Double beta decay: yesterday, today, tomorrow

Bruno Pontecorvo in **KIEV** and **Balatonfured**

Then not **"on fashion"** (Few believed on lepton number non conservation)

But important for the two of us

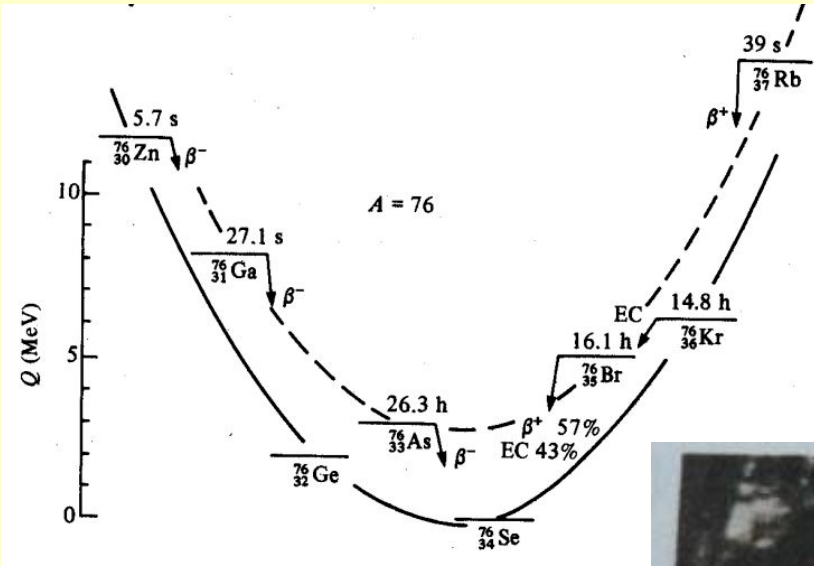
Experiments source = detector

$^{48}Ca \Rightarrow {}^{48}Ti + 2\,e^- + (\mathbf{2\ \bar{\nu}_e})$ Matheosian & Goldhaber

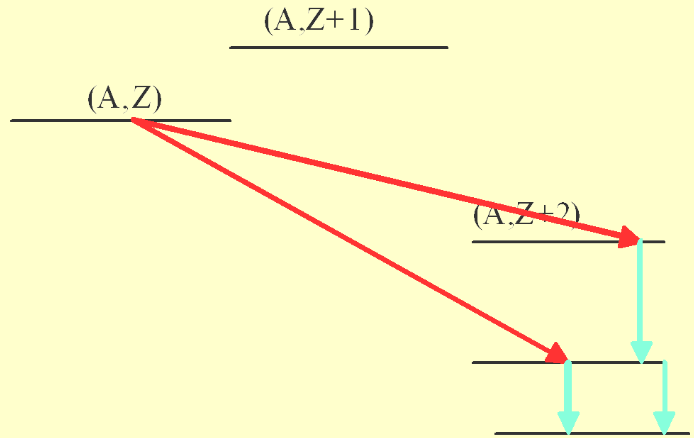
$^{76}Ge \Rightarrow {}^{76}Se + 2\,e^- + (\mathbf{2\ \bar{\nu}_e})$ E.Fiorini et al

Bruno =.> **$\Delta L = 2$ vs $\Delta S = 2$**

A comment by **Mrs. Wu**



5.7 s
$^{76}_{30}$Zn
β⁻
10
A = 76
27.1 s
$^{76}_{31}$Ga
β⁻
Q (MeV)
5
26.3 h
$^{76}_{33}$As
β⁻
$^{76}_{32}$Ge
0
$^{76}_{34}$Se
β⁺ 57%
EC 43%
16.1 h
$^{76}_{35}$Br
EC
14.8 h
$^{76}_{36}$Kr
39 s
$^{76}_{37}$Rb
β⁺



(A,Z+1)
(A,Z)
(A,Z+2)

1. (A,Z) => (A,Z+2) + 2 e^- + 2 $\bar{\nu}_e$

Two neutrino double beta decay Allowed by the standard model
Found in eleven nuclei (^{130}Xe is new!) to ground state and in two to excited state

2. (A,Z) => (A,Z+2) + 2 e^- + χ (…2,3 χ)

Emission of a massless Goldston boson named Majoron

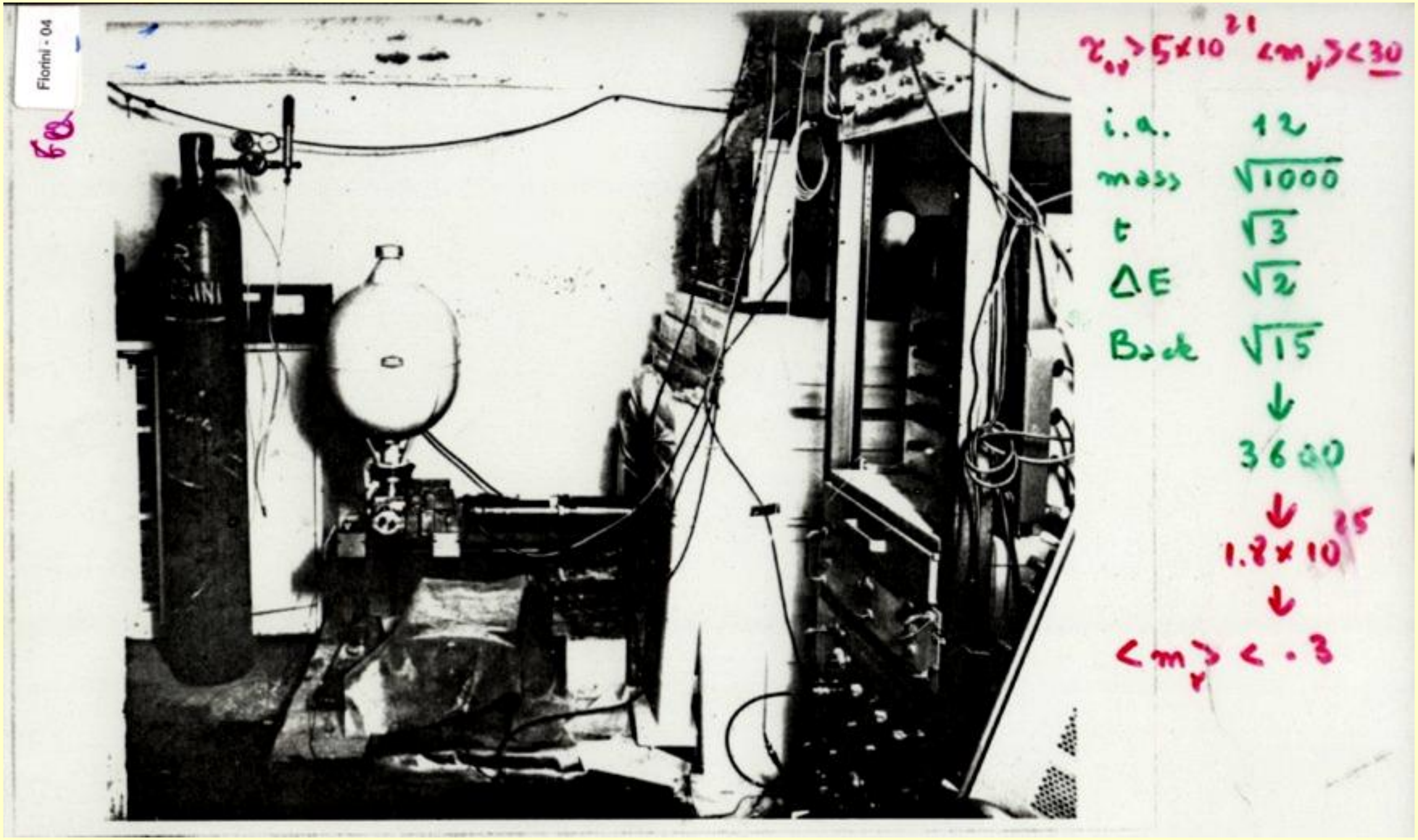
3. (A,Z) => (A,Z+2) + 2 e^-

Neutrinoless double beta decay. The two electrons share the total transition energy E_1 + E_2 => ΔE => a peak appers in the sum spectrum of the two electrons

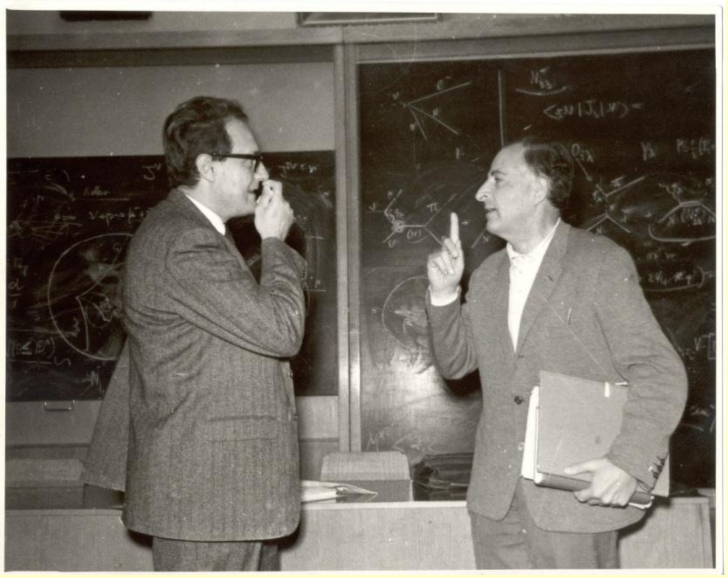
Other possible "$\Delta L=2$" decays

- Double positron decay => $\beta^+ \beta^+$
- Positron decay + Electron Capture => EC- β^+
- Double electron capture => EC-EC

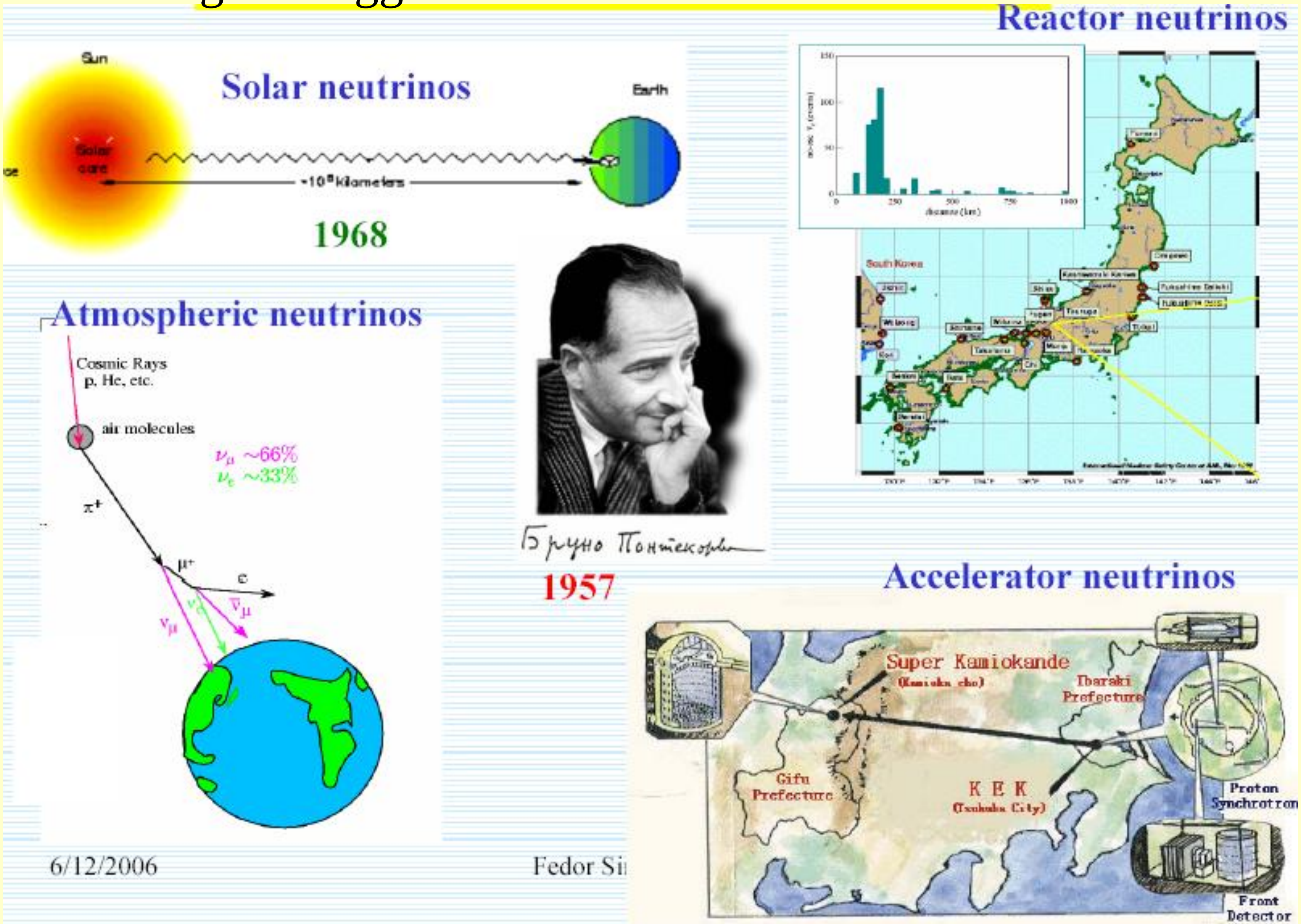
The first Germanium experiment



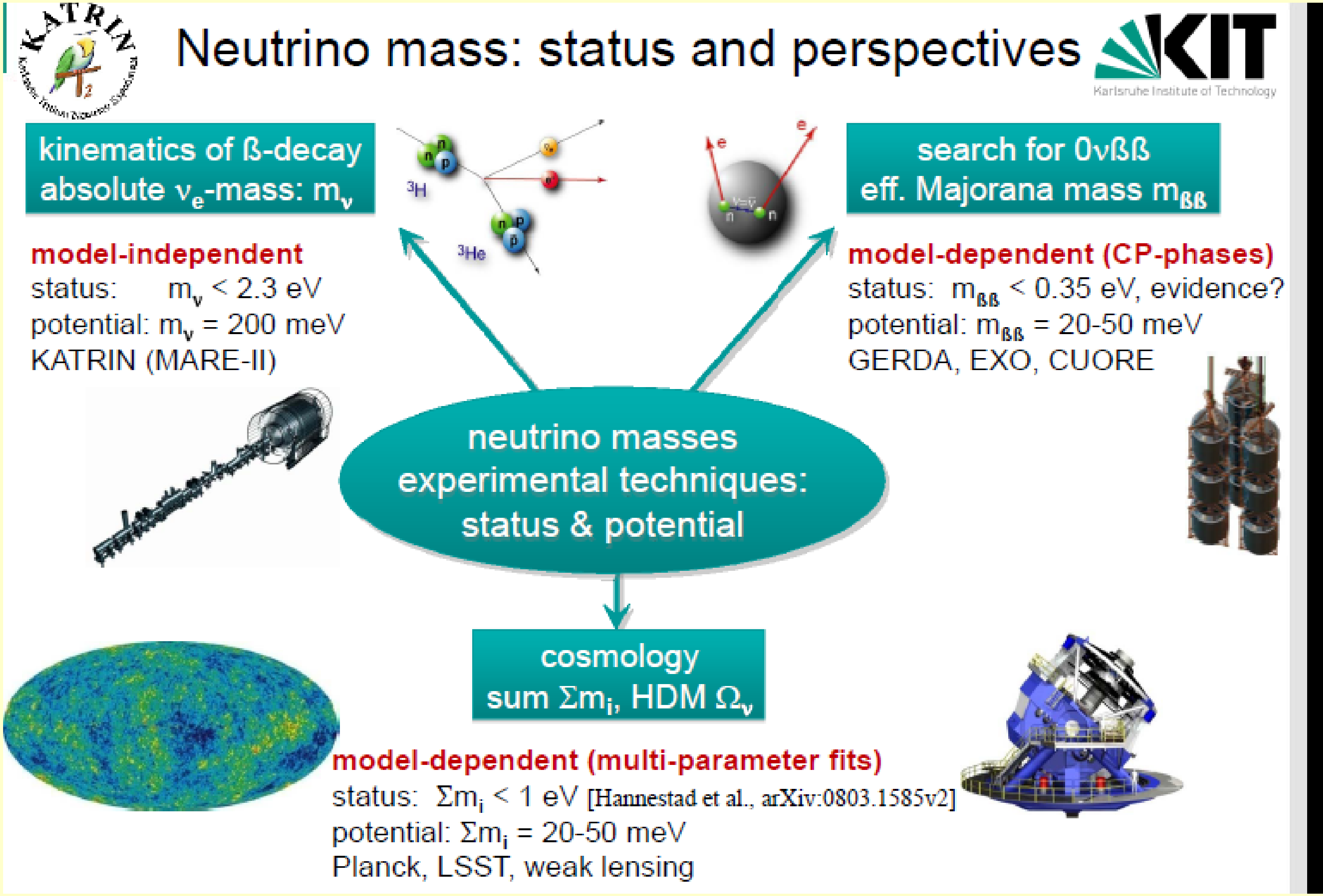
BRUNO returns to Italy !

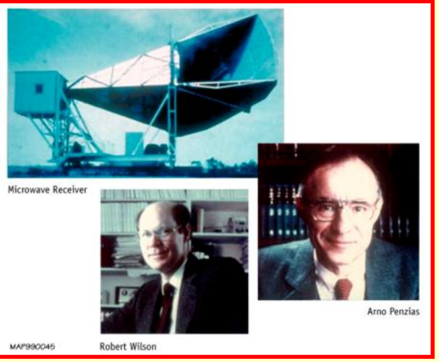


The great suggestion of Bruno => Neutrino oscillations

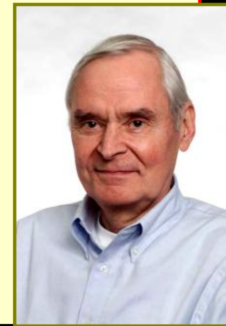


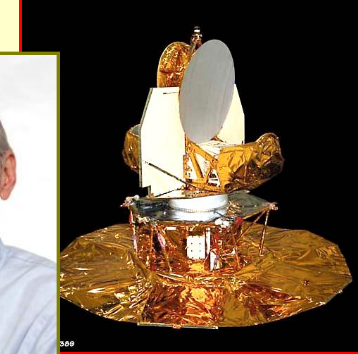
Neutrino oscillations => $M_{\nu a} - M_{\nu b} \neq 0$



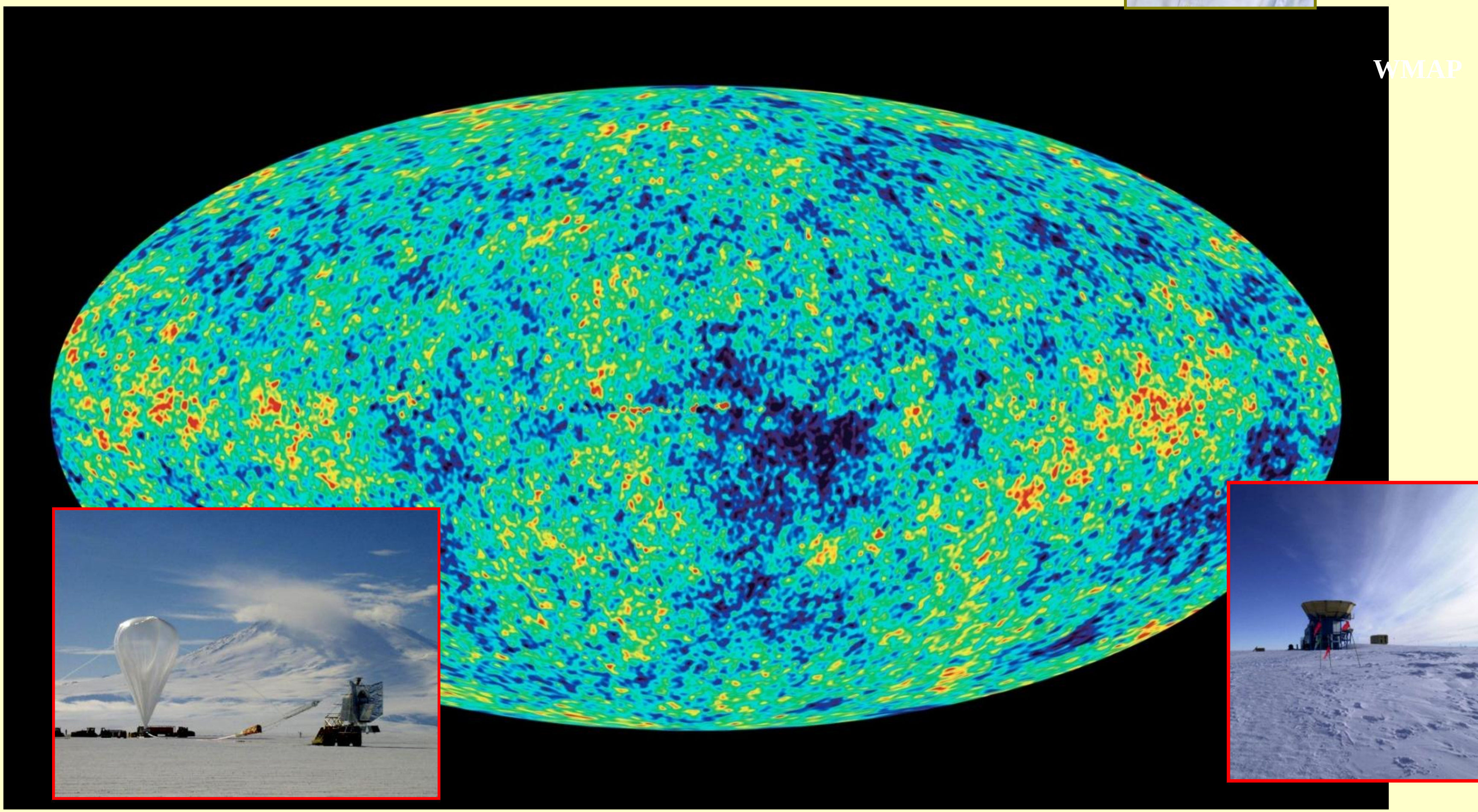


Σm_ν from cosmology
<440-760=>~100 meV





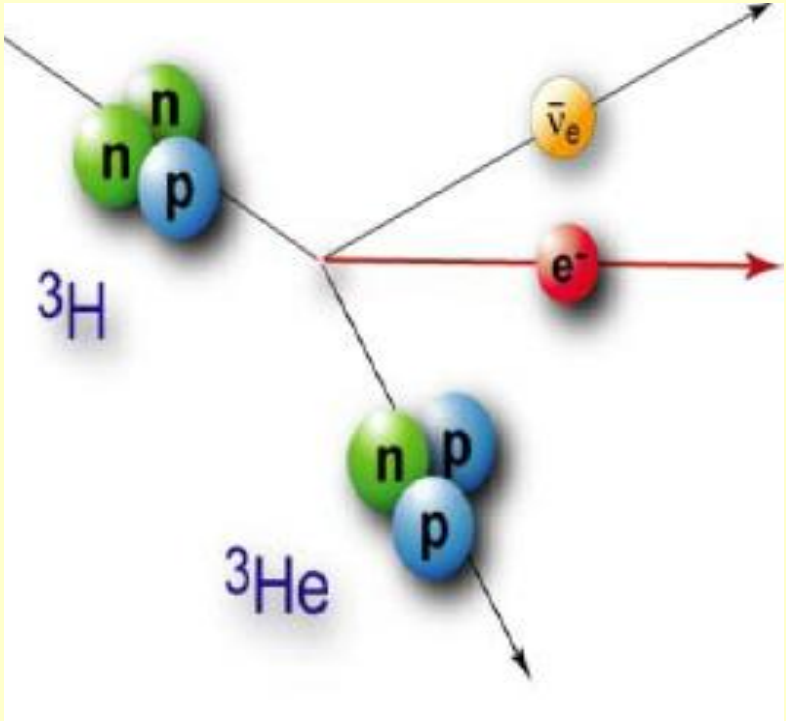
WMAP



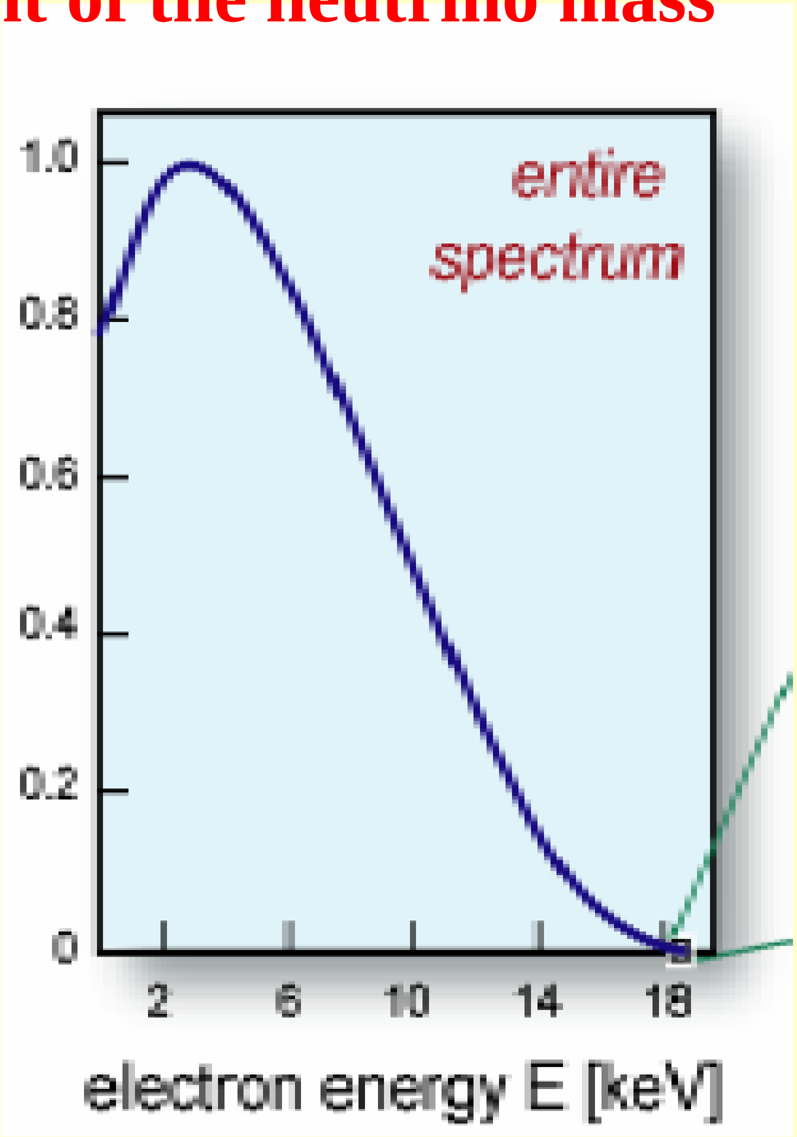
DASI

Direct measurement of the neutrino mass

β decay



Limite attuale **< 2 eV**



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.

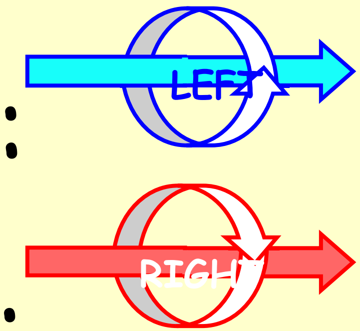
Chi l'ha visto?

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.

Dirac or Majorana neutrino?

ν:

$\bar{\nu}$:



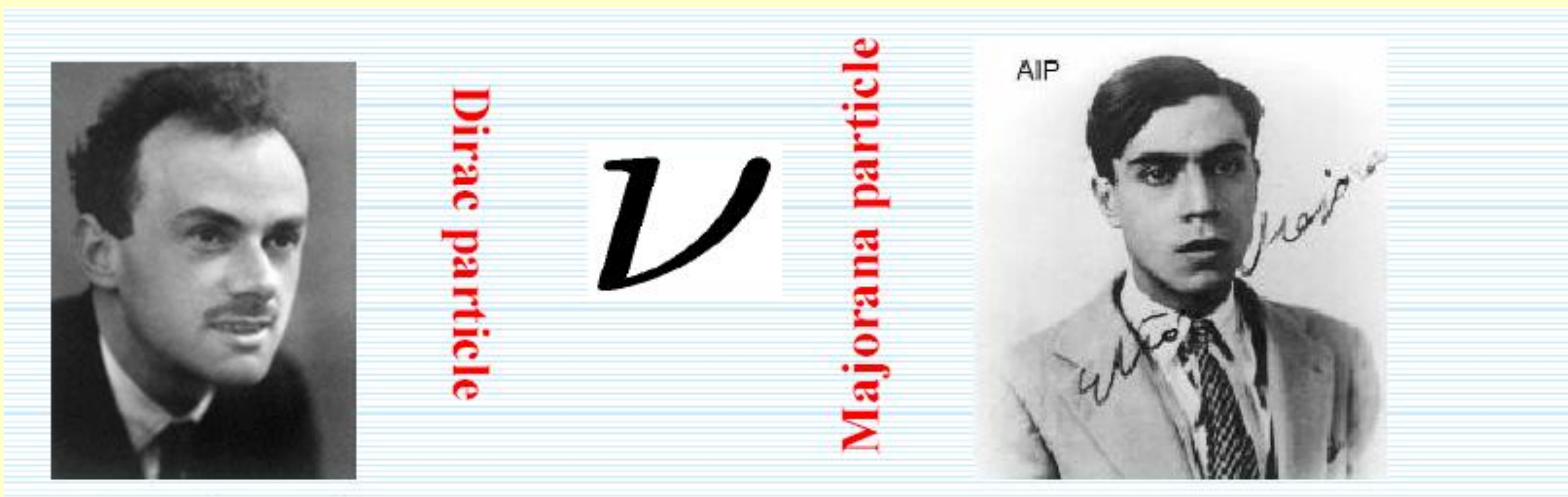
$\nu \neq \bar{\nu}$

→ →

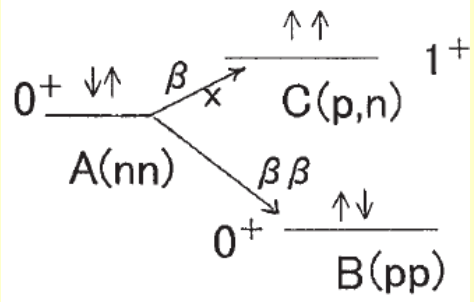
<= =>

$\nu = \bar{\nu}$

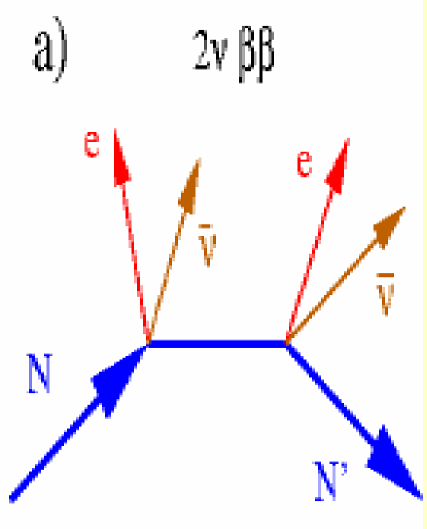
Majorana
=>1937



Double beta decays



2nbb SM DL=0



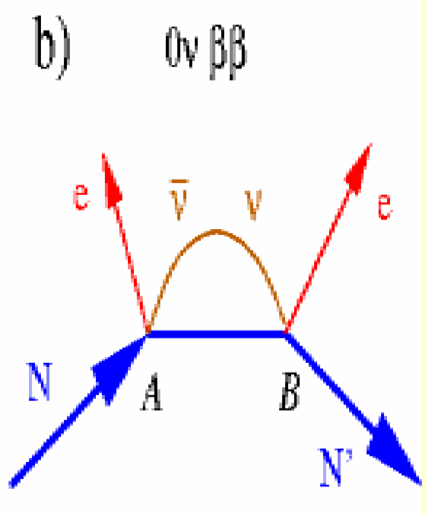
1935 M.Goeppert-Mayer, P.R. 48 (1935) 512 T>10^{20}

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

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

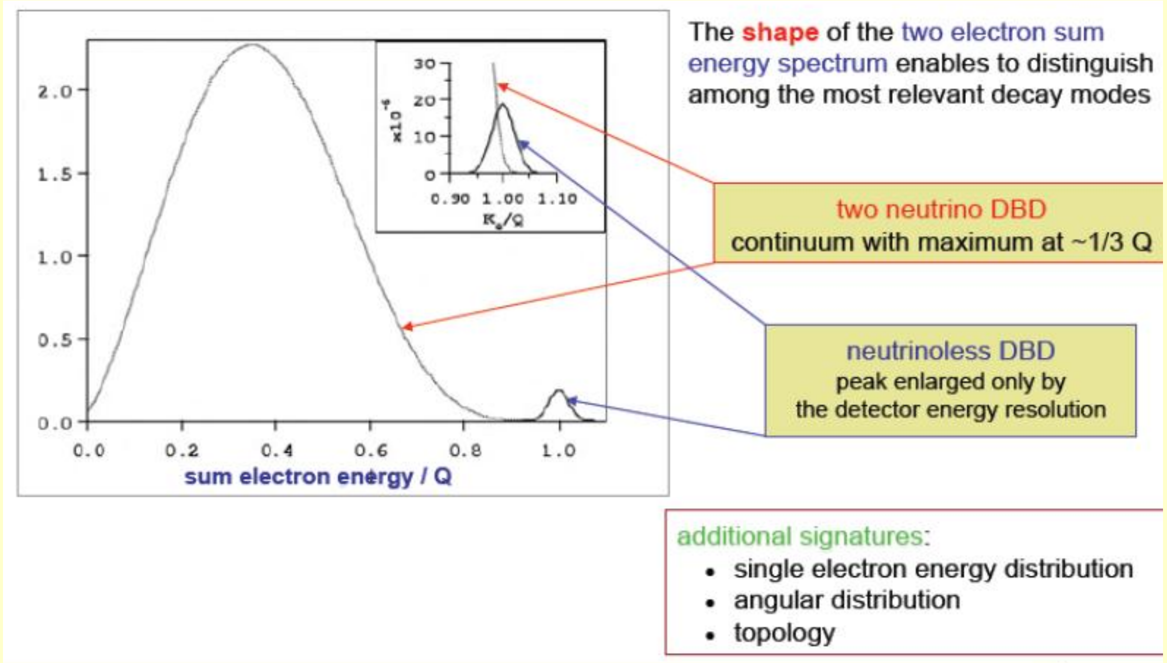
1989 -2008 ^{100}Mo, ^{116}Cd, ^{76}Ge etc.
ELEGANT V, NEMO, HM-IGEX, etc

0nbb beyond SM DL=2



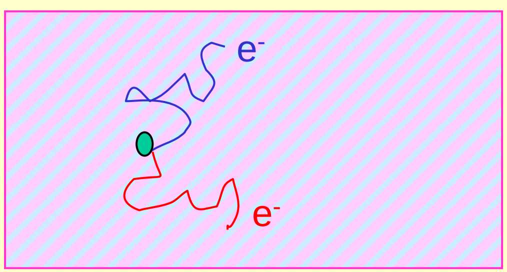
E. Majorana, Nuovo Cimento 14 (1937) 171
Symmetric Theory of Electron and Positron

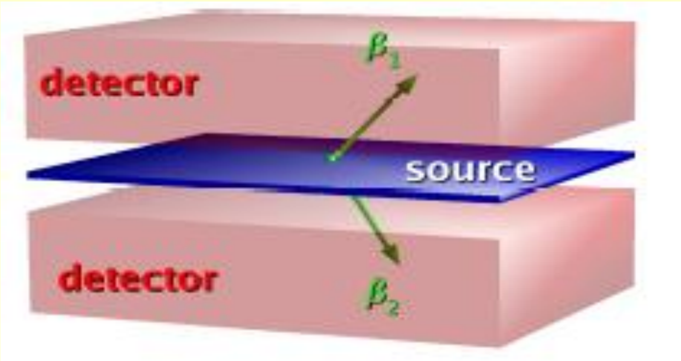
G. Racah, Nuovo Cimento 14 (1937) 322
0nbb for Majorana



Source = detector

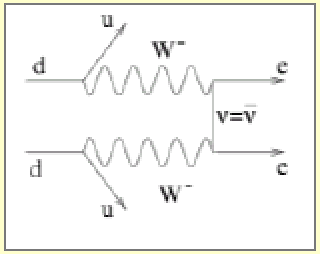
Source ≠ detectors





0ν-DBD and neutrino physics

how **0ν-DBD** is connected to neutrino mixing matrix and masses in case of process induced by mass mechanism



neutrinoless Double Beta Decay **rate**

Phase space

Nuclear matrix elements

Effective **Majorana mass**

$$\frac{1}{\tau} = G(Q,Z)\,|M_{nucl}|^2 \langle M_{\beta\beta}\rangle^2$$

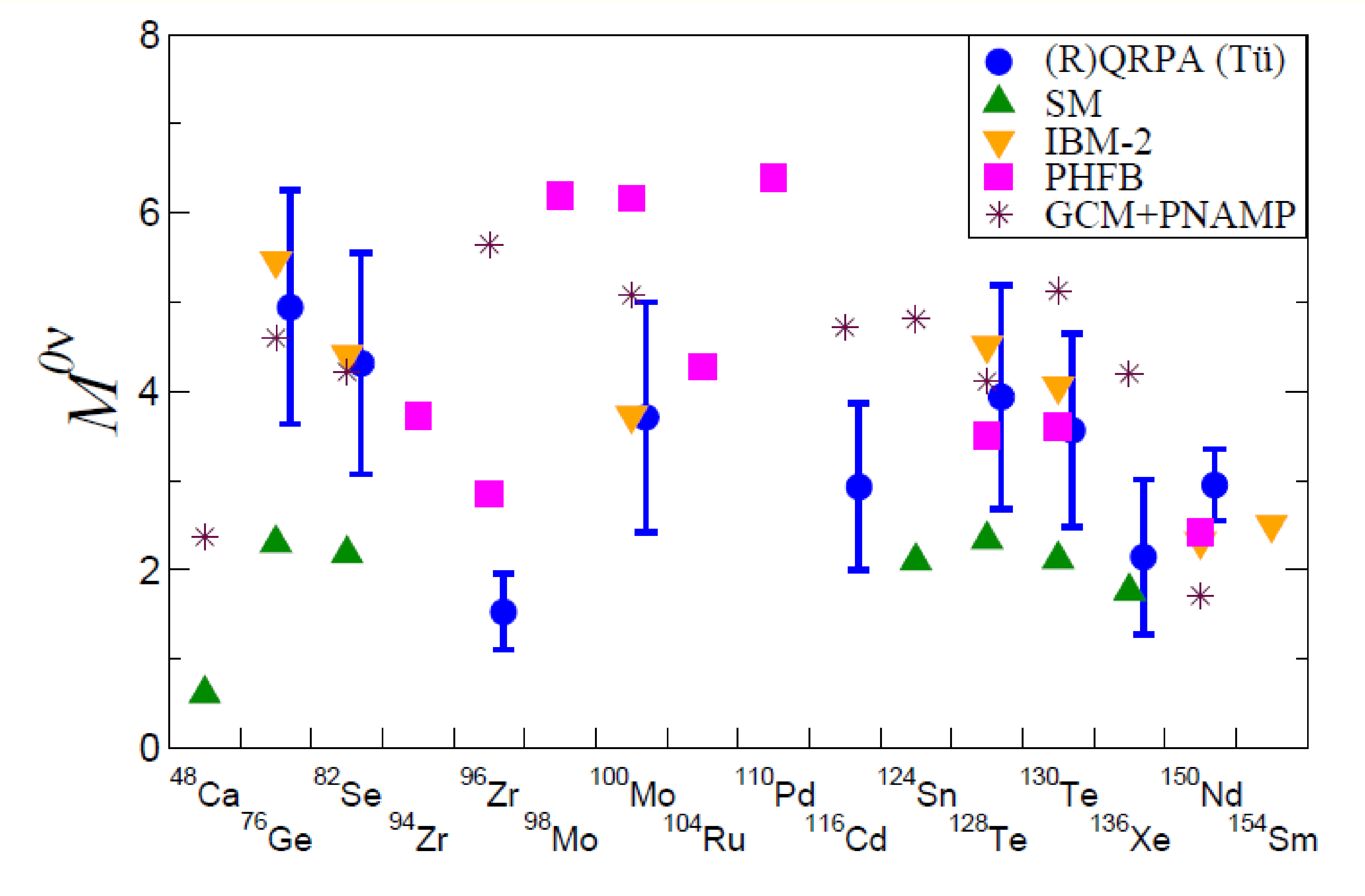
what the experimentalists try to measure

what the nuclear theorists try to calculate

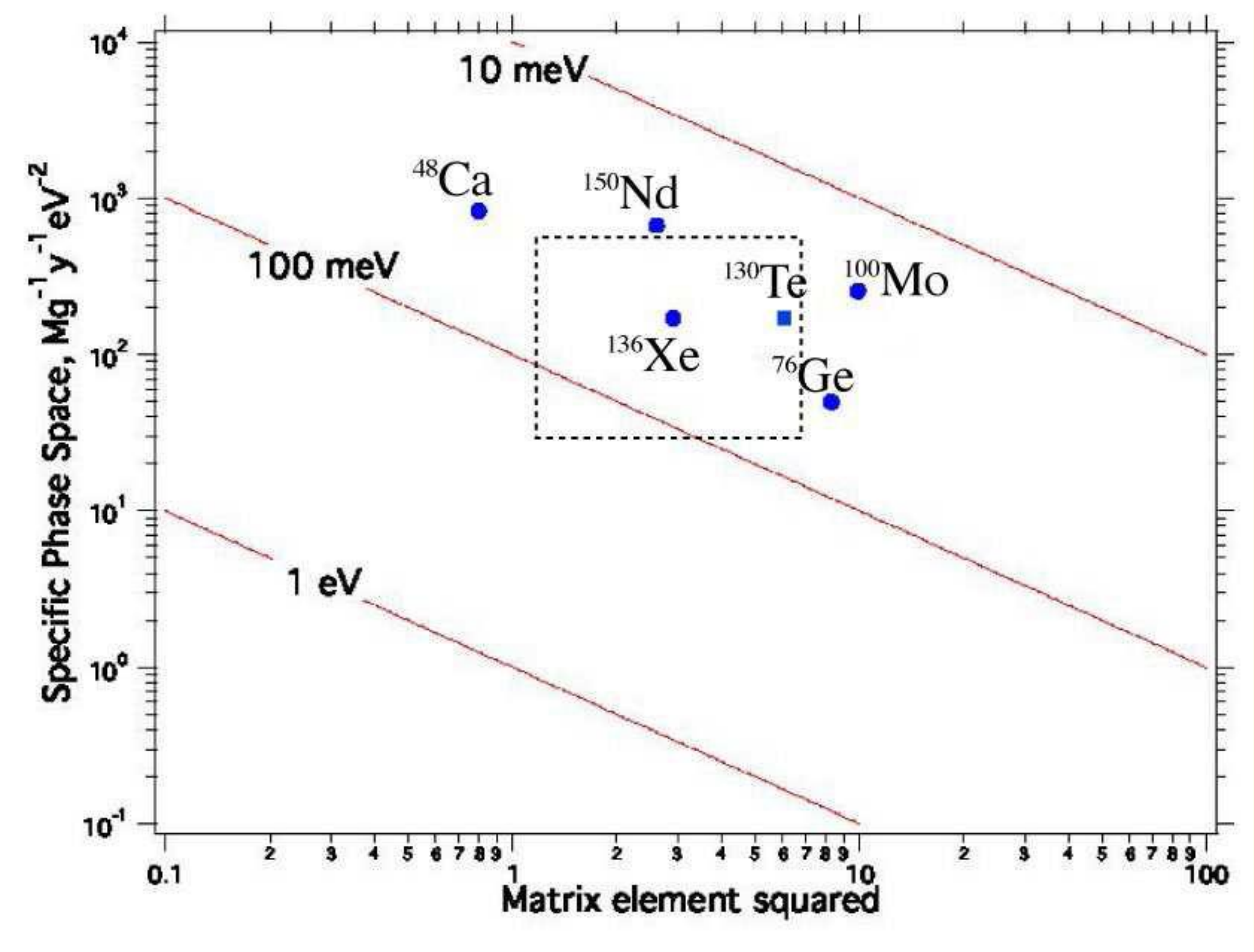
parameter containing the neutrino physics

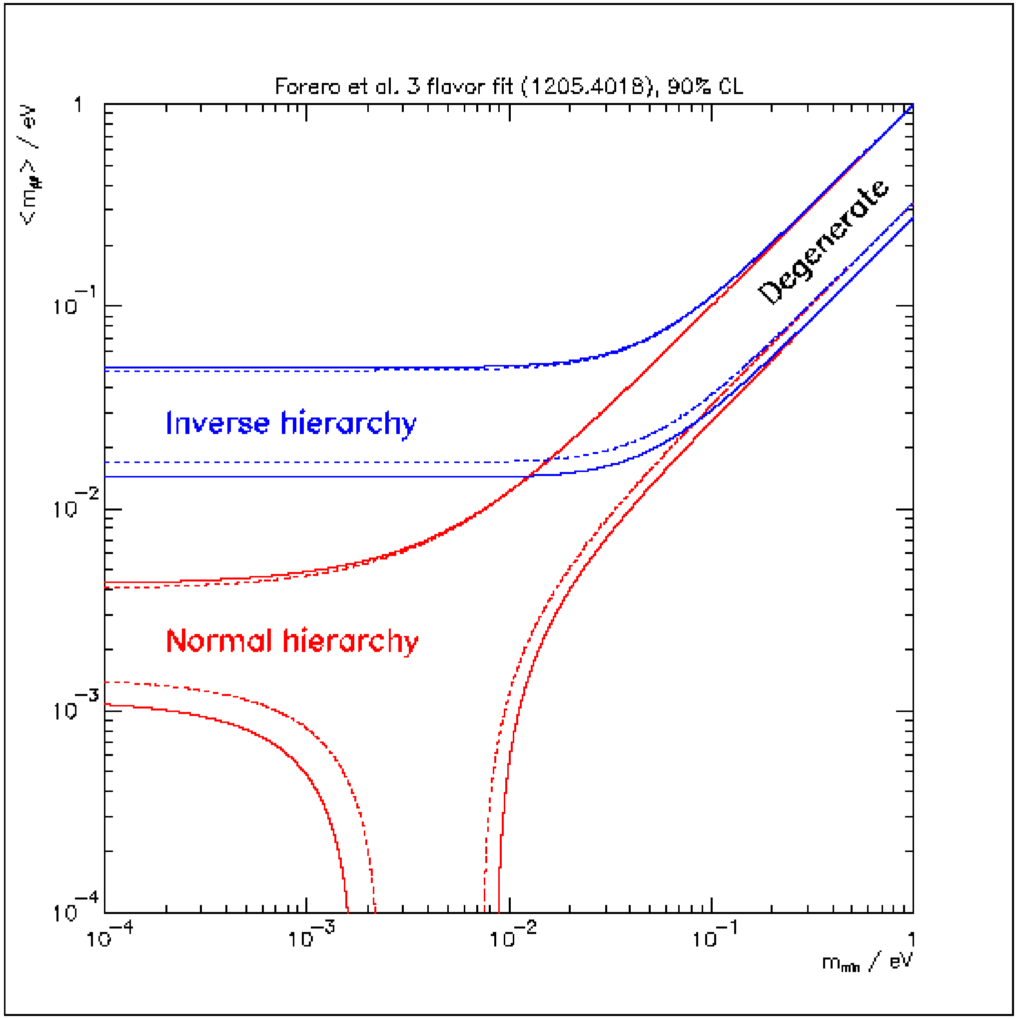
$$\langle M_{\beta\beta}\rangle = \left|\, |U_{e1}|^2 M_1 + e^{i\alpha_1} |U_{e2}|^2 M_2 + e^{i\alpha_2} |U_{e3}|^2 M_3 \,\right|$$

Nuclear Matrix Elements



The simplified approach by H.Robertson

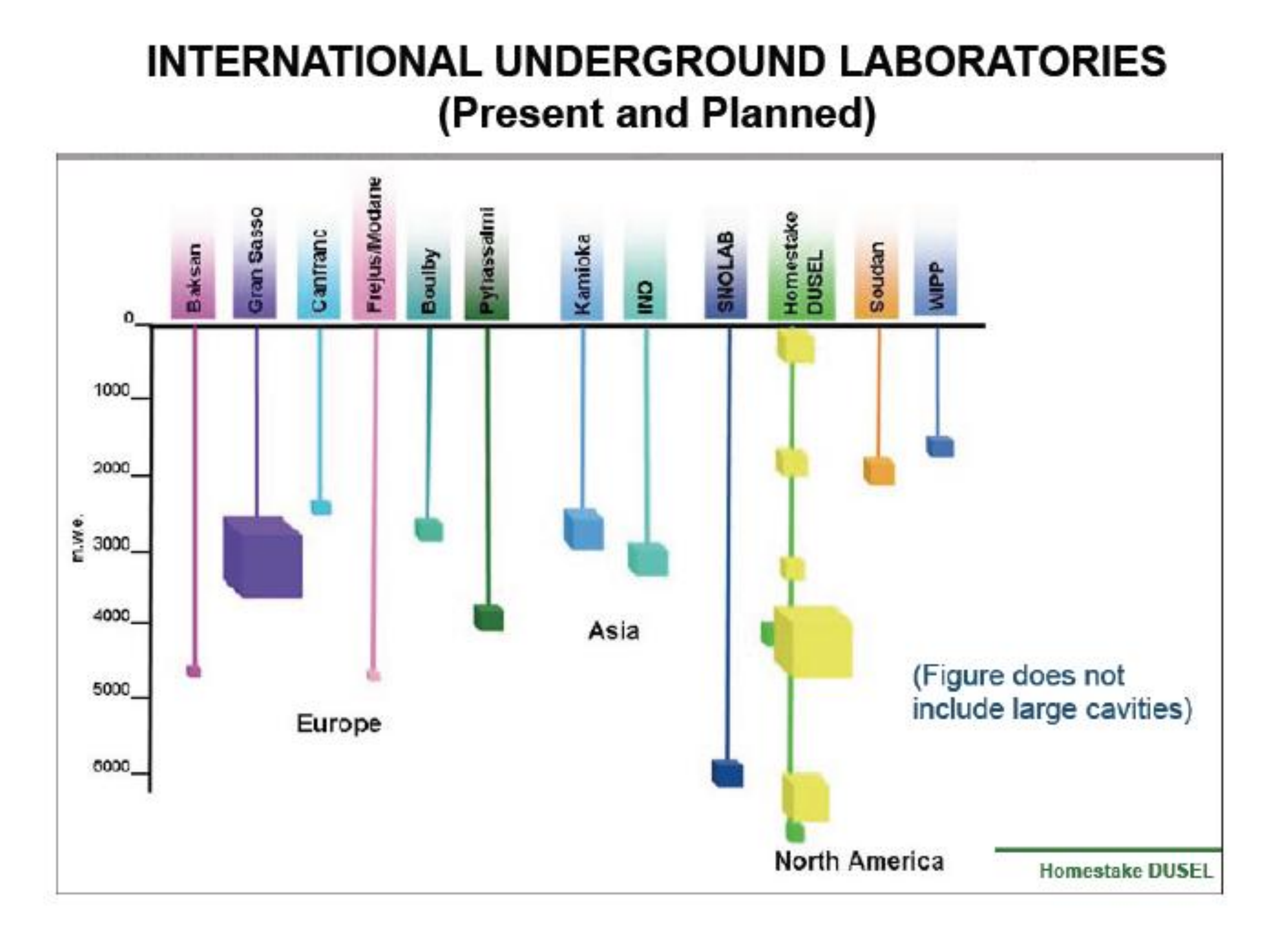




<=

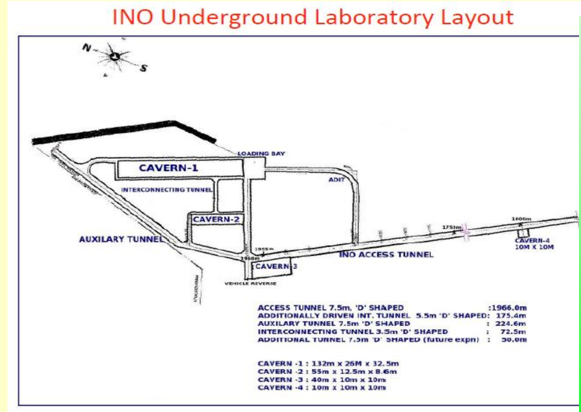
^{76}Ge: (1.4-7.7)· 10^{28} yr
^{130}Te: (0.22-1.3) 10^{28} yr
^{136}Xe: (0.32-2.2)·1028 yr

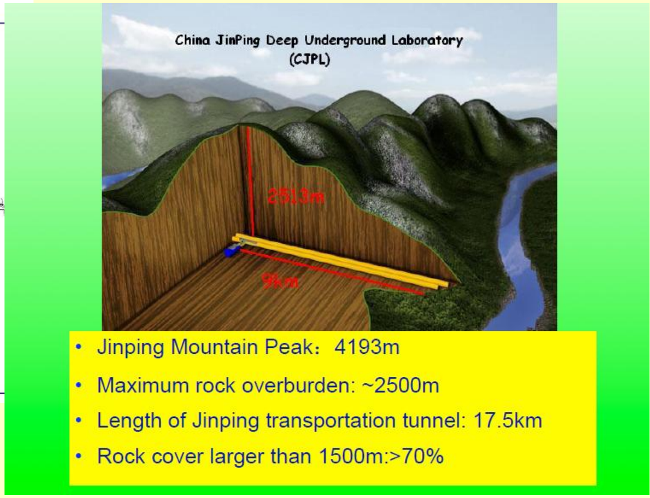
Where to go ?



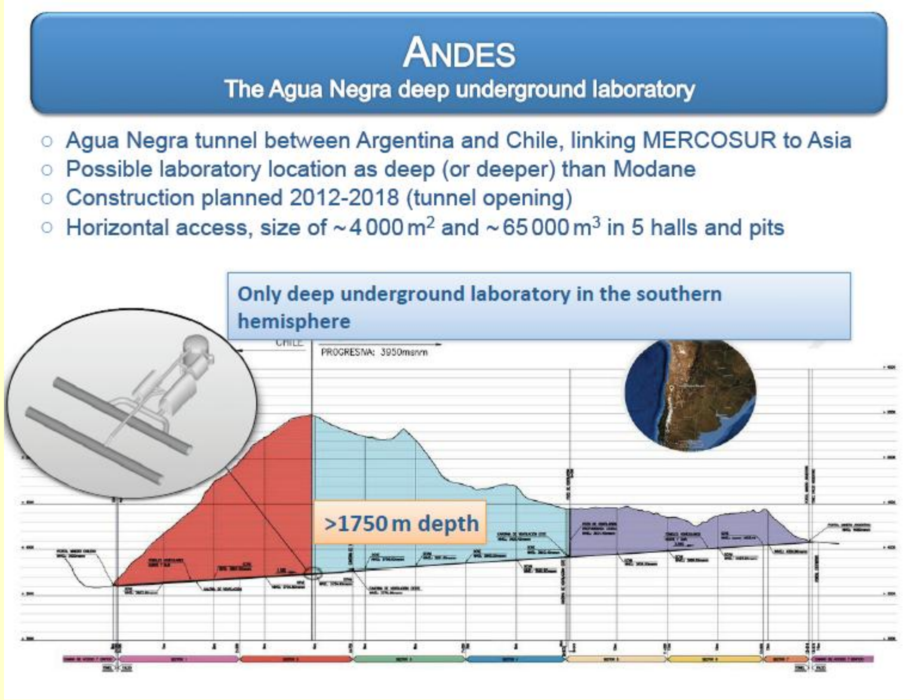
INTERNATIONAL UNDERGROUND LABORATORIES
(Present and Planned)
Baksan
Gran Sasso
Canfranc
Frejus/Modane
Boulby
Pyhassalmi
Kamioka
INO
SNOLAB
Homestake DUSEL
Soudan
WIPP
0
1000
2000
3000
4000
5000
6000
m.w.e.
Europe
Asia
North America
(Figure does not include large cavities)
Homestake DUSEL


Yangyang Underground Laboratory
Korea Middleland Power Co.
Yangyang Pumped Storage Power Plant
(Upper Dam)
(Power Plant)
(Lower Dam)
Minimum
Access to the lab by car (~2km)
양양양수발전소


INO Underground Laboratory Layout
CAVERN-1
CAVERN-2
CAVERN-3
AUXILARY TUNNEL
INO ACCESS TUNNEL


China JinPing Deep Underground Laboratory
(CJPL)
Jinping Mountain Peak：4193m
Maximum rock overburden: ~2500m
Length of Jinping transportation tunnel: 17.5km
Rock cover larger than 1500m:>70%


LNGS
CUORE
Cuoricino
GERDA
COBRA
CUORE R&D
DAMA


ANDES
The Agua Negra deep underground laboratory
Agua Negra tunnel between Argentina and Chile, linking MERCOSUR to Asia
Possible laboratory location as deep (or deeper) than Modane
Construction planned 2012-2018 (tunnel opening)
Horizontal access, size of ~4 000 m² and ~65 000 m³ in 5 halls and pits
Only deep underground laboratory in the southern hemisphere
>1750 m depth

$T^{2\nu}_{1/2}$ (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 => $T^{2\nu}_{1/2}$ $2.71 \pm 0.017(stat.) \pm 0.06(sys.) \times 10^{21}$ yr.

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

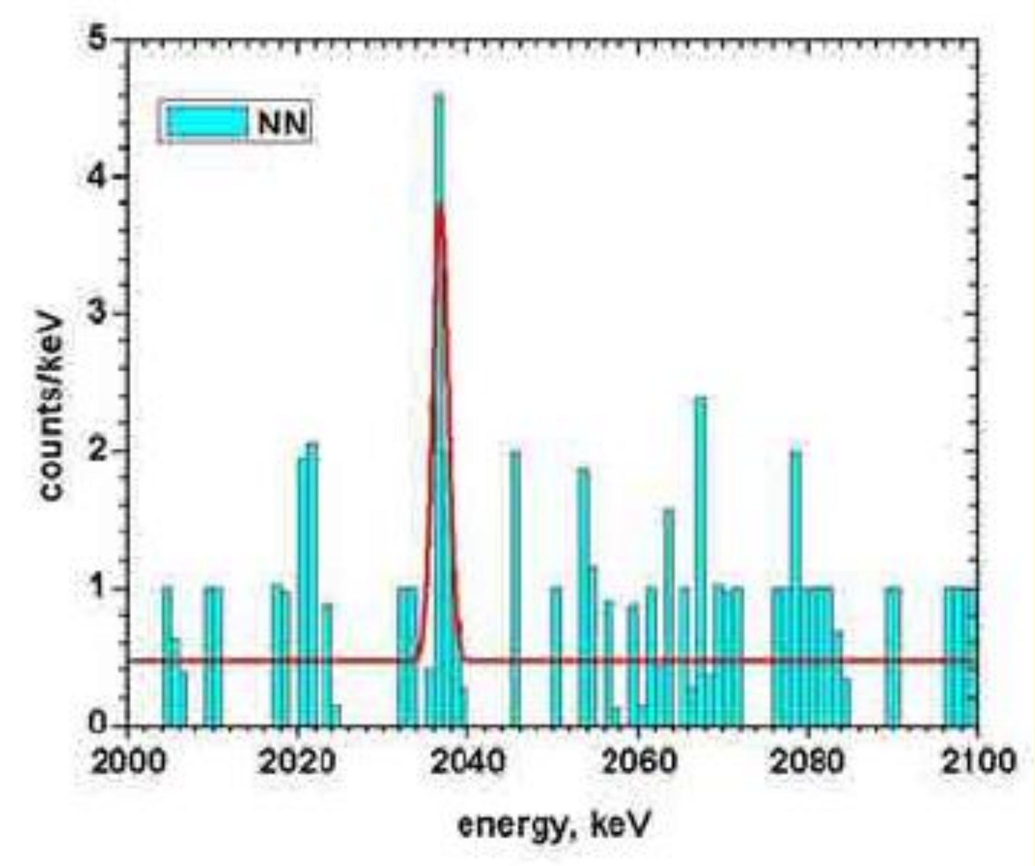
GERDA I $1.84 +0.14 -10(stat) \times 10^{21}$ yr

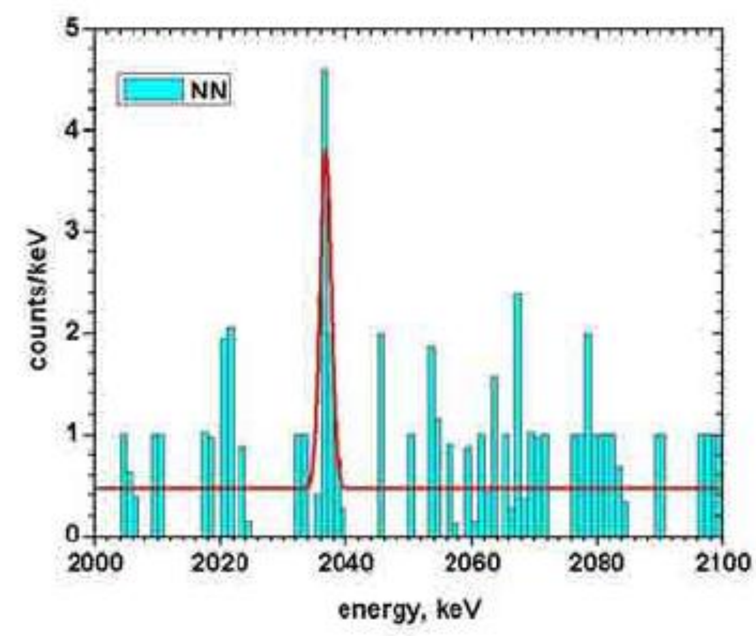
Possible evidence in $0\nu\beta\beta$ in ^{76}Ge

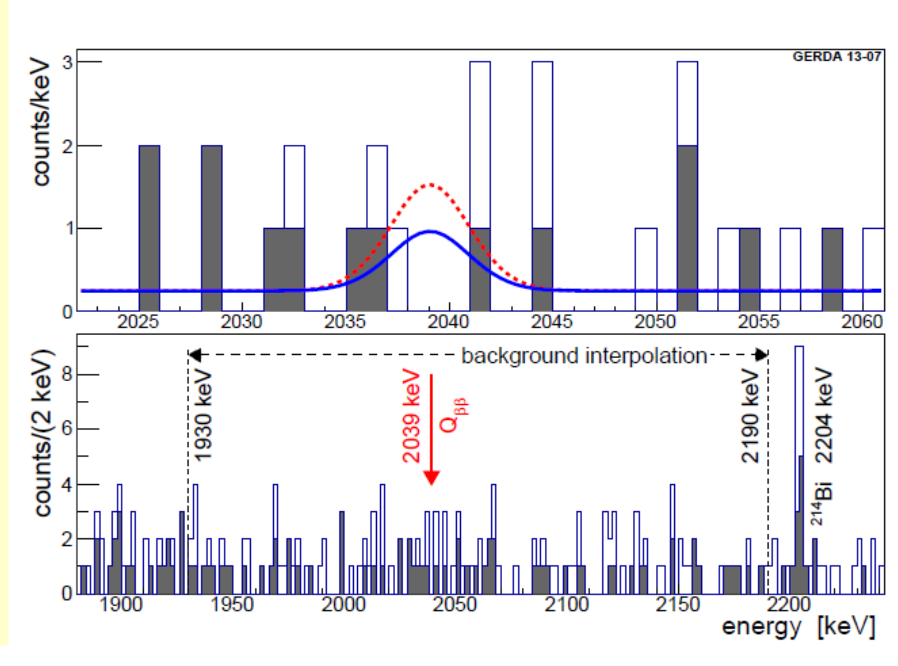
(H.Klapdor et al)

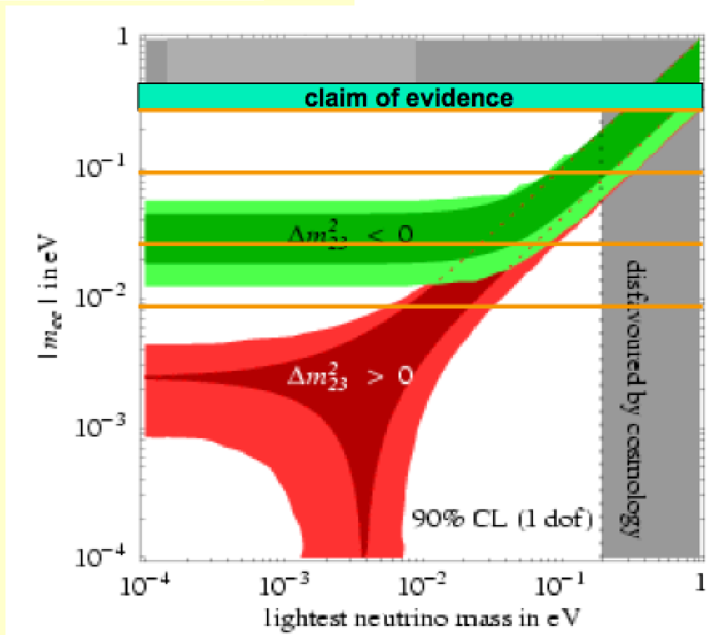
$$T_{1/2}^{0\nu} = (2.23^{+0.44}_{-0.31}) \times 10^{25}\ \mathrm{y}.$$

$<m_\nu> \sim$ 0.34eV



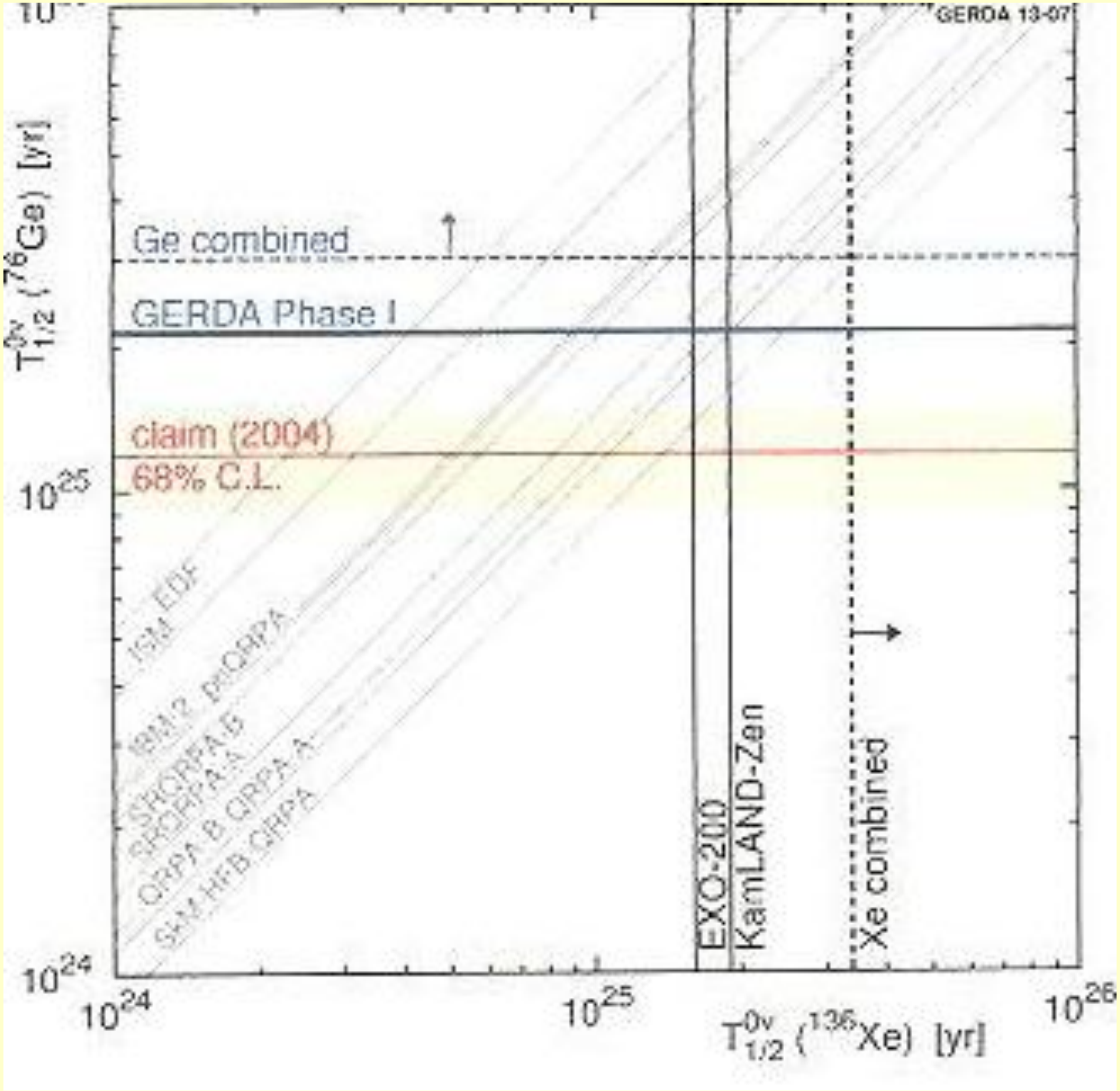

NN
counts/keV
energy, keV
0
1
2
3
4
5
2000
2020
2040
2060
2080
2100


GERDA 13-07
counts/keV
2025
2030
2035
2040
2045
2050
2055
2060
counts/(2 keV)
background interpolation
1930 keV
2039 keV
$Q_{\beta\beta}$
2190 keV
2204 keV
^{214}Bi
1900
1950
2000
2050
2100
2150
2200
energy [keV]


claim of evidence
$\Delta m^2_{23} < 0$
$\Delta m^2_{23} > 0$
90% CL (1 dof)
disfavoured by cosmology
$|m_{ee}|$ in eV
lightest neutrino mass in eV
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}

Present results on neutrinoless DBD

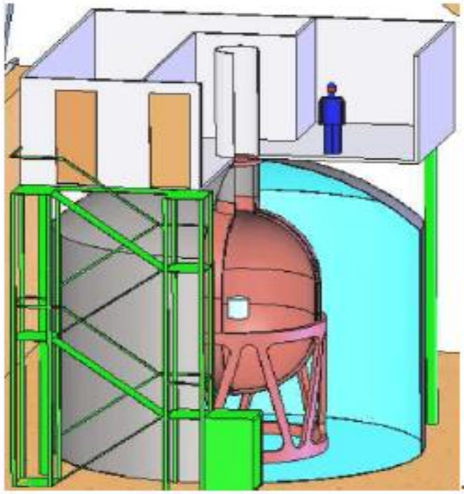
Isotope	Technique	$\tau^{0\nu}_{1/2\,(y)}$	$<m_{\beta\beta}>$ eV
^{48}Ca	CaF_2 scint	$>1.4x10^{22}$	<7-45
^{76}Ge (HM)	Ge diode	$>1.9x10^{25}$	<(0.3-1.27)
^{76}Ge (IGEX)	Ge diode	$>1.6x10^{25}$	<(0.33-1.35)
^{76}Ge (Klapdor 2004)	Ge diode	$1.2x10^{25}$	.38
^{76}Ge (Klapdor 2006)	Ge diode	$2.2x10^{25}$	.28
^{76}Ge (GERDA I)	Ge diode	$>2.1x10^{25}$	<(.29-1.1)
^{76}Ge (GERDA+HM+IGEX)	Ge diode	$>3x10^{25}$	<(.25-.98)
^{82}Se	Foil&track	$>.6x10^{23}$	<(0.89-2.)
^{96}Zr	Foil&track	$>9.2x10^{21}$	<(7.2-19.5)
^{100}Mo	Foil&track	$>1.1x10^{24}$	<(0.31-.79)
^{116}Cd	Scintillator	$>1.7x10^{23}$	<1.7
^{128}Te	Geochem	$>7.7x10^{24}$	<(1.1-1.35)
^{130}Te	Bolometer	$>2.8x10^{24}$	<(0.3-.7)
^{136}Xe	EXO	$>1.6x10^{25}$	<140-380
^{136}Xe	Kamland Zen	$>1.9x10^{25}$	**<128-349**
^{136}Xe	EXO+Kamzen		<120-250
^{150}Nd	Foil TPC	$>1.8x10^{22}$	



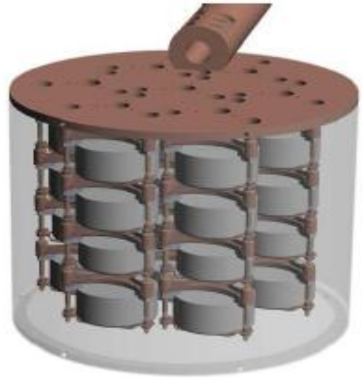
GERDA 13-07
Ge combined
GERDA Phase I
claim (2004)
68% C.L.
ISM EDF
IBM-2 pnQRPA
SRQRPA B
SRQRPA A
QRPA B QRPA A
SkM-HFB QRPA
EXO-200
KamLAND-Zen
Xe combined
10^{25}
10^{24}
10^{24}
10^{25}
10^{26}
$T^{0\nu}_{1/2}$ (^{76}Ge) [yr]
$T^{0\nu}_{1/2}$ (^{136}Xe) [yr]

Experimental Status

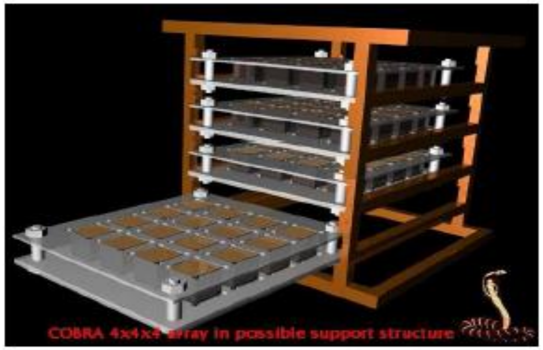
Experiment	Nucleus	Fiducial Mass (ββ)	Technique	Location	Date
		Current experiments (funded, construction, running)			
GERDA I/II	^{76}Ge	15/33	ionization	LNGS	2011/13
EXO200	^{136}Xe	89	liquid TPC	WIPP	2011
CUORE0/CUORE	^{130}Te	11/206	bolometer	LNGS	2013/15
Kamland-Zen	^{136}Xe	140	liquid scintillator	Kamioka	2011
SNO+	^{130}Te	468	liquid scintillator	Sudbury	2014
		Demonstrators			
Majorana D	^{76}Ge	30	ionization	SUSEL	2014
SuperNEMO D	^{82}Se	7/140	track/calorimeter	Modane	2013/?
Lucifer	^{82}Se	18	scintillating bolometer	LNGS	2015
		R&D (funding, prototyping)			
NEXT	^{136}Xe	90	gas TPC	Canfranc	2013+
Candles III	^{48}Ca	0.35	scintillating crystals	Oto Cosmo	2011
MOON	^{82}Se/^{150}Nd				
DCBA	^{150}Nd	32	tracking		
Cobra	^{116}Cd		solid TPC	LNGS	
XMASS	^{136}Xe		liquid scintillator	Kamioka	



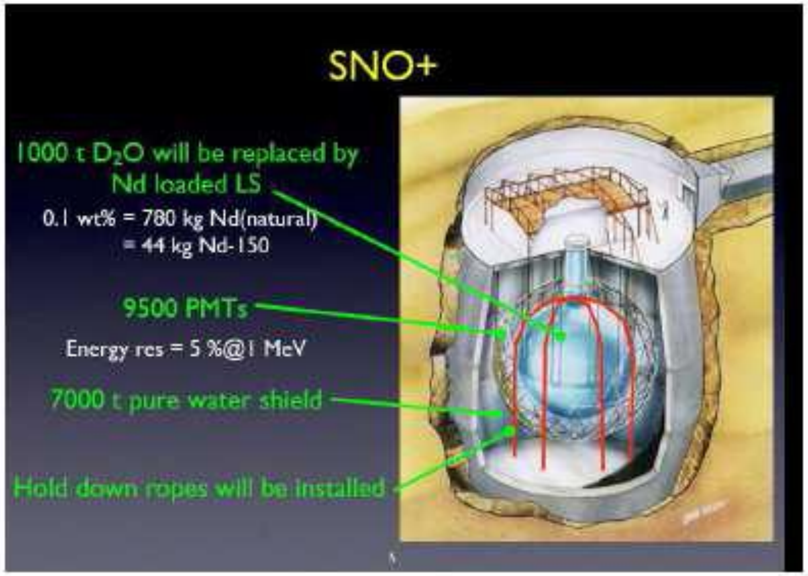
GERDA



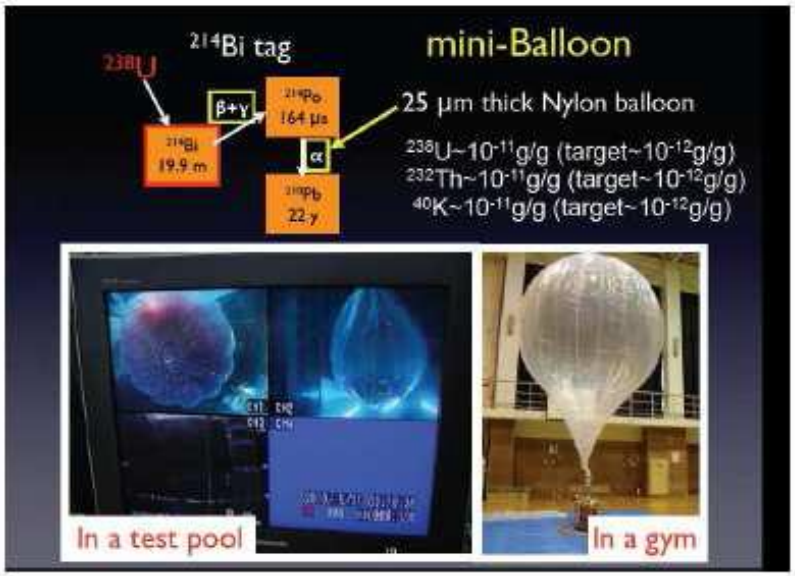
Majorana



Cobra



SNO

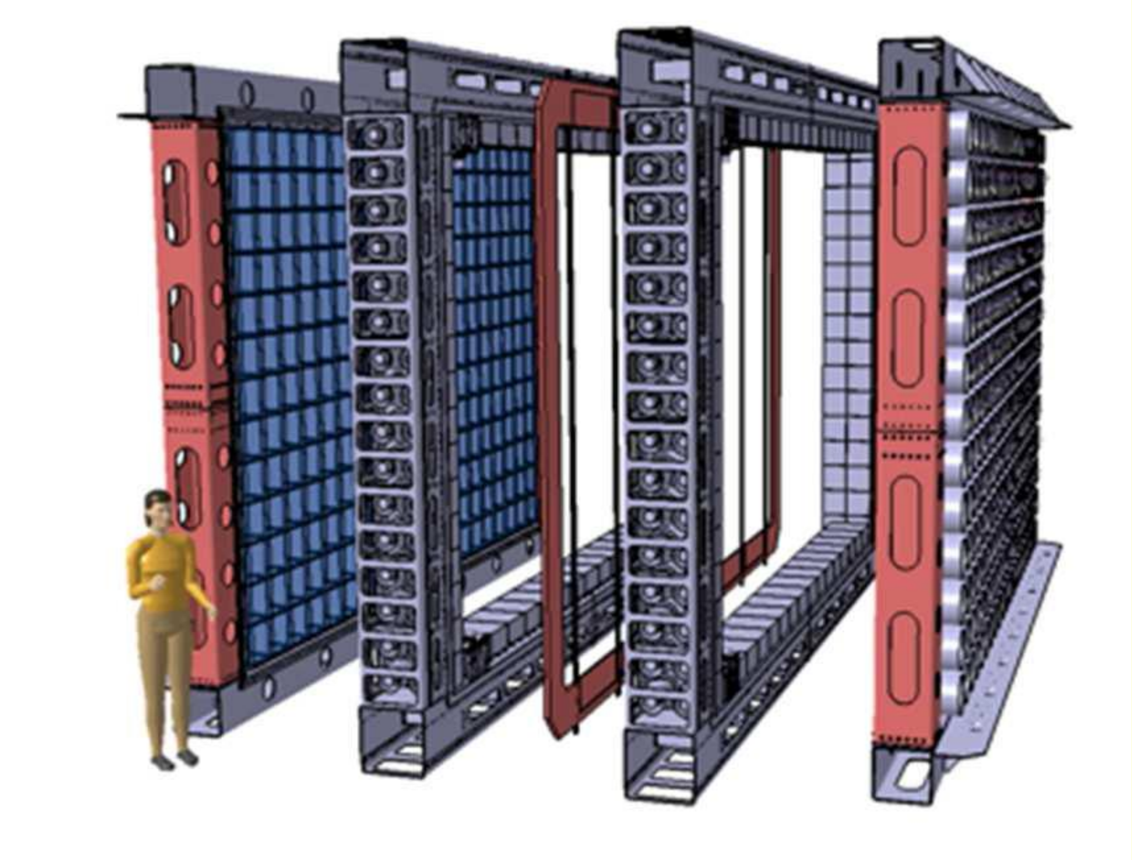


KAMLAND-ZEN

SUPERNEMO

1. **Central source** foil frame : 7 kg of isotope2
2. Tracking : 2 000 drift chambers
3. Calorimeter : 712 scintillators+ PMTs

Shielded by iron (300 tons) and water



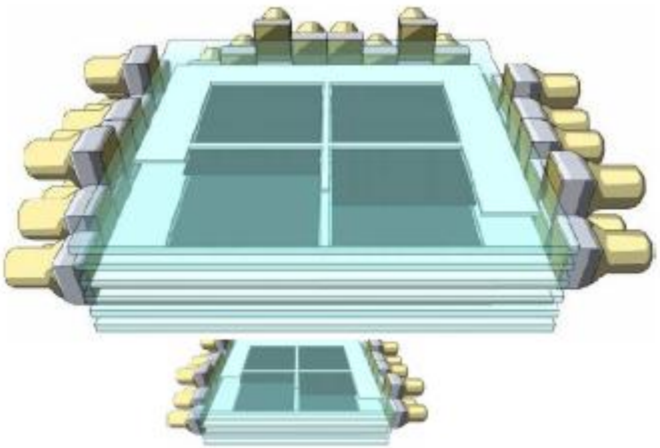


Fig.10: Moon1

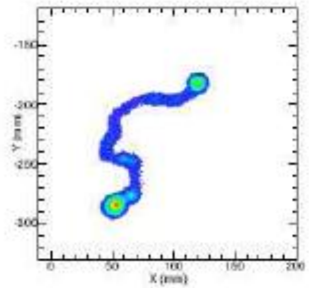


Figure 1.4: The topological signature in NEXT is a "spaghetti with two meat balls", that is, a track that ends in two "blobs" of energy, corresponding to ranging-out electrons. The trajectory of electrons contains no information, being dominated by multiple scattering in the dense gaseous xenon.

Fig.11 NEXT

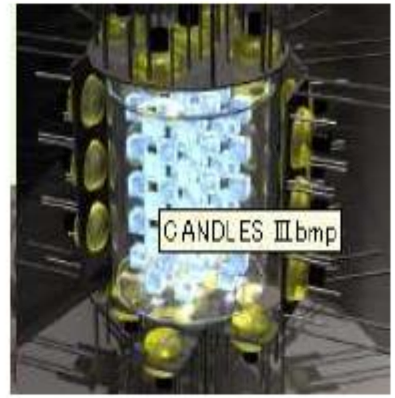


Fig.12 Candles

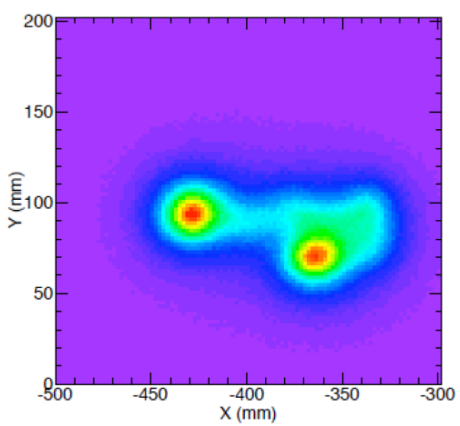
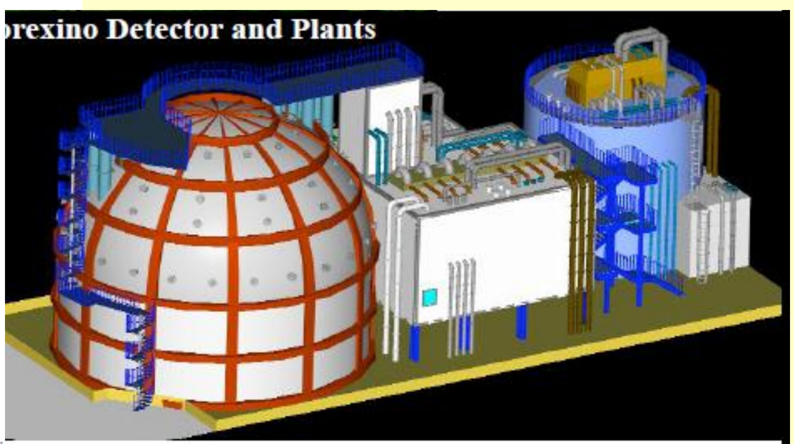
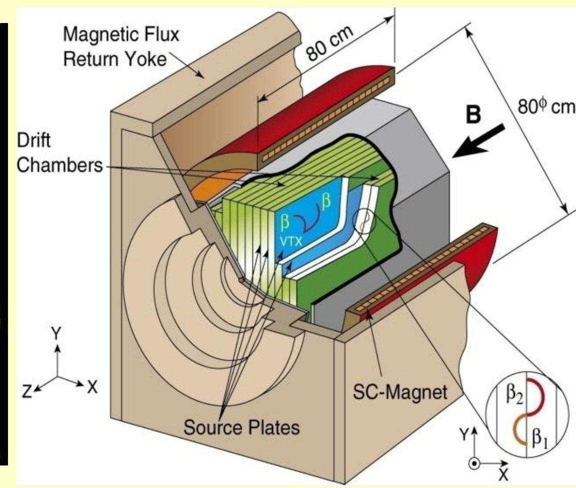
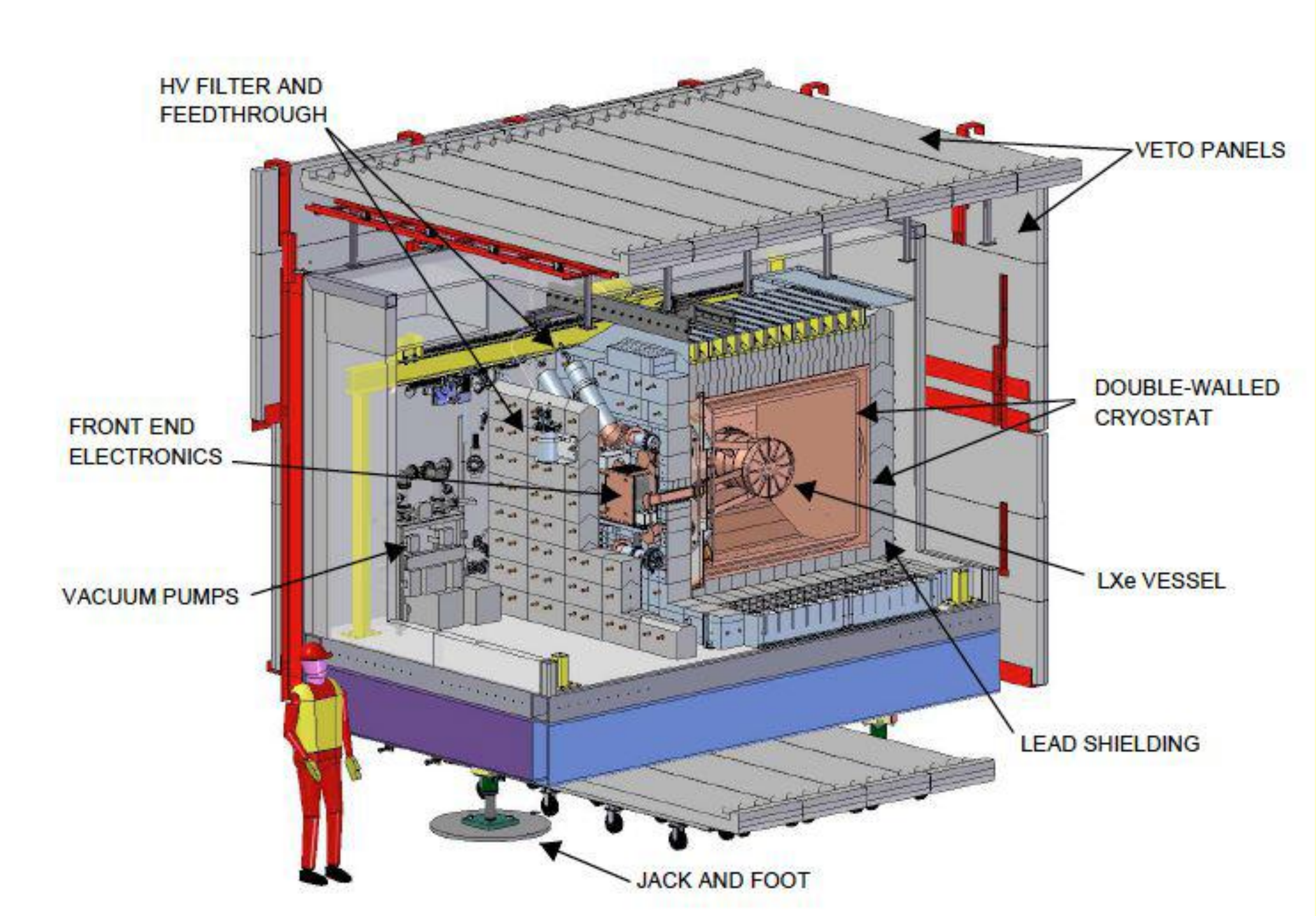


Figure 3.15: Monte Carlo simulation of the image of $\beta\beta0\nu$ event in a plane of SiPMs





EXO


HV FILTER AND
FEEDTHROUGH
VETO PANELS
DOUBLE-WALLED
CRYOSTAT
FRONT END
ELECTRONICS
VACUUM PUMPS
LXe VESSEL
LEAD SHIELDING
JACK AND FOOT

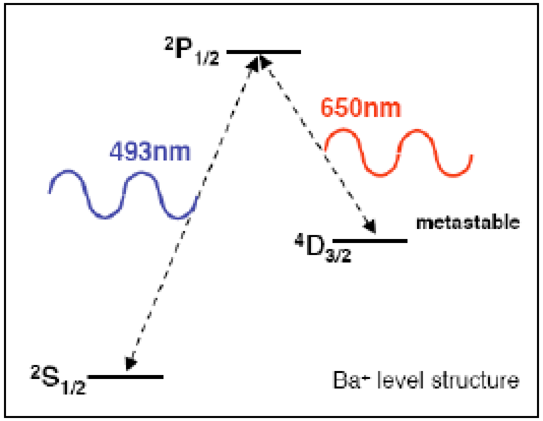
Ba^+ Spectroscopy

$^{136}Xe \rightarrow ^{136}Ba^{++} + 2e^-$

•Ba^+ system is well studied. See H. Dehmelt et al. *Phys. Rev.* A**22**, 1137 (1980).

•Very specific signature with laser induced fluorescence.

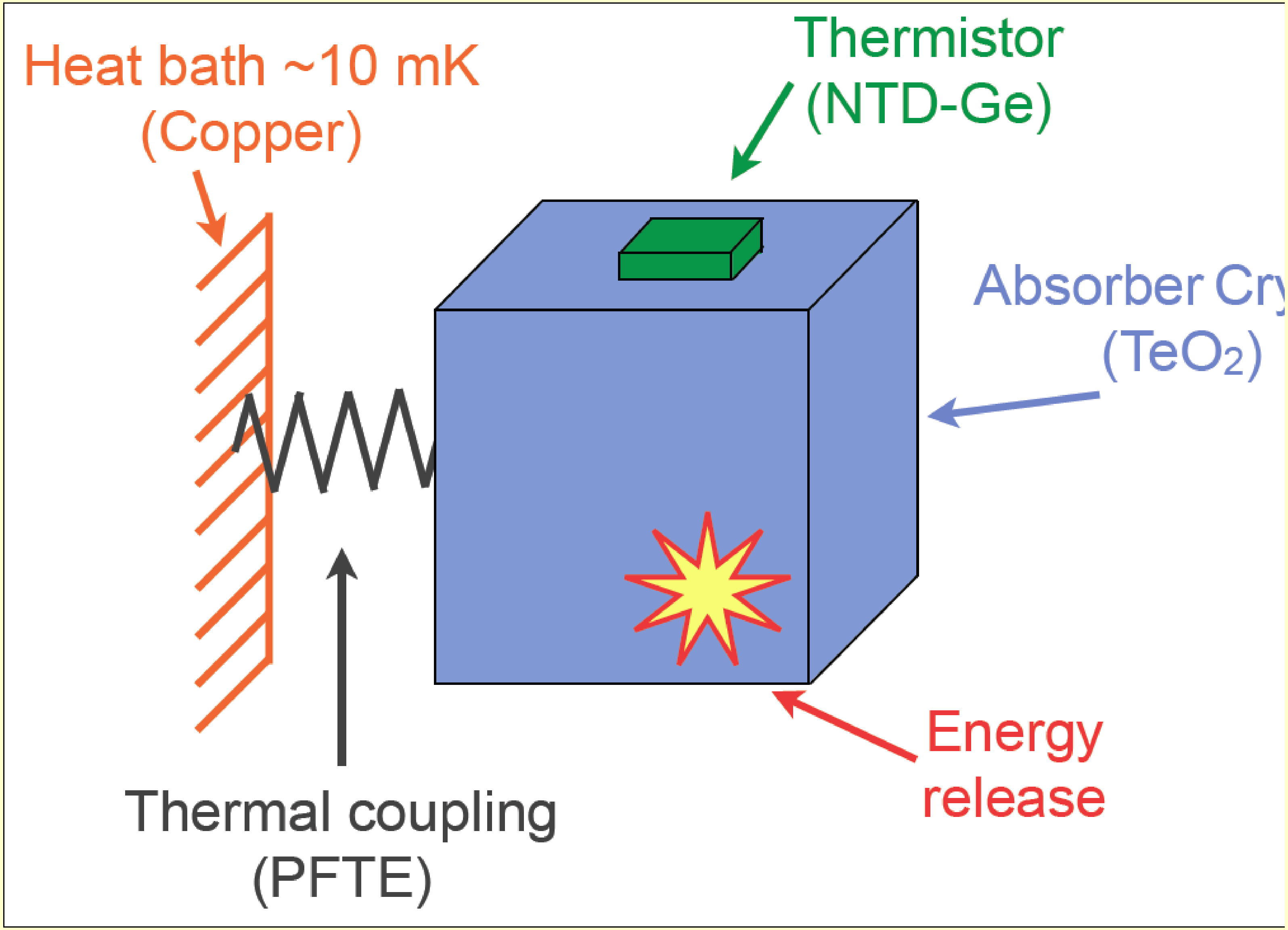
•Single ions can be detected from a photon rate of 10^7/s

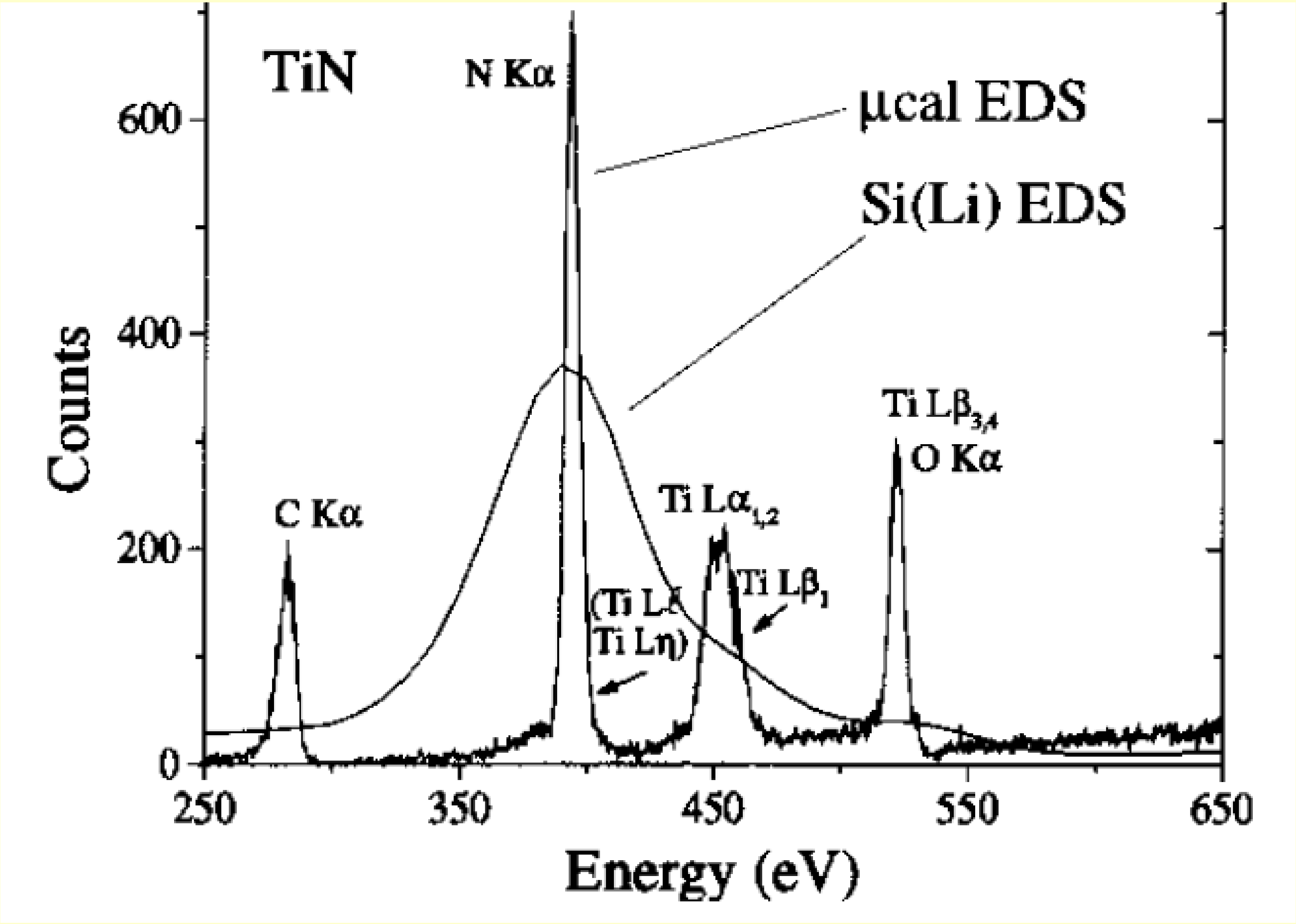


Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	$2\nu\beta\beta$ Background (events)	$T_{1/2}^{0\nu}$ (yr, 90%CL)	Majorana mass (meV)	
							QRPA‡	NSM#
Conservative	1	70	5	1.6*	0.5 (use 1)	2×10^{27}	50	68
Aggressive	10	70	10	1†	0.7 (use 1)	4.1×10^{28}	11	15

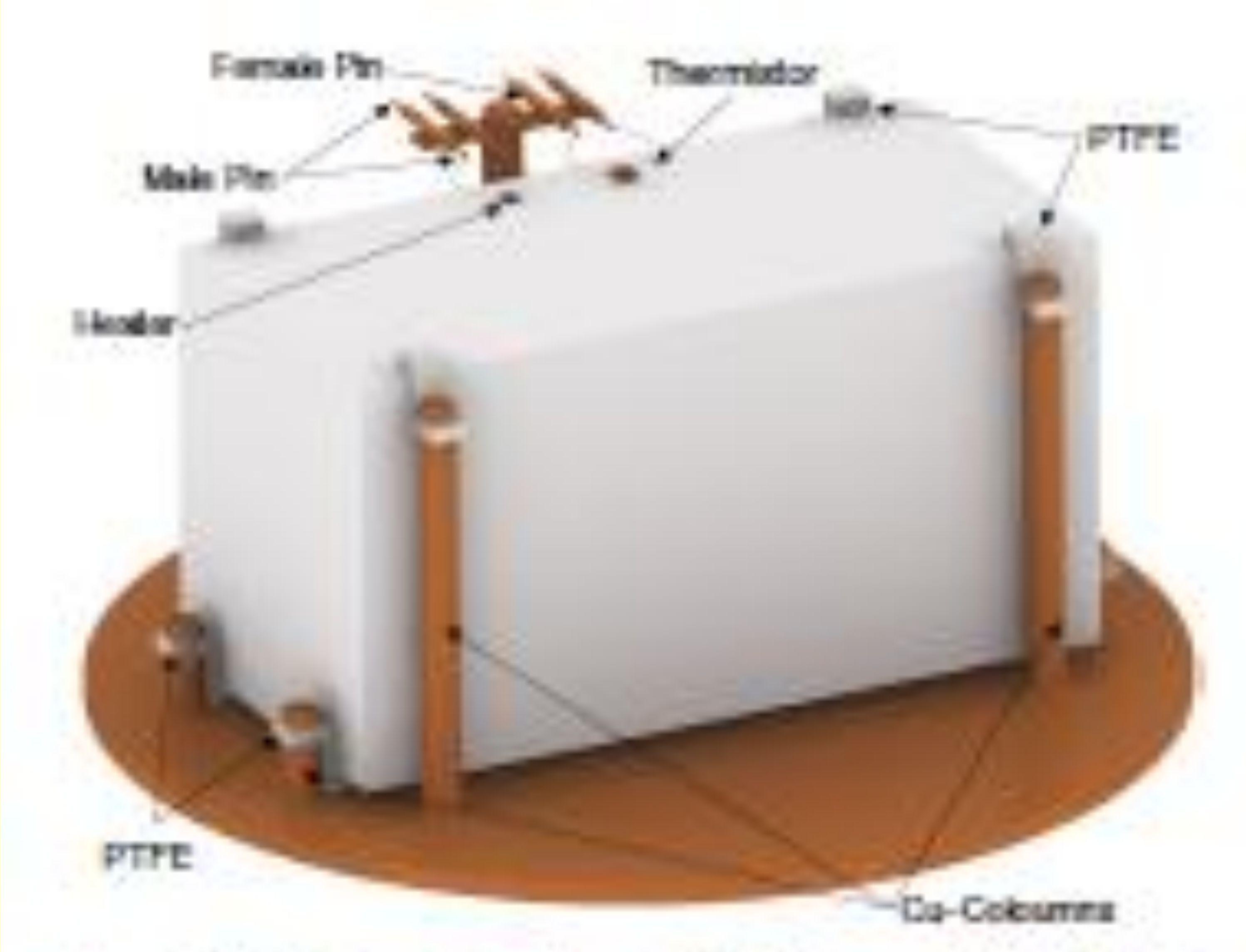
* s(E)/E = 1.4% obtained in EXO R&D, Conti et al Phys Rev B 68 (2003) 054201

Cryogenic Detectors




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

A 2.2 kg TeO_2



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

:

0.8 keV FWHM @ 46 keV

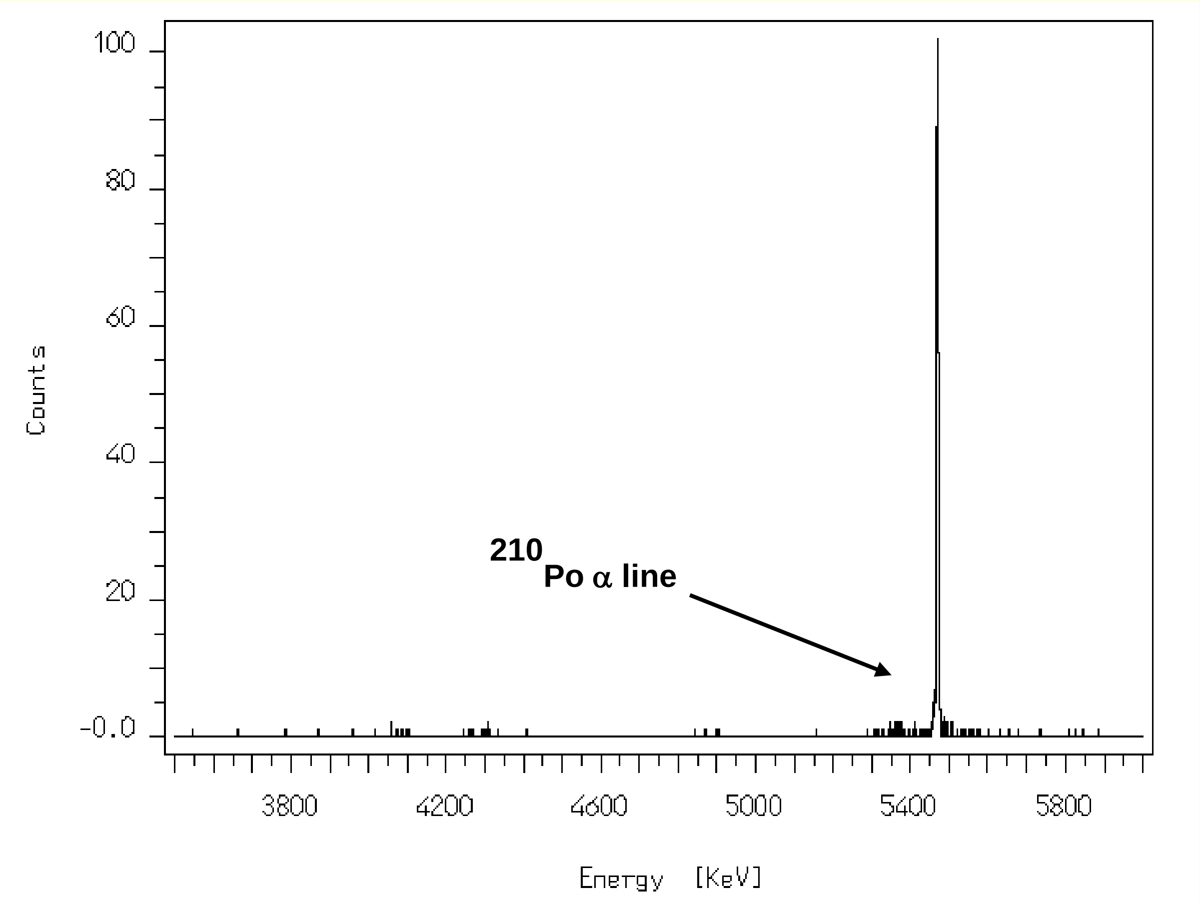
1.4 keV FWHM @ 0.351 MeV

2.1 keV FWHM @ 0.911 MeV

2.6 keV FWHM @ 2.615 MeV

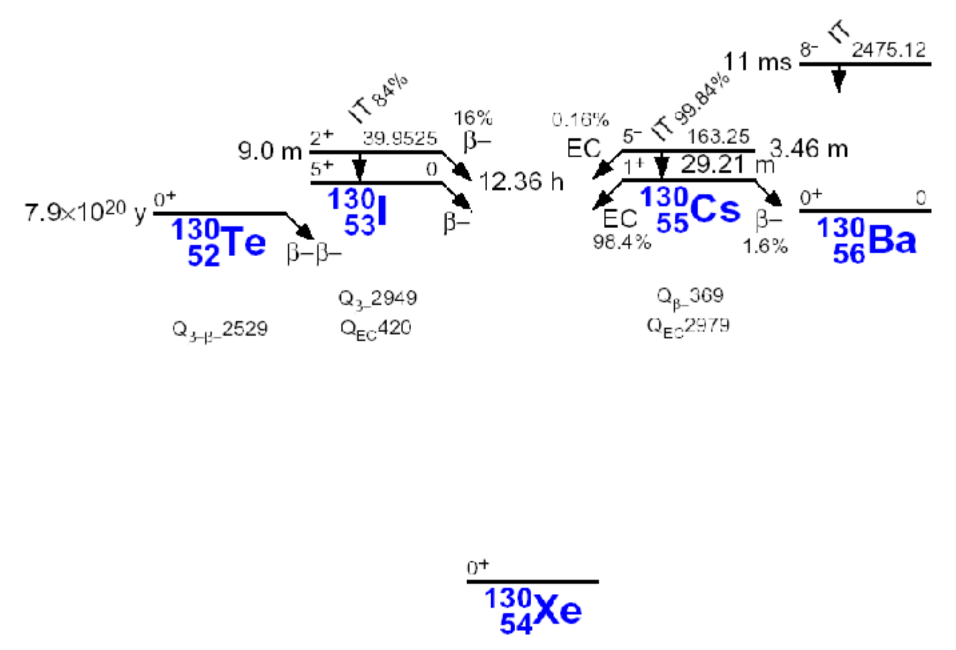
3.2 keV FWHM @ 5.407 MeV

(the best α spectrometer so far



Searches of ββ decay with thermal detectors

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



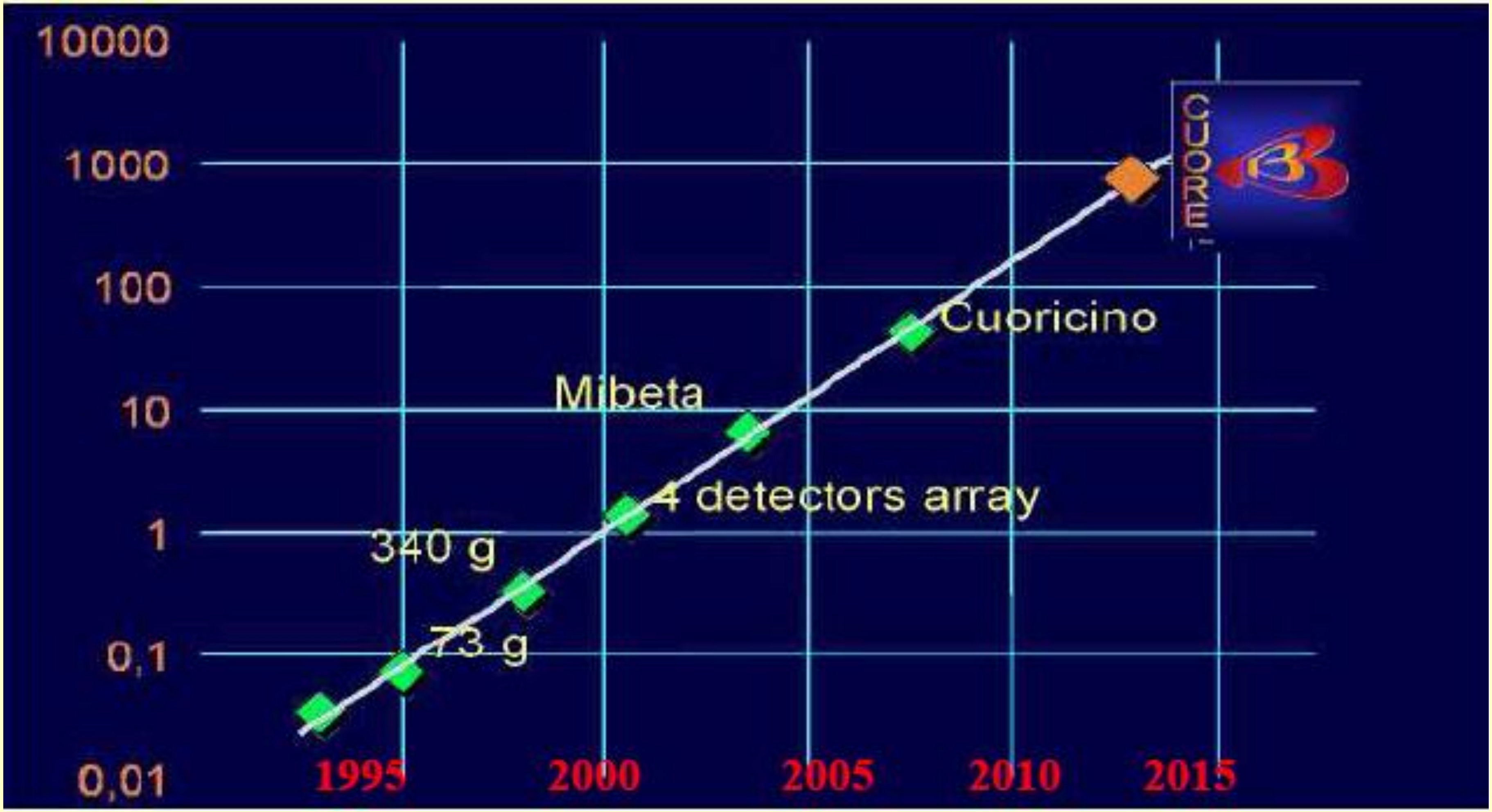
Mibeta (Milan) an array of 20 bolometers of TeO_2 of 320 => **6.8 kg**

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

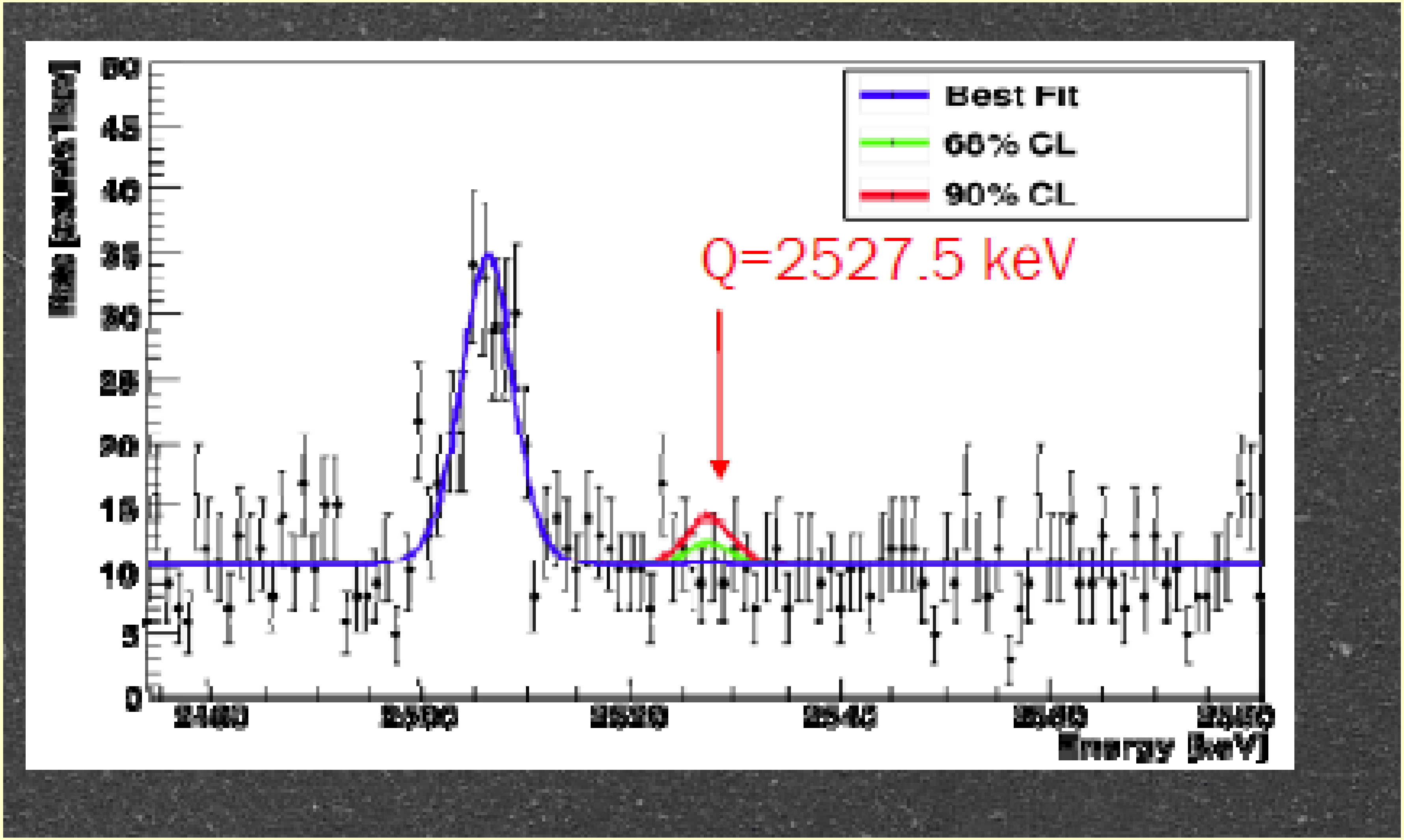
CUORE (CUORE coll)   988 crystals of 750 g   =>   **741 kg**

E. FIORINI: **CUORE: a Cryogenic Underground Observatory** for **R**are **E**vents, Physics Reports 307 (1998) 309

Progress of thermal detectors

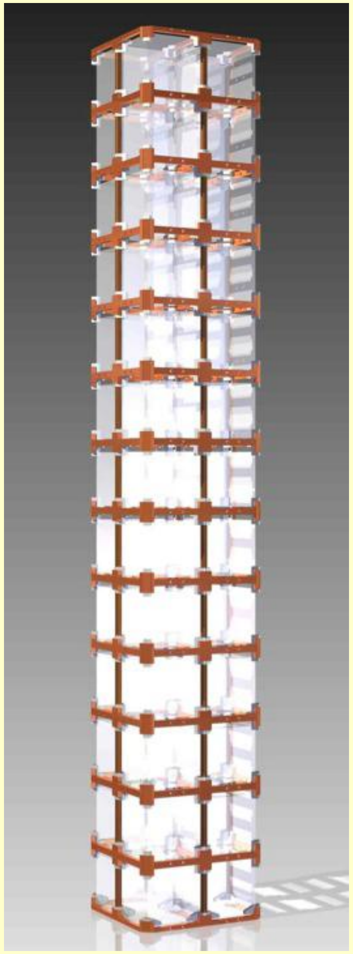


CUORICINO

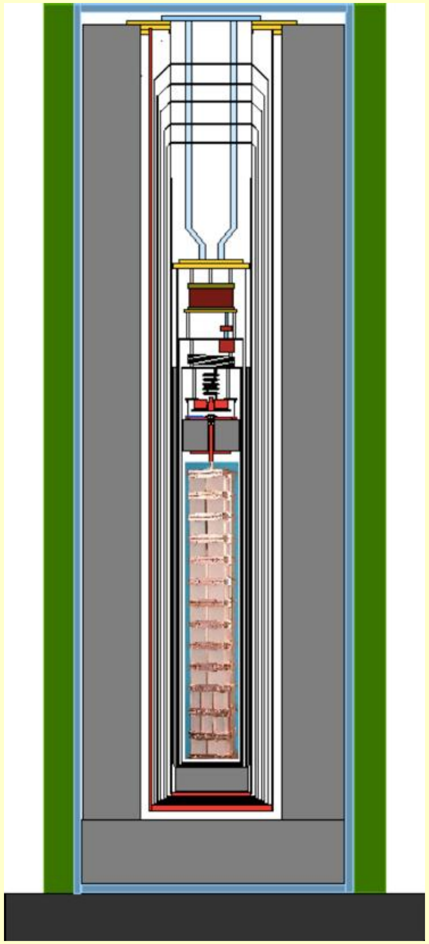


19.75 kg y => 90% limit $\tau_{1/2} > 2.8 \times 10^{24}$ a => $\langle m_\nu \rangle$ 300-710 meV

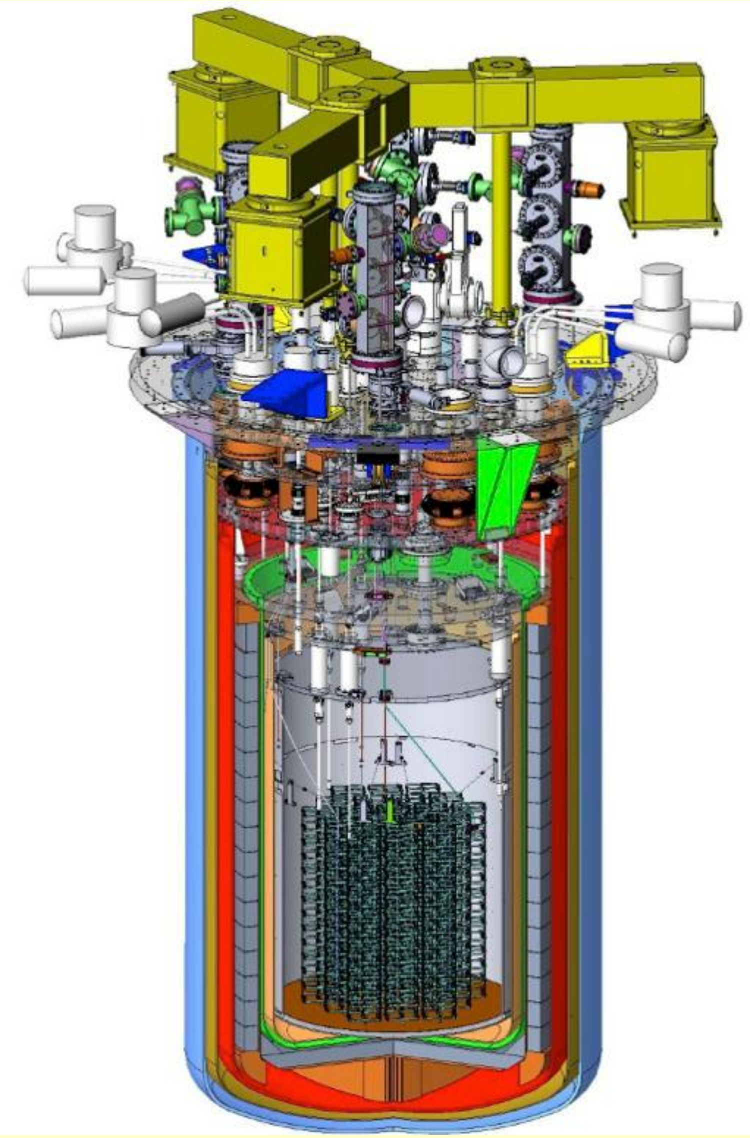
CUORICINO



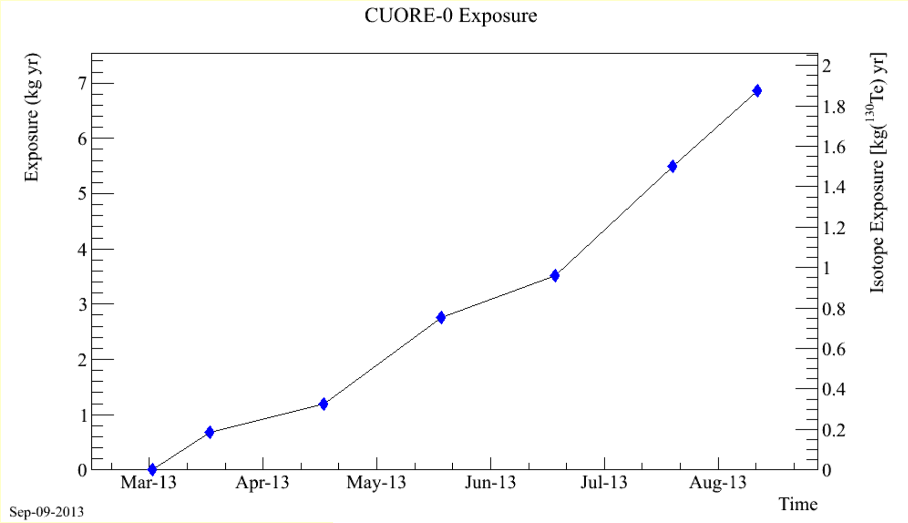
CUORE0

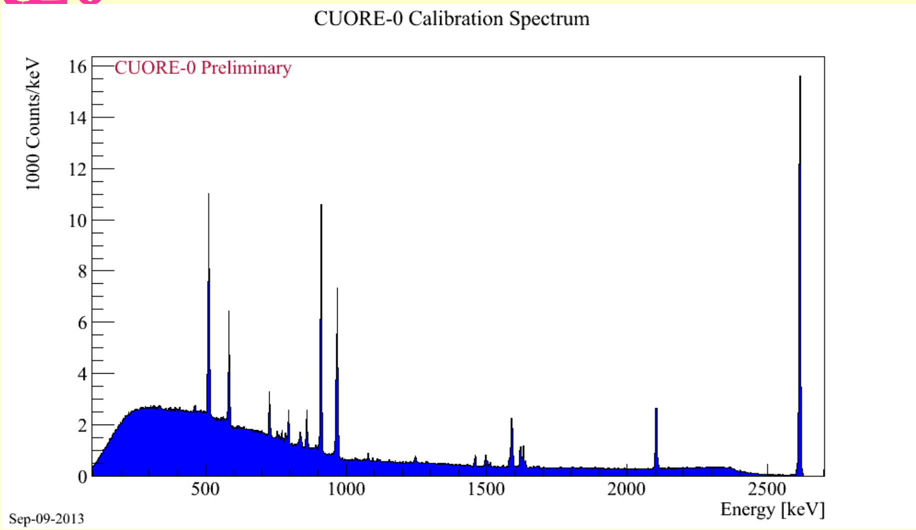


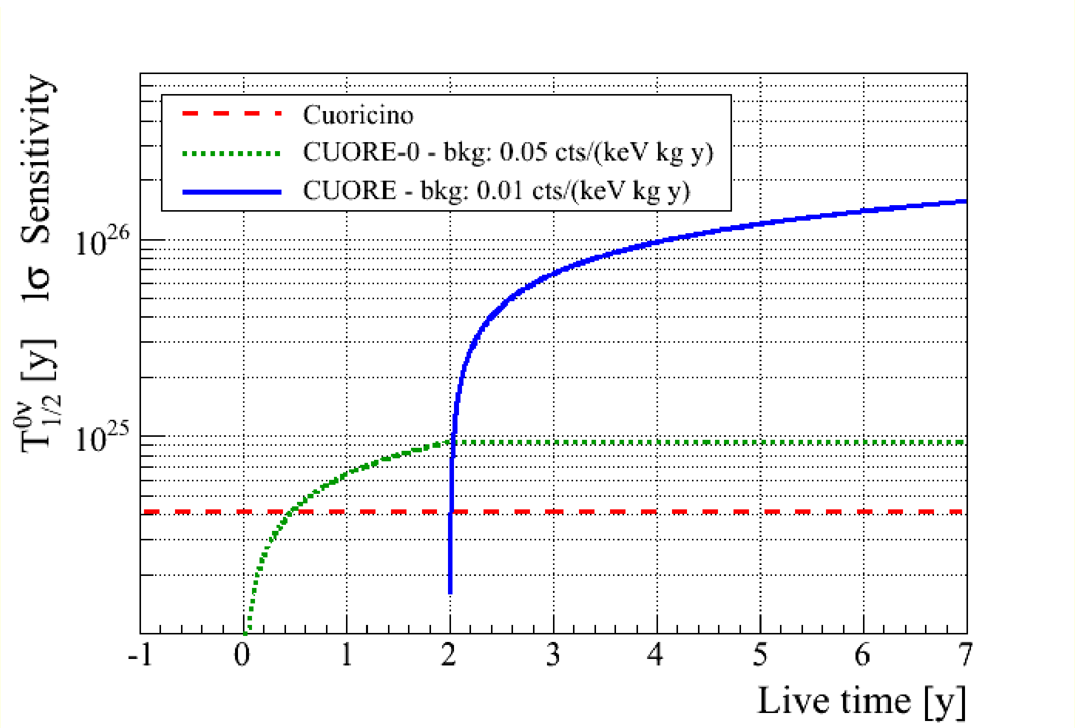
CUORE



CUORE0


CUORE-0 Exposure
Exposure (kg yr)
Isotope Exposure [kg(^{130}Te) yr]
Mar-13
Apr-13
May-13
Jun-13
Jul-13
Aug-13
Time
Sep-09-2013

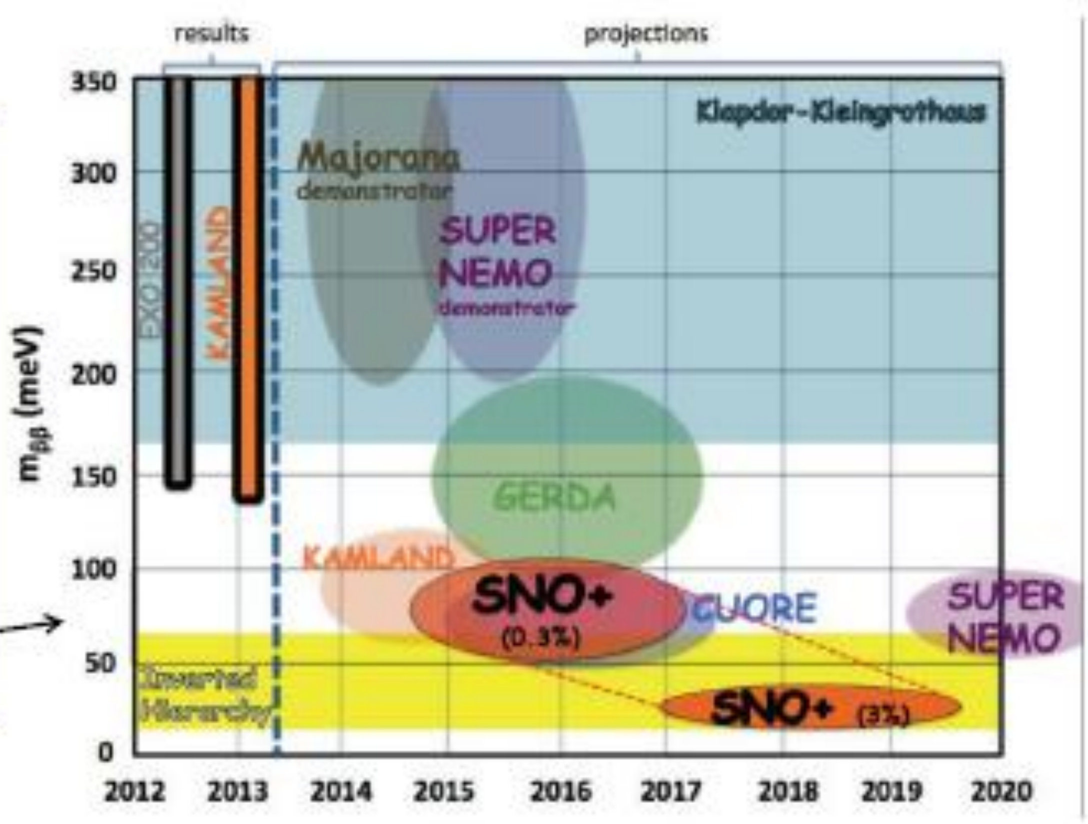

CUORE-0 Calibration Spectrum
CUORE-0 Preliminary
1000 Counts/keV
Energy [keV]
Sep-09-2013


Cuoricino
CUORE-0 - bkg: 0.05 cts/(keV kg y)
CUORE - bkg: 0.01 cts/(keV kg y)
$T^{0\nu}_{1/2}$ [y] 1σ Sensitivity
10^{26}
10^{25}
Live time [y]

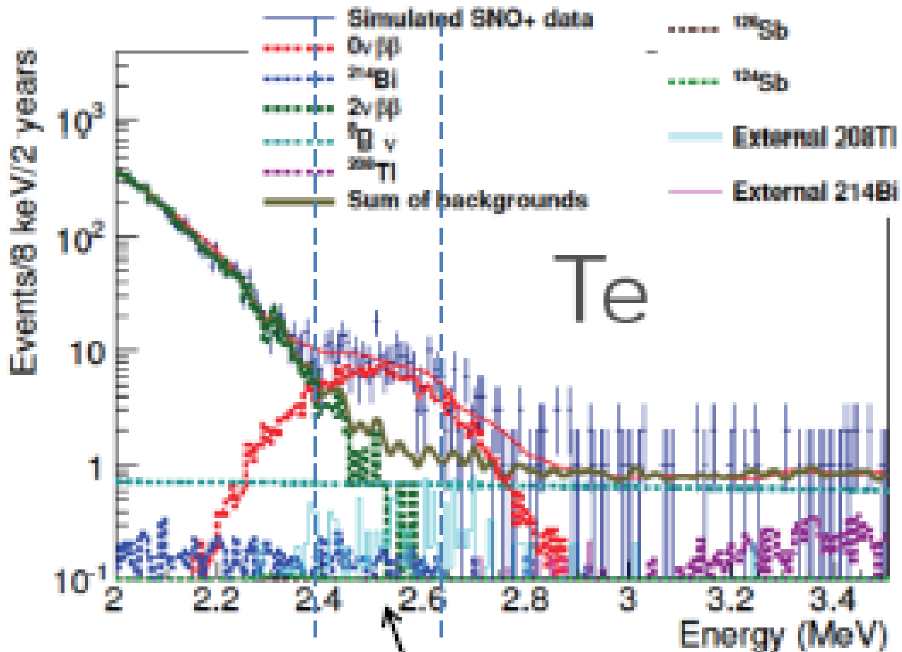
Now a competitor

SNO+ dissolves Te in the scintillator

- Now using 20% fiducial volume instead of 50% to keep external backgrounds low
- Resolution at 2528 keV is σ = 4.5% → 270 keV FWHM instead of 160 keV
- This sensitivity plot follows our lead in showing **1σ** significance, not 90% C.L.



His backup slides contained the following simulated spectrum for 0.3% Te loading, 2 y live time, 20% fiducial volume:



I estimate a background rate of roughly 0.0000008 c/(keV kg y) from this energy window, which agrees well with their estimated sensitivity now that I know they're using 1σ…

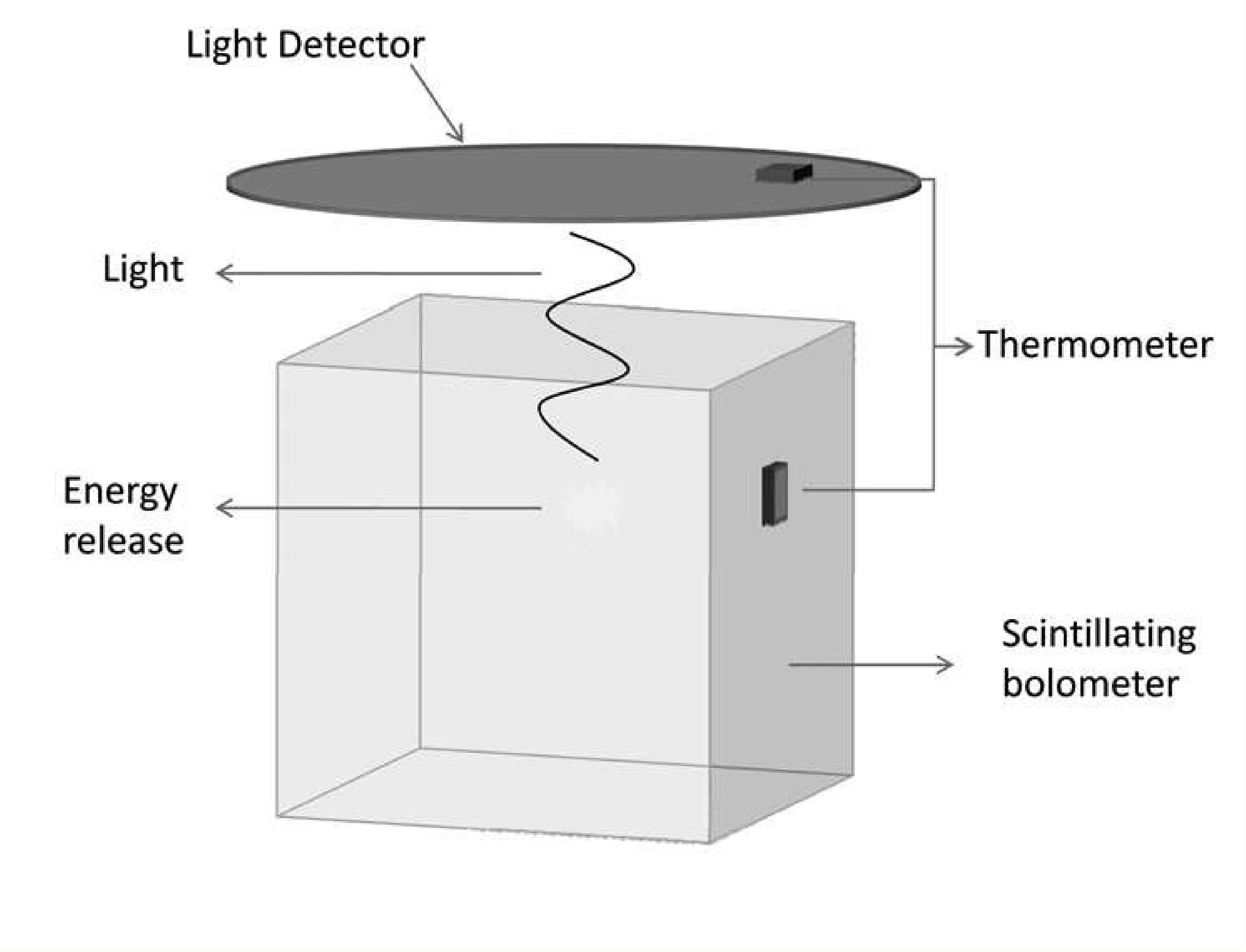
(corresponds to about 0.0008 c/(keV kg(^{130}Te) y)

The future

Other possible candidates for ββ decay

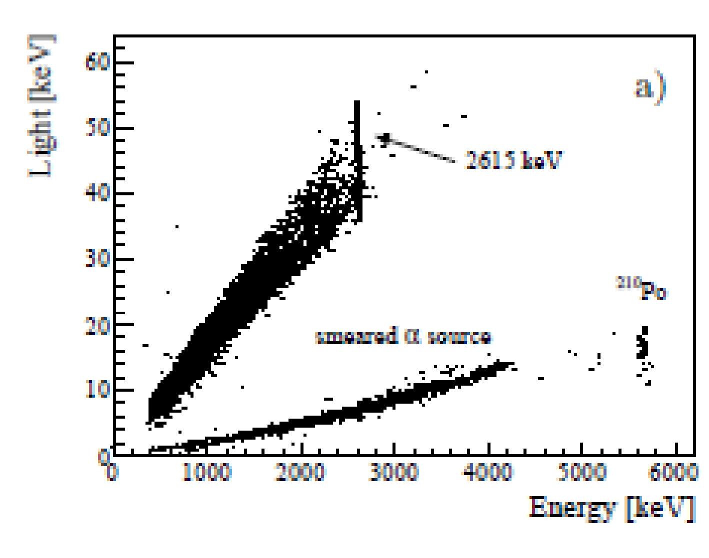
Compound	Isotopic abundance	Transiton energy
$^{48}CaF_2$	.0187 %	4272keV
^{76}Ge	7.44 "	2038.7 "
$^{100}MoPbO_4$	9.63 "	3034 "
$^{116}CdWO_4$	7.49 "	2804 "
$^{130}TeO_2$	34 "	2528 "
$^{150}NdF_3$ $^{150}NdGaO_3$	5.64 "	3368“

Scintillation plus Heat

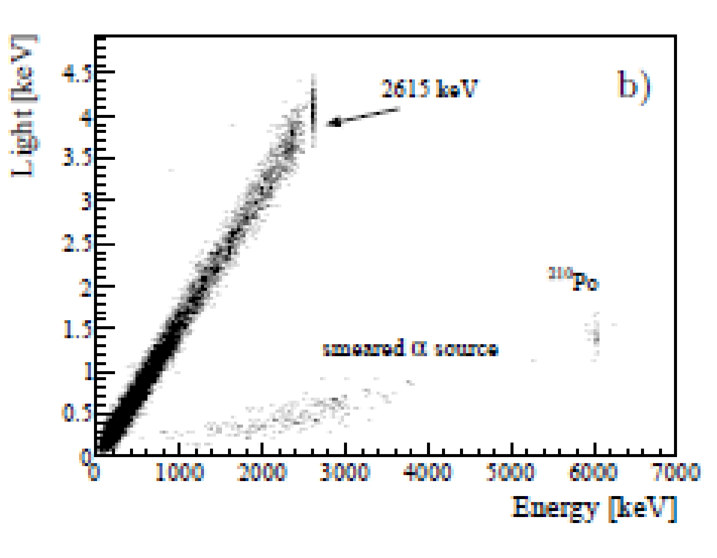


CUORE - LUCIFER

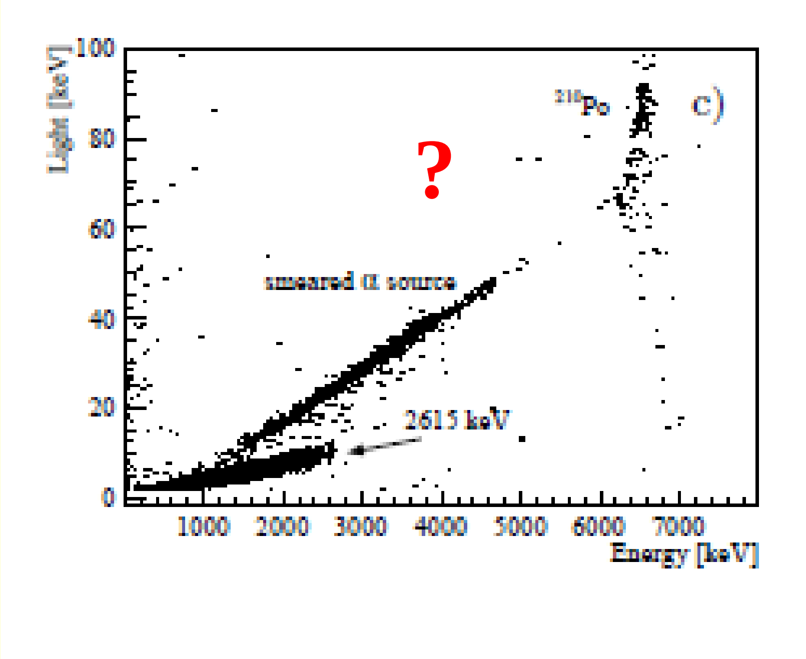
CdWO4



$ZnMoO_4$



ZnSe



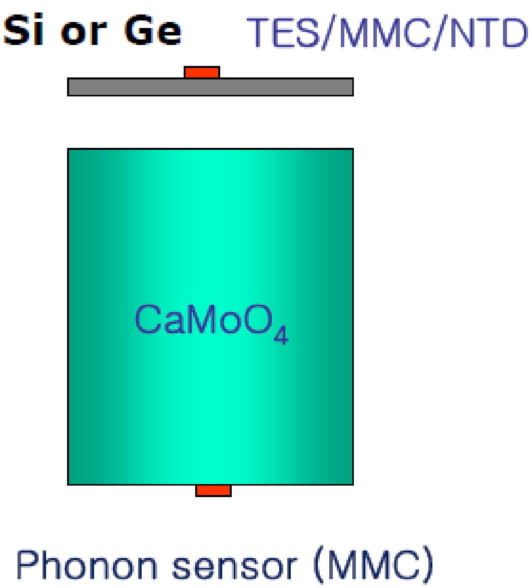
Now a **competitor** AMORE

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

AMoRE:

$^{40}Ca^{100}MoO_4$ cryogenic scintillation detector

Light detector →



1. Absorber:

-Isotope enrichment
-Purification
-Crystals growing
-Isotope recovery from waste

2. Bolometer: R&D on

MMC&SQUID
TES &SQUID

A **non conventional** conclusion

An Italian and a Russian

Two examples :

1.The cabbage

2 The pioneers house

The best week of my life

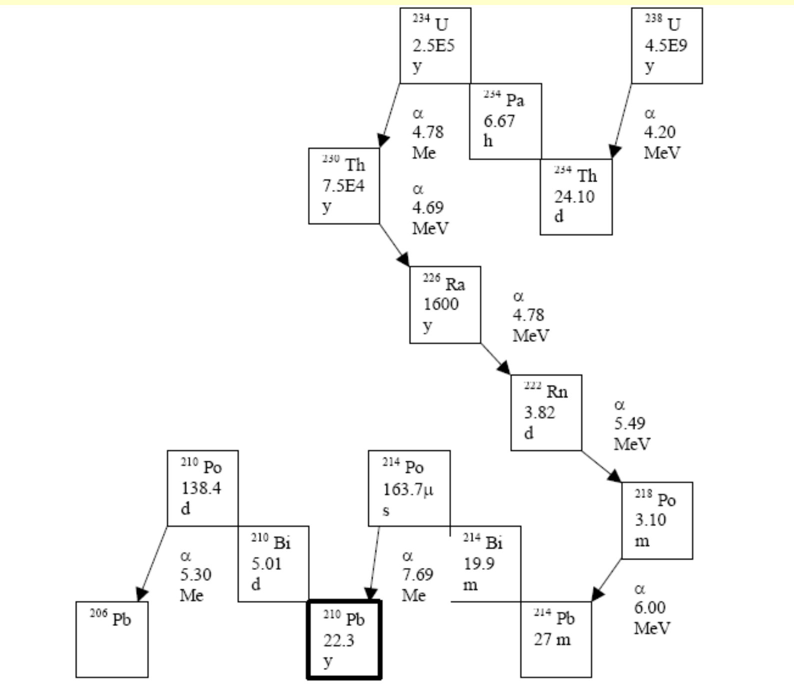
Mail by Samoel :

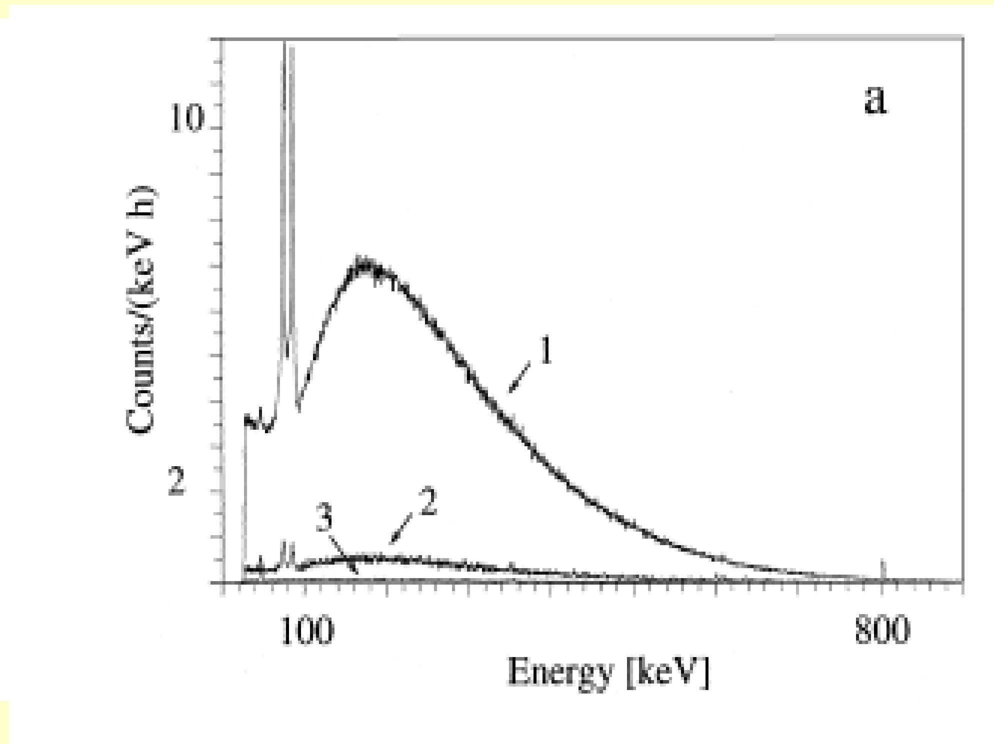
“Dear Ettore,

Bruno died yesterday night by pneumonia in the Dubna Hospital.

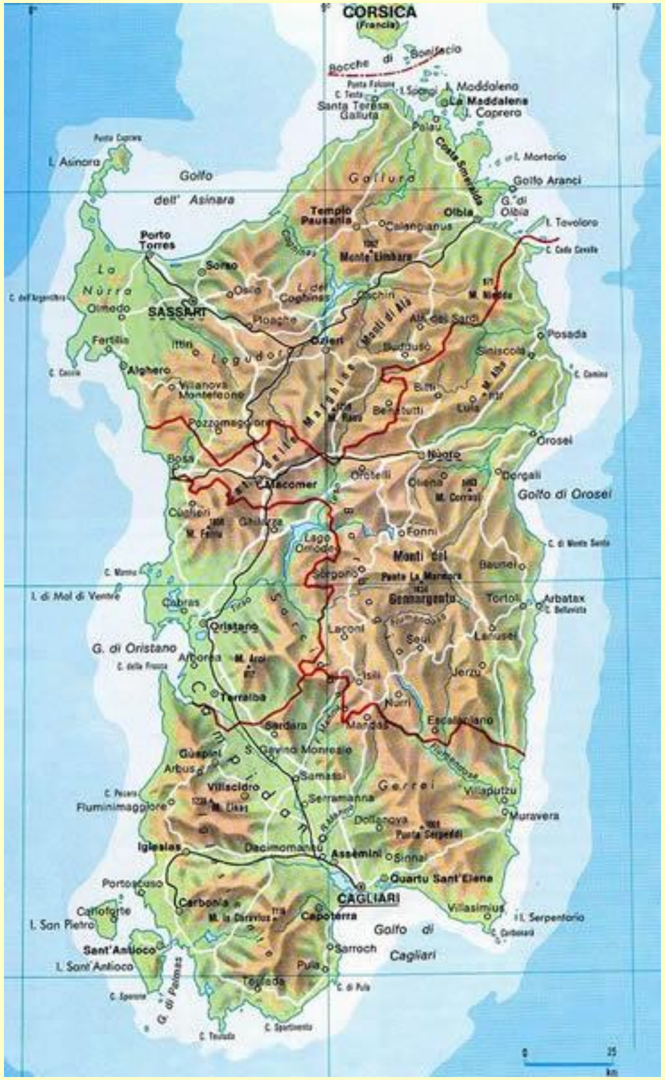
It is a great loss for our science and his friends. I worked with him for 20years and thank God for that”

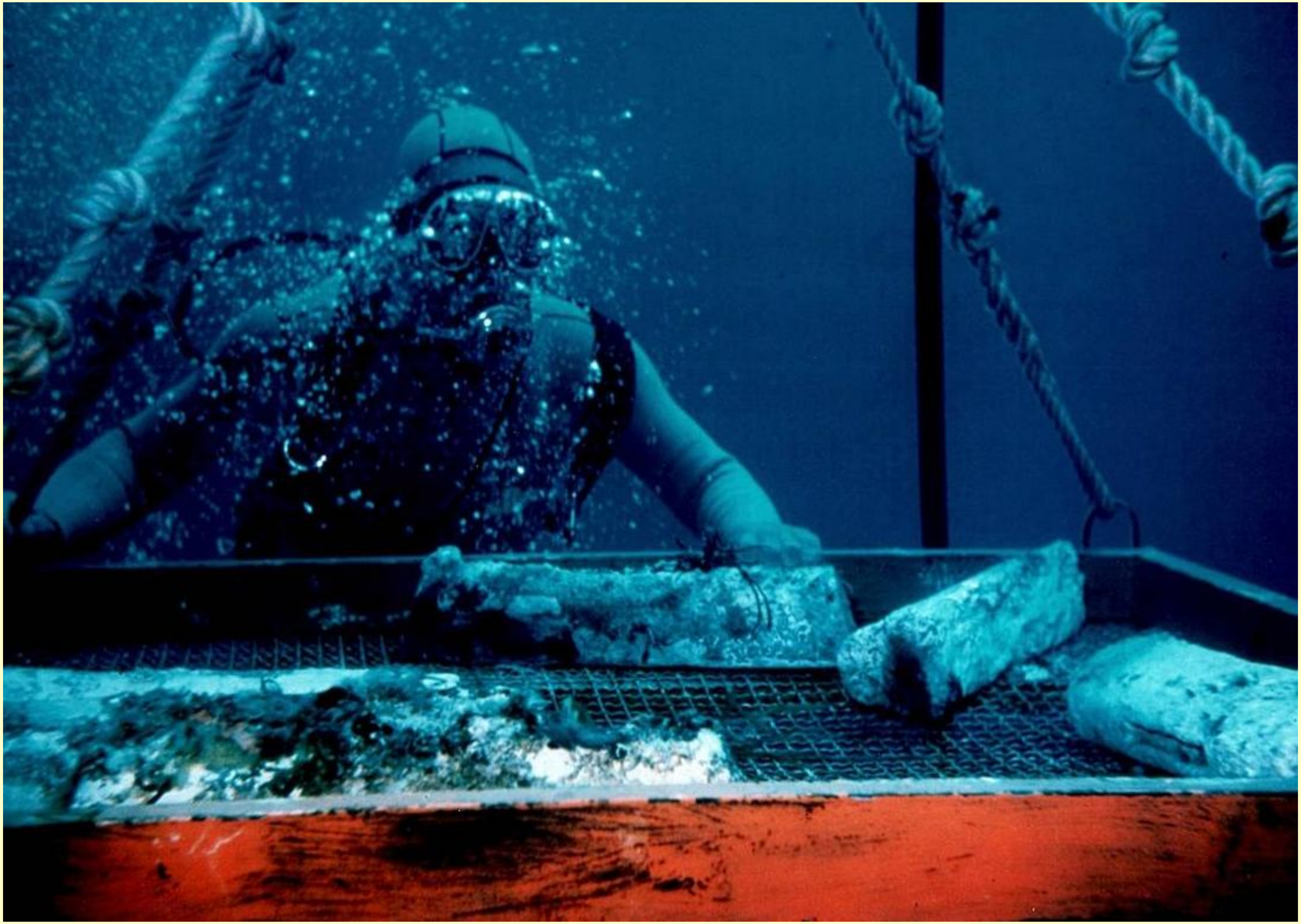
But Bruno was interested also in our problem of the Roman lead





A Roman *“navis oneraria”* sunk in Sardinia






SOC·M·C·PONTILIENORVM·M·F