Il Neutrino
tra Majorana e Dirac
con il Doppio Decadimento Beta
come giudice supremo

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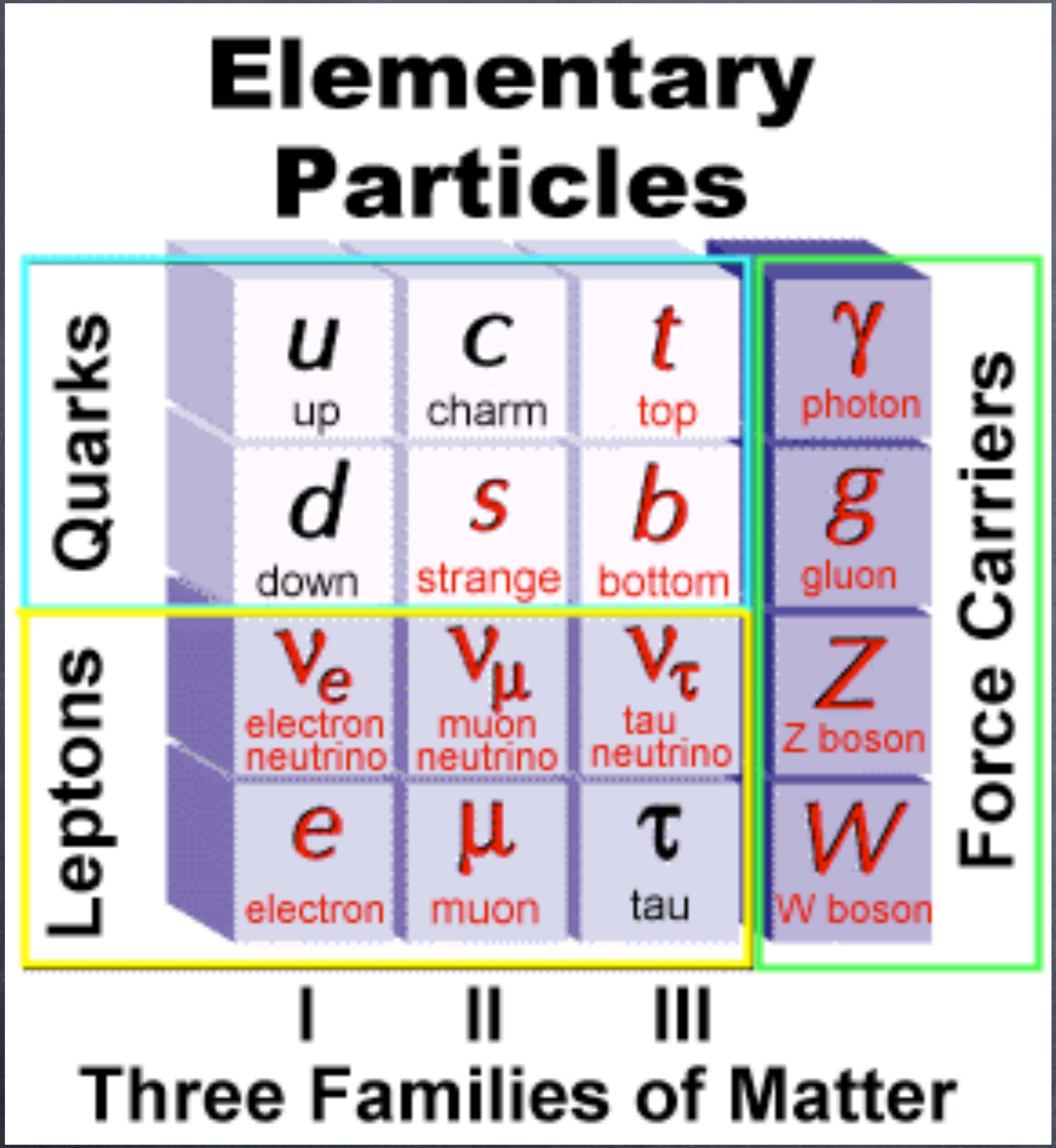
Indice

- Il neutrino nello Standard Model
- La scoperta della massa
- Majorana o Dirac
- Come si sceglie : il Decadimento Doppio Beta
- La difficolta' sperimentale
  - I laboratori del Gran Sasso
  - Il Piombo romano
  - CUORE
- Una storia da seguire

Il neutrino nello SM



Elementary Particles

	I	II	III	Force Carriers
Quarks	u up	c charm	t top	γ photon
Quarks	d down	s strange	b bottom	g gluon
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z Z boson
Leptons	e electron	μ muon	τ tau	W W boson

Three Families of Matter

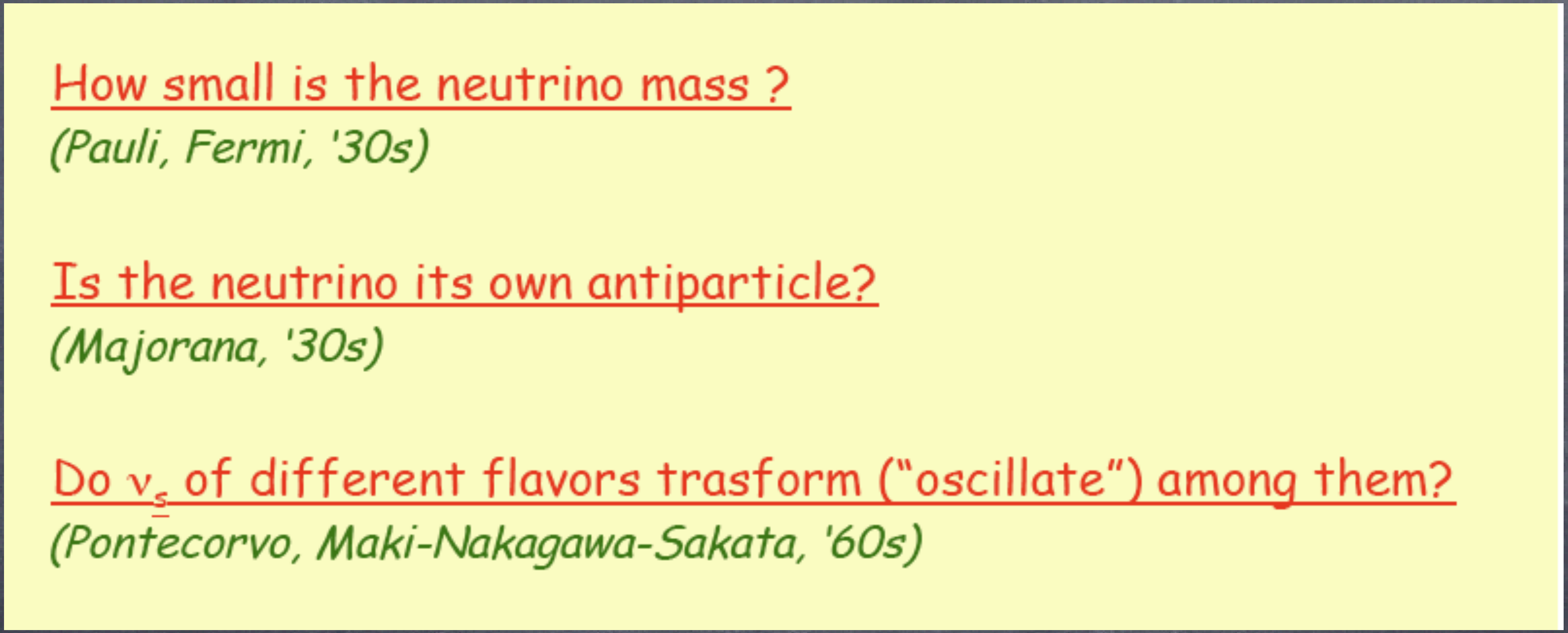
Ognuno fa quello che puo'. Al tempo della costruzione del Modello Standard il neutrino era pensato essere privo di massa. Quindi il modello e' stato costruito con questa ipotesi.

La massa dei neutrini

(bignami-like)

Le domande chiave

pero'erano state tutte gia' poste



How small is the neutrino mass ?

(Pauli, Fermi, '30s)

Is the neutrino its own antiparticle?

(Majorana, '30s)

Do ν_s of different flavors trasform ("oscillate") among them?

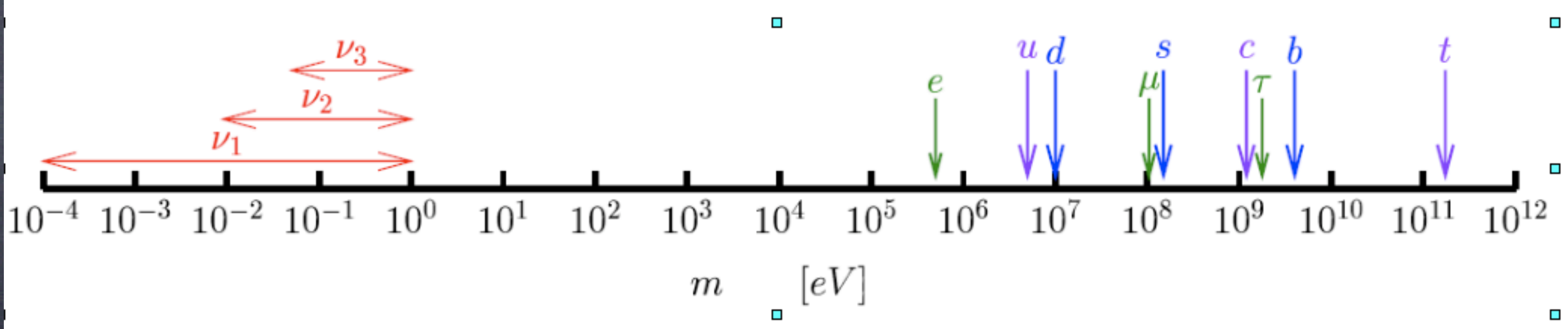
(Pontecorvo, Maki-Nakagawa-Sakata, '60s)

c'e' qualcosa di familiare

Atmospheric Cross-Mixing Solar

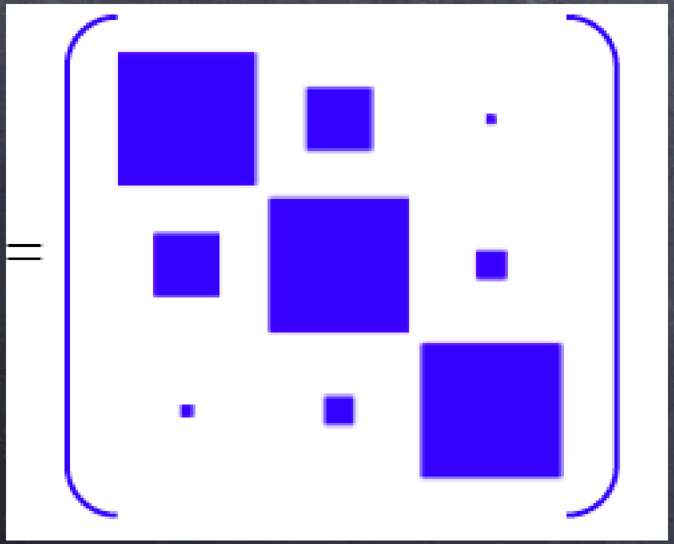
$$U=\begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix}\begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{bmatrix}\begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}$$

eccetto che

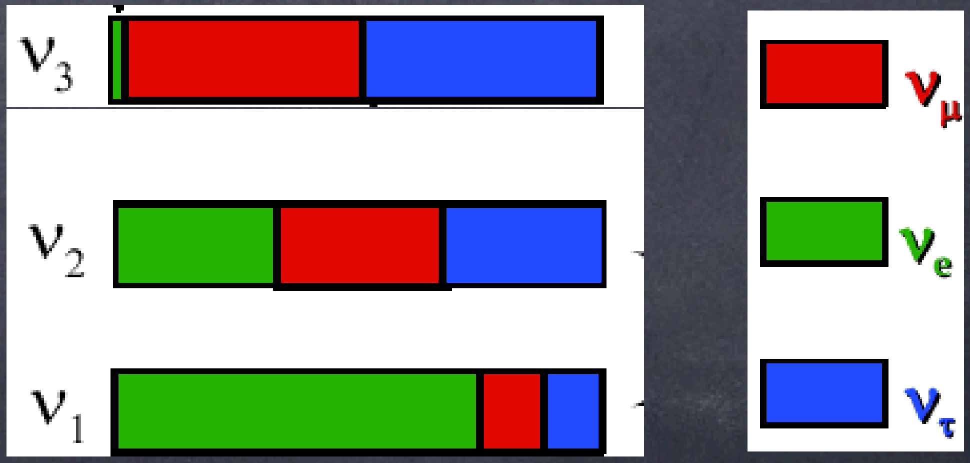


e

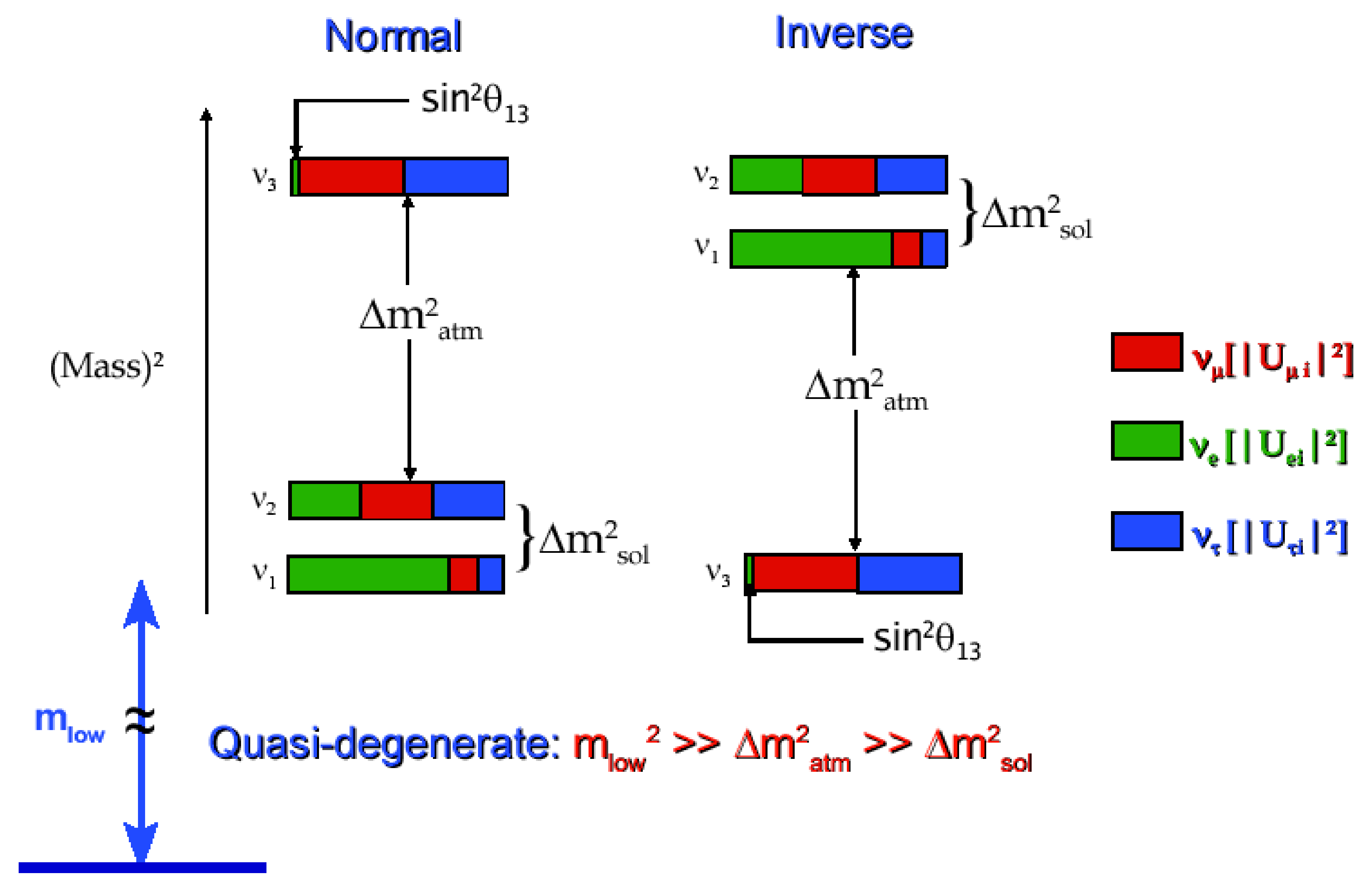
V_{CKM} =



V_{PMNS}



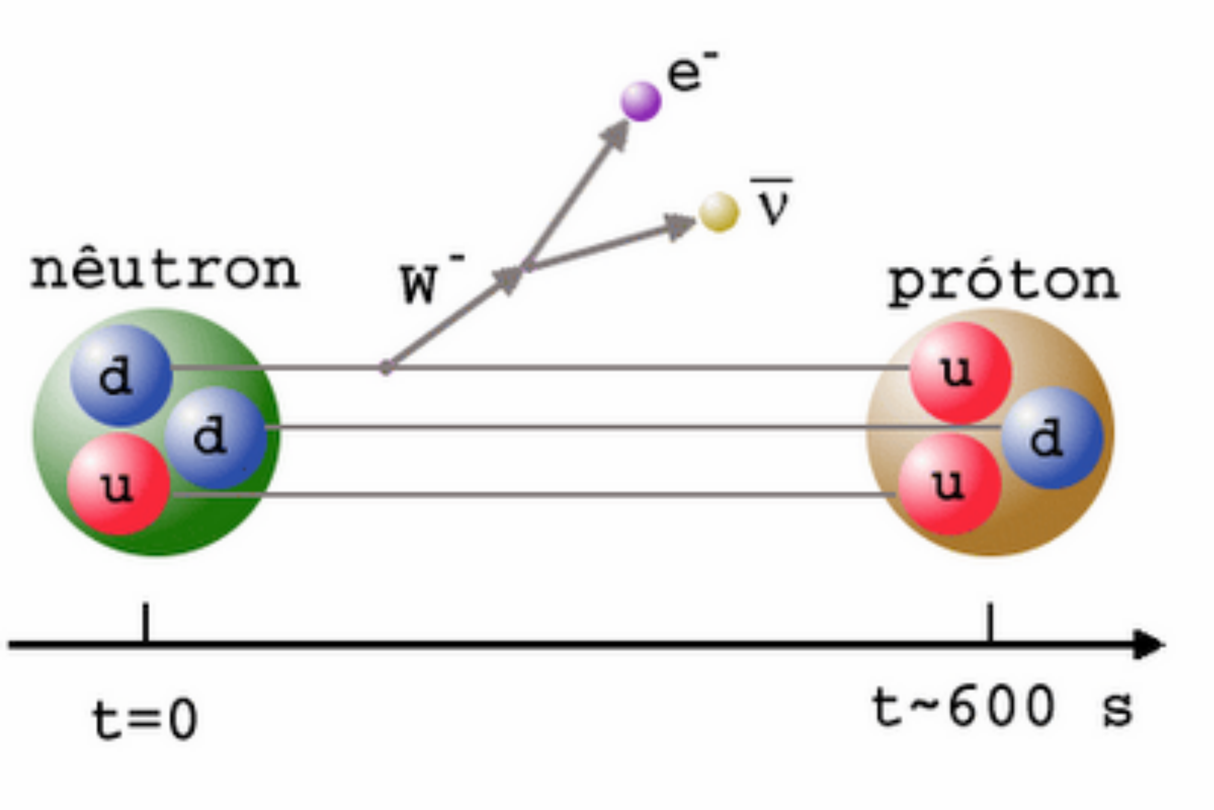
Ben tre possibilita'....


Normal
Inverse
$\sin^2\theta_{13}$
ν_3
ν_2
ν_1
Δm^2_{atm}
Δm^2_{sol}
(Mass)²
ν_2
ν_1
Δm^2_{sol}
Δm^2_{atm}
ν_3
$\sin^2\theta_{13}$
$\nu_\mu[|U_{\mu i}|^2]$
$\nu_e[|U_{ei}|^2]$
$\nu_\tau[|U_{\tau i}|^2]$
m_{low} ≈

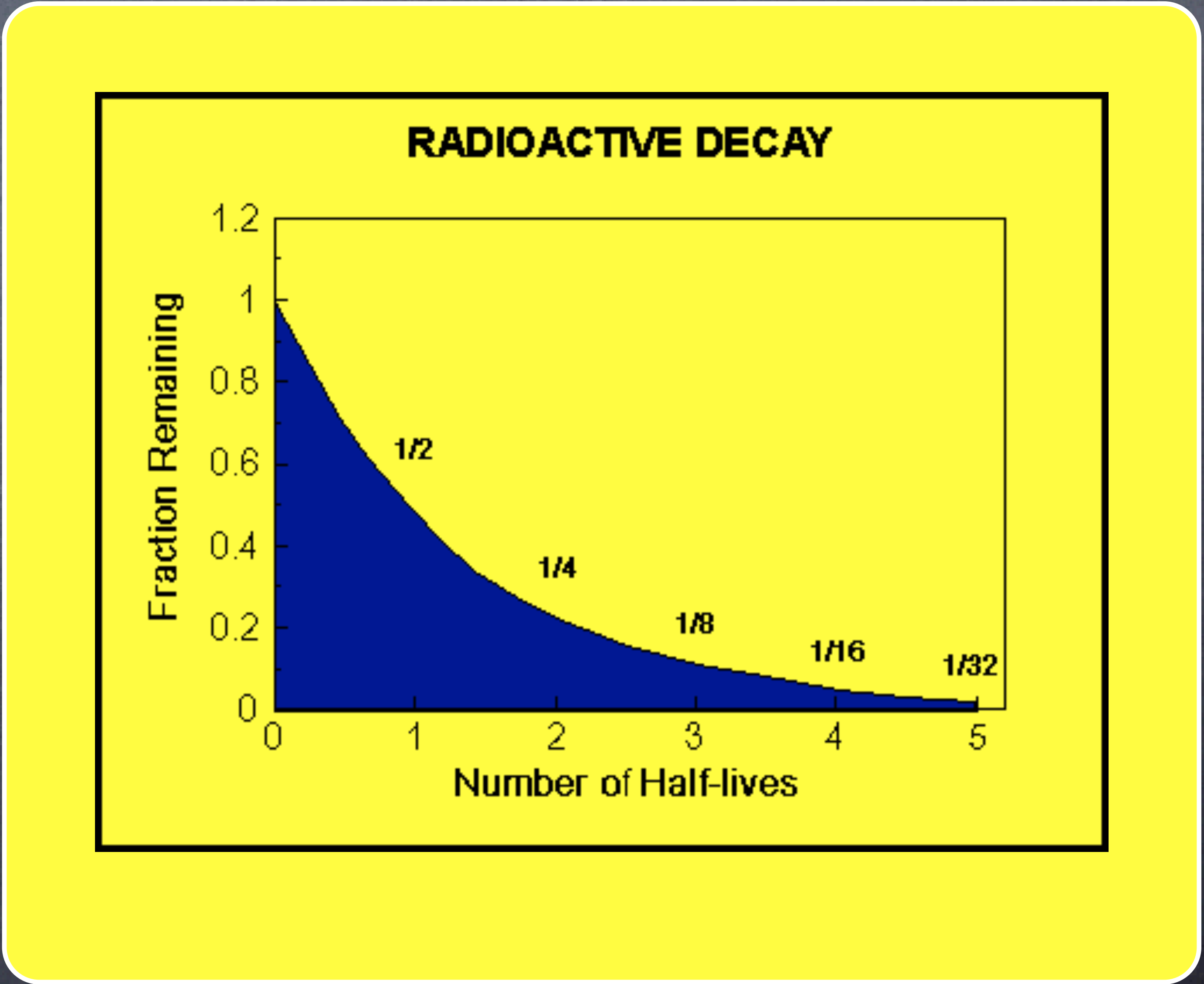
Quasi-degenerate: $m_{low}^2 >> \Delta m^2_{atm} >> \Delta m^2_{sol}$

Il decadimento Beta

Il decadimento del neutrone


e-
ν̄
nêutron
W-
próton
d
d
u
u
d
u
t=0
t~600 s

simpatico no ? Ogni 10 minuti il numero di neutroni si dimezza !



ma noi ci siamo ancora !!

Pauli e l’ipotesi folle

Dear Radioactive Ladies and Gentlemen,

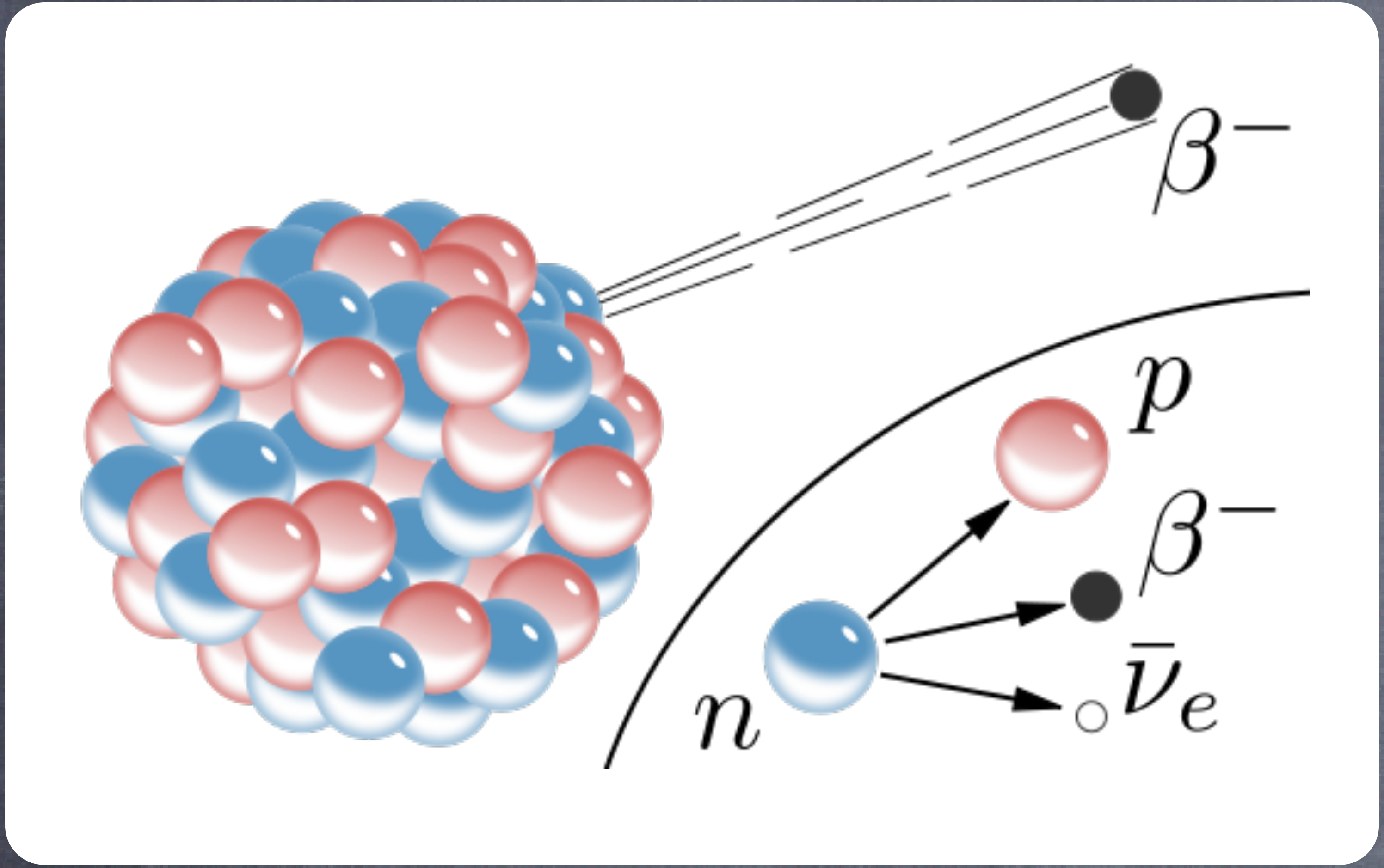
As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

I agree that my remedy could seem incredible because one should have seen those neutrons very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's well better not to think to this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge. Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant
W. Pauli

(nel 1932 Chadwick scopre il neutrone, che non assomiglia neanche un poco a quello di Pauli !)

Il decadimento beta dei nuclei



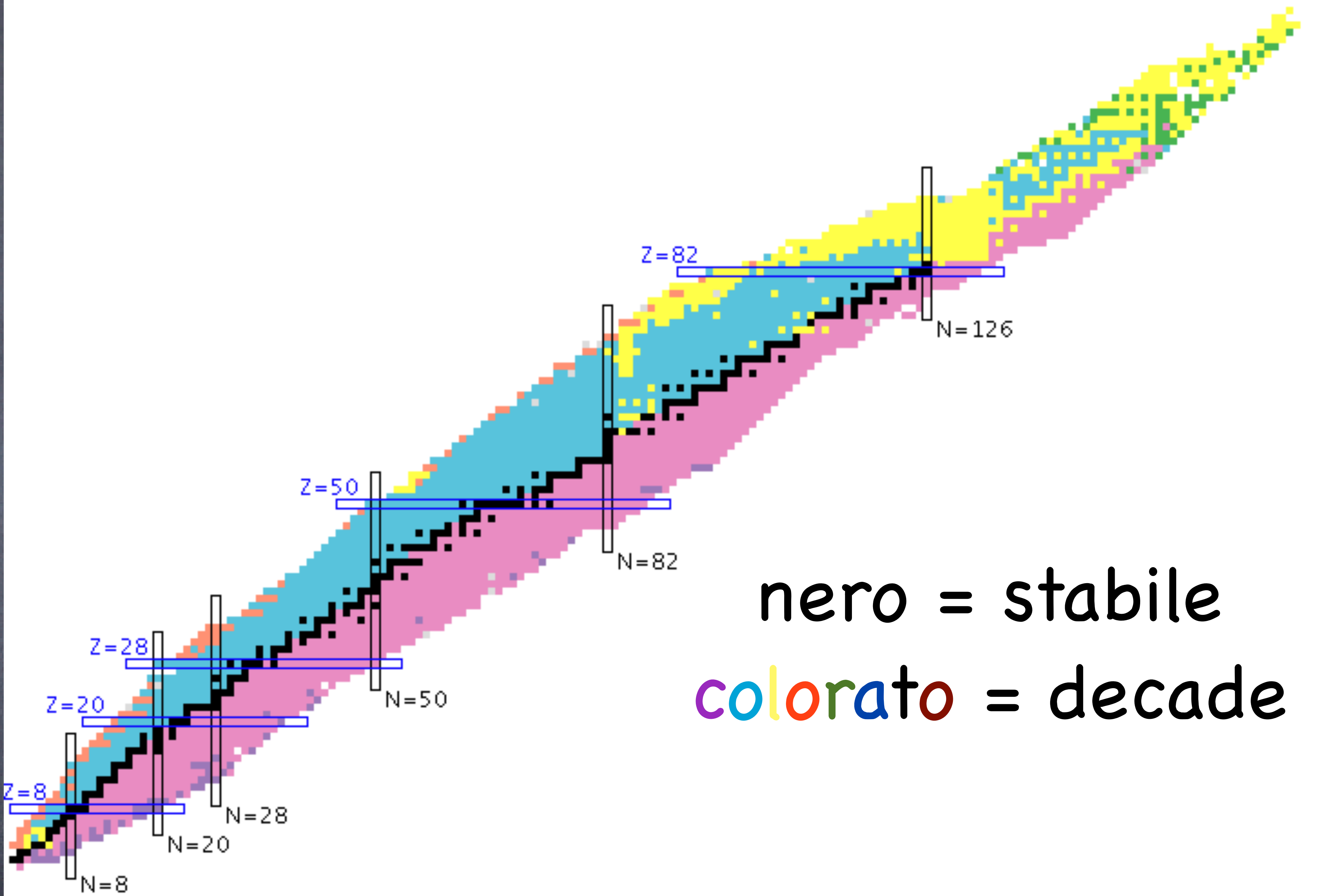
La maggior parte dei nuclei non permette al neutrone di decadere. L'energia di legame glielo impedisce

Gli isotopi 'radioattivi' lo possono pero' fare.
Un nucleo (Z,A) diventa (Z+1,A) e si trasmuta !

L'alchimista in fondo aveva ragione....

certo...pero'....lui cercava l'Oro, l'elemento Z-1 dell'oro e' il Platino

La valle della morte



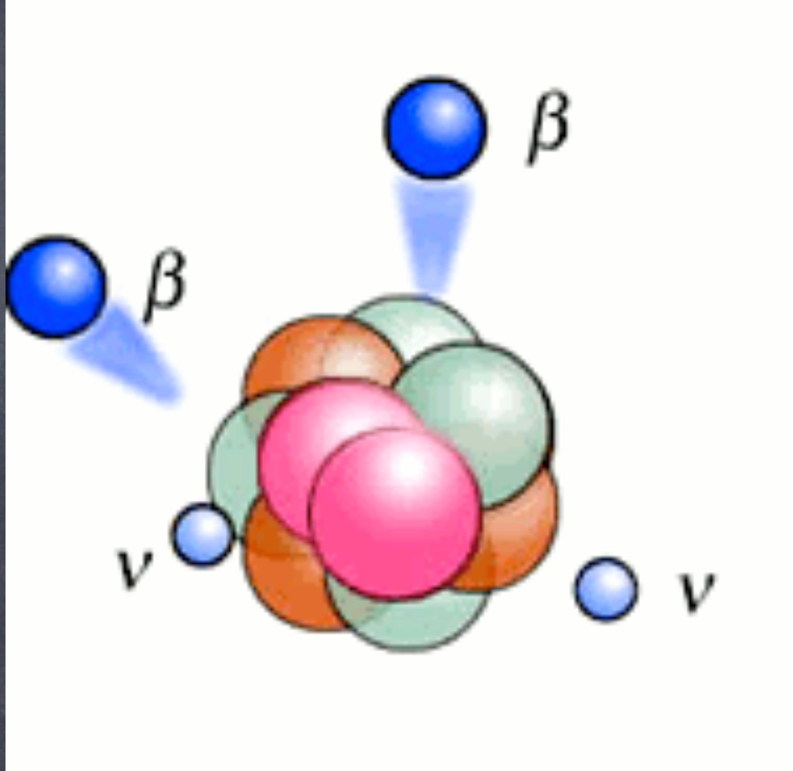
nero = stabile

colorato = decade

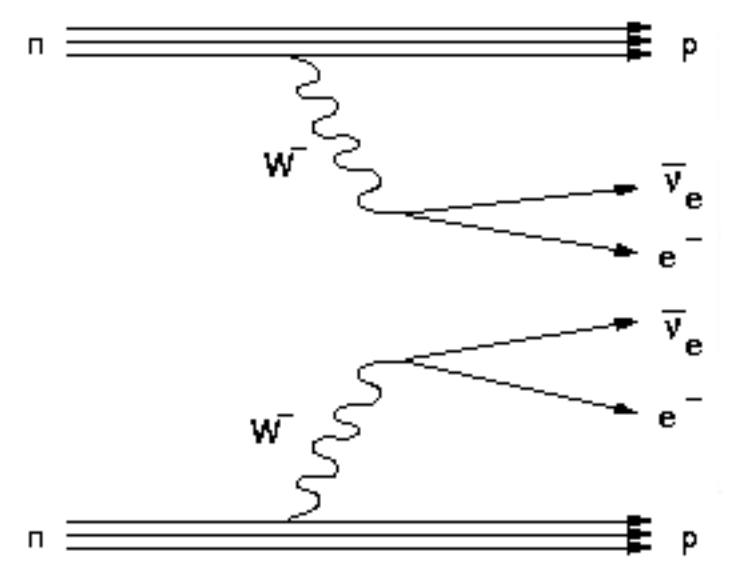
La linea della vita

Doppio Beta

Qui pero’ si esagera !!!!



β
β
ν
ν

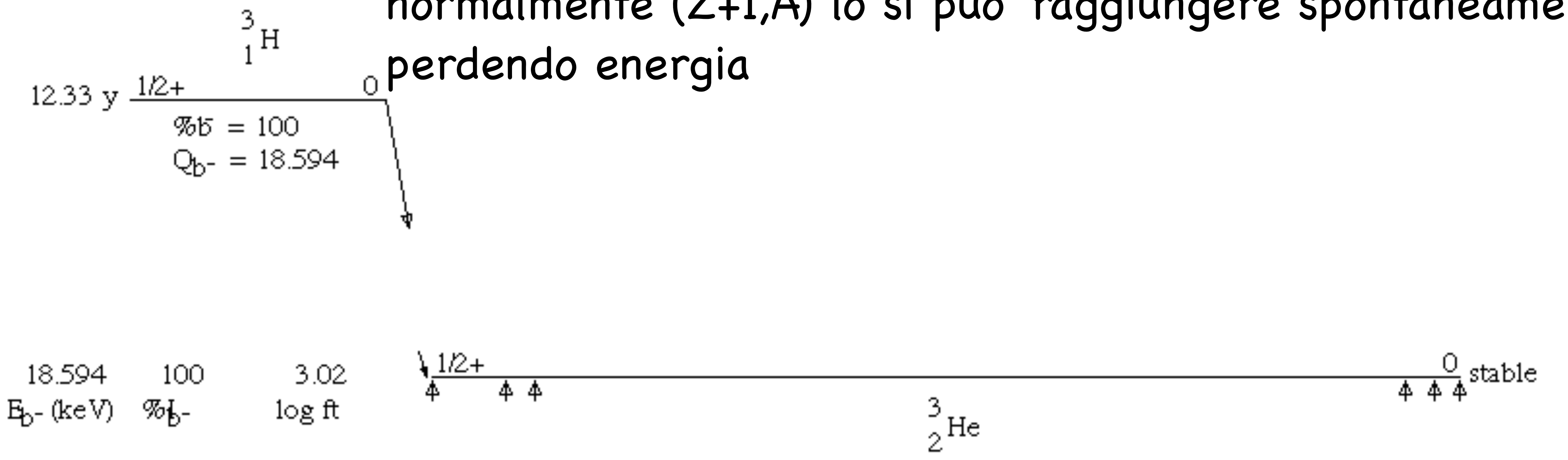


n
p
W^-
$\bar{\nu}_e$
e^-
$\bar{\nu}_e$
e^-
W^-
n
p

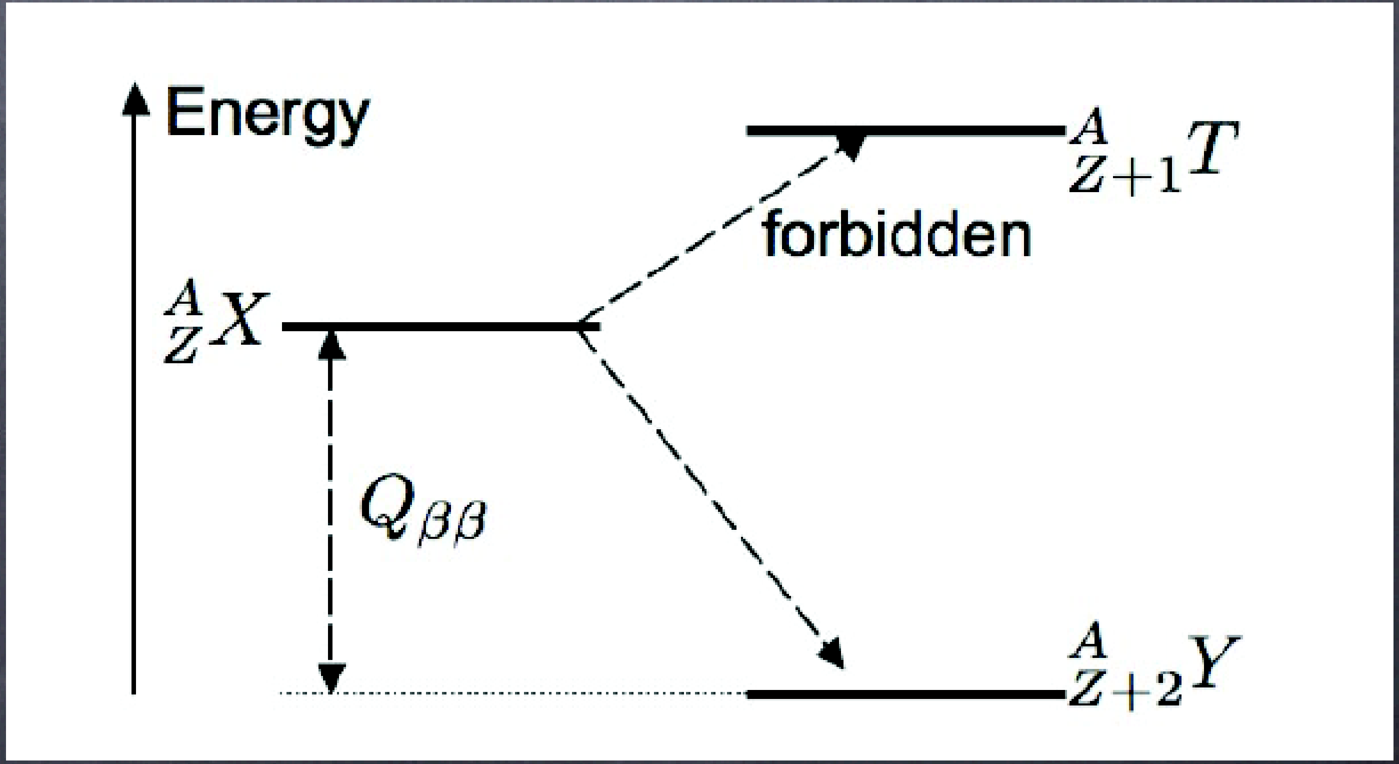
Due neutroni che decadono simultaneamente

come puo' succedere ?

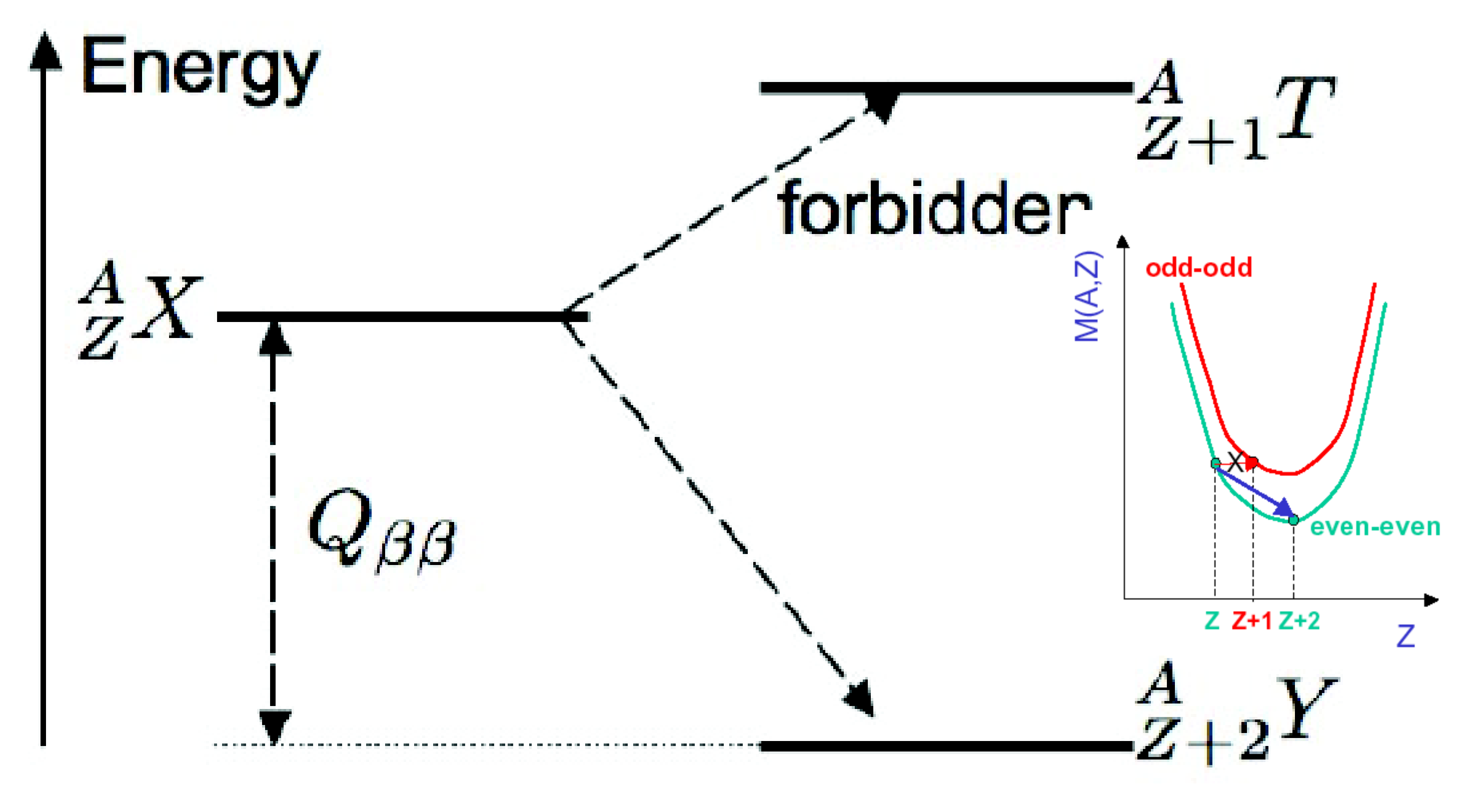
normalmente (Z+1,A) lo si puo' raggiungere spontaneamente perdendo energia


3
1 H
12.33 y
1/2+
0
%b- = 100
Qb- = 18.594
18.594
100
3.02
Eb- (keV)
%Ib-
log ft
1/2+
0
stable
3
2 He

ma se cosi' non fosse......................


Energy
$^{A}_{Z}X$
$^{A}_{Z+1}T$
forbidden
$Q_{\beta\beta}$
$^{A}_{Z+2}Y$

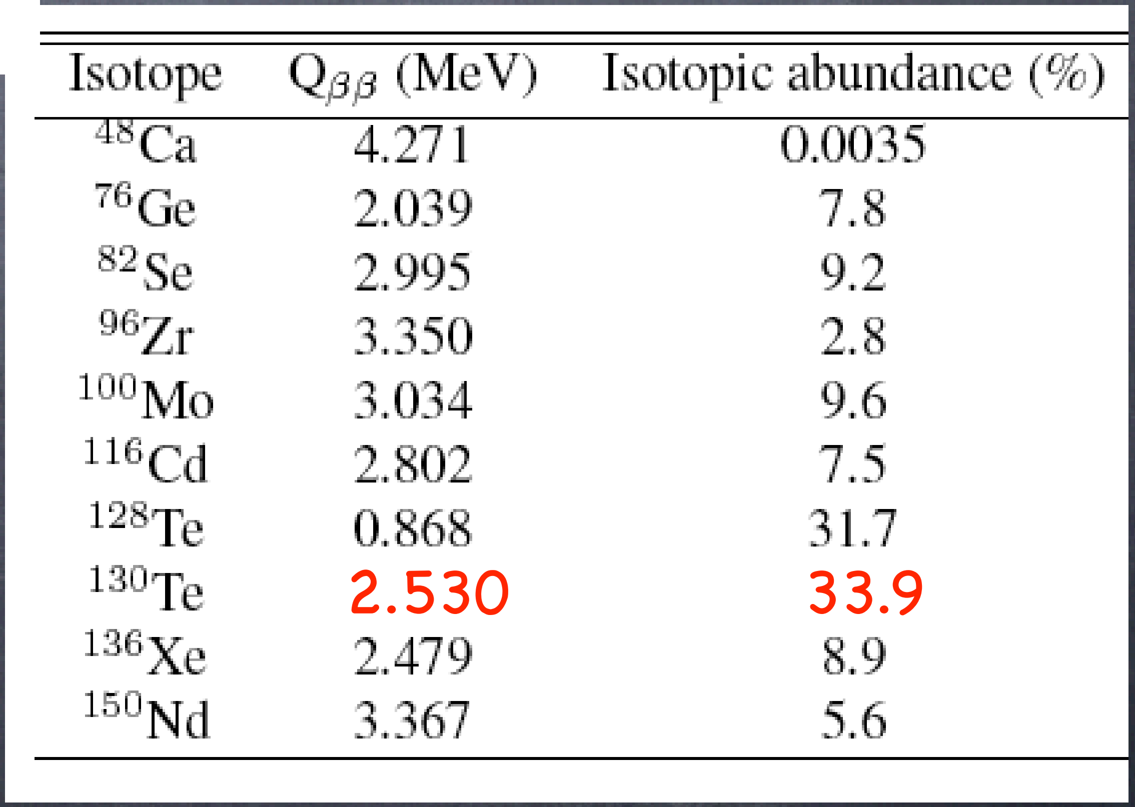
Double Beta Decay


Energy
$^{A}_{Z+1}T$
forbidden
$^{A}_{Z}X$
$Q_{\beta\beta}$
$^{A}_{Z+2}Y$
M(A,Z)
odd-odd
X
even-even
Z Z+1 Z+2
Z

Gia' predetto da Maria Goeppert-Mayer nel 1935

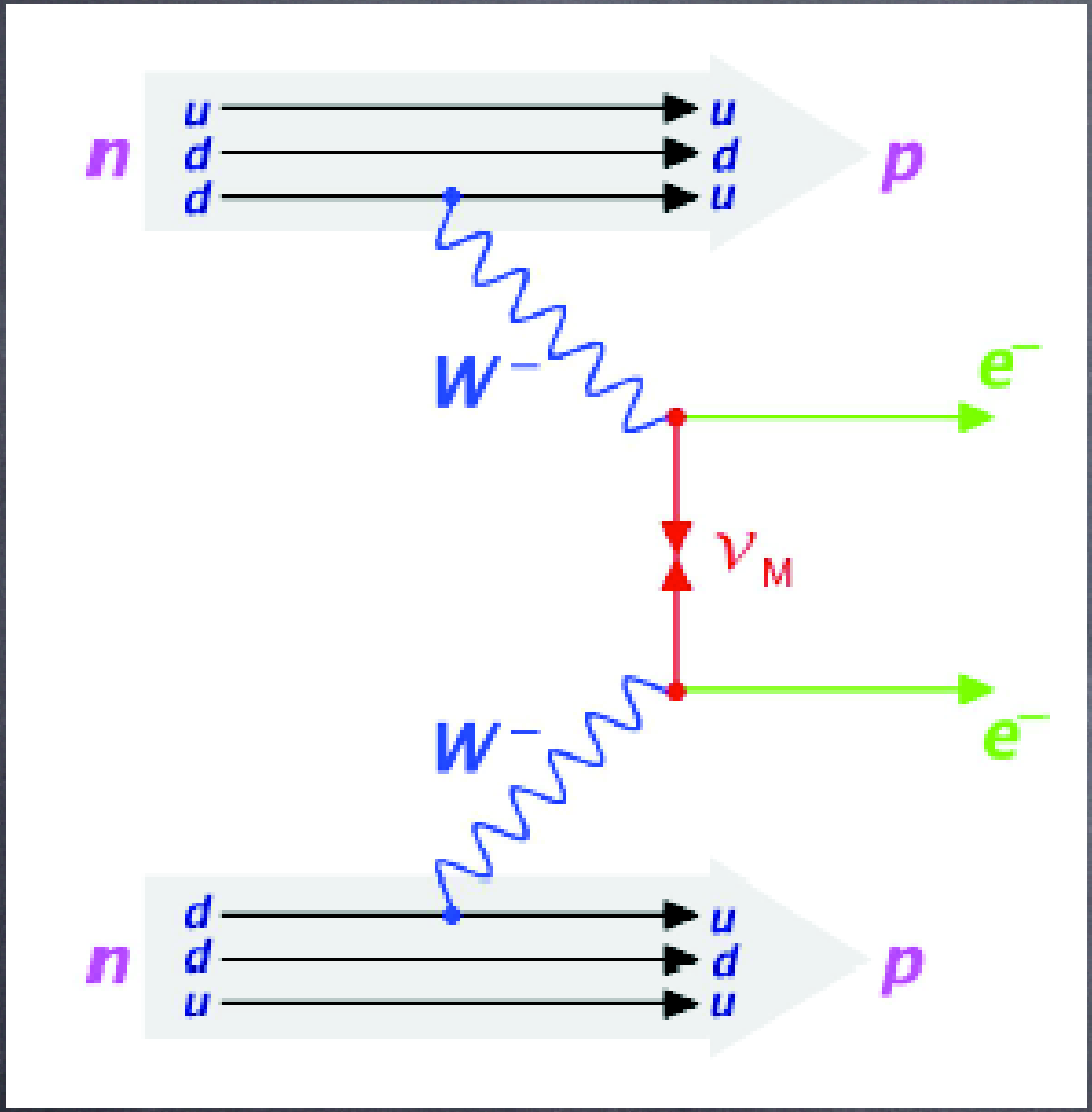
Prima evidenze geochimiche poi osservazione diretta nel ^{82}Se (S. Elliot & M. Moe 1986)

$T_{1/2}$ ~ 10^{20} years !! (poi ci torniamo)



Isotope	$Q_{\beta\beta}$ (MeV)	Isotopic abundance (%)
^{48}Ca	4.271	0.0035
^{76}Ge	2.039	7.8
^{82}Se	2.995	9.2
^{96}Zr	3.350	2.8
^{100}Mo	3.034	9.6
^{116}Cd	2.802	7.5
^{128}Te	0.868	31.7
^{130}Te	2.530	33.9
^{136}Xe	2.479	8.9
^{150}Nd	3.367	5.6

Sempre piu' difficile (0νββ)



n
u
d
d
u
d
u
p
W⁻
e⁻
ν_M
W⁻
e⁻
n
d
d
u
u
d
u
p

Un momento ...

c'e' un problema

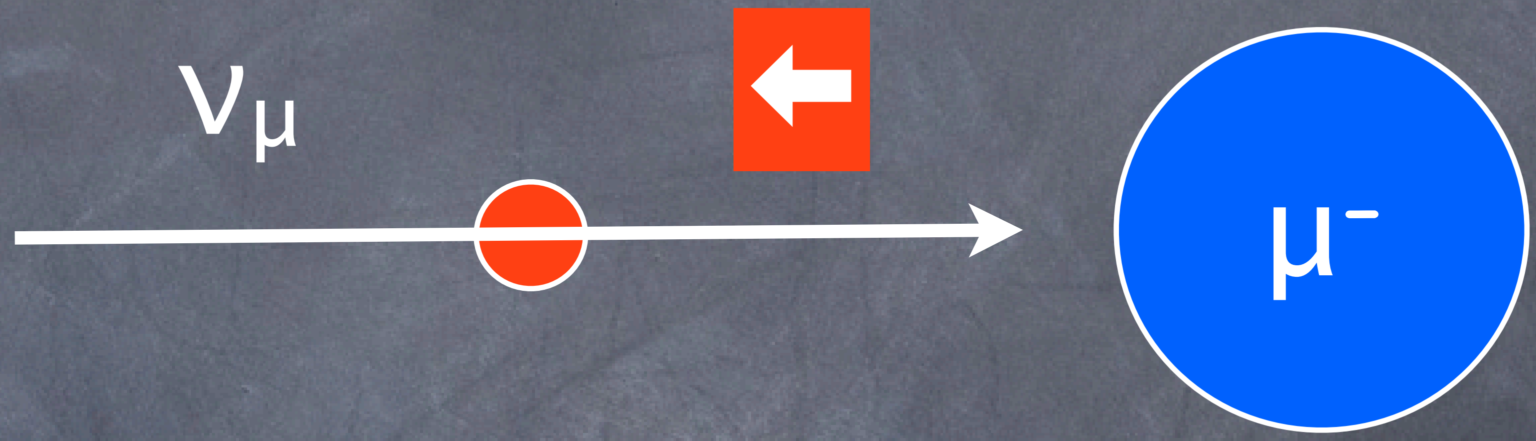
sia da sopra che da sotto escono neutrini

un neutrino che esce non puo' rientrare (sarebbe un antineutrino)

[Time Out: una lunga digressione]

Dirac

Il numero leptonico e' conservato



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

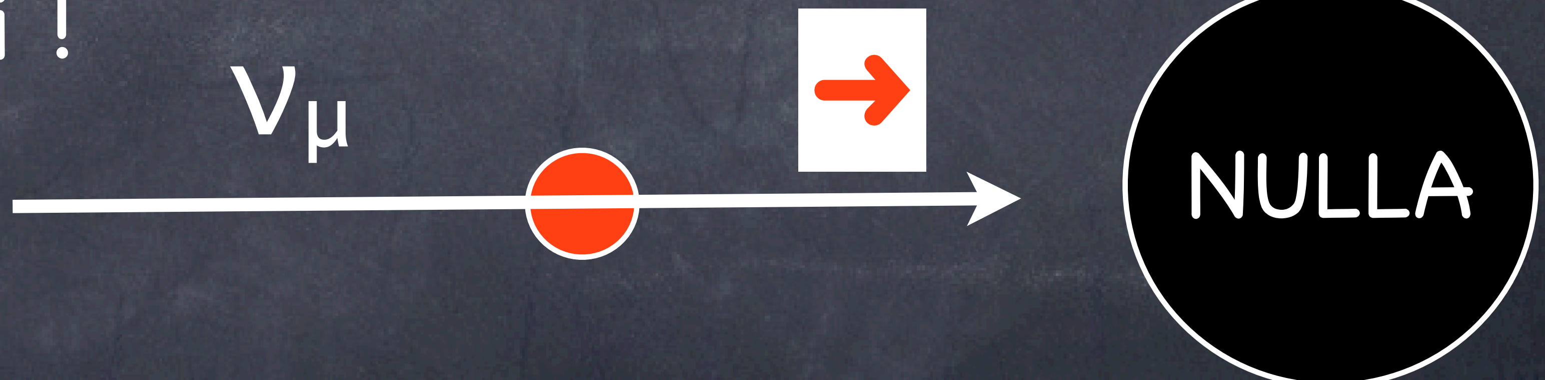
L=-1/+1

$\nu_\mu \to \mu^-$

$\bar{\nu}_\mu \to \mu^+$

L'interazione debole e' V-A
(i leptoni destrogiri non interagiscono)

Quando il ν non aveva massa nel mondo di Dirac questo non poteva succedere, ora che la hanno, invece si !



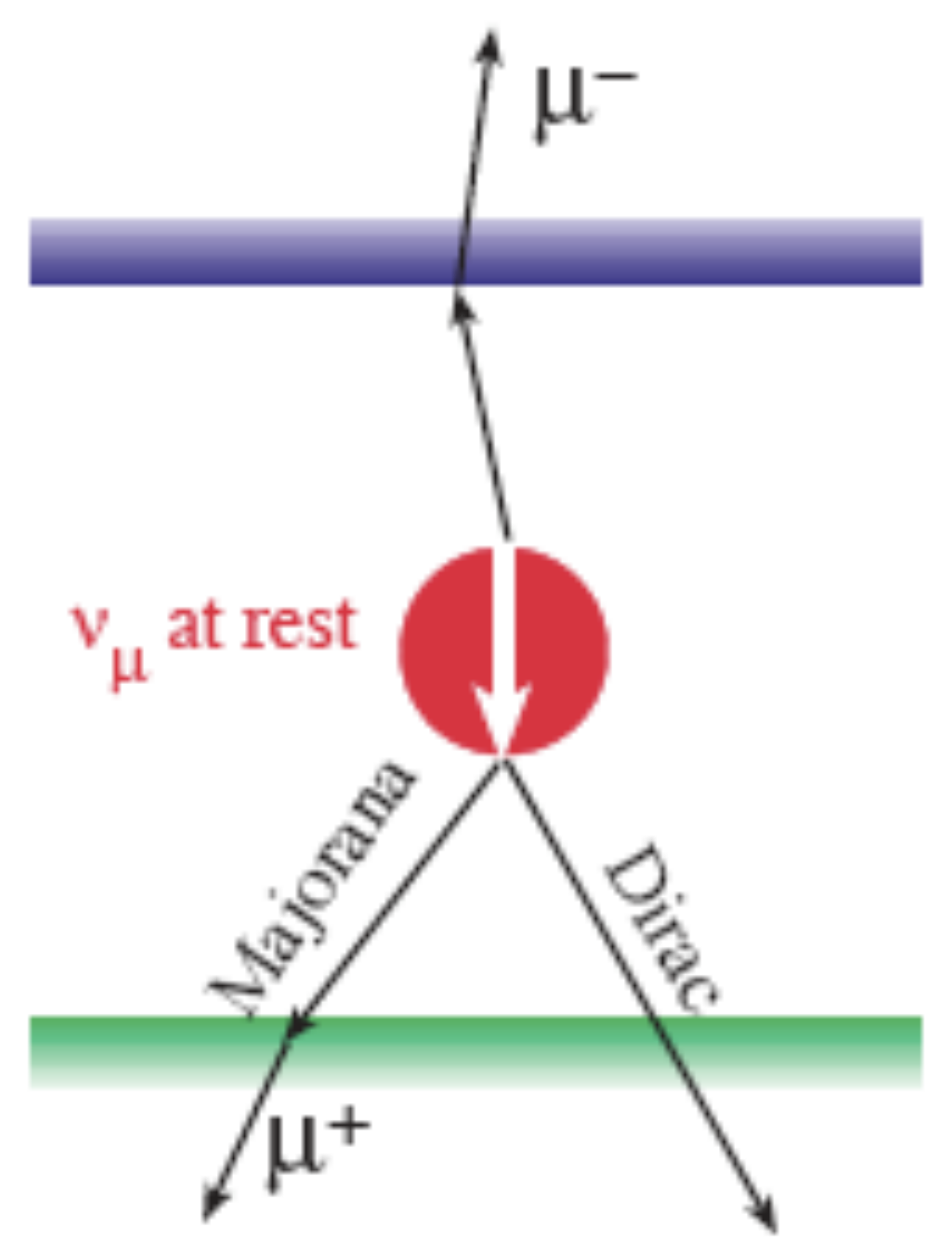
la congettura di Majorana

$$\nu = \overline{\nu}$$

Il numero leptonico e' violato

(il neutrino che esce puo' rientrare come antineutrino)

Caveat: i neutrini senza massa non permettono di dimostrare l'ipotesi di Majorana in pratica. Non si puo' correre piu' veloci di loro per vedere lo spin che si gitra !!


μ^-
ν_μ at rest
Majorana
Dirac
μ^+

se Majorana avesse avuto ragione ....

- quello che ci aspettiamo di misurare e':

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

dove pero' ....

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

$$m_{\beta\beta} = \sum m_{\nu_k} U_{ek}^2 = \cos^2\theta_{13}\left(m_1\cos^2\theta_{12} + m_2 e^{2i\alpha}\sin^2\theta_{12}\right) + m_3 e^{2i\beta}\sin^2\theta_{13}$$

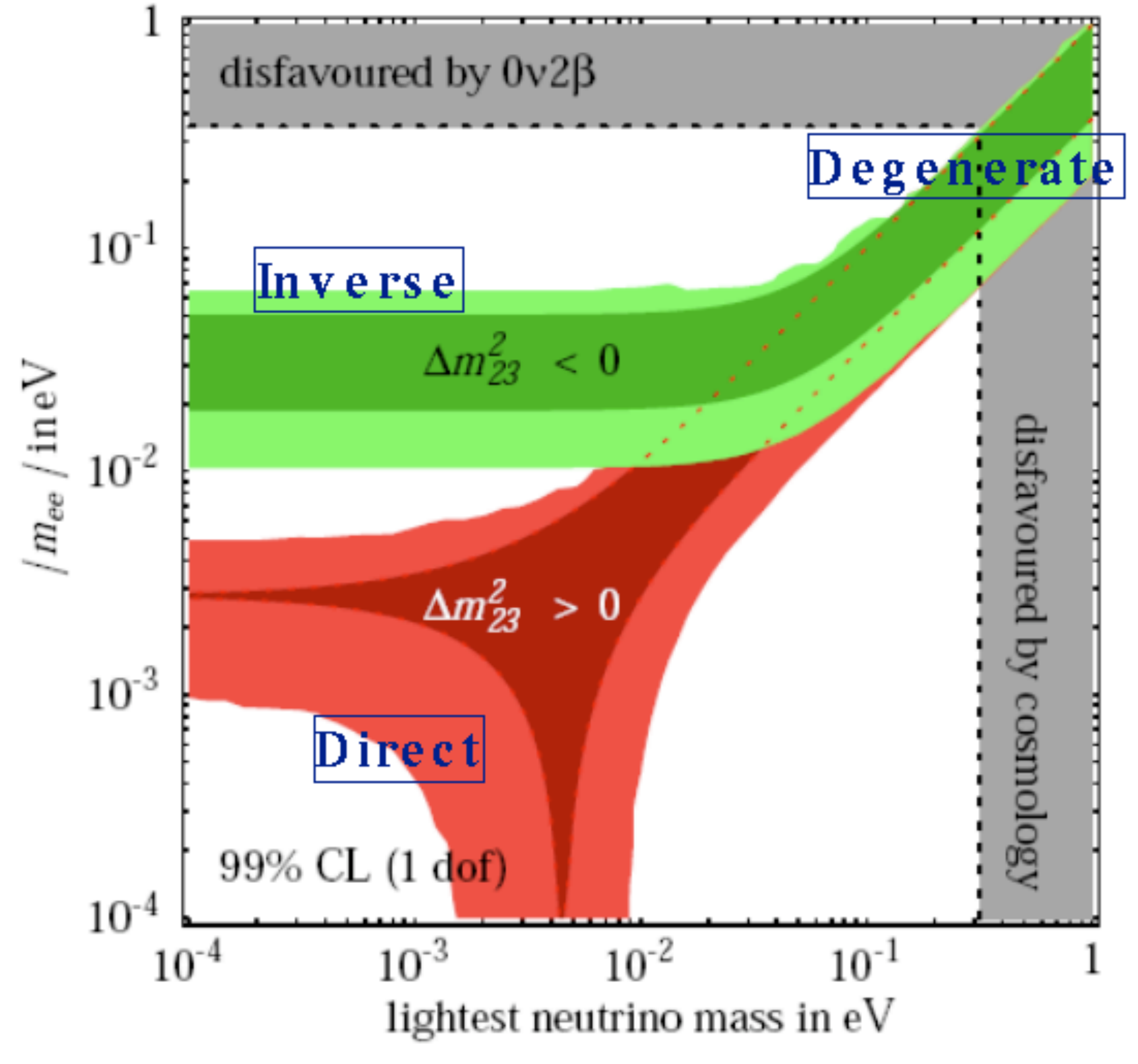
$$U = \overset{\text{Atmospheric}}{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}} \overset{\text{Cross-Mixing}}{\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}} \overset{\text{Solar}}{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}$$

in termini (poco) meno esotici

$$\left[T^{0\nu}_{1/2}\right]^{-1} = C \cdot \frac{\langle m_{\beta\beta}\rangle^{2}}{m_e^{2}}$$

$$C = |M^{0\nu}|^{2} \bullet G^{0\nu} \quad [y^{-1}]$$

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



in termini brutali

- 10^{25} , 10^{26}, forse di piu` (anni)

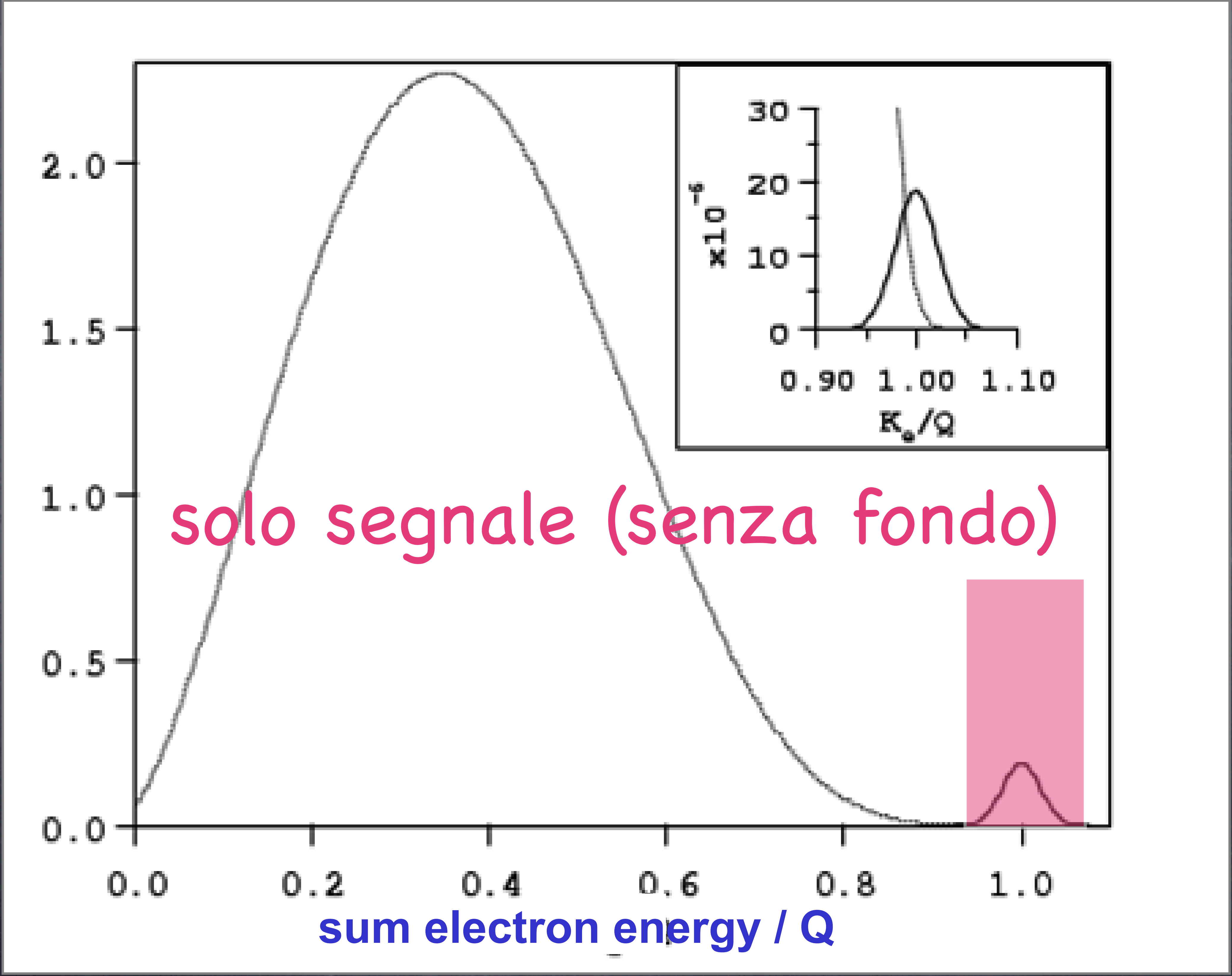
che vuol dire ?

per esempio, l’eta’ dell’universo e’ 1.5 10^{9} anni

pero’ il Numero di Avogadro e’ 6 10^{23}

che ci si impara ?

Come appare in pratica ?



solo segnale (senza fondo)

sum electron energy / Q

Quanti eventi ?

Numero di eventi = (Numero di moli* Numero di Avogadro*Numero di anni)/Tempo di vita

$N_A = 6 * 10^{23}$

$N_y = 1$

$\tau = 10^{26}$

$N_{eventi} = 10$

Quante moli ?

1600

per un elemento di peso atomico 100 sono 160 Kg

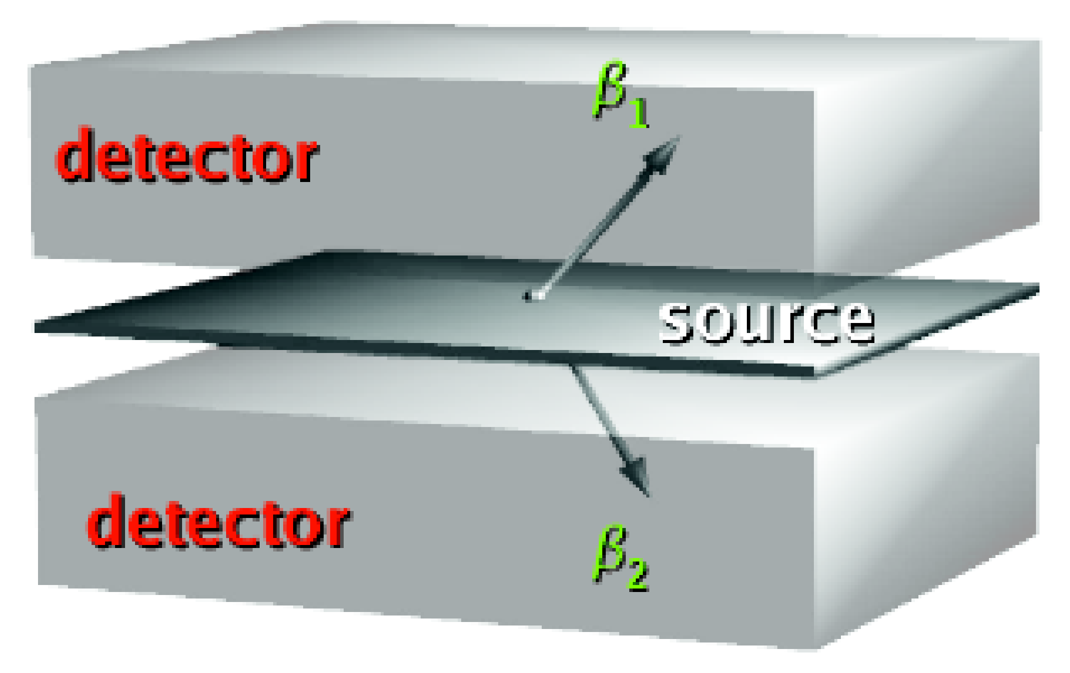
Purtroppo c'e' anche il fondo

- Interno alla sorgente
  - primordiale (^{232}Th, ^{238}U, ^{40}K)
  - di attivazione cosmogenica
- Esterno alla sorgente
  - primordiale nei materiali esterni
  - neutroni
  - raggi cosmici
- altro (che purtroppo c'e' sempre)

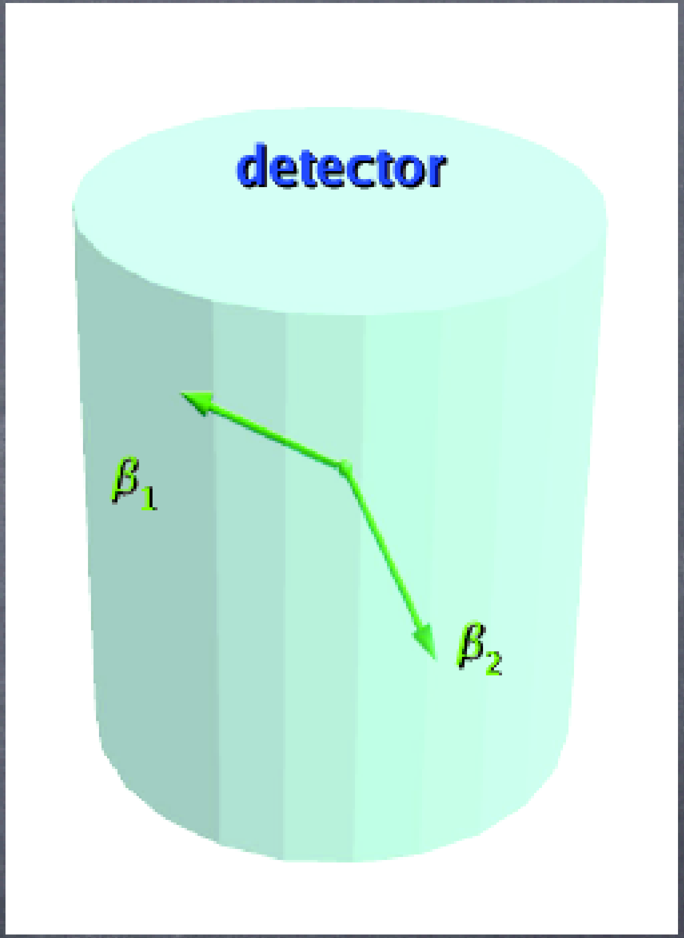
Due filosofie della rivelazione

Emettitore ≠ Rivelatore

Emettitore ⊆ Rivelatore



β_1
detector
source
detector
β_2



detector
β_1
β_2

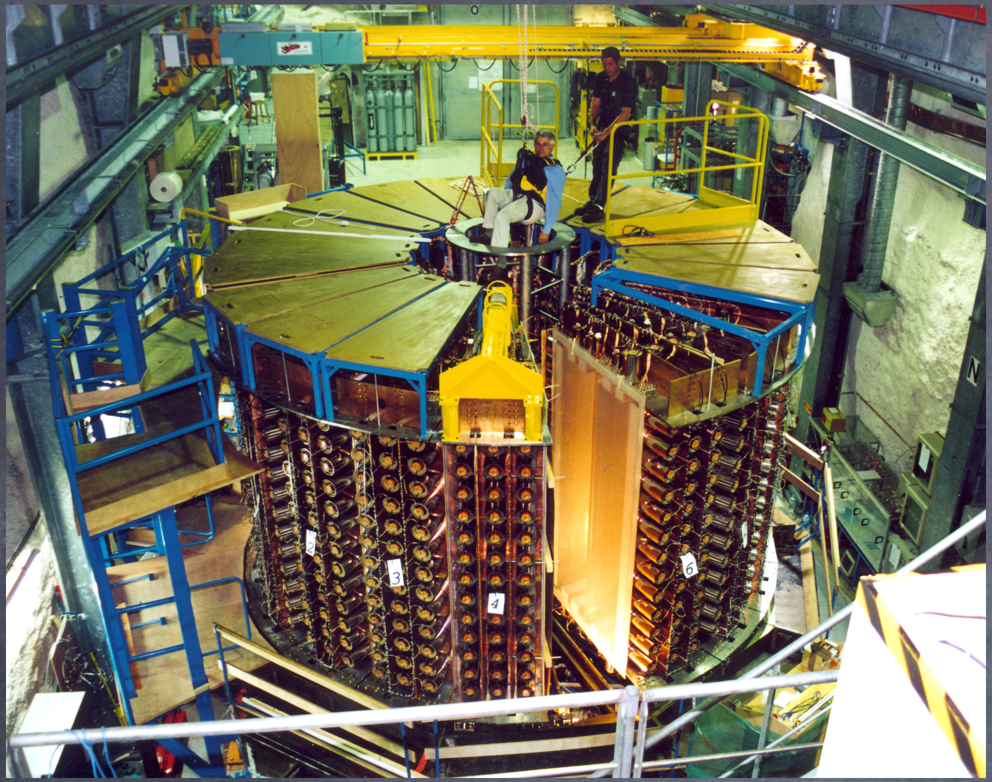
+++ Topologia, Rumore

--- M, ΔE, ε

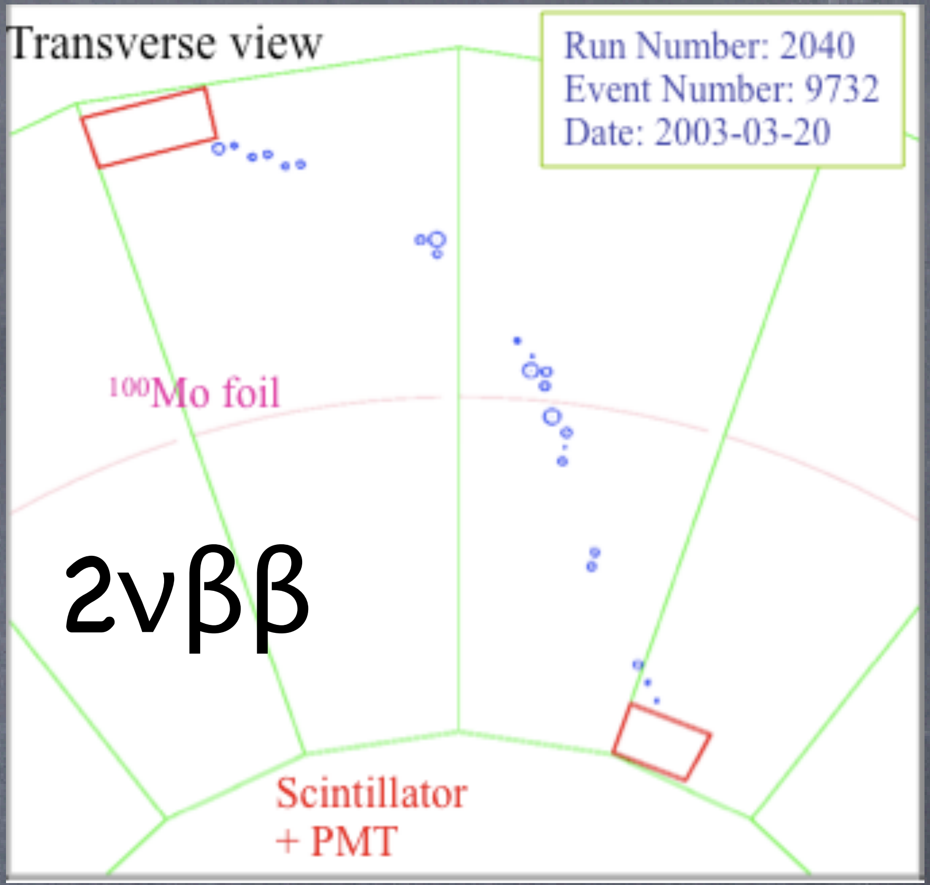
+++ M, ΔE, ε

--- Topologia, Rumore

NEMO: il prototipo di E≠R



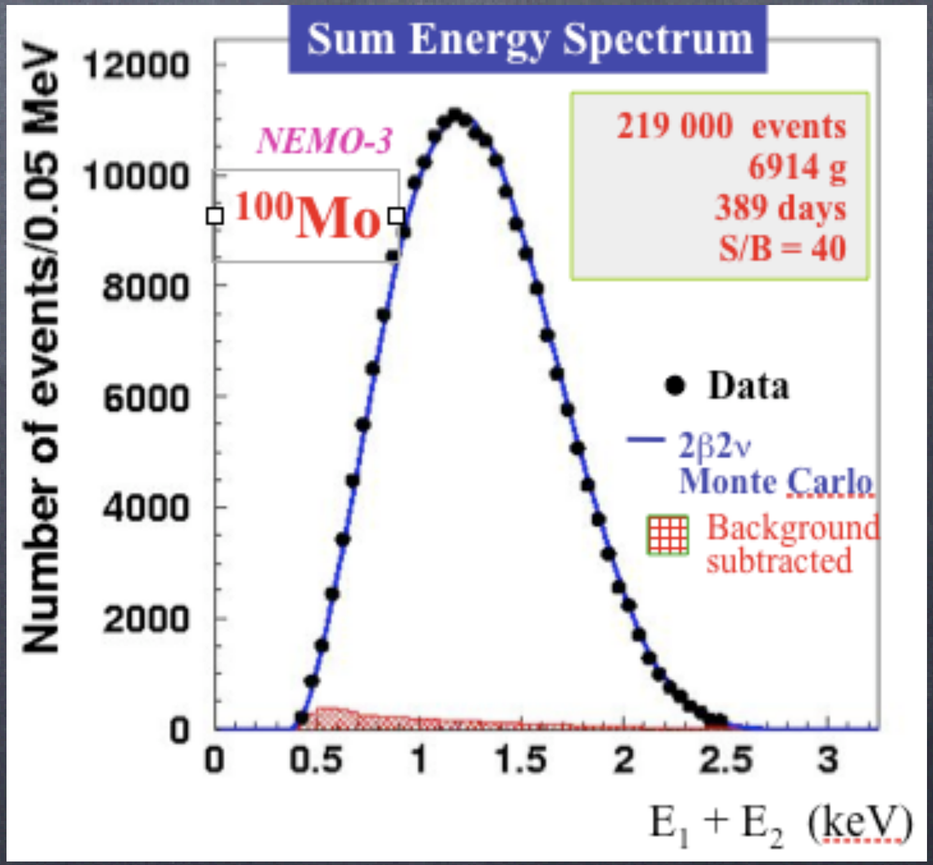
richiede
centinaia
di
m^2
per
essere
competitivo


Transverse view
Run Number: 2040
Event Number: 9732
Date: 2003-03-20
100Mo foil
2νββ
Scintillator
+ PMT

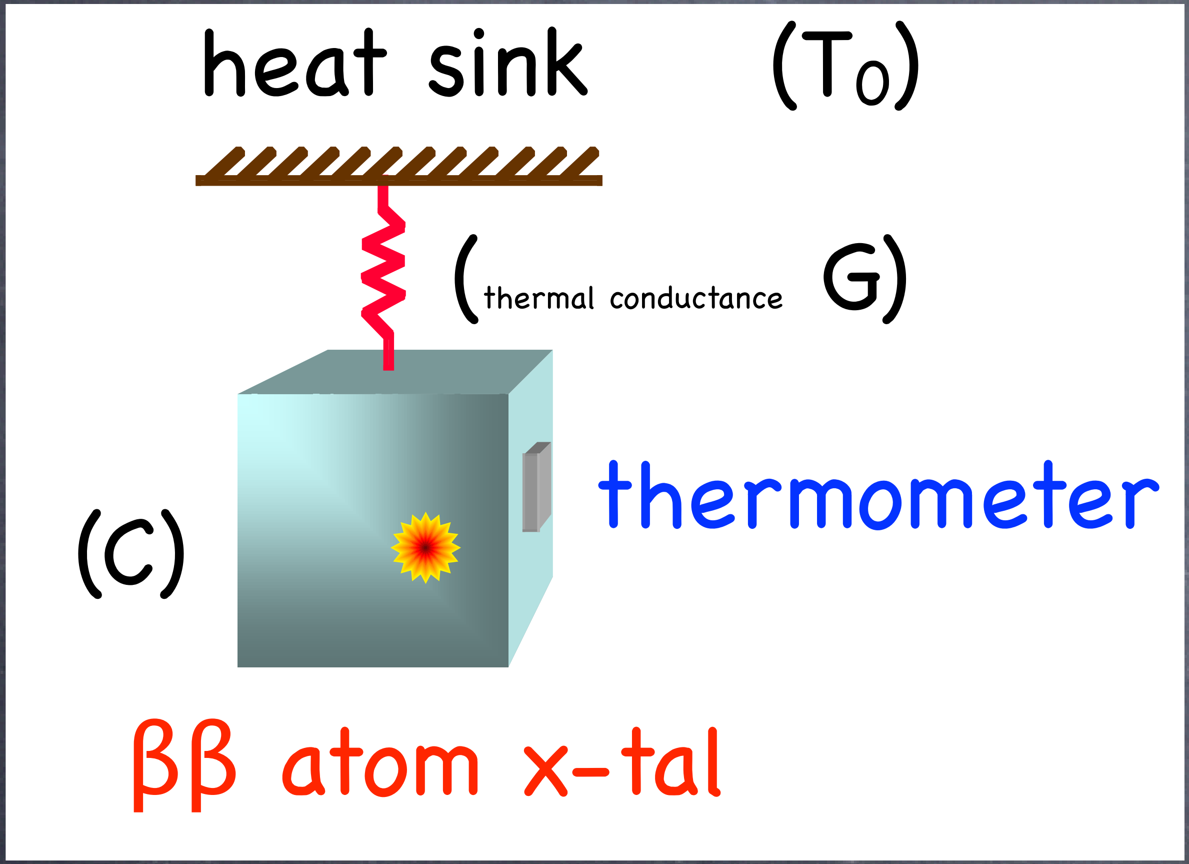
Source: 10 kg of ββ isotopes
cylindrical, S = 20 m^2, e ~ 60 mg/cm^2

Tracking detector:
drift wire chamber operating
in Geiger mode (6180 cells)
Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

Calorimeter:
1940 plastic scintillators
coupled to low radioactivity PMTs



Calorimetria a temperature ultra basse


heat sink
(T_0)
(thermal conductance G)
(C)
thermometer
ββ atom x-tal

Fisica: $\Delta T = E/C$

(Energia/ Capacita' termica)

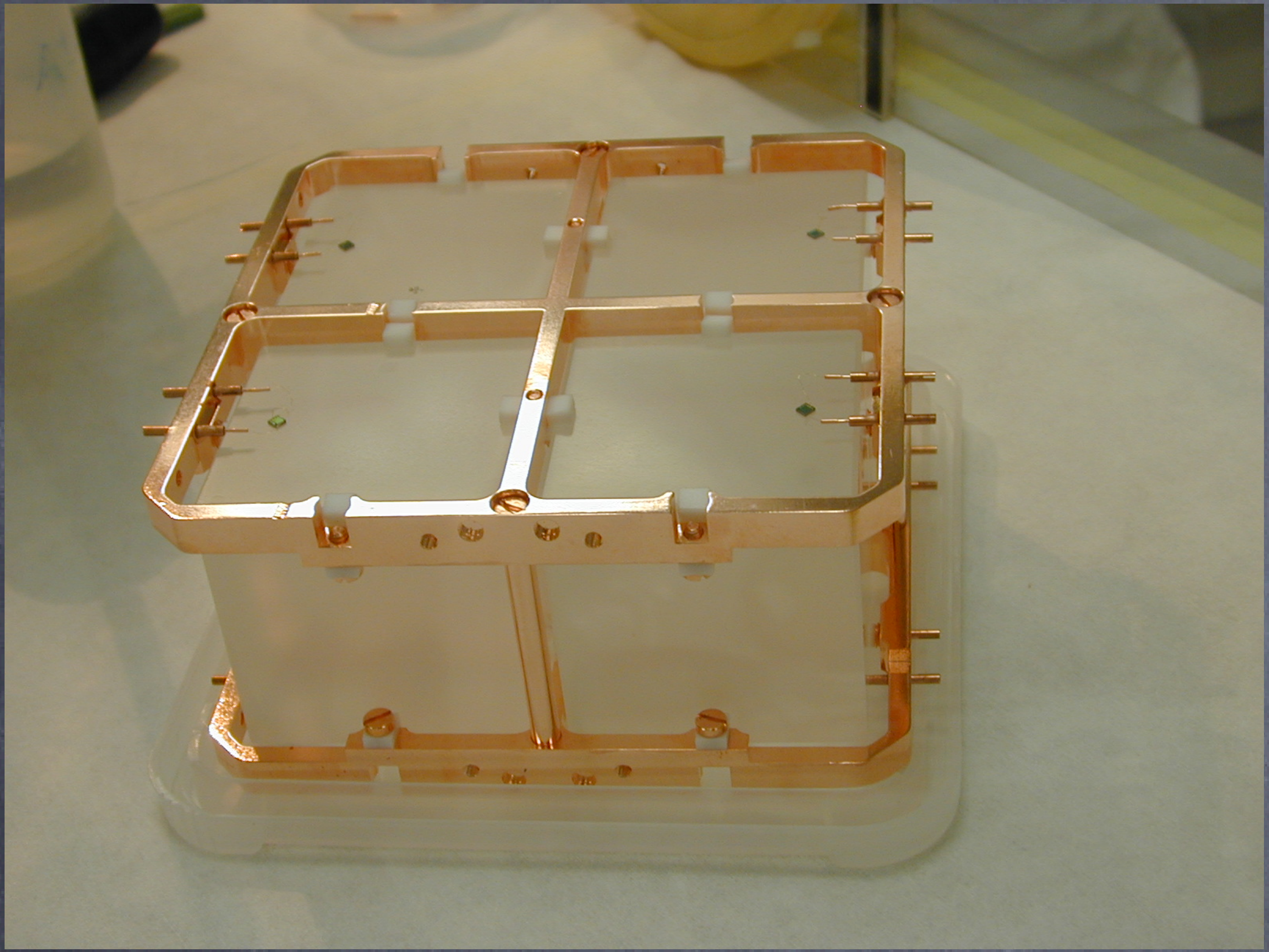
richiede: bassa C ⇒ bassa T

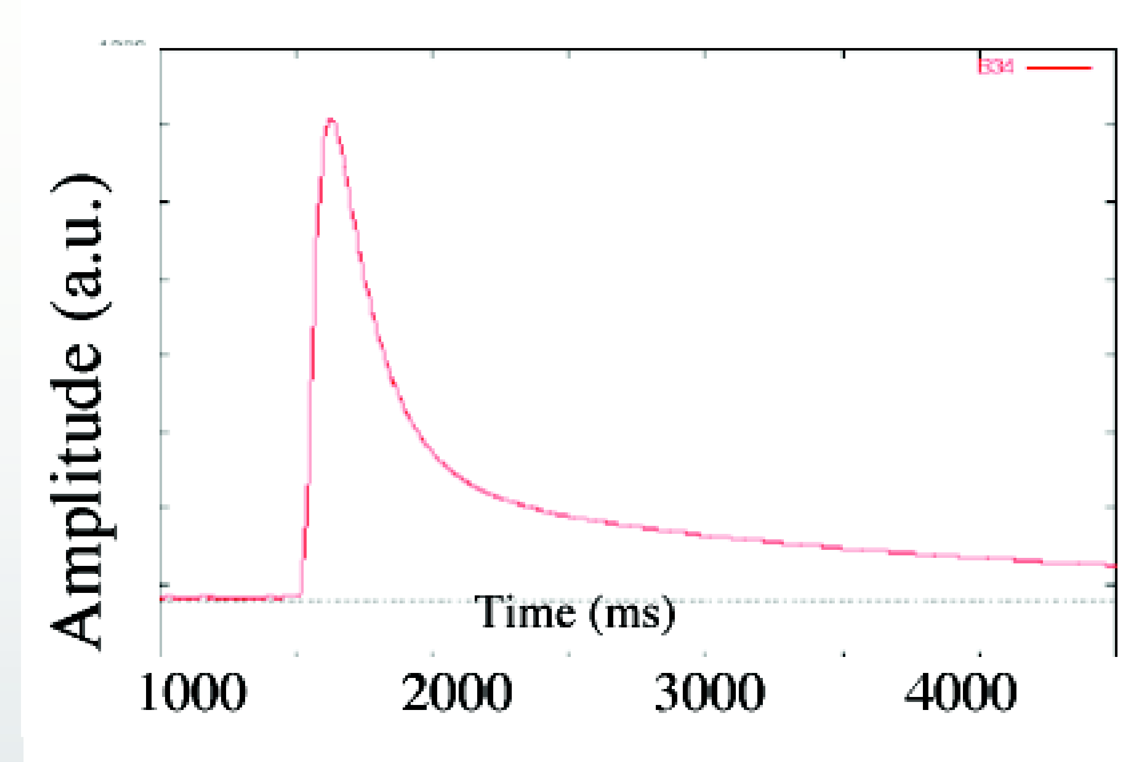
Bonus: ottima ΔE $(k_B T^2 C)$

$$C(T) = \beta \frac{m}{M} \left(\frac{T}{\Theta_D} \right)^3$$

$$\Delta T(t) = \frac{\Delta E}{C} \exp\left(-\frac{t}{\tau} \right)$$

TeO_2 : il bolometro migliore





T_0 ~ 10 mK

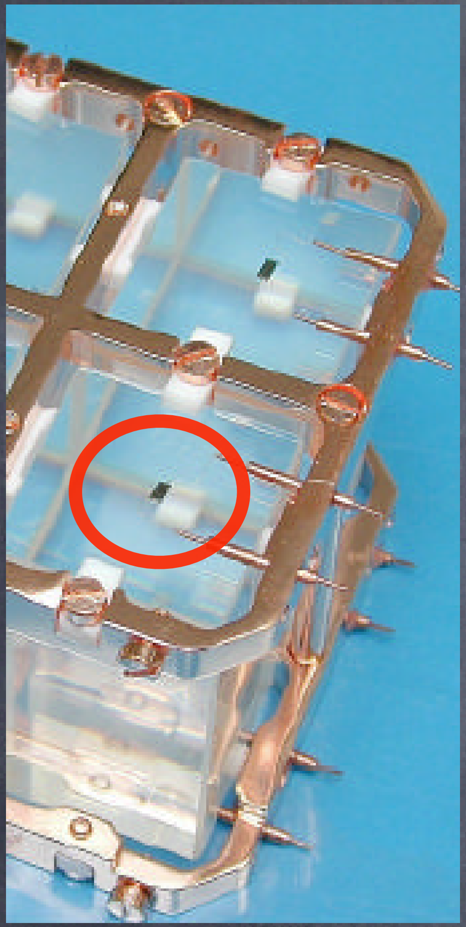
C ~ 2 nJ/K ~ 1 MeV/0.1 mK

G ~ 4 pW/mK

Il solo problemino e' quello di misurare le frazioni di μK (se volete una risoluzione del permille sui segnali del MeV)

per misurare la temperatura dovete avere un termometro

$$A(T) = \left| \frac{d \ln R}{d \ln T} \right|$$

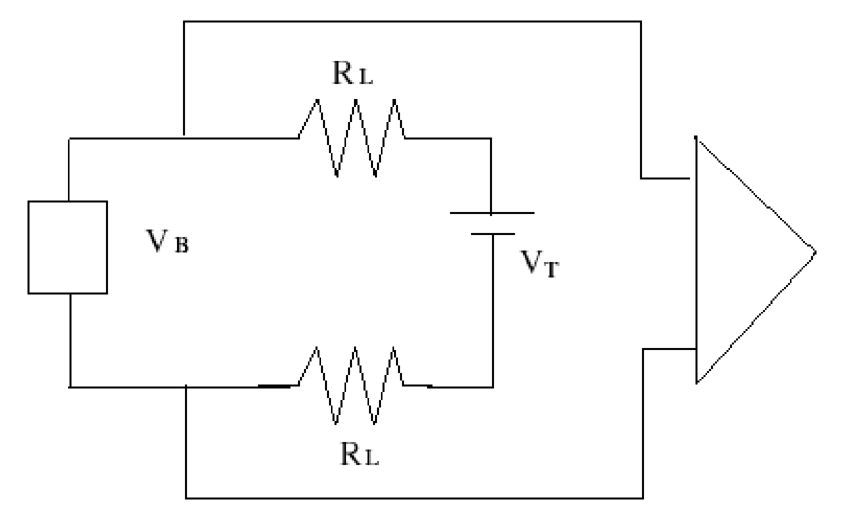


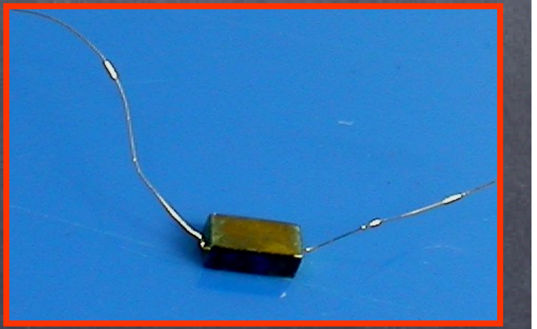
Neutron Transmutation Doped (NTD) Germanium Thermistor

I ~ 50 pA

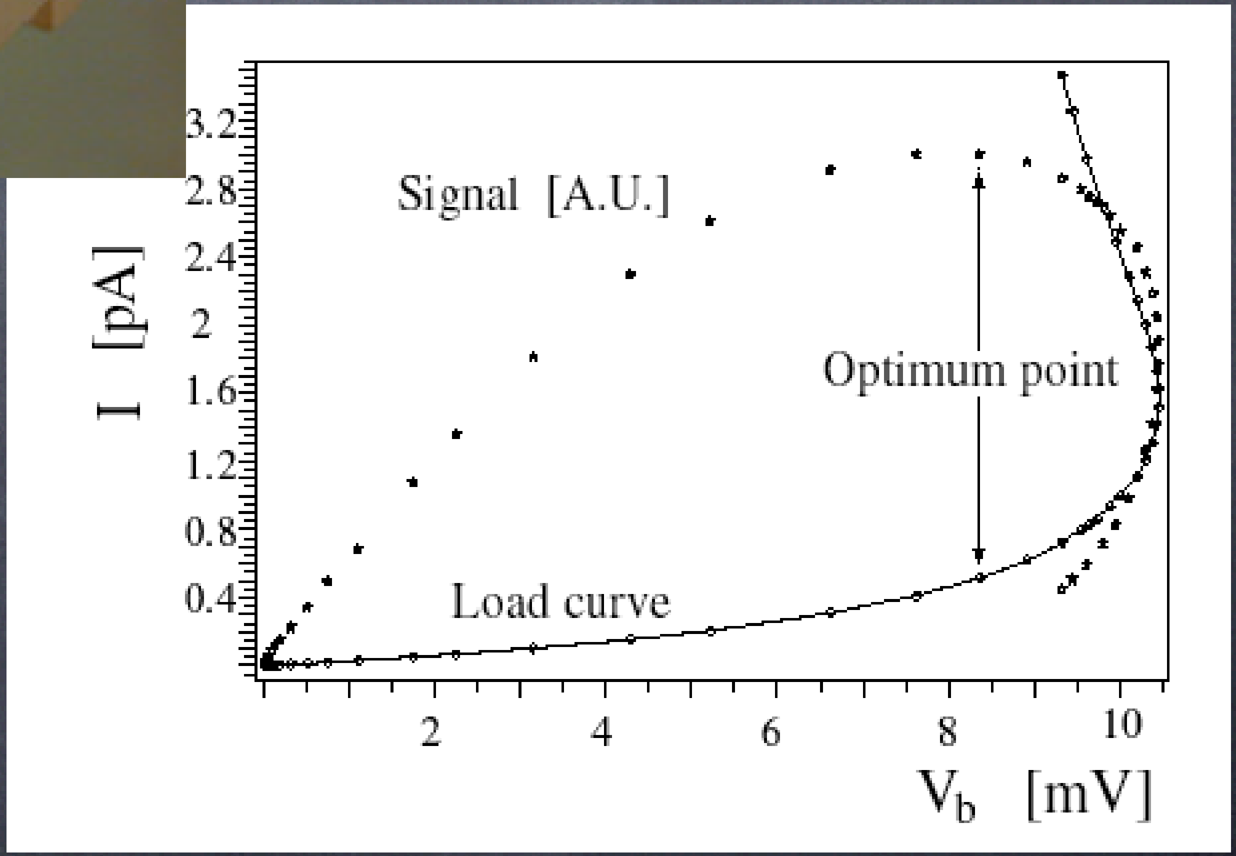
dR/dE ~ 20kΩ/KeV

0.2mV/MeV



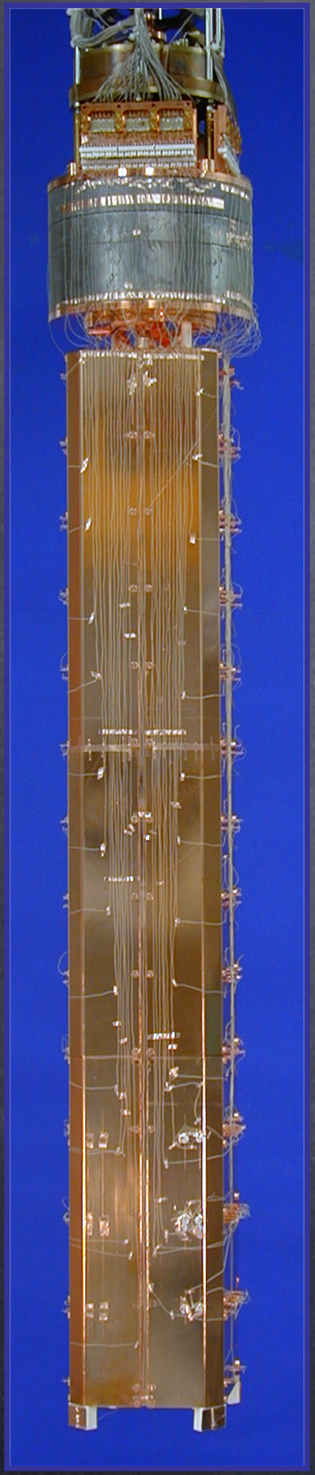


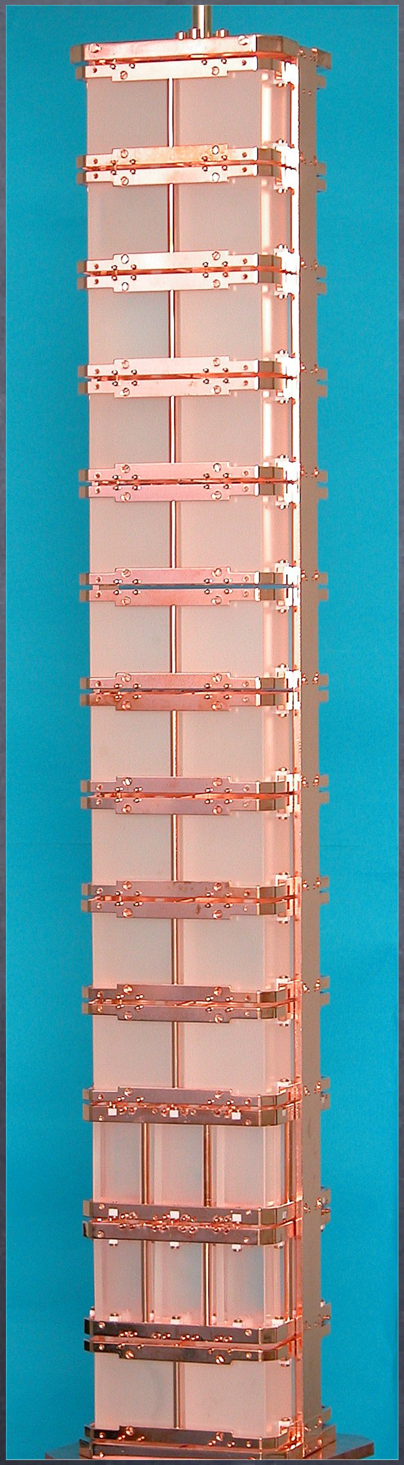
$$T_b = T_0 + \frac{P}{G}$$

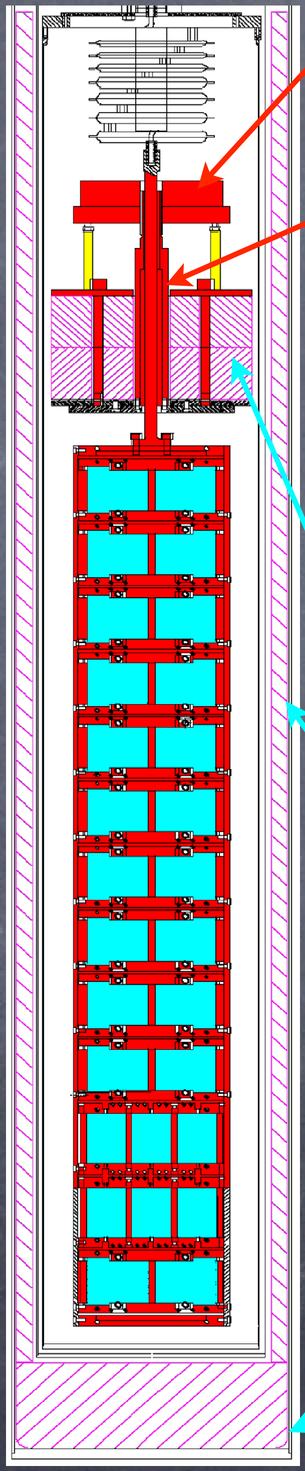


Cuoricino

Cuoricino is currently the largest operating
bolometer in the world





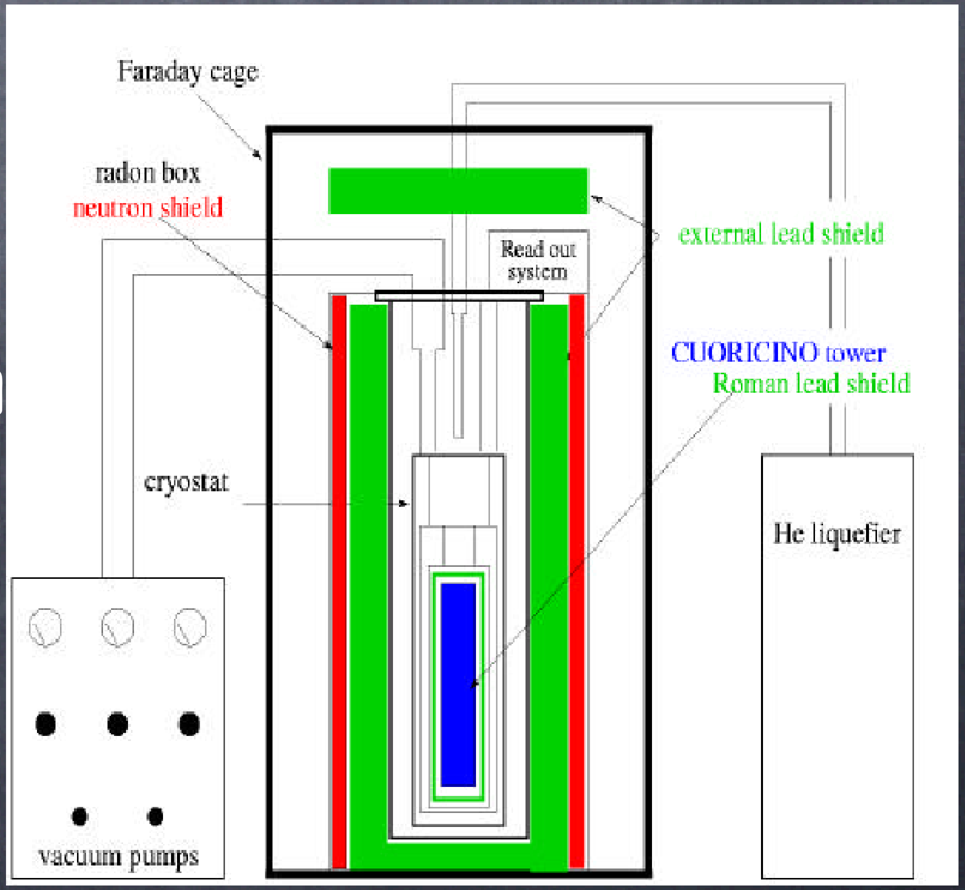


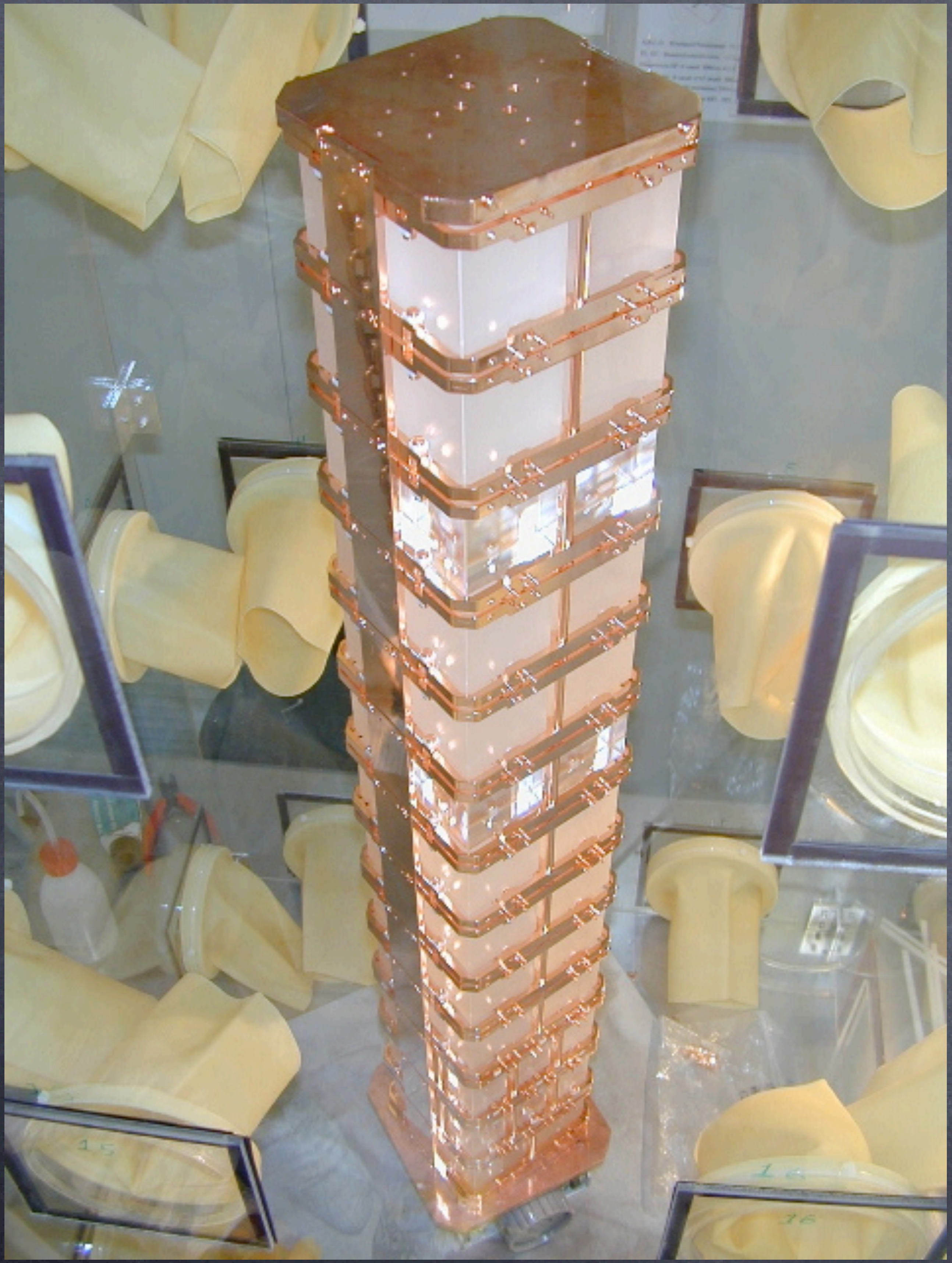
Mixing chamber

Cold finger

10 mK

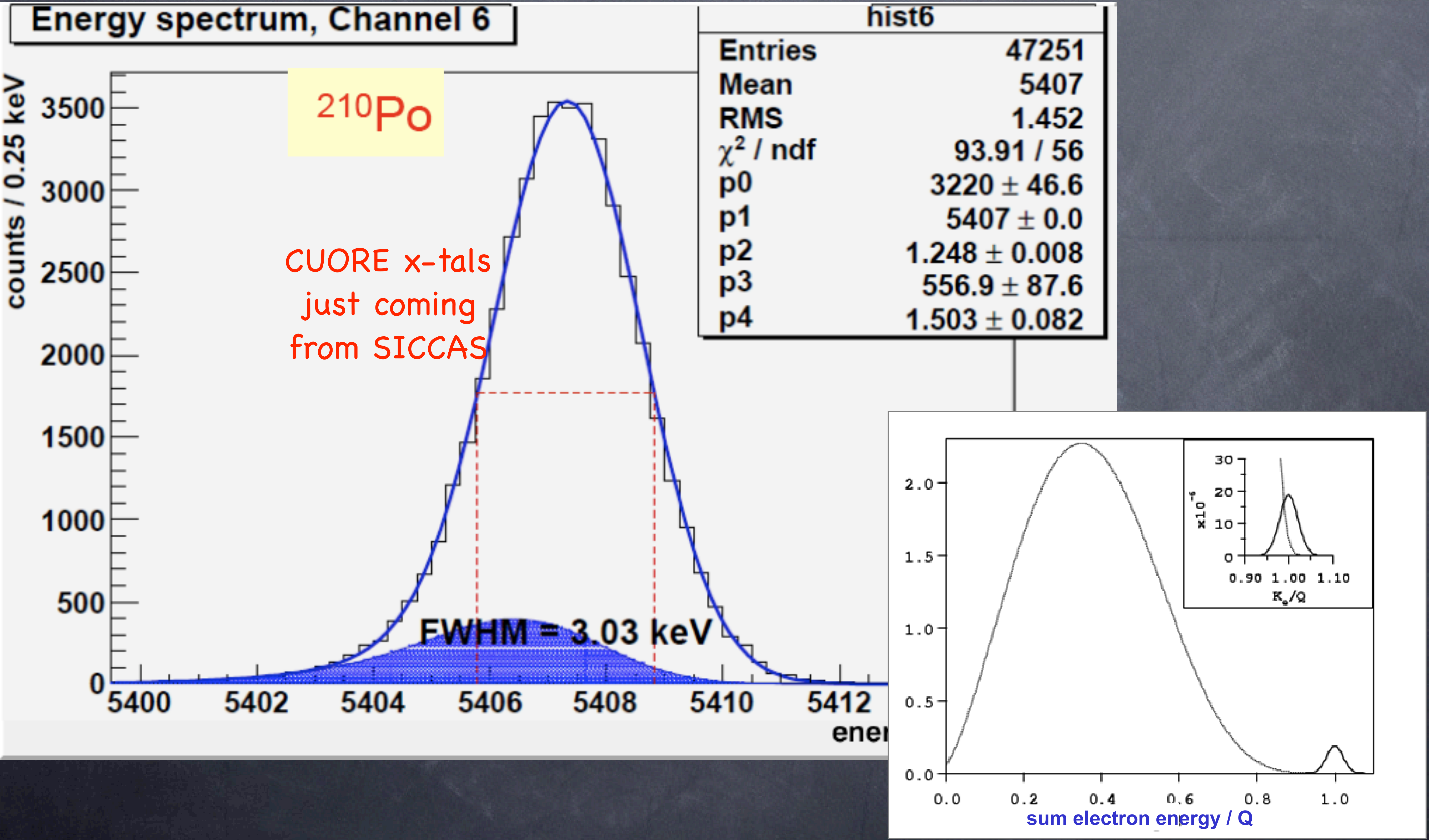
Roman
Lead
Shield


Faraday cage
radon box
neutron shield
external lead shield
Read out system
CUORICINO tower
Roman lead shield
cryostat
He liquefier
vacuum pumps



Vista artistica
di
CUORICINO

Risoluzione di energia

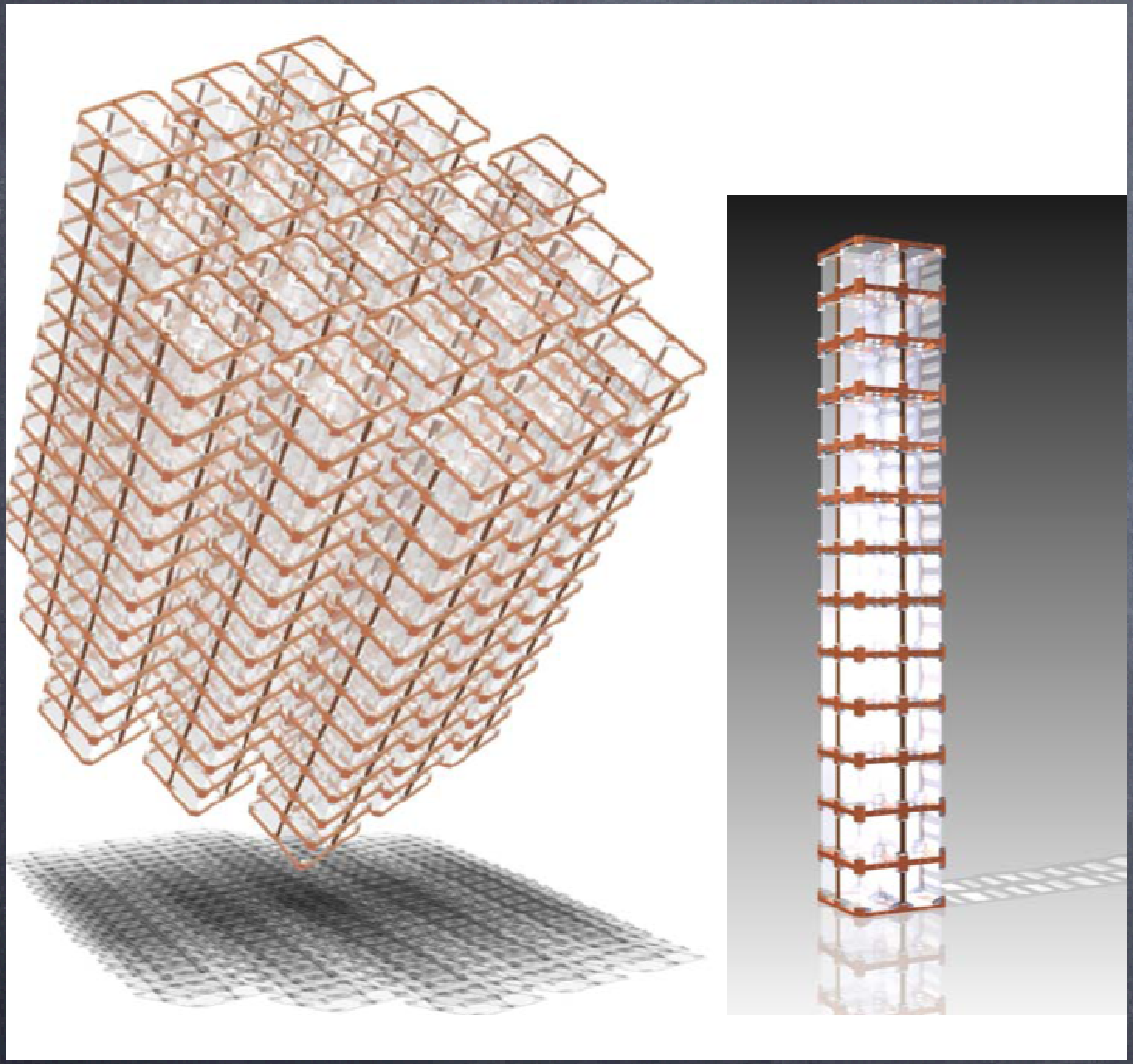


hist6	
Entries	47251
Mean	5407
RMS	1.452
χ^2 / ndf	93.91 / 56
p0	3220 ± 46.6
p1	5407 ± 0.0
p2	1.248 ± 0.008
p3	556.9 ± 87.6
p4	1.503 ± 0.082

CUORE x-tals
just coming
from SICCAS

CUORE design

19 volte Cuoricino



988 TeO_2 Cristalli

19 Torri di 52 cristalli

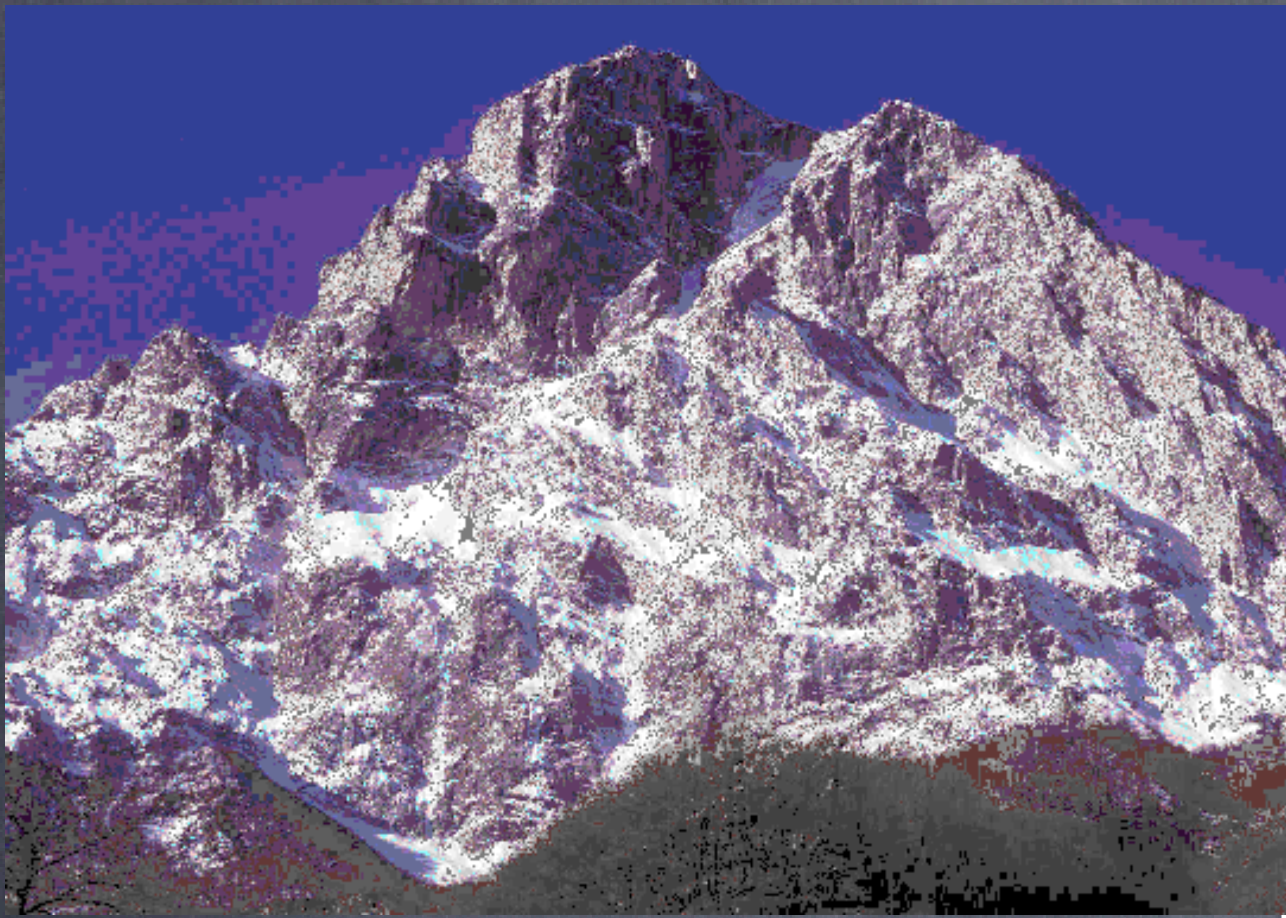
741 Kg di TeO_2

Massa attiva (^{130}Te) 204 Kg

Il Fondo

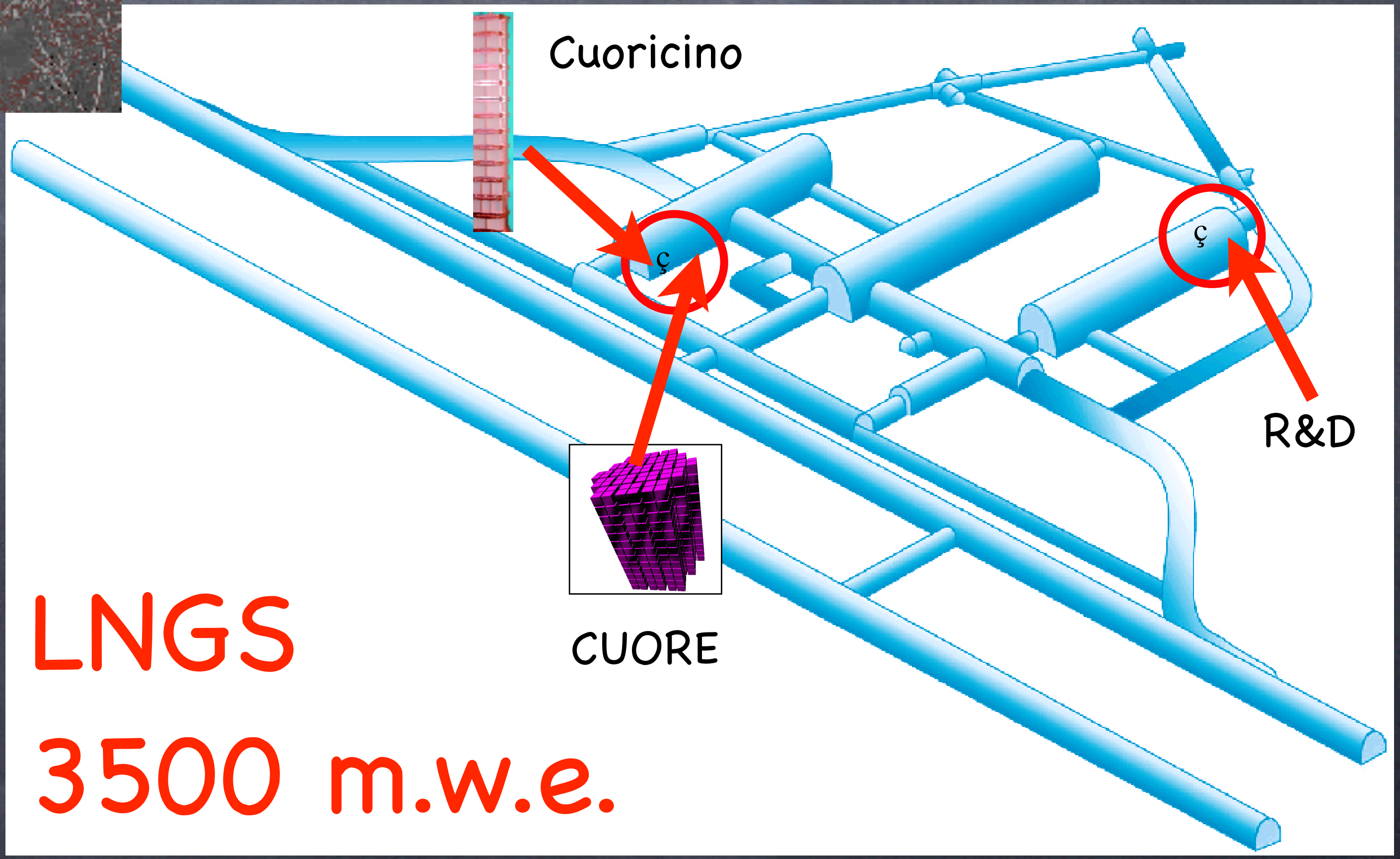
- questo conosciuto !

Cuoricino, where ?



Il Grande Schermo

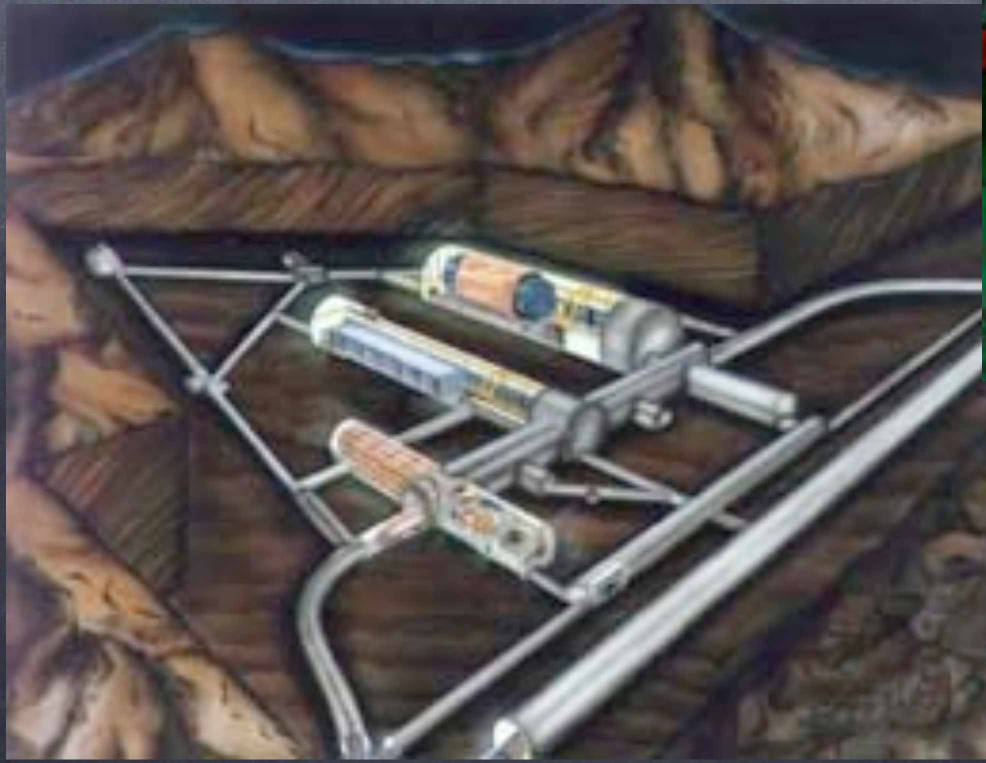
Corno Grande 2916 m


Cuoricino
R&D
CUORE
LNGS
3500 m.w.e.

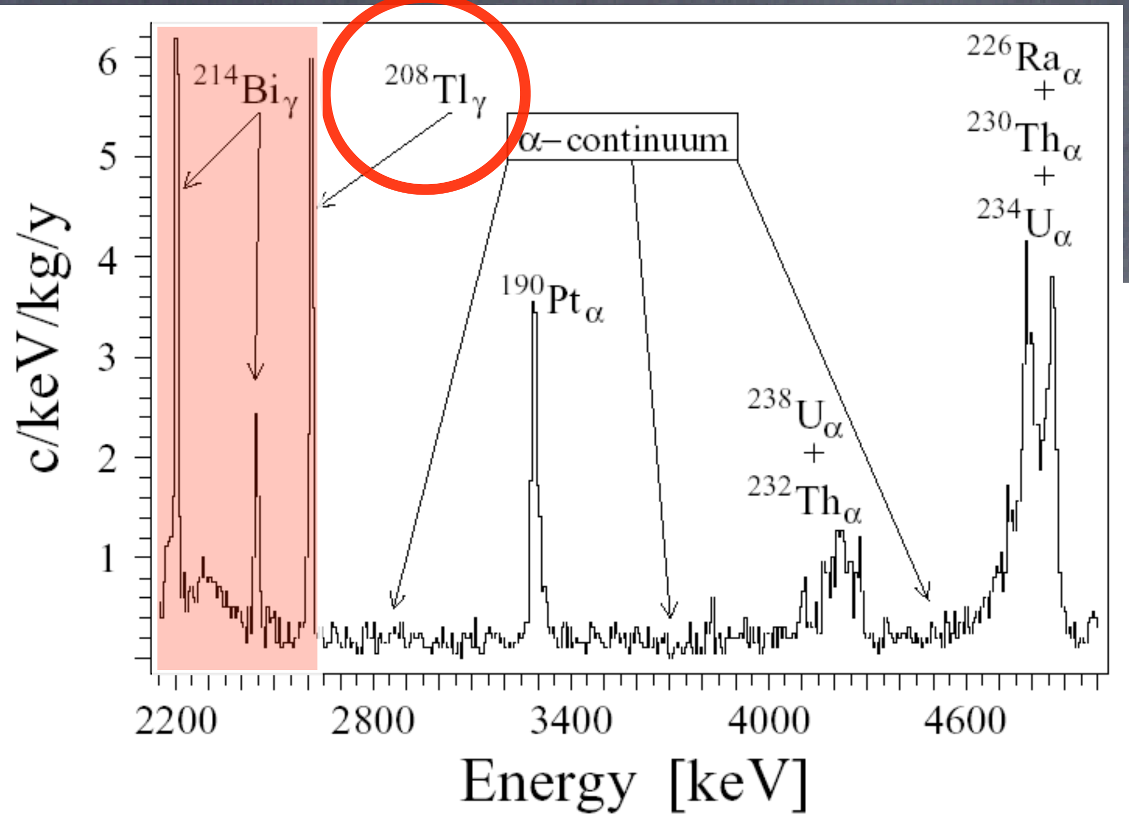
I raggi cosmici

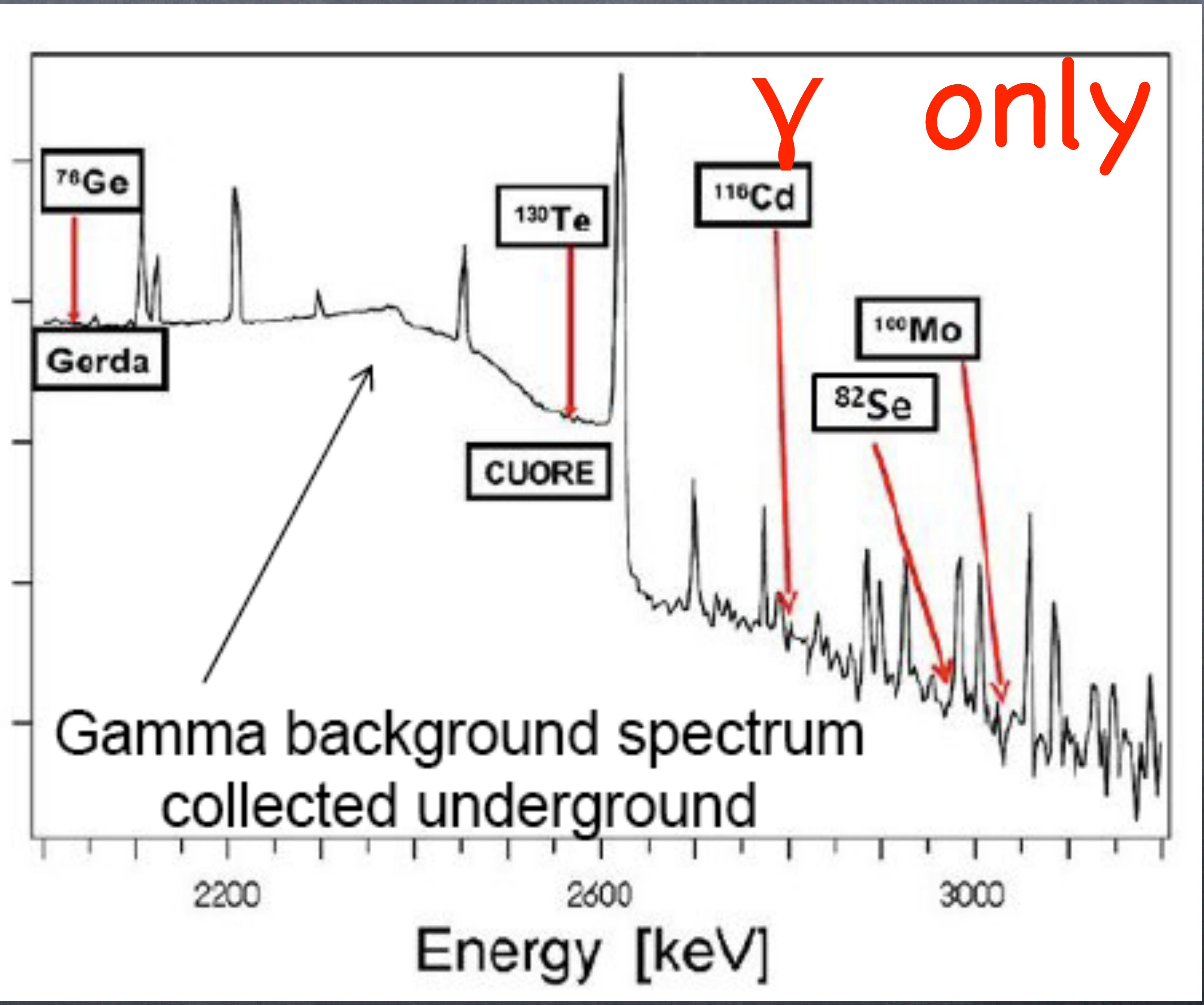
- qui, dove siete voi
    - 1 muone ogni m^2 ogni secondo
- lì, sotto il Corno Grande
    - 1 muone ogni m^2 ogni 12 giorni

LNGS



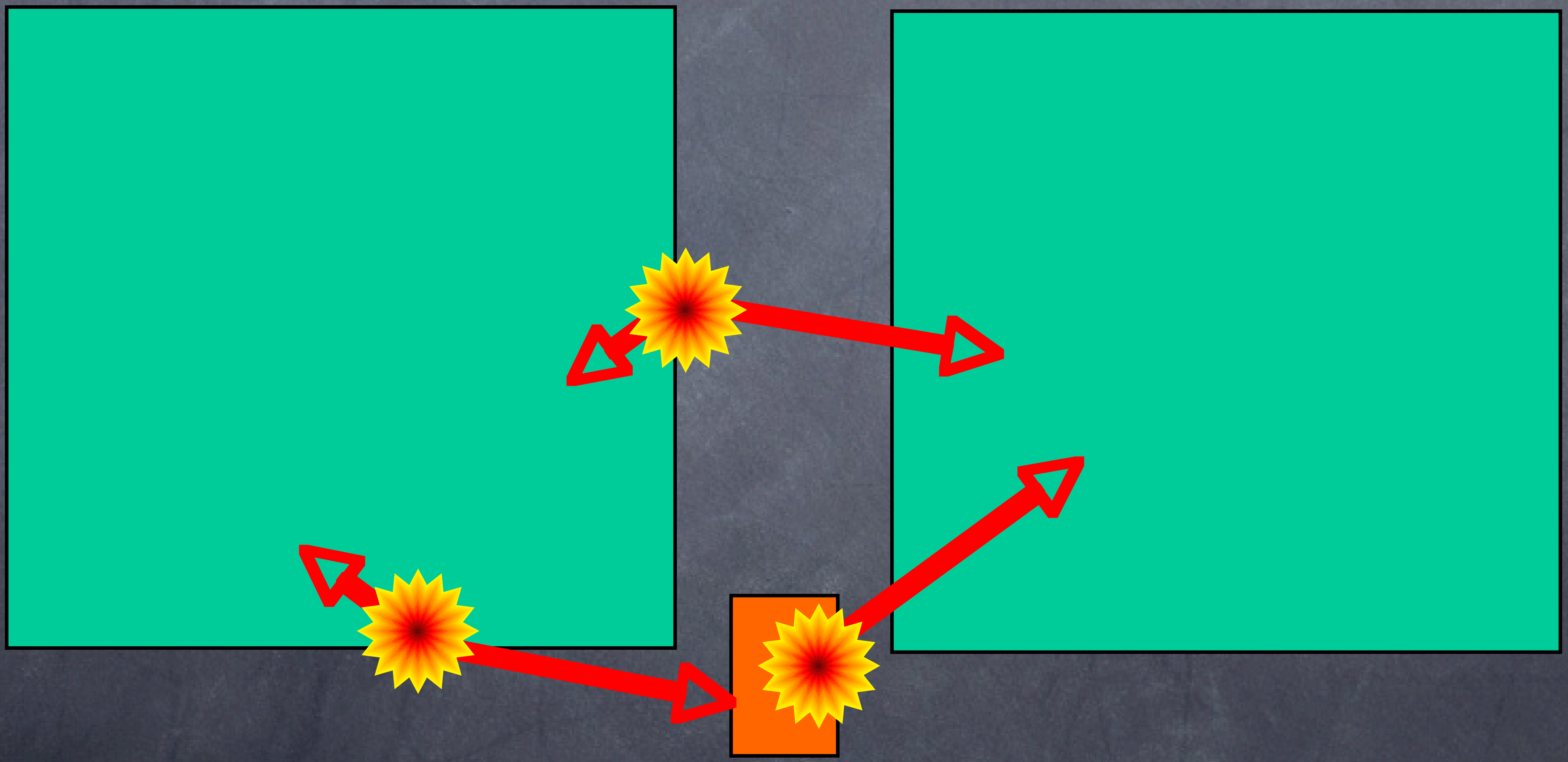
Spettro della radioattivita' naturale





sopra il ^{208}Tl
c'e' la landa
delle α

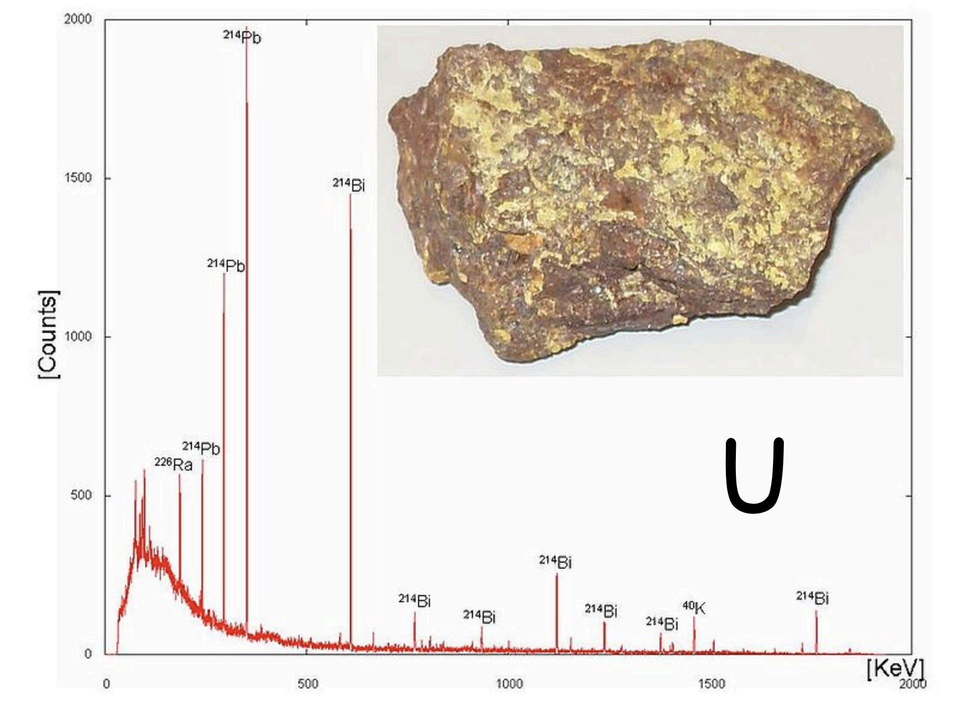
The standard interpretation of the background



α degradate

Il Piombo

- nonostante il silenzio cosmico del Gran Sasso
- le strutture che circondano il rivelatore dei nostri rarissimi decadimenti emettono $\alpha/\beta/\gamma$ dovuti principalmente al loro contenuto in U e Th
- questo va schermato nei limiti del possibile



Tutti noi abbiamo fatto una radiografia e...

1
Economic
3
Giacca/gonna con maniche corte
5
Camice doppio con maniche corte
2
Elegant
4
Giacca/gonna con maniche lunghe
6
Camice doppio con maniche lunghe

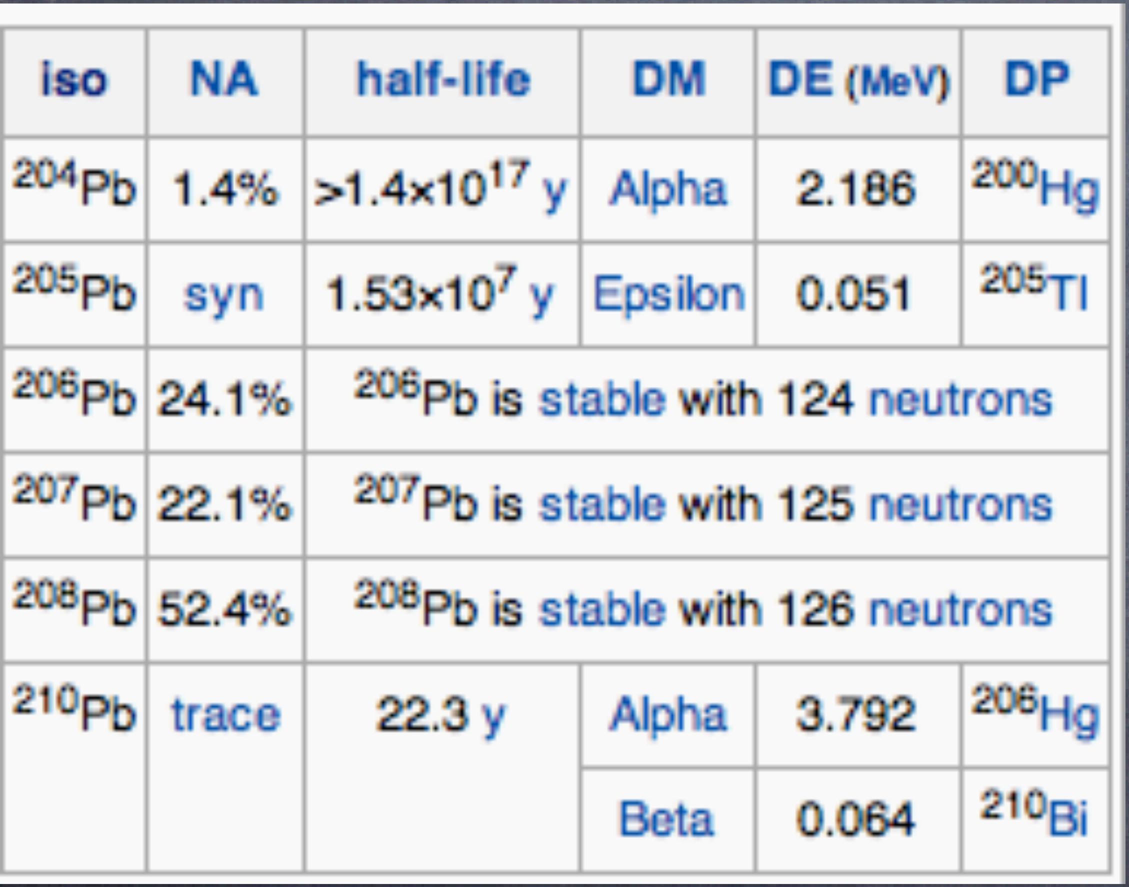
sappiamo che l'operatore indossa un simpatico grembiulino che contiene

Pb

Anche il nostro schermo sara' di Pb

CAUTION
RADIOACTIVE
MATERIAL

Pb: Schermo efficacissimo...ma....



iso	NA	half-life	DM	DE (MeV)	DP
^{204}Pb	1.4%	>1.4×10^{17} y	Alpha	2.186	^{200}Hg
^{205}Pb	syn	1.53×10^{7} y	Epsilon	0.051	^{205}Tl
^{206}Pb	24.1%	^{206}Pb is stable with 124 neutrons			
^{207}Pb	22.1%	^{207}Pb is stable with 125 neutrons			
^{208}Pb	52.4%	^{208}Pb is stable with 126 neutrons			
^{210}Pb	trace	22.3 y	Alpha	3.792	^{206}Hg
			Beta	0.064	^{210}Bi

^{210}Pb e' una presenza sgradita

Ha 22 anni di emivita

Troppo per la nostra pazienza

Poco per non dare fastidio

Soluzione: Pb antico

(molte unita' di 22 anni passate)

Bosa
Macomer
Cuglieri
Ghilarza
M. Ferru
C. Mannu
I. di Mal di Ventre
Cabras
Oristano
Tirso
G. di Oristano
C. della Frasca
Arborea
M. Arci
Terralba
Sardara

Nave affondata

Recupero

Stoccaggio

Esposizione museale

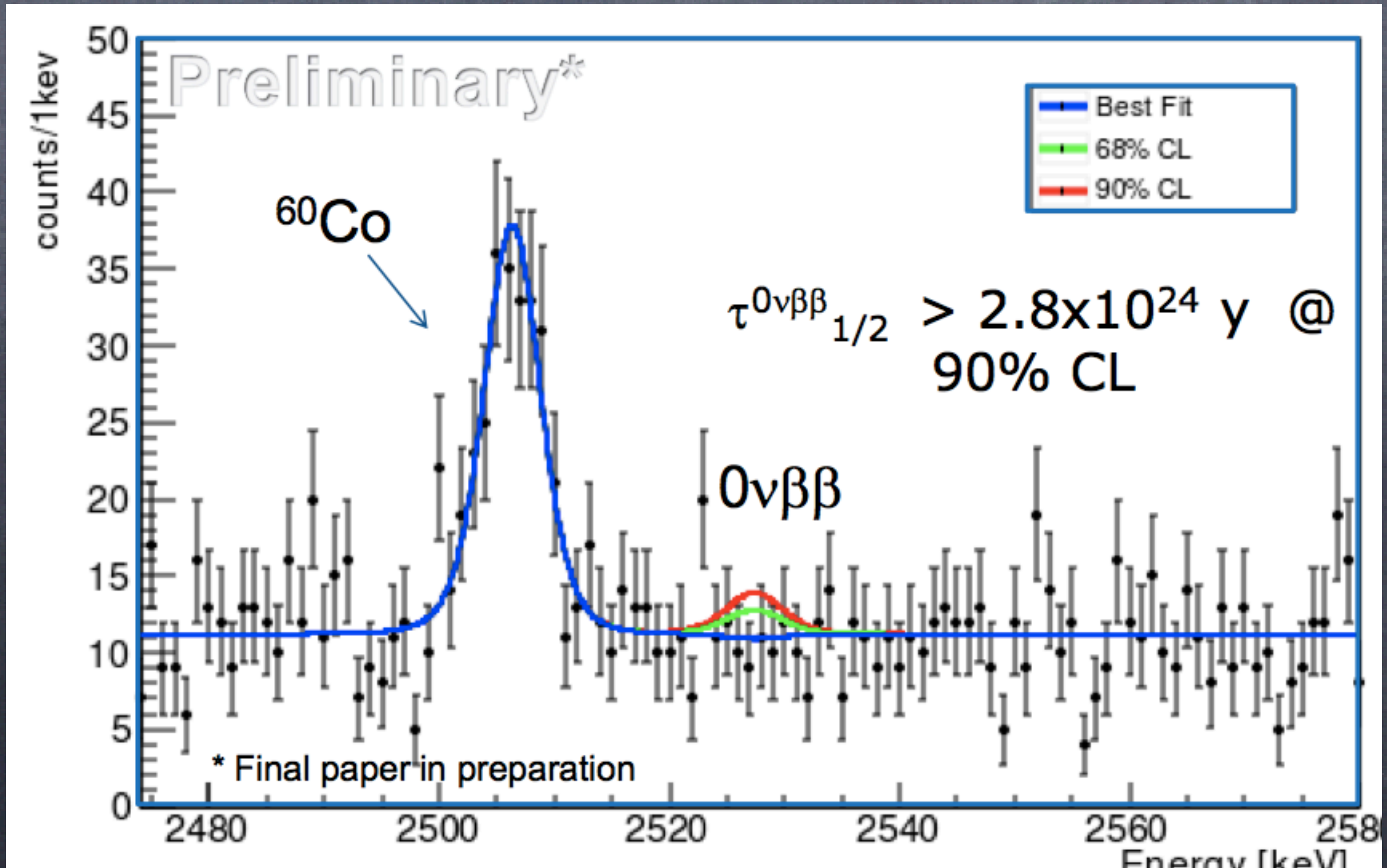
Una operazione preveggente

proposta
da
Ettore
Fiorini

e
finanziata
da
INFN
grazie a
Nicola
Cabibbo

500 MLire ben spesi per la scienza e la cultura

insomma…se esistesse e avessimo fatto l'esperimento giusto cosa si vedrebbe ?



Conclusione

- lo so , la lezione era troppo difficile
- se uno cerca una cosa che capita una volta l'anno (forse) in 100 kg di nuclei e' pero' ovvio che non deve essere una cosa semplice !
- e' la mia unica giustificazione
- scusatemi se potete