Ecole Internationale Daniel Chalonge
Workshop CIAS Meudon 2012
WARM DARK MATTER GALAXY FORMATION
IN AGREEMENT WITH OBSERVATIONS
CIAS Observatoire de Paris, Chateau de Meudon, Meudon campus
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Status of MARE for the keV sterile detection

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Outline

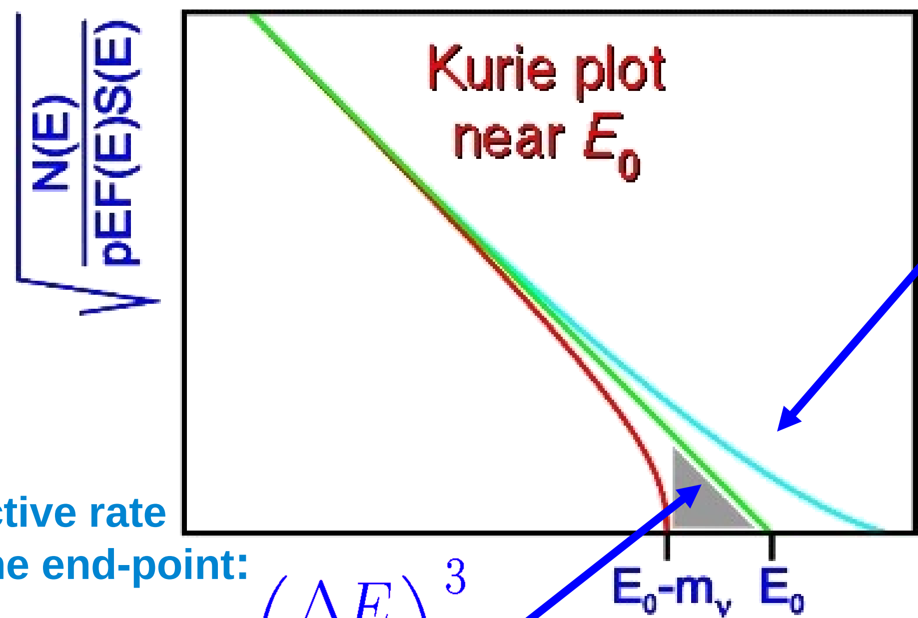
- **Direct neutrino mass measurement**
  - spectrometers vs. calorimeters
- **MARE: Microcalorimeter Array for a Rhenium Experiment**
  - calorimetric measurement sensitivity to light neutrinos
  - ^{187}Re vs. ^{163}Ho
  - heavy (sterile) neutrinos detection
- **MARE 1 @ Milano**
  - Re option
  - Ho option
- **Conclusions**

Direct neutrino mass measurements

neutrino oscillations evidence → $m_\nu \neq 0$

BUT oscillation experiments give only Δm^2!

direct neutrino mass measurement



effective rate at the end-point:

$$F_{\Delta E}(0) \approx \left(\frac{\Delta E}{E_0}\right)^3$$

effect of:
- **energy resolution**
- **background**
- **Pile up**

$$K(E_\beta) = (E_0 - E_\beta)\sqrt[4]{1 - \frac{m_\nu^2}{(E_0 - E_\beta)^2}}$$

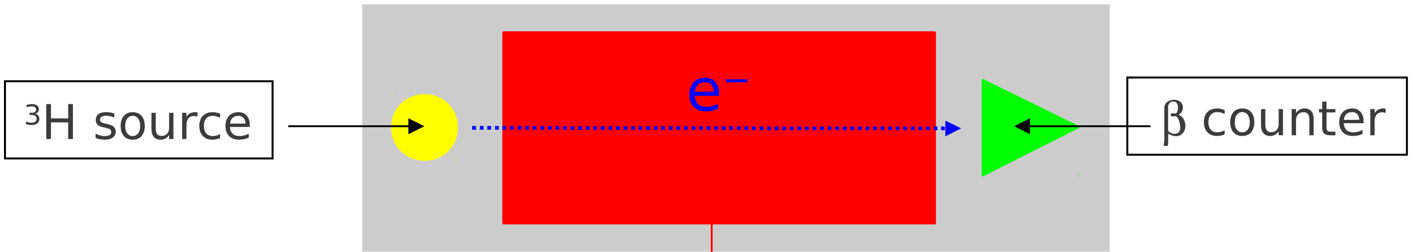
$m_\nu = (\Sigma m^2_i |U_{ei}|^2)^{1/2}$

2 eV → ^3H (E_0=18.6keV) & spectrometers

15 eV → ^{187}Re(E_0=2.47keV) & calorimeters

Different approaches to direct measurement

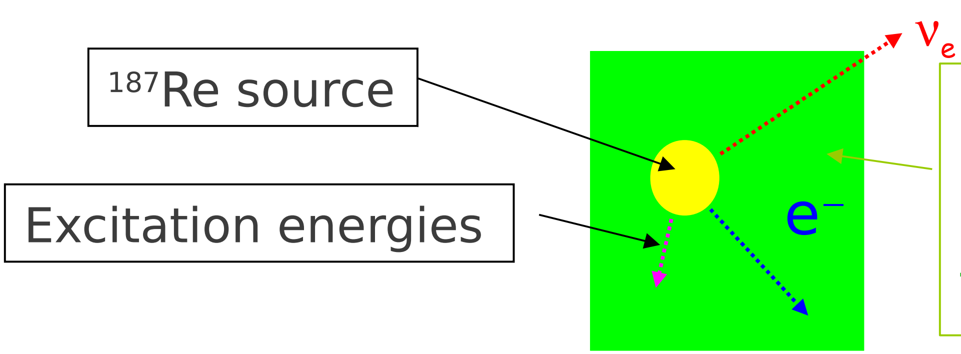
- **Spectrometers: source ≠ detector**



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 ν_e energy

Calorimeters vs Spectrometers

General experimental requirements:

- High statistics at the beta spectrum end-point:
  - low end point energy E_0
  - high source activity and high efficiency
- high energy resolution ΔE (same order of magnitude of m_ν sensitivity)
- high Signal to Noise ratio
- small systematic effects

Spectrometer: β source ≠ detector

Advantages:

✓ high statistics
✓ high energy resolution

Disavantages:

✗ systematics due to source effect
✗ systematics due to decay to excitated states
✗ background

Calorimeter: β source ⊆ detector

Advantages:

✓ no backscattering
✓ no energy losses in the source
✓ no solid state excitation
✓ no atomic/molecular final state effects

Disavantages:

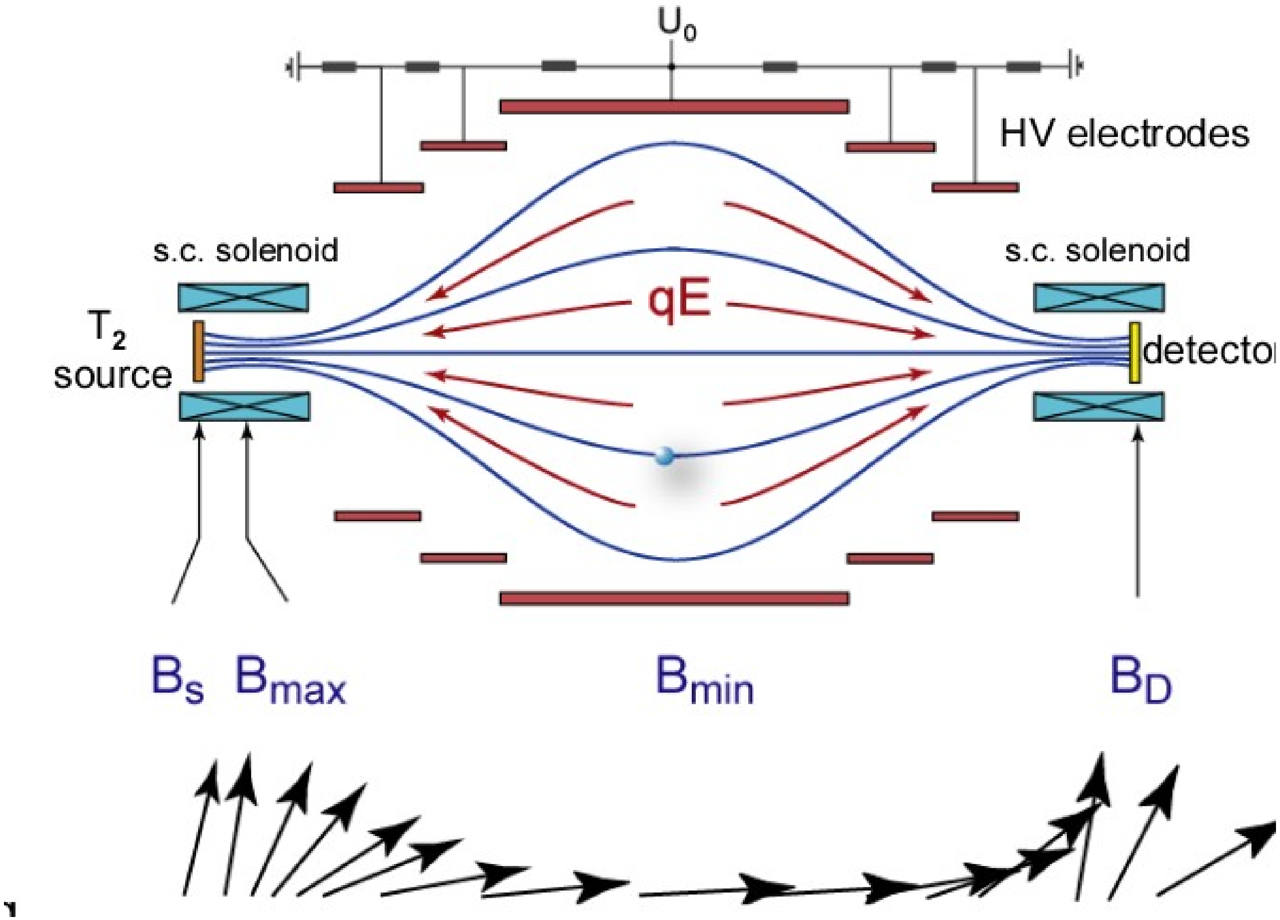
✗ limited statistics
✗ systematics due to pile-up
✗ background

Spectrometers present results

electrostatic integrating spectrometers (MAC-E filter)

- Mainz with solid ^3H source
- Troitsk with gaseous ^3H source

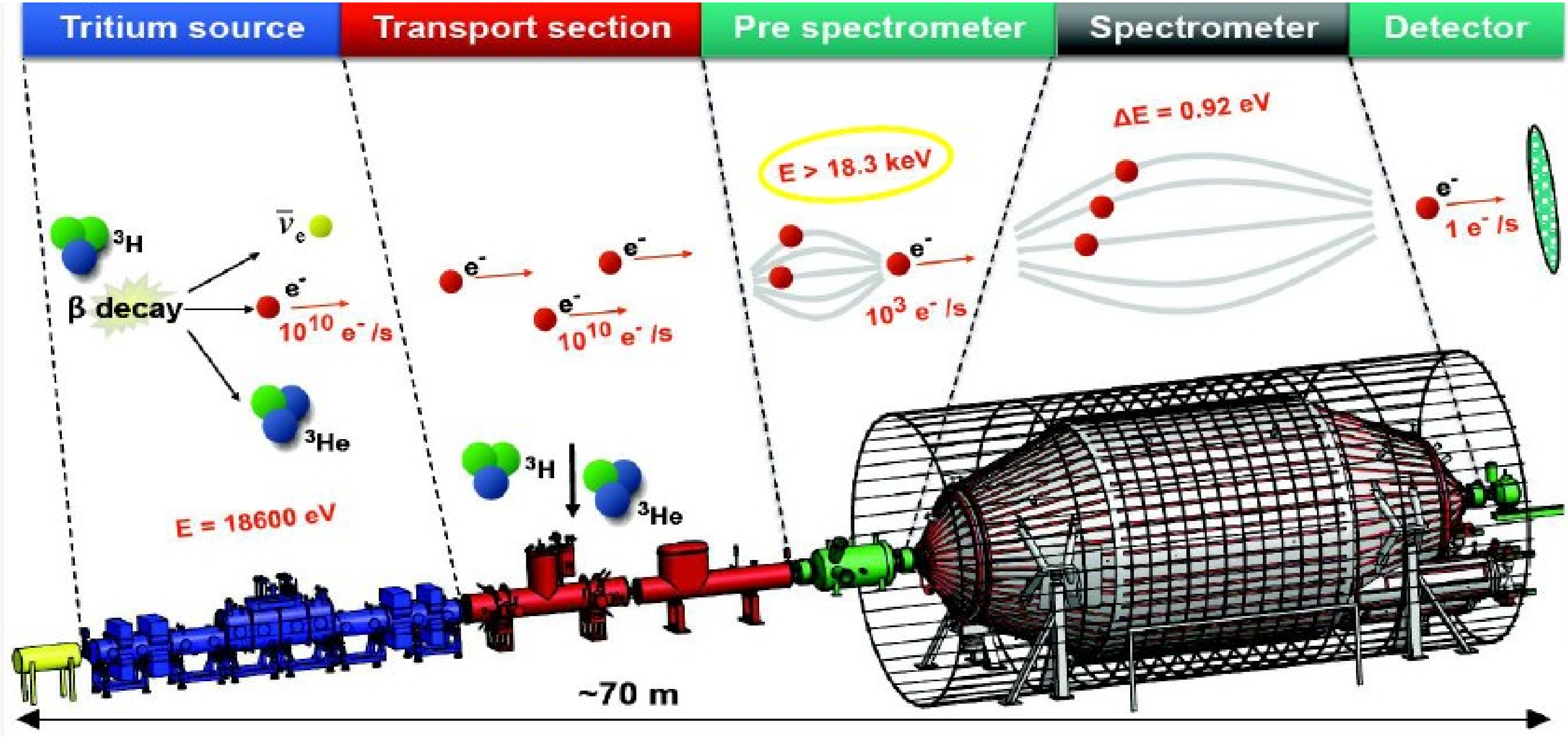
$m_{\nu e}$ < 2.2 eV 95% CL



Spectrometers future: KATRIN

large electrostatic spectrometer
with gaseous ^{3}H source

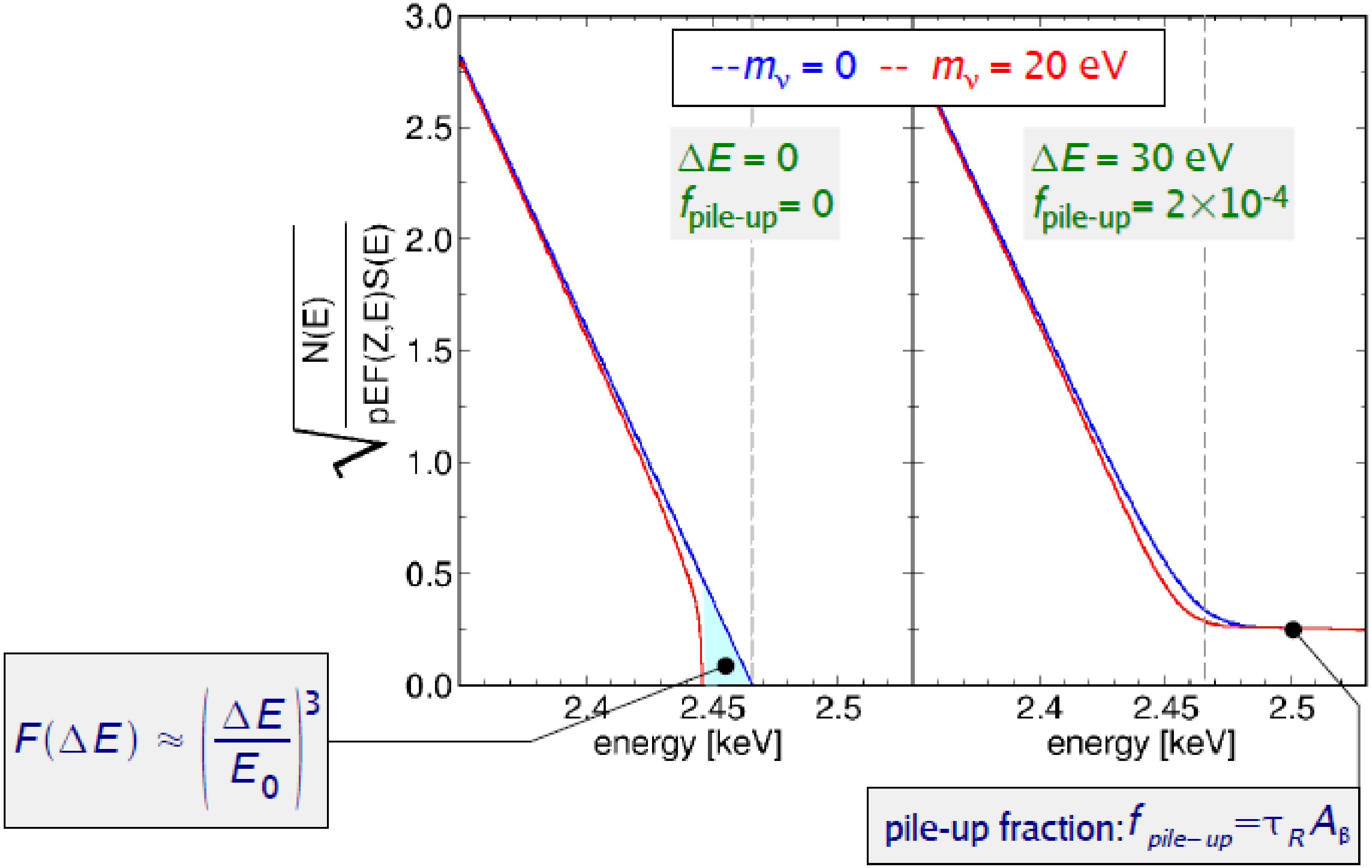
▶ expected statistical sensitivity
$m_{\nu e} < 0.2$ eV 90% CL



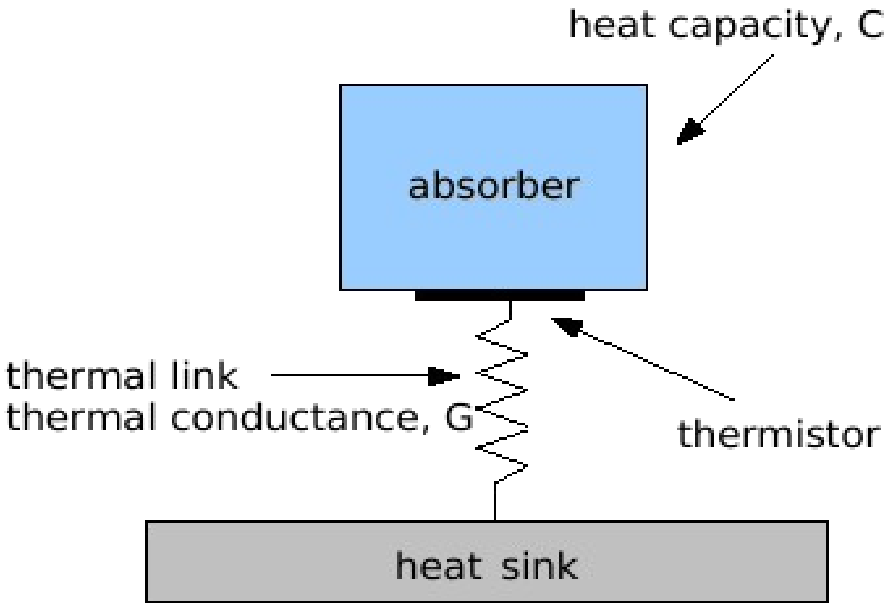
Calorimetry of beta sources

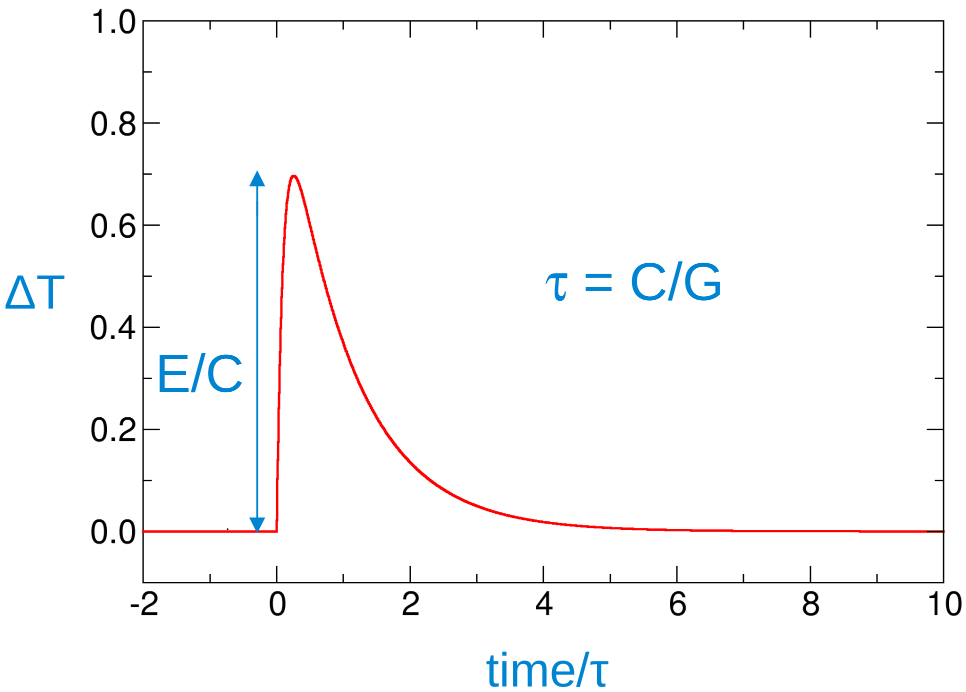
Calorimeters measure the entire spectrum at once:

- Low E_0 β decaying isotopes for more statistics near the end-point
- best choice ^{187}Re: E_0 = 2.5 keV, τ½ = 4×10^{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, τ½ ≈ 4600 y



Cryogenic detectors as calorimeters





Detection Principle:

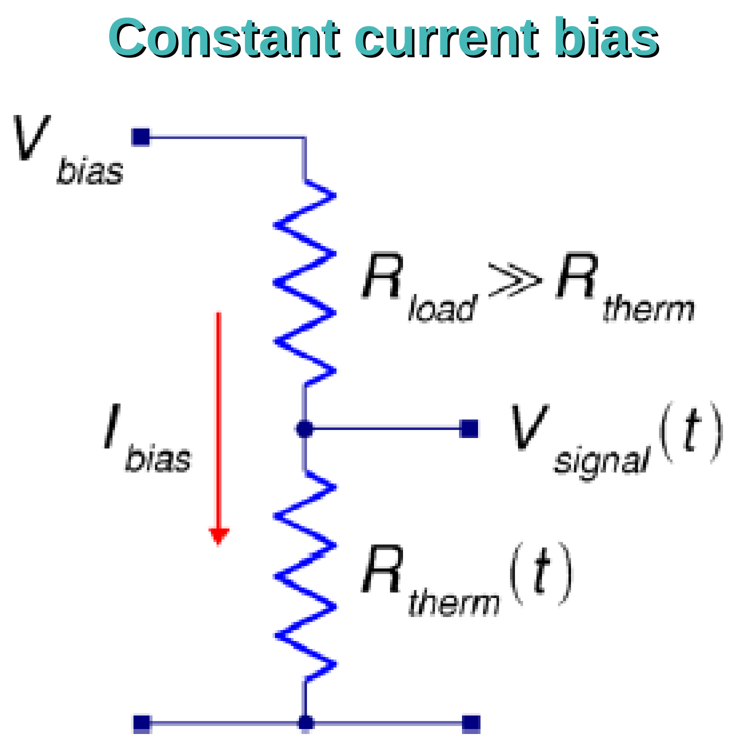
- $\Delta T = E/C$ where C is the total thermal capacity
  - low C: $C \sim (T/\Theta_D)^3$ in superconductors below T_C & dieletric
    - low T (10 ÷ 100 mK)
- ultimate limit to energy resolution:
  - statistical fluctuation of internal energy $\Delta E = (k_B T^2 C)^{1/2}$
- detect all deposited energy, including short-lived excited states (100 μs)
- achieve very good energy resolution in the keV range

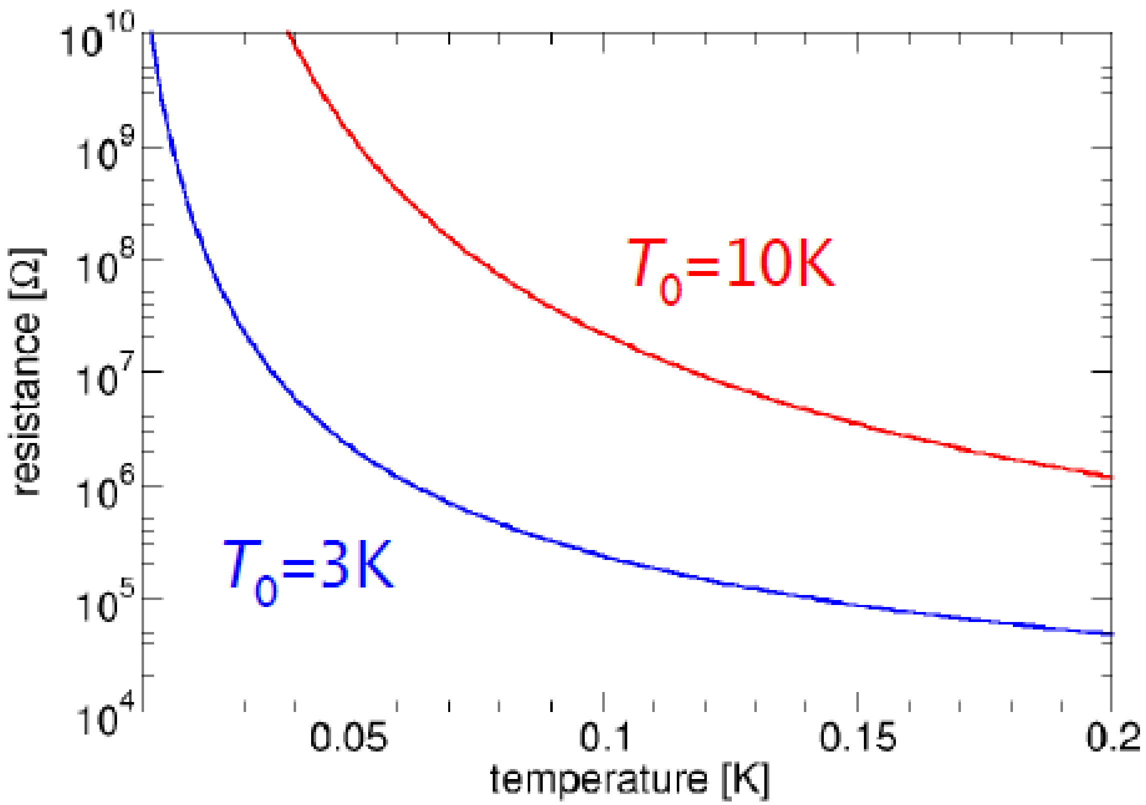
Resistive thermometers:thermistors

- doped semiconductors at Metal-Insulator-Transition
- at T≪10K → phonon assisted variable range hopping conduction (VRH)

$$\rho(T) = \rho_0 \exp(T_0/T)^\gamma$$

▶ T_0 increases with decreasing net doping N
▶ $T < 1$ K ⇒ $\gamma = 1/2$ (VRH with Coulomb Gap)





High impedance devices: 1MΩ → 100MΩ

Thermal detectors for calorimetric experiments

^{187}Re β decay

- 5/2^{+}→ 1/2^{-} unique first forbidden transition ⇒ S(Eβ)
- end point E_0 = 2.47 keV

$$^{187}Re \rightarrow {}^{187}Os + e^{-} + \bar{\nu}_e$$

- half-life time $\tau_{1/2}$ = 43.2 Gy
- natural abundance a.i. = 63%
- 1 mg metallic Rhenium ⇒ ≈1.0 decay/s

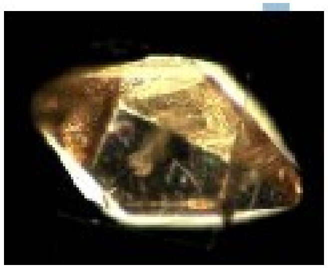
metallic rhenium single crystals

- superconductor with Tc=1.6K
- NTD thermistors
- MANU experiment (Genova)

m_ν <15 eV

dielectric rhenium compound ($AgReO_4$) crystals

- Silicon implanted thermistors
- MIBETA experiment (Milano)

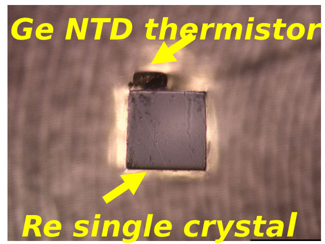


Precursors of ^{187}Re experiment

MANU (1999)

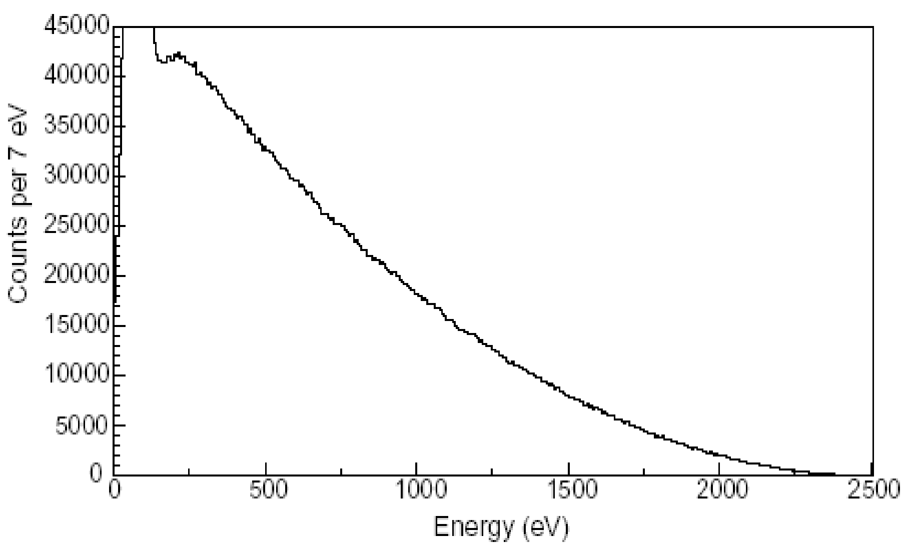
Genova

- 1 crystal of metallic Re: 1.6 mg
- ^{187}Re activity ≈ 1.6 Hz
- Ge-NTD thermistor
- ΔE=96 eV FWHM
- 0.5 years live-time



- $m_\nu^2 = -462\ ^{+579}_{-679}\ \mathrm{eV}^2$
- $m_\nu \leq 26$ eV (95 % C.L.)

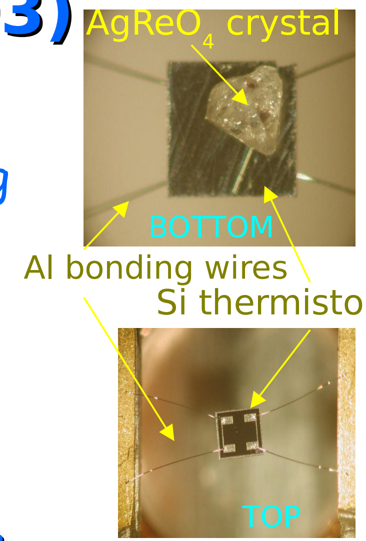
6.0×10^6 ^{187}Re decays above 420 eV



MIBETA (2002-2003)

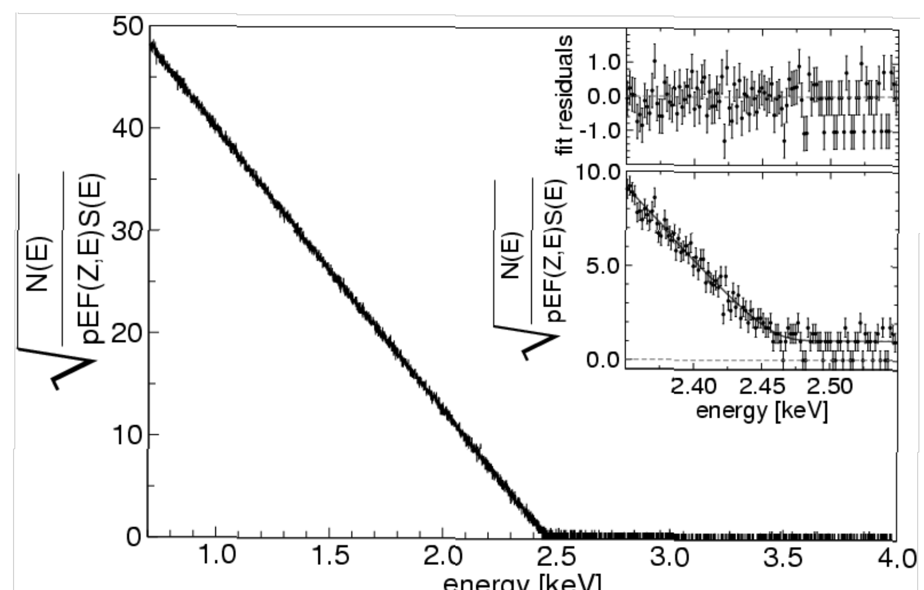
Milano, Como, Trento

- 10 $AgReO_4$ crystals: 2.71 mg
- ^{187}Re activity = 0.54 Hz/mg
- Si thermistors (ITC-irst)
- ΔE= 28.5 eV FWHM
- 0.6 years live time



- $m_\nu^2 = -112 \pm 207_{stat} \pm 90_{sys}\ \mathrm{eV}^2$
- $m_\nu \leq 15$ eV (90 % C.L.)

6.2×10^6 ^{187}Re decays above 700 eV



MARE - A project for a new Rhenium experiment

Goal: a direct neutrino mass measurement with the calorimetric approach

MARE 1

- activities aiming at isotope/technique selection (^{187}Re or ^{163}Ho options)
- activities using medium sized arrays to improve ^{187}Re measurement understanding and possibly calorimetric m_ν limit
- detector and absorber coupling R&D activities

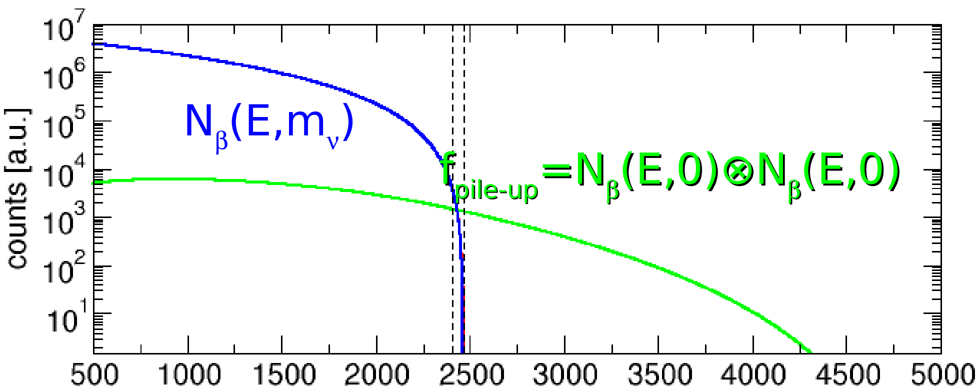
~ 100 detectors → 2-4 eV m_ν sensitivity

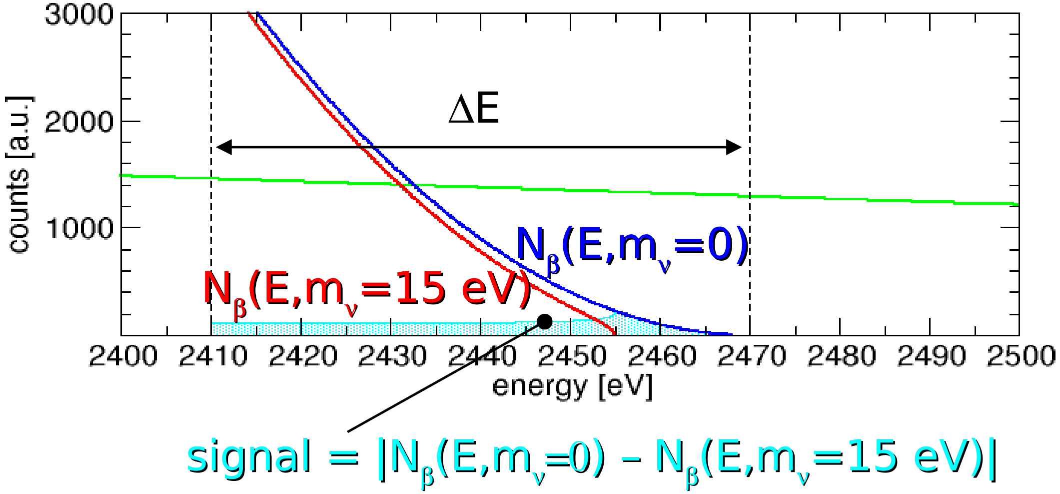
After MARE 1 - MARE 2

- very large experiment with a m_ν statistical sensitivity close to KATRIN
- new detector technologies are required

~1000 detectors → 0.2 eV m_ν sensitivity

^{187}Re – Statistical sensitivity 1





$$F_{\Delta E}(m_\nu) \approx \int_{E_0-\Delta E}^{E_0} N_\beta(E,m_\nu)\,dE$$

$$F_{\Delta E}(0) \approx A_\beta N_{det} \frac{\Delta E^3}{E_0^3}$$

$$F_{\Delta E}^{pp} \approx \tau_R A_\beta^2 N_{det} \int_{E_0-\Delta E}^{E_0} N_\beta(E,0) \wedge N_\beta(E,0)\,dE$$

Beta activity $\mathbf{A_\beta}$

Resolving time $\boldsymbol{\tau_R}$

Number of detectors $\mathbf{N_{det}}$

Analysis interval ΔE

Pile-up fraction $f_{pp}=\tau_R x A_\beta$

Experimental exposure $\mathbf{t_M=T\times N_{det}}$

^{187}Re – Statistical sensitivity 2

$$\frac{\text{signal}}{\text{background}} = \sqrt{A_\beta N_{det} t_M} \frac{\left|F_{\Delta E}(m_\nu) - F_{\Delta E}(0)\right| t_M}{\sqrt{F_{\Delta E}(0) t_M + F_{\Delta E}^{pp} t_M + b \Delta E / A_\beta}} = 1.7 \quad \text{for} \quad 90\% \quad \text{C.L.}$$

$$\sum_{90}(m_\nu) \approx 1.13 \frac{E_0}{\sqrt[4]{N_{ev}}} \left[\frac{\Delta E}{E_0} + \frac{E_0}{\Delta E} \left(\frac{3}{10} f_{pp} + b \frac{E_0}{A_\beta} \right) \right]^{1/4}$$

Optimal energy interval: $\Delta E = max\left(E_0 \sqrt{0.3 f_{pp} + b \frac{E_0}{A_\beta}} \,,\; \Delta E_{FWHM} \right)$

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

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

Experimental challenges :

- Energy resolution ΔE_{FWHM}
- Resolving time τ_R
- Experimental exposure $t_M = N_{det} \times T$
- Beta activity A_β

MonteCarlo Code

A MonteCarlo code has been developed to estimate the sensitivity of a neutrino mass measurement performed with thermal detectors

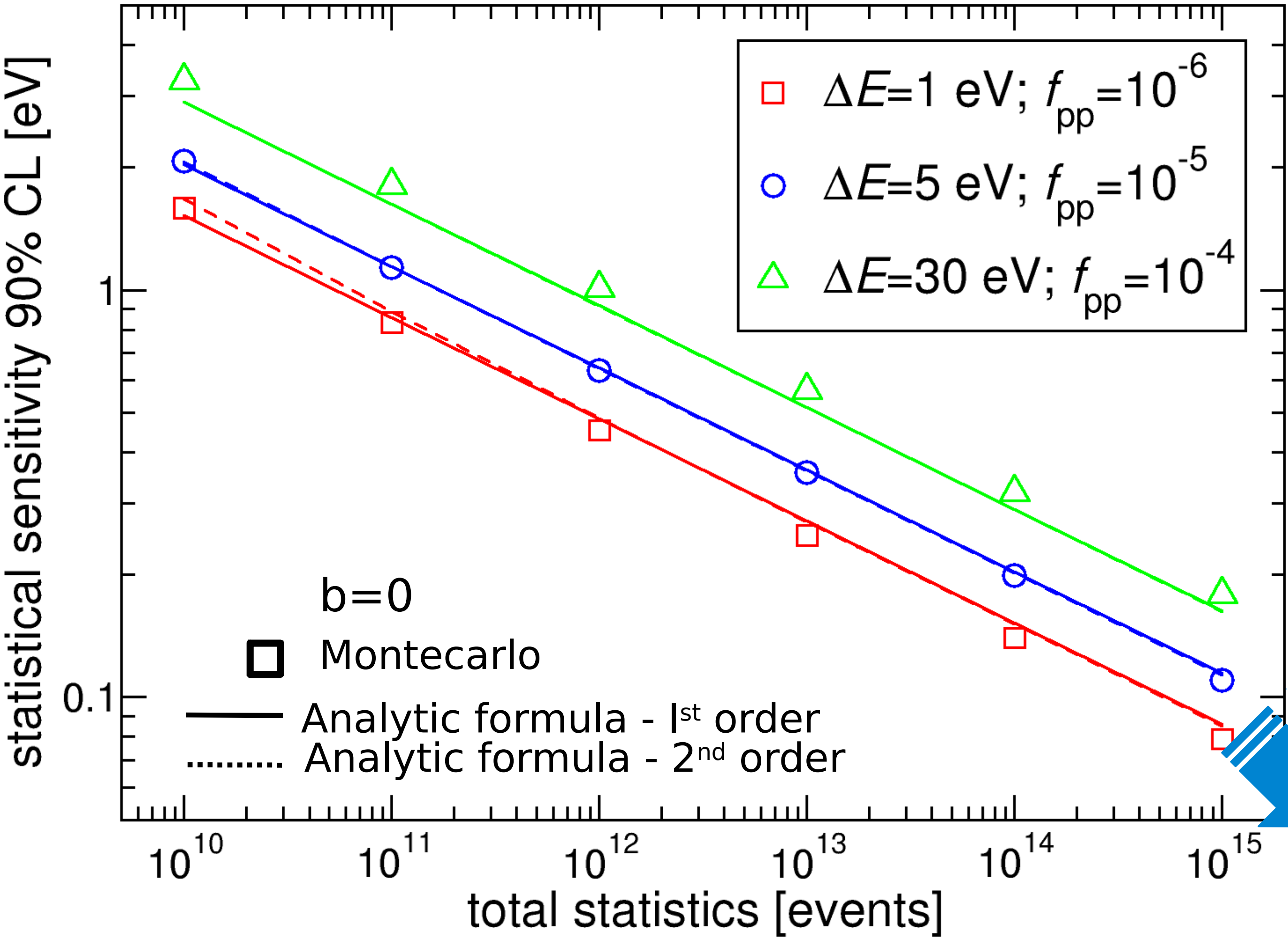
- Large number of simulated spectra N = 100÷1000
- Spectra are analysed as the real ones
- Input parameters:
  - Total statistics N_{ev}
  - Energy resolution ΔE_{FWHM}
  - Fraction of pile-up events f_{pp}
  - Constat background b
- Sensitivity at 90% CL:

Standard deviation of the distribution of the m_ν^2 found by fitting the spectra

$$\Sigma_{90}(m_\nu) = \sqrt{1.7\,\sigma_\nu^2}$$

- At this scale the MonteCarlo errors are negligible. In fact, the statistical error on the MonteCarlo results is around 3% and 1% for about 100 and 1000 simulated spectra.

Sub-eV m_ν statistical sensitivity with ^{187}Re



Possible to scale MonteCarlo results for different statistics

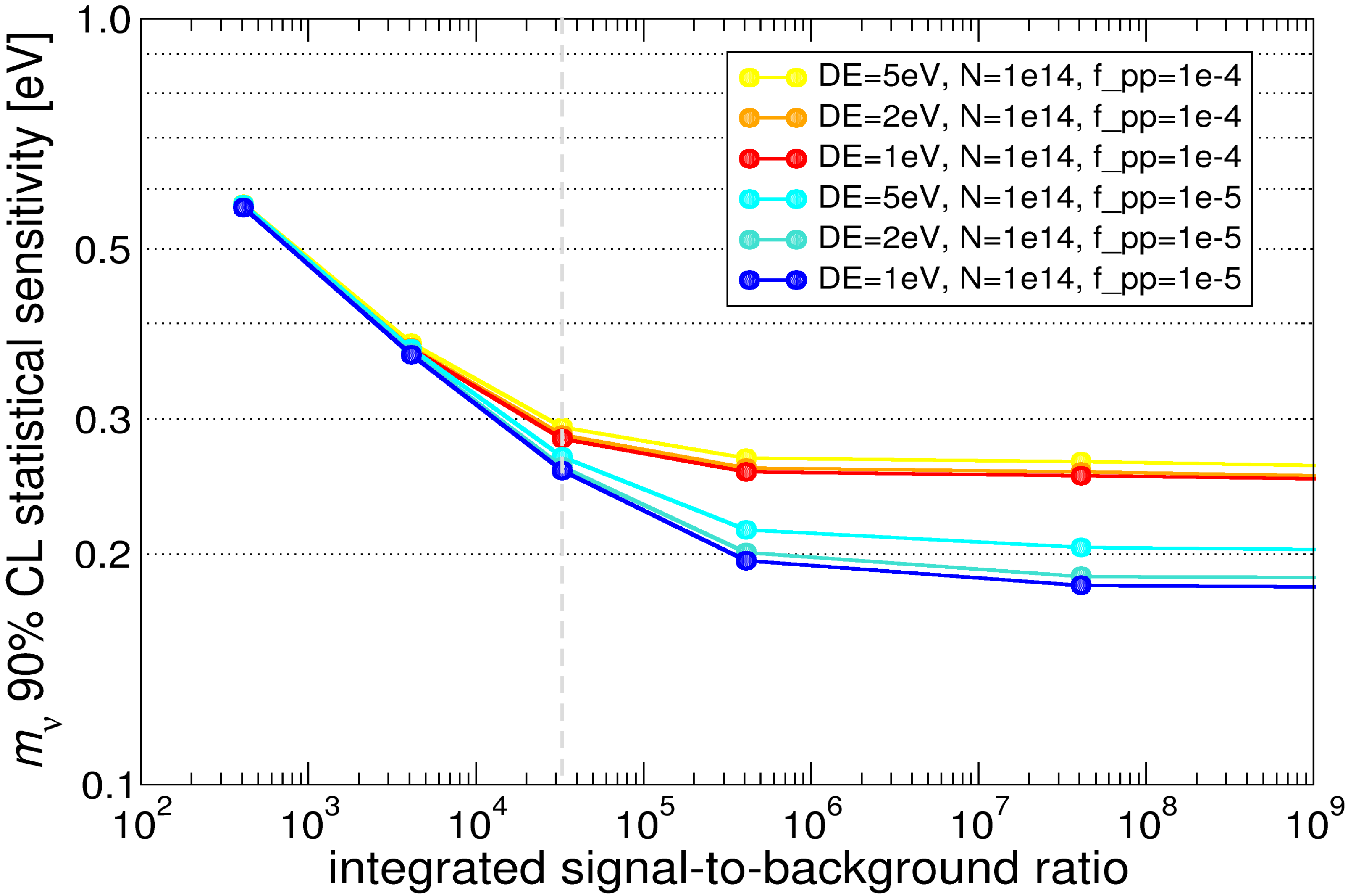
$$\sum_{90}(m_\nu) \propto \sqrt[4]{\frac{1}{N_{ev}}}$$

A.Nucciotti, E. Ferri and O. Cremonesi Astropart. Phys., 34 (2010) 80 [arXiv:0912.4638v1]

Effect of background on statistical sensitivity

$$\sum_{90}(m_\nu) \approx 1.13 \frac{E_0}{\sqrt[4]{N_{ev}}} \left[\frac{\Delta E}{E_0} + \frac{E_0}{\Delta E} \left(\frac{3}{10} f_{pp} + b \frac{E_0}{A_\beta} \right) \right]^{1/4}$$

b bkg counts/keV



$S/B = N_{ev}/N_{bkg}$

$N_{bkg} = b E_0 T$

MARE statistical sensitivity: Re option

- only statistical analysis
- 50000+ detectors gradually deployed
  - arrays distributed in many laboratories around the world
  - about $10^{13} \div 10^{14}$ events after 5 years

Exposure required for 0.2 eV m_n 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

bkg = 0

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

Exposure required for 0.1 eV m_n sensitivity

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

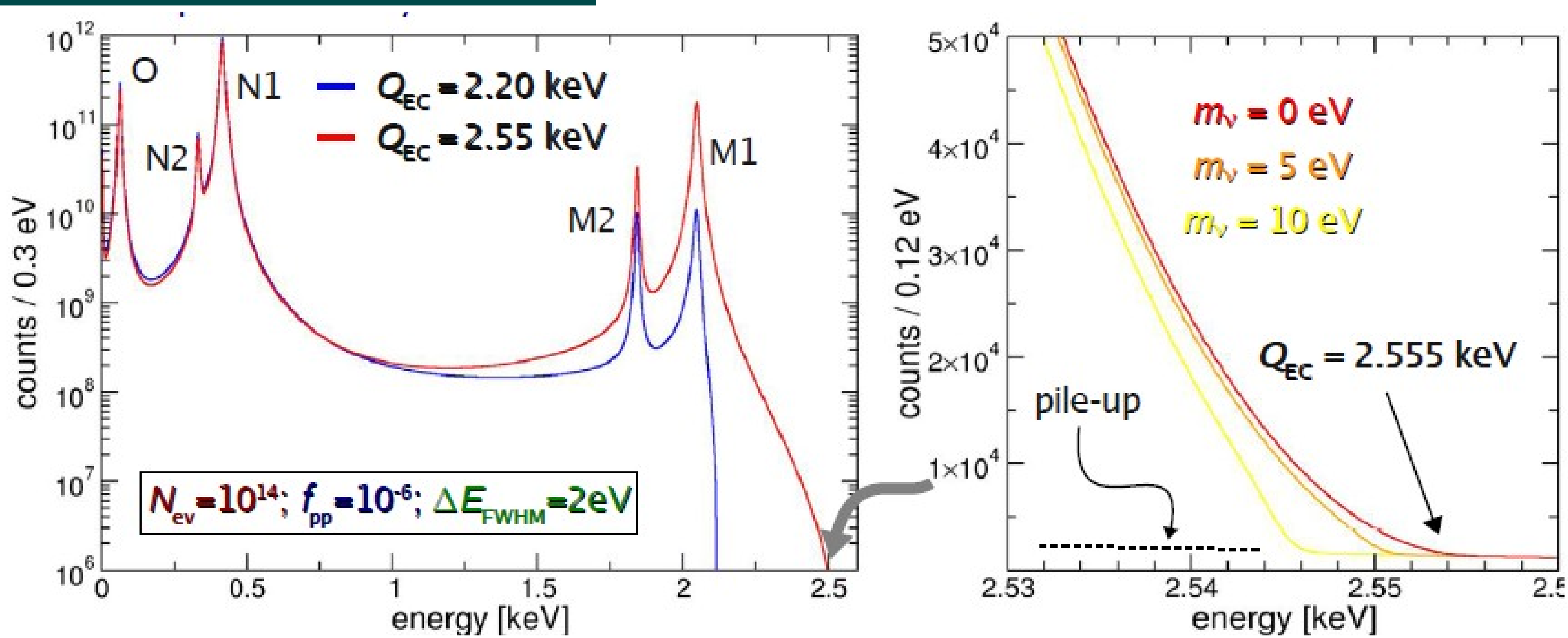
bkg = 0

MARE extensions: ^{163}Ho EC 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 non-radiative Dy atomic de-excitations
- Breit Wigner M,N,O lines have an end-point at the Q value
- rate at end-point may be as high as for ^{187}Re but depends on Q_{EC}
    - Q_{EC}? Measured: Q_{EC} = 2.3÷2.8 keV. Recommended: 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

MARE statistical sensitivity: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}	9×10^{5}
1	0.1	1	1.3×10^{13}	4.3×10^{5}
100	0.1	1	4.6×10^{14}	1.5×10^{5}
10	0.1	1	2.8×10^{14}	9.0×10^{5}
10	1	1	4.6×10^{14}	1.5×10^{5}

Q_{EC} = 2.2keV

bkg = 0

5000 pixels/array
3 arrays
1 year
$\approx2\times10^{17}$ ^{163}Ho nuclei

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}	2×10^{6}
100	0.1	1	7.4×10^{14}	2.4×10^{6}
10	0.1	1	4.5×10^{14}	1.5×10^{6}
10	1	1	7.4×10^{14}	2.4×10^{6}

bkg = 0

5000 pixels/array
4 arrays
10 years
$\approx3\times10^{17}$ ^{163}Ho nuclei

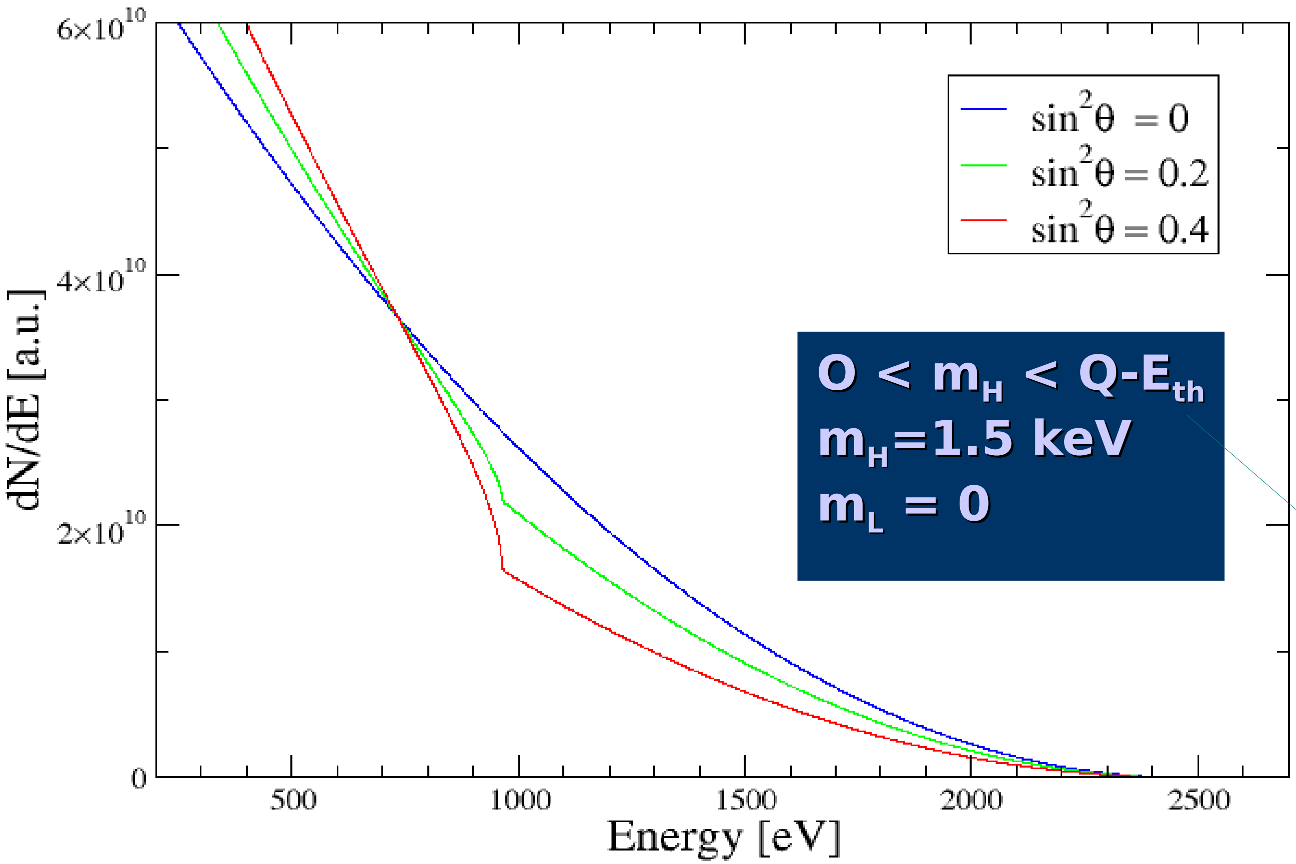
Heavy neutrino and single beta decay

Connection point between astrophysics, cosmology and elementary particle physics is the explanation of the Dark Matter.

- a possible Warm Dark Matter candidate is a sterile neutrino with a mass in the keV range
- to test the assumption of heavy neutrino existence: ^{187}Re beta decay

$$\nu_e = \nu_L \cos\theta + \nu_H \sin\theta$$

$$N_\beta(E, m_L, m_H, \theta) = \cos^2\theta\, N_\beta(E, m_L) + \sin^2\theta\, N_\beta(E, m_H)$$

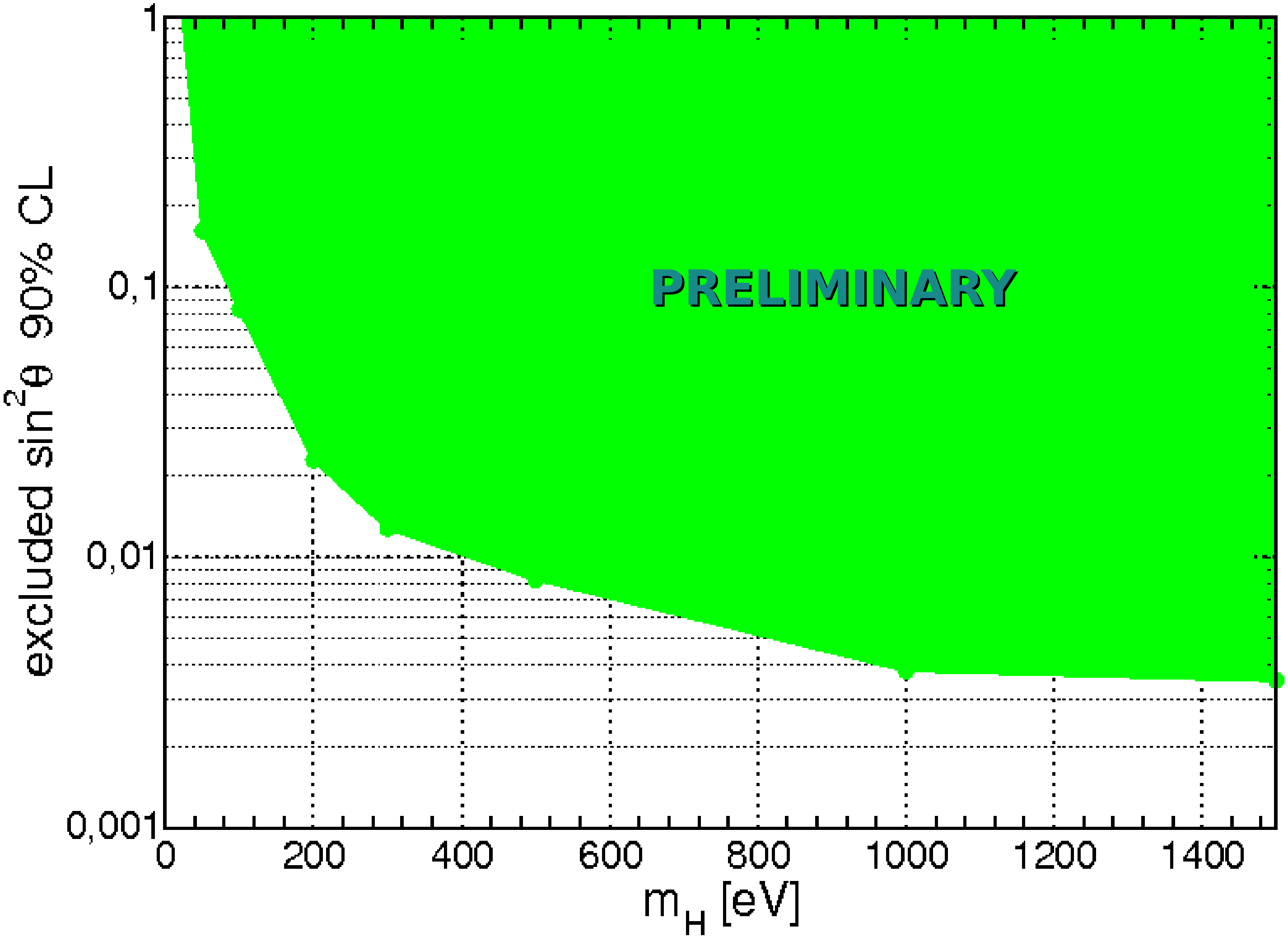


$0 < m_H < Q - E_{th}$
$m_H = 1.5$ keV
$m_L = 0$

the emission of heavy neutrino would manifest as a kink in the spectrum at energy $Q - m_H$

E_{th} is the experimental energy threshold

Heavy neutrino limit form the past - MIBETA



$0 < m_H < Q - E_{th}$

$Q = 2465$ eV

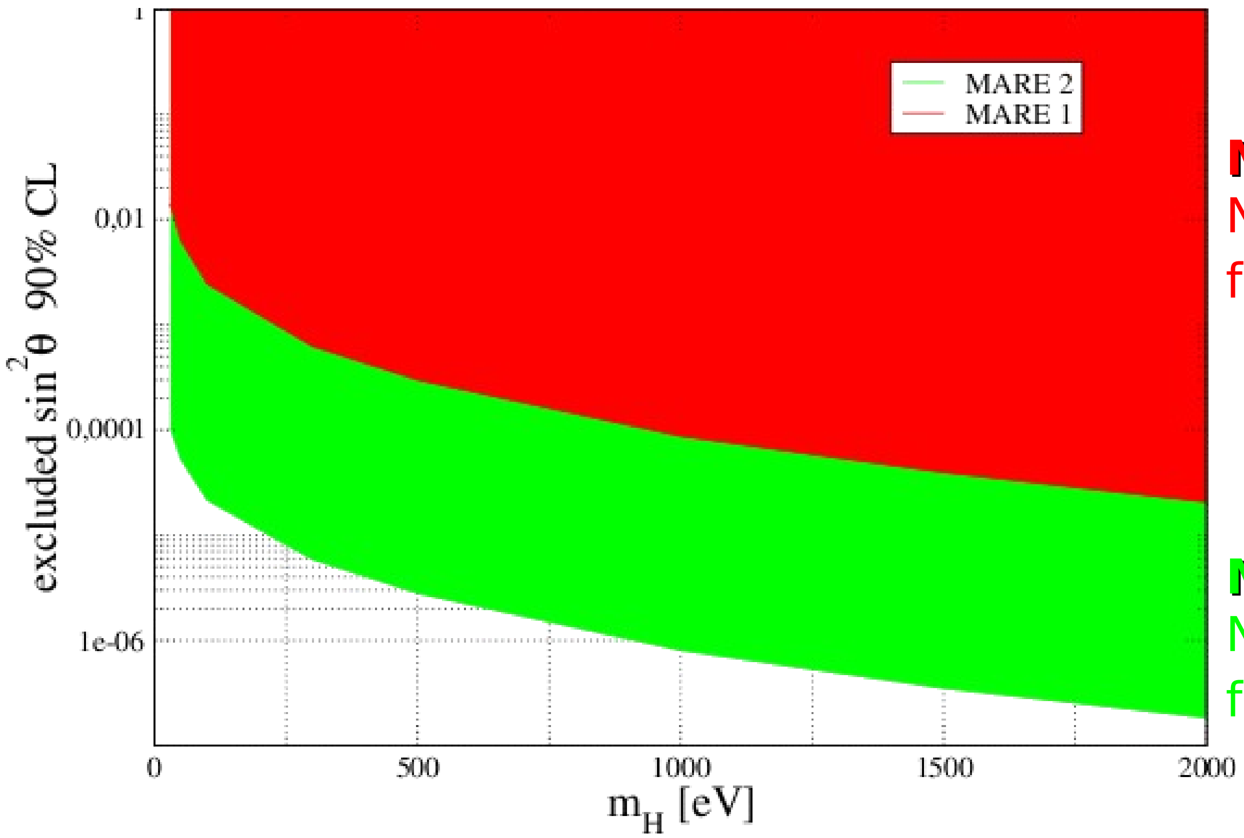
$E_{th} = 700$ eV

↓

$0 < m_H < 1765$ eV

MARE sensitivity to heavy neutrinos – Re option

Modification of the the MonteCarlo code to evaluate the capability of the MARE experiment to measure the mass of an heavy neutrino from some tens of eV to 2.5 keV.

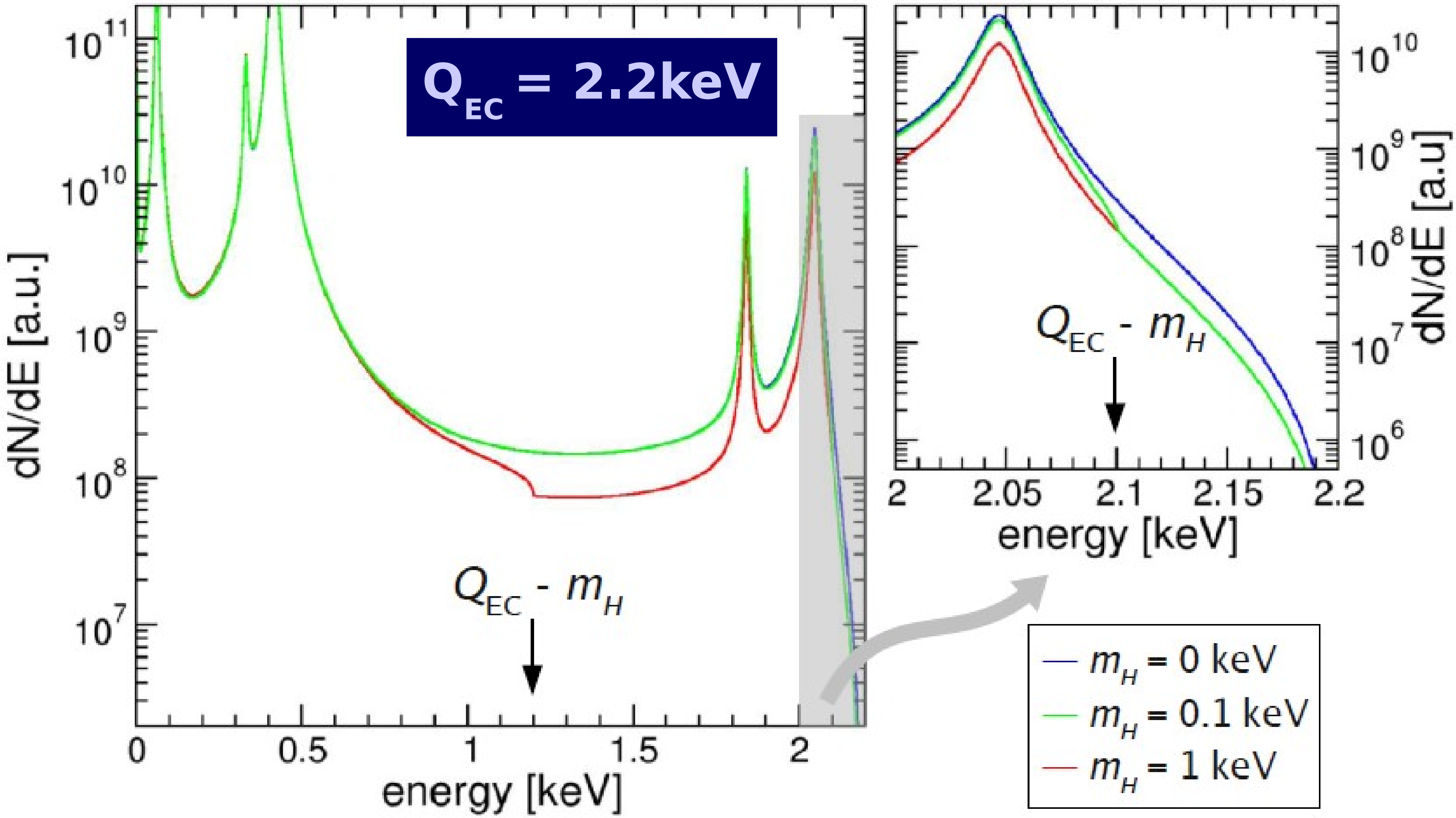


MARE 1:
$N_{ev}=10^{10}$, $\Delta E_{FWHM}=30$ eV
$f_{pp}=10^{-4}$, b=0

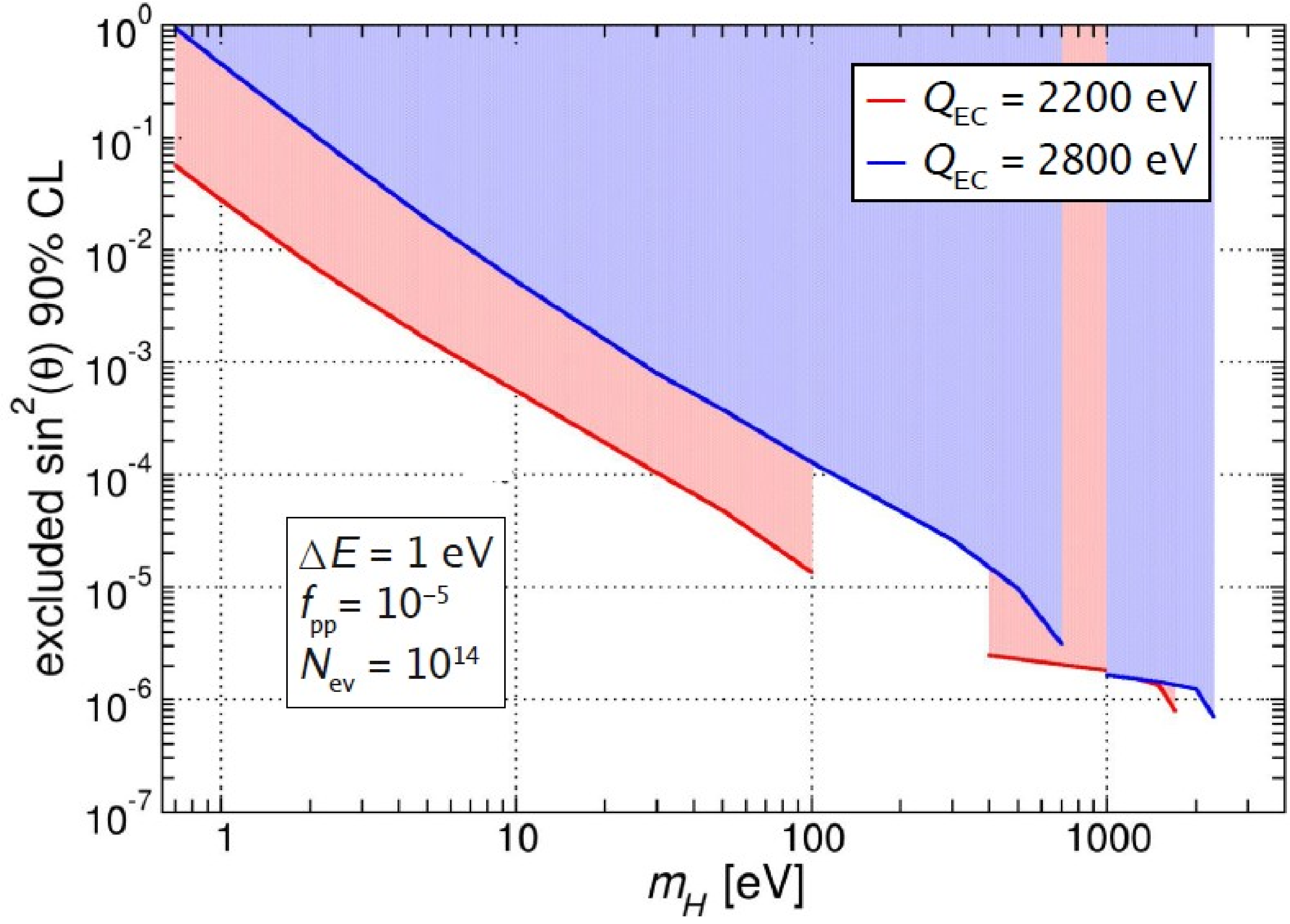
MARE 2:
$N_{ev}=10^{14}$, $\Delta E_{FWHM}=1$ eV
$f_{pp}=10^{-5}$, b=0

MARE sensitivity to heavy neutrinos: Ho option 1

heavy neutrino emission in ^{163}Ho EC decay



MARE sensitivity to heavy neutrinos: Ho option 2



MARE-1 in Milan / Re option

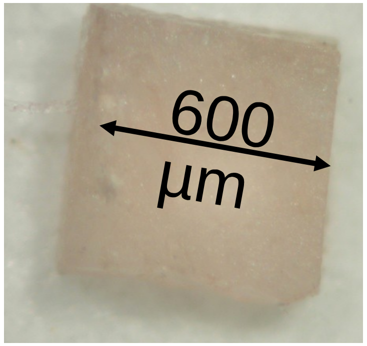
MARE-1 in Milan: Milano/FBK/Wisconsin/NASA

- $m_{\nu e} < 2$ eV/c^2
- 10^{10} events - 300 sensors
- 8 arrays of Si:P thermistors with $AgReO_4$ absorbers
- energy resolution 25 eV @ 2.6 keV

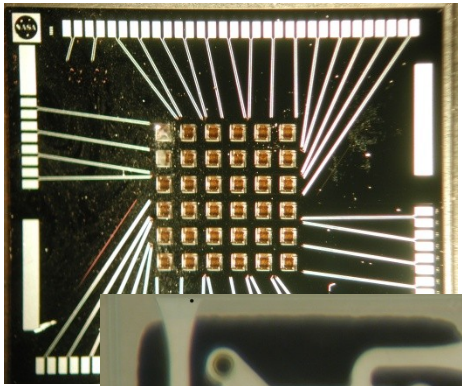
This experiment is needed:
- because it's the only possible one with present technology
- To investigate systematics in thermal calorimeters

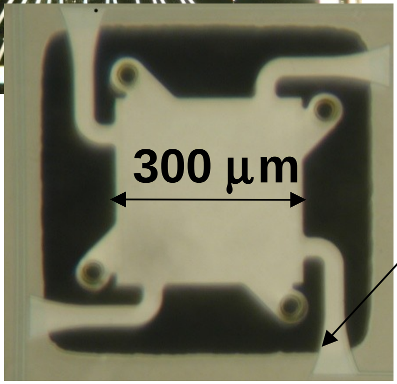
↳ **very important to cross-check spectrometer results**

MARE-1 detectors /Re option



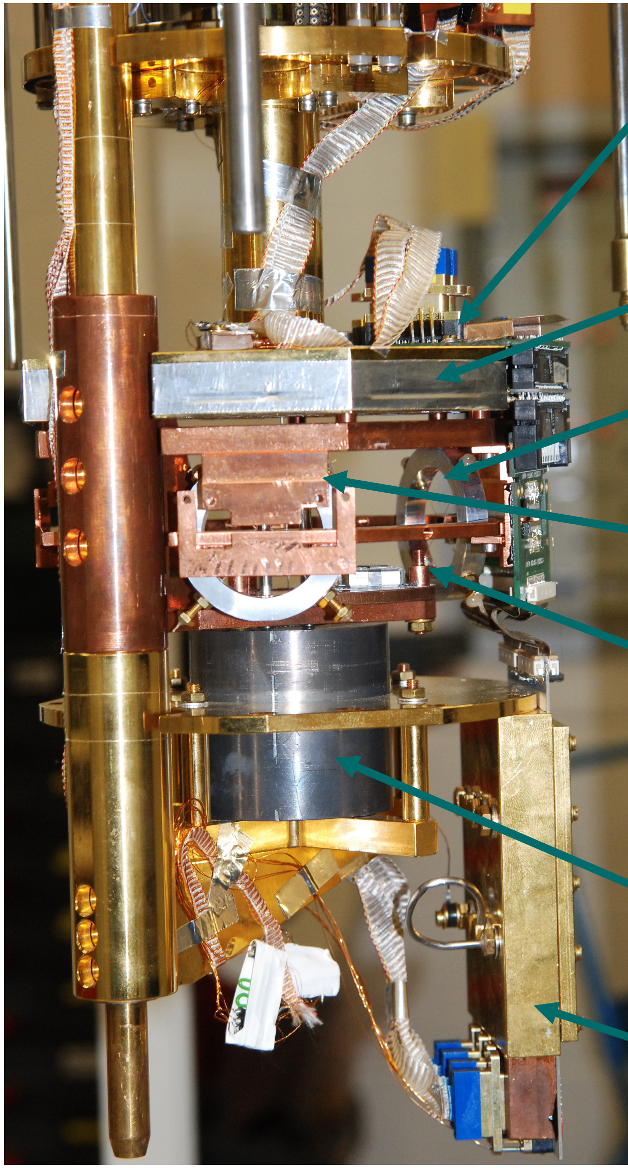
- ^{187}Re β-decay
  - $^{187}Re \rightarrow {}^{187}Os + e^- + \nu_e$ E_0=2.47 keV
  - i. a. 63% and τ=42.3 Gy
- Single crystal of silver perrhenate ($AgReO_4$)
  - mass ~ 500 μg per pixel (A_β~ 0.3 decay/sec)
  - regular shape (600x600x250 μm^3)
  - low heat capacity due to Debye law
- 6x6 array of Si:P semiconductors (NASA-GSFC)
  - pixel: 300x300x1.5 μm^3
  - high energy resolution
  - developed for X-ray spectroscopy with HgTe absorber (ASTRO-E2)





Si support

Cryogenic set-up of MARE 1 @ Milano Bicocca



Load Resistence 50 MΩ

Detector holder

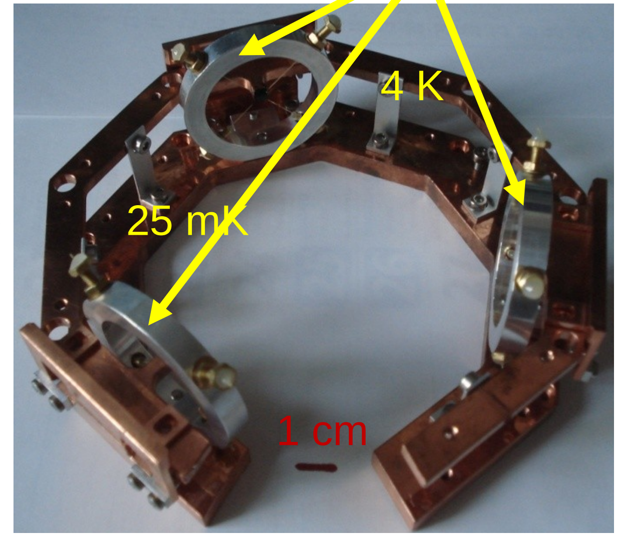
Calibration source ^{55}Fe

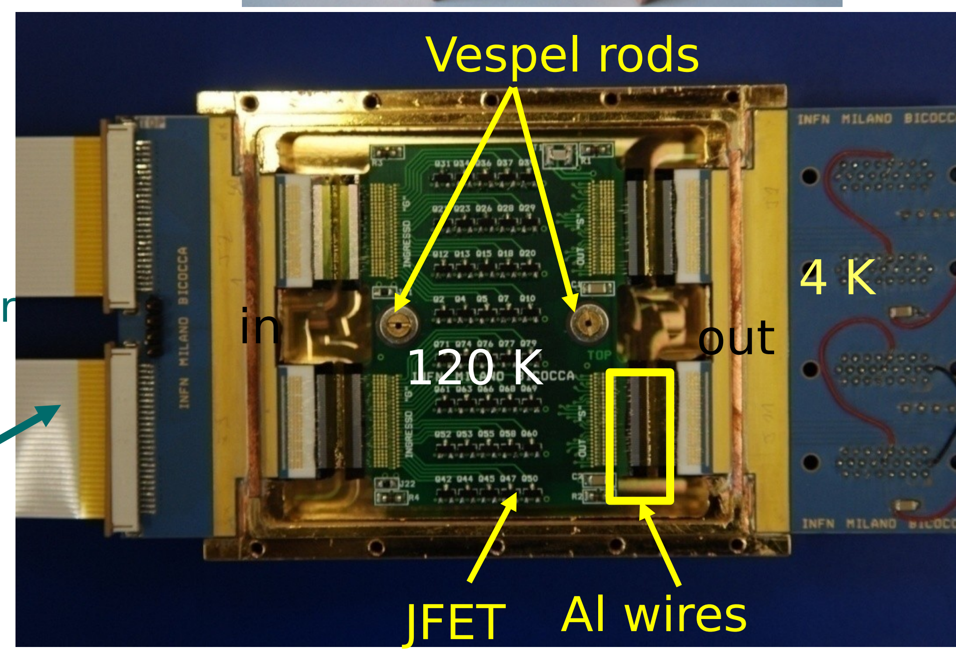
Calibration targets

Pb shield for calibration source

JFET box

Kevlar crosses



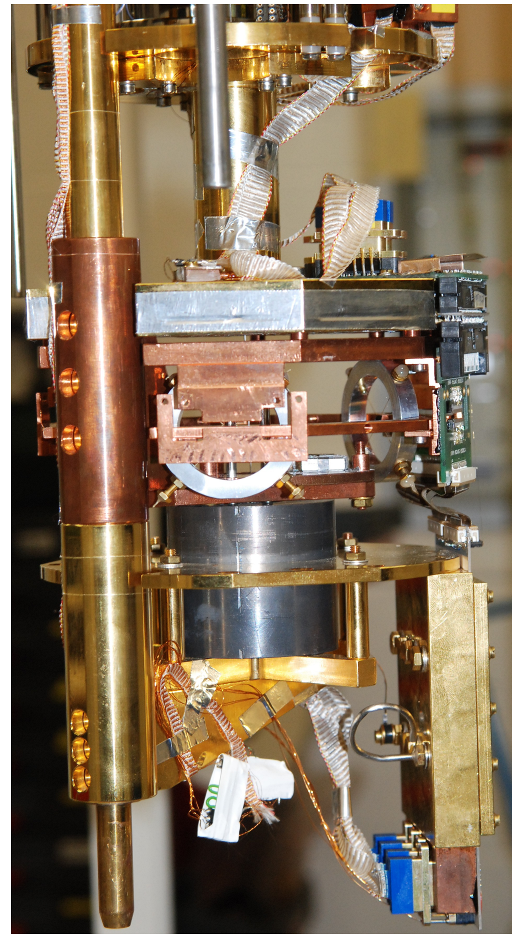


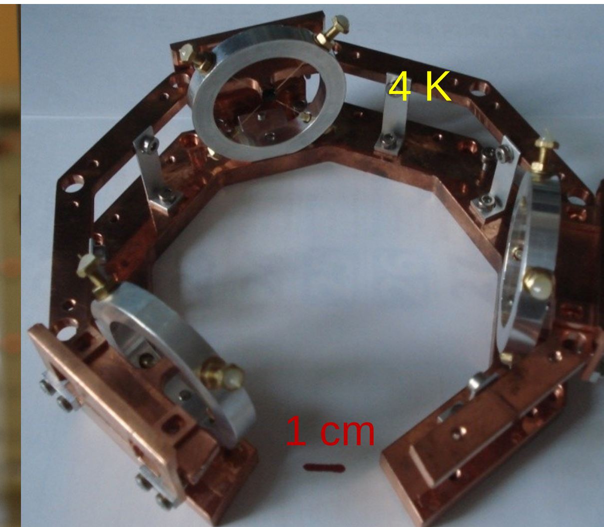
MARE 1 @ Milano-Bicocca

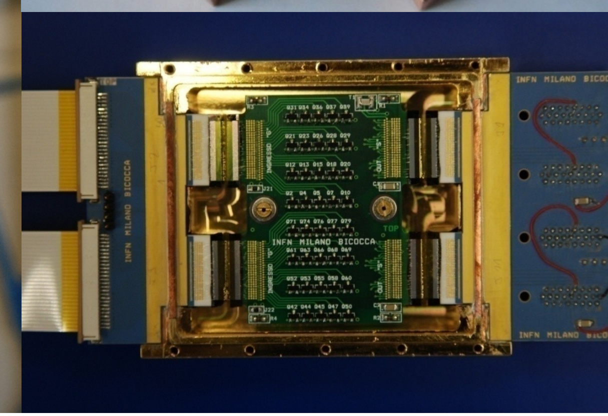
All the problems concerning the cryogenic set-up have been solved.

Thanks to the improvements added to the cryogenic set-up the detector target performances have been achieved.

- First spectra acquired
- Completed assembly of the first array

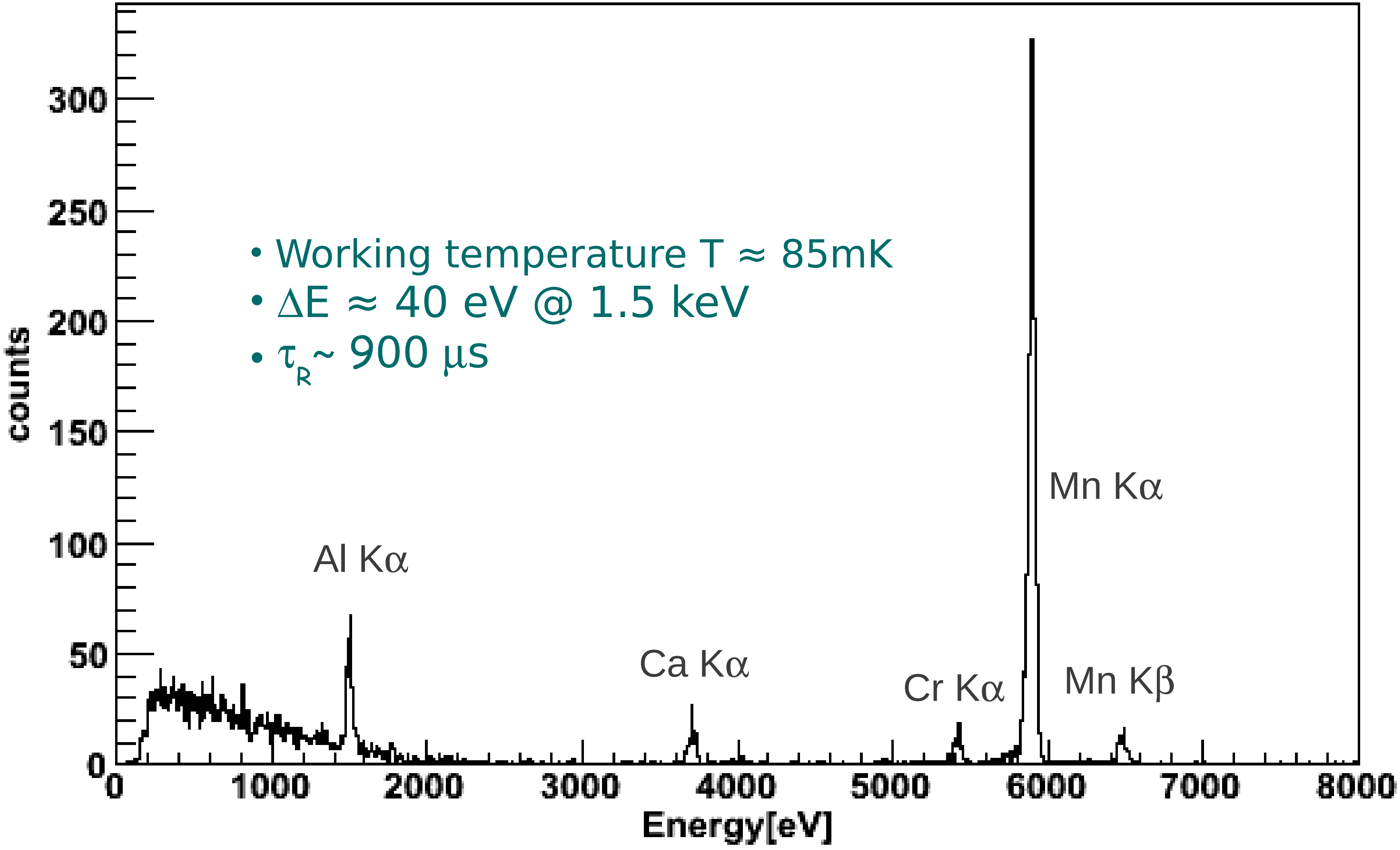






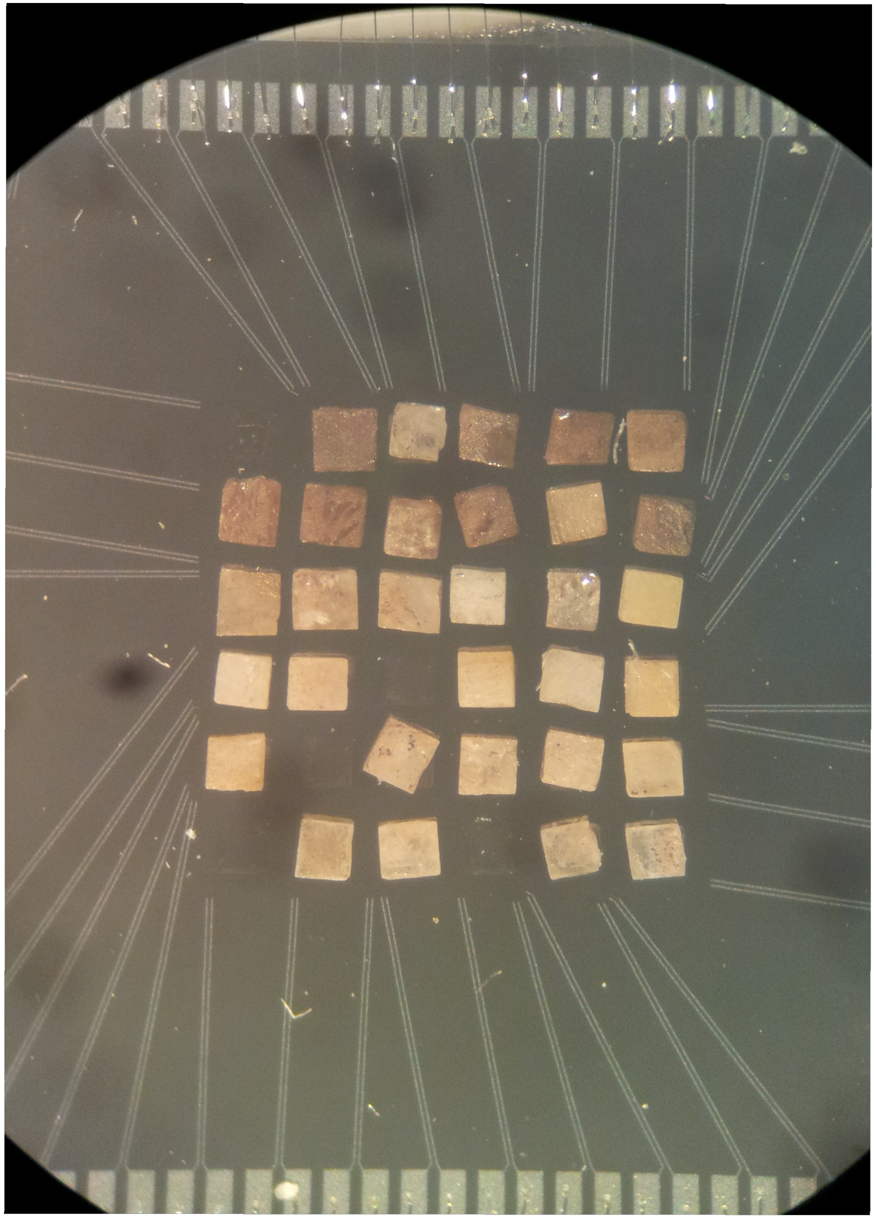
MARE 1 @ Milano-Bicocca

first spectrum acquired after the improvements added to MARE-1 cryogenic set-up



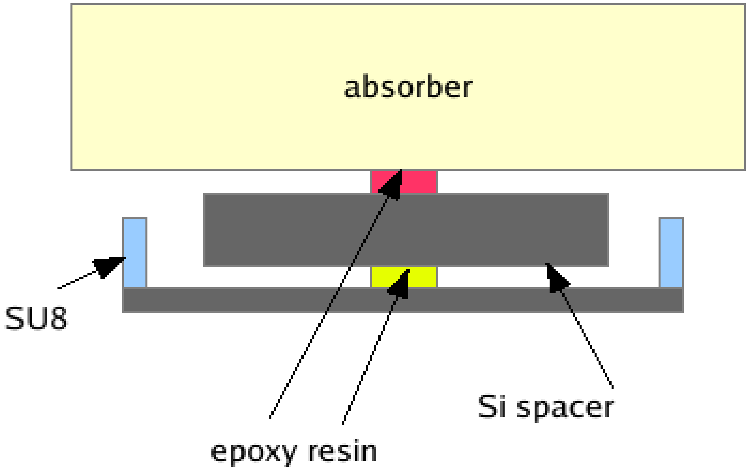
Measured 7 pixels: ΔE_{ave}~30eV @ 1,5keV

First array of MARE-1



Thermal coupling

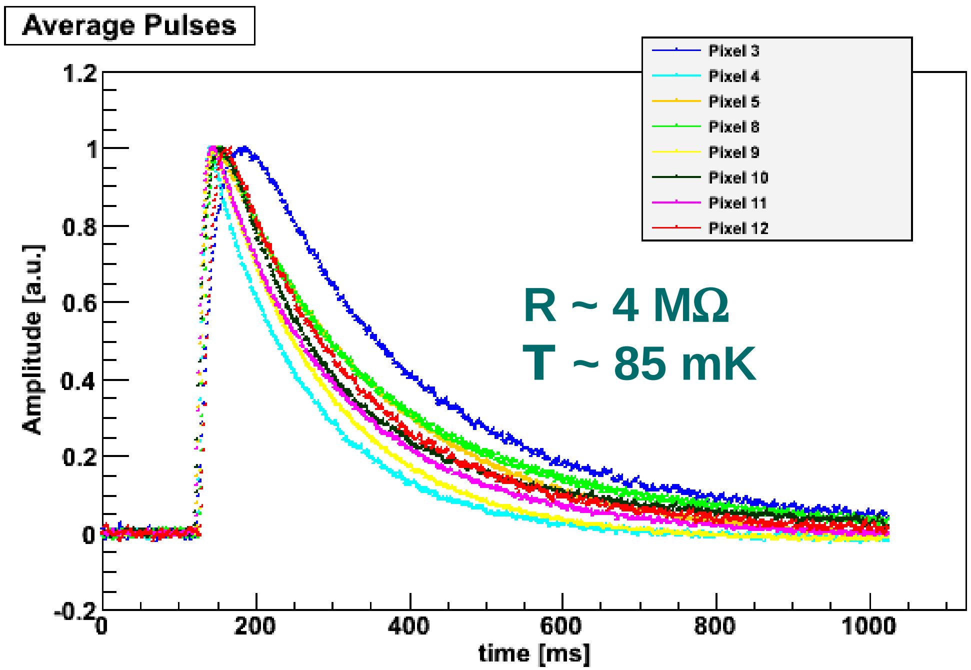
- **Araldit or ST1266:** thermistor/spacer
- **ST2850:** spacer/$AgReO_4$

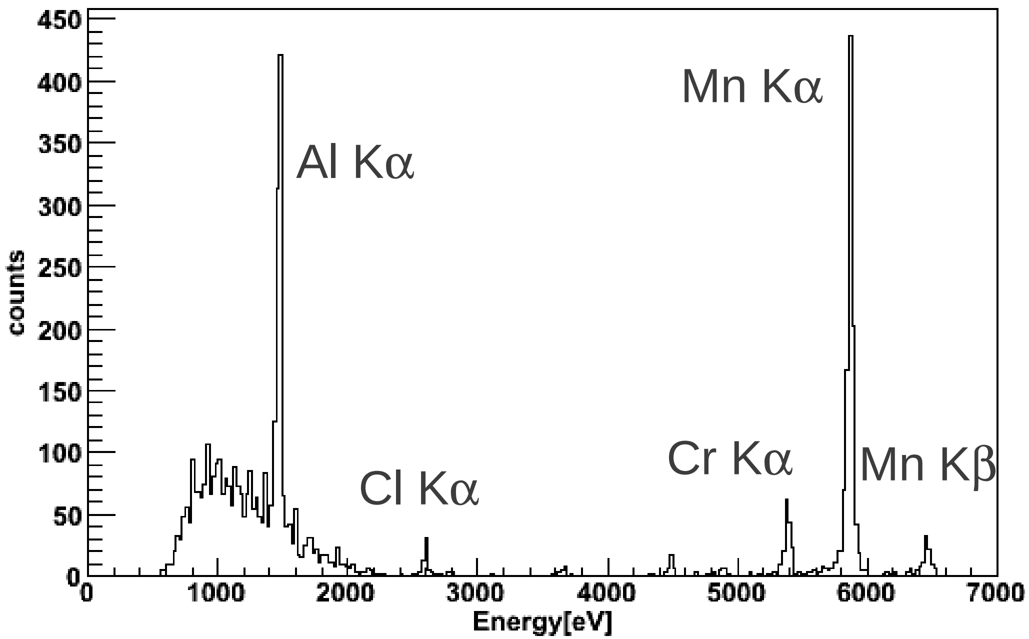


- 6 silicon spacers are attached with **Araldite Normal**
- 10 with **Araldite Rapid**
- 15 with **ST1266**

First array of MARE-1

A run aimed to test the performance of this setup is ongoing, after which the absorbers will be glued also on the second array. With two arrays, a sensitivity of 4.5 eV at 90% C.L. is expected in three years running time.

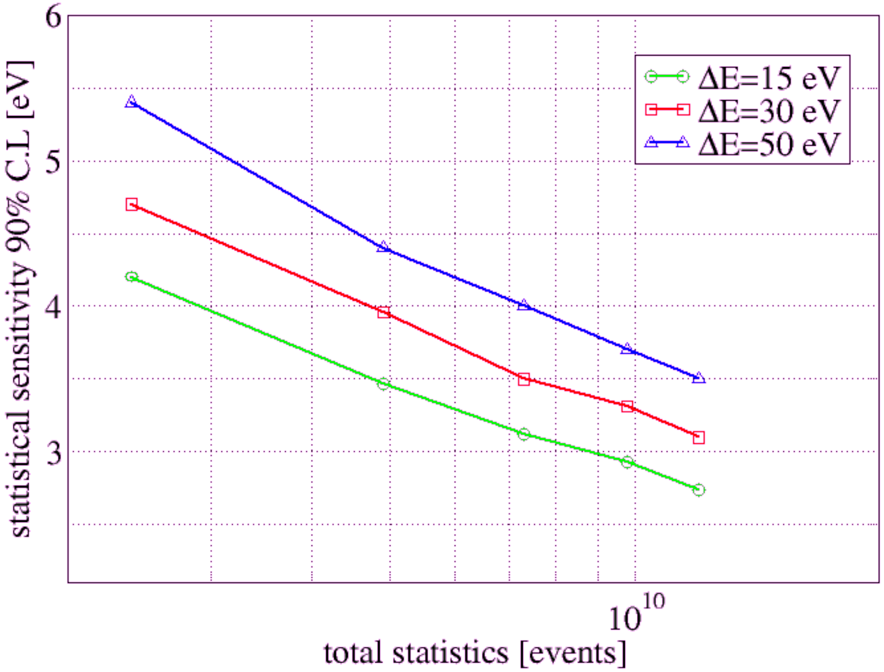




- Working temperature T ≈ 88mK
- $\Delta E \approx 24$ eV @ 1.5 keV
- $\tau_R \sim 1$ ms

MARE 1 in Milano: sensitivity

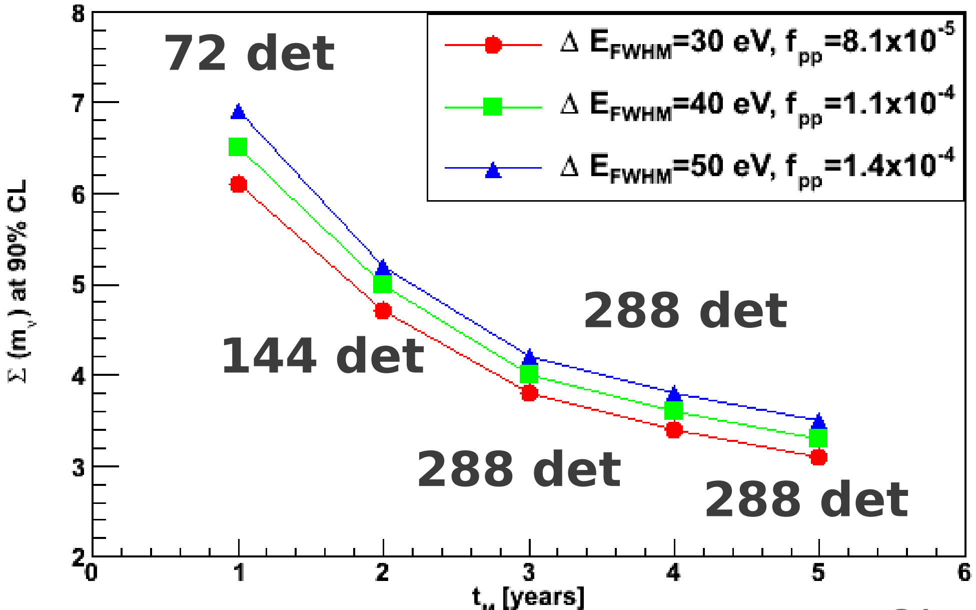
MonteCarlo approach



- setup designed to host up to 8 arrays
- 288 $AgReO_4$ crystals
- start with 2 arrays (72 ch.)
- gradual deployment

Since only two arrays are available up to now, it is useful to estimate the sensitivity on neutrino mass over the years by increasing the detectors number from year to year.

Analytic approach (1st order)

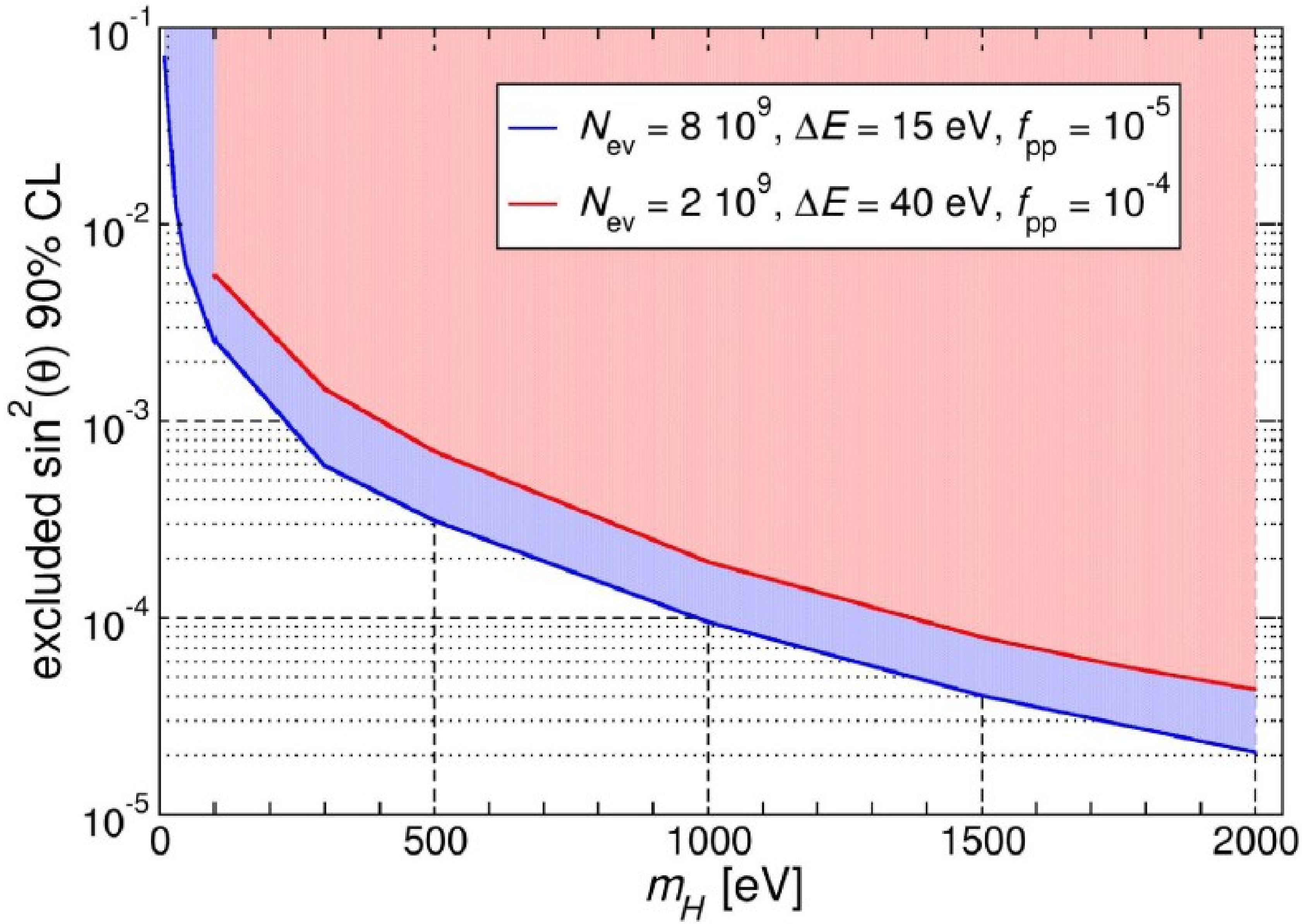


Detectors

ΔE_{FWHM} ~ 50 eV and τ_R ~ 500 μs
1 year and 72 channels → $\Sigma(m_\nu)$ ~7eV
3 years and 288 channels → $\Sigma(m_\nu)$ ~ 4.2eV

ΔE_{FWHM} ~ 30 eV and τ_R ~ 300 μs
1 year and 72 channels → $\Sigma(m_\nu)$ ~6eV
3 years and 288 channels → $\Sigma(m_\nu)$ ~ 3.8eV

MARE 1 @ Milano-Bicocca and heavy neutrinos

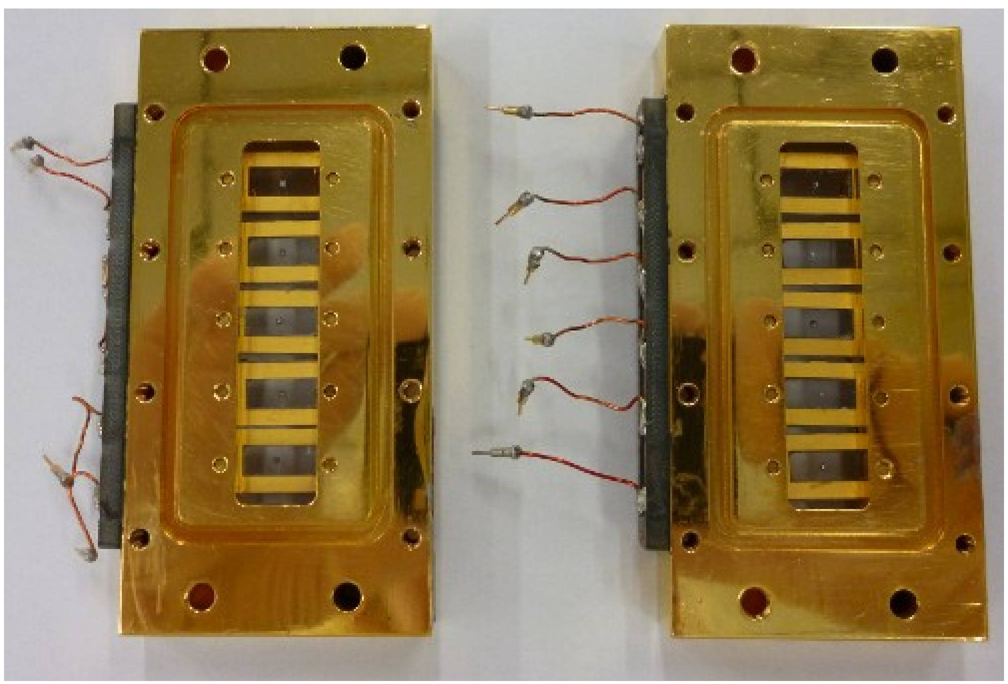


MARE 1 in Milano/Ho option

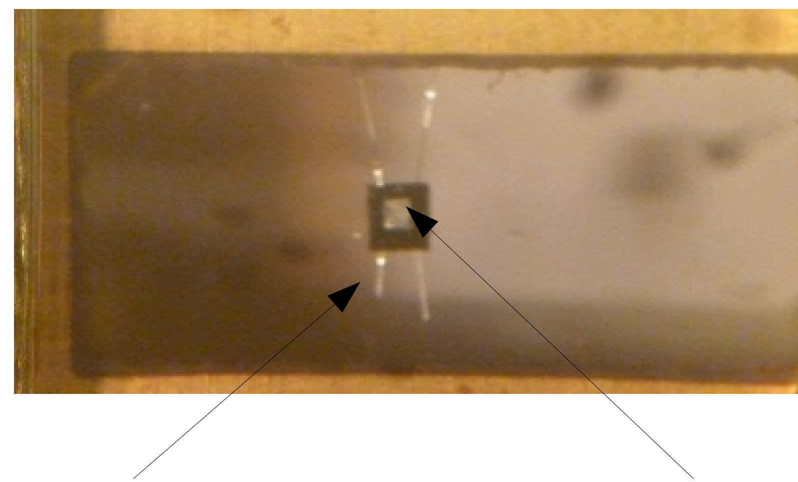
A run aimed to test new absorbers made of Sn/Ho/Sn is ongoing @ Milano-Bicocca.

The absorbers, produced by the Genova Group (Flavio Gatti and his staff), have been glued on Si thermistors.

10 detectors



Zoom of one single detector



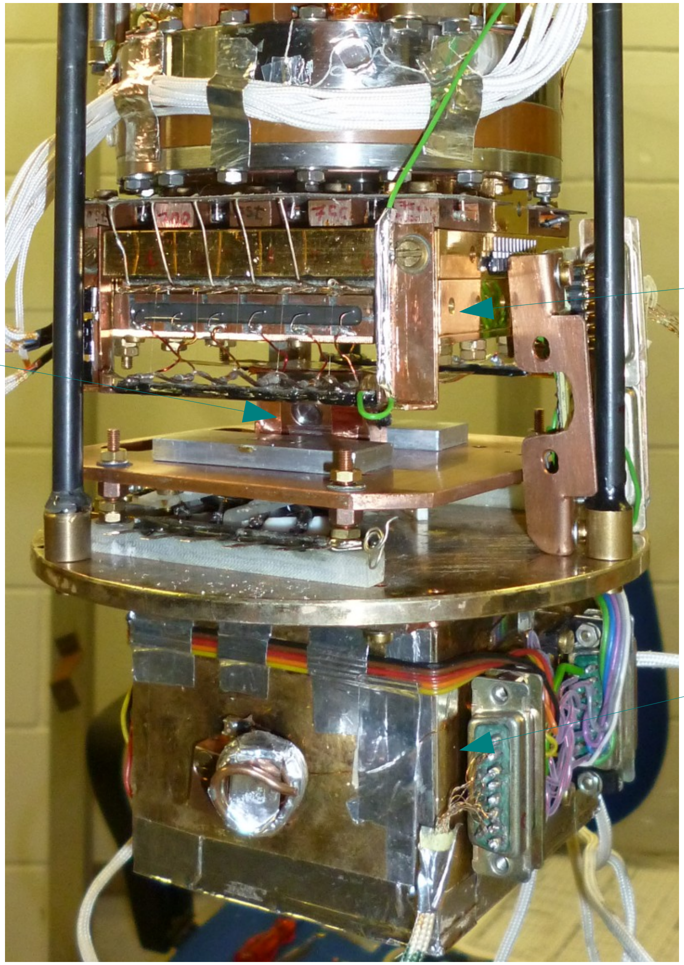
Al bonding wires

Sn/Ho/Sn absorber Glued on Si thermistor

MARE 1 in Milano/Ho option

The cryogenic set-up and electronics and DAQ system are the one used in the Mibeta experiment as well as the dilution unit.

55Fe calibration source
with targets

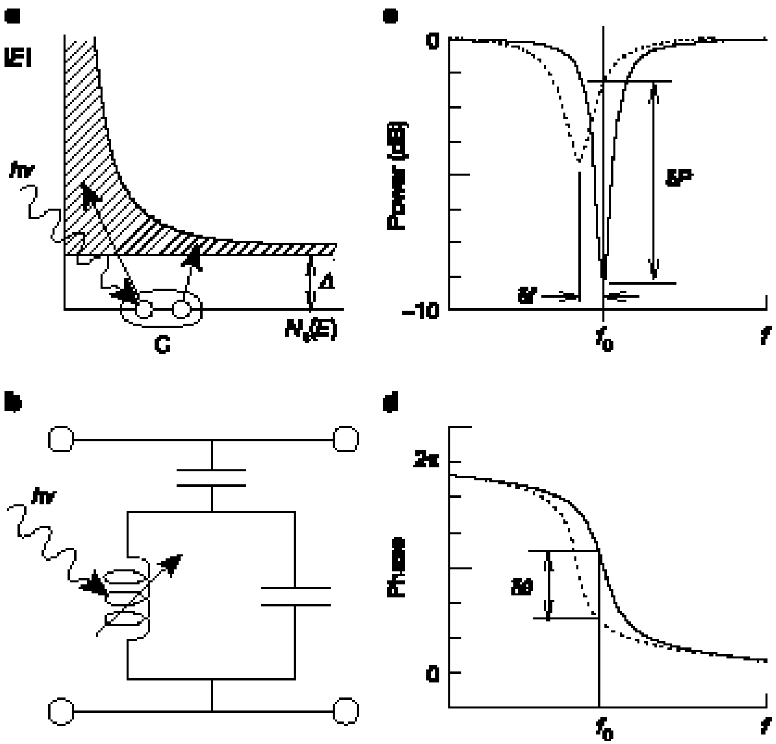


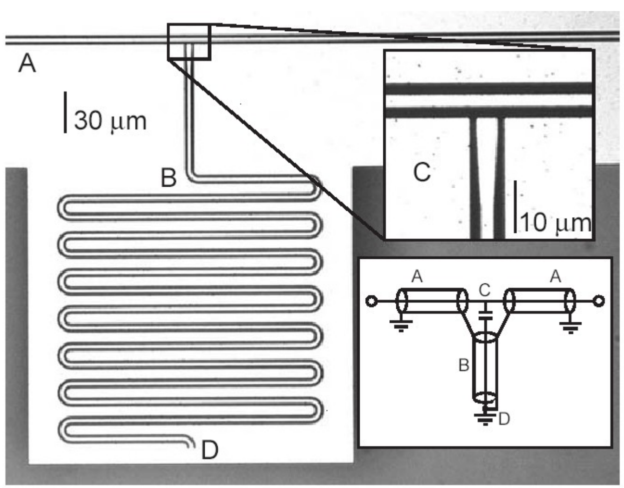
Detector holders
mounted under
the MC

Cold electronic
JFET

MKIDs R&D @ Milano-Bicocca

fondazione cariplo





- resonator exploiting the *T* dependence of inductance in a superconducting film
  - **detectors** suitable for large absorbers
  - **Good time resolution** (low pile-up f_{pp})
  - **high energy resolution**
  - **multiplexing** for very large number of pixel

Sensitivity

$\Delta E = 5$ eV

$t_M = 36000$ detectors x 3 years

$A_\beta = 20$ c/s/det

$\tau_{rise} = 1\ \mu s \Rightarrow m_\nu < 0.2$ eV

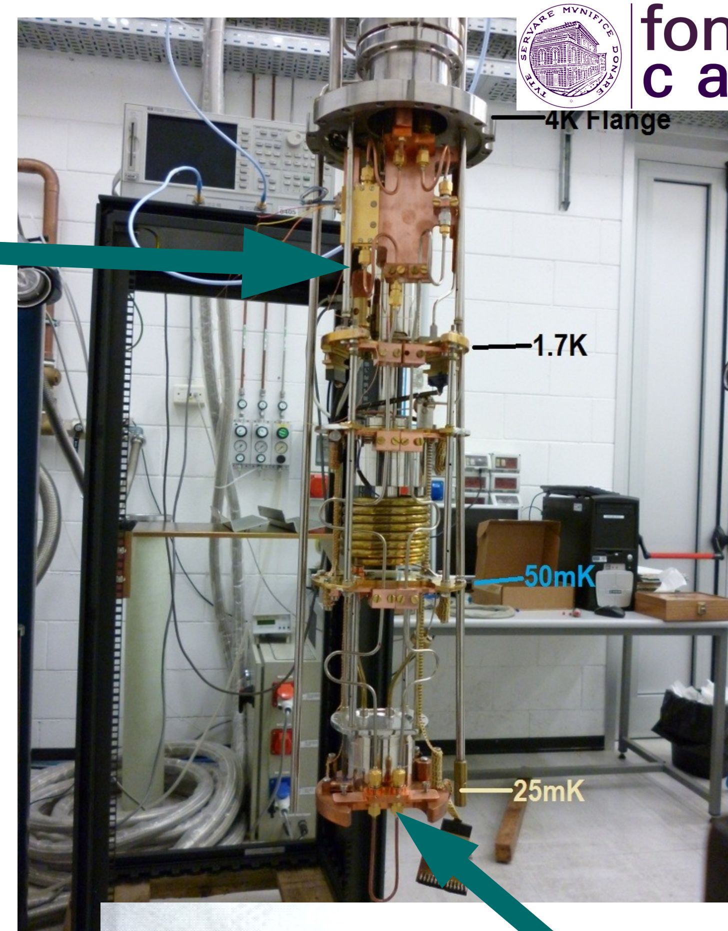
$\tau_{rise} = 100\ \mu s \Rightarrow m_\nu < 0.4$ eV

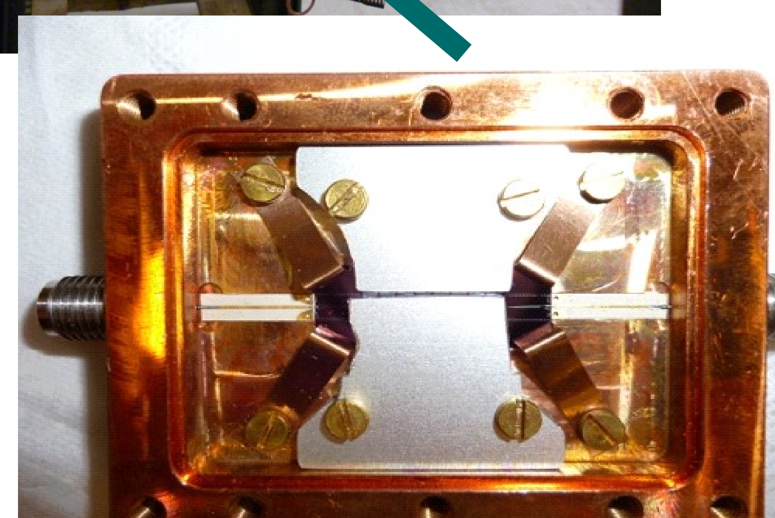
application to bulky absorber still requires further efforts

MKIDs for ^{163}Ho EC decay end point measurement

fondazione cariplo

4-12 GHz cryo amp





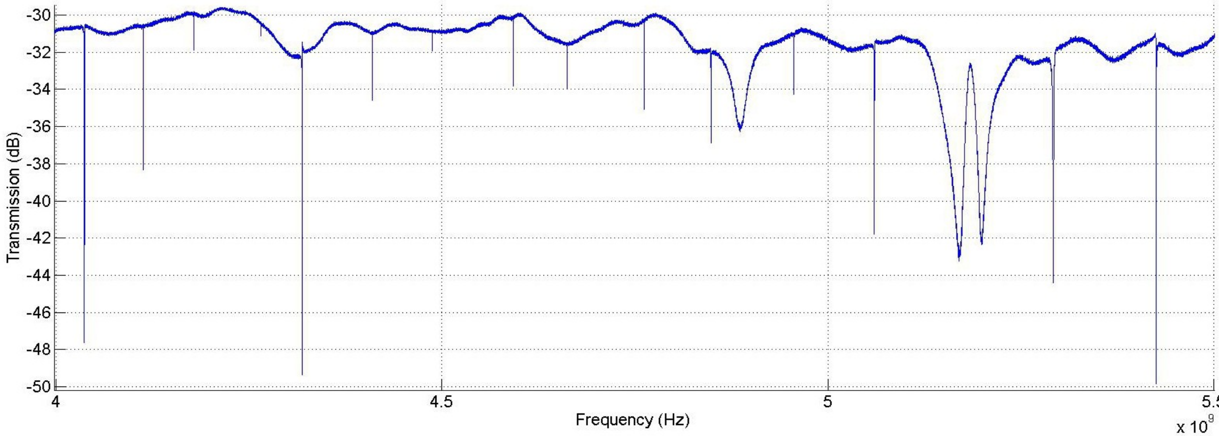
So far tested stoichiometric TiN (T_c=4,6K) films and Ti/TiN multilayer (produced by FBK), which behaves like a sub-stoichiometric TiN film (T_c=1,6K)

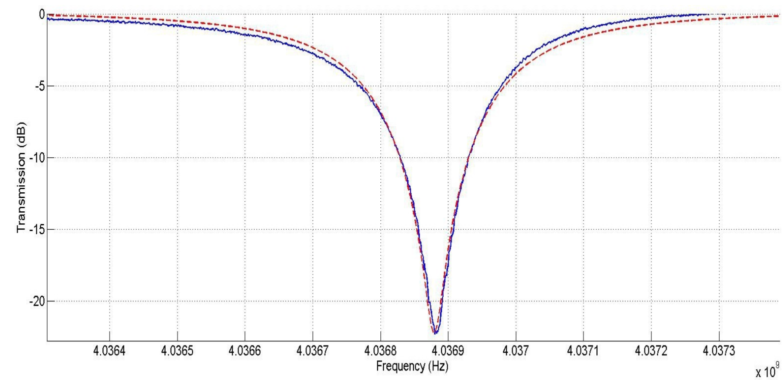
Gap parameter:
- TiN 0.8 meV
- Ti/TiN 0.26 meV

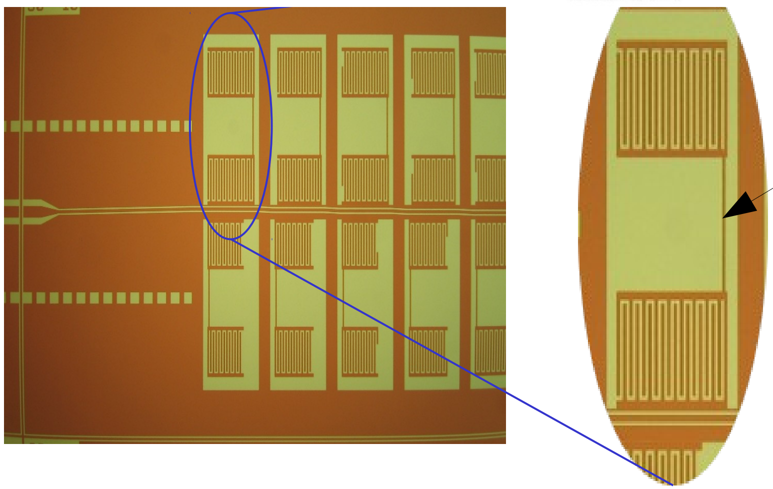
The devices were tested with ^{55}Fe (6keV) and Al X-ray (1,5keV) and the first pulses were acquired

Not resolving yet because of events interacting in the Si substrate under the superconductor

MKIDs for ^{163}Ho EC decay end point







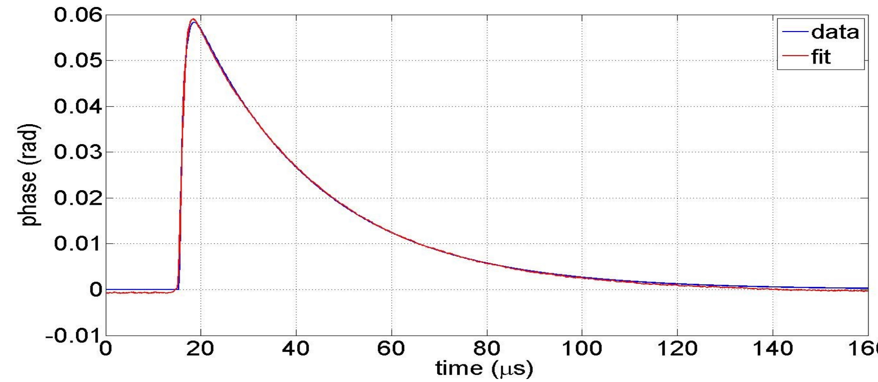
The ^{163}Ho will be embedded in the center of the inductive part of the resonator, deep enough to ensure low escape probability. A thickness of <500nm will be enough

10^{12} Ho nuclei are needed for a count rate of 10 Hz

theoretical resolution

$$\Delta E_{th} = 2keV/N_{qp}^{1/2} = 1.5 \text{ eV}$$

This work is supported by Fondazione Cariplo through the project "Development of Microresonator Detectors for Neutrino Physics" (grant 2010-2351).



Conclusion

- Thermal calorimeter with Re can give a sub-eV sensitivity on neutrino mass
- Calorimetry of ^{163}Ho electron capture decay is an interesting alternative
- ^{187}Re and ^{163}Ho calorimetry is sensitive to 1 keV scale heavy neutrinos
- MARE-1 activities @ Milano-Bicocca are in progress
- **Re option**
  - First array of MARE-1 has been assembled
    - 31 thermistors are equipped with AgReO4 absorbers
    - The goal performances of the detectors have been achieved
- **Ho option**
- Investigation of the ^{163}Ho decay spectrum
    - ^{163}Ho isotope has been produced and is ready for first tests
- In the meanwhile new detector technology under investigation
    - → ^{163}Ho EC measurements with MKIDs