Sensitivity of neutrino mass measurements with microcalorimeters

A. Nucciotti, E. Ferri, O.Cremonesi
Dipartimento di Fisica "G. Occhialini",Università di Milano-Bicocca
INFN - Sezione di Milano-Bicocca

- direct neutrino mass measurement introduction
  - spectrometers vs. calorimeters
  - calorimeters
- calorimeter statistical sensitivity
  - analytic approach
  - montercarlo approach
- calorimeter systematics

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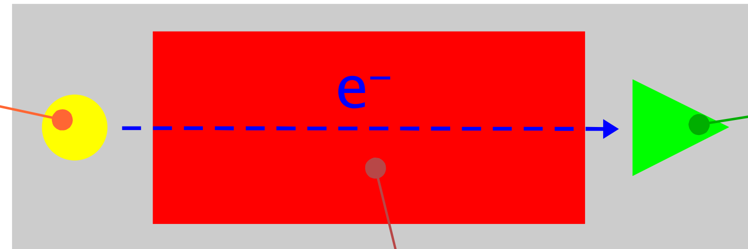
INT Workshop - The Future of Neutrino Mass Measurements:
Terrestrial, Astrophysical, and Cosmological Measurements in the Next Decade
Seattle WA, USA, February 8-11, 2010

Experimental approaches for direct measurements

Spectrometers: source ≠ detector

^{3}H source

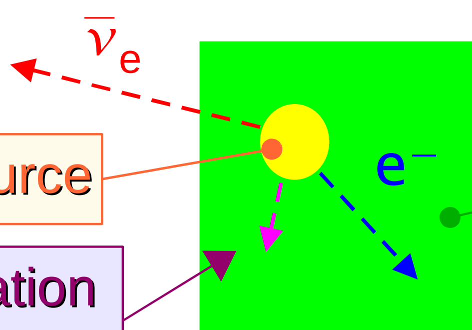


β counter

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 source

excitation energies

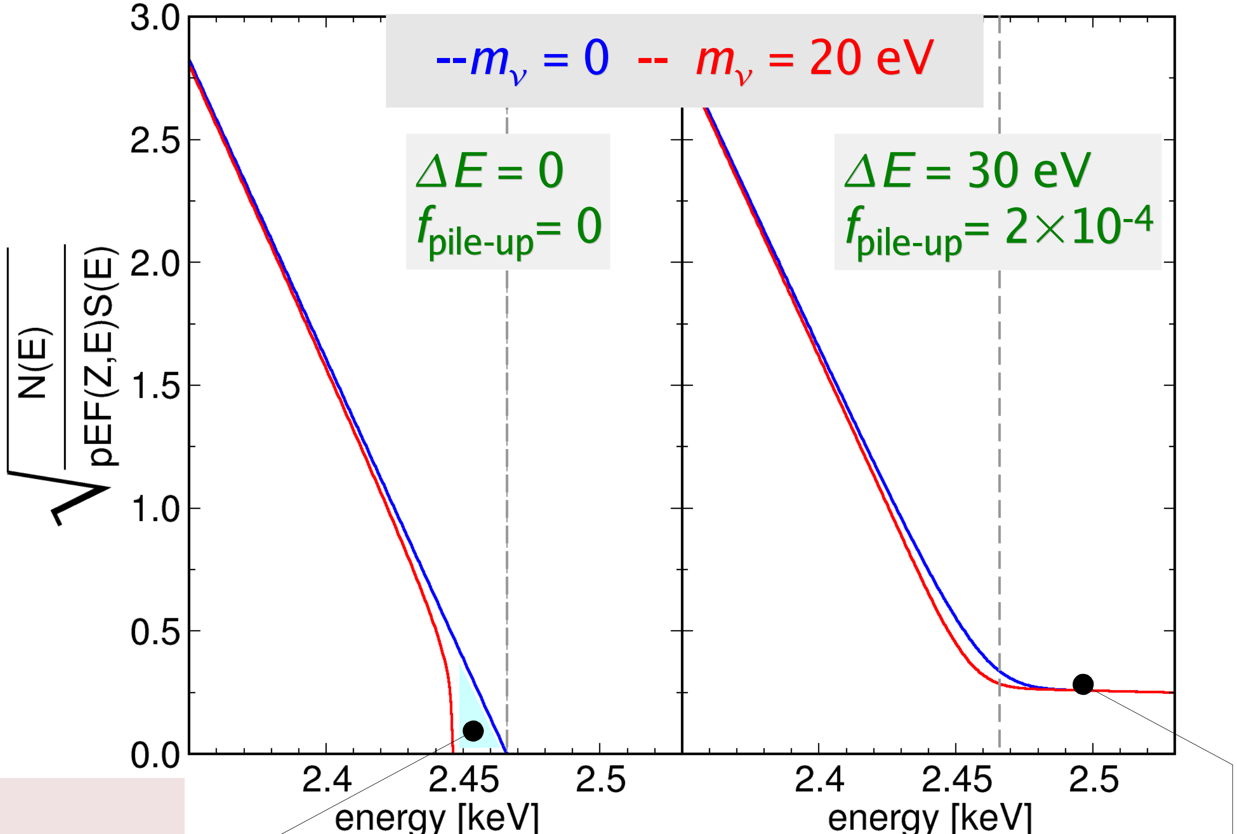
β calorimeter

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 $\Rightarrow$ $F(\delta E{=}10\text{ eV}) \sim (\delta E/E_0)^3 = 7\times10^{-8}$

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

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

Pile-up

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

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

^{187}Re calorimetric experiment statistical sensitivity / 1

resolving time τ_R

source activity A_β

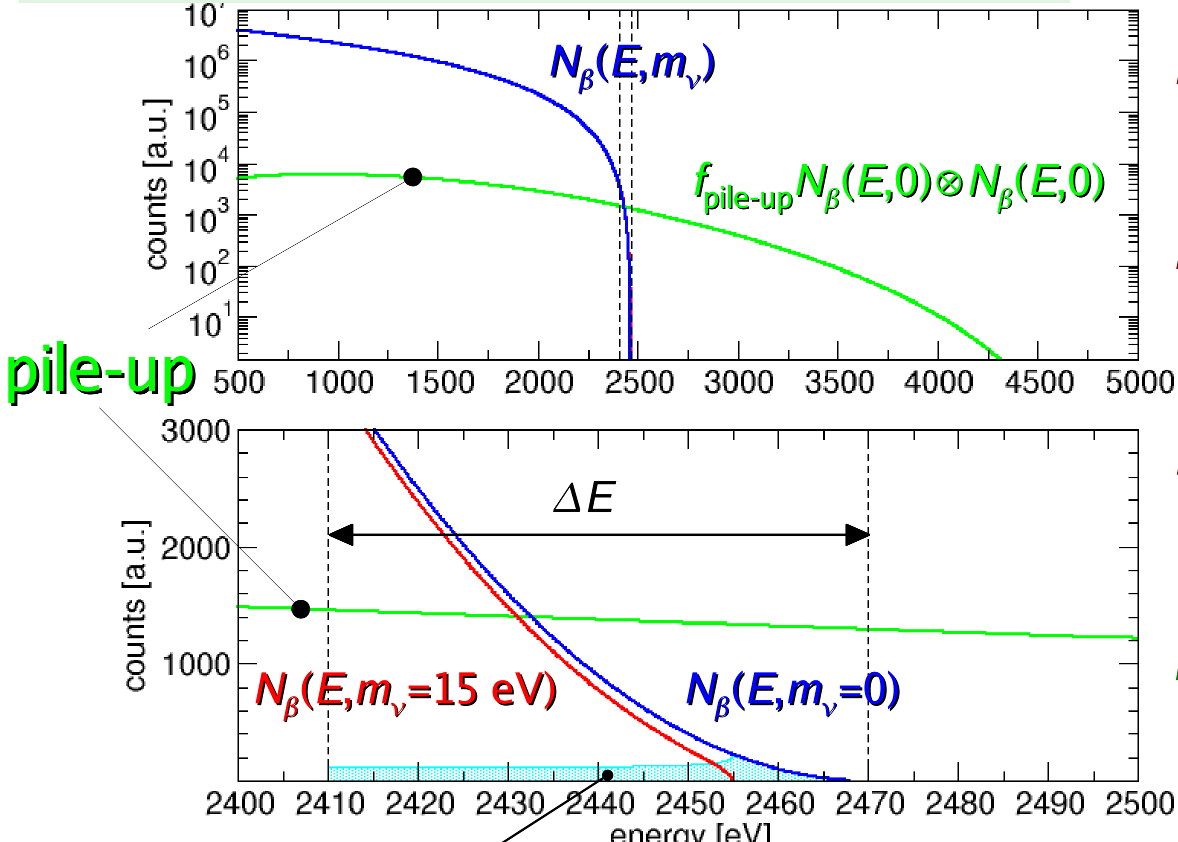
pile-up fraction $f_{\text{pile-up}} = \tau_R A_\beta$

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

analysis interval ΔE

number of detectors N_{det}

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



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

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

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

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

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

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

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

Calorimetric experiment statistical sensitivity / 2

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

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

Optimal energy interval ΔE

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

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

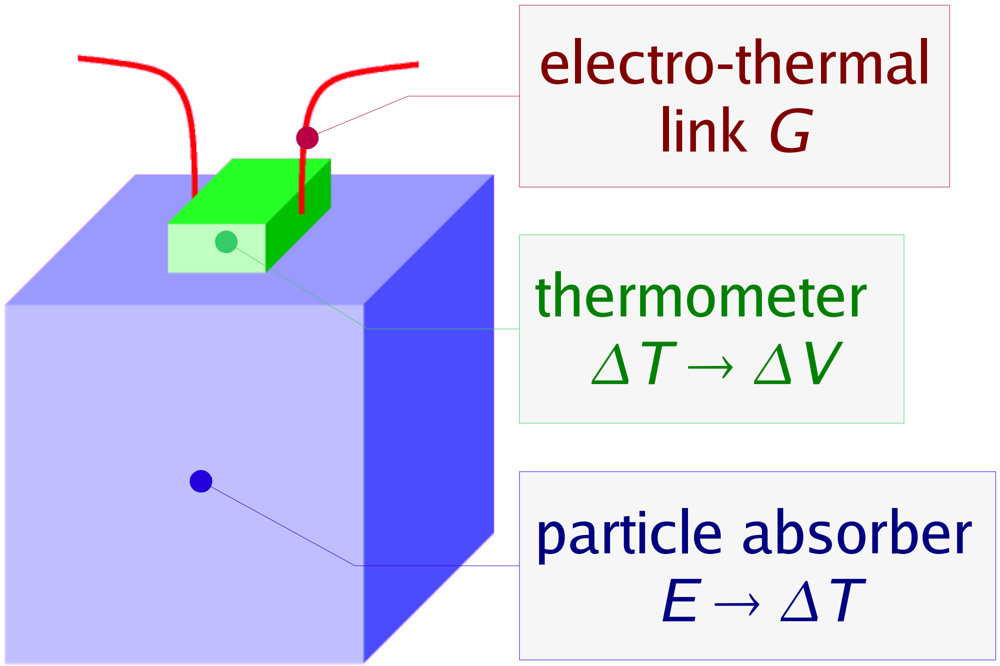
$$\Sigma_{90}(m_\nu) \approx 0.89 \sqrt[4]{\frac{E_0^3 \Delta E}{A_\beta t_M}}$$

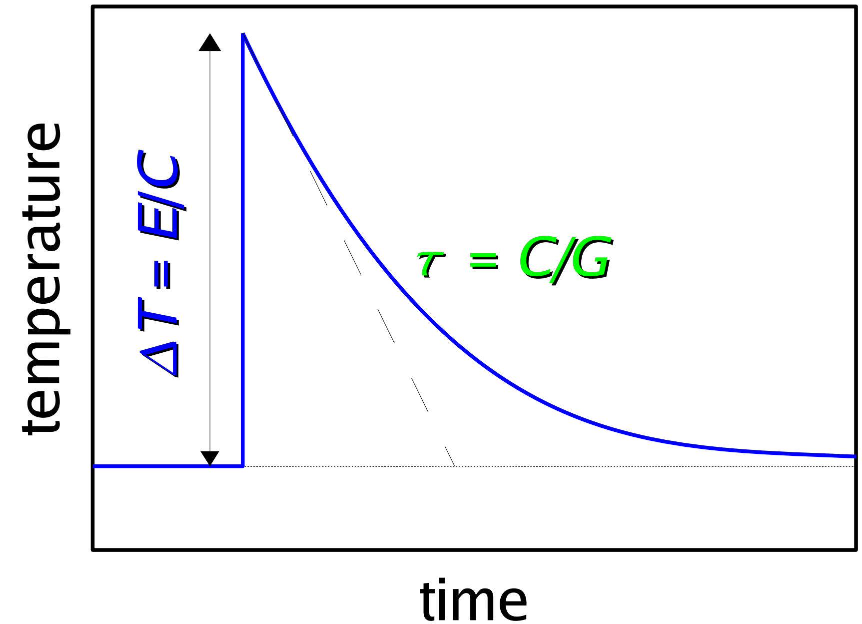
$$\Delta E \approx \Delta E_{FWHM}$$

experimental challenges

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

Cryogenic detectors as calorimeters





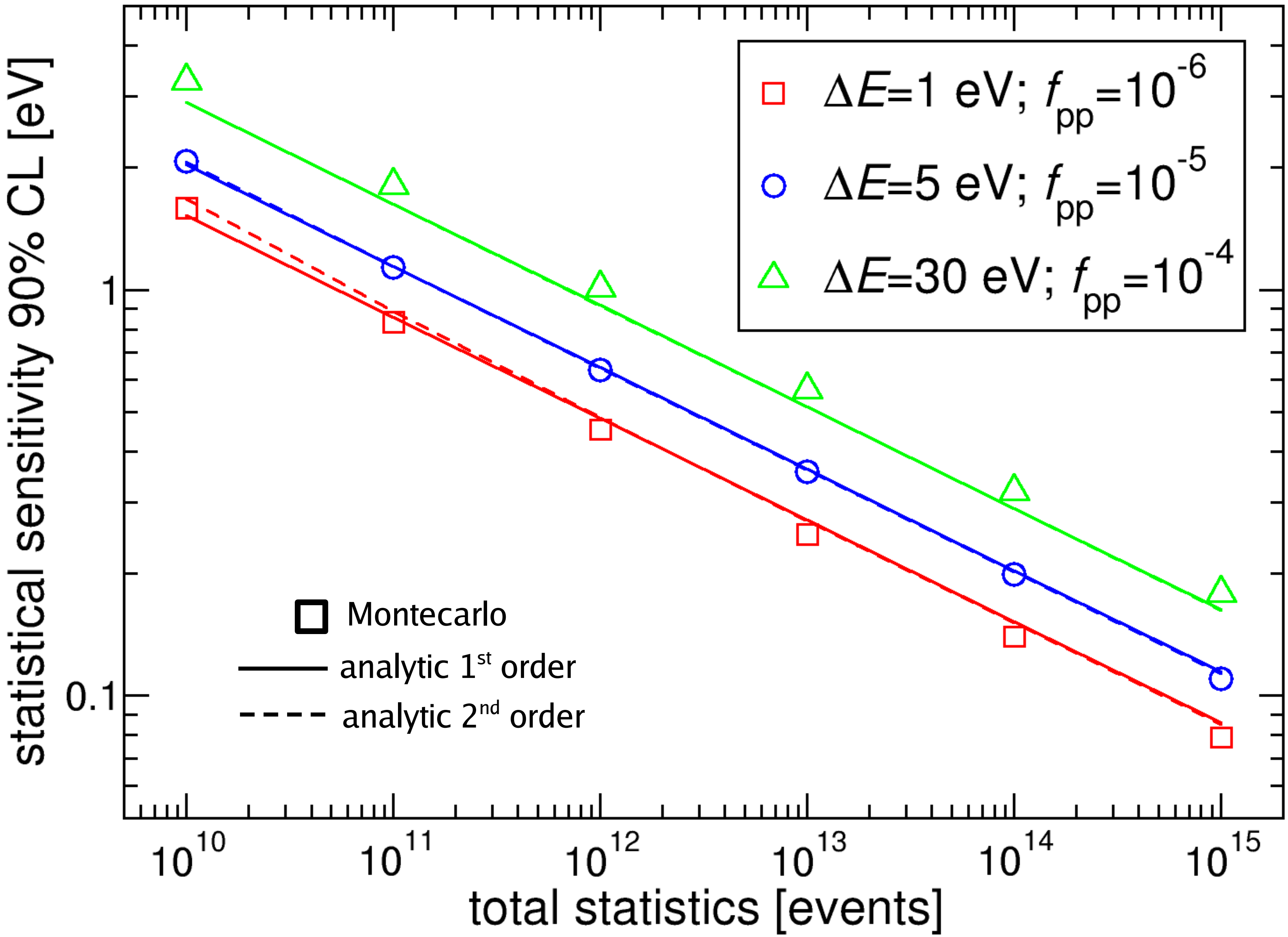
- **1 mg of Re @ 100 mK**
  $C \sim T^3$ (Debye) $\Rightarrow C \sim 10^{-13}$ J/K
  $\Rightarrow \Delta E_{rms} \sim 1$ eV
  6 keV x-ray $\Rightarrow \Delta T \sim 10$ mK
  $G \sim 10^{-11}$ W/K $\Rightarrow \tau = C/G \sim 10$ ms

- 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

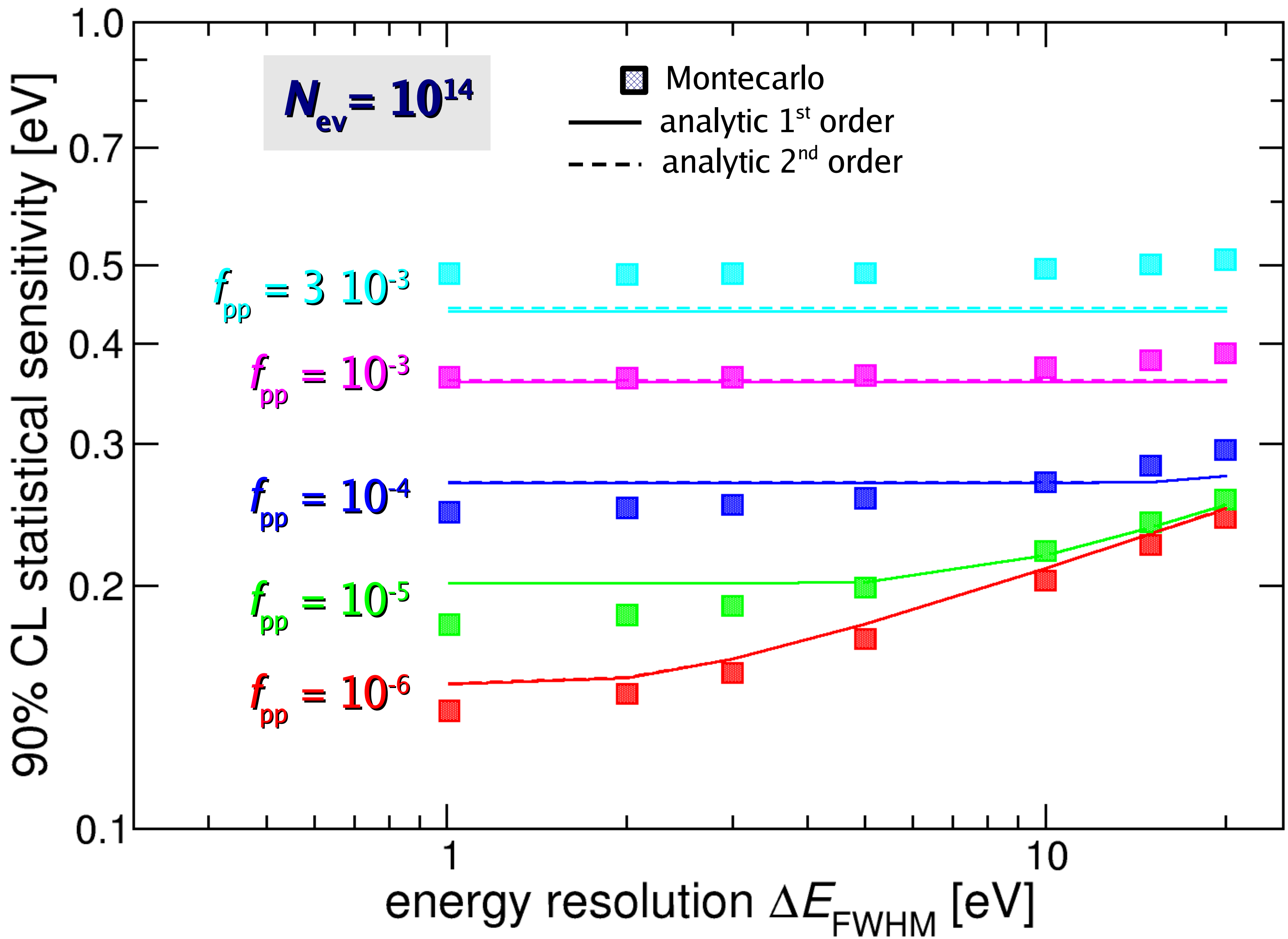
Montecarlo simulations: statistical sensitivity

- generate many (500-1000) simulated experiments
  - calculate total β spectrum
  - $S(E) = (N_{ev}\ (N_\beta(E,0) + f_{pp} N_\beta(E,0) \otimes N_\beta(E\ 0)) + b(E)) \otimes R(E)$
    - 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)
    - $R(E)$ detector energy response function (usually gaussian)
  - generate spectra introducing Poisson fluctuations in $S(E)$
  - fit the spectra with standard technique (m_ν^2, E_0, N_{ev}, f_{pp}, $b(E)$ free)
  - 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
  - $N_{ev} = N_{det}\ t_M\ A_\beta$
  - $f_{pp} \approx \tau_R\ A_\beta \quad (\tau_R \approx \tau_{rise})$

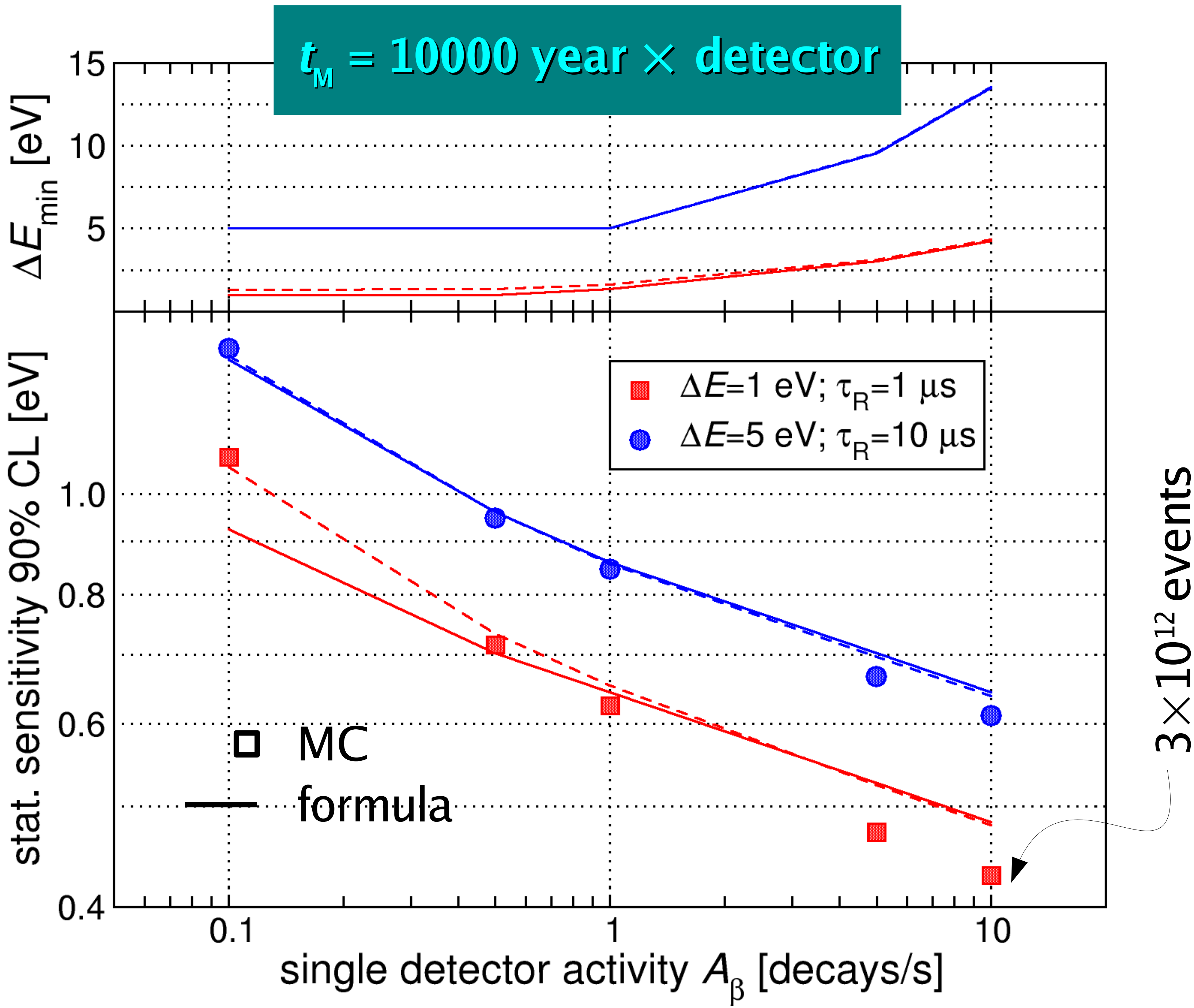
Sub-eV m_ν statistical sensitivity



Sub-eV m_ν statistical sensitivity / 2



Sub-eV m_ν, statistical sensitivity / 3

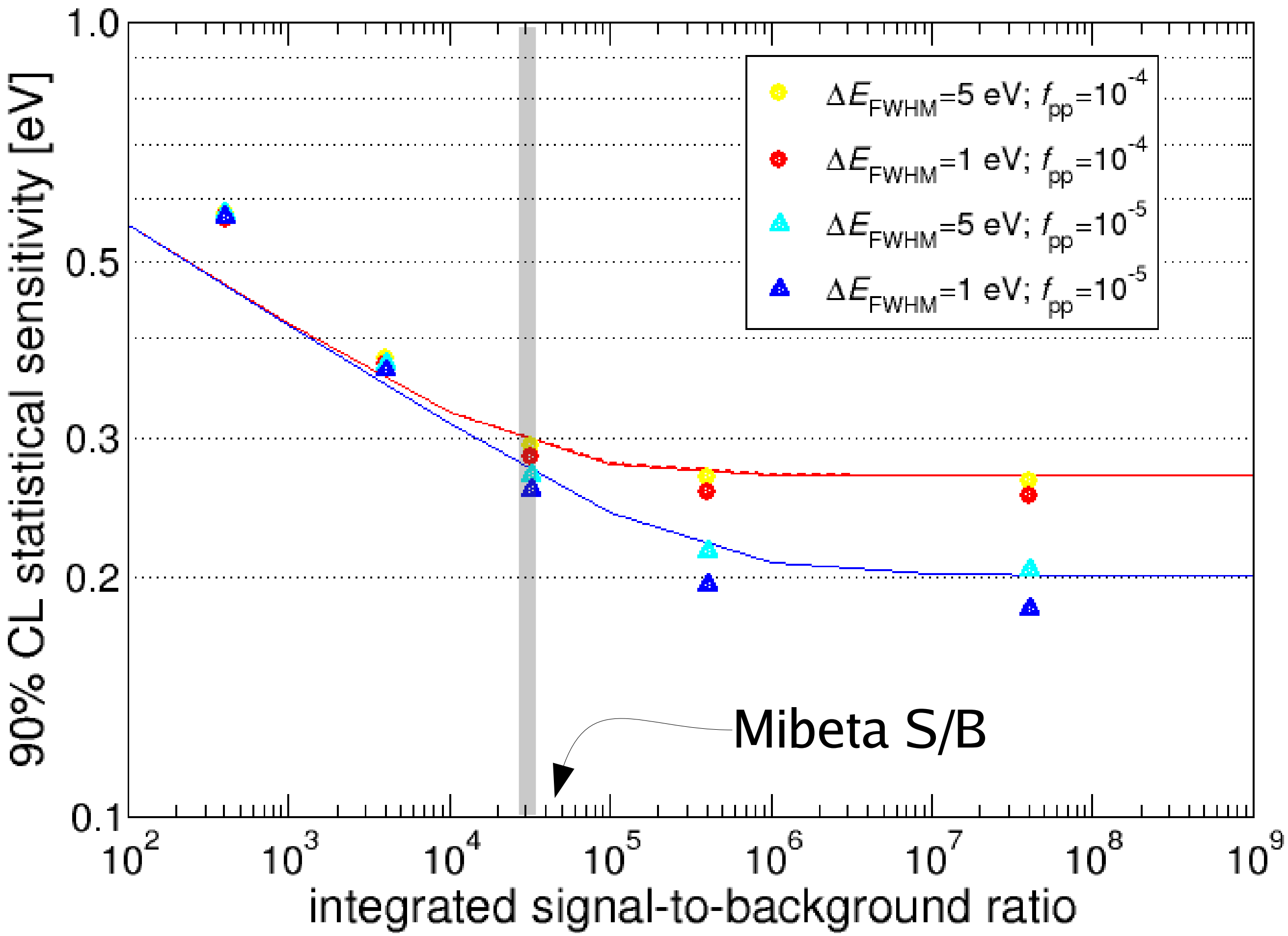


Effect of background on statistical sensitivity

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

b bkg counts/keV/s/det

Optimal energy interval ΔE $\quad \Delta E = max\left(E_0 \sqrt{\frac{3}{10} f_{pp} + b \frac{E_0}{A_\beta}},\ \Delta E_{FWHM}\right)$



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

$N_{bkg} = bE_0T$

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

exposure required for 0.1 eV m_ν sensitivity

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

$b = 0$

8 arrays
5000 pixels
10 years
400 g Rhenium

16 arrays
20000 pixels
10 years
3.2 kg Rhenium

Montecarlo simulations: analysis of systematics

Assessing systematic uncertainties with Montecarlo simulations

- effects due to incomplete/incorrect data modeling
  - ▷ generate simulated experimental spectra with systematic effect
  - ▷ analyze spectra without effect
  - ▷ obtain $\Sigma_{90}(m_\nu)$ and Δm_ν^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 $\Sigma_{90}(m_\nu)$ and Δm_ν^2 as function of uncertainty magnitude
- systematic uncertainties analyzed for $N_{ev}=10^{14}$, $\Delta E_{FWHM}=1.5$ eV and $f_{pp}=10^{-6}$

two main classes of systematics

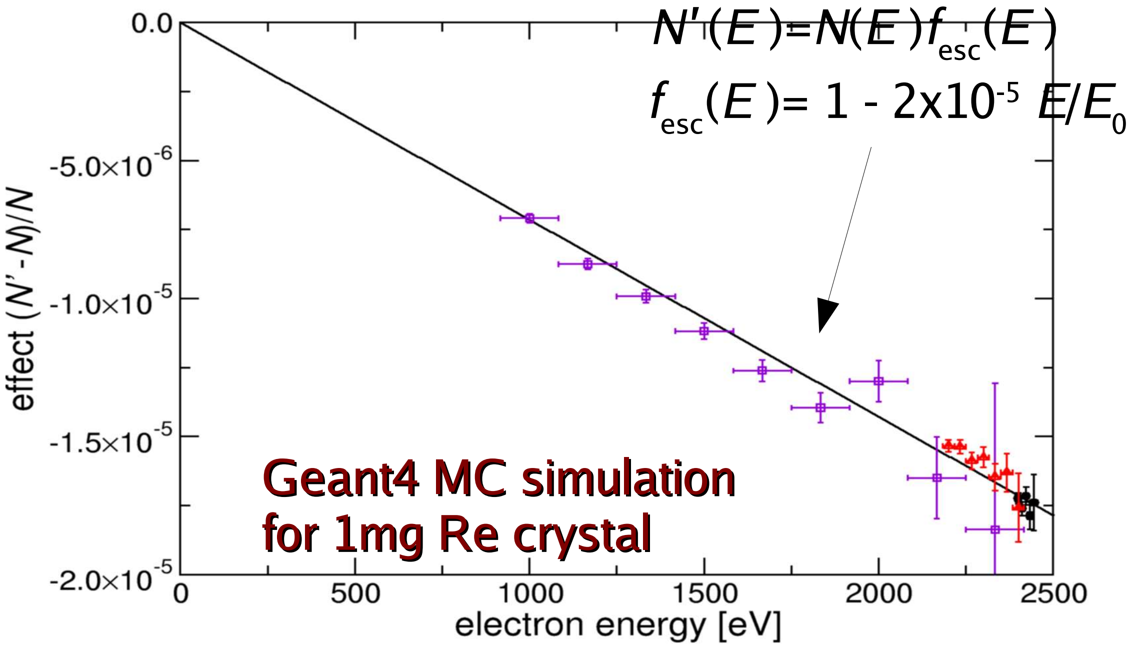
- source related systematic effects
- instrumental systematic uncertainties

Source related systematic uncertainties: summary

- **electron surface escape**
  - investigation with MC methods
  - $N'(E) = N(E)\,(1 - a_{esc}\,E/E_0)$
  - for 1mg Re crystal → $a_{esc} \approx 2\times10^{-5}$
- **^{187}Re decay spectral shape**
  - improve theoretical description of electron spectrum
  - $N'(E) = N(E)\,(1 + a_1\,E + a_2\,E^2)$
  - from Dvornicky-Simkovic (Medex09) → $f(E) = 1 - 2\times10^{-5}E + 3\times10^{-10}E^2 - 4\times10^{-15}E^3 + \ldots$
- **condensed matter effects: BEFS**
  - observed in Re and $AgReO_4$: improve modeling and parametrization
- **pile-up spectrum spectral shape**
  - energy dependent rejection efficiency: investigation with MC methods
  - $\tau_R^{eff} = f(\tau_R, A_1/A_2) \rightarrow N'_{pp}(E) = N_{pp}(E)\,f_{corr}(E, f_{pp})$

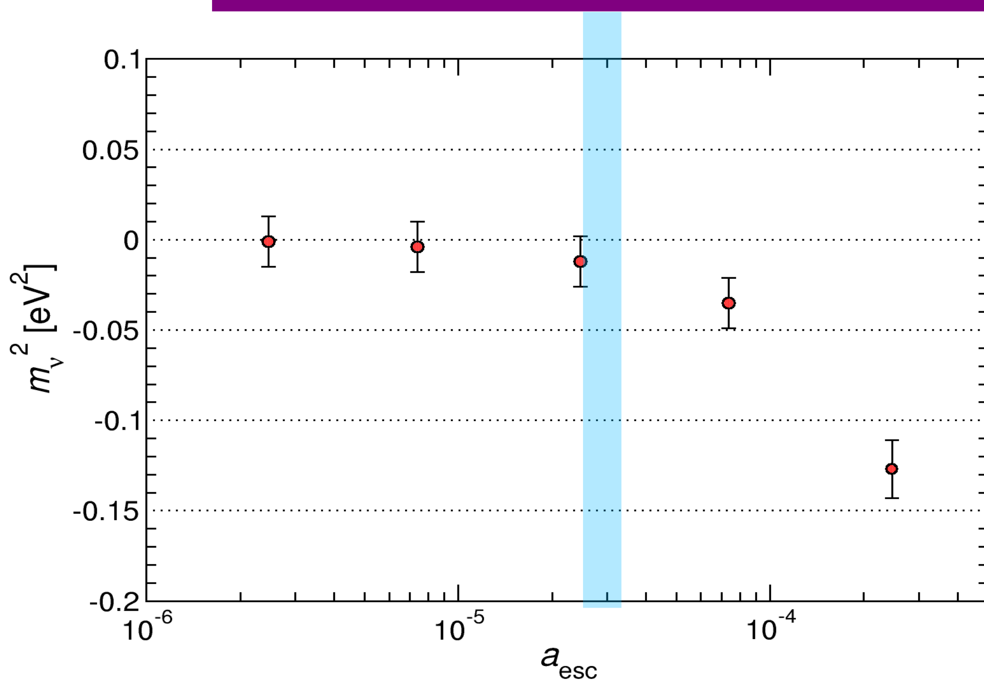
source of uncertainty	quantity describing the effect	maximum effect for $\Delta m_\nu^2 < 0.01$ eV^2
electron surface escape	a_{esc}	10^{-5}
correction to quadratic β spectral shape	$\|a_1\|$ (a_2=0)	10^{-9} eV^{-1}
	$\|a_2\|$ (a_1=0)	10^{-12} eV^{-2}
correction to pile-up spectral shape	f_{pp}	10^{-7}

Electron escape systematic uncertainties



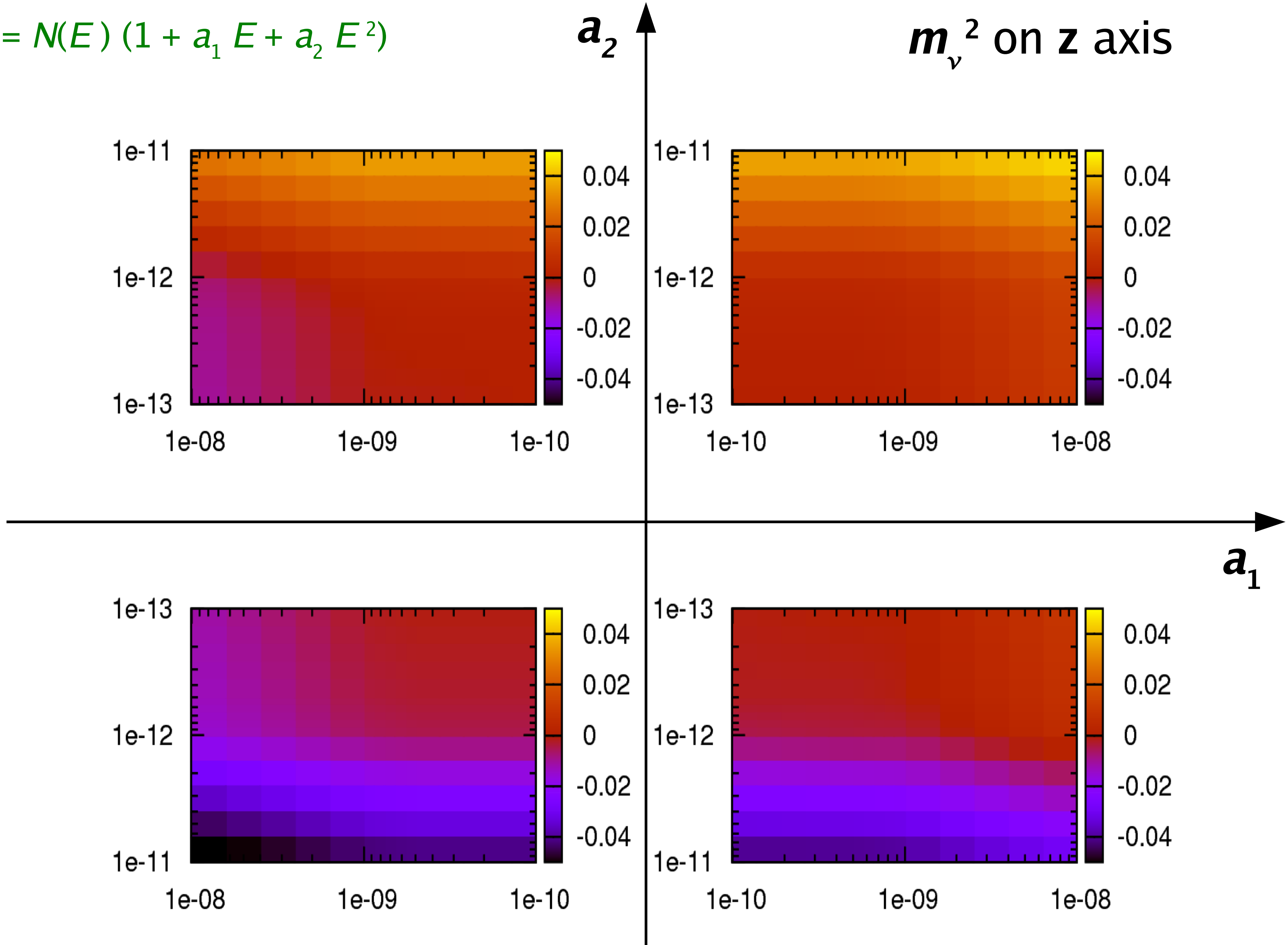
ΔE = 1.5 eV; $f_{pp} = 10^{-6}$; $N_{ev} = 10^{14}$

systematic effect with escape neglected



Beta spectrum shape systematic uncertainties

$N'(E) = N(E)\,(1 + a_1 E + a_2 E^2)$



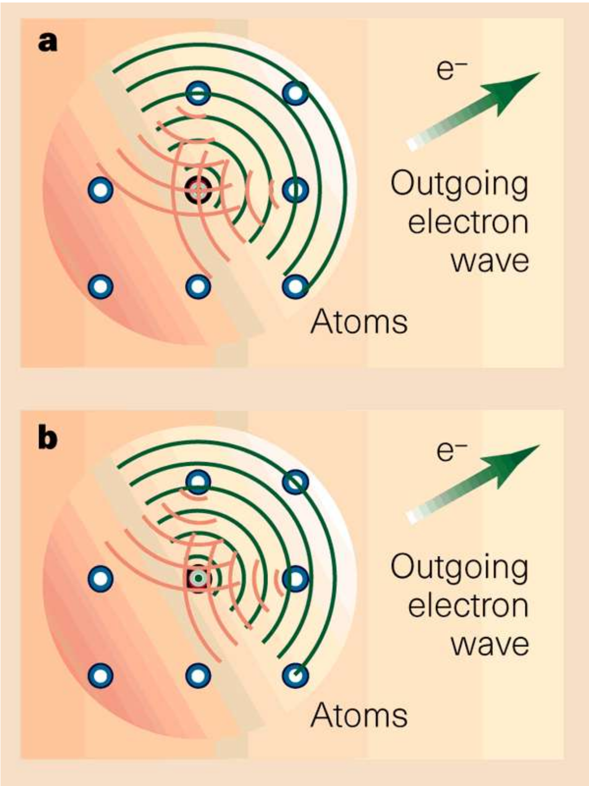
$\Delta E = 1.5$ eV; $f_{pp} = 10^{-6}$; $N_{ev} = 10^{14}$

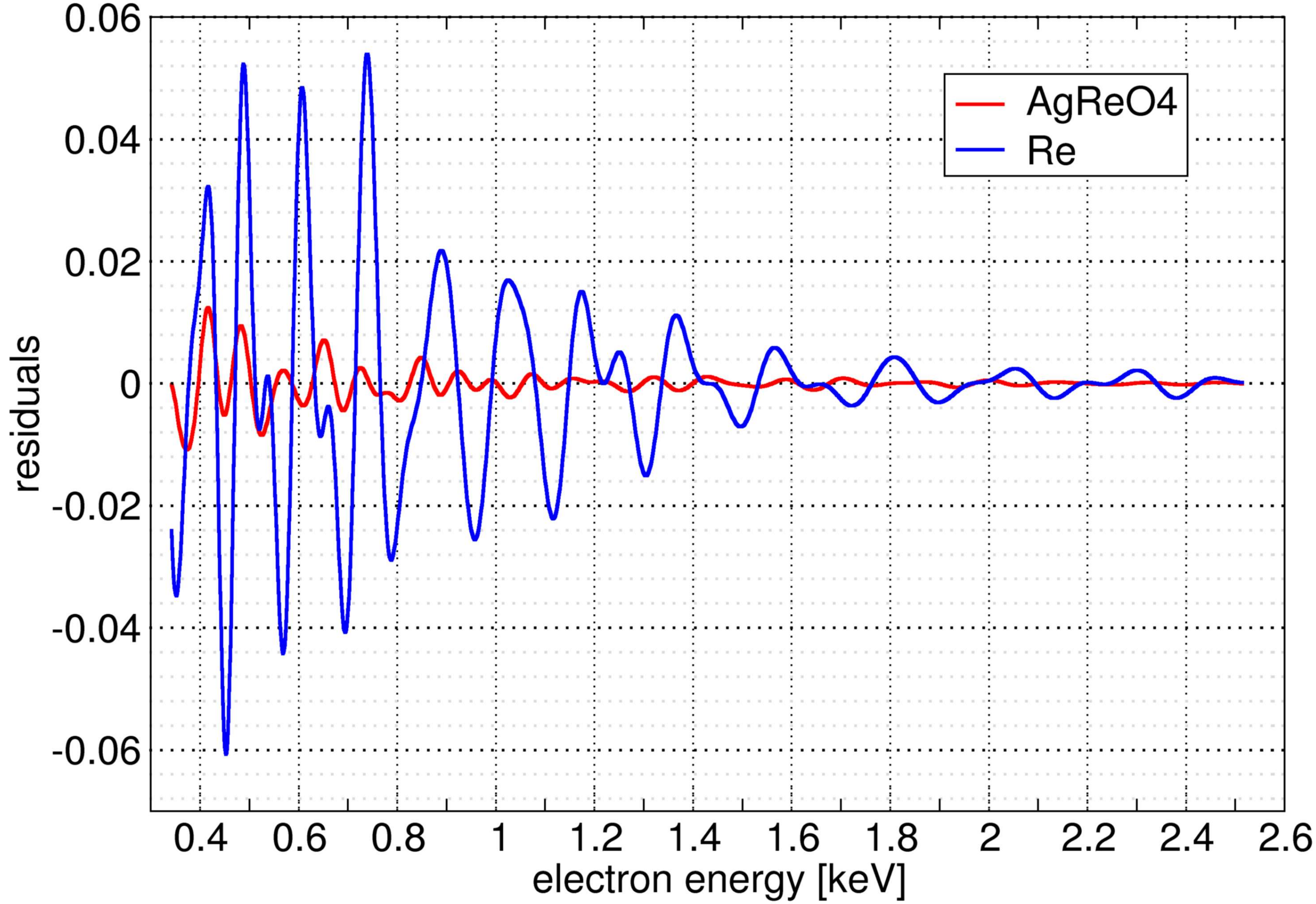
BEFS: Re vs. $AgReO_4$

BEFS: Beta Environmental Fine Structure

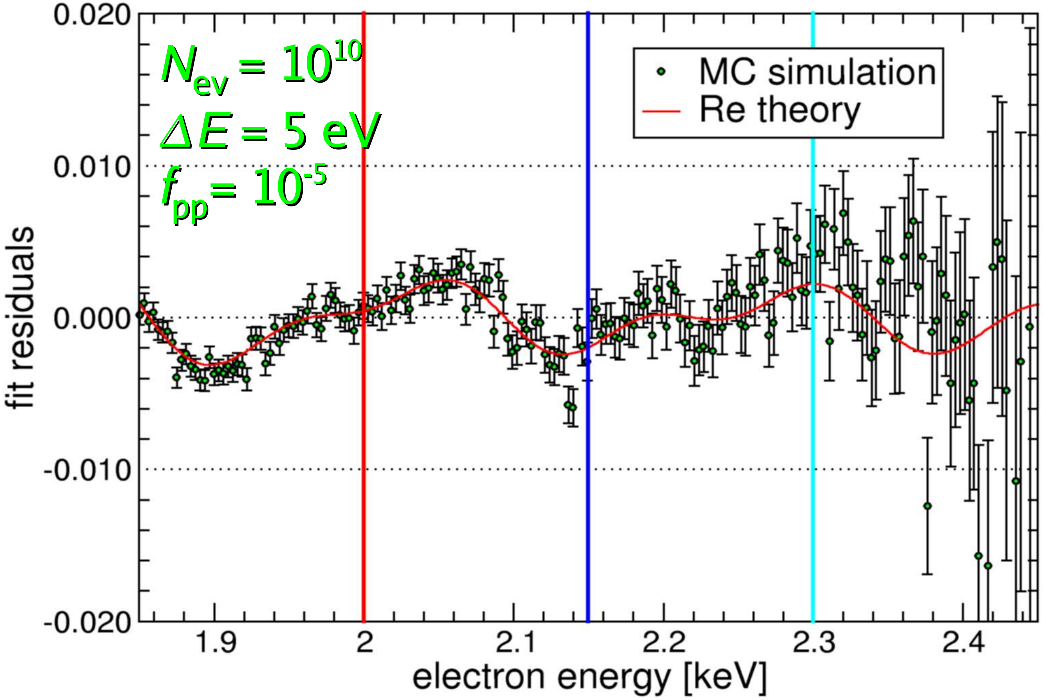
Modulation of the electron emission probability due to the atomic and molecular surrounding of the decaying nucleus: it is explained by the wave structure of the electron

(analogous of EXAFS)



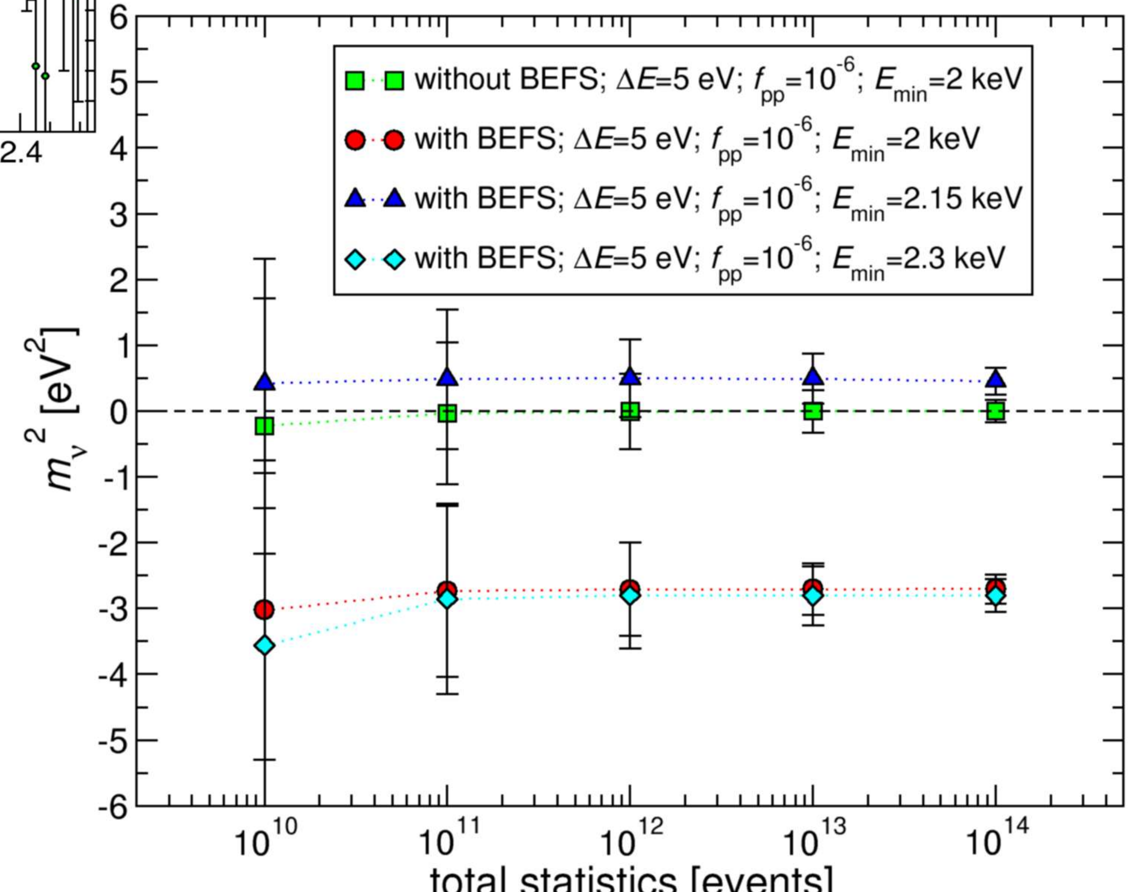


Systematics from BEFS



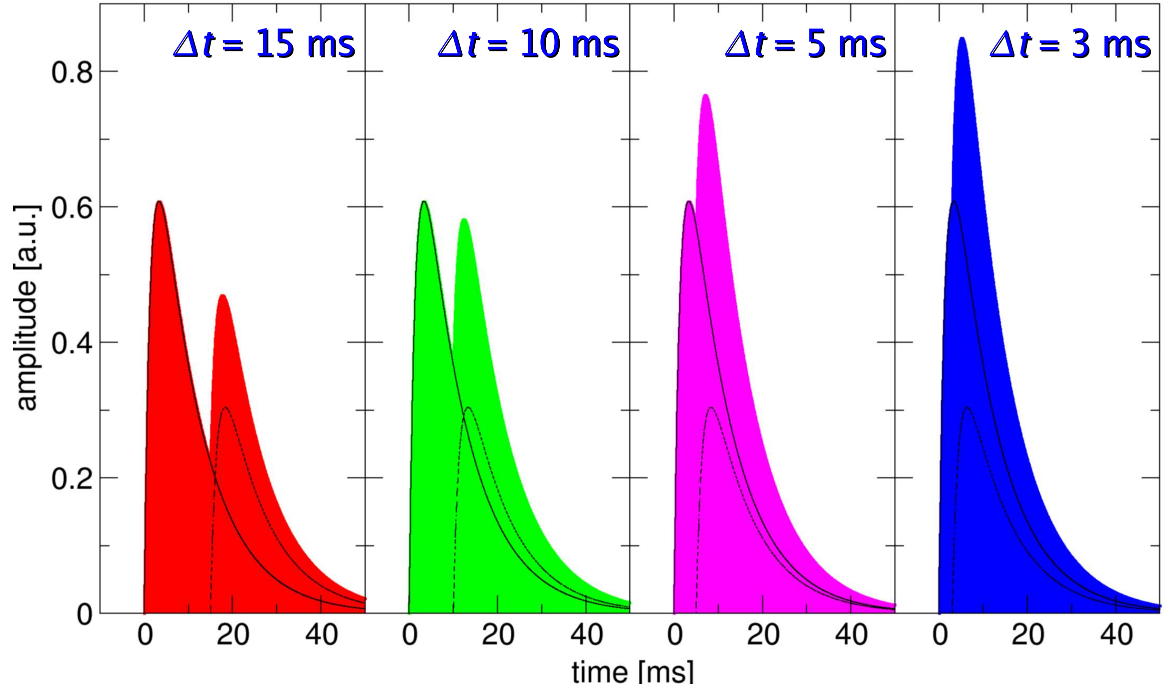
expected **end-point** spectral deformation

systematic shift with BEFS neglected



Pile-up spectrum systematic uncertainties / 1

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

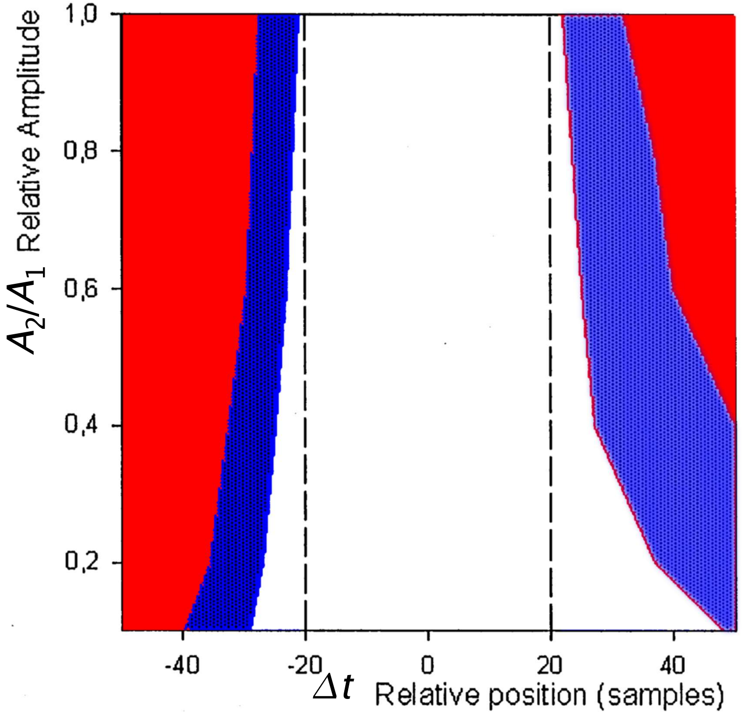


Example

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

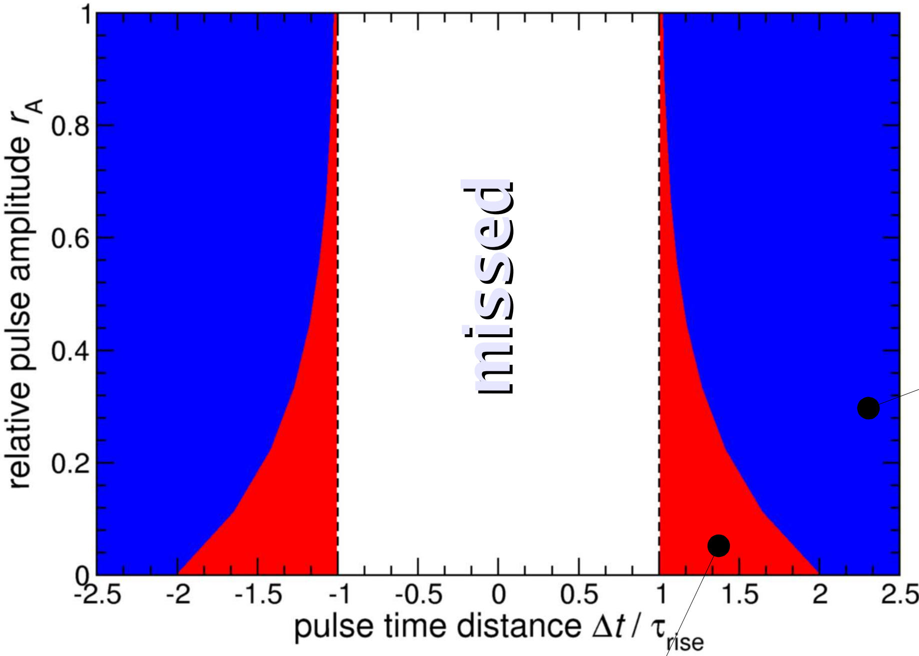
Montecarlo with simulated pulses

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



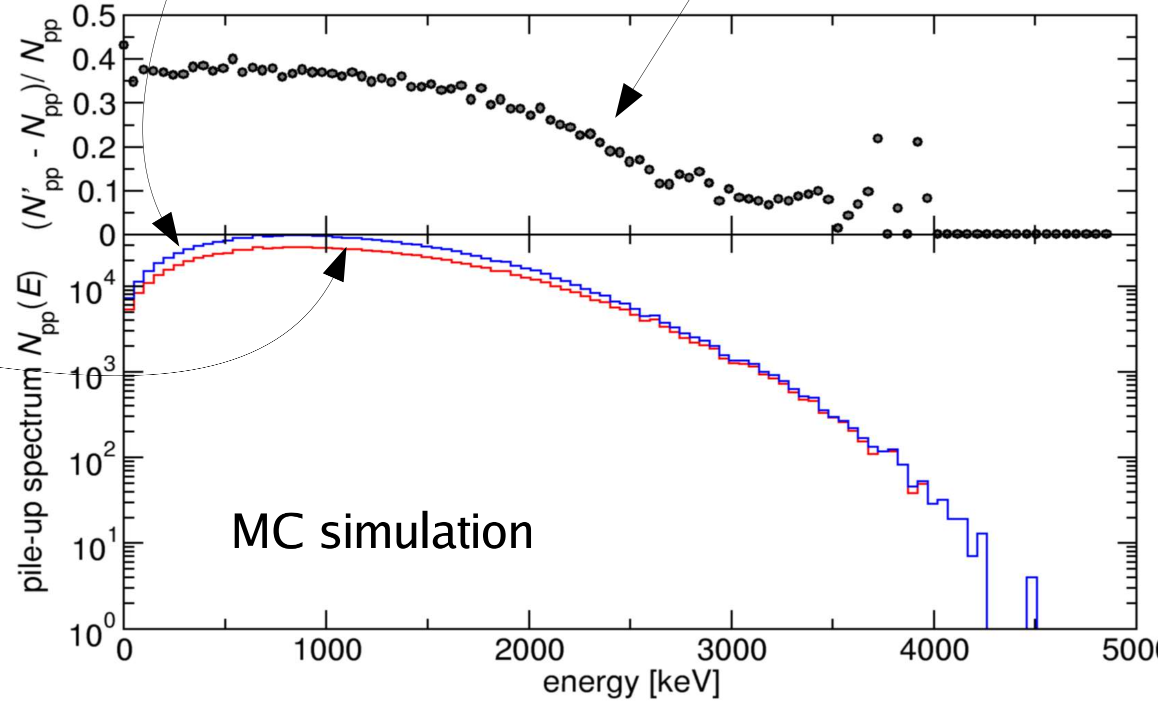
F. Fontanelli et al., NIM A 421 (1999) 464

Pile-up spectrum systematic uncertainties / 2



energy dependent pile-up resolving time τ_{eff}

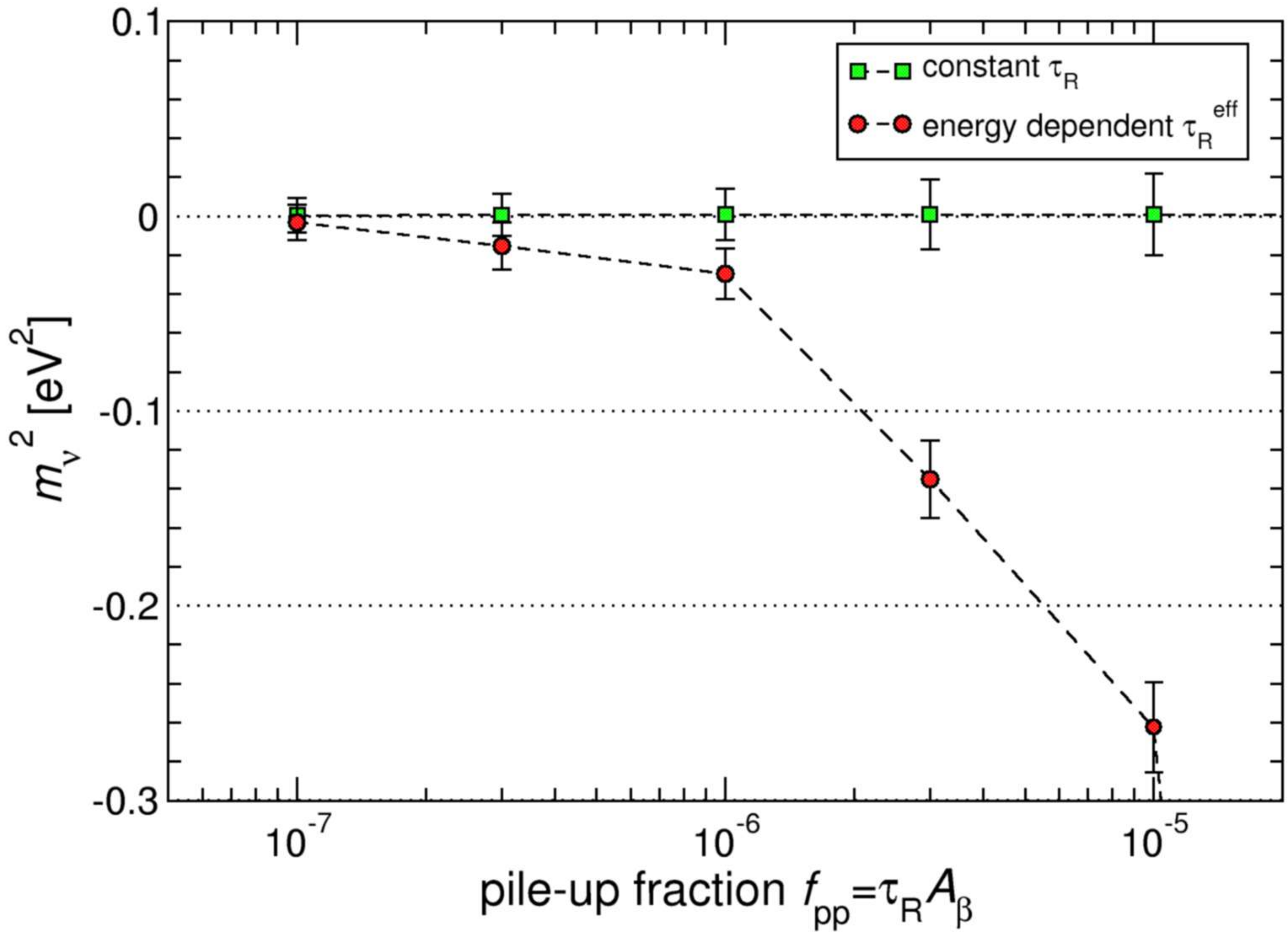
$$f_{corr}(E, f_{pp}=10^{-6}) \approx 1 + \frac{0.4}{e^{(E-E_0)/(480\,eV)}+1}$$



constant pile-up resolving time τ_R

Pile-up spectrum systematic uncertainties / 3

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

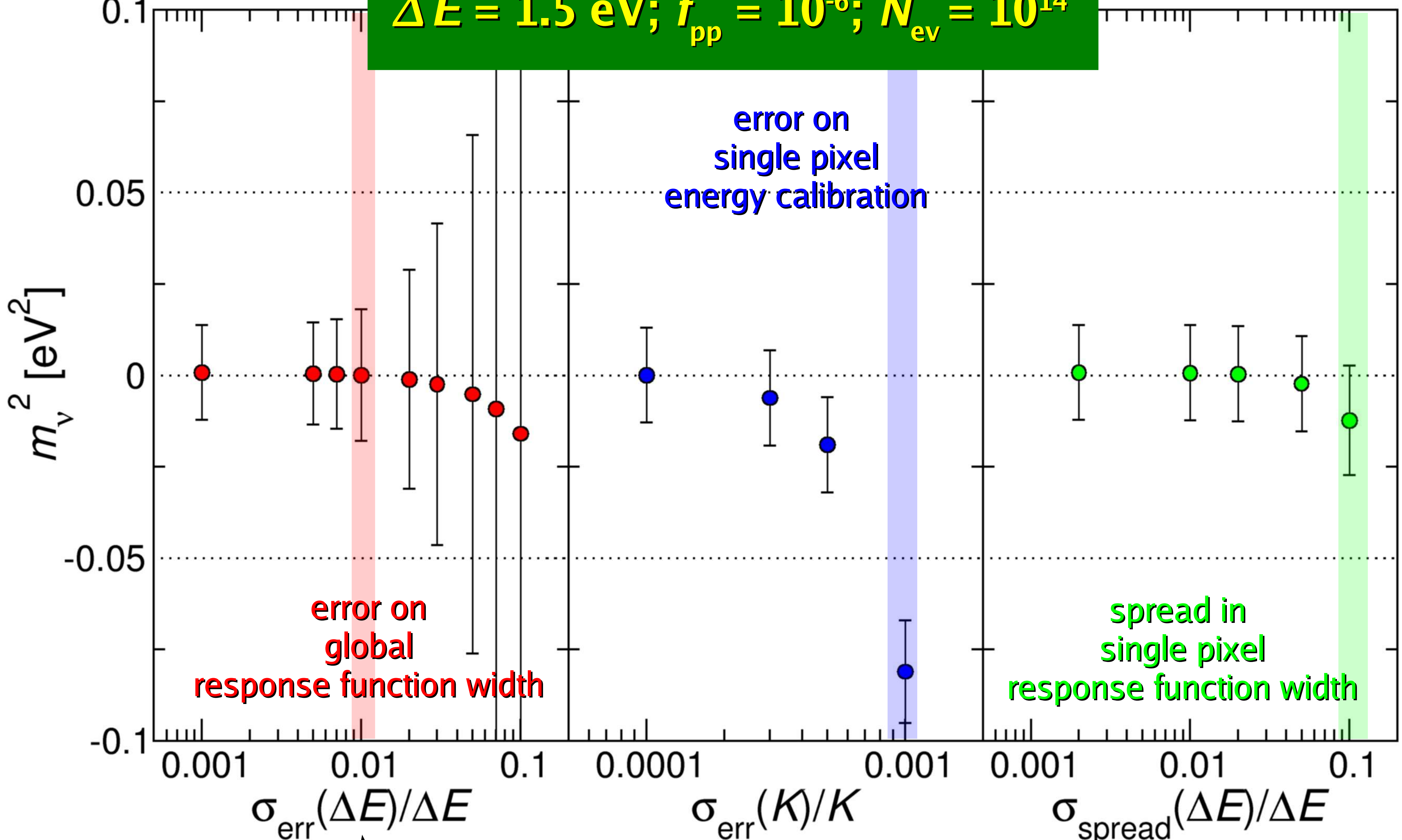


Systematics from instrumental uncertainties: summary

source of uncertainty	*quantity describing the uncertainty*	*maximum uncertainty for $\Delta m_\nu^2 < 0.01$ eV²*
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=10^5c/eV)	b_1	0.1

Instrumental uncertainties: large arrays

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

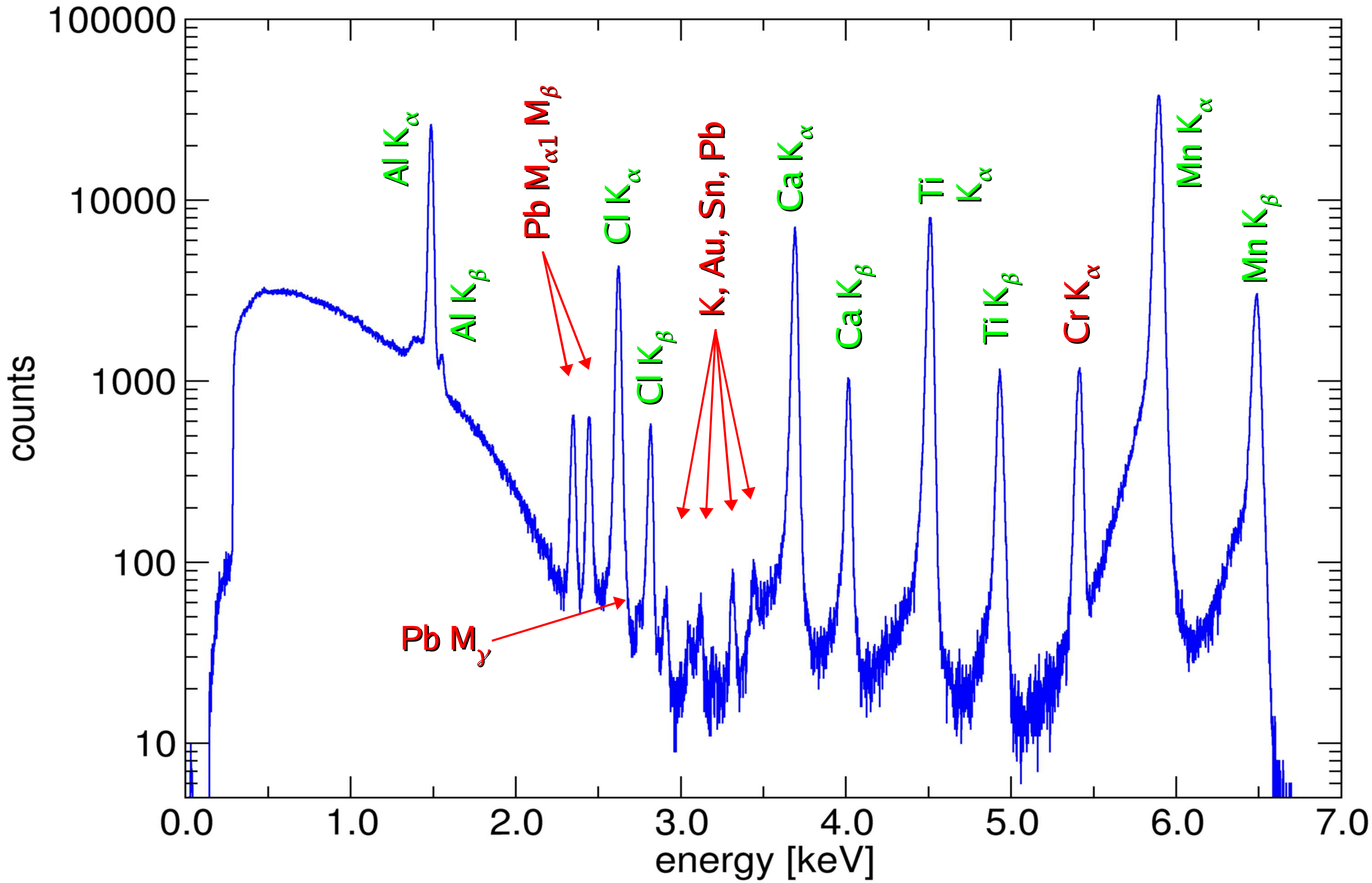


spectrum calibration accuracy improves with statistics

technological issue

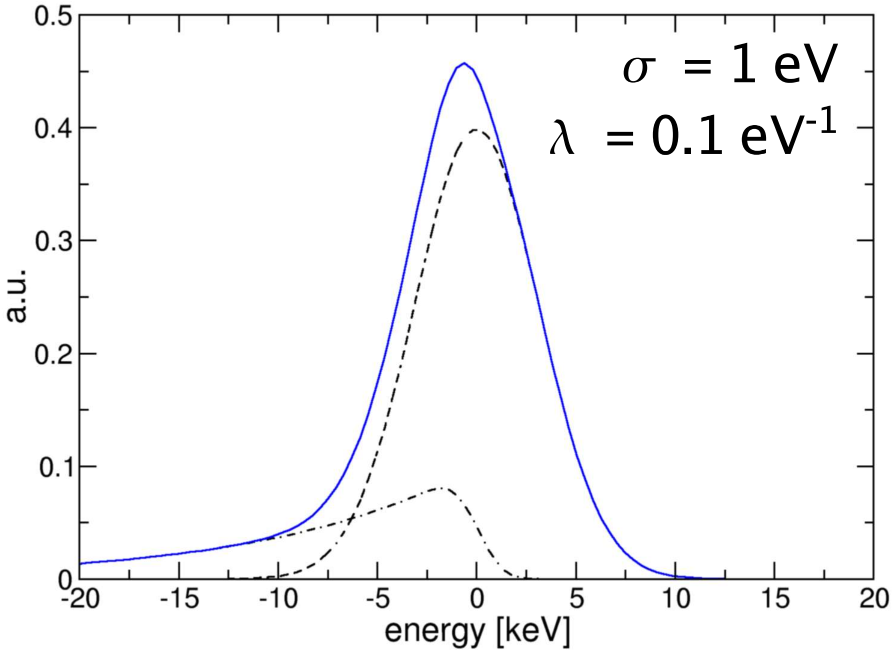
Detector response function

- 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

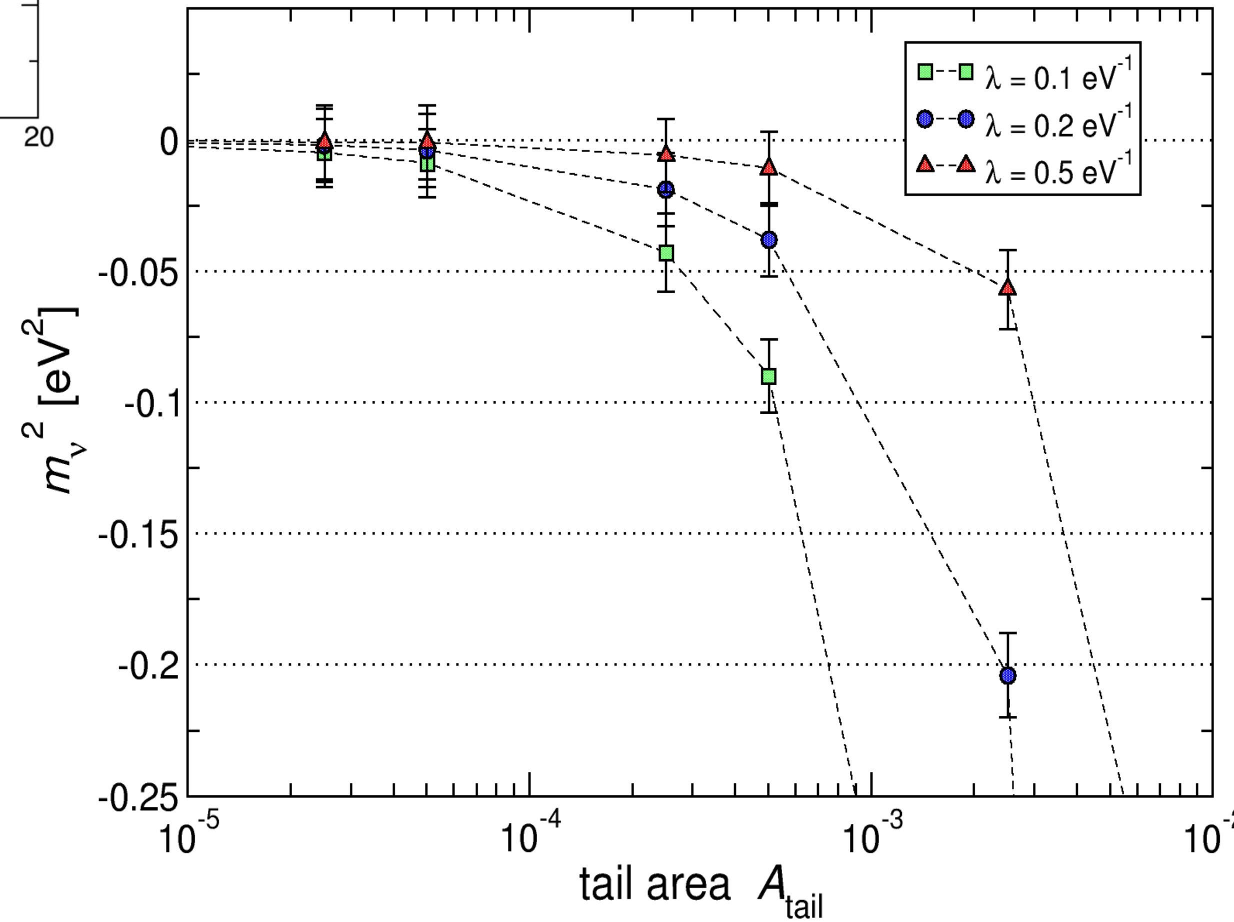
Instrumental uncertainties: response function tail



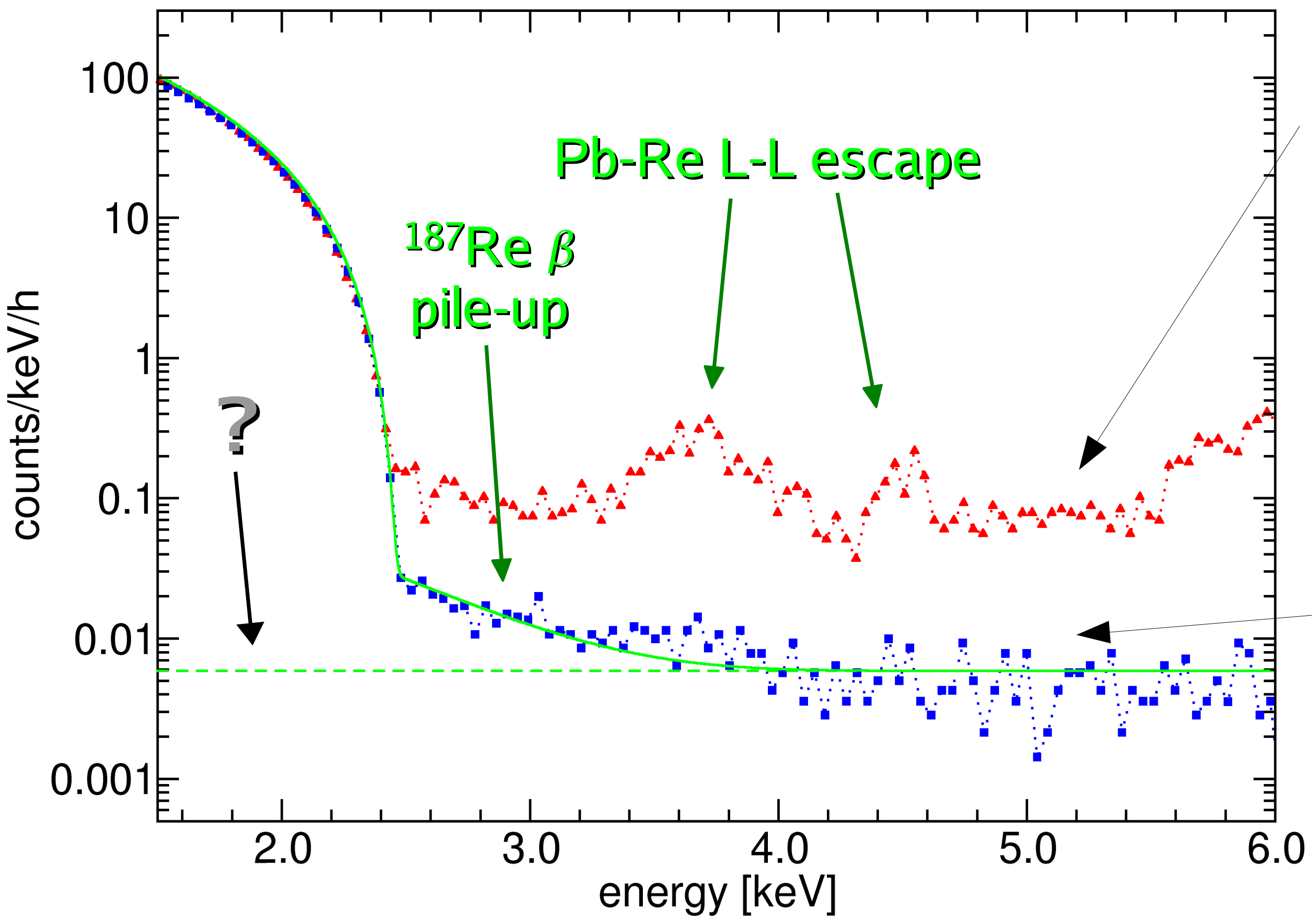
$$T(E)=A_{tail}\frac{\lambda}{2}exp\left[(E-E_0)\lambda+\left(\frac{\sigma\lambda}{\sqrt{2}}\right)^2\right]\left[1-erf\left(\frac{E-E_0}{\sigma\sqrt{2}}+\frac{\sigma\lambda}{\sqrt{2}}\right)\right]$$

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

calibration statistics



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

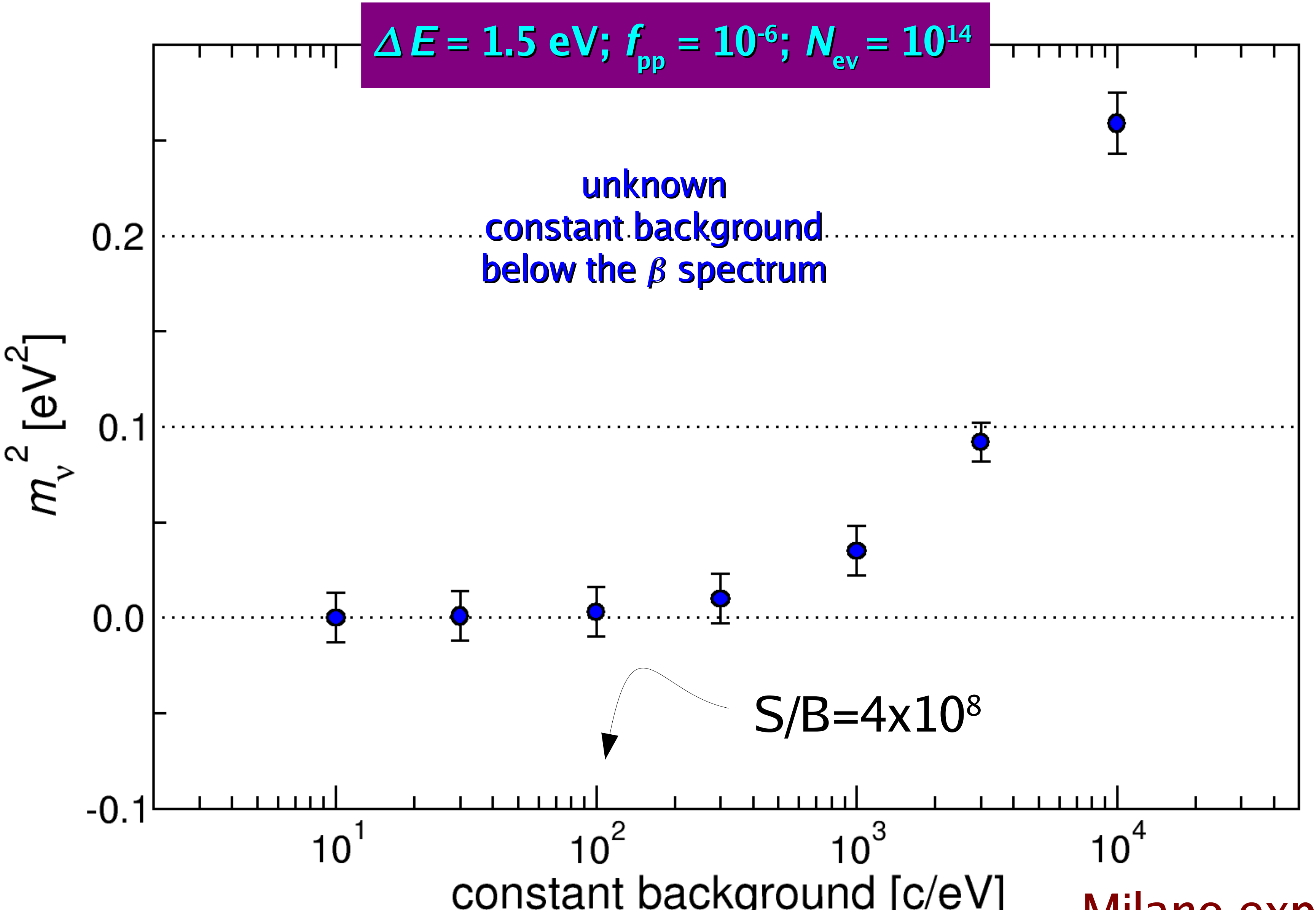
lead shielded
^{55}Fe calibration source

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

the hidden background is a source of systematic uncertainties

Go underground?

Instrumental uncertainties: constant background



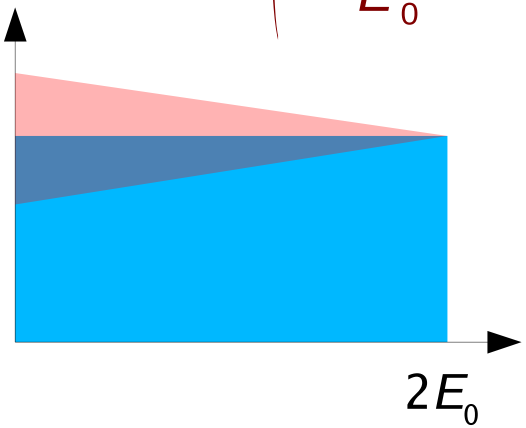
$S/B = N_{ev}/N_{bkg}$

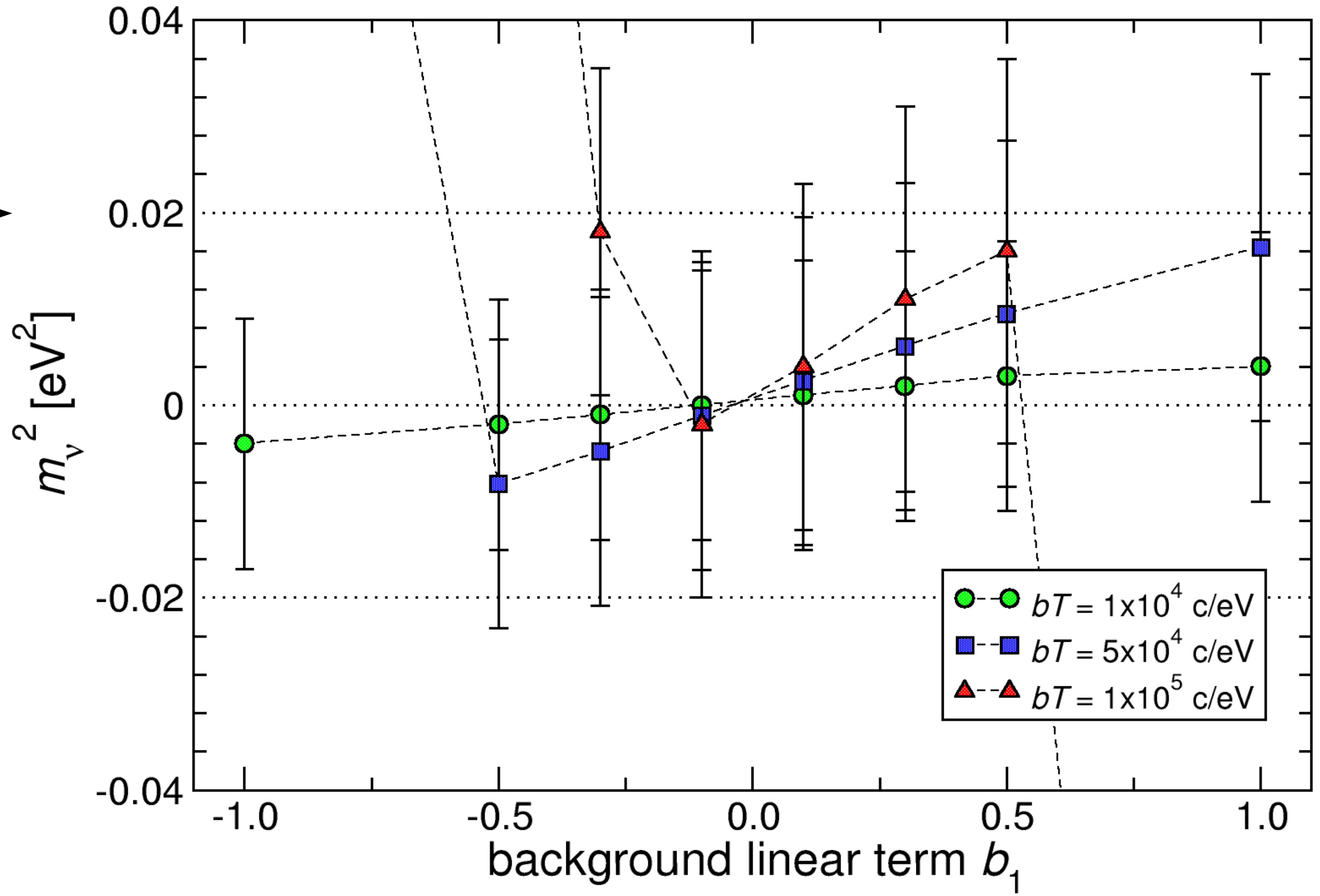
Milano experiment
$S/B \approx 3\text{x}10^4$
$bT \approx 10^6$ c/eV on this plot

Instrumental uncertainties: background linear term

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

$$B(E) = bT\left(1 + \frac{b_1}{E_0}(2E_0 - E)\right)$$





Conclusions

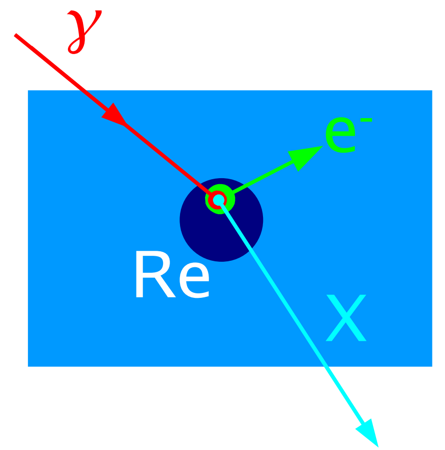
- thermal calorimetry of ^{187}Re decay can give **sub-eV sensitivity on m_ν**
- preliminary systematics estimate by Montecarlo methods shows
  - ▷ **source related systematics** require more investigations
    - Beta Environmental Fine Structure
    - ^{187}Re spectral shape
    - ...
  - ▷ **instrumental systematic uncertainties** seem to be more controllable
- more systematics will show up increasing the statistics in the β spectra
  - ▷ **intermediate size experiments** are crucial

Backups ...

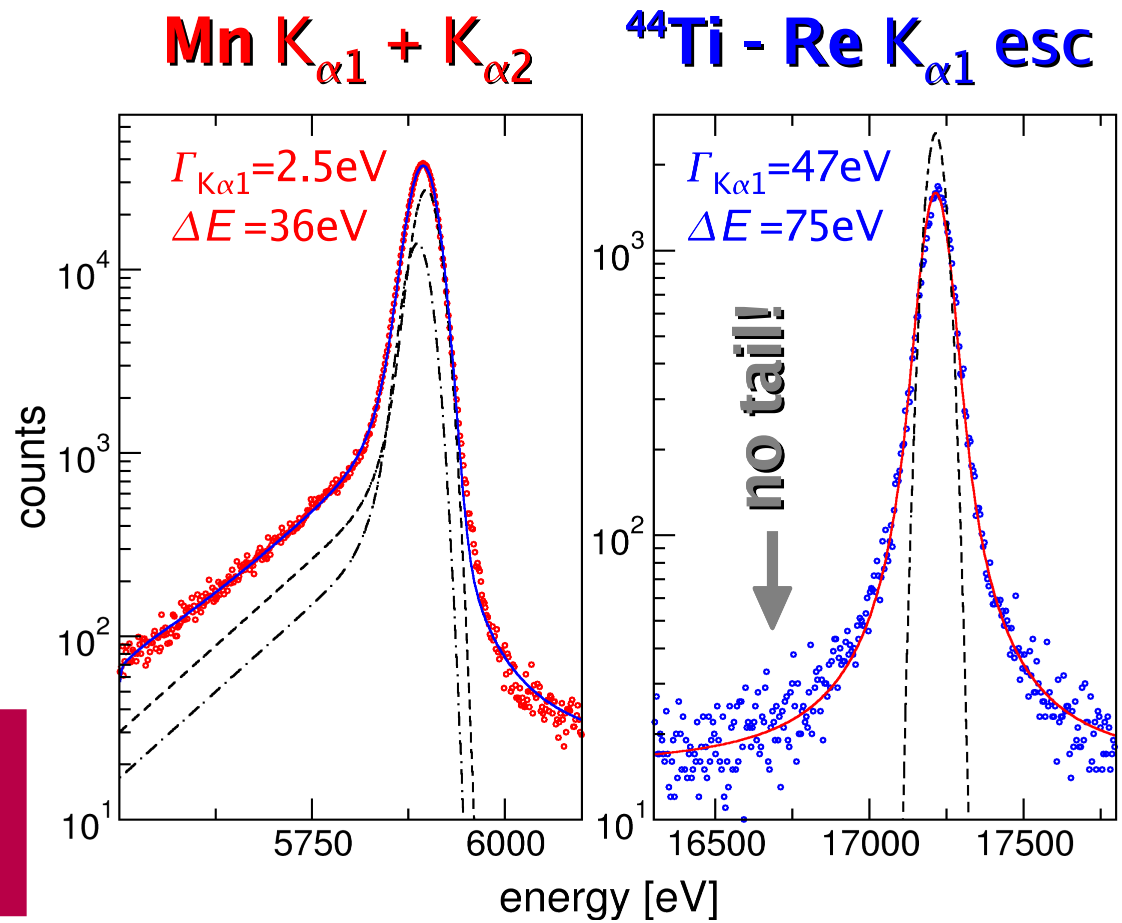
MIBETA: Measurement of response function (2004)

- 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

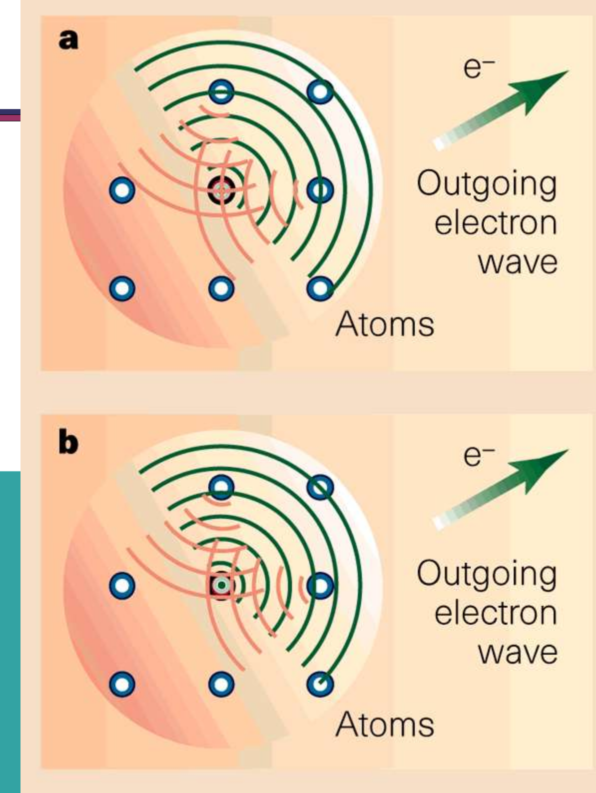


- Re K-edge @ 71.7 keV
  - ▷ E_γ > 71.7 keV
  - ▷ **internal calibration with ^{44}Ti**
- γ rays @ 78.4 keV
- ▶ γ-X escape peaks have only Re K natural width (Γ_{ReK}~47 eV)



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

MIBETA: BEFS analysis (2005)

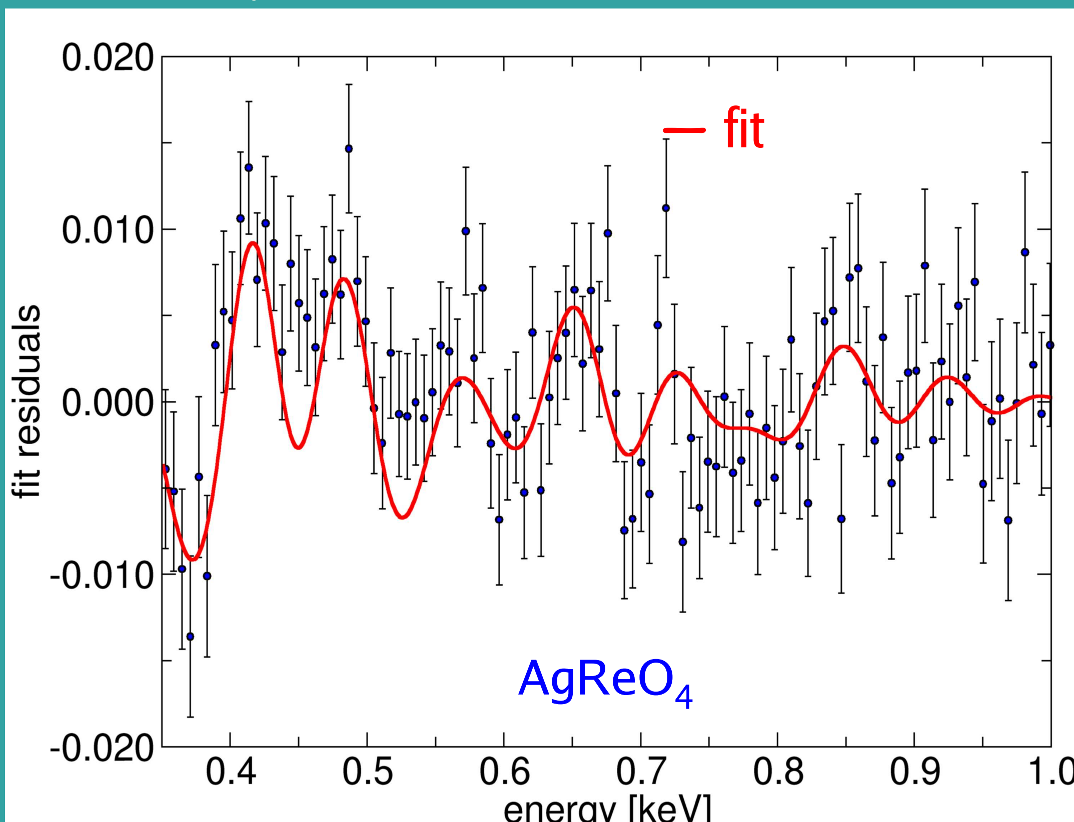


BEFS: Beta Environmental Fine Structure

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

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

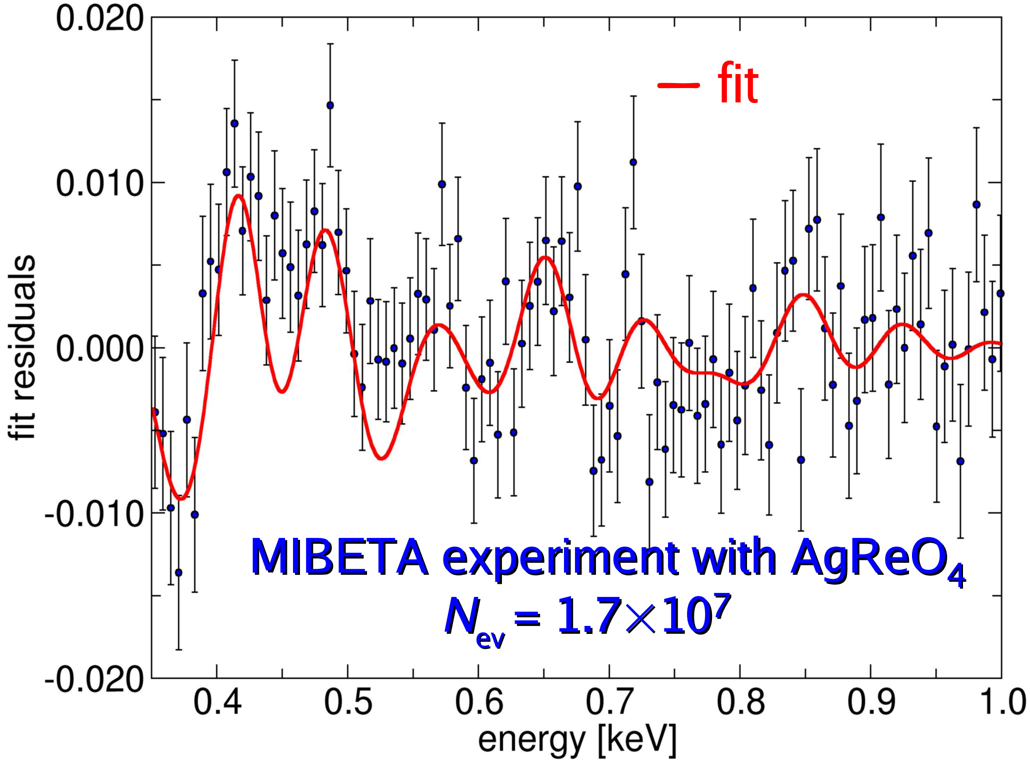
$$\chi^{l}_{EXAFS}(k_e) = (-1)^l \sum_{n=1}^{N} B_{nl}(k_e, R_n) e^{-2k_e^2\sigma_n^2} \sin(2k_e R_n + \delta_{0l} + \delta_{nl})$$

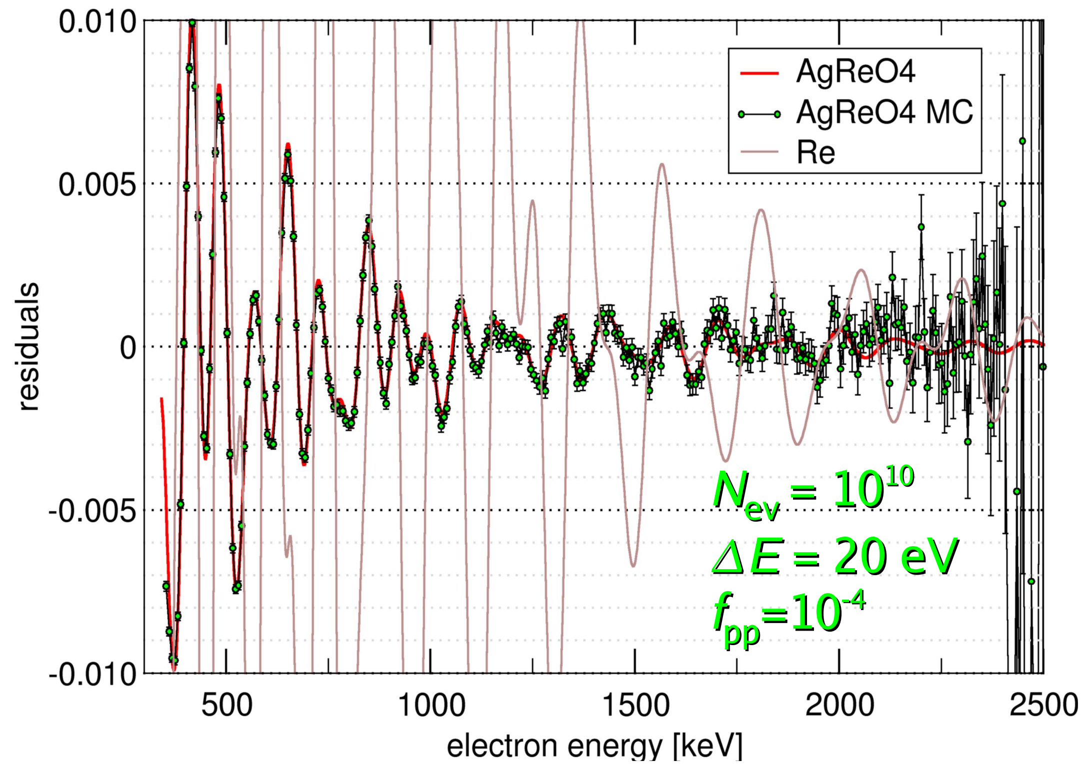
→ $F_p = 0.84 \pm 0.30$

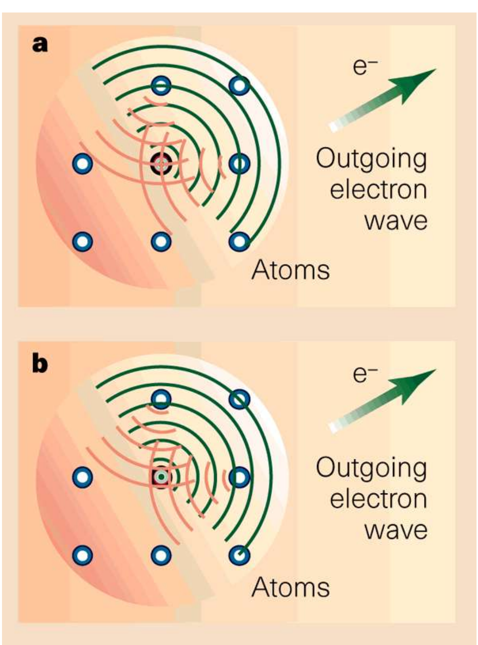
BEFS is a possible source of systematic uncertainties in ^{187}Re neutrino mass experiments

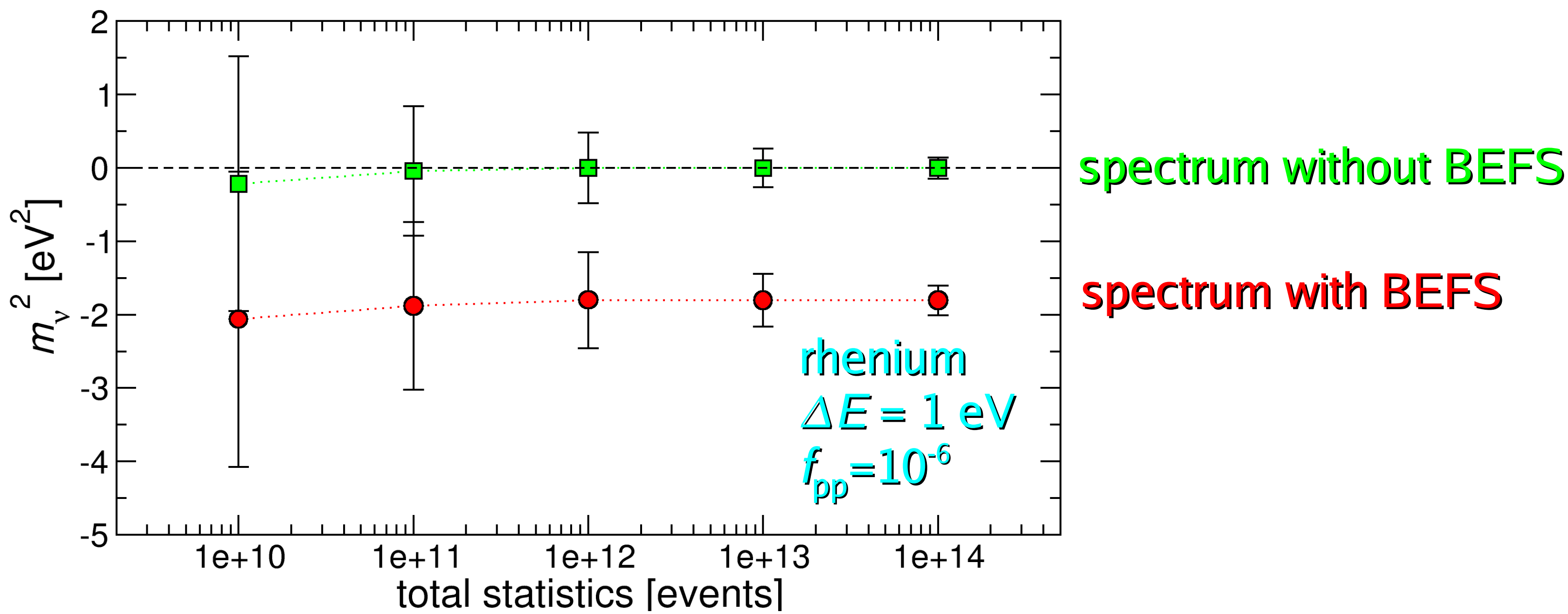
⇒ EXAFS measurements
⇒ better models

MC analysis of systematics: BEFS

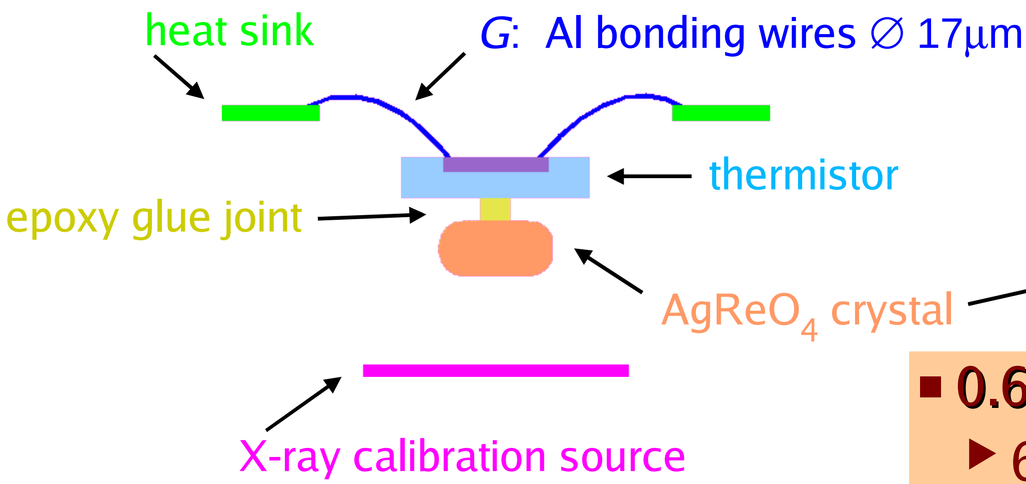


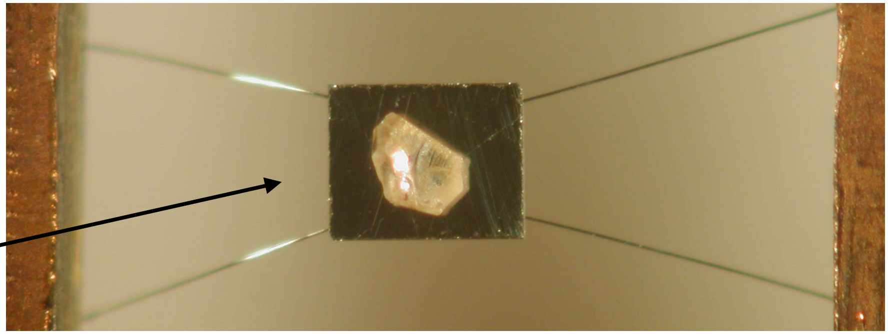






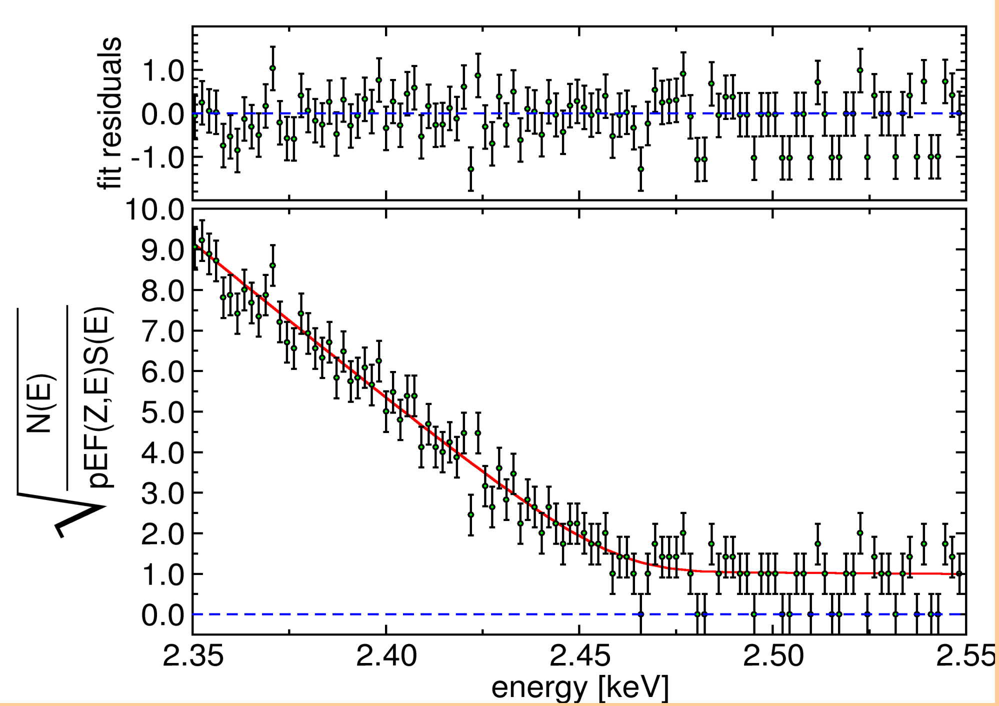
MIBETA experiment: 2002/03





- 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
  - $\langle \tau_{rise} \rangle = 490\ \mu s$
    - $f_{pile\text{-}up} \approx 2\times10^{-4}$

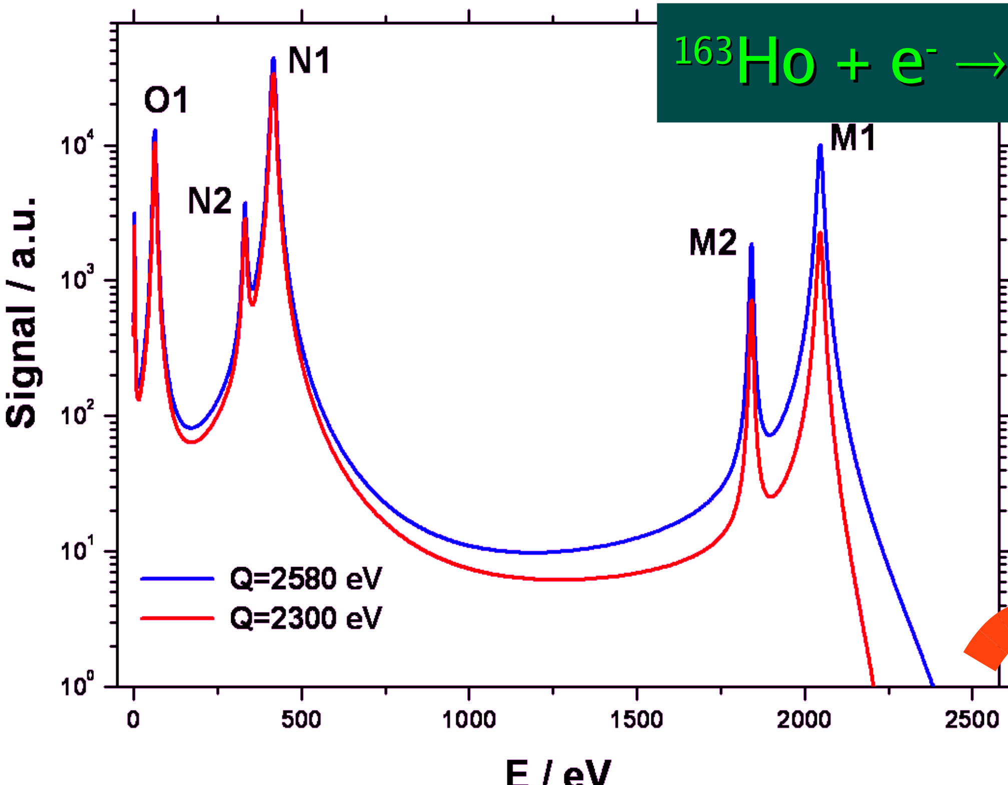
- 0.6 years live time (0.45 years only β)
  - 6.2×10^6 ^{187}Re decays above 700 eV
  - $m_\nu^2 = -96 \pm 189_{stat} \pm 63_{sys}\ eV^2$
    - $m_\nu < 15.2 \pm 2.0_{sys}$ eV (90 % C.L.)

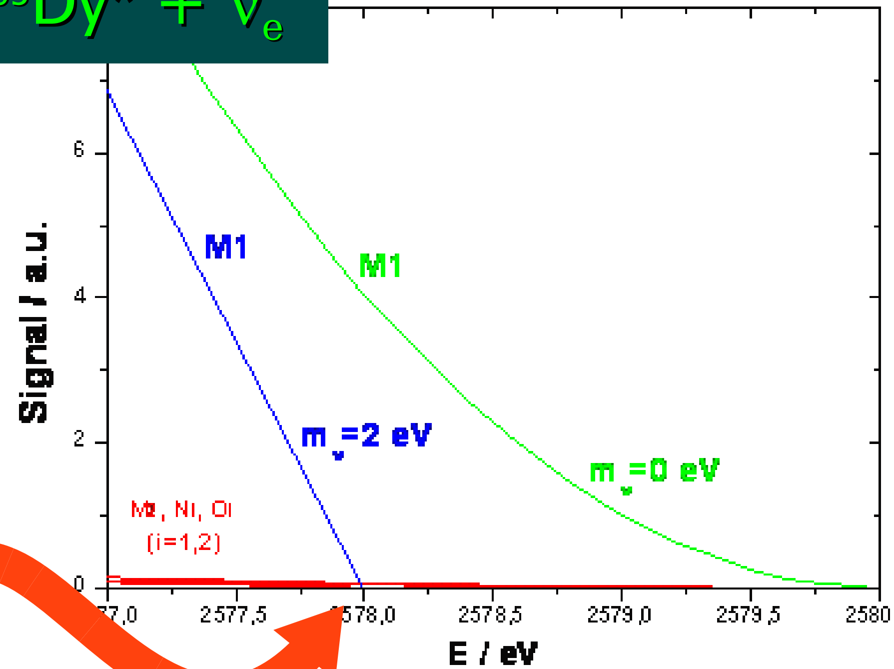


C. Arnaboldi et al., Phys. Rev. Lett. 91 (2003) 161802
M. Sisti et al, NIM A 520 (2004) 125

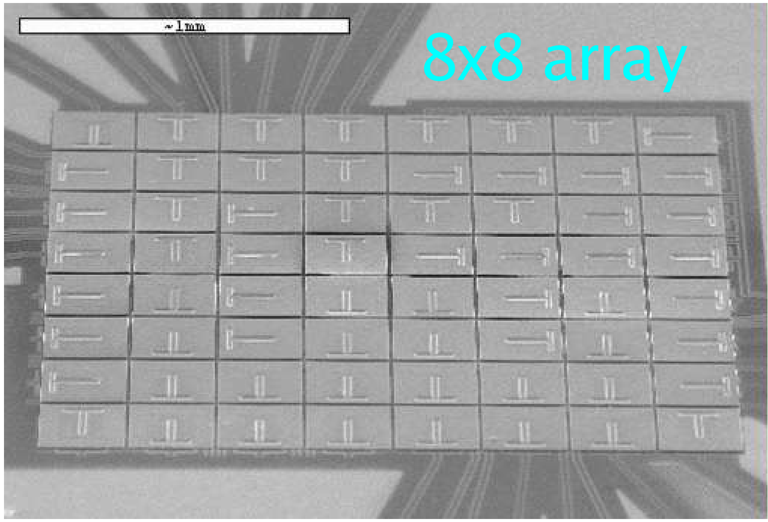
MARE extensions: ^{163}Ho electron capture measurement

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

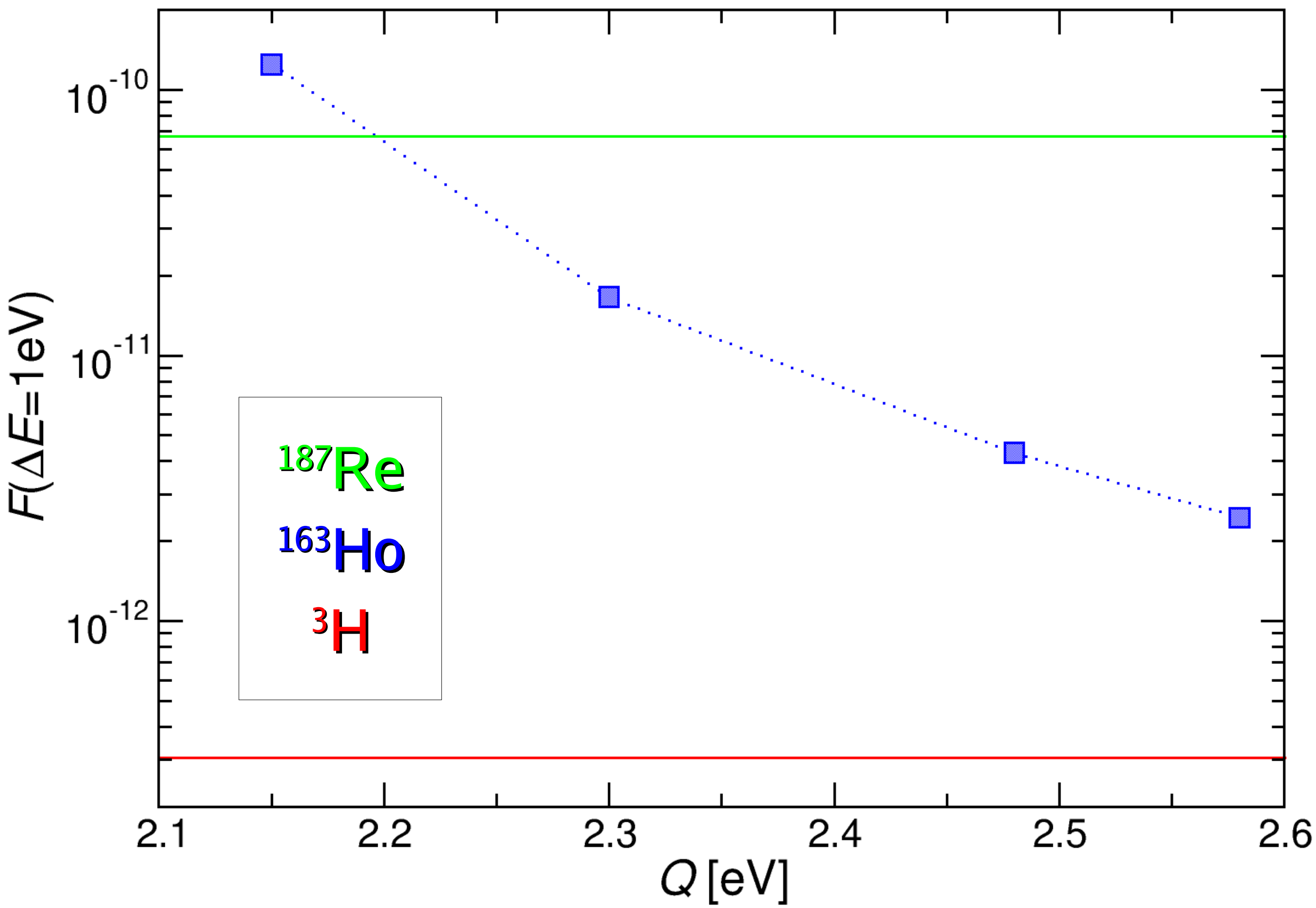




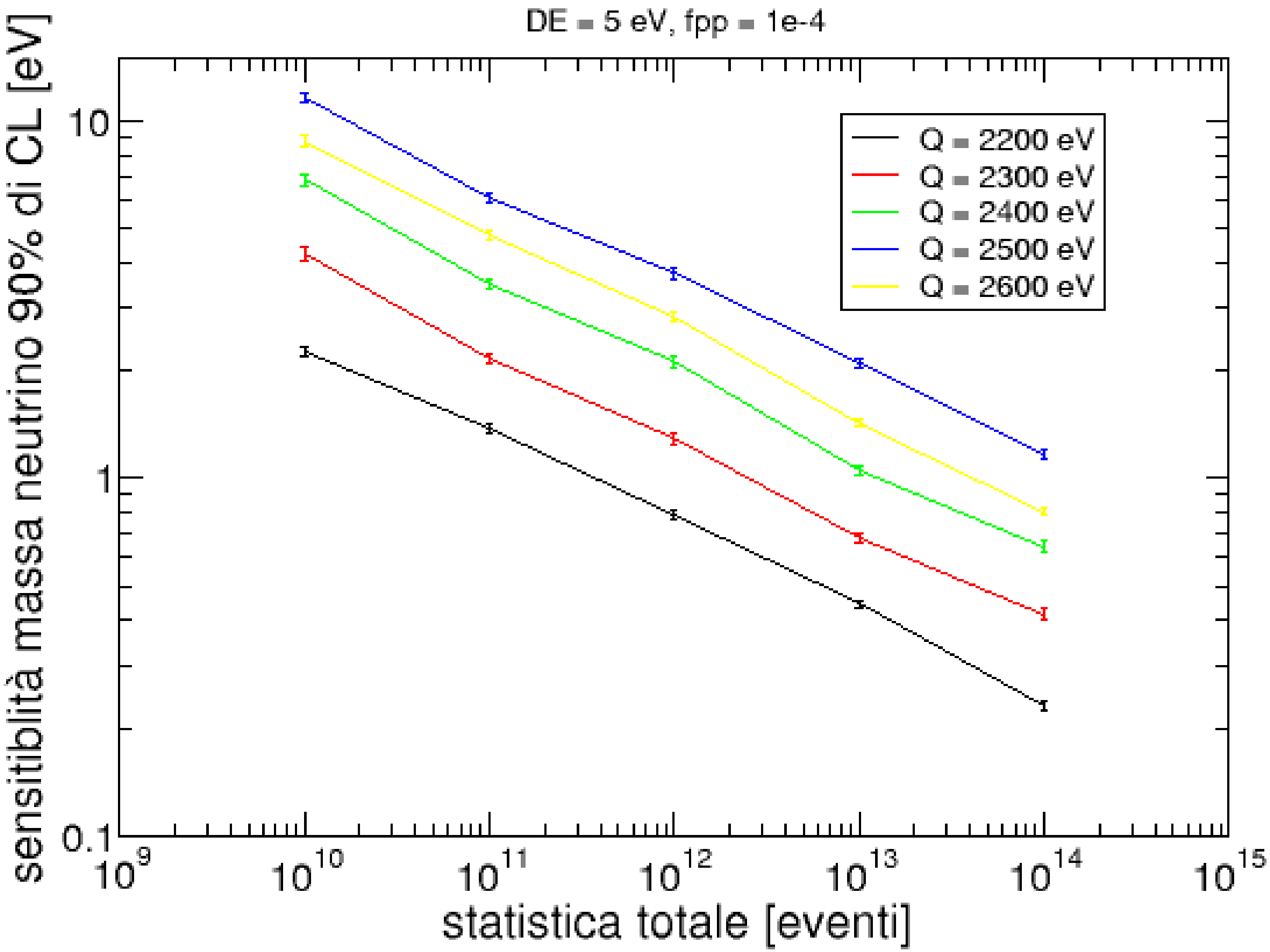
- calorimetric measurement of non-radiative Dy atomic de-excitations (Coster-Kronig, Auger...)
- fraction of events at end-point may be as high as for ^{187}Re: depends on Q_{EC} (≈2.5 keV)
  - Q_{EC}?
- fewer active nuclei are needed (τ ≈ 4000 y)
  - can be implanted in any suitable absorber
  - first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



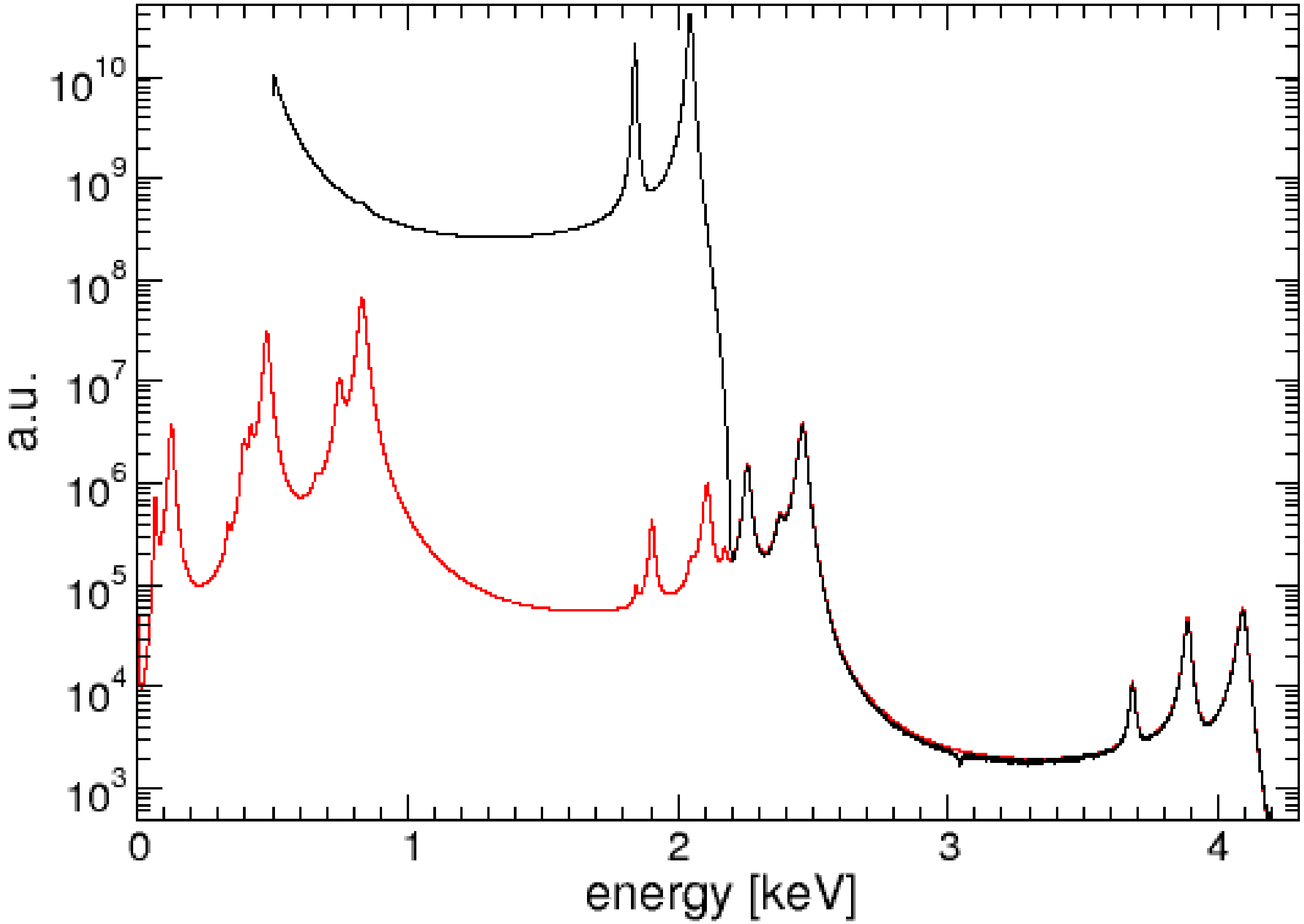
^{163}Ho end-point statistics



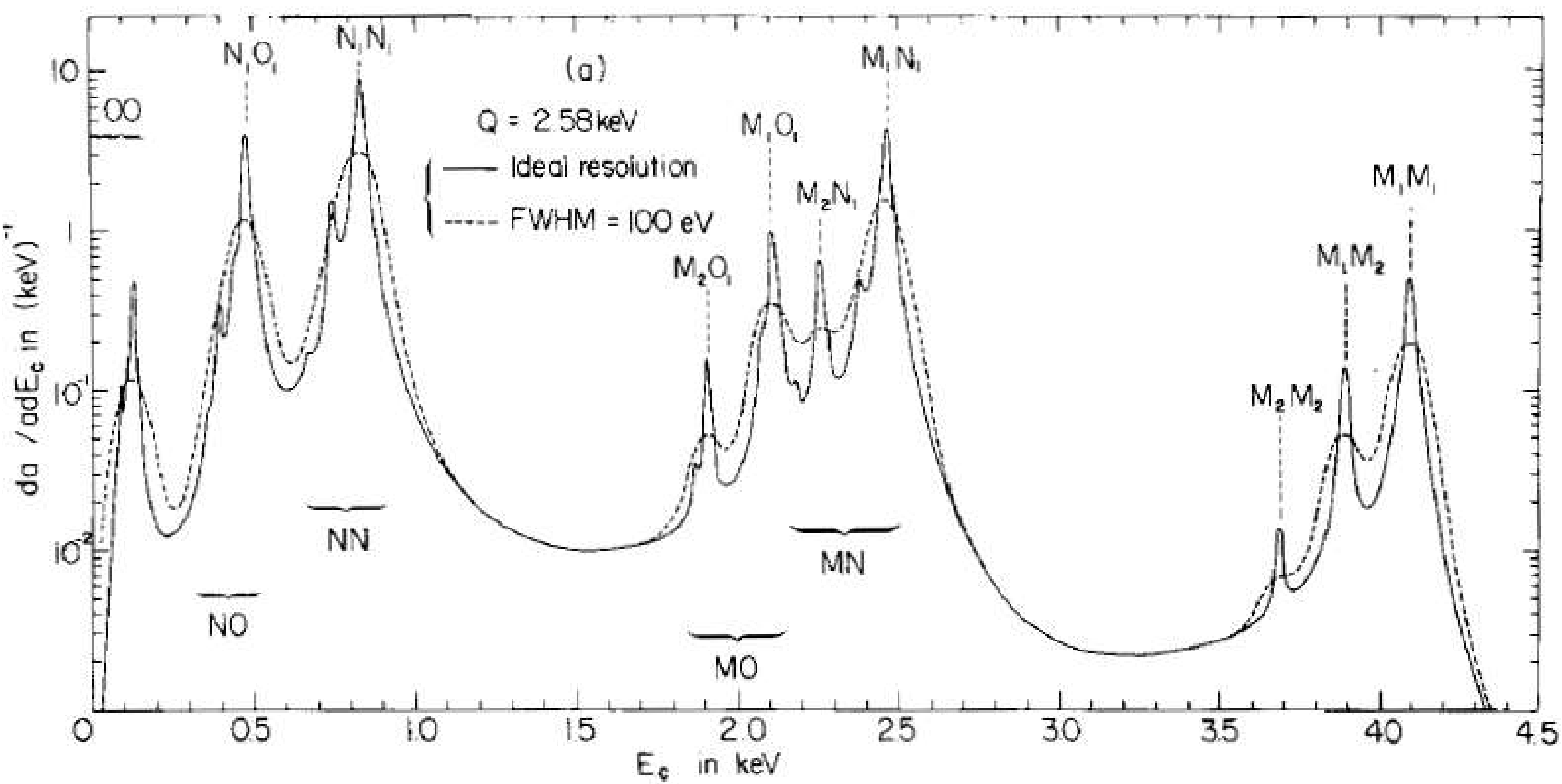
^{163}Ho MC sensitivity estimate



^{163}Ho spectrum simulation



^{163}Ho pile-up spectrum



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

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