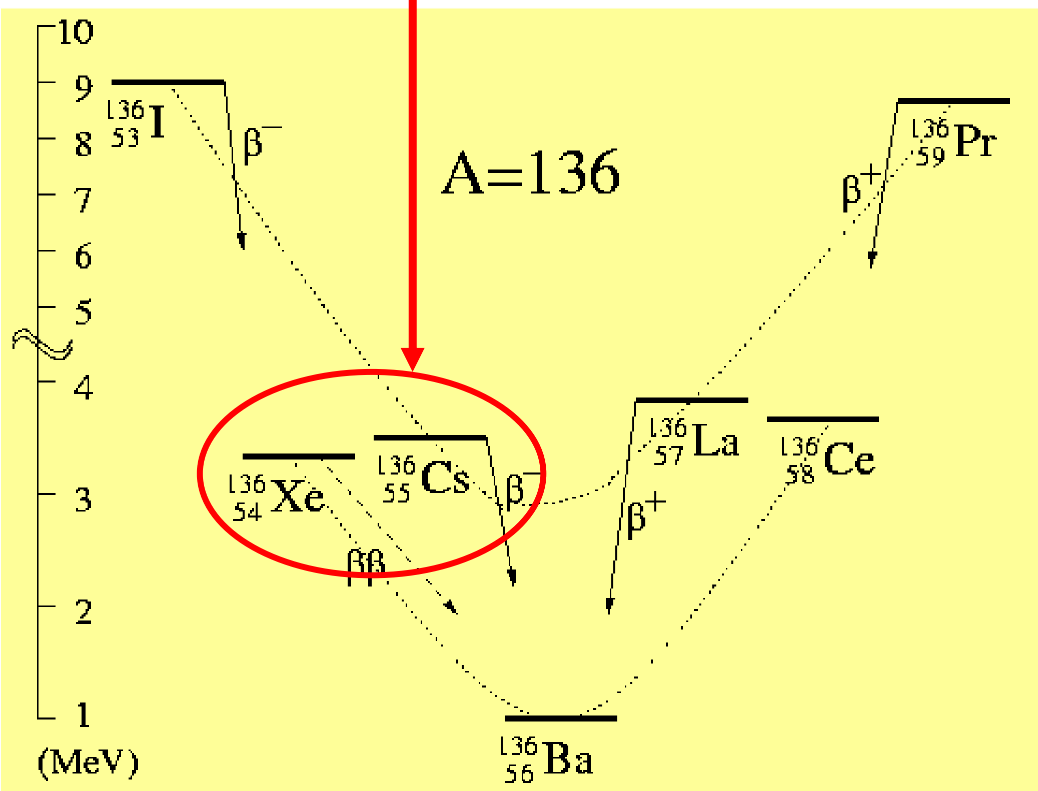
The future of double-beta decay experiments

NOW 2008

Conca Specchiulla, 6-13 Sept 2008

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
2^{nd} order process
in nuclear physics

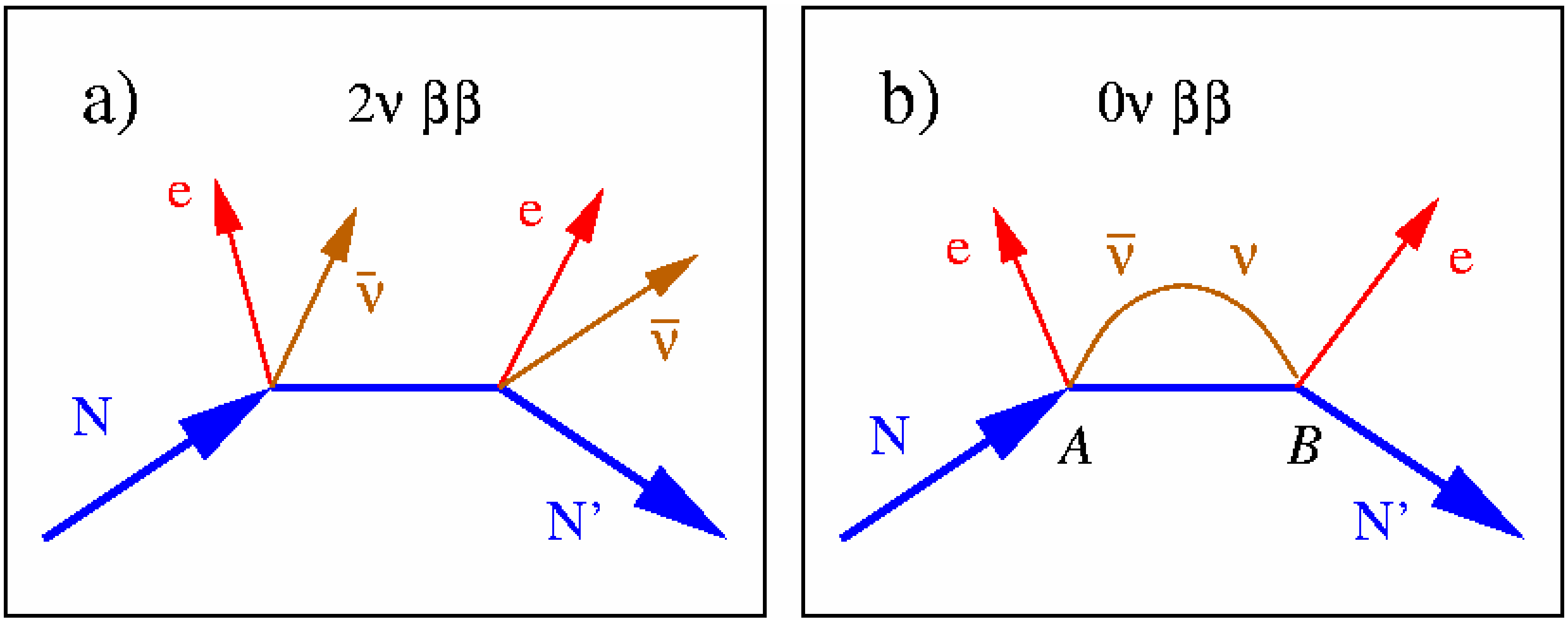
0ν mode: a hypothetical process can happen only if:

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

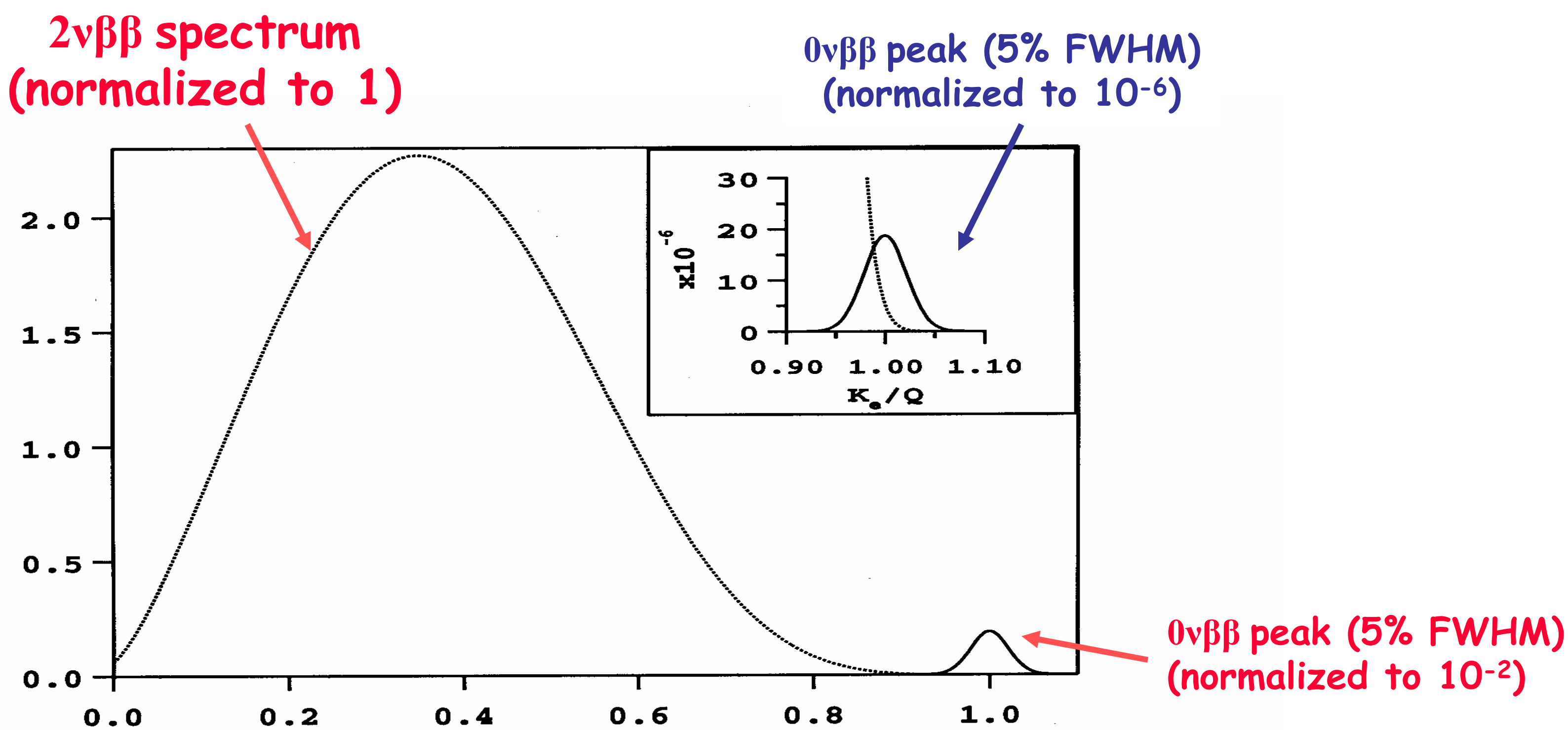
Since helicity has to "flip"

$|\Delta L| = 2$

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



Background due to the Standard Model 2νββ decay



Summed electron energy in units of the kinematic endpoint (Q)

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

$$\langle m_\nu \rangle^2 = \left(T_{1/2}^{0\nu\beta\beta} \, G^{0\nu\beta\beta}(E_0, Z) \left| M_{GT}^{0\nu\beta\beta} - \frac{g_V^2}{g_A^2} M_F^{0\nu\beta\beta} \right|^2 \right)^{-1}$$

$M_F^{0\nu\beta\beta}$ 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

$$\langle m_\nu \rangle = \sum_{i=1}^{3} \left| U_{e,i} \right|^2 m_i \, \varepsilon_i$$

effective Majorana ν mass ($\varepsilon_i = \pm 1$ if CP is conserved)

Cancellations are possible…

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			$>5.8*10^{23}$ (90%CL)	
^{116}Cd			$>1.7*10^{23}$ (90%CL)	
^{128}Te	TeO_2 cryo		$>1.1*10^{23}$ (90%CL)	
^{130}Te	TeO_2 cryo	~12	$>3*10^{24}$ (90%CL)	<0.19 - 0.68
^{136}Xe	Xe scint	~4.5	$>1.2*10^{24}$ (90%CL)	<1.1 - 2.9
^{150}Nd			$>1.2*10^{21}$ (90%CL)	
^{160}Gd			$>1.3*10^{21}$ (90%CL)	

** But also claim of signal by part of same group (see Cattadori's talk)*

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

EVIDENCE FOR NEUTRINOLESS DOUBLE BETA DECAY

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A. DIETZ[1], H.L. HARNEY[1], I.V. KRIVOSHEINA[1,2]
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[3] *Spokesman of the GENIUS and HEIDELBERG-MOSCOW Collaborations,*

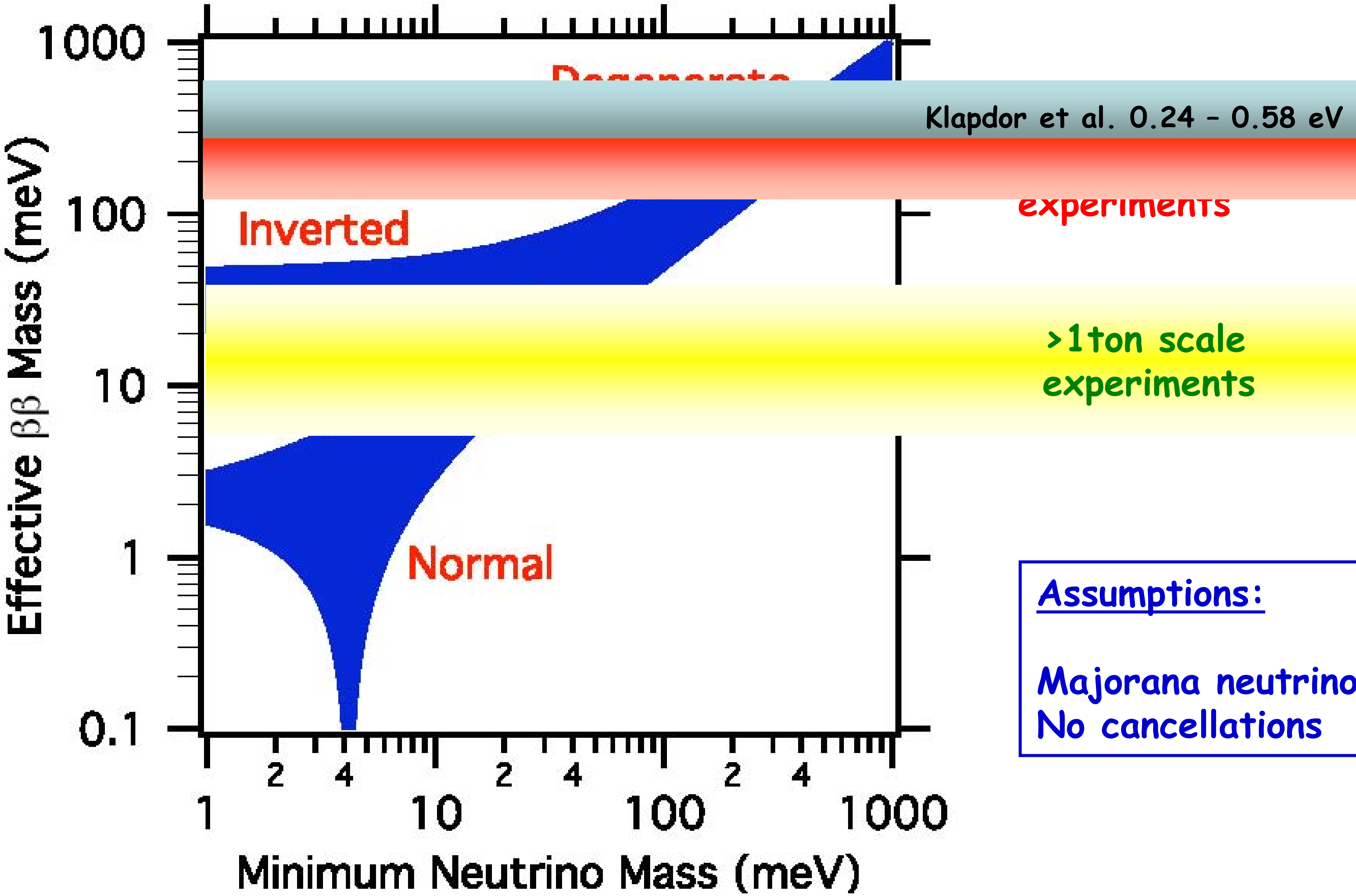
Part of the Heidelberg-Moscow collaboration
Mod. Phys Lett. A27 (2001) 2409

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 arXiv:0708.1033 (2007)

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 $0\nu\beta\beta$ decay:

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

To reach <m_ν> ~ 10 meV very large fiducial mass (tons)

(except for Te) need massive isotopic enrichment

Need to reduce and control backgrounds in qualitatively new ways

these are the lowest background experiment ever built

For no bkgnd $$\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0\nu\beta\beta}} \propto 1/\sqrt{Nt}$$

Scaling with bkgd goes like *Nt* $$\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0\nu\beta\beta}} \propto 1/(Nt)^{1/4}$$

In addition a multi-parameter experiment, if feasible, would provide information for cross checks with more than one single variable, if a discovery is made.

$\beta\beta$ decay experiments are at the leading edge of "low background" techniques

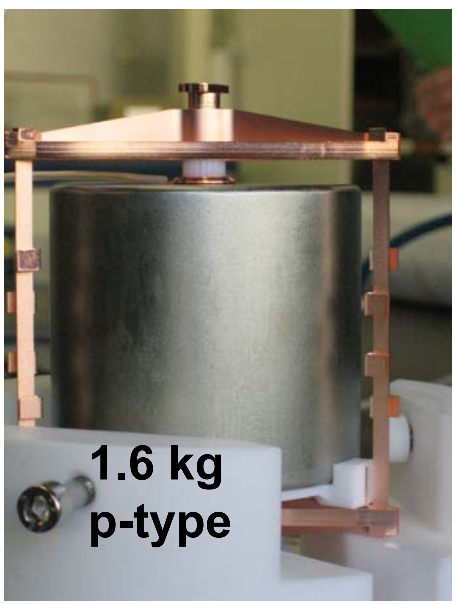
- Final state ID: 1) "Geochemical": search for an abnormal abundance of (A,Z+2) in a material containing (A,Z)
  2) "Radiochemical": store in a mine some material (A,Z) and after some time try to find (A,Z+2) in it
  - + Very specific signature
  - + Large live times (particularly for 1)
  - + Large masses
  - - Possible only for a few isotopes (in the case of 1)
  - - No distinction between 0ν, 2ν or other modes
- "Real time": ionization or scintillation is detected in the decay
  a) "Homogeneous": source=detector
  b) "Heterogeneous": source≠detector
  - + Energy/some tracking available (can distinguish modes)
  - + In principle universal (b)
  - - Many γ backgrounds can fake signature
  - - Exposure is limited by human patience

Future projects# (a broad brush, personal view)

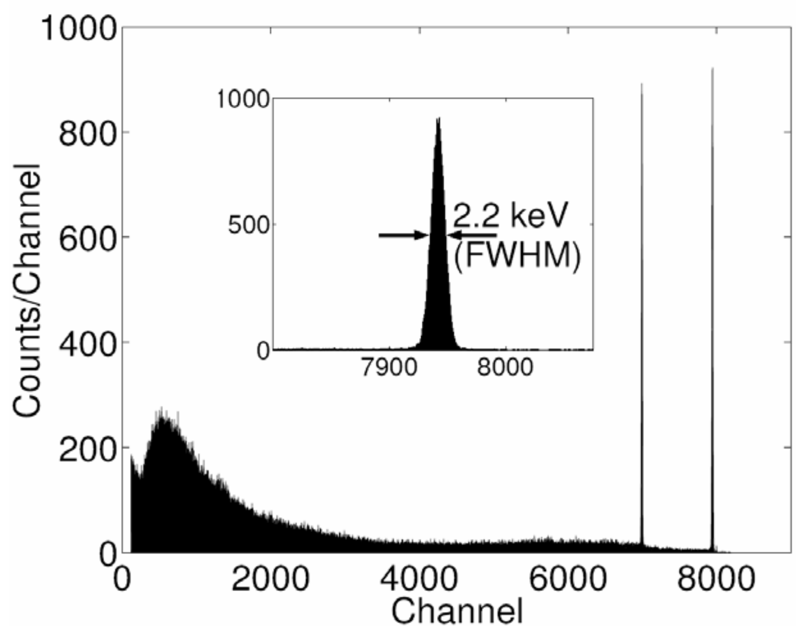
Isotope	Experiment	Main principle	Fid mass	Lab
^{76}Ge	Majorana†	Eres,2site tag, Cu shield	30+30kg	SUSEL
	Gerda†	Eres,2site tag, LAr shield	18→40 kg	G Sasso
	MaGe/GeMa	See above	~1ton	DUSEL? G Sasso?
^{150}Nd	SNO+	Size/shielding	56 kg	SNOlab
^{150}Nd or ^{82}Se	SuperNEMO‡	Tracking	100-200 kg	Canfranc 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



^{60}Co



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

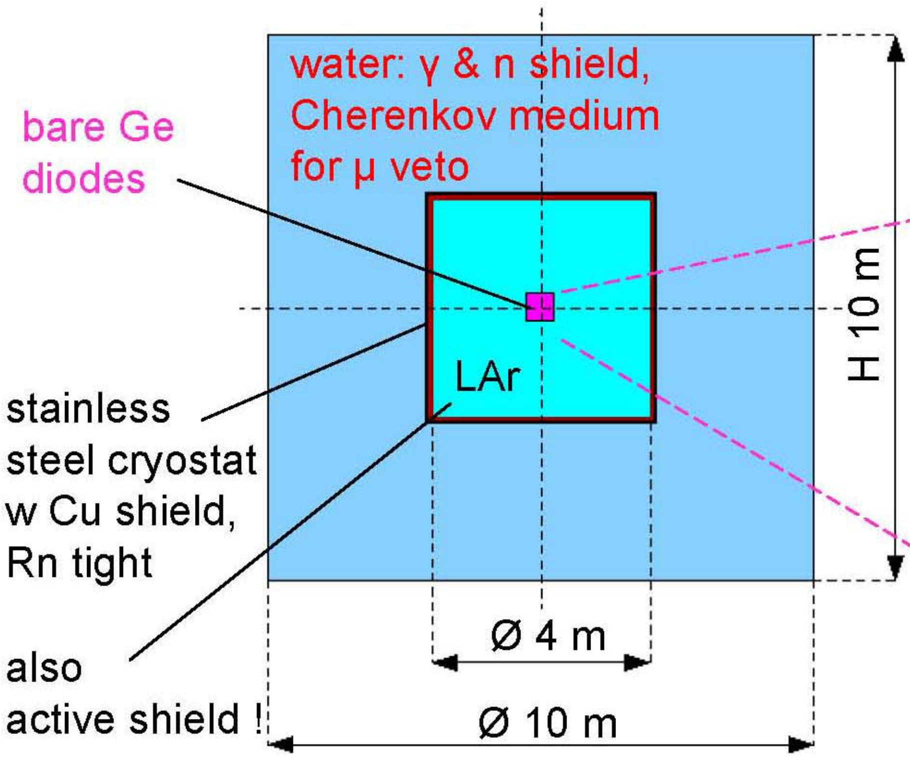
(this contradicts an earlier claim of stability problems [Klapdor-Kleingrothaus & Krivosheina NIM A 566 (2006) 472])

Dealing with different backgrounds

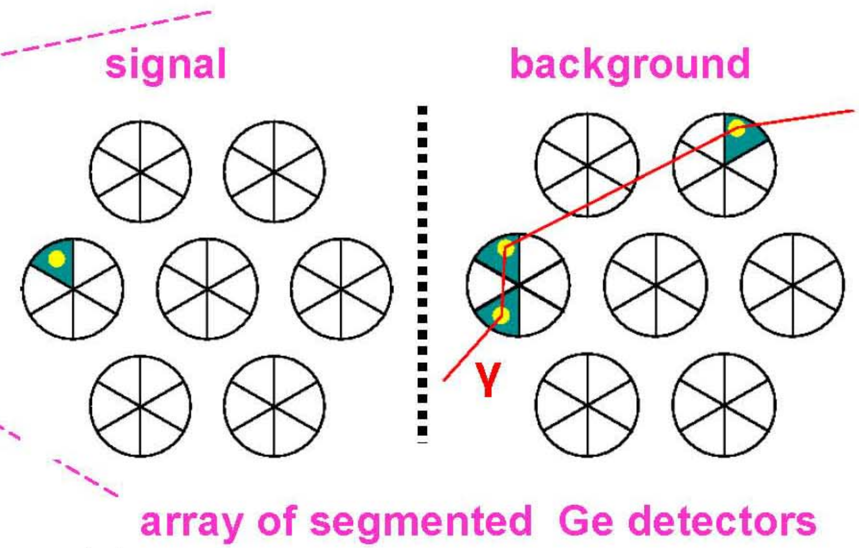
EXTERNAL bgnds: γ(Th, U), n, μ

Shielding possible

INTRINSIC or VERY CLOSE bgnds :
cosmogenic - ^{60}Co (5.3 a), ^{68}Ge (270 d)-
radioactive surface contaminations



Discriminate single & multi site events !
► SSE: ßß, DEP ►MSE: Compton



► anti-coincidence of detectors & detector segments
► pulse shape analysis (PSA)

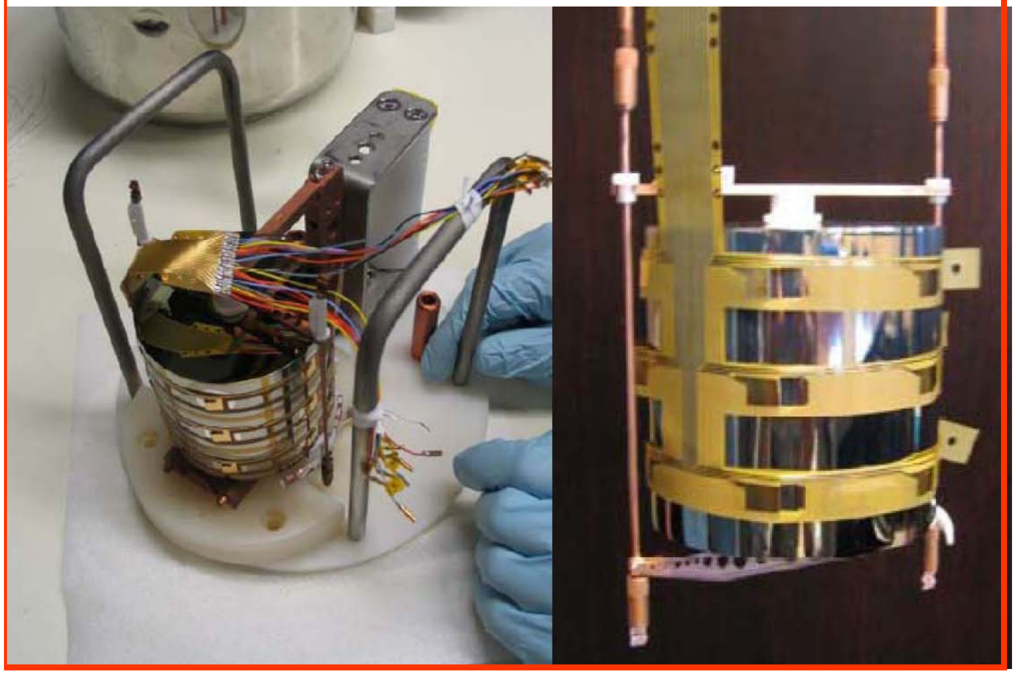
α(LAr) = 0.050/cm α(Cu) = 0.34/cm
$\alpha(H_2O)$ = 0.043/cm α(Pb) = 0.48/cm

(from K.T.Knopfle, ICHEP 2008)

Shielding requirements make these detectors large…

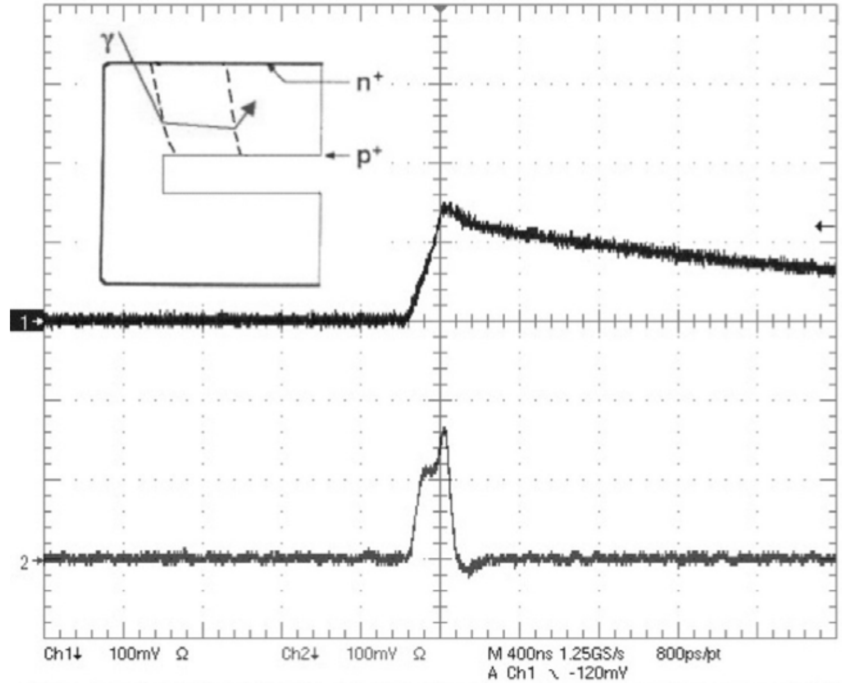
Installing the GERDA cryostat

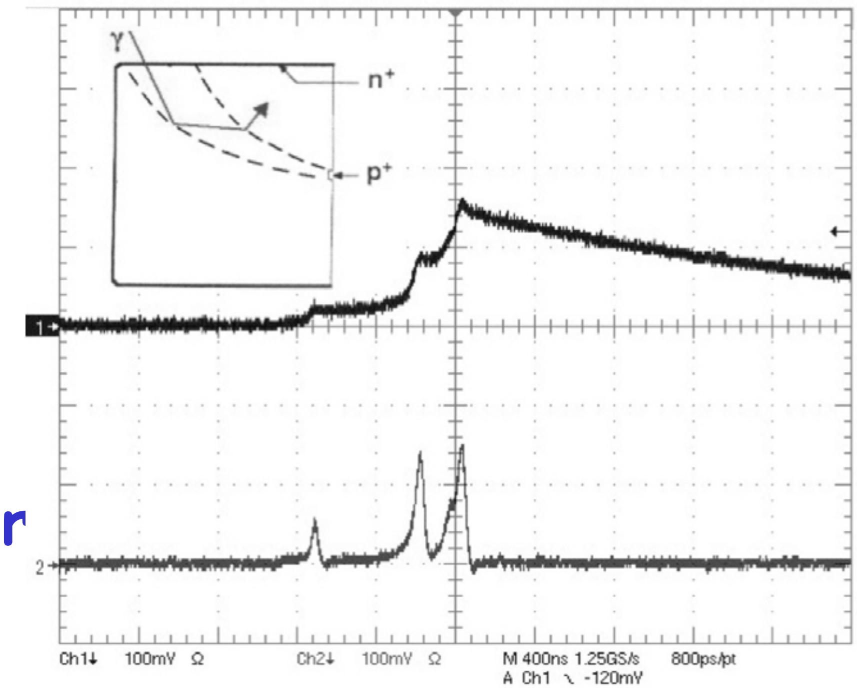
R&D for Phase II (40kg) well advanced



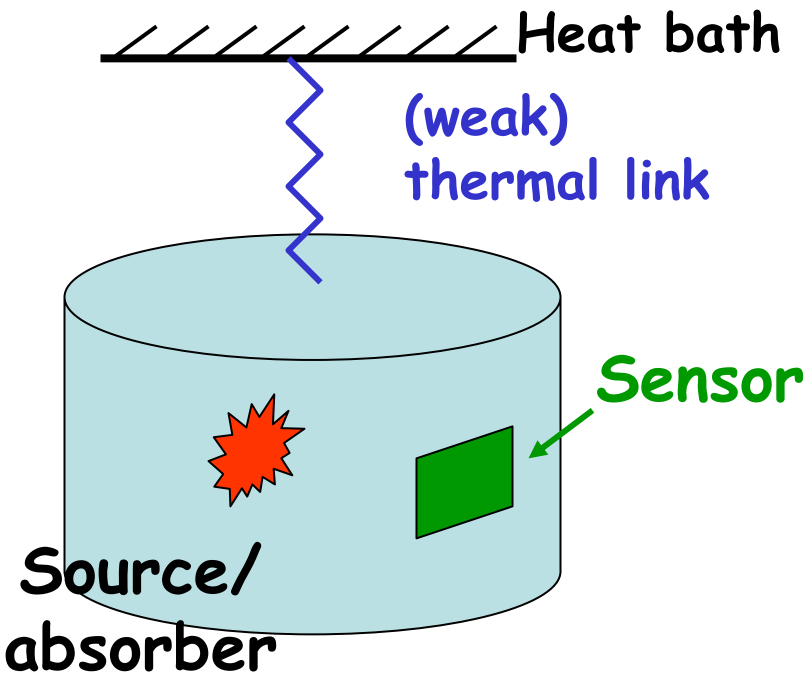
In addition new development (Majorana group) with point contact detectors: crude "tracking" in a Ge detector

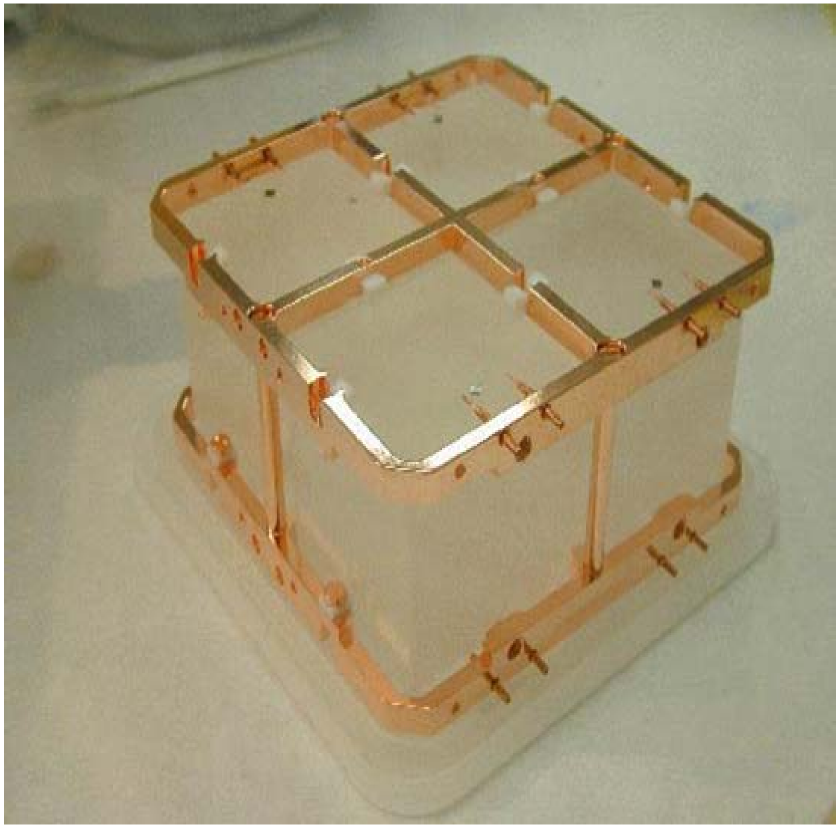
P.S. Barbeau et al. nucl-ex/0701012 Jan 2007





Calorimetric detectors



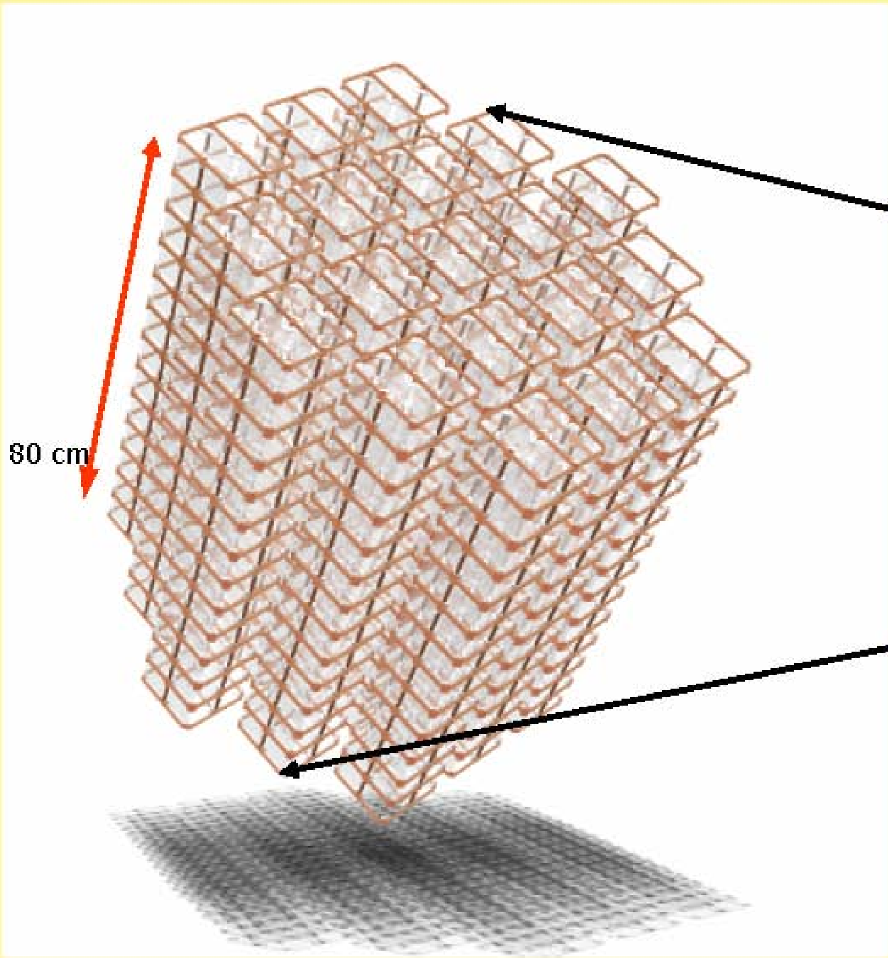


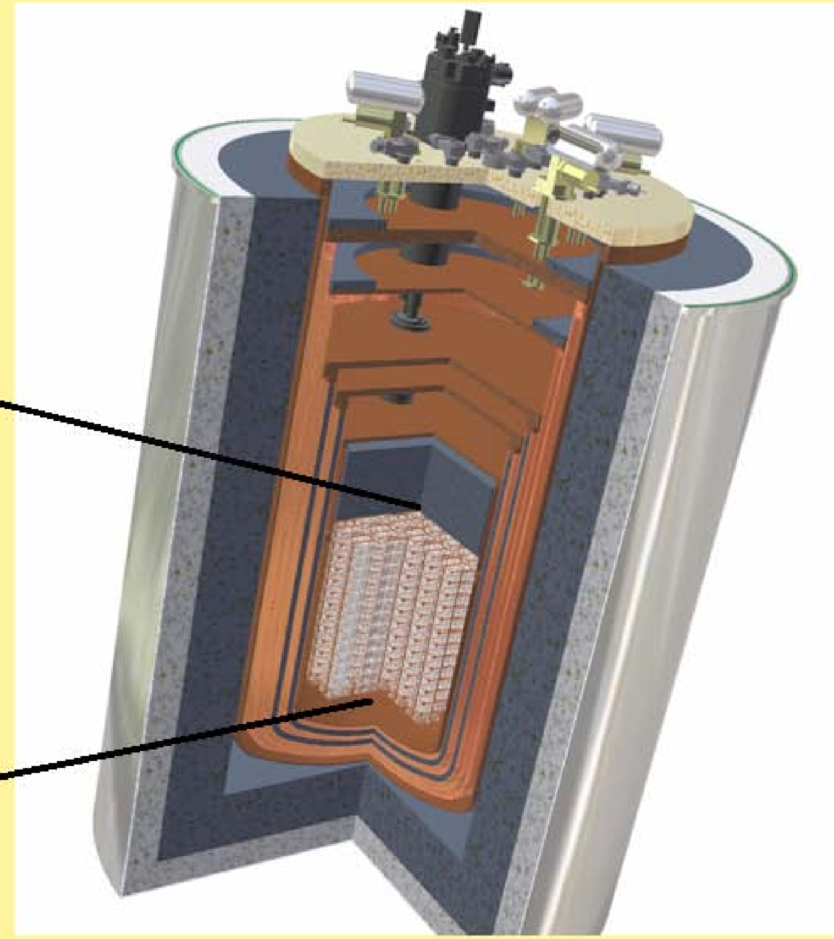
- ΔT = E/heat capacity
- Need mK temperatures to have small heat cap.
- Very generic technique: in principle can use for many materials

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

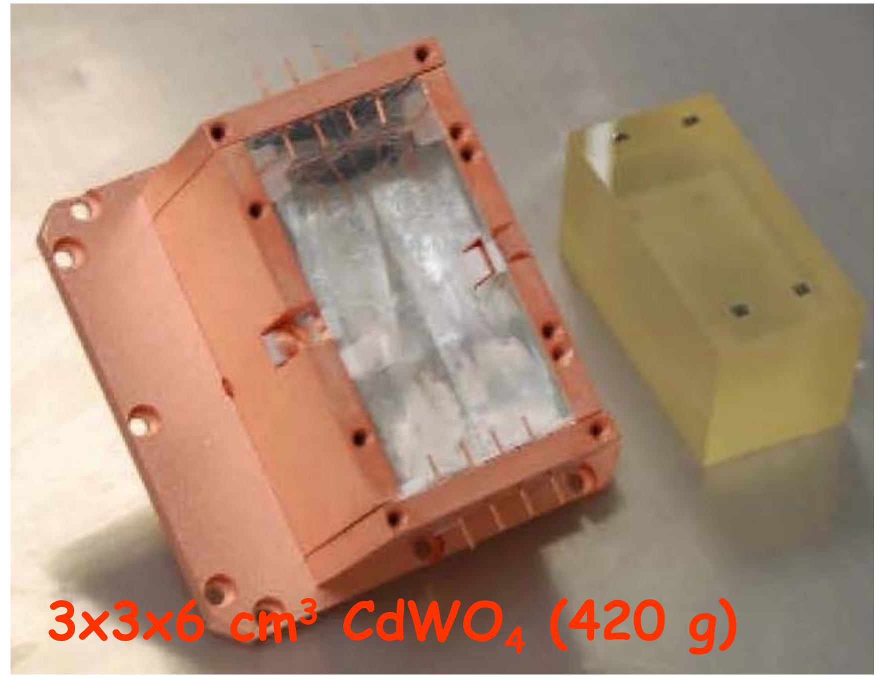
C.Brofferio Neutrino 2008, Christchurch, NZ

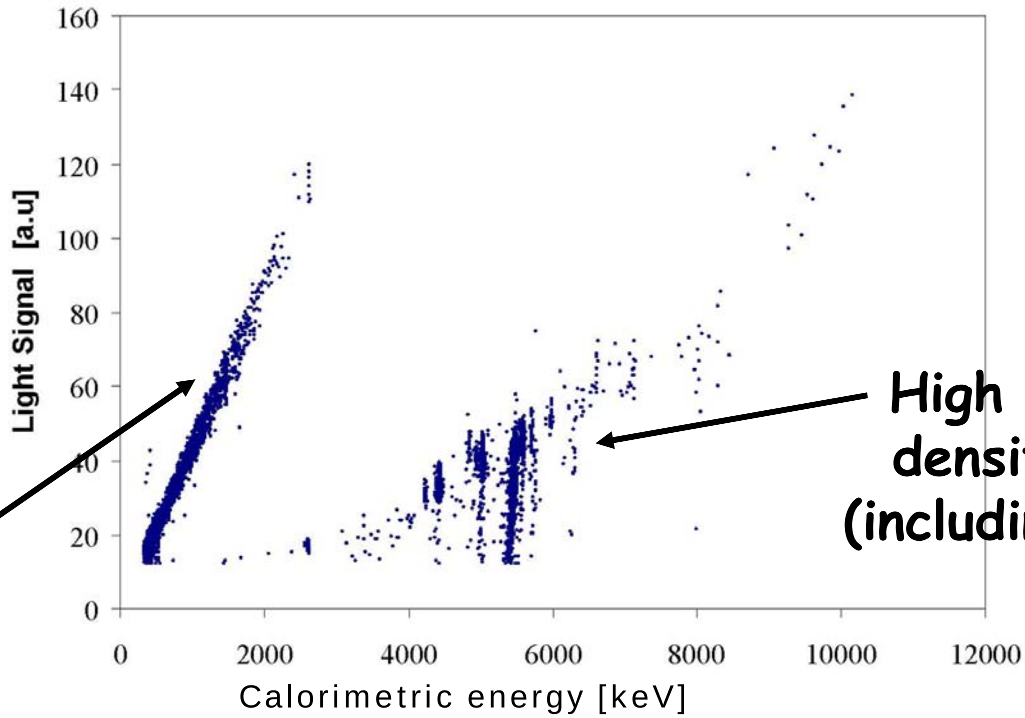
Substantial confidence on backgrounds for CUORE since extrapolation from Cuoricino should be straight forward

"Soft start"
CUORE 0: one CUORE tower
(out of 19) running in the Cuoricino fridge
- Test technical improvements over Cuoricino
- Lower background crystals and assembly
- Already a sensitive double beta decay experiment

Several new materials can be used as calorimeters with, in addition, scintillation

Good scintillator	Fair scintillator	No scintillation
$PbMoO_2$	ZrO_2	$MgMoO_4$
$ZnSe$	$LiMoO_4$	TeO_2
$CdMoO_4$		
$SrMoO_4$		
$CdWO_4$		
CaF_2		

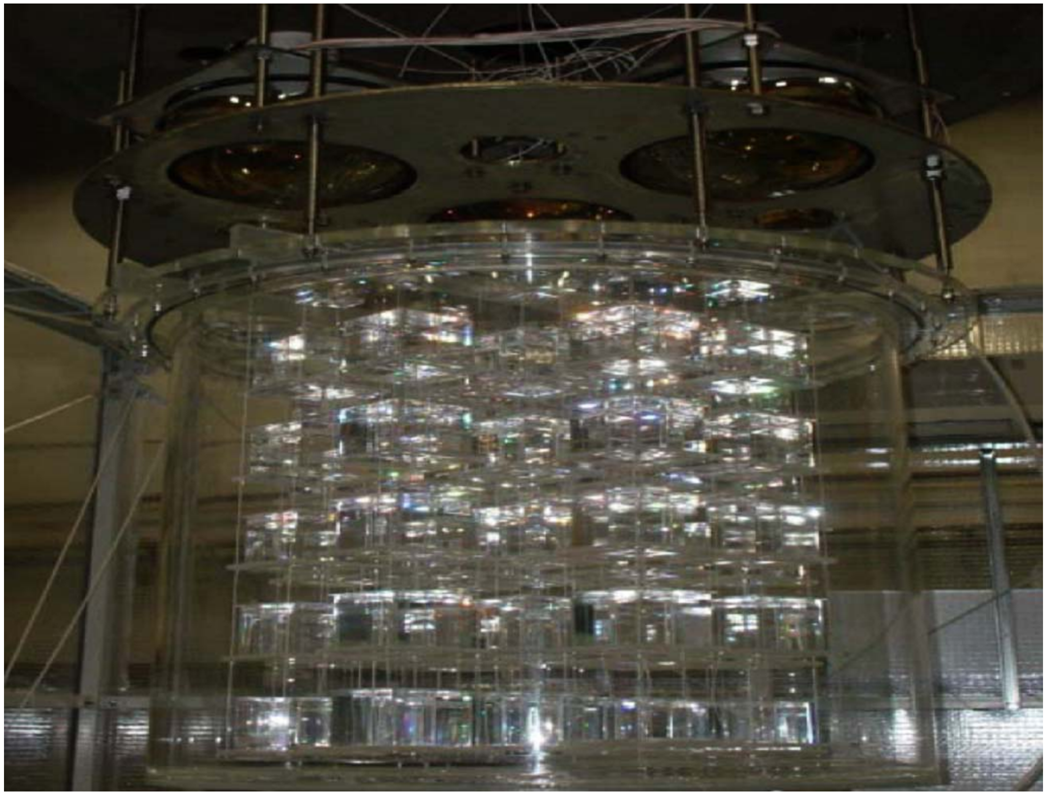




Scintillators

Poor energy resolution/tracking compensated by

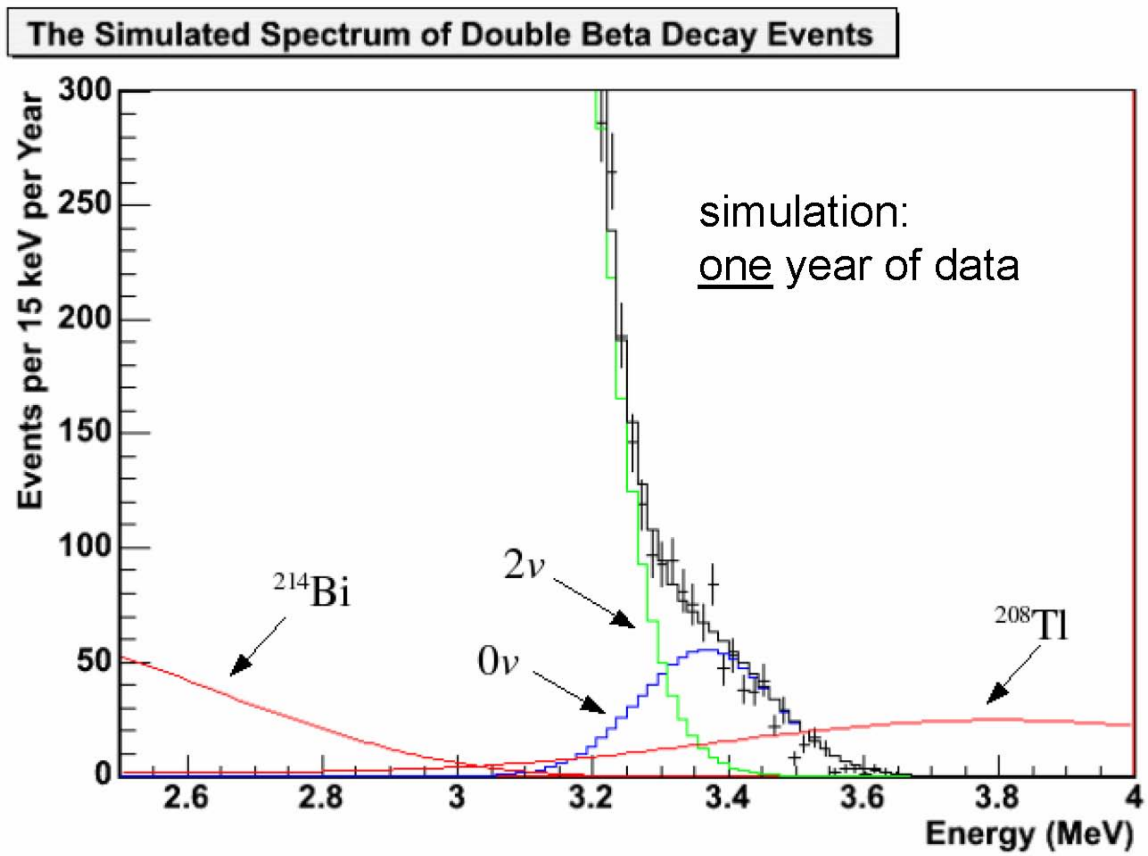
- Well known technology
- (relatively) simple detectors
- Little material near fiducial volume (if the source is part of the scintillator)
- Cheaper self-shielding



Candles
(CaF in liquid scintillator)

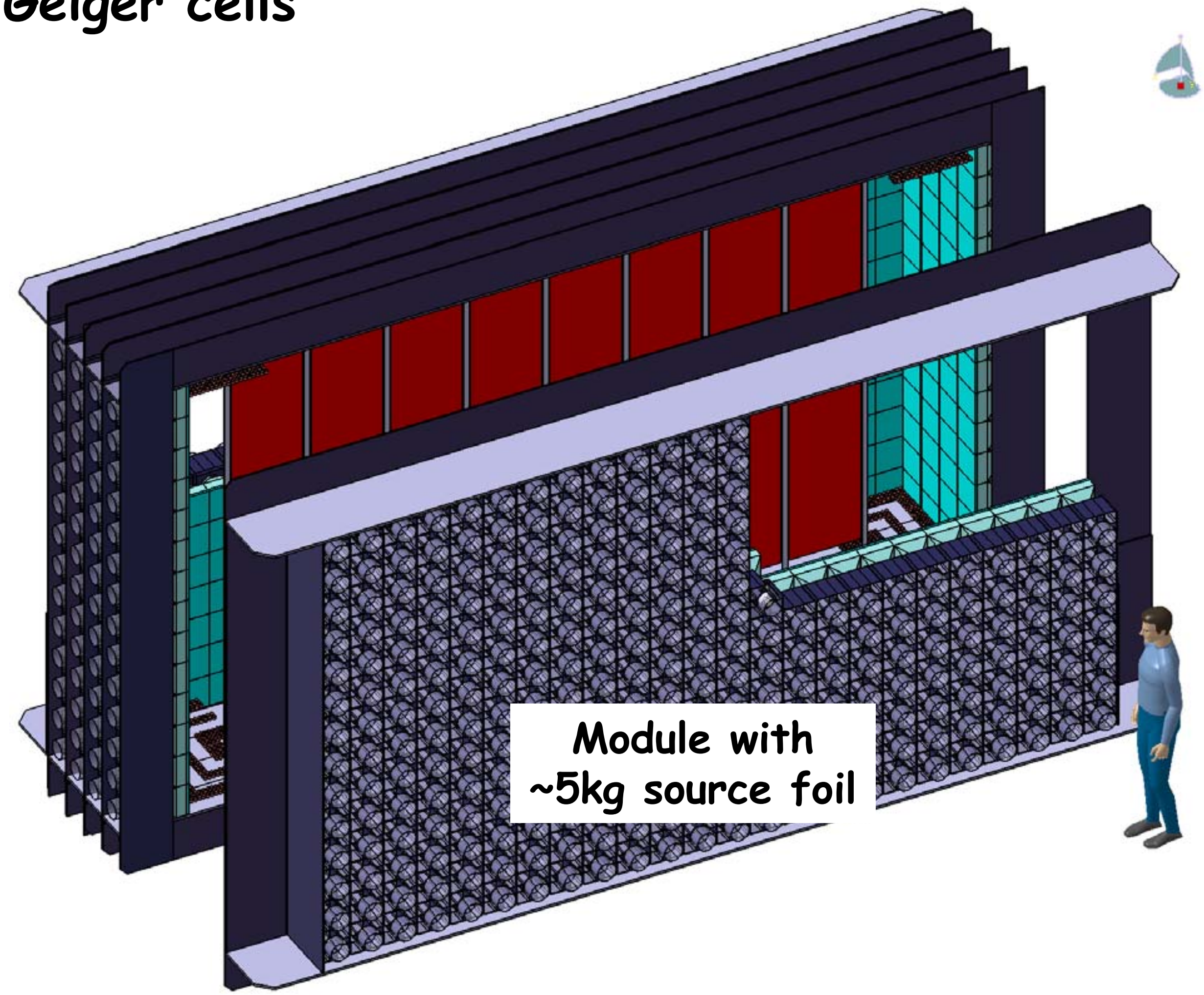
- 1000 tons liquid scintillator in the SNO cavern
- 0.1% ^{nat}Nd dissolved in the scintillator containing 56 kg of ^{150}Nd isotope
- ^{150}Nd has a high (3.37MeV) endpoint
- Much of the infrastructure recycled from SNO (need to reverse the acrylic sphere tethering system and acquire LAB-based scintillator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

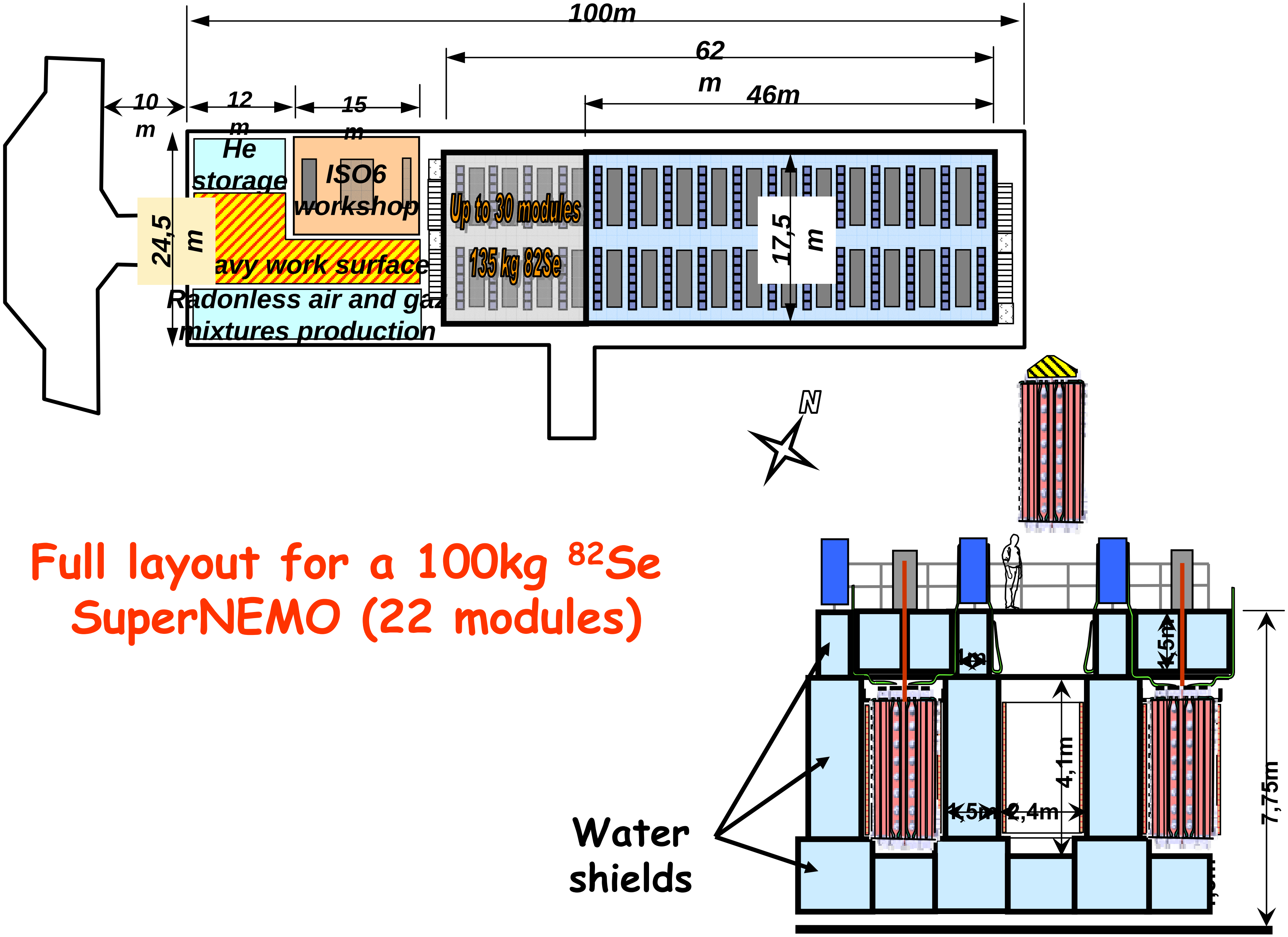
Background shape needs to be very well understood in order to extract meaningful results



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)

Water shields

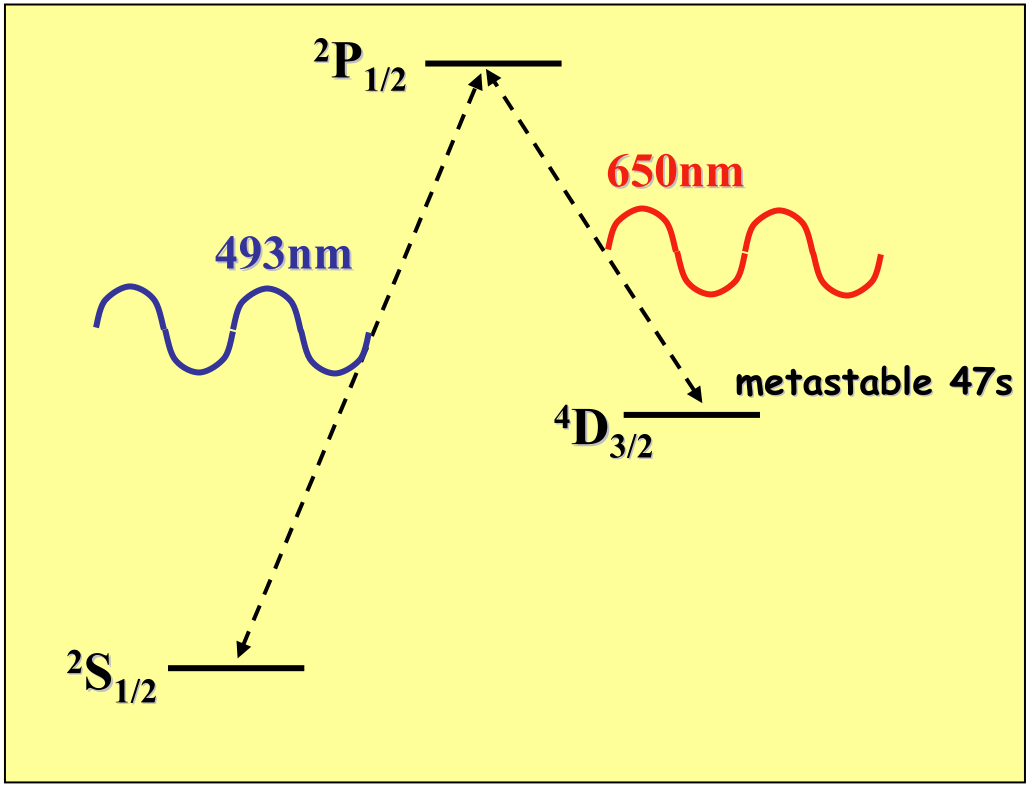
Xe is ideal for a large experiment

- 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



Parallel activities within the EXO collaboration

- EXO-200: a LXe detector *without* Ba tagging using 200 kg of Xe enriched to 80% in ^{136}Xe with ~150 meV sensitivity to Majorana masses

- Ba-tagging R&D: - Transfer from LXe to ion trap
  - Directly tag in LXe volume

- High pressure GXe detector R&D: - Energy resolution and readout scheme
  - Tracking: pressure and light gas mixes
  - Ba tagging in gas

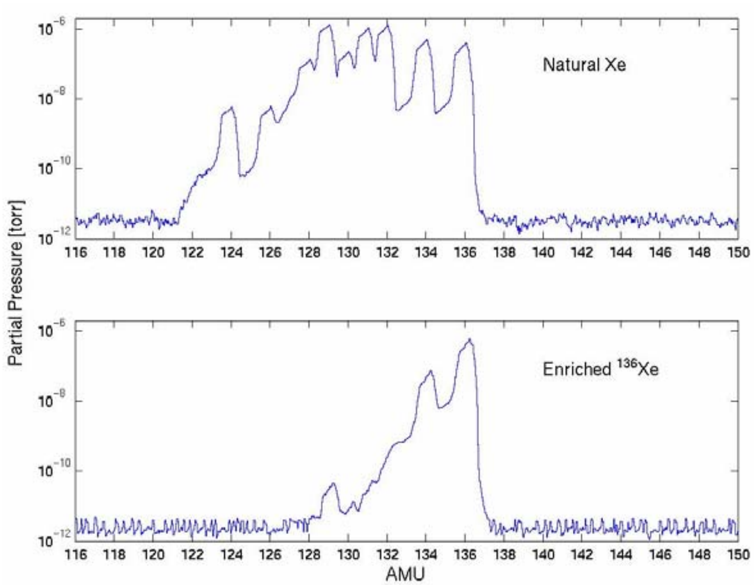
Well matched to the different phases of the study of 0νββ decay:

- Discovery requires a large (and of unknown size!) detector capable of observing the new phenomena with high significance and confidence

- The further study of the process will require the study of electron correlations, as can be done only in GXe (and, maybe, only at low pressure)

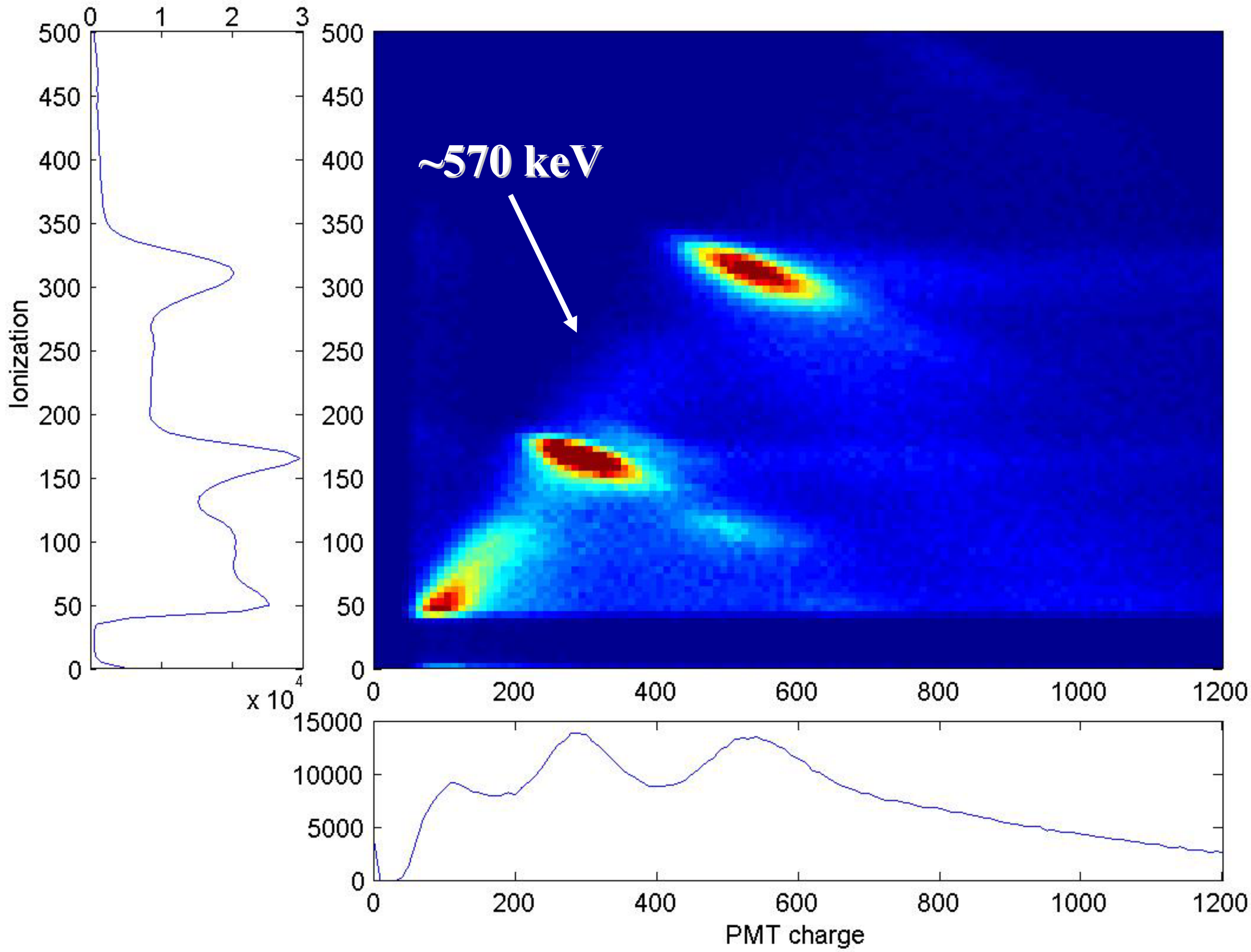
→ Both phases can use the same enriched Xe

200 kg ^{136}Xe test production completed in spring '03 (80% enrichment)

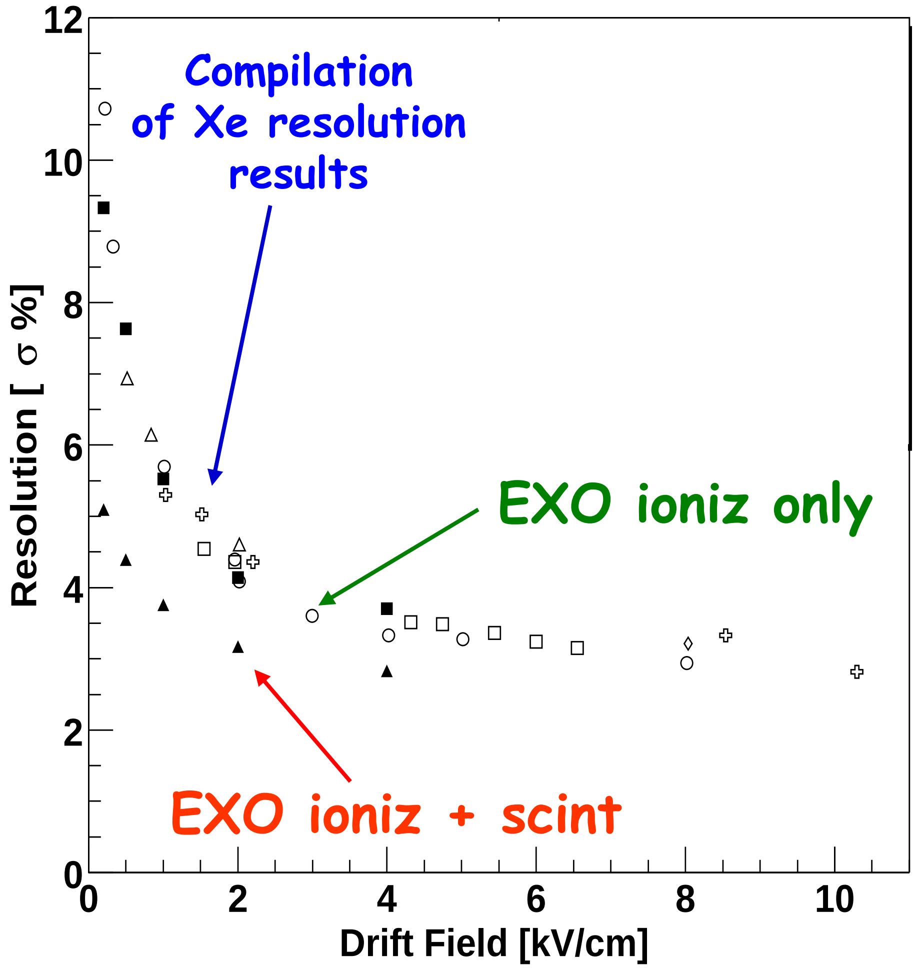


- Largest highly enriched stockpile not related to nuclear industry
- Largest sample of separated $\beta\beta$ isotope

Improved energy resolution in LXe:
Use (anti)correlations between ionization and scintillation signals (now also used in DM detectors)



Anti-correlated ionization and scintillation improves the energy resolution in LXe



Ionization alone:

$\sigma(E)/E$ = 3.8% @ 570 keV
or 1.8% @ $Q_{\beta\beta}$

Ionization & Scintillation:

$\sigma(E)/E$ = 3.0% @ 570 keV
or 1.4% @ $Q_{\beta\beta}$

(a factor of 2 better than the Gotthard TPC)

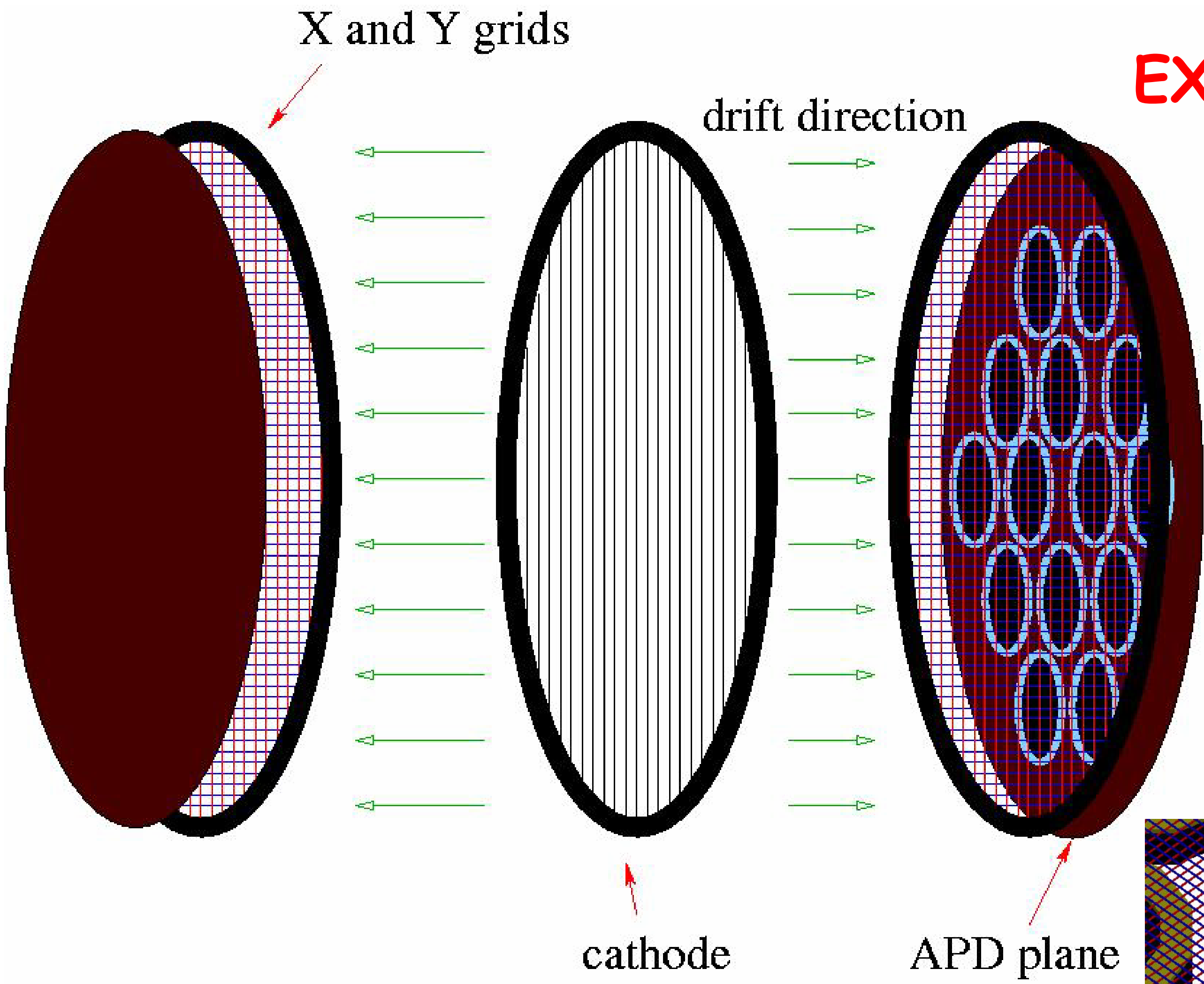
E.Conti et al.

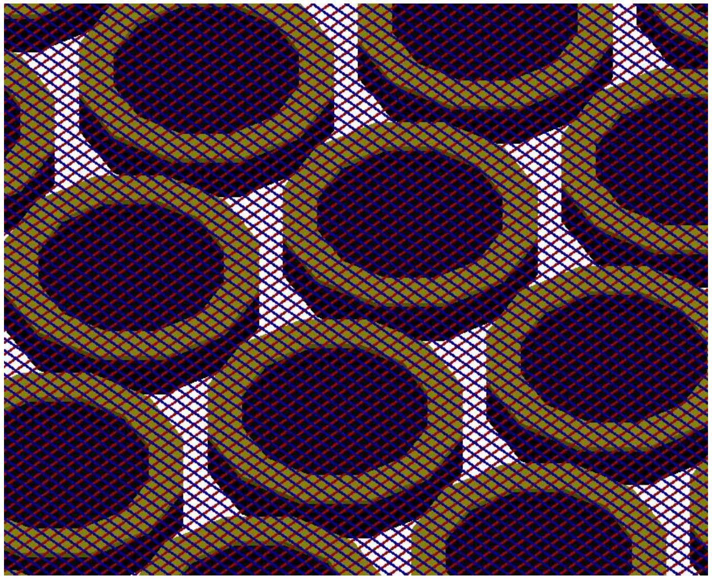
Phys. Rev. B: 68 054201 (2003)

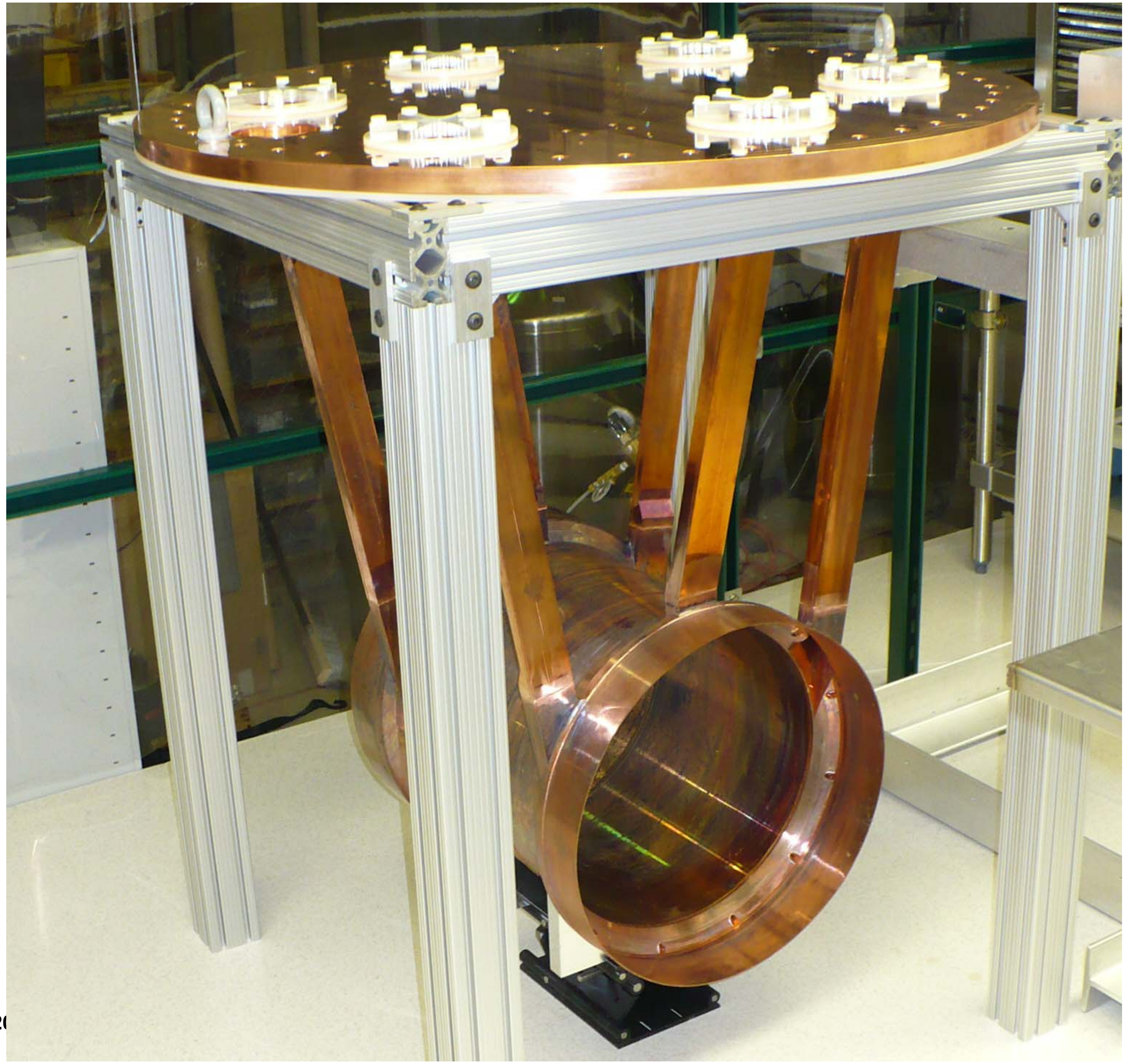
(by now observed by other groups too)

EXO-200 will collect 3-4 times as much scintillation… further improvement likely

EXO-200 TPC basics



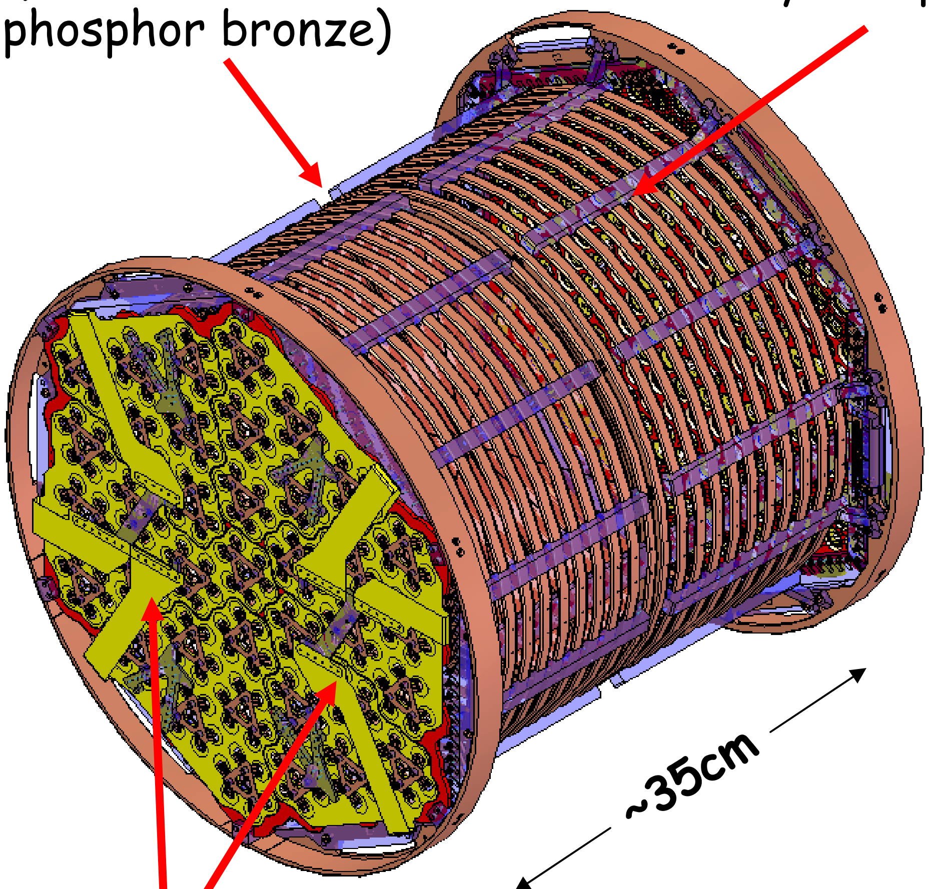




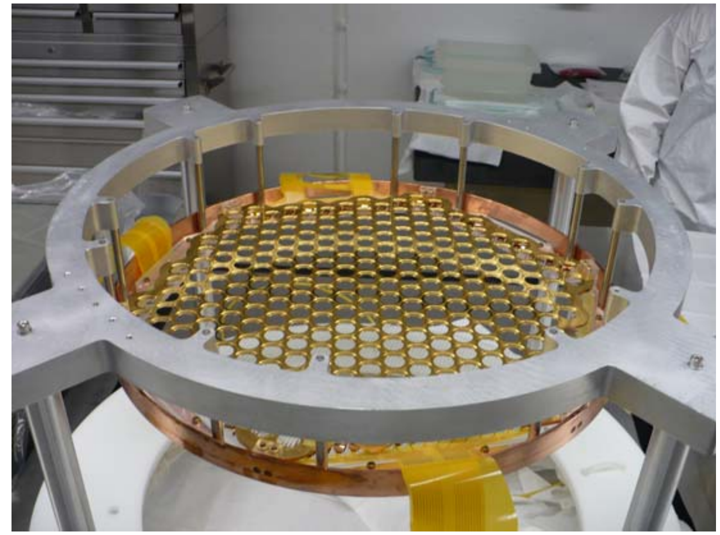
EXO-200 LXe TPC field cage & readout planes

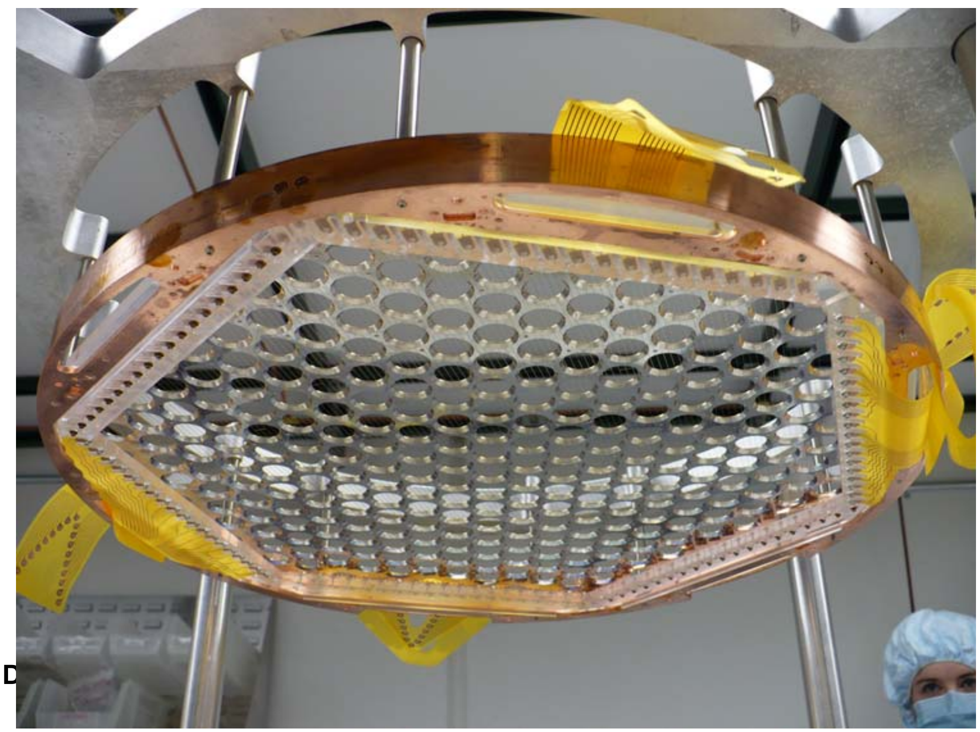
Central HV plane
(photo-etched
phosphor bronze)

acrylic supports



flex cables on back of APD plane



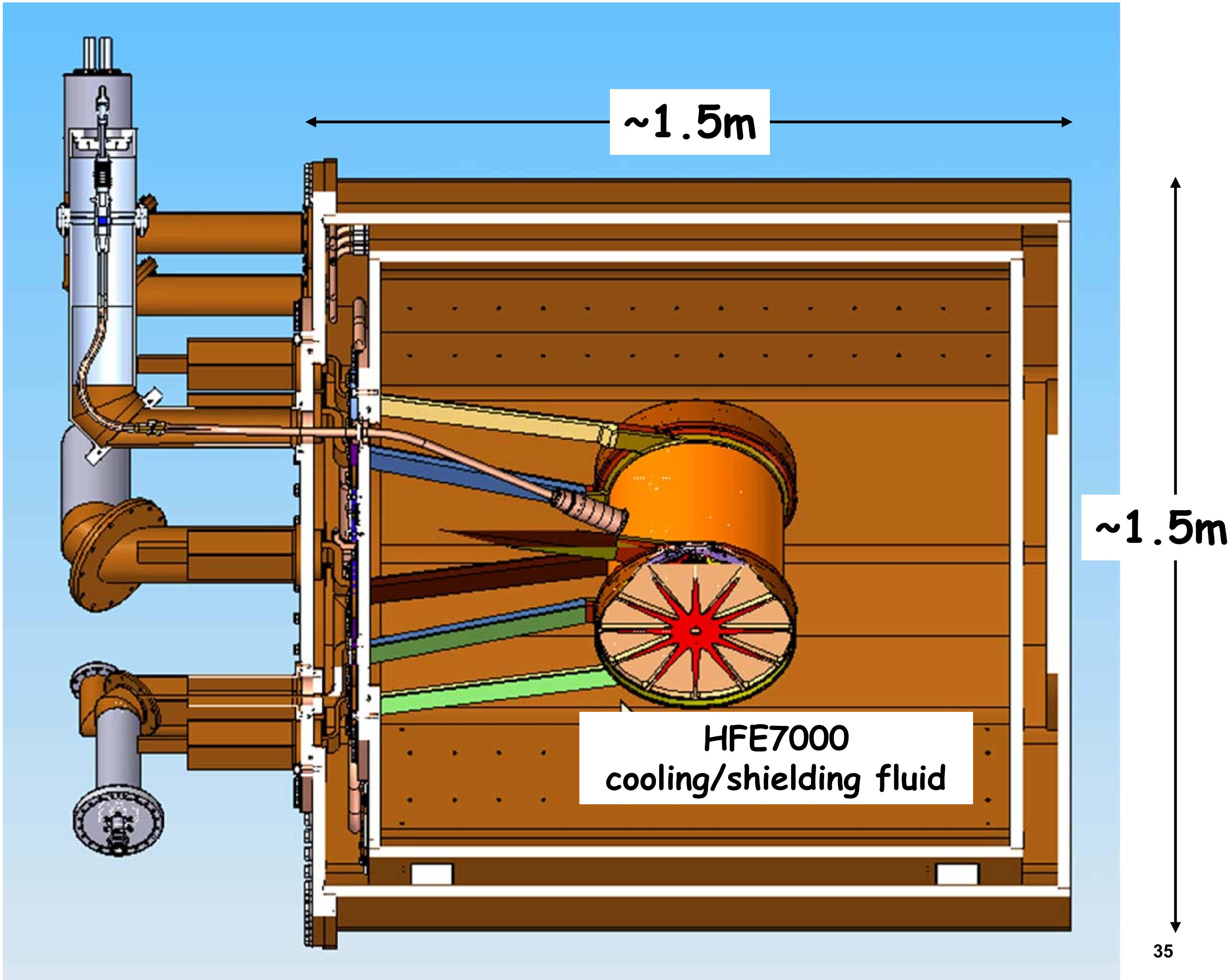


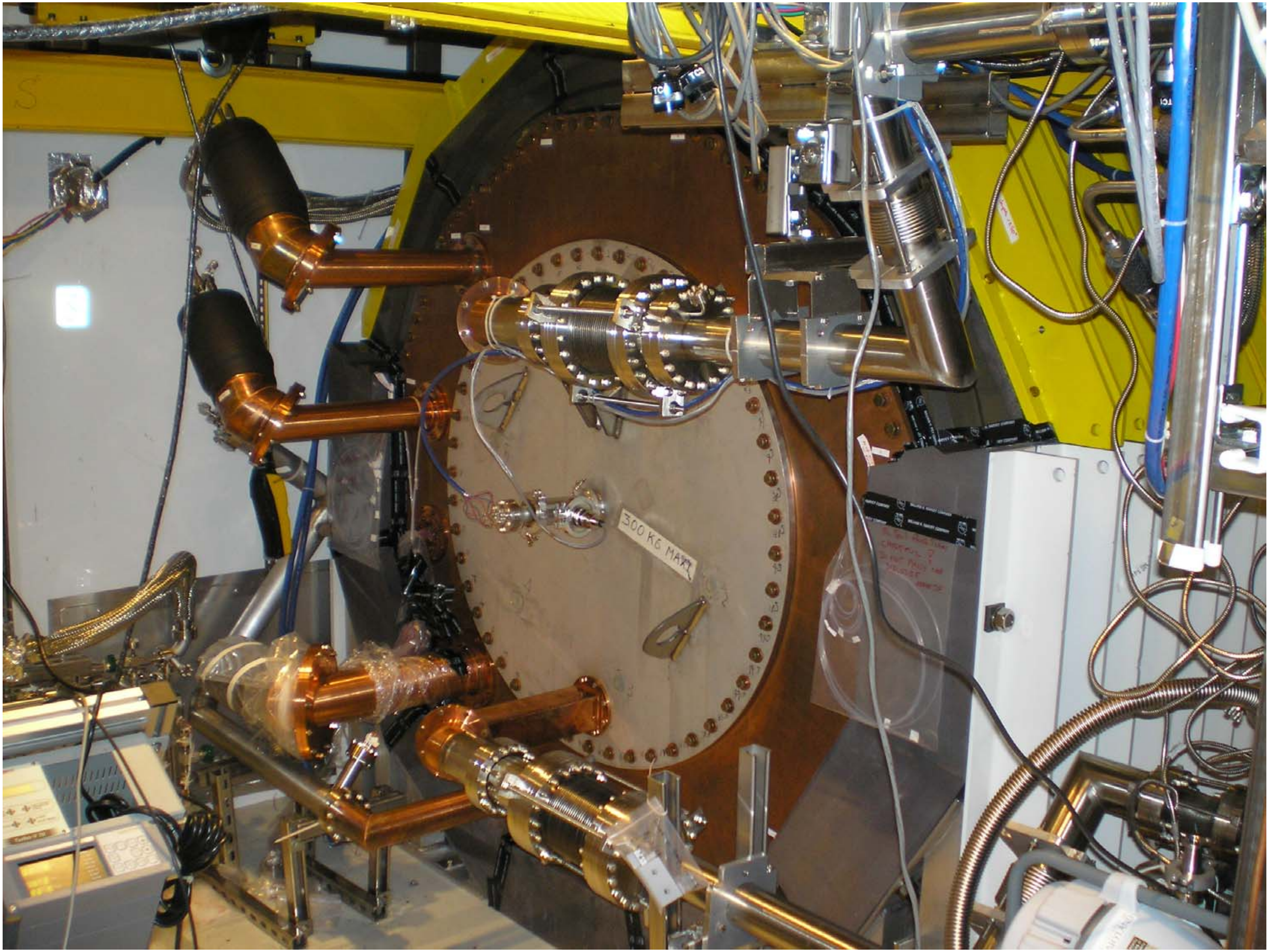
~500 "Bare" LAAPD

QE > 1 at 175nm

Gain set at 100-150
V~1500V
ΔV < ±0.5V
ΔT < ±1K APD is the driver for temperature stability
Leakage current OK cold

APDs are ideal for our application:
- very clean & light-weight,
- very sensitive to VUV


~1.5m
~1.5m
HFE7000
cooling/shielding fluid


300 KG MAX

Massive effort on material radioactive qualification using:

- NAA
- Low background γ-spectroscopy
- α-counting
- Radon counting
- High sensitivity GD-MS and ICP-MS

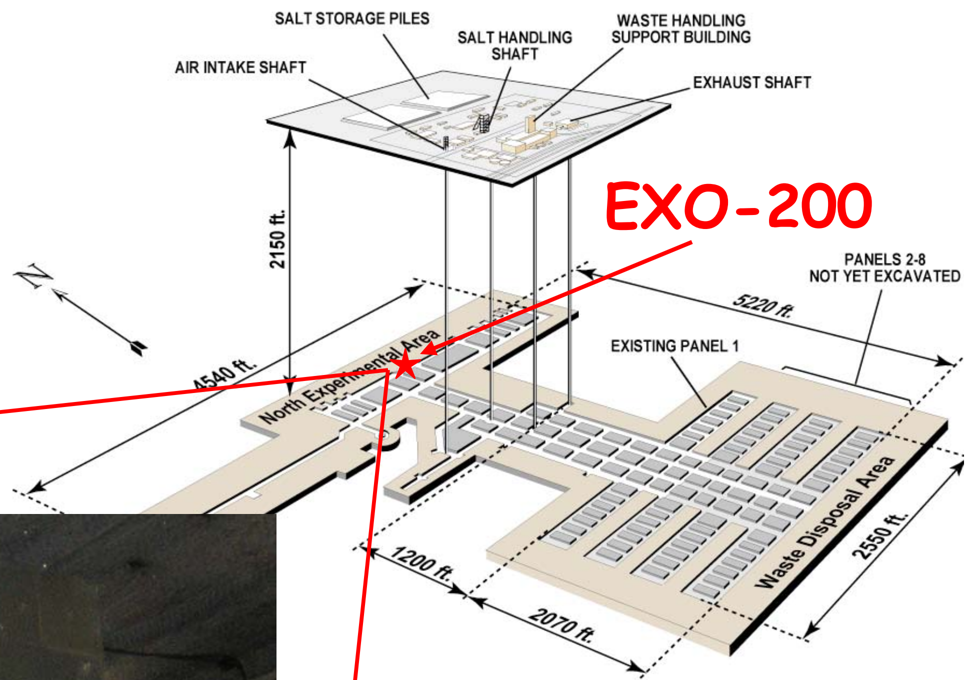
At present the database of characterized materials includes >300 entries

MC simulation of backgrounds

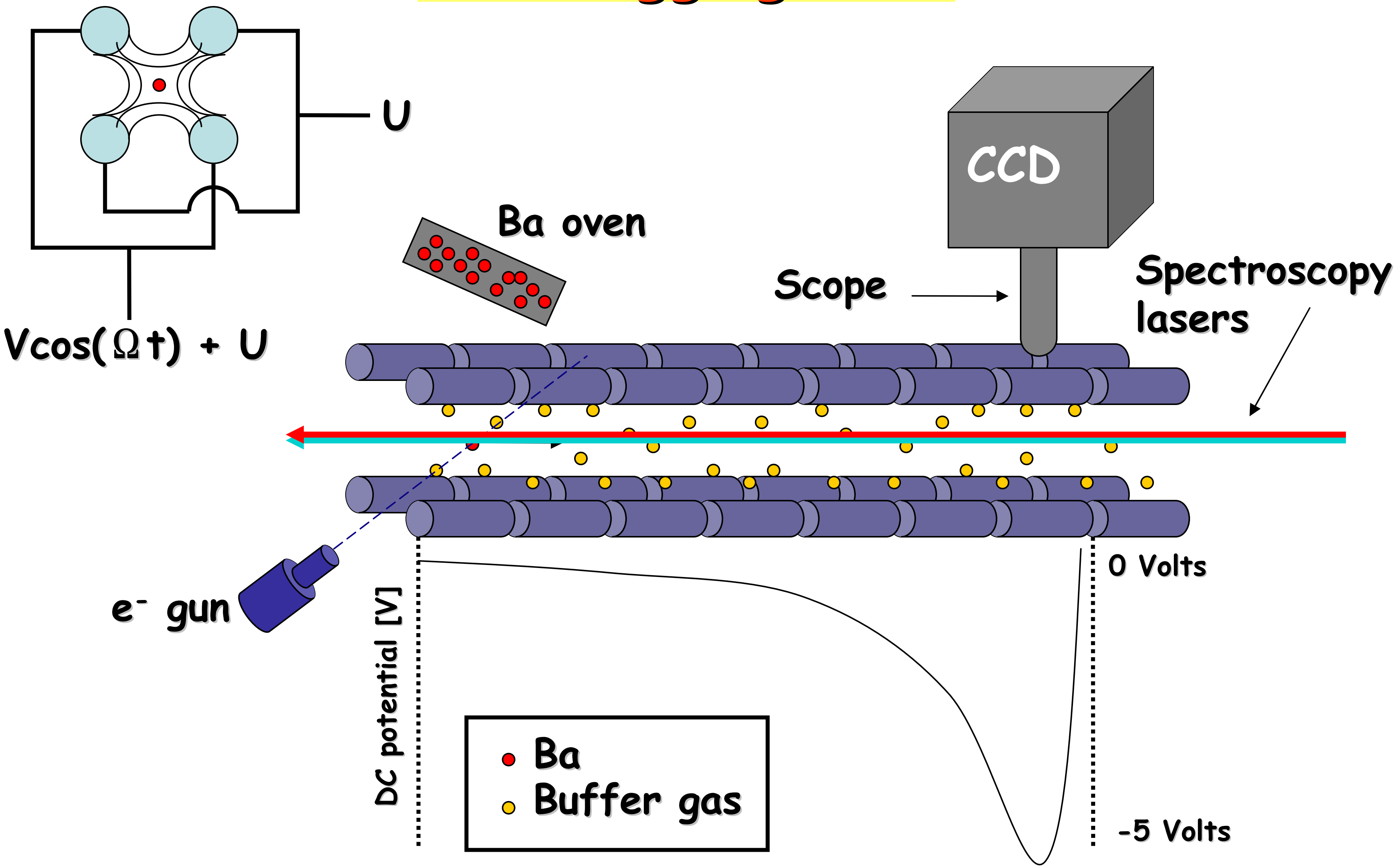
The impact of every screw within the Pb shielding is evaluated before acceptance

NIM article published on the subject with entries for 225 materials [D.Leonard et al., arXiv:0709.4524 to appear on NIM A]

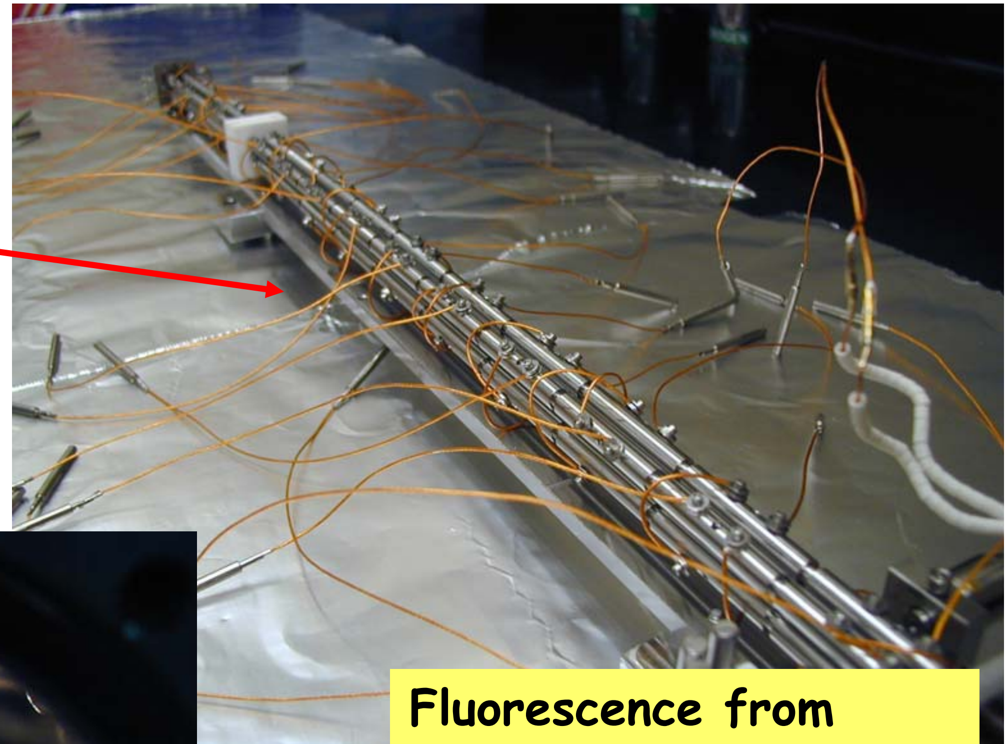
EXO-200 at WIPP



Ba^+ Tagging R&D



Electrode structure being prepared



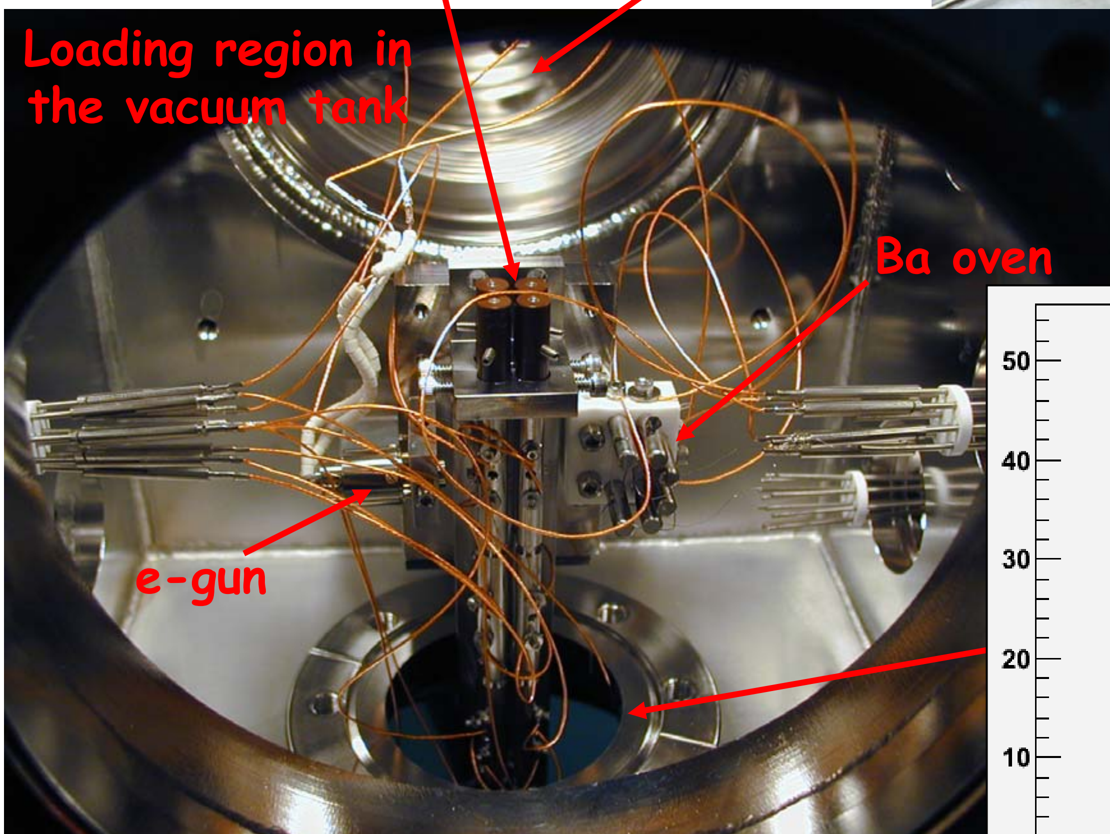
Tip loading access

Main turbo port

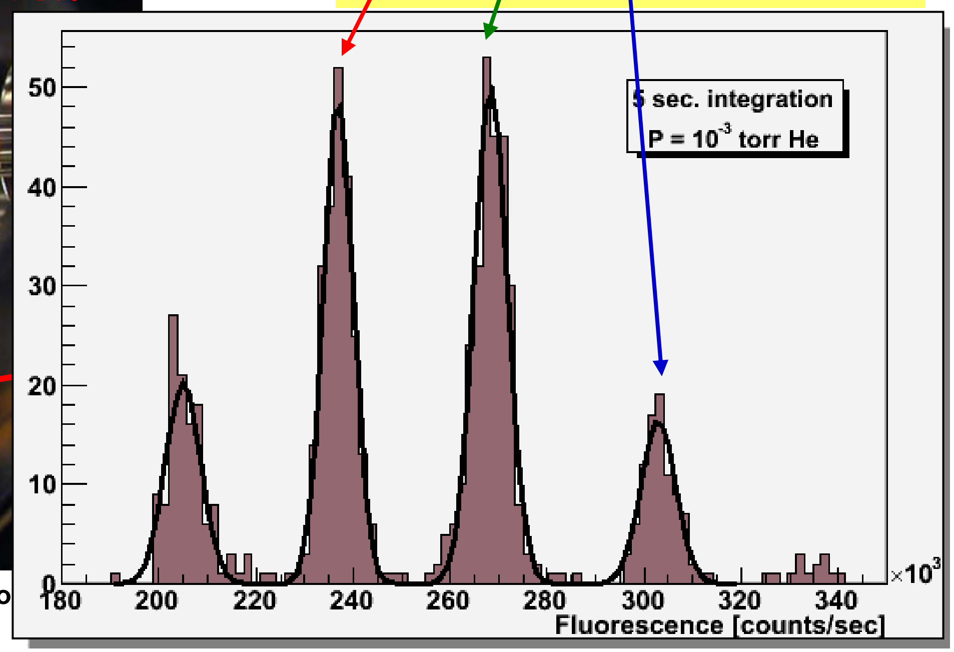
Loading region in the vacuum tank

Ba oven

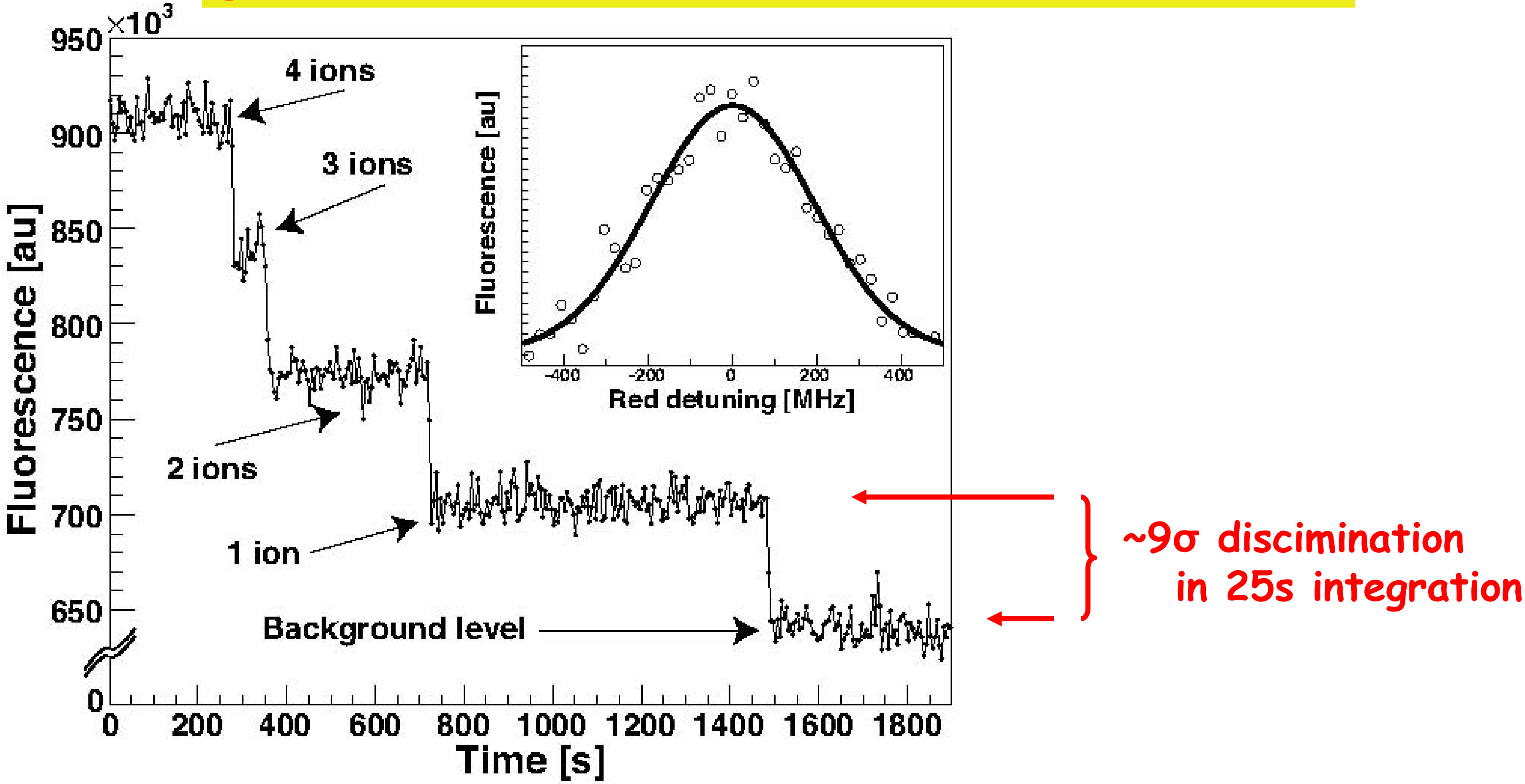
e-gun



Fluorescence from 1, 2, 3 Ba-ions

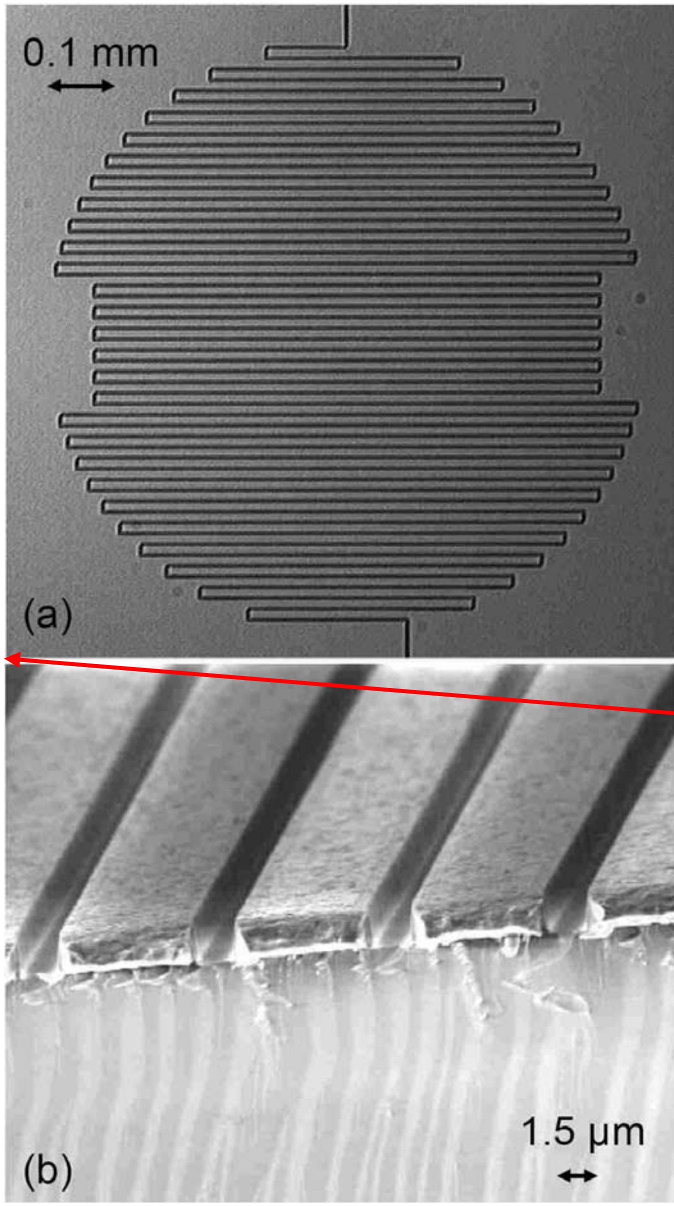


First single ion detection in high pressure gas (He, Ar)



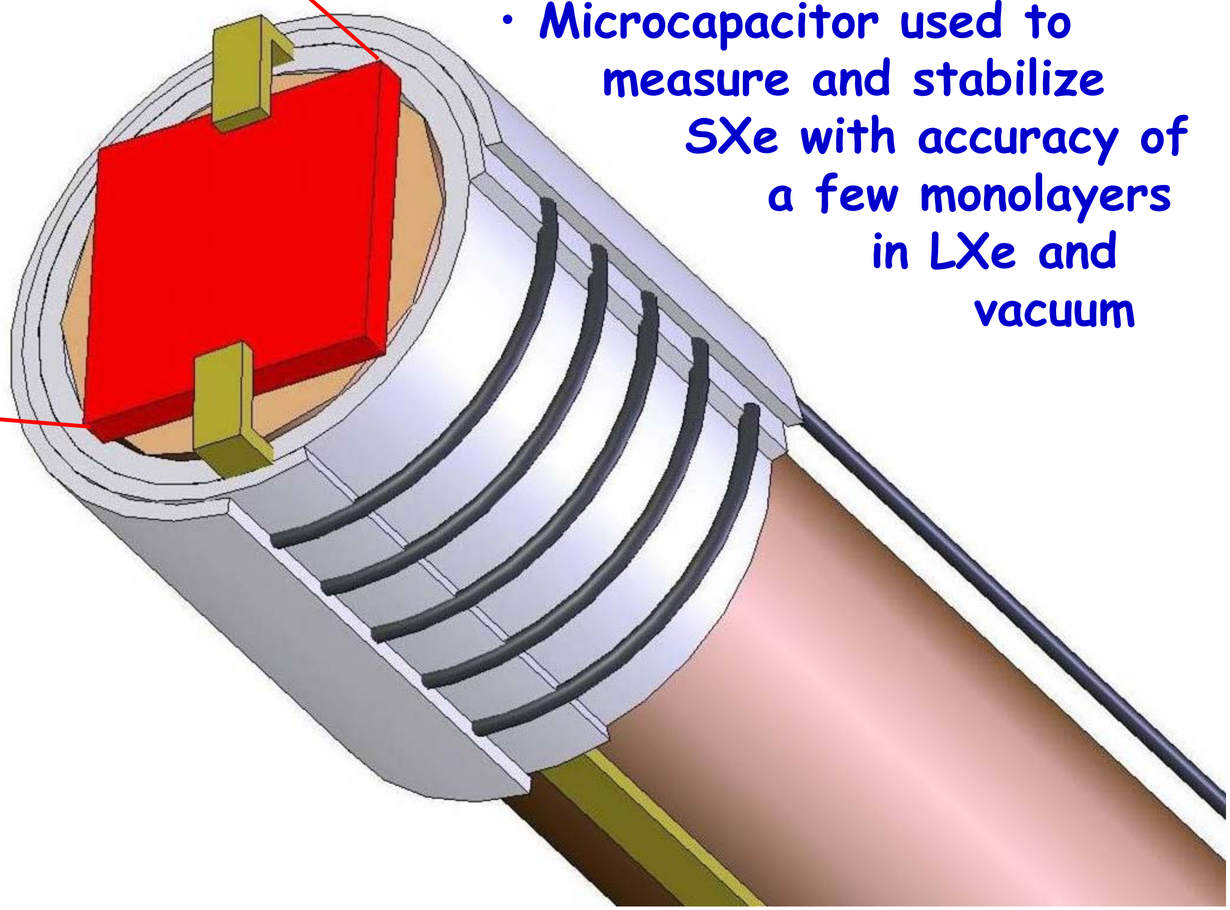
M.Green et al. arXiv:0702122, Phys Rev A 76 (2007) 023404
B.Flatt et al. arXiv:0704.1646, NIM A 578 (2007) 409

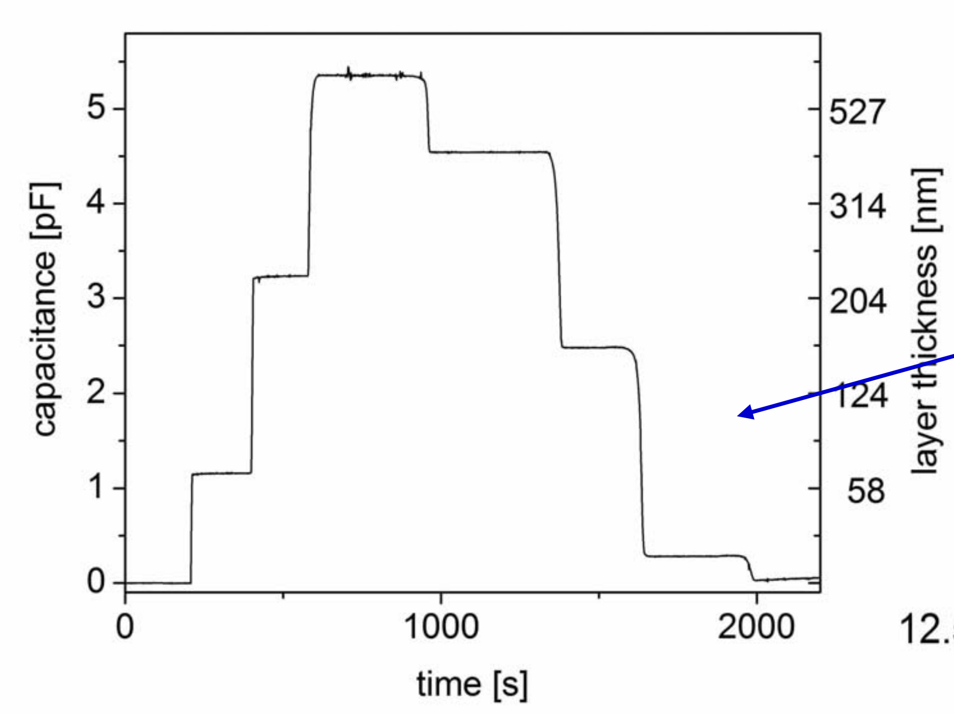
Remaining challenge is the efficient transfer of single Ba ions from LXe to the ion trap



Cryogenic dipstick

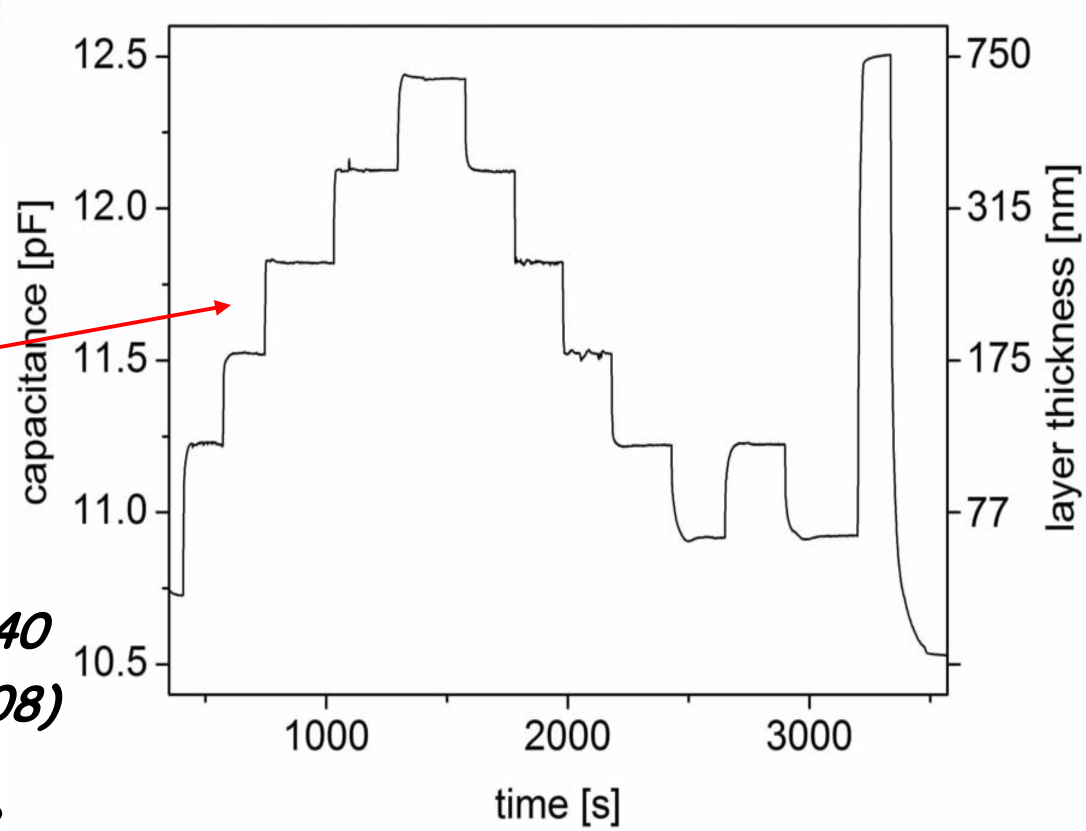
- Capture ion on SXe coating
- LHe cooling (~20K) to maintain stable SXe coating in 10^{-8} torr vacuum
- Microcapacitor used to measure and stabilize SXe with accuracy of a few monolayers in LXe and vacuum





Growing SXe layers from metered amounts of GXe in the vacuum chamber

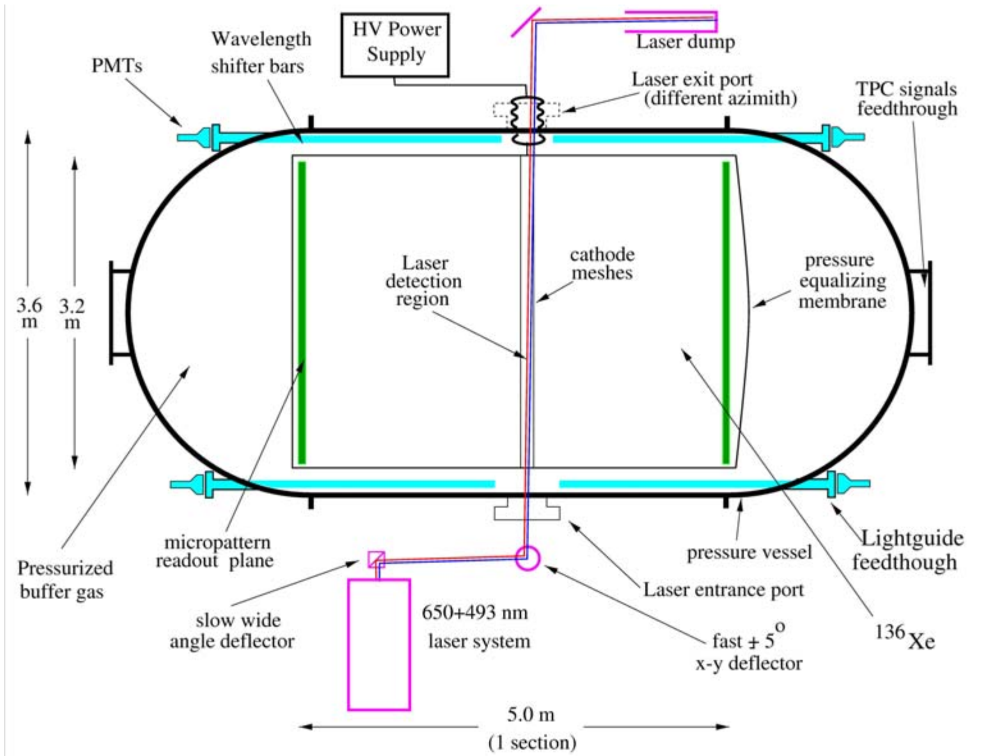
Growing and maintaining SXe layers in a LXe bath with active feedback



P.Fierlinger et al, arXiv:0706.0540

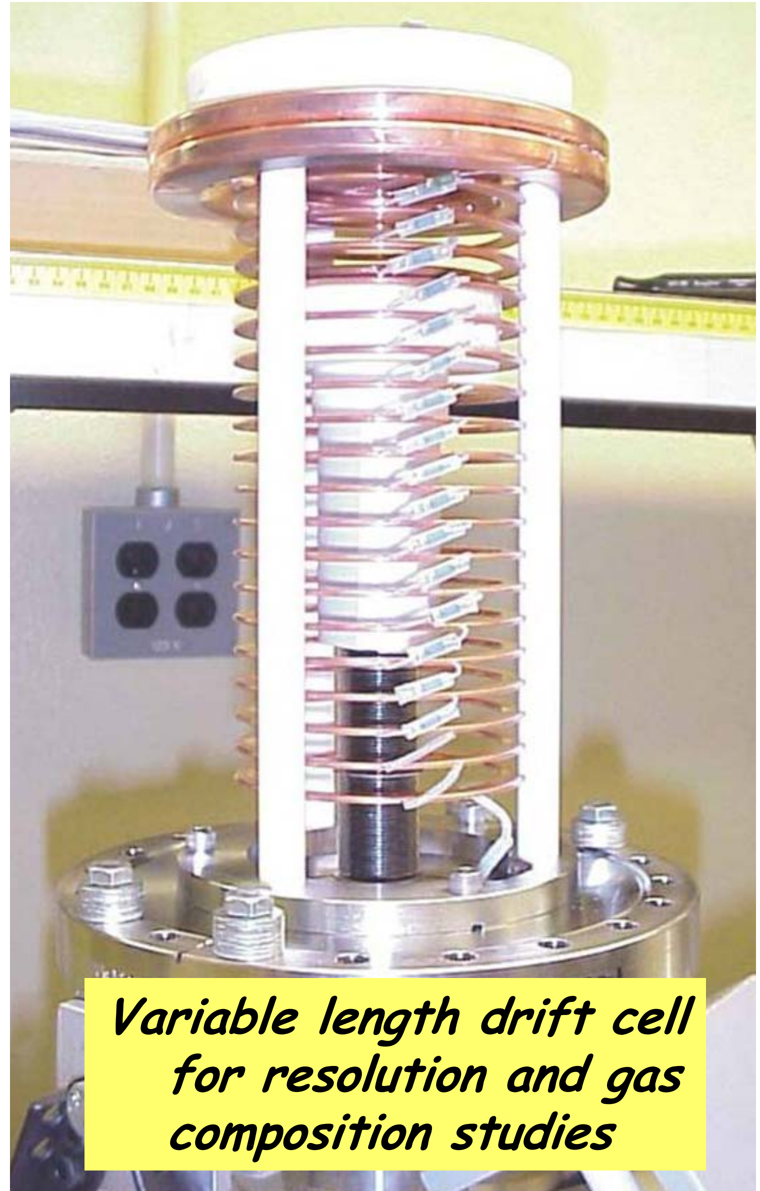
Rev. Sci. Instr. 79, 045101 (2008)

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

→ ***See also NEXT talk on Tuesday***

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.

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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 $\pm2\sigma$ interval centered around the 2.481MeV endpoint
4) Negligible background from $2\nu\beta\beta$ ($T_{1/2}>1\cdot10^{22}$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	Majorana mass (eV) 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) = $1.2^{+3}_{-0.5}\cdot10^{25}$, ($\pm3\sigma$)
(Phys. Left. 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 $T_{1/2} > 1 \cdot 10^{22}$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