CRYOGENIC EXPERIMENTS FOR DOUBLE BETA DECAY AND DARK MATTER

DBD and DM started together and are going to work together

Origin and development of thermal detectors

- **Microcalorimenters:**

  Single beta decay and the neutrino mass

- **Macrocalorimeters:**

  WIMPS

  The second mystery of Ettore Majorana

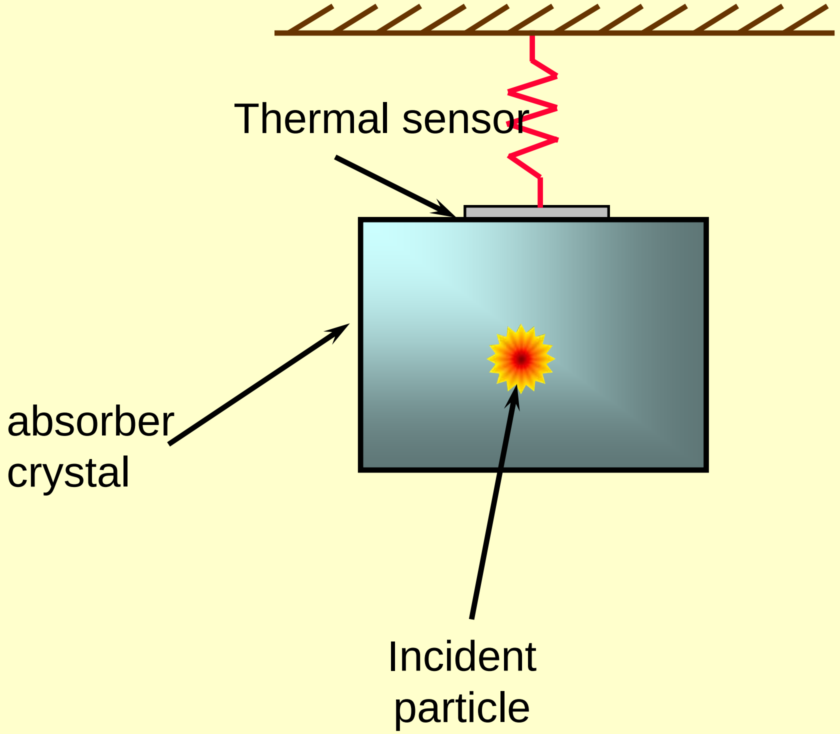
- **Expected and unexpected future of cryogenic detectors**
- **Conclusions**

Thermal detectors

$$\Delta T = \frac{Q}{C_V}$$

$$C_V = 1944 \frac{v}{v_m} \left(\frac{T}{\Theta}\right)^3 \text{ J/K}$$

$$\Delta E_{RMS} \propto \sqrt{\frac{k_B T_0^2 C_0}{\alpha}}$$



Energy resolution	<1 eV	**~ 2eV**	@ 6 keV
	~10 eV	**~keV**	@ 2 MeV

First ideas

1880 => Langley => resistive bolometers for infrared rays from SUN

1903 => Curie et Laborde => calorimetric measurement of radioactivity

1927 => Ellis and Wuster => heat less then expected => **the neutrino**

1949 => D. Andrews, R. Fowler, M. Williams => α particle detection

1983 => T.Niinikoski =>observe pulses in resistors due to cosmic rays

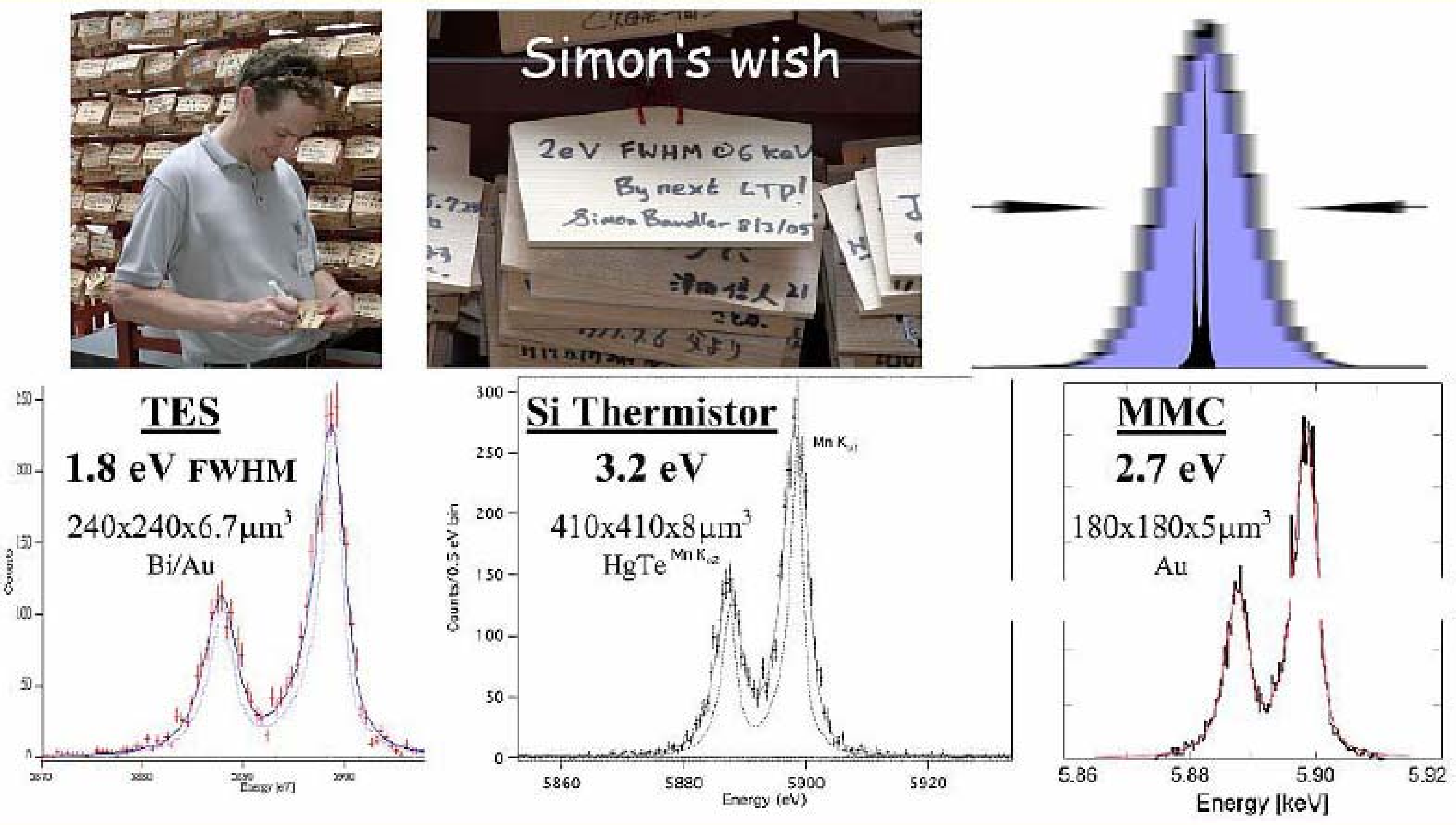
1984 => S.H.Moseley et LT detectors for astrophysics and ν mass

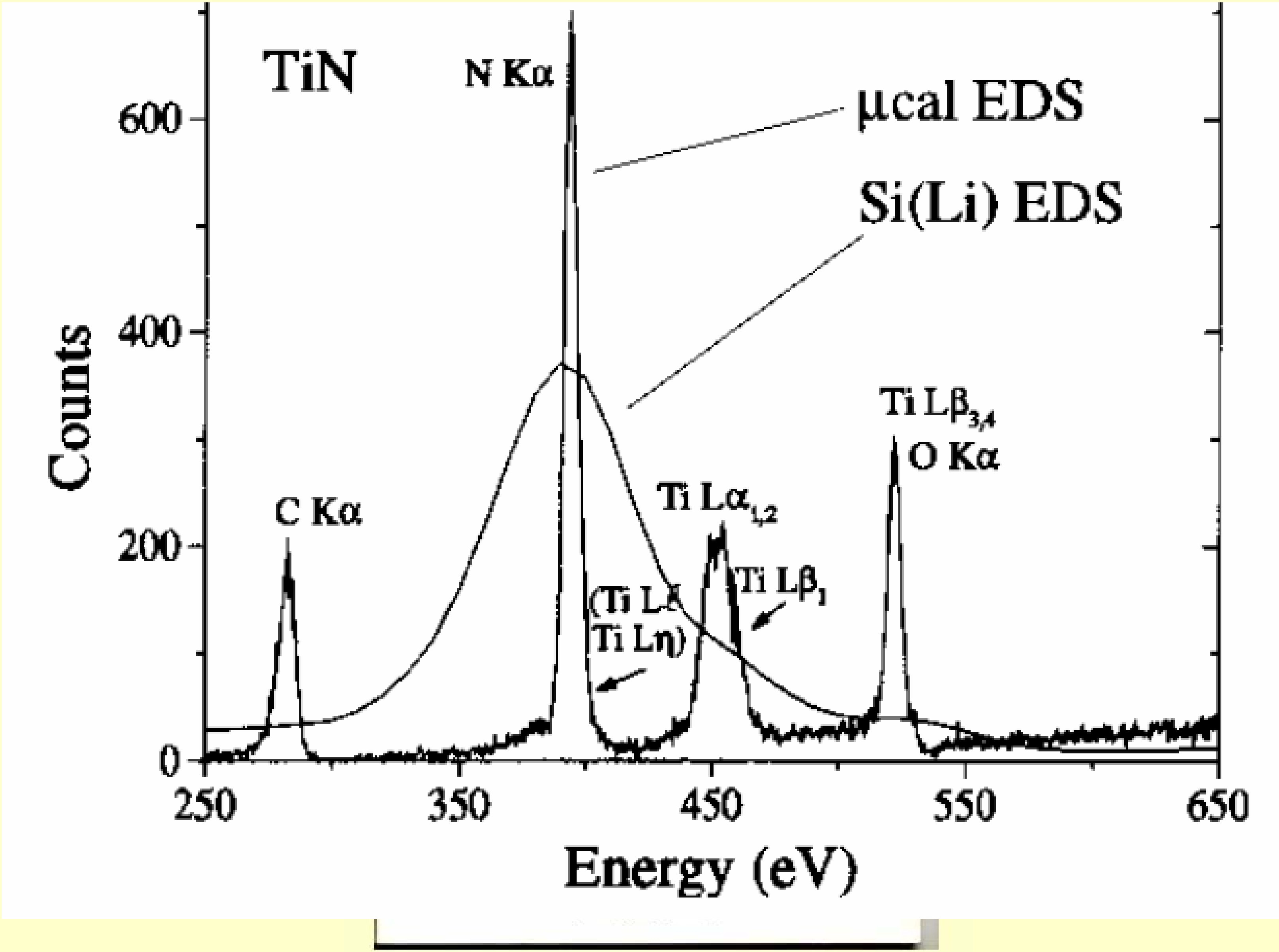
=> Fiorini and Niinikoski Low temperature detectors for rare events

=> A. Drukier, L. Stodolsky, => neutrino physics and astronomy

The first mini-meeting on thermal detectors
(Ringberg castle 1986)

Applications and results




TiN
N Kα
μcal EDS
Si(Li) EDS
Counts
600
400
200
0
C Kα
Ti Lα1,2
(Ti Lℓ
Ti Lη)
Ti Lβ1
Ti Lβ3,4
O Kα
250
350
450
550
650
Energy (eV)

Energy resolution of ea crystal of TeO_2 5x5x5 cm^3 (~ 760 g)

:

0.8 keV **FWHM @ 46 keV**

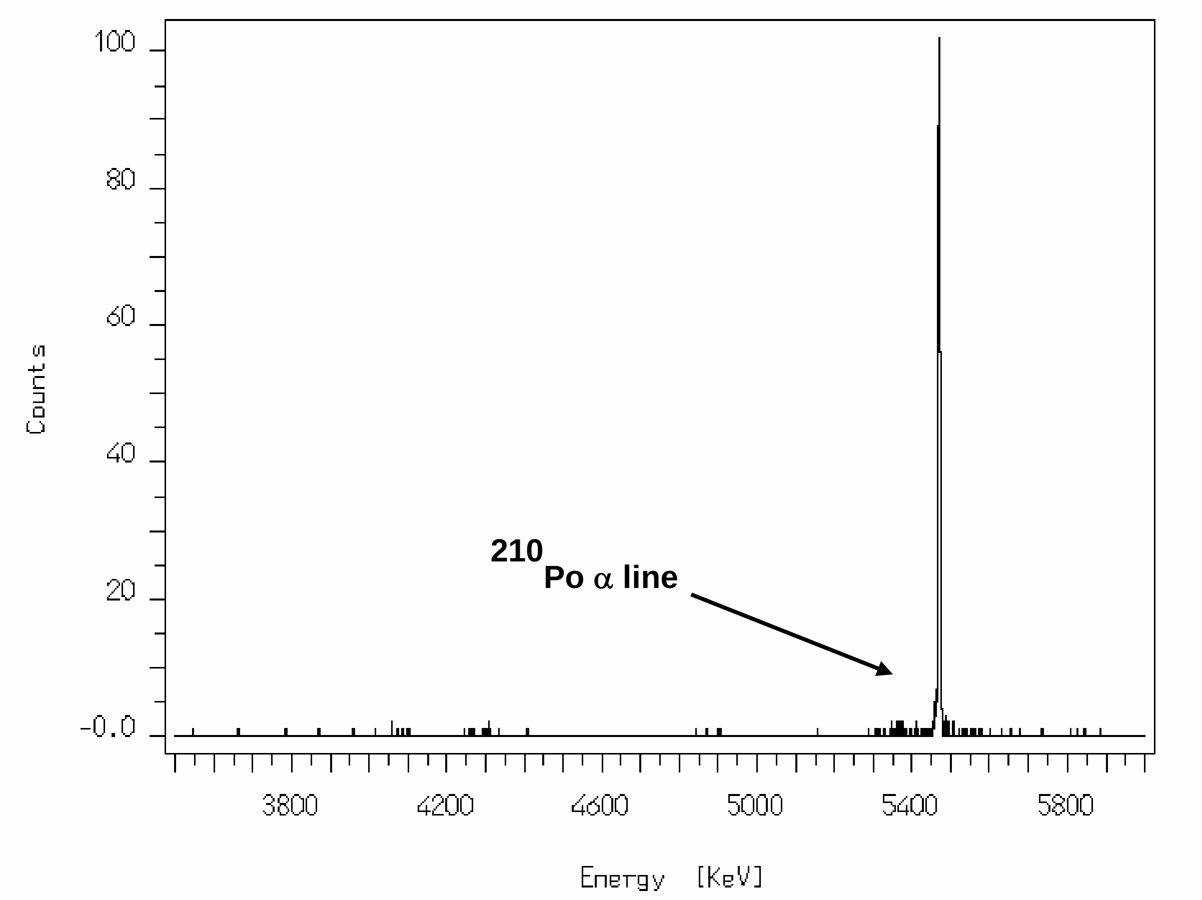
1.4 keV **FWHM @ 0.351 MeV**

2.1 keV **FWHM @ 0.911 MeV**

2.6 keV **FWHM @ 2.615 MeV**

3.2 keV **FWHM @ 5.407 MeV**

(the best α spectrometer so far



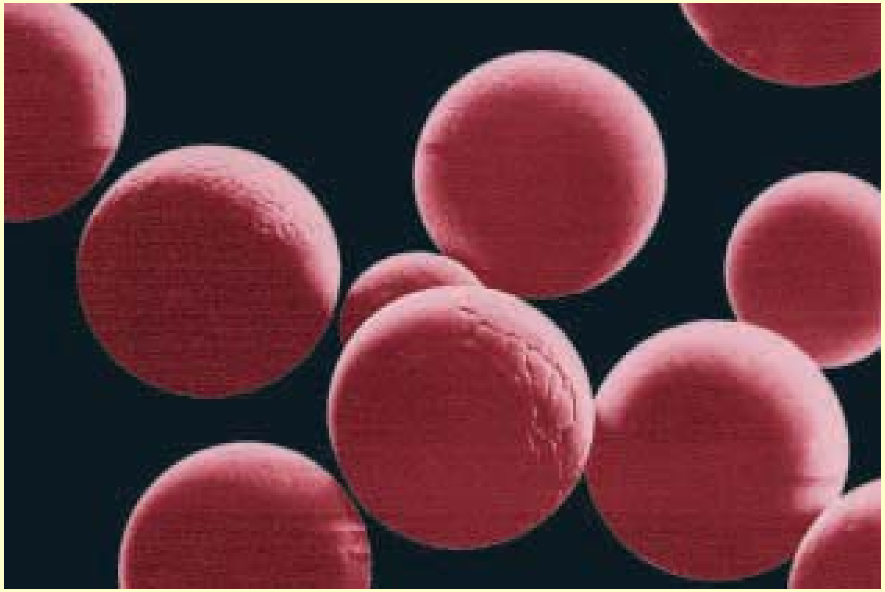
Science applications

- **Neutrino mass experiments**
- **Dark matter searches**
- **Double beta decay**
- Alpha & beta spectroscopy, mass spectroscopy, heavy ions, and neutrons
- X-ray & gamma spectroscopy in atomic, nuclear, astrophysics & other fields
- UV to IR single photon detection
- Bolometers in mm / sub-mm wave for astronomy, THz applications
- Others

Two types of thermal detectors

-Equilibrium detectors => a possibly dielectric and diamagnetic crystal in thermal contact with a thermal sensor

-Non equilibrium detectors
=> kinetic inductance detectors (KIDs) [8]
=> superconducting
=> tunnel junctions (STJs) [9]
=> superheated superconducting granules



- Various types of thermometers

=> a thermistor

=> a transition edge sensor (TES)

=> an Equilibrium Absorber weakly coupled to a heat bath
superconducting tunnel junction (STJ) Cooper pair
breaking

=> a magnetic thermometer . The temperature information is
obtained from the change of a paramagnetic sensor
placed in a small magnetic field

Caveat => possibility that the heat capacity of the thermometer
be comparable or larger than the absorber one:

Three most popular thermometers are used today

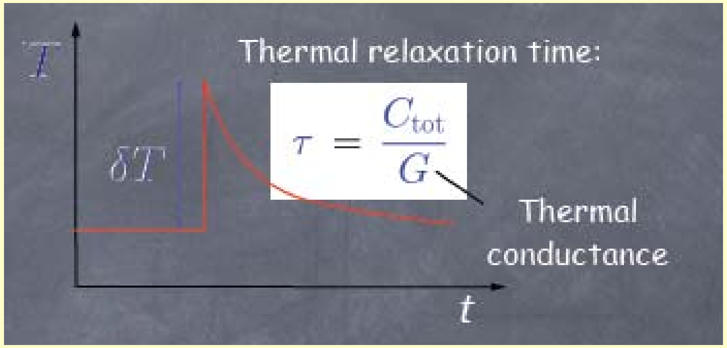
=> highly doped semiconductors,

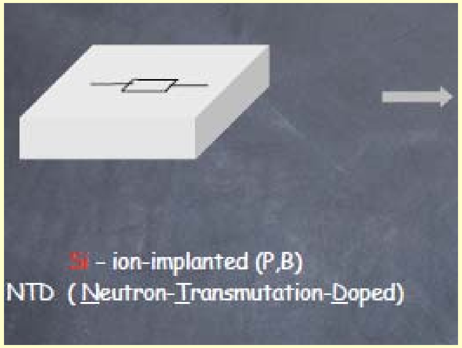
=> superconductors operated at the superconducting to normal transition (TES)

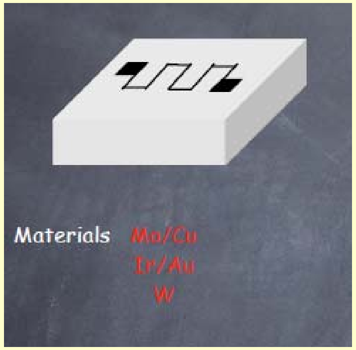
=> metallic paramagnets

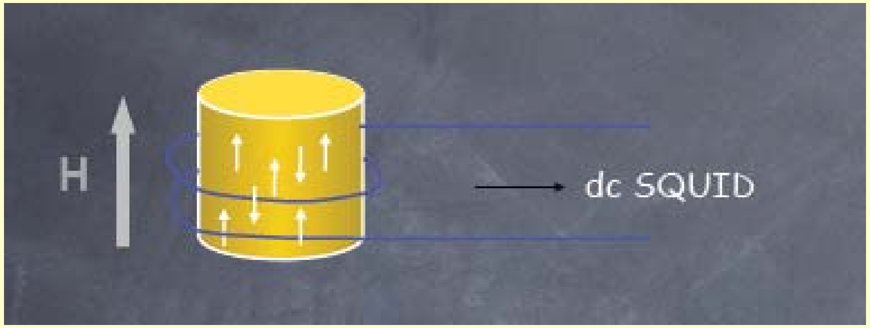
Thermometers

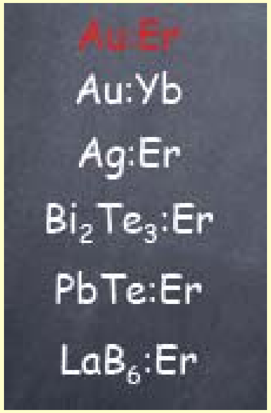
Thermal detectors with NTD Ge sensors
Thermal sensors with doped semiconductors
Superconducting Tunnel Junctions
Superconducting Phase Transition sensors
Superconducting Transition Edge Sensors
Superconducting Kinetic Inductance Devices





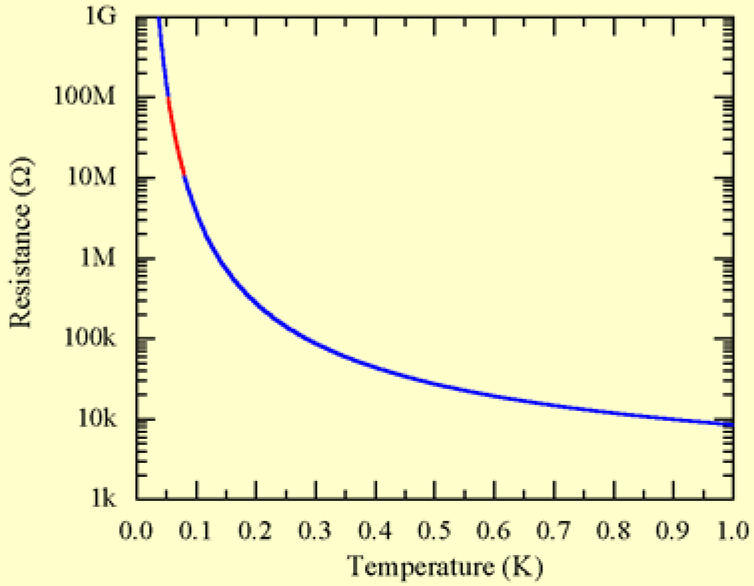


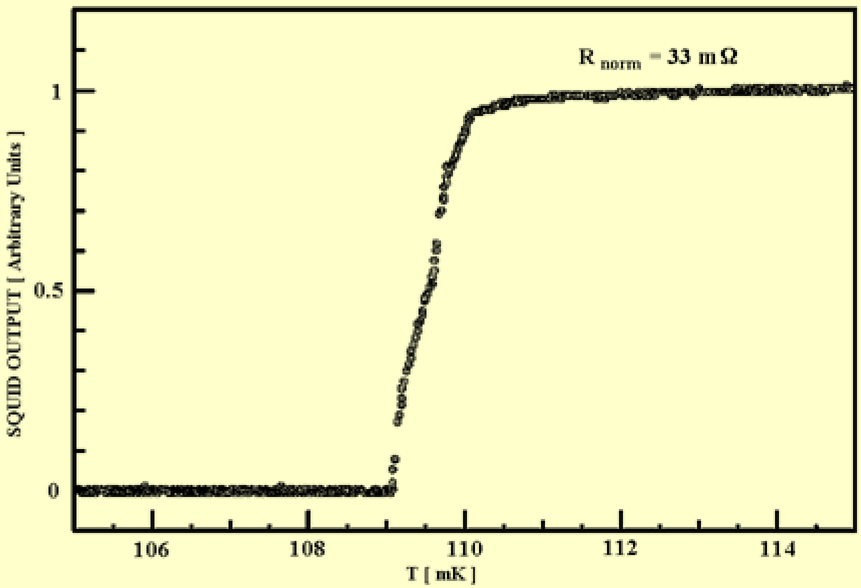




Transition Edge Sensors (TES)

Superconductors operated at the superconducting to normal transition





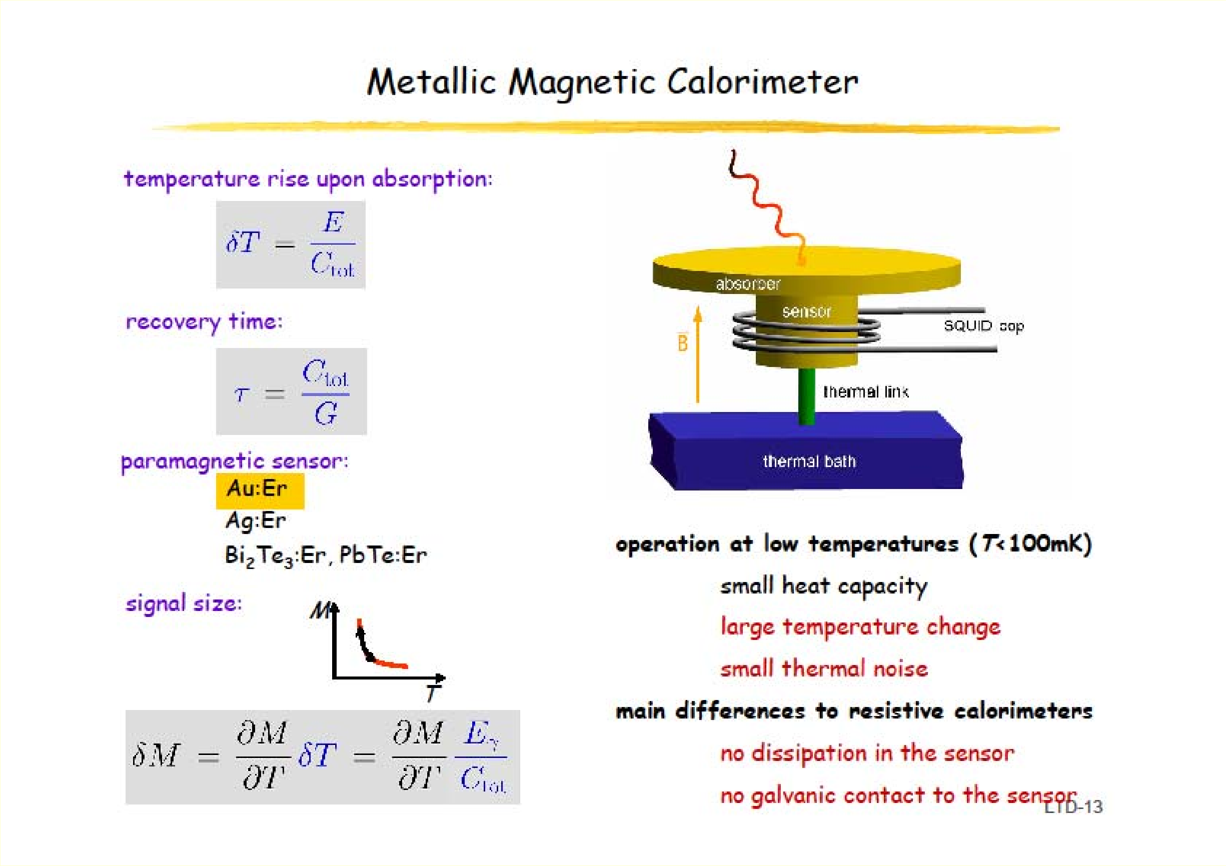
Thermistors

- Very high resistance
- Negative "low" sensitivity
- FET readout

TES

- Very low Resistance
- Positive "high" sensitivity
- SQUID readout

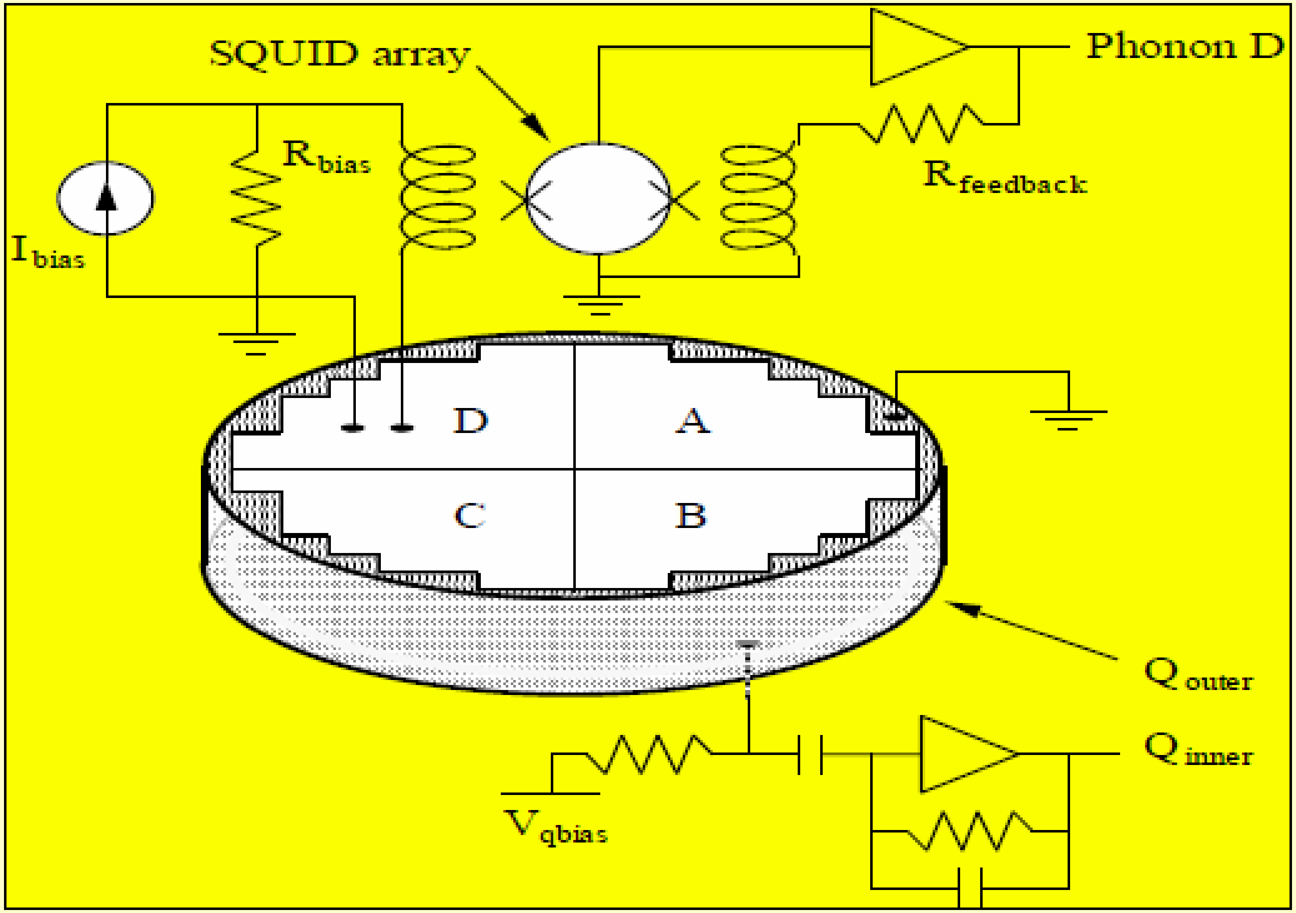
Temperature => change of magnetization of a paramagnetic sensor => e.g. Au:Eu



MKID a superconducting thin film microwave resonator to detect changes in the surface impedance of the superconducting film by detecting changes in properties of the resonance circuit: the microwave kinetic inductance detector,

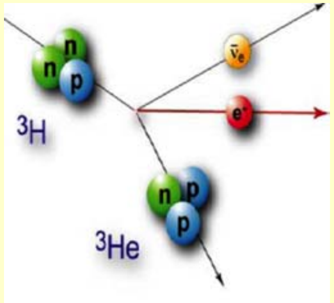
Hybrid techniques

heat + ionization or heat + scintillation

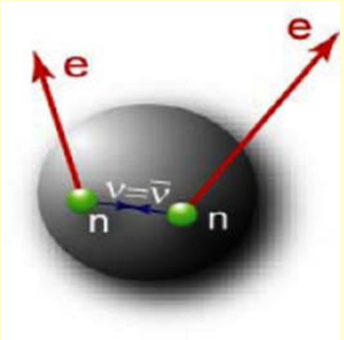


Direct measurement of the neutrino mass

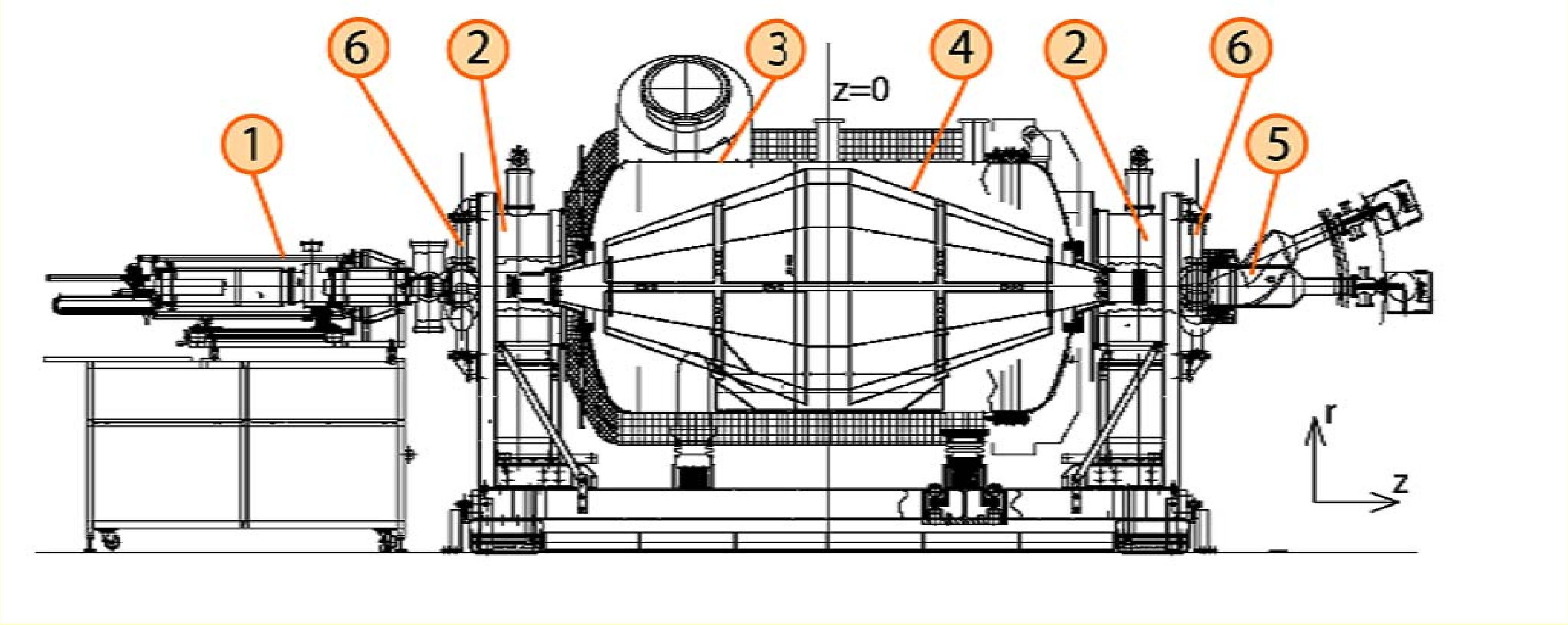
β decay



Electron capture



Beta spectrometers $^3H \Rightarrow {}^3He + e^- + \bar{\nu}_e$ KATRIN 2 => 0.2 eV



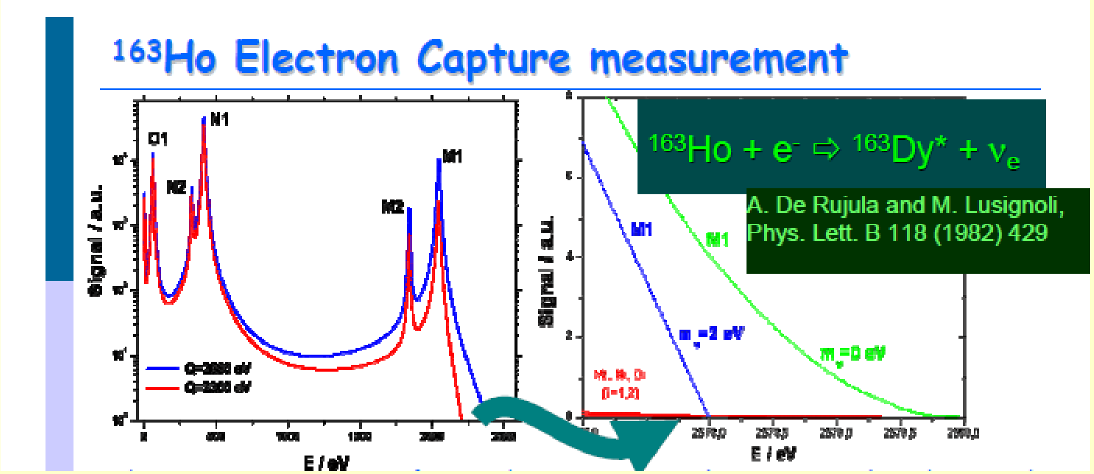
Thermal detectors for searches on neutrino mass in single β decay

An alternative measurement of the antineutrino mass

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

Nucleus with the lowest beta transition energy (~ 2.5 keV)
Source inside the detector => all energy spent inside the detector is measured
It corresponds to the entire decay energy apart the antineutrino one
If the beta decay occurs to an exited
state also the decay of this state is measured

$$^{163}Os + e^- \Rightarrow {}^{163}Dy + \bar{\nu}_e$$

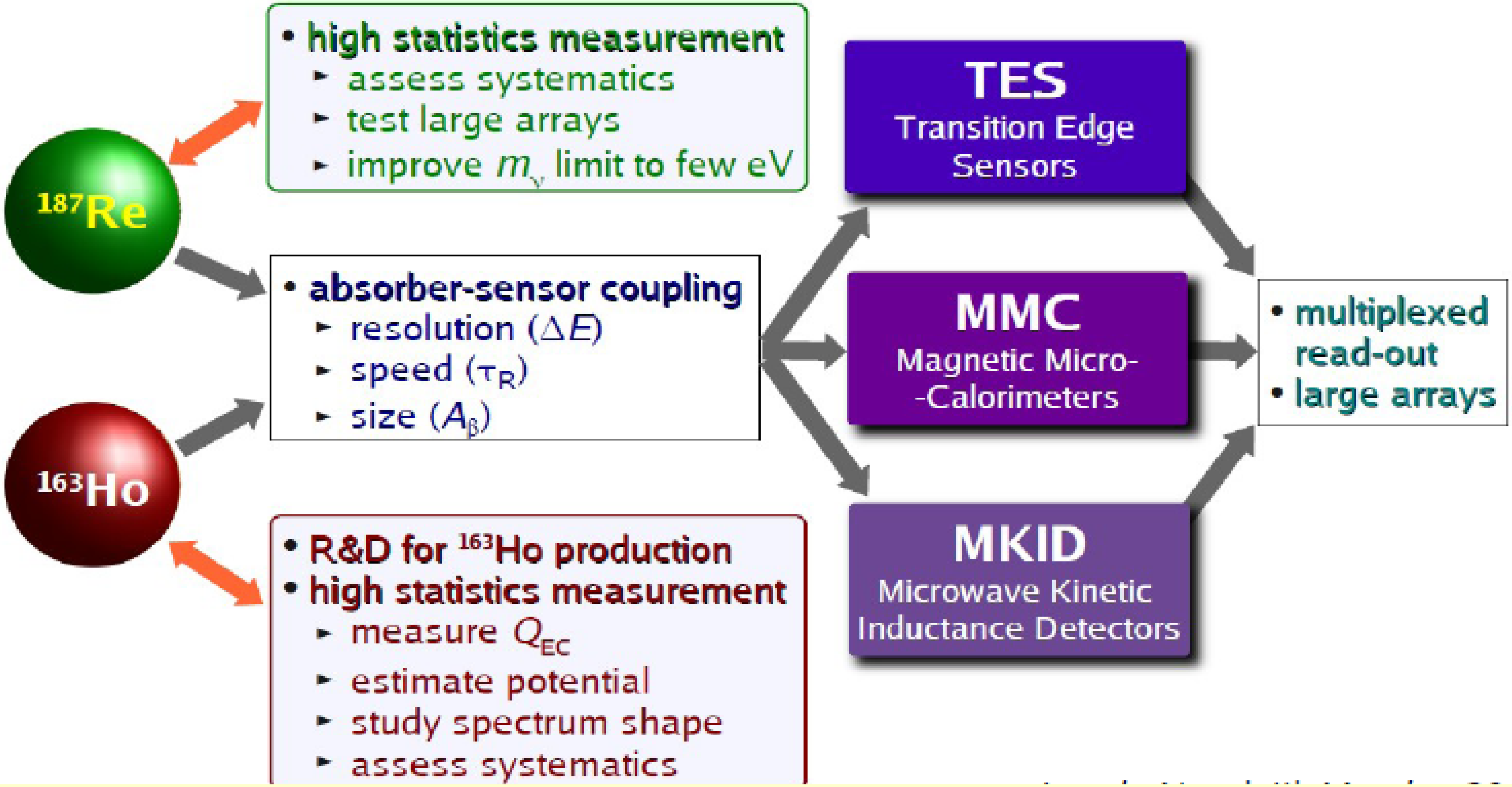


MARE phase 1 / phase 2 objectives

Westfälische Wilhelms-Universität Münster

MARE-1 : - collection of activities aiming at isotope / technique selection
- setup of a ^{187}Re experiment with few eV light ν sensitivity

MARE-2 : - full scale experiment with several 10^4 - 10^5 detector pixels aiming at 0.1 eV - 0.2 eV statistical sensitivity



New developments: ECHO

Westfälische Wilhelms-Universität Münster

Electron Capture ^{163}Ho Experiment

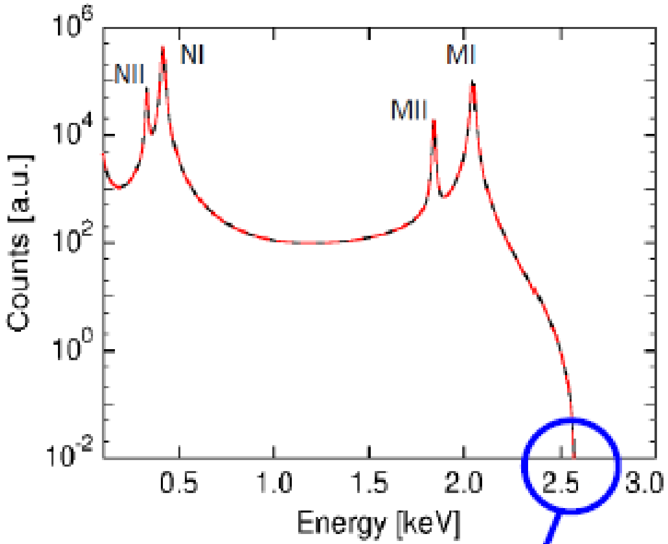
(Uni Heidelberg, MPIK Heidelberg, Saha Inst. of Nucl. Phys., ISOLDE CERN, Petersburg Nucl. Phys. Inst.)

A non-zero neutrino mass affects the de-excitation spectrum of electron capture decays

→ calorimetric measurement of the de-excitation energy spectrum

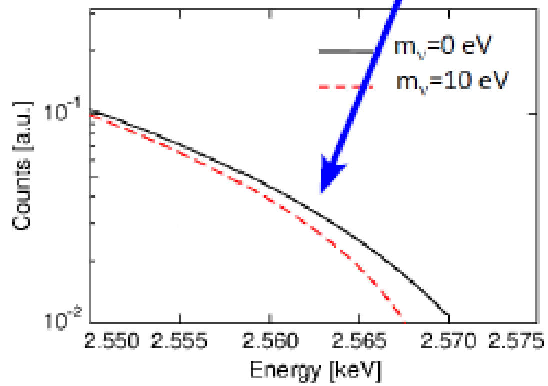
Suitable candidate: ^{163}Ho → $Q_{EC} \approx 2.5$ keV

$T_{1/2} \approx 4570$ y



$$^{163}_{67}\mathrm{Ho} + e^- \rightarrow {}^{163}_{66}\mathrm{Dy}^* + \nu_e$$

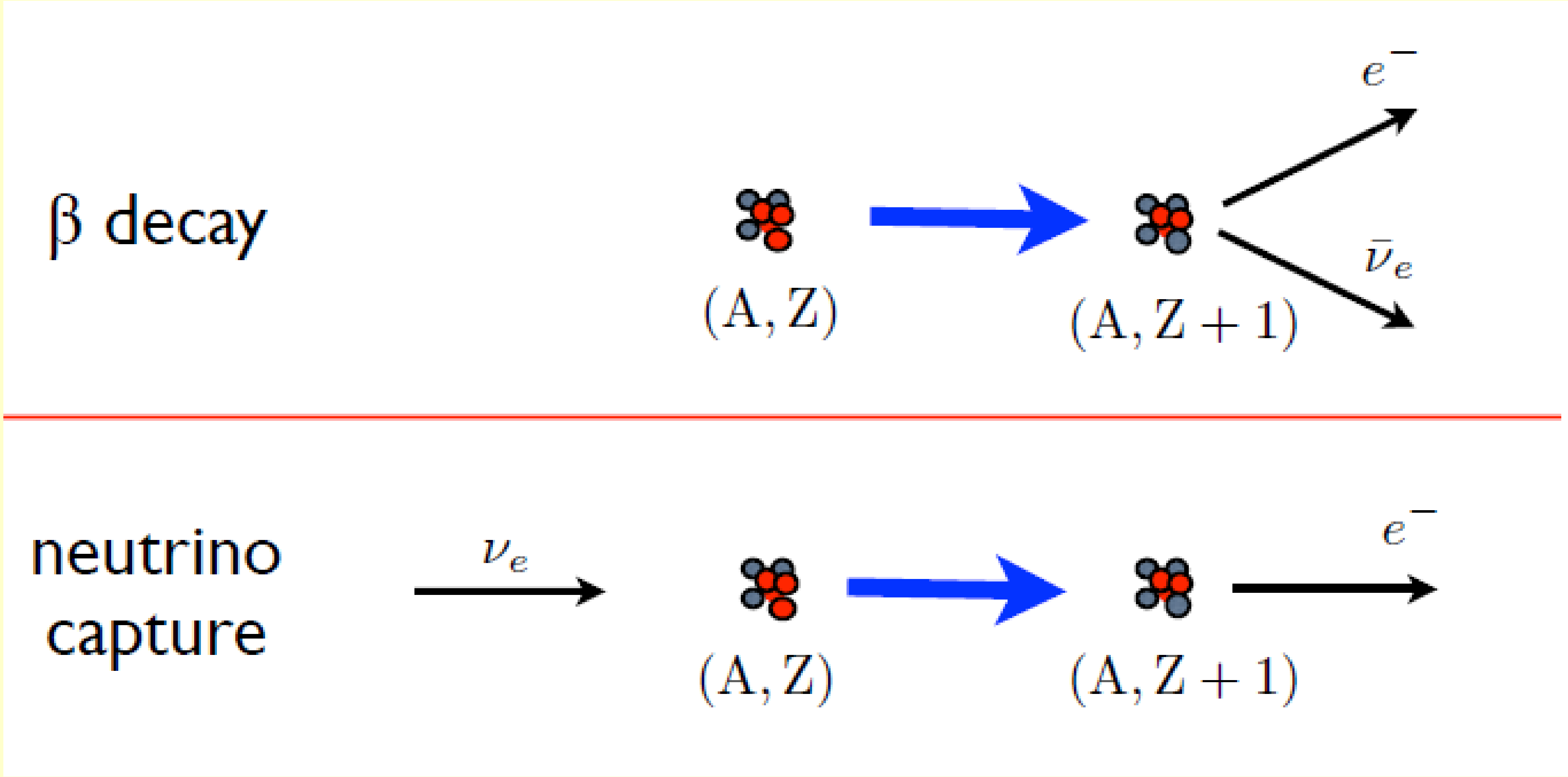
$$^{163}_{66}\mathrm{Dy}^* \rightarrow {}^{163}_{66}\mathrm{Dy} + E_C$$



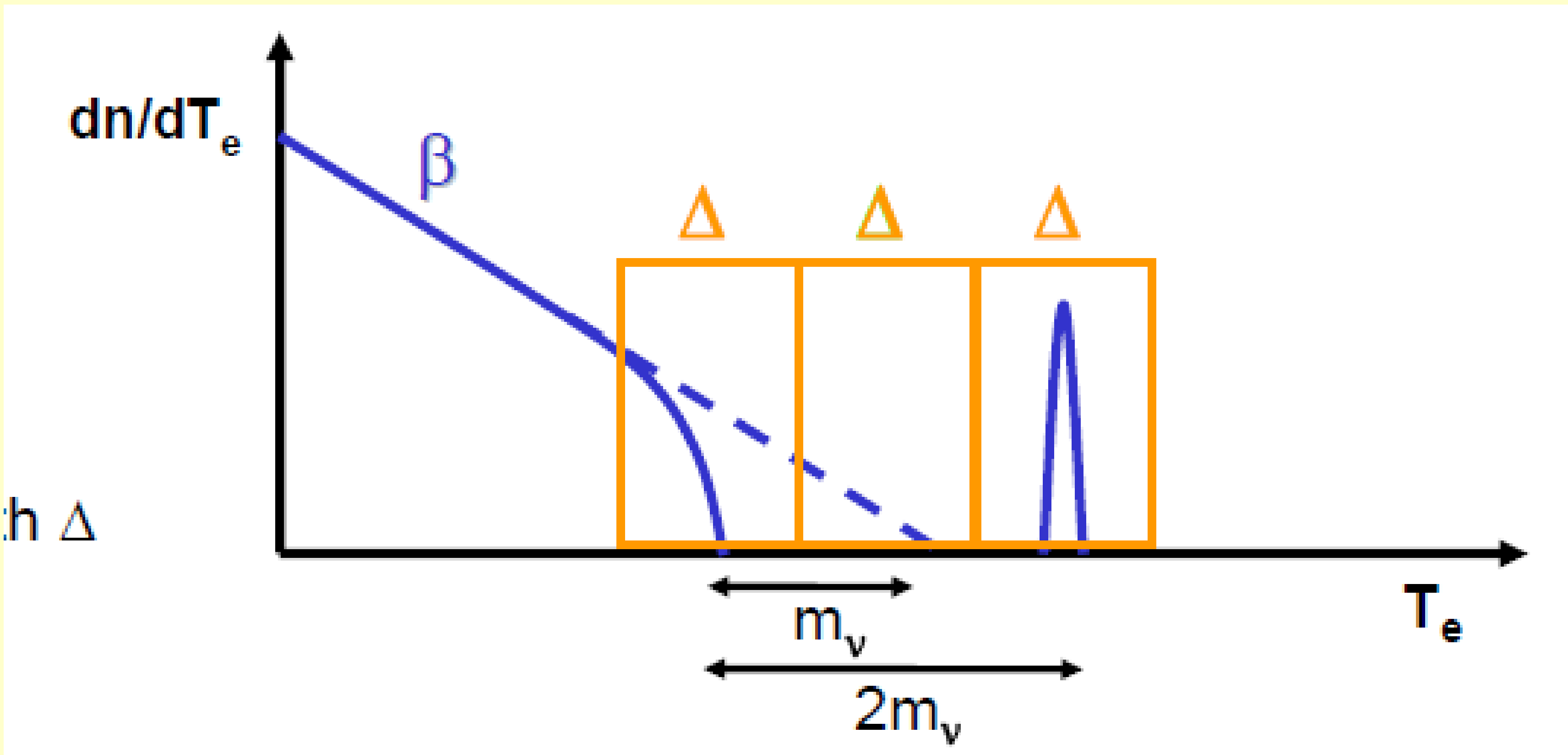
$$\frac{dW}{dE_C} = A(Q_{EC} - E_C)^2 \sqrt{1 - \frac{m_\nu^2}{(Q_{EC} - E_C)^2}} \sum_H \varphi_H^2(0) \frac{\frac{\Gamma_H}{2\pi}}{(E_C - E_H)^2 + \frac{\Gamma_H^2}{4}}$$

courtesy L. Gastaldo

A dream => detection of relic neutrinos



$$\Omega_\nu h^2 = \frac{\Sigma m_\nu}{93.2eV}$$



$\bar{\nu}_e + {}^3H \Rightarrow {}^3He + e^-$ $\qquad$ $\bar{\nu}_e + {}^{187}Re \Rightarrow {}^{187}Os + e^-$

Isotope	Decay	Q (keV)	Half-life (sec)	$\sigma_{NCB}(v_\nu/c)$ (10^{-41} cm^2)
^{3}H	β^-	18.591	3.8878×10^8	7.84×10^{-4}
^{63}Ni	β^-	66.945	3.1588×10^9	1.38×10^{-6}
^{93}Zr	β^-	60.63	4.952×10^{13}	2.39×10^{-10}
^{106}Ru	β^-	39.4	3.2278×10^7	5.88×10^{-4}
^{107}Pd	β^-	33	2.0512×10^{14}	2.58×10^{-10}
^{187}Re	β^-	2.64	1.3727×10^{18}	4.32×10^{-11}
^{11}C	β^+	960.2	1.226×10^3	4.66×10^{-3}
^{13}N	β^+	1198.5	5.99×10^2	5.3×10^{-3}
^{15}O	β^+	1732	1.224×10^2	9.75×10^{-3}
^{18}F	β^+	633.5	6.809×10^3	2.63×10^{-3}
^{22}Na	β^+	545.6	9.07×10^7	3.04×10^{-7}
^{45}Ti	β^+	1040.4	1.307×10^4	3.87×10^{-4}

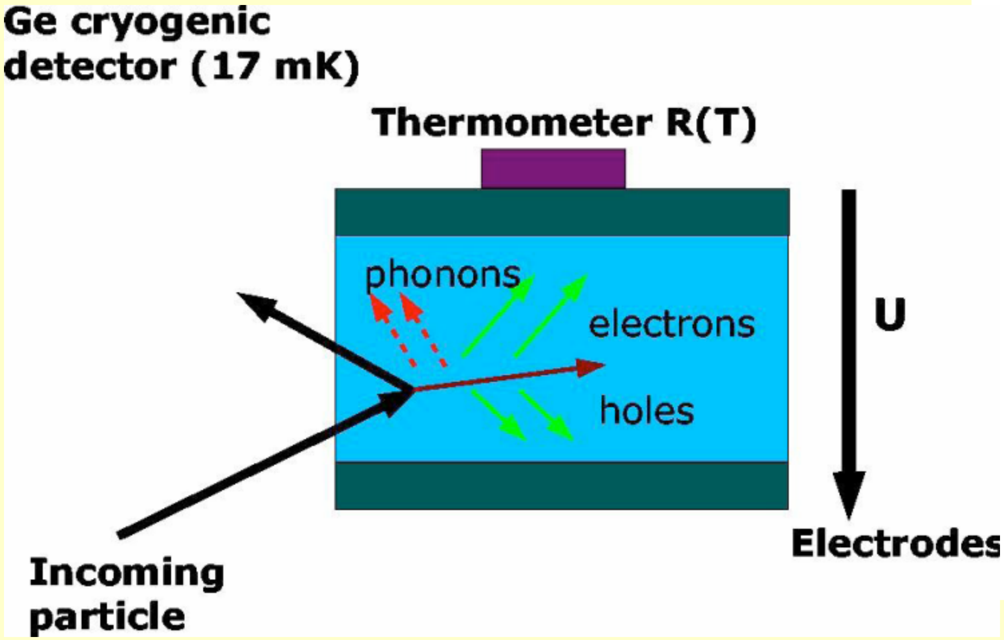
Dark Matter

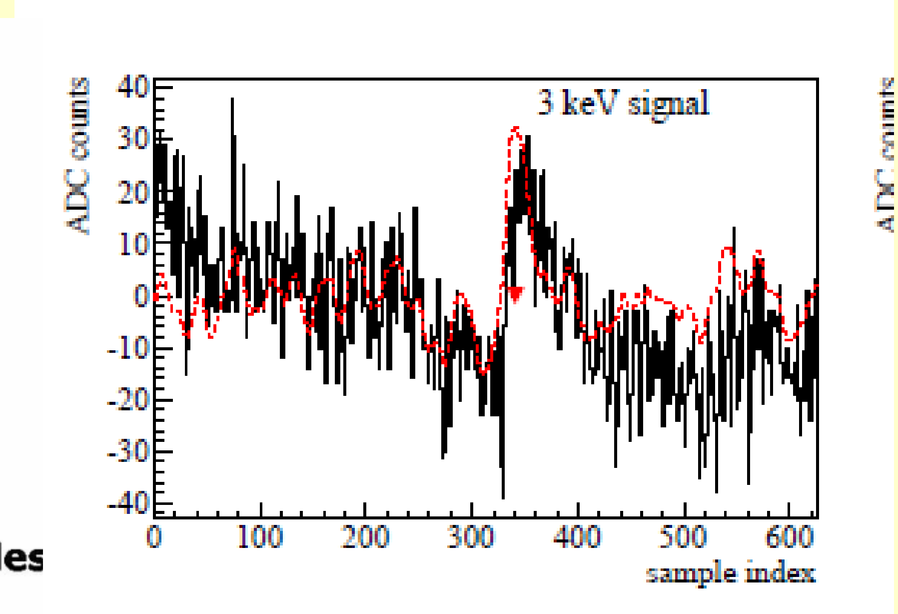
Thermal detectors => **100% quenching factor**

⇒ **Scintillation** + heat (CRESST and Rosebud)

⇒ **Ionization** + heat (CDMS II and Edelweiss)

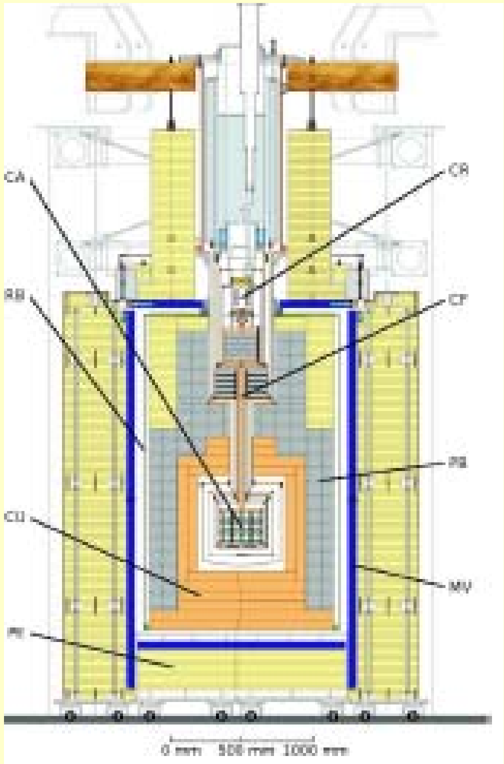
=> **Seasonal modulation** (if a low threshold is reached)

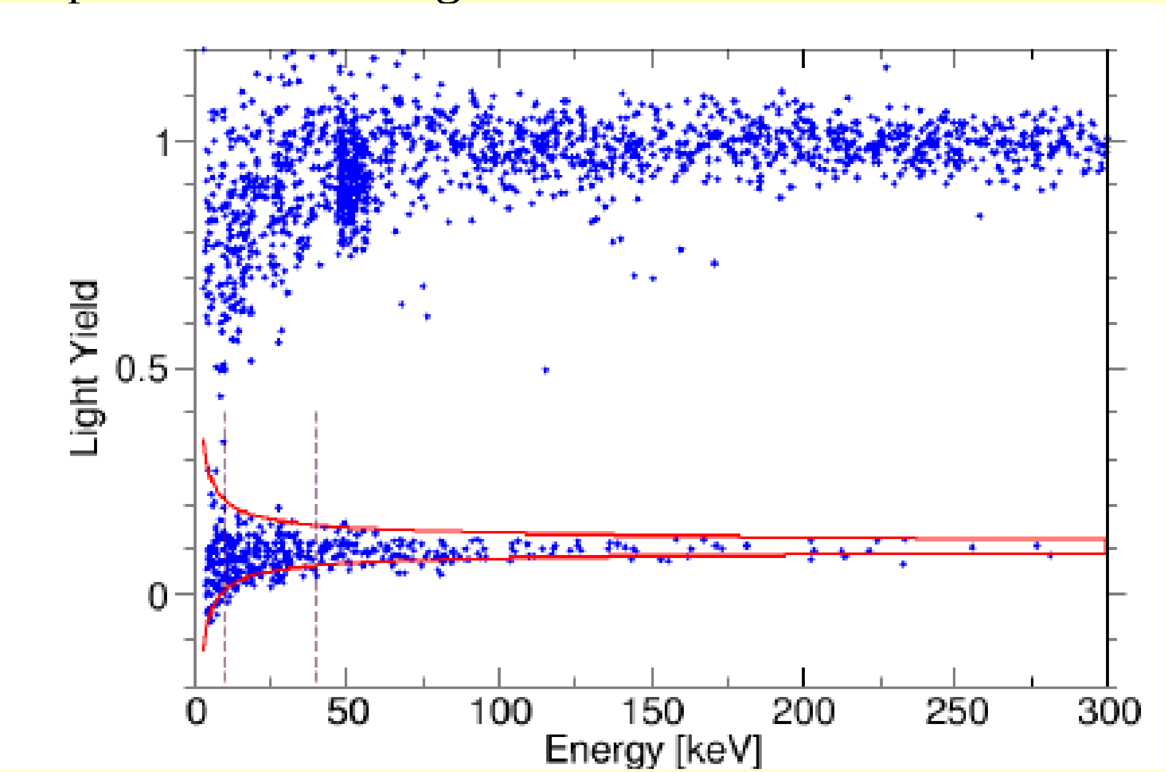




CRESST

- **$CaWO_4$** crystals cooled to **10 mK**
- Heat measured with **W TES** (red with SQUIDS)
. Scintillation light by detectors optimized for **light collection**
  Collected 730 kg x day
- **67 events found** Non compatible with background

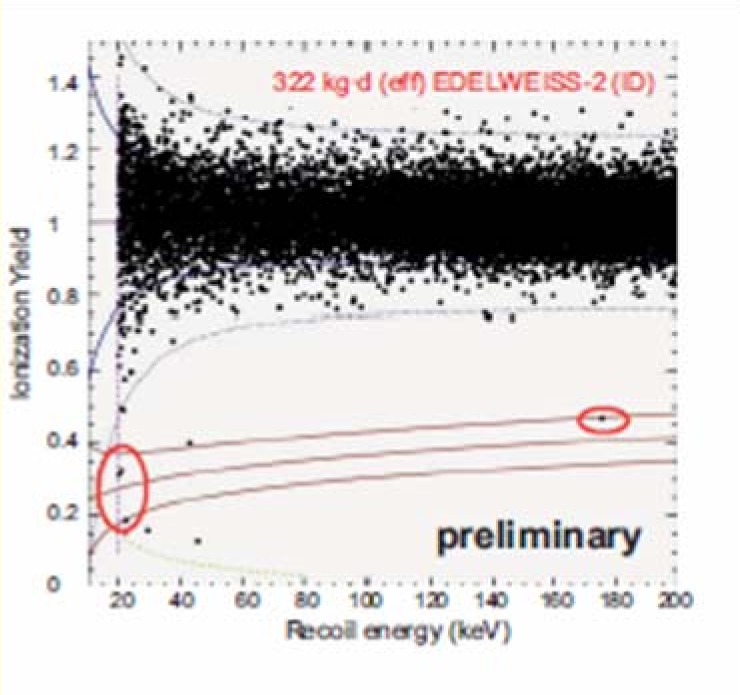




Edelweiss

- **ionization** signal, as second readout channel.
- **Ge crystals** operated below 100 mK.
- **NTD** based Ge thermistors
- **electron-recoil** background events that occurs **near the surface** **of the crystals**
- EDELWEISS and SuperCDMS have opted for an **interdigitated electrode scheme**
- Events near the surface => ionization signal in **only one** charge readout channel, in the bulk ionization signals in **more than one** charge readout channel

Joins with CDMSII



CDMS and SuperCDMS

CDMS use **athermal phonon readout** => phonons are initially absorbed in **superconducting Al collectors** on the surface of the crystal

=> liberated quasiparticles drift and **trapped in W TES**

⇒ Non-equilibrium sequence of events maintains **additional position and event-type information** in the phonon readout channel

CDMSII

=> 612 kgxday including CDMS => two events **12.3 and 15.5 keV**

backgrounds of **0.8±0.2 and 0.03±0.06**

=> Low threshold analysis lowering the threshold to 2 keV => no event < 10 keV

CDMS and EDELWEISS COMBINED

$\sigma < 3.3\ 10^{-44}$ cm^2 @ 90 GeV

Non thermal detectors

DAMA/LIBRA

1.7 ton x year 13 annual cicles => 8.9 σ Peak at end of may

KIMS

24524.3 kg x day no event below 8 keV => no recoil on iodine Limit on inelastis because both I and Cs are heavy

CoGeNT

Seasonal variation at 2.8 σ

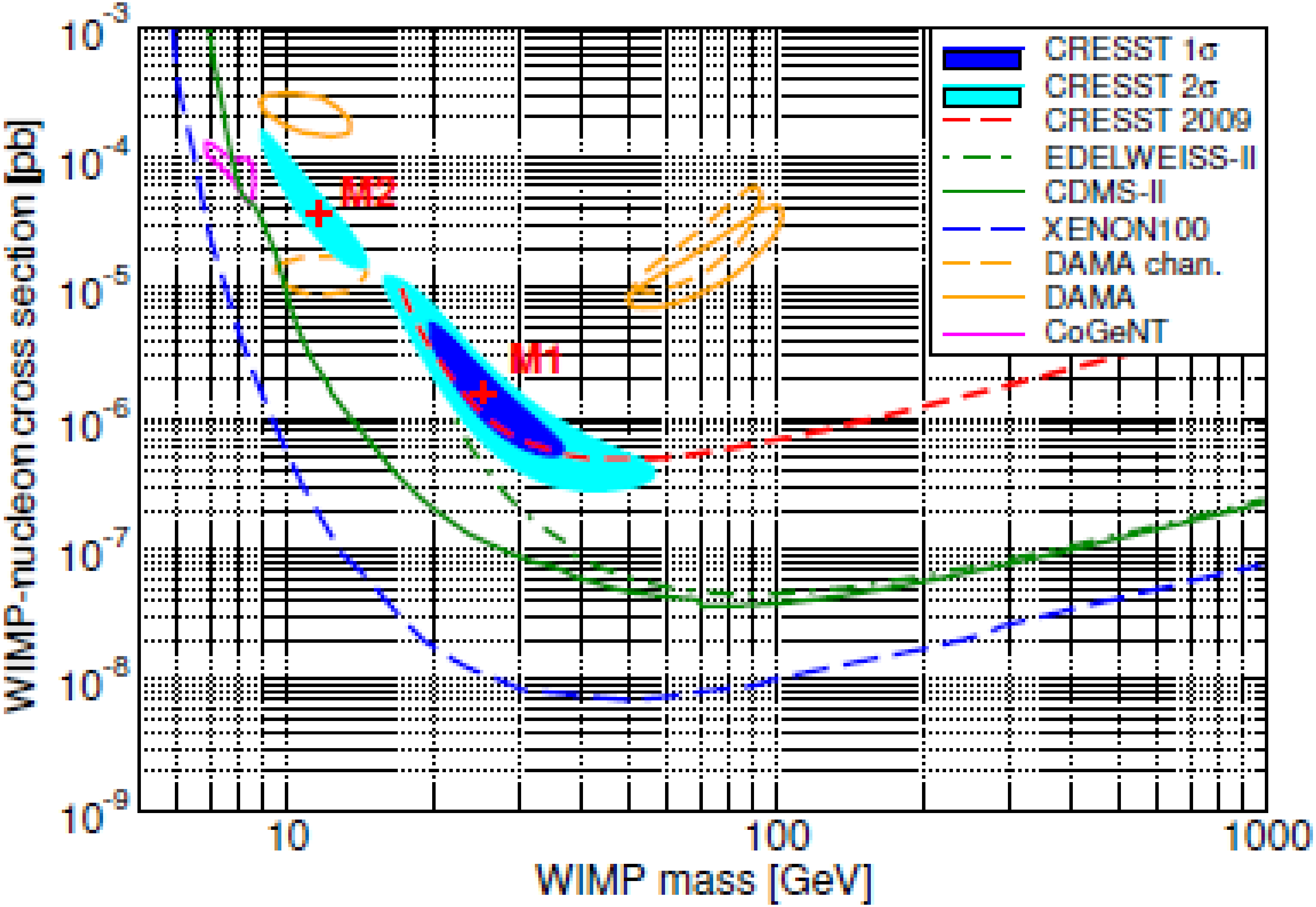
XENON-100

4843 kg day three events with background 1.8 $\pm$ 0.6

PICASSO

Superheated liquid droplets 0.72 kg ^{19}F 114 kg day

COUPP and Milano-Bococca Bubble chambers



CRESST 1σ
CRESST 2σ
CRESST 2009
EDELWEISS-II
CDMS-II
XENON100
DAMA chan.
DAMA
CoGeNT
M2
M1
WIMP-nucleon cross section [pb]
WIMP mass [GeV]
10
100
1000

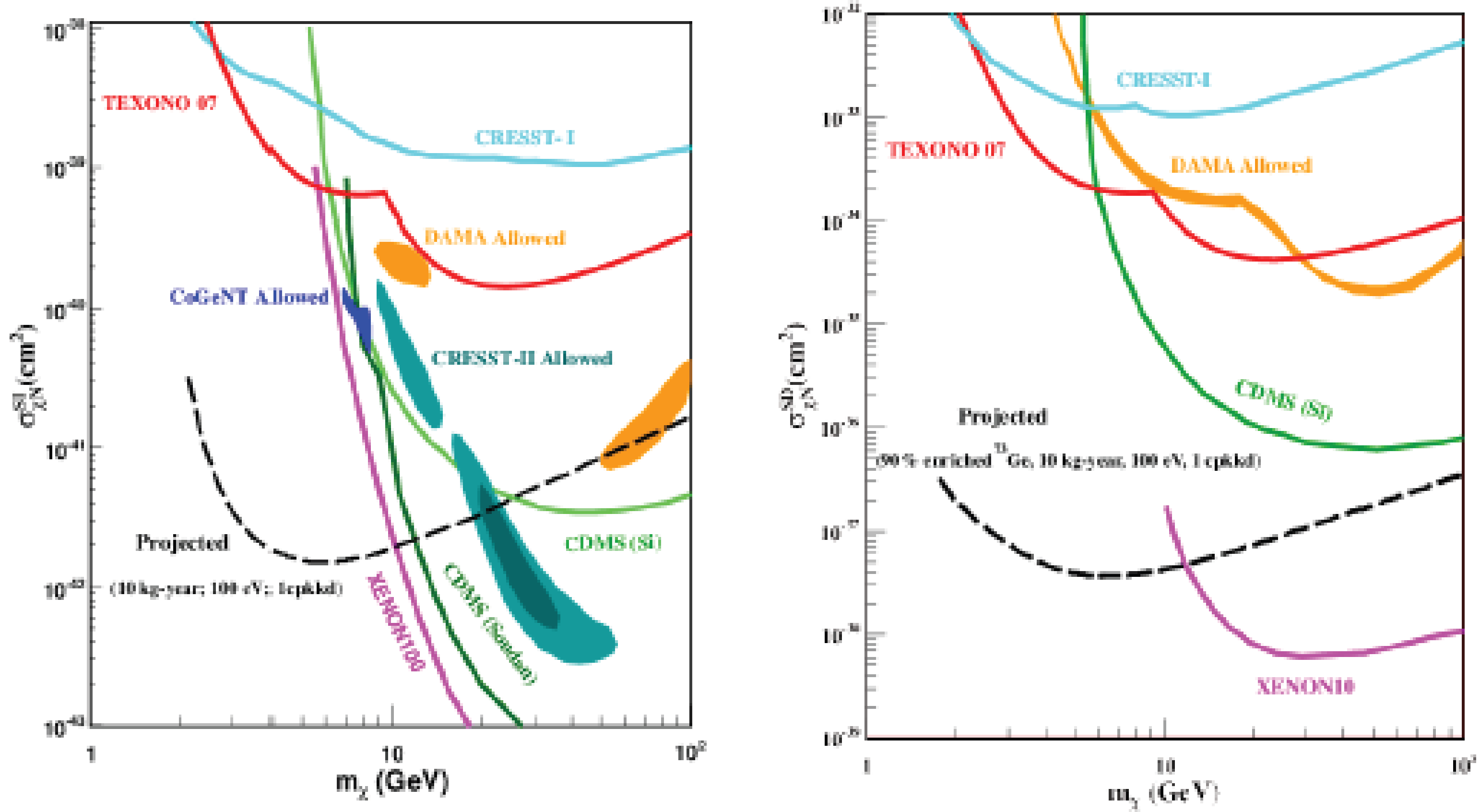
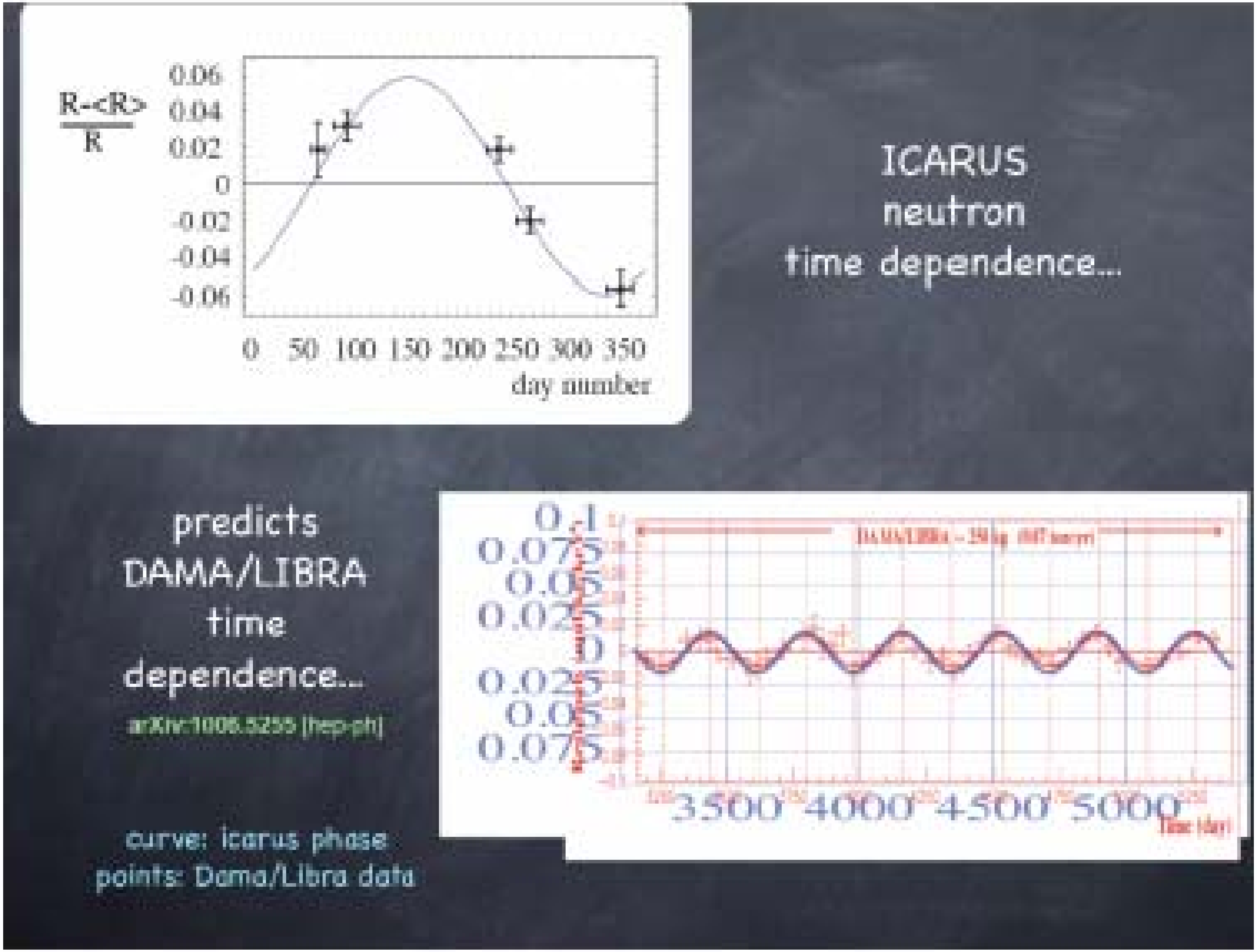


Figure 2. Exclusion plots of (a) Left: spin-independent χN and (b) Right: spin-dependent χN cross-sections versus WIMP-mass, displaying the KSNL-ULEGe limits [5] and those defining the current boundaries [4, 6]. The DAMA, CoGeNT and CRESST-II allowed regions [6, 7] are superimposed. Projected reach of experiments at benchmark sensitivities are indicated as dotted lines.


R-<R> / R
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
0 50 100 150 200 250 300 350
day number
ICARUS
neutron
time dependence...
predicts
DAMA/LIBRA
time
dependence...
arXiv:1006.5255 [hep-ph]
0.1
0.075
0.05
0.025
0
0.025
0.05
0.075
3500 4000 4500 5000
curve: icarus phase
points: Dama/Libra data

The second mystery of Ettore Majorana

Teoria simmetrica dell'elettrone e del positrone

NOTA DI ETTORE MAJORANA

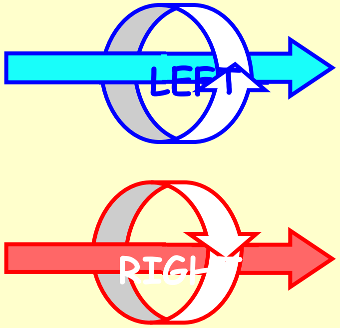
"Il Nuovo Cimento", vol. 14, 1937, pp. 171-184.

Sunto. — Si dimostra la possibilità di pervenire a una piena simmetrizzazione formale della teoria quantistica dell'elettrone e del positrone facendo uso di un nuovo processo di quantizzazione. Il significato delle equazioni di DIRAC ne risulta alquanto modificato e non vi è più luogo a parlare di stati di energia negativa; né a presumere per ogni altro tipo di particelle, particolarmente neutre, l'esistenza di "antiparticelle" corrispondenti ai "vuoti" di energia negativa.

Neutrinoless double beta decay and Majorana neutrinos

ν:

$\bar{\nu}$:



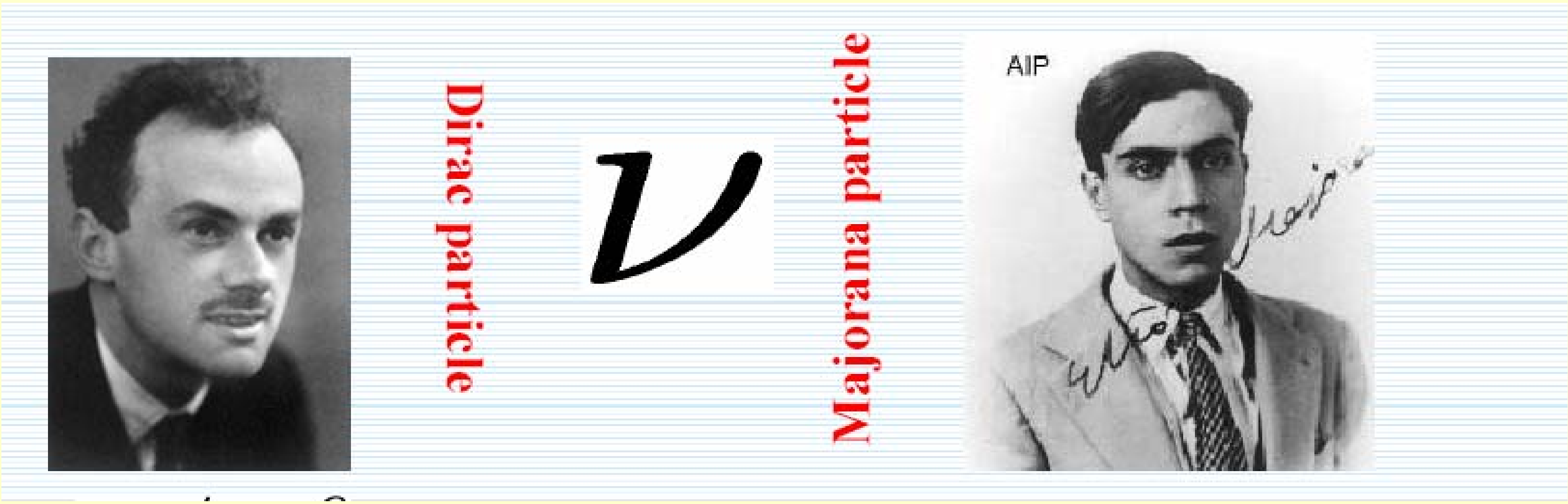
$\nu \neq \bar{\nu}$

$\nu = \bar{\nu}$

→ →

<= =>

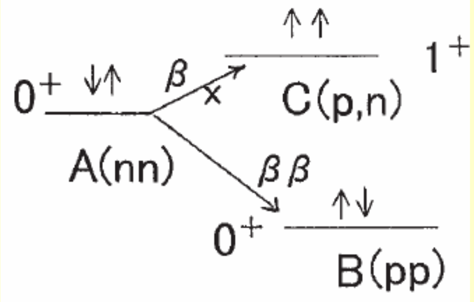
Majorana
=>1937



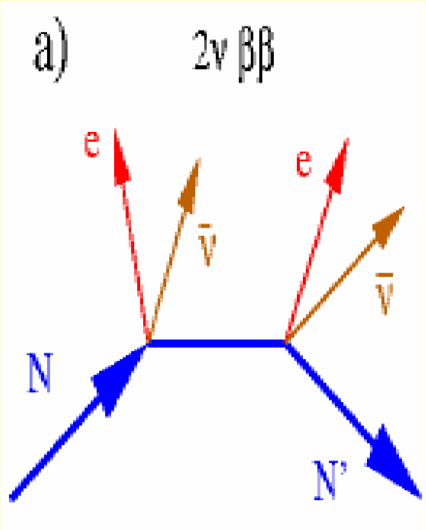
Chi l'ha visto ?

Ettore Majorana, ordinario di fisica teorica all'Università di Napoli, è misteriosamente scomparso dagli ultimi di marzo. Di anni 31, alto metri 1,70, snello, con capelli neri, occhi scuri, una lunga cicatrice sul dorso di una mano. Chi ne sapesse qualcosa è pregato di scrivere al R. P. E. Marianecci, Viale Regina Margherita 66 - Roma.

Double beta decays



2nbb SM DL=0



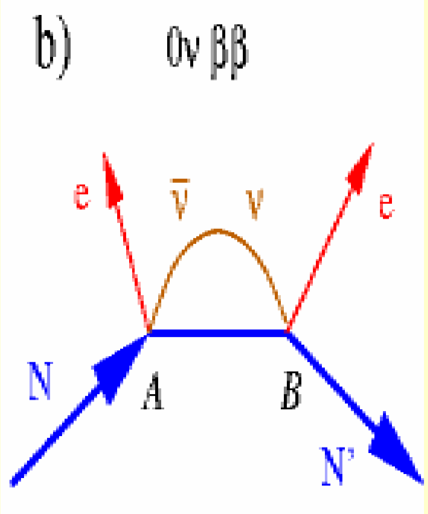
1935 M.Goeppert-Mayer, P.R. 48 (1935) 512 T>10^{20}

1967: ^{130}Te, Geochemical
Ogata and Takaoka, Kirsten et

1987: ^{82}Se, Direct counting Moe et al .

1989 -2008 ^{100}Mo, ^{116}Cd, ^{76}Ge etc.
ELEGANT V, NEMO, HM-IGEX, etc

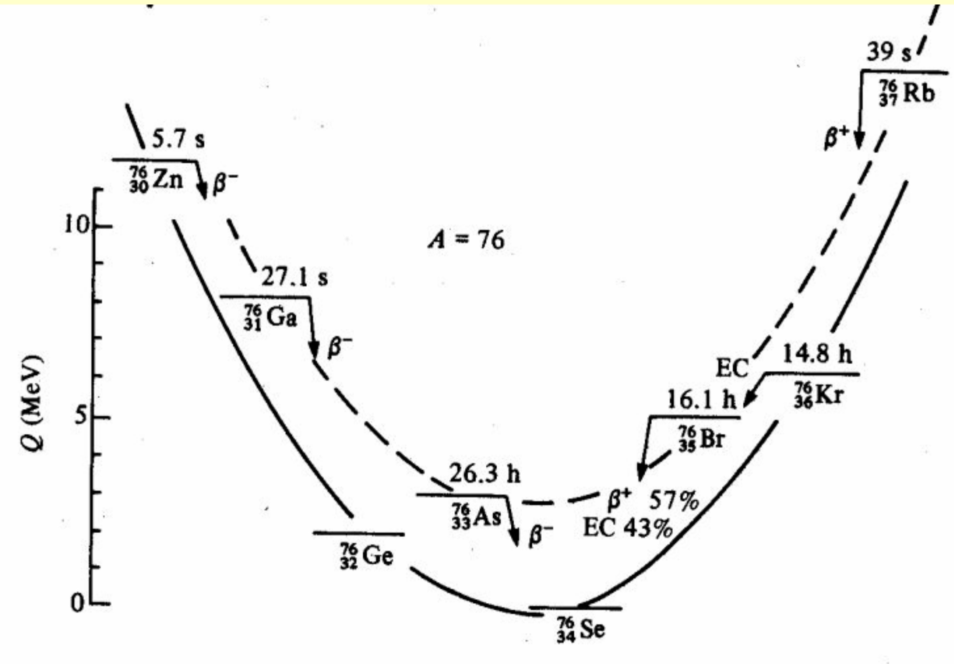
0nbb beyond SM DL=2

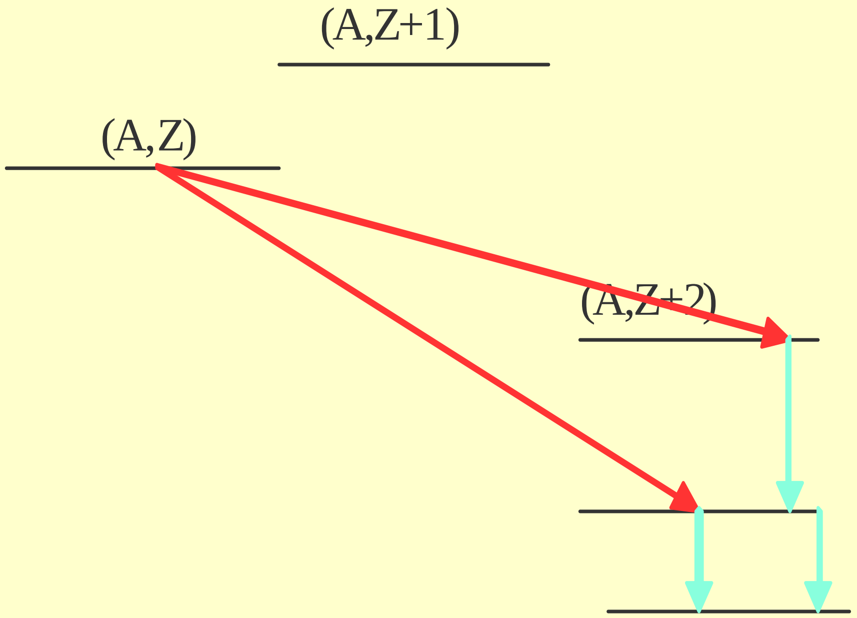


E. Majorana, Nuovo Cimento 14 (1937) 171
Symmetric Theory of Electron and Positron

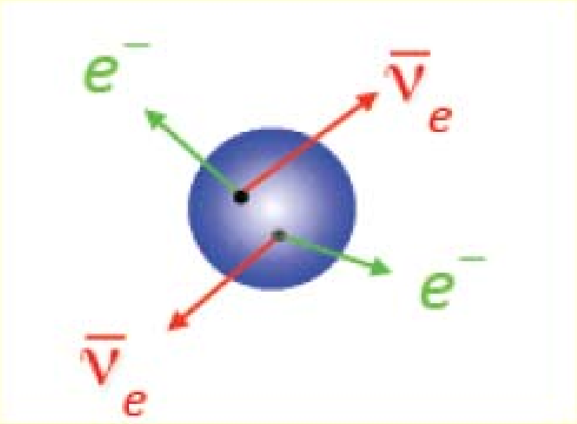
G. Racah, Nuovo Cimento 14 (1937) 322
0nbb for Majorana

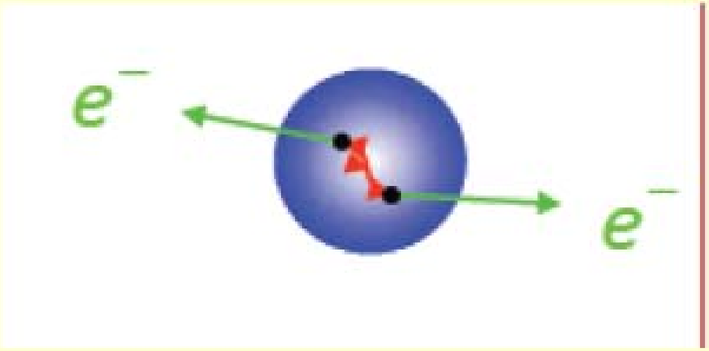
Double beta decay

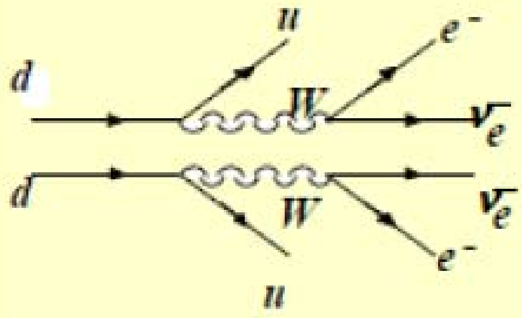




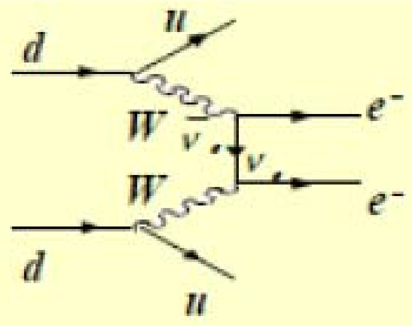
Two neutrino and neutrinoless double beta decay



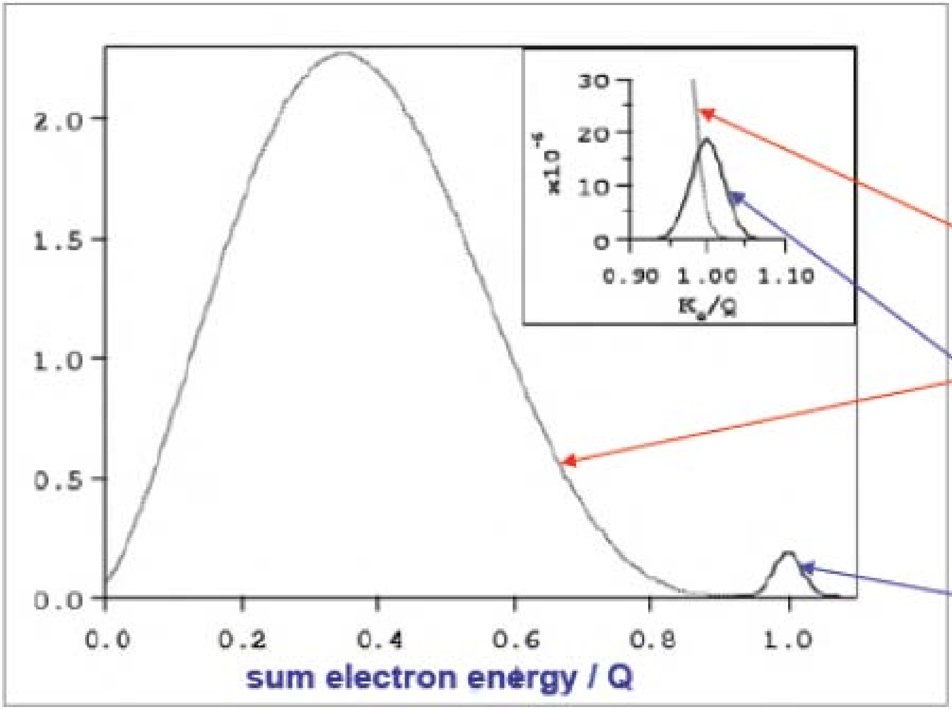




$2\nu - \beta\beta$ decay



$0\nu - \beta\beta$ decay



The **shape** of the two electron sum energy spectrum enables to distinguish among the most relevant decay modes

two neutrino DBD
continuum with maximum at ~1/3 Q

neutrinoless DBD
peak enlarged only by the detector energy resolution

additional signatures:

- single electron energy distribution
- angular distribution
- topology

6

How to search for ββ decay

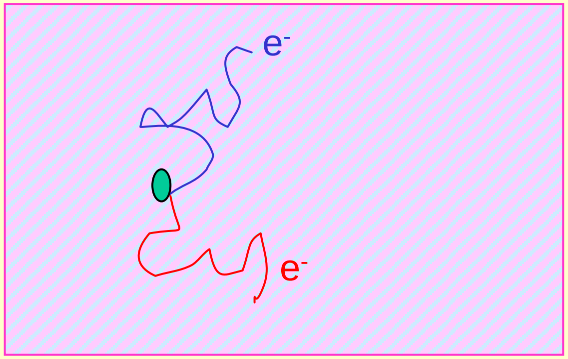
Geochemical experiments

^{82}Se = > ^{82}Kr, ^{96}Zr = > ^{96}Mo, ^{128}Te = > ^{128}Xe (non confirmed), ^{130}Te = > ^{130}Te

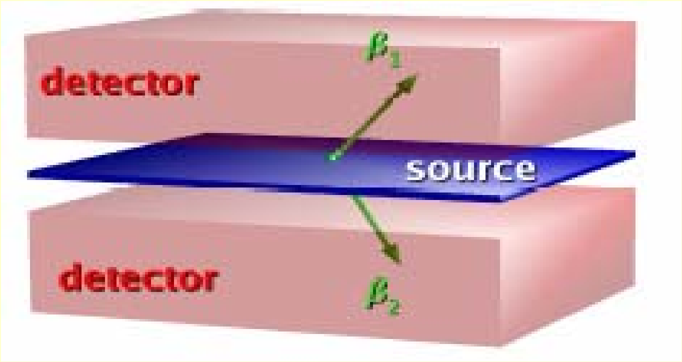
Radiochemical experiments ^{238}U = > ^{238}Pu (non confirmed)

Direct experiments

Source = detector



Source ≠ detectors



$T^{2\nu}_{1/2}$ (compilation of A. Barabash, PRC **81** 2010)

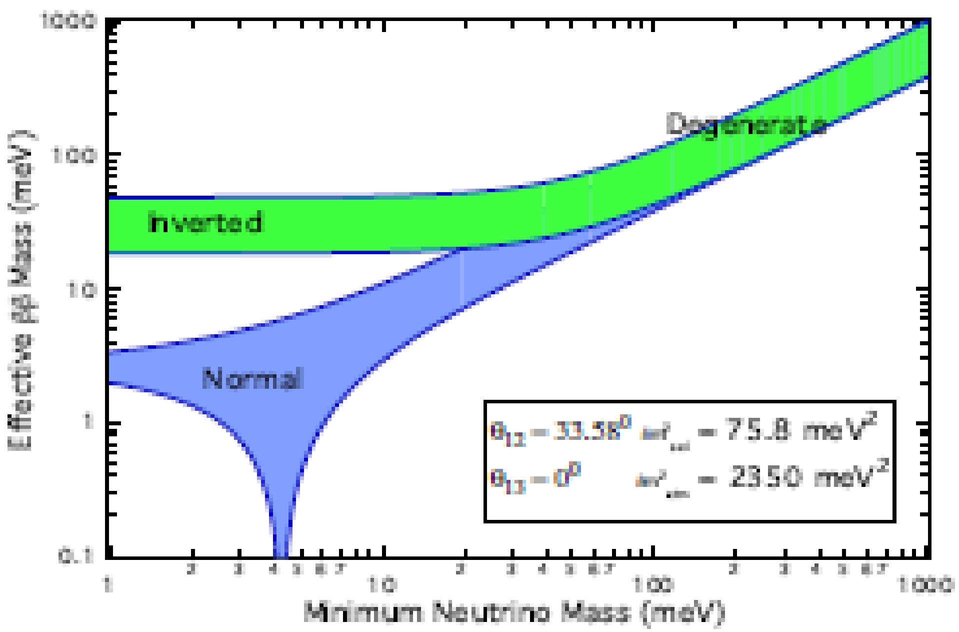
Isotope	$T^{2\nu}_{1/2}$, in 10^{19} y
^{48}Ca	$4.4^{+0.6}_{-0.5}$
^{76}Ge	150 ± 10
^{82}Se	9.2 ± 0.7
^{96}Zr	2.3 ± 0.2
^{100}Mo	0.71 ± 0.04
^{116}Cd	2.8 ± 0.2
^{128}Te	$(1.9 \pm 0.4) \times 10^5$
^{130}Te	68^{+12}_{-11}
^{136}Xe	211 ± 25 ← EXO-200, 1108.4193
^{150}Nd	0.82 ± 0.09
^{238}U	200 ± 60

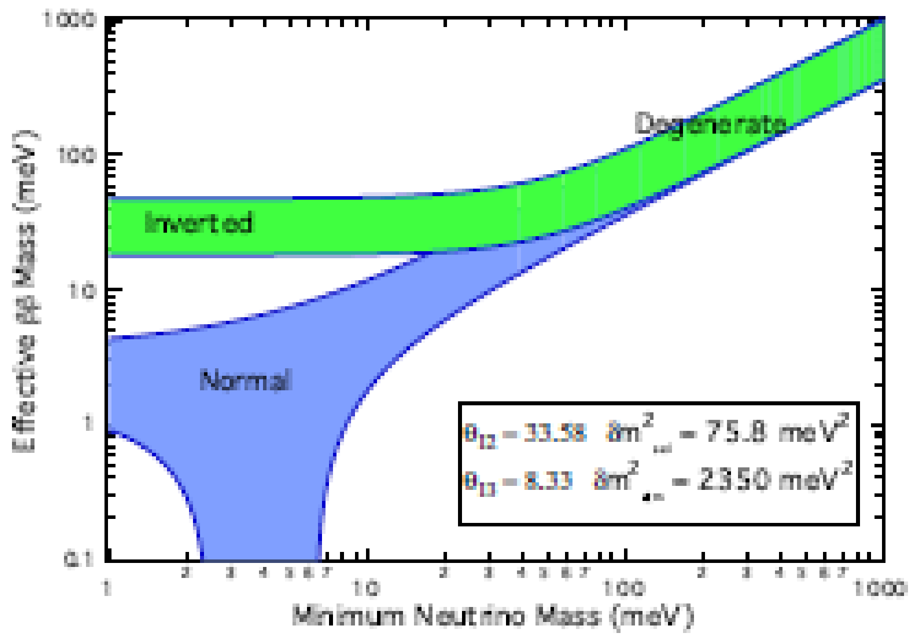
EXO-200 => $T^{2\nu}_{1/2}$ $2.11 \pm 0.04(\text{stat.}) \pm 0.21(\text{sys.}) \times 10^{21}$ yr.

Kamland-Zen $2.38 \pm 0.02(\text{stat}) \pm 0.14(\text{syst}) \times 10^{21}$ yr

GERDA 1.88 ± 0.10 (stat) $\times 10^{21}$ yr (preliminary)

Predictions from neutrino oscillations

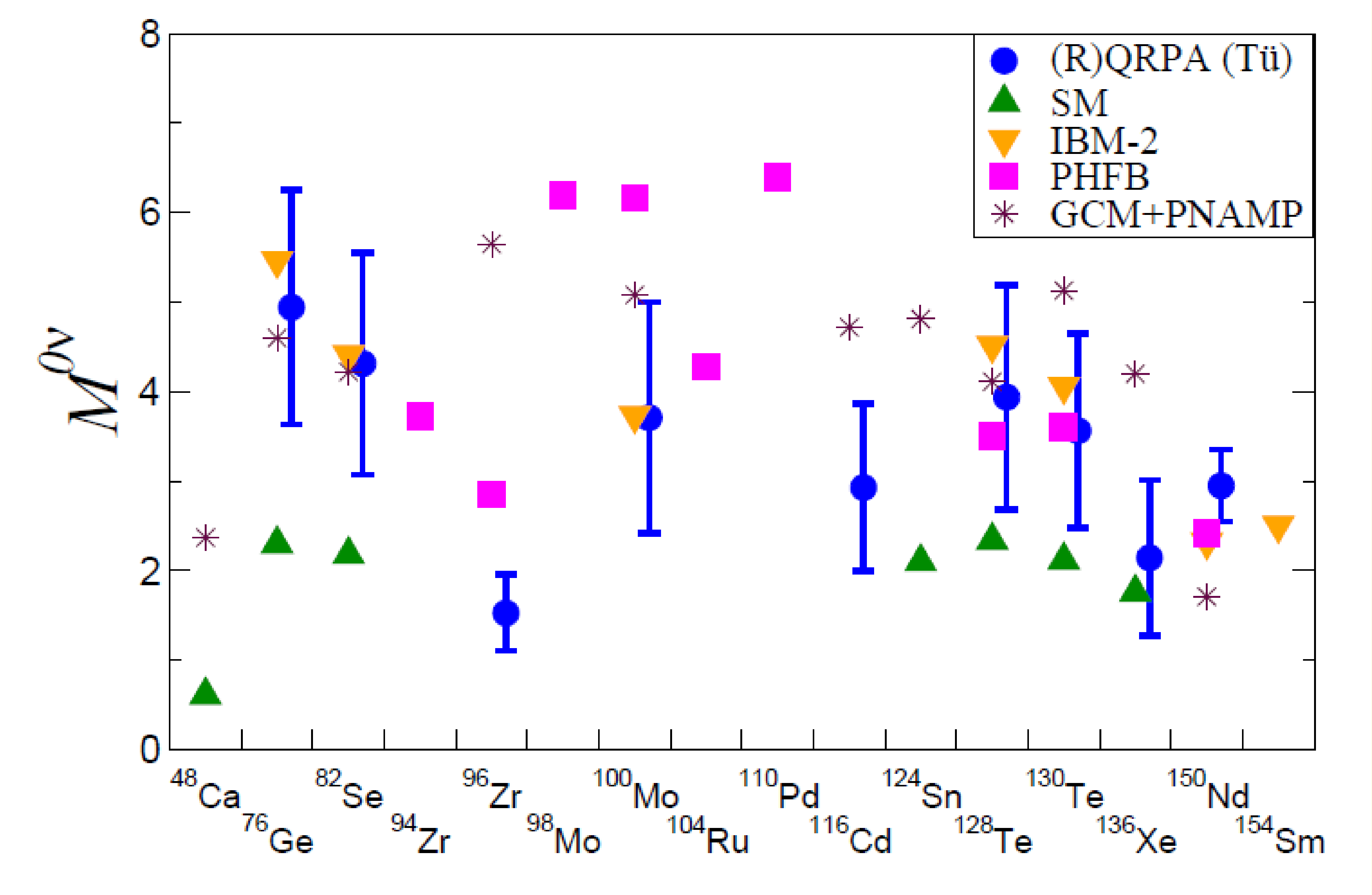




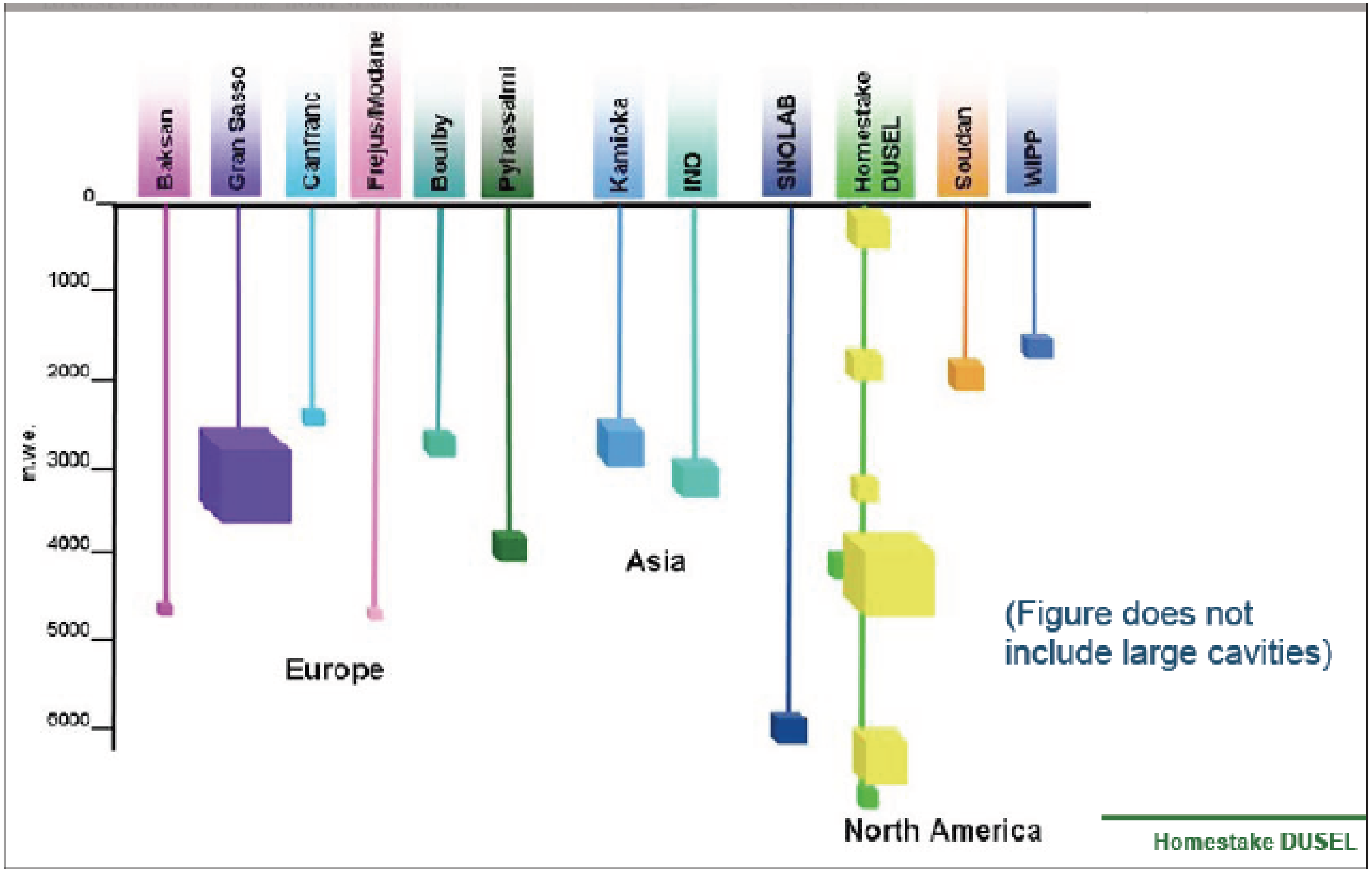
$\Theta_{13} = 0$

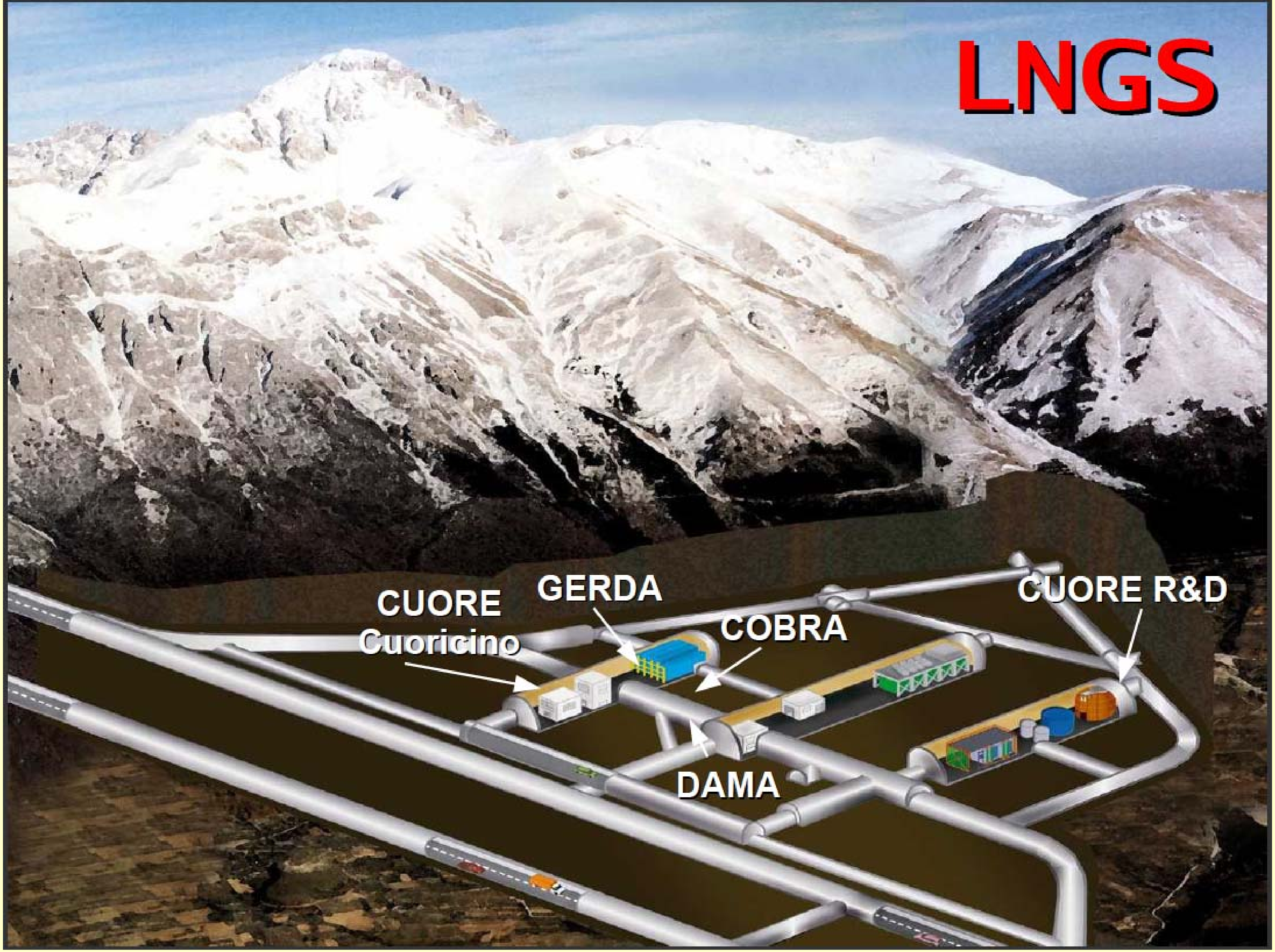
Θ_{13} best

Nuclear Matrix Elements



INTERNATIONAL UNDERGROUND LABORATORIES
(Present and Planned)



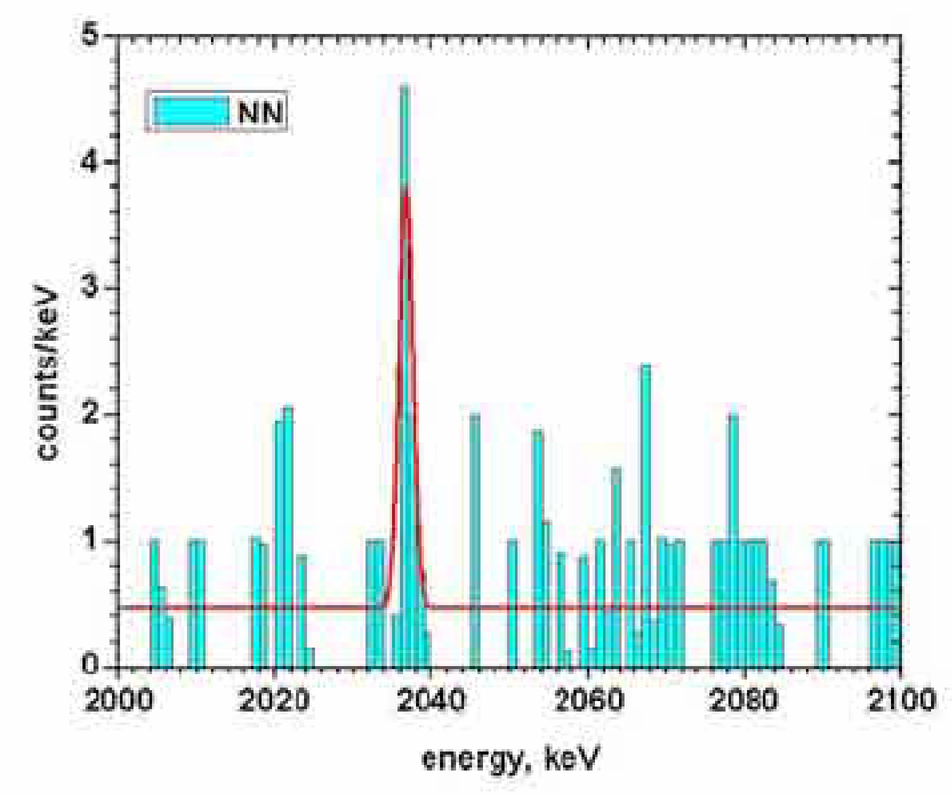

LNGS
CUORE
Cuoricino
GERDA
COBRA
CUORE R&D
DAMA

Possible evidence in $0\nu\beta\beta$ in ^{76}Ge

(H.Klapdor et al)

$$T^{0\nu}_{1/2} = (2.23^{+0.44}_{-0.31}) \times 10^{25}\ y.$$

$\langle m_\nu \rangle \sim$ 0.34eV



Single-site events in detectors 2, 3, 4, 5 (56.6 kg-y).
H.V. Klapdor-Kleingrothaus, Int. J. Mod. Phys. E17, 505 (2008)

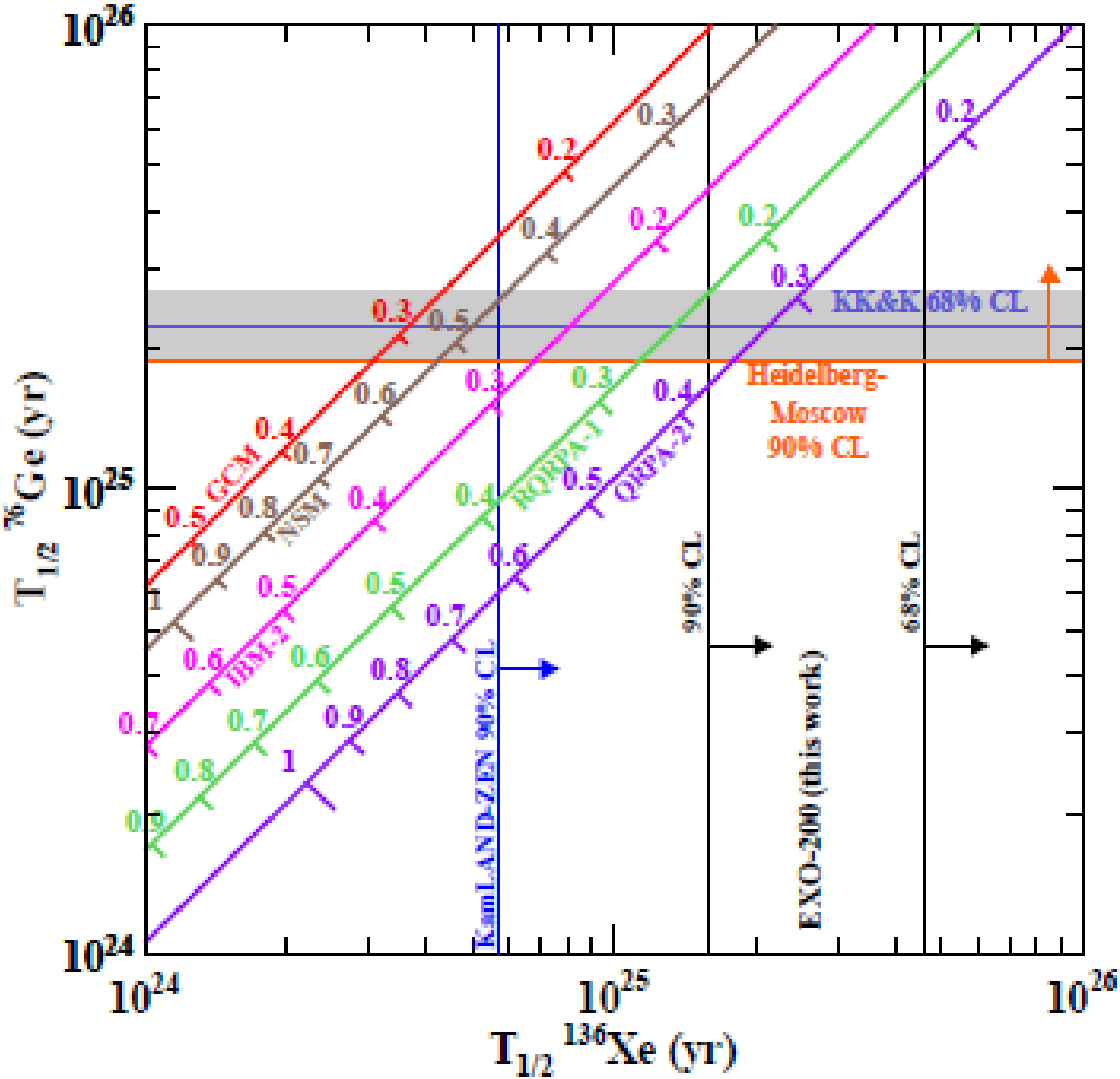
Present results on neutrinoless DBD

Table I: present results on neutrinoless DBD

Nucleus	Experiment	%	$Q_{\beta\beta}$	Enrich	Technique	$T_{0\nu}$ (y)	$<m_\nu>$
48Ca	Elegant IV	0.19	4271		scintillator	>1.4x1022	20-28
76Ge	IGEX	7.8	2039	87	Ionization	>1.6x1025	.23 – .64
76Ge	Klapdor et al	7.8	2039	87	ionization	1.2x1025	.29-.81
82Se	NEMO 3	9.2	2995	97	tracking	>1.x1023	1.7-4.5
100Mo	NEMO 3	9.6	3034	95-99	tracking	>1x1024	.46-1.1
116Cd	Solotvina	7.5	3034	83	scintillator	>1.7x1023	1.2 – 2.7
128Te	Bernatovitz	34	2529		geochem	>7.7 × 1024	.82-1.9
130Te	Cuoricino	33.8	2529		bolometric	>2.8 x1024	.3-.7
136Xe	DAMA	8.9	2476	69	scintillator	>1.2x1024	.64 -1.6
150Nd	Irvine	5.6	3367	91	tracking	>1.2x1021	14 - ?

EXO $T^{0\nu}_{1/2}$ (136Xe) $> 1.6 \times 10^{25}$ yr correspond $<m_\nu>$ 140–380me

KAMLAND-ZEN $> 5.7 \times 10^{24}$ yr 300-600



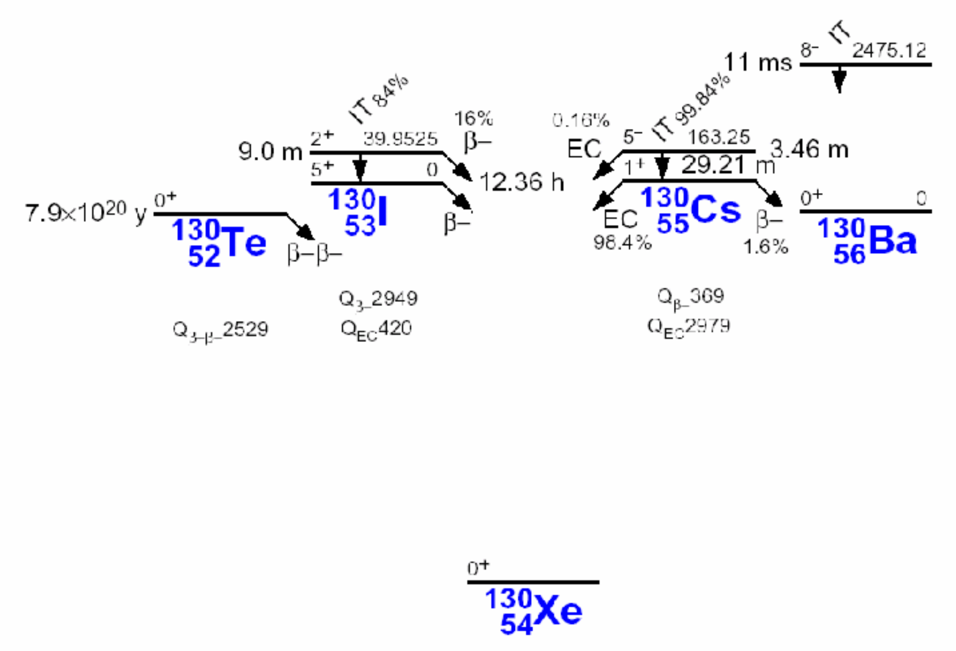
$T_{1/2}$ ^{76}Ge (yr)
$T_{1/2}$ ^{136}Xe (yr)
10^{24}
10^{25}
10^{26}
GCM
NSM
IBM-2
RQRPA-1
QRPA-2
KK&K 68% CL
Heidelberg-Moscow 90% CL
KamLAND-ZEN 90% CL
EXO-200 (this work)
90% CL
68% CL

Future experiments on neutrinoless DBD

Name	Nucleus	Mass	Method	Location	Time
Past/Recent experiments					
Heidelberg-Moscow	^{76}Ge	11	ionization	LNGS	-2003
IGEX	^{76}Ge	6	ionization	Canfranc	-2000
Cuoricino	^{130}Te	11	bolometer	LNGS	-2008
NEMO-3	$^{100}Mo/^{82}Se$	7/1	track./calor.	Modane	-2011
Current experiments (funded, under construction or running)					
GERDA I/II	^{76}Ge	15/35	ionization	LNGS	2011/13
Majorana	^{76}Ge	30	ionization	SUSEL	2013
EXO200	^{136}Xe	200	liquid TPC	WIPP	2011
Cuore0/Cuore	^{130}Te	10/200	bolometer	LNGS	2011/14
Kamland-Zen	^{136}Xe	400	LS	Kamioka	2011
SNO+	^{150}Nd	44	LS	Sudbury	2014
(substantial) R&D funding, proto-typing					
NEXT	^{136}Xe	100	gas TPC	Canfranc	2013+
CandlesIII	^{48}Ca	0.35	scint crystal	Oto Cosmo	2011
MOON	$^{82}Se, ^{150}Nd$				
DCBA	^{150}Nd	32	tracking		
Cobra	^{116}Cd		solid TPC	LNGS	
SuperNEMO	^{82}Se	7/100-200	track./calor.	Modane	2014/-
XMASS	^{136}Xe		liquid SC	Kamioka	
Lucifer	^{82}Se		bolom+scint		

Searches of ββ decay with thermal detectors

^{130}Te => ^{130}Xe + 2 e   a.i,. ~ 34% ΔE = 2527 keV

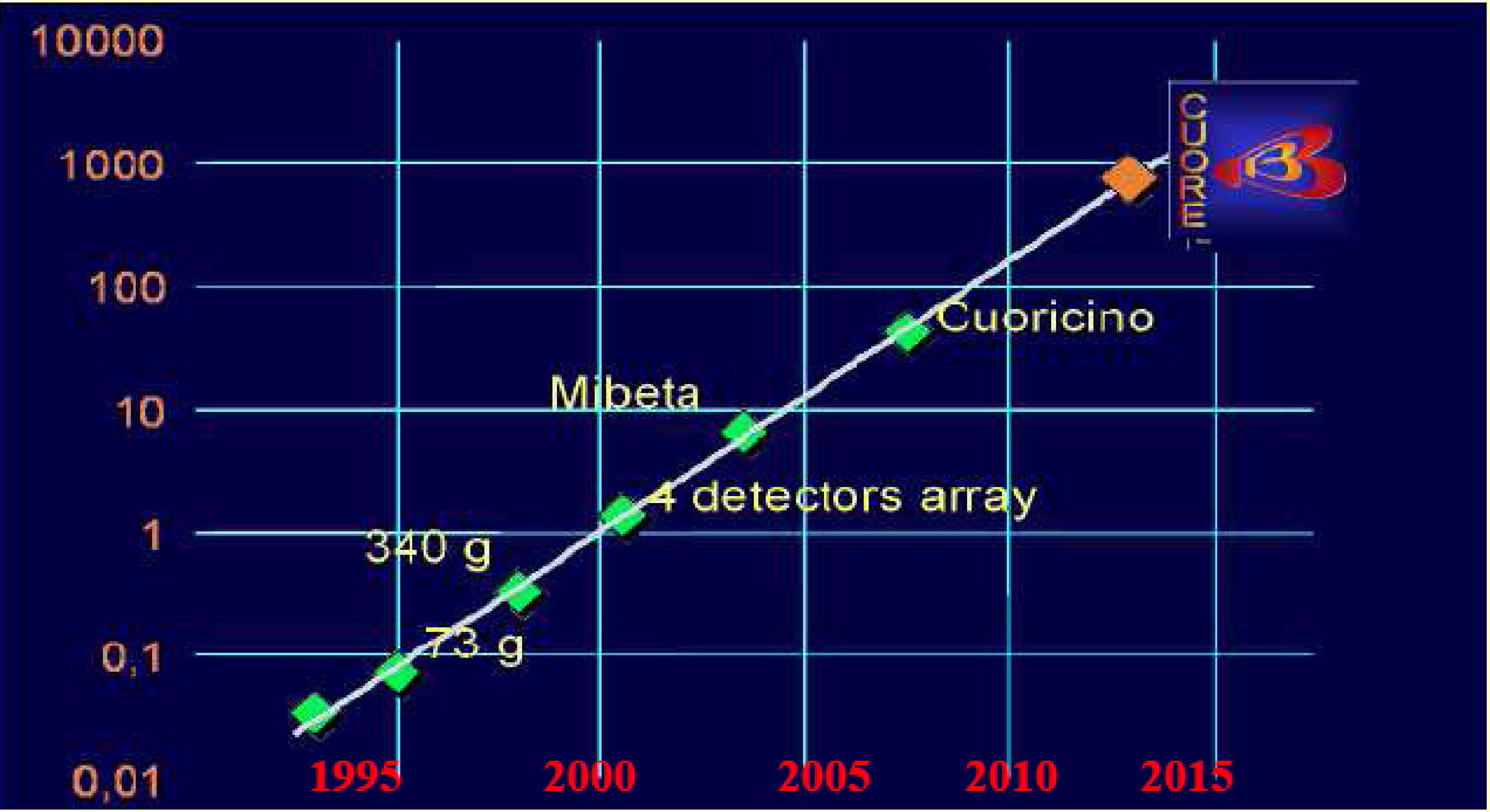


Mibeta (Milan) an array of 20 bolometers of TeO_2 of 320 => **6.8 kg**

CUORICINO (CUORICINO Coll.) => **40.7 kg**

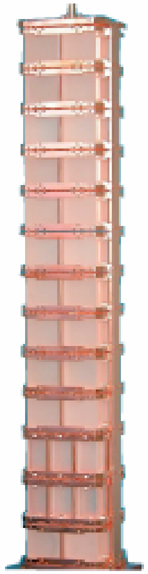
CUORE (CUORE coll) 988 crystals of 750 g => **741 kg** (Orio)

Progress of thermal detectors



CUORICINO

2003 - 2008



1 Tower

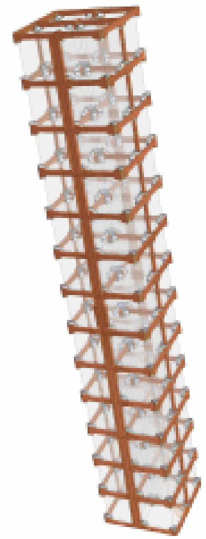
$44 + 18 = 62$ crystals

$\simeq 11$ kg of ^{130}Te

$B = 0.153$ c/keV/kg/y

CUORE-0

2011 - 2014



1 Tower

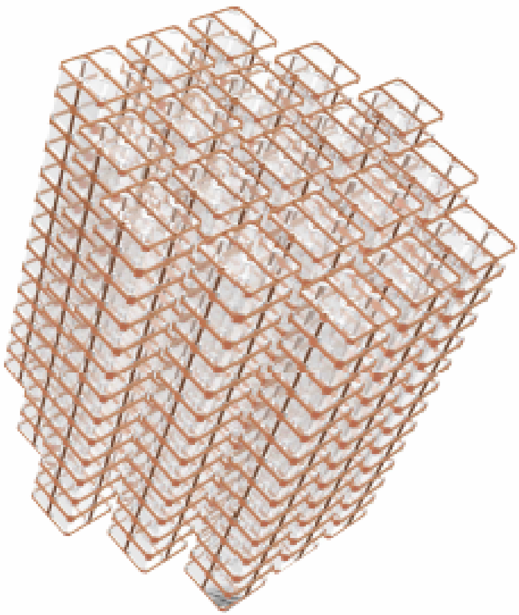
52 crystals

$\simeq 11$ kg of ^{130}Te

$B = (0.05 \div 0.18)$ c/keV/kg/y

CUORE

2013 - 2018



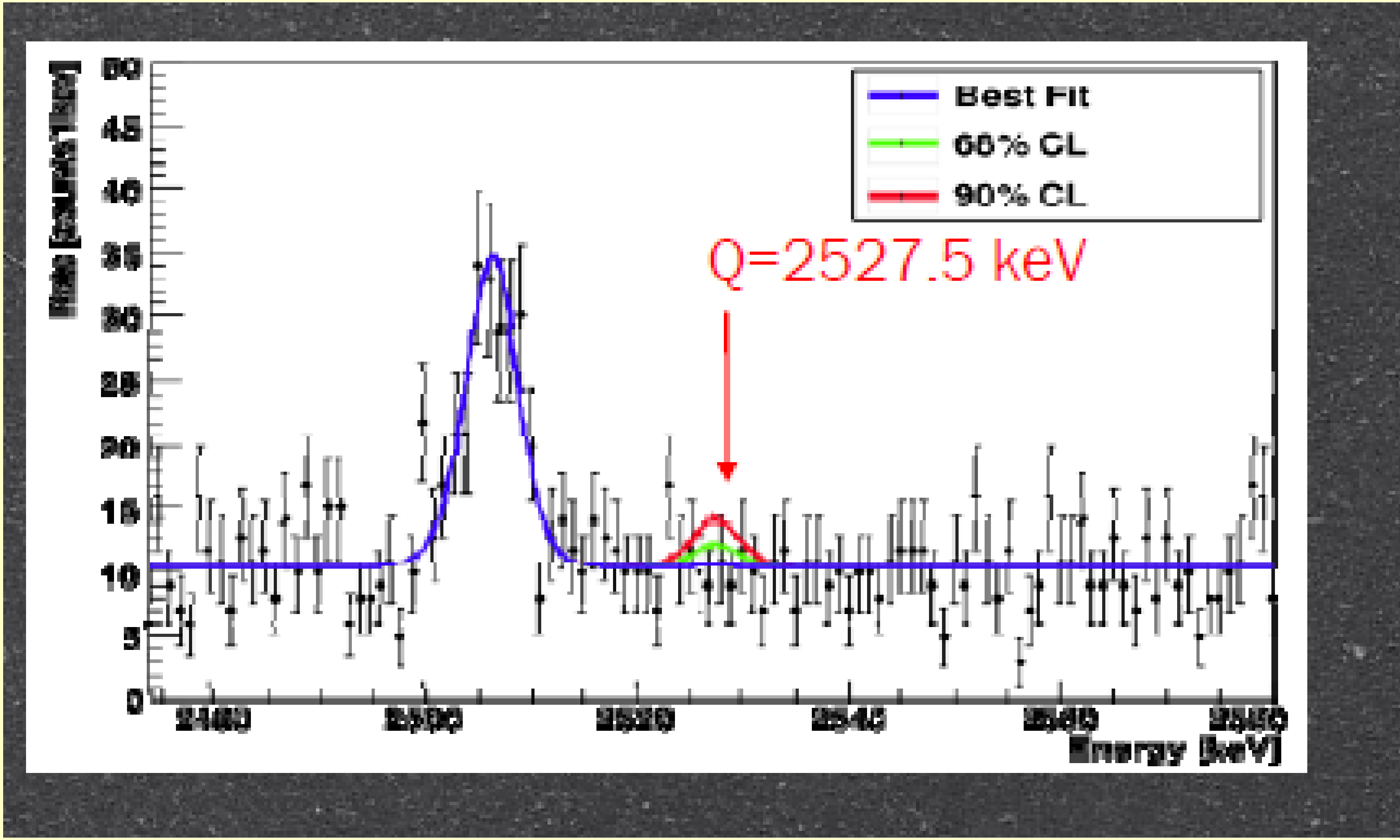
19 Towers, 52 crystals each

988 crystals

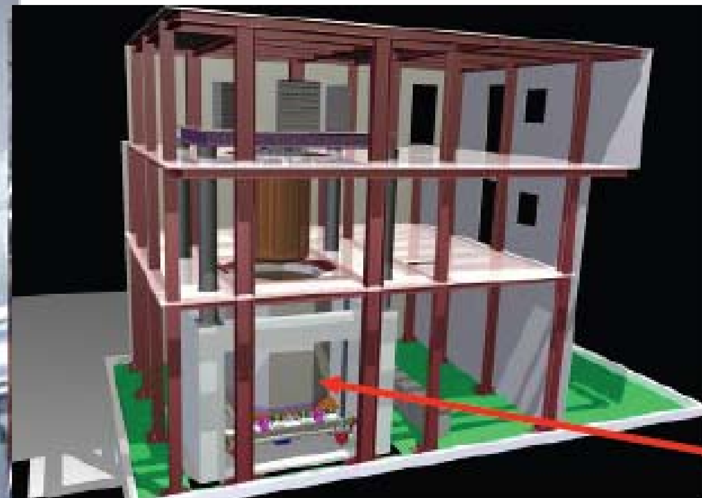
$\simeq 206$ kg of ^{130}Te

$B = (0.01 \div 0.001)$ c/keV/kg/y

CUORICINO

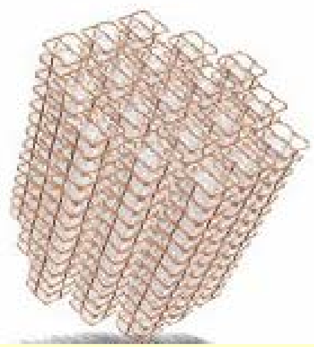


19.75 kg y => 90% limit $\tau_{1/2}$ > 2.8 x 10^{24} a => $\langle m_\nu \rangle$ 300-710 meV

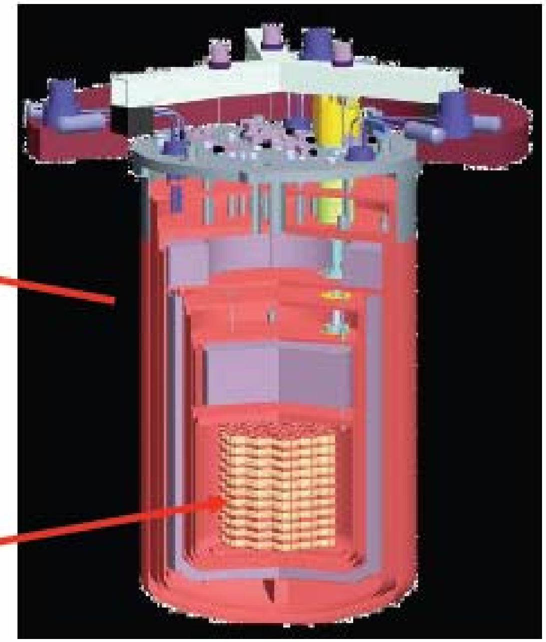


The COURE building in hall A of LNGS

988 TeO_2 5x5x5 cm3 crystals => 741 kg TeO_2 => 204 kg ^{130}Te



Cryostat order placed



1) Kushan Jincheng Chemical Reagent Co. Ltd

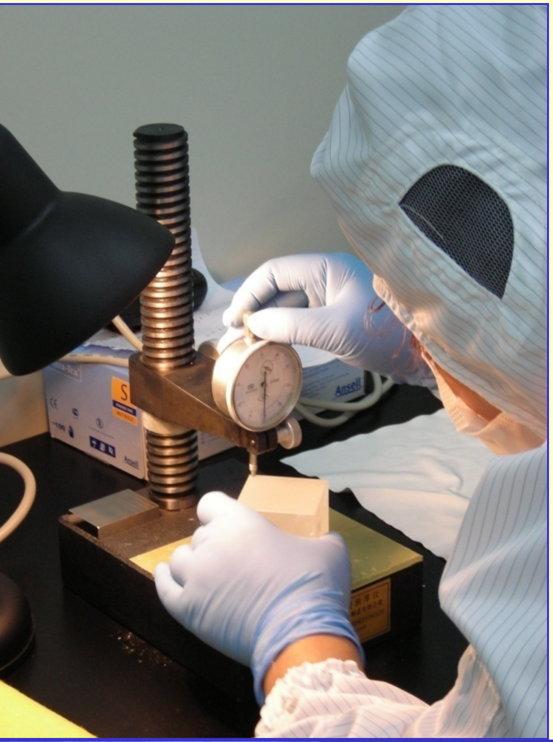
high purity grade TeO2 powder production unit

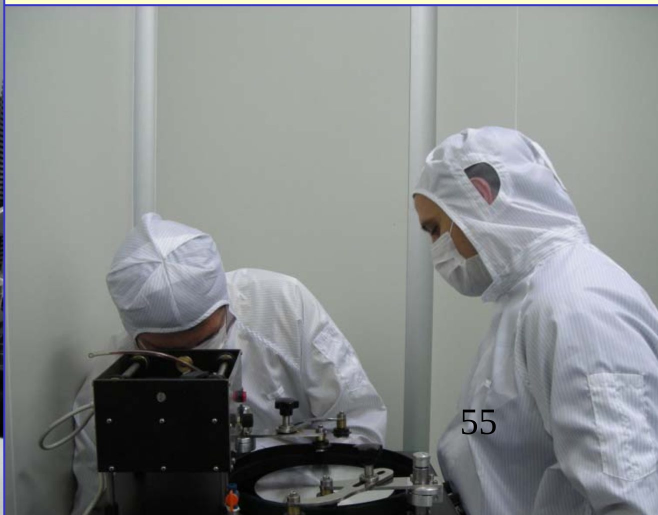


high purity water and reagents production units



SICCAS/INFN Clean Room





The future

Other possible candidates for ββ decay

Compound	Isotopic abundance	Transiton energy
$^{48}CaF_2$	.0187 %	4272keV
^{76}Ge	7.44 "	2038.7 "
$^{100}MoPbO_4$	9.63 "	3034 "
$^{116}CdWO_4$	7.49 "	2804 "
$^{130}TeO_2$	34 "	2528 "
$^{150}NdF_3$ $^{150}NdGaO_3$	5.64 "	3368“

Reduce contribution from surface

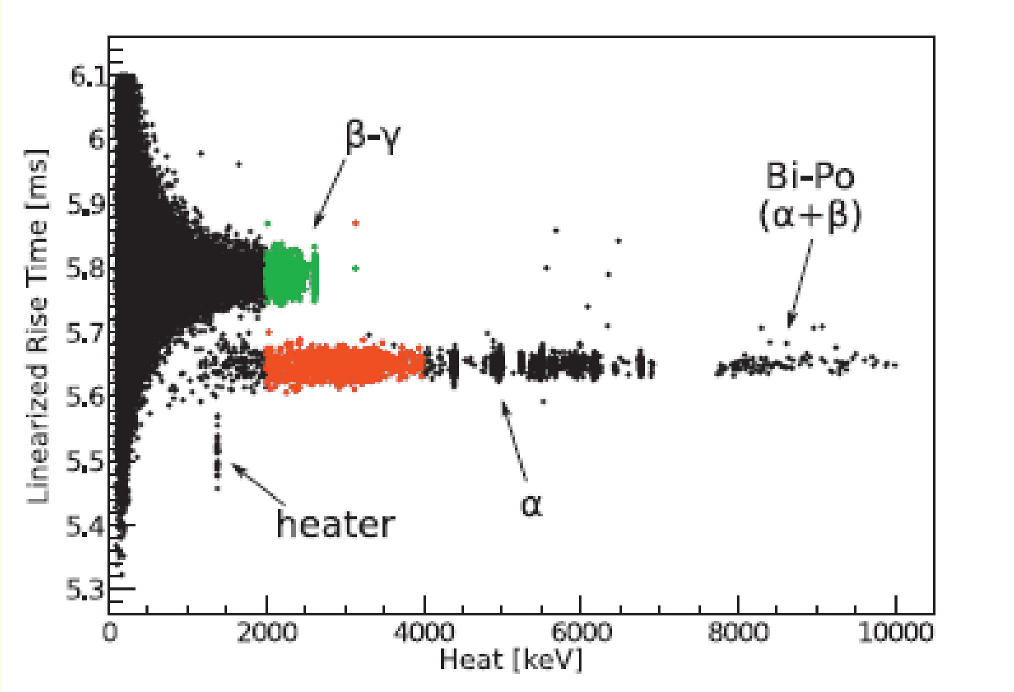
=> **Degraded** α => cover polyethylene or parylene

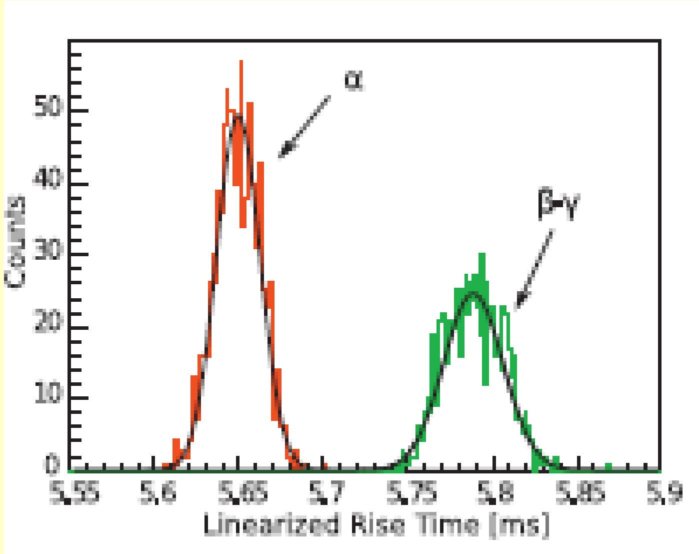
=> **Surface-sensitive** composite bolometers (eg. thin TeO_2 slabs or NbSi)

=> **Reflecting film** and light detector

⇒ **Cherenkov light** at 2.5 Mev 125 photons => 350 eV (in TeO_2)

⇒ **Scintillation + heat and pulse shape discrimination**(for scintillating sources)

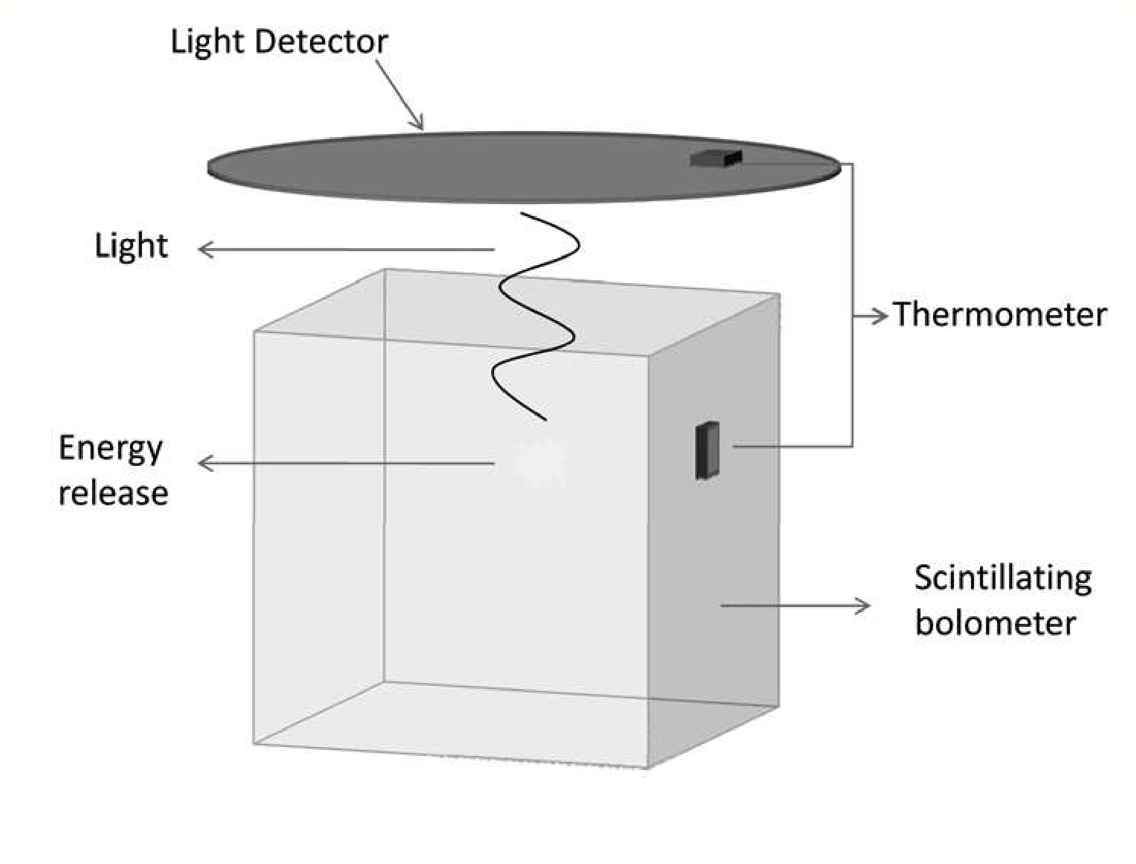




Hybrid techniques

Ionization + heat
Scintillation+ heat

Opposite with respext to DM => back from degraded alpha particles
Coincidence needed

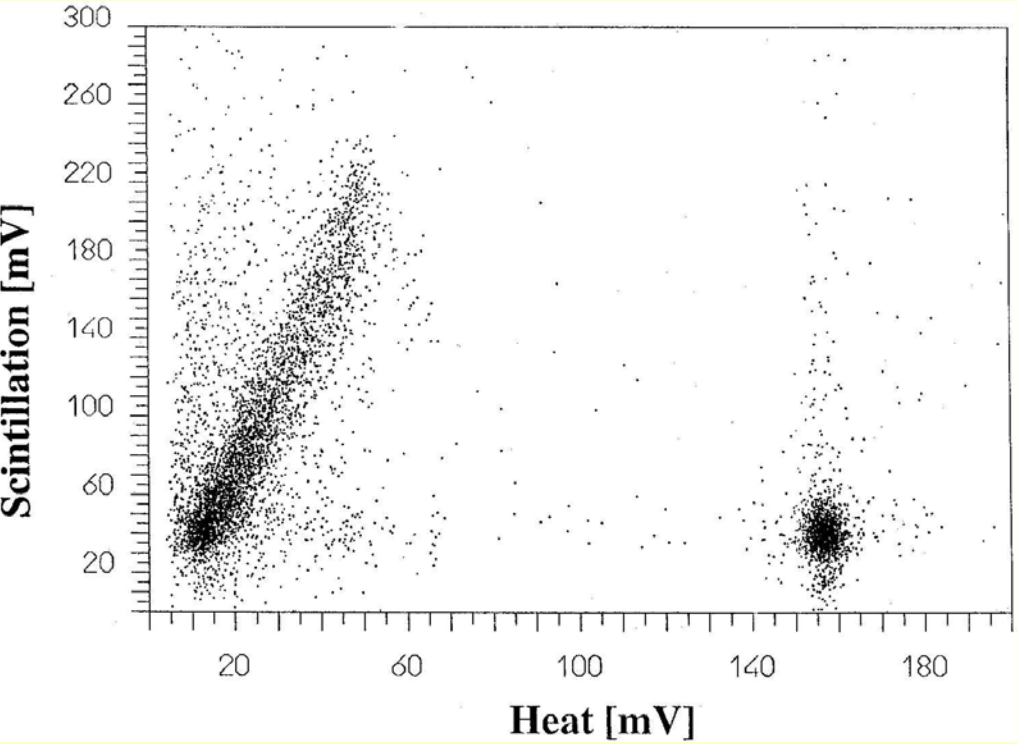


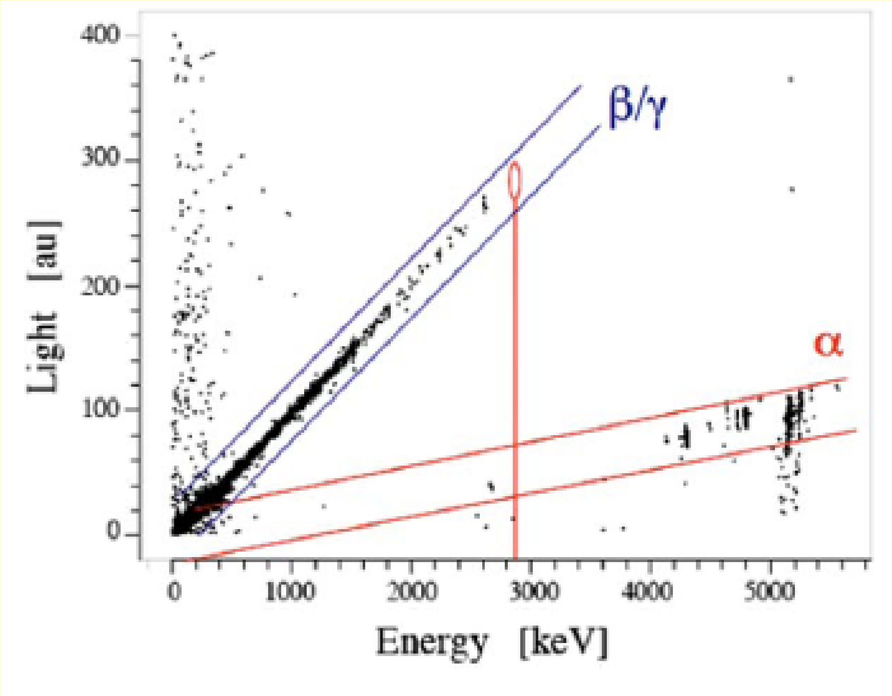
Now (CUORE&Lucifer)

First scintillating bolometer (1991)

CaF_2

$CdWO_2$





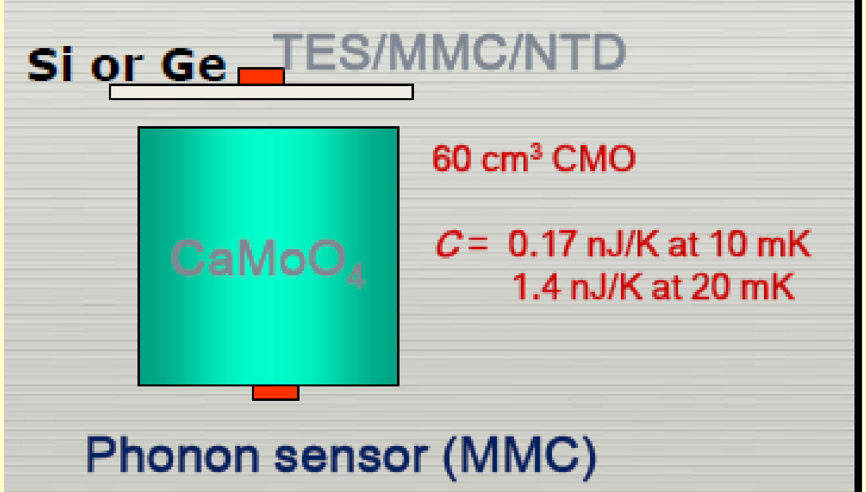
Now a **competitor** AMORE

Advanced **Mo** based **R**are process **E**xperiment

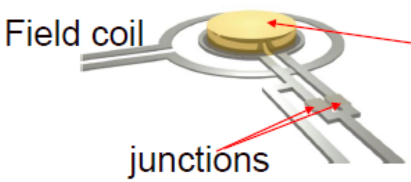
$^{40}Ca^{100}MoO_4$ cryogenic scintillation detector as a tool for Mo-100 DBD search

"Detector = Source": ε ~ 80 - 90% efficiency;

- High content of working isotope (Mo) in compound: 50% (stoichiometry ratio);
- Good energy resolution and high light yield for scintillation mode;
- High energy resolution for phonon mode (comparable with the resolution for HPGe detectors): no $2\nu\beta\beta$ of Mo–100 background;
- α/β- pulse shape discrimination (α/β-ratio = 0,20)
- Scalability of the experiment (increasing of mass by break-in "crystal by crystal");
- Chochralsky technology of the production → High purity, including radioactive isotopes
- Mo-100 production at **hundred kg scale**: centrifuges

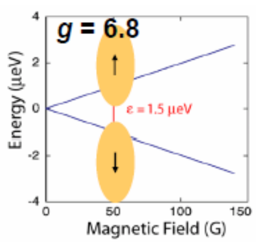


Metallic Magnetic Calorimeter

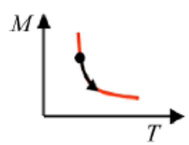


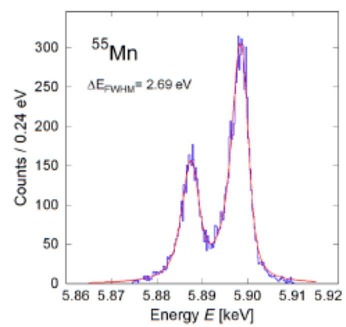
Magnetic material (Au:Er) in dc SQUID

Au:Er(10~1000ppm)
paramagnetic system
metallic host: fast thermalization (~ 1ms)
Can control heat capacity by magnetic field



$5\ \mathrm{mT} \rightarrow \Delta\varepsilon = 1.5\ \mu\mathrm{eV}$
$1\ \mathrm{keV} \rightarrow 10^9$ spin flips





U. of Heidelberg

- **Fast**
- **Wide working temperature**
- **Absorber friendly**

Other applications

Astrophysics

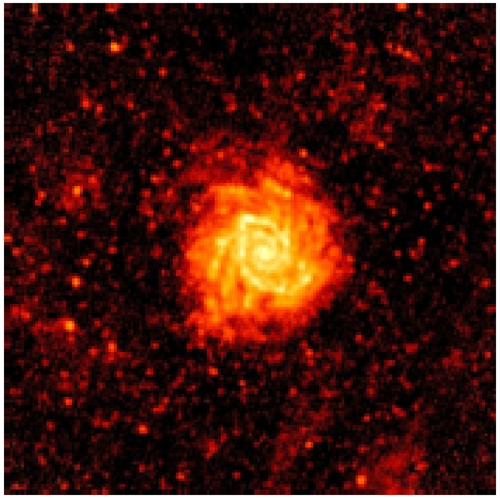
Herschel and Planck

Herschel

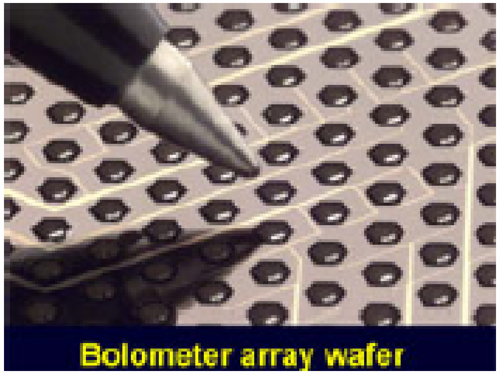
- Sub-mm, study intergalactic space, star forming regions
- Total of ~ 300 NTD-Ge bolometers in 3 bands (520, 360, 250 mm)

Planck

- High angular resolution measurements of the CMB
- 52 NTD-Ge bolometers 22 recievers



Herschel

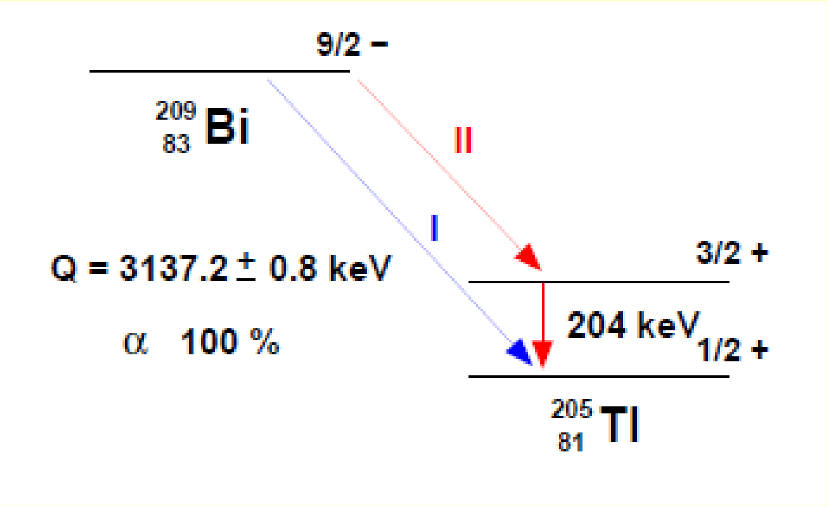


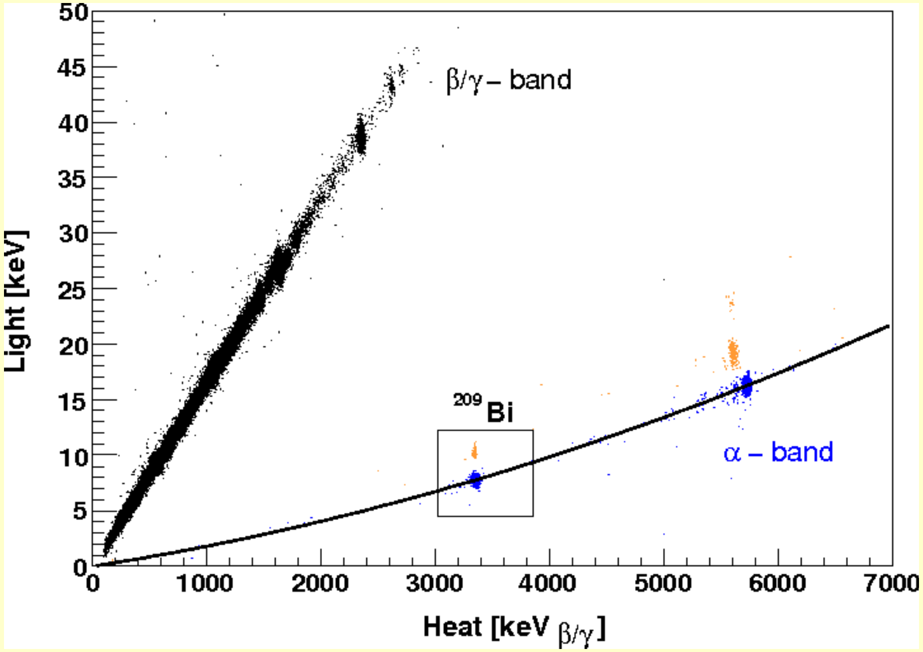
Bock JPL

Nuclear physics => the decay of ^{209}Bi

^{209}Bi considered the stable with the higher atomic number => it is not !

Paris and Milan with BGO crystal





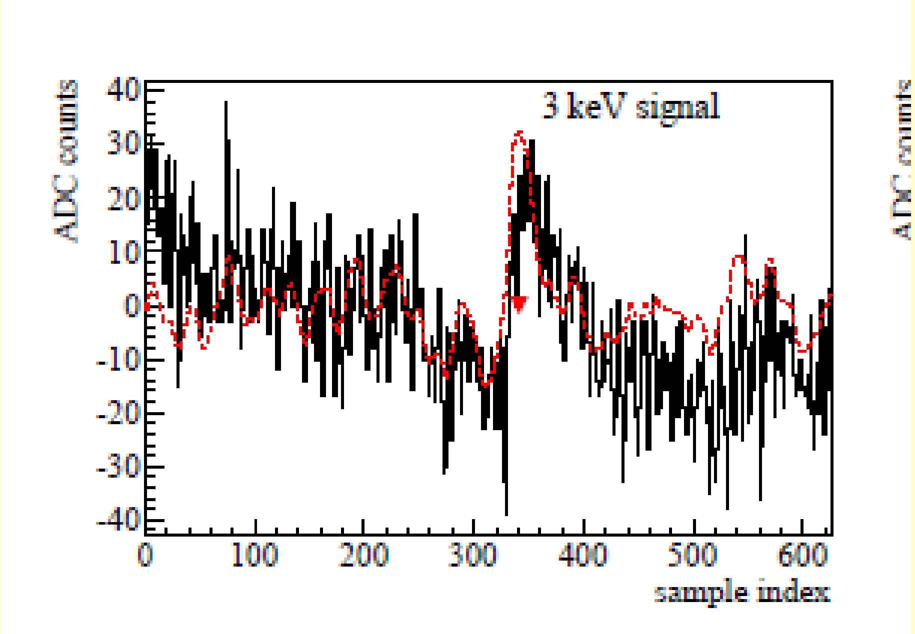
$\tau_{1/2} = (2.01 \pm 0.08) \cdot 10^{19}$ y

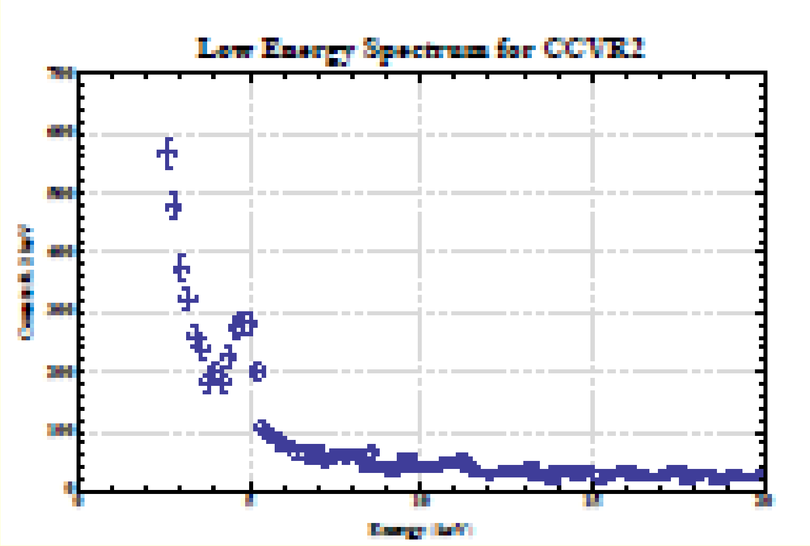
BR to the ground-state (98.8±0.3)%.

Dark Matter

Quenching factor (measured for thermal detectors => **~ 100 %**

Recent result to **decrease the threshold**





AXIONS

Requirements **as for Dark Matter**

e.g.=> search for **14.4 M1** transition from **^{57}Fe** in the Sun's core.

Axio-electric effects in TeO2 bolometers

Analysis of 43.65 kg day ***in progress***

Coherent elastic neutrino-nucleus scattering

Same technique as for Dark Matter

Not yet found , but **cross section enhanced by coherence**

=> **high intensity π and μ decay-at-rest** (DAR) (maximum neutrino energy ≈52 MeV)

=> Maybe also from **SNS** and **Supernovae**

Polonium monitoring by Alpha Particle Spectrometry with TES

Spectroscopic Measurement of L X-Rays Emitted by 241Am Source by TES Microcalorimeter

Nondestructive **plutonium monitoring** during reprocessing of nuclear fuel

L X-rays ranging from 10 to 20 keV decay 425 μs, 48 eV FWHM at Np Lβ1 X-ray of 17.75 keV

High resolution X Ray spectroscopy

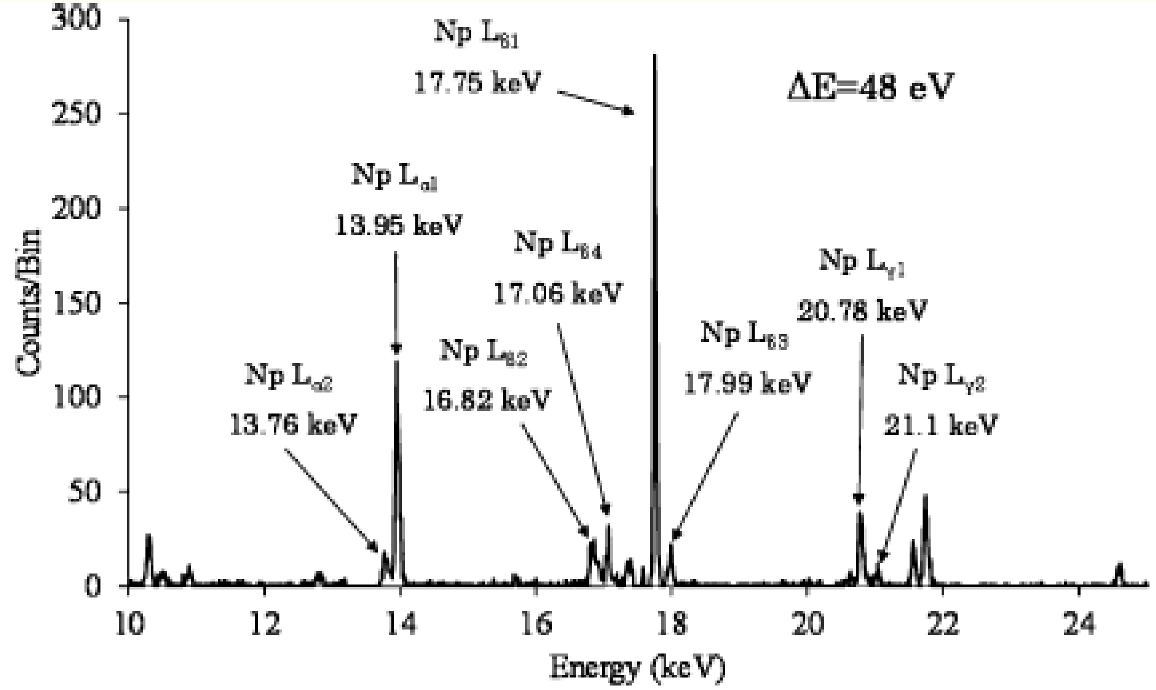


Fig. 3 Np L X-ray energy spectrum. Each legend marks a peak and corresponding energy; the subscript to each "L" identifies the transition

There are more things in Earth and Heaven Polonius that can be dream't of by our Philosophy

W.Shakespeare

Archaeometry

Roman Lead

^{210}Pb (22.3 y) => ^{210}Bi => ^{210}Po => ^{206}Pb Thermally < 4 mBq

Isotopic lead geochronology

^{206}Pb, ^{207}Pb - ^{204} Pb (reference)