NOW 2010
Neutrino Oscillation Workshop
Conca Specchiulla (Otranto, Lecce, Italy)
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Advances in the detection of $0\nu2\beta$ decay

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Italy

Outline

- Introduction to Double Beta Decay
- Experimental challenge and strategies
- Overview of the projects under development
- Some very promising experiments
- Prospects and conclusions

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

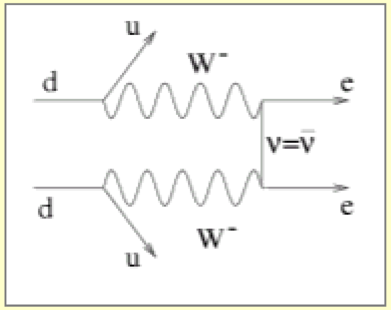
violation of total lepton number conservation

Observation of **0ν-DBD** ⇒ $m_\nu \neq 0$ $\nu \equiv \overline{\nu}$

Majorana
nature of
neutrino

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**

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

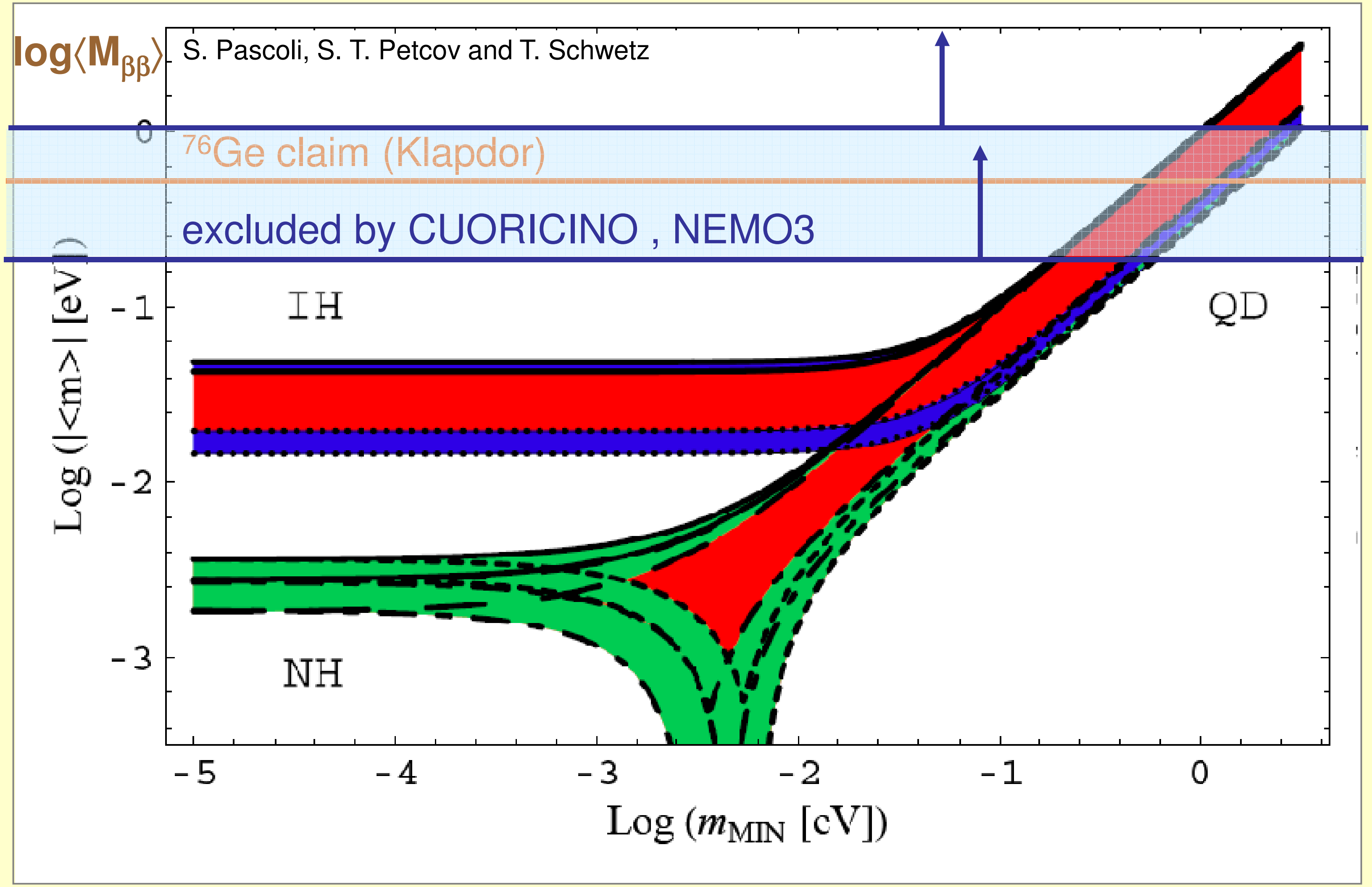
what the experimentalists try to measure

what the nuclear theorists try to calculate

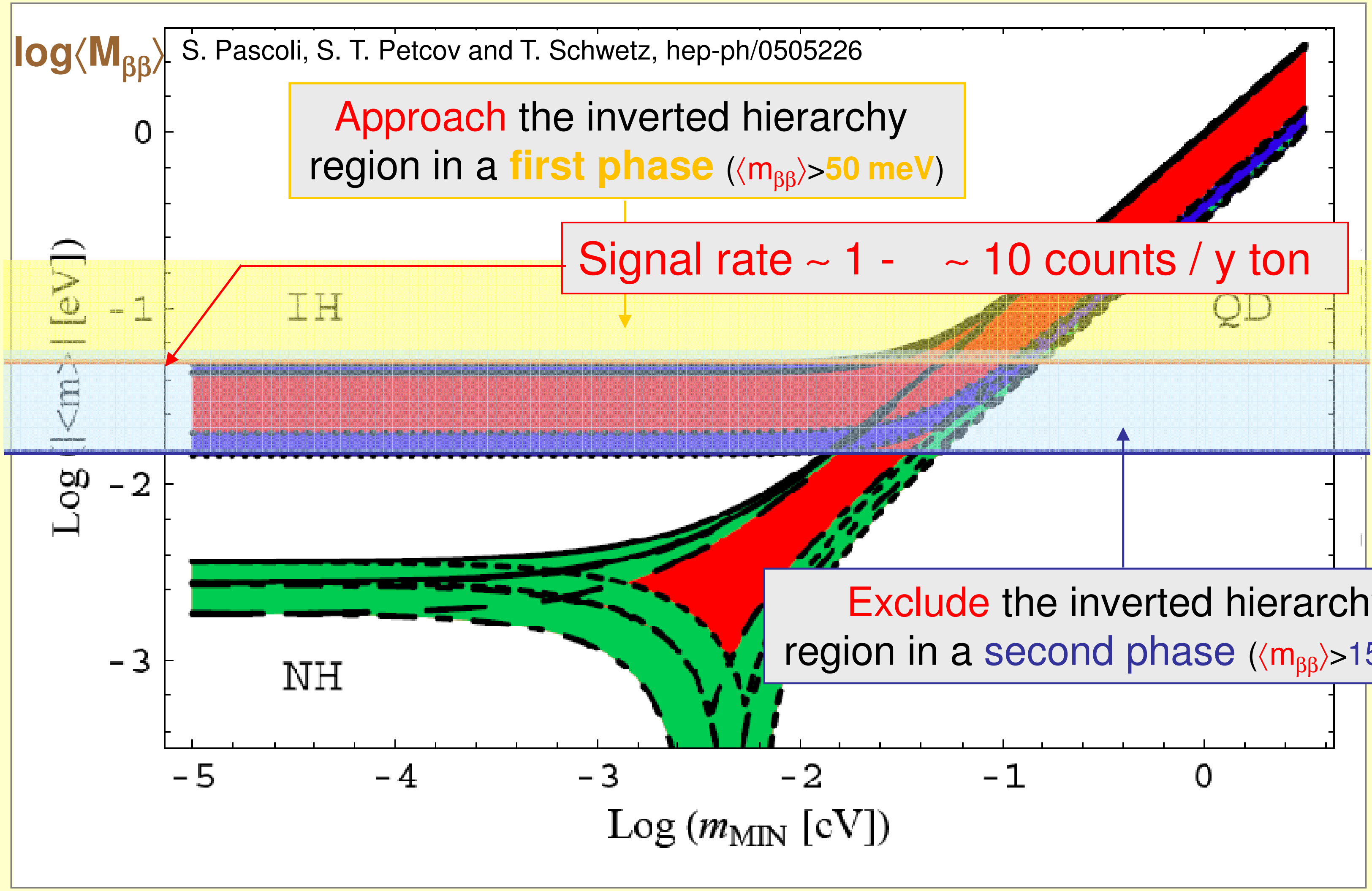
parameter containing the neutrino physics

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

From where we start…



…and where we want to go



S. Pascoli, S. T. Petcov and T. Schwetz, hep-ph/0505226

Approach the inverted hierarchy region in a **first phase** ($\langle m_{\beta\beta}\rangle$>50 meV)

Signal rate ~ 1 - ~ 10 counts / y ton

Exclude the inverted hierarchy region in a second phase ($\langle m_{\beta\beta}\rangle$>15 meV)

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

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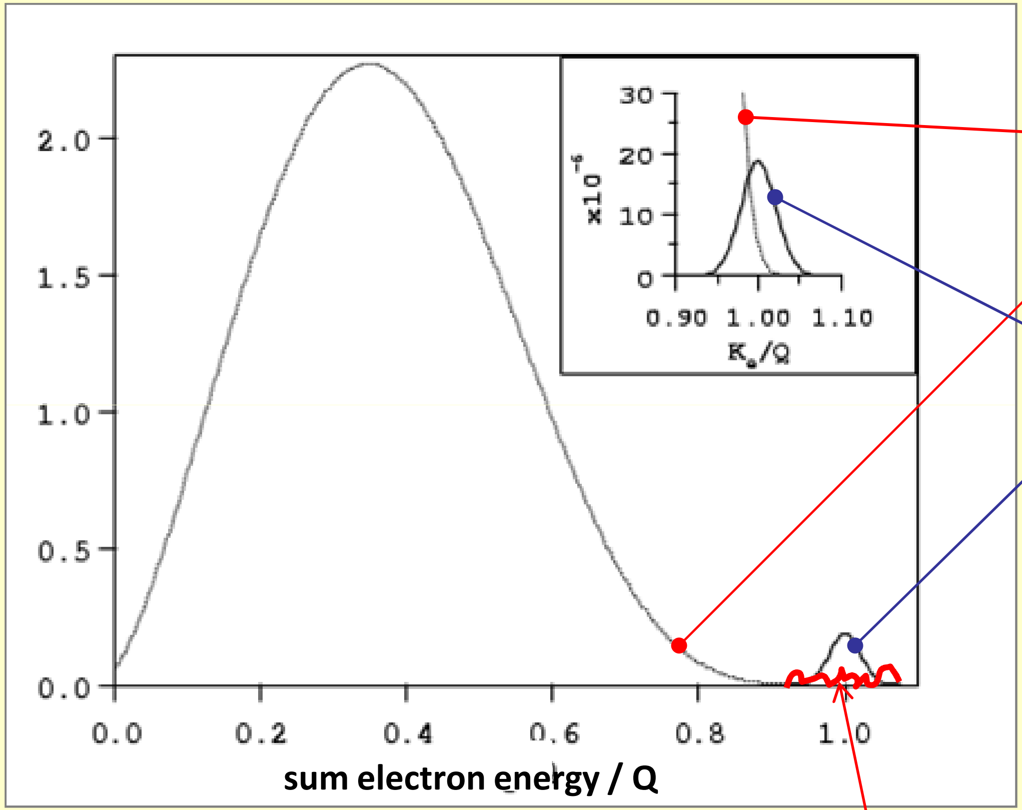
The main signature: electron sum energy spectra in DBD

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,

- Target bakground of the order of ~ **few counts / y ton**
- Sensitive mass of the order of ~100's kg → **10^{26} – 10^{27} nuclides**

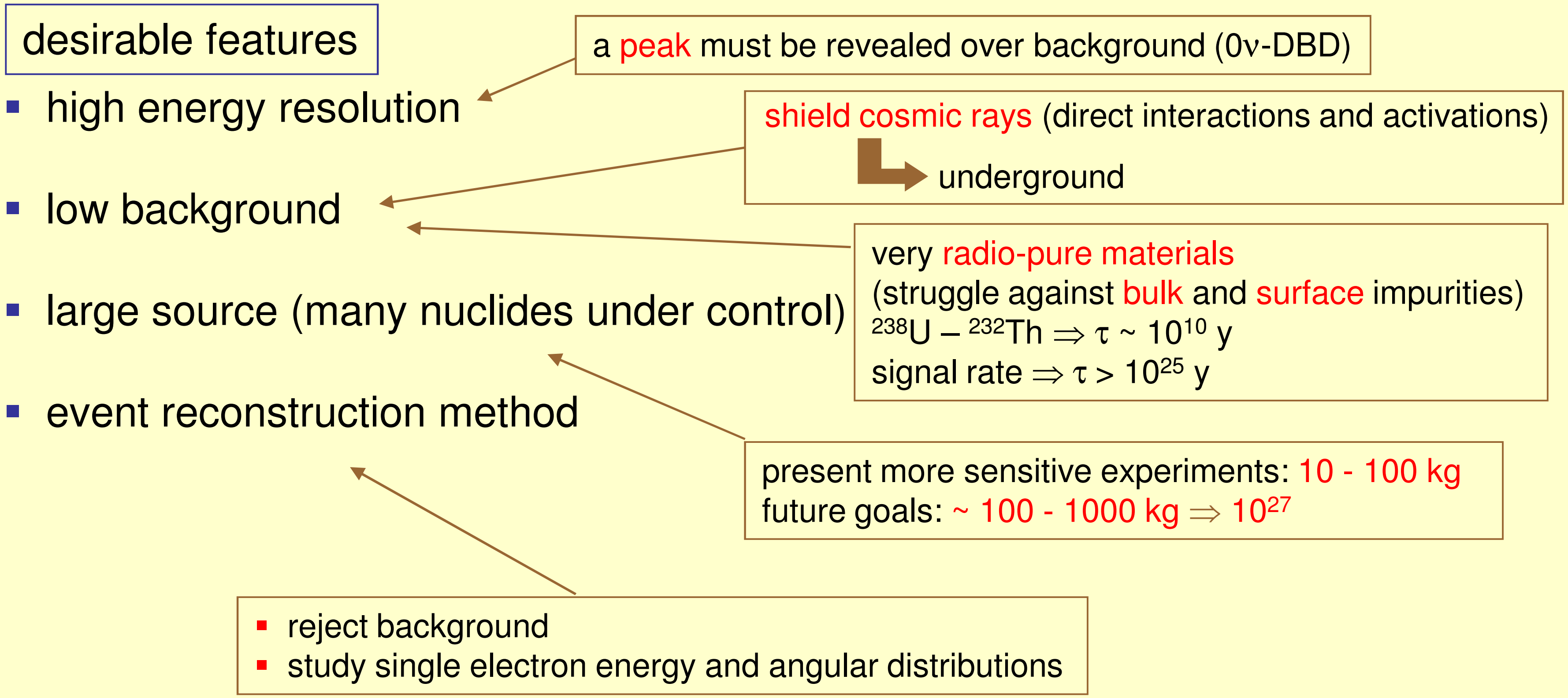
Experimental strategies

① Detect and identify the daughter nuclei (indirect search)

geochemical experiments
radiochemical experiments

it is not possible to distinguish the decay channel
important in the 70s-80s – no more pursued now

② Detect the two electrons with a proper nuclear detector (direct search)



desirable features

- high energy resolution
- low background
- large source (many nuclides under control)
- event reconstruction method

a peak must be revealed over background (0ν-DBD)

shield cosmic rays (direct interactions and activations)
underground

very radio-pure materials
(struggle against bulk and surface impurities)
$^{238}U - ^{232}Th \Rightarrow \tau \sim 10^{10}$ y
signal rate $\Rightarrow \tau > 10^{25}$ y

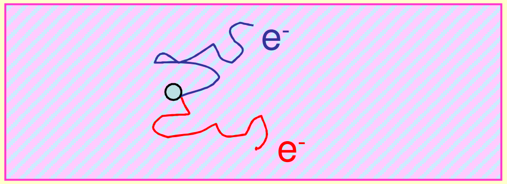
present more sensitive experiments: 10 - 100 kg
future goals: ~ 100 - 1000 kg $\Rightarrow 10^{27}$

- reject background
- study single electron energy and angular distributions

Possible approaches to direct searches

Two approaches:

①



Source ≡ Detector →

(calorimetric technique)

- scintillation
- phonon-mediated detection
- solid-state devices
- gaseous detectors

☹ constraints on detector materials

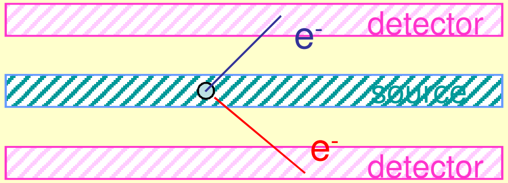
☺ very large masses are possible
demonstrated: up to ~ 50 kg
proposed: up to ~ 1000 kg
with efficiency close to 1

☺ with proper choice of the detector, very high energy resolution
- ➢ Ge-diodes
- ➢ bolometers

☺ in gaseous/liquid xenon detector, indication of event topology

→ ☹ in contradiction

②



Source ≠ Detector →

- scintillation
- gaseous TPC
- gaseous drift chamber
- magnetic field and TOF

☹ it is difficult to get large source mass and high efficiency

☺ neat reconstruction of event topology

☺ several candidates can be studied with the same detector

2ν–ββ decay: irreducible background

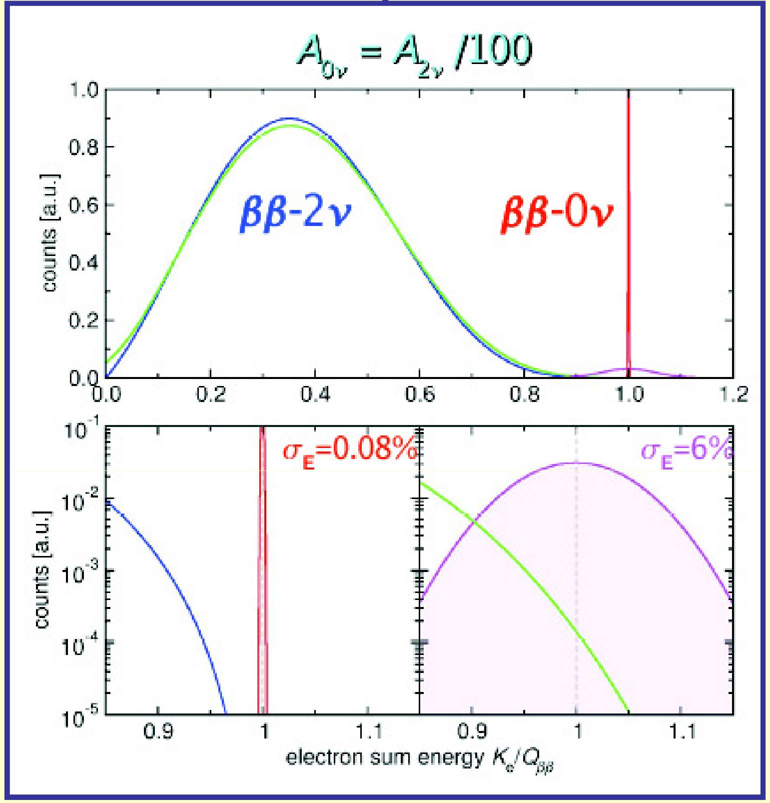
The **2ν–ββ tail** is an irreducible source of background and cannot be rejected just exploiting the event topology

The main weapon is the energy resolution

$$\delta = \frac{\Delta E^{FWHM}}{Q_{\beta\beta}}$$

$$\frac{S}{B} \approx \frac{m_e}{7Q_{\beta\beta}\delta^6}\frac{T^{2\nu}_{1/2}}{T^{0\nu}_{1/2}}$$

Very strong dependence on ΔE_{FWHM}



Typical requirements

$$T^{0\nu} \simeq 10^{28} y \quad S/B = 1$$

$$T^{2\nu} \simeq 10^{20} y \quad Q \simeq 3\,\mathrm{MeV}$$

$$\delta = \Delta E^{FWHM}/Q = 2.5\%$$

Experimental sensitivity to 0ν-DBD

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)]**

$b \neq 0$

$b = 0$

source mass

live time

energy resolution

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

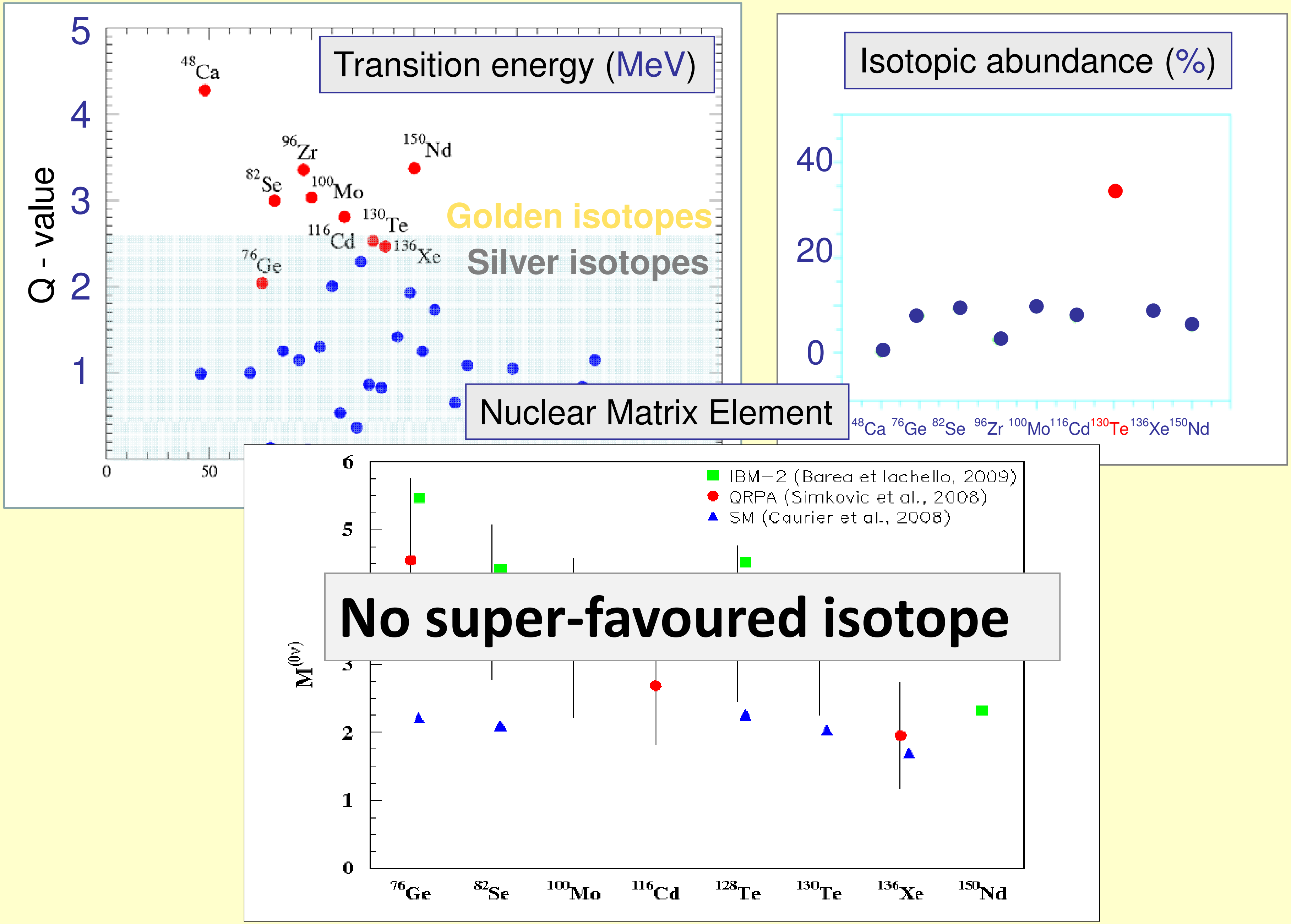
$$F \propto MT$$

importance of the nuclide choice

(but large uncertainty due to nuclear physics)

sensitivity to $\langle \mathbf{M} \rangle$ $\propto (F/Q\ |M_{nucl}|^2)^{1/2} \propto \dfrac{1}{G^{1/2}\ \ |M_{nucl}|} \left(\dfrac{b\Delta E}{MT} \right)^{1/4}$

Choice of the nuclide



Transition energy (MeV)

Isotopic abundance (%)

Nuclear Matrix Element

No super-favoured isotope

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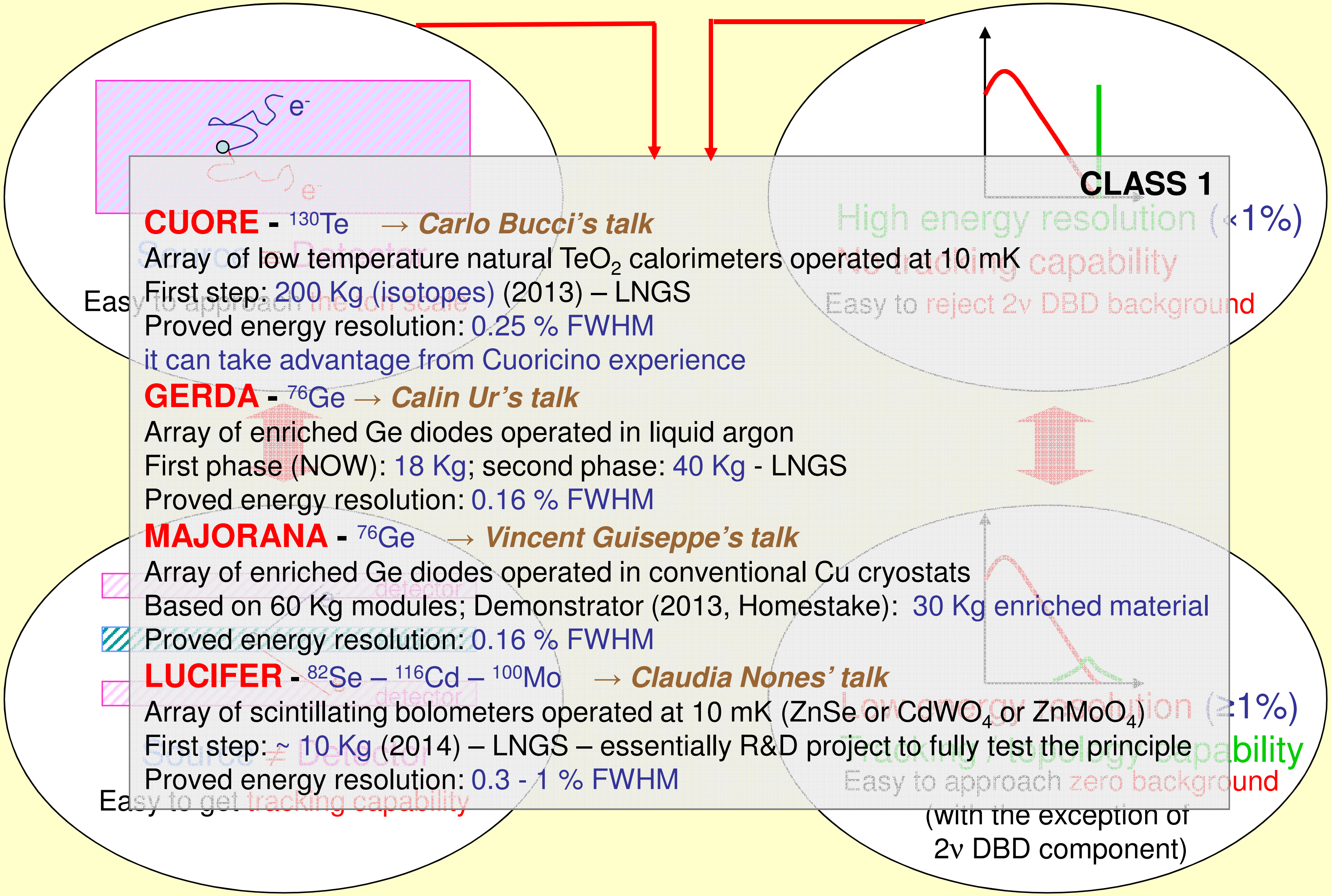
Experiments and techniques



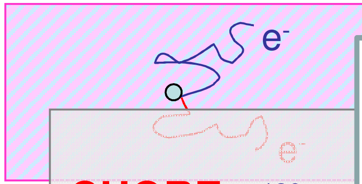
CUORE - ^{130}Te → ***Carlo Bucci's talk***
Array of low temperature natural TeO_2 calorimeters operated at 10 mK
First step: 200 Kg (isotopes) (2013) – LNGS
Proved energy resolution: 0.25 % FWHM
it can take advantage from Cuoricino experience

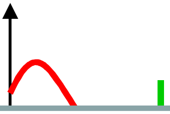
GERDA - ^{76}Ge → ***Calin Ur's talk***
Array of enriched Ge diodes operated in liquid argon
First phase (NOW): 18 Kg; second phase: 40 Kg - LNGS
Proved energy resolution: 0.16 % FWHM

MAJORANA - ^{76}Ge → ***Vincent Guiseppe's talk***
Array of enriched Ge diodes operated in conventional Cu cryostats
Based on 60 Kg modules; Demonstrator (2013, Homestake): 30 Kg enriched material
Proved energy resolution: 0.16 % FWHM

LUCIFER - ^{82}Se – ^{116}Cd – ^{100}Mo → ***Claudia Nones' talk***
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

Experiments and techniques





CUORE - ^{130}Te

Array of low temp

First step: 200 Kg

Proved energy re

it can take advant

GERDA - ^{76}Ge

Array of enriched

First phase (NOW

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MAJORANA -

Array of enriched

Based on 60 Kg r

Proved energy re

LUCIFER - ^{82}Se

Array of scintillati

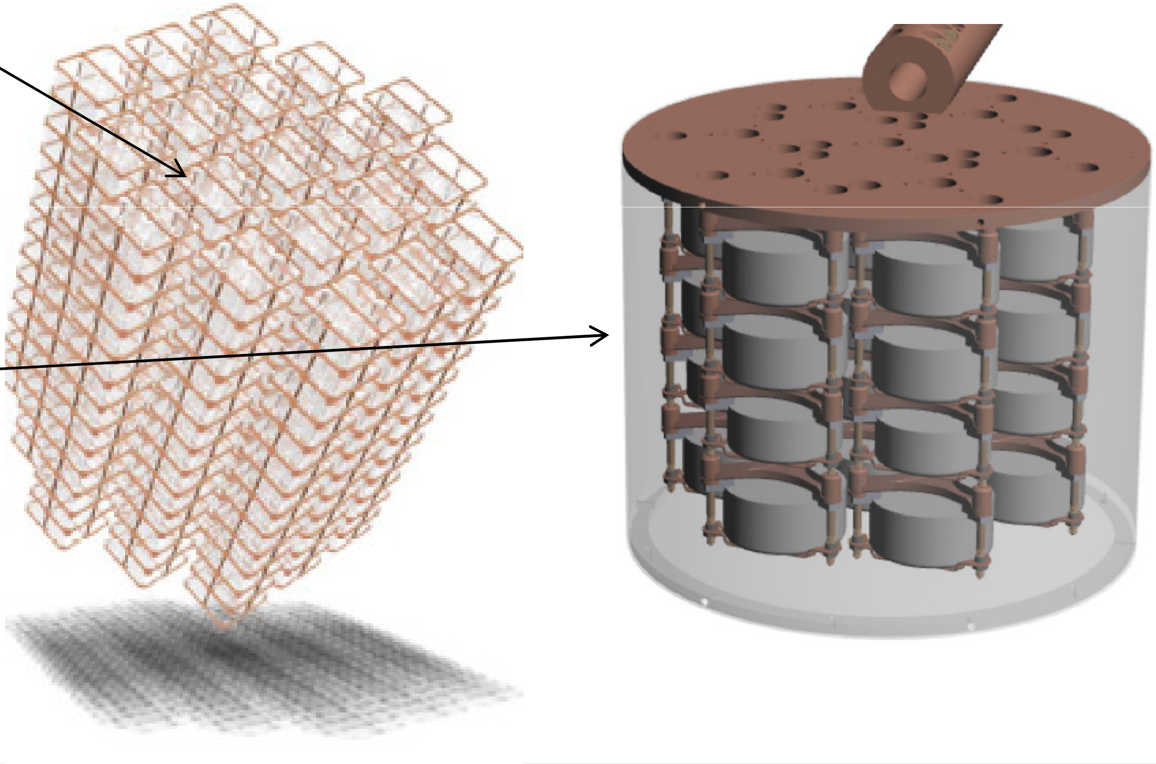
First step: ~ 10 Kg

Proved energy re

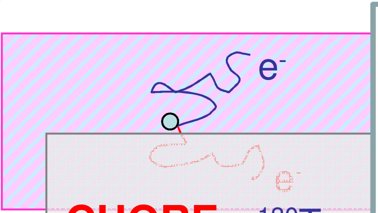
Easy to get tracking

2ν DBD component)

Granularity



Experiments and techniques



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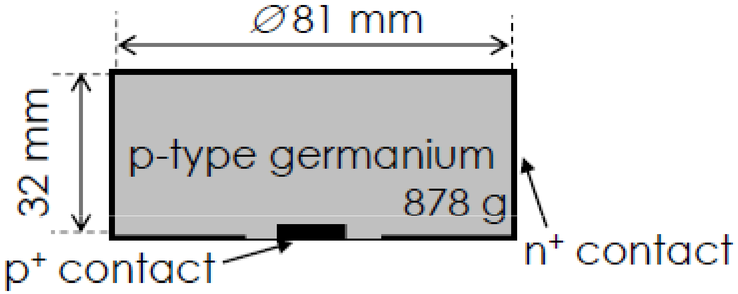
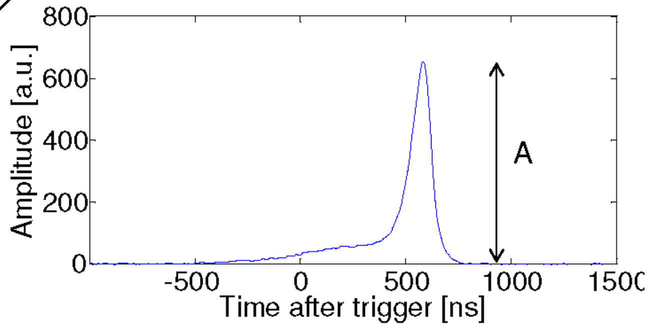
LUCIFER - ^{82}Se
Array of scintillatin
First step: ~ 10 Kg
Proved energy res

Easy to get tracking ca

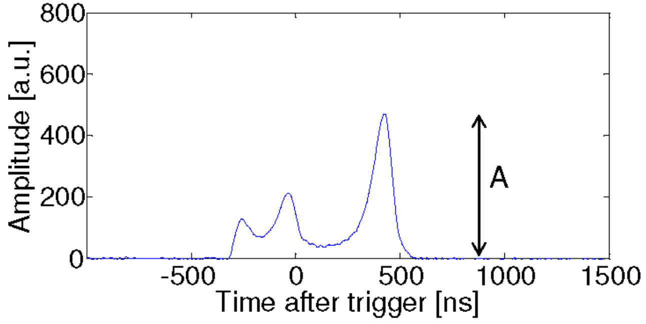
Multi-site events

BEGe technology



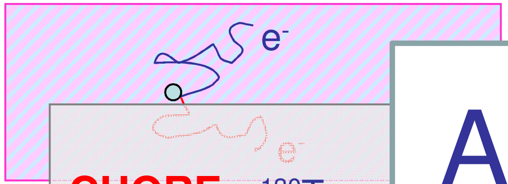


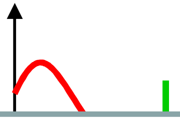
Single-site event



Multi-site event

Experiments and techniques





Easy to approach the

Source = Detector

CUORE - ^{130}Te →

Array of low tempe

First step: 200 Kg (i

Proved energy reso

it can take advantag

GERDA - ^{76}Ge →

Array of enriched G

First phase (NOW):

Proved energy reso

MAJORANA - ^{76}(

Array of enriched G

Based on 60 Kg mo

Proved energy reso

LUCIFER - ^{82}Se –

Array of scintillating

First step: ~ 10 Kg (

Proved energy resolution: 0.5 – 1 % FWHM

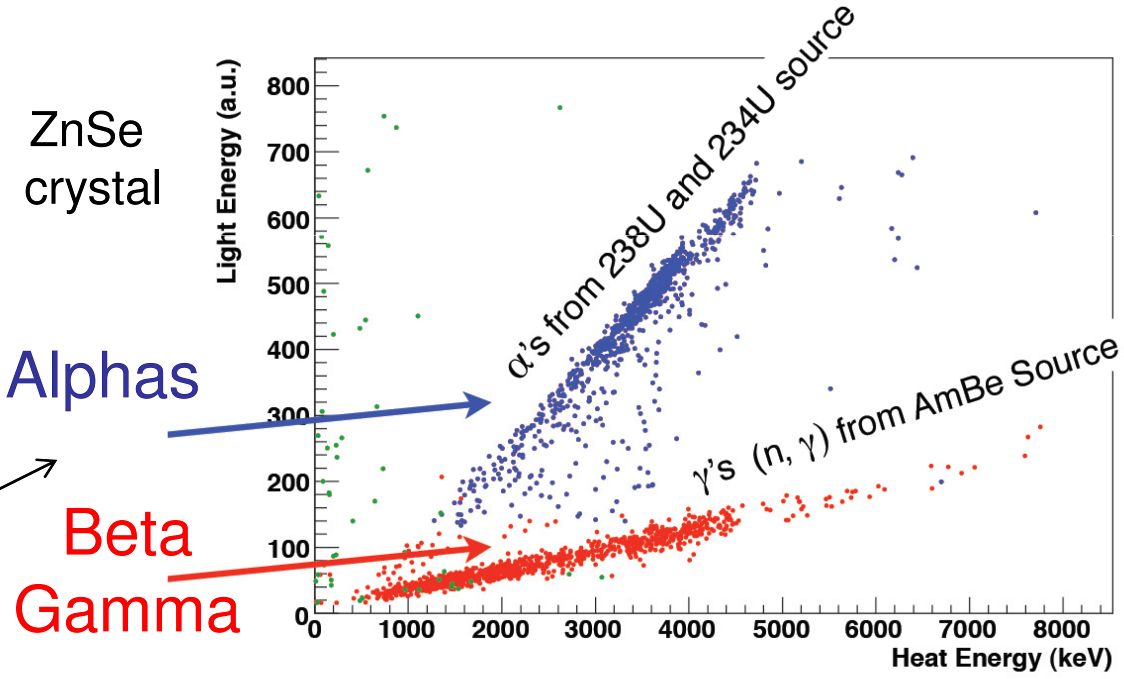
Source ≠ Detector

Easy to get tracking capability

Easy to approach zero background

(with the exception of
2ν DBD component)

Alpha/beta discrimination



Experiments and techniques

CUORE - ^{130}Te
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Proved energy re
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First phase (NOW
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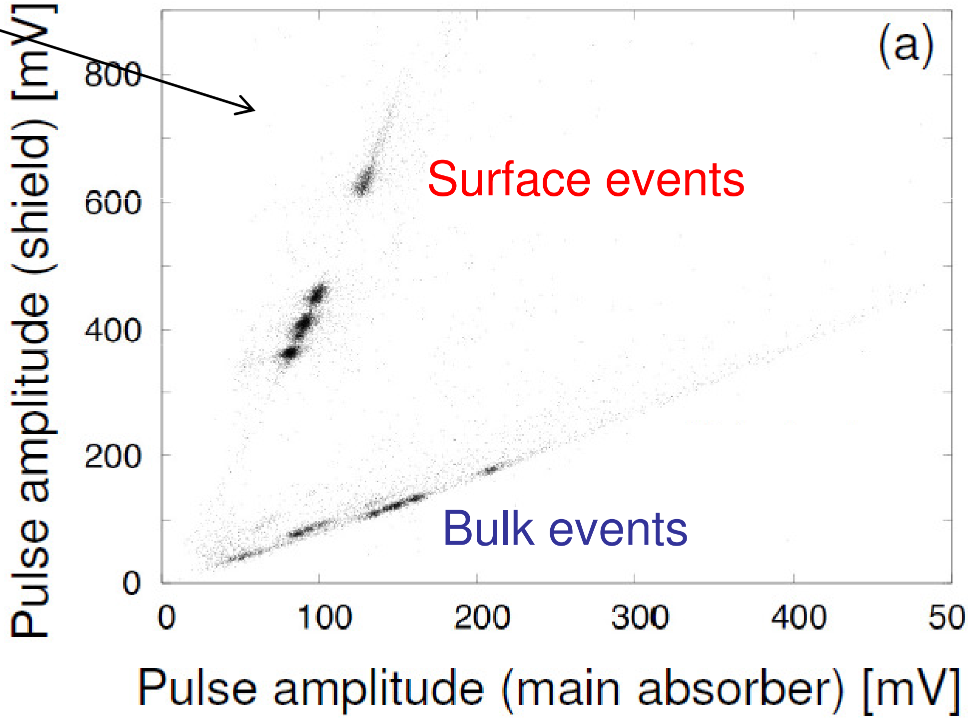
MAJORANA -
Array of enriched
Based on 60 Kg
Proved energy re

LUCIFER - ^{82}S
Array of scintillat
First step: ~ 10 K
Proved energy re

Easy to get tracking

Surface sensitive bolometers



2ν DBD component)

Experiments and techniques

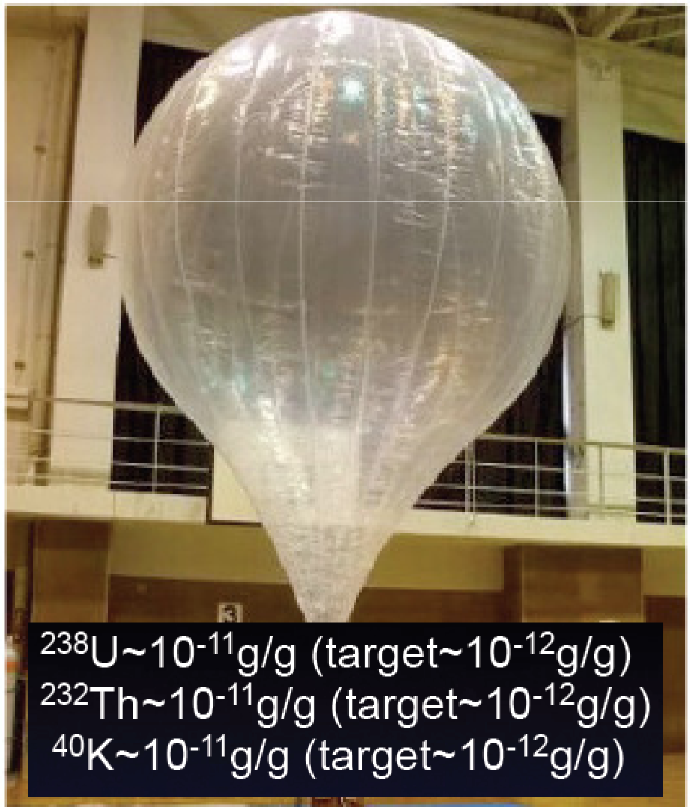
SNO+ – ^{150}Nd → ***José Maneira***
SNO detector filled with Nd-loaded
0.1% loading in wieght with natural
Crucial points: Nd radio-purity and,

KamLAND-Zen – ^{136}Xe
Insert a mini-balloon containing Xe
400 kg of enriched Xe (2.7% w)
Data taking in 2011

XMASS – ^{136}Xe
Multipurpose scintillating liquid Xe
Three development stages: 3 Kg (p
DBD option: low background in the
High light yield and collection effici
Target: to cover inverted hierarchy

CANDLES – ^{48}Ca
Array of natural pure (not Eu dope
Prove of principle completed –p rov
The good point of this search is the
⇒out of γ (2.6 MeV end point), β (3
Other background cuts come from

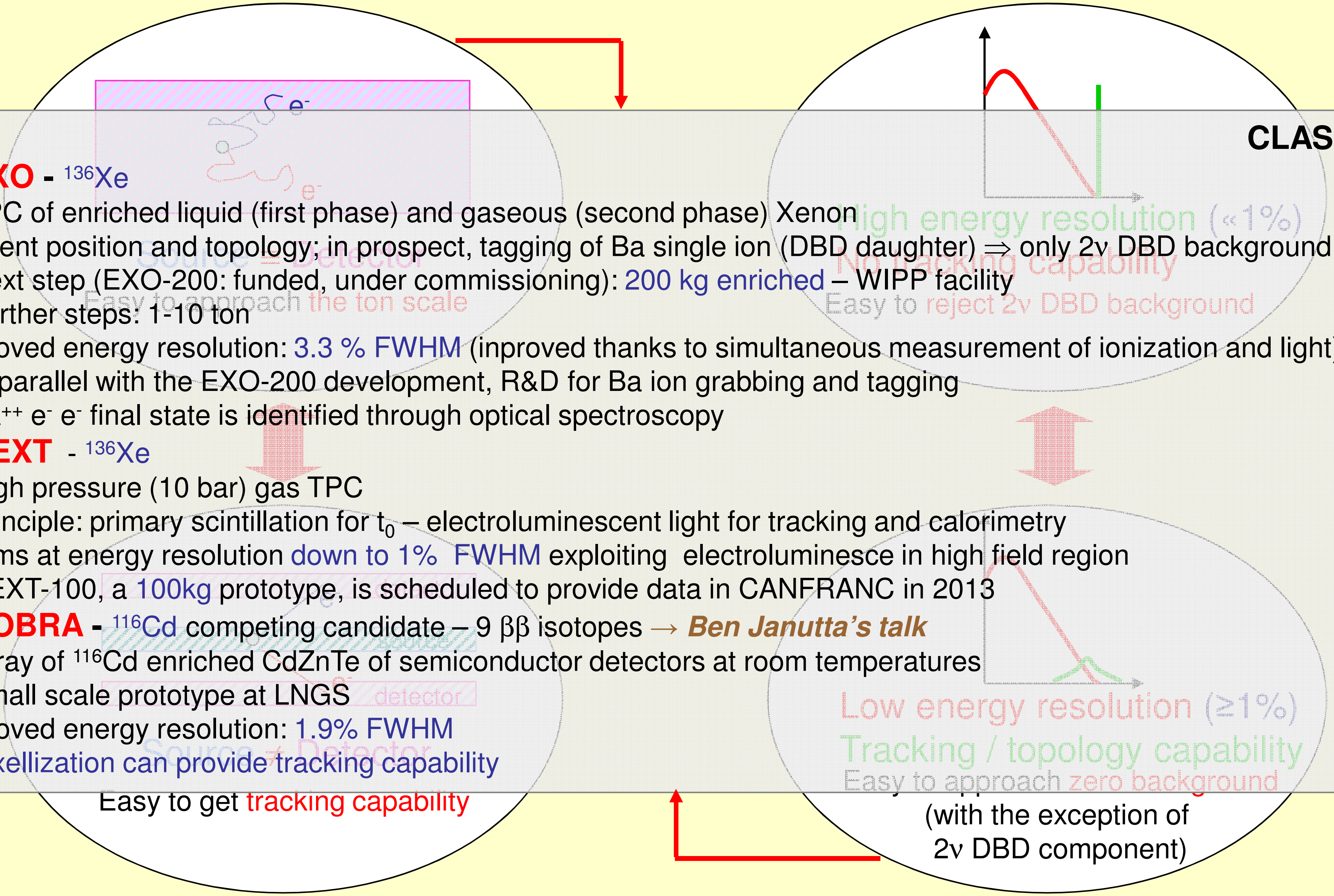
Mini Balloon study



^{238}U~10^{-11}g/g (target~10^{-12}g/g)
^{232}Th~10^{-11}g/g (target~10^{-12}g/g)
^{40}K~10^{-11}g/g (target~10^{-12}g/g)

S 2
activity
d Bi-Tl

Experiments and techniques



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 enriched – WIPP facility
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 (10 bar) gas TPC
Principle: primary scintillation for t_0 – electroluminescent light for tracking and calorimetry
Aims at energy resolution down to 1% FWHM exploiting electroluminese in high field region
NEXT-100, a 100kg prototype, is scheduled to provide data in CANFRANC in 2013

COBRA - ^{116}Cd competing candidate – 9 ββ isotopes → ***Ben Janutta's talk***
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

Experiments and techniques

EXO - ^{136}Xe
TPC of enriched liquid (first p
Event position and topology;
Next step (EXO-200: funded
Further steps: 1-10 ton
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COBRA - ^{116}Cd competing
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Pixellization can provide trac

Source = D
Easy to approach t
Source ≠ D
Easy to get tracki

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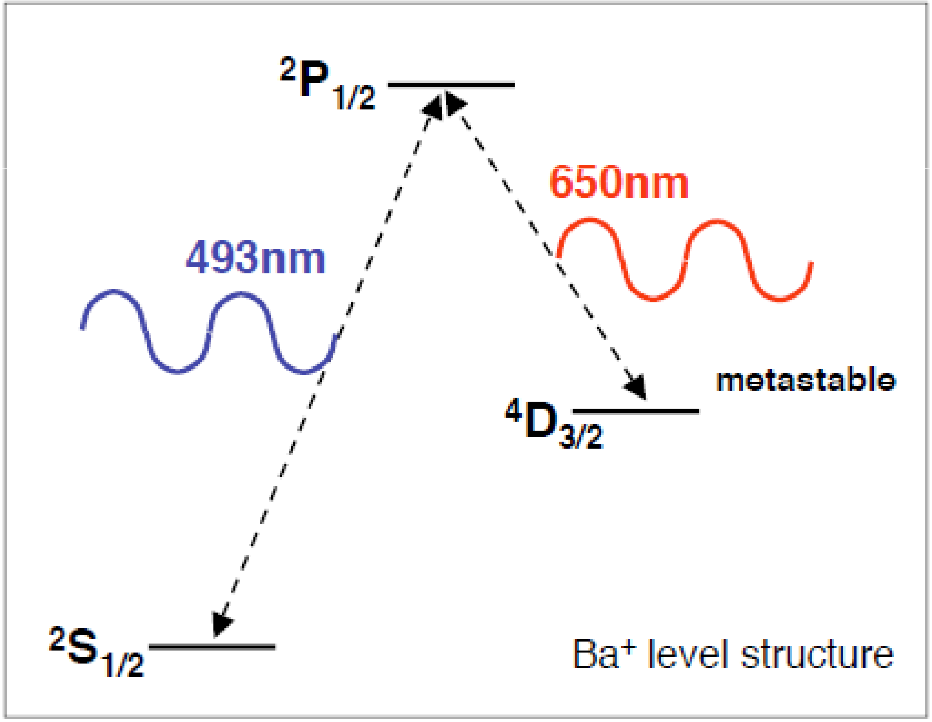
Ba tagging

Laser –induced fluorescence of Ba+ ion
→ emission of 10^7 photons/s



Ba$^+$ level structure

Experiments and techniques

EXO - ^{136}Xe
TPC of enriched liqu
Event position and t
Next step (EXO-200
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In parallel with the E
Ba^{++} e^{-} e^{-} final state
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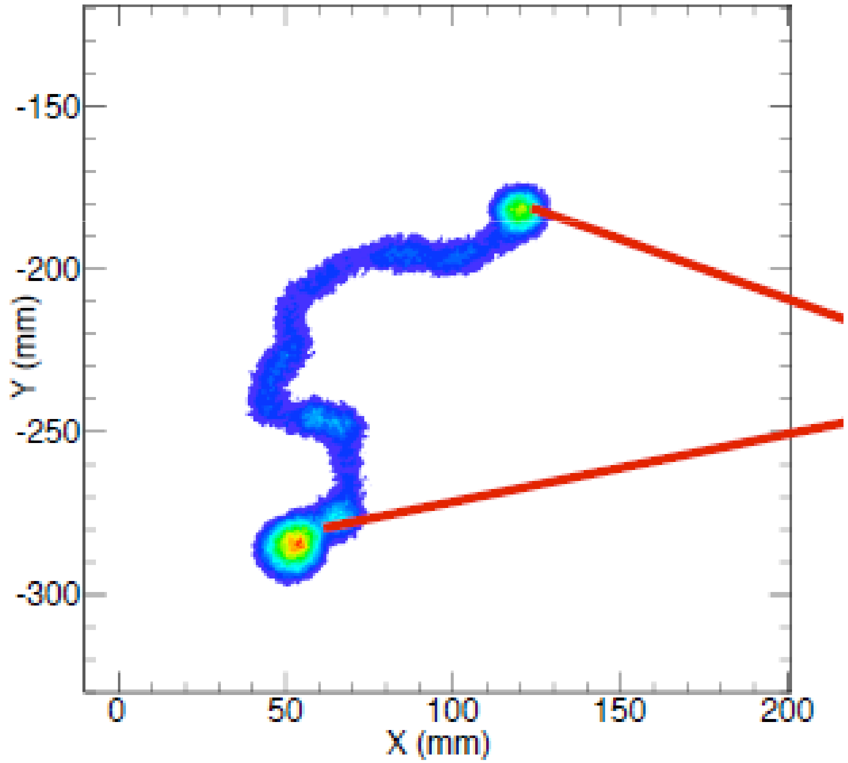
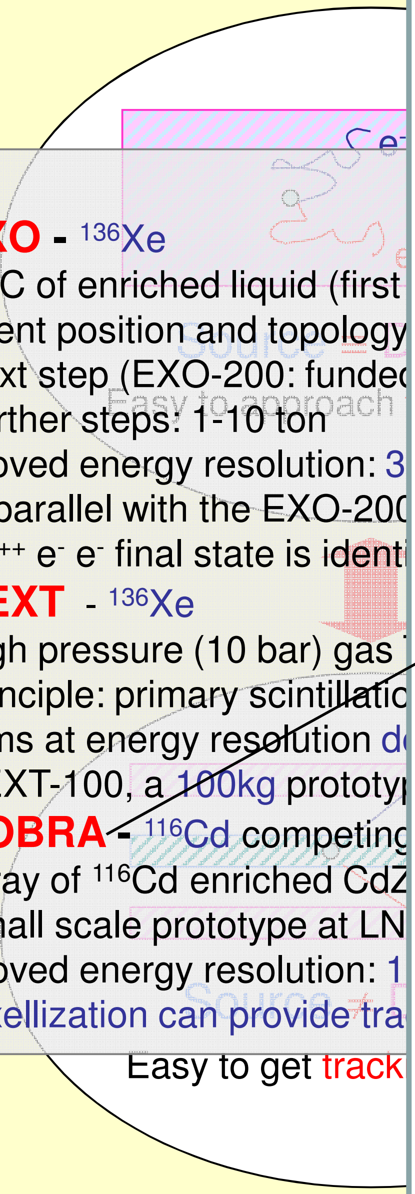
Event identification



Two electron tracks with blobs at the end (simulation)

Experiments and techniques



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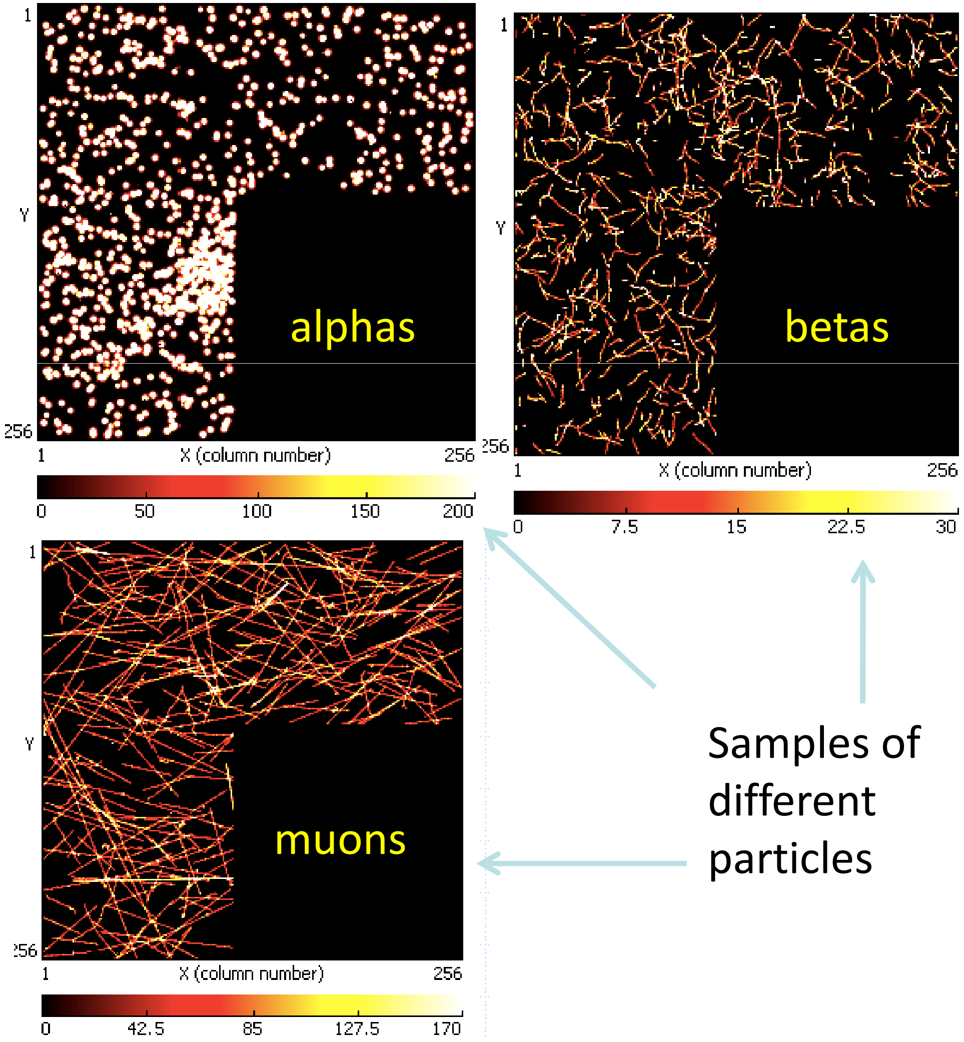
COBRA - ^{116}Cd competing
Array of ^{116}Cd enriched CdZ
Small scale prototype at LN
Proved energy resolution: 1
Pixellization can provide tra

Easy to get track

Semiconductor tracker

Real data: 55 µm pixel size



Samples of different particles

Experiments and techniques

CLASS 4

SUPERNEMO - ^{82}Se or ^{150}Nd → ***Robert Flack's talk***

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

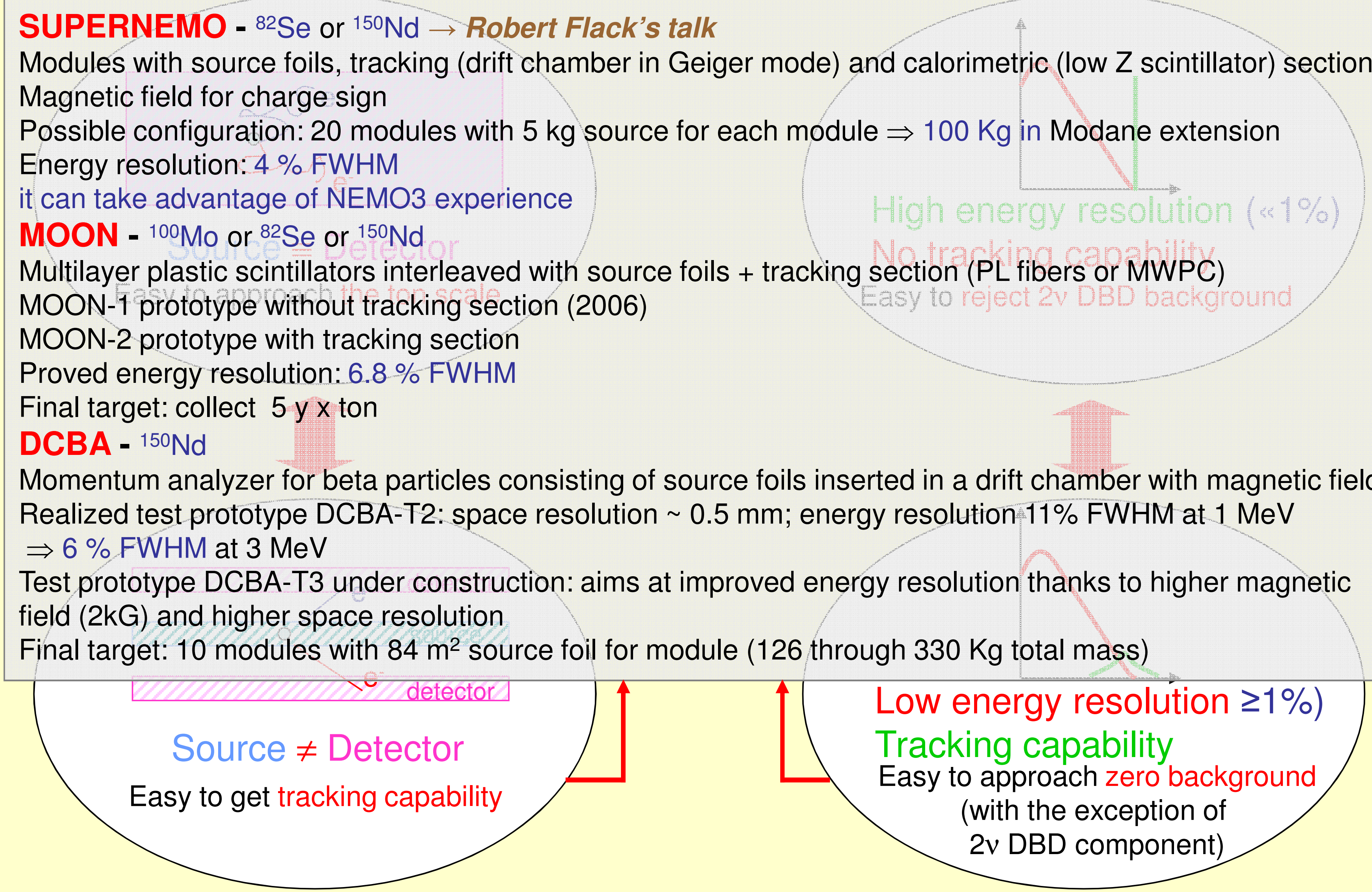
Momentum analyzer for beta particles consisting of source foils inserted in a drift chamber with magnetic field

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 m² source foil for module (126 through 330 Kg total mass)



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CLASS 1

CUORE

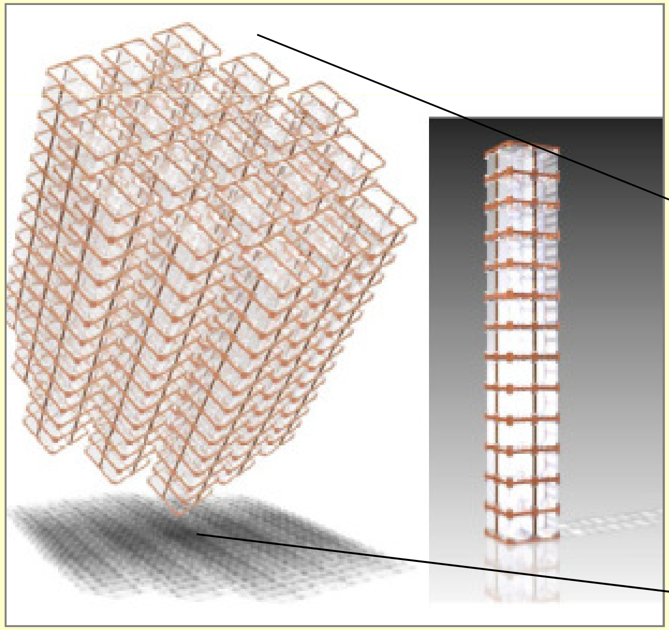
Technique/location: natural TeO_2 bolometers at 10 mK– LNGS (Italy)
evolution of Cuoricino

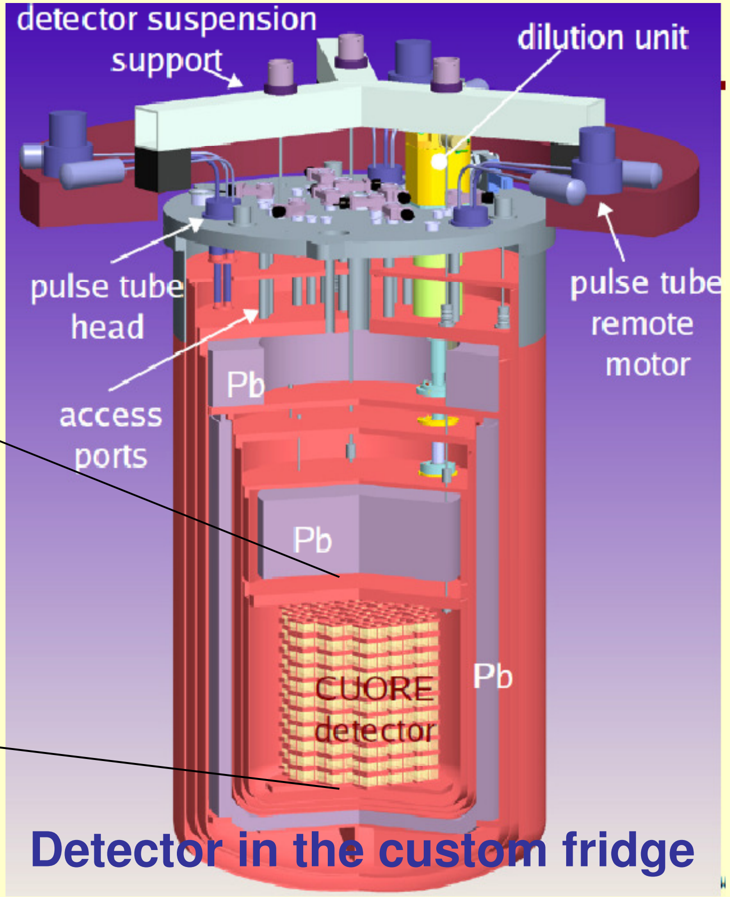
Source: TeO_2 – 741 kg with natural tellurium - **9.5×10^{26} nuclides** of ^{130}Te

Sensitivity: 35 – 82 meV

Timeline: first CUORE tower in 2011 – data taking with full apparatus in 2013

Structure of the detector





Detector in the custom fridge

CLASS 1

GERDA – phase 1

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

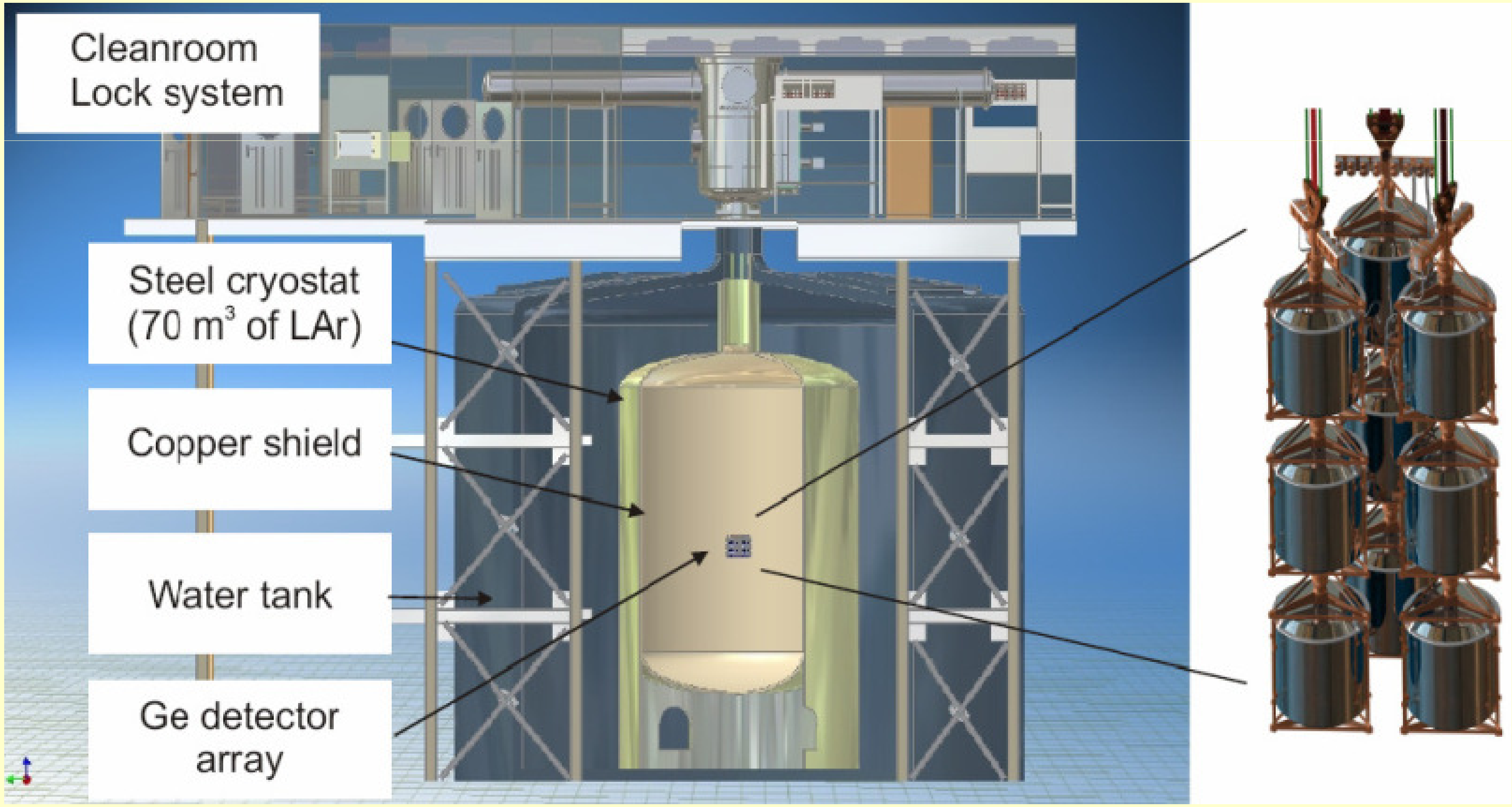
Source: Ge - 17.66 kg – ^{76}Ge enriched at 86% - **1.2x10^{26} nuclides**

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

Background contribution from ^{42}Ar higher than expected

→ understand before inserting enriched detectors



CLASS 4

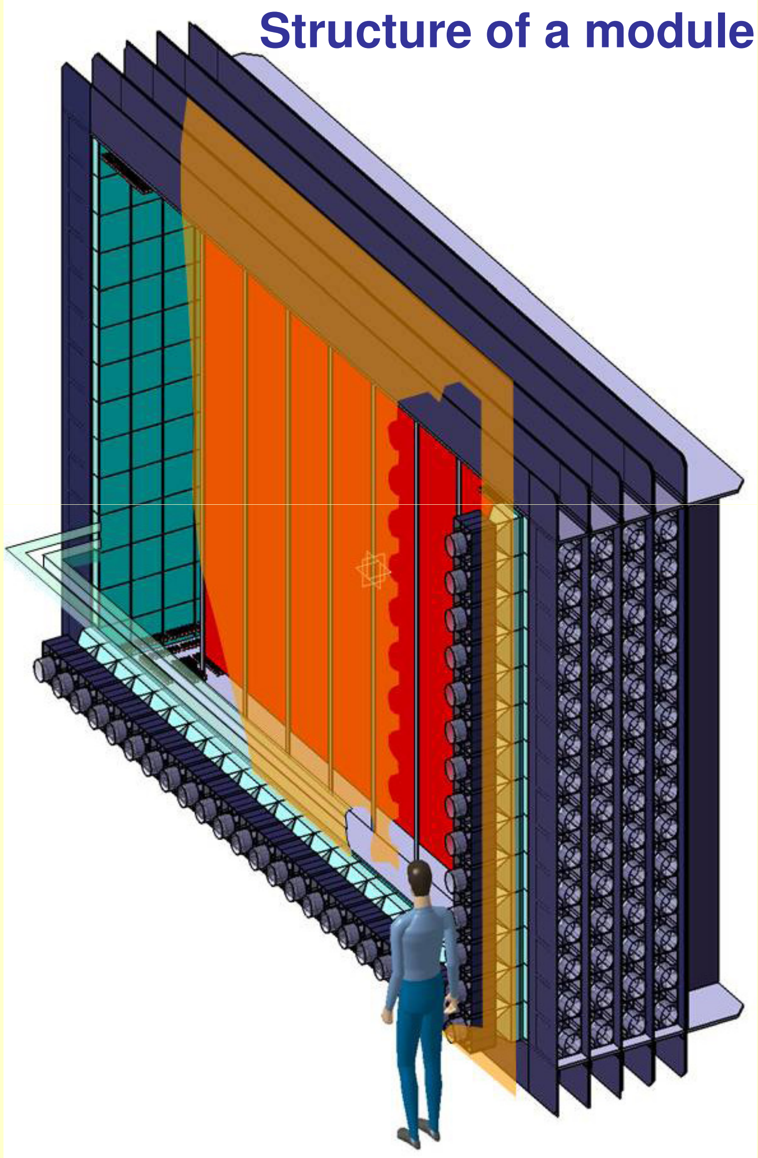
SUPERNEMO

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)

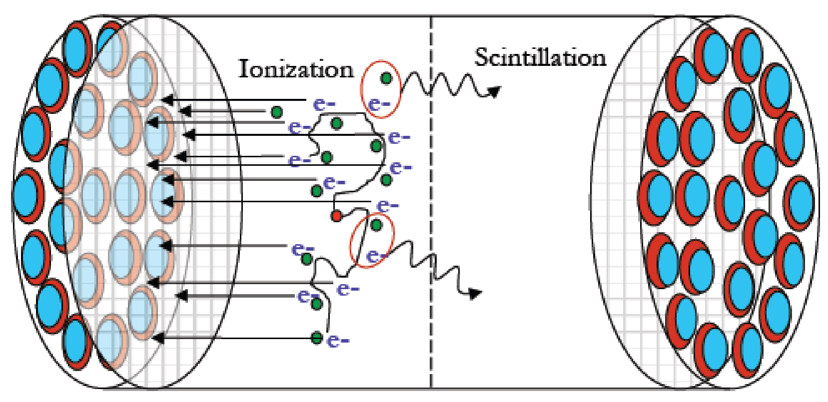
Timeline: demonstrator module in 2013 (~7 kg) – construction of 20 modules: 2014-2015



CLASS 3

EXO-200

Technique/location: phase 1: liquid enriched xenon TPC – WIPP (New Mexico, US)

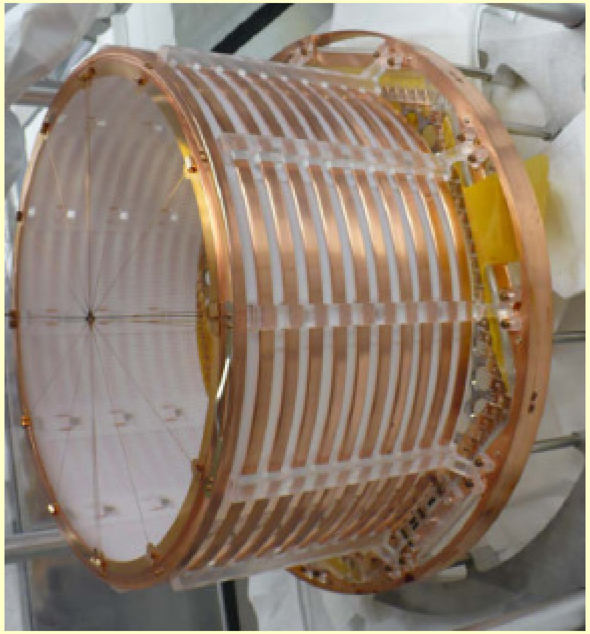


Source: Xe - 200 kg – ^{136}Xe enriched at 80%
7.1x10^{26} nuclides

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

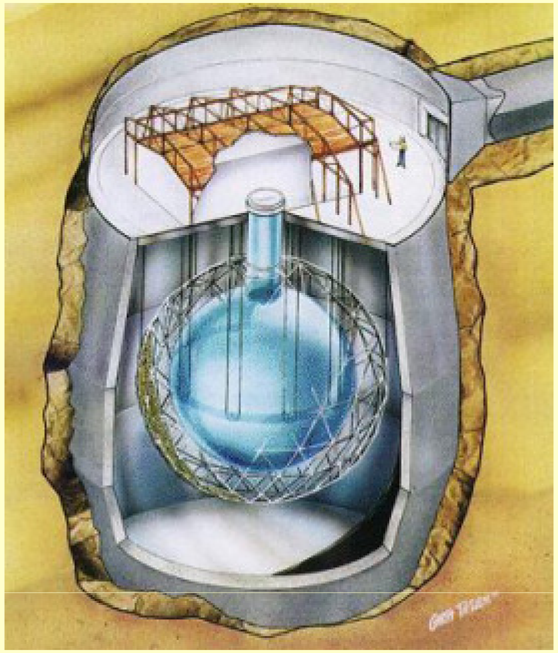
SNO+

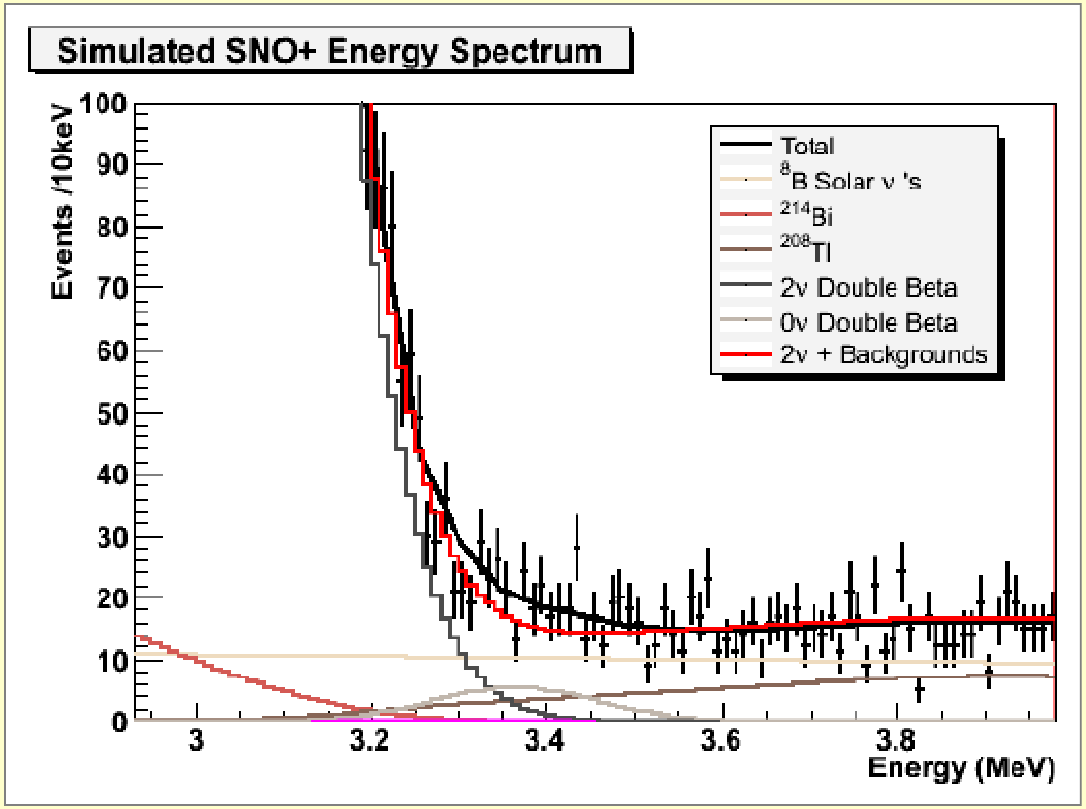
Technique/location: upgrade of SNO with Nd-loaded liquid scintillator

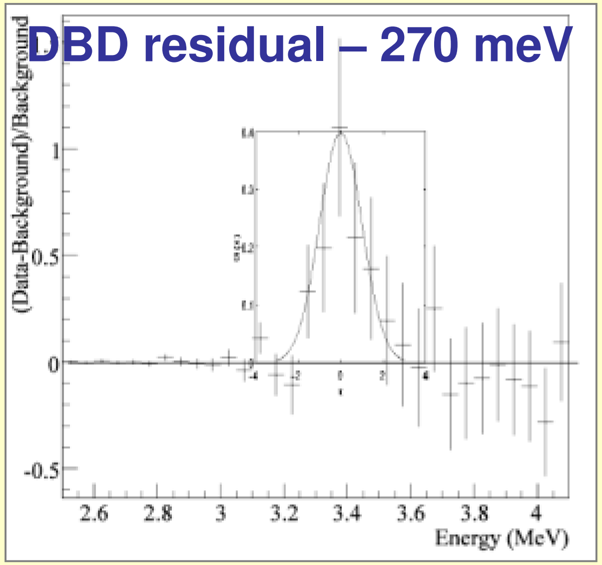
Source: 1000 tons with 0.1 % w/w natural Nd
(44 kg of ^{150}Nd): **1.7x10^{26} nuclides**

Sensitivity: 100 meV

Timeline: data taking in 2012







DBD residual – 270 meV

Outline

- Introduction to Double Beta Decay
- Experimental challenge and strategies
- Overview of the projects under development
- Some very promising experiments
- Prospects and conclusions

Future scenarios and branching points in terms of discovery

sensitivity to $\langle M_{\beta\beta} \rangle$	experimental situation
100 - 500 meV	degenerate hierarchy 100-200 kg isotope – 1-5 year scale
15 - 50 meV	inverted hierarchy - atmospheric ΔM^2 region 1000 kg isotope – 5-10 year scale
2 - 5 meV	direct hierarchy - solar ΔM^2 region 100 tons of isotopes is the typical scale discovery if neutrino is a Majorana particle unpredictable time scale

Future scenarios and branching points in terms of discovery

sensitivity to $\langle M_{\beta\beta} \rangle$

experimental situation

100 - 500 meV

degenerate hierarchy
100-200 kg isotope – 1-5 year scale

15 - 50

2 - 5 n

if this range holds (and/or ^{76}Ge claim is confirmed):
- CUORE will see it in ^{130}Te and may do multi-isotope searches simultaneously (^{130}Te - ^{116}Cd - ^{100}Mo)
- 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
- 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

Future

sensitivit

100 - 50

if this range holds:

- 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

SuperNEMO could marginally see it in ^{82}Se or ^{150}Nd

- SNO+ could see it in ^{150}Nd only if enriched
- GERDA phase III / MAJORANA could see it in ^{76}Ge

large scale enrichment required

discovery in 3 or 4 isotopes necessary (and possible...)

to confirm the observation and to improve $\langle M_{\beta\beta} \rangle$ estimate

15 - 50 meV

inverted hierarchy - atmospheric ΔM^2 region

1000 kg isotope – 5-10 year scale

2 - 5 meV

direct hierarchy - solar ΔM^2 region

100 tons of isotopes is the typical scale

discovery if neutrino is a Majorana particle

unpredictable time scale

Future scenarios and branching points in terms of discovery

sensitivity to $\langle M_{\beta\beta}\rangle$	experimental situation
100 - 500 meV	degenerate hierarchy 100-200 kg isotope – 1-5 year scale
15 - 50 meV	on
2 - 5 meV	direct hierarchy - solar ΔM^2 region 100 tons of isotopes is the typical scale discovery if neutrino is a Majorana particle unpredictable time scale

if this range holds:
- new strategies have to be developed
- next generation experiments are precious for the selection of the future approaches
- a colossal investment in enrichment is required