Neutrino mass calorimetric searches in the MARE experiment

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Outline

- ▷ MARE: Microcalorimeter Array for a Rhenium Experiment
  - ▷ spectrometers vs. calorimeters
  - ▷ calorimetric measurement sensitivity
  - ▷ ^{187}Re vs. ^{163}Ho
- ▷ MARE-1 and MARE-2
  - ▷ path for isotope and technique selection
  - ▷ MARE-1 activities update
- ▷ Conclusions

MARE project for sub-eV calorimetric m_ν measurement

MARE: Microcalorimeter Arrays for a Rhenium Experiment

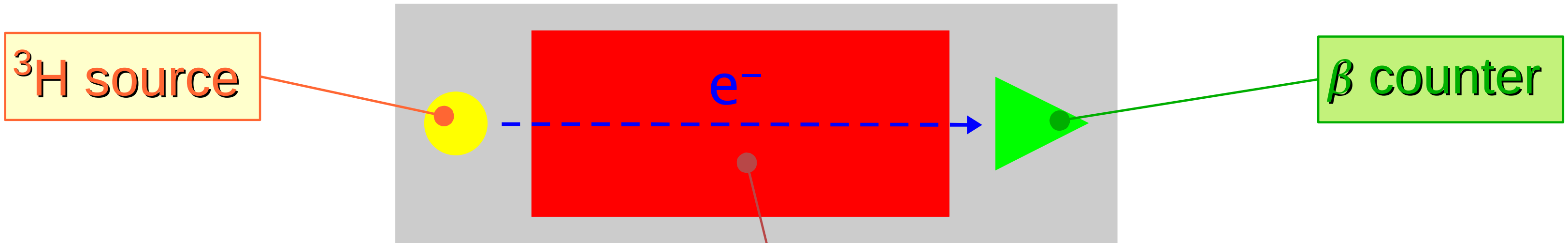
Università di Genova e INFN Sez. di Genova, Italy
Univ. di Milano-Bicocca, Univ. dell'Insubria e INFN Sez. di Milano-Bicocca, Italy
Kirkhhof-Institute Physik, Universität Heidelberg, Germany
University of Miami, Florida, USA
Wisconsin University, Madison, Wisconsin, USA
Universidade de Lisboa and ITN, Portugal
Università di Roma "La Sapienza" e INFN Sez. di Roma1, Italy
Goddard Space Flight Center, NASA, Maryland, USA
PTB, Berlin, Germany
FBK, Trento e INFN Sez. di Padova, Italy
NIST, Boulder, Colorado, USA
SISSA - Trieste, GSI Darmstad, JPL/Caltech, CNRS Grenoble, ...

funded R&D

http://crio.mib.infn.it/wig/silicini/proposal/

Experimental approaches for direct m_ν measurements

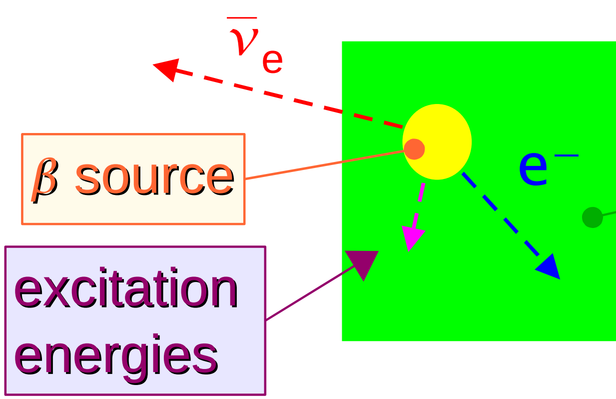
Spectrometers: source ≠ detector



β analyzer

differential or integral spectrometer: βs from the ^{3}H spectrum δE are magnetically and/or electrostatically selected and transported to the counter

Calorimeters: source ⊆ detector



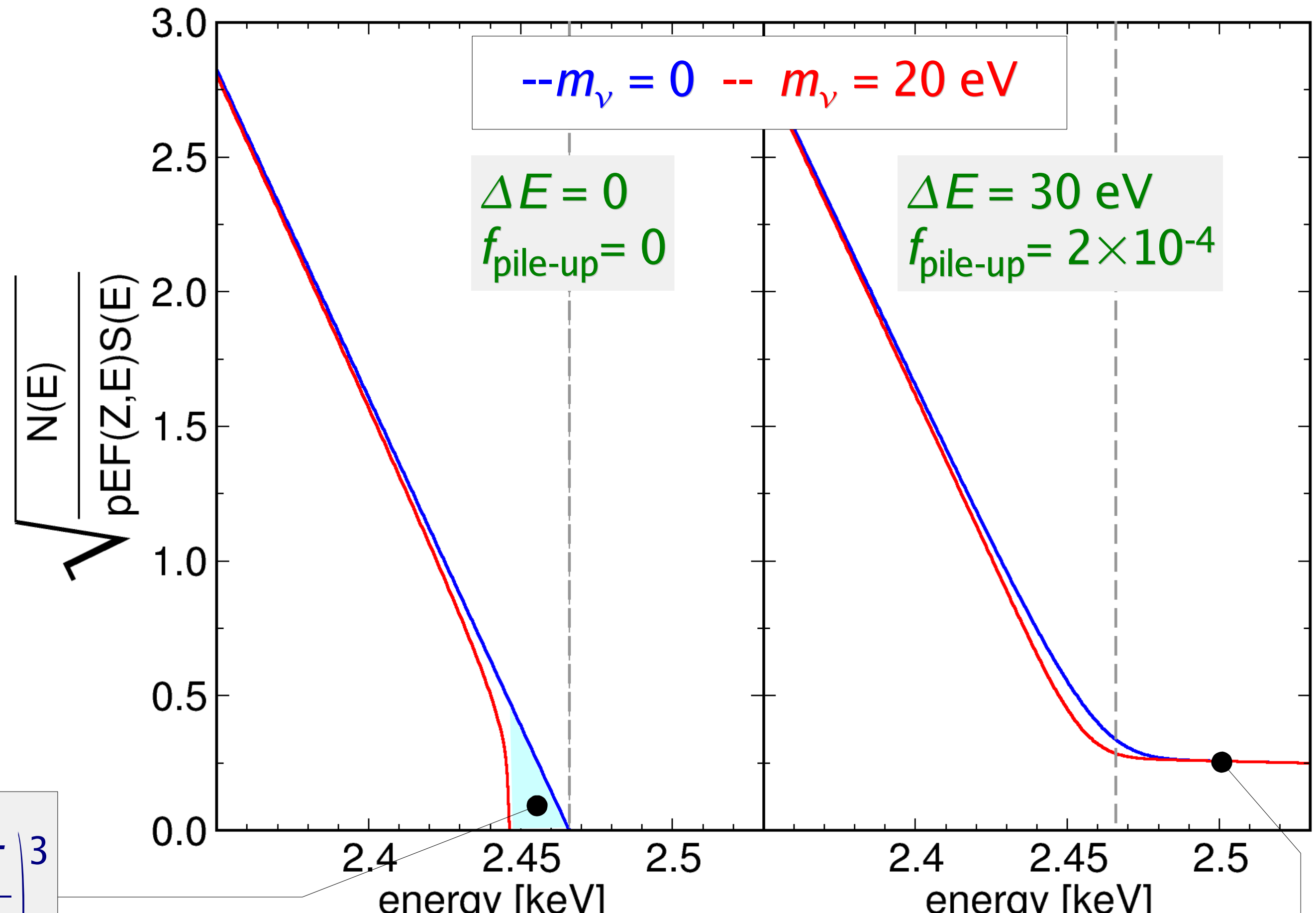
β calorimeter

ideally measures all the energy E released in the decay except for the $\bar{\nu}_e$ energy: $E=E_0-E_\nu$

Calorimetry of beta sources

- **calorimeters measure the entire spectrum at once**
  - low E_0 β decaying isotopes for more statistics near the end-point
  - best choice ^{187}**Re**: $E_0 = 2.5$ **keV**, $\tau_{1/2} = 4\times10^{10}$ **y** $\Rightarrow$ $F(\Delta E{=}10\ \text{eV}) \sim (\Delta E/E_0)^3 = 7\times10^{-8}$
  - other option ^{163}**Ho electron capture**: $E_0 \approx 2.6$ **keV**, $\tau_{1/2} \approx 4600$ **y**

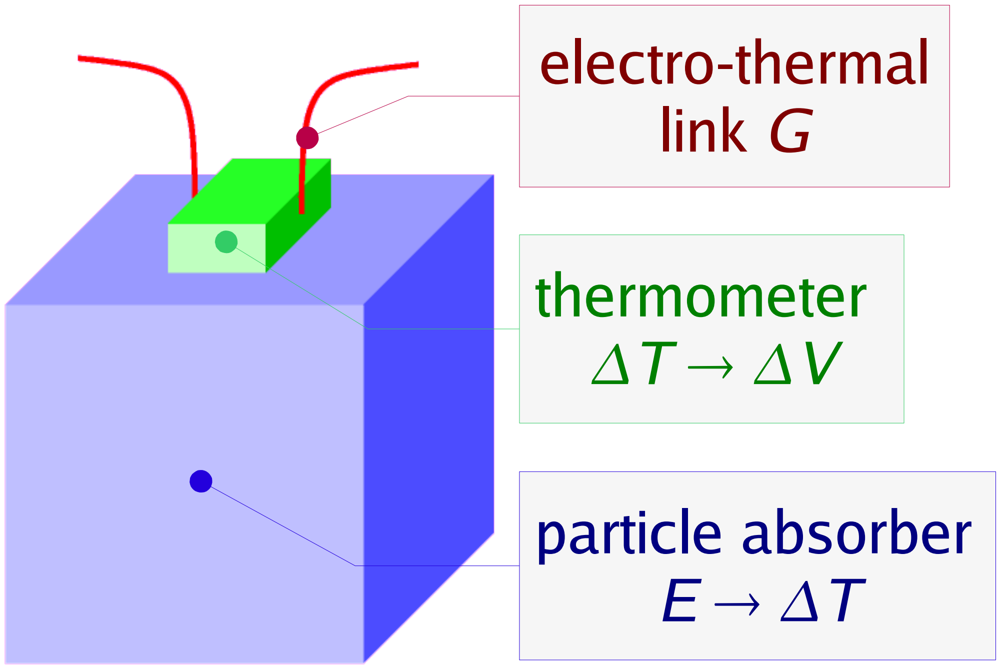
- **Calorimetry advantages**
  - no back-scattering
  - no energy losses in the source
  - no atomic/molecular final state effects
  - no solid state excitation
- **Calorimetry drawbacks**
  - limited statistics
  - pile-up background
  - spectrum related systematics

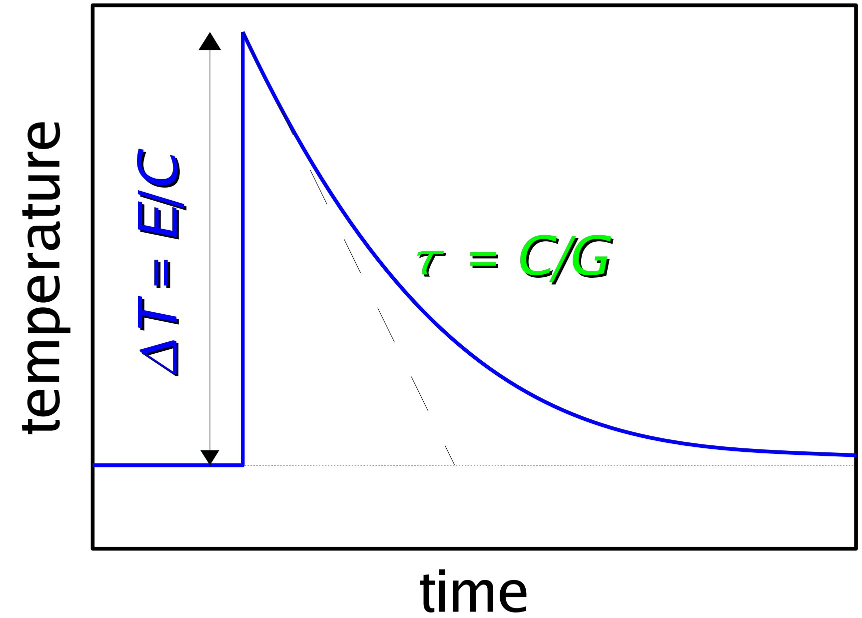


$$F(\Delta E) \approx \left(\frac{\Delta E}{E_0}\right)^3$$

pile-up fraction: $f_{pile-up} = \tau_R A_\beta$

Cryogenic detectors as calorimeters





- 1 mg of Re @ 100 mK → 1 β decay/s
  - $C \sim T^3$ $\Rightarrow C \sim 10^{-13}$ J/K
  - $\Rightarrow \Delta E_{rms} \sim 1$ eV
  - 6 keV x-ray $\Rightarrow \Delta T \sim 10$ mK
  - $G \sim 10^{-11}$ W/K $\Rightarrow \tau = C/G \sim 10$ ms

- complete energy *thermalization* (ionization, excitation → heat)
  - ⇨ calorimetry
- $\Delta T = E/C$ with C total thermal capacity (phonons, electrons, spins...)
  - ⇨ phonons: $C \sim T^3$ (Debye law) in dielectrics or superconductors below T_c
  - ⇨ low T (i.e. $T \ll 1$K)
- $\Delta E_{rms} = (k_B T^2 C)^{1/2}$ due statistical fluctuations of internal energy E
- $\Delta T(t) = E/C\, e^{-t/\tau}$ with $\tau = C/G$ and G thermal conductance

^{187}Re calorimetric experiment statistical sensitivity / 1

resolving time τ_R analysis interval ΔE

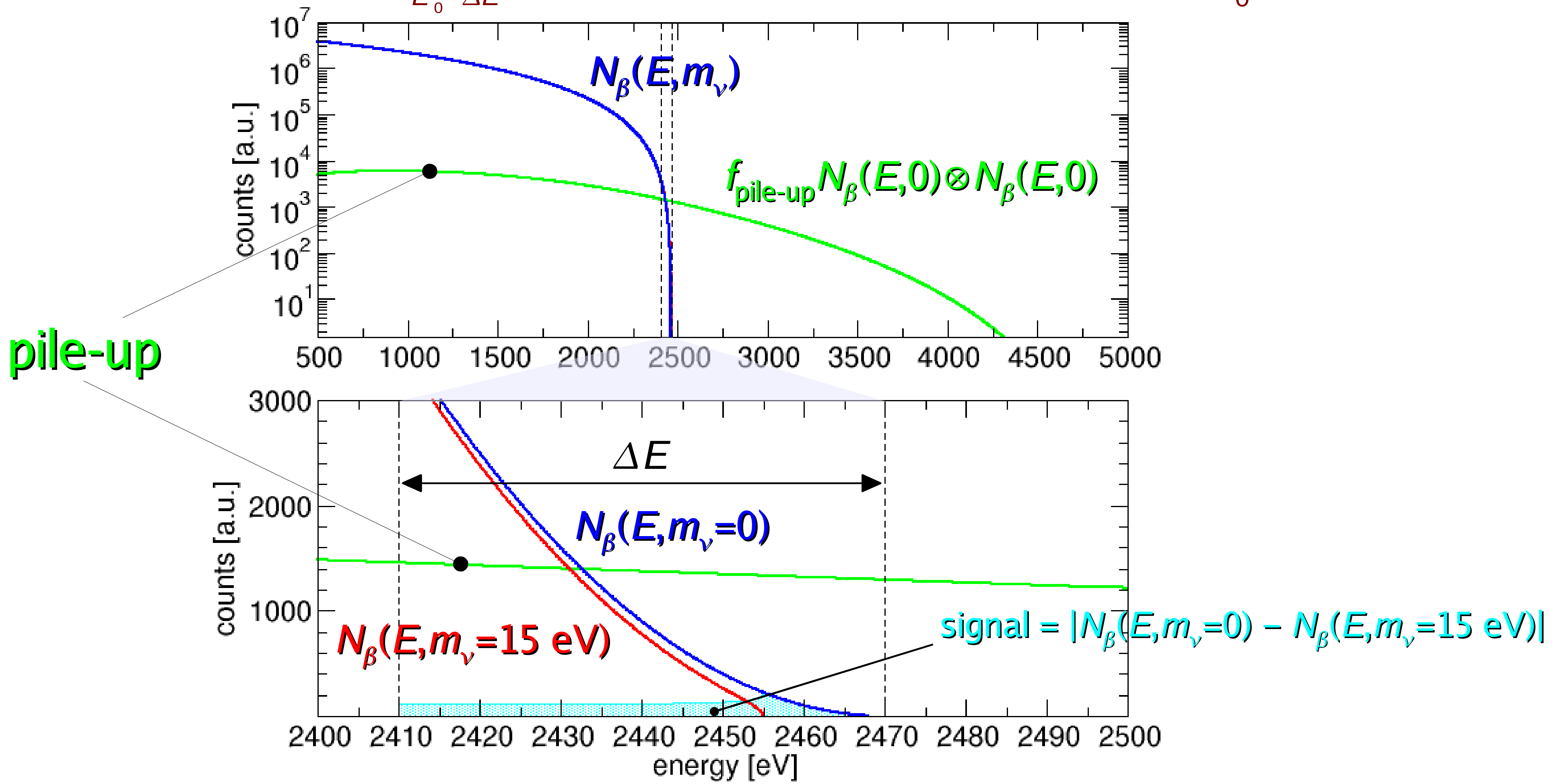
source activity A_β number of detectors N_{det}

pile-up fraction $f_{pile\text{-}up} = \tau_R A_\beta$

experimental exposure $t_M = T \times N_{det}$

$$N_\beta(E, m_\nu) \approx \frac{3}{E_0^3}(E_0 - E)^2 \sqrt{1 - \frac{m_\nu^2}{(E_0 - E)^2}}$$

$$F_{\Delta E}(m_\nu) = A_\beta N_{det} \int_{E_0 - \Delta E}^{E_0} N_\beta(E, m_\nu) dE \qquad F_{\Delta E}(0) \approx A_\beta N_{det} \frac{\Delta E^3}{E_0^3}$$



^{187}Re calorimetric experiment statistical sensitivity / 2

$$\frac{\text{signal}}{\text{bkg}} = \frac{\left|F_{\Delta E}(m_\nu) - F_{\Delta E}(0)\right| t_M}{\sqrt{F_{\Delta E}(0) t_M + F^{pp}_{\Delta E} t_M}} \approx \sqrt{t_M} \frac{A_\beta N_{det} \frac{\Delta E^3}{E_0^3} \frac{3 m_\nu^2}{2 \Delta E^2}}{\sqrt{A_\beta N_{det} \frac{\Delta E^3}{E_0^3} + 0.3 \tau_R A_\beta^2 N_{det} \frac{\Delta E}{E_0}}} = 1.7 \text{ for } 90\% \text{ C.L.}$$

$$\Sigma_{90}(m_\nu) \approx 1.13 \frac{E_0}{\sqrt[4]{N_{ev}}} \left[\frac{\Delta E}{E_0} + \frac{3}{10} f_{pile-up} \frac{E_0}{\Delta E} \right]^{1/4}$$

Optimal energy interval ΔE

$$\Delta E = max\left(0.55 E_0 \sqrt{\tau_R A_\beta}, \ \Delta E_{FWHM}\right)$$

$$f_{pile-up} = \tau_R A_\beta \ll \frac{\Delta E^2}{E_0^2}$$ $\Rightarrow$ pile-up is negligible

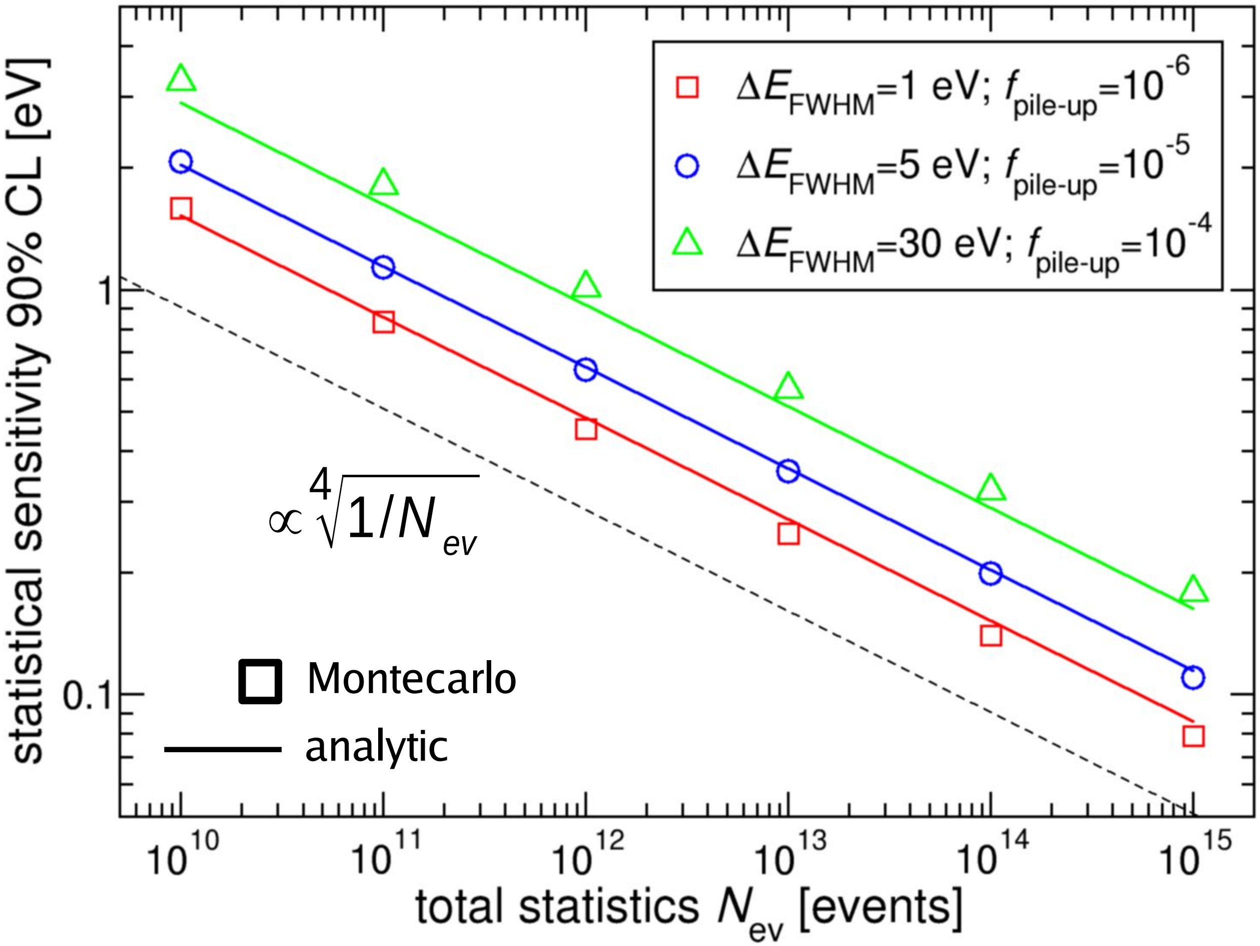
$$\Sigma_{90}(m_\nu) \approx 0.89 \sqrt[4]{\frac{E_0^3 \Delta E}{A_\beta t_M}}$$

$$\Delta E \approx \Delta E_{FWHM}$$

experimental challenges

- energy resolution ΔE_{FWHM}
- time resolution τ_R
- exposure $t_M = N_{det} \times T$
- single channel activity A_β

Sub-eV m_ν sensitivity with ^{187}Re: Montecarlo results



^{187}Re present status

- total statistics $N_{ev} \approx 10^7$ events
- MIBETA@MiB with $AgReO_4$
  - $m_\nu < 15$ eV 90% C.L.
- MANU@Ge with metallic Re
  - $m_\nu < 26$ eV 95% C.L.

A.Nucciotti et al., accepted for publication on Astropart. Phys. (arXiv:0912.4638v1)

Systematic uncertainties Montecarlo analysis

- those related to the β spectrum shape require further investigation
  - Beta Environmental Fine Structure (BEFS)
  - ^{187}Re β decay spectrum shape
  - pile-up, background, ...
- instrumental uncertainties seem under control

MARE statistical sensitivity: ^{187}Re option

bkg = 0

exposure required for 0.2 eV m_ν sensitivity

A_β [Hz]	τ_R [μs]	ΔE [eV]	N_{ev} [counts]	exposure [det×year]
1	1	1	0.2×10^{14}	7.6×10^{5}
10	1	1	0.7×10^{14}	2.1×10^{5}
10	3	3	1.3×10^{14}	4.1×10^{5}
10	5	5	1.9×10^{14}	6.1×10^{5}
10	10	10	3.3×10^{14}	10.5×10^{5}

5000 pixels/array
8 arrays
10 years
400 g ^{nat}Re

exposure required for 0.1 eV m_ν sensitivity

A_β [Hz]	τ_R [μs]	ΔE [eV]	N_{ev} [counts]	exposure [det×year]
1	0.1	0.1	1.7×10^{14}	5.4×10^{6}
10	0.1	0.1	5.3×10^{14}	1.7×10^{6}
10	1	1	10.3×10^{14}	3.3×10^{6}
10	3	3	21.4×10^{14}	6.8×10^{6}
10	5	5	43.6×10^{14}	13.9×10^{6}

20000 pixels/array
16 arrays
10 years
3.2 kg ^{nat}Re

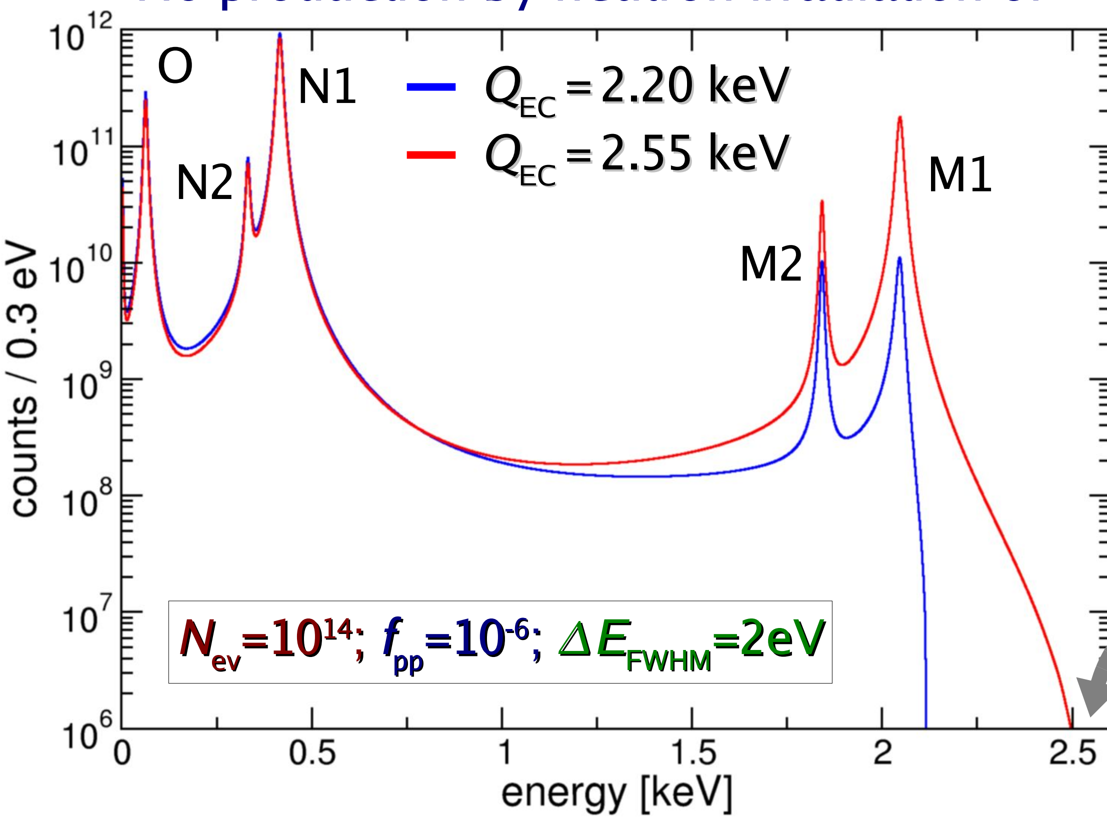
MARE extensions: ^{163}Ho electron capture measurement

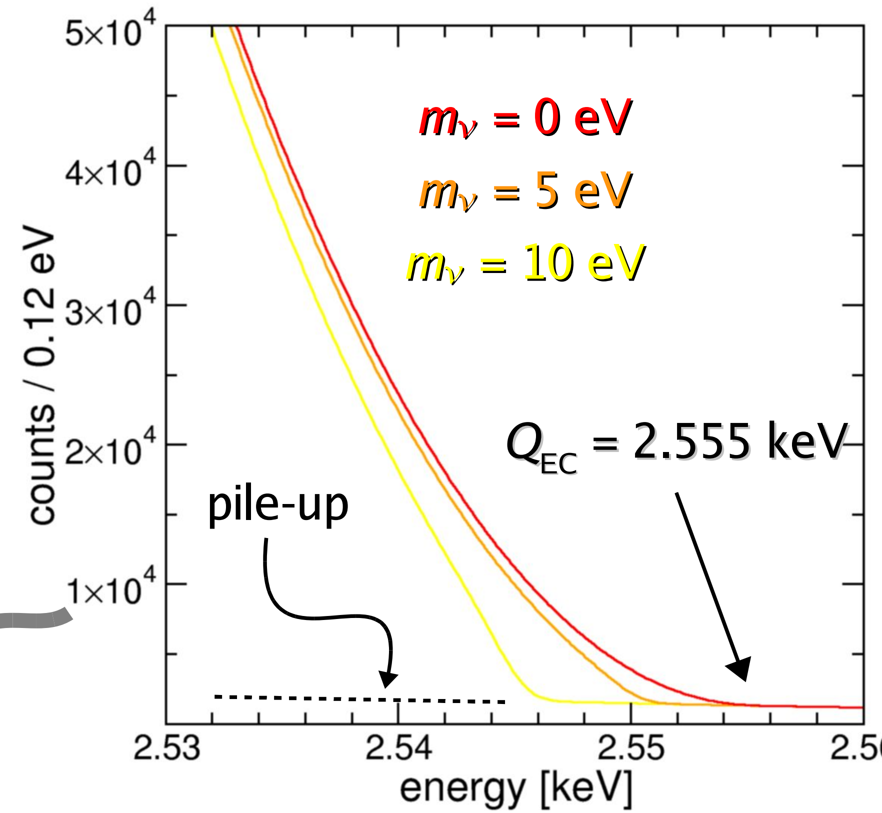
$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e$

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 may be as high as for ^{187}Re but depends on Q_{EC}
  - ▸ $\boldsymbol{Q_{EC}}$**?** Measured: $Q_{EC} = 2.3 \div 2.8$ keV. Recommended: $\boldsymbol{Q_{EC} = 2.555}$ **keV**
- $\tau_{1/2} \approx$ **4570 years**: few active nuclei are needed
  - ▸ can be implanted in any suitable microcalorimeter absorber
- ^{163}Ho production by neutron irradiation of ^{162}Er enriched Er

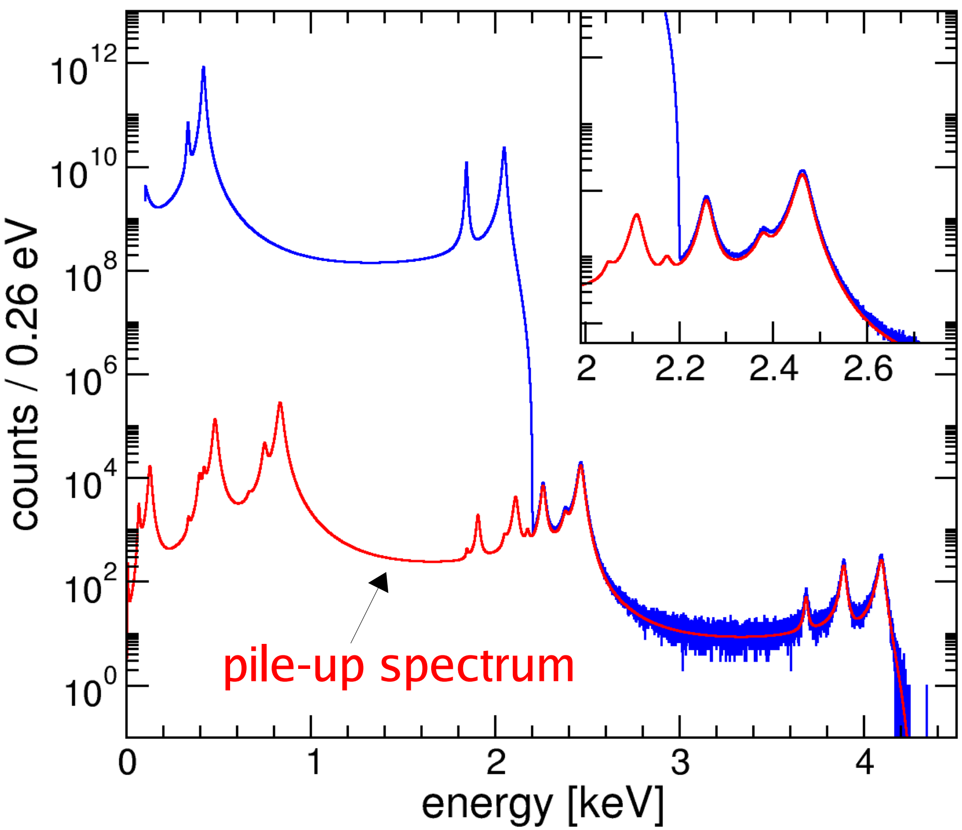




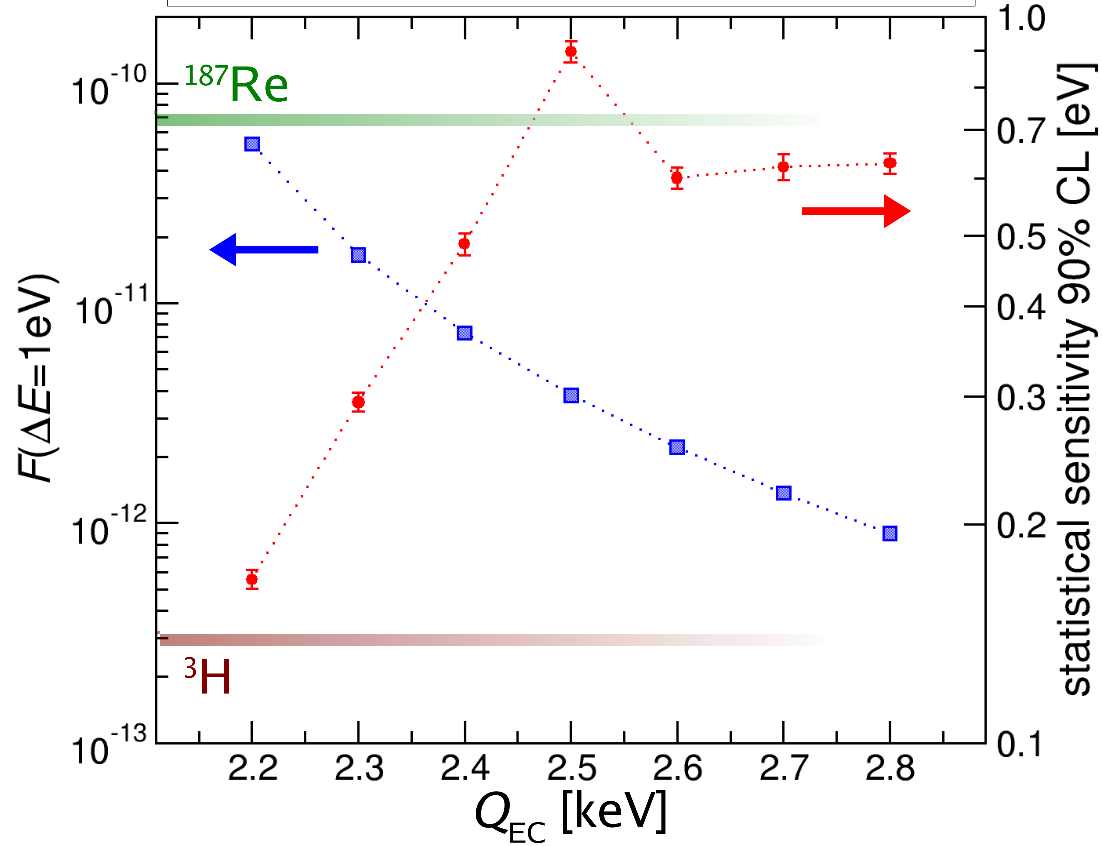
^{163}Ho spectrum simulation

- no high statistics and clean calorimetric measurement so far
  - see for example F. Gatti et al., Phys. Lett. B, 398 (1997) 415 and P. Porst poster C26
- Q_{EC} and atomic de-excitation spectrum poorly known
- complex pile-up spectrum

$N_{ev}=10^{14}$; $f_{pp}=10^{-6}$; $\Delta E_{FWHM}=2$eV



$N_{ev}=10^{14}$; $f_{pp}=10^{-5}$; $\Delta E_{FWHM}=1$eV



MARE statistical sensitivity: ^{163}Ho option

exposure required for 0.2 eV m_ν sensitivity

A_β [Hz]	τ_R [μs]	ΔE [eV]	N_{ev} [counts]	exposure [det×year]
1	1	1	2.8×10^{13}	9.0×10^{5}
1	0.1	1	1.3×10^{13}	4.3×10^{5}
100	0.1	1	4.6×10^{13}	1.5×10^{4}
10	0.1	1	2.8×10^{13}	9.0×10^{4}
10	1	1	4.6×10^{13}	1.5×10^{5}

exposure required for 0.1 eV m_ν sensitivity

A_β [Hz]	τ_R [μs]	ΔE [eV]	N_{ev} [counts]	exposure [det×year]
1	0.1	0.3	1.2×10^{14}	3.9×10^{6}
100	0.1	0.3	6.4×10^{14}	2.0×10^{5}
100	0.1	1	7.4×10^{14}	2.4×10^{5}
10	0.1	1	4.5×10^{14}	1.5×10^{6}
10	1	1	7.4×10^{14}	2.4×10^{6}

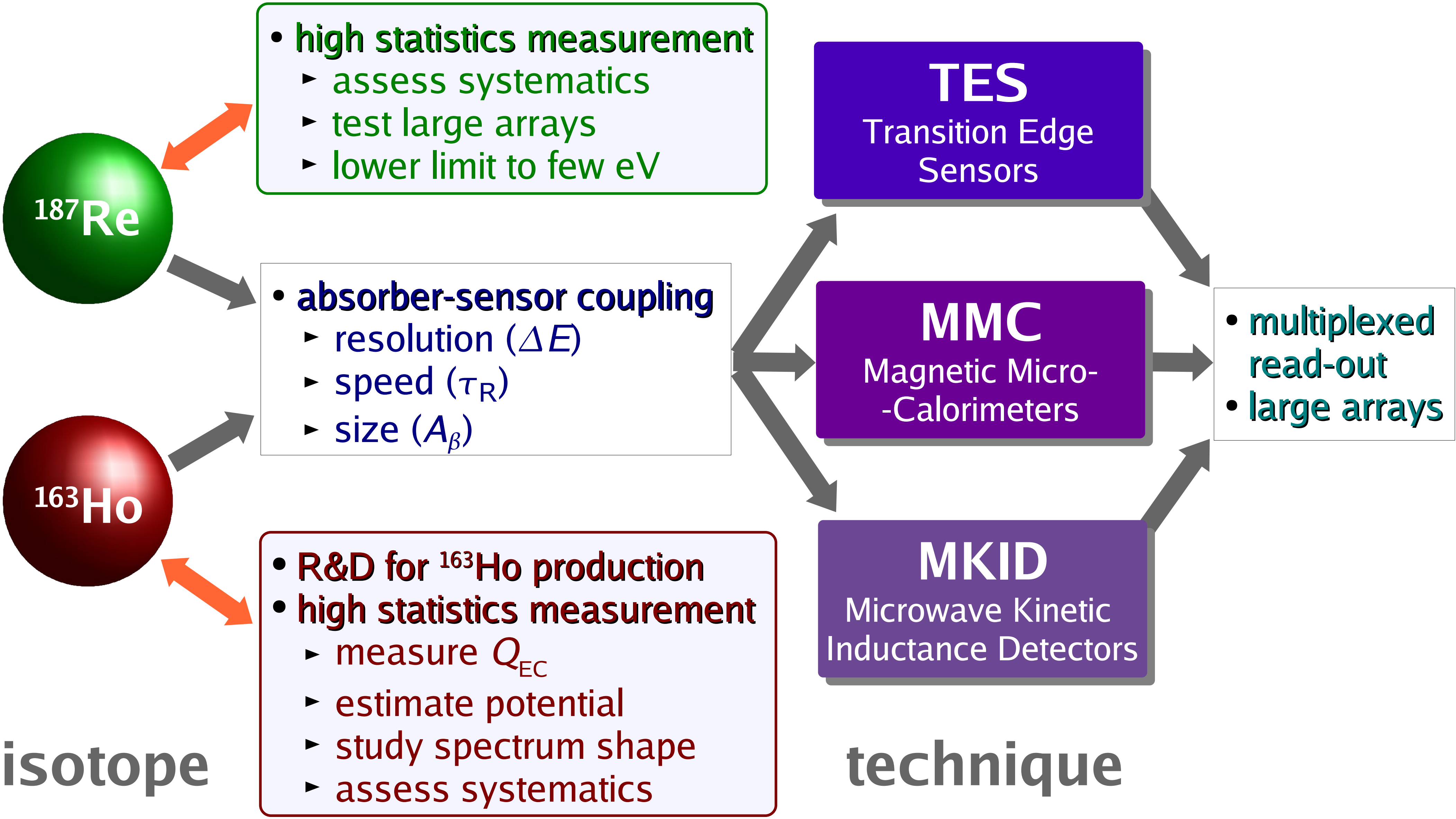
Q_{EC} = 2200 eV
***bkg* = 0**

5000 pixels/array
3 arrays
1 year
$\approx 2\times10^{17}$ ^{163}Ho nuclei

5000 pixels/array
4 arrays
10 years
$\approx 3\times10^{17}$ ^{163}Ho nuclei

Two phases: MARE-1 and MARE-2

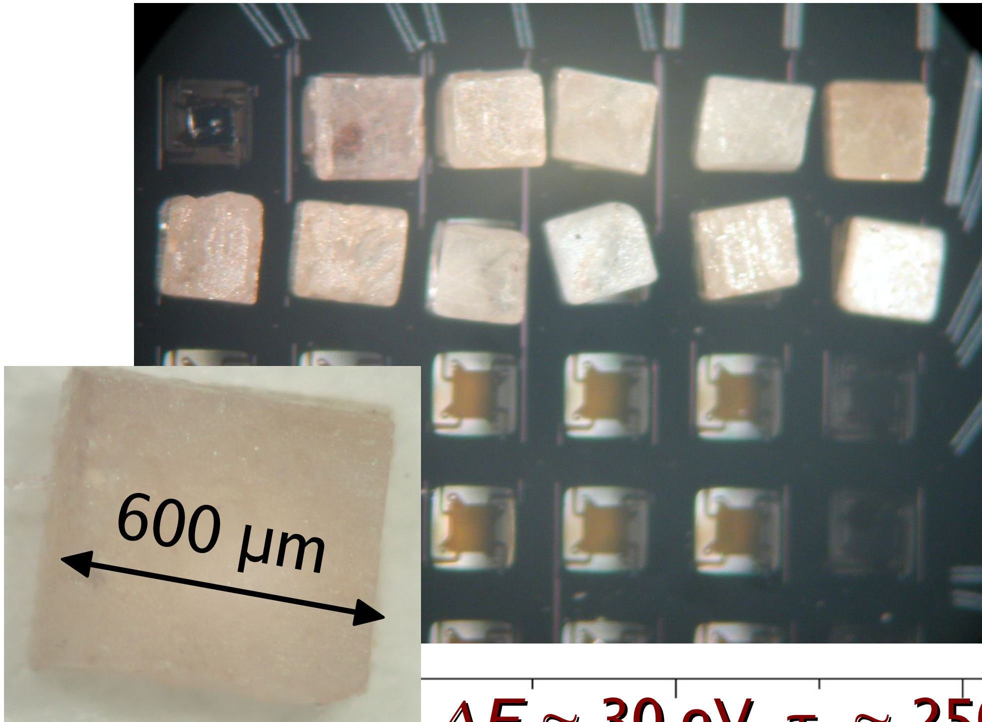
- **MARE-2** full scale experiment aiming at **0.2÷0.1 eV m_ν statistical sensitivity**
- **MARE-1** collection of activities aiming at **isotope/technique selection**



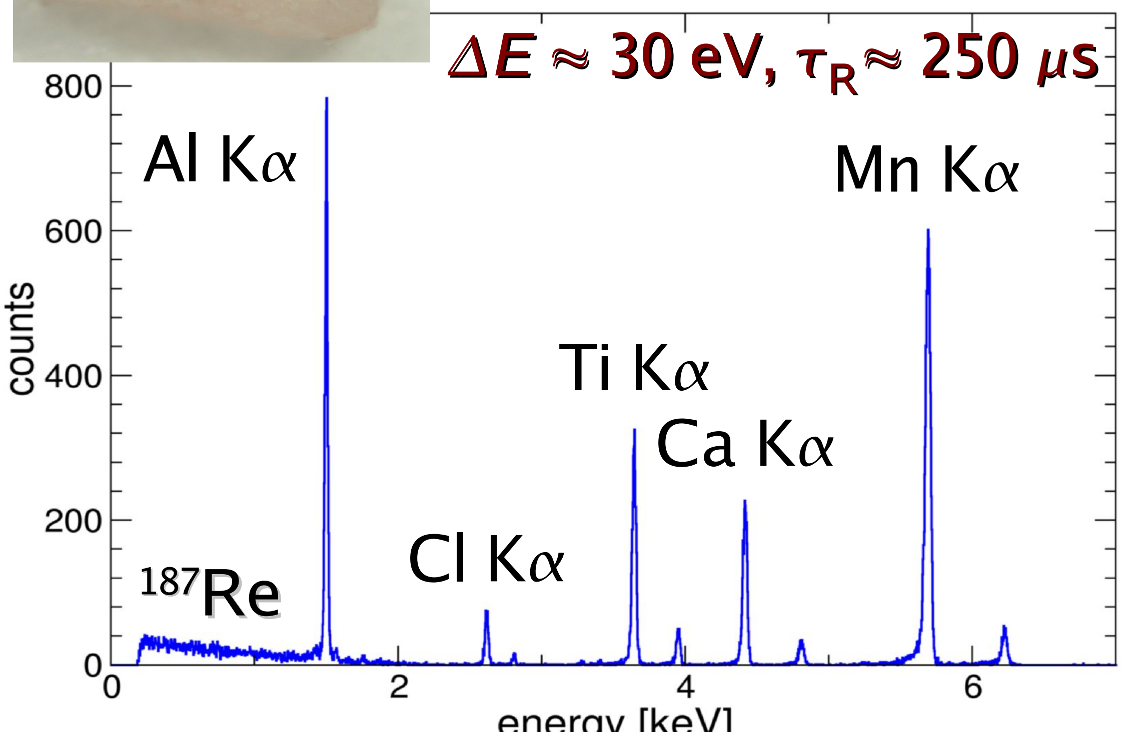
MARE-1 activities summary

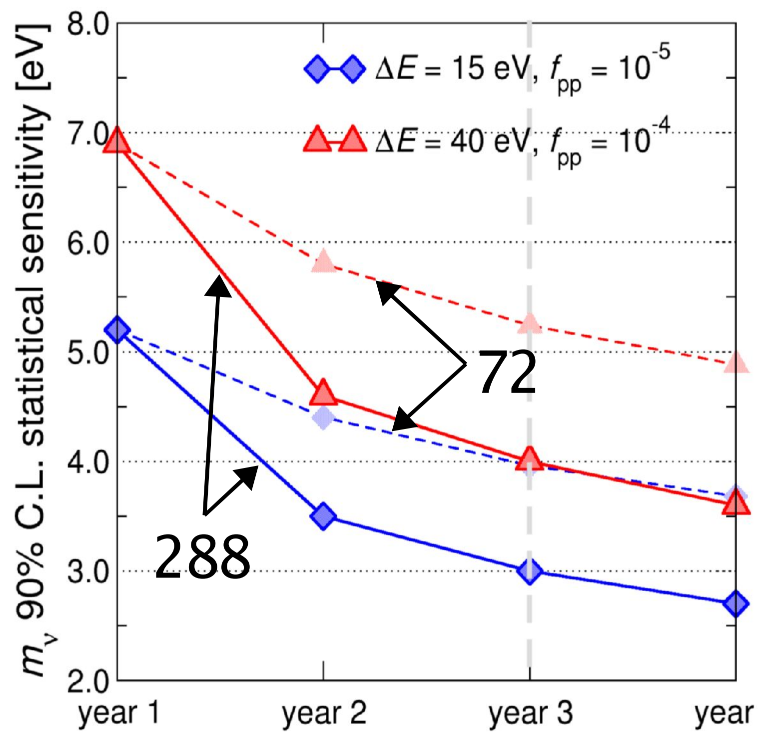
- **Isotope physics investigation and systematics assessment**
  - ^{163}Ho + Si-impl/TES (U Genova - U Milano-Bicocca – U Lisbon/ITN)
  - $AgReO_4$ + Si-impl (U Milano-Bicocca - U Como - NASA/GSFC – UW Madison)
- **Sensor-Absorber coupling (^{187}Re/^{163}Ho) and single pixel design**
  - ^{187}Re + TES (U Genova – U Miami – U Lisbon/ITN)
  - ^{187}Re + MMC (U Heidelberg) → P. Porst poster C26
  - ^{163}Ho + TES (U Genova)
  - ^{163}Ho + MMC (U Heidelberg) → P. Porst poster C26
  - ^{163}Ho/^{187}Re + MKID (U Milano-Bicocca - JPL/Caltech - U Roma - FBK)
- **Multiplexed sensor read-out**
  - SQUID multiplexing (U Genova - PTB)
  - SQUID microwave multiplexing (U Heidelberg) → P. Porst poster C26
- **Software tools**
  - Data Analysis (U Miami)
  - Montecarlo simulations (U Miami - U Milano-Bicocca)

MARE-1 @ Milano-Bicocca with Si implanted thermistors



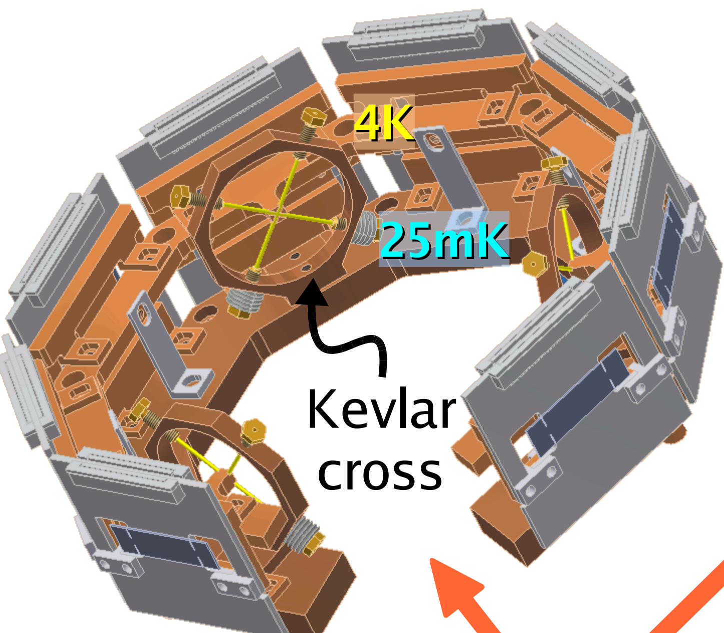
- NASA/GSFC XRS2-2 arrays
  - ▷ 6×6 Si-implanted pixels
- flat **$AgReO_4$** single crystals
  - ▷ $m \approx$ 0.5 mg
- **experiment designed for 8 arrays**
  - ▷ up to **10^{10} events** in 4 years
  - ▷ **eV sensitivity** to test spectrometers
  - ▷ high statistics to **assess systematics**
- **starting with 72 crystals**



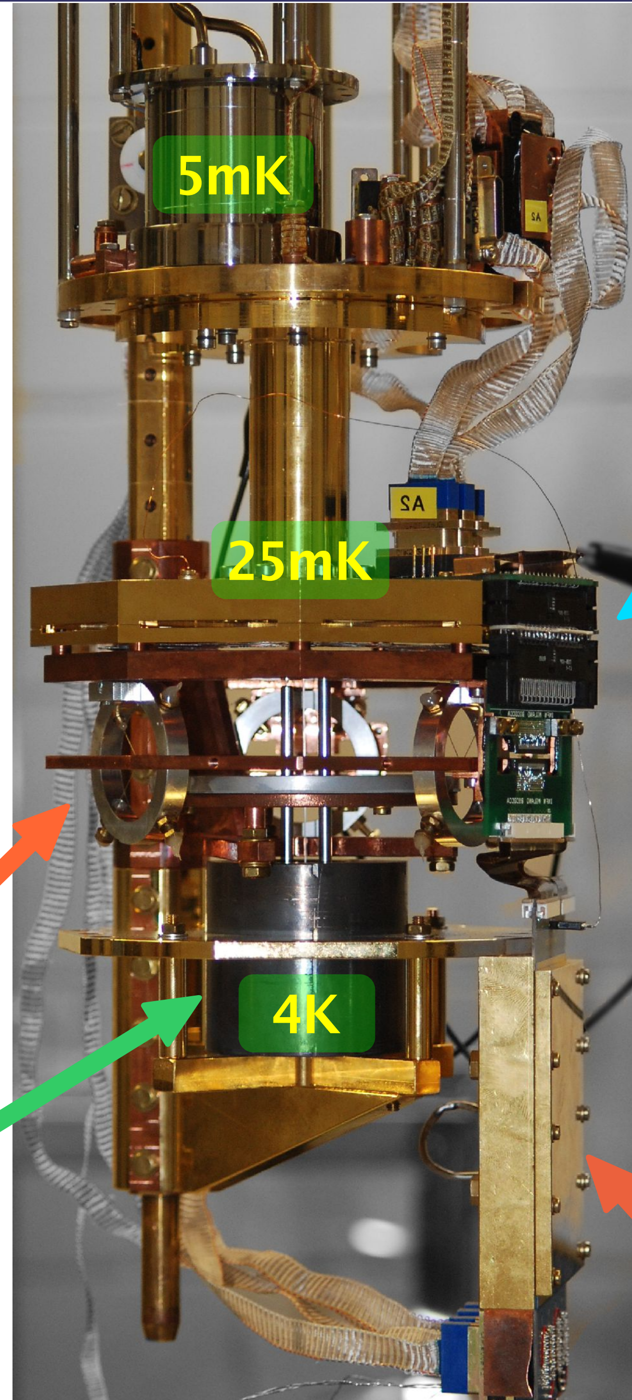


MARE-1 @ Milano-Bicocca ... / 2

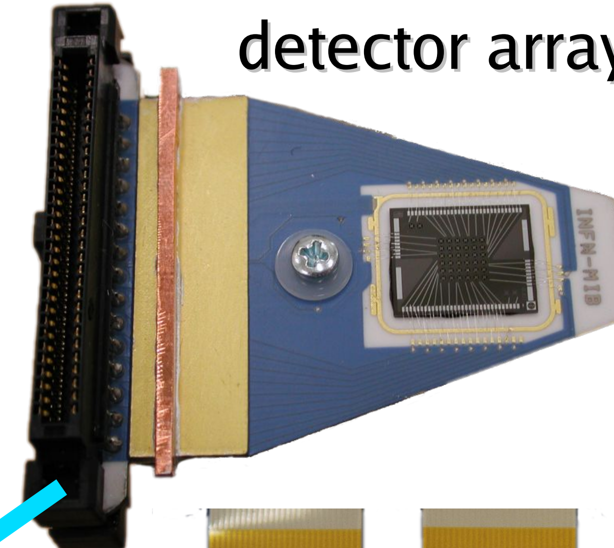
cryogenic and 300K experimental set-up completed

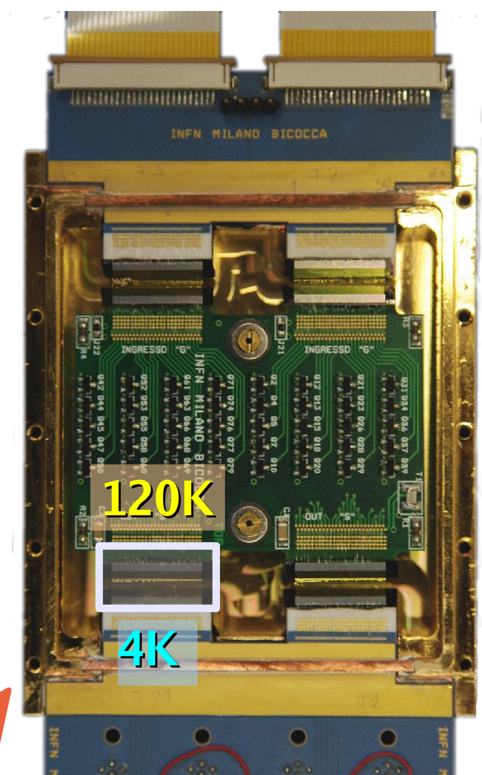


Kevlar cross



detector array





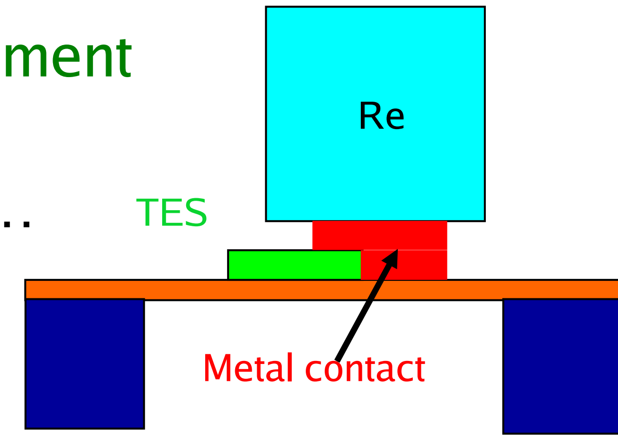
decoupling jig

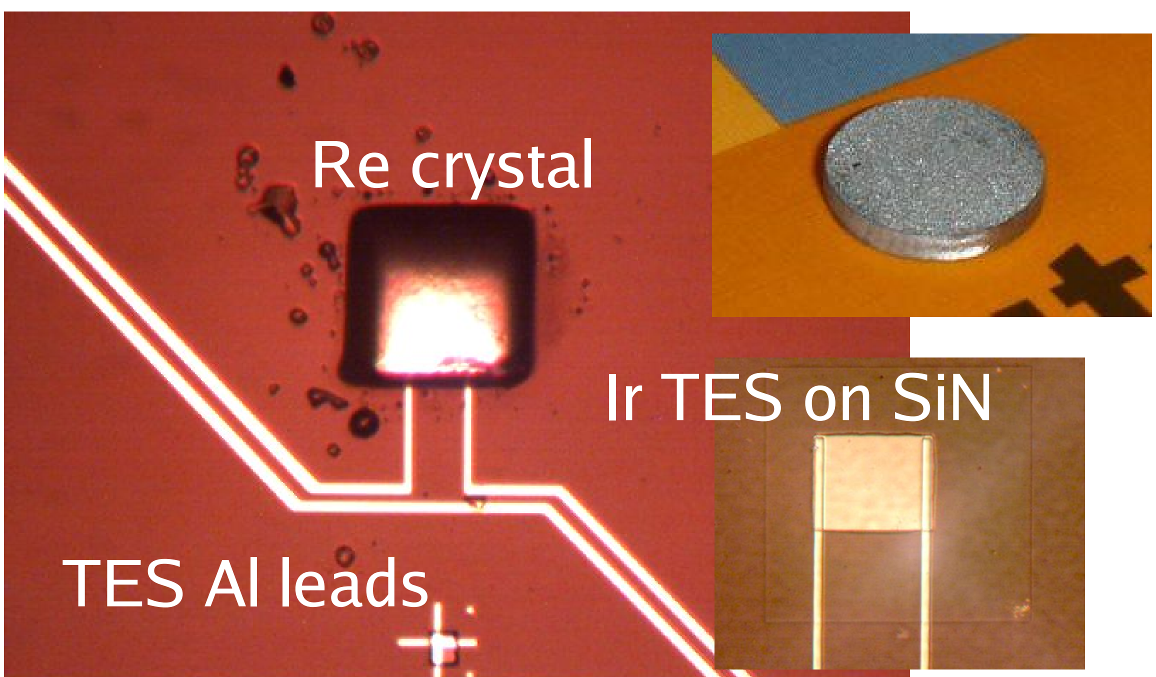
fluorescence calibration source with lead shield

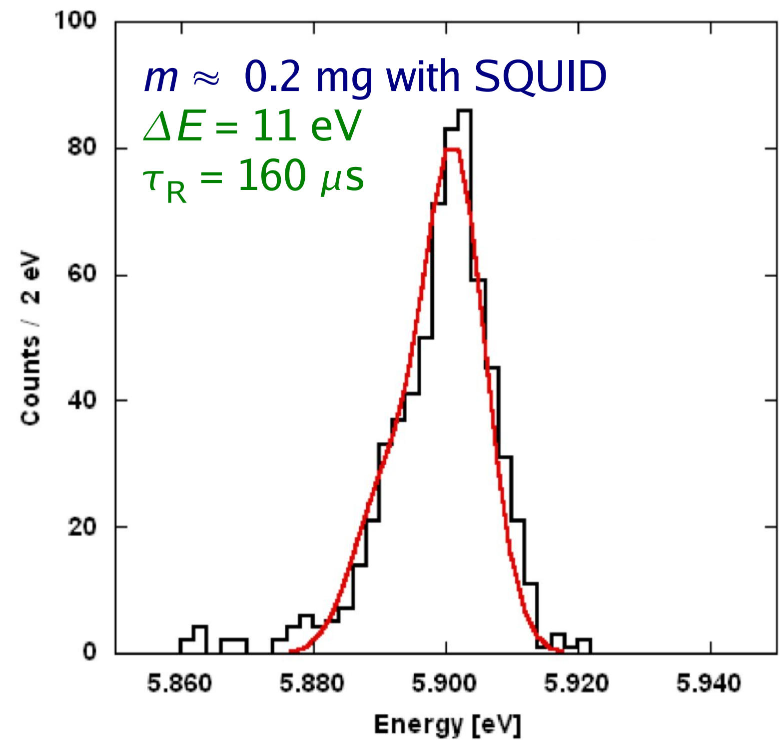
80 channel JFET box

MARE-1 @ Genova with TES

- Single TES-Re pixel R&D
  - improve pulse rise time to $\approx\mu$s
  - improve energy resolution from 10 eV to few eV
- Large arrays ($\approx 10^3$ pixels) for 10^4 -10^5 detector experiment
- Array design large scale experiment oriented
  - high reproducibility, stability, fully energy calibrated…
- Multiplexed SQUID read-out with large bandwidth
- ^{163}Ho loaded absorbers preparation
- ^{163}Ho spectrum high statistics measurement

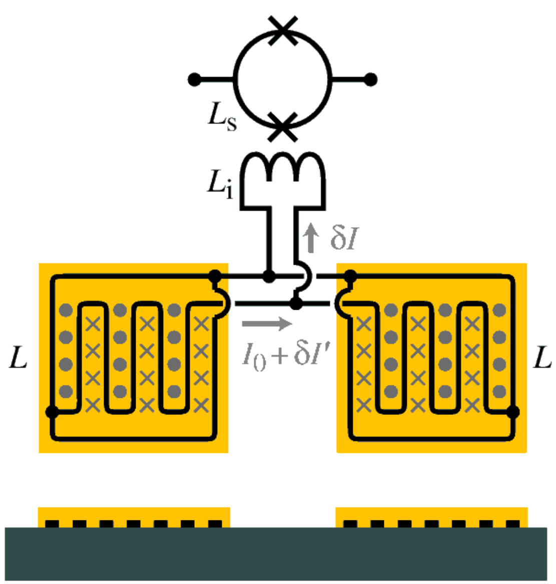


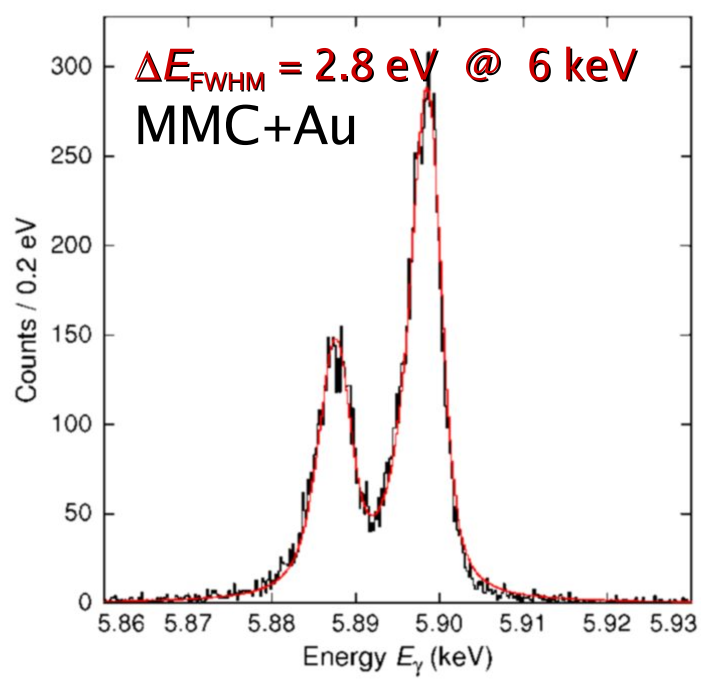


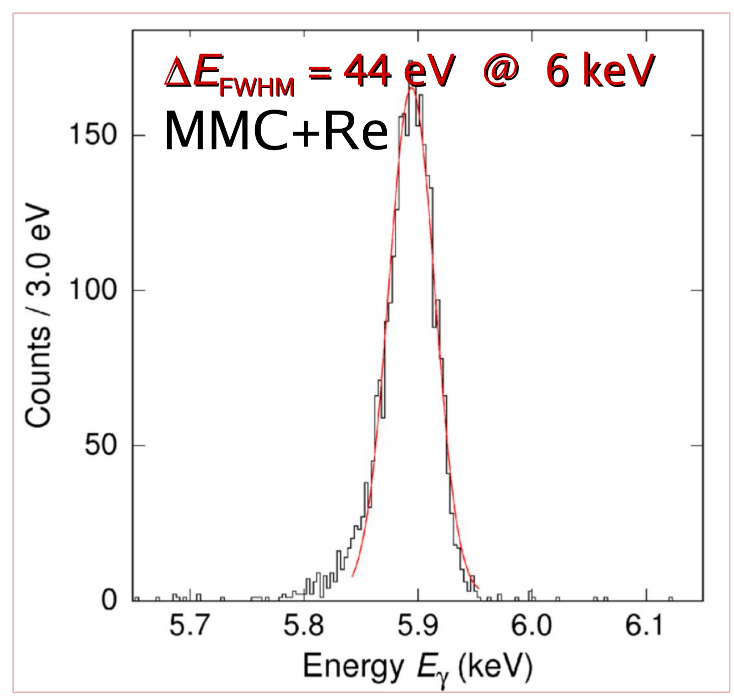


MARE-1 @ Heidelberg with Magnetic Micro Calorimeters

- Planar sensors on meander shaped pickup coils
- Optimization of MMCs with superconducting rhenium absorber
  - minimization of the rise-time
  - investigation of energy down-conversion in superconducting absorbers
  - investigating the energy resolution achievable with superconducting absorber
- Calorimetric investigation of new candidates for the neutrino mass direct measurements by electron capture decay
  - ^{163}Ho, ^{157}Tb, ^{194}Hg, ^{202}Hg
  - Development of micro-structured MMCs for ion implantation at ISOLDE
- Microwave SQUID multiplexing for MMCs

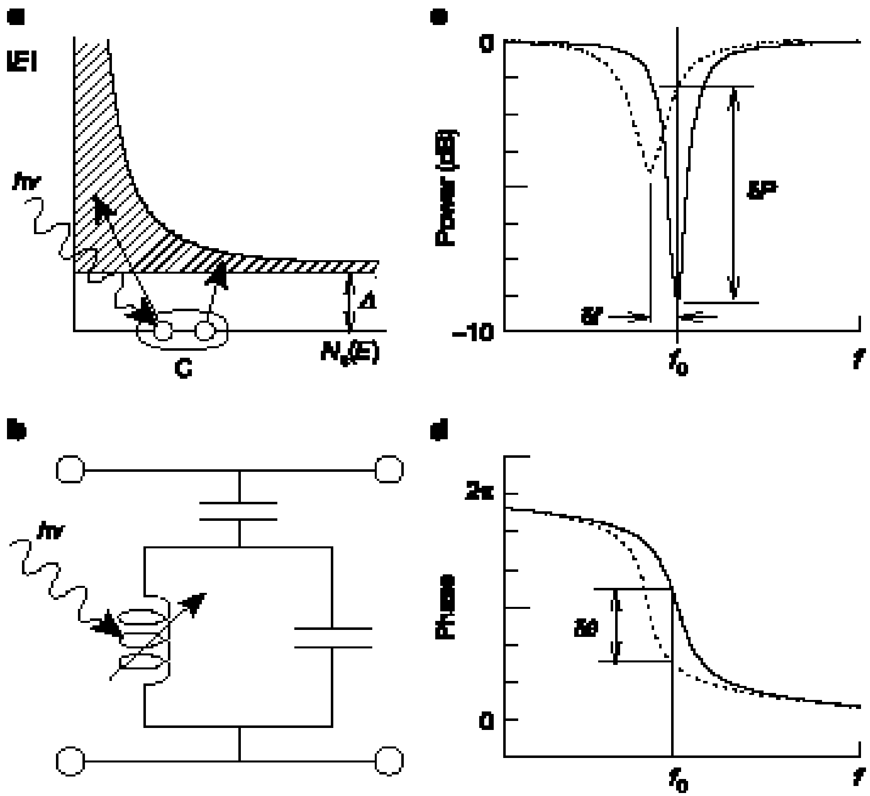




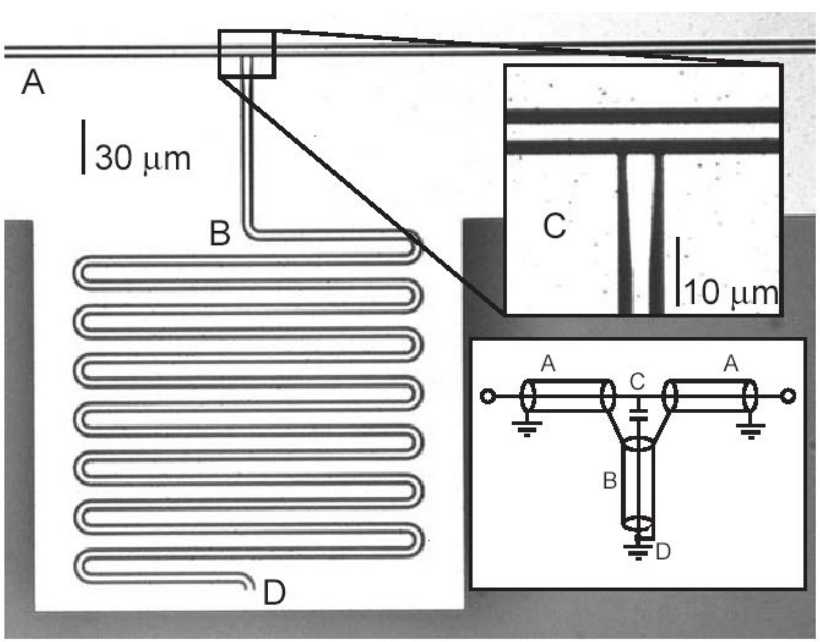


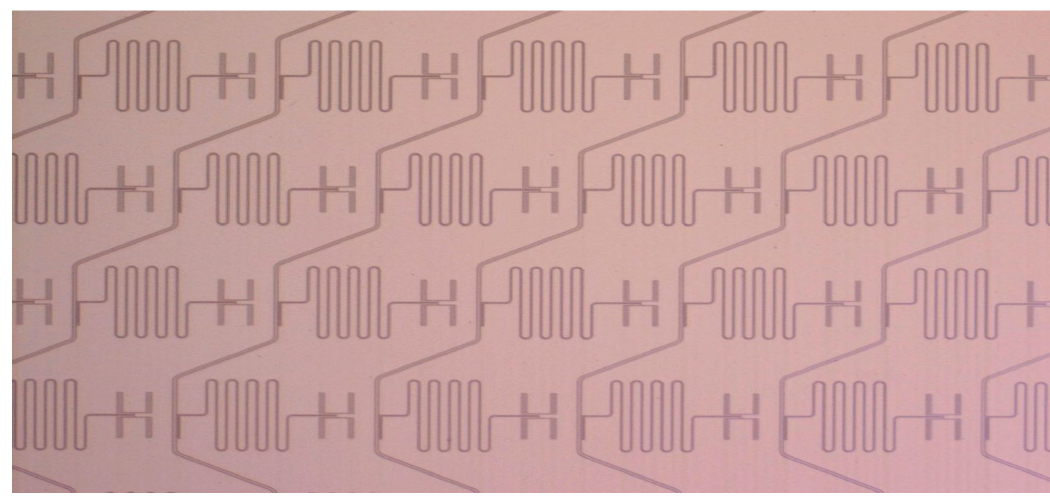
P. Porst poster C26

MKIDs R&D



- microwave (1-10 GHz) resonating superconducting devices
- exploit the temperature dependence of inductance in a superconducting film
  - **qp detectors** suitable for large absorbers
  - **fast** devices for high single pixel activity A_β and low pile-up f_{pp}
  - **high energy resolution**
  - easy **multiplexing** for large number of pixel





Conclusions

- thermal calorimetry of ^{187}Re decay can give **sub-eV sensitivity on m_ν**
- calorimetry of ^{163}Ho electron capture decay is an interesting alternative
- MARE-1 activities are in progress to
  - improve the understanding of ^{187}Re experiment systematics
  - investigate ^{163}Ho production and decay spectrum
  - develop the single MARE pixel
  - implement read-out multiplexing schemes
- **isotope and detection technique selection** for MARE-2 is in progress