

Lawrence Livermore National Laboratory

**Doppio Decadimento Beta
Senza Neutrini
(0ν DBD)**



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Sommario

- Il doppio decadimento beta senza neutrini
- Requisiti per un esperimento competitivo
- Stato dell'arte: esperimenti presenti e futuri
- Conclusioni
 - cosa succede nel futuro prossimo?
 - cosa ci possiamo aspettare nel medio periodo?



Perche' cercare il DDB0 ν ?

I risultati degli esperimenti di oscillazioni di neutrino hanno focalizzato l'attenzione della comunita' scientifica sulle proprieta' di questa particella elusiva



Massa del neutrino non nulla

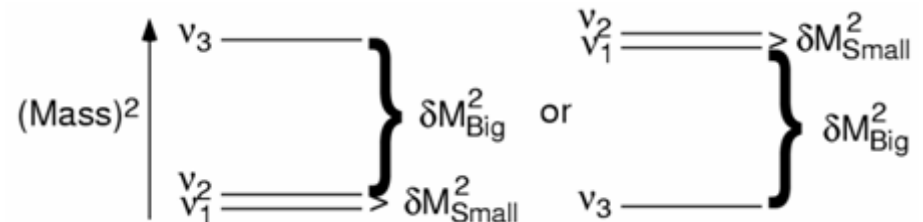
Autostati di sapore →

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

← Autostati di massa con autovalori di massa M_1, M_2, M_3

↑ Neutrino Mixing Matrix

3 autostati di massa M_1, M_2, M_3 ma oscillazioni di ν possono misurare **solo** le $\Delta M_{ij}^2 = M_i^2 - M_j^2$



Cosa non sappiamo

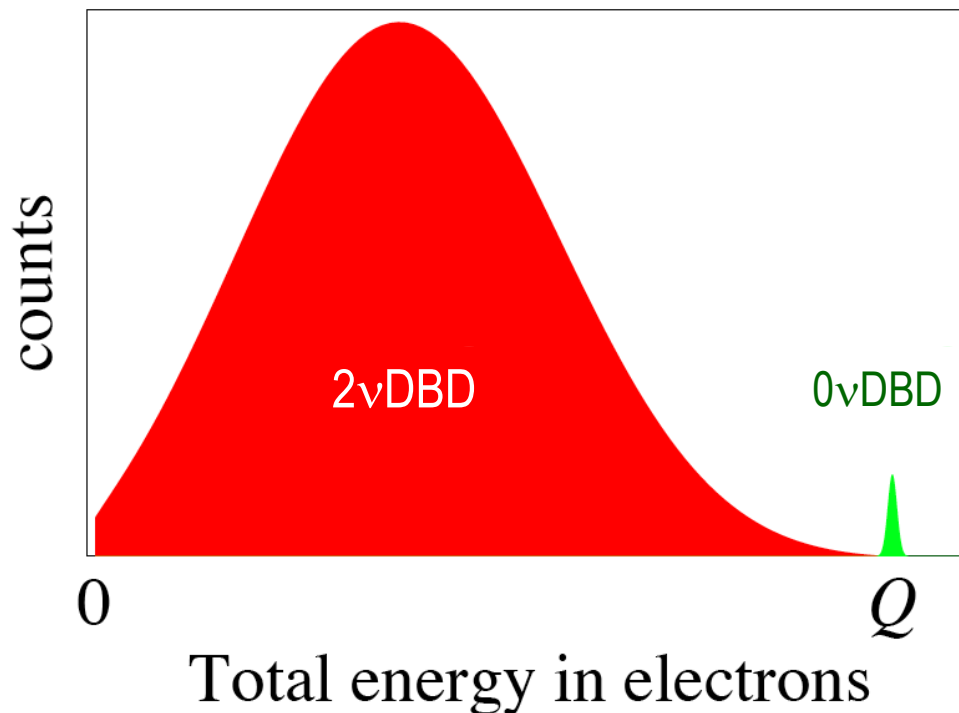
- valore assoluto delle masse
- la natura del ν



Firma del Doppio decadimento beta senza neutrini

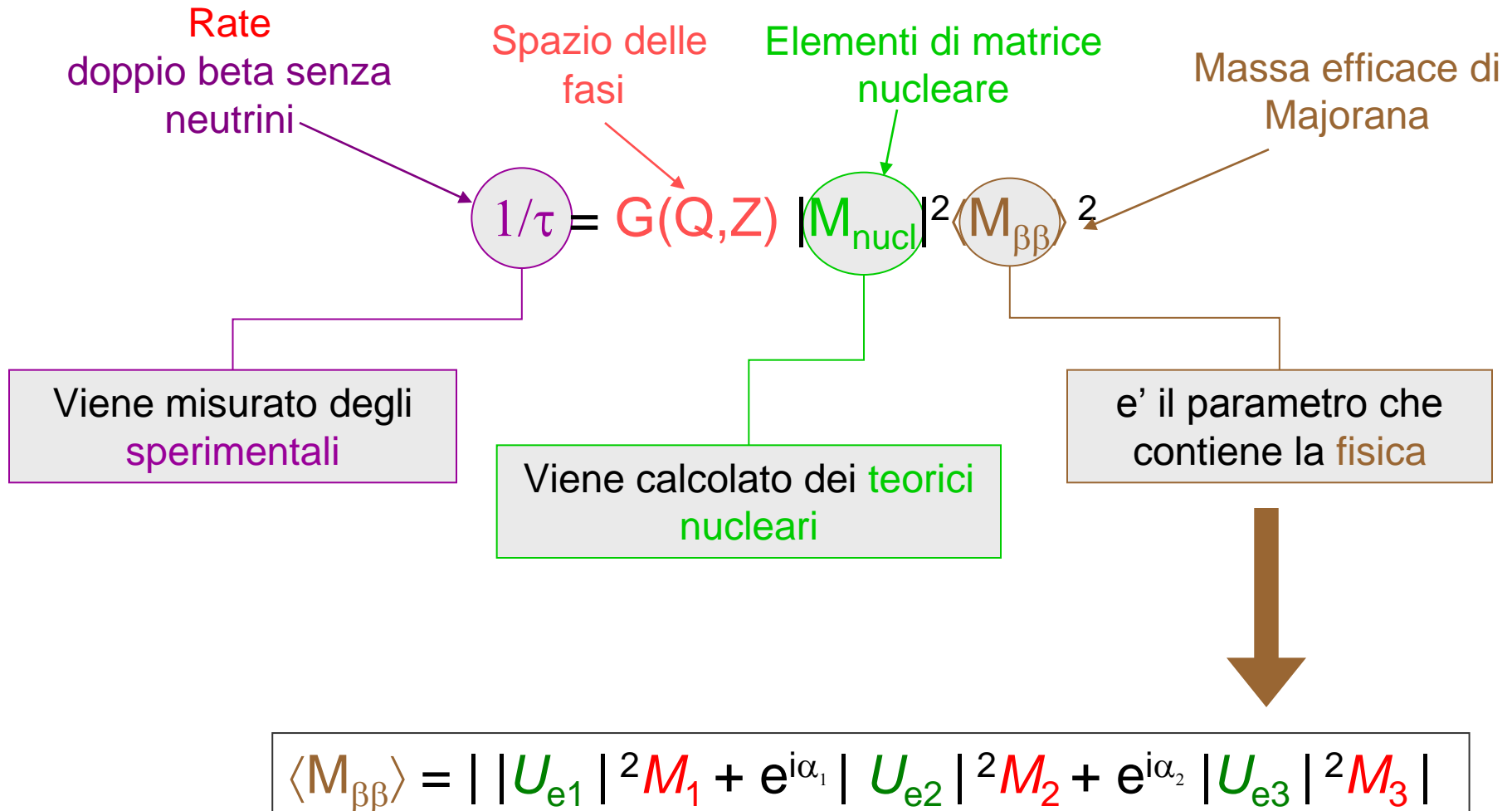
L'unico decadimento che puo' dare risposte sulla natura del neutrino e' un decadimento raro chiamato Doppio Decadimento Beta senza neutrini.

- ① $2\nu\text{DBD}$: $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e \longrightarrow$ Permesso dal Modello Standard
- ② $0\nu\text{DBD}$: $(A,Z) \rightarrow (A,Z+2) + 2e^- \longrightarrow$ Nuova fisica oltre il MS



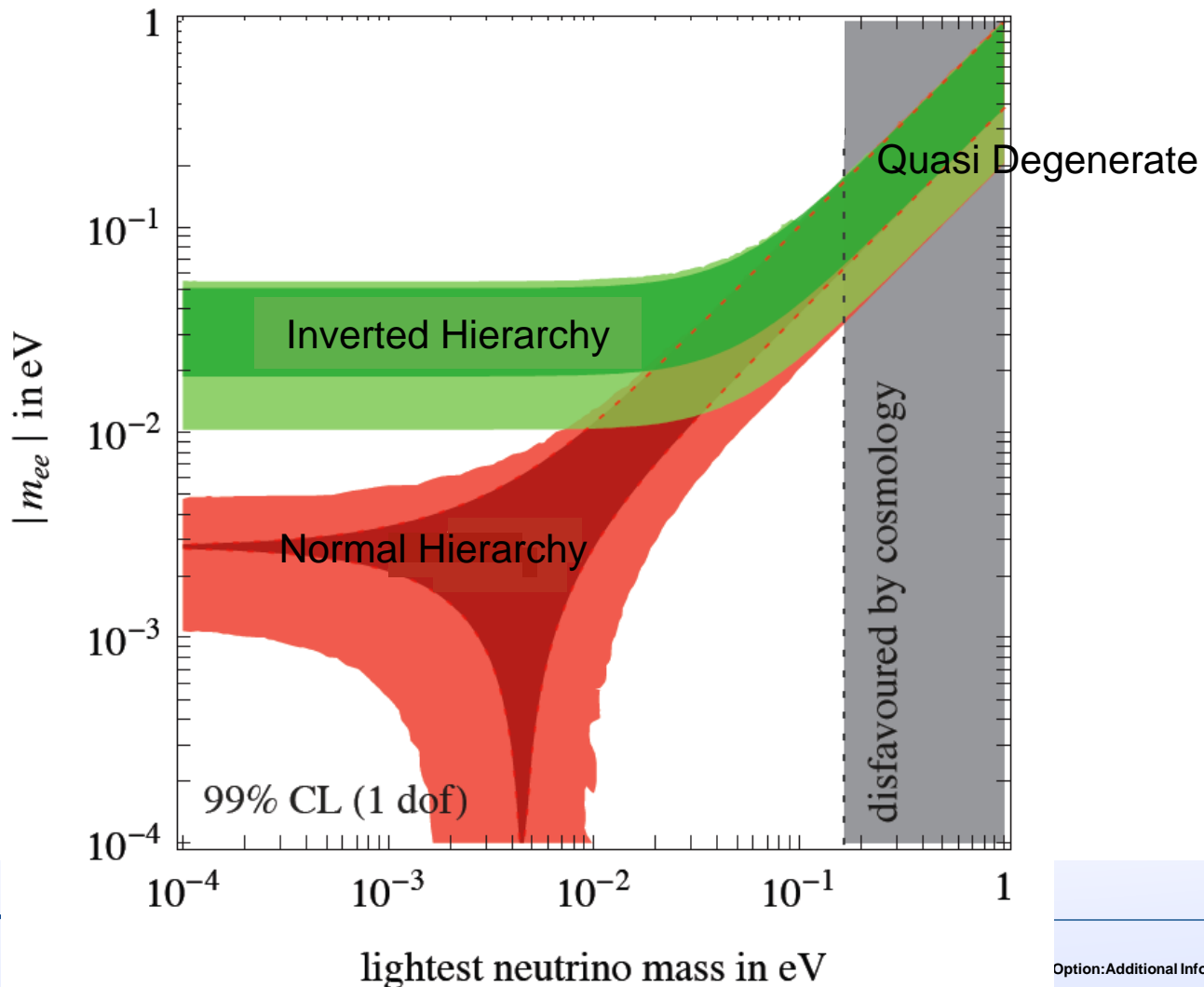
Il picco del doppio decadimento beta senza neutrini si allarga solo a causa della risoluzione energetica del rivelatore

Come il $0\nu\text{DBD}$ e' connesso alla matrice di mixing e ai valori di massa del neutrino?



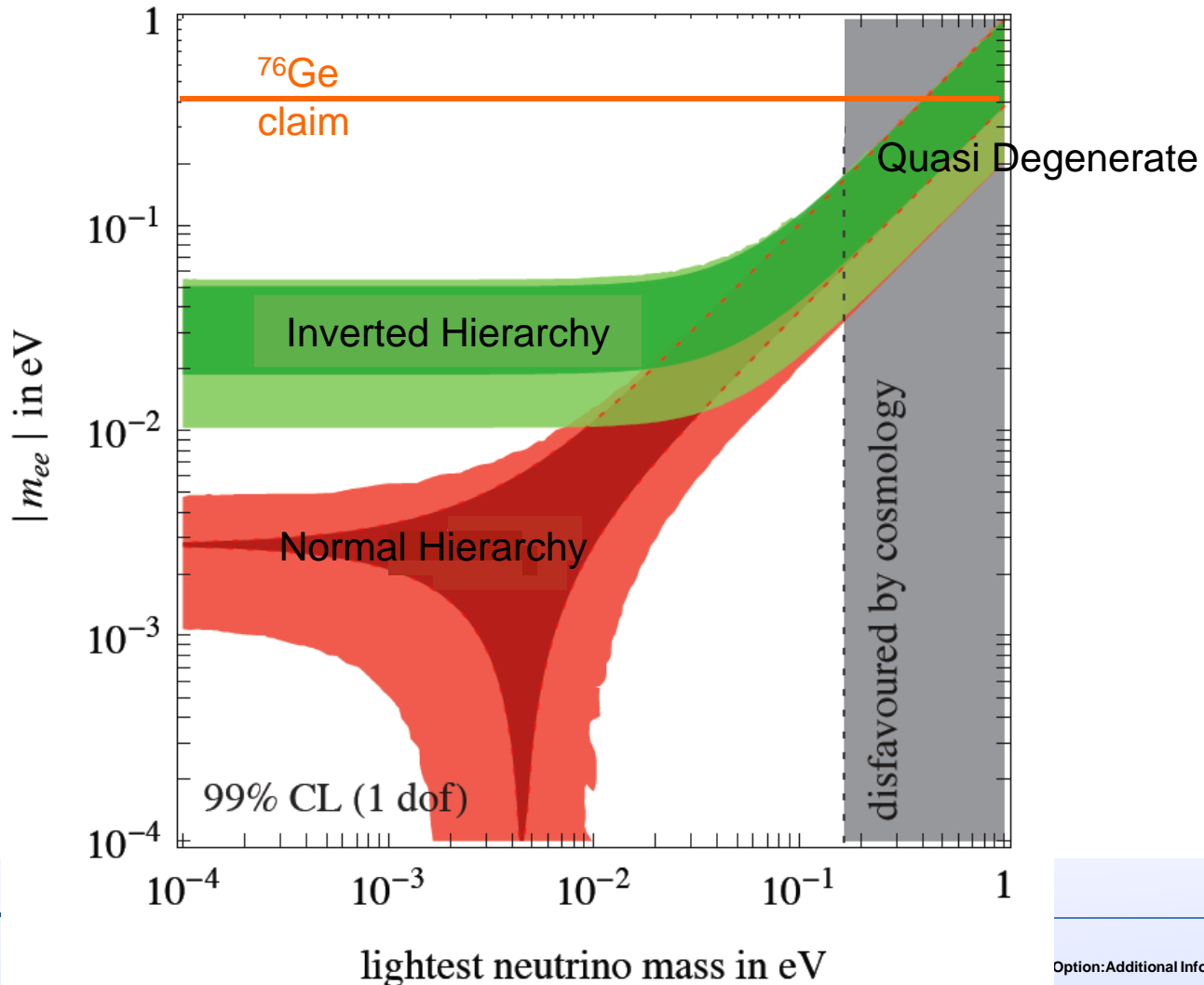
$0\nu\text{DBD}$ e massa dei neutrini

$$\langle M_{\beta\beta} \rangle \propto |U_{e1}|^2 M_1 + |U_{e2}|^2 M_2 + |U_{e3}|^2 M_3$$



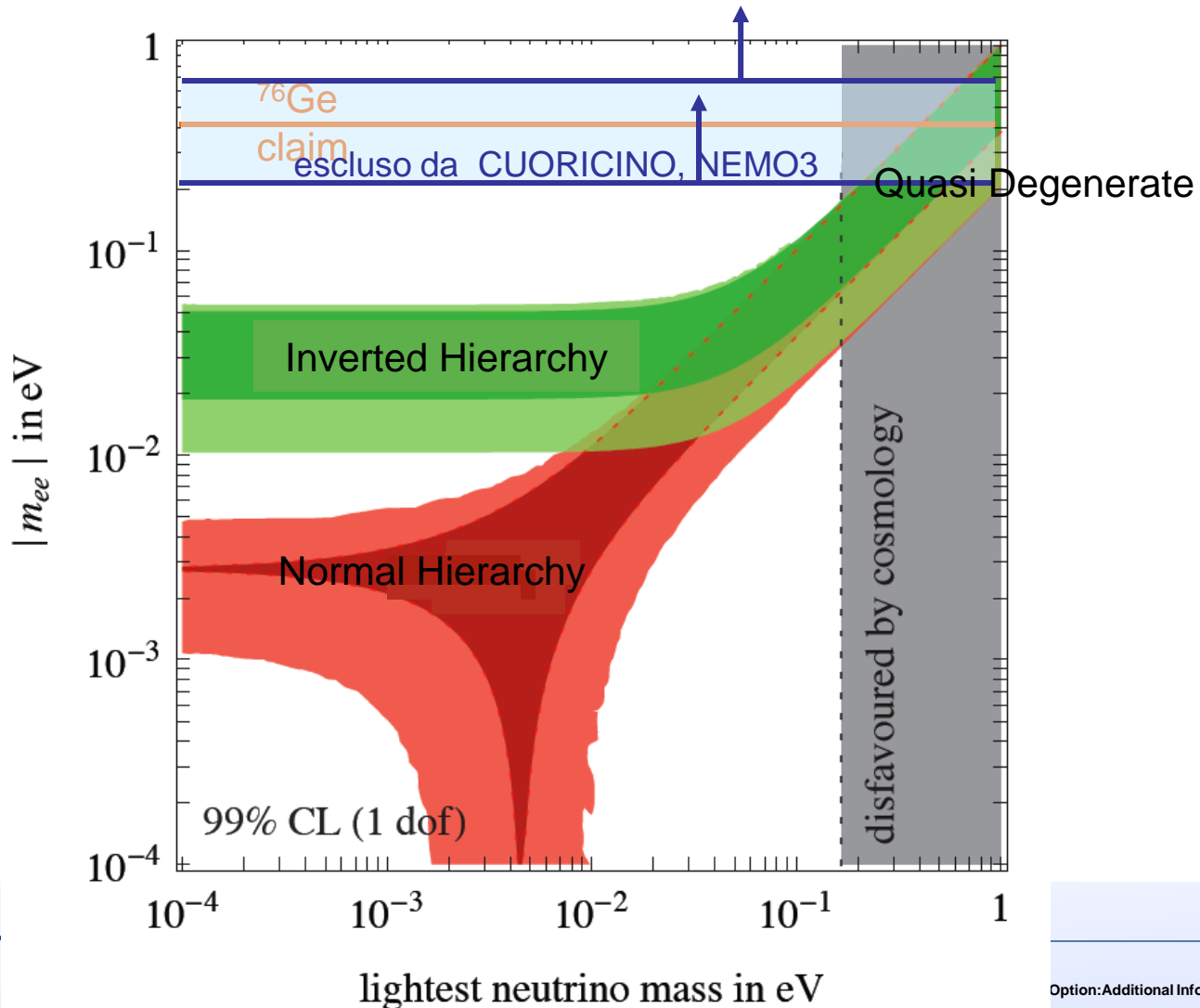
$0\nu\text{DBD}$ e massa dei neutrini

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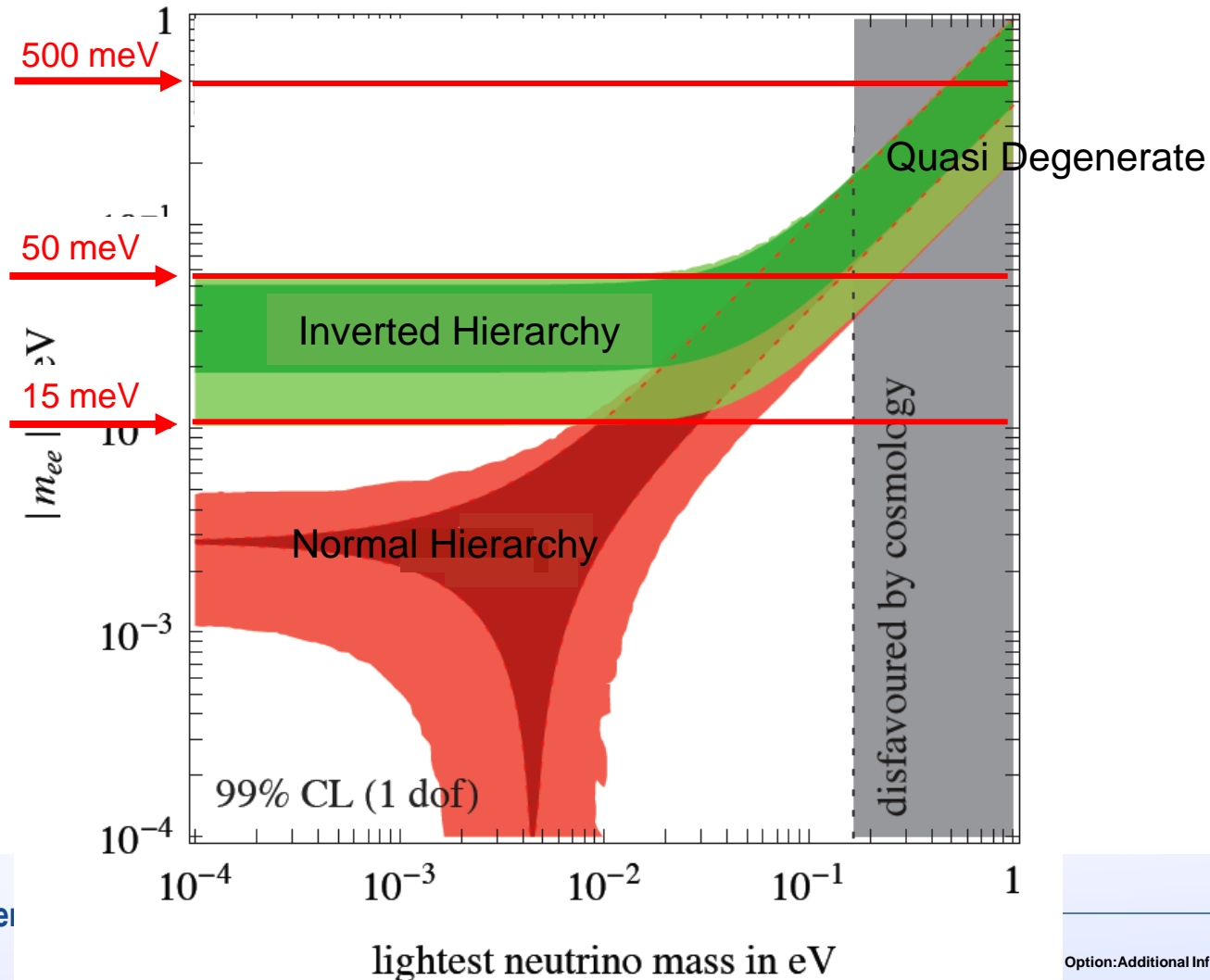
$0\nu\text{DBD}$ e massa dei neutrini

$$\langle M_{\beta\beta} \rangle \propto |U_{e1}|^2 M_1 + |U_{e2}|^2 M_2 + |U_{e3}|^2 M_3$$



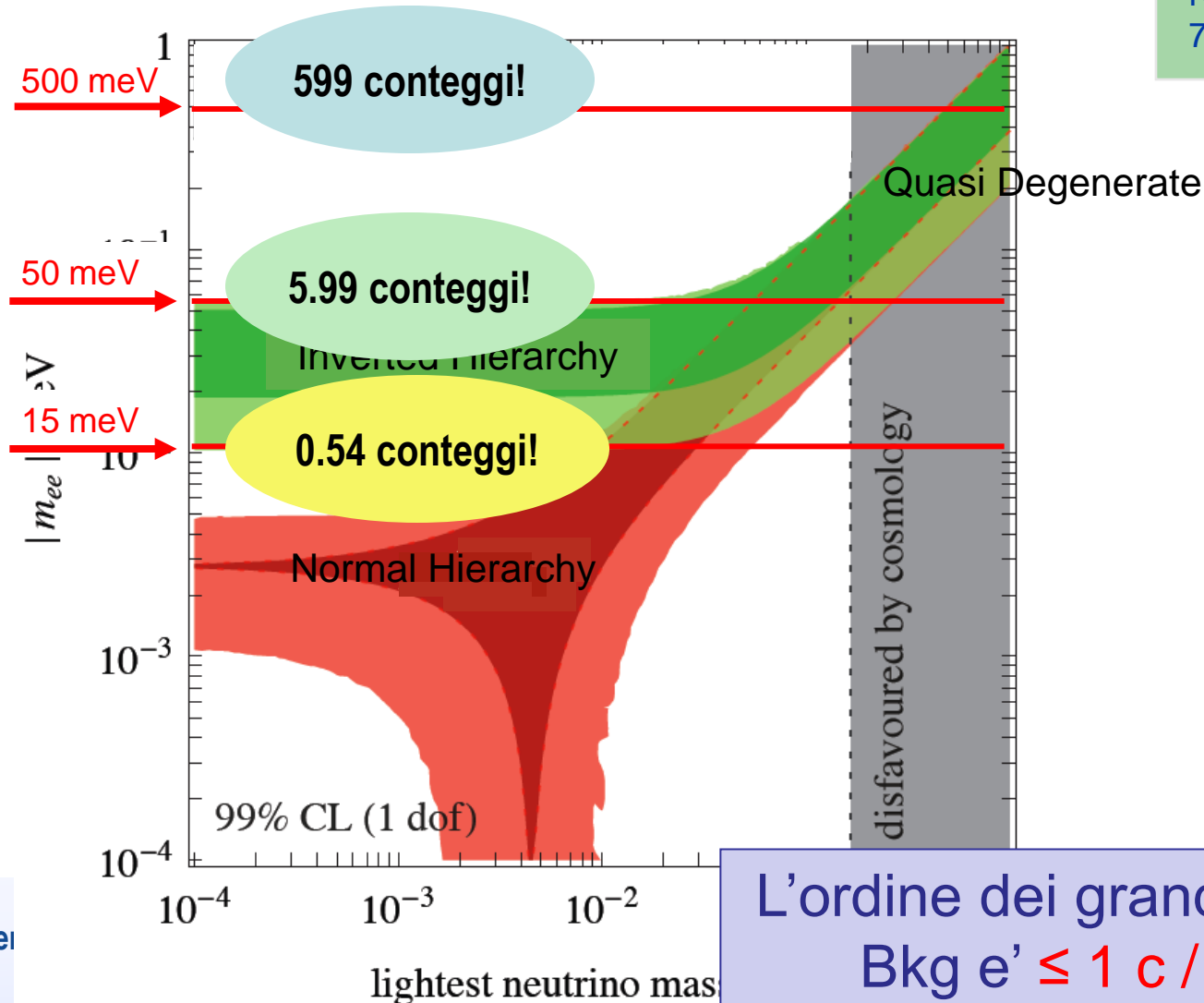
$0\nu\text{DBD}$ e massa dei neutrini

3 valori di massa del neutrino possono essere visti come futuri obiettivi:



QUANTI CONTEGGI SI ASPETTA DI OSSERVARE **IN UN ANNO** UN ESPERIMENTO CHE USA **UNA TONNELLATA** DI GERMANIO **ARRICCHITO**

Rodin et al.
Nucl. Phys. A
793, 213 (2007)



L'ordine di grandezza del Bkg e' ≤ 1 c / y ton

Requisiti per un esperimento competitivo di 0nDBD

Sensibilita' $S_{0\nu}$: tempo di vita corrispondente al minimo numero rilevabile di eventi sopra un fondo a un dato livello di confidenza

$$S_{0\nu} \propto \sqrt{\frac{M \cdot T}{\Gamma \cdot b}}$$

Massa della sorgente

Tempo vivo di misura

Livello del fondo

Risoluzione energetica

- elevato numero di nuclei sorgente in osservazione
- lungo tempo di misura
- buona risoluzione energetica
- **basso fondo**

Esperimenti di 0vDBD

| Nome | Nucleo | Metodo | Location | Stato |
|-------------|----------------------------------|---------------|----------|-------------------------------------|
| Cuoricino | ^{130}Te | bolometric | LNGS | Completato |
| Nemo-3 | ^{82}Se | tracking | Frejus | Completato |
| CUORE | ^{130}Te | bolometric | LNGS | Finanziato – in costruzione |
| GERDA | ^{76}Ge | ionization | LNGS | Finanziato (I & II) – in presa dati |
| LUCIFER | ^{82}Se | bolometric | LNGS | Finanziato (R&D e esperimento) |
| KamLAND-ZEN | ^{136}Xe | scintillation | Kamioka | Finanziata I fase - in costruzione |
| EXO | ^{136}Xe | tracking | WIPP | Finanziato R&D dimostratore |
| SNO+ | ^{150}Nd | scintillation | SNOLAB | Finanziato (Nd naturale) |
| SuperNEMO | $^{82}\text{Se}/^{150}\text{Nd}$ | tracking | Frejus | Finanziato R&D e dimostratore |
| MAJORANA | ^{76}Ge | ionization | SUSEL | Finanziato R&D e dimostratore |
| COBRA | ^{116}Cd | semiconductor | LNGS | R&D |

Il primo passo per questi esperimenti e' il confronto con il claim HM-KK

GERDA



→ ^{76}Ge

$Q_{\text{bb}} = 2039 \text{ keV}$

Rivelatore: Array Ge arricchiti (~86%)

Buona risoluzione energetica $< 0.19\%$ a Q_{bb}

Location: Hall A @ LNGS (Italia)

Fase I: test claim

8 cristalli da HM e IGEX (18 Kg)

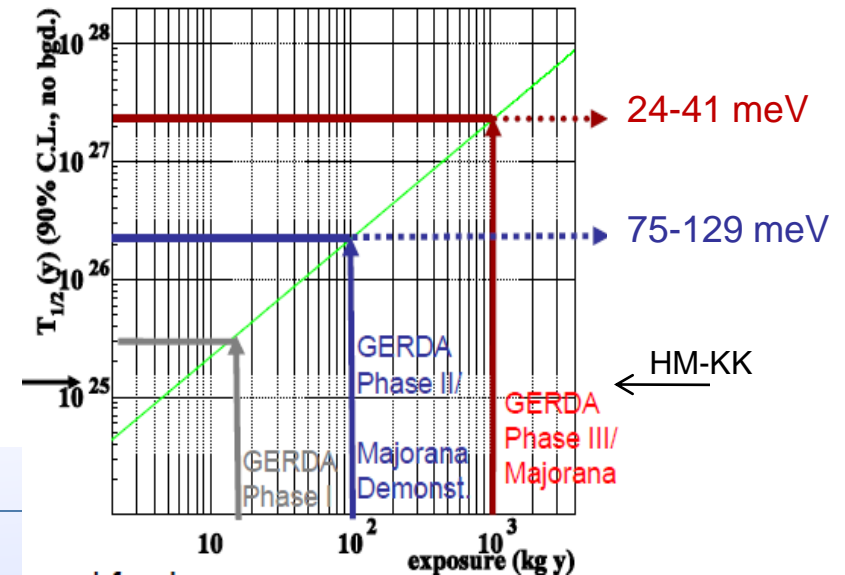
bkg: 10^{-2} cnt/(keV kg y)

Fase II:

nuovi rivelatori **segmentati**

bkg: 10^{-3} cnt/(keV kg y)

→ $\langle M \rangle < 90 - 290 \text{ meV}$

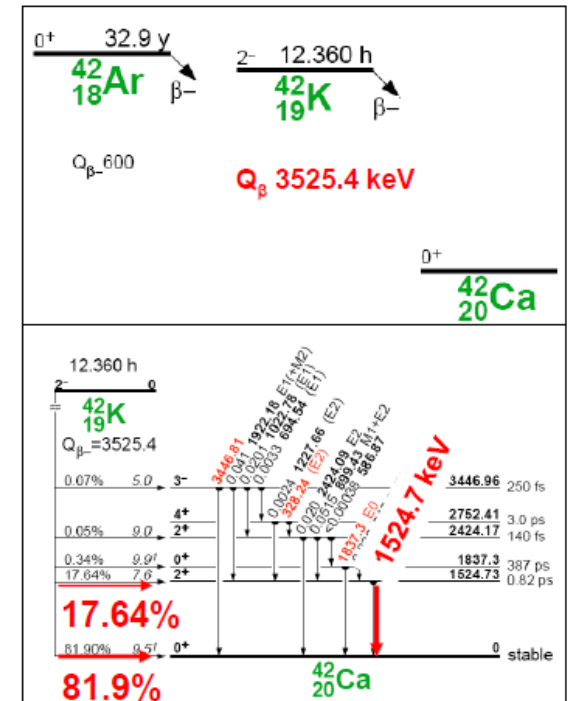
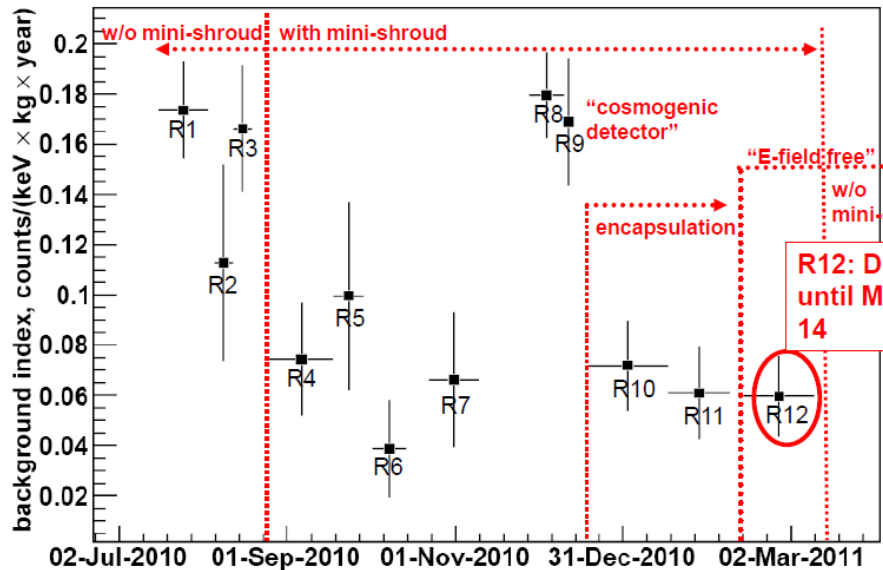


GERDA – stato dell'arte



Estate 2010 installazione di 3 rivelatori Ge naturale per lo studio delle prestazioni e del fondo

Fondo inaspettato dovuto allo spettro beta del ^{42}K



Problema “risolto”. → presto studio del fondo con stringhe di rivelatori arricchiti per lo studio del fondo e inizio della fase di fisica.



CUORE



→ ^{130}Te

$Q_{\text{bb}} = 2527 \text{ keV}$

Abbondanza naturale: ~ 34%

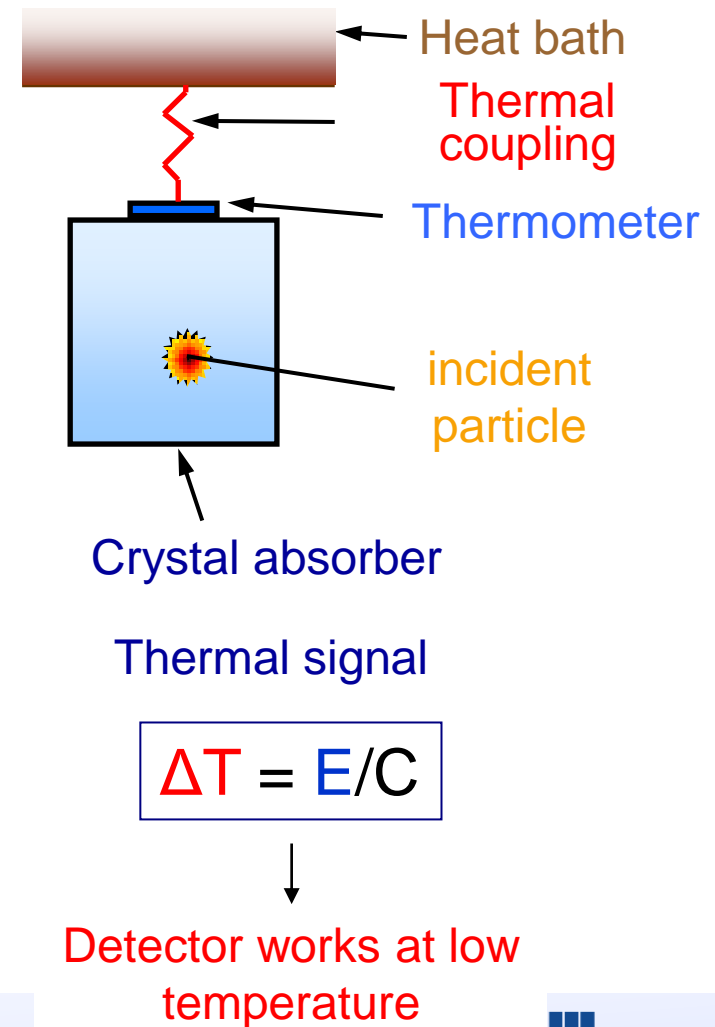
Rivelatori: 19 torri di 52 cristalli $5 \times 5 \times 5 \text{ cm}^3$
bolometri di TeO_2 @ ~ 10 mKelvin

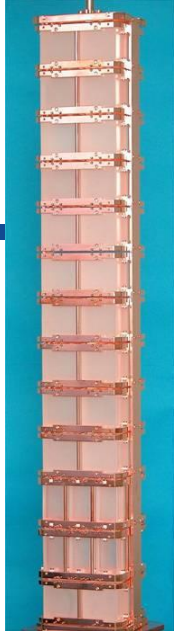
$\Delta E = 0.2\%$ @ Qvalue

Location: Hall A @ LNGS (Italia)

Sensitivity (5 y): $T^{1/2} = 2.1 \cdot 10^{26} \text{ y}$
 $m_\nu = 35 - 82 \text{ meV}$

NME from F.Simkovic et al. Phys.Rev. C77 - J.Suhonen et al. Int.Jou.Mod.Phys. E17 -
J.Menendez et al. Nucl. Phys. A818 - J.Barea et al. Phys. Rev. C79

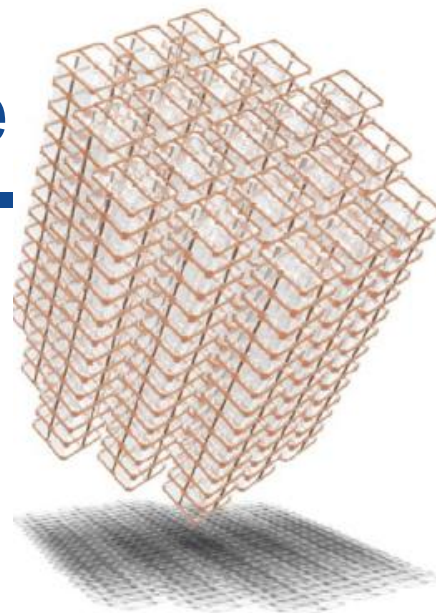




CUORE -



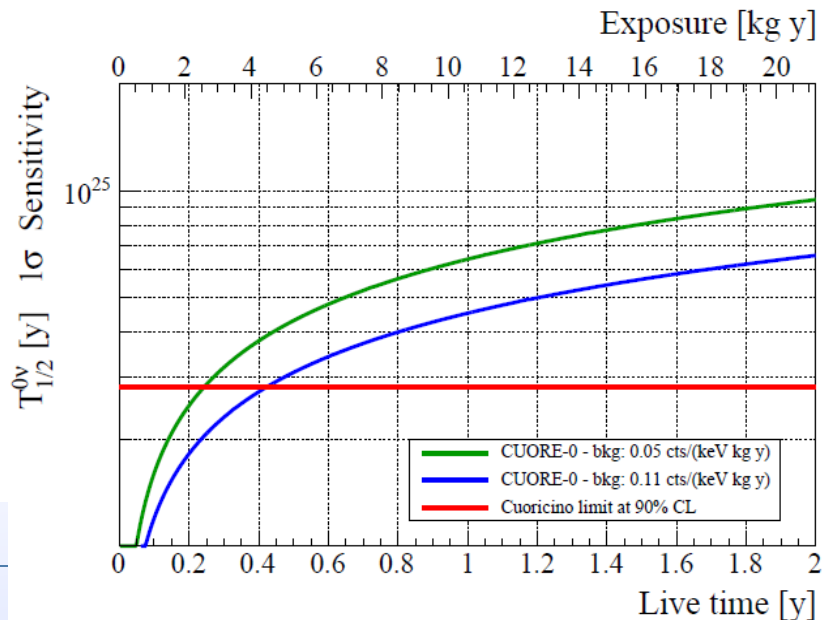
stato dell'arte



il prossimo passo verso CUORE e' CUORE-0

E' una torre costruita esattamente come le torri di CUORE e prendera' dati a partire dall'autunno 2011 nel vecchio refrigeratore di Cuoricino. Lo scopo e' quello di test dei sistemi di assemblaggio del rivelatore, di test del fondo, degli skill della collaborazione.

Inoltre CUORE-0 e' anche esperimento vero e proprio che in pochi mesi raggiungera' la sensibilita' di cuoricino!



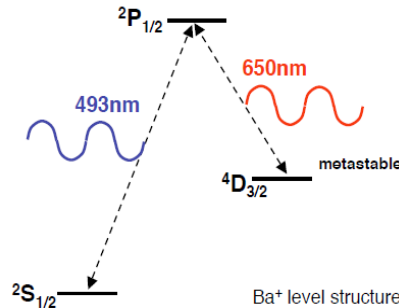
Panorama (parziale) internazionale (→ lucidi successivi per maggiori dettagli)

EXO (EXO-200)



^{136}Xe

Tecnica: TPC di Xe liquido arricchito (ricostruzione dell'evento).
Abbattimento del fondo (tranne quello dei due neutrini) con la tecnica del Ba-tagging.



KamLAND-ZEN



^{136}Xe

Tecnica: usato in kamLAND - sfera di scintillatore caricato in Xe arricchito immerso in scintillatore e circondato da fototubi.

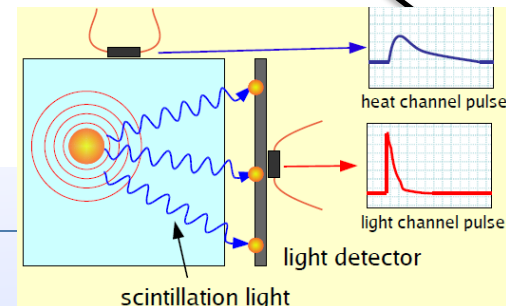
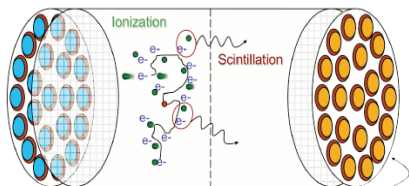
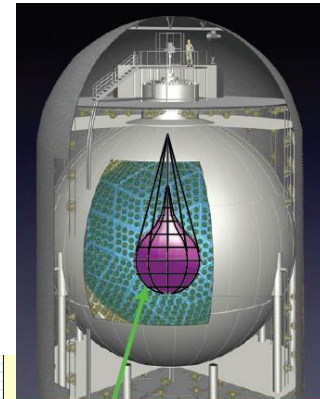
Vantaggio: fondo ultra basso ($10^{-17} \div 10^{-18}$ g/g Th e U) non bisogna modificare il rivelatore



LUCIFER

^{82}Se

Tecnica: bolometri scintillanti (permette la riduzione del fondo alfa) con ZnSe arricchito



Progetto già finanziato per una prima fase di R&D e quindi costruzione di una torre.

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Option:UCRL#

formation



LUCIFER



→ ^{82}Se

$Q_{\text{bb}} = 2995 \text{ keV}$

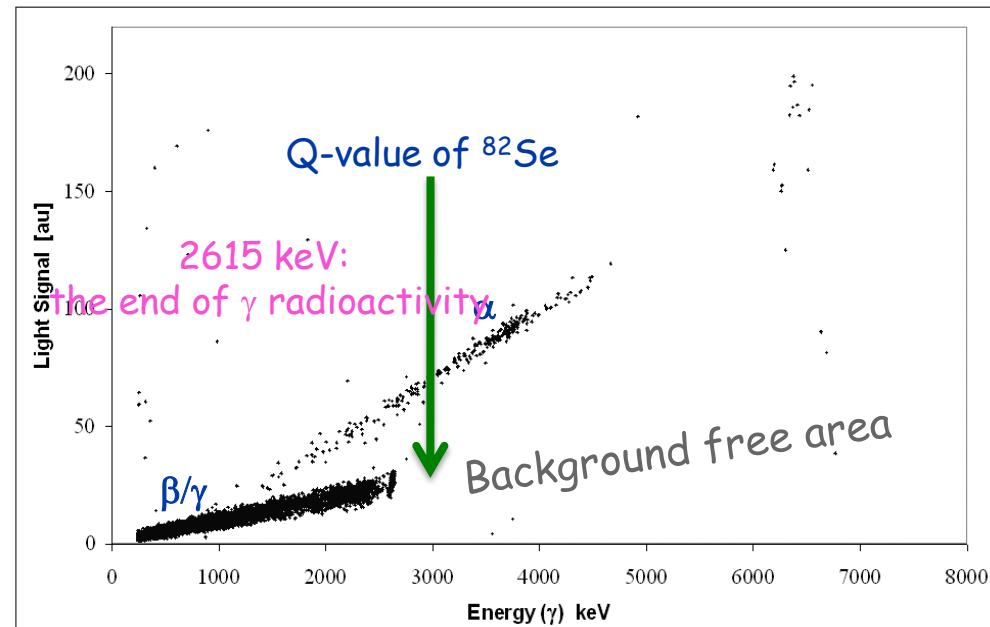
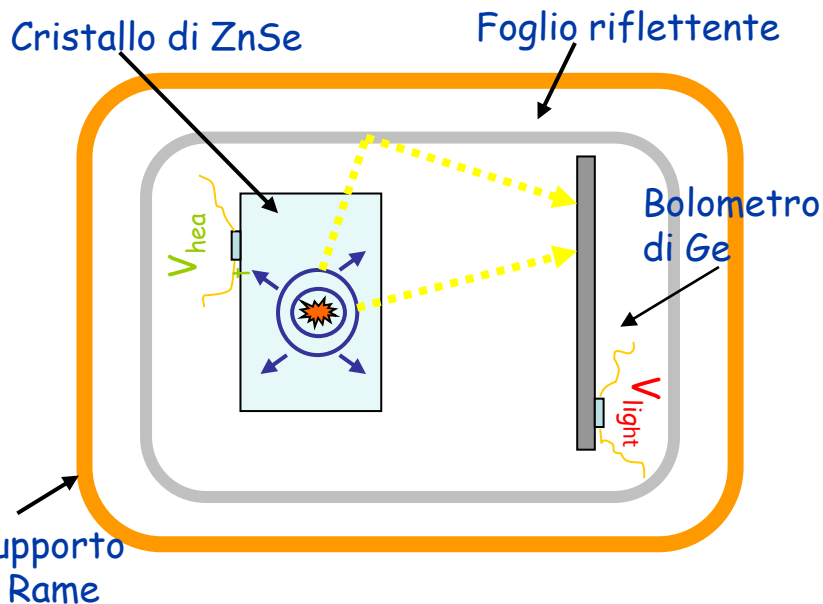
Abbondanza isotopica: 9%

Rivelatore: Bolometri scintillanti

Risoluzione Energetica: $\sim 0.3 \%$

Possible Location: Hall A @ LNGS (Italia)

| Option | Isotope weight | Half Life limit (10^{26}y) | Sensitivity* to m_{ee} (meV) |
|----------|--------------------------|---------------------------------------|--------------------------------|
| baseline | ^{82}Se 17.6 kg | 2.31 | 52-65 |
| option 1 | ^{82}Se 20.5 kg | 2.59 | 49-61 |
| option 2 | ^{82}Se 27.8 kg | 3.20 | 44-55 |



EXO - 200

→ ^{136}Xe

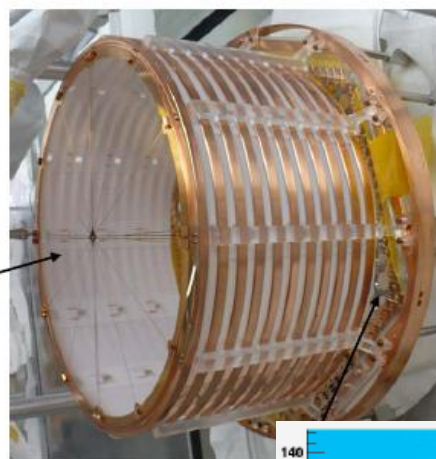
$Q_{bb} = 2458 \text{ keV}$

200 kg of Xe enriched to 80% in 136

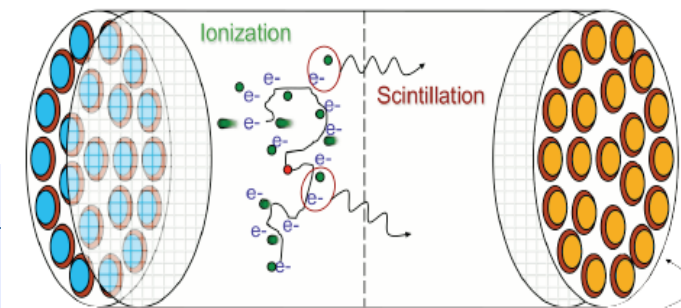
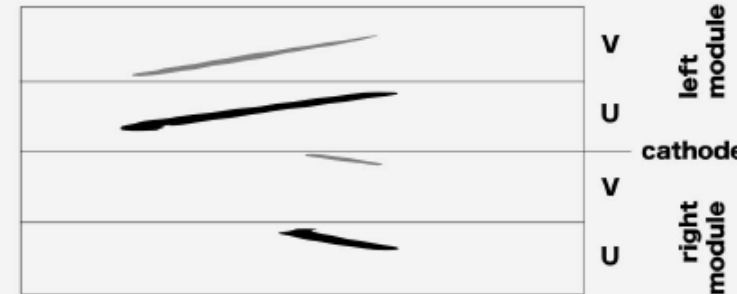
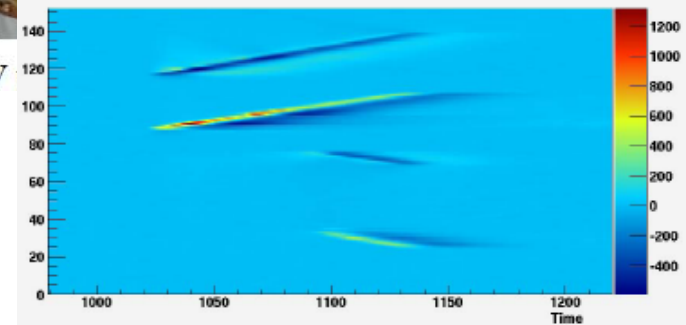
Rivelatore: TPC di Xe liquido arricchito (ricostruzione dell'evento). Senza Ba-tagging.

- GOALS
- test del claim di KK-HM
 - capire come funziona, le prestazioni e il fondo del rivelatore
 - primo step del progetto EXO

Cathode



U and V



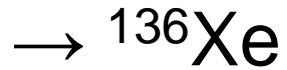
In due anni

| Mass (ton) | Eff. (%) | Run Time (yr) | $\sigma_E/E @ 2.5\text{MeV}$ (%) | Radioactive Background (events) | $T_{1/2}^{0\nu}$ (yr, 90%CL) | Majorana mass (eV) | |
|------------|----------|---------------|----------------------------------|---------------------------------|------------------------------|--------------------|--------|
| | | | | | | QRPA | NSM |
| 0.2 | 70 | 2 | 1.6* | 40 | $6.4 \cdot 10^{25}$ | 0.109† | 0.135* |

• Worst case (QRPA, 1σ upper limit) 51 evts on top of 40 evts bkgd → 5.4σ

• Best case (NSM, 1σ lower limit) 91 events on top of 40 bkgd → 8.0σ

KamLAND - ZEN

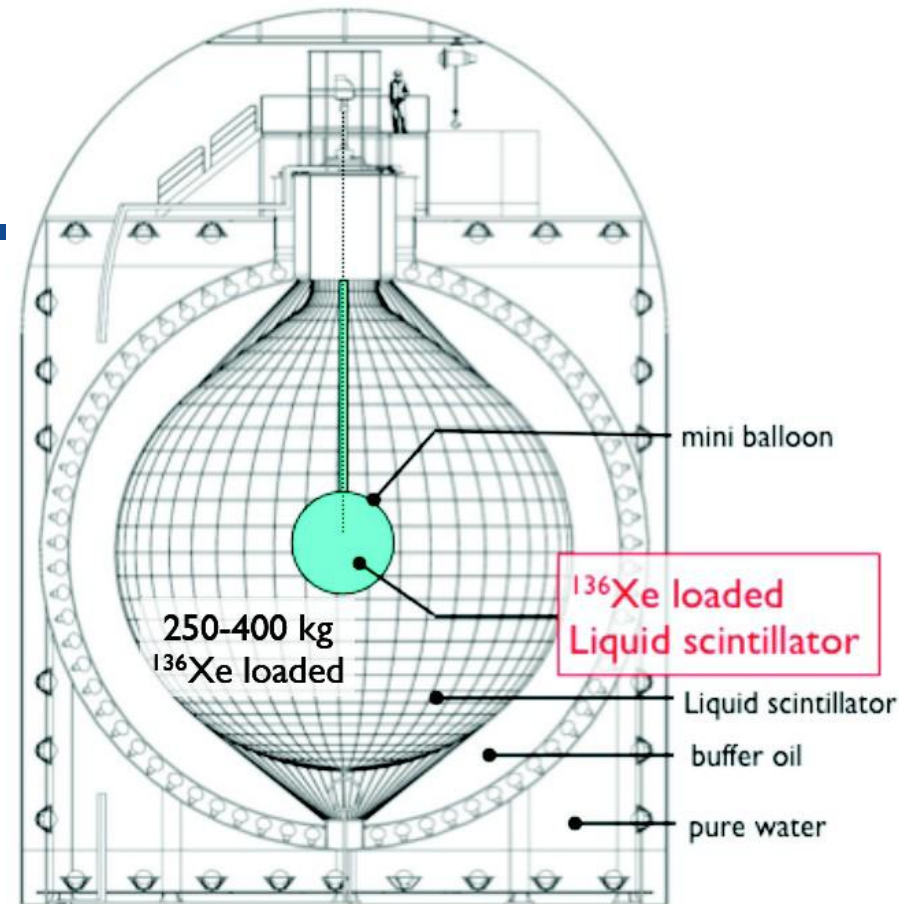


$Q_{\text{bb}} = 2458 \text{ keV}$

Rivelatore: usato in kamLAND - sfera di scintillatore caricato in Xe arricchito immerso in scintillatore e circondato da fototubi.

Risoluzione energetica.: ~ 7%

Vantaggio: Ultra low radioactivity ($10^{-17} \div 10^{-18} \text{ g/g Th and U}$)



**FASE – I
(2011 – 2013)**

400 kg of enriched Xe (>90%)
goal: ~60 meV in 1.5 years

**FASE – II
(dal 2013)**

1000 kg of enriched Xe (>90%)
goal: ~ 25 meV in 5 years



Conclusioni

La ricerca del doppio decadimento beta senza neutrino e' diventata uno degli hot topics della fisica nucleare.

Per gli esperimenti si possono individuare 3 obiettivi in termini di sensibilita' alla massa efficace di Majorana del neutrino.

KK-HM (500 – 100 meV)

→ Nei prossimi 3 anni, esperimenti come GERDA e CUORE potrebbero dare una parola definitiva sul claim. Se confermato potrebbe iniziare l'era delle misure di precisione per questo decadimento.

Attacco alla Gerarchia Inversa (fino alla prima parte della banda)

→ Se la massa del neutrino e' in questa regione nei prossimi 10 anni ci potrebbero essere molte osservazioni (CUORE, Gerda+Majorana, KamLAND-ZEN, SuperNEMO, SNO+)

Test completo della Gerarchia Inversa (fino a 15 meV)

→ Golden experiment (?): esperimento di una tonnellata di materiale arricchito con fondo basso e buona risoluzione

BACK UP SLIDES



SNO+

→ ^{150}Nd

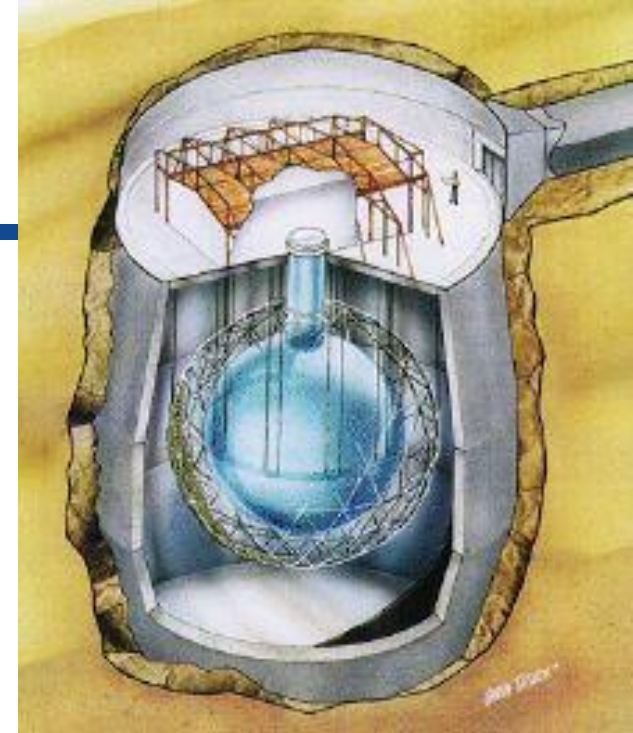
$$Q_{bb} = 3368 \text{ keV}$$

Rivelatore: rivelatore di SNO riempito di scintillatore liquido (linear alkylbenzene - LAB) caricato allo 0.1% con Nd naturale
→ 56 kg di ^{150}Nd

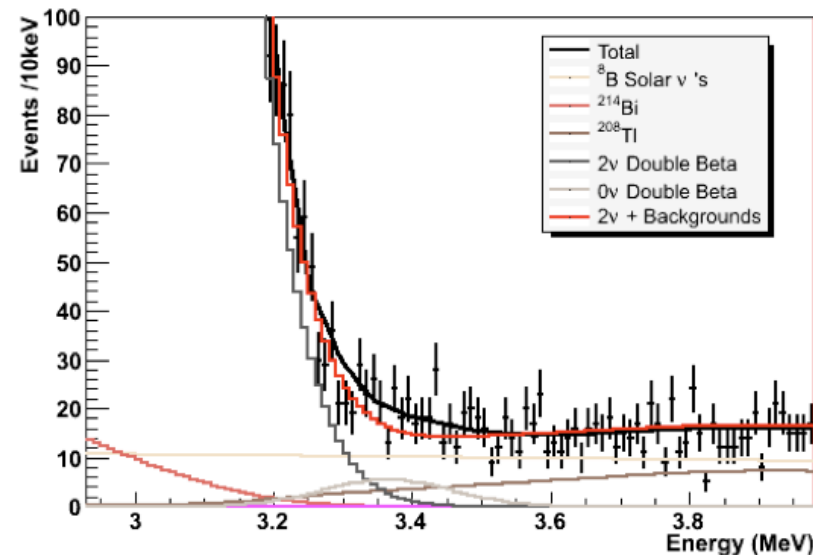
Location: Sudbury (Canada)

Risoluzione energetica: 6.4%

SNO+ si aspetta di raggiungere una sensibilita' $< 100 \text{ meV}$ in 2 anni di presa dati



Simulated SNO+ Energy Spectrum



CUORICINO

→ ^{130}Te

$Q_{\text{bb}} = 2530 \text{ keV}$

~ 34% abbondanza naturale

Rivelatore: array of 62 $5 \times 5 \times 5 \text{ cm}^3 \text{ TeO}_2$
bolometri @ ~ 10 mKelvin

Risoluzione energetica: 0.28% @ Qvalue

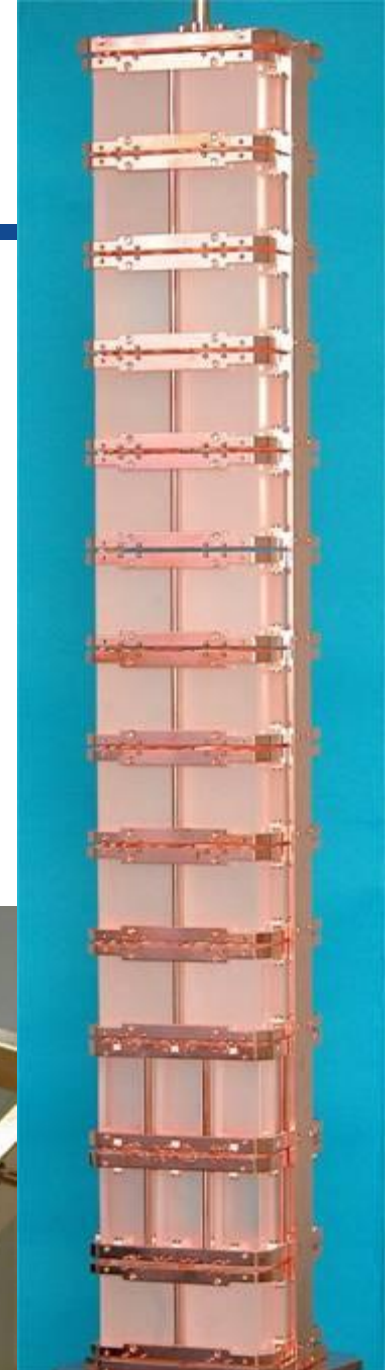
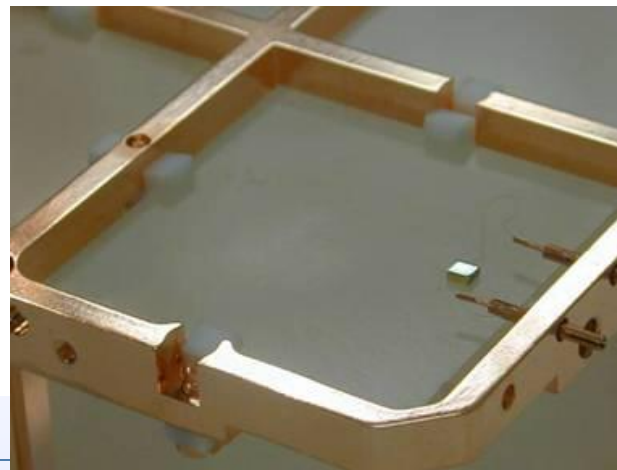
Location: LNGS (Italy)

Risultato finale - ^{130}Te 0nDBD

bkg ~ $0.18 \pm 0.01 \text{ c/keV/kg/y}$

$t_{1/2}^{\text{0n}} (\text{y}) > 2.8 \times 10^{24} \text{ y}$ (90% CL)

$m_{\text{ee}} < 0.3 - 0.71 \text{ eV}$



NEMO - 3

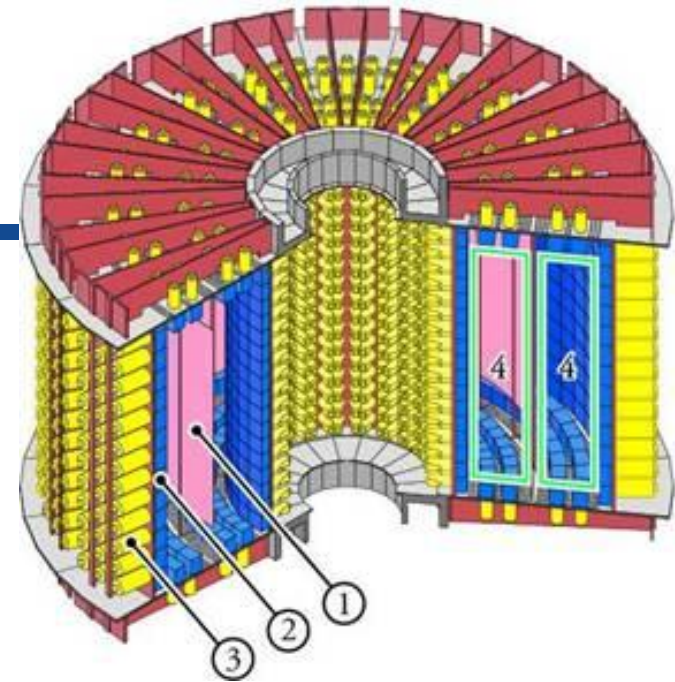
→ ^{100}Mo

$Q_{\text{bb}} = 3034 \text{ keV}$

Detector: tracking detector with different sources

Energy resolution: 8% @ Qvalue

Location: Modane Underground Laboratory



- 1 Source plane
- 2 Tracking volume (3-D readout wire drift chamber with 6180 cells)
- 3 Calorimeter volume (1940 plastic scintillator block)

Other sources

| Isotope | Study | Mass(g) |
|-------------------|------------------------------------|---------|
| ^{100}Mo | $\beta\beta 0\nu, \beta\beta 2\nu$ | 6914 |
| ^{82}Se | $\beta\beta 0\nu, \beta\beta 2\nu$ | 932 |
| ^{116}Cd | $\beta\beta 0\nu, \beta\beta 2\nu$ | 405 |
| ^{130}Te | $\beta\beta 0\nu, \beta\beta 2\nu$ | 454 |
| ^{150}Nd | $\beta\beta 2\nu$ | 36.6 |
| ^{96}Zr | $\beta\beta 2\nu$ | 9.4 |
| ^{48}Ca | $\beta\beta 2\nu$ | 7.0 |

Limite attuale con ^{100}Mo 0nDBD

bkg $\sim 0.3 \text{ c/y/kg}$ [2.8-3.2] MeV

$t_{1/2}^{\text{on}} (\text{y}) > 1 \times 10^{24} \text{ y}$ (90% CL)

$m_{\text{ee}} < 0.47 - 0.96 \text{ eV}$

SuperNEMO

Expansion of NEMO-3

→ ^{82}Se

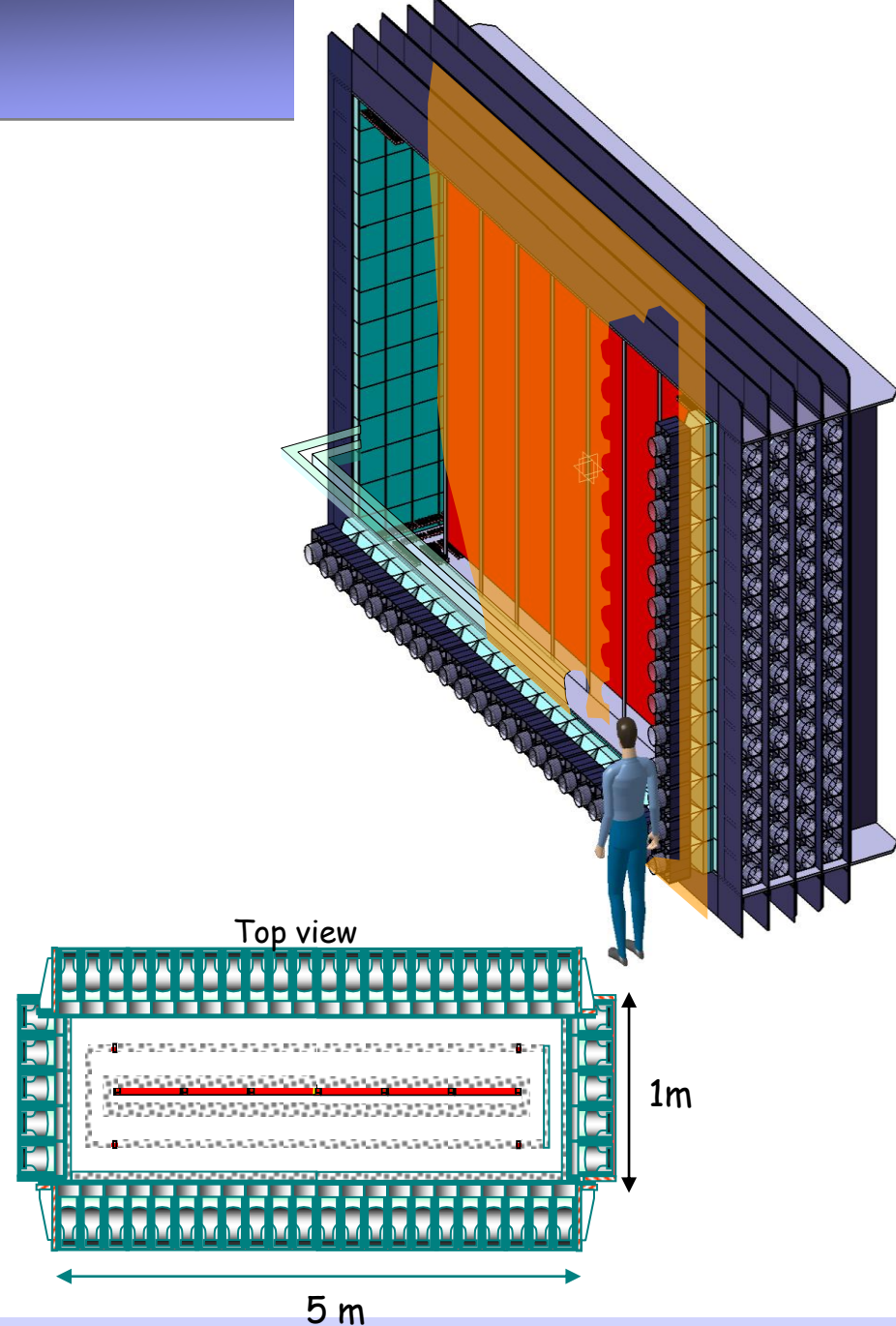
$Q_{\beta\beta} = 2995 \text{ keV}$

→ ^{150}Nd

$Q_{\beta\beta} = 3367 \text{ keV}$

Detector: tracking detector
with different sources

Tracking: drift chamber ~3000 cell (Gaiger mode)
Calorimeter: scintillators + PM ~ 1000 if sc. blocks
~ 100 scint. bars



SuperNEMO

Improvement with respect to NEMO-3:

| NEMO-3 | | SuperNEMO |
|---|------------------------|--|
| ^{100}Mo | Choice of isotope | ^{150}Nd or ^{82}Se |
| 7 kg | Isotope Mass | 100 kg |
| 8% | Efficiency | 30% |
| $^{208}\text{Tl} < 20 \text{ mBq/Kg}$ $^{214}\text{Bi} < 300 \text{ mBq/Kg}$ | Internal contamination | $^{208}\text{Tl} < 2 \text{ mBq/Kg}$ $^{214}\text{Bi} < 10 \text{ mBq/Kg}$ |
| 8% @ 3MeV | Energy resolution | 4% @ 3MeV |
| $\tau_{1/2}^{0\nu} (\text{y}) \sim 2 \times 10^{24} \text{ y}$ $\langle m \rangle \sim 0.3 - 1.3 \text{ eV}$ | SENSITIVITY | $\tau_{1/2}^{0\nu} (\text{y}) \sim 2 \times 10^{26} \text{ y}$ $\langle m \rangle \sim 50 - 90 \text{ meV}$ |

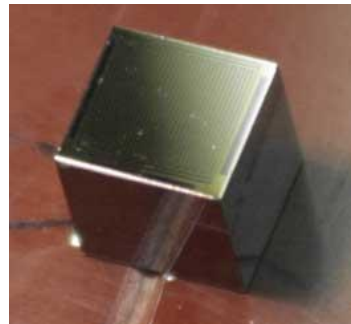
Demonstrator running 2012 – 2013
(first module of 5 kg of ^{82}Se)

COBRA (CZT 0-neutrino Beta-decay Research Apparatus)

→ ^{116}Cd

$Q_{\beta\beta} = 2809 \text{ keV}$

Enriched to 90%



Detector: 64000 1 cm^3 CZT detectors
for a total mass of 418 kg → 183 kg of
interesting isotope

Location: LNGS (Italy)

| | nat. ab. (%) | Q (keV) | Decay mode |
|-------|--------------|---------|------------------------------|
| Zn70 | 0.62 | 1001 | $\beta\text{-}\beta\text{-}$ |
| Cd114 | 28.7 | 534 | $\beta\text{-}\beta\text{-}$ |
| Cd116 | 7.5 | 2809 | $\beta\text{-}\beta\text{-}$ |
| Te128 | 31.7 | 868 | $\beta\text{-}\beta\text{-}$ |
| Te130 | 33.8 | 2529 | $\beta\text{-}\beta\text{-}$ |
| Zn64 | 48.6 | 1096 | $\beta\text{+}/\text{EC}$ |
| Cd106 | 1.21 | 2771 | $\beta\text{+}\beta\text{+}$ |
| Cd108 | 0.9 | 231 | EC/EC |
| Te120 | 0.1 | 1722 | $\beta\text{+}/\text{EC}$ |

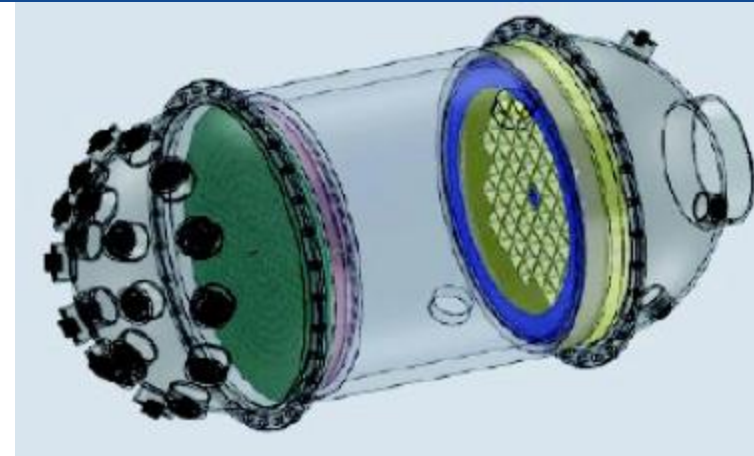
NEXT

High pressure Xenon gas TPC (100 kg)

Target: $T_{1/2}^{0n} > 1.8 \times 10^{26}$ @ 90% C.L
Bkg $< 10^{-3}$ c/keV/kg/y
1% FWHM @ Qbb

Advantages of HPGXe:

- Energy resolution
- Event topology



| Liquid xenon | | Gas xenon | |
|--------------|---------------|-----------|--|
| YES | Scalability | YES | |
| YES | Compactness | NO | |
| Cryogenics | Complexity | H.P. | |
| YES | Fully Active | YES | |
| NO | Topology | YES | |
| YES | E. resolution | YES | |

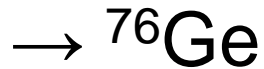


MAJORANA

MAJORANA DEMONSTRATOR

(first step: 2x60 Kgmodules)

- Goals
 - demonstrate backgrounds low enough to justify building a tonne scale Ge experiment
 - establish feasibility of constructing and fielding modular Ge detector arrays
 - test the KKDC claim
 - exploit the low-energy sensitivity to perform search for dark matter

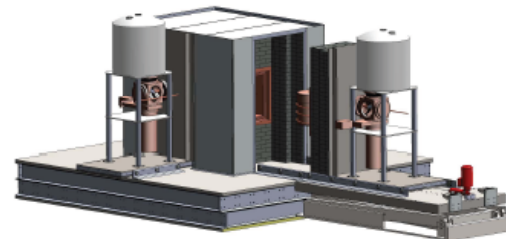


$Q_{bb} = 2039 \text{ keV}$

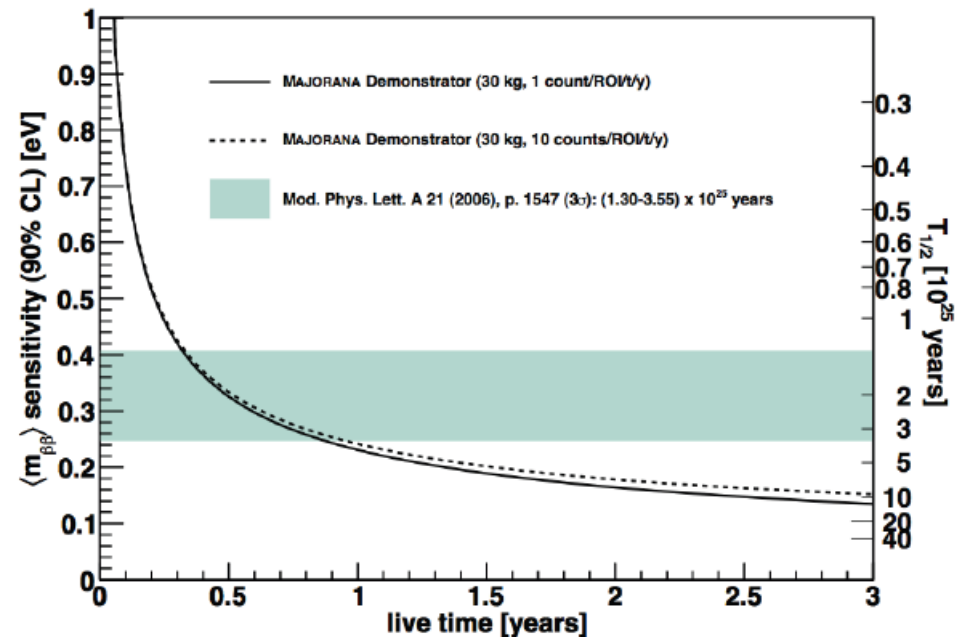
Rivelatore: Array Ge arricchiti (~86%) Ge diodes operated in conventional Cu cryostats

Buona risol en < 0.16% a Q_{bb}

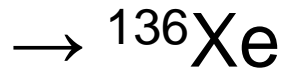
Location: Dusek (USA)



sensitivity to $T_{1/2} \geq 1.0 \times 10^{26} \text{ y}$ (90% CL), $\langle m_{\nu} \rangle < 140 \text{ meV}$ (90% CL) using [Rod06] NME



EXO

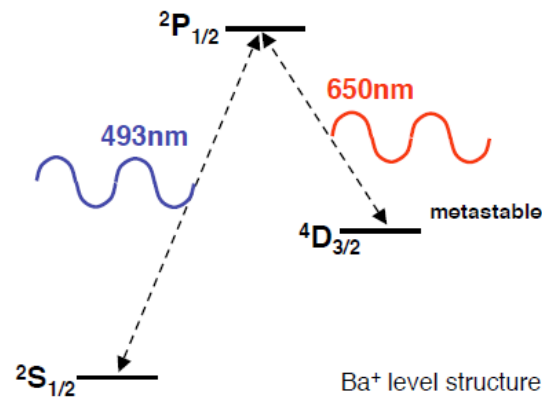
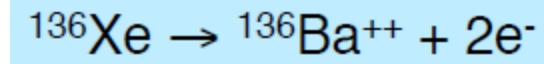


$Q_{bb} = 2458 \text{ keV}$

Ba⁺ tagging would allow for the elimination of all backgrounds other than the background from $2\nu\beta\beta$.

There are several challenges for Ba tagging:

1. Locate the ion in the detector (Ba⁺ mobility)
2. Extract the ion and release it into a low pressure region
3. Trap the ion and identify it spectroscopically
4. Characterize the efficiency of this process



| Case | Mass (tonne) | Efficiency (%) | Run time (yr) | $\sigma(E)E$ @ 2.5 MeV (%) | $2\nu\beta\beta$ background (events) | $T_{1/2}^{0\nu}$, 90% C.L. (yr) | Majorana mass (meV) | |
|--------------|--------------|----------------|---------------|----------------------------|--------------------------------------|----------------------------------|---------------------|------------------|
| | | | | | | | RQRPA ¹ | NSM ² |
| Conservative | 1 | 70 | 5 | 1.6 | 0.5 (use 1) | 2×10^{27} | 19 | 24 |
| Aggressive | 10 | 70 | 10 | 1 | 0.7 (use 1) | 4.1×10^{28} | 4.3 | 5.3 |

Cuore-0 sensitivity

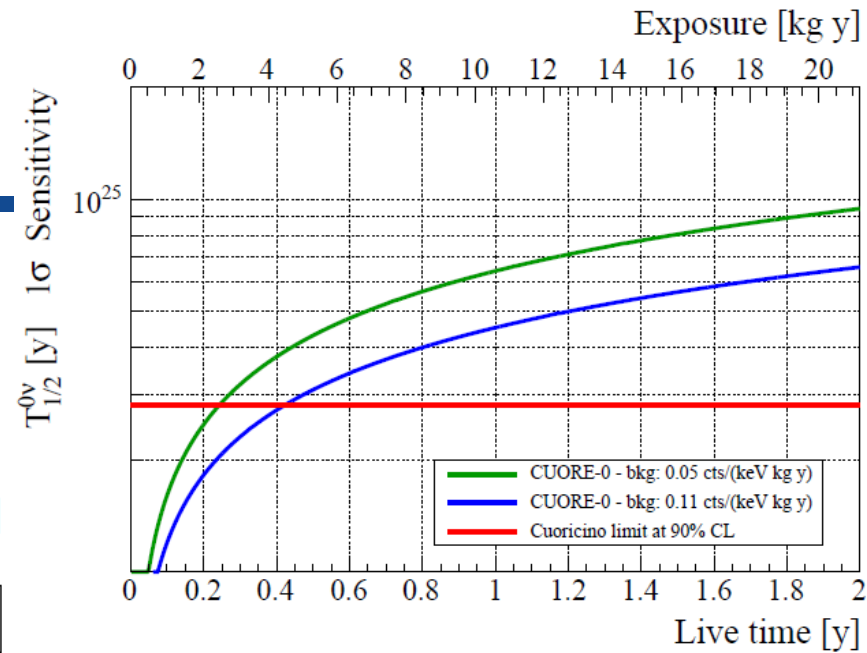
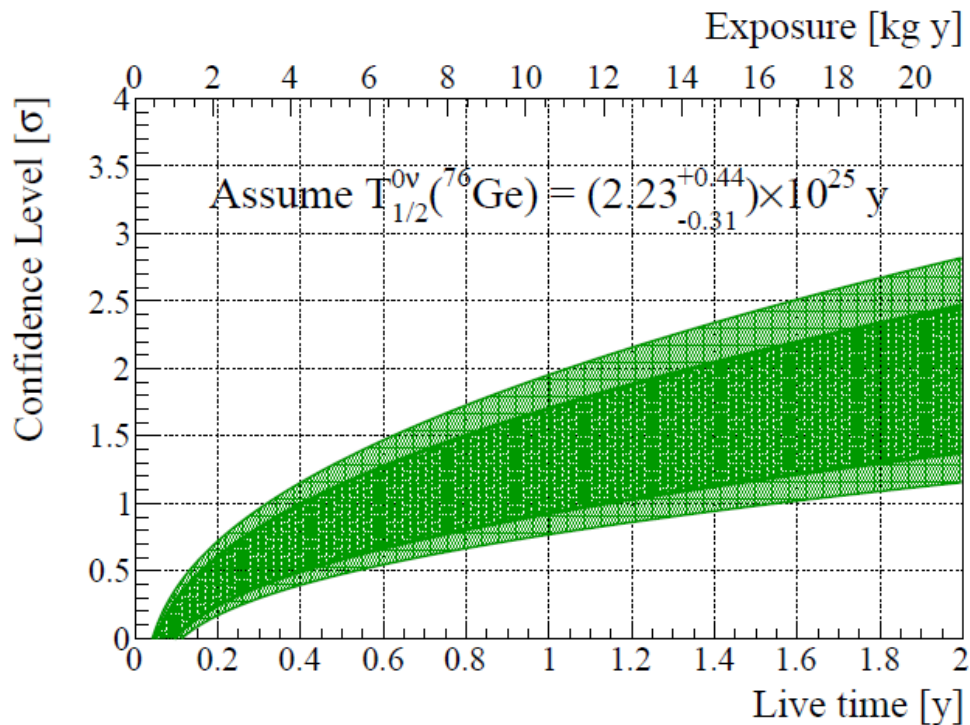
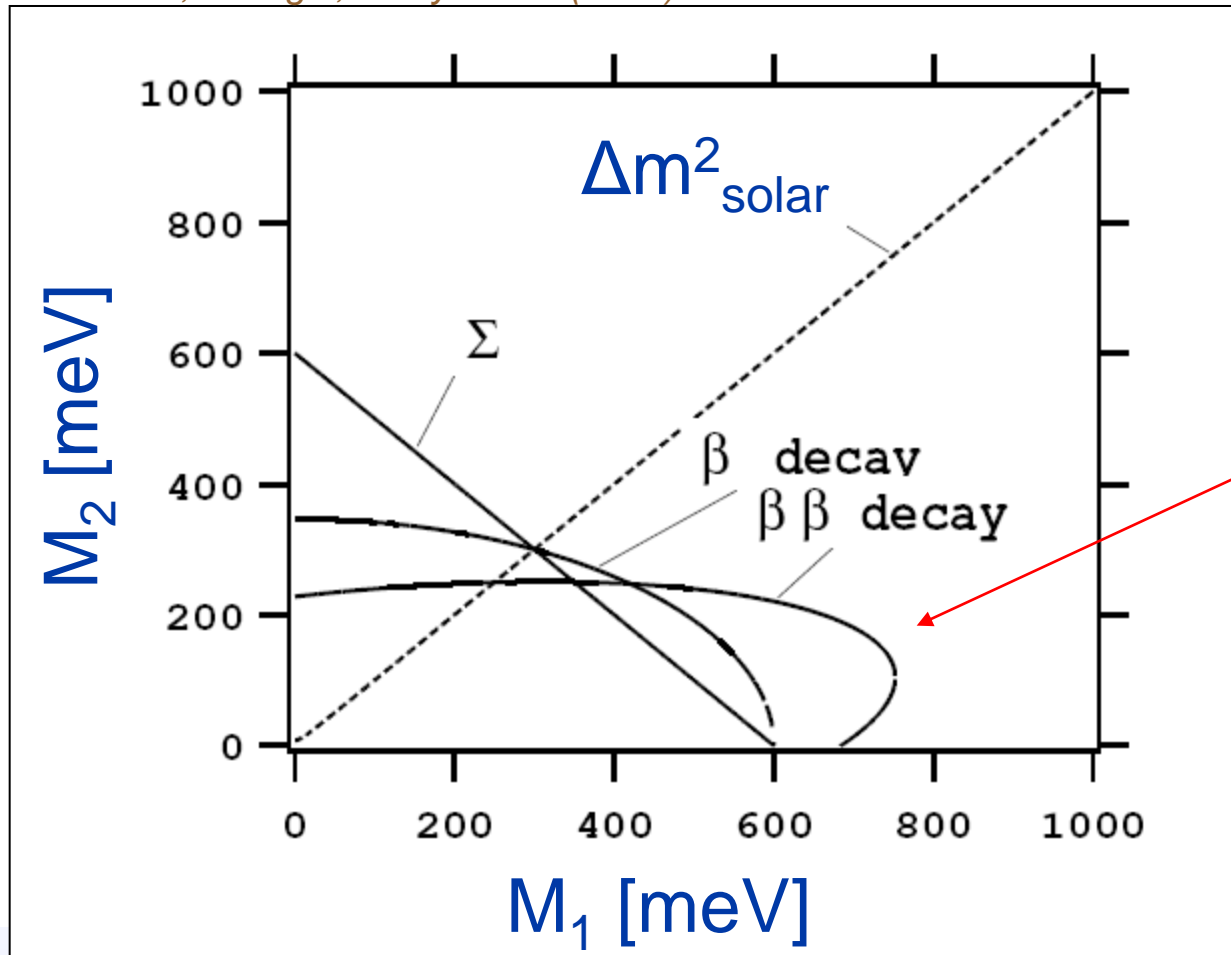


Figure 4: Confidence level at which CUORE-0 can observe a signal corresponding to the ${}^{76}\text{Ge}$ claim, assuming the best expected background of 0.05 cts/(keV kg y). The inner band assumes the best-fit value of the ${}^{76}\text{Ge}$ claim, and its width arises from the range of NMEs. The outer band accounts for the uncertainty on the ${}^{76}\text{Ge}$ claim in addition to the NMEs.

Fasi di majorana

S.R. Elliott, J. Engel, J.Phys. G30 (2004) R183

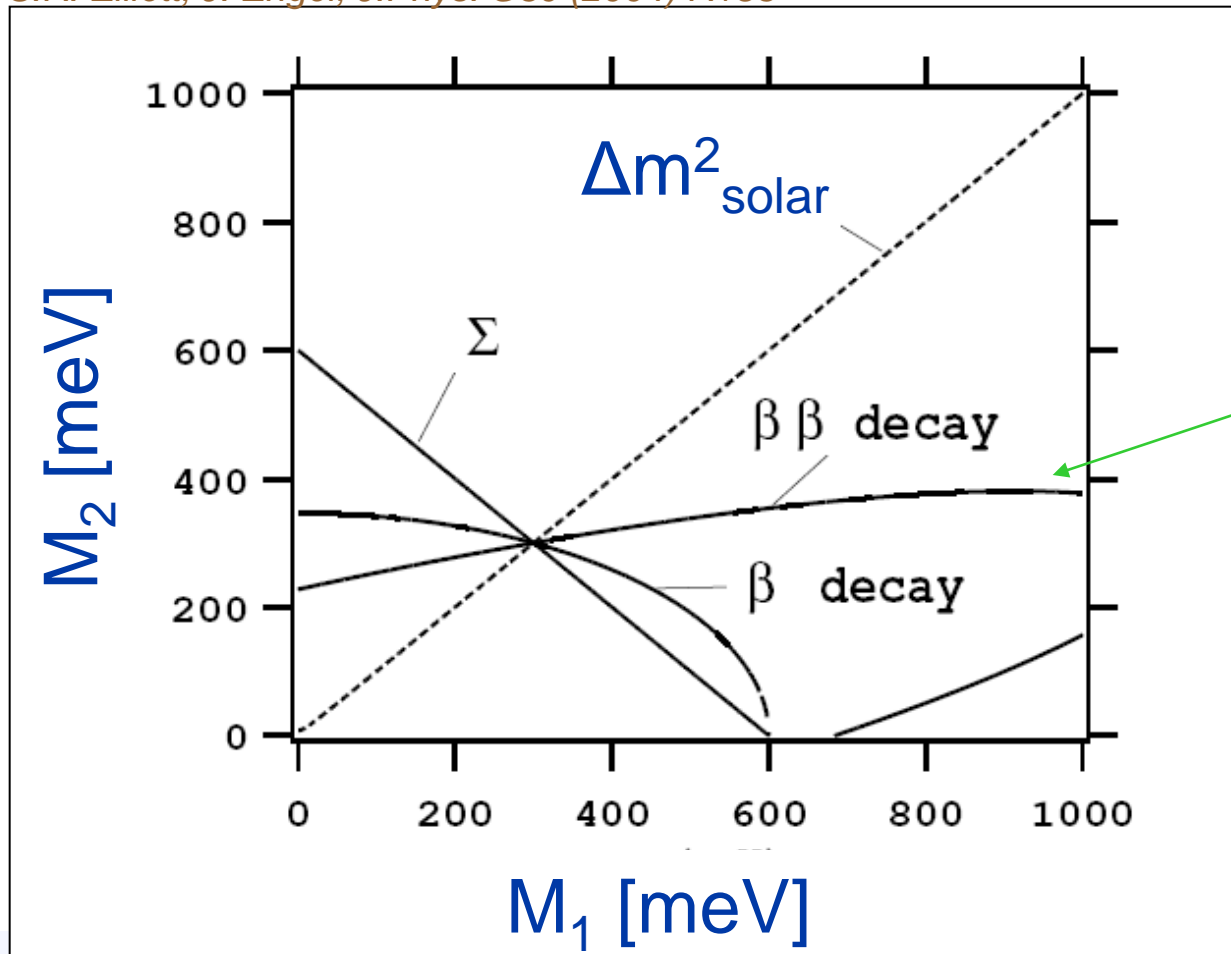


wrong value
of the Majorana
phase



Fasi di majorana

S.R. Elliott, J. Engel, J.Phys. G30 (2004) R183



In a standard three active neutrino scenario:

$$\Sigma \equiv \sum_{i=1}^3 M_i$$

cosmology
simple sum
pure kinematical effect

$$\langle M_{\beta} \rangle \equiv \left(\sum_{i=1}^3 M_i^2 |U_{ei}|^2 \right)^{1/2}$$

beta decay
incoherent sum
real neutrino

$$\langle M_{\beta\beta} \rangle \equiv \left| \sum_{i=1}^3 M_i |U_{ei}|^2 e^{i\alpha_i} \right|$$

double beta decay
coherent sum
virtual neutrino
Majorana phases

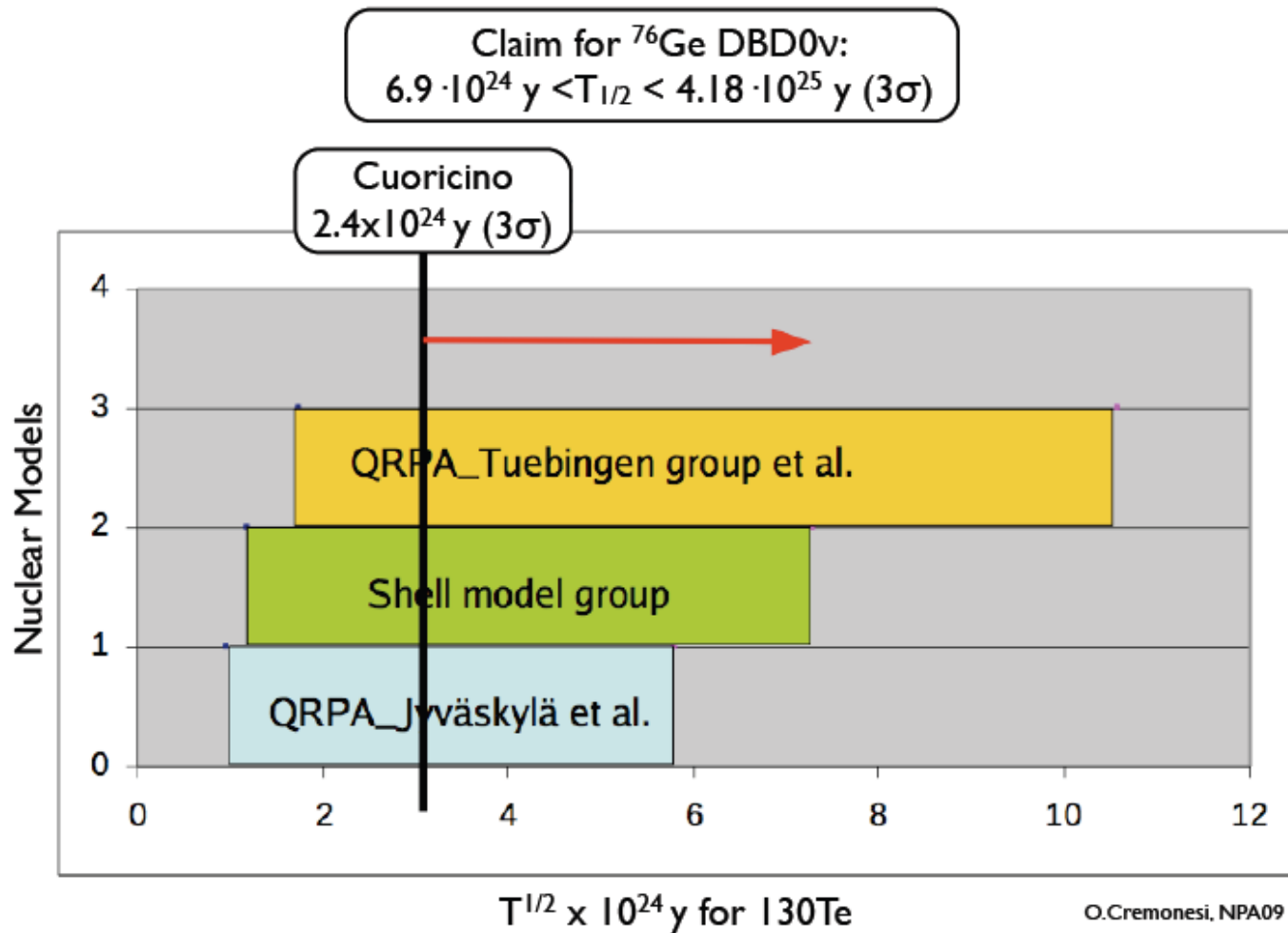


TABLE II. Input cosmological data sets for seven representative cases considered in this work, together with their 2σ (95% C.L.) constraints on the sum of neutrino masses Σ .

| Case | Cosmological data set | Σ bound (2σ) |
|------|---|------------------------------|
| 1 | WMAP | <2.3 eV |
| 2 | WMAP + SDSS | <1.2 eV |
| 3 | WMAP + SDSS + SN_{Riess} + HST + BBN | <0.78 eV |
| 4 | CMB + LSS + SN_{Astier} | <0.75 eV |
| 5 | CMB + LSS + SN_{Astier} + BAO | <0.58 eV |
| 6 | CMB + LSS + SN_{Astier} + Ly- α | <0.21 eV |
| 7 | CMB + LSS + SN_{Astier} + BAO + Ly- α | <0.17 eV |



Cuoricino e HM-KK



Tuebingen's group: erratum of nucl-th/0503063

Suhonen's group: nucl-th/0208005

Shell Model: Poves' talk @ 4th ILIAS Annual Meeting - Chambéry