From CUORICINO to CUORE: a ββ0υ experiment

Cecilia G. Maiano
Università degli Studi e Sezione INFN
di Milano Bicocca

Outline:

* Introduction **$\beta\beta0\nu$** and **$\beta\beta2\nu$**

    *Process description

    *NME: Nuclear Matrix Elements

        - How to translate the observed experimental rate $\tau_{1/2}^{0\nu}$ in to effective ν mass $<m_{\nu e}>$:

* Experimental strategies: the *bolometric technique*

* CUORICINO: a pilot **$\beta\beta$** experiment and test

* CCVR & TTT & CUORE-0

* CUORE: **$\beta\beta$** experiment, the final goal

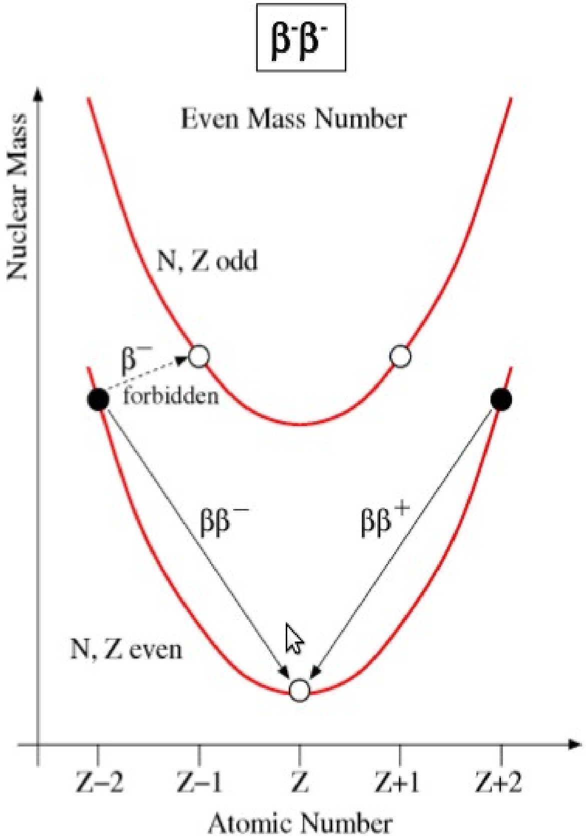
Double Beta Decay ββ2ν

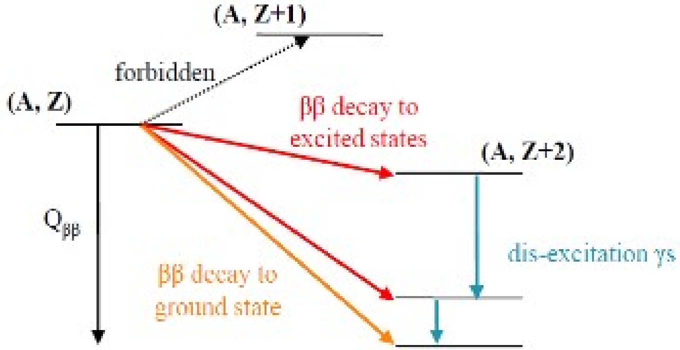
$(A, Z) \rightarrow (A, Z+2) + 2e^- + \ldots$

*It is a second-order - allowed SM ΔL=0 - nuclear transition, favored with respect to the sequence of two single beta decays for 35 isotopes
*Continuum - max@ ~1/3 Q-value

It can undergo through many decay modes:
$\beta^-\beta^-$, $\beta^+\beta^+$, EC β^+ , ECEC

$\beta^-\beta^-$ has the highest rates
observed for 11 isotopes: $T_{1/2} \geq 10^{18}$ y

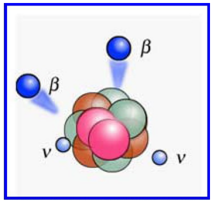


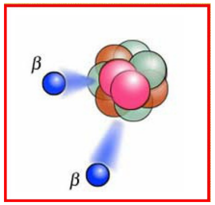


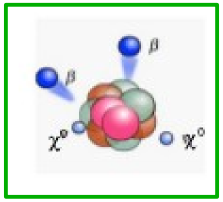
Neutrinoless Double Beta Decay ββ2ν

Besides the Standard Model allowed $\beta^-\beta^-$, other more intriguing channels have been proposed, i.e. 0νββ, $0\nu\chi^0(\chi^0)\beta\beta$

ββ0ν channel has become particularly compelling after the evidence of neutrino oscillations (i.e. evidence of a non zero neutrino mass)







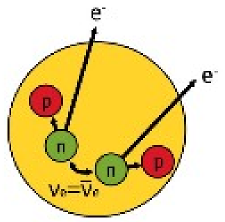
0νββ IMPLICATIONS IN PARTICLE PHYSICS :

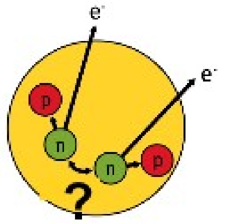
1. L violation ΔL≠0
2. ν Majorana nature
3. Absolute ν mass scale measurement
4. Neutrino mass hierarchy determination
5. CP violation measurement in the leptonic sector

ββ0ν via light ν

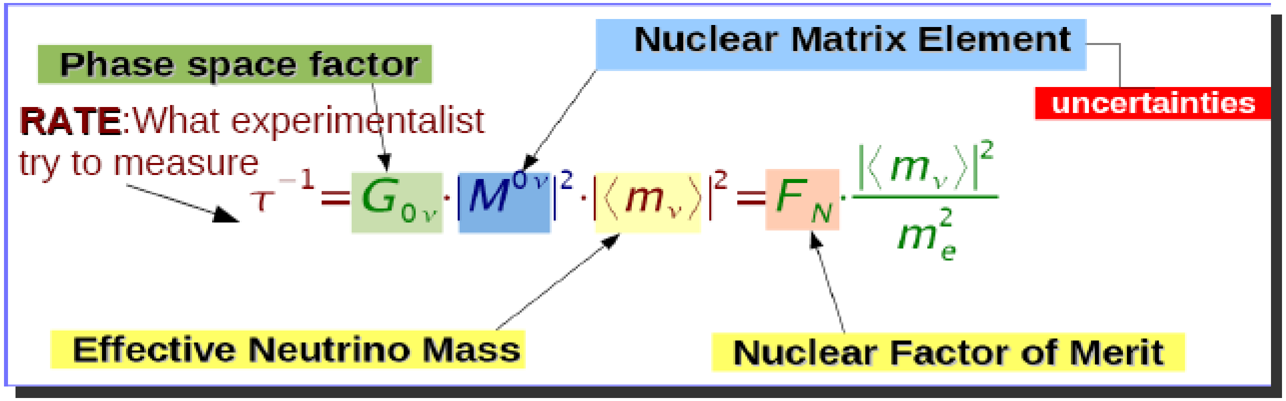
0νββ can be mediated by the exchange of a variety of unconventional particles

It́s amplitude depends on their mass and coupling constants





For light νM exchange the Decay Rate is:



RATE:What experimentalist try to measure

$$\tau^{-1} = G_{0\nu}\cdot|M^{0\nu}|^2\cdot|\langle m_\nu\rangle|^2 = F_N\cdot\frac{|\langle m_\nu\rangle|^2}{m_e^2}$$

$$\langle m\nu\rangle = \left||U_{e1}|^2 M_1 + e^{i\alpha_1}|U_{e2}|^2 M_2 + e^{i\alpha_2}|U_{e3}|^2 M_3\right|$$

- $G_{0\nu-}$ -> atomic physics
- $M_{0\nu}$ -> nuclear physics
- $<m_\nu>$ → Partilce Physics

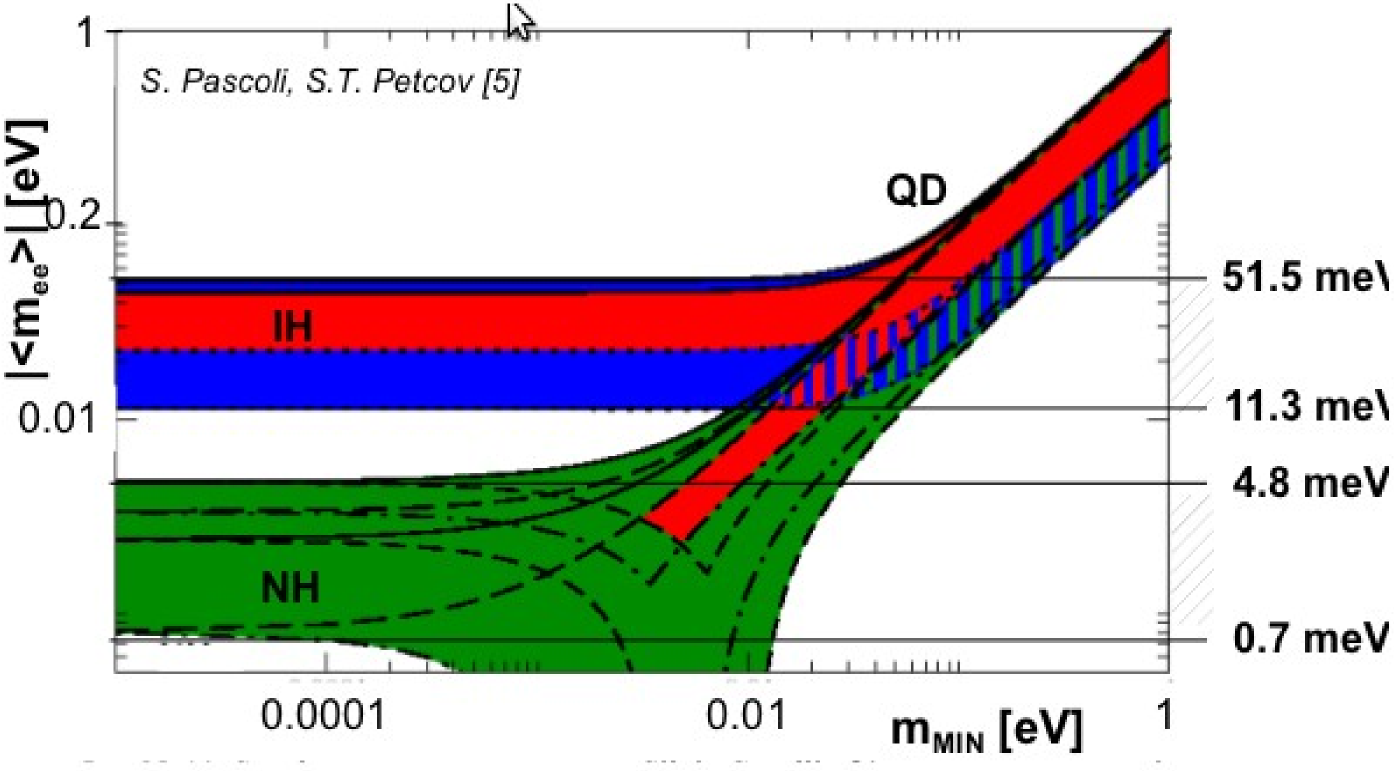
<m$_\nu$> ν mass spectrum

$$\langle m_{ee}\rangle = \left|\sum |U_{ei}|^2 m_i e^{i\alpha_i}\right|$$

* 3 unknown quantities: m_{MIN}, α_1, α_2

* Cancellations are possible due to α_i

* ββ0ν can access mass hierarchy



Needed sensitivity:

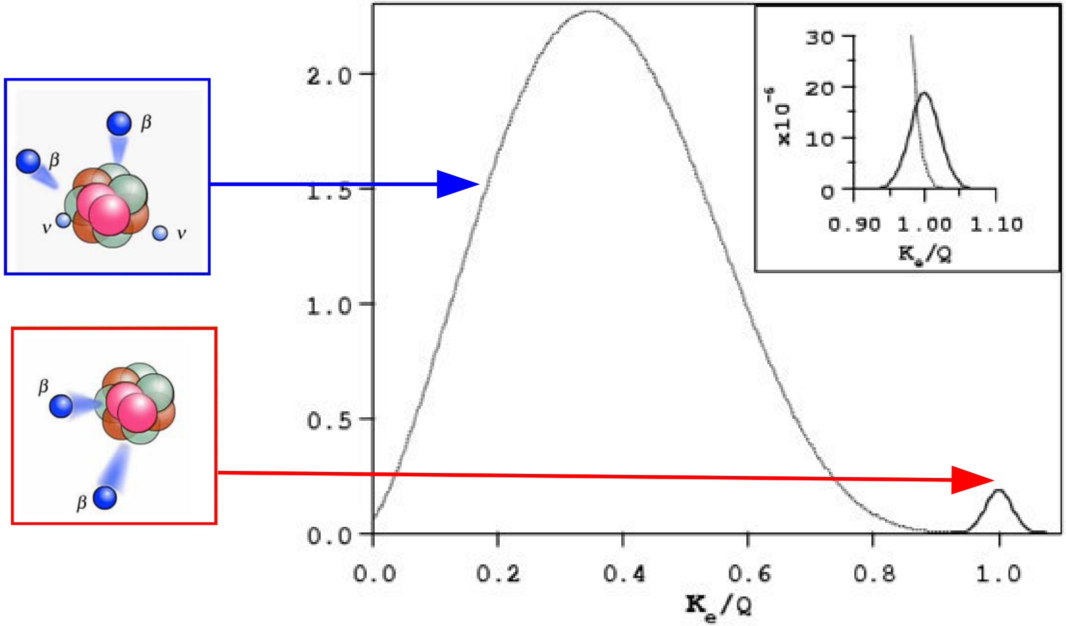
* < 50 meV for IH

* < 10 meV for NH

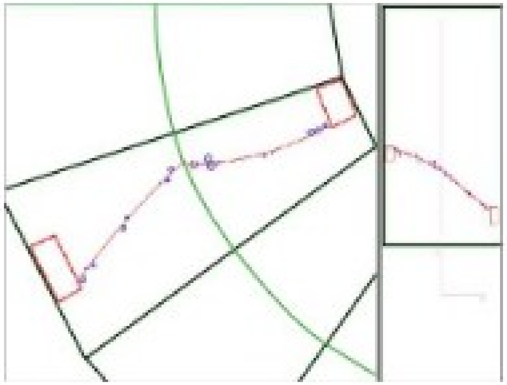
0νββ experimental signature

Minimal information:
two e- energy sum spectrum

ββ0ν exhibits a peak at Q
over ββ2ν tail
enlarged only by detector resolution



Additional signatures:
* Single electron energy spectrum
* Angular correlation between the two electrons
* Track and event topology
* Time Of Flight
* Daughter nuclear specie



Experimental sensitivity in $\tau^{0\nu}$

Defined as the lifetime corresponding to the minimum detectable number of events over background at a given C.L.

$$F_0 = \ln(2) N_{\beta\beta} \frac{T_{meas}}{n_{peak}} \epsilon$$

$$F_0 \propto \frac{\epsilon\, a.i.}{A} \left(\frac{M\,T}{b\,\Delta E} \right)^{1/2}$$

$$F_0 \propto \frac{\epsilon\, a.i.}{A} (M\,T)$$

$F_{0\nu}$ involves only detector and set-up parameters:

- Source mass: M [kg]
- Measured bkg in the ROI: b [c/keV/kg/y]
- Detector resolution in the ROI: ΔE [keV]
- Measure livetime: T [y]
- Detecting efficiency for ββ0ν events: ε
- Isotopic abundance: ai

Improvements on $F_{0\nu}$:

- Increasing exposition (MT)
- Better technology and detector performances (ΔE, ε)
- Lower background in the ROI (b)
- Isotopic enrichment

Sensitivity in $<m_{ee}>$

$$F_m \propto \left(\frac{A}{\epsilon\, a.i.} \right)^{1/2} \frac{1}{G_{0\nu}(Q,Z)^{1/2} \left| M_{0\nu} \right|} \left(\frac{b \Delta E}{M T} \right)^{1/4} \quad b \neq 0$$

Fm involves also atomic and nuclear properties:

- Phase Space Factor: $\mathbf{G^{0\nu}(Q,Z) \div Q^5}$
- Nuclear Matrix Elements: $\mathbf{M^{0\nu}}$

Improvements on F_m :

Good isotope choice

Discrepancies between NME calculations with different models: a factor ~ 2 – 3

Isotope Choice: $M^{0\nu}$

$$F_N \rightarrow G^{0\nu} * |M^{0\nu}|^2$$

Phase Space Factors $G^{0\nu}$

* Known and univoque
* Nuclear Model independent

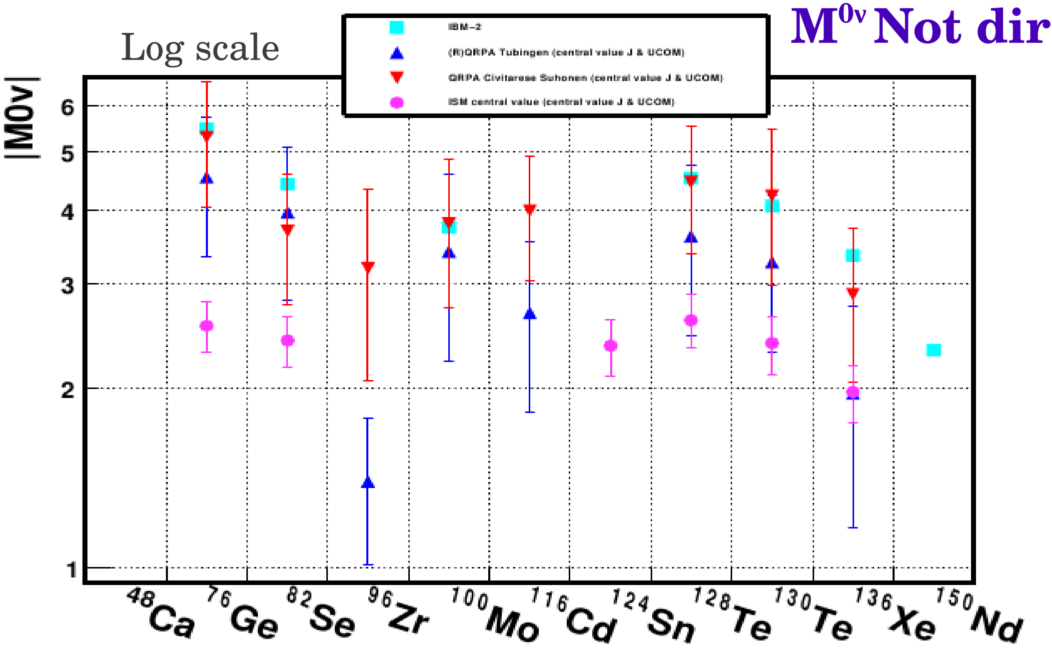
NME $|M^{0\nu}|$

* Initial & Final state dependent
* Nuclear Model dependent

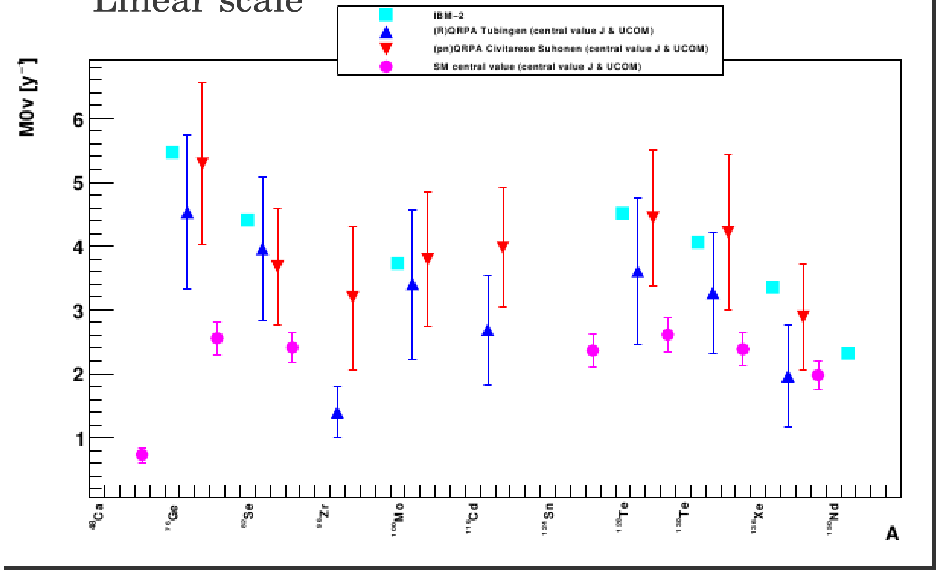
** Several phase space factors, not standard
** Different Nuclear Models use different starting hypothesis, but converge

$M^{0\nu}$ Not directly comparable!

Log scale



Linear scale



NME

ββ2ν nuclear structure NME inherited from β decay
ββ0ν dominant players NME $0^+ \rightarrow 0^{+\cdot}$ GT & F operators

$$M_F^{0\nu} = - < N_f | \sum_{ij} \vec{\tau}^{-}(i) \vec{\tau}^{-}(j) H | (\vec{x}_i - \vec{x}_j) || N_i >$$

$$c_A^2 M_{GT}^{0\nu} = c_A^2 < N_f | \sum_{ij} \vec{\sigma}(i) \vec{\tau}^{-}(i) \vec{\sigma}(j) \vec{\tau}^{-}(j) H | (\vec{x}_i - \vec{x}_j) || N_i >$$

Total NME potential parametrization.
X_F – Fermi part

$$R_0 M^{0\nu} = c_A^2 (1 - X_F) R_0 M_{GT}^{0\nu}$$

$M^{0\nu}$ ruled by :

- * Hadronic currents density
- * i & f hamiltonian states
- * Nuclear Model

Phase Space Factors $G^{0\nu}$ & SRC (Short Range Correlations)

Mid-eighties: scaling factor R introduced in ν potential (r_0=1.1 or 1.2 fm!)

Critical and not unique parameters

$R = r_0 A^{1/3}$, g_A

$$(T^{0\nu}_{1/2})^{-1} = |M^{(0\nu)}|^2 \cdot G_{01} \left(\frac{< m_{\nu e} >}{m_e} \right)^2$$

$$G_{01} = \frac{a_{01}}{m_e^2 ln2} \int d\omega_{0\nu} F_0(Z, \epsilon_1) F_0(Z, \epsilon_2)$$

$$a_{0\nu} = \frac{(G g_A)^4 m_e^9}{64\pi^5}$$

$$G^S_{01}(R) = \frac{a_{01}}{(m_e R)^2 ln2} \int d\omega_{0\nu} F_0(Z, \epsilon_1) F_0(Z, \epsilon_2)$$

Nuclear models in ββ decay calculations: independent particle picture.

* Long-range correlations taken into account (mixing of states within their model spaces),

* Short-range repulsive correlations (nucleon hard core) absent in wavefunctions.

* SRC effect relevant for operators ~ order of the hard core radius.

Approximate way to correct for this: correlation function f(|r1 – r2|)

$$< ppJ_p||O^J||nn'J_n > = < ppJ_p f||O^J||f nn'J_n >$$

Estimate for f

* Step function

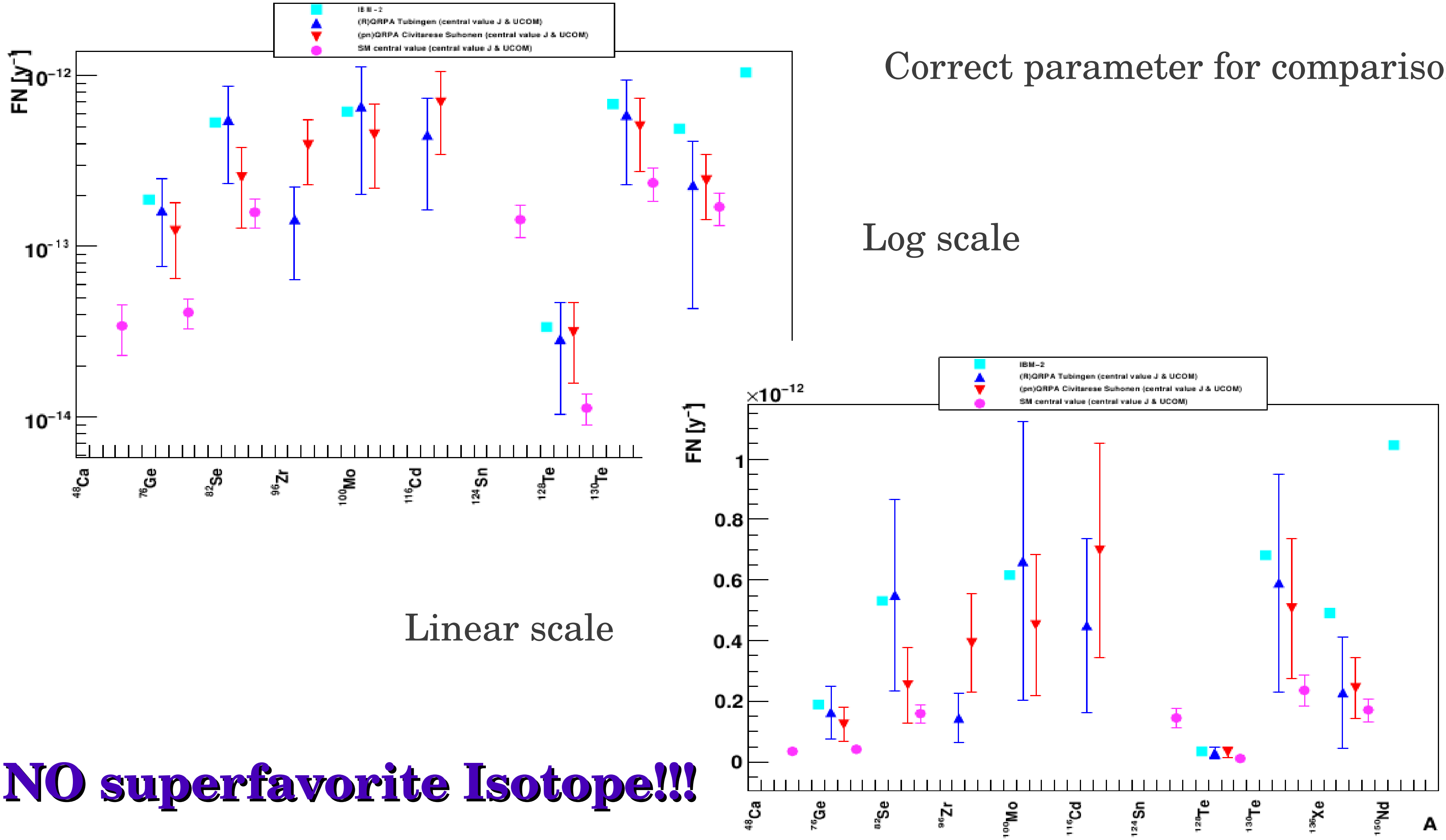
* Miller-Spencer f(r)

a=1.1 fm^{-2} b=0.68 fm^{-2}

$$f(r) = 1 - e^{ar^2}(1 - br^2)$$

$$a = 1.1 fm^{-2} b = 0.68 fm{-}2$$

Correct Comparison: $F^{0\nu}$



Correct parameter for comparison

Log scale

Linear scale

NO superfavorite Isotope!!!

The background issue

Which is the required bkg to have sensitivity to IH and NH (1σ CL)?
Let´s take ^{76}Ge as an example, M=1 t, i.a. 86%, ε=1, FWHM~0.15%, T=5y

IH: $<m_{ee}> = 50$ meV: $n_{\beta\beta} \sim 30$ => $b \sim 0.05$ c/keV/kg/y
NH: $<m_{ee}> = 15$ meV: $n_{\beta\beta} \sim 2.5$ => $b \sim 4x10\text{-}4$ c/keV/kg/y

For ~3 signal events an almost ¨background free¨ experiment is needed

Background reduction techniques:

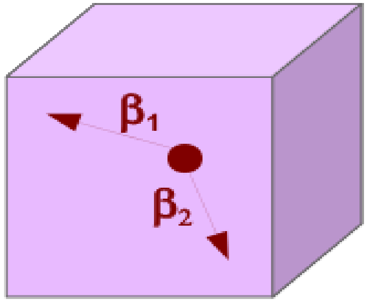
- Operating underground
- Shields with increasing cleanliness + active vetoes
- Select clean materials for detector and set-up construction
- Select isotope with high Q-value (eg. ^{48}Ca, ^{82}Se, ^{100}Mo, ^{150}Nd
- Particle Id & location (eg. with tracking, PSA, light/heat...)
- Spectroscopic id of daughter nucleus (eg. ^{136}Ba^{++} tag)
- Good energy resolution (for 2νββ bkg a σ<2% is needed)

Experimental Techniques

Two main approaches: calorimetric (source ≤ detector) or external-source detector

Calorimeters

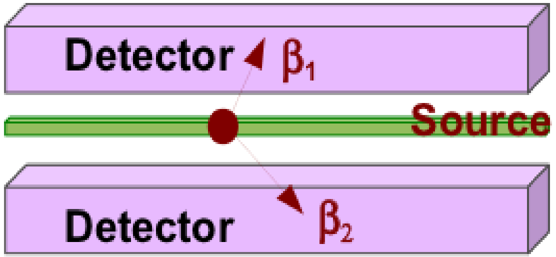
Solid-state devices, bolometers, scintillators, gas/L detectors



- Constraints on detector choice (except for bolometers)
- Very large M possibles (demonstrated ~50kg, proposed ~1t)
- High efficiency (ε~1)
- Very high resolution (ΔE~0.15%) with Ge-diodes, bolometers
- Event topology in gas/liquid Xe detectors or pixellization

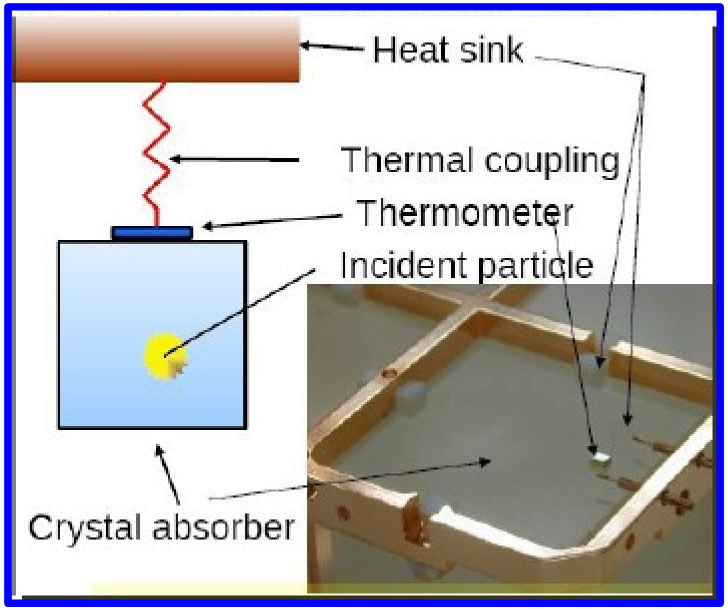
External-source detectors

Scintillators, gas TPC, gas DC, magnetic field and TOF



- Difficult to get large source M
- Difficult to get high efficiency
- Difficult to get good resolution
- Event topology allowing ¨clean bkg¨ (except 2νββ)
- Several ββ candidates can be studied with same det.

Experimental Techniques (2): Bolometers



Detection principle

$\Delta T = E/C$

C: heat capacity

$T < 1K$

Energy resolution's intrinsic limitation:

Statistical Energy fluctuations

$$\langle \Delta U^2 \rangle = k_B T^2 C$$

...Electronic noise...etc

✔Whole deposited energy measured

✔The detector is fully sensitive

Thermal Detectors features

▲ Excellent Energy Resolution.

▲Wide material choice.

▼ Only Energy info

▼ Slow time response

TeO_2 absorbers:

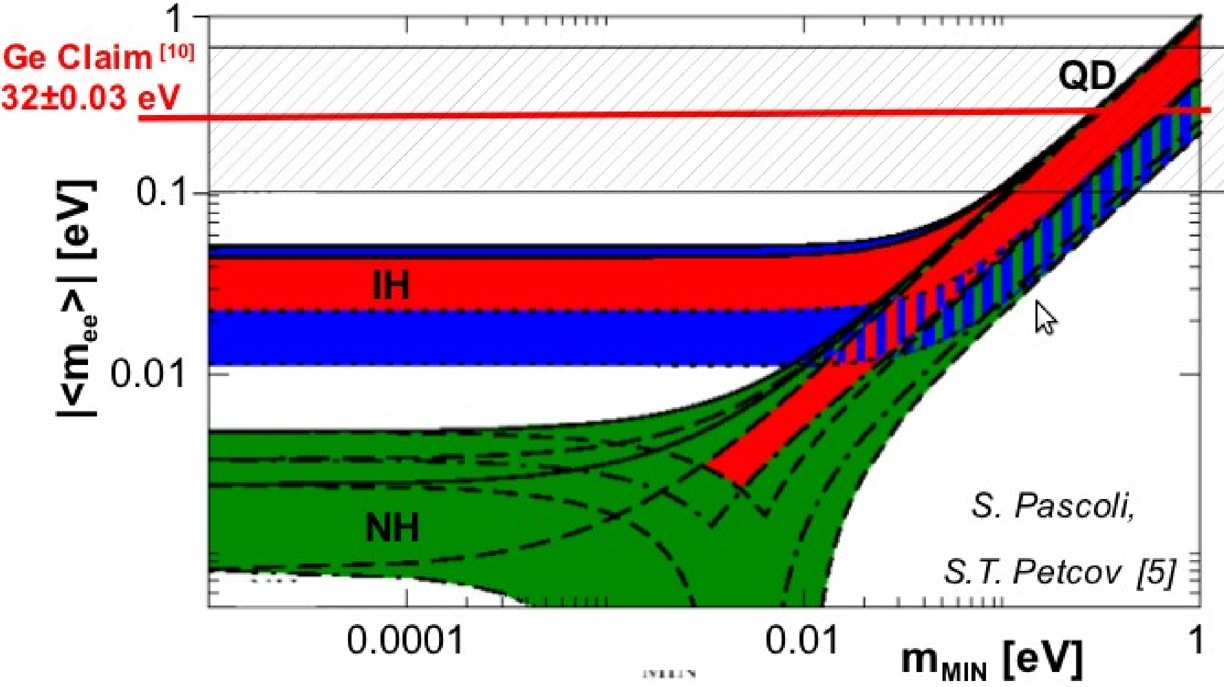
▲ Low specific heat

▲ relatively big crystals available

▲ radiopure

0νββ status of the art

Experiments carried out so far had masses of ~ tens of kg of the ββ candidate
Sensitivity in the QD region of the ν mass spectrum



^{76}Ge Claim [10]
0.32±0.03 eV

Spread due to NME uncertainties

HM [6] , IGEX [7]
Cuoricino [8]
Nemo3 [9], DAMA[10]

Touching ^{76}Ge claim region but not covering it

CUORICINO (qino): ^{130}Te ββ0ν decay to the GS

Bkg at Q-value: 0.17 counts/(keV kg y)
Statistics: 19.75 kg(^{130}Te) y

Maximum likelihood fit with 8 free parameters:

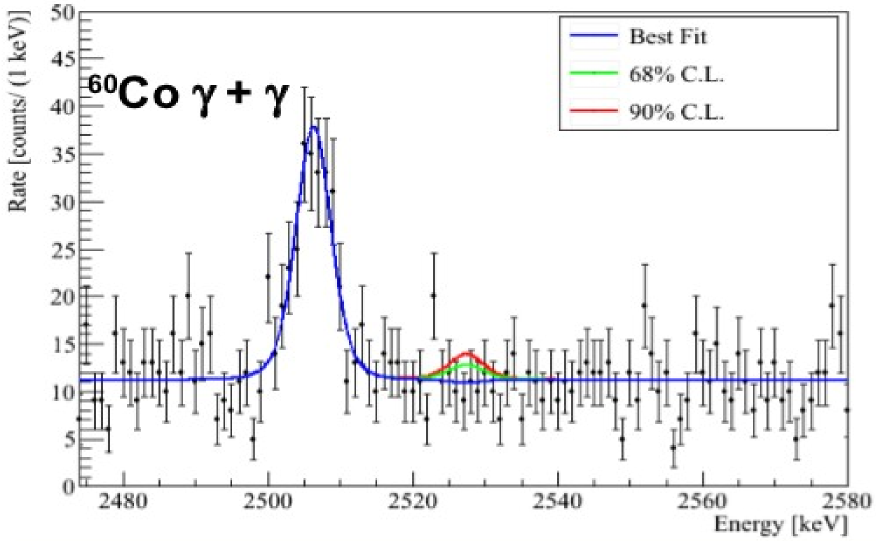
- ββ0ν rate
- 3 flat bkg rates (big, small and enriched xtals)
- 3 ^{60}Co rates (big, small and enriched xtals)
- ^{60}Co sum energy (same for all detectors)

$$\Gamma^{0\nu} = (-0.2 \pm 1.4(stat) \pm 0.3(syst)) \times 10^{-25}\, y^{-1}$$

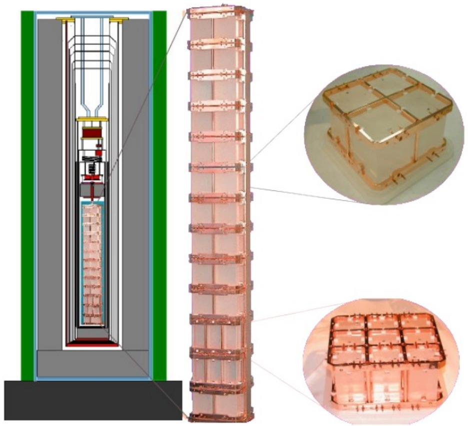
Half life limit: Bayesian approach with flat prior

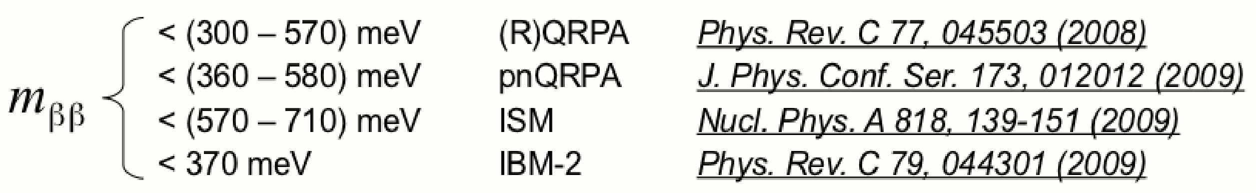
$$T_{1/2}^{0\nu} > 2.8 \times 10^{24}\, y \quad @90\%\, CL$$

Astropart. Phys. 34 (2011) 822–831



The CUORICINO limit on $m_{\beta\beta}$ is comparable with the one reported by the Heidelberg-Moscow experiment in ^{76}Ge, but can not exclude the claim of observation





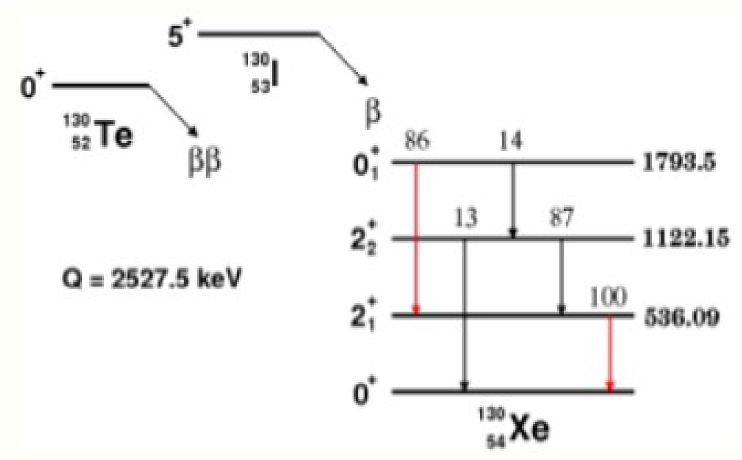
$m_{\beta\beta}$	< (300 – 570) meV	(R)QRPA	*Phys. Rev. C 77, 045503 (2008)*
	< (360 – 580) meV	pnQRPA	*J. Phys. Conf. Ser. 173, 012012 (2009)*
	< (570 – 710) meV	ISM	*Nucl. Phys. A 818, 139-151 (2009)*
	< 370 meV	IBM-2	*Phys. Rev. C 79, 044301 (2009)*

QINO : ^{130}Te ββ on 0^+ excited ^{130}Xe

Decay accompanied by the emission of two γ's:

1257 keV and 536 keV

The electrons (and neutrinos, in the 2ν decay mode) share a total energy of 734 keV



Theoretical calculations:

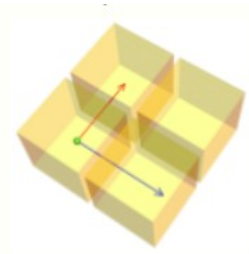
0ν (mββ = 1 eV): $T_{1/2}=7.5\times10^{25}$ y

2ν: $T_{1/2}=(0.5\div1.4)\times10^{23}$ y

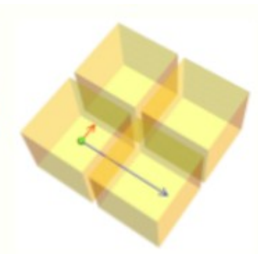
Coincidence-based analysis

Search for events involving two or three crystals ββ

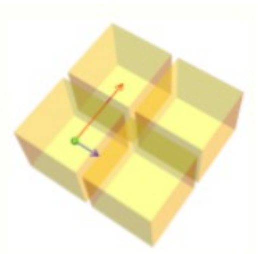
- Require that the photons are completely absorbed in one crystal
- Three possible scenarios:



Both γ's escape the decay crystal



The1257 keV γ escapes. The 536 keV γ is trapped in the decay crystal



The 536 keV γ escapes. The 1257 keV γ is trapped in the decay crystal

Signature [keV]	Decay	Efficiency [%]
734 ⊕ 536 ⊕ 1257	0ν	0.44 ± 0.02
1257 ⊕ 1270	0ν	1.79 ± 0.04
536 ⊕ 1991	0ν	1.10 ± 0.03
(0 – 734) ⊕ 536 ⊕ 1257	2ν	0.41 ± 0.02
(536 – 1270) ⊕ 1257	2ν	2.29 ± 0.05

QINO: ^{120}Te β /EC double beta decay

$$^{120}Te \rightarrow {}^{120}Sn + e^{+}(+2\nu)$$

Q = (1714.8 ± 1.3) keV

Theoretical calculations:

0ν: not available
2ν: $T_{1/2}^{2\nu} = 4.4 \times 10^{26}\ y$

Isotopic abundance: **0.096%**

Statistics: **0.0573 kg(^{120}Te) y**

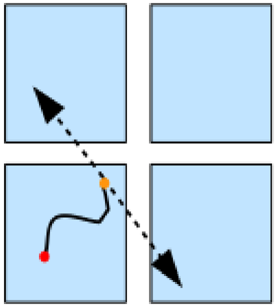
Analysis approach

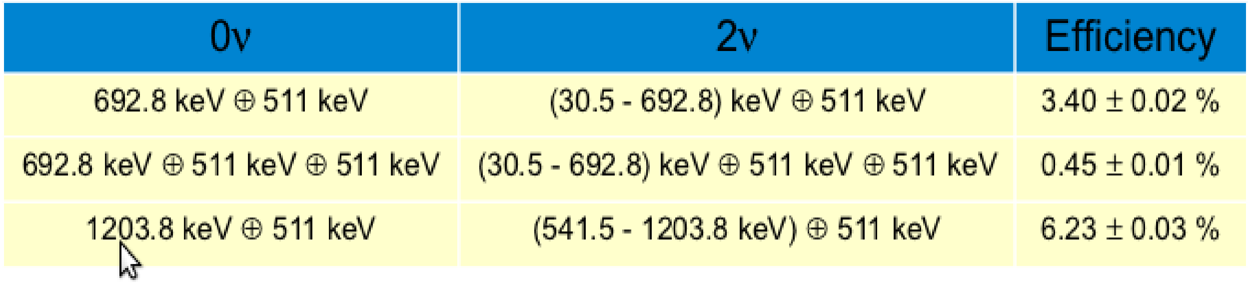
In the 0ν decay mode, the energy transferred to the positron is
$K_{max} = Q - 2\ m_ec^2 - E_b$ (E_b binding energy of the captured e^-).
If E_b is contained in the detector, the total energy release is $E_0 = K_{max} + E_b = 692.8$ keV

In the 2ν decay mode the kinetic energy of the positron has a continuous distribution between E_b and K_{max} (E_b = 30.5 keV if the capture proceeds through the K shell).

Coincidence-based analysis:

search for events in coincidence with one or two 511 keV gammas (from positron annihilation)

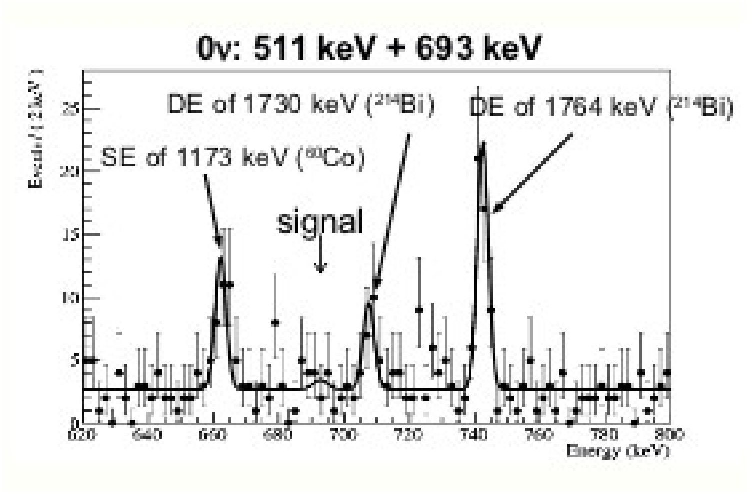




0ν	2ν	Efficiency
692.8 keV ⊕ 511 keV	(30.5 - 692.8) keV ⊕ 511 keV	3.40 ± 0.02 %
692.8 keV ⊕ 511 keV ⊕ 511 keV	(30.5 - 692.8) keV ⊕ 511 keV ⊕ 511 keV	0.45 ± 0.01 %
1203.8 keV ⊕ 511 keV	(541.5 - 1203.8 keV) ⊕ 511 keV	6.23 ± 0.03 %

Efficiencies evaluated using a GEANT4-based simulation

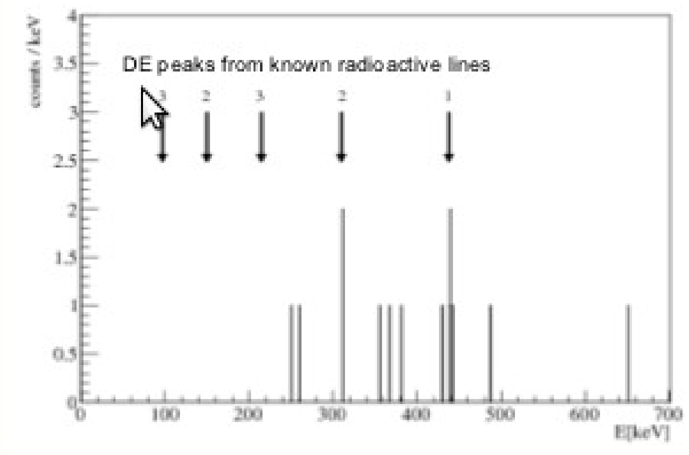
QINO ^{120}Te : ββ0ν & ββ2ν results



Global upper limit for the number of signal counts obtained by combining the posterior p.d.f.s of the three considered signatures

$$T^{0\nu}_{1/2} > 1.9\times10^{21}\,y \quad @90\%\,CL$$

Upper limit on the number of signal counts estimated using a Bayesian approach
Assume 4 bkg events over 8 observed events:
$n_{SIG} < 9$ @ 90% CL



$$T^{2\nu}_{1/2} > 0.9\times10^{20}\,y \quad @90\%\,CL$$

CUORE

988 TeO2 (34.167% ai 130Te) bolometers at ~ 10 mK in a granular structure
(741 kg mass) @LNGS
Phase-I: starts ~ end 2011 Phase-II: ~ 2014 Future: enr., scintill. bolom...

ββ candidate:
^{130}Te – Q 2527.5 keV

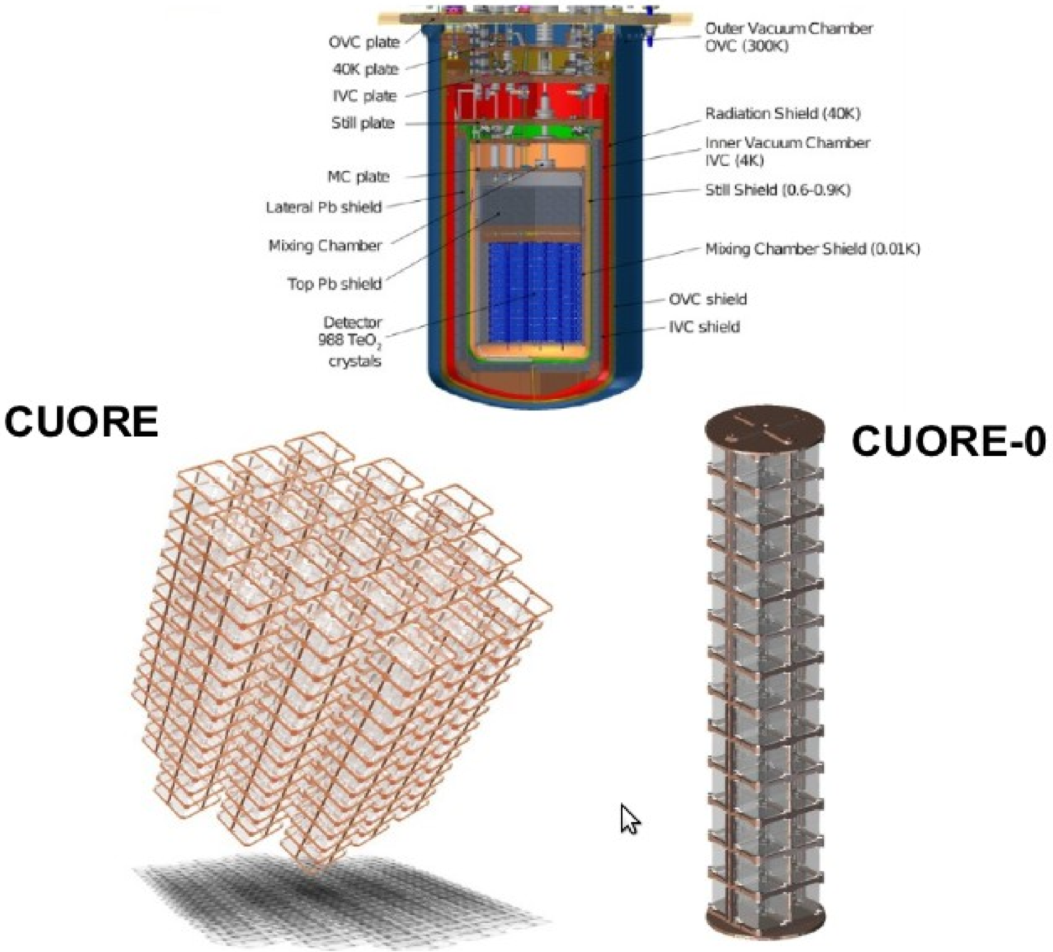
Source Mass:
Phase-I: 10.8 kg 130Te – Nββ 5.0 x1025
Phase-II: 206 kg 130Te – Nββ 9.6 x1026

Projected Bkg:
Phase-I: 0.05 c/keV/kg/y
Phase-II: 0.01 c/keV/kg/y

Resolution
FWHM: ~ 0.2% @ROI

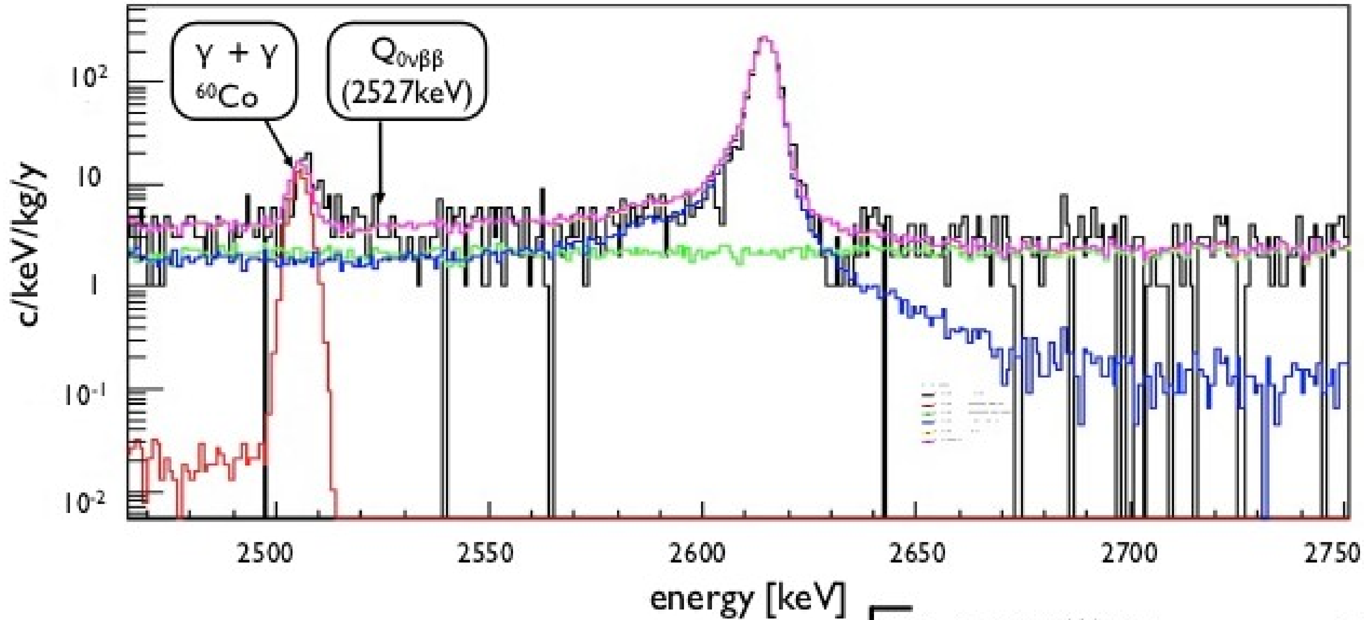
Sensitivity T1/20ν:
Phase-I: 4.2x10^{24} y in 1 y
Phase-II: 1.6x10^{26} y in 5 y

Sensitivity Phase-II <mee>:
$\langle m_{ee} \rangle < 40 \div 94$ meV in 5y – IH region



CUORE(2) Starting Point: Qino bkg

In the 0νDBD region:



- 30 ± 10 % ^{232}Th in cryostat (γ)
- 10 ± 5 % TeO_2 surface (α)
- 50 ± 20 % Cu surface (α)

Bkg @ 0νDBD region = 0.161 +/- 0.006 c/keV/kg/y
(ainticoincidence spectrum, 5x5x5 cm³ crystals)

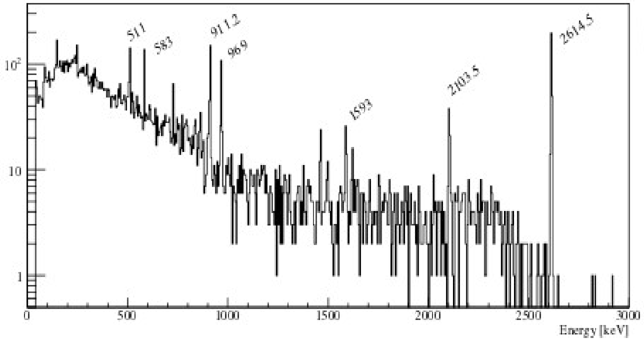
Flat background in the energy region above the ^{208}Tl 2615 keV line: contribution to the counting rate in the 0νDBD region: ~ 60% . Origin: **degraded alpha particles.**

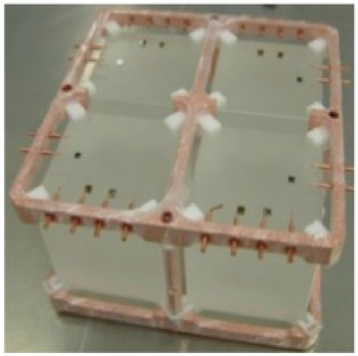
CUORE(3) CCVR & TTT

- The production of CUORE crystals started at SICCAS Jiading in 2008
  - ~ 30 crystals/month
  - ~ 700 crystals already at LNGS

- 7 CCVR already performed:
  - the bulk activity is within the limit specified in the contract with the crystals producer
  - improved the Cuoricino bolometric performance: FWHM on the calibration gamma line from ^{208}Tl (2615 keV) = 4.6 +/- 1.2 keV (excluding CCVR4 didn't reach the base T due to cryostat lems)

CUORE Crystals Validation Run: a dedicated cryogenic setup to test crystals extracted by every production batch.





Three Towers Test: a large mass detector to test the Cu contaminations in 3 different configurations inside the CUORICINO cryostat (same background and operation conditions).

T1
Polyethylene

Cleaning:
- Soap
- H_2O_2 + H_2O + Citric acid

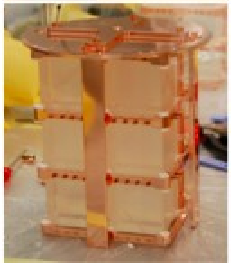
Polyethylene:
7 layers
Complete coverage

T2
Chemical New

Cleaning:
- Soap
- Electro erosion: 85% phosphoric acid, 5% butanol, 10% H_2O
- Etching: Nitric acid
- Passivation: H_2O_2 + H_2O + Citric acid

T3
Plasma cleaning

Chemical and
electrochemical
+
plasma cleaning



CUORE Status

CUORE-0: - in commissioning, will start in a few months (end 2011) in CUORICINO cryostat

CUORE: - Hut construction, detector engineering and design completed

- Crystal production, cryogenics (new cryostat, shields), electronics, DAQ in progress

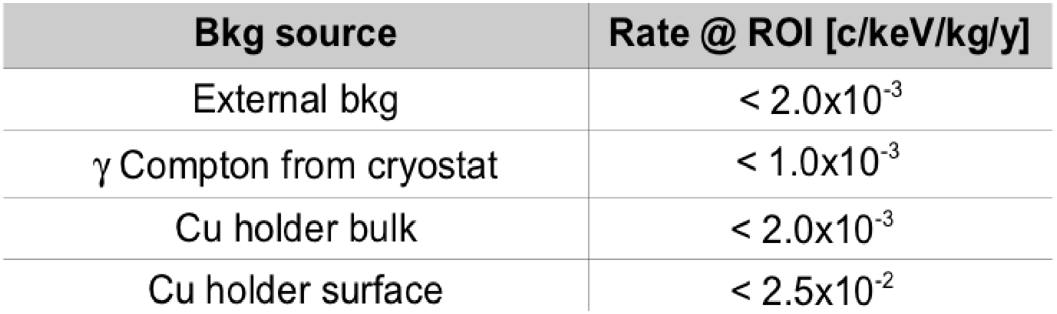
Resolution FWHM: 0.2% @ Qββ (already achieved)

Demonstrated bkg for CUORE-0: (TTT test): < 0.05 c/keV/kg/y

(mainly degraded α from near surfaces, γ Compton from cryostat)

Bkg reduction strategy for CUORE: new cryostat with optimized shields, controlled low activity materials, minimization of facing materials, surface contamination reduction, anticoincidence cut

up to date a projection
of bkg <0.025 c/keV/kg/y



Bkg source	Rate @ ROI [c/keV/kg/y]
External bkg	$< 2.0\times10^{-3}$
γ Compton from cryostat	$< 1.0\times10^{-3}$
Cu holder bulk	$< 2.0\times10^{-3}$
Cu holder surface	$< 2.5\times10^{-2}$

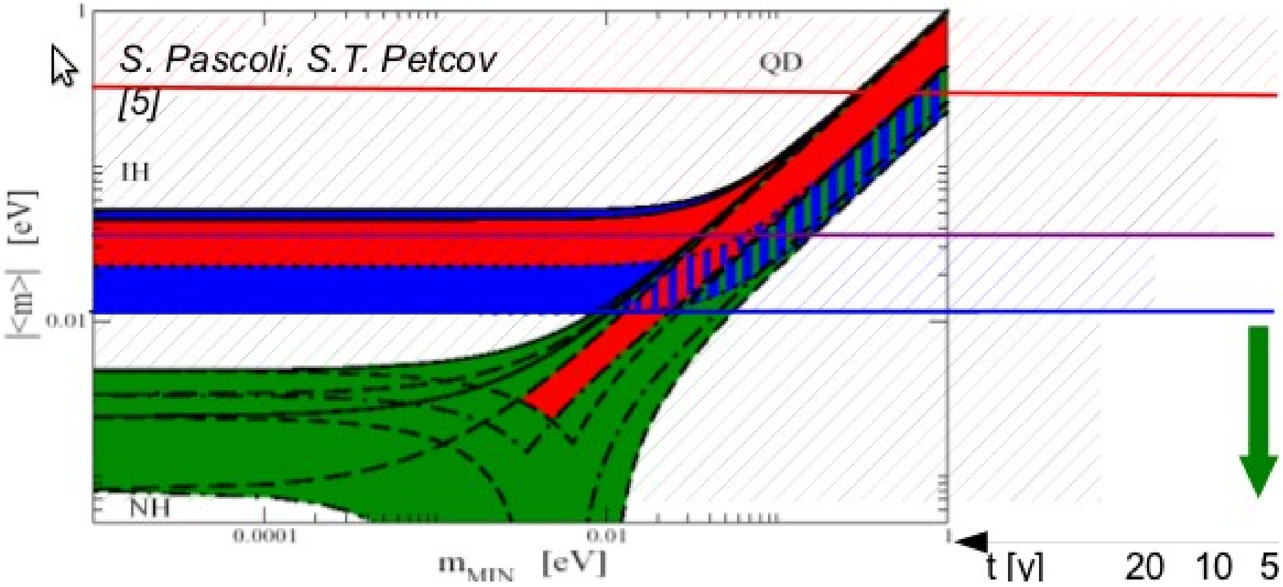
Conclusions

* ββ0ν search is well motivated (L violation, ν nature etc.) and is actually a hot topic

* Claim for evidence in ^{76}Ge with $<m_{ee}> \sim 0.3$ eV (DH) at > 6σ by part of the HM collaboration

* In 5 y: many 100-200 kg ββ isotope experiments currently under preparation should be able toscrutinize Ge claim in many isotopes

* In 5-10 y: many ~1 ton ββ isotope experiments will enter the IH region (10-50 meV) but without being able to completely cover it.



Scrutinize claim
In 5 y

1st phase: enter IH
10 years scenery

2nd phase: cover IH
Enr., bkg free

Future: NH ?
~10t, New strategies