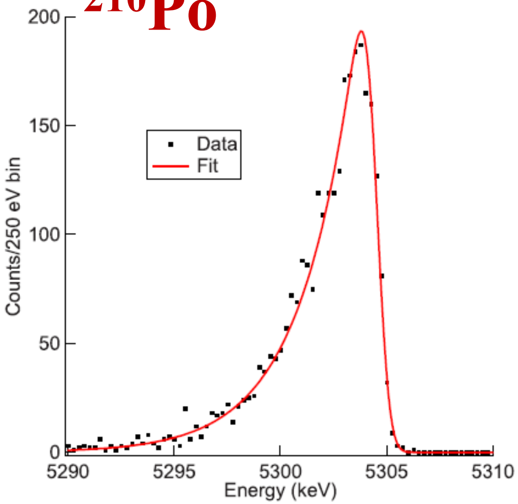
- Thermistors (doped Si) :
  $(\Delta E)_{FWHM}$ = 3.2 eV
  2009, NASA GSFC
- Transition edge sensors :
  $(\Delta E)_{FWHM}$ = 1.6 eV
  2011, NASA GSFC
- Metallic magnetic calorimeters :
  $(\Delta E)_{FWHM}$ = 1.6 eV
  2013, Heidelberg

<Smith et al., 2011 at LTD14, with TES at NASA GSFC>



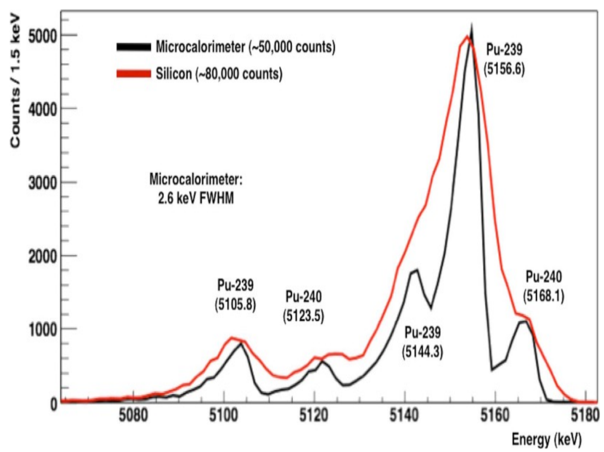
Alpha spectrometers (external source)

^{210}Po



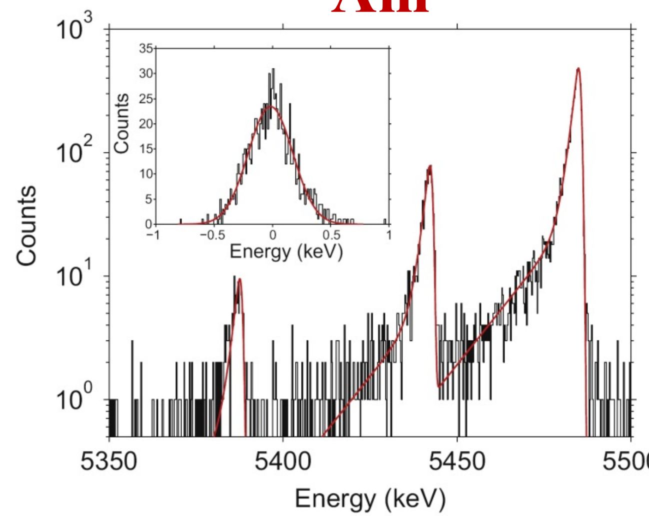
<2009 NIST>
1.1 keV FWHM

$^{229}Pu + ^{240}Pu$



<2011 LANL>
2.6 keV FWHM

^{241}Am



<2013 KRISS>
1.2 keV FWHM

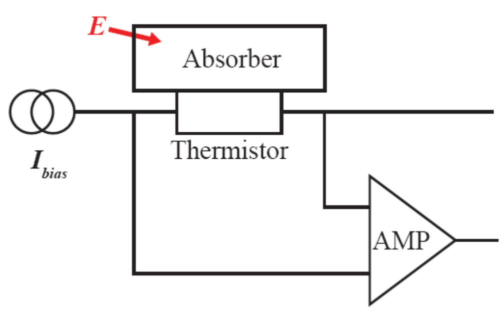
Measured broadening of thermal detectors for alpha spectrometry

➔ **straggling on the source + detector resolution**

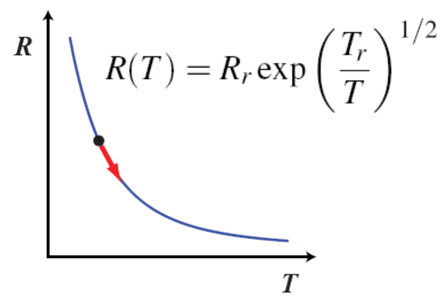
Sensor Technologies

Thermistors

- Doped semiconductors
  - Neutron transmuted doped (NTD) Ge thermistors
  - Ion implantation doped Si thermistors
- *R(T)* : 1 MΩ ~100 MΩ
- Readout: (cold) JFET
- High resolution + High linearity + Wide dynamic range + Absorber friendly
- Require very low bias current(sensitive to micro-phonics and electromagnetic interference), Slow response



<Current bias and read voltage >



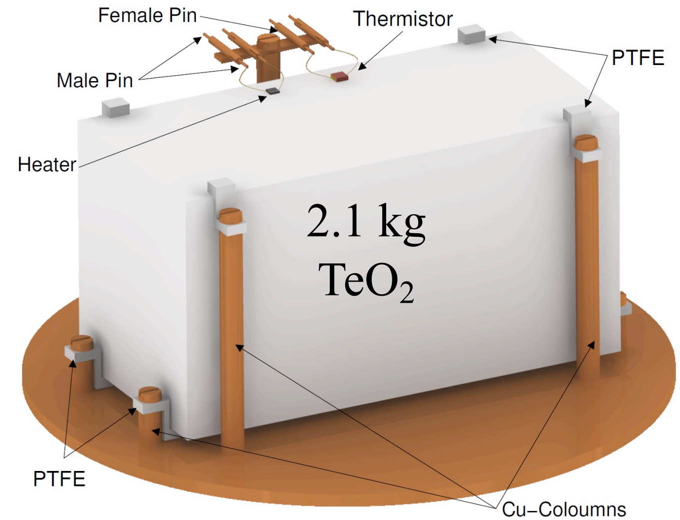
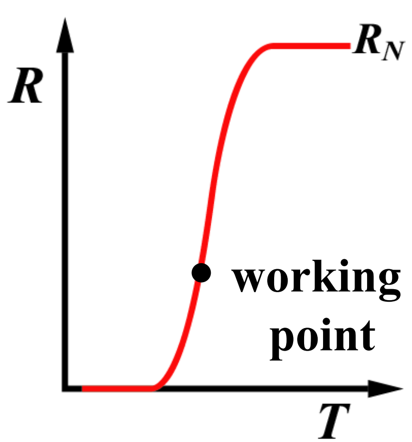
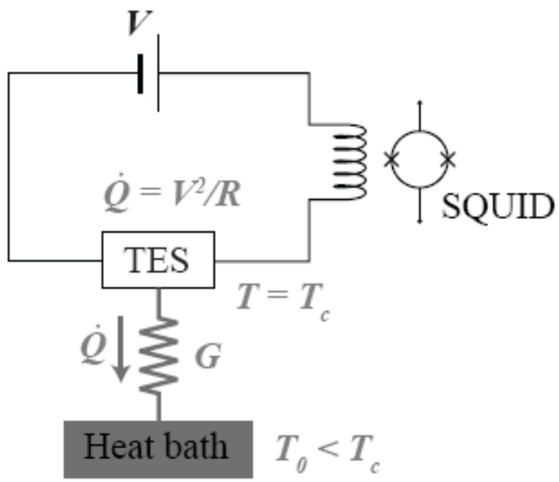


fig. from Cardani et al arXiv.1106.0568

Transition Edge Sensor (TES)

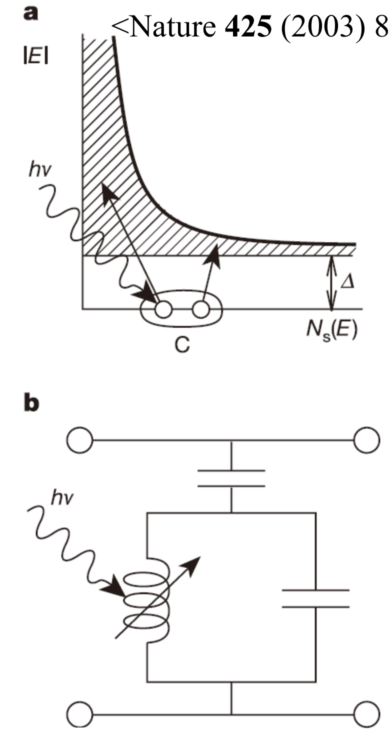
- Superconducting strip at T_c
  - Elemental superconductors: Ti, Ir, W
  - Proximity bilayers: Mo/Au, Mo/Cu, Al/Ag, Ir/Au, Ir/Pt, etc.
- R_N : 10 mΩ ~1 Ω
- Readout: SQUID
- High energy resolution + Low energy threshold + Fast + MUX
- Limited linearity and limited dynamic range, Absorber selective (or chip carrier)



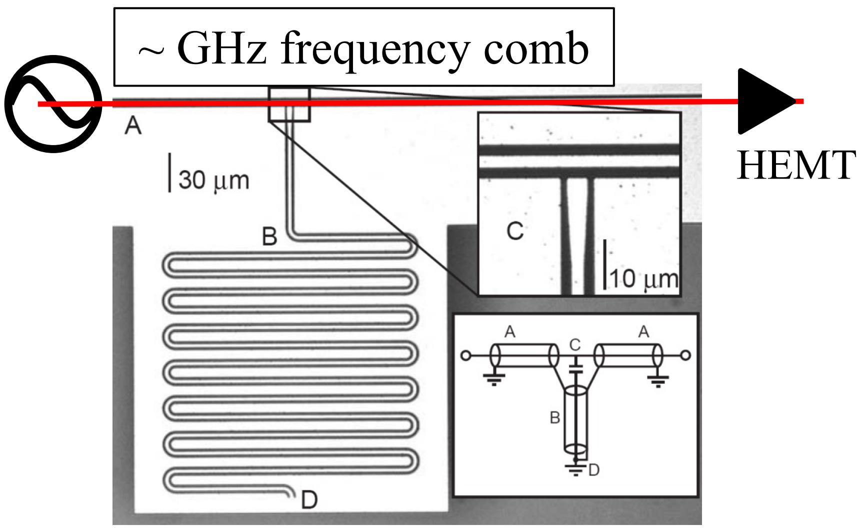


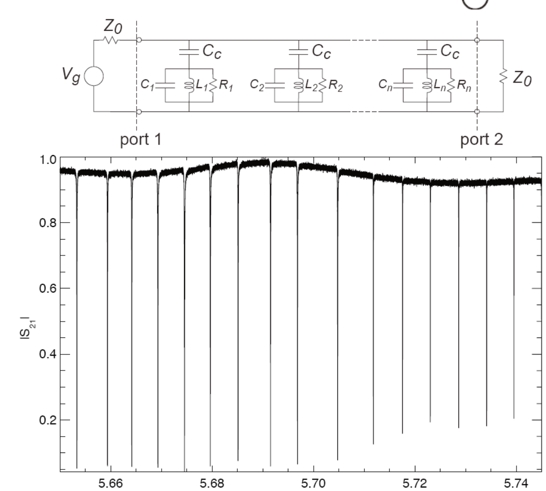
Kinetic Inductance Detectors

<Nature **425** (2003) 817 >



- Pair breaking superconducting detector:
  Quasiparticles are electron-like excitations in superconductors from breaking Cooper pairs
- Superconductor as the inductor in a LC resonance circuit
- Breaking pairs changes the Kinetic inductance
- Easy to MUX (on one chip)
- Non-equilibrium detector





MMC

Metallic Magnetic Calorimeter (MMC)

"Magnetic Micro-Calorimeters"

- Paramagnetic alloy in a magnetic field

  Au:Er(300-1000 ppm), Ag:Er(300-1000 ppm)

  → Magnetization variation with temperature
- Readout: SQUID
- High resolution + High linearity + Wide dynamic range + Absorber friendly + No bias heating + Relatively fast + MUX
- More wires & materials are needed for SQUIDs and MMCs

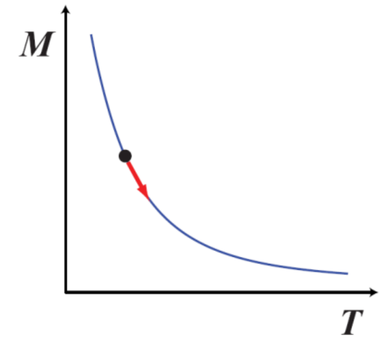
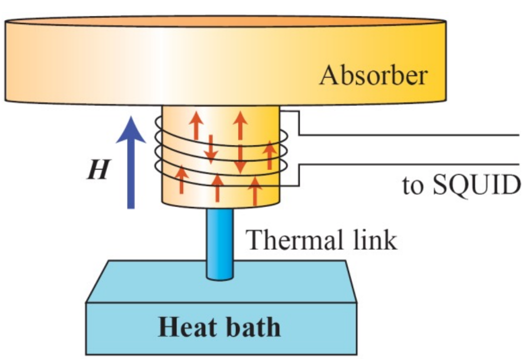
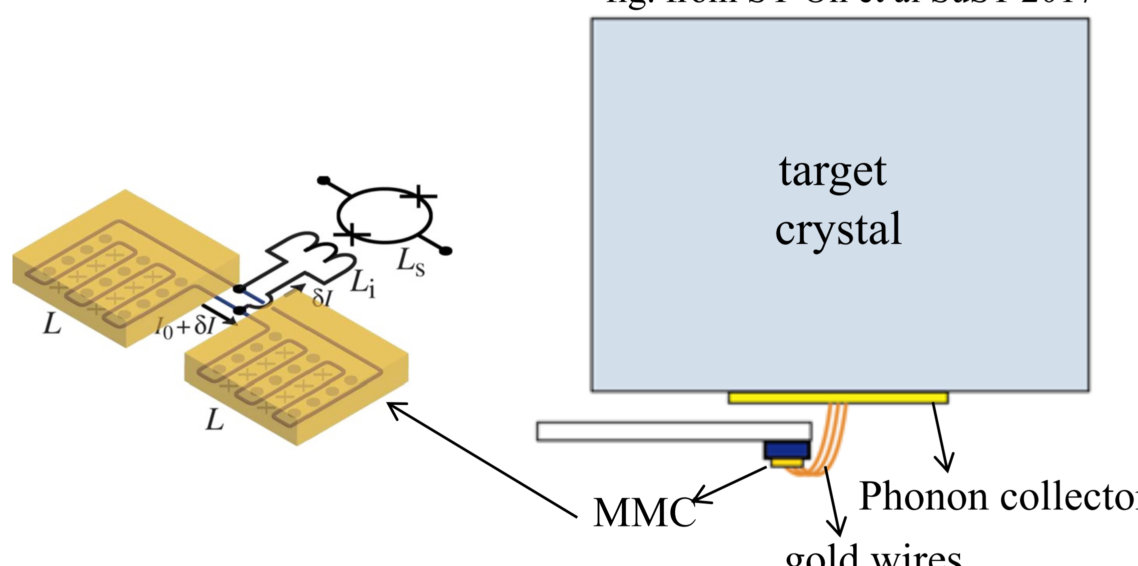
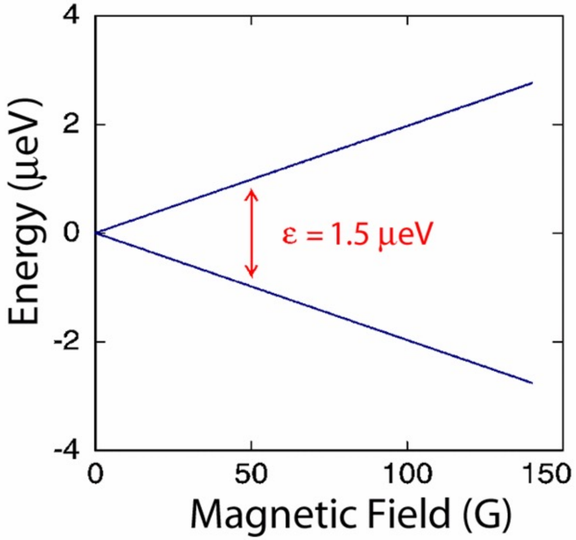


fig. from SY Oh et al SuST 2017





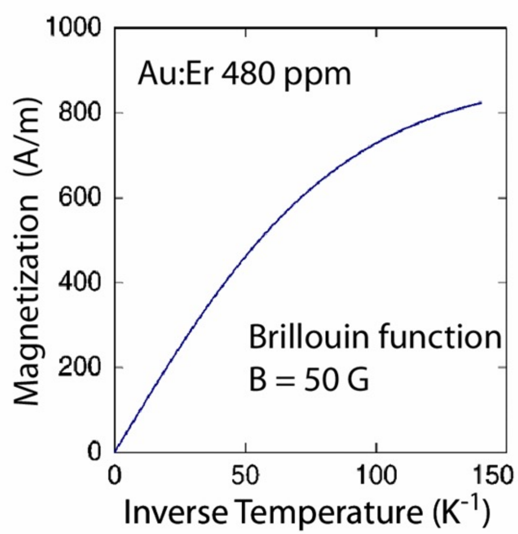
Spin doublet system in MMC

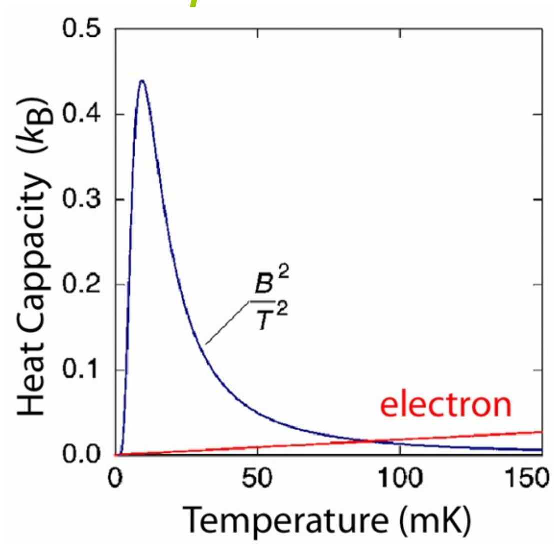


5 mT → ε = 1.5 µeV

1 keV → 10^9 spin flips

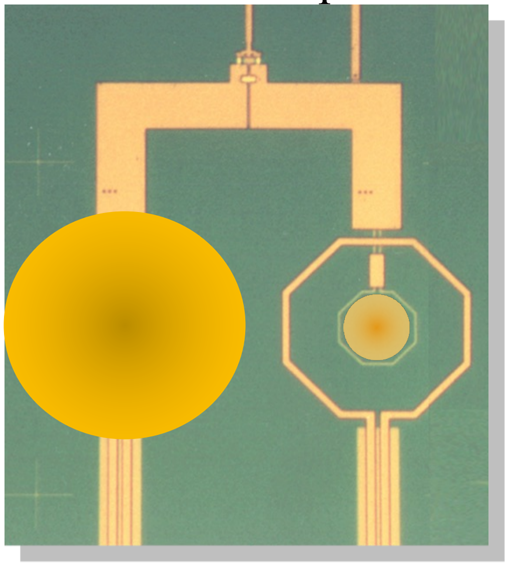
$$\delta\Phi_S = f(r,h)\,\frac{\partial M}{\partial T}\,\frac{1}{C_{tot}}\,\delta E$$



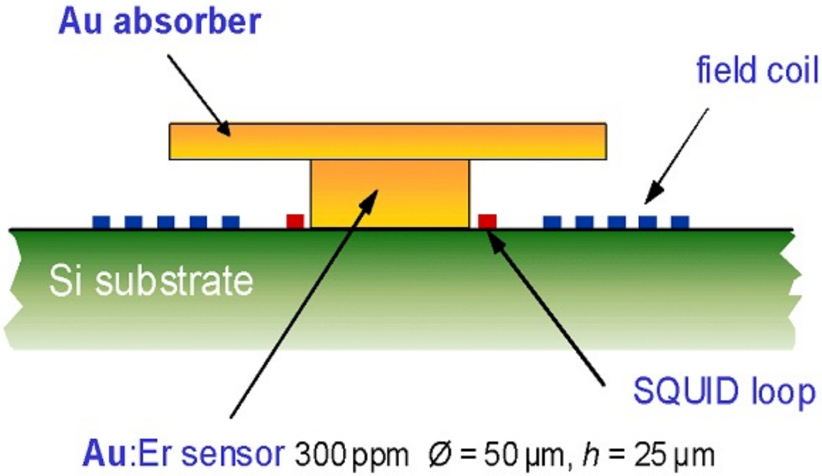


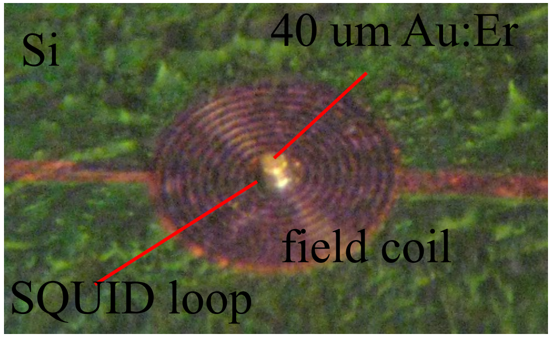
Sensor in SQUID Loop in early setups

<Ketchen's susceptometer>

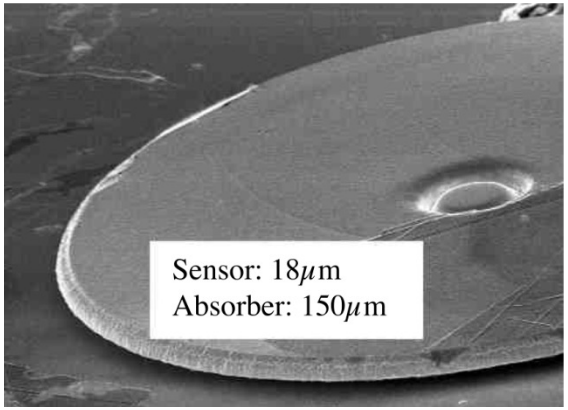


Au:Er sensors

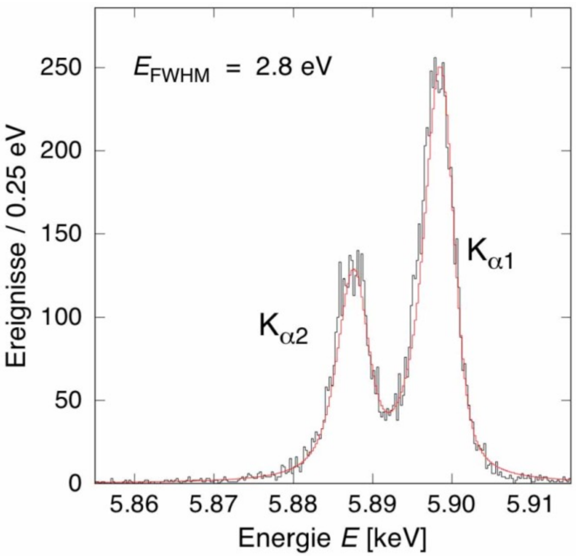




<KRISS, 2006>

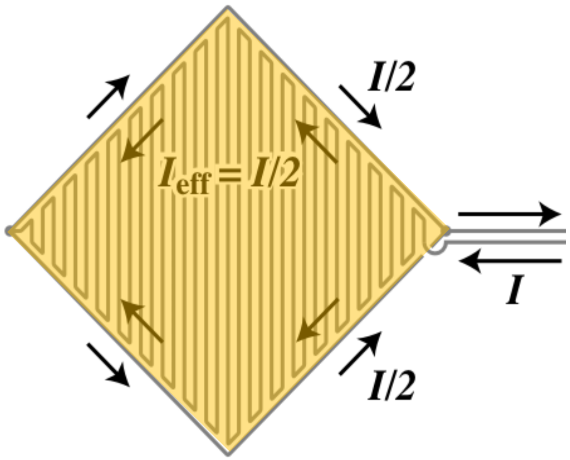


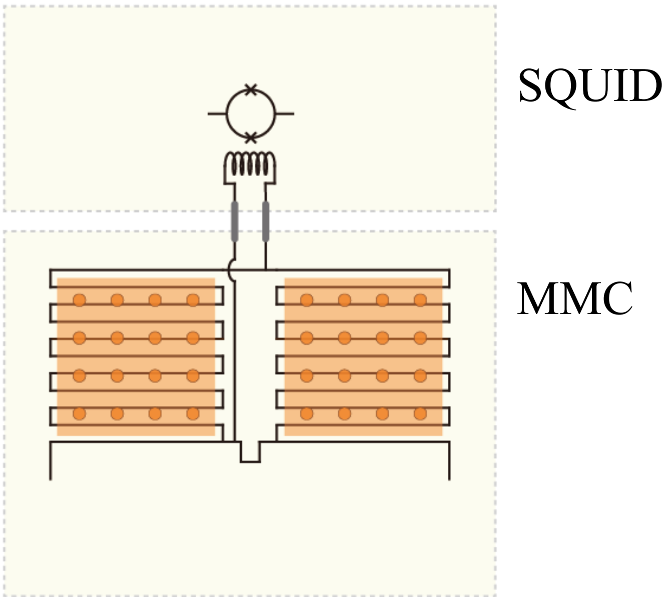
<Heidelberg, 2009>

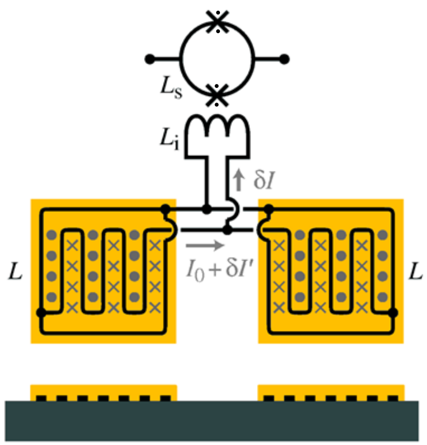


Sensor on Meander-shaped superconducting coil

"Field generation" & "Signal pickup"



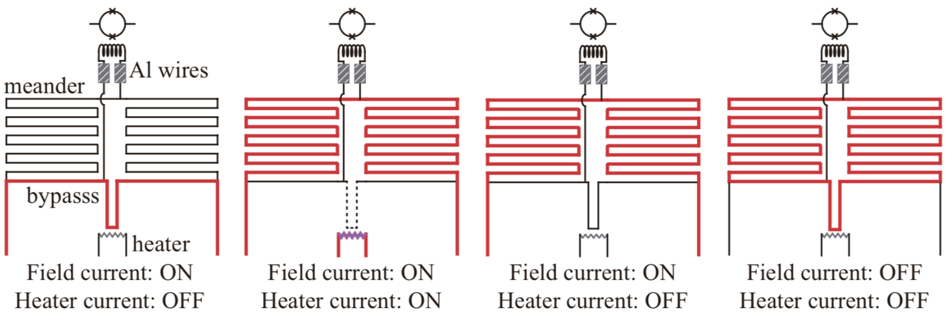


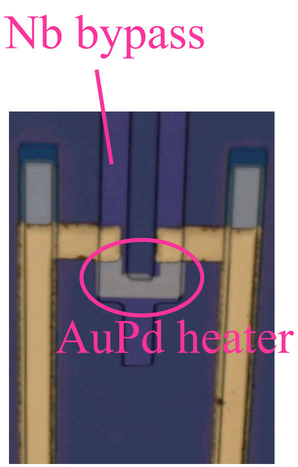


- No heat dissipation
- Smaller magnetic cross-talk
- Easier to fabricate
- Reduced pickup of magnetic Johnson noise

Persistent current injection

Heat-pulse switch

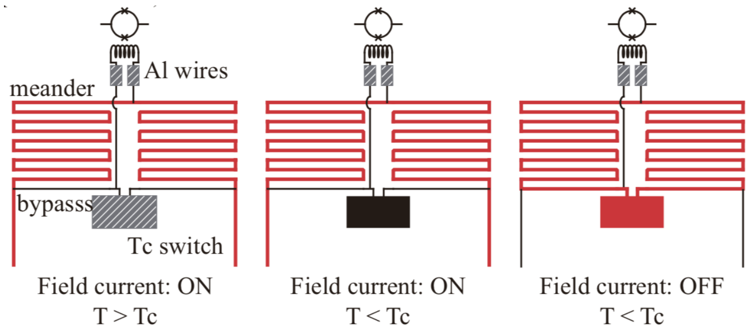


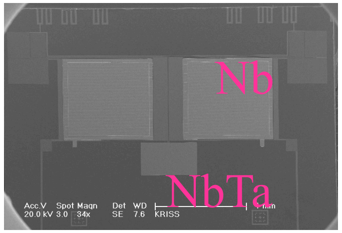


At T < T_c (Nb)

1. Field current On
2. Heat pulse On
3. Heat pulse Off
4. Field current Off

Temperature switch





SR Kim, et al., SUST (2019)

From T_c (Switch) < T < T_c (Nb)

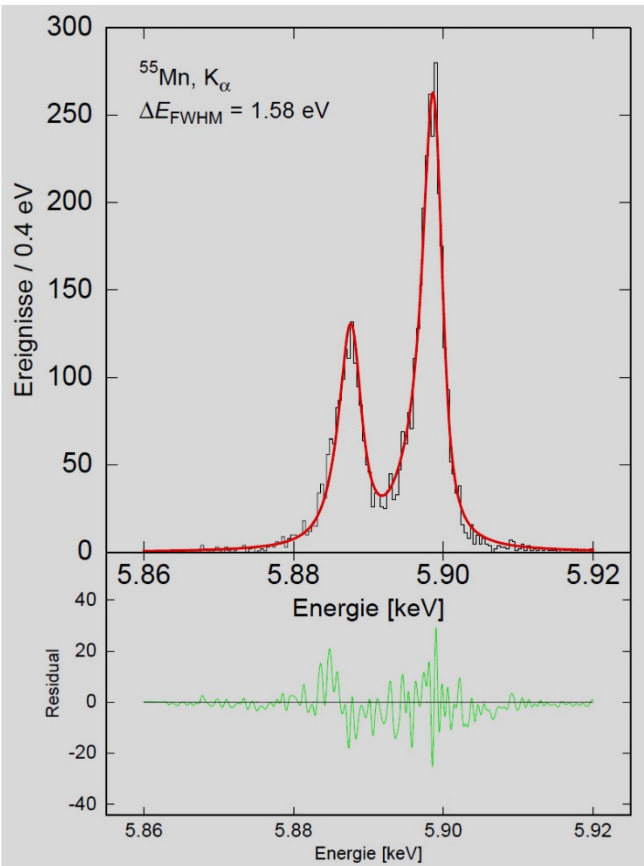
1. Field current On
2. Cool **T < T_c (Switch)**
3. Field current Off

"Once charged, go forever with no field noise."

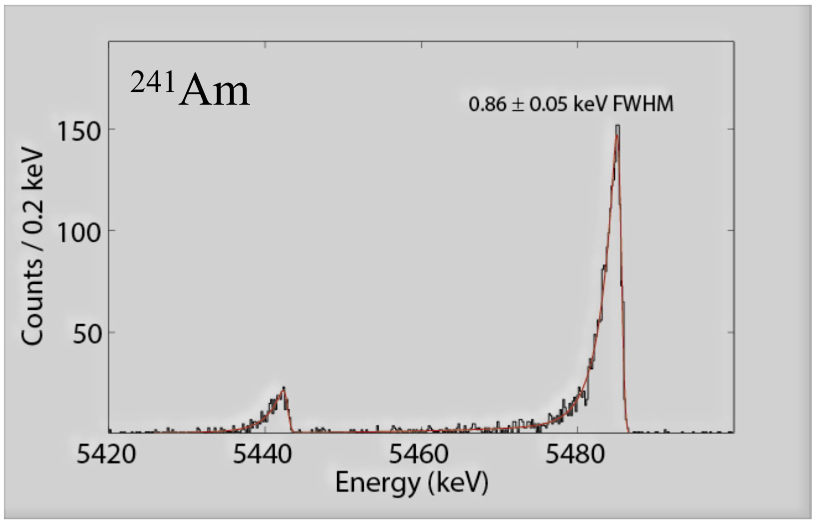
A current sensing SQUID measures the change.

Best resolutions have been achieved with MMCs

1.6 eV FWHM for 6 keV X-rays
(Heidelberg)



0.9 eV FWHM for 5.5 MeV α-rays
(IBS/KRISS)



I Kim, et al., SUST (2017)

Applications of MMCs

Flexible MMCs for many applications

- Low temperature properties of MMCs are well-known.
  - Heat capacity, Magnetization, Sensitivity

- One can design an detector for an optimal sensitivity for given experimental conditions
  - Possible requirements: Absorber selection, Energy resolution, Timing resolution (count rate), etc.
  - Tuning parameters: Sensor geometry, Er concentration, Temperature, Field current

Institutions working on magnetic calorimeters

- Brown University, USA
- CEA Saclay*, France
- Heidelberg University, Germany
- IBS, Korea
- KRISS*, Korea
- Lawrence Livermore National Lab, USA
- Karlsruhe Institute of Technology, Germany
- Osaka University, Japan
- NASA/GSFC, USA
- PTB*, Germany
- University of New Mexico, USA
- Star cryoelectronics, USA

Color codes: Universities
National institutes
*National metrology institute for radiation standards
Private company

Applications

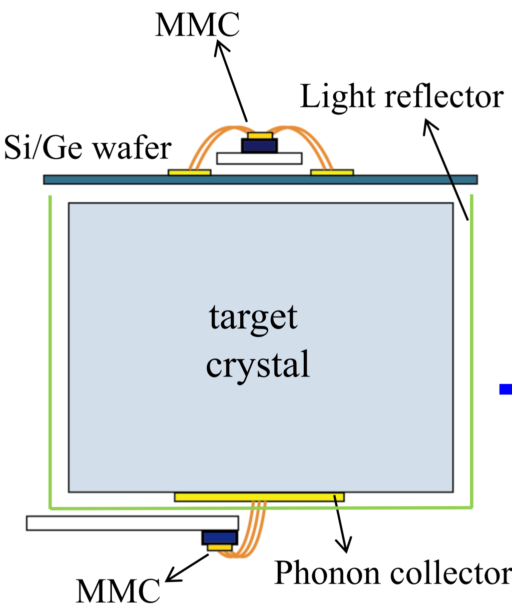
- Visible photons, X-rays, gamma-rays, alpha particles
  CEA, Heidelberg, KRISS, LLNL, NASA, UNM
- Metrology and Nuclear data
  CEA KRISS, LLNL, PTB, UNM
- Neutral molecules
  Heidelberg
- X-ray astronomy
  NASA
- Neutrino mass, Double beta decay
  IBS, Heidelberg, Osaka
- Dark matter detection, Sterile neutrinos
  IBS

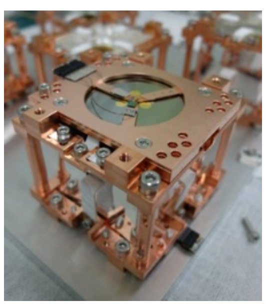
MMCs for astroparticle physics

- Search for neutrinoless double beta decay
  - Majorana or Dirac? Lepton number conservation?
  - Neutrino mass
- Precise end-point measurement of beta decay spectrum
  - Model independent measurement of neutrino mass
- Direct dark matter detection
  - WIMPs?   Sterile neutrinos?
- X-ray astronomy

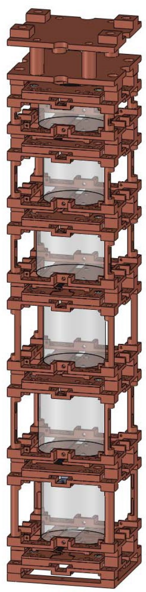
0νββ Projects with MMC

AMoRE

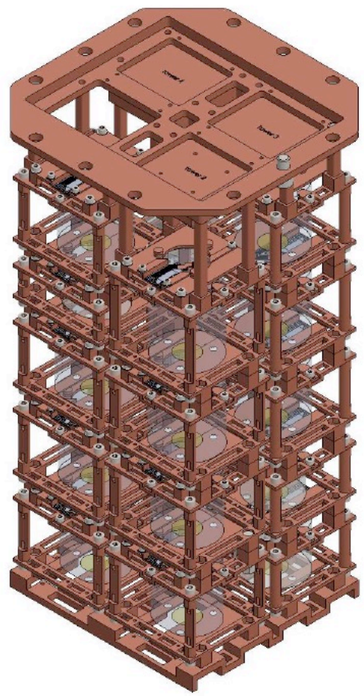




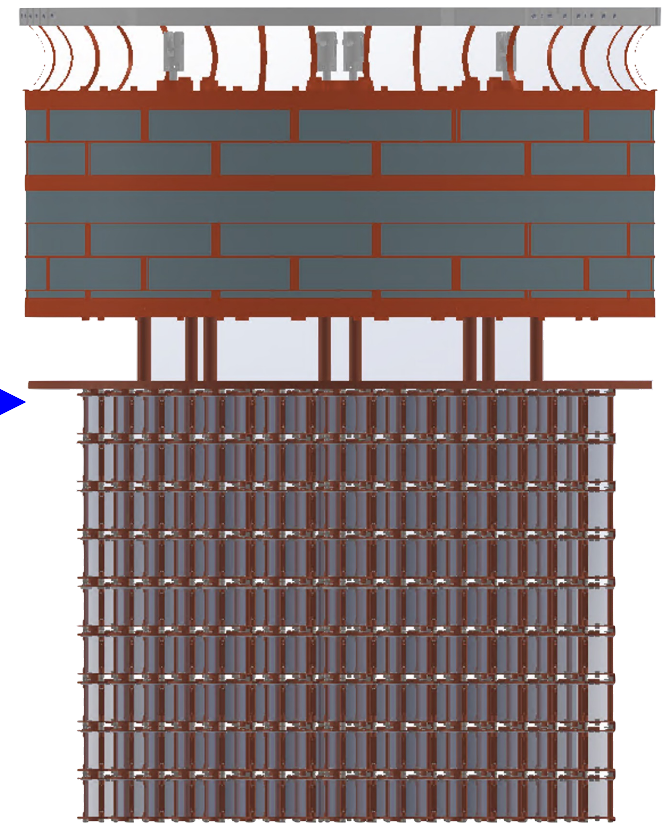
Single module



AMoRE-Pilot
- 2018



AMoRE-I
~2023

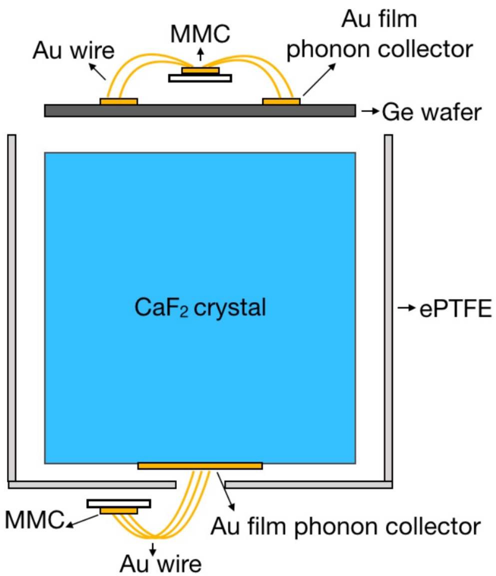


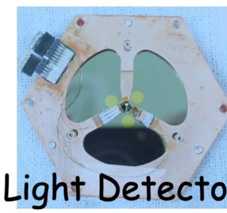
AMoRE-II
2023~

CANDLES R&D with MMCs

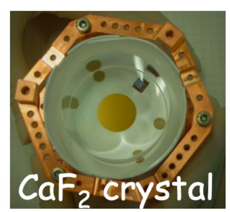
The CANDLES experiment is a project to search for $0\nu\beta\beta$ of ^{48}Ca with CaF_2 scintillators.

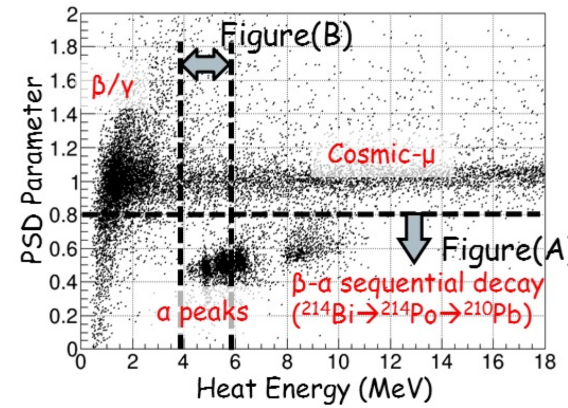
Low Temp. R&D : Osaka Univ. + IBS/KRISS

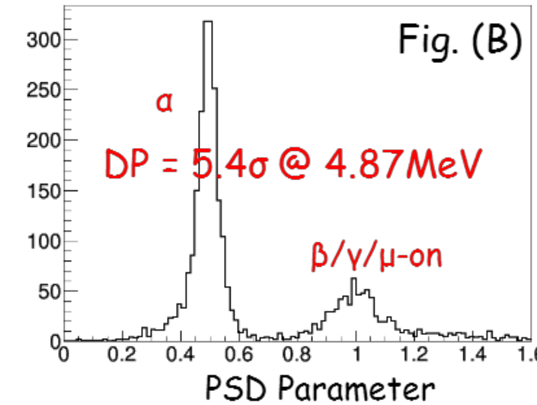


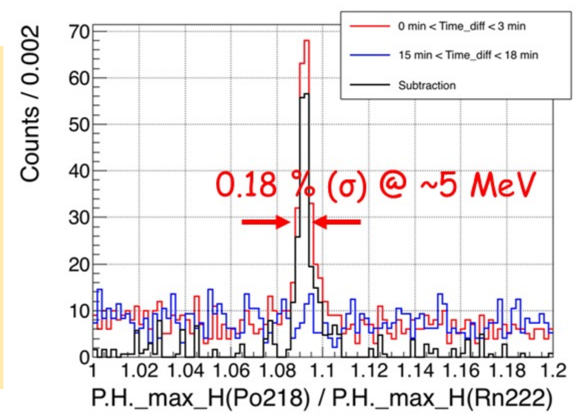


Ge wafer(2 inch) as scintillation absorber





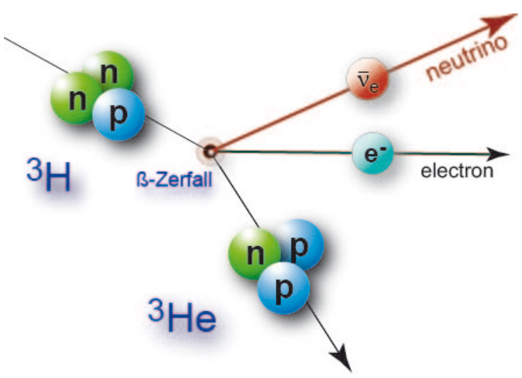


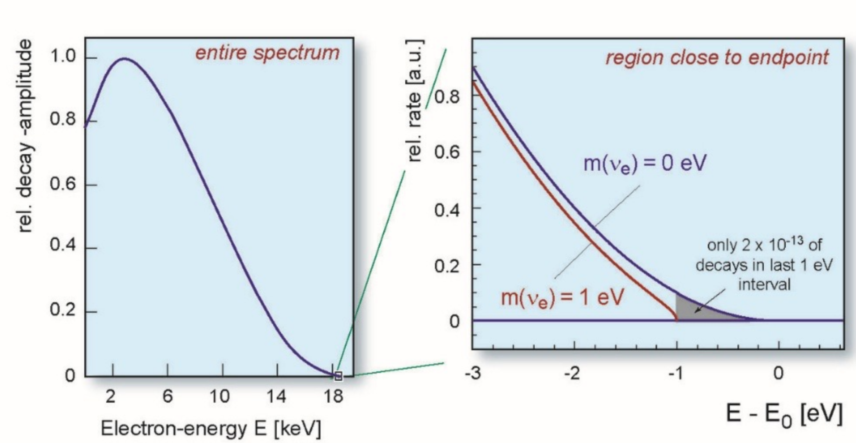


- Promissing demostrtion for heat-light detection with MMCs from CaF_2 crystals at 10-20 mK
- Clear particle identifcation
- High resoltuion with position dependence correction
- Further R&D should continue.

Neutrino mass study with MMC

Beta decay, ν and ν mass





Images from Katrin

$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-} + \bar{\nu}_e \quad (\mathrm{Q} = 18.6\ \mathrm{keV})$$

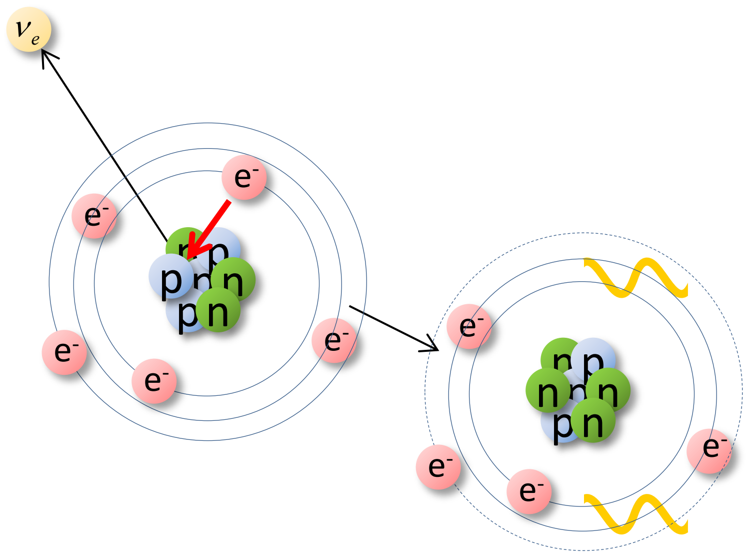
$$^{187}\mathrm{Re} \rightarrow {}^{187}\mathrm{Os} + e^{-} + \bar{\nu}_e \quad (\mathrm{Q} = 2.5\ \mathrm{keV})$$

$$^{163}\mathrm{Ho} + e^{-} \rightarrow {}^{163}\mathrm{Dy}^{*} + \nu_e \quad (\mathrm{Q} = 2.8\ \mathrm{keV})$$

Electron Capture in ^{163}Ho experiment - ECHo

Thank Loredana Gastaldo at Heidelberg Univ.
for sharing her slides and discussions.

^{163}Ho ele. capture & Calorimetric spectrum



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

ECHo: MMC
Holmes: TES

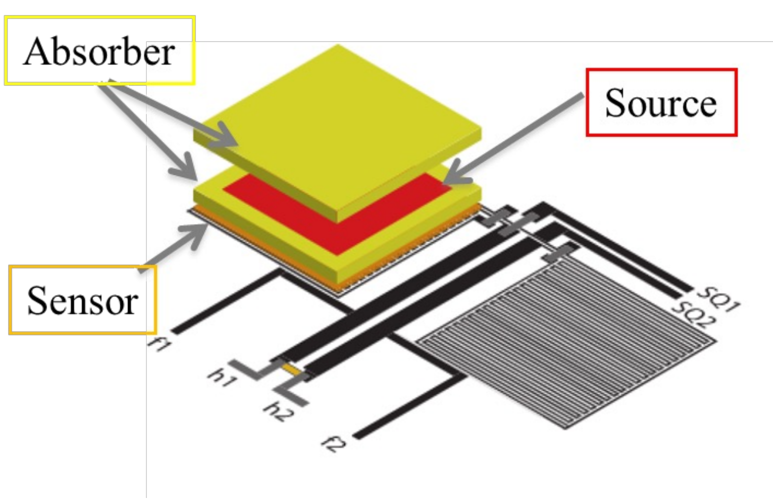
$$^{163}_{66}\mathrm{Dy}^* \rightarrow ^{163}_{66}\mathrm{Dy} + E_\mathrm{C}$$

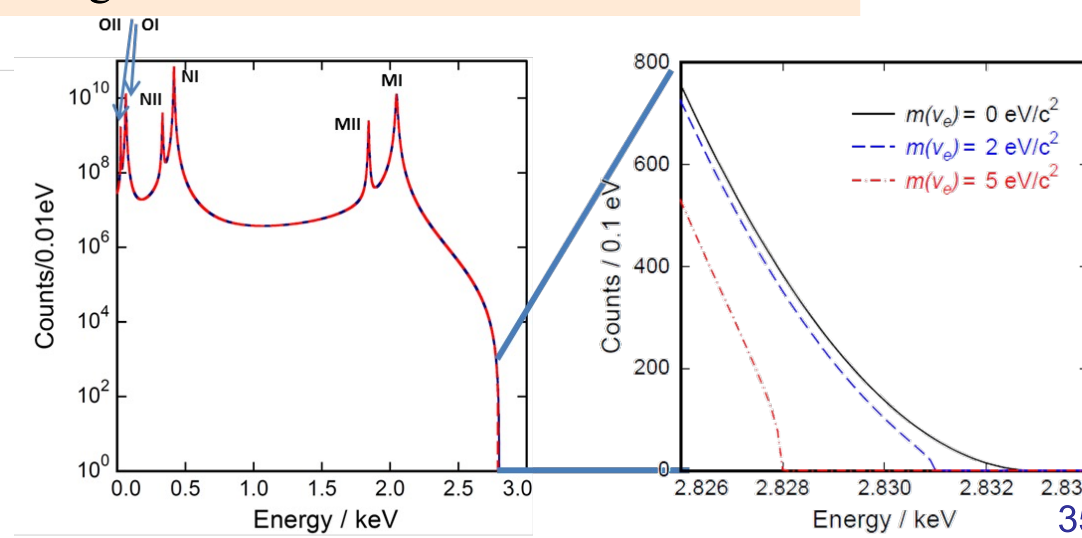
Q_{EC} = $(2.833 \pm 0.030^{stat} \pm 0.015^{syst})$ keV

S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501

- $\tau_{1/2} \cong$ 4570 years (2*10^{11} atoms for 1 Bq)

No energy loss in measuring atomic de-excitation in a 4π absorber





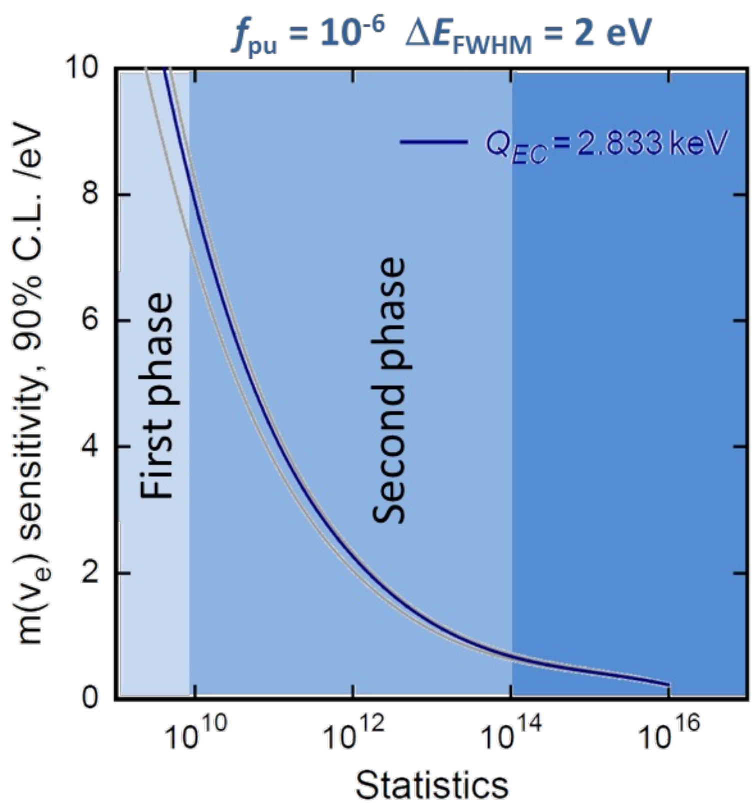
Requirements for sub-eV sensitivity in ECHo

Statitics near endpoint
- $N_{ev} > 10^{14}$ → **A ≈ 1 MBq**

Unresolved pile-up ($f_{pu} \sim a \cdot \tau_r$)
- $\boldsymbol{f_{pu} < 10^{-5}}$
- $\tau_r < 1\ \mu s$ → a ~ 10 Bq
- 10^5 pixels → **multiplexing**

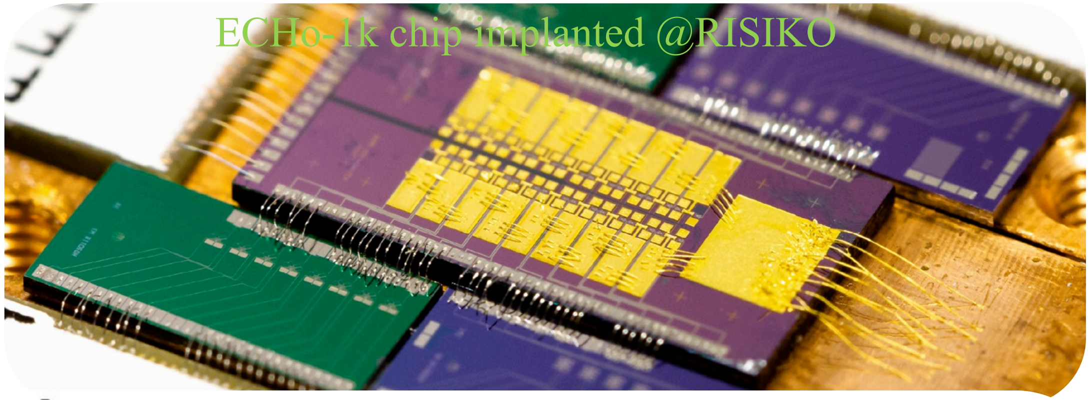
Precision characterization near endpoint
- $\boldsymbol{\Delta E_{FWHM} < 3}$ **eV**

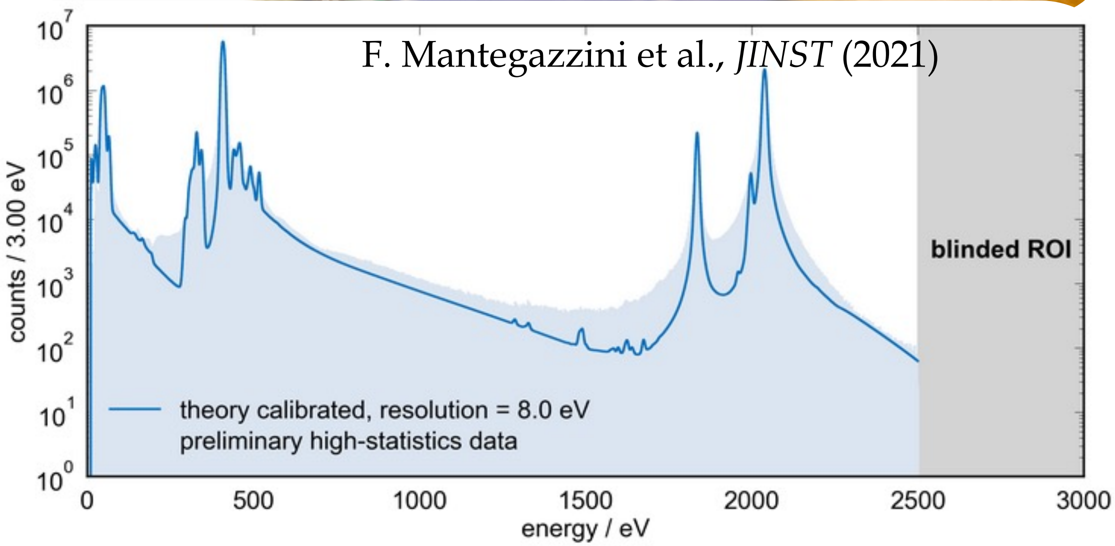
Background level
- **< 10^{-5} events/eV/det/day**



The ECHo Collaboration, *EPJ-ST* **226** 8 (2017) 1623

ECHo-1k Detector set-up





F. Mantegazzini et al., *JINST* (2021)

- High purity ^{163}Ho source
  → activity per pixel $a \approx 1$ Bq , 10^7 events in ROI
- 4 Front-end chips each with 8 dc-SQUIDs for parallel readout
- (32 ch, 64 pixel) x m

ECHo-100k – MMC array

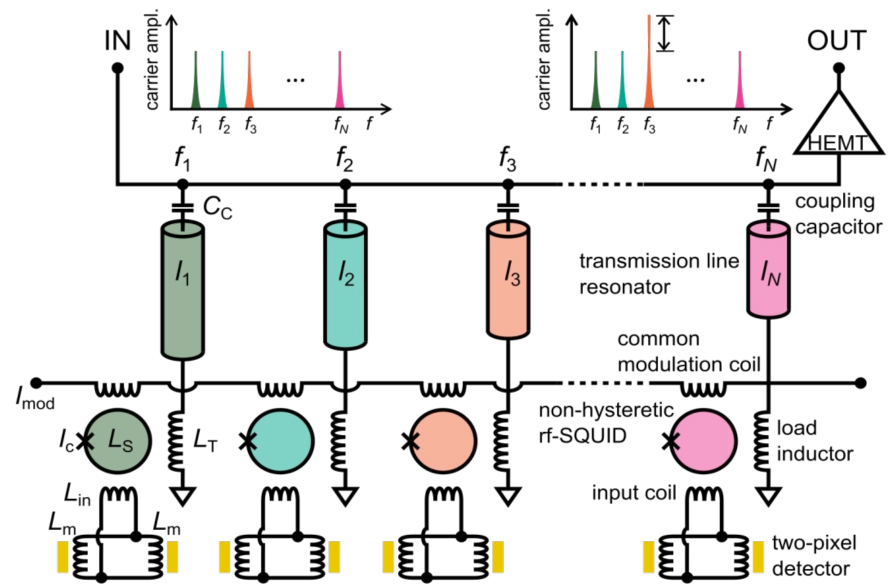
Microwave SQUID multiplexing

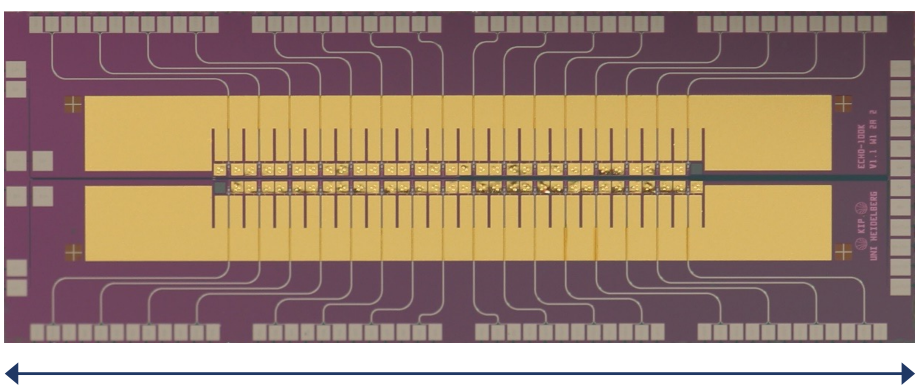
Single HEMT amplifier and 2 coaxes to read out **1000** detectors

ECHo-100k

10 Bq / pixel

12000 MMCs





14 cm

- ✓ **Design and fabrication** completed
- ✓ **Characterised** with ^{55}Fe external source
  implanted ^{163}Ho

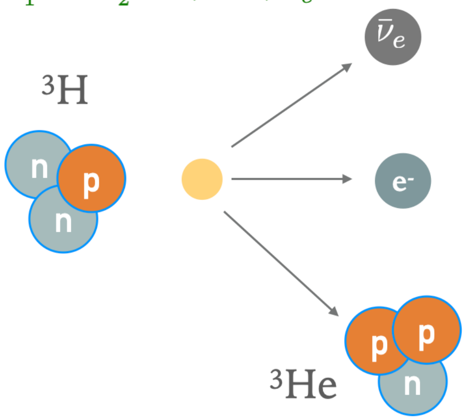
L. Gastaldo v2022

Lab-scale experiment for sterile neutrino search

Lab scale experiment for sterile ν studies

β decay of ^{3}H

$${}^3_1\mathrm{H} \longrightarrow {}^3_2\mathrm{He} + e^- + \bar{\nu}_e$$



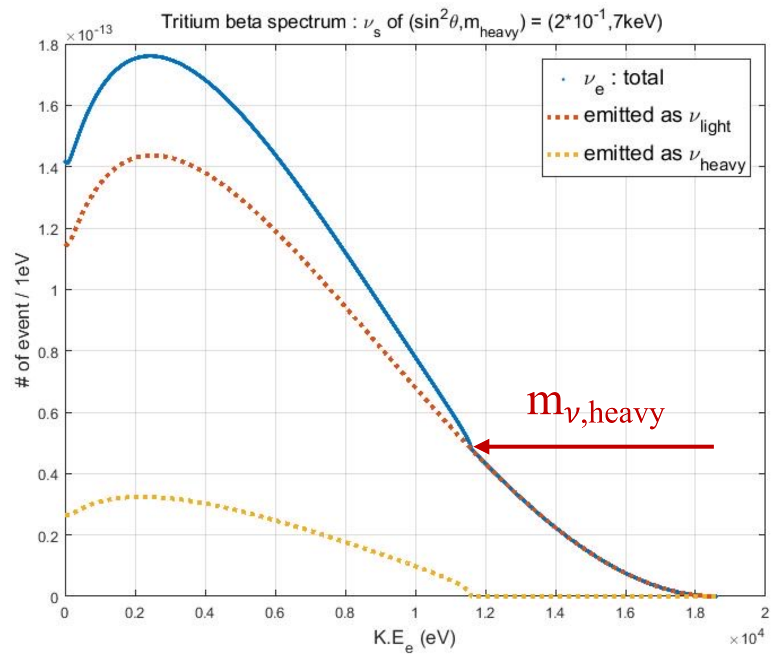
Q:18.59 keV, $\tau_{½}$: 12.32 y

Possible mixing

$$\nu_e = \cos\theta\,\nu_{light} + \sin\theta\,\nu_{heavy}$$

$$\nu_s = -\sin\theta\,\nu_{light} + \cos\theta\,\nu_{heavy}$$

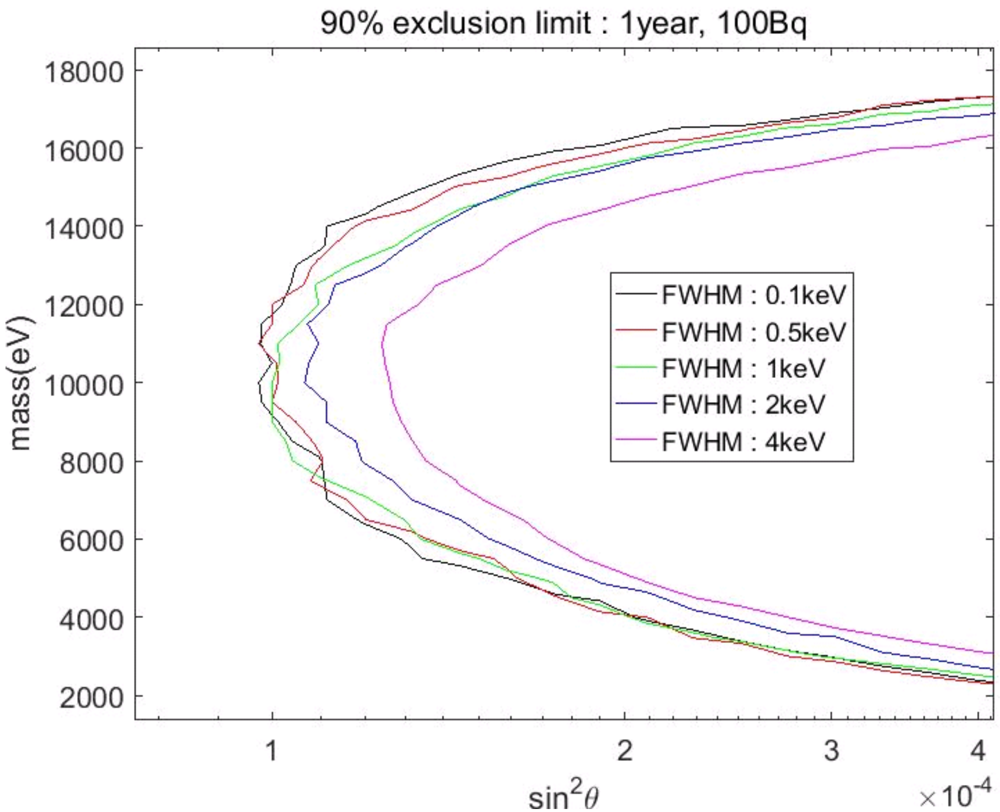
From β decay spectrums, we can investigate the presence of sterile neutrinos



For $\sin^2\theta = 0.2$, $m_{\nu,heavy} = 7$ keV

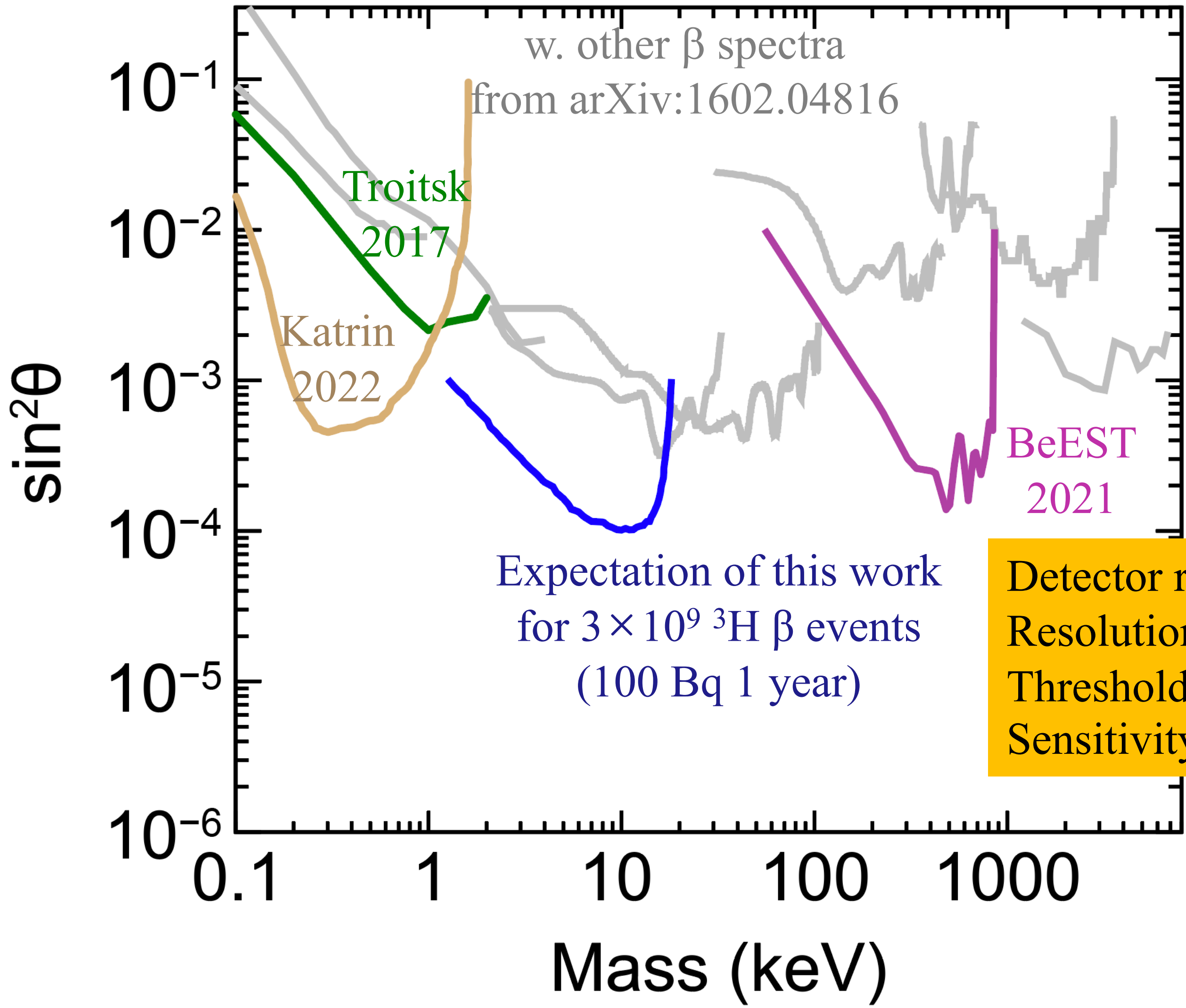
Statistical sensitivity and energy resolution

Pseudo experiments for the sensitivity limit using **3×10^9 ^{3}H β events**



- No apparent sensitivity difference with $\delta E_{\mathrm{FWHM}} < 1$keV
- The # of events matters ~ $(N)^{1/2}$

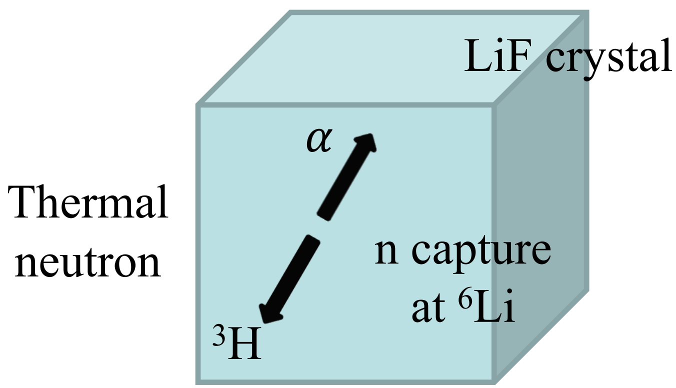
Experimental bounds of keV sterile ν



Detector requirement
Resolution: < 1 keV FWHM
Threshold: < 2~3 keV
Sensitivity limit: ~ $(N)^{-1/2}$

^3H generation in LiF crystals

- ^3H ions are implanted in $1\times1\times1$ cm^3 LiF crystals by $^6Li(n,\alpha)^3H$ reaction using two AmBe and one ^{252}Cf neutron sources surrounded by PE bricks.

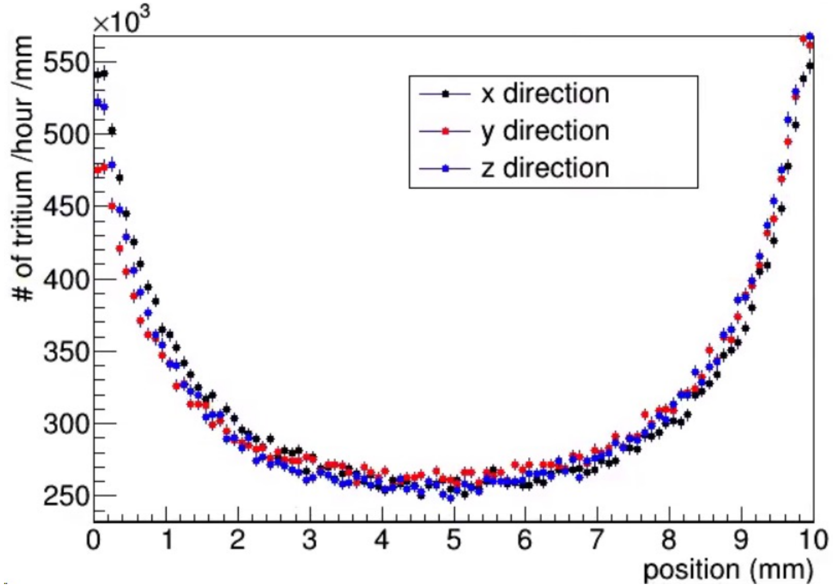


Mean free path of thermal neutrons:
2.3 mm in LiF (7.6% ^6Li)

- Irradiation time : 7 days
- Event rate: ~ 20 Bq (measured)

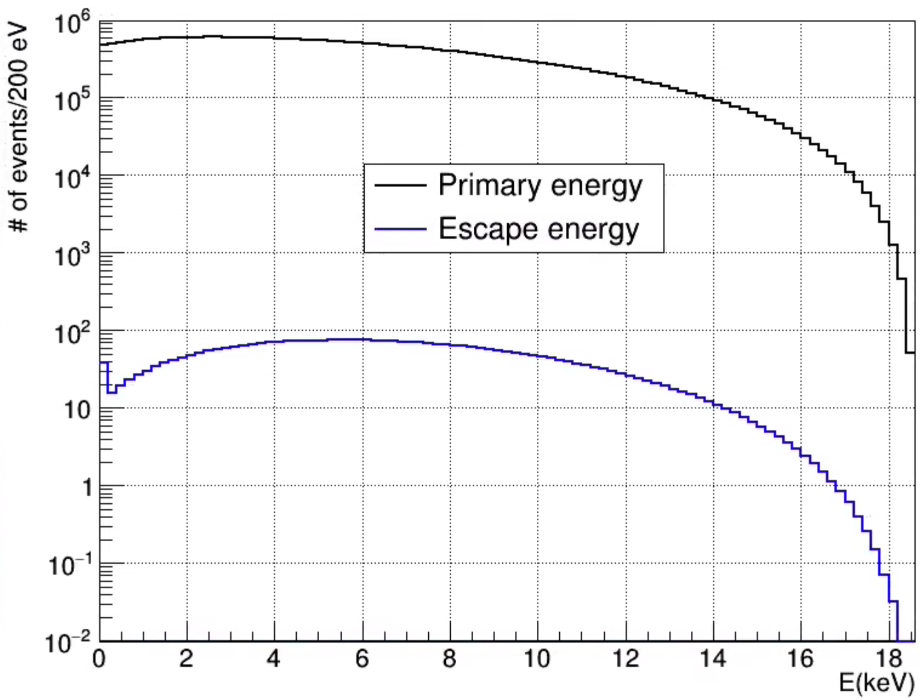
^{3}H distribution in LiF

^{3}H location in 1x1x1 cm^3 LiF



- Tritium distribution in the crystal is nearly uniform.
- From Geant-4 simulation using realistic geometry and source activities

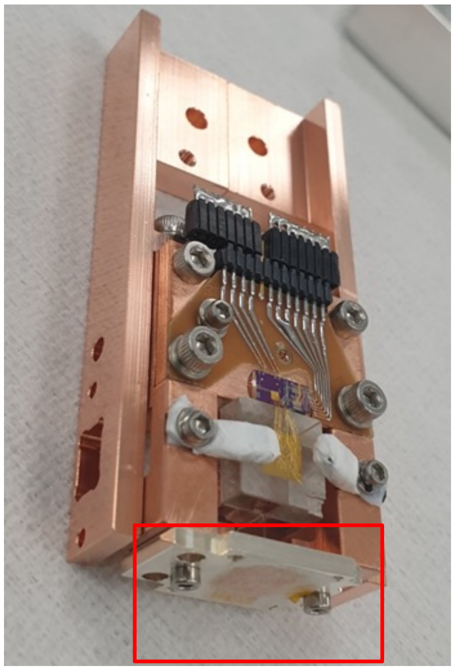
Energy loss at the surface



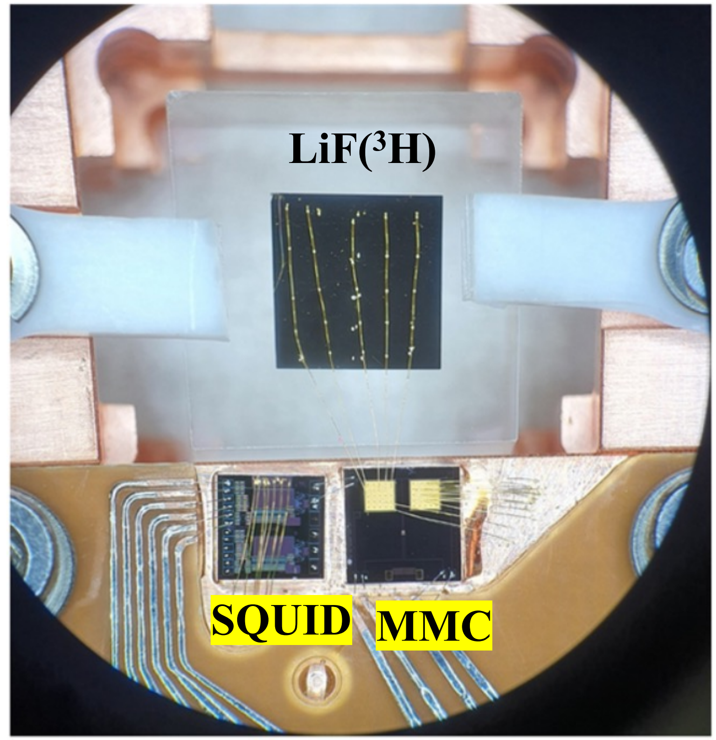
- Using the ^3H distribution, the MC shows a negligible effect would result in a spectrum for 10^8 counts.
- The MC result should be compared with C omparison between the measured for high s ensitivity analysis

Low Temperature test setup

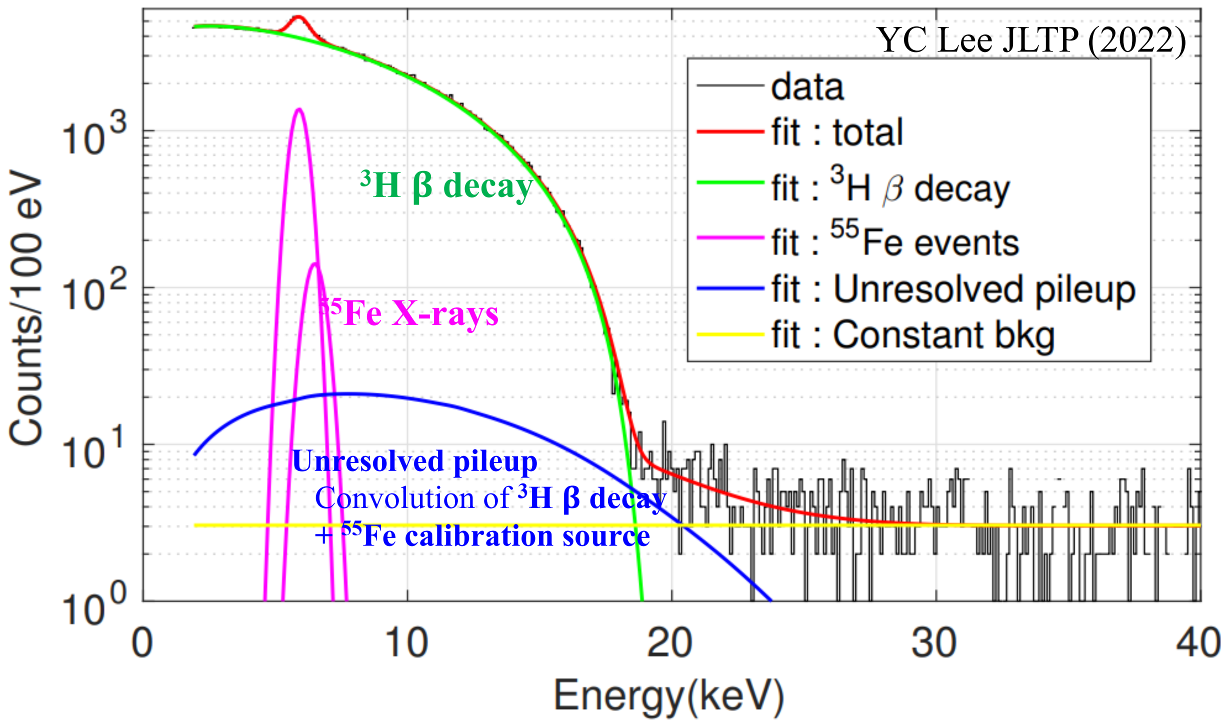
LTD setup with LiF(^{3}H)+MMC



^{55}Fe source w. Ag collimator



Measured spectrum

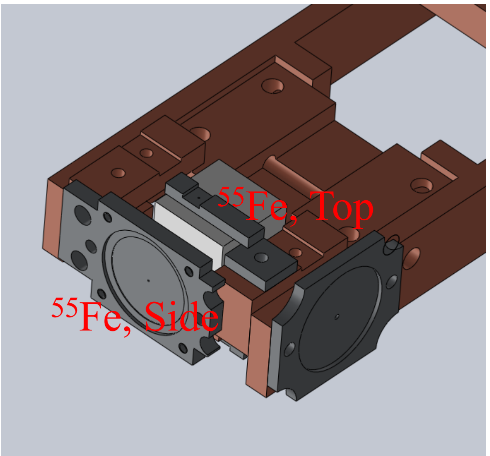


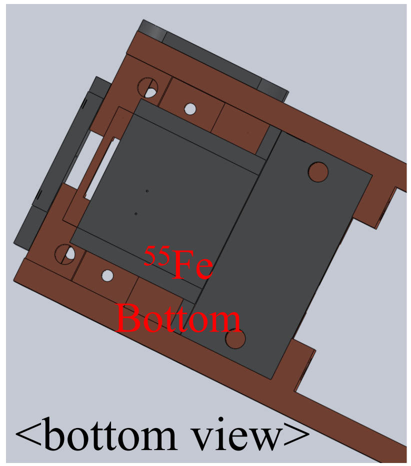
- Energy resolution in FWHM = 792eV$\pm$25eV@6keV
- Unresolved pileup fraction = 0.43%$\pm$0.05%
  Rise-time: 340 us.
- Good agreement between the measured and the expected.

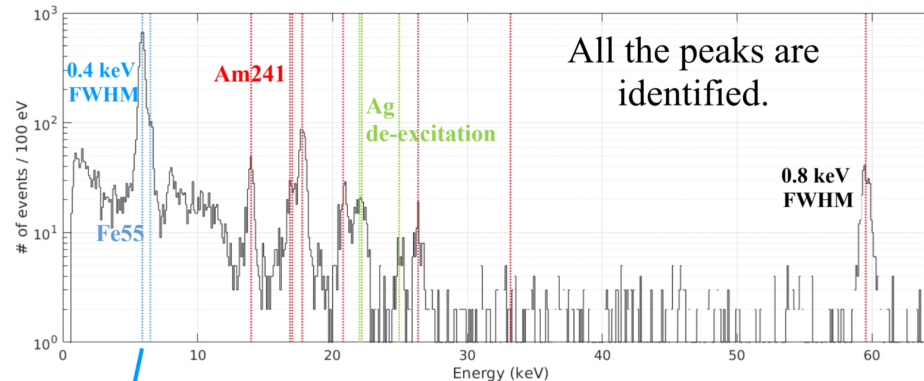
- In newer setup: 400 eV FWHM@6keV, 800 eV FWHM @60keV
  Rise-time: ~ 210 us

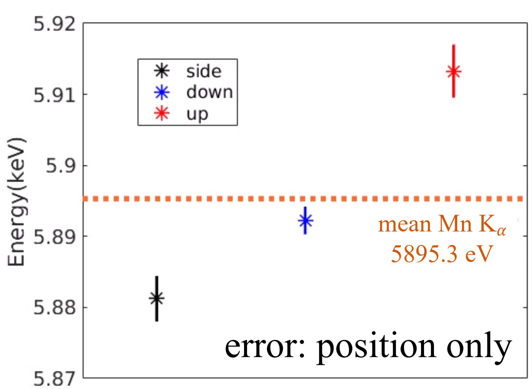
Position dependence study

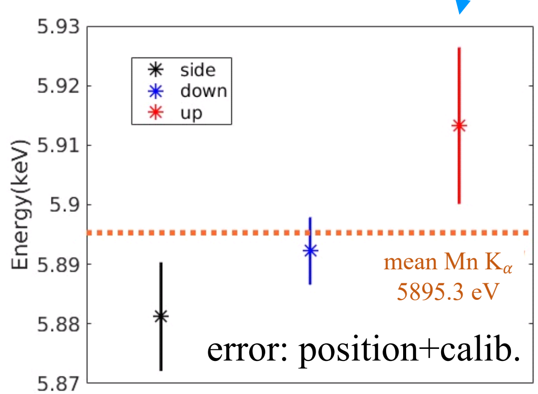
Three measurements with different ^{55}Fe locations + ^{241}Am gammas

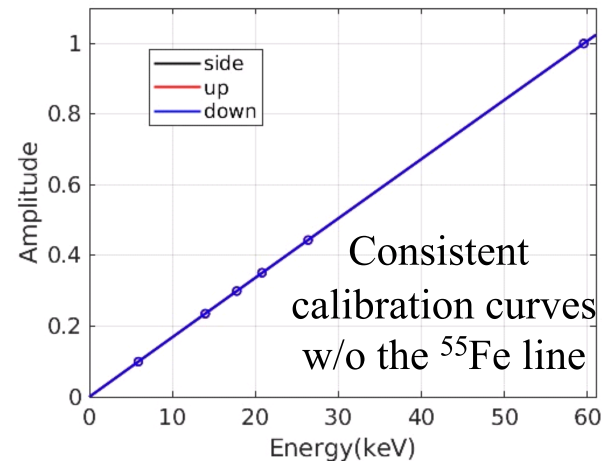






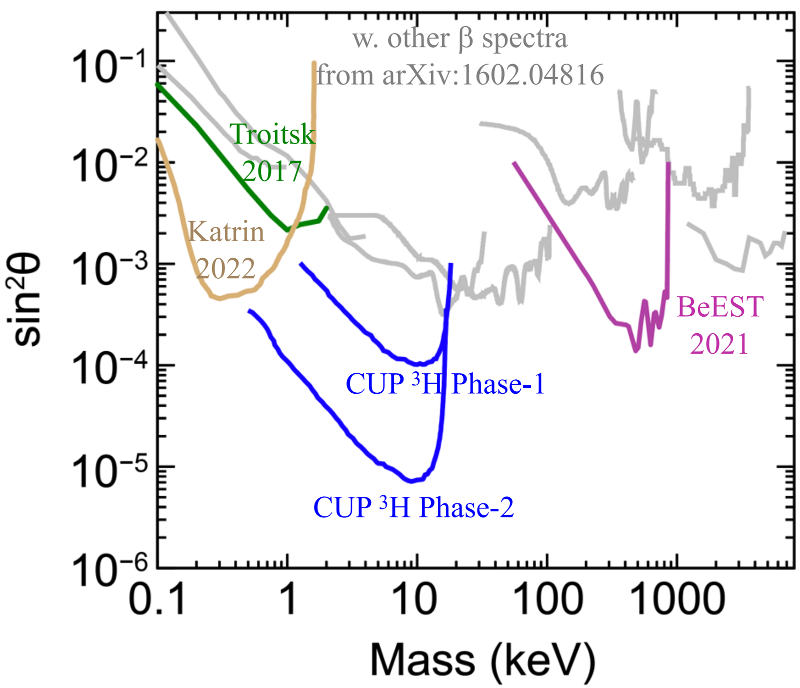






- +20eV (Top) & -15eV(Side) from the calibration line for the two extreme cases.
- Small compared to δE(=400 eV FWHM) but significant.
- We will add this result to the detector modeling (empirical & linear).

Future plan and expected bounds for sterile ν



- **Future plan: CUP ^{3}H Phase1**
- Search region of mixing amplitude $|U_{e4}|^2 (= \sin^2\theta)$: $10^{-4} - 10^{-3}$
- Target statistics : 3 detectors × 40 Bq × 10 month
- Currently in preparation to begin 2023

- **Future plan: CUP ^{3}H Phase2**
- Search region of mixing amplitude $|U_{e4}|^2 (= \sin^2\theta)$: $10^{-5} - 10^{-4}$
- Target statistics : 100 detectors × 100 Bq × 3 year
- To be arranged

Summary on keV sterile ν study

Possible systematics:

- Position dependence → Detector modeling from the measurements with differ source locations
- Unresolved pileup → Faster rise-time (200 us now) + MC studies
- Long-term stability → (Gain drift, calibration) Use AMoRE know-how
- Possible backgrounds → Measurement with no ^3H source

Summary

- ^3H was embeded in a LiF crystal with reasonable activty.
- The beta spectrum shows a good agreement with the expected.
- Further analysis to come for sterile neutrio presence.
- We plan a long term (several months) experiment with multi-channel setups

Summary

- MMCs using superconducting sensor tech have great performance and applications in many aspects of science.
- Excellence in energy resolution, timing resolution, linearity, dynamic range.

MMCs for astroparticle physics applications (neutrino studies)

- ECHo for direct neutrino mass measurement
- AMoRE $0\nu\beta\beta$ search to check Majorana ν, $\Delta L \neq 0$, and ν mass
- Sterile ν search from ^{3}H β spectrum with $LiF(^{3}H)$.

Stay tuned to us !