the MARE project: the calorimetric approach potential

Angelo Nucciotti

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

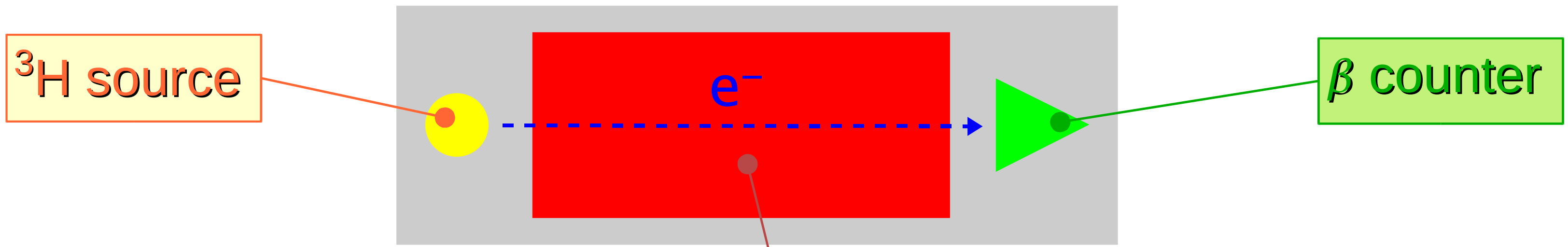
- direct neutrino mass measurement
  - spectrometers vs. calorimeters
  - calorimeter statistical sensitivity
- ^{187}Re calorimetric experiment state-of-the-art
- future of calorimetric experiments: the MARE project
- MARE project status
  - MARE-1 and MARE R&D

New Instruments for Neutrino Relics and Mass

08 December 2008

Experimental approaches for direct measurements

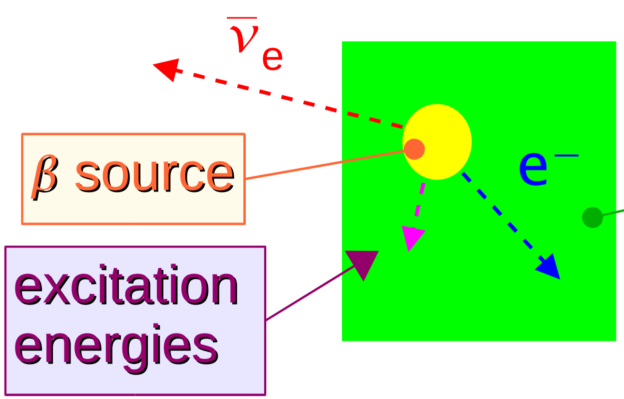
Spectrometers: source ≠ detector



β analyzer

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

Calorimeters: source ⊆ detector



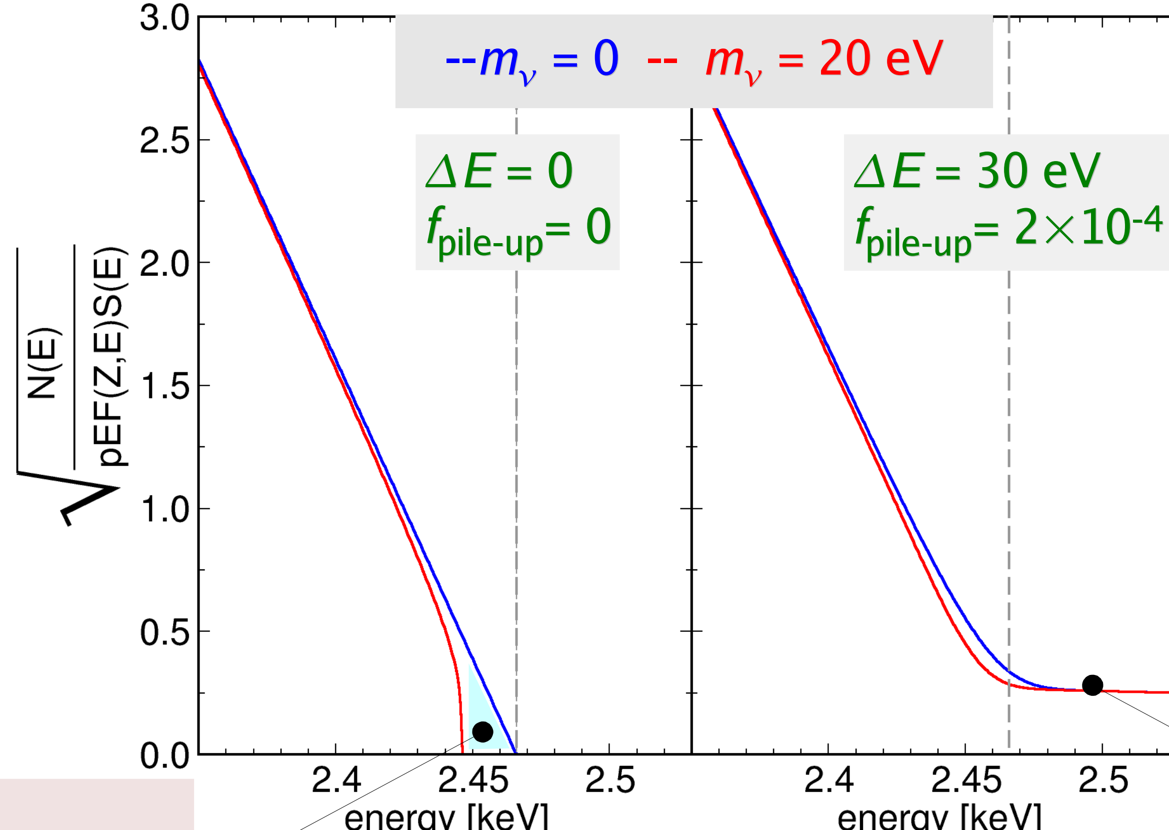
β calorimeter

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

Calorimetry of beta sources

- calorimeters measure the entire spectrum at once
  - use low E_0 β decaying isotopes to achieve enough statistics near the end-point
  - best choice ^{187}Re: **E_0 = 2.47 keV** $\Rightarrow$ $F(\delta E{=}10\ \text{eV}) \sim 2\,(\delta E/E_0)^3 = 1.3\times10^{-7}$

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

$$F(\delta E) \approx 2\left(\frac{\delta E}{E_0}\right)^3$$

Pile-up

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

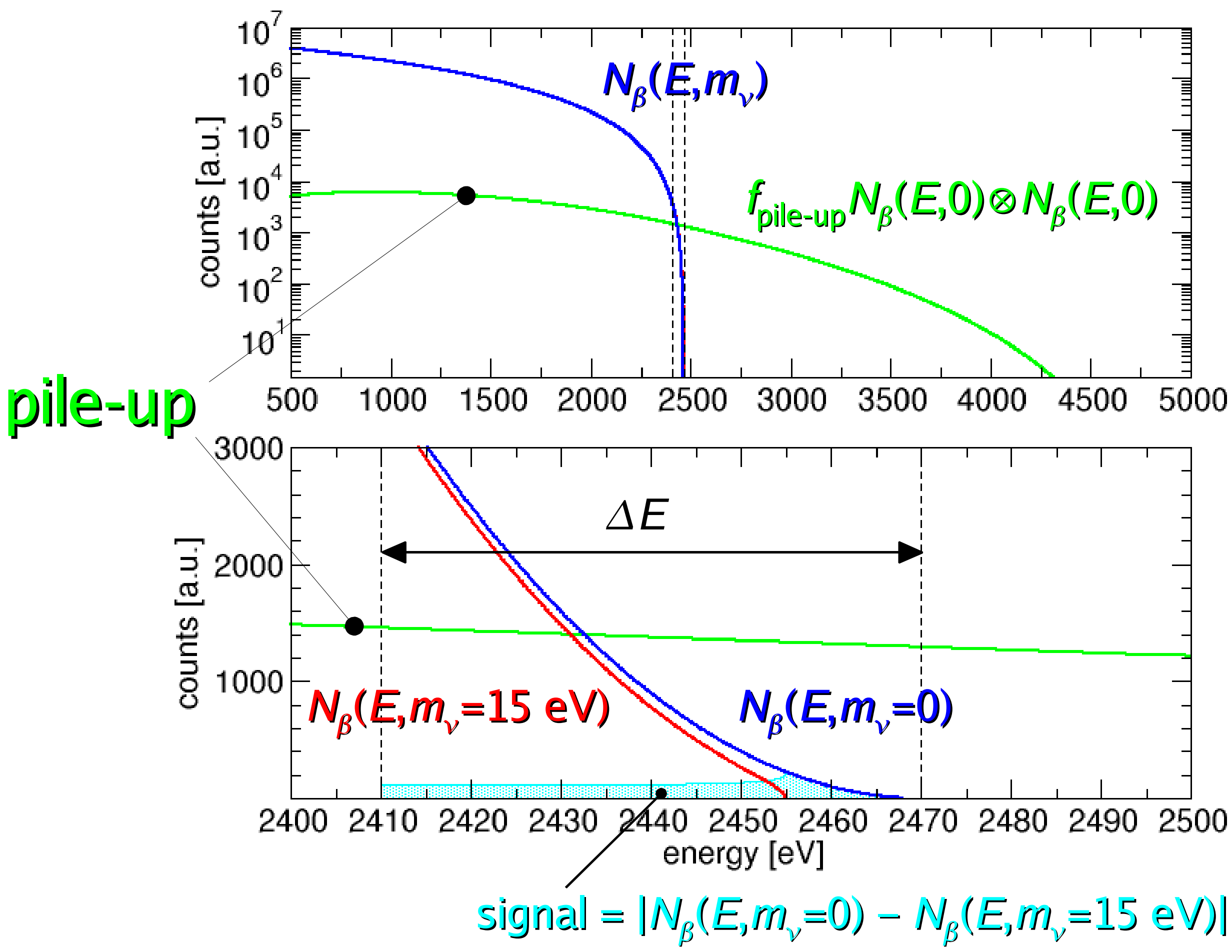
$$N^{\exp}(E) \approx (N(E) + \tau_R A_\beta \cdot N(E) \otimes N(E)) \otimes R(E)$$

Calorimetric experiment statistical sensitivity / 1

resolving time τ_R energy resolution ΔE_{FWHM}

optimal energy interval for analysis $\Delta E \approx 2\Delta E_{FWHM}$

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



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

$$F_{\Delta E}(0) \approx 2A_\beta \frac{\Delta E^3}{E_0^3}$$

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

$$F_{\Delta E}^{pp} \approx \tau_R A_\beta^2 \int_{E_0-\Delta E}^{E_0} N_\beta(E,0) \otimes N_\beta(E,0)\,dE \approx \frac{9}{5}\tau_R A_\beta^2 \frac{\Delta E}{E_0}$$

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

Calorimetric experiment statistical sensitivity / 2

$$\frac{\text{signal}}{\text{background}} = \frac{\left|F_{\Delta E}(m_\nu) - F_{\Delta E}(0)\right| t_M}{\sqrt{F_{\Delta E}(0) t_M + F^{pp}_{\Delta E} t_M}} = \sqrt{t_M}\,\frac{2A_\beta \dfrac{\Delta E^3}{E_0^3}\dfrac{3m_\nu^2}{2\Delta E^2}}{\sqrt{2A_\beta \dfrac{\Delta E^3}{E_0^3} + \dfrac{9}{5}\tau_R A_\beta^2 \dfrac{\Delta E}{E_0}}} = 1.7 \text{ for } 90\% \text{ C.L.}$$

$$\Sigma_{90}(m_\nu) \approx 0.74 \sqrt[4]{\frac{2E_0^3 \Delta E}{A_\beta t_M} + \frac{9\tau_R E_0^5}{5 t_M \Delta E}}$$

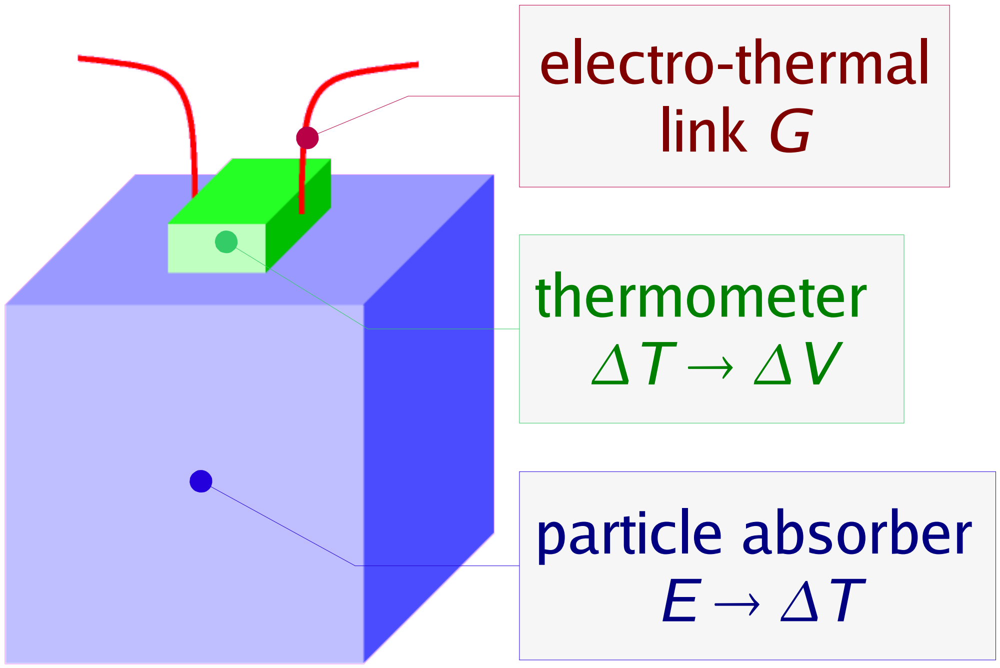
$$f_{pile-up} = \tau_R A_\beta \ll \frac{\Delta E^2}{E_0^2}$$ ⇒ pile-up is negligible

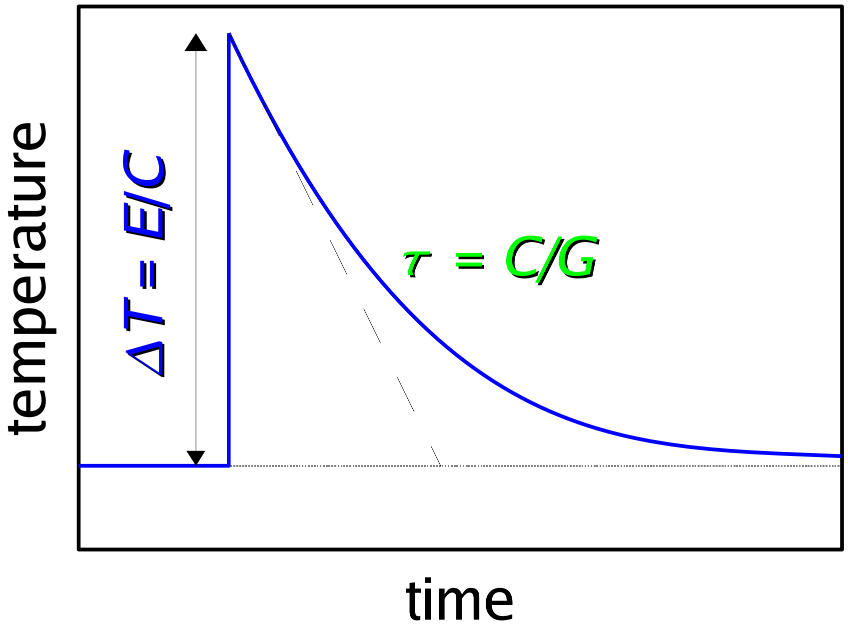
$$\Sigma_{90}(m_\nu) \approx 0.89 \sqrt[4]{\frac{E_0^3 \Delta E}{A_\beta t_M}}$$

experimental challenges

- energy resolution ΔE
- 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

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_ν < ≈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!

^{187}Re calorimetric experiment statistical sensitivity

$$\Sigma_{90}(m_\nu) \approx 0.89 \sqrt[4]{\frac{E_0^3 \Delta E}{A_\beta t_M}}$$ (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**, τ_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**, τ_R=100 μs
  - ▷ 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**, τ_R=1 μs
  - ▷ 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 = 13×10^6 y×det (4×10^{13} evts)

A better statistical analysis: analytical vs. MC

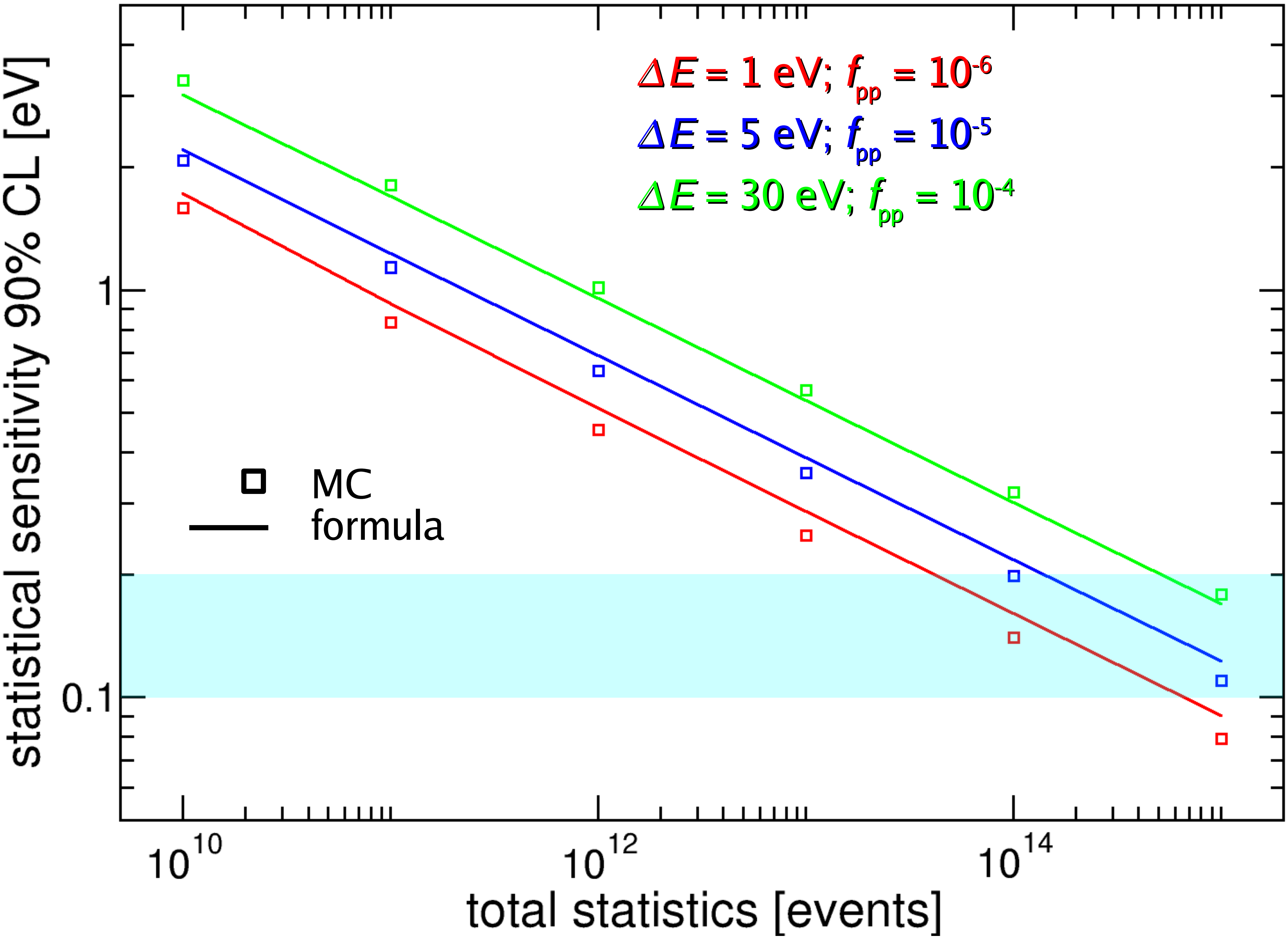
Montecarlo analysis

- **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
  - ▷ $f_{pile\text{-}up} \approx \tau_R \times A_\beta$ pile-up event fraction
    - $\tau_R \approx \tau_{rise}$ time resolution for pile-up identification
  - ▷ $g(E)$: gaussian energy resolution function
    - ΔE FWHM detector energy resolution

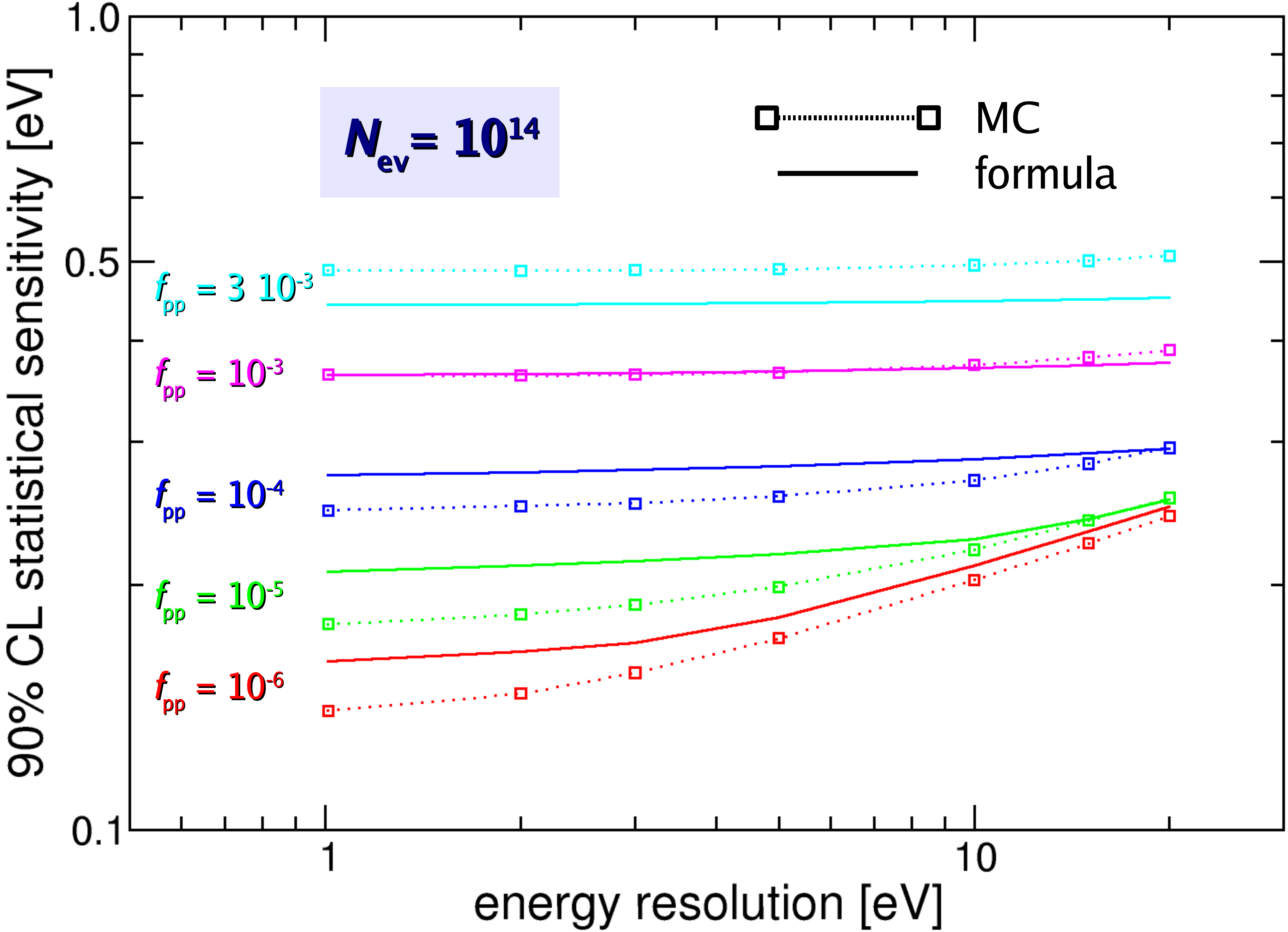
to be compared with a better expression for the statistical sensitivity:

$$\Sigma_{90}(m_\nu) = \sqrt{\frac{71\Delta E_{\rm opt}^2 N_{\rm ev} - 7.5\sqrt{84\Delta E_{\rm opt}^4 N_{\rm ev}^2 - 17\Delta E_{\rm opt} N_{\rm ev} Q^3\sqrt{\frac{10 f_{\rm pp}\Delta E_{\rm opt} N_{\rm ev} Q^2 + 31\Delta E_{\rm opt}^3 N_{\rm ev}}{Q^3}}}}{35 N_{\rm ev}}}$$

Sub-eV m_ν statistical sensitivity

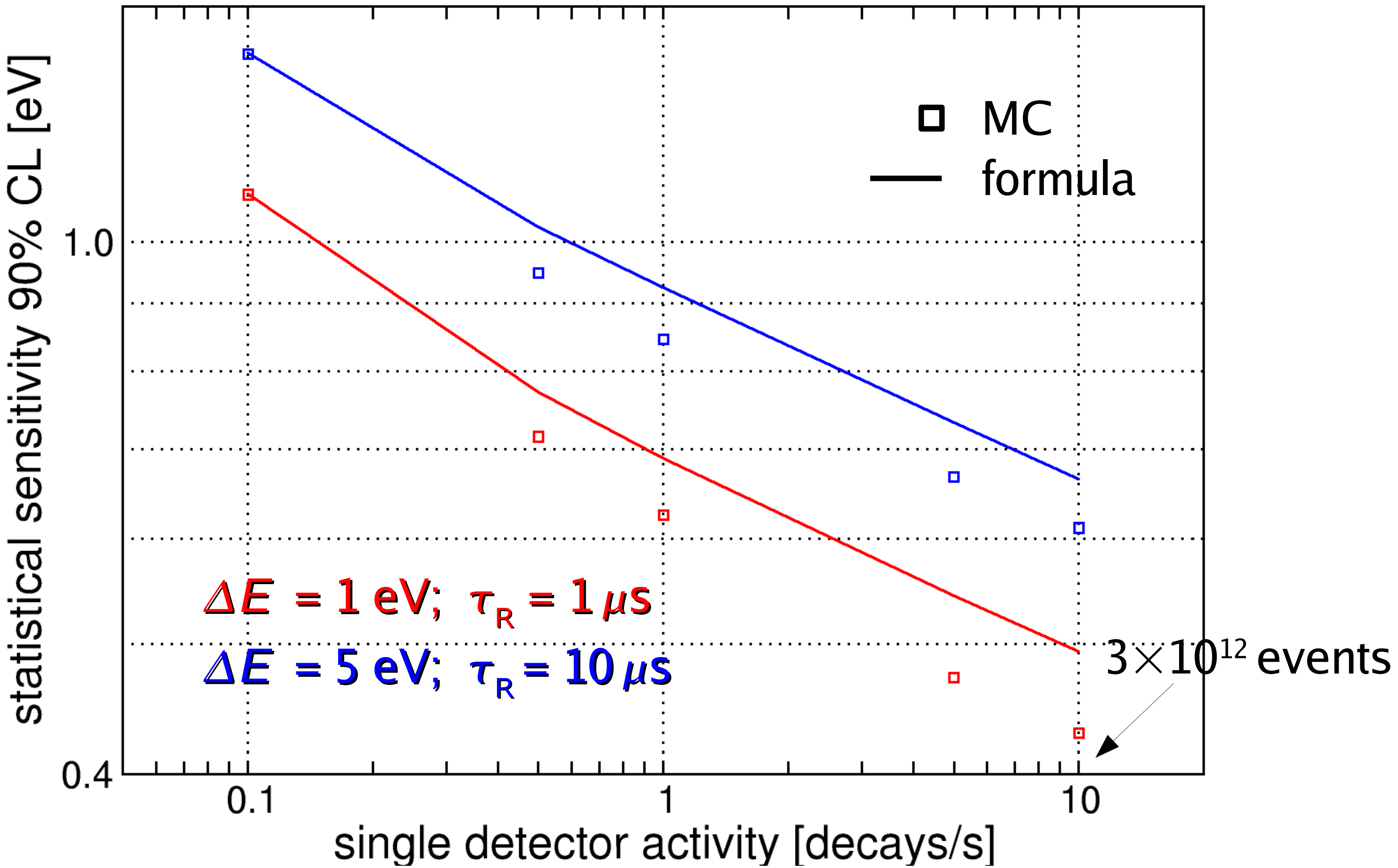


Sub-eV m_ν statistical sensitivity



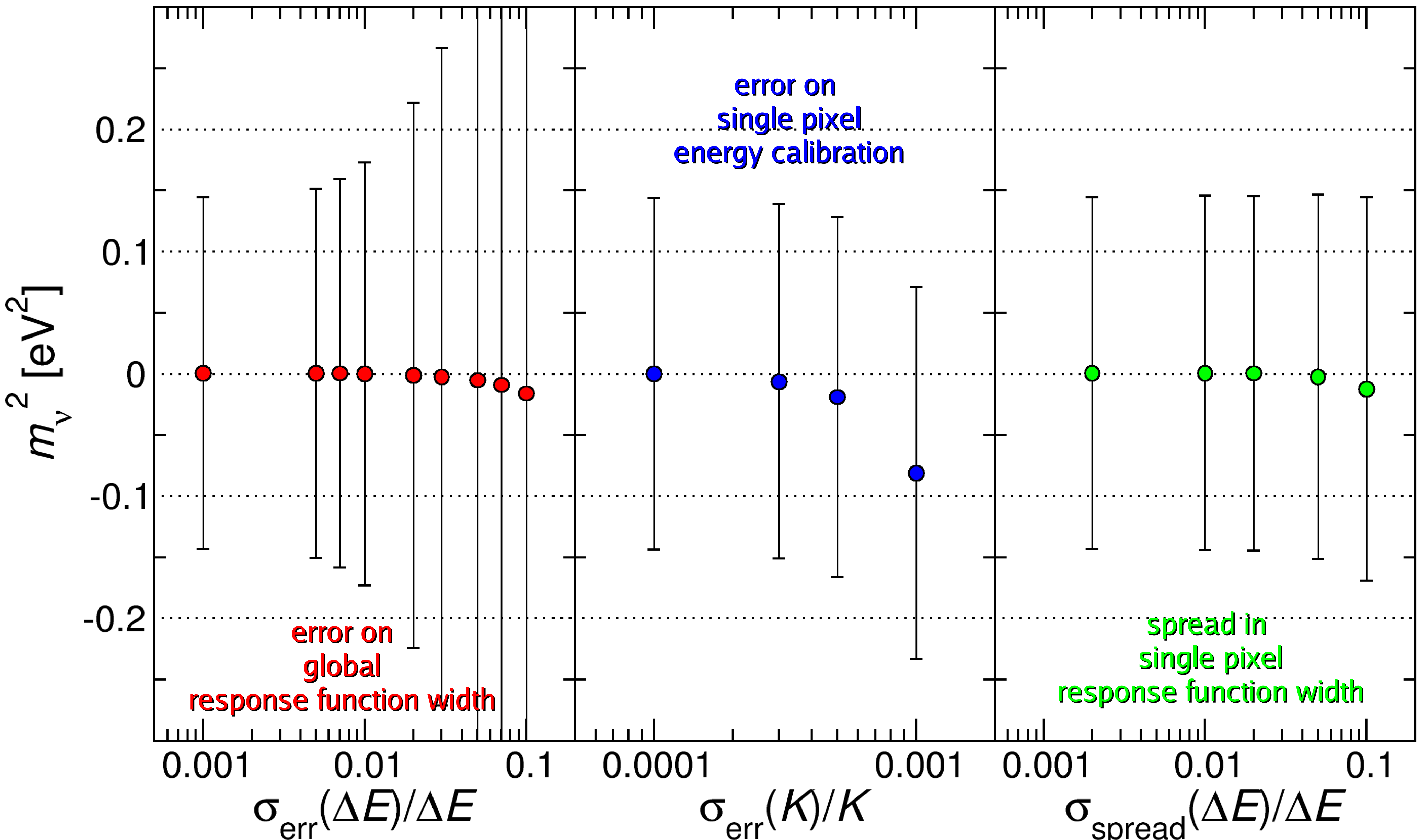
Sub-eV m_ν statistical sensitivity / 3

t_M = 10000 year × detector

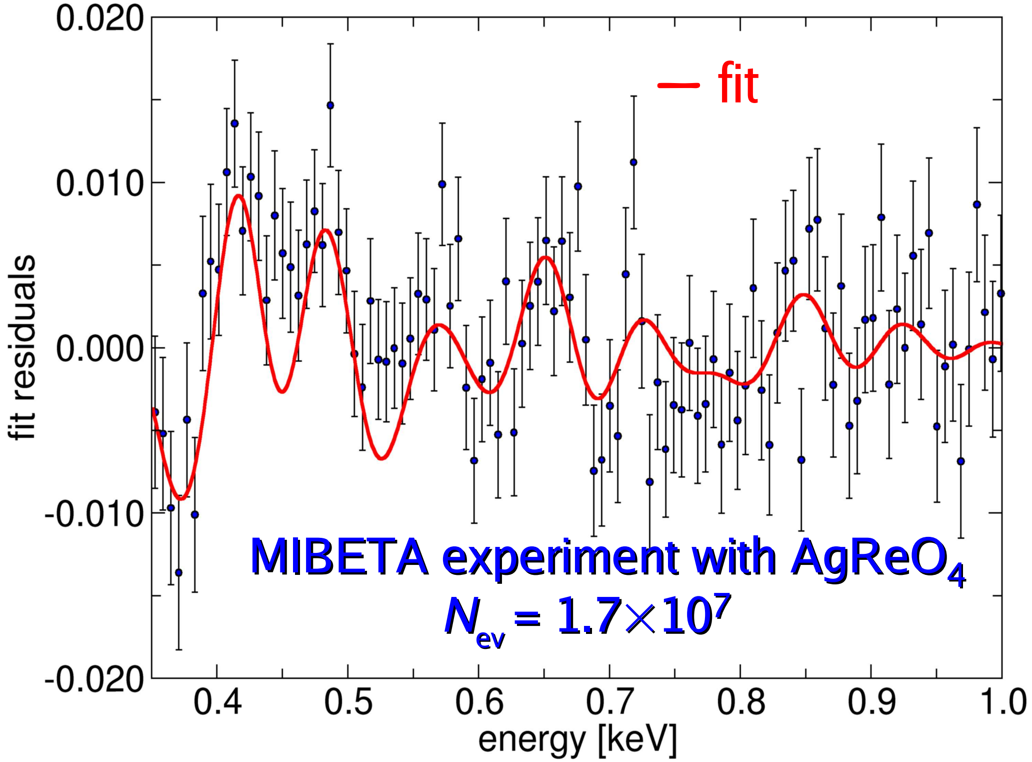


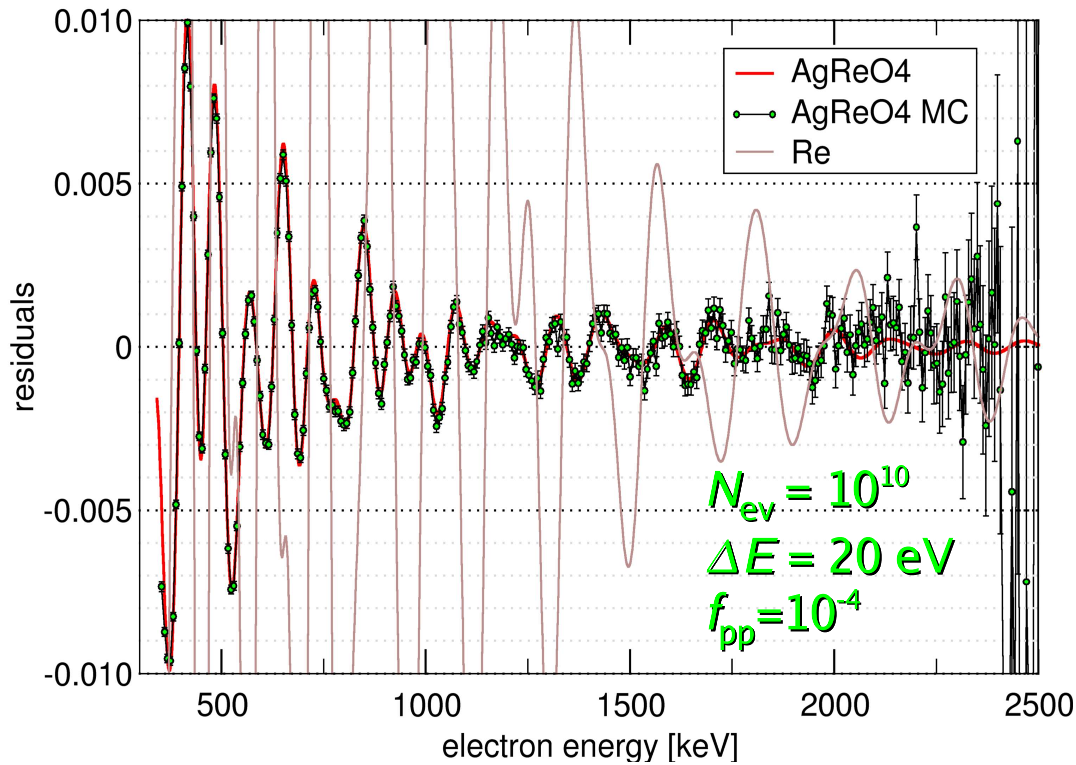
MC analysis of systematics: large arrays

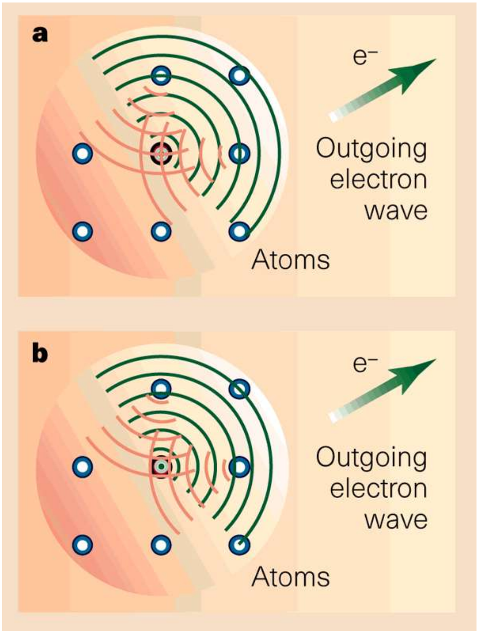
ΔE = 1 eV; $f_{pp} = 10^{-6}$; $N_{ev} = 10^{14}$

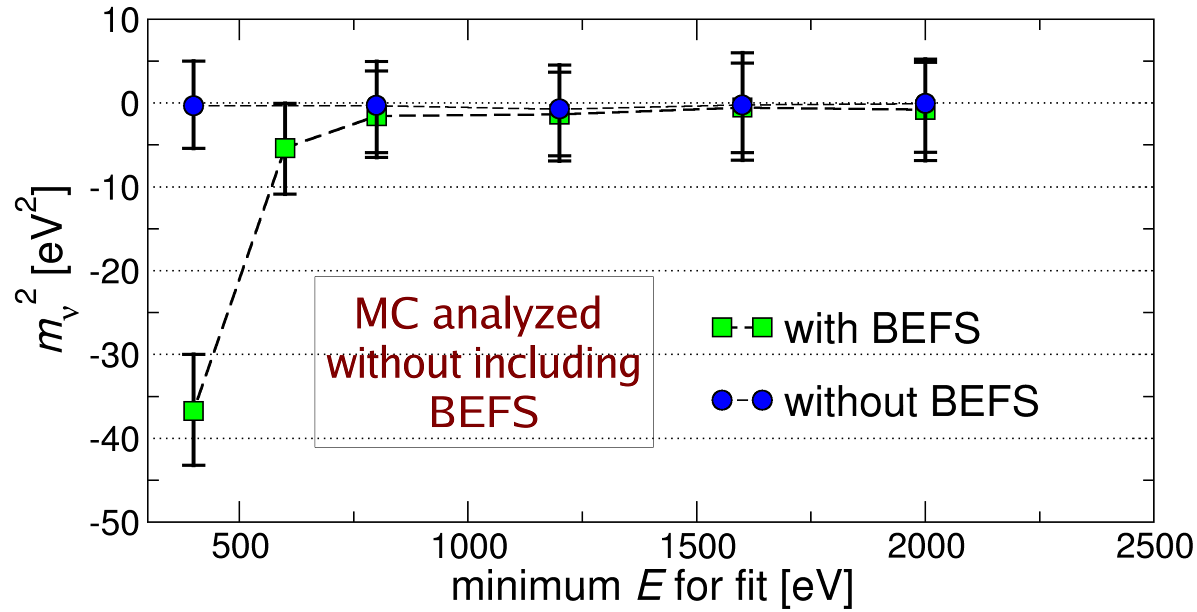


MC analysis of systematics: BEFS









$AgReO_4$

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

$\Delta E = 20$ eV

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

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 Collaboration

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

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

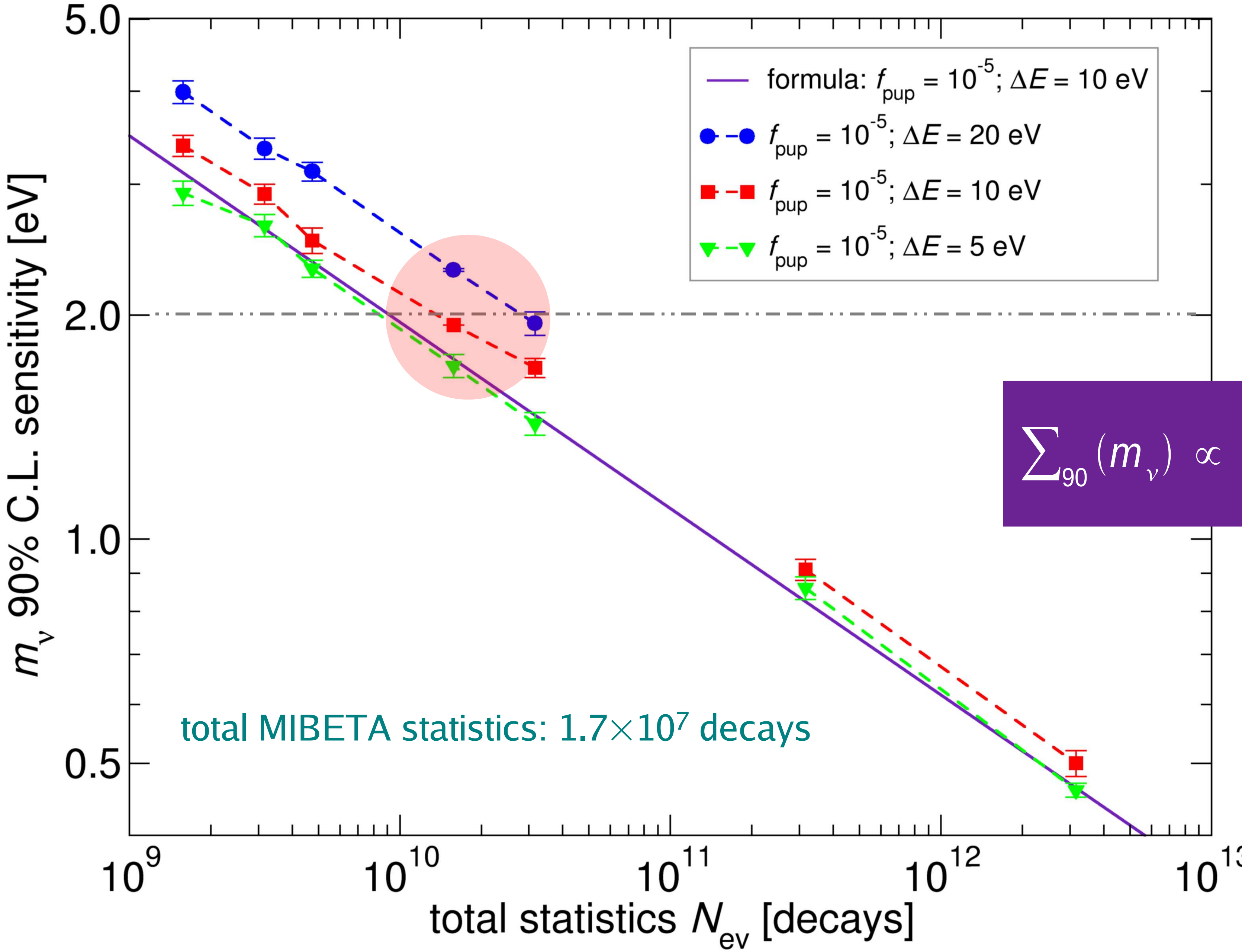
MARE-1 TES
(MANU2)

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

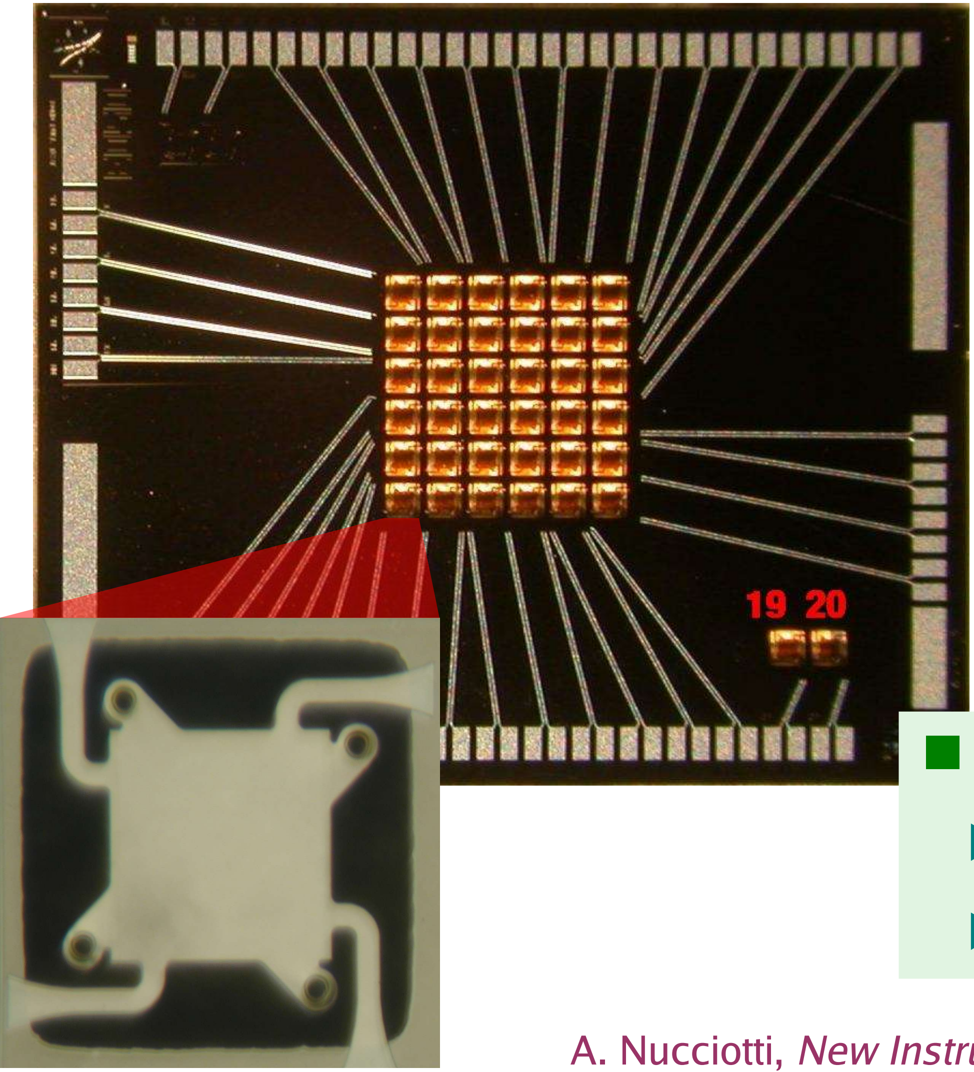


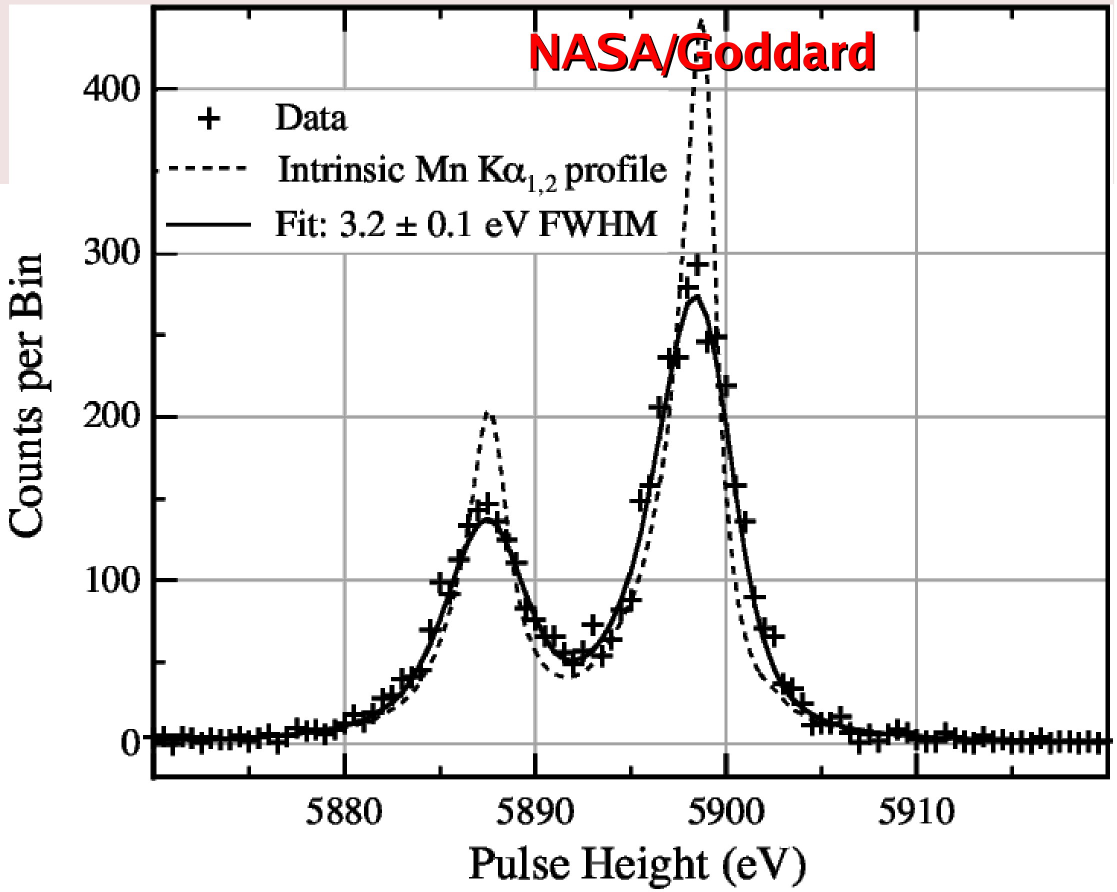
$$\sum\nolimits_{90}(m_\nu) \propto \sqrt[4]{\frac{1}{N_{ev}}}$$

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

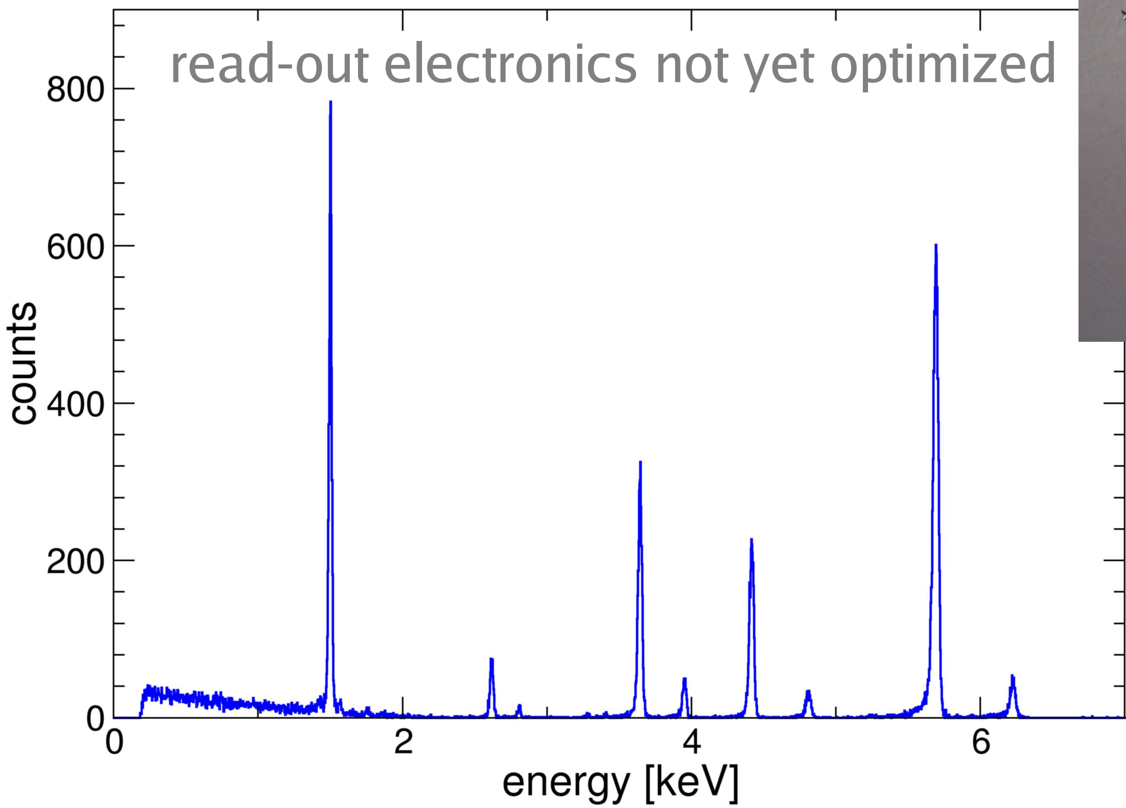


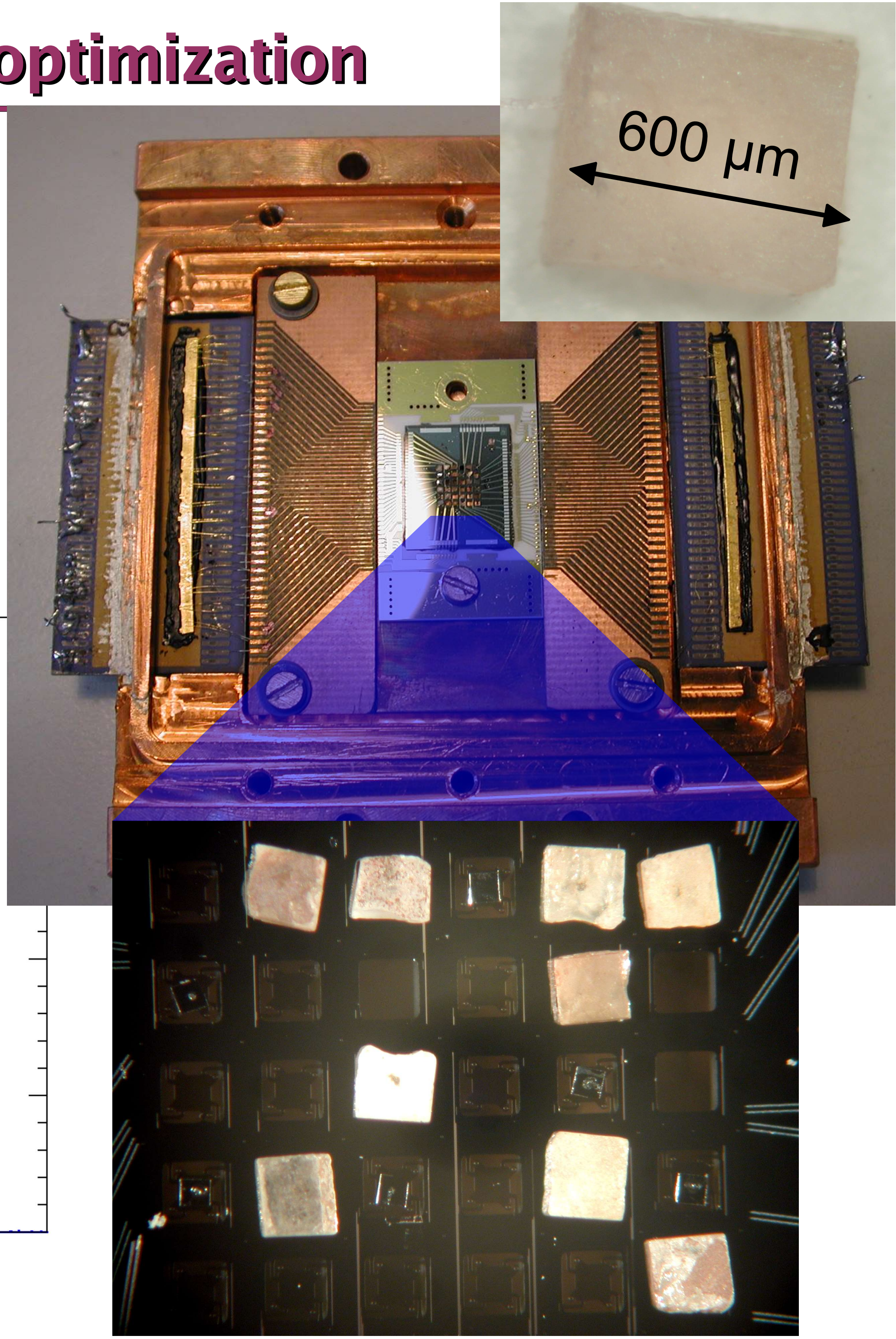


- MARE-1 SEMICON detectors
  - $AgReO_4$ has larger heat capacity
  - operating temperature must be higher

MARE-1 SEMICON detector optimization

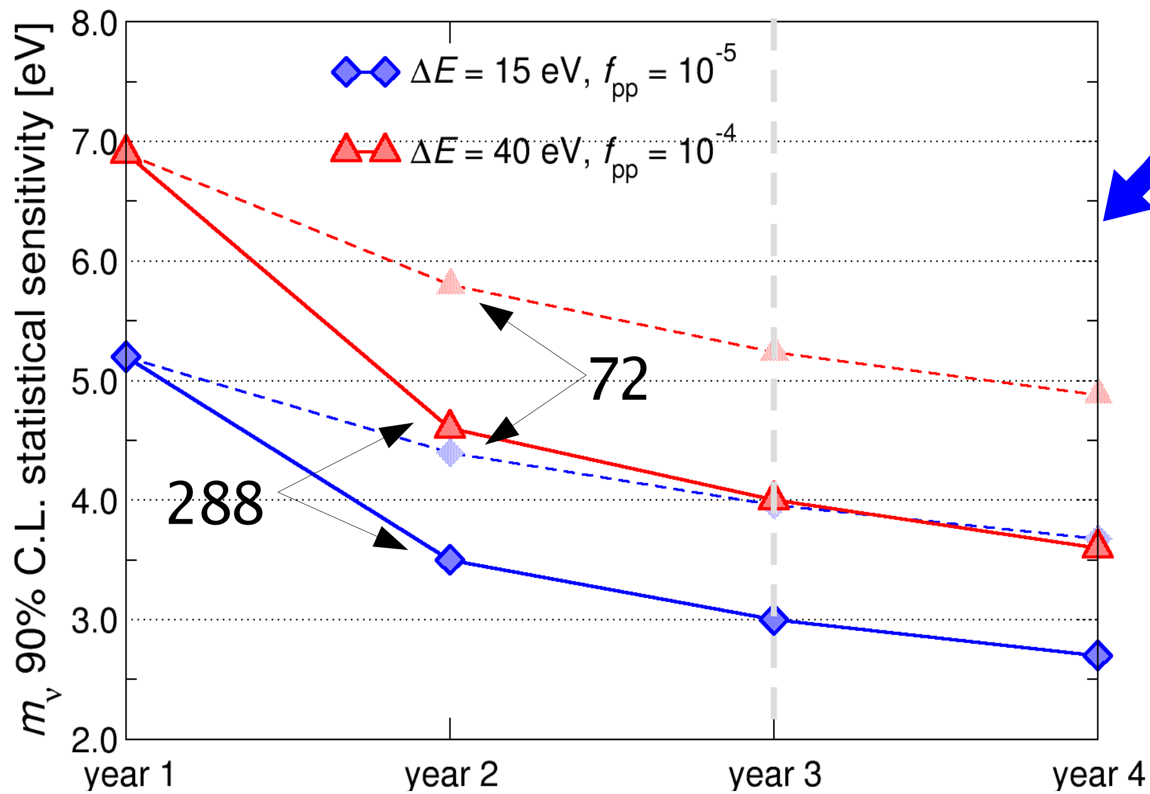
- NASA/Goddard array XRS2-2 C3
- testing $AgReO_4$ "flattened" crystals
  - ▷ *m* ≈0.5 mg
- crystal-sensor coupling tests
  - ▷ best operating *T* around 90mK
  - ▷ **$\Delta E \approx$ 30 eV, $\tau_R \approx$ 250 μs**



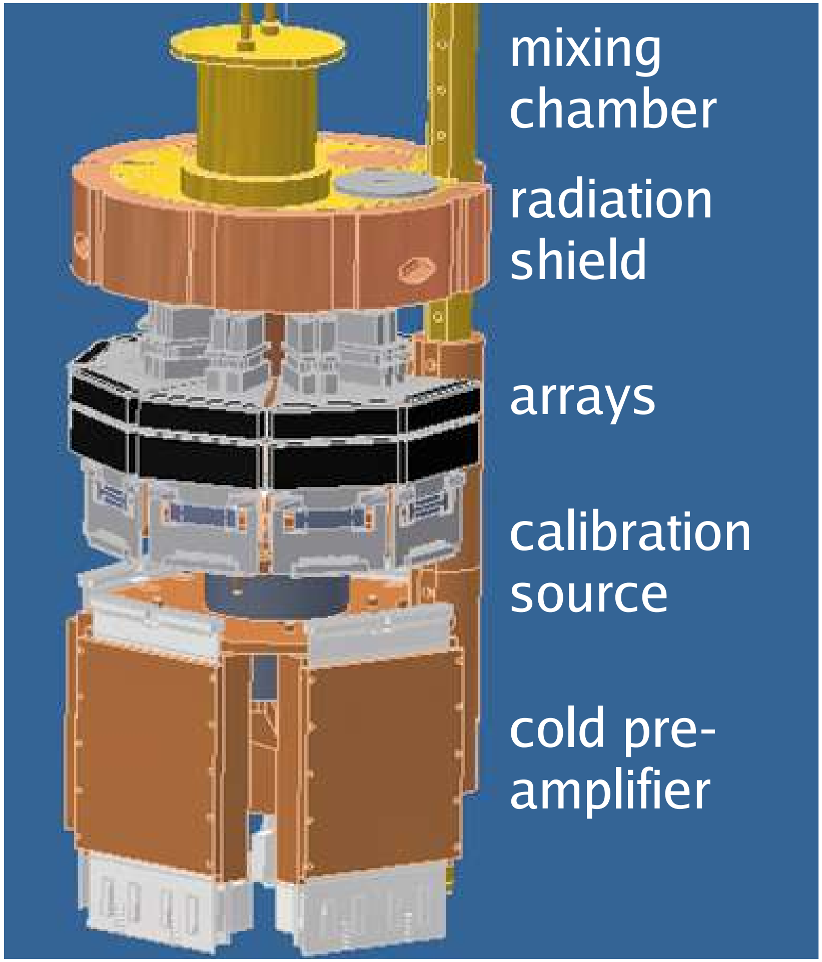


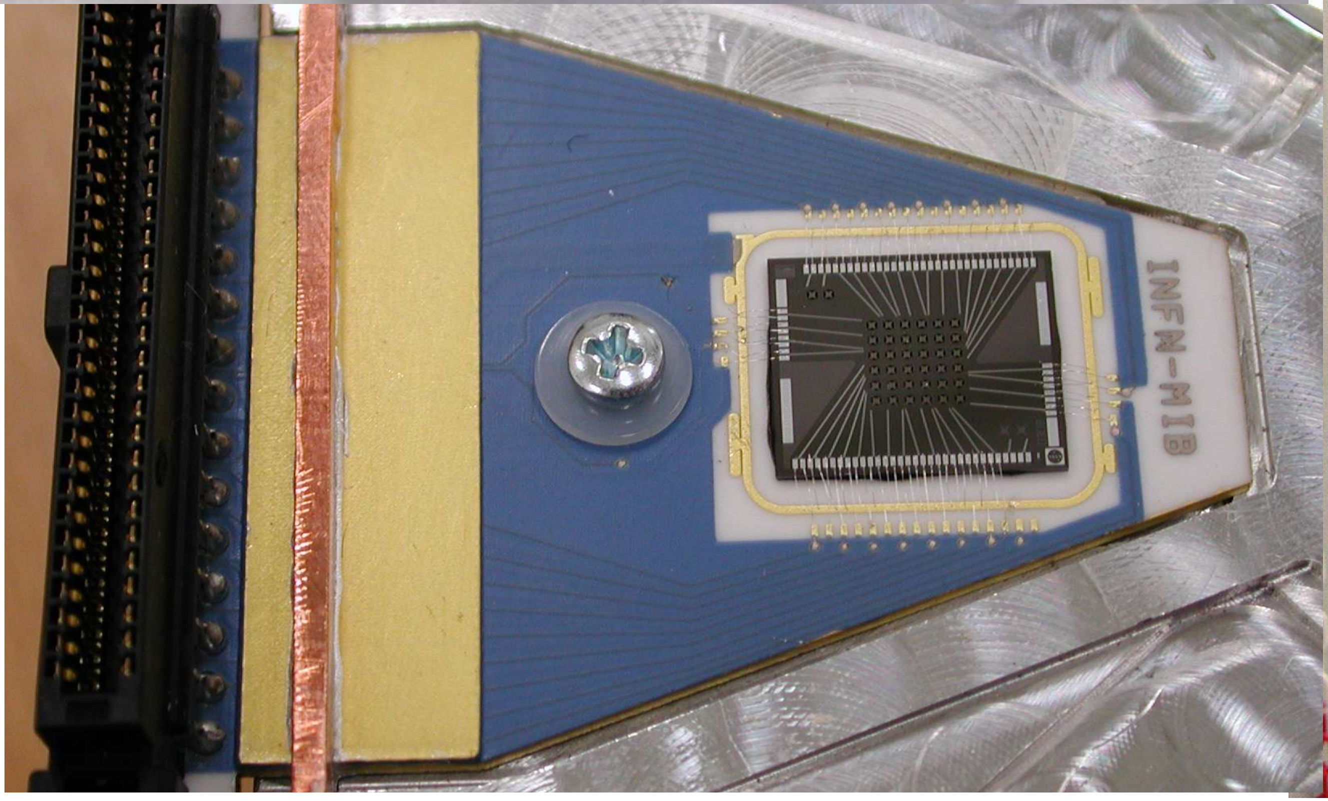
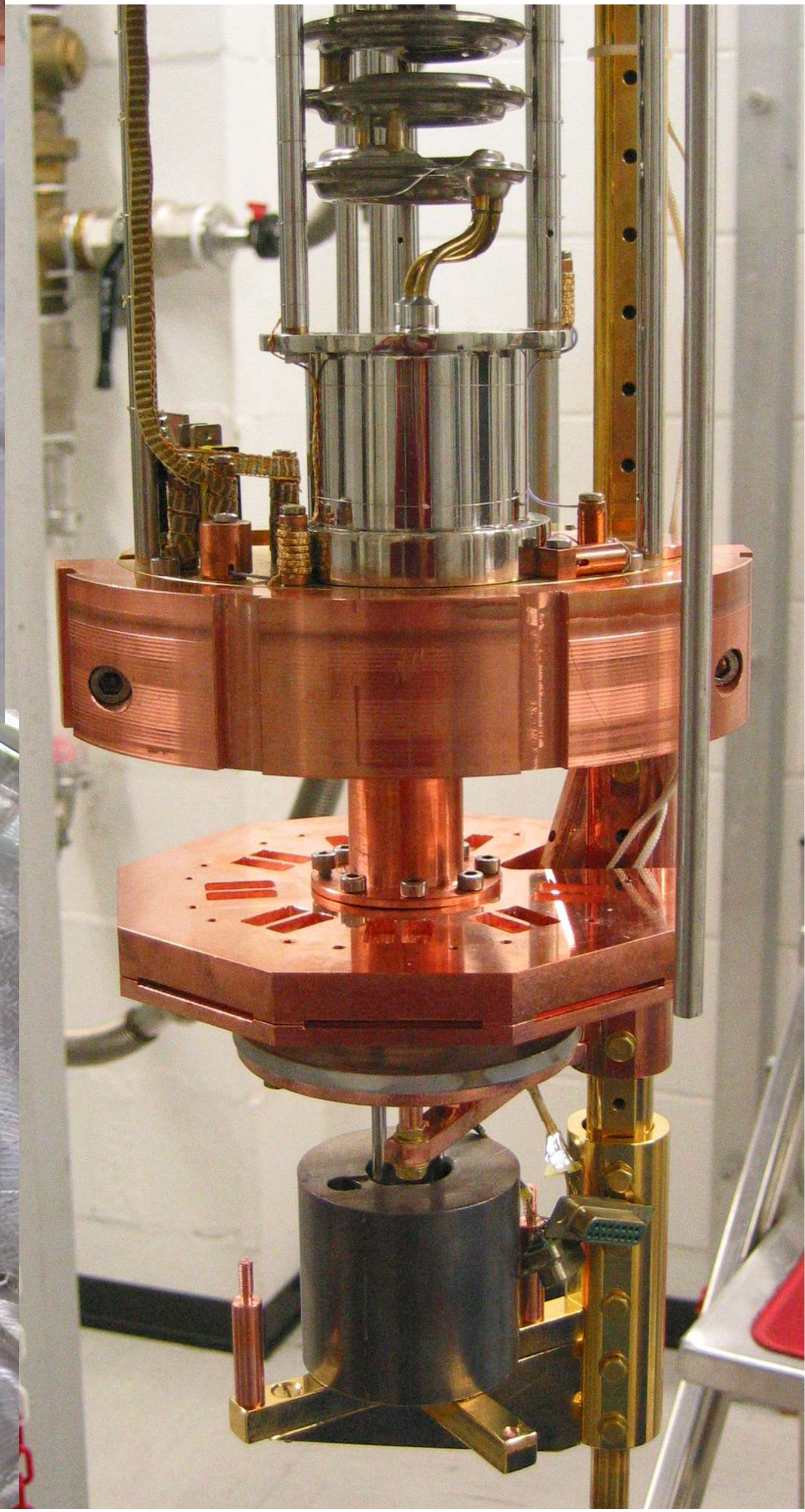
MARE-1 SEMICON: statistical sensitivity from MC

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



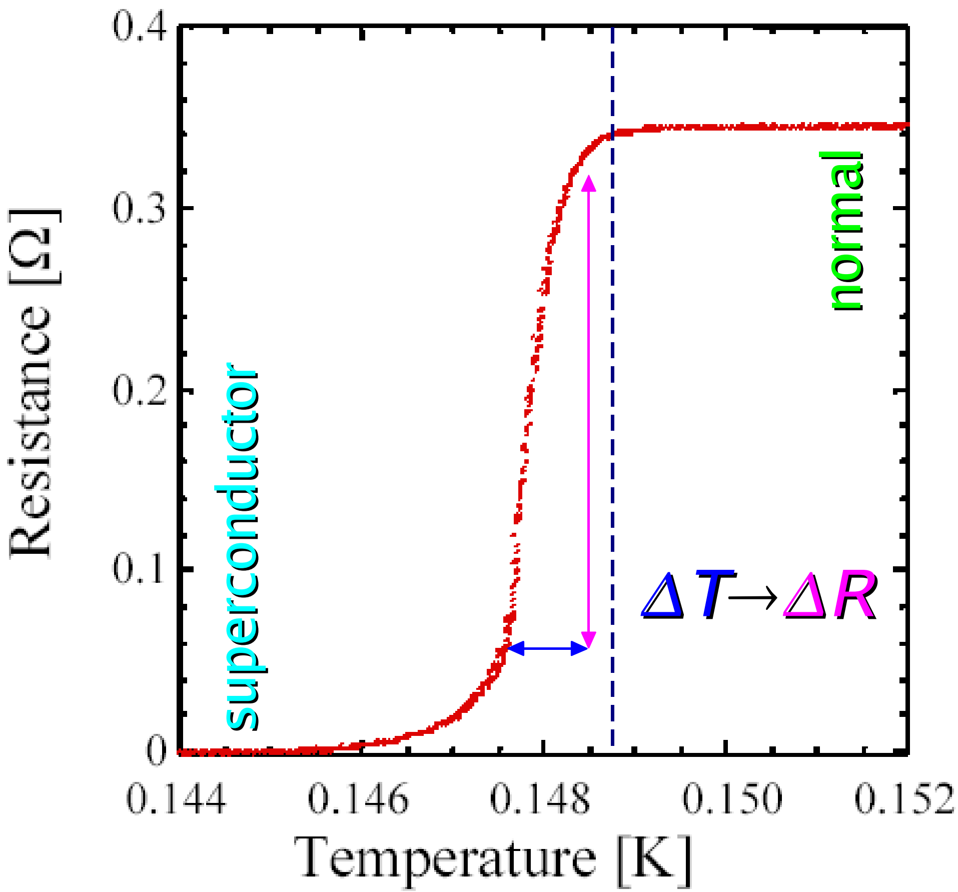
- 8 arrays
- 288 $AgReO_4$ crystals
- **start with 2 arrays**
- **start data taking by end of 2008**
- gradual deployment
  - ▷ further detector optimization

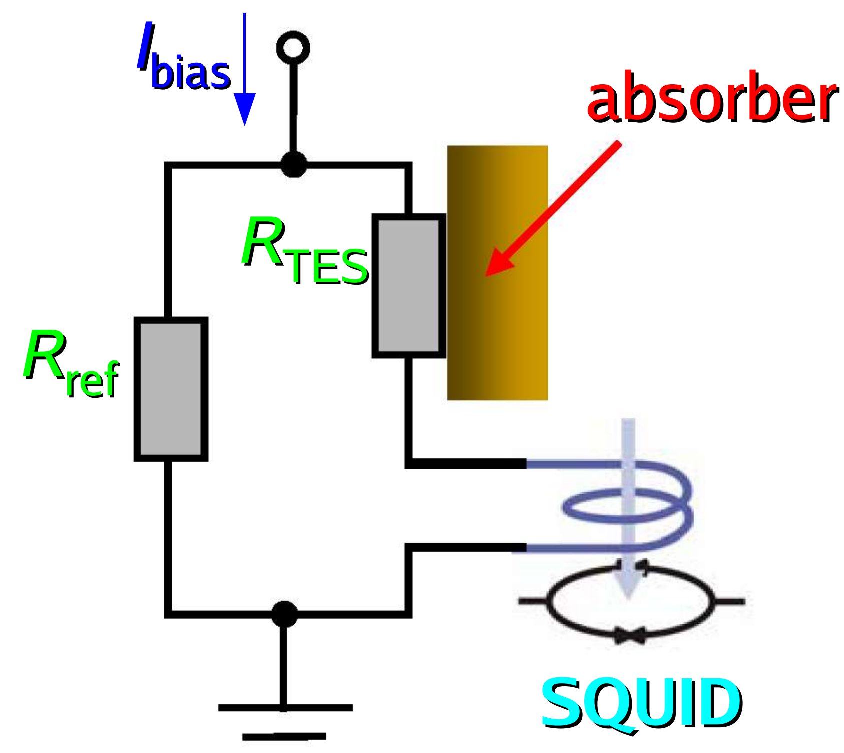



TOP
J2
TOP

INFN-MIB


MARE-1 TES: Superconducting transition edge sensors

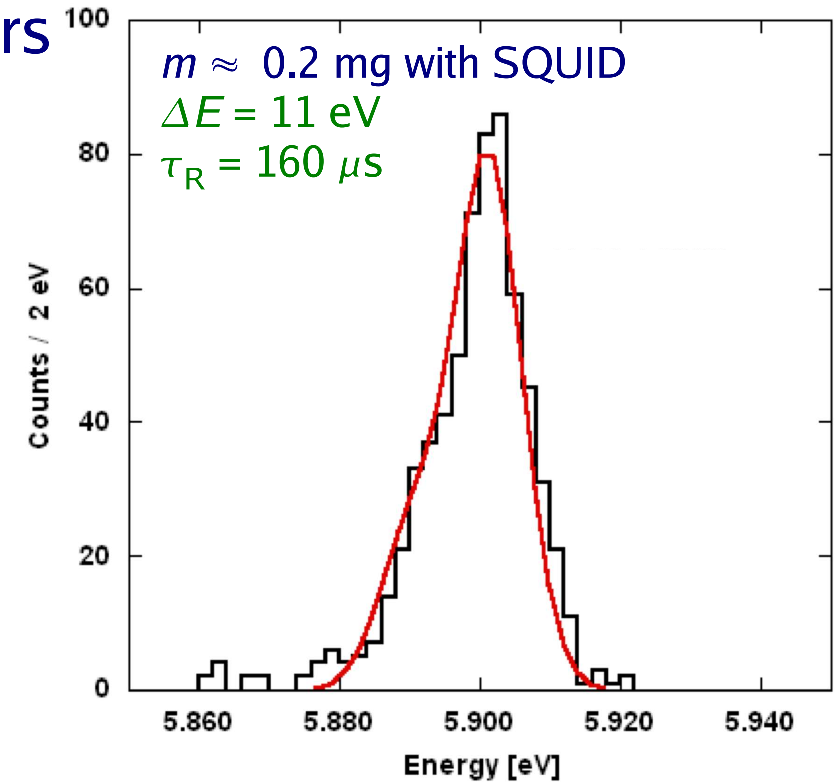
- **superconductor thin films** used inside the phase transition at T_c
  - ▶ pure superconductors: **Ir** (T_c= 112 mK), **W** (T_c= 15 mK), ...
  - ▶ metal-superconductor bilayers ⇒ tunable T_c (20÷200 mK) : **Mo/Cu, Tl/Au, Ir/Au**, ...
    - high sensitivity ($A \approx 100$) ⇒ **high energy resolution**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

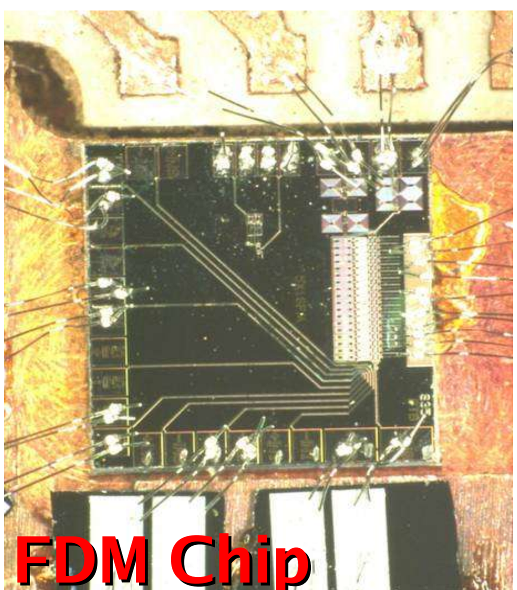


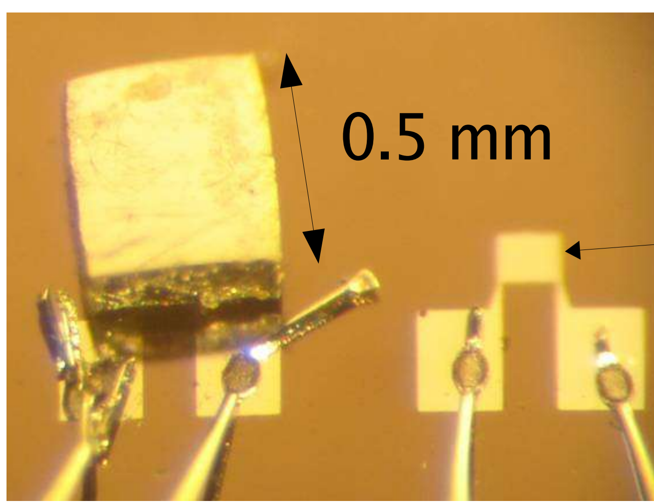


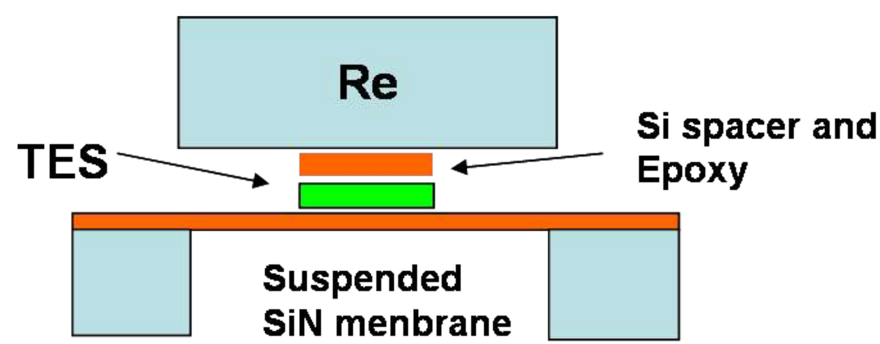
MARE-1 TES: sensor development

- 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: $\Delta E = 5$ eV, $\tau_R = 10$ 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**

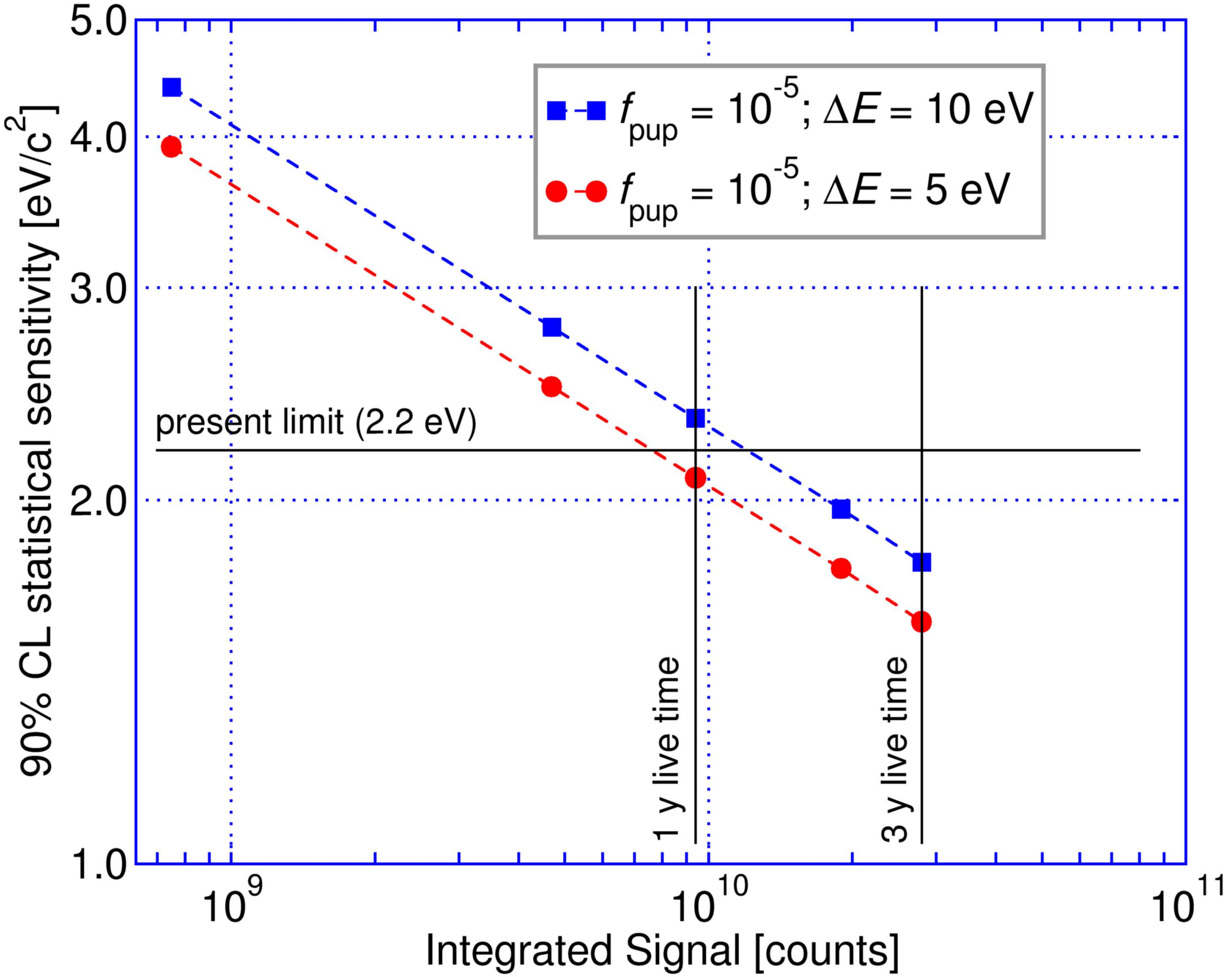








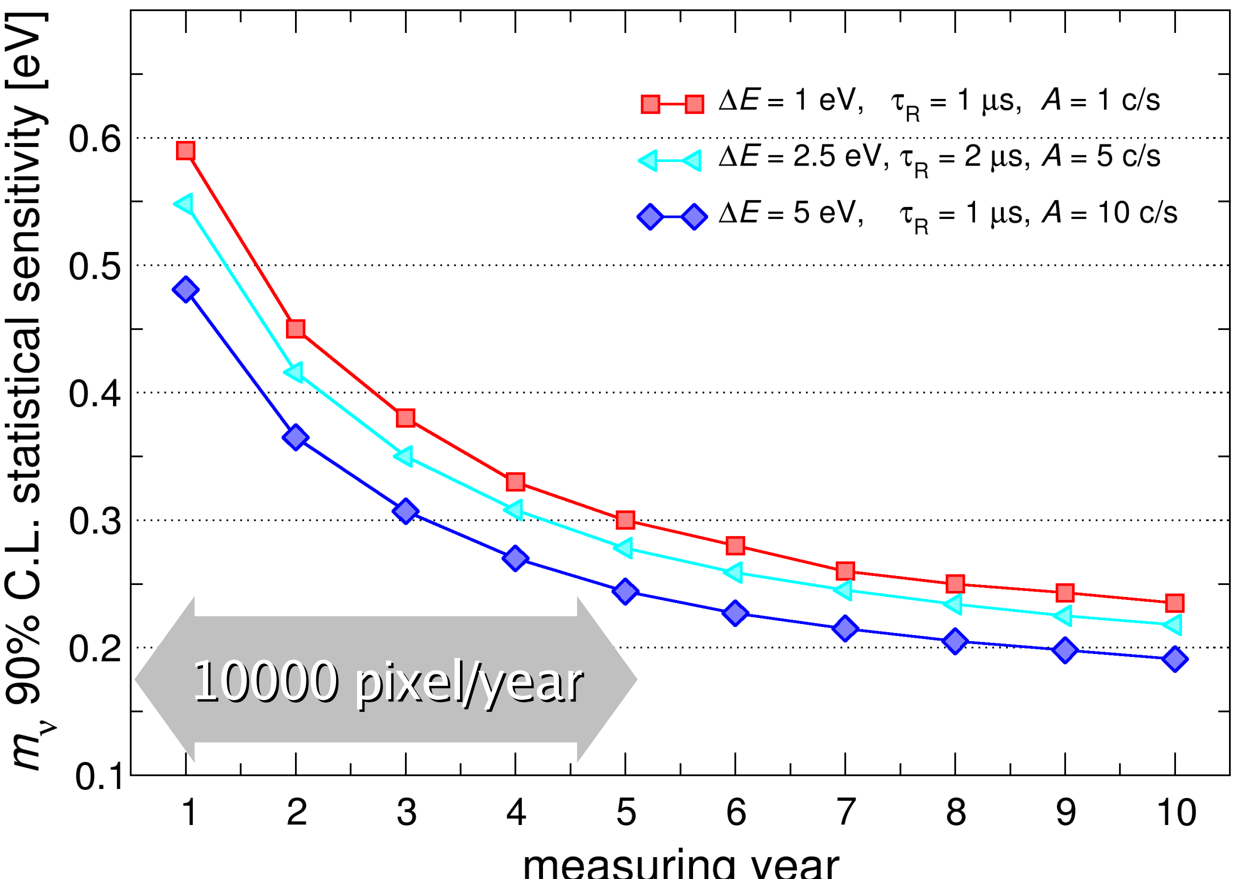
MARE-1 TES: statistical sensitivity



- 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

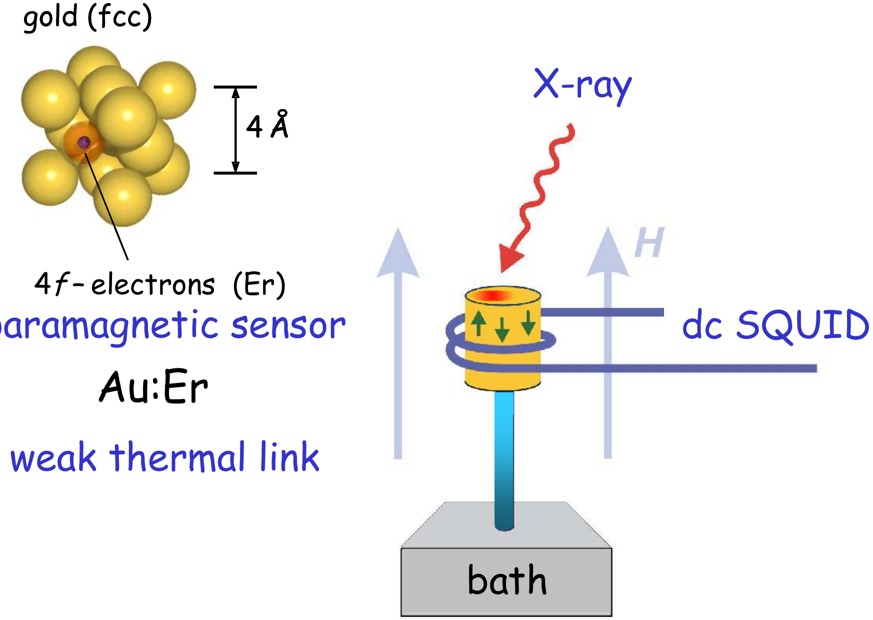
- only statistical analysis
- 50000+ detectors gradually deployed
  - ▷ 5 arrays with 10000 detectors each
  - ▷ one array deployed per year for the first 5 years
  - ▷ arrays distributed in many laboratories around the world
  - ▷ about $10^{13} \div 10^{14}$ events after 5 years
- technical requirements 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

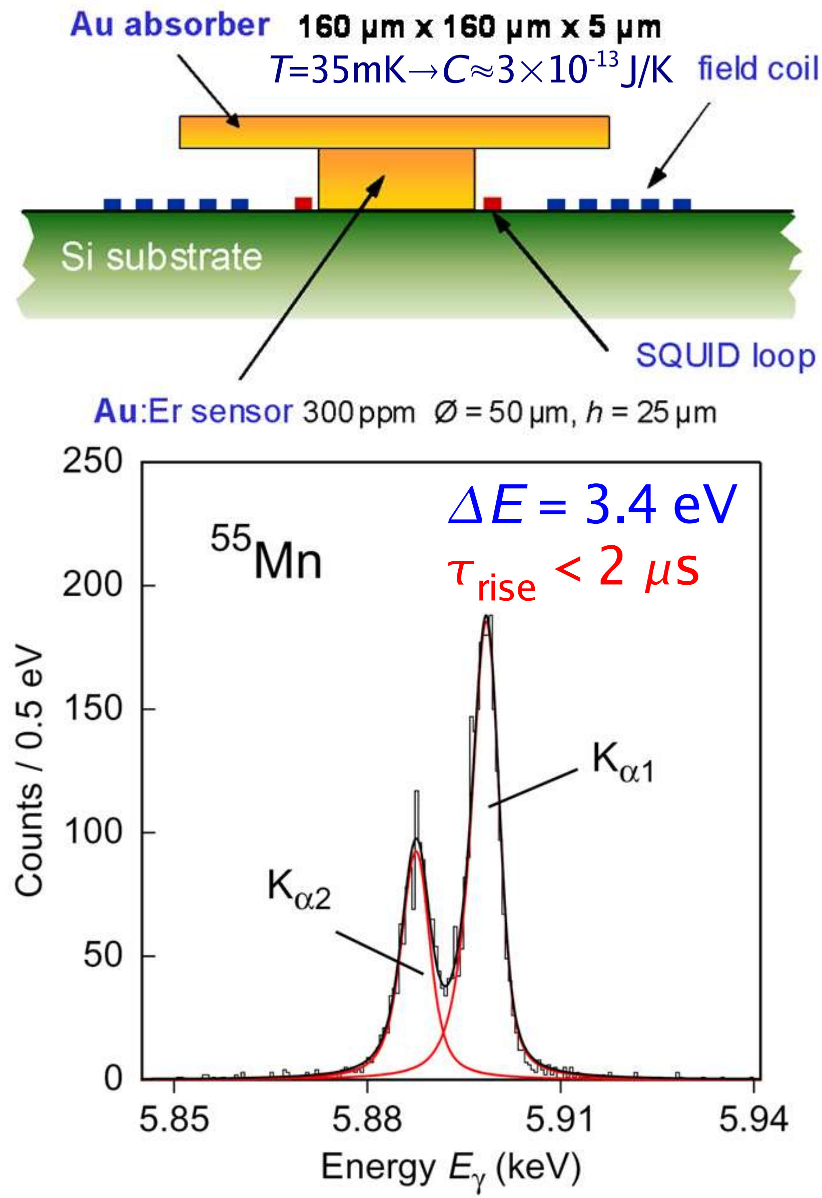
need for
new sensor R&D
and
new read-out techniques

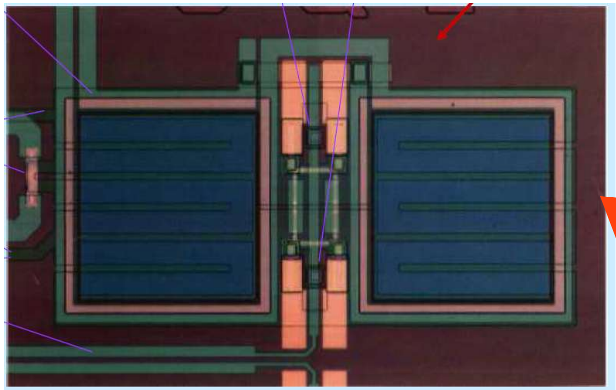
MMC – Magnetic Micro Calorimeters (Heidelberg)



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

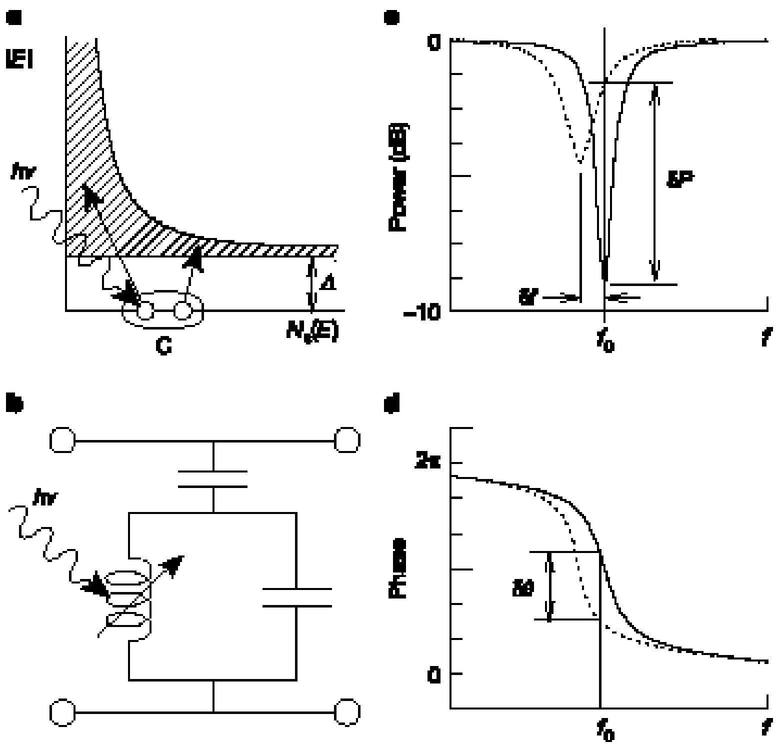
- suitable for **large capacity absorbers**
- **very fast** $\sim\mu$s
- **high energy resolution** $\sim$eV

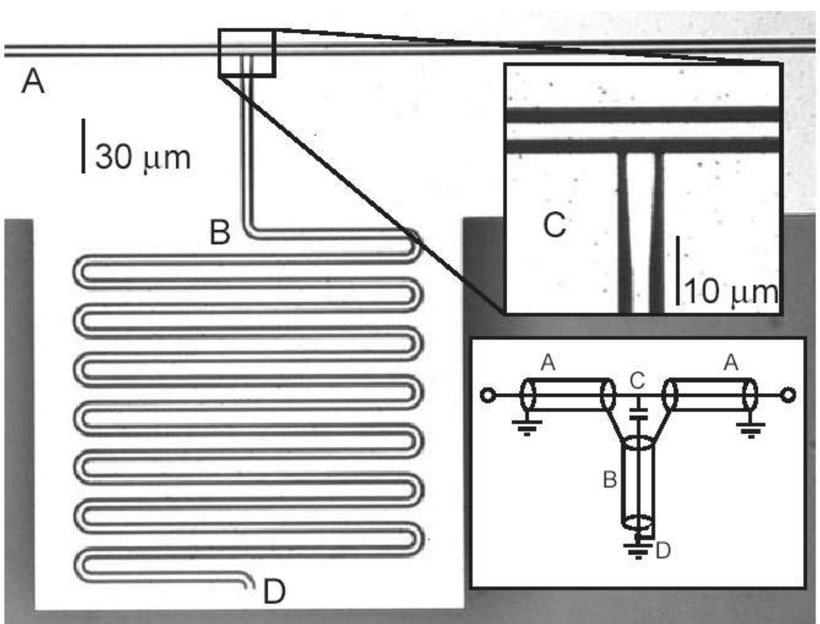




sensor design optimization for MARE-2 rhenium absorbers is in progress
⇨ meander pick-up coils without external B field

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

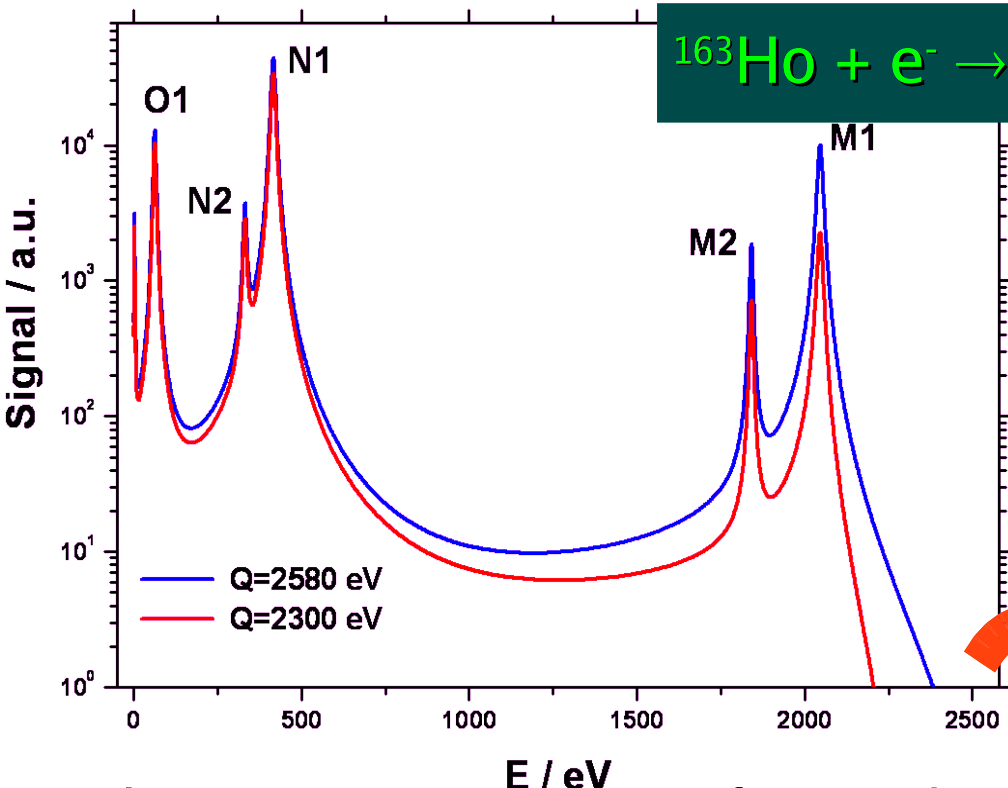
ΔE = 5 eV
t_M = 36000 detectors x 3 years
A_β = 20 c/s/det
- τ_{rise} = 1 μs ⇒ m_ν < 0.2 eV
- τ_{rise} = 100 μs ⇒ m_ν < 0.4 eV

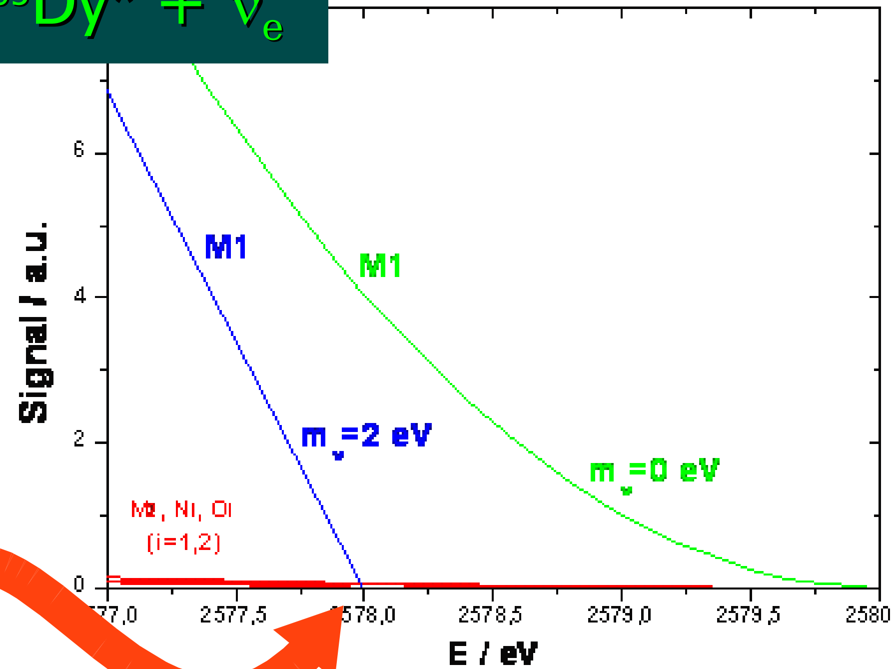
Technique largely still to be proved!!

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

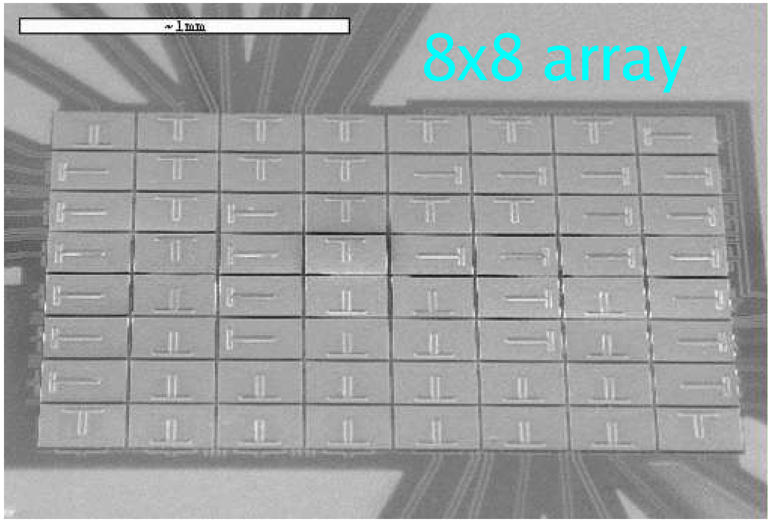
MARE extensions: ^{163}Ho electron capture measurement

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





- 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 (τ ≈ 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 has taken 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
  - US groups are applying for fundings (TES, MUX, ... R&D)
  - New ideas are coming up (MKIDs, ^{163}Ho)

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 = 10 μs and 10 decays/s per detector
  - **3.2×10^6 detector$\times$year...** ☹

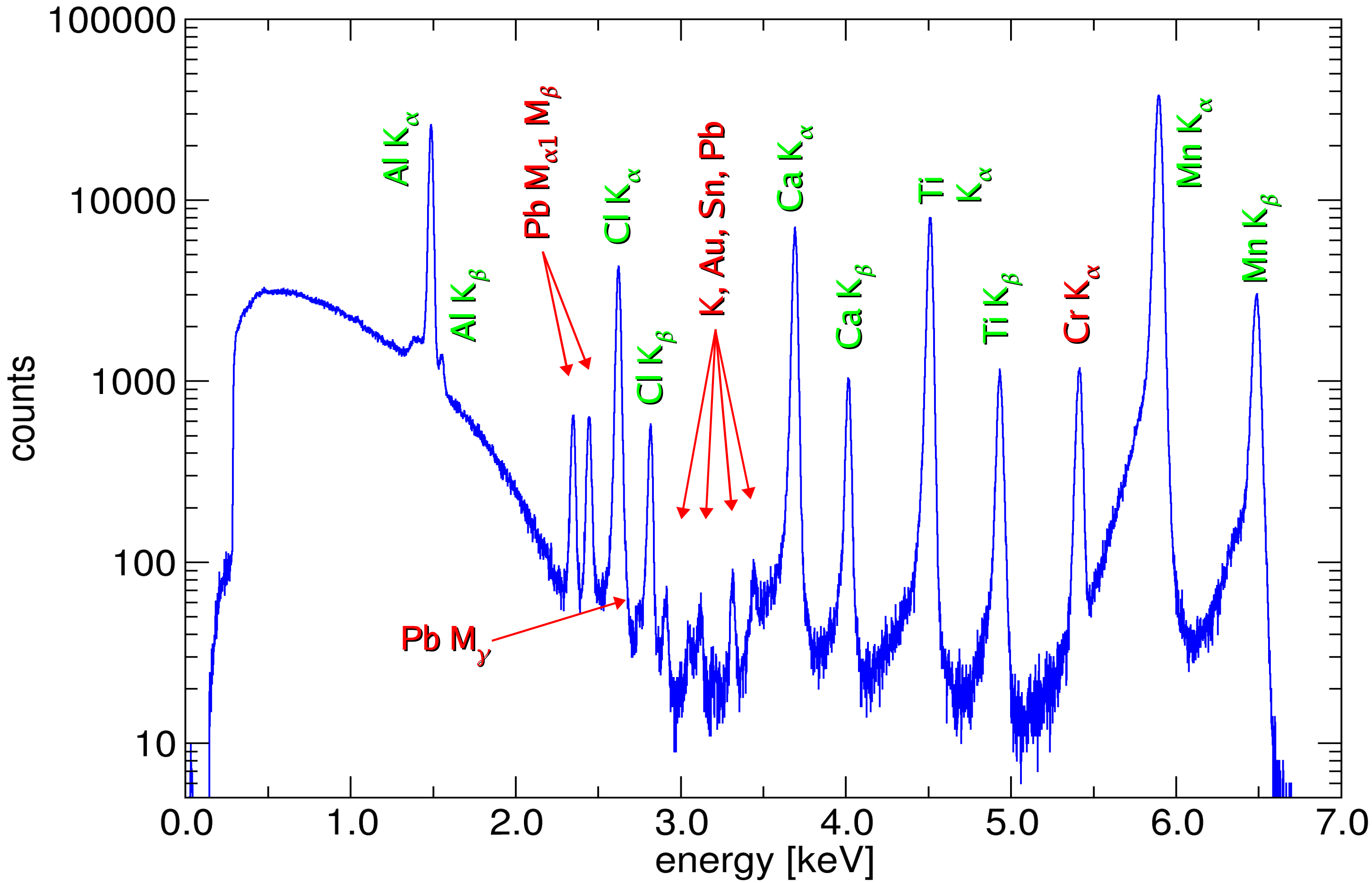
Backups ...

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**

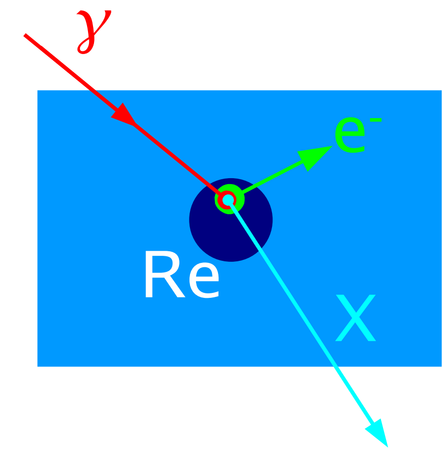


- ◆ X-ray peaks have tails on low energy side
- ◆ 1~6 keV X-rays in $AgReO_4$ have an attenuation length $\lambda < 2$ μm
  - ► are the response functions for X-rays and for βs from ^{187}Re decay the same?
- ◆ need for a good phenomenological description of the X-ray peak shape

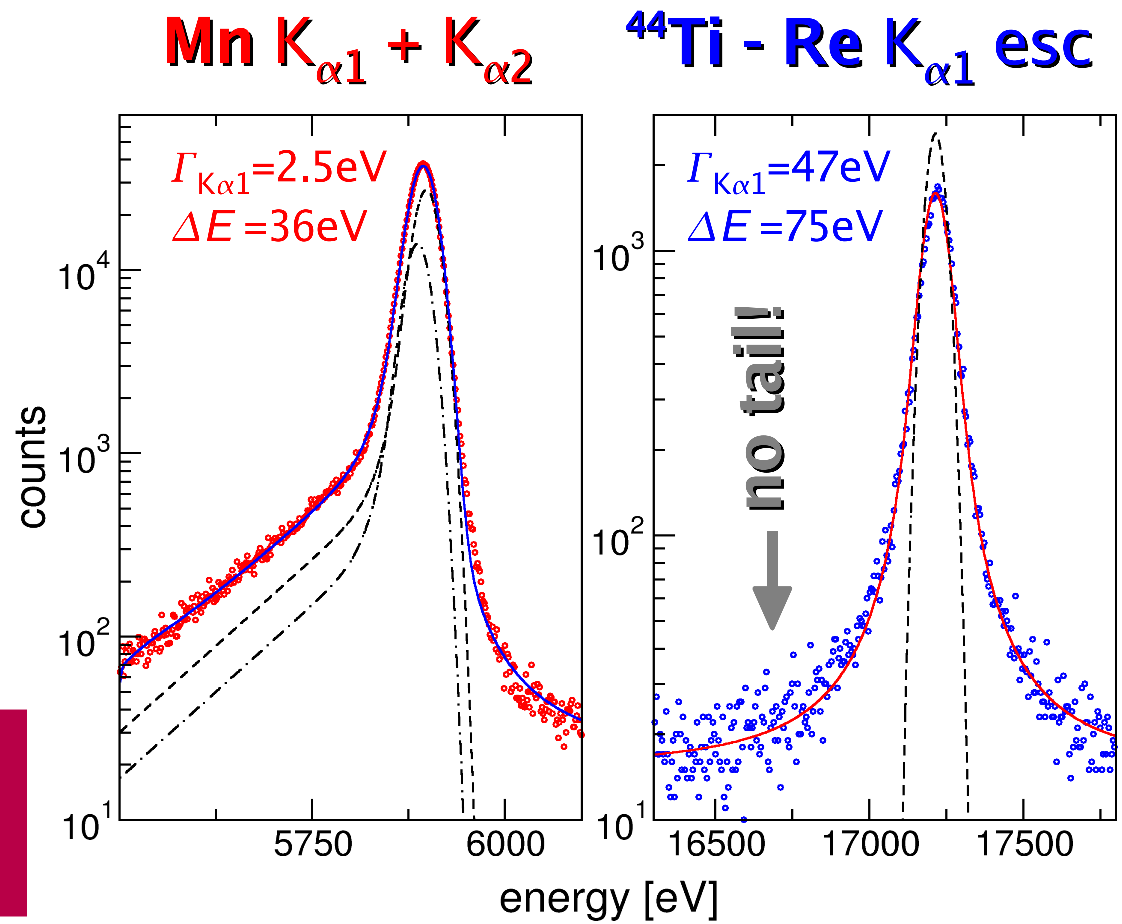
MIBETA: Measurement of response function (2004)

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

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

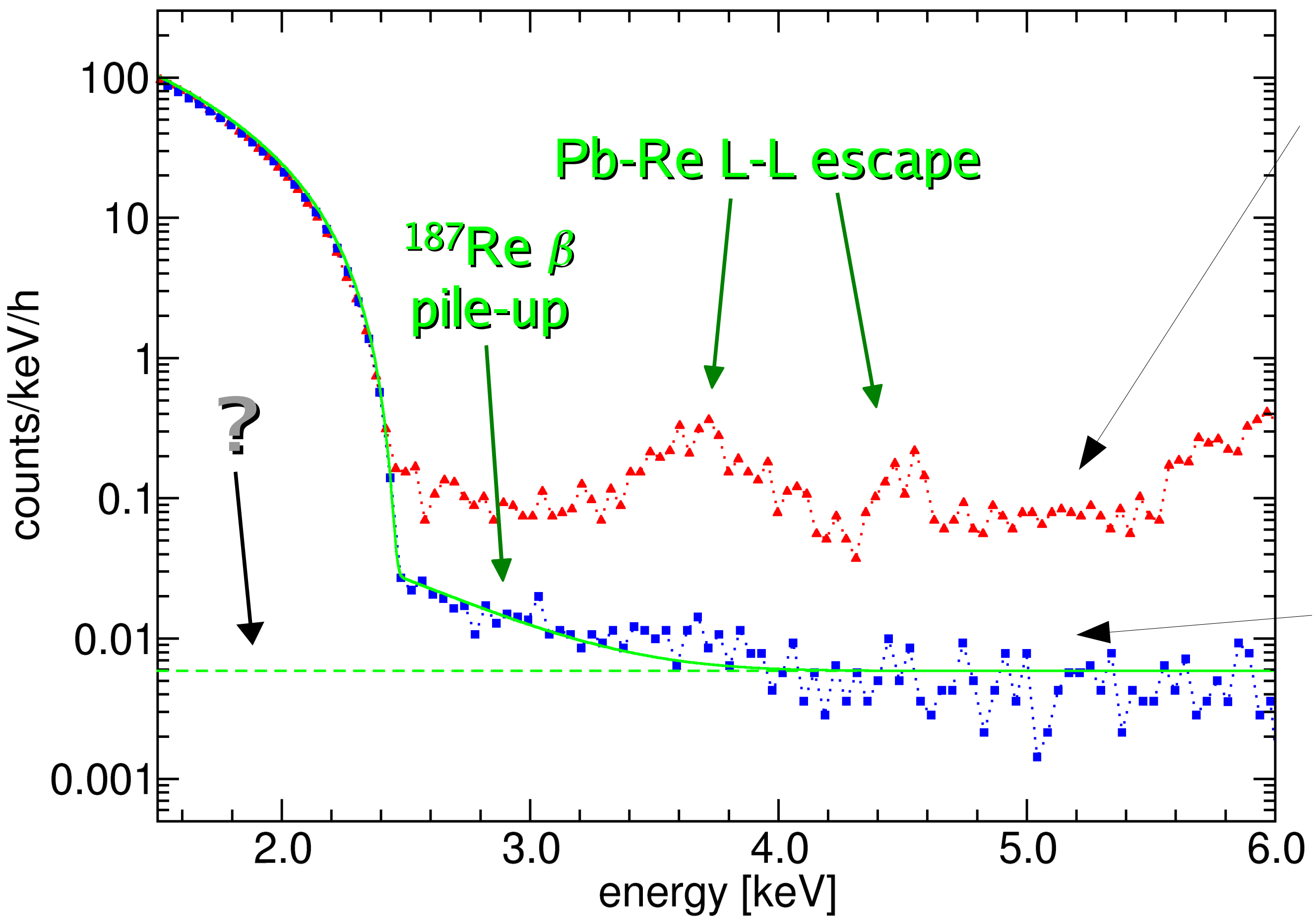


- Re K-edge @ 71.7 keV
  - ▷ E_γ > 71.7 keV
  - ▷ **internal calibration with ^{44}Ti**
- γ rays @ 78.4 keV
- ▶ γ-X escape peaks have only Re K natural width (Γ_{ReK}~47 eV)



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

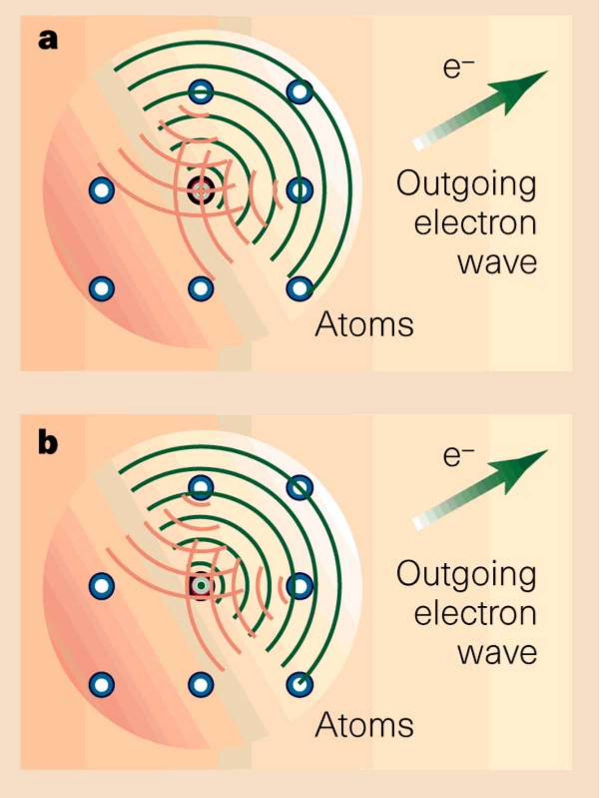
the hidden background is a source of systematic uncertainties

Go underground?

MIBETA: BEFS analysis (2005)

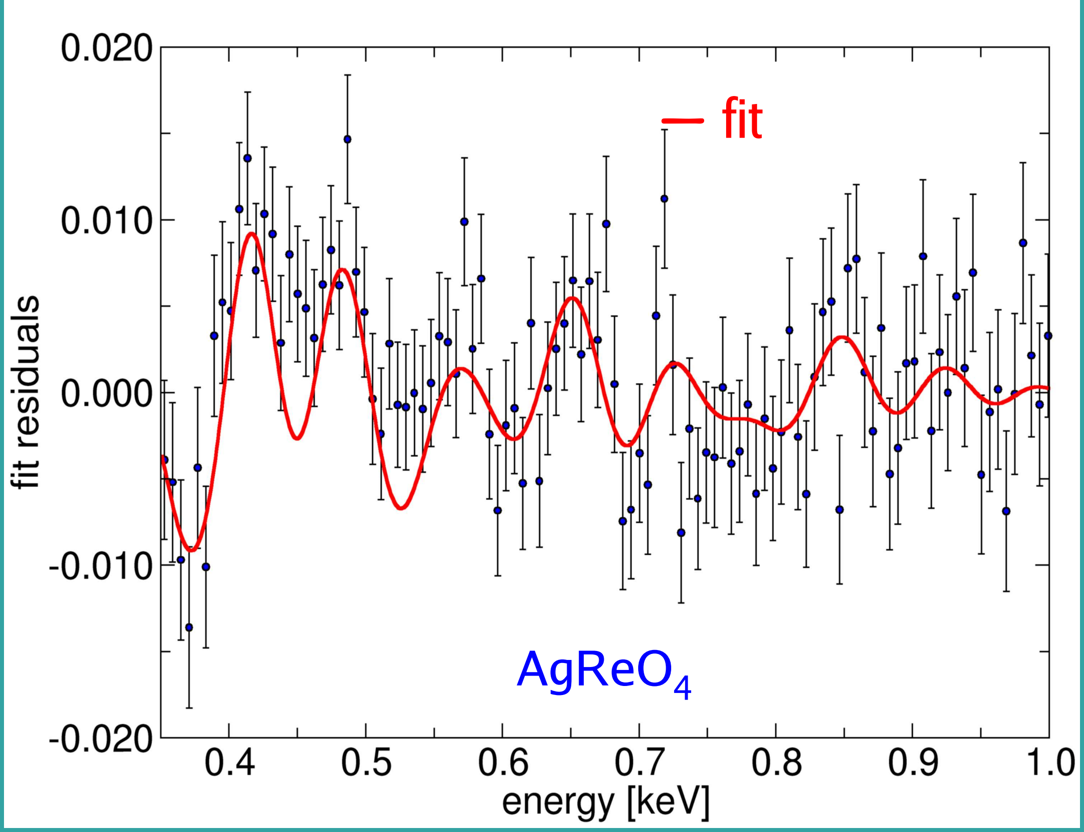
BEFS: Beta Environmental Fine Structure

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

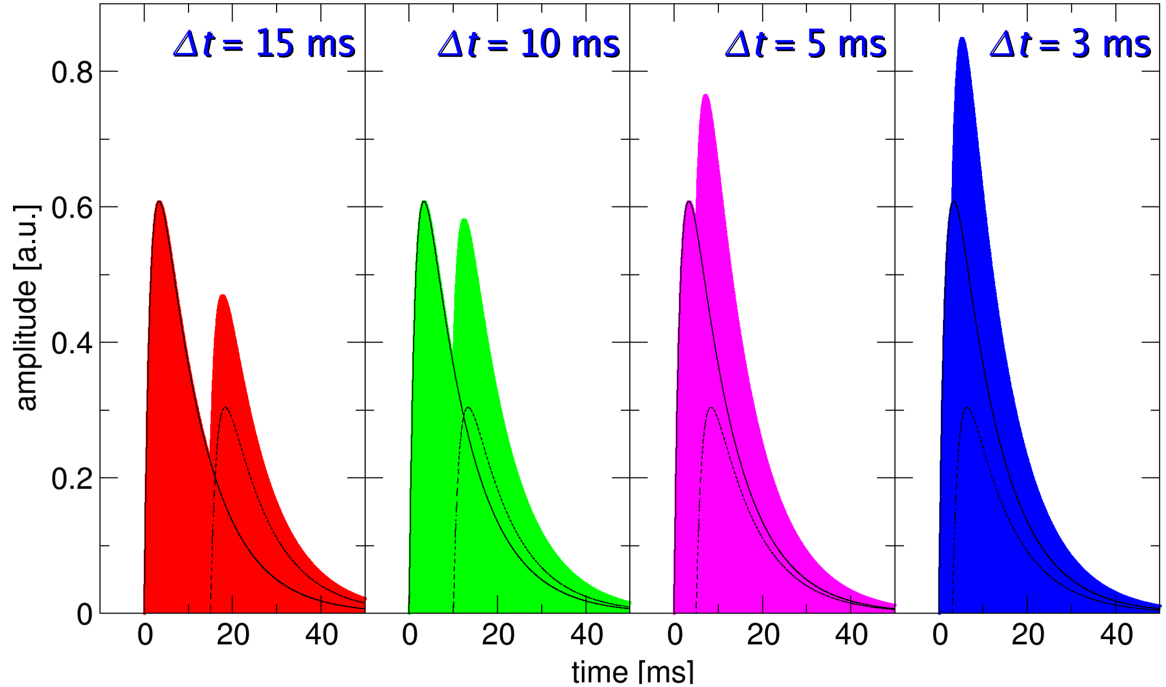
⇒ EXAFS measurements
⇒ better models

Pile-up (MANU)

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

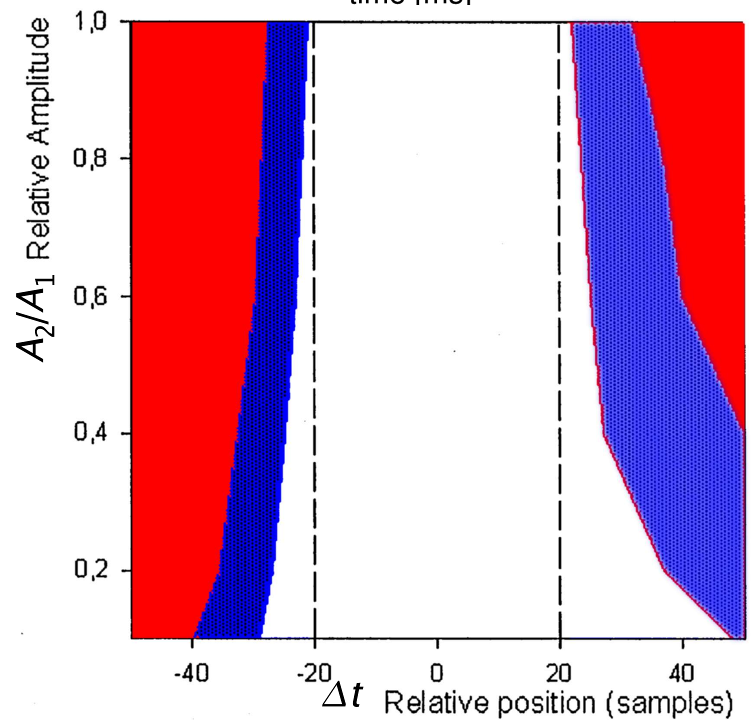
Example

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



Montecarlo with simulated pulses

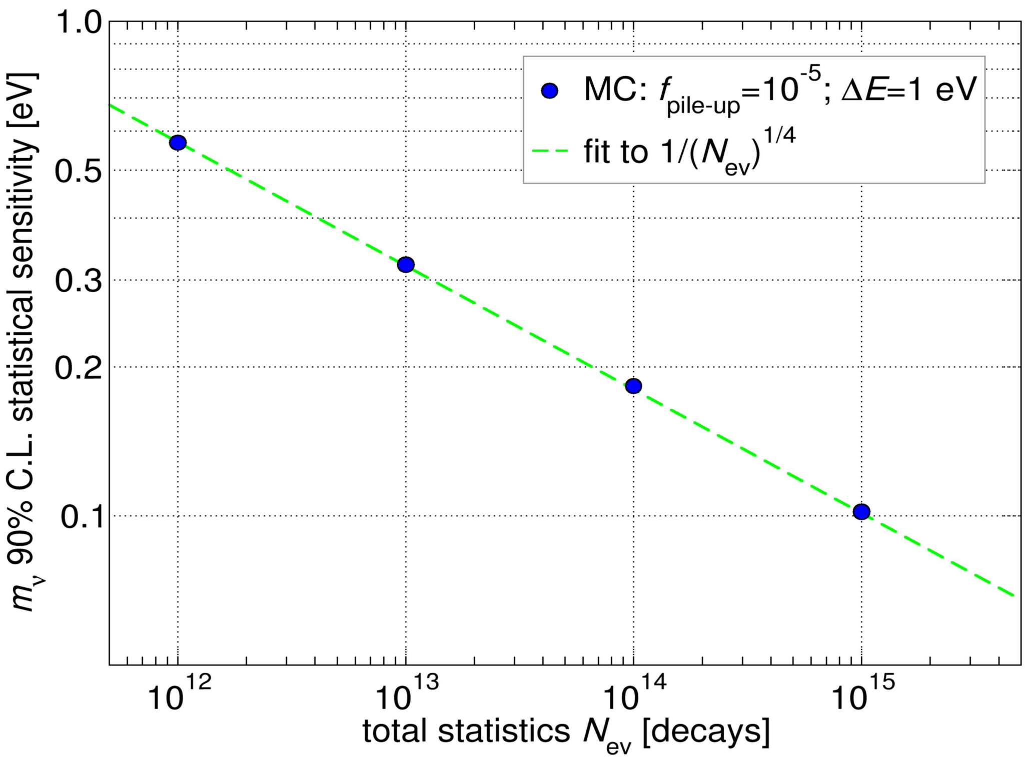
- $\tau_{rise} \approx$ 2 ms = 10 samples
  - resolving time $\tau_R = \tau_R\ (A_2/A_1\ ,\ \Delta t) \approx \tau_{rise}$
  - source of systematics
- new MC tools and new algorithms

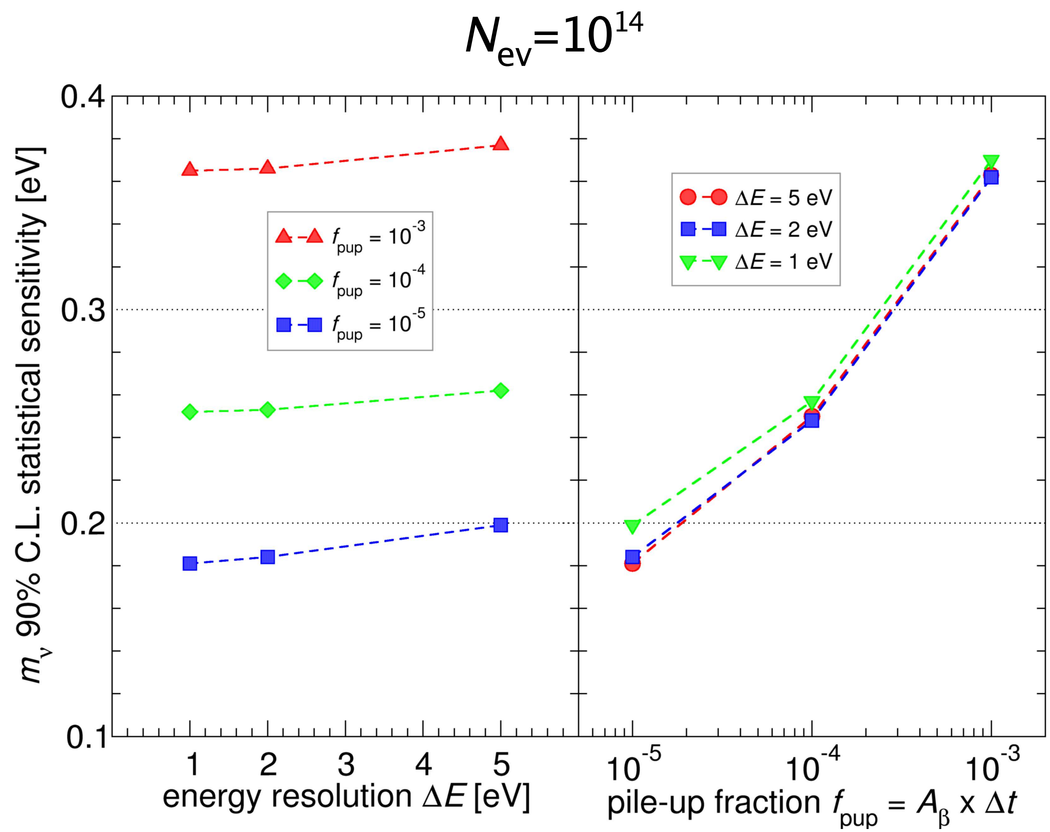


F. Fontanelli et al., NIM A 421 (1999) 464

MARE-2 MC simulations for 0.2 eV m_ν sensitivity

- statistics N_{ev}
- energy resolution ΔE
- time resolution Δt





MC analysis of systematics: BEFS