Measuring the electron neutrino mass with bolometer detectors

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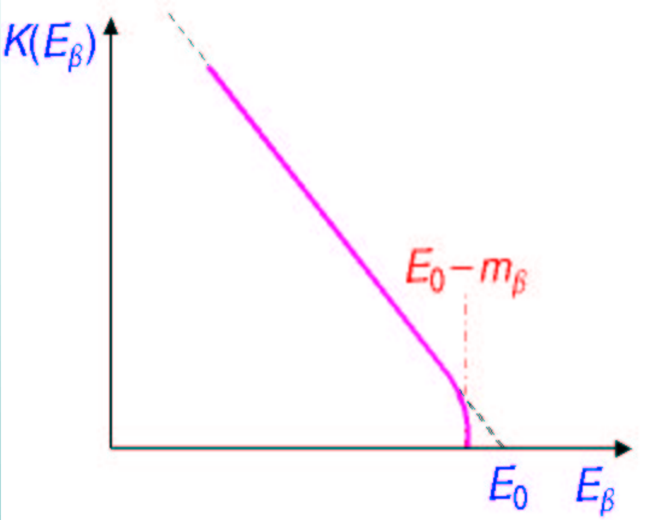
Direct neutrino mass measurement

- neutrino oscillation evidence ⇒ finite m_ν
- neutrino oscillations give only Δm^2
- to fix absolute scale ⇒ study of β decay

kinematics:

- gives electron antineutrino mass
- 2 possible experimental approaches
  - spectrometry (β source ≠ detector)
  - calorimetry (β source ⊆ detector)



- in case of mixing with 3 degenerate neutrinos:

$$m_\beta \equiv \frac{\sum m_i |U_{e\,i}|^2}{\sum |U_{e\,i}|^2}$$

- in case of no mixing:

$$m_\beta \equiv m_{\overline{\nu}_e}$$

calorimeters measure **all the energy released** in the decay except for that carried away by the $\overline{\nu}_e$

due to the **different systematic effects** calorimetric and spectrometric approaches are complementary

Calorimetric approach /1

- **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
    - $\Rightarrow F(\delta E = 10\ \text{eV}) \sim 2\ (\delta E/E_0)^3 = 1.3 \times 10^{-7}$
- **Calorimetry advantages** (in principle)
  - ▲ no backscattering
  - ▲ no energy losses in the source
  - ▲ no atomic/molecular final state effects
  - ▲ no solid state excitation
- **Calorimetry drawbacks**
  - ▼ systematics due to pile-up effects
  - ▼ energy dependent background

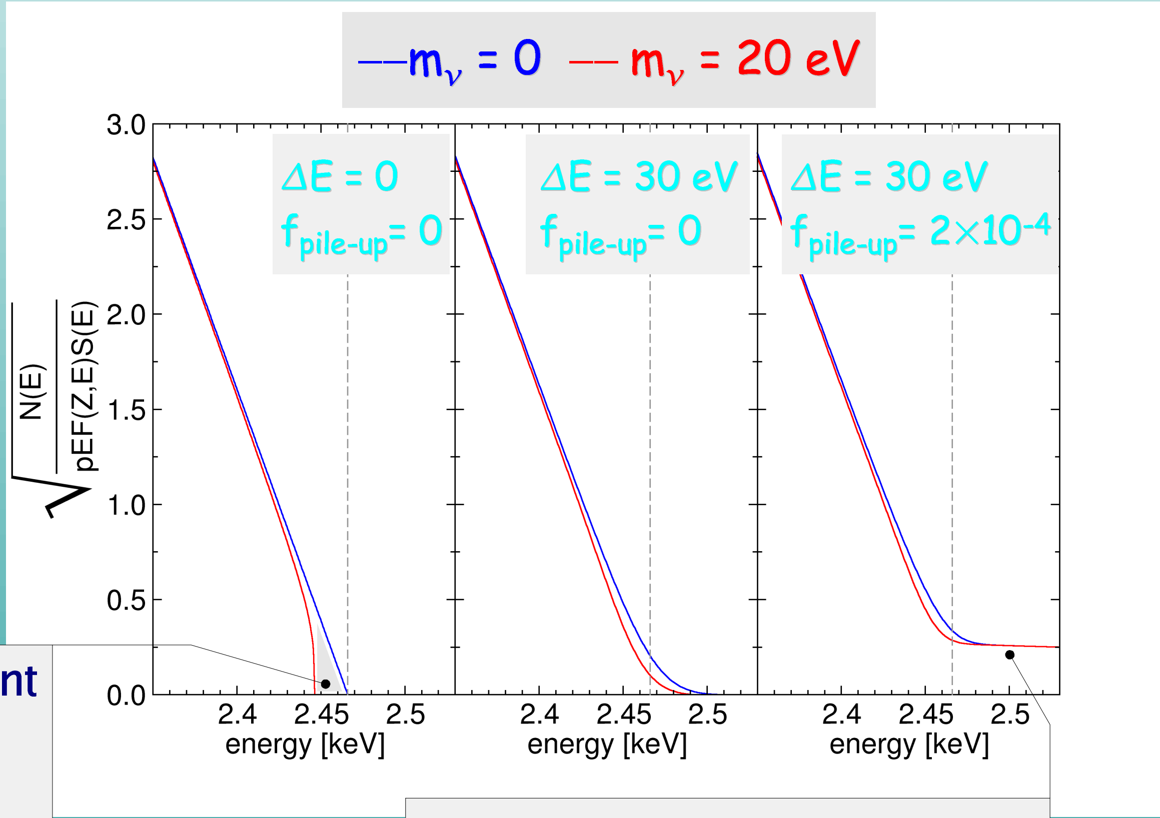
Calorimetric approach /2

Pile-up:

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

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

Pile-up and energy resolution effects:

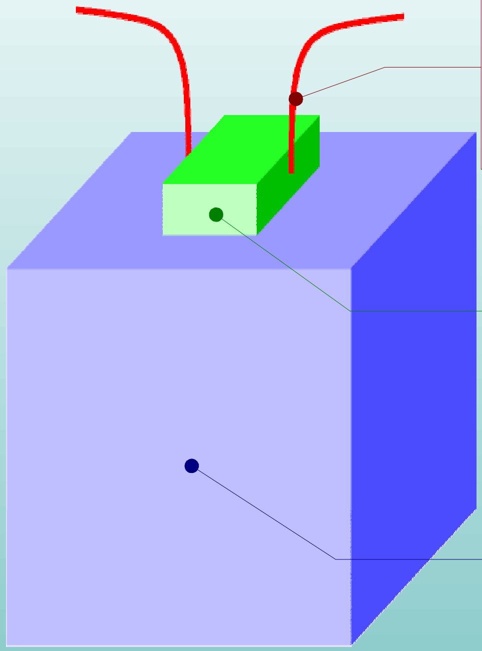


fraction F of decays below the end-point

$$F(\delta E) = \int_{E_0 - \delta E}^{E_0} N(E_\beta, m_{\bar{\nu}_e} = 0)\, dE \approx 2\left(\frac{\delta E}{E_0}\right)^3$$

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

Thermal detectors



Detection principle:

- $\Delta T = E/C$
  C thermal capacity
  - low C
    - low T (i.e. $T \ll 1K$)
    - dielectrics, superconductors
- ultimate limit to energy resolution: statistical fluctuation of internal energy U

$$\langle \Delta U^2 \rangle = k_B T^2 C$$

- example: 1 mg of Si @ 100 mK
  $C \sim T^3$ (Debye) $\Rightarrow C \sim 10^{-13}$ J/K
  6 keV X-ray $\Rightarrow \Delta T \sim 10$ mK
  $\Rightarrow \Delta U \sim 1$ eV

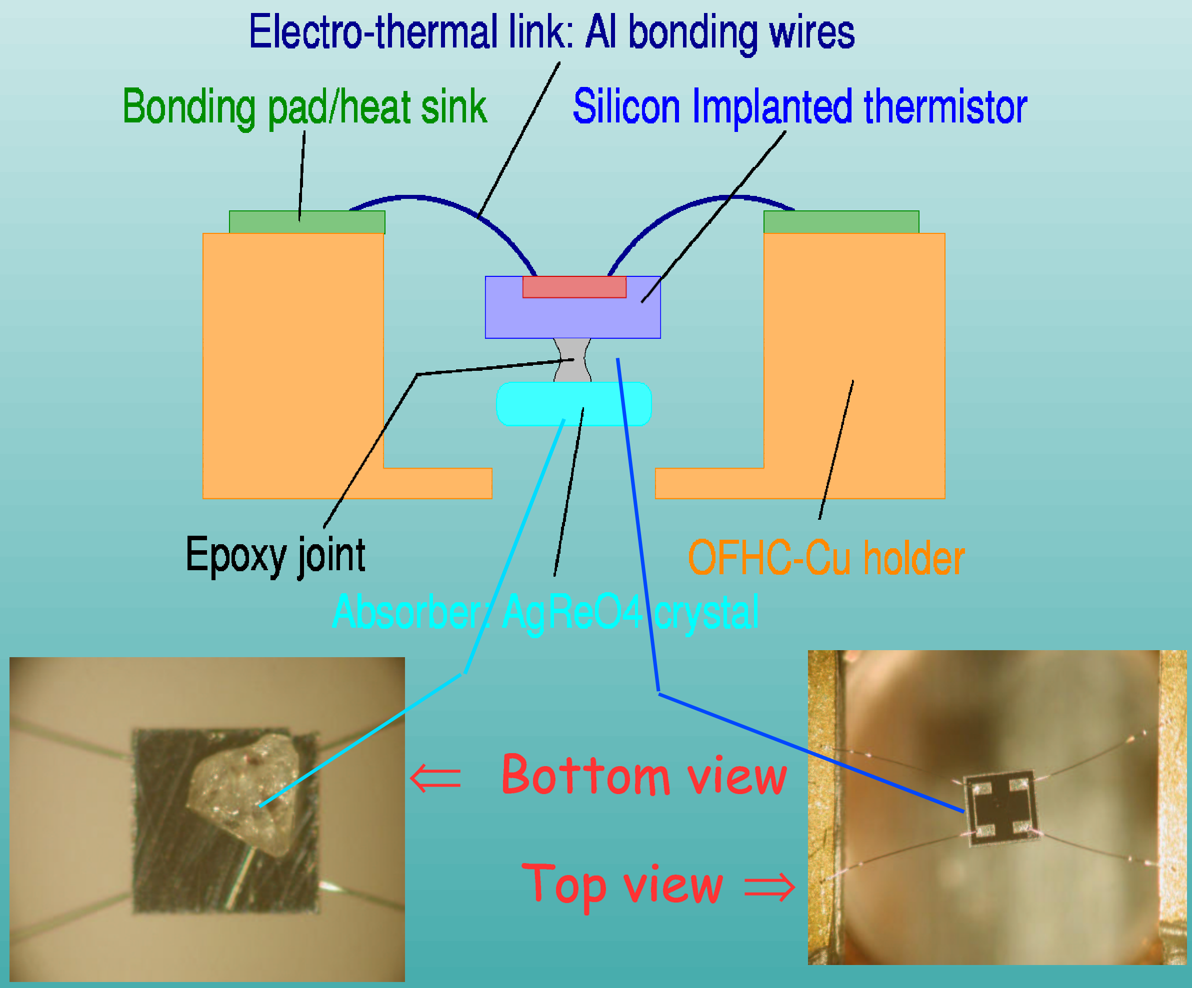
Thermal detector properties

- ▲ high energy resolution
- ▲ large choice of absorber materials
- ▲ true calorimeters
- ▼ slow $\tau = C/G \sim 10^{-1} \div 10^{3}$ ms

Milano μ-calorimeters for ^{187}Re β decay study

Neutrino mass measurement with arrays of 10 $AgReO_4$ μ-calorimeters. ⇨

- lower pile-up
- higher statistics



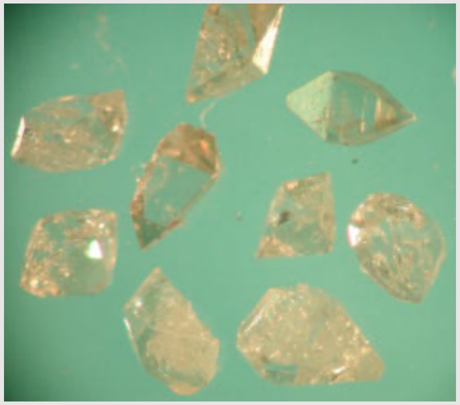
Absorbers

$AgReO_4$ single crystals

^{187}Re fraction ~0.32

$A_\beta \approx 5.4 \times 10^{-4}$ Hz/μg

Mass 250 ~ 300 μg



Measurement statistics and Detector performance

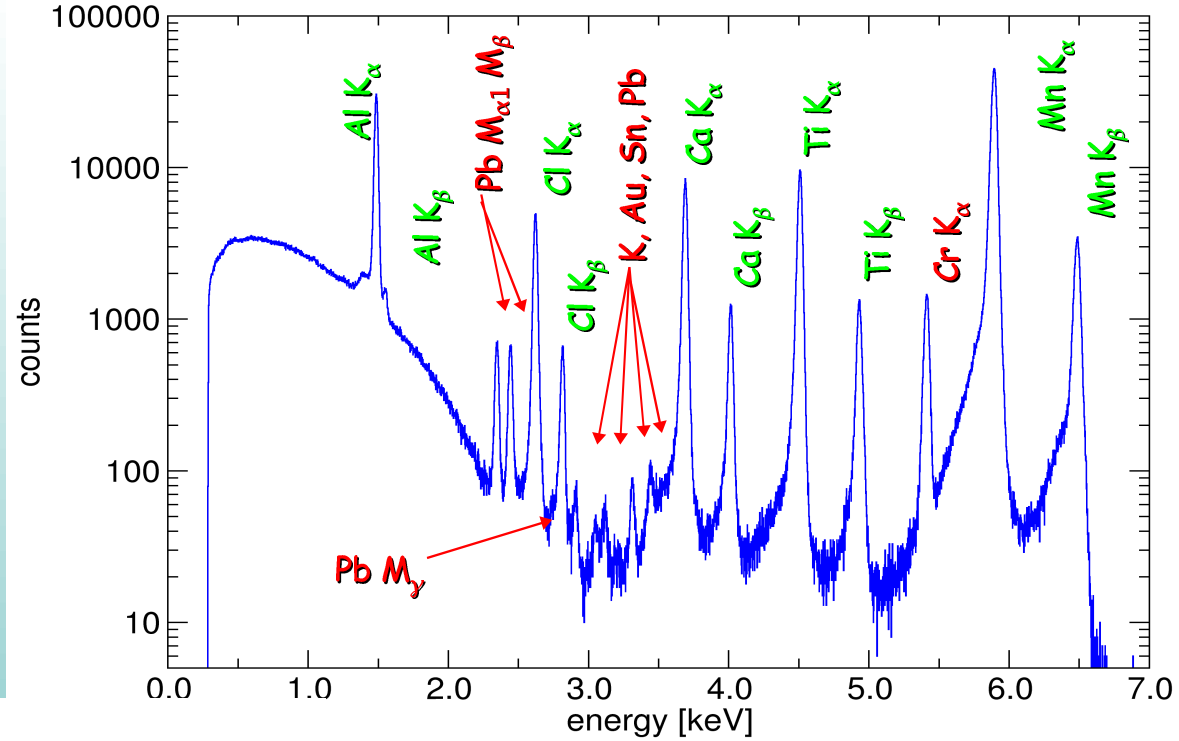
- Measurement started on June 21st 2002 and ended on April 29th 2003
  - ⇨ 313 days of measurement (including daily service to cryostat, test calibrations, ...)
- Total acquired $AgReO_4$ mass: 2.174 mg ⇒ ^{187}Re activity: 1.17 Hz
- total statistics of β decay acquisition: 168 days ➡ "beta acquisition efficiency": 54%
  - ⇨ 8751 hours×mg ($AgReO_4$)
  - ⇨ 16.8×10^6 ^{187}Re decays
- total statistics of calibration (X-ray source open): 42 days ⇨ 2168 hours×mg ($AgReO_4$)
- Total effective measuring time: 210 days ➡ "measurement efficiency": 67%

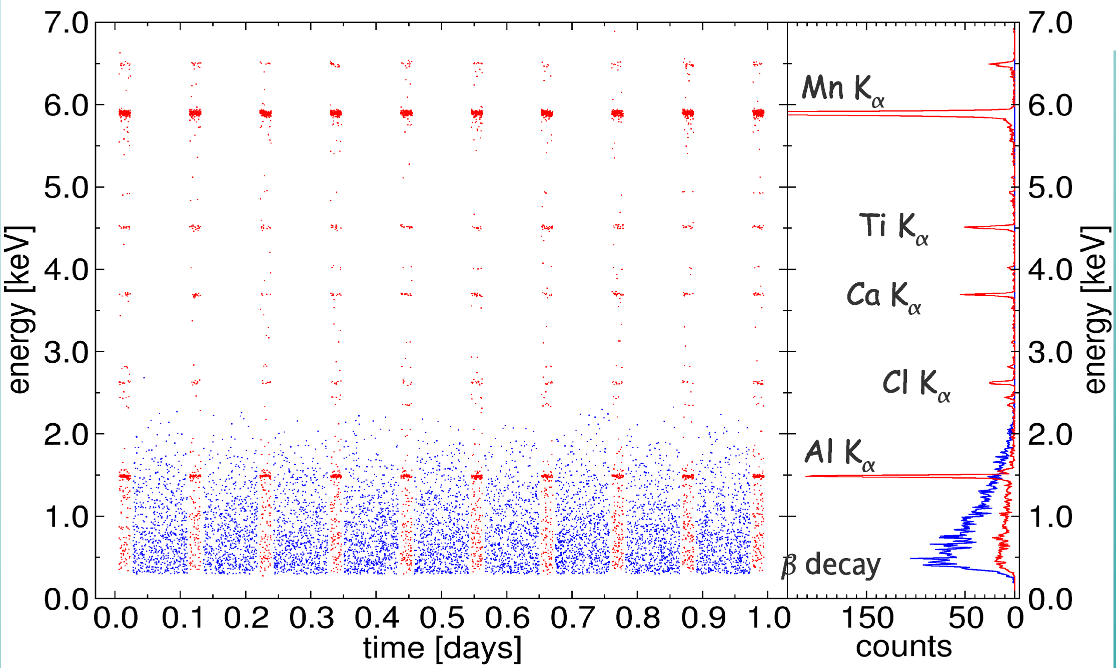
	$AgReO_4$ mass [μg]	T_{op} [mK]	R_{op} [MΩ]	shutter ON [h]	shutter OFF [h]	Beta threshold [eV]	ΔE_{FWHM} baseline [eV]	ΔE_{FWHM} at 1.5 keV [eV]	ΔE_{FWHM} at 2.6 keV [eV]	τ_{rise} [μs]
1	272.0±3.0	104.0	1.3	996.7	4037.2	350	20.1	23.7	26.3	440
2	259.0±6.0	91.3	1.9	991.7	4069.2	350	19.4	23.2	26.6	340
3	280.3±6.5	104.0	1.3	1005.9	4105.2	350	25.8	28.7	30.5	670
4	227.7±3.2							bad perfomances		375
5	249.7±2.0	107.1	1.2	996.3	3803.2	470	21.0	25.4	28.9	590
6	284.0±3.0	86.9	2.2	1006.7	4075.2	350	22.5	25.7	29.2	500
7	281.0±3.7							broken crystal		370
8	282.0±3.4	72.2	4.0	1013.9	4106.4	400	24.6	29.3	33.4	510
9	268.7±5.9	96.7	1.6	981.5	4017.1	400	18.4	21.3	24.9	430
10	278.3±1.5	101.3	1.4	981.9	3967.1	700	23.9	29.2	34.5	445
			TOT:	7974.65	32180.7		21.9	25.5	29.1	
							Array summed spectrum			

Calibration spectra

7975 hours×detector with fluorescence source open

a typical single channel one-day measurement ➘

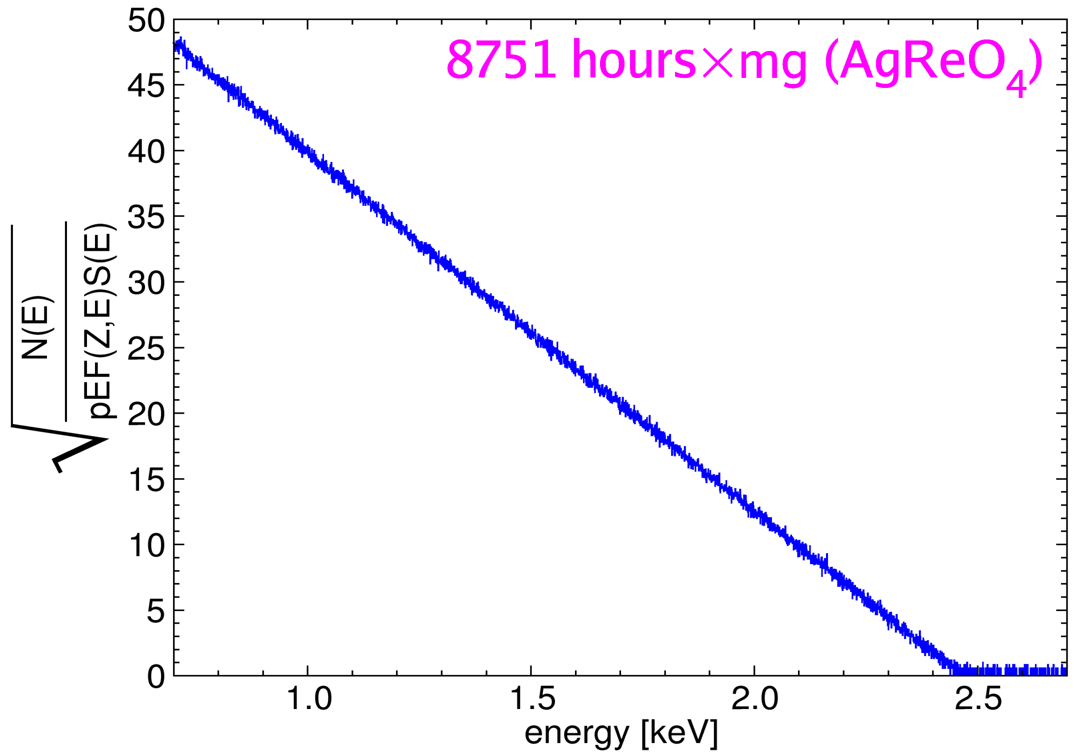




- many extra peaks due to fluorescence of surrounding materials
- Cl K_α position nominal position ($E_{Cl\ K\alpha}$=2.6217 keV) missed by 0.3 eV

^{187}Re β spectrum – summed Kurie plot

- 6.2×10^6 ^{187}Re decays collected above 700 eV
- Fit with the function: $F = (f_{th}+f_{pup}+f_{bck}) \otimes f_{det}$
  - f_{th} ➞ theoretical spectrum
  - $f_{pup} \propto f_{th} \otimes f_{th}$ ➞ pile-up spectrum
  - f_{bck} ➞ background spectrum
  - f_{det} ➞ detector response function



Free fit parameters:

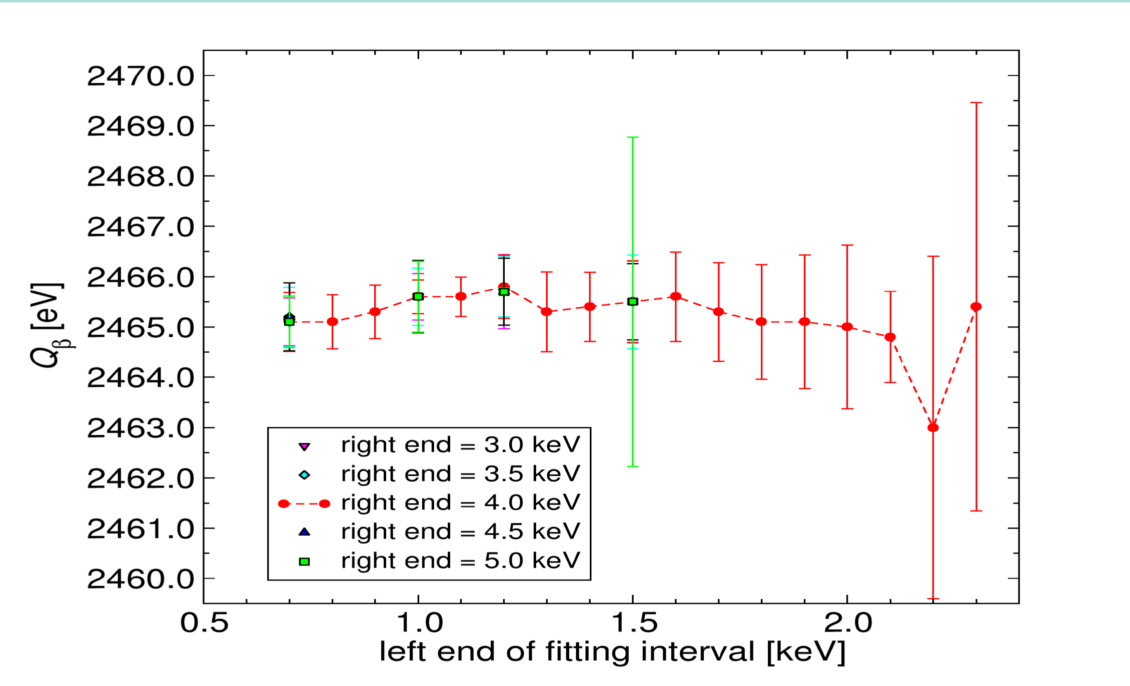
- β end-point
- m^2_ν
- β spectrum normalization
- pile-up spectrum normalization
- background level

^{187}Re end-point energy

$$Q = 2465.3 \pm 0.5_{stat} \pm 1.6_{sys}\ \text{eV}$$

Fitting interval: 0.9 ÷ 4 keV

➔ *Most precise value for ^{187}Re*



Systematic errors come from uncertainties in:

- ✓ theoretical function for ^{187}Re decay;
- ✓ detector response function and energy resolution;
- ✓ background shape below the β spectrum.

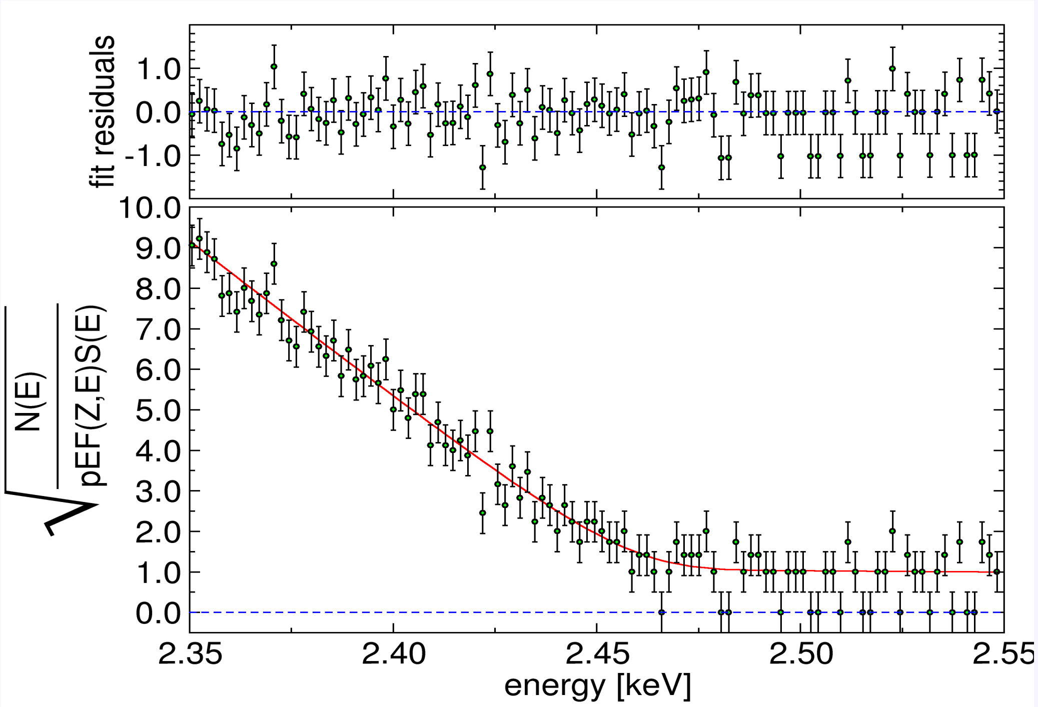
⤷ Q value is stable with respect to fitting interval ⇨ good description by fit function F

Neutrino mass

$m_\nu^2 = -112 \pm 207_{stat} \pm 90_{sys}\ eV^2$

⇓

$m_\nu < 15$ eV (90 % C.L.)



Fitting interval: 0.9 ÷ 4 keV

- gaussian response function with ΔE_{FWHM} = 28.5 eV
- free constant backg.: 7×10^{-3} c/keV/h
  ⇨ S/N (Q–30 eV ÷ Q) ~ 12
- free pile-up fraction $f_{pile\text{-}up}$: 1.9×10^{-4}
  ⇨ χ^2/d.o.f. = 0.905

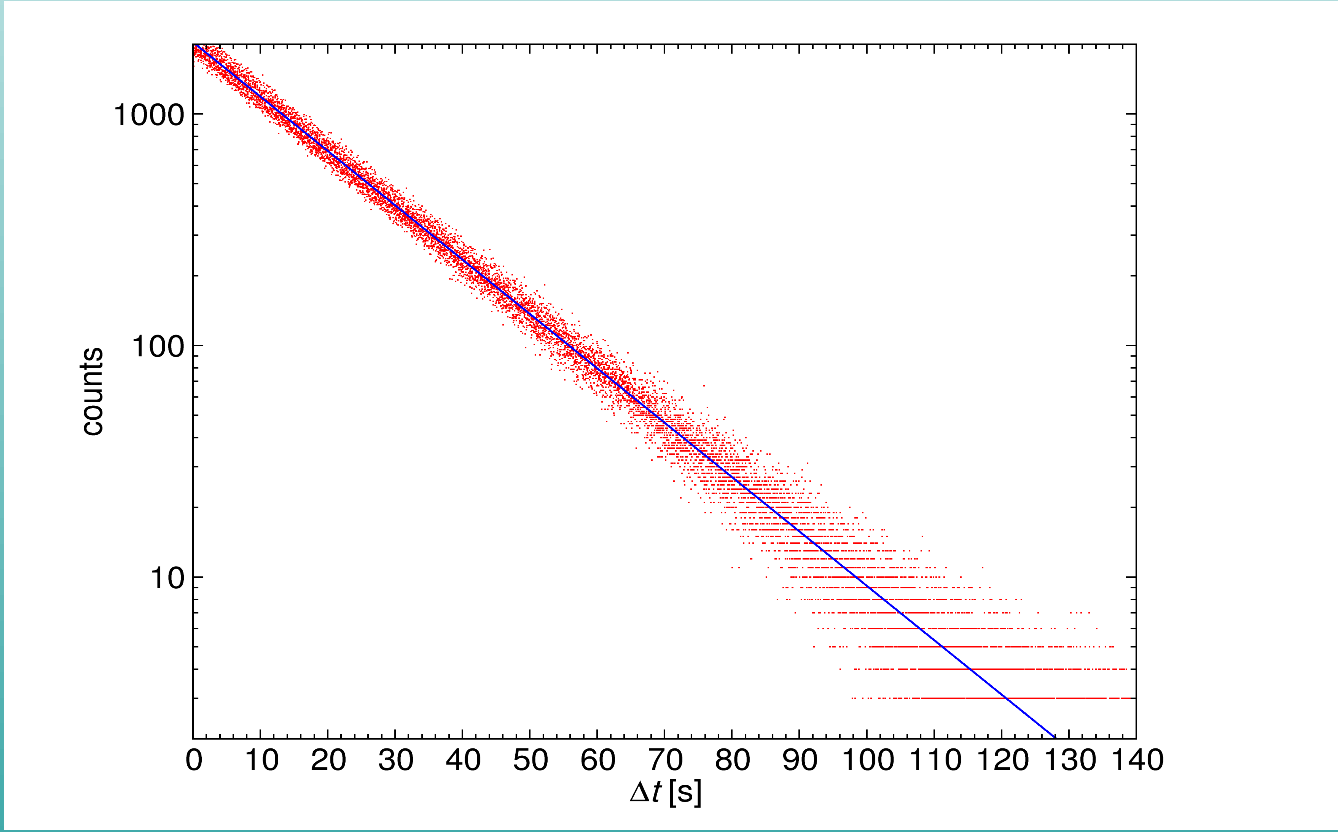
➡ same sources of systematics as for the end-point

Preliminary results on a smaller data set in:
C.Arnaboldi et al., Phys. Rev. Letters 91 (2003) 161802

^{187}Re half lifetime

$$\tau_{1/2} = 43.2 \pm 0.2_{stat} \pm 0.1_{sys}\ Gy$$

- from distribution of time intervals Δt between ^{187}Re β decays
- statistical error mainly from uncertainties in the masses
- systematic error mainly from uncertainties in the pile-up discrimination
  - ⇨ most precise published value; especially relevant for geochronology



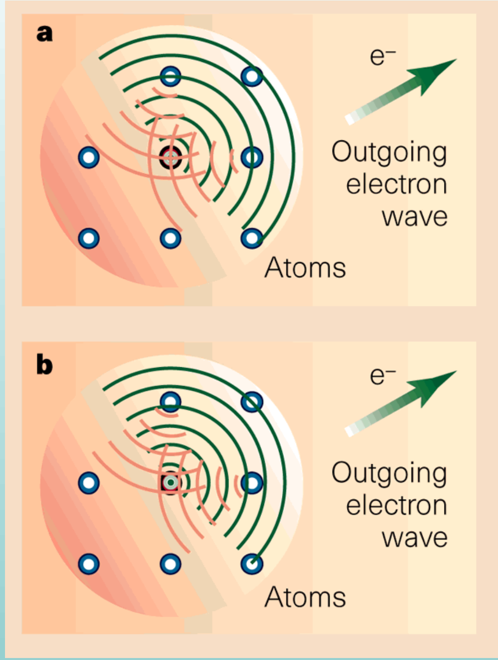
$N(\Delta t) = A\, e^{-r\,\Delta t}$

$r \equiv \beta$ decay rate

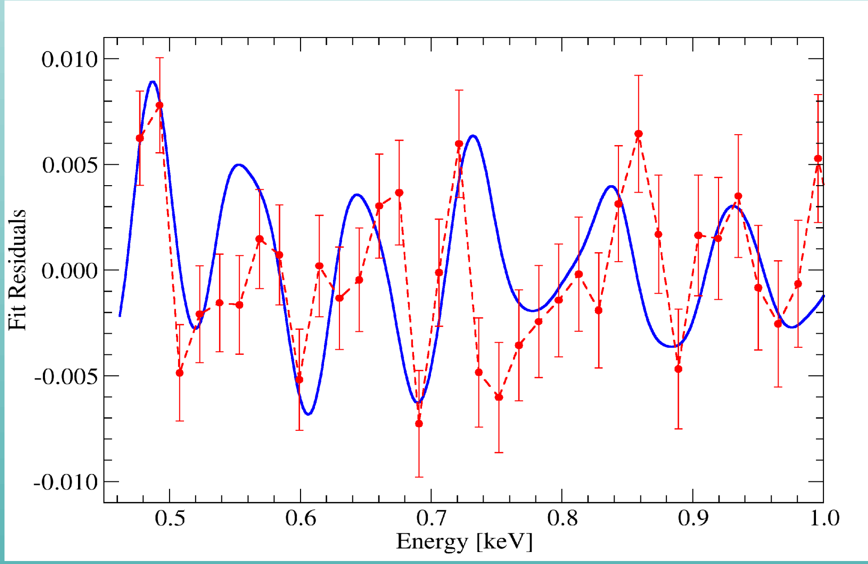
$r \propto 1 / \tau_{1/2}$

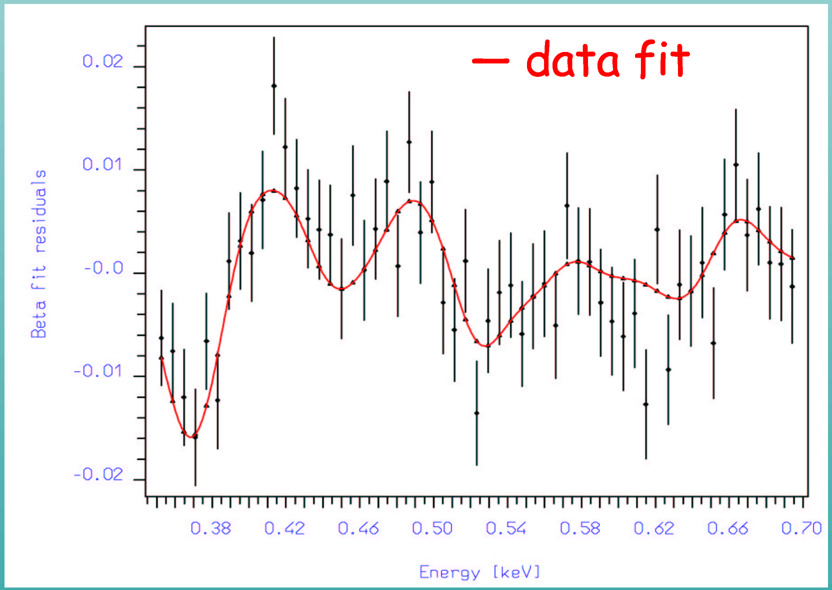
Beta Environmental Fine Structure (BEFS)

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



BEFS experimental evidence in $AgReO_4$





↳ analysis still in progress ...

Future strategy

an experiment for the measurement of m_ν with an approach other than the spectrometric one is important

phase I: experiment that reaches a sensitivity of **≈ 2 eV** before the end of Katrin experiment

phase 2: experiment with a sensitivity similar to that of Katrin **≈ 0.3 eV**

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Katrin					0.3 eV						
phase I					2 eV						
phase II (?)									0.3 eV		

phase I is needed:

- because it's the only possible one with present technology
- to check systematics

$$\Sigma(m_{\bar{\nu}_e}) \propto \sqrt[4]{\frac{E_0^3 \Delta E}{A_\beta t_M}} \propto \sqrt[4]{\frac{1}{N_{eventi}}}$$

m_ν sensitivity estimation by Montecarlo method

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
- $f_{pile\text{-}up} \approx \Delta t \times A_\beta$ pile-up event fraction
  - $\Delta t \approx 3\tau_{rise}$ time resolution for pile-up identification
- $g(E)$: gaussian energy resolution function
  - ΔE FWHM detector energy resolution

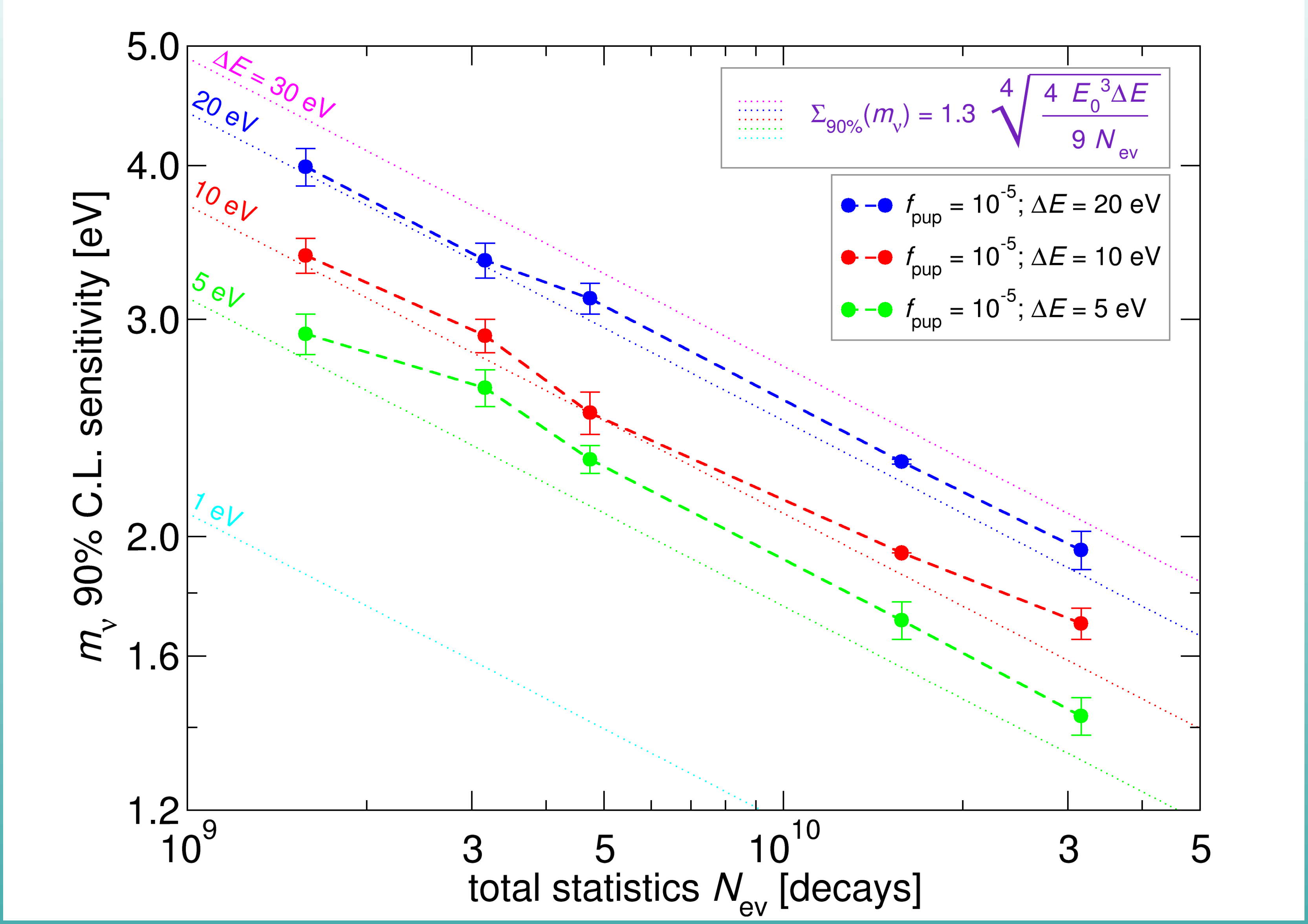
experiment

N_{det}	8
t_M [y]	0.59
$\langle A_\beta \rangle$ [dec/s]	0.15
$\langle m_{AgReO_4} \rangle$ [μg]	271
N_{ev} [$\times 10^6$]	16.7
$\langle \tau_{rise} \rangle$ [μs]	490
$\langle \Delta E \rangle$ [eV]	28.5
$\langle b \rangle$ [c/keV/det]	26.3
m_ν 90% CL limit [eV]	15

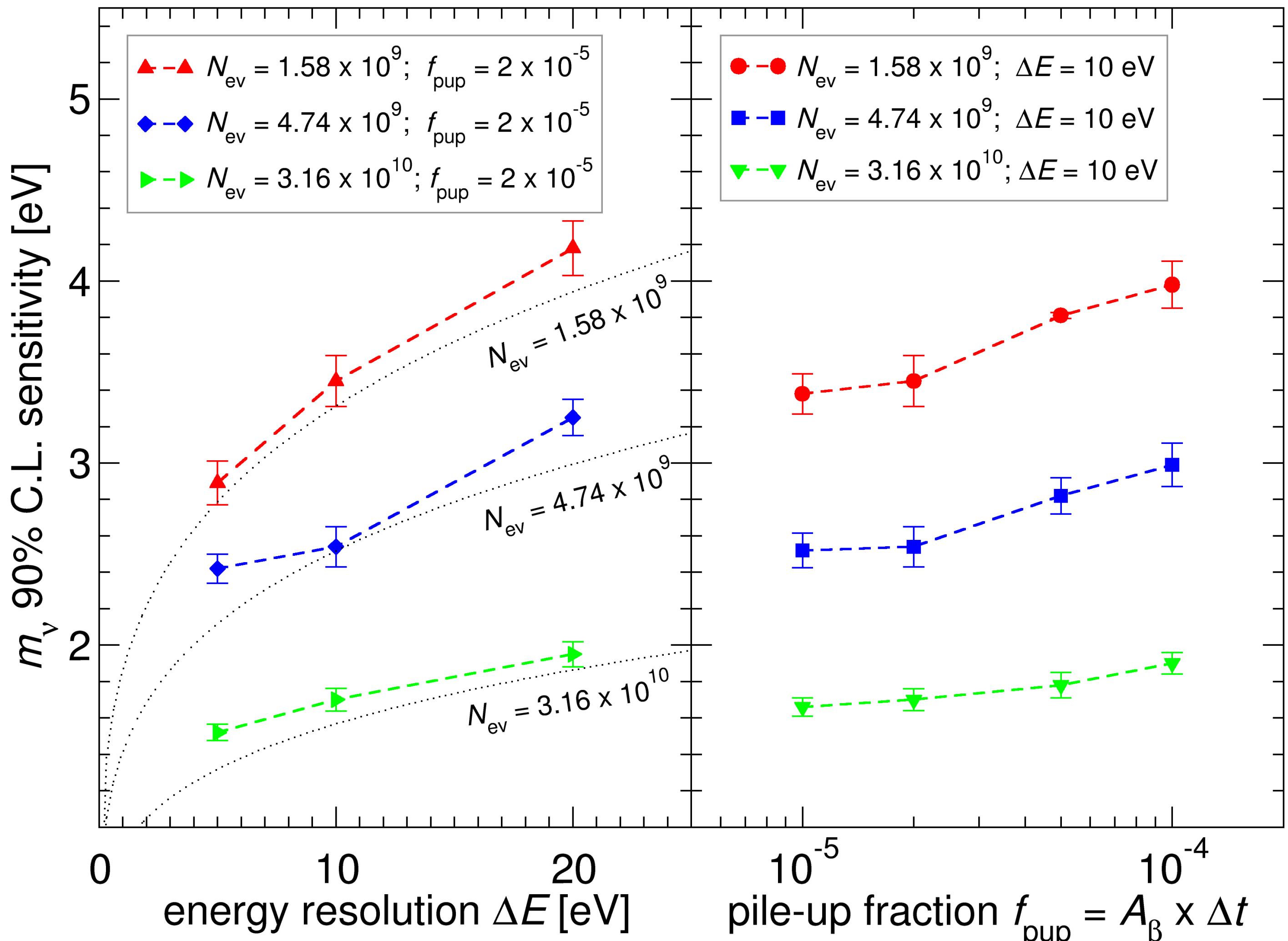
MC simulation

N_{ev} [$\times 10^6$]	17
$f_{pile\text{-}up}$	2×10^{-4}
ΔE [eV]	29
b [c/keV]	210
m_ν 90% CL limit [eV]	16±1

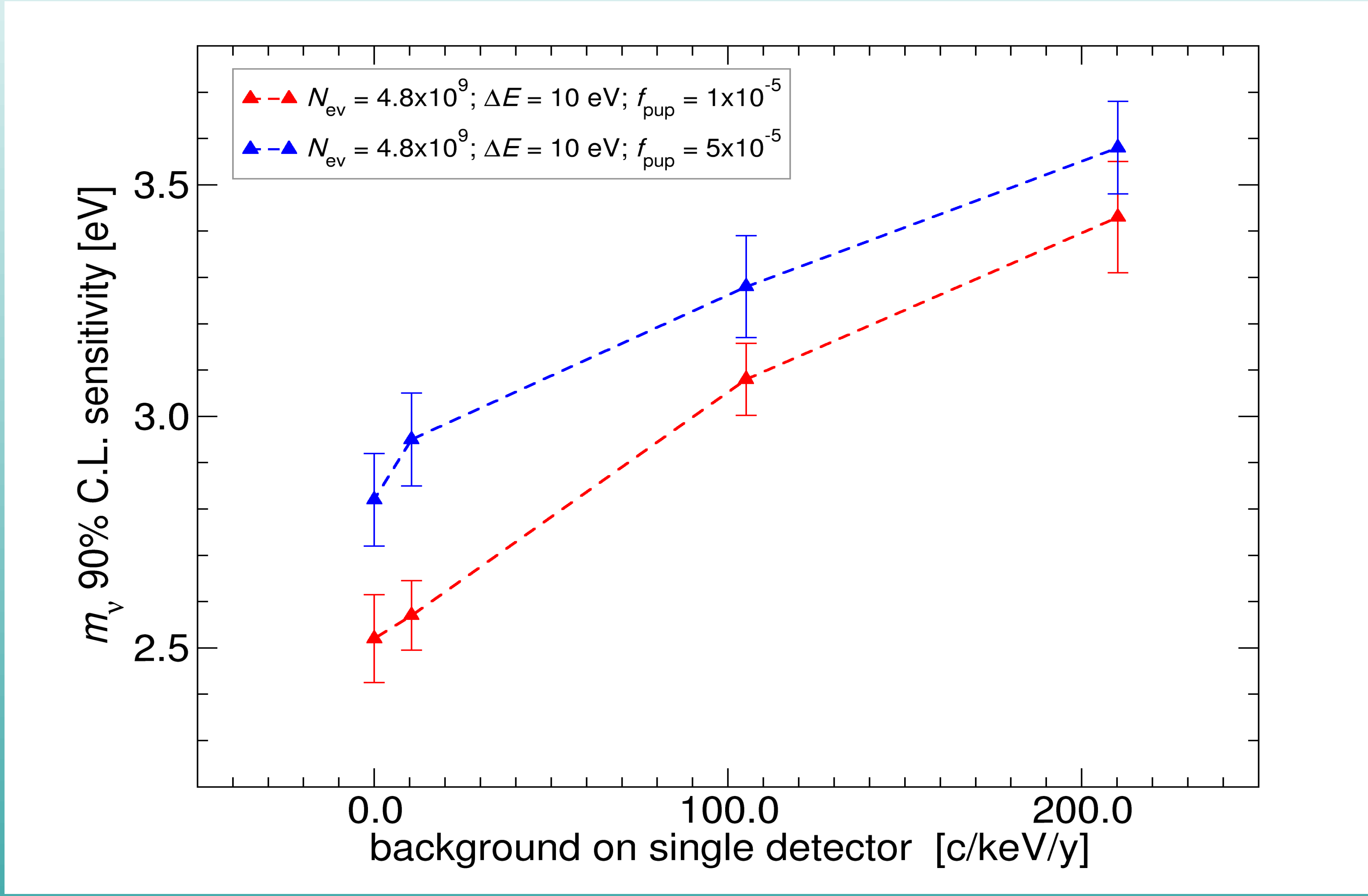
m_ν sensitivity vs. statistics



m_ν sensitivity vs. energy resolution
m_ν sensitivity vs. time resolution



m_ν sensitivity vs. background



Phase I: experimental configuration

Montecarlo input parameters			90% CL sensitivity	Possible experimental configurations			
N_{ev} [$\times 10^9$]	$f_{pile\text{-}up}$ [$\times 10^{-5}$]	ΔE [eV]	m_ν [eV]	N_{det}	t_M [y]	$\langle A_\beta \rangle$ [dec/s]	$\langle \Delta t \rangle$ [μs]
1.4	2.0	10	3.5	100	2	0.20	100
3.2	2.5	10	3.0	200	2	0.25	100
4.7	2.5	10	2.5	200	3	0.25	100

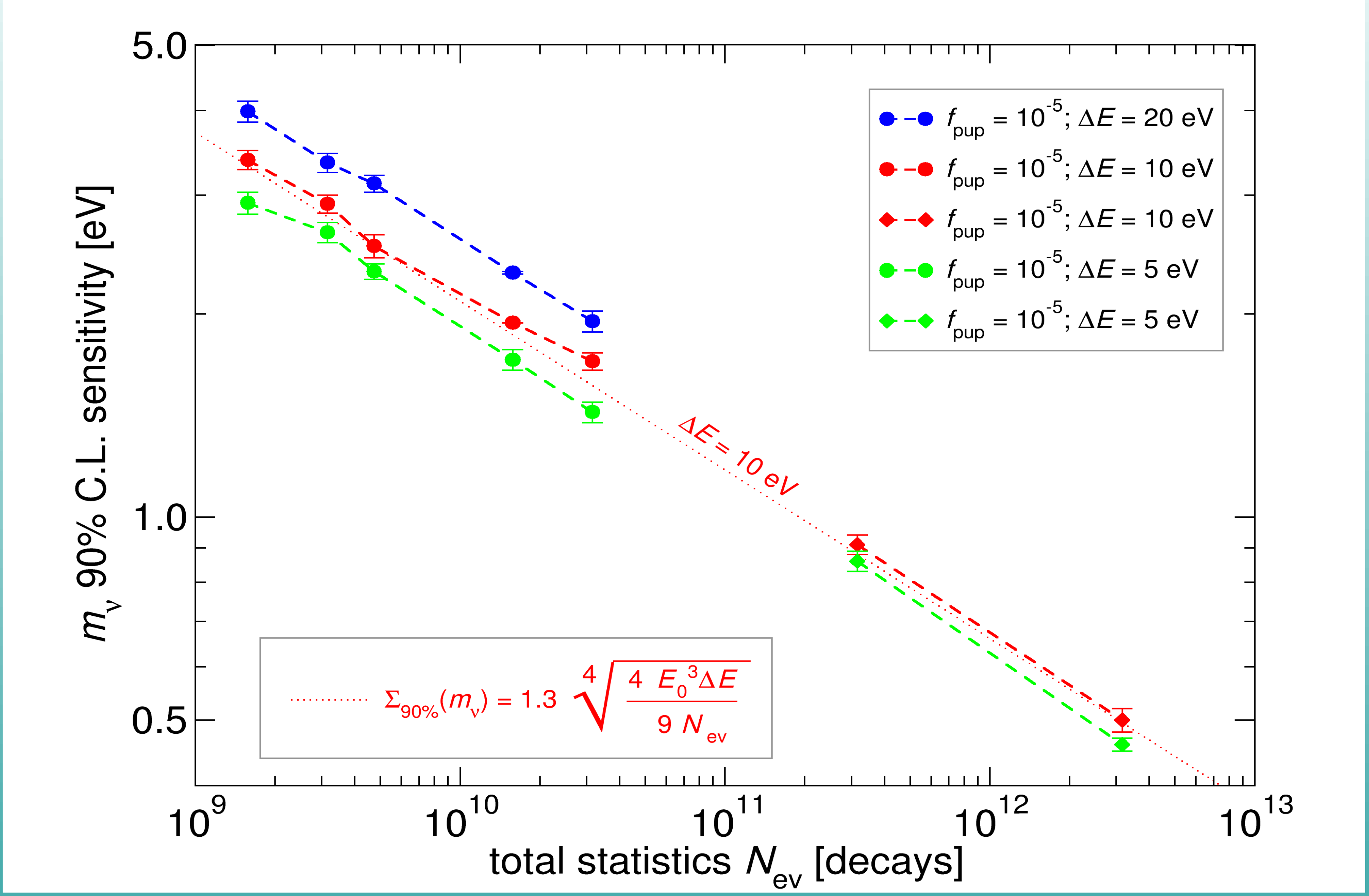
our present μcalorimeters

- $m_{AgReO4} = 250 \div 285\ \mu g$
  - $\langle m_{AgReO4} \rangle = 270\ \mu g$
  - $\langle A_\beta \rangle = 0.15$ Hz
- $\tau_R = 340 \div 670\ \mu s$
  - $\langle \tau_R \rangle = 490\ \mu s$
- $\langle f_{pup} \rangle = \langle \Delta\tau \cdot A_\beta \rangle = 2\times 10^{-4}$
  - $\Delta\tau \approx 3 \cdot \tau_R \approx 1 \div 2$ ms
- $\Delta E_{FWHM} = 24 \div 34$ eV
  - $\langle \Delta E_{FWHM} \rangle = 28$ eV

required μcalorimeters

- $A_\beta = 0.25$ Hz
  - $m_{AgReO4} = 460\ \mu g$
- $\langle f_{pup} \rangle = \langle \Delta\tau \cdot A_\beta \rangle = 2.5\times 10^{-5}$
  - $\Delta\tau \approx 3 \cdot \tau_R = 100\ \mu s$
- $\Delta E_{FWHM} = 10$ eV

Phase II: m_ν sensitivity vs. statistics



Phase II: possible experimental configurations

Montecarlo input parameters			90% CL sensitivity	Possible experimental configurations			
N_{ev}	$f_{\text{pile-up}}$ [$\times 10^{-4}$]	ΔE [eV]	m_ν [eV]	N_{det}	t_M [y]	$\langle A_\beta \rangle$ [dec/s]	$\langle \Delta t \rangle$ [μs]
3.2×10^{10}	1.0	5	1.7	500	2	1	100
3.2×10^{12}	1.0	5	0.5	1000	10	10	10
3.2×10^{13}	1.0	5	0.3	1000	10	100	1

- goal: be an alternative to the KATRIN experiment
- conditions to meet to go for phase II:
  - phase I must be successful
    - no unexpected source of systematics
  - a very large collaboration is needed
  - really innovative techniques are required
- phase II results would come much later than the KATRIN experiment
  - it must be also considered that KATRIN could fail

Conclusions

✔ Bolometric detectors, even if relatively young, are giving interesting and competitive scientific results (e.g. double beta decay, dark matter, etc.)

✔ Calorimetric technique for the direct measurement of the neutrino mass is an appealing complementary approach

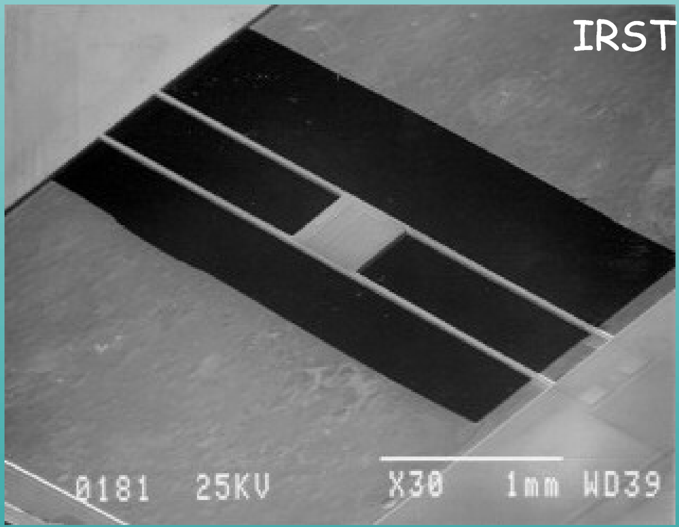
✔ The Milano neutrino mass experiment with microbolometers has set un upper limit of 15 eV on m_ν after less than 1 year of continuous running

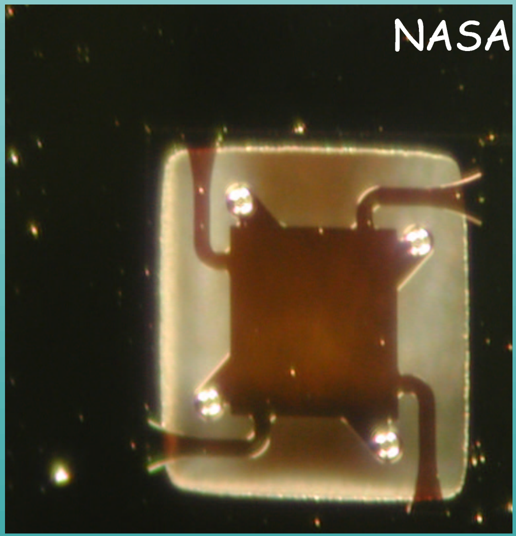
✔ A new experiment to improve this limit is now starting the R&D phase

more info at http://crio.mib.infn.it/wig

Phase I R&D

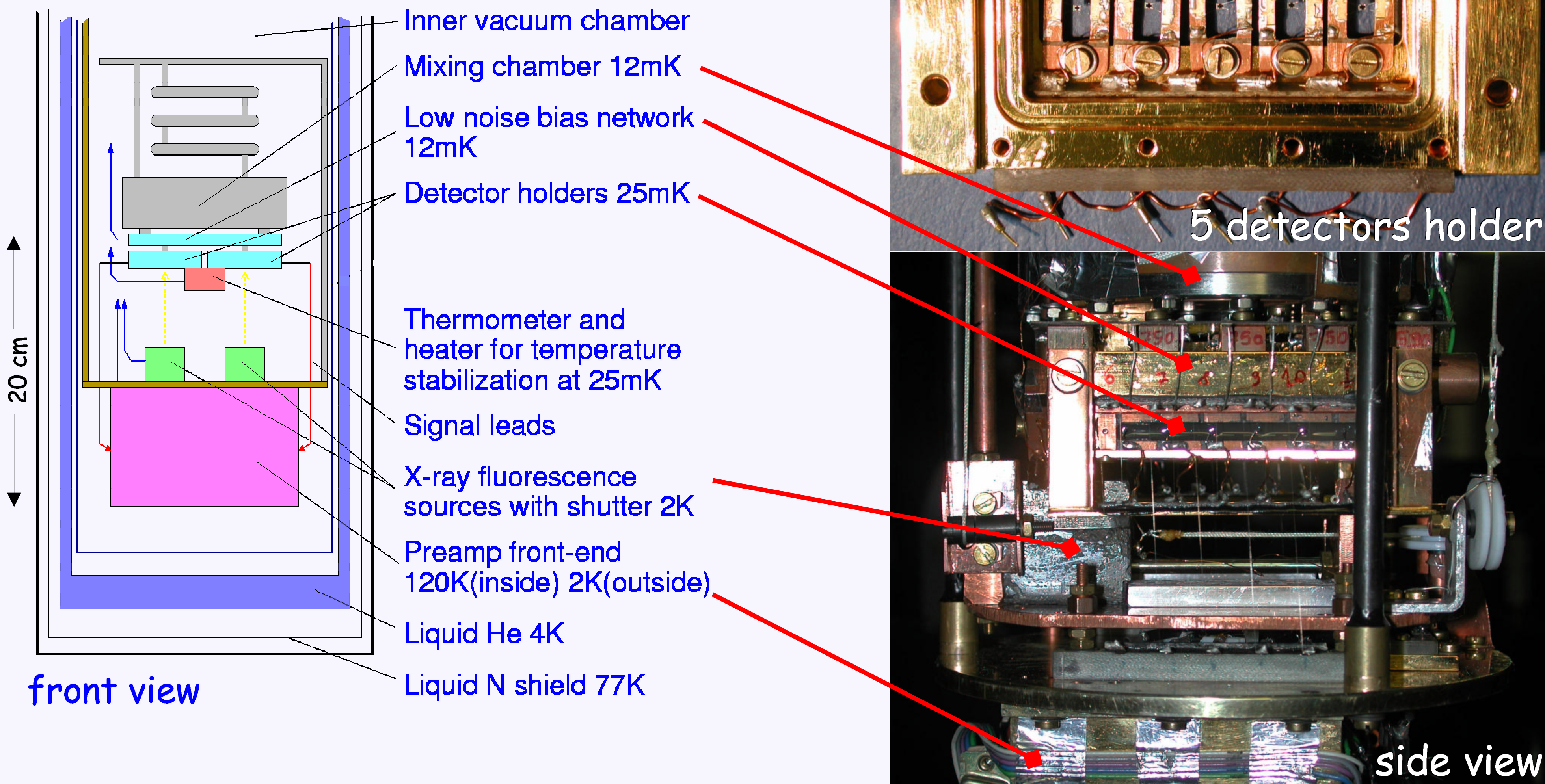
- apply and improve silicon micromachined devices (collaboration with **IRST** and **NASA/Wisconsin** groups)
- optimize implant doping and geometry
- improve $AgReO_4$ crystal quality
- optimize and standardize crystal-thermistor coupling
- improve electronic cryogenic front-end with new JFETs and new design
- develop new gain stabilization techniques
  - 200 hundred microcalorimeters array
  - single detector absorber mass increased to 450 μg
  - energy resolution ΔE_{FWHM} improved to 10 ÷ 15 eV
  - time resolution $\Delta\tau$ improved to 0.2 ÷ 0.1 ms



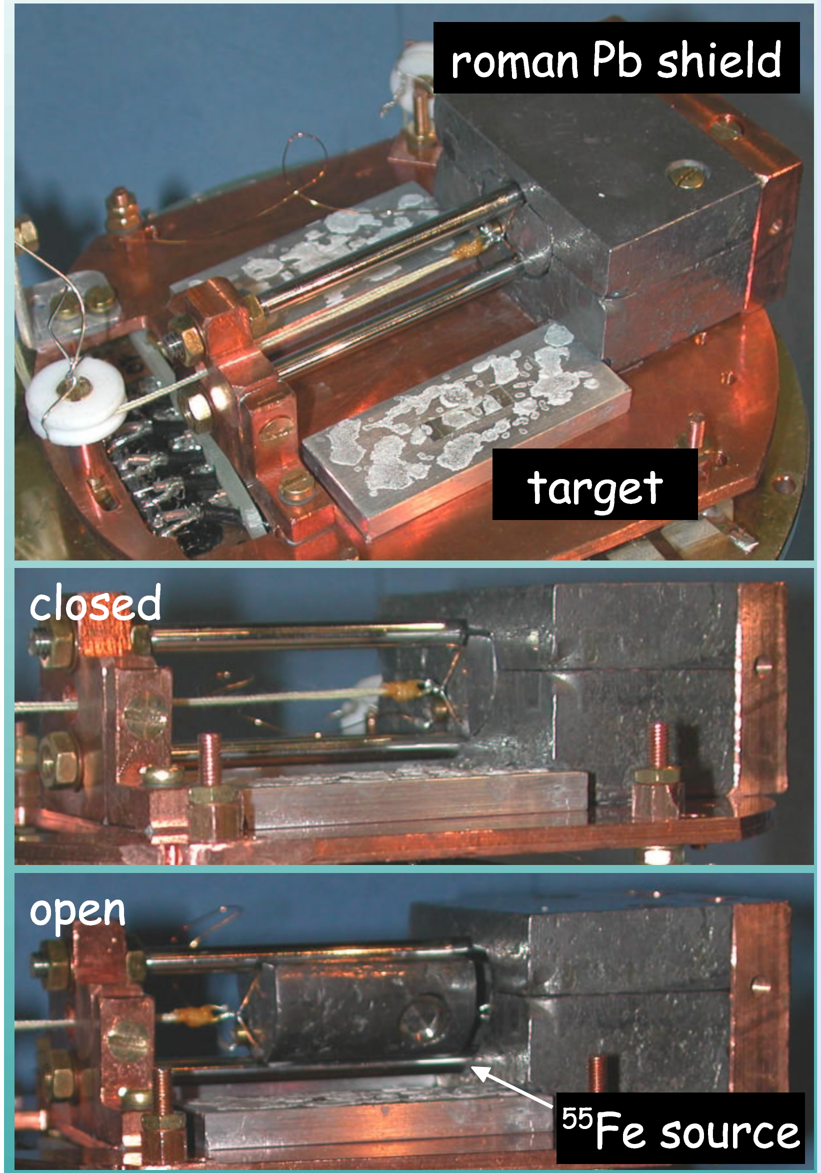


Experimental set-up

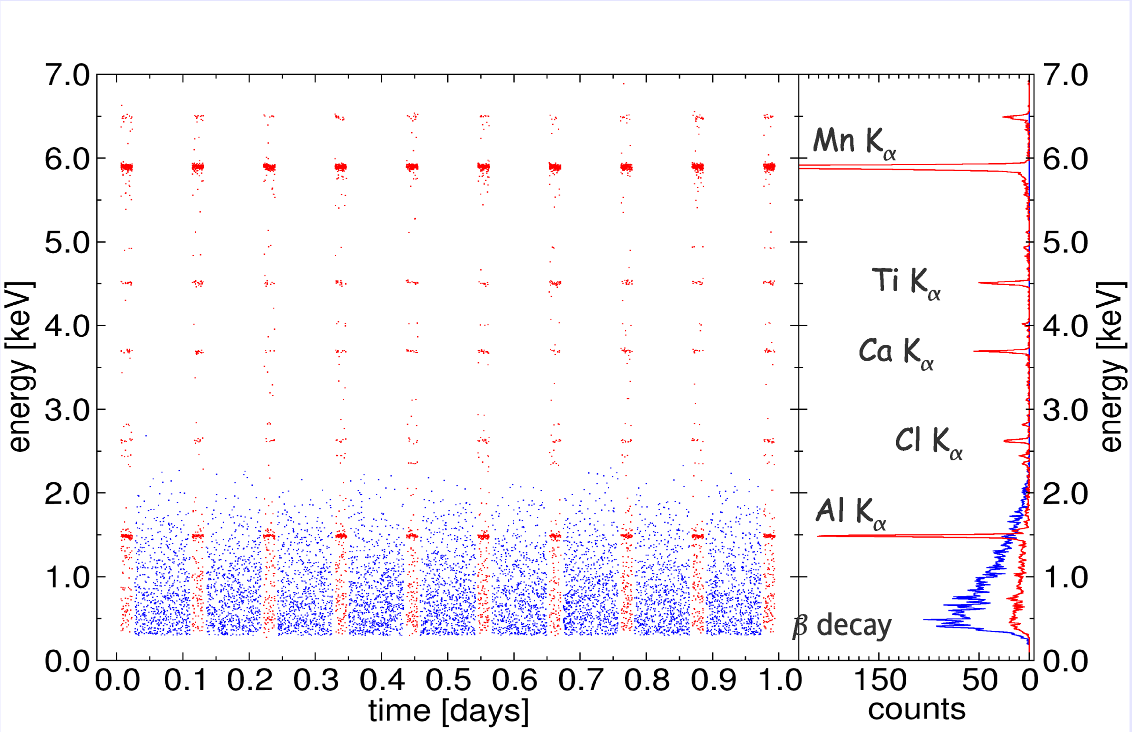
Dilution refrigerator set-up for 10 detector experiment



X-ray fluorescence source for periodic calibration

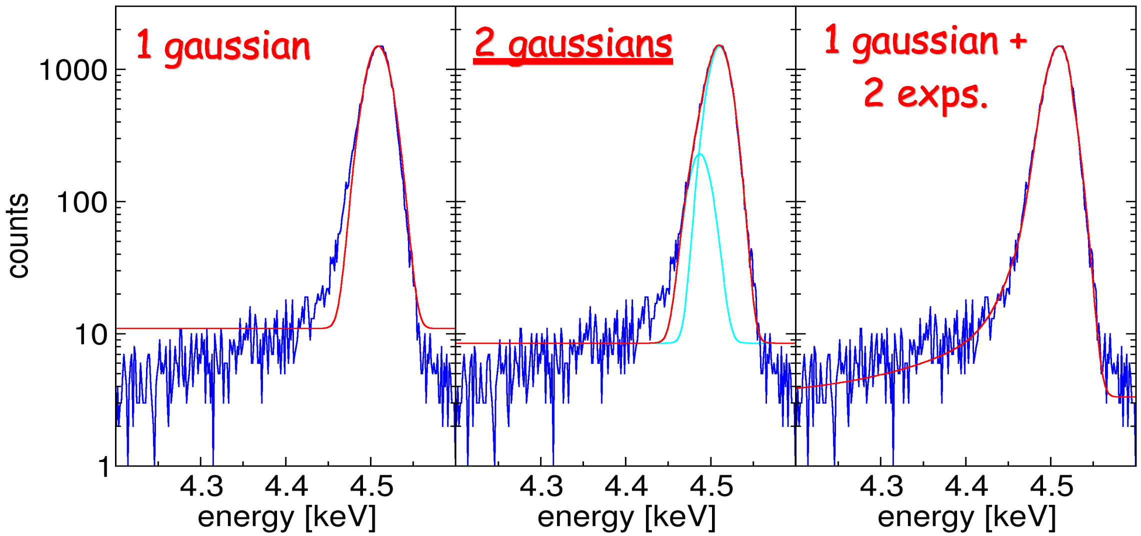


- remotely controlled for continuous stability control
  → 1 cycle: 25 minutes open, 2 hours closed
- primary sources: $2\times{}^{55}$Fe 5 mCi
- roman lead to shield ^{55}Fe Inner-Bremsstrahlung
- fluorescence target:
  - Al K_α → 1.5 keV
  - Cl K_α → 2.6 keV
  - Ca K_α → 3.7 keV
  - Ti K_α → 4.5 keV



Detector response function

- are the response functions for X-rays and for βs from ^{187}Re decay the

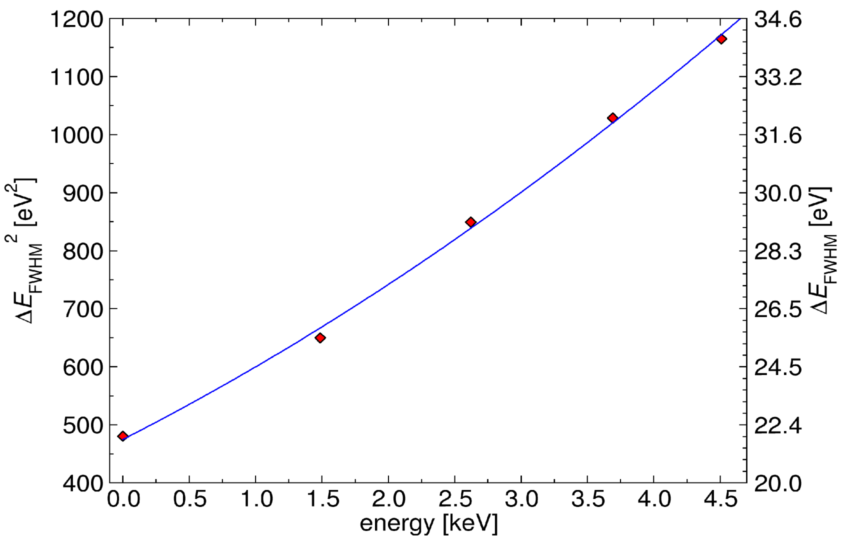


- λ(6 keV) ≈ 3 μm
- Absorber dimension ≈ 300 μm

Ti K_α line: E = 4.511 keV

- Energy resolution depends on energy

ΔE_{FWHM} = 28.5 eV
at E = 2.466 keV
(^{187}Re β end-point)



"Internal" calibration of $AgReO_4$ detectors

- Escape peaks allow internal calibration
  - ▷ λ(6 keV) ≈ 3 μm
  - ▷ λ(70 keV) ≈ 400 μm
- Escape peaks following incident X-rays are intrinsically broad ⇨ seen in previous high statistic measurement with Pb-Re K-K escapes
  - ▷ $\Gamma_{\text{escape KK}} = \Gamma_{\text{PbK}} + \Gamma_{\text{ReK}} \approx$ 60.2 eV + 42.1 eV = 102 eV

Internal calibration with ^{44}Ti

➡ γ rays @ 78.4 keV

⇨ no intrinsic broadening

Re K-edge @ 71.7 keV

γ-X escape peaks have only ReK intrinsic width (~42 eV)