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

Angelo Nucciotti
for the MARE collaboration
Dipartimento di Fisica "G. Occhialini", Università di Milano-Bicocca
INFN - Sezione di Milano-Bicocca, Milano, Italy

Ecole Internationale Daniel Chalonge
Workshop CIAS Meudon 2011
WARM DARK MATTER IN THE GALAXIES:
THEORETICAL AND OBSERVATIONAL PROGRESSES
CIAS Observatoire de Paris, Château de Meudon, Meudon campus
8, 9 and 10 June 2011

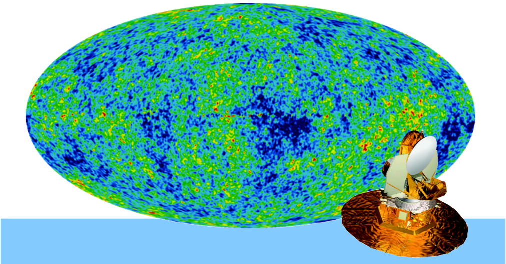
Outline

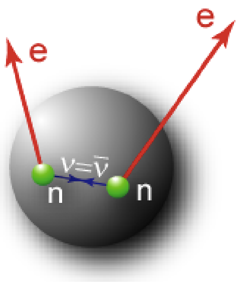
- Direct neutrino mass measurement
  - spectrometers vs. calorimeters
- MARE: Microcalorimeter Array for a Rhenium Experiment
  - calorimetric measurement sensitivity to light neutrinos
  - ^{187}Re vs. ^{163}Ho
  - ^{187}Re measurement systematics
  - heavy (sterile) neutrinos detection
  - cosmological relic neutrinos (light and heavy)
- MARE project status
  - path for isotope and technique selection
  - MARE-1 experimental activities
  - MARE-2 prospects
- Conclusions

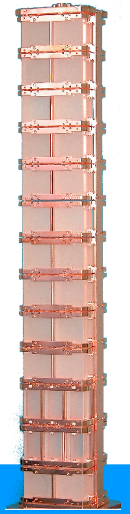
Neutrino mass measurements

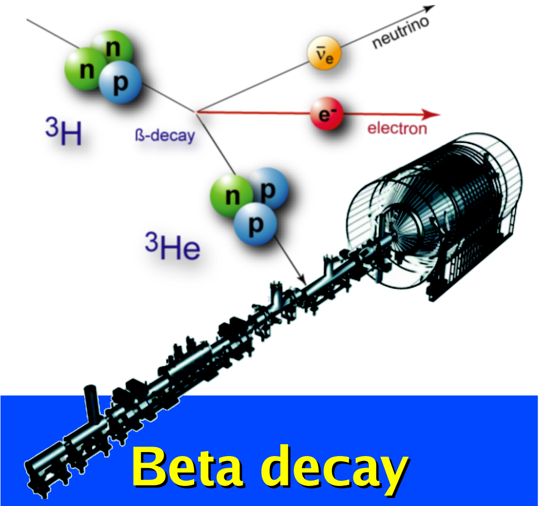
Open questions:

- absolute mass scale
- mass hierarchy
- Majorana or Dirac neutrinos
- …



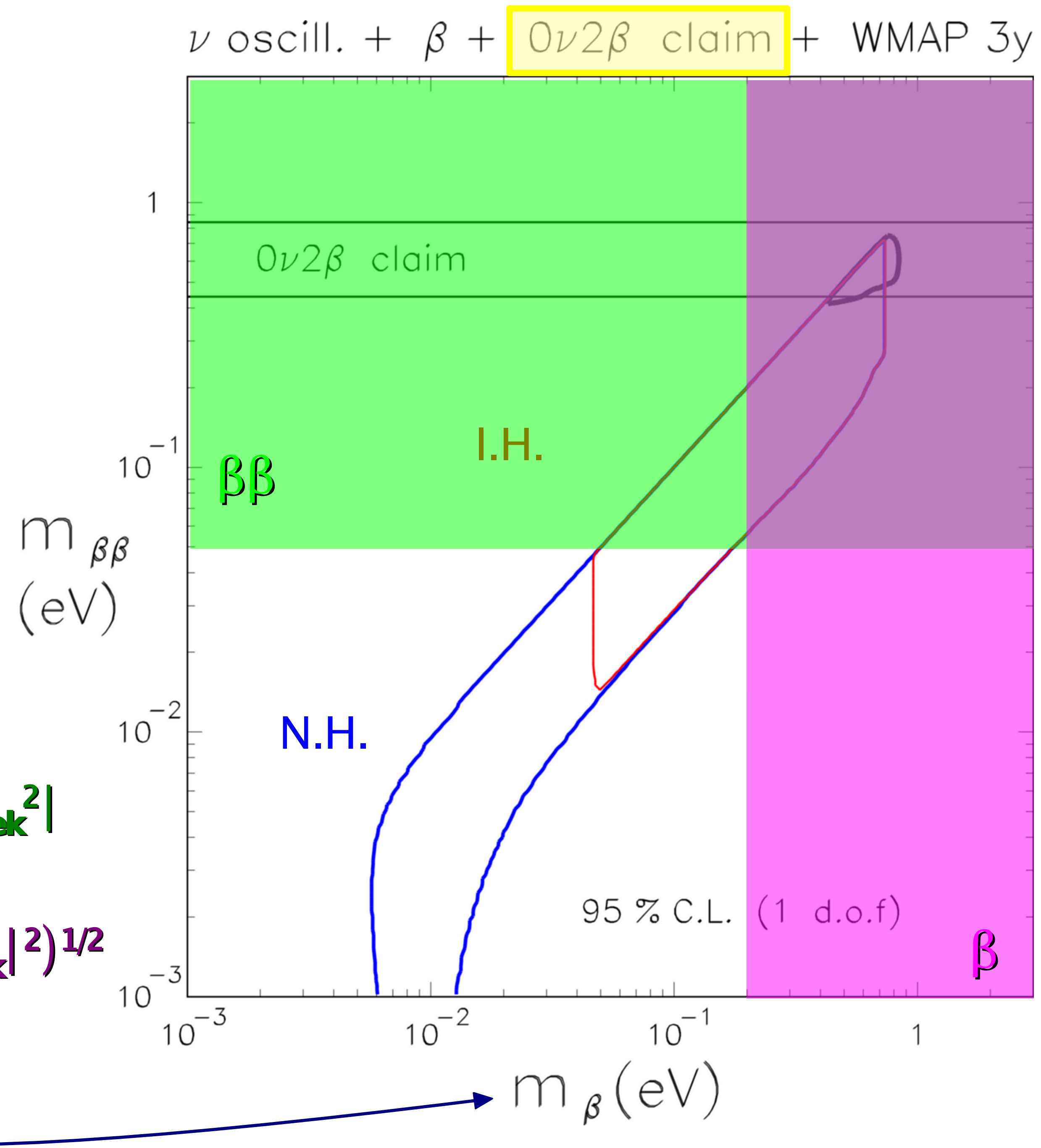






tool	**Cosmology CMB+LSS+...**	**Neutrinoless Double Beta decay**	**Beta decay end-point**
observable	$m_\Sigma = \Sigma_k m_{\nu_k}$	$m_{\beta\beta} = \lvert \Sigma_k m_{\nu_k} U_{ek}^2 \rvert$	$m_\beta = (\Sigma_k m_{\nu_k}^2 \lvert U_{ek} \rvert^2)^{1/2}$
present sensitivity	0.7 ÷ 1 eV	0.5 eV	2 eV
future sensitivity	**0.05 eV**	**0.05 eV**	**0.2 eV**
model dependency	yes ☹	yes ☹	no ☺
systematics	large ☹	yes 😐	large ☹

Neutrinos masses from single β and ββ-0ν decays



from **ββ-0ν searches**

$m_{\beta\beta} \equiv \langle m_\nu \rangle = |\Sigma_k m_{\nu k} U_{ek}^2|$

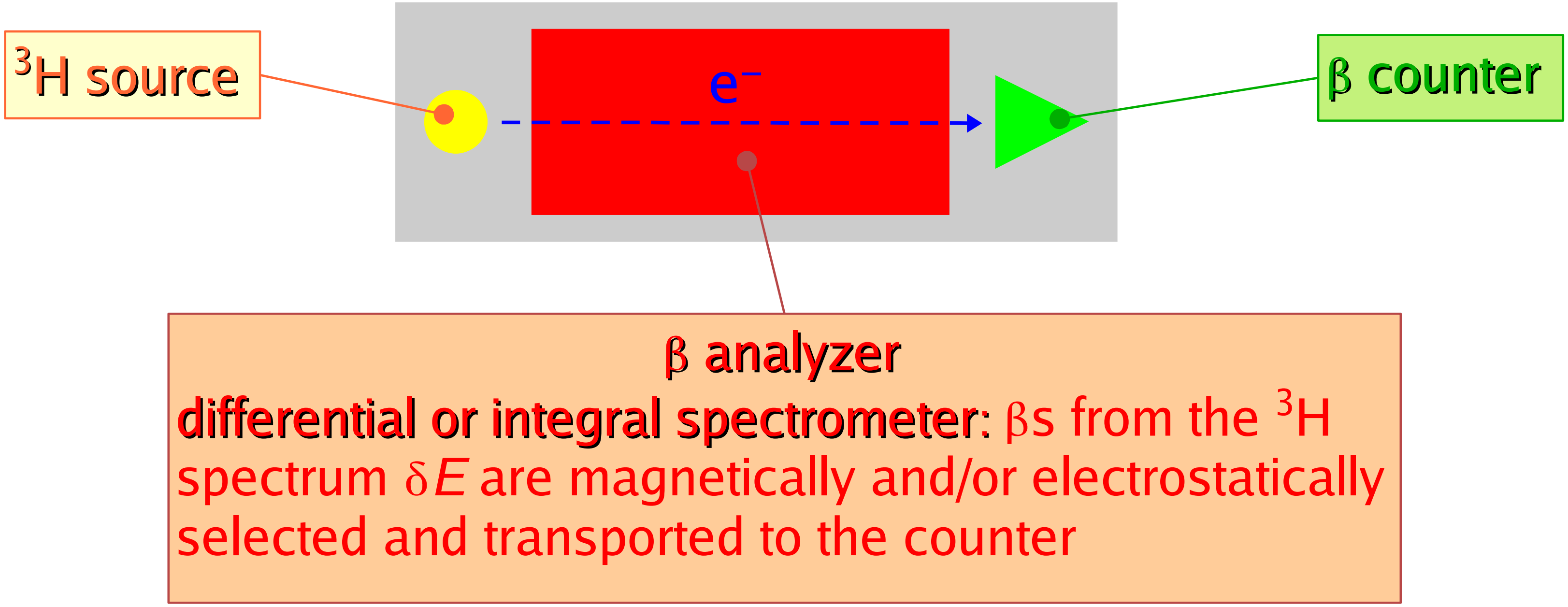
from **β decay**

$m_\beta \equiv m_\nu = (\Sigma_k m_{\nu k}^2 |U_{ek}|^2)^{1/2}$

Fogli et al. hep-ph/0608060

Experimental approaches for direct m_ν measurements

Spectrometers: source ≠ detector



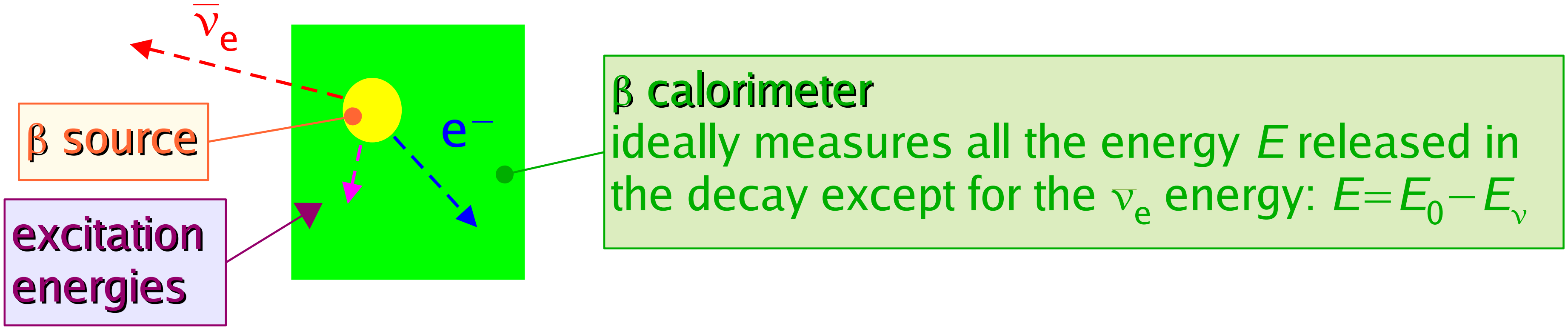
^{3}H source

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

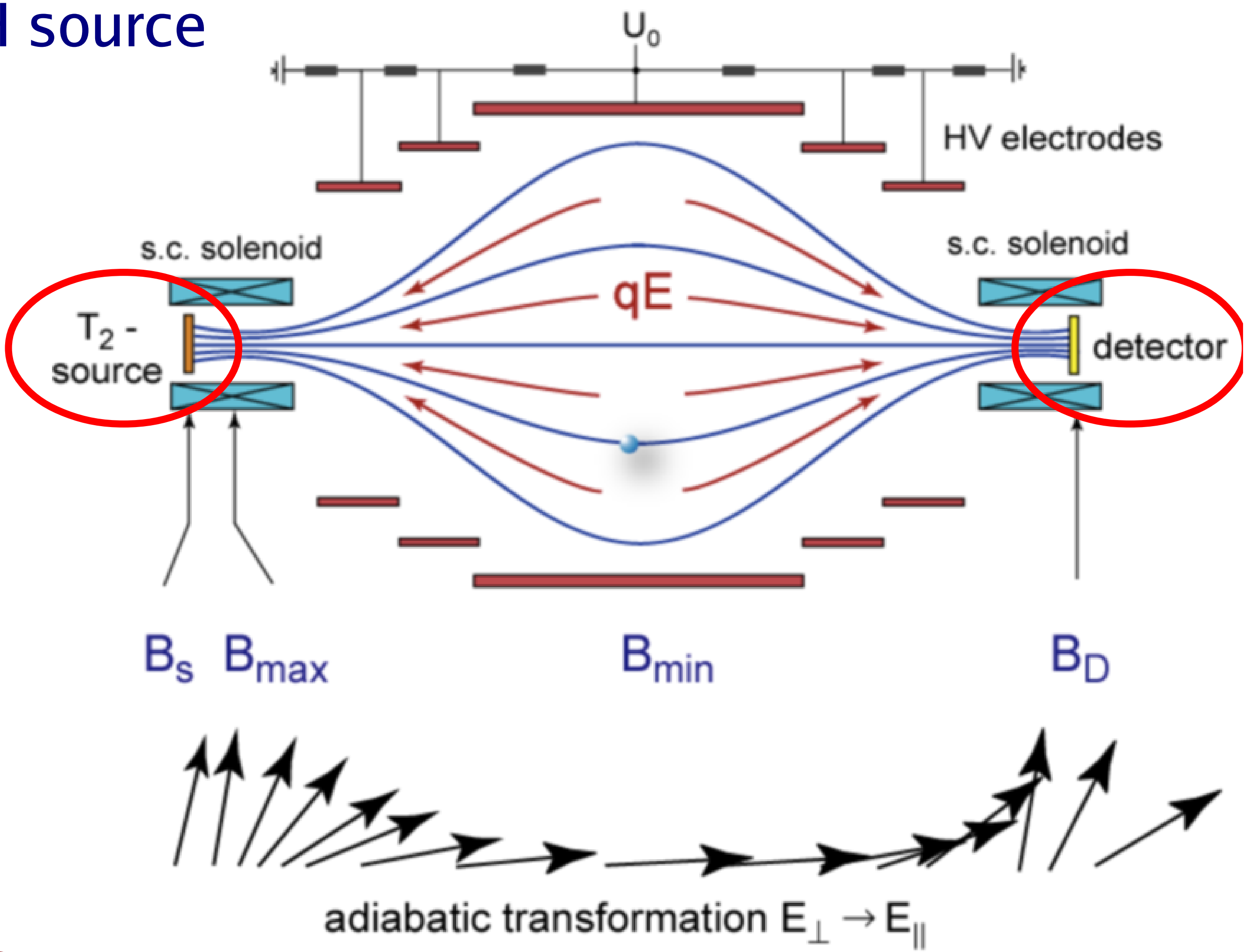
β calorimeter

ideally measures all the energy E released in the decay except for the ν_e energy: $E = E_0 - E_\nu$

Spectrometers present results

electrostatic integrating spectrometers (MAC-E filter)

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



Spectrometer advantages

- ▲ high statistics
- ▲ high energy resolution

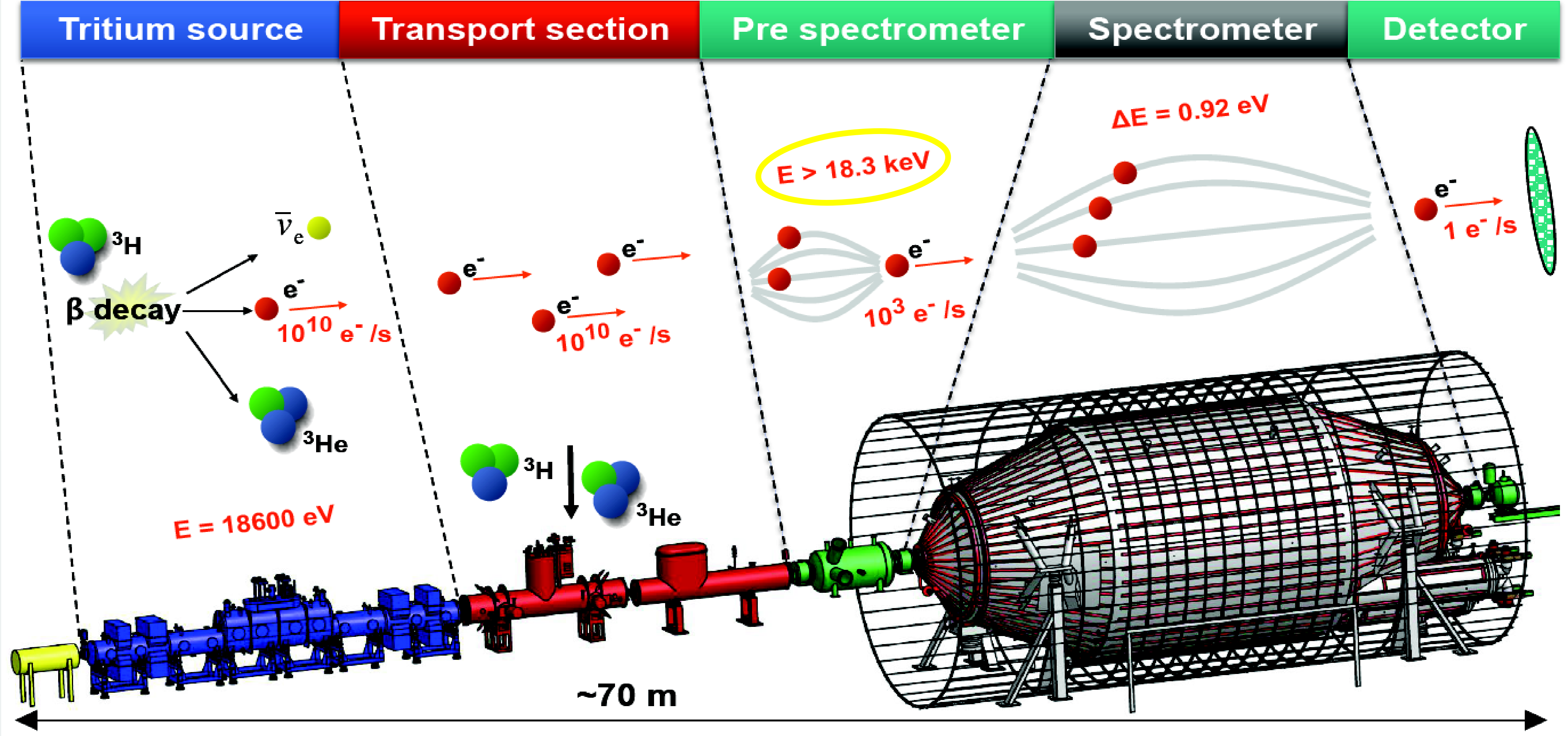
Spectrometer drawbacks

- ▼ large systematics
  - ◆ source effects
  - ◆ decays to excited states
- ▼ background

Spectrometers future: KATRIN

large electrostatic spectrometer with **gaseous ^{3}H source**

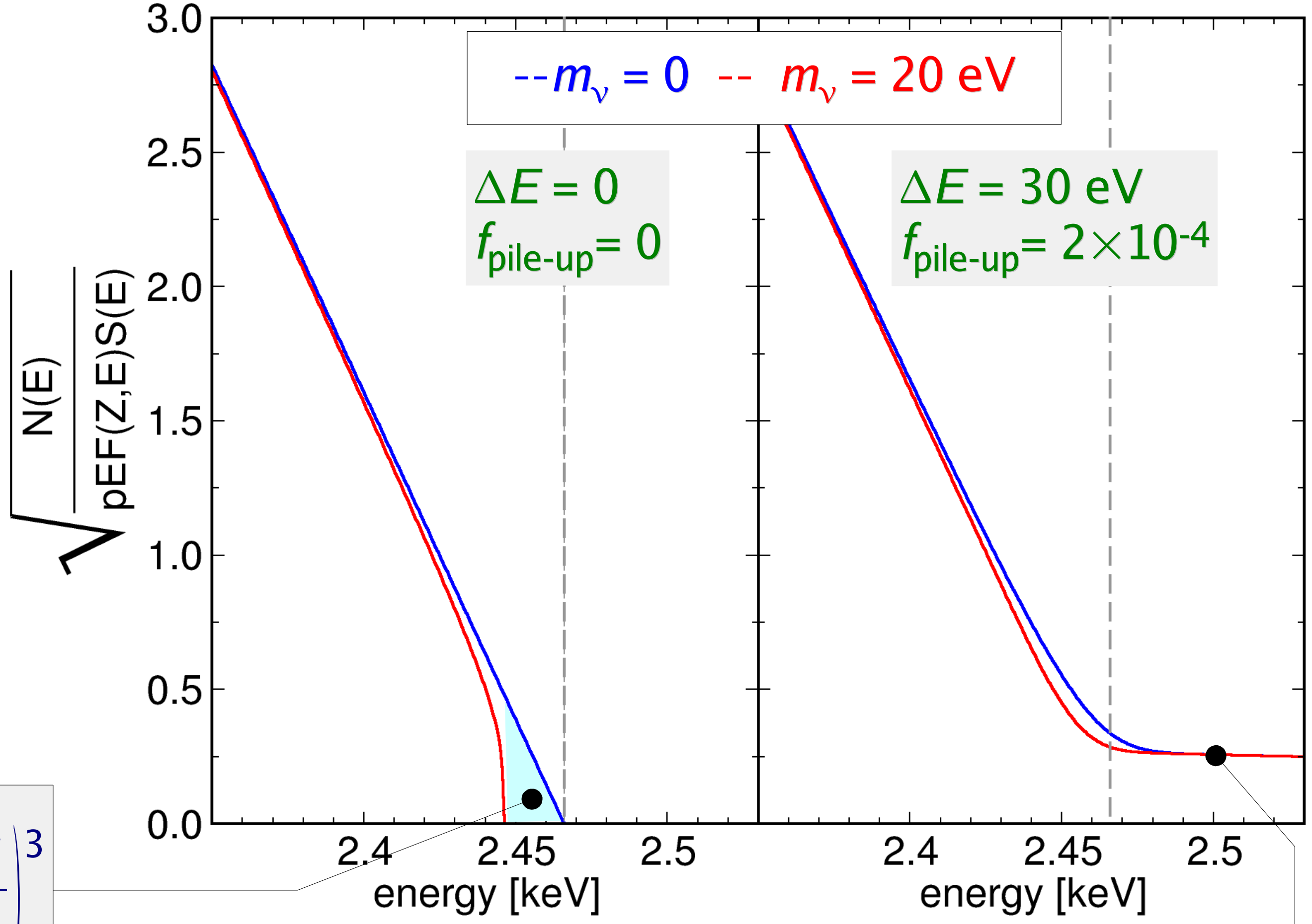
- expected statistical sensitivity **$m_{\nu e}$ < 0.2 eV 90% CL**
- start data taking in **2013/2014**



Calorimetry of beta sources

- calorimeters measure the entire spectrum at once
  - low E_0 β decaying isotopes for more statistics near the end-point
  - best choice ^{187}Re: $E_0 = 2.5$ keV, $\tau_{1/2} = 4\times10^{10}$ y $\Rightarrow F(\Delta E=10\text{ eV})\sim(\Delta E/E_0)^3=7\times10^{-8}$
  - other option ^{163}Ho electron capture: $E_0 \approx 2.6$ keV, $\tau_{1/2} \approx 4600$ y

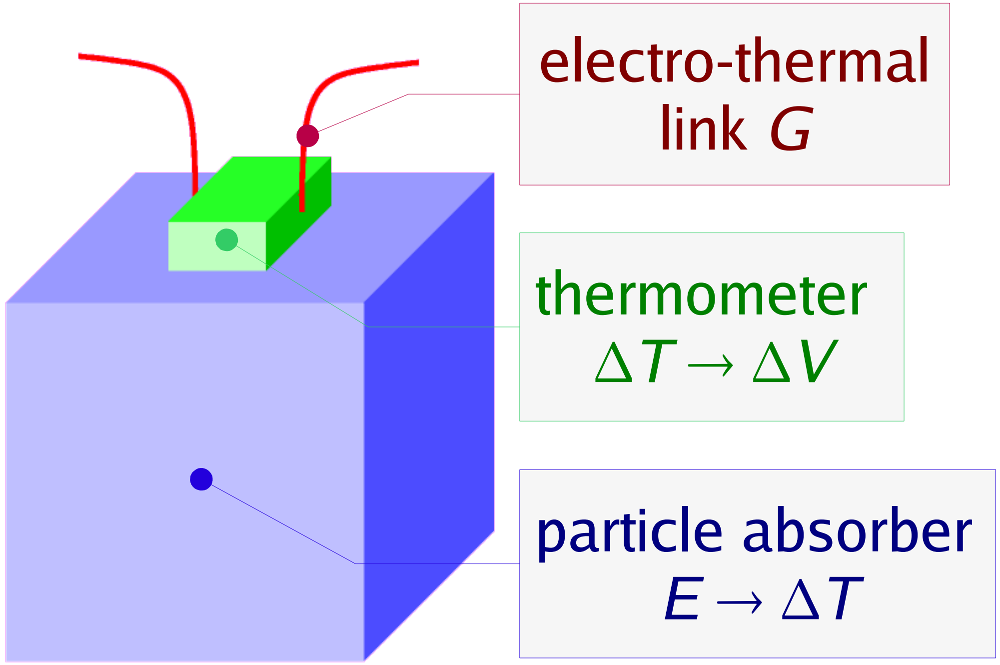
- **Calorimetry advantages**
  - ▲ no back-scattering
  - ▲ no energy losses in the source
  - ▲ no atomic/molecular final state effects
  - ▲ no solid state excitation
- **Calorimetry drawbacks**
  - ▼ limited statistics
  - ▼ pile-up background
  - ▼ spectrum related systematics



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

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

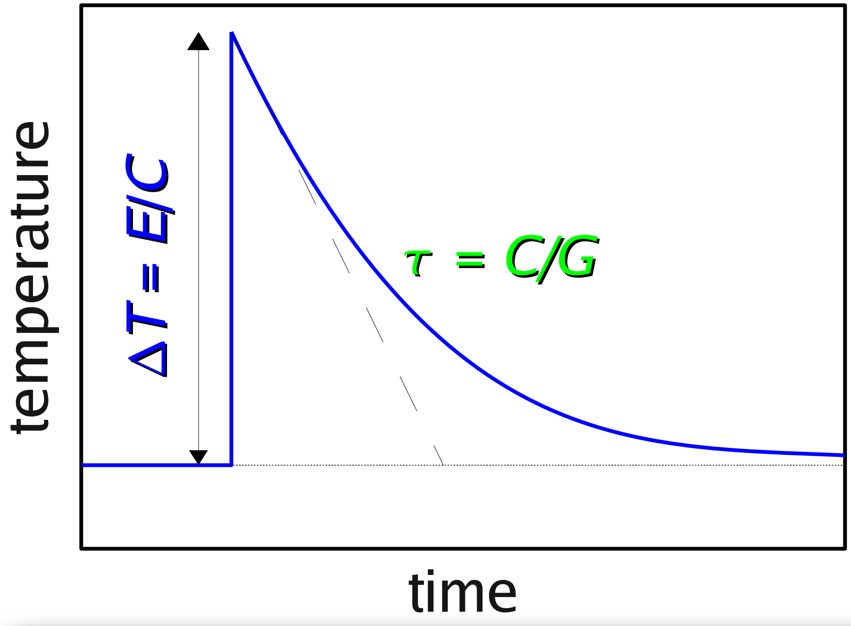
Cryogenic detectors as calorimeters



electro-thermal link *G*

thermometer $\Delta T \rightarrow \Delta V$

particle absorber $E \rightarrow \Delta T$



- **1 mg of Re @ 100 mK → 1 β decay/s**
  $C \sim T^3$ ⇒ $C \sim 10^{-13}$ J/K
  ⇒ $\Delta E_{rms} \sim 1$ eV
  6 keV x-ray ⇒ $\Delta T \sim 10$ mK
  $G \sim 10^{-11}$ W/K ⇒ $\tau = C/G \sim 10$ 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

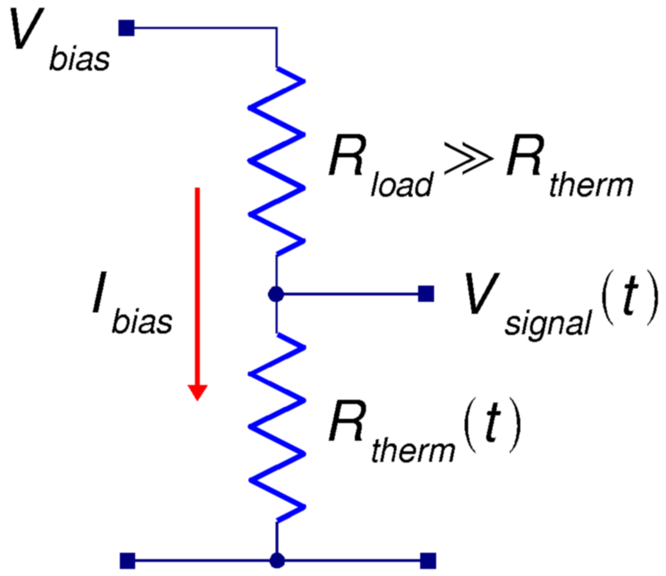
Resistive thermometers: thermistors

- **doped semiconductors** at Metal-Insulator-Transition ($N_c=3.74\times10^{18}$ cm^{-3} for Si:P)
- at $T \ll 10$K → **phonon assisted variable range hopping** conduction (**VRH**)

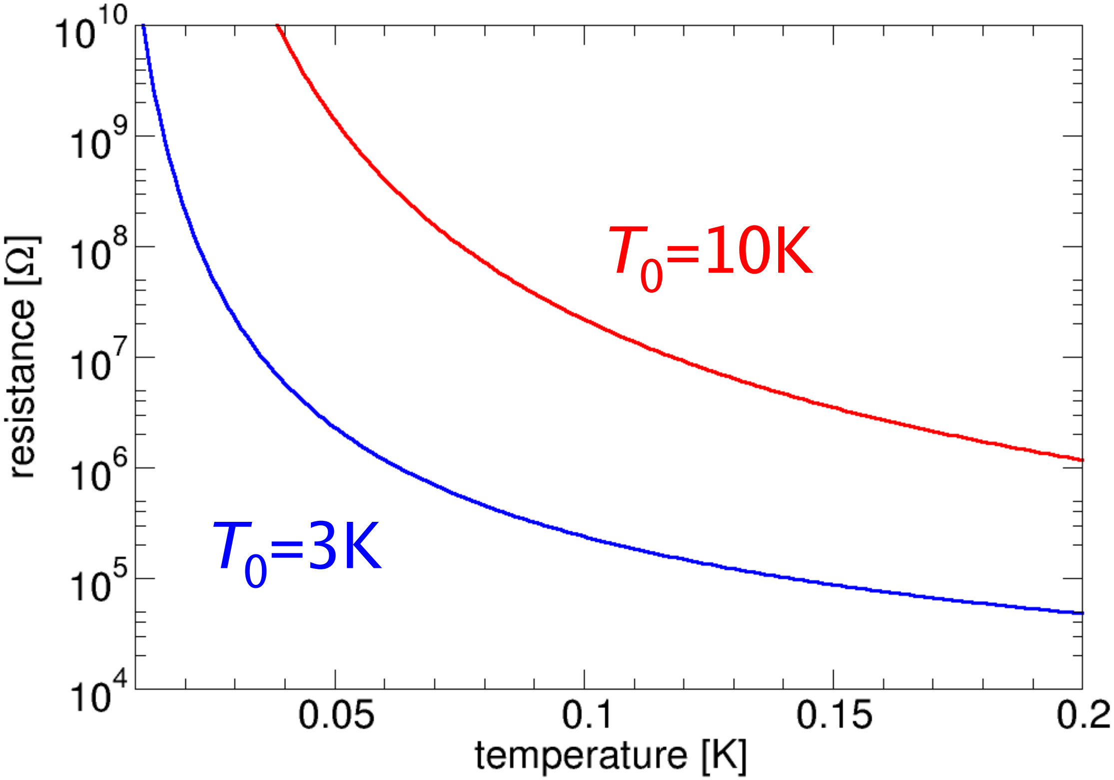
$$\rho(T) = \rho_0 \exp(T_0/T)^{\gamma}$$

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

Costant current bias

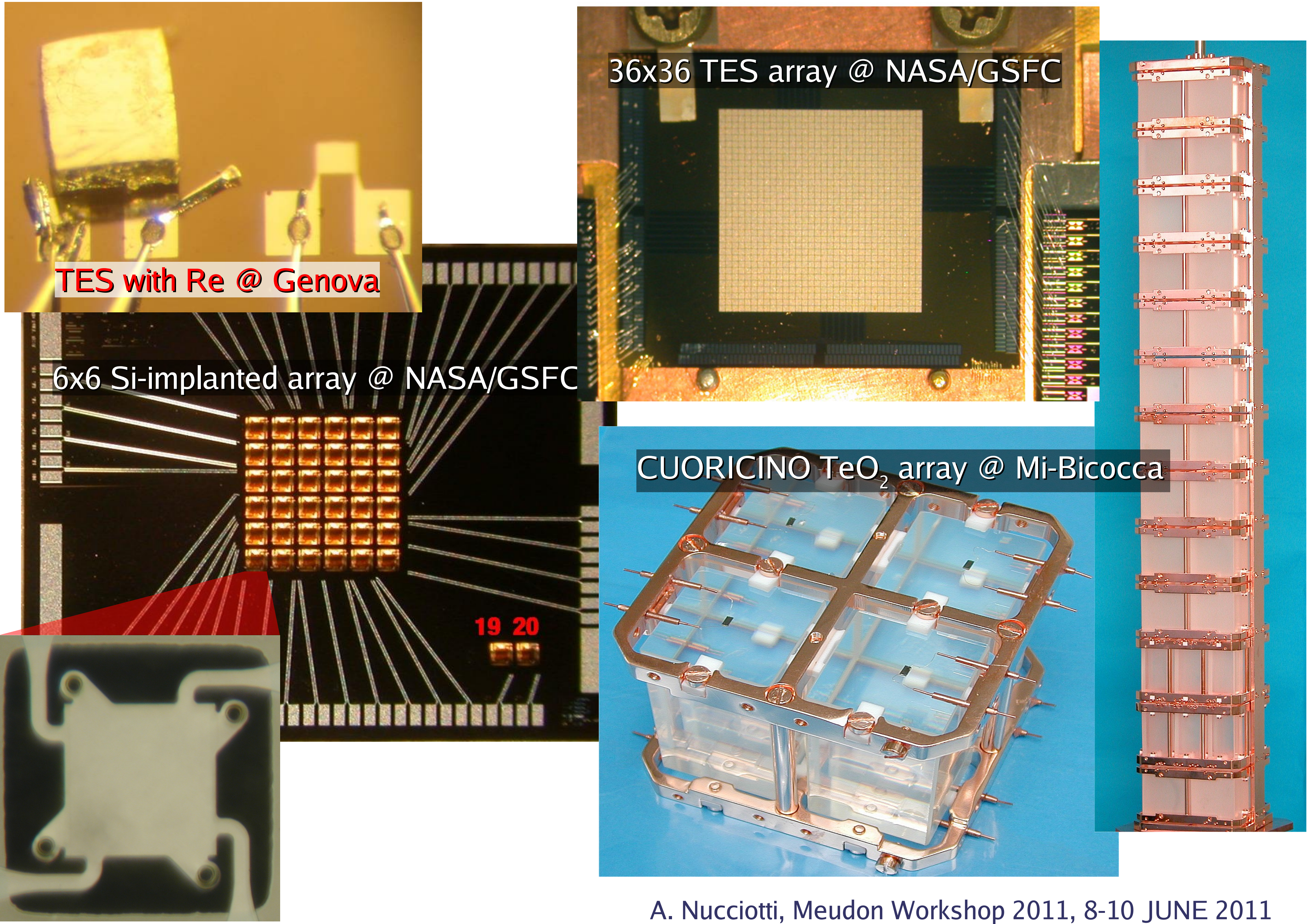


$\Delta E \Rightarrow \Delta T \Rightarrow \Delta R \Rightarrow \Delta V$



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

Cryogenic detectors



TES with Re @ Genova

36x36 TES array @ NASA/GSFC

6x6 Si-implanted array @ NASA/GSFC

CUORICINO TeO_2 array @ Mi-Bicocca

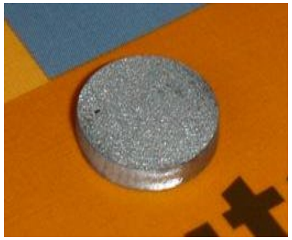
Thermal detectors for calorimetric experiments

^{187}Re β decay

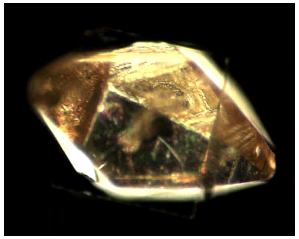
$$^{187}_{75}\mathrm{Re} \rightarrow {}^{187}_{76}\mathrm{Os} + e^{-} + \bar{\nu}_e$$

- $5/2^{+} \rightarrow 1/2^{-}$ unique first forbidden transition ⇒ $S(E_\beta)$
- 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)**



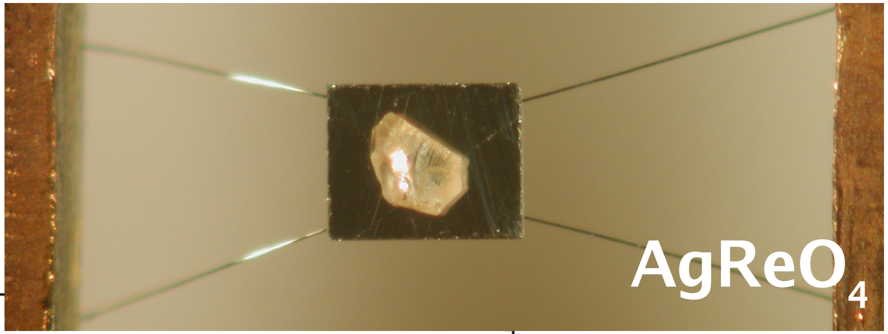
- **dielectric rhenium compound** ($AgReO_4$) crystals
  - Silicon implanted thermistors
  - **MIBETA experiment (Milano)**

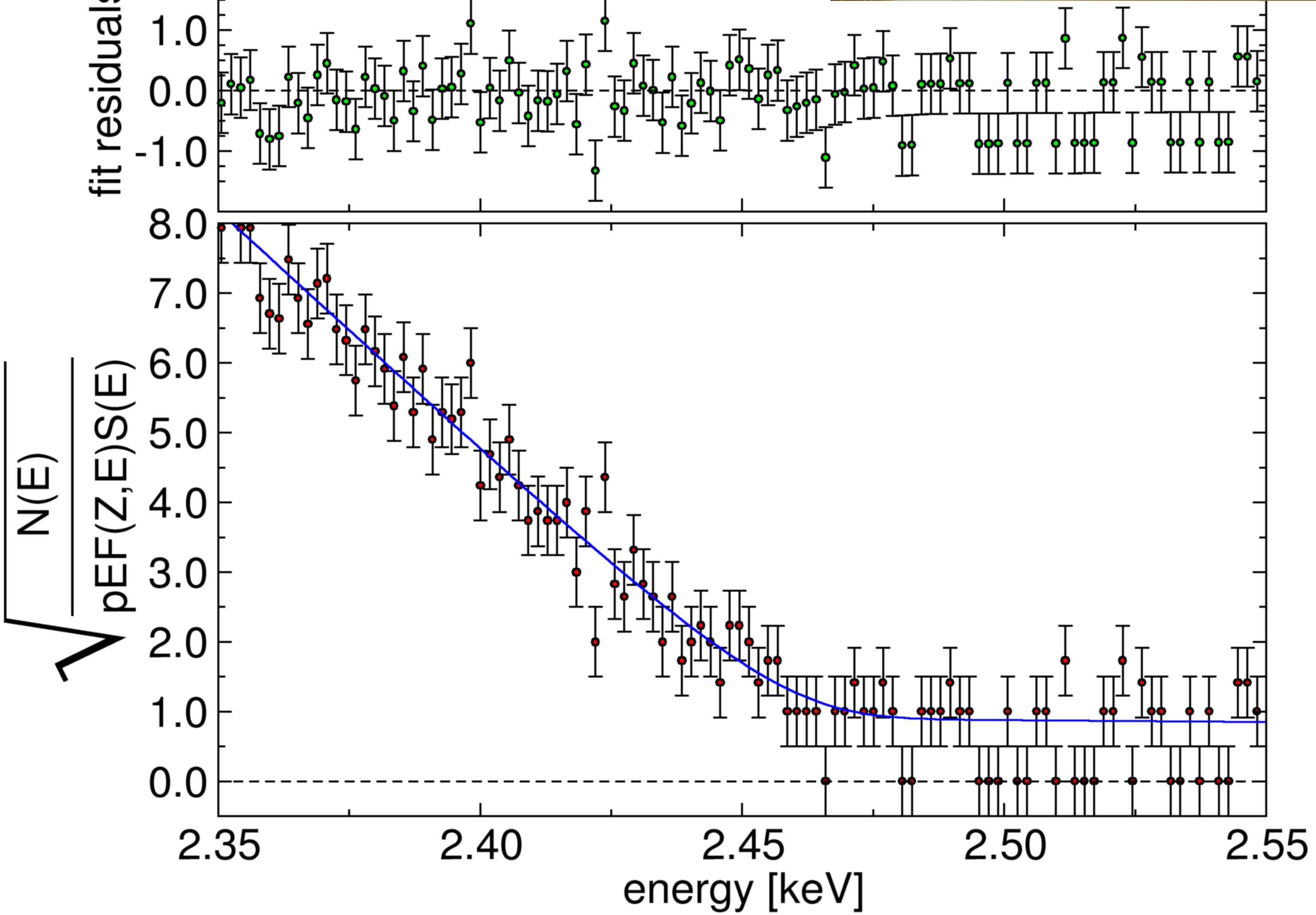


$m_\nu < \approx 15$ eV

MIBETA experiment results

- **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.)**





A project for a New Rhenium Experiment: MARE

- goal: a sub-eV direct neutrino mass measurement complementary to the KATRIN experiment
- **MARE-1**
  - ▷ activities using medium sized arrays to improve ^{187}Re measurement understanding and possibly calorimetric m_ν limit
  - ▷ detector and absorber coupling R&D activities

~100 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
  - ▷ requires new improved detector technologies

~10000 element array → **0.2 eV m_ν sensitivity**

MARE project for sub-eV calorimetric m_ν measurement

MARE: Microcalorimeter Arrays for a Rhenium Experiment

Università di Genova e INFN Sez. di Genova, Italy
Univ. di Milano-Bicocca, Univ. dell'Insubria e INFN Sez. di Milano-Bicocca, Italy
Kirkhhof-Institute Physik, Universität Heidelberg, Germany
University of Miami, Florida, USA
Wisconsin University, Madison, Wisconsin, USA
Universidade de Lisboa and ITN, Portugal
Università di Roma "La Sapienza" e INFN Sez. di Roma1, Italy
Goddard Space Flight Center, NASA, Maryland, USA
PTB, Berlin, Germany
FBK, Trento e INFN Sez. di Padova, Italy
NIST, Boulder, Colorado, USA
SISSA - Trieste, GSI Darmstad, JPL/Caltech, CNRS Grenoble, ...

funded R&D

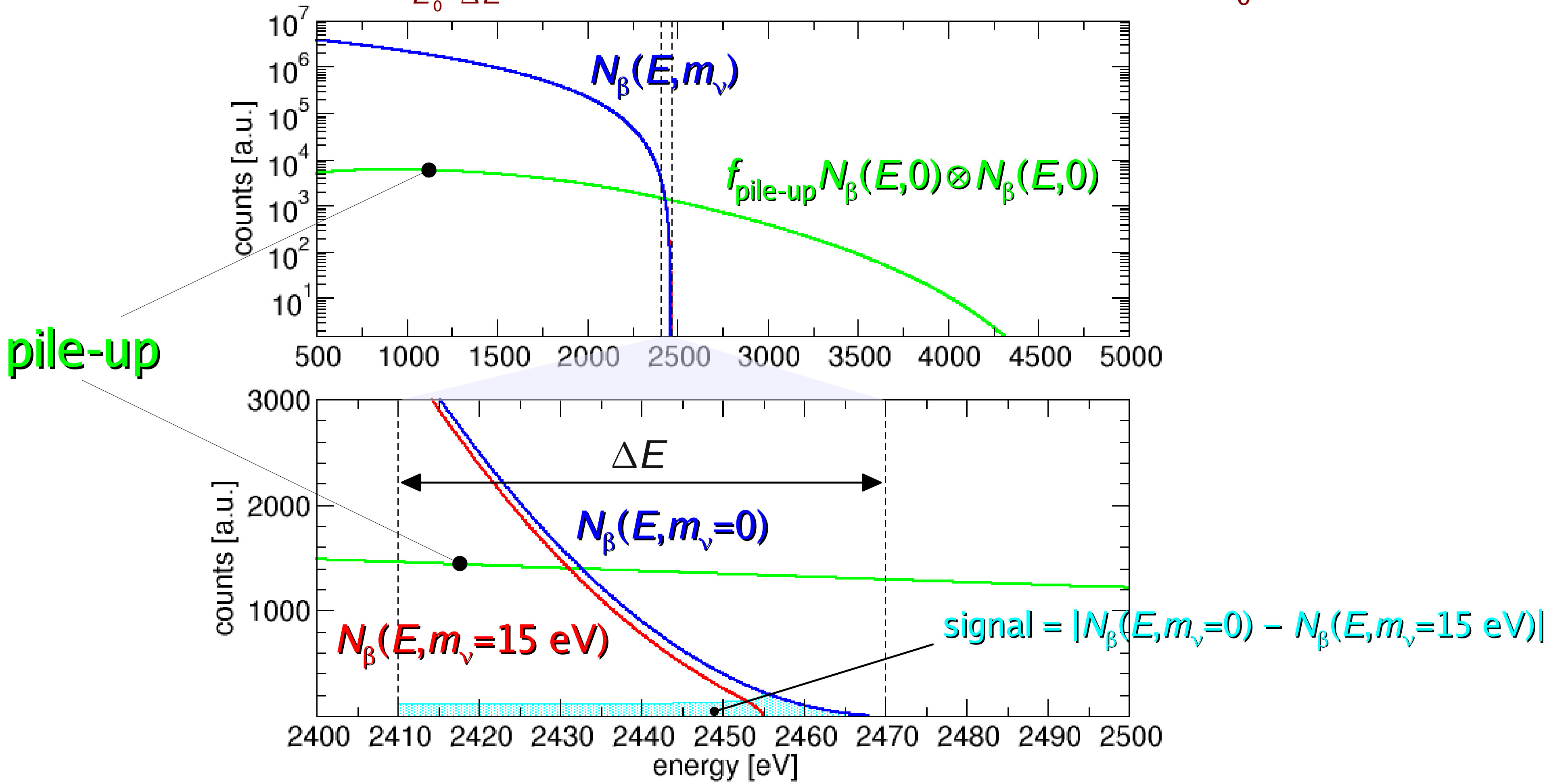
http://crio.mib.infn.it/wig/silicini/proposal/

^{187}Re calorimetric experiment statistical sensitivity / 1

resolving time τ_R analysis interval ΔE
source activity A_β number of detectors N_{det}
pile-up fraction $f_{pile\text{-}up}=\tau_R A_\beta$
experimental exposure $t_M=T\times N_{det}$

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

$$F_{\Delta E}(m_\nu)=A_\beta N_{det}\int_{E_0-\Delta E}^{E_0}N_\beta(E,m_\nu)dE \qquad F_{\Delta E}(0)\approx A_\beta N_{det}\frac{\Delta E^3}{E_0^3}$$



^{187}Re calorimetric experiment statistical sensitivity / 2

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

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

Optimal energy interval ΔE

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

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

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

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

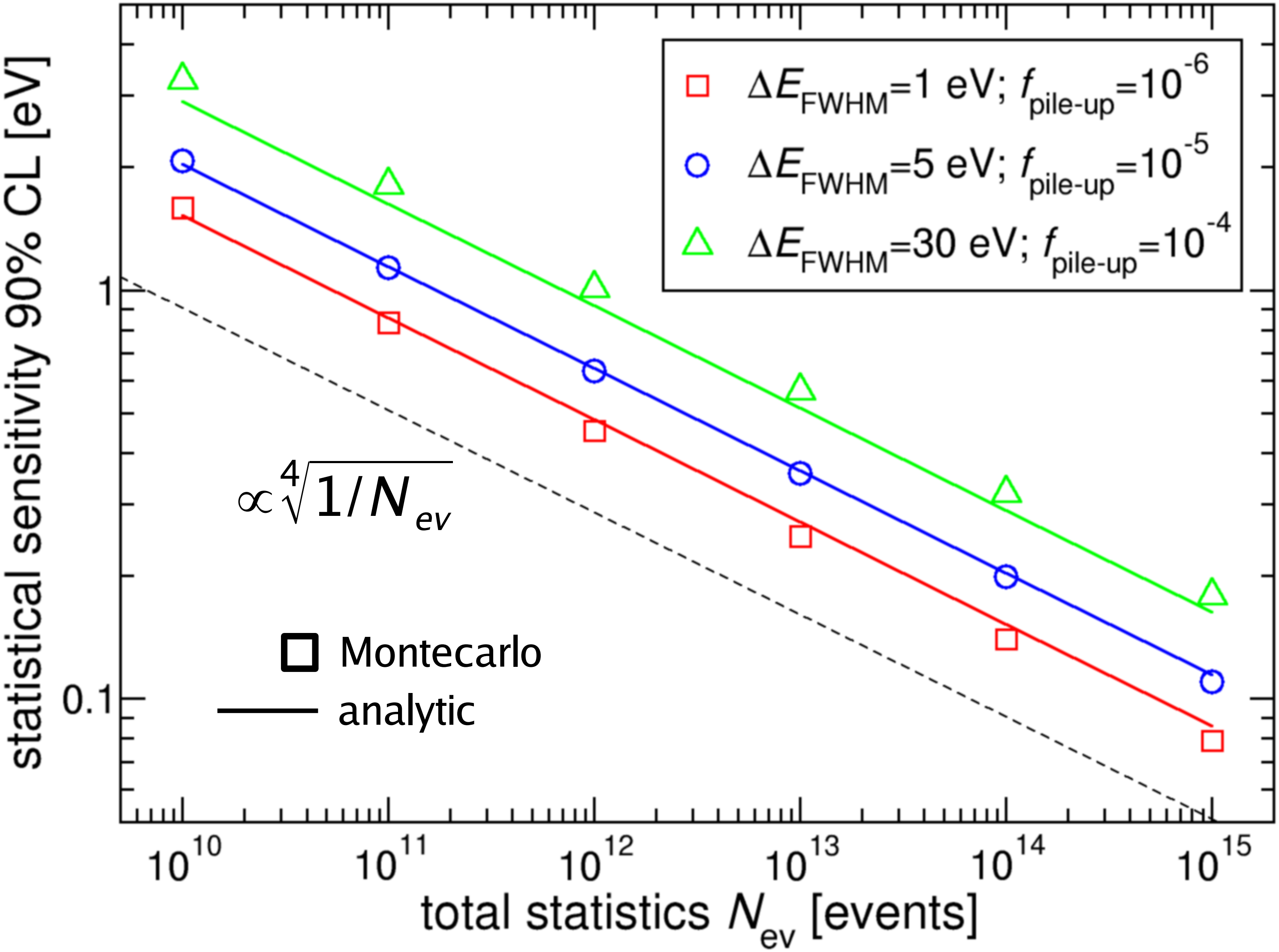
experimental challenges

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

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

^{187}Re past mesurements

- total statistics $N_{ev} \approx 10^7$ events



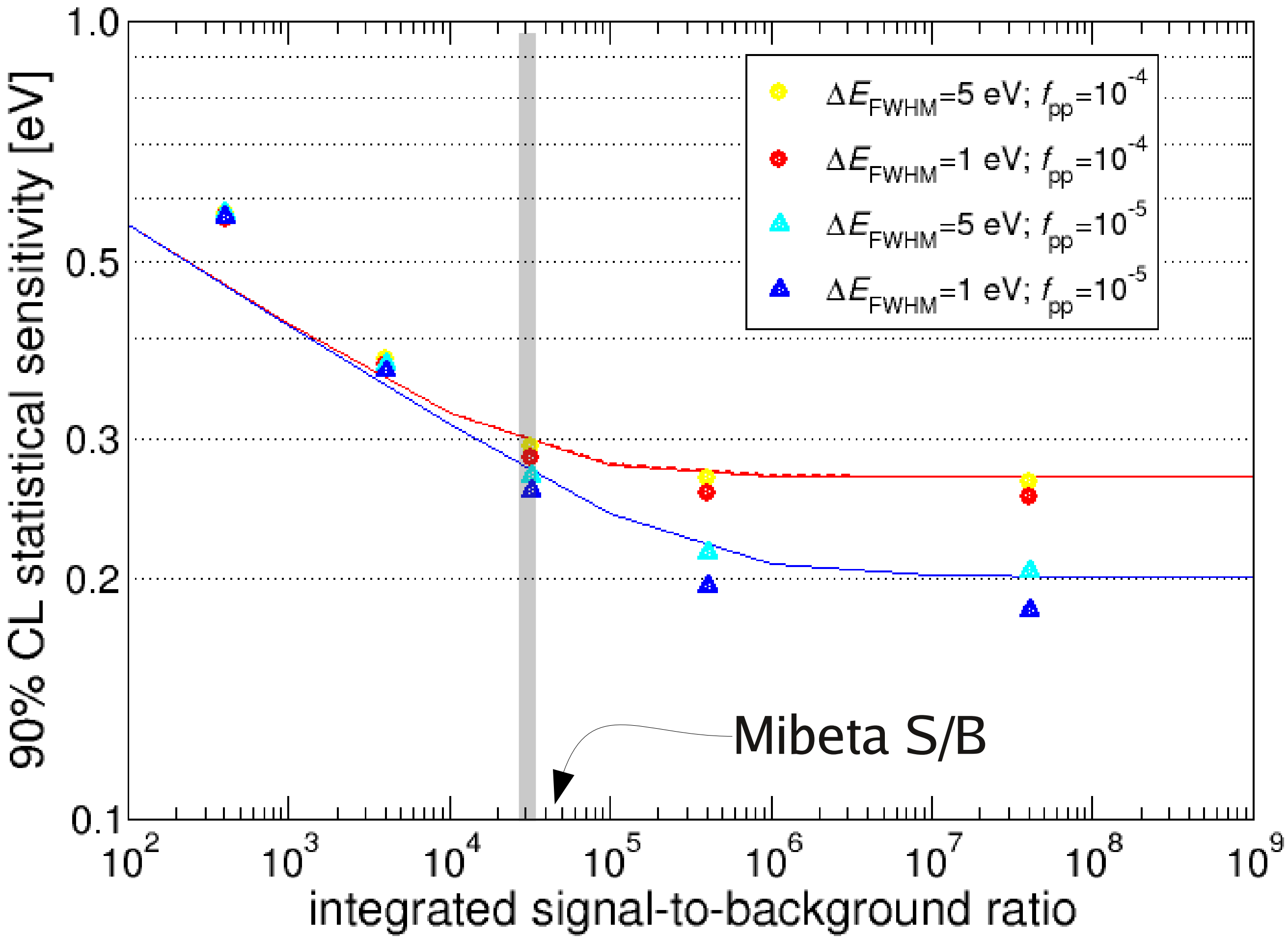
A.Nucciotti et al., Astropart. Phys., 34 (2010) 80 (arXiv:0912.4638v1)

Effect of background on statistical sensitivity

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

b bkg counts/keV/s/det

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



Mibeta S/B

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

$N_{bkg} = bE_0T$

MARE statistical sensitivity: ^{187}Re option

bkg = 0

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}

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

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}

20000 pixels/array
16 arrays
10 years
3.2 kg ^{nat}Re

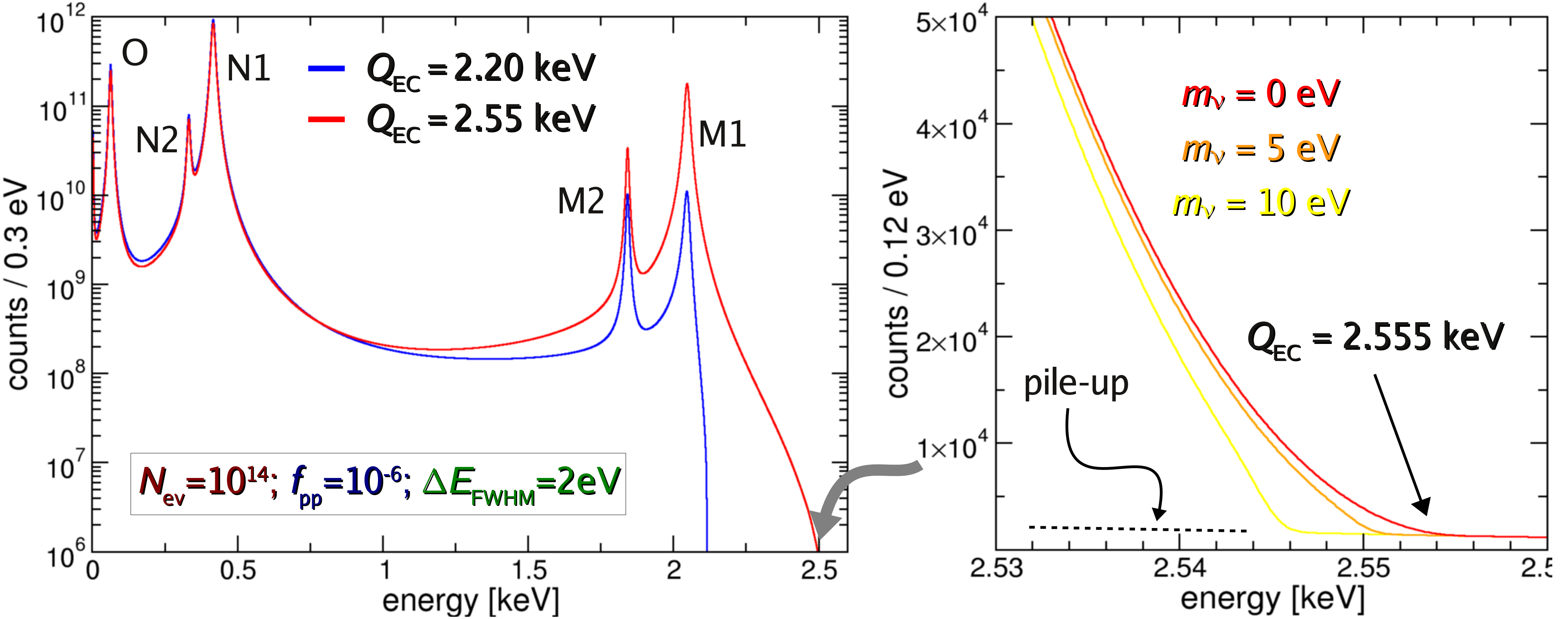
MARE extensions: ^{163}Ho electron capture measurement

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

electron capture from shell ⩾ M1

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

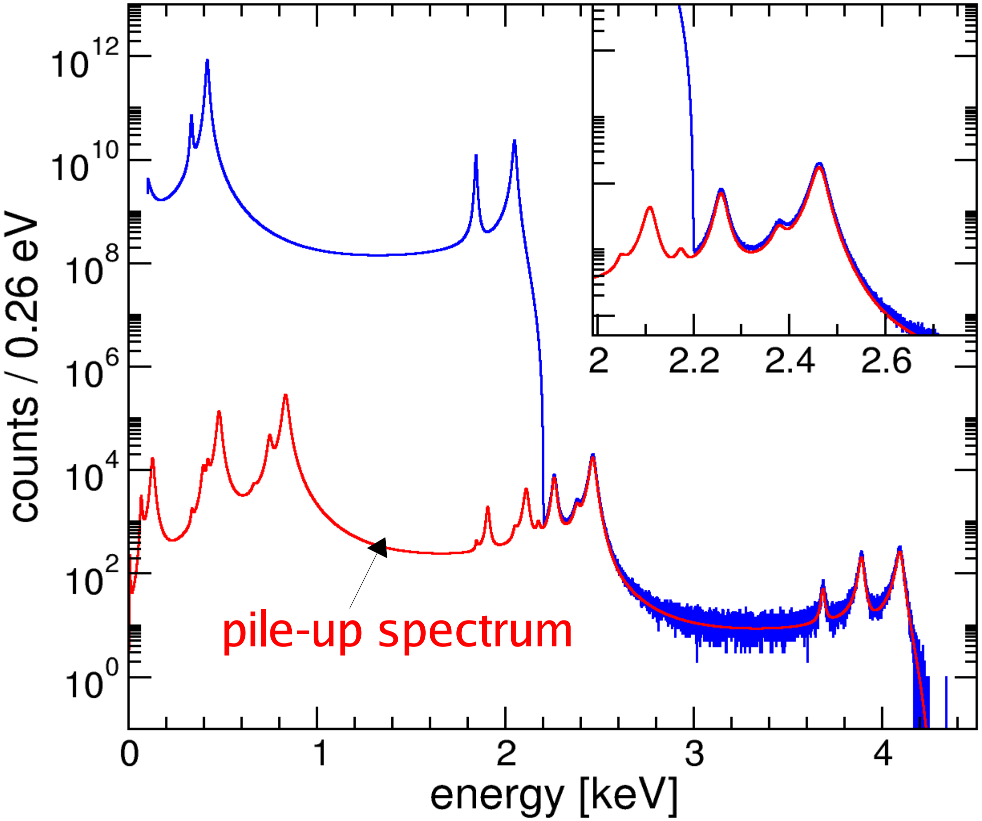
- **calorimetric measurement of Dy atomic de-excitations** (mostly non-radiative)
- rate at end-point may be as high as for ^{187}Re but depends on Q_{EC}
  - ▸ **Q_{EC}?** Measured: $Q_{EC} = 2.3 \div 2.8$ keV. Recommended: **$Q_{EC} = 2.555$ keV**
- $\tau_{1/2} \approx$ **4570 years**: few active nuclei are needed
  - ▸ can be implanted in any suitable microcalorimeter absorber
- ^{163}Ho production by neutron irradiation of ^{162}Er enriched Er



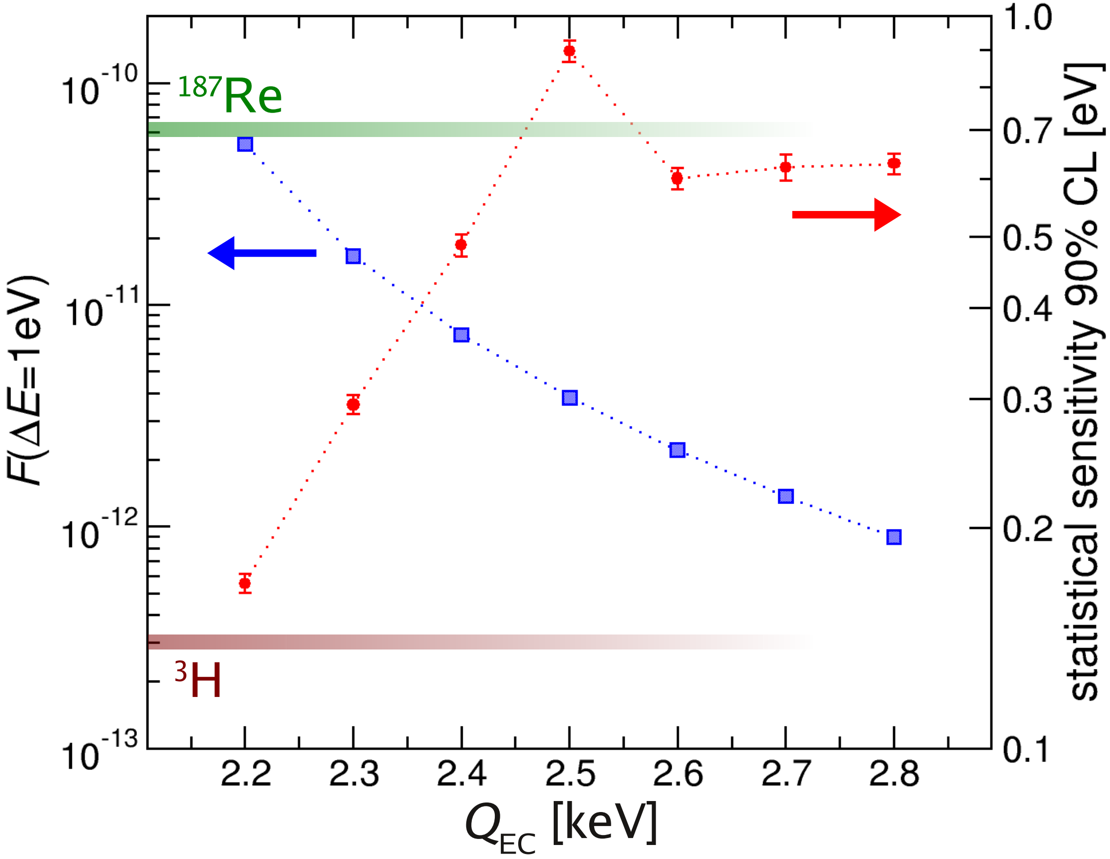
^{163}Ho spectrum simulation

- no high statistics and clean calorimetric measurement so far
  - see for example F. Gatti et al., Phys. Lett. B, 398 (1997) 41
- Q_{EC} and atomic de-excitation spectrum poorly known
- complex pile-up spectrum

$N_{ev}=10^{14}$; $f_{pp}=10^{-6}$; $\Delta E_{FWHM}=2$eV



$N_{ev}=10^{14}$; $f_{pp}=10^{-5}$; $\Delta E_{FWHM}=1$eV



MARE statistical sensitivity: ^{163}Ho option

Q_{EC} = 2200 eV

bkg = 0

exposure required for 0.2 eV m_ν sensitivity

A_β [Hz]	τ_R [μs]	ΔE [eV]	N_{ev} [counts]	exposure [det×year]
1	1	1	2.8×10^{13}	9.0×10^{5}
1	0.1	1	1.3×10^{13}	4.3×10^{5}
100	0.1	1	4.6×10^{13}	1.5×10^{4}
10	0.1	1	2.8×10^{13}	9.0×10^{4}
10	1	1	4.6×10^{13}	1.5×10^{5}

5000 pixels/array

3 arrays

1 year

$\approx 2\times10^{17}$ ^{163}Ho nuclei

exposure required for 0.1 eV m_ν sensitivity

A_β [Hz]	τ_R [μs]	ΔE [eV]	N_{ev} [counts]	exposure [det×year]
1	0.1	0.3	1.2×10^{14}	3.9×10^{6}
100	0.1	0.3	6.4×10^{14}	2.0×10^{5}
100	0.1	1	7.4×10^{14}	2.4×10^{5}
10	0.1	1	4.5×10^{14}	1.5×10^{6}
10	1	1	7.4×10^{14}	2.4×10^{6}

5000 pixels/array

4 arrays

10 years

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

Montecarlo analysis of systematics for ^{187}Re

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
  - $\tau_R^{eff} = f(\tau_R, A_1/A_2) \rightarrow N'_{pp}(E) = N_{pp}(E)\,f_{corr}(E,f_{pp})$

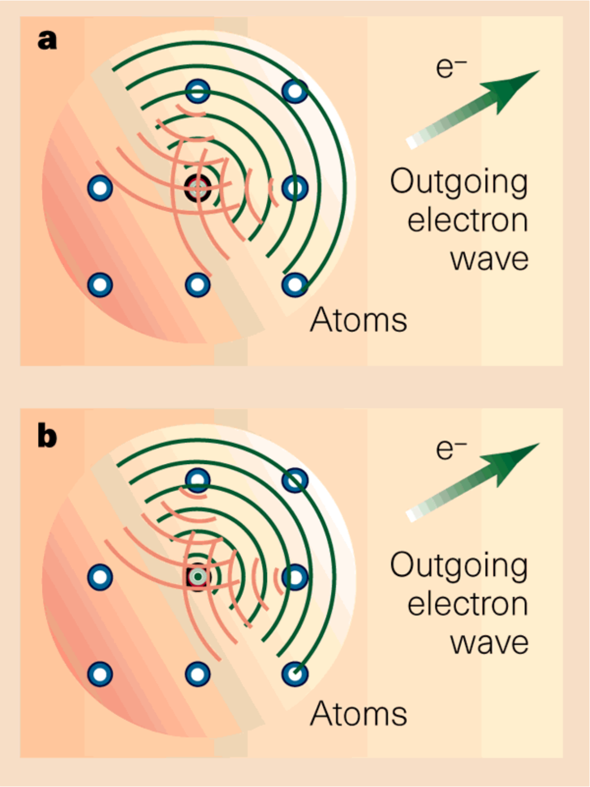
source of uncertainty	***quantity describing the effect***	***maximum effect for Δm_ν^2<0.01 eV^2***
electron surface escape	a_{esc}	10^{-5}
correction to quadratic β spectral shape	$\lvert a_1\rvert\ (a_2=0)$ $\lvert a_2\rvert\ (a_1=0)$	10^{-9} eV^{-1} 10^{-12} eV^{-2}
correction to pile-up spectral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

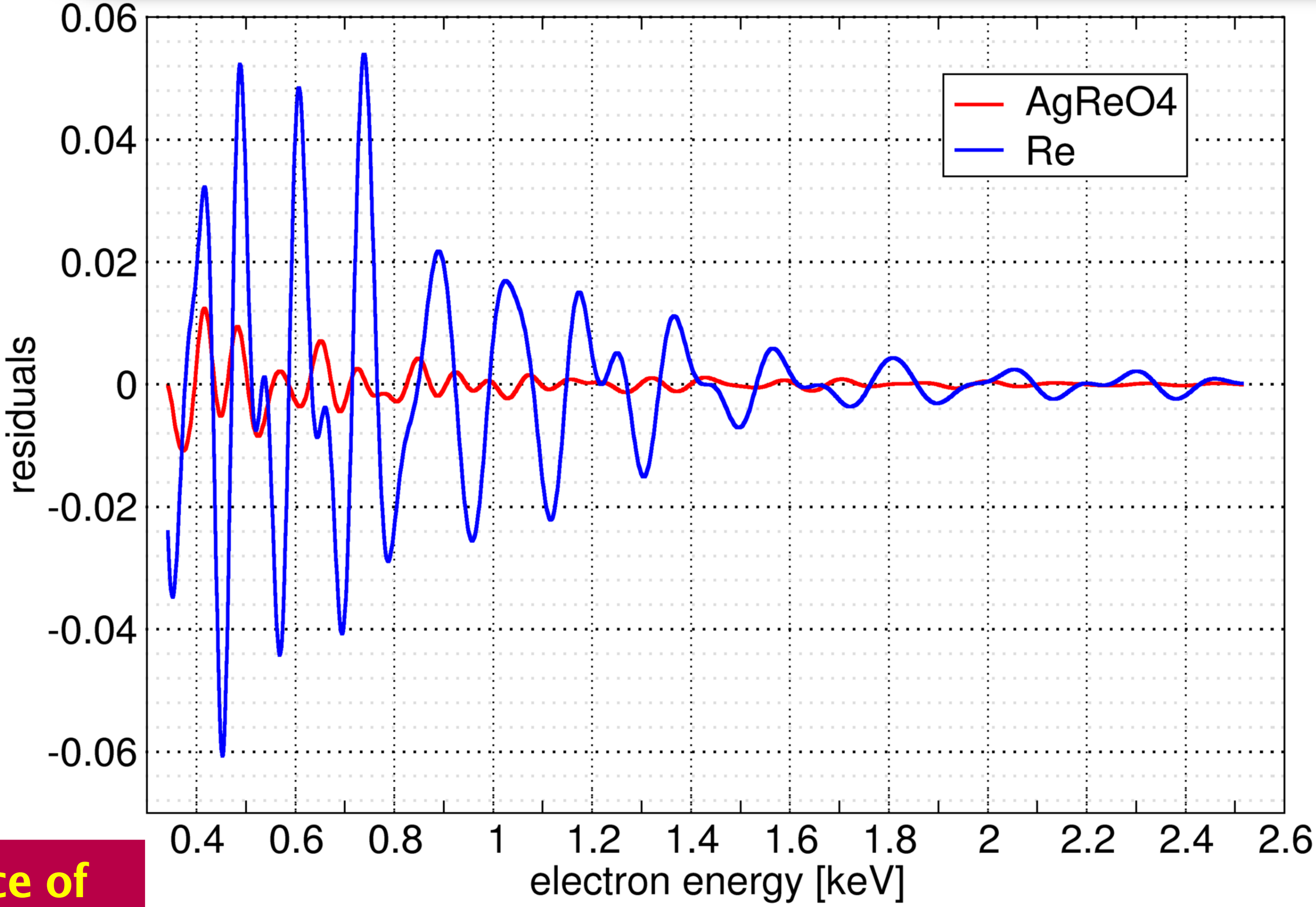
BEFS: Re vs. $AgReO_4$

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)



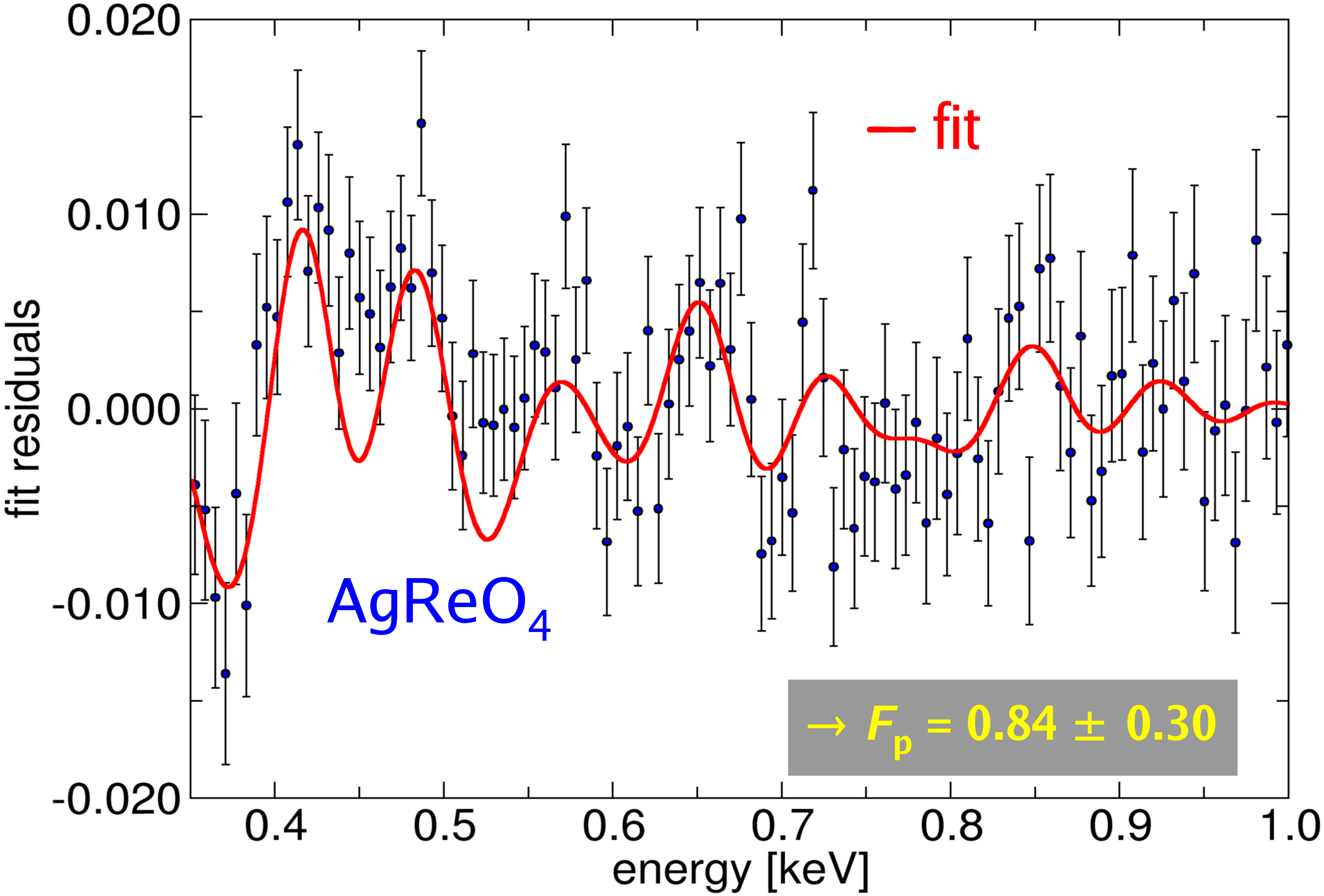


BEFS is a possible source of systematic uncertainties in ^{187}Re neutrino mass experiments

BEFS in MIBETA spectrum with $AgReO_4$

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

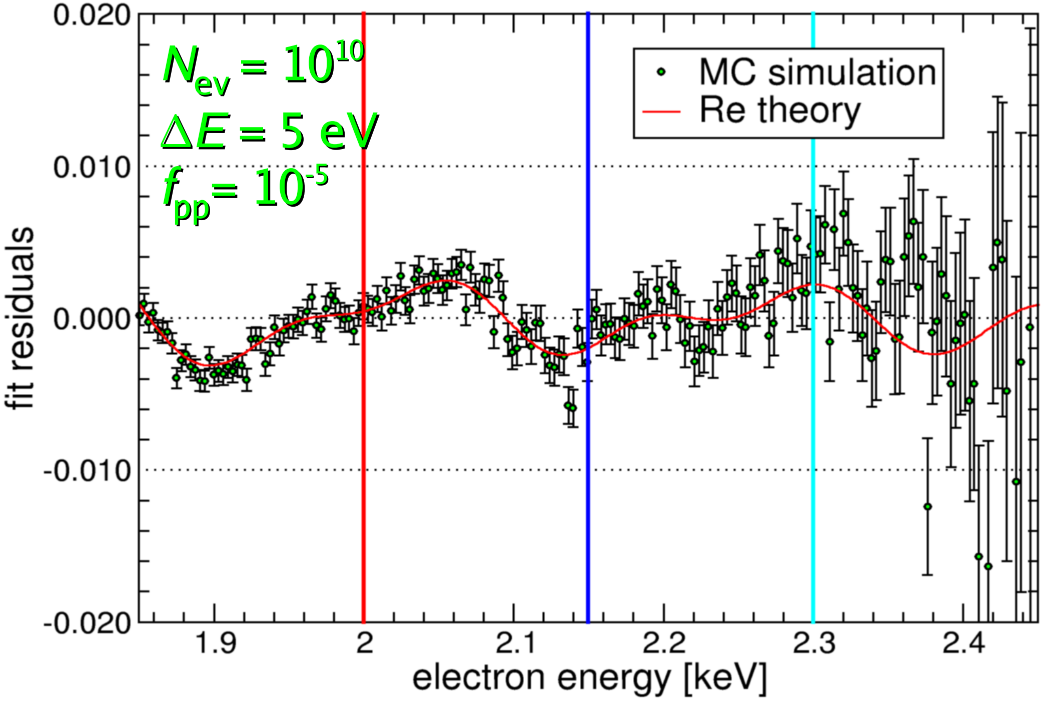
$$\chi^{l}_{EXAFS}(k_e)=(-1)^l\sum_{n=1}^{N}B_{nl}(k_e,R_n)e^{-2k_e^2\sigma_n^2}\sin(2k_eR_n+\delta_{0l}+\delta_{nl})$$



→ $F_p = 0.84 \pm 0.30$

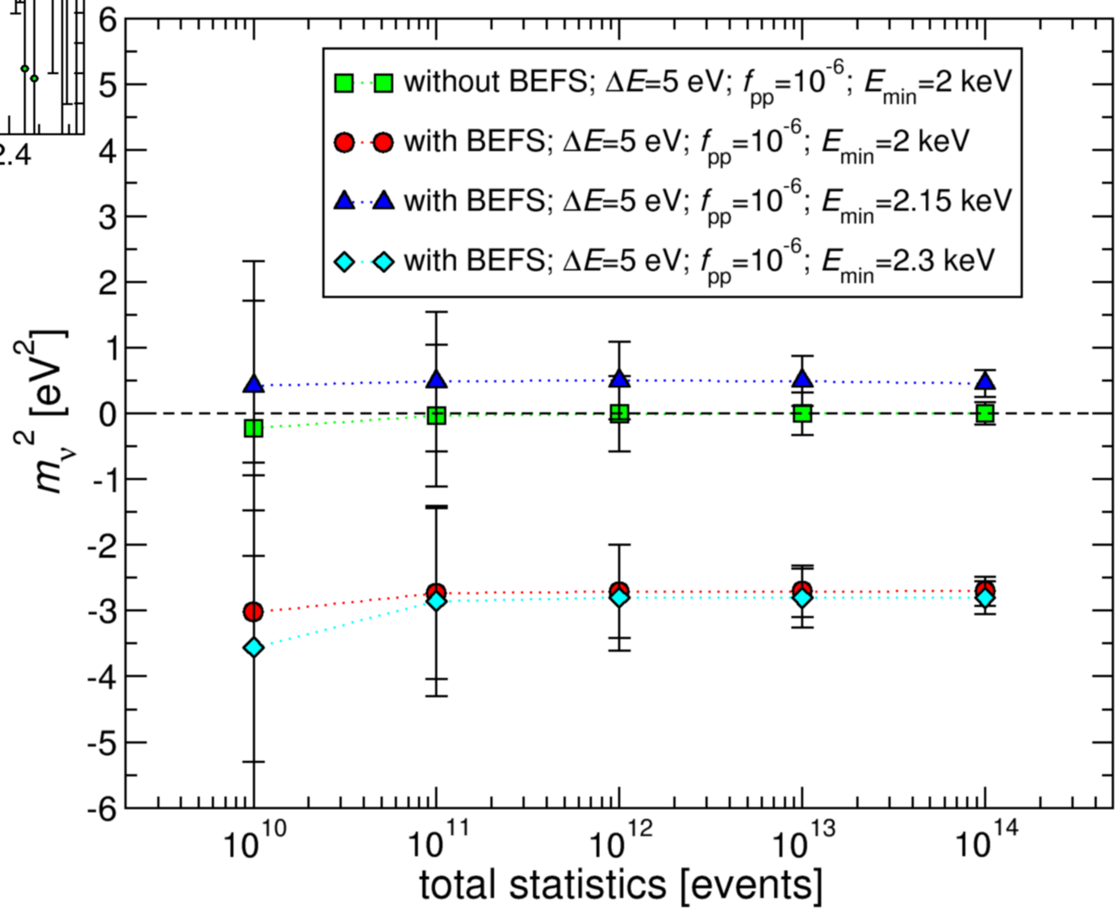
C. Arnaboldi et al., Phys. Rev. Lett. 96 (2006) 042503
(for BEFS in Rhenium: F. Gatti et al. Nature, 397 (1999) 137)

Systematics from BEFS



expected **end-point** spectral deformation

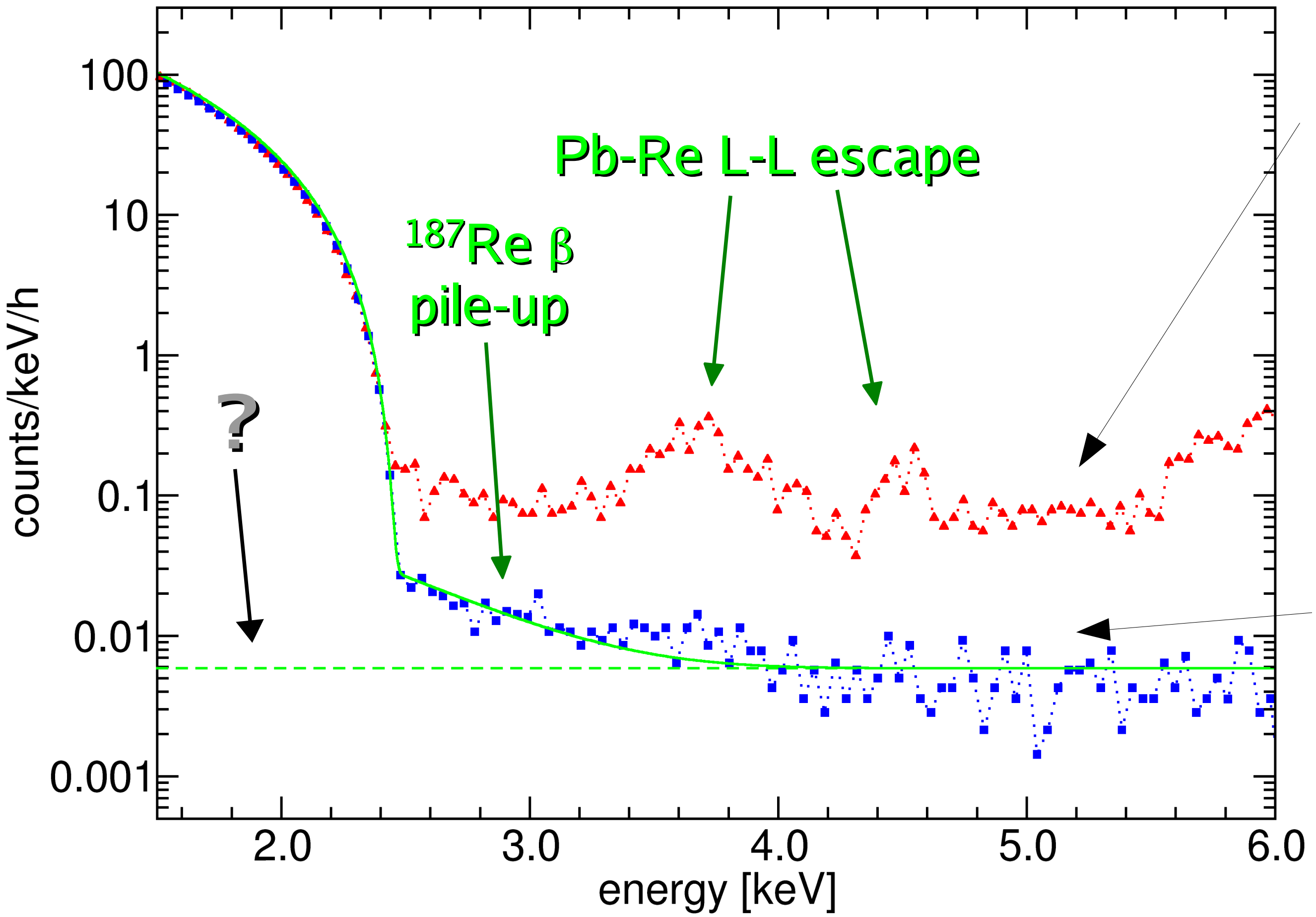
systematic m^2_ν shift with BEFS neglected



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 ($\lambda = 0.2 eV^{-1}$)	A_{tail}	10^{-4}
error on single pixel energy calibration K	$\sigma(K)/K$	0.0004
spread in energy resolution ΔE in the array	$\sigma_{spread}(\Delta E)/\Delta E$	0.1
hidden constant background	N_{ev}/N_{bkg}	10^8
background linear deviation ($bT = 10^5$c/eV)	b_1	0.1

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

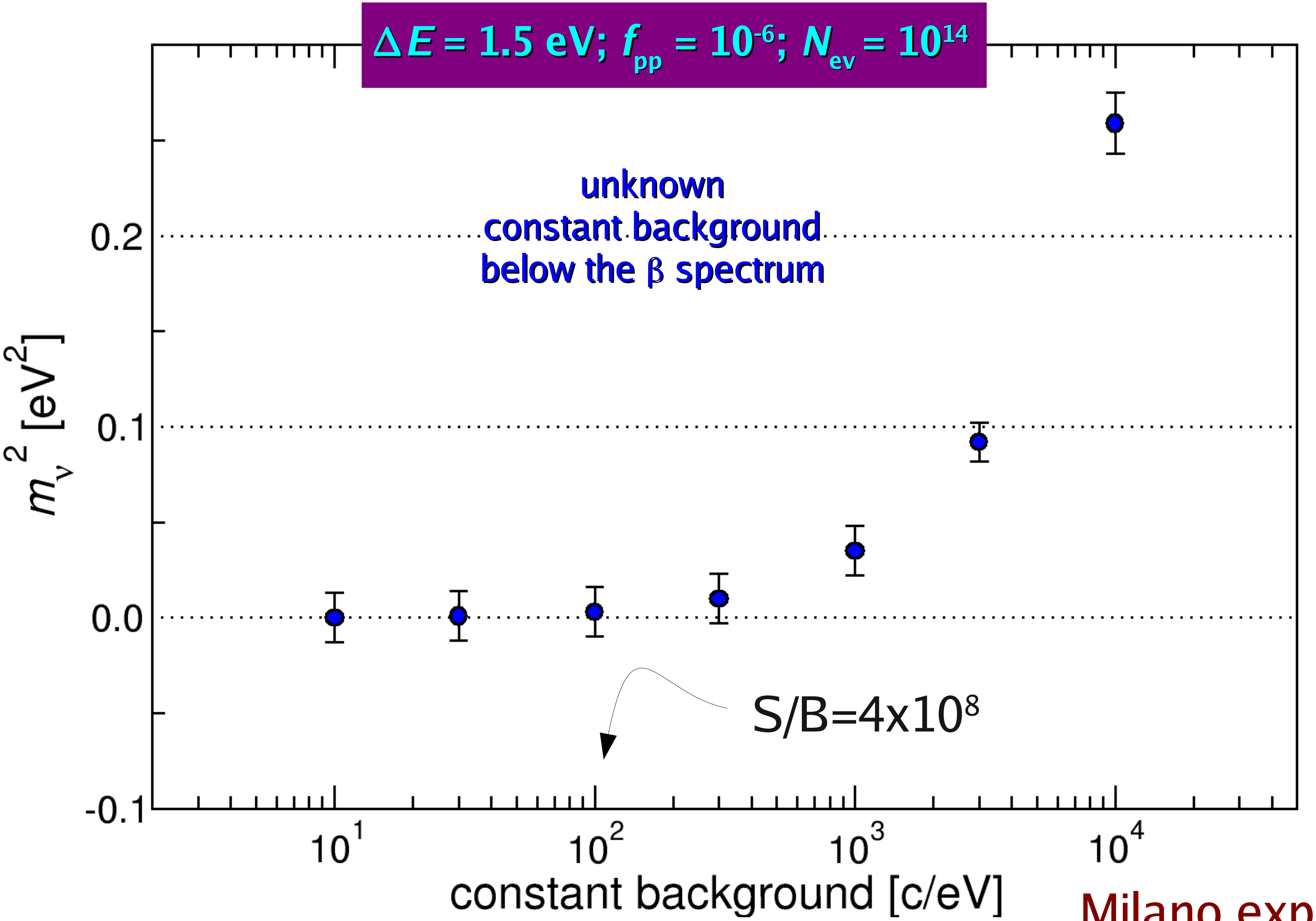
lead shielded
^{55}Fe calibration source

- 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



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

unknown
constant background
below the β spectrum

S/B=4×10^8

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

Milano experiment
S/B $\approx 3 \times 10^4$
$bT \approx 10^6$ c/eV on this plot

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
- ...?

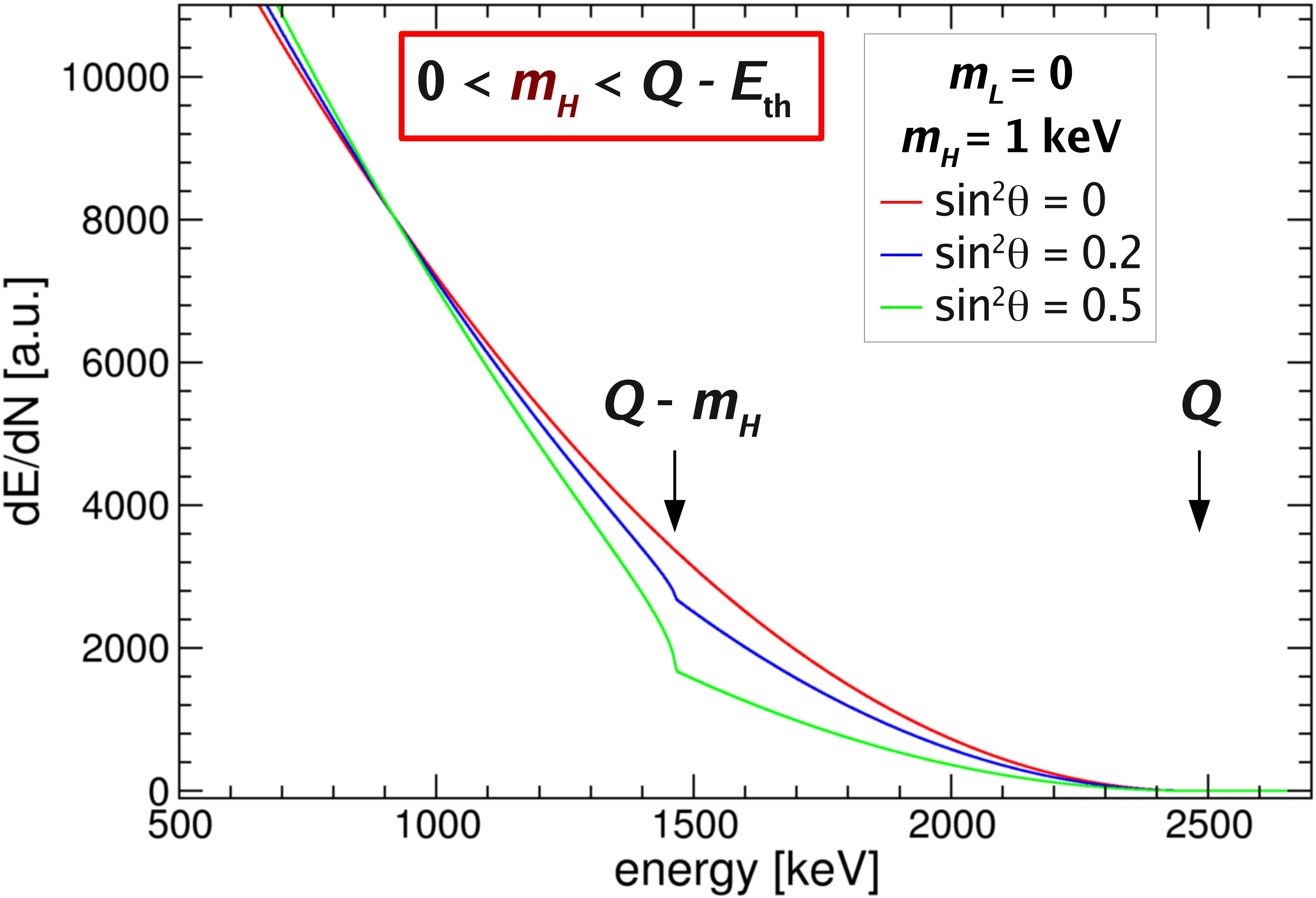
⇨ completely different systematics!

Heavy neutrinos experimental approaches

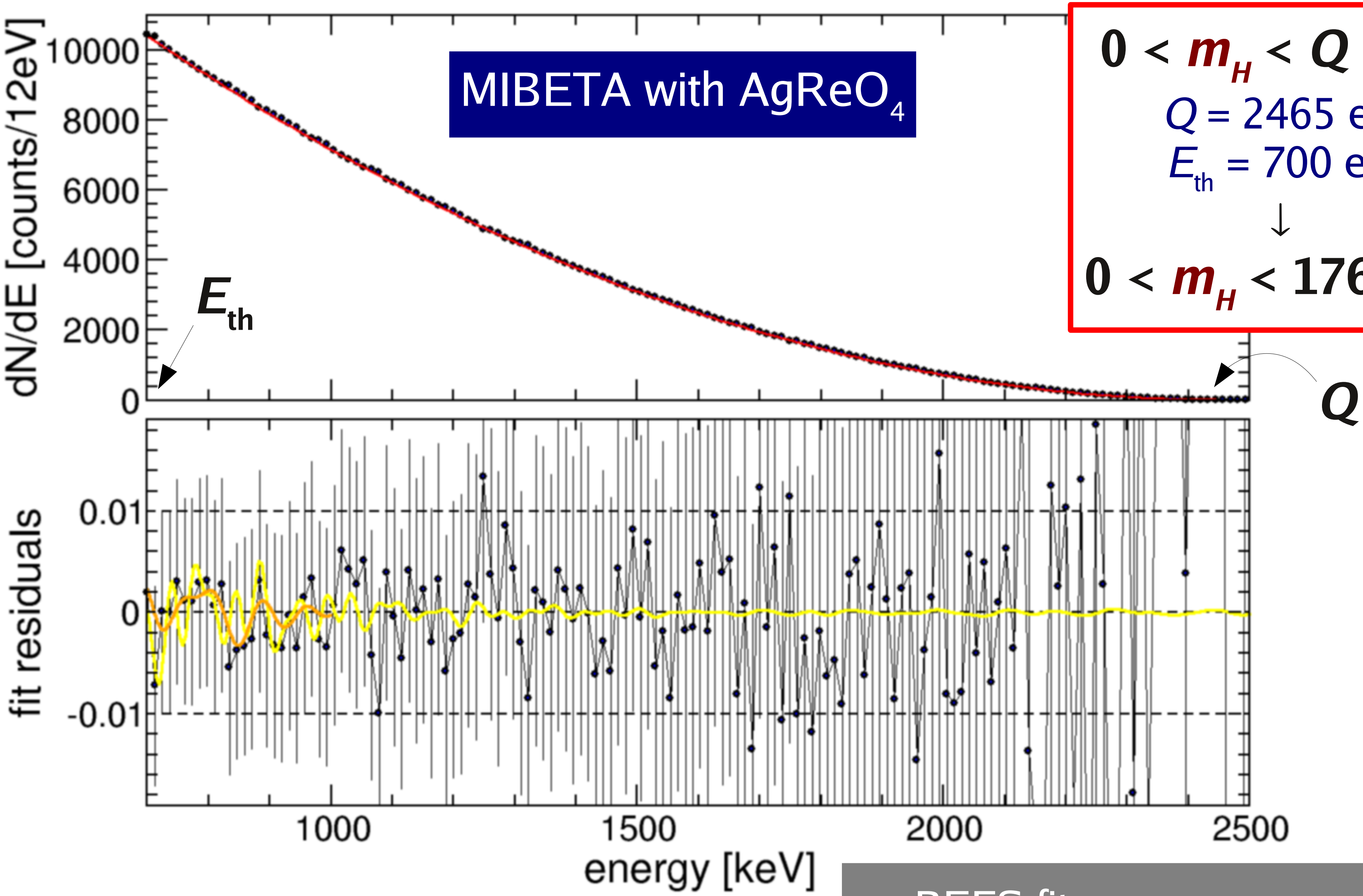
heavy neutrino emission in ^{187}Re β decay

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

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



Heavy neutrinos limits from past ^{187}Re experiments / 1



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

$Q = 2465$ eV

$E_{th} = 700$ eV

↓

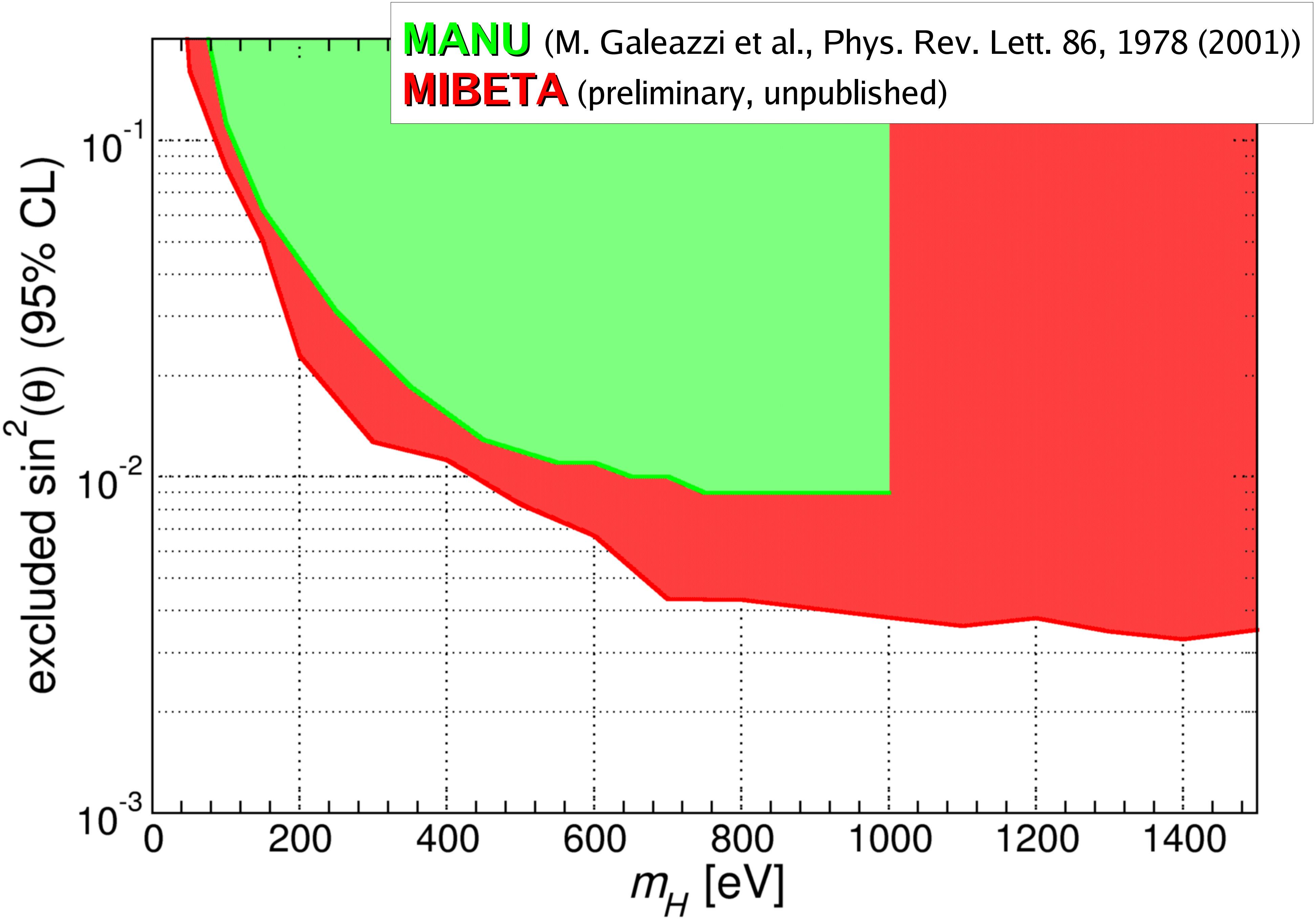
$$0 < m_H < 1765 \text{ eV}$$

— BEFS fit

— extrapolated BEFS with ΔE=0

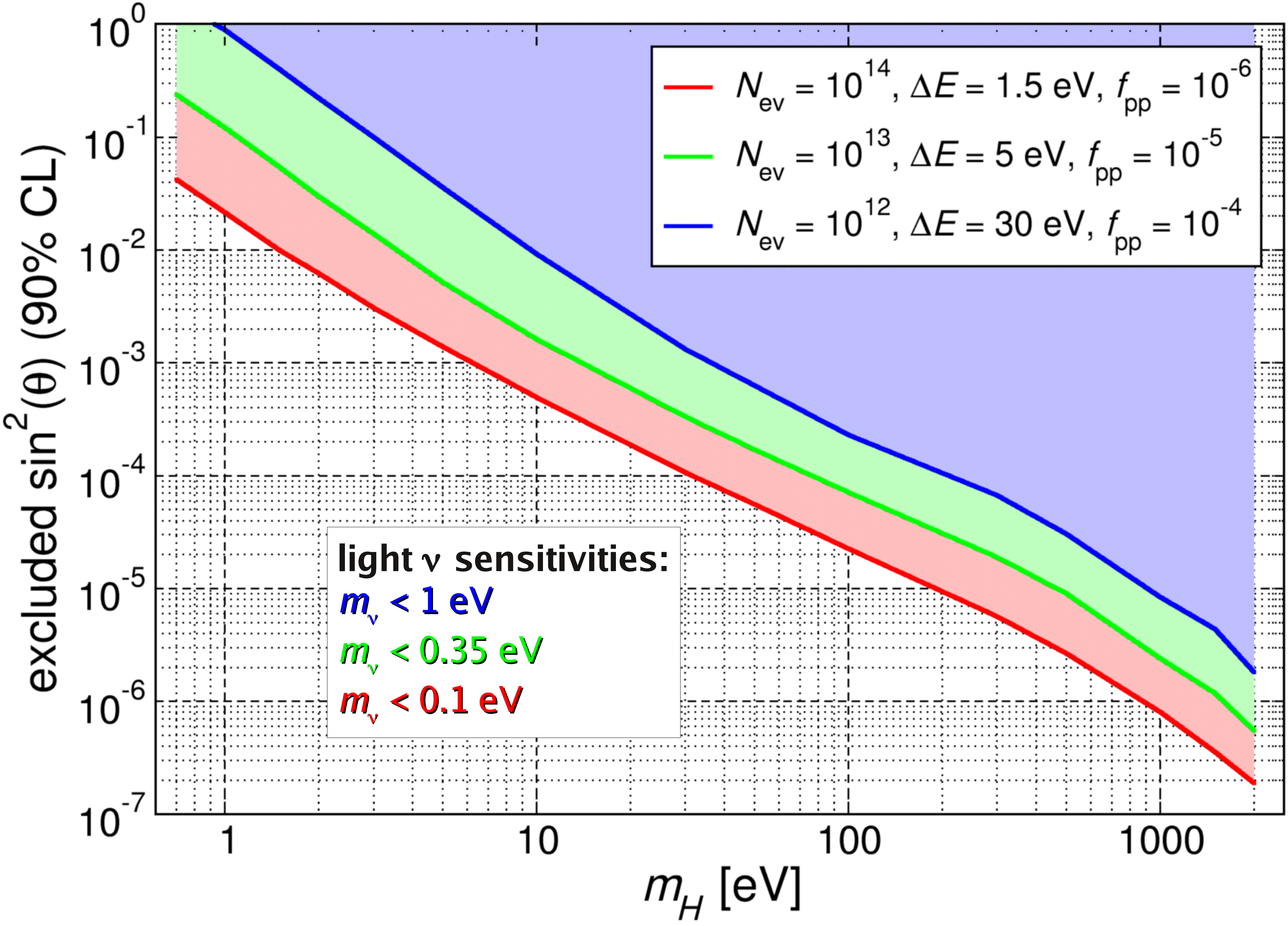
background and **BEFS** may be sources of **systematic uncertainties**

Heavy neutrinos limits from past ^{187}Re experiments / 2



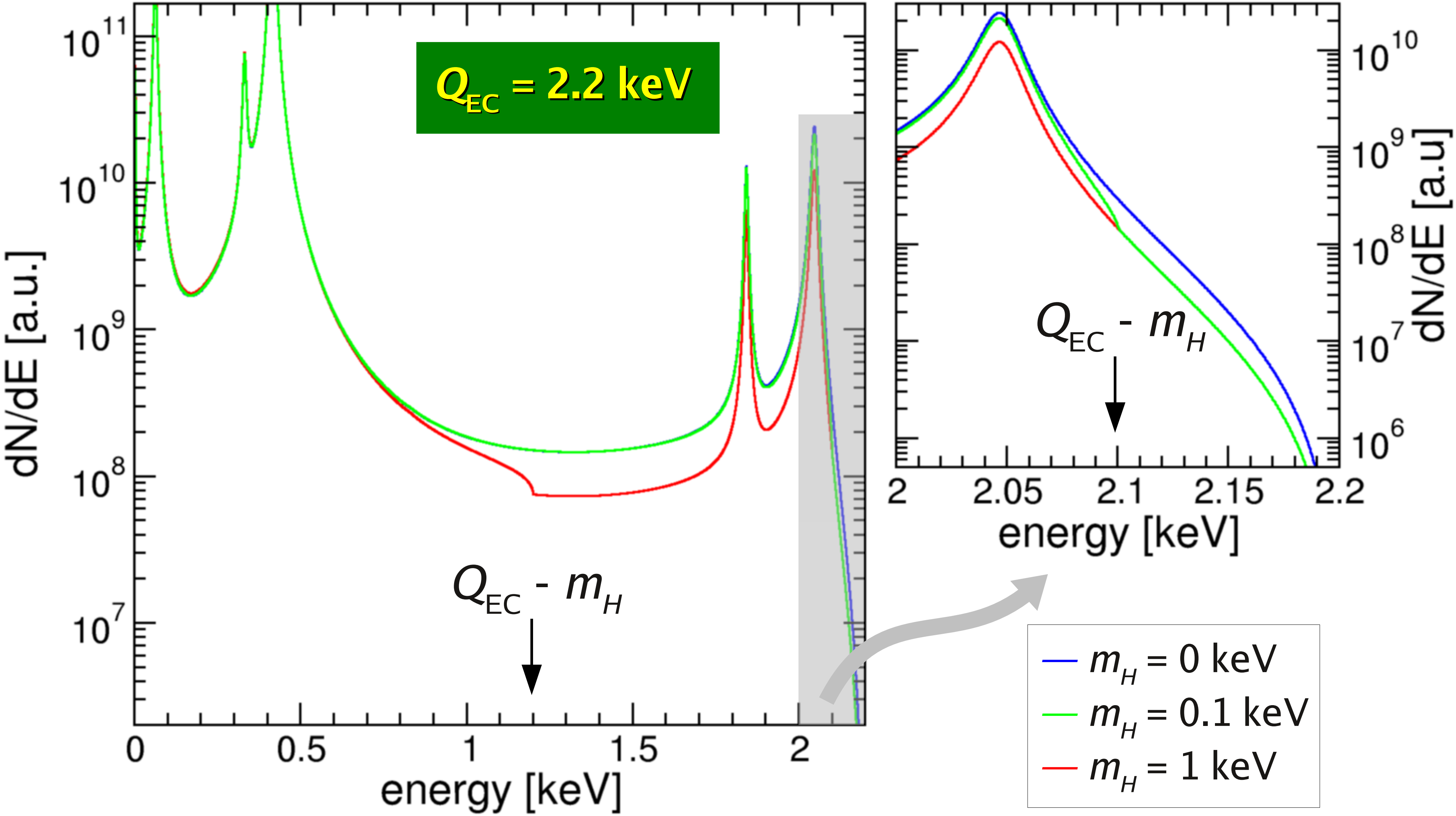
MANU (M. Galeazzi et al., Phys. Rev. Lett. 86, 1978 (2001))
MIBETA (preliminary, unpublished)

MARE sensitivity to heavy neutrinos: ^{187}Re option



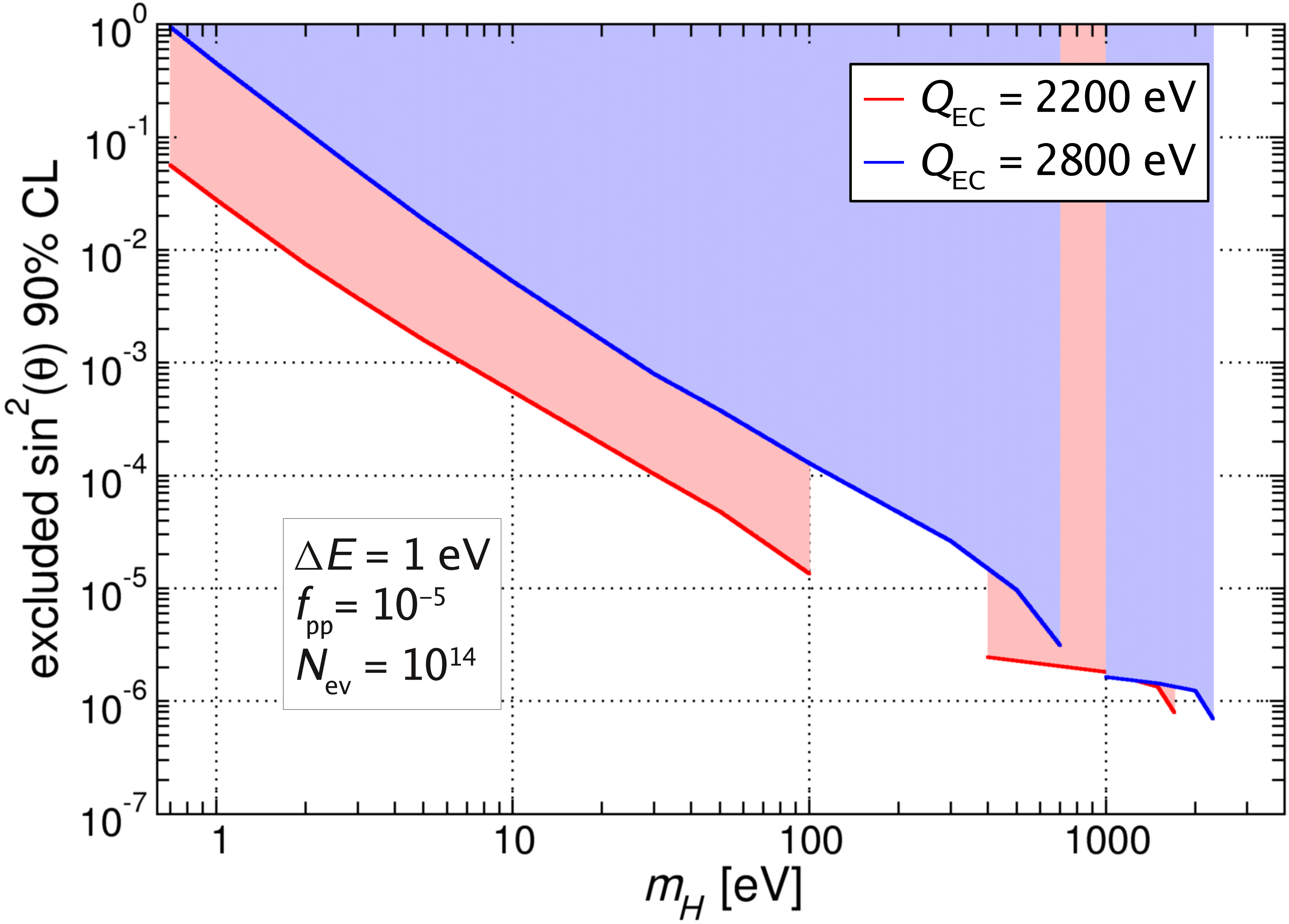
MARE sensitivity to heavy neutrinos: ^{163}Ho option / 1

heavy neutrino emission in ^{163}Ho EC decay

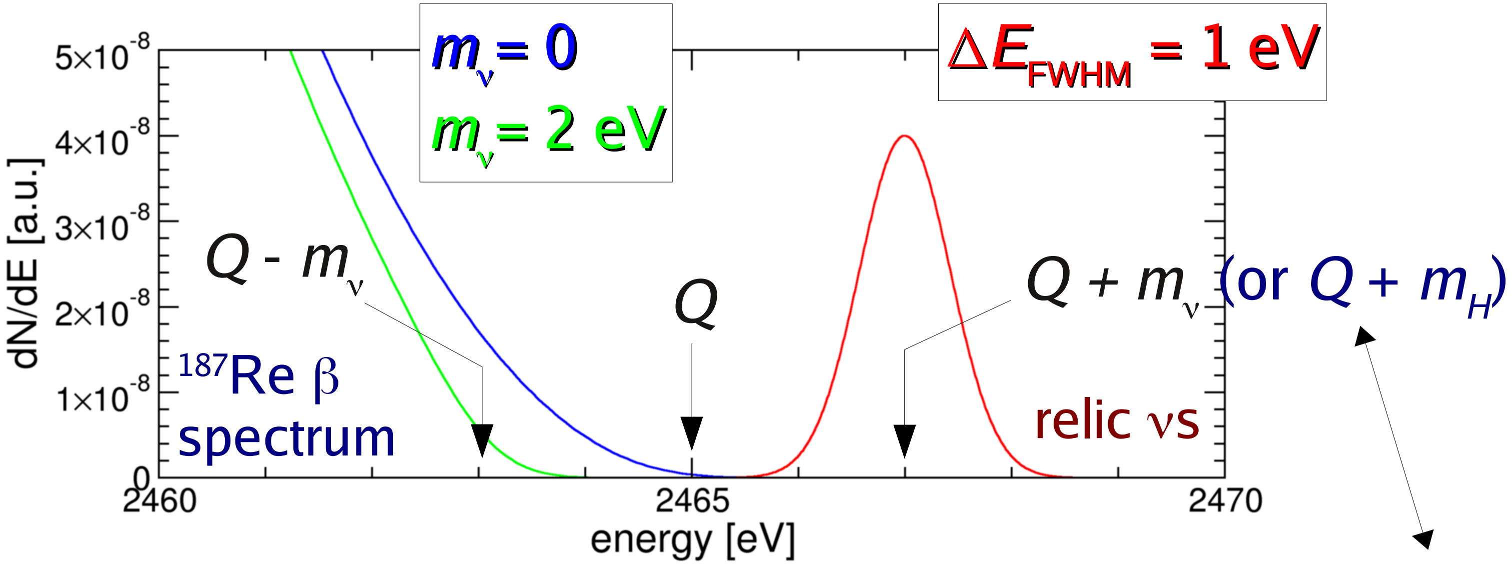


Q_{EC} = 2.2 keV

MARE sensitivity to heavy neutrinos: ^{163}Ho option / 2



Light and heavy relic neutrino detection in MARE?



Interaction rates in KATRIN and MARE	**relic ν_e (CνB)**	**isotope mass**	**rate**	**sterile ν_H $m_H = 1$ keV**
$\nu + {}^3H \rightarrow {}^3He + e^-$	$0.1\ y^{-1}\ g^{-1}$ (1)	100 μg	$10^{-5}\ y^{-1}$	$100\ \sin^2\theta\ y^{-1}\ g^{-1}$ (4)
$\nu + {}^{187}Re \rightarrow {}^{187}Os + e^-$	$10^{-10}\ y^{-1}\ g^{-1}$ (2)	1000 g	$10^{-7}\ y^{-1}$	$10^{-7}\ \sin^2\theta\ y^{-1}\ g^{-1}$
$\bar{\nu} + e^- + {}^{163}Ho \rightarrow {}^{163}Dy^*$	$10^{-5}\ y^{-1}\ g^{-1}$ (3)	100 μg	$10^{-9}\ y^{-1}$	$10^{-3}\ \sin^2\theta\ y^{-1}\ g^{-1}$ (5)

ν densities

CνB: $n_\nu \approx 55\ \nu_e/\text{cm}^3$

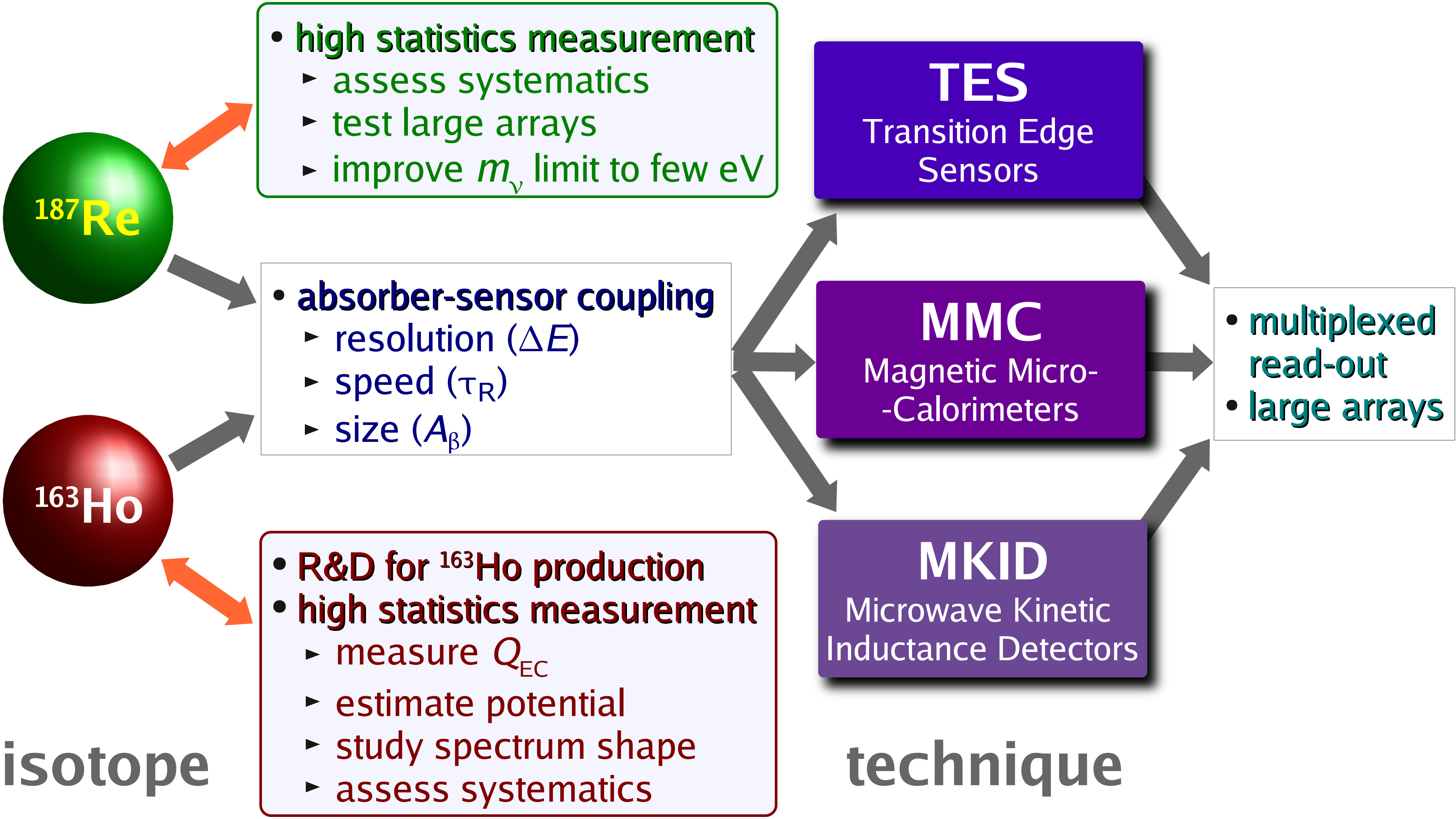
WDM: $n_\nu \approx 3\times10^5\ \nu_H/\text{cm}^3$

$Q_{EC} = 2.5$ keV

(1) R.Lazauskas et al., J. Phys. G: Part. Phys. 35, 025001 (2008)
(2) A.G.Cocco et al., J. Cosmol. Astropart. Phys. 06, 15 (2007)
R.Hodak et al., Progr. in Part. and Nucl. Phys. 66, 452 (2011)
(3) M.Lusignoli, M.Vignati, Phys. Lett., B697, 11 (2011) (arXiv:1012.0760 [hep-ph])
(4) W.Liao, Phys. Rev., D82, 73001 (2010)
Y.F.Li, Z.Z.Xing, Phys. Lett. B695, 205 (2011)
(5) Y.F.Li, Z.Z.Xing, arXiv:1104-4000 [astro-ph]

Two experimental phases: MARE-1 and MARE-2

- **MARE-2** full scale experiment aiming at **0.2÷0.1 eV m_ν statistical sensitivity**
- **MARE-1** collection of activities aiming at **isotope/technique selection**



- **high statistics measurement**
  - assess systematics
  - test large arrays
  - improve m_ν limit to few eV

- **absorber-sensor coupling**
  - resolution (ΔE)
  - speed (τ_R)
  - size (A_β)

- **R&D for ^{163}Ho production**
- **high statistics measurement**
  - measure Q_{EC}
  - estimate potential
  - study spectrum shape
  - assess systematics

TES
Transition Edge Sensors

MMC
Magnetic Micro-Calorimeters

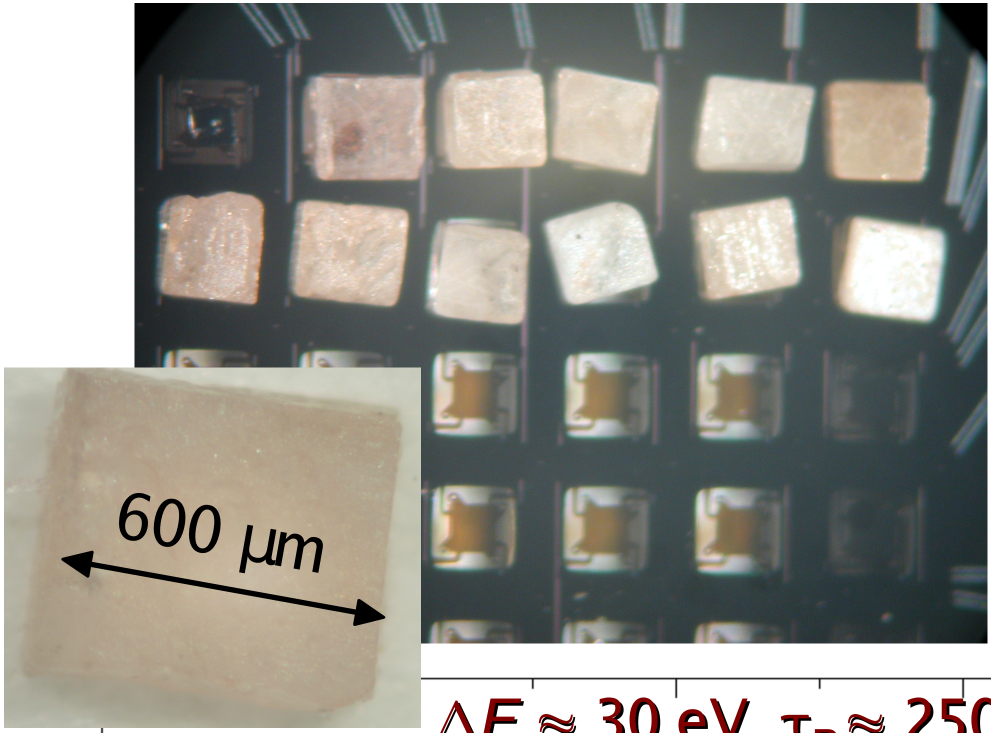
MKID
Microwave Kinetic Inductance Detectors

- **multiplexed read-out**
- **large arrays**

MARE-1 activities summary

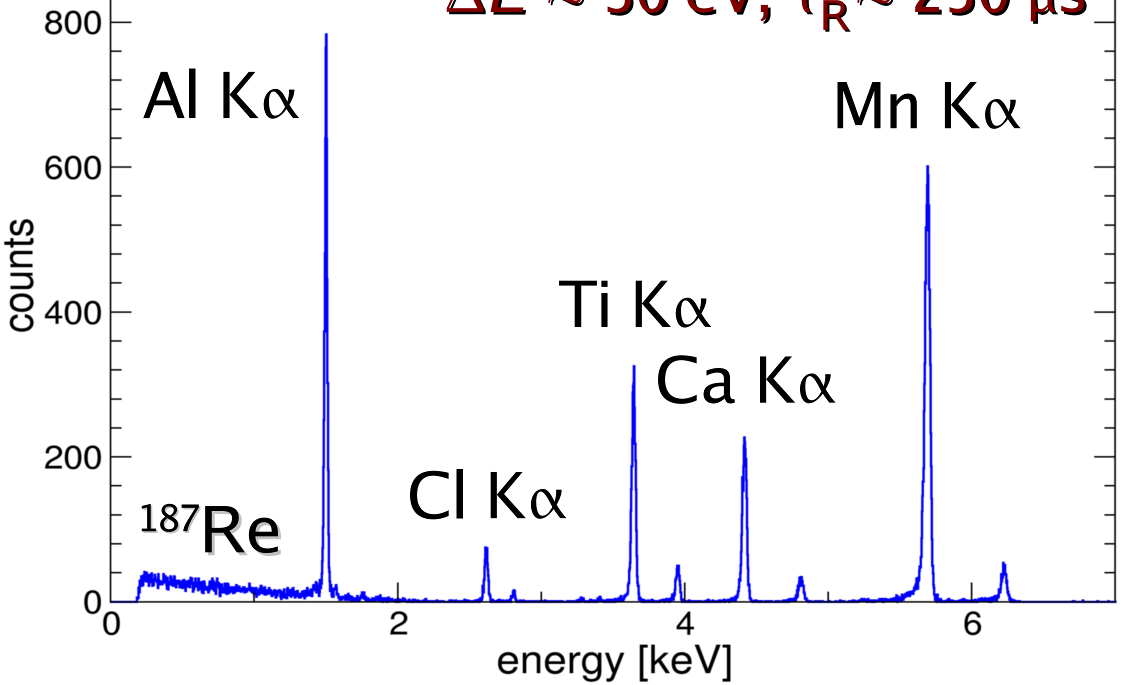
- **Isotope physics investigation and systematics assessment**
  - ^{163}Ho + Si-impl/TES (U Genova - U Milano-Bicocca – U Lisbon/ITN)
  - $AgReO_4$ + Si-impl (U Milano-Bicocca - U Como - NASA/GSFC – UW Madison)
- **Sensor-Absorber coupling (^{187}Re/^{163}Ho) and single pixel design**
  - ^{187}Re + TES (U Genova – U Miami – U Lisbon/ITN)
  - ^{187}Re + MMC (U Heidelberg)
  - ^{163}Ho + TES (U Genova)
  - ^{163}Ho + MMC (U Heidelberg)
  - ^{163}Ho/^{187}Re + MKID (U Milano-Bicocca - JPL/Caltech - U Roma - FBK)
- **Multiplexed sensor read-out**
  - SQUID multiplexing (U Genova - PTB)
  - SQUID microwave multiplexing (U Heidelberg)
- **Software tools**
  - Data Analysis (U Miami)
  - Montecarlo simulations (U Miami - U Milano-Bicocca)

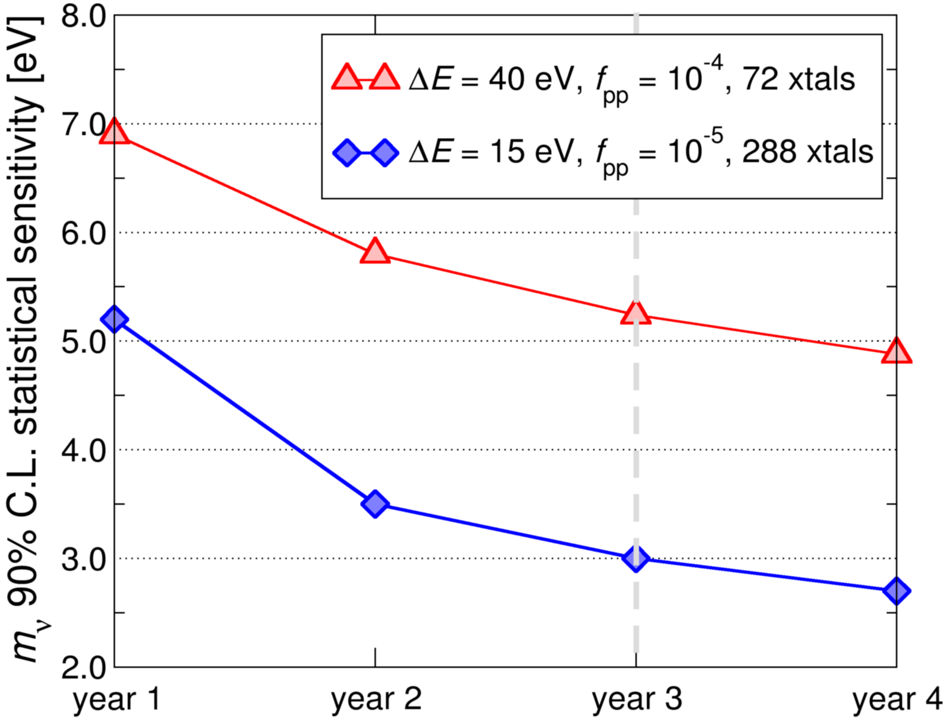
MARE-1 @ Milano-Bicocca with Si implanted thermistors



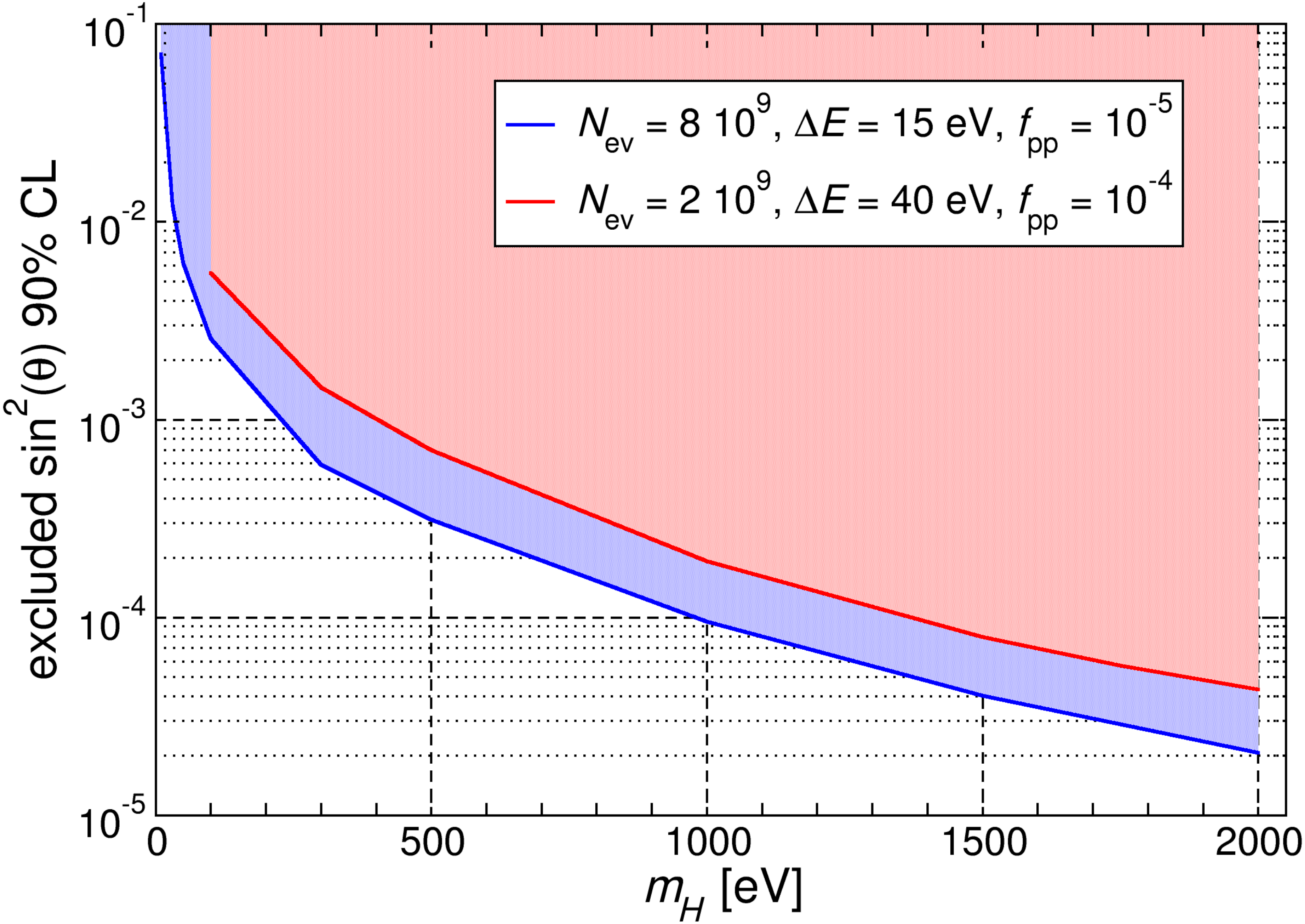
- NASA/GSFC XRS2-2 arrays
  - ▷ 6×6 Si-implanted pixels
- flat **$AgReO_4$** single crystals
  - ▷ $m \approx$ 0.5 mg
- **experiment designed for 8 arrays**
  - ▷ up to **10^{10} events** in 4 years
  - ▷ **eV sensitivity** to test spectrometers
  - ▷ high statistics to **assess systematics**
- **starting with 72 crystals in 2011**

$\Delta E \approx$ 30 eV, $\tau_R \approx$ 250 μs



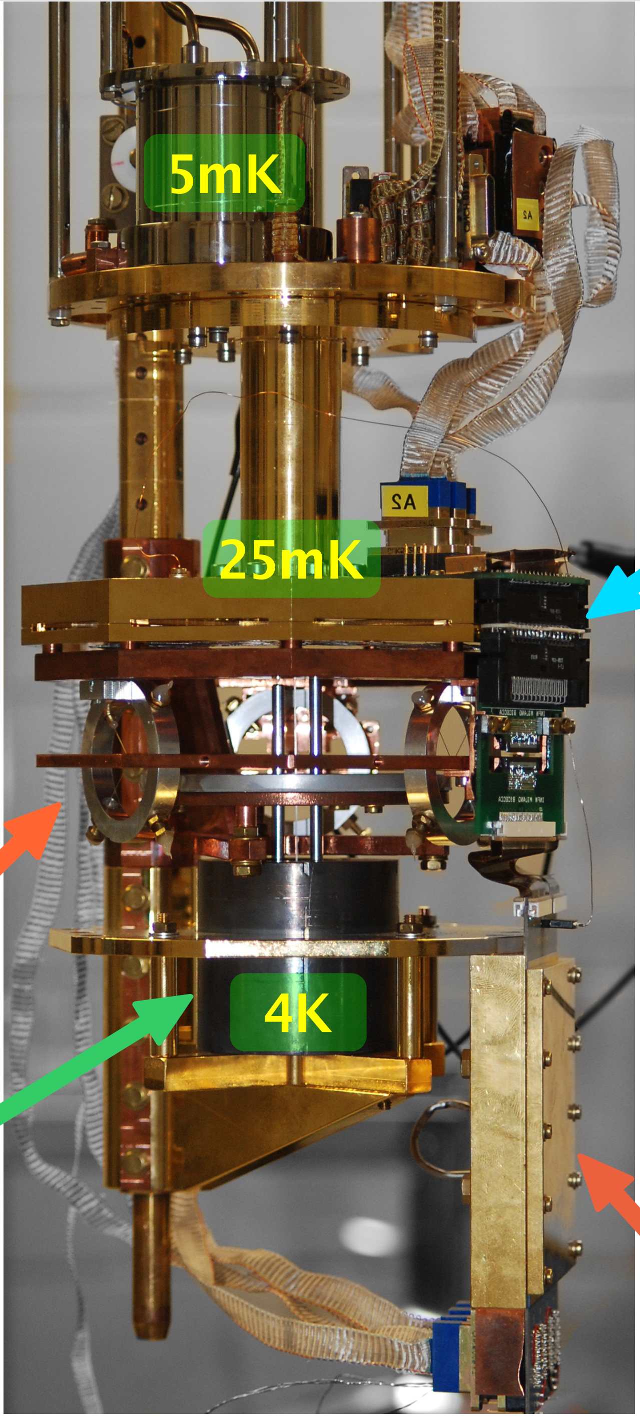


MARE-1 @ Milano-Bicocca and heavy neutrinos

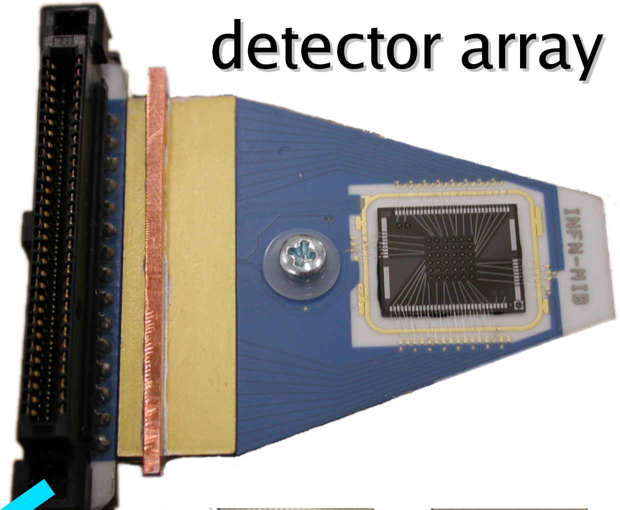


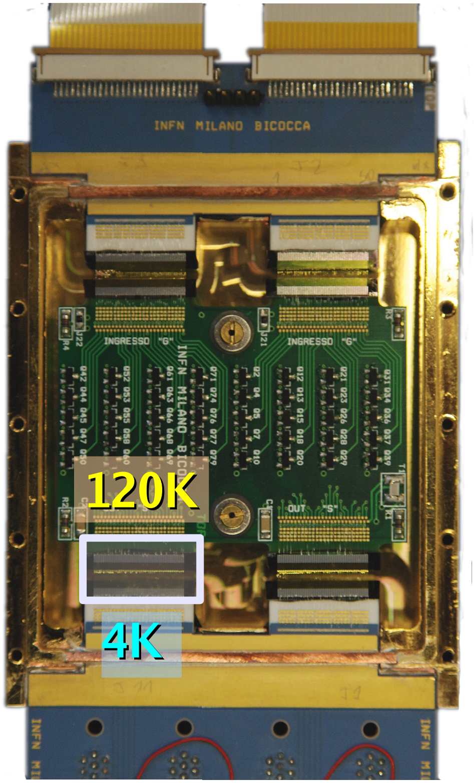
MARE-1 @ Milano-Bicocca ... / 2

- experimental set-up completed
- optimization in progress



detector array





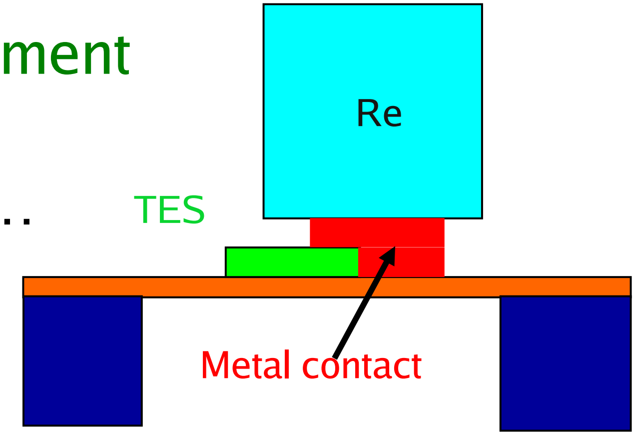
decoupling jig

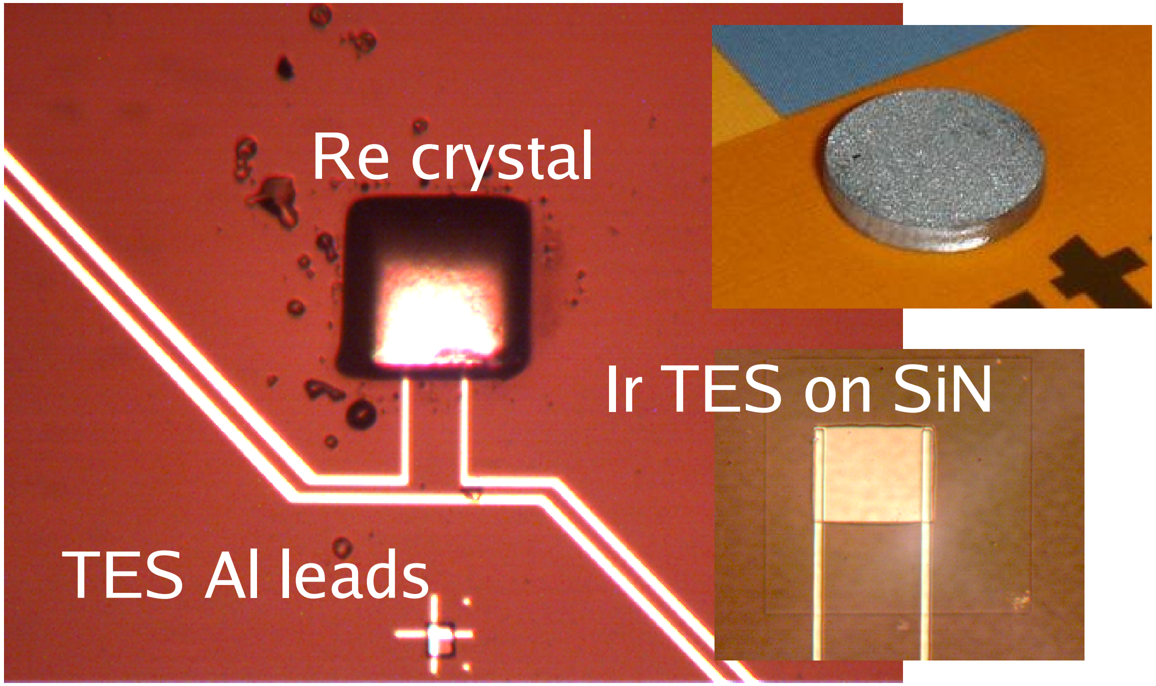
fluorescence calibration source with lead shield

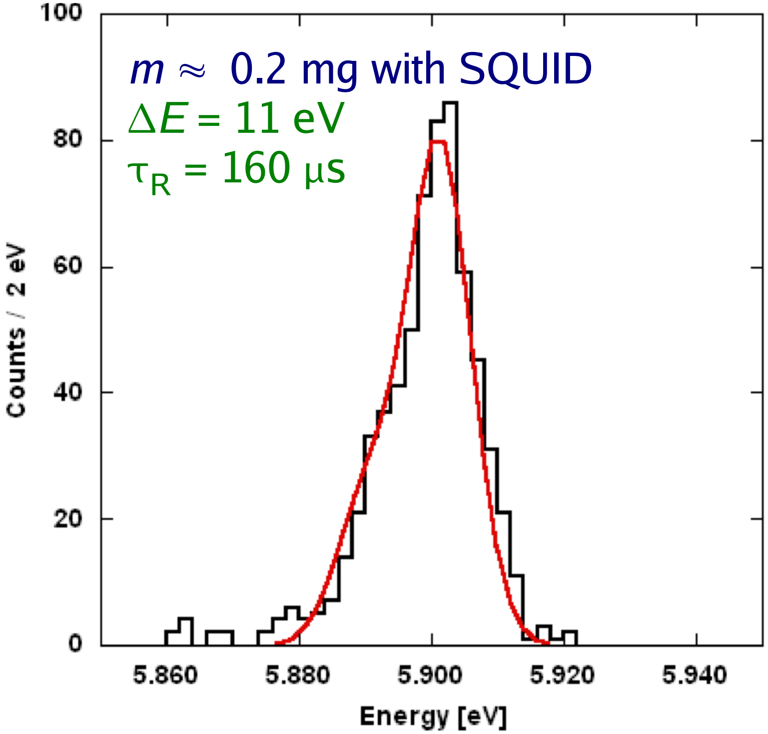
80 channel JFET box

MARE-1 @ Genova with TES

- Single TES-Re pixel R&D
  - improve pulse rise time to ≈µs
  - improve energy resolution from 10 eV to few eV
- Large arrays (≈10^3 pixels) for 10^4 -10^5 detector experiment
- Array design large scale experiment oriented
  - high reproducibility, stability, fully energy calibrated…
- Multiplexed SQUID read-out with large bandwidth
- ^{163}Ho loaded absorbers: **few kBq of ^{163}Ho produced**
- ^{163}Ho spectrum high statistics measurement

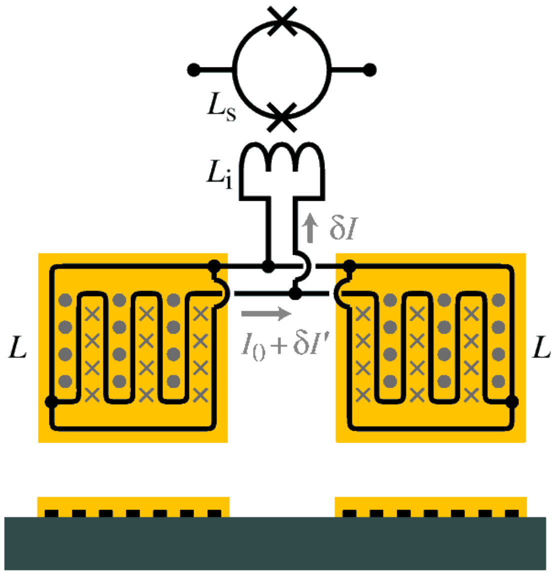


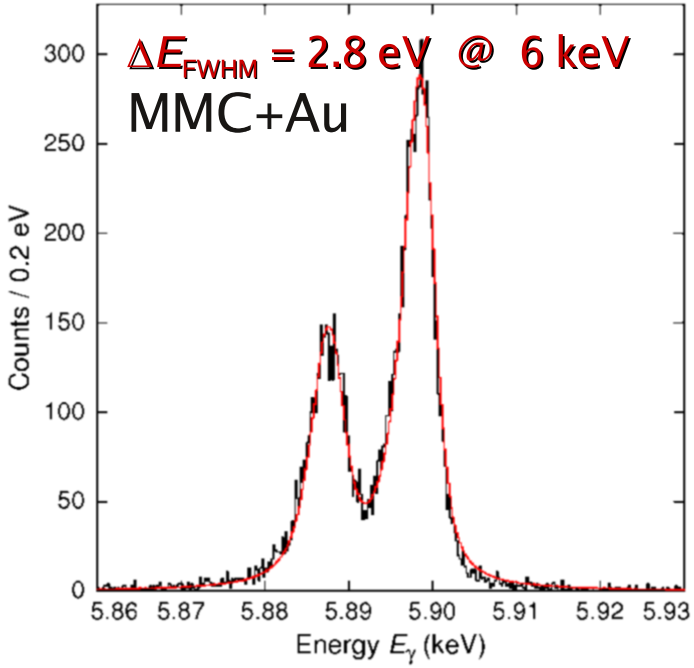


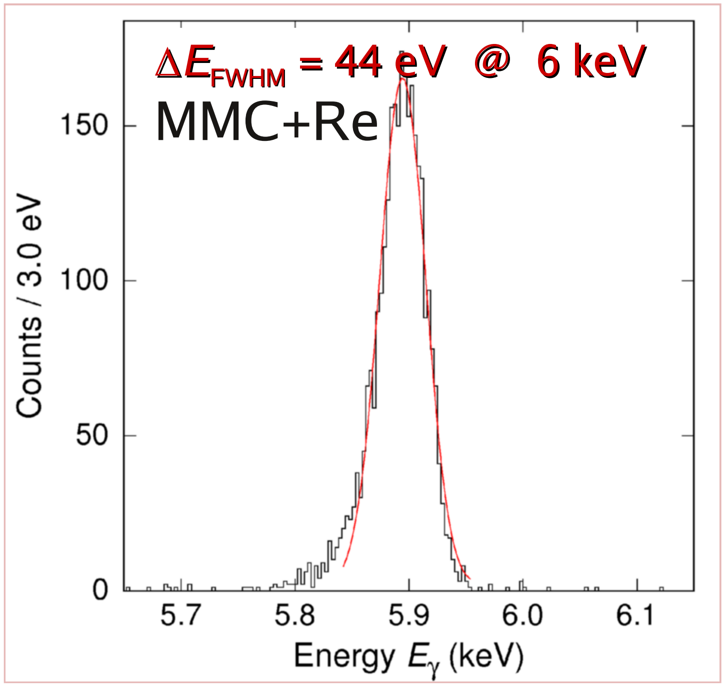


MARE-1 @ Heidelberg with Magnetic Micro Calorimeters

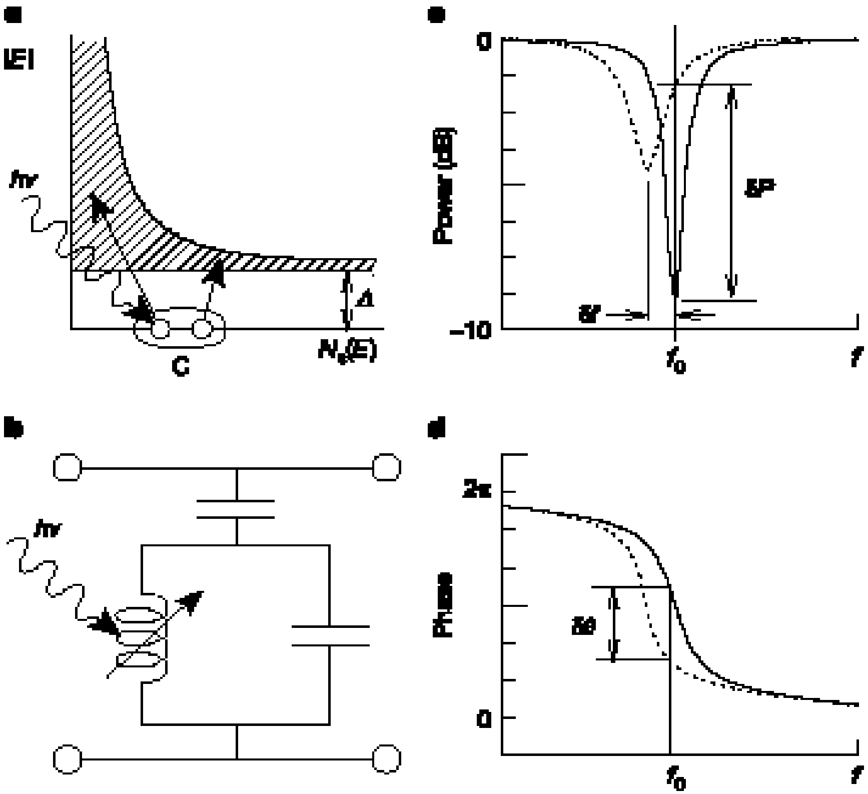
- Planar sensors on meander shaped pickup coils
- Optimization of MMCs with superconducting rhenium absorber
  - minimization of the rise-time
  - investigation of energy down-conversion in superconducting absorbers
  - investigating the energy resolution achievable with superconducting absorber
- Calorimetric investigation of new candidates for the neutrino mass direct measurements by electron capture decay
  - ^{163}Ho, ^{157}Tb, ^{194}Hg, ^{202}Hg
  - Development of micro-structured MMCs for ion implantation at ISOLDE
- Microwave SQUID multiplexing for MMCs



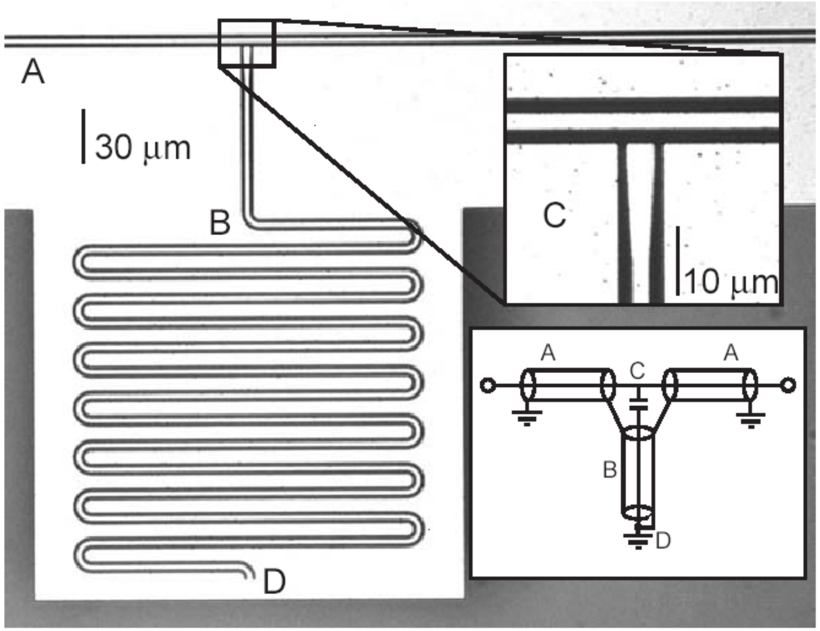


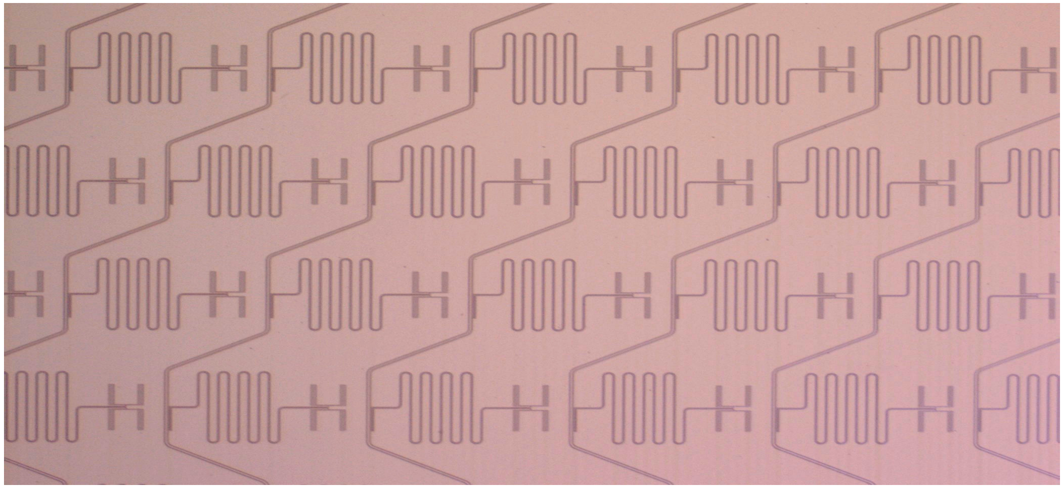


MKIDs R&D @ Milano-Bicocca



- microwave (1-10 GHz) resonating superconducting devices
- 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**
  - easy **multiplexing** for large number of pixel



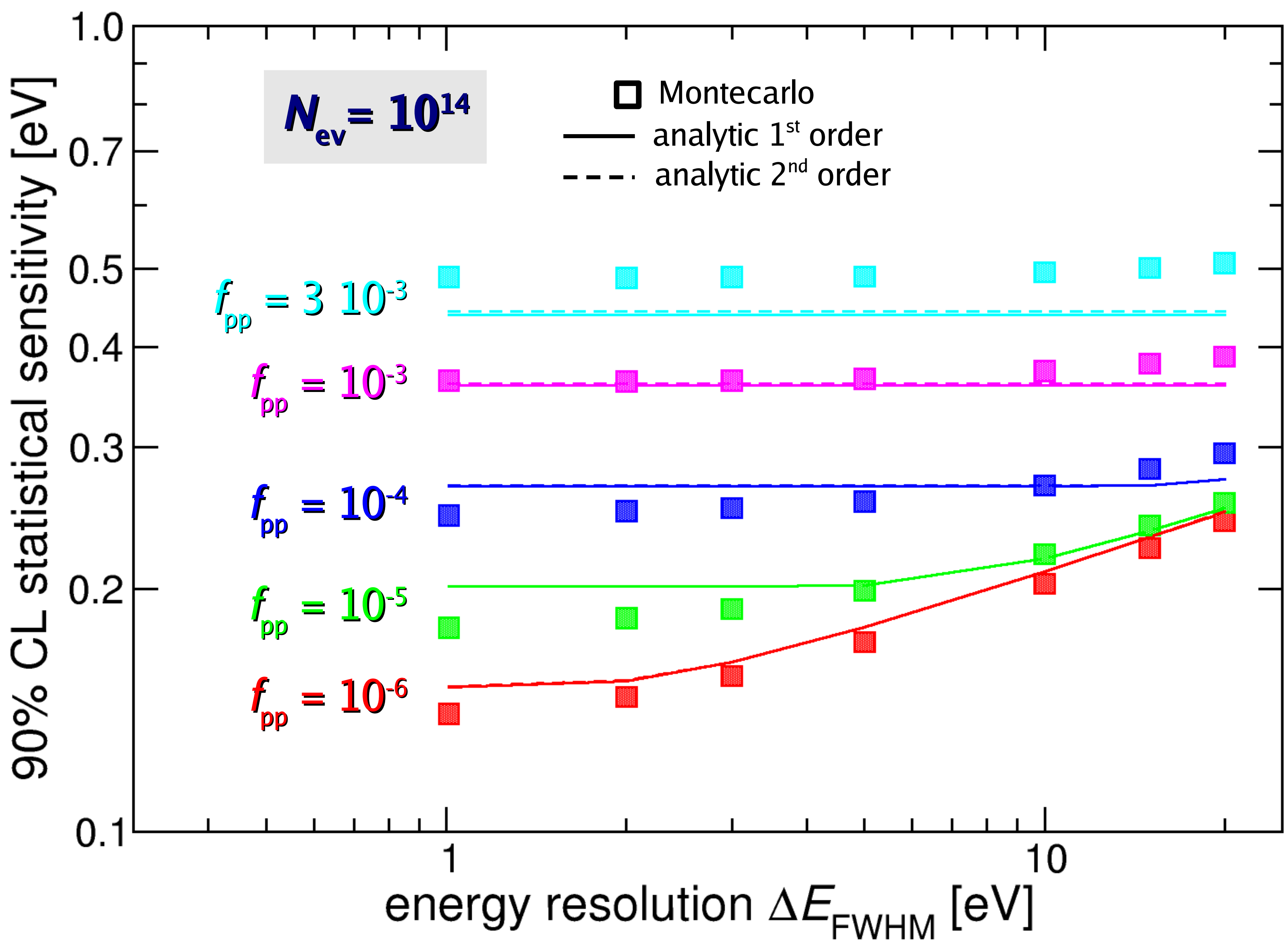


Conclusions

- thermal calorimetry of ^{187}Re decay can give **sub-eV sensitivity on m_ν**
- calorimetry of ^{163}Ho electron capture decay is an interesting alternative
- ^{187}Re and ^{163}Ho calorimetry is sensitive to **1 keV scale heavy neutrinos**
- MARE-1 activities are in progress to
  - ▷ improve the understanding of ^{187}Re experiment systematics
    - a few eVs light neutrino sensitivity ^{187}Re experiment is starting soon
  - ▷ investigate ^{163}Ho decay spectrum
    - ^{163}Ho isotope has been produced and is ready for first tests
  - ▷ develop the single MARE pixel
    - R&D for coupling TES, MMC and MKID with ^{187}Re/^{163}Ho is in progress
  - ▷ implement read-out multiplexing schemes
- **isotope and technique selection for MARE-2 is in progress**

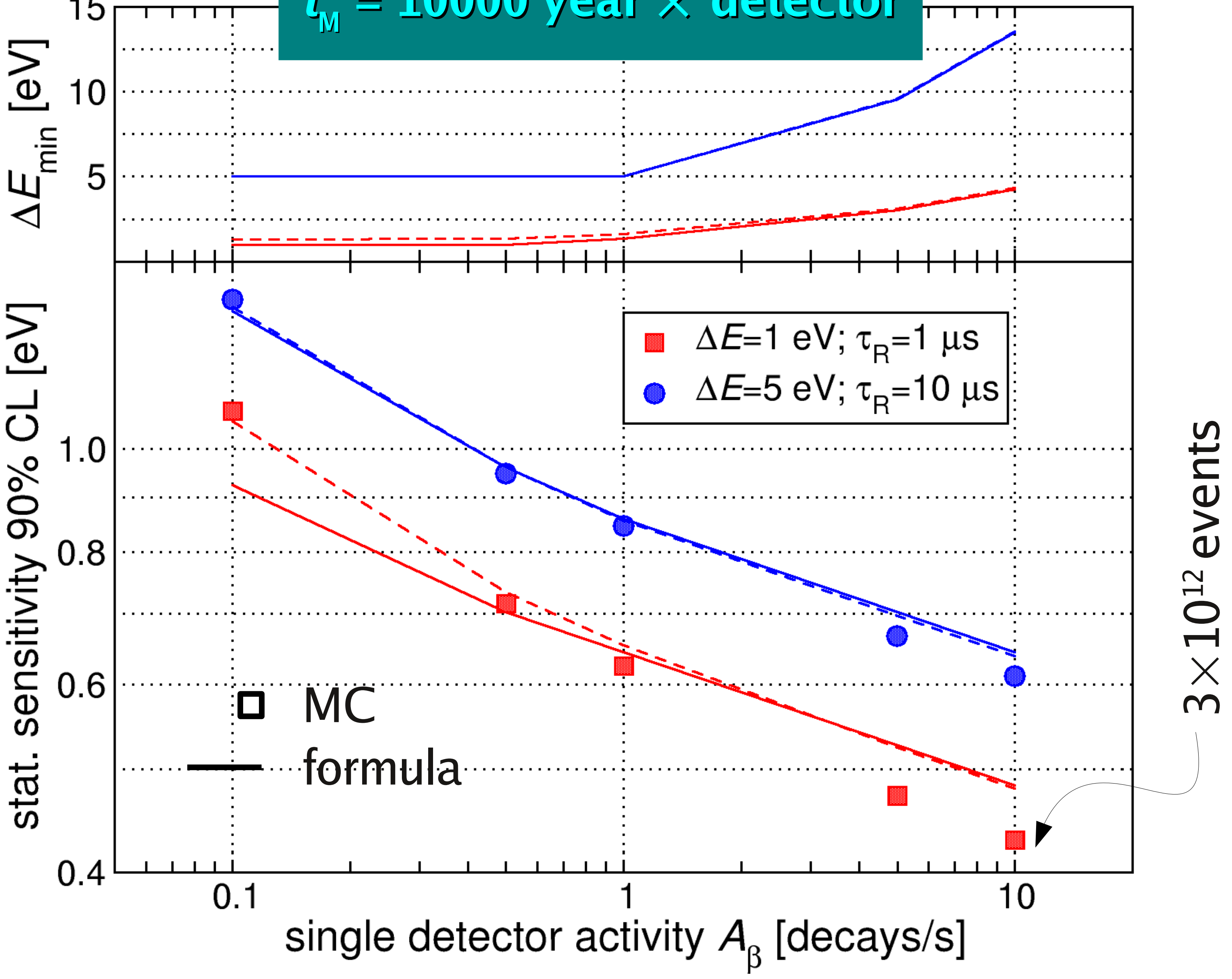
Backups ...

Sub-eV m_ν statistical sensitivity / 2

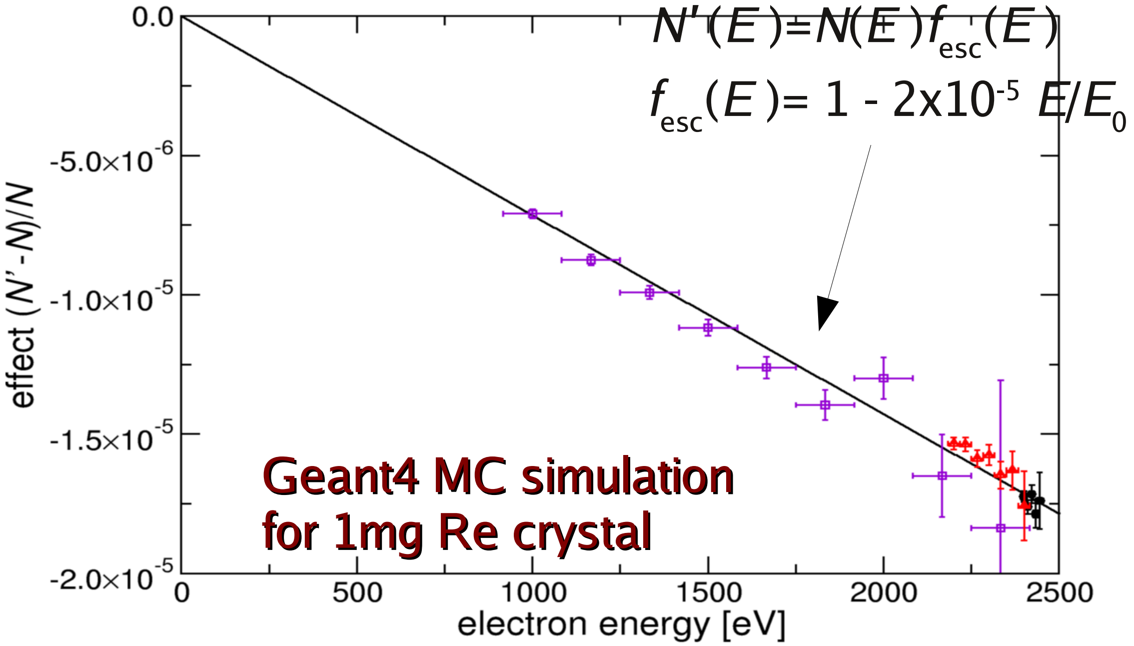


Sub-eV m_ν, statistical sensitivity / 3

t_M = 10000 year × detector



Electron escape systematic uncertainties



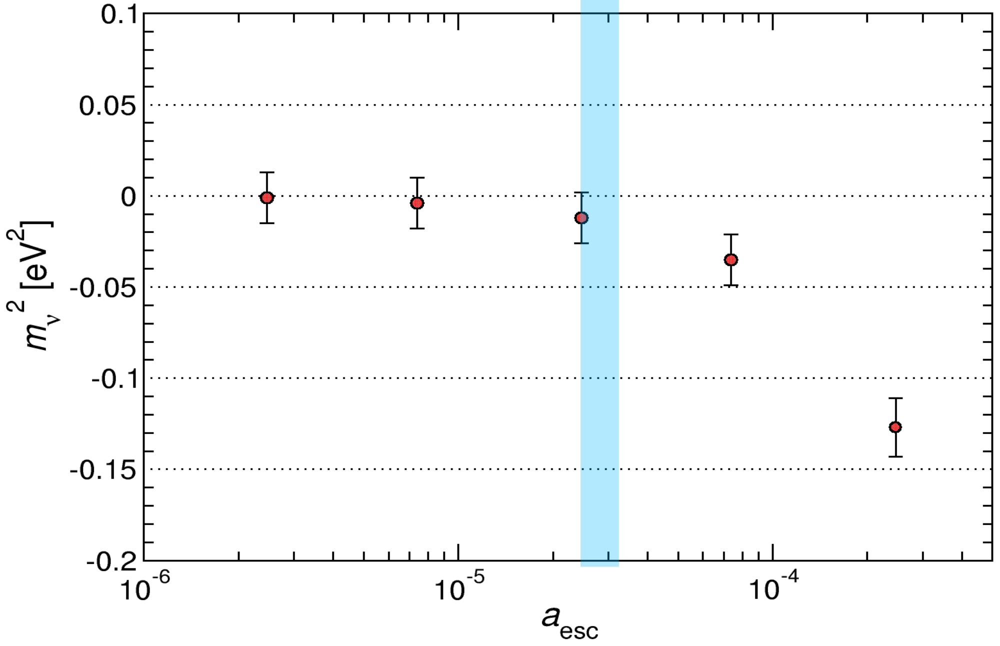
$N'(E) = N(E) f_{esc}(E)$

$f_{esc}(E) = 1 - 2\text{x}10^{-5}\, E/E_0$

Geant4 MC simulation
for 1mg Re crystal

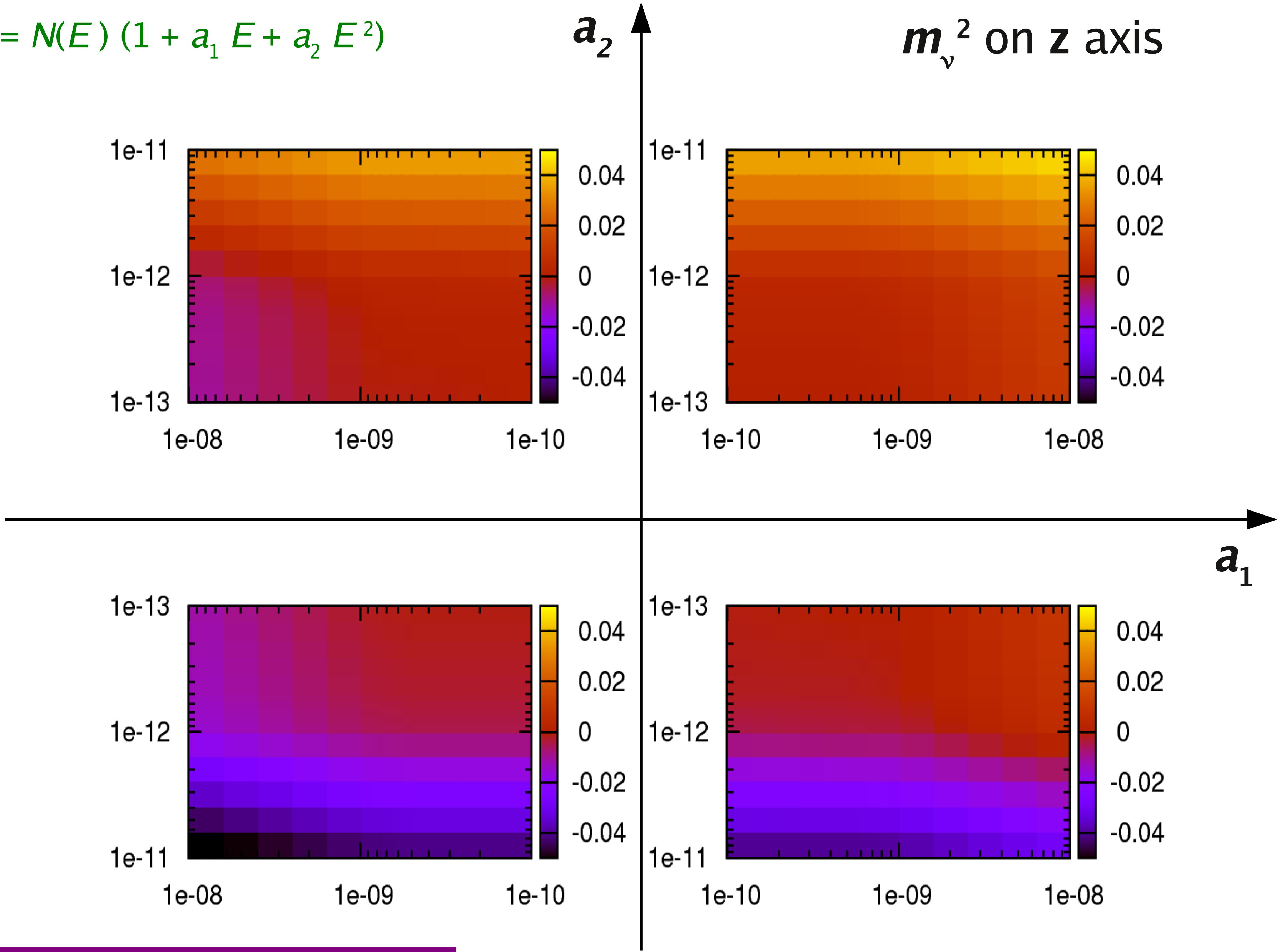
ΔE = 1.5 eV; f_{pp} = 10^{-6}; N_{ev} = 10^{14}

systematic effect with escape neglected



Beta spectrum shape systematic uncertainties

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



m_ν^2 on **z** axis

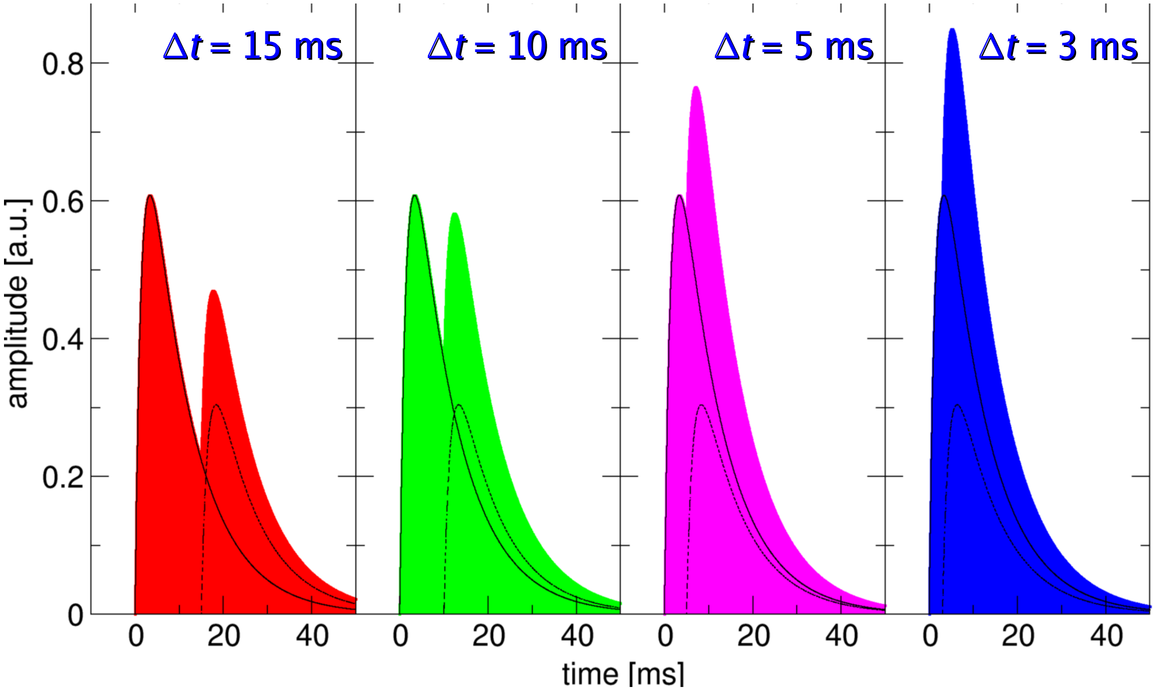
$\Delta E = 1.5$ eV; $f_{pp} = 10^{-6}$; $N_{ev} = 10^{14}$

Pile-up spectrum systematic uncertainties / 1

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

Example

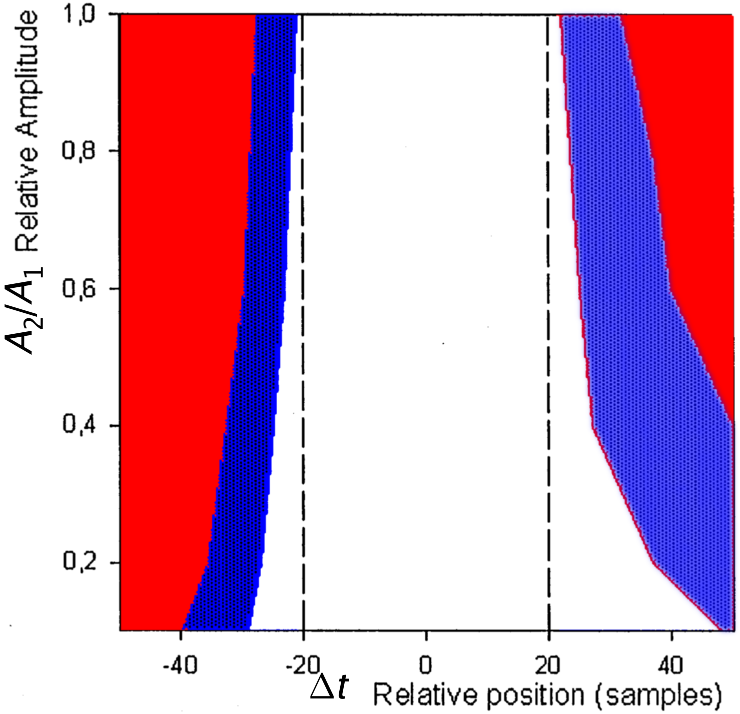
- 2 pulses with:
  - τ_{rise}= 1.5 ms
  - τ_{decay}= 10 ms
  - A_2/A_1 = 0.5



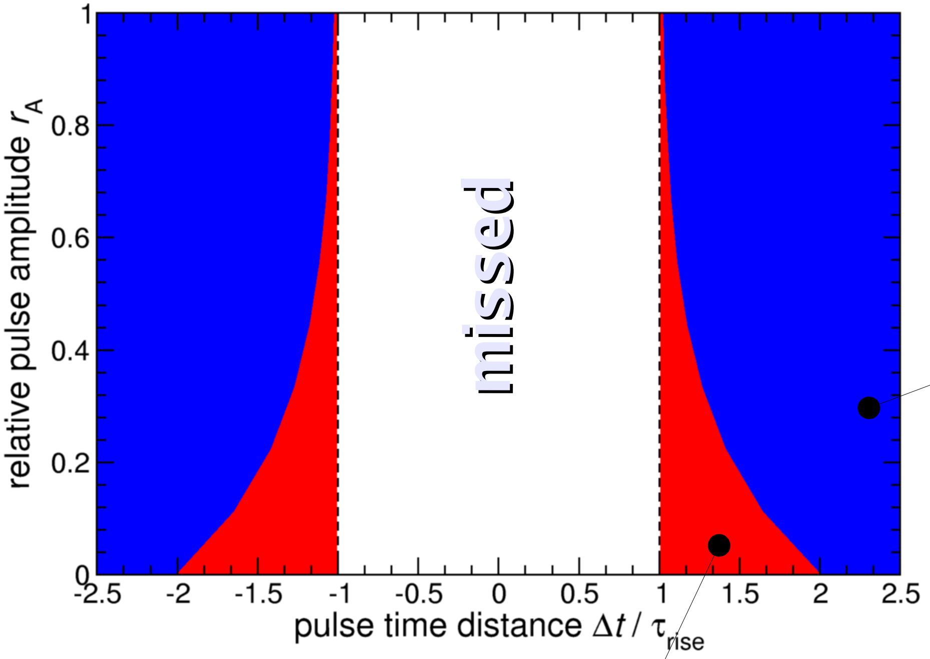
Montecarlo with simulated pulses

- $\tau_{rise} \approx$ 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

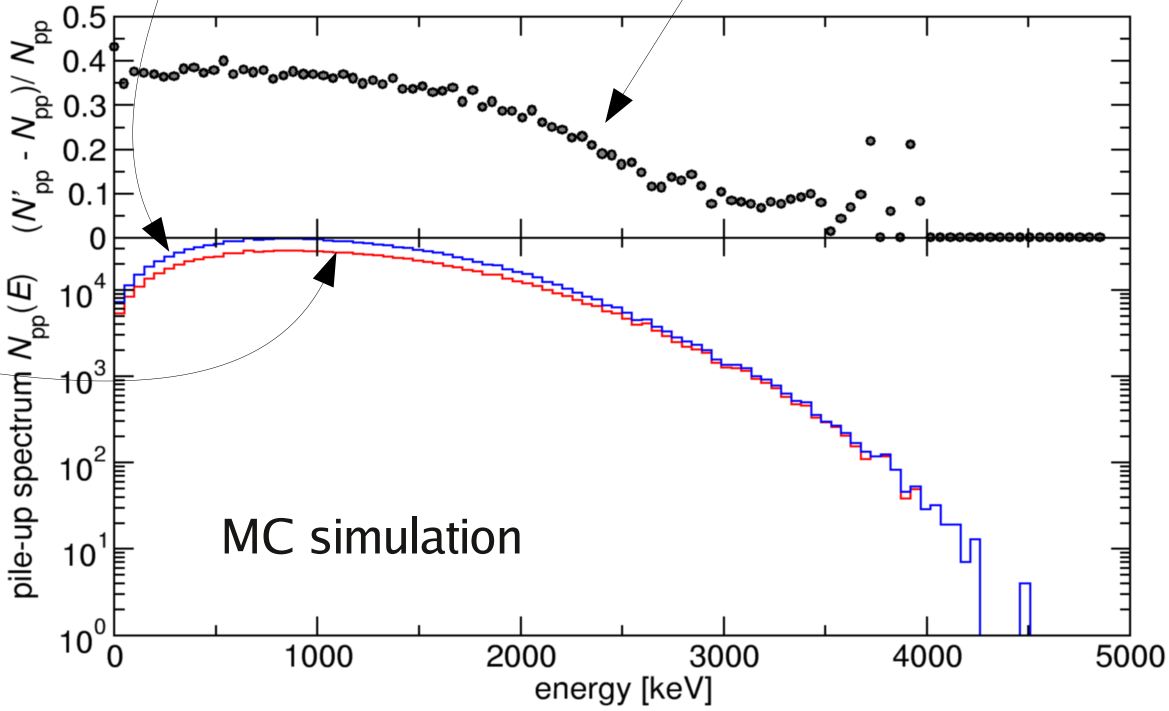


Pile-up spectrum systematic uncertainties / 2



energy dependent pile-up resolving time τ_{eff}

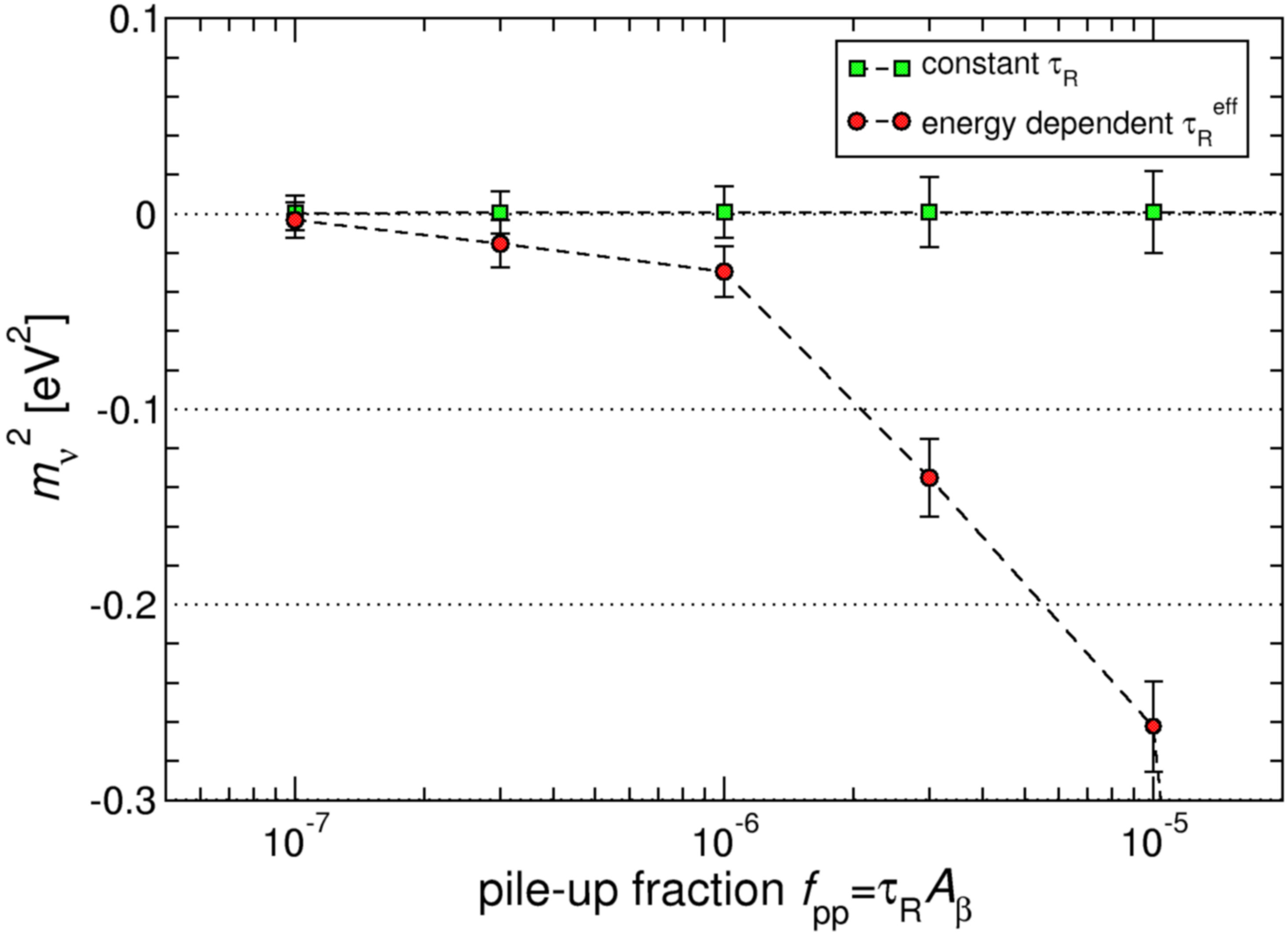
$$f_{corr}(E,f_{pp}=10^{-6})\approx 1+\frac{0.4}{e^{(E-E_0)/(480\,eV)}+1}$$



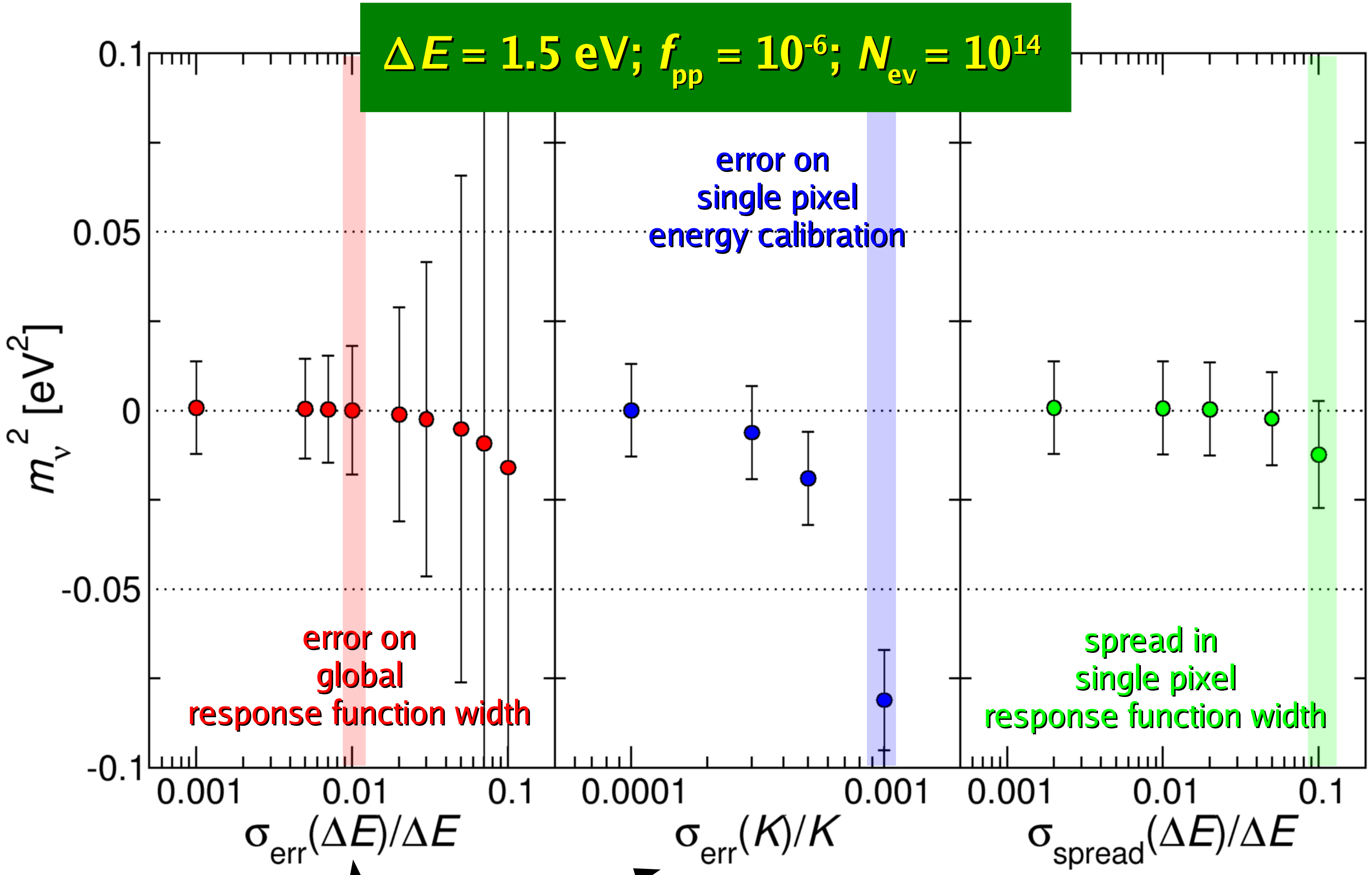
constant pile-up resolving time τ_R

Pile-up spectrum systematic uncertainties / 3

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



Instrumental uncertainties: large arrays



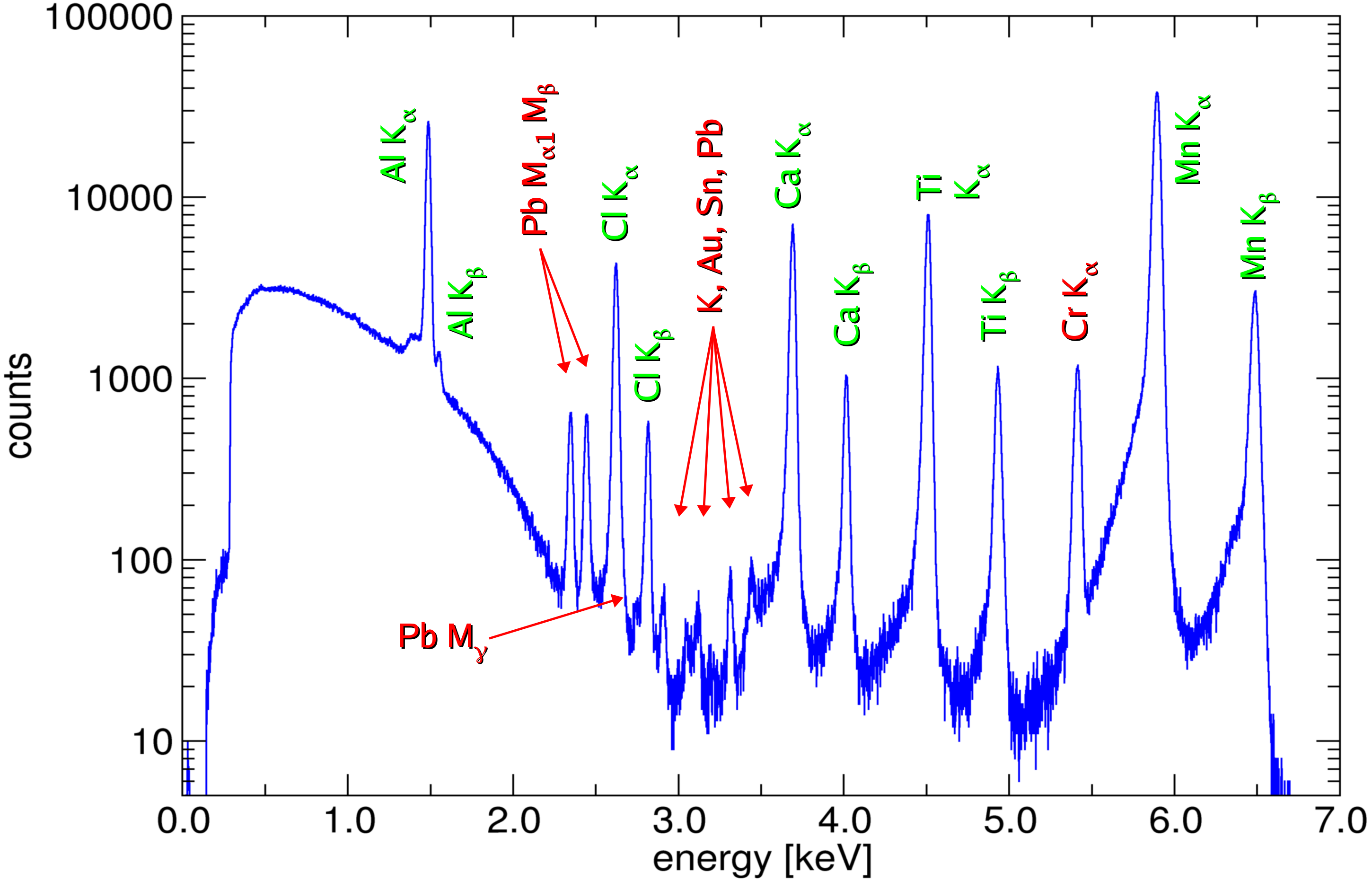
$\Delta E = 1.5$ eV; $f_{pp} = 10^{-6}$; $N_{ev} = 10^{14}$

spectrum calibration accuracy
improves with statistics

technological issue

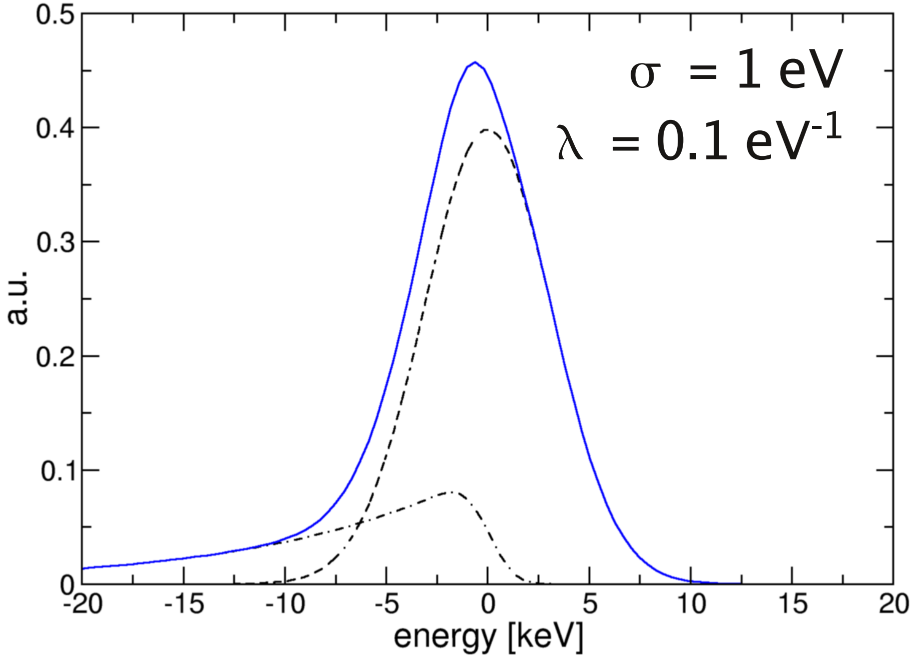
Detector response function

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



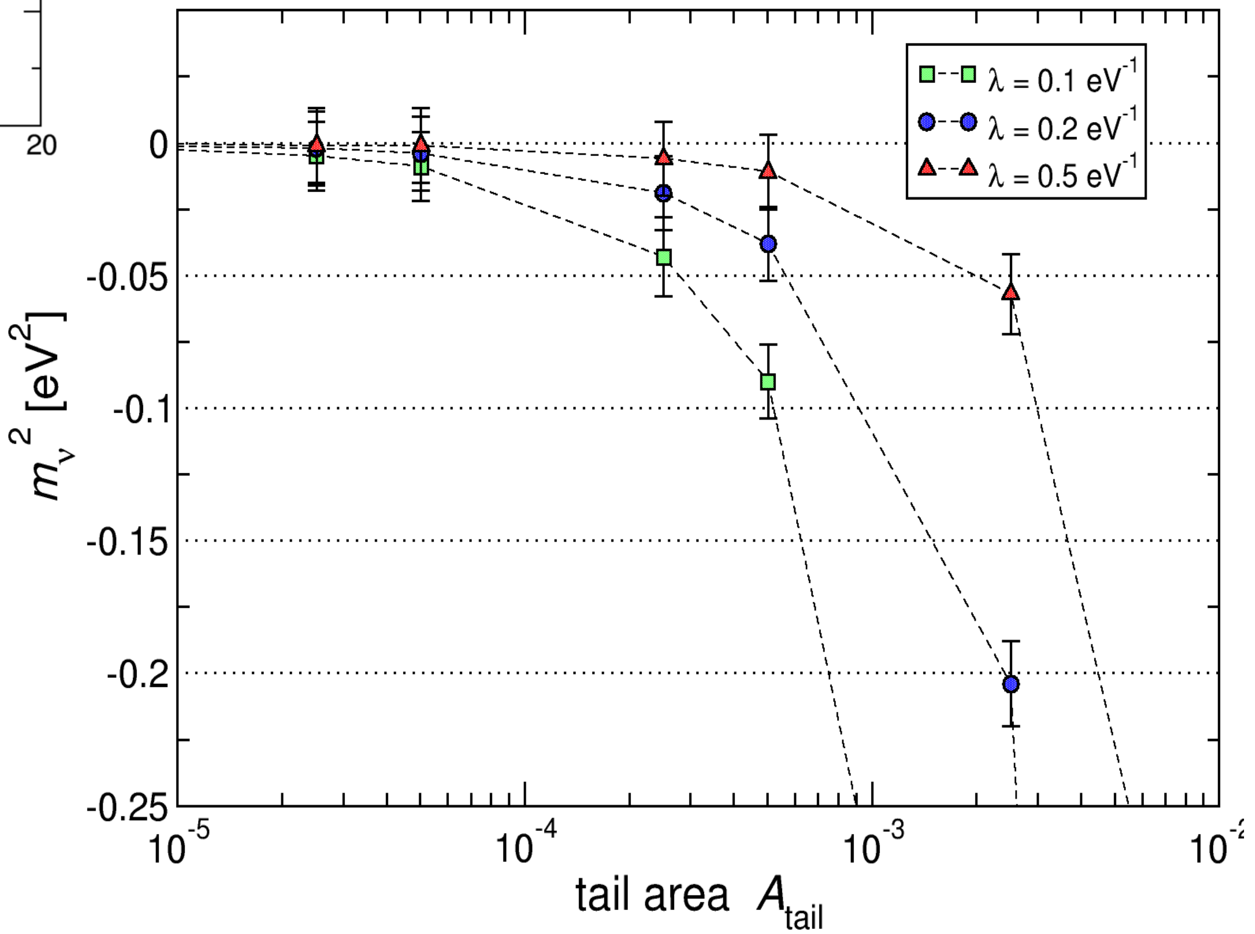
- X-ray peaks have tails on low energy side
- 1~6 keV X-rays in $AgReO_4$ have an attenuation length $\lambda < 2\ \mu m$
  - ► are the response functions for X-rays and for βs from ^{187}Re decay the same?
- need for a good phenomenological description of the X-ray peak shape

Instrumental uncertainties: response function tail

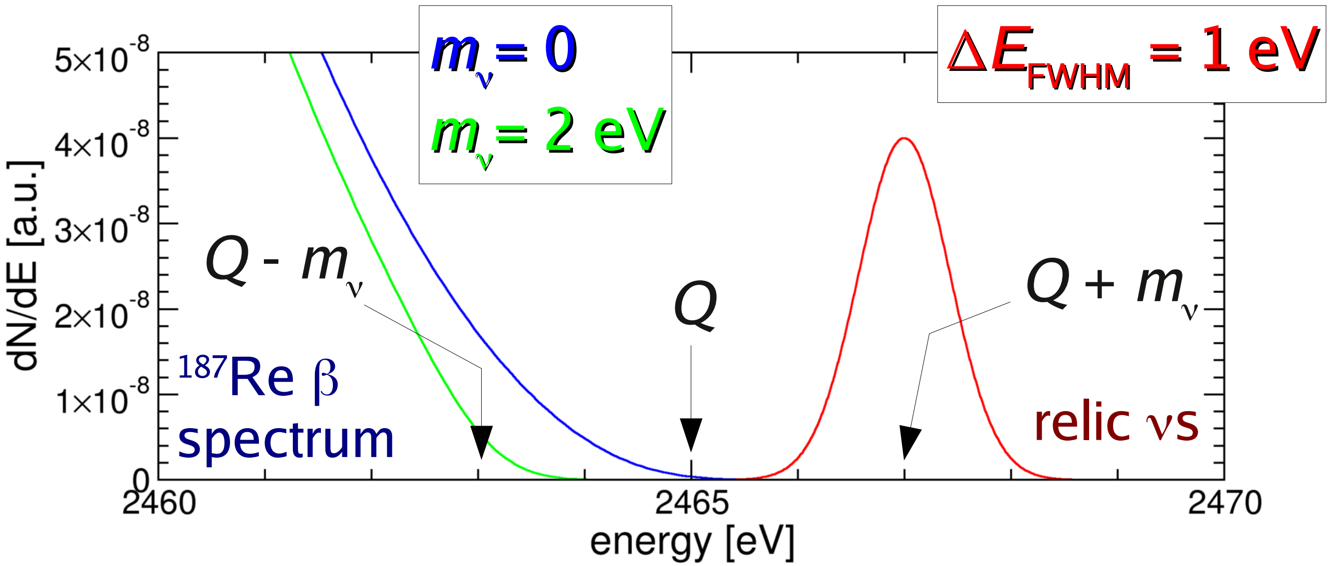


$$T(E)=A_{tail}\frac{\lambda}{2}\exp\left[(E-E_0)\lambda+\left(\frac{\sigma\lambda}{\sqrt{2}}\right)^2\right]\left[1-erf\left(\frac{E-E_0}{\sigma\sqrt{2}}+\frac{\sigma\lambda}{\sqrt{2}}\right)\right]$$

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



calibration statistics



	relic ν_e (CνB)	**isotope mass**	**rate**	**sterile ν_H $m_H = 1$ keV**
$\nu + {}^3H \rightarrow {}^3He + e^-$	$0.08\ y^{-1}\ g^{-1}$	50 μg	$4\times10^{-6}\ y^{-1}$	$200\ \sin^2\theta\ y^{-1}\ g^{-1}$
$\nu + {}^{187}Re \rightarrow {}^{187}Os + e^-$	$9\times10^{-11}\ y^{-1}\ g^{-1}$	1900 g	$2\times10^{-7}\ y^{-1}$	$2\times10^{-7}\ \sin^2\theta\ y^{-1}\ g^{-1}$
$\bar{\nu} + e^- + {}^{163}Ho \rightarrow {}^{163}Dy^*$	$3\times10^{-5}\ y^{-1}\ g^{-1}$	100 μg	$2\times10^{-9}\ y^{-1}$	$2\times10^{-3}\ \sin^2\theta\ y^{-1}\ g^{-1}$