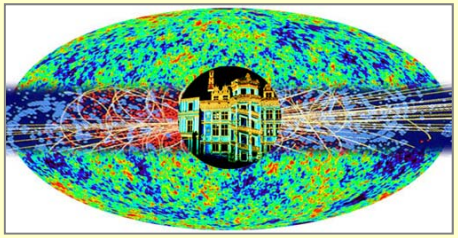


22nd Rencontres de Blois
15th - 20th July, 2010

Status and Prospects of the Searches for Neutrinoless Double Beta Decay

Andrea Giuliani

University of Insubria (Como) and INFN Milano-Bicocca

Italy

Decay modes for Double Beta Decay

Double Beta Decay is a very rare, second-order weak nuclear transition which is possible for a few tens of even-even nuclides

Two decay modes are usually discussed:

① $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$ ← 2ν Double Beta Decay allowed by the Standard Model already observed – $\tau \sim 10^{19} - 10^{21}$ 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

Process ② would imply new physics beyond the Standard Model

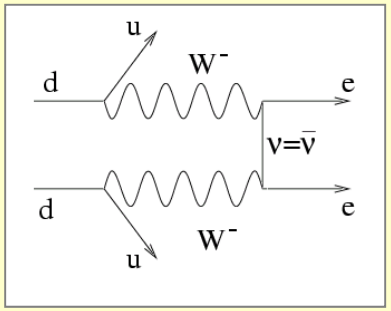
violation of total lepton number conservation

Observation of **0ν-DBD** → $m_\nu \neq 0$, $\nu \equiv \bar{\nu}$ → Majorana nature of neutrino

More details on Monday morning: Boris Kayser 's and Belen Gavela's talks

0ν-DBD and neutrino physics

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



neutrinoless Double Beta Decay **rate**

Phase space

Nuclear matrix elements

Effective **Majorana mass**

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

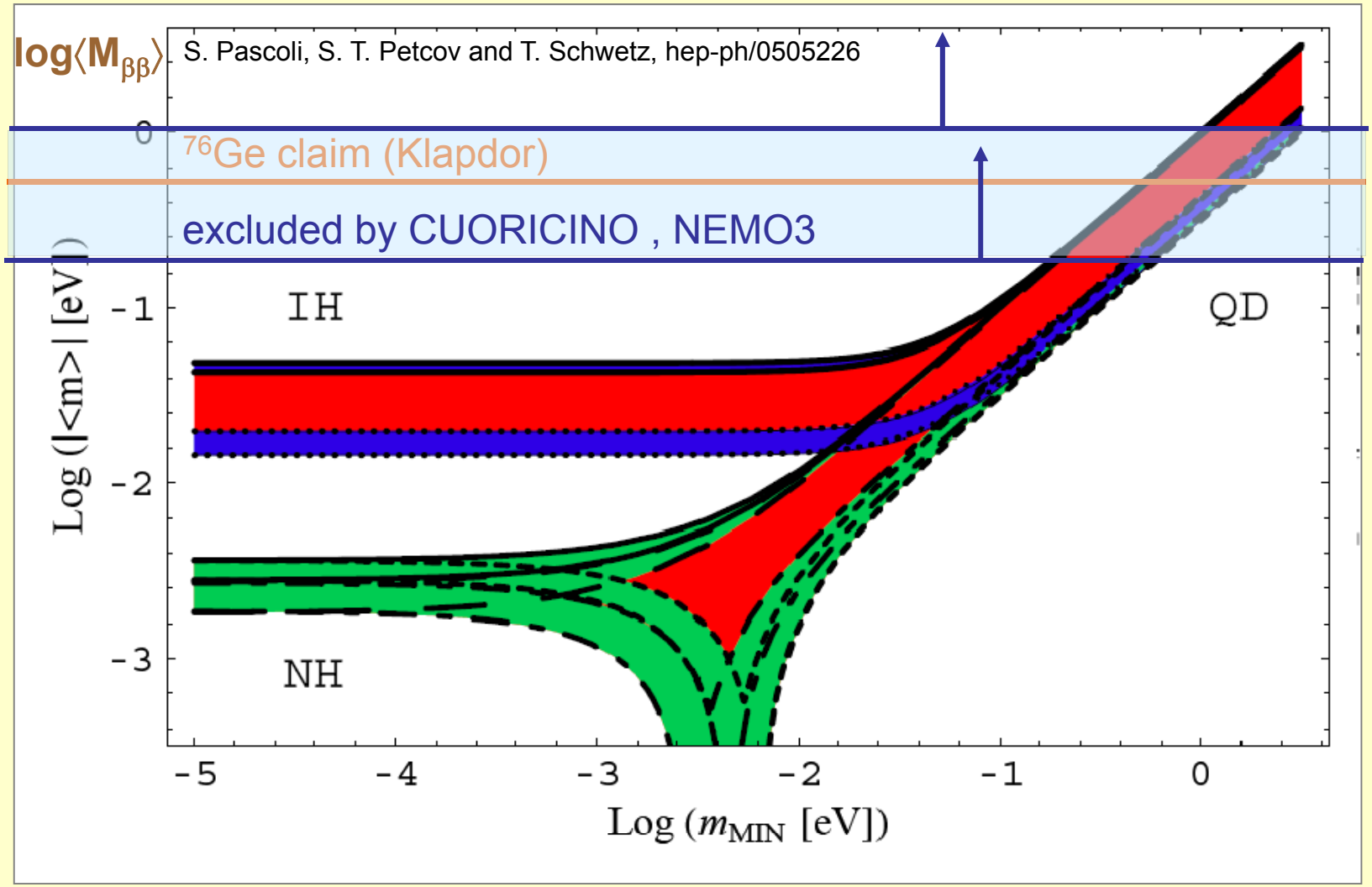
what the experimentalists try to measure

what the nuclear theorists try to calculate

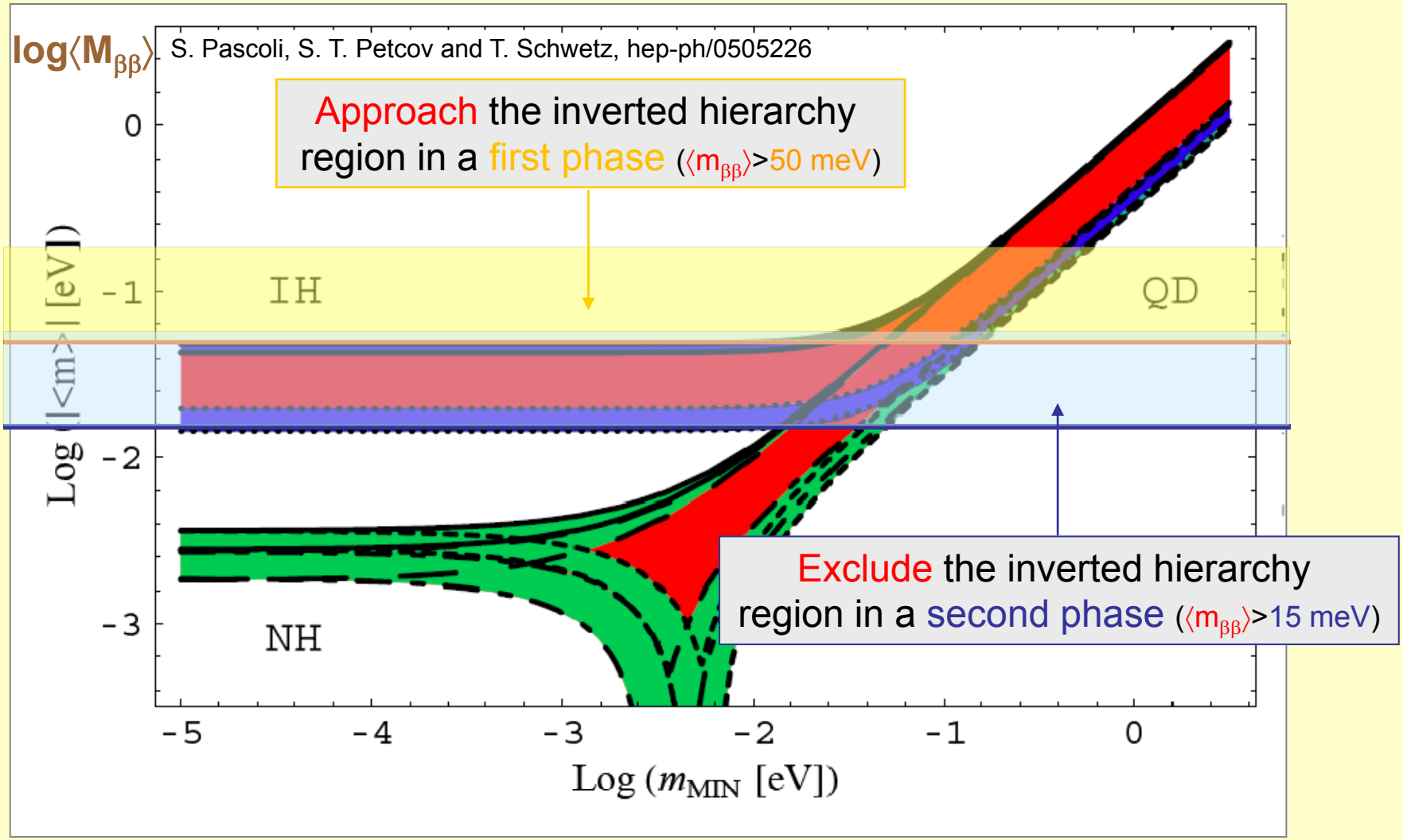
parameter containing the neutrino physics

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

From where we start…



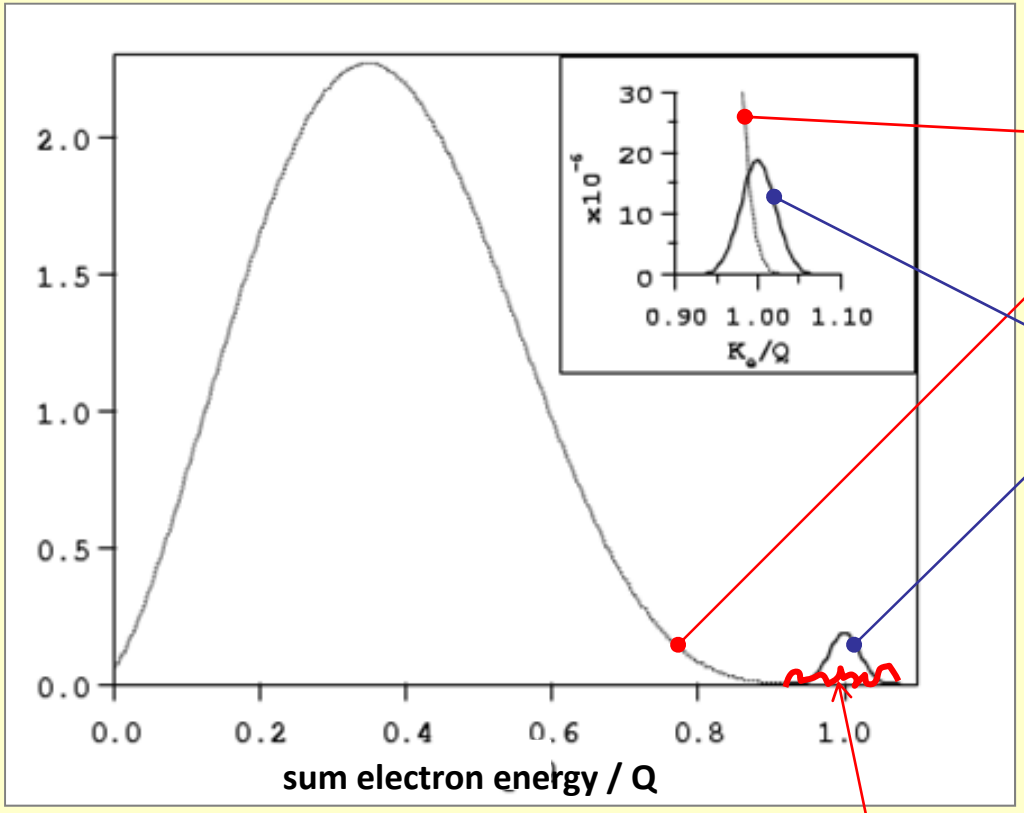
...and where we want to go



There are techniques and experiments in preparation which have the potential to reach these sensitivities

The main signature: electron sum energy spectra in DBD

The shape of the two electron sum energy spectrum enables to distinguish among the two different decay modes



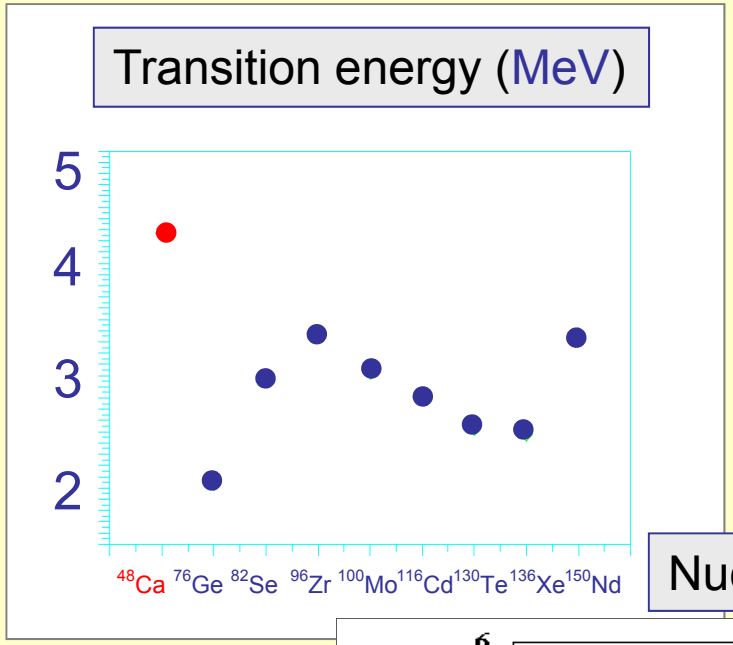
two neutrino DBD
continuum with maximum at ~1/3 Q

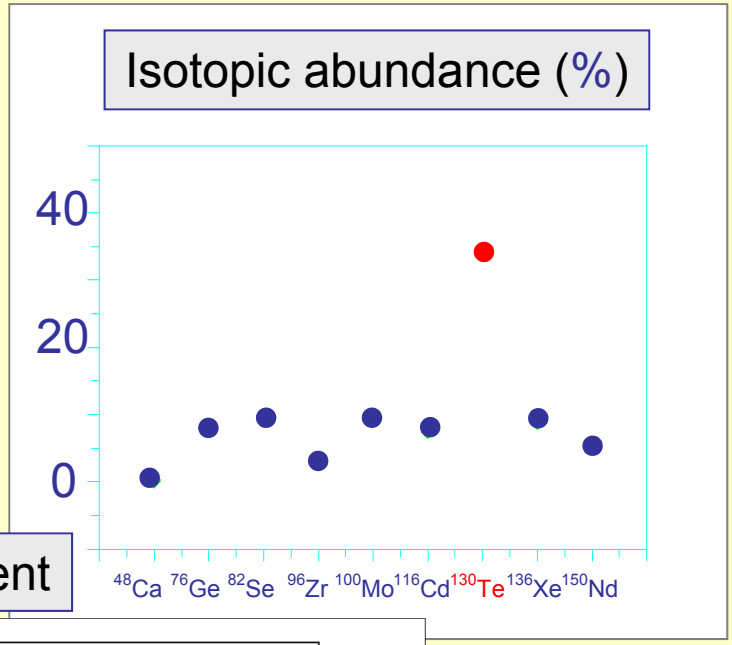
neutrinoless DBD
peak enlarged only by
the detector energy resolution

Q ~ 2-3 MeV for the most promising candidates

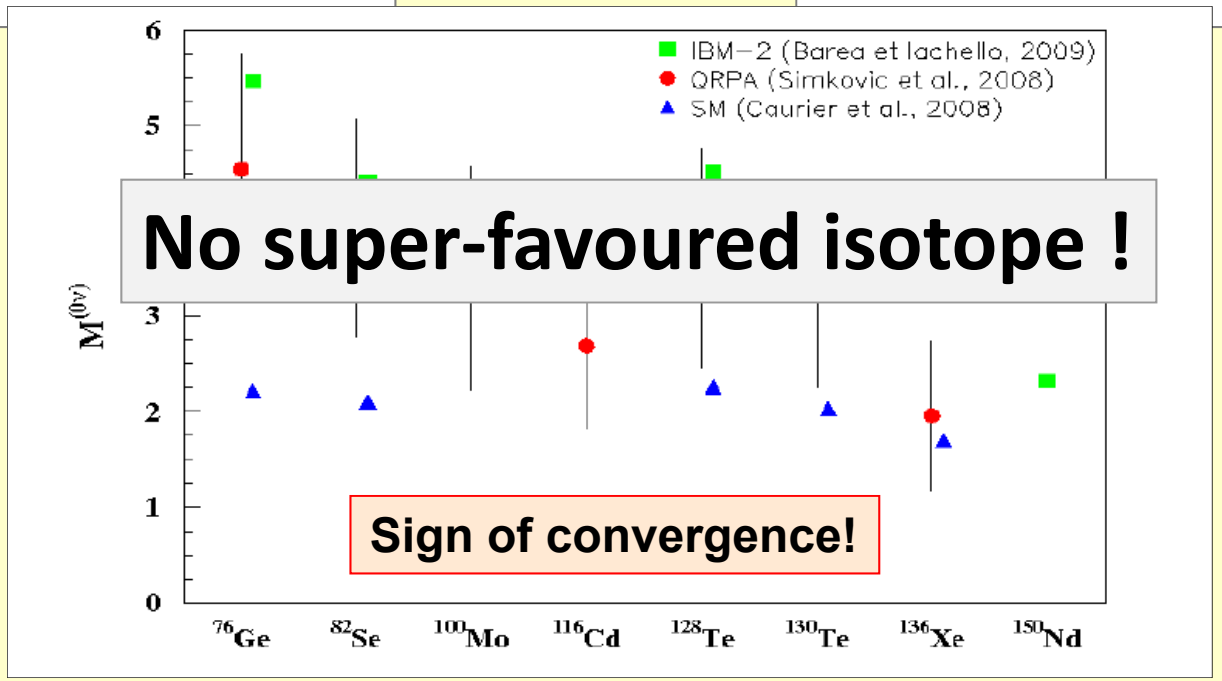
In order to start to explore the inverted hiererachy region,
1) target bakground of the order of **~ few counts / y ton**
2) Sensitive mass of the order of ~100's kg → **10^{26} – 10^{27} nuclides**

Choice of the nuclide





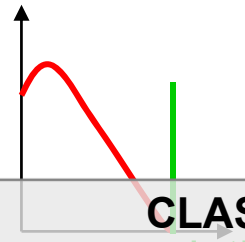
Nuclear Matrix Element



No super-favoured isotope !

Sign of convergence!

Experiments and techniques



CLASS 1

High energy resolution (≪1%)

No tracking capability

Easy to reject 2ν DBD background

Source = Detector

Easy to approach the ton scale

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

GERDA - ^{76}Ge

Array of enriched Ge diodes operated in liquid nitrogen or liquid argon

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

Proved energy resolution: 0.16 % FWHM

MAJORANA - ^{76}Ge

Array of enriched Ge diodes operated in conventional Cu cryostats

Based on 60 Kg modules; first step: 2x60 Kg modules

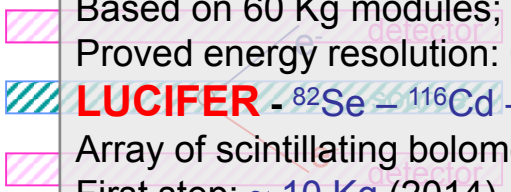
Proved energy resolution: 0.16 % FWHM

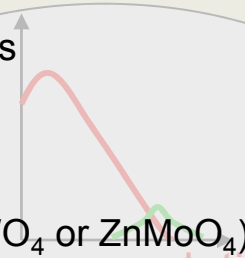
LUCIFER - ^{82}Se – ^{116}Cd – ^{100}Mo

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





Low energy resolution (≥1%)

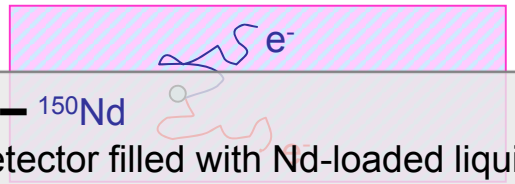
Tracking / topology capability

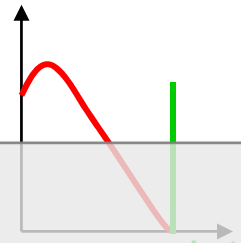
Source = Detector

Easy to get tracking capability

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

Experiments and techniques





CLASS 2

High energy resolution («1%)
No tracking capability
Easy to reject 2ν DBD background

SNO+ – ^{150}Nd

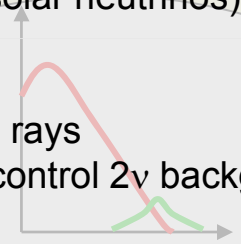
SNO detector filled with Nd-loaded liquid scintillator
0.1% loading with natural Nd → 56 Kg of isotope
Very interesting and original approach.
Crucial points: Nd enrichment and purity; ^{150}Nd nuclear matrix elements

KAMLAND – ^{136}Xe or ^{150}Nd

Dissolve Xe gas in KAMLAND liquid scintillator – feasable at 2% wt - 440 meV sensitivity
Load KAMLAND liquid scintillator with Nd at 1% wt - R&D required – more competitive (50 meV)
Improve light yield of scintillator by 50%

XMASS – ^{136}Xe

Multipurpose scintillating liquid Xe detector (Dark Matter, Double Beta Decay, solar neutrinos)
Three development stages: 3 Kg (prototype) ⇒ 1 ton ⇒ 10 ton
DBD option: low background in the MeV region
⇒Special development with an elliptic water tank to shield high energy gamma rays
High light yield and collection efficiency ⇒ energy resolution down to 1.4% ⇒ control 2ν background
Target: to cover inverted hierarchy with 10 ton natural or 1 ton enriched

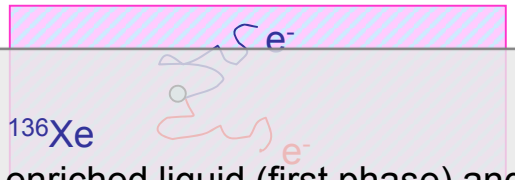


Low energy resolution (≥1%)
Tracking / topology capability
Easy to approach zero background
(with the exception of
2ν DBD component)

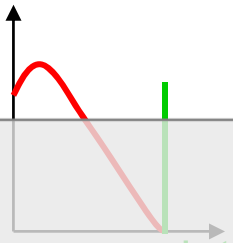
CANDLES – ^{48}Ca

Array of natural pure (not Eu doped) CaF_2 scintillators
Prove of principle completed (CANDLES I and II)
Proved energy resolution: 3.4 % FWHM (extrapolated from 9.1 % at 662 keV)
The good point of this search is the high Q-value of ^{48}Ca: 4.27 MeV
⇒out of γ (2.6 MeV end point), β (3.3 MeV end point) and α (max 2.5 MeV with quench) natural radioactivity
Other background cuts come from PSD (α/β different timing) and space-time correlation for Bi-Po and Bi-Tl

Experiments and techniques



Source = Detector
Easy to approach the ton scale



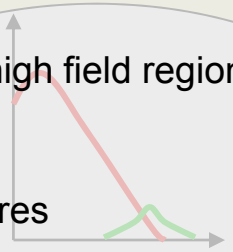
High energy resolution («1%)
No tracking capability
Easy to reject 2ν DBD background

CLASS 3

EXO - ^{136}Xe
TPC of enriched liquid (first phase) and gaseous (second phase) Xenon
Event position and topology; in prospect, tagging of Ba single ion (DBD daughter) ⇒ only 2ν DBD background
Next step (EXO-200: funded, under commissioning): 200 kg – WIPP facility – sensitivity: 270-380 meV
Further steps: 1-10 ton
Proved energy resolution: 3.3 % FWHM (inproved thanks to simultaneous measurement of ionization and light)
In parallel with the EXO-200 development, R&D for Ba ion grabbing and tagging
Ba^{++} e^- e^- final state is identified through optical spectroscopy

NEXT - ^{136}Xe
High pressure gas TPC
Total mass: 80 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 trackin capability



Low energy resolution (≥1%)
Tracking / topology capability
Easy to approach zero background
(with the exception of
2ν DBD component)

Source = Detector
Easy to get tracking capability

Experiments and techniques

CLASS 4

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

MOON - ^{100}Mo or ^{82}Se or ^{150}Nd

Multilayer plastic scintillators interleaved with source foils + tracking section (PL fibers or MWPC)

MOON-1 prototype without tracking section (2006)

MOON-2 prototype with tracking section

Proved energy resolution: 6.8 % FWHM

Final target: collect 5 y x ton

DCBA - ^{150}Nd

Momentum analyzer for beta particles consisting of source foils inserted in a drift chamber with magnetic field

Realized test prototype DCBA-T2: space resolution ~ 0.5 mm; energy resolution 11% FWHM at 1 MeV

⇒ 6 % FWHM at 3 MeV

Test prototype DCBA-T3 under construction: aims at improved energy resolution thanks to higher magnetic field (2kG) and higher space resolution

Final target: 10 modules with 84 m^2 source foil for module (126 through 330 Kg total mass)

Source ≠ Detector

Easy to get tracking capability

Low energy resolution ≥1%)

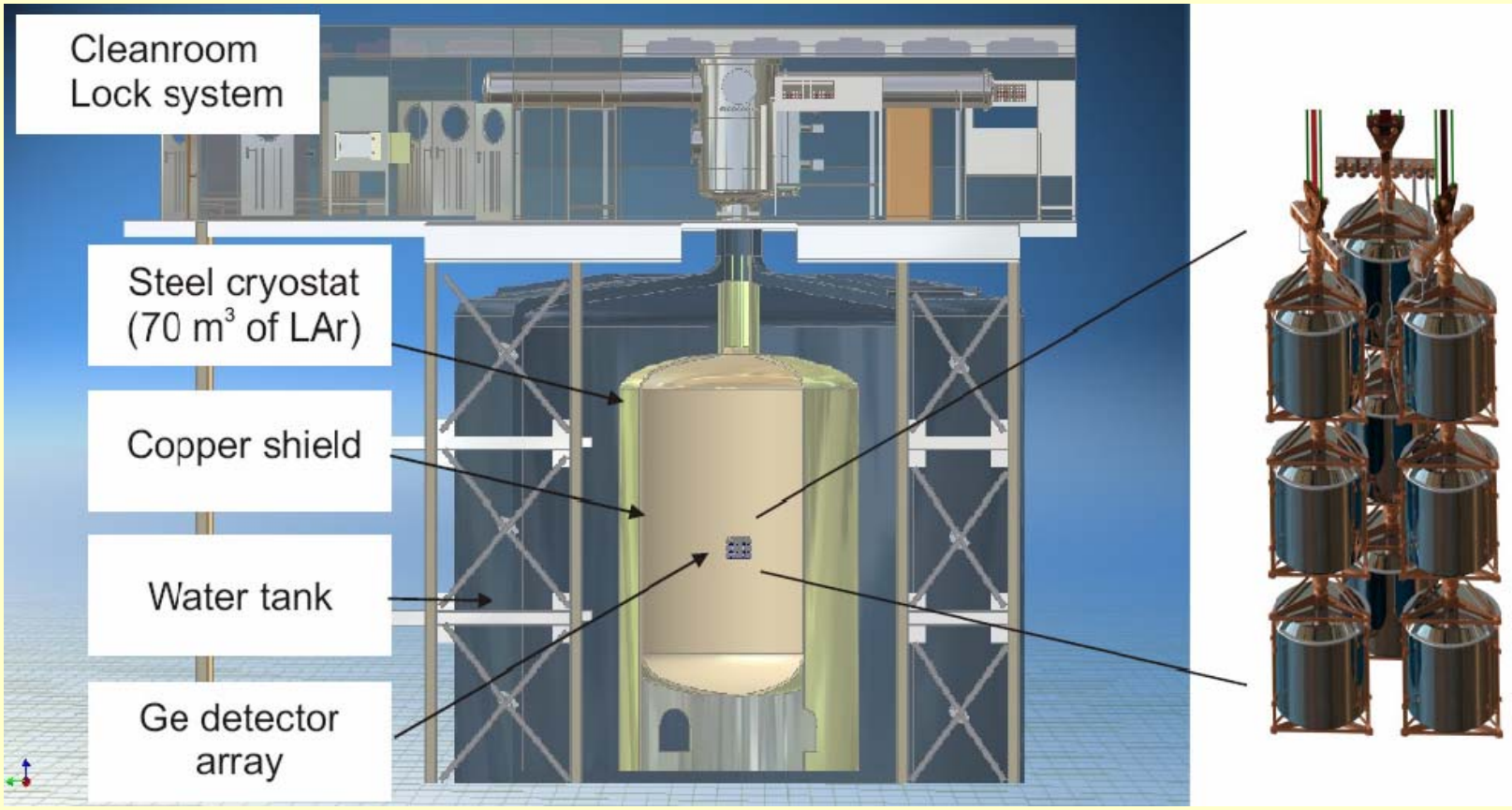
Tracking capability

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

CLASS 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: can scrutinize Klapdor's claim in ~1 year data taking
Timeline: GERDA phase-I is working now with normal Ge diodes for system debugging
Very soon the insertion of the enriched detectors

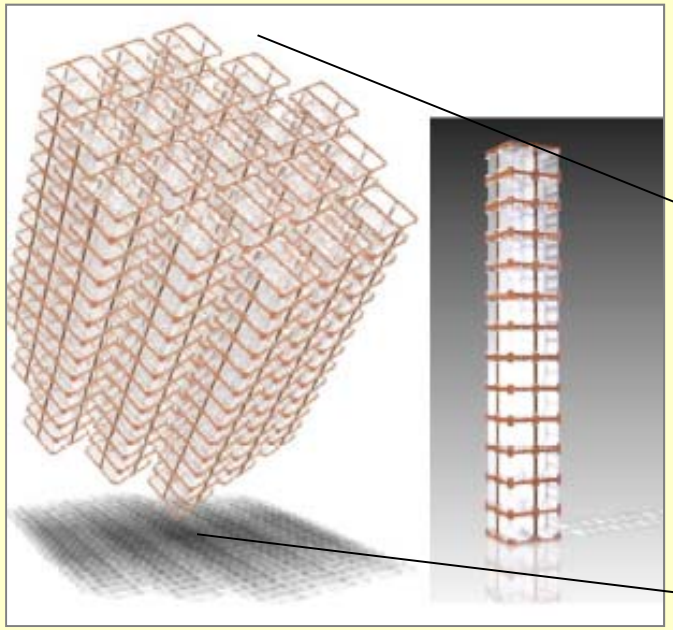


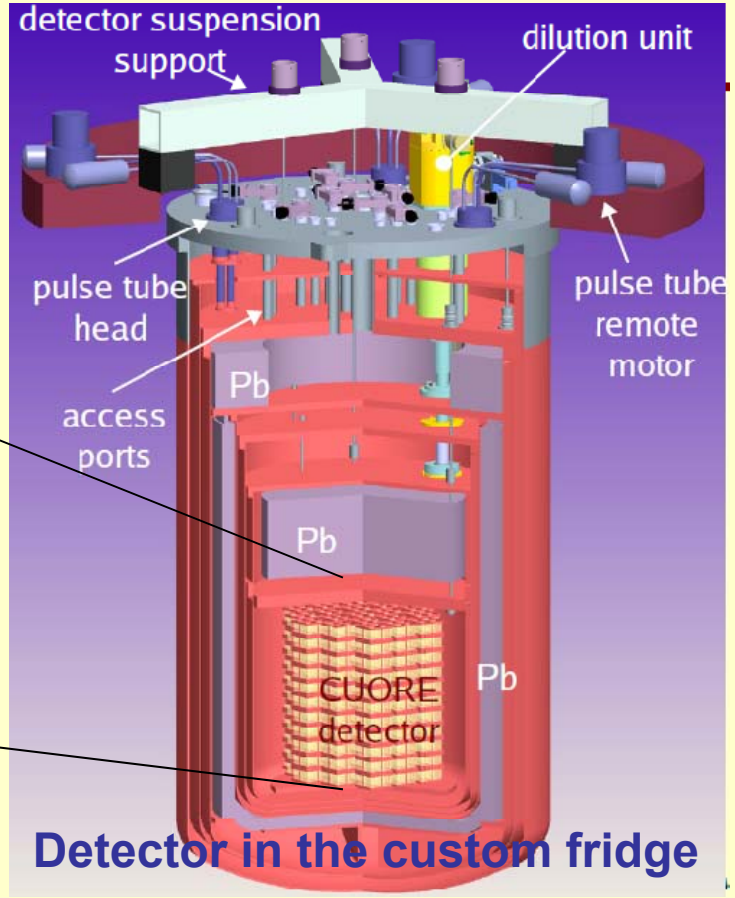
CLASS 1

CUORE

Technique/location: natural TeO_2 bolometers at 10 mK– LNGS (Italy)
evolution of Cuoricino
Source: TeO_2 – 741 kg with natural tellurium - **9.5×10^{26} nuclides** of ^{130}Te
Sensitivity: 35 – 82 meV
Timeline: first CUORE tower in 2011 – data taking with full apparatus in 2014

Structure of the detector



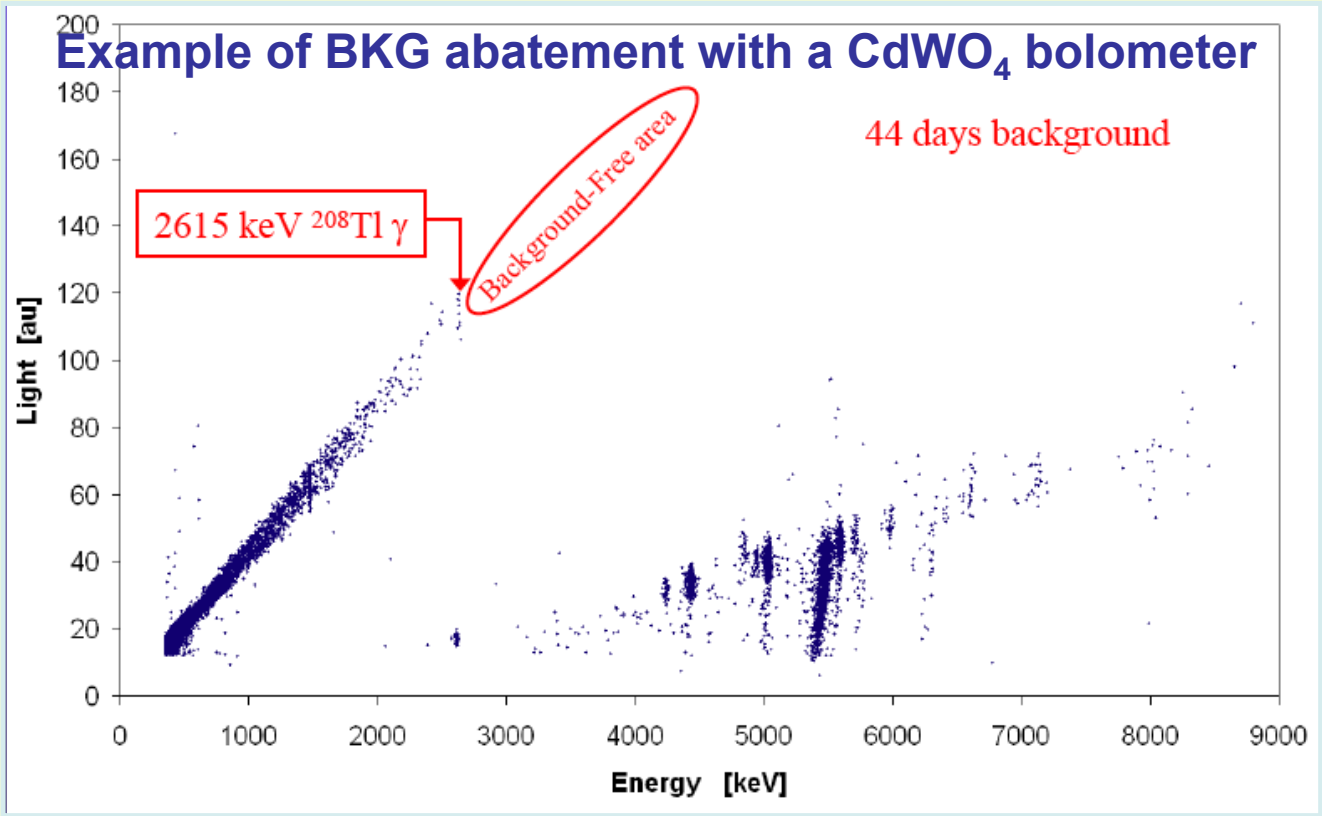


Detector in the custom fridge

CLASS 1

LUCIFER

Technique/location: scintillating enriched bolometers at 10 mK – LNGS (Italy)
Source: to be decided (^{82}Se, ^{116}Cd, ^{100}Mo) – realistic amount: **7x10^{25} ^{82}Se nuclides**
Sensitivity: ~100 meV but difficult to state now
(uncertainty on enrichment and purification processes)
Timeline: R&D set-up with significant mass: 2014

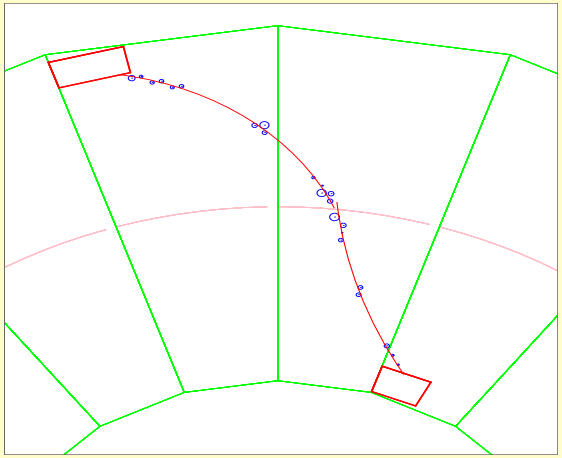


CLASS 4

SUPERNEMO

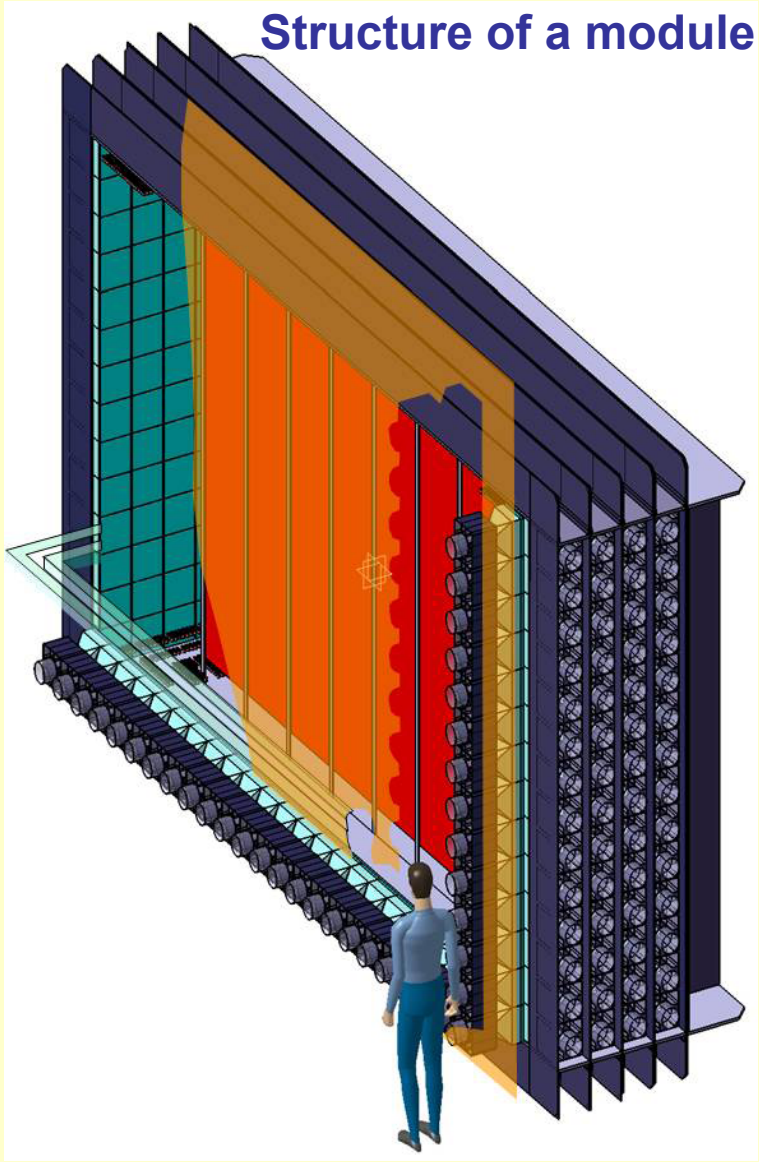
Technique/location:
tracking geiger cells+ plastic scintillator – Modane (France) – evolution of NEMO-3
Source: to be decided (^{82}Se, ^{150}Nd, ^{48}Ca)
options (assuming 100 kg of materials):
- 7x10^{26} ^{82}Se nuclides
- 2.5x10^{26} ^{150}Nd nuclides (it depends on the possibility of laser isotope separation)
Sensitivity: 53 – 145 meV (for ^{82}Se)
Timeline: demonstrator module in 2013 (~7 kg) – construction of 20 modules: 2014-2015

Example of event reconstruction in NEMO3



See Mathieu Bongrand's talk

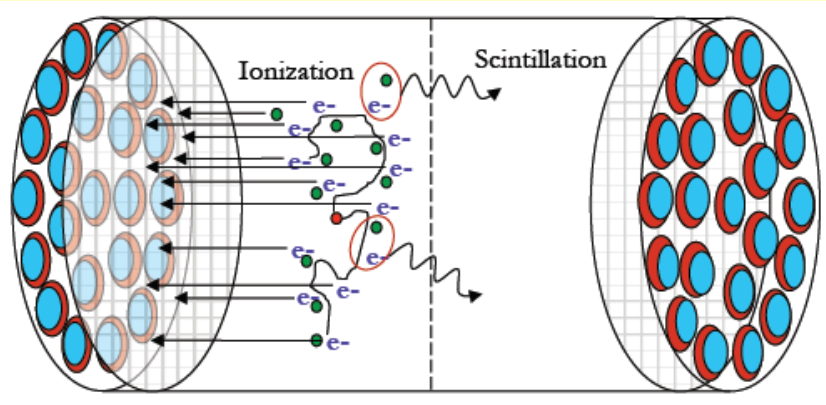
Structure of a module



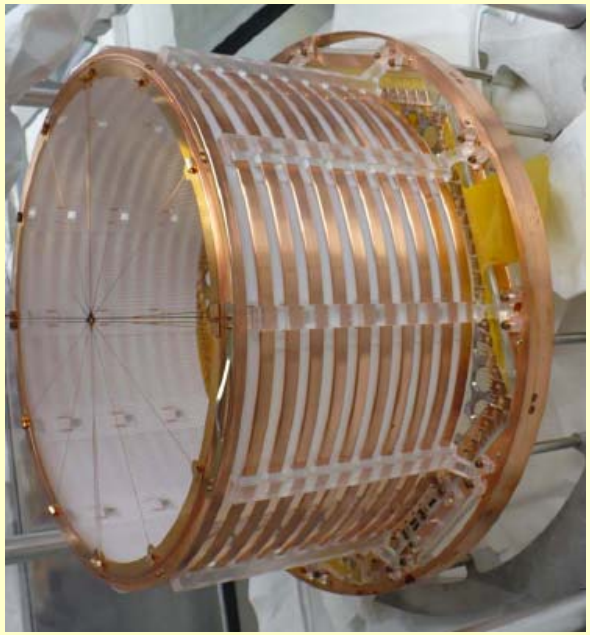
CLASS 3

EXO-200

Technique/location: phase 1: liquid enriched xenon TPC – WIPP (New Mexico, US)
Source: Xe - 200 kg – ^{136}Xe enriched at 80%
7.1x10^{26} nuclides
Sensitivity: 133 – 186 meV
Timeline: phase 1 under commissioning – phase 2: R&D (Ba tagging)



Detail of the TPC electrodes



Detail of the read-out plane

CLASS 2

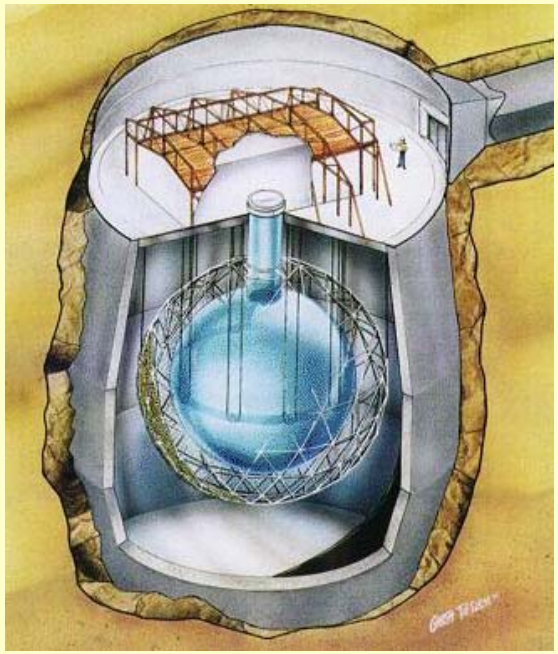
SNO+

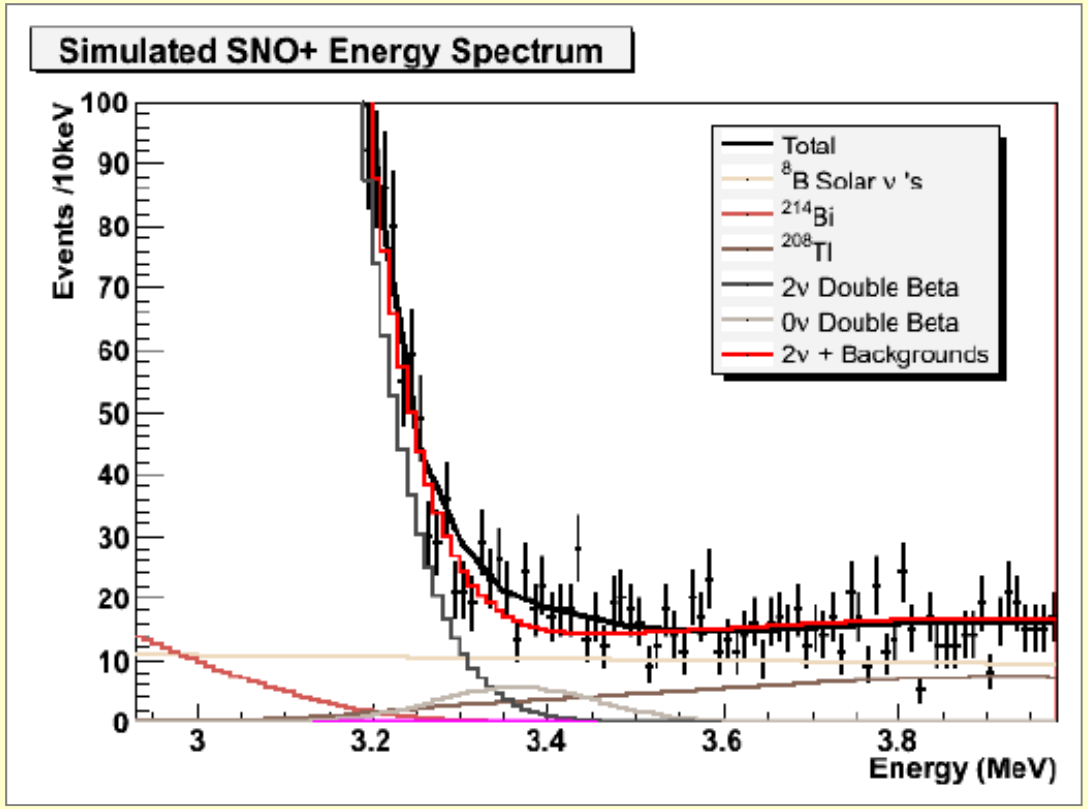
Technique/location: upgrade of SNO with Nd-loaded liquid scintillator

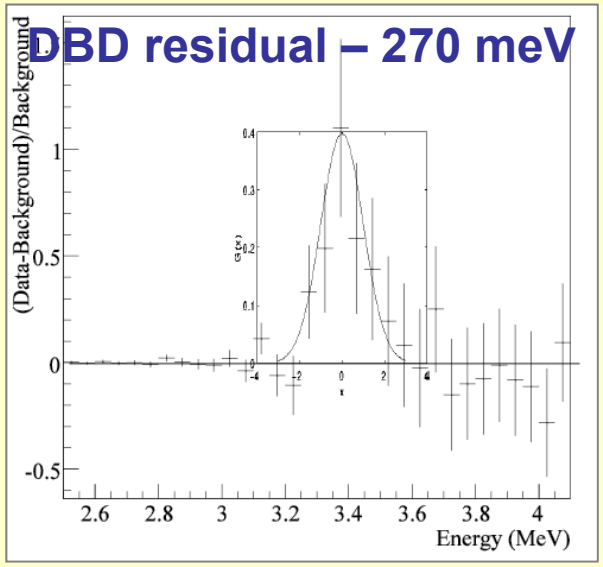
Source: 1000 tons with 0.1 % w/w natural Nd (56 kg of ^{150}Nd): **2.2×10^{26} nuclides**

Sensitivity: 100 meV

Timeline: data taking in 2012







Future scenarios and branching points in terms of discovery

sensitivity

100 - 50

15 - 50

2 - 5 m

if this range holds:
- SuperNEMO could marginally see it in ^{82}Se or ^{150}Nd
- SNO+ enriched could see it in ^{150}Nd
- GERDA phase III / MAJORANA could see it in ^{76}Ge
- CUORE could marginally see it, but could clearly detect it in ^{130}Te if enriched or in ^{82}Se / ^{116}Cd / ^{100}Mo if upgraded to LUCIFER-mode

large scale enrichment required

if this range holds (or if ^{76}Ge claim is right):
- GERDA phase I / II will see it 0ν-DBD ^{76}Ge
- EXO-200 will see it in ^{136}Xe
- SNO+ could see it in ^{150}Nd
- CUORE will see it in ^{130}Te and may do multi-isotope searches simultaneously (^{130}Te - ^{116}Cd - ^{100}Mo)
- LUCIFER R&D could marginally see it in ^{82}Se or ^{116}Cd or ^{100}Mo
- SuperNEMO may investigate the mechanism (^{82}Se or ^{150}Nd)

reduction of uncertainties in NME

precision measurement era for 0ν-DBD!

discovery if neutrino is a Majorana particle

unpredictable time scale