Neutrinoless Double Beta Decay: Experimental Review

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Outline

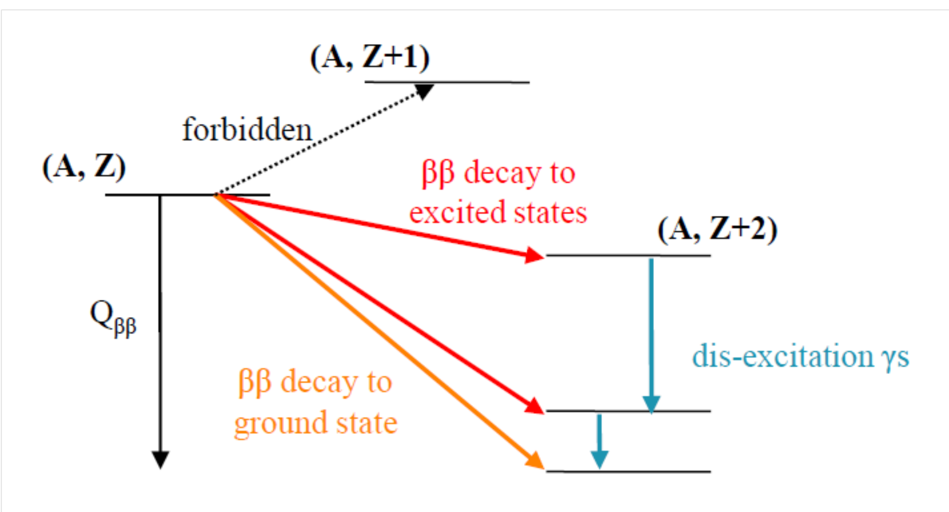
- Introduction to $\beta\beta$ and $0\nu\beta\beta$ decay
- Experimental strategies
- Best achieved results to date
- Projects under development
- Prospects and conclusions
- Bibliography

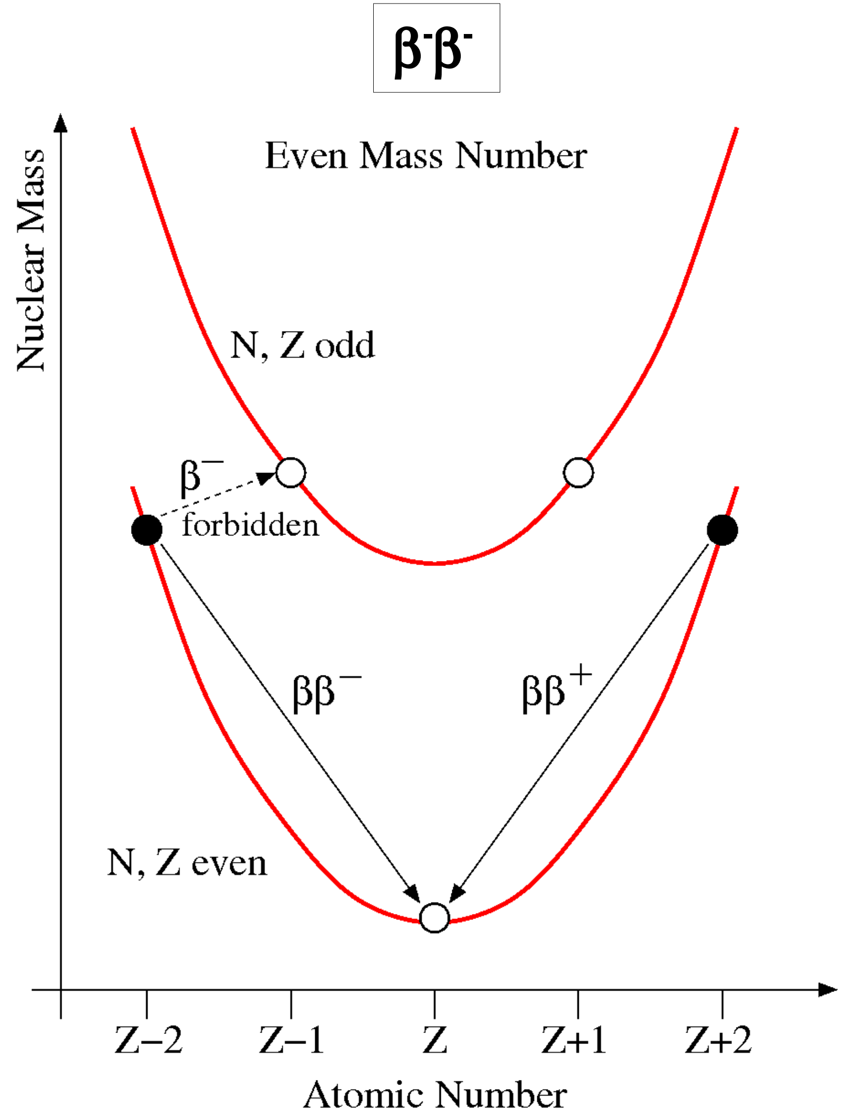
Double Beta Decay

It is a **second-order nuclear transition**, favored with respect to the sequence of two single beta decays for 35 isotopes

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

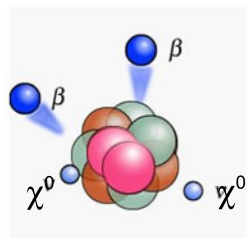
$\beta^-\beta^-$ has the highest rates
observed for 11 isotopes: $T_{1/2} \geq 10^{18}$ y

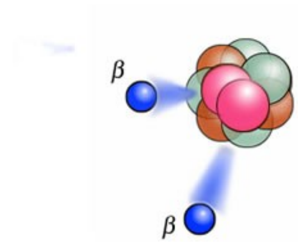




Neutrinoless Double Beta Decay

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





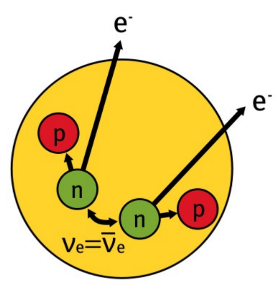
$0\nu\beta\beta$ channel has become particularly compelling after the evidence of neutrino oscillations (i.e. evidence of a non zero neutrino mass)

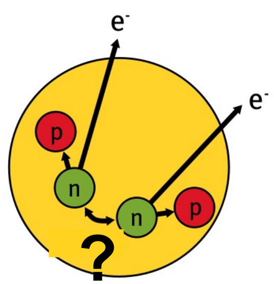
$0\nu\beta\beta$ IMPLICATIONS IN PARTICLE PHYSICS :

1. **L** non conservation
2. **Majorana nature** of ν
3. Measure of absolute ν **mass scale**
4. Determination of neutrino **mass hierarchy**
5. **CP** violation measure in the leptonic sector

$0\nu\beta\beta$ via light ν_M

$0\nu\beta\beta$ can be mediated by the exchange of a variety of unconventional particles
It´s **amplitude depends** on their mass and coupling constants





For **light ν_M** exchange the **Decay Rate** is:

$$(T_{0\nu})^{-1} \propto G_{0\nu}(Q,Z) \left| M^{0\nu} \right|^2 \langle m_{ee} \rangle^2 \quad \textbf{(1)}$$

Phase Space Factor
ATOMIC PHYS.

NME
NUCLEAR PHYS.

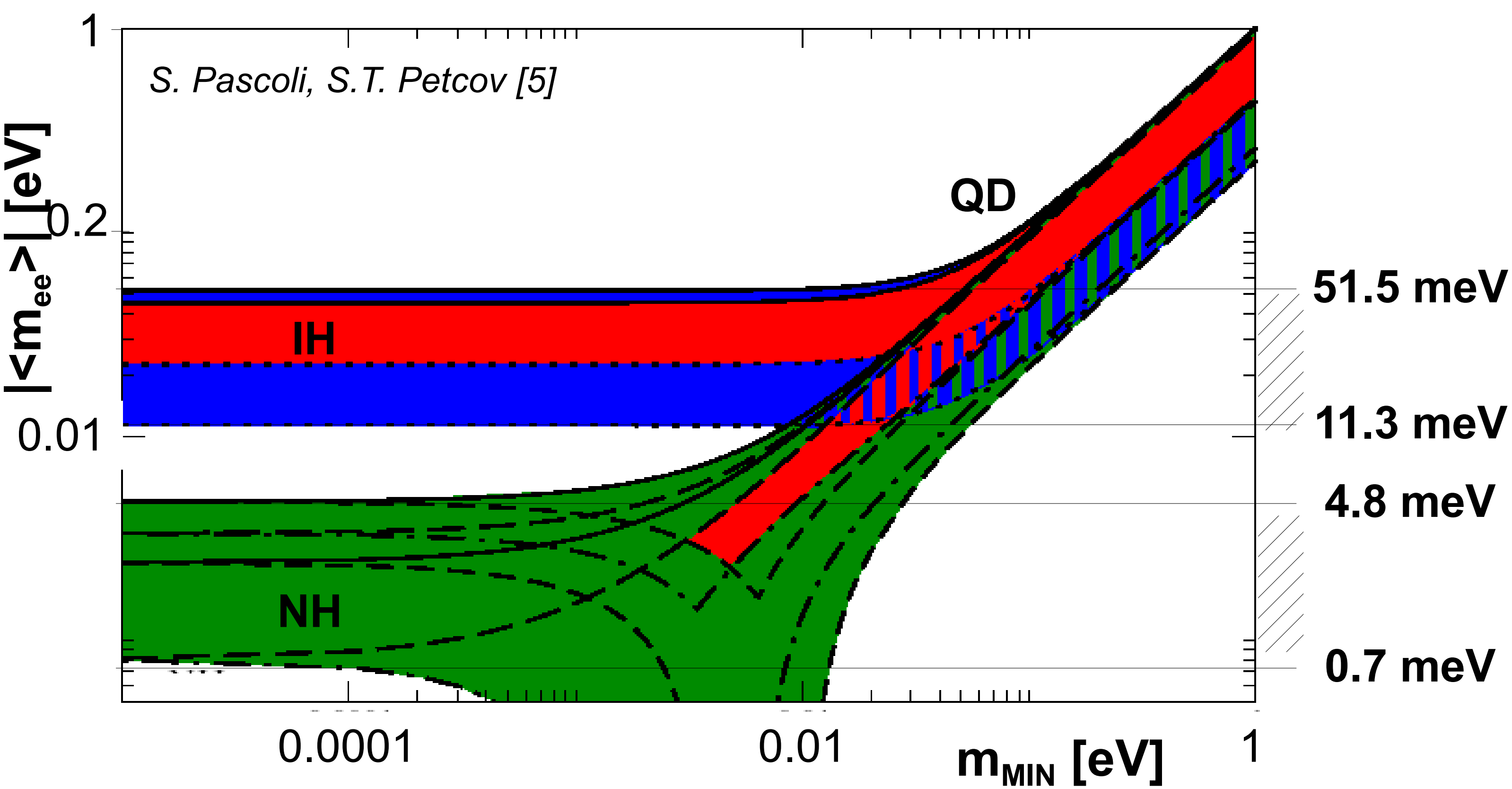
Effective Majorana mass
PARTICLE PHYS.

$<m_{ee}>$ and ν mass spectrum

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

- **neutrino mixing matrix**
- **neutrino mass eigenstates**
- **Majorana phases related to CP**

- **3 unknown quantities**: m_{MIN}, α_1, α_2
- **Cancellations** are possible due to α_i
- $0\nu\beta\beta$ can **access mass hierarchy**



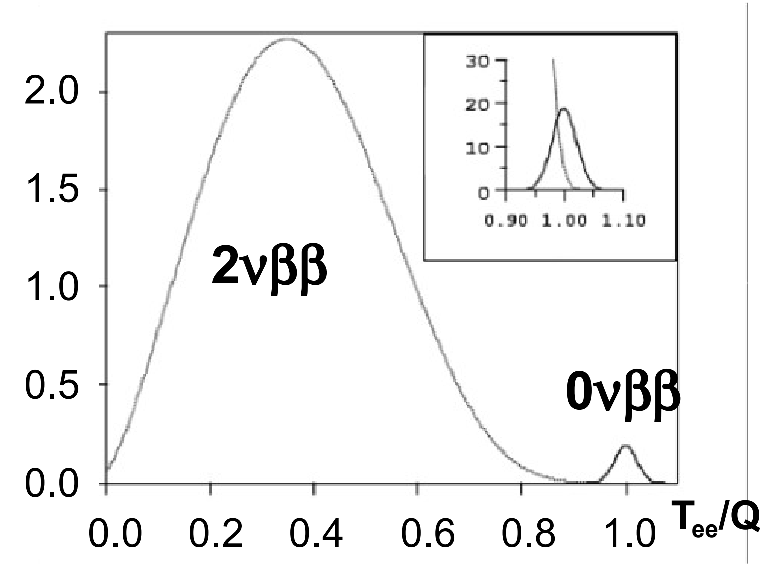
Needed sensitivity:

< 50 meV for IH
< 10 meV for NH

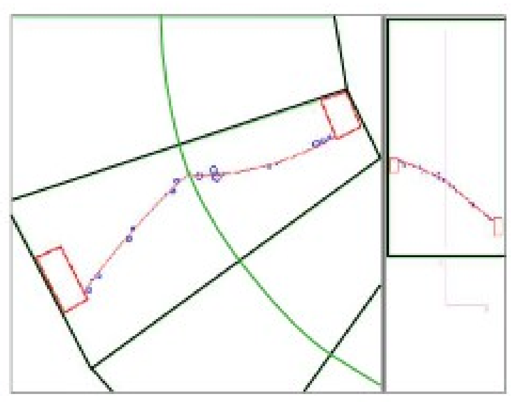
$0\nu\beta\beta$ experimental signature (*)

Minimal information:
two e^- energy sum spectrum

$0\nu\beta\beta$ exhibits a **peak at Q** over $2\nu\beta\beta$ 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



(*) Dealing only with direct counting experiments

Experimental sensitivity on $T^{0\nu}$

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

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

$$F_0 \propto \frac{\epsilon\, a.i.}{A} \left(\frac{M\,T}{b\,\Delta E} \right)^{1/2} \quad b \neq 0$$

$$F_0 \propto \frac{\epsilon\, a.i.}{A} (M\,T) \quad b = 0$$

(3)

$F_{0\nu}$ 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 0νββ 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 to $<m_{ee}>$

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

F_m involves also atomic and nuclear properties:

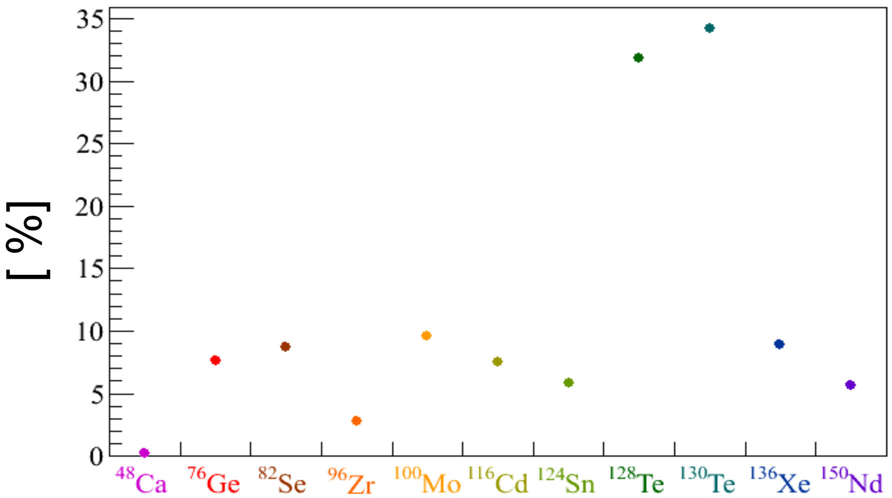
- Phase Space Factor: $\mathbf{G_{0\nu}(Q,Z) \div Q^5}$
- Nuclear Matrix Elements: $\mathbf{M_{0\nu}}$

Improvements on F_m :
Good isotope choice

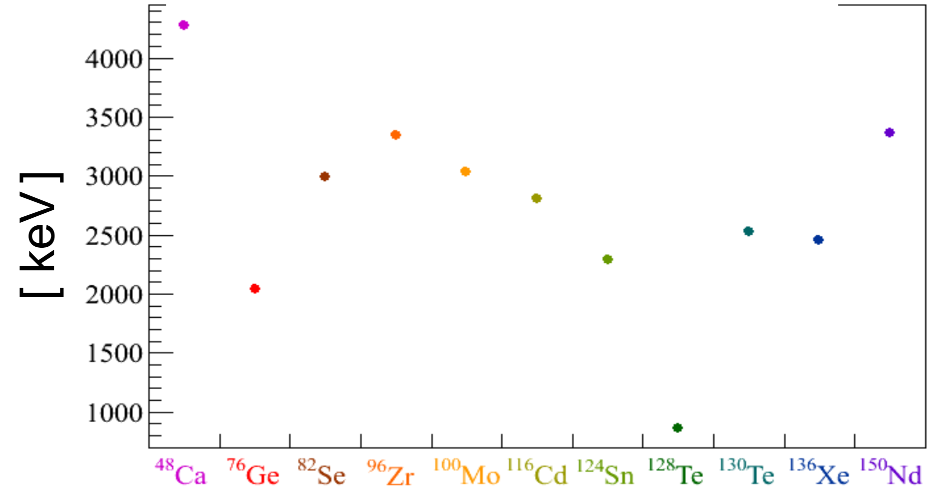
Discrepancies between **NME calculations** with different models: a **factor ~ 2 – 3** [1-4]

Isotope choice

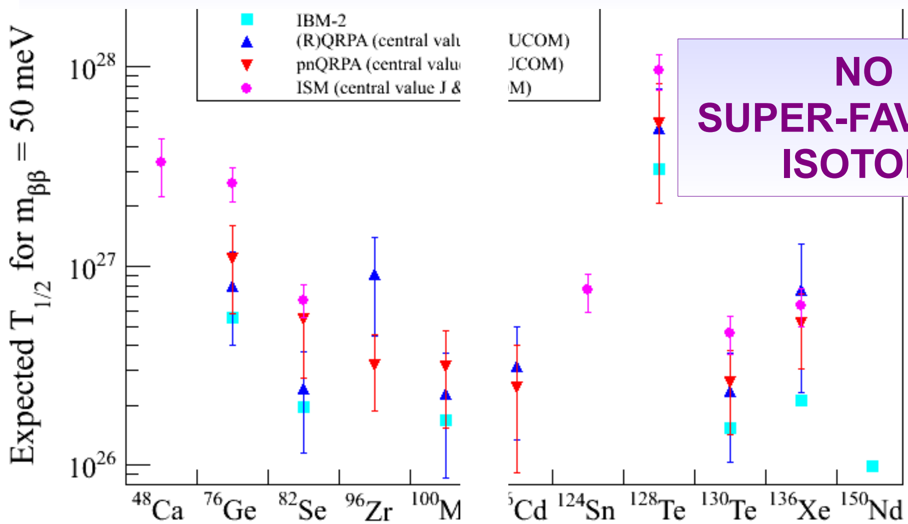
i.a.



Q-value



Expected $T_{1/2}$ for <m_{ee}> = 50meV



[1-4]

NO SUPER-FAVORITE 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: $\mathbf{n_{\beta\beta} \sim 30}$ => **b~0.05 c/keV/kg/y**

NH: $<m_{ee}>$ = 15 meV: $\mathbf{n_{\beta\beta} \sim 2.5}$ => **b~4x10^{-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)

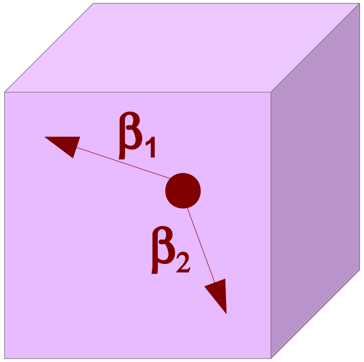
Experimental techniques

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

Calorimeters

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

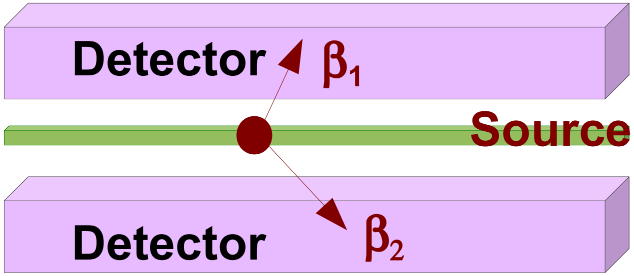
- Constraints on **detector choice** (except for bolometers)
- Very **large M possibles** (demonstrated ~50kg, proposed ~1t)
- **High efficiency** ($\varepsilon \sim 1$)
- Very **high resolution** ($\Delta E \sim 0.15\%$) with Ge-diodes, bolometers
- **Event topology** in gas/liquid Xe detectors or pixellization



External-source detectors

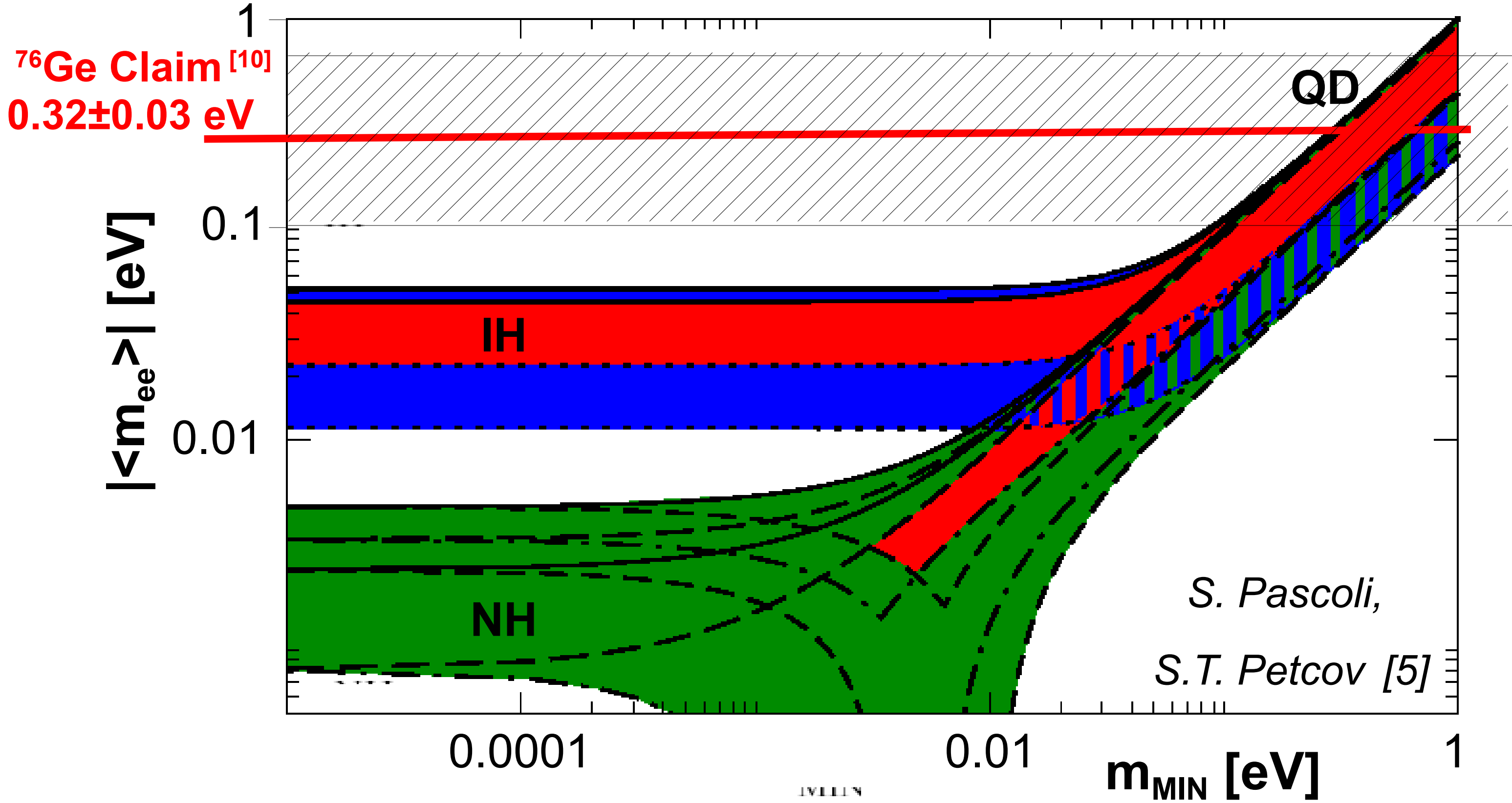
Scintillators, gas TPC, gas DC, magnetic field and TOF

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



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



Spread due to NME uncertainties

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

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

Heidelberg-Moscow Experiment

@LNGS 1990-2003

5 p-type **HPGe detectors** - 86% enriched in ^{76}Ge – 11 kg ^{76}**Ge**

$N_{\beta\beta}$= 8.7x10^{25} ε ~ 80% ΔE/E (FWHM) ~ 0.15% Bkg ~ 0.11 c/keV/kg/y

2001- whole collaboration [6]:

no 0νββ peak evidence

35.5 kg·y with PSA

$T_{1/2}^{0\nu}$> 1.9 x 10^{25} y @90% CL

<m_{ee}> < 0.22 ÷ 0.64 meV [1-4]

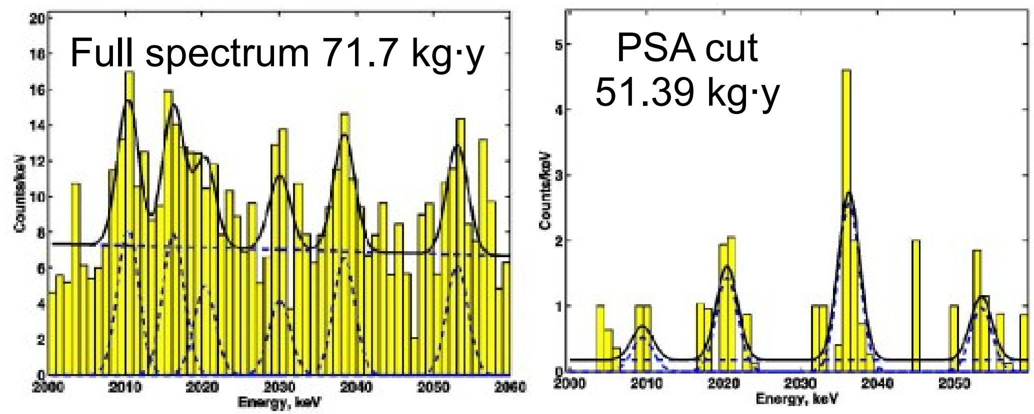
Part of the collaboration:

2001 [13]: **First claim for evidence at 2.2σ**
with 54.98 kg·y statistics

2004 [12]: **Claim for evidence at 4.2σ**
Added new statistics: 71.7 kg·y
Bkg = 0.11 ± 0.01 c/keV/kg/y

2006 [11]: **Claim for evidence at > 6σ**
New PSA methods
partial statistics: 51.39 kg·y

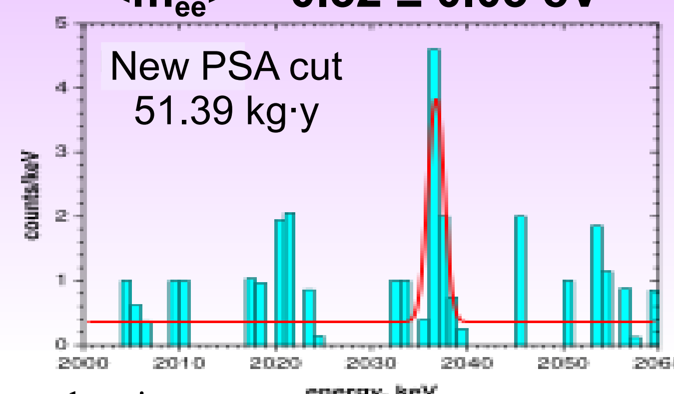
2004: Claim at 4.2 σ



2006: Claim at > 6 σ

$T_{1/2}^{0\nu}$ ≈ 2.2 x 10^{25} y

<m_{ee}> = 0.32 ± 0.03 eV

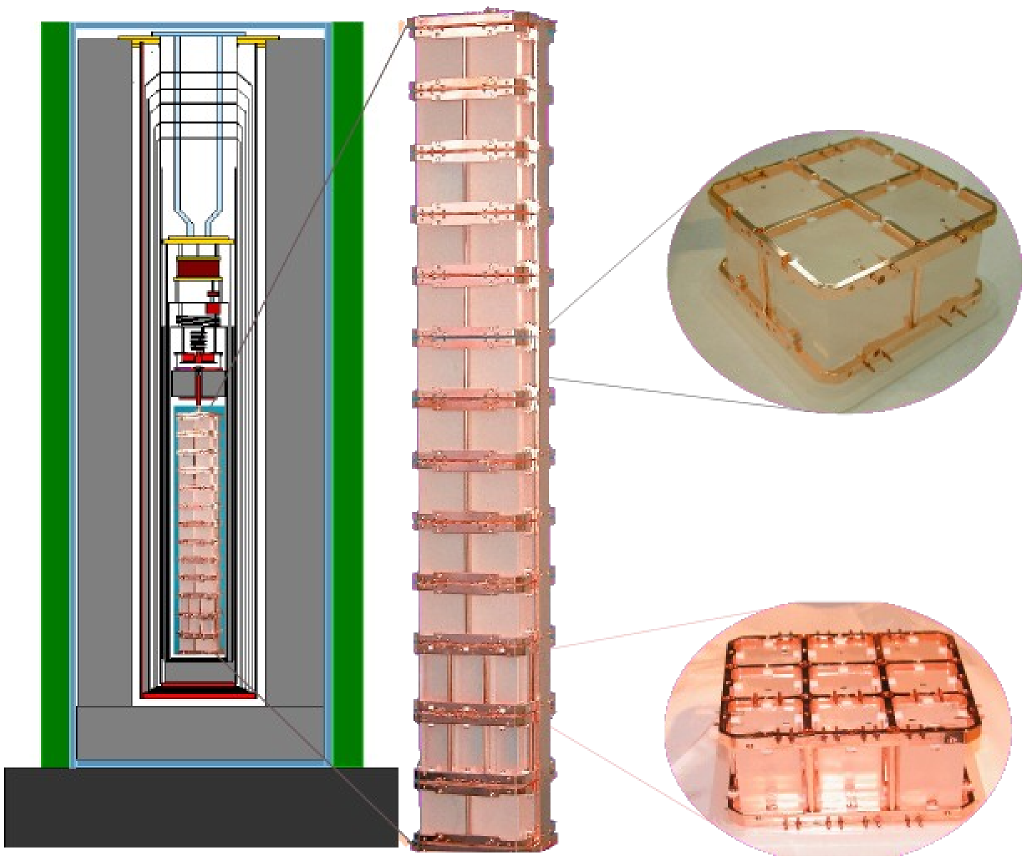


Cuoricino Ref.[8]

@LNGS 2003-2008

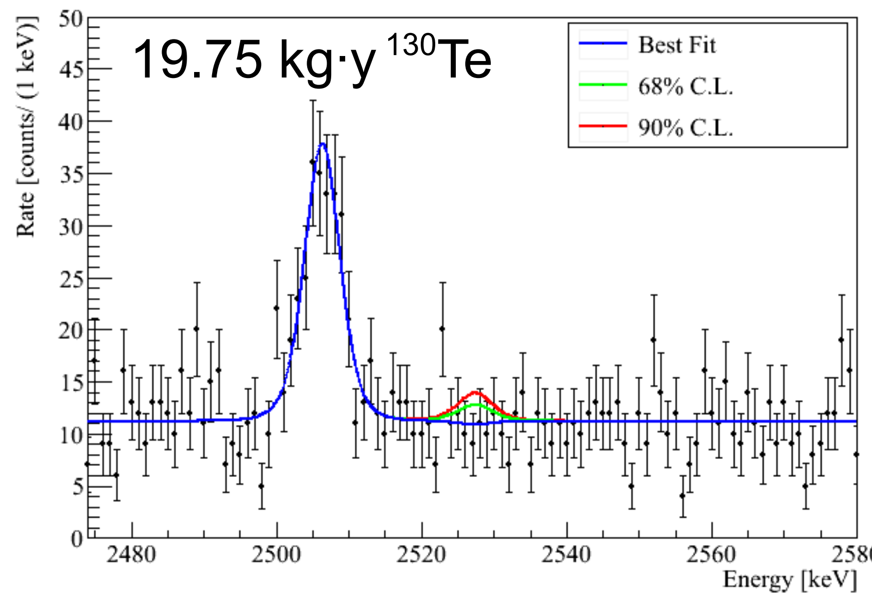
TeO_2 bolometric detector - with natural Te - 11.34 kg **^{130}Te** (34.167% i.a.)

$N_{\beta\beta}$= 5.2x10^{25} ε ~ 87% ΔE/E (FWHM) ~ 0.24% Bkg ~ 0.17 c/keV/kg/y



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

<m_{ee}> < 0.30 ÷ 0.71 meV [1-4]



$T_{1/2}^{0\nu}$ limit for decay on first 0^+ ^{130}Xe excited state also reported in Ref.[15]

Nemo3 detector

@LSM 2002-2011

External source detector (50 mg/cm^2 foils)

Tracking chamber (6180 DC in Geiger Mode)

Calorimeter for E, TOF (1940 Pl. Sc. blocks + PMTs)

B=26 G for e^+/e^- separation

Rn box installed in October 2004

ΔE/E (FWHM)~8%@3MeV ε ~ 18 % $2\nu\beta\beta$ bkg

7 Investigated isotopes:

^{48}Ca, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{150}Nd

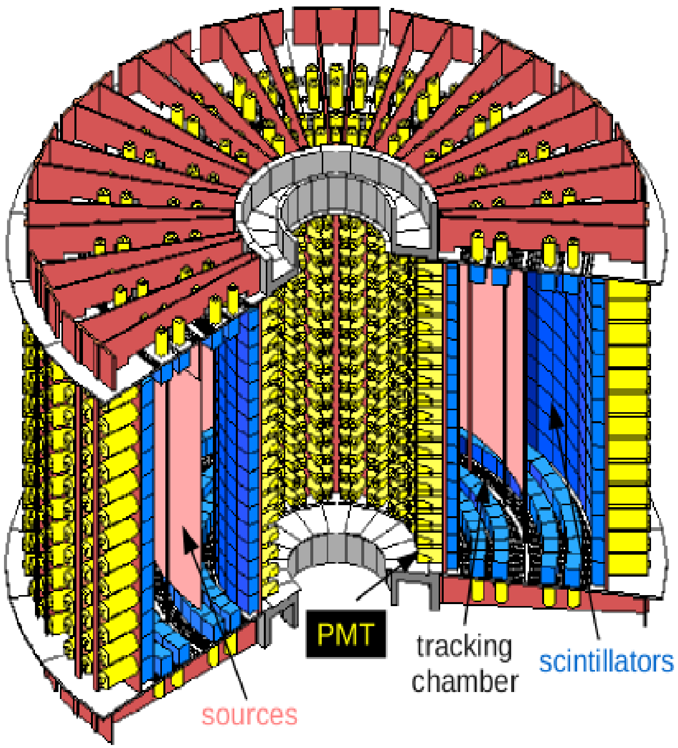
$N_{\beta\beta}$:

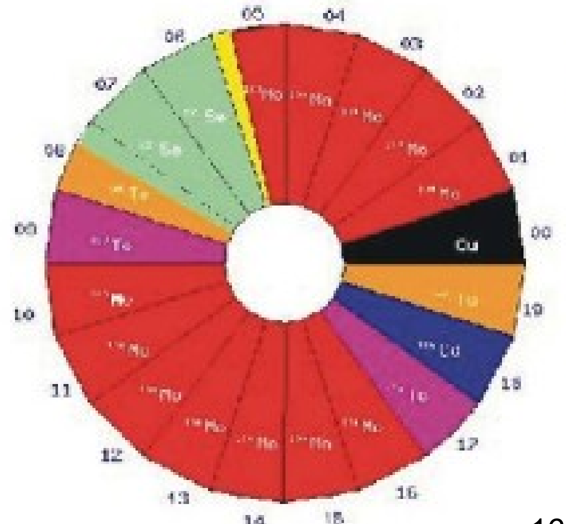
^{100}Mo: 7 kg - 4.2x10^{25} ^{82}Se: 1 kg - 6.8x10^{24}

^{116}Cd: 0.4 kg - 2.1x10^{24} ^{130}Te: 0.45 kg - 2.1x10^{24}

^{150}Nd: 37 g - 1.5x10^{23} ^{48}Ca: 7 g - 8.8x10^{22}

^{96}Zr: 9.4 g - 5.9x10^{22}





Nemo3 results Ref.[14]

Precision **measurement of $T_{1/2}^{2\nu}$** and evaluation of **$T_{1/2}^{0\nu}$ lower limits @90%CL**

^{48}Ca: $T_{1/2}^{0\nu} < 1.3\times10^{22}$ y   **^{96}Zr: $T_{1/2}^{0\nu} < 9.2\times10^{21}$ y**

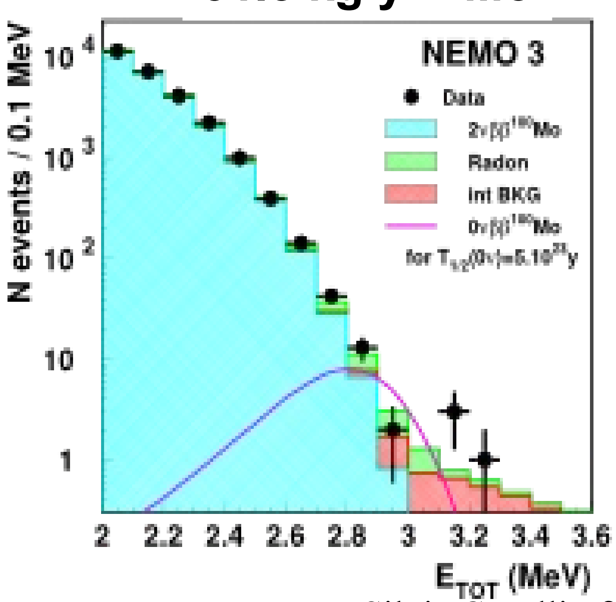
^{116}Cd: $T_{1/2}^{0\nu} < 1.6\times10^{22}$ y   **^{130}Te: $T_{1/2}^{0\nu} < 1\times10^{23}$ y**

^{150}Nd: $T_{1/2}^{0\nu} < 1.8\times10^{22}$ y

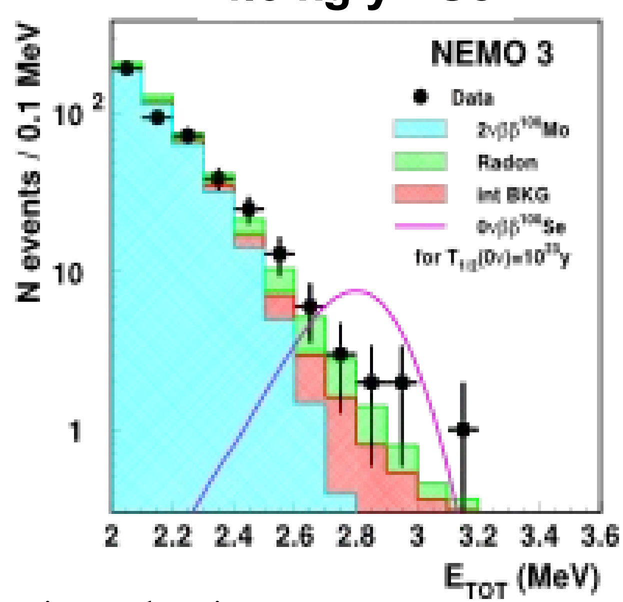
^{100}Mo **$T_{1/2}^{0\nu} > 1.1 \times 10^{24}$ y @90%CL**
$\langle m_{ee} \rangle < 0.44 \div 1.0$ meV [1-4]

^{82}Se **$T_{1/2}^{0\nu} > 3.6 \times 10^{23}$ y @90%C**
$\langle m_{ee} \rangle < 0.89 \div 2.37$ meV [1-4]

31.5 kg·y ^{100}Mo



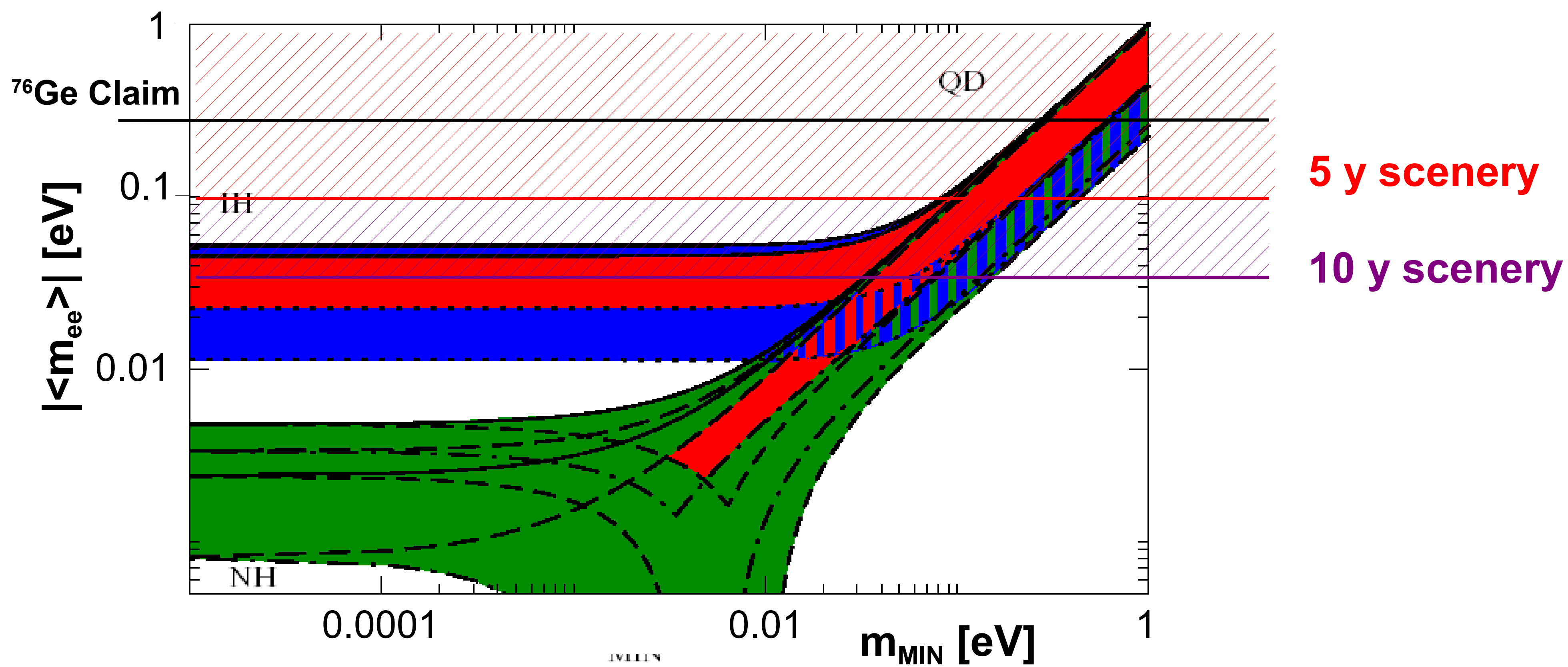
4.5 kg·y ^{82}Se



0νββ near future

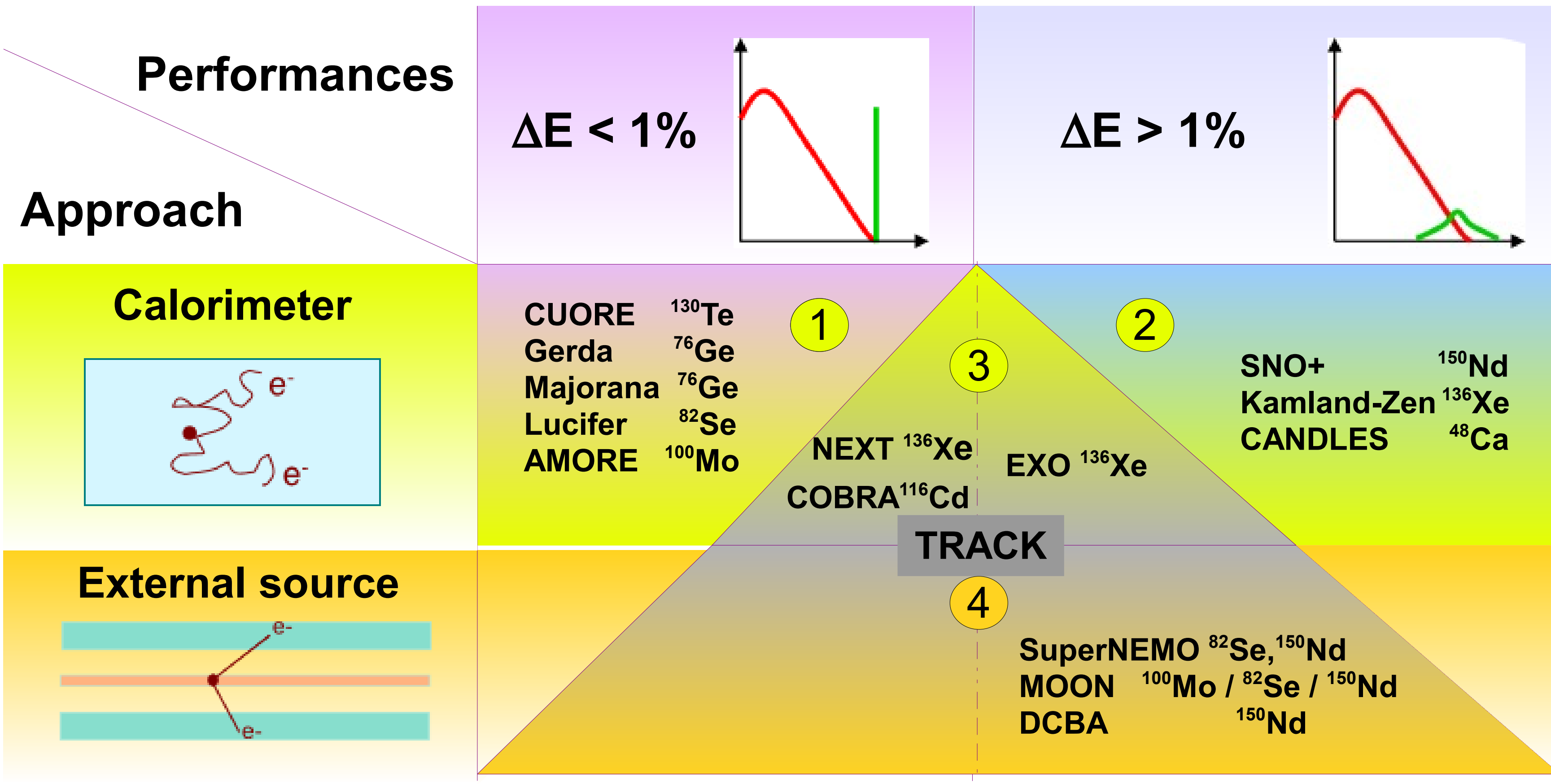
1- 5 y: many experiments with **M ~100-200 kg of ββ isotope** will be able to scrutinize **QD region** (100-500 meV) **and ^{76}Ge claim** with different isotopes and methods.
=> a negative result will rule out QD hierarchy

5 - 10 y: many experiments with **M ~ 1 t of ββ isotope** will have sensitivity to **enter the IH region** (10-50 meV) of the ν mass spectrum



Planned experiments

4 complementary approaches with different isotopes can be identified



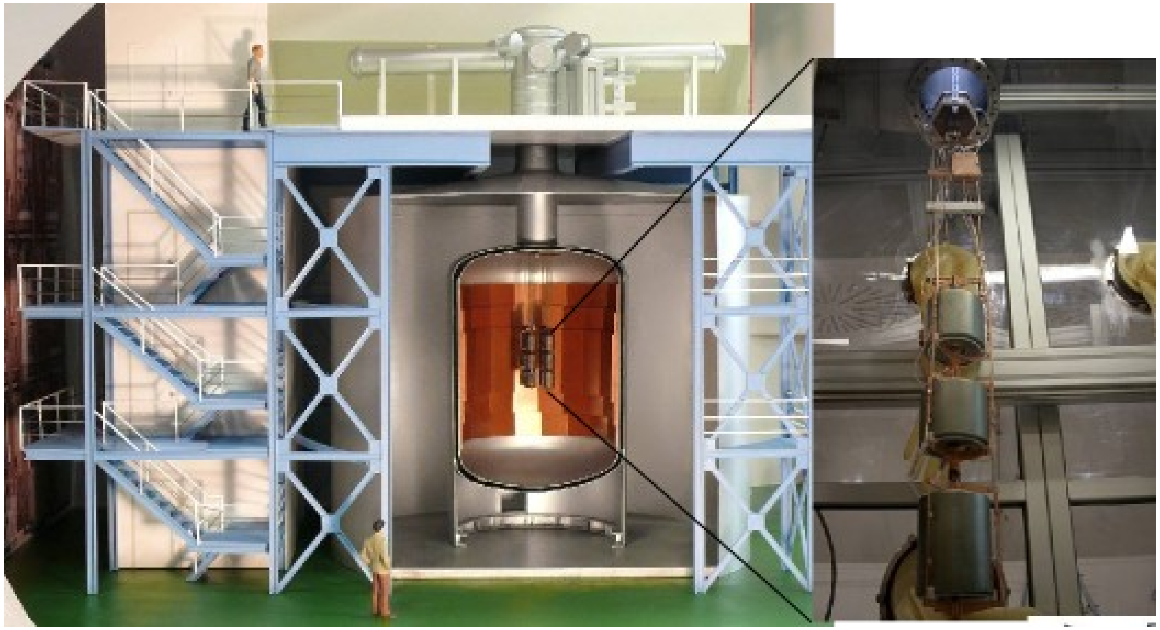
Many project are proposed, I apologize for the ones that are not shown in this talk

1

Gerda [17]

Ge diodes (86% enriched ^{76}Ge) **in LAr cryostat** (active in Phase II) **in water tank** (active)
BEGe technology in Phase-II**:** better E resolution, Multi/Single interaction discrimination
@LNGS Phase-I ~ end 2011 **Phase-II ~ 2013**

ββ candidate: ^{76}Ge **– Q** 2039 keV



Source Mass:
Phase-I: 18 kg ^{76}Ge – $\mathbf{N}_{\beta\beta}$ 1.4 x10^{26}
Phase-II: 40 kg ^{76}Ge – $\mathbf{N}_{\beta\beta}$ 3.2 x10^{26}

Projected Bkg:
Phase-I: 0.01 c/keV/kg/y
Phase-II: 0.001 c/keV/kg/y

Sensitivity $T_{1/2}^{0\nu}$:
Phase-I: 2.5x10^{25} y in 1 y
Phase-II: 1.9x10^{26} y in 5 y

Sensitivity on $<m_{ee}>$:
Phase-I: Scrutinize **KK claim** (if true 7 ββ cts over 0.5 cts of bkg) in 1 y data taking
Phase-II: $<m_{ee}> < 73 \div 203$ meV in 5 y **- QD region**

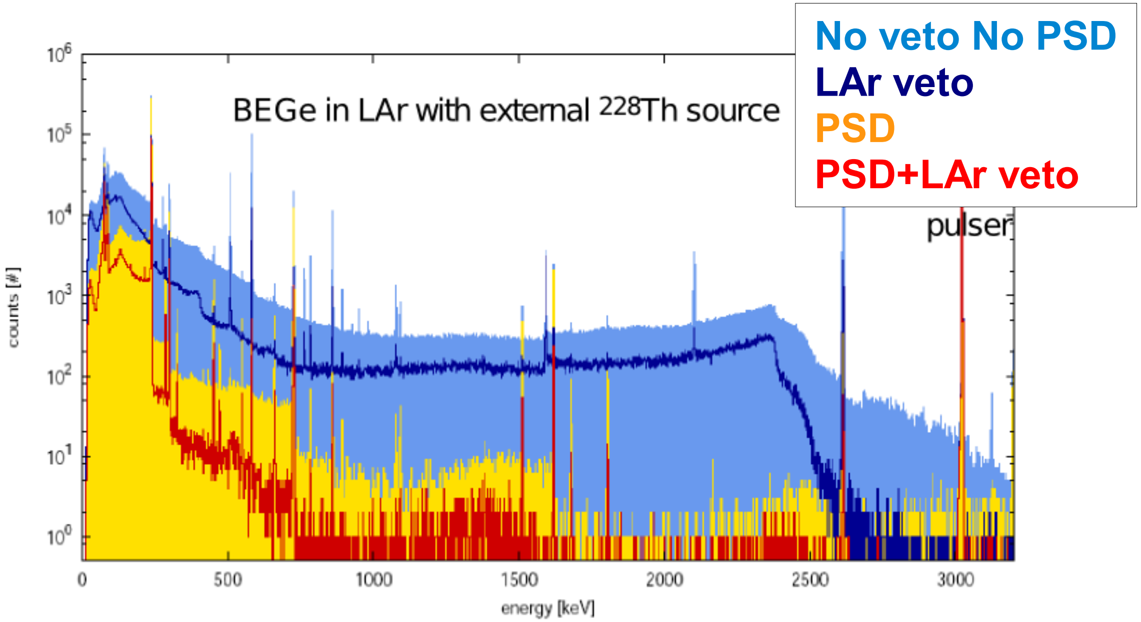
Gerda Status

Commissioning started in June 2010 with 1 string of 3 ^{nat}Ge for **setup bkg investigation** (found high ^{42}K contamination – from ^{42} Ar - but mostly solved)
In June 2011 deployed **1st string of ^{enr}Ge**

Resolution FWHM: 0.12% @ 1.3 MeV (obtained in a test with a BEGe prototype in LAr)

Demonstrated bkg: (^{enr}Ge string): **< 0.06 c/keV/kg/y 90% CL** (better than HM, IGEX)

Bkg reduction strategy: LAr active, BEGe technology allowing ID event topology



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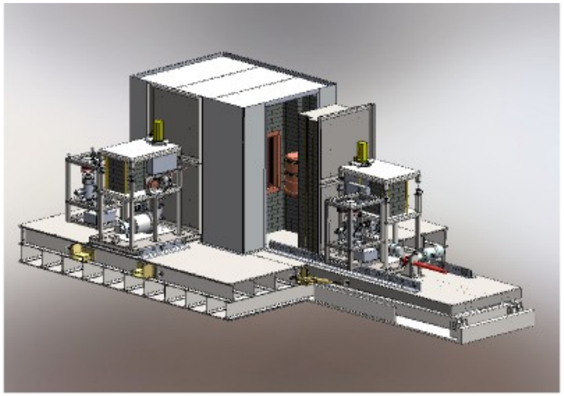
Majorana Demonstrator

BEGe detectors (20 kg ^{nat}Ge + 20 kg 86% enriched ^{76}Ge) **in 2 conventional cryostats**

GOAL: **demonstrate bkg and feasibility, test KK claim**
@Sanford UL Start ~ 2014

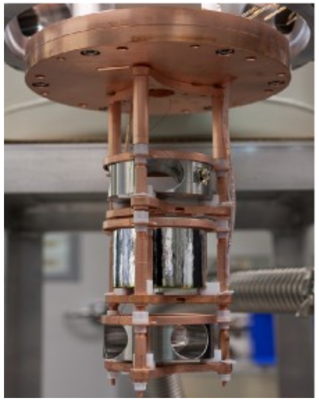
ββ candidate: ^{76}Ge **– Q** 2039 keV



Source Mass:
30 kg ^{76}Ge – $\mathbf{N}_{\beta\beta}$ 2.4 x10^{26}

Projected Bkg:
0.001 c/keV/kg/y (shields + BEGe techn.)

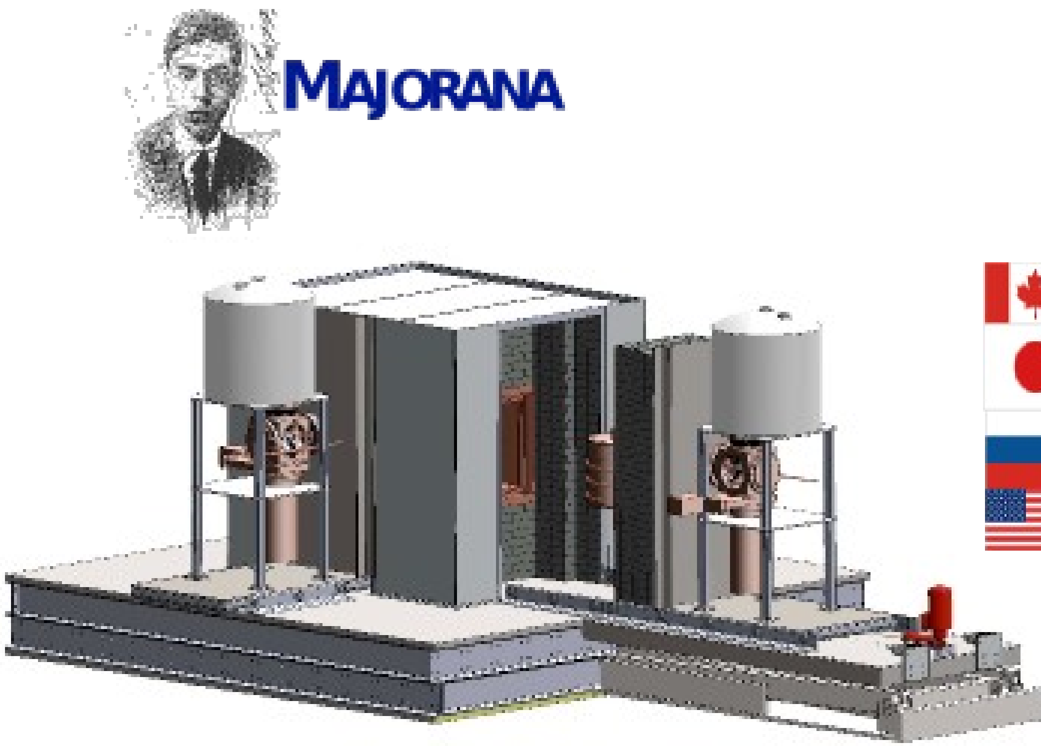
Sensitivity $T_{1/2}^{0\nu}$:
9x10^{25} y in 5 y

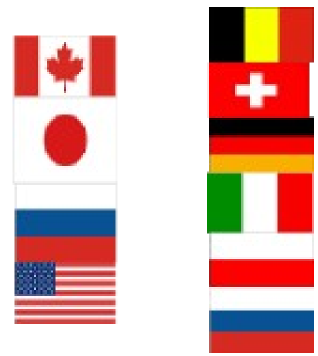


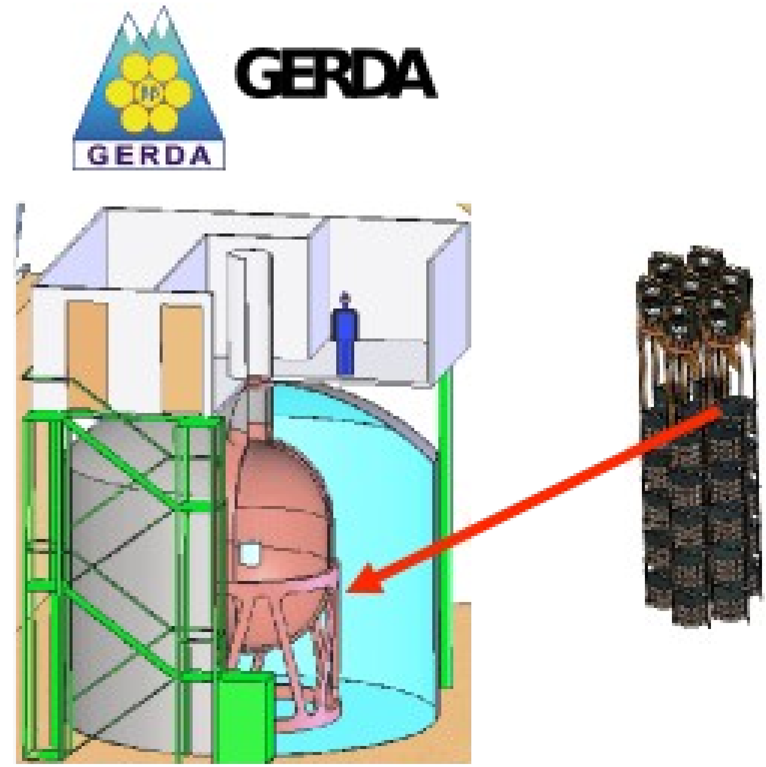
Sensitivity $<m_{ee}>$:
Scrutinize KK claim in < 2 y data taking
$<m_{ee}> < 106 \div 295$ meV in 5y **- QD region**

Schedule: 2012: 2-3 ^{nat}Ge strings in prototype cryostat (19 ^{nat}Ge diodes in hand)
2013: 3 strings ^{nat}Ge + 4 strings ^{enr}Ge below ground (1st cryostat)
2014: full experiment

MAjorana-GErda







Joint Cooperative Agreement:

Open exchange of knowledge and technologies

Select best technique developed and tested in GERDA and Majorana

Intention to merge for 1 ton exp. (~ 2020)

=> factor ~ 2.5 on $<m_{ee}>$: 43 ÷ 120 meV in 5 y (enter IH region)

1

CUORE [18-20]

988 TeO_2 (34.167% ai ^{130}Te) **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 ^{130}Te – $\mathbf{N_{\beta\beta}}$ 5.0 x10^{25}

Phase-II: **206 kg** ^{130}Te – $\mathbf{N_{\beta\beta}}$ 9.6 x10^{26}

Projected Bkg:

Phase-I: 0.05 c/keV/kg/y

Phase-II: 0.01 c/keV/kg/y

Resolution FWHM: ~ 0.2% @ROI

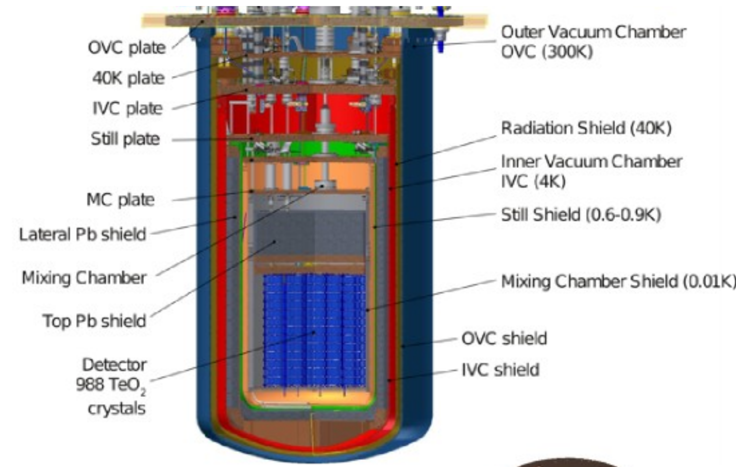
Sensitivity $T_{1/2}^{0\nu}$:

Phase-I: 4.2x10^{24} y in 1 y

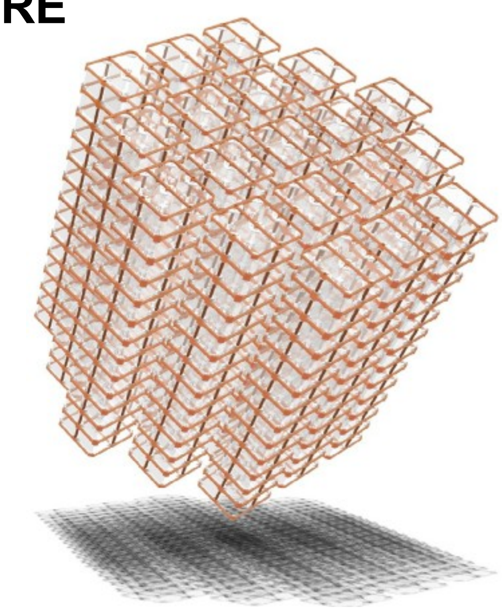
Phase-II: 1.6x10^{26} y in 5 y

Sensitivity Phase-II <m_{ee}>:

<m_{ee}> < 40 ÷ 94 meV in 5y **– IH region**



CUORE



CUORE-0

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% @ $Q_{\beta\beta}$ (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 cryostatwith 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	$< 2.0 \times 10^{-3}$
γ Compton from cryostat	$< 1.0 \times 10^{-3}$
Cu holder bulk	$< 2.0 \times 10^{-3}$
Cu holder surface	$< 2.5 \times 10^{-2}$
TeO_2 bulk/surface	$< 5.6 \times 10^{-3}$

1

Lucifer [21-23]

ZnSe scintillating bolometers (95% enriched ^{82}Se) at ~ 10 mK
with double read-out **(heat/light)** for **alpha bkg** suppression
GOAL: demonstrate feasibility of large M exp with this technique
@LNGS Cuoricino/CUORE-0 cryostat start ~ 2014

ββ candidate: ^{82}Se **– Q** 2995 keV

Source Mass:
17.6 kg ^{82}Se – $\mathbf{N}_{\beta\beta}$ 1.3 x10^{26}

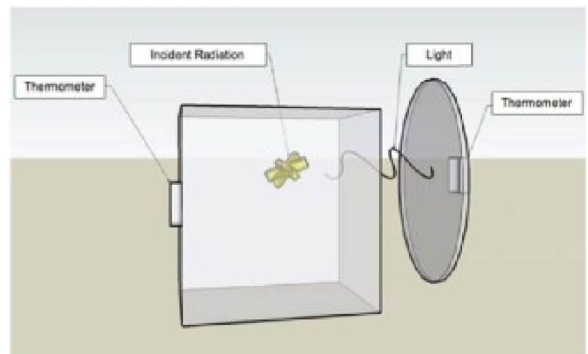
Projected Bkg:
0.001 c/keV/kg/y

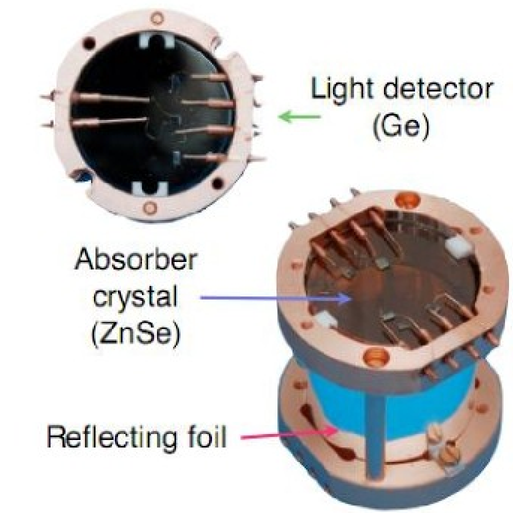
Projected FWHM: ~ 0.17% @ROI
Measured FWHM: ~ 0.34% @2615 keV

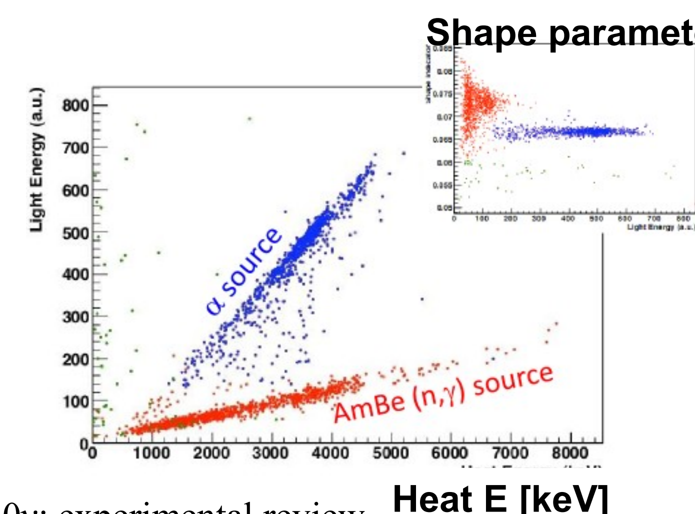
LY: 7.4 keV/MeV (~3700 phot/MeV)

Sensitivity $T_{1/2}^{0\nu}$:
2.3x10^{26} y in 5 y

Sensitivity $<m_{ee}>$:
$<m_{ee}>$ < 35 ÷ 94 meV in 5y **– IH region**







AMORE [24]

1

100 kg $^{40}Ca^{100}MoO_4$ scintillating bolometers (96% ^{100}Mo enriched, <0.001% ^{48}Ca depletion) at low T with double read-out **(heat/light) or shape analysis** for **alpha bkg** suppression

@YangYangUL R&D phase

ββ candidate: ^{100}Mo **– Q** 3034 keV

Source Mass:
50 kg ^{100}Mo – $\mathbf{N_{\beta\beta}}$ 3.0 x10^{26}

Projected Bkg:
0.001 c/keV/kg/y

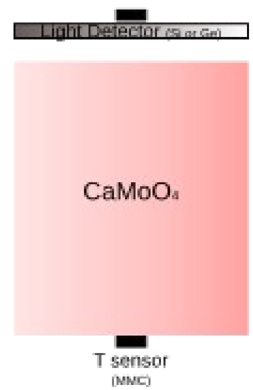
Projected FWHM: ~ 0.07% @ROI
Measured FWHM: ~ 0.2% @ 5 MeV

LY (RoomT): ~9300 phot/MeV

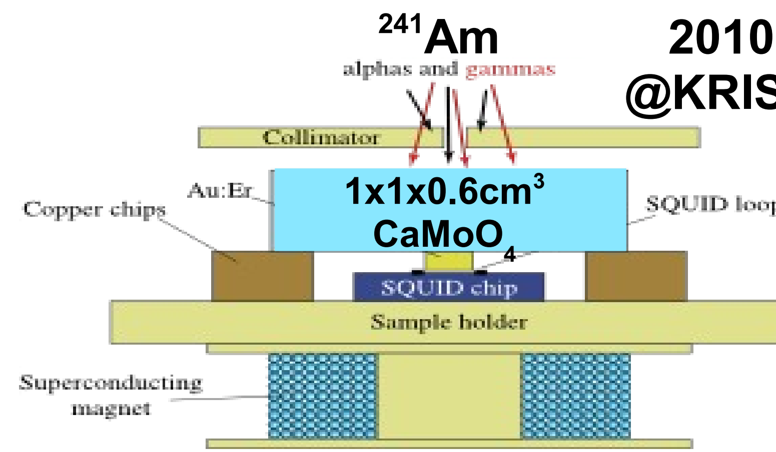
Sensitivity $T_{1/2}^{0\nu}$:
3x10^{26} y in 5 y

Sensitivity <m_{ee}>:
<m_{ee}> < 27 ÷ 63 meV in 5y – **IH region**

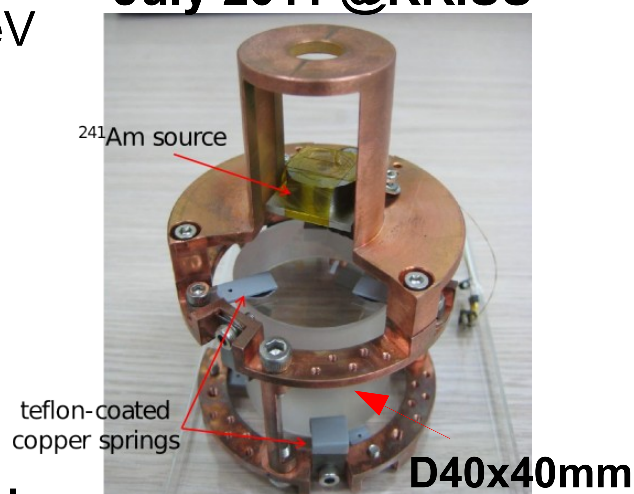
T sensor
(MMC/TES/NTD)



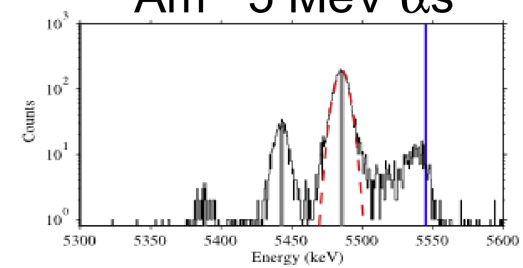
2010 @KRISS



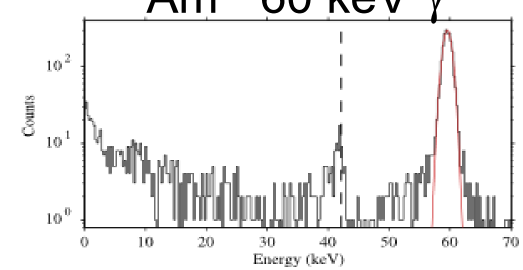
July 2011 @KRISS



^{241}Am ~5 MeV αs



^{241}Am ~60 keV γ



2

SNO+ [25]

See M.Chen talk

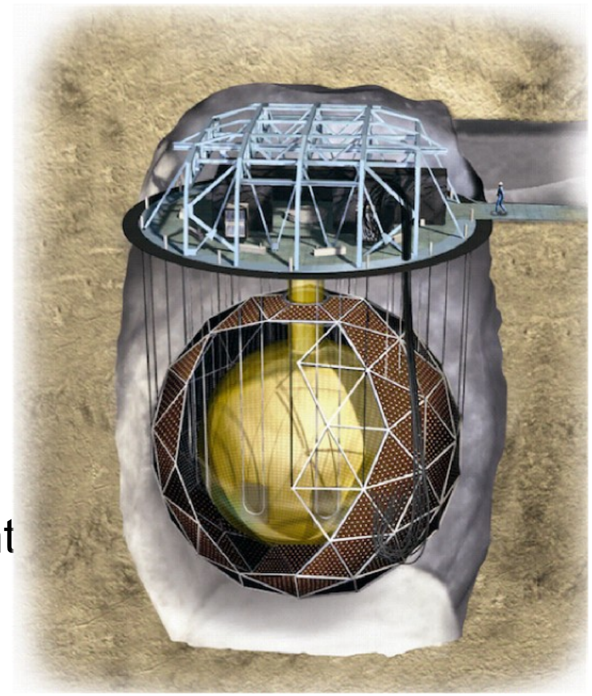
~ 780 t Liquid Scintillator 0.1% ^{nat}Nd loaded (5.6% a.i. of ^{150}Nd) in a Ø6m Acrylic Vessel surrounded by 7000 t ultrapure H_2O and ~9000 PMT.
@SNO Lab Start ~ 2014

ββ candidate: ^{150}Nd **– Q** 3370 keV

Source Mass:
43.7 kg ^{150}Nd – $N_{\beta\beta}$ 1.8 x10^{26}

Trade off ΔE / Nd loading

Main Bkg:
Th/U in LS ->negligible and tagged
2νββ → Spectrum shape fit at End Point
^{8}B solar ν



Schedule:
2011:- Finish cavity
- AV hold-down-net
- Sand in AV

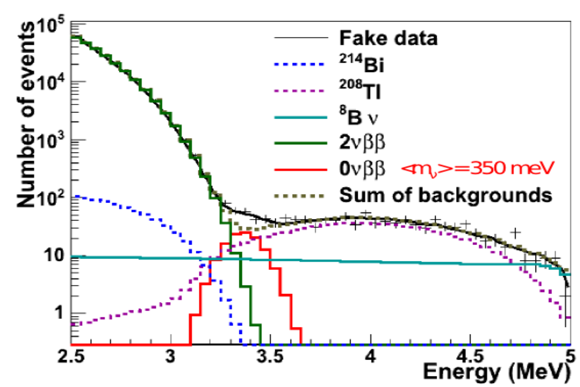
2012: - LS process system
- Water fill: cal runs

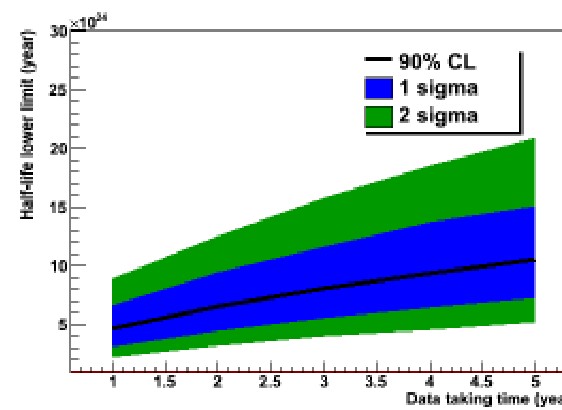
2013: - Pure LS phase
2014: - **Nd-loaded phase**
Then: - 0.3% Nd loading?
- ^{150}Nd enrichment?

Projected FWHM: ~ 6.4% @ROI

Sensitivity $T_{1/2}^{0\nu}$**:**
7.7x10^{24} in 5 y

Sensitivity <m_{ee}>**:**
<m_{ee}> < 172 ÷ 180 meV in 5 y **-QD region**





Kamland-Zen [26]

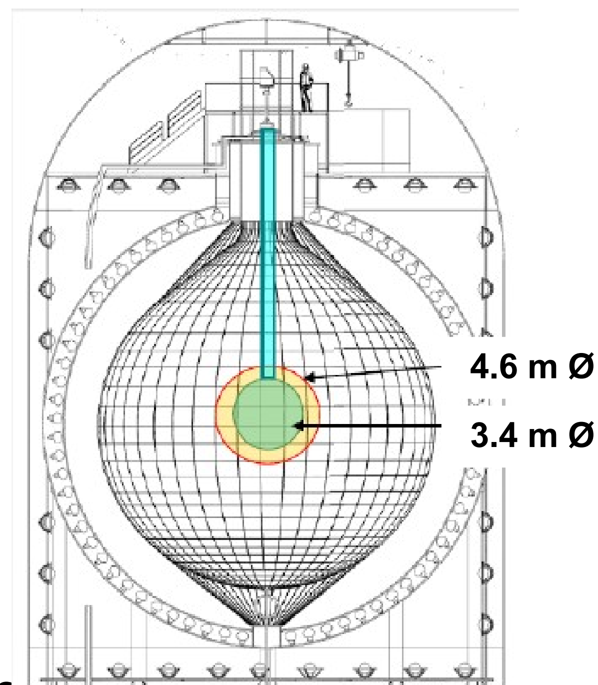
See Y.Gando talk

~16 t (40 t in 2nd phase) **Liquid Scintillator 2.5wt% enrXe loaded** (91% enrichment of ^{136}Xe) in a Ø3.4m Mini Baloon in Kamland detector (1000t LS+Buffer Oil+Water Cherenkov Outer Detector)
@Kamioka mine — 1st Phase~ end 2011 — 2nd Phase >2013-2015

ββ candidate: ^{136}Xe **– Q** 2476 keV

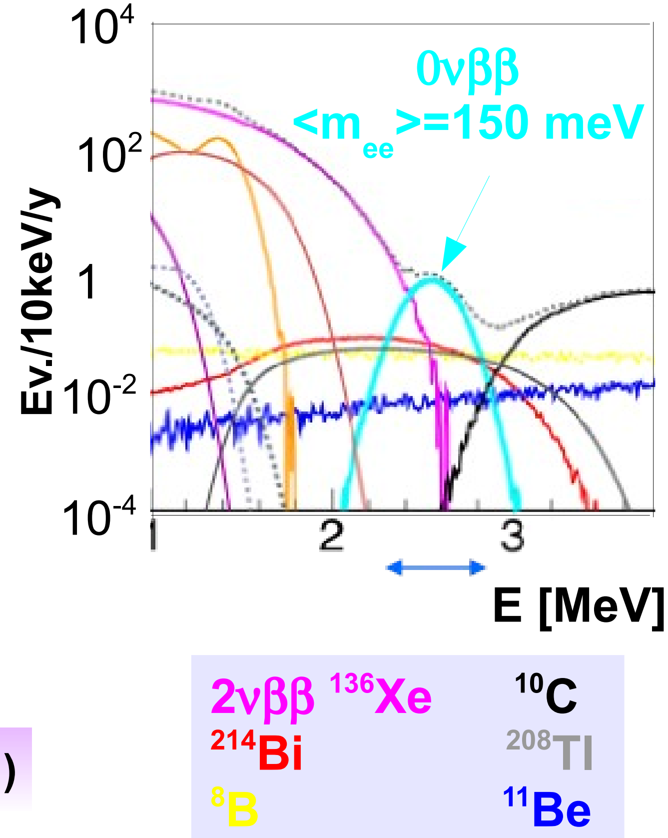
Source Mass:
1st Phase: 364 kg ^{136}Xe – $N_{\beta\beta}$ 1.6 x10^{27}
2nd Phase: 910 kg ^{136}Xe – $N_{\beta\beta}$ 4.0 x10^{27}

Main Bkg:
2νββ ^{136}Xe → slow: $T_{1/2}$~10^{22} y
^{10}C, ^{11}Be in LS → 1/10 with tag
^{8}B solar ν
^{214}Bi, ^{208}Tl from MB contam. → vertex cut
=> expected S/Bkg ~ 2



MB installed and filled (Sept.2011)

Simulated E Spectrum



Measured FWHM: ~ 10% @ROI

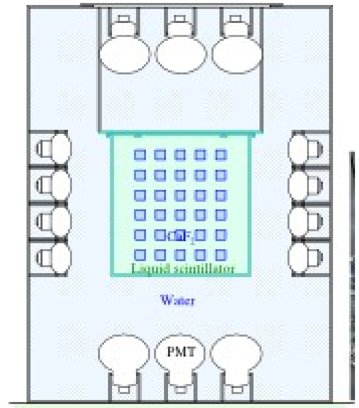
2nd Phase: Brighter LS + Winstone Cones

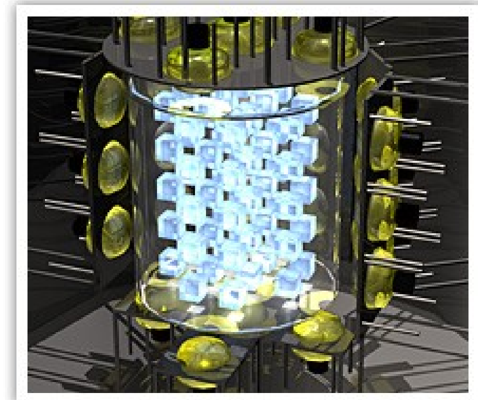
Target Sensitivity:
1st phase: <m_{ee}> ~ 60 meV @5 y
2nd phase: <m_{ee}> ~ 25 meV @5 y **- IH region**

CANDLES [27]

CANDLES-III: 96 CaF_2 scintillators (0.187% ai of ^{48}Ca) **in a granular structure (~305 kg)**
with **4π LS active shield** and H_2O buffer passive shield
GOAL: 1st step towards a ~tons CaF_2 experiment for IH

@Kamioka mine — 1st phase: commissioning started in June 2011 — 2nd phase: enrichm.?





ββ candidate: ^{48}Ca **– Q** 4270 keV !!

Source Mass:
1st phase: 350 g ^{48}Ca – $\mathbf{N_{\beta\beta}}$ 4.4 x10^{24}
2nd phase: $\mathbf{N_{\beta\beta}}$ ~10^{26}

Bkg Strategy:
- 2νββ negligible if ΔE 4% FWHM
- 4π LS shield for external γ
- PSD + time/position (internal Bi-Po,Bi-Tl)

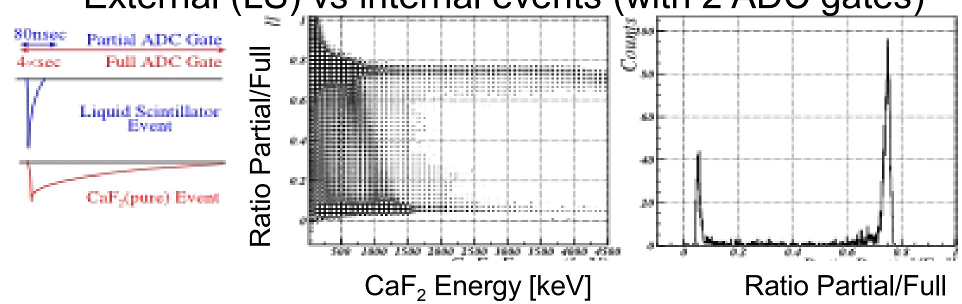
=> ~ bkg free experiment

Measured FWHM: ~ 3.4% @ROI

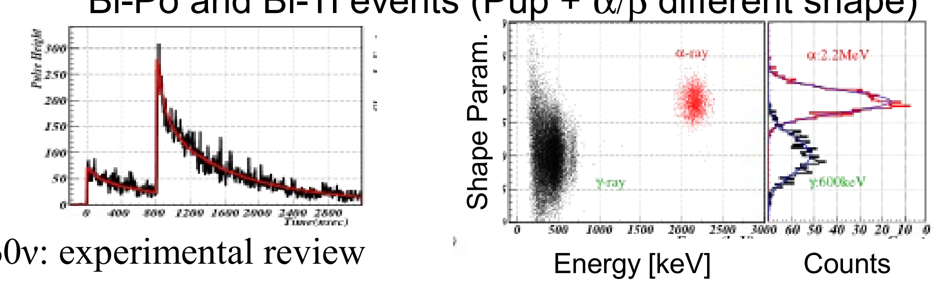
Target Sensitivity:
1st phase: <m_{ee}> ~ 500 meV @3 y **– QD region**
2nd phase: **IH region**

Preceding tests:

External (LS) vs internal events (with 2 ADC gates)



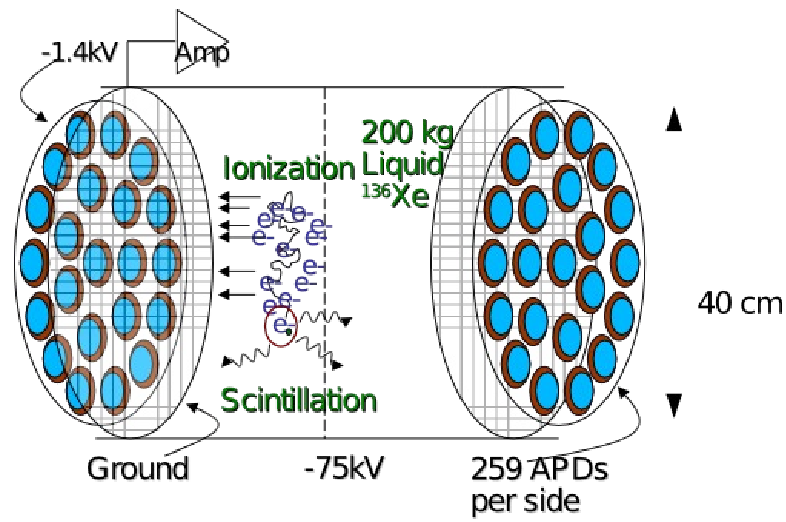
Bi-Po and Bi-Tl events (Pup + α/β different shape)



③

EXO [28,29]

~ 1 ton TPC of liquid ^{enr}Xe (80.6% of ^{136}Xe) at 167 K with double read-out **(ion+scint)** allowing event **3D tracking** and **α/β discrimination + Ba^+ daughter tag** for **free bkg exp**.
GOAL of EXO-200: 1st step without Ba^+ tag for QD region
@WIPP Exo-200: Started 2011 – 2νββ result: $T_{1/2}$ ~ 2.1×10^{21} y Start Exo-full ?



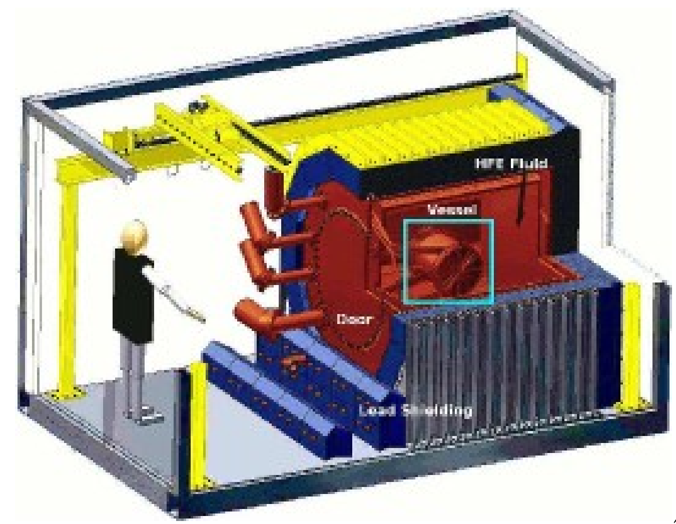
ββ candidate: ^{136}Xe – **Q** 2476 keV

Source Mass:
Exo-200: ~ 50 kg FMass ^{136}Xe – $N_{\beta\beta}$ 2.3 x10^{26}

Bkg Strategy:
- low activity materials / LXe purity check
- conventional screening techniques+ FV cut
- 3D track (double grid (xy) + Avalanche Photo Diodes (t_0->z))
- α/β discrimination through ion. vs. light
- Ba^+ tag with Resonant Ionization Spectrosc.

Projected Bkg: ~ 10^{-4} c/keV/kg/y

Projected FWHM: ~ 3.7% @ROI (maybe better if gas Xe)



Target Sensitivity:
Exo-200: $T_{1/2}$ ~ 6.4×10^{25} y @2y <m_{ee}> < 87 ÷ 224 meV in 2y
Exo-full: $T_{1/2}$ ~ 2.0×10^{27} y @ 5y <m_{ee}> < 16 ÷ 40 meV in 5y

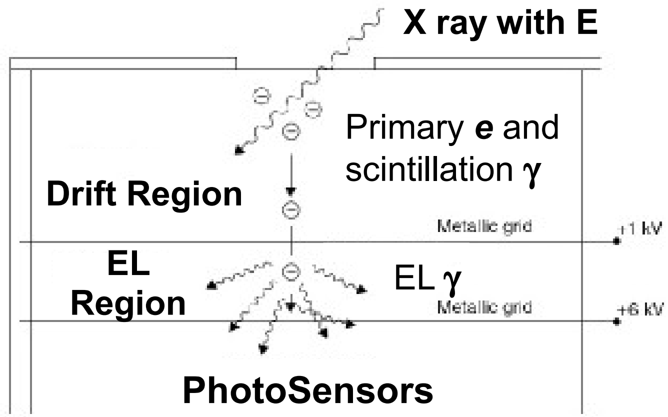
3

NEXT-100 [29]

119 kg High Pressure Gas- ^{enr}Xe EL TPC (~ 90% of ^{136}Xe) **at 15 bar** with double read-out **(ion+scint/EL)** allowing **good ΔE** + event **3D tracking** and **topology** for a **free bkg exp**.
@SLC Next-1: on-going Next-100: ~ 2015 Future 1t?

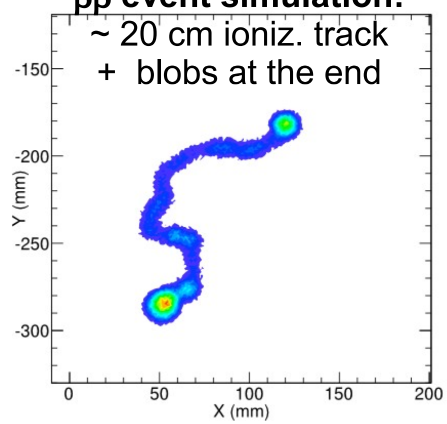
ββ candidate: ^{136}Xe **– Q** 2476 keV

Source Mass:
~ 90 kg FMass ^{136}Xe – $\mathbf{N}_{\beta\beta}$ 4.0 x10^{26}



Bkg Strategy:
- low activity materials / GasXe purity monitor
- conventional screening techniques
- 3 cuts: FV + ROI + topology

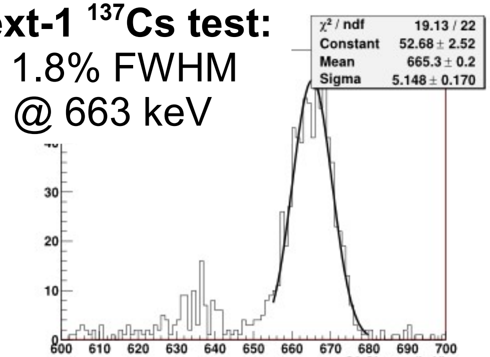
ββ event simulation:



Projected Bkg: ~ $2\cdot10^{-4}$ c/keV/kg/y

Projected FWHM: ~ 1% @ROI (EL!)

Next-1 ^{137}Cs test:
~ 1.8% FWHM
@ 663 keV



Target Sensitivity:
Next-100: <m_{ee} > ~ 89 meV @6y
Next-100+Next-1t: <m_{ee} > ~ 38 meV @6y (3+3) – **IH region**

3

COBRA [30]

Solid state TPC made of a **Large Array** (total 420 kg) of **CdZnTe smc detectors** (^{116}Cd enr.) at room temperature with **tracking capability**.

@LNGS R&D: on-going with 2 types of det. COBRA: technical design report ~2013

ββ candidate: 9 candidates
Most promising (high Q) ^{116}Cd – **Q** 2809 keV

2 types of detectors under consideration:
- CoPlanar Grid Detectors (CPG)
  * little ¨location¨ info (with PSA) + simple read-out
- Pixelated Detectors
  * 3D ¨location¨ + Particle ID if small pixels.
  * Complex read-out

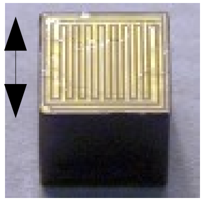
Bkg Strategy:
- low activity materials
- Conventional screening techniques
- R&D for operation in LS (active veto)
- Multi/Single hit event with both types
- Tracking with Pixelated + topology (small Pix)

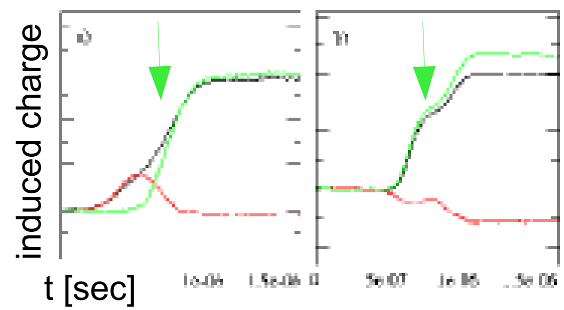
Projected ΔE: < 2 (1) % @ROI with CGD(Pix)

Target Sensitivity:
$<m_{ee}>$ ~ 50 meV – **IH region**

CPG: 18kg·d data with 4x4 array
2011 new setup: 8 det -> 64 soon

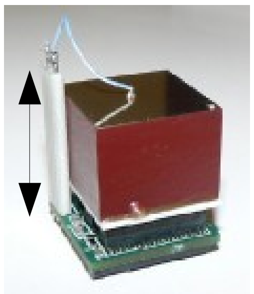
1cm

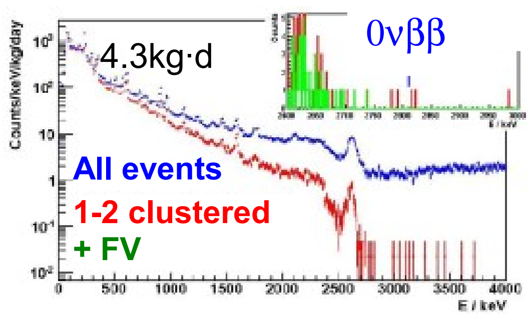




Large Pixel (11x11):

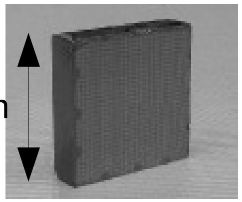
1.5cm





Small Pixel (128x128):

1.4cm



Topology

SuperNEMO [31]

4

20 modules of **tracker-calorimeter** with 40 mg/cm^2 source foil each (~5 kg ^{82}Se each).
@LSM Demonstrator (1 module) start-up ~ 2013 Full: start-up ~2014

ββ candidate: ^{82}Se – **Q** 2995 keV

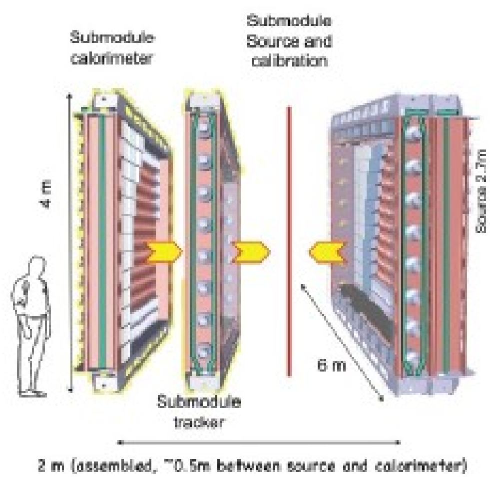
Source mass:
Demonstrator: 5 kg ^{82}Se - $\mathbf{N}_{\beta\beta}$ 1.8 x10^{25}
Full: 100 kg ^{82}Se - $\mathbf{N}_{\beta\beta}$ 7.3 x10^{25}

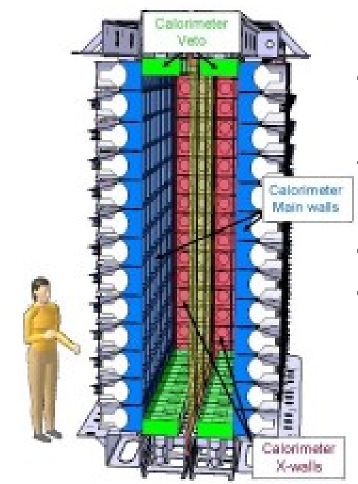
Bkg Strategy:
- Standard shieldings
- Low $^{208}Tl/^{214}Bi$ contam. in source foils
- tracking
- 2νββ reduced with better ΔE

Measured ΔE: ~4 % @ROI
with best calorimeter/PMT choice

Target Sensitivity:
Demonstrator: KK claim within 2015
Full: $T_{1/2}^{0\nu}$ ~ 1.2 x10^{26} 90%CL @ 5y
<m$_{ee}$> ~ 40-105 meV @ 5y – **IH region**

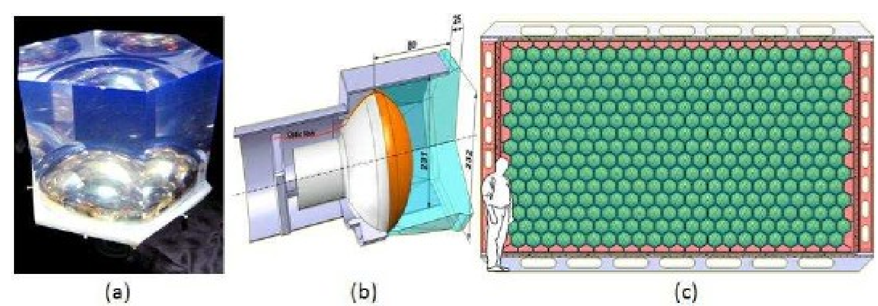
Single-Module: 5x4x1 m^3





- **track** (2000 wire Drift Cells in Geiger Mode)
- **calorimeter wall** (550 PVT +PMTs)
- **γ veto**
- 25 Gauss B

Calorimeter: PVT (plastic scintillator) + PMT (~550/module)



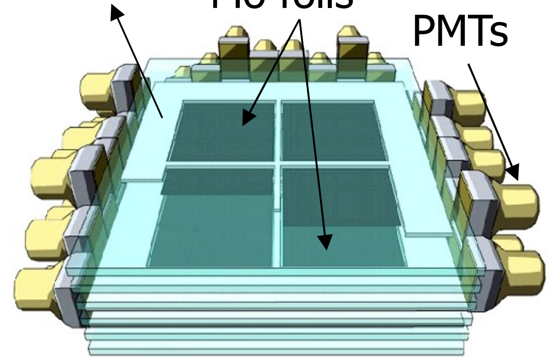
MOON [32-33]

4

Multi-layer detector modules: **PL scint. planes** (E+t) / **PL-fibers** (V,φ) / 50mg/cm^2 **source** foils
@Oto U.L. MOON-1: prototype ~ 2006 3 Phases of increasing mass (start Phase-III ?)

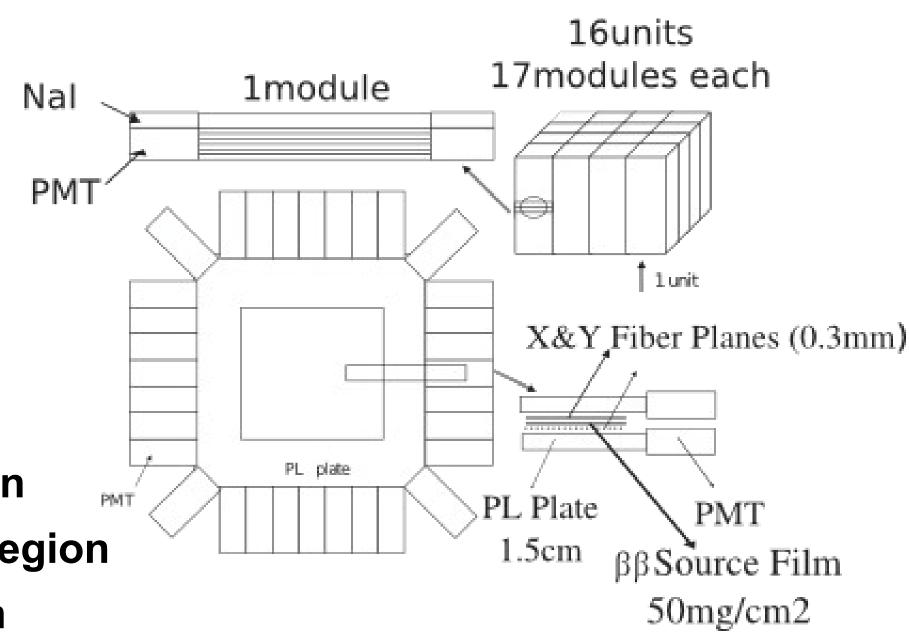
ββ candidate: ^{82}Se – **Q** 2995 keV
^{100}Mo – **Q** 3134 keV

Source mass:
Phase-I: 0.03 t isotope
Phase-II: 0.12 t isotope
Phase-III: 0.48 t isotope (3x10^{27} $N_{\beta\beta}$)



Bkg Strategy:
- Standard shieldings
- Active veto from Multi-layer structure
- Low ^{208}Tl/^{214}Bi contam. in source foils
- M=2 event with same Vertex
- E1+E2 @ROI (Q-ΔE_{source} within 3σ)
- no delayed coincidence (Δt~hours)
- 2νββ reduced with good ΔE

Measured ΔE: σ~2.2 % @ROI (Foreseen σ ~1.7 %)



Target Sensitivity:
Phase-I: $T_{1/2}^{0\nu}$~ 0.32(0.15) x10^{26} @ 1y for Se(Mo) **- QD region**
Phase-II: $T_{1/2}^{0\nu}$~ 1.12(0.41) x10^{26} @ 1y for Se(Mo) **- LowQD region**
Phase-III: $T_{1/2}^{0\nu}$~ 5.90(2.00) x10^{26} @ 1y for Se(Mo) **-IH region**

4 Drift Chamber Beta-ray Analyzer [34,35]

Momentum analyzer consisting of tracking detectors (DC) with solenoid magnet for uniform B @KEK **DCBA-T2**: prototype~ 2009 **DCBA-T3** in construction for ΔE improvements
Future: MTD-full ~200 mol ^{150}Nd source Start ?

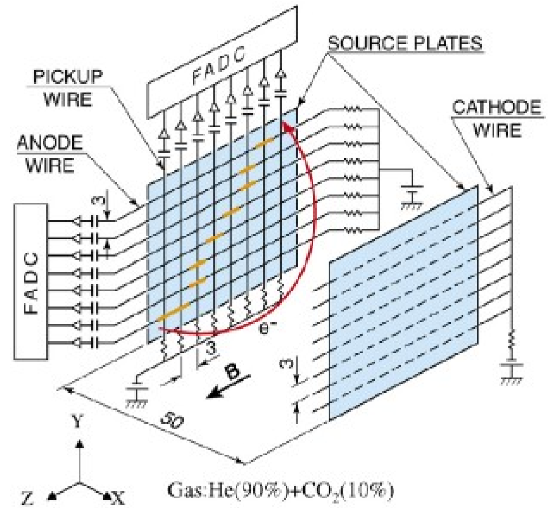
ββ candidate: ^{150}Nd – **Q** 3370 keV

Source mass:
DCBA-T2: 0.03 mol ^{100}Mo for test with 2νββ
DCBA-T3: 0.18 mol ^{150}Nd ($^{nat}Nd_2O_3$ foils)
MTD-1: 1.3x10^{26} ^{150}Nd ($^{enr}Nd_2O_3$ – 60% enr)
MTD-full: 10 x MTD-1

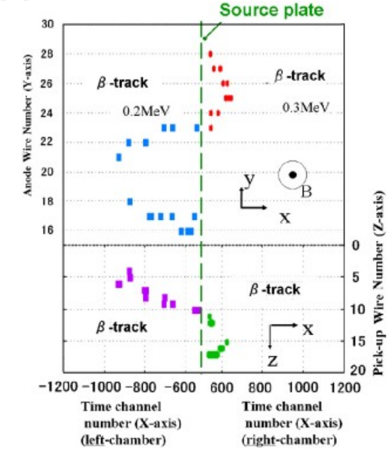
Bkg Strategy:
-Vetoes for cosmic rays
-3D track in uniform B
(search for 2 circled curves in X,Y + sin in Z)
-p and T from track

DCBA-T2 ΔE FWHM: ~6.2 % @ROI
DCBA-T3 foreseen ~3.4 % (>B)

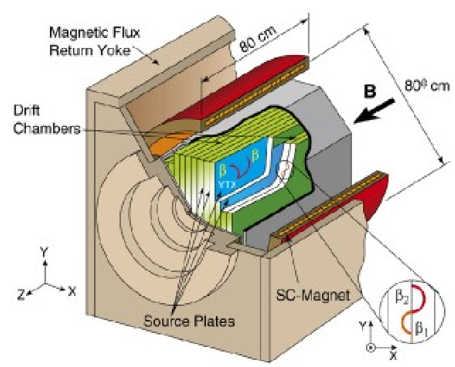
Target Sensitivity:
DCBA-T3: **<m$_{ee}$> ~ 4 eV**
MTD-1: **<m$_{ee}$> ~ 100 meV**
MTD-full: <m$_{ee}$> ~ 30 meV

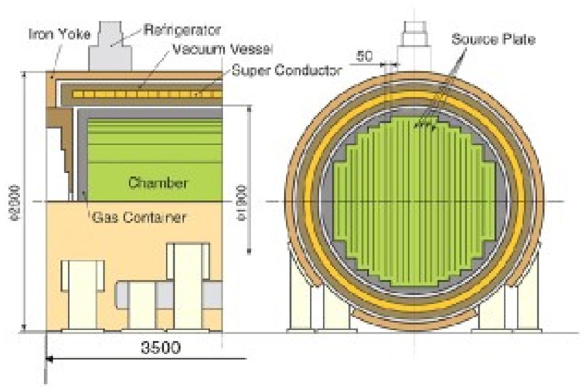


2νββ track with ^{100}Mo source



DCBA-T3 and MTD (vs. DCBA-T2):
12 Drift Chambers (vs. 2)
3 mm wire pitch (vs. 6 mm)
B=3 kG (vs. 0.8 kG) with Sup. Sol. Magn. (vs. conventional S.M.)
^{150}Nd in Nd_2O_3 plates -^{nat}Nd @T3, ^{enr}Nd @MTD (vs. ^{100}Mo in ^{nat}Mo)

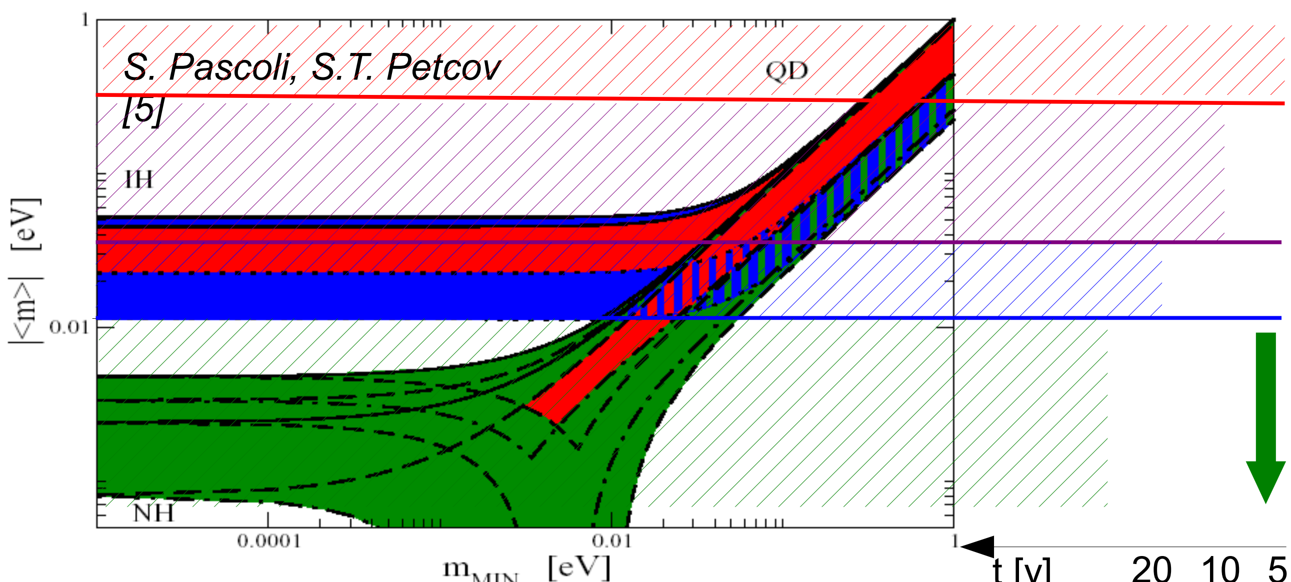




Experiment	ββ candidate	Q-value[keV]	Enrichm.	$N_{\beta\beta}$ x10^{26}	Start [y]	<m_{ee}>[meV]@5y
GERDA	^{76}Ge	2039	yes	3.2	2013	73-203
Majorana	^{76}Ge	2039	yes	2.4	2014	106-295
MaGe	^{76}Ge	2039	yes	68	2020	43-120
CUORE	^{130}Te	2527.5	no	9.6	2014	40-94
Lucifer	^{82}Se	2995	yes	1.3	2014	35-94
AMore	^{100}Mo	3034	yes	3	?	27-63
SNO+	^{150}Nd	3370	no	1.8	2014	172-180
Kamland-Zen	^{136}Xe	2476	yes	4	2013-2015	25
Candles	^{48}Ca	4270	no	0.04	2011	500
Candles-enr	^{48}Ca	4270	yes	1	?	IH
Exo-200	^{136}Xe	2476	yes	2.3	2011	87-221 @2y
Exo-Full	^{136}Xe	2476	yes	20	?	16-40
Next-100	^{136}Xe	2476	yes	4	2015	90 @6y
Next-1t	^{136}Xe	2476	yes	30	?	38 @(3+3)y
COBRA	^{116}Cd	2809	yes	nd	?	50
SuperNemo	^{82}Se	2995	yes	7.3	2014	40-105
Moon	^{82}Se/^{100}Mo	2995/3134	yes	30	?	IH
DCBA	^{150}Nd	3370	yes	10	?	30

Conclusions

- **0νββ search** is well motivated (L violation, ν nature etc.) and is actually a **hot topic**
- **Claim for evidence** in ^{76}Ge with $<m_{ee}>$ ~ 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 to scrutinize 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

[1] F.Simkovic et al., Phys. Rev. C77 (2008) 045503

[2] J. Suhonen and O.Civitarese, J. Phys. Conf. Ser. 173 (2009) 012012

[3] J. Menendez et al., Nucl. Phys. A 818 (2009) 139

[4] F. Iachello and J.Barea, Phys. Rev. C79 (2009) 044301

[5] S. Pascoli, S.T. Petcov, Phys.Rev. D77 (2008) 113003

[6] H.V. Klapdor-Kleingrothaus et al., Eur. Phys. J. A 12 (2001) 147

[7] C.E. Aalseth et al., Phys. Rev. D 65 (2002) 092007

[8] E. Andreotti et al., Astrop. Phys. 34 (2011) 822-831

[9] R. Arnold et al., ArXiv:1104.3716v3

[10] R. Bernabei et al., Phys. Lett. B 546 (2002) 23

[11] H.V. Klapdor-Kleingrothaus et al., Mod. Phys. Lett. A 21 (2006) 1547

[12] H.V. Klapdor-Kleingrothaus et al., Phys. Lett. B 586 (2004) 198-212

[13] H.V. Klapdor-Kleingrothaus et al., Mod. Phys. Lett. A 16 (2001) 2409-2420

[14] A.S. Barabash and V.D.Brudanin, Phys.Atom.Nucl. 74 (2011) 312-317

[15] E. Andreotti et al., ArXiv:1108.4313

[16] R. Bernabei et al., Phys. Lett. B 546 (2002) 23-28

[17] A.C. Ur for GERDA Coll., Nucl.Phys.Proc.Suppl.217 (2011) 38-40

[18] F. Bellini et al., Astrop. Phys. 33 (2010) 169

Bibliography

[19] F. Alessandria et al., ArXive:1109.0494v1

[20] C. Arnaboldi et al., Phys. Rev. C 78 (2008) 035502

[21] A. Alessandrello et al., Nucl. Phys. B Proc. Suppl. 28 (1992) 233-235

[22] S. Pirro et al., Phys. Atom. Nucl. 69 (2006) 2109-2116

[23] C. Arnaboldi et al., Astrop. Phys. 34 (2010) 143-150

[24] S.J. Lee et al., Astrop. Phys. 34 (2010) 732-737

[25] J. Maneira for SNO coll., Nucl.Phys.Proc.Suppl. 217 (2011) 50-52

[26] K. Masayuki talk at ICHEP 2010

[27] S. Umehara et al., AIP Conf. Proceed. 1235 (2010) 287-293

[28] G. Razvan on behalf of EXO coll., J. Phys. Conf. Ser. 309 (2011) 012003

[29] N. Ackerman et al., ArXiv:1108/4193v1

[30] J.McGrath et al., Nucl. Instrum. Meth. A 615 (2010) 57-61

[31] Yu.A.Shitov for SuperNEMO Coll., arXiv:1006.4775v2

[32] H. Ejiri et al., Eur. Phys. J. Spec. Top. 162 (2008) 239-250

[33] H.Ejiri et al., J. Phys. Soc. Jap. 76 (2007) 114201

[34] N. Hishihara et al., J. Phys. Conf. Ser. 120 (2008) 052049

[35] T. Ishikawa et al., Nucl. Instr. And Meth. In Phys. Res. A 628 (2011) 209-211

Thank you...

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