the MARE project

Angelo Nucciotti
Dipartimento di Fisica "G. Occhialini", Università di Milano-Bicocca
INFN - Sezione di Milano-Bicocca

- direct neutrino mass measurement
  - spectrometers vs. calorimeters
  - calorimeter statistical sensitivity
- ^{187}Re calorimetric experiment state-of-the-art
  - know systematics
- future of calorimetric experiments: the MARE project
- MARE project status
  - MARE-1
  - MARE R&D

Wisconsin University, Madison, July 27th, 2009

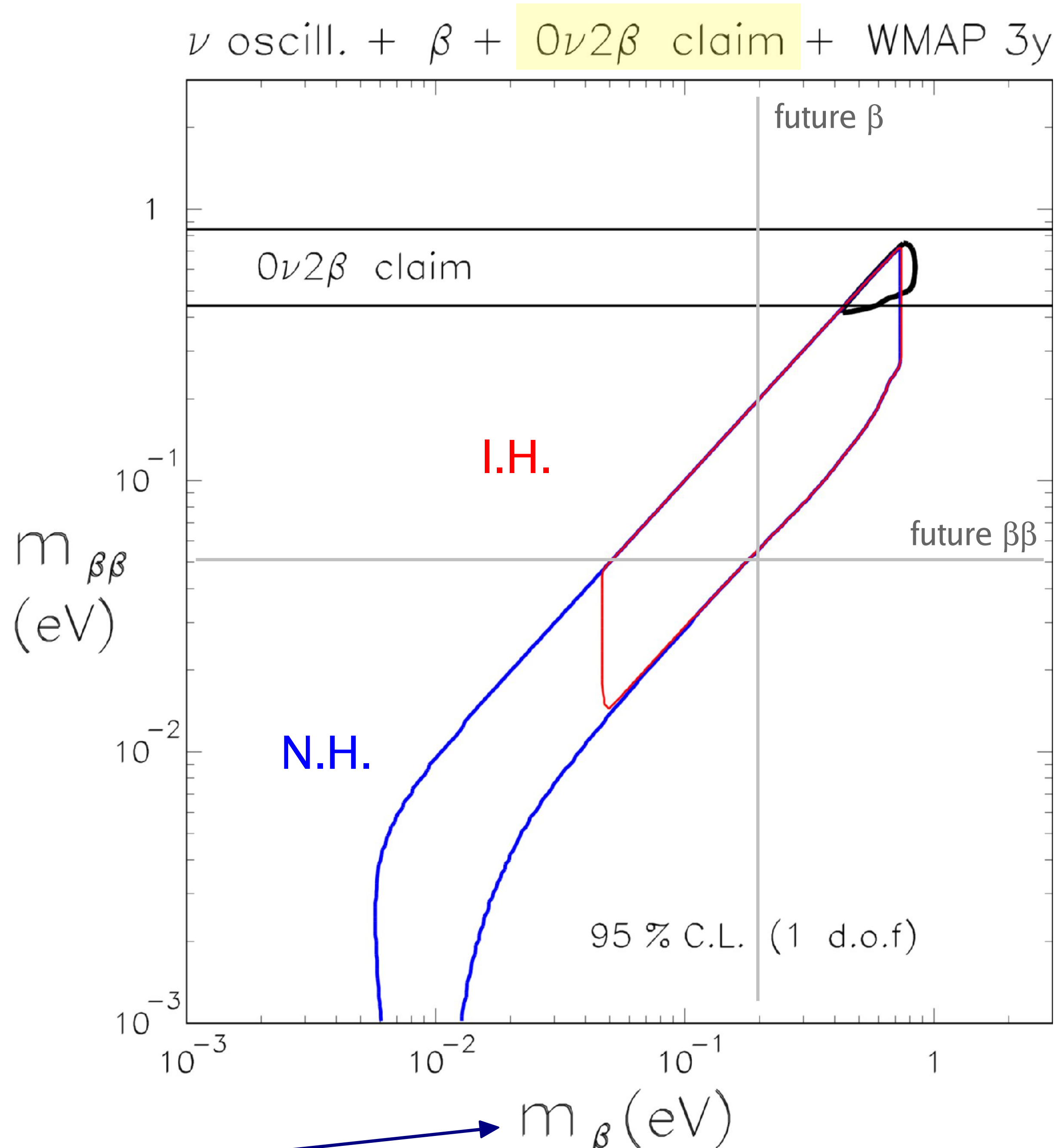
Neutrino mass measurements

tool	measured quantity	present sensitivity	future sensitivity		
Cosmology CMB+LSS	$m_\Sigma \equiv \sum m_i$	0.7÷1 eV	0.05 eV	yes	large
Neutrinoless Double Beta decay	$m_{\beta\beta} \equiv \lvert \sum m_i U_{ei}^2 \rvert$	0.5 eV	0.05 eV	yes	yes
Beta decay end-point	$m_\beta \equiv (\sum m_i^2 \lvert U_{ei} \rvert^2)^{1/2}$	2 eV	0.2 eV	no	large

model dependency

systematic uncertainties

Neutrinos masses in single β and ββ-0ν decays



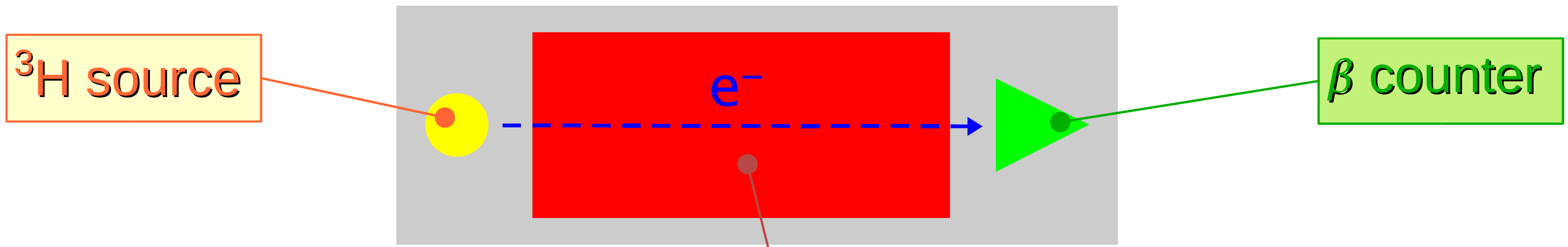
$m_{\beta\beta} \equiv \langle m_\nu \rangle$ from **$\beta\beta$-0ν**

$m_\beta \equiv m_\nu$ from ***β*** **decay**

Fogli et al. hep-ph/0608060

Experimental approaches for direct measurements

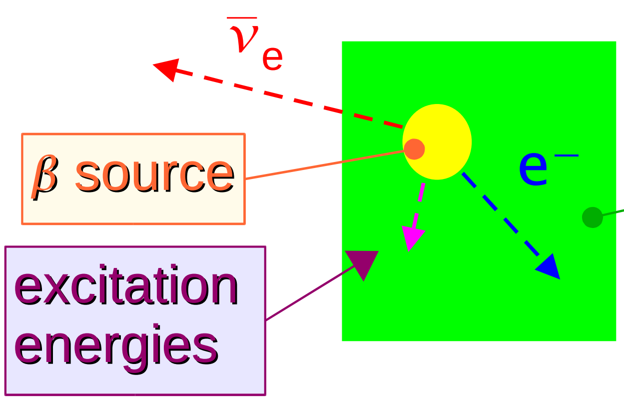
Spectrometers: source ≠ detector



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

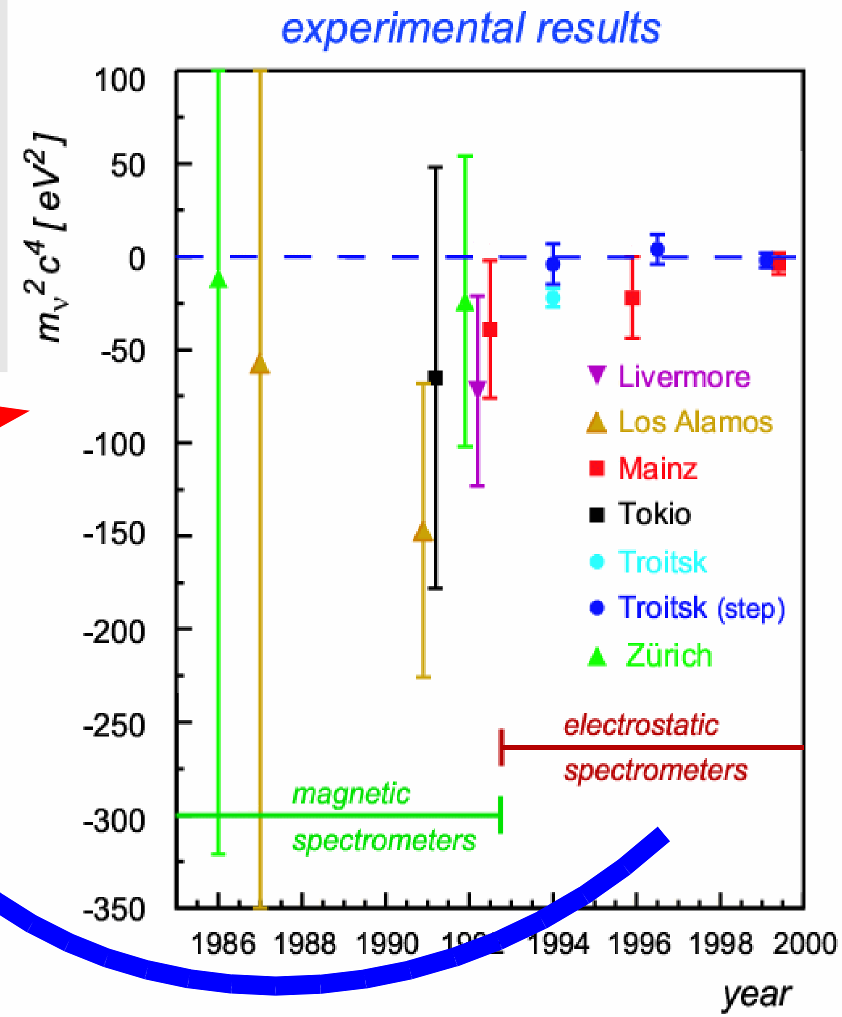


β calorimeter

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

Spectrometers present results

- **Spectrometer advantages**
  - high statistics
  - high energy resolution
- **Spectrometer drawbacks**
  - systematics due to source effects
  - systematics due to decays to excited states
  - background



electrostatic spectrometers

- **Mainz** with solid ^3H source
- **Troitsk** with gaseous ^3H source
  - $m_{\nu e} < 2.2$ eV 95% CL

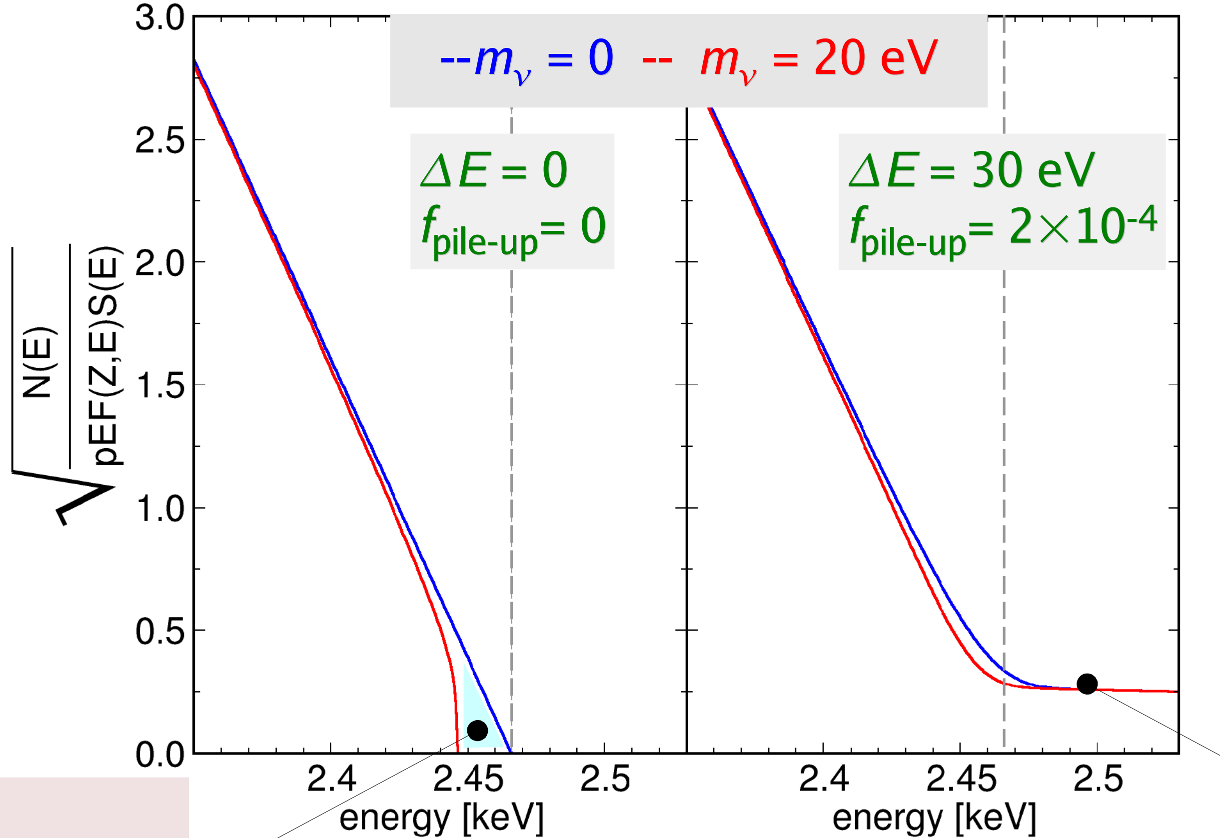
KATRIN

- large electrostatic spectrometer with gaseous and solid ^3H sources
  - expected statistical sensitivity **$m_{\nu e} < 0.2$ eV 90% CL**

Calorimetry of beta sources

- calorimeters measure the entire spectrum at once
  - use low E_0 β decaying isotopes to achieve enough statistics near the end-point
  - best choice ^{187}**Re**: $E_0 = 2.47$ **keV** $\Rightarrow F(\delta E{=}10\text{ eV}) \sim (\delta E/E_0)^3 = 7\times10^{-8}$

- **Calorimetry advantages**
  - no backscattering
  - no energy losses in the source
  - no atomic/molecular final state effects
  - no solid state excitation
- **Calorimetry drawbacks**
  - limited statistics
  - systematics due to pile-up
  - other systematics...



Pile-up
- time unresolved superposition of β decays
- for a source activity A_β, a time resolution τ_R and an energy resolution function $R(E)$

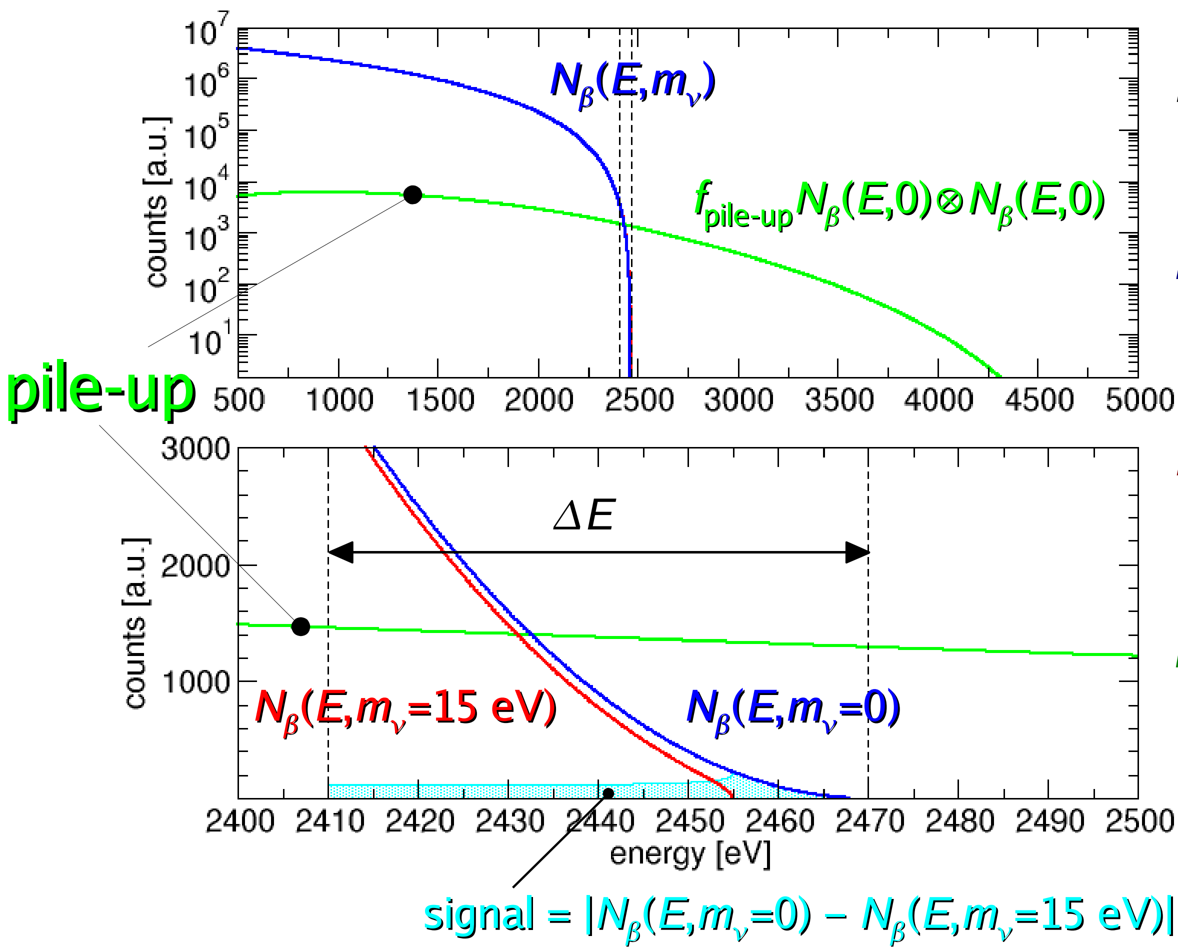
$$N^{\text{exp}}(E) \approx (N(E) + \tau_R A_\beta \cdot N(E)\otimes N(E)) \otimes R(E)$$

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

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

Calorimetric experiment statistical sensitivity / 1

resolving time τ_R analysis interval ΔE
source activity A_β number of detectors N_{det}
experimental exposure $t_M = T \times N_{det}$



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

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

$$F_{\Delta E}(m_\nu) \approx F_{\Delta E}(0)\left(1 - \frac{3m_\nu^2}{2\Delta E^2}\right)$$

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

$$\approx 0.3\,\tau_R A_\beta^2 N_{det} \frac{\Delta E}{E_0}$$

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

Calorimetric experiment statistical sensitivity / 2

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

$$\Sigma_{90}(m_\nu) \approx 1.13 \sqrt[4]{\frac{E_0^3 \Delta E}{A_\beta t_M N_{det}} + 0.3 \frac{\tau_R E_0^5}{t_M N_{det} \Delta E}}$$

Optimal energy interval ΔE

$$\Delta E = max\left(0.56 E_0 \sqrt{\tau_R A_\beta},\ \Delta E_{FWHM}\right)$$

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

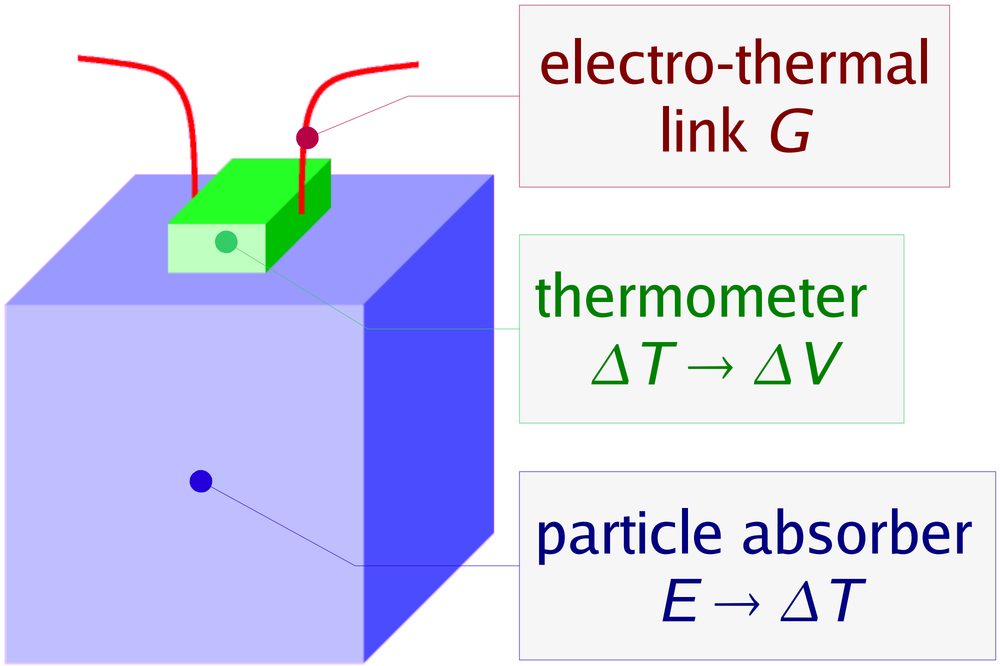
$$\Sigma_{90}(m_\nu) \approx 0.89 \sqrt[4]{\frac{E_0^3 \Delta E}{A_\beta t_M}}$$

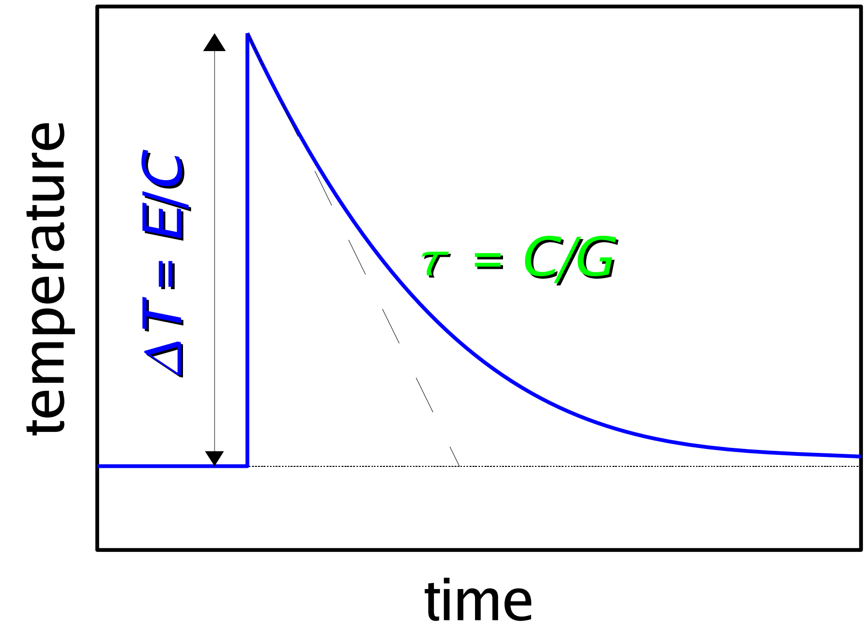
$$\Delta E \approx \Delta E_{FWHM}$$

experimental challenges

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

Cryogenic detectors as calorimeters





- **1 mg of Re @ 100 mK**
  $C \sim T^3$ (Debye) $\Rightarrow C \sim 10^{-13}$ 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

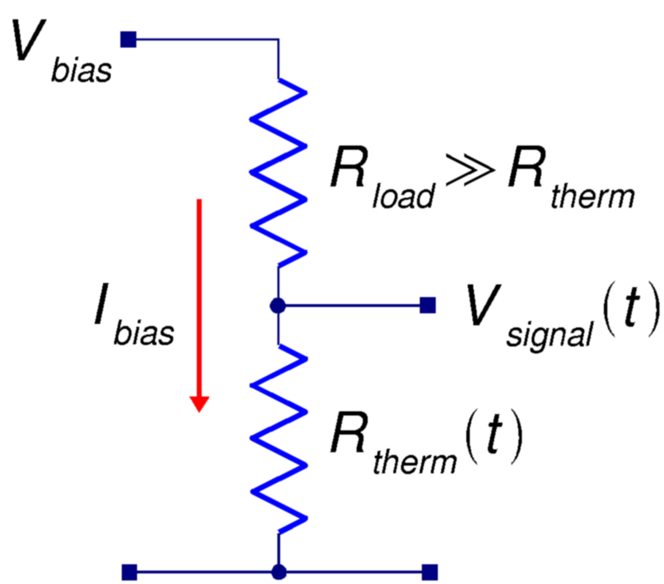
Resistive thermometers: thermistors

- **doped semiconductors** at Metal-Insulator-Transition (N_c=3.74×10[18] cm[-3] for Si:P)
- at $T \ll 10\text{K}$ → **phonon assisted variable range hopping** conduction (**VRH**)

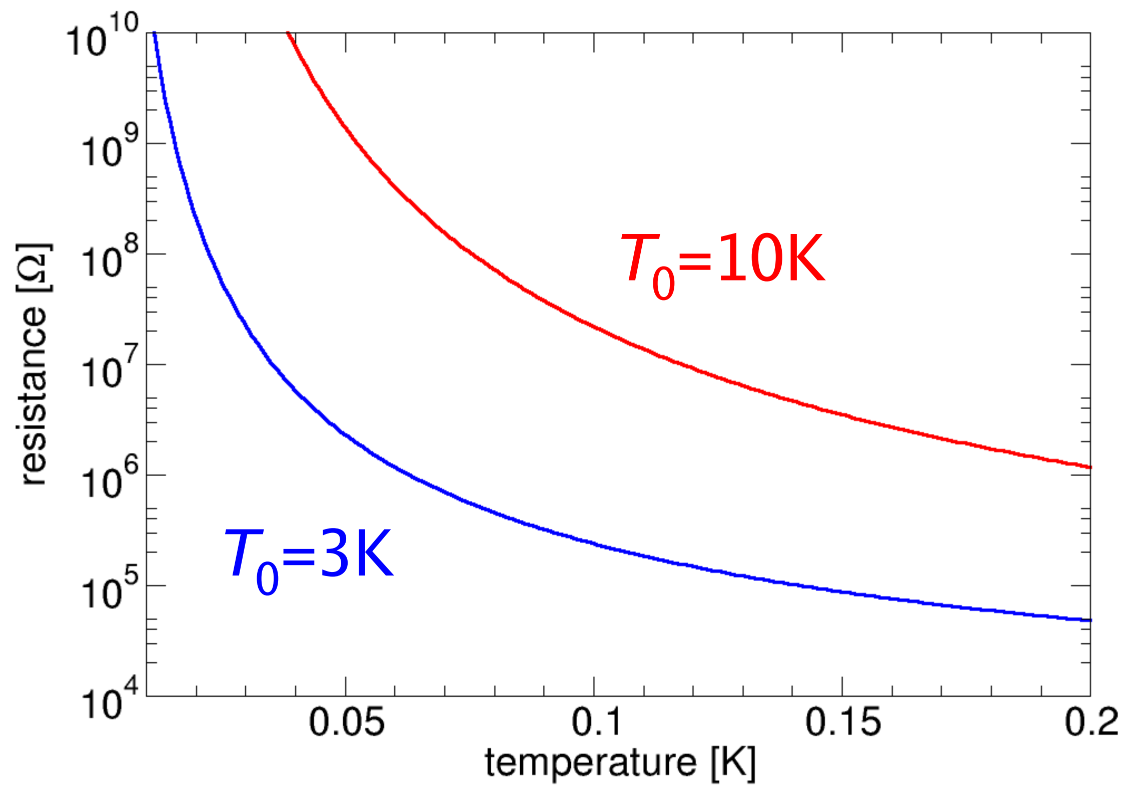
$$\rho(T) = \rho_0 \exp(T_0/T)^\gamma$$

- ▸ T_0 increases with decreasing net doping N
- ▸ $T < 1$ K ⇒ $\gamma = ½$ (VRH with Coulomb Gap)

Costant current bias



$\Delta E \Rightarrow \Delta T \Rightarrow \Delta R \Rightarrow \Delta V$



high impedance devices: R_{therm} = 1MΩ→100MΩ

Thermal detectors for calorimetric experiments

^{187}Re β decay

$$^{187}_{75}\mathrm{Re} \rightarrow ^{187}_{76}\mathrm{Os} + e^{-} + \bar{\nu}_e$$

- $5/2^{+} \rightarrow 1/2^{-}$ unique first forbidden transition $\Rightarrow S(E_\beta)$
- end point **E_0 = 2.47 keV**
  - 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 T_c=1.6K
  - NTD thermistors
  - **MANU experiment (Genova)**
- **dielectric rhenium compound** ($AgReO_4$) crystals
  - Silicon implanted thermistors
  - **MIBETA experiment (Milano)**

⇒ $m_\nu < \approx 15$ eV

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
  - ...?

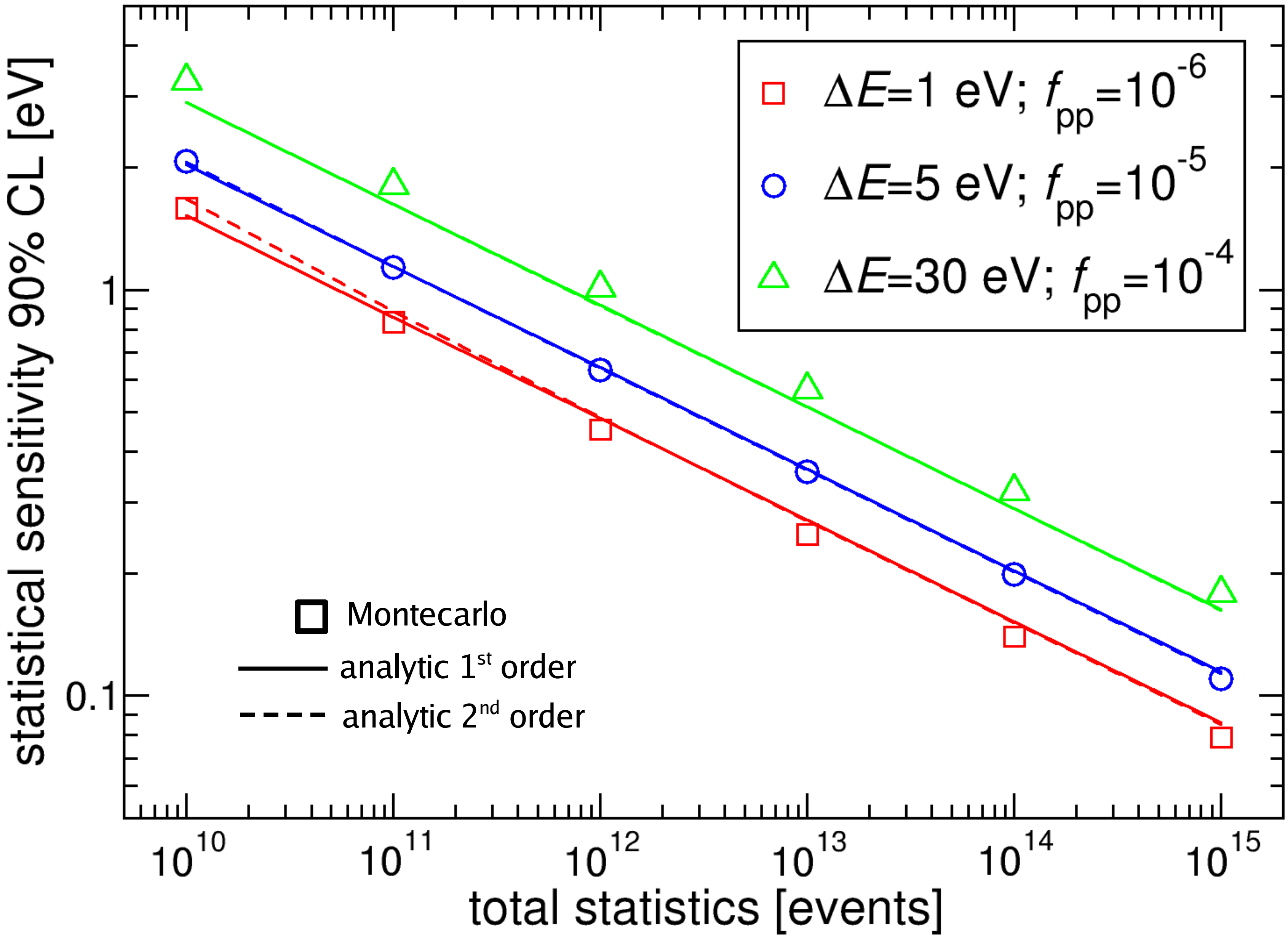
⇨ completely different systematics!

Montecarlo simulations: statistics and systematics

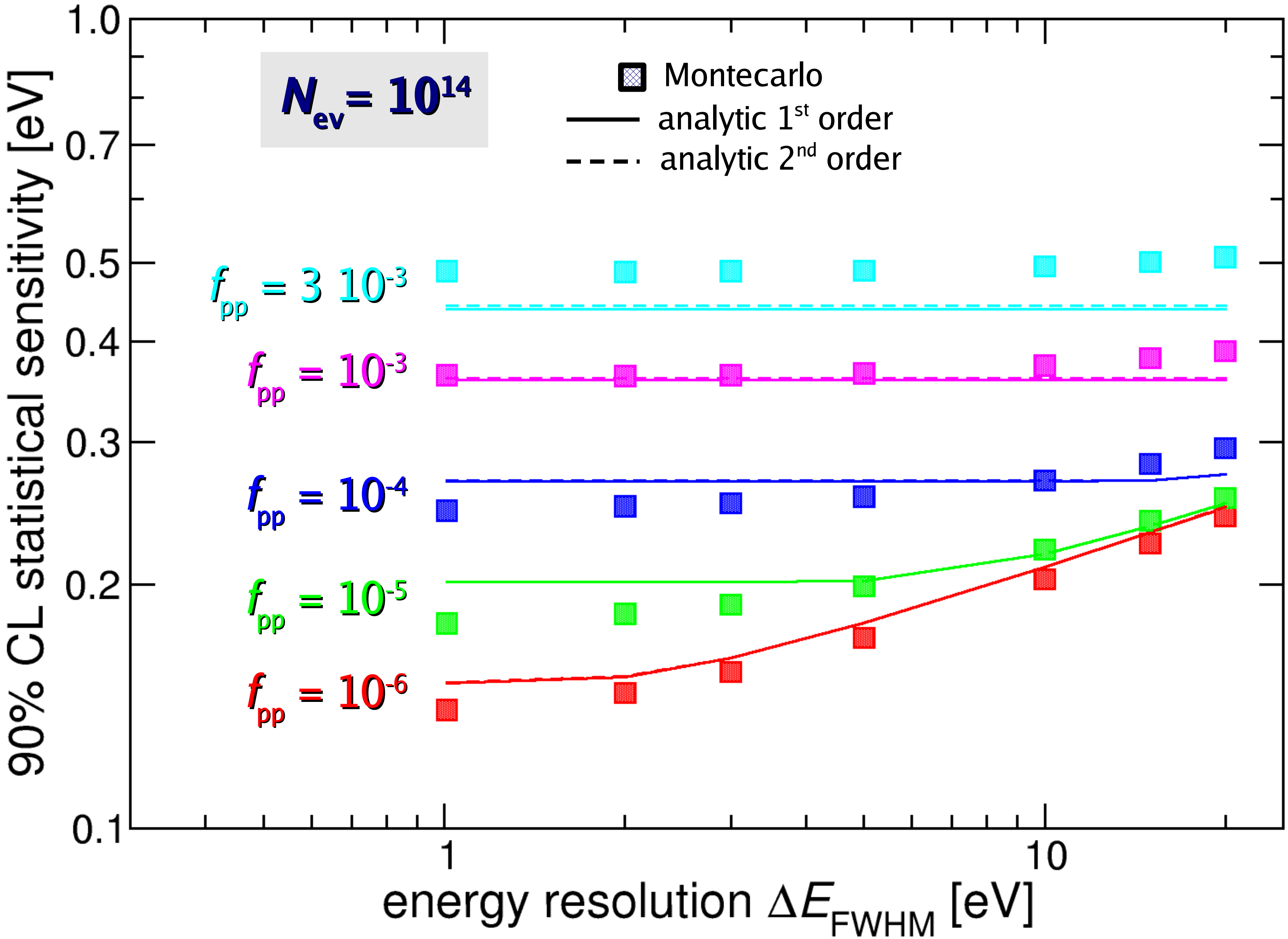
- generate many (500-1000) simulated experiments
  - calculate total β spectrum
  - $S(E) = (N_{ev}\ (N_\beta(E,0) + f_{pp} N_\beta(E,0) \otimes N_\beta(E\ 0)) + b(E)) \otimes g(E)$
    - N_{ev} total β statistics
    - $N_\beta(E,0)$ normalized ^{187}Re spectrum for $m_\nu = 0$
    - f_{pp} fraction of unresolved β pile-up events
    - $b(E)$ background (usually constant)
    - $g(E)$ detector energy resolution function (usually gaussian)
  - generate spectra introducing Poisson fluctuations in $S(E)$
  - fit the spectra with standard technique
  - obtain 90% C.L. m_ν sensitivity $\Sigma_{90}(m_\nu)$ from $\sqrt{(1.7\sigma)}$ of m_ν^2 distribution
- Montecarlo input parameters vs. real experiment parameters
  - $N_{ev} = N_{det}\ \ t_M\ \ A_\beta$
  - $f_{pp} \approx \tau_R\ \ A_\beta\ \ \ (\tau_R \approx \tau_{rise})$

- Assessing systematic uncertainties with Montecarlo simulations
  - generate simulated experimental spectra with systematic effect
  - analyze spectra without effect
  - obtain $\Sigma_{90}(m_\nu)$ and Δm_ν^2 as function of effect magnitude

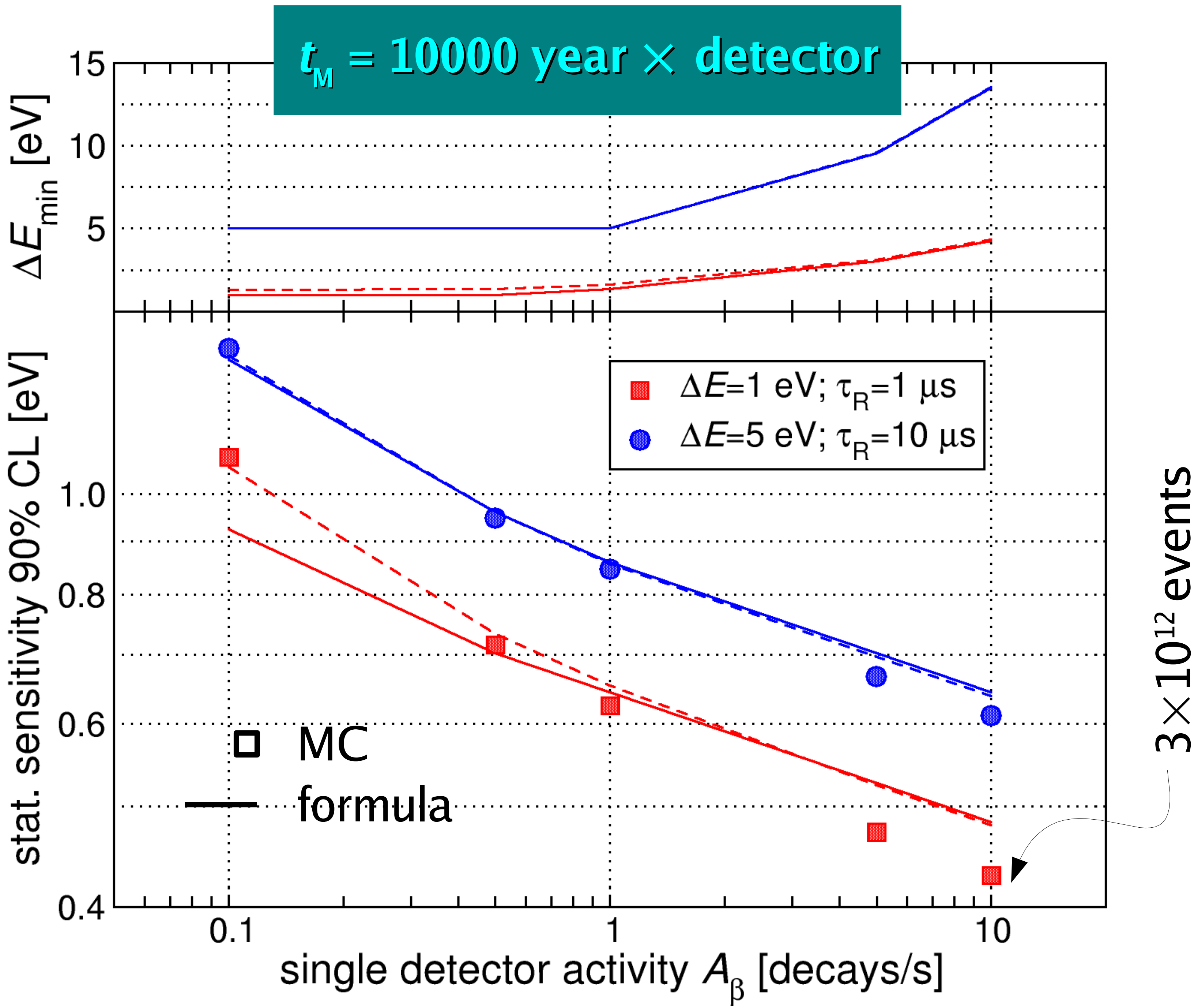
Sub-eV m_ν statistical sensitivity



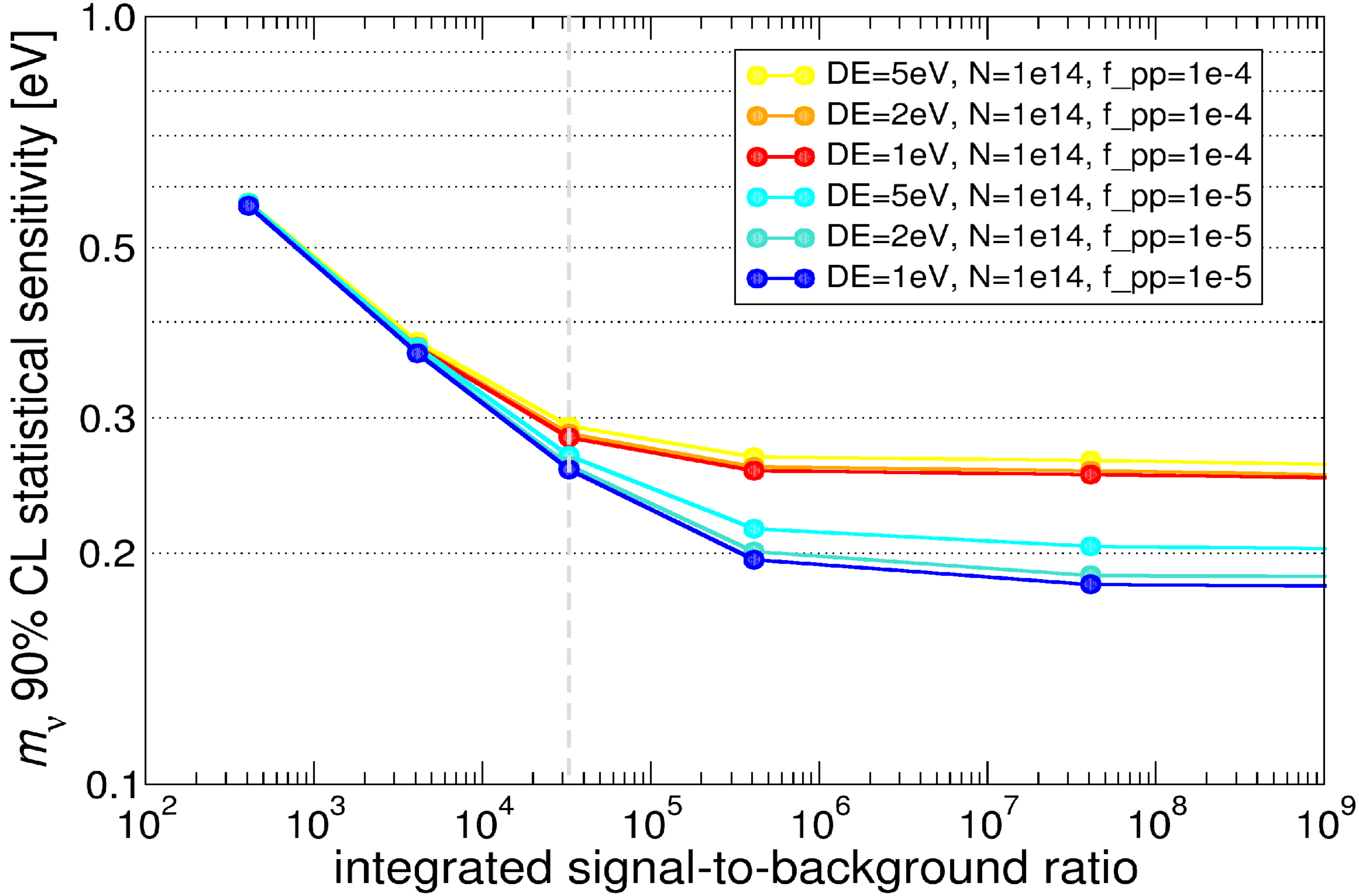
Sub-eV m_ν statistical sensitivity / 2



Sub-eV m_ν, statistical sensitivity / 3

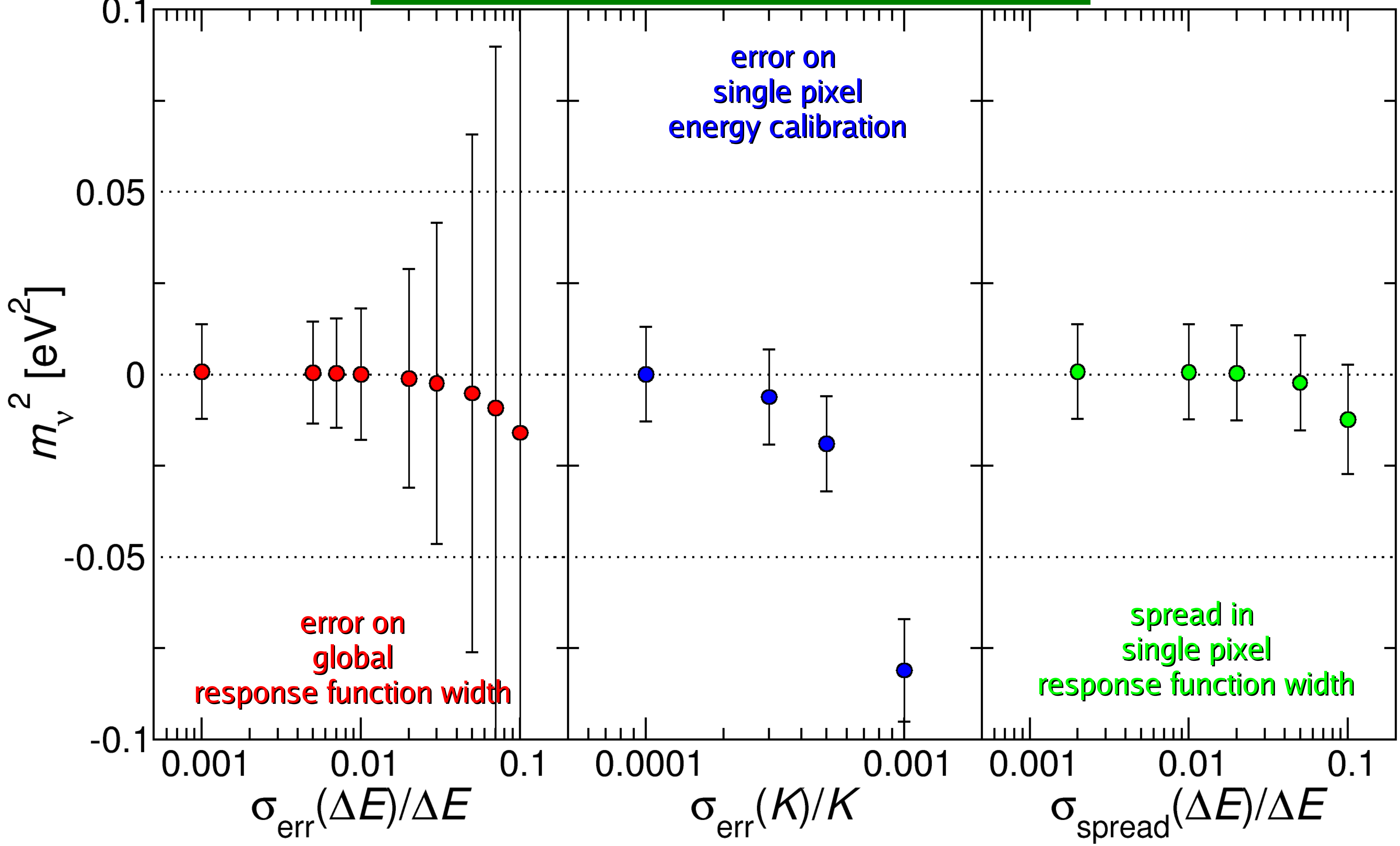


Effect of background on statistical sensitivity

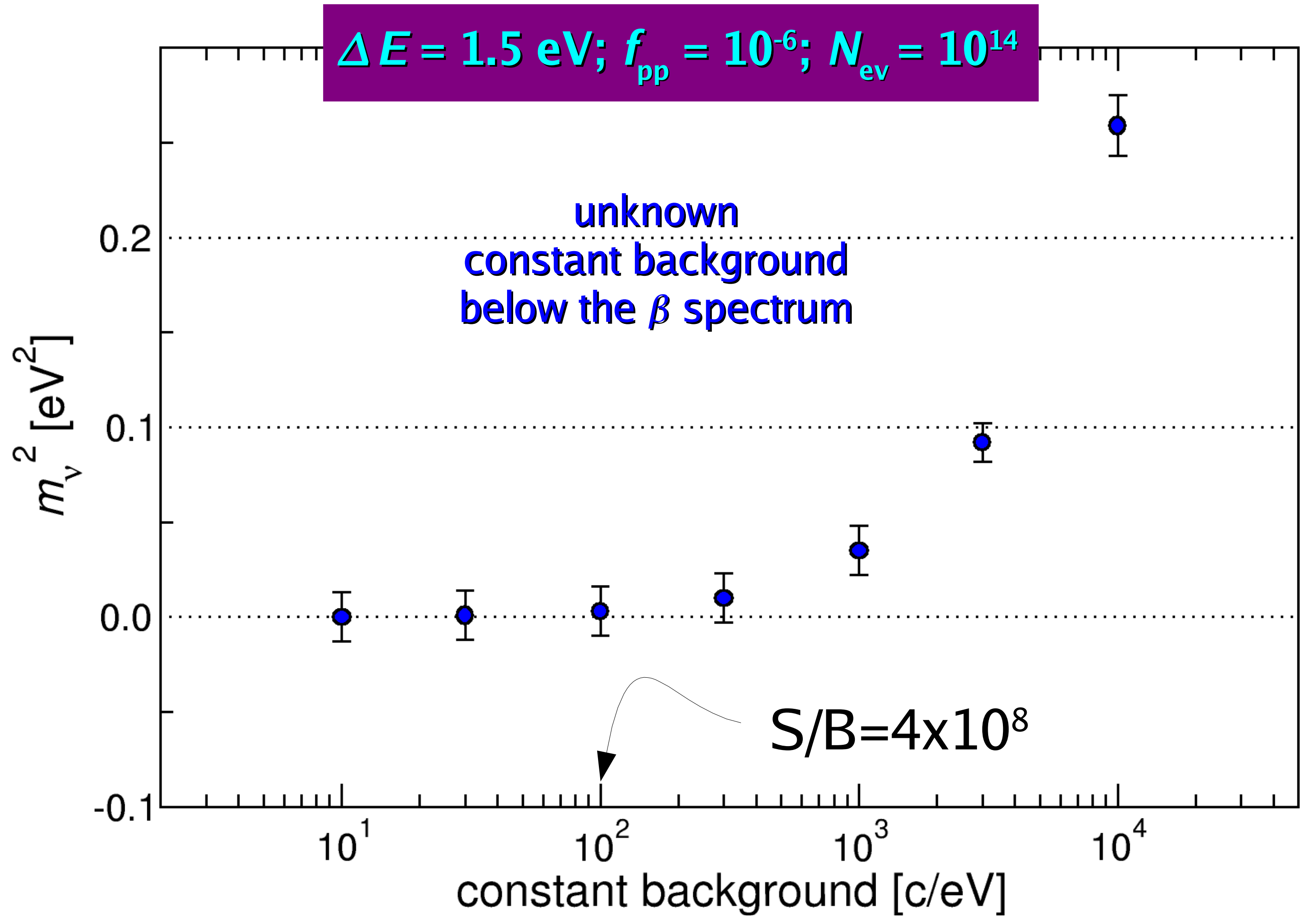


MC analysis of systematics: large arrays

ΔE = 1.5 eV; f_{pp} = 10^{-6}; N_{ev} = 10^{14}



MC analysis of systematics: more effects...



... and

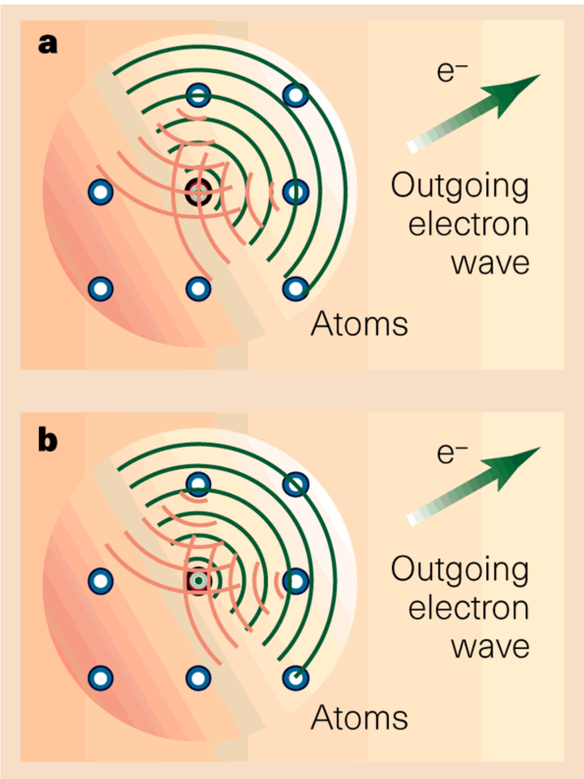
- linear term in background
- linear deviation from quadratic beta spectrum
- ...

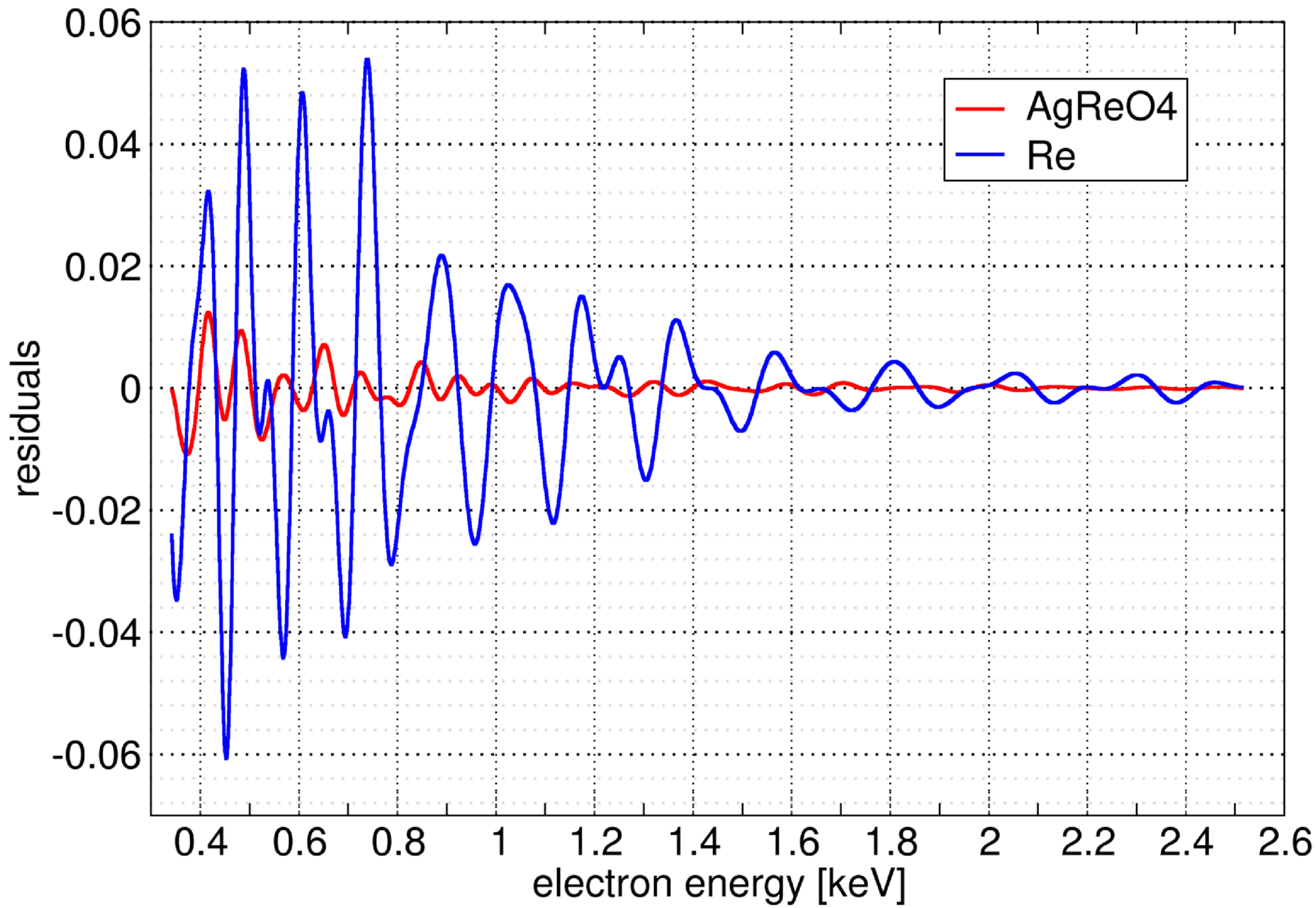
BEFS: Re vs. $AgReO_4$

BEFS: Beta Environmental Fine Structure

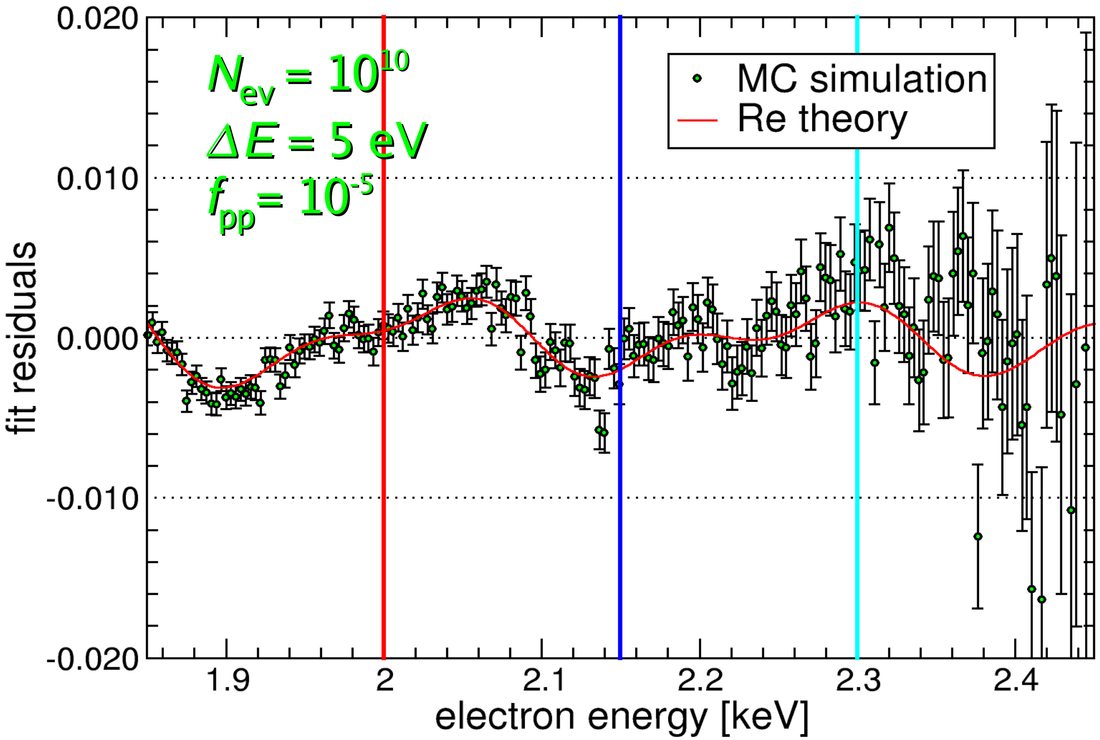
Modulation of the electron emission probability due to the atomic and molecular surrounding of the decaying nucleus: it is explained by the wave structure of the electron

(analogous of EXAFS)

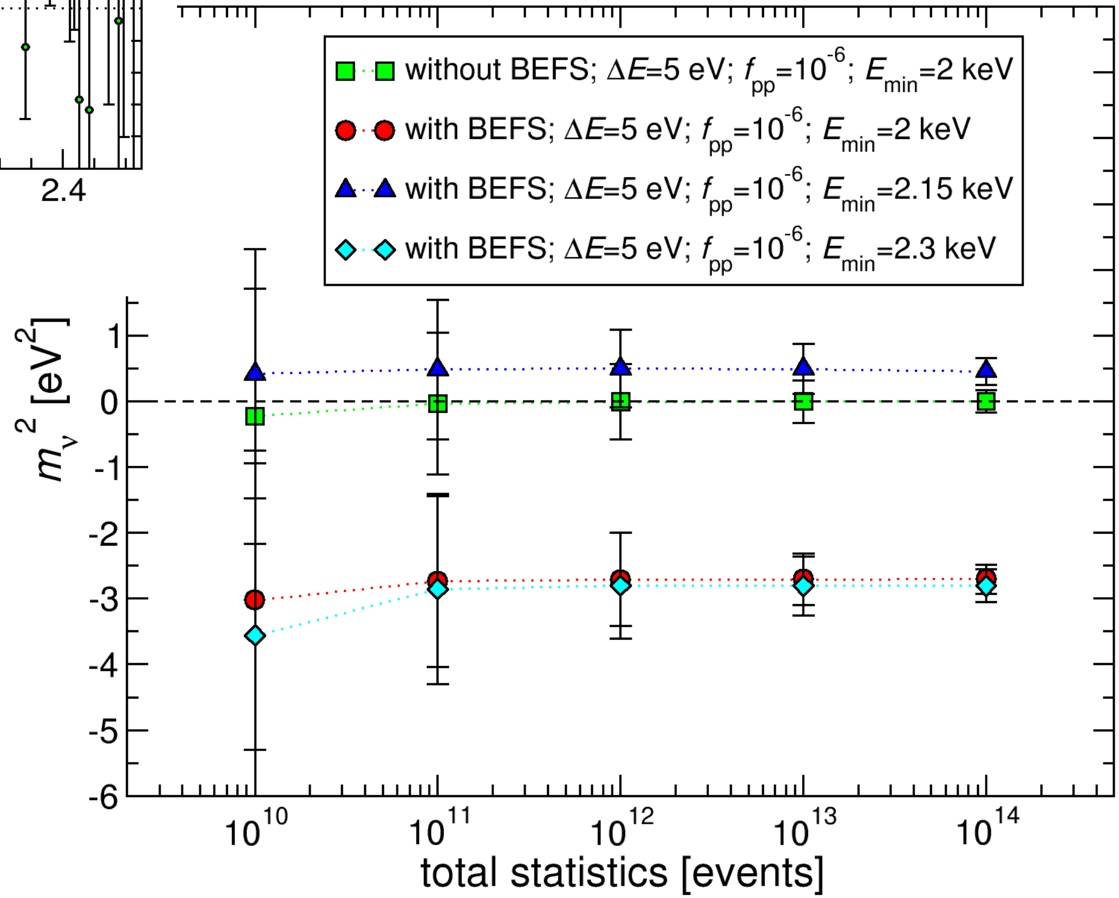




BEFS in MARE



$N_{ev} = 10^{10}$
$\Delta E = 5$ eV
$f_{pp} = 10^{-5}$
MC simulation
Re theory
fit residuals
electron energy [keV]
0.020
0.010
0.000
-0.010
-0.020
1.9
2
2.1
2.2
2.3
2.4



without BEFS; ΔE=5 eV; $f_{pp}=10^{-6}$; E_{min}=2 keV
with BEFS; ΔE=5 eV; $f_{pp}=10^{-6}$; E_{min}=2 keV
with BEFS; ΔE=5 eV; $f_{pp}=10^{-6}$; E_{min}=2.15 keV
with BEFS; ΔE=5 eV; $f_{pp}=10^{-6}$; E_{min}=2.3 keV
m_ν^2 [eV^2]
total statistics [events]
1
0
-1
-2
-3
-4
-5
-6
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}

Statistics and systematics summary

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	$3.3\ 10^{14}$	$10.5\ 10^5$

source of uncertainty	*quantity describing the uncertainty*	*maximum uncertainty for Δm_ν^2<0.01 eV^2*
error on energy resolution ΔE	$\sigma_{err}(\Delta E)/\Delta E$	0.02
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
underlying constant background	N_{bkg}/N_{ev}	10^{-8}

^{187}Re calorimetric experiment statistical sensitivity

$\Sigma(m_\nu) \approx$ **20 eV**

- MIBETA detectors with ΔE_{FWHM}= **30 eV**, τ_R=1.5 ms
  - ▷ for A_β = 0.15 decay/s → f_{pp}= 2×10^{-4}
  - ▷ t_M = 3.6 y×det → 1.6×10^{6} events
  - ▷ $\Sigma_{exp}(m_\nu)$= 15 eV

1/10

$\Sigma(m_\nu)$= **2 eV**

- detectors with ΔE_{FWHM}= **10 eV**, τ_R=100 μs
  - ▷ for A_β = 0.3 decay/s → f_{pp}= 3×10^{-5}
  - ▷ $\Sigma_{MC}(m_\nu)$= 2 eV with 2×10^{10} events
  - ▷ t_M = 2000 y×det

1/10

$\Sigma(m_\nu)$= **0.2 eV**

- detectors with ΔE_{FWHM}= **1 eV**, τ_R=1 μs
  - ▷ for A_β = 1 decay/s → f_{pp}= 10^{-6}
  - ▷ $\Sigma_{MC}(m_\nu)$= 0.2 eV with → 2.5×10^{13} events
  - ▷ t_M = 8×10^{5} y×det

A project for a New Rhenium Experiment: MARE

- goal: a sub-eV direct neutrino mass measurement complementary to the KATRIN experiment
- MARE-1
  - ▷ new experiments with large arrays using available technology and ready to start as soon as possible (i.e. 2008..2009)

Transition Edge Sensors
Semiconductor Thermistors → 300 element array → 2 ~ 4 eV m_ν sensitivity

- MARE-2
  - ▷ very large experiment with a m_ν statistical sensitivity close to KATRIN but still improvable: 5 years from now for further detector R&D

Transition Edge Sensors
Magnetic Calorimeters
Kinetic Inductance Detectors → 50000 element array → 0.2 eV m_ν sensitivity

MARE Project: interested institutions

MARE: Microcalorimeter Arrays for a Rhenium Experiment

Università di Genova e INFN Sez. di Genova
Goddard Space Flight Center, NASA, Maryland, USA
Kirkhhof-Institute Physik, Universität Heidelberg, Germany
Università dell'Insubria, Università di Milano-Bicocca e INFN Sez. di Milano-Bicocca
NIST, Boulder, Colorado, USA
ITC-irst, Trento e INFN Sez. di Padova
PTB, Berlin, Germany
University of Miami, Florida, USA
Università di Roma “La Sapienza” e INFN Sez. di Roma1
SISSA, Trieste
Wisconsin University, Madison, Wisconsin, USA
GSI Darmstad, Caltech, CNRS Grenoble, ...

funded R&D

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

MARE-1: TES vs. silicon implanted thermistors

- **aim**: high statistics measurement with a *ready-to-use* technology
  - ▷ few eV statistical sensitivity in few years
  - ▷ investigate systematics in thermal calorimeters with $10^9 \div 10^{10}$ events
  - ▷ cross-check spectrometer results

MARE-1 SEMICON (MIBETA2)

U. Milano-Bicocca / INFN Sez. Mi-Bicocca
U. Insubria / INFN Sez. Mi-Bicocca
ITC-Irst / INFN Sez. Padova
U. Wisconsin, Madison
NASA/Goddard

- ○ about 300 element arrays
- ○ well known Si implanted thermistors
- ○ $AgReO_4$ crystals

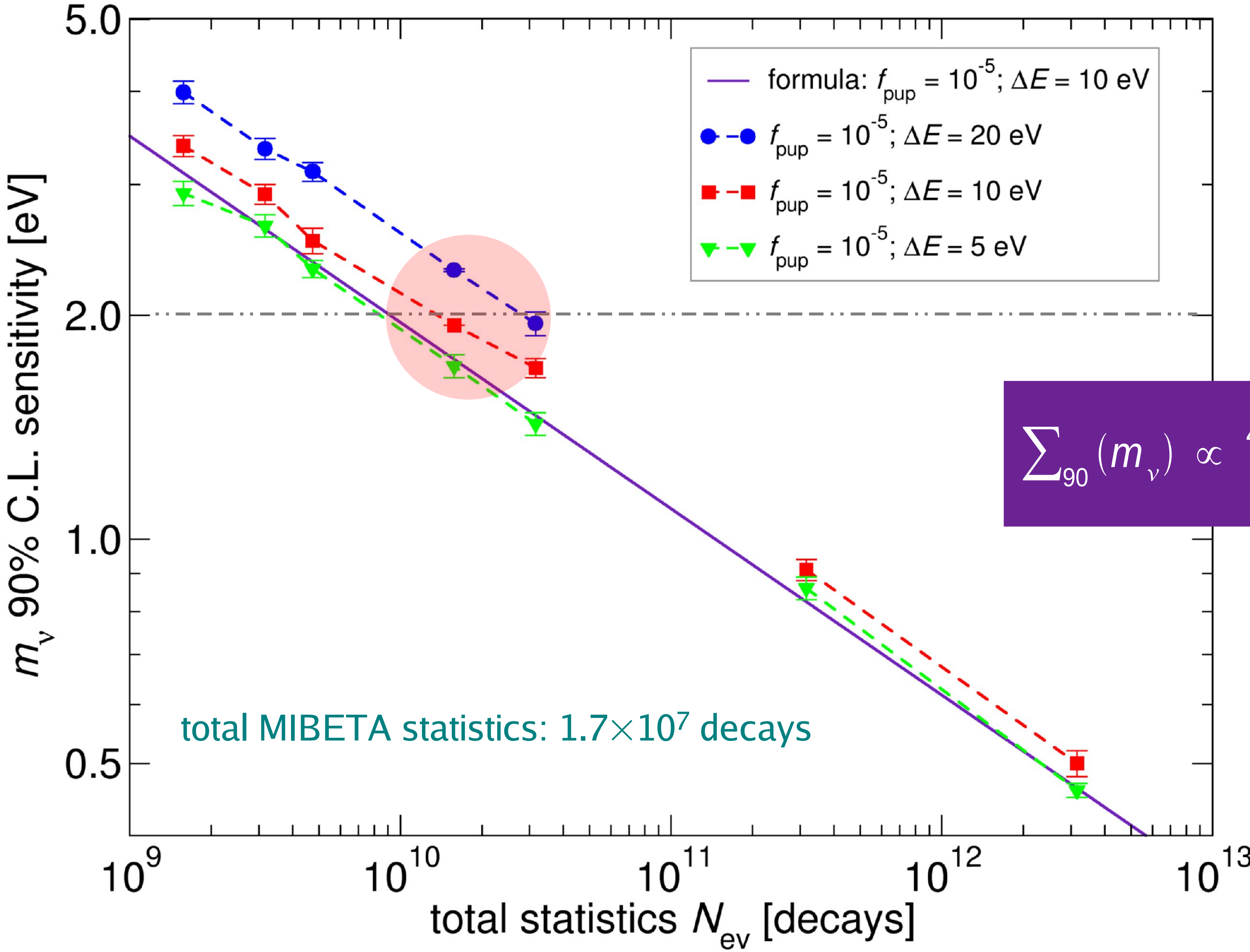
MARE-1 TES (MANU2)

U. Genova / INFN Sez. Genova
U. Miami, Florida
PTB Berlin, Germany

- ○ about 300 element arrays
- ○ newly developed transition edge sensors
- ○ Re crystals

- ▷ cross check
- ▷ common effort on systematics
- ▷ joint analysis to improve limit

MARE-1: MC simulations vs. formula



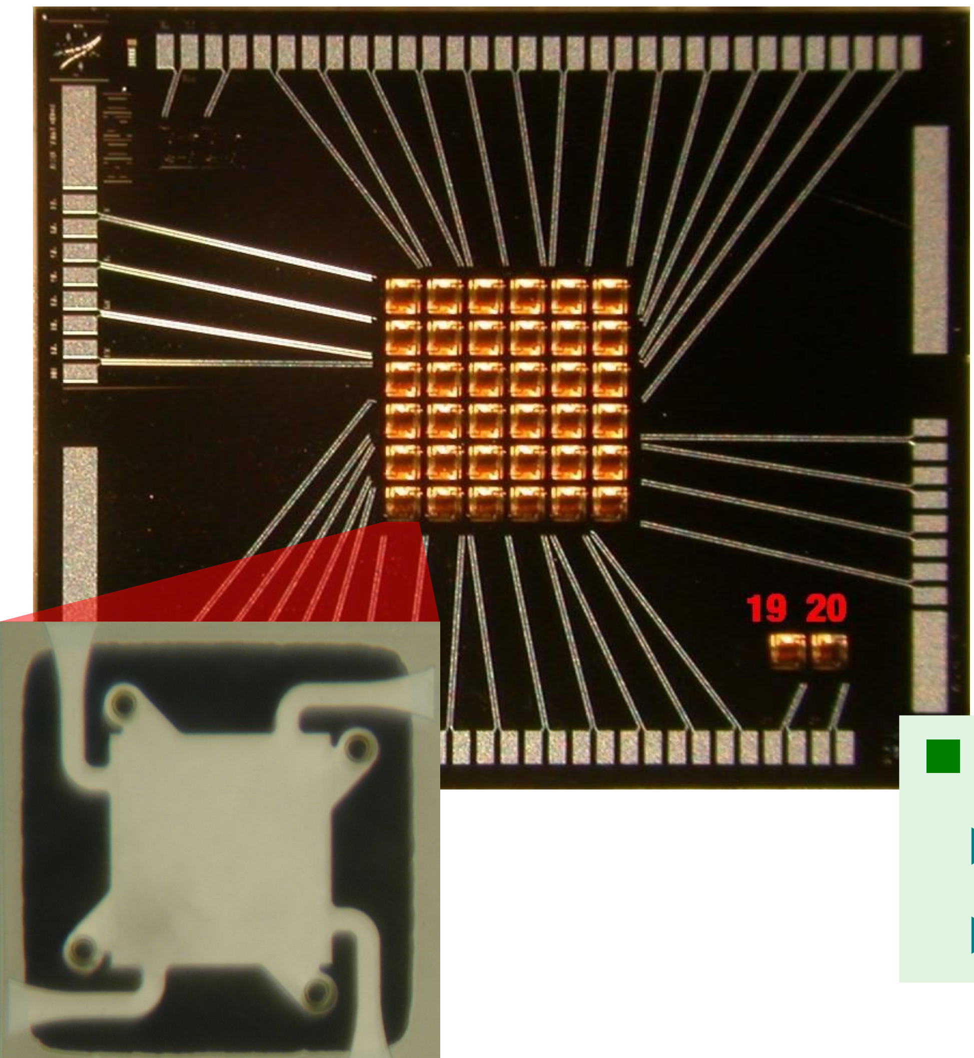
$$\sum_{90}(m_\nu) \propto \sqrt[4]{\frac{1}{N_{ev}}}$$

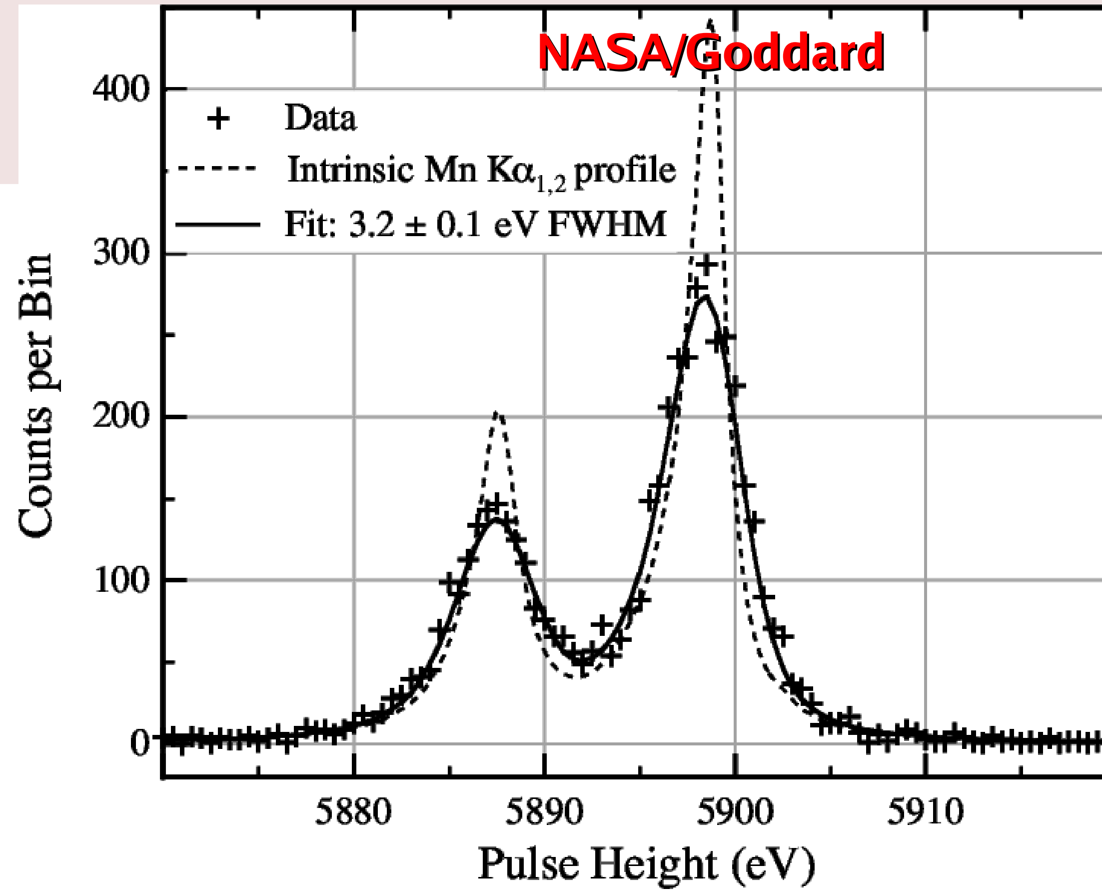
MARE-1 SEMICON: the NASA/Goddard XRS2 array

6×6 array: optimized for X-ray spectroscopy → ASTRO-E2 mission

detectors: silicon implanted thermistor with HgTe absorber at $T = 60$ mK

- ▷ $C_{tot} \approx 10^{-13}$ J/K
- ▷ $\Delta E_{theory} = 2$ eV



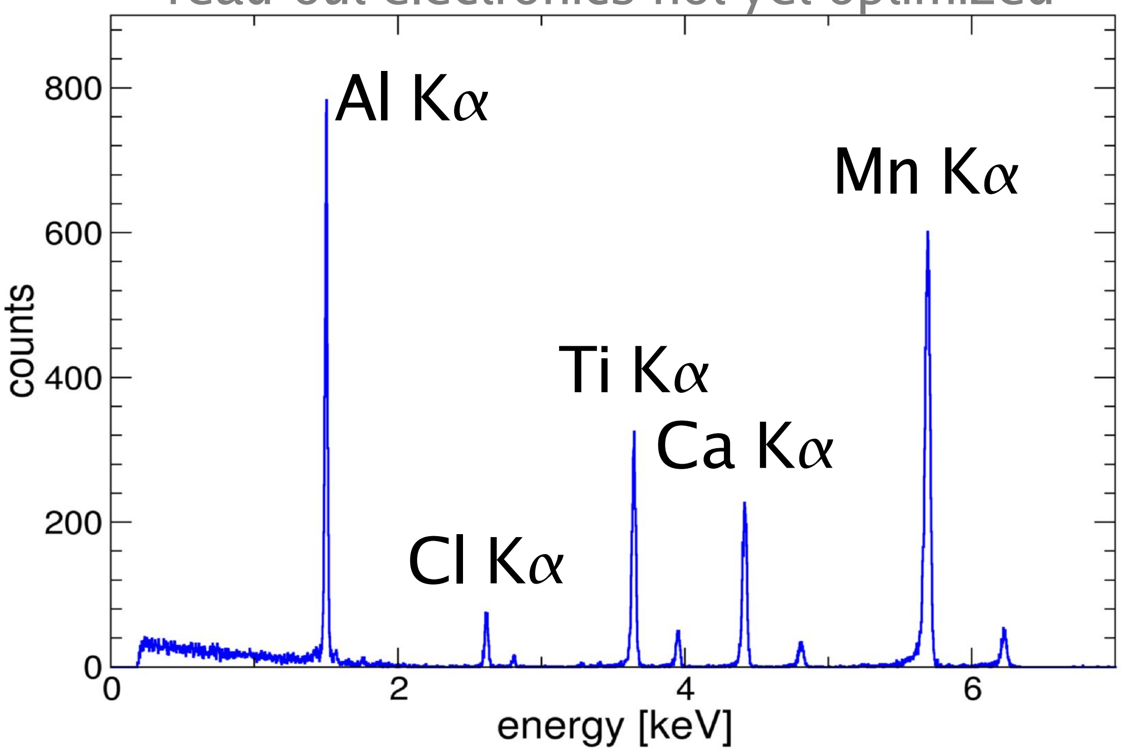


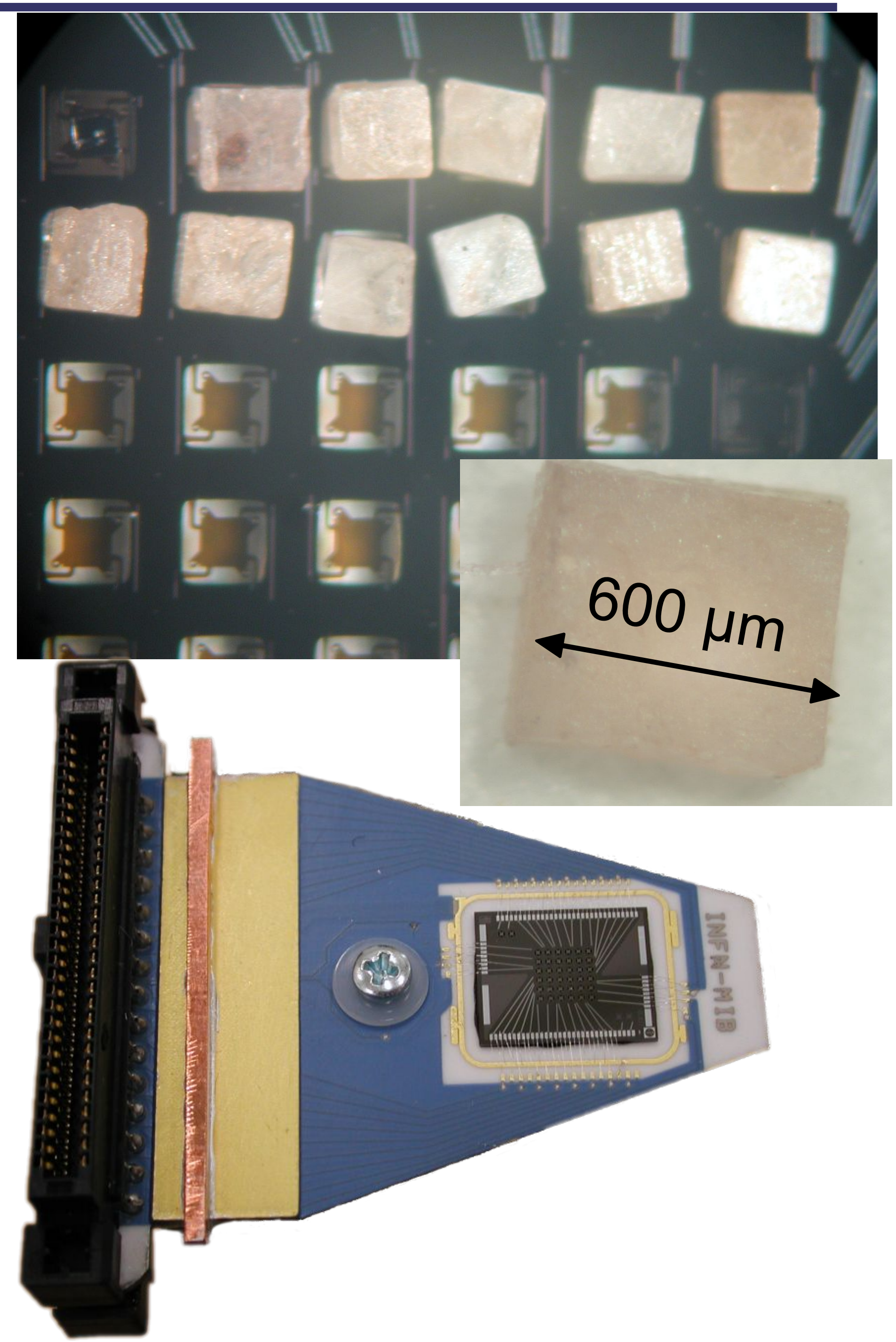
- **MARE-1 SEMICON detectors**
  - $AgReO_4$ has larger heat capacity
  - operating temperature must be higher

MARE-1 SEMICON

- NASA/GSFC XRS2-2 arrays
  - ▷ 6x6 pixels
- flat $AgReO_4$ single crystals
  - ▷ $m \approx 0.5$ mg
- detector R&D phase results
  - ▷ best operating $T \approx$ 90mK
  - ▷ **$\Delta E \approx$ 30 eV, $\tau_R \approx$ 250 μs**

read-out electronics not yet optimized

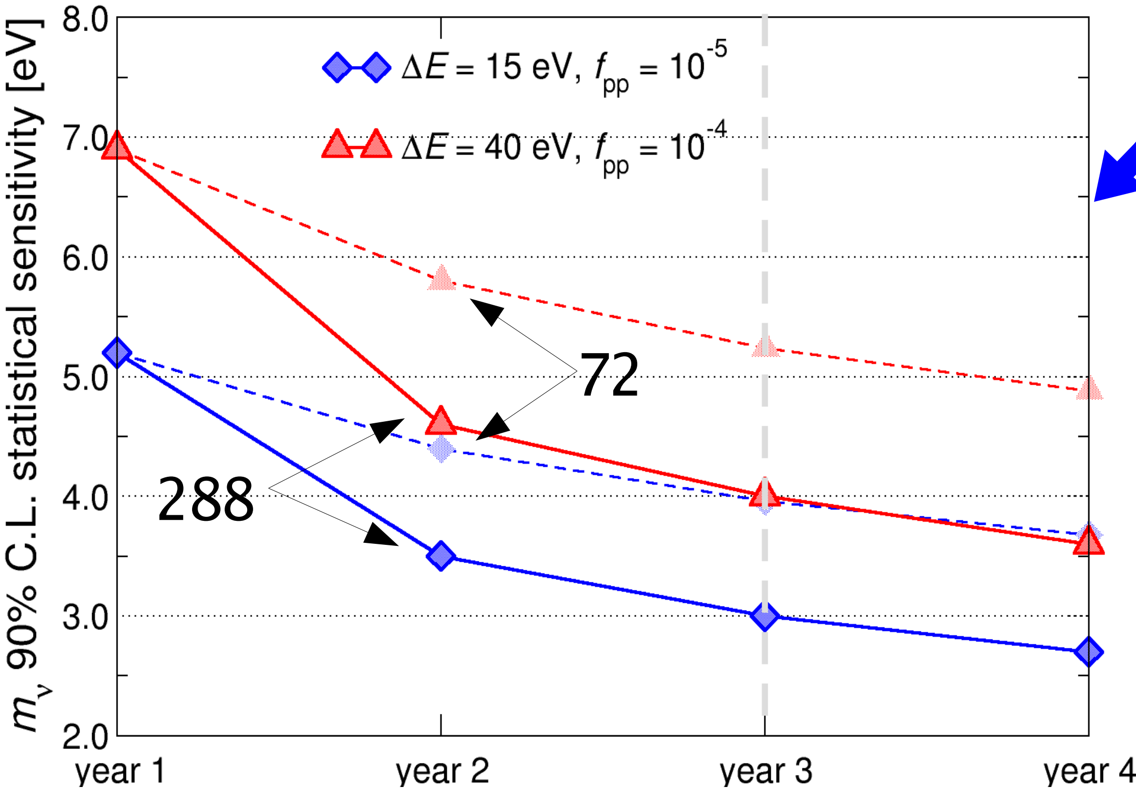


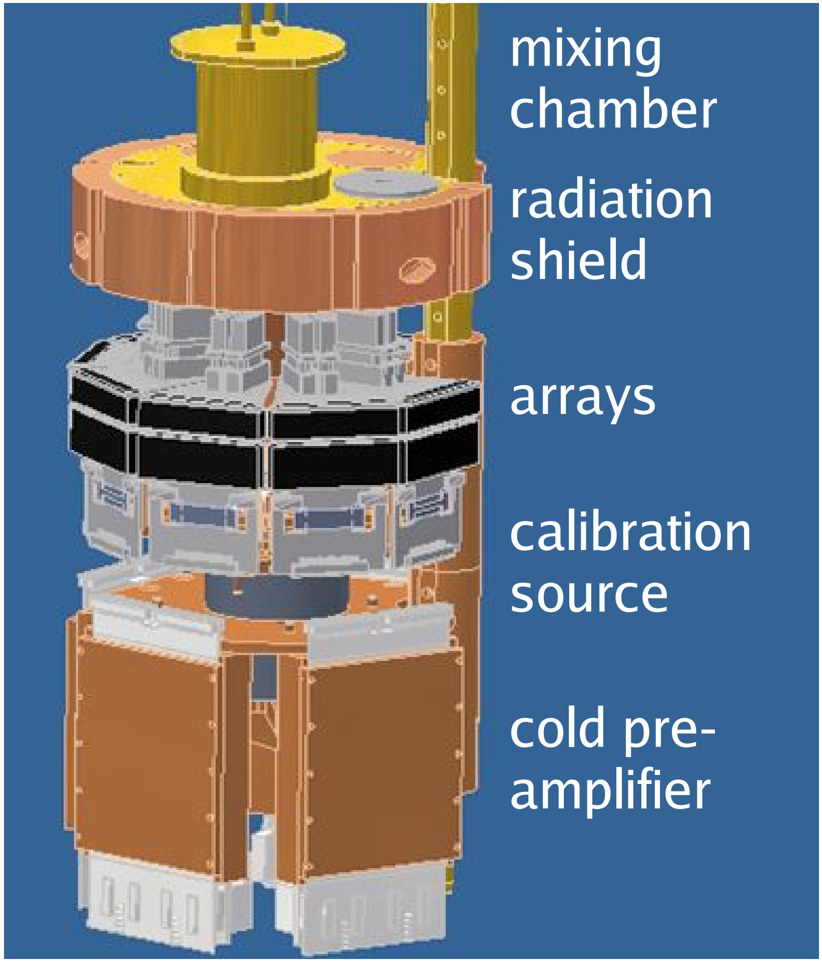


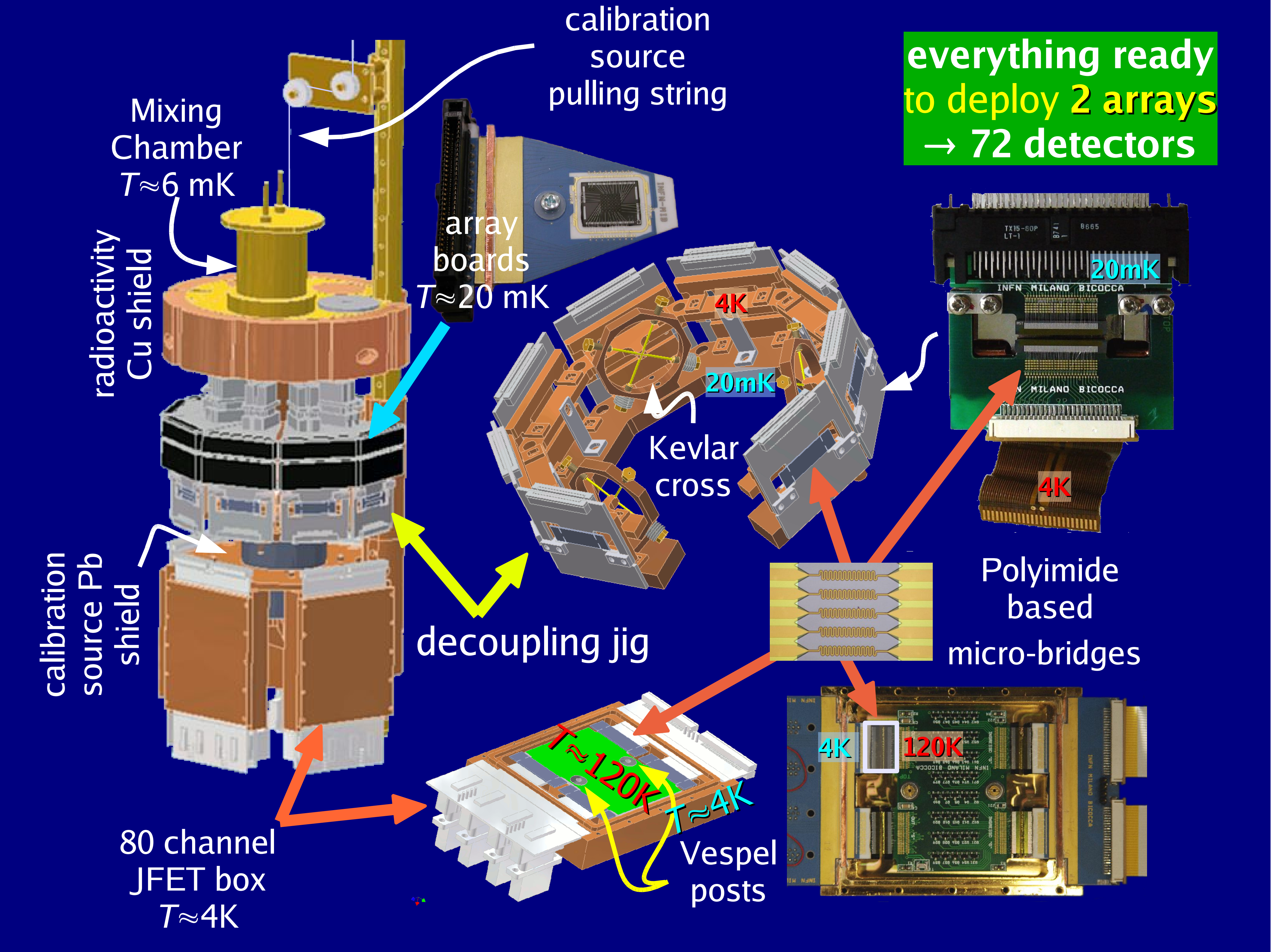
MARE-1 SEMICON: statistical sensitivity from MC

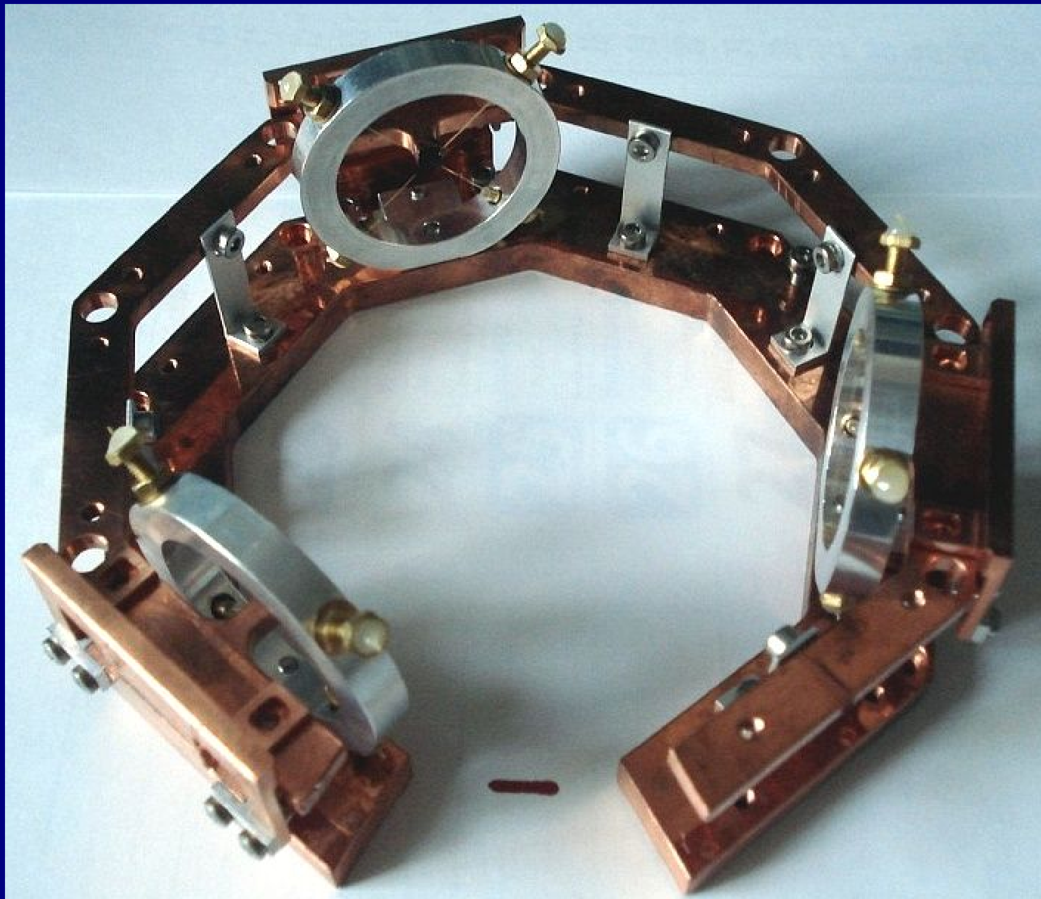
year	1	2	3	4
new detectors	72	216	0	0
total detectors	72	288	288	288
statistics [det*y]	72	360	648	936
activity [c/s]	0.27	m_{AgReO4} = 500 μg		
statistics [events]	6.10E+08	3.05E+09	5.49E+09	7.94E+09
ΔE = 40 eV	τ = 400μ s	f_{pp} = 1.0E-4		
m_ν sensitivity (90%)	6.9	4.6	4.0	3.6
ΔE = 15 eV	τ = 50μ s	f_{pp} = 1.0E-5		
m_ν sensitivity (90%)	5.2	3.5	3.0	2.7

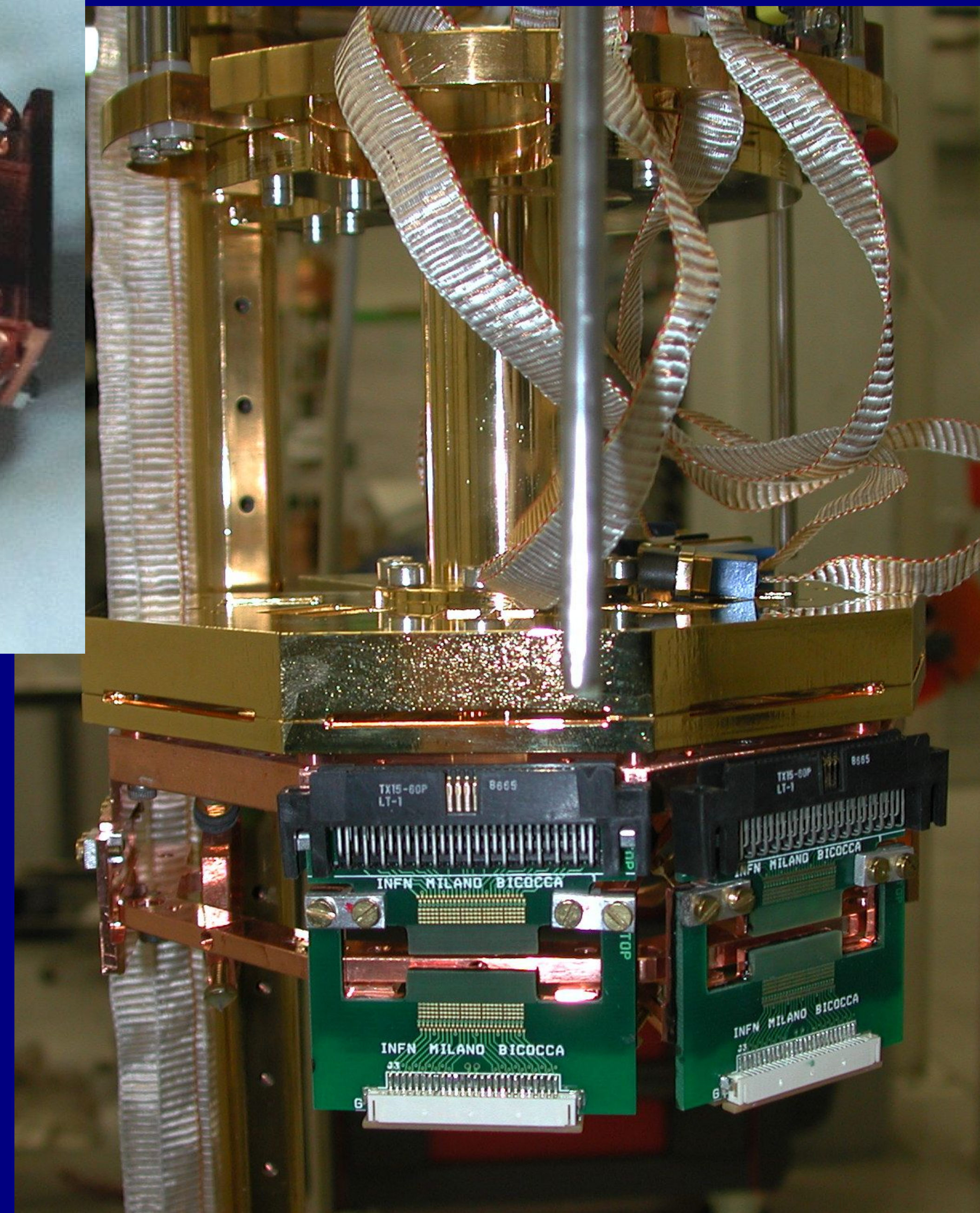
- setup ready for 8 arrays
- 288 $AgReO_4$ crystals
- now starting with 2 arrays (72 ch.)
- gradual deployment
  - further detector optimization



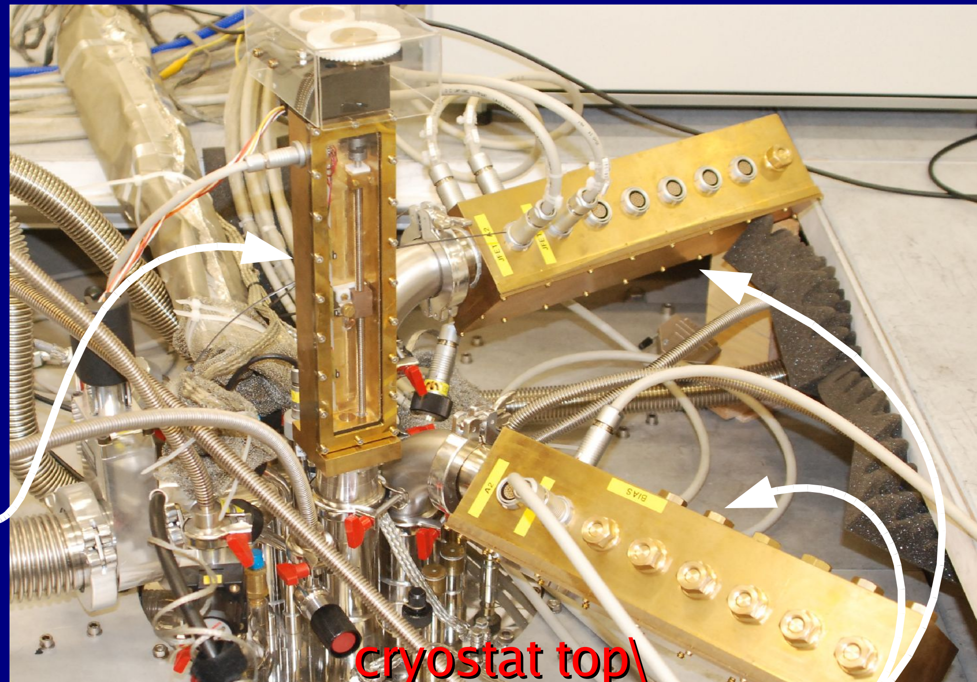



everything ready
to deploy 2 arrays
→ 72 detectors
calibration
source
pulling string
Mixing
Chamber
T≈6 mK
radioactivity
Cu shield
array
boards
T≈20 mK
TX15-80P
LT-1
20mK
INFN MILANO BICOCCA
4K
20mK
Kevlar
cross
4K
calibration
source Pb
shield
decoupling jig
Polyimide
based
micro-bridges
4K
120K
T≈120K
T≈4K
80 channel
JFET box
T≈4K
Vespel
posts

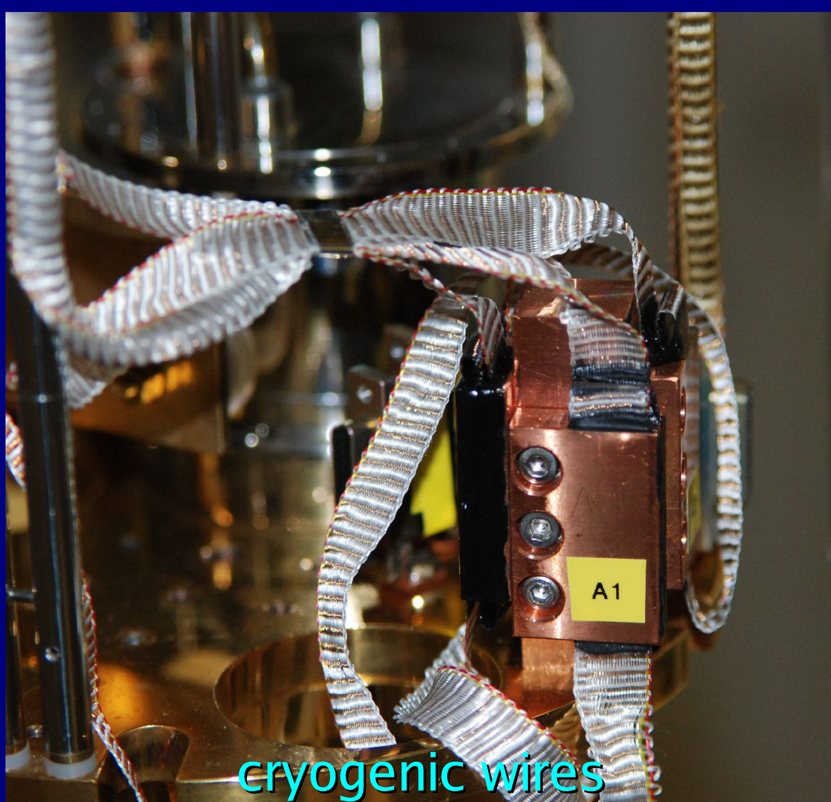


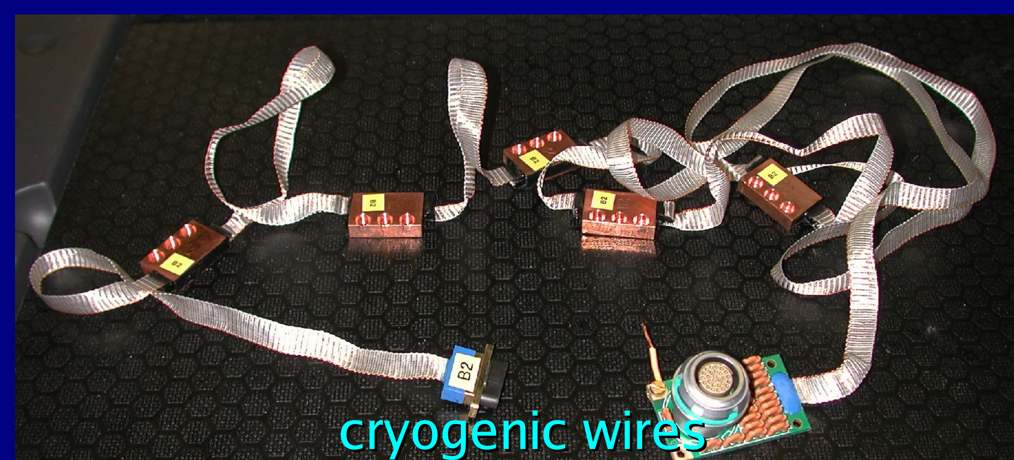

TX15-60P
LT-1
8665
INFN MILANO BICOCCA
TOP
INFN MILANO BICOCCA
INFN MILANO BICOCCA
INFN MILANO BICOCCA

calibration source pulling string



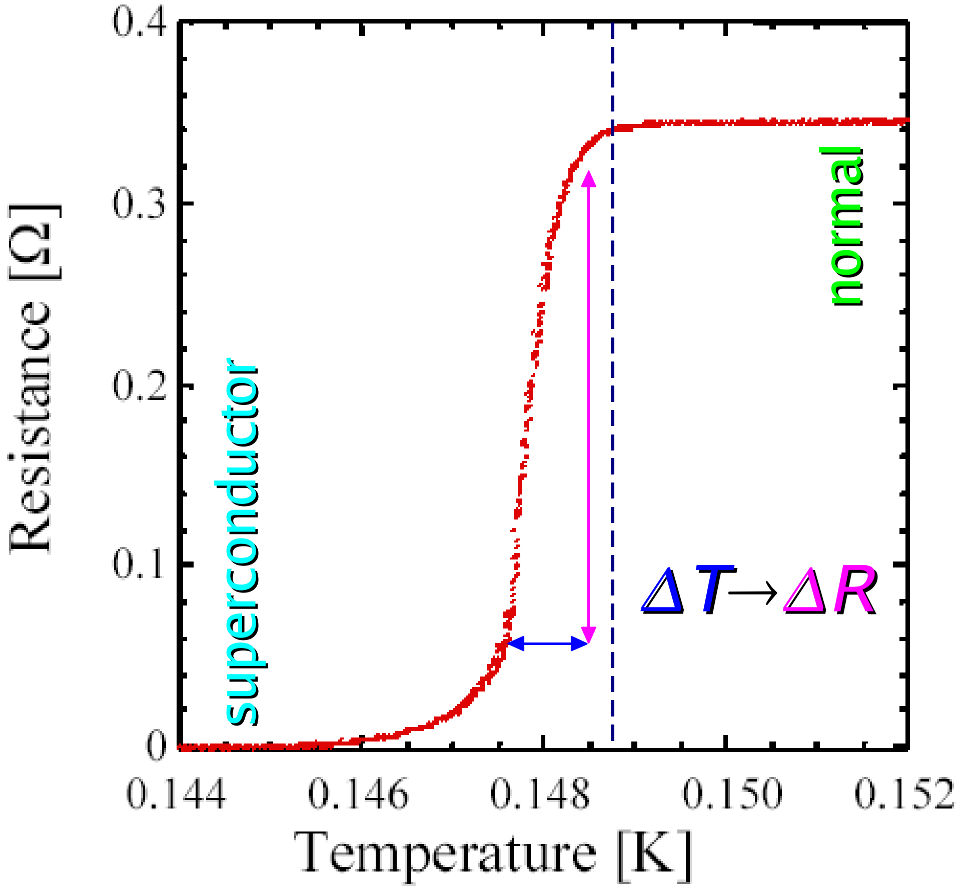
connection boxes

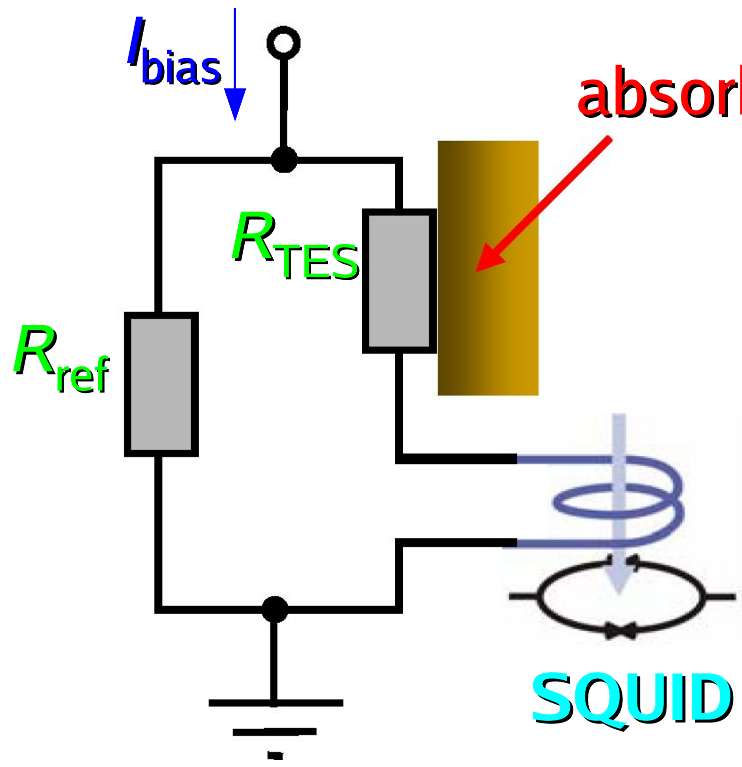




MARE-1 TES: Superconducting transition edge sensors

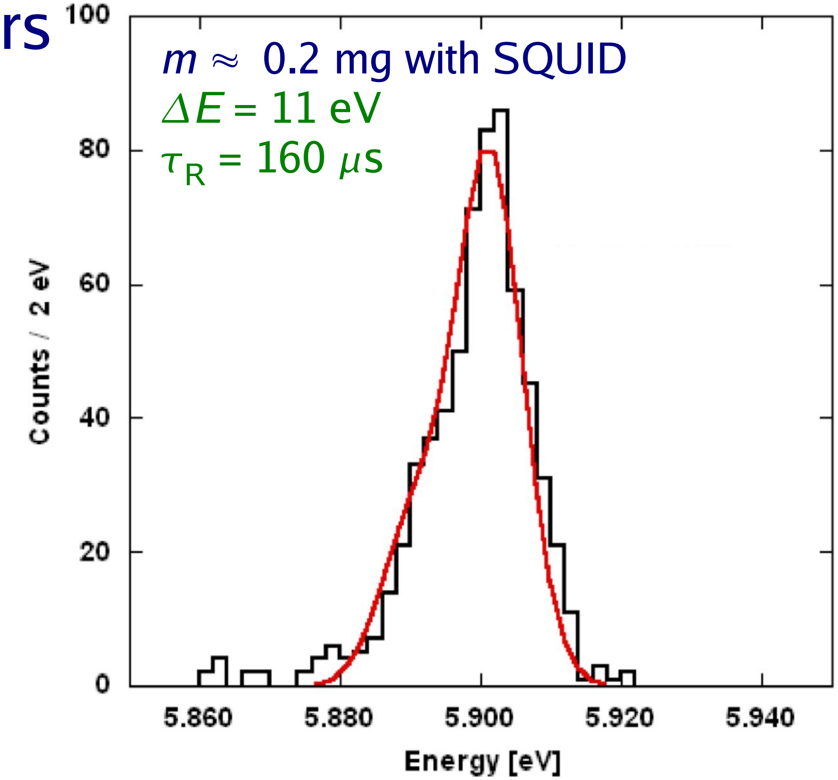
- **superconductor thin films** used inside the phase transition at T_c
  - ▶ pure superconductors: **Ir** (T_c= 112 mK), **W** (T_c= 15 mK), ...
  - ▶ metal-superconductor bilayers ⇒ tunable T_c (20÷200 mK) : **Mo/Cu, Tl/Au, Ir/Au, ...**
    - high sensitivity (A≈100) ⇒ **high energy resolution**
    - high electron-phonon coupling ⇒ **high intrinsic speed**
    - low impedance ⇒ SQUID read-out ⇒ **multiplexing for large arrays**

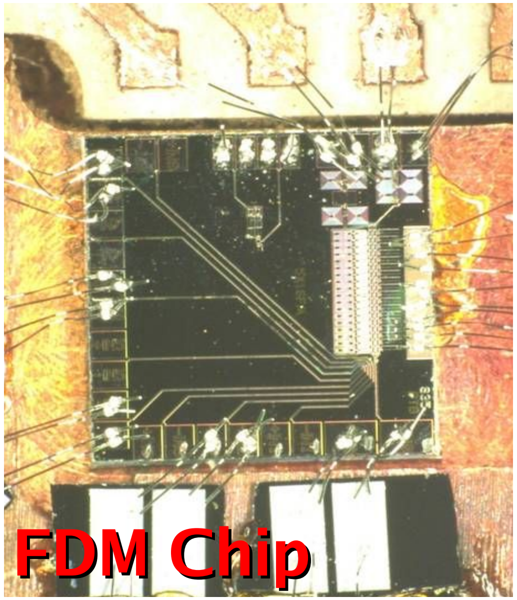


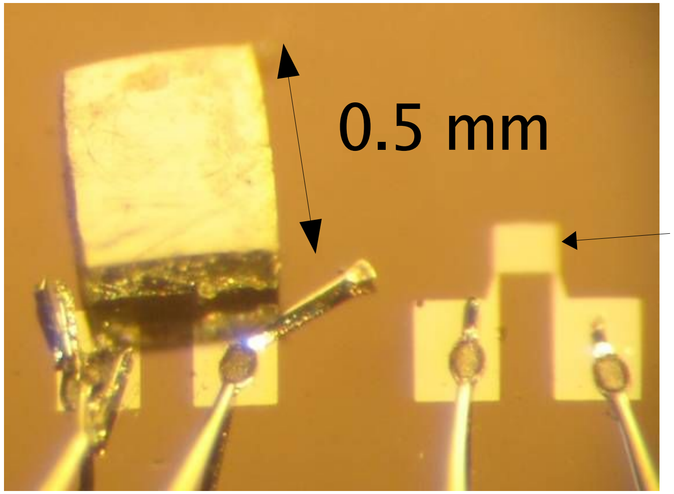


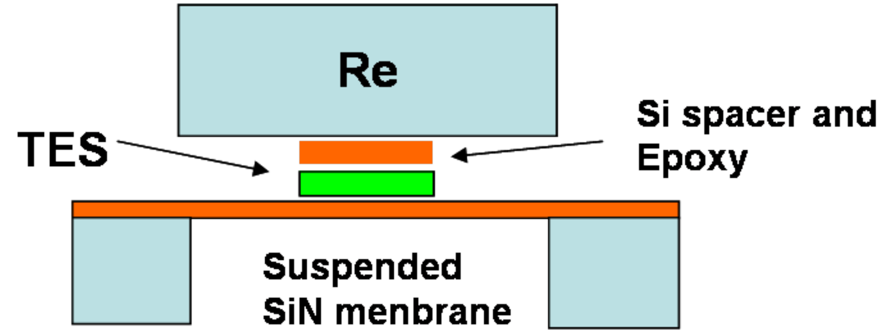
MARE-1 TES: sensor development

- Pulsed Laser Deposition of thin films: pure **Ir** or **Ir bilayers**
- detectors with **metallic rhenium** absorbers
- **300 channel array**
- detector R&D goal:
  - **1 mg** Re crystals with: **ΔE = 5 eV, τ_R = 10 μs**
  - a further step towards MARE-2
- two read-out options
  - JFETs with **cold impedance transformer**
  - frequency **multiplexed SQUIDs (FDM)**
    - **first 3x3 FDM chip is under test now**

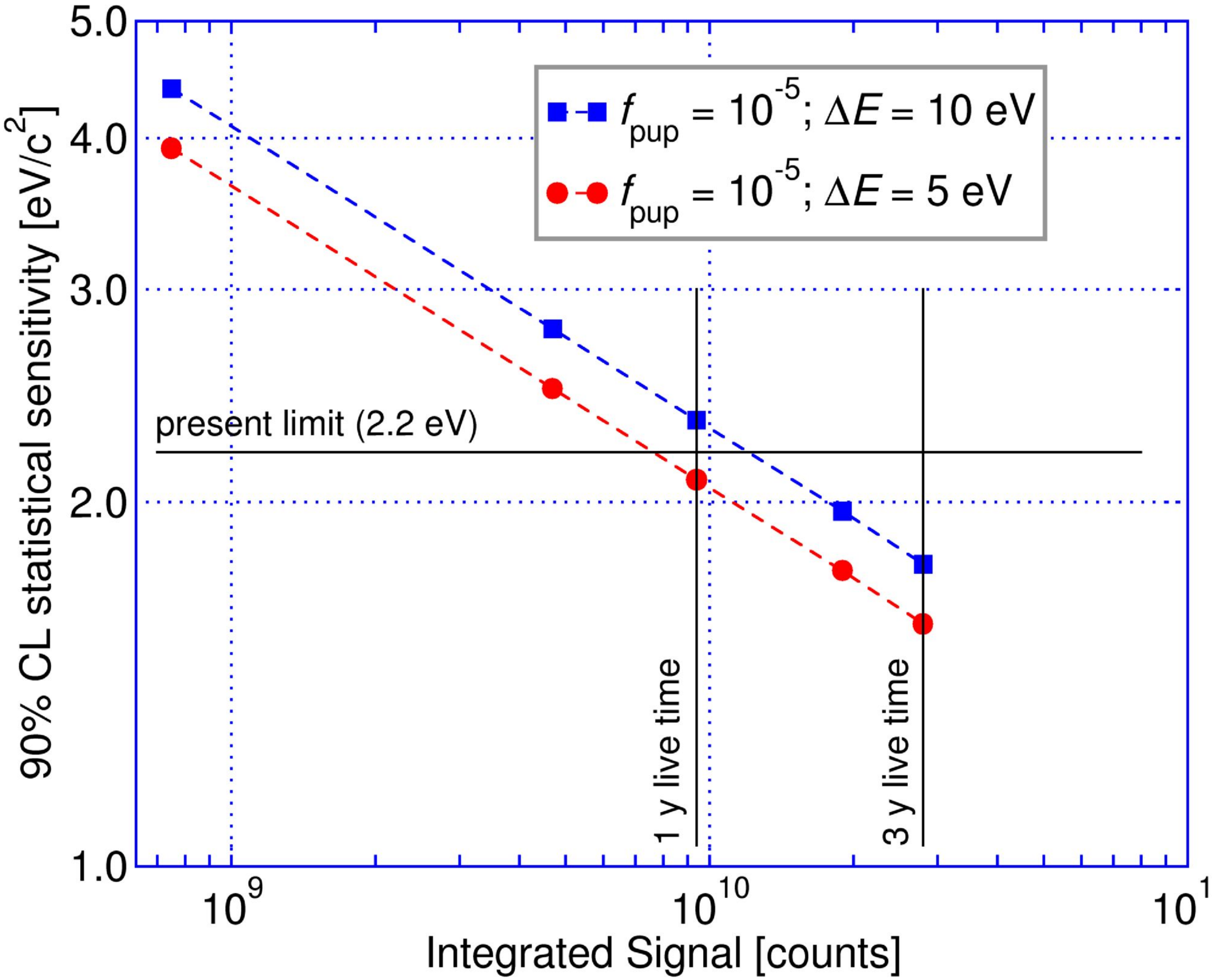








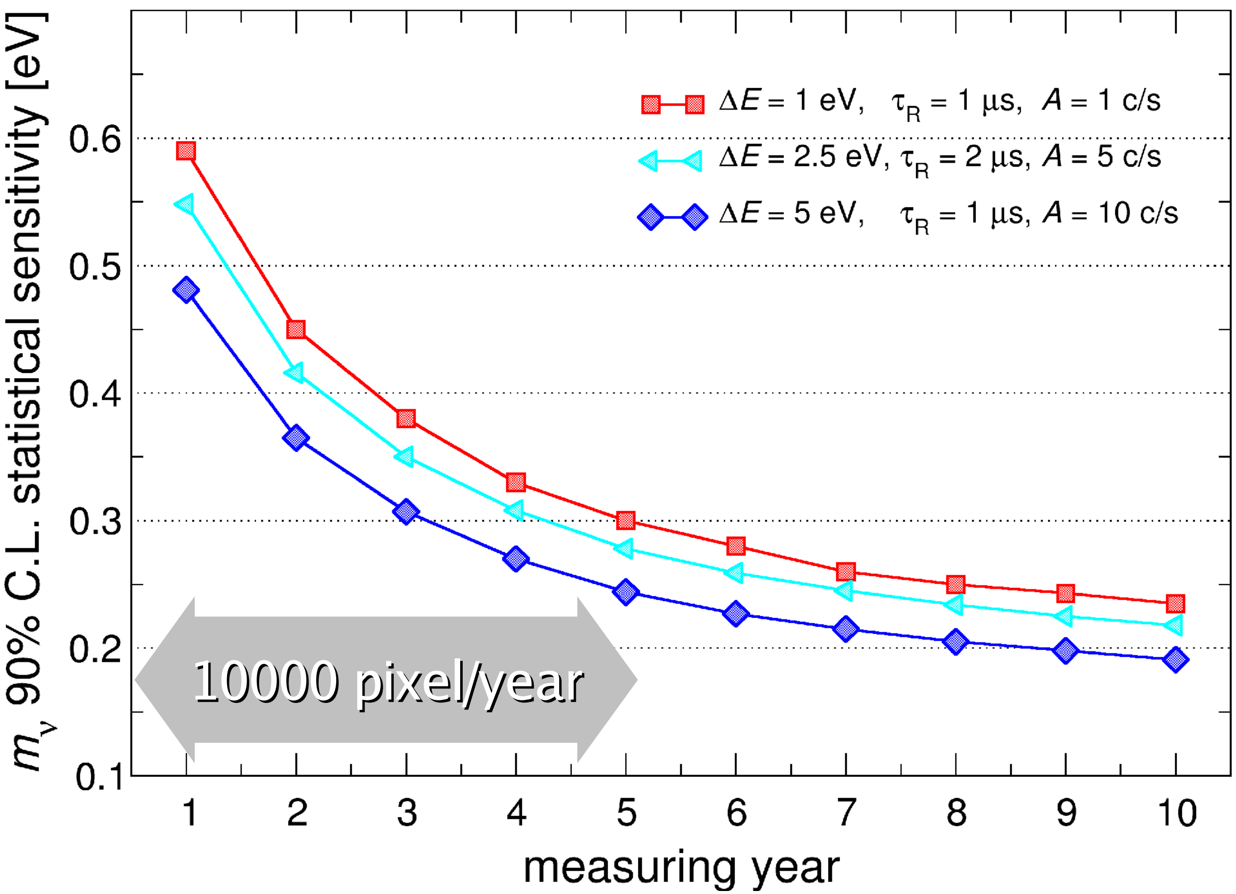
MARE-1 TES: statistical sensitivity

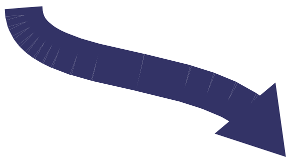


- 300 rhenium crystals in 2 refrigerators
  - $m \approx$ 1 mg
- Ir/Au or Al/Ag TES at 100 mK
  - **ΔE = 10 eV, τ_R = 10 μs, $f_{pp} = 10^{-5}$**
- about 3×10^{10} events in 3 years ⇒ **m_ν < 1.8 eV**

MARE-2

- only statistical analysis
- 50000+ detectors gradually deployed
  - ▷ 5 arrays with 10000 detectors each
  - ▷ one array deployed per year for the first 5 years
  - ▷ arrays distributed in many laboratories around the world
  - ▷ about $10^{13} \div 10^{14}$ events after 5 years
- technical requirements not far from that for next generation X-ray space observatory (i.e. XEUS, Con-X)

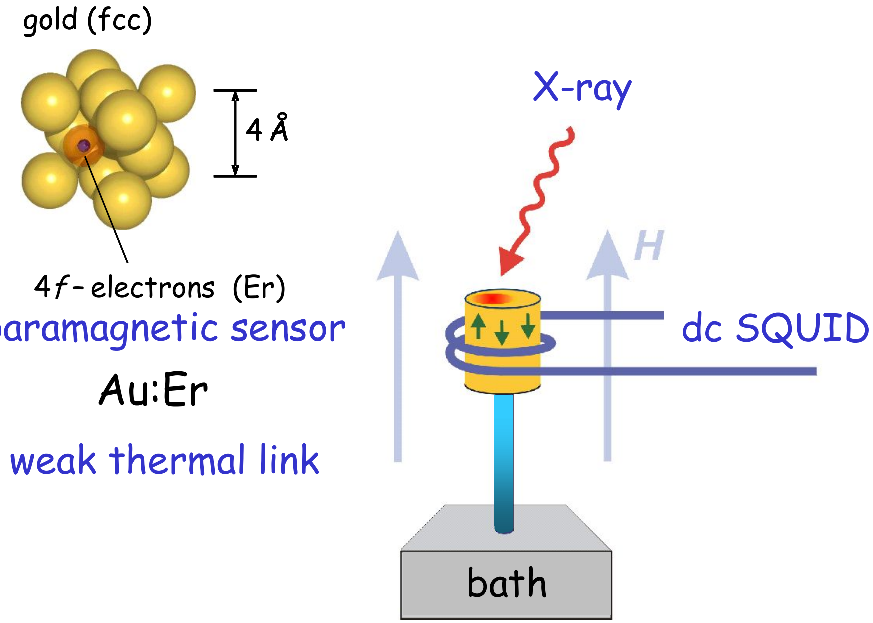


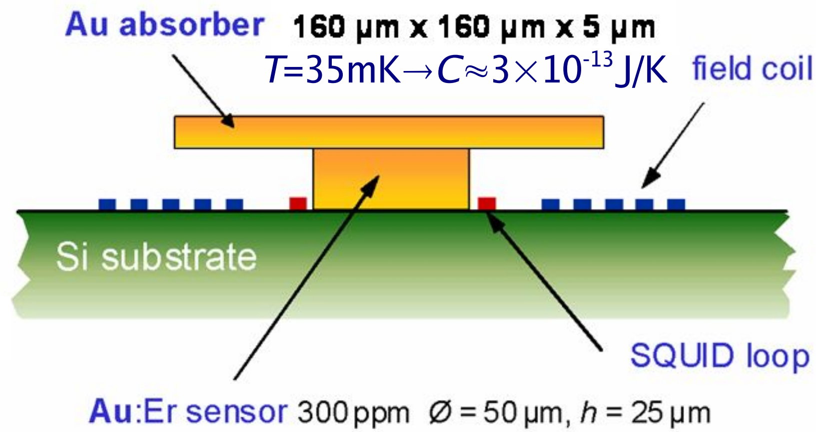


10000 pixel *kits*
$\Delta E \approx 1$ eV
$\tau_R \approx 1\ \mu s$
$A_\beta \approx 1 \div 10$ Hz

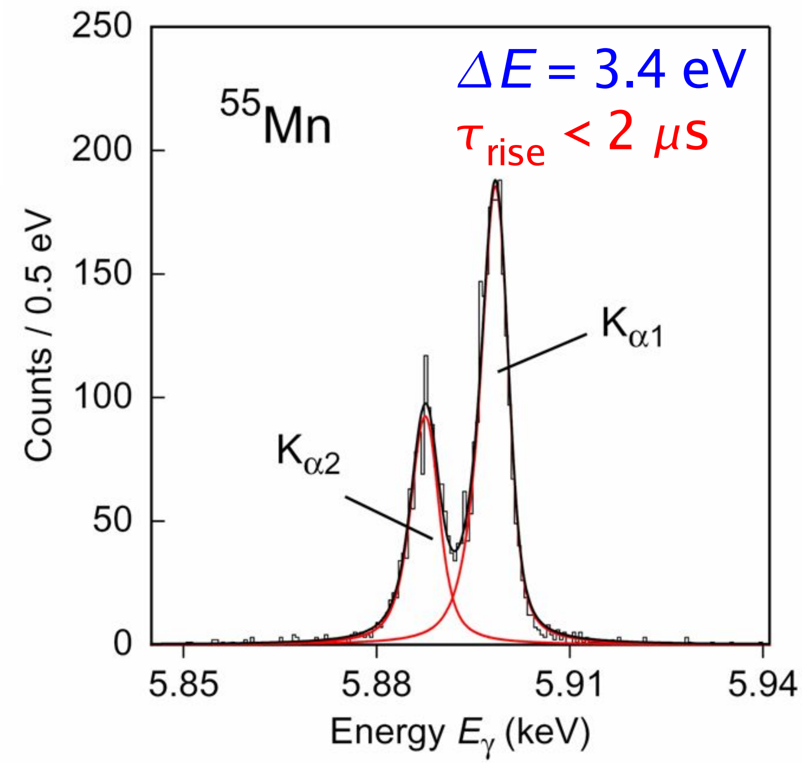
need for
new sensor R&D
and
new read-out techniques

MMC – Magnetic Micro Calorimeters (Heidelberg)

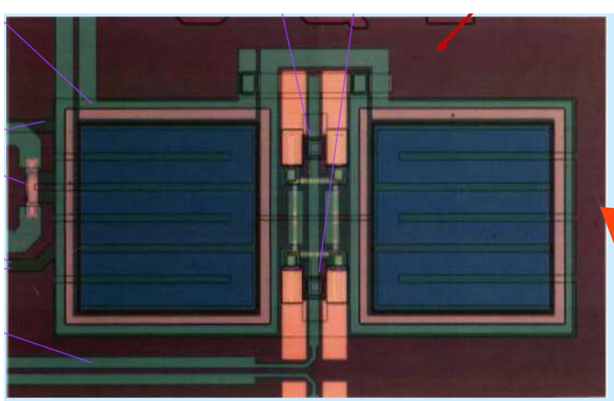




$$\delta M = \frac{\partial M}{\partial T}\delta T = \frac{\partial M}{\partial T}\frac{E_\gamma}{C_{ges}}$$

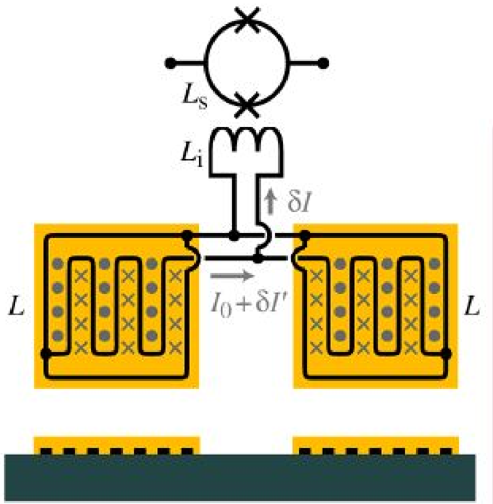


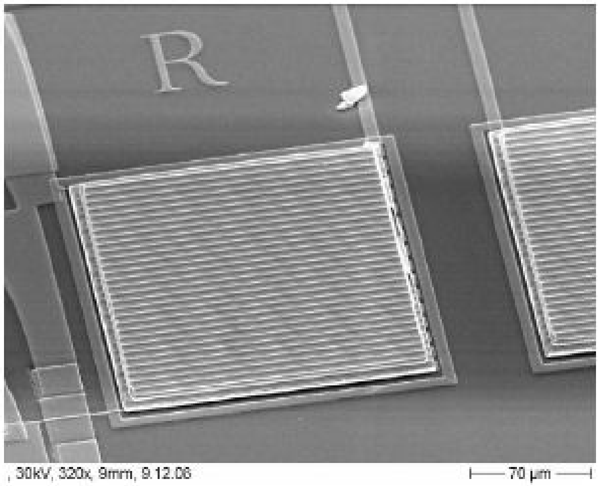
- suitable for **large capacity absorbers**
- **very fast** $\sim\mu$s
- **high energy resolution** $\sim$eV



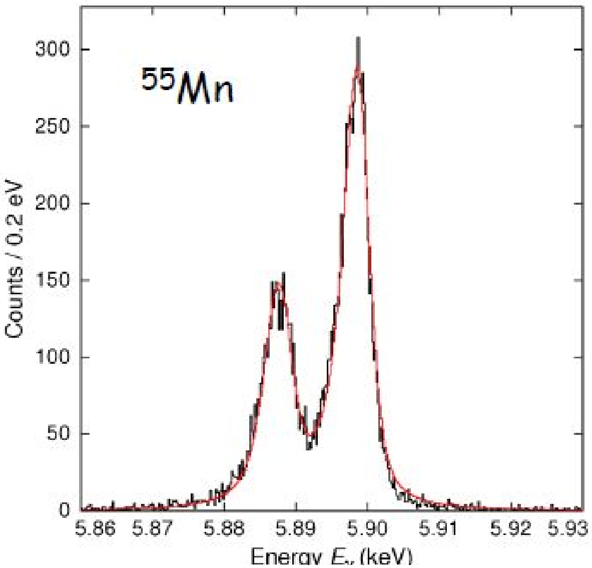
sensor design optimization for MARE-2 rhenium absorbers is in progress
⇨ meander pick-up coils without external *B* field

MMC: recent achievements (Heidelberg)

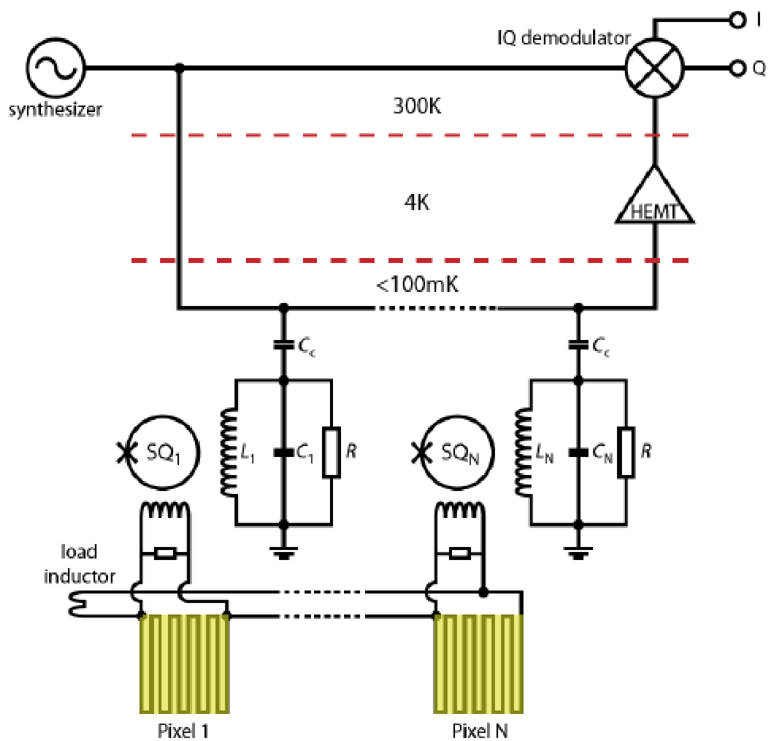




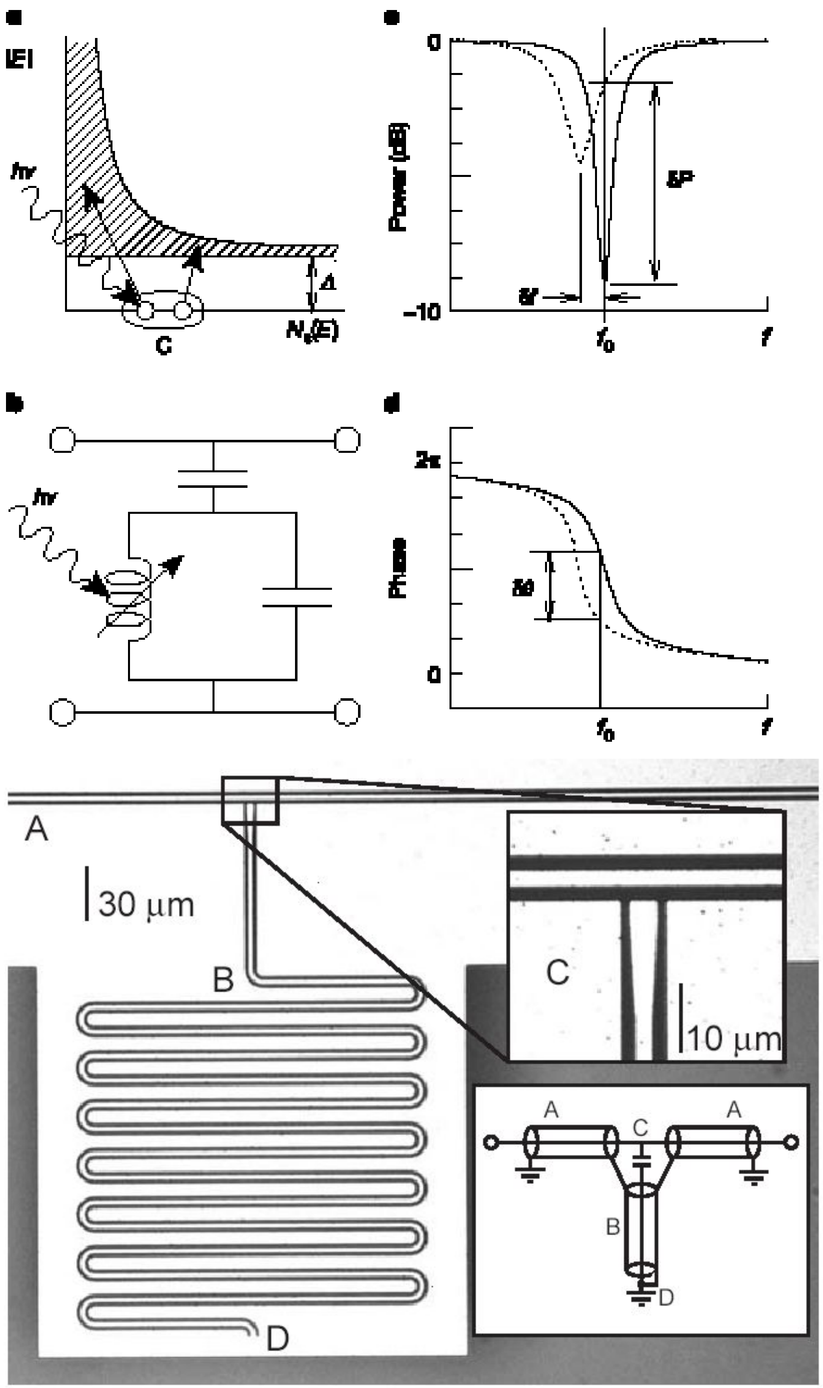
ΔE = 2.8 eV



- first micro-fabricated MMCs
- first tests of microwave SQUID multiplexing
- and more...
  - devices with 90 ns rise time



MKIDs R&D for MARE-2



- 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**
  - **multiplexing** for very large number of

Sensitivity

ΔE = 5 eV

t_M = 36000 detectors x 3 years

A_β = 20 c/s/det

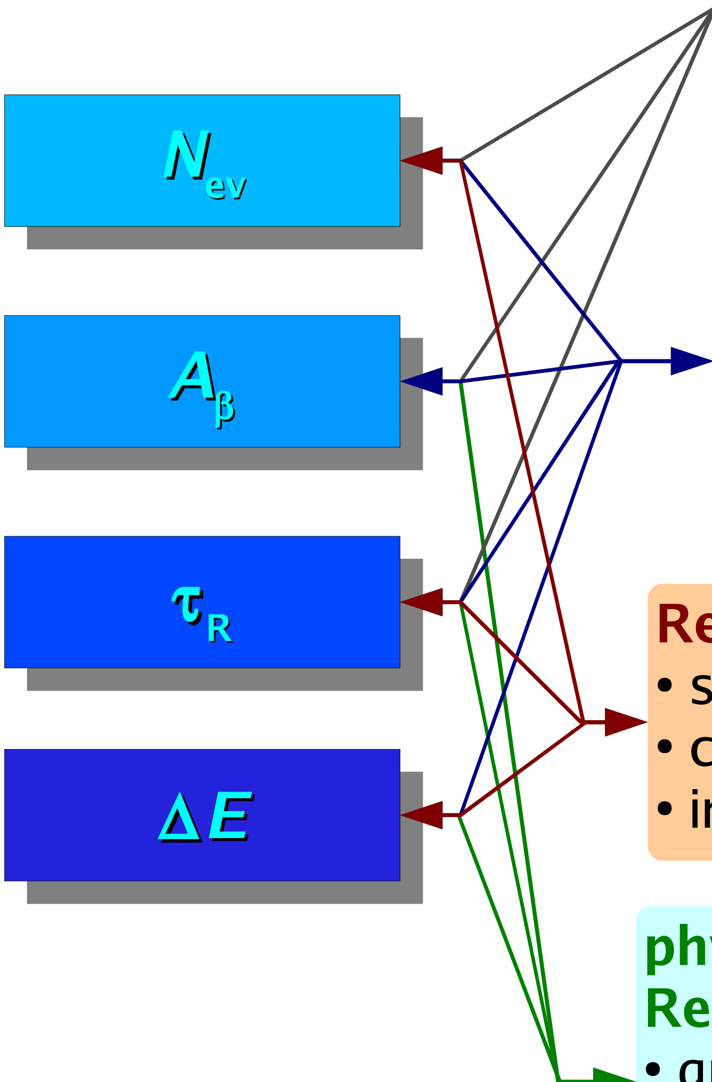
- τ_{rise} = 1 μs ⇒ m_ν < 0.2 eV
- τ_{rise} = 100 μs ⇒ m_ν < 0.4 eV

Technique largely still to be proved!!

Interested institutions

- INFN Milano-Bicocca
- INFN Roma (exp. Rich: R&D for CMB)
- ITC-irst
- Caltech
- CNRS Grenoble

MARE-2: topics in single pixel design

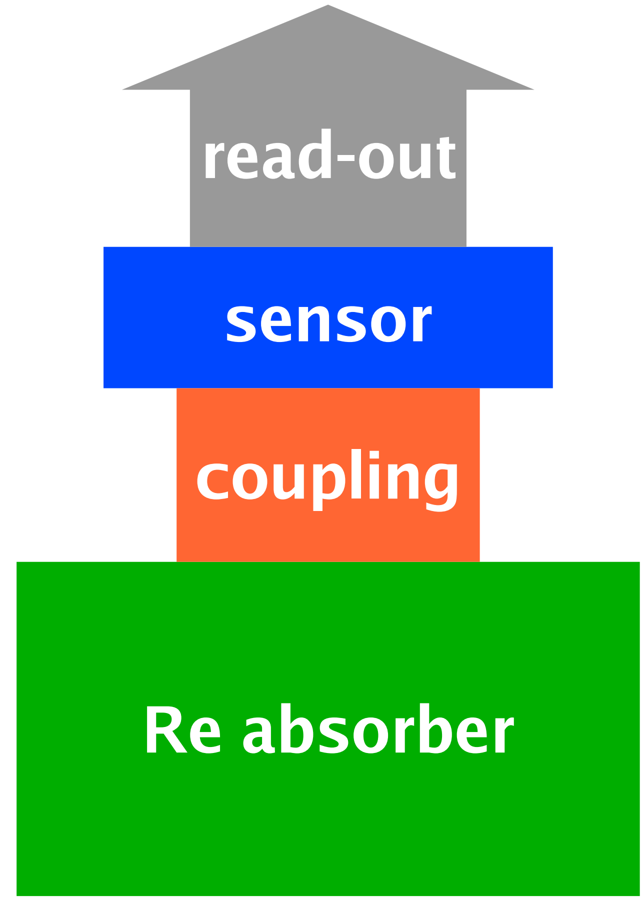


Read-out
- bandwidth
- multiplexable
- contacting

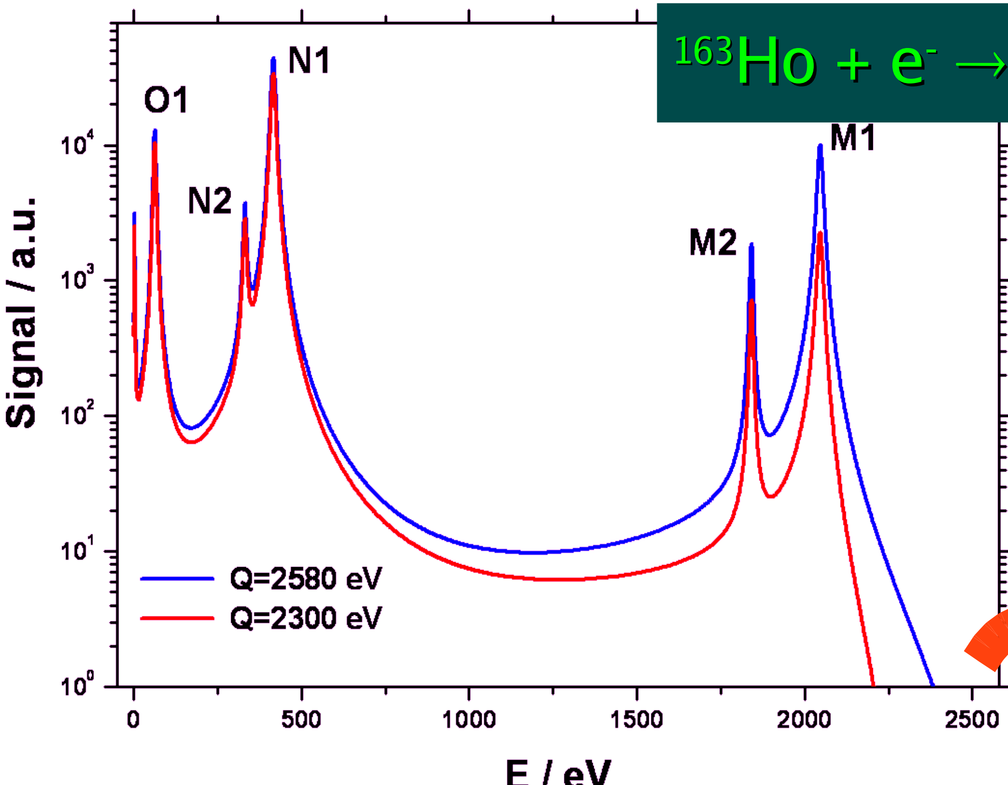
Sensor optimization
- intrinsic speed
- energy resolution with large absorbers
- large array fabrication

Re-sensor coupling
- signal transmission speed
- compatibility (magnetic fields)
- integration

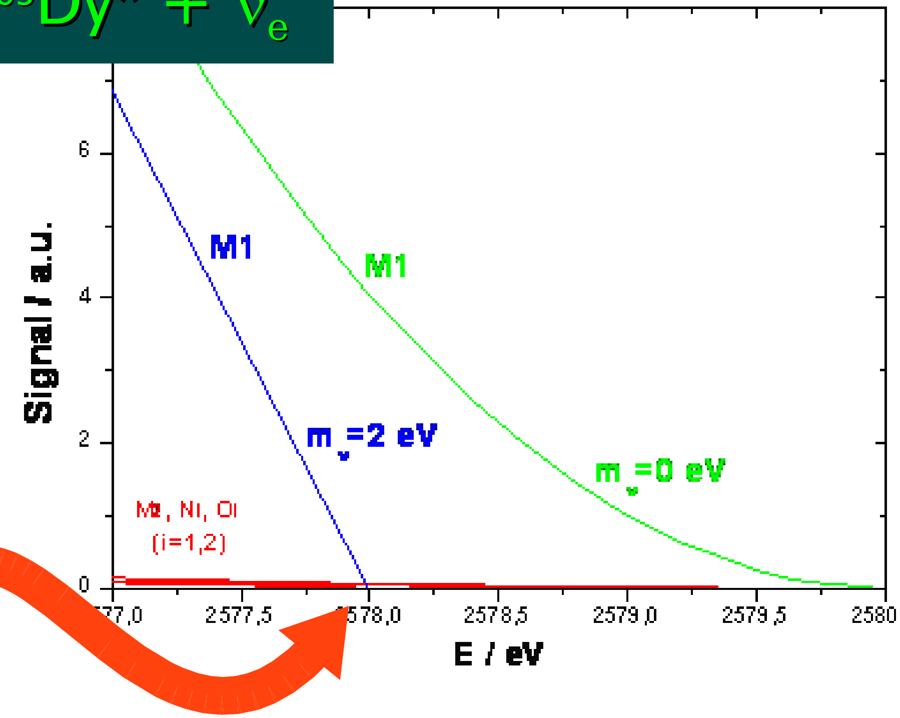
physics of superconducting Re absorbers
- qp lifetime and thermalization
- crystal purity and quality
- heat capacity



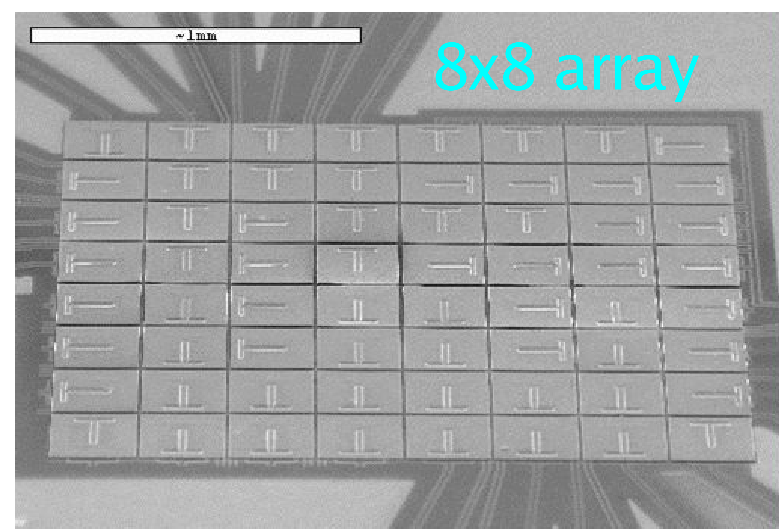
MARE extensions: ^{163}Ho electron capture measurement



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



- calorimetric measurement of non-radiative Dy atomic de-excitations (Coster-Kronig, Auger...)
- fraction of events at end-point may be as high as for ^{187}Re: depends on Q_{EC} (≈2.5 keV)
  - ***Q_{EC}?***
- fewer active nuclei are needed ($\tau \approx$ 4000 y)
  - can be implanted in any suitable absorber
  - first implantation tests at ISOLDE are encouraging
- new NASA/Goddard TES arrays (ΔE = 2eV) can be implanted with ^{163}Ho



Conclusions

- thermal calorimetry of ^{187}Re decay can give sub-eV sensitivity on m_ν
- the MARE project is taking off
- MARE-1 intermediate scale experiments are starting
- R&D for MARE-2 large scale sub-eV experiment is starting
  - MMC R&D is already in progress
    - array microfabrication ha made huge progresses
    - sensor performances are close to what is needed for MARE
    - new MUX schemes are being developed
  - New ideas are coming up (MKIDs, ^{163}Ho)

Backups ...

MARE and the cosmological relic neutrino background

- MARE-2: 50000 detectors, 20 mg each
  - ▷ 650 g of ^{187}Re
  - ▷ 4×10^{-8} counts/year... ☹

A. G. Cocco, G. Mangano and M. Messina, arXiv:hep-ph/0703075v2

MARE reach: 0.1 eV?

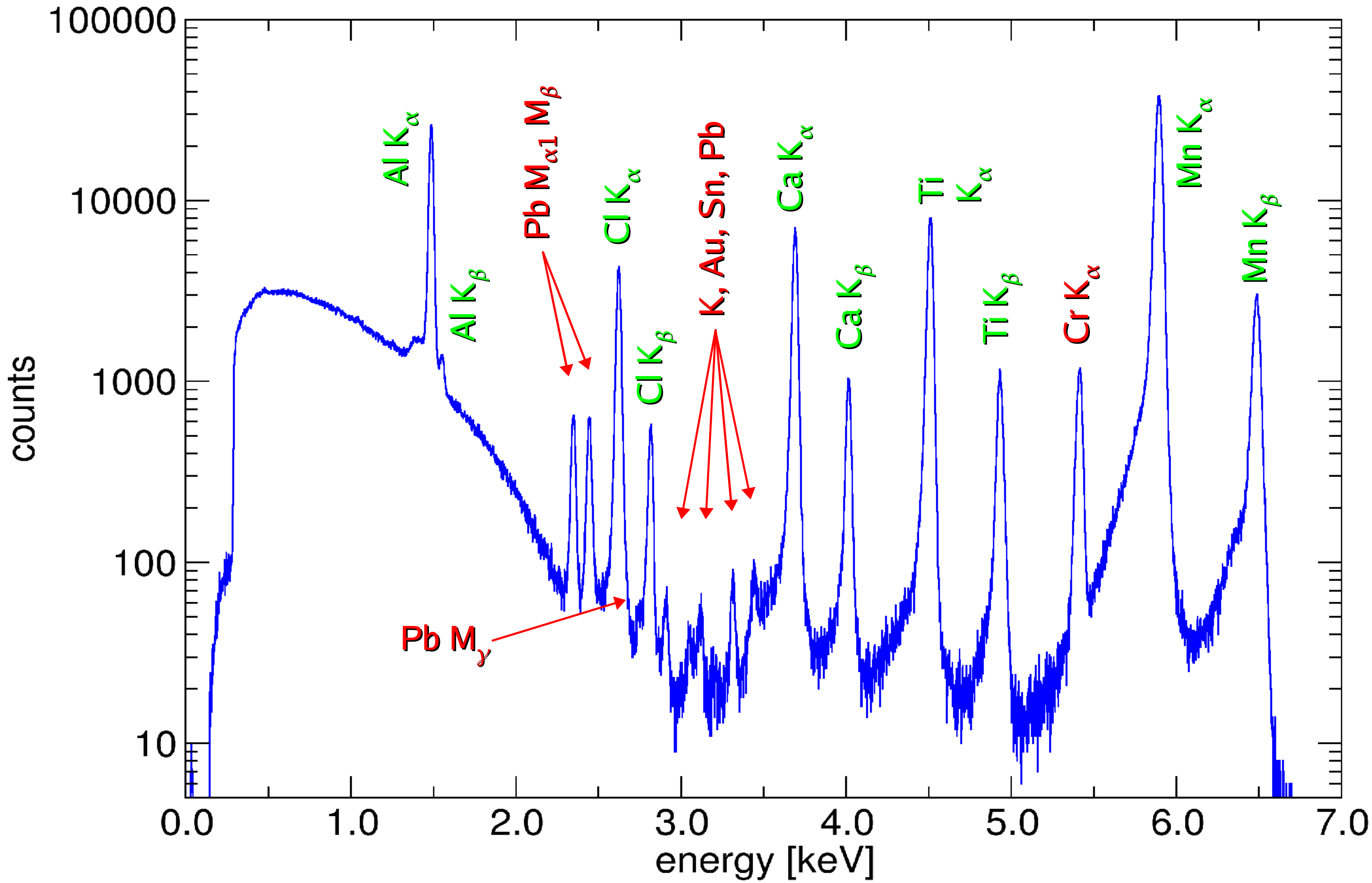
- $\Sigma_{90}(m_\nu)$ **= 0.1eV** for $N_{ev} = 10^{15}$; ΔE = 3 eV; $f_{pp} = 10^{-5}$
  - τ_R = 1 μs and 10 decays/s per detector
  - **3.2×10⁶ detector×year...** ☹

Recognized systematics in calorimeters

- detector response function (energy dependence, shape,...)
  - important in $AgReO_4$ (→)
- energy dependent background
  - study low energy environmental and material radioactivity (→)
- condensed matter effects: BEFS
  - observed in Re and $AgReO_4$: improve modeling (→)
- pile-up effects
  - under investigation with MC methods (→)
- analysis artifacts
  - to be studied by MC methods
- ^{187}Re decay spectral shape
  - improve Buhring parametrization
- long term metastable excited states
  - should be negligible
- electron surface escape
  - should be negligible
- ...?
  - more statistics

Detector response function

- 2168 hours×mg with fluorescence source open
- calibration gives the **energy scale** and the **response function**

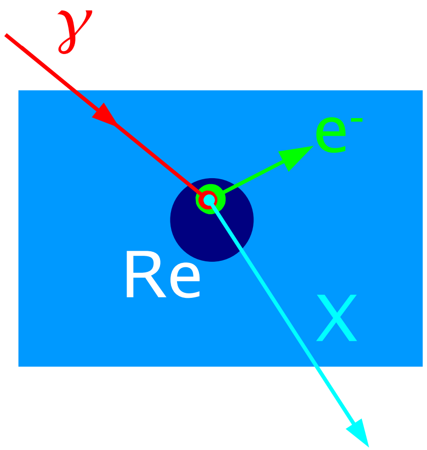


- X-ray peaks have tails on low energy side
- 1~6 keV X-rays in $AgReO_4$ have an attenuation length $\lambda < 2$ μm
  - ► are the response functions for X-rays and for βs from ^{187}Re decay the same?
- need for a good phenomenological description of the X-ray peak shape

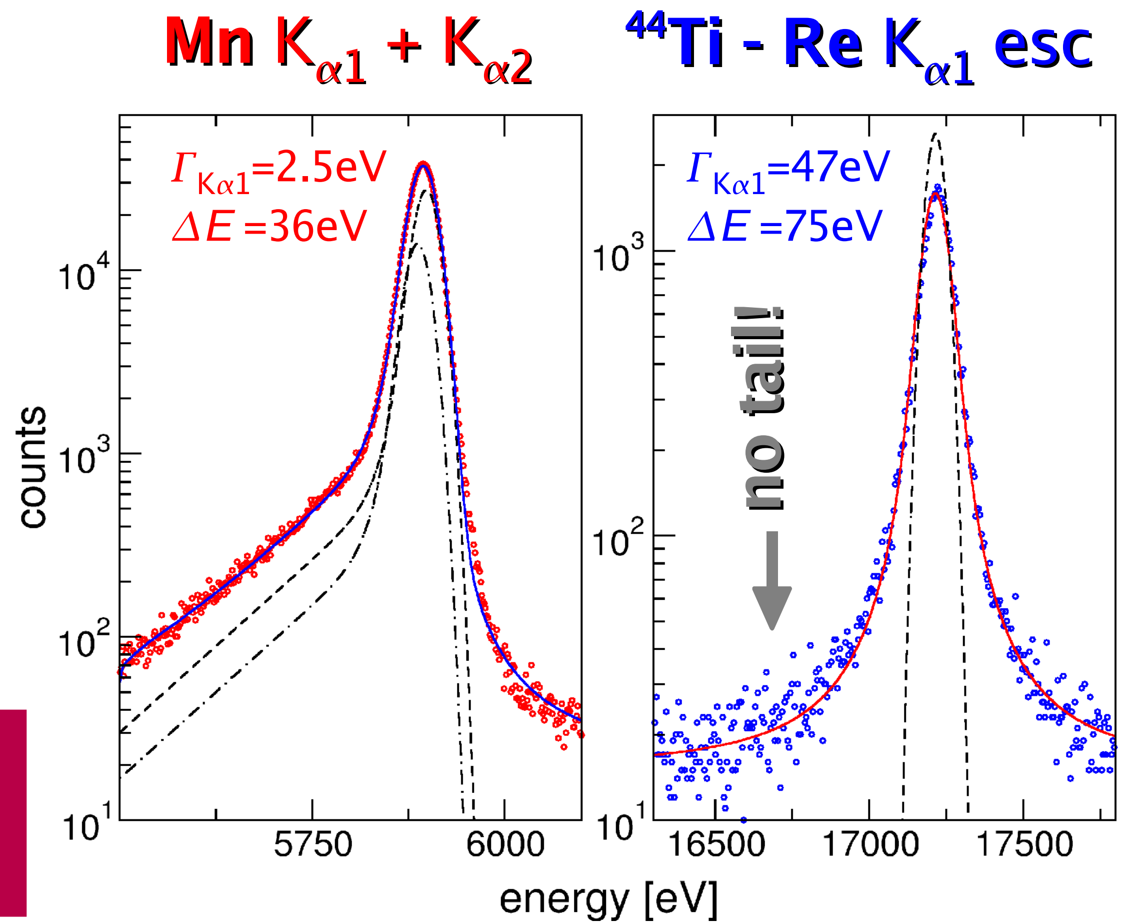
MIBETA: Measurement of response function (2004)

- external X-rays probe only detector surface
- escape peaks allow internal calibration
  - ▷ λ(6 keV) $\approx$ 3 μm
  - ▷ λ(70 keV) $\approx$ 400 μm

  in $AgReO_4$
- escape peaks are broad because of natural widths of atomic transitions

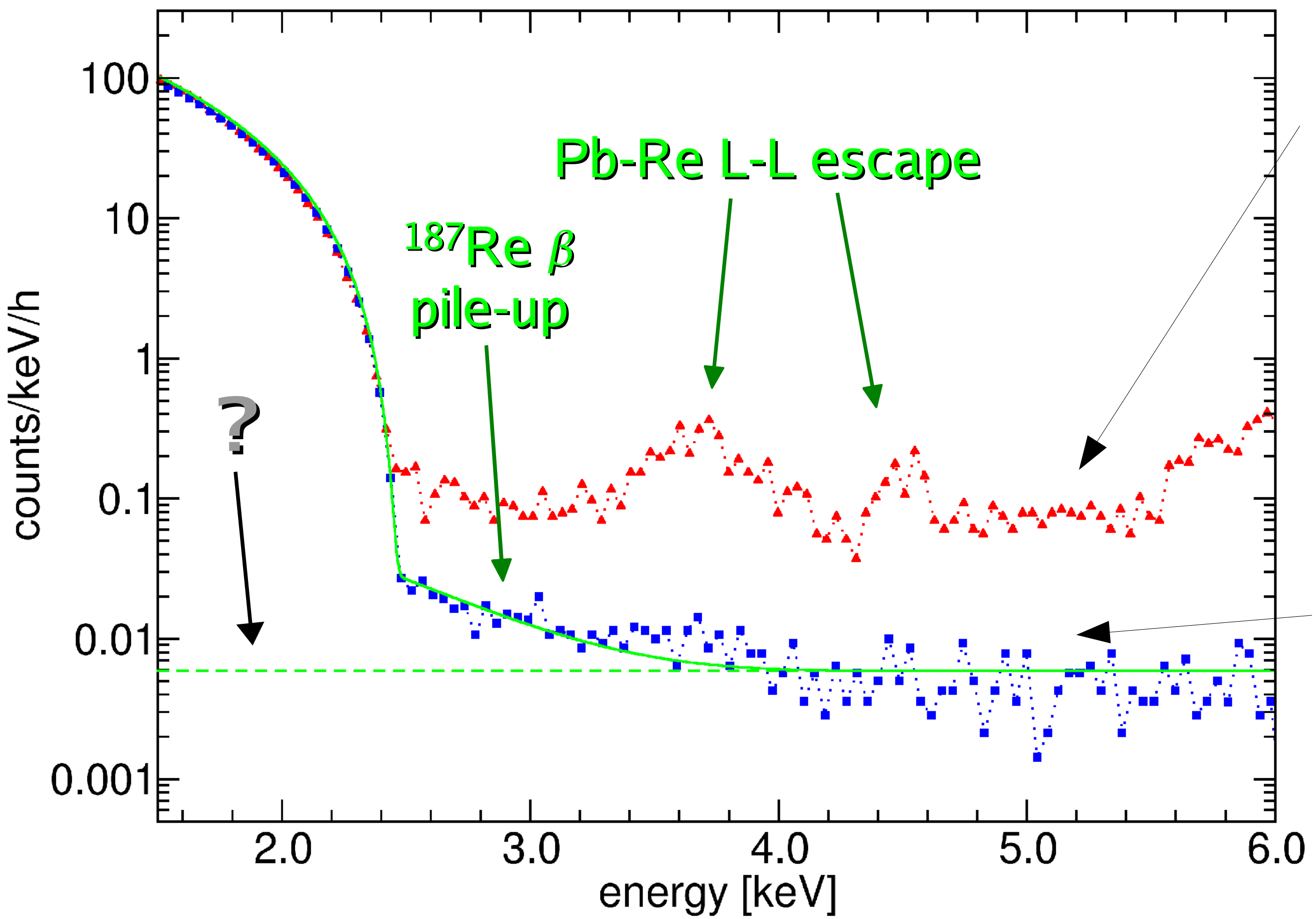


- Re K-edge @ 71.7 keV
  - ▷ E_γ > 71.7 keV
  - ▷ **internal calibration with ^{44}Ti**
- γ rays @ 78.4 keV
- ▶ γ-X escape peaks have only Re K natural width (Γ_{ReK}~47 eV)



the response function is a possible source of systematic uncertainties in calorimetric neutrino mass experiments

Background (MIBETA)



unshielded
^{55}Fe calibration source

- ^{55}Fe *Inner-Bremsstrahlung* (Q_{IB} = 232 keV, A_{IB} = 12 kBq) causes too high background
  - ▷ fluorescence from surroundings
  - ▷ Re X-ray escape peaks
  - ▷ continuum

lead shielded
^{55}Fe calibration source

- remaining background to be understood and reduced
  - ▷ cosmic rays
  - ▷ environmental radioactivity

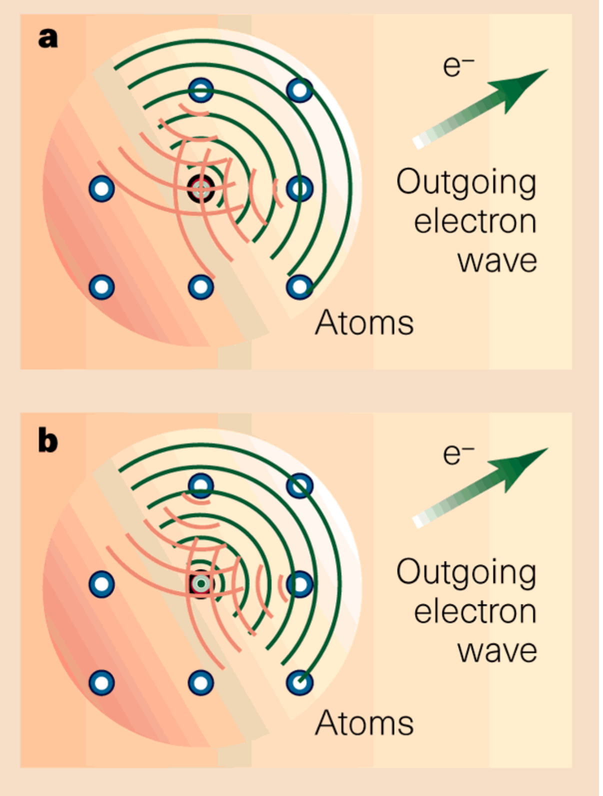
the hidden background is a source of systematic uncertainties

Go underground?

MIBETA: BEFS analysis (2005)

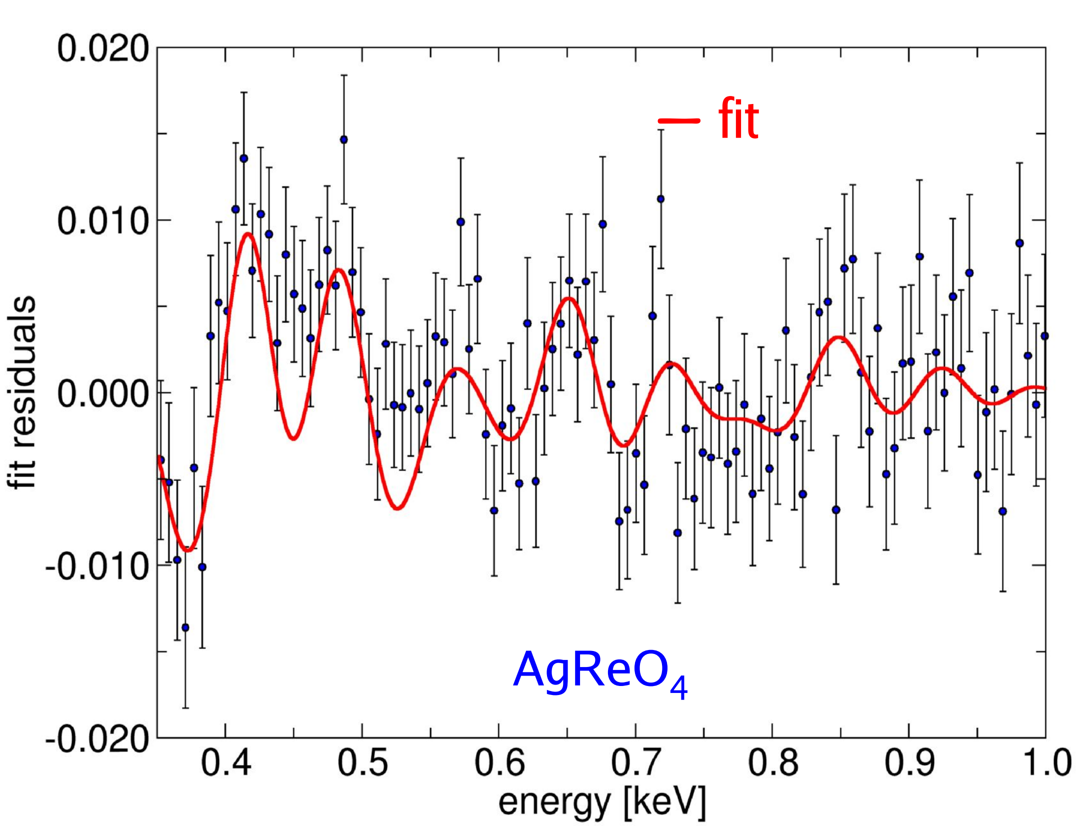
BEFS: Beta Environmental Fine Structure

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)



BEFS experimental evidence in ^{187}Re β decay

- in $AgReO_4$ less pronounced than in metallic rhenium



C. Arnaboldi et al., Phys. Rev. Lett. 96 (2006) 042503

$$\chi_{BEFS}(k_e) = F_s \chi^{l=0}_{EXAFS} + F_p \chi^{l=1}_{EXAFS}$$

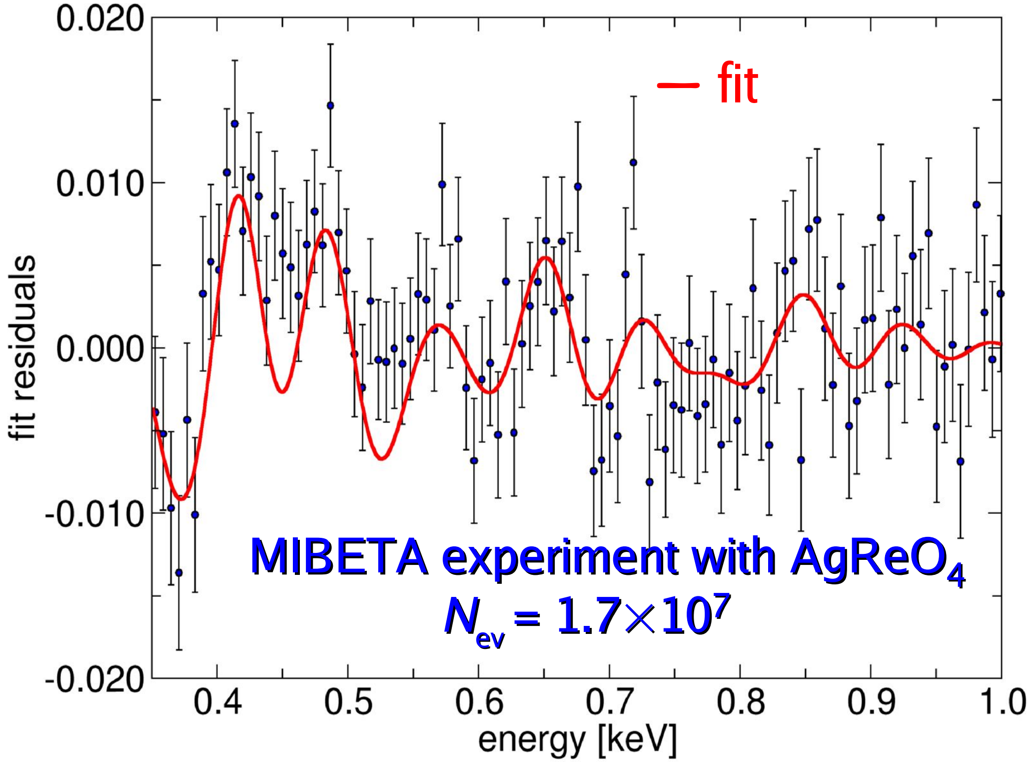
$$\chi^{l}_{EXAFS}(k_e) = $$
$$= (-1)^l \sum_{n=1}^{N} B_{nl}(k_e, R_n) e^{-2k_e^2\sigma_n^2} \sin(2k_e R_n + \delta_{0l} + \delta_{nl})$$

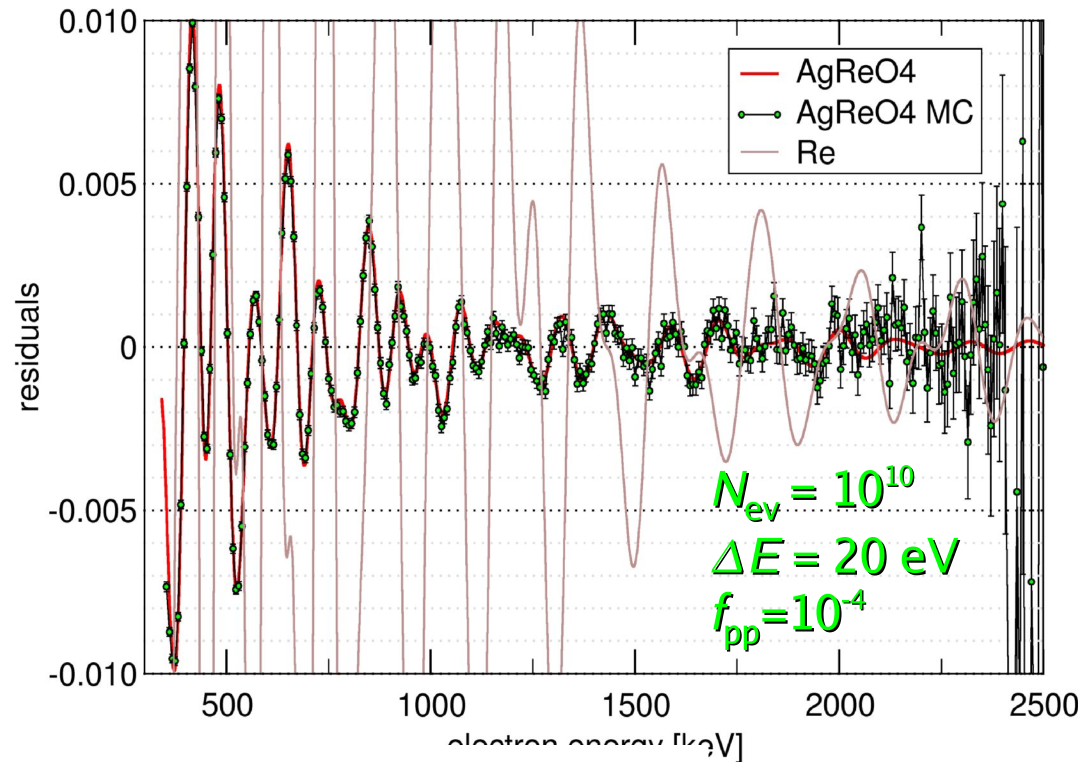
→ $F_p = 0.84 \pm 0.30$

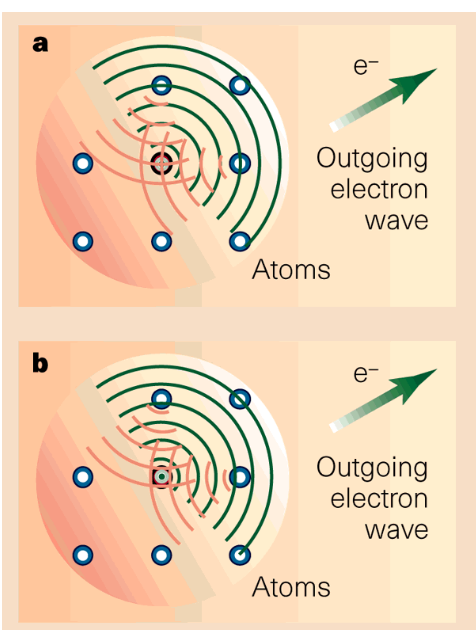
BEFS is a possible source of systematic uncertainties in ^{187}Re neutrino mass experiments

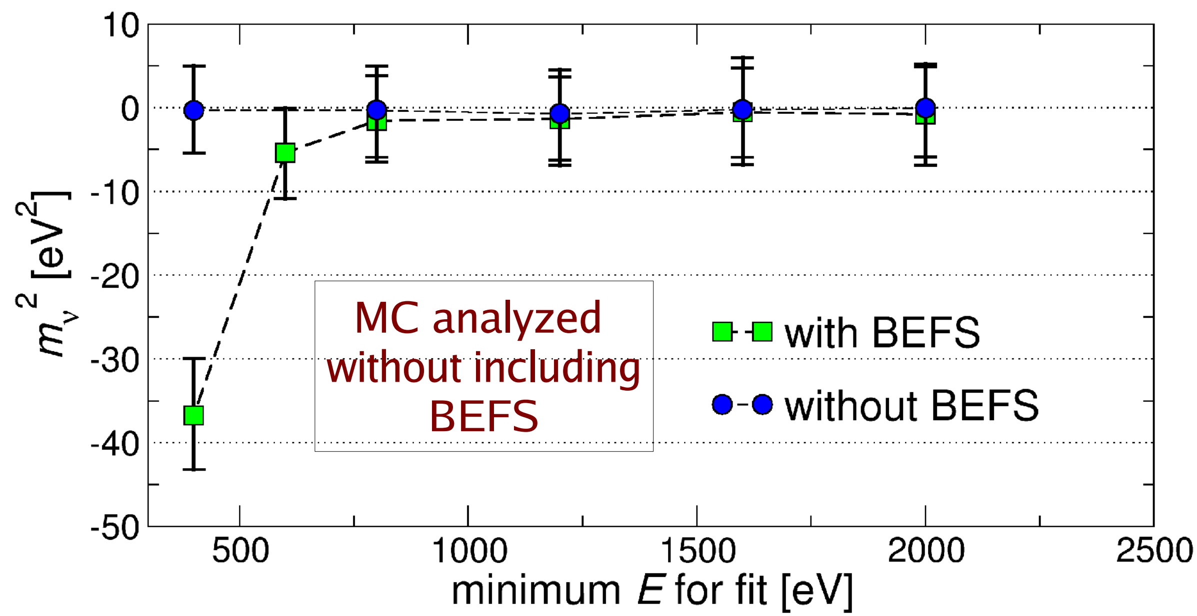
⇒ EXAFS measurements
⇒ better models

MC analysis of systematics: BEFS









$AgReO_4$

$N_{ev} = 10^{10}$

$\Delta E = 20$ eV

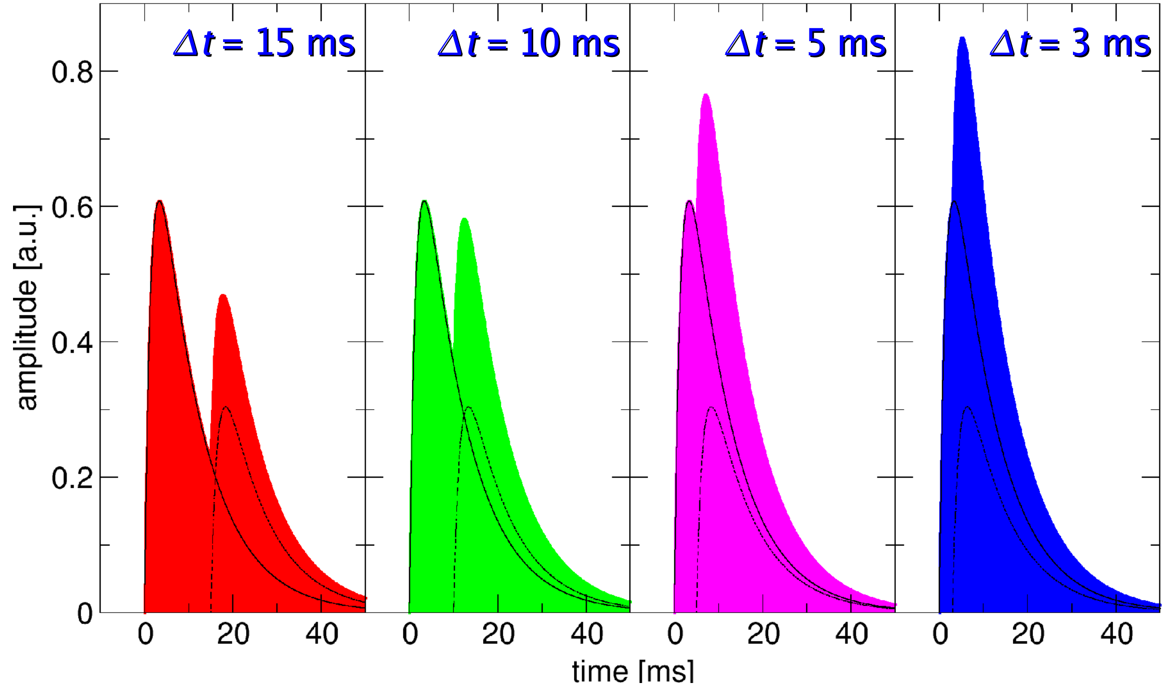
$f_{pp}=10^{-4}$

Pile-up (MANU)

$$A(t) = A\left(e^{-t/\tau_{decay}} - e^{-t/\tau_{rise}}\right)$$

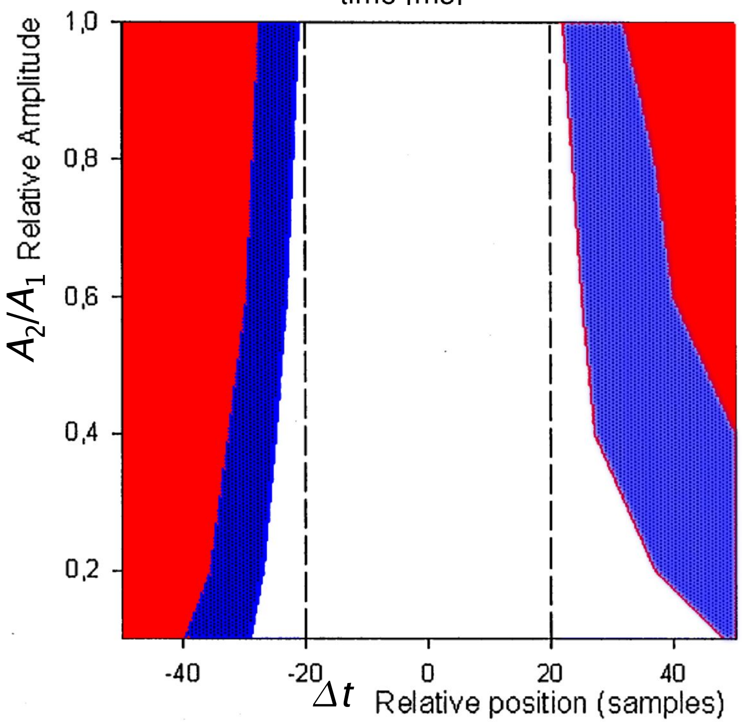
Example

- 2 pulses with:
  - τ_{rise} = 1.5 ms
  - τ_{decay} = 10 ms
  - A_2/A_1 = 0.5



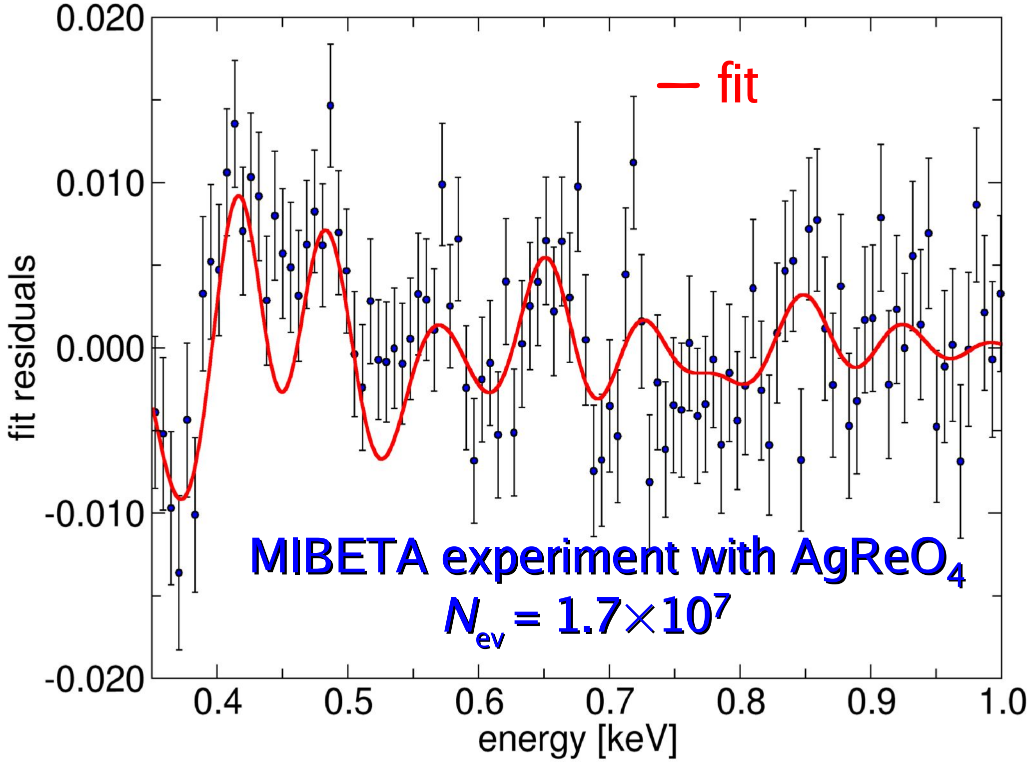
Montecarlo with simulated pulses

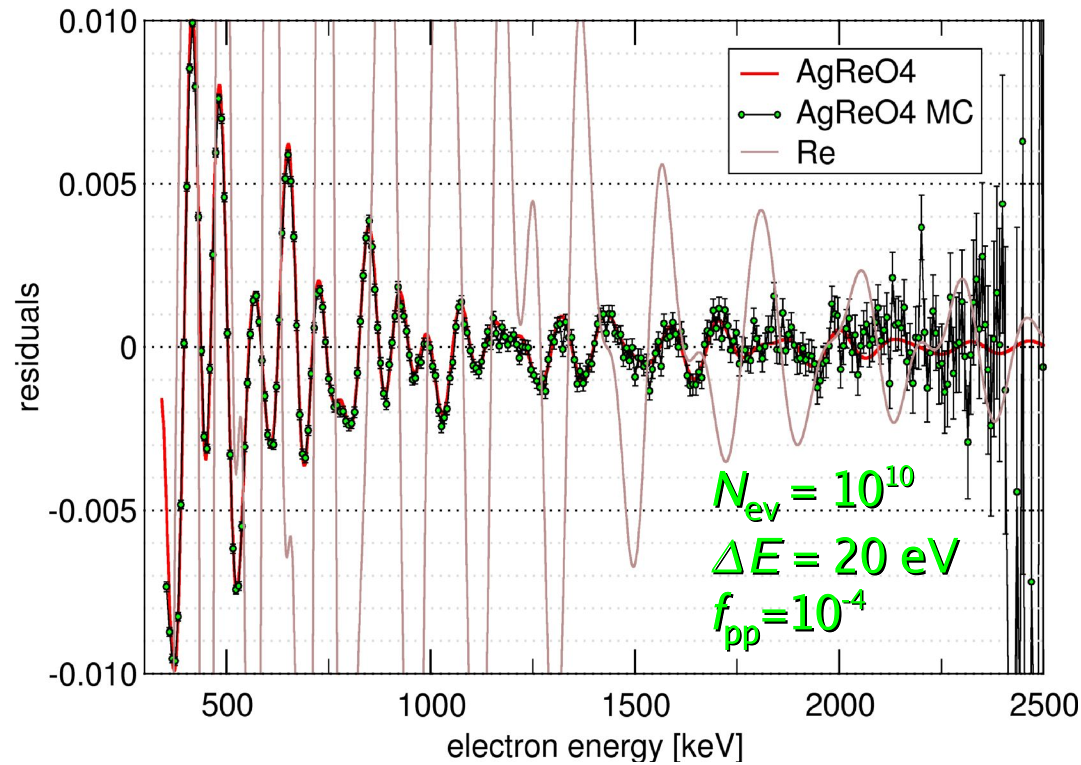
- $\tau_{rise} \approx$ 2 ms = 10 samples
  - resolving time $\tau_R = \tau_R\ (A_2/A_1, \Delta t) \approx \tau_{rise}$
  - source of systematics
- new MC tools and new algorithms

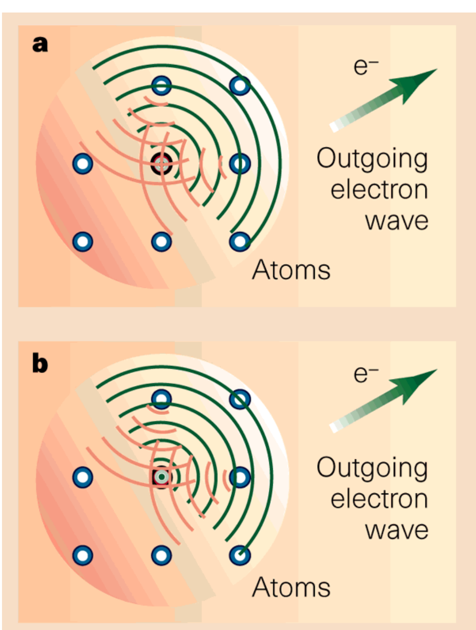


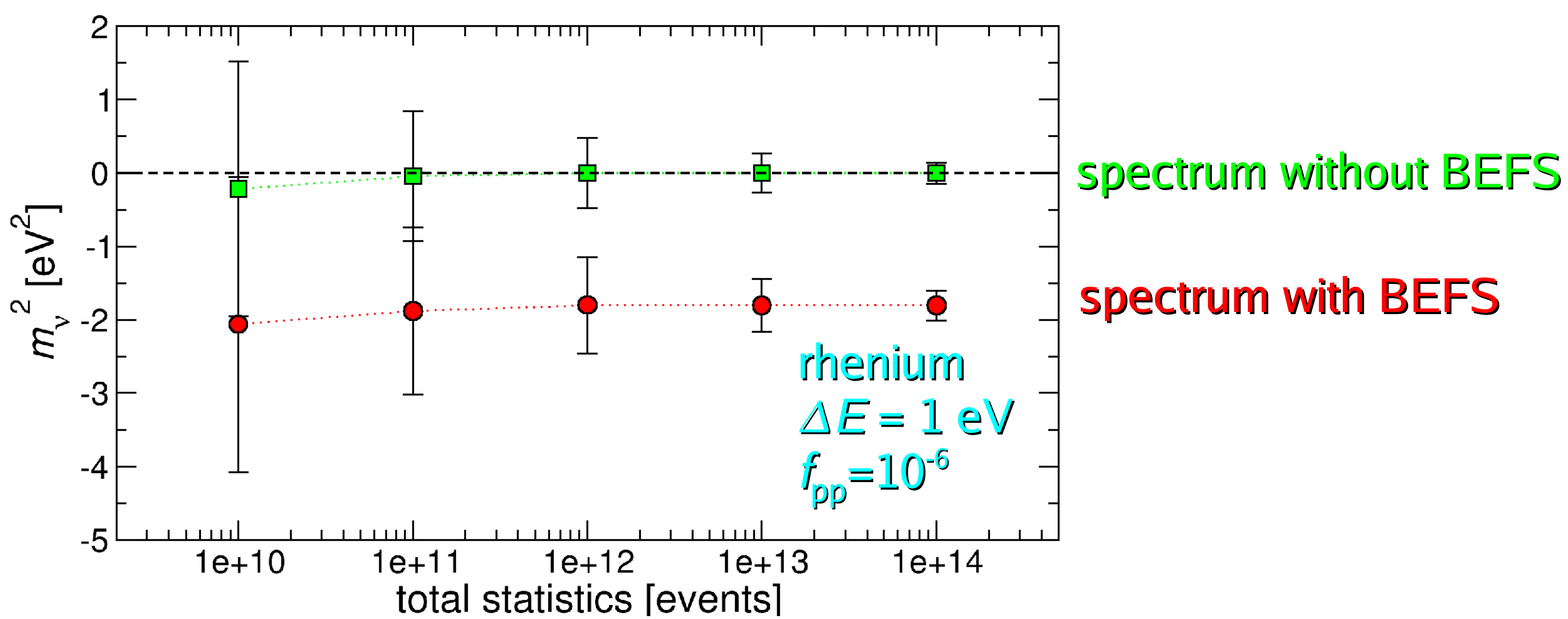
F. Fontanelli et al., NIM A 421 (1999) 464

MC analysis of systematics: BEFS









A better statistical analysis: analytical vs. MC

Montecarlo analysis

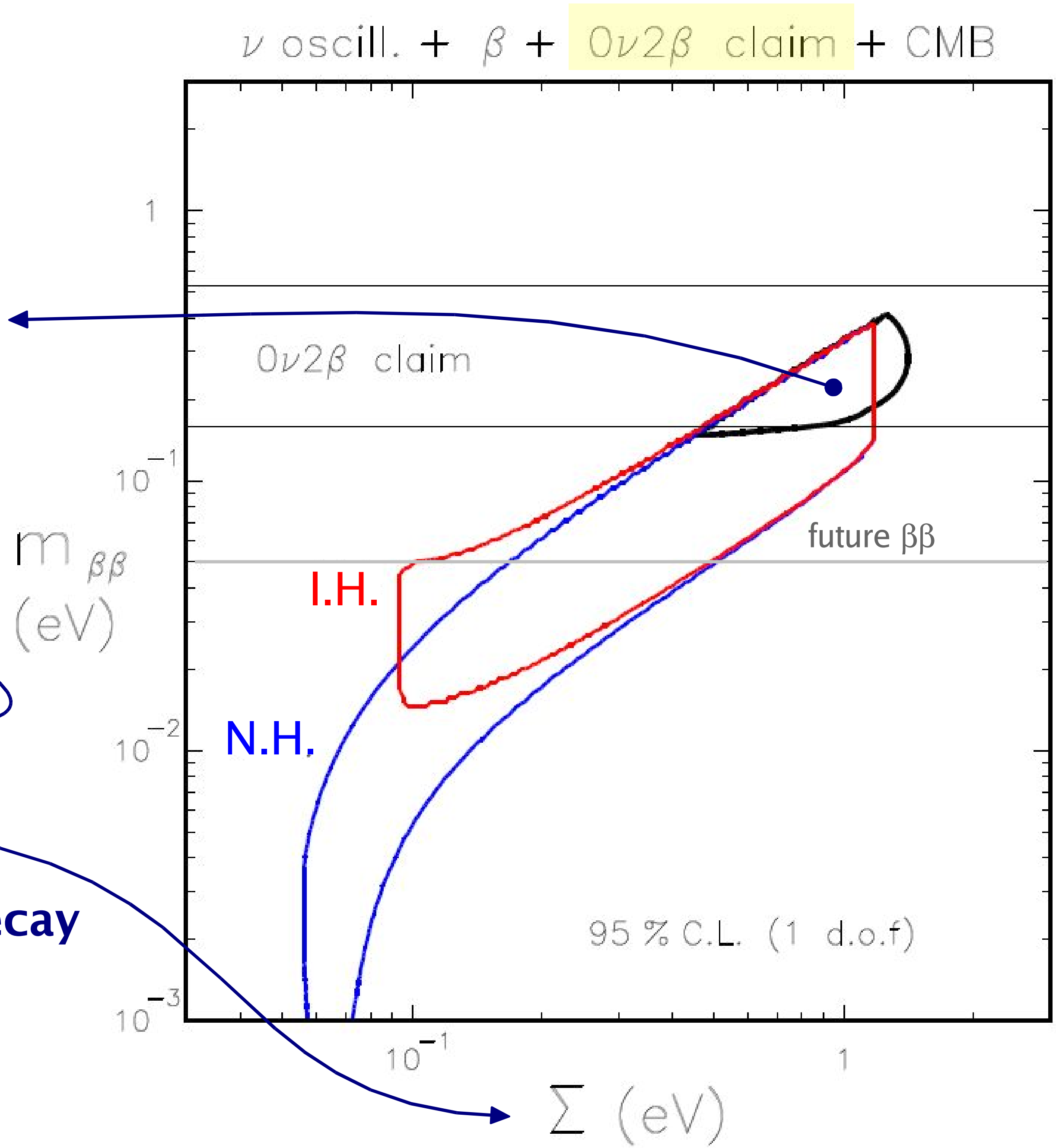
- **Many experiment MC simulation**
  - ▷ 90% C.L. m_ν sensitivity from $\sqrt{(1.64\ \sigma)}$ of m_ν^2 distributions
  - ▷ useful for statistical sensitivity and systematic effects analysis
- **Simulation inputs**
  - ▷ $N_{ev} = N_{det} \times t_M \times A_\beta$ total number of events
    - N_{det} number of detectors
    - t_M measuring time
    - A_β ^{187}Re activity for single detector
  - ▷ $f_{pile\text{-}up} \approx \tau_R \times A_\beta$ unresolved pile-up event fraction
    - $\tau_R \approx \tau_{rise}$ time resolution for pile-up identification
  - ▷ $g(E)$: detector energy resolution function (usually gaussian)
    - ΔE FWHM detector energy resolution

- Assessing systematic uncertainties with Montecarlo simulations
  - ▷ generate simulated experimental spectra with systematic effect
  - ▷ analyze spectra without effect
  - ▷ obtain Δm_ν^2<0 as function of effect magnitude

Neutrinos masses in single β and ββ-0ν decays

$m_1 \simeq m_2 \simeq m_3 \in [0.16, 0.46]$ eV

$m_\beta \in [0.16, 0.46]$ eV



$m_{\beta\beta} \equiv |\sum m_i U_{ei}^2|$ from ***ββ-0ν***

$\Sigma \equiv m_\Sigma \equiv \sum m_i$ from **CMB**

$m_\beta \equiv m_\nu \equiv (\sum m_i^2 |U_{ei}|^2)^{1/2}$ from ***β*** **decay**

Fogli et al., Phys. Rev. D 78, 033010 (2008)

^{187}Re calorimetric experiment statistical sensitivity

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

$\Sigma(m_\nu) \approx$ **20 eV**

1/10

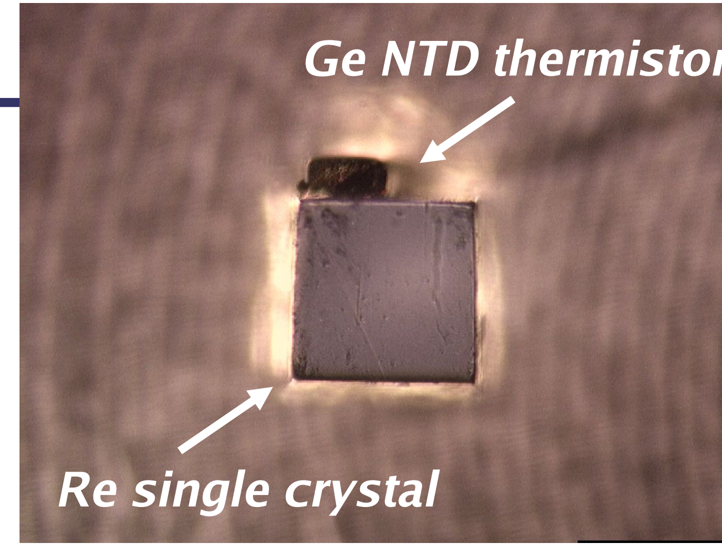
$\Sigma(m_\nu) =$ **2 eV**

1/10

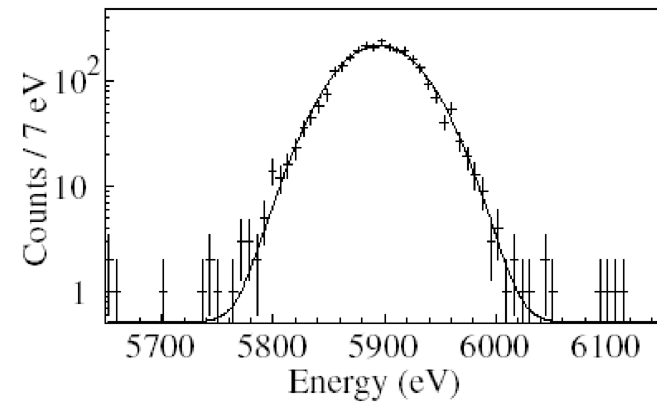
$\Sigma(m_\nu) =$ **0.2 eV**

- MIBETA detectors with $\Delta E_{FWHM} =$ **30 eV**, $\tau_R = 1.5$ ms
  - ▷ pile-up dominates for $A_\beta \gg$ 0.1 decay/s
  - ▷ for A_β = 0.15 decay/s and t_M = 3.6 y×det (1.7×10^6 evts)
    - ⇒ $\Sigma(m_\nu) = 14.7$ eV
- detectors with $\Delta E_{FWHM} =$ **10 eV**, $\tau_R = 100\ \mu$s
  - ▷ pile-up dominates for $A_\beta \gg$ 0.7 decay/s
  - ▷ for A_β = 0.5 decay/s < 0.7 decay/s
    - ⇒ $\Sigma(m_\nu) = 2$ eV in t_M = 1450 y×det (2.3×10^{10} evts)
- detectors with $\Delta E_{FWHM} =$ **1 eV**, $\tau_R = 1\ \mu$s
  - ▷ pile-up dominates for $A_\beta \gg$ 3 decay/s
  - ▷ for A_β = 1 decay/s < 3 decay/s
    - ⇒ $\Sigma(m_\nu) = 0.2$ eV in $t_M = 1.3\times10^6$ y×det (4×10^{13} evts)

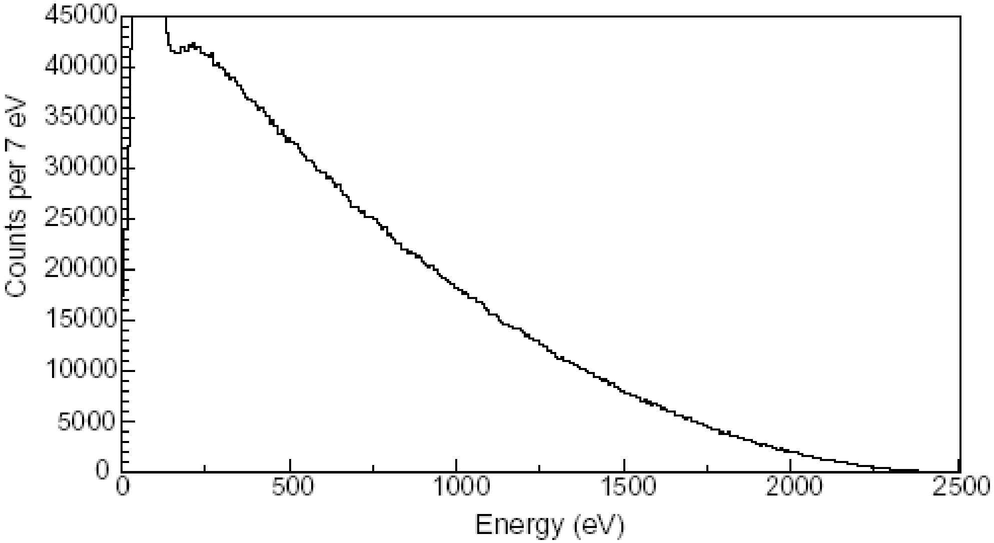
MANU experiment (1999)

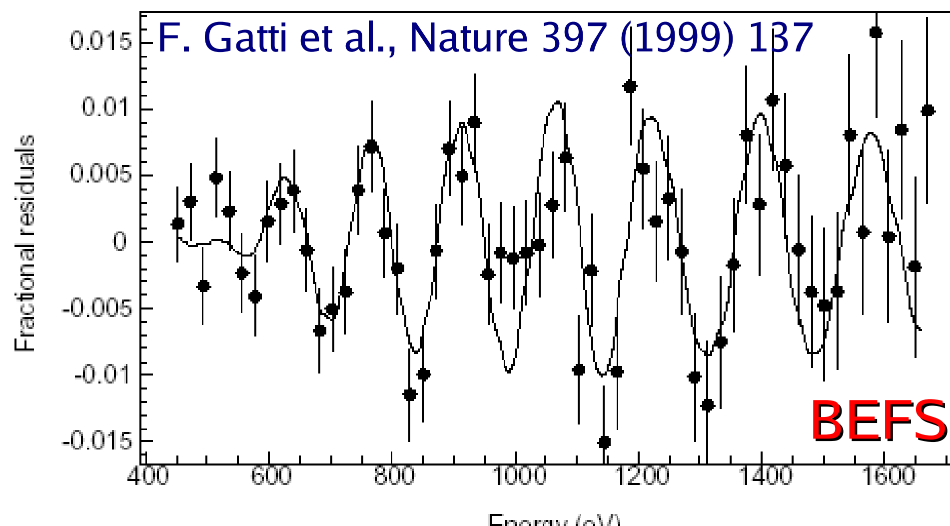


- 1.6 mg metallic rhenium single crystal
- one detector only
- Ge-NTD thermistor
  - ▷ ΔE=96 eV FWHM
  - ▷ symmetric and without tails
- 0.5 years live-time
  - ▷ 6.0×10^{6} ^{187}Re decays above 420 eV
  - ▷ $m_{\nu}^{2} = -462\ ^{+579}_{-679}\ \mathrm{eV}^2$
  - ▷ **m_{ν} < 26 eV (95 % C.L.)**
- first observation of BEFS in ^{187}Re decay

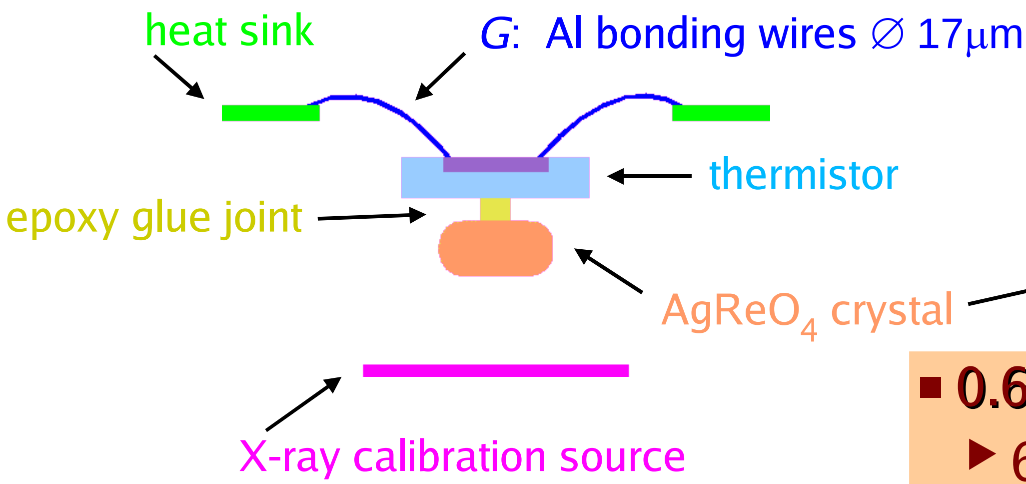


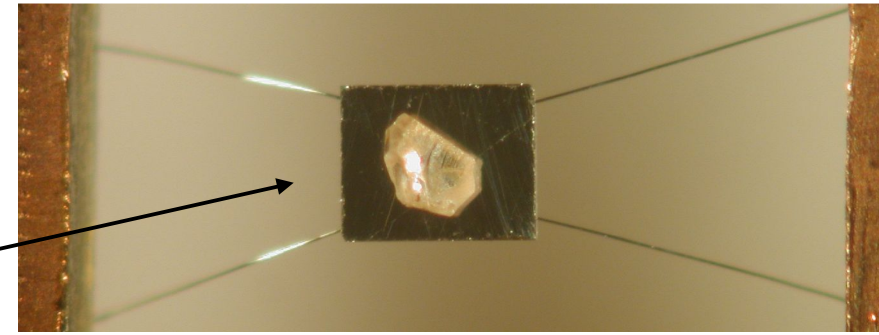
M. Galeazzi et al., Phys. Rev. C 63, 014302 (2001)
F. Gatti, Nucl. Phys. B 91, 293 (2001)





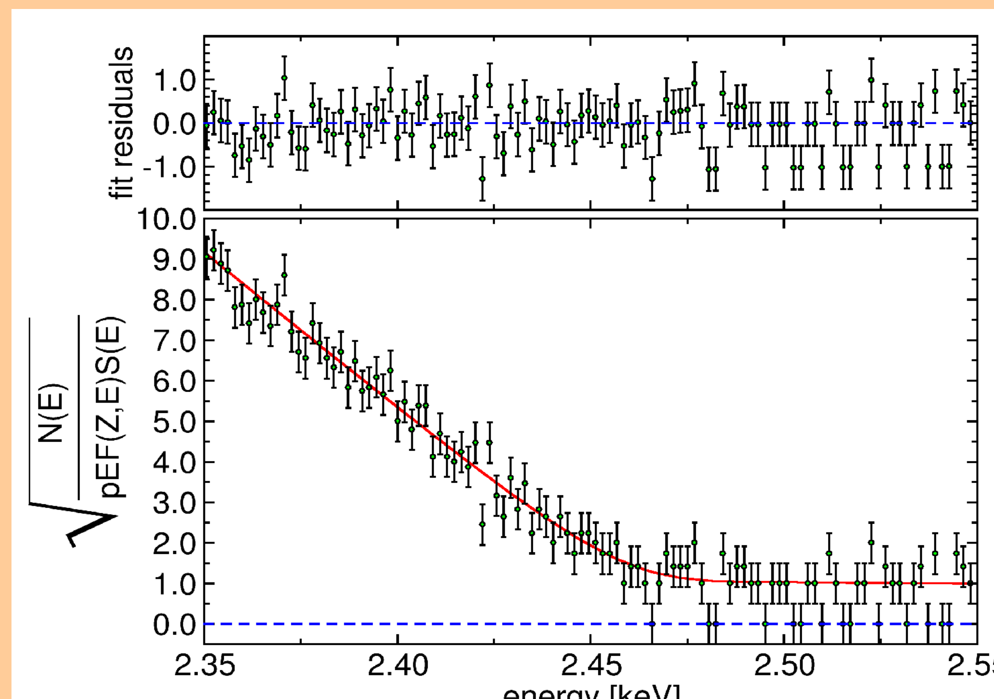
MIBETA experiment: 2002/03





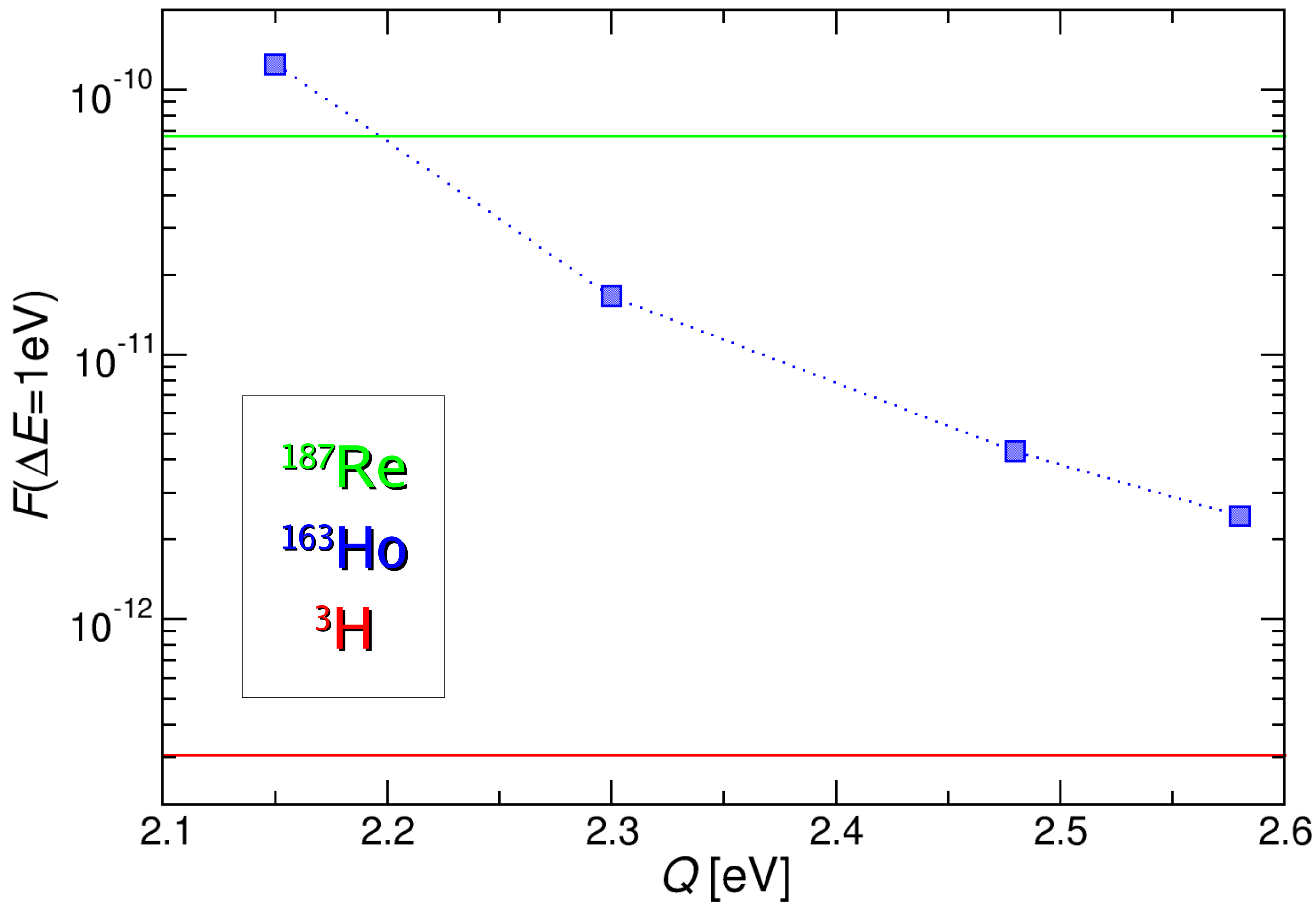
- Si-implanted thermistors (ITC-irst)
- $AgReO_4$ single crystals
  - ^{187}Re activity A_β = 0.54 dec/mg/s
- 10 microcalorimeter array
  - $\langle m_{AgReO_4} \rangle = 271\ \mu g$
    - $\langle A_\beta \rangle$ = 0.15 decay/s
    - m_{tot} = 2.71 mg
  - $\langle \Delta E_{FWHM} \rangle$ = 28.5 eV
  - $\langle \tau_{rise} \rangle = 490\ \mu s$
    - $f_{pile\text{-}up} \approx 2\times10^{-4}$

- 0.6 years live time (0.45 years only β)
  - 6.2×10^6 ^{187}Re decays above 700 eV
  - $m_\nu^2 = -96 \pm 189_{stat} \pm 63_{sys}$ eV^2
  - **$m_\nu < 15.2 \pm 2.0_{sys}$ eV (90 % C.L.)**

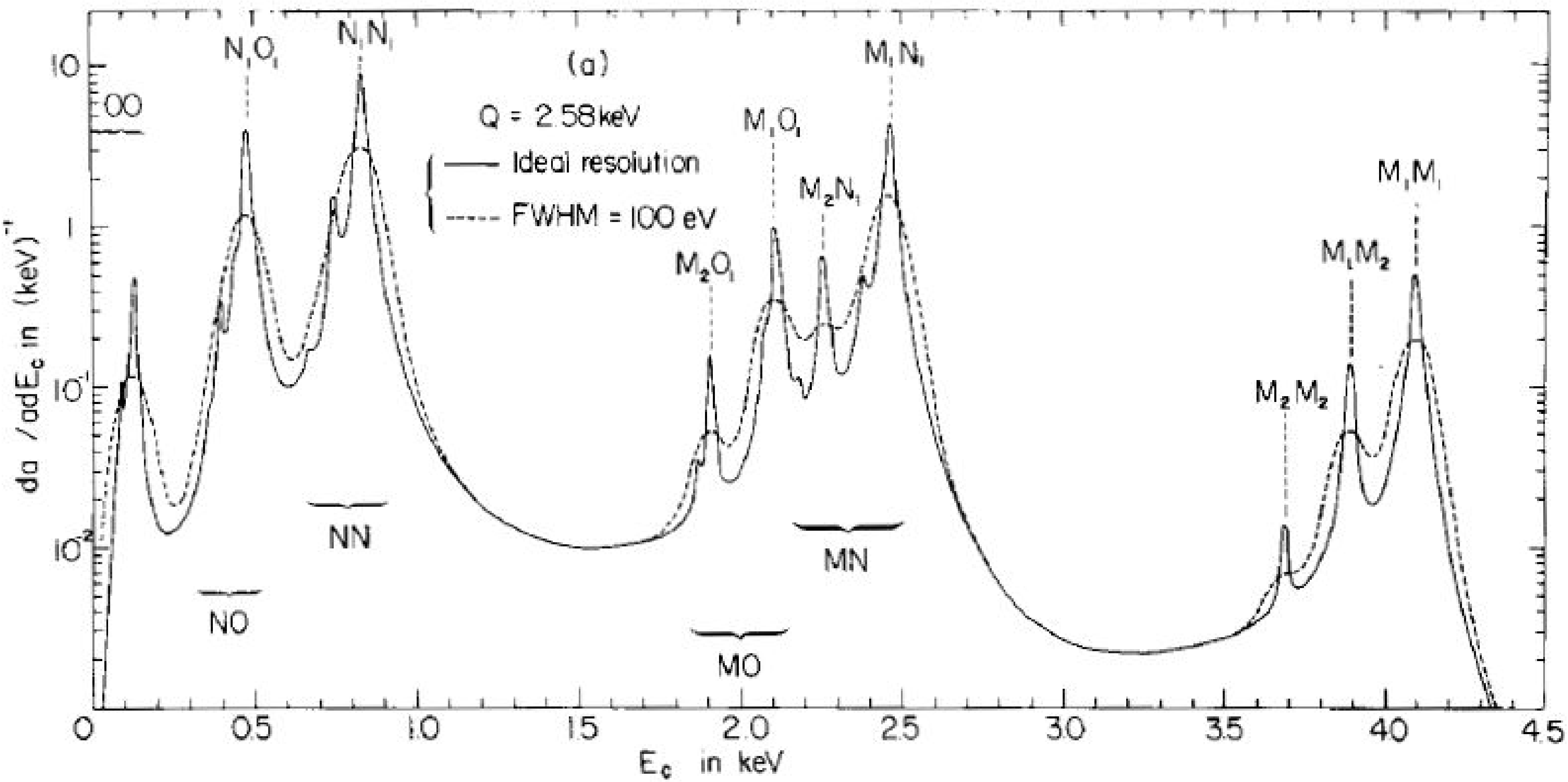


C. Arnaboldi et al., Phys. Rev. Lett. 91 (2003) 161802
M. Sisti et al, NIM A 520 (2004) 125

^{163}Ho end-point statistics



^{163}Ho pile-up spectrum



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