My debts to Luciano: from neutral currents to CUORE

Milan vs Rome => Ettore & Luciano

Roma in fanteria e Milano in fureria
Roma in infantry and the Milan in quartermaster office Rome

Roma in fureria e Milano in fanteria
Roma in QUATERMASTER OFFICE and the Milan in infantry Milan

But not for us => many episodes

- **Discovery of neutral currents**
- **Neutrino mass and double beta decay**
- **Single beta decay and relic neutrinos**
- **The second mistery of Ettore Majorana**

Discovery of neutral currents

- Innovative ideas by **Carlo Franzinetti**
- Proposal for an heavy liquid bubble chamber in Italy (E.F.,L.Guerriero, I.Mannelli,P.Negri and L. Scotoni) **well considered by INFN**

GARGAMELLE

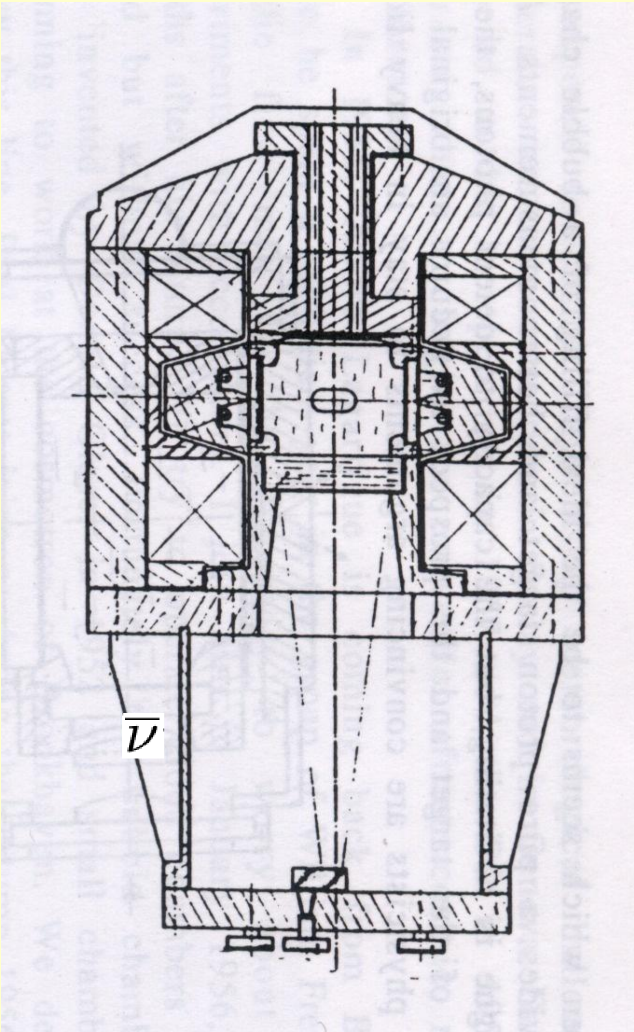
- **Andre' Lagarrigue** -> Contract CERN-France
- Very generous offer by A.Lagarrigue to our group (le vieux copain)
- Gargamelle Users Committee
- Construction of Gargamelle in France and its installation at CERN.
- The first Gargamelle collaboration: Aachen, Bruxelles, CERN, E.P.Paris, Milano, Orsay and U.C.London
- Special projectors ARGO " e gli occhi d' ARGO se fosser vivi sarebber cotali"

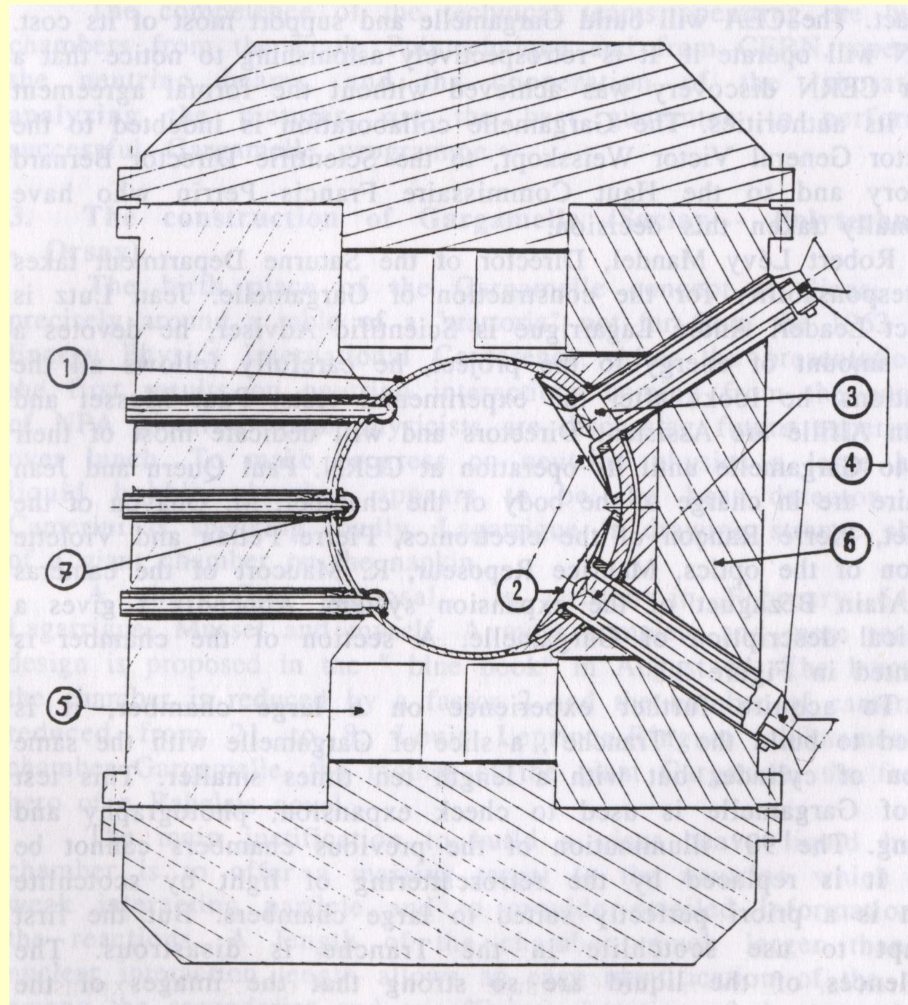
Not only neutral currents.

- The first evidence for single hyperon production by antineutrinos
- $\bar{\nu}_\mu + p \Rightarrow \mu^+ + \Lambda_o$ in excellent agreement with Cabibbo theory
- Cross section of neutrinos and antineutrinos as a function of energy
- Evidence for production of charmed particles (later, 1975)

The structure of Gargamelle

Wife of Grangousier and Mother of Gargantua- see F. Rablais ≈1550)





Neutral currents not particularly popular :

" Le correnti neutre le lascio a Fiorini ! Carlo Franzinetti"

Two reasons:

- Experimenters attracted by the **new discoveries on partons** at SLAC and by the opportunity to measure their **quantum numbers** by the interactions with neutrinos (D.Perkins)
- No evidence in strange particle production like $K^+ \Rightarrow \pi^+ + \nu + \bar{\nu}$

However I was impressed by the paper by **Glashow, Iliopoulos and Maiani** postulating a mechanism with a fourth quark which suppressed the strangeness changing neutral currents . Strong interest in Milan for N.C. interactions without outgoing electrons or muons

Group meeting in **A.Pullia** house (department occupied for two months by student unrest) and reports by Tonino in Paris 0n March 2 and 3 1973 followed by a conference by P.Musset at CERN on July 19,1973 paper published in Phys.Lett. On September 3, 1973

Almost contemporarily one event

$$\bar{\nu}_{\mu} + e = \bar{\nu}_{\mu} + e$$

- 1 -

TC-L/PA
DC/MH/ju

9.3.1972

RESUMÉ OF THE GARGAMELLE NEUTRINO COLLABORATION MEETING
HELD IN PARIS ON MARCH 2 AND 3 1972

1. ORGANIZATION OF THE MEETING

a. Thursday morning : Comparison of event rates

b. Thursday afternoon : Hyperon discussion

c. Friday morning : Subgroups

d. Friday afternoon : Conclusions and priorities definition.

6. NEUTRAL CURRENTS

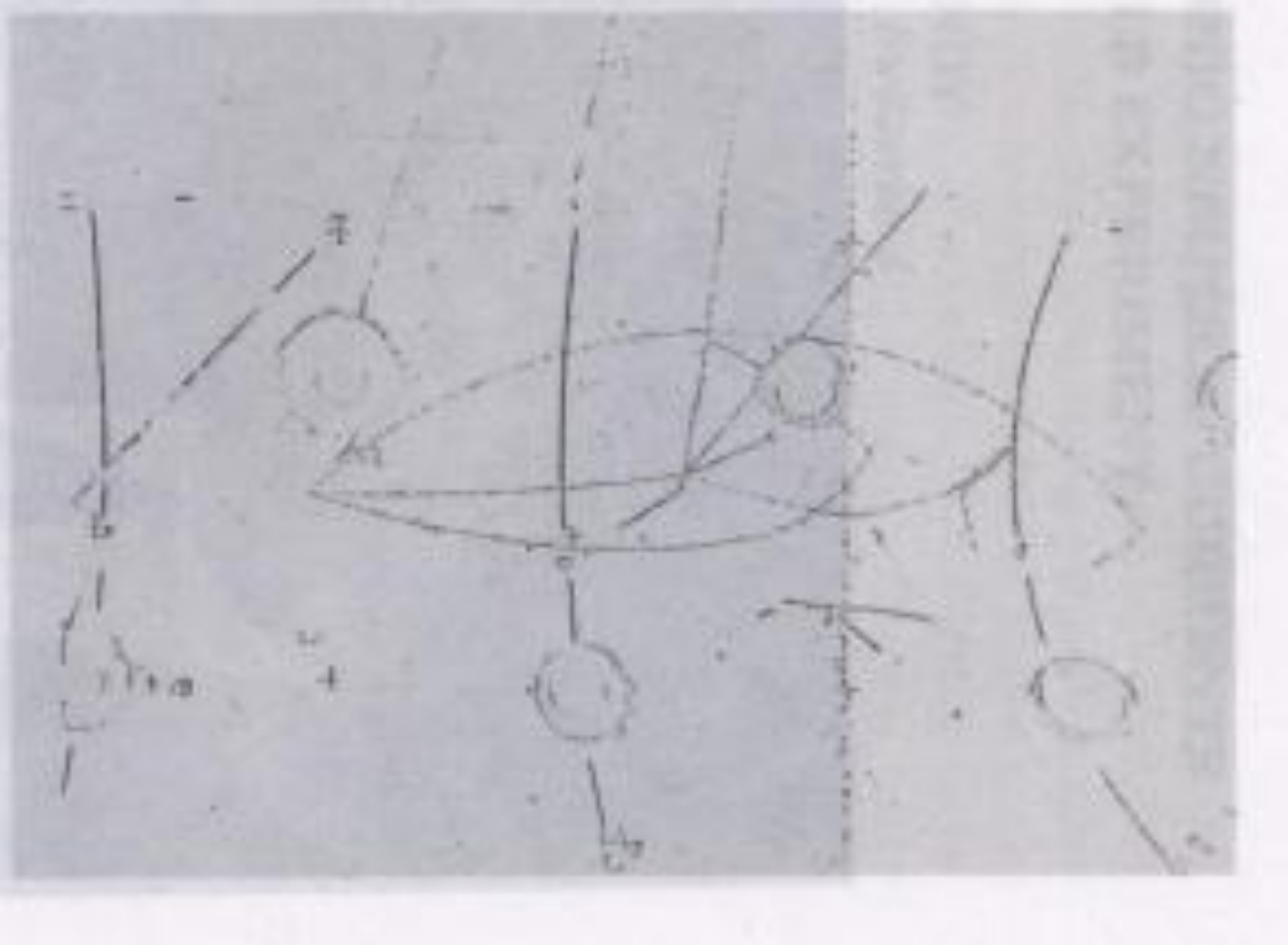
Some preliminary results were presented by Pullia based on 16 neutrino rolls. The apices of events, with at least one pion, and without muon candidates, were measured.

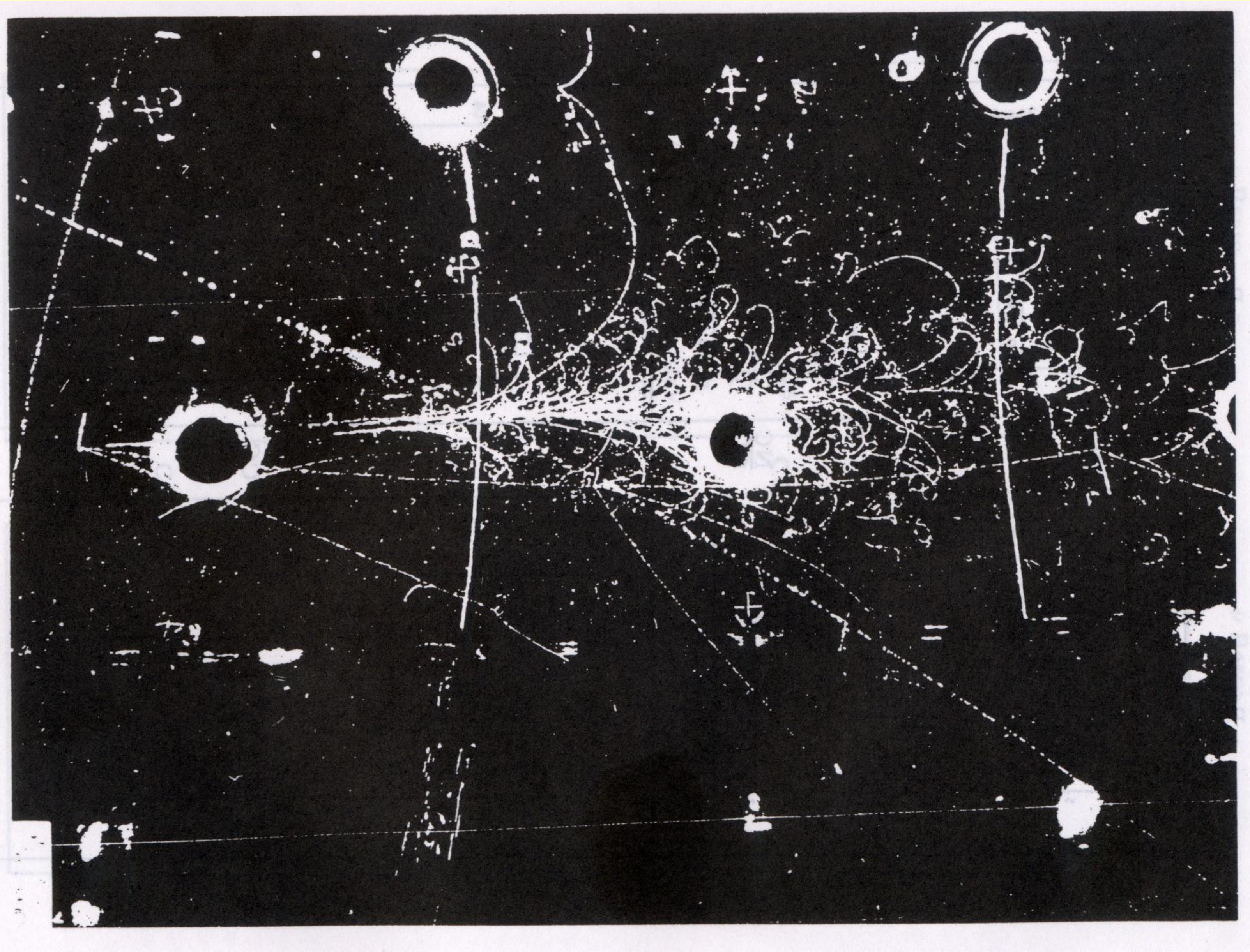
- The event rate of 5/roll rules out cosmic ray origin.
- The x distribution is flat and seems to exclude a neutron flux from the shielding.
- The radial distribution, which is the same as the neutrino events, seems to exclude secondary interactions from neutrino interactions in the magnet.

These findings will be pursued by the laboratories having the available effort.

Next meeting will be held at the beginning of May.

D.C. Cundy
M. Haguenauer.



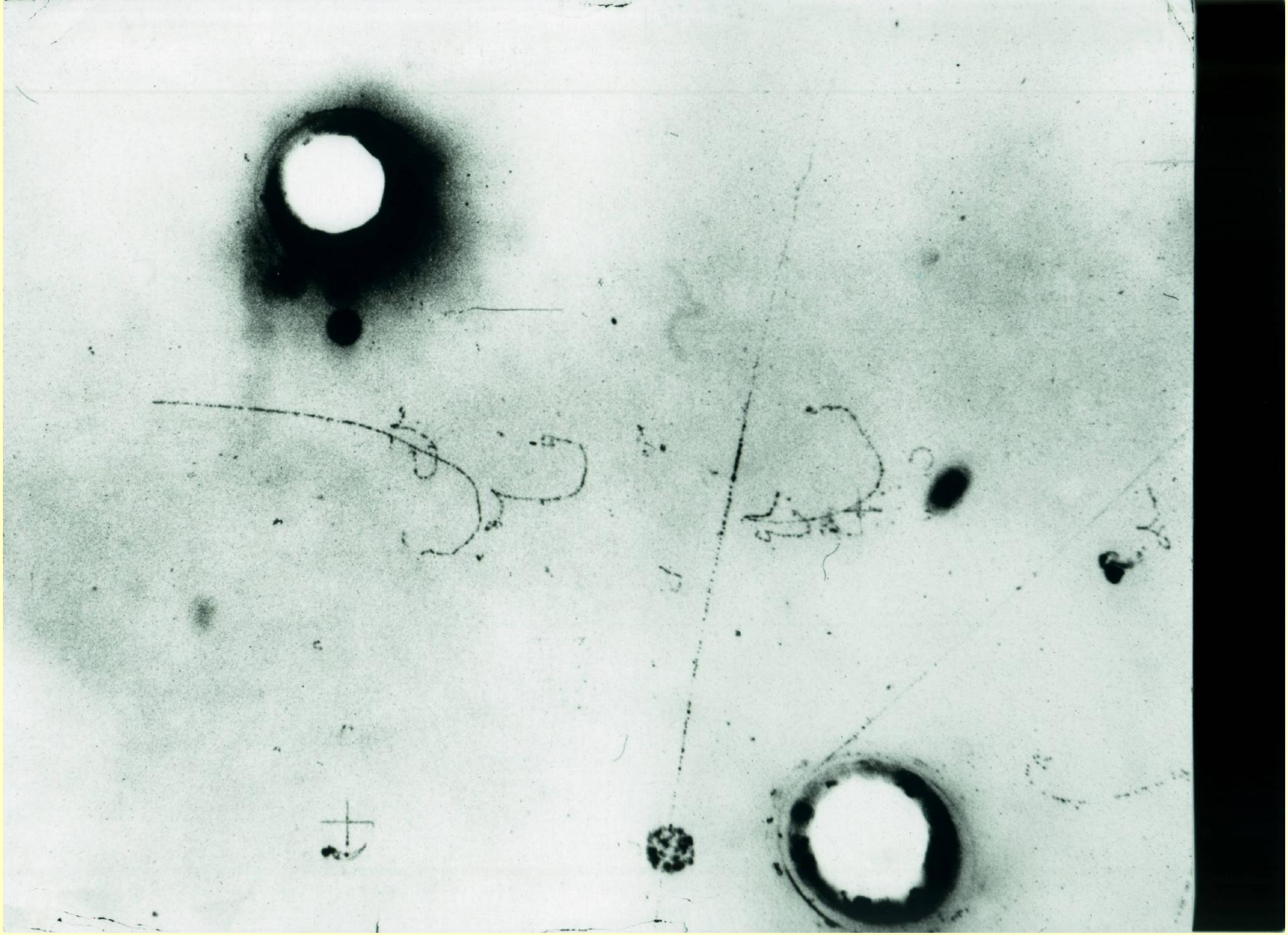


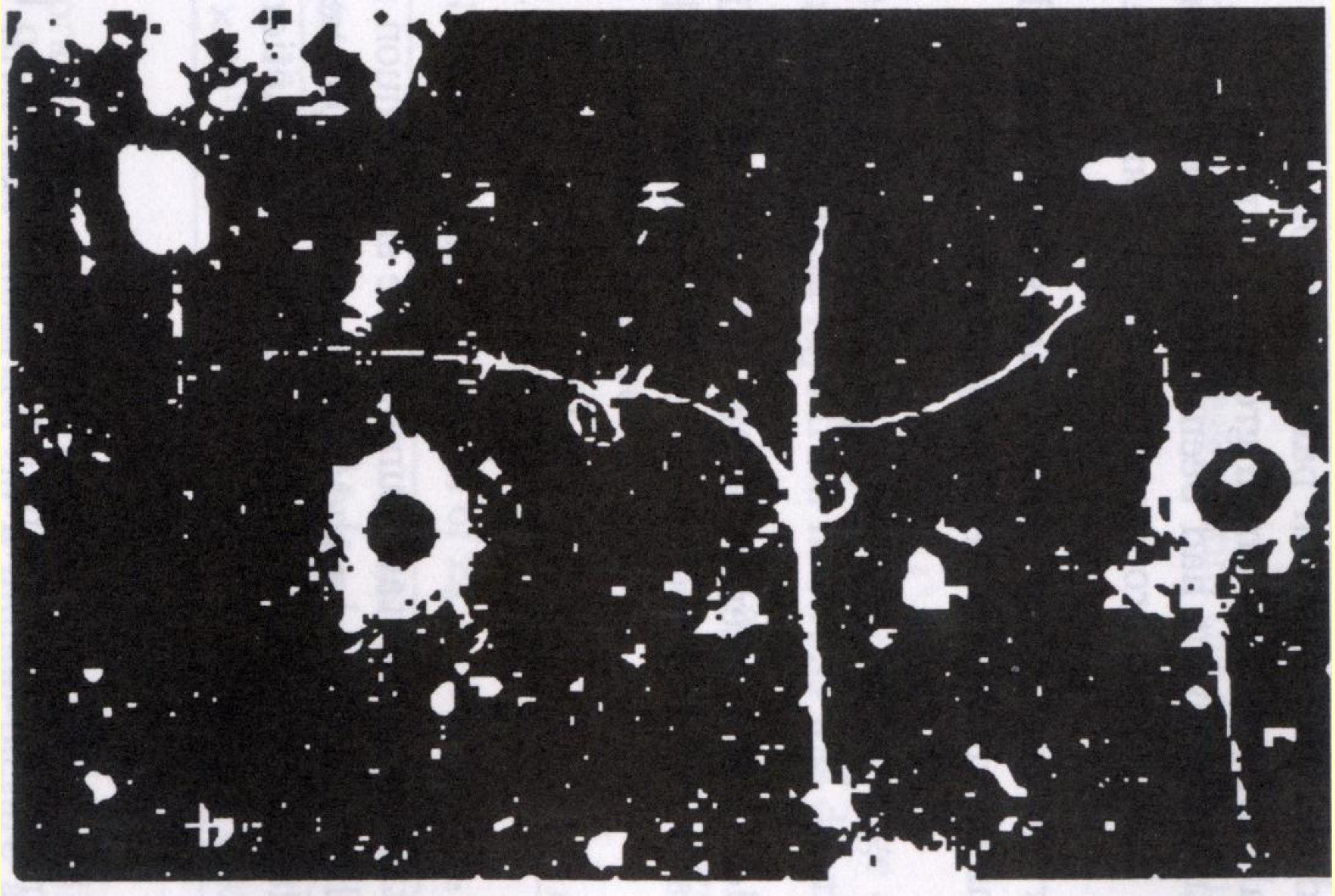
My visit to **Rome**

Long discussion with **N.Cabibbo and L.Maiani**

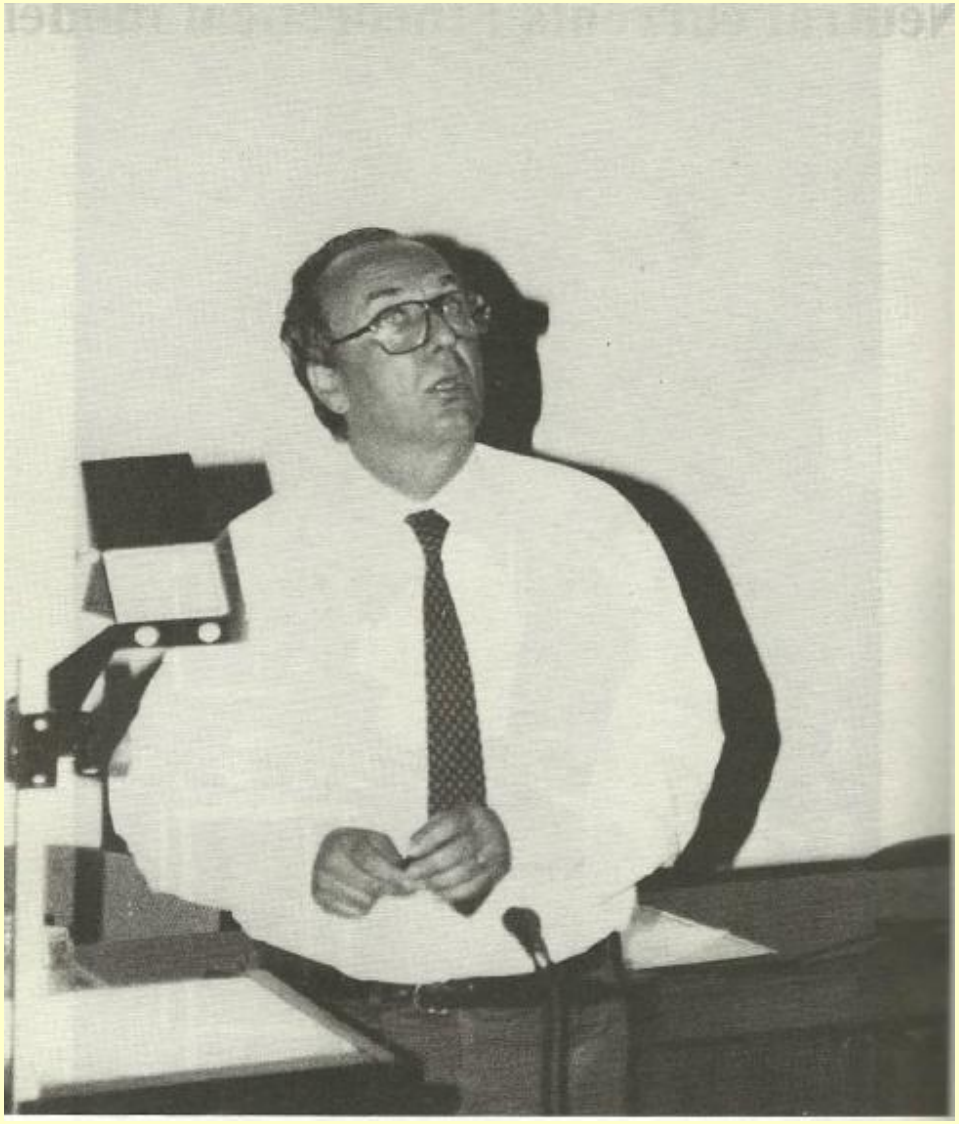
AACHEN, BRUXELLES, CERN, ECOLE POLYTECHNIQUE, MILANO, ORSAY, U.C. LONDON COLL. : Observation of neutrino-like interactions without muon or electron in the Gargamelle neutrino experiment – Phys. Lett. 46B, 138 (1973)
Events induced by neutral particles and **producing hadrons, but no muon or electron**, have been observed in the CERN neutrino experiment. These events behave as expected if they arise **from neutral current** induced processes. The rates relative to the corresponding charged current processes are evaluated.

AACHEN, BRUXELLES, CERN, ECOLE POLYTECHNIQUE, MILANO, ORSAY, U.C. LONDON COLL. : Search for elastic muon neutrino electron scattering - Phys. Lett. 46B, 121 (1973)
One possible event of the process $\bar{\nu}_{\mu} + e^- \rightarrow \bar{\nu}_{\mu} + e^-$ has been observed. The various background processes are discussed and the event interpreted in terms of the Weinberg theory. The 90% confidence limits on the Weinberg parameter are 0.1 < sin2θW < 0.6.





1973 Neutral currents : **twenty years later**



The existence of charm is confirmed

S.L. Glashow, J. lliopoulos and L. Maiani, Phys. Rev. D2 (1970) 128

AACHEN, BRUXELLES, ECOLE POLYTECHINIQUE, MILANO, ORSAY, U.C. LONDON COLL. : Strange particle production and charmed particle search in the Gargamelle neutrino experiment - Phys. Lett. 58B, 361 (1975)
Data is given for single and multiple strange particle production in neutrino reactions in both charged and neutral current channels. A total of 15000 neutrino and antineutrino events has been examined for possible evidence of semi-leptonic decay of a charmed particle. **One candidate has been observed**. Upper limits on charmed particle production cross-sections are given as a function of the neutrino energy and the invariant mass of the final state hadrons

- Gargamelle was moved to SPS to **"continue its noble career"** (J.Steinberger) , but **"died"** in 1979 for her initial sickness, a bad quality of its weldings
- Even now **ICARUS** is quoted as "**an electronic Gargamelle**" .

To the charm discovered party

$$\nu_\mu + p = \mu^- + \Sigma_c^{++}$$

$$\Downarrow$$

$$\Lambda_c^+ + \pi^+$$

$$\Downarrow$$

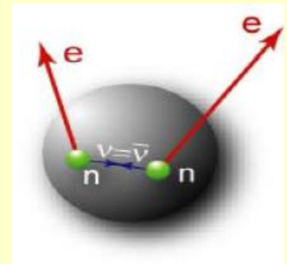
$$e^+ + \Lambda^0 + \nu_e$$

An unexpected help from Luciano :

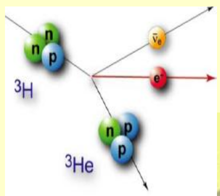
Single beta decay and cosmic neutrinos

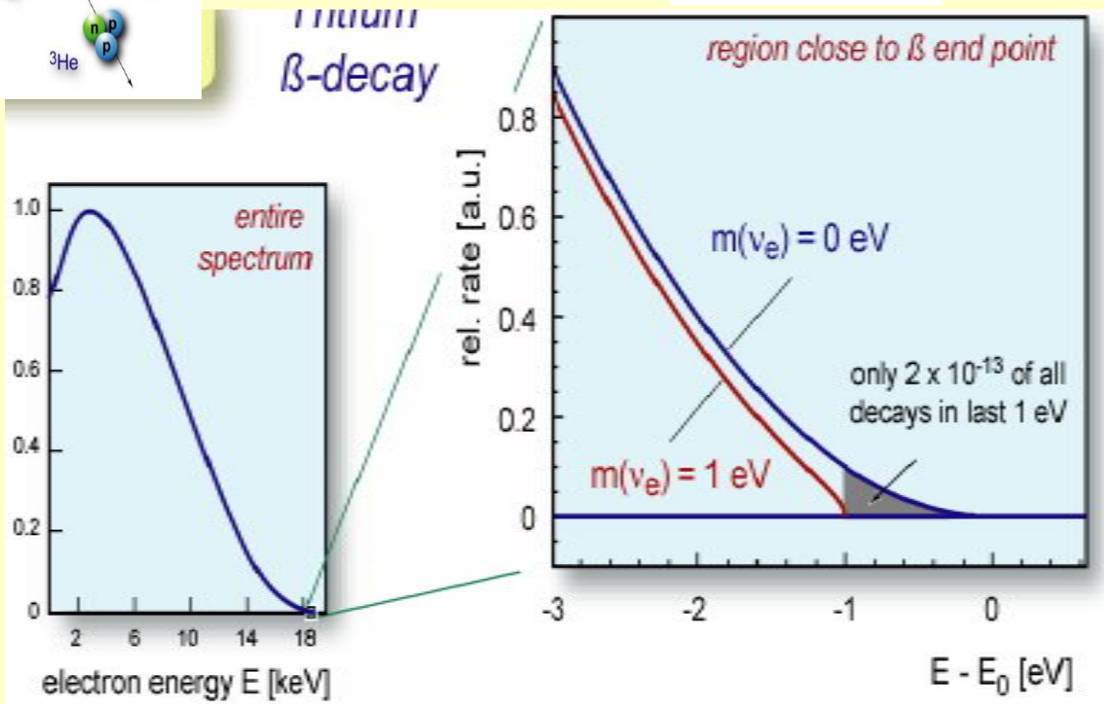
Direct measurement of the neutrino mass

Electron capture

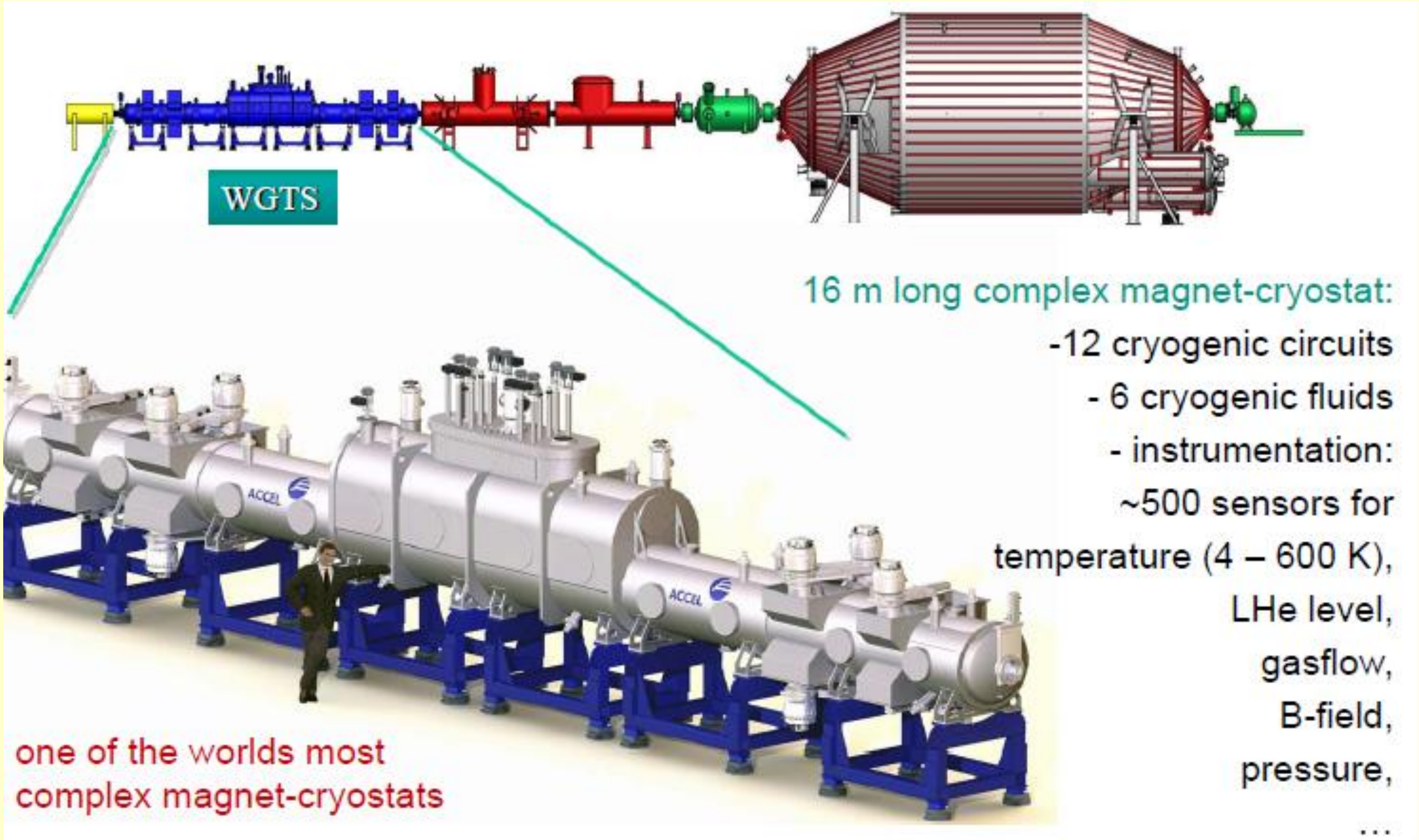


β decay

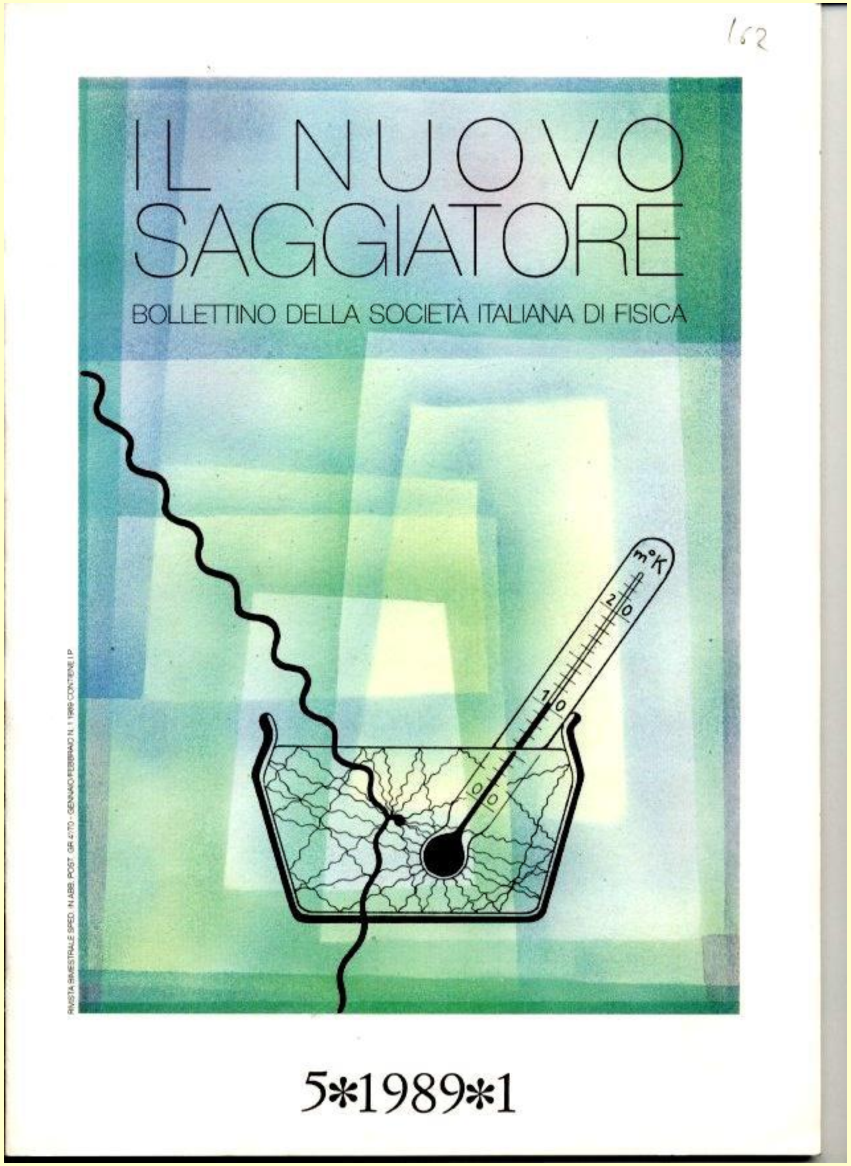




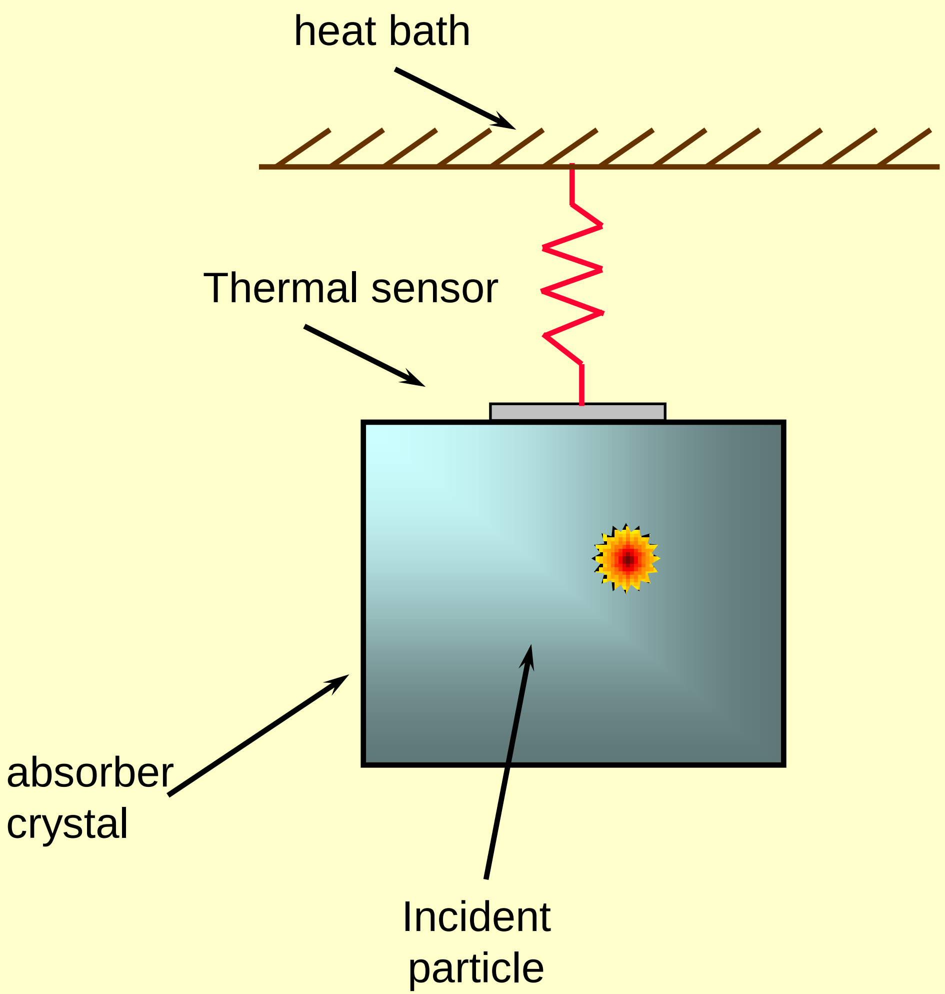
The Karlsruhe Tritium Neutrino (KATRIN)



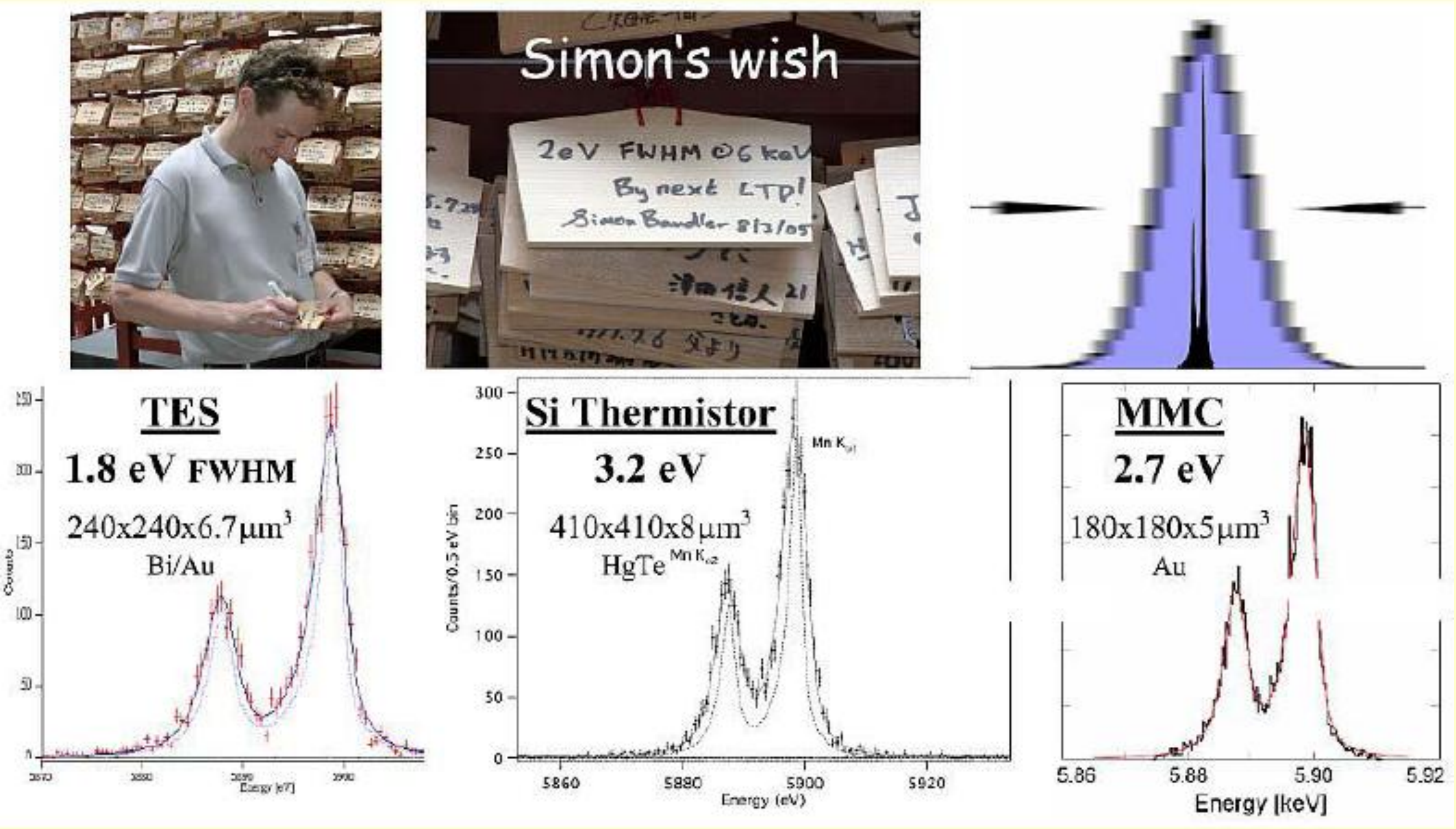
A picture by Enzo Iarocci

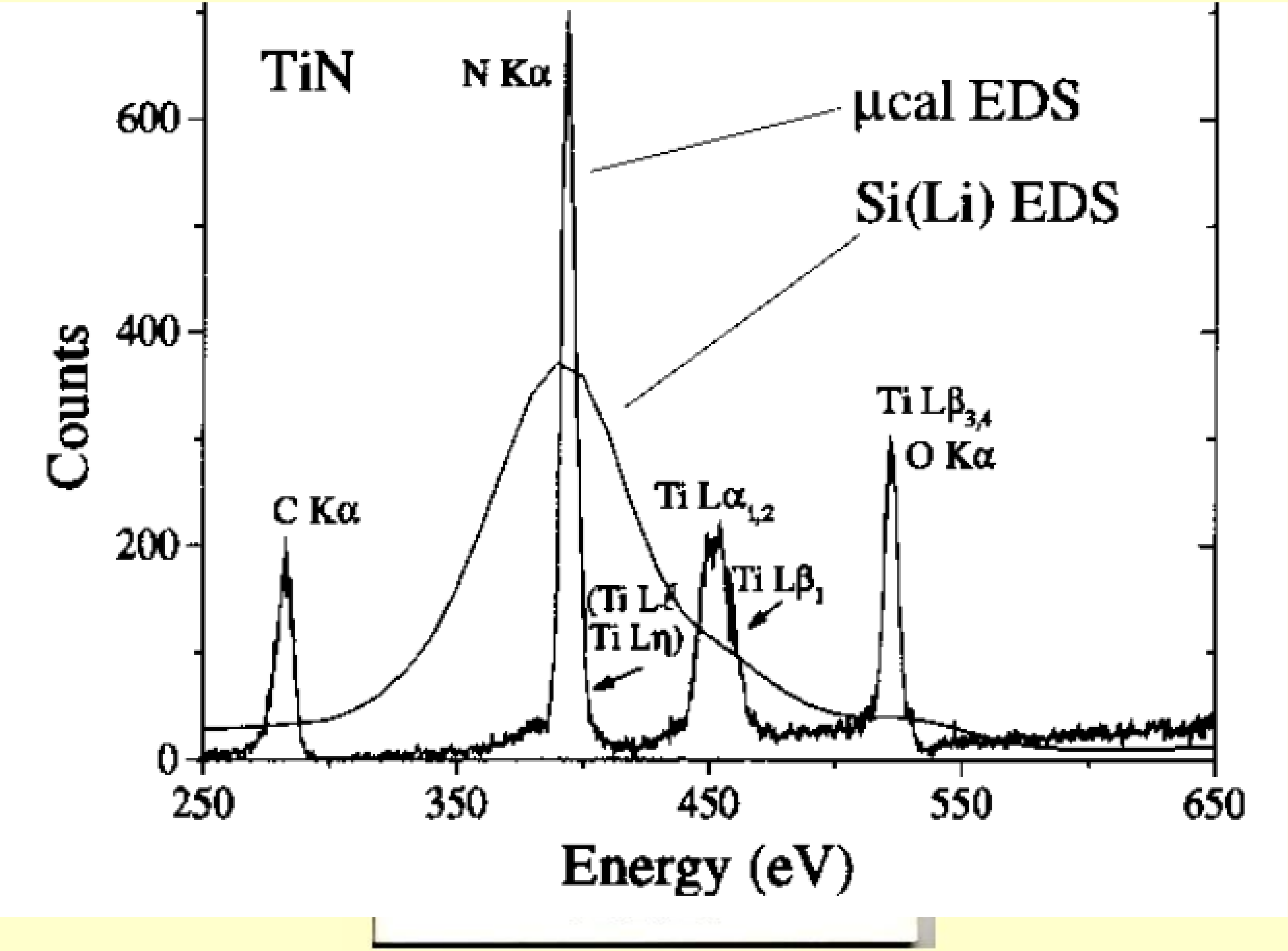


Thermal Detectors



Another approach: thermal detectors




TiN
N Kα
μcal EDS
Si(Li) EDS
Counts
600
400
200
0
C Kα
(Ti Lℓ
Ti Lη)
Ti Lα1,2
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**

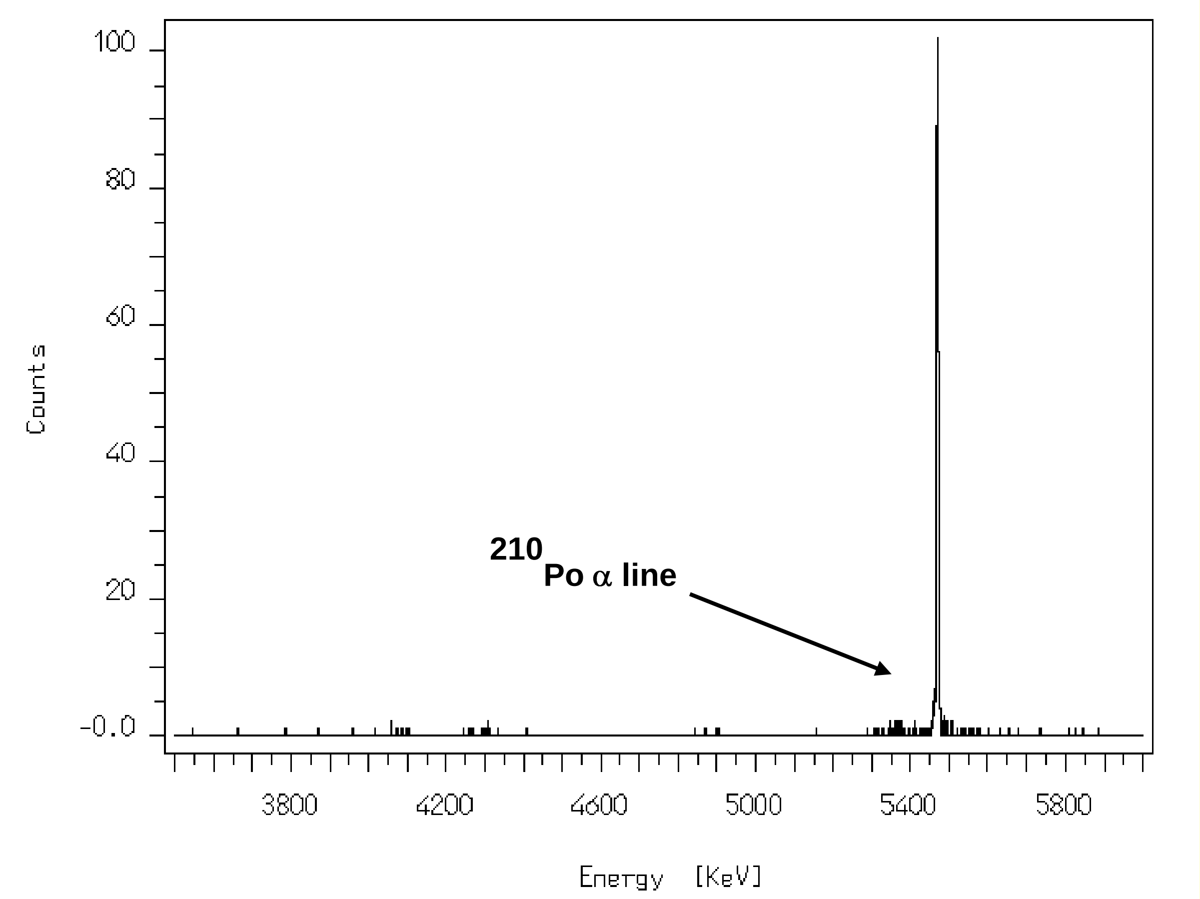
1.4 keV **FWHM @ 0.351 MeV**

2.1 keV **FWHM @ 0.911 MeV**

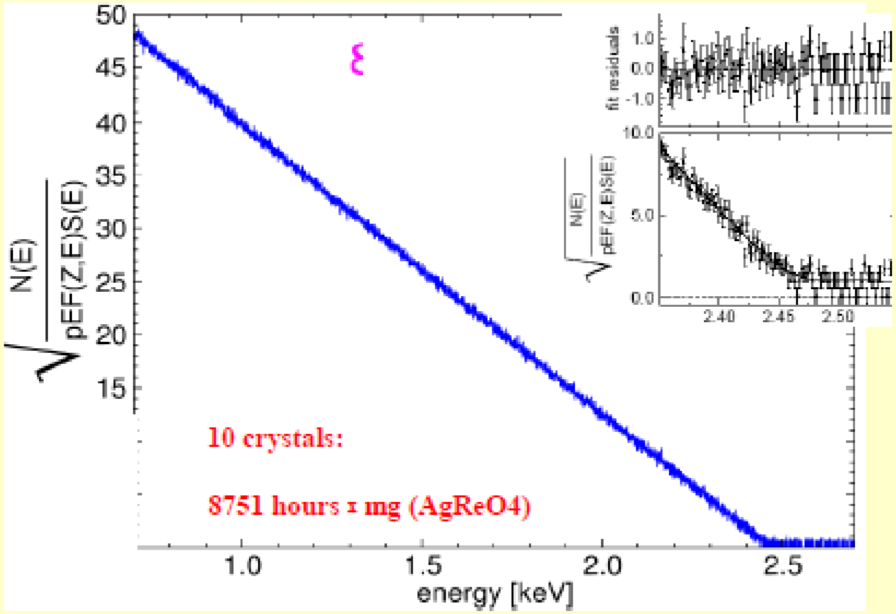
2.6 keV **FWHM @ 2.615 MeV**

3.2 keV **FWHM @ 5.407 MeV**

(the best α spectrometer so far



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



MANU2 (Genoa)
metallic Rhenium
$m_\nu < 26$ eV

Nucl. Phys. B (Proc.Suppl.) 91 (2001) 293

MIBETA (Milano)
AgReO4
$m_\nu < 15$ eV

Nucl. Instr. Meth. 125 (2004) 125

MARE (Milano, Como, Genoa, Trento, US, D)
Phase I : $m_\nu < 2.5$ eV

E0 = (2465.3 ± 0.5stat ± 1.6syst) eV

$m^2_\nu = (-112 \pm 207 \pm 90)$ eV^2

A dream => Detection of cosmic ray neutrinos

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

Isotope	Decay	Q (keV)	Half-life (sec)	$\sigma_{NCB}(v_\nu/c)$ $(10^{-41}\ cm^2)$
^3H	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}

Ettore => Angela => Luciano again

Which is the nature of neutrino and its mass

The second mystery of Ettore Majorana

Teoria simmetrica dell'elettrone e del positrone

NOTA DI ETTORE MAJORANA

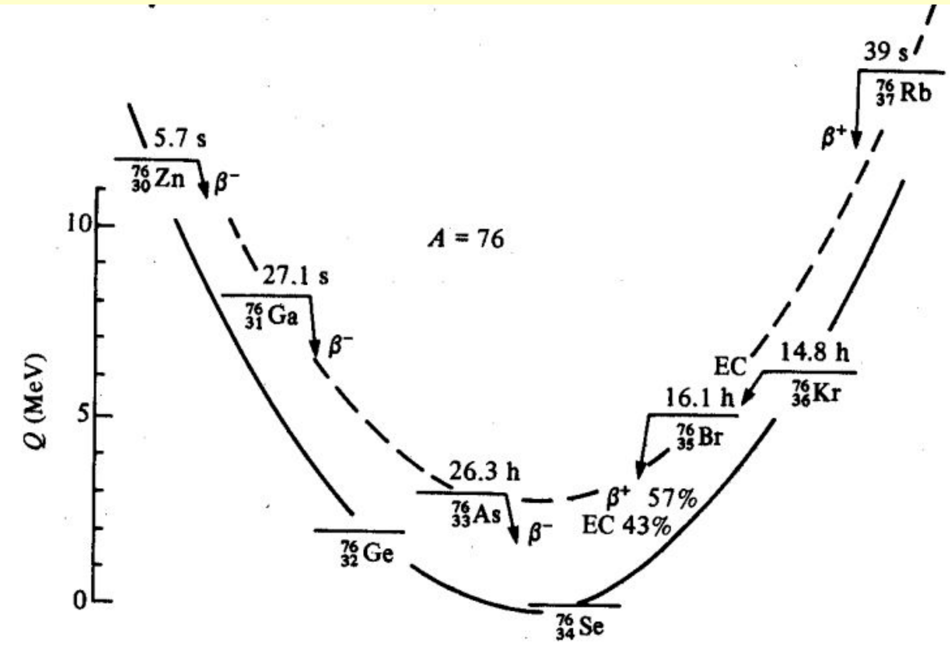
"Il Nuovo Cimento", vol. 14, 1937, pp. 171-184.

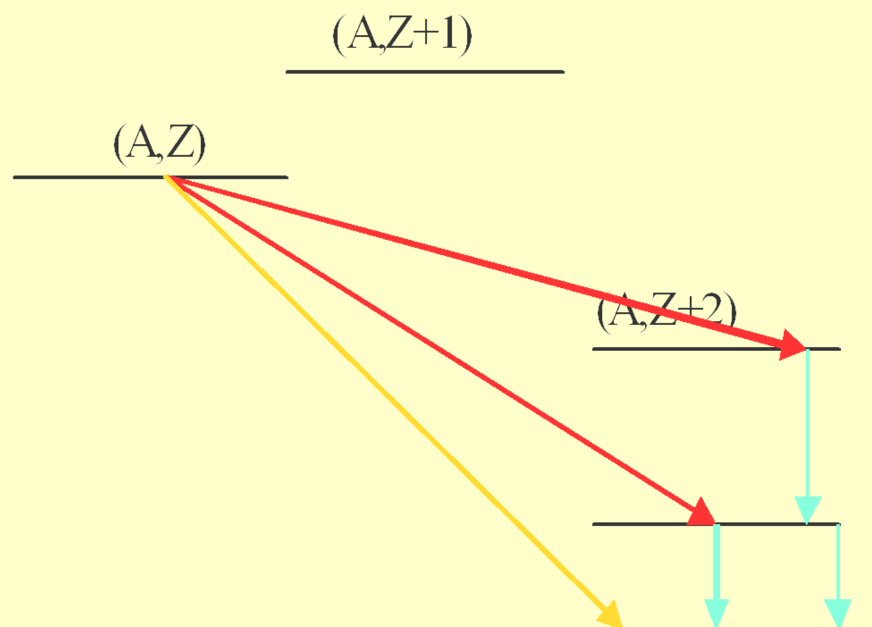
Sunto. — Si dimostra la possibilità di pervenire a una piena simmetrizzazione formale della teoria quantistica dell'elettrone e del positrone facendo uso di un nuovo processo di quantizzazione. Il significato delle equazioni di DIRAC ne risulta alquanto modificato e non vi è più luogo a parlare di stati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

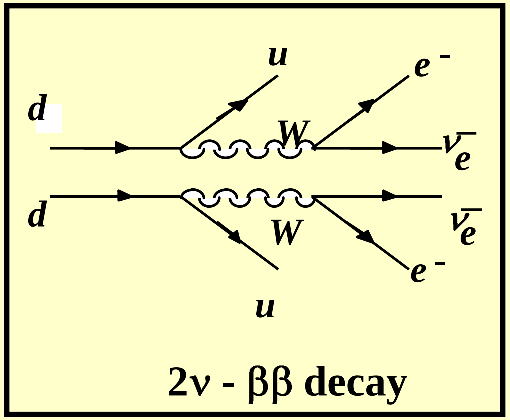
Chi l'ha visto ?

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.

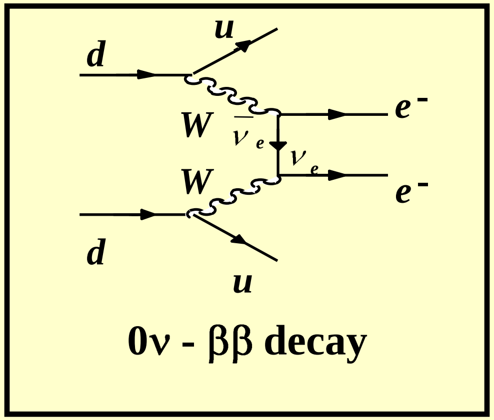
Double beta decay Ettore => Luciano and Nicola



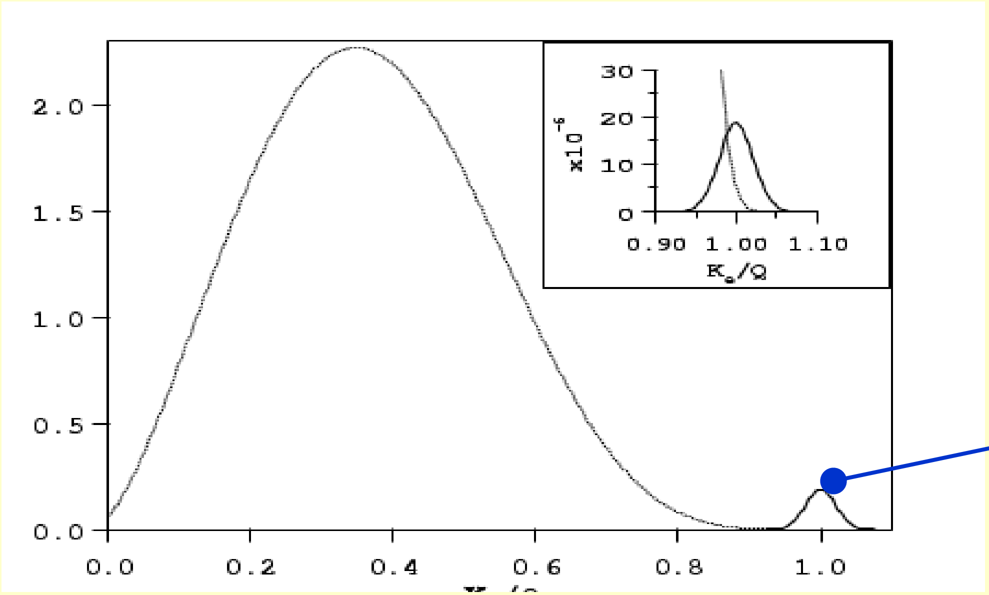




2ν - ββ decay



0ν - ββ decay



Neutrinoless ββ decay

Two neutrino ββ decay has been detected in ten nuclei also into exited states

Experimental approach

Geochemical experiments

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

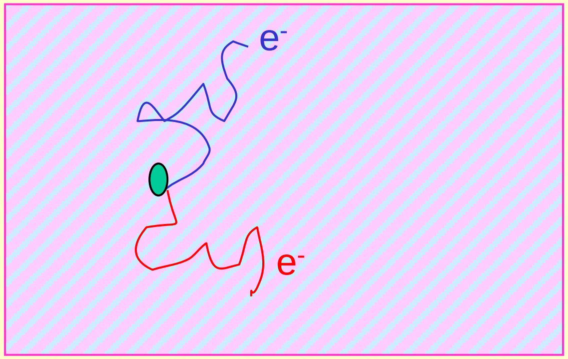
Radiochemical experiments

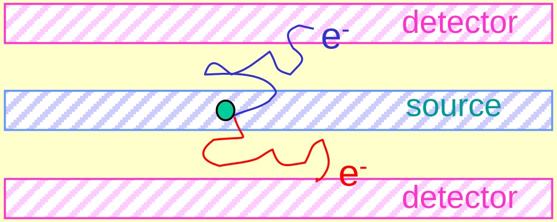
^{238}U = > ^{238}Pu (non confirmed)

Direct experiments

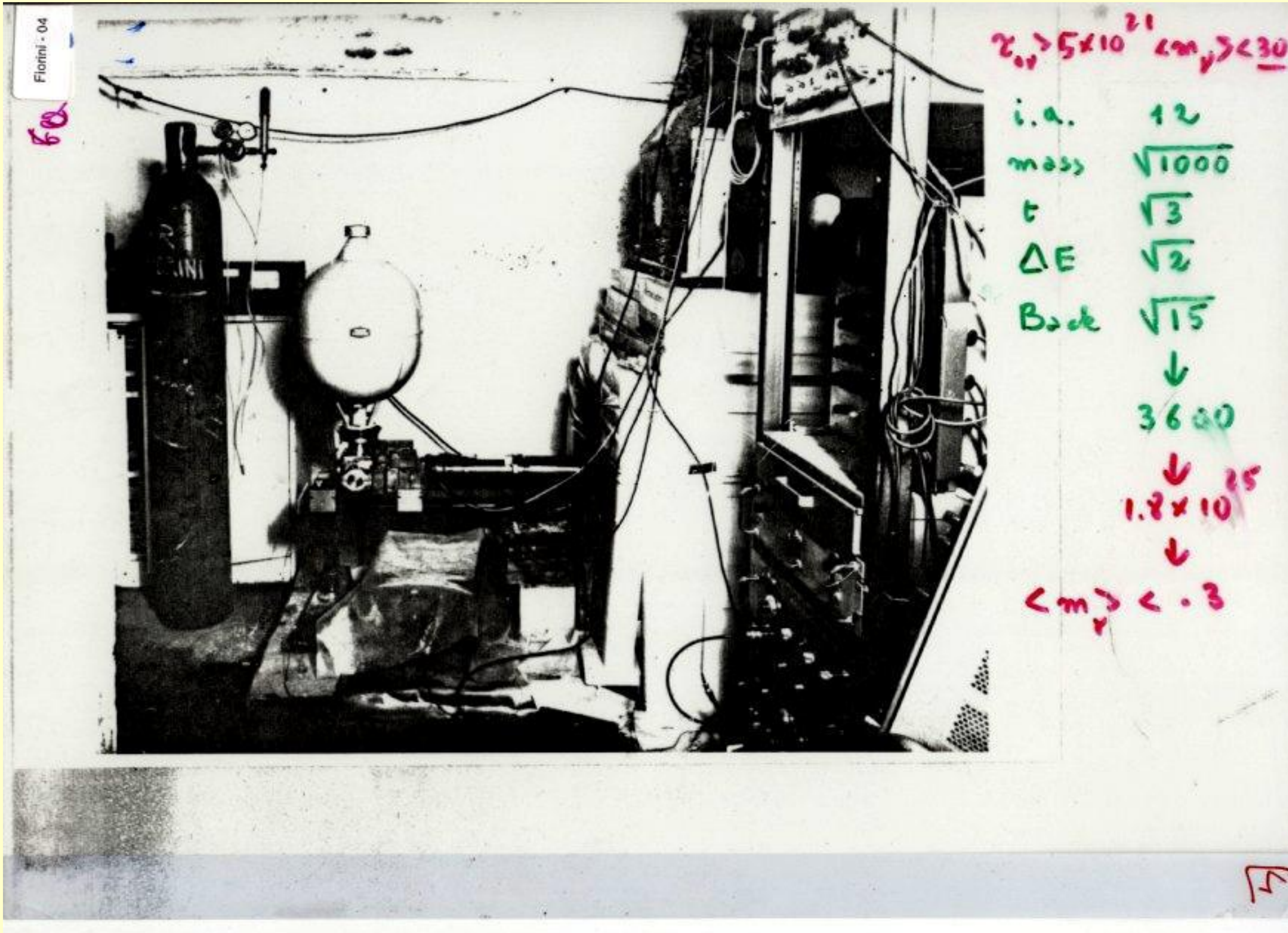
Source = detector (calorimetric)

Source ≠ detector

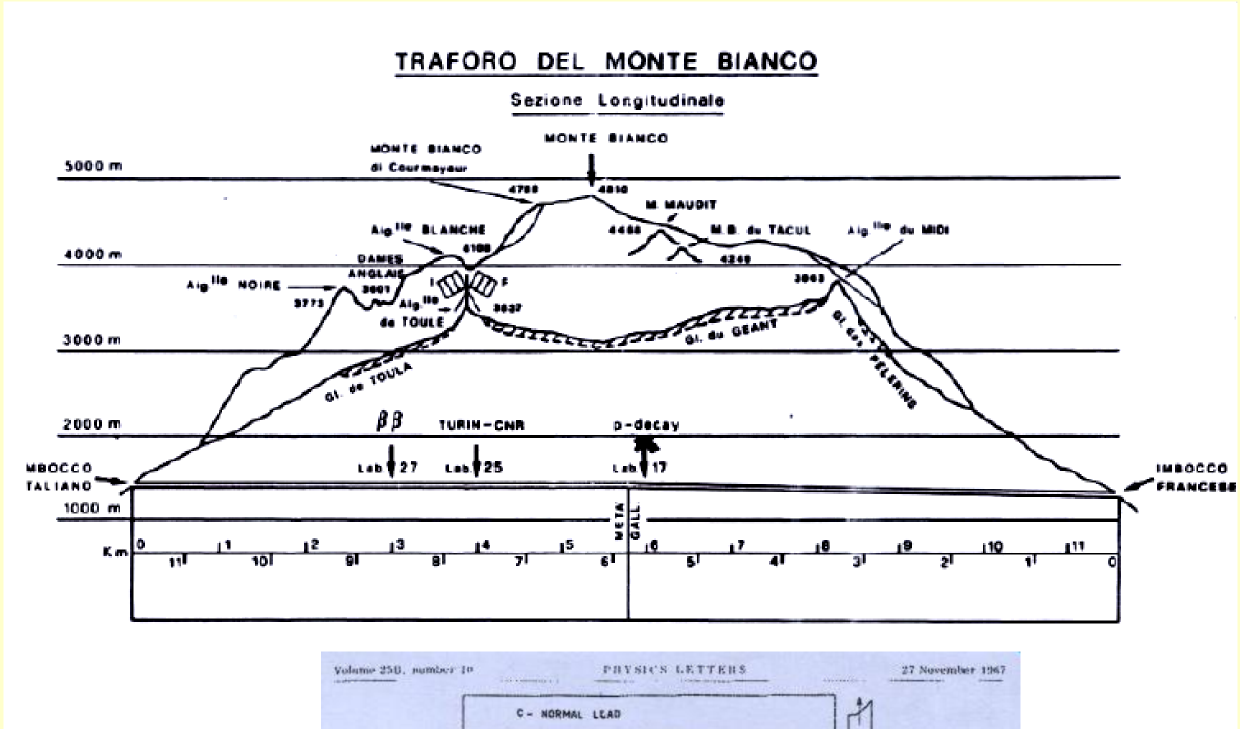


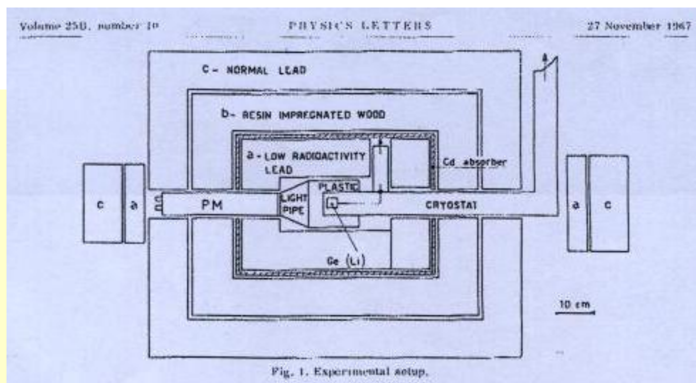


Source ≠ Detector


Fiorini - 04
τ0ν > 5×10^21 <mν> < 30
i.a. 12
mass √1000
t √3
ΔE √2
Back √15
3600
1.8×10^25
<mν> < .3

Experiment in the Mont Blanc Tunnel

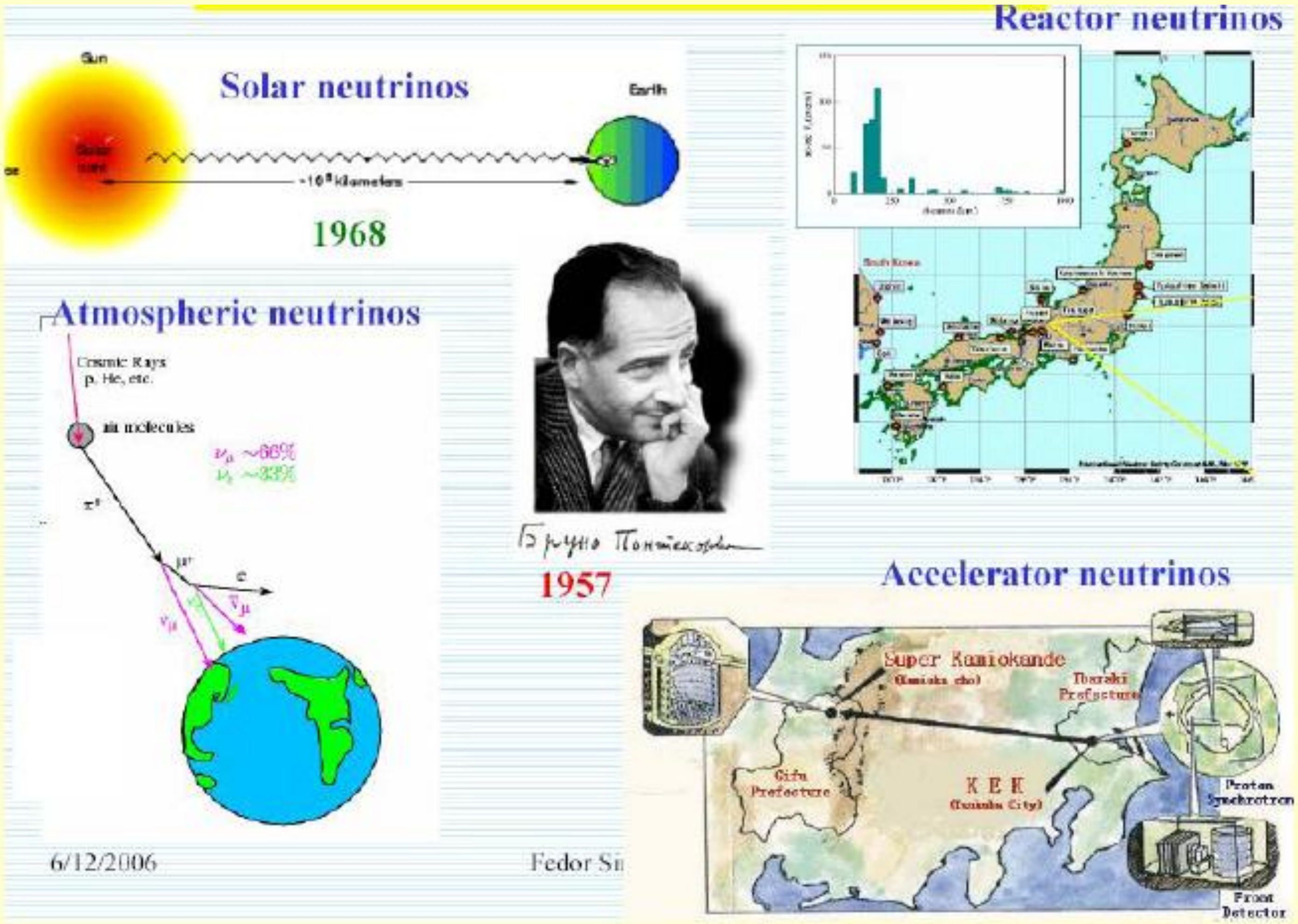


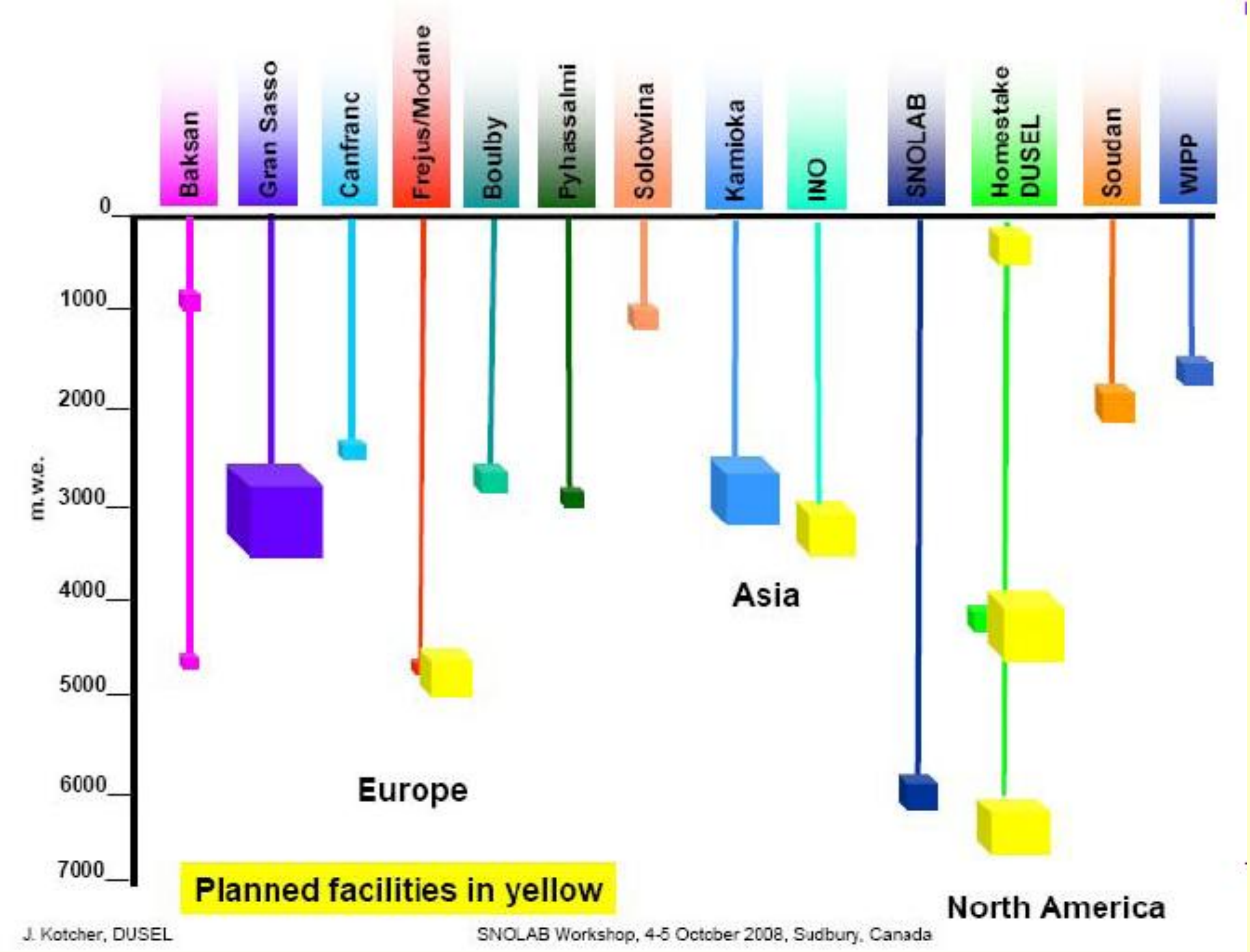


A good example for experimentalists **Cabibbo** and the **2.8 σ** effect

Discovery of neutrino oscillations

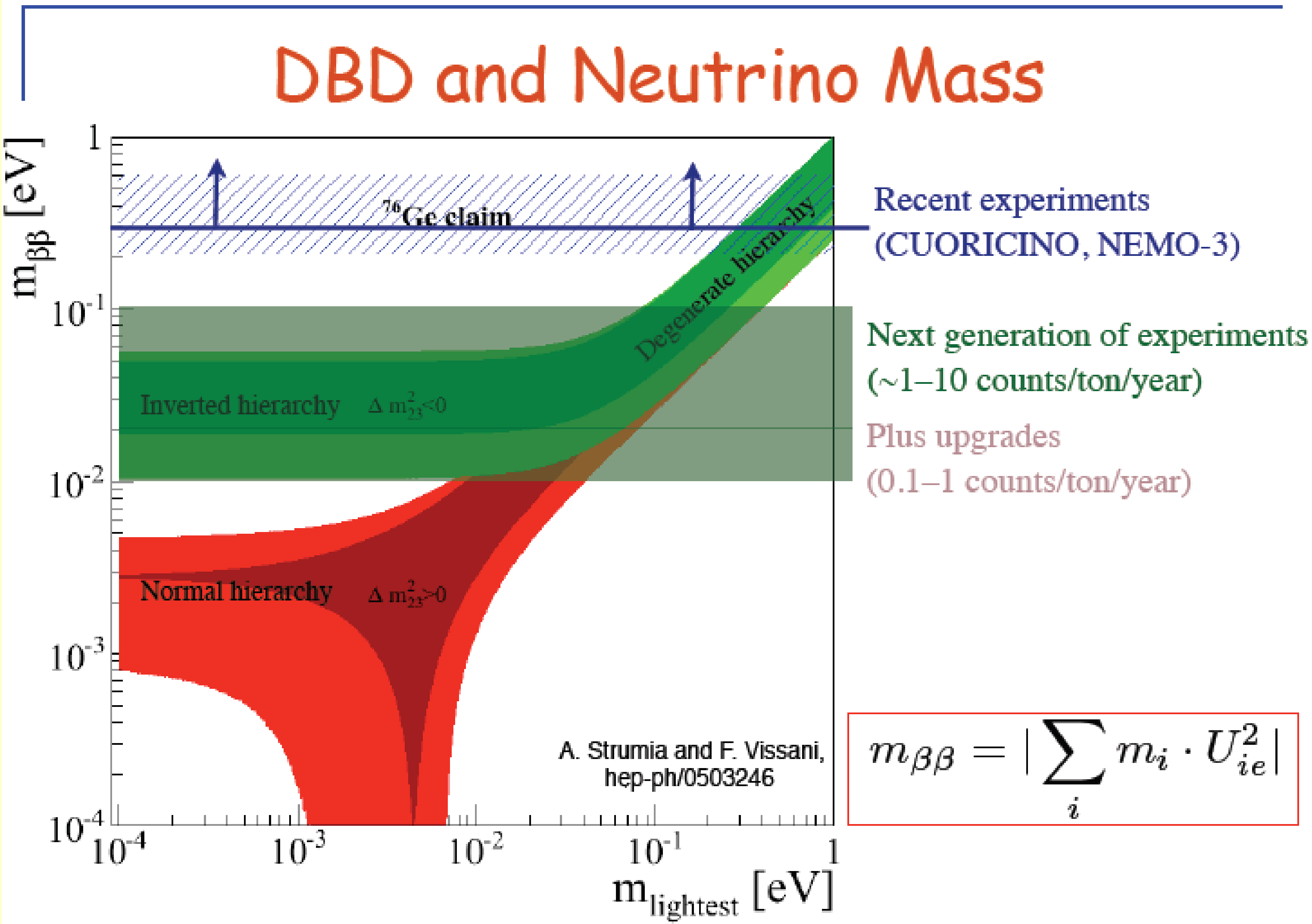
Neutrinoless Double beta Decay becomes very fashionable





Baksan
Gran Sasso
Canfranc
Frejus/Modane
Boulby
Pyhassalmi
Solotwina
Kamioka
INO
SNOLAB
Homestake DUSEL
Soudan
WIPP
m.w.e.
0
1000
2000
3000
4000
5000
6000
7000
Asia
Europe
North America
Planned facilities in yellow
J. Kotcher, DUSEL
SNOLAB Workshop, 4-5 October 2008, Sudbury, Canada

Oscillations indicate that $<m_\nu> \neq 0$



$$m_{\beta\beta} = \left| \sum_i m_i \cdot U_{ie}^2 \right|$$

Present situation on neutrinoless ββ decay

Nucleus	Experiment	%	$Q_{\beta\beta}$	Enr	Technique	$T_{0\nu}$ (y)	$\langle m_\nu \rangle$
^{48}Ca	Elegant IV	0.19	4271		scintillator	$>1.4\times10^{22}$	7-45
^{76}Ge	Heidelberg-Moscow	7.8	2039	87	ionization	$>1.9\times10^{25}$	.12 - 1
^{76}Ge	IGEX	7.8	2039	87	Ionization	$>1.6\times10^{25}$	.14 – 1.2
^{76}Ge	Klapdor et al	7.8	2039	87	ionization	1.2×10^{25}	.44
^{82}Se	NEMO 3	9.2	2995	97	tracking	$>1.\times10^{23}$	1.8-4.9
^{100}Mo	NEMO 3	9.6	3034	95-99	tracking	$>1\times10^{24}$	.5-1.9
^{116}Cd	Solotvina	7.5	3034	83	scintillator	$>1.7\times10^{23}$	1.7 - ?
^{128}Te	Bernatovitz	34	2529		geochem	$>7.7 \times 10^{24}$	.1-4
^{130}Te	Cuoricino	33.8	2529		bolometric	$>2.8\times10^{24}$	.3-.7
^{136}Xe	DAMA	8.9	2476	69	scintillator	$>1.2\times10^{24}$	1.1 -2.9
^{150}Nd	Irvine	5.6	3367	91	tracking	$>1.2\times10^{21}$	3 - ?

Future experiments

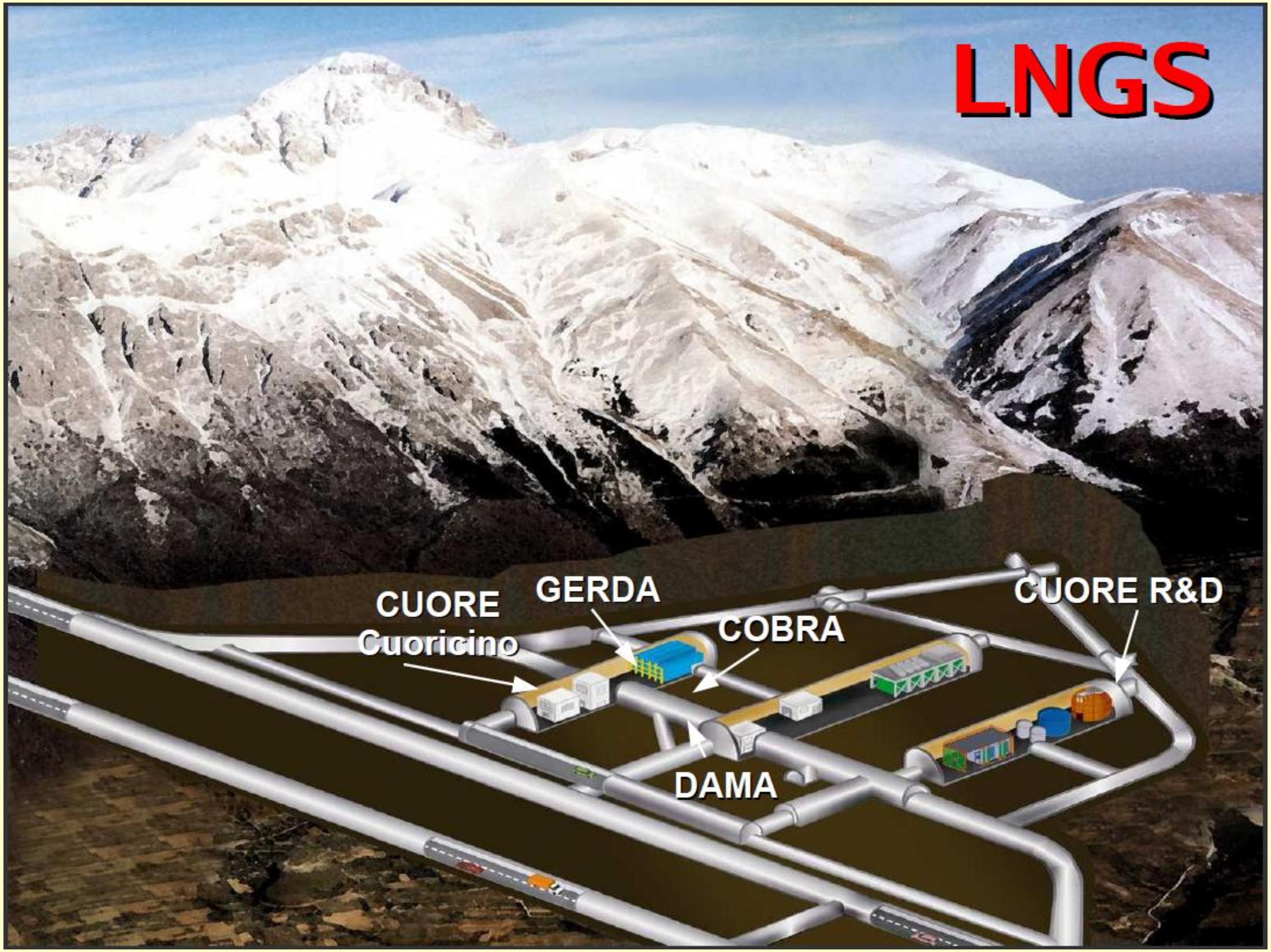
Summary

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	$(1-2)\times10^{26}$	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

Help by **Nicola, Luciano, INFN presidents** and LNGS directors not only to **CUORE**, but to **ββ experiment**

Experiment	Isotope	Mass [kg]	$T^{0\nu}_{1/2}$[y]	<m_ν >[meV]	Comment
CUORICINO	^{130}Te	40	$2.8x10^{24}$	300-700	Best sensitivity so far
CUORE0	^{130}Te	40	**$4x10^{24}$**	**210-490**	**End of 2011**
CUORE	^{130}Xe	200	**$2x10^{26}$**	**35-80**	**2014 => possible enrich**
DAMA	^{136}Te	6.5	$1.\ 2x10^{24}$	1.1-2.9	Also Dark Matter
LUCIFER	Various		R&D and possible development of CUORE		
COBRA	Various		R&D		
GERDA I	^{76}Ge	17	**$3x10^{25}$**	300-700	Running
GERDA I I	^{76}Ge	40	**$2x10^{26}$**	70-200	2012-2014
GERDA III	^{76}Ge	100	**$6x10^{27}$**	10-40	2012-2014

Experiments in LNGS



I like to think that the answer to Majorana 70 years ago may be found precisely in Italy and give also a possible explanation to the dominance of matter over antimatter in our Universe, from which our very same existence depends.

But =>

Majorana returns

Frank Wilczek

In his short career, Ettore Majorana made several profound contributions. One of them, his concept of 'Majorana fermions' — particles that are their own antiparticle — is finding ever wider relevance in modern physics.

Majorana "spin-flip" and ultra-low temperature atomic physics by Massimo Inguscio

Ettore Majorana's legacy and the Physics of the XXI centuryOctober 5-6, 2006 Catania, Italy

C. Xu and S. Sachdev **Majorana Liquids**: The Complete Fractionalization of the Electron

Jason Alicea: **Majorana fermions in a tunable semiconductor device**

Jacob Linder et al :Unconventional Superconductivity on a Topological Insulator

Roman M. Lutchyn, Jay D. Sau, and S. Das Sarma Majorana Fermions and a Topological Phase Transitionin Semiconductor-Superconductor Heterostructures

I am interested, but a poor experimentalist: Luciano please help!