

# Dreaming Majorana

## $\text{O}_\nu \beta\beta$



**XXV GIORNATE DI STUDIO  
SUI RIVELATORI**  
**Scuola F. Bonaudi**

Scuola di Alta Formazione  
Villaggio dei Miserati  
Cogne - Aosta

PHD, Post-Doc and  
young Researchers

23 - 26 February 2016

**SCIENTIFIC TOPICS**

- E. Compton: The CMS Upgrade
- F. Cervelli: Positron Emission Tomography in Hadrontherapy
- F. Ferroni: Searches in Double Beta Decay
- F. Giubellino: The ALICE Upgrade
- F. Marchetto: The NA62 Experiment
- M. Moretti: The Super-Kamiokande Experiment
- F. Piroli: Electronic Devices
- F. Solfi: Micro-IPNP Gas Detectors
- F. Valente: Dark Matter Searches with PADME

**ORGANIZING COMMITTEE**

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- S. Bertoli (Secretary)

Information and registration: [tiny.cc/meyarj](http://tiny.cc/meyarj)

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# 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

$$\mathcal{V} = \bar{\mathcal{V}}$$

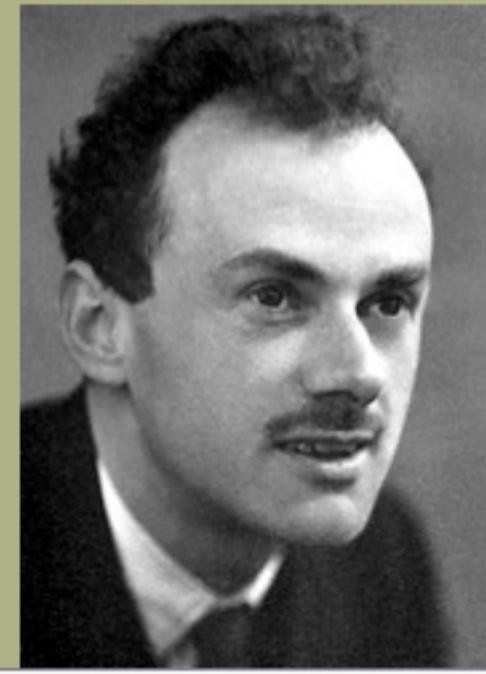
Main consequence :  
Lepton Number Violation

# Majorana vs. Dirac



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

Majorana



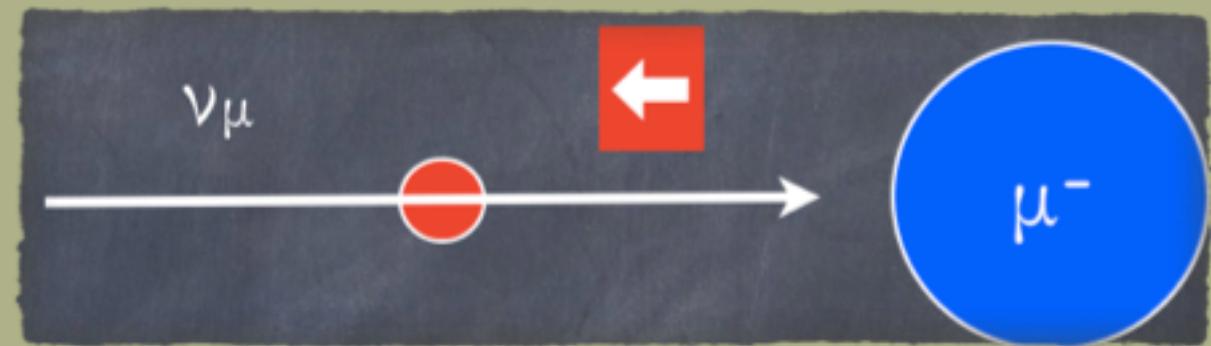
$$\begin{array}{ccc} V_L^D & \xleftarrow{\text{Lorentz}} & V_R^D \\ \uparrow \text{CPT} & & \downarrow \text{CPT} \\ \overline{V}_R^D & \xleftarrow{\text{Lorentz}} & \overline{V}_L^D \end{array}$$

Dirac

# How to solve ?

in principle it is easy

you take a neutrino beam. It does interact with a target and makes muons. If some of the neutrinos flip helicity in the final state you observe antineutrinos

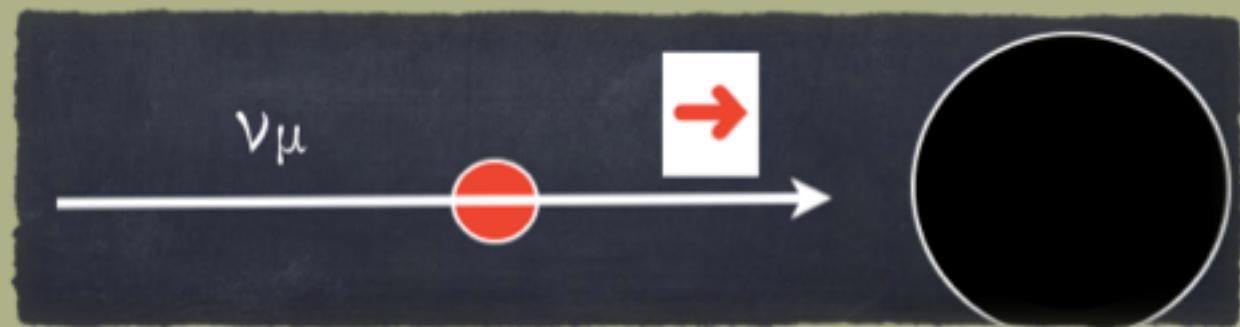


Wait, there is a problem !!!!

# 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

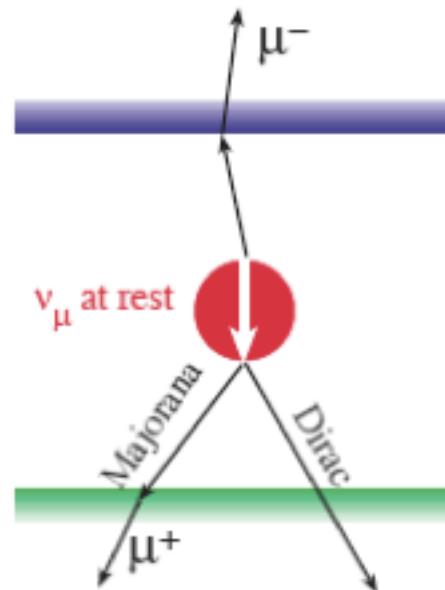
Prize share: 1/2



Photo: A. Mahmoud

Arthur B. McDonald

Prize share: 1/2

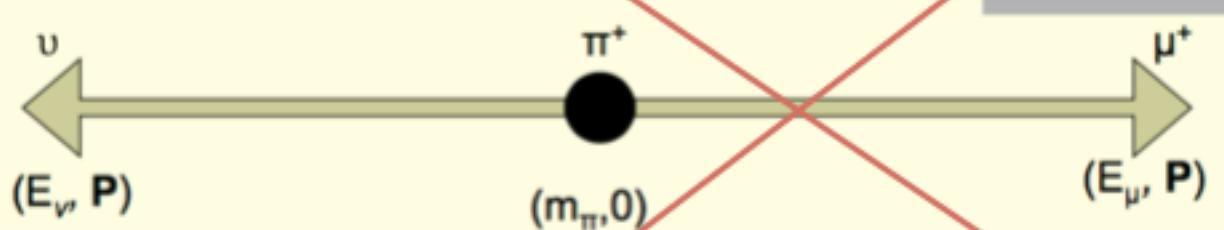


The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

# Yes , but...

## How to produce a right handed neutrino

### Pion Decay



CM Frame

$$E_\nu + E_\mu = E_\pi$$

$$\sqrt{m_\nu^2 + P^2} + \sqrt{m_\mu^2 + P^2} = m_\pi$$

Lab Frame

$$\gamma = \frac{E_\nu}{m_\nu} \quad E_\pi = \gamma m_\pi$$

$$E_\pi = \frac{m_\pi^2 - m_\mu^2}{2m_\nu}$$

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  
 $E=80000\text{ TeV}$

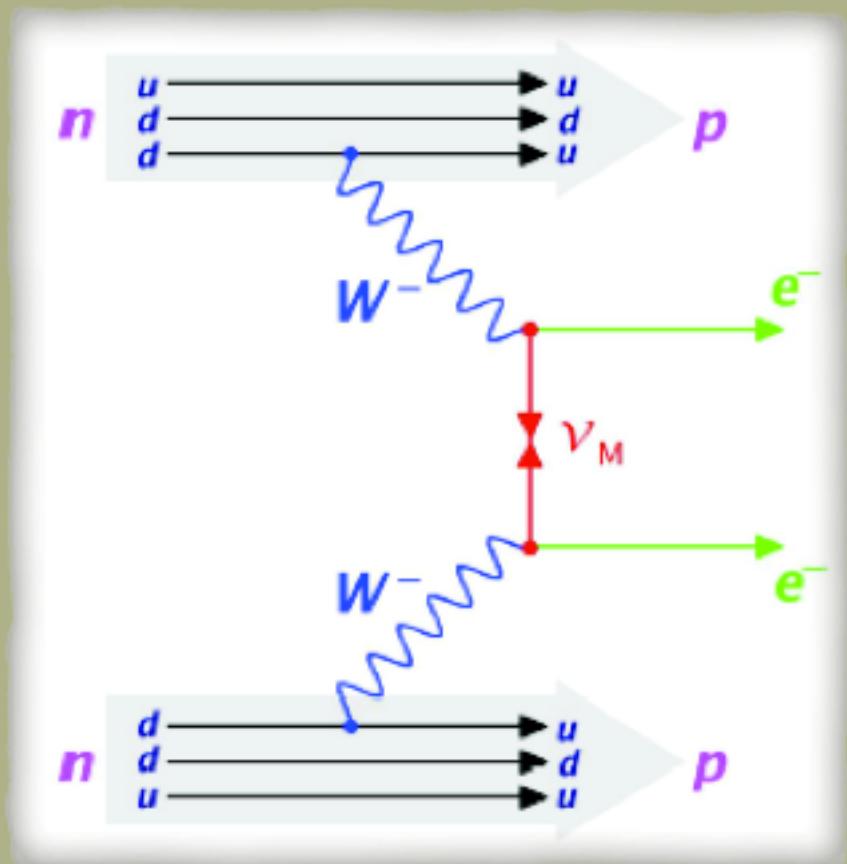
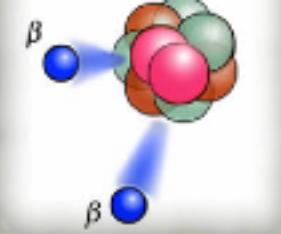
# therefore back to 30's

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

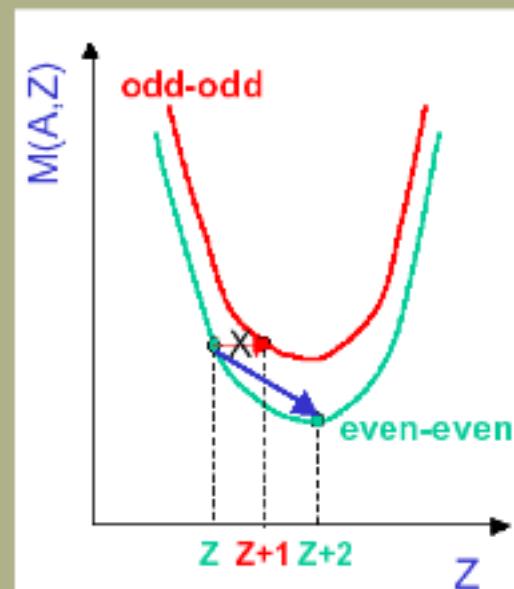
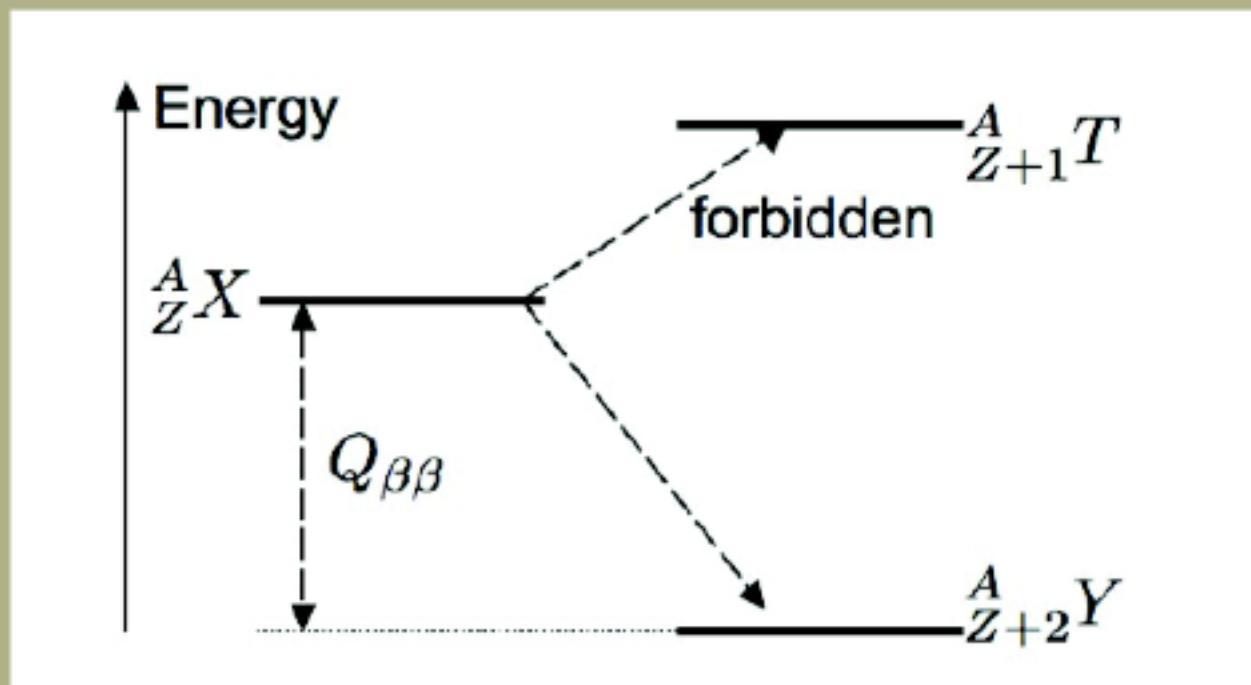
# just at first glance...

it looks unlikely to happen frequently

two neutrons that beta-decay at the ‘same’ time in  
the ‘same’ place

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

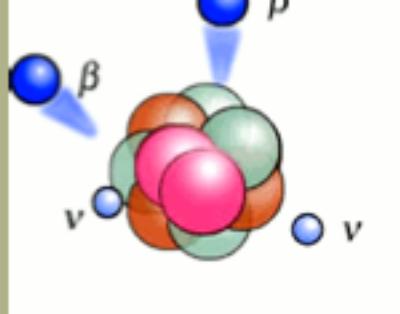
MARIA GOEPPERT MAYER

1963

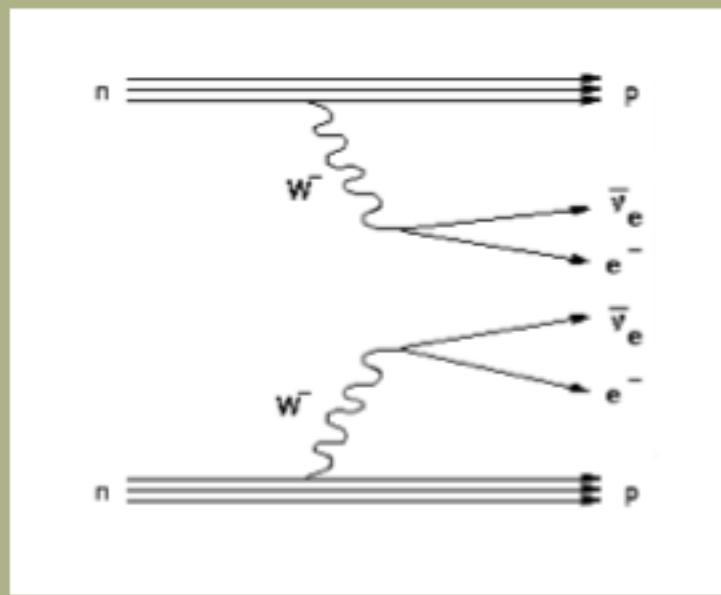


only few nuclei stay in the list

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
$^{150}\text{Nd}$	3.367	5.6



the ‘normal’ one



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

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

the ‘special’ one !

# the "special" one ? how patients should we be ?

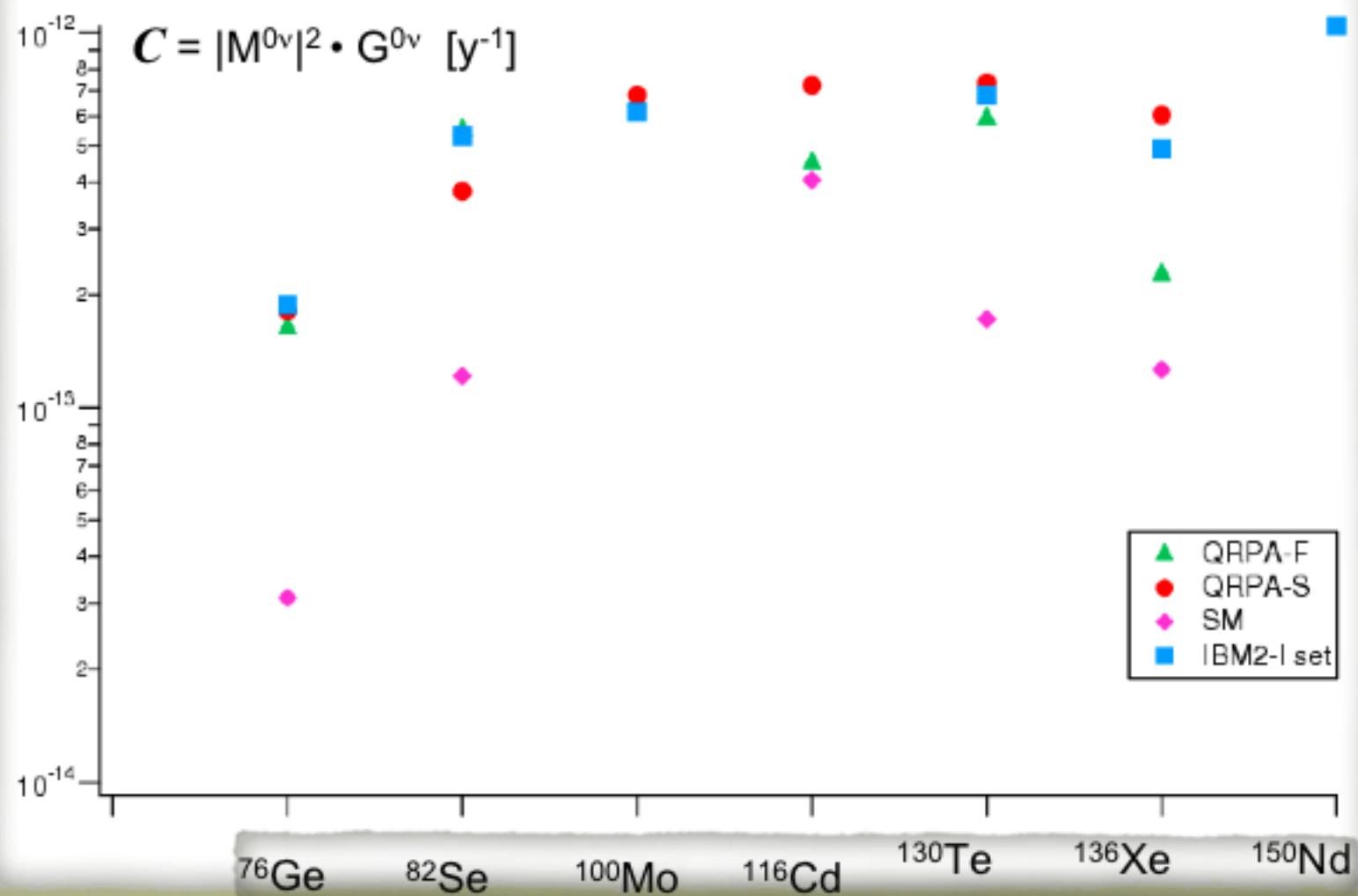
parameter containing  
the **physics**

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

what the **experimentalists**  
try to measure

what the **nuclear theorists**  
try to calculate

# The role of NME



just on the back

just on the back  
of the envelope

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

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

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

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

something more worrisome

# Something more worrisome

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

$$g_A = \begin{cases} g_{\text{nucleon}} &= 1.269 \\ g_{\text{quark}} &= 1 \\ g_{\text{phen.}} &= g_{\text{nucleon}} \cdot A^{-0.18} \end{cases} \quad \left. \right\} \text{who knows ?}$$

$$g_A \rightarrow g_A \cdot (1 - \delta) \quad S \cdot (1 - \delta)^4$$

For instance, if we have a decrease by  $\delta = 10$  (20)% of the axial coupling, we will obtain the same measurement after a time of data that is larger by a factor of  $1/(1 - \delta)^8 = 2.3$  (6)

$2\nu\beta\beta$

for  ${}^{82}\text{Se}$   
 $\delta = 0.55$   
the ‘factor’  
would be  
570 !!!!!

well ... the truth is hidden

Well ....the truth is hidden  
in some difficult calculation

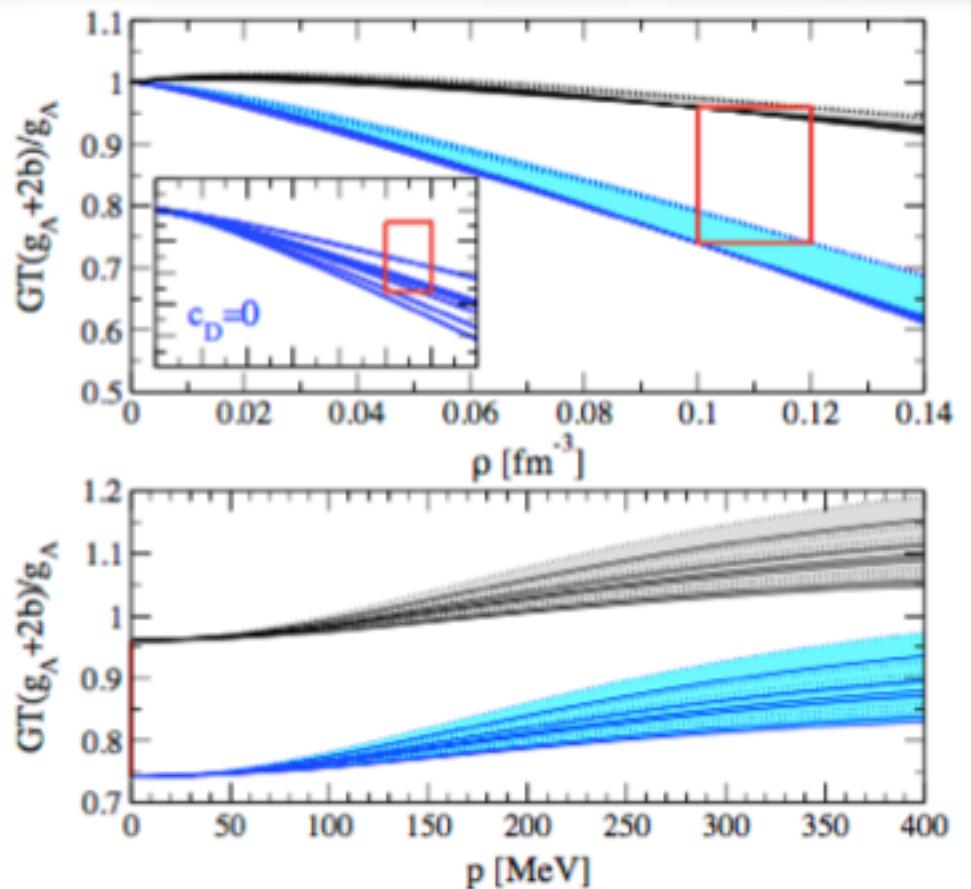


FIG. 3: (Color online) Top panel:  $g_A$  plus 2b-current con-

here the claim is

$$-30\% < q < 10\%$$

# 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

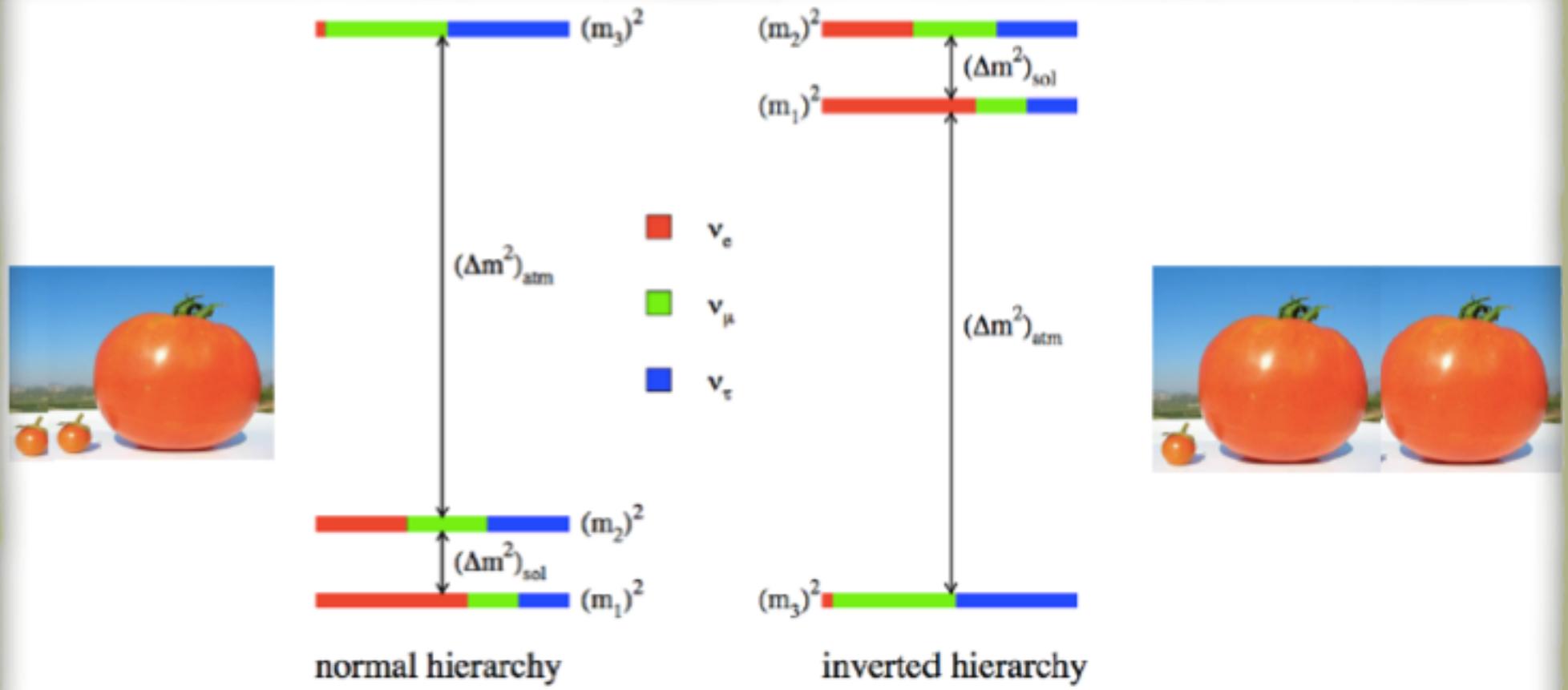
$$m_{\beta\beta} = f(U_{ek}, m_{lightest}, \delta m_{sol}, \Delta m_{atm})$$

Here what we know

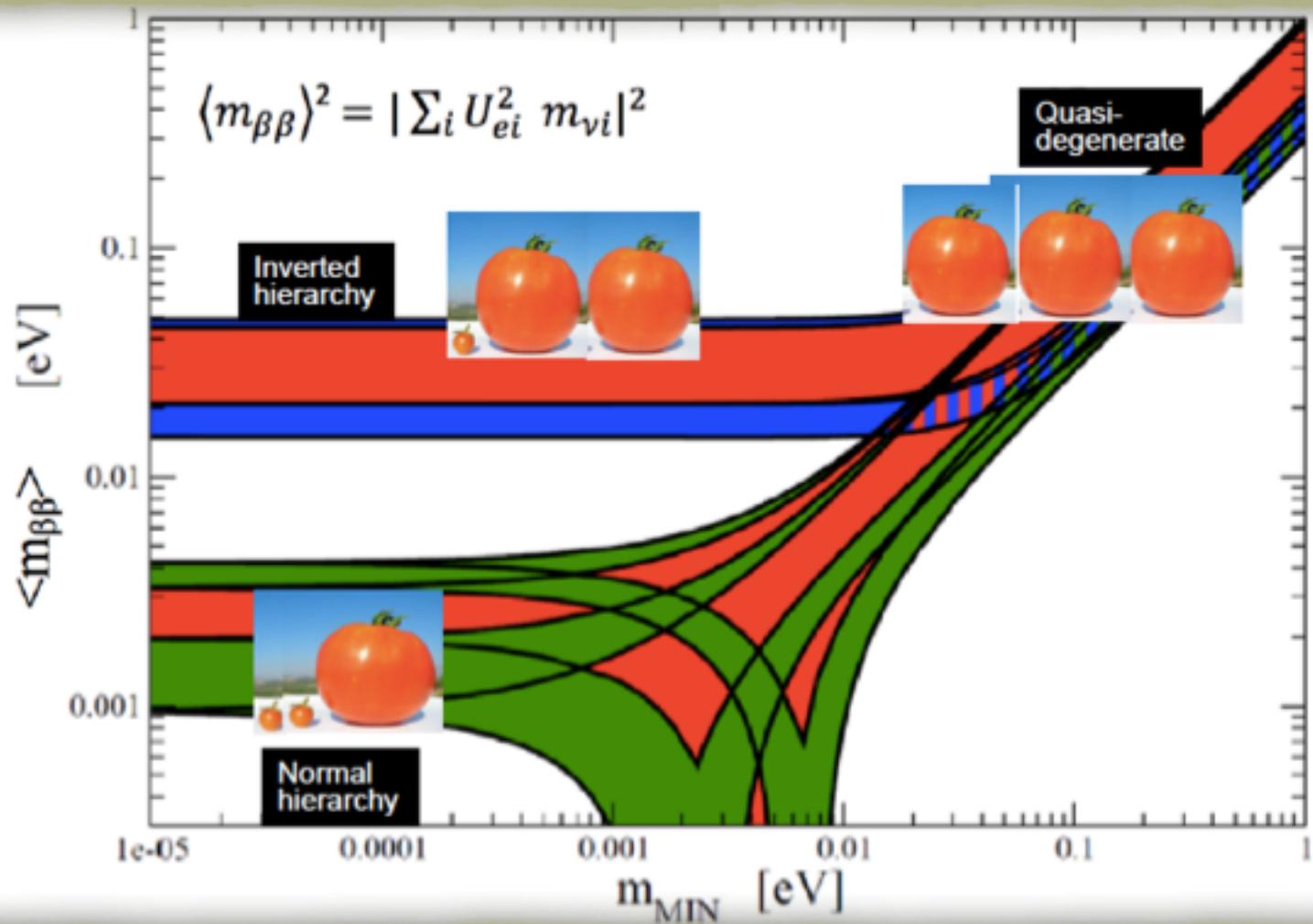
	$3\sigma$ range	$3\sigma$ knowledge
$\sin^2 \theta_{12}$	$0.270 \rightarrow 0.344$	
$\theta_{12}/^\circ$	$31.29 \rightarrow 35.91$	$\sim 14\%$
$\sin^2 \theta_{23}$	$0.385 \rightarrow 0.644$	
$\theta_{23}/^\circ$	$38.3 \rightarrow 53.3$	$\sim 33\%$
$\sin^2 \theta_{13}$	$0.0188 \rightarrow 0.0251$	
$\theta_{13}/^\circ$	$7.87 \rightarrow 9.11$	$\sim 15\%$
$\delta_{\text{CP}}/^\circ$	$0 \rightarrow 360$	$\sim \text{no info}$
$\frac{\Delta m_{21}^2}{10^{-5} \text{ eV}^2}$	$7.02 \rightarrow 8.09$	$\sim 14\%$
$\frac{\Delta m_{3\ell}^2}{10^{-3} \text{ eV}^2}$	$[+2.325 \rightarrow +2.599]$ $[-2.590 \rightarrow -2.307]$	$\sim 12\%$

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      /      \ /  
                        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

$$N_A = 6 \times 10^{23}$$

$$N_y = 1$$

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

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

**1600 moles**

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

and how little background?

# 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) !

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

Sensitivity is  $S/\sqrt{R}$

# Sensitivity is S/N

Sensitivity

$$\propto K \sqrt{\frac{M \cdot t}{B \cdot \Delta E}} \quad (\text{i.a.} \bullet \epsilon)$$

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

which way?

# 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)

## 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

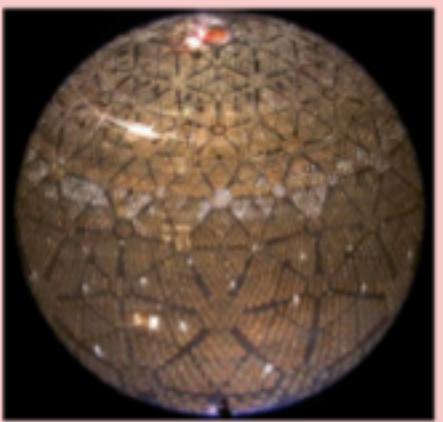
t      500 y instead of 5 y

$\Delta E$     50 eV instead of 5 keV

B    0.001 instead of 0.1

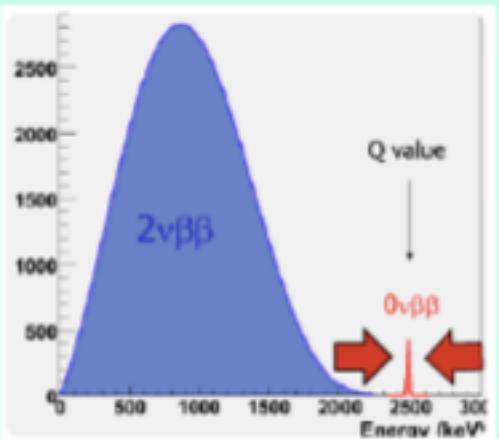
meaning :

## The Brute Force Approach



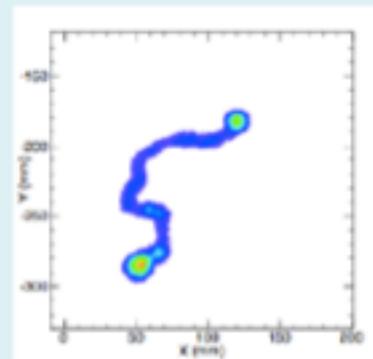
focus on the numerator  
with **a huge amount  
of material**  
(often sacrificing  
resolution)

## The Peak-Squeeze Approach



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

## The "Final-State Judgement" Approach

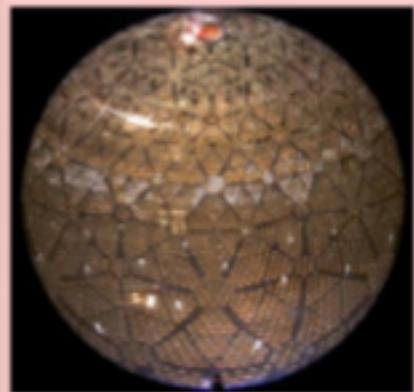


try to make the  
background zero by  
**tracking or  
tagging**

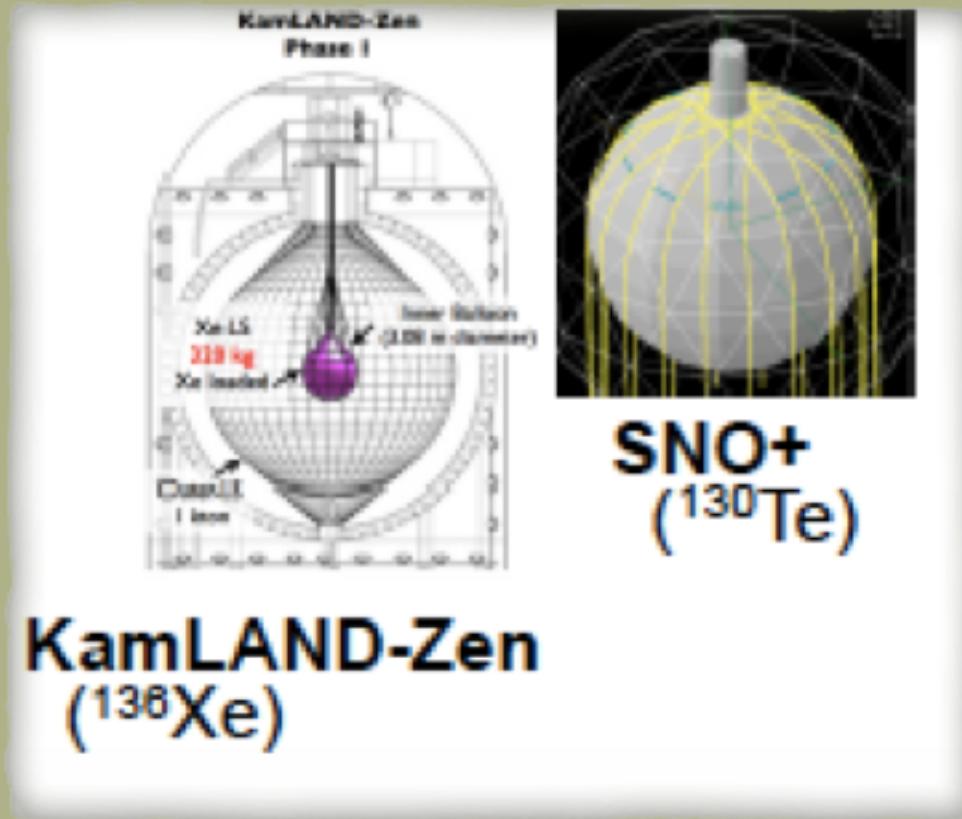
or better make the right cocktail of all of the above

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  
intradouble physics background

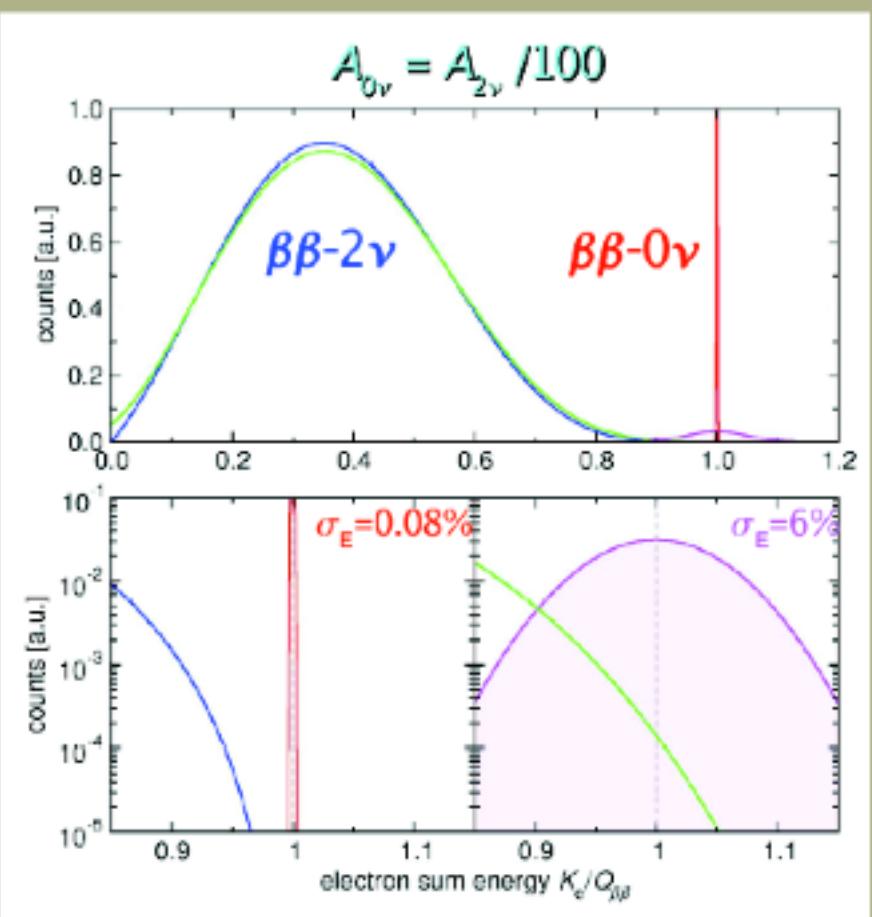
# irreducible physics background

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

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

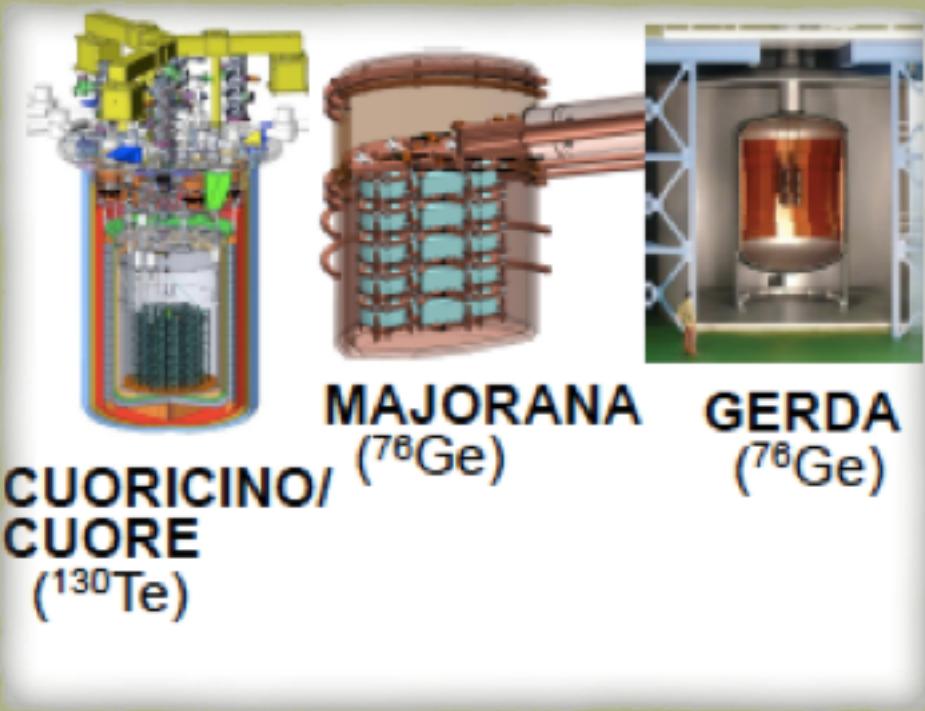
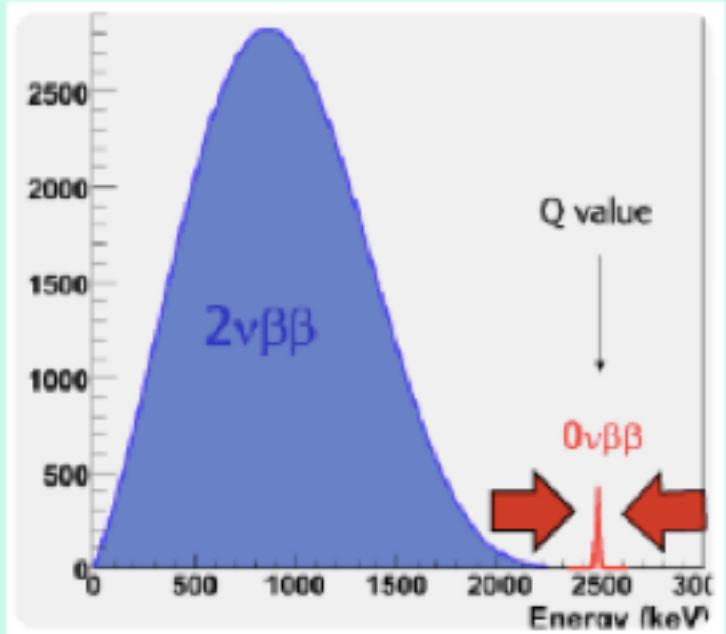
Please note  $\delta^6$

$$\begin{aligned} T^{0\nu} &\simeq 10^{28} y & S/B = 1 \\ T^{2\nu} &\simeq 10^{20} y & Q \simeq 3 \text{ MeV} \end{aligned} \longrightarrow \delta = \Delta E^{FWHM}/Q \simeq 2.5\%$$

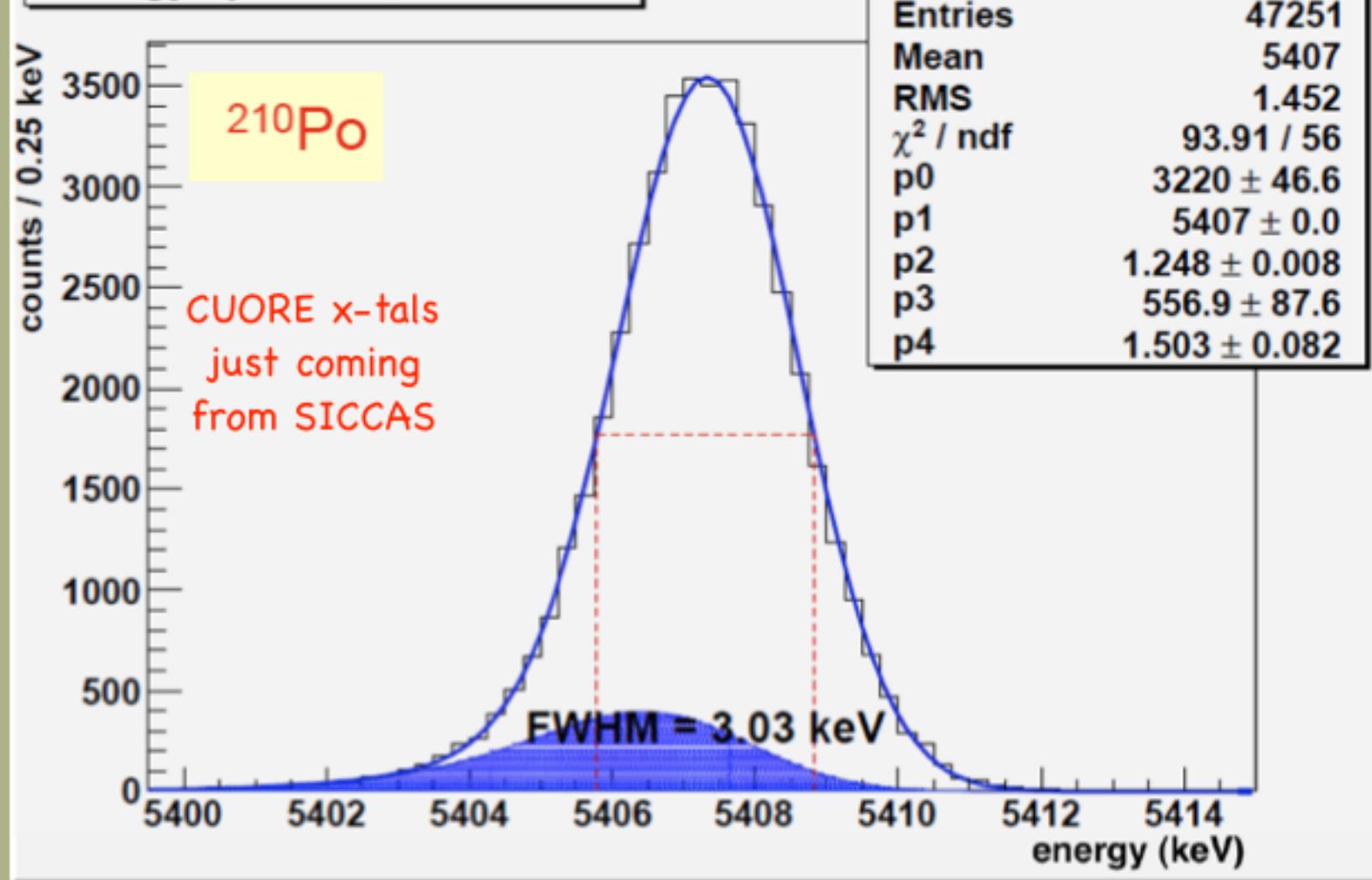


the state of the art: peak squeezer

# The “Peak-Squeezer” Approach

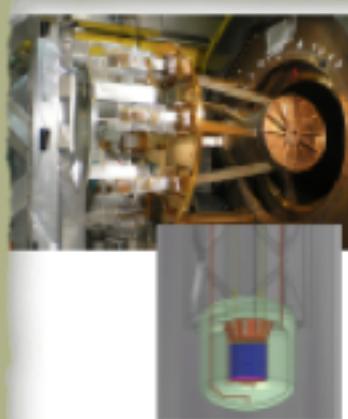
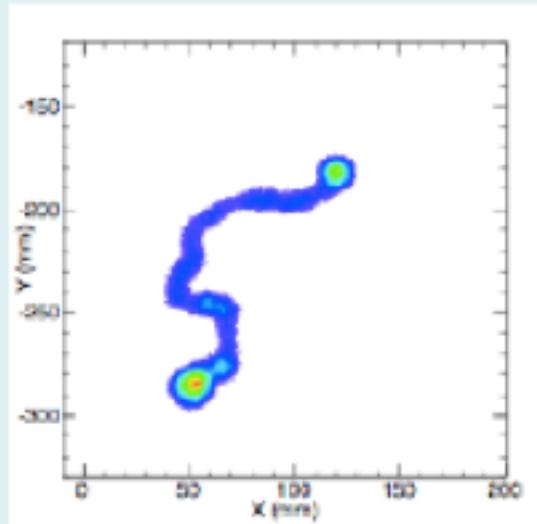


how much can you squeeze ?

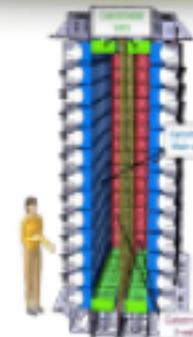


the state of the art: tracking

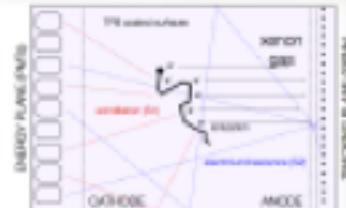
# The “Final-State Judgement” Approach



EXO/nEXO  
 $(^{136}\text{Xe})$



NEMO/  
SuperNEMO  
(various/ $^{82}\text{Se}$ )



NEXT  
 $(^{136}\text{Xe})$

nicely working but...





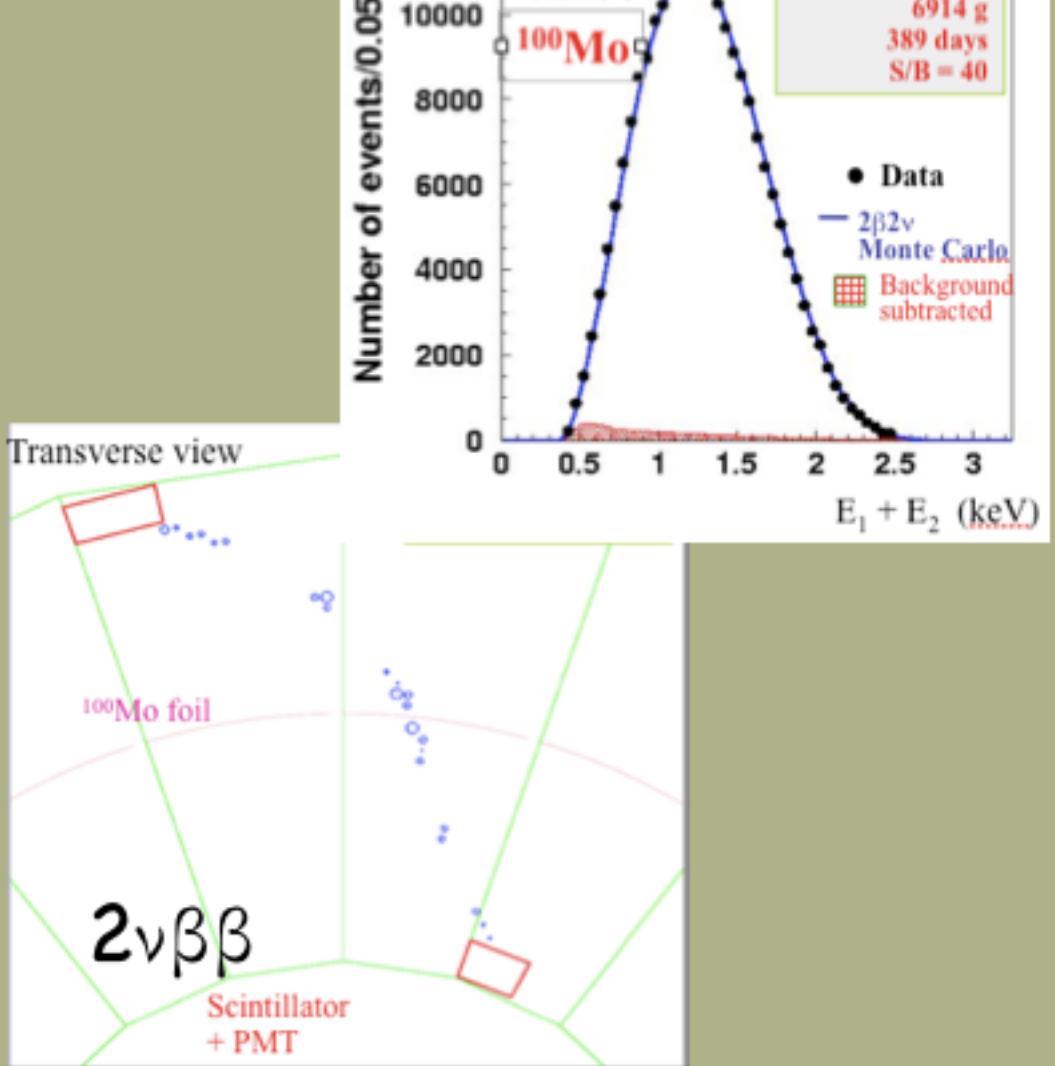
Source: 10 kg of  $\beta\beta$  isotopes  
cylindrical,  $S = 20 \text{ m}^2$ ,  $e \sim 60 \text{ mg/cm}^2$

#### 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

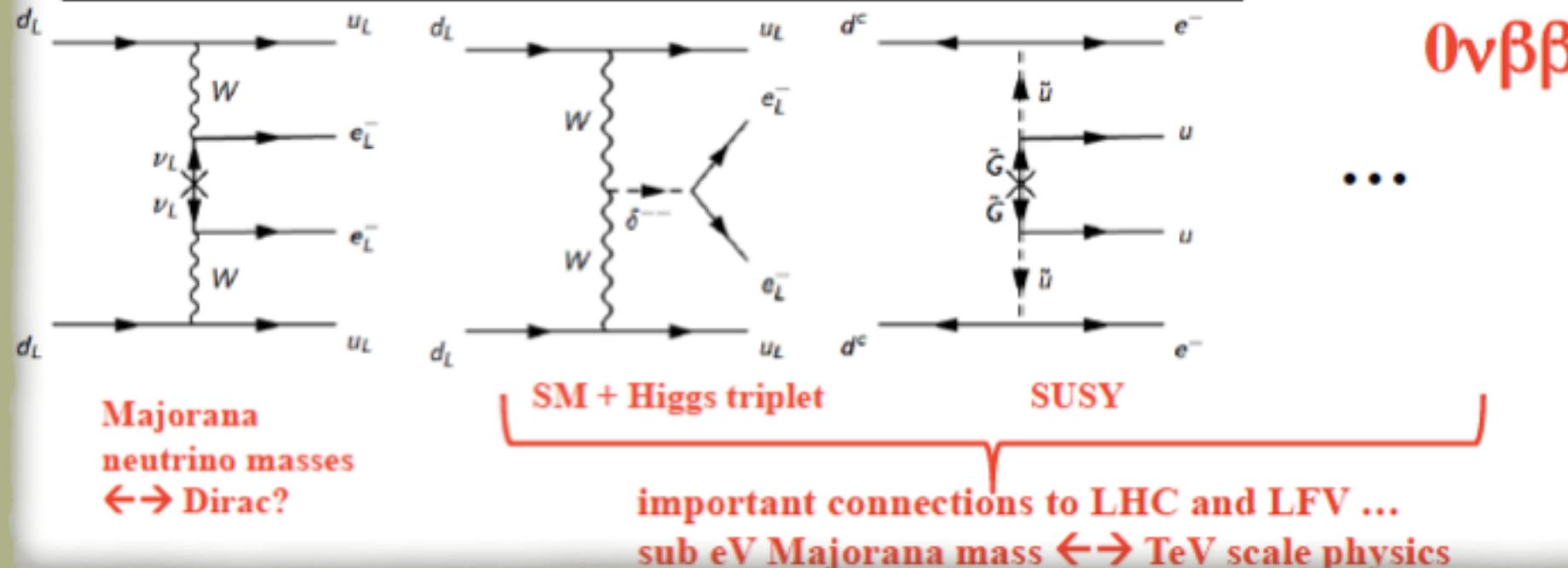
#### Calorimeter:

1940 plastic scintillators  
coupled to low radioactivity PMTs



back to physics  
do not forget ‘New Physics’

## Majorana $\nu$ -masses or other $\Delta L=2$ physics: $\rightarrow$ 2 electrons

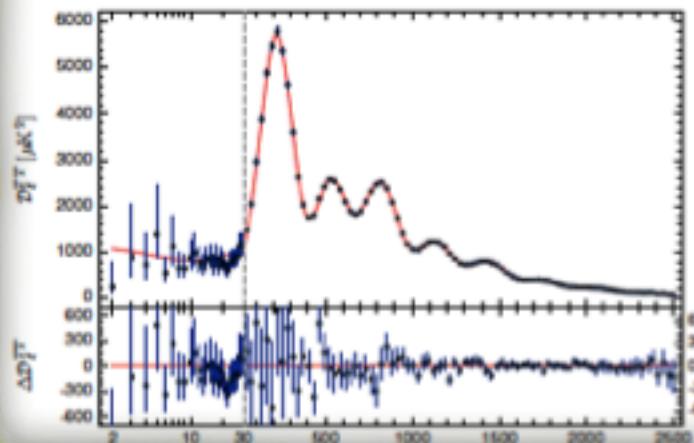
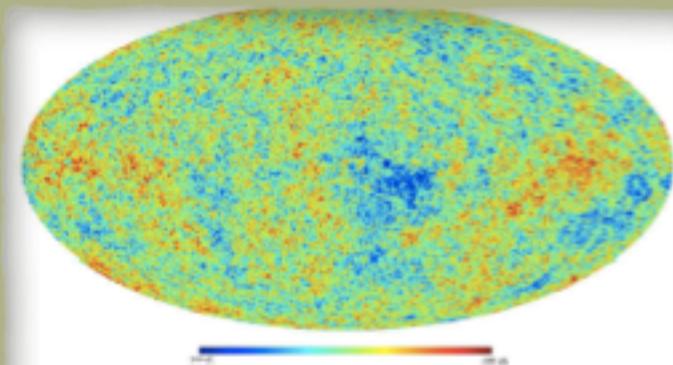


although we go after  $0\nu\beta\beta$  induced by Majorana's thoughts we might find something else !

do we have any solid limit ?

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

## CMB fit



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

From the Planck Collaboration  
Planck Results XIII (2015)  
[arXiv:1502.01589](https://arxiv.org/abs/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  $T = 1.923 \times 10^{-3} T_c$

$$T_\nu = (4/11)^{1/3} T_0$$

- 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  $Y_p = 4n_{\text{He}}/n_0$  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  $H_0 = 100 h \text{km/sec}^{-1}\text{Mpc}$  ( $\Omega_\Lambda = 1 - (\omega_b + \omega_c)/h^2$ ).

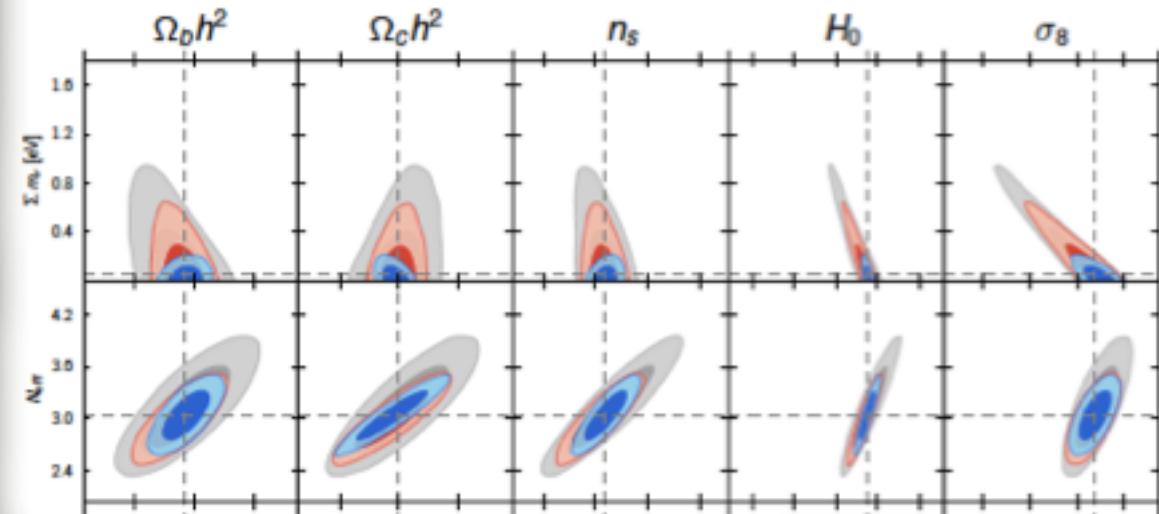
Single extension best constraints:

$$N_{\text{eff}} = 3.04 \pm 0.2 \text{ (0.18)}$$

$$\sum_i m_i = 0.49 \text{ (0.17) eV}$$

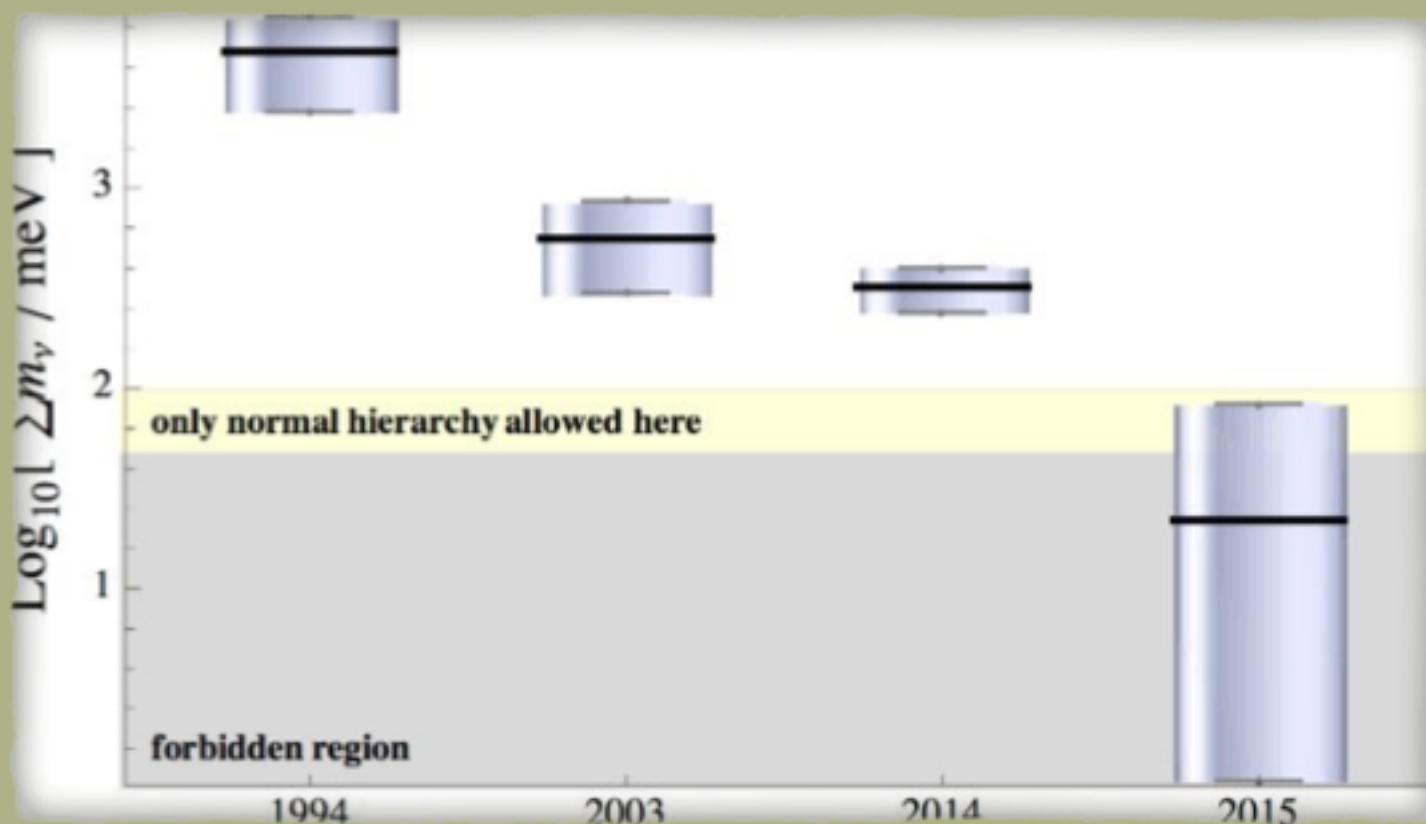
Planck (+ BAO)

95% Planck (+ BAO)



should we believe it ?

# time evolution of CMB prediction on neutrino mass



a better  
understanding  
brings more  
solidity to  
results

the best bet today is

# The contribution of light Majorana neutrinos to neutrinoless double beta decay and cosmology

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

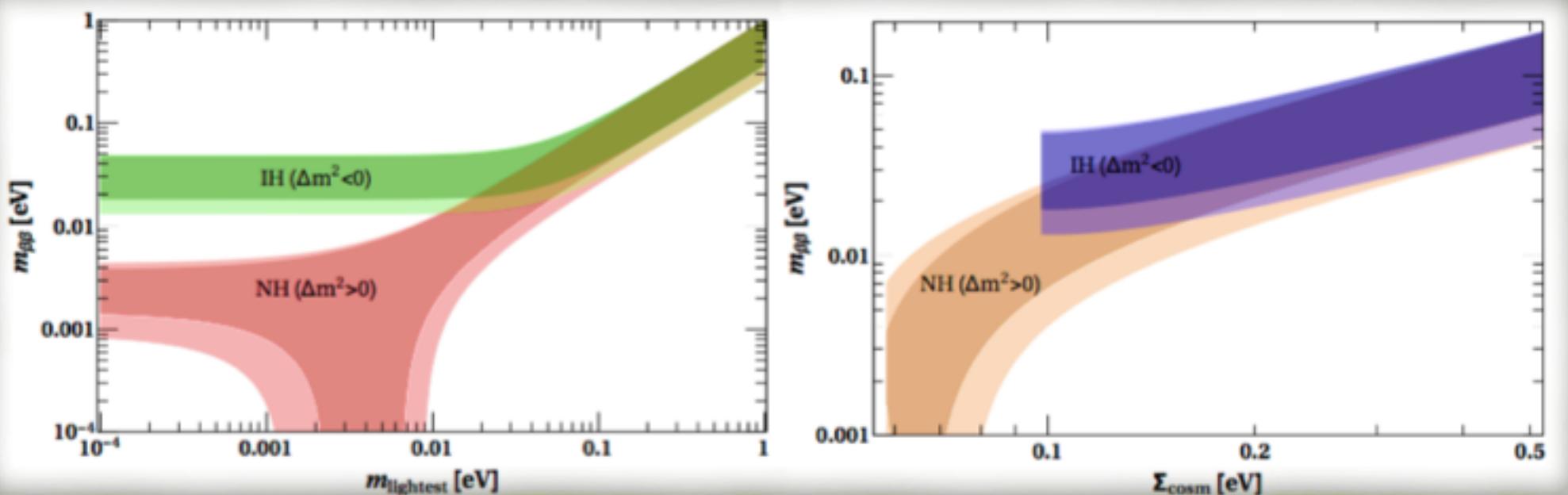
<sup>1</sup>*INFN, Gran Sasso Science Institute, Viale F. Crispi 7, 67100 L'Aquila, Italy*

<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: December 15, 2015)

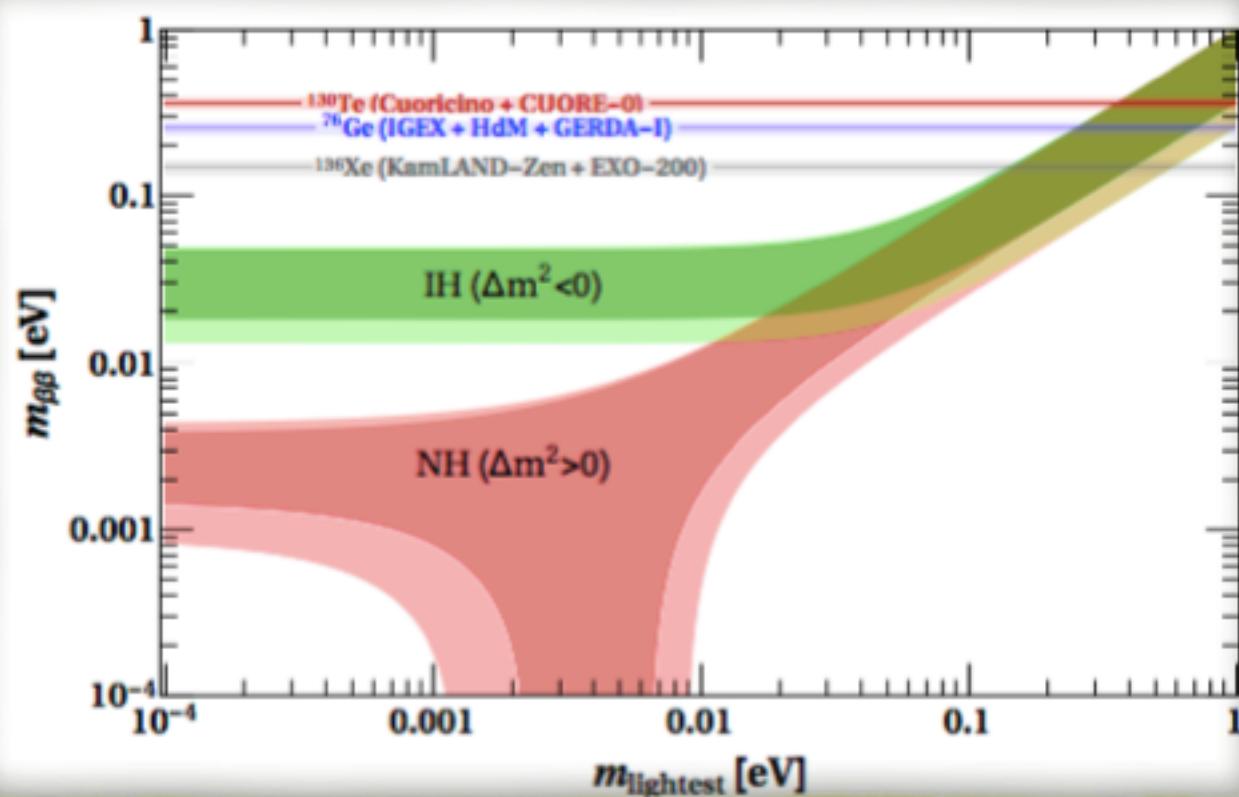


existing results from  
 $0\nu\beta\beta$  searches

Experiment	Isotope	Technique	Total mass [kg]	Exposure [kg yr]	FWHM @ $Q_{\beta\beta}$ [keV]	Background [counts/keV/kg/yr]	$S^{0\nu}$ (90% C. L.) [ $10^{25}$ yr]
<i>Past</i>							
Cuoricino, [177]	$^{130}\text{Te}$	bolometers	40.7 ( $\text{TeO}_2$ )	19.75	$5.8 \pm 2.1$	$0.153 \pm 0.006$	0.24
CUORE-0, [178]	$^{130}\text{Te}$	bolometers	39 ( $\text{TeO}_2$ )	9.8	$5.1 \pm 0.3$	$0.058 \pm 0.006$	0.29
Heidelberg-Moscow, [179]	$^{76}\text{Ge}$	Ge diodes	11 ( $^{enr}\text{Ge}$ )	35.5	$4.23 \pm 0.14$	$0.06 \pm 0.01$	1.9
IGEX, [180, 181]	$^{76}\text{Ge}$	Ge diodes	8.1 ( $^{enr}\text{Ge}$ )	8.9	$\sim 4$	$\lesssim 0.06$	1.57
GERDA-I, [165, 182]	$^{76}\text{Ge}$	Ge diodes	17.7 ( $^{enr}\text{Ge}$ )	21.64	$3.2 \pm 0.2$	$\sim 0.01$	2.1
NEMO-3, [183]	$^{100}\text{Mo}$	tracker + calorimeter	6.9 ( $^{100}\text{Mo}$ )	34.7	350	0.013	0.11
<i>Present</i>							
EXO-200, [184]	$^{136}\text{Xe}$	LXe TPC	175 ( $^{enr}\text{Xe}$ )	100	$89 \pm 3$	$(1.7 \pm 0.2) \cdot 10^{-3}$	1.1
KamLAND-Zen, [185, 186]	$^{136}\text{Xe}$	loaded liquid scintillator	348 ( $^{enr}\text{Xe}$ )	89.5	$244 \pm 11$	$\sim 0.01$	1.9

Let's say  $> 2 * 10^{25} \text{ y}$

which translate in



assuming no  $g_A$  quenching

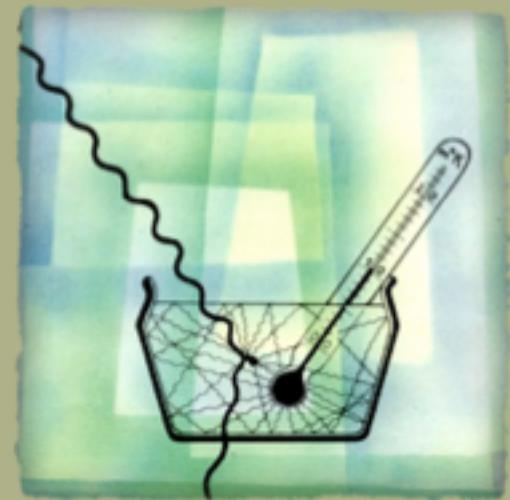
end of part I

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Bolometric technique

from MiBeta to CUORE via Cuoricino and Cuore0

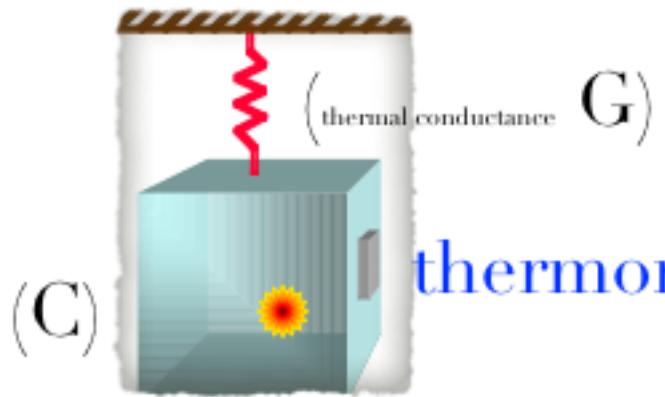
Scintillating bolometers as an evolution toward Zero  
Background



(very) Low Temperature Calorimeter

A True Calorimeter

heat sink      ( $T_0$ )



$\beta\beta$  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 :  $\tau = C/G \sim 1s$

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

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

Why a bolometer

$M$ ,  $t$ ,  $B$ ,  $\Delta E$  are the parameters of the game

$t$  is irrelevant

$M$  is ‘easy’ with a calorimeter

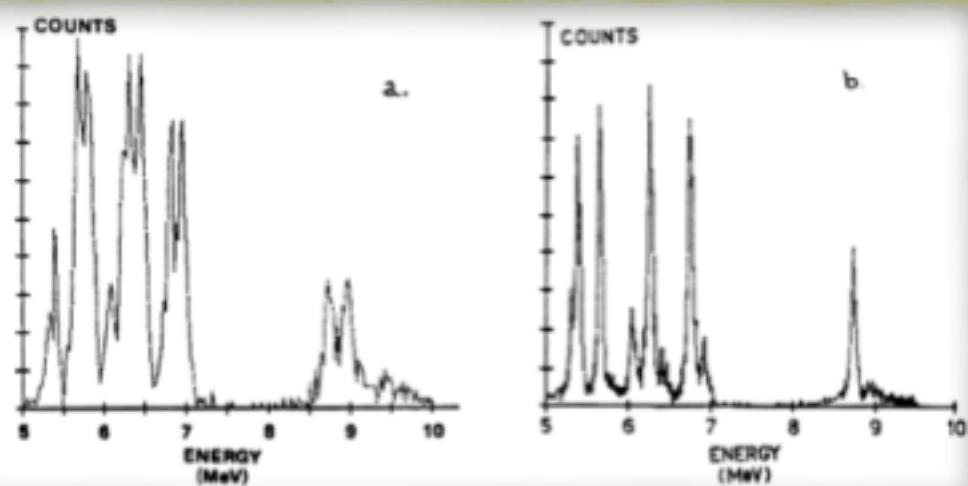
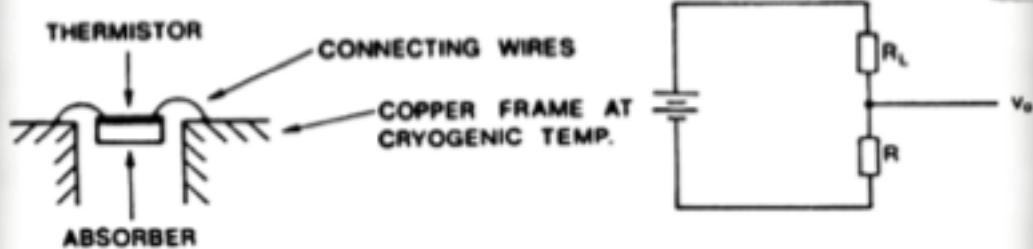
$\Delta E$  is a definite bonus

$B$  is what this part of the talk is mostly about

the Dawn !

T.O. Niinikoski

CERN, Geneva, Switzerland



### Low-temperature calorimetry for rare decays

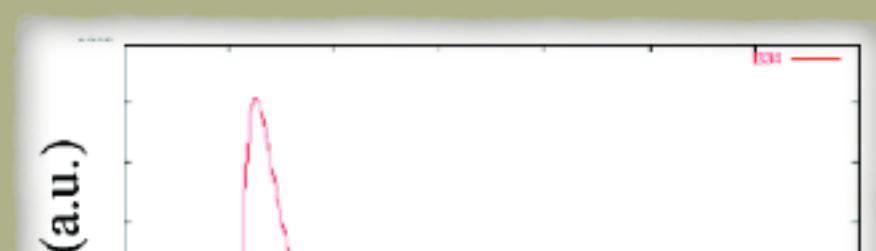
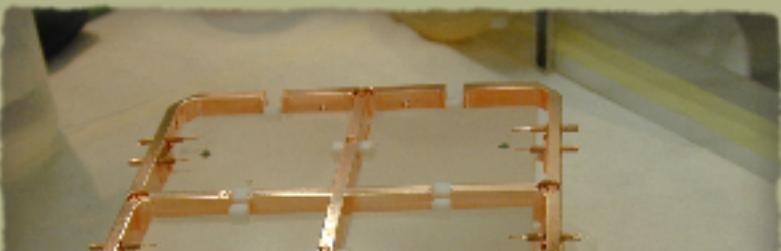
E. Fiorini

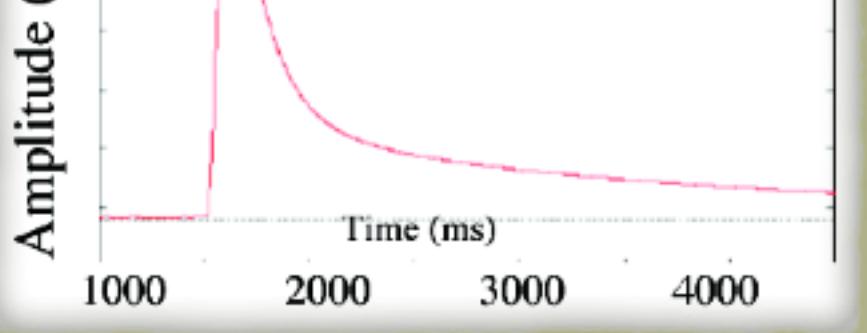
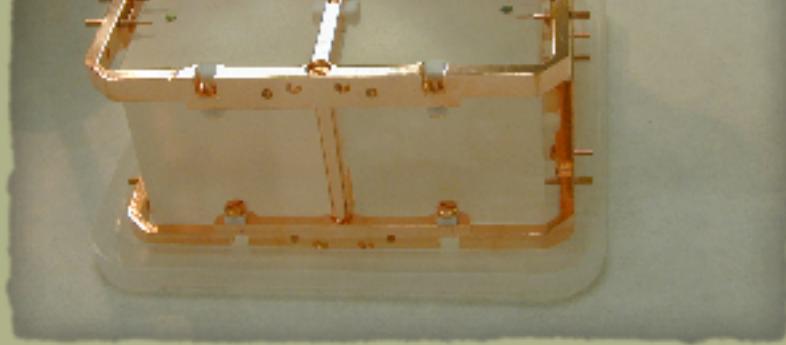
Dipartimento di Fisica dell'Università and INFN, Milano, Italy

T.O. Niinikoski

CERN, Geneva, Switzerland

# TeO<sub>2</sub> : 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)

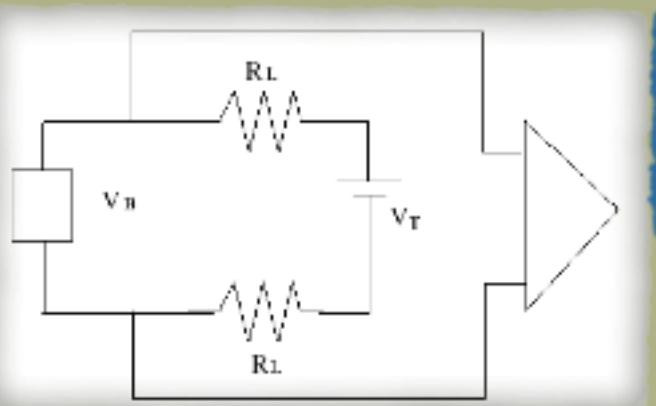
to read the temperature  
you need a thermometer

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

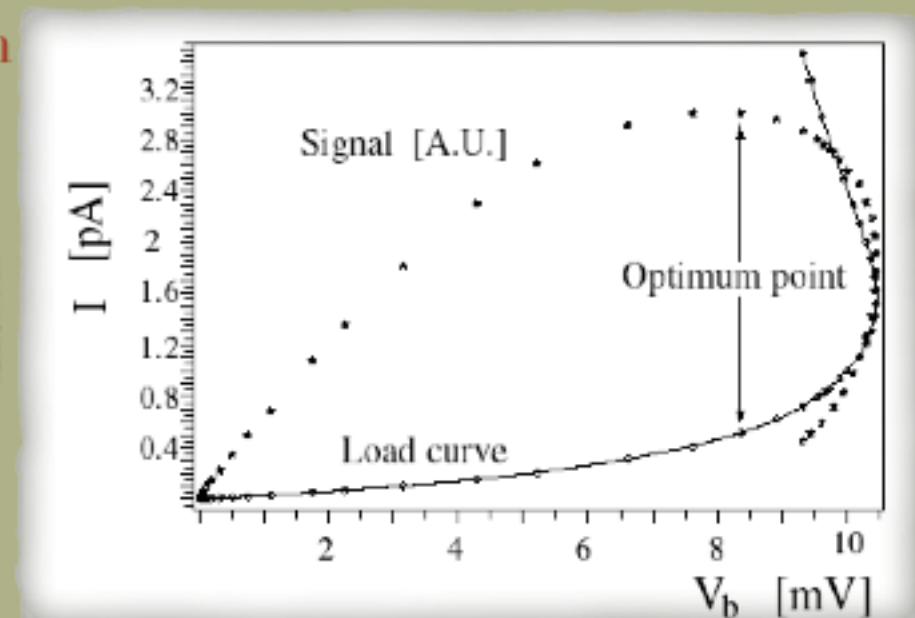


$dR/dE \sim 3M\Omega/\text{MeV}$

### Neutron Transmutation Doped (NTD) Germanium Thermistor



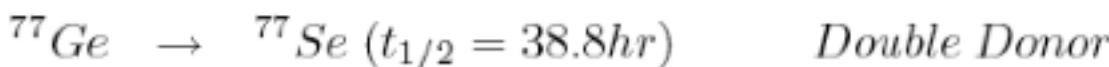
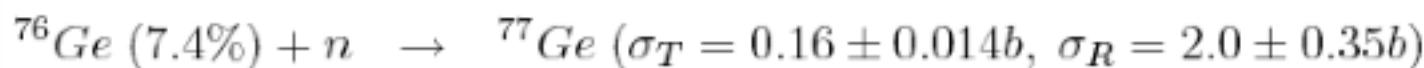
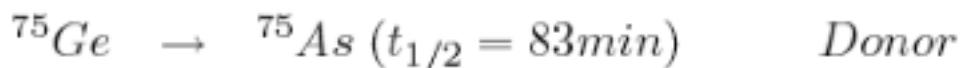
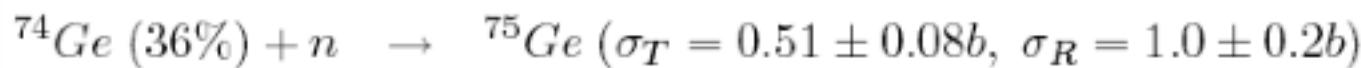
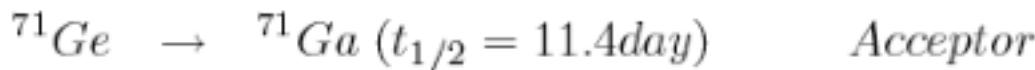
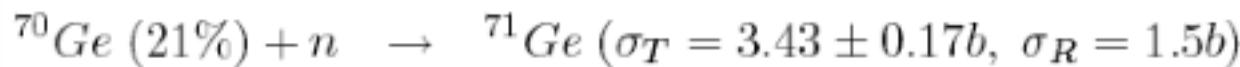
$$T_b = T_0 + \frac{P}{G}$$



## 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>.

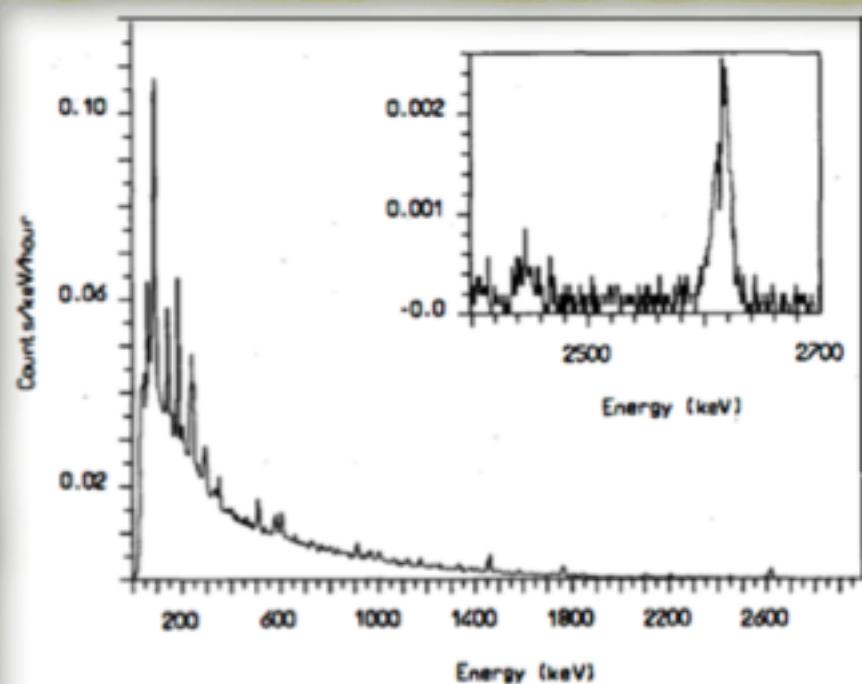
Required fluence is  $3.5 \times 10^{18}$  n/cm<sup>2</sup>.

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 TeO<sub>2</sub> crystal has collected data for about 10500 h live time setting a new lower limit of  $2.1 \cdot 10^{22}$  y (90% C.L.) for <sup>130</sup>Te neutrinoless double beta decay.



330 g TeO<sub>2</sub> detector final spectrum (10510 h), low energy portion of the spectrum and  $\beta\beta_{0\nu}$  region in the insert.

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

resolution was 17keV

background high

BUT THE WAY  
WAS OPEN !

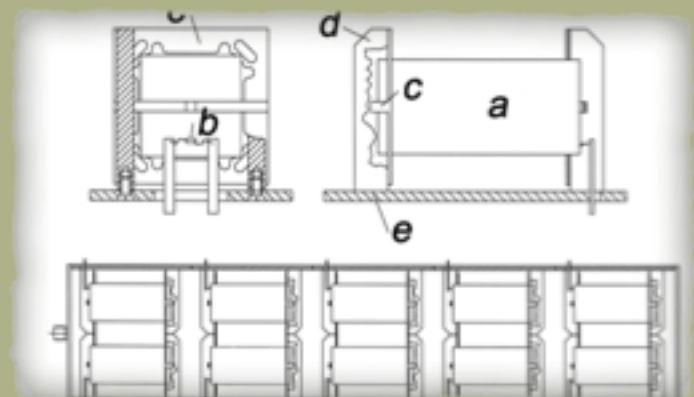
step after step

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  $2.3 \text{ } ^{130}\text{Te}$ )

set a limit of  $5.6 \text{ } 10^{22} \text{ y}$

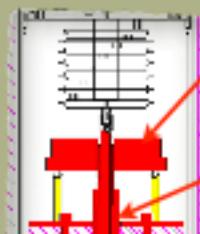
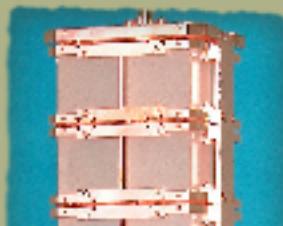


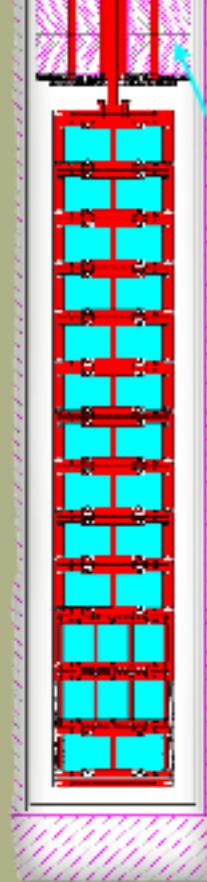
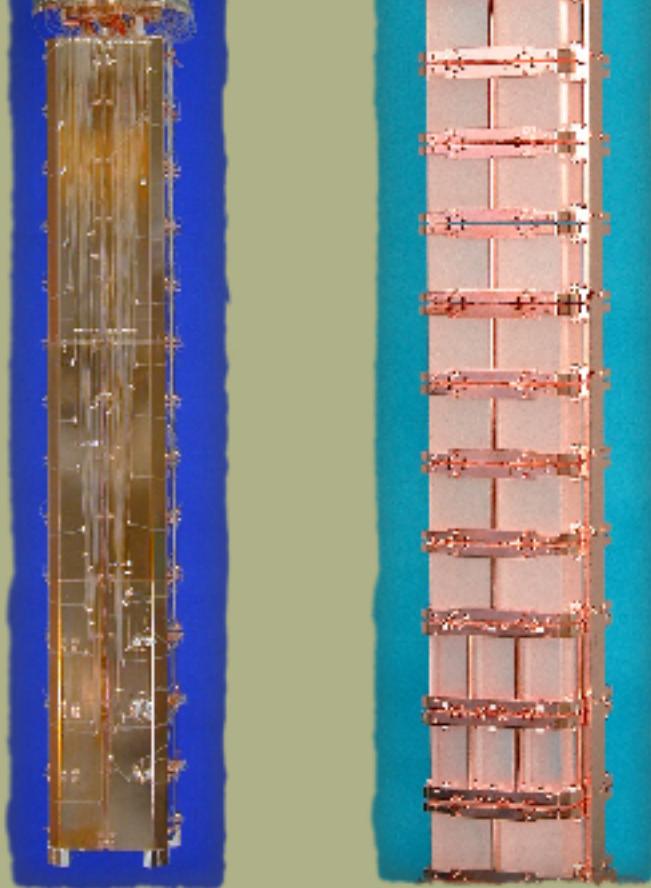
ready for a tougher game

# Cuoricino

Mixing chamber

Cold finger

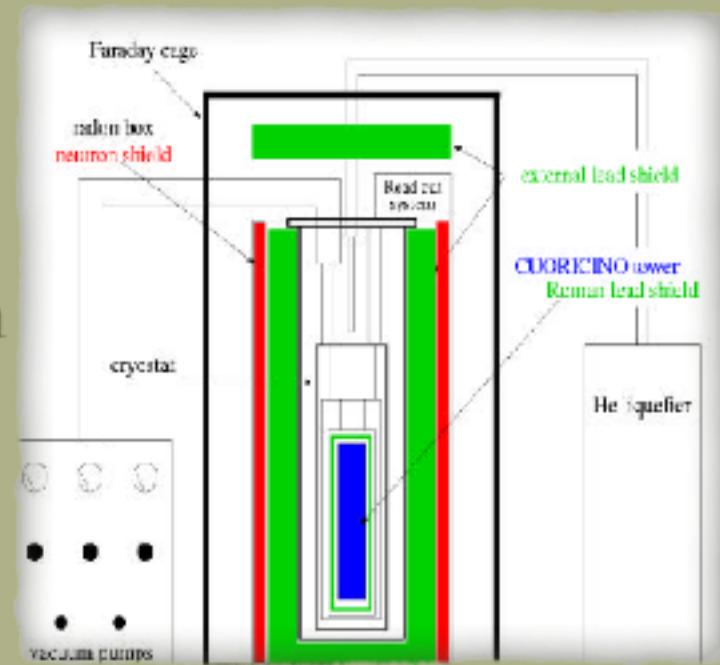




10 mK



Roman  
Lead  
Shield



a digression on Roman Lead  
Lead is a very good shield from external radioactivity



however it has

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	$^{205}\text{Tl}$



got a problem

Pb	% by wt	Neutrons	Alpha	Beta	C
$^{206}\text{Pb}$	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

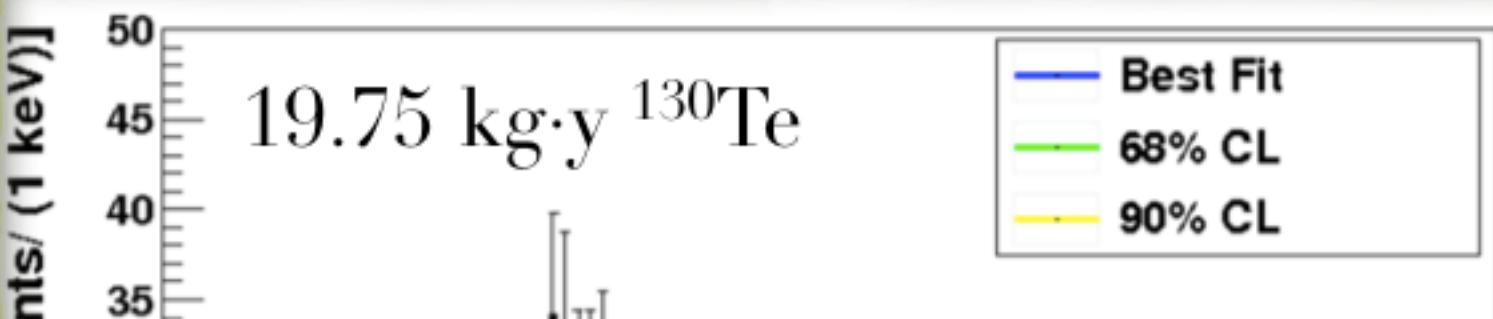


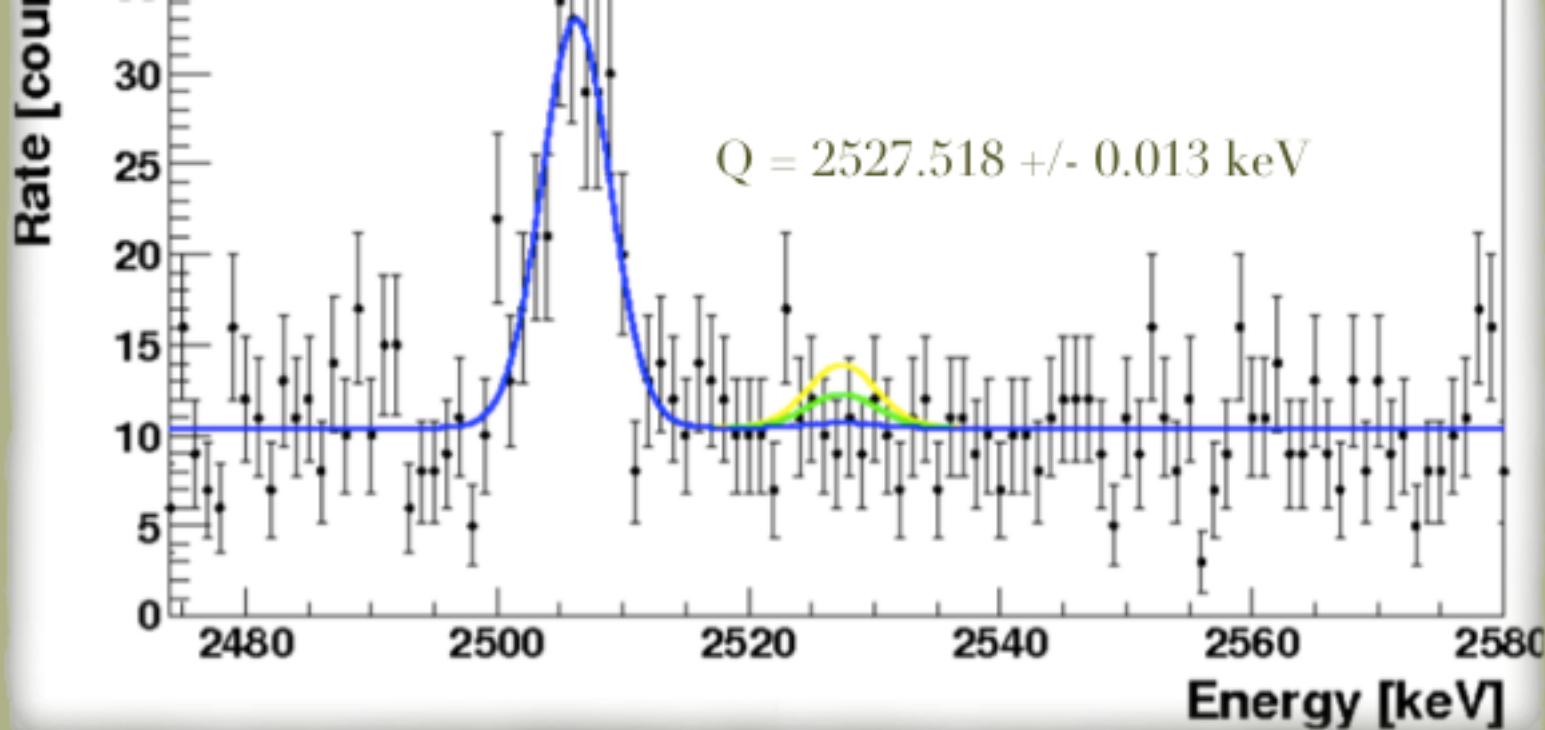


a collaborative  
effort by  
INFN and  
Cultural Heritage  
Ministry



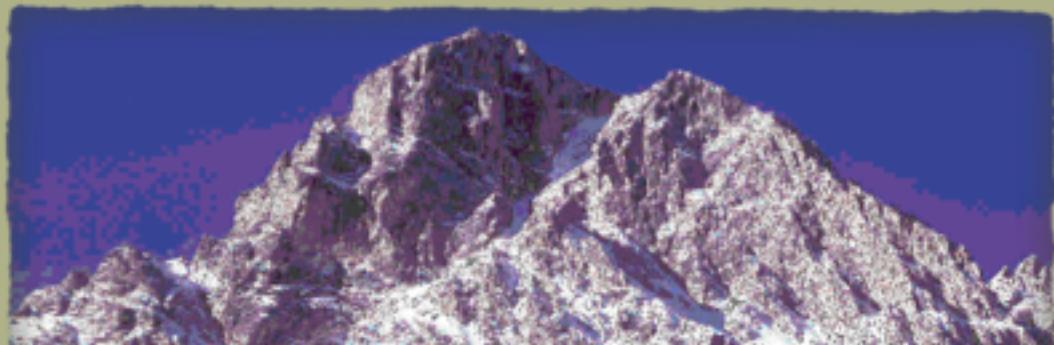
# Cuoricino final result





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

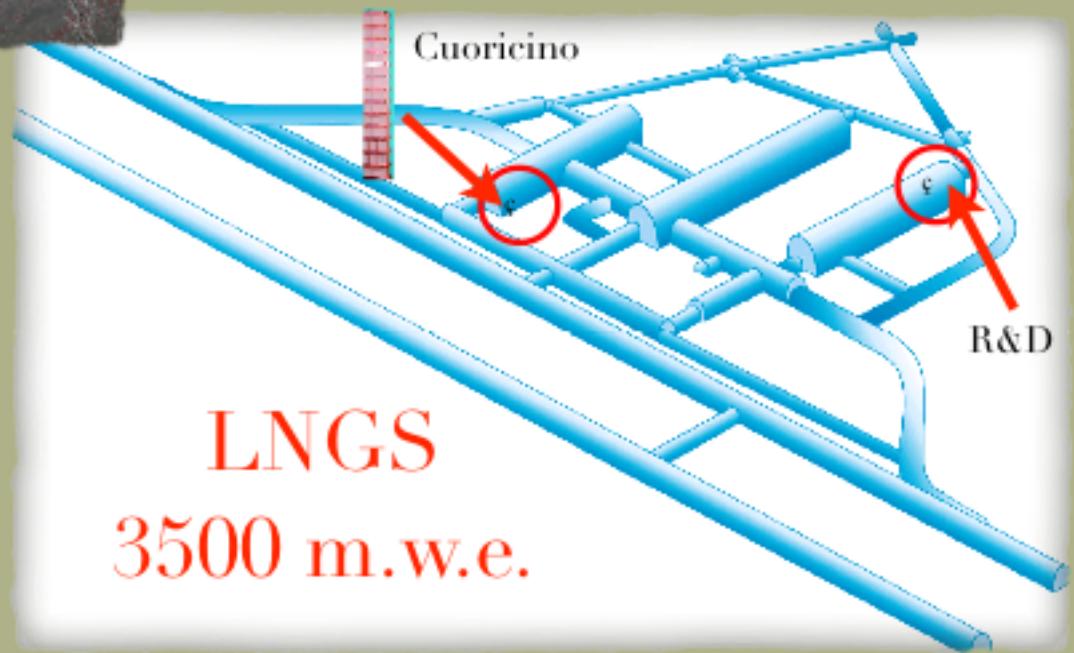
Cuoricino, where ?





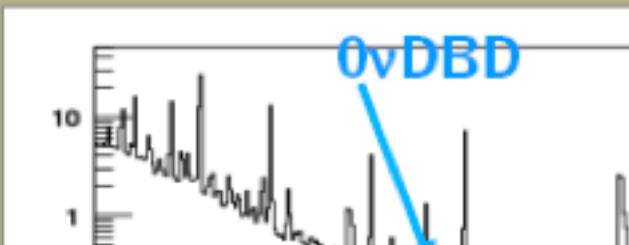
## The Shield Corno Grande 2916 m

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**  
 $b = 0.18 \pm 0.02$

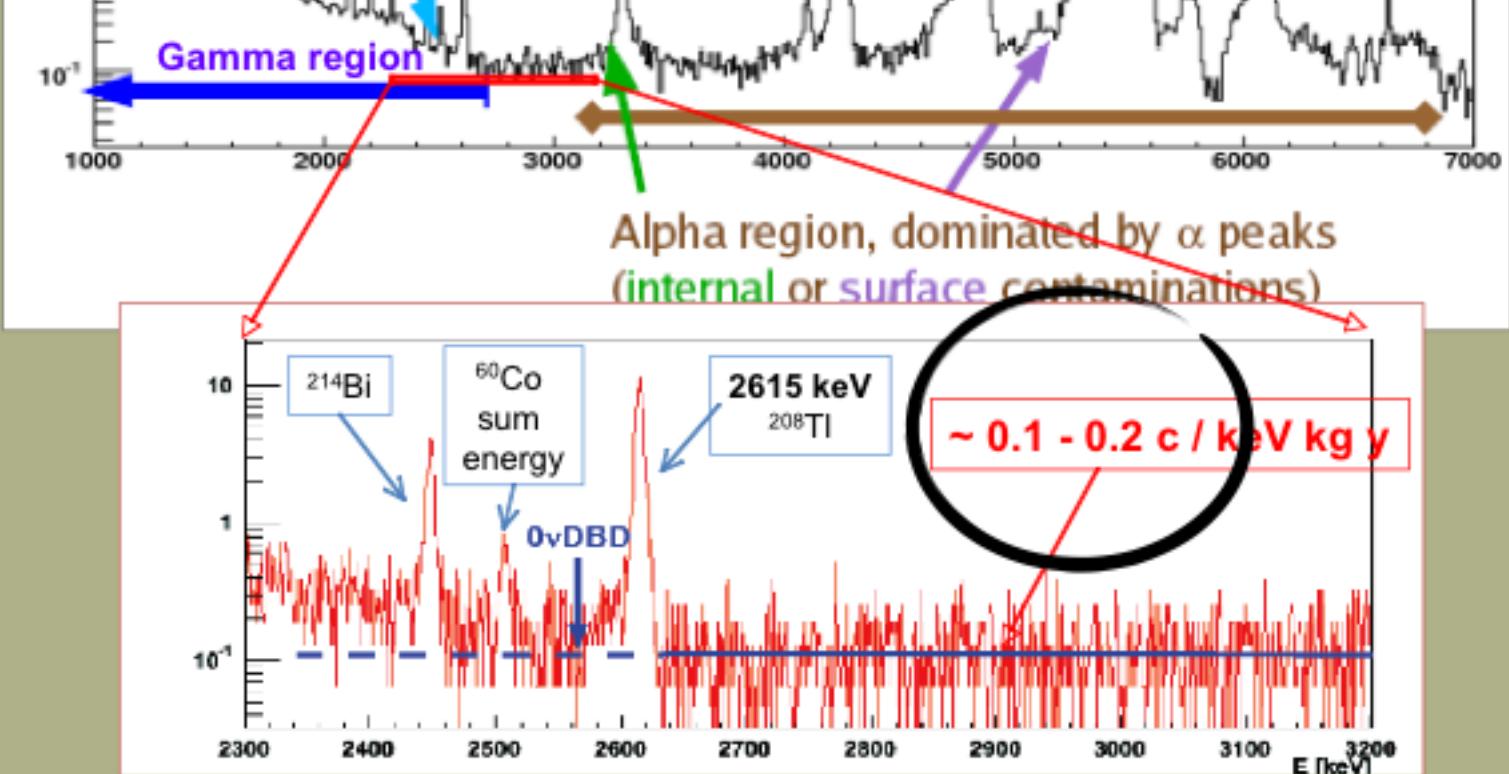


Typical shape of a background spectrum  
in **Cuoricino**, a pure bolometric experiment



c/keV/kg/y

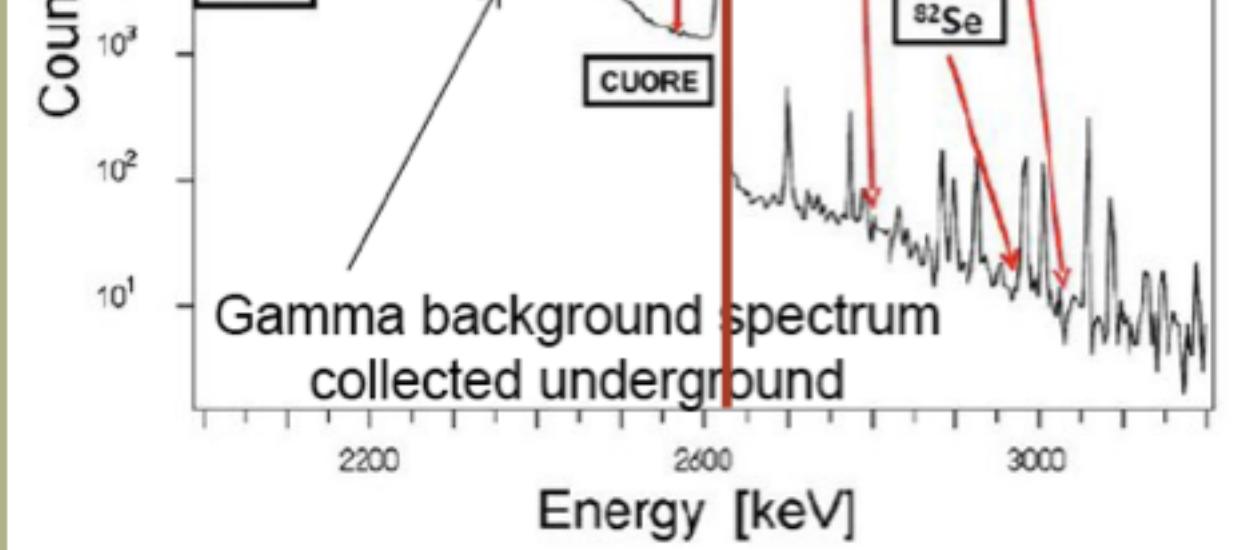
B  
is  
experiment  
dependent.  
Cuoricino  
as an  
example



we have two enemies then



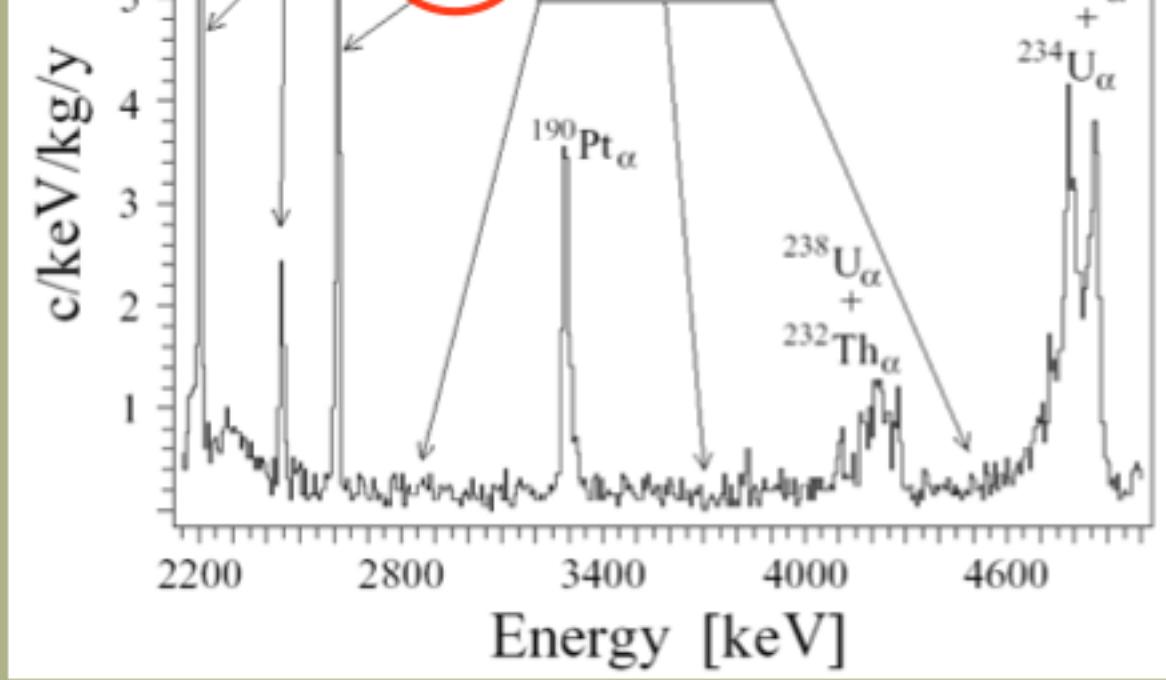
# Photons



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

and...

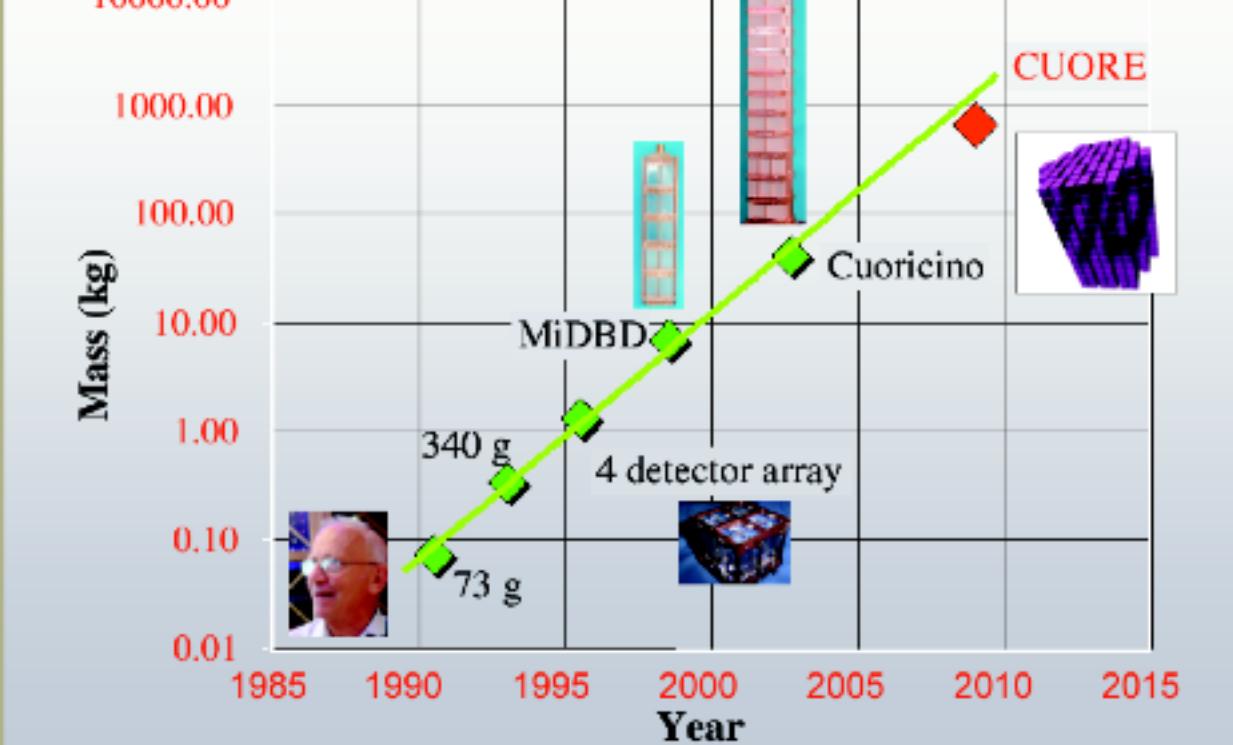




the  $\alpha$  land

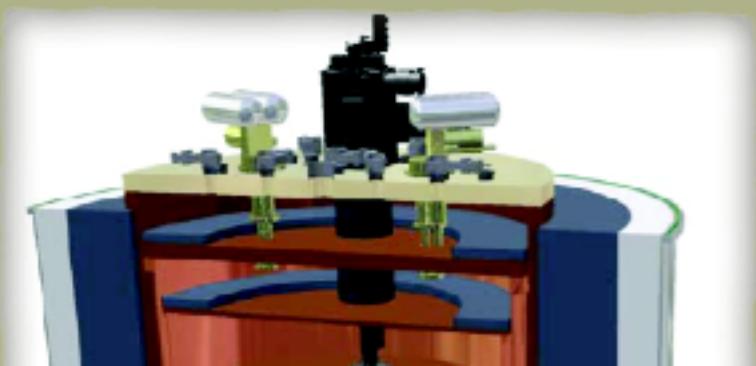
The last child of the  
evolution: CUORE





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

# CUORE



988 TeO<sub>2</sub> Crystals



19 Towers of 52 crystals  
each

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

Active Mass 204 Kg

Pulse Tube Cooler

## Scaling Cuoricino to CUORE

$$a \left( M T \right)^{1/2}$$

$$M = m \times 20$$

$$T = t \times 6$$

$$l = R / 20$$

A [ b ΔE ]

$$b = B / 20$$

$$\Delta E = \Delta E / 1.5$$

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

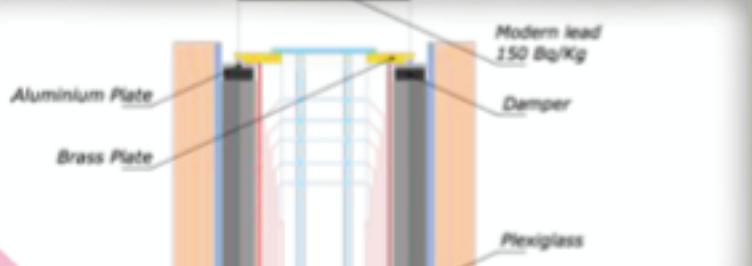
$$\tau_{1/2} (\text{CUORE}) \sim 1.2 \times 10^{26}$$

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:

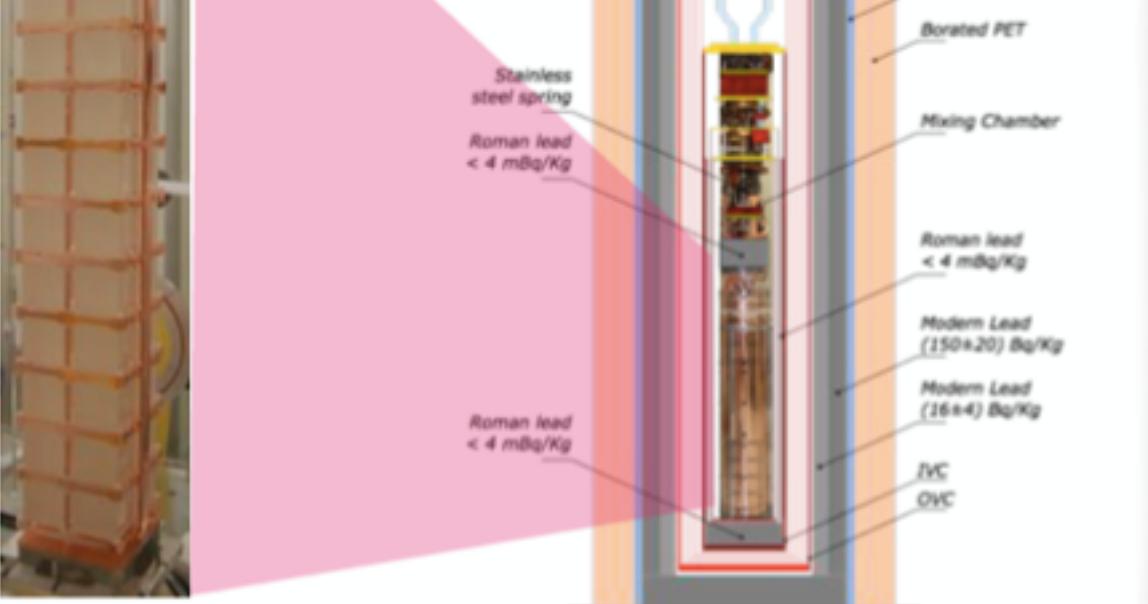
- 52x750g crystals



- 13 floor of  
4 crystals each

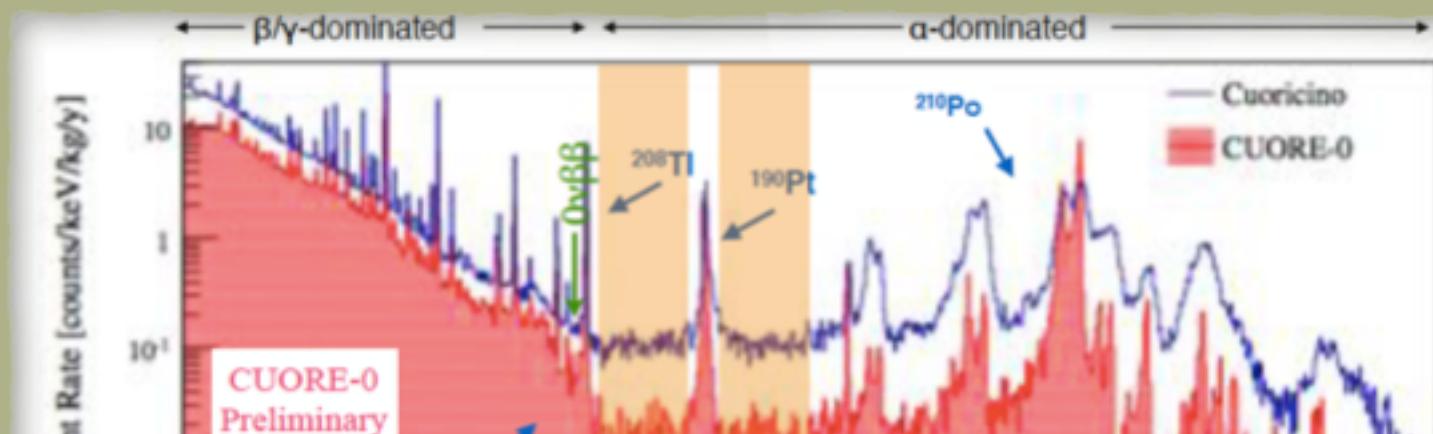
Active mass:

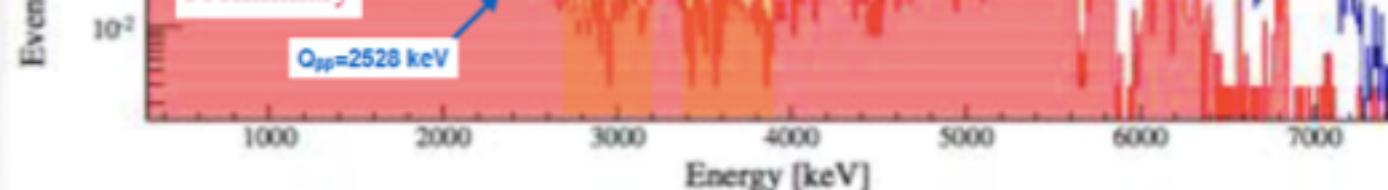
- $\text{TeO}_2$ : 39 kg
- $^{130}\text{Te}$ : ~11 kg  
( $5 \cdot 10^{25}$  nuclei)



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

# which says...



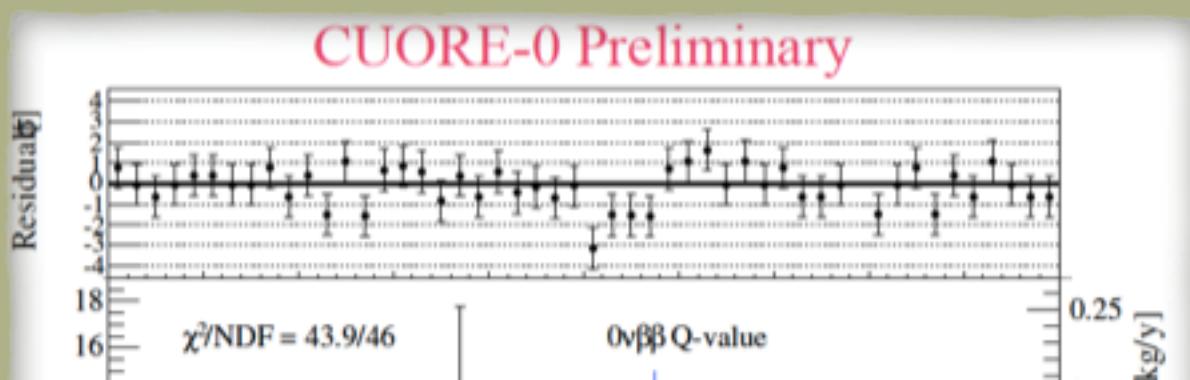


	Avg. flat bkg. [c/(keV · kg · yr)]	
	0νββ region	2700-3900 keV
CUORICINO ε = 83%	$0.169 \pm 0.006$	$0.110 \pm 0.001$
CUORE-0 ε = 81%	$0.058 \pm 0.04$	$0.016 \pm 0.001$

- $^{238}\text{U}$   $\gamma$  lines reduced by ~2 (better radon control)
- $^{232}\text{Th}$   $\gamma$  lines not reduced (originate from the cryostat)
- $^{238}\text{U}/^{232}\text{Th}$   $\alpha$  lines reduced (detector surface treatment)

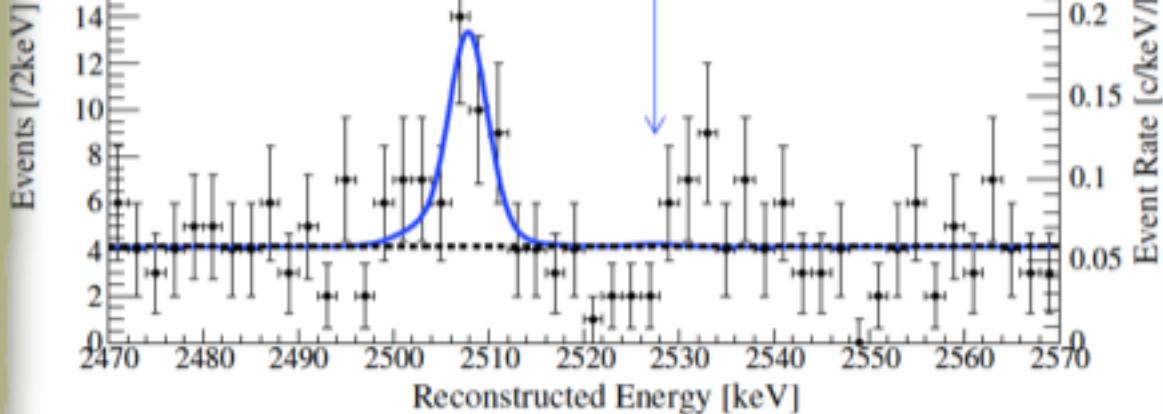
now with a MC extrapolation to CUORE  
it says that the goal of  $B=0.01$  is reachable

# BTW...on the fly



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

9.8 kg·y  $^{130}\text{Te}$

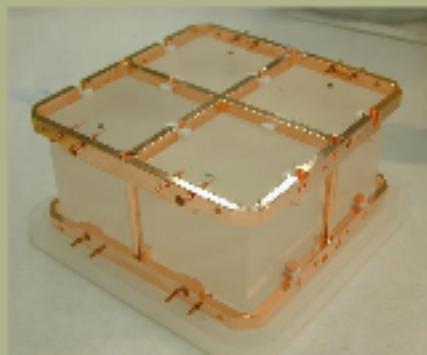


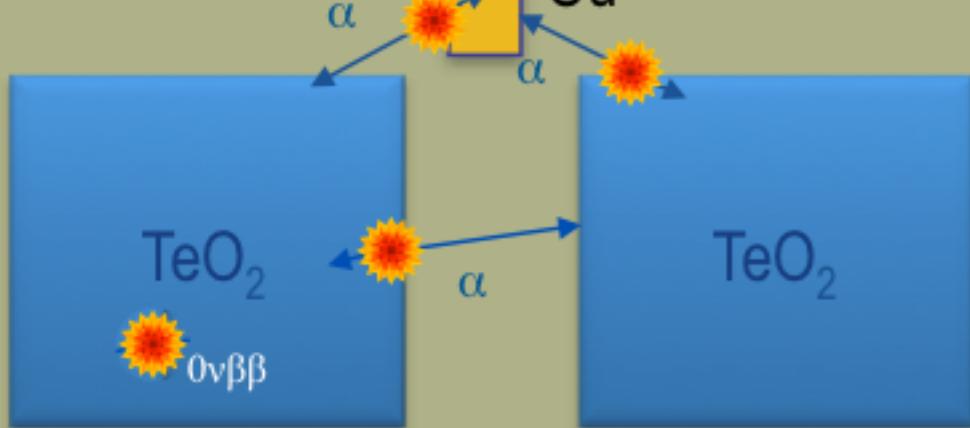
note the same  
Cuoricino limit  
in half time

Combine CUORE-0 and CUORICINO limit

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

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)

## The Problem

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

Sensitivity

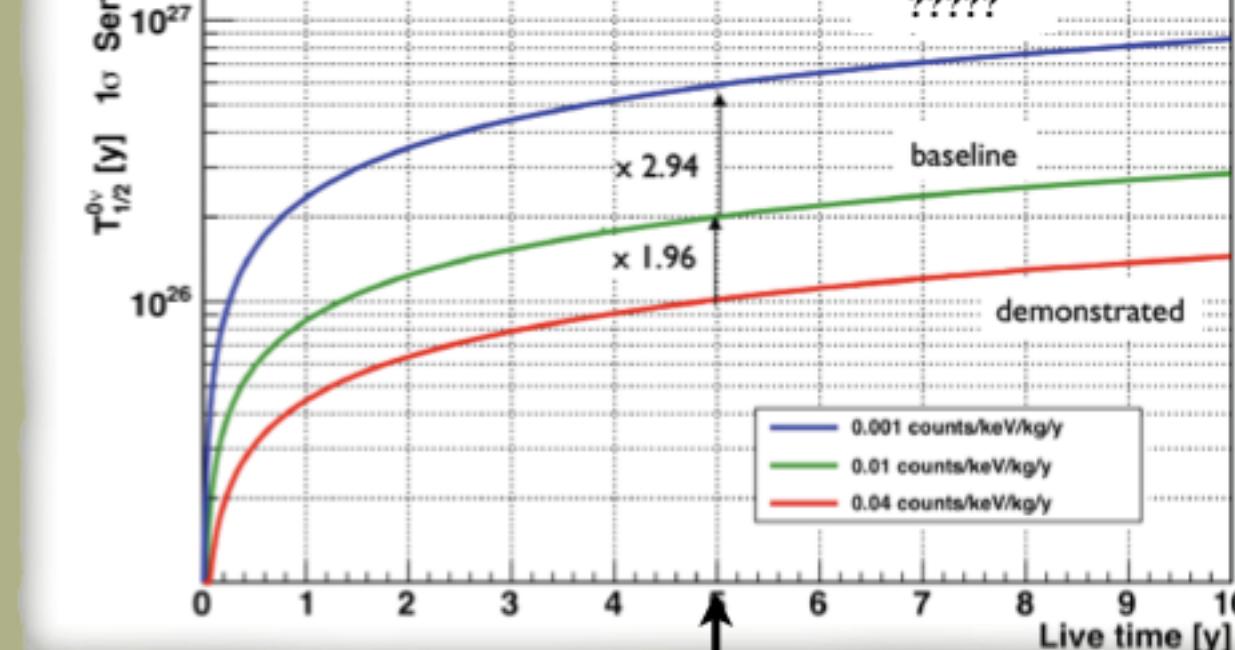


740 Kg

of which

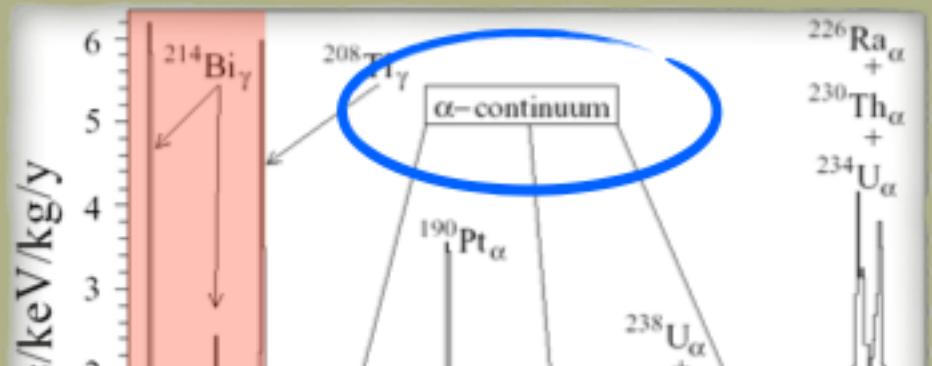
200 Kg

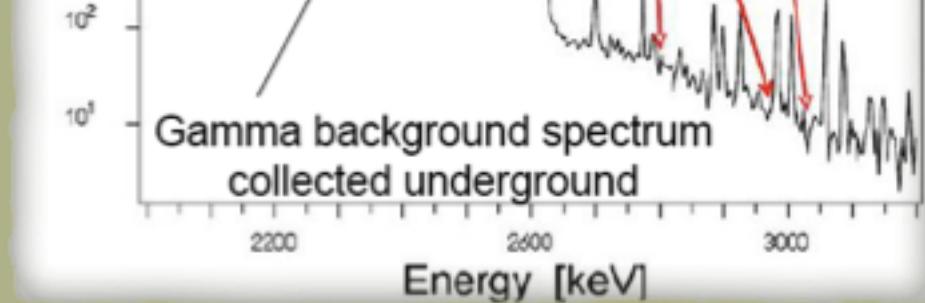
of  $^{130}\text{Te}$



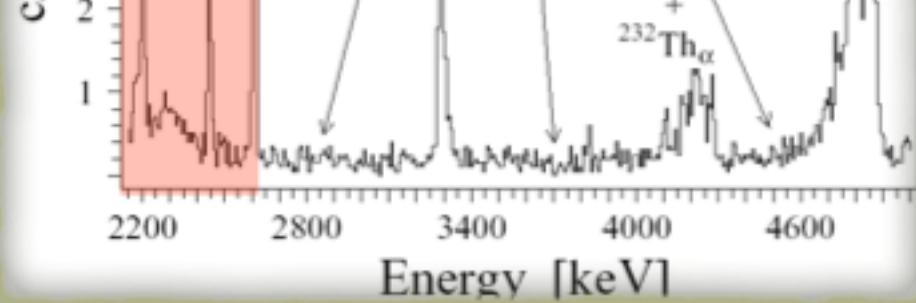
1 ton•y

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*  
from the Latin *lumen*, meaning

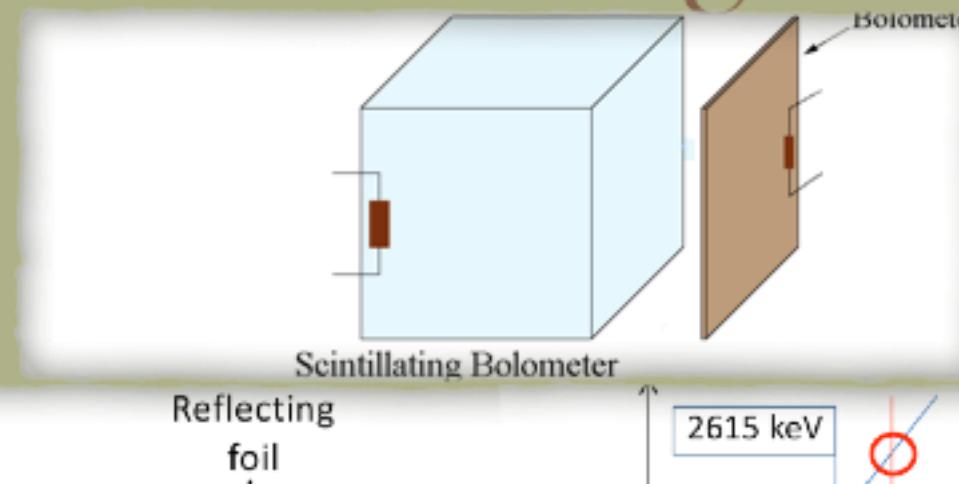
Bringing

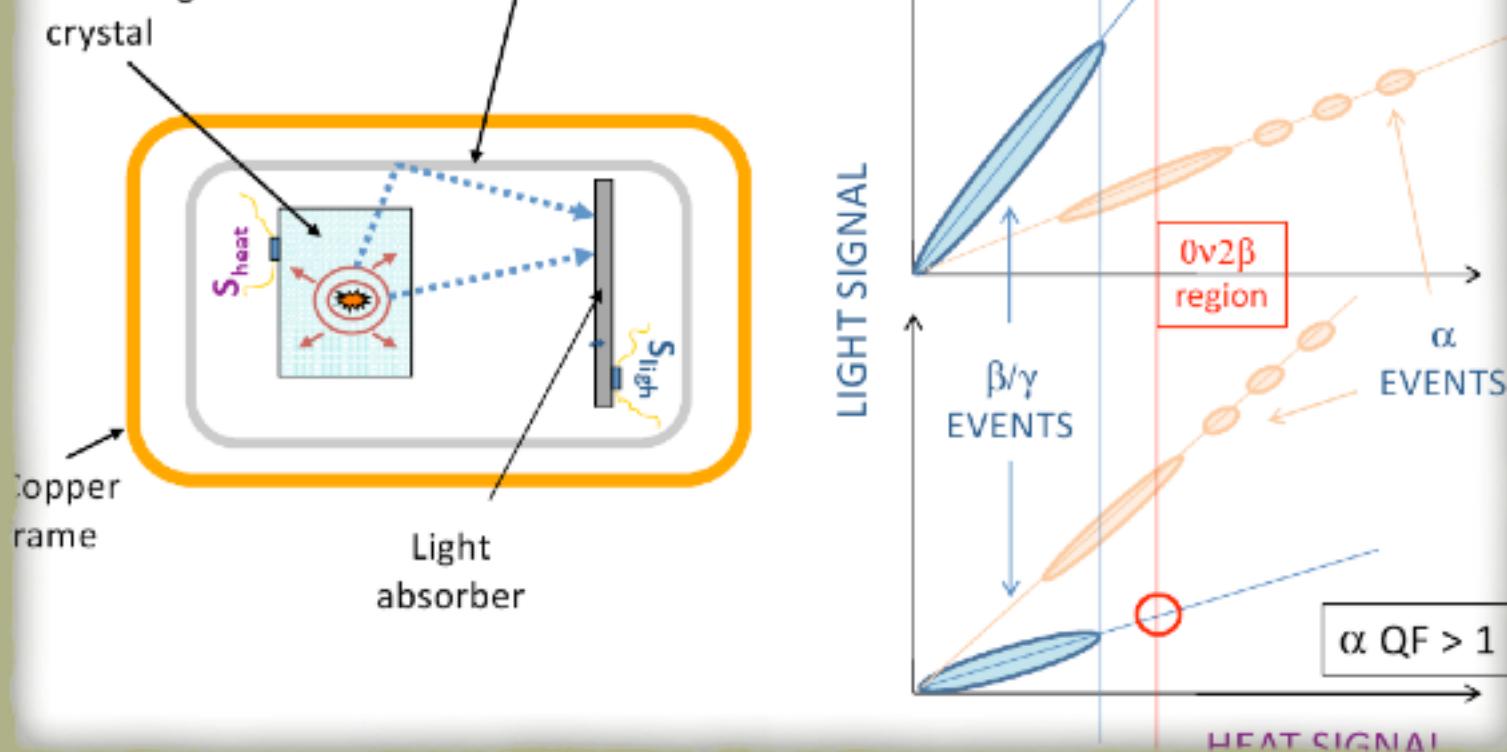
*terre*), literally meaning "light-bearer", which in that language is used as a name for the dawn appearance of the planet Venus, heralding daylight.



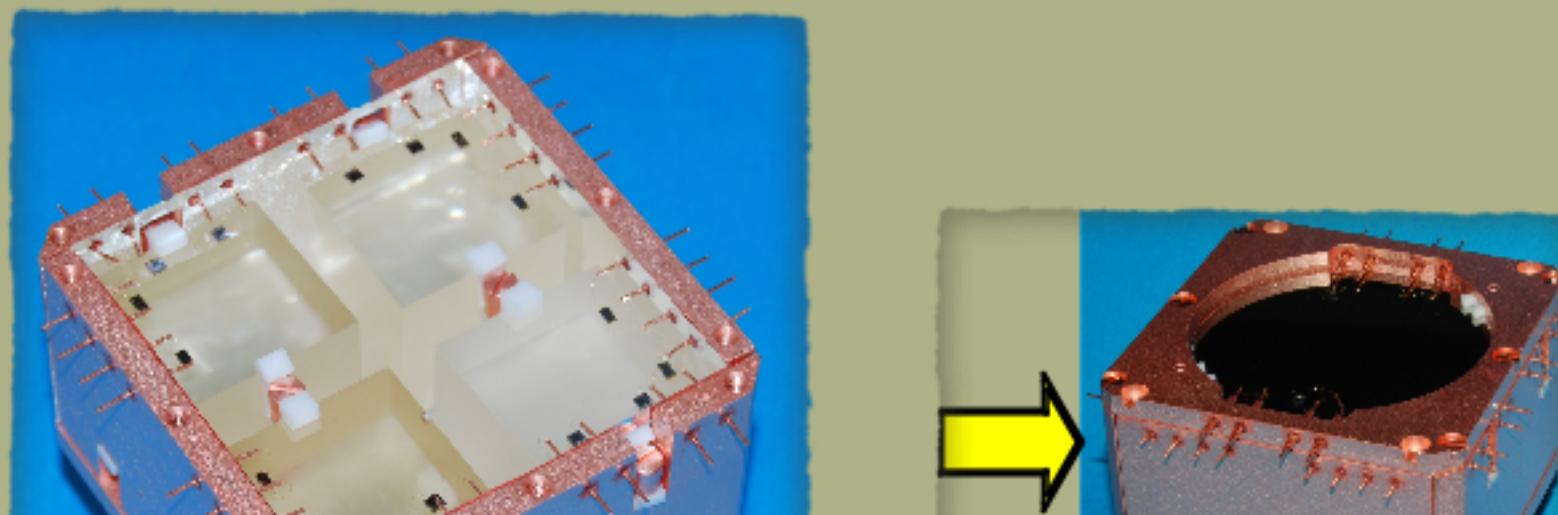
light  
underground

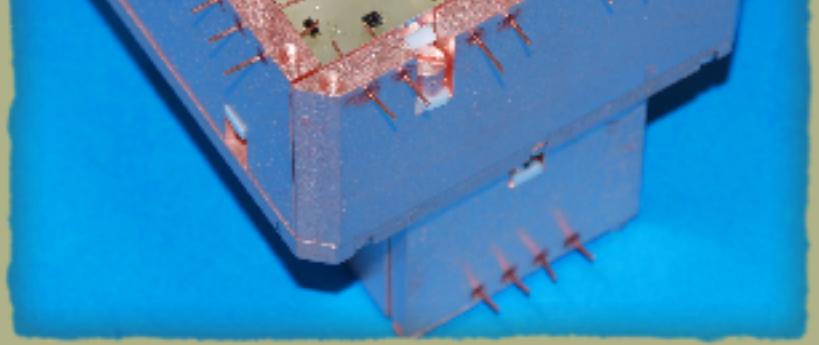
# Heat & Light





# demonstration of the concept

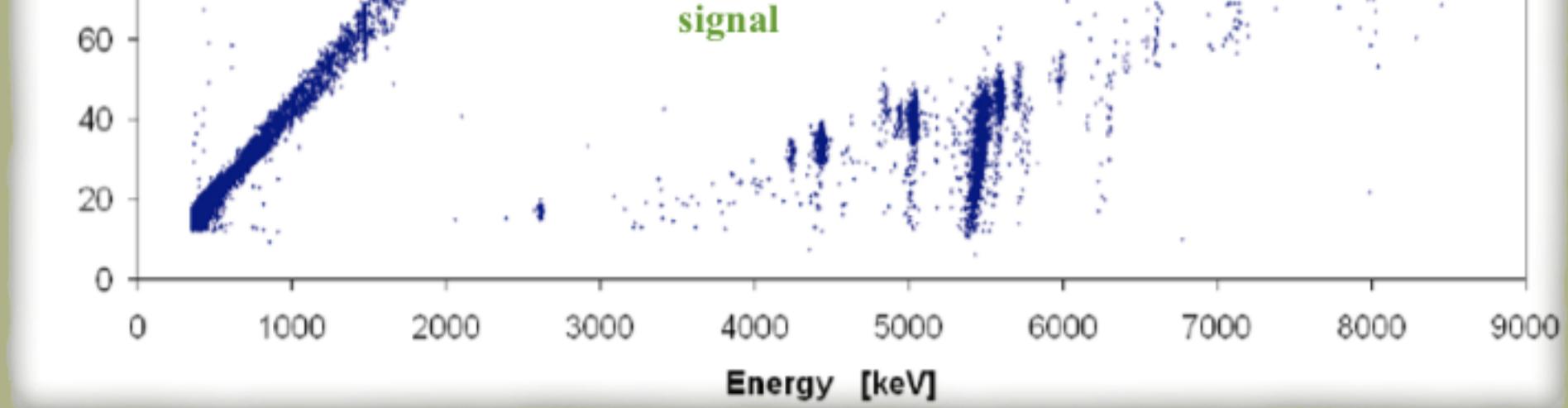




4 CdWO<sub>4</sub> bolometers  
1 Ge Light detector

Roman  
Pb shield

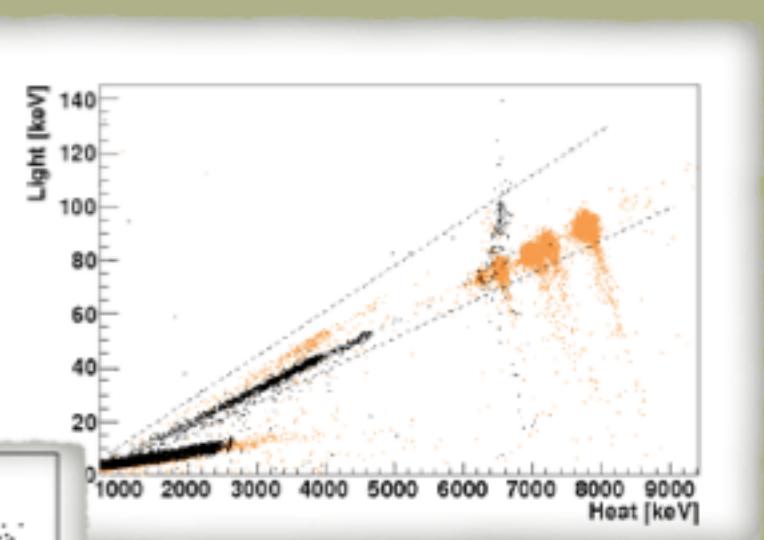
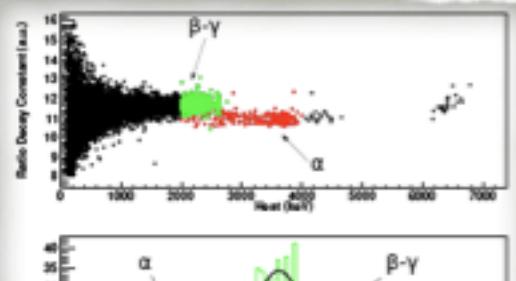


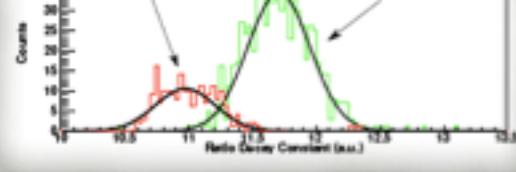
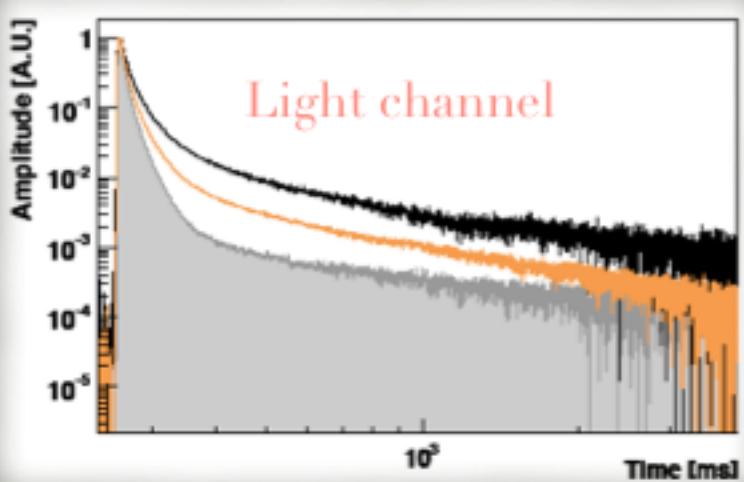


Cadmium makes nice crystals but it is a scary element for an experiment ( $n$  x-section)!

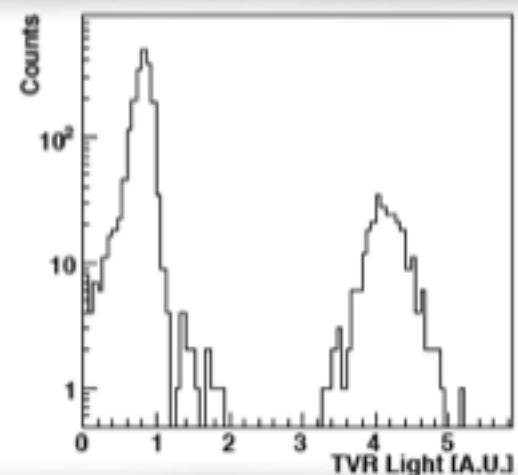
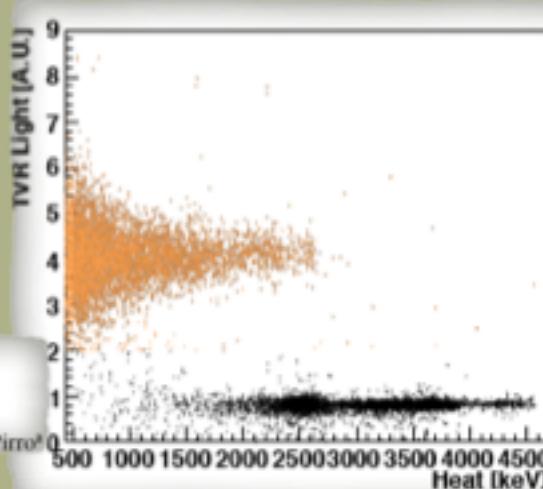


ZnSe





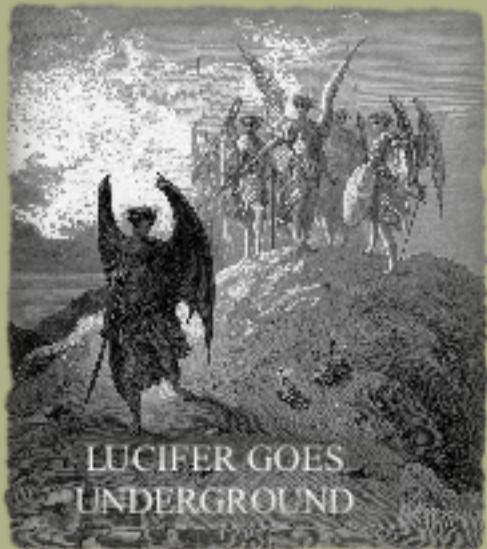
Heat channel



### ZnSe scintillating bolometers for Double Beta Decay

[Astropart.Phys. 34 \(2011\) 344-353](#)

C. Amaboldi<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>



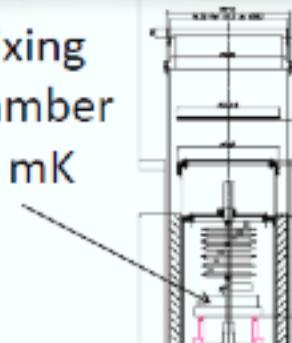
## LUCIFER demonstrator

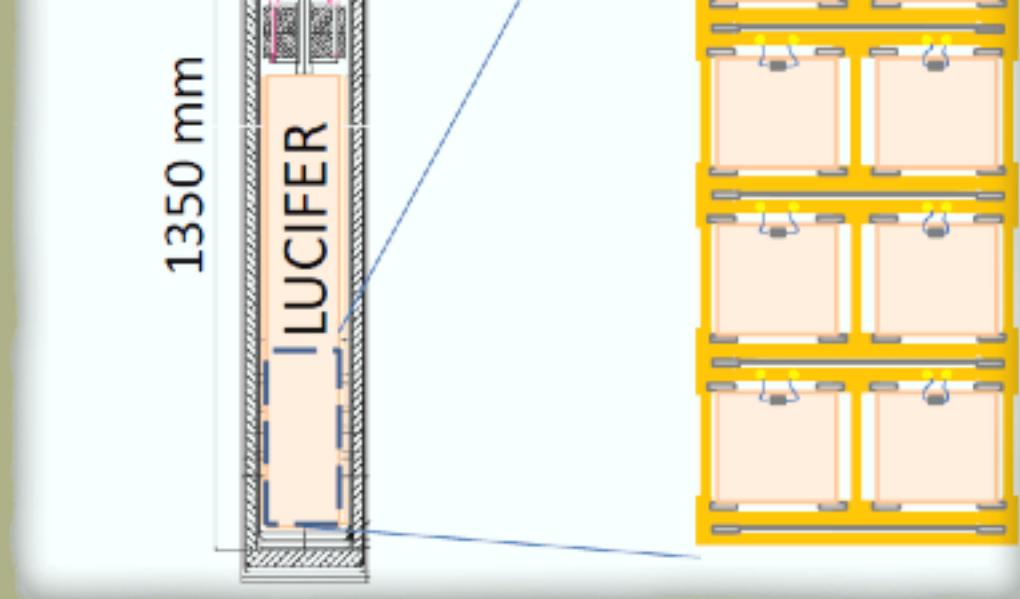
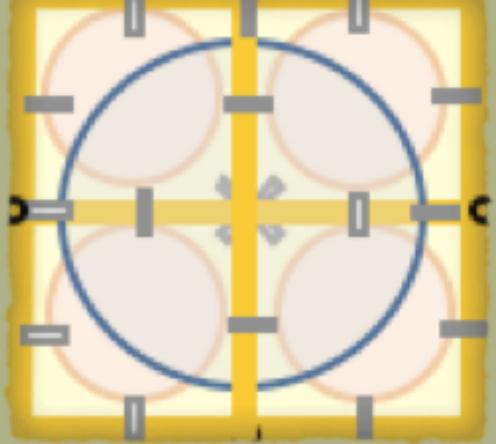
Low-background Underground Cryogenic Installation For Elusive Rates

ERC-2009-AdG 247115

Mixing  
chamber

5 mK





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

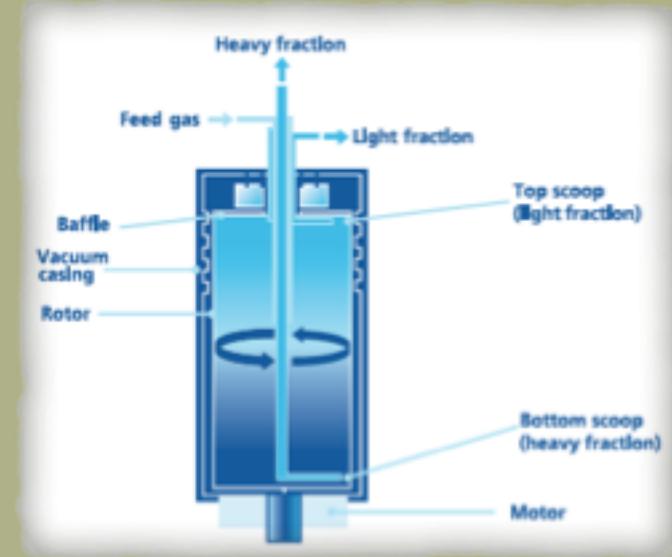
 **Stable Isotopes**

urenc  
**(Almelo, NL)**



an interesting  
cooperation

however,  
it has to be  
known that  
the cost is 75Euro/gram



# crystals production

INSTITUTE FOR SINGLE CRYSTALS NAS of UKRAINE

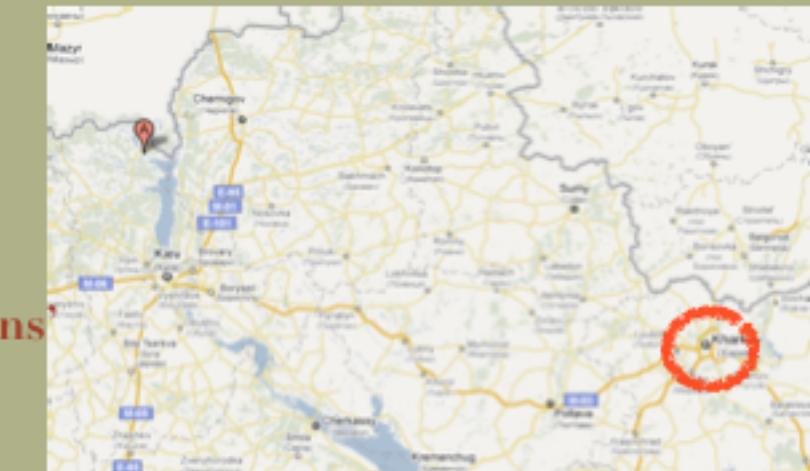
science  
crystals  
progress  
technology

ISC

State Scientific Institution "Institute for Single Crystals" National Academy of Scientists of Ukraine



the ‘political tensions  
made the task  
quite tough

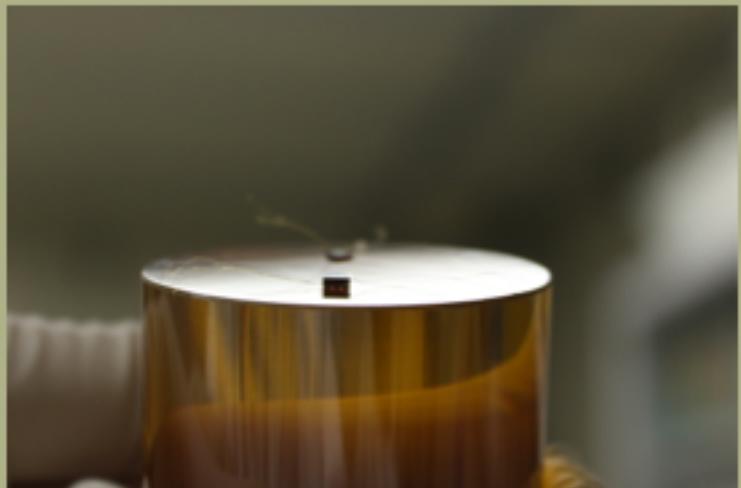


# and the $\text{Zn}^{82}\text{Se}$ crystals





# mounting the experiment



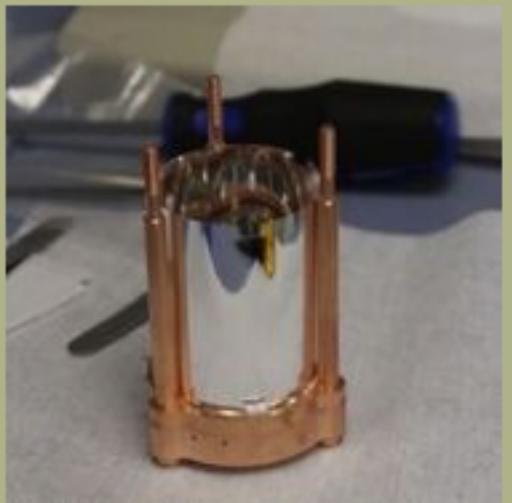
Sensors attached to crystal



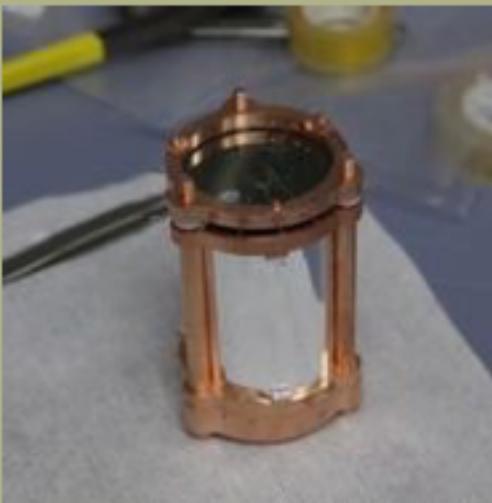
ZnSe assembled in copper frames



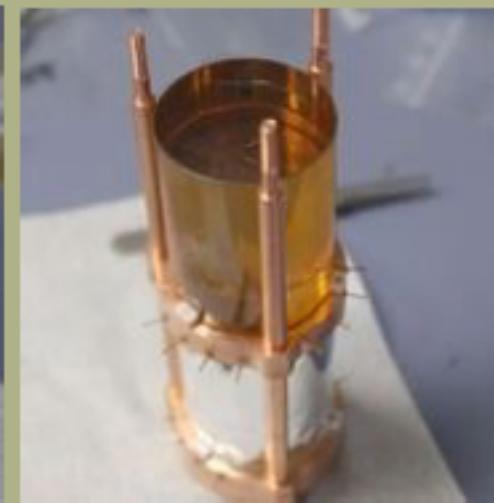
Assembly of light detector



Reflecting foil



Coupling of light detector

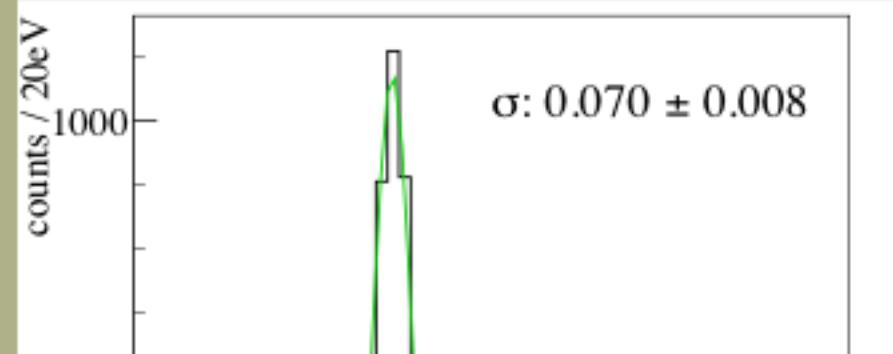
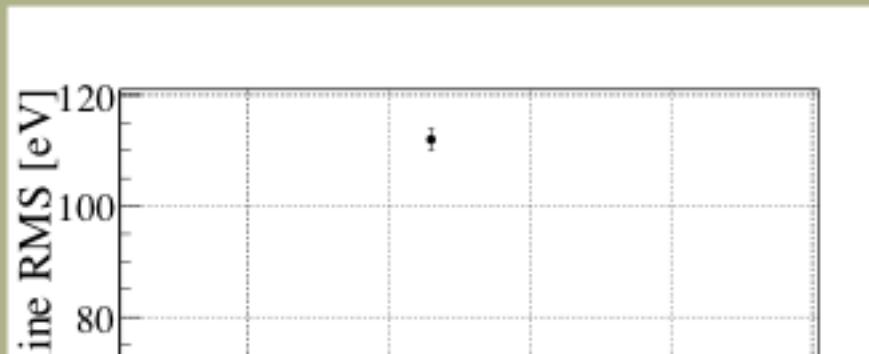


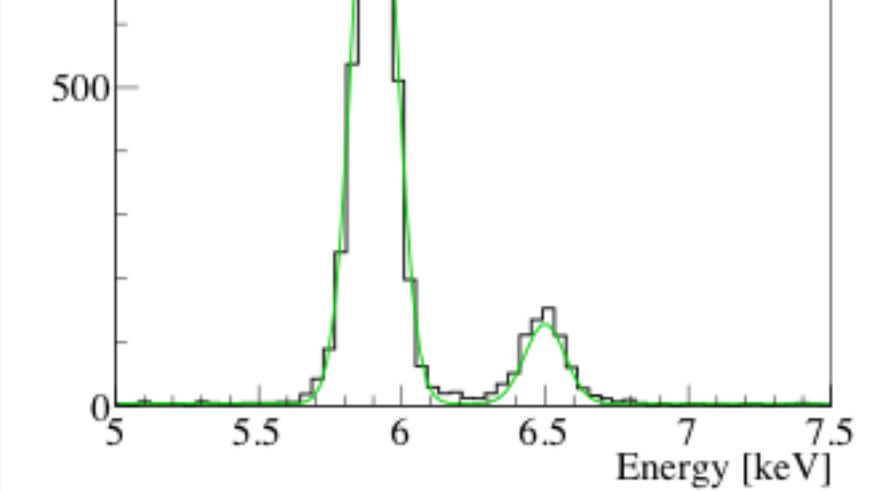
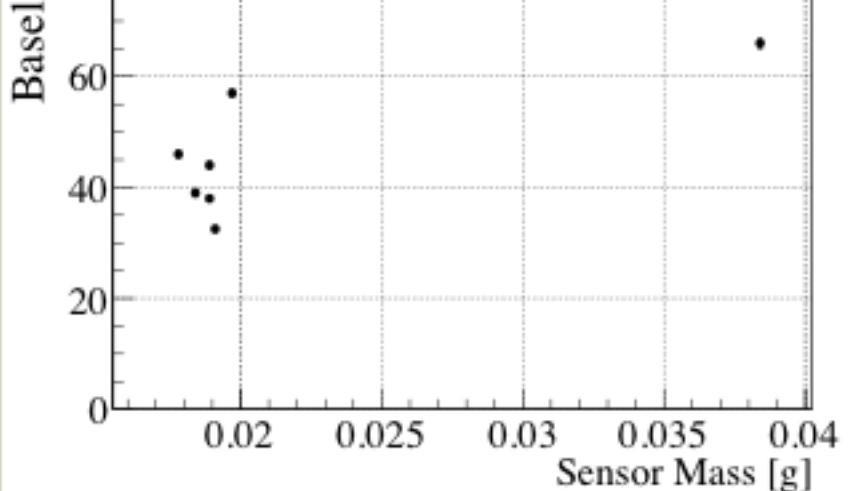
Second ZnSe



Final array

with spectacular L.D.





# the near future

<i>Future</i>	Sensitivity							
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	$S_{0\nu}^{0\nu}$ (90% C. L.) [ $10^{25}$ 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	$0.084 \pm 0.008$	$0.14 \pm 0.01$	$0.41 \pm 0.04$

# the dream

TABLE X. Sensitivity and exposure necessary to discriminate between  $\mathcal{NH}$  and  $\mathcal{IH}$ : the goal is  $m_{\beta\beta} = 8$  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	$S_{0B}^{0\nu}$ [yr]	Exposure (estimate)	
			$M \cdot T$ [ton·yr]	$B \cdot \Delta_{(\text{zero bkg})}$ [counts $\text{kg}^{-1} \text{yr}^{-1}$ ]
more Ge	$^{76}\text{Ge}$	$3.0 \cdot 10^{28}$	5.5	$1.8 \cdot 10^{-4}$

mega Ge	$^{76}\text{Ge}$	$3.0 \cdot 10^{-2}$	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:

<http://arxiv.org/pdf/1601.07512.pdf>

### 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: January 28, 2016)

The discovery of neutrino masses through the observation of oscillations boosted the importance of neutrinoless double beta decay ( $0\nu\beta\beta$ ). In this paper, we review the main features of this process, underlining its key role both from the experimental and theoretical point of view. In particular, we contextualize the  $0\nu\beta\beta$  in the panorama of lepton-number violating processes, also assessing some possible particle physics mechanisms mediating the process. Since the  $0\nu\beta\beta$  existence is correlated with neutrino masses, we also review the state-of-art of the theoretical understanding of neutrino masses. In the final part, the status of current  $0\nu\beta\beta$  experiments is presented and the prospects for the future hunt for  $0\nu\beta\beta$  are discussed. Also, experimental data coming from cosmological surveys are considered and their impact on  $0\nu\beta\beta$  expectations is examined.

# 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

Neutrino-less DBD might possibly be the sole chance to give a measure of neutrino mass

The second generation experiments might not be enough to win.

We have to prepare for third generation. **Toward 0 background.**