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The MARE experiment: calorimetric approach for the direct measurement of the neutrino mass

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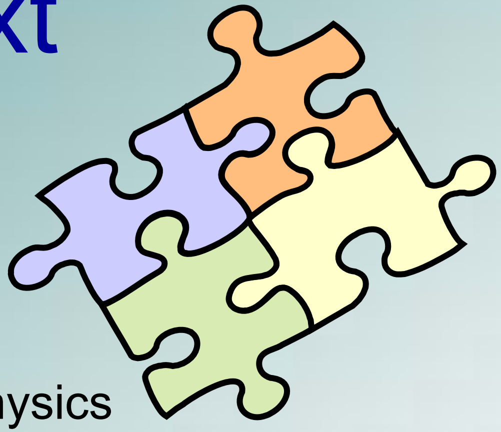
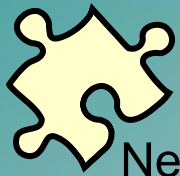
on behalf of the MARE collaboration

Summary

- The physical context
- Basic concepts & experimental requirements for the direct measurement of m_ν
- Spectrometers versus Calorimeters
- Re-based μcalorimeters: basic concepts & state-of-the-art (special care to MIBETA & semiconductor thermistors)
- The MARE project: aims, potentiality & experimental requirements

The physical context





Oscillation experiments

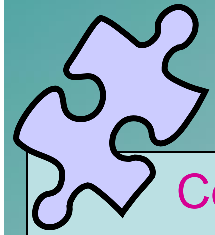
↓

Neutrinos have non-zero mass

ν mass scale is crucial over 2 fronts:
elementary particles physics & astroparticle physics

WE NEED TO KNOW:

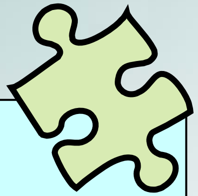
- absolute ν mass scale
- nature of ν mass



Cosmology

$\sum m_{\nu i} \leq 0.7 - 2$ eV/c^2

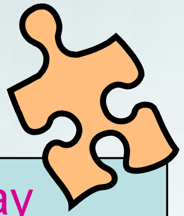
- ❖ very sensitive
- ❖ spread in recent results
- ❖ model dependent



Direct search through β decay

Potential sensitivity
$m(\nu_e) \sim 0.2$ eV/c^2

- ❖ completely model free
- ❖ in the game if m_ν quasi-degenerate



0ν-$\beta\beta$ decay

$\langle m_\nu \rangle = 0.4$ eV/c^2
(to be confirmed)

- ❖ planned sensitivity 0.05 eV
- ❖ works only if neutrino is a Majorana particle

Direct m_ν measurements via β decay

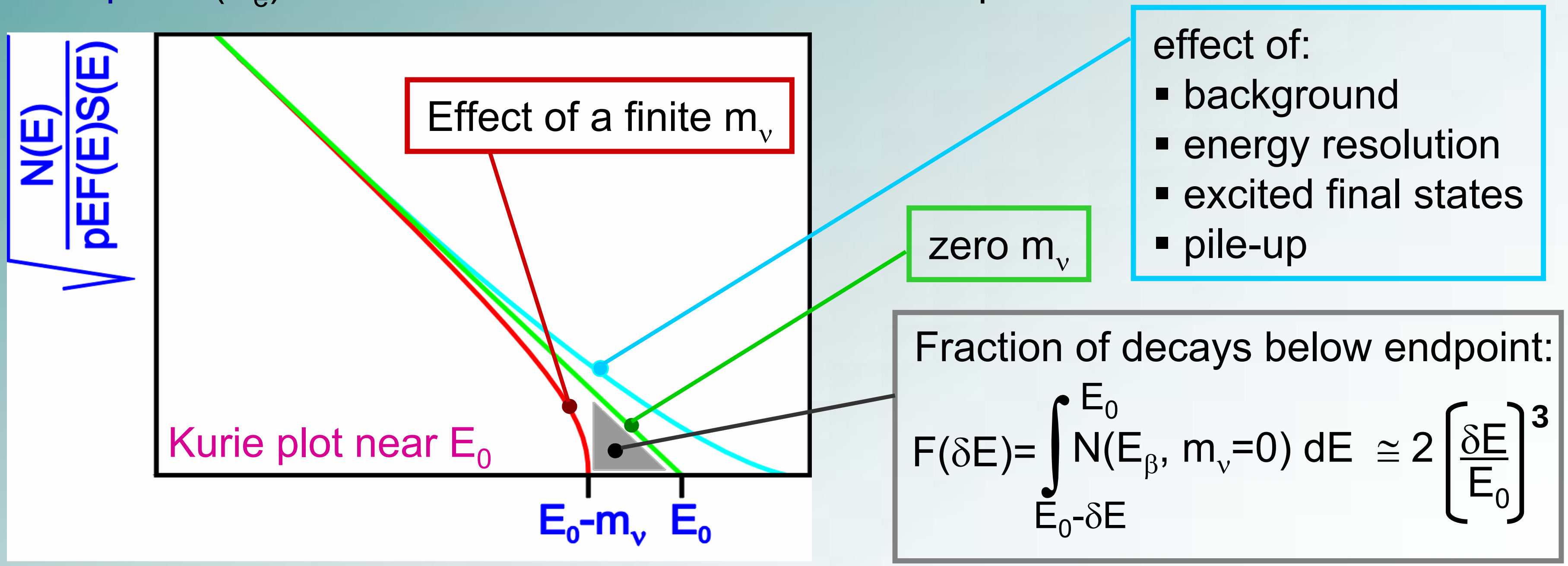
$(A,Z) \rightarrow (A,Z+1) + e^- + \nu_e$ ⇨ $E_0 = M_{at}(A,Z) - M_{at}(A,Z+1) \cong E_e + E_\nu$

basic idea:
study the distribution of the e^- energy in proximity of the end-point

For a finite m_ν:

$$N_\beta(Z,E_\beta,m_{\nu_e}) = p_\beta E_\beta (E_0 - E_\beta)\sqrt{(E_0 - E_\beta)^2 - m_{\nu_e}^2 c^4}\, F(Z,E_\beta) S(E_\beta)[1+\delta_R(Z,E_\beta)]$$

Kurie plot $K(E_e)$: convenient linearization of the beta spectrum



effect of:
- background
- energy resolution
- excited final states
- pile-up

Fraction of decays below endpoint:

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

Experimental requirements

- ➢ High statistics at the end-point

$$F(\delta E) \sim 2\left[\frac{\delta E}{E_0}\right]^3 \Longrightarrow$$ **Low E_0 required!**

- ➢ High energy resolution ⇒ a tiny spectral distortion must be observed

- ➢ Approximate evaluation of sensitivity to m_ν

High energy resolution

$$\sigma(M_\nu) \cong \sqrt[4]{\frac{1.6\, E_0^3\, \Delta E}{A\, T_M}}$$

live time

total source activity

High statistics

- ➢ Small & well known systematic effects ⇒ they could distort the spectral shape

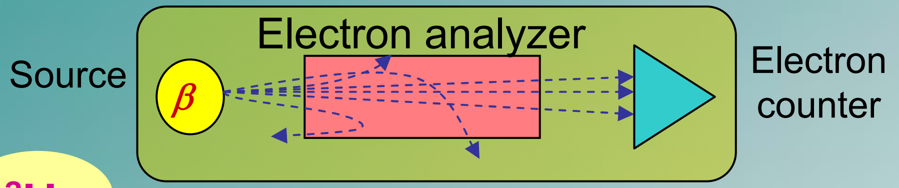
- unaccounted background gives negative $m(\nu_e)^2$
- response of the detector (i.e. energy resolution)
- problem of excited final state
- pile-up effects

⇒ **At least two different & complementary approaches required!**

Two complementary experimental approaches

spectrometer
source ≠ detector

Only the useful fraction of electrons with
$E \sim E_0$ selected



^3H

$^3H \rightarrow {}^3He^+ + e^- + \overline{\nu}_e$

E_0 = **18.57 keV** → high statistics at the end-point
$T_{1/2}$ = **12.3 y** → high specific activity β–source
Superallowed transition → no problem for analytical determination of β–spectrum

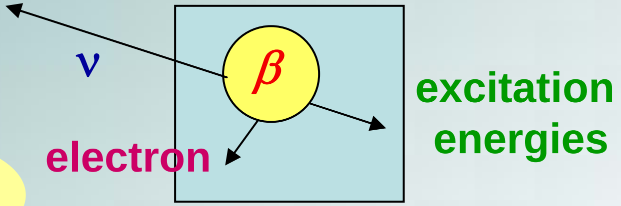
Many sources of systematics:

- deconvolve **detector response function**
- **self-absorption** in the source
- **inelastic scattered** electrons
- problem of **final excited states**

90's MAINZ-TROITZK ⇒ m_ν < 2.2 eV
KATRIN will start in 2010 ⇒ m_ν ~ **0.2 eV**

calorimeter
source = detector

Determines all the visible energy:
→ ν energy as a **missing energy**



^{187}Re

E_0 = **2.47 keV** → the lowest in nature!
$T_{1/2}$ = **43.2 Gy** → 1 Bq/mg, ideal for bolometers
Unique 1st forbidden transition → computable nuclear matrix element

- Main advantage: excited final states
- Main problem: pile-up

Completely different systematics!

MIBETA, MANU ⇒ m_ν < 15.0 eV
Future: MARE ⇒ m_ν ~ **0.2 eV**

Re-based μcalorimeters

Calorimeters measure the entire spectrum at once

- use low E_0 β-decaying isotopes to achieve enough statistic close to E_0

Best choice: ^{187}Re – Q = 2.47 keV

event frac. in the last 10 eV: 1.3×10^{-7} ←→ vs. 3×10^{-10} for T beta spectrum

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

Large isotopic aboundance: 62.8% → No need of isotopic separation

- Main advantage: excited final states

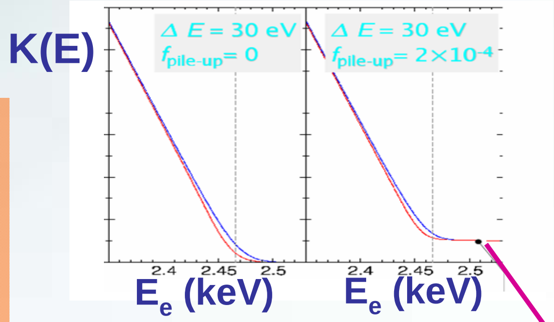
The neutrino energy is measured as a "**missing energy**"

When in presence of decays to **excited states**, the calorimeter measures the **de-excitation energy**

- Main problem: pile-up

Bolometers **intrinsically slow** + **whole** β spectrum acquired

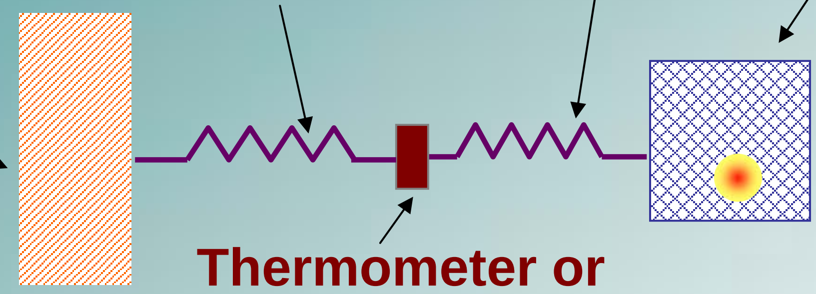
^{187}Re - $T_{1/2}$ = 43.2 Gy
→ 1Bq/mg: ideal!



pile-up fraction ~ **A x** τ_r

Development of arrays of many small detectors (μcalorimeters)
High reproducibility required!

Bolometric detectors of particles: basic concepts



Thermal coupling

basic parameter: G (thermal conductance)

$G \cong 0.02$ pW / mK

Heat sink

T ~ 80 mK

dilution refrigerator

read-out wires
in the future
μ-machined legs

Sensor-absorber
joint (epoxy)

Energy absorber

crystal containing Re

M ~ 0.25 mg

basic parameter:

C (heat capacity)

- ➢ absorbed particle with E
- ➢ production of phonons, quasiparticles
- ➢ temperature signal: $\Delta T = E/C$

Thermometer or phonon sensor

Converts ΔT to an electrical signal

Low C for a better sensitivity

Low temperature & small dimentions!

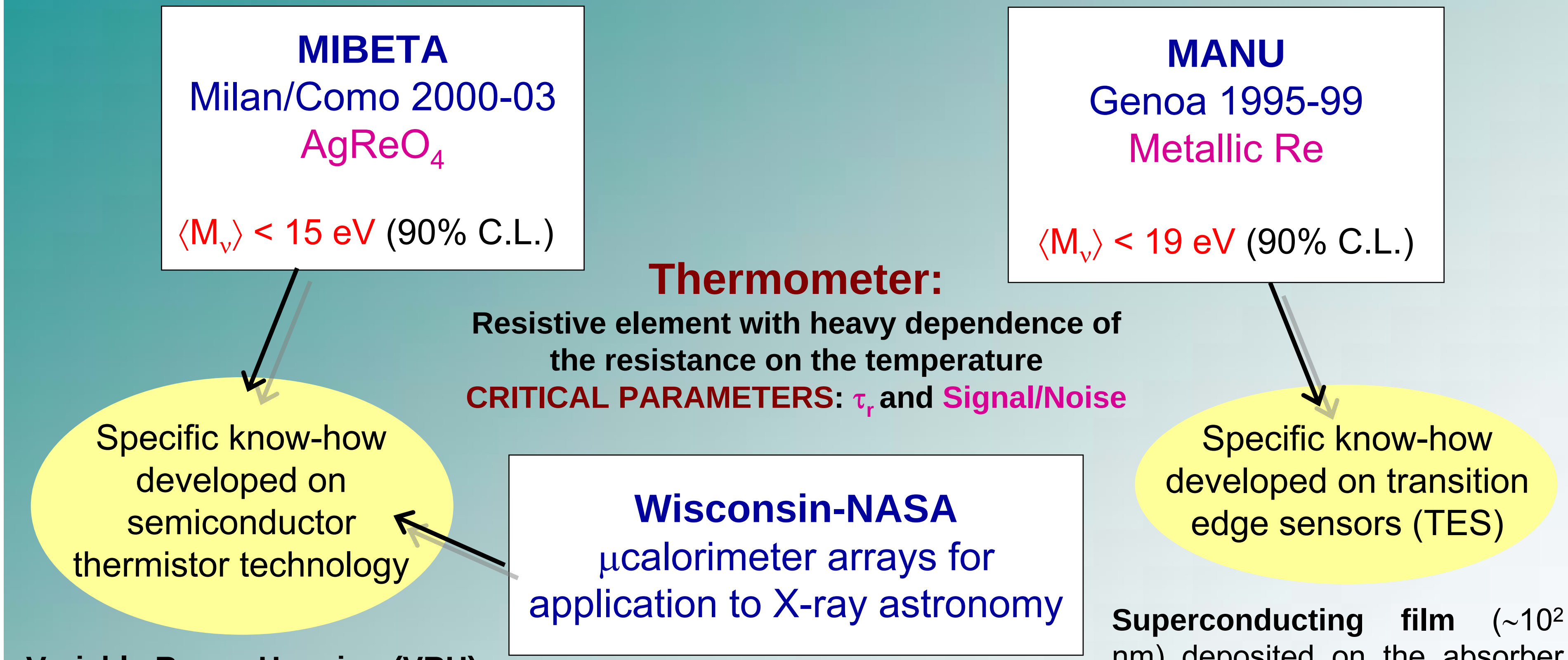
Two possibilities:

- crystal of dielectric material
→ $AgReO_4$ $(C(T) \propto (T/\theta_D)^3)$
- superconductor → metallic Re
$C_s \propto T_c exp(-bT_c /T)$

Advantages over conventional techniques:

- high energy resolution
↔ energy for a single exitation ~ 10 meV (θ_D)
- wide choice for absorber material

Thermistors technology & precursors experiments



MIBETA
Milan/Como 2000-03
$AgReO_4$

$\langle M_\nu \rangle < 15$ eV (90% C.L.)

MANU
Genoa 1995-99
Metallic Re

$\langle M_\nu \rangle < 19$ eV (90% C.L.)

Thermometer:

Resistive element with heavy dependence of the resistance on the temperature

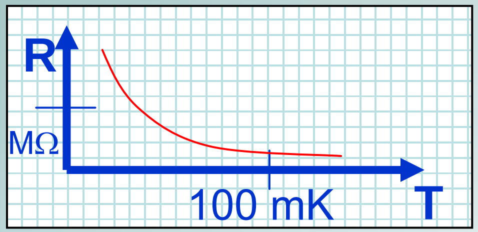
CRITICAL PARAMETERS: τ_r and Signal/Noise

Specific know-how developed on semiconductor thermistor technology

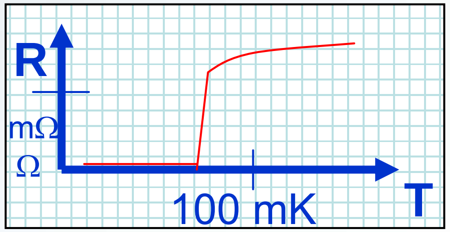
Specific know-how developed on transition edge sensors (TES)

Wisconsin-NASA
µcalorimeter arrays for application to X-ray astronomy

Variable Range Hopping (VRH) conduction regime: **exponential** increase of R with decreasing T

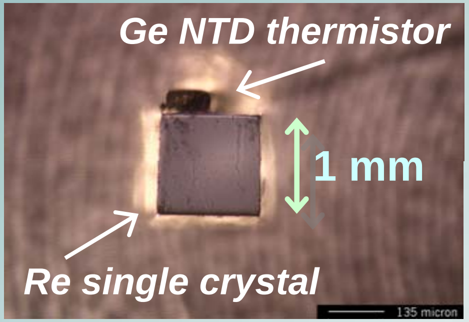


Superconducting film (~10^2 nm) deposited on the absorber kept at the transition edge $\mathbf{T_c}$ → resistivity changes rapidly with temperature fluctuation



Precursors experiments: MANU (Genoa 1995-99)

- Metallic Re single crystal → ONE detector only
- mass 1.6 mg → Activity A_β = 1.6 Hz
- thermometer: Ge NTD thermistor (VRH),
  size = 0.1 x 0.1 x 0.23 mm^3
- live time: 0.5 year
- ΔE_{FWHM} = 96 eV
- $\tau_r \sim$ 200 μs



Total collected statistics:

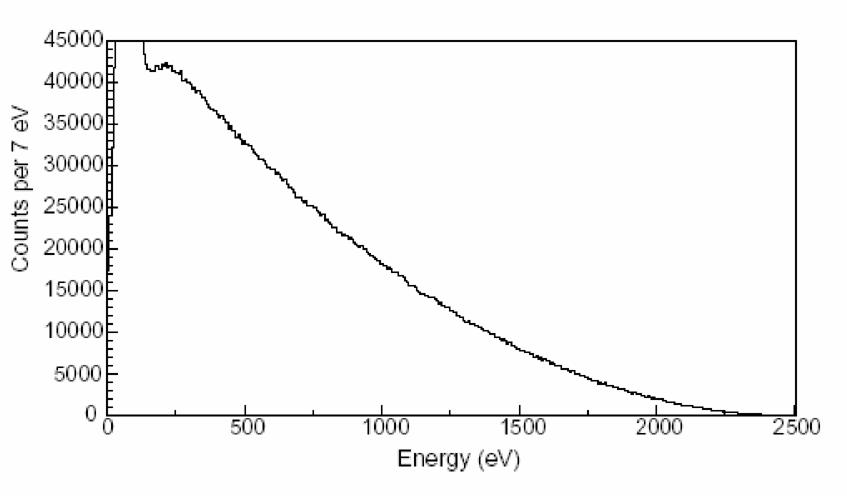
6×10^6 β decays of ^{187}Re above 420 eV

$$E_0 = 2470 \pm 1_{stat} \pm 4_{sys}\, eV$$

$$\tau_{1/2} = 41.2 \pm 0.2_{stat} \pm 1.1_{sys}\, Gyr$$

$$m^2_{\bar{\nu}_e} = -462 \pm 579_{stat} \pm 679_{sys}\, (eV)^2/c^4$$

$$m_{\bar{\nu}_e} \leq 19.0 eV/c^2 (90\% c.l.)$$

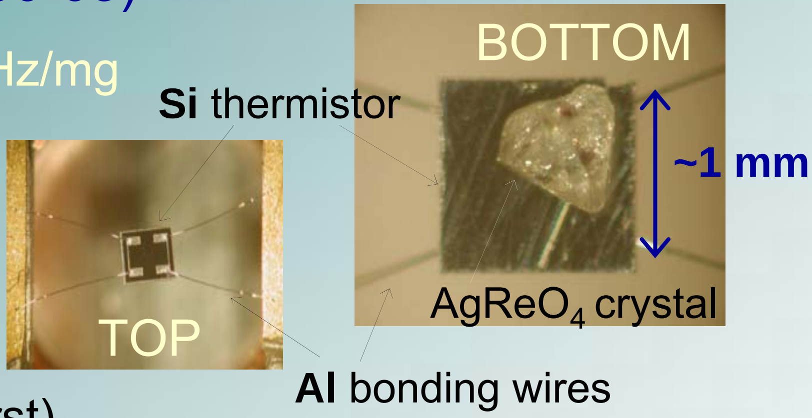


Future improvements based on new technology thermistors:
transition edge sensors (TES)

Precursors experiments: MIBETA

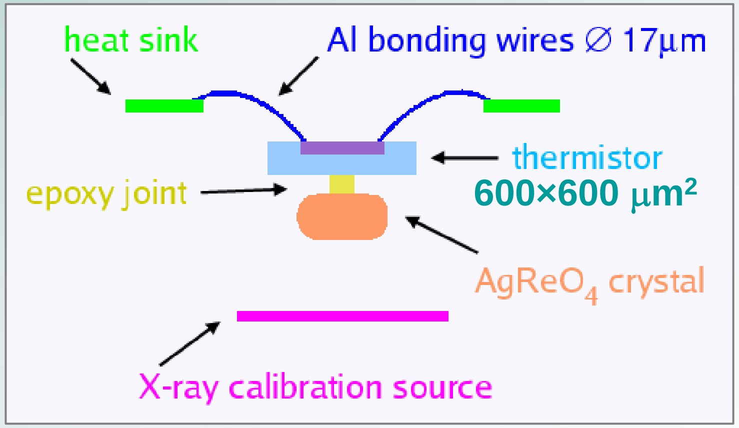
(Milan-Como 2000-03)

- $AgReO_4$ single crystals → ^{187}Re activity ≅ 0.54 Hz/mg
- Mass ≅ 0.25 mg → A_β ≅ 0.13 Hz
  - → to limit pile-up
- Array of 10 detectors
  - → to increase statistics
- Phonon sensor: Si-implanted thermistors (ITC-irst)
  - → high sensitivity
    high reproducibility ⇒ arrays
    possibility of μ-machining



Technologies available for simultaneous fabrication of a large number, small dimension thermistors with fully integrated electrical connections

→ Reduced microphonism and problems of assembly



→ Useful for future expansion of arrays

MIBETA: Si-implanted thermistors

Semiconductor thermistors:
Ge or **Si** small crystals doped slightly below the **metal-insulator transition** (MIT)

- Neutron Transmutation Doping (NTD)
→ applied to Ge
- Ion Implantation
→ applied to Si

} MIBETA

Variable Range Hopping
conduction regime:
phonon assisted tunneling of e^-

$$R(T) = R_0 \exp (T_0 / T)^p$$

$T<1K \quad p=1/2$

T0 & R0 depends on doping level

C must not exceed the absorber heat capacity

High T_0

Small volume

Goal: optimize S/N & τ_r

Low T: thermal decoupling between phonons and e^-
→ ***HEM: Hot Electron Model***
Conduction electrons with T_e coupled to phonon bath through G_{ep} which:
-increases with Volume ($G_{ep} \propto V$)
-decreases with T_0

Low T_0 + large volume

OPTIMUM values for Volume & T_0

Determined through an accurate characterization

Principle of operation of a μbolometer coupled to a Si-thermistor:

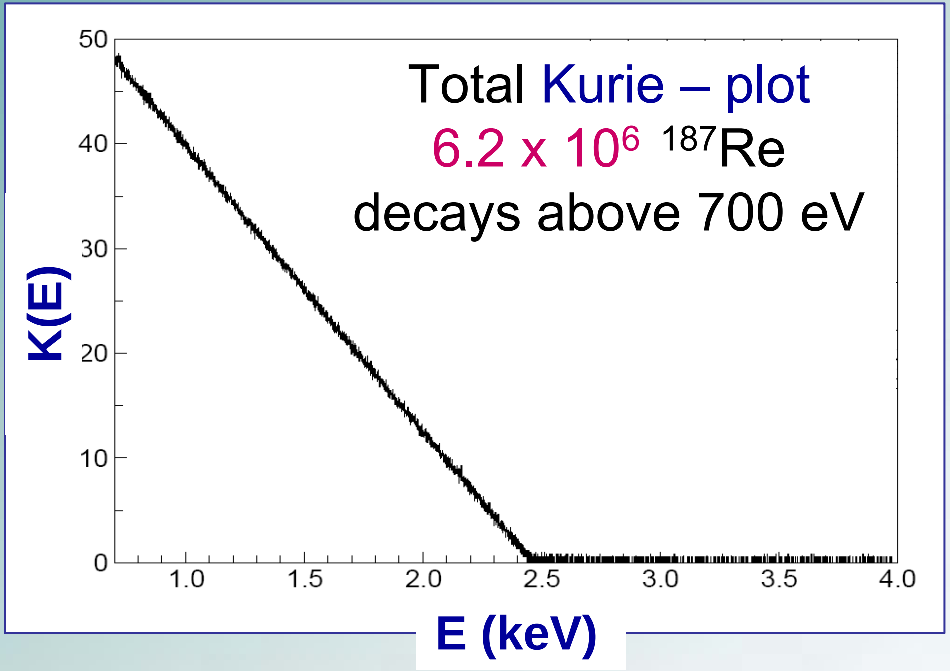
- Temperature signal in the absorber: $\Delta T = E/C \cong 1$ mK for $E = 2.5$ keV
- Constant current Biased thermistor: $I \cong 0.5$ nA ⇒ Joule power dissipated ≅ 0.4 pW ⇒Temperature rise ≅ 20 mK
- Voltage signal due to ΔT: $\Delta V = I \times dR/dT \times \Delta T \Rightarrow \Delta V \cong 30\ \mu V$ for $E = 2.5$ keV

Results of MIBETA

Total live time = 0.6 yr

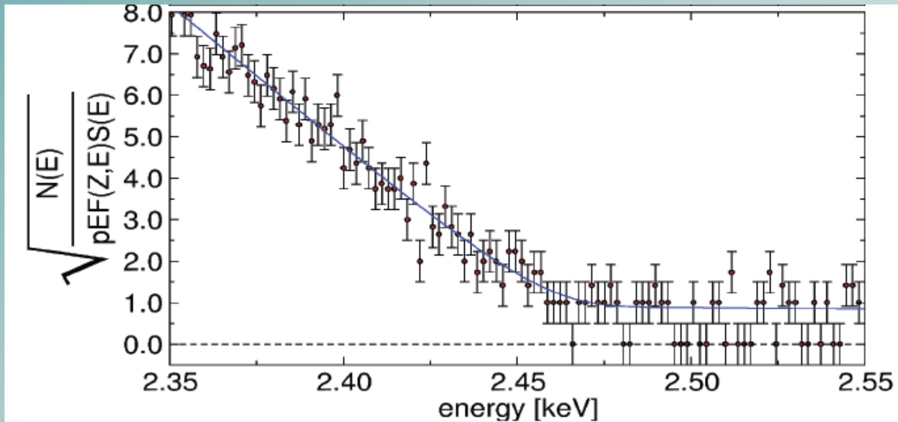
Average ΔE_{FWHM} = 28.5 eV

Average τ_r = 490 μs



β spectrum fit

$F = (f_{th} + f_{pp} + f_{bck}) \otimes f_{det}$



$$E_0 = 2465.3 \pm 0.5_{stat} \pm 1.6_{sys}\, eV$$

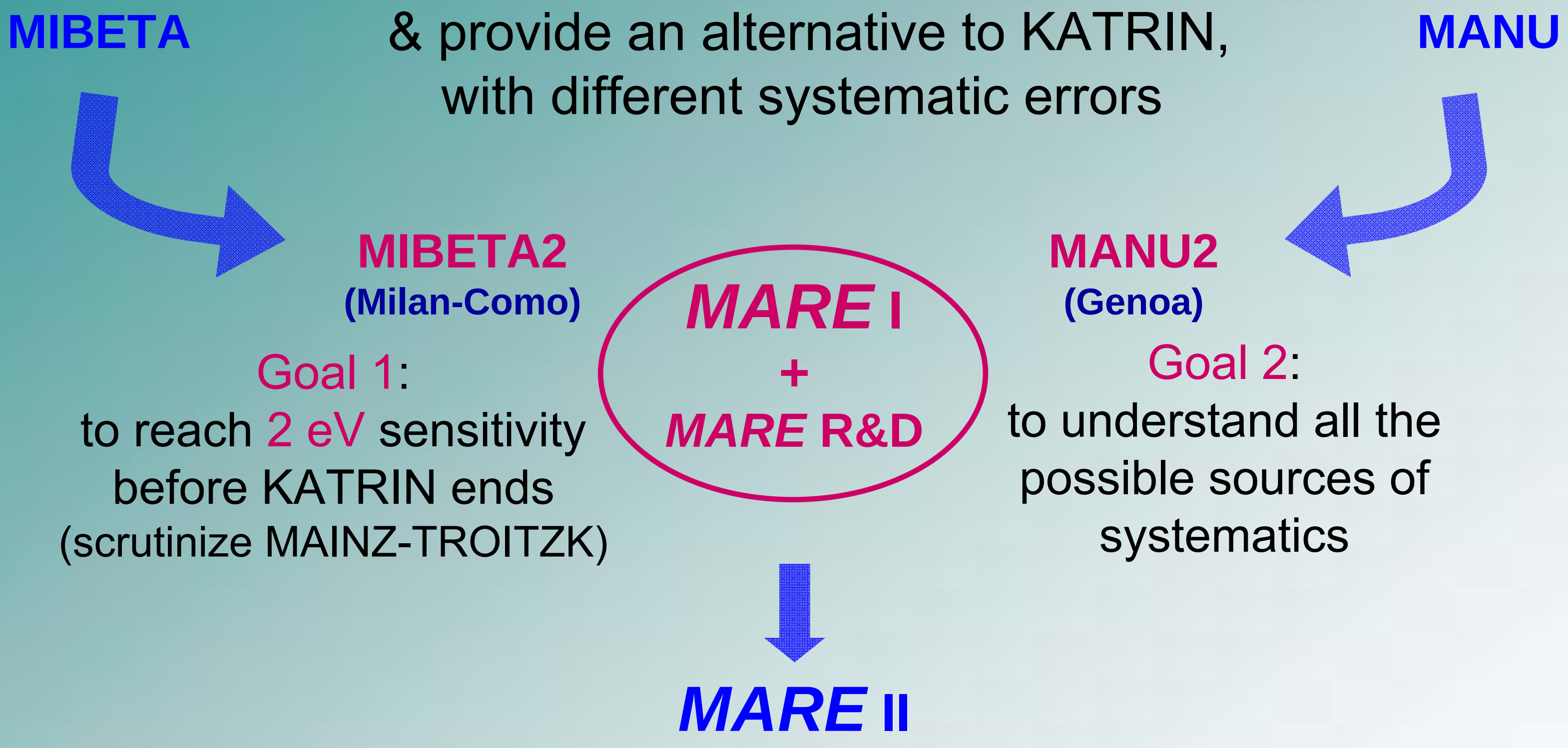
$$\tau_{1/2} = 43.2 \pm 0.2_{stat} \pm 0.1_{sys}\, Gyr$$

$$m^2_{\bar{\nu}_e} = -112 \pm 207_{stat} \pm 90_{sys}\, (eV)^2/c^4$$

$$m_{\bar{\nu}_e} \leq 15.0 eV/c^2 (90\% c.l.)$$

The future

Main goal: reach 0.2 eV sensitivity
& provide an alternative to KATRIN,
with different systematic errors



MIBETA

MANU

MIBETA2
(Milan-Como)

Goal 1:
to reach 2 eV sensitivity
before KATRIN ends
(scrutinize MAINZ-TROITZK)

***MARE* I**
+
***MARE* R&D**

MANU2
(Genoa)

Goal 2:
to understand all the
possible sources of
systematics

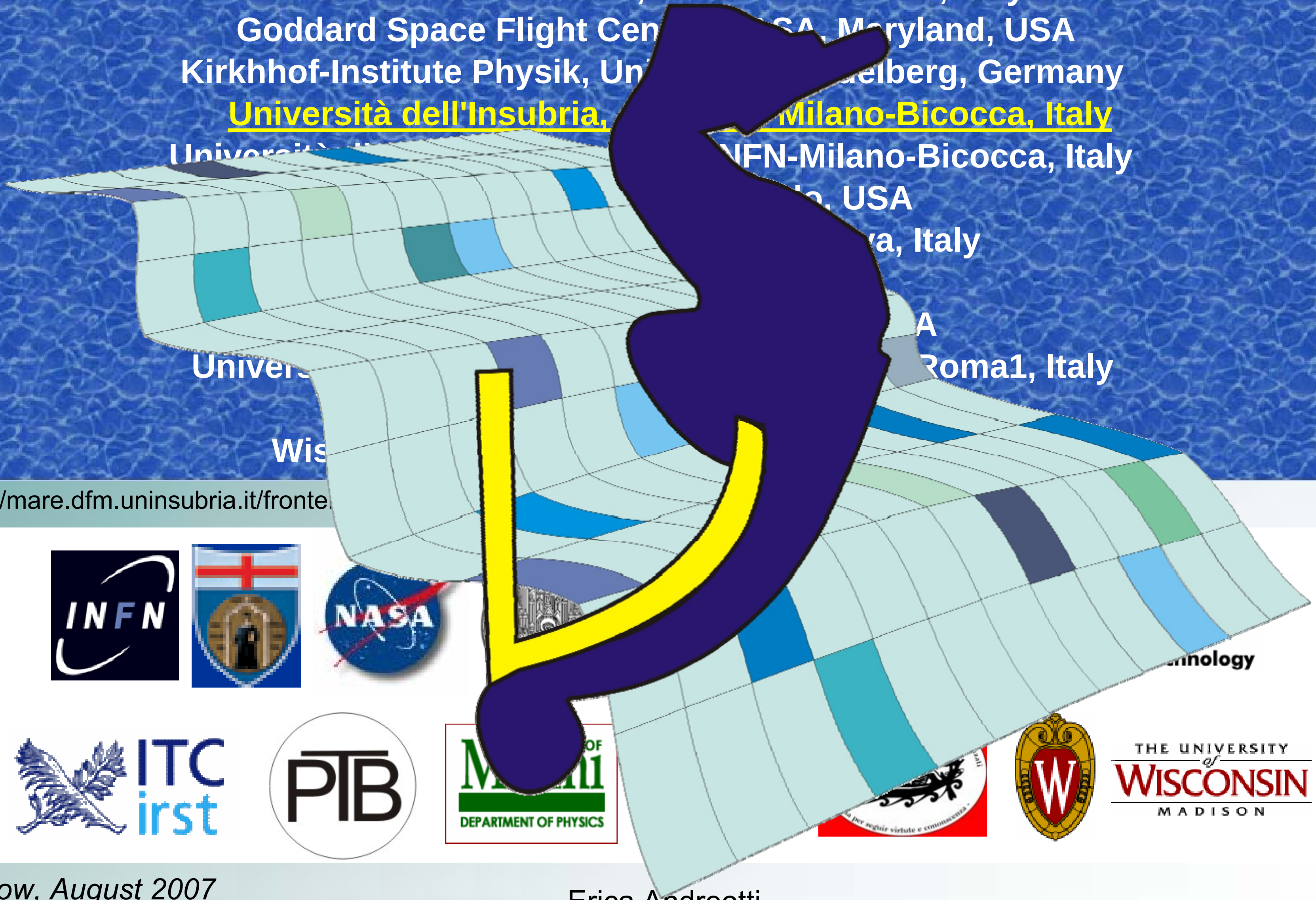
***MARE* II**

General requirements:

- increase the number of events
- decrease pile-up, by decreasing τ_r
- improve energy resolution

The MARE collaboration

MARE: Microcalorimeter Arrays for a Rhenium Experiment



Università di Genova, and INFN-Genova, Italy
Goddard Space Flight Cen SA, Maryland, USA
Kirkhhof-Institute Physik, Un delberg, Germany
Università dell'Insubria, Milano-Bicocca, Italy
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INFN
NASA
nology
ITC irst
PTB
OF
DEPARTMENT OF PHYSICS
THE UNIVERSITY of WISCONSIN
MADISON

MARE I

GOALS

1. Reach 2 eV sensitivity:

- Present technology detectors
- Single channel optimization
- Scaling up to hundreds devices

ΔE = 10 eV, τ_r = 150 μs

A_β = 0.3 Hz, $f_{pp}=3\text{x}10^{-5}$

~ 300 detectors array

Total statistics ~ 10^{10} events

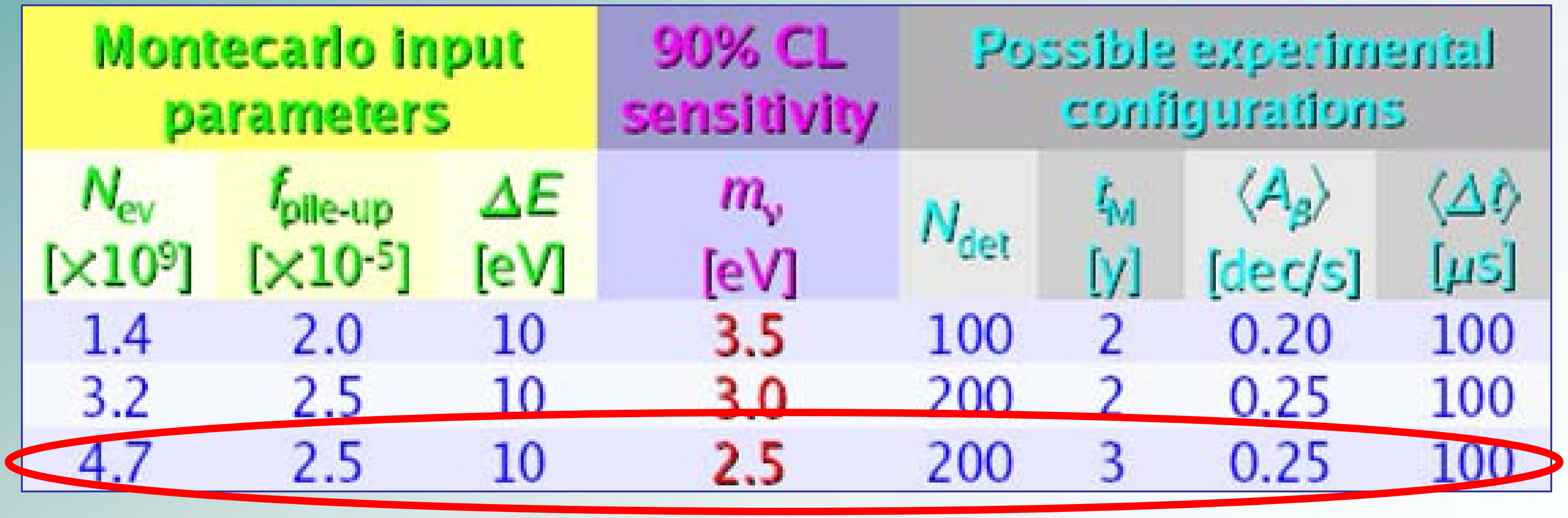
2. Improve understanding on systematics

- Theoretical spectral shape of decay
- Detector response function
- Unidentified pile-up
- Data reduction
- …

3. R&D for *MARE* II

Data taking for *MARE* I is starting now (summer 2007)

MONTECARLO simulations *MARE* I

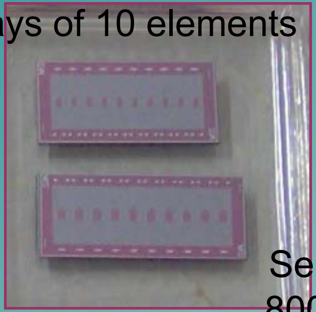


Montecarlo input parameters			90% CL sensitivity	Possible experimental configurations			
N_{ev} [×10⁹]	$f_{pile\text{-}up}$ [×10⁻⁵]	ΔE [eV]	m_ν [eV]	N_{det}	t_M [y]	$\langle A_\beta \rangle$ [dec/s]	$\langle \Delta t \rangle$ [μs]
1.4	2.0	10	3.5	100	2	0.20	100
3.2	2.5	10	3.0	200	2	0.25	100
4.7	2.5	10	2.5	200	3	0.25	100

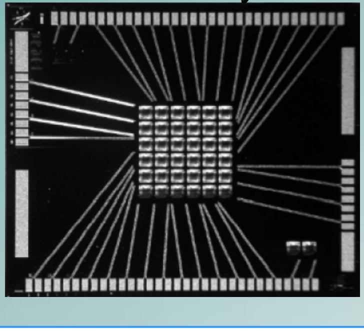
MARE I: thermistors

A_β ~ 0.3 Hz → doubling absorber mass while preserving ΔE and τ_r → **Detectors require some improvements!**

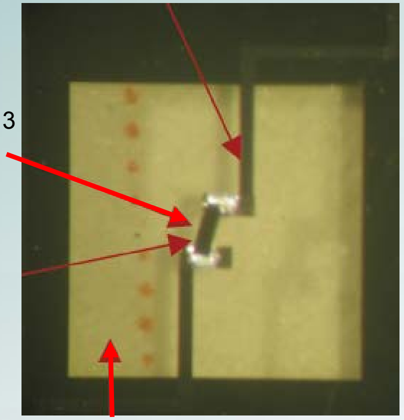
MIBETA2: available technologies



ITC-irst micromachined array.
Si-implanted produced by improving the technology developed for MIBETA.
Status: ongoing production & tests



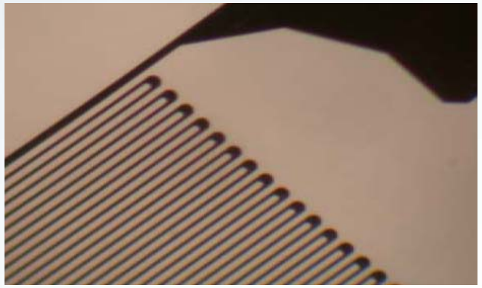
NASA/GSFC 6x6 silicon array.
Status: encouraging first results. Coupling and electronics to be optimized.



LBL+Bonn NTD Ge array.
Status: excess noise observed; reproducibility to be demostrated.

MANU2:

Transition Edge Sensor (TES)
Instead of NTD thermistors
» faster risetime and better S/N



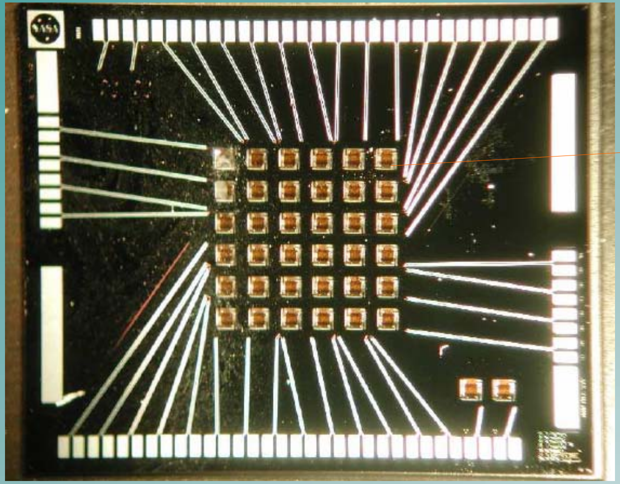
MIBETA 2: previous tests

Array of 288 elements achieved through a gradual approach

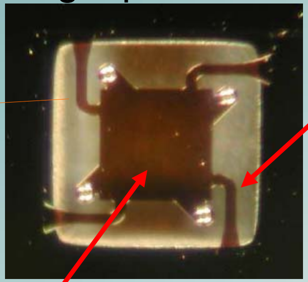
Single channel:

- $AgReO_4$ + semiconductor thermistor
- single crystal mass ~ **0.45 mg** → A_β ~ 0.3 Hz

NASA/GSFC XRS2: 6×6 Si-implanted array



single pixel

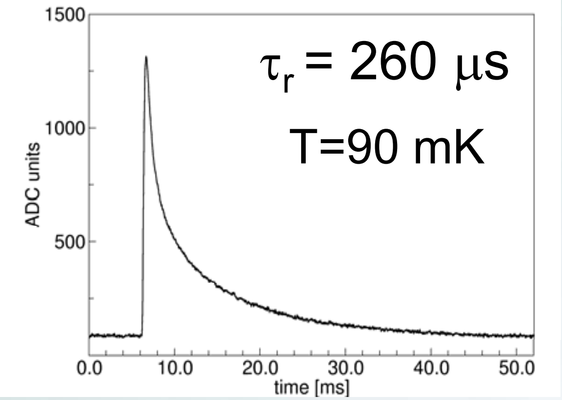


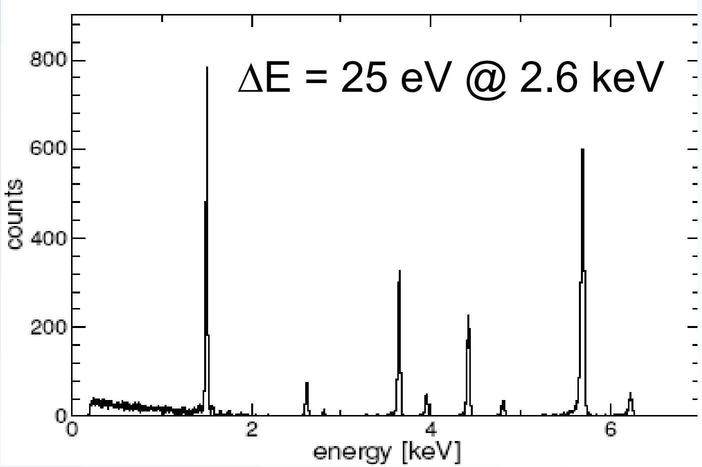
Si thermal links 3µm

Si-thermistor 300×300×1.5 µm³

Already tested at ≠ temperatures with glued crystals (in Milan)

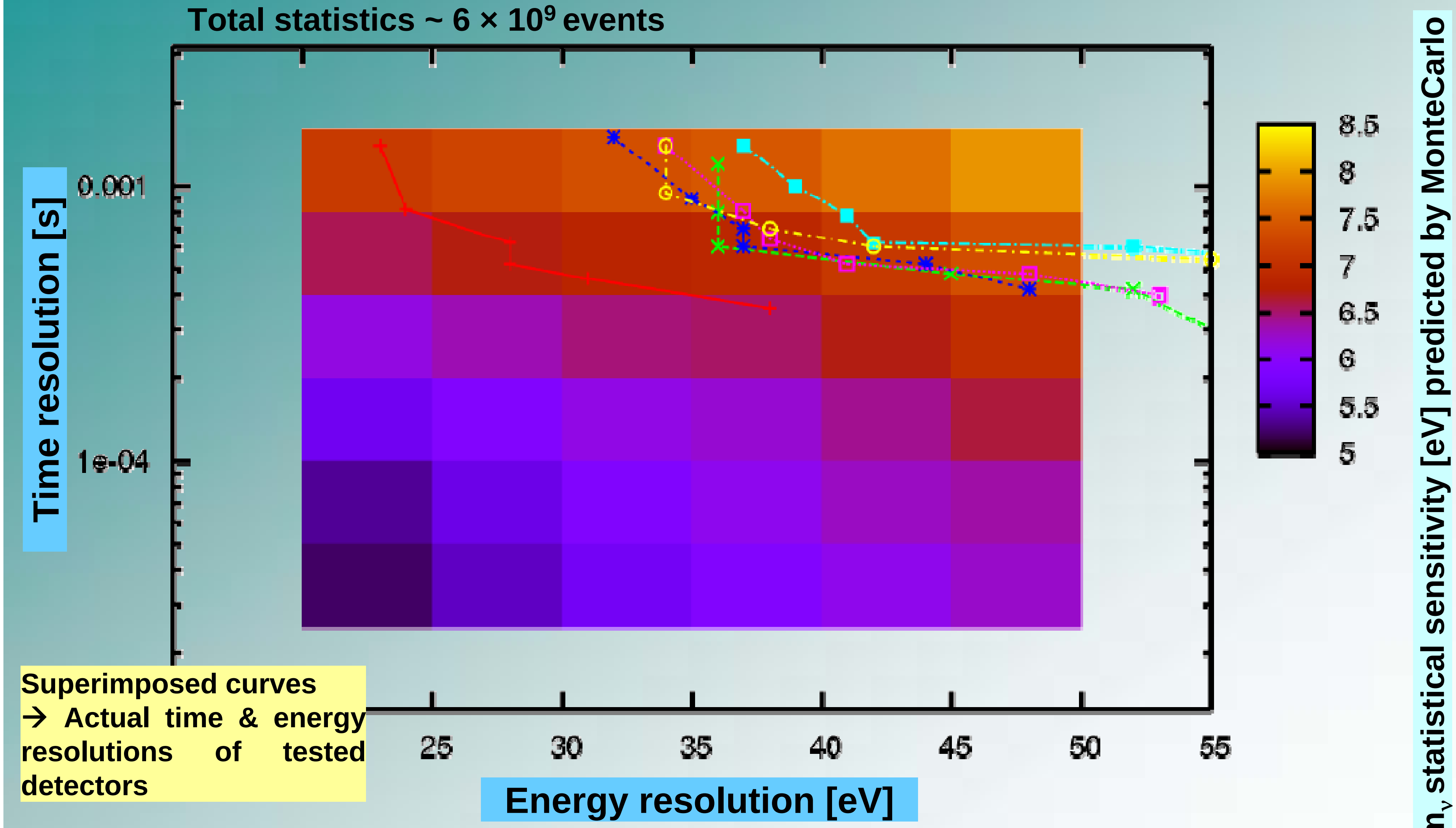
Single channel best performances:





Further improvements attainable thanks to the new developed cold electronics (JFETs)

MIBETA 2: detectors performance & sensitivity



Superimposed curves
→ Actual time & energy resolutions of tested detectors

Tested detectors are an acceptable baseline design for MIBETA 2

Moscow, August 2007

Erica Andreotti

MIBETA 2: schedule & sensitivity

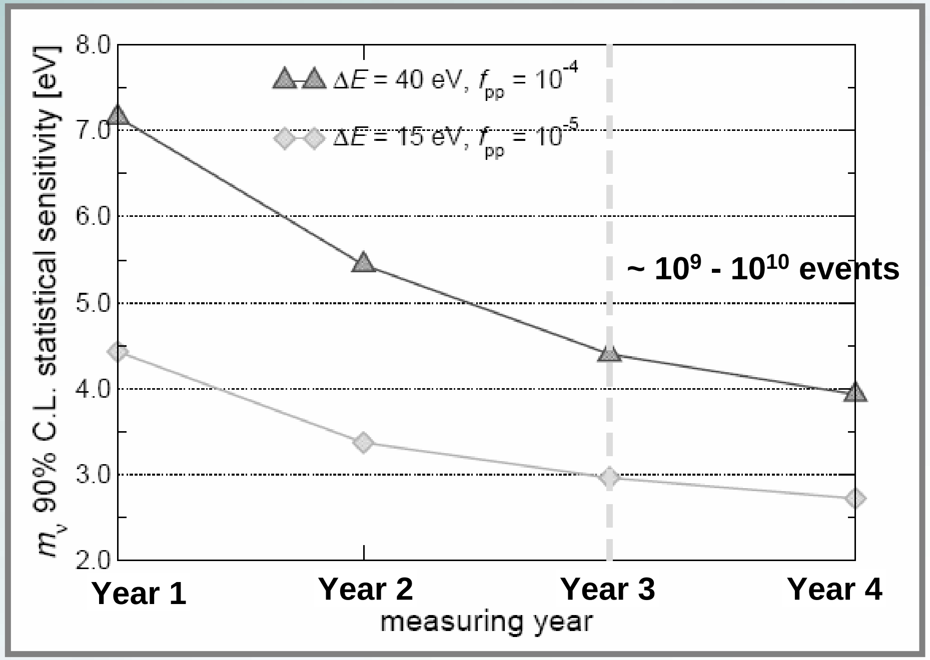
Gradual deployment of the whole 288 elements array:

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

- Array design based on XRS2 array
- Possible alternatives based on different (previously mentioned) thermistors

Two approaches to evaluate the sensitivity:

- *conservative*:
  $\Delta E = 40$ eV & $\tau_r \sim 400\ \mu s$
- *improved:*
  $\Delta E = 15$ eV & $\tau_r \sim 50\ \mu s$



MARE II

GOAL

reach 0.2 eV sensitivity around 2015

Requirements
(from MonteCarlo simulations)

Total statistics ~ 10^{14} events τ_r **~ 1 - 10 μs**
Activity/element ~ 1-10 Hz ΔE_{FWHM} **~ 5 eV**

Data taking should start not later than 2011!

Kick-off of MARE II subordinated to:

- safe reduction of known sources of systematics;
- verification that no new sources appear;
- complete understanding of the ^{187}Re decay spectrum;
- demonstration that the estimated sensitivity can be maintained through the experiment segmentation & expansion

Substancial improvements are needed:

- sensors: TES or MMC or MKID
- electronics: multiplexed SQUID
- methods: modularity

→ scaling up to **thousands** devices!

Technologies already under study in several other experiments

The full **MARE phase I** dataset is required to drawn a definitive conclusion.

MARE II

Thermometer: a rise time of ~ 1 – 10 μs is required

higher statistics with lower pile-up

Multiplexed kinetic inductance detectors (MKIDS)

(Roma, ITC-irst, Cardiff)

Superconductive strip below T_c whose surface inductance L_s and impedance Z_s are changed by absorption of quasi particles; the signal is read as a phase variation when the strip is part of a resonant circuit

Magnetic MicroCalorimeters (MMC)

(Heidelberg)

Paramagnetic material in a small magnetic field with temperature dipendent magnetization

Transition Edge Sensors (TES)

(MANU 2)

Already mensioned

Temperature sensitivity ~ 60 times larger than for doped semiconductor thermistors

Metallic → e-ph coupling time shorter than for doped semiconductors

Electronics: front-end multiplexed SQUID

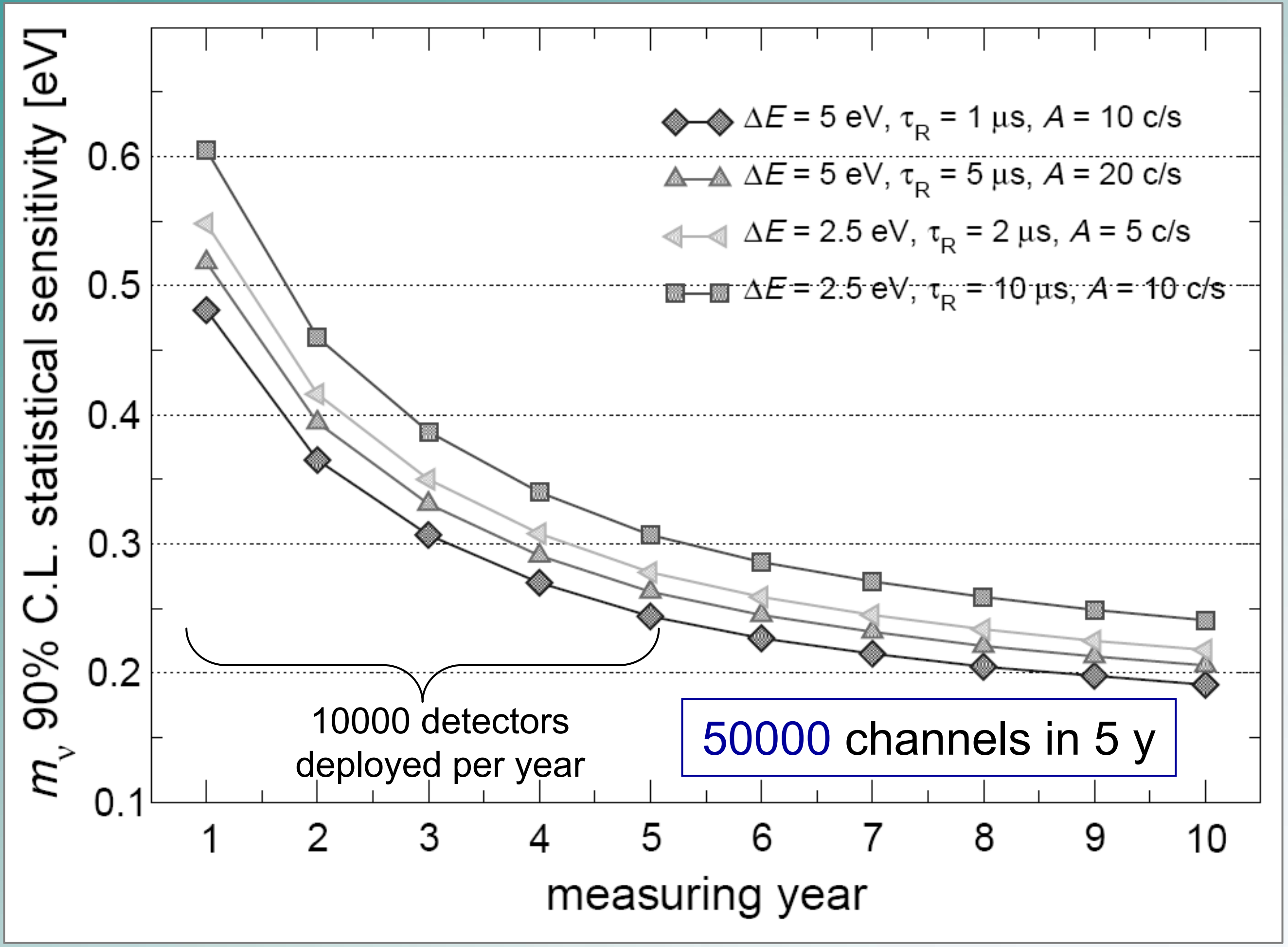
Very good noise performance allows construction of multiplexers that read out a number of sensors on a single channel; couples very well to TES, MMC, MKIDs

(NIST, PTB)

MARE II

Approach: design a kind of modular 10000 pixel array *kit* which can be relatively easily installed in any available refrigerator

Simulations MARE II



10000 detectors deployed per year

Moscow, August 2007

Erica Andreotti

Conclusions

- The calorimetric technique can reach sub-eV sensitivity on m_ν being complementary to KATRIN

- The *MARE* experiment will be developed into 2 phases:
  - *MARE* I: important to understand all sources of systematics by implementing the specific know-how developed by the involved groups
  - *MARE* II: new technology thermistors & read-out are needed to achieve the experimental requirements

- Thanks to the *modularity* of the calorimetric approach a further expansion of the experiment will simply consist in the repeated replication of the first matrix (unlike spectrometers)

Thanks!