Neutrino Frontiers
Minneapolis, 23-26 October 2008

Calorimetric approach to the direct measurement of the neutrino mass: the MARE project

Erica Andreotti

University of Insubria & INFN – Milano Bicocca

on behalf of the MARE collaboration

Summary

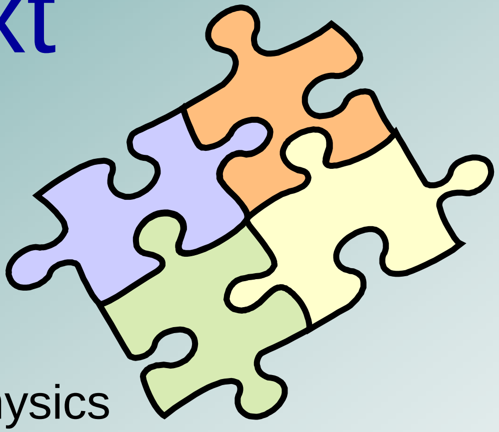
- The physical context
- Basic concepts & experimental requirements for the direct measurement of m_ν
- Spectrometers versus Calorimeters
- Re-based μcalorimeters: basic concepts & state-of-the-art (special care to MIBETA & semiconductor thermistors)
- The MARE project: aims, potentiality & experimental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

The physical context

Oscillation experiments

↓

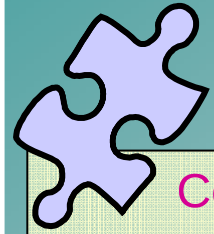
Neutrinos have non-zero mass



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

WE NEED TO KNOW:

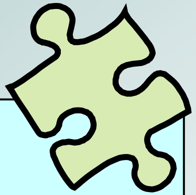
- ➢ absolute ν mass scale
- ➢ nature of ν mass



Cosmology

$\Sigma m_{\nu i} \leq 1$ eV/c^2

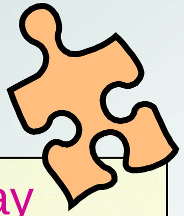
- ❖ planned sensitivity 0.05 eV
- ❖ spread in recent results
- ❖ model dependent



Direct search through β decay

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

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



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

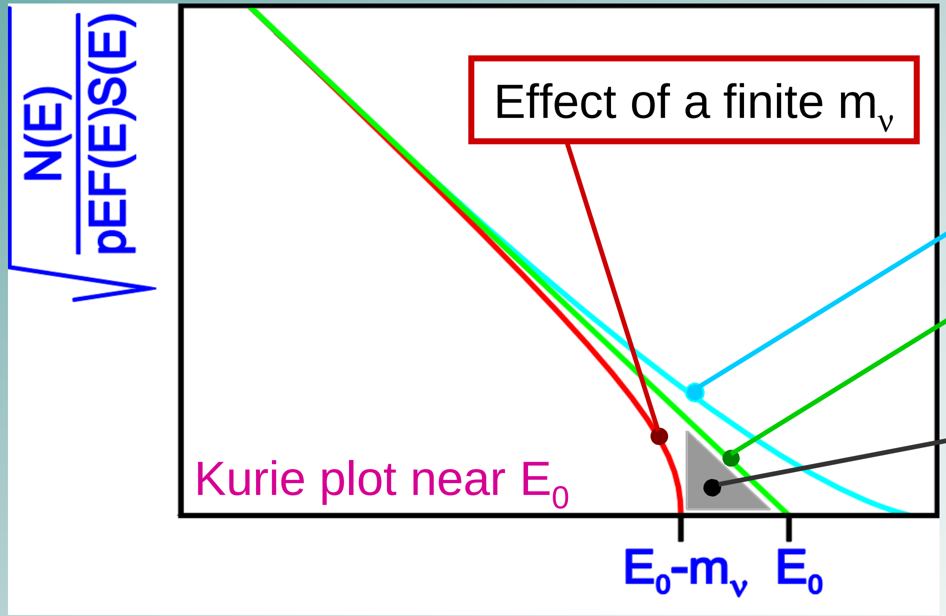
$(A,Z) \rightarrow (A,Z+1) + e^- + \nu_e$ ⇒ $E_0 = M_{at}(A,Z) - M_{at}(A,Z+1) \cong E_e + E_\nu$

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



zero m_ν

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

$$F(\delta E) \sim 2\left[\frac{\delta E}{E_0}\right]^3 \Rightarrow$$

Low E_0 β–decaying isotopes required!

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

- Approximate evaluation of sensitivity to m_ν

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

High energy resolution

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!

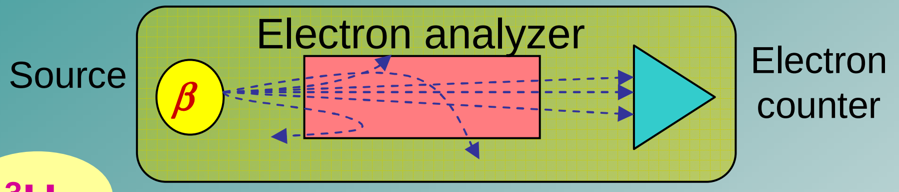
Two complementary experimental approaches

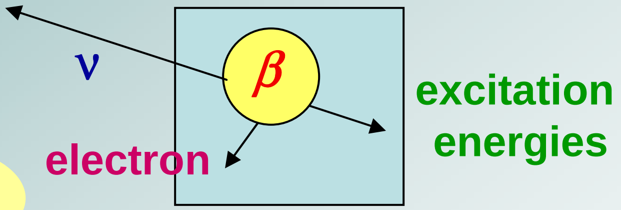
spectrometer
source ≠ detector

calorimeter
source = detector

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

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





^{3}H

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

^{187}Re

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

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

Many sources of systematics:

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

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

Completely different systematics!

90's MAINZ-TROITZK ⇒ m_ν < 2.2 eV
KATRIN will start in 2011 ⇒ $m_\nu \sim$ **0.2 eV**

MIBETA, MANU ⇒ m_ν < 15.0 eV
Future: MARE ⇒ $m_\nu \sim$ **0.2 eV**

Re-based μcalorimeters

Calorimeters measure the entire spectrum at once

→ low E_0 to achieve enough statistic close to E_0

Best choice: ^{187}Re > $E_0 = 2.47$ keV

→ event frac. in the last 10 eV: 1.3×10^{-7} ⟷ vs. 3×10^{-10} for ^{3}H 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

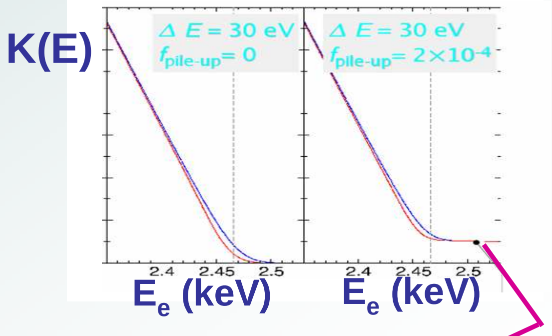
The neutrino energy is measured as a "**missing energy**"

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

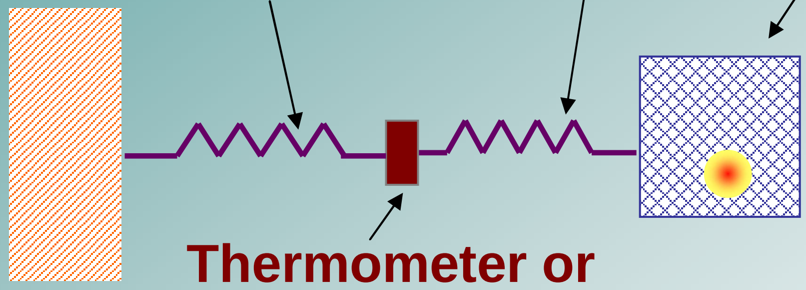
^{187}Re - $T_{1/2} = 43.2$ Gy
→ 1Bq/mg: ideal!



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

$T \sim 80$ 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: $\Delta T=E/C$

Low C for a better sensitivity

Thermometer or phonon sensor

Converts ΔT to an electrical signal

Low temperature & small dimentions!

Two possibilities:

- crystal of dielectric material

$\rightarrow$ $AgReO_4$ $(C(T) \propto (T/\theta_D)^3)$

- 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

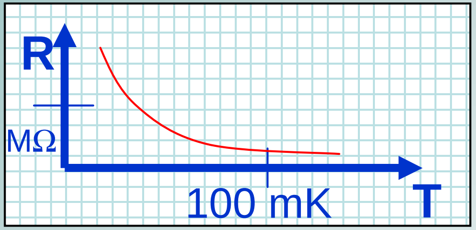
CRITICAL PARAMETERS: τ_r and Signal/Noise

Specific know-how developed on semiconductor thermistor technology

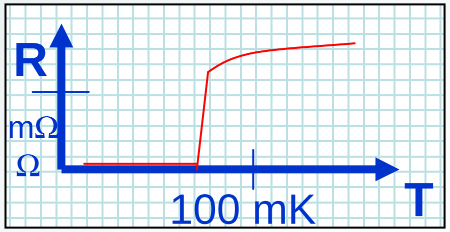
Wisconsin-NASA
μcalorimeter arrays for application to X-ray astronomy

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

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

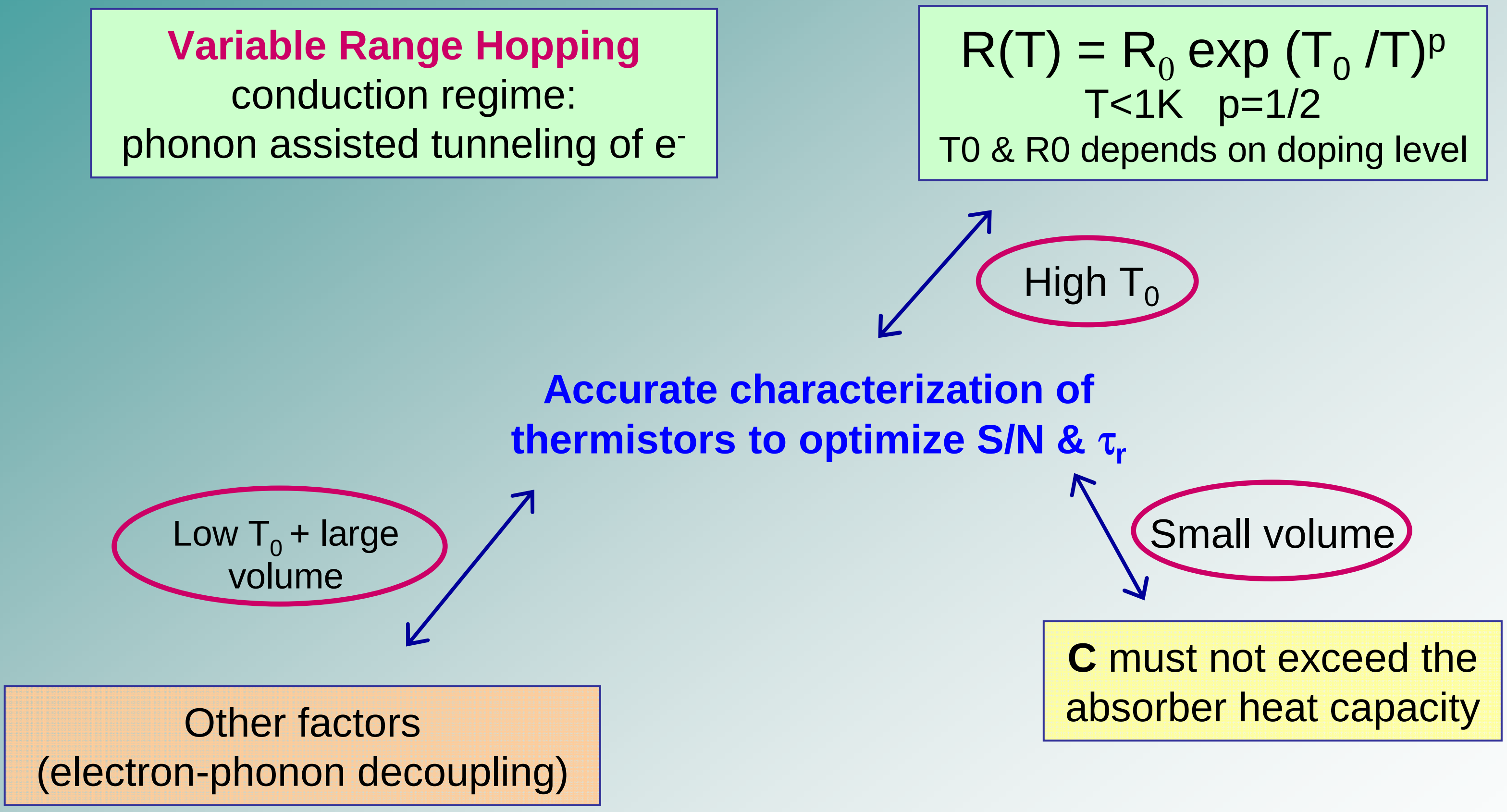


Superconducting film (~10^2 nm) deposited on the absorber kept at the transition edge T_c → resistivity changes rapidly with temperature fluctuation



Semiconductor thermistors

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



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

High T_0

Accurate characterization of thermistors to optimize S/N & τ_r

Low T_0 + large volume

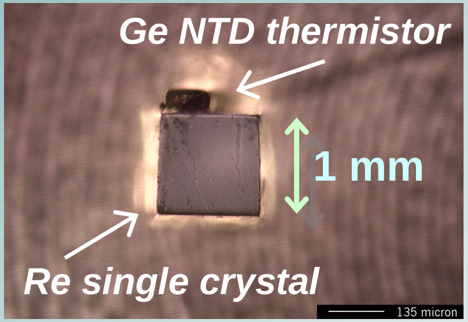
Small volume

Other factors
(electron-phonon decoupling)

C must not exceed the absorber heat capacity

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
- τ_r ~ 200 μs



Total collected statistics:

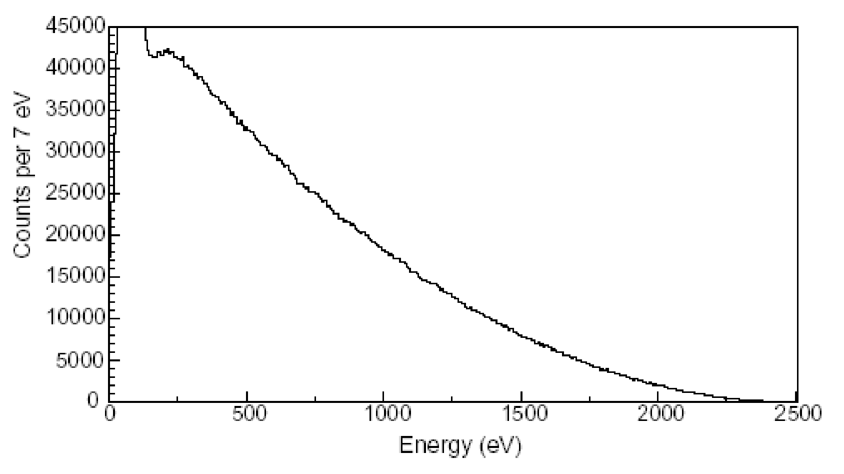
6×10^6 β decays of ^{187}Re above 420 eV

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

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

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

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

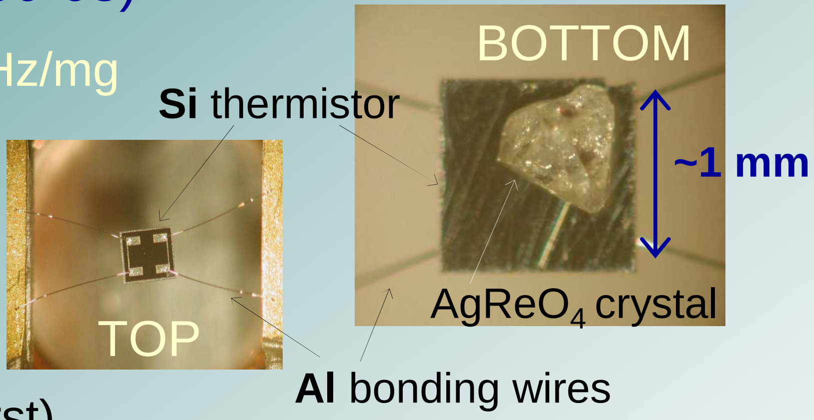


Future improvements based on new technology thermistors: transition edge sensors (TES)

Precursors experiments: MIBETA

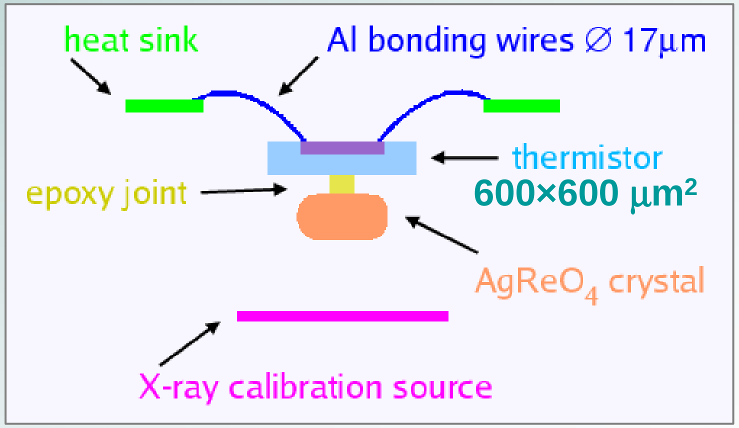
(Milan-Como 2000-03)

- $AgReO_4$ 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

Results of MIBETA

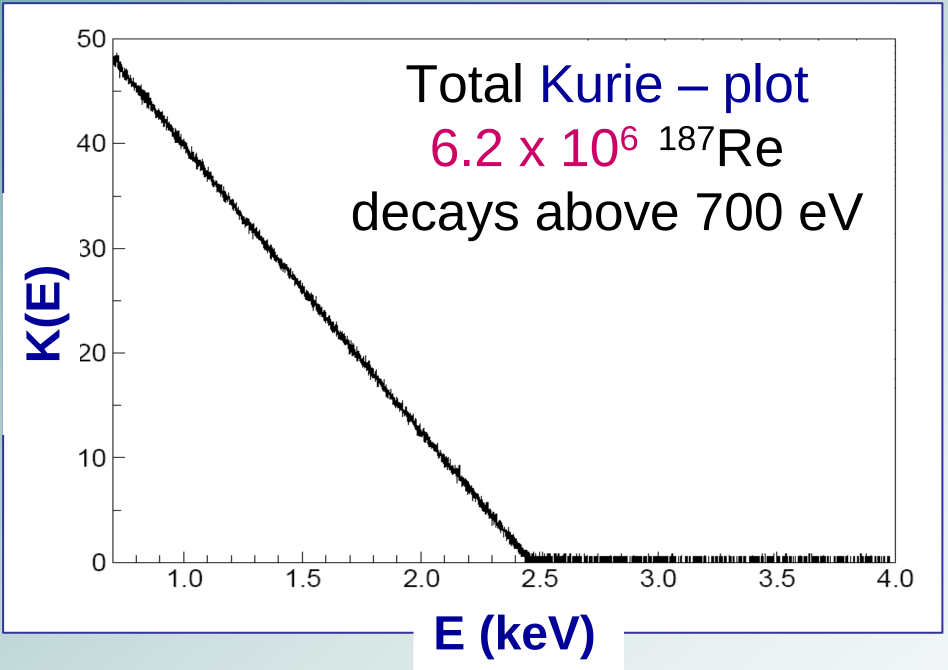
Total live time = 0.6 yr

Average ΔE_{FWHM} = 28.5 eV

Average τ_r = 490 μs

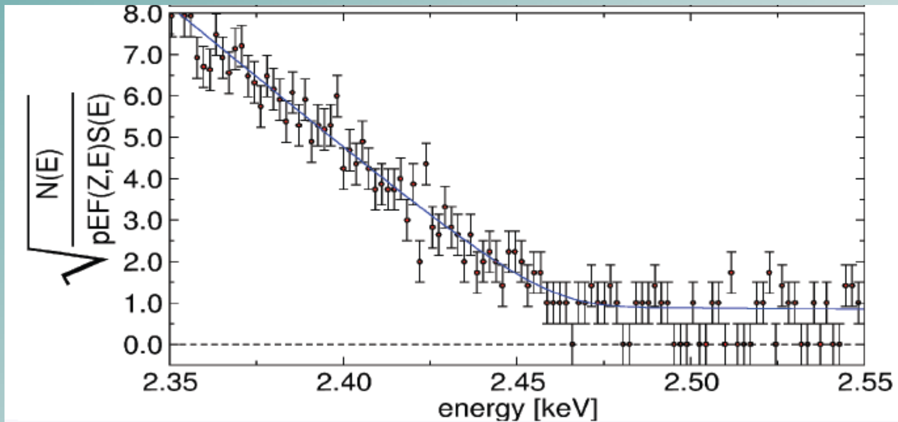
β spectrum fit

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


Total Kurie – plot

6.2×10^6 ^{187}Re

decays above 700 eV



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

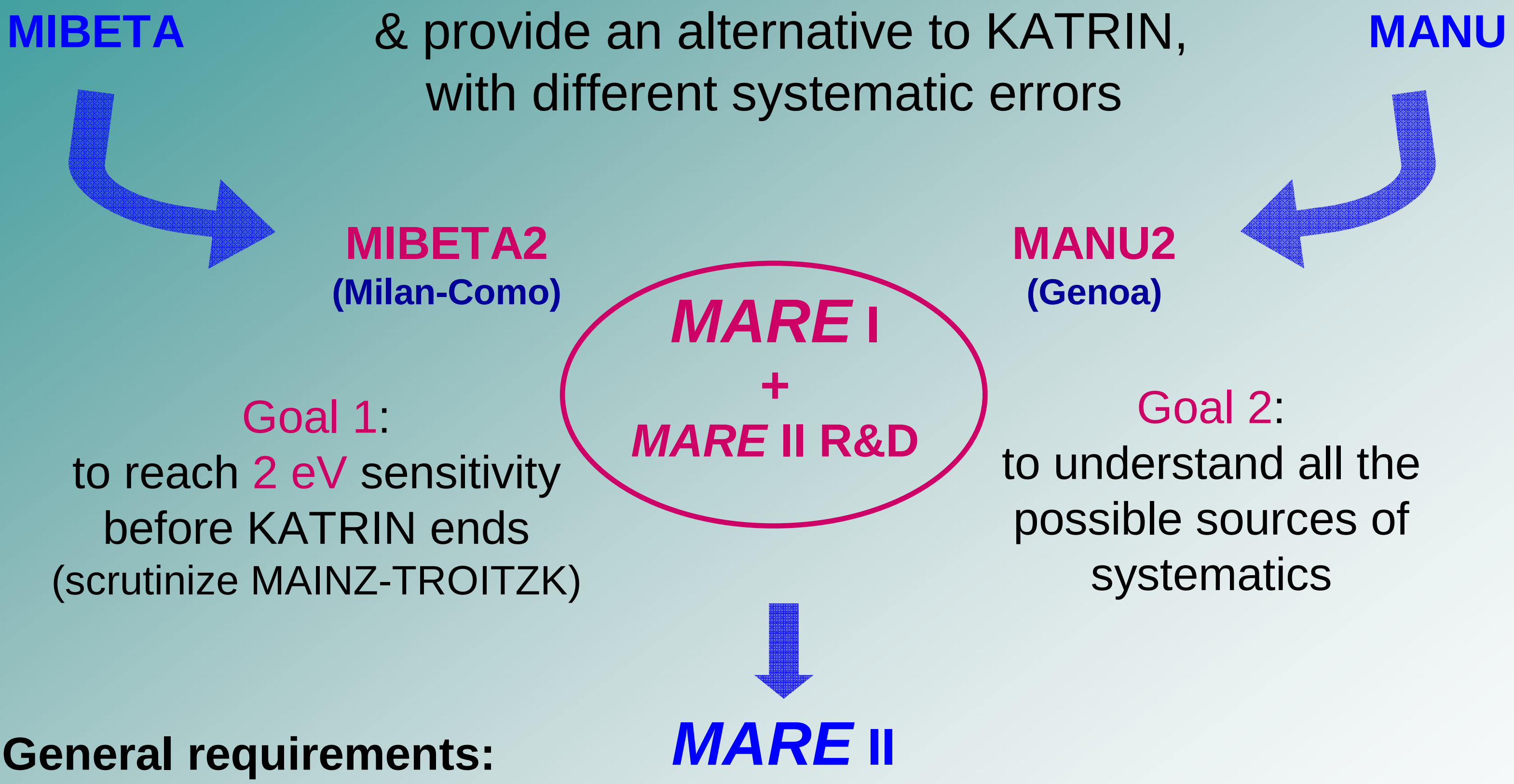
$$\tau_{1/2} = 43.2 \pm 0.2_{stat} \pm 0.1_{sys}\, Gyr$$

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

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

The future

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



MIBETA

MANU

MIBETA2
(Milan-Como)

MANU2
(Genoa)

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

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

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 Center, NASA, Maryland, USA
Kirkhhof-Institute Physik, Universität Heidelberg, Germany
Università dell'Insubria, and INFN-Milano-Bicocca, Italy
Università di Milano-Bicocca,and INFN-Milano-Bicocca, Italy
NIST, Boulder, Colorado, USA
ITC-irst, Trento, and INFN-Padova, Italy
PTB, Berlin, Germany
University of Miami, Florida, USA
Università di Roma “La Sapienza”, and INFN-Roma1, Italy
SISSA, Trieste, Italy
Wisconsin University, Madison, Wisconsin, USA

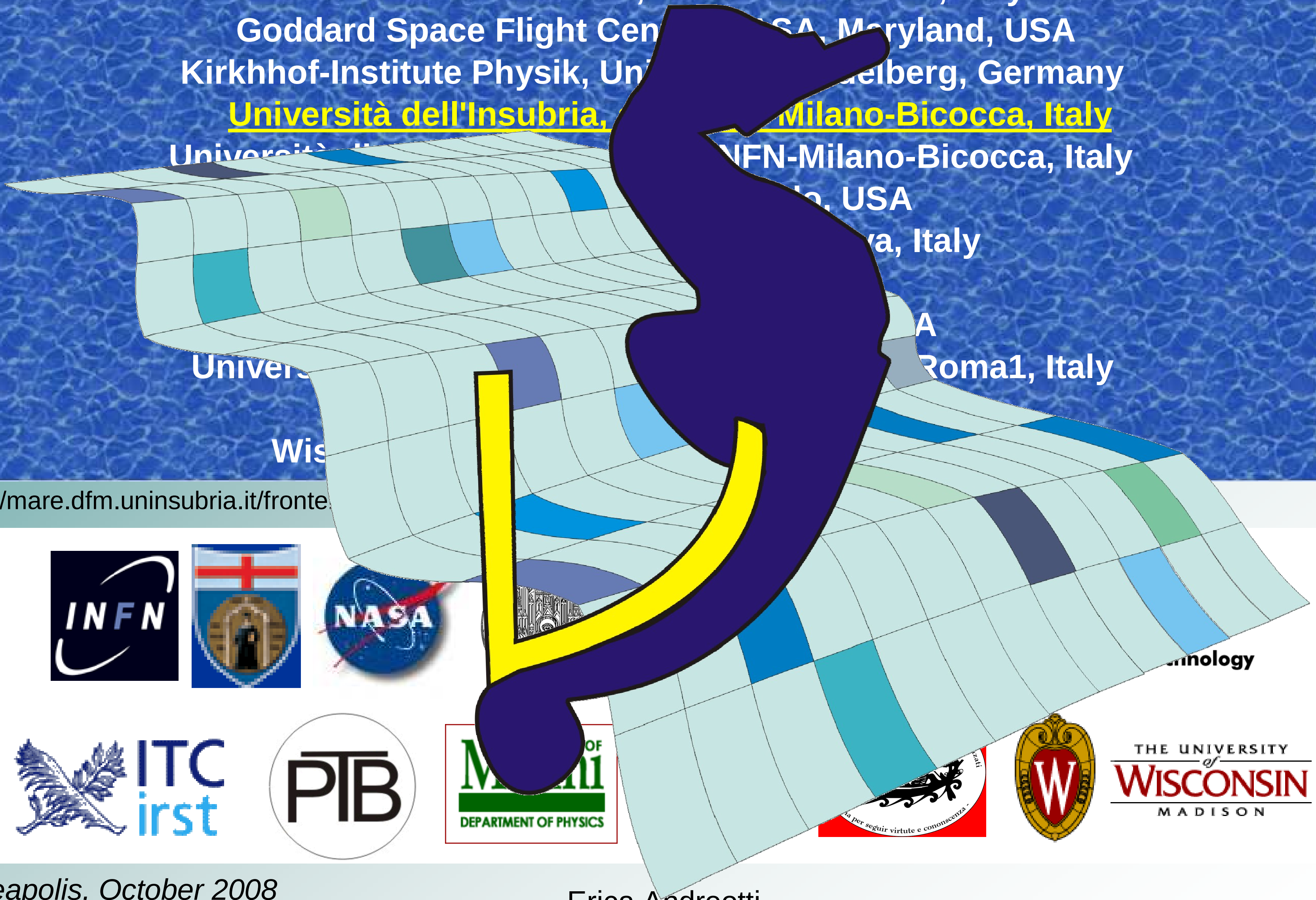
http://mare.dfm.uninsubria.it/frontend/exec.php

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 elberg, Germany
Università dell'Insubria, Milano-Bicocca, Italy
Università NFN-Milano-Bicocca, Italy
lo, USA
va, Italy
A
Univer Roma1, Italy
Wis

http://mare.dfm.uninsubria.it/fronte



nology

MARE I

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, $f_{pp}=3\times10^{-5}$

~ 300 detectors array

Total statistics ~ 10^{10} events

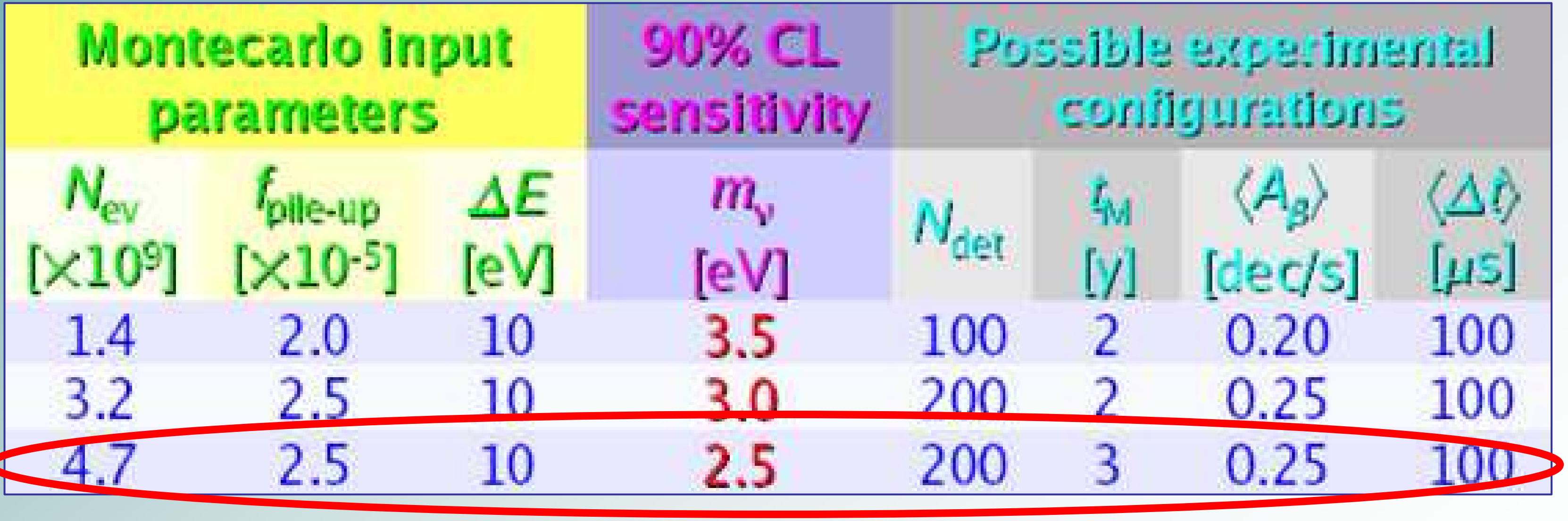
GOALS

2. Improve understanding on systematics

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

3. R&D for *MARE* II

MONTECARLO simulations *MARE* I



Montecarlo input parameters			90% CL sensitivity	Possible experimental configurations			
N_{ev} [$\times10^9$]	$f_{pile-up}$ [$\times10^{-5}$]	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

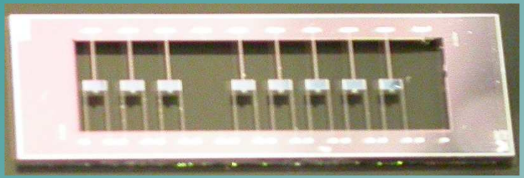
MARE I: thermistors

$A_\beta \sim 0.3$ Hz → doubling absorber mass while preserving ΔE and τ_r

Detectors require some improvements!

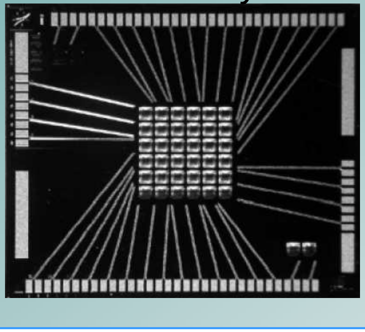
MIBETA2: available technologies

Arrays of 10 elements



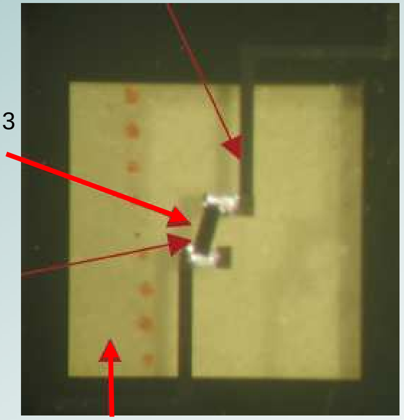
Sensor area 800×800 μm²

6×6 Si array



Nb electrical contact

NTD
300×200×25 μm³



SiN thermal link

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

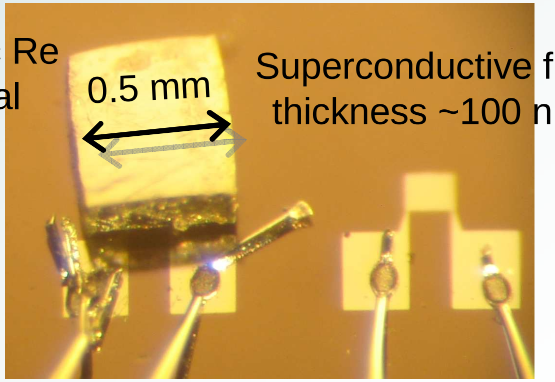
NASA/GSFC 6x6 silicon array.
Status: encouraging first results. Coupling and electronics are being optimized.

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

MANU2:

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

Metallic Re
crystal



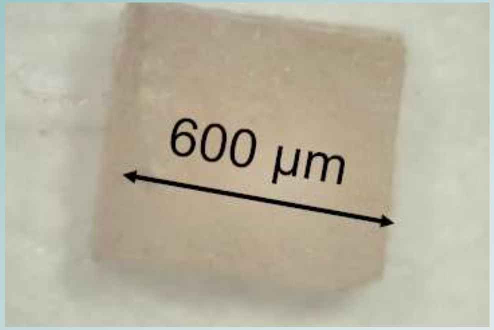
Superconductive film
thickness ~100 nm

MIBETA 2: previous tests

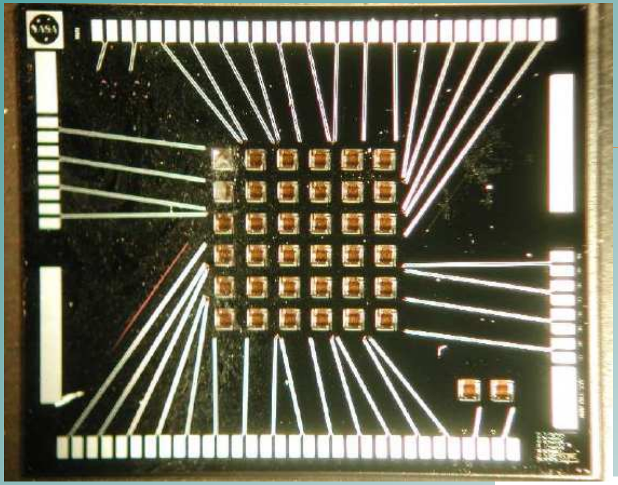
Array of 288 elements achieved through a gradual approach

Single channel:

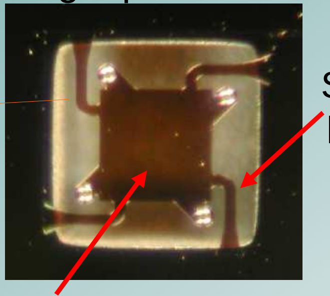
- $AgReO_4$ + semiconductor thermistor
- single crystal mass ~ **0.45 mg** → A_β ~ 0.3 Hz



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



single pixel



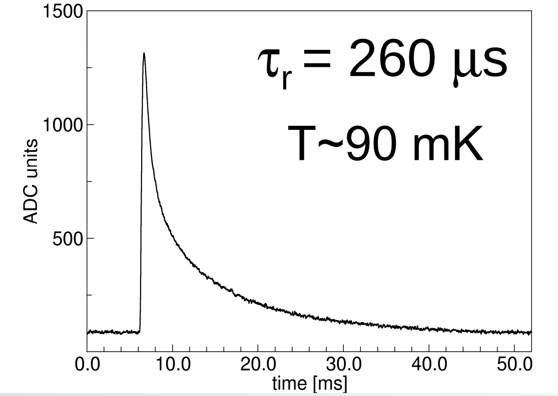
Si thermal links 3µm

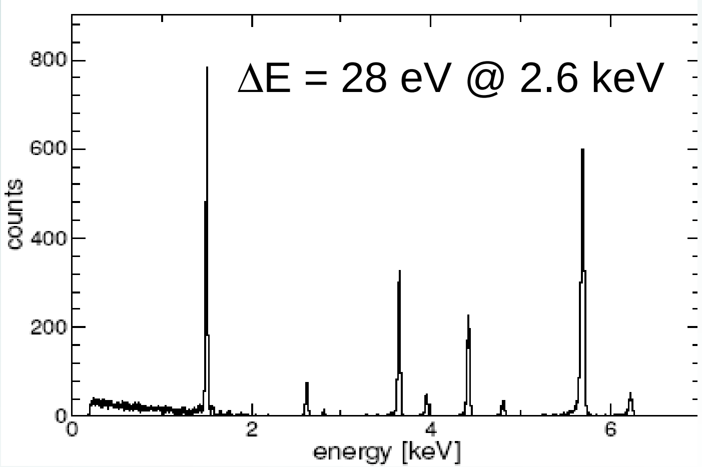
Si-thermistor 300×300×1.5 μm^3

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: schedule & sensitivity

Gradual deployment of the whole 288 elements array:

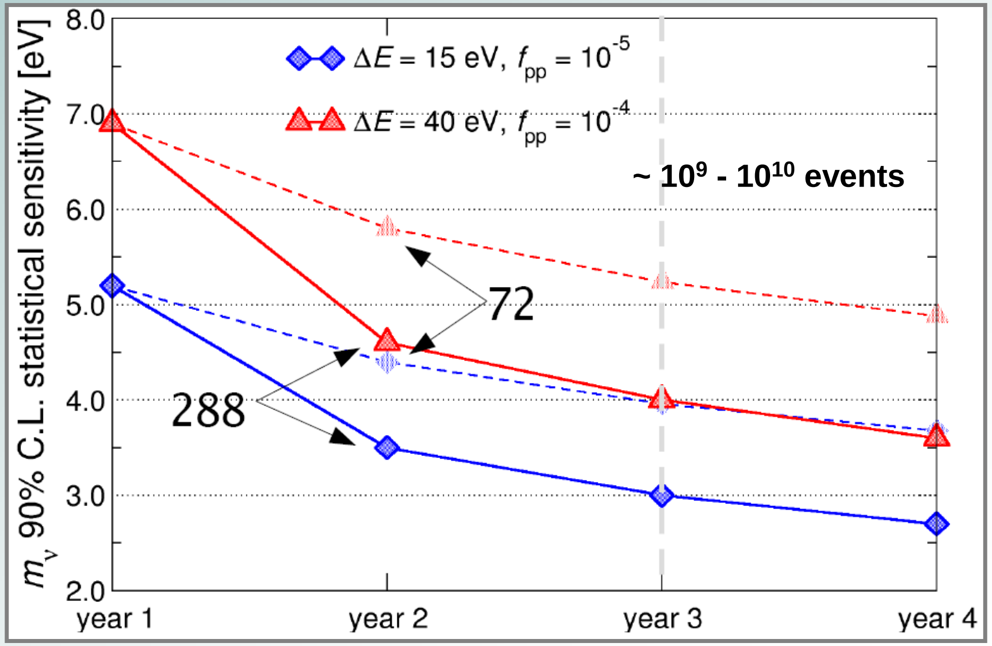
year	**1**	**2**	**3**	**4**
new detectors	72	216	0	0
total detectors	72	288	288	288
statistics [det*y]	72	360	648	936
statistics [events]	6.10×10^{8}	3.05×10^{9}	5.49×10^{9}	7.94×10^{9}

- ➢ Array design based on XRS2 array
- ➢ Possible alternatives based on different (previously mentioned) thermistors
- ➢ Single channel activity: ~0.27 Hz

Two approaches to evaluate the sensitivity:

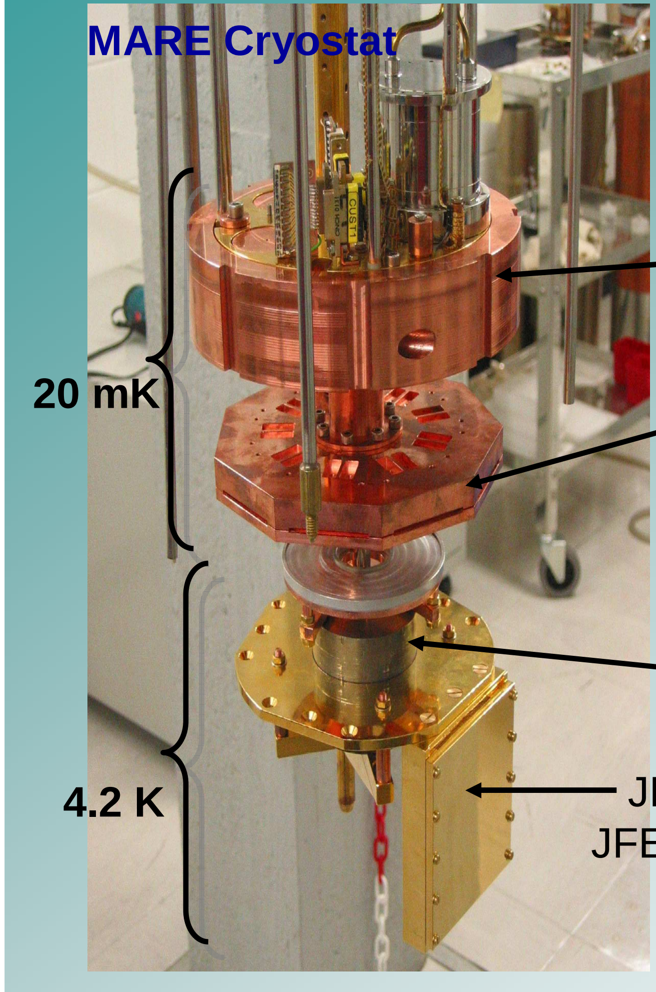
❖ *conservative*:
$\Delta E = 40$ eV & $\tau_r \sim 400\ \mu s$

❖ *improved:*
$\Delta E = 15$ eV & $\tau_r \sim 50\ \mu s$



MIBETA 2: status

- Cryogenic set-up (for 300 detectors) assembled in Milan
- 72 AgReO4 crystals and 2 XRS2 arrays ready to be assembled
- Tests for better crystal-thermistor coupling already performed
- Cold electronics is being assembled
- DAQ almost ready

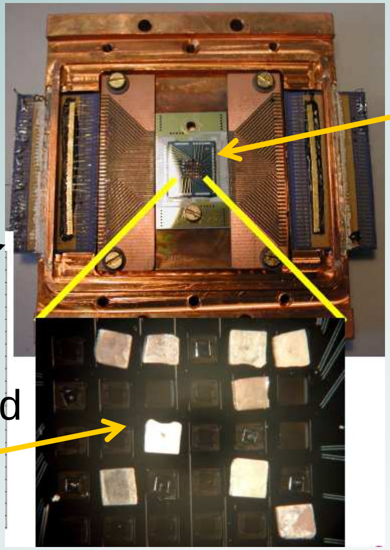


Cu shield against environmental radioactivity

Array holder

Calibration X-ray source

JFET boxes (inside: JFETs heated to 150 K)



Data taking with first 72 channels expected to start at the end 2008 - beginning 2009

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**

~ 4 years R&D

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.

Minneapolis, October 2008

Erica Andreotti

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

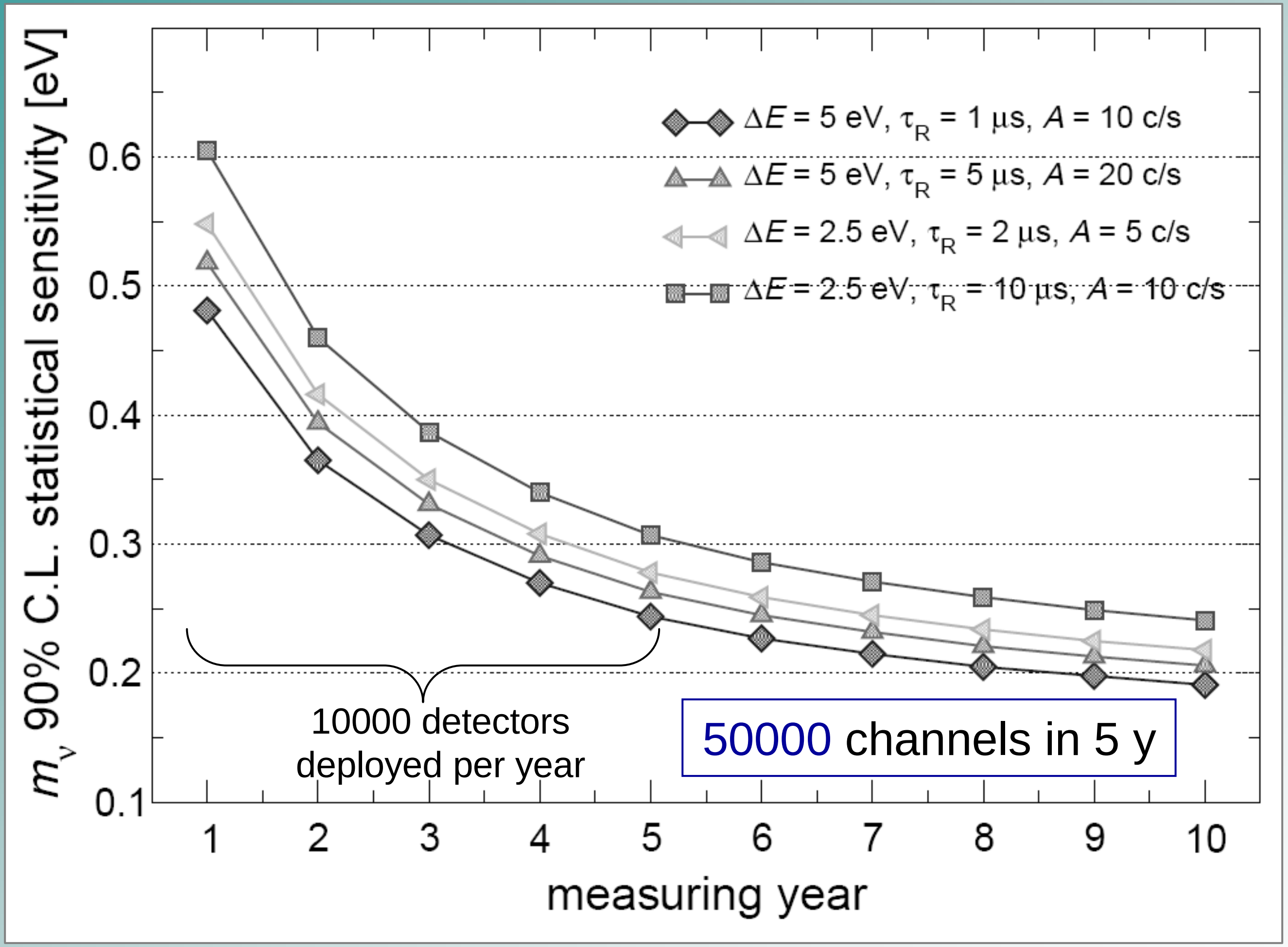
Electronics: front-end multiplexed SQUID (NIST, PTB)

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

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

50000 channels in 5 y

10000 detectors deployed per year

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!