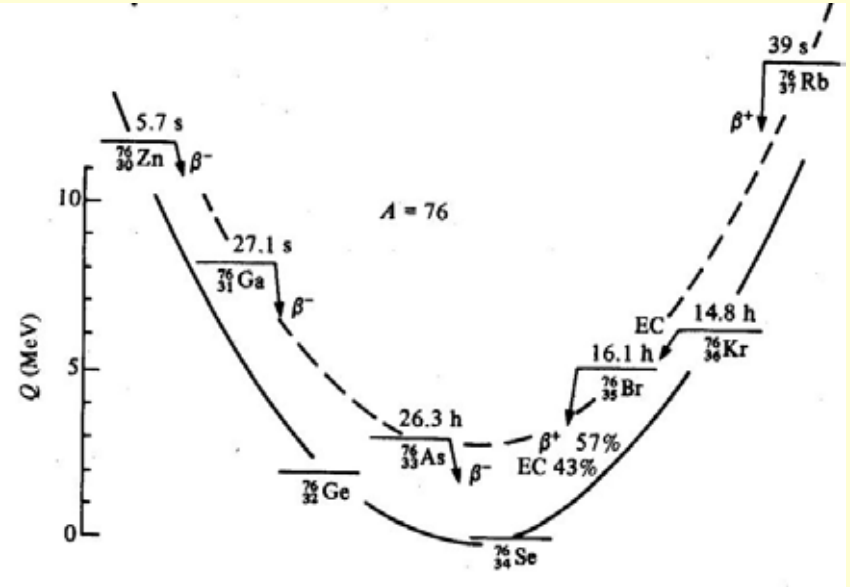
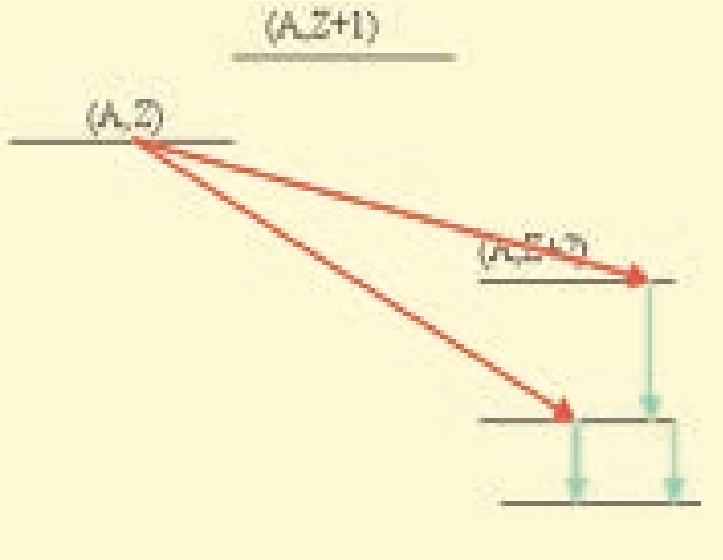
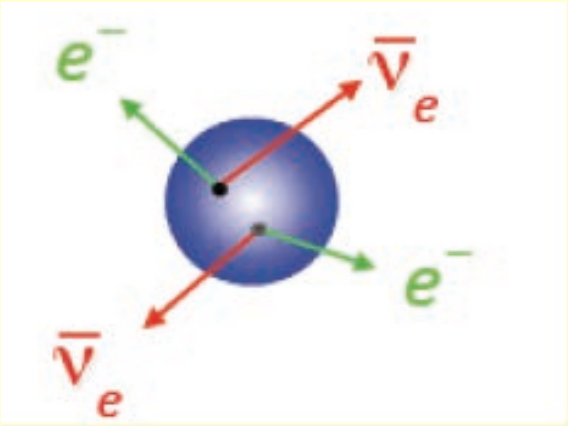
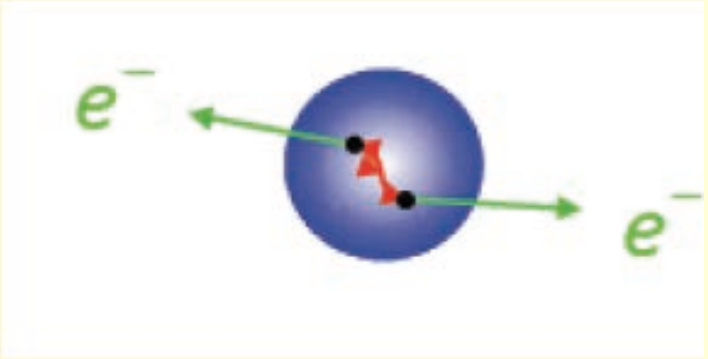
My debts to Bruno

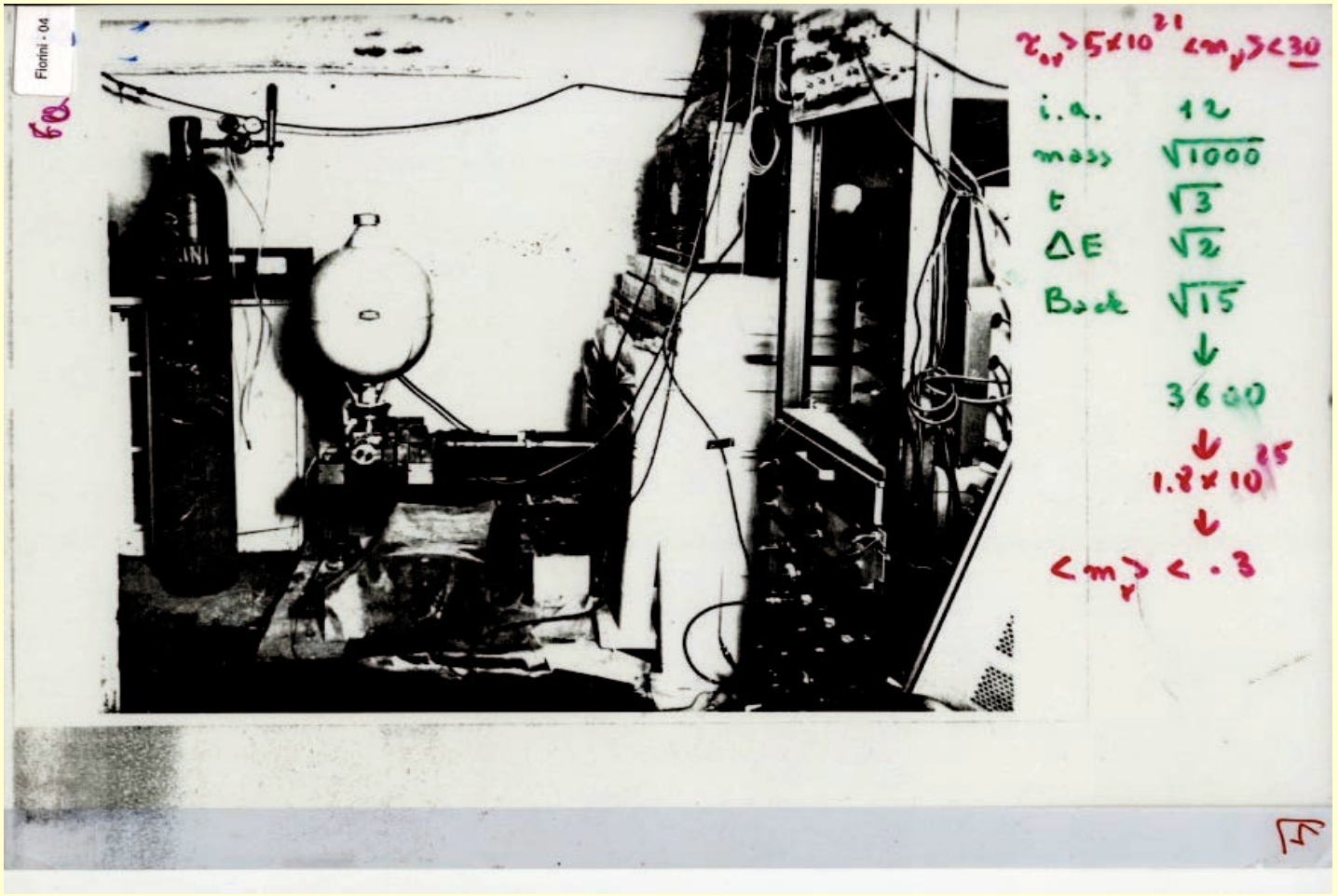
1. Double beta decay (then not on fashion)









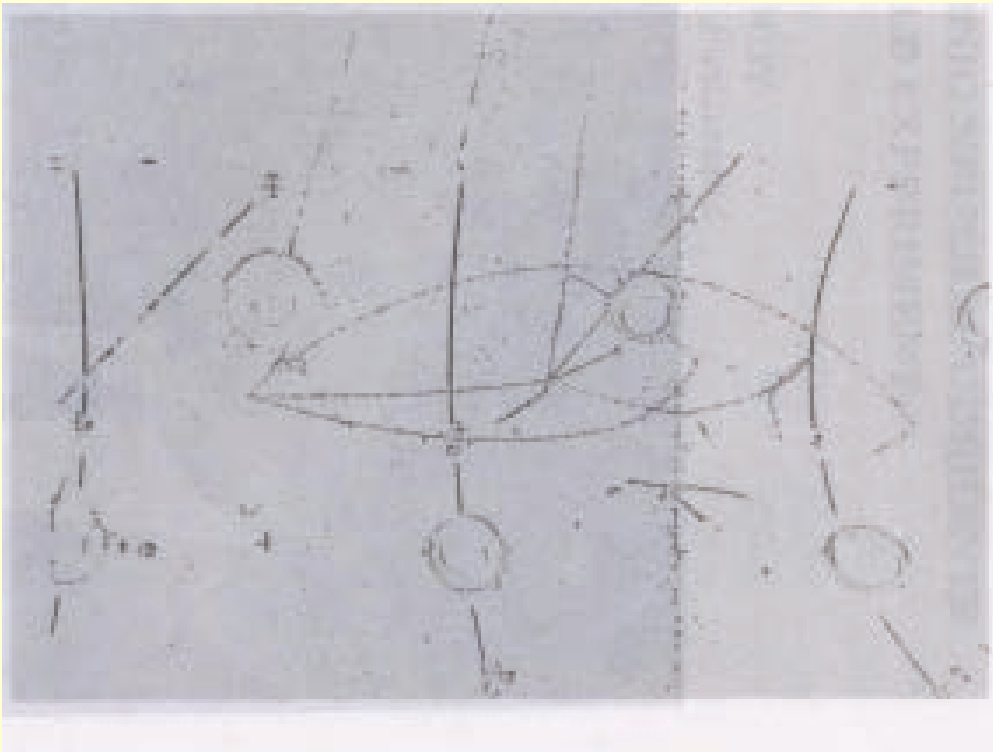


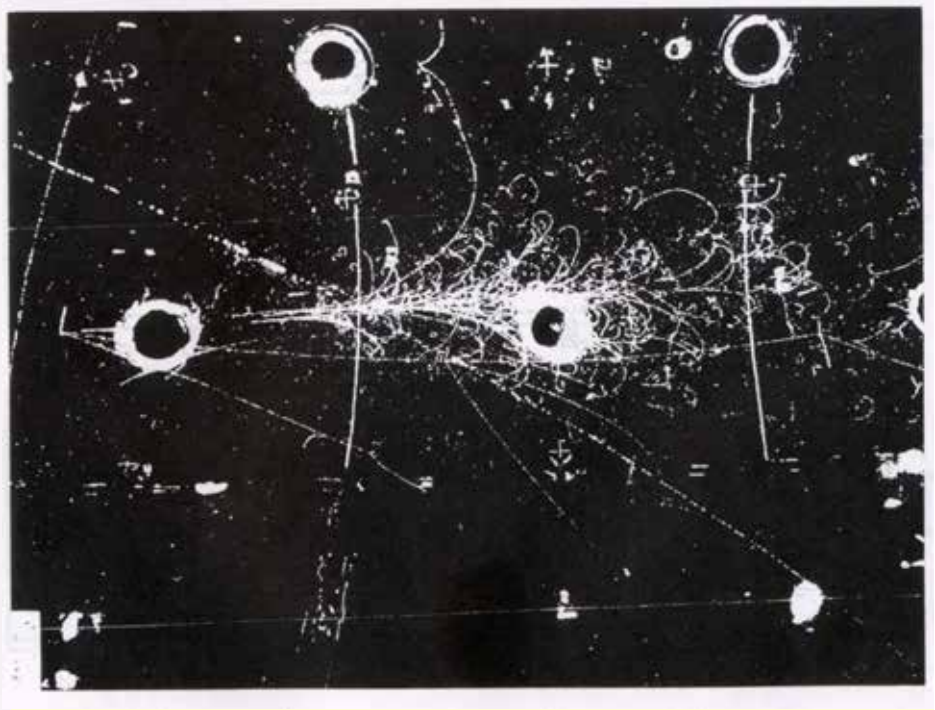
Then not **“on fashion”** (Few believed on lepton number **non conservation**)
But important for the two of us **Bruno =.> ΔL =2 vs ΔS=0**
My first experiment of **ββ decay of 60Ge**
Meeting with Bruno in Kiev and in **Balatonfured**

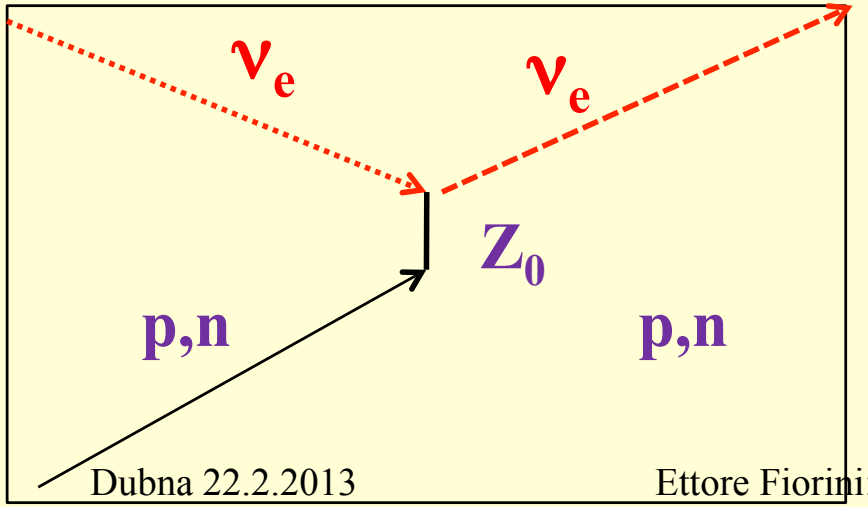
The great suggestion of Bruno
Neutrino oscillations

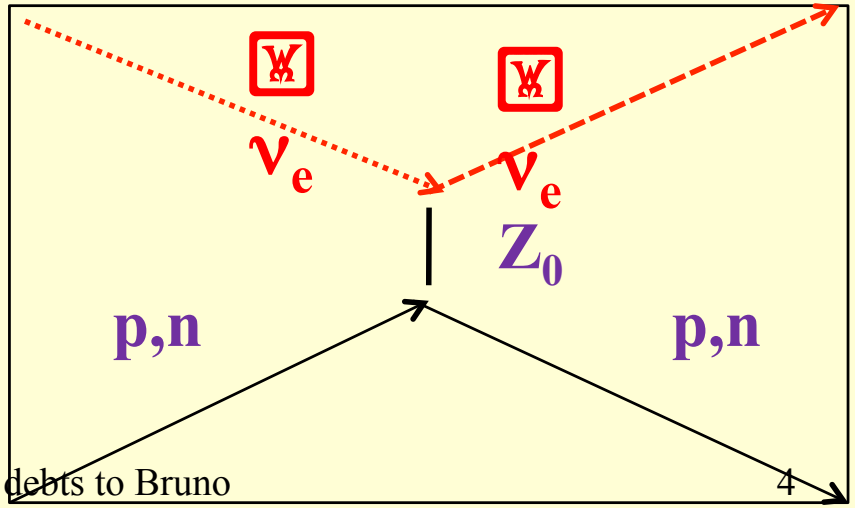
2. My first approach to a Reactor

3. The discovery of *weak neutral currents*



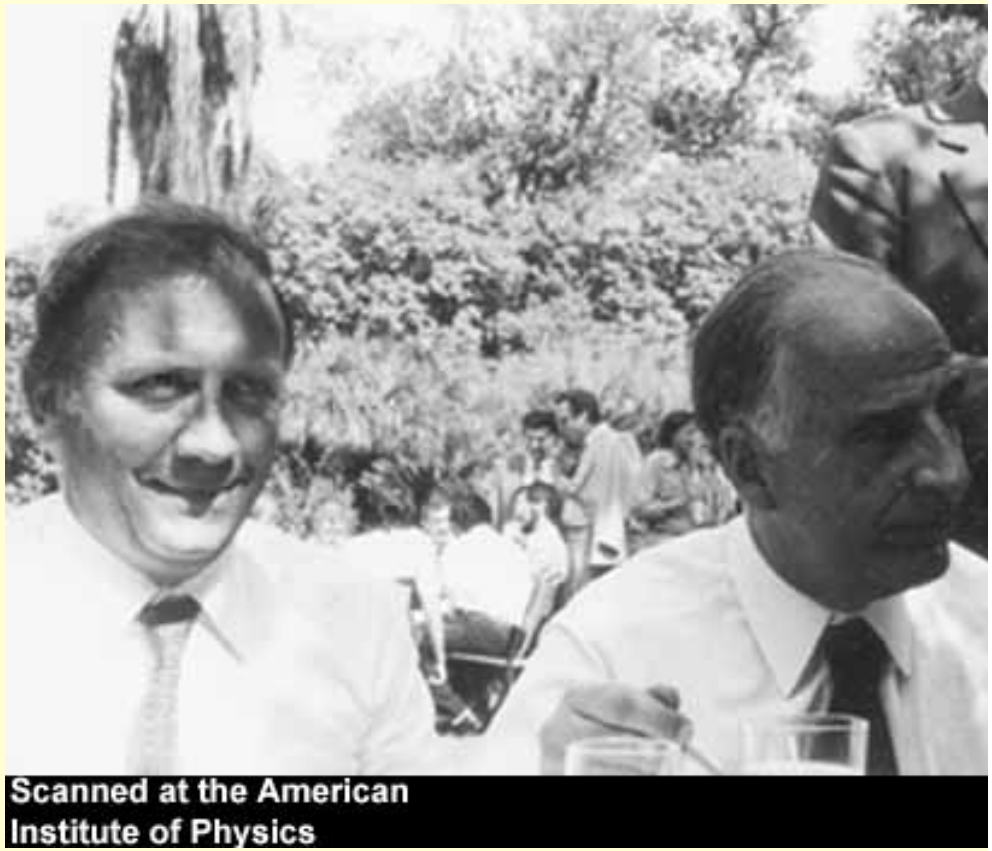


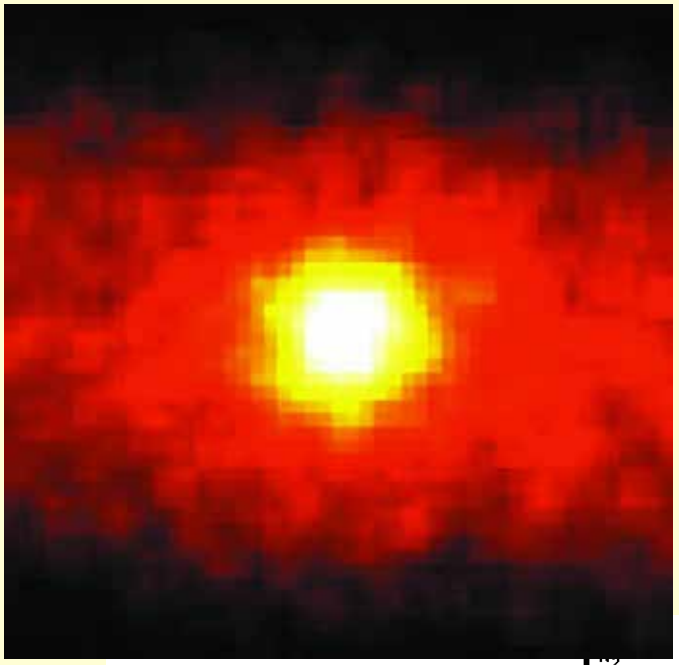


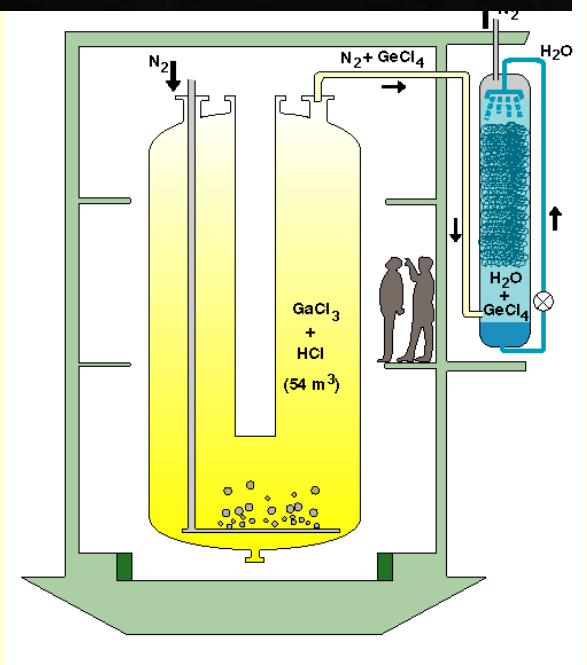


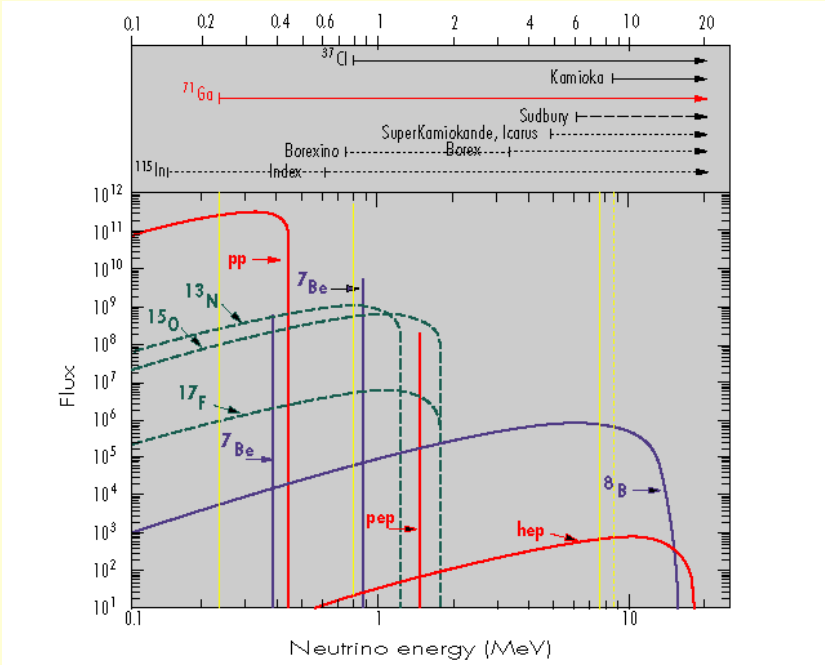
4. **Solar neutrinos** : the **GALLEX** and **SAGE** experiments

Bruno comes to Italy for the first time!





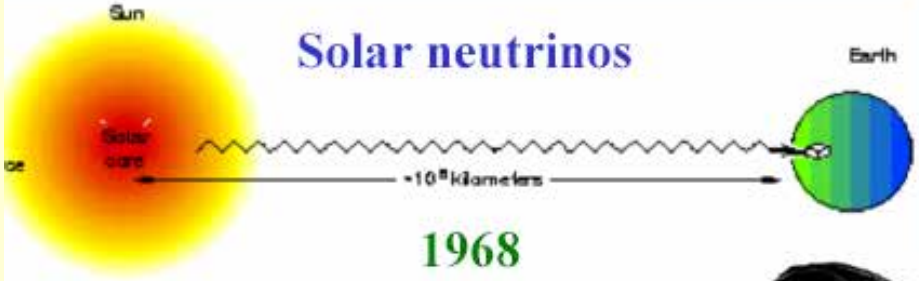

N_2
N_2+ $GeCl_4$
H_2O
$GaCl_3$
+
HCl
(54 m^3)
H_2O
+
$GeCl_4$


^{37}Cl
Kamioka
^{71}Ga
Sudbury
SuperKamiokande, Icarus
Borexino
Borex
^{115}In
Index
pp
^{7}Be
^{13}N
^{15}O
^{17}F
^{7}Be
^{8}B
pep
hep
Flux
Neutrino energy (MeV)


LNGS
CUORE
Cuoricino
GERDA
COBRA
CUORE R&D
DAMA

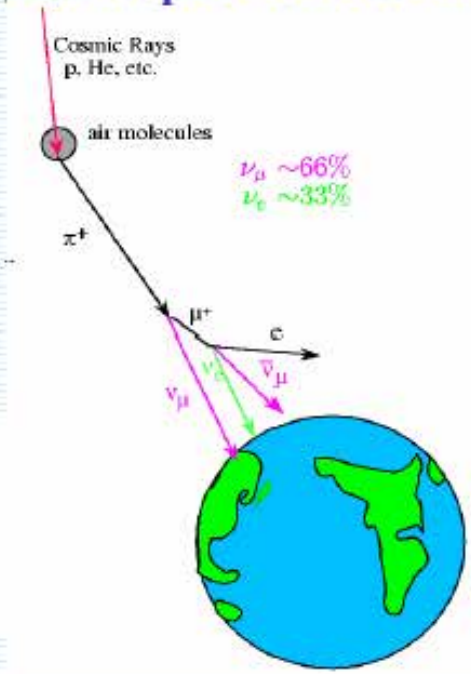
Neutrino oscillations =>

Solar neutrinos



1968

Atmospheric neutrinos

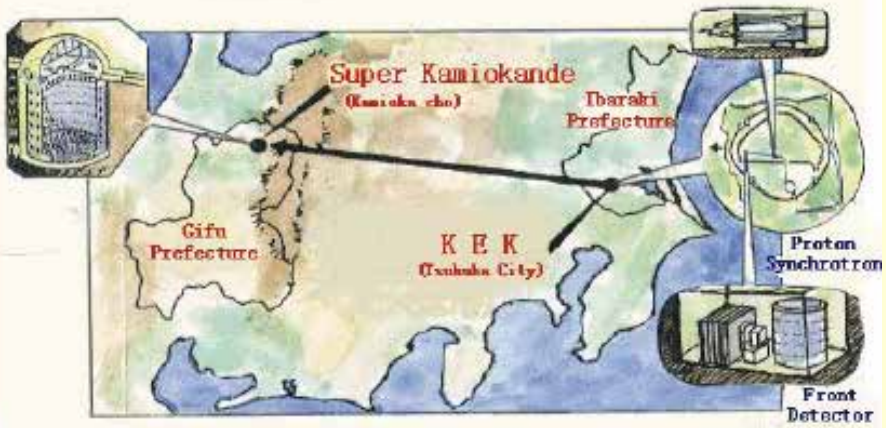


Бруно Понтекорво

1957

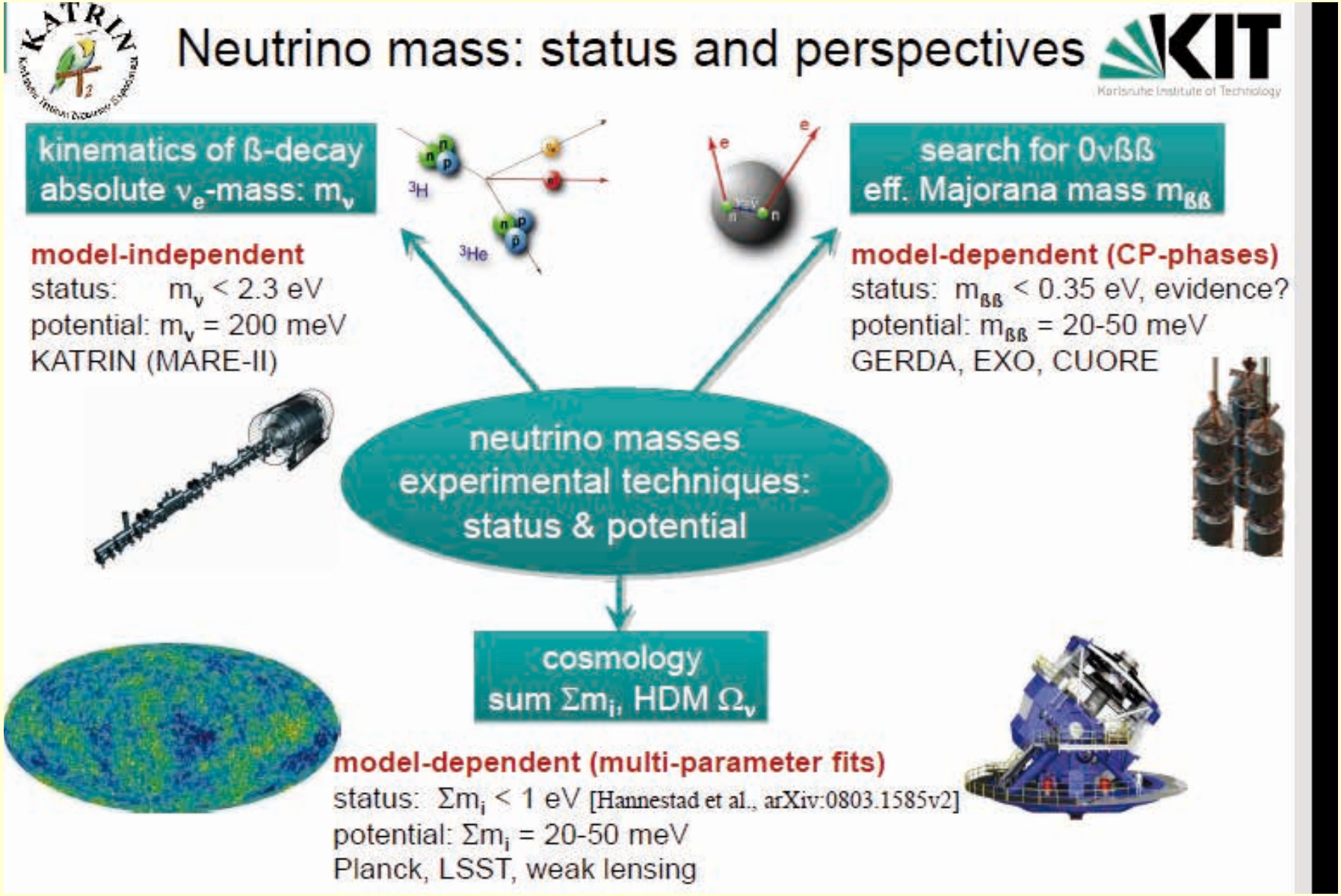
Reactor neutrinos

Accelerator neutrinos



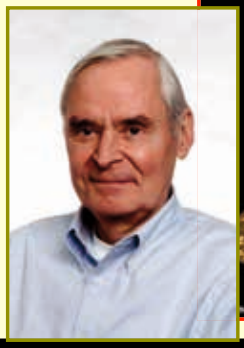
6/12/2006 Fedor Si

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

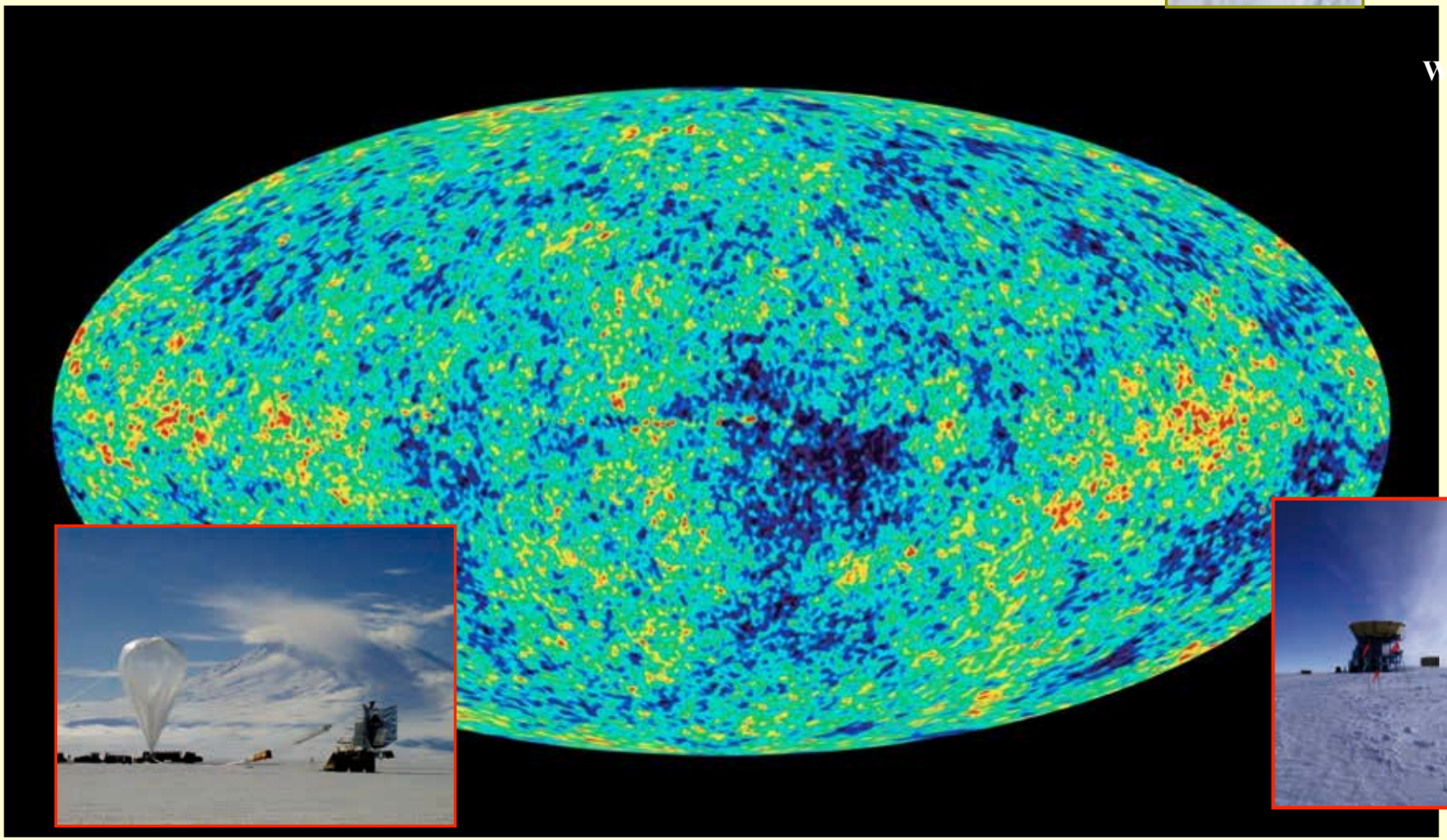


<m_ν> from cosmology

CMB Anisotropy
μK → nK



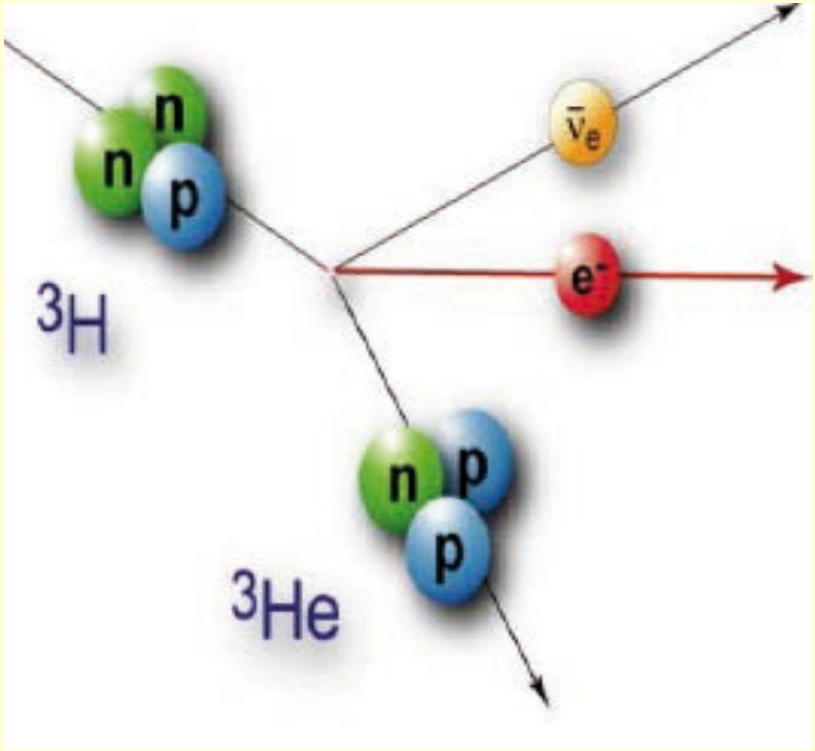
WMAP



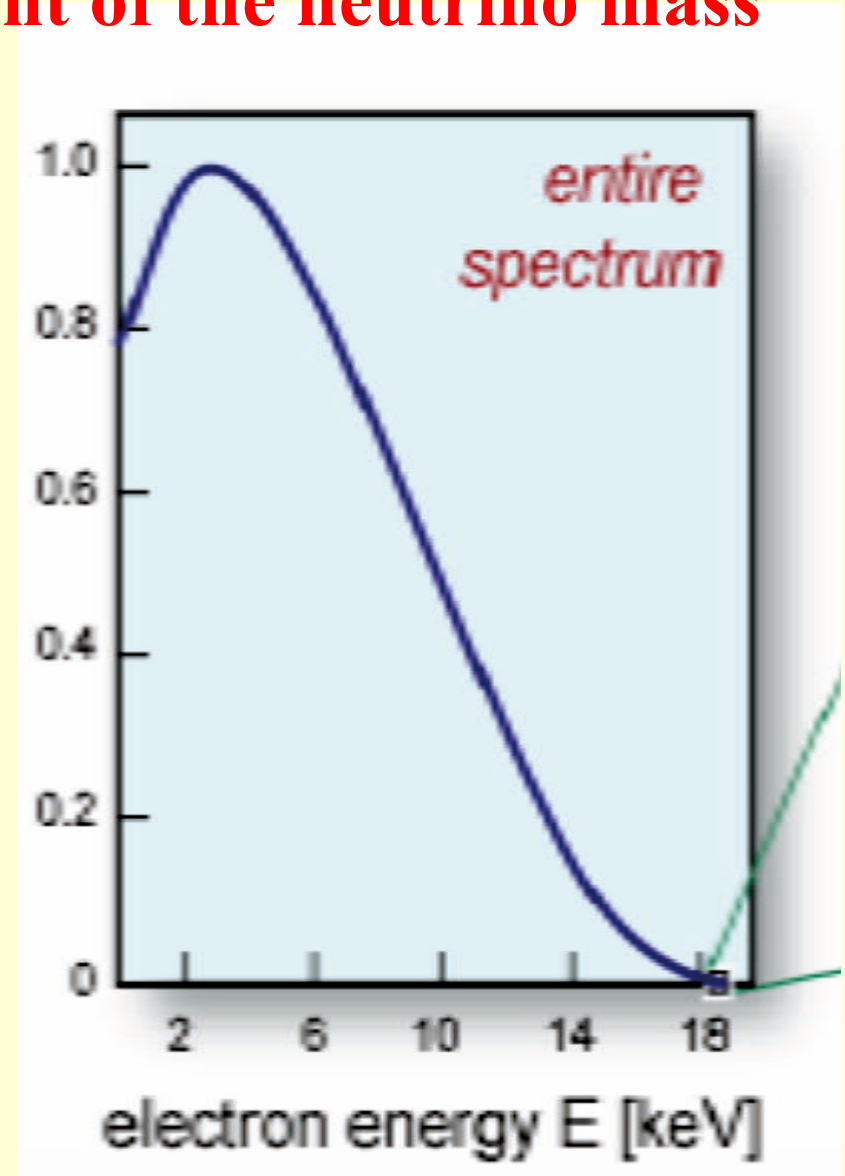
DASI

Direct measurement of the neutrino mass

β decay



Limite attuale < 2 eV



The second mystery of Ettore Majorana

Double beta decay revisited !

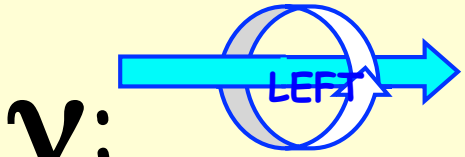
Teoria simmetrica dell'elettrone e del positrone

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.

Dirac or Majorana neutrino?



$\bar{\nu}$:

$\nu \neq \bar{\nu}$ $\qquad$ $\nu = \bar{\nu}$

$\rightarrow$ $\qquad$ $\rightarrow$

<= $\qquad$ =>

Majorana
=>1937

Dirac particle

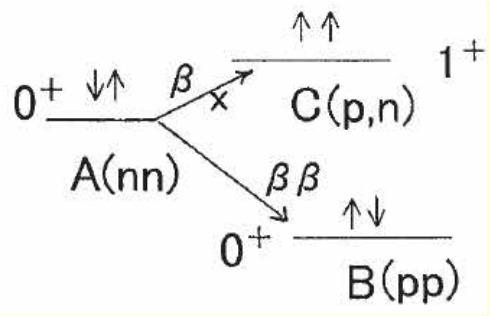
ν

Majorana particle

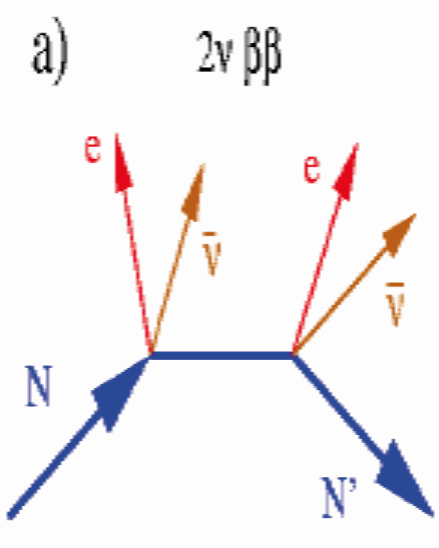
Chi l'ha visto ?

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

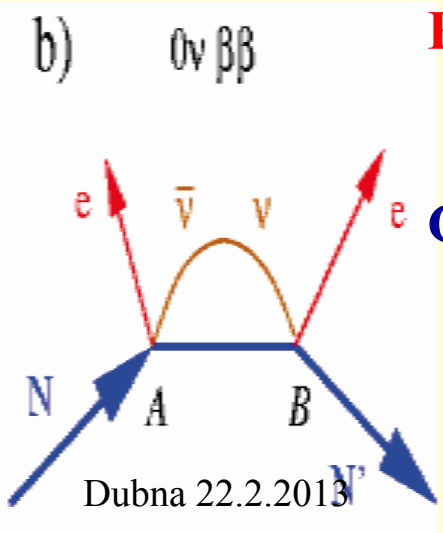


1935 M.Goeppert-Mayer, P.R. 48 (1935) 512 $T>10^{20}$

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

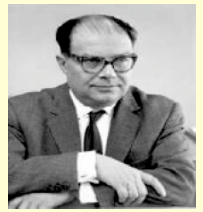
1987: ^{82}Se, Direct counting Moe et al .

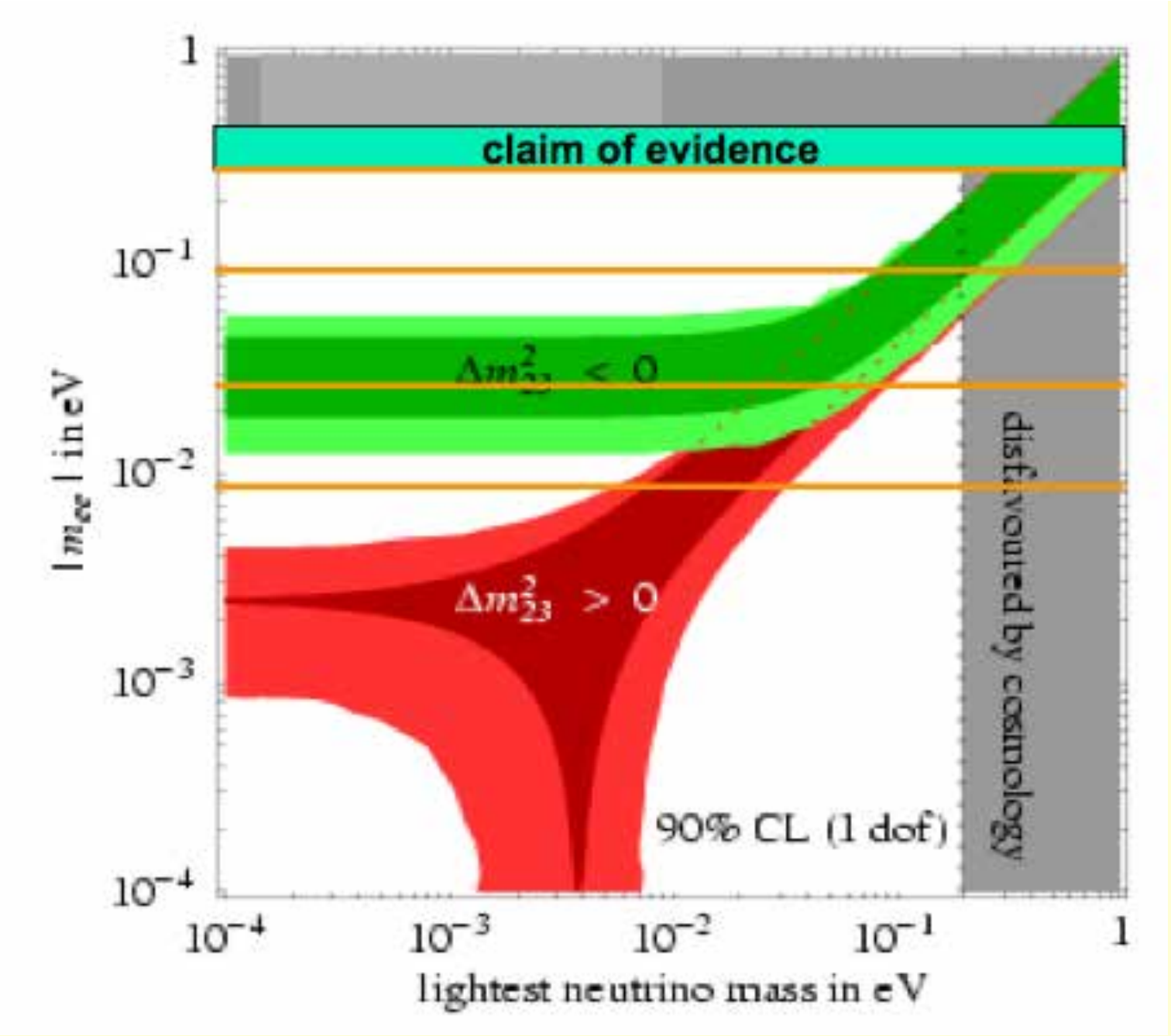
1989 -2008 ^{100}Mo, ^{116}Cd, ^{76}Ge etc.
ELEGANT V, NEMO, HM-IGEX, etc



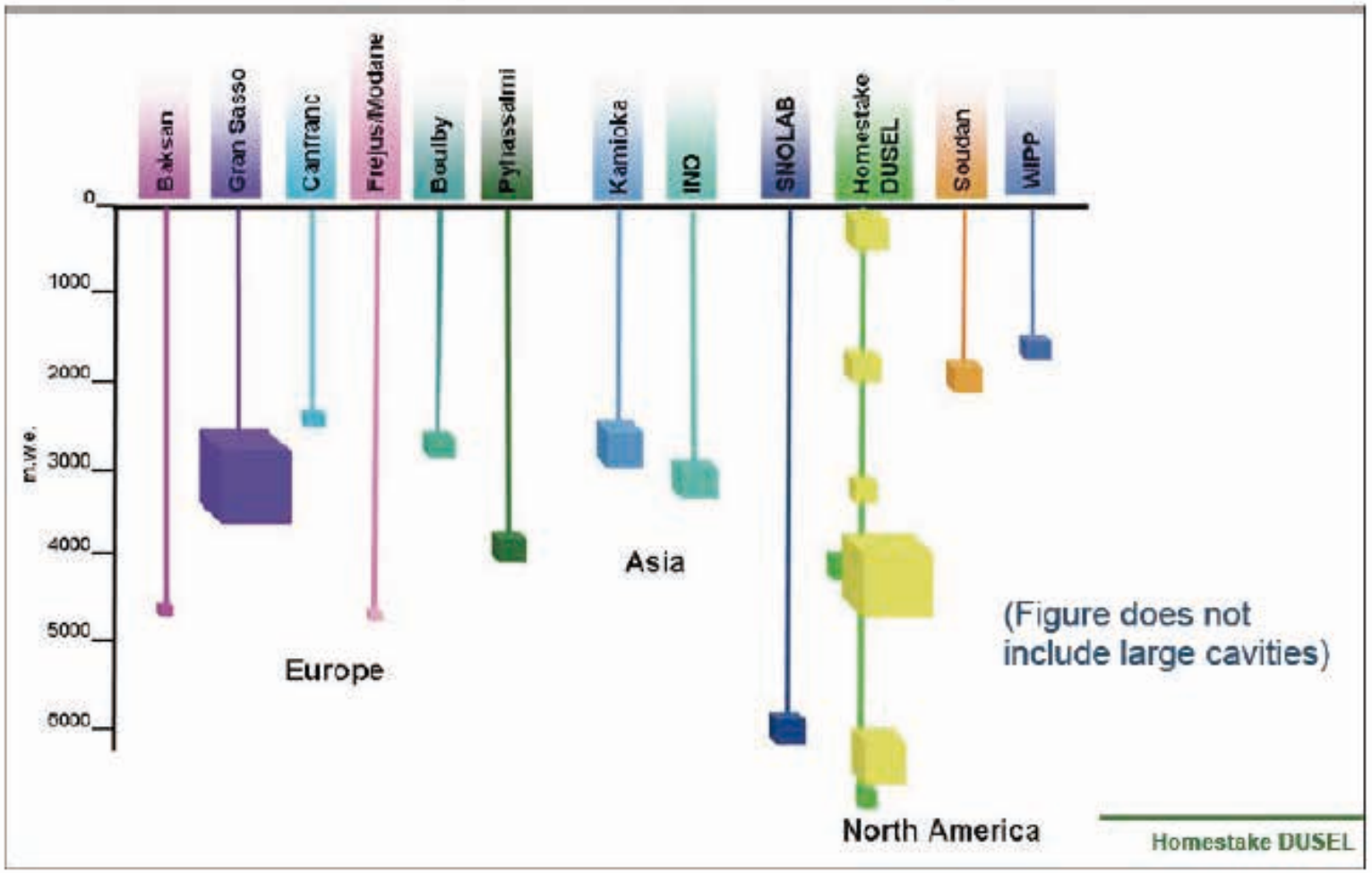
E. Majorana, Nuovo Cimento 14 (1937) 171
Symmetric Theory of Electron and Positron

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

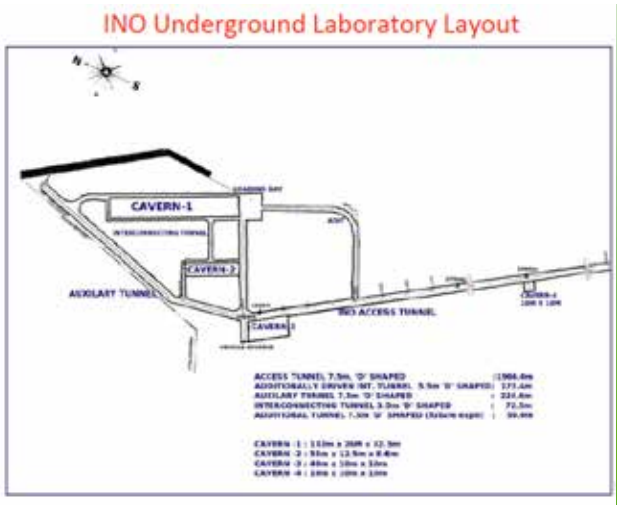


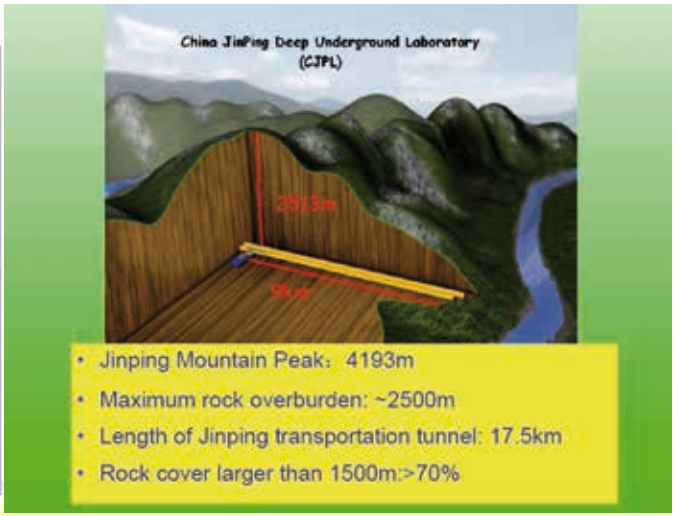

claim of evidence
$\Delta m^2_{23} < 0$
$\Delta m^2_{23} > 0$
90% CL (1 dof)
disfavoured by cosmology
$|m_{ee}|$ in eV
lightest neutrino mass in eV
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}

Where to go ?


INTERNATIONAL UNDERGROUND LABORATORIES
(Present and Planned)
Baksan
Gran Sasso
Canfranc
Frejus/Modane
Boulby
Pyhasalmi
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
AUXILARY TUNNEL
ACCESS TUNNEL


China JinPing Deep Underground Laboratory
(CJPL)
2513m
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

Nucleus	Experiment	%	$Q_{\beta\beta}$	Enrich	Technique	$T_{0\nu}$ (y)	$\langle m_\nu \rangle$
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 - ?

Experiment	Isotope	Mass [kg]	$\tau^{0\nu}_{1/2}$ [y]	$m_{\beta\beta}$ [meV]	When
CUORE	^{130}Te	200	2×10^{26}	35-80	2014-2019
GERDA	^{76}Ge	17 40 1000	3×10^{25} 2×10^{26} 6×10^{27}	180-500 70-200 10-40	2010-2012 2012-2014 2015-2025
MAJORANA	^{76}Ge	33 1000	1.5×10^{26} 6×10^{27}	70-200 10-40	2012-2013 2015-2025
EXO	^{136}Xe	200 1000	6×10^{25} 8×10^{26}	130-190 30-60	2010-2012 2015-2025
SuperNEMO	^{82}Se	100-200	$(1\text{-}2)\times10^{26}$	40-140	2013-2019
KamLAND-Zen	^{136}Xe	400 1000	4×10^{26} $\sim10^{27}$	40-80 25-50	2011-2013 2014-2016
SNO+	^{150}Nd	40-120 500	$\sim4\times10^{24}$ $\sim3\times10^{25}$	80-130 40-100	2013-2016 2016-2020

From CUORICINO to CUORE

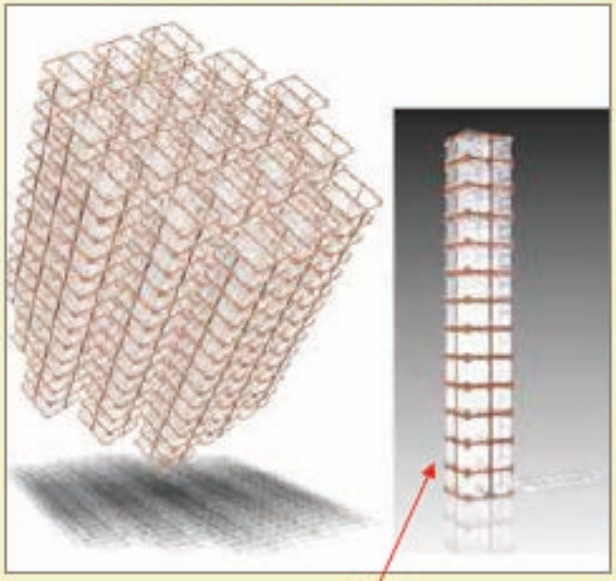
(Cryogenic Underground Observatory for Rare Events)

CUORE = closely packed array of 988 detectors

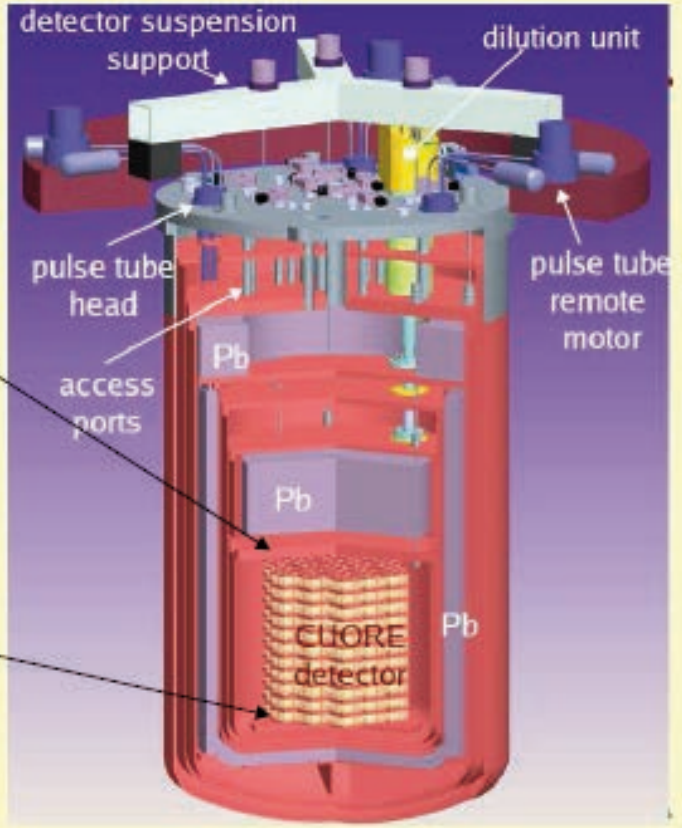
19 towers - 13 modules/tower - 4 detectors/module

M = 741 kg ⇒ ~ 10^{27} ^{130}Te nuclides

Compact structure, ideal for active shielding

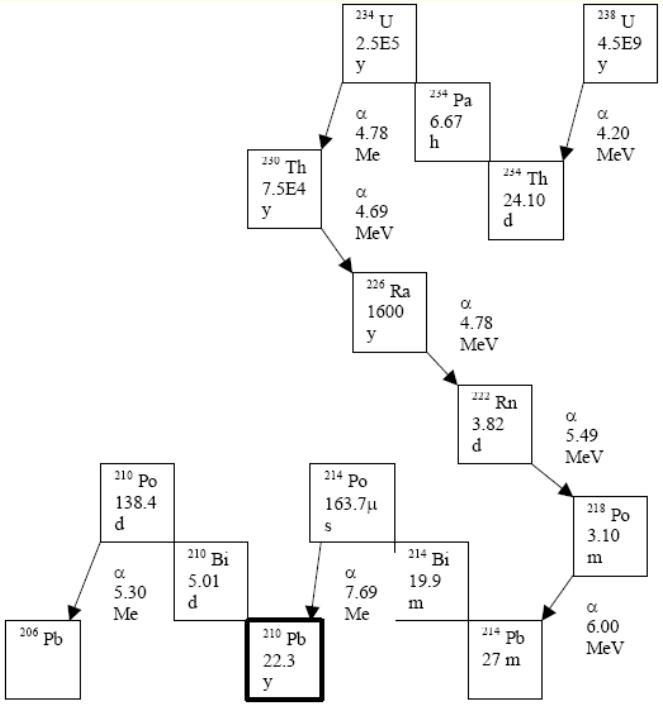


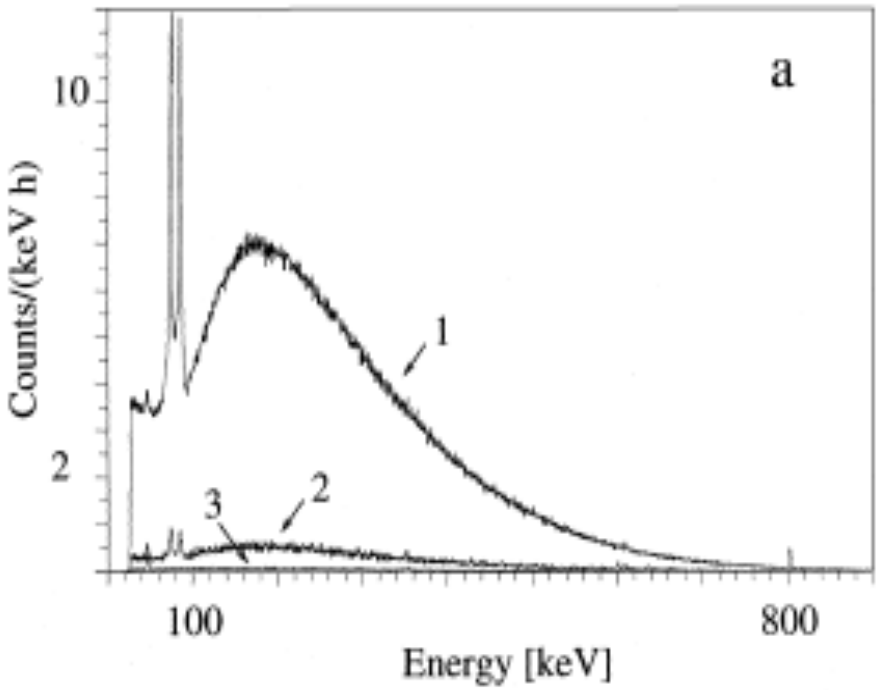
Each tower is a CUORICINO-like detector



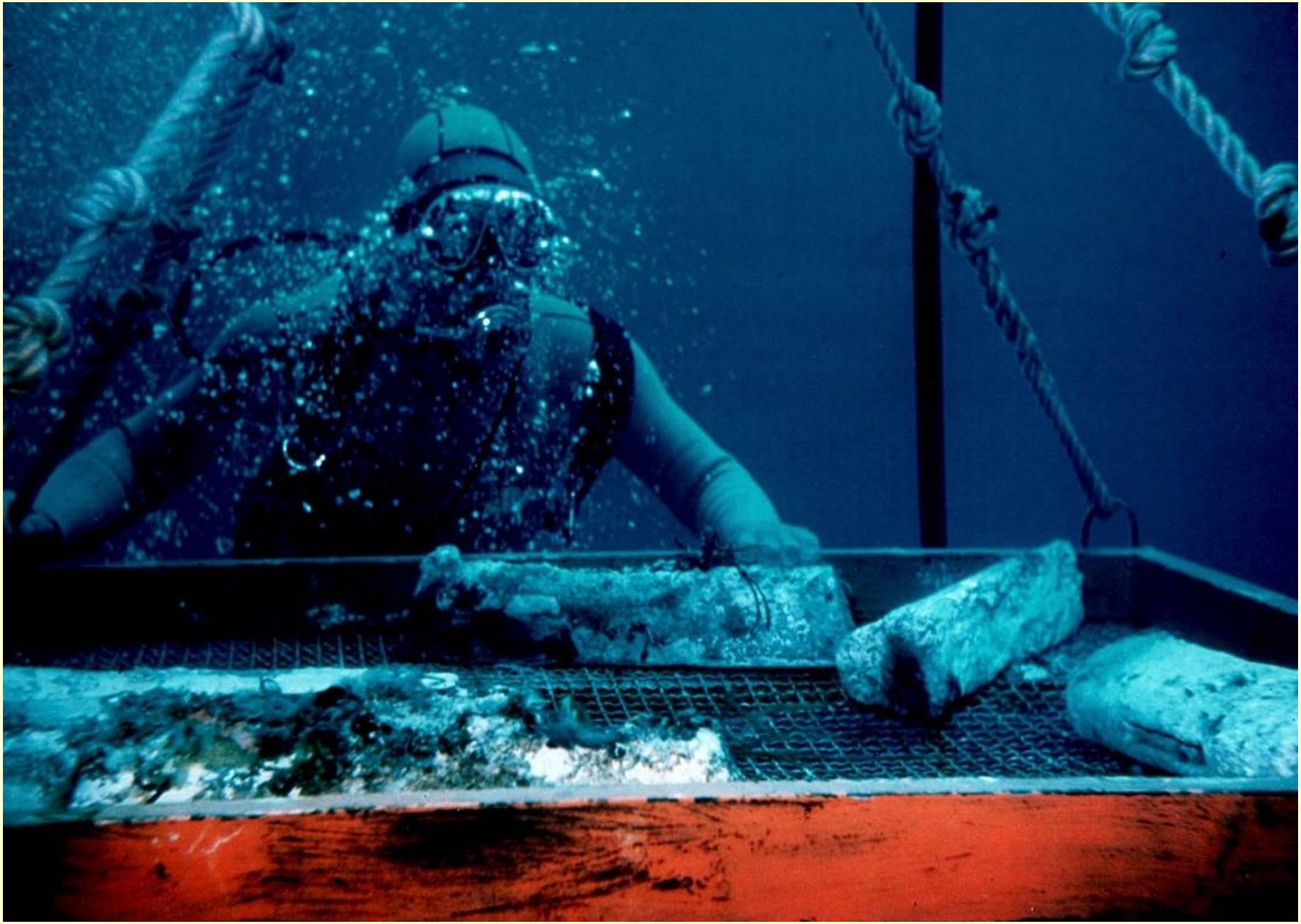
Custom dilution refrigerator

The problem of the Roman lead





A Roman *"navis oneraria"* shunk in Sardinia




SOCMEPONTILIENORVM·M·F

AN INPORTANT RECENT RESULT ON NEUTRINO OSCILLATIONS

$$P(\nu_a - \nu_b) = \text{sen}^2\theta[1.27\ \Delta m^2\ L(\text{km})/E(\text{GeV})]$$

Only θ_{13} was missing !

After an indication by Double Chooz e Japan Risults from Orient: Daya Bay (China) and RENO (South Corea)

$$\sin^2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$$

$$\sin^2\theta_{13} = 0.103 \pm 0{:}013(\text{stat}) \pm 0{:}011(\text{syst})$$

If Bruno would still be alive what a triumph for him!