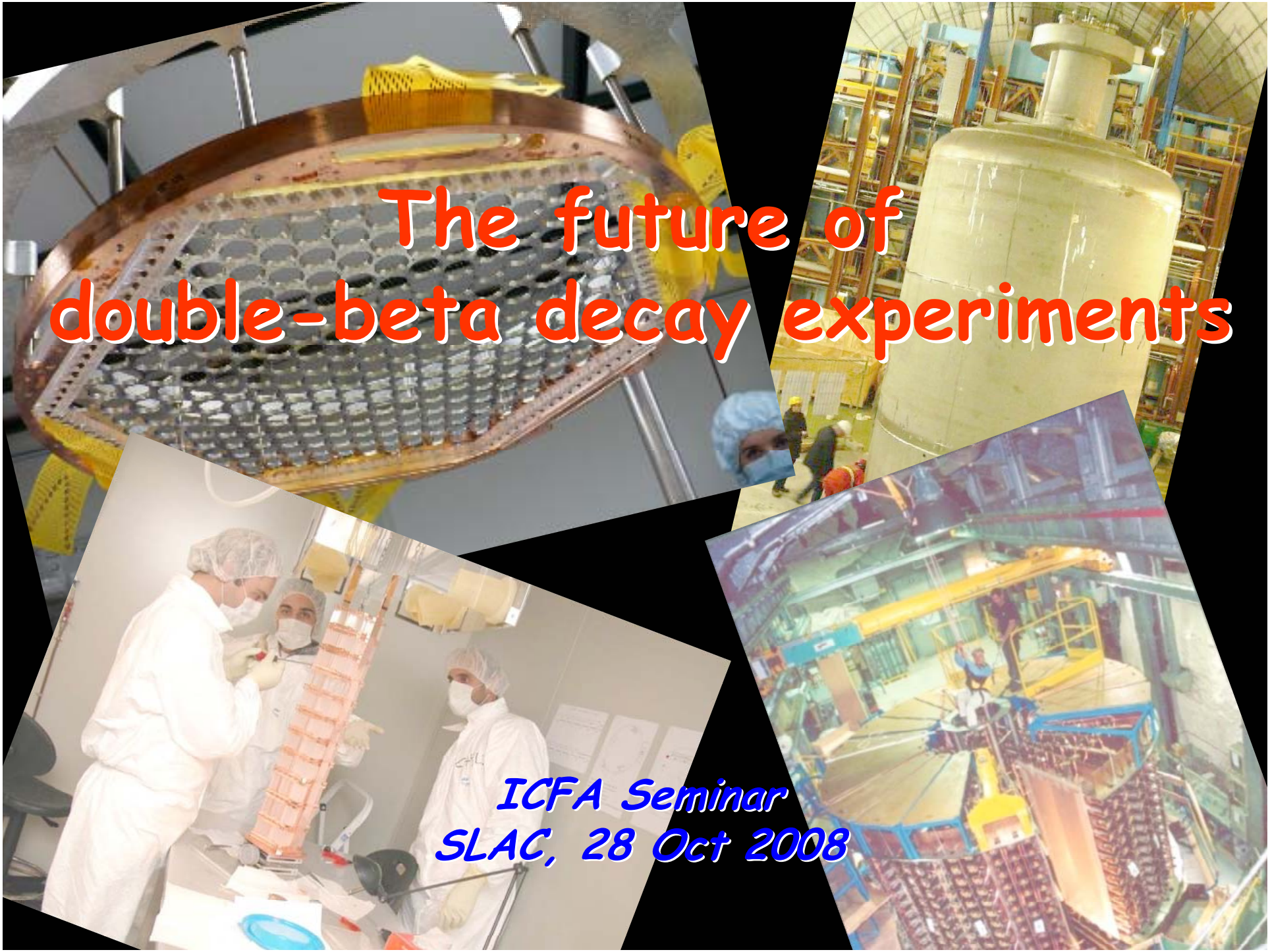
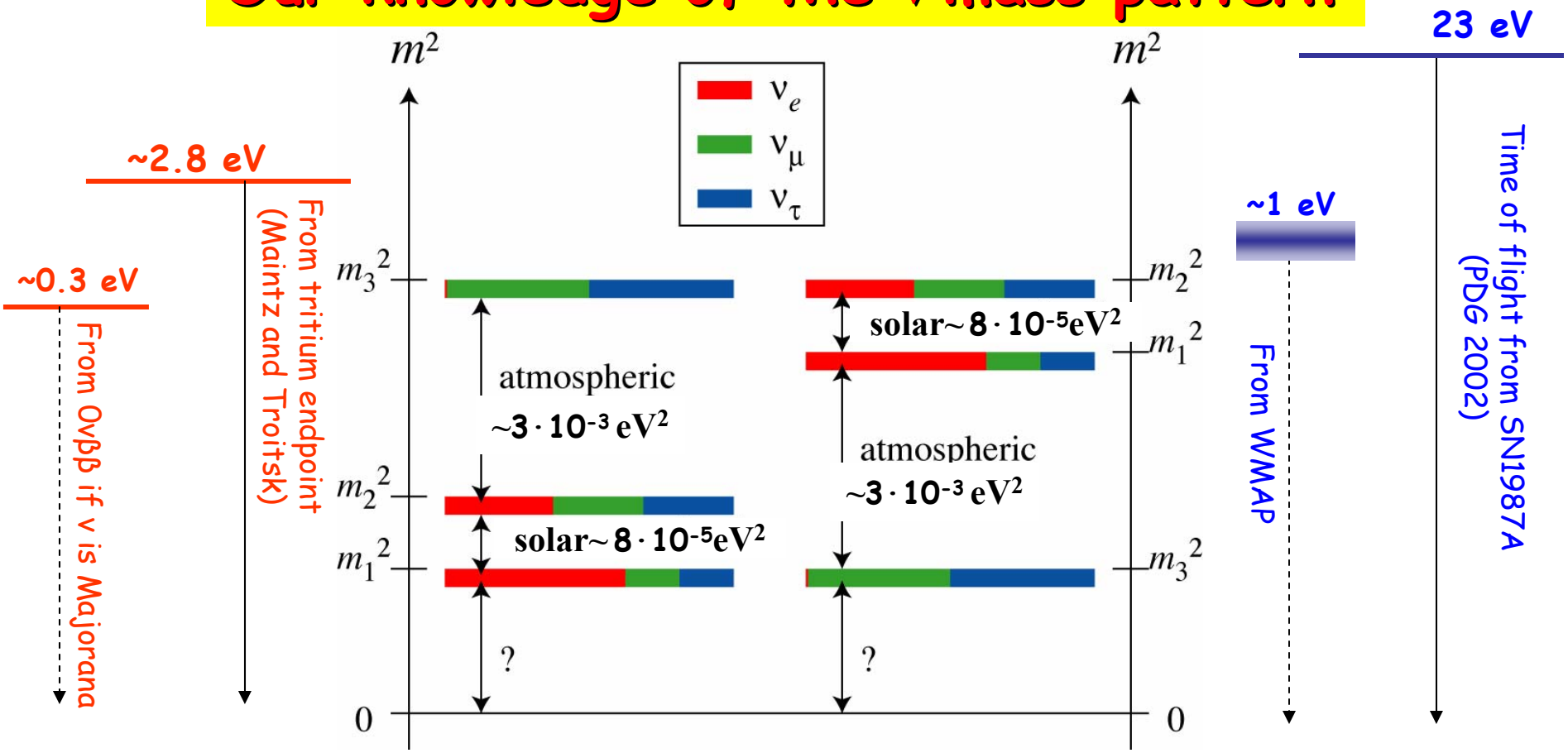
The future of double-beta decay experiments



ICFA Seminar
SLAC, 28 Oct 2008

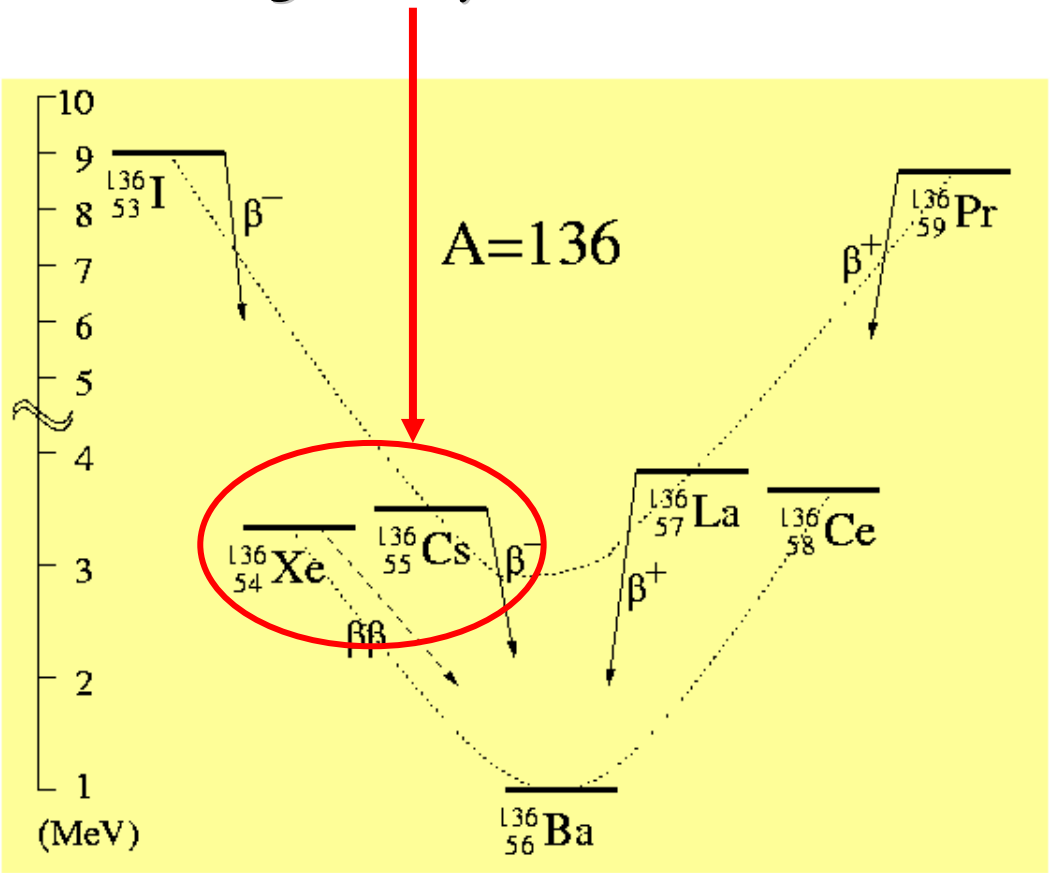
Our knowledge of the ν mass pattern



The measurement of the absolute mass scale, θ_{13} and the choice of hierarchy are the next big challenges in neutrino physics

Double-beta decay:

a second-order process only detectable if first order beta decay is energetically forbidden



Candidate nuclei with Q>2 MeV

Candidate	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

There are two varieties of ββ decay

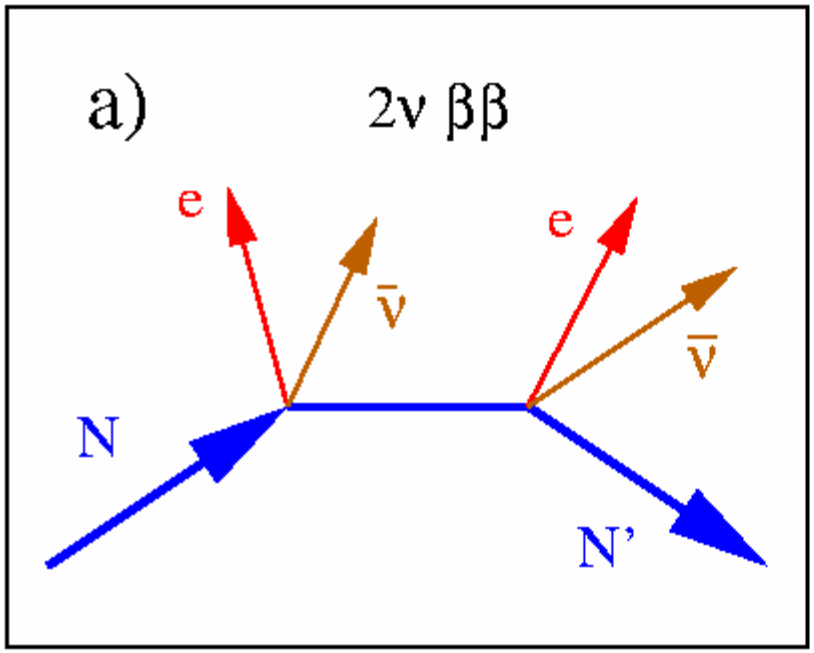
2ν mode:
a conventional
2nd order process
in nuclear physics

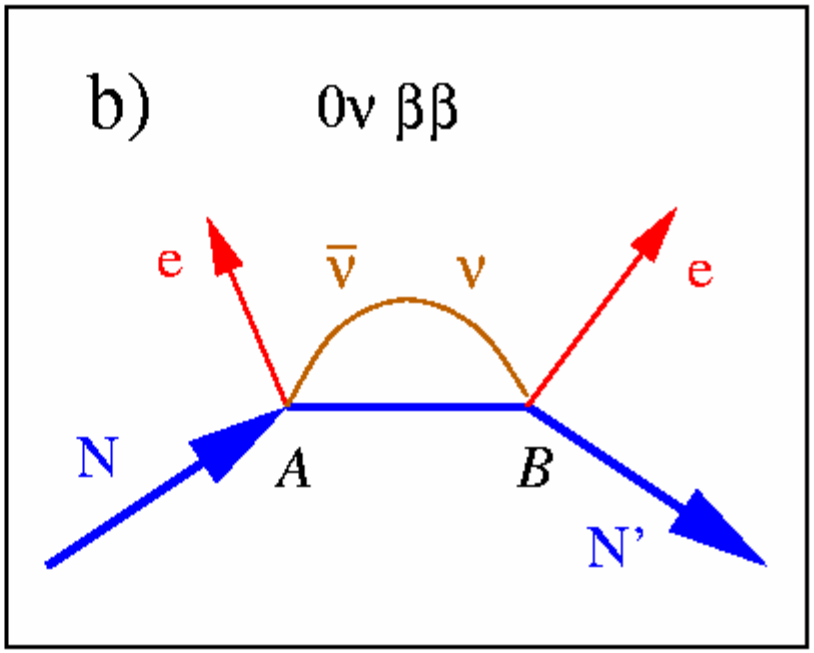
0ν mode: a hypothetical process can happen only if:

$M_\nu \neq 0$
$\nu = \bar{\nu}$

$|\Delta L| = 2$
$|\Delta(B-L)| = 2$

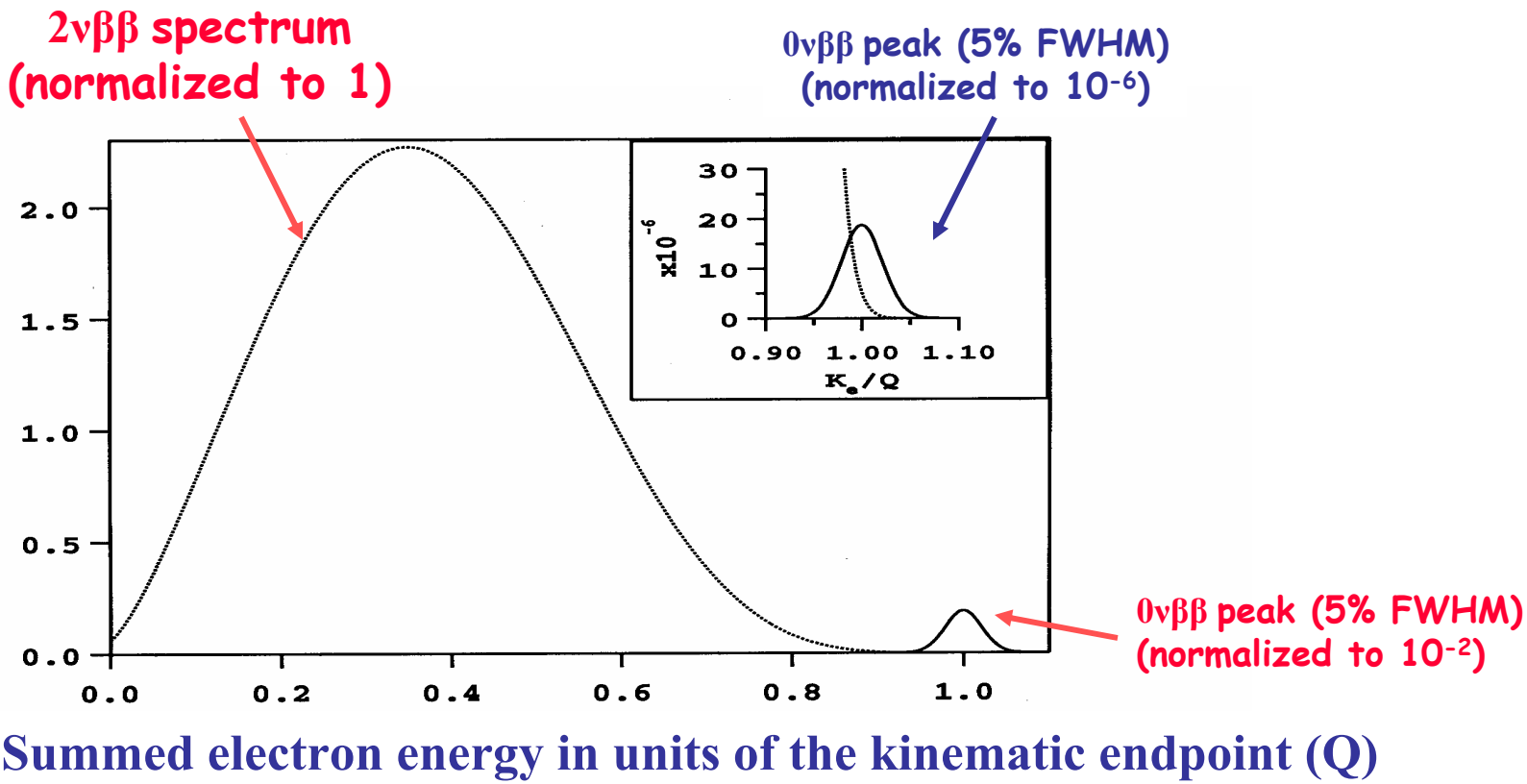
Since helicity has to "flip"





Background due to the Standard Model 2νββ decay

from S.R. Elliott and P. Vogel, Ann.Rev.Nucl.Part.Sci. **52** (2002) 115.



The two can be separated in a detector with good energy resolution

If $0\nu\beta\beta$ is due to light ν Majorana masses

$$\left\langle m_{\beta\beta} \right\rangle^2 = \left(T_{1/2}^{0\nu\beta\beta}\, G^{0\nu\beta\beta}\left(Q_{\beta\beta}, Z\right) \left| M_{GT}^{0\nu\beta\beta} - \frac{g_V^2}{g_A^2} M_F^{0\nu\beta\beta} \right|^2 \right)^{-1}$$

$M_F^{0\nu\beta\beta}$ and $M_{GT}^{0\nu\beta\beta}$ can be calculated within particular nuclear models

$G^{0\nu\beta\beta}$ a known phasespace factor

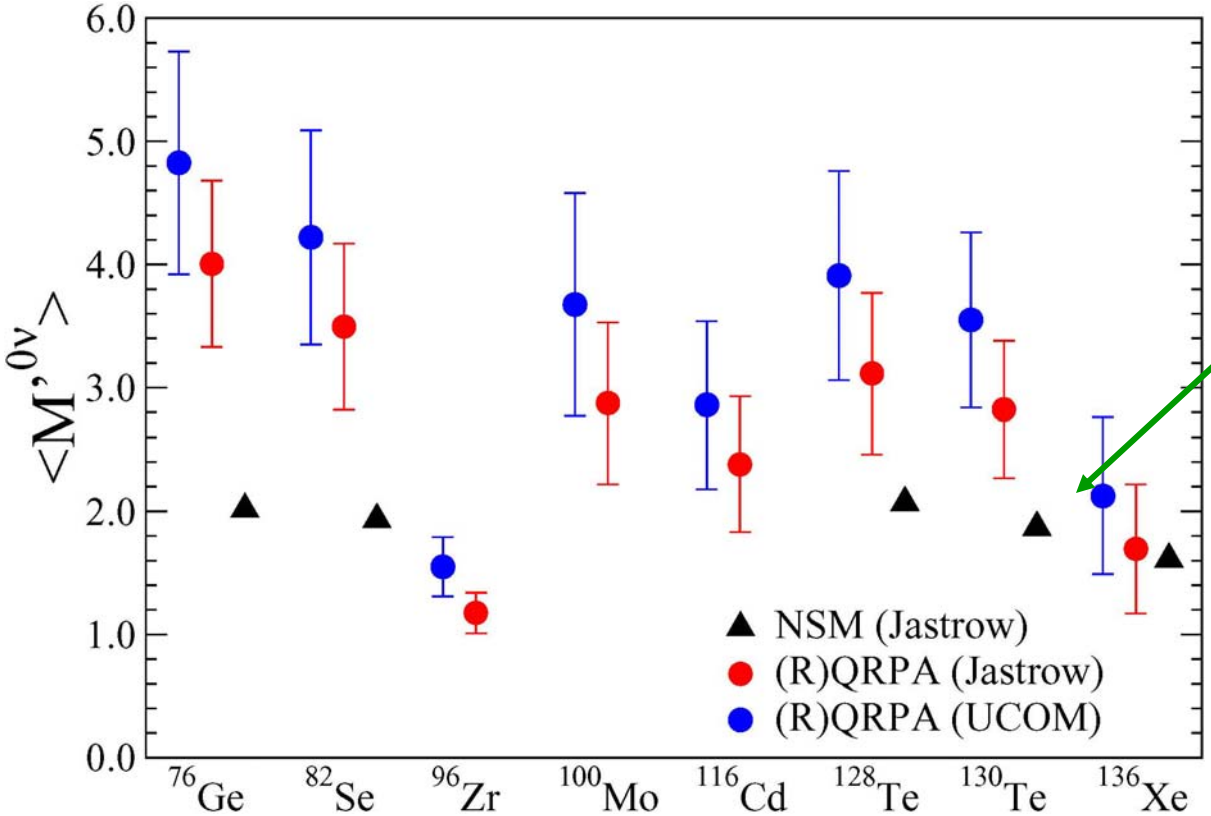
$T_{1/2}^{0\nu\beta\beta}$ is the quantity to be measured

$$\left\langle m_{\beta\beta} \right\rangle = \sum_{k=1}^{3} \left| U_{e,k} \right|^2 m_k \; e^{i\alpha_k}$$

effective Majorana ν mass

($e^{i\alpha_k} = \pm 1$ if CP is conserved)

Much progress made recently in accuracy of nuclear matrix elements.
(e.g. was found that main uncertainly in (R)QRPA calculations comes from the single particle space around the Fermi surface.
→ Can *use the measured 2νββ $T_{1/2}$ to make a correction.*)



Lower bound on $T_{1/2}$ used for ^{136}Xe

F.Simkovic et al.
Phys.Rev.C77:045503,2008

Still, if/once 0νββ decay is discovered, the $T_{1/2}$ in more than one nucleus will be needed to pin down neutrino masses

Present Limits for 0ν double beta decay

Candidate nucleus	Detector type	(kg yr)	Present $T_{1/2}^{0\nu\beta\beta}$ (yr)	<m> (eV)
^{48}Ca			$>1.4*10^{22}$ (90%CL)	
^{76}Ge	Ge diode	~47.7	$>1.9*10^{25}$ (90%CL)	<0.35*
^{82}Se			$>2.1*10^{23}$ (90%CL)	
^{100}Mo	foil/tracking	~13	$>5.8*10^{23}$ (90%CL)	<0.6-2.7
^{116}Cd			$>1.7*10^{23}$ (90%CL)	
^{128}Te			$>7.7*10^{24}$ (90%CL)	
^{130}Te	TeO_2 cryo	~12	$>3.0*10^{24}$ (90%CL)	<0.41 – 0.98
^{136}Xe	Xe scint	~4.5	$>1.2*10^{24}$ (90%CL)	<0.8 – 5.6
^{150}Nd			$>3.6*10^{21}$ (90%CL)	
^{160}Gd			$>1.3*10^{21}$ (90%CL)	

** But also claim of signal by part of same group*

Adapted from Avignone, Elliott, Engel; Rev Mod Phys 80 (2008) 481

There is also a discovery claim (using ^{76}Ge)

EVIDENCE FOR NEUTRINOLESS DOUBLE BETA DECAY

H.V. KLAPDOR-KLEINGROTHAUS[1,3],
A. DIETZ[1], H.L. HARNEY[1], I.V. KRIVOSHEINA[1,2]
[1] *Max-Planck-Institut für Kernphysik, Postfach 10 39 80, D-69029 Heidelberg, Germany*
[2] *Radiophysical-Research Institute, Nishnii-Novgorod, Russia*
[3] *Spokesman of the GENIUS and HEIDELBERG-MOSCOW Collaborations,*

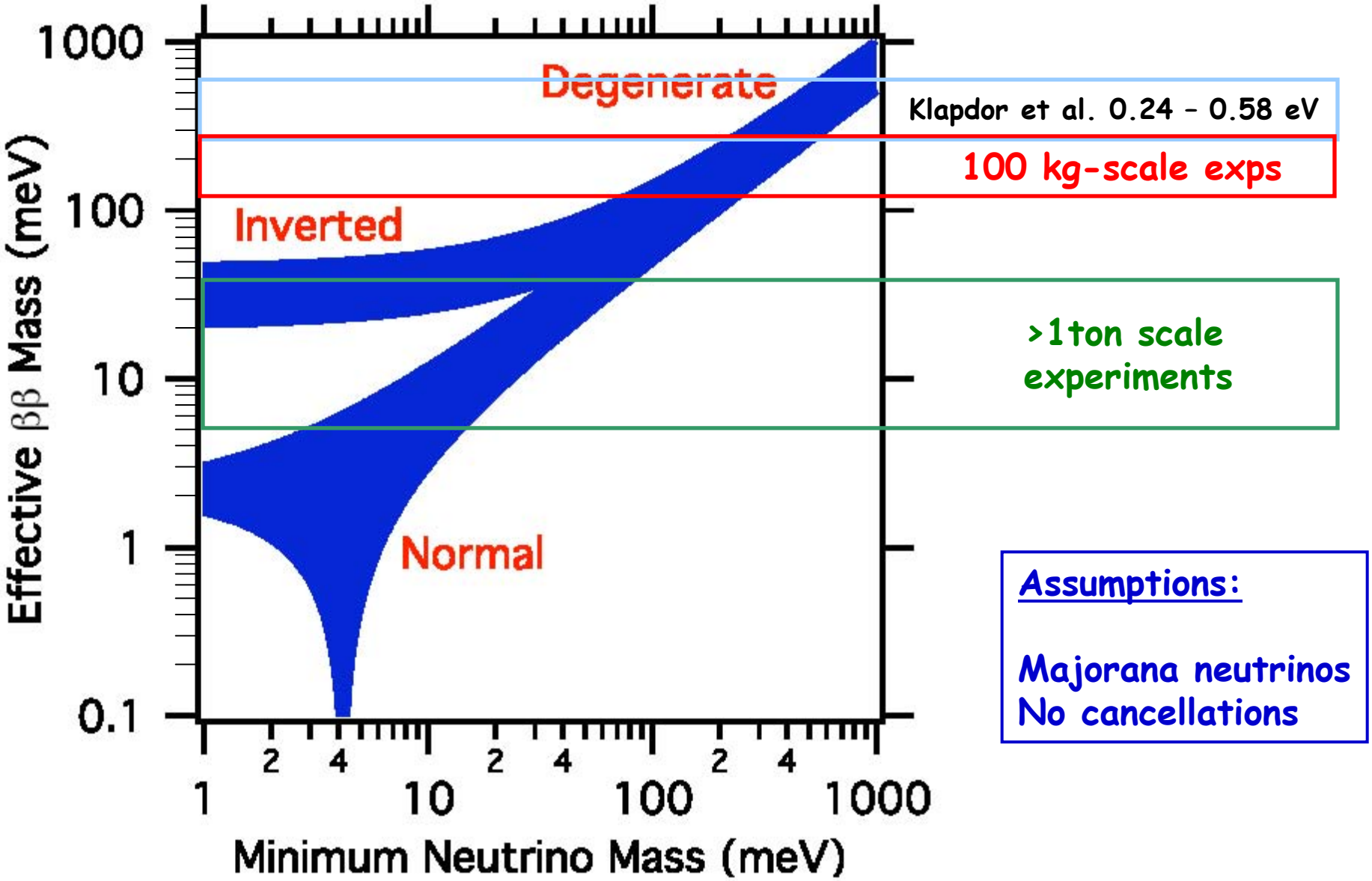
Part of the Heidelberg-Moscow collaboration
Mod. Phys Lett. A27 (2001) 2409

With the values $T_{1/2}^{0\nu\beta\beta} = 2.23^{+0.44}_{-0.31}$ $m_\nu^{eff}=0.32\pm0.03$

…but this is a controversial matter (see details in)

C.A.Aalseth Mod. Phys. Lett. A17 (2002) 1475
F.Feruglio et al. Nucl.Phys. B637 (2002) 345
Addendum-ibid. B659 (2003) 359
Yu.Zdesenko et al. Phys.Lett. B 546 (2002) 206
H.L.Harney Mod.Phys.Lett. A16 (2001) 2409
A.M.Bakalyarov et al. hep-ex/0309016
H.V.Klapdor-Kleingrouthaus et al. Phys. Lett. B 586 (2004) 198
H.V.Klapdor-Kleingrouthaus et al. Mod. Phys. Lett. 21 (2006) 1547

For the first time there is a clear opportunity to make an important discovery if one pushes the <m> sensitivity to the 0.01 - 1 eV region



Assumptions:

Majorana neutrinos
No cancellations

Plot from Avignone, Elliott, Engel; Rev Mod Phys 80 (2008) 481

In the last 10 years there has been a transition

1) From a few kg detectors to 100s or 1000s kg detectors
→ Think big: qualitative transition from cottage industry to large experiments

2) From "random shooting" to the knowledge that at least the inverted hierarchy will be tested

Discovering 0νββ decay:

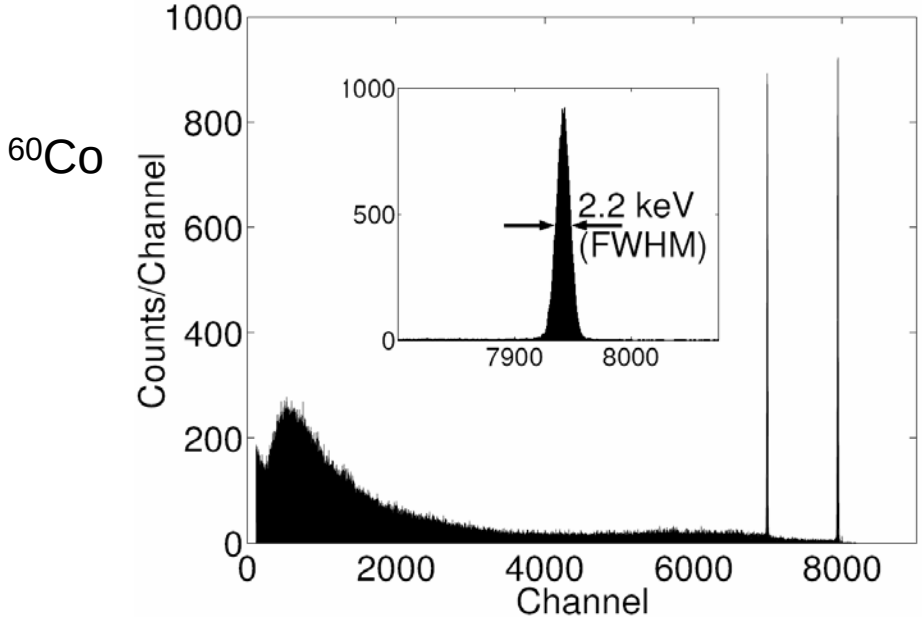
→ *Discovery of the neutrino mass scale*
→ *Discovery of Majorana particles*
→ *Discovery of lepton number violation*

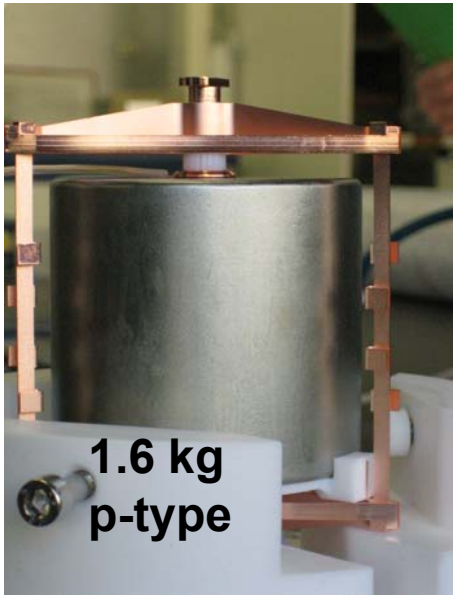
Future projects# (a broad brush, personal view)

Isotope	Experiment	Main principle	Fid mass	Lab
^{76}Ge	Majorana†	Eres,2site tag, Cu shield	30+30kg	SUSEL
	Gerda†	Eres,2site tag, LAr shield	18→40 kg	G Sasso
	MaGe/GeMa	See above	~1ton	DUSEL? G Sasso?
^{150}Nd	SNO+	Size/shielding	56 kg	SNOlab
^{150}Nd or ^{82}Se	SuperNEMO‡	Tracking	100-200 kg	Canfranc Frejus
^{130}Te*	CUORE	E Res.	204 kg	G Sasso
^{136}Xe	EXO	Tracking	150 kg	WIPP
		Ba tag, Tracking	1-10ton	DUSEL?

Many other ideas for the future are omitted in the interest of time
* No isotopic enrichment in baseline design
† Plan to merge efforts for ton-scale experiment
‡ Non-homogeneous detector

Bare Ge crystals in LAr



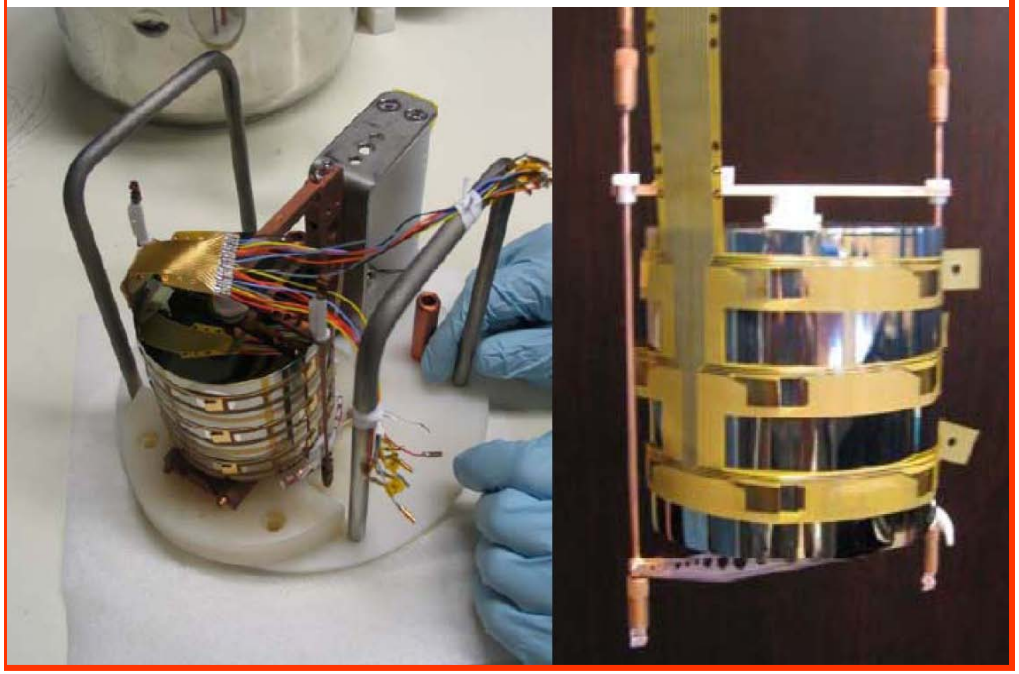


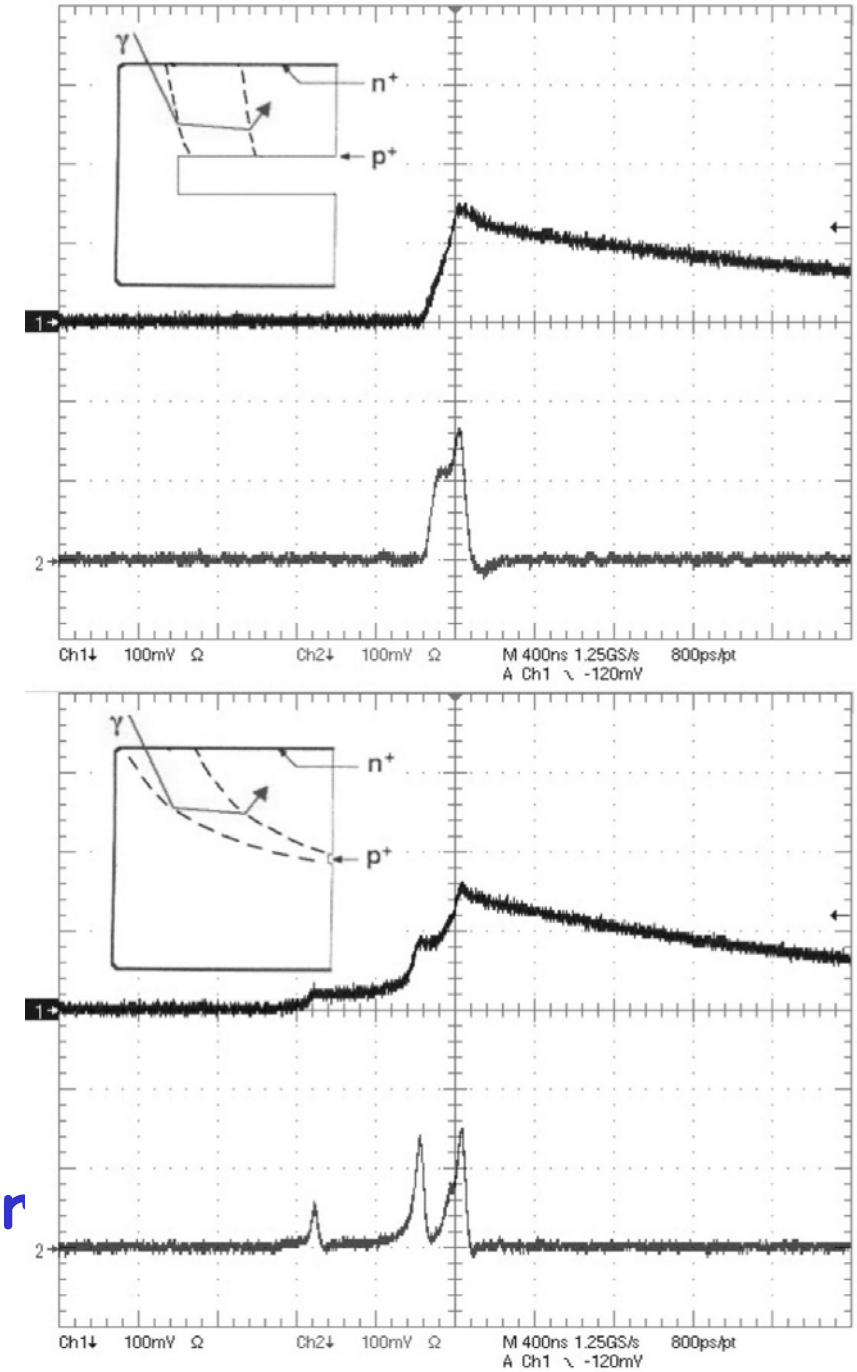
More than 1 year of operation at low leakage current in LAr with prototype detector detector; parameters are not deteriorated

(this contradicts an earlier claim of stability problems [Klapdor-Kleingrothaus & Krivosheina NIM A 566 (2006) 472])

Shielding requirements make these detectors large…

R&D for Phase II (40kg) well advanced

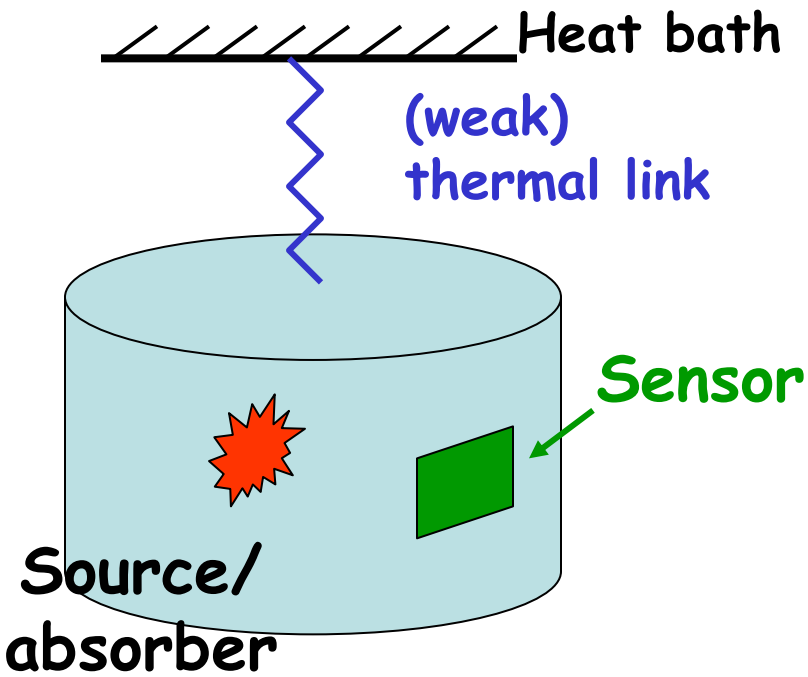




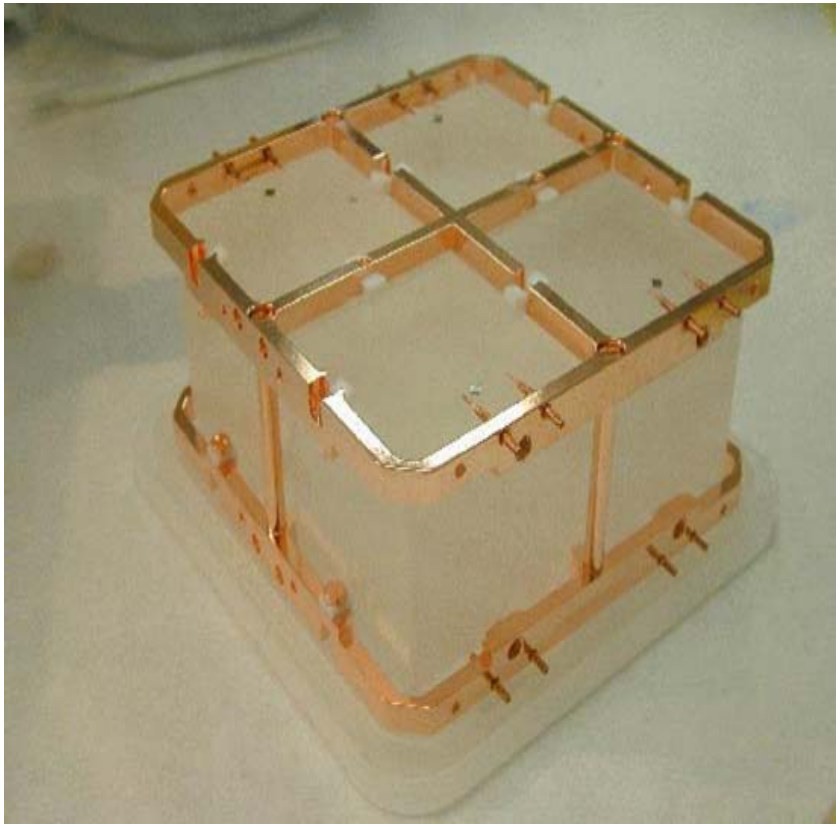
In addition new development (Majorana group) with point contact detectors: crude "tracking" in a Ge detector

P.S. Barbeau et al. nucl-ex/0701012 Jan 2007

Calorimetric detectors



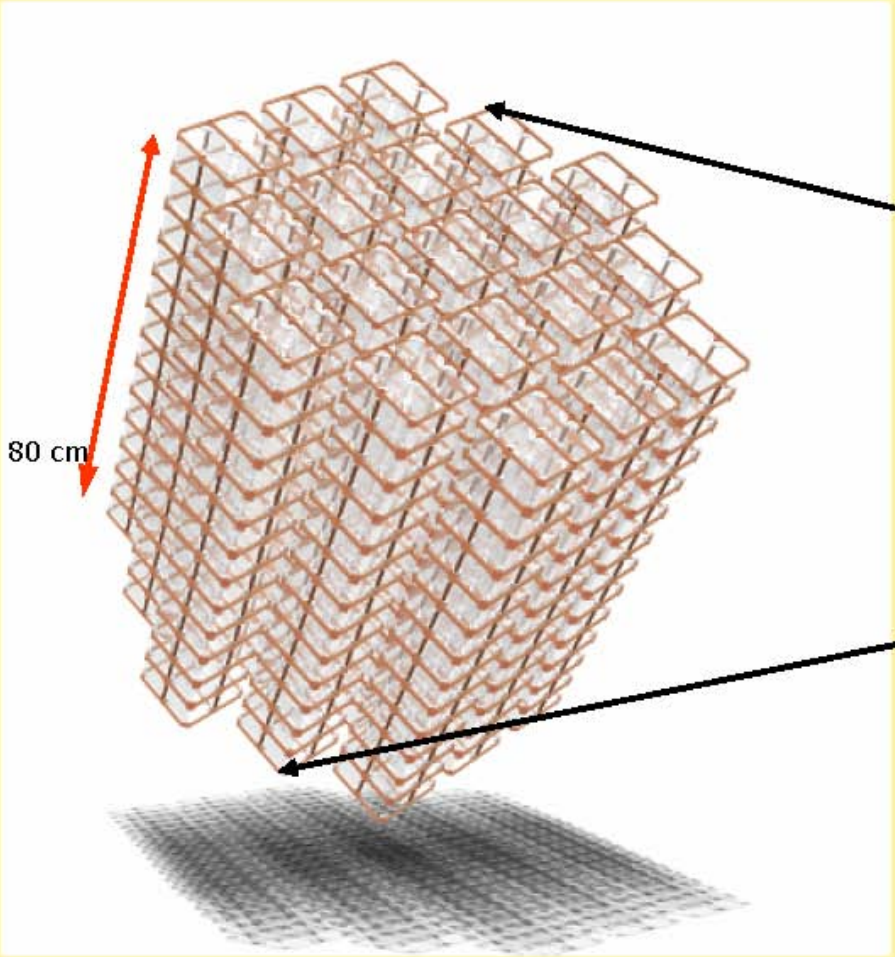
- ΔT = E/heat capacity
- Need mK temperatures to have small heat cap.
- Very generic technique: in principle can use for many materials

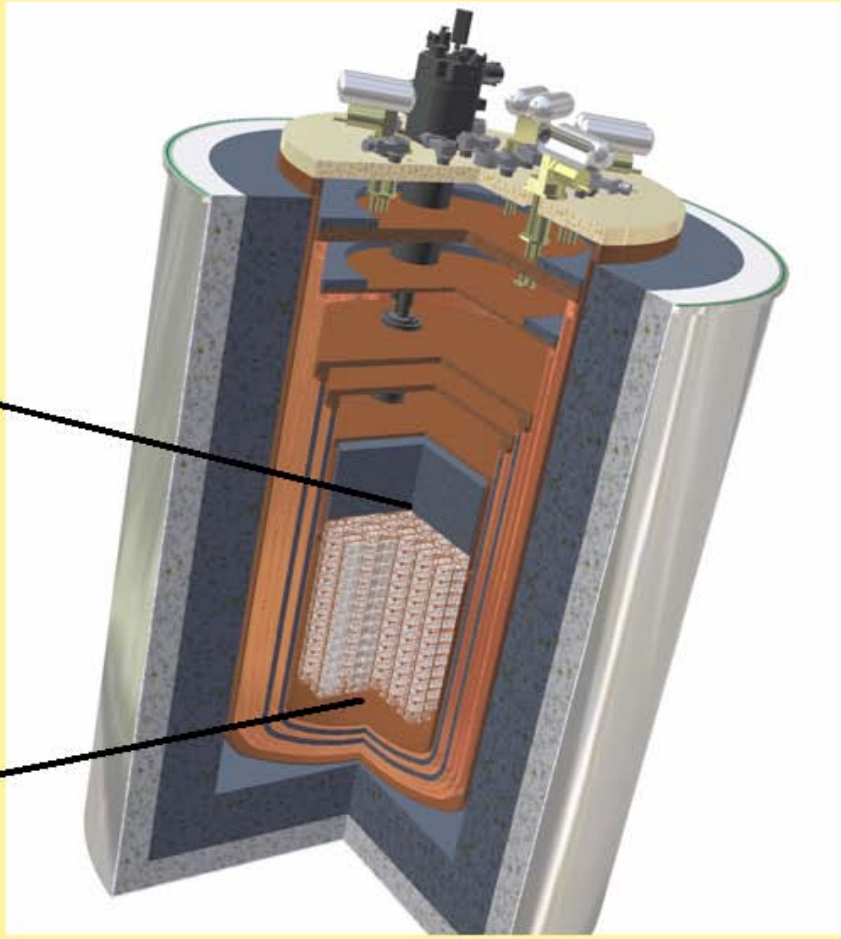


Cuoricino TeO_2 crystals ran at Gran Sasso in a dilution refrigerator at ~10 mK
(can use Te that is at ~30% the right isotope [^{130}Te])

NTD thermistor readout:
1 MeV = ΔT = 300 μV

CUORE will be a closely packed array of
988 detectors
741 kg of TeO_2
204 kg of ^{130}Te





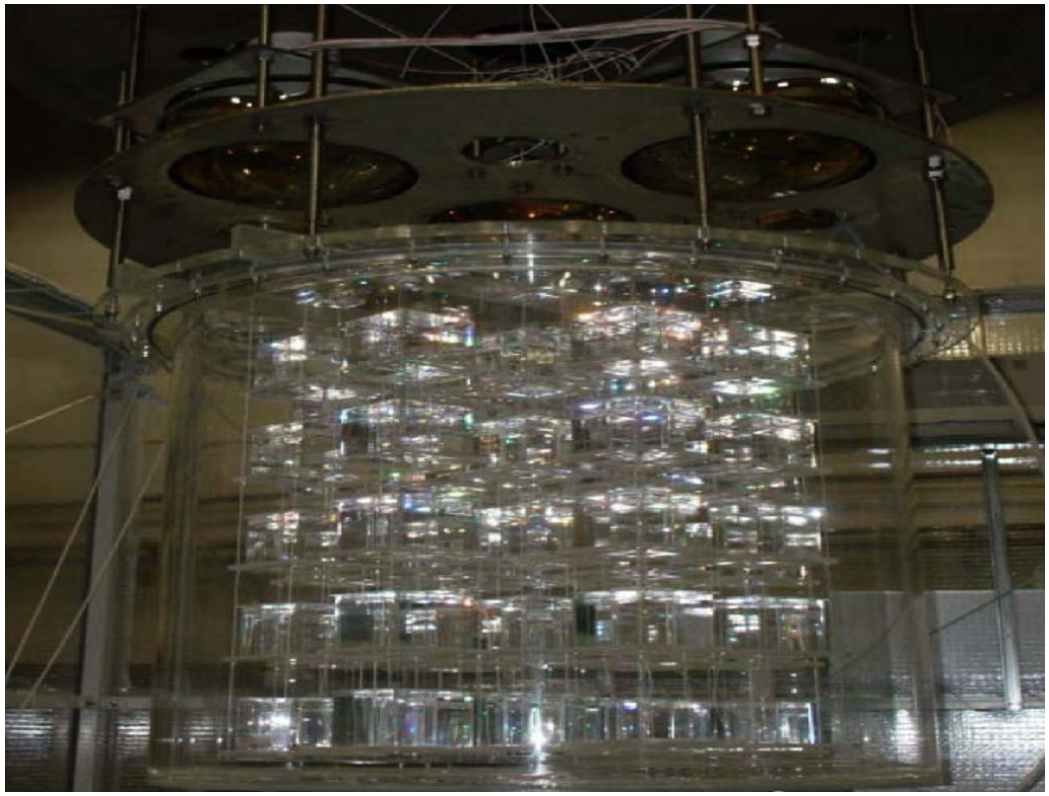
19 towers with
13 planes of
4 crystals each

C.Brofferio Neutrino 2008, Christchurch, NZ

Scintillators

Poor energy resolution/tracking compensated by

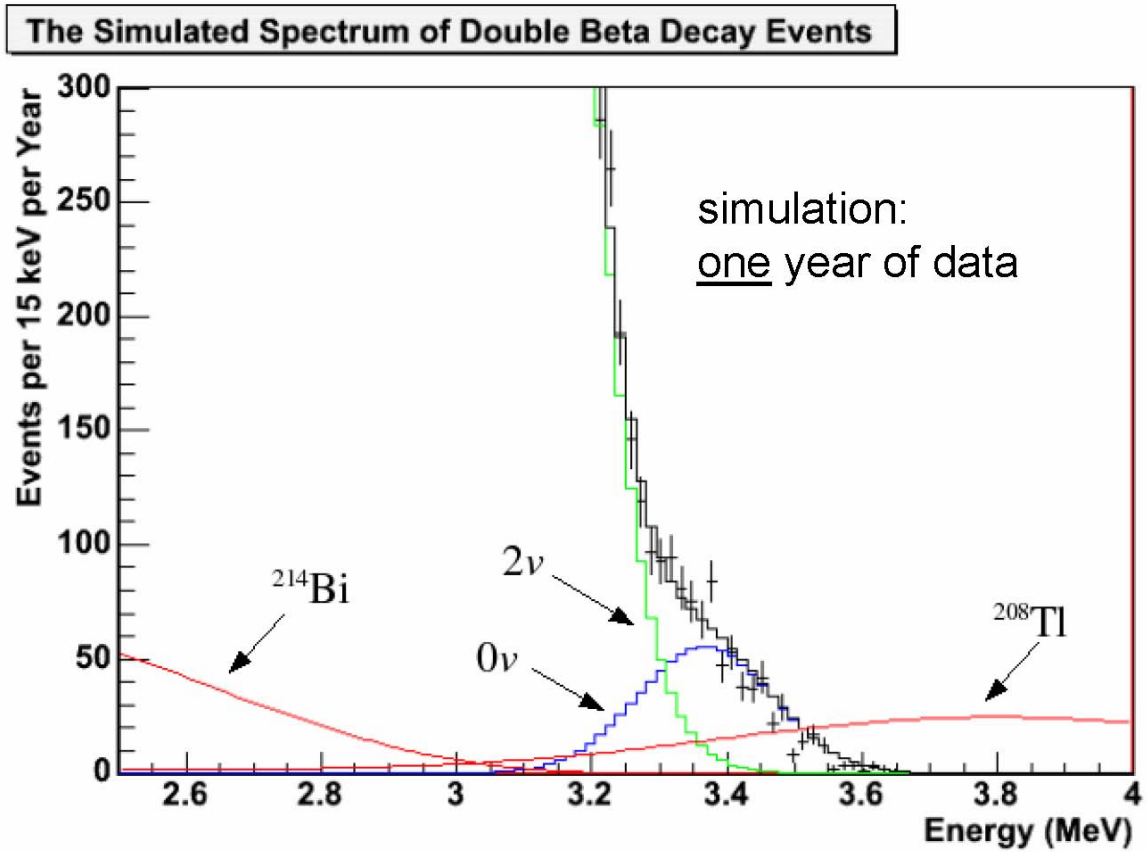
- Well known technology
- (relatively) simple detectors
- Little material near fiducial volume (if the source is part of the scintillator)
- Cheaper self-shielding



Candles
(CaF in liquid scintillator)

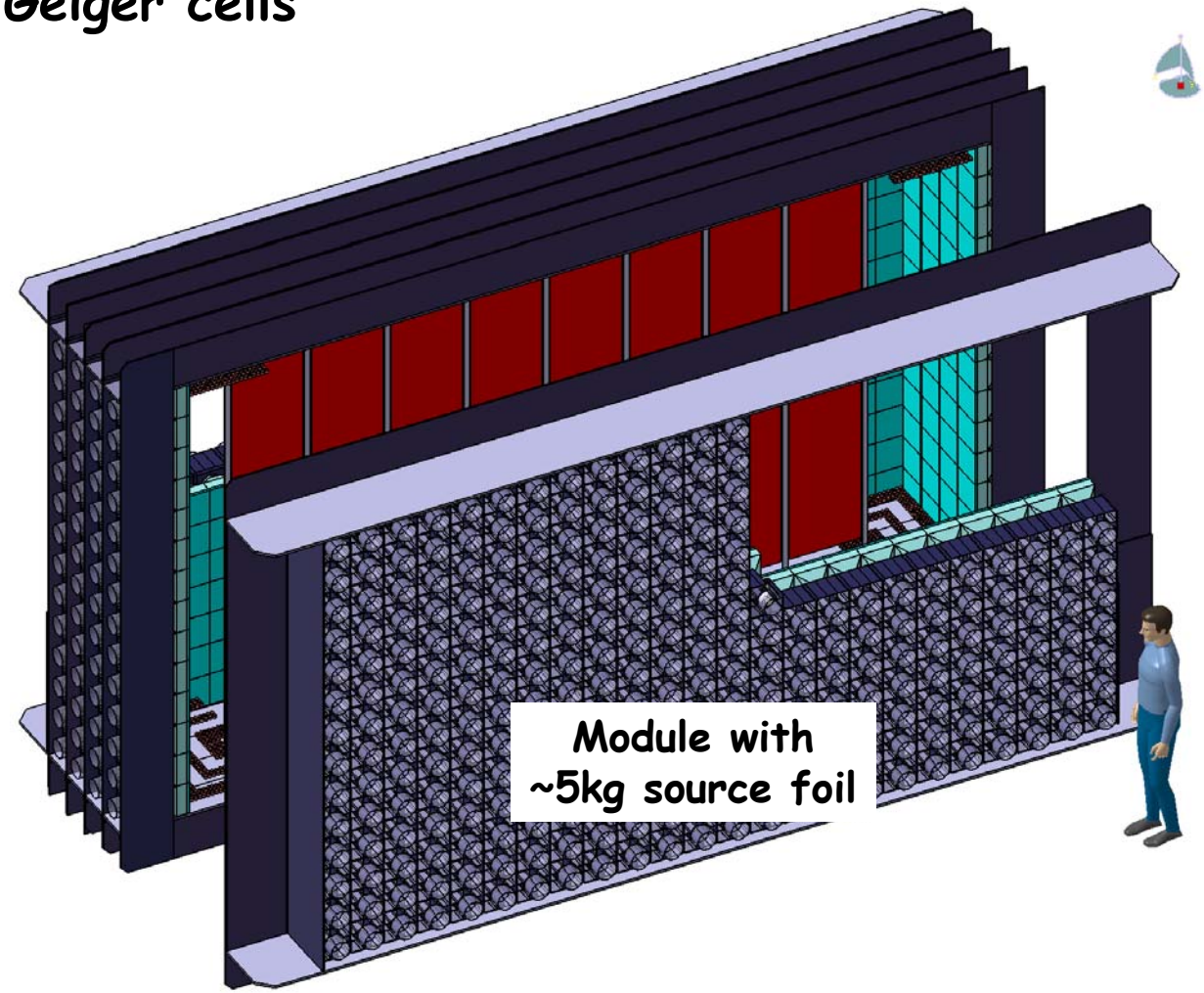
- 1000 tons liquid scintillator in the SNO cavern
- 0.1% ^{nat}Nd dissolved in the scintillator containing 56 kg of ^{150}Nd isotope
- ^{150}Nd has a high (3.37MeV) endpoint
- Much of the infrastructure recycled from SNO (need to reverse the acrylic sphere tethering system and acquire LAB-based scintillator compatible with the Nd compound)
- Possibility to enrich Nd at AVLIS facility (France)

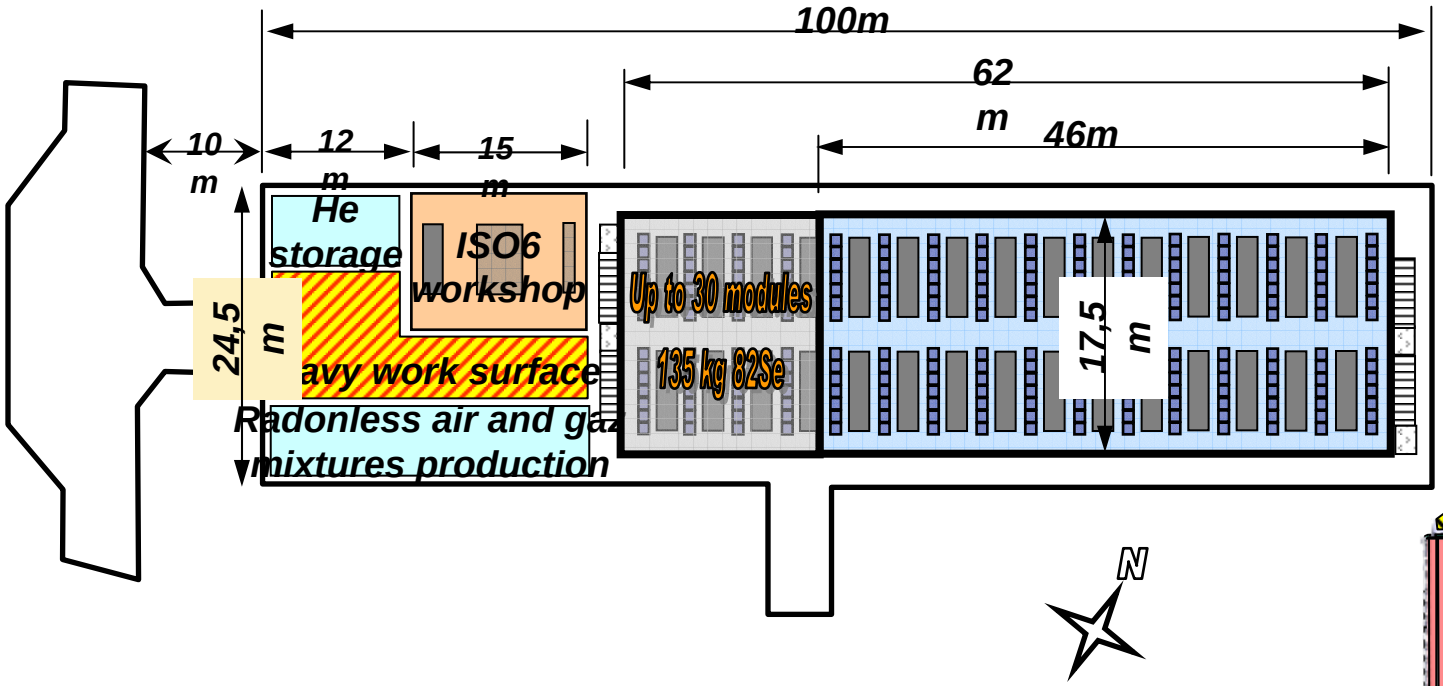
Background shape needs to be very well understood in order to extract meaningful results



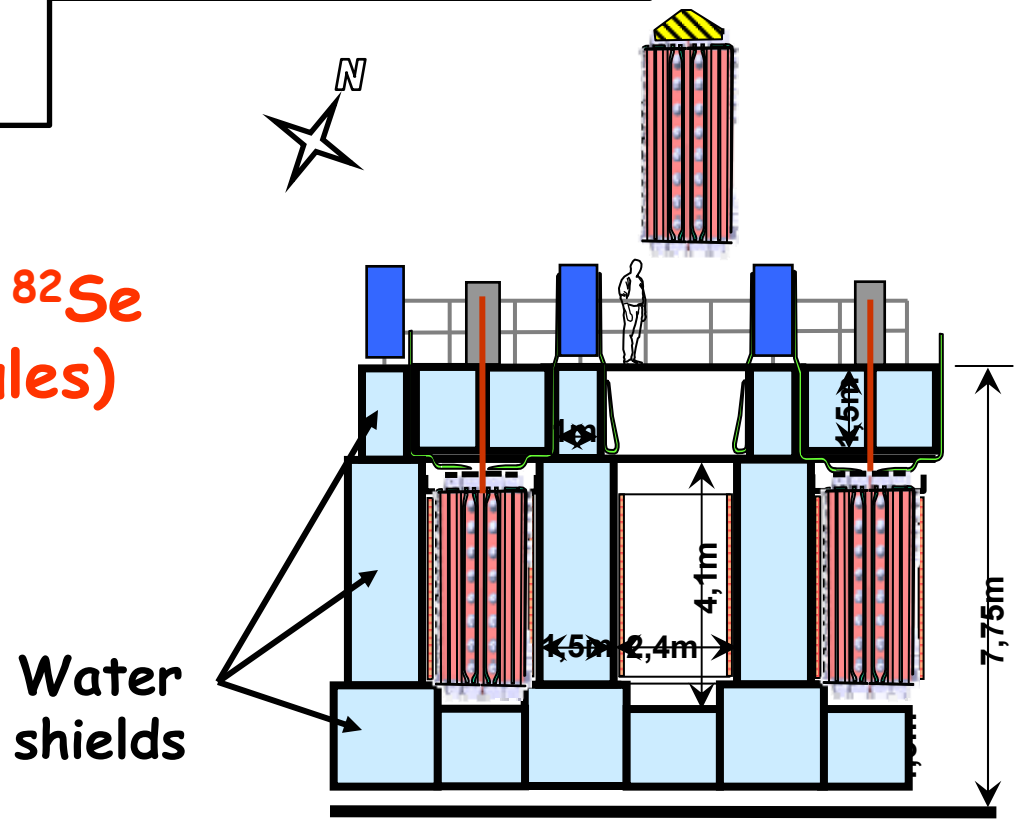
Tracking with very large fiducial masses is hard… SuperNEMO

- Planar geometry with 20 modules for 100kg source
- Source is 40mg/cm^2, 3x4m^2, ^{150}Nd or ^{82}Se
- Each module has 2000 Geiger cells and 600 PMT calorimetry channels for a total of ~40k Geiger channels and 12k PMTs
- Coils to provide 25 Gauss magnetic field in each module (PMTs have mumetal shields)





Full layout for a 100kg ^{82}Se SuperNEMO (22 modules)



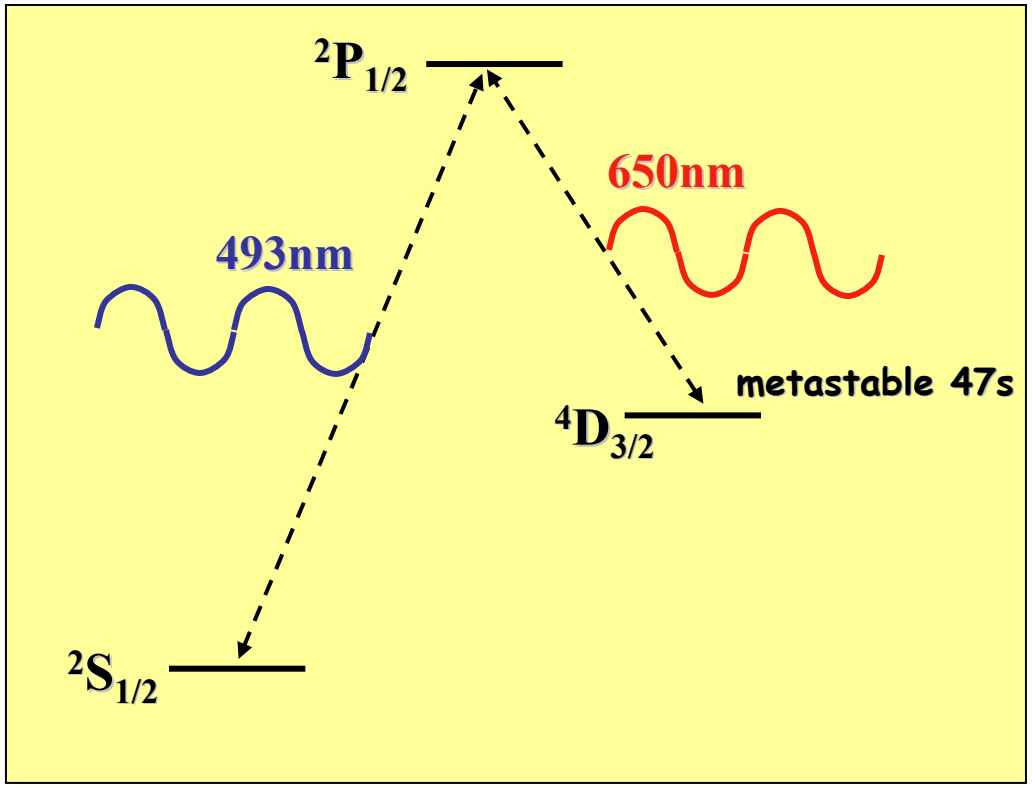
Xe is ideal for a large experiment

- No need to grow crystals
- Can be re-purified during the experiment
- No long lived Xe isotopes to activate
- Can be easily transferred from one detector to another if new technologies become available
- Noble gas: easy(er) to purify
- ^{136}Xe enrichment easier and safer:
  - noble gas (no chemistry involved)
  - centrifuge feed rate in gram/s, all mass useful
  - centrifuge efficiency ~ Δm. For Xe 4.7 amu
- ^{129}Xe is a hyperpolarizable nucleus, under study for NMR tomography… a joint enrichment program ?

Xe offers a qualitatively new tool against background: $^{136}Xe \rightarrow {}^{136}Ba^{++}\, e^-\, e^-$ final state can be identified using optical spectroscopy (M.Moe PRC44 (1991) 931)

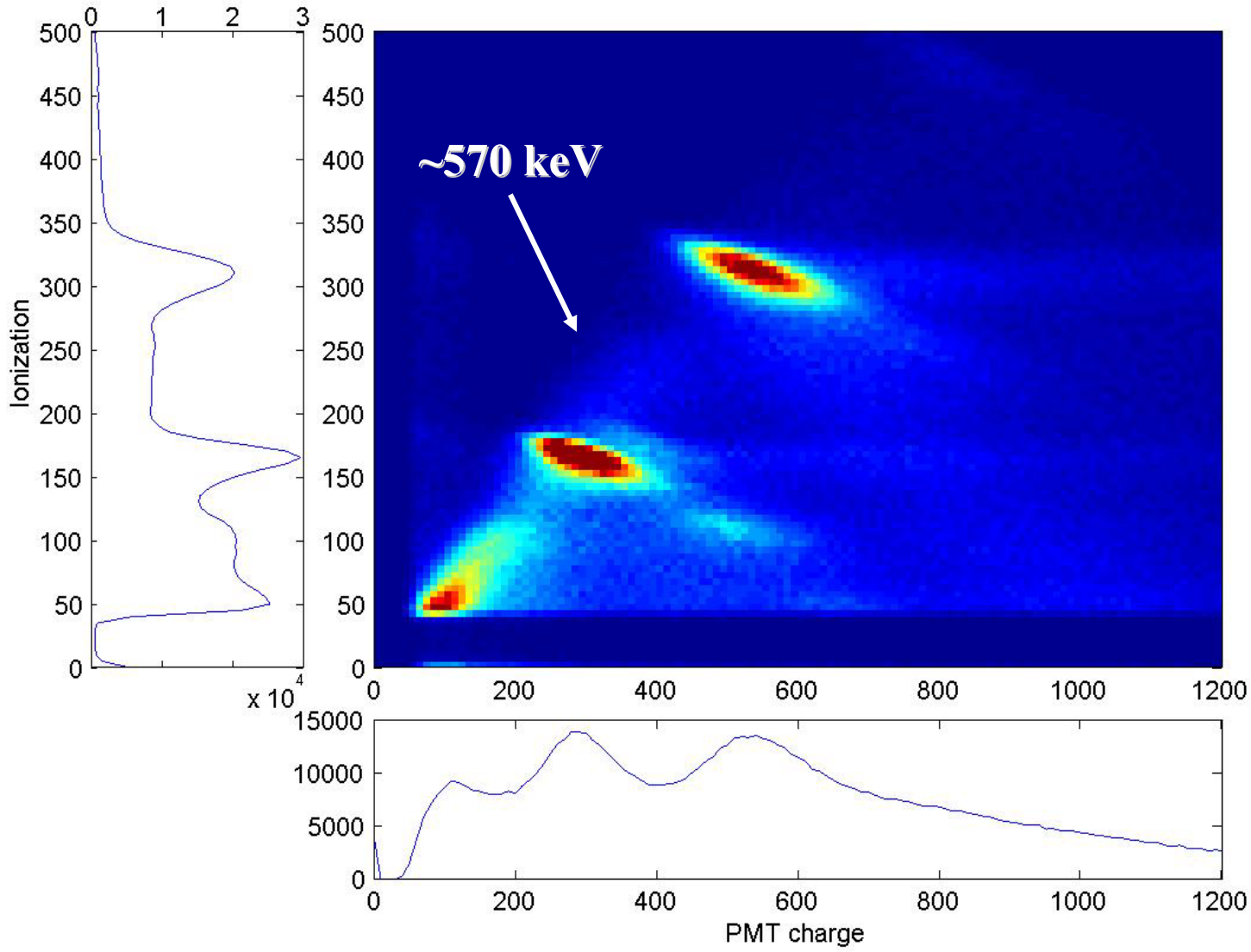
Ba^+ system best studied (Neuhauser, Hohenstatt, Toshek, Dehmelt 1980)
Very specific signature "shelving"
Single ions can be detected from a photon rate of 10^7/s

- Important additional constraint
- Drastic background reduction

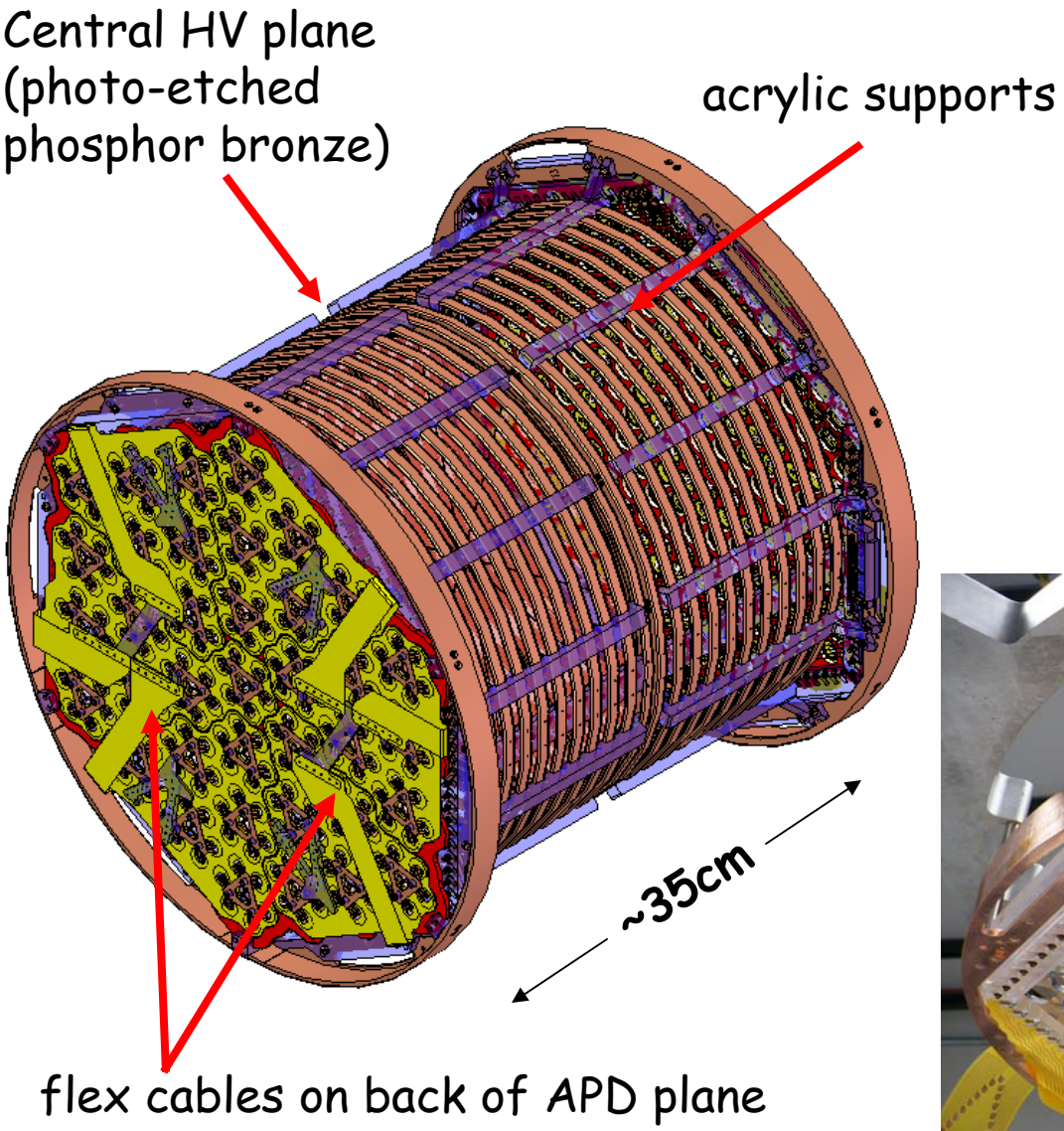


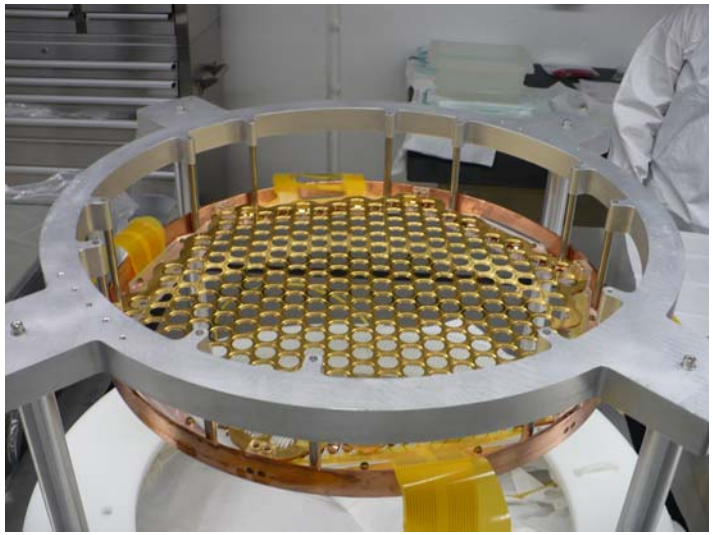
Improved energy resolution in LXe:

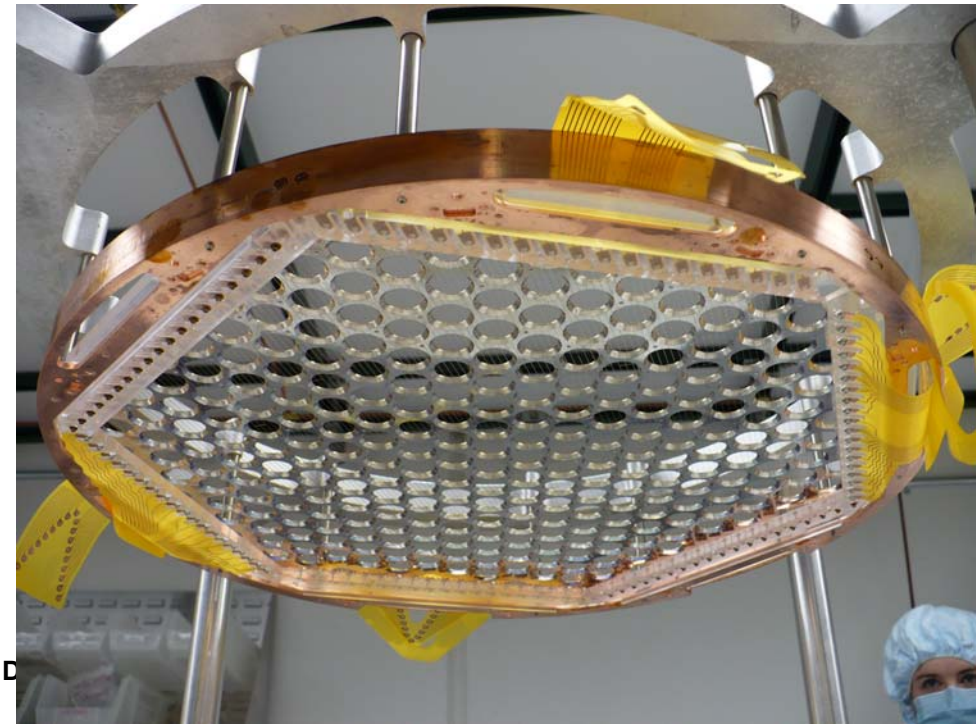
Use (anti)correlations between ionization and scintillation signals (now also used in DM detectors)

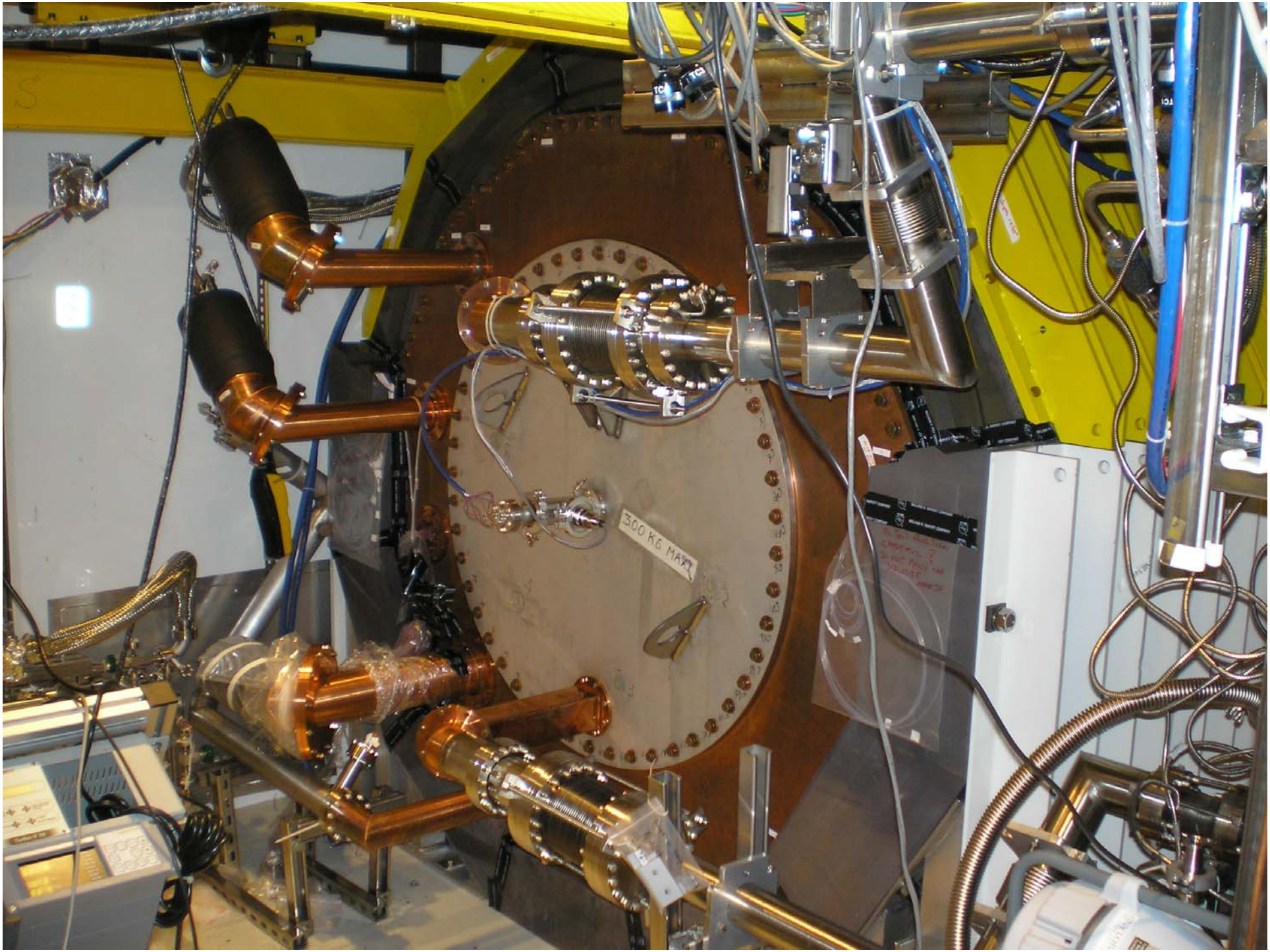


EXO-200 LXe TPC field cage & readout planes

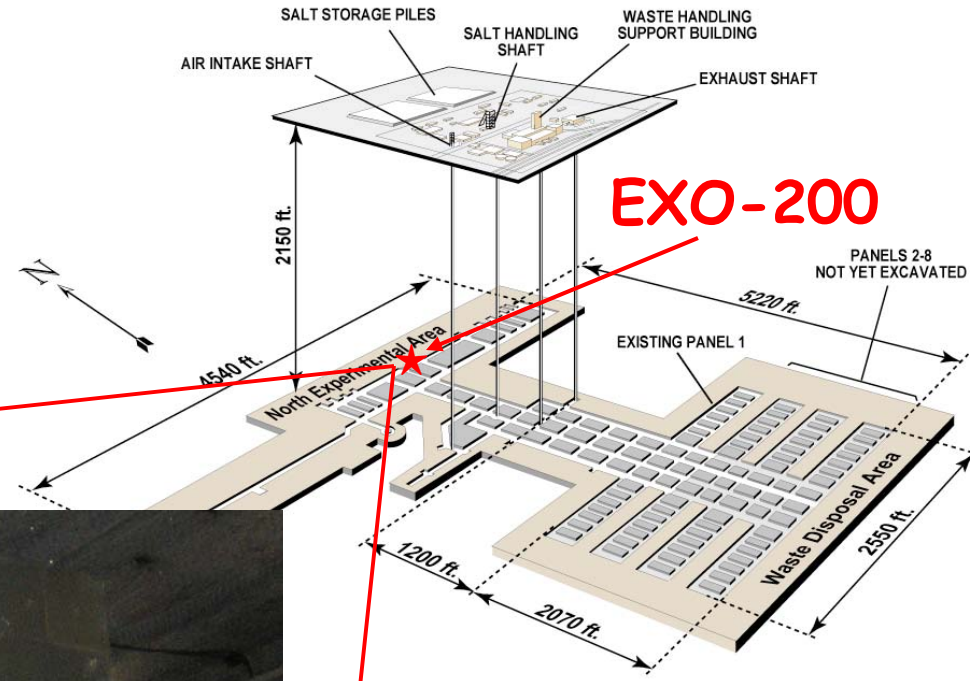




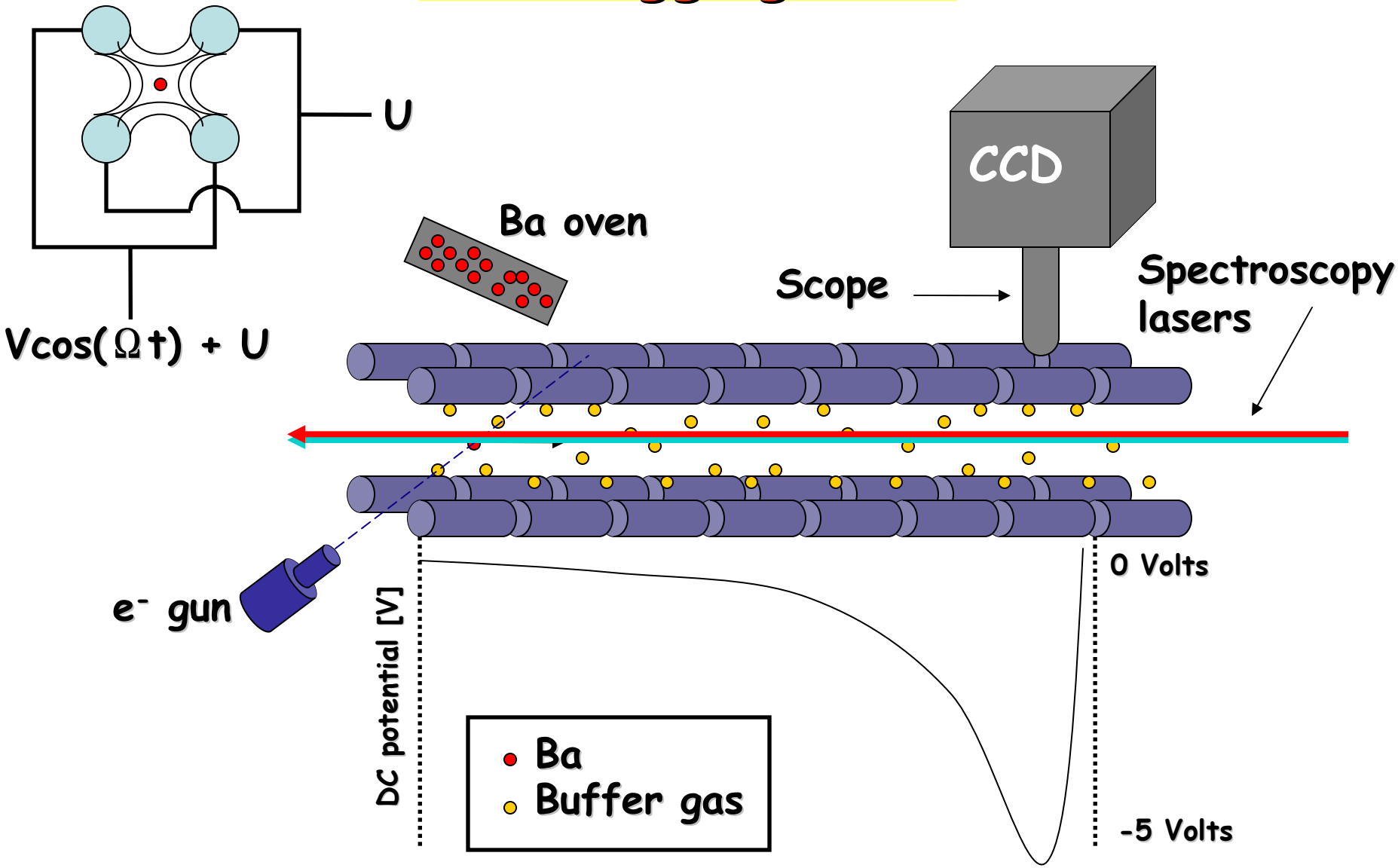



300 K6 MAX

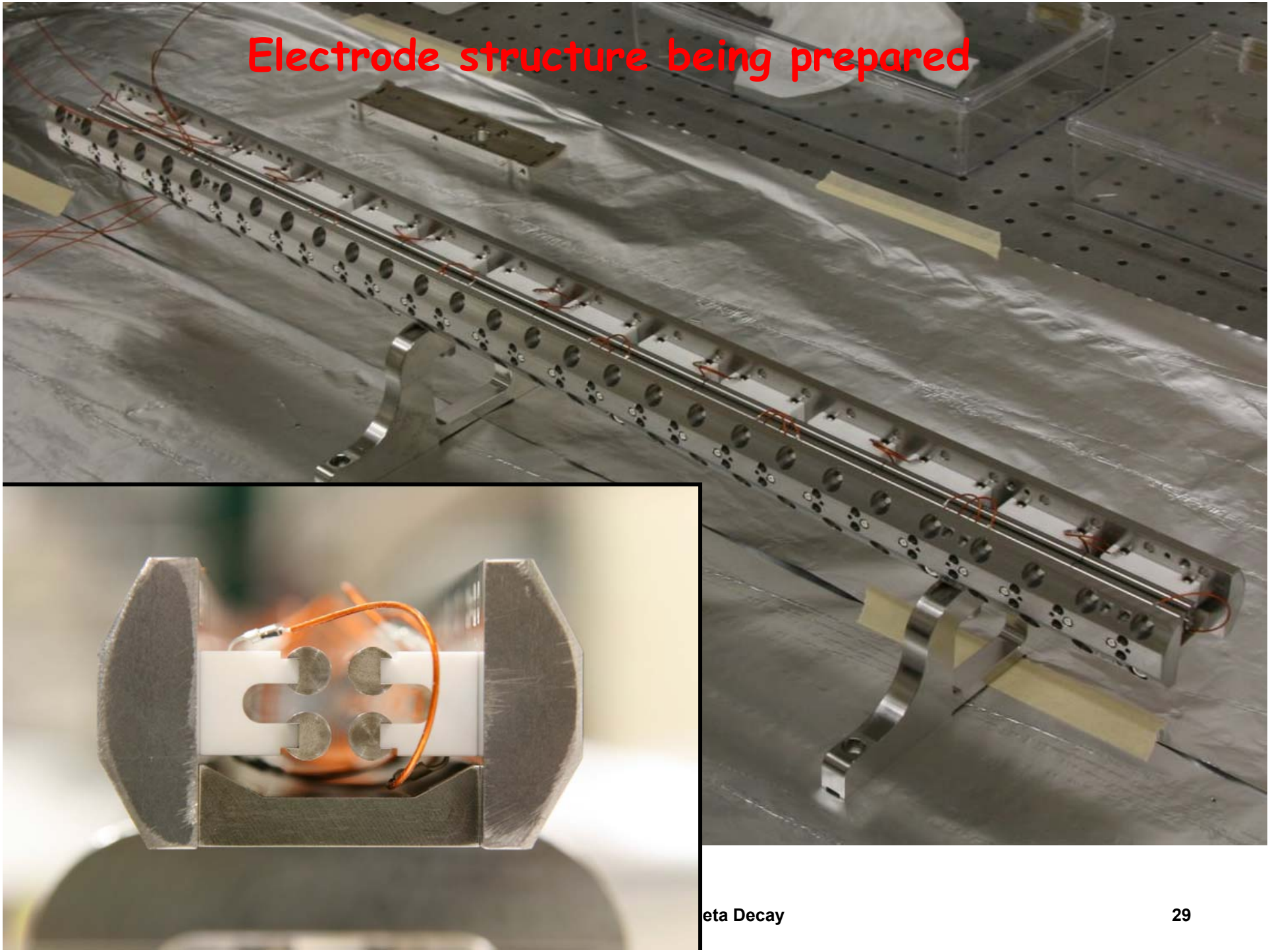
EXO-200 at WIPP



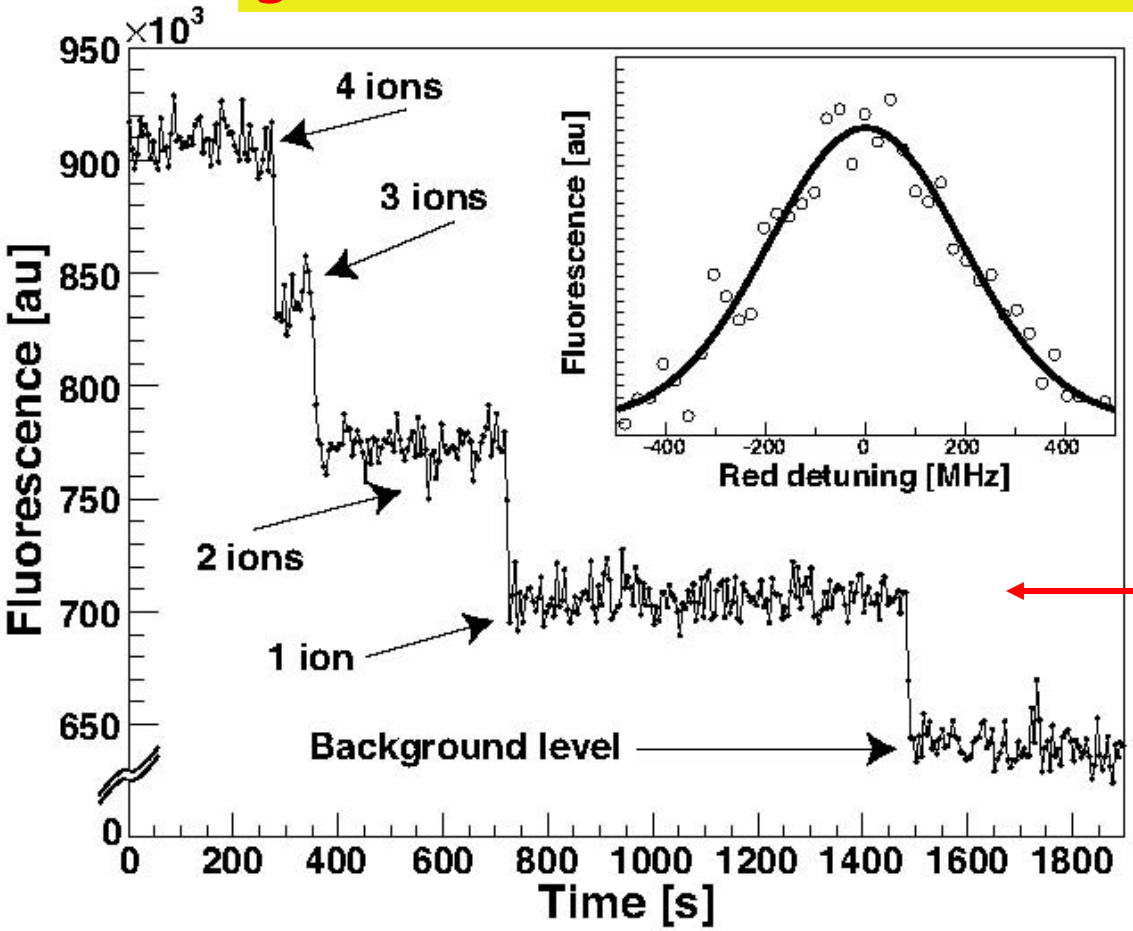
Ba^+ Tagging R&D



Electrode structure being prepared



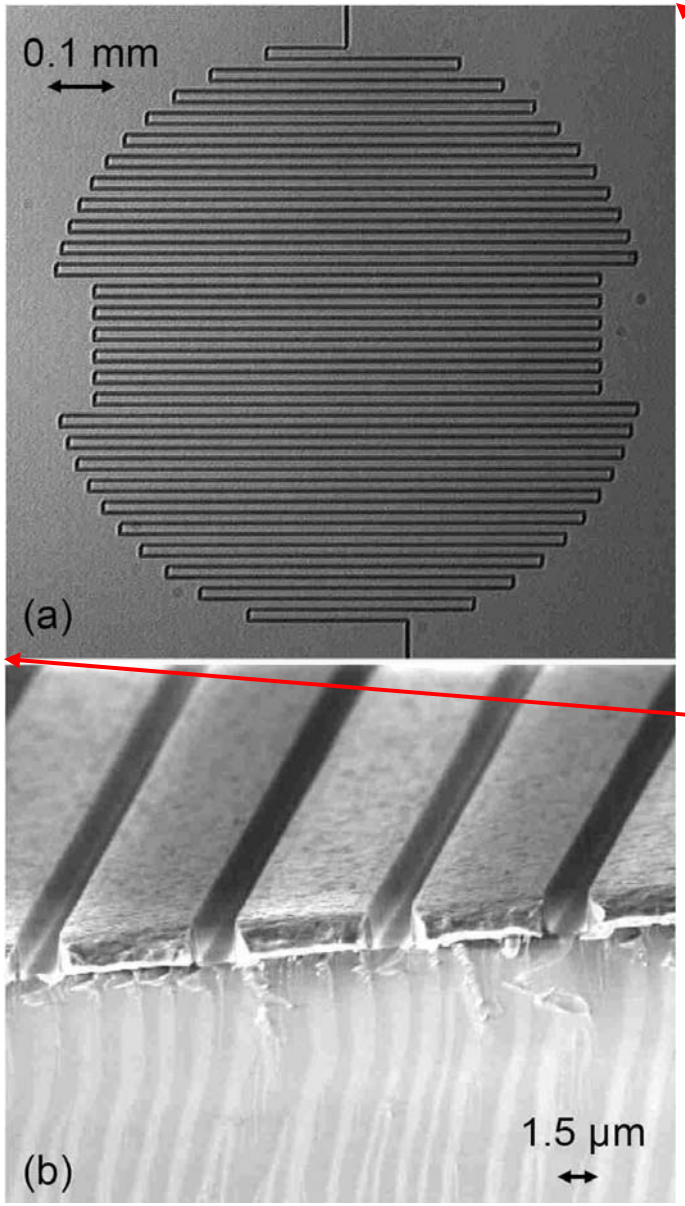
First single ion detection in high pressure gas (He, Ar)

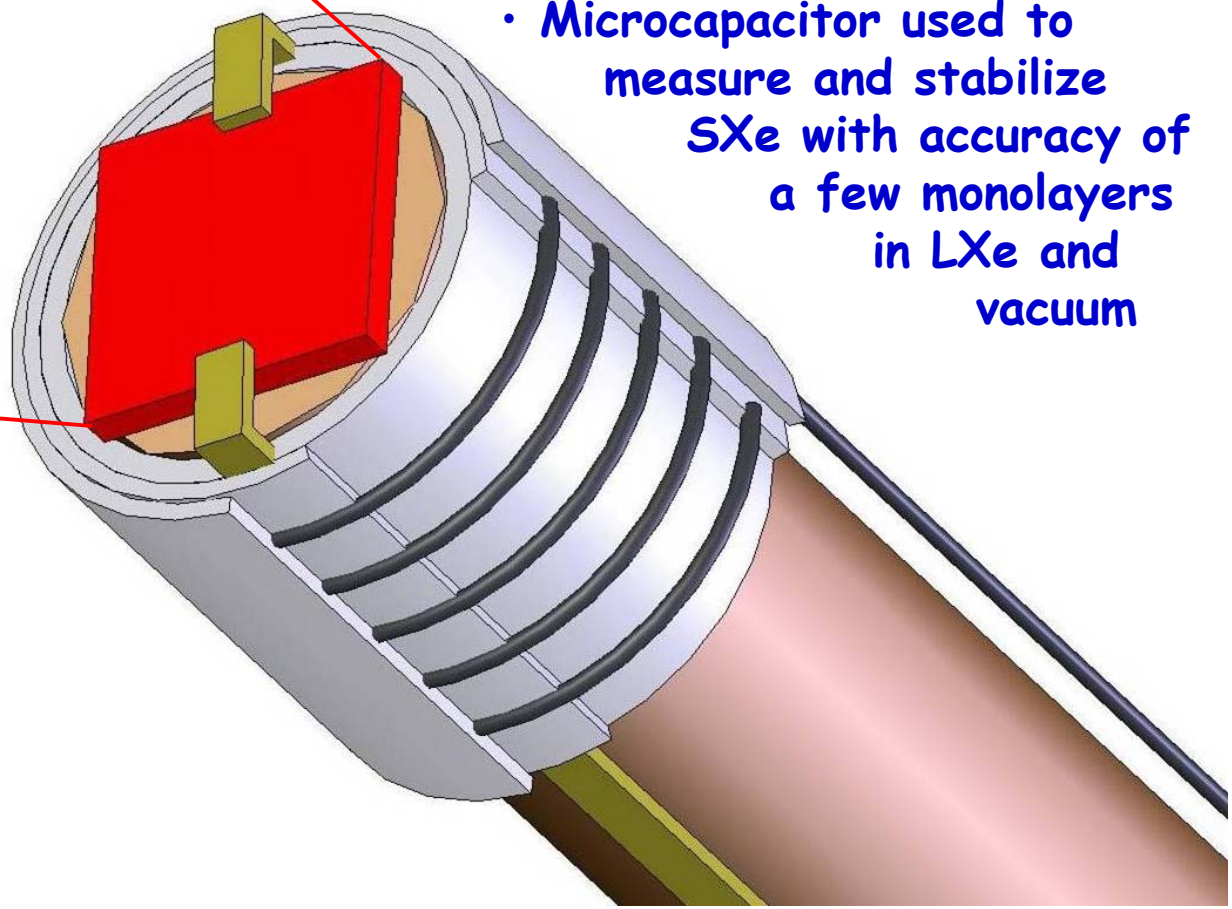


~9σ discimination in 25s integration

M.Green et al. arXiv:0702122, Phys Rev A 76 (2007) 023404
B.Flatt et al. arXiv:0704.1646, NIM A 578 (2007) 409

Remaining challenge is the efficient transfer of single Ba ions from LXe to the ion trap



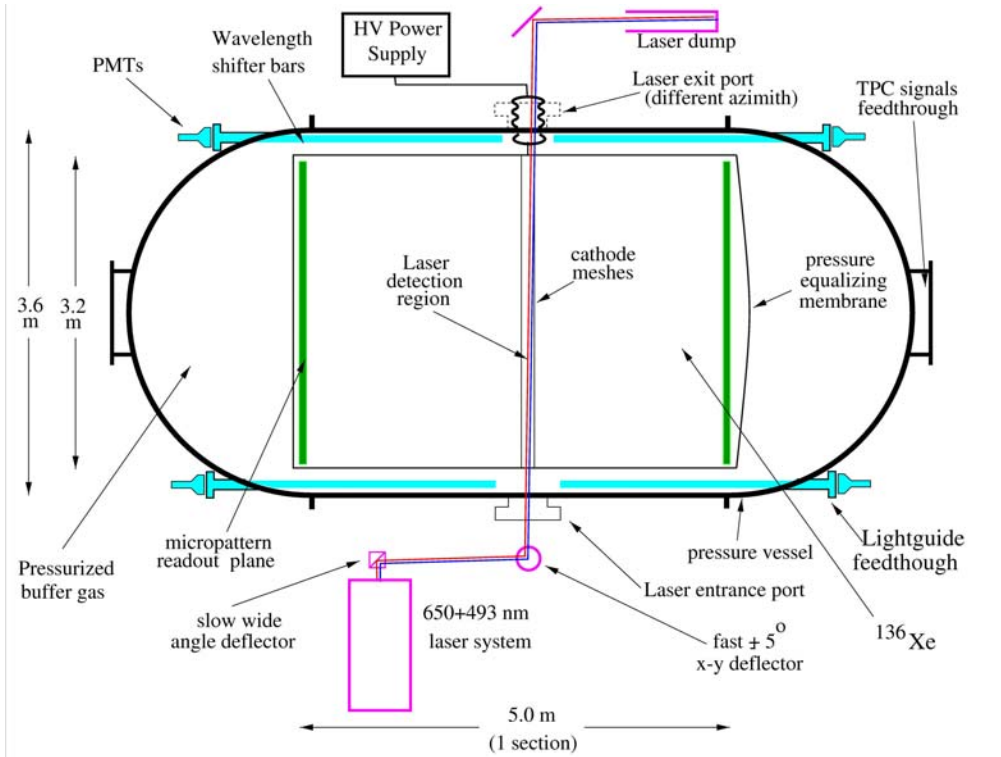


Cryogenic dipstick

- Capture ion on SXe coating
- LHe cooling (~20K) to maintain stable SXe coating in 10^{-8} torr vacuum
- Microcapacitor used to measure and stabilize SXe with accuracy of a few monolayers in LXe and vacuum

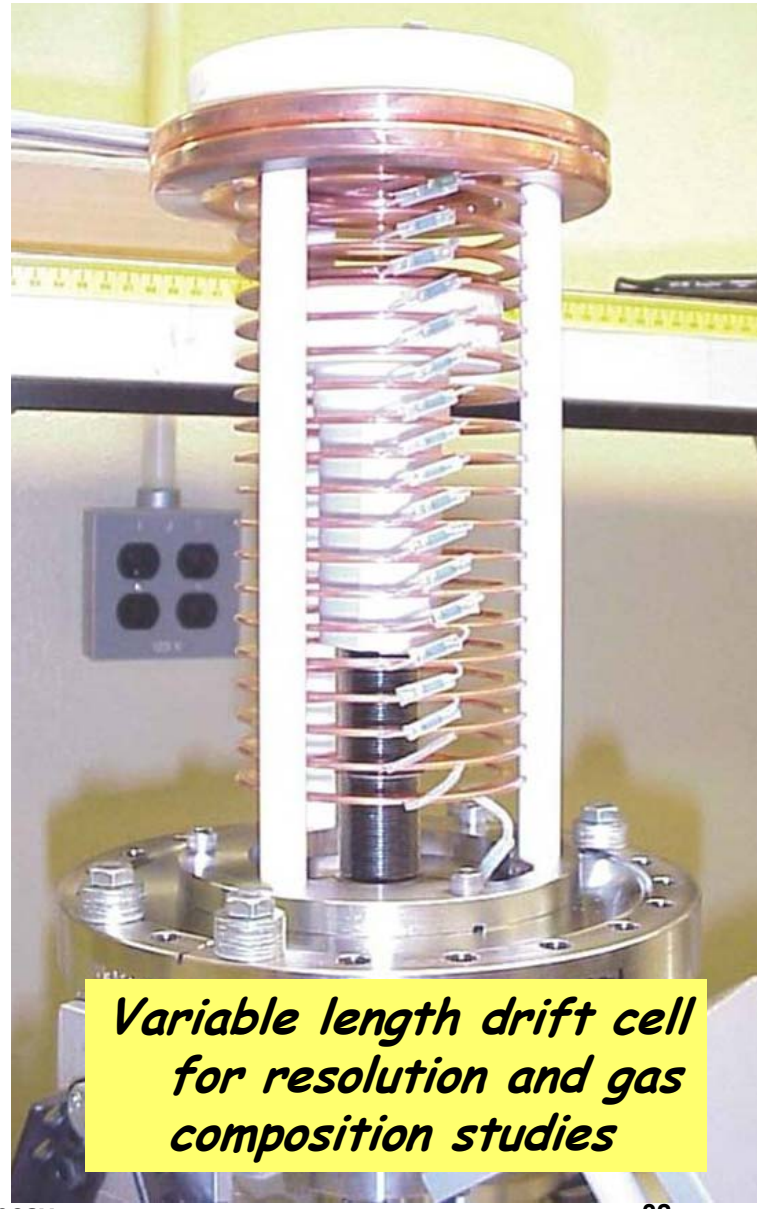
With EXO-200 closer to data taking

GXe R&D activities are picking up speed



EXO GXe concept

M.Danilov et al, Phys Lett 480 (2000) 12



Variable length drift cell for resolution and gas composition studies

→ *This is also pursued by the NEXT collaboration*

Conclusions

Exciting time for neutrino-less double beta decay!

Several 100kg-class experiments will start data taking in the next 2-3 years.
R&D for ton-class experiments is on-going.

General reflections about these experiments:
The bad news… they are really difficult experiments. We all tend to underestimate difficulty (less optimistic people would not start!)
The good news… they are happening!

We may soon know whether Ettore Majorana was right and what the mass scale of the neutrino is.

The EXO Collaboration

K.Barry, D.Leonard, E.Niner, A.Piepke *Physics Dept, University of Alabama, Tuscaloosa AL*
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EXO-200kg Majorana mass sensitivity

Assumptions:

1) 200kg of Xe enriched to 80% in 136
2) $\sigma(E)/E$ = 1.4% obtained in EXO R&D, Conti et al Phys Rev B 68 (2003) 054201
3) Low but finite radioactive background:
   20 events/year in the $\pm 2\sigma$ interval centered around the 2.481MeV endpoint
4) Negligible background from $2\nu\beta\beta$ ($T_{1/2} > 1 \cdot 10^{22}$yr R.Bernabei et al. measurement)

Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	Radioactive Background (events)	$T_{1/2}^{0\nu}$ (yr, 90%CL)	Majorana mass (eV) QRPA	NSM
EXO-200	0.2	70	2	1.6*	40	$6.4 * 10^{25}$	0.133†	0.186*

What if Klapdor's observation is correct ?

Central value $T_{1/2}$ (Ge) = $1.2^{+3}_{-0.5} \cdot 10^{25}$, ($\pm 3\sigma$)
(Phys. Lett. B 586 (2004) 198-212
consistently use Rodin's matrix elements for both Ge and Xe)

In 200kg EXO, 2yr:

- Worst case (QRPA, upper limit) 15 events on top of 40 events bkgd → 2σ
- Best case (NSM, lower limit) 162 events on top of 40 bkgd → 11σ

EXO neutrino effective mass sensitivity

Assumptions:

1) 80% enrichment in 136
2) Intrinsic low background + Ba tagging eliminate all radioactive background
3) Energy res only used to separate the 0ν from 2ν modes:
   Select 0ν events in a ±2σ interval centered around the 2.481MeV endpoint
4) Use for 2νββ $T_{1/2}>1\cdot10^{22}$yr (Bernabei et al. measurement)

Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	2νββ Background (events)	$T_{1/2}^{0\nu}$ (yr, 90%CL)	Majorana mass (meV) QRPA‡	NSM#
Conservative	1	70	5	1.6*	0.5 (use 1)	$2*10^{27}$	24	33
Aggressive	10	70	10	1†	0.7 (use 1)	$4.1*10^{28}$	5.3	7.3

* σ(E)/E = 1.4% obtained in EXO R&D, Conti et al Phys Rev B 68 (2003) 054201

† σ(E)/E = 1.0% considered as an aggressive but realistic guess with large light collection area

‡ Rodin, *et. al.*, Nucl. Phys. A 793 (2007) 213-215

\# Caurier, *et. al.*, arXiv:0709.2137v1