the MARE project

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- direct neutrino mass measurement
  - spectrometers and calorimeters
- ^{187}Re calorimetric experiment state-of-the-art
- statistical sensitivity and systematics
- future calorimetric experiments: MARE
  - MARE-1: semiconductor thermistors and TES
  - MARE-2

GERDA collaboration meeting, Dip. di Fisica, Univ. Milano-Bicocca, Milano, Nov 13-15, 2006

Neutrino mass measurements

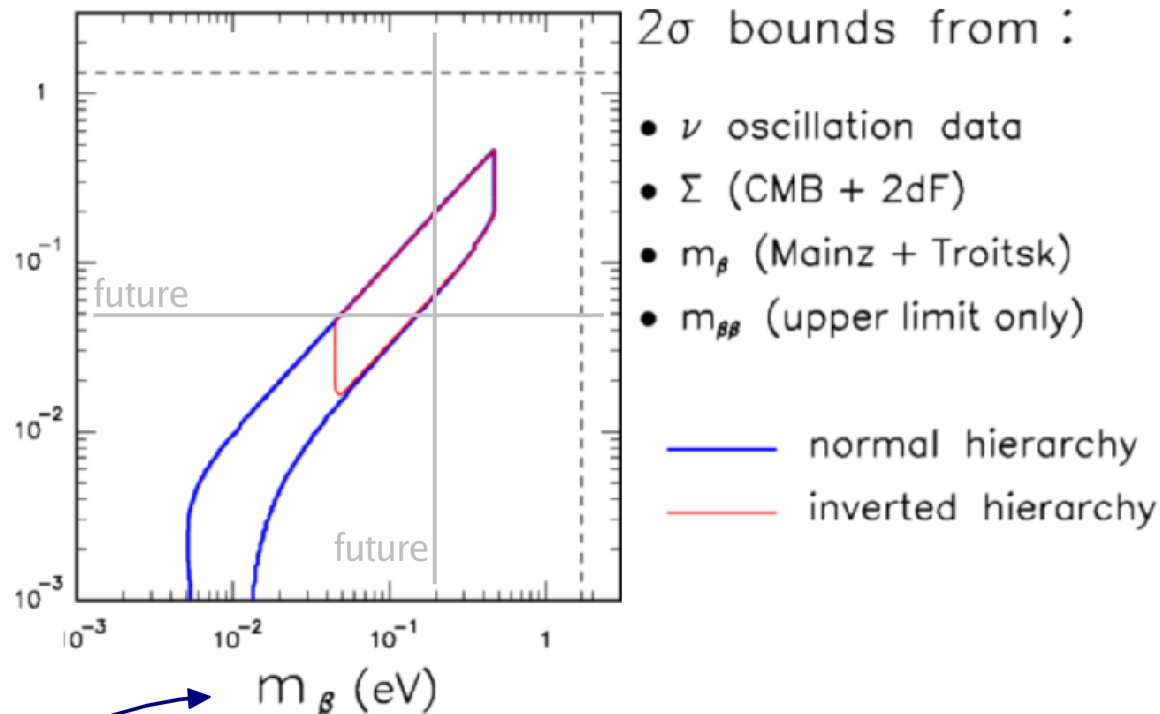
tool	measured quantity	present sensitivity	future sensitivity		
Cosmology CMB+LSS	$m_{\Sigma} \equiv \sum m_i$	$0.7 \div 1$ eV	0.05 eV	yes	large
Neutrinoless Double Beta decay	$m_{\beta\beta} \equiv \lvert \sum m_i U_{ei}^2 \rvert$	0.5 eV	0.05 eV	yes	yes
Beta decay end-point	$m_{\beta} \equiv (\sum m_i^2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

model dependency

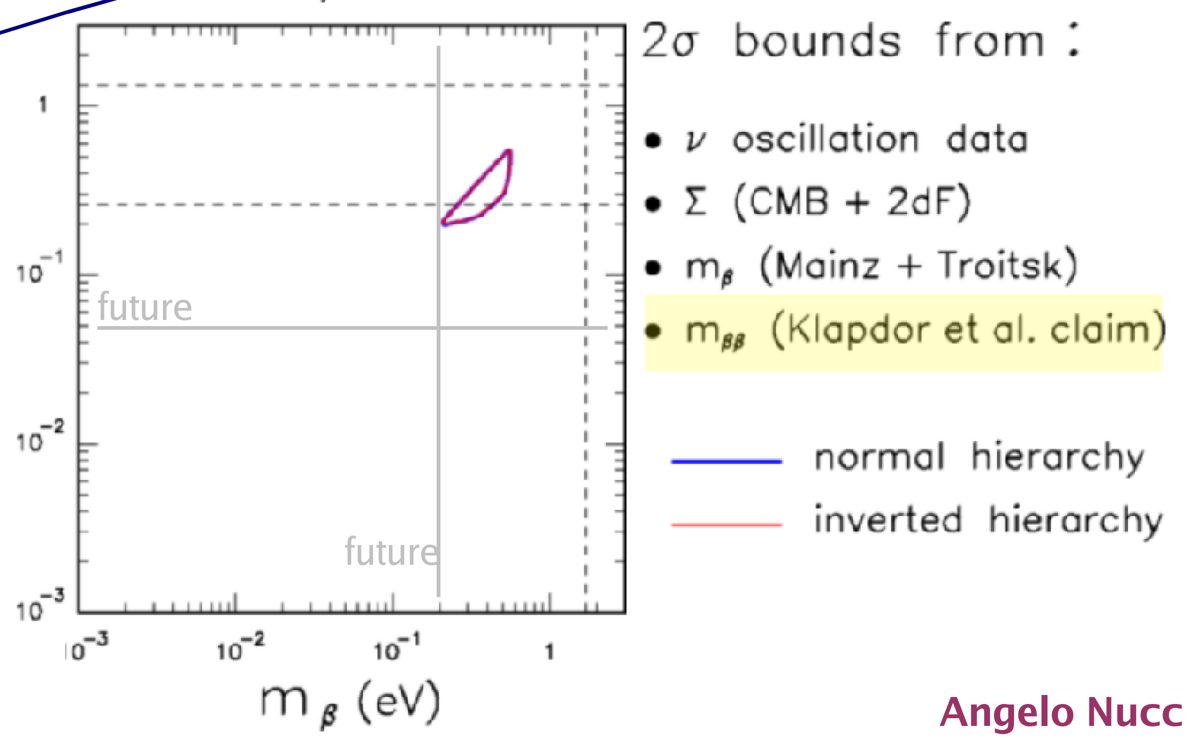
systematic uncertainties

Neutrinos masses in single β and $\beta\beta$-0ν decays

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

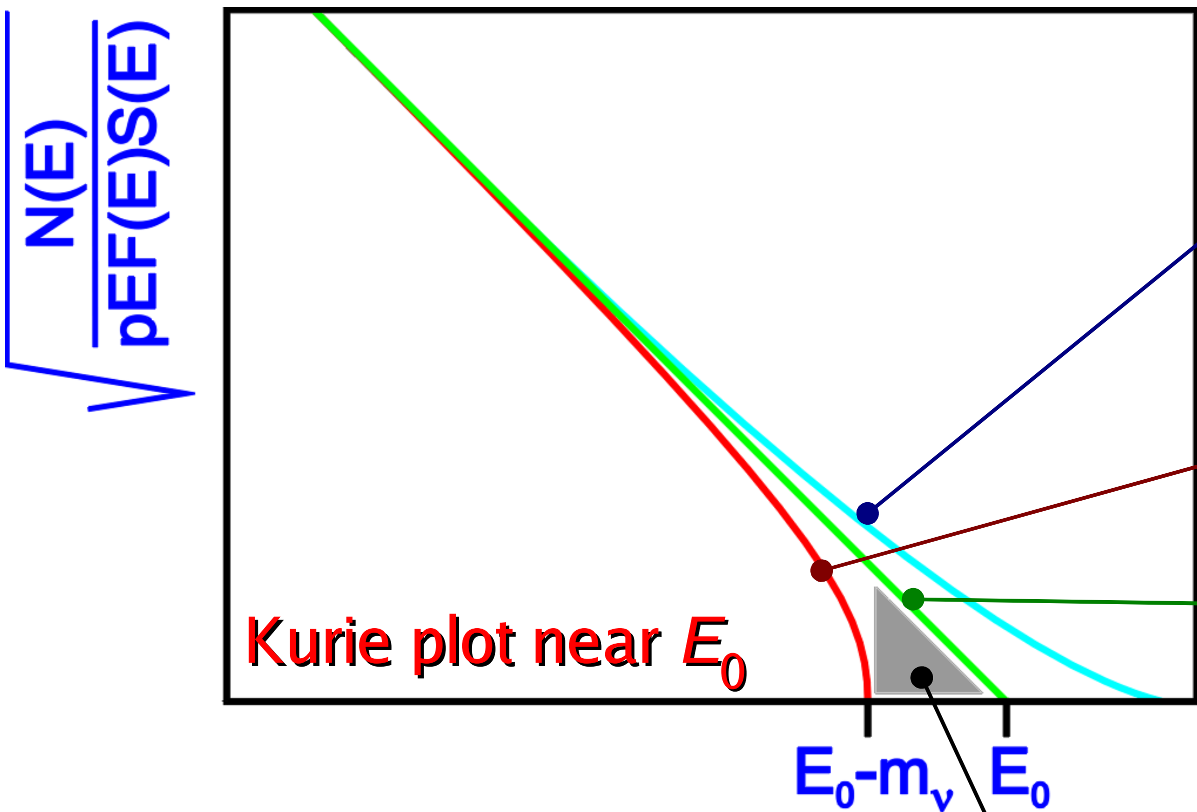


$m_\beta \equiv m_\nu$ from β decay



Fogli et al. hep-ph/0408045

Direct neutrino mass measurement



effect of:
- detector energy resolution
- background counts
- β decays to excited states

effect of $m_\nu \neq 0$

$N(E_\beta, m_{\bar{\nu}_e} = 0)$

fraction F of decays below the end-point

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

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

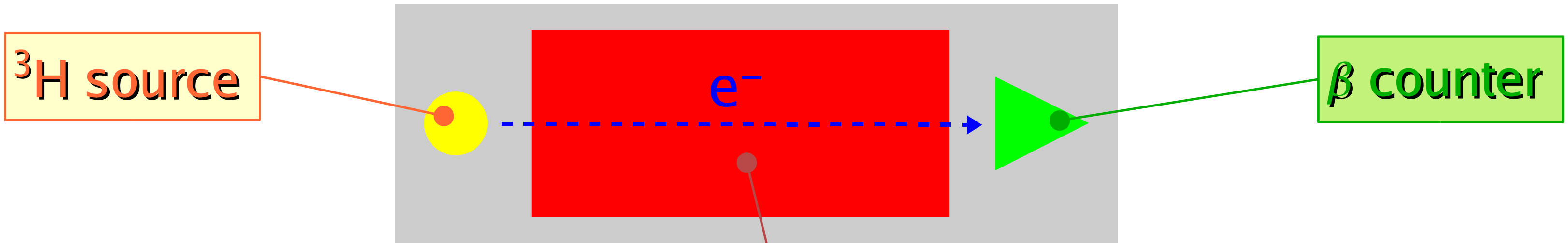
for ^3H β decay $F(10\text{ eV}) \approx 3 \times 10^{-10}$

General experimental requirements

- high statistics at the β spectrum end-point
- high energy resolution ΔE
- high signal-to-background ratio at the end-point
- small systematic effects

Experimental approaches for direct measurements

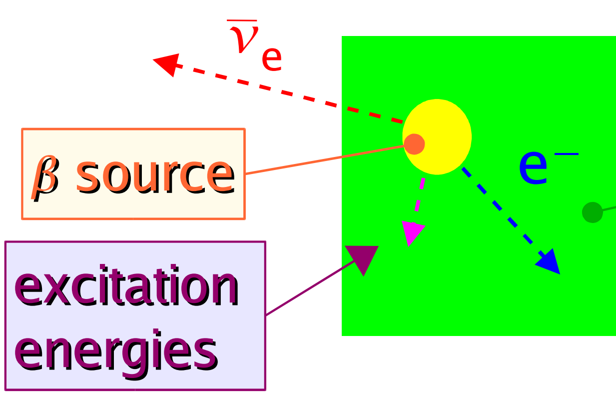
Spectrometers: source $\neq$ detector



β analyzer

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

Calorimeters: source $\subseteq$ detector

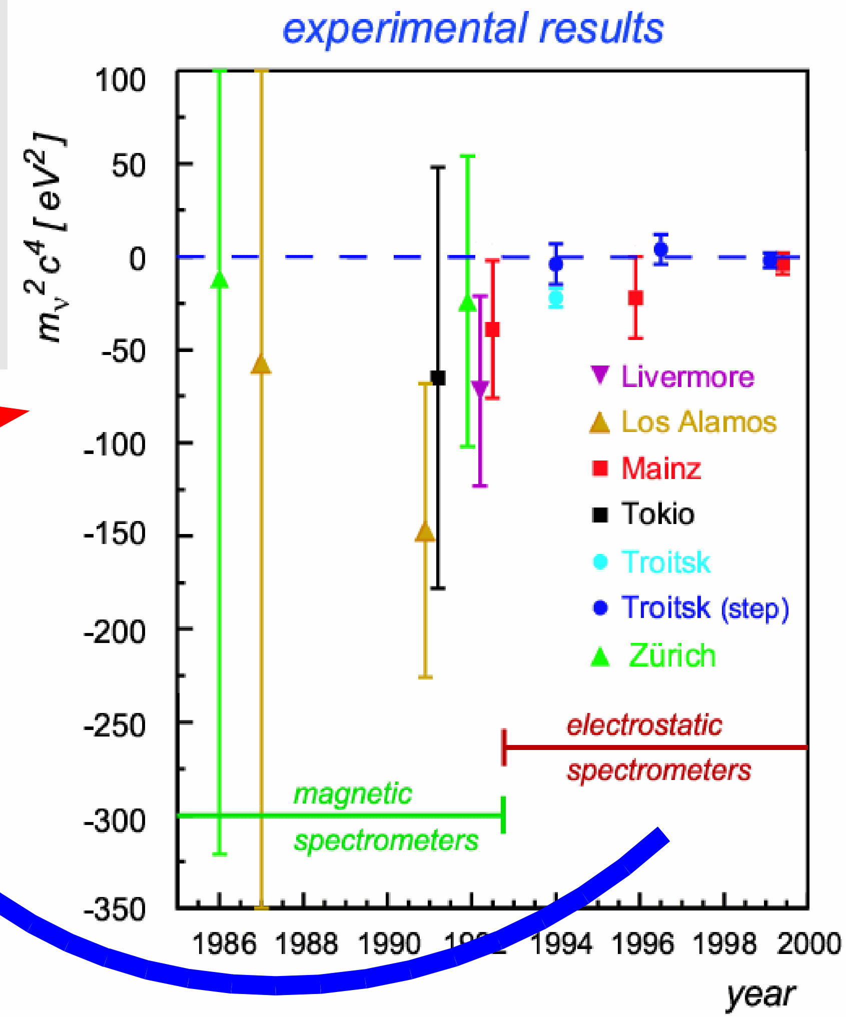


β calorimeter

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

Spectrometers present results

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



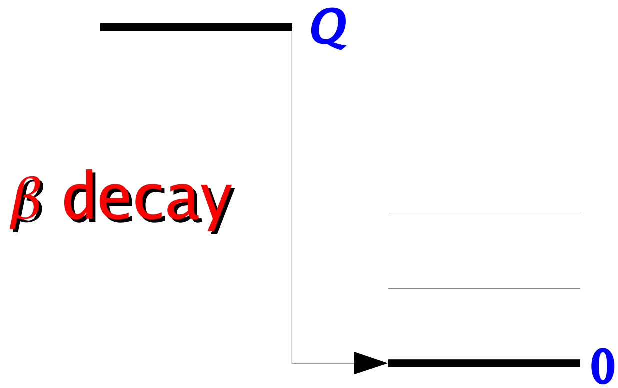
electrostatic spectrometers

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

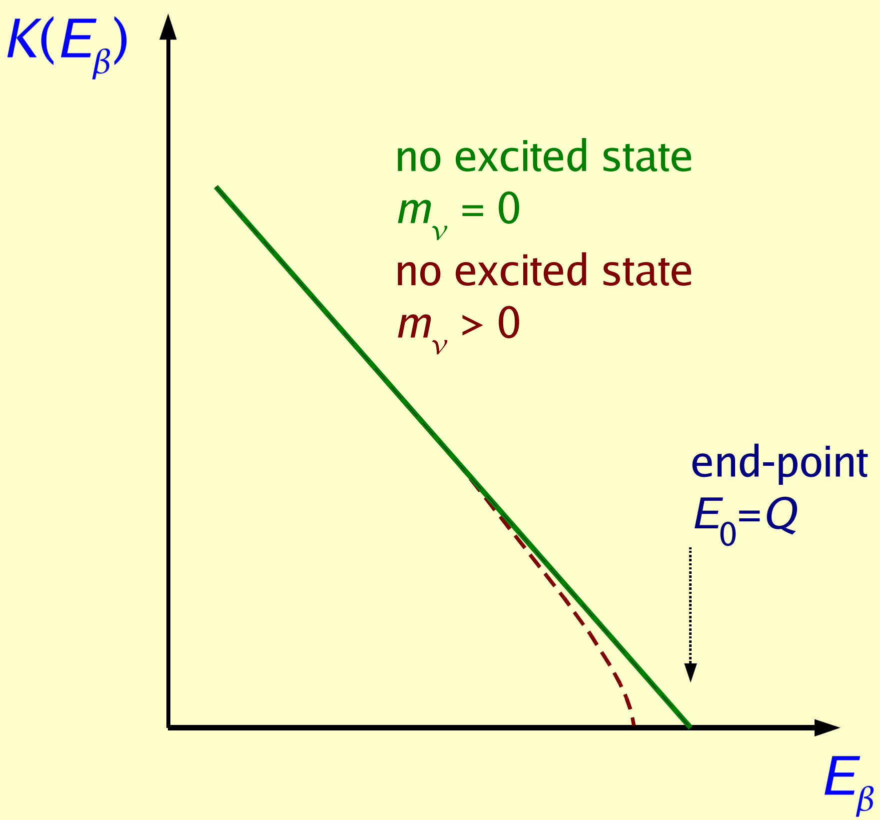
KATRIN

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

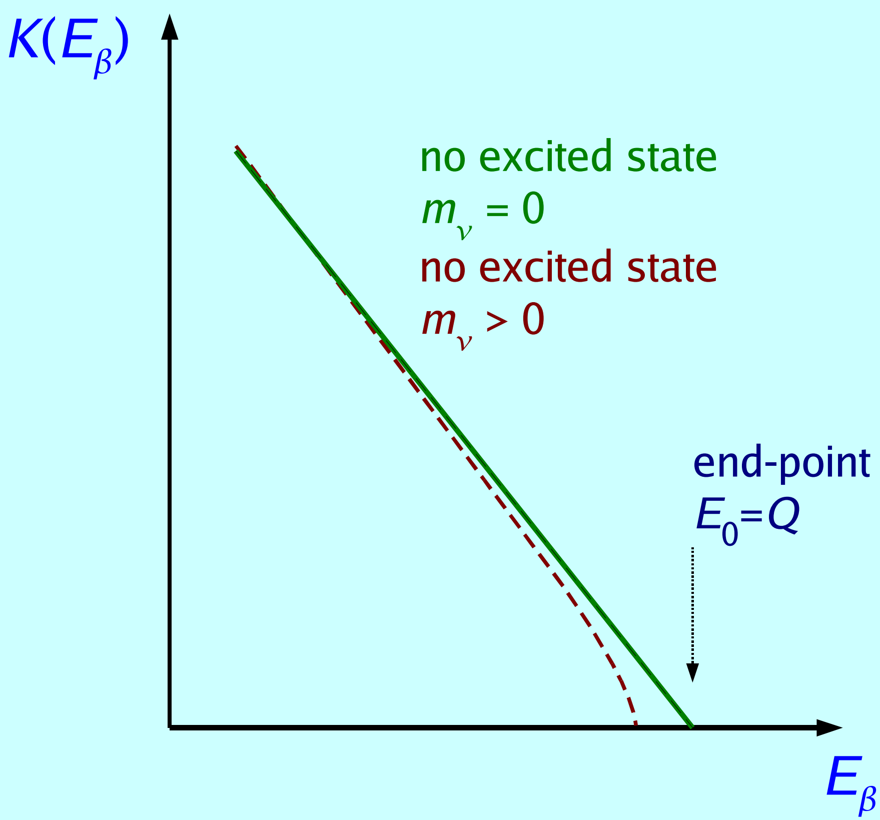
Decays on excited states / 1



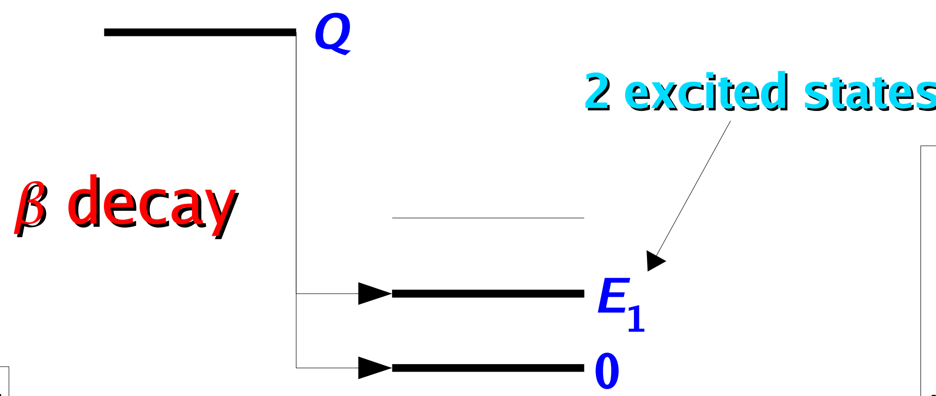
Spectrometers



Calorimeters



Decays on excited states / 2



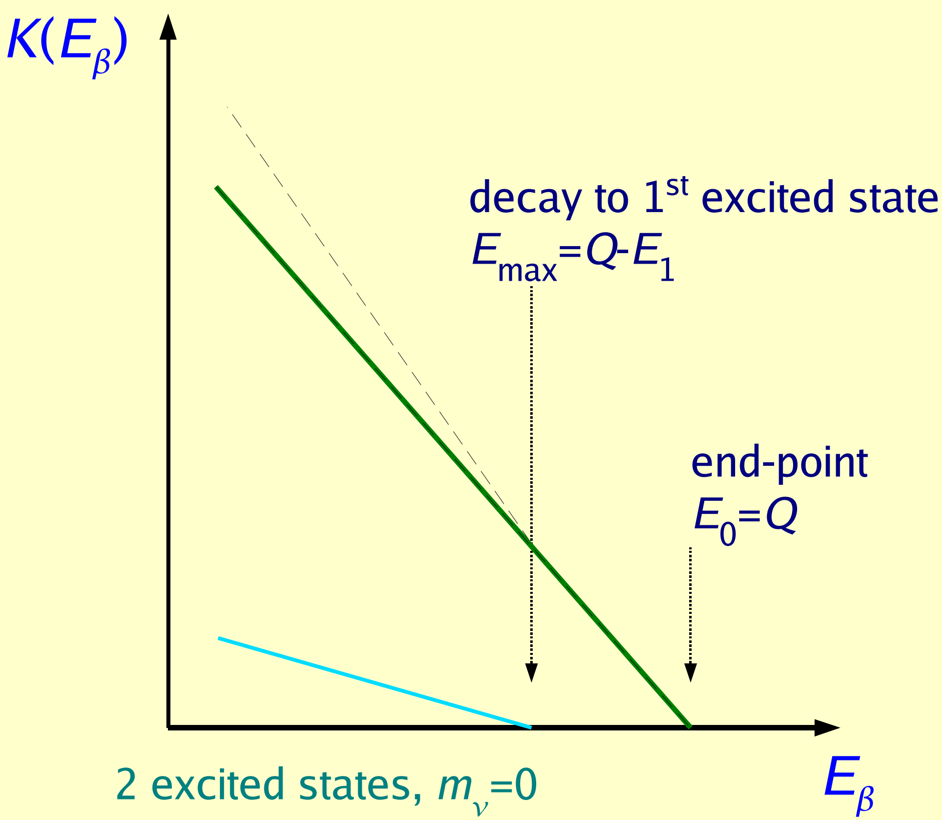
excitation energy is lost

de-excitation faster than detector response time $t_d \sim 1\ \mu s$

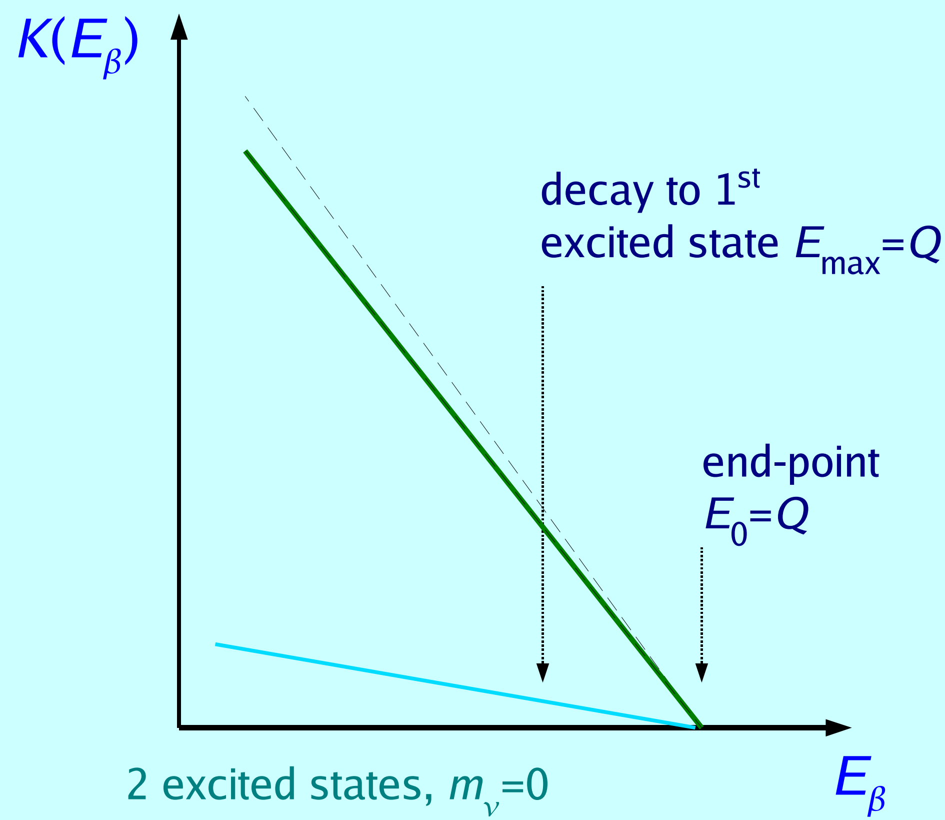
⇩

excitation energy is measured together with β energy

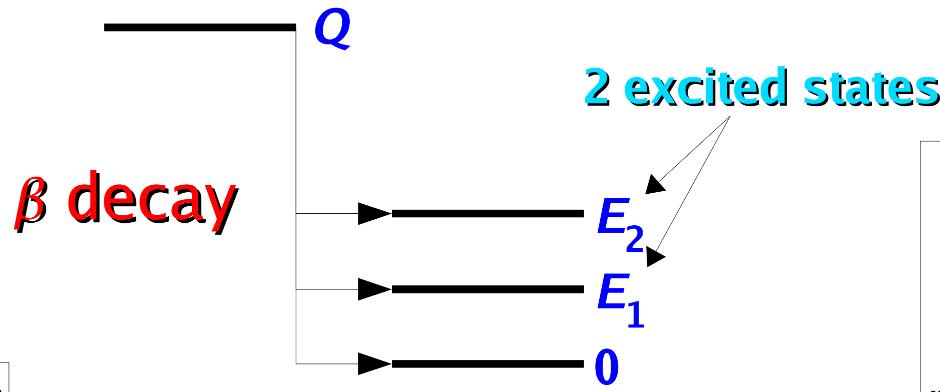
Spectrometers



Calorimeters



Decays on excited states / 3



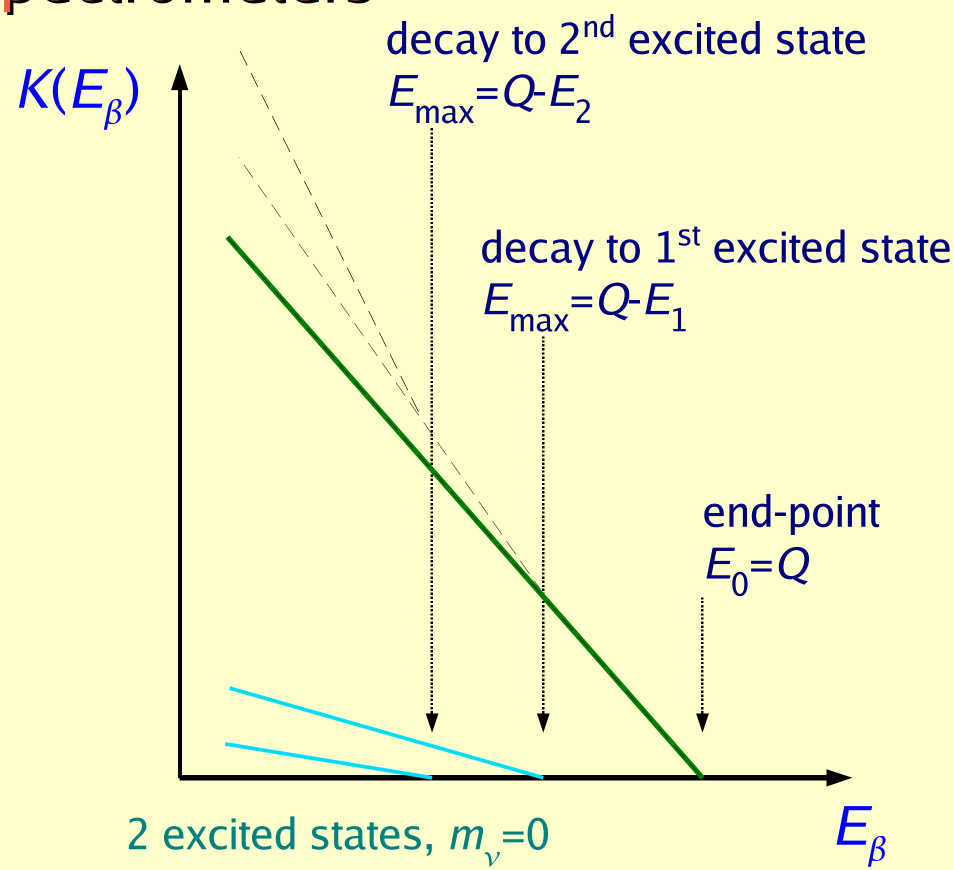
excitation energy is lost

de-excitation faster than detector response time $t_d \sim 1\ \mu s$

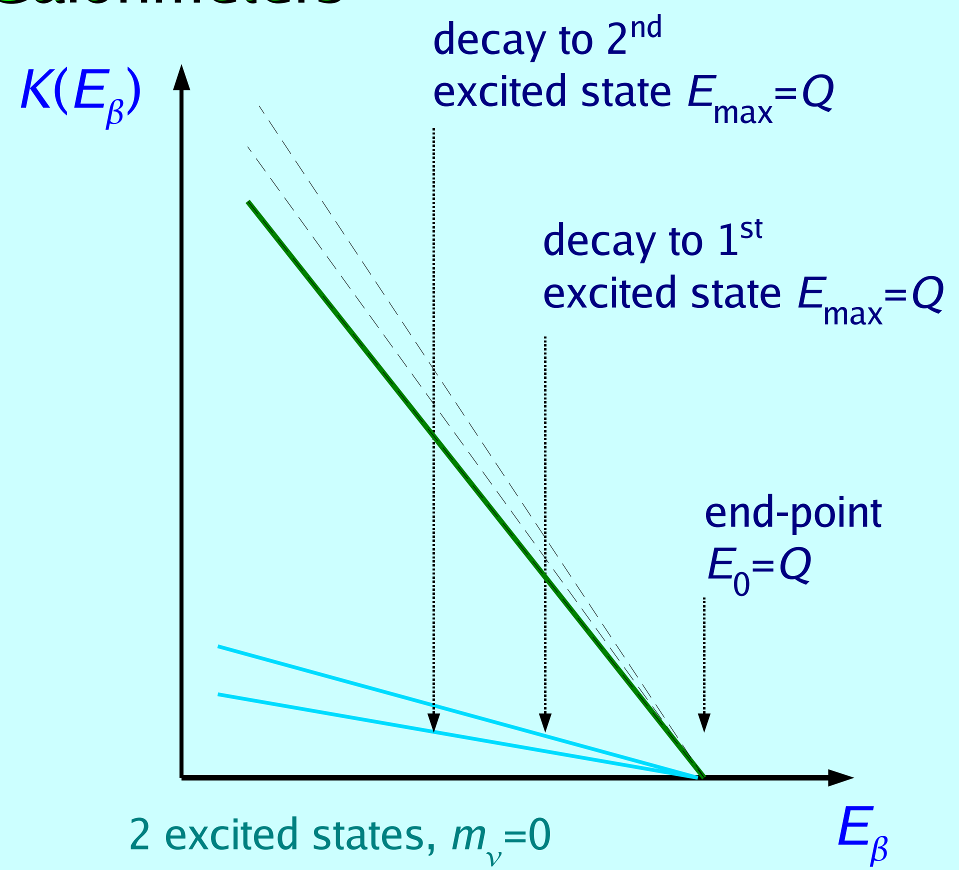
⇩

excitation energy is measured together with β energy

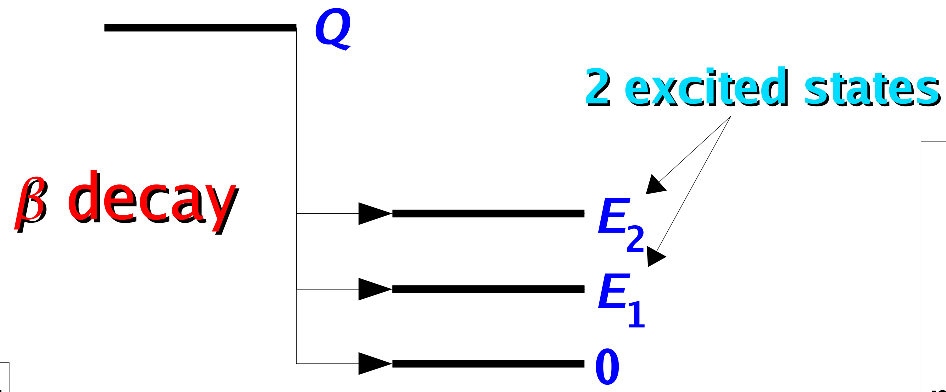
Spectrometers



Calorimeters



Decays on excited states / 4



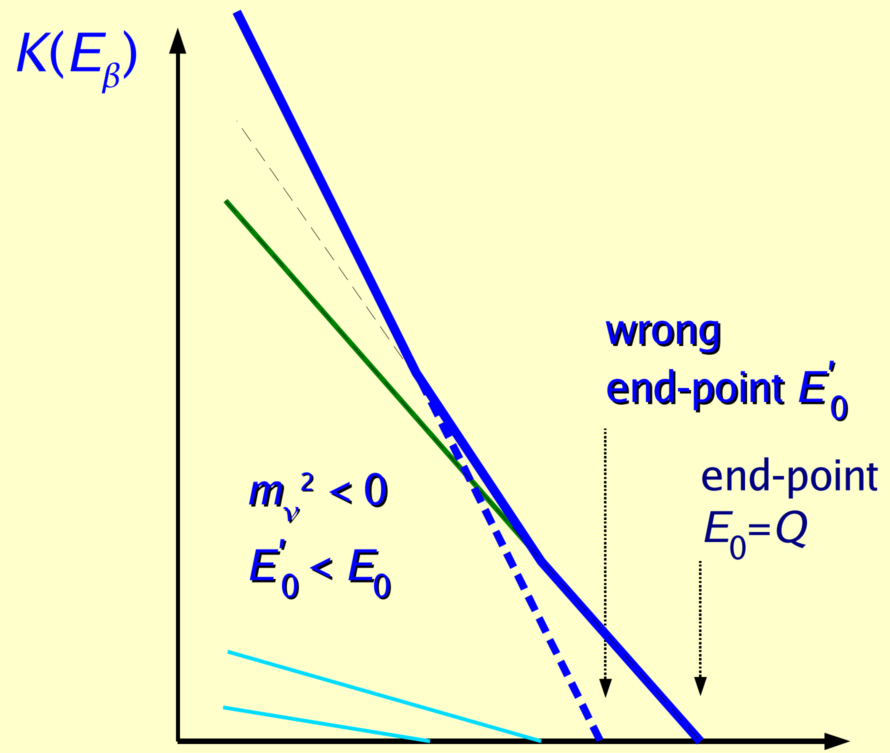
excitation energy is lost

de-excitation faster than detector response time $t_d \sim 1\ \mu s$

⇩

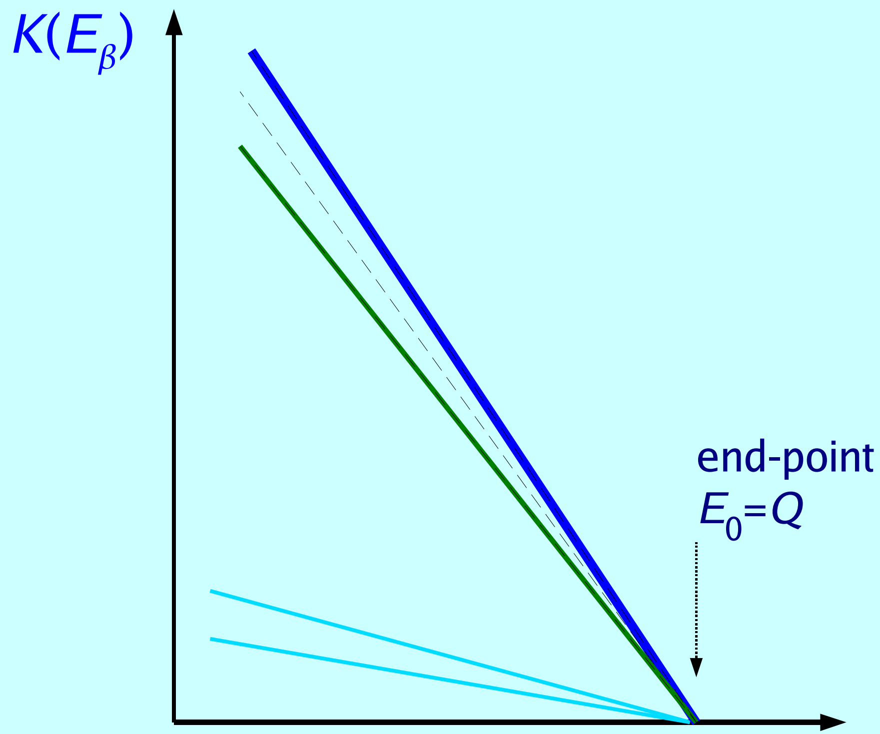
excitation energy is measured together with β energy

Spectrometers



2 excited states, $m_\nu=0$

Calorimeters



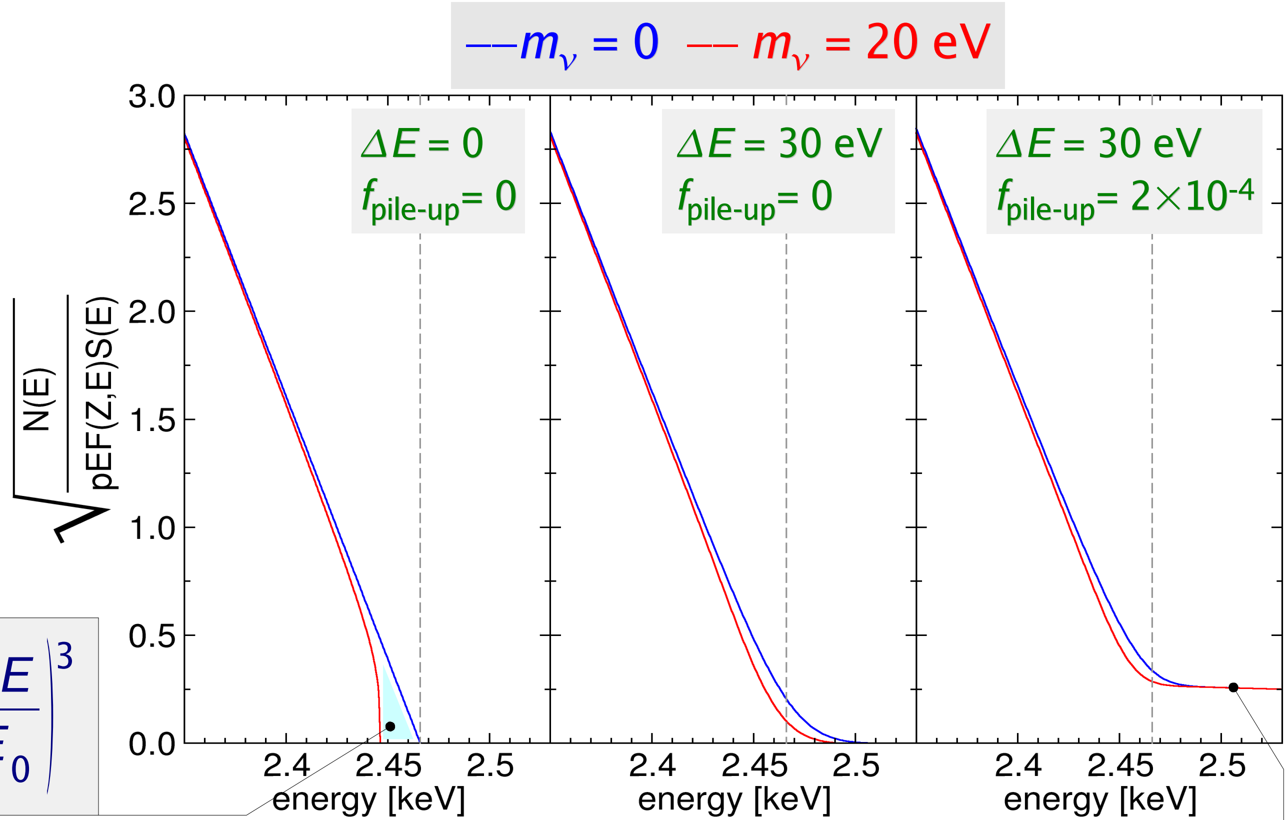
2 excited states, $m_\nu=0$

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

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



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

Pile-up

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

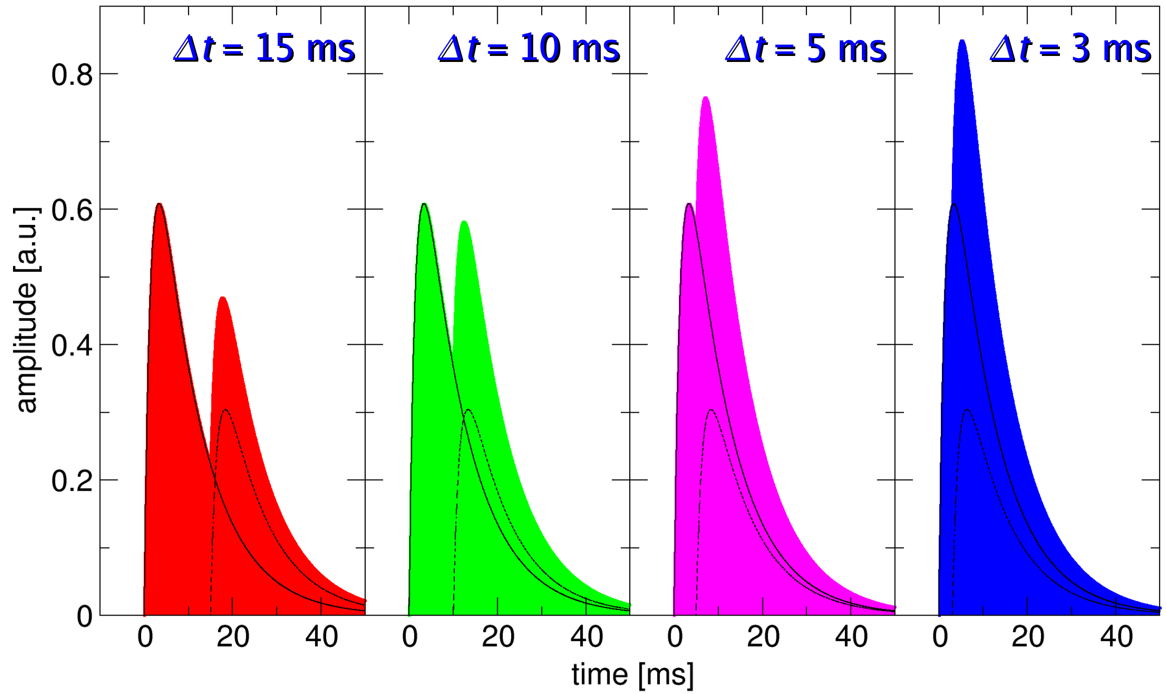
$$N^{exp}(E_\beta) \approx (N(E_\beta) + \tau_R A_\beta \cdot N(E_\beta) \otimes N(E_\beta)) \otimes R(E_\beta)$$

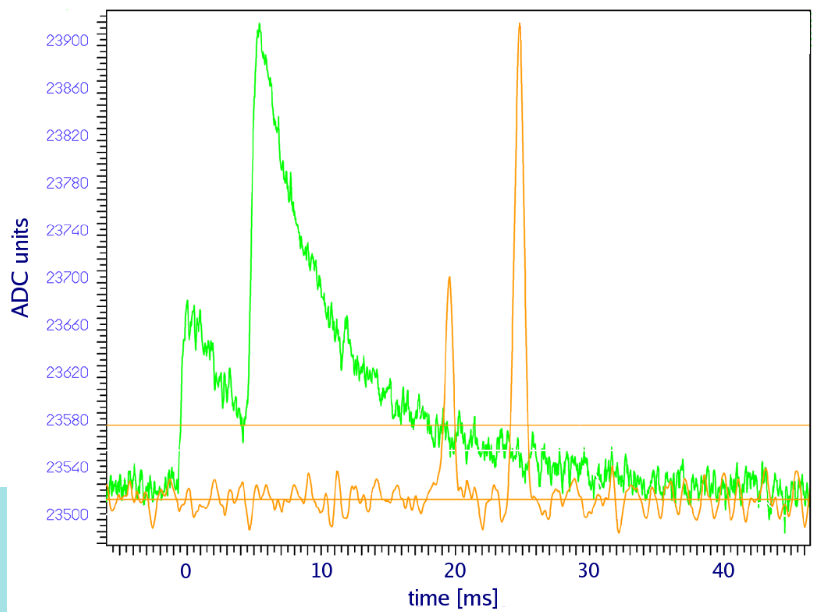
Calorimetry drawbacks: pile-up

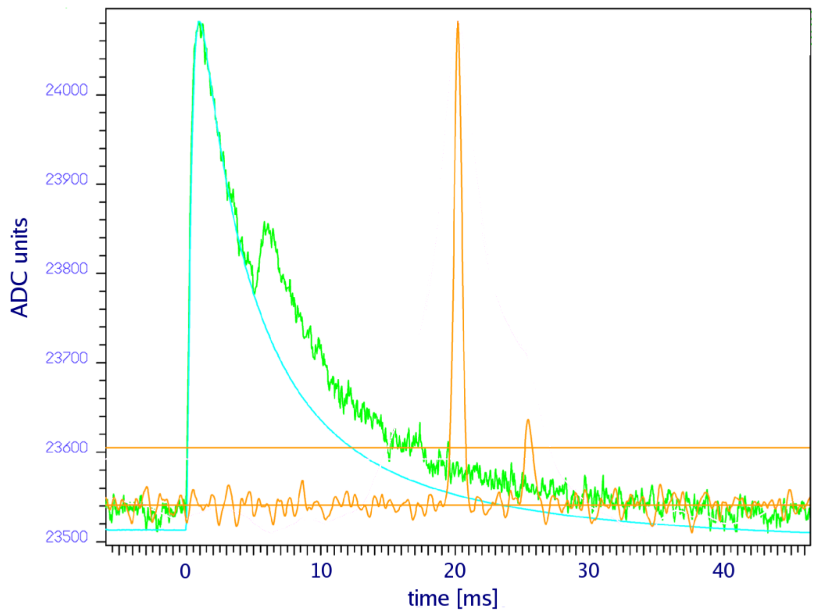
$$A(t)=A\left(e^{-t/\tau_{decay}}-e^{-t/\tau_{rise}}\right)$$

Example

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



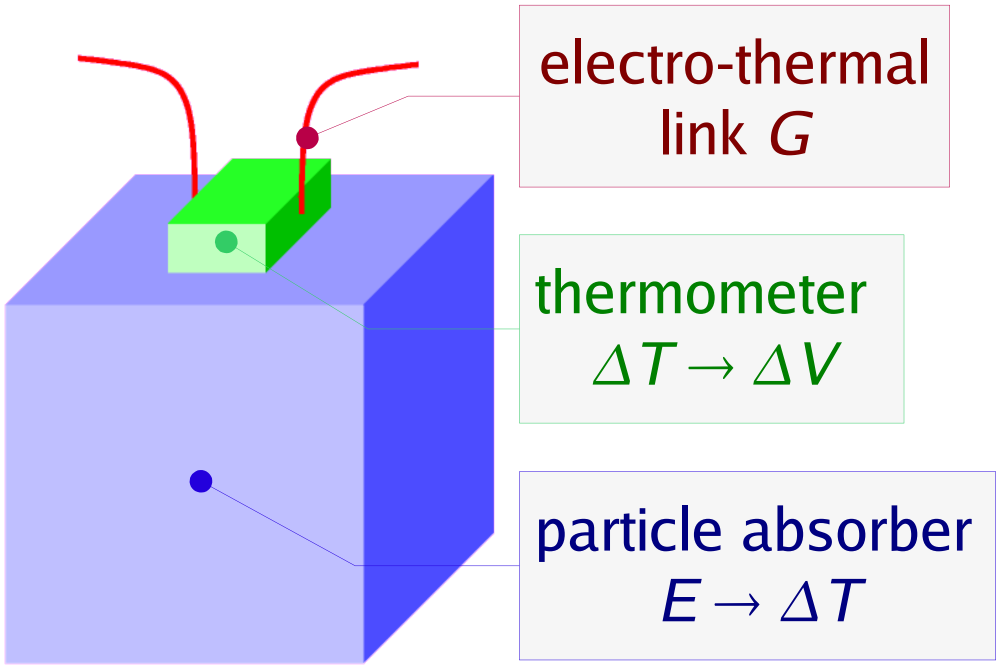


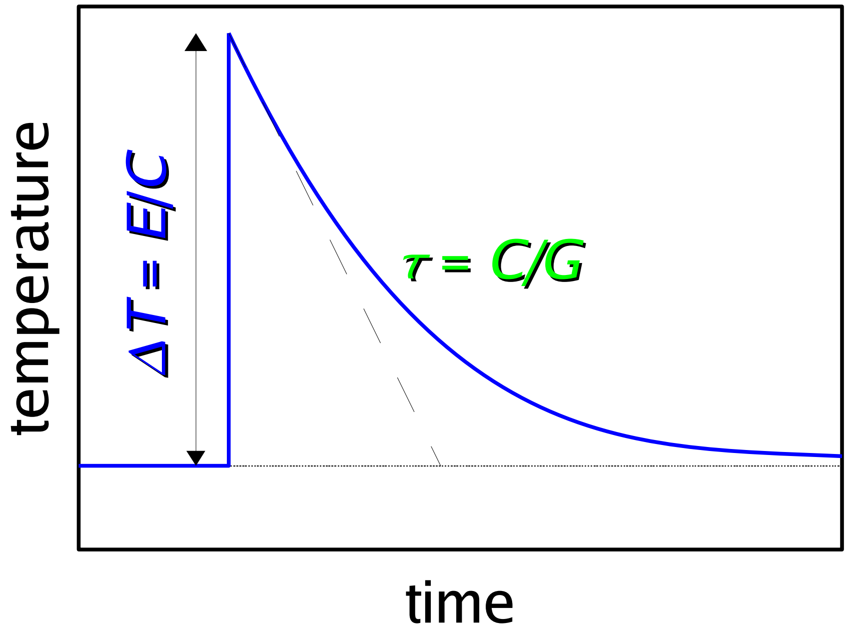


Real pulses

- $\tau_{rise} \approx 1$ ms
  - ▸ resolving time $\tau_R \approx 3\ \tau_{rise}$

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. $T \ll 1\mathrm{K}$)
- $\Delta E_{rms} = (k_B T^2 C)^{1/2}$ due statistical fluctuations of internal energy E
- $\Delta T(t) = E/C\, e^{-t/\tau}$ with $\tau = C/G$ and G thermal conductance

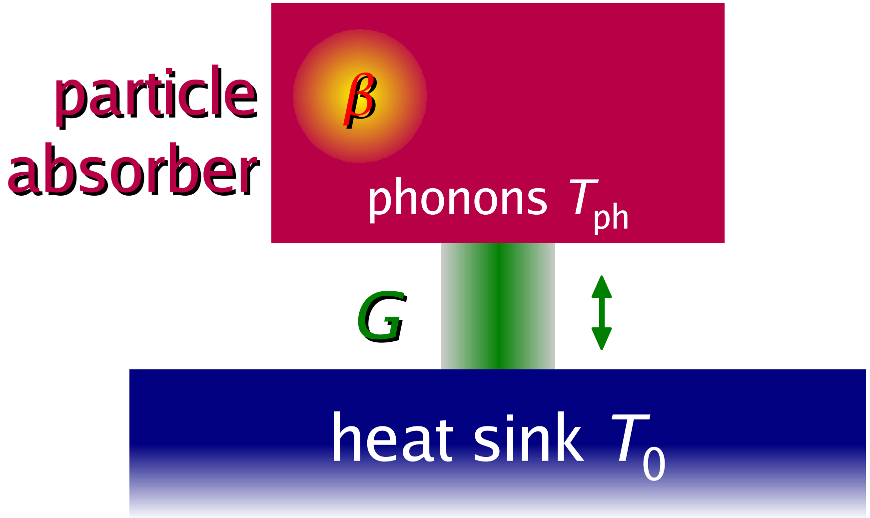
Resolution limit: cryogenic vs. ionization detectors

Ionization detectors

- measure only the energy that goes into ionization (~1/3)
  - in semiconductors: energy to create an *e*-*h* pair $W_0 \approx 3$ eV $\Rightarrow N_{eh} = E/W_0$
  - statistical fluctuations on N_{eh} limit the energy resolution: $\sigma_E = \sqrt{F N_{eh}} W_0 = \sqrt{F E W_0}$
  - in practice: $\Delta E_{FWHM} \approx$ **115 eV at 6 keV for silicon**
- other limitations from electron transport properties (material restriction, purity...)

Cryogenic detectors

- measure the energy that goes into heat (100%)
  - no branching ⇒ no statistical fluctuations
  - resolution limit: random energy flow through G
  - statistical fluctuations of internal energy $U = \langle U \rangle \pm \Delta U_{rms}$



$$N_{ph} = \frac{\langle U \rangle}{\langle E_{ph} \rangle} = \frac{C T}{k_B T}$$

$$\Delta U_{rms} = \sqrt{N_{ph}} (k_B T) = \sqrt{k_B T^2 C}$$

- **1 mg of Si @ 100 mK**
  - $C \sim 10^{-13}$ J/K ⇒ $\Delta U_{rms} \sim$ **1 eV**

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 ⇒ ≈1.5 decay/s**

- **metallic rhenium** single crystals
  - superconductor with T_c=1.6K
  - NTD thermistors
  - **MANU experiment (Genova)**
- **dielectric rhenium compound** crystals
  - Silicon implanted thermistors
  - **MIBETA experiment (Milano)**

→ **m_ν < ≈15 eV**

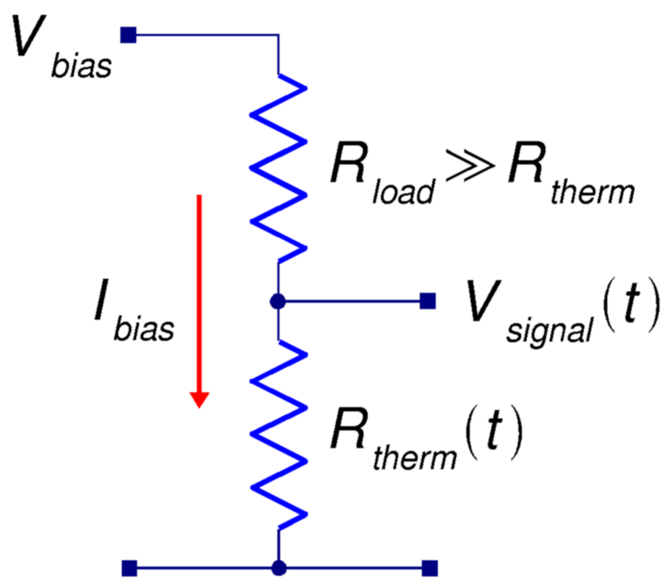
Resistive thermometers: thermistors

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

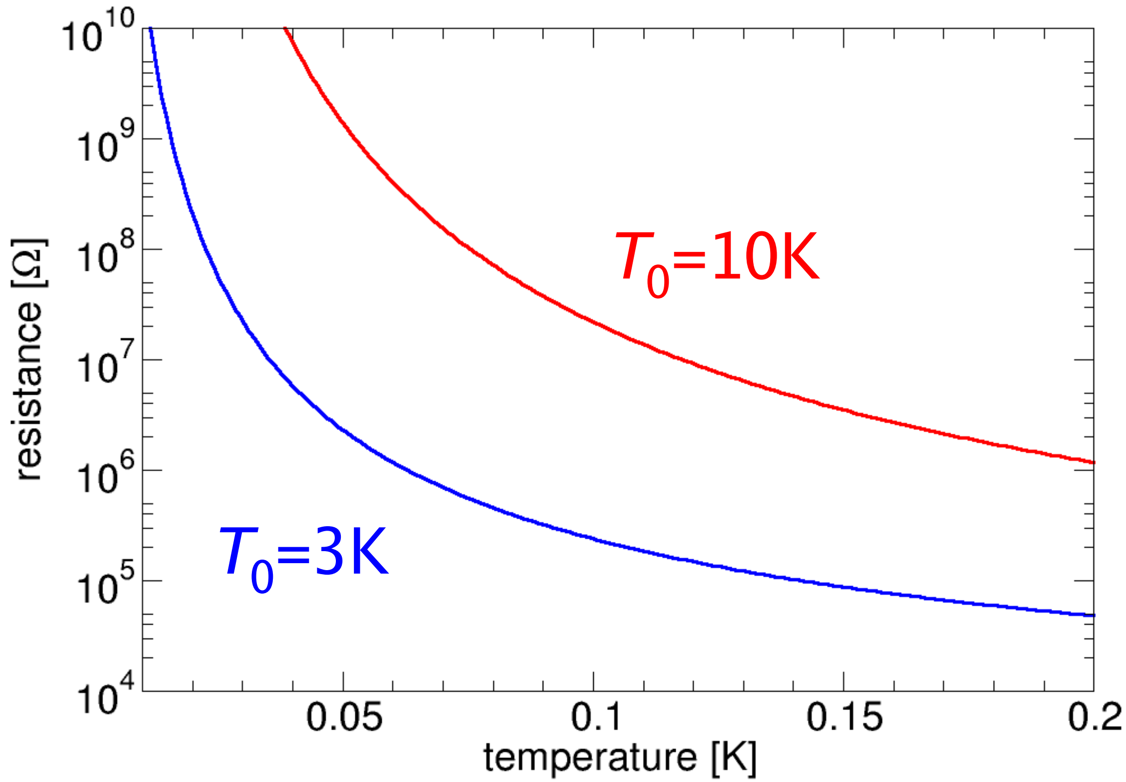
$$\rho(T) = \rho_0 \exp(T_0/T)^\gamma$$

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

Costant current bias

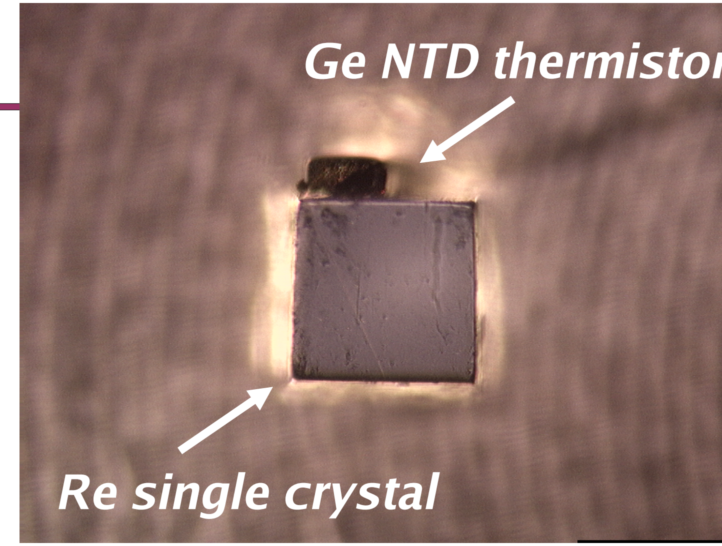


$\Delta E \Rightarrow \Delta T \Rightarrow \Delta R \Rightarrow \Delta V$

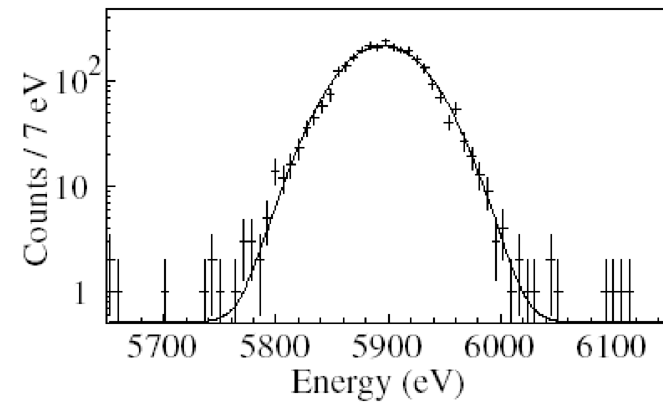


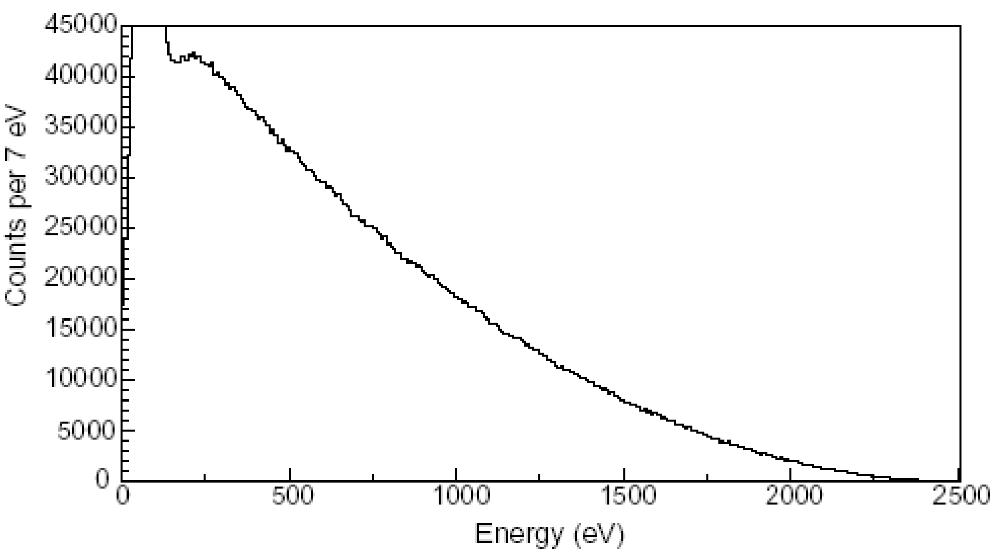
high impedance devices: R_{therm} = 1MΩ→100MΩ

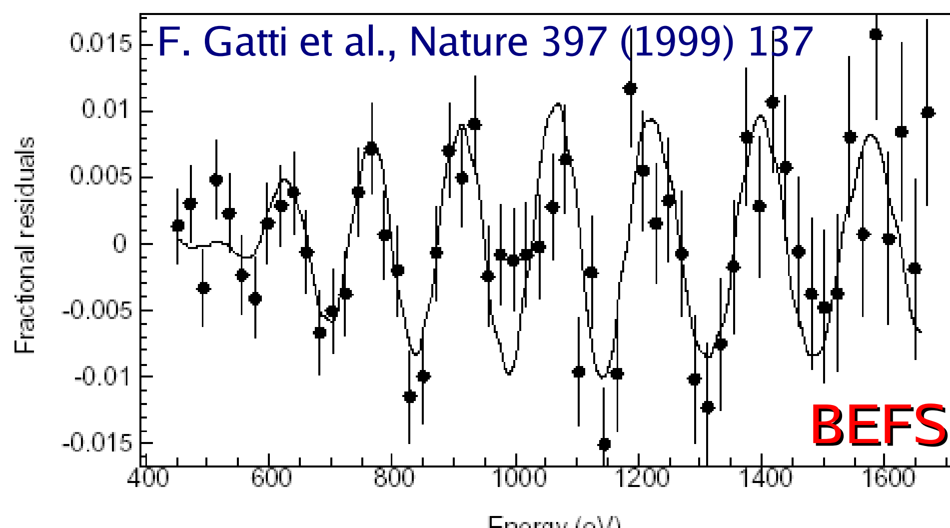
MANU experiment (1999)



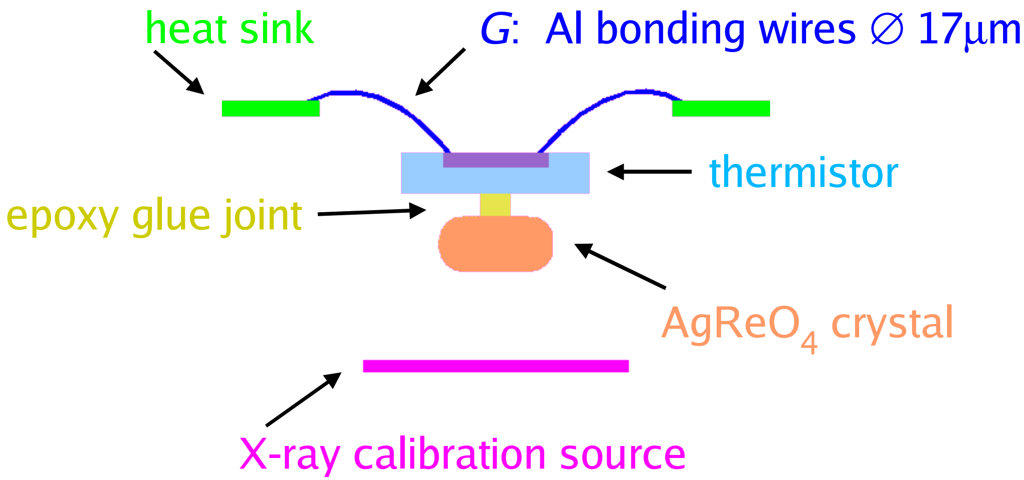
- 1.6 mg metallic rhenium single crystal
- one detector only
- Ge-NTD thermistor
  - ▷ ΔE=96 eV FWHM
  - ▷ symmetric and without tails
- 0.5 years live-time
  - ▷ 6.0×10^{6} ^{187}Re decays above 420 eV
  - ▷ $m_{\nu}^{2} = -\,462\ ^{+579}_{-679}\ \mathrm{eV}^2$
  - ▷ **m_{ν} < 19 eV (90 % C.L.)**
- first observation of BEFS in ^{187}Re decay



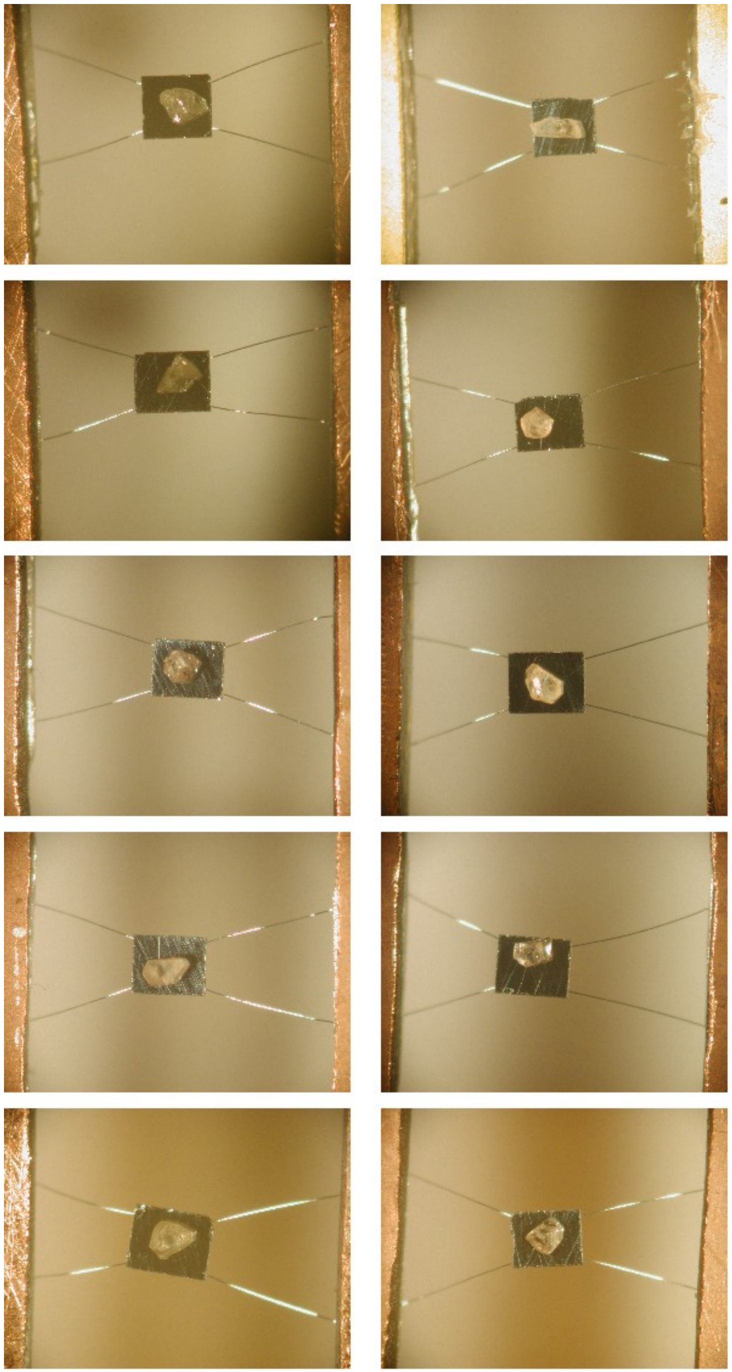




MIBETA experiment array: 2002/03

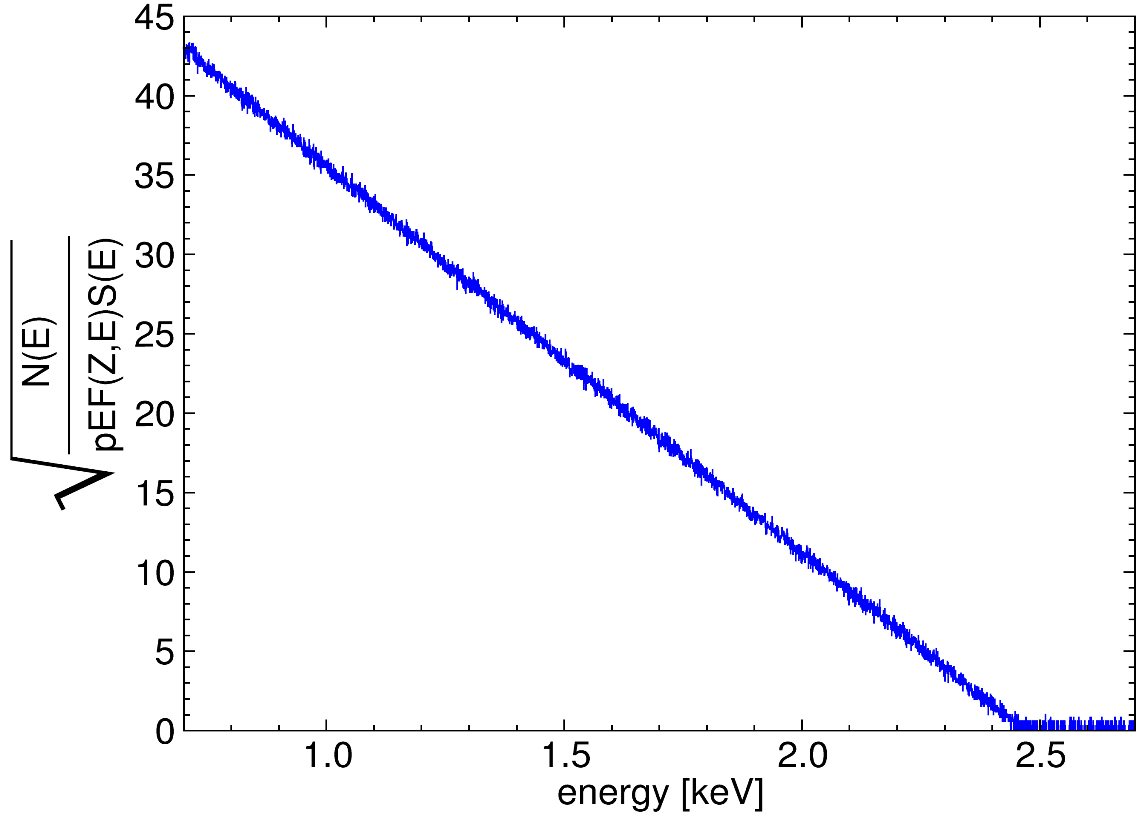


- silicon implanted thermistors (ITC-irst)
- $AgReO_4$ single crystals
  - ^{187}Re activity A_β = 0.54 decay/s/mg
  - mass ≈ 200÷300 μg → A_β ≈ 0.15 decay/s
- 10 microcalorimeter array
  - $\langle m_{AgReO4} \rangle$ = 271 μg
    - $\langle A_\beta \rangle$ = 0.15 decay/s
    - m_{tot} = 2.71 mg
  - $\langle \tau_{rise} \rangle$ = 490 μs
  - τ_R ≈ 1.5 ms
    - $f_{pile-up} \approx 2\times10^{-4}$
  - t_M = 0.6 years



MIBETA final β spectrum

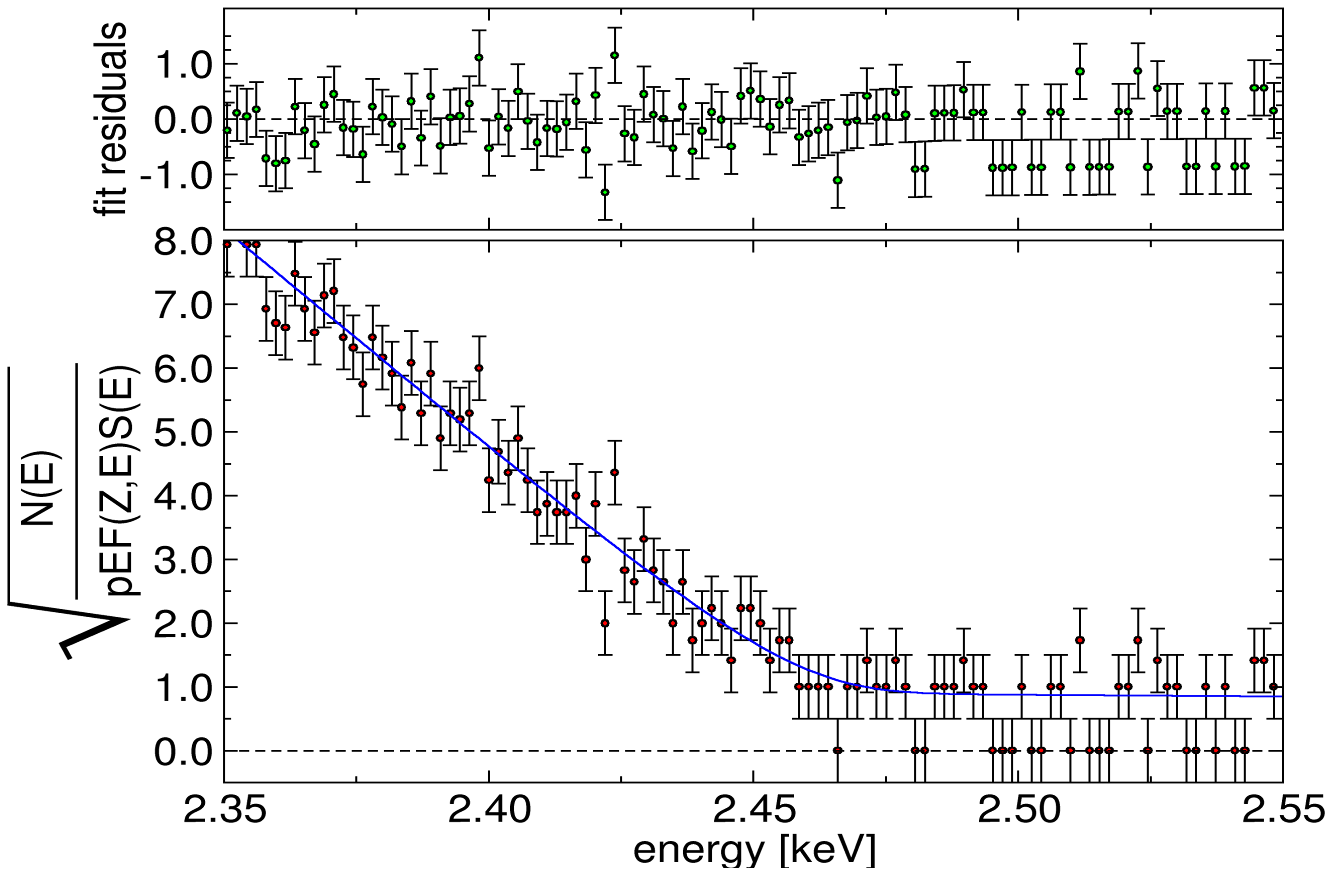
◆ 8751 hours×mg ($AgReO_4$) with source shutter closed
◆ 6.2×10^6 ^{187}Re decays collected above 700 eV



β spectrum analysis

- fit function: $f(E) = [N_{theo}(E, m_\nu) + N_{pile-up}(E, m_\nu) + b(E)] \otimes R(E)$
  - ▷ $N_{theo}(E, m_\nu)$ first forbidden unique Buhring spectrum
  - ▷ $N_{pile-up}(E, m_\nu) = A_\beta \tau_R [N_{theo}(E, m_\nu) \otimes N_{theo}(E, m_\nu)]$ pile-up spectrum
  - ▷ $b(E)$ polynomial background spectrum; $R(E)$ response function
  - ▷ free parameters: N_{theo} and $N_{pile-up}$ normalizations, Q_β end-point, $b(E)$ parameters, m_ν^2
- estimator: $\Xi^2 \overset{def}{=} 2\sum_i[f_i - y_i - y_i \ln(f_i / y_i)]$ with f_i fit values, y_i measured data
- Bayesian approach for non physical regions

MIBETA end-point analysis



- from analysis of 8751 hours×mg data set

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

⬇

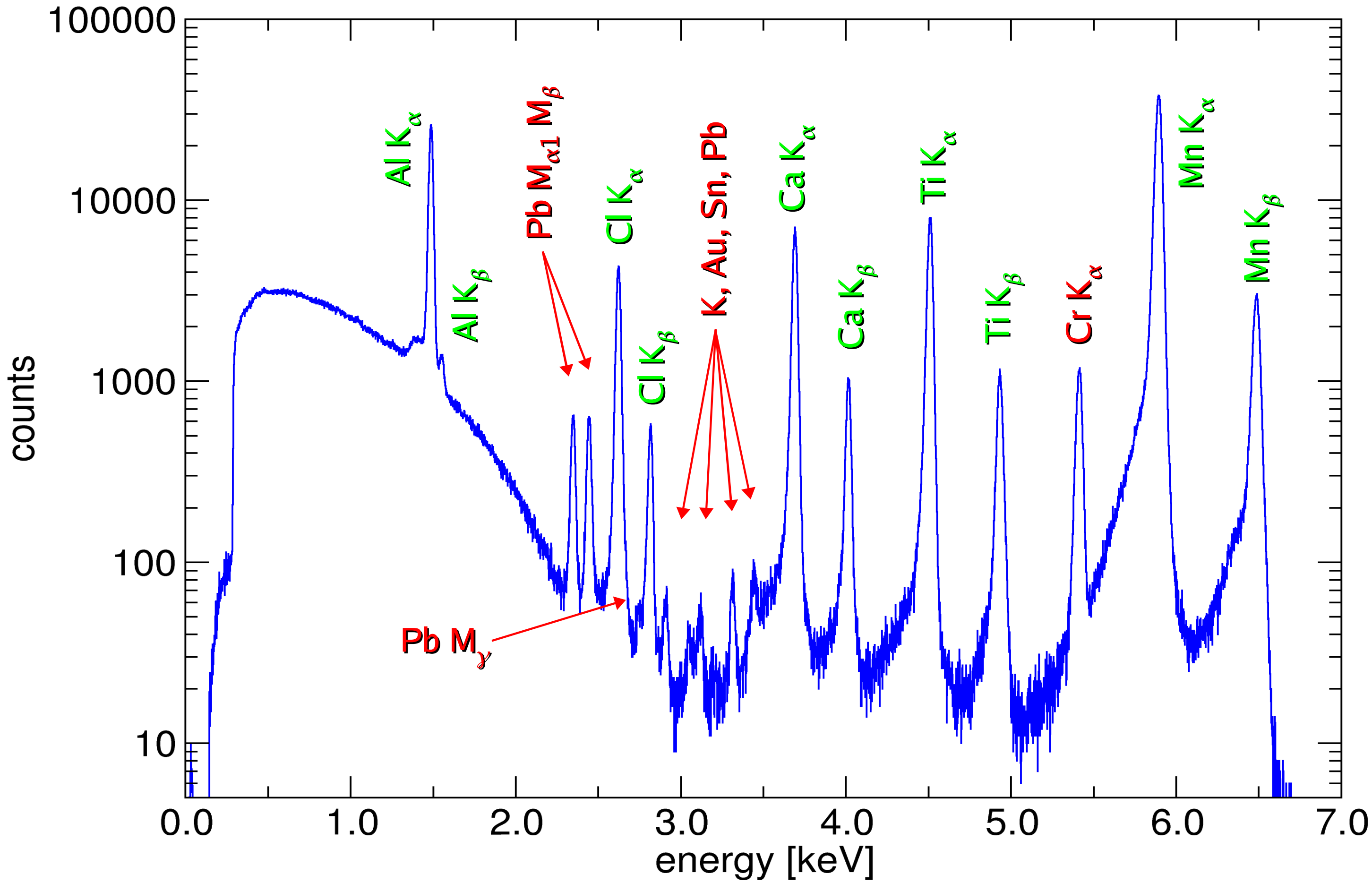
$$m_\nu < 15 \text{ eV (90 \% C.L.)}$$

- single gaussian: ΔE_{FWHM} = 28.5 eV
- fitting interval 0.9 ÷ 4.0 keV
- free constant background: 7×10^{-3} c/keV/h
- free pile-up fraction $f_{pile\text{-}up}$: 1.9×10^{-4}

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

Calibration: detector response function

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



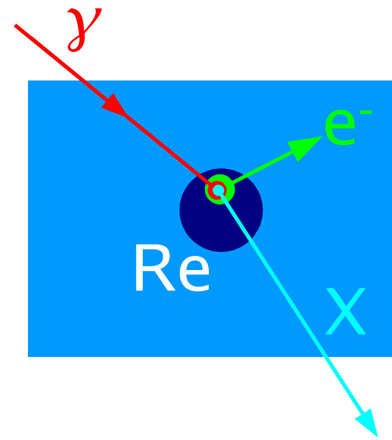
- X-ray peaks have tails on low energy side
- 1~6 keV X-rays in $AgReO_4$ have an attenuation length $\lambda < 2\ \mu$m

  ⇨ 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

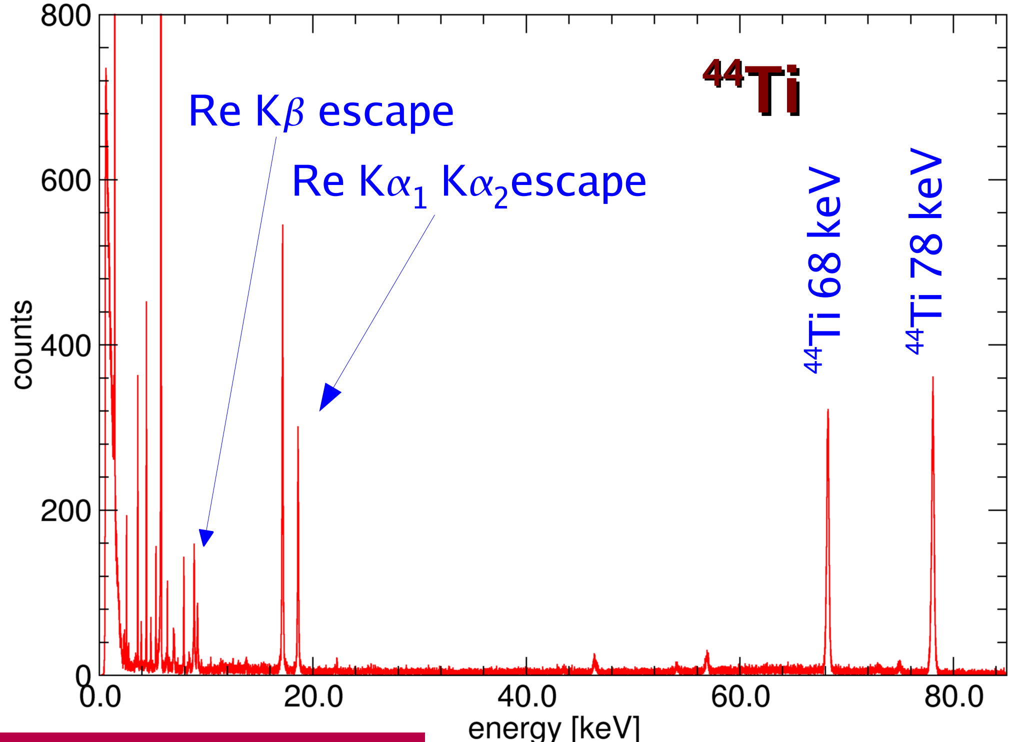
MIBETA: Measurement of response function (2004)

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

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

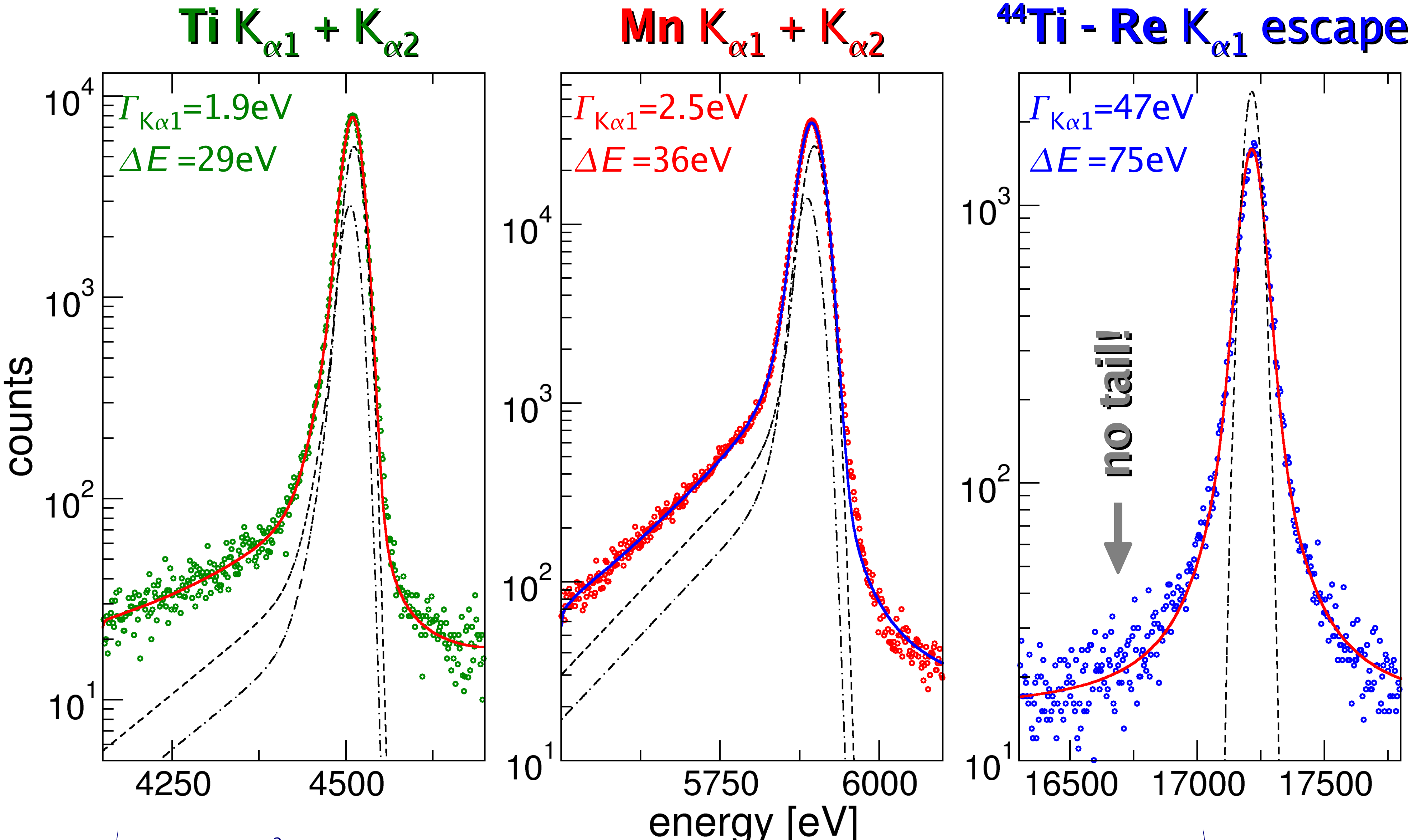


- Re K-edge @ 71.7 keV
  - ▷ E_γ > 71.7 keV
  - ▷ **internal calibration with ^{44}Ti**
- γ rays @ 78.4 keV
- ▶ γ-X escape peaks have only Re K natural width (Γ_{ReK}~47 eV)



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

Measurement with ^{44}Ti (2004)



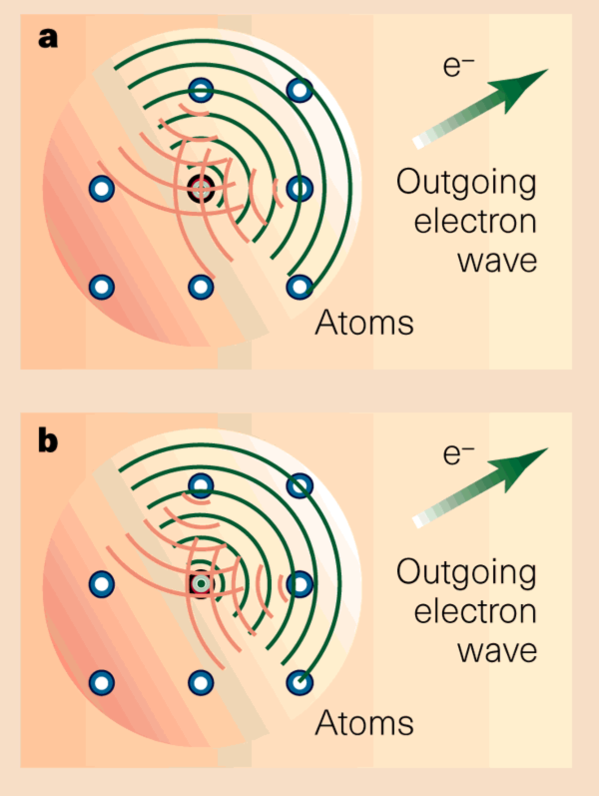
$$f(E)=\left(A_1 e^{\frac{-(E-E_0)^2}{2\sigma^2}}+A_2 e^{\left((E-E_0)\lambda_1+\frac{\sigma^2\lambda_1^2}{2}\right)}\operatorname{erfc}\left(\frac{E-E_0}{\sqrt{2}\sigma}+\frac{\sigma\lambda_1}{\sqrt{2}}\right)+A_3 e^{\left((E-E_0)\lambda_2+\frac{\sigma^2\lambda_2^2}{2}\right)}\operatorname{erfc}\left(\frac{E-E_0}{\sqrt{2}\sigma}+\frac{\sigma\lambda_2}{\sqrt{2}}\right)\right)\otimes\frac{A_4}{1+4\frac{(E-E_0)^2}{\Gamma^2}}$$

analysis still in progress...

MIBETA: BEFS analysis (2005)

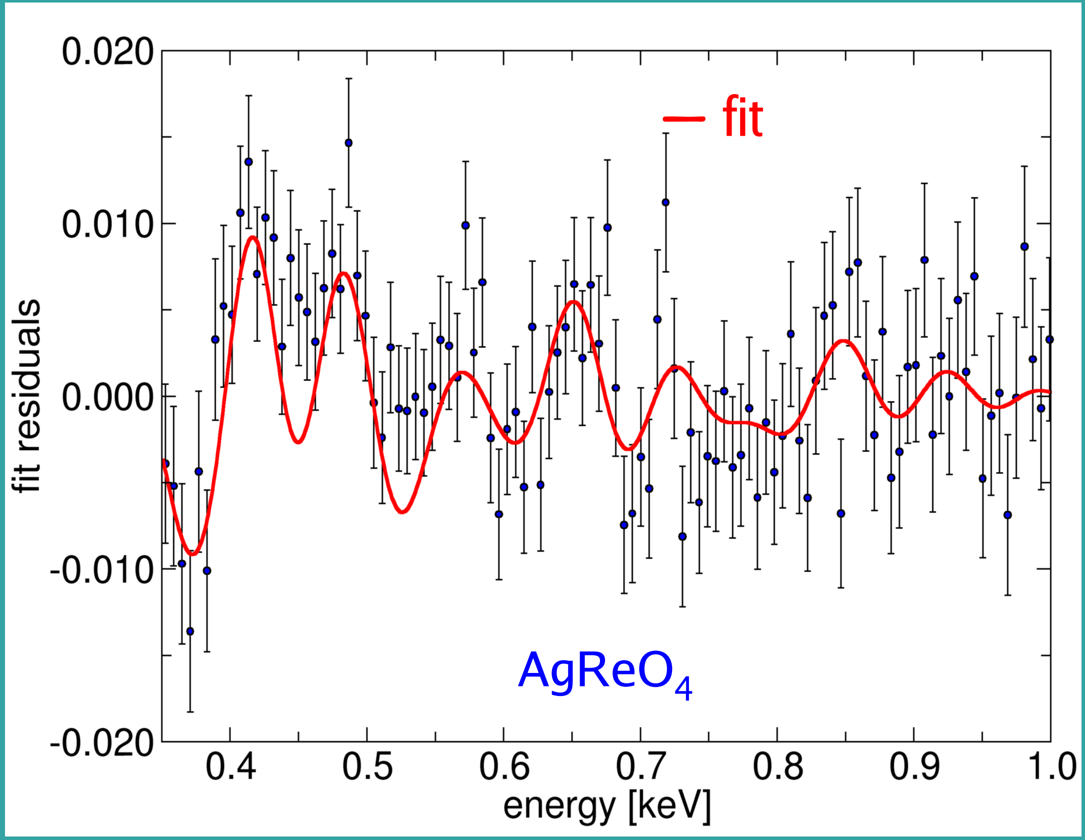
BEFS: Beta Environmental Fine Structure

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



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

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

→ $F_p = 0.84 \pm 0.30$

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

⇒ EXAFS measurements @ ESRF (oct 06)

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

Systematics summary: calorimeters vs. spectrometers

- **Calorimetry systematics**
  - detector response function (energy dependence, shape,...)
  - energy dependent background
  - ^{187}Re decay spectral shape
  - condensed matter effects: BEFS
  - pile-up effects
  - ...?

- **Spectrometers 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
  - ...?

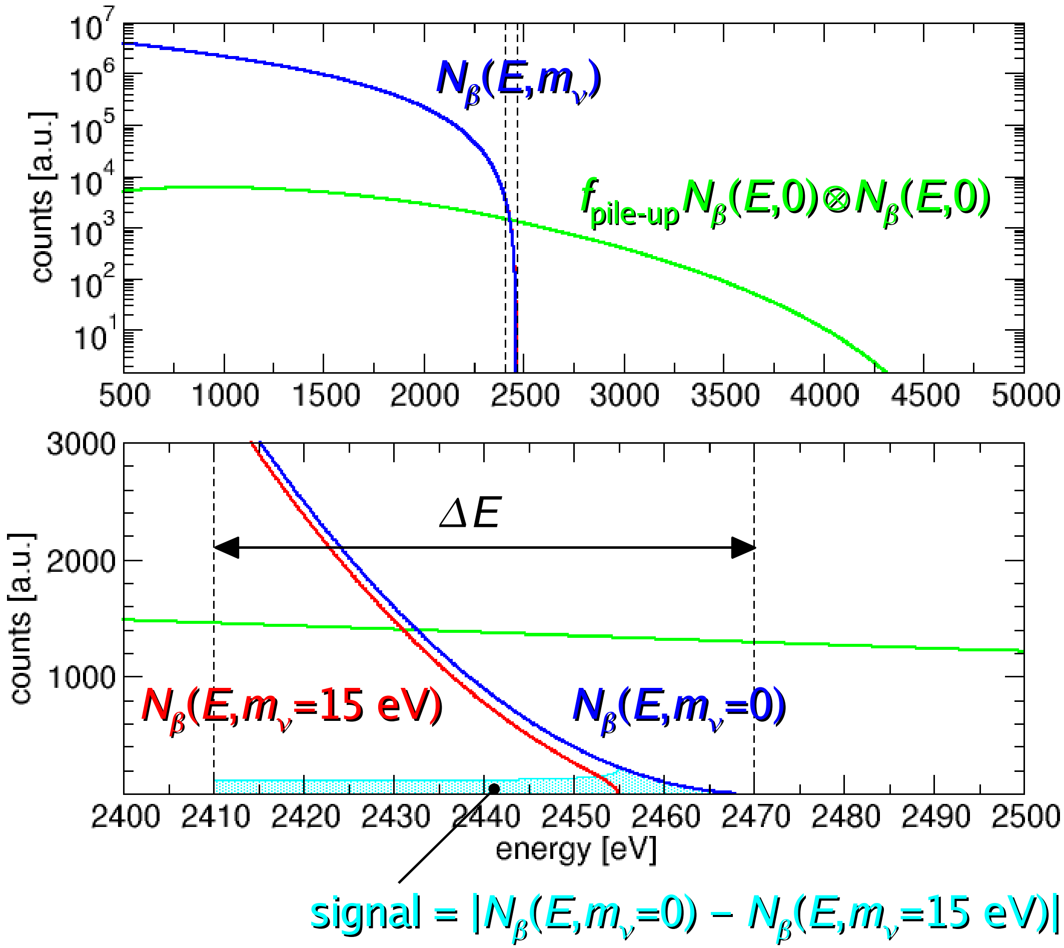
⇨ completely different systematics!

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 $t_M = T \times N_{det}$



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

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

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

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

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

Calorimetric experiment statistical sensitivity / 2

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

$$f_{pile-up} = \tau_R A_\beta \ll \frac{10}{9}\frac{\Delta E^2}{E_0^2}$$ $\Rightarrow$ pile-up is negligible

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

$$f_{pile-up} = \tau_R A_\beta \gg \frac{10}{9}\frac{\Delta E^2}{E_0^2}$$ $\Rightarrow$ pile-up dominates background

$$\Sigma_{90}(m_\nu) \approx 0.87 \sqrt[4]{\frac{E_0^5 \tau_R}{t_M \Delta E}}$$

^{187}Re calorimetric experiment statistical sensitivity

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

- MIBETA detectors with ΔE_{FWHM} = 30 eV, τ_R=1.5 ms
  - ▷ pile-up dominates for $A_\beta \gg 0.1$ decay/s
  - ▷ for $A_\beta = 0.15$ decay/s and t_M = 3.6 y×det (1.7×10^6 evts)
    - ⇒ $\Sigma(m_\nu)$= 12.3 eV

1/10

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

- detectors with ΔE_{FWHM}= 10 eV, τ_R=100 μs
  - ▷ pile-up dominates for $A_\beta \gg$ 0.7 decay/s
    - ⇒ $\Sigma(m_\nu)$= 2 eV in t_M = 520 y×det
  - ▷ for $A_\beta = 0.3$ decay/s < 0.7 decay/s
    - ⇒ $\Sigma(m_\nu)$= 2 eV in t_M = 1250 y×det (1.2×10^{10} evts)

1/10

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

- detectors with ΔE_{FWHM}= 1 eV, τ_R=1 μs
  - ▷ pile-up dominates for $A_\beta \gg$ 3 decay/s
  - ▷ for $A_\beta = 1$ decay/s < 3 decay/s
    - ⇒ $\Sigma(m_\nu)$= 0.2 eV in t_M = 190000 y×det (6×10^{12} evts)

Statistical sensitivity: MC simulations

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
  - $\tau_R \approx 3\tau_{rise}$ time resolution for pile-up identification
- $g(E)$: gaussian energy resolution function
  - ΔE FWHM detector energy resolution

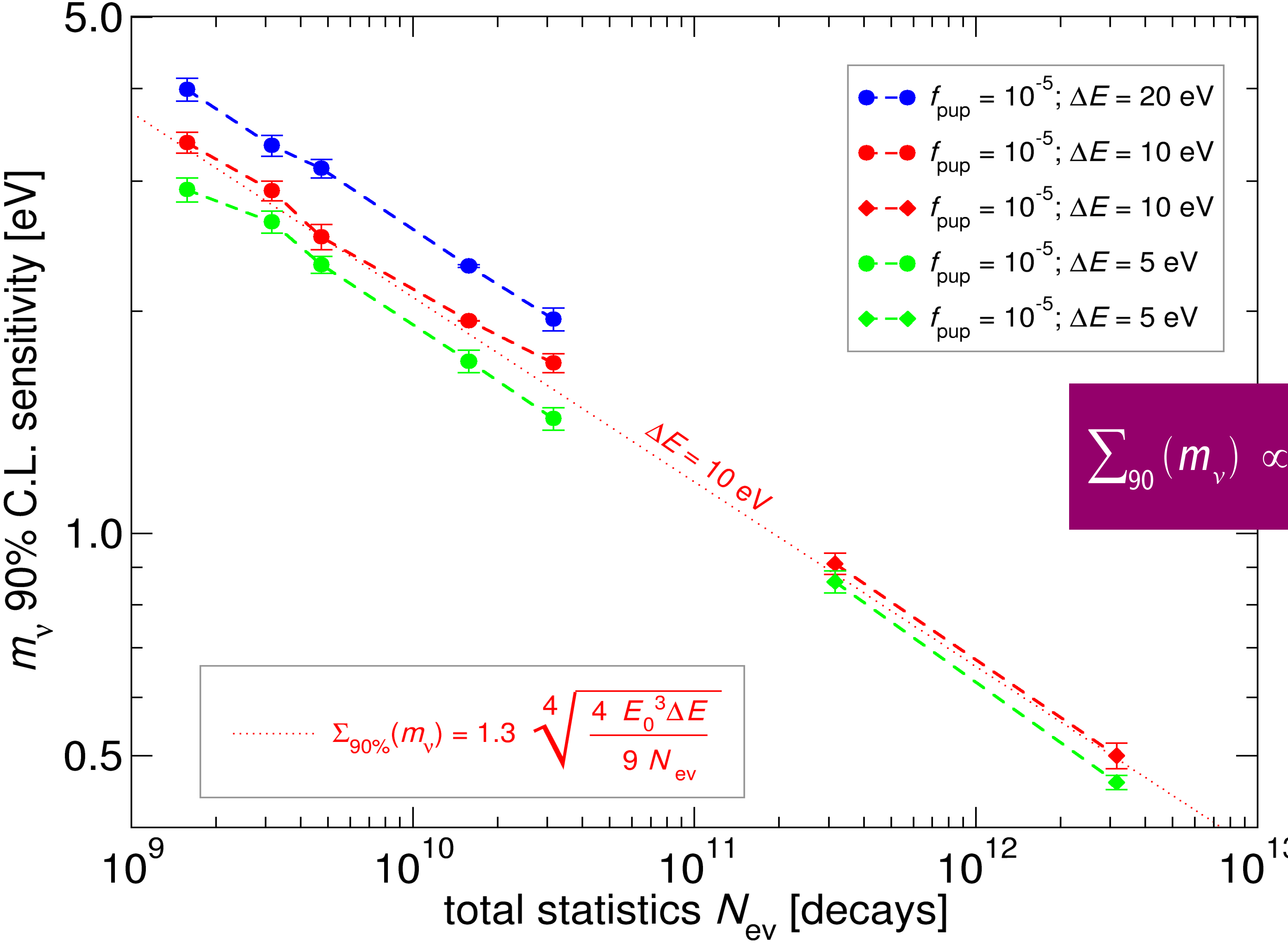
MIBETA experiment

N_{det}	8
t_M [y]	0.59
$\langle A_\beta \rangle$[dec/s]	0.15
$\langle m_{AgReO_4} \rangle$[$\mu$g]	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

MC simulations results: importance of statistics



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

total MIBETA statistics: 1.6×10^7 decays

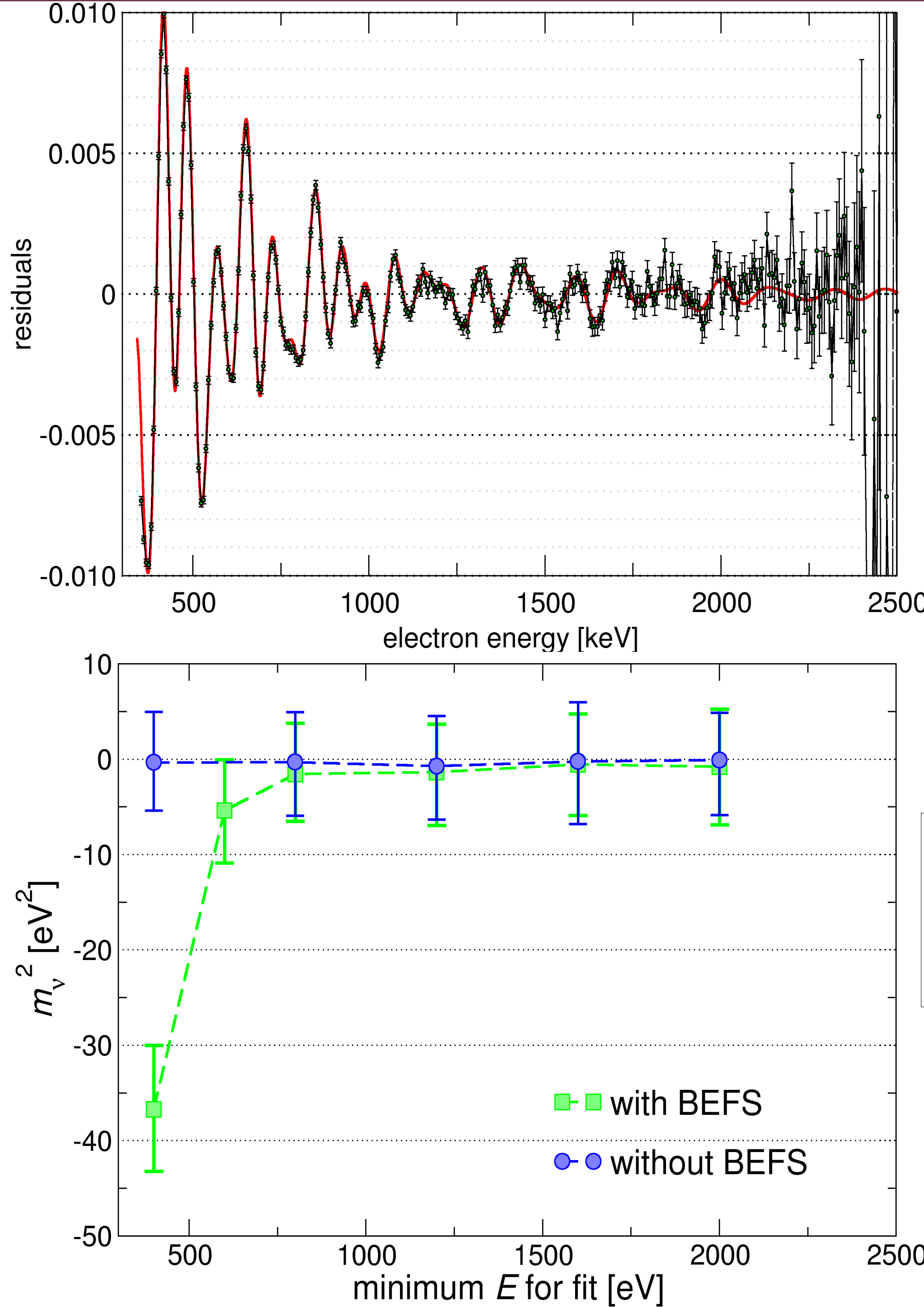
MC study of systematics: BEFS case

AgReO$_4$

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

$\Delta E = 20$ eV

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



analyzed without including BEFS

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 immediately (2007)

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
...

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

MARE project: Working Group structure

Spokesman
F. Gatti (Genova)

US Co-spokesman
K. M. Heeger (Madison)

10 Mare WGs

Technical Coordinator
A. Nucciotti (Milano)

- **^{187}Re spectrum** — M.Sisti (Milano)
- **Background** — T. Saab (Miami)

MARE-1 ⇨ 2 eV

- **TES-1** — F. Gatti (Genova)
- **SEMICON** — A. Nucciotti (Milano)

MARE-2 ⇨ 0.2 eV

- **TES-2** — C. K. Stahle (NASA/GFSC)
- **MMC** — C. Henss (Heidelberg)
- **MKID** — A. Giuliani (Como)
- **qp in Re** — A. Fleischmann (Heidelberg)

- **DAQ** — E. Previtali (Milano)
- **Read-out** — G. Pessina (Milano)
- **SQUID&MUX** — K. D. Irwin (NIST/Boulder)

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 silicon implanted thermistor technology
- $AgReO_4$ crystals

MARE-1 TES (MANU2)

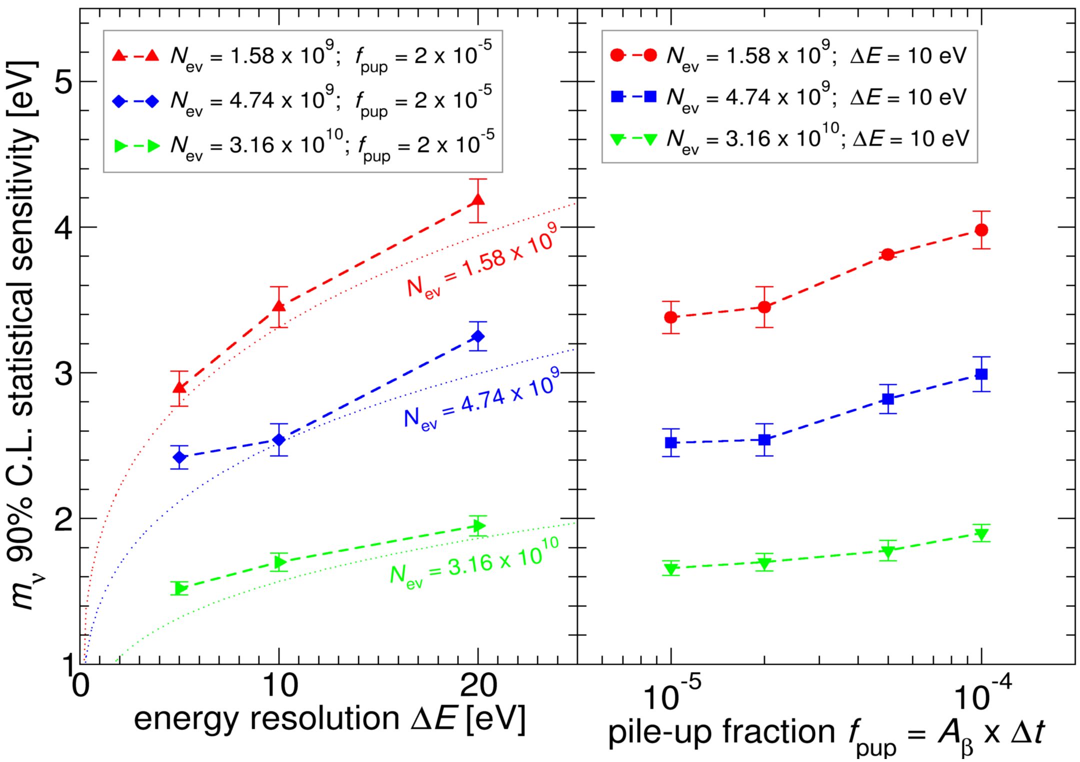
U. Genova / INFN Sez. Genova

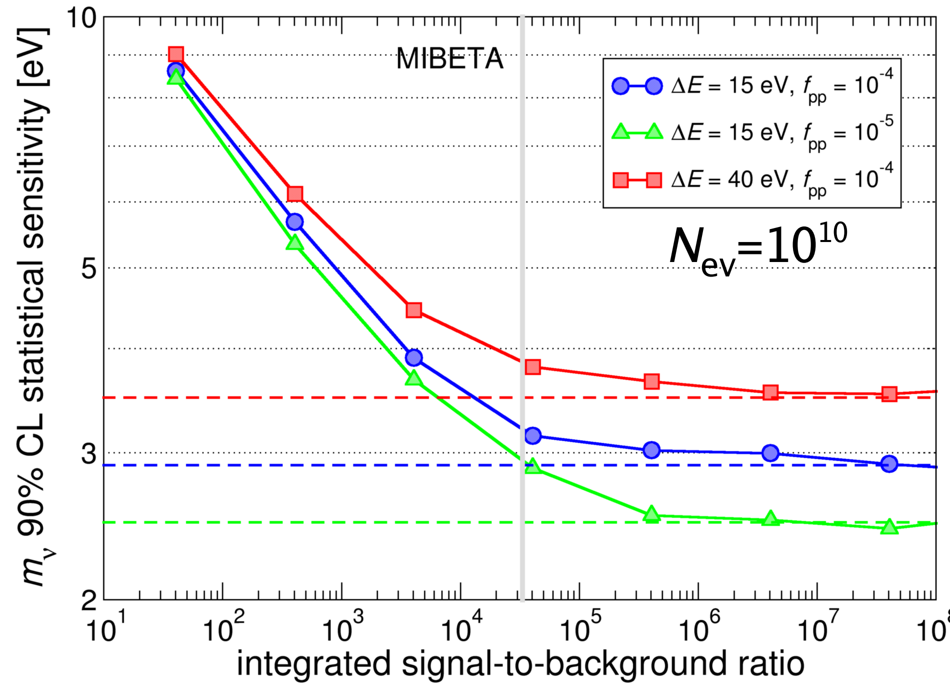
- about 300 element arrays
- newly developed transition edge sensors
- Re crystals

MARE-1 critical parameters for few eV m_ν sensitivity

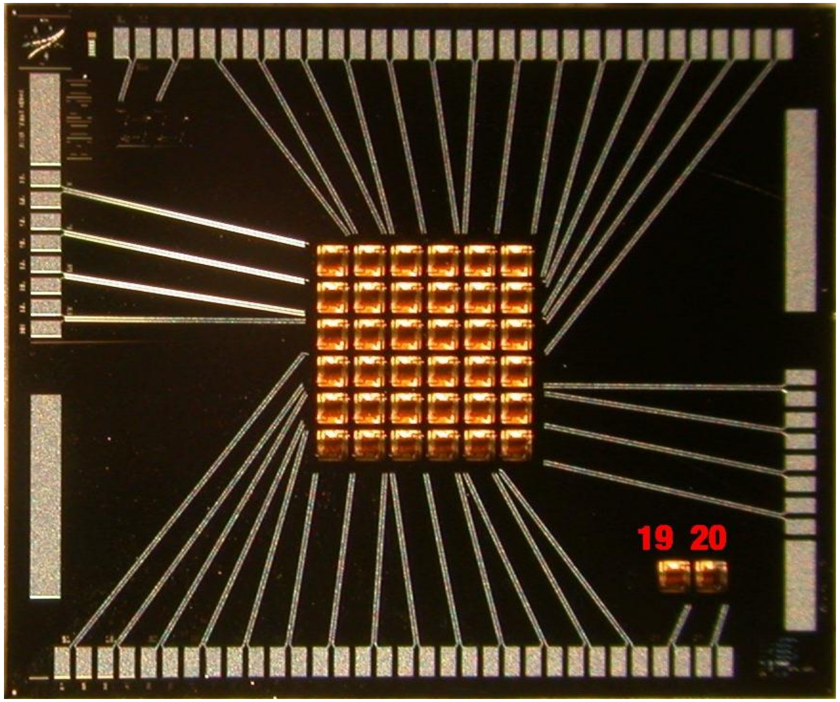
$N_{ev} \approx 10^{10}$

- ▷ energy resolution ΔE
- ▷ time resolution Δt
- ▷ background

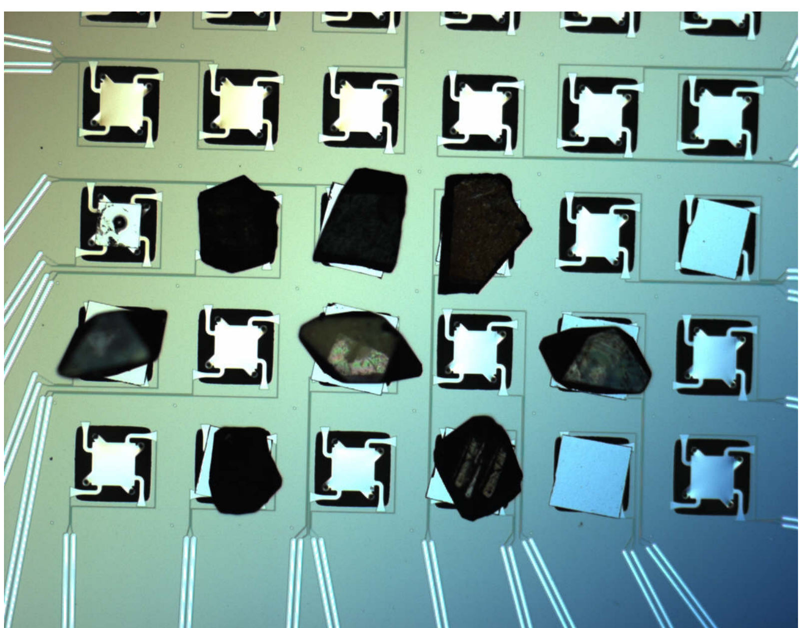


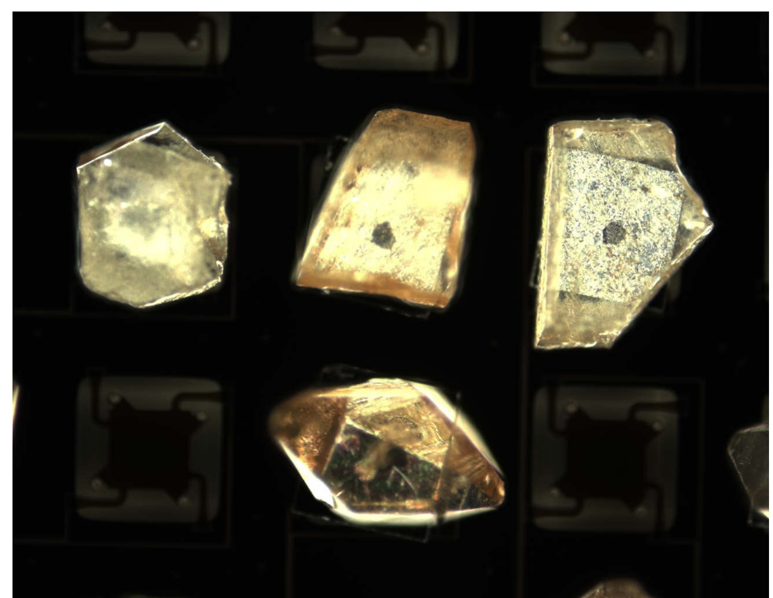


MARE-1 SEMICON: NASA/Goddard XRS2 silicon array



6×6
array



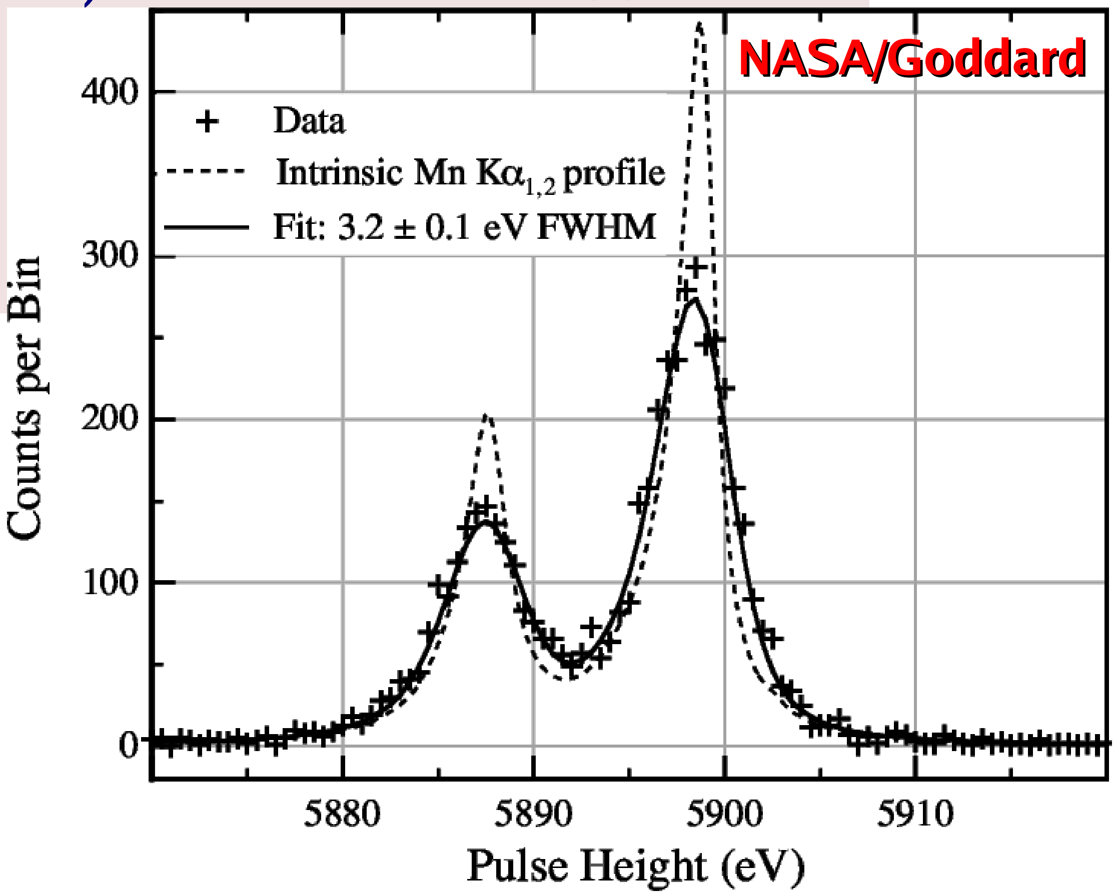


$AgReO_4$
crystals

XRS2 array optimized for X-ray spectroscopy

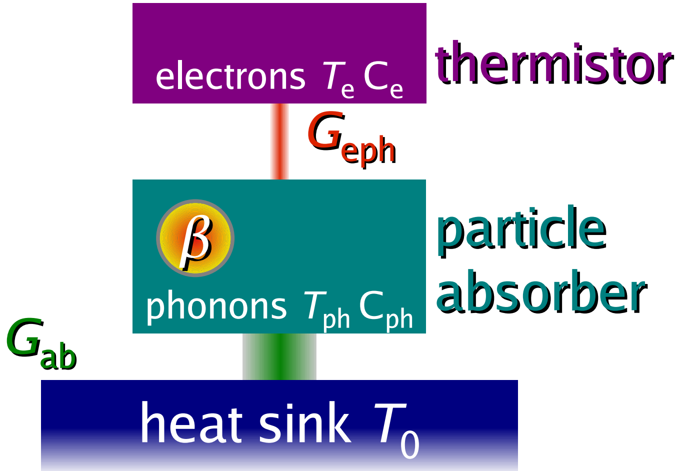
XRS2 detectors: silicon implanted thermistor with HgTe ($625\times625\times8\mu m^3$) absorber at $T = 60$ mK

- ▷ $C_{tot} \approx 10^{-13}$ J/K
- ▷ $T_0 = 7$ K $\rightarrow A \approx 5.4$
- ▷ $\Delta E_{theory} = 2$ eV



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

Low temperature electrical properties of thermistors



Silicon implanted thermistors
electron-phonon coupling G_{eph}
sets an intrinsic limit to detector resolving time $\tau_R \approx 3\tau_0$

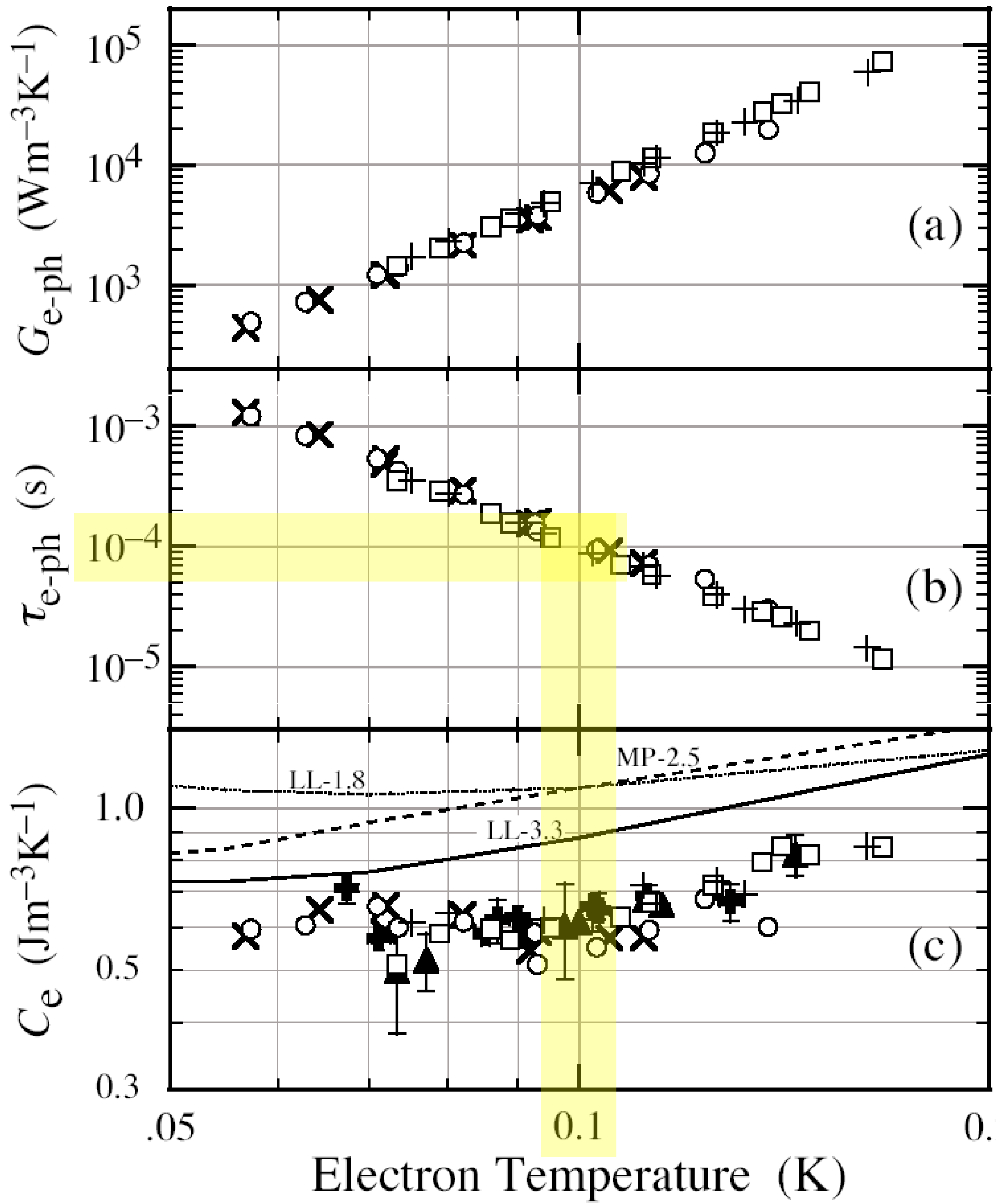
$$\tau_0 \approx \frac{1}{G_{e-ph}}\left(\frac{C_a C_e}{C_a + C_e}\right)$$

for $C_a \gg C_e$

$$\tau_0 \approx \tau_{e-ph} \approx \frac{C_e}{G_{e-ph}} \propto T_e^{-4}$$

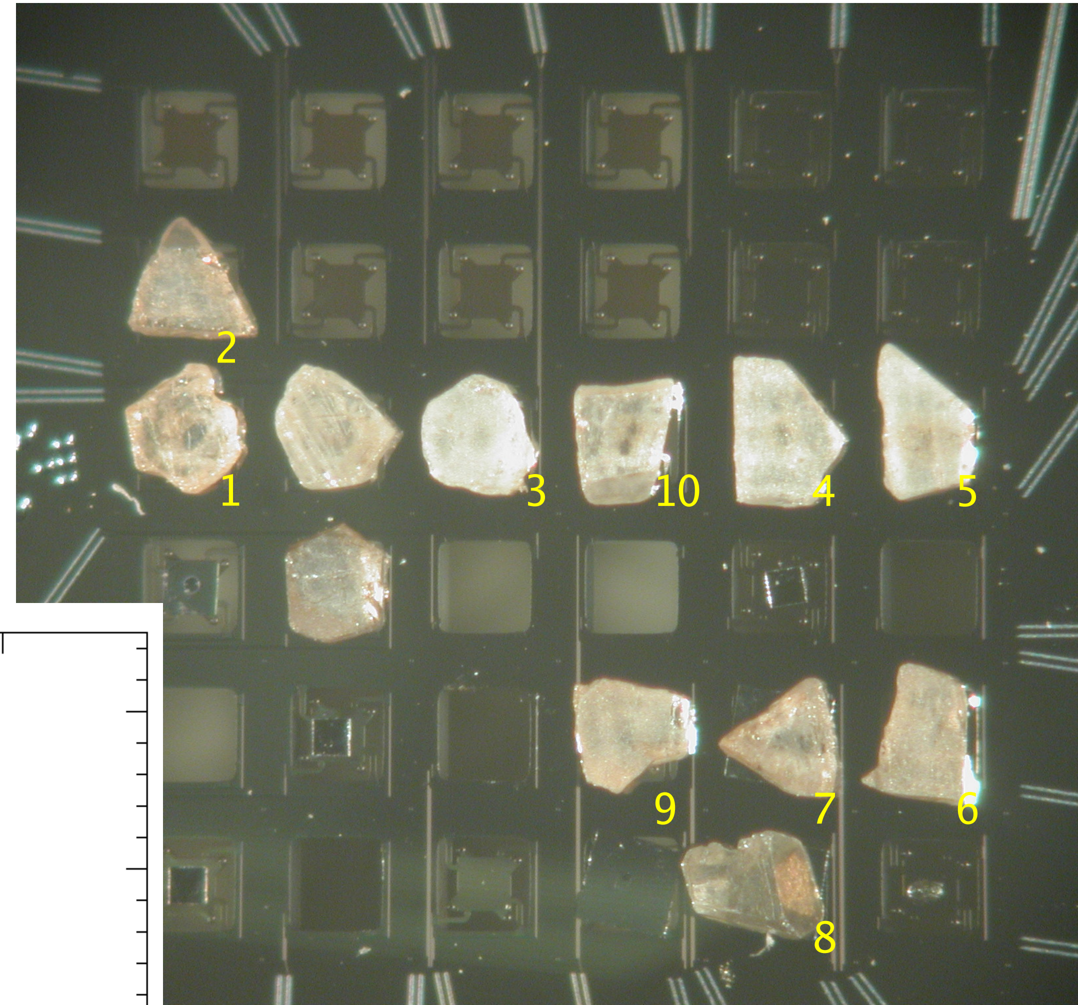
$C_e \propto$ thermistor volume

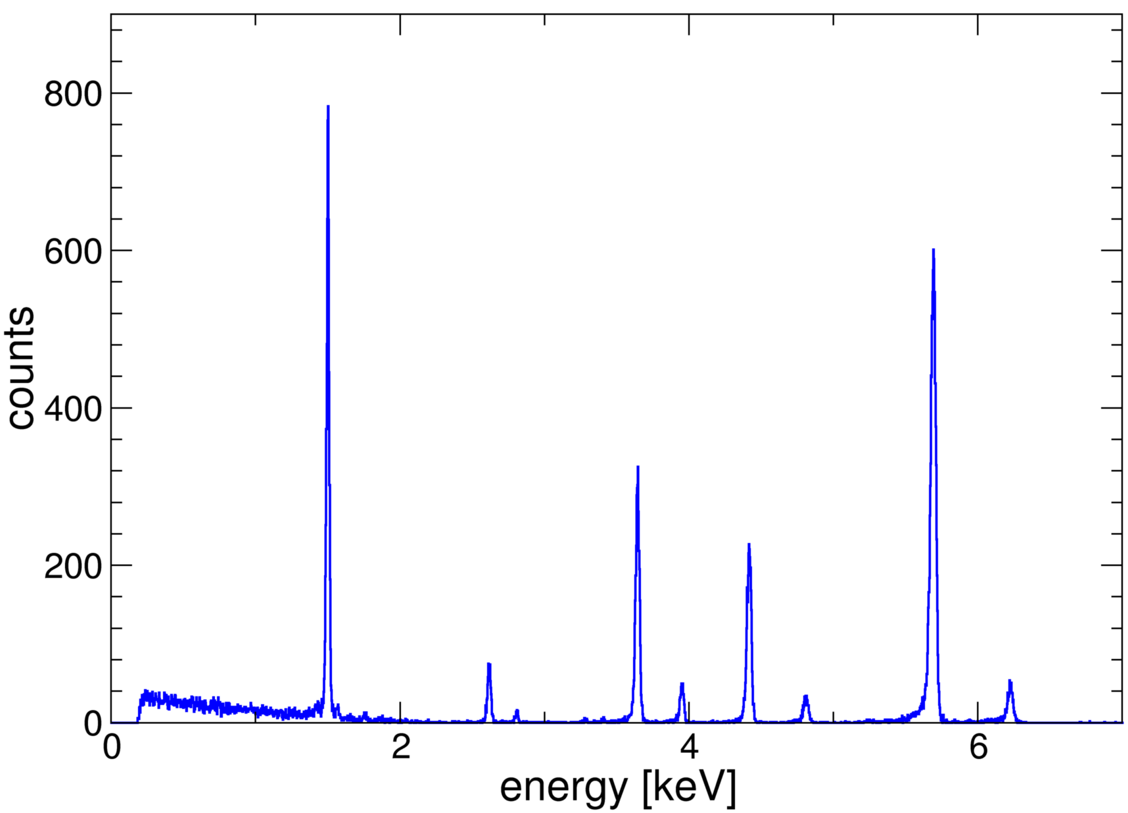
$G_{e-ph} \propto$ thermistor volume



MARE-1 SEMICON detector optimization

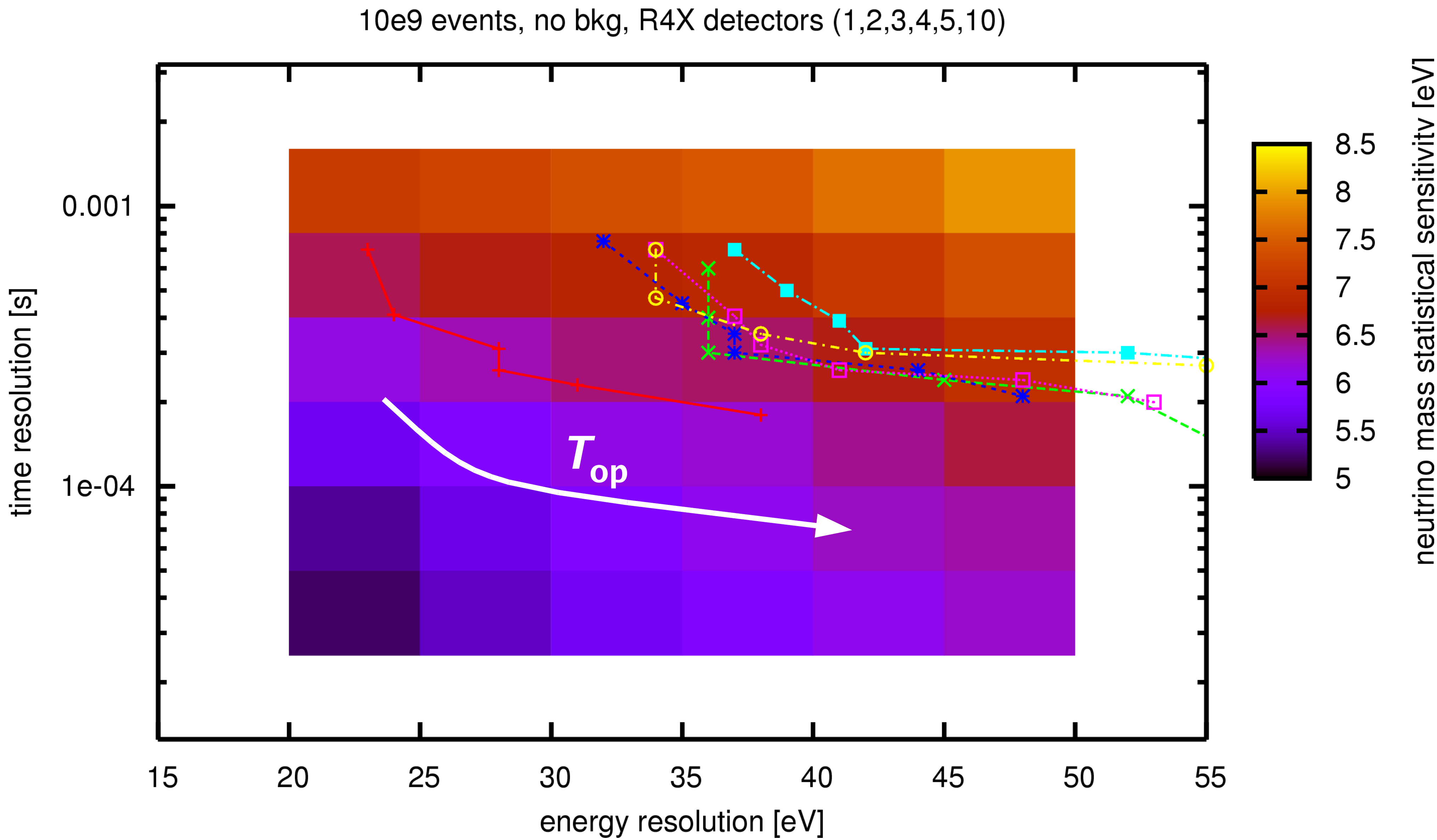
- NASA/Goddard array XRS2-2 C3
- 10 $AgReO_4$ “flattened” crystals
  - ▷ $m \approx 0.386 \div 0.506$ mg
- crystal-sensor coupling tests
  - ▷ best operating T around 90mK
  - ▷ **ΔE = 28 eV, τ_R = 260 μs**





read-out electronics not yet optimized

MARE-1 detector optimization: ΔE vs. τ_R



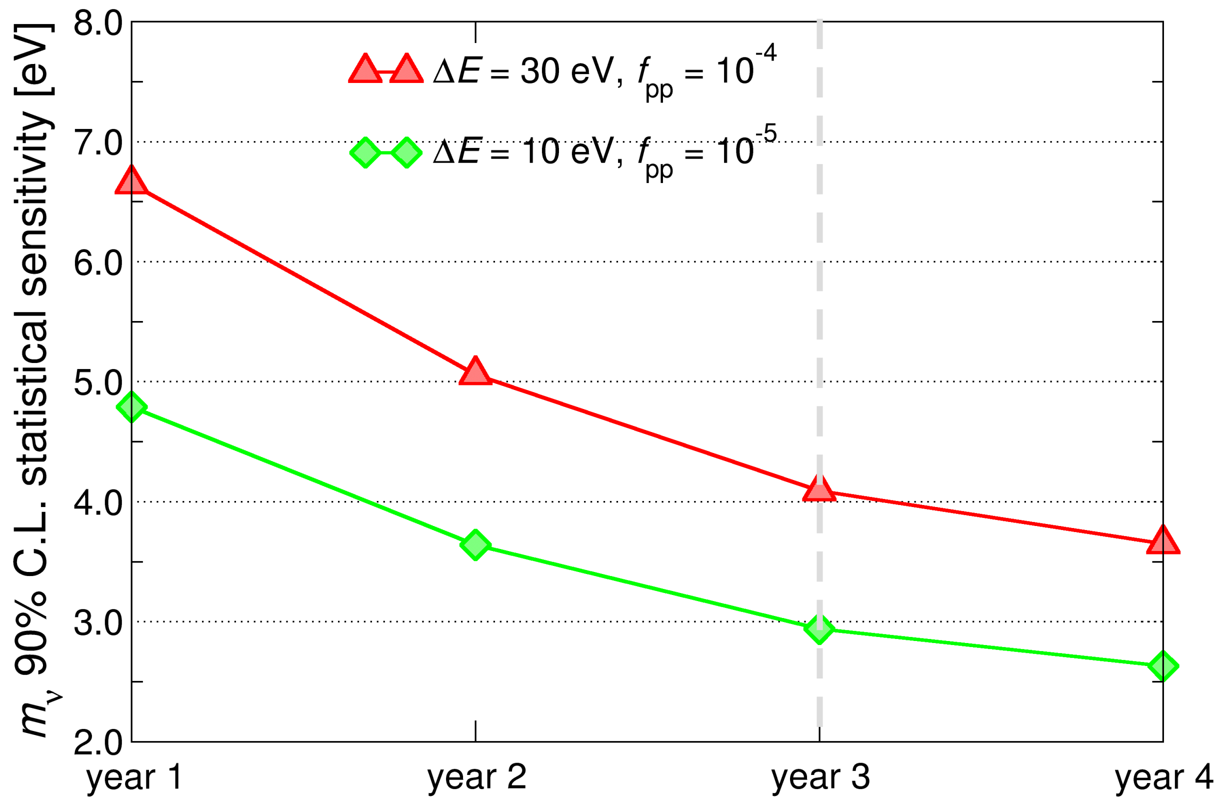
target MARE-1 statistics is about 7×10^9 ⇒ 1.6 times better than above sensitivity

MARE-1 SEMICON: statistical sensitivity

year	1	2	3	4	5
new detectors	72	72	144	0	0
total detectors	72	144	288	288	288
statistics [det*y]	72	216	504	792	1080
activity [c/s] = 0.27		m_{AgReO4} = 500 μg			
statistics [events]	6.1E+08	1.8E+09	4.3E+09	6.7E+09	9.2E+09
ΔE = 30 eV	τ = 200μ s	f_{pp} = 1.0E-4			
m_ν sensitivity (90%)	6.6	5.0	4.1	3.6	3.4
ΔE = 10 eV	τ = 50μ s	f_{pp} = 1.0E-5			
m_ν sensitivity (90%)	4.8	3.6	2.9	2.6	2.4

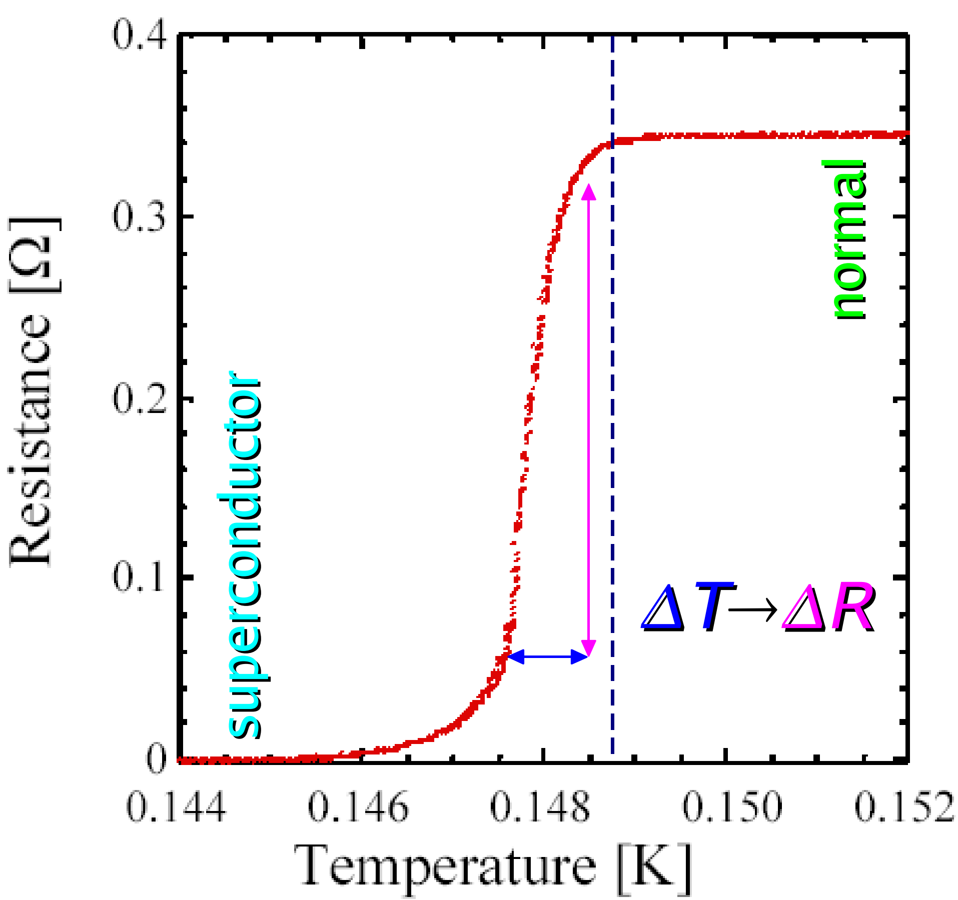
a faster deployment is possible

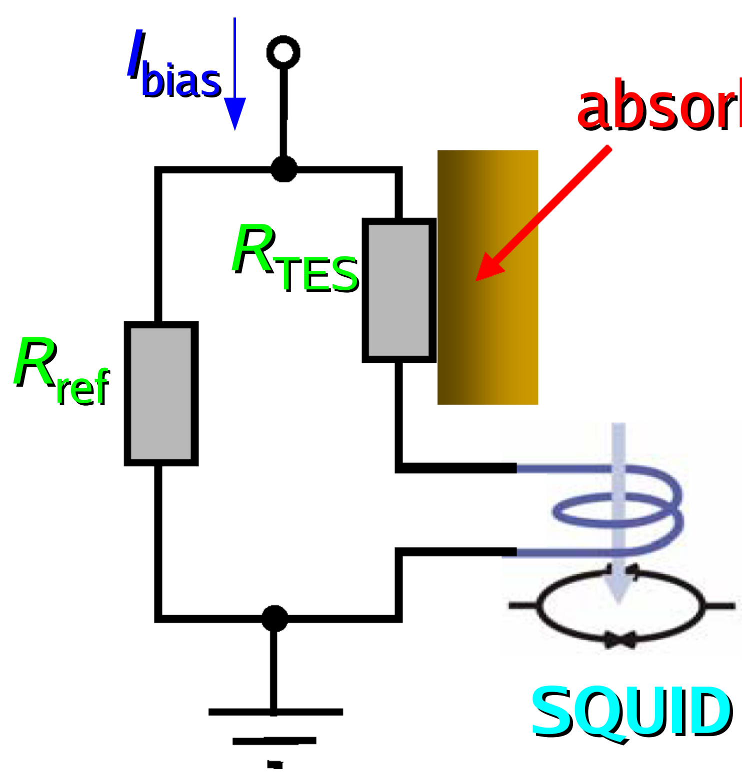
- 8 arrays
- 288 $AgReO_4$ crystals
- gradual deployment
  - further optimization
  - new array development at ITC-irst



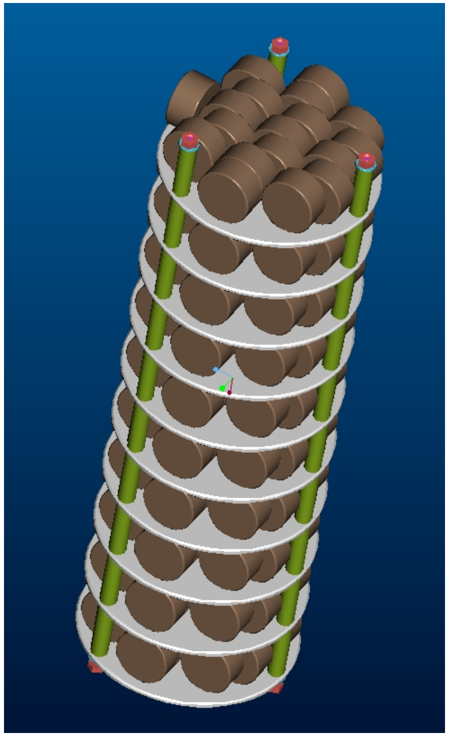
MARE-1 TES: Superconducting transition edge sensors

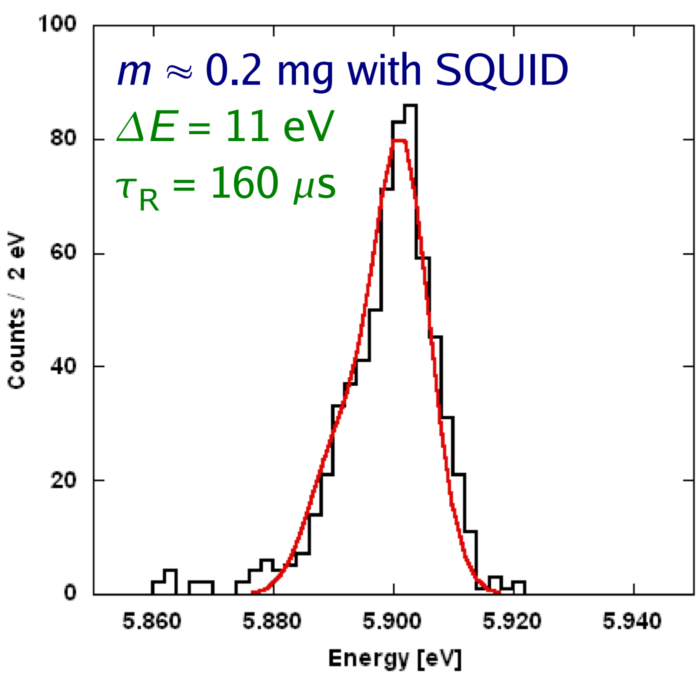
- **superconductor thin films** used inside the phase transition at T_c
  - pure superconductors: **Ir** (T_c= 112 mK), **W** (T_c= 15 mK), ...
  - metal-superconductor bilayers ⇒ tunable T_c (20÷200 mK) : **Mo/Cu, Tl/Au, Ir/Au**, ...
    - high sensitivity (A≈100) ⇒ **high energy resolution**
    -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

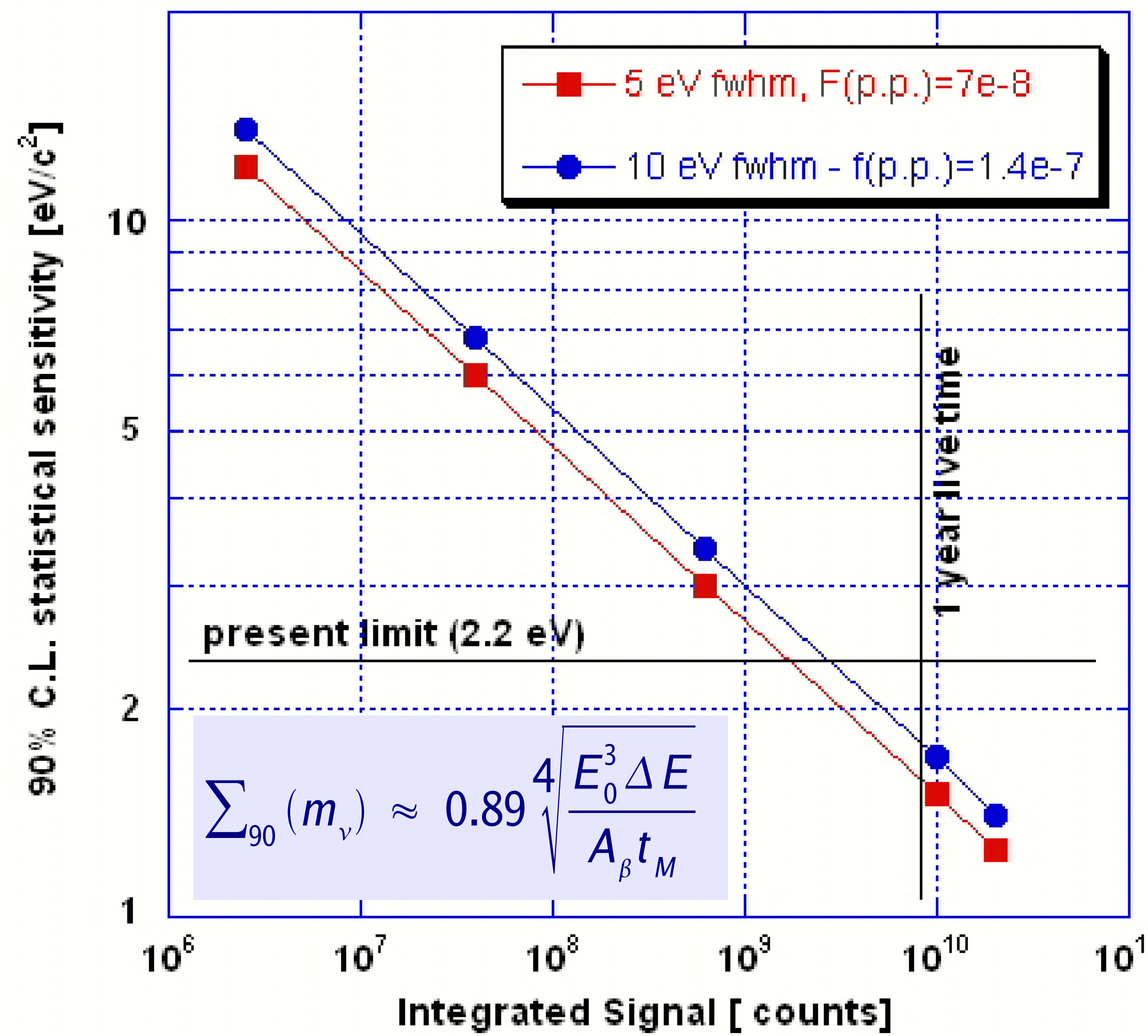




MARE-1 TES: statistical sensitivity



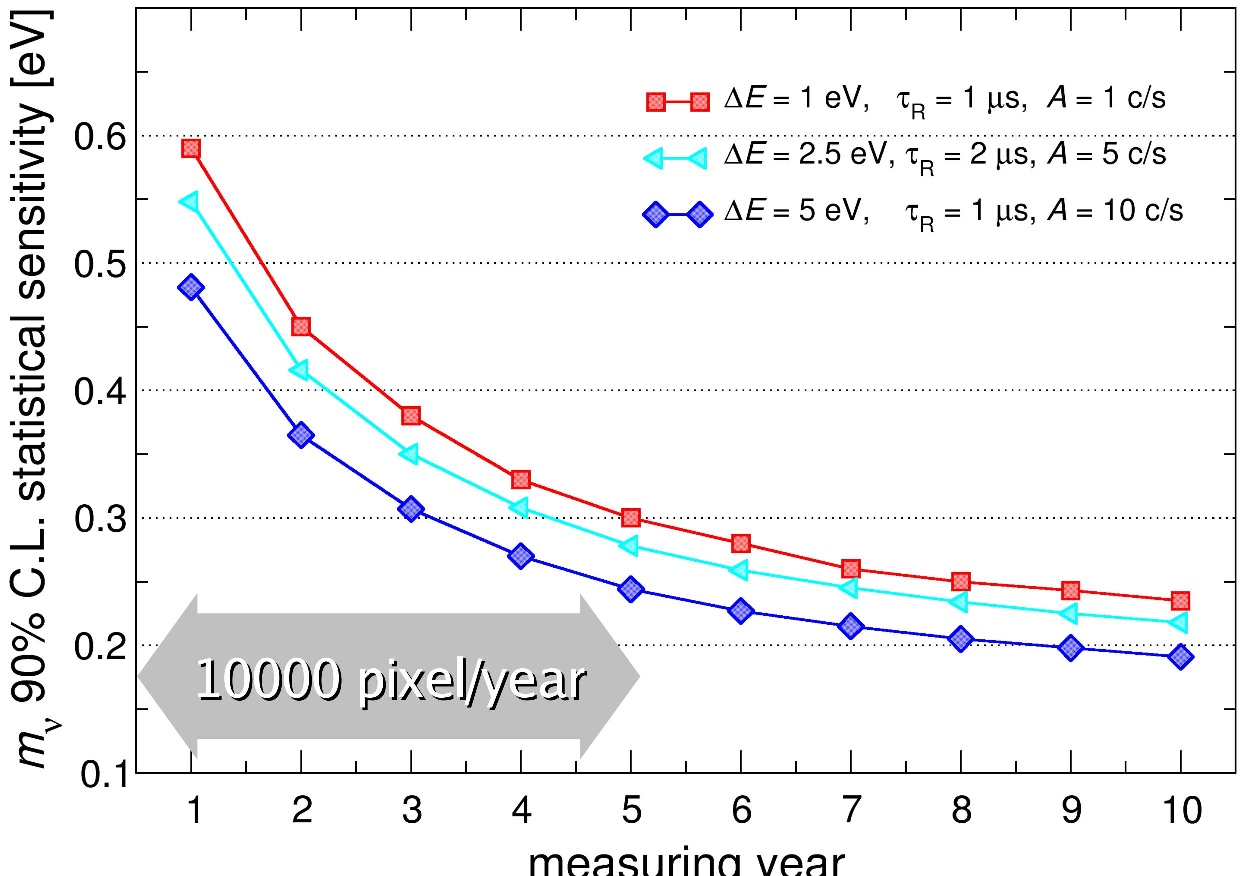




- 300 rhenium crystals in 2 refrigerators
  - $m \approx$ 1 mg
- Ir/Au or Al/Ag TES at 100 mK with no-SQUID read-out
  - **$\Delta E = 10$ eV, $\tau_R = 10\ \mu s$, $f_{pp} = 2\times10^{-5}$**
- **about 10^{10} events in 1 year ⇒ $m_\nu < 1.5$ eV**

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)

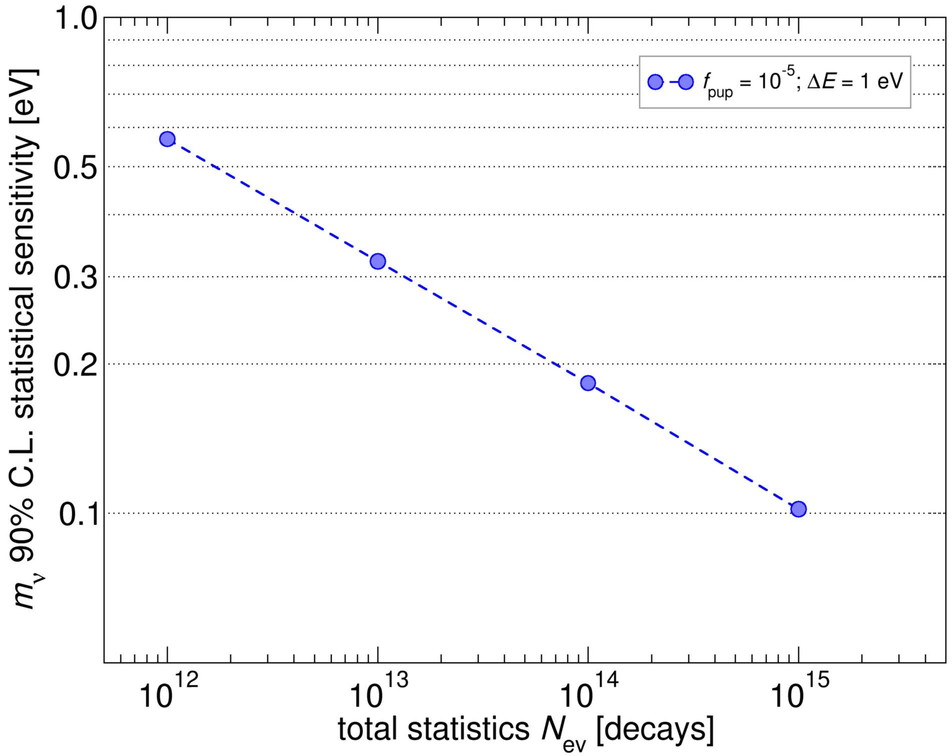


10000 pixel *kits*
$\Delta E \approx 1$ eV
$\tau_R \approx 1\ \mu s$
$A_\beta \approx 1 \div 10$ Hz

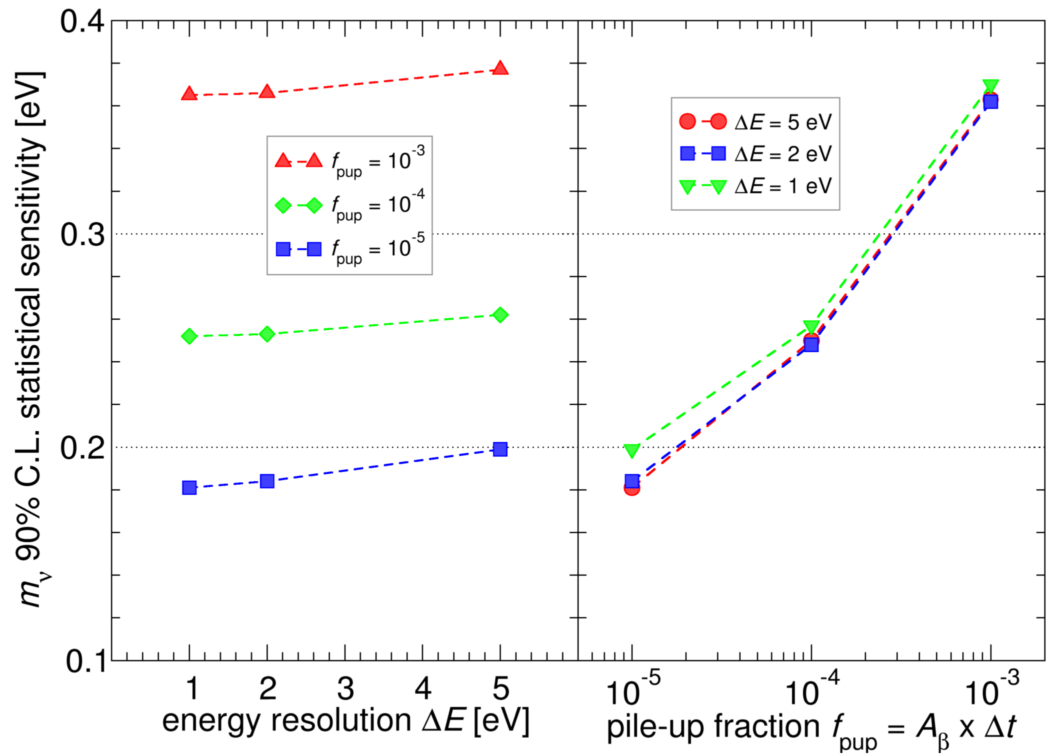
need for
new sensor R&D
and
new read-out techniques

MARE-2 MC simulations for 0.2 eV m_ν sensitivity

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

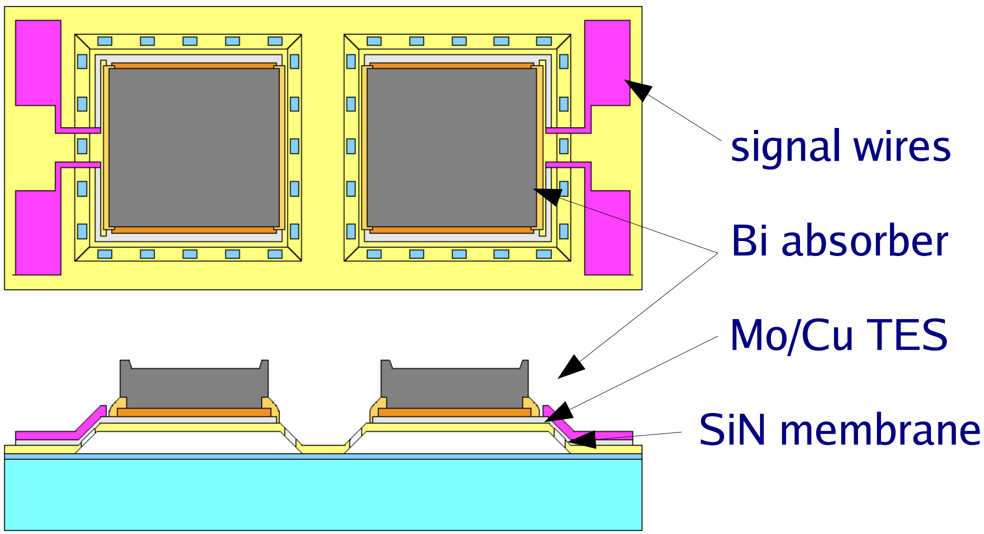


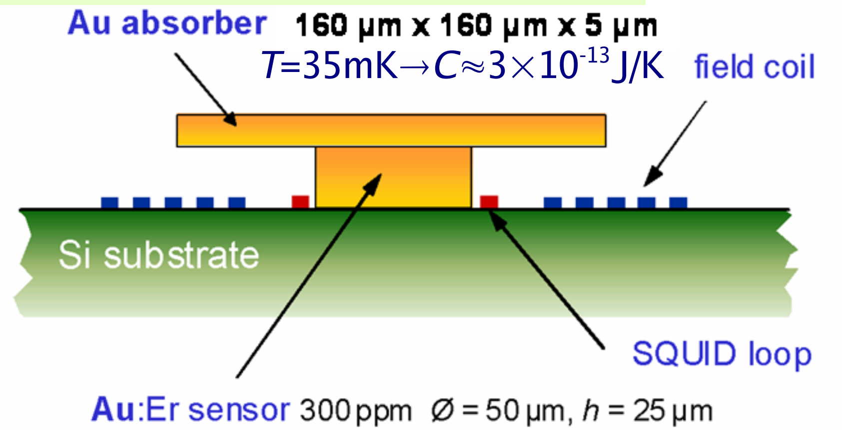
$N_{ev}=10^{14}$

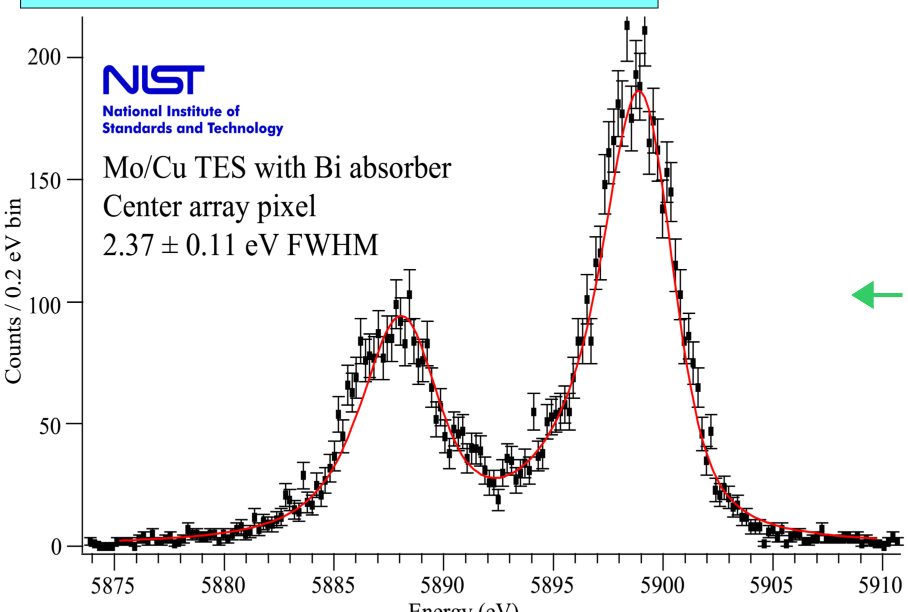


Sensor R&D for MARE-2: Goddard, NIST, Heidelberg,...

- **fast** devices for high single pixel activity A_β and low pile-up f_{pp}
- **high energy resolution** with large heat capacity absorbers
- **multiplexing** for very large number of pixel

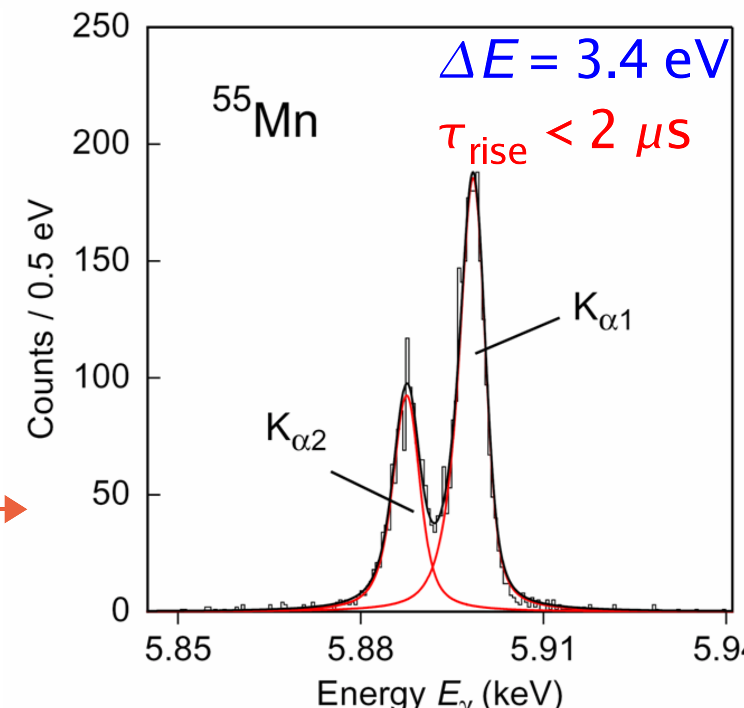




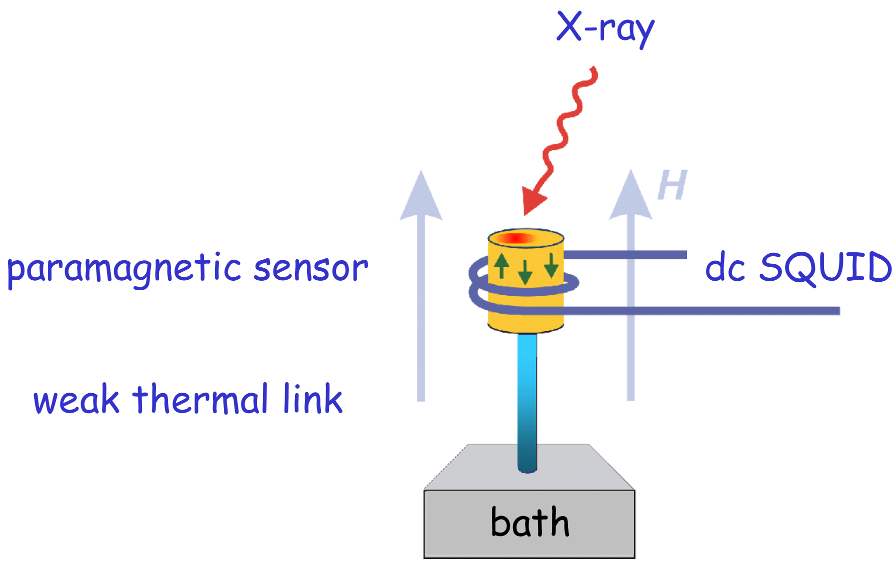


← **TES**

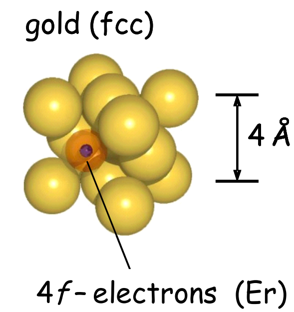
MMC →



MMC – Magnetic Micro Calorimeters (Heidelberg)

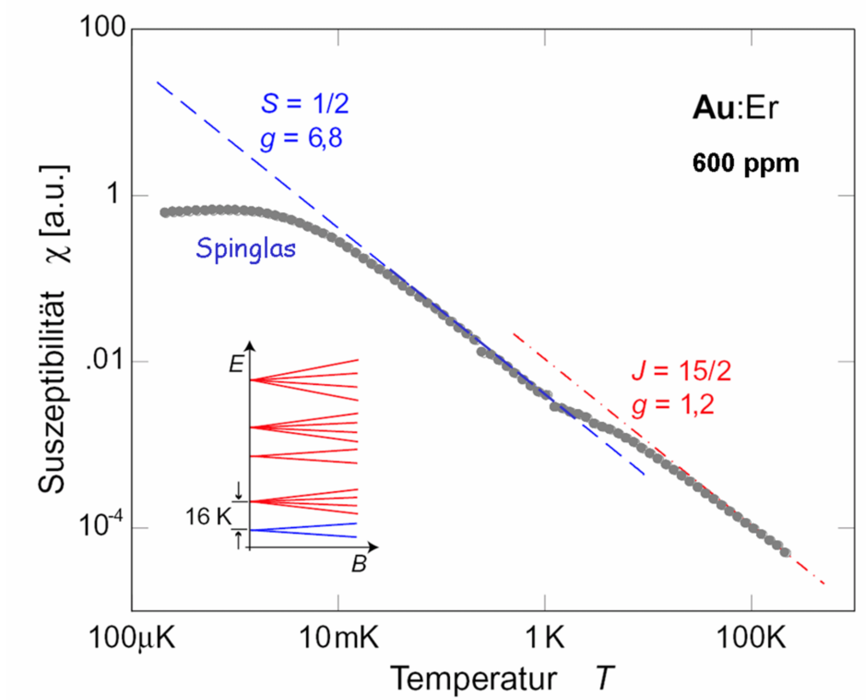


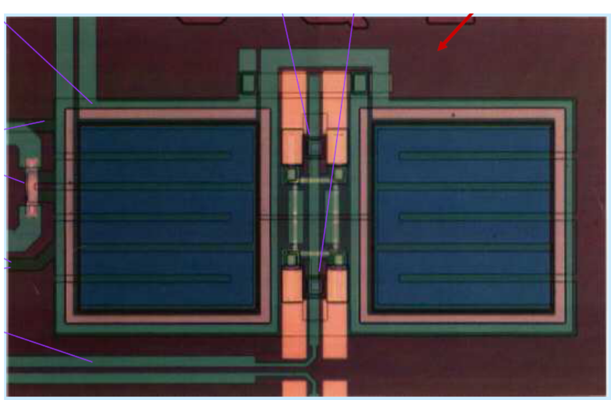
Sensor: Au:Er
Au:Yb
Bi_2Te_3:Er
PbTe:Er



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

- suitable for large capacity absorbers
- very fast ~μs
- high energy resolution ~eV



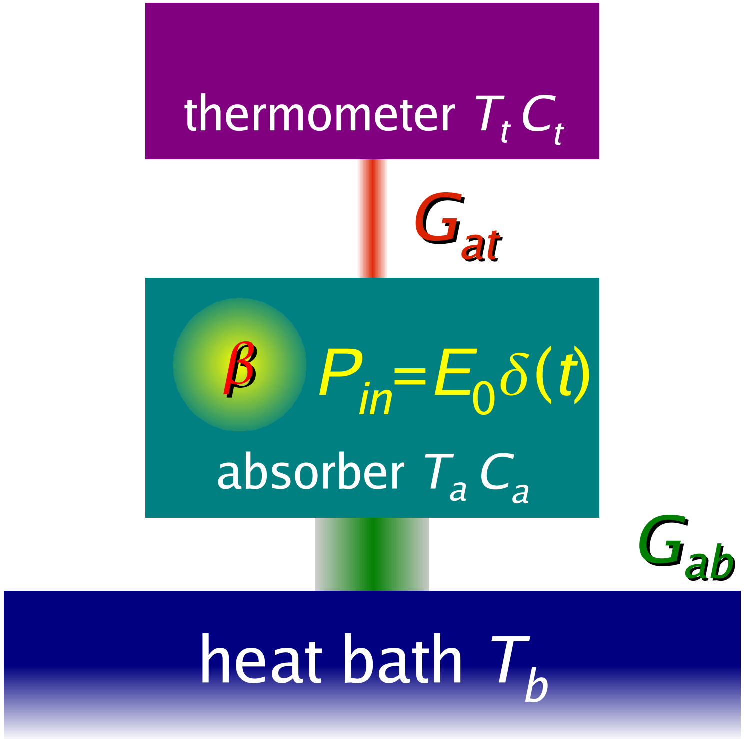


sensor design optimization for MARE-2 rhenium absorbers is in progress
⇨ meander pick-up coils without external B field

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)

More realistic detector model / 1



- power flow in the small signal approximation

$$P = \frac{dE}{dt} = C\frac{dT}{dt} \approx G\Delta T$$

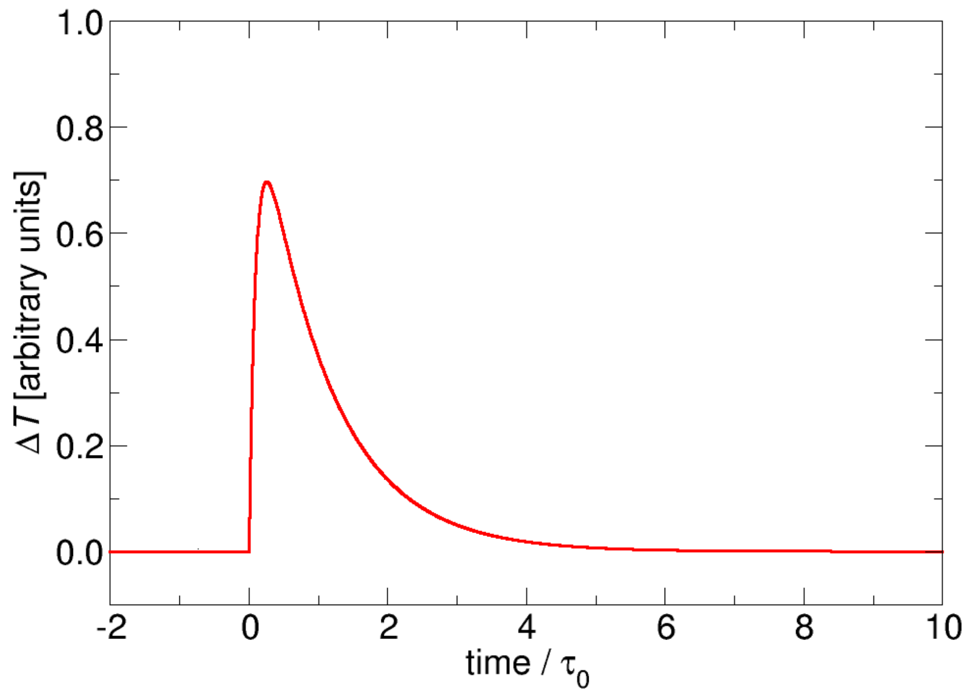
$$C_a \frac{dT_a}{dt} = -(T_a - T_t)G_{at} - (T_a - T_b)G_{ab} + E_0\delta(t)$$

$$C_t \frac{dT_t}{dt} = -(T_t - T_a)G_{at}$$

solution for $G_{ab} \ll G_{at}$

$$\Delta T_t(t) \approx \frac{E_0}{C_a + C_t}\left[e^{-t/\tau_1} - e^{-t/\tau_0}\right]$$

$$\tau_0 \approx \frac{1}{G_{at}}\left(\frac{C_a C_t}{C_a + C_t}\right); \quad \tau_1 \approx \frac{1}{G_{ab}}(C_a + C_t)$$



MARE

Microcalorimeter Arrays for a Rhenium Experiment

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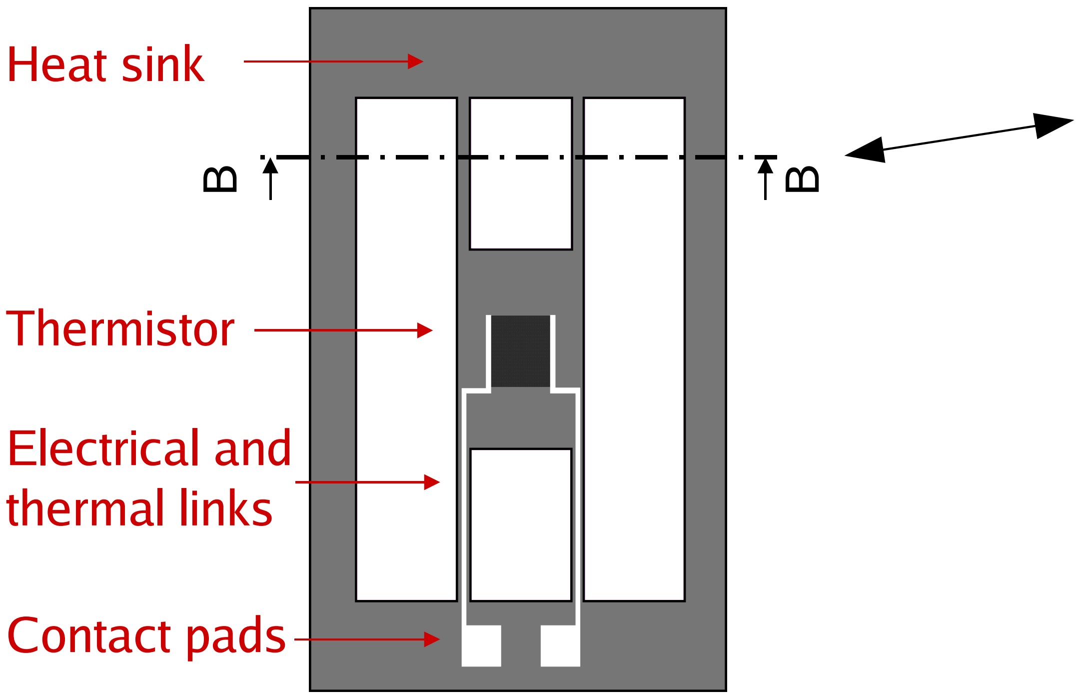
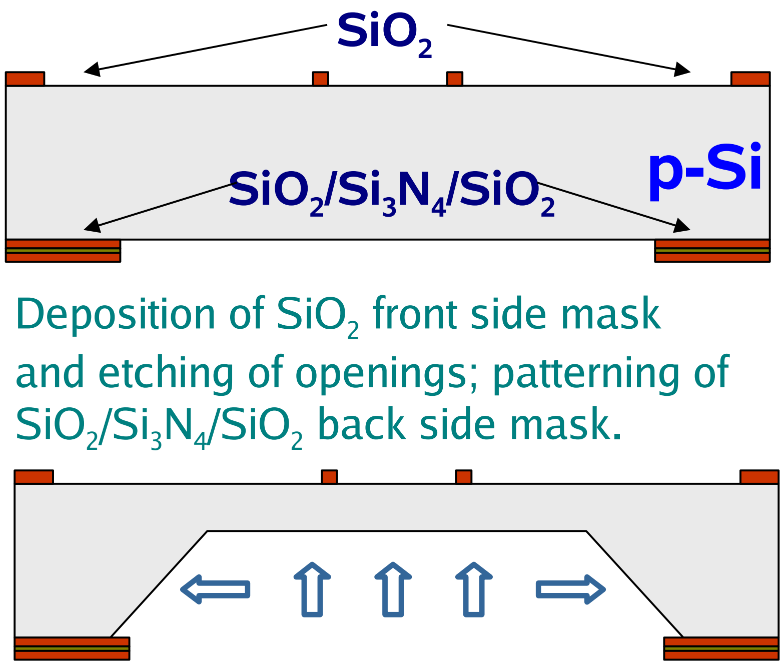
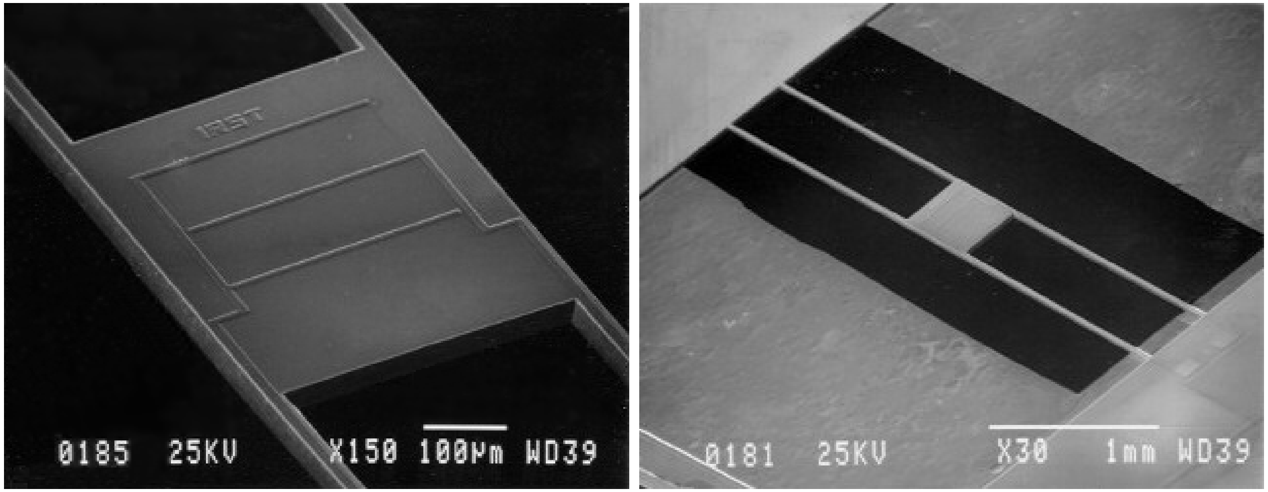
Silicon micromachined detectors @ IRST

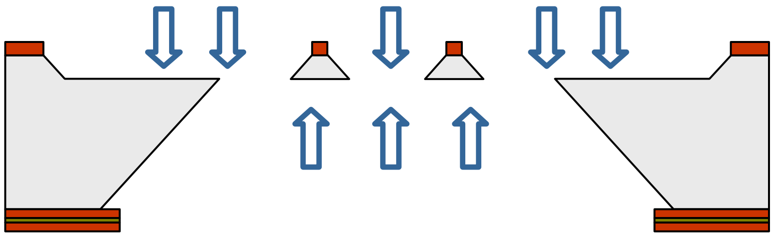




Deposition of SiO_2 front side mask and etching of openings; patterning of $SiO_2/Si_3N_4/SiO_2$ back side mask.

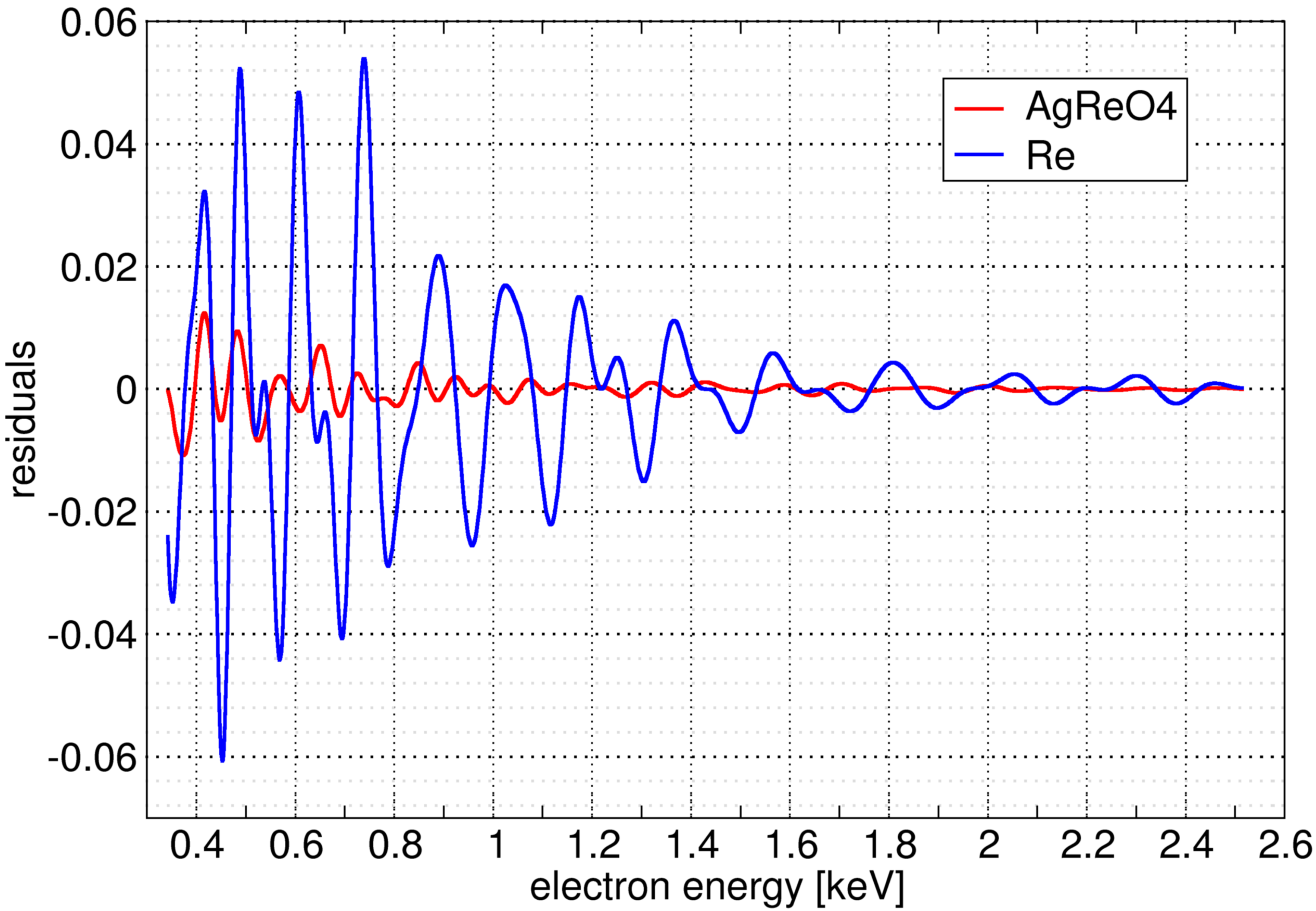
Anisotropic silicon etching in TMAH from rear side.





Anisotropic silicon etching in TMAH+silicic acid+$(NH_4)S_2O_8$ to release thermistor and links.

BEFS: Re vs. $AgReO_4$



^{187}Re calorimetric experiment statistical sensitivity

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

1/10

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

1/10

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

- MIBETA detectors with ΔE_{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 → f_{pp} = 2×10^{-4}
  - ▷ t_M = 3.6 y×det → 1.6×10^6 events
  - ▷ $\Sigma_{exp}(m_\nu)$ = 15 eV
- detectors with ΔE_{FWHM} = 10 eV, τ_R=100 μs
  - ▷ pile-up dominates for $A_\beta \gg$0.7 decay/s
  - ▷ for A_β = 0.3 decay/s → f_{pp} = 3×10^{-5}
  - ▷ $\Sigma_{MC}(m_\nu)$ = 2 eV with 2×10^{10} events
  - ▷ t_M = 2000 y×det
- detectors with ΔE_{FWHM} = 1 eV, τ_R=1 μs
  - ▷ pile-up dominates for $A_\beta \gg$ 3 decay/s
  - ▷ for A_β = 1 decay/s → f_{pp} = 10^{-6}
  - ▷ $\Sigma_{MC}(m_\nu)$ = 0.2 eV with → 2.5×10^{13} events
  - ▷ t_M = 8×10^5 y×det