

Challenging ν -mass with CUORE



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Outline

- Neutrino today
- Neutrino-less Double Beta Decay
- Experimental status: Cuoricino
- CUORE

Neutrino today

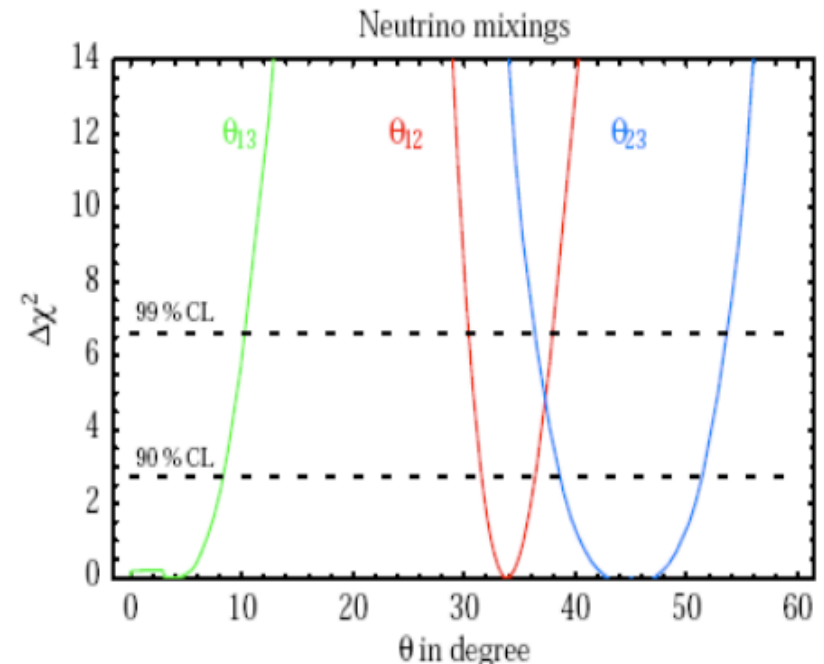
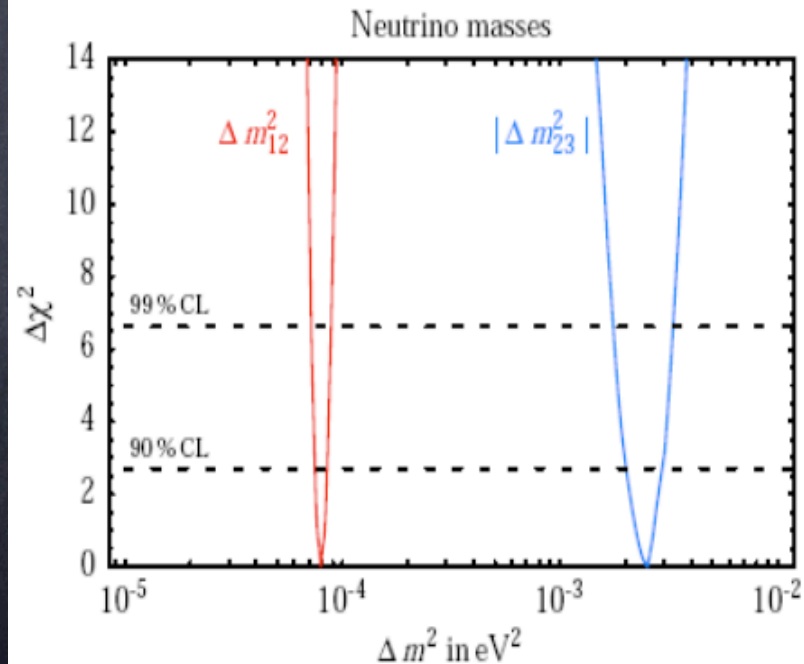
- while Standard Model proved to be able to resist at all attacks in the quark and charged lepton sector
- while waiting for the (so much awaited) fireworks from the LHC
- something new was going on in the neutrino sector

The oscillations

- ❶ Kamiokande serendipitous discovery of atmospheric neutrino oscillations (ν_μ disappearance)
- ❷ The string of solar neutrino experiments (Homestake, Gallex-Sage-GNO, SuperK, SNO, Kamland) that confirmed Standard **Solar** Model and proved solar neutrino oscillations (ν_e disappearance)

Our knowledge as of today

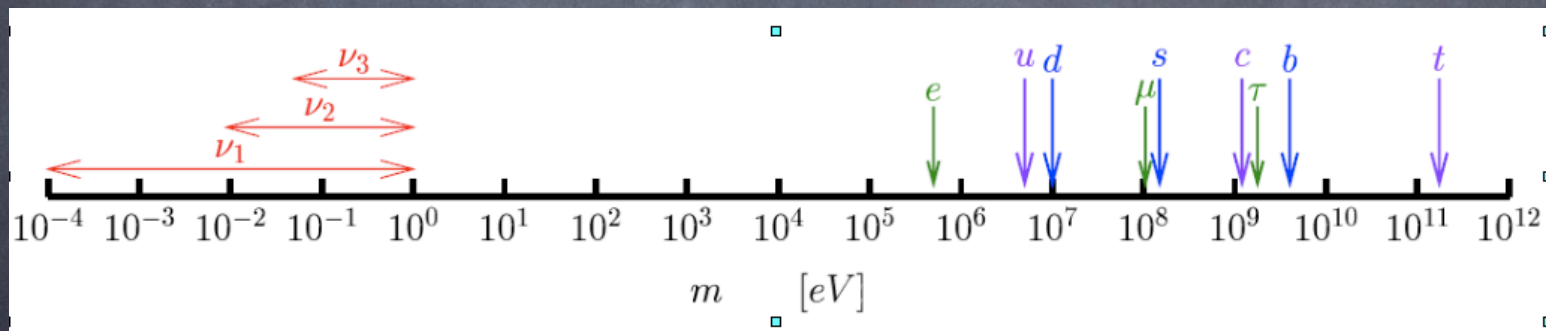
solar mass splitting	$\Delta m_{12}^2 = (8.0 \pm 0.3) 10^{-5} \text{eV}^2$	$(7.2 \div 8.9) 10^{-5} \text{eV}^2$
atmospheric mass splitting	$ \Delta m_{23}^2 = (2.5 \pm 0.3) 10^{-3} \text{eV}^2$	$(1.7 \div 3.3) 10^{-3} \text{eV}^2$
solar mixing angle	$\tan^2 \theta_{12} = 0.45 \pm 0.05$	$30^\circ < \theta_{12} < 38^\circ$
atmospheric mixing angle	$\sin^2 2\theta_{23} = 1.02 \pm 0.04$	$36^\circ < \theta_{23} < 54^\circ$
'CHOOZ' mixing angle	$\sin^2 2\theta_{13} = 0 \pm 0.05$	$\theta_{13} < 10^\circ$



It looks very much familiar

$$U = \begin{array}{c} \text{Atmospheric} \\ \left[\begin{array}{ccc} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{array} \right] \end{array} \begin{array}{c} \text{Cross-Mixing} \\ \left[\begin{array}{ccc} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{array} \right] \end{array} \begin{array}{c} \text{Solar} \\ \left[\begin{array}{ccc} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{array} \right] \end{array}$$

except that



and

$$V_{\text{CKM}} = \begin{pmatrix} \blacksquare & \blacksquare & \cdot \\ \blacksquare & \blacksquare & \blacksquare \\ \cdot & \blacksquare & \blacksquare \end{pmatrix}$$

V_{PMNS}



one elegant explanation (beyond the SM)

Mass Term $\frac{1}{2} \begin{bmatrix} \nu_L & (\nu_R)^c \end{bmatrix} C \begin{pmatrix} M_{M,L} & m_D \\ m_D & M_{M,R} \end{pmatrix} \begin{bmatrix} \nu_L \\ (\nu_R)^c \end{bmatrix} + h.c.$

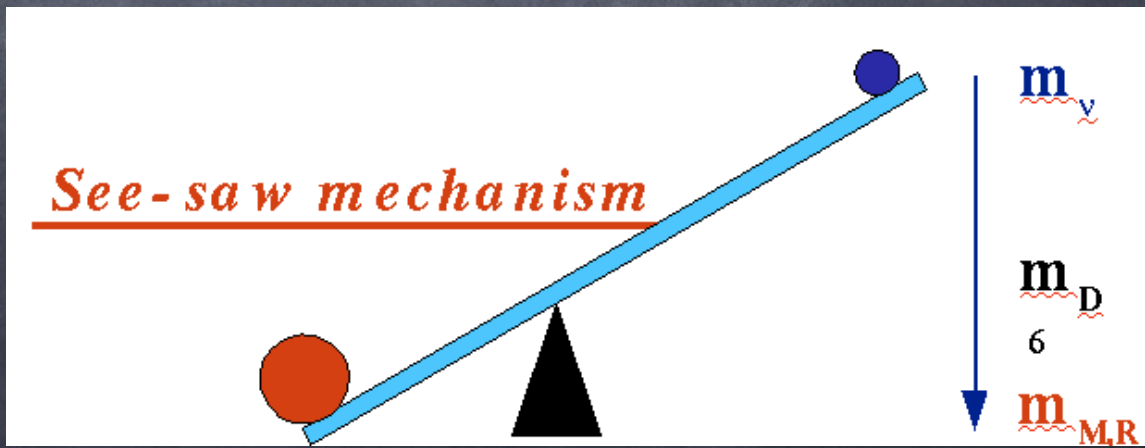
where $M_{M,L} \sim 0$ (Higgs Triplet)

$M_D \sim M_{EW} \sim 100 \text{ GeV}$

$M_{M,R} \sim \text{Gauge singlet unprotected} \sim M_{GUT}$

$$m_N \simeq M_{M,R}$$

$$m_\nu \simeq \frac{m_D^2}{M_{M,R}}$$



the Majorana conjecture



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

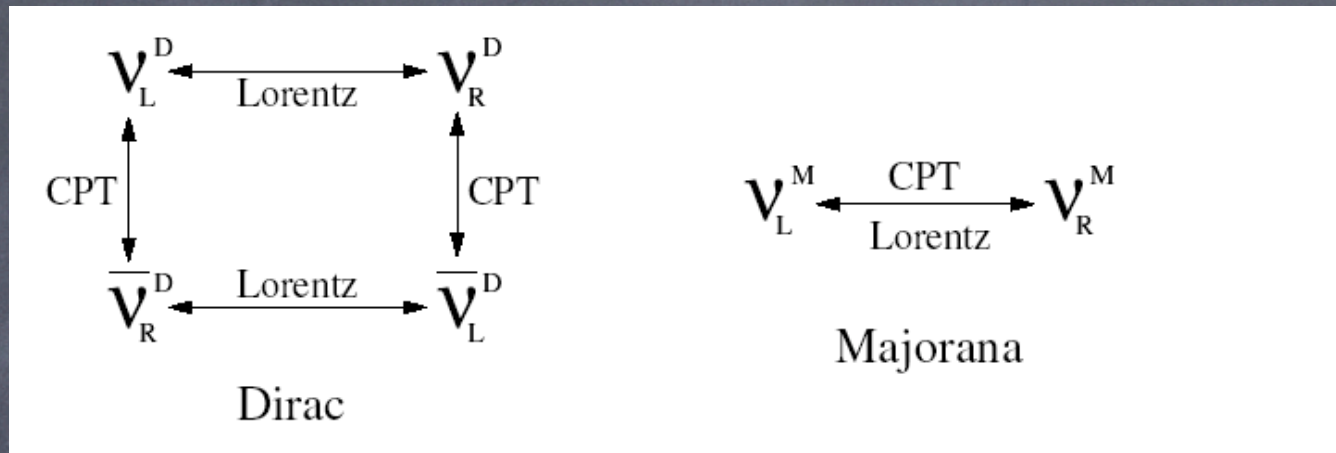
Practical consequence :

Lepton Number Violation

Caveat: massless neutrinos do not
allow testing of the Majorana nature

Indeed nobody paid 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 ($0\nu\beta\beta$)

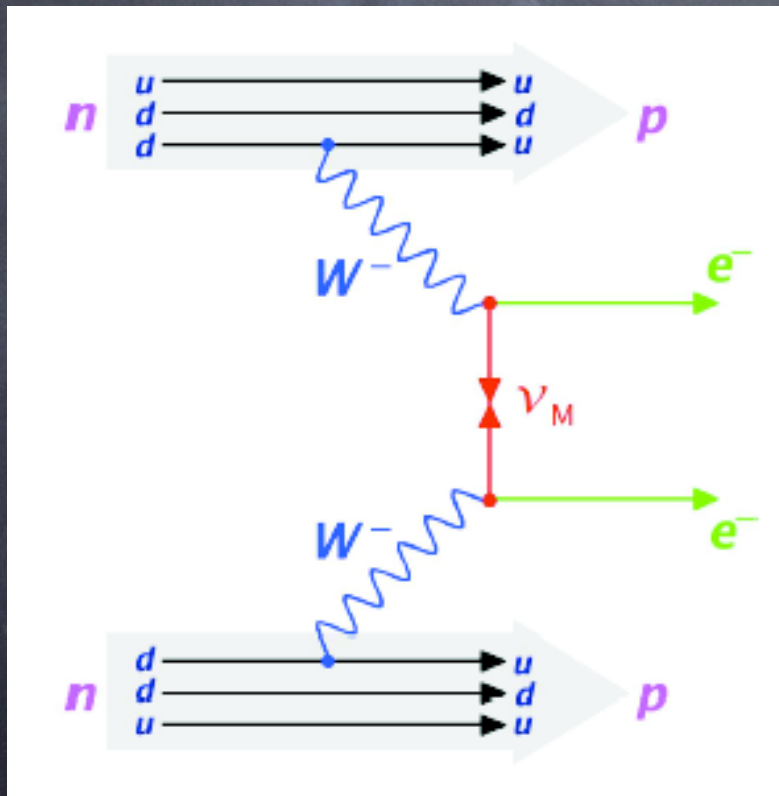
Only if:

Majorana Neutrinos

Massive Neutrinos

If observed:

Proof of the Majorana
nature of Neutrino



Does it also measure the mass ?

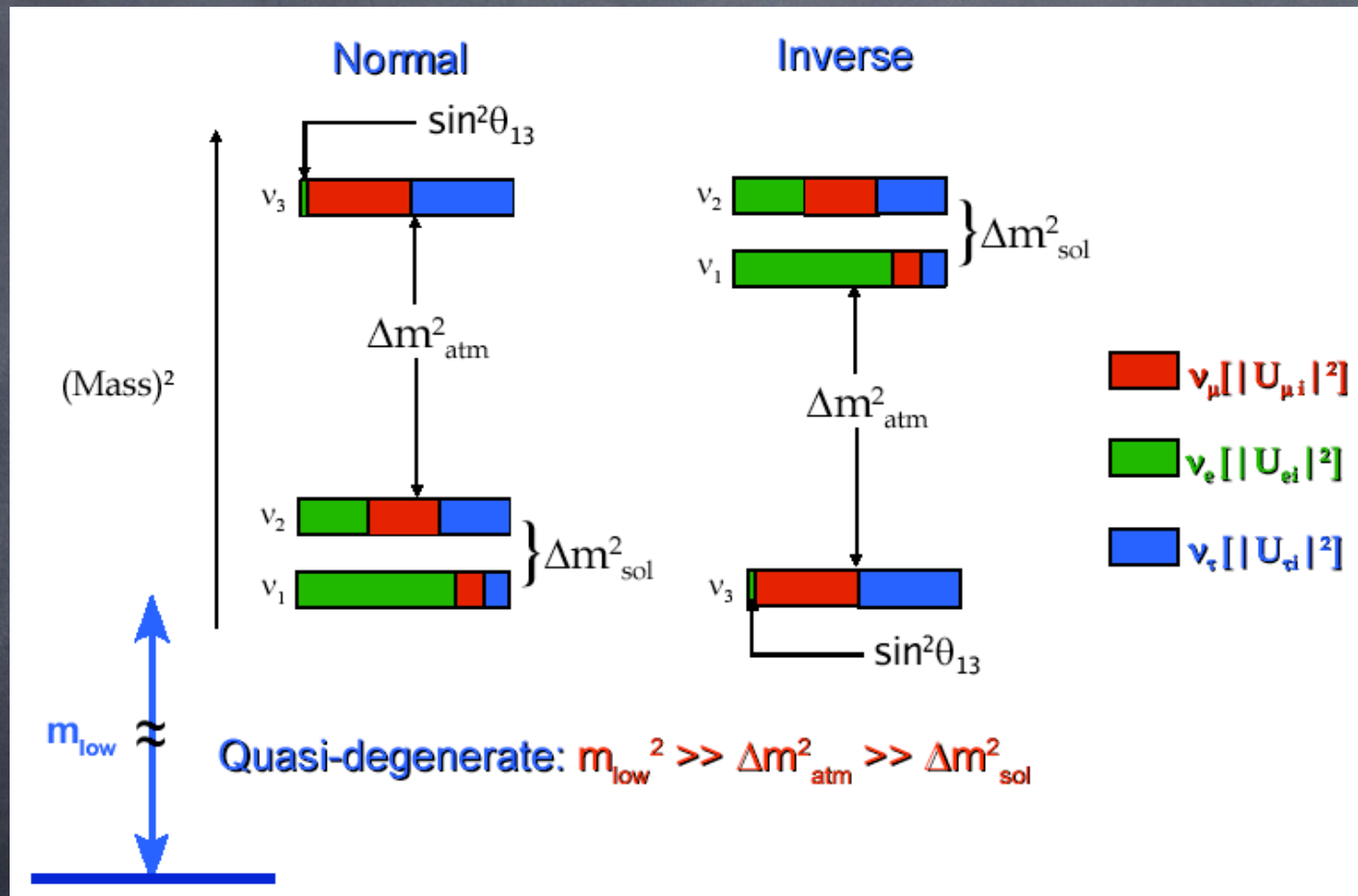
$$m_{\beta\beta} = \sum m_{\nu_k} U_{ek}^2 = \cos^2 \theta_{13} (m_1 \cos^2 \theta_{12} + m_2 e^{2i\alpha} \sin^2 \theta_{12}) + m_3 e^{2i\beta} \sin^2 \theta_{13}$$

well...not so straight. It comes as a combination of the three neutrino masses, the mixing angles and the Majorana phases.

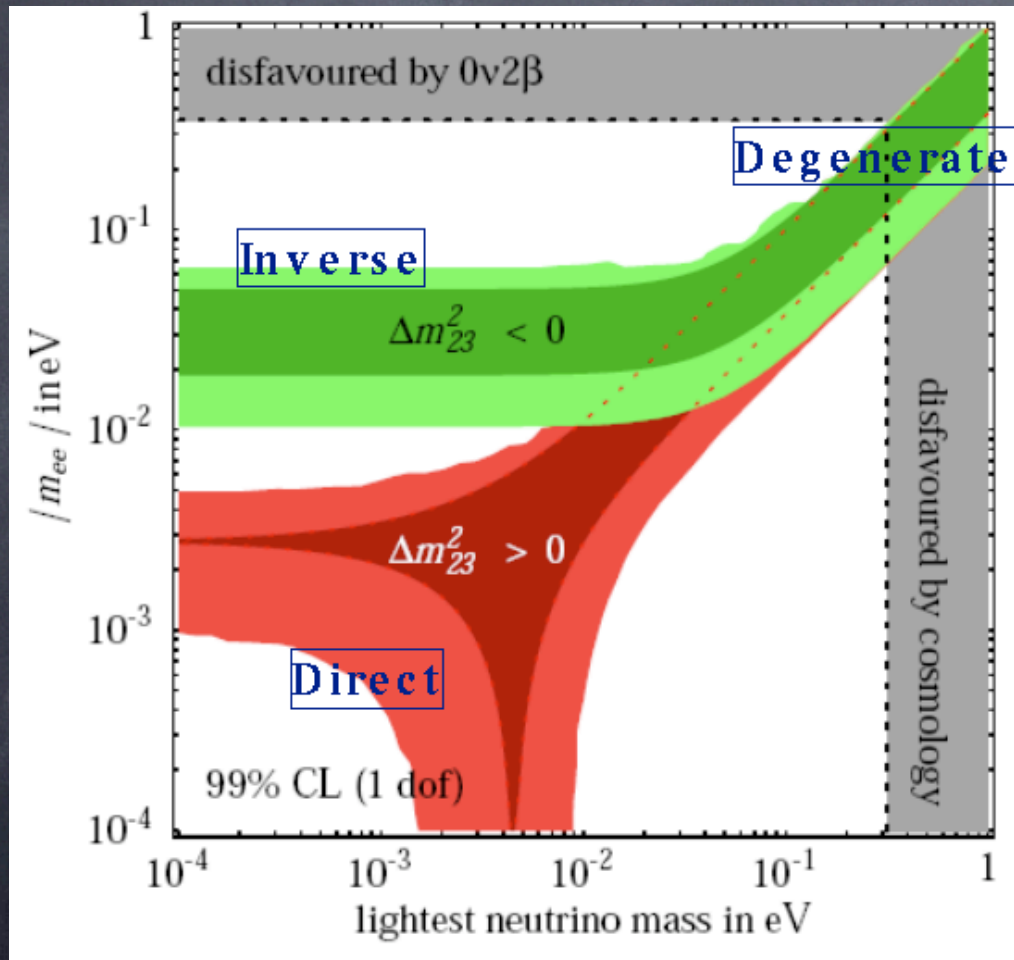
Exercise: parameterize as a function of the known parameters:

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

Three possibilities:



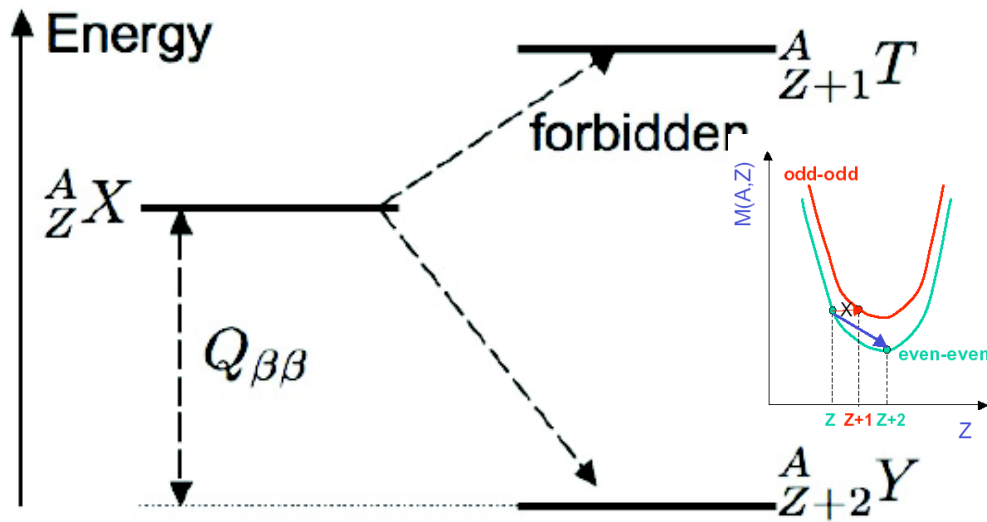
that translates in a nice plot



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

We take a detour, in order to answer this question. Be patient !

Double Beta Decay



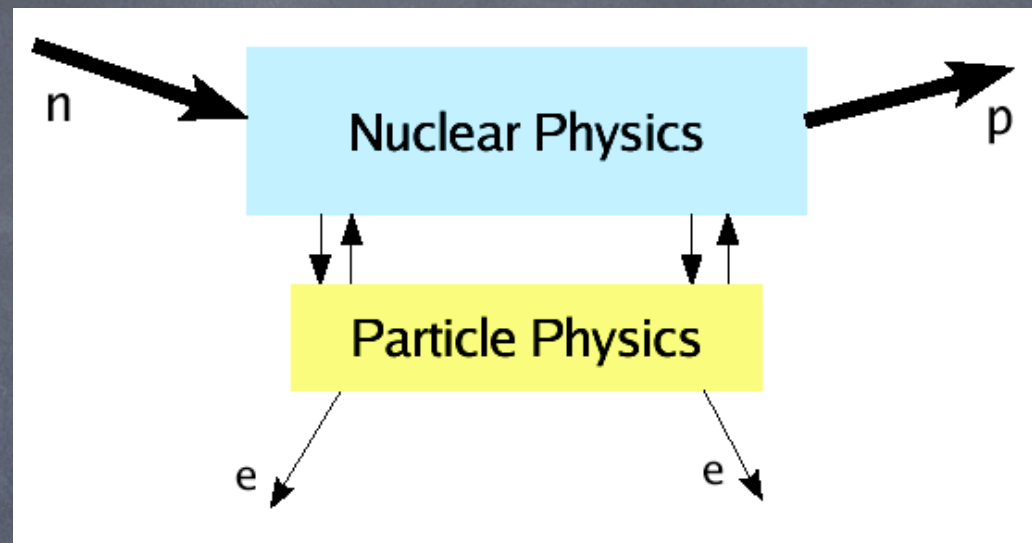
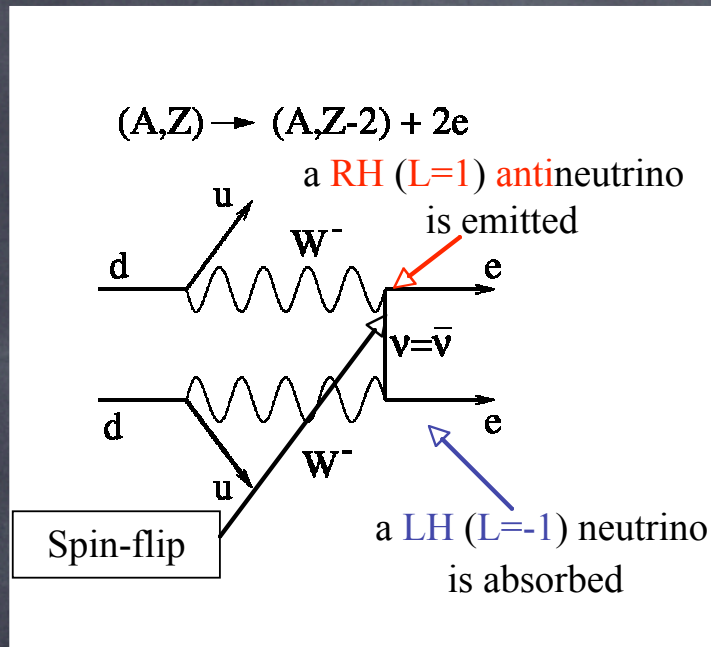
Predicted by Maria Goeppert-Mayer in 1935

Geochemical evidence followed by direct observation of DBD in ${}^{82}\text{Se}$ (S. Elliot & M. Moe 1986)

$T_{1/2} \sim 10^{20}$ years !!

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
${}^{130}\text{Te}$	2.530	33.9
${}^{136}\text{Xe}$	2.479	8.9
${}^{150}\text{Nd}$	3.367	5.6

The elements of the game



$0\nu\text{-DBD rate}$

Phase space $\propto Q^5$

Nuclear matrix element

Effective neutrino mass

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

The killer element shall have:

- A large Q

- because rate $\propto Q^5$

- because the natural γ -lines end around 2.6 MeV (^{208}Tl from ^{232}Th)

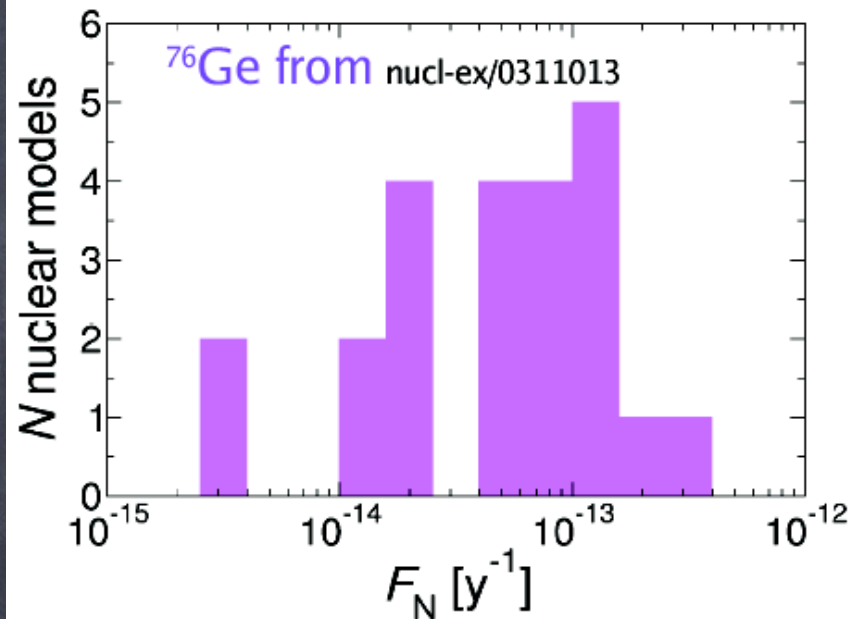
- A large Matrix Element

- A large isotopic abundance

Of course the element by far best in Q is also the one worst of all for isotopic abundance (^{48}Ca)

One factor is rather messy

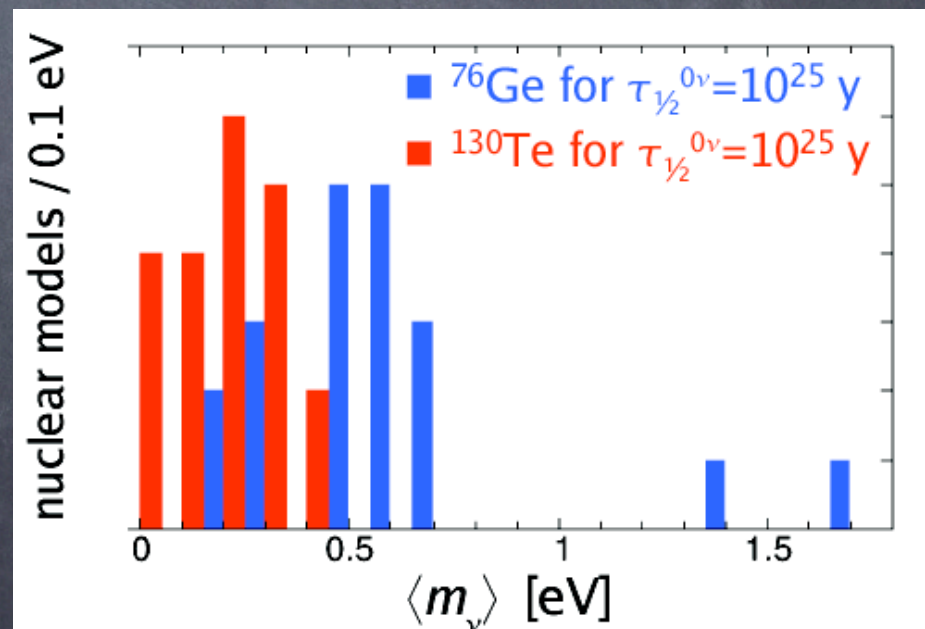
Nuclear Matrix Elements (NME)



large uncertainties in NME calculation

about factor of 100 in F_N
of the order of 2-3 in $|\langle m_\nu \rangle|$

It will not prevent to assert
the Majorana nature of
neutrino but it will leave a
big uncertainty in the mass



The OofM of the results

Isotope	[22]	[23]	[24]	[2]	[25]	[26]
^{48}Ca	8.83	-	-	-	2.5	-
^{76}Ge	17.7	14.0	2.33	6.0	3.6	3.7
^{82}Se	2.4	5.6	0.6	1.8	1.5	0.81
^{100}Mo	-	1.0	1.28	3.5	3.9	0.65
^{116}Cd	-	-	0.48	2.4	4.7	0.39
^{130}Te	5.8	0.7	0.5	3.0	0.85	0.52
^{136}Xe	12.1	3.3	2.2	7.3	1.8	0.27
^{150}Nd	-	-	0.025	> 0.3	-	-

OvDBD half-lives in units of 10^{28} years calculated with different nuclear prescriptions for $\langle m_\nu \rangle = 10 \text{ meV}$

The name of the game: sensitivity

$$S_{n\sigma}^{0\nu} \propto \frac{a}{A} \left[\frac{M T}{b \Delta E} \right]^{1/2} \times \epsilon$$

Isotopic abundance (points to a)
 Mass(Kg) (points to M)
 Time (y) (points to T)
 efficiency (points to ϵ)
 Atomic Mass (points to A)
 background (counts/keV/Kg/y) (points to b)
 Energy Resolution (KeV) (points to ΔE)

Sensitivity: half life corresponding to the minimal number of detectable events above background, for a given C.L

Tough life for doing an expt

$$m_{\beta\beta} \propto \left(\frac{1}{\tau_{1/2}^{0\nu}} \right)^{1/2}$$

$$m_{\beta\beta} \propto \frac{1}{(a \cdot \epsilon \cdot G)^{1/2} \cdot |M_{nuc}|} \cdot \left(\frac{b \cdot \Delta E}{M \cdot T} \right)^{1/4}$$

Patience is not enough, a factor 2 improvement would cost 625 years of your life (well, if it were mine I would accept !) (after the first 5)

- If you want to get to 10^{28} years half-life with 3 events in a Zero Background experiment you would need $N \cdot \beta\beta \sim 10^{28} / \ln 2$ $\beta\beta$ nuclei $\sim 24 \cdot 10^3$ moles that makes O(1 Ton)
- Brute force does not bring you far. A factor 10 gain in neutrino mass scale (inverted to normal hierarchy) would call for 100 ideal Tons. Realistically the Eiffel Tower.
- Better to play with isotopical abundance. Ge has 8%. If you go to 90% you gain as $(90/10)^2 = 81$. One Ton indeed becomes 100 !!!!! Te, that has already the best natural ratio still would allow for $(90/30)^2 = 9$. Indeed practical, however not cheap.

What about ΔE ?

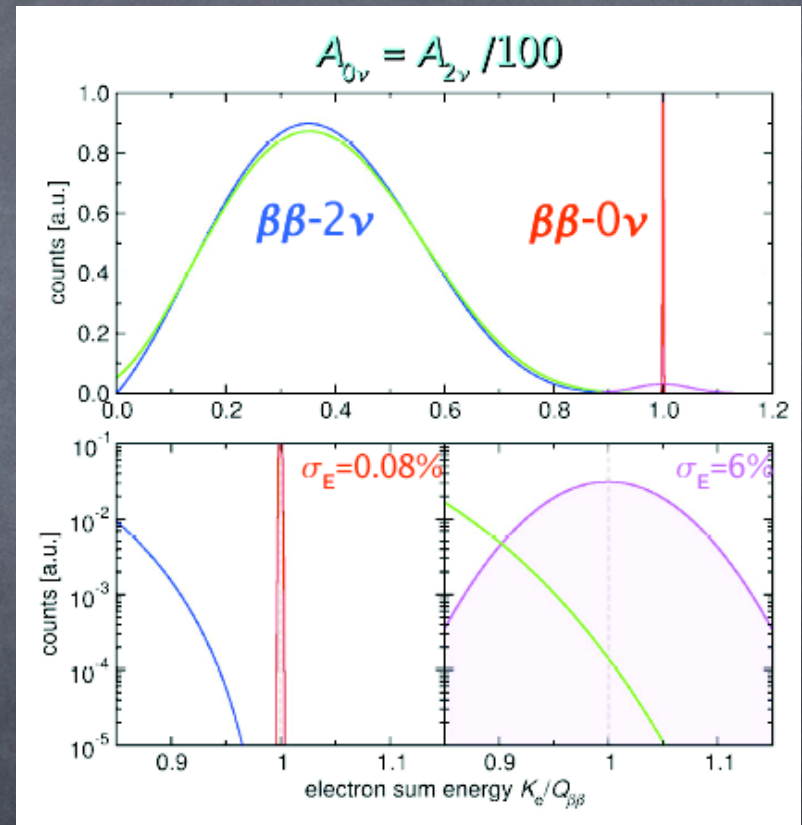
- reducible background will accumulate proportionally to the window dictated by the energy resolution. You can always hope to reduce the background and alleviate the problem
- irreducible background however cannot be reduced !!
The 2ν DBD tail will always be there

On the back of the envelope

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

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

Please note δ^6



$$T^{0\nu} \simeq 10^{28}y \quad S/B = 1$$

$$T^{2\nu} \simeq 10^{20}y \quad Q \simeq 3\text{MeV}$$



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

The less noble background

👁 Internal to source

- 👁 primordial (^{232}Th , ^{238}U , ^{40}K)
- 👁 cosmogenic activation

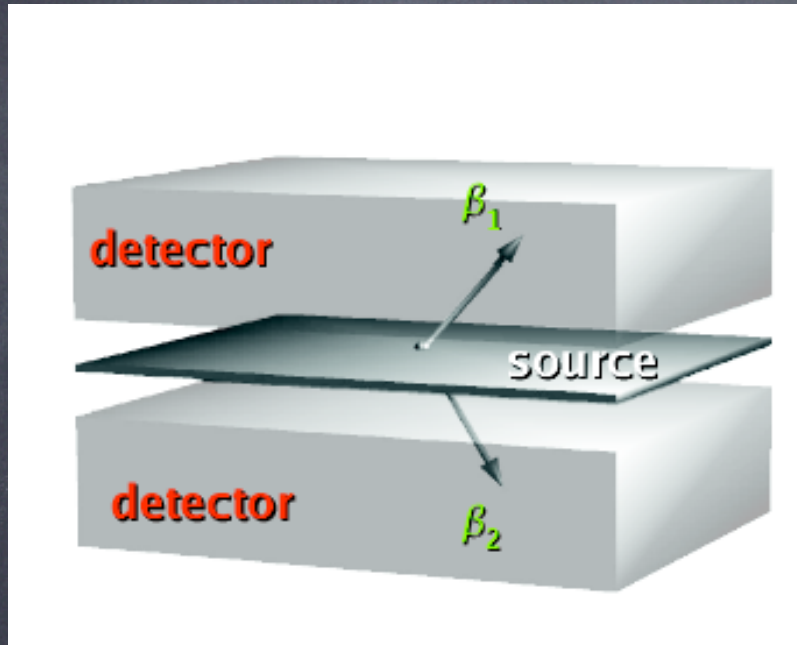
👁 External to source

- 👁 primordial in external materials
- 👁 neutrons
- 👁 cosmic rays

👁 Detector specific

Two techniques (and a few variations)

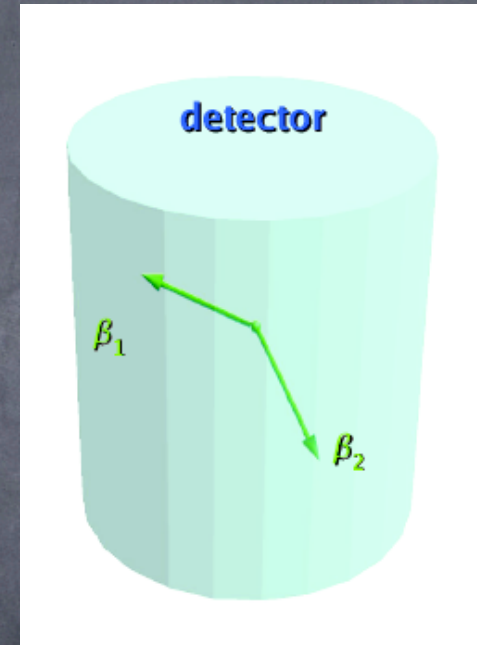
Source $\neq$ Detector



+++ Topology, Background

--- M , ΔE , ϵ

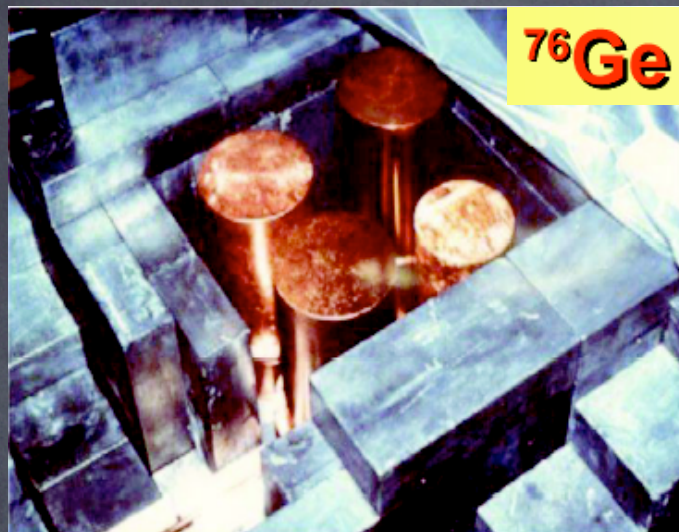
Source $\subseteq$ Detector



+++ M , ΔE , ϵ

--- Topology, Background

Heidelberg-Moscow / Klapdor et al.



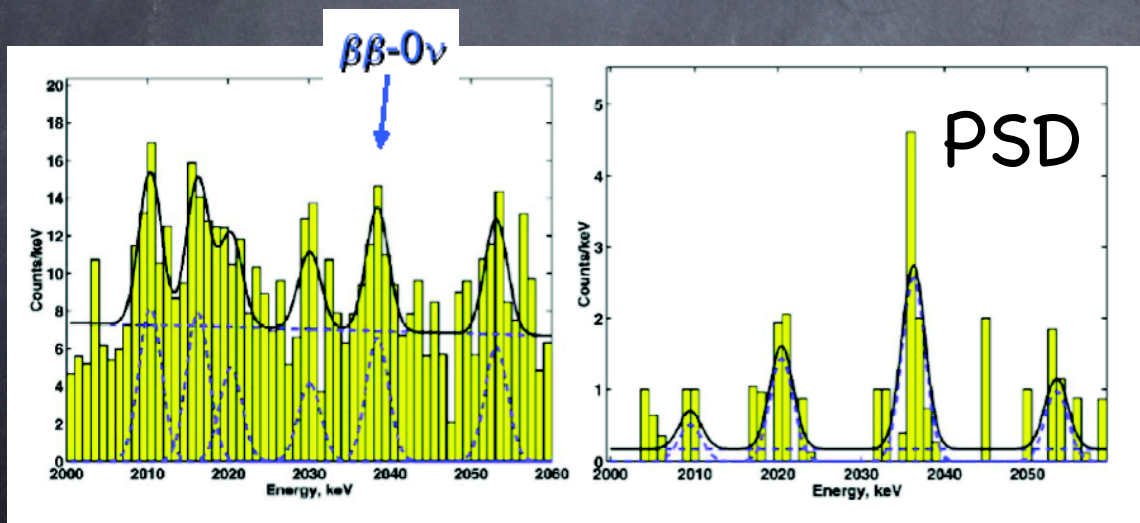
5 HP-Ge crystals, enriched to 87%

1990 – 2001 data

exposure = 35.5 kg×y SSD

$$\tau_{1/2}^{0\nu} > 1.9 \times 10^{25} \text{ years}$$

$$\langle m_\nu \rangle < 0.35 \text{ eV (0.3 – 1.24 eV)}$$



1990 – 2003 data, all 5 detectors

exposure = 71.7 kg×y

$$\tau_{1/2}^{0\nu} = 1.2 \times 10^{25} \text{ years}$$

$$\langle m_\nu \rangle = 0.44 \text{ eV}$$

The pioneering experiments

- positive result
- running experiments

isotope	experiment	latest result	i.a. [%]	$Q_{\beta\beta}$ [eV]	enrich [%]	exp [kg×y]	tech	material	$\tau_{1/2}^{0\nu}$ [10 ²³ y]	$\langle m_\nu \rangle$ [eV]
										min max
⁴⁸ Ca	Elegant VI	2004	0.19	4271	-	4.2	s	CaF ₂	0.14	7.20 44.70
⁷⁶ Ge	Heidelberg/Moscow	2001	7.8	2039	87	71.7	i	Ge	190.0	0.12 1.00
⁷⁶ Ge	Klapdor et al.	2004	7.8	2039	87	71.7	i	Ge	120.0	0.44 -
⁸² Se	NEMO-3	2005	9.2	2995	97	0.93	t	Se	1.0	1.75 4.86
¹⁰⁰ Mo	NEMO-3	2005	9.6	3034	95-99	6.9	t	Mo	4.6	0.66 2.81
¹¹⁶ Cd	Solotvina	2003	7.5	3034	83	0.5	s	CdWO ₄	1.7	1.70 -
¹³⁰ Te	Cuoricino	2005	33.8	2529	-	5	b	TeO ₂	18.0	0.20 1.10
¹³⁶ Xe	DAMA	2002	8.9	2476	69	4.5	s	Xe	12.00	1.10 2.90
¹⁵⁰ Nd	Irvine TPC	1997	5.6	3367	91	0.01	t	Nd ₂ O ₃	0.012	3.00 -

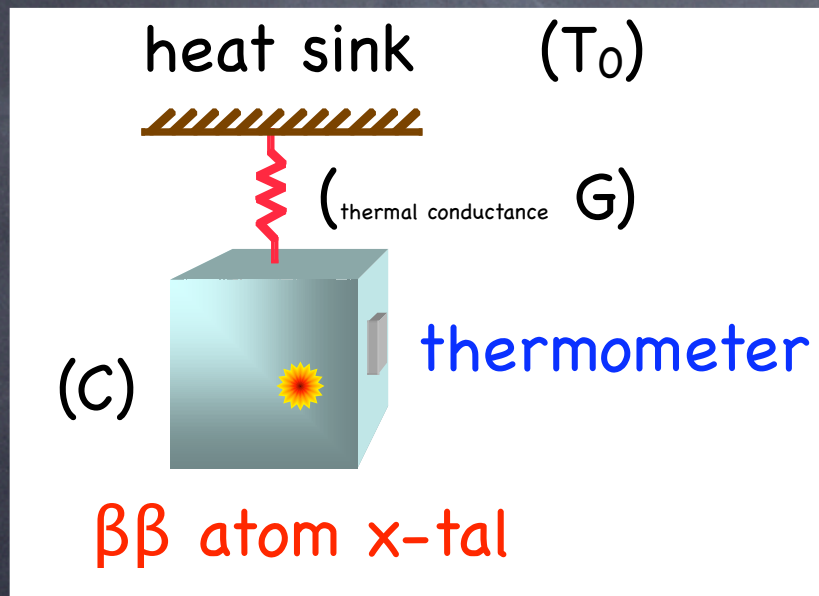
s scintillation
 i ionization
 t tracking
 b bolometric

Range of uncertainties in NME

2 of them are relevant for what comes next:
 'Klapdor et al.' and Cuoricino

(very) Low Temperature Calorimeter

The True Calorimeter



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

(Energy release/ Thermal capacity)

Implication: Low $C \Rightarrow$ Low T

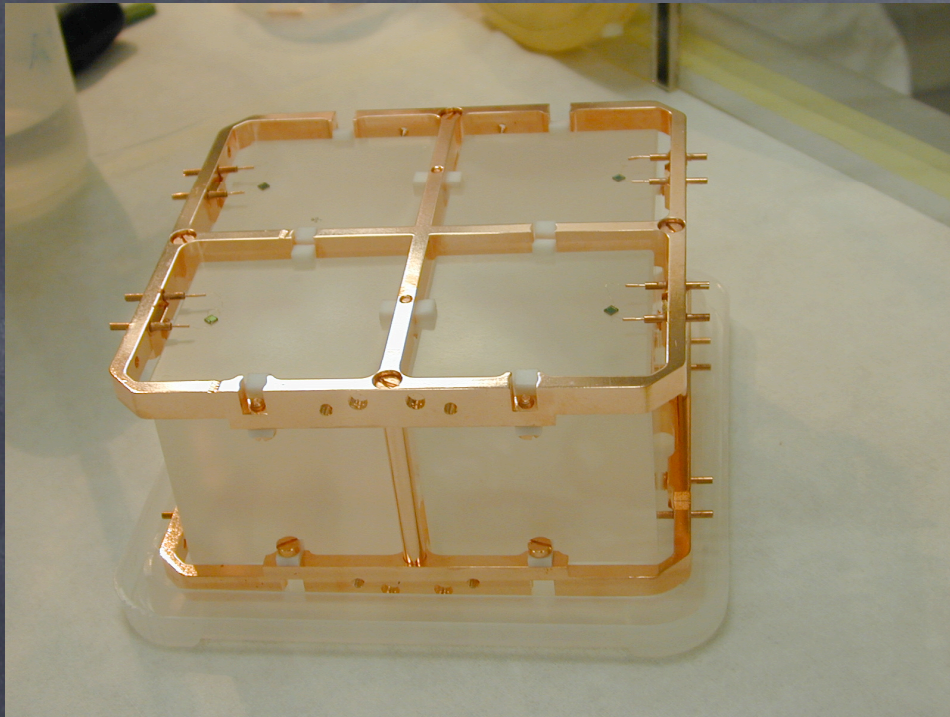
Bonus: (almost) No limit to ΔE ($k_B T^2 C$)

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

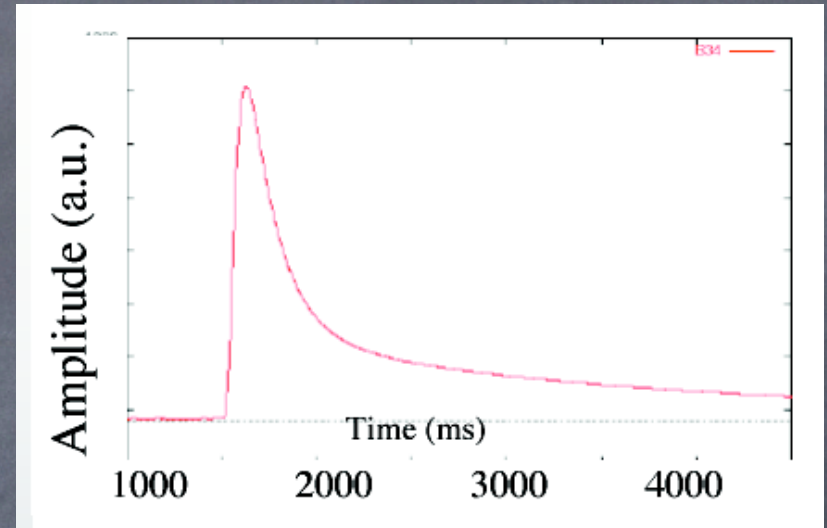
$$C(T) = \beta \frac{m}{M} \left(\frac{T}{\Theta_D} \right)^3$$

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

TeO₂ : a viable (show)case



$T_0 \sim 10 \text{ mK}$ **Numerology:**
 $C \sim 2 \text{ nJ/K} \sim 1 \text{ MeV/0.1 mK}$
 $G \sim 4 \text{ pW/mK}$

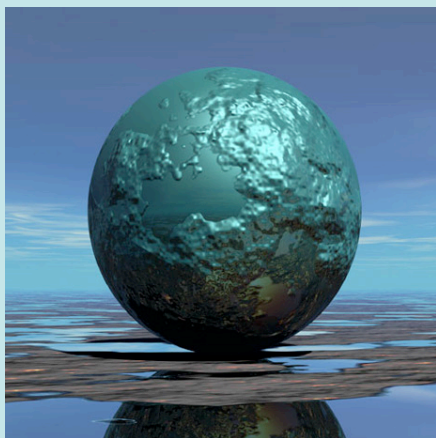


Need to be able to
detect temperature jumps
of a fraction of μK (per
mil resolution on MeV
signals)

TeO₂ : something you do not know about

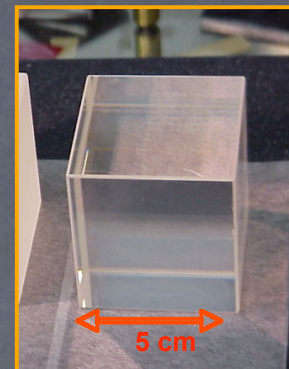
Discovered : by Baron
Franz Muller von
Reichenstein in 1783
Isolated in Sibiu, Romania
Origin : The name is
derived from the Latin
‘tellus’, meaning Earth.

¹³⁰Te



“Its compounds are to be avoided because not only are they poisonous but contact with even the tiniest amounts leads to unpleasant body odors!”

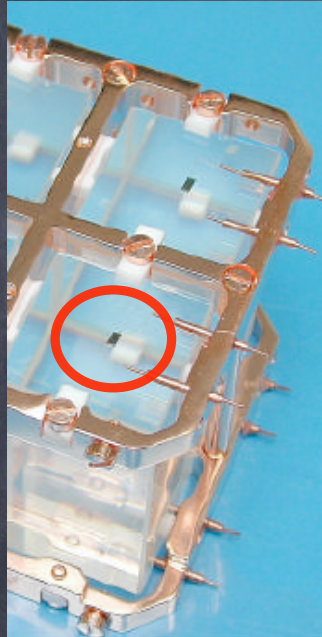
TeO₂ crystals used today in very high end opto-acoustic laser printers for lithography



Forgetting for the stink what makes Te attractive is the fact that its crystals are industrially done. So you can get them without reinventing the wheel. They are not cheap though (~ 40 \$/cc for this rather large samples (5x5x5 cm³).

to read the temperature you need a thermometer

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



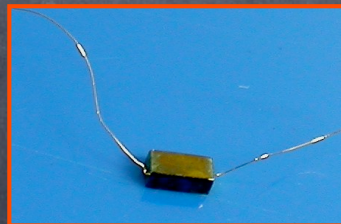
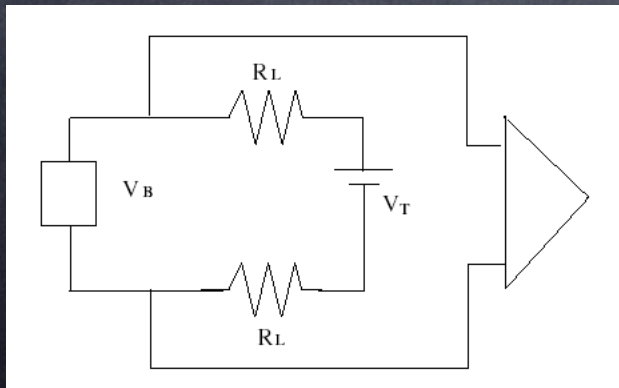
Neutron Transmutation
Doped (NTD) Germanium
Thermistor



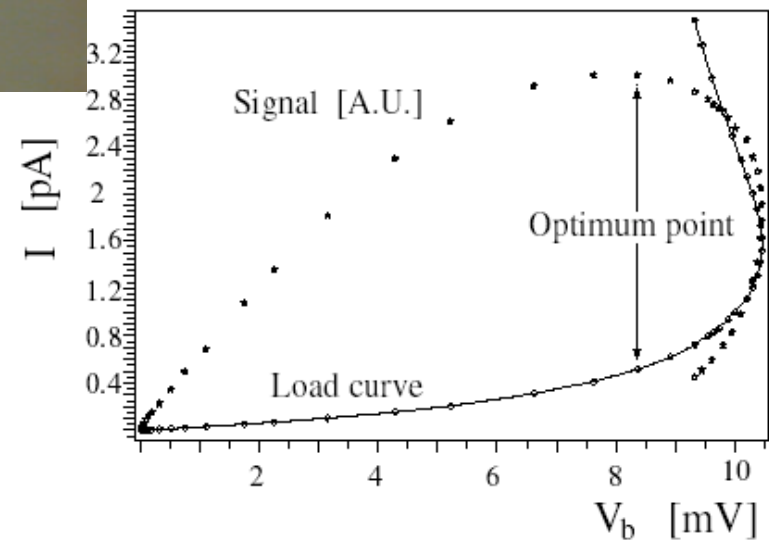
$I \sim 50 \text{ pA}$

$dR/dE \sim 20 \text{ k}\Omega/\text{KeV}$

1mV/1MeV

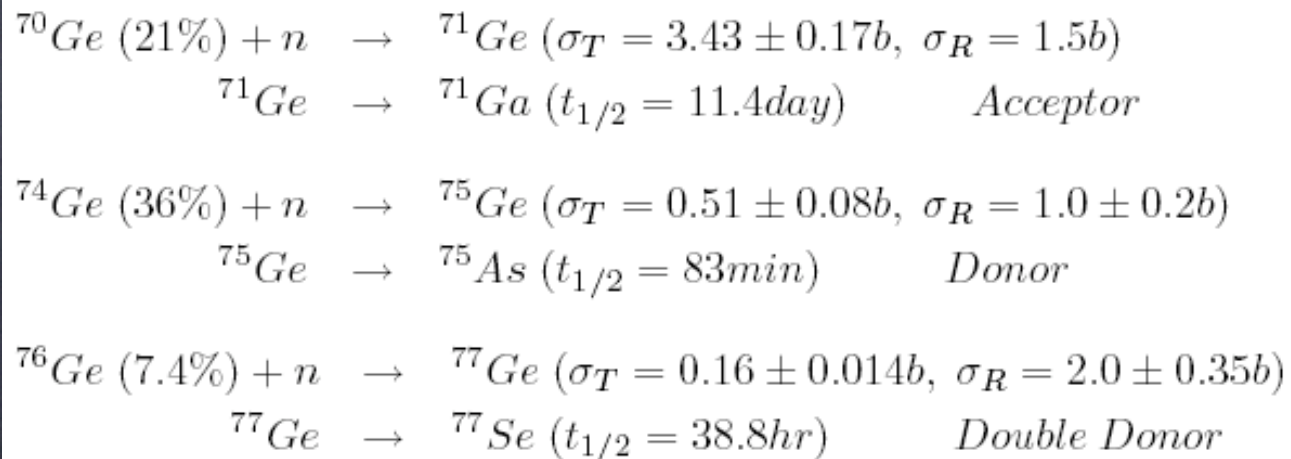


$$T_b = T_0 + \frac{P}{G}$$



Neutron Transmutation Doping

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

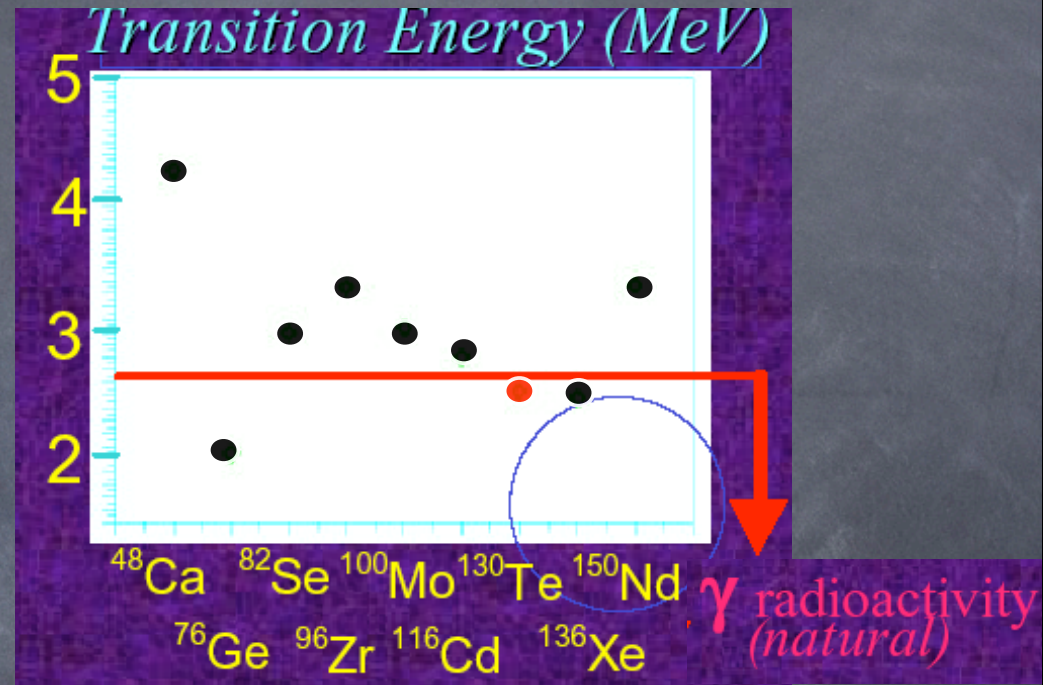
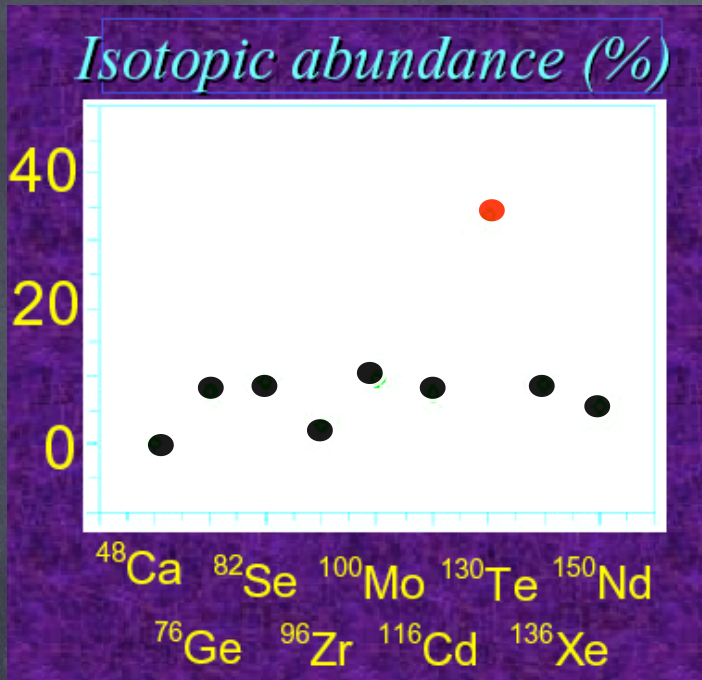


Highly
Uniform

Doping level is 10^{17} atoms/cm³.

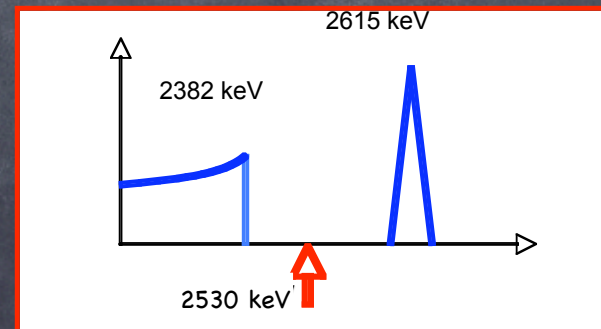
Required fluence is 3.5×10^{18} n/cm².

Te: why ?

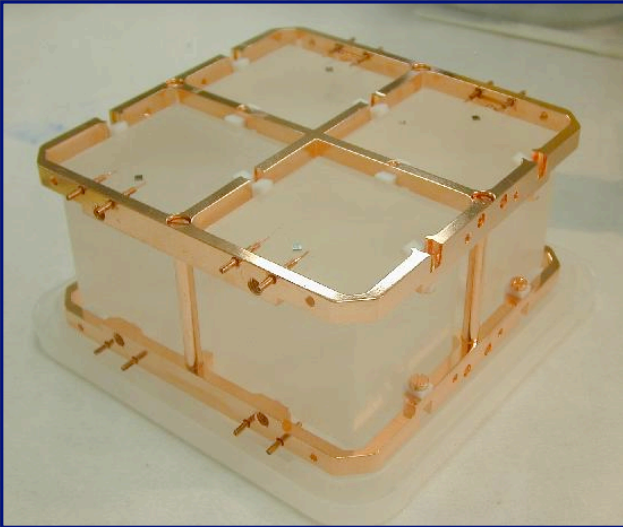


TeO₂ crystals

- low heat capacity
- large crystals available
- radio-pure crystals



Cuoricino: the demonstrator



The bulk of Cuoricino calorimeter is made by 44 TeO_2 crystals of $5 \times 5 \times 5 \text{ cm}^3$ (790 gr of weight). There are 18 additional crystals of $3 \times 3 \times 6 \text{ cm}^3$ (330 gr)

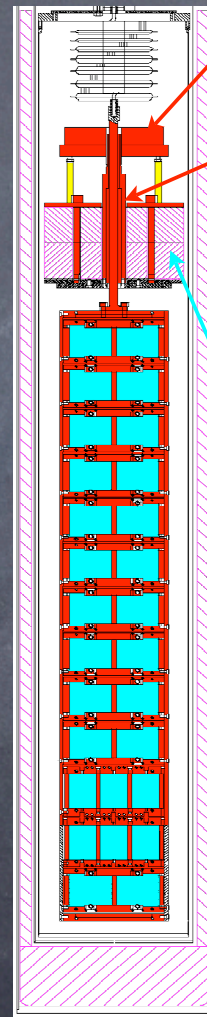
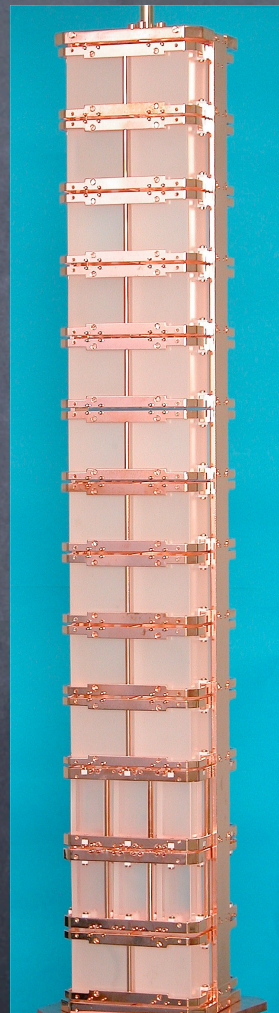
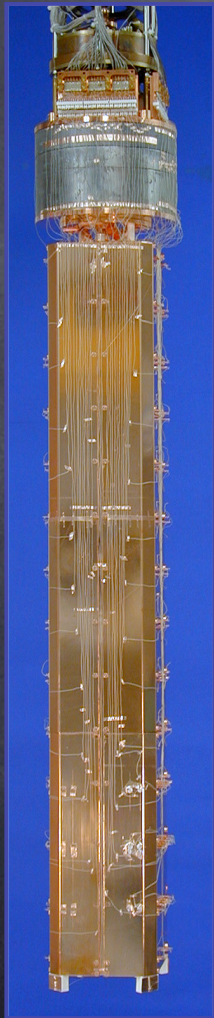


Total mass = 40.7 Kg

$^{130}\text{Te} \sim 11.2 \text{ Kg}$

Cuoricino

Cuoricino is currently the largest
operating
bolometer in the world

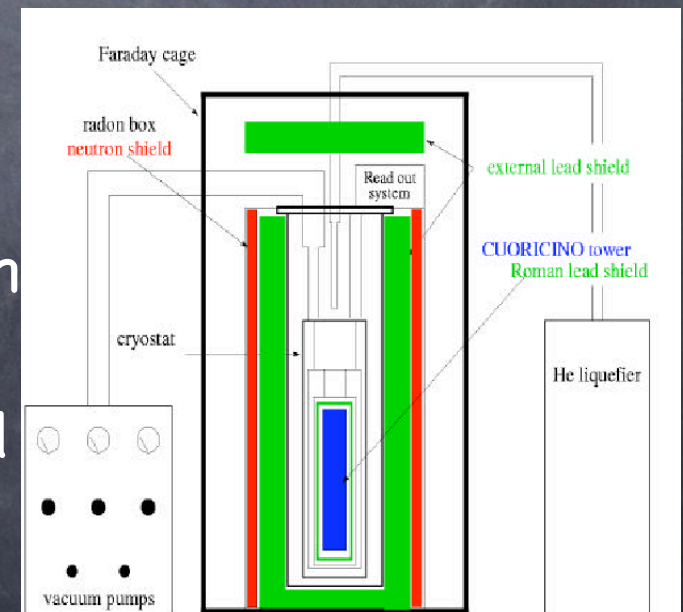


Mixing chamber

Cold finger

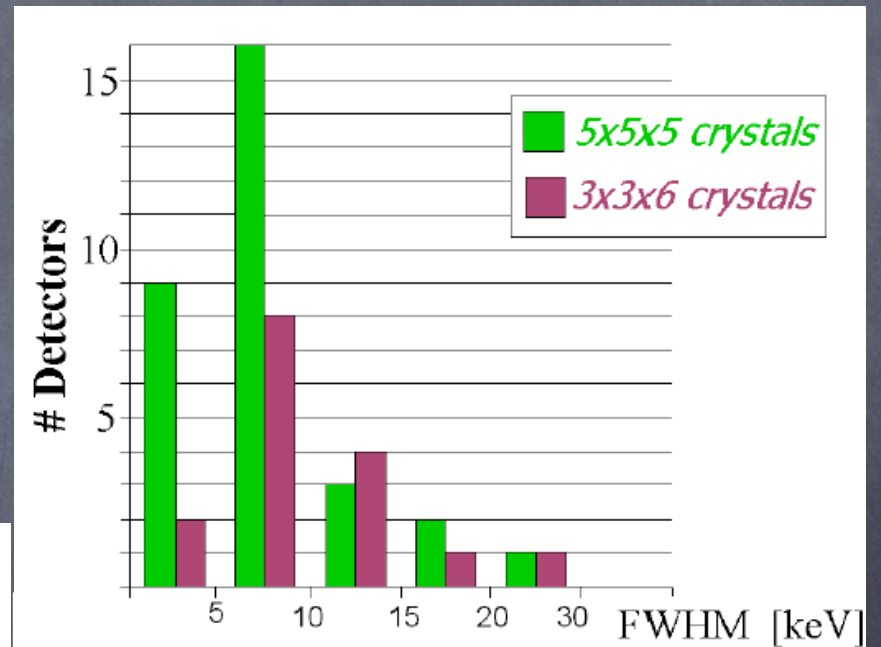
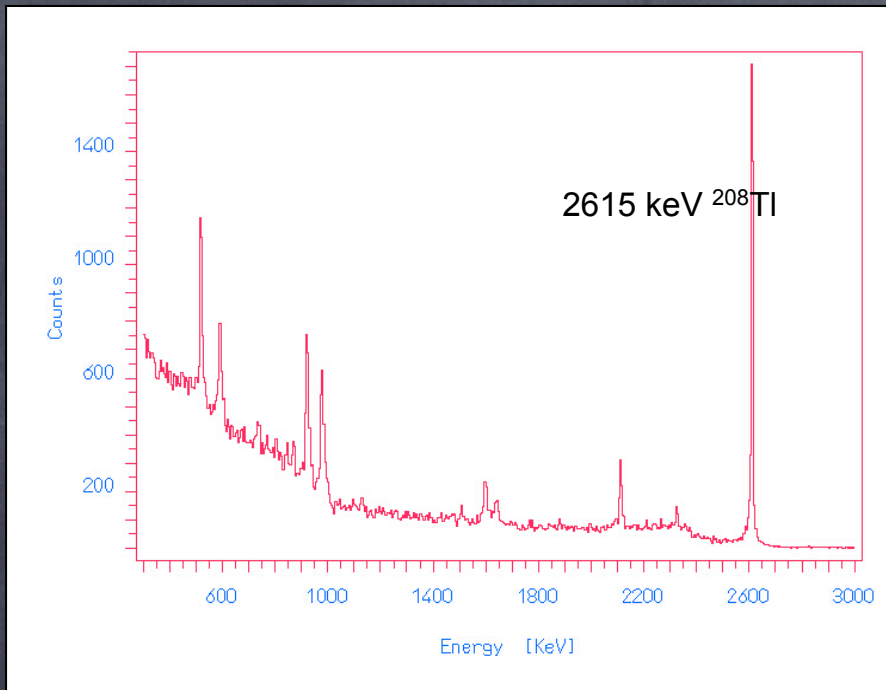
10 mK

Roman
Lead
Shield

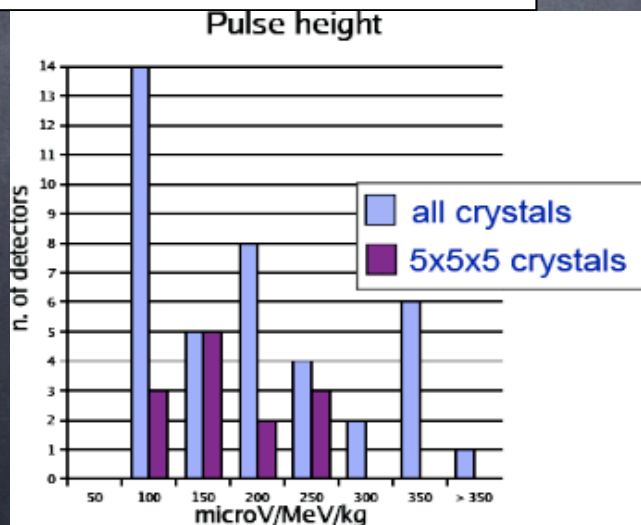


Energy resolution

Sum all over the crystals
(calibration with ^{232}Th source)



Average resolution 5x5x5 : 7.5 keV
Average resolution 3x3x6 : 9.6 keV
Best of all : 3.9 keV



Resolution limited by

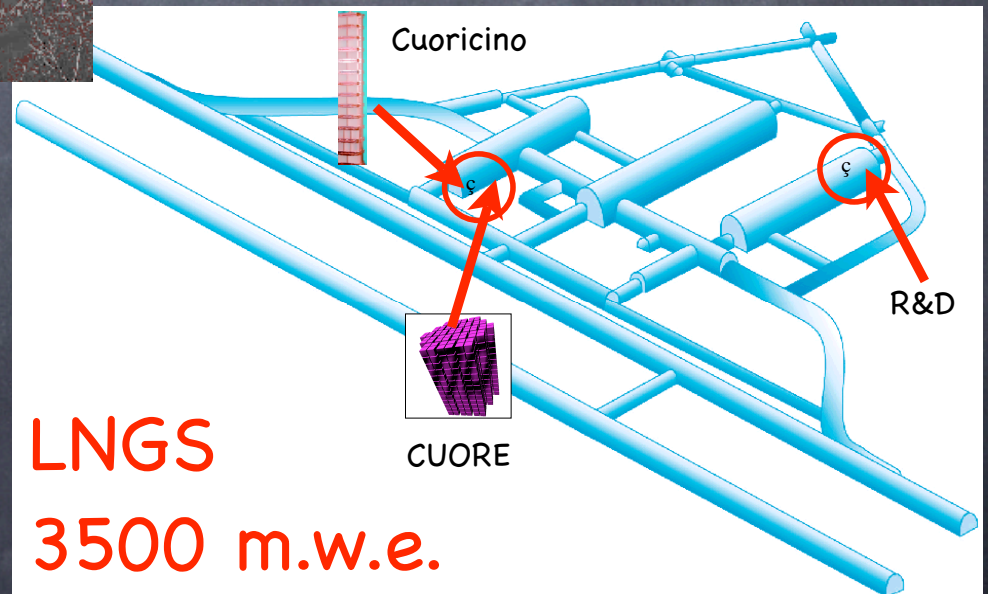
- Thermal/Phononic ($\Delta \sim \text{eV}$)
- Electronic noise ($\Delta \leq 1 \text{ keV}$)
- Microphonics ($\Delta \leq 1 \text{ keV}$)
- Detector responses $\Delta \sim \text{keV}$

Cuoricino, where ?

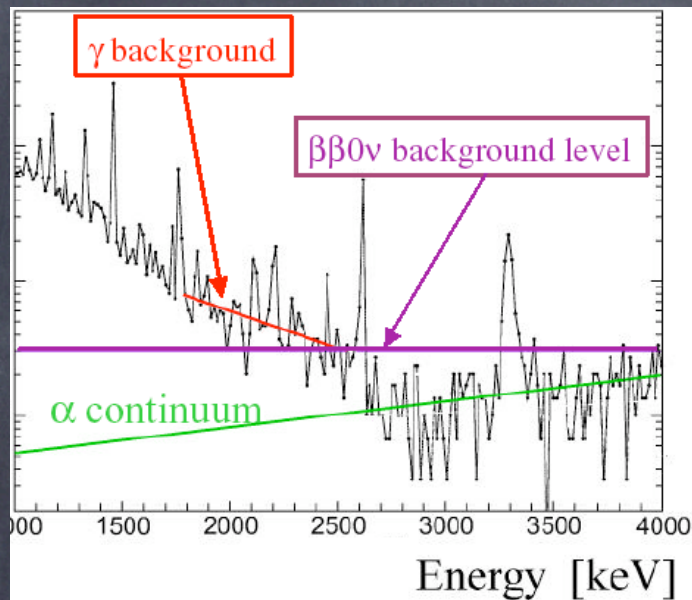


The Shield
Corno Grande 2916 m

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

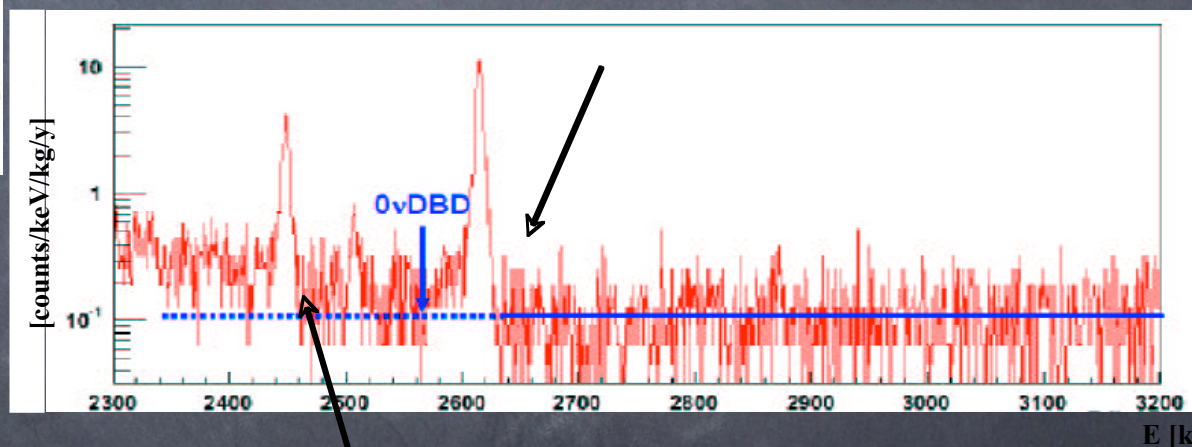


Cuoricino: Background



2615 keV Tl line: contribution to the DBD bkg due to a Th contamination (multicompton).

Th (Tl) contribution to DBD background: **~ 40%**



2505 keV line: sum of the 2 ⁶⁰Co gammas (1173 and 1332 keV)

Most probable source: neutron activation of the Copper

Contribution to DBD background: negligible

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

Flat background in the energy region above the ²⁰⁸Tl 2615 line

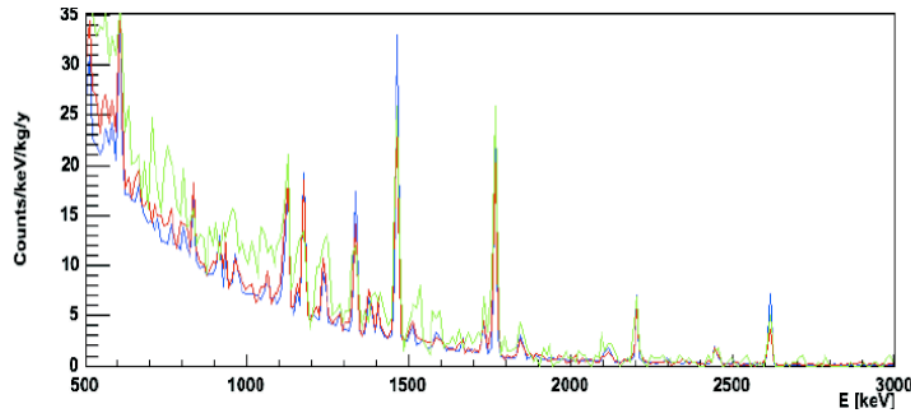
Contribution to the counting rate in the 0νDBD region: **~ 60%**

Degraded alpha particles

Cuoricino: result

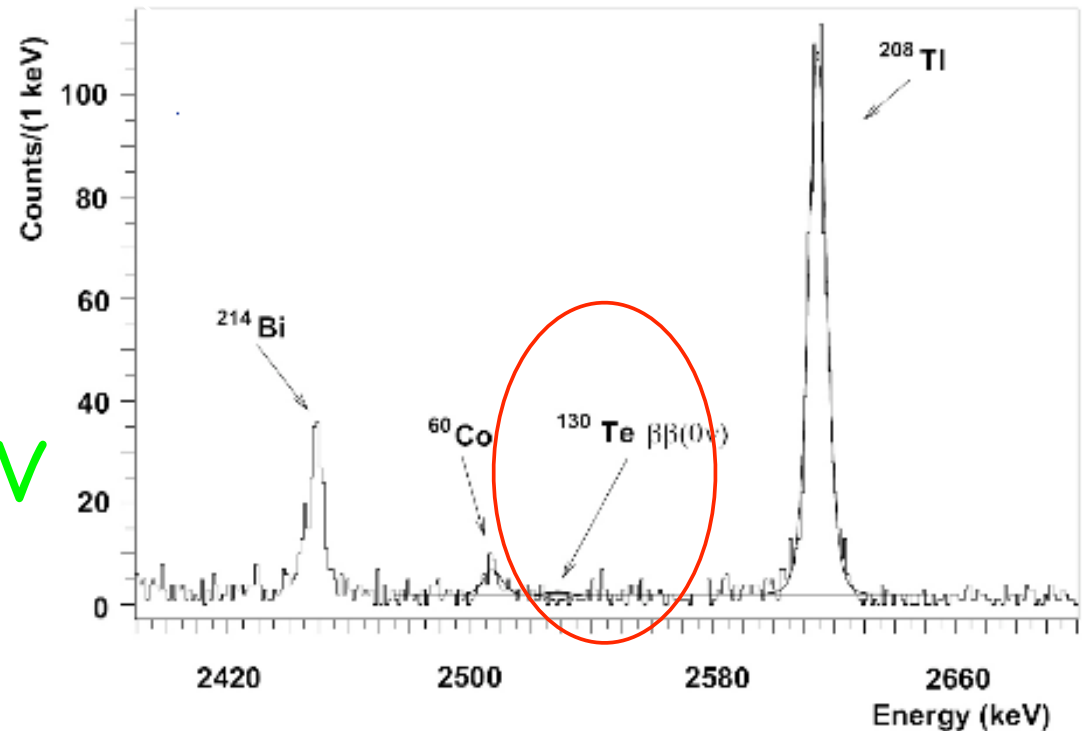
Total statistics

8.3 Kg•y ^{130}Te



$T_{1/2} \geq 2.4 \cdot 10^{24} \text{ y}$
at 90% CL

$\langle m_\nu \rangle \leq 0.18 \div 0.94 \text{ eV}$
↑
NME !



How does it compare ?

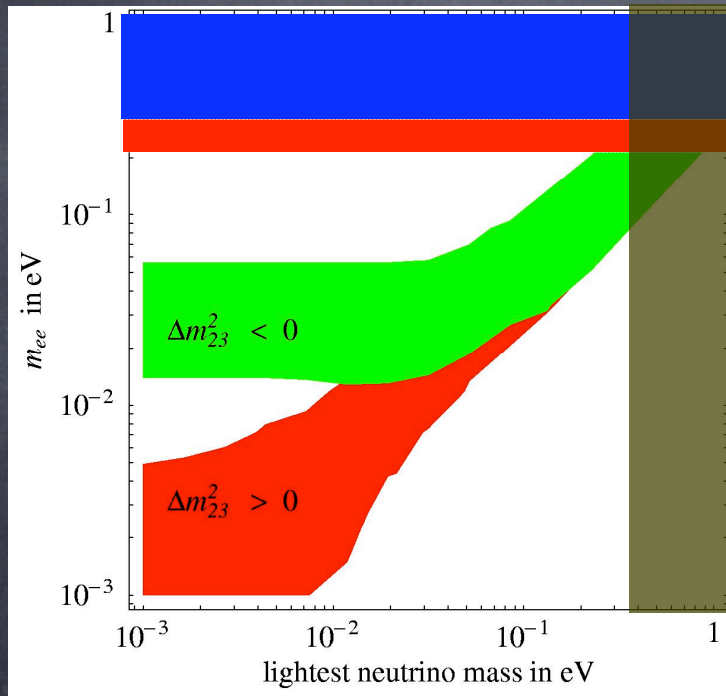
- positive result
- running experiments

isotope	experiment	latest result	i.a. [%]	$Q_{\beta\beta}$ [eV]	enrich [%]	exp [kg×y]	tech	material	$\tau_{1/2}^{0\nu}$ [10^{23} y]	$\langle m_\nu \rangle$ [eV]	
										min	max
⁴⁸ Ca	Elegant VI	2004	0.19	4271	-	4.2	s	CaF ₂	0.14	7.20	44.70
⁷⁶ Ge	Heidelberg/Moscow	2001	7.8	2039	87	71.7	i	Ge	190.0	0.12	1.00
⁷⁶ Ge	Klapdor et al.	2004	7.8	2039	87	71.7	i	Ge	120.0	0.44	-
⁸² Se	NEMO-3	2005	9.2	2995	97	0.93	t	Se	1.0	1.75	4.86
¹⁰⁰ Mo	NEMO-3	2005	9.6	3034	95-99	6.9	t	Mo	4.6	0.66	2.81
¹¹⁶ Cd	Solotvina	2003	7.5	3034	83	0.5	s	CdWO ₄	1.7	1.70	-
¹³⁰ Te	Cuoricino	2005	33.9	2530	-	8.3	b	TeO ₂	24.0	0.18	0.94
¹³⁶ Xe	DAMA	2002	8.9	2476	69	4.5	s	Xe	12.00	1.10	2.90
¹⁵⁰ Nd	Irvine TPC	1997	5.6	3367	91	0.01	t	Nd ₂ O ₃	0.012	3.00	-

- s scintillation
- i ionization
- t tracking
- b bolometric

Range of uncertainties in NME

in the parameter space



Cuoricino
'Klapdor et al.'
WMAP

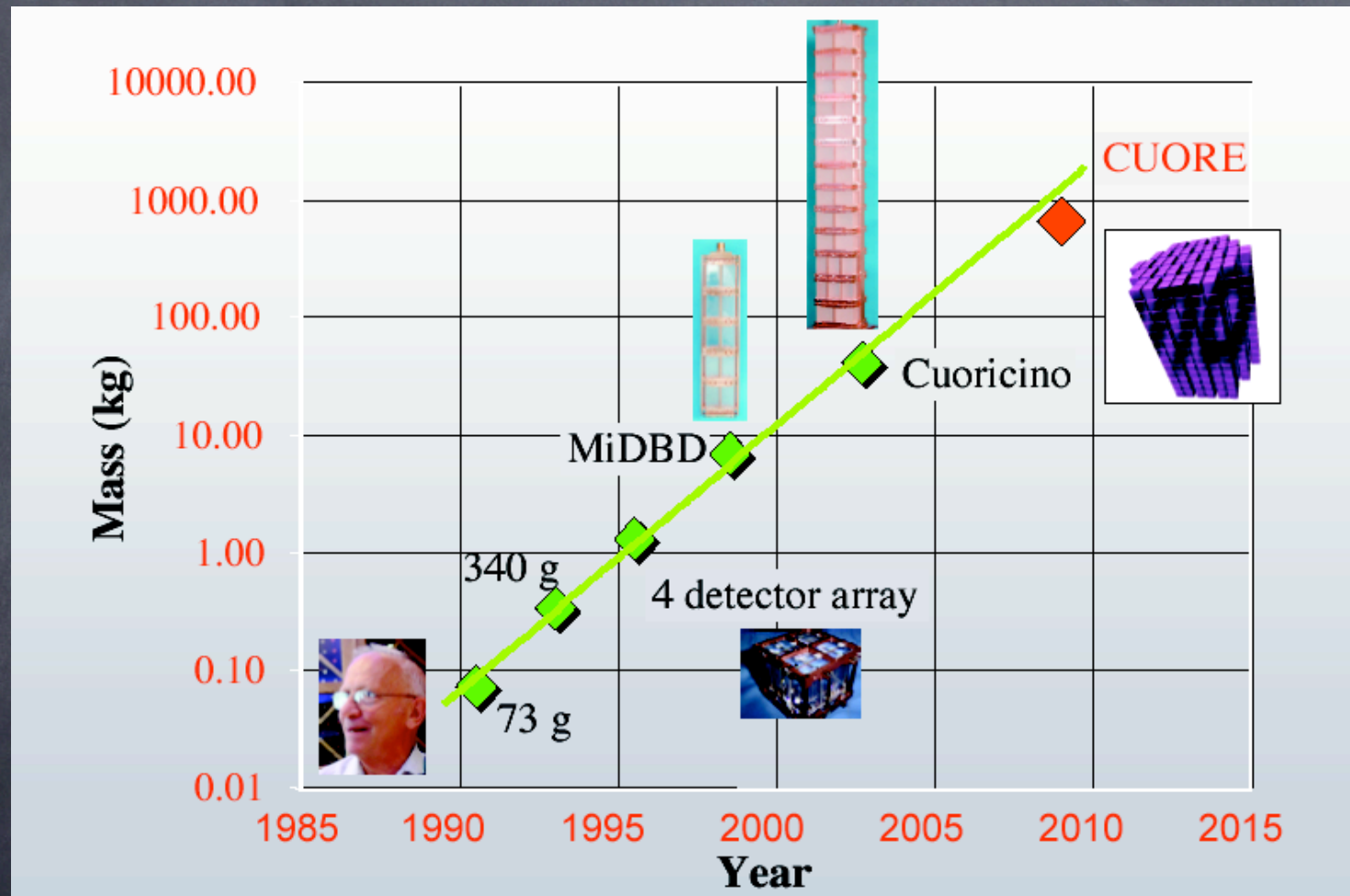
Cuoricino might discover DBD
but cannot disprove 'Klapdor'

Cuoricino sensitivity
after 3 y run

$$\tau_{1/2} \geq 6.1 \times 10^{24} \text{ y}$$

$$\langle m_\nu \rangle \leq 0.1 \div 0.6 \text{ eV}$$

The Moore's Law of Bolometry

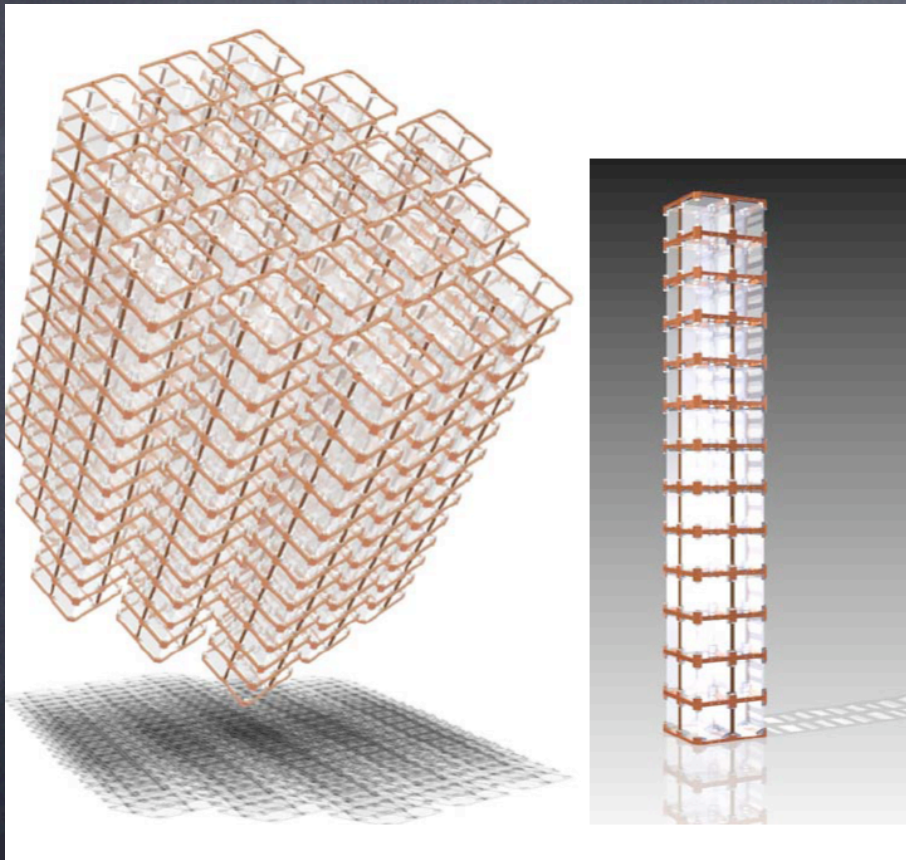


CUORE : who ?



CUORE design

Cuoricino times 19



988 TeO_2 Crystals

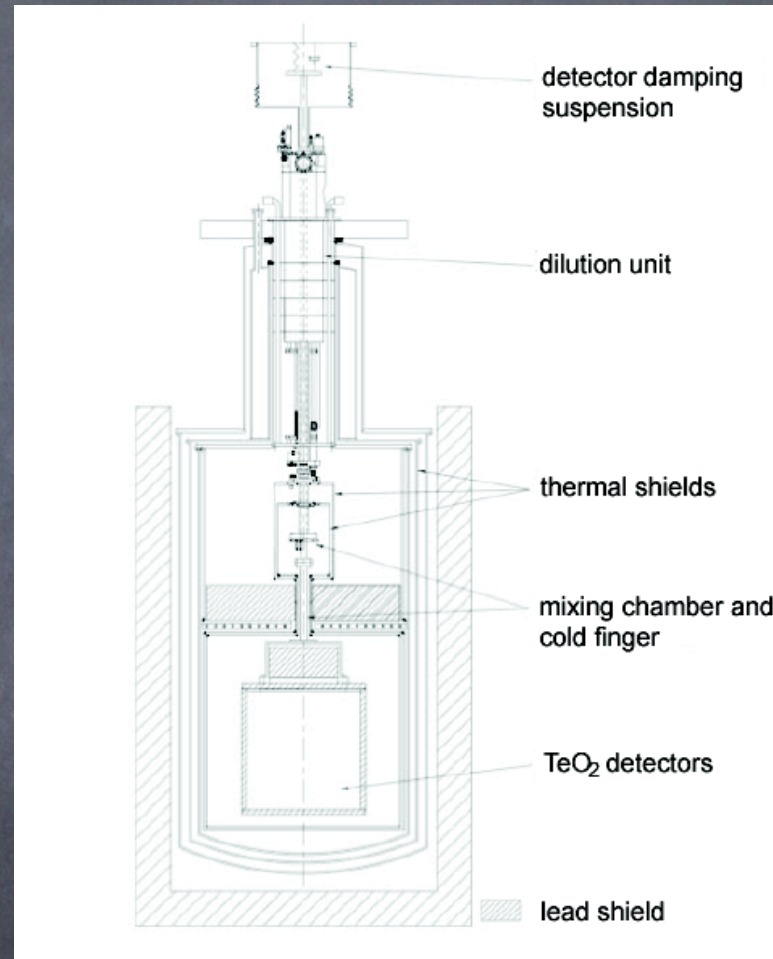
19 Towers of 52 crystals each

741 Kg of TeO_2

Active Mass 204 Kg

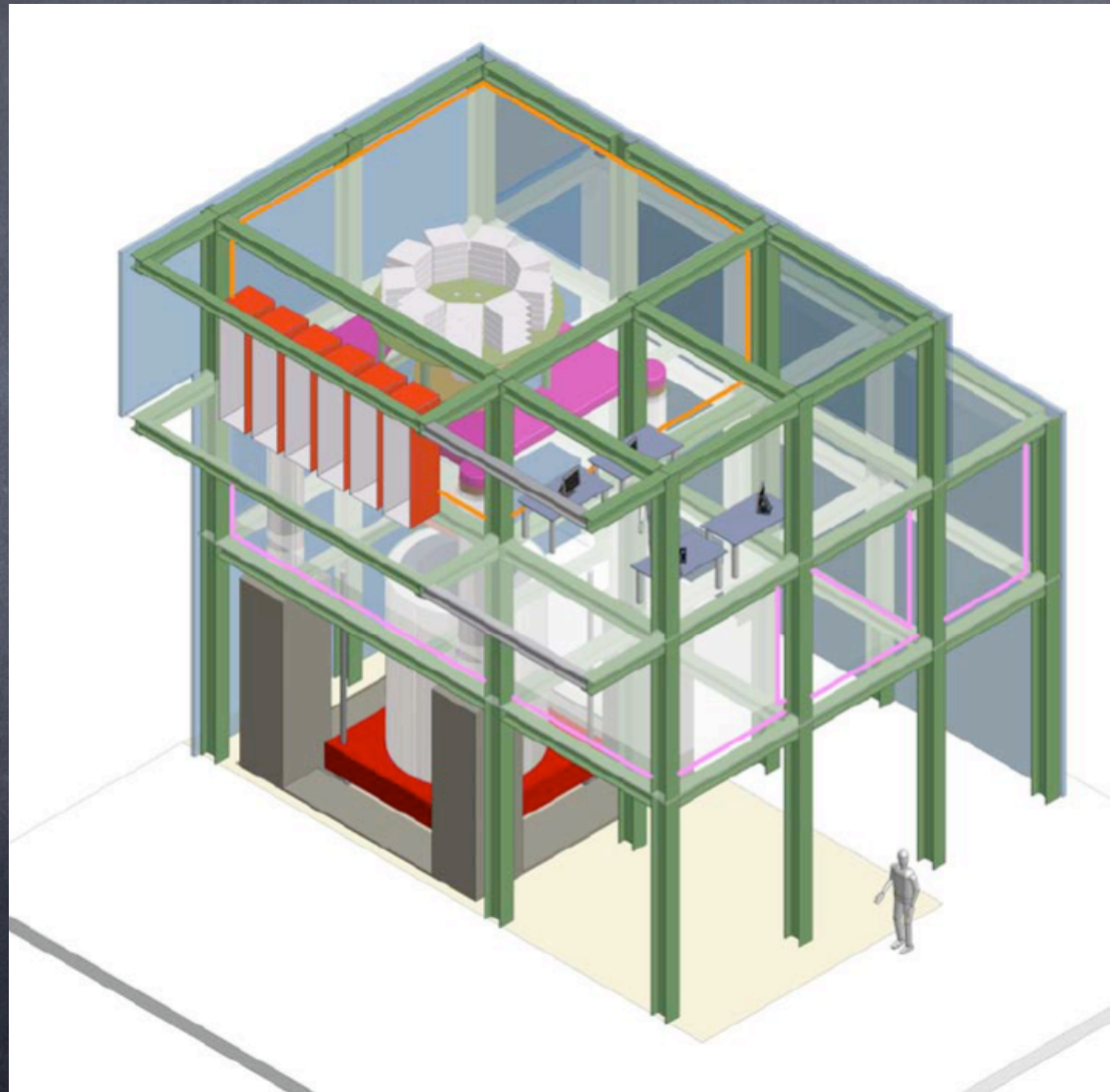
Keep the possibility of replacement with enriched Te Crystals

CUORE cryostat

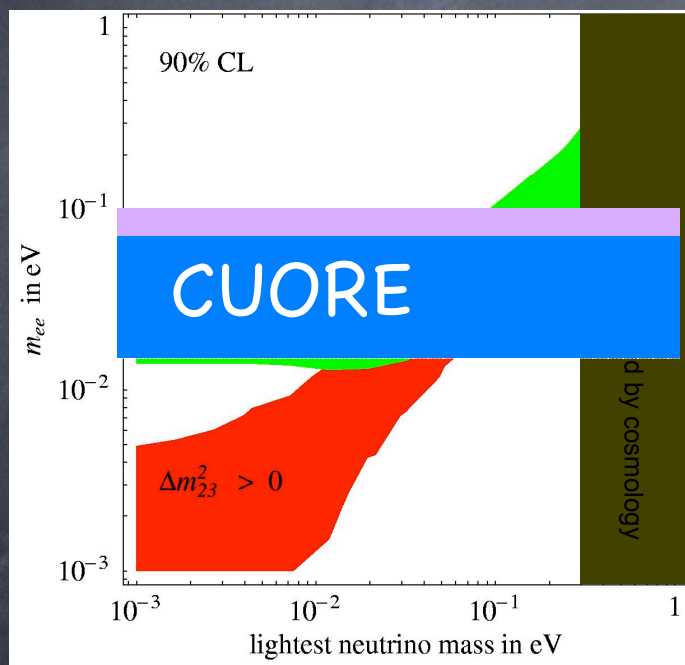


Pulse Tube Cooler

CUORE housing



CUORE physics goal (5 years run)



The first generation was mainly devoted to the proof of the technology.

CUORE is a second generation experiment with the possibility of exploring most of the inverted hierarchy

Backgrounds	Sensitivity	Effective Majorana Mass
0.01 counts/keV·kg·yr	$T_{1/2}^{0\nu} = 2.1 \times 10^{26}$ yr	19 – 100 meV
0.001 counts/keV·kg·yr	$T_{1/2}^{0\nu} = 6.5 \times 10^{26}$ yr	11 – 57 meV

Scaling Cuoricino to CUORE

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

$$M = m \times 20$$

$$T = t \times 10$$

$$b = B / 20$$

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

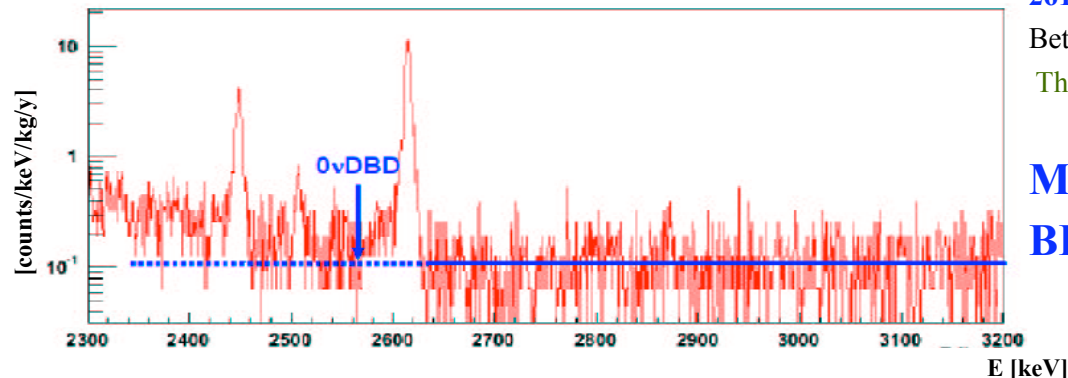
$$S_{\text{CUORE}} = \sqrt{6000} \quad S_{\text{Cuoricino}} \sim 78 S_{\text{Cuoricino}}$$

$$T_{1/2} (\text{CUORE}) \sim 1.7 \times 10^{26}$$

$$\langle m_\nu \rangle_{\text{CUORE}} \sim \langle m_\nu \rangle_{\text{Cuoricino}} / 9 \sim 19 \div 100 \text{ meV}$$

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

Background reduction



2615 keV Tl line

Between the inner Roman lead shield and the external lead shield.

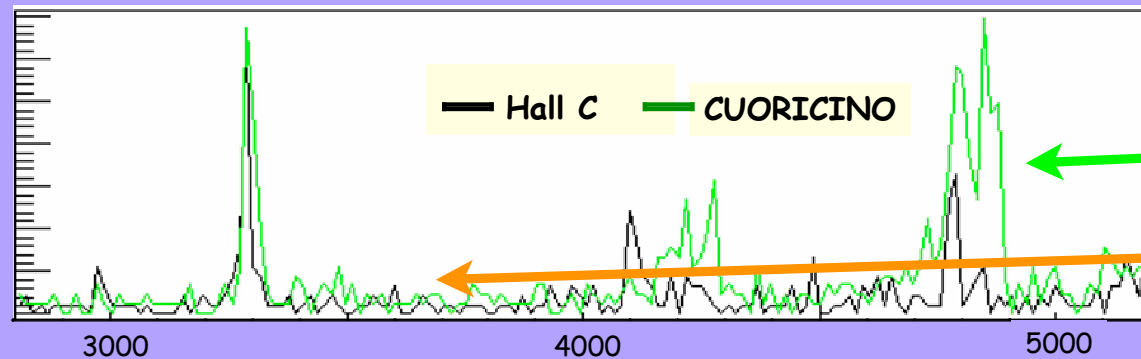
Th (Tl) contribution to DBD background: ~40%

**MORE ROMAN LEAD:
BETTER CRYOSTAT DESIGN**

Flat background in the energy region above the ^{208}Tl 2615 line

Contribution to the counting rate in the 0νDBD region: ~60%

Origin: degraded alpha particles (20 +/- 10) % crystal surface contamination
(80 +/- 10) % "Cu" surface contamination ~

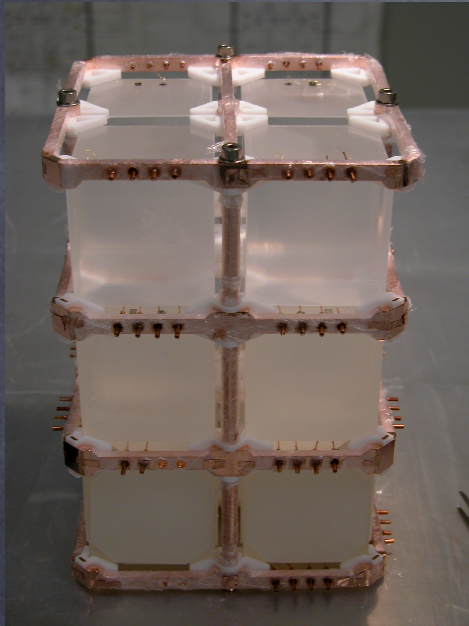


Reduction of a factor ~4
on crystal surface
contaminations.

Reduction of a factor ~2
on Copper surface
contaminations.

The fight is not over yet

Array of 8 Detectors: cleaned with ultra-radiopure materials and procedures



Crystal surface contaminations in CUORE	$< 3 \times 10^{-3} \text{ c/kev/kg/y}$
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Crystal internal contaminations in CUORE	$< 8 \times 10^{-5} \text{ c/kev/kg/y}$
--	---

Copper surface contaminations in CUORE	$< 5 \times 10^{-2} \text{ c/kev/kg/y}$
--	---

New structure with reduced Cu amount (MC simul.)	$< 2.5 \times 10^{-2} \text{ c/kev/kg/y}$
--	---

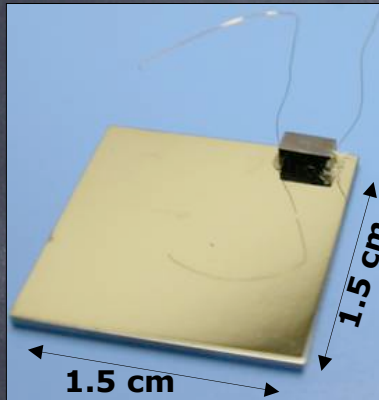
CUORE goal: 0.01 c/kev/kg/y

Still a factor no less than 2.5 to go

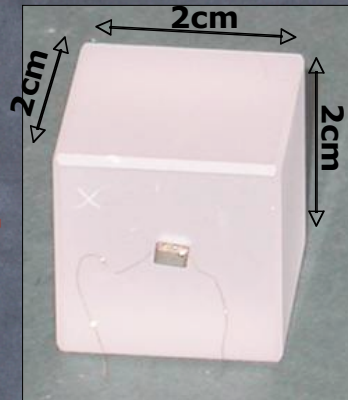
The 'doomsday machine'*

Superficial
Sensitivity
Bolometers

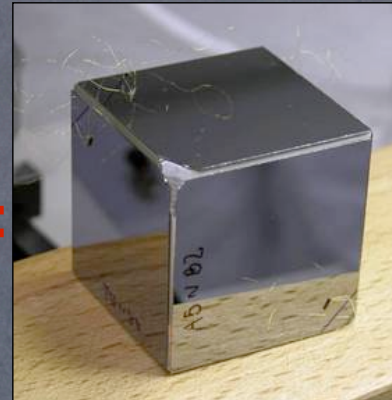
Ge/Si Bolometer



TeO₂ Bolometer

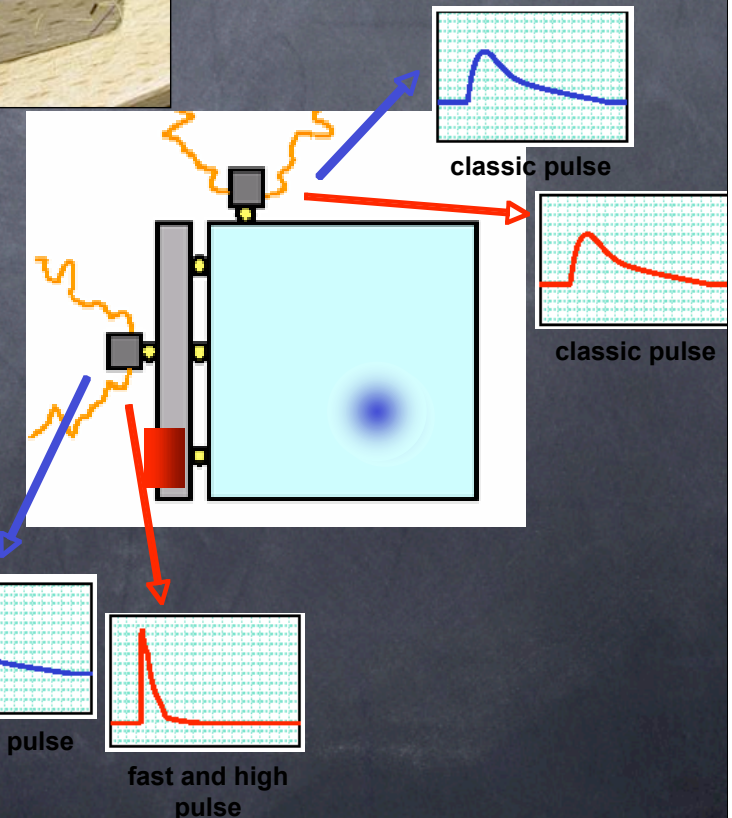
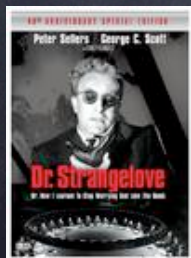
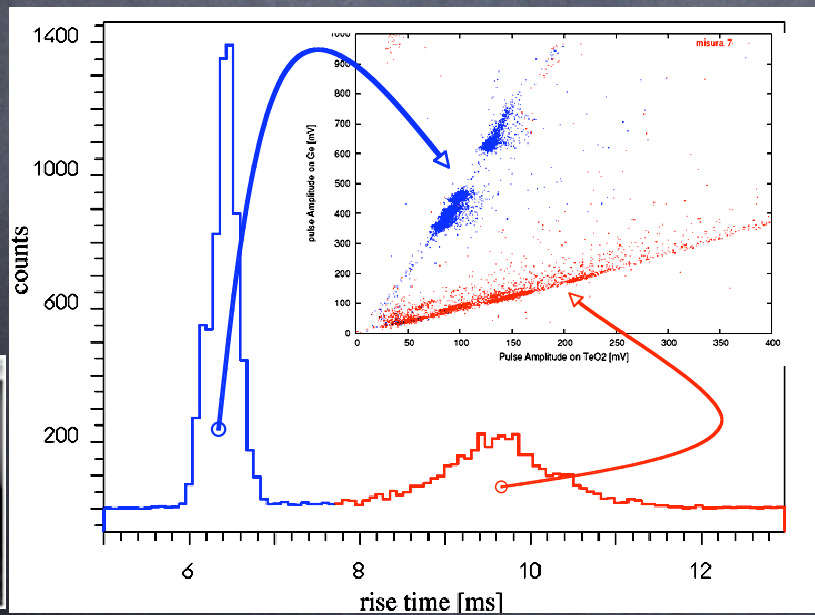


Composite Bolometer



+

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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
- CUORE is the most promising of the next generation project