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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The MARE experiment and its capabilities to measure the mass of light (active) and heavy (sterile) neutrino

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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
  - ^{187}Re measurement systematics
  - heavy (sterile) neutrinos detection

- **MARE project status**
  - path for isotope and technique selection
  - MARE-1 experimental activities

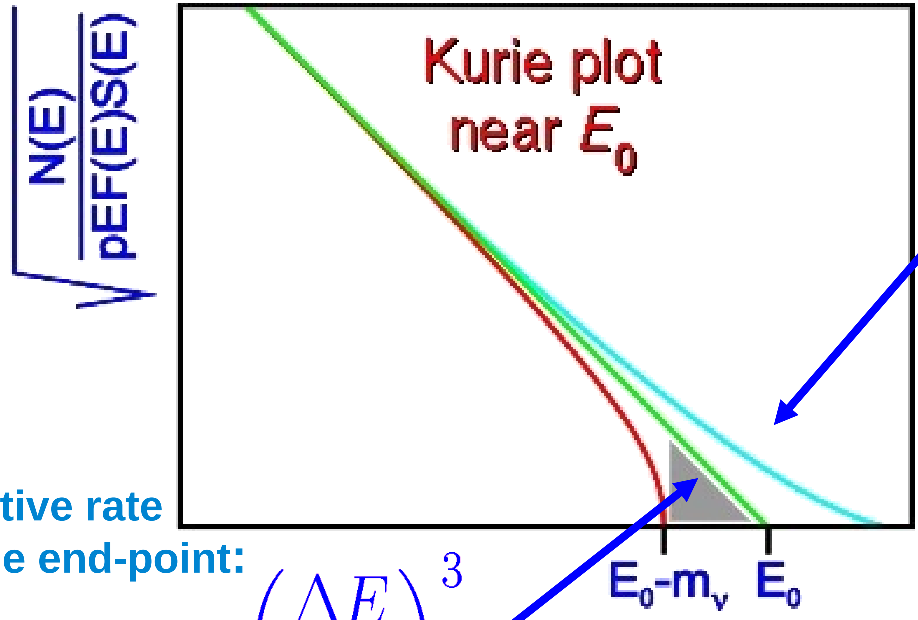
- **Conclusions**

Direct neutrino mass measurements

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

BUT oscillation experiments give only Δm^2!

direct neutrino mass measurement



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

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

effective rate at the end-point:

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

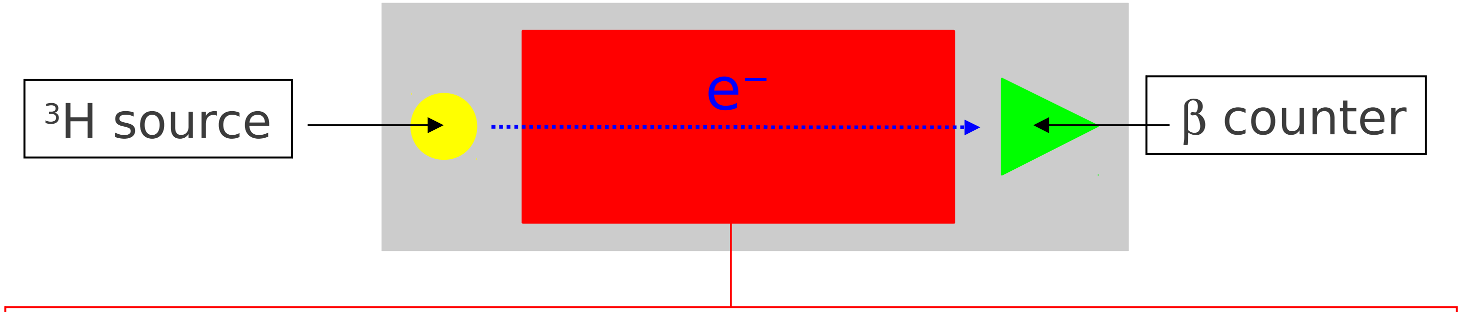
$m_\nu = (\Sigma m^2_i |U_{ei}|^2)^{1/2}$

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

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

Different approaches to direct measurement

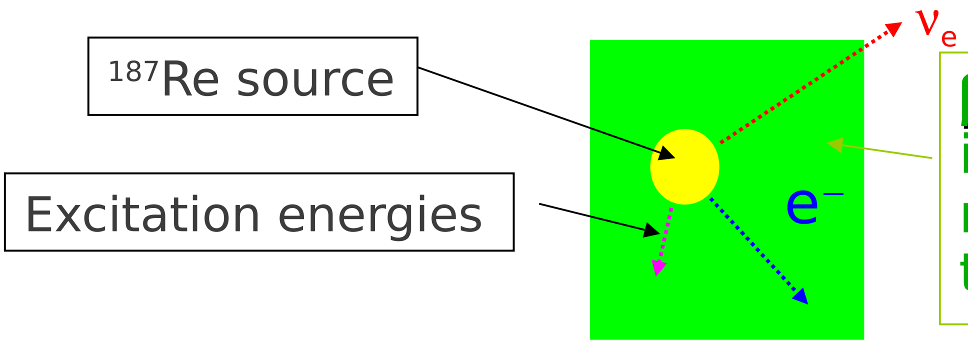
- **Spectrometers: source ≠ detector**



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 $\subseteq$ 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 $\neq$ detector

Advantages:

✓high statistics
✓high energy resolution

Disavantages:

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

Calorimeter: β source $\subseteq$ detector

Advantages:

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

Disavantages:

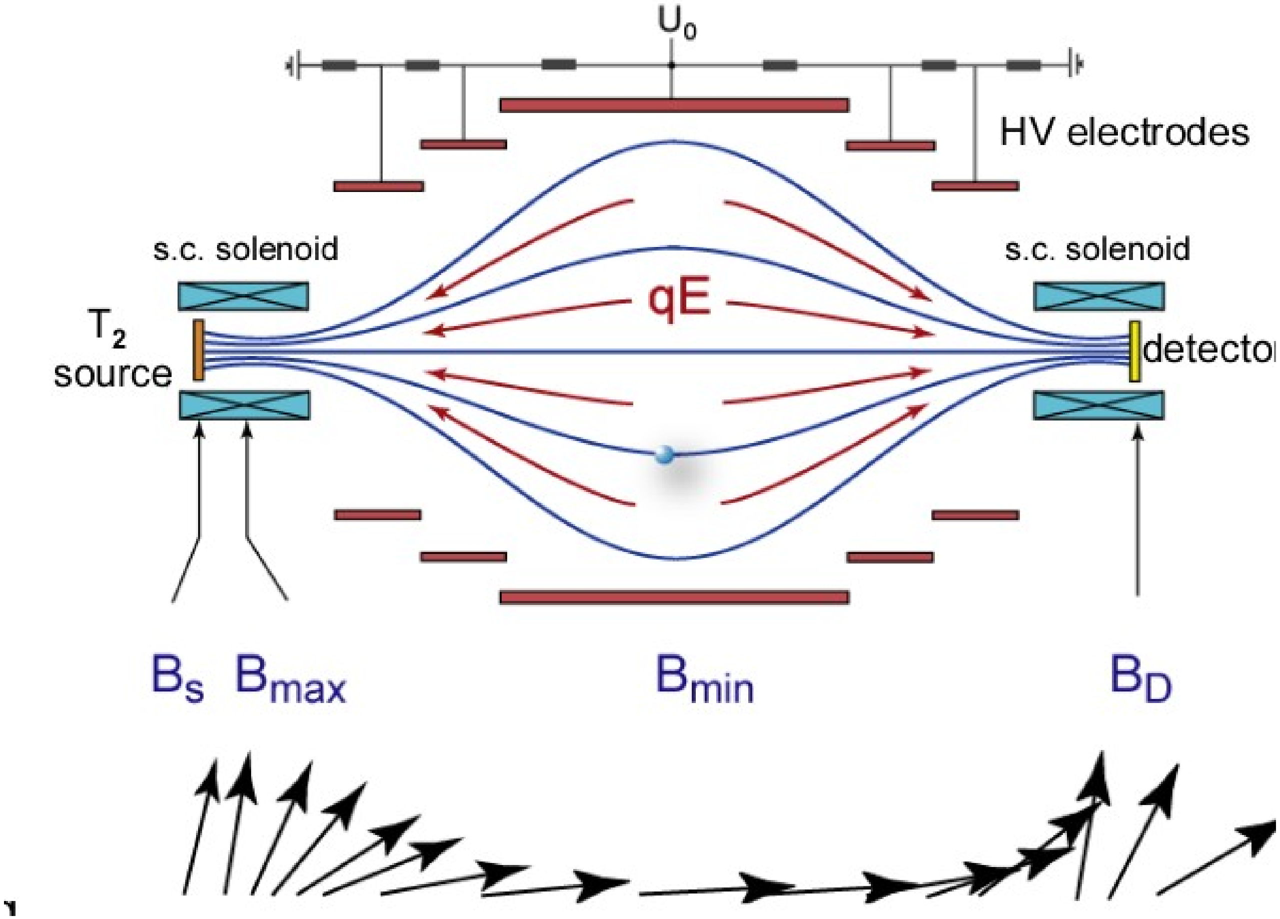
✗ limited statistics
✗ systematics due to pile-up
✗ background

Spectrometers present results

electrostatic integrating spectrometers (MAC-E filter)

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

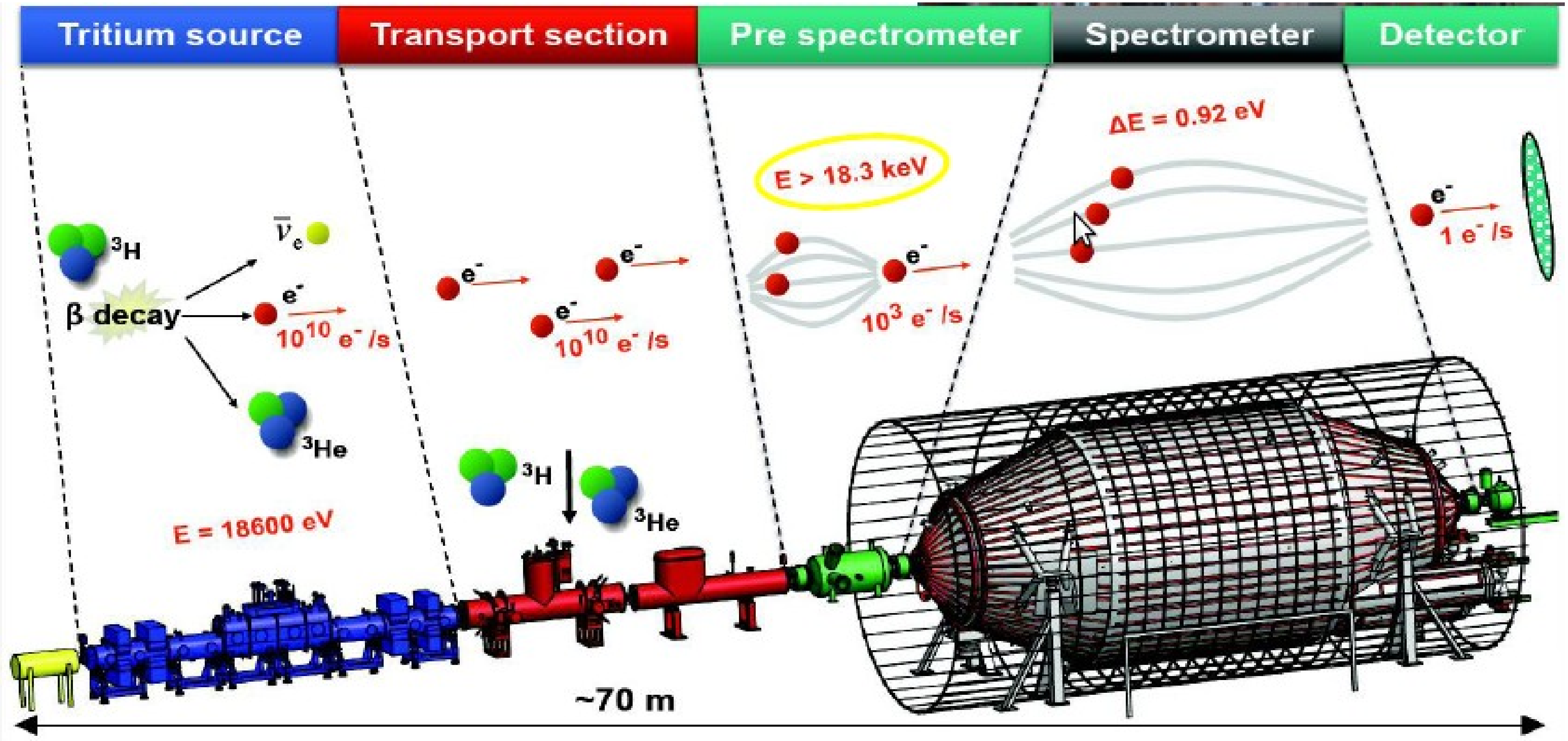
$$\mathbf{m_{\nu e} < 2.2\ eV\ 95\%\ CL}$$



Spectrometers future: KATRIN

large electrostatic spectrometer
with gaseous ^{3}H source

- ▶ expected statistical sensitivity
  $m_{\nu e} < 0.2$ eV 90% CL
- ▶ start data taking in 2013/2014

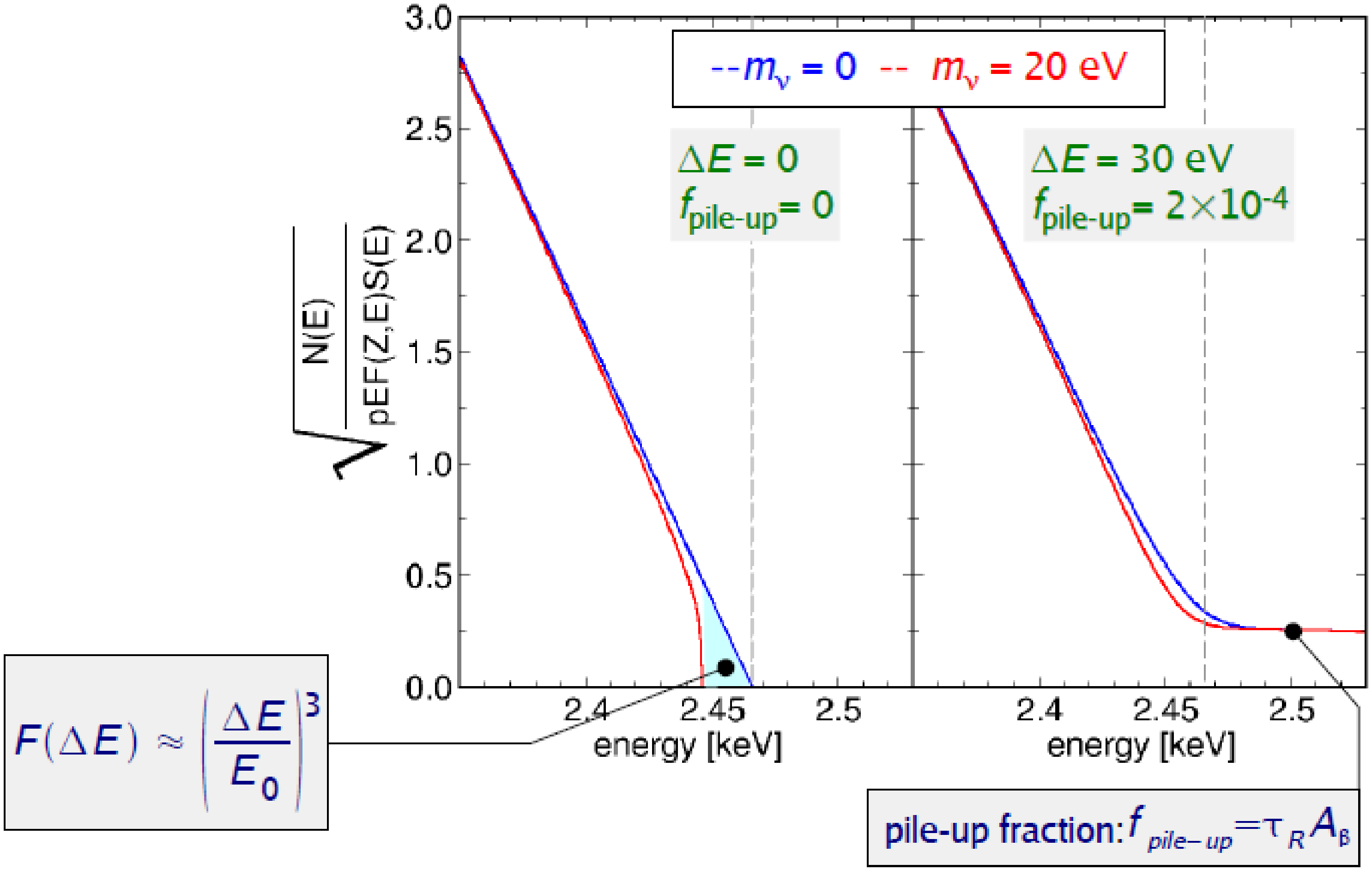


Calorimetry of beta sources

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, $\tau_{½} = 4\times10^{10}$ y

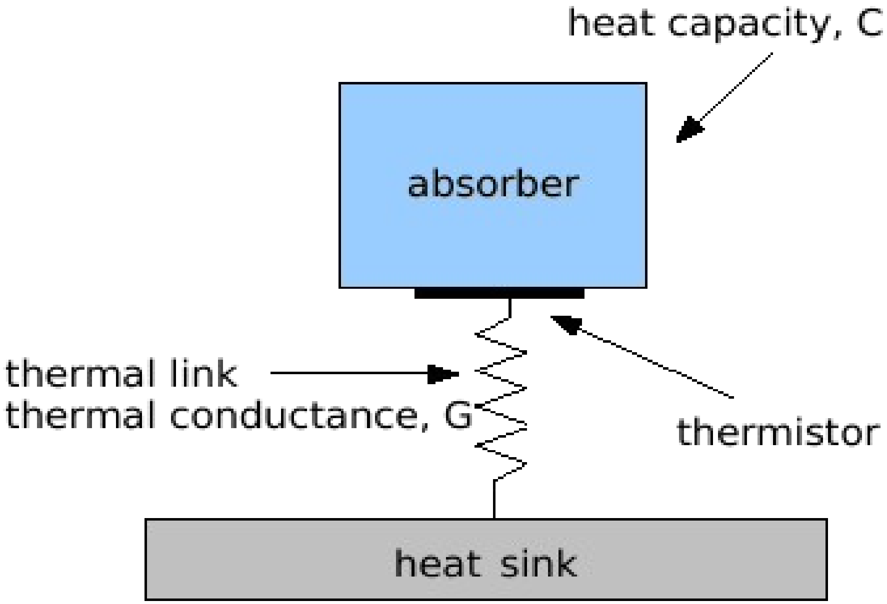
  $\Rightarrow F(\Delta E=10\ \mathrm{eV}) \sim (\Delta E/E_0)^3 = 7\times10^{-8}$
- other option ^{163}Ho electron capture: $E_0 \approx 2.6$ keV, $\tau_{½} \approx 4600$ y

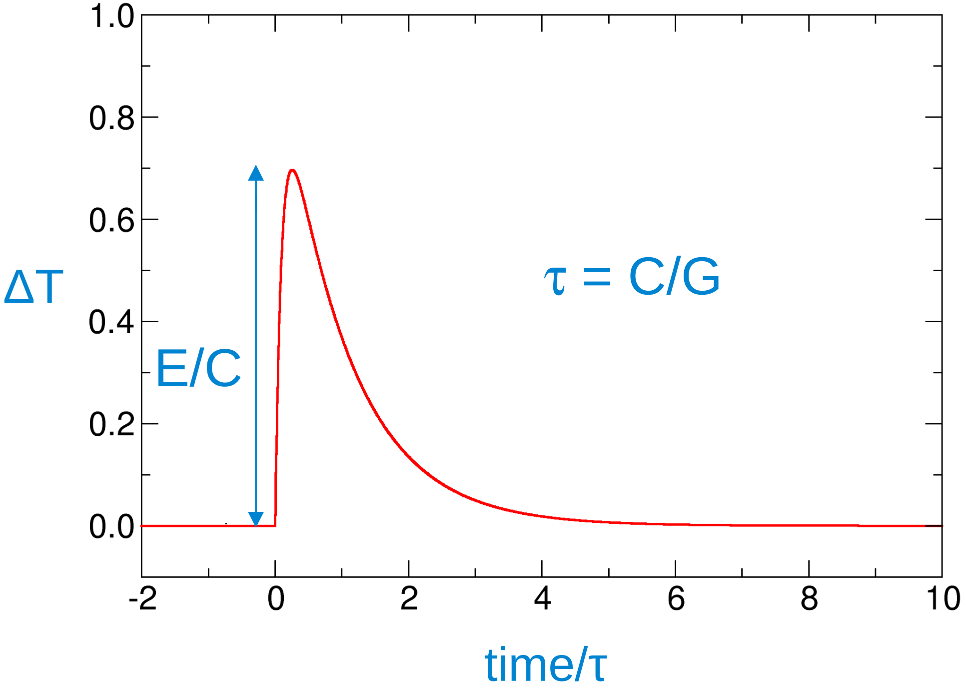


$$F(\Delta E) \approx \left(\frac{\Delta E}{E_0}\right)^3$$

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

Cryogenic detectors as calorimeters





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

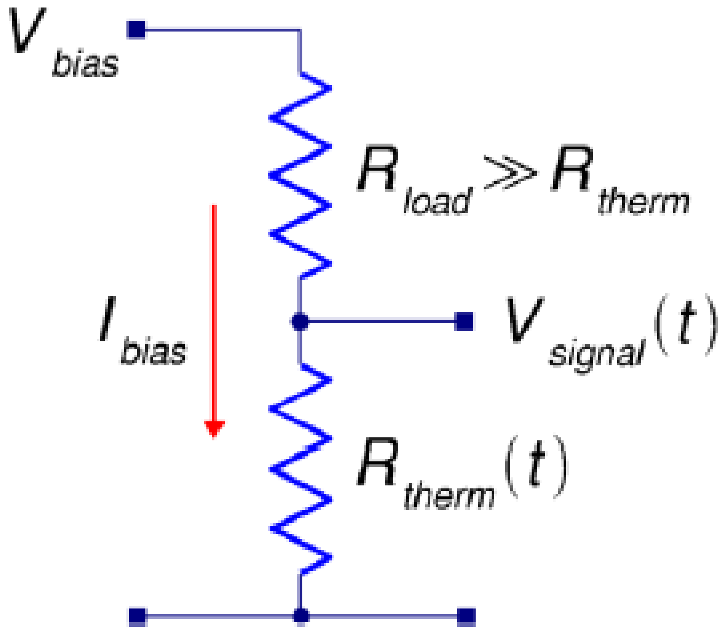
Resistive thermometers:thermistors

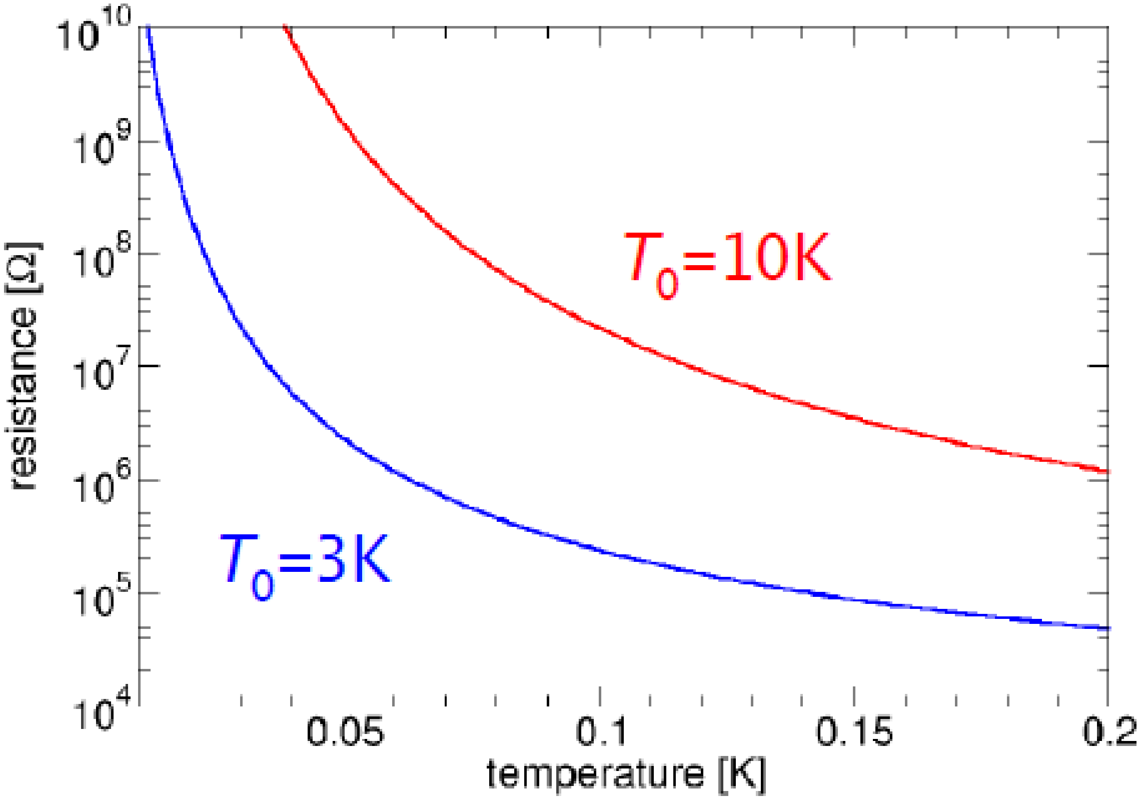
- doped semiconductors at Metal-Insulator-Transition
- at $T \ll 10K$ → phonon assisted variable range hopping conduction (VRH)

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

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

Constant current bias





High impedance devices: 1MΩ → 100MΩ

Thermal detectors for calorimetric experiments

^{187}Re β decay

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

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

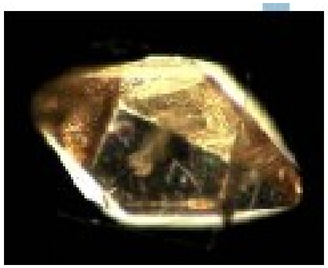
- half-life time $\tau_{1/2} = 43.2$ Gy
- natural abundance a.i. = 63%
- 1 mg metallic Rhenium ⇒ ≈1.0 decay/s

metallic rhenium single crystals

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

m_ν <15 eV

dielectric rhenium compound ($AgReO_4$) crystals



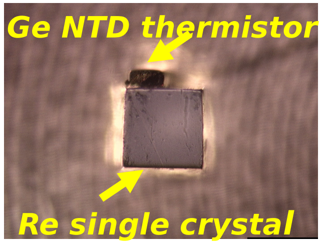
- Silicon implanted thermistors
- MIBETA experiment (Milano)

Precursors of ^{187}Re experiment

MANU (1999)

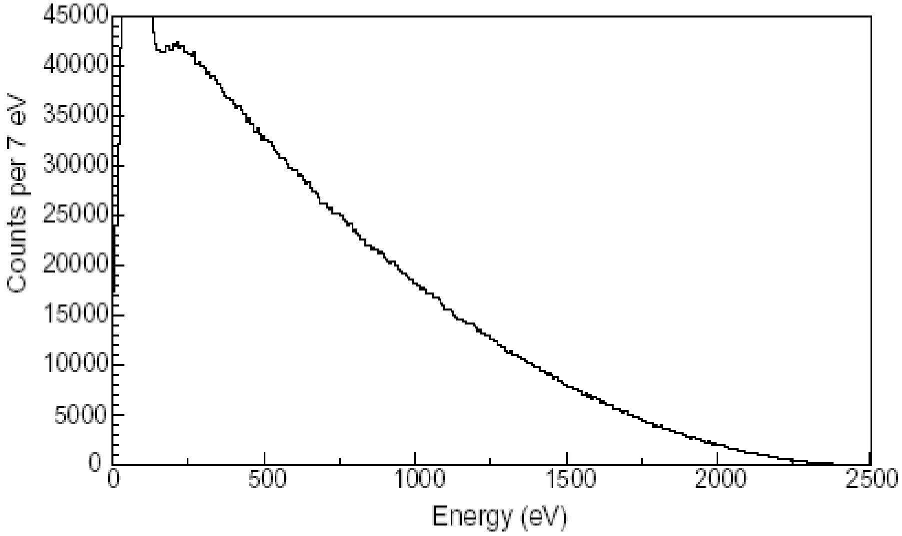
Genova

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



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

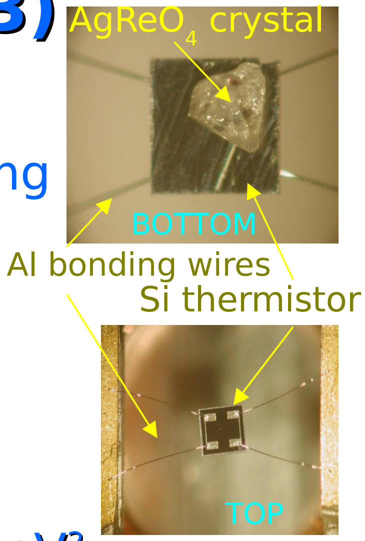
6.0×10^6 ^{187}Re decays above 420 eV



MIBETA (2002-2003)

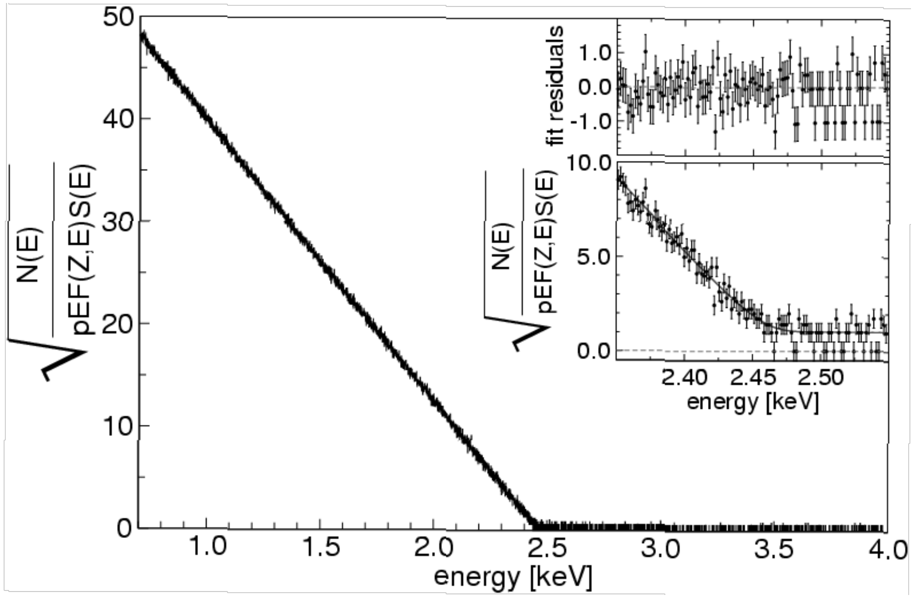
Milano, Como, Trento

- 10 AgReO$_4$ crystals: 2.71 mg
- ^{187}Re activity = 0.54 Hz/mg
- Si thermistors (ITC-irst)
- $\Delta E = 28.5$ eV FWHM
- 0.6 years live time



- $m_\nu^2 = -112 \pm 207_{stat} \pm 90_{sys}$ 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 sub-eV direct neutrino mass measurement complementary to the KATRIN experiment

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

MARE 2

- very large experiment with a m_ν statistical sensitivity close to KATRIN but still improvable
- requires new improved detector technologies

~1000 detectors → 0.2 eV m_ν sensitivity

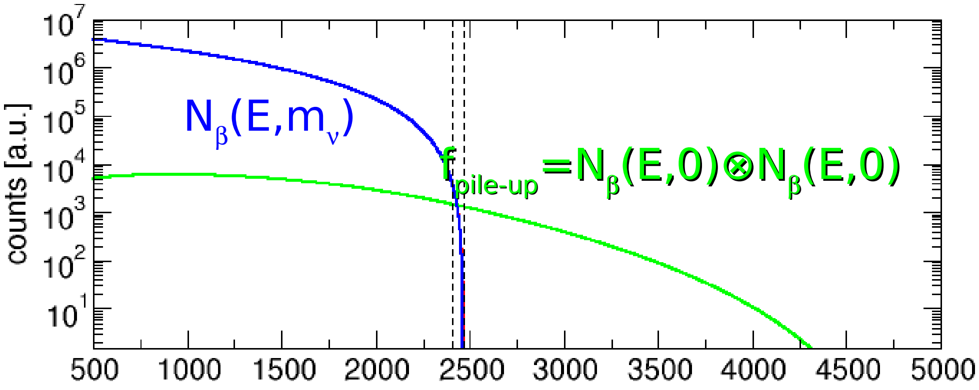
MARE for sub-eV calorimetric m_ν measurement

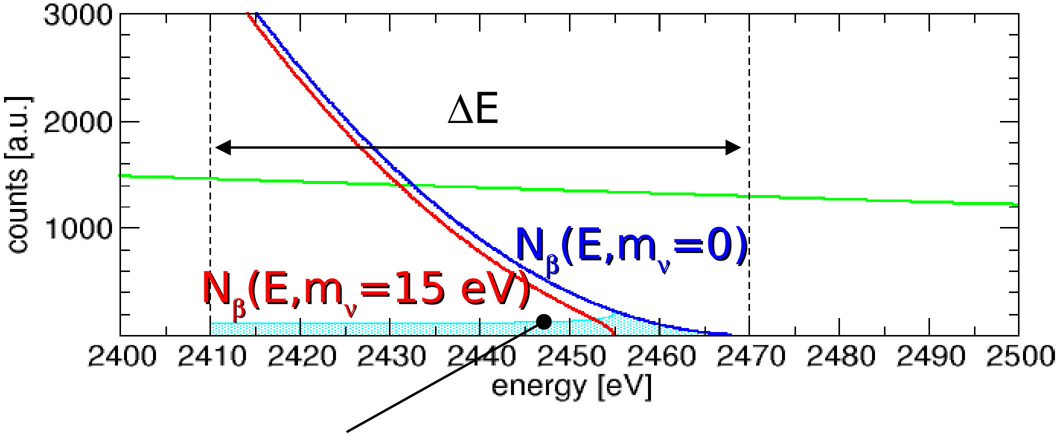
MARE: Microcalorimeter Arrays for a Rhenium Experiment

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, UniversitÃ¤t Heidelberg, Germany
University of Miami, Florida, USA
Wisconsin University, Madison, Wisconsin, USA
Universidade de Lisboa and ITN, Portugal
UniversitÃ 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, ...

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

^{187}Re – Statistical sensitivity 1





signal = $|N_\beta(E,m_\nu=0) - N_\beta(E,m_\nu=15\ eV)|$

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

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

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

Beta activity $\mathbf{A_\beta}$

Resolving time $\boldsymbol{\tau_R}$

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

Analysis interval ΔE

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

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

^{187}Re – Statistical sensitivity 2

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

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

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**

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

Experimental challenges :

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

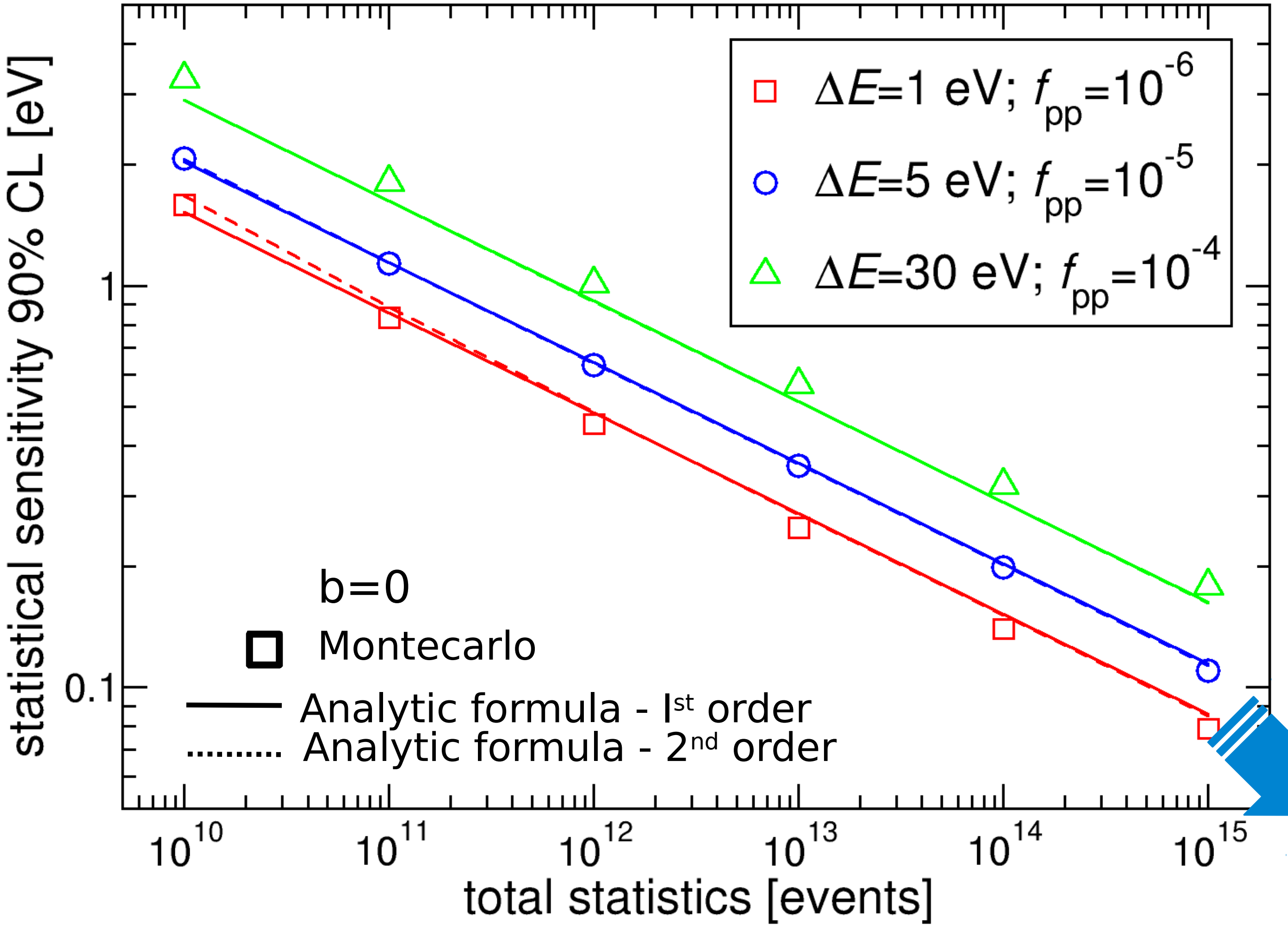
- Large number of simulated spectra N = 100÷1000
- Spectra are analysed as the real ones
- Input parameters:
  - Total statistics N_{ev}
  - Energy resolution ΔE_{FWHM}
  - Fraction of pile-up events f_{pp}
  - Constat background b
- Sensitivity at 90% CL:

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

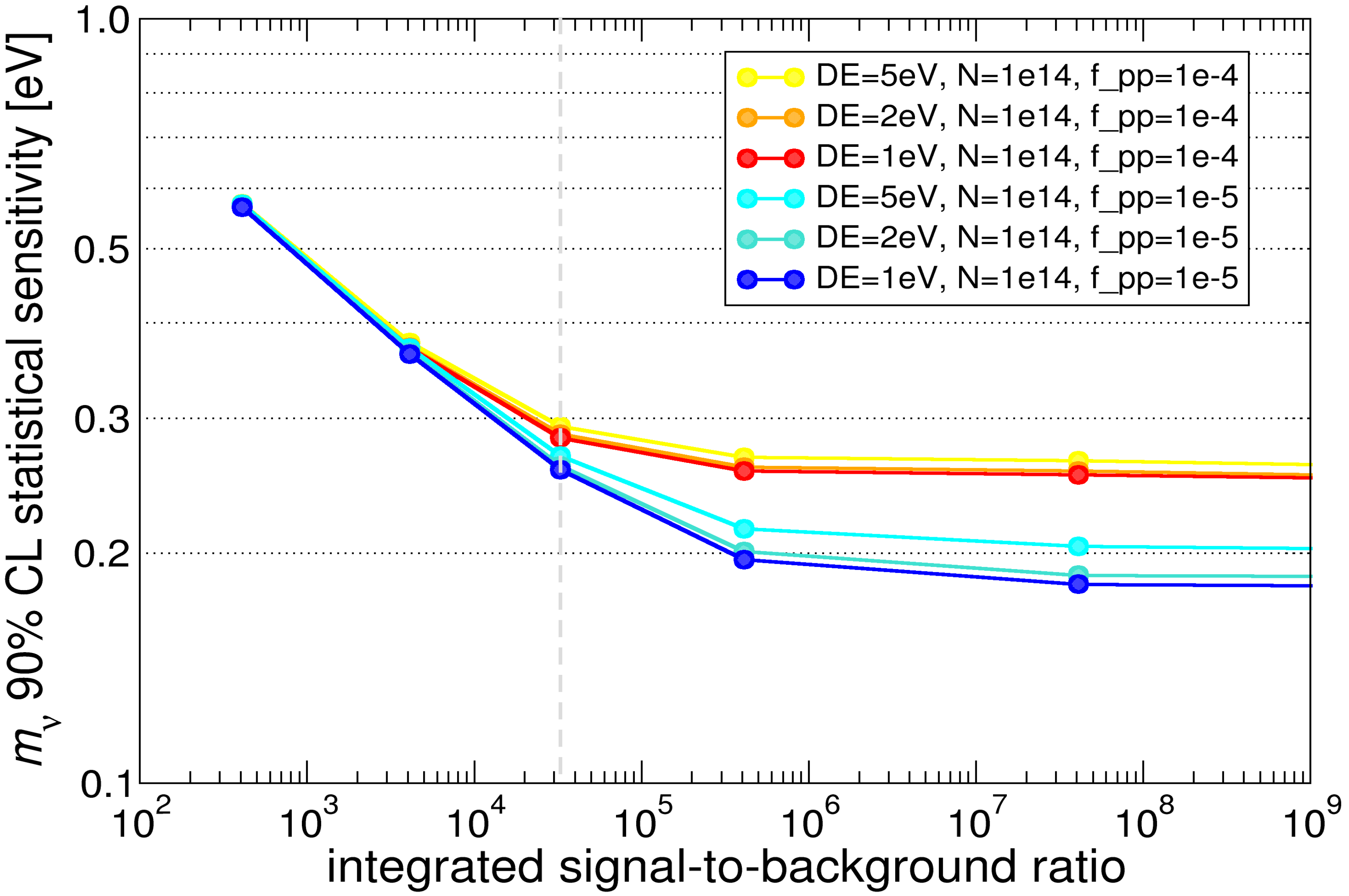
$$\sum\nolimits_{90}\left(m_\nu\right) \propto \sqrt[4]{\frac{1}{N_{ev}}}$$

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



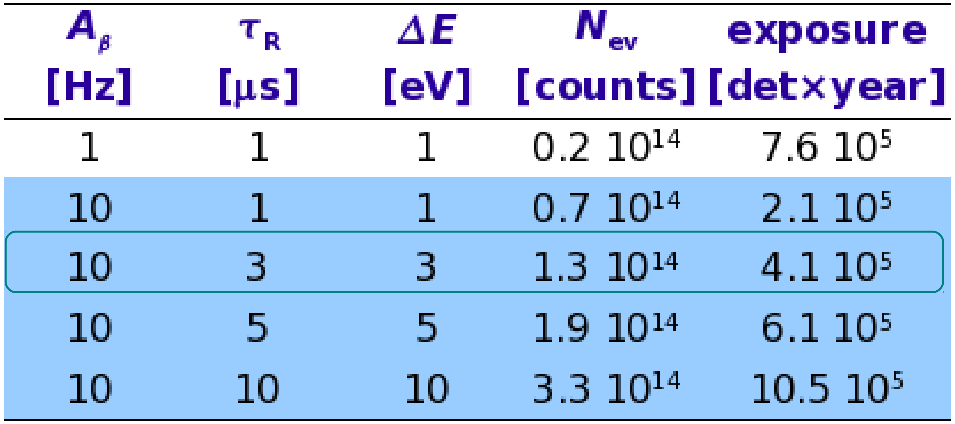
$S/B = N_{ev}/N_{bkg}$

$N_{bkg} = bE_0T$

MARE statistical sensitivity: Re option

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

Exposure required for 0.2 eV m_n sensitivity

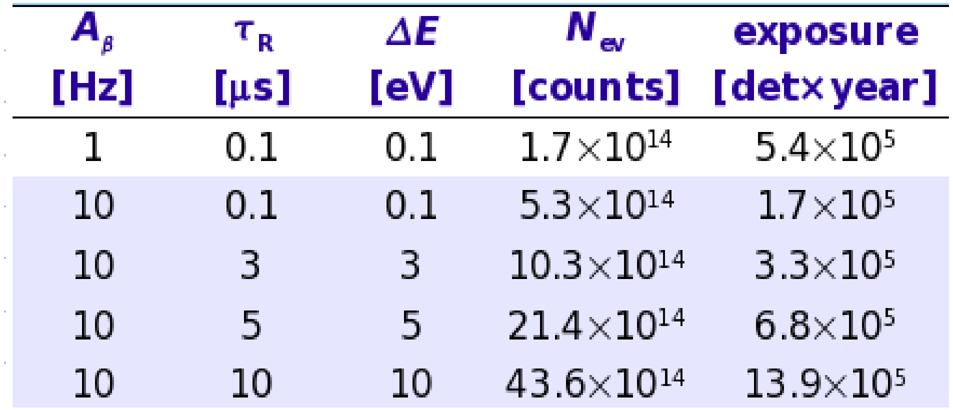


A_β [Hz]	τ_R [μs]	ΔE [eV]	N_{ev} [counts]	exposure [det×year]
1	1	1	$0.2\ 10^{14}$	$7.6\ 10^5$
10	1	1	$0.7\ 10^{14}$	$2.1\ 10^5$
10	3	3	$1.3\ 10^{14}$	$4.1\ 10^5$
10	5	5	$1.9\ 10^{14}$	$6.1\ 10^5$
10	10	10	$3.3\ 10^{14}$	$10.5\ 10^5$

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

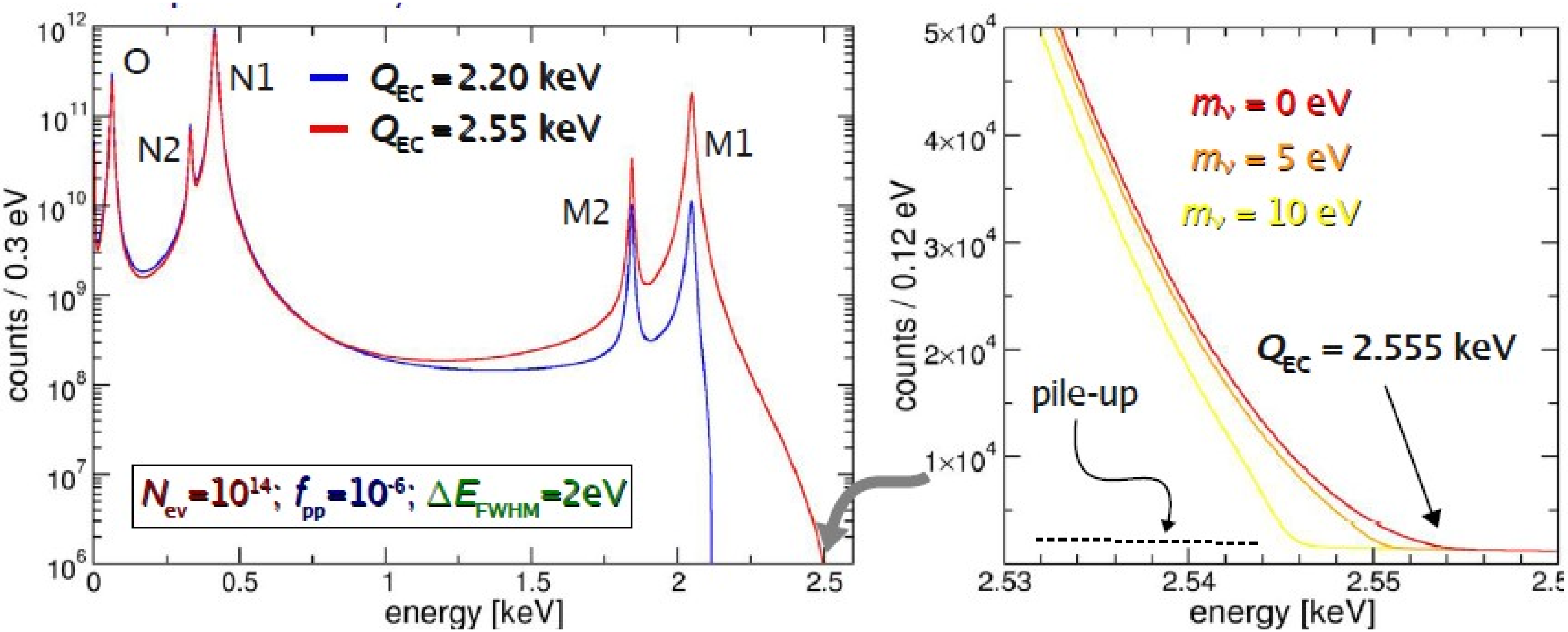
bkg = 0

MARE extensions: ^{163}Ho EC measurement

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

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: $Q_{EC} = 2.3 \div 2.8$ 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

Q_{EC} = 2.2keV

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	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}

bkg = 0

→

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

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	0.3	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
$\approx 3\times10^{17}$ ^{163}Ho nuclei

Montecarlo analysis for systematics of ^{187}Re

Assessing systematic uncertainties with MonteCarlo simulations:

- Effects due to incomplete/incorrect data modelling
  - generate simulated experimental spectra with systematic effect
  - analyze spectra without effect
  - obtain $\Sigma(m_\nu)$ and Δm^2 as function of effect size
- Uncertainty due to experimental parameter finite accuracy
  - generate simulated experimental spectra with randomly fluctuated parameter
  - analyze spectra with fixed average parameter
  - obtain $\Sigma(m_\nu)$ and Δm^2 as function of effect size
- systematic uncertainties analyzed for $N_{ev}=10^{14}$, $\Delta E_{FWHM}=1.5$ eV and $f_{pp}=10^{-6}$

Two main classes of systematics:

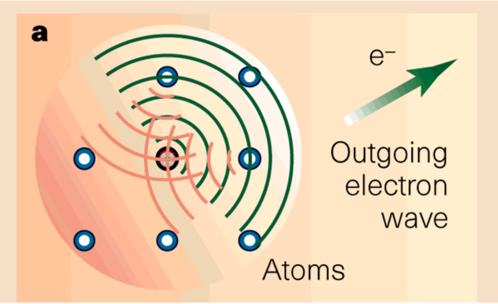
- source related systematics effect
- Instrumental systematics uncertainties

Summary of source related systematic uncertainties

- **Electron surface escape**
  - $N'(E) = N(E)(1 - a_{esc}\, E/E_0)$
  - for 1 mg Re crystal → $a_{esc} = 2\ 10^{-5}$
- **Spectral shape**
  - improve theoretical description of beta spectrum
  - $N'(E) = N(E)(1 + a_1 E + a_2 E^2)$
  - from Dvornicky-Simkovic (Medex09) $f(E) = 1 – 2\times10^{-5}E + 3\times10^{-10}E^2 – 4\times10^{-15}E^3 +$
- **Beta Environmental Fine structure**
  - observe in Re and in $AgReO_4$ improve modelling and parametrization
- **Pile up spectrum**
  - $\tau_R^{eff} = f(\tau_R, A_1/A_2) \rightarrow N'_{pp}(E) = N_{pp}(E)\, f_{corr}(E, f_{pp})$

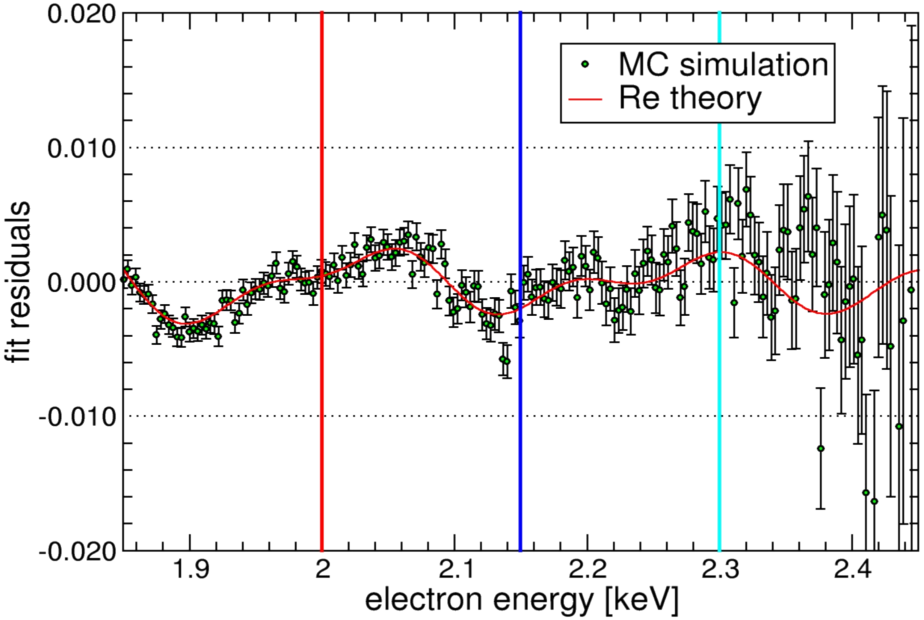
Source of uncertainties	Quantity describing the effect	Maximum effect for $\Delta m^2 < 0.1\ eV^2$
Electron surface effect	a_{esc}	10^{-5}
Correction to quadratic β spectral shape	$\lvert a_1\rvert\ (a_2=0)$ $\lvert a_2\rvert\ (a_1=0)$	$10^{-9}\ eV^{-1}$ $10^{-12}\ eV^{-1}$
Correction to pile up spectral shape	f_{pp}	10^{-7}

Systematics from BEFS



BEFS: Beta Environmental Fine Structure

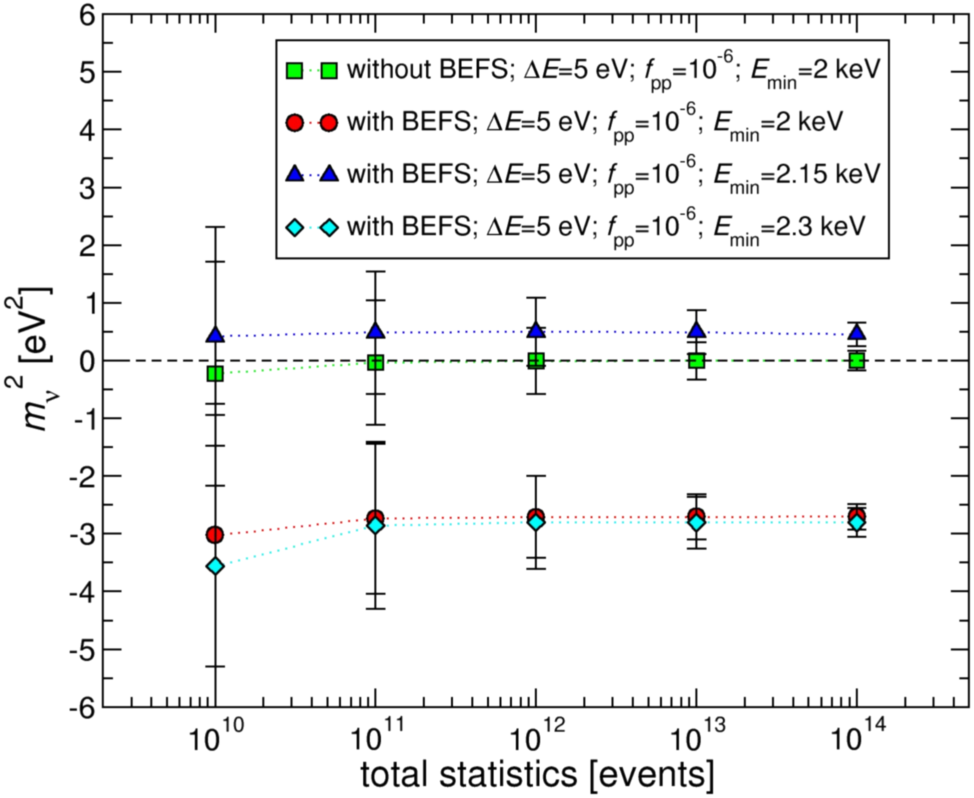
Modulation of the electron emission probability due to the atomic and molecular surrounding of the decaying nucleus: it is explained by the wave structure of the electron (analogous of EXAFS)



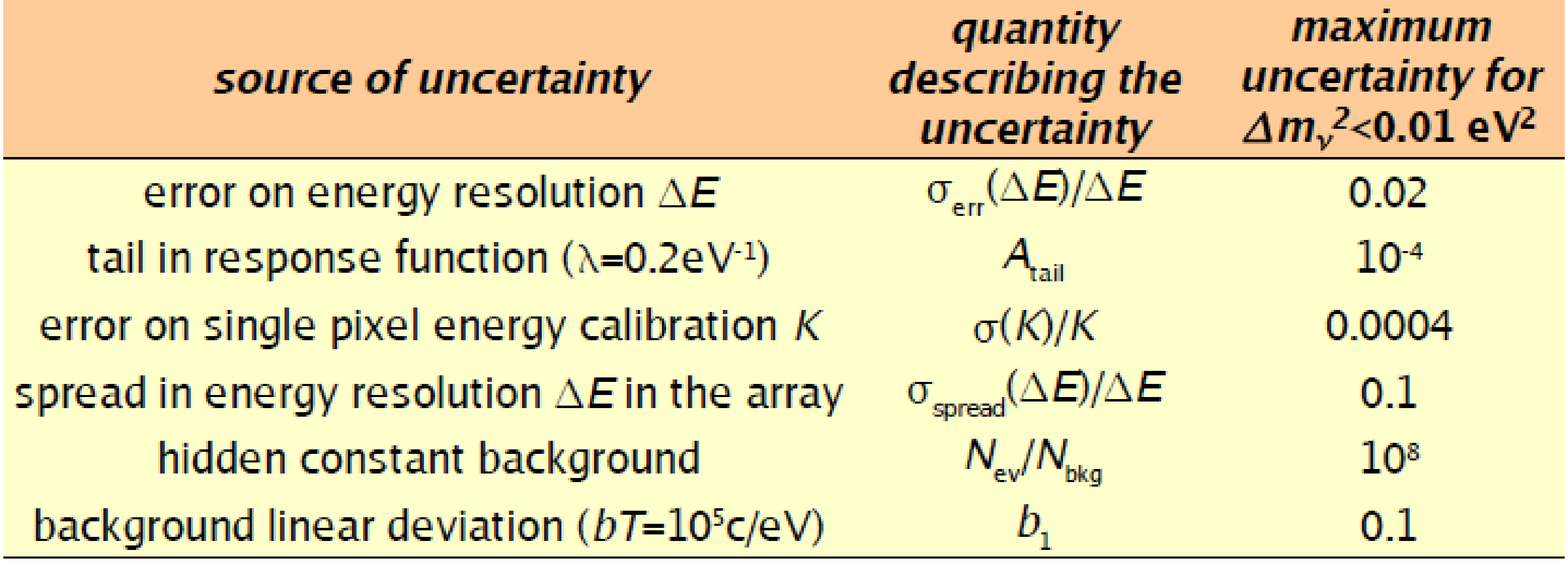
Expected end point spectra deformation

$N_{ev} = 10^{10}$ $\Delta E = 5$ eV $f_{pp} = 10^{-5}$

Systematic shift with BEFS neglected



Systematics from instrumental uncertainties



source of uncertainty	*quantity describing the uncertainty*	*maximum uncertainty for $\Delta m_\nu^2 < 0.01$ eV^2*
error on energy resolution ΔE	$\sigma_{err}(\Delta E)/\Delta E$	0.02
tail in response function (λ=0.2eV^{-1})	A_{tail}	10^{-4}
error on single pixel energy calibration K	$\sigma(K)/K$	0.0004
spread in energy resolution ΔE in the array	$\sigma_{spread}(\Delta E)/\Delta E$	0.1
hidden constant background	N_{ev}/N_{bkg}	10^8
background linear deviation (bT=10^{5}c/eV)	b_1	0.1

Systematics summary: calorimeters vs spectrometers

Calorimetry systematics

- detector response function (energy dependence, shape,...)
- energy dependent background
- pile-up effects
- condensed matter effects: BEFS
- ^{187}Re decay spectral shape
- ...?

Spectrometer systematics

- decays to excited final states
- energy losses in the source
- e^{-} - T_2 elastic scattering
- spectrometer stability (HV)
- source stability (density, potential, charging...)
- energy dependent background
- ...?

⇨ **completely different systematics!**

⇨ **very important to cross-check results!**

Heavy neutrino and single beta decay

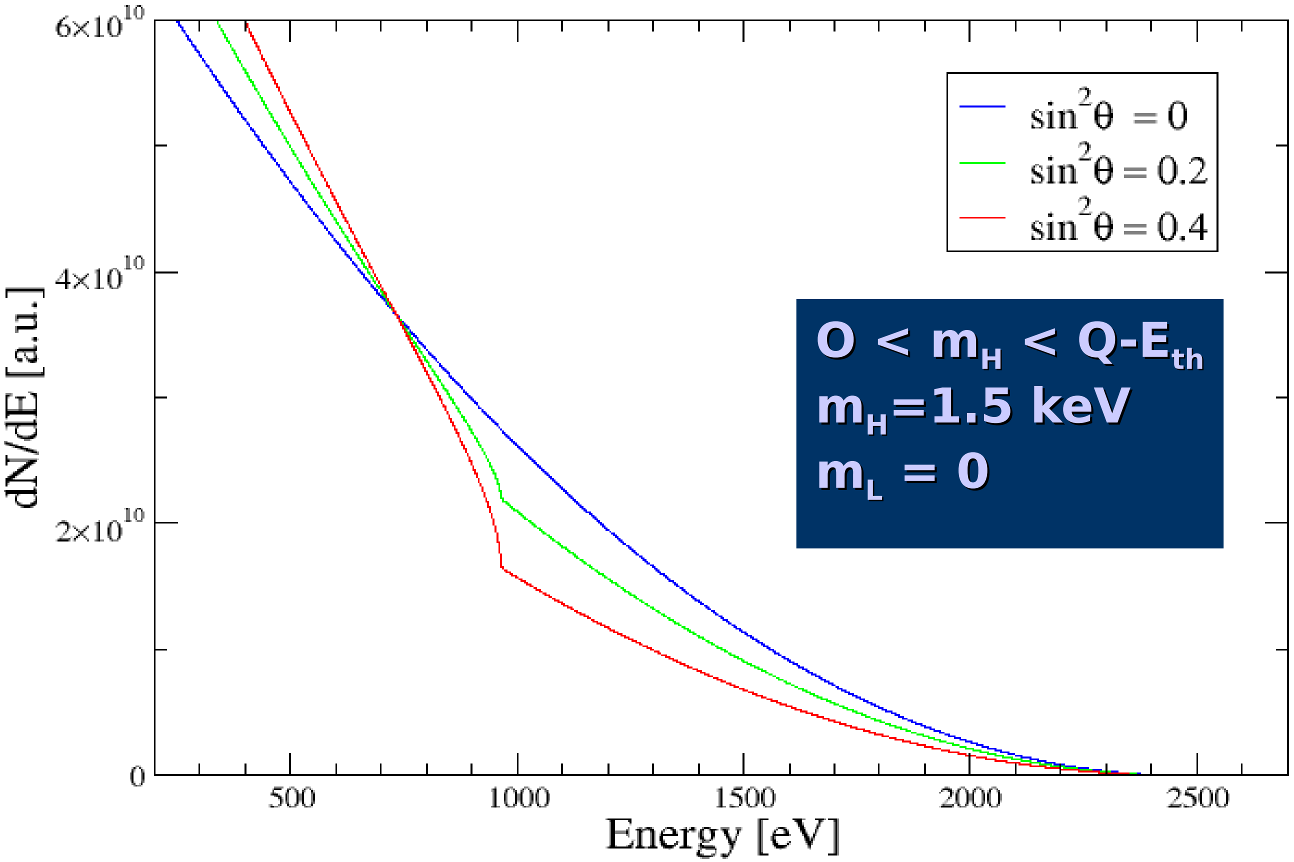
Connection point between astrophysics, cosmology and elementary particle physics is the explanation of the Dark Matter (DM).

⇨ A possible Warm Dark Matter (WDM) candidate is a sterile neutrino with a mass in the keV range

⇨ to test the assumption of heavy neutrino existence: ^{187}Re beta decay

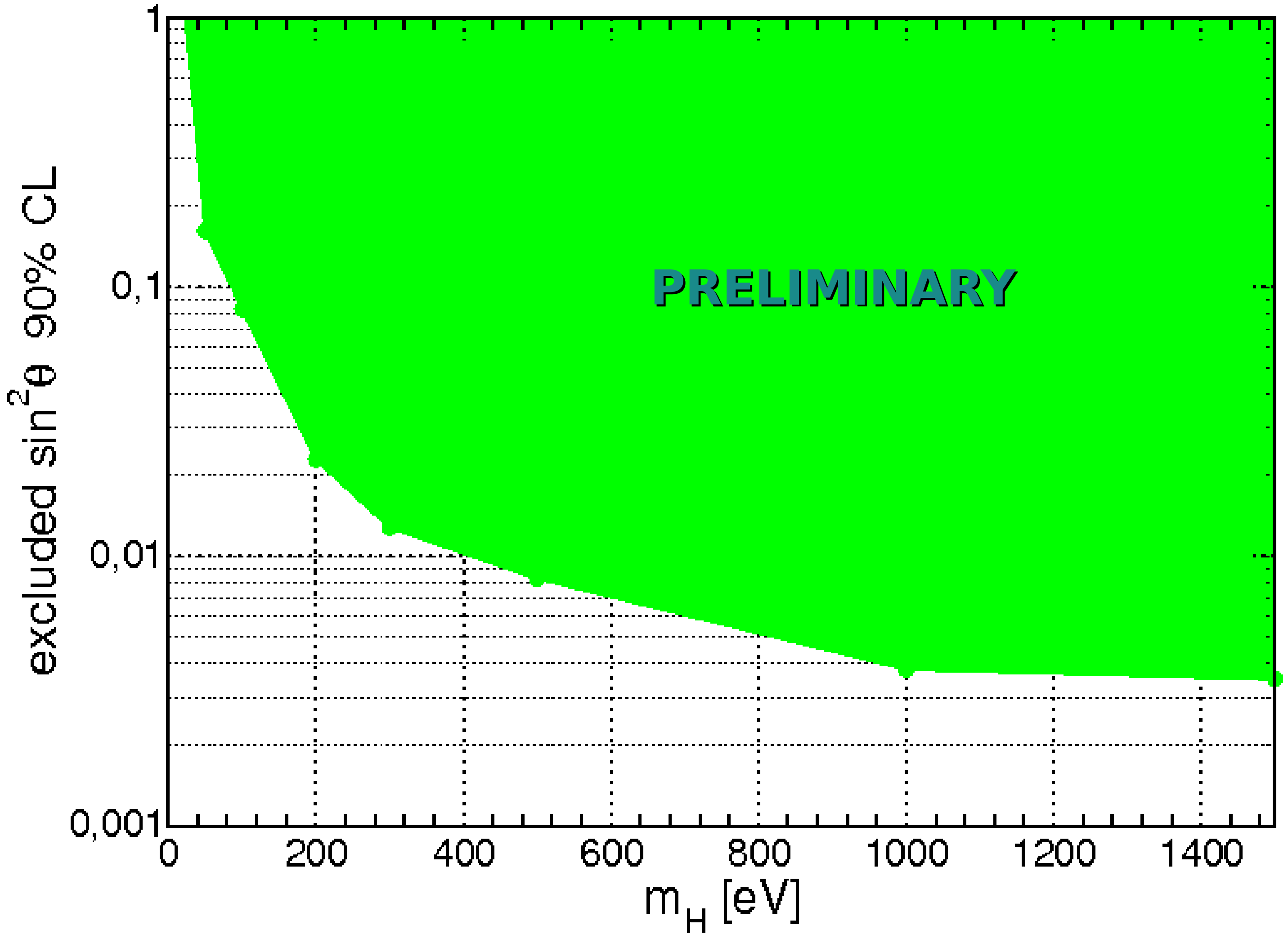
$$\nu_e = \nu_L \cos\theta + \nu_H \sin\theta$$

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



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

Heavy neutrino limit form the past - MIBETA



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

$Q = 2465$ eV

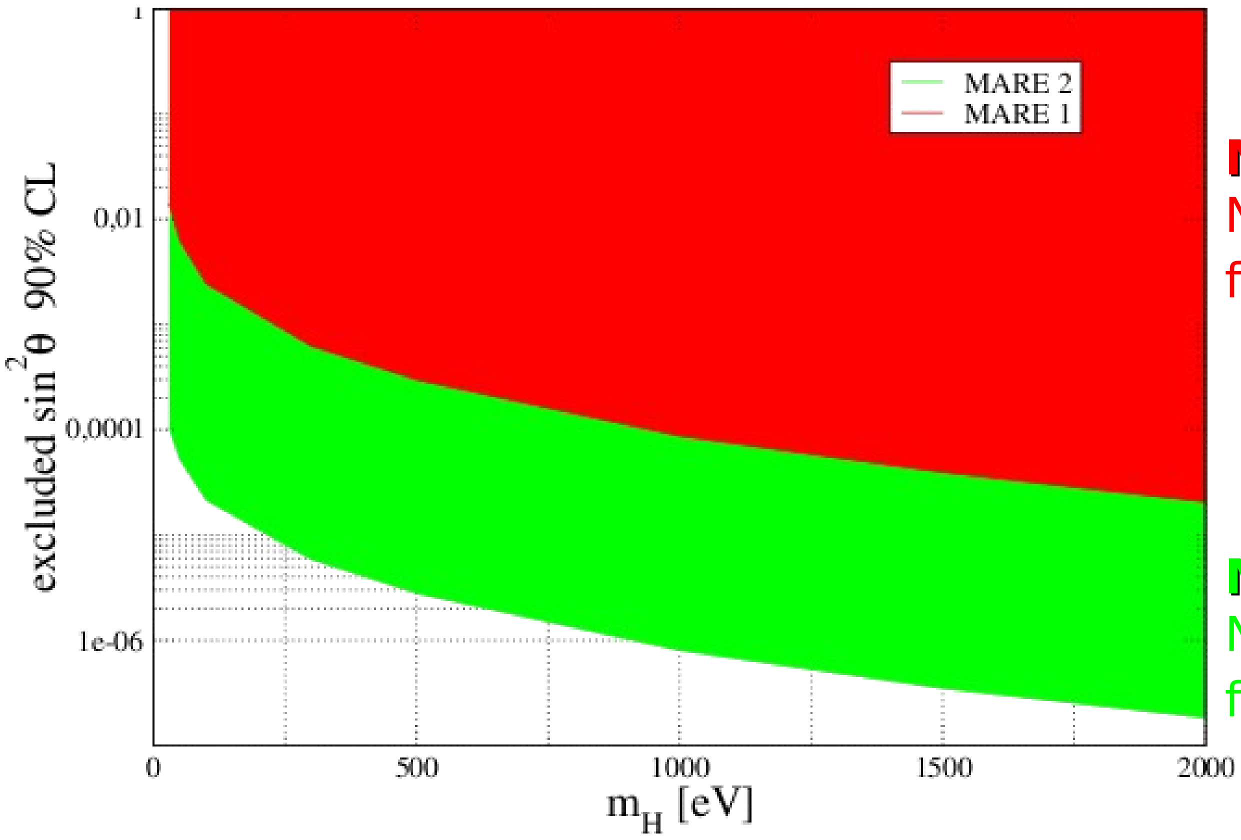
$E_{th} = 700$ eV

↓

$0 < m_H < 1765$ 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

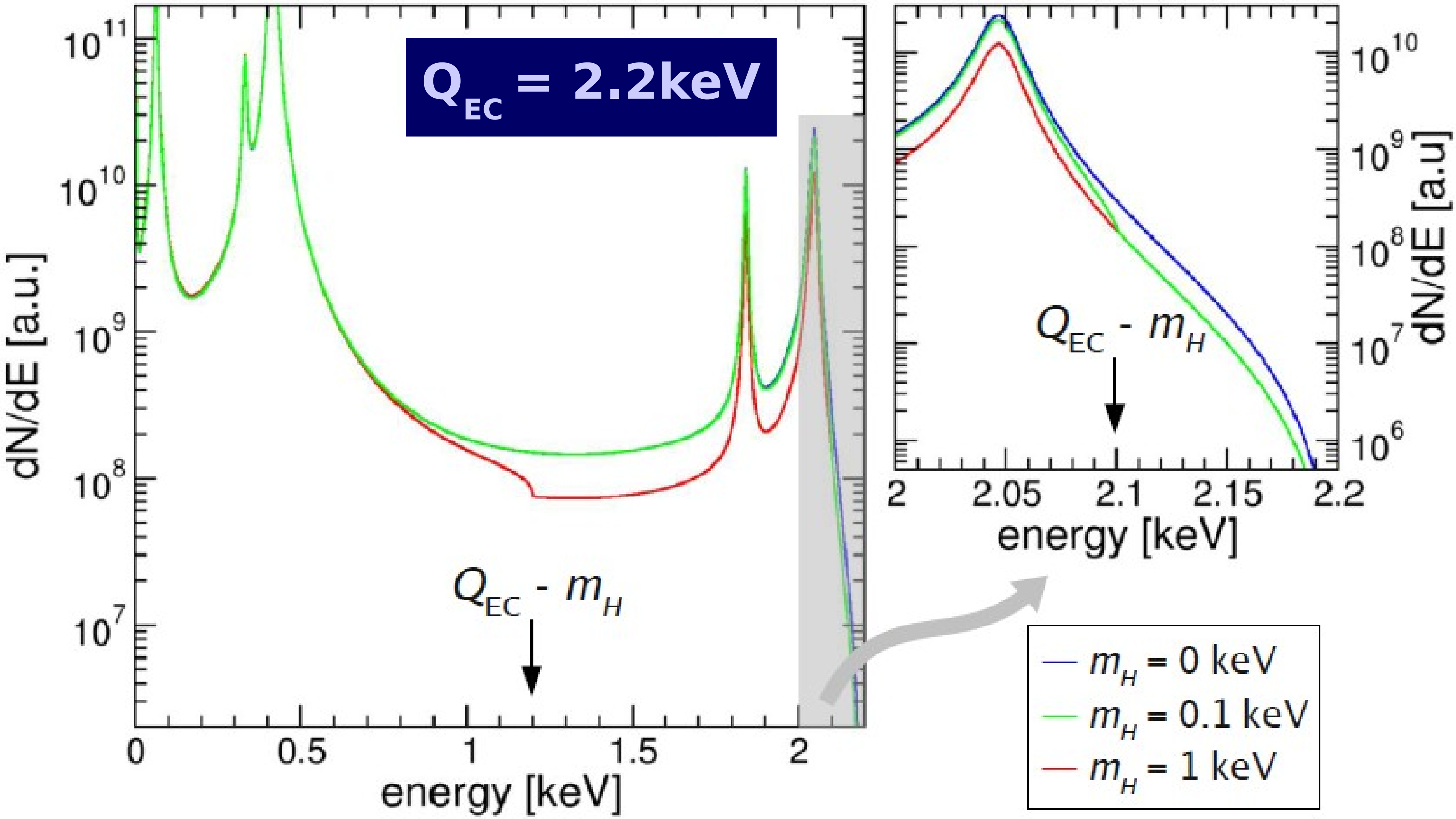
MARE 2:

$N_{ev}=10^{14}$, $\Delta E_{FWHM}=1$ eV

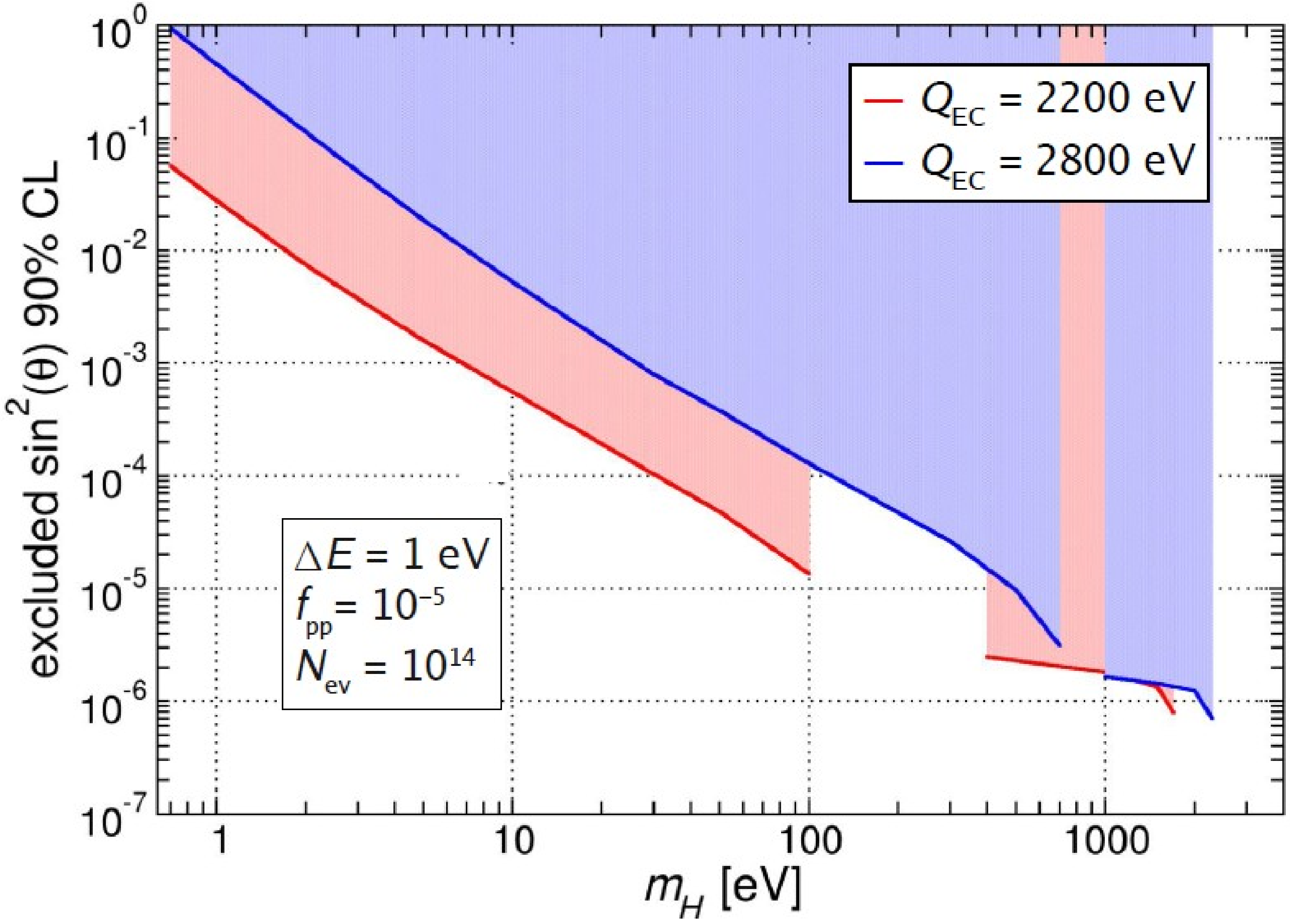
$f_{pp}=10^{-5}$, b=0

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

Goal: a sub-eV direct neutrino mass measurement complementary to the KATRIN experiment

MARE-1: collection of activities aiming at isotope/technique selection

- **^{187}Re** – high statistics measurement
  - asses systematics
  - test large arrays
  - lower limit to few eV
- ^{163}**Ho** – high statistics measurement – R&D for ^{163}Ho production
  - measure Q_{EC}
  - study spectrum shape
  - asses systematics

Different techniques:

- TES – Transition Edge Sensor
- MMC – Magnetic MicroCalorimeter
- MKID – Microwave Kinetic Inductance Detector
  - **multiplexed readout**
  - **large arrays**

MARE 1 activities

- **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)
  - ^{163}Ho + TES (U Genova)
  - ^{163}Ho + MMC (U Heidelberg)
  - ^{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)
- **Software tools**
  - Data Analysis (U Miami)
  - Montecarlo simulations (U Miami - U Milano-Bicocca)

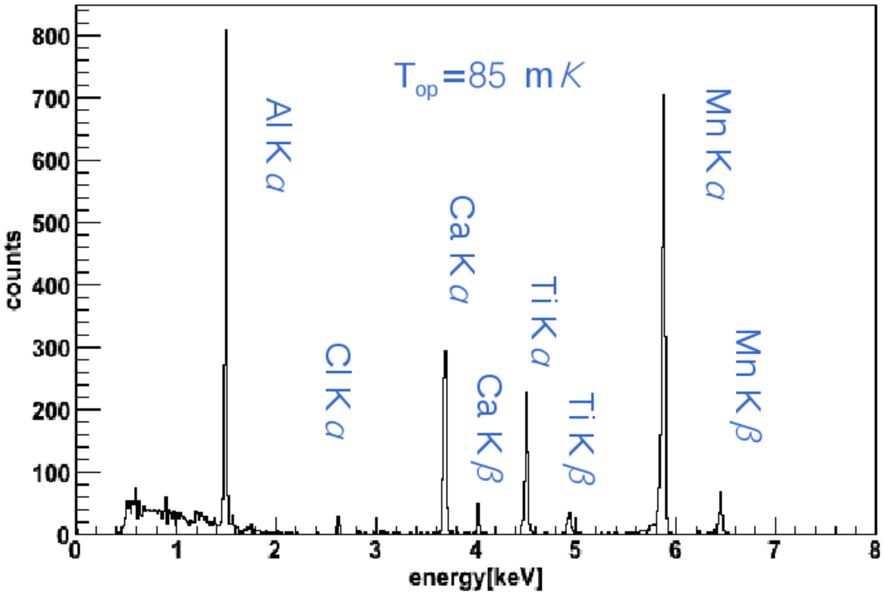
MARE 1 @ Milano-Bicocca

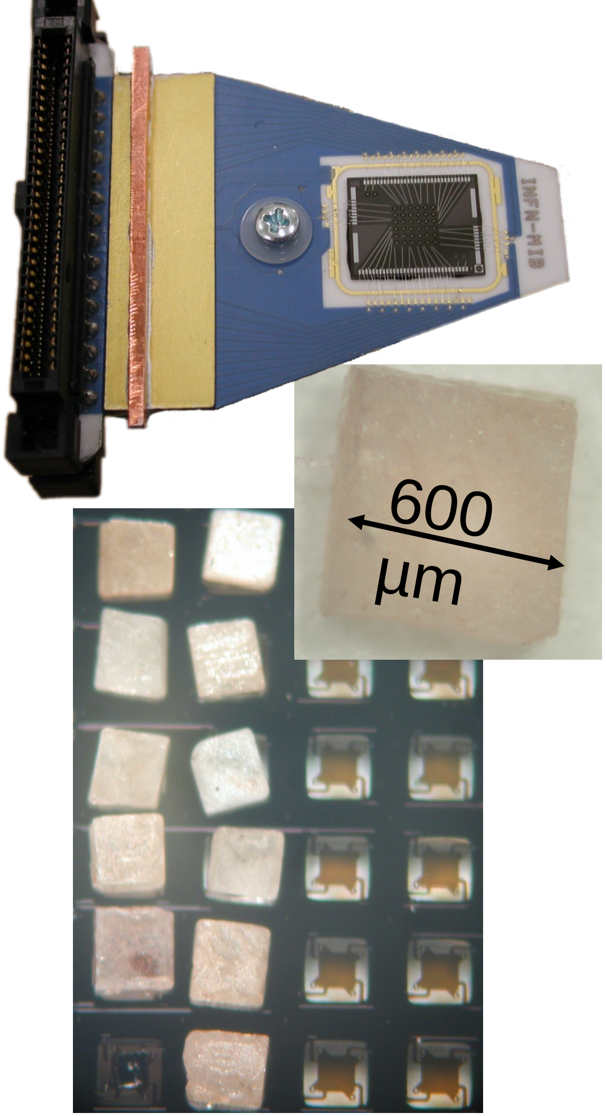
- **6x6 NASA/GSFC arrays**
  - pixel 300x300x1.5 μm^3
  - developed for X-ray spectroscopy with HgTe absorber (ASTRO-E2)

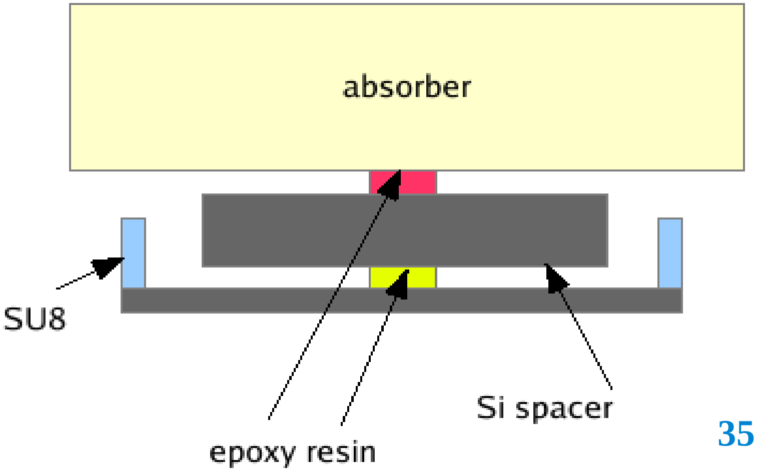
- **flat $AgReO_4$ single crystal**
  - mass ~ 500μg per pixel (A_β ~ 0.3 dec/sec)

- **Detector R&D results**
  - best operating T ≈ 85mK
  - $\Delta E \approx 30$ eV, $\tau \approx 250$ μs

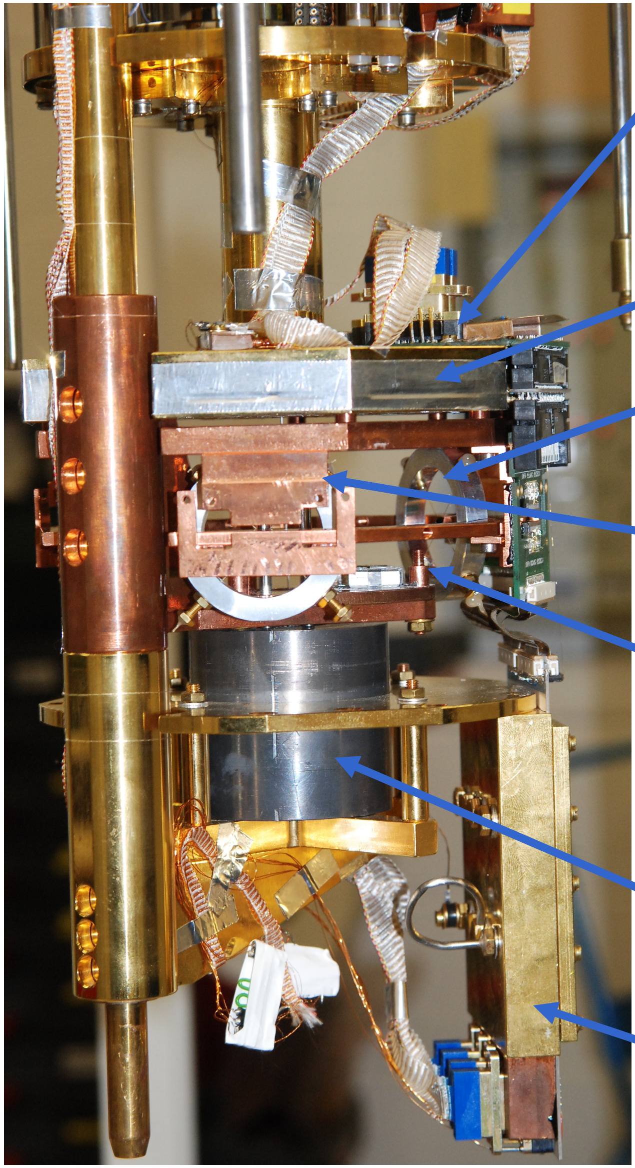
Calibration Spectrum







Cryogenic set-up of MARE 1 @ Milano Bicocca



Load Resistence 50 MΩ

Detector holder

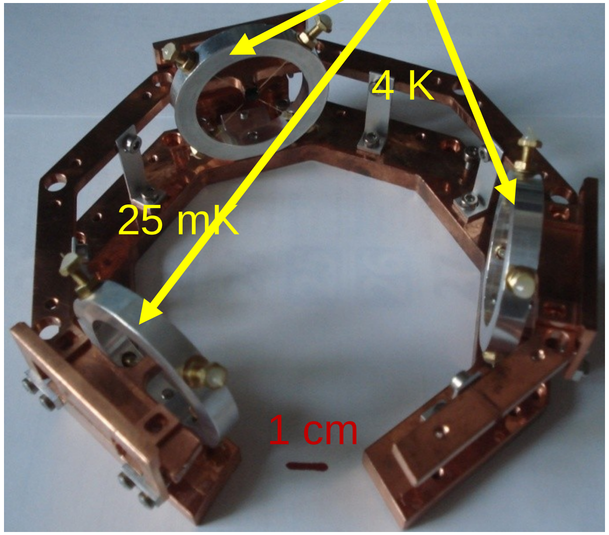
Calibration source ^{55}Fe

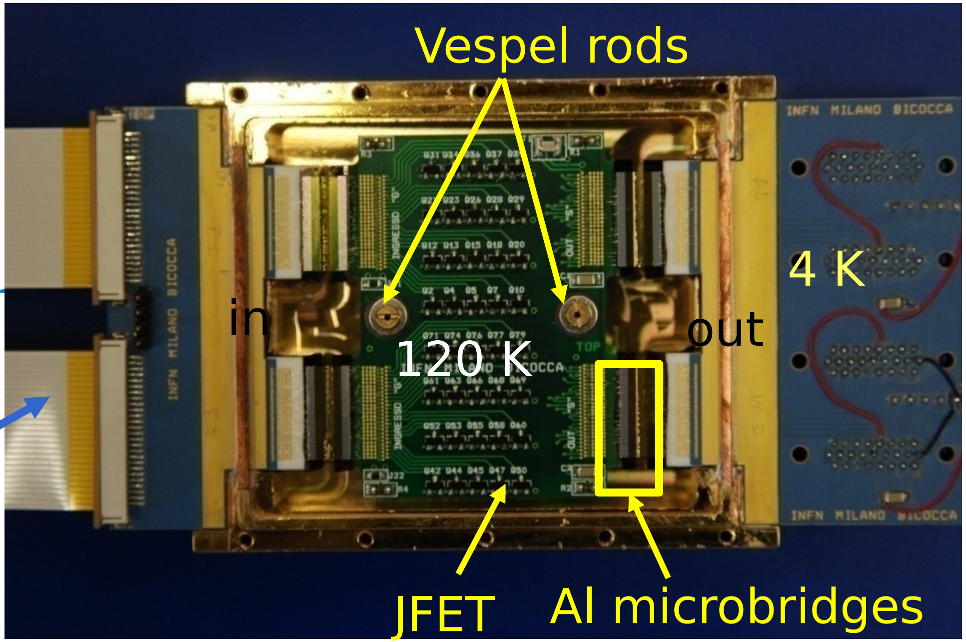
Calibration targets

Pb shield for calibration source

JFET box

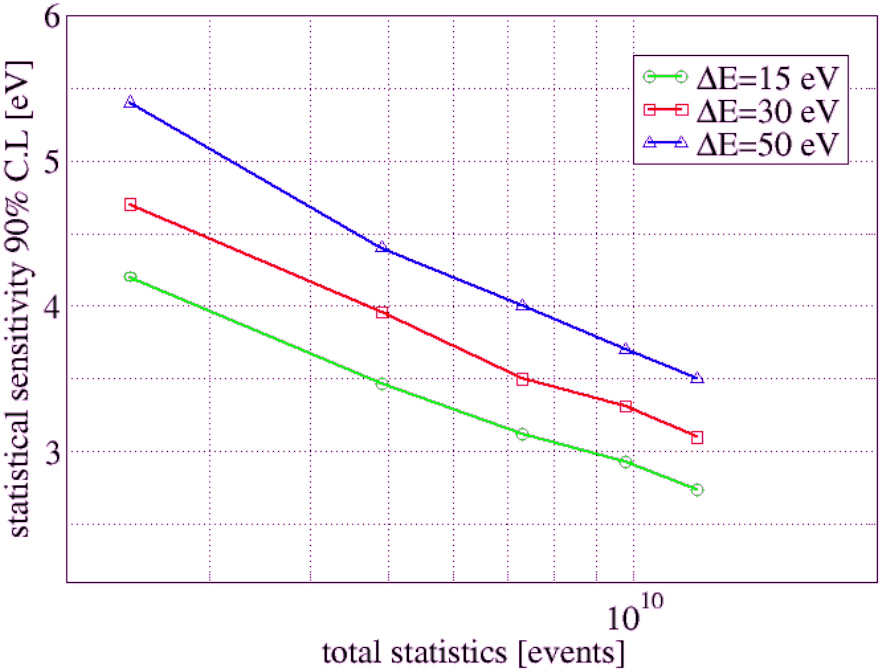
Kevlar crosses





MARE 1 in Milano: sensitivity

MonteCarlo approach



Detectors

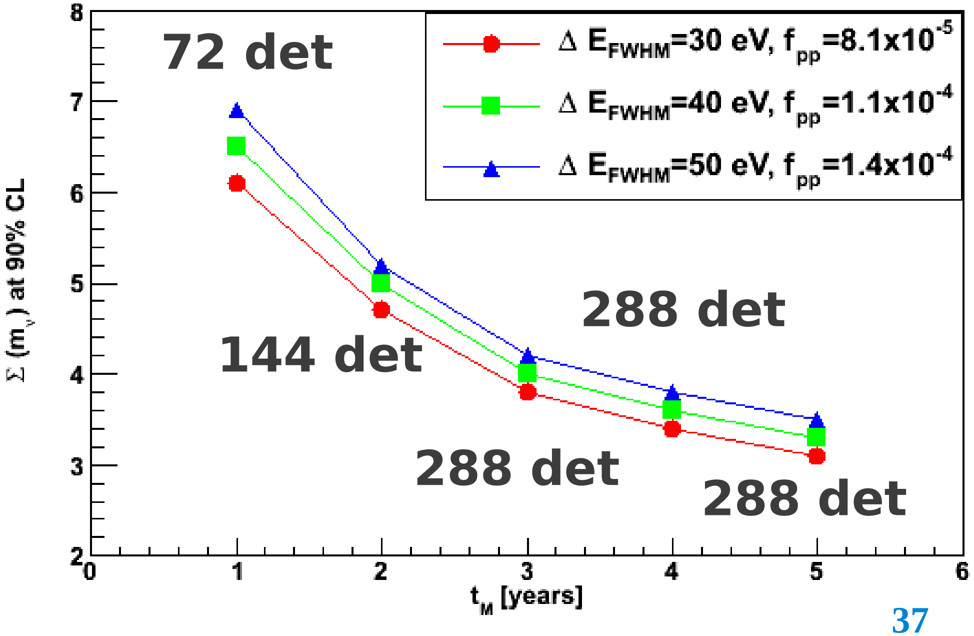
ΔE_{FWHM} ~ 50 eV e τ_R ~ 500 µs
1 year and 72 channels → $\Sigma(m_\nu)$ ~7eV
3 years and 288 channels → $\Sigma(m_\nu)$ ~ 4.2eV

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

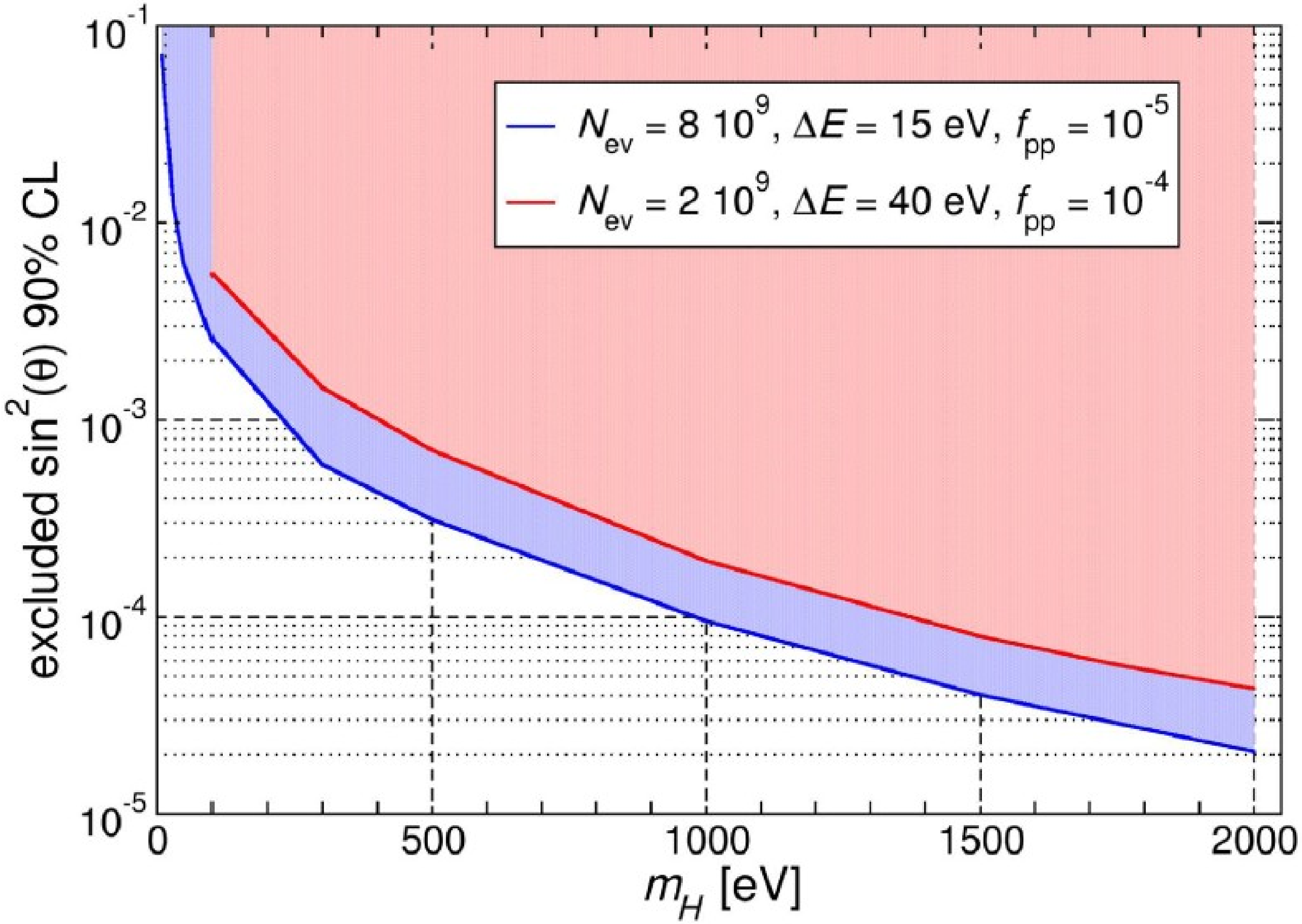
- setup designed for 8 arrays
- 288 $AgReO_4$ crystals
- now starting with 2 arrays (72 ch.)
- gradual deployment

Since only two arrays are installed 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.

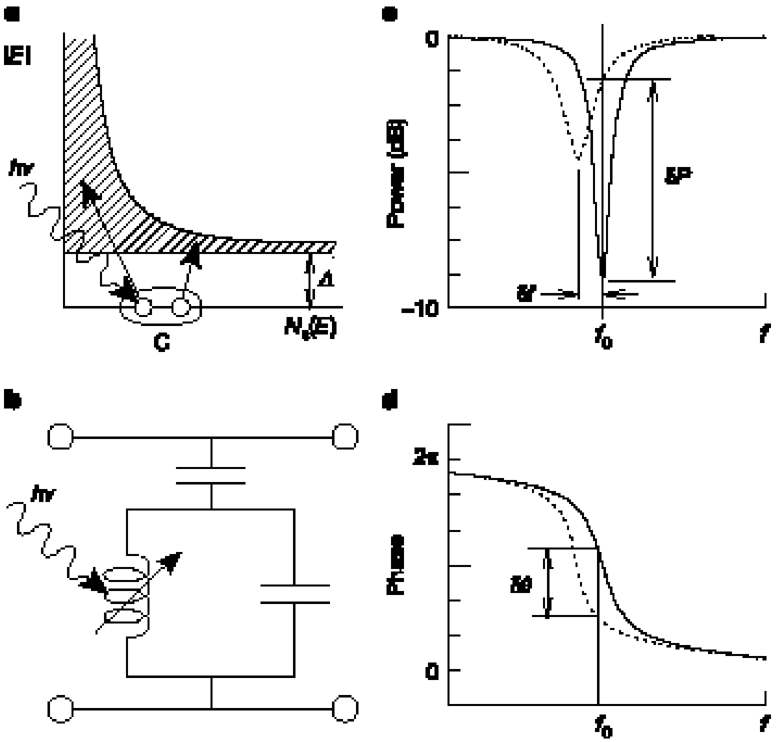
Analytic approach (1st order)

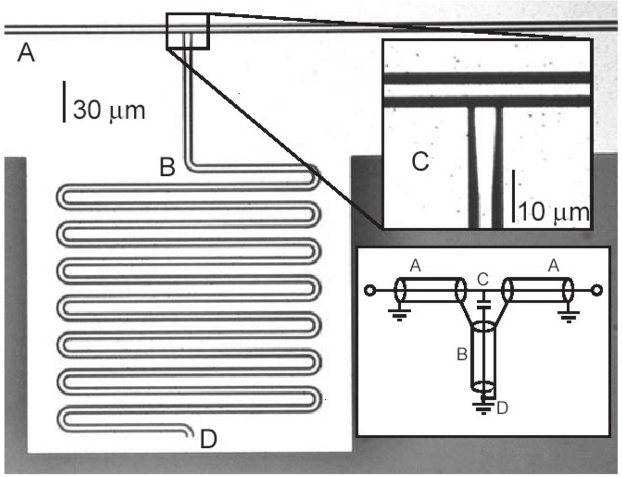


MARE 1 @ Milano-Bicocca and heavy neutrinos



MKDs R&D @ Milano-Bicocca





- resonator exploiting the *T* dependence of inductance in a superconducting film
  - **up detectors** suitable for large absorbers
  - **fast** devices for high single pixel activity A_b and 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

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

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

- **KIDs developed for astrophysics**
- **application to bulky absorber still requires further efforts**

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

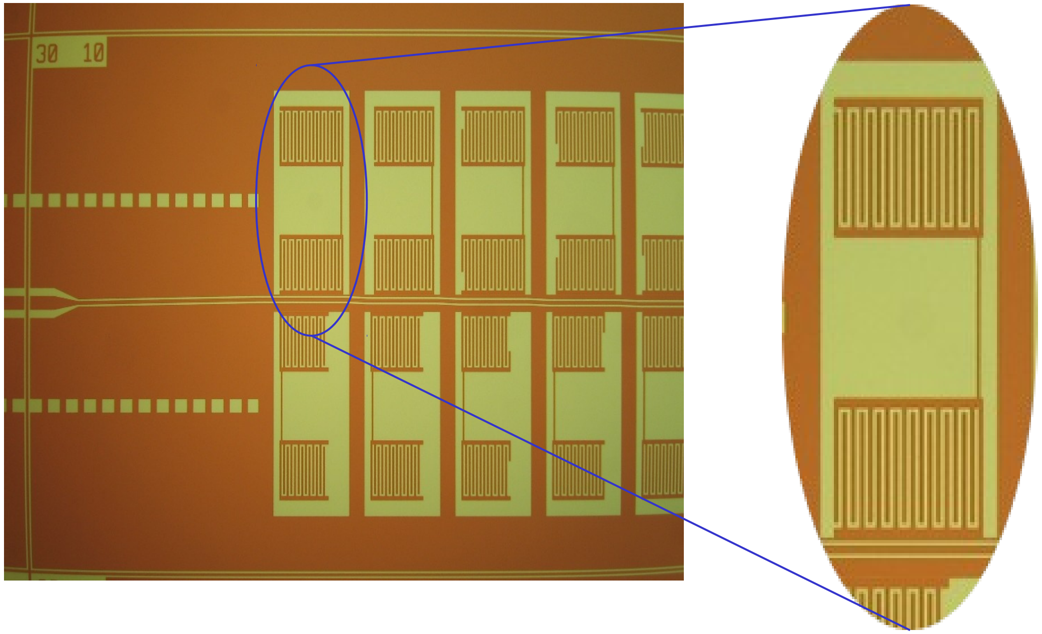
The length of the inductive section is much shorter than the wavelength at resonator frequency, ensuring uniform response.

The ^{163}Ho will be embedded in the inductive part of the resonator. 10^{12} Ho nuclei are needed for a count rate of 10 Hz

The Ho needs to be deep enough to ensure low escape probability for 2 keV electrons.

But very thick films are difficult to grow

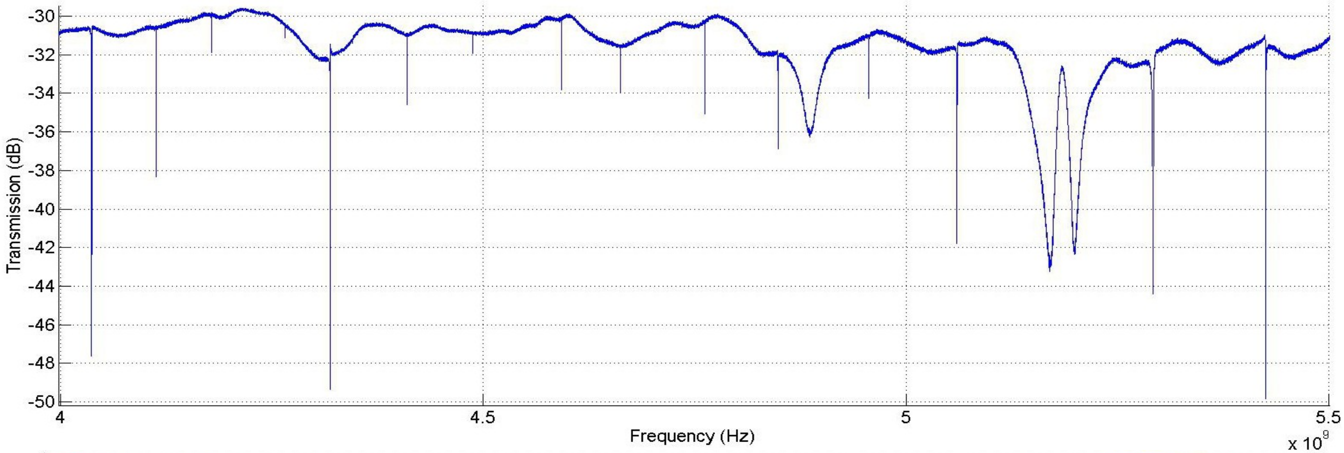
Nitrides with like TiN, TaN and HfN, will be investigated- A thickness of ~ 0.5μm can be enough

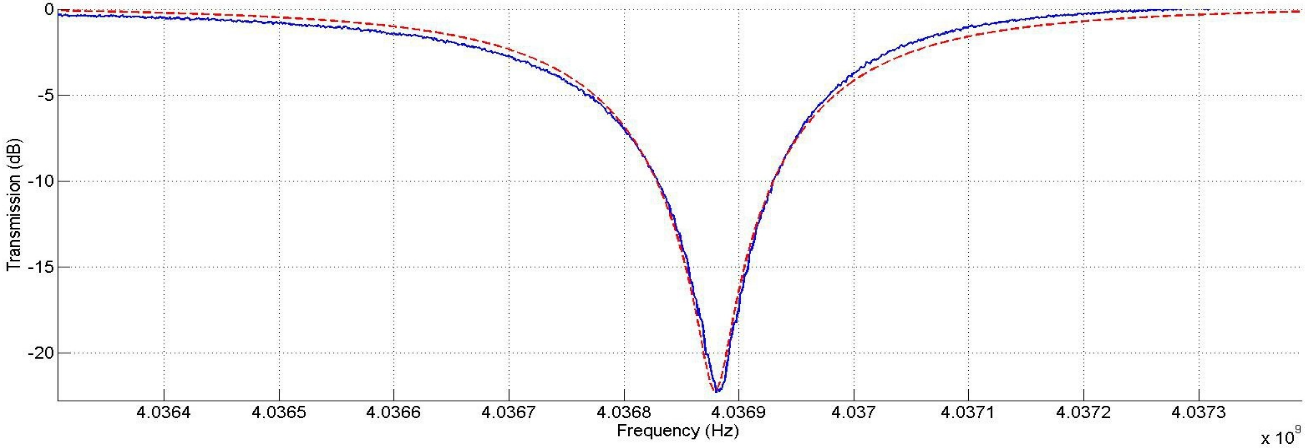


theoretical resolution

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

MKDs R&D @ Milano-Bicocca





Resonances can be fitted by the analytical formula:

$$T_{21} = C(f)\left[1 - \frac{Q/Q_c \, e^{i\phi_0}}{1 + 2jQ(\frac{f - f_0}{f_0})}\right]$$

- *Jiansong Gao, Fitting the resonance data from network analyzer, 2005,* (unpublished manuscript)

For our resonators, we obtained Q = 7x10^4÷10^5 and Q$_c$ = 10^5÷10^6. Consequently, since $Q^{-1}=Q_c^{-1}+Q_i^{-1}$, Q_i = 2x10^5÷ 4x10^5

Sweeping the temperature from 30mK up to ~1K it is possible to extract the gap parameter. For TiN a gap parameter of 0.7 meV has been measured, wich, accordingly to the BCS theroy, means T_c ~ 4.6K.

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 are in progress to
    - improve the understanding of ^{187}Re experiment systematics
        - a few eVs light neutrino sensitivity ^{187}Re experiment is starting soon
    - investigate ^{163}Ho decay spectrum
        - ^{163}Ho isotope has been produced and is ready for first tests
    - develop the single MARE pixel
        - R&D for coupling TES, MMC and MKID with ^{187}Re/^{163}Ho is in progress
    - implement read-out multiplexing schemes
- isotope and technique selection for MARE-2 is in progress