

# $O\nu\beta\beta$ :an extreme challenge



Fernando Ferroni  
GSSI & INFN



# Outline

- ▷ The mysterious neutrino
- ▷ Dirac or Majorana
- ▷ Neutrino-less Double Beta Decay
- ▷ Experimental status
- ▷ Description of the bolometric approach
- ▷ What next ?

a number of questions  
with us since long ago

- How much does a neutrino weigh ?
- What is the mass ordering (hierarchy)
- Is neutrino a Majorana or Dirac particle
- Do more (sterile) neutrinos exist ?
- Do neutrinos violate CP ?
- Can we observe the CNB (a picture of a universe 1 second old)



# Majorana conjecture

$$\nu = \bar{\nu}$$

Main consequence :  
Lepton Number Violation

# Majorana vs. Dirac



$$V_L^M \xleftarrow[\text{Lorentz}]{\text{CPT}} V_R^M$$

Majorana



$$\begin{array}{ccccc} & & V_L^D & \xleftarrow{\text{Lorentz}} & V_R^D \\ & \uparrow & & & \downarrow \\ & \text{CPT} & & & \text{CPT} \\ \overline{V}_R^D & \xleftarrow{\text{Lorentz}} & & \xrightarrow{\text{Lorentz}} & \overline{V}_L^D \end{array}$$

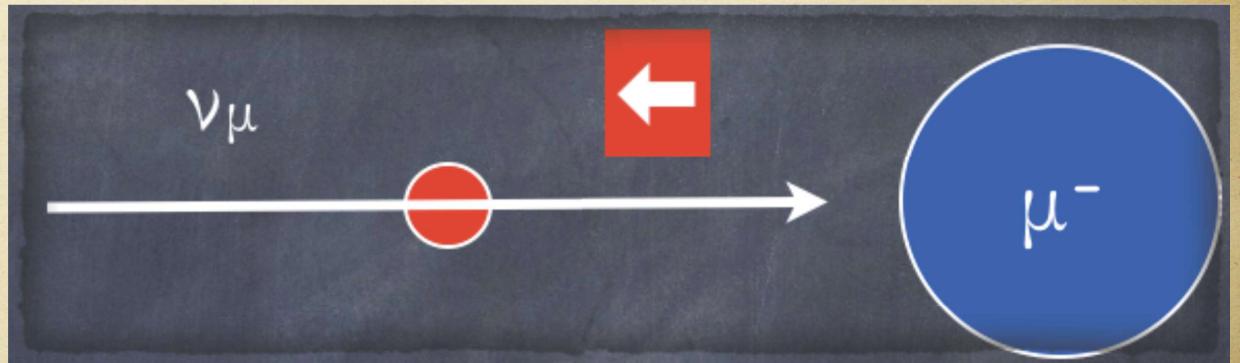
Dirac

# Majorana neutrinos

- in the SM, neutrinos (antineutrinos) are strictly produced as left-handed (right-handed) particles. Since neutrino masses are non-zero, this cannot be exactly true.
- the hypothesis of Majorana can be formulated as follows: in the rest frame, neutrinos and antineutrinos are just the same particle and are distinguished only by the spin.
- Majorana neutrinos are the only fermions to be matter and antimatter at the same time. The difference between neutrinos and antineutrinos is not a Lorentz invariant concept, and  $L$  must be violated at the order  $m_\nu/p_\nu$ .
- since in usual conditions neutrinos are ultra-relativistic, so that  $m_\nu \ll p_\nu$ , the deviation from this limit is not observable in most cases.

# How to solve ?

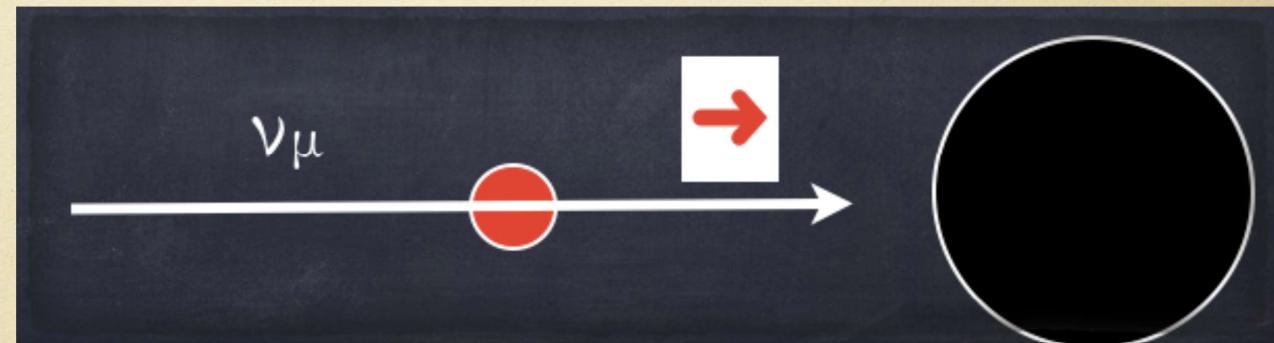
- ❖ in principle it is easy
- ❖ you take a neutrino beam. It does interact with a target and makes negative muons. If some of the neutrinos flip helicity in the final state you observe antineutrinos produced positive muons



Wait, there is a problem !!!!

# Massive neutrinos required

- ▷ in case of Dirac  $\nu \neq \bar{\nu}$  and  $\nu$  has  $L=-1$  (as the  $\mu^-$ )
- ▷ if you have a massless  $\nu$  (lepton) right handed (helicity flip) the result would be



- ▷ weak interaction is V-A

# No problem: neutrinos are massive

## The Nobel Prize in Physics 2015



Photo: A. Mahmoud  
**Takaaki Kajita**

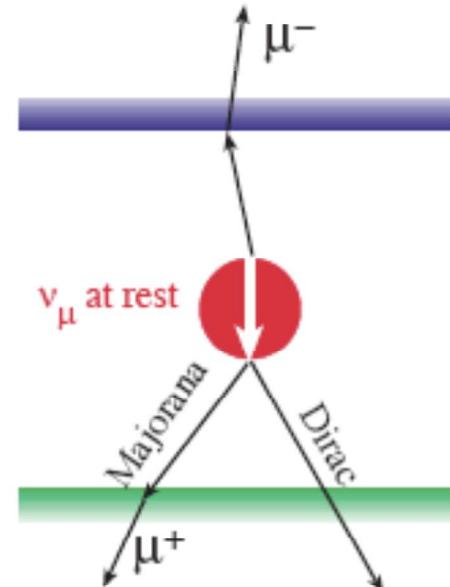
Prize share: 1/2



Photo: A. Mahmoud  
**Arthur B. McDonald**

Prize share: 1/2

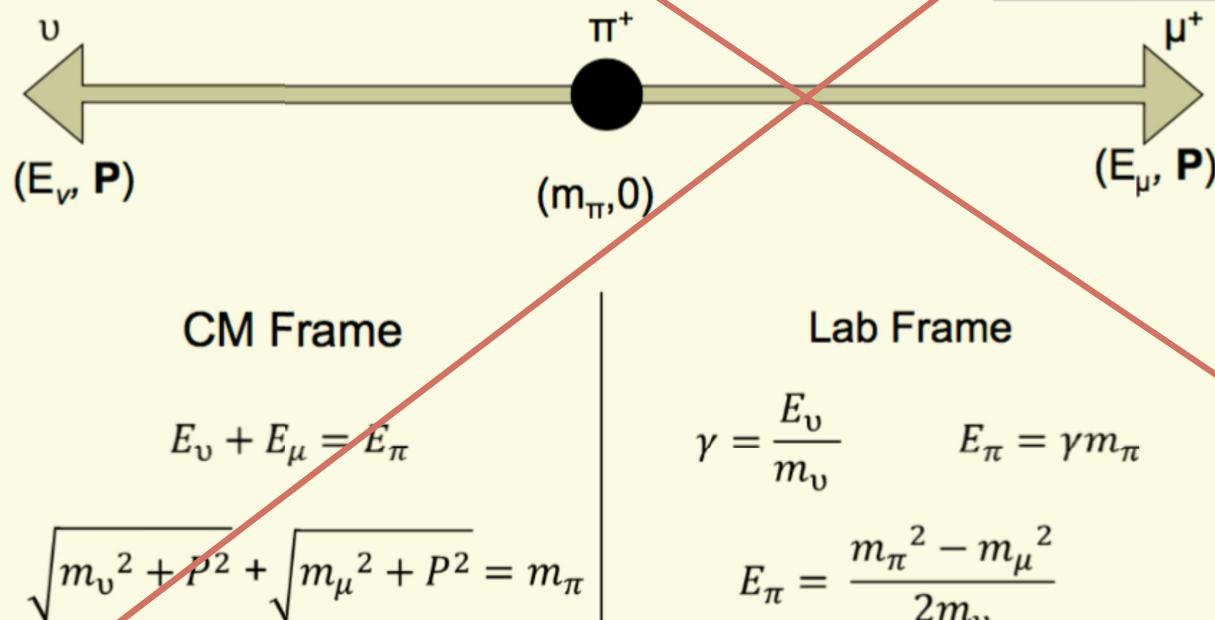
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass"



# Yes , but...

## How to produce a right handed neutrino

### Pion Decay



This will produce a neutrino at rest in the lab frame.

to make the story short:

for 50meV of  $\nu$  mass

pion need to have  
 $E=80000\text{ TeV}$

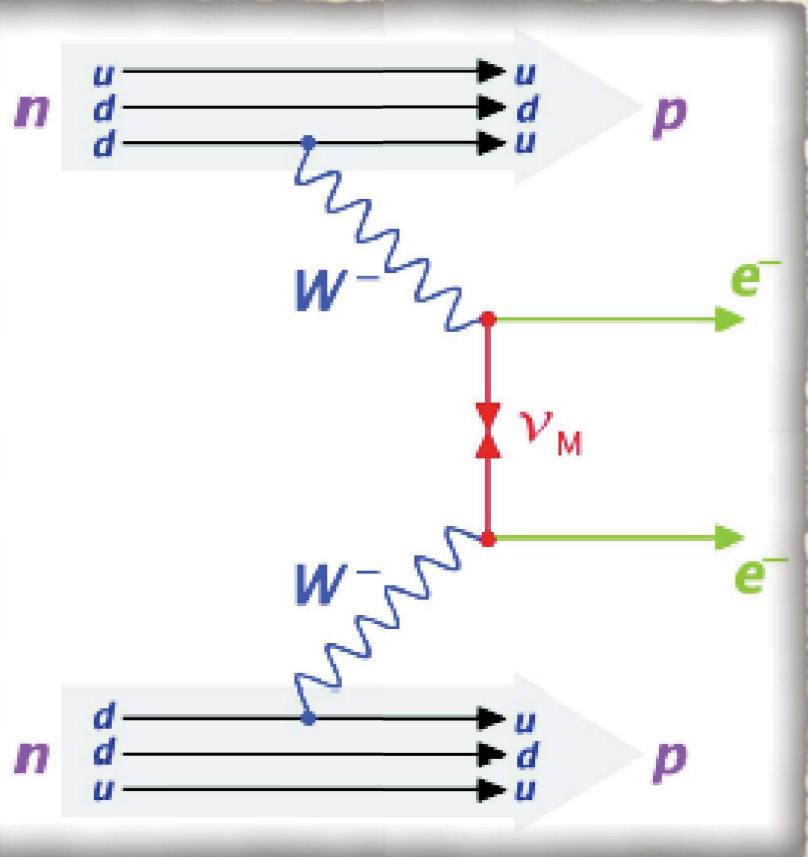
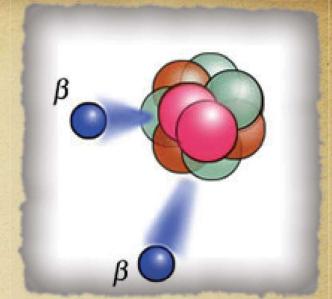
therefore back to 30's

Indeed nobody payed much attention to the Furry hypothesis (1939) that a Majorana neutrino could induce Neutrino-less DBD via helicity flip

Massive (!!) neutrinos makes  
the story much more attractive

Now helicity flip can happen in both Dirac and Majorana cases. However Dirac **forbids** the absorption of an anti-neutrino right that was emitted as a neutrino left because the **Lepton Number Conservation**

# Neutrino-less DBD ( $0\nu\beta\beta$ )



Only if:

Majorana Neutrinos

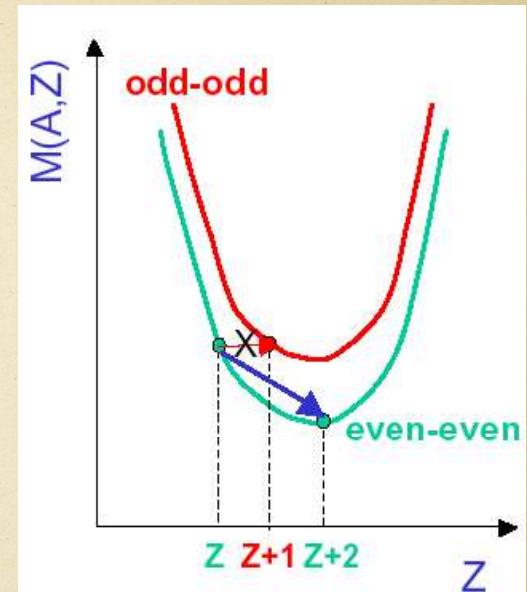
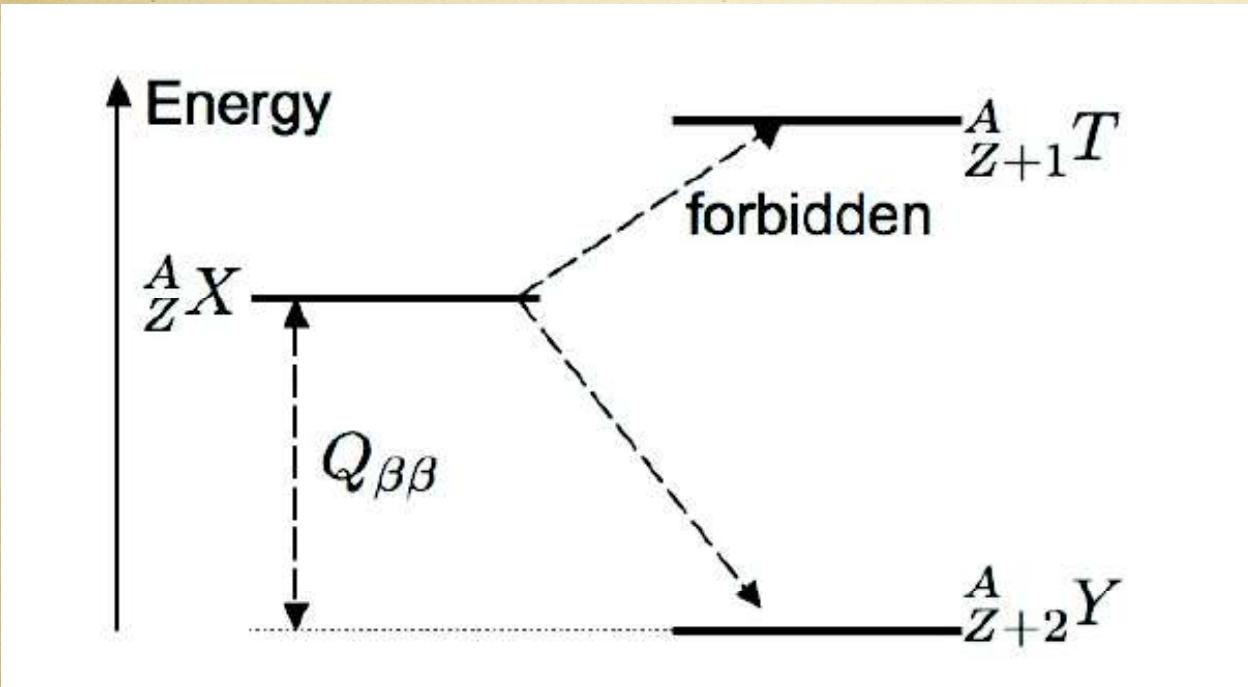
If observed:

Proof of the Majorana  
nature of Neutrino

# just at first glance...

- ▷ it looks unlikely to happen frequently
- ▷ two neutrons that beta-decay at the ‘same’ time in the ‘same’ place (Heisenberg concept of ‘same’)
- ▷ well...let’s see first how a ‘normal’ double beta decay (with emission of two neutrinos) happens and how often it happens

# again from the 30's



1935

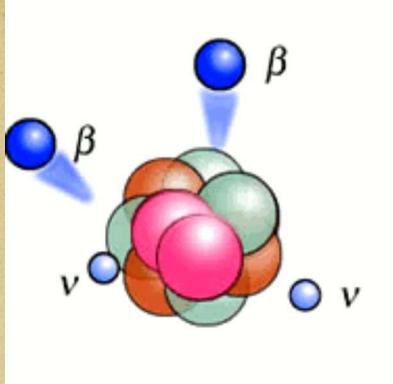
MARIA GOEPPERT MAYER

1963

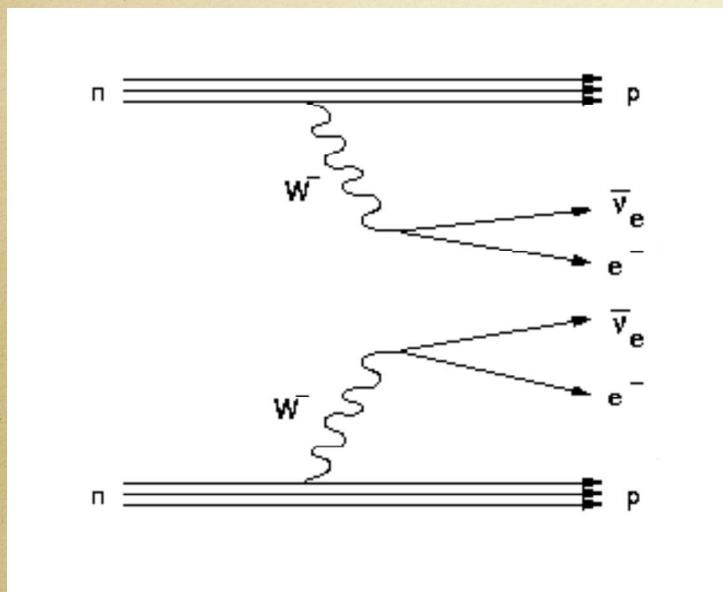


only few nuclei can do it

Isotope	$Q_{\beta\beta}$ (MeV)	Isotopic abundance (%)
$^{48}\text{Ca}$	4.271	0.0035
$^{76}\text{Ge}$	2.039	7.8
$^{82}\text{Se}$	2.995	9.2
$^{96}\text{Zr}$	3.350	2.8
$^{100}\text{Mo}$	3.034	9.6
$^{116}\text{Cd}$	2.802	7.5
$^{128}\text{Te}$	0.868	31.7
$^{130}\text{Te}$	2.533	34.5
$^{136}\text{Xe}$	2.479	8.9
$^{150}\text{Nd}$	3.567	5.6



# the ‘normal’ one



Nuclide	Half-life, $10^{21}$ years
$^{48}\text{Ca}$	$0.044_{-0.004}^{+0.005} \pm 0.004$
$^{76}\text{Ge}$	$1.84_{-0.08}^{+0.09} +0.11 -0.06$
$^{82}\text{Se}$	$0.096 \pm 0.003 \pm 0.010$
$^{96}\text{Zr}$	$0.0235 \pm 0.0014 \pm 0.0016$
$^{100}\text{Mo}$	$0.00711 \pm 0.00002 \pm 0.00054$
$^{116}\text{Cd}$	$0.69_{-0.08}^{+0.10} \pm 0.07$
$^{128}\text{Te}$	$0.028 \pm 0.001 \pm 0.003$
$^{130}\text{Te}$	$7200 \pm 400$
$^{136}\text{Xe}$	$0.7 \pm 0.09 \pm 0.11$
$^{150}\text{Nd}$	$2.165 \pm 0.016 \pm 0.059$
$^{238}\text{U}$	$0.00911_{-0.00022}^{+0.00025} \pm 0.00063$
	$2.0 \pm 0.6$

overall....  $10^{20} - 10^{21}$  years

# the ‘special’ one ! how long should we wait ?

phase space

parameter containing  
the **physics**

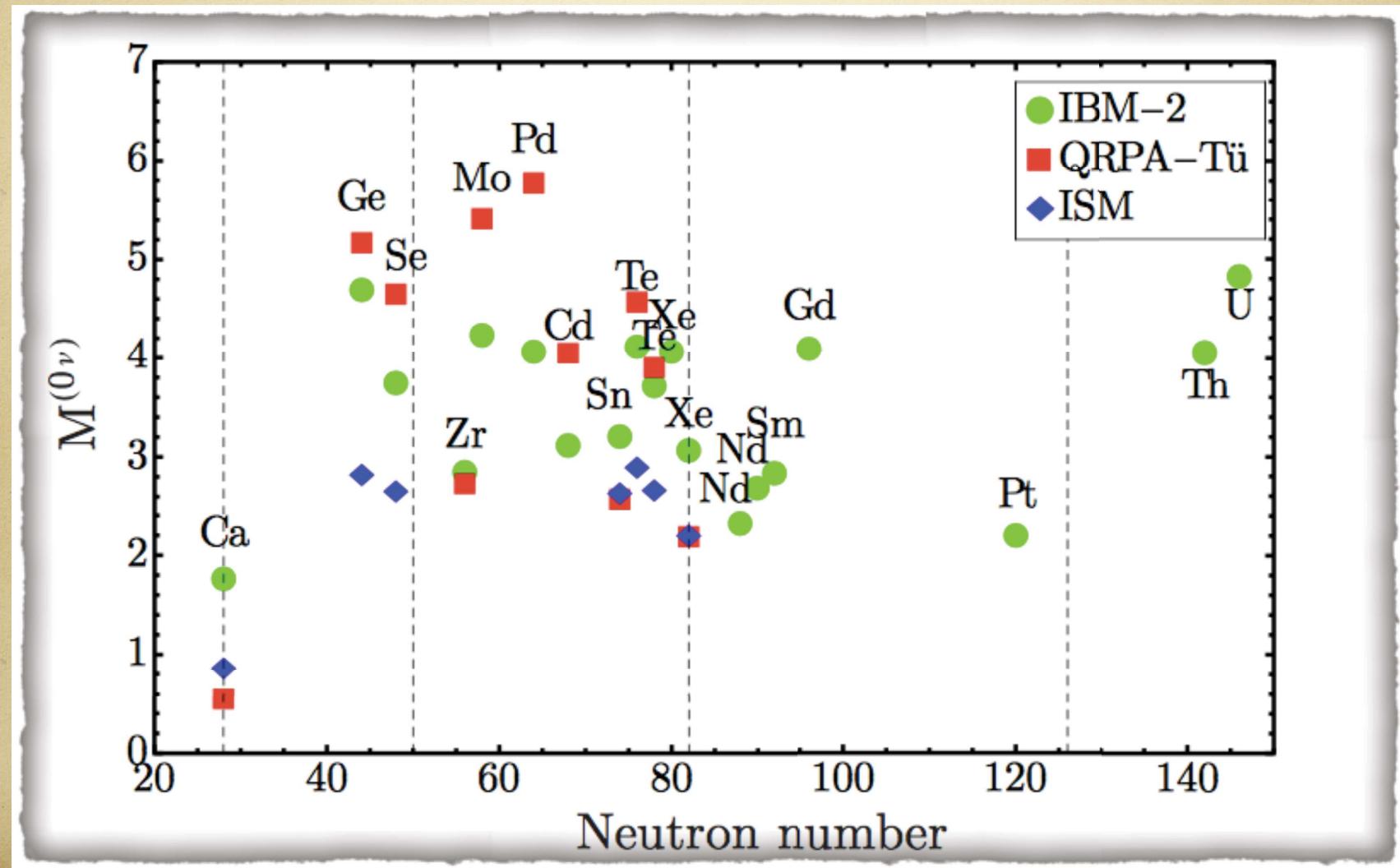
$$1/\tau = G(Q, Z) |M_{\text{nucl}}|^2 \langle M_{\beta\beta} \rangle^2$$

what the **experimentalists**  
try to measure

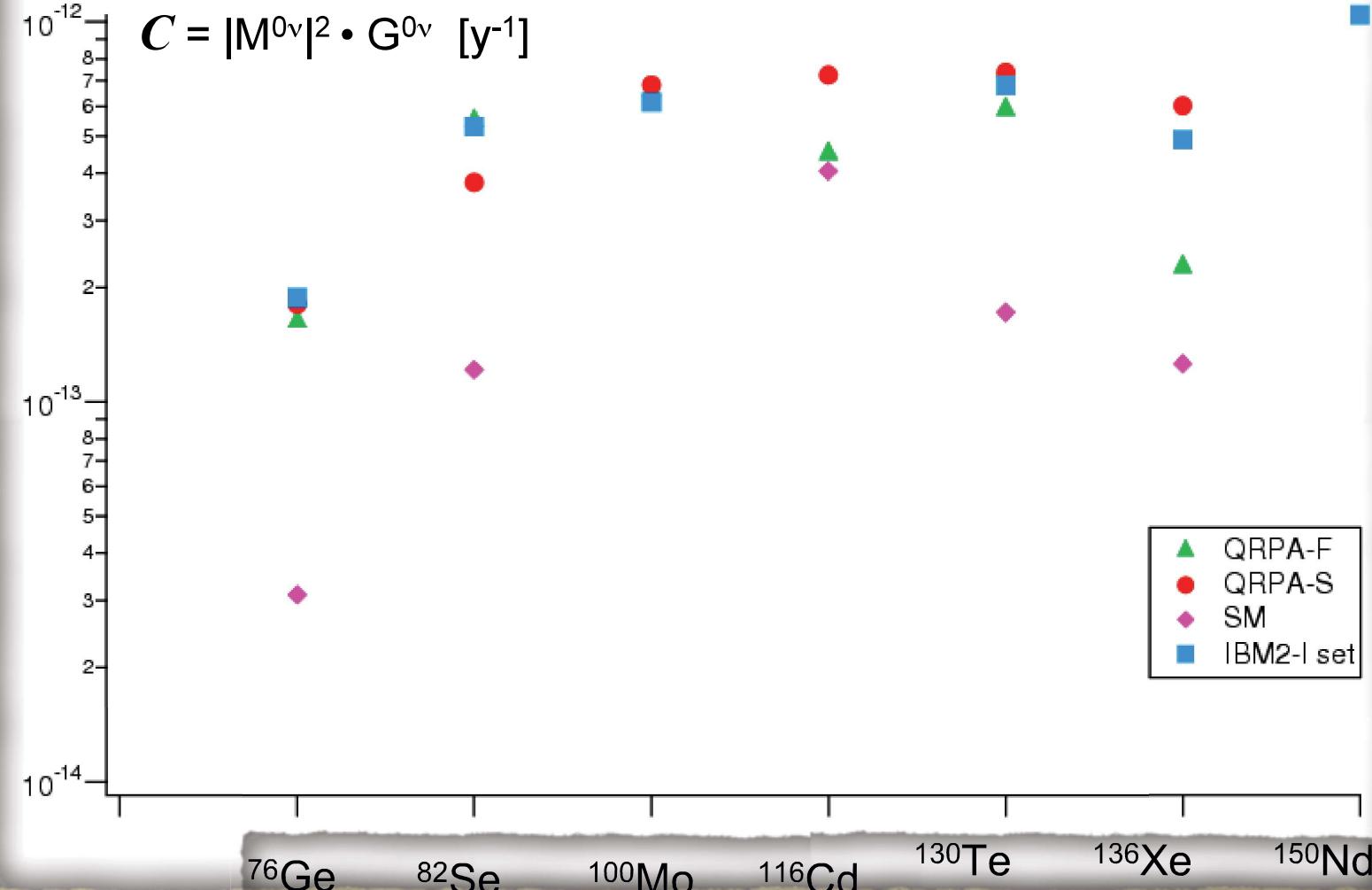
what the **nuclear theorists**  
try to calculate

# NME

## Different models, some discrepancy



# $M^*(\text{Phase Space})$



just on the back  
of the envelope

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

$C \sim 10^{-12} \text{ y}^{-1}$ ,  $m_e \sim 500 \text{ keV}$ ,  $m_{\beta\beta} \sim 50 \text{ meV}$

$$\tau_{1/2}^{0\nu} > 10^{24} \text{ y}$$

[ universe life  $15 \cdot 10^9 \text{ y}$ , Avogadro number  $6 \cdot 10^{23}$  ]

# something more worrisome

$$\mathcal{M} \equiv g_A^2 \mathcal{M}_{0\nu} = g_A^2 \left( M_{GT}^{(0\nu)} - \left( \frac{g_V}{g_A} \right)^2 M_F^{(0\nu)} + M_T^{(0\nu)} \right)$$

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

$$g_A = \begin{cases} g_{\text{nucleon}} &= 1.269 \\ g_{\text{quark}} &= 1 \\ g_{\text{phen.}} &= g_{\text{nucleon}} \cdot A^{-0.18} \end{cases}$$

} who knows ?

$$g_A \rightarrow g_A \cdot (1 - \delta)$$

$$S \cdot (1 - \delta)^4$$

$2\nu\beta\beta$

for  $^{82}\text{Se}$

$\delta = 0.55$

the ‘factor’ would be 11 !!!!!!

For instance, if we have a decrease by  $\delta = 10$  (20)% of the axial coupling, lifetime would increase by a factor of  $1/(1 - \delta)^4 = 1.5$  (2.5)

# what are we looking at ?

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

The observable comes as a combination of the three neutrino masses, the mixing angles and the Majorana phases.

Let's parameterize as a function of the known parameters

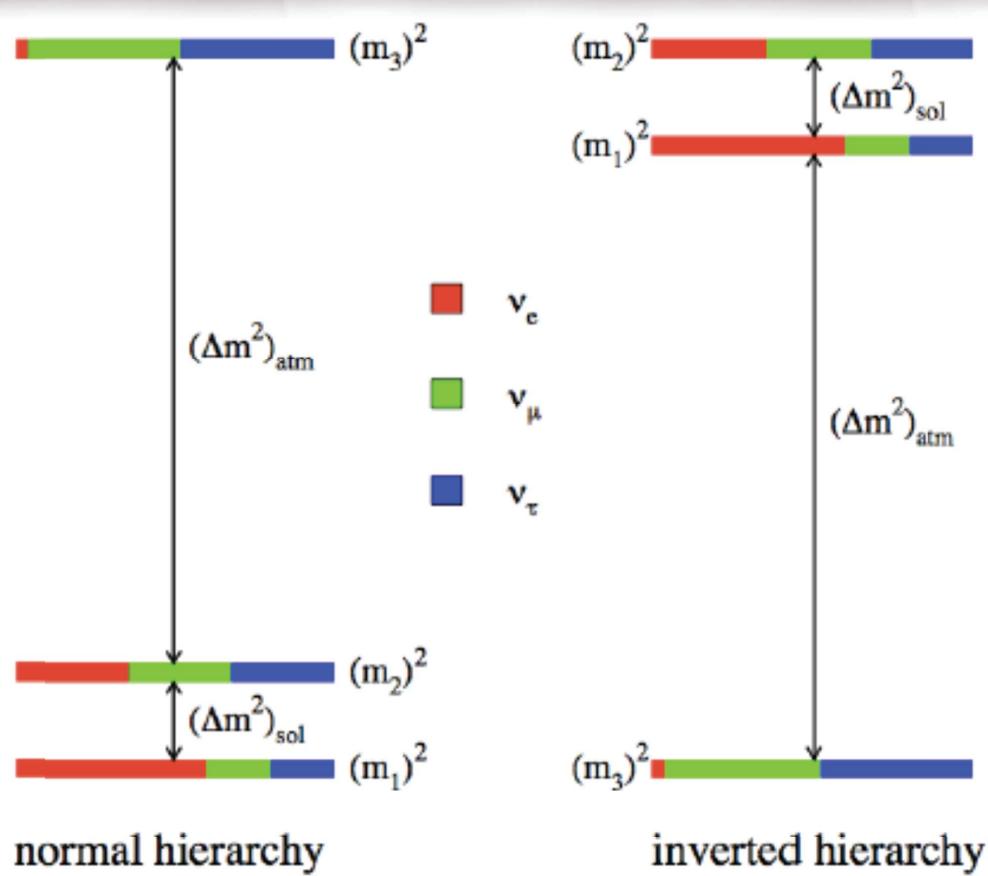
$$m_{\beta\beta} = f(U_{ek}, m_{lightest}, \delta m_{sol}, \Delta m_{atm})$$

# Here what we know

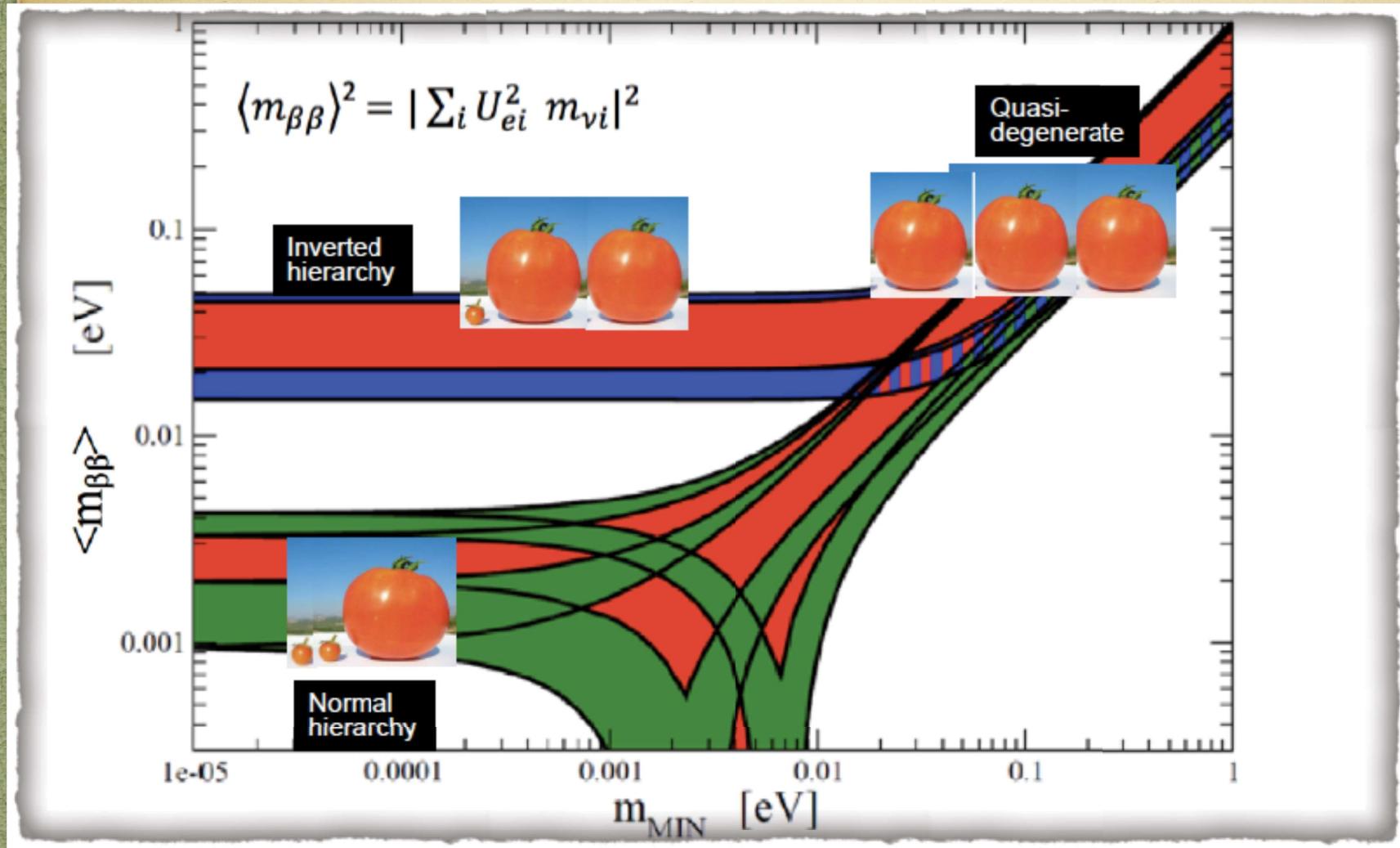
parameter	best fit $\pm 1\sigma$
$\Delta m_{21}^2 [10^{-5}\text{eV}^2]$	$7.56 \pm 0.19$
$ \Delta m_{31}^2  [10^{-3}\text{eV}^2] (\text{NH})$	$2.55 \pm 0.04$
$ \Delta m_{31}^2  [10^{-3}\text{eV}^2] (\text{IH})$	$2.49 \pm 0.04$
$\sin^2 \theta_{12}/10^{-1}$	$3.21^{+0.18}_{-0.16}$
$\sin^2 \theta_{23}/10^{-1} (\text{NH})$	$4.30^{+0.20}_{-0.18} \text{ a}$
$\sin^2 \theta_{23}/10^{-1} (\text{IH})$	$5.96^{+0.17}_{-0.18} \text{ b}$
$\sin^2 \theta_{13}/10^{-2} (\text{NH})$	$2.155^{+0.090}_{-0.075}$
$\sin^2 \theta_{13}/10^{-2} (\text{IH})$	$2.140^{+0.082}_{-0.085}$
$\delta/\pi (\text{NH})$	$1.40^{+0.31}_{-0.20}$
$\delta/\pi (\text{IH})$	$1.44^{+0.26}_{-0.23}$

sign of  $\Delta m^2$   
unknown  
(ordering  
of masses)

# Two possibilities:



# the final result is :



The question is which, if any, part of this phase space can be attained by a realistic experiment

set a goal of exploring IH. Get down to 10-20 meV

# The name of the game

expected  
number of  
 $\beta\beta 0\nu$  events

$$S = \frac{M \cdot N_A \cdot a}{W} \cdot \ln(2) \cdot \frac{t}{T_{1/2}^{0\nu}} \cdot \varepsilon$$

detector mass      isotopic abundance      live time  
molecular mass      /      \ efficiency  
                        ββ0ν half-life

mean number of  
background counts  
around the Q-value

$$B = b \cdot M \cdot \Delta E \cdot t$$

background rate in  
counts/keV/kg/y      energy resolution  
(detector FWHM)  
detector mass      live time

# how many events ?

Number of events = (Number of moles \* Avogadro number \* data collection time) / lifetime

$$N_A = 6 * 10^{23}$$

$$N_y = 1$$

$$\tau = 10^{26}$$

$$N_{\text{events}} = 10$$

1600 moles

that for  $^{130}\text{Te}$  makes 200 Kg

# and how little background?

$$B = b \cdot M \cdot \Delta E \cdot t$$

background rate in counts/keV/kg/y      energy resolution (detector FWHM)

detector mass      live time

1 count of background with a detector of 200 kg of (good)\* mass and an energy resolution of 10 keV requires 0.001 counts/keV/kg/y (if you want to be more impressed is 1 count per ton per year) !

\* if the good isotope is not 100%, the mass that generates background is the total one !

Sensitivity is  $S/\sqrt{B}$

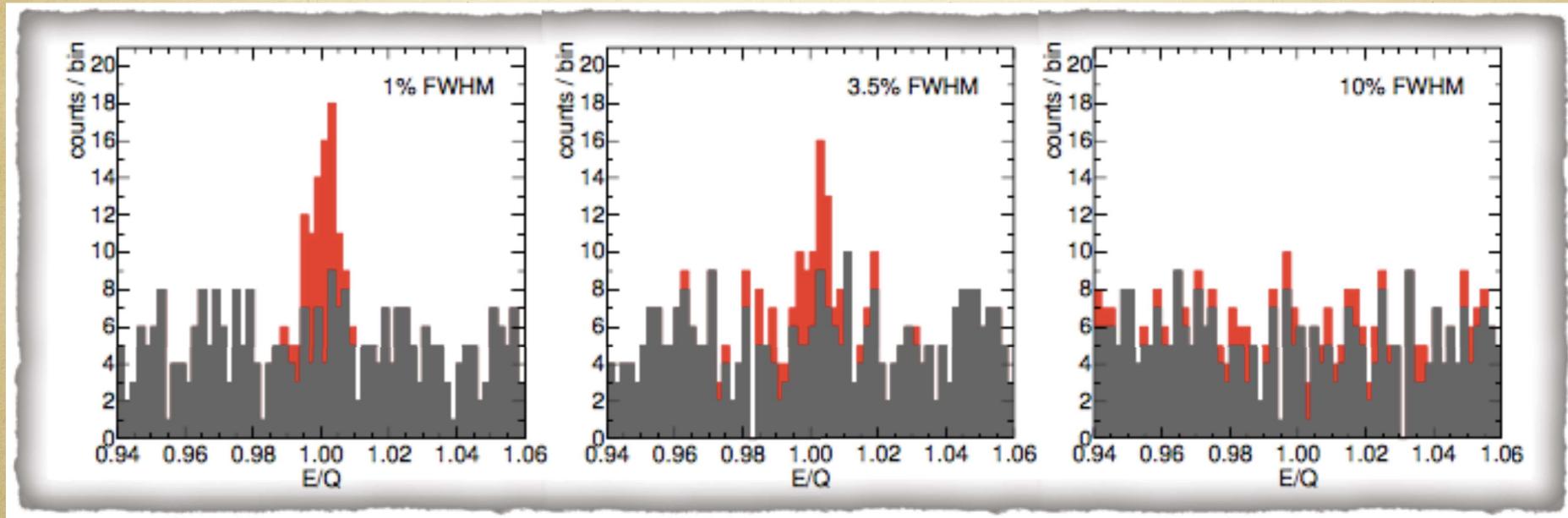
Sensitivity  $\propto K \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$  (i.a. • ε)

$$m_{\beta\beta} \propto \sqrt{(1/\tau)}$$

# which way ?

- ▷ increase abundance of the right isotope (linear)
- ▷ increase M a lot (square root)
- ▷ decrease B (ideally get to mythical zero background and get rid of the square root)
- ▷ get an extraordinary good energy resolution  
(remember we are talking of a signal of a few MeV but still gaining only by a square root)

# effect of energy resolution



$S = 50$  events

$B = 1$  count/keV

# brutal consideration

Sensitivity  $\propto K \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$  (i.a. • ε)

$$m_{\beta\beta} \propto \sqrt{(1/\tau)}$$

To get a factor 10 in  $m_{\beta\beta}$  you have a choice :

M      100 Ton instead of 1 Ton

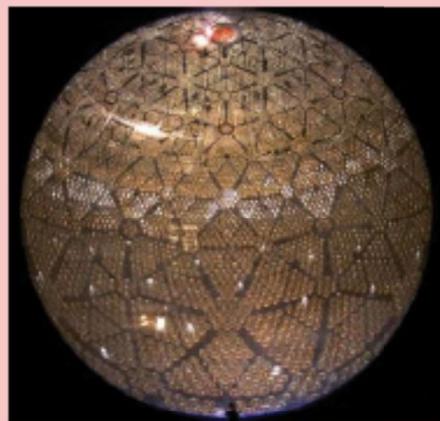
t      500 y instead of 5 y

$\Delta E$     50 eV instead of 5 keV

B    0.001 instead of 0.1

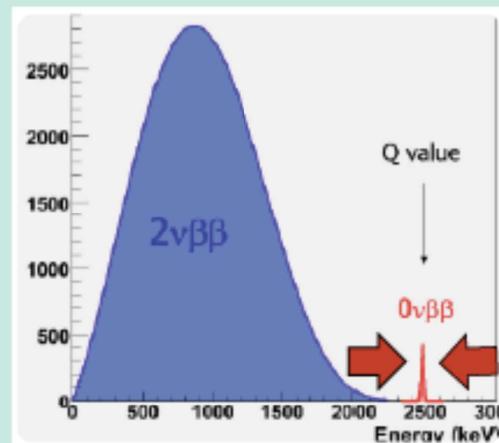
# meaning :

## The “Brute Force” Approach



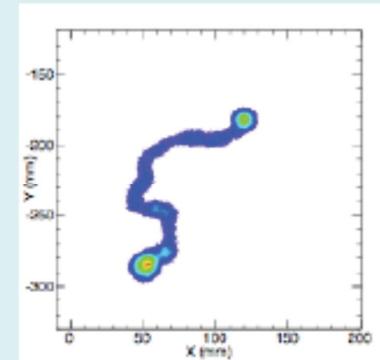
focus on the numerator  
with a **huge amount**  
**of material**  
(often sacrificing  
resolution)

## The “Peak-Squeezer” Approach



focus on the denominator  
by **squeezing down**  $\Delta E$   
(various technologies)

## The “Final-State Judgement” Approach

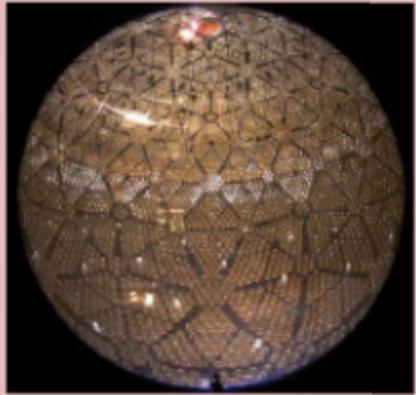


try to make the  
background zero by  
**tracking or**  
**tagging**

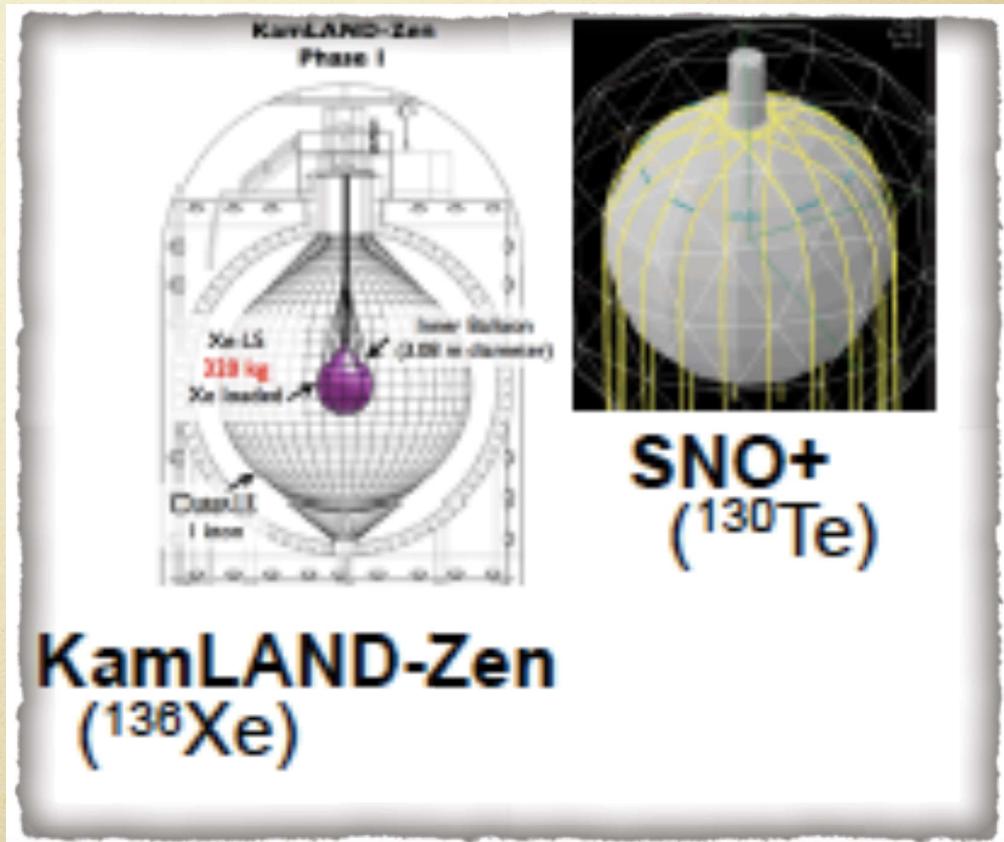
or better make the right cocktail of all of the above

# the state of the art: brute force

## The “Brute Force” Approach



focus on the numerator  
with a **huge amount**  
**of material**  
(often sacrificing  
resolution)



# a caveat on energy resolution

## irreducible physics background

$$\delta = \frac{\Delta E^{FWHM}}{Q_{\beta\beta}}$$

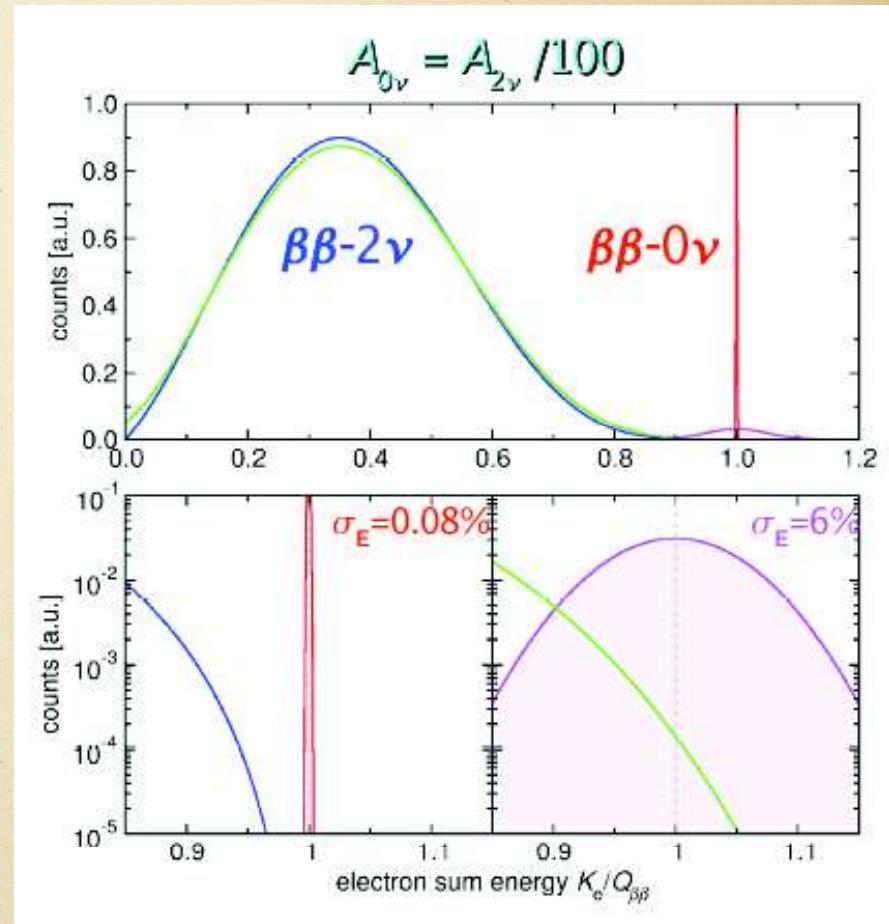
$$\frac{S}{B} \approx \frac{m_e}{7Q_{\beta\beta}\delta^6} \frac{T_{1/2}^{2\nu}}{T_{1/2}^{0\nu}}$$

Please note  $\delta^6$

$$\begin{aligned} T^{0\nu} &\simeq 10^{28} y & S/B = 1 \\ T^{2\nu} &\simeq 10^{20} y & Q \simeq 3 \text{ MeV} \end{aligned}$$

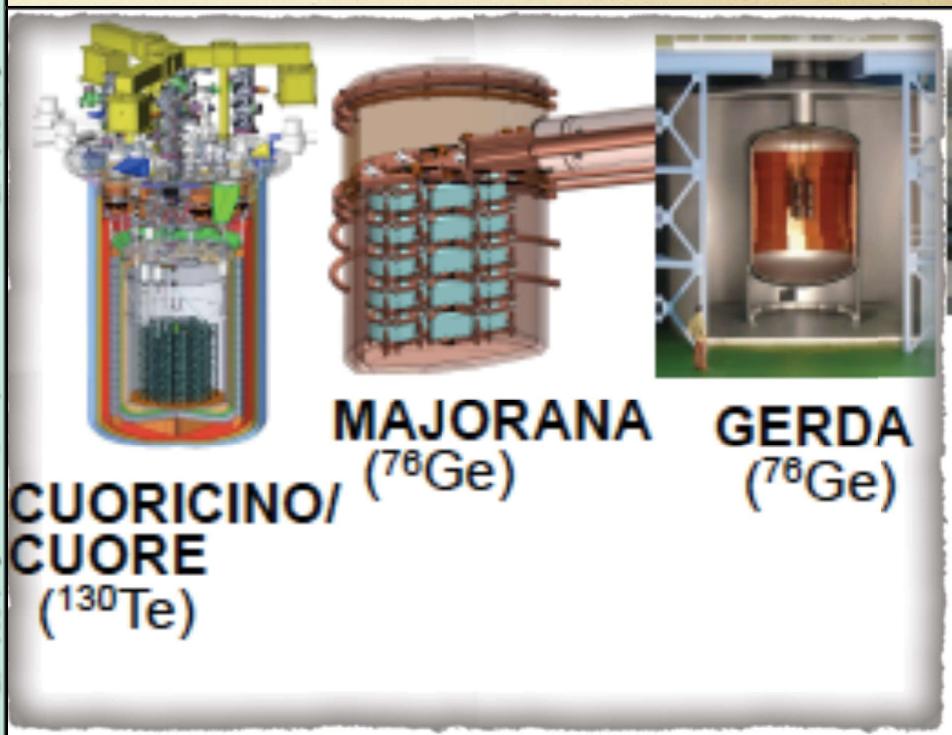
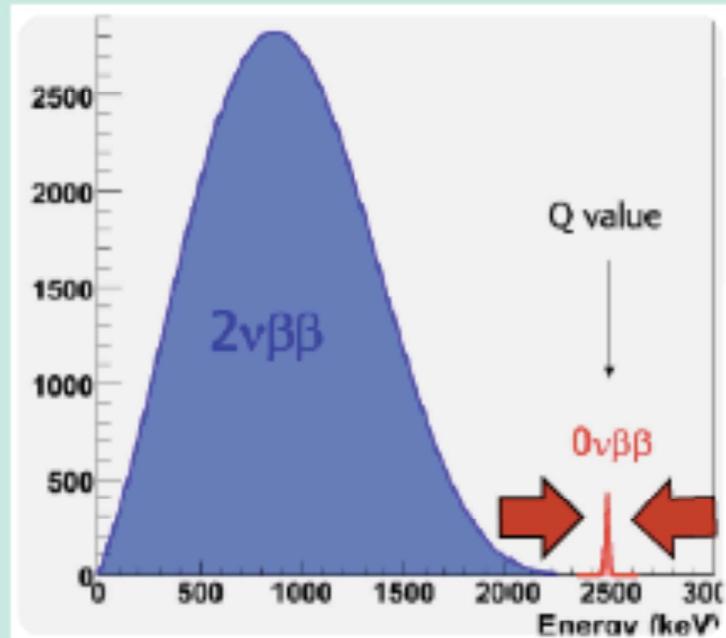


$$\delta = \Delta E^{FWHM}/Q \simeq 2.5\%$$

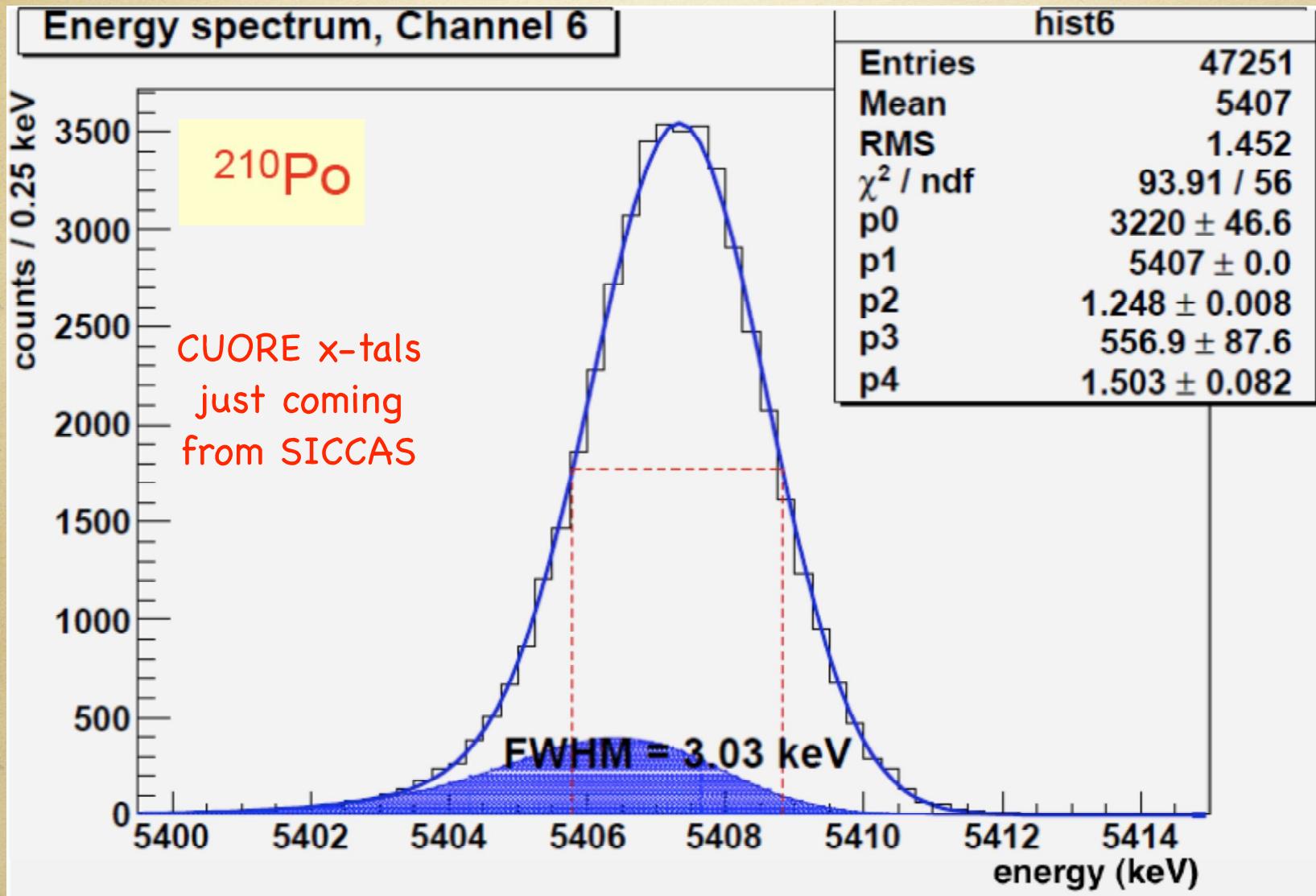


# the state of the art: peak squeezer

## The “Peak-Squeezer” Approach

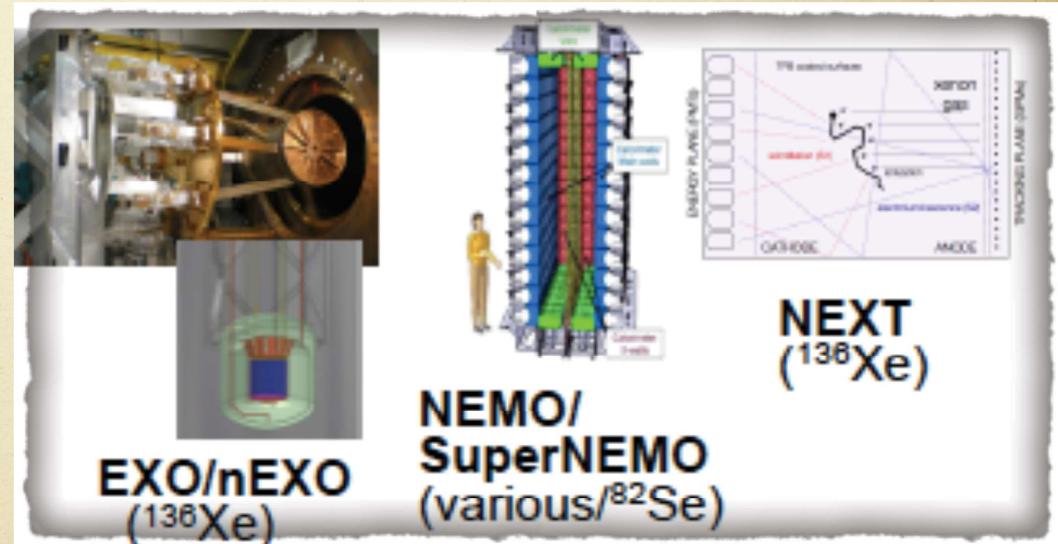
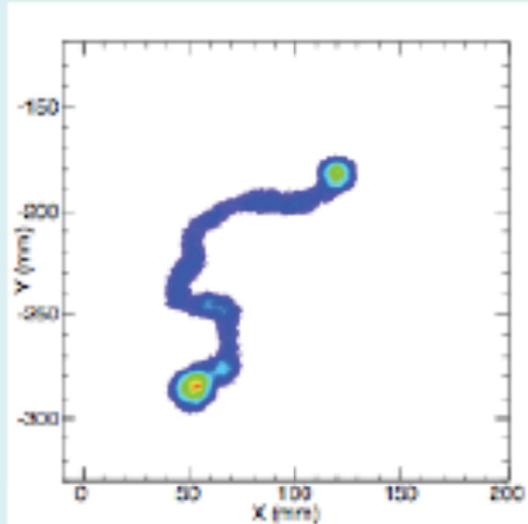


# how much can you squeeze ?

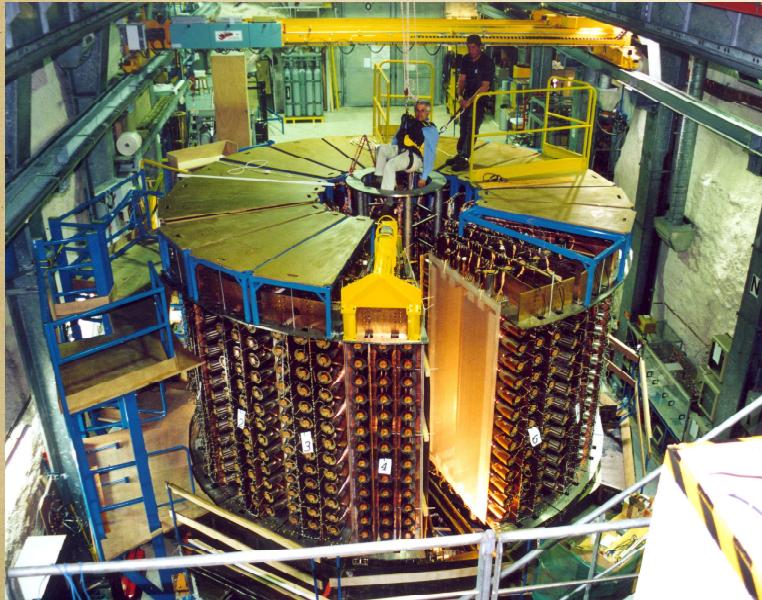


# the state of the art: tracking

## The “Final-State Judgement” Approach



# nicely working but...



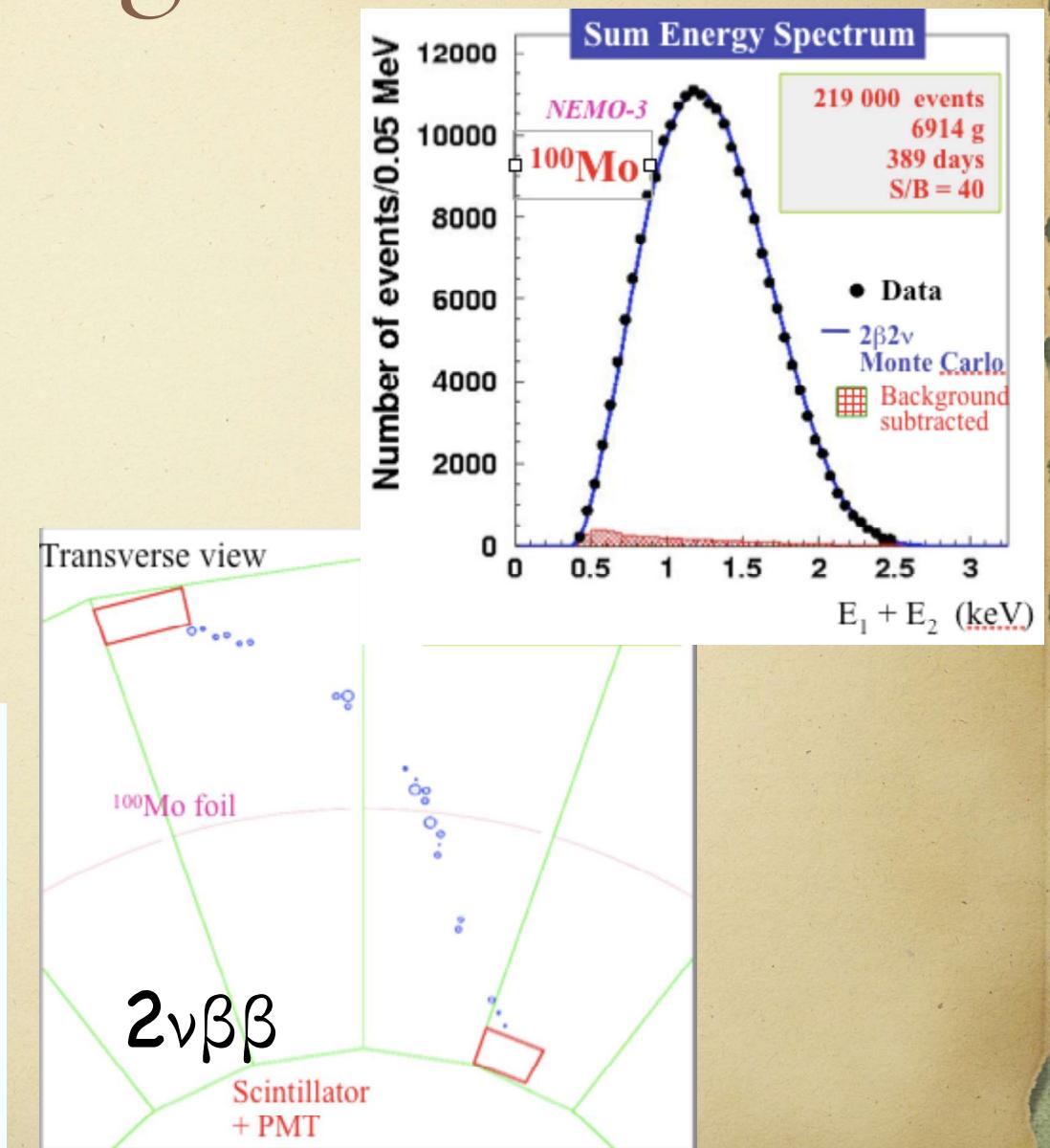
Source: 10 kg of  $\beta\beta$  isotopes  
cylindrical,  $S = 20 \text{ m}^2$ ,  $e \sim 60 \text{ mg/cm}^2$

## Tracking detector:

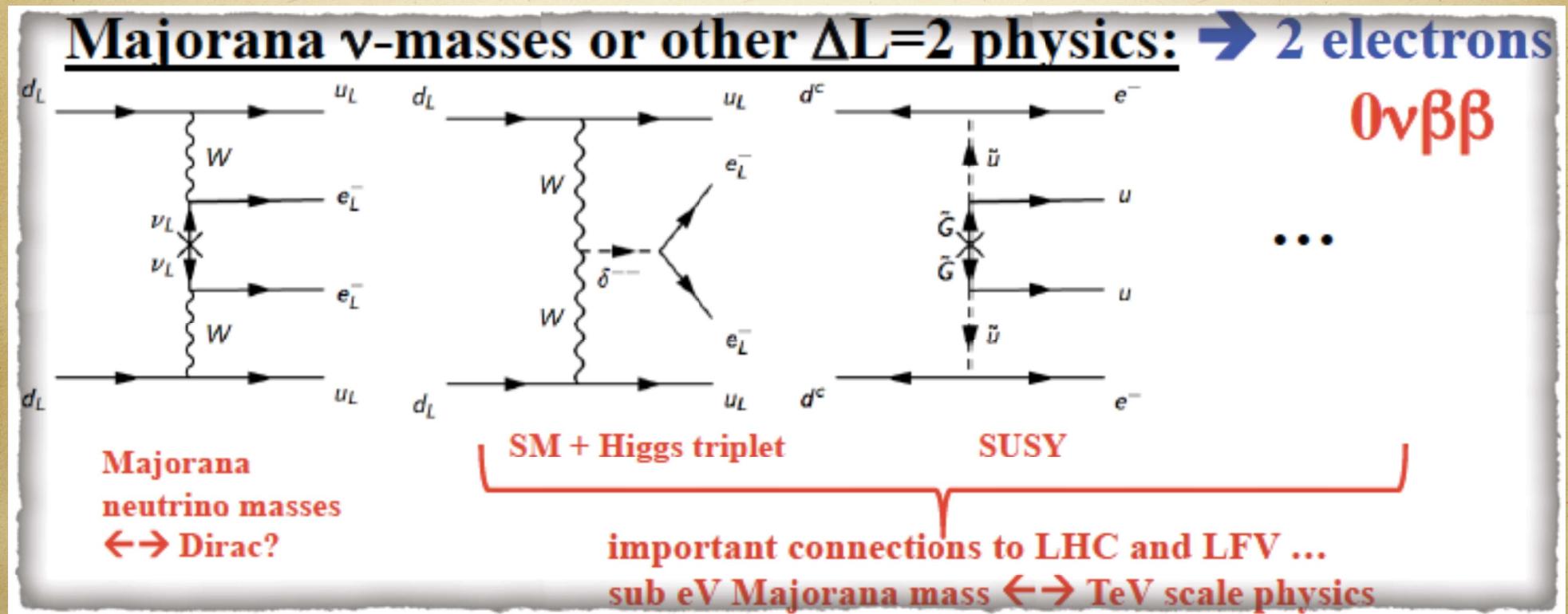
drift wire chamber operating  
in Geiger mode (6180 cells)  
Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H<sub>2</sub>O

## Calorimeter:

1940 plastic scintillators  
coupled to low radioactivity PMTs



# back to physics do not forget ‘New Physics’

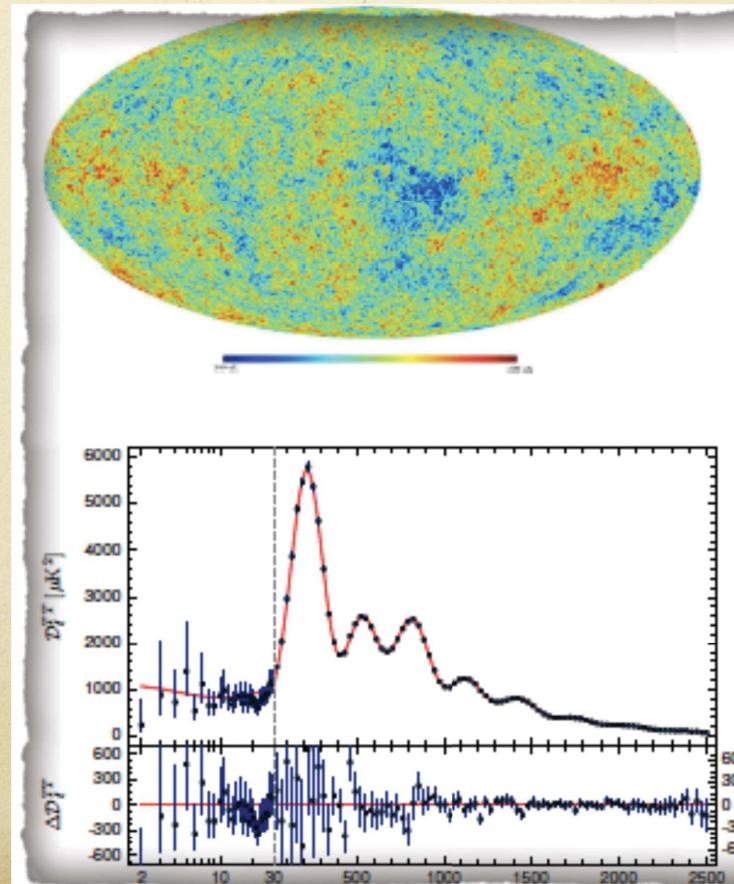


although we go after  $0\nu\beta\beta$  induced by Majorana's thoughts we might find something else !

# do we have any solid limit ?

what do we know about neutrino mass or at least on their sum ?

CMB fit



$$T_0 = 2.7255K$$
$$\Delta T(\mathbf{n}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\mathbf{n})$$
$$C_\ell = \langle |a_{\ell m}|^2 \rangle,$$
$$D_\ell = \ell(\ell+1)C_\ell/(2\pi)$$

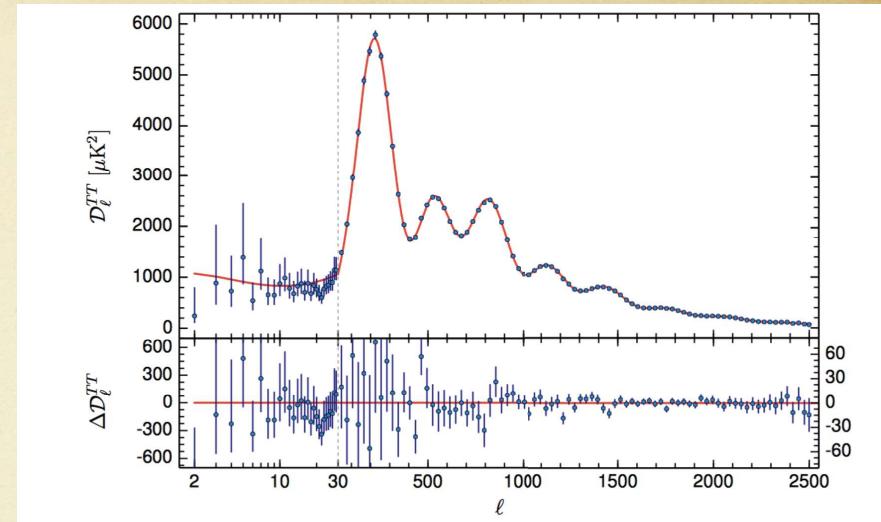
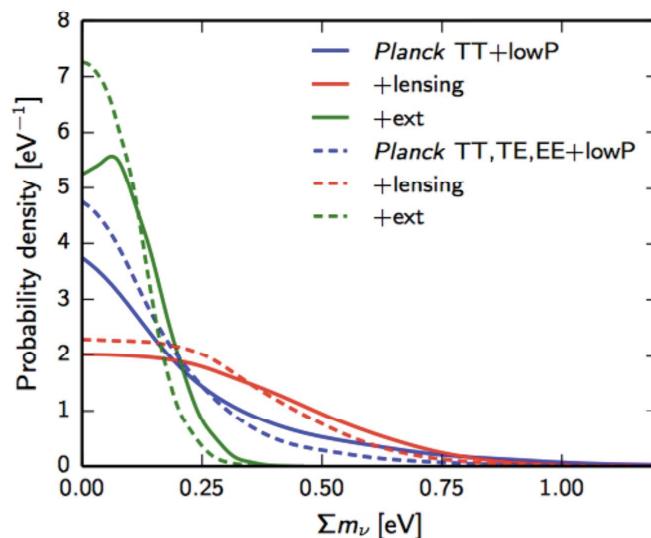
From the Planck Collaboration  
Planck Results XIII (2015)  
arXiv:1502.01589

# The CMB fit

- Curvature  $K = 0$
- No tensor perturbations,  $r = 0$
- Three species of thermal neutrinos,  $N_{\text{eff}} = 3.046$  with temperature  $T_\nu = (4/11)^{1/3} T_0$
- 2 neutrino species are massless and the third has  $m_3 = 0.06\text{eV}$  such that  $\sum_i m_i = 0.06\text{eV}$ .
- Helium fraction  $Y_p = 4n_{\text{He}}/n_b$  is calculated from  $N_{\text{eff}}$  and  $\omega_b$ .

## Parameters

- Amplitude of curvature perturbations,  $A_s$
- Scalar spectral index,  $n_s$
- Baryon density  $\omega_b = \Omega_b h^2$
- Cold dark matter density  $\omega_c = \Omega_c h^2$
- Present value of Hubble parameter  $H_0 = 100 \text{km/sec/Mpc}$   
 $(\Omega_\Lambda = 1 - (\omega_b + \omega_c)/h^2)$ .



## Info from Planck: Neutrino # and mass

$\Sigma m_\nu < 0.23 \text{ eV}$  (95% CL)  
 $N_{\text{eff}} = 3.15 \pm 0.23$

Planck + Lyman alpha

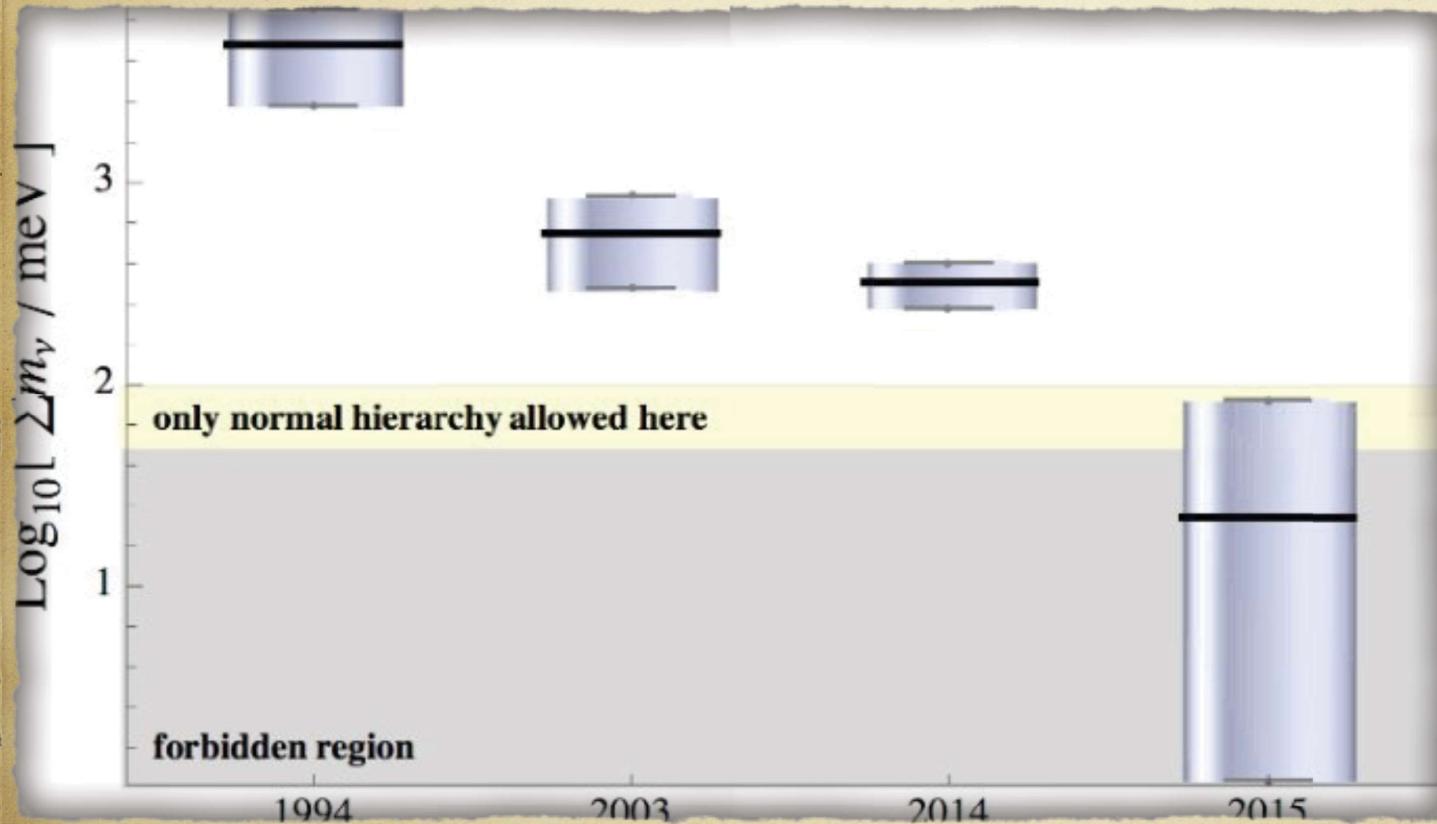
$\Sigma m_\nu < 0.14 \text{ eV}$  (C.L)

Prospects for PLANCK + EUCLID

$\Delta m_\nu \sim 0.03 \text{ eV}$  &  $\Delta N_{\text{eff}} \sim 0.08$

# should we believe it ?

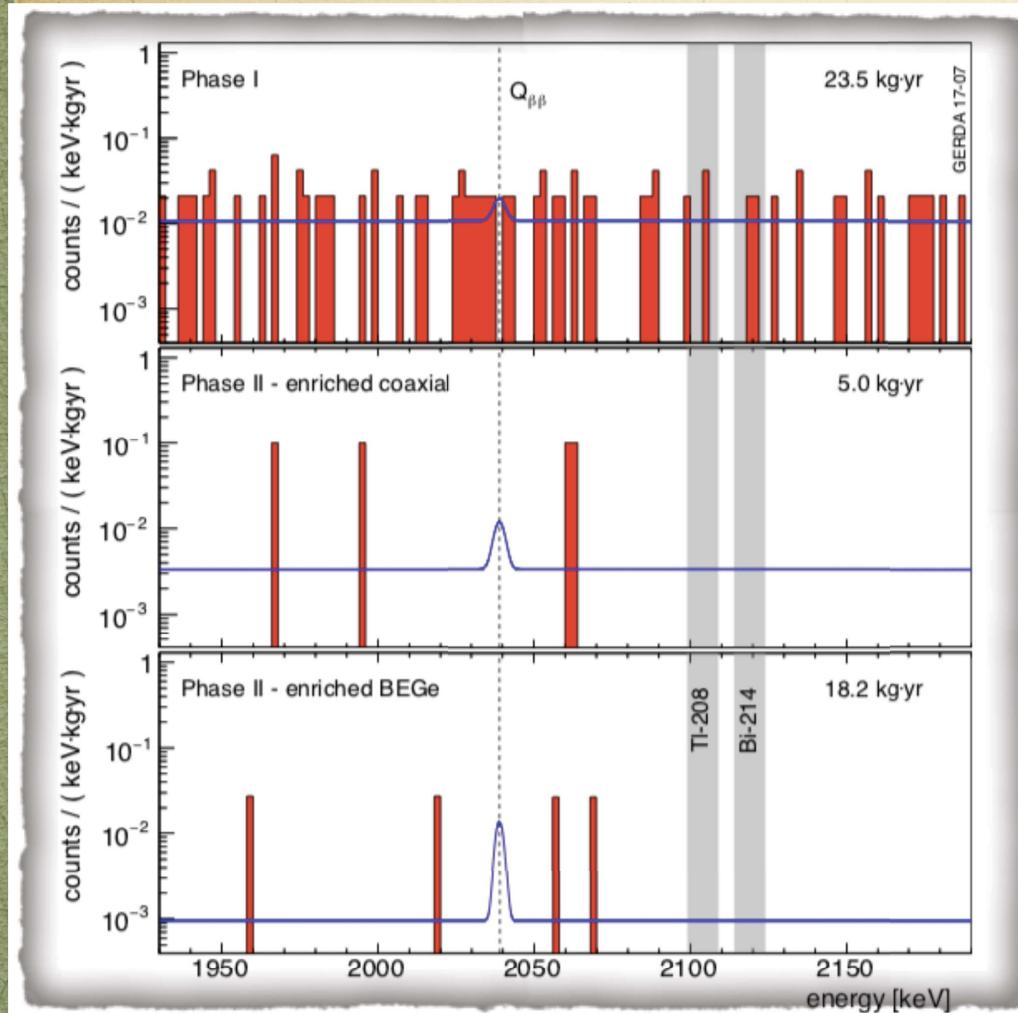
time evolution of CMB prediction on neutrino mass



a better  
understanding  
brings more  
solidity to  
results

# State of the art: GERDA

$^{76}\text{Ge}$  ( $^{76}\text{Ge} \rightarrow ^{76}\text{Se} + 2e^-$ )

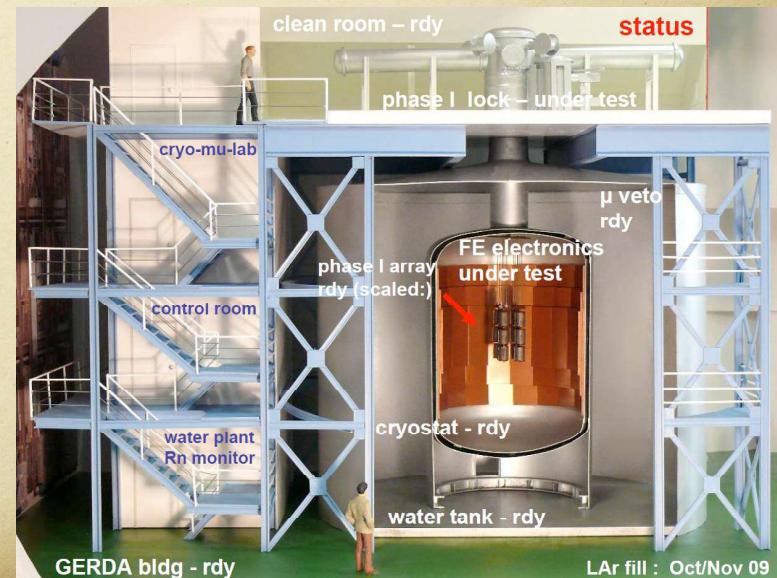


$$T_{1/2}^{0\nu} > 8.0 \cdot 10^{25} \text{ yr}$$

limit on  $m_{\beta\beta}$  is 0.12–0.26 eV

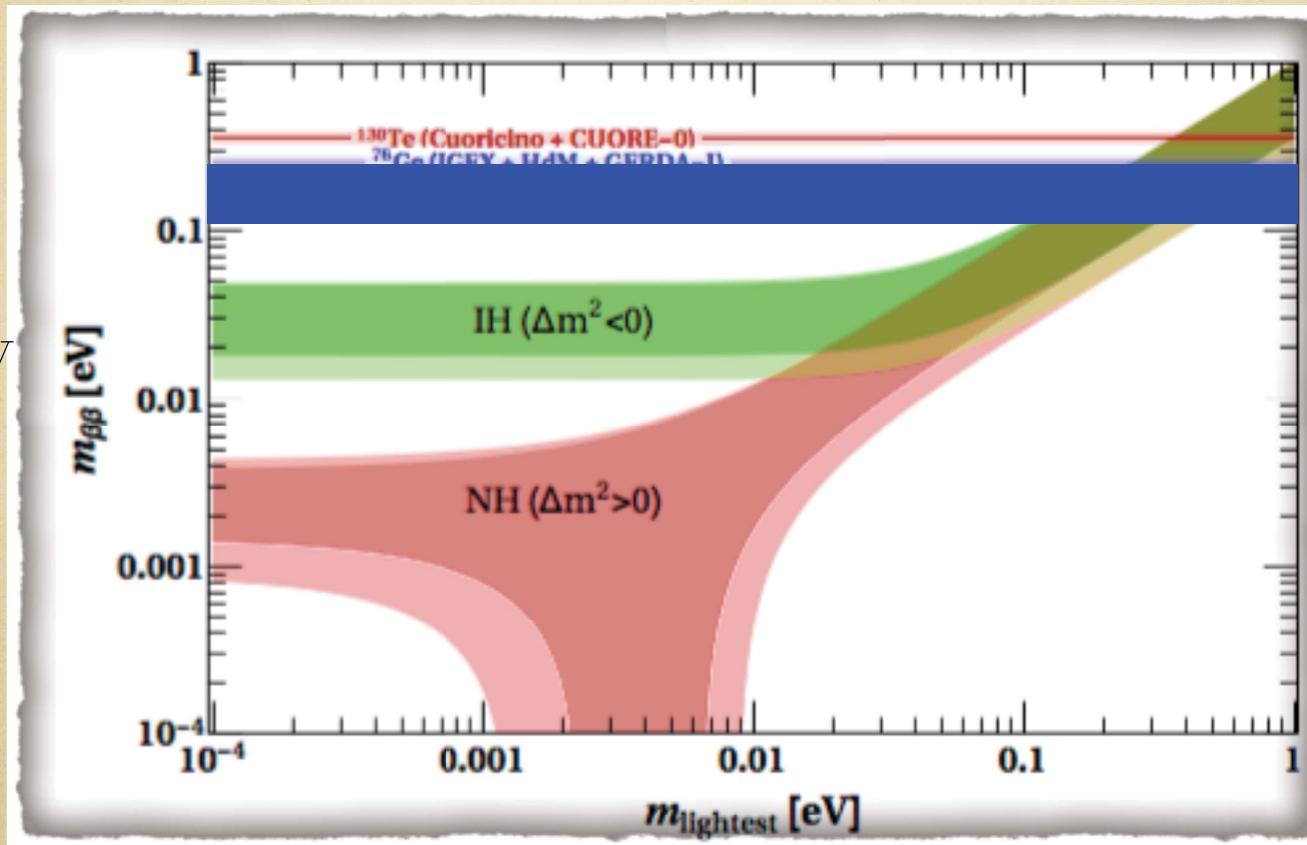
$$BI = 1.0_{-0.4}^{+0.6} \cdot 10^{-3} \text{ cts/(keV·kg·yr)}$$

$$BI \cdot \text{FWHM}/\epsilon = 4.9_{-1.9}^{+2.9} \text{ cts/(ton·yr)}$$



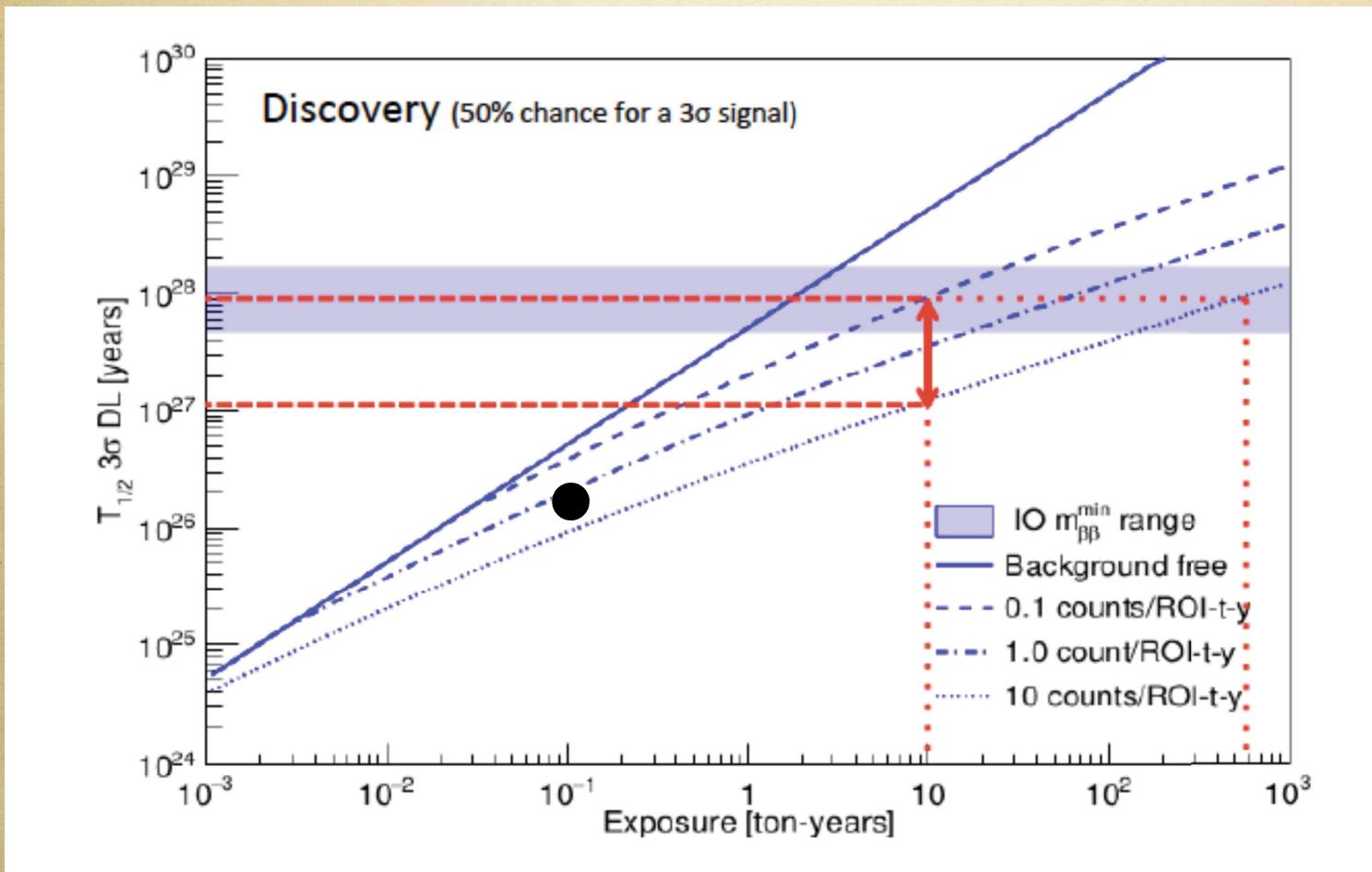
a very  
long way  
to IH

which translate in



assuming no  $g_A$  quenching

# Tough future

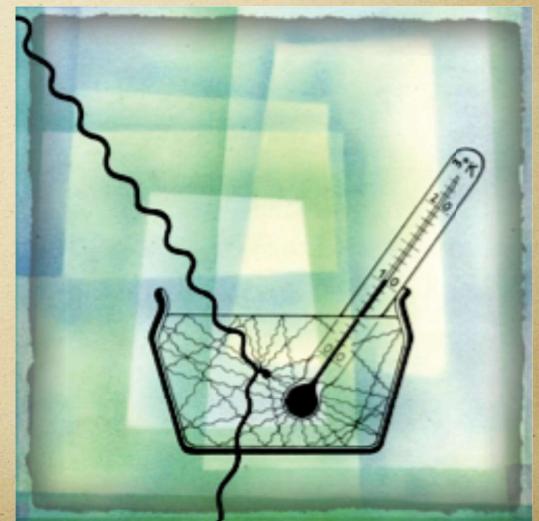


- GERDA discovery potential for 100kg/y with actual level of backg

end of part I

# Bolometric technique

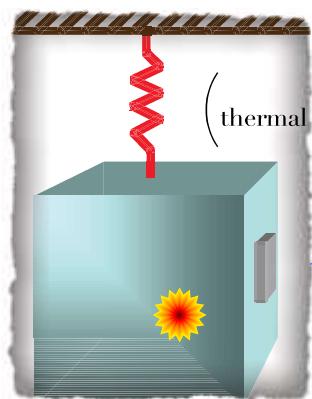
- ▷ from MiBeta to CUORE via Cuoricino and Cuore0
- ▷ Scintillating bolometers as an evolution toward Zero Background



# (very) Low Temperature Calorimeter

## A True Calorimeter

heat sink      ( $T_0$ )



(C)      thermometer

$\beta\beta$  atom x-tal

Basic Physics:  $\Delta T = E/C$

(Energy release/ Thermal capacity)

Implication: Low C  $\Rightarrow$  Low T

Bonus: (almost) No limit to  $\Delta E$   
( $k_B T^2 C$ )

Not for all apps :  $\tau = C/G \sim 1s$

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

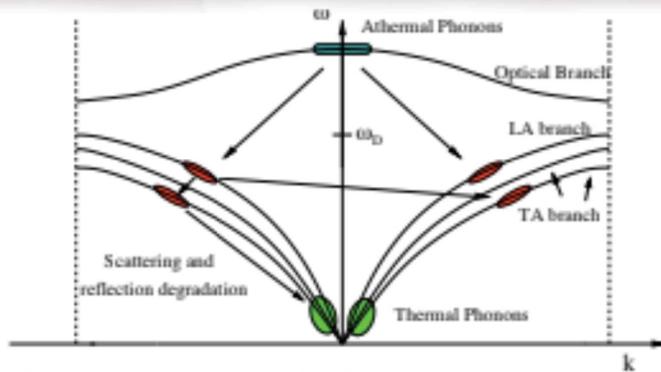
$$\Delta T(t) = \frac{\Delta E}{C} \exp \left( -\frac{t}{\tau} \right)$$

# Energy absorber and resolution

Particles can interact with the absorber by scattering on nuclei or electrons —> athermal phonons.

New phenomena of phonon energy degradation can occur —> thermal phonons

The thermodynamic equilibrium between the absorber and the heat bath is hold by a continuum exchange of phonons through the conductance G.



Intrinsic energy resolution  
thermodynamic energy fluctuation in the absorber

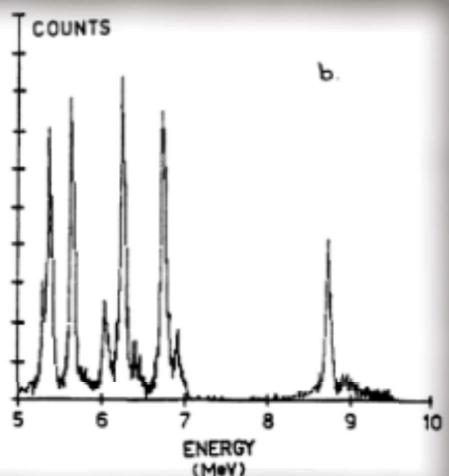
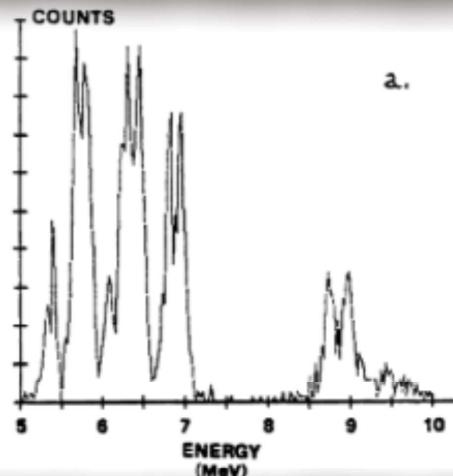
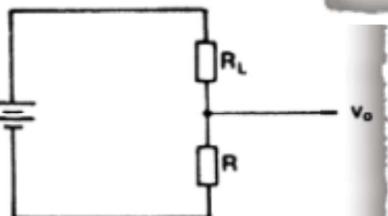
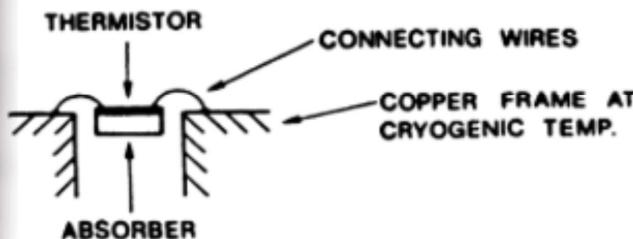
$$\langle \Delta U^2 \rangle = (k_B T)^2 \cdot N = k_B \cdot T^2 \cdot C(T)$$

# Why a bolometer

- ▷  $M, t, B, \Delta E$  are the parameters of the game
- ▷  $t$  is irrelevant
- ▷  $M$  is ‘easy’ with a calorimeter
- ▷  $\Delta E$  is a definite bonus
- ▷  $B$  is what this part of the talk is mostly about

# the Dawn !

Cryogenic Detectors and Materials Research in Physics and Astrophysics  
E. Fiorini



## Prehistory and future of thermal detectors

T.O. Niinikoski

CERN, Geneva, Switzerland

1983

## Low-temperature calorimetry for rare decays

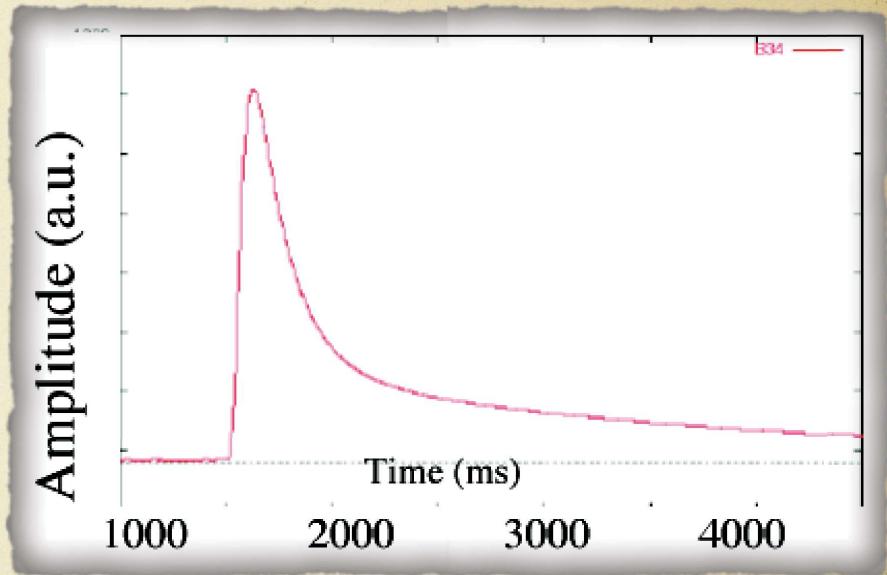
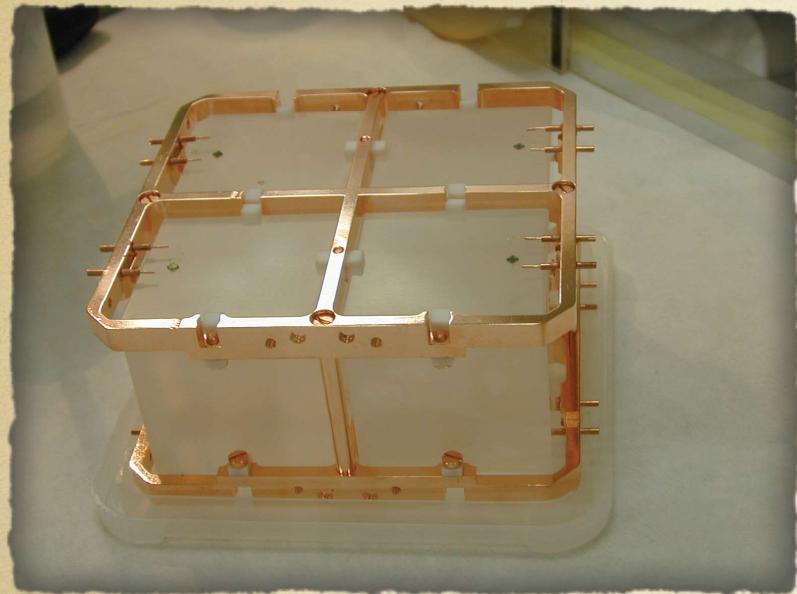
E. Fiorini

Dipartimento di Fisica dell'Università and INFN, Milano, Italy

[T.O. Niinikoski](#)

CERN, Geneva, Switzerland

# $\text{TeO}_2$ : a viable (show)case



Numerology:

$$T_0 \sim 10 \text{ mK}$$

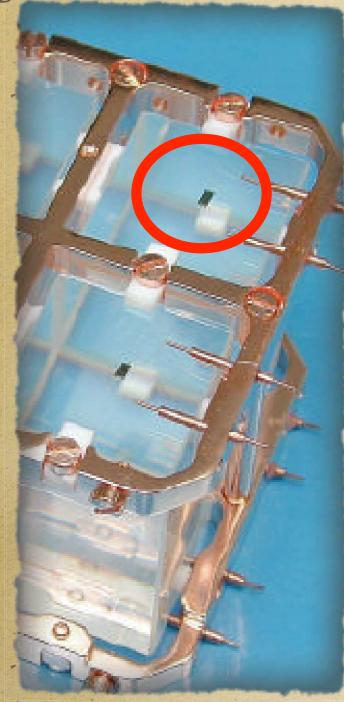
$$C \sim 2 \text{ nJ/K} \sim 1 \text{ MeV}/0.1 \text{ mK}$$

$$G \sim 4 \text{ pW/mK}$$

Need to be able to detect temperature jumps of a fraction of  $\mu\text{K}$  (per mil resolution on MeV signals)

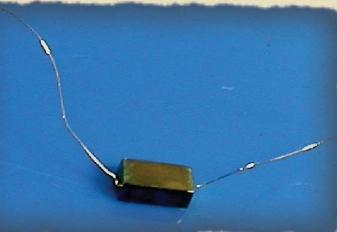
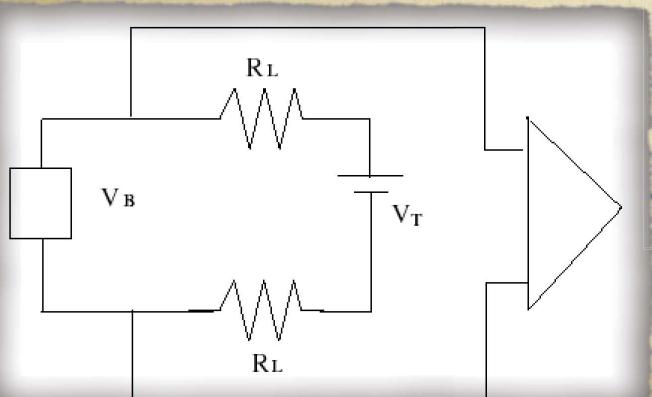
to read the temperature  
you need a thermometer

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

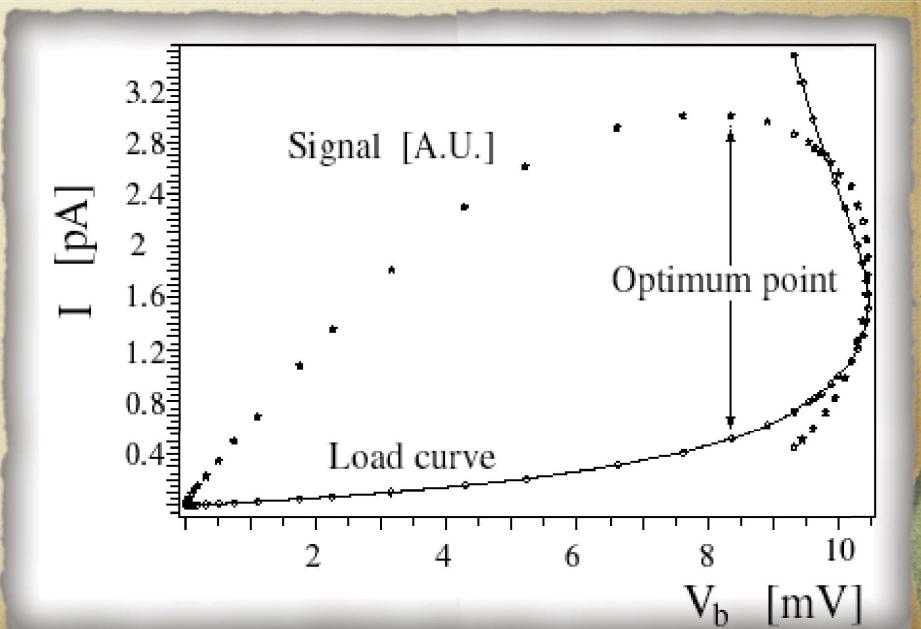


$$dR/dE \sim 3M\Omega/\text{MeV}$$

Neutron Transmutation  
Doped (NTD) Germanium  
Thermistor

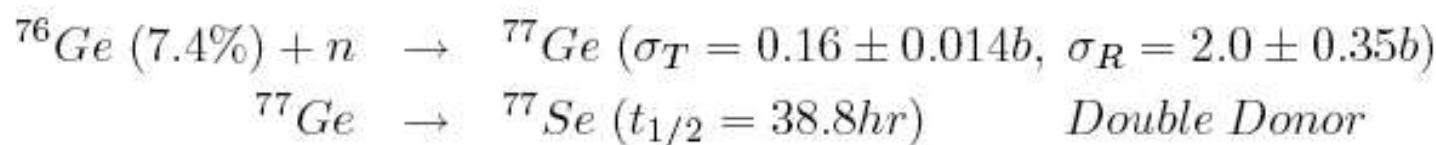
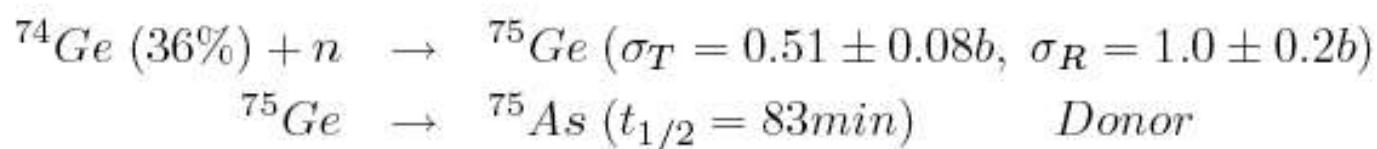
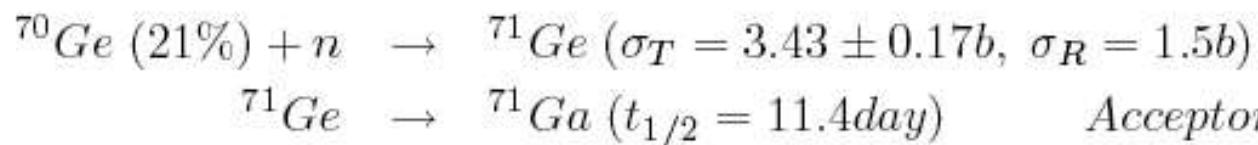


$$T_b = T_0 + \frac{P}{G}$$



# Neutron Transmutation Doping

A pure Ge Crystal is exposed to the thermal neutron flux of a nuclear reactor. Some Ge gets transmuted into dopants.



Higly  
Uniform

Doping level is  $10^{17}$  atoms/cm<sup>3</sup>.

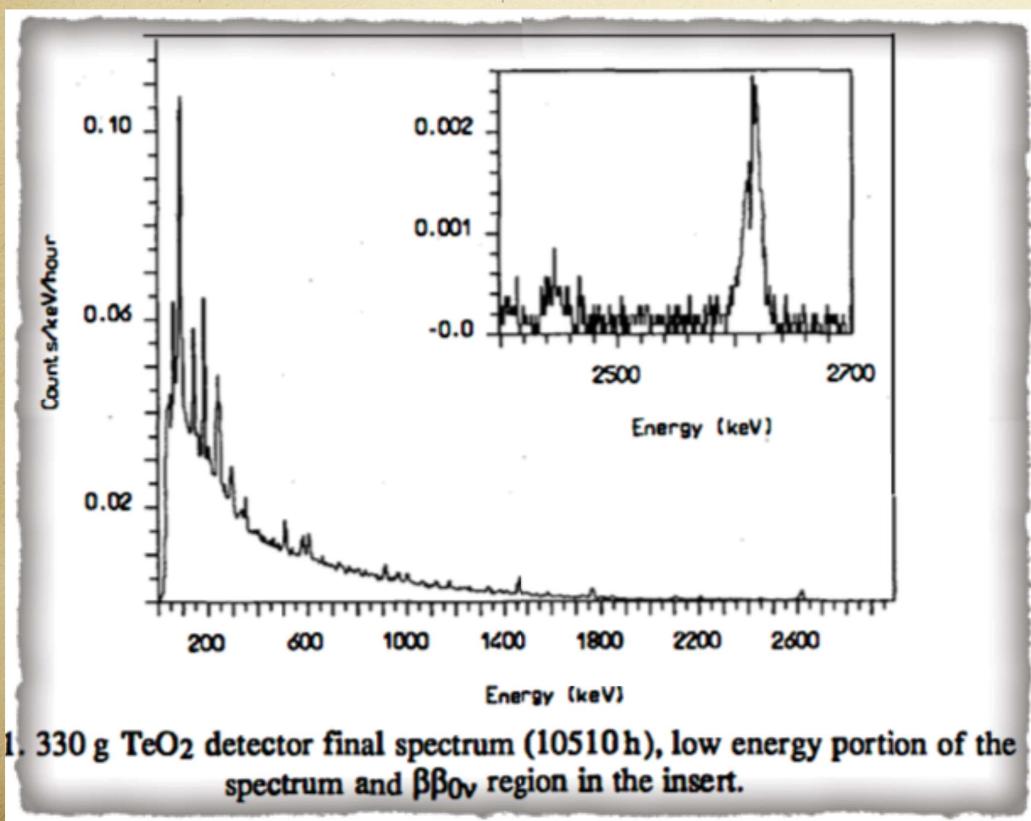
Required fluence is  $3.5 \times 10^{18}$  n/cm<sup>2</sup>.

# The long saga of the ultra cold $^{130}\text{Te}$

MILANO  $^{130}\text{Te}$  NEUTRINOLESS DOUBLE BETA DECAY SEARCH  
WITH THERMAL DETECTORS

A.Alessandrello, C.Brofferio, D.V.Camin, P.Caspani, O.Cremonesi, E.Fiorini,  
A.Foraboschi, A.Giuliani, A.Nucciotti, M.Pavan, G.Pessina, E.Previtali, L.Zanotti  
*Dipartimento di Fisica dell'Università di Milano, I-20133 Milano, Italy*

A 330 g  $\text{TeO}_2$  crystal has collected data for about 10500 h live time setting a new lower limit of  $2.1 \cdot 10^{22} \text{ y}$  (90% C.L.) for  $^{130}\text{Te}$  neutrinoless double beta decay.



pls. note that the scale quotes counts/hour (!!)

resolution was 17keV

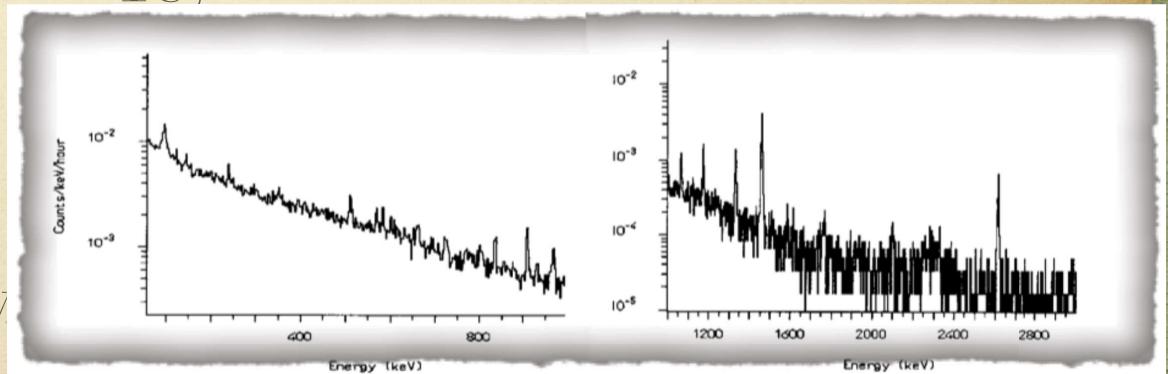
background high

BUT THE WAY  
WAS OPEN !

# step after step

- ▷ limit from that single crystal was  $2.1 \cdot 10^{22}$  y
- ▷ next step, 4 crystals, 1.3 kg
- ▷ and then Mi-Beta, 20 crystals, 6.8 kg (natural tellurium, meaning  $2.3 \cdot 130\text{Te}$ )

- ▷ set a limit of  $9.5 \cdot 10^{22}$  y



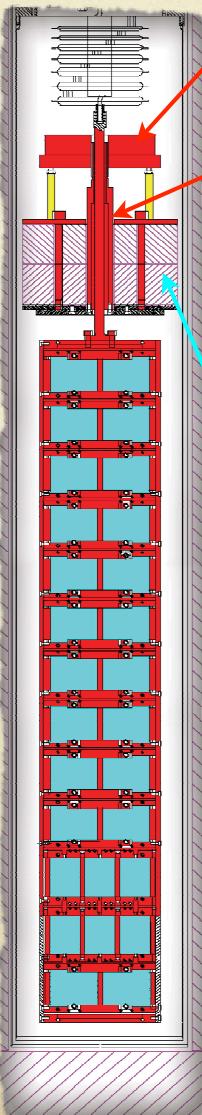
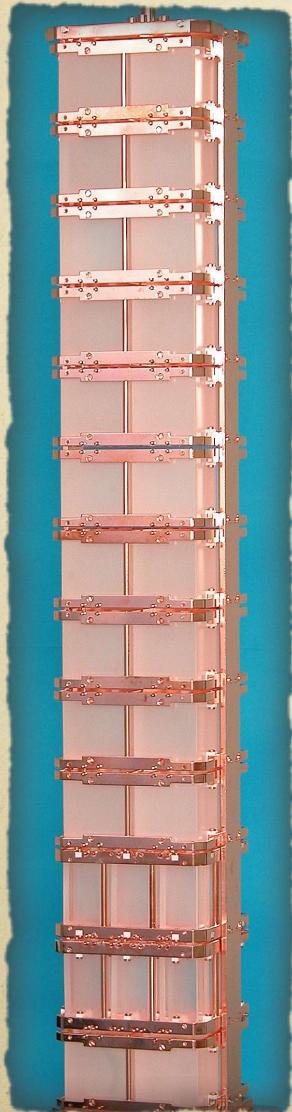
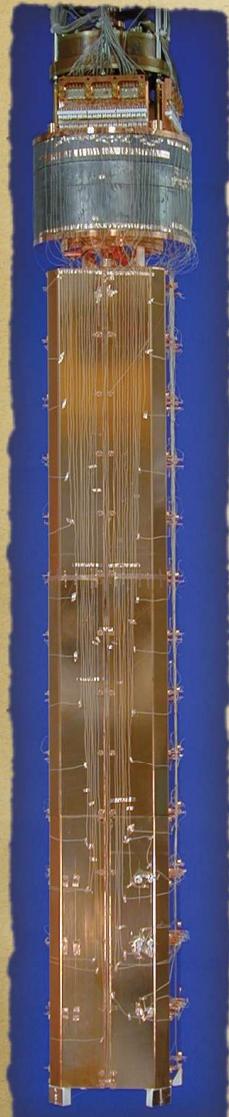
ready for a tougher game

# Guoricino

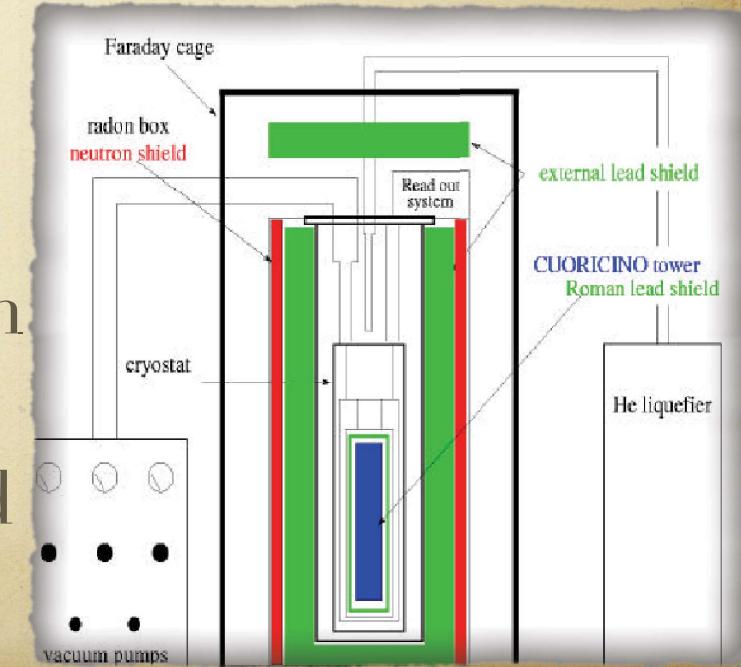
Mixing chamber

Cold finger

10 mK



Roman  
Lead  
Shield



# a digression on Roman Lead

## Lead is a very good shield from external radioactivity

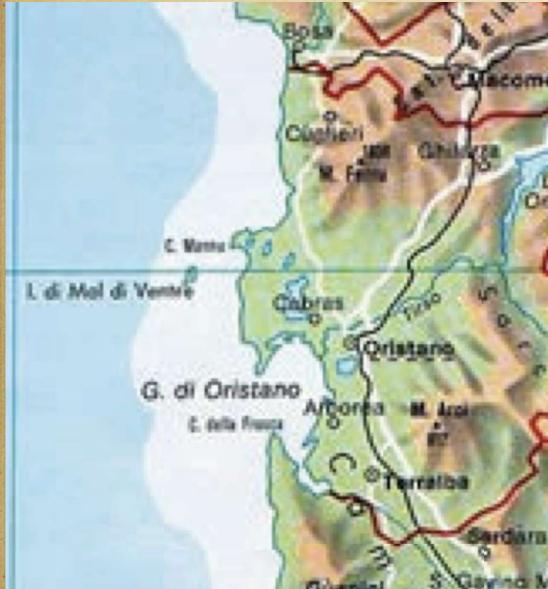


however it has  
got a problem

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

the half-life of isotope 210 is 22 years  
too long for our patience to let it disappears !  
too short for not harming us !

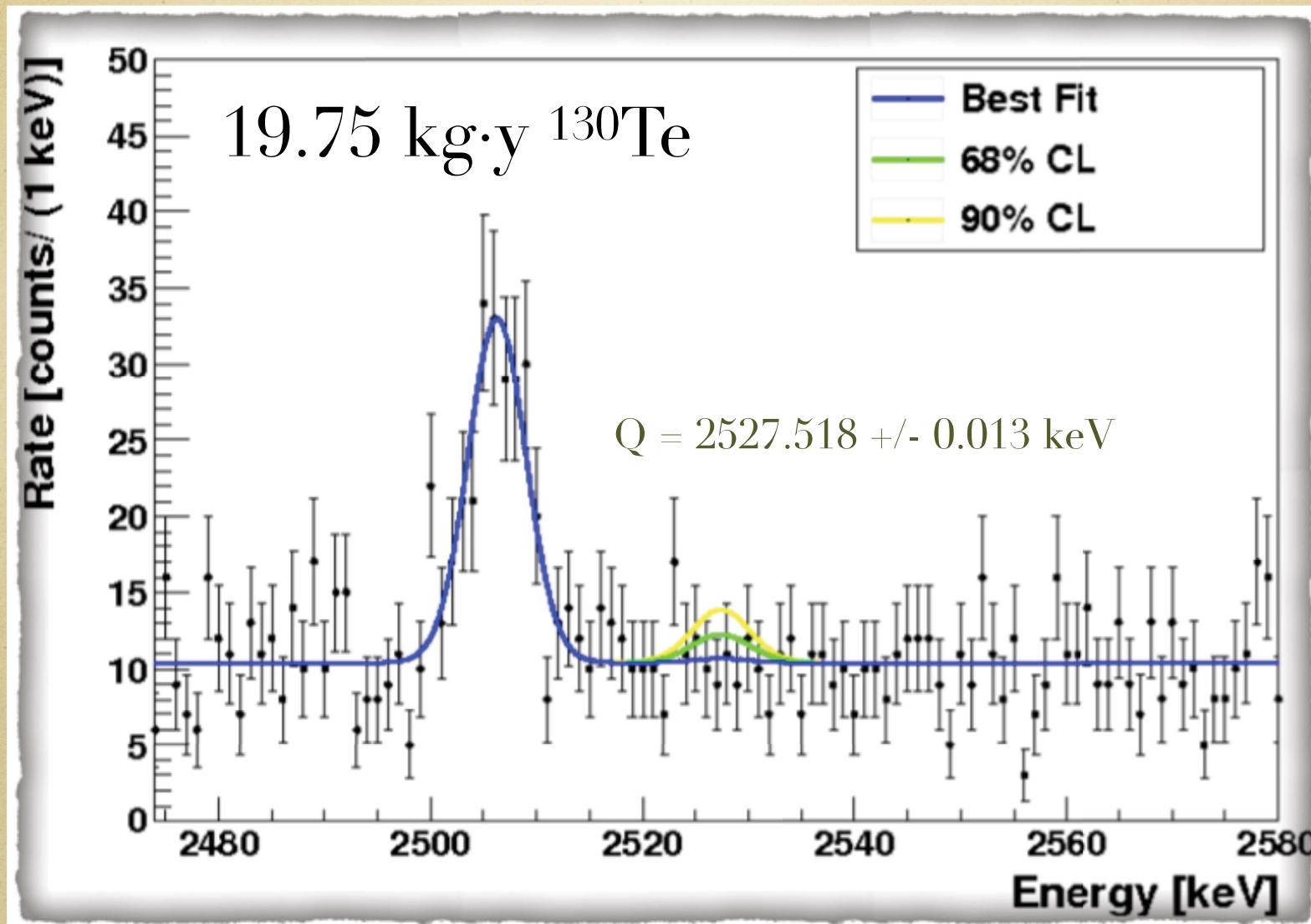
# Elegant solution although with a strong component of luck



a collaborative  
effort by  
INFN and  
Cultural Heritage  
Ministry



# Cuoricino final result



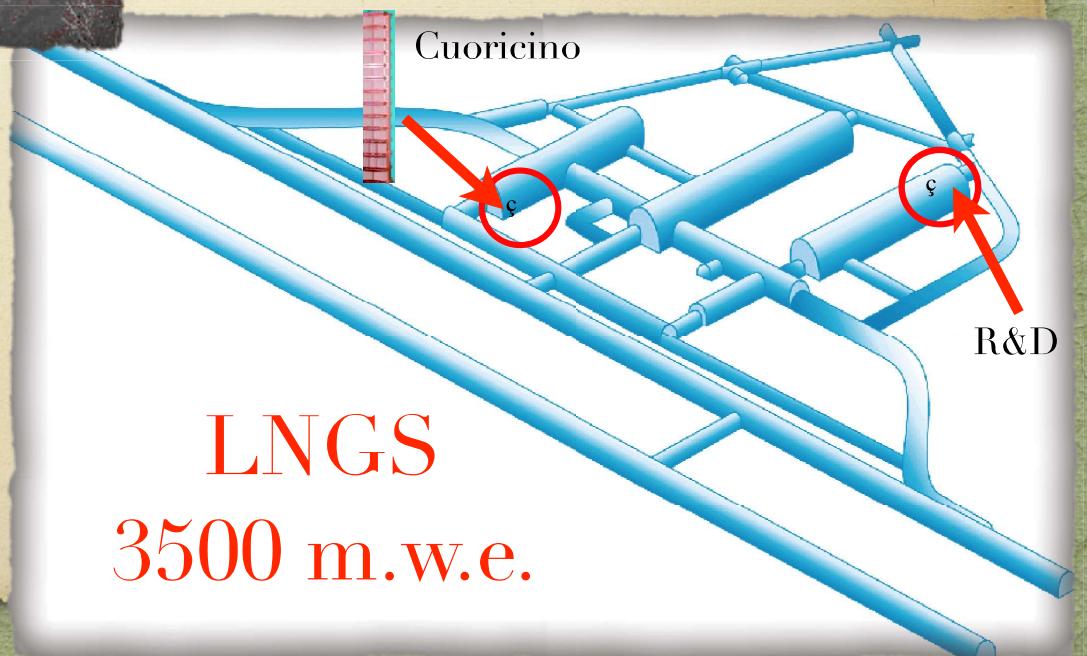
$$\tau_{1/2}^{0\nu} = 2.8 \cdot 10^{24} \text{ y}$$

# Cuoricino, where ?



The Shield  
Corno Grande 2916 m

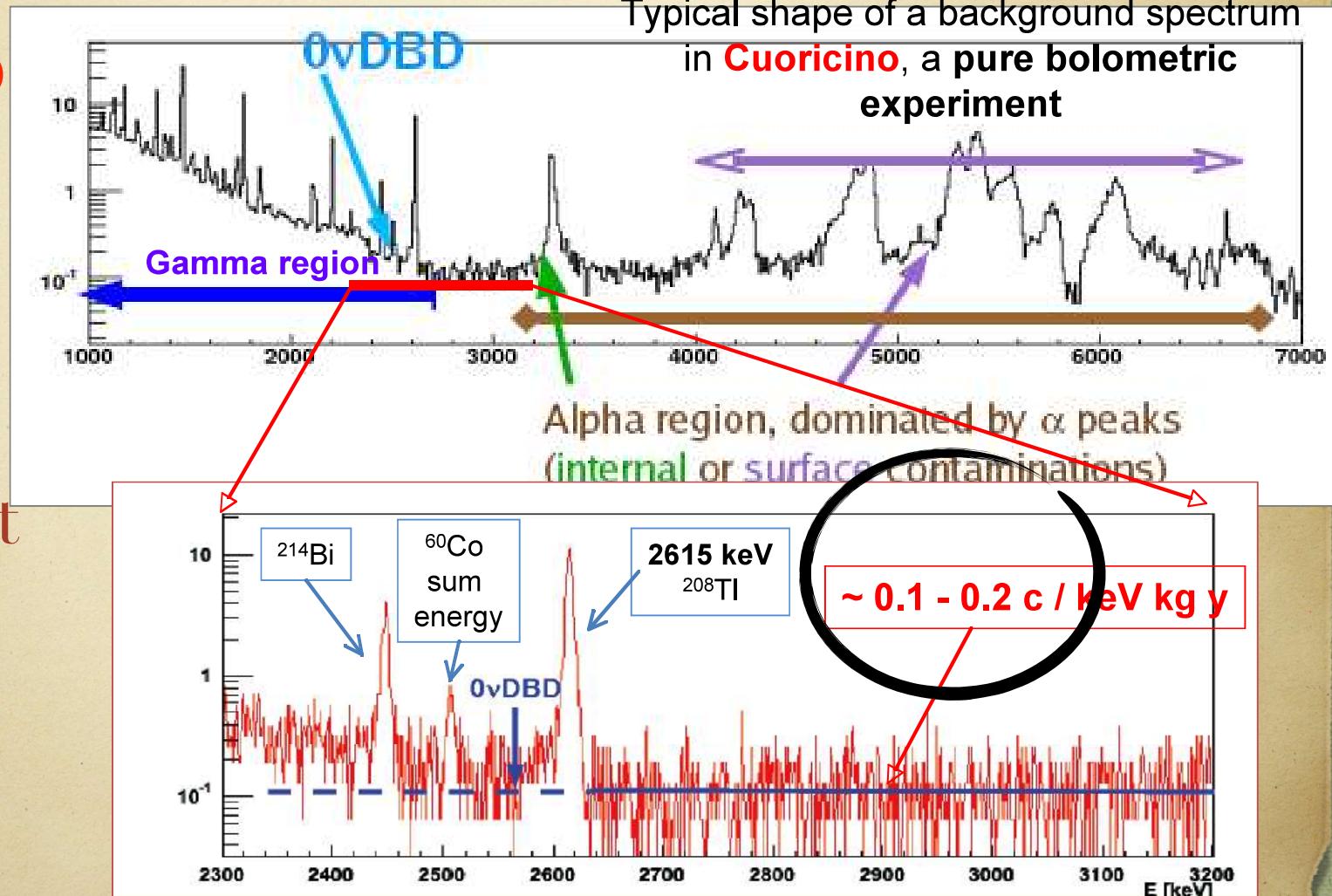
A National Park providing great opportunity for walking, trekking, climbing, cross and backcountry skiing



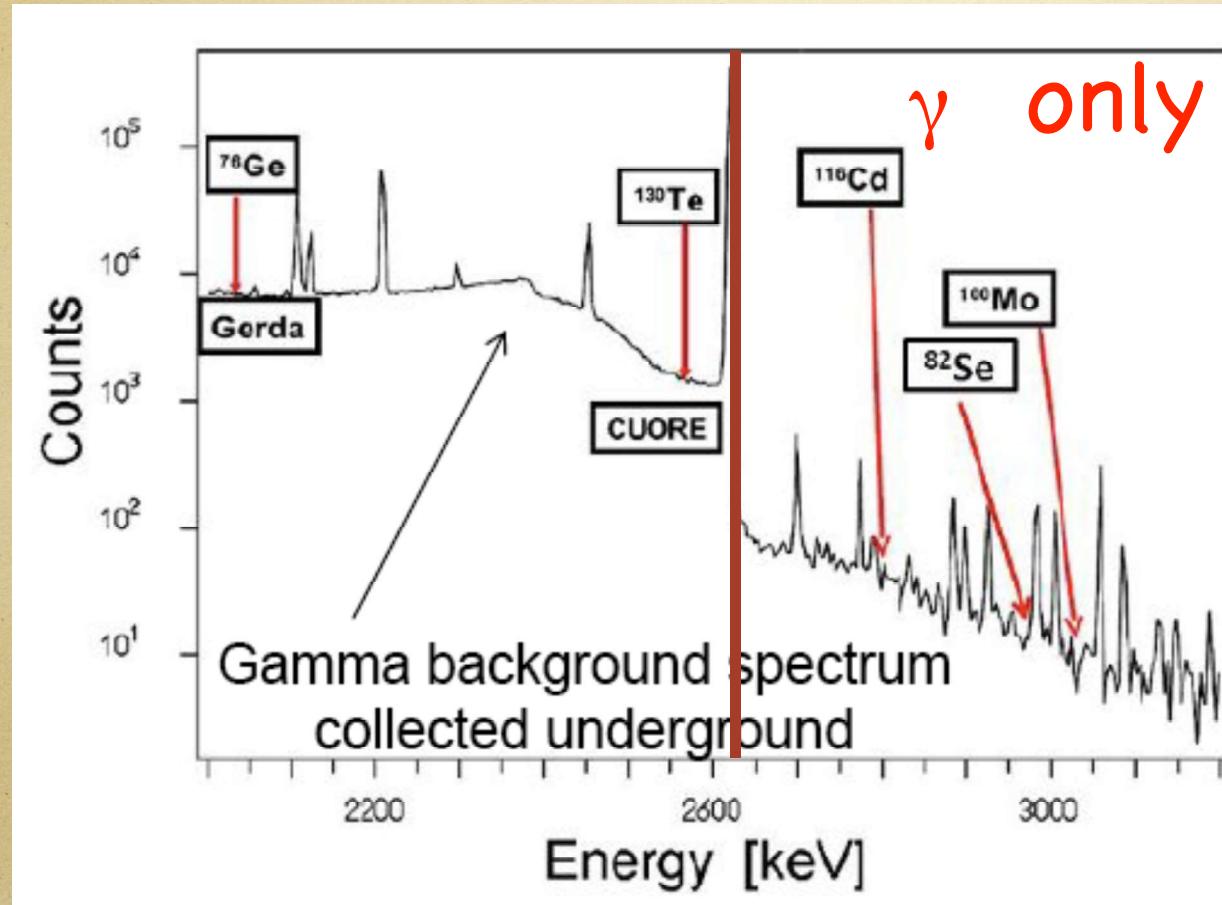
# it is time to deal with the enemy: what is the background ?

**Cuoricino**  
 $b = 0.18 \pm 0.02$   
c/keV/kg/y

B  
is experiment  
dependent.  
Cuoricino  
as an  
example



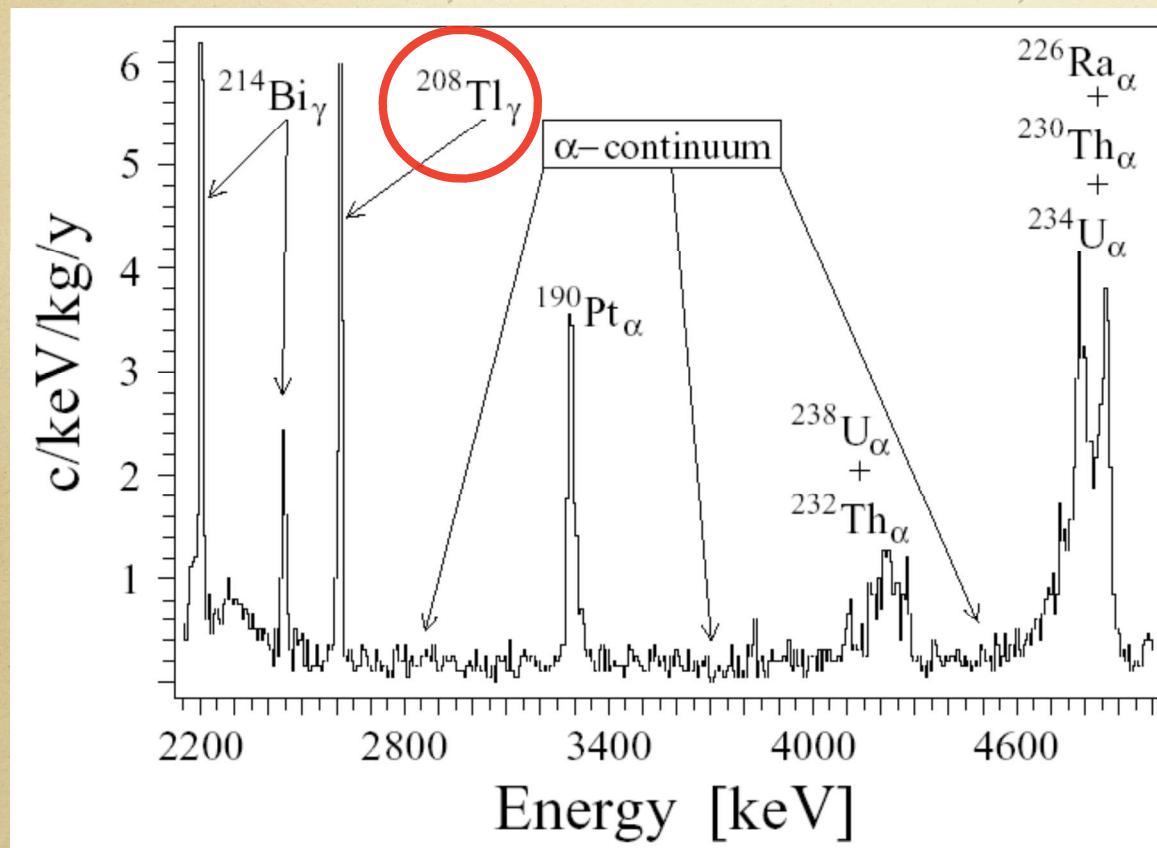
we have two enemies then



Photons

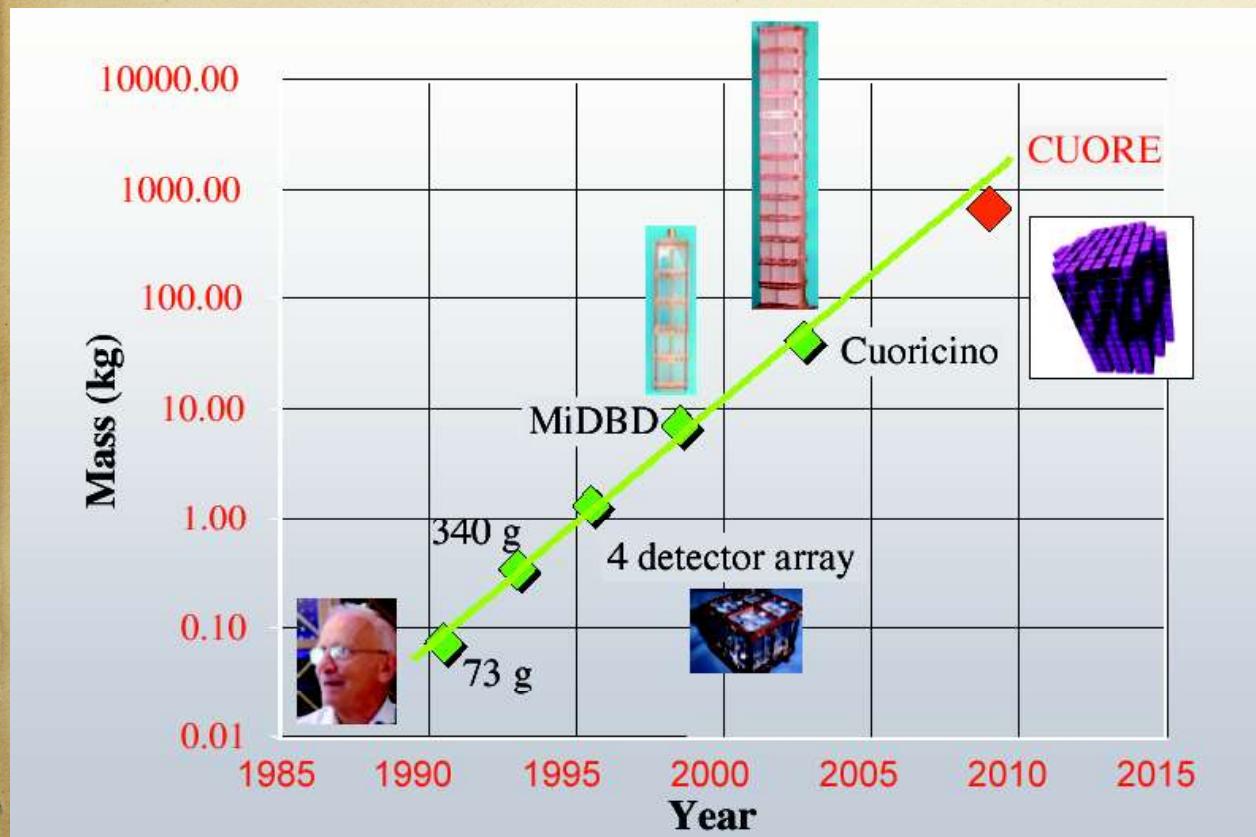
$^{208}\text{Tl}$  is where photons start to disappear  
Keep it in mind !

and...



the  $\alpha$ -land

# The last child of the evolution: CUORE



this kind of Moore's law for bolometers is not very precise but it gives the time scale of the generation evolution

# CUORE



Pulse Tube Cooler

988 TeO<sub>2</sub> Crystals

19 Towers of 52 crystals  
each

741 Kg of TeO<sub>2</sub>

Active Mass 204 Kg

# Scaling Cuoricino to CUORE

$$\frac{a}{A} \left[ \frac{M T}{b \Delta E} \right]^{1/2}$$

$$\begin{aligned} M &= m \times 20 \\ T &= t \times 6 \\ b &= B / 20 \\ \Delta E &= \Delta E / 1.5 \end{aligned}$$

$$S_{\text{CUORE}} = \sqrt{3600} S_{\text{Cuoricino}} \sim 60 S_{\text{Cuoricino}}$$

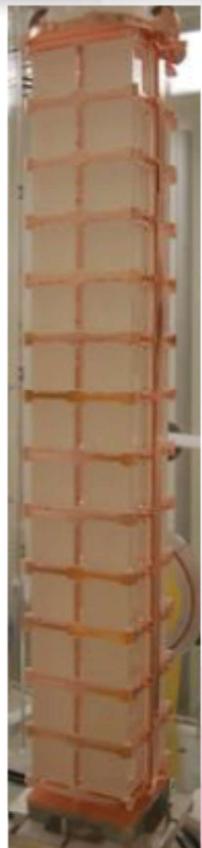
$$\tau_{1/2}(\text{CUORE}) \sim 1.2 \times 10^{26}$$

One step is non trivial. Getting to 0.01 c/Kg/y/KeV  
(CUORE is 1 Ton. It means 10 c/y/KeV)

# a sanity check: CUORE-0

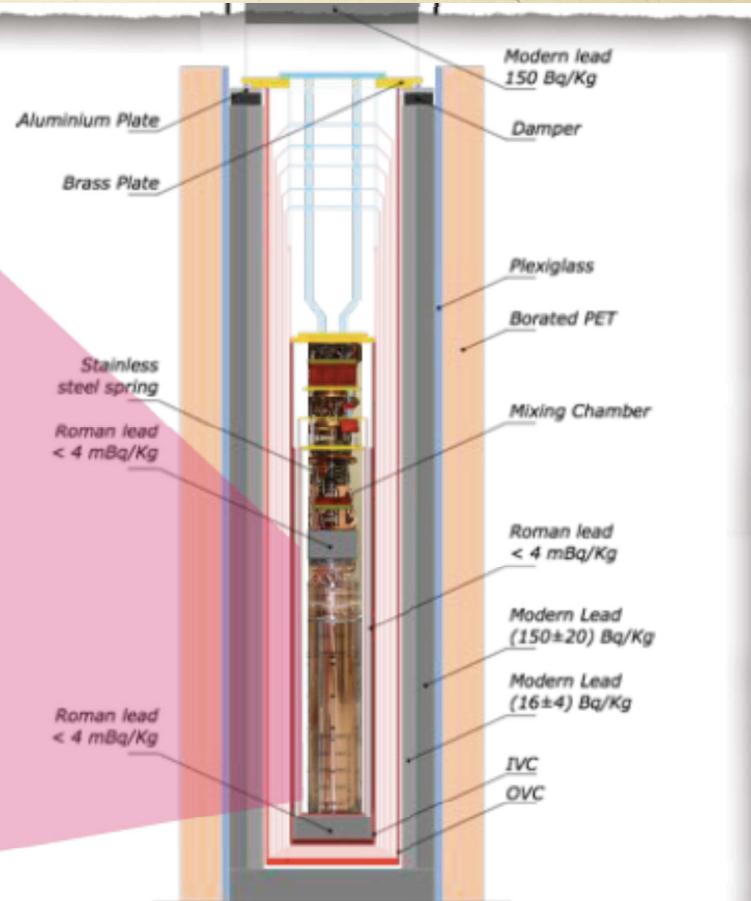
Size similar to CUORICINO:

- 52x750g crystals
- 13 floor of 4 crystals each



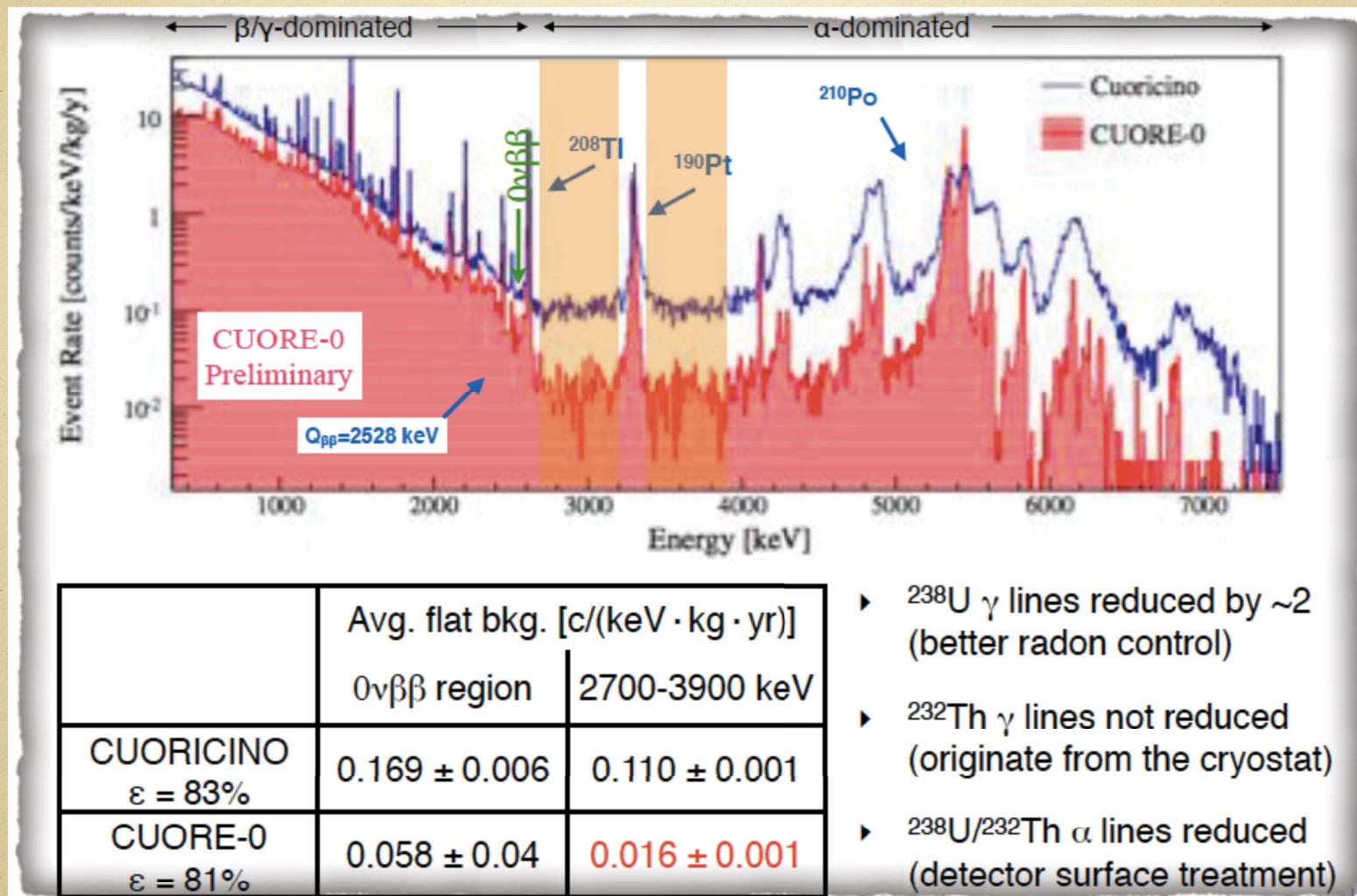
Active mass:

- $\text{TeO}_2$ : 39 kg
- $^{130}\text{Te}$ : ~11 kg  
( $5 \cdot 10^{25}$  nuclei)



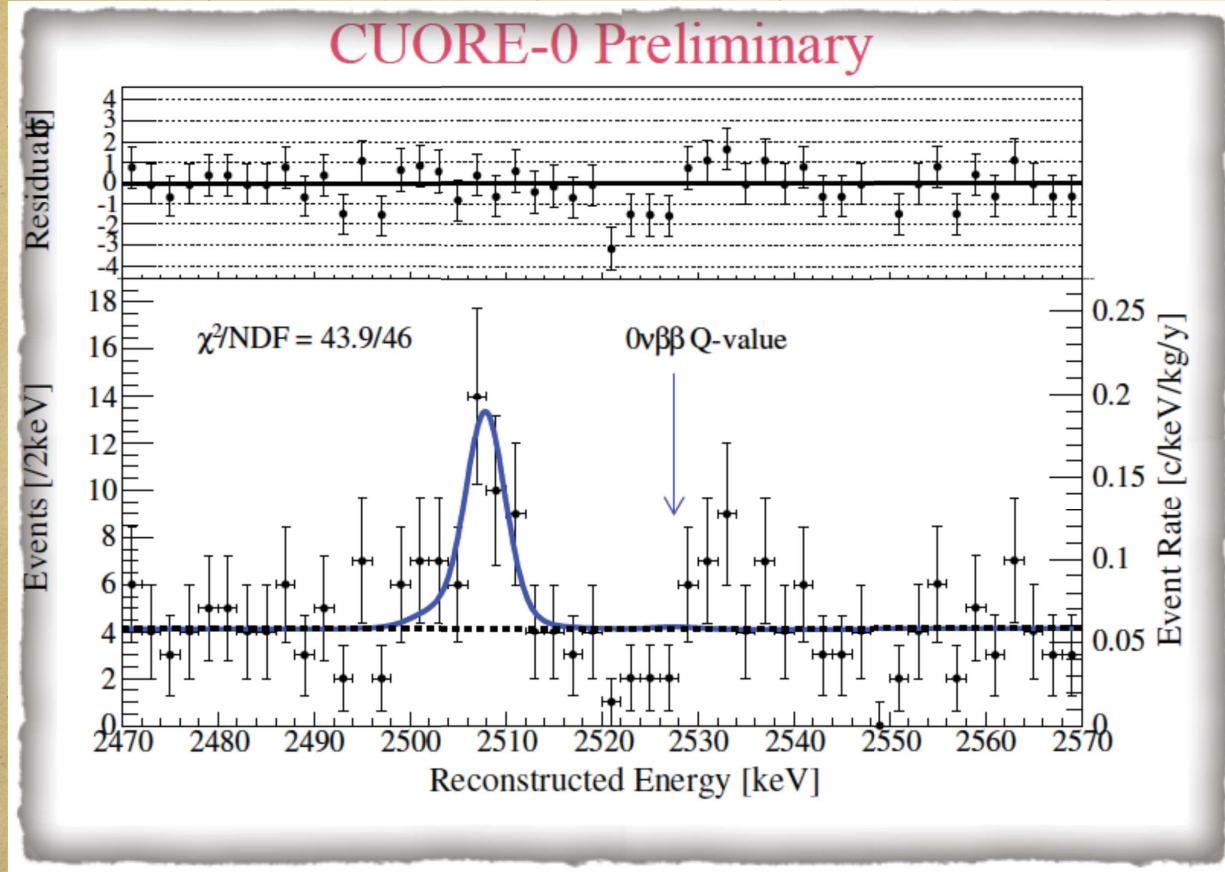
Same cryostat as CUORICINO:  
 $\gamma$  background ( $^{232}\text{Th}$ ) not expected to change  $\Rightarrow$  test the  $\alpha$  background

# which says...



now with a MC extrapolation to CUORE  
it says that the goal of  $B=0.01$  is reachable

# BTW...on the fly



$$T^{0\nu}_{1/2} > 2.7 \cdot 10^{24} \text{ yr}$$

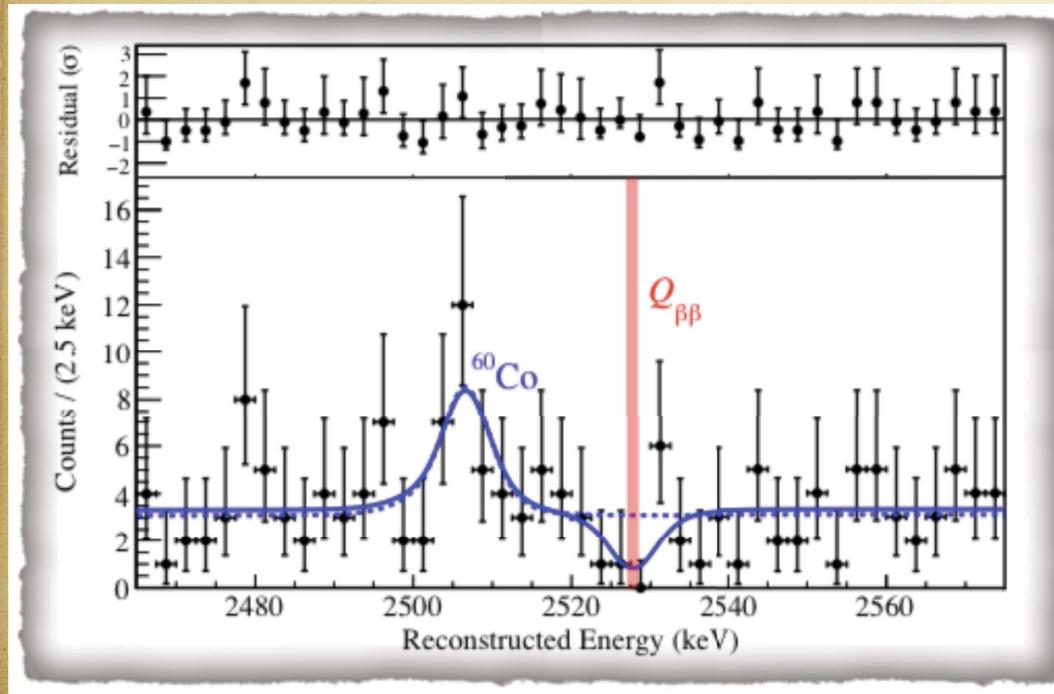
$9.8 \text{ kg}\cdot\text{y}^{-1} {}^{130}\text{Te}$

note the same  
Cuoricino limit  
in half time

Combine CUORE-0 and CUORICINO limit

$$T^{0\nu}_{1/2} > 4.0 \cdot 10^{24} \text{ yr} @ 90\% \text{ CL}$$

# and CUORE first result



## Performance Parameters

Channels used	876	935
TeO <sub>2</sub> exposure (kg·yr)	37.6	48.7
Effective resolution (keV)	$8.3 \pm 0.4$	$7.4 \pm 0.7$
Background ( $10^{-2}$ c/(keV·kg·yr))	$1.49 \pm 0.18$	$1.35 \pm 0.19$

$$T_{1/2}^{0\nu} > 1.5 \times 10^{25} \text{ yr}$$

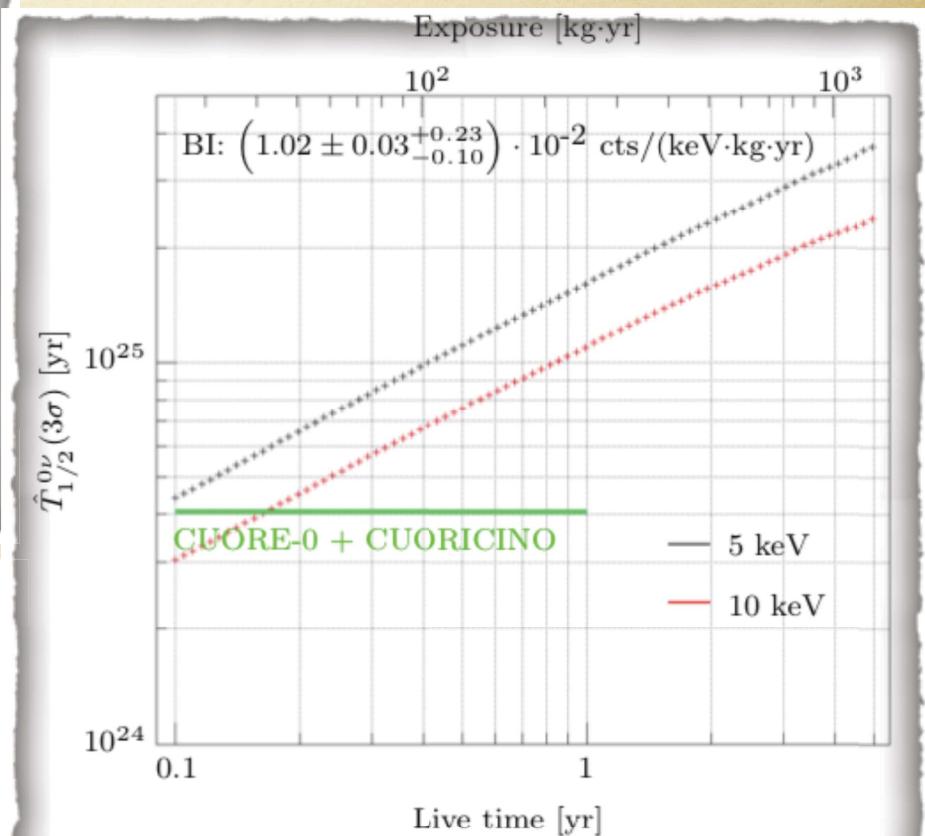
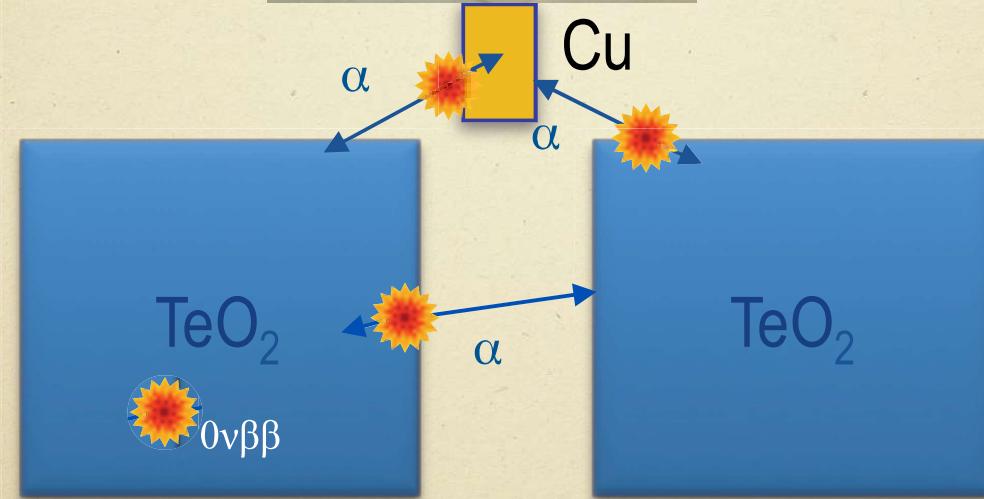
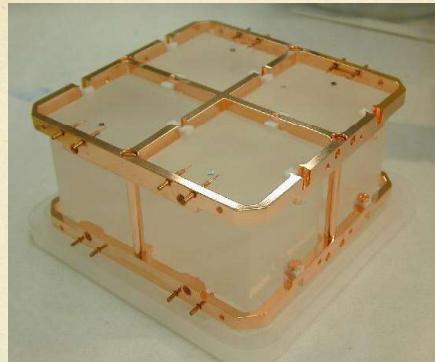


Fig. 3:  $3\sigma$  discovery sensitivity with a  $BI$  of  $1.02 \cdot 10^{-2}$  cts/(keV·kg·yr) and an FWHM of 5 keV.

# the nasty $\alpha$ background



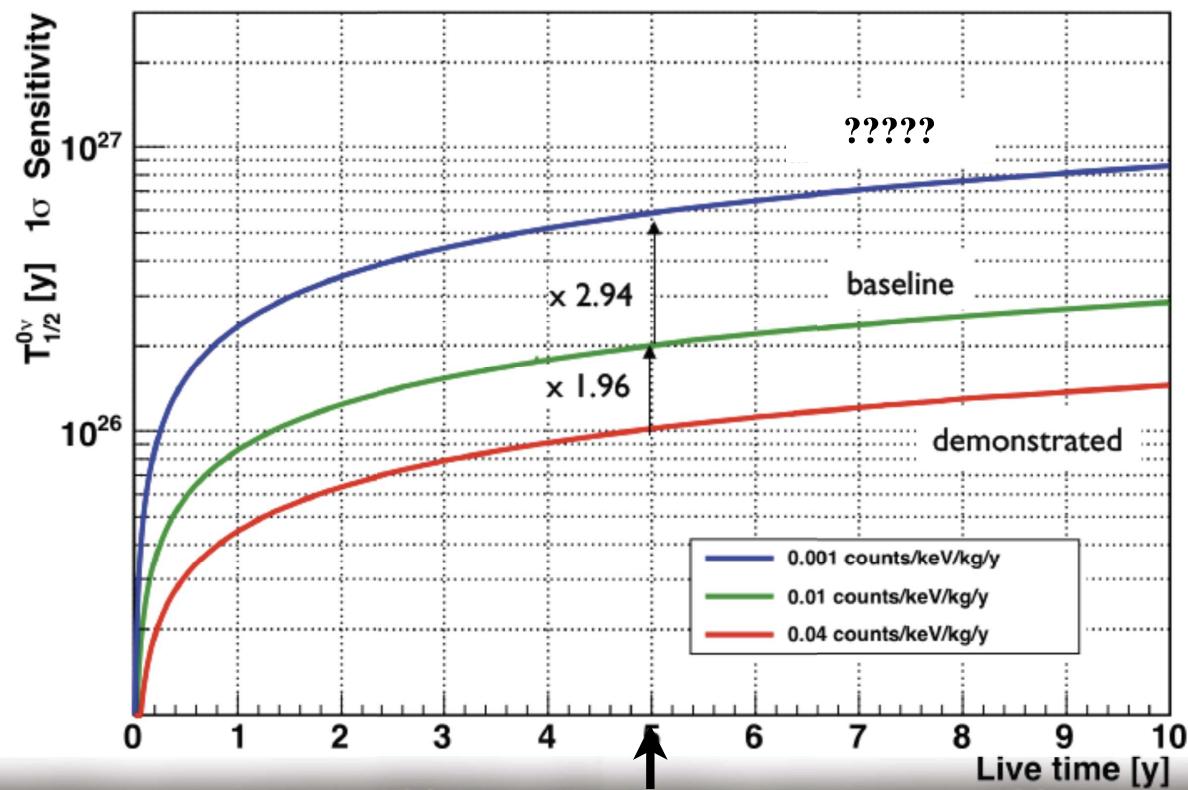
what is measured is part of the  $\alpha$  energy  
(if it were an internal emission...no problem !)  
that induces a flat background

$\text{TeO}_2$   
case  
(CUORE)

740 Kg  
of which  
200 Kg  
of  $^{130}\text{Te}$

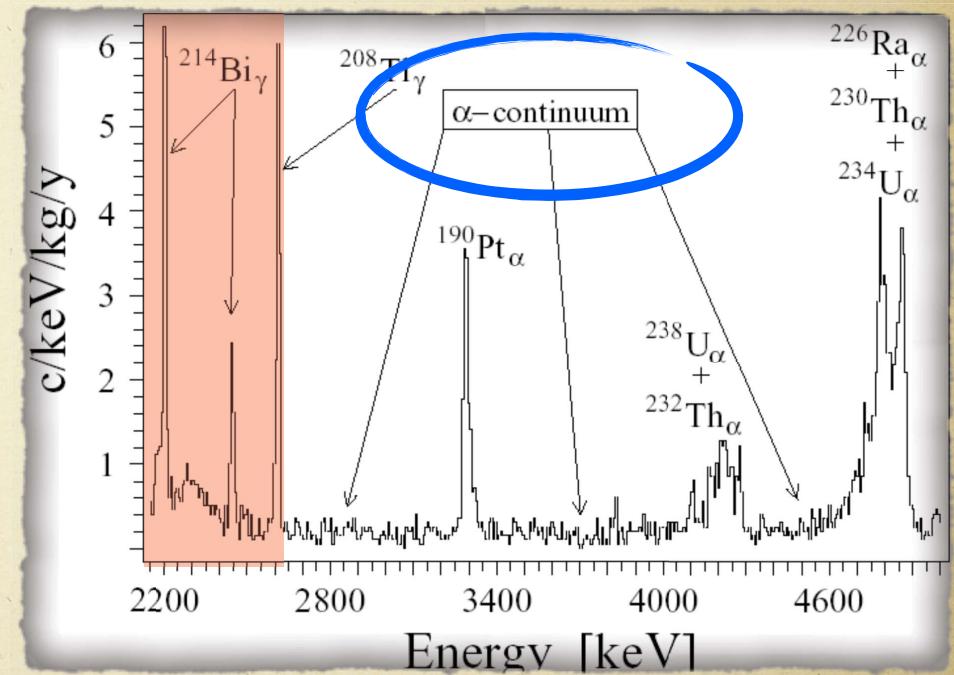
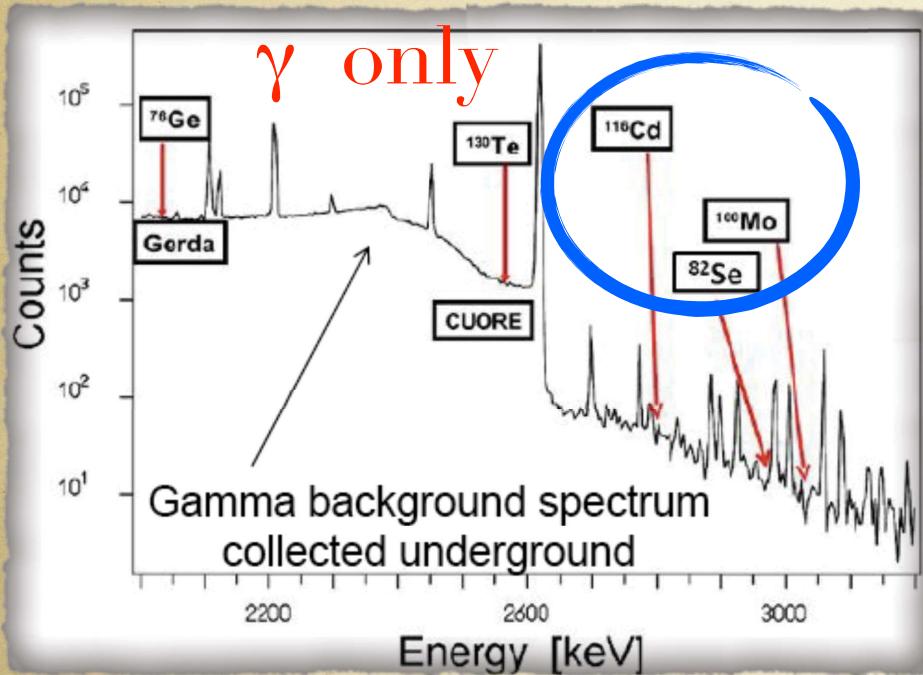
# The Problem

$B=0.01$  can be achieved  
 $B=0.001$  cannot be achieved unless..



1 ton•y

# unless.....



move above of the  $^{208}\text{Tl}$  line

identify the  $\alpha$ 's  
event by event

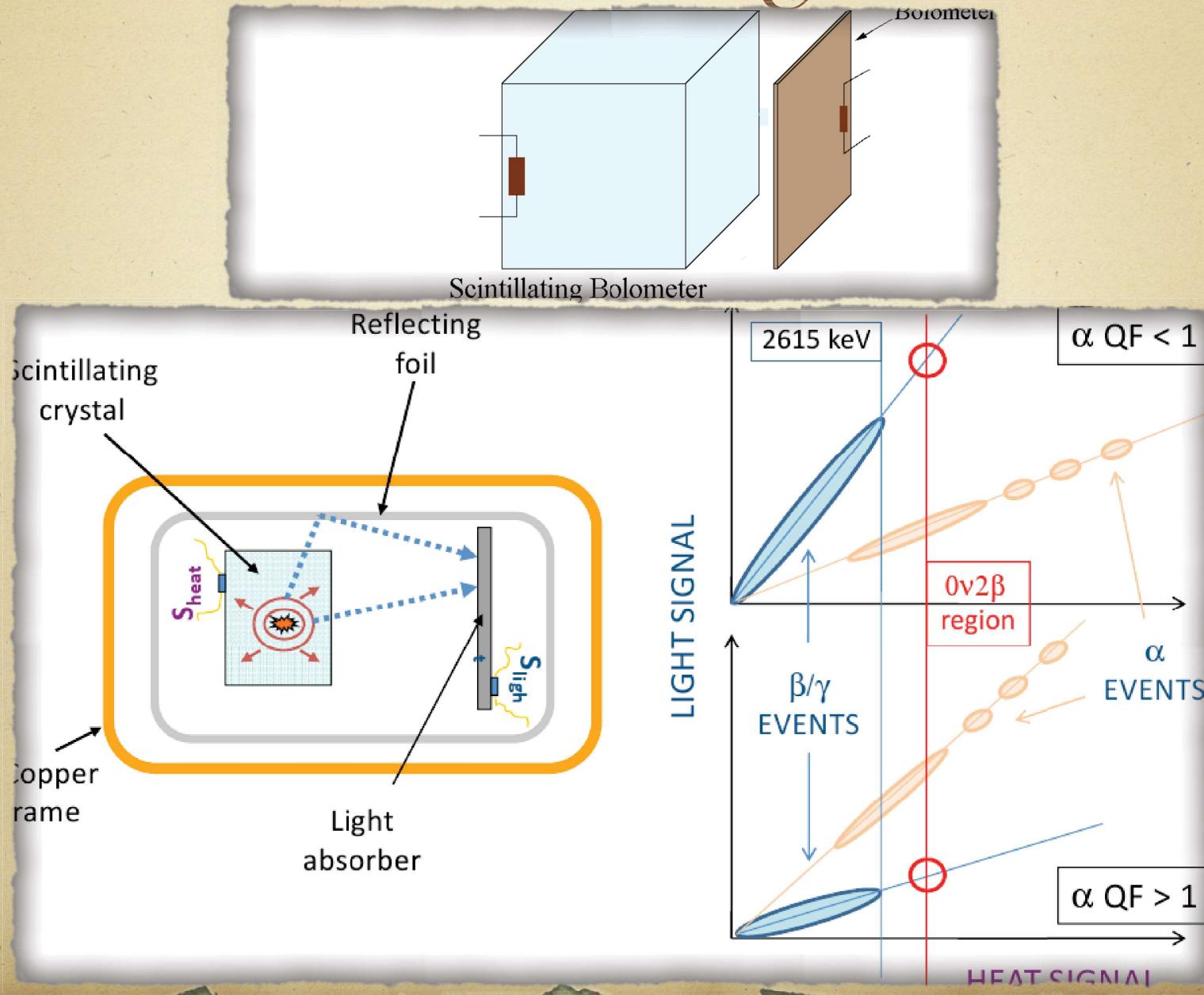
# The LUCIFER concept

**Lucifer** is a Latin word (from the words *lucem ferre*), literally meaning "light-bearer", which in that language is used as a name for the dawn appearance of the planet Venus, heralding daylight.

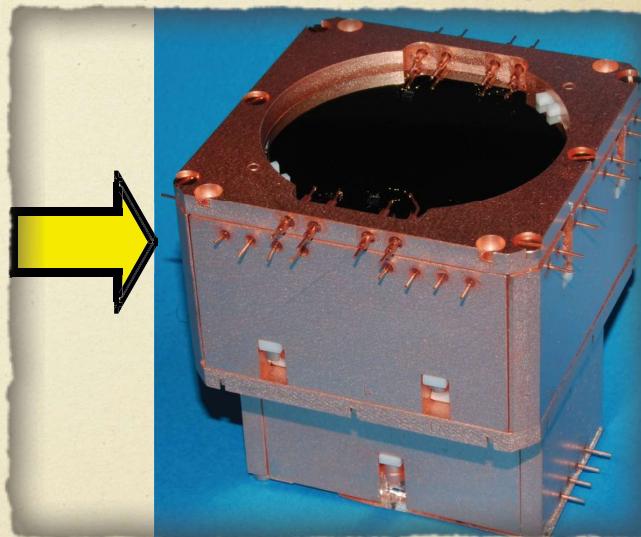
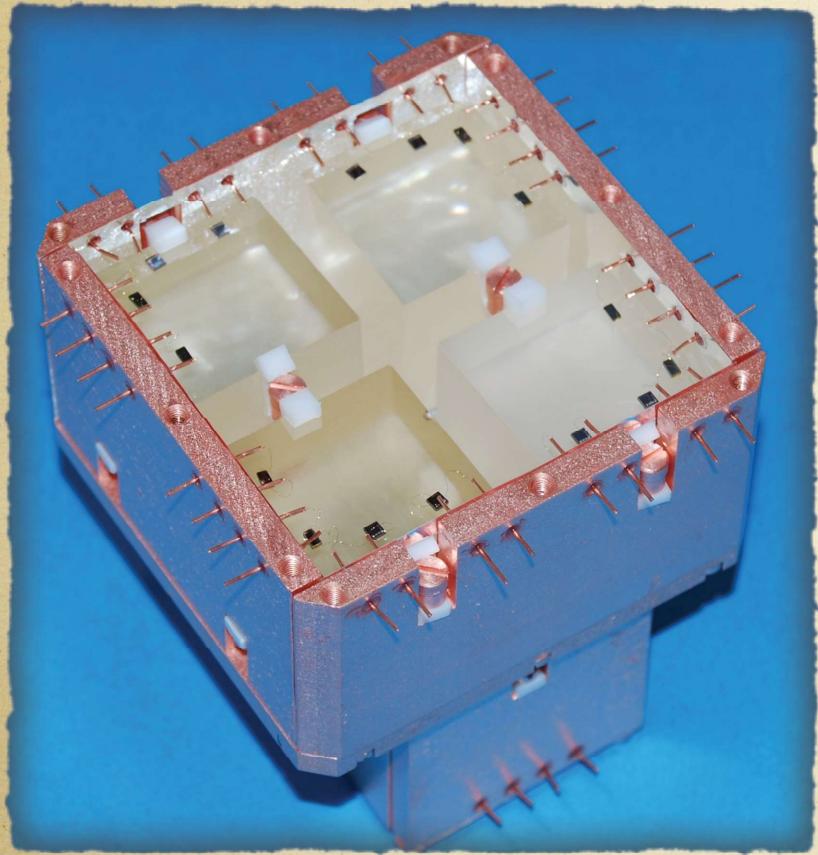


Bringing  
light  
underground

# Heat & Light



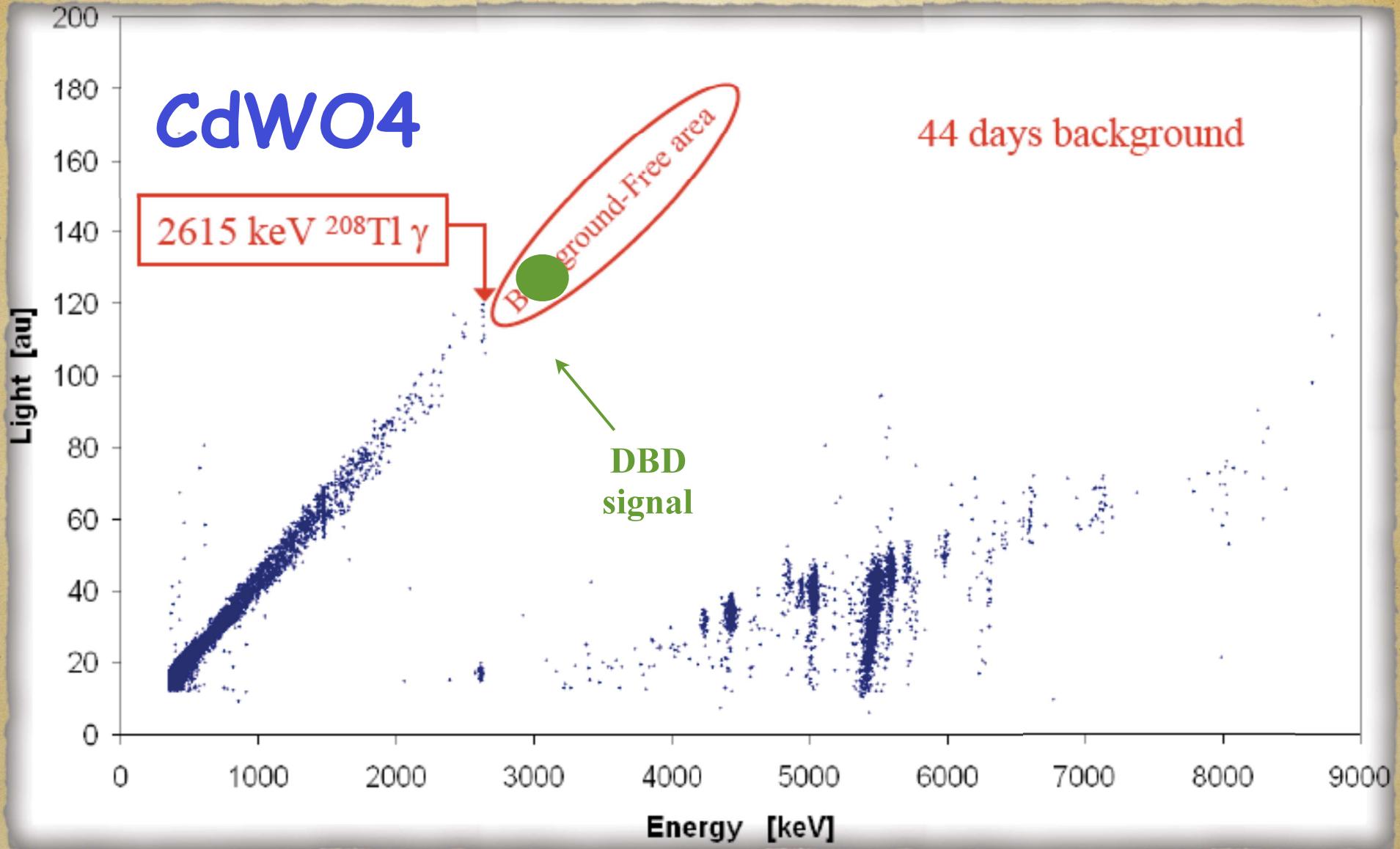
# demonstration of the concept



4 CdWO<sub>4</sub> bolometers  
1 Ge Light detector

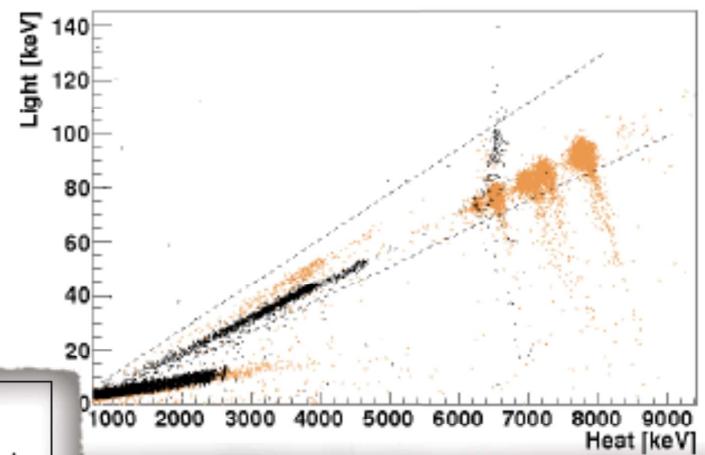
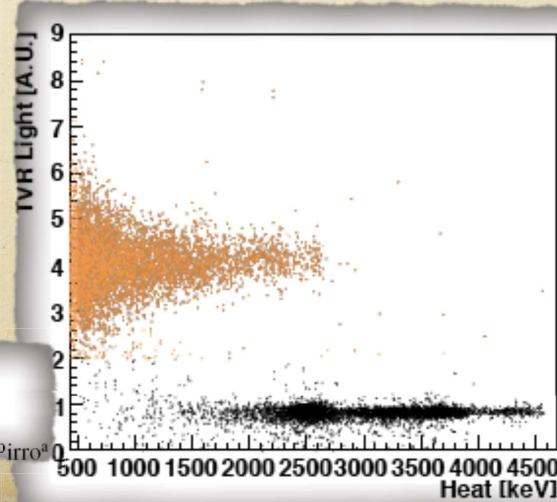
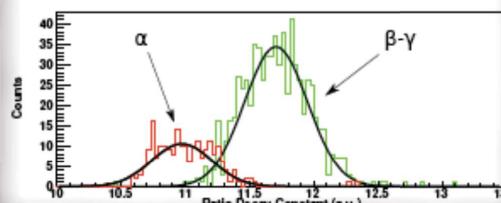
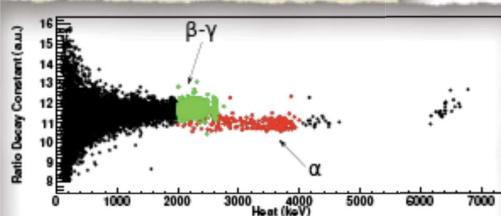
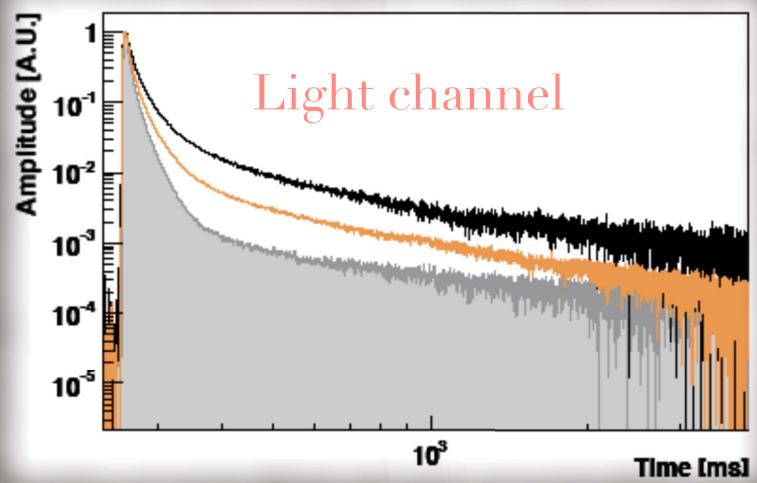
Roman  
Pb shield



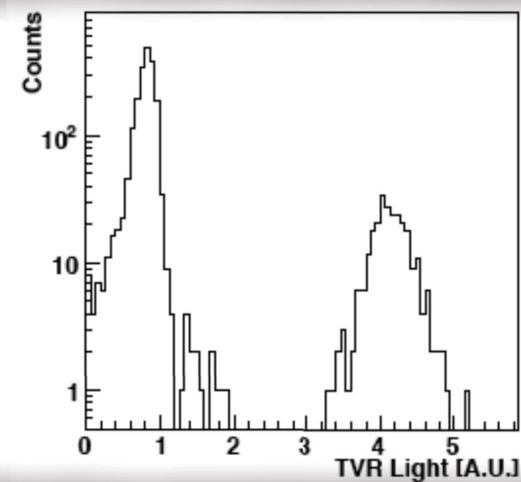


Cadmium makes nice crystals but it is a scary element for an experiment ( $n$  x-section)!

# ZnSe



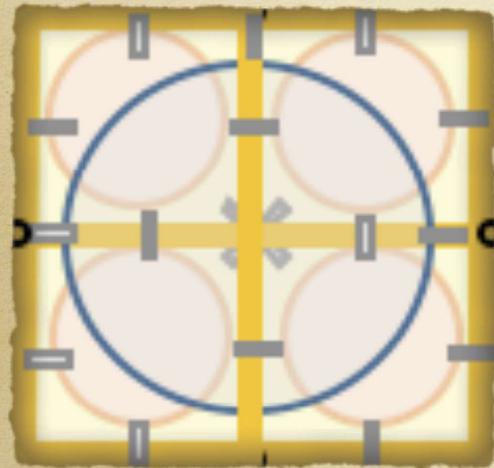
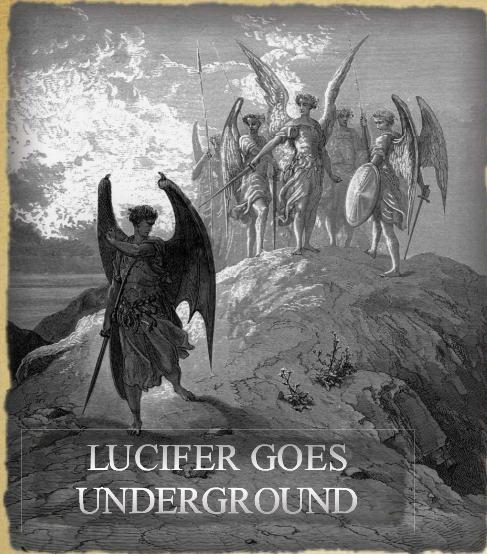
**Heat channel**



ZnSe scintillating bolometers for Double Beta Decay

*Astropart.Phys.* 34 (2011) 344-353

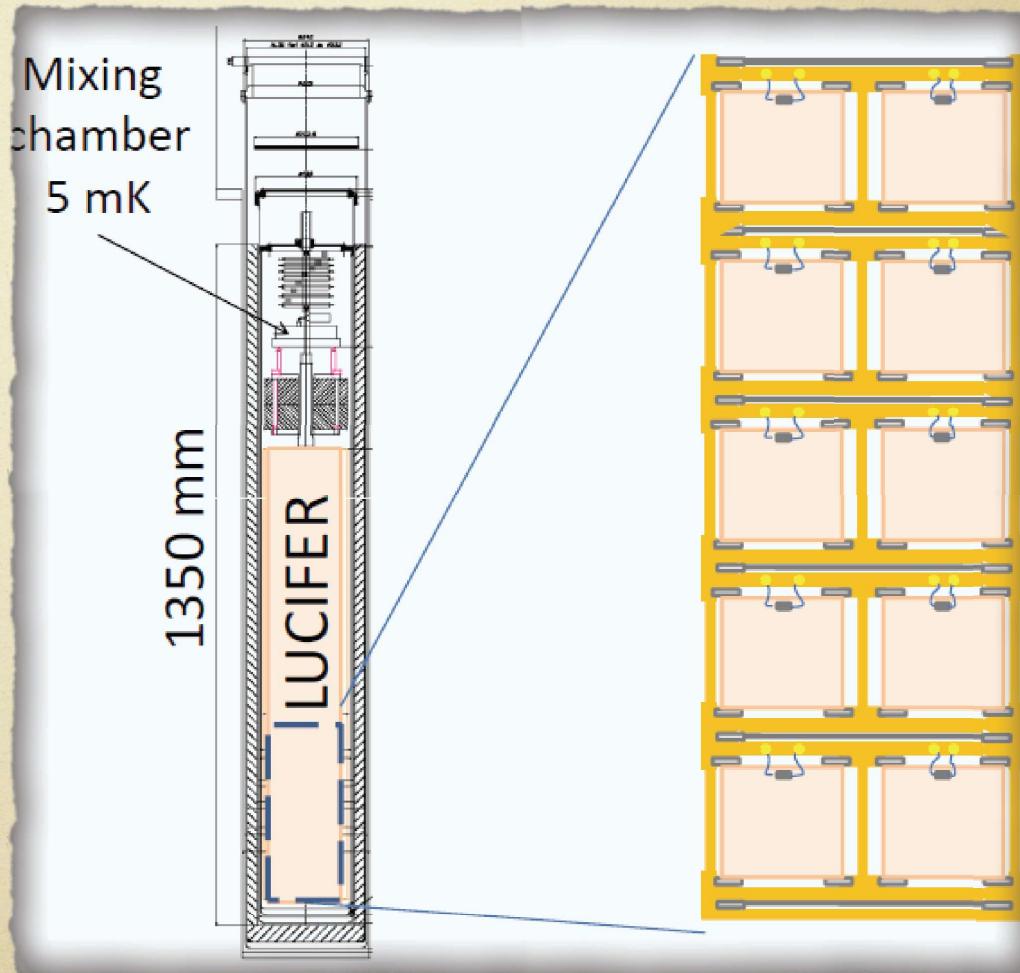
C. Arnaboldi<sup>a</sup>, S. Capelli<sup>b,a</sup>, O. Cremonesi<sup>a</sup>, L. Gironi<sup>b,a</sup>, M. Pavan<sup>b,a</sup>, G. Pessina<sup>a</sup>, S. Pirro<sup>a</sup>



# LUCIFER demonstrator

Low-background Underground Cryogenic Installation For Elusive Rates

ERC-2009-AdG 247115



# Enrichment, going from Se to $^{82}\text{Se}$

 **Stable Isotopes**

  
urenco

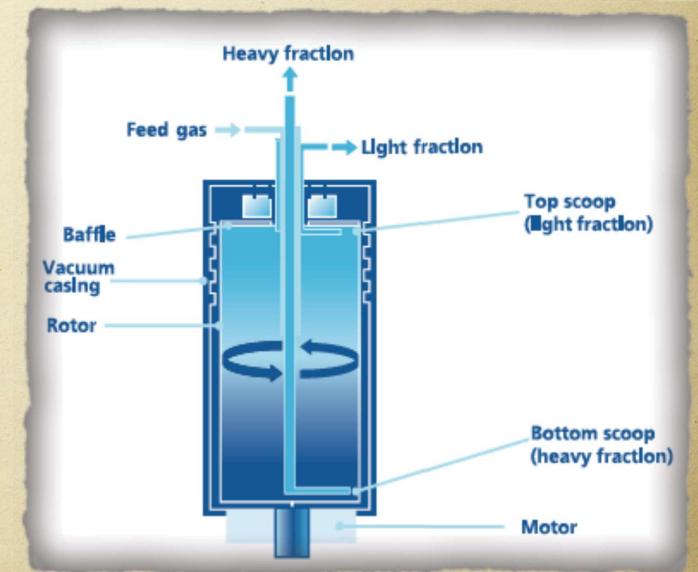
(Almelo, NL)



an interesting  
cooperation

however,  
it has to be  
known that

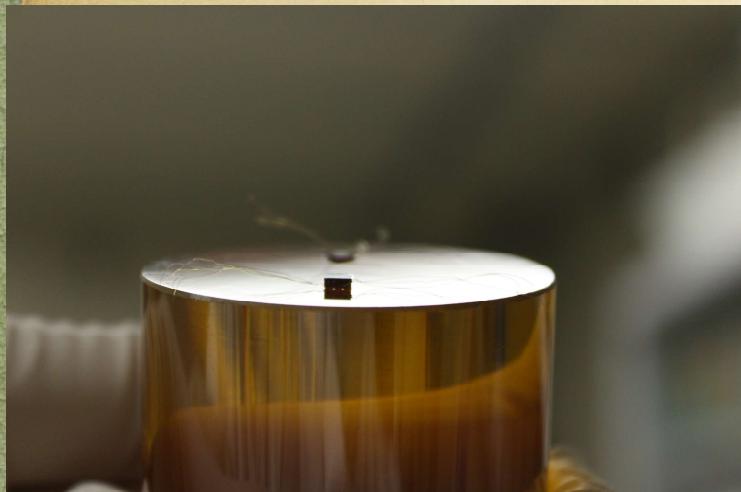
the cost is 75 Euro/gram



# Zn<sup>82</sup>Se crystals



# mounting the experiment



Sensors attached to crystal



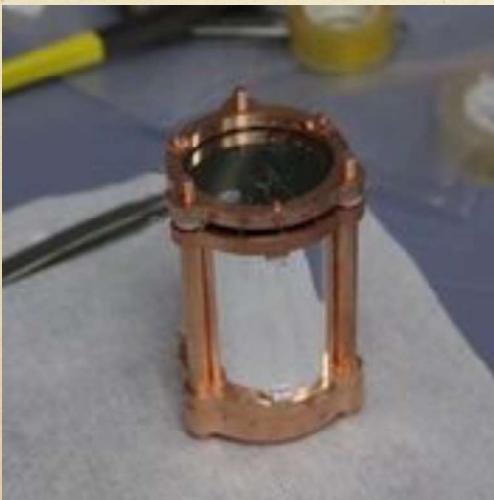
ZnSe assembled in copper frames



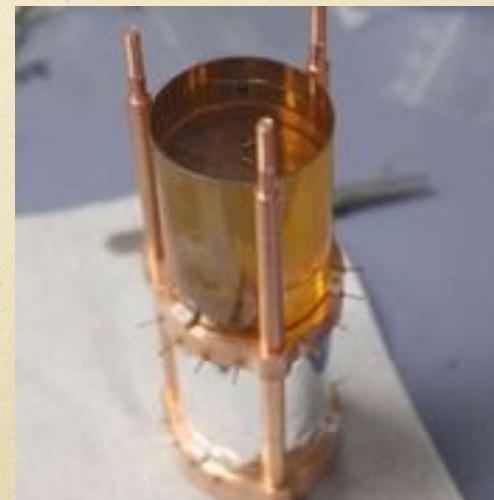
Assembly of light detector



Reflecting foil



Coupling of light detector

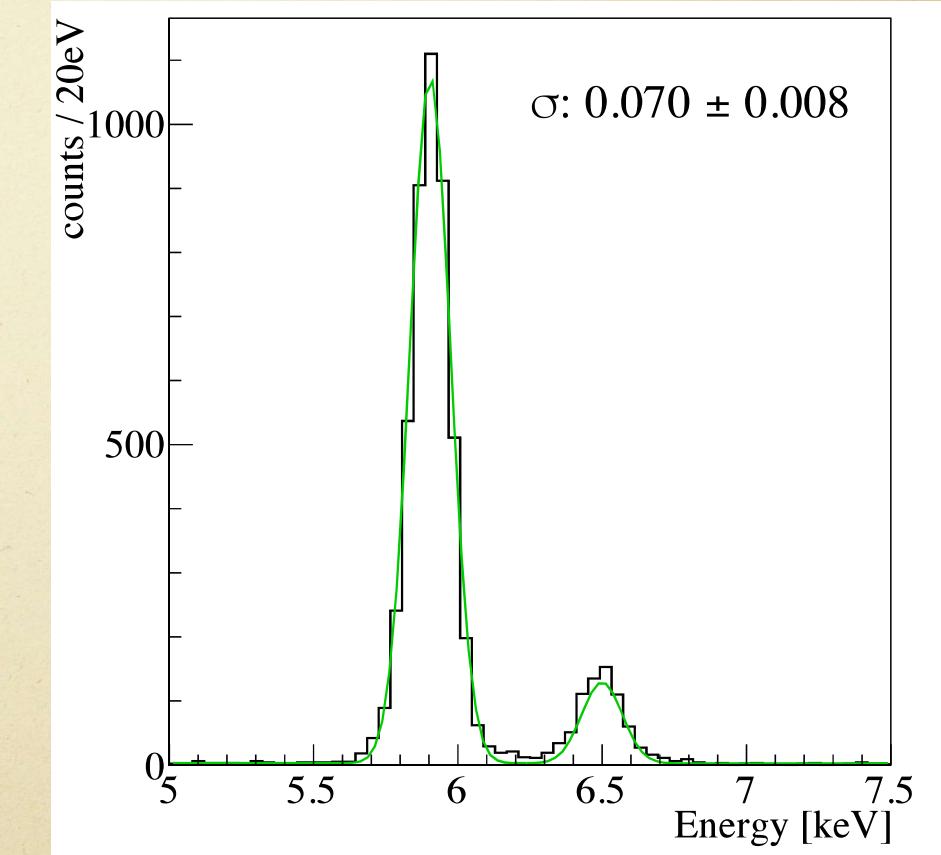
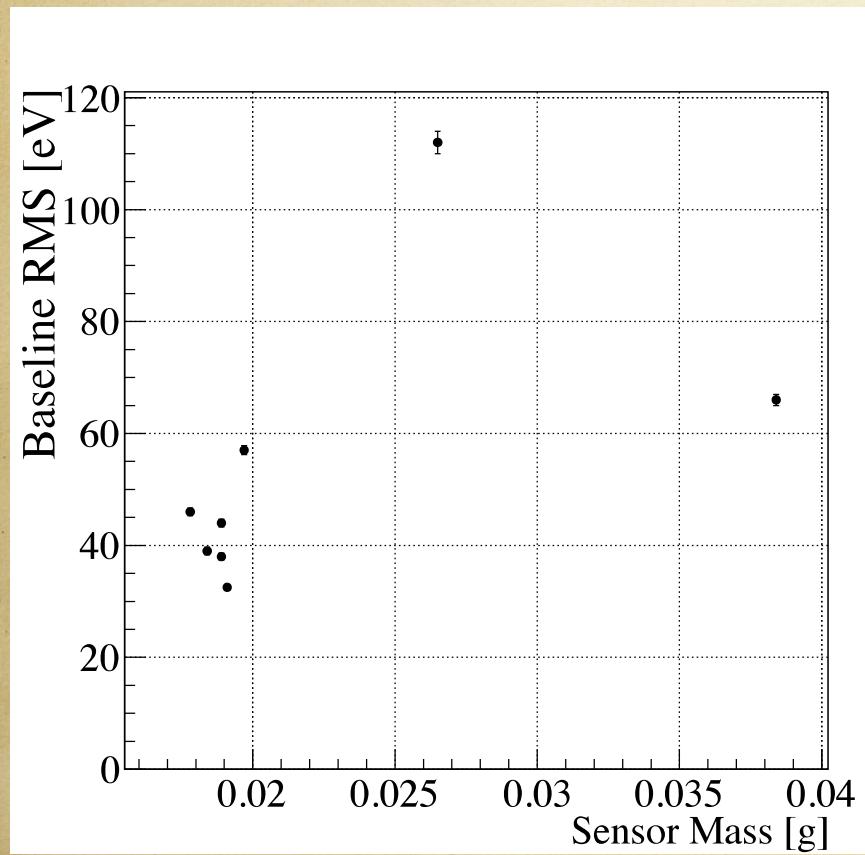


Second ZnSe

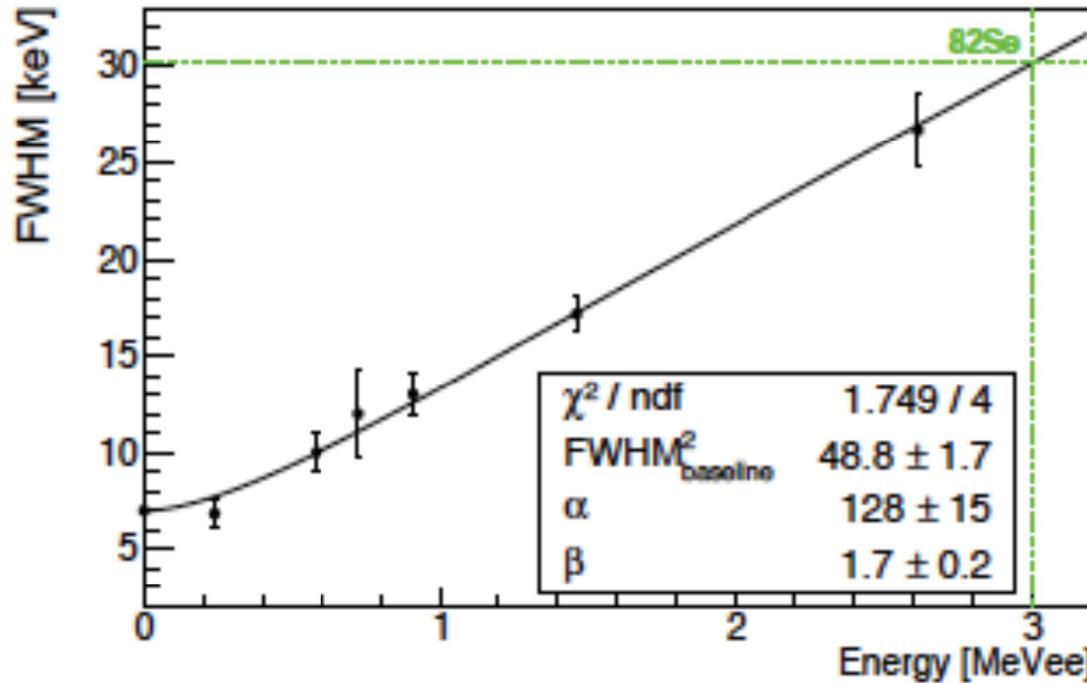


Final array

# with spectacular L.D.

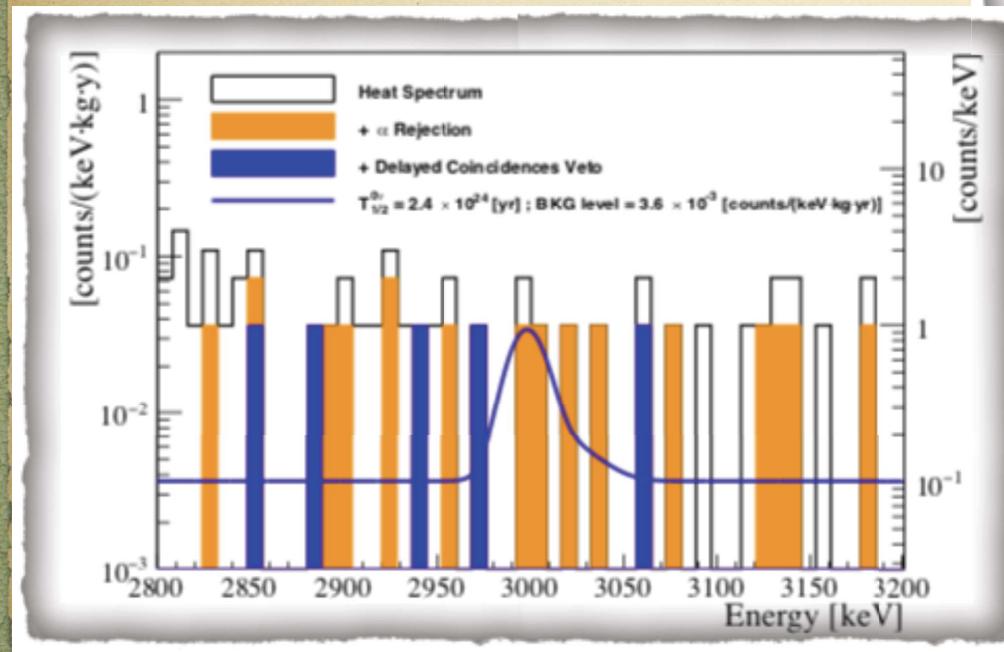
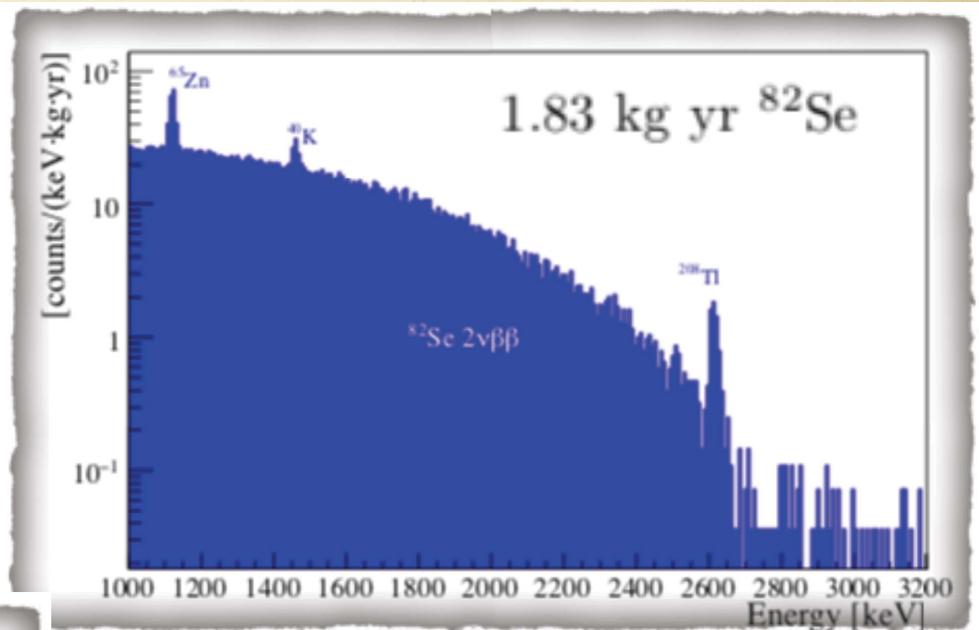
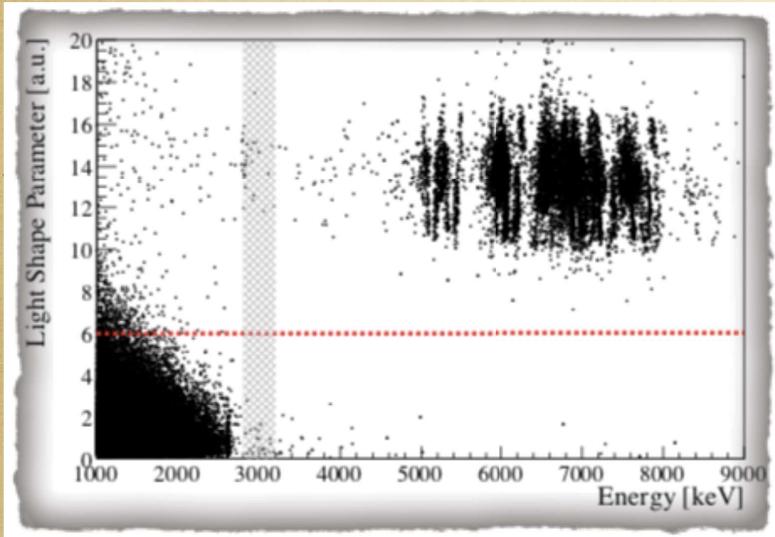


# well behaving



**Fig. 4** FWHM energy resolution as a function of the energy (Zn<sup>82</sup>Se-1) for the most intense  $\gamma$  peaks produced by <sup>228</sup>Th and <sup>40</sup>K sources. The point at zero energy is the baseline energy resolution reported in Table 1. The black line is the fit function:  $\text{FWHM}^2(E) = \text{FWHM}_{\text{baseline}}^2 + \alpha E^\beta$ . The green dotted lines indicate the <sup>82</sup>Se Q-value.

# first results



$$T_{1/2}^{0\nu} > 2.4 \times 10^{24} \text{ yr (90\% C.I.)}.$$

$$\text{BI} = (3.6^{+1.9}_{-1.4}) \times 10^{-3} \text{ counts/(keV kg yr)},$$

extrapolate to 1 after cosmic veto  
and proper shielding

# The future competition

- ▷ Xe (EXO, NEXT, Kamland-Zen)
- ▷ Ge (Gerda + Legend )
- ▷ CUPID (Bolometers with alpha rejection)

# the dream

TABLE X. Sensitivity and exposure necessary to discriminate between  $\mathcal{NH}$  and  $\mathcal{IH}$ : the goal is  $m_{\beta\beta} = 8 \text{ meV}$ . The two cases refer to the unquenched value of  $g_A = g_{\text{nucleon}}$  (mega) and  $g_A = g_{\text{phen.}}$  (ultimate). The calculations are performed assuming *zero background* experiments with 100% detection efficiency and no fiducial volume cuts. The last column shows the maximum value of the product  $B \cdot \Delta$  in order to actually comply with the zero background condition.

Experiment	Isotope	$S_{0B}^{0\nu} [\text{yr}]$	Exposure (estimate)	
			$M \cdot T [\text{ton}\cdot\text{yr}]$	$B \cdot \Delta_{(\text{zero bkg})} [\text{counts kg}^{-1} \text{yr}^{-1}]$
mega Ge	$^{76}\text{Ge}$	$3.0 \cdot 10^{28}$	5.5	$1.8 \cdot 10^{-4}$
mega Te	$^{130}\text{Te}$	$8.1 \cdot 10^{27}$	2.5	$4.0 \cdot 10^{-4}$
mega Xe	$^{136}\text{Xe}$	$1.2 \cdot 10^{28}$	3.8	$2.7 \cdot 10^{-4}$
ultimate Ge	$^{76}\text{Ge}$	$6.9 \cdot 10^{29}$	125	$8.0 \cdot 10^{-6}$
ultimate Te	$^{130}\text{Te}$	$2.7 \cdot 10^{29}$	84	$1.2 \cdot 10^{-5}$
ultimate Xe	$^{136}\text{Xe}$	$4.0 \cdot 10^{29}$	130	$7.7 \cdot 10^{-6}$

if you want to know all...  
pls. read:

[\*\*arXiv:1601.07512\*\*](https://arxiv.org/abs/1601.07512)

**Neutrinoless double beta decay: 2015 review**

Stefano Dell'Oro,<sup>1,\*</sup> Simone Marcocci,<sup>1,†</sup> Matteo Viel,<sup>2,3,‡</sup> and Francesco Vissani<sup>4,1,§</sup>

<sup>1</sup>*INFN, Gran Sasso Science Institute, Viale F. Crispi 7, 67100 L'Aquila, Italy*

<sup>2</sup>*INAF, Osservatorio Astronomico di Trieste, Via G. B. Tiepolo 11, 34131 Trieste, Italy*

<sup>3</sup>*INFN, Sezione di Trieste, Via Valerio 2, 34127 Trieste, Italy*

<sup>4</sup>*INFN, Laboratori Nazionali del Gran Sasso, Via G. Acitelli 22, 67100 Assergi (AQ), Italy*

(Dated: April 20, 2016)

# Conclusions

- ▷ Neutrino Physics is one of the leading field in HEP today
- ▷ Dirac or Majorana nature of neutrino mass is a fundamental question that needs to be answered at (almost) all cost(s)
- ▷ Neutrino-less DBD might possibly be the sole chance to give a measure of neutrino mass
- ▷ The second generation experiments will not be enough to win.
- ▷ We have to prepare for third generation. **Toward 0 background.**

# the best bet today is

## Neutrinoless double beta decay: 2015 review

Stefano Dell'Oro,<sup>1,\*</sup> Simone Marcocci,<sup>1,†</sup> Matteo Viel,<sup>2,3,‡</sup> and Francesco Vissani<sup>4,1,§</sup>

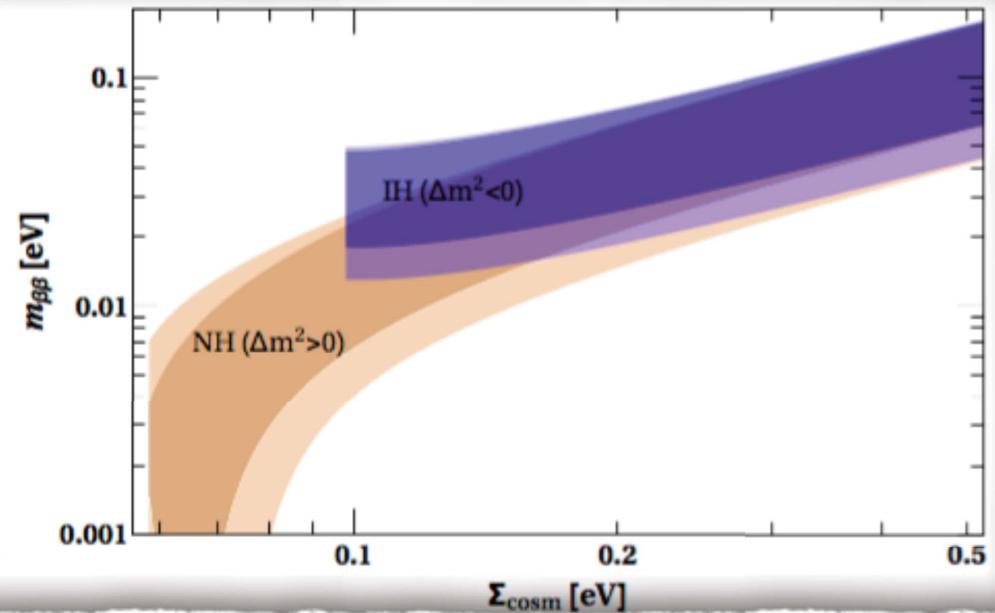
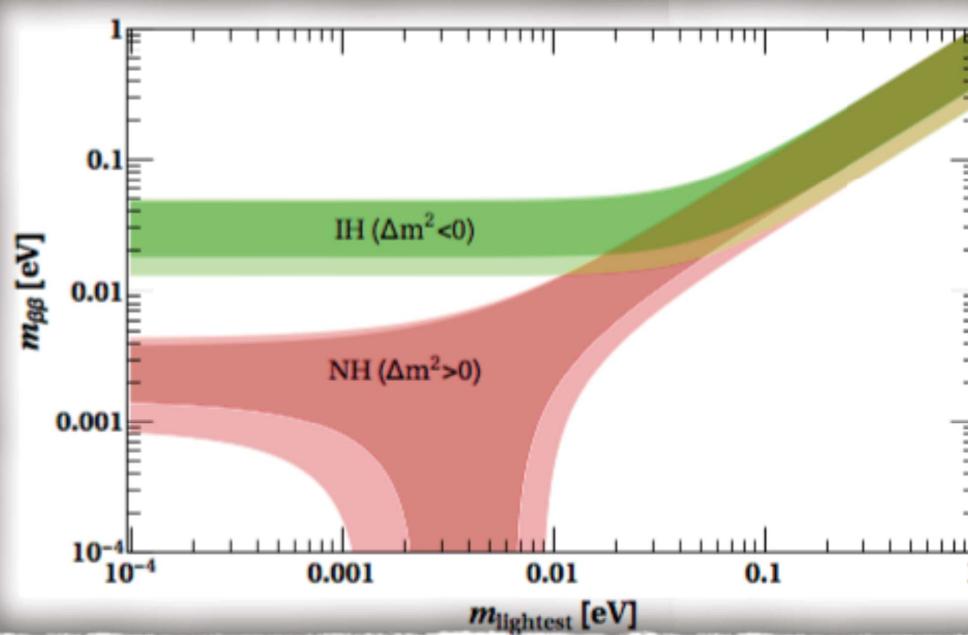
<sup>1</sup>*INFN, Gran Sasso Science Institute, Viale F. Crispi 7, 67100 L'Aquila, Italy*

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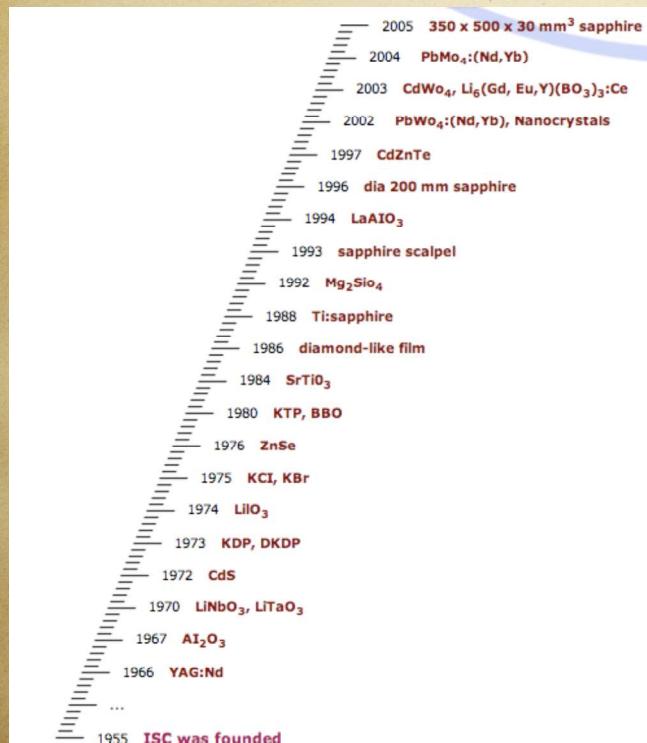
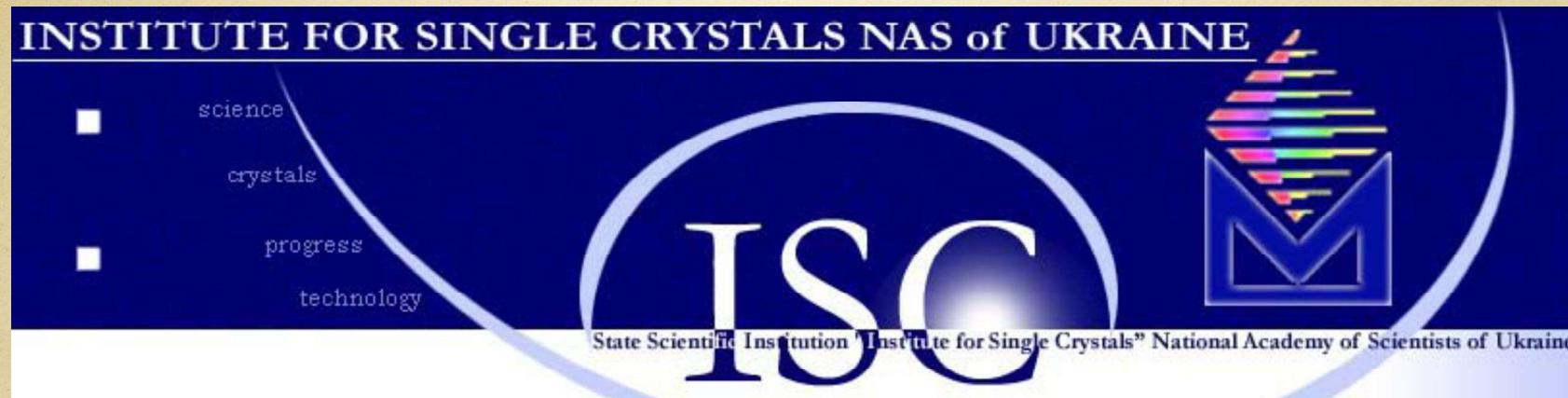
<sup>3</sup>*INFN, Sezione di Trieste, Via Valerio 2, 34127 Trieste, Italy*

<sup>4</sup>*INFN, Laboratori Nazionali del Gran Sasso, Via G. Acitelli 22, 67100 Assergi (AQ), Italy*

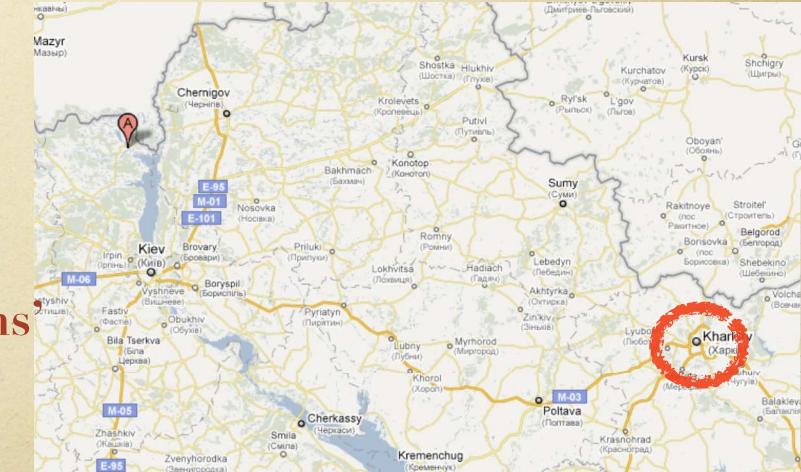
(Dated: April 20, 2016)



# crystals production



the ‘political tensions’  
made the task  
quite tough



possibly the only place

# the near future

Experiment	Isotope	Technique	Total mass [kg]	Exposure [kg yr]	FWHM @ $Q_{\beta\beta}$ [keV]	Background [counts/keV/kg/yr]	$S^{0\nu}_{(90\% \text{ C. L.})}$ [ $10^{25} \text{ yr}$ ]
<b><i>Future</i></b>							
CUORE, [187]	$^{130}\text{Te}$	bolometers	741 ( $\text{TeO}_2$ )	1030	5	0.01	9.5
GERDA-II, [172]	$^{76}\text{Ge}$	Ge diodes	37.8 ( $^{\text{enr}}\text{Ge}$ )	100	3	0.001	15
LUCIFER, [188]	$^{82}\text{Se}$	bolometers	17 ( $\text{Zn}^{82}\text{Se}$ )	18	10	0.001	1.8
MAJORANA D., [189]	$^{76}\text{Ge}$	Ge diodes	44.8 ( $^{\text{enr/nat}}\text{Ge}$ )	100 <sup>a</sup>	4	0.003	12
NEXT, [190, 191]	$^{136}\text{Xe}$	Xe TPC	100 ( $^{\text{enr}}\text{Xe}$ )	300	12.3 – 17.2	$5 \cdot 10^{-4}$	5
AMoRE, [192]	$^{100}\text{Mo}$	bolometers	200 ( $\text{Ca}^{\text{enr}}\text{MoO}_4$ )	295	9	$1 \cdot 10^{-4}$	5
nEXO, [193]	$^{136}\text{Xe}$	LXe TPC	4780 ( $^{\text{enr}}\text{Xe}$ )	12150 <sup>b</sup>	58	$1.7 \cdot 10^{-5}$ <sup>b</sup>	66
PandaX-III, [194]	$^{136}\text{Xe}$	Xe TPC	1000 ( $^{\text{enr}}\text{Xe}$ )	3000 <sup>c</sup>	12 – 76	0.001	11 <sup>c</sup>
SNO+, [195]	$^{130}\text{Te}$	loaded liquid scintillator	2340 ( $^{\text{nat}}\text{Te}$ )	3980	270	$2 \cdot 10^{-4}$	9
SuperNEMO, [196, 197]	$^{82}\text{Se}$	tracker +	100 ( $^{82}\text{Se}$ )	500	120	0.01	10

Experiment	Isotope	$S^{0\nu}_{(90\% \text{ C. L.})}$ [ $10^{25} \text{ yr}$ ]	Lower bound for $m_{\beta\beta}$ [eV]		
			$g_{\text{nucleon}}$	$g_{\text{quark}}$	$g_{\text{phen.}}$
CUORE, [187]	$^{130}\text{Te}$	9.5	$0.073 \pm 0.008$	$0.14 \pm 0.01$	$0.44 \pm 0.04$
GERDA-II, [172]	$^{76}\text{Ge}$	15	$0.11 \pm 0.01$	$0.18 \pm 0.02$	$0.54 \pm 0.05$
LUCIFER, [188]	$^{82}\text{Se}$	1.8	$0.20 \pm 0.02$	$0.32 \pm 0.03$	$0.97 \pm 0.09$
MAJORANA D., [189]	$^{76}\text{Ge}$	12	$0.13 \pm 0.01$	$0.20 \pm 0.02$	$0.61 \pm 0.06$
NEXT, [191]	$^{136}\text{Xe}$	5	$0.12 \pm 0.01$	$0.20 \pm 0.02$	$0.71 \pm 0.08$
AMoRE, [192]	$^{100}\text{Mo}$	5	$0.084 \pm 0.008$	$0.14 \pm 0.01$	$0.44 \pm 0.04$
nEXO, [193]	$^{136}\text{Xe}$	66	$0.034 \pm 0.004$	$0.054 \pm 0.006$	$0.20 \pm 0.02$
PandaX-III, [194]	$^{136}\text{Xe}$	11	$0.082 \pm 0.009$	$0.13 \pm 0.01$	$0.48 \pm 0.05$
SNO+, [195]	$^{130}\text{Te}$	9	$0.076 \pm 0.007$	$0.12 \pm 0.01$	$0.44 \pm 0.04$
SuperNEMO, [196]	$^{82}\text{Se}$	10	$0.084 \pm 0.008$	$0.14 \pm 0.01$	$0.41 \pm 0.04$

# however...

This transition takes place inside nuclei and the momentum of the virtual nucleon is large,  $Q \sim \mathcal{O}(100\text{MeV})$  (inverse of the nucleonic size). It is thus much larger than the neutrino mass.

The issue of the quenching/renormalization of  $g_A$  should not be considered as a theory. However, if there is a physical cause for this effect, this is likely to depend upon the momentum  $Q$ , since at very high  $Q$  nucleons can be treated as free particles and free nucleons do not suffer any quenching. And maybe there is only a loose connection between the two processes of double electron emission when two or no neutrinos are emitted: In fact, the transferred momentum is quite different. When  $Q$  is larger, as in the case of no neutrino emission in which we are interested,  $g_A$  could be closer to the free nucleon value ( $\simeq 1.269$ ), or to that of quark matter (= 1) [19, 20].