The next generation projects
in Deep Underground Laboratories
30 June 2011 - 2 July 2011,
Zaragoza, Spain

Neutrino mass in Europe

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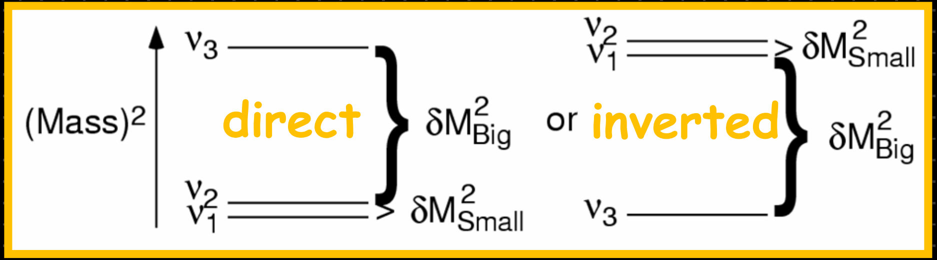
France

What ν oscillations don't tell us

① absolute neutrino mass scale

② neutrino mass hierarchy →



Hierarchy could be identified in a few years (θ_{13} looks "big"...)

③ DIRAC or MAJORANA nature of neutrinos

$\nu \neq \bar{\nu}$

$\nu \equiv \bar{\nu}$

Cosmology, single and double β decay

Cosmology, **single** and **double β decay** measure different combinations of the neutrino mass eigenvalues, constraining the neutrino mass scale

In a standard three active neutrino scenario:

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

cosmology
simple sum
pure kinematical effect

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

β 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 β decay
coherent sum
virtual neutrino
Majorana phases

Decay modes for Double Beta Decay

① $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$

2ν Double Beta Decay
allowed by the Standard Model
already observed – $\tau \geq 10^{19}$ y

② $(A,Z) \rightarrow (A,Z+2) + 2e^-$

neutrinoless Double Beta Decay (0ν-DBD)
never observed (except a discussed claim)
$\tau > 10^{25}$ y

Processe ② would imply new physics beyond the Standard Model

violation of total lepton number conservation

The mass mechanism

how 0ν-DBD is connected to neutrino mixing matrix and masses in case of process induced by light ν exchange (mass mechanism)

neutrinoless Double Beta Decay **rate**

Phase space

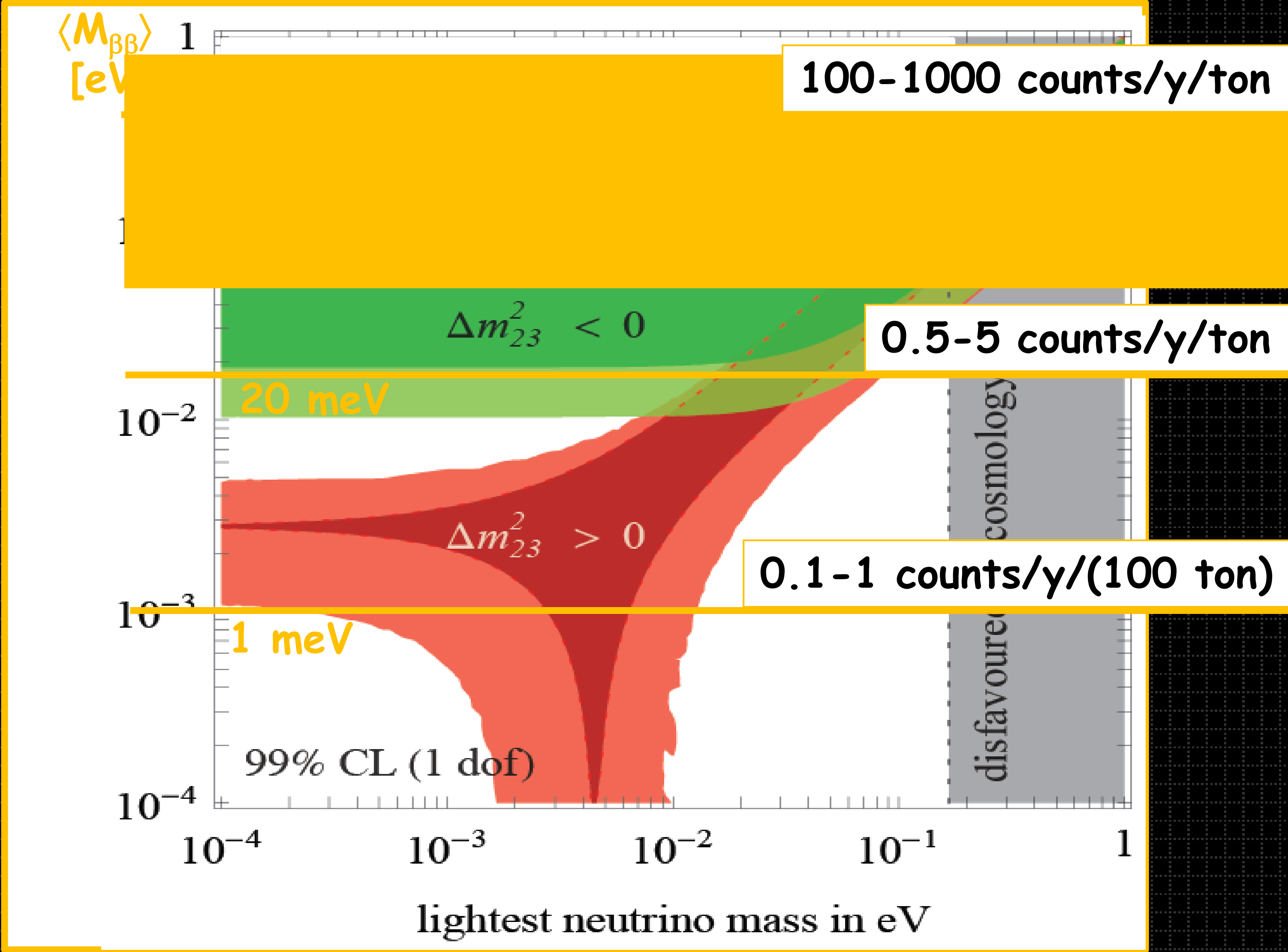
Nuclear matrix elements

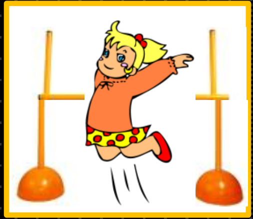
Effective **Majorana mass**

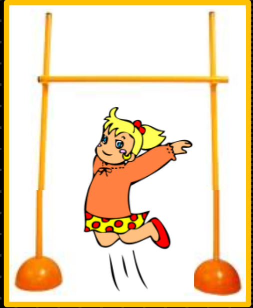
$$1/\tau = G(Q,Z)\,|M_{nucl}|^2 \langle M_{\beta\beta}\rangle^2$$

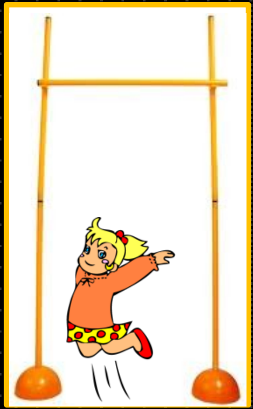
$$\langle M_{\beta\beta}\rangle = \left|\,|U_{e1}|^2 M_1 + e^{i\alpha_1}|U_{e2}|^2 M_2 + e^{i\alpha_2}|U_{e3}|^2 M_3\,\right|$$

Three hurdles to leap over









The sensitivity

sensitivity F: lifetime corresponding to the minimum detectable number of events over background at a given confidence level

b: specific background coefficient [counts/(keV kg y)]

live time

source mass

energy resolution

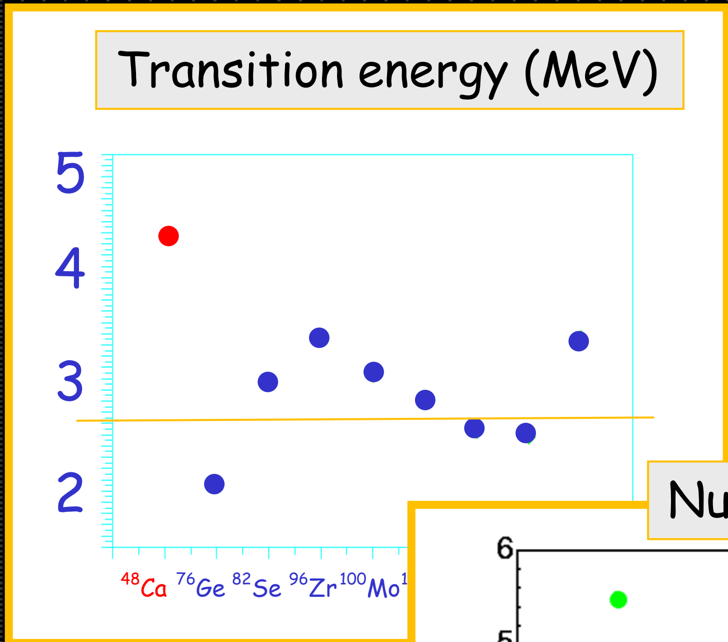
$$\boxed{F \propto (MT / b\Delta E)^{1/2}}$$

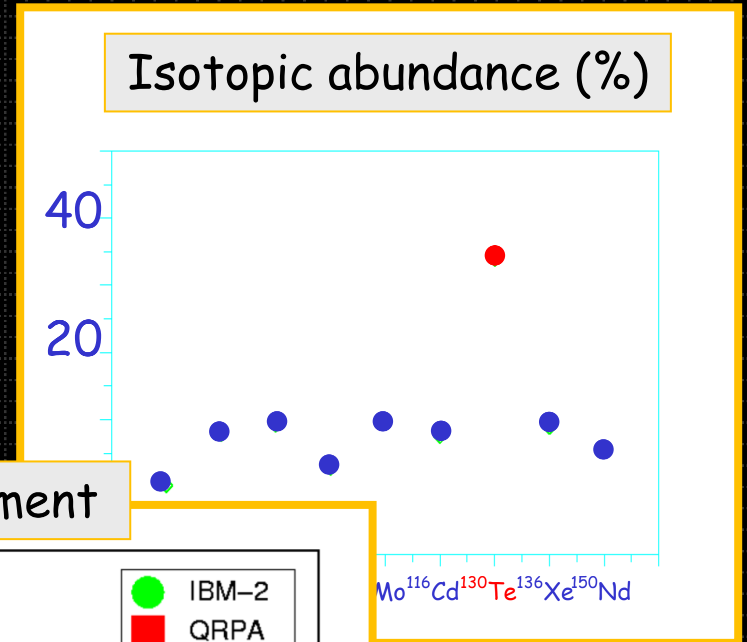
If (b ΔE X exposure) < 1, then the background can be considered ~0

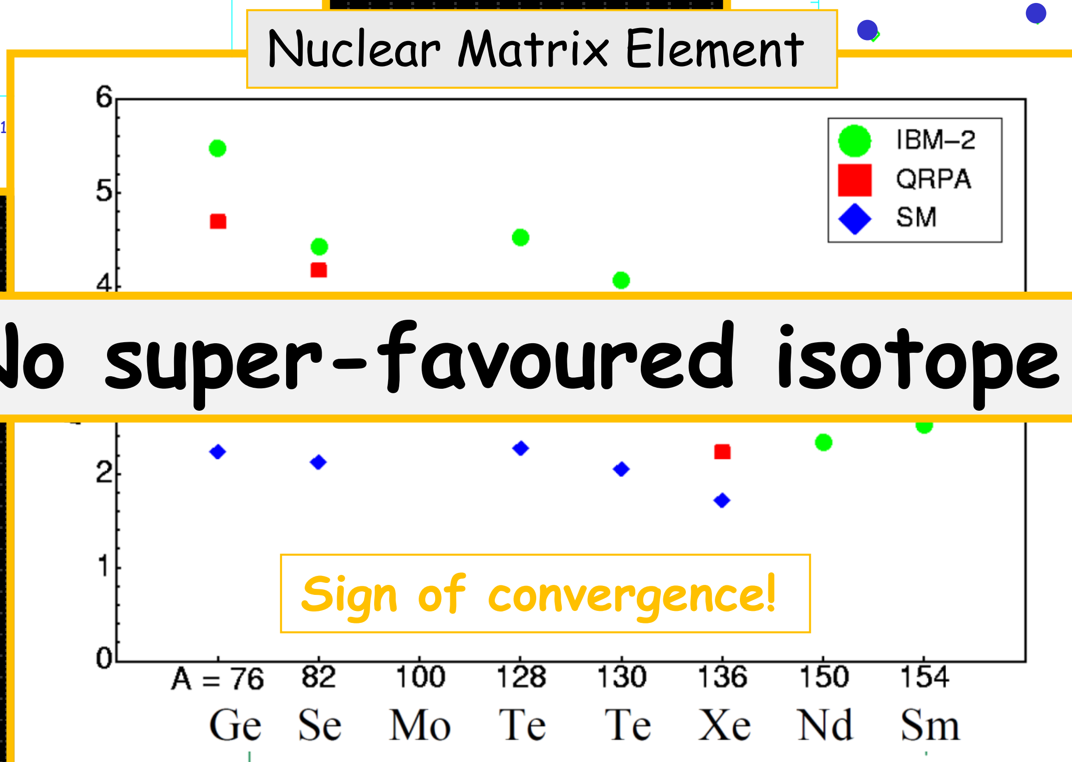
$$\boxed{F \propto MT}$$

The order of magnitude of the target bakground is **≤ 1 counts / y ton** to explore inverted hierarchy

Choice of the nuclide

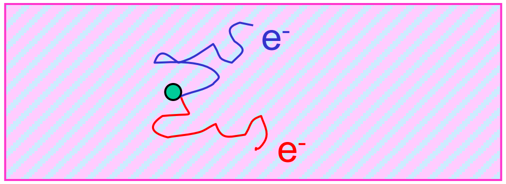






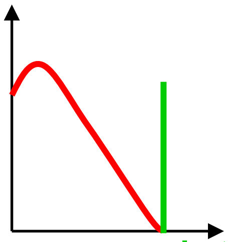
No super-favoured isotope !

Class 1 experiments



Source ≡ Detector

Easy to approach the ton scale



High energy resolution («1%)

No tracking capability

Easy to reject 2ν DBD background

GERDA – ^{76}Ge

Array of enriched Ge diodes operated in liquid argon

First phase: 18 Kg; second phase: 40 Kg - LNGS

Proved energy resolution: 0.16 % FWHM

CUORE – ^{130}Te

Array of low temperature natural TeO_2 calorimeters operated at 10 mK

First step: 200 Kg (2014) – LNGS – it can take advantage from Cuoricino experience

Proved energy resolution: 0.25 % FWHM

LUCIFER / scintillating bolometers – ^{82}Se – ^{116}Cd – ^{100}Mo

Array of scintillating bolometers operated at 10 mK (ZnSe or $CdWO_4$ or $ZnMoO_4$)

First step: ~ 10 Kg (2014) – LNGS – essentially R&D project to fully test the principle

Proved energy resolution: 0.3 - 1 % FWHM

Easy to get tracking capability

(with the exception of
2ν DBD component)

CLASS 1

GERDA – phase 1

Technique/location: bare enriched Ge diodes in liquid argon – LNGS (Italy)

Source: Ge - 17.66 kg – ^{76}Ge enriched at 86% - **1.2x10^{26} nuclides**

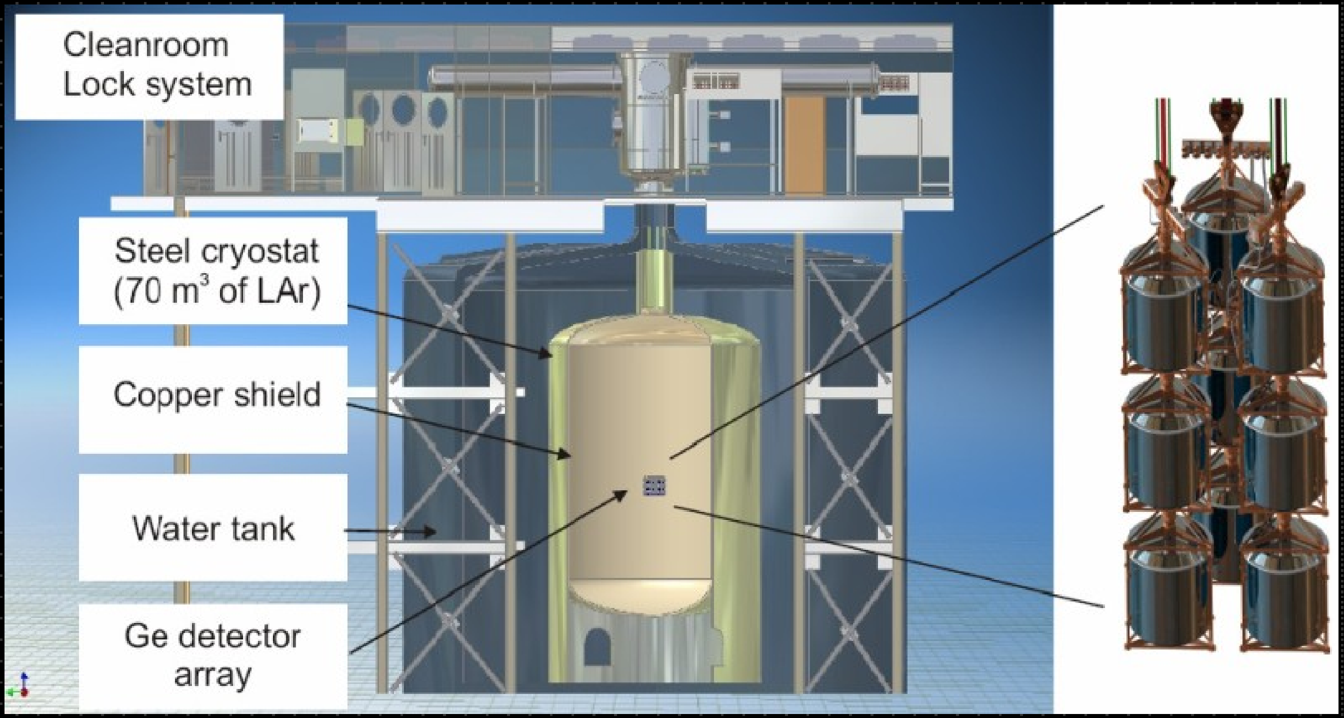
Sensitivity: designed to scrutinize Klapdor's claim in ~1 year data taking

Timeline: GERDA phase 1 is working now with normal Ge diodes for debugging

Background target: 0.01 counts/(keV y kg)

Background contribution from ^{42}Ar higher than expected

→ now improved, insertion of enriched detector is ongoing



CLASS 1

GERDA – phase 1
^{42}Ar contamination

^{42}Ar is present in natural Ar due to cosmogenic production

Decay scheme

^{42}Ar (33 yr, Qβ= 600 keV) ⟶ ^{42}K (12.36 h, Qβ = 3.52 MeV)
Eγ = 1.524 MeV,…

Considered in the proposal and contribution evaluated (30 μBq/kg)

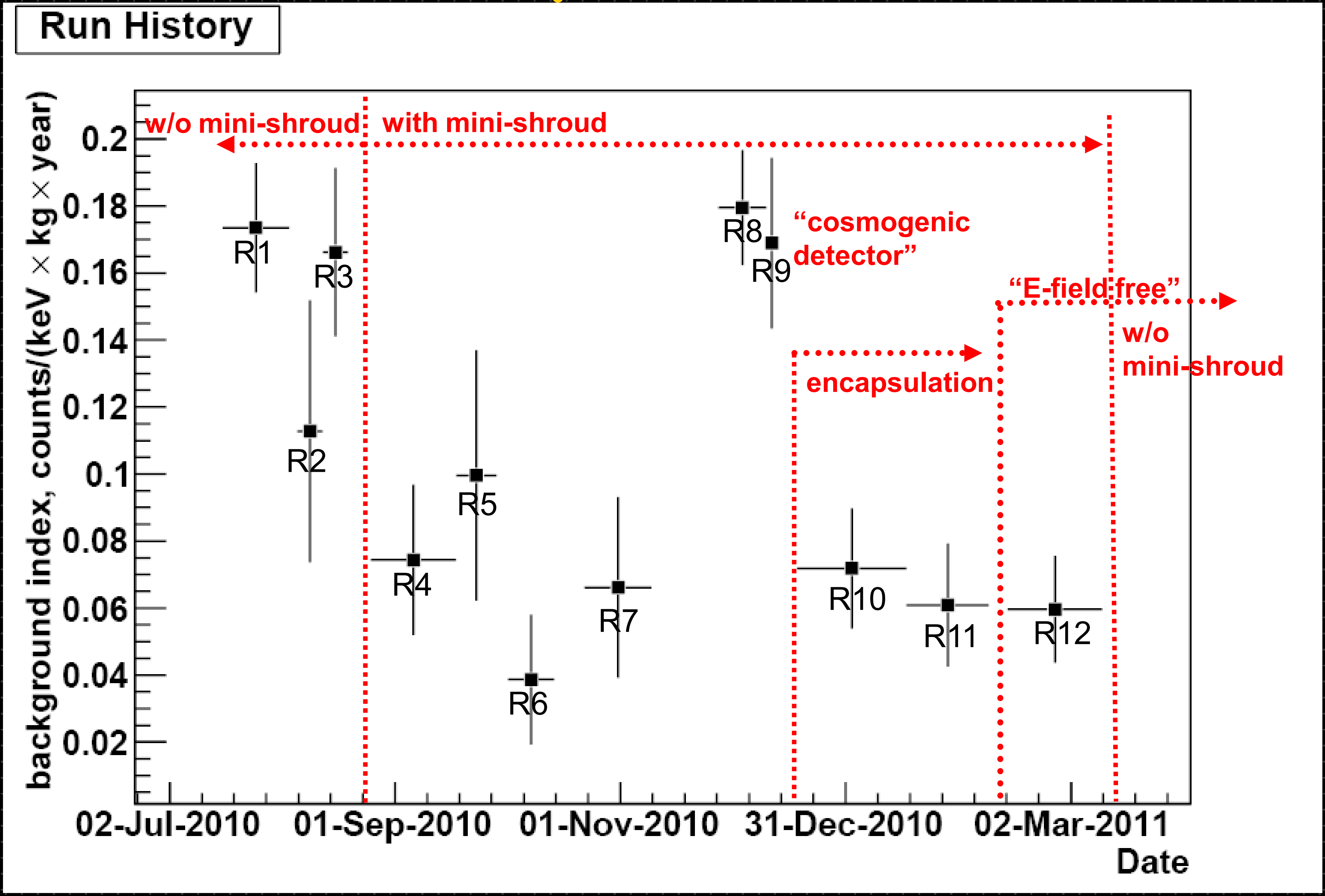
However: 1) natural concentration underestimated
2) migration of the charged daughter ions due to detector E field → higher concentration close to detector

Measures: 1) introduction of a mini-shroud to shield the detectors
2) change of detector field configuration

→ The problem is mitigated

CLASS 1

GERDA – phase 1 – ^{42}Ar



CLASS 1

GERDA – phase 1 – status

- Detector commissioning with non-enriched detectors started in summer 2010
- 12 commissioning runs with different detectors, read-out schemes, E-field configurations
  (best resolution: ΔE_{FWHM}=3.6 keV at 2.6 MeV)
- Background with non-enriched detectors currently at **0.05 cts/(keV kg year)**. Goal for Phase I: 0.01 cts/(keV kg year).
- Deployment of first string with enriched detectors: this week
- After summer: development of the remaining enriched detectors

Phase I soon will study background with enriched detectors
$\Rightarrow$ start of Phase I physics run

CLASS 1

GERDA - phase 2 and 3

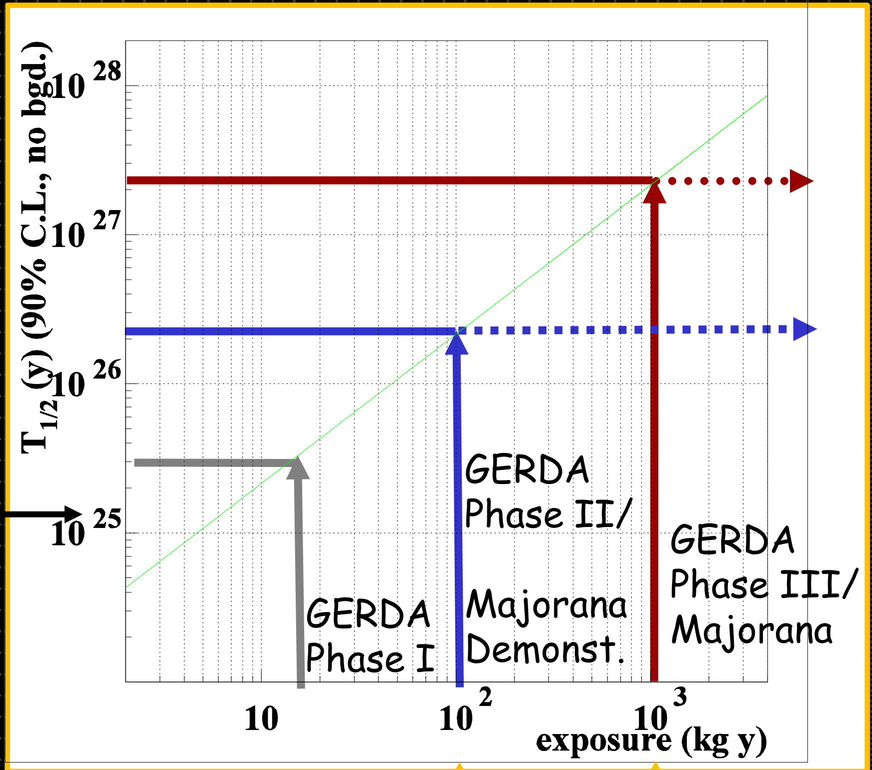
$2\cdot 10^{27}$ (90 % CL)

$2\cdot 10^{26}$ (90 % CL)

$3\cdot 10^{25}$ (90 % CL)

KK

(no event in ROI)



<24 - 41 meV

<75 - 129 meV

assuming $|M^{0\nu}|$=2.99-8.99 [Smol&Grab PRC'10] and 86% enrichment

required for 'background free' exp. with ΔE~3.3 keV (FWHM): $O(10^{-3})$ $O(10^{-4})$ counts/(kg·y·keV)

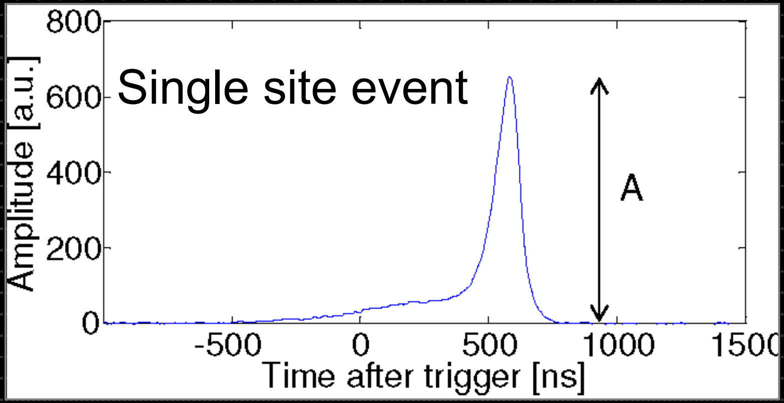
Background requirement for GERDA/Majorana:

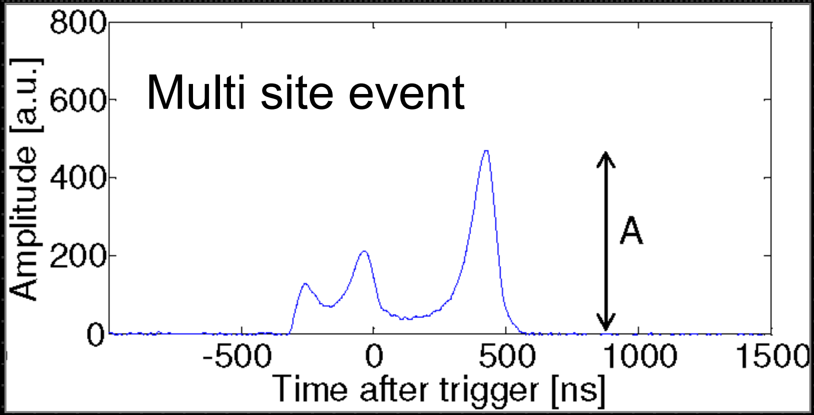
$\Rightarrow$Background reduction by factor 10^2 - 10^3 required w.r. to precursor exps.

GERDA – elements for phase 2

- Production of prototypes with depleted germanium at CANBERRA has been successful
  Production of detector for phase 2 in 2012 (30 additional kg)

- Pulse shape discrimination with p-type BEGe detectors





- Possible instrumentation of Liquid argon

CLASS 1

CUORE

Technique/location: natural TeO_2 bolometers at 10 mK– LNGS (Italy)

⇒ evolution of **Cuoricino**

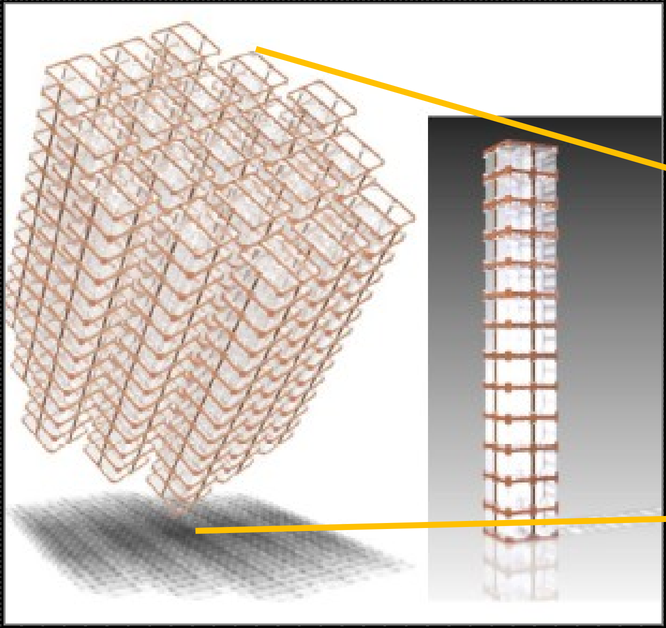
Source: TeO_2 – 741 kg with natural tellurium - **9.5x10^{26} nuclides** of ^{130}Te

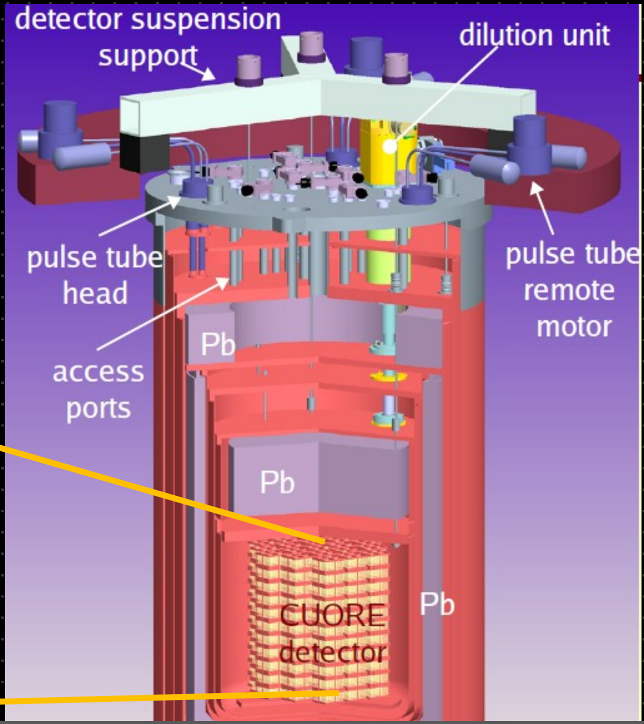
Sensitivity: 35 – 82 meV (with target background ~ 10^{-2} counts/(keV kg y))

Timeline: first CUORE tower in 2011 – data taking with full apparatus in 2014

CUORE-0 under commissioning

Structure of the detector





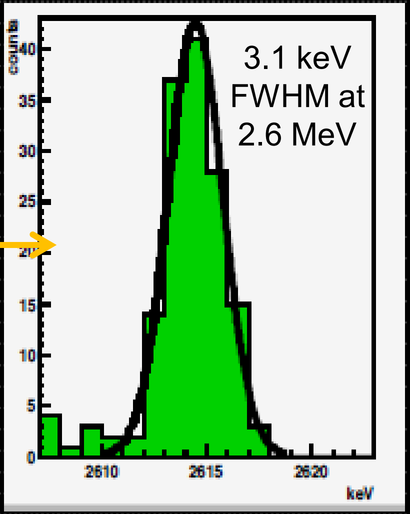
Detector in the custom fridge

CLASS 1

CUORE - status

- The production of the crystals in SICCAS (Shanghai) is going on smoothly

- The crystals are tested as bolometers in CUORE configuration by sampling.
  Excellent results are routinely obtained in:
    - Bolometric performance
    - Radiopurity



- The CUORE assembly line is ready and will be used this summer to assemble CUORE-0

- The first base temperature test of the CUORE cryostat is foreseen for 2012

- Only concern for background comes from alpha surface radioactivity in Copper ⇒ Cleaning procedure are well established – a background of the order of 5×10^{-2} was measured in a dedicated test in hall A – this number will be lower in CUORE just for geometry

CLASS 1

LUCIFER / scintillating bolometers

Technique/location: scintillating bolometers containing high Q-value candidates (**^{82}Se, ^{100}Mo, ^{116}Cd**) ⇒ high phase space, beyond natural gamma radioactivity

Site: for LUCIFER, LNGS is the most natural location; possibility of a scintillating bolometer section in EURECA (Modane extension)

Source: ZnSe, $ZnMoO_4$, $CdWO_4$ single crystals

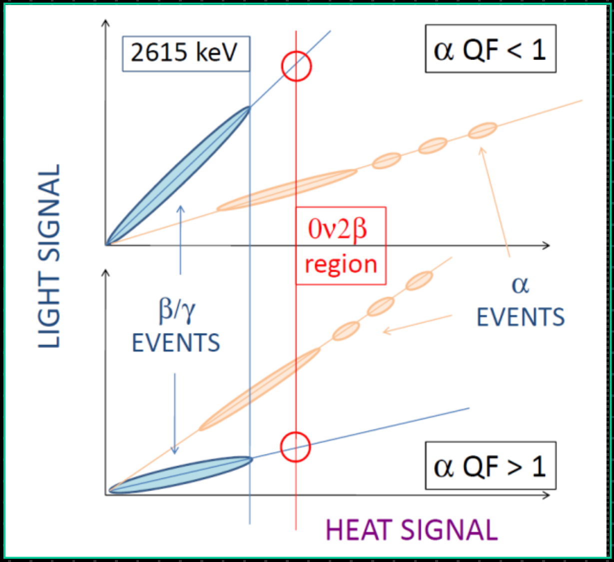
Sensitivity: for LUCIFER, 10 kg enriched Se is feasible with present funding corresponding to ~100 meV (with target background ~ 10^{-3} counts/(keV kg y))

Timeline: LUCIFER ready to take data within 2015 – main difficulty: quality and reproducibility of the crystals ⇒ enrichment, purification, crystal growth chain

Basic idea: Alphas emit a different amount of light with respect to beta/gamma of the same energy (normally lower → **α QF < 1, but not in all cases**).

↓

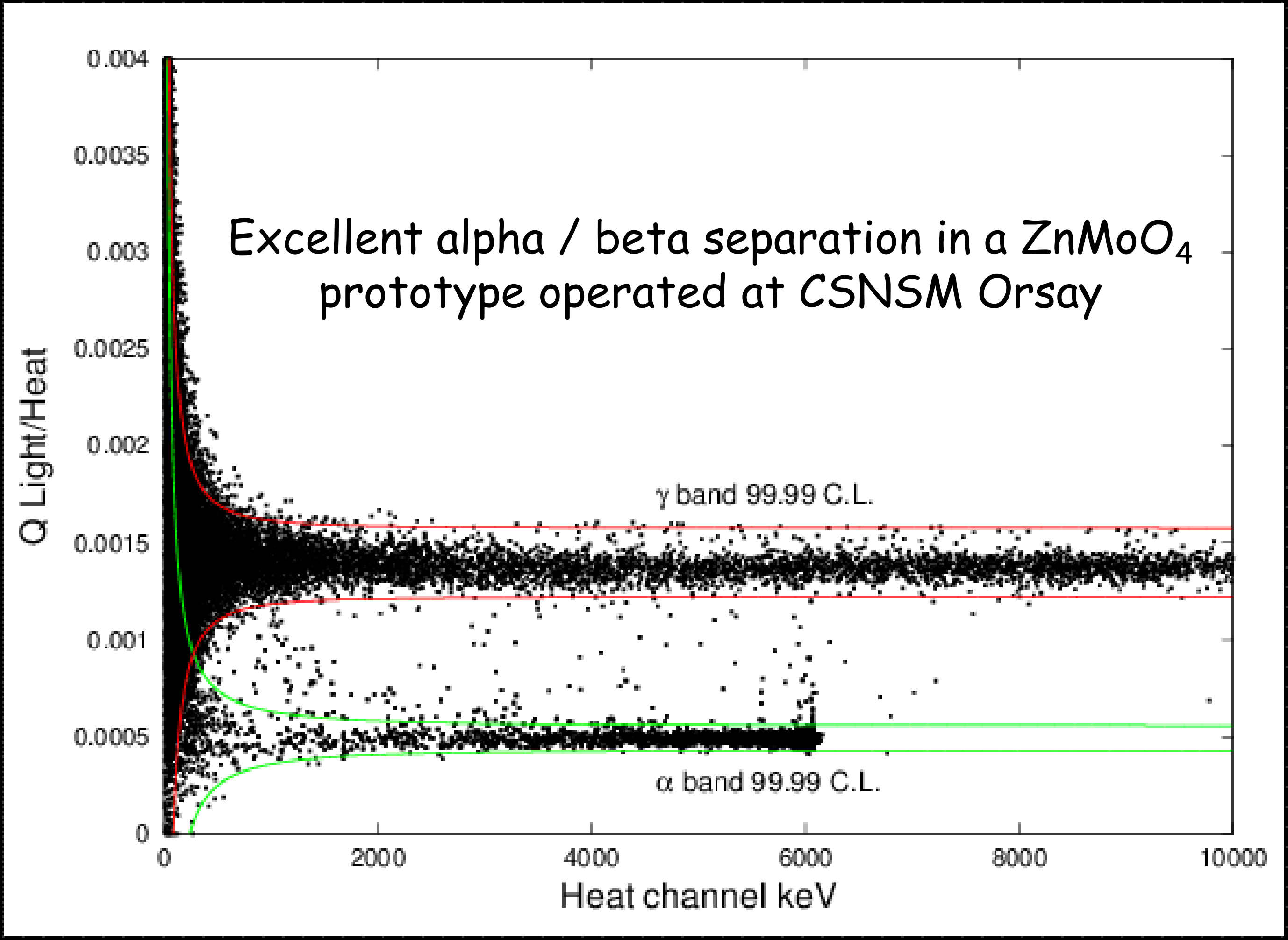
Alpha background can be fully rejected in a region where it dominates



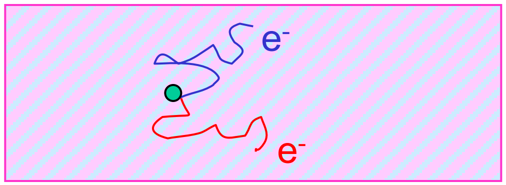
CLASS 1

Scintillating bolometers

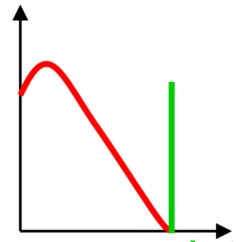
The Molybdenum way is very promising, based on $ZnMoO_4$ crystals
Search is active also with $CaMoO_4$ crystals (AMORE experiment)



Class 2 experiments



Source = Detector

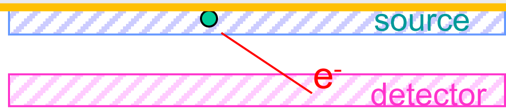


High energy resolution («1%)

No tracking capability

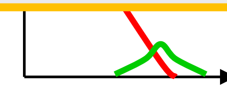
NEXT – ^{136}Xe
High pressure gas TPC
Total mass: 100 kg
Aims at energy resolution down to 1% FWHM exploiting electroluminesce in high field region
NEXT-10, a 10kg prototype, should provide data in CANFRANC in 2013

COBRA - ^{116}Cd competing candidate – 9 ββ isotopes
Array of ^{116}Cd enriched CdZnTe of semiconductor detectors at room temperatures
Small scale prototype at LNGS
Proved energy resolution: 1.9% FWHM
Pixellization can provide tracking capability



Source ≠ Detector

Easy to get tracking capability



Low energy resolution (≥1%)

Tracking / topology capability

Easy to approach zero background
(with the exception of
2ν DBD component)

CLASS 2

NEXT

Technique/location: High pressure (~10 bar) gaseous Xe TPC in Canfranc

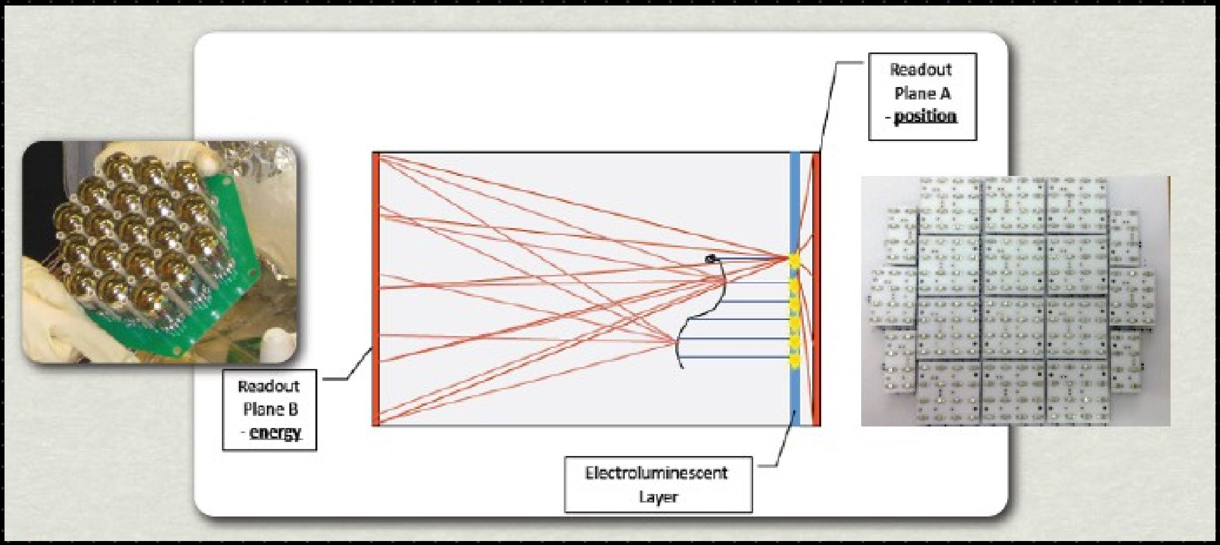
Source: ^{136}Xe - 100 Kg of enriched Xe in Canfranc

Sensitivity: target background ~ 2×10^{-4} counts/(keV kg y) – target energy resolution: 1% FWHM at the Q-value ⇒ ~60 meV with 1 (ton x y) exposure

Timeline: complete NEXT1 (1 kg prototypes) in 2011 – start construction larger systems in 2012 – complete construction final detector in 2013 –depleted Xenon run in 2014

Basic idea: **exploit electroluminescence in Xenon to get high energy resolution and tracking**

Cathode: energy measurement with PMTs

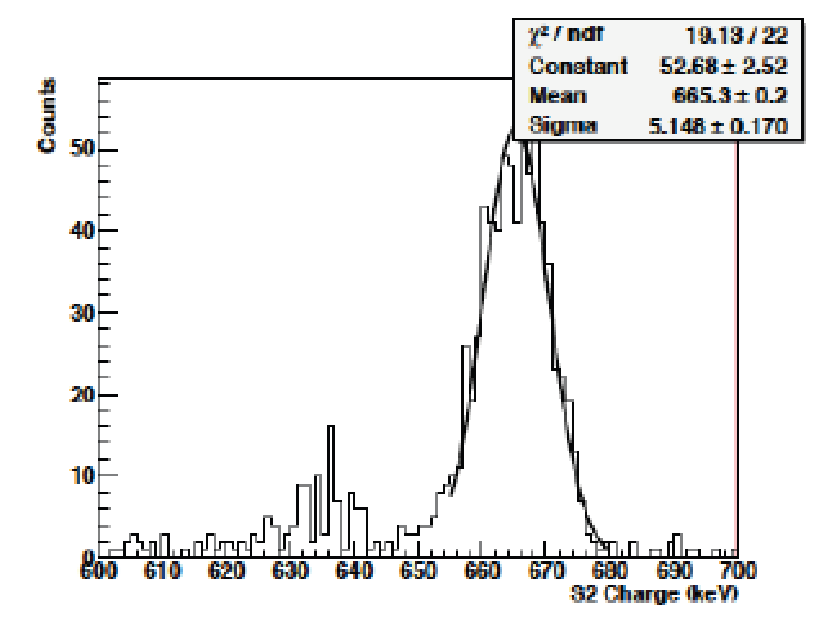


Anode: position measurement with SiPMs

CLASS 2

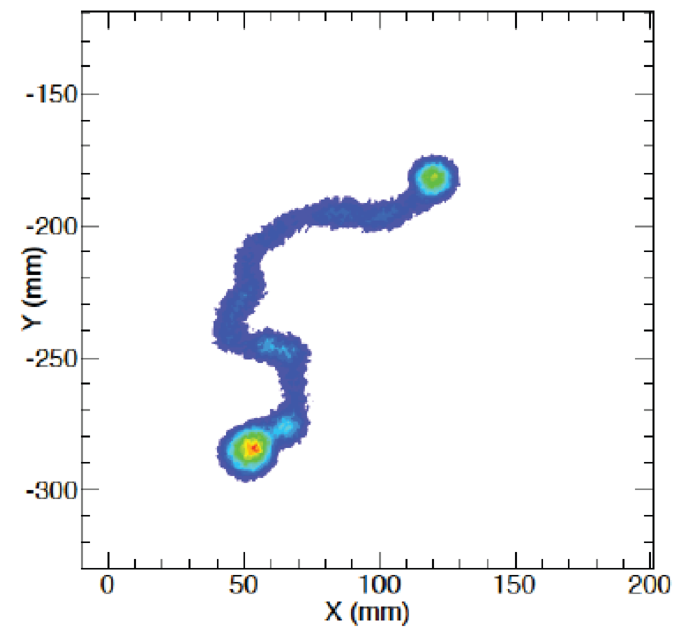
NEXT

Energy resolution



^{137}Cs line measured in LBNL prototype $\Rightarrow$ 1.8% FWHM corresponding to <1% at Q-value

Topology



Simulation of DBD event

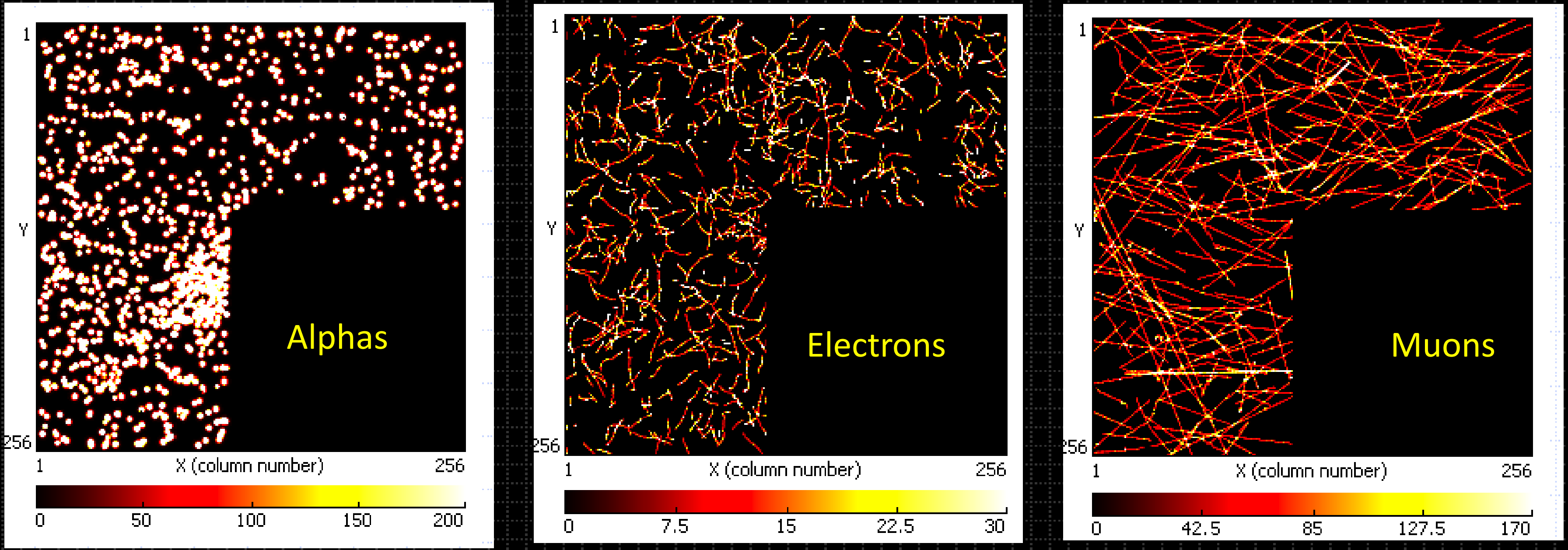
CLASS 2

COBRA

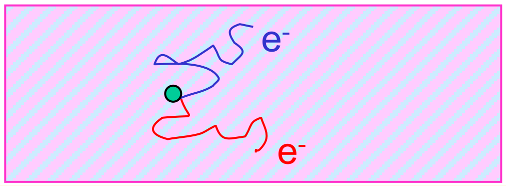
Technique/location: CdZnTe crystals operated as semiconductor detectors - LNGS
Source: nine DBD candidates, but focus on ^{116}Cd – the crystals are small (typically 1 cm side cubes) and the detector is operated with high granularity
Status: present background at the Q-value: 5 counts/(keV kg y) but massive reduction is expected thanks to pixellization (solid state TPC) which allows particle identification.

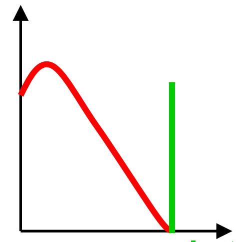
⇒ Upgrade of 64 element array in LNGS – pulse shape and multipixel

256x256 pixels, 55μm

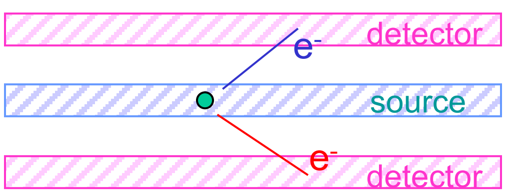


Class 3 experiments



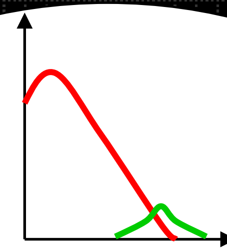


SUPERNEMO – ^{82}Se or ^{150}Nd
Modules with source foils, tracking (drift chamber in Geiger mode) and calorimetric (low Z scintillator) sections
Magnetic field for charge sign
Possible configuration: 20 modules with 5 kg source for each module ⇒ 100 Kg in Modane extension
Energy resolution: 4 % FWHM
it can take advantage of NEMO3 experience



Source ≠ Detector

Easy to get tracking capability



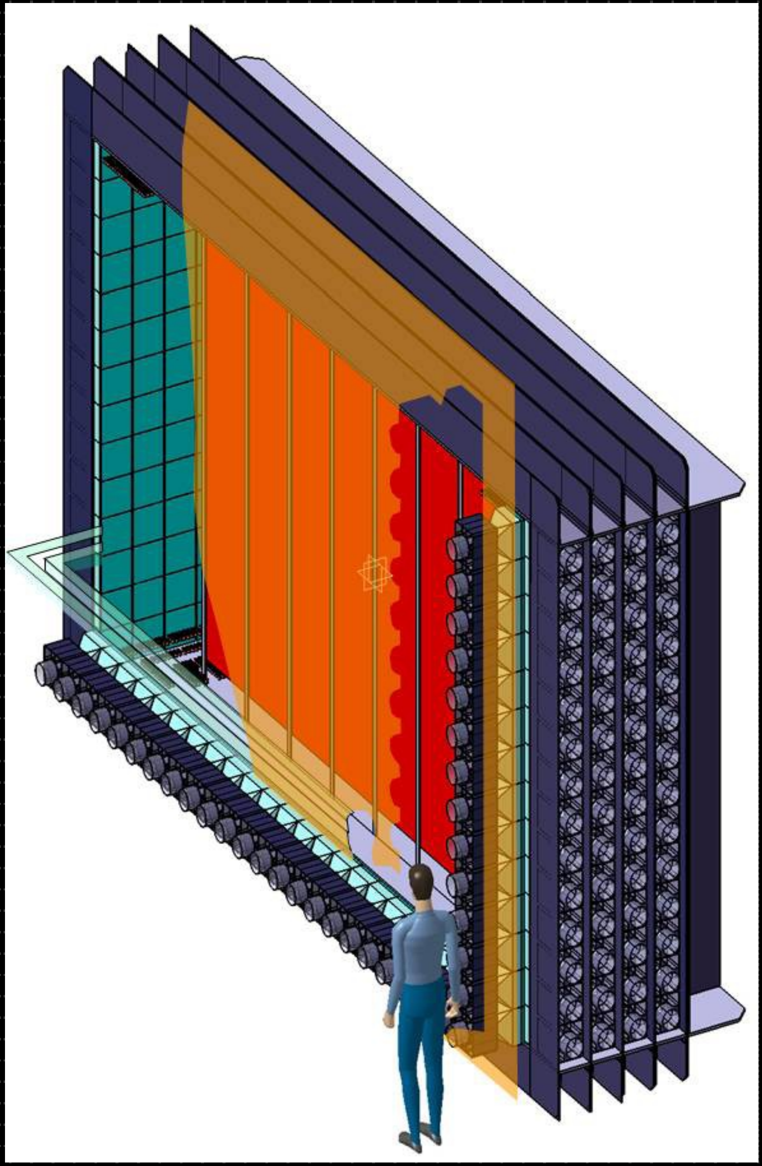
Low energy resolution ≥1%)

Tracking capability

Easy to approach zero background (with the exception of 2ν DBD component)

CLASS 3

SuperNEMO



Technique/location:
tracking Geiger cells+ plastic scintillator –
Modane (France) – evolution of NEMO-3

Source: choice flexibility (^{82}Se, ^{150}Nd, ^{48}Ca)
⇒ options (assuming 100 kg of materials):
- **7×10^{26} ^{82}Se nuclides (baseline)**
- **2.5×10^{26} ^{150}Nd nuclides** (it depends on the possibility of laser isotope separation – now revival at CEA)

It is in the form of a thin foil (~40 mg/cm^2)

Sensitivity: 53 – 145 meV (for ^{82}Se)

Status/Timeline: demonstrator module in 2014 (~7 kg)
After that, construction of 20 modules estimated in 2 years

CLASS 3

SuperNEMO - challenges

Improvements wrt NEMO3

Isotope	^{100}Mo	^{82}Se or other
Mass (kg)	7	100
Exposure (kg.yr)	31.5	500
Efficiency $0\nu\beta\beta$ (%)	18	$\simeq 30$
Energy resolution at 1 MeV e^- (calorimeter), FWHM (%)	~ 15	~ 8
^{208}Tl in foil (μBq/kg)	< 20	< 2
^{214}Bi in foil (μBq/kg)	< 300	< 10 (only for ^{82}Se)
^{222}Rn in gas (mBq/m^3)	$\simeq 5$	< 0.2 (only for ^{82}Se)
^{220}Rn in gas (mBq/m^3)	$\simeq 0.15$	< 0.03 (only for ^{82}Se)

Demonstrated

This target contamination corresponds to 1 event /(100 kg y) in the ROI (same level expected from 2ν DBD)

Crucial: process of purification of Se and subsequent diagnostic

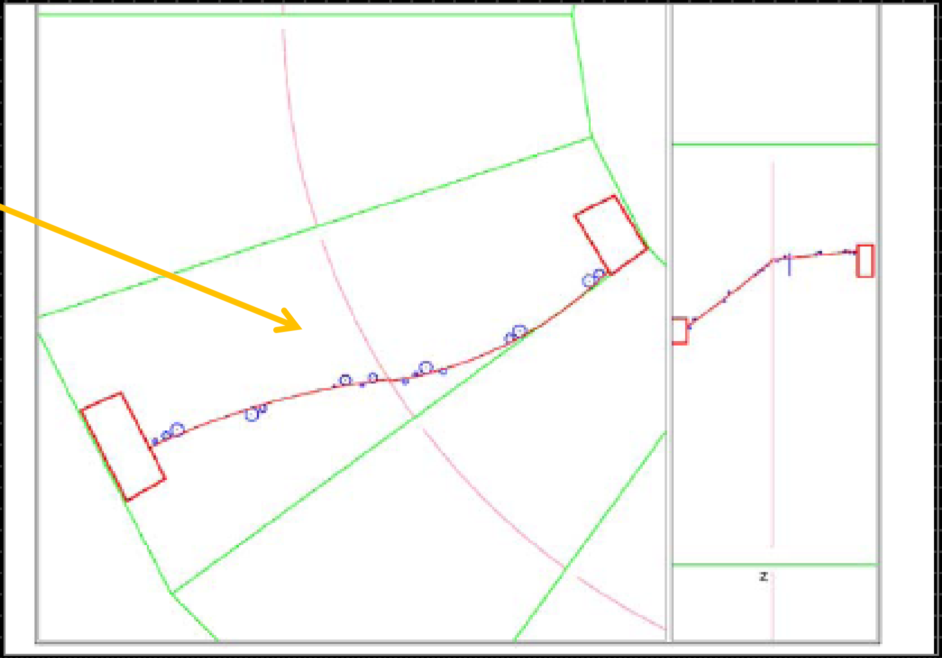
BiPo3 in in Canfranc $\Rightarrow$ start data taking at the end of 2011

SuperNEMO - features

Unique in its capability to reconstruct electron tracks

↓

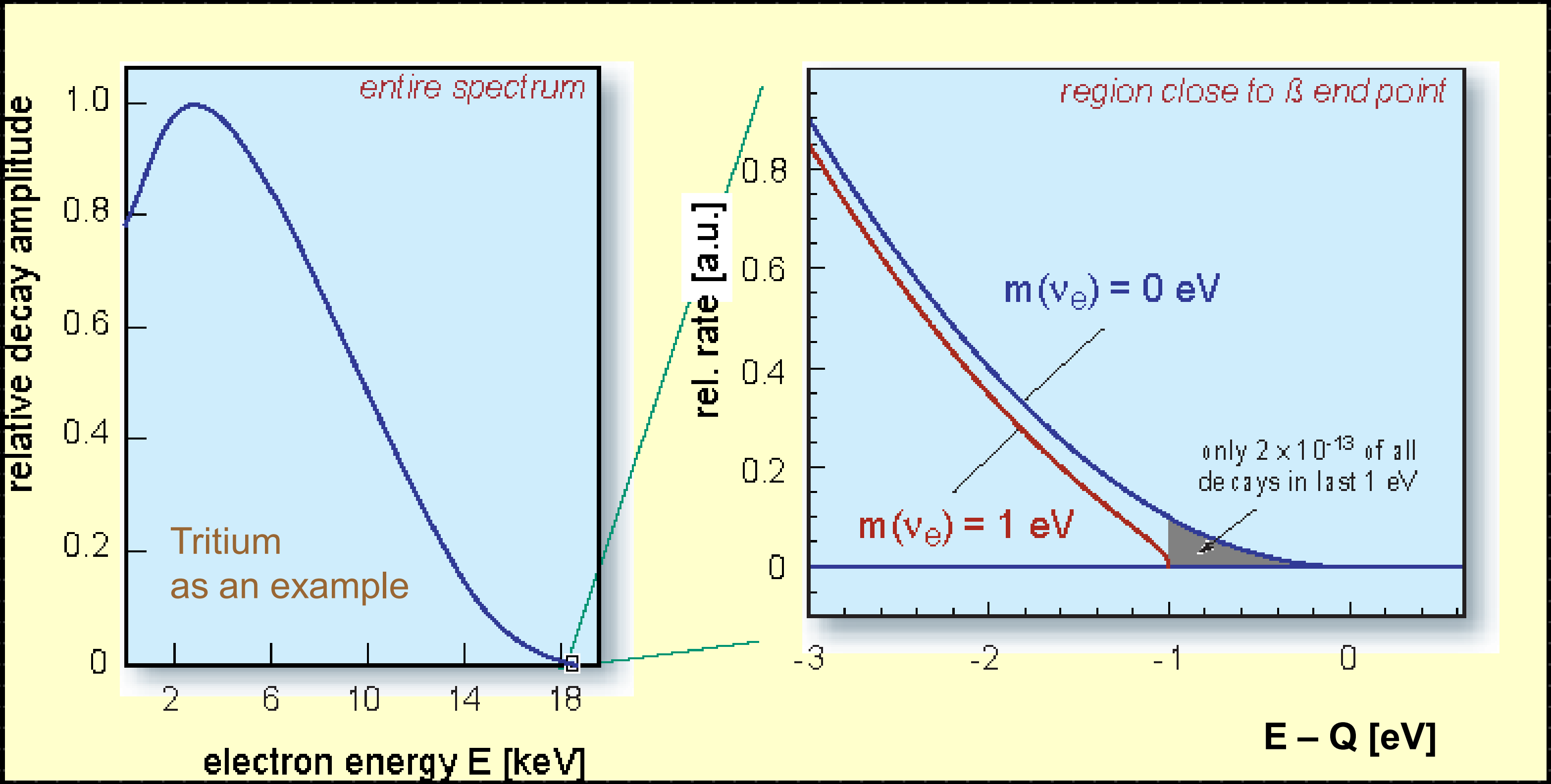
Very useful to identify the 0ν DBD mechanism and exotic processes



BUT it is not easy to achieve 1 ton sensitive mass (importance of ^{150}Nd option)

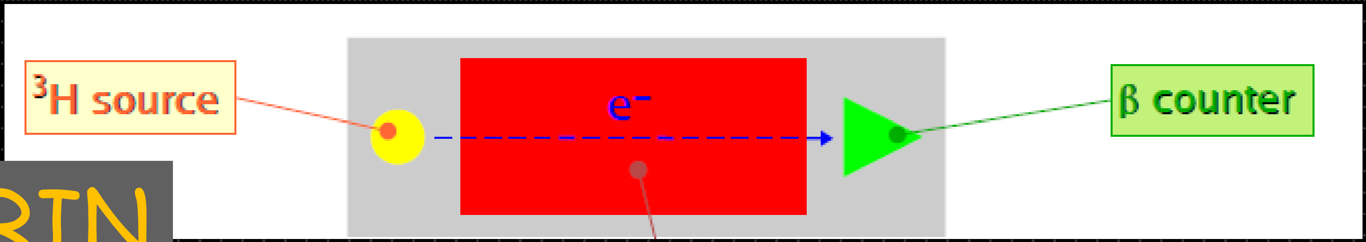
Direct measurement of ν mass

A beta spectrum is modified by a finite ν mass close to the end-point Q



Approaches

① source separate from detector (the source is T - Q=18.6 keV)

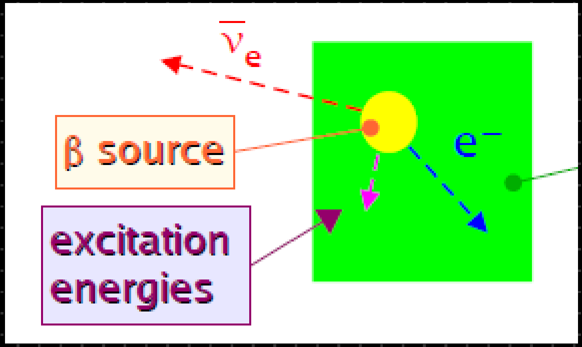


KATRIN

Karlsruhe

- measurement of the electron energy out of the source
- selection of the electrons by an electrostatic spectrometer
- and magnetic adiabatic collimation
- future planned sensitivity: ~ 0.2 eV

② source ≡ detector (the source is ^{187}Re - Q=2.5 keV)

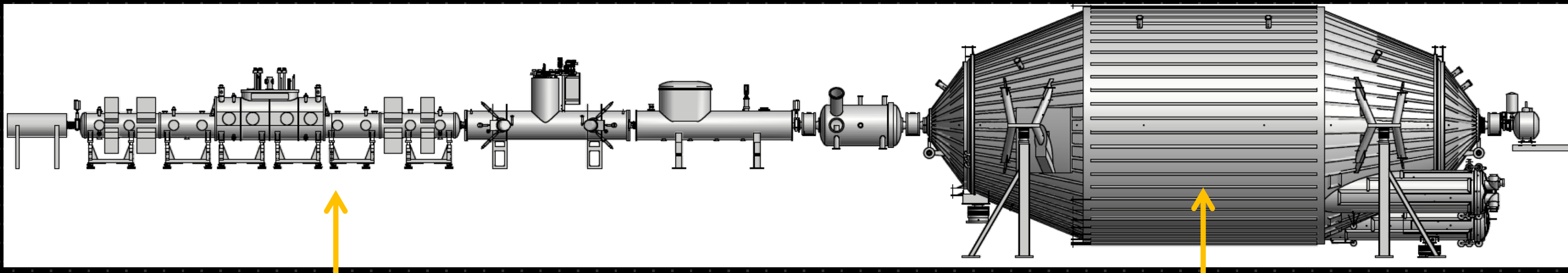


MARE

Milano, Genoa

- determine all the "visible" energy of the decay with a high resolution low energy "nuclear" detector
- cryogenic microcalorimeters
- present achieved sensitivity: ~ 10 eV
- future planned sensitivity: under study

KATRIN status



Tritium bearing components Spectrometer and detector

- Tritium close cycle operational in 2011 (40 g of T)
- Windowless T gaseous source: presently demonstrator (main system: 2013)
- T retention system: early 2012
- Pre-spectrometer: validating and refining the design
- Main spectrometer: electrode installed – start commissioning in early 2012 (issue: background induced by ^{219,220}Rn alpha decays)
- Focal plane system: commissioning in early 2012

sensitivity (90% CL)
$m(\nu) < 200$ meV

discovery potential
$m(\nu) = 350$ meV (5σ)

Sensitivity to sterile neutrino: in 3+1 scenario, 3σ detection by kink in beta spectrum if $|U_{es}|^2 > 0.055$

Start data taking: 2013/2014

MARE status

Precursors (MANU, MIBETA)

Semiconductors	Single element Array of 10 elements Statistics: $N = 10^6$ events	$\sigma(\langle M_\beta \rangle) \sim 20$ eV

MARE-1 – commissioning in Milan – $\Delta E \sim 10 - 30$ eV – $\tau_R \sim 100\ \mu s$

Transition Edge Sensors Semiconductors	Arrays of 300 elements Statistics: $N = 10^{10}$ events	$\sigma(\langle M_\beta \rangle) \sim 2$ eV

MARE-2 –R&D in Genoa – $\Delta E \sim 5 - 10$ eV – $\tau_R \sim 1 - 10\ \mu s$

Transition Edge Sensors Magnetic calorimeters Kinetic Inductance Det.	Arrays of 50000 elementi Statistics: $N = 10^{13}$ events	$\sigma(\langle M_\beta \rangle) \sim 0.2$ eV

Alternative to ^{187}Re : ^{163}Ho EC source to be implanted in the detector

Sensitivity to ~1 keV sterile neutrinos

Conclusions

In the next five years in Europe:

- 3 / 4 projects in DBD could approach the inverted hierarchy region
- Technology to explore inverted hierarchy region should be established soon
- KATRIN will take data
- Rich R&D program in various sectors could provide new solutions to increase the sensitivity