Enriched Xenon Observatory for double beta decay

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Last decade: the age of ν physics

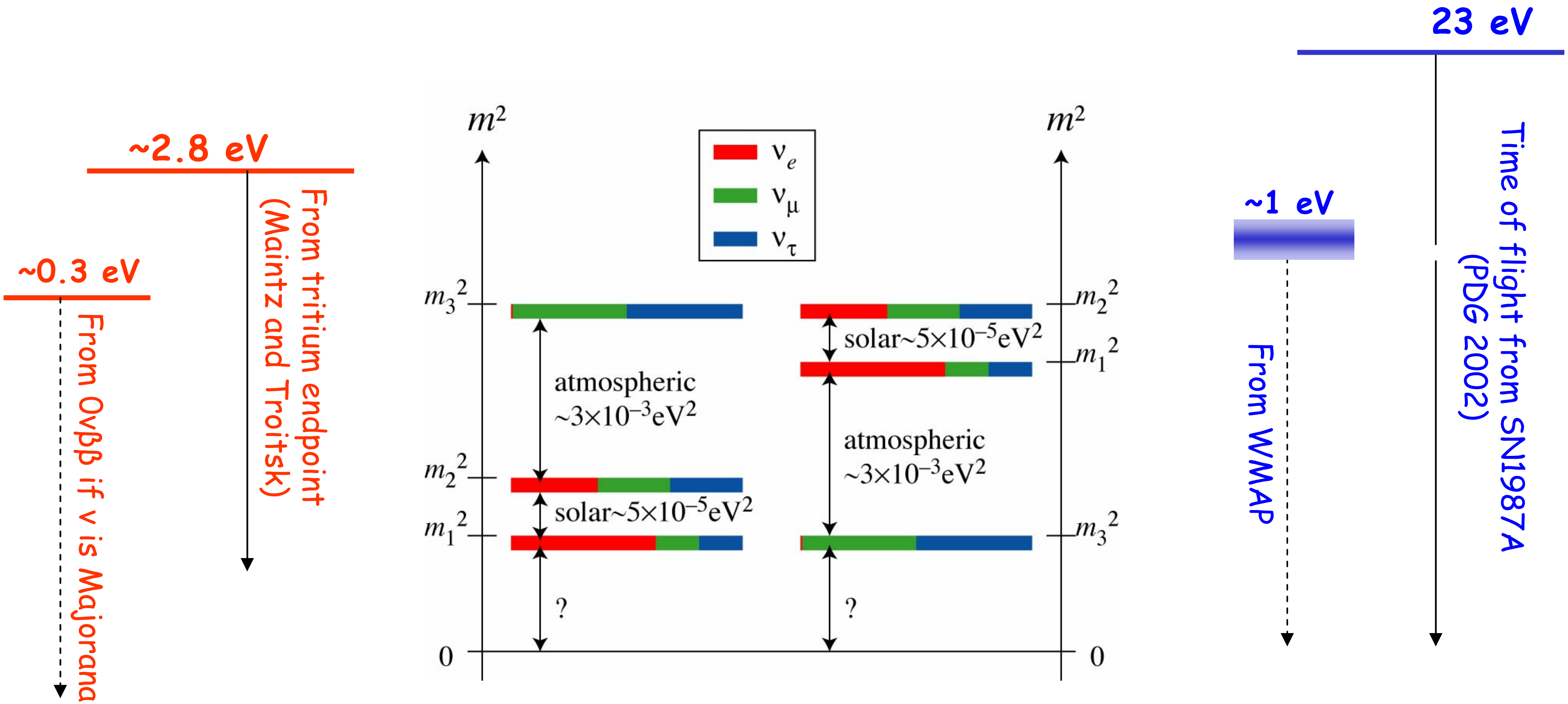
Discovery of ν flavor change

- *Solar neutrinos (MSW effect)*
- *Reactor neutrinos (vacuum oscillation)*
- *Atmospheric neutrinos (vacuum oscillation)*
- *K2K (vacuum oscillation)*
- *Loose ends: LSND/Karmen/miniBoone*

So, assuming miniBoone sees no oscillations,
we know that:

- ν masses are non-zero
- there are 2.981±0.008 ν (Z lineshape)
- 3 ν flavors were active in Big Bang Nucleosynthesis

Yet, we still do not know: - the neutrino mass scale
- the choice of mass hierarchy



~0.3 eV

From 0νββ if ν is Majorana

~2.8 eV

From tritium endpoint (Maintz and Troitsk)

~1 eV

From WMAP

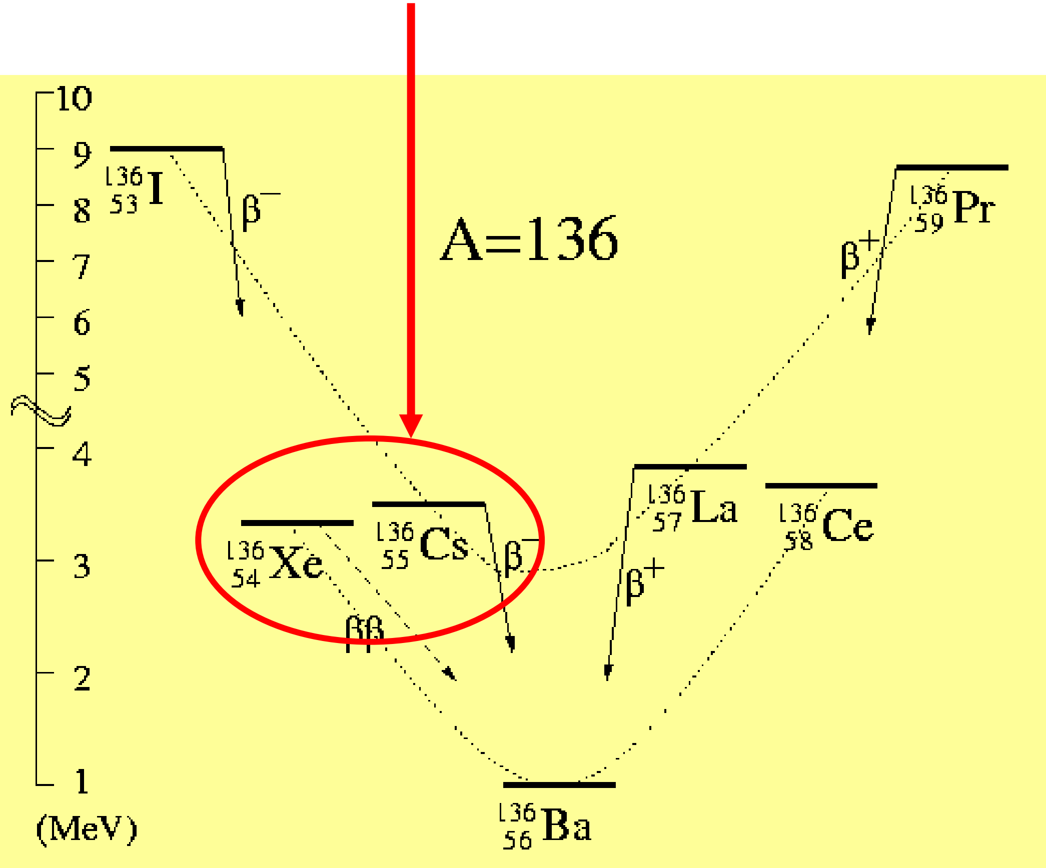
23 eV

Time of flight from SN1987A (PDG 2002)

These *experimental* problems take a central place in the future of Particle Physics

Double-beta decay:

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



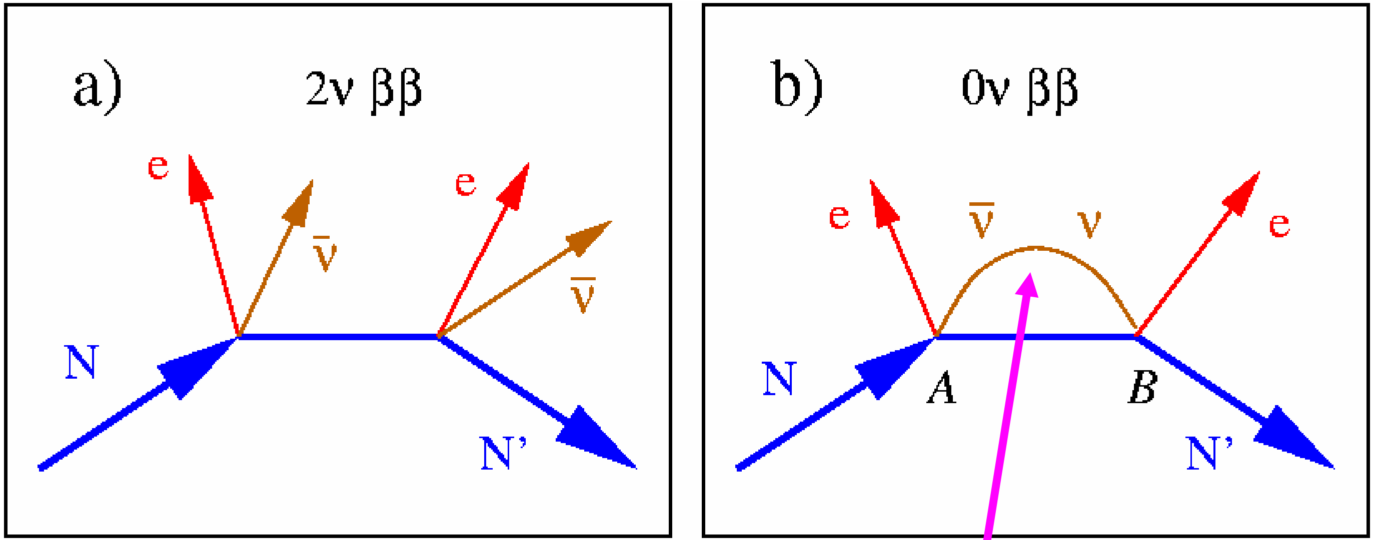
Candidate nuclei with Q>2 MeV

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

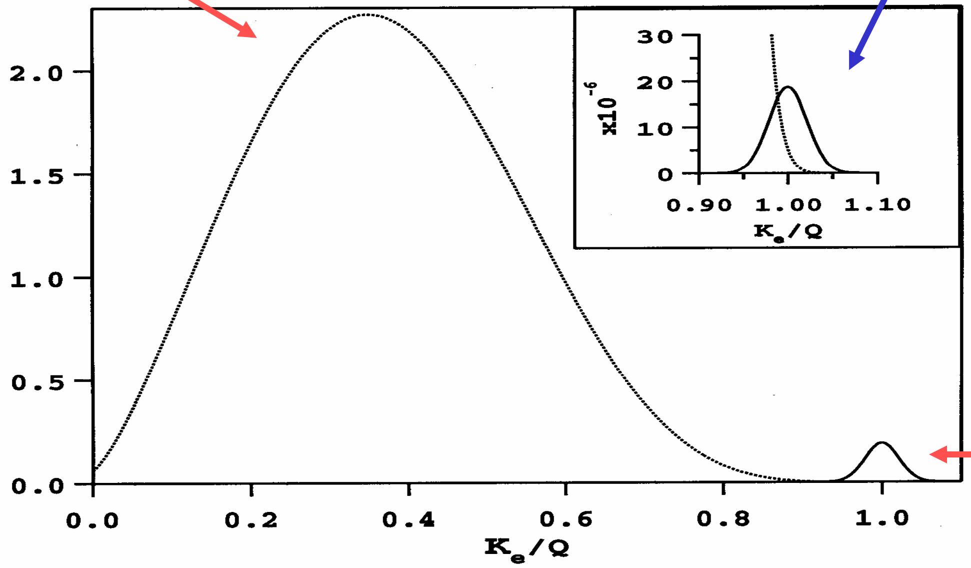
0ν mode: a hypothetical
process can happen
only if:
- $M_\nu \neq 0$ Since helicity has to "flip"
- $\nu = \bar{\nu}$



Several new particles can take
the place of the virtual ν

But 0νββ decay always implies new physics

Background due to the Standard Model $2\nu\beta\beta$ decay



$2\nu\beta\beta$ spectrum
(normalized to 1)

$0\nu\beta\beta$ peak (5% FWHM)
(normalized to 10^{-6})

$0\nu\beta\beta$ peak (5% FWHM)
(normalized to 10^{-2})

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 only effective tool here is 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

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

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			$>9.5*10^{21}$ (76%CL)	
^{76}Ge	Ge diode	~30	$>1.9*10^{25}$ (90%CL)	$<0.39^{+0.17}_{-0.28}$
^{82}Se			$>9.5*10^{21}$ (90%CL)	
^{100}Mo			$>5.5*10^{22}$ (90%CL)	
^{116}Cd			$>7.0*10^{22}$ (90%CL)	
^{128}Te	TeO_2 cryo	~3	$>1.1*10^{23}$ (90%CL)	
^{130}Te	TeO_2 cryo	~3	$>2.1*10^{23}$ (90%CL)	<1.1 - 2.6
^{136}Xe	Xe scint	~10	$>1.2*10^{24}$ (90%CL)	<2.9
^{150}Nd			$>1.2*10^{21}$ (90%CL)	
^{160}Gd			$>1.3*10^{21}$ (90%CL)	

Adapted from the Particle Data Group 2003

Main challenge in 0νββ decay

1) Very large fiducial mass (tons)

need large-scale isotopic enrichment

2) Reduce and control backgrounds in qualitatively new ways

existing experiments are already background limited, unlikely to gain big factors without new techniques

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

For a background scaling like Nt $\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0\nu\beta\beta}} \propto 1/(Nt)^{1/4}$

Need 2) to fully utilize 1) and make a worthwhile experiment

Xe is ideal for a large experiment

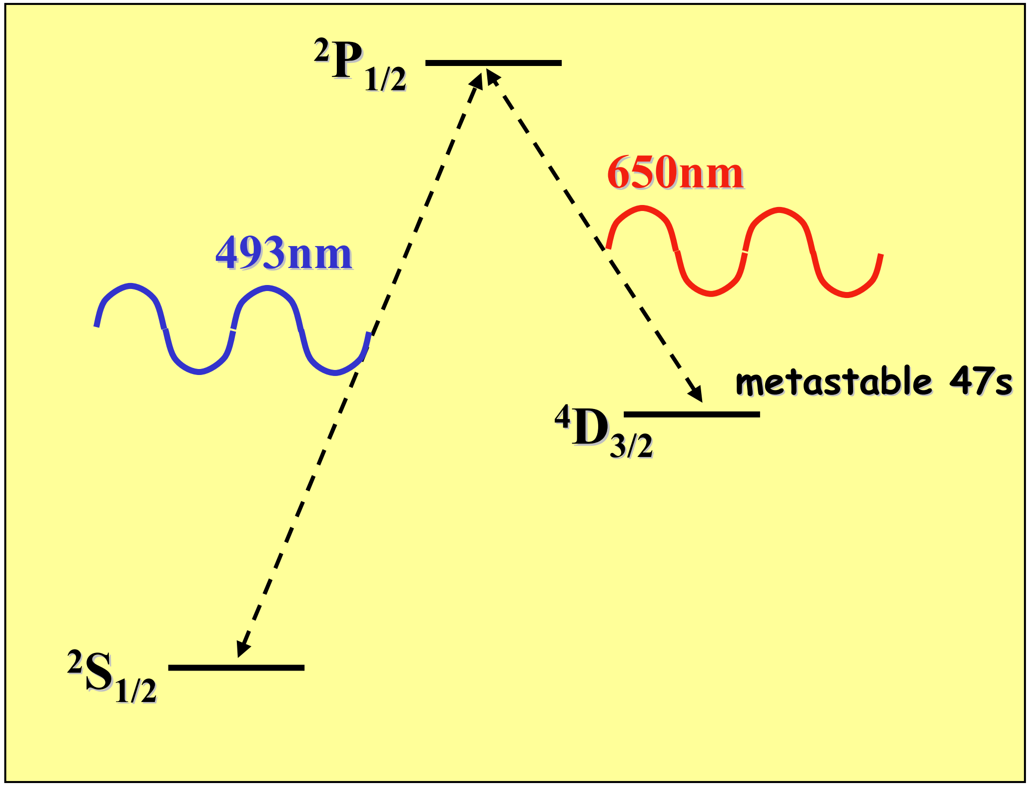
- No need to grow crystals
- Can be re-purified during the experiment
- No long lived Xe isotopes to activate
- Can be easily transferred from one detector to another if new technologies become available
- Noble gas: easy(er) to purify
- ^{136}Xe enrichment easier and safer:
  - noble gas (no chemistry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



The Ba-tagging, added to a conventional Xe TPC rejection power provides the tools to develop a background-free next-generation ββ experiment

Energy resolution is still an all-important parameter to disentangle the 0νββ mode from 2νββ

Fiducial mass between 1 and 10 tons, of ^{136}Xe at 80% depending on the status of the field when we finalize the design

Prototype LXe chamber for 200 kg of 80% ^{136}Xe under construction

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)	$2 * 10^{27}$	33	(95)
Aggressive	10	70	10	1[†]	0.7 (use 1)	$4.1 * 10^{28}$	7.3	(21)

[*] $\sigma(E)/E$ = 1.6% obtained in EXO R&D, Conti et al Phys Rev B 68 (2003) 054201

[†] $\sigma(E)/E$ = 1.0% considered as an aggressive but realistic guess with large light collection area

[‡] QRPA: A.Staudt et al. Europhys. Lett.13 (1990) 31; Phys. Lett. B268 (1991) 312

[#] NSM: E.Caurier et al. Phys Rev Lett 77 (1996) 1954

A LXe detector more elegant BUT technology needs testing → prototype detector

- Very small detector (3m^3 for 10tons)
- Need good E resolution
- Position info but blobs not resolved
- Readout Xe scintillation
- Can extract Ba from hi-density Xe
- Spectroscopy at low pressure:
  ^{136}Ba (7.8% nat'l) different signature from natural Ba (71.7% ^{138}Ba)
- No quencher needed, neutralization done outside the Xe

High Pressure gas TPC backup technology

- 20 atm, 35 m^3 modules, 4.2 ton/module, 2 modules
- Xe enclosed in a non-structural bag
- β range ~5cm: can resolve 2 blobs
- 2.5m e-drift at ~250kV
- Readout Xe scintillation with WLSB (T0)
- Additive gas: quenching and $Ba^{++} \rightarrow Ba^{+}$ neutralization
- Steer lasers or drift Ba-ion to detection region

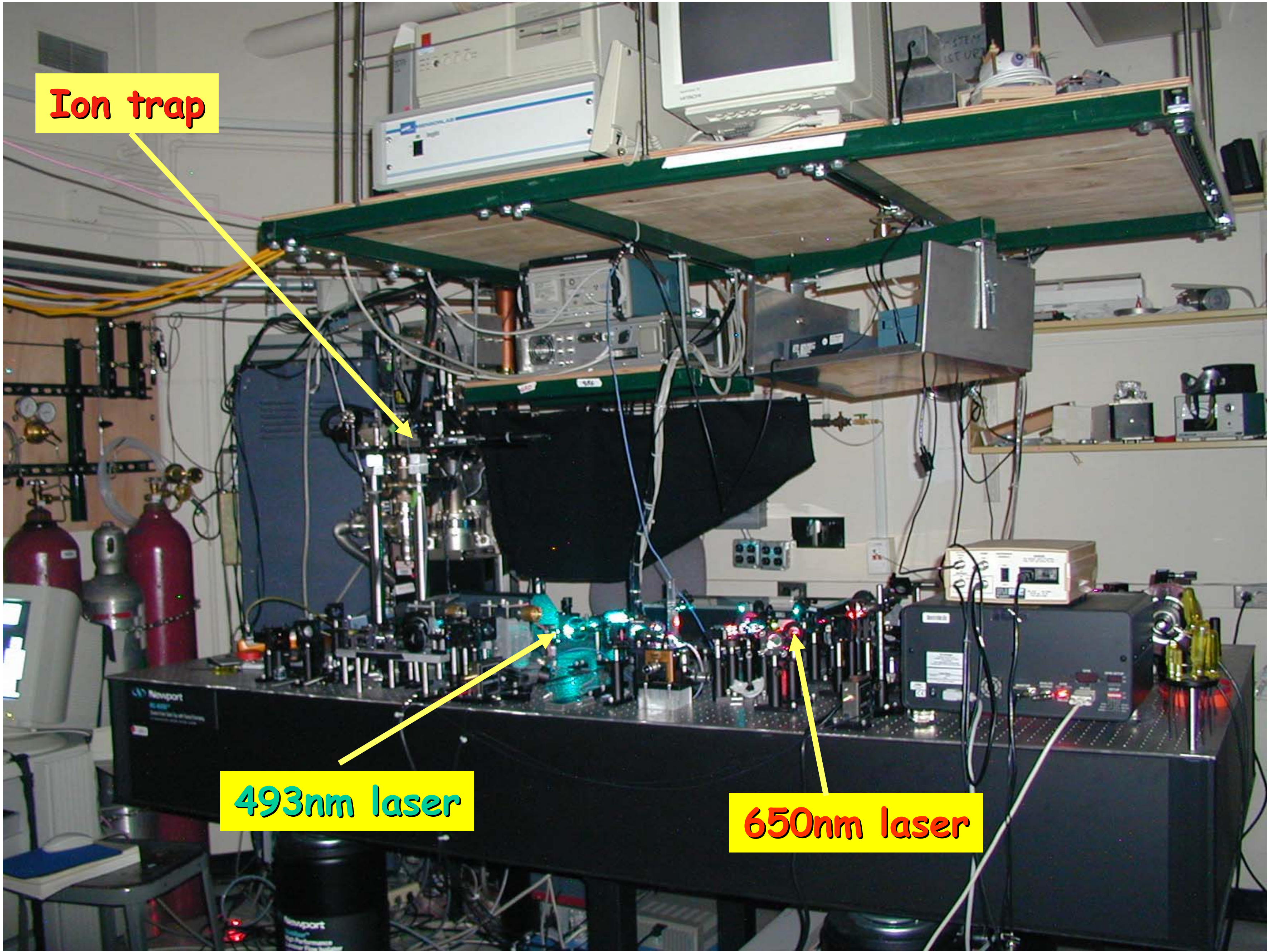
R&D mainly at Neuchatel & ITEP

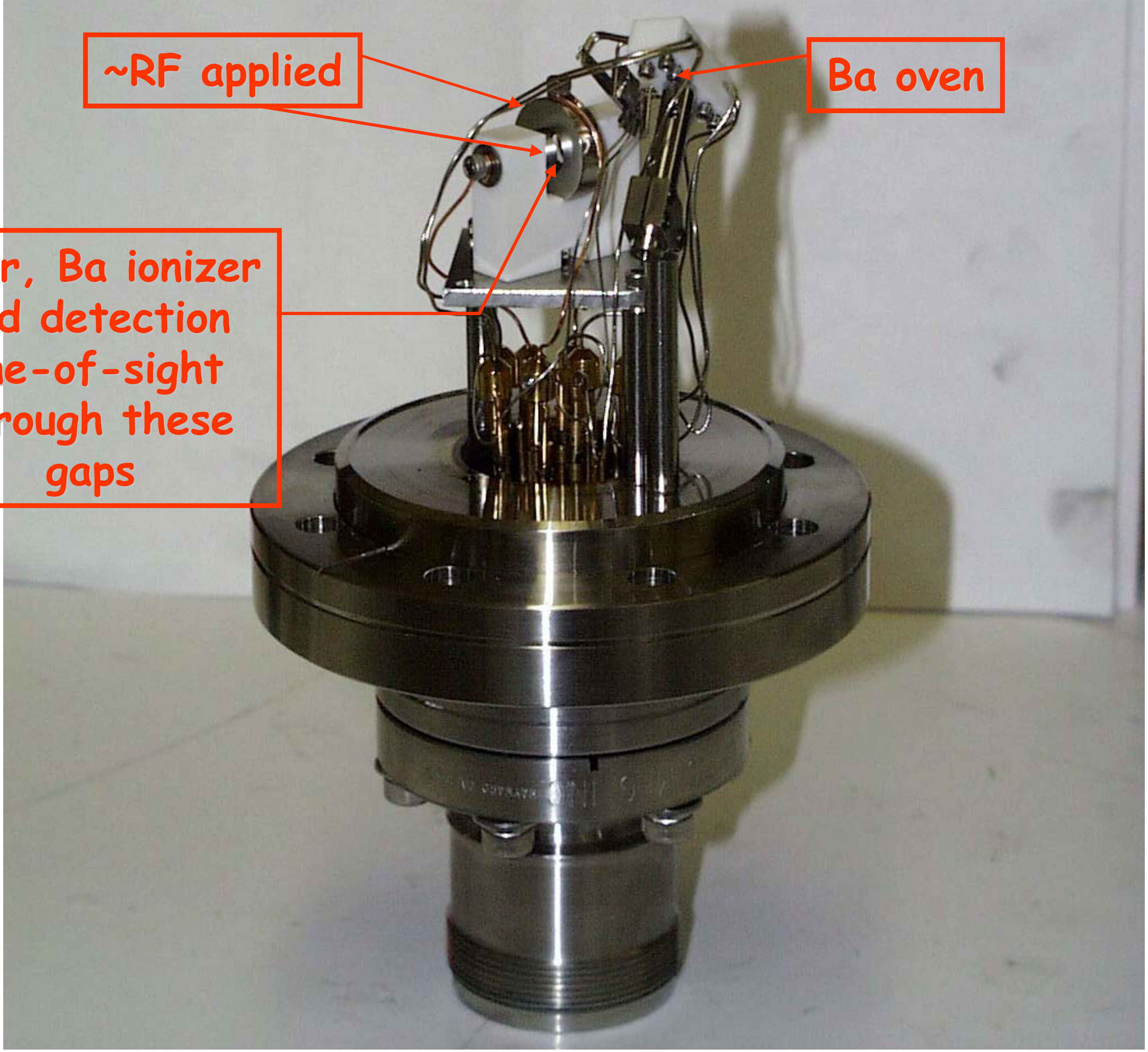
R&D status

- Single ion Ba$^+$ tagging at different residual Xe pressures
- ⚡ LXe energy resolution
- ⚡ Xe purification for long e$^-$ lifetime
- Xe radiopurity
- Ba ion lifetime and grabbing from LXe
- Single ion Ba tagging in directly LXe
- ⚡ Drift velocity of Ba$^+$ in LXe
- ⚡ Procurement/qualification of low background materials
- ⚡ Isotopic enrichment of large amounts of ^{136}Xe
- Construction/operation of 200 kg ^{136}Xe prototype detector

⚡ = *Achieved*

EXO spectroscopy lab



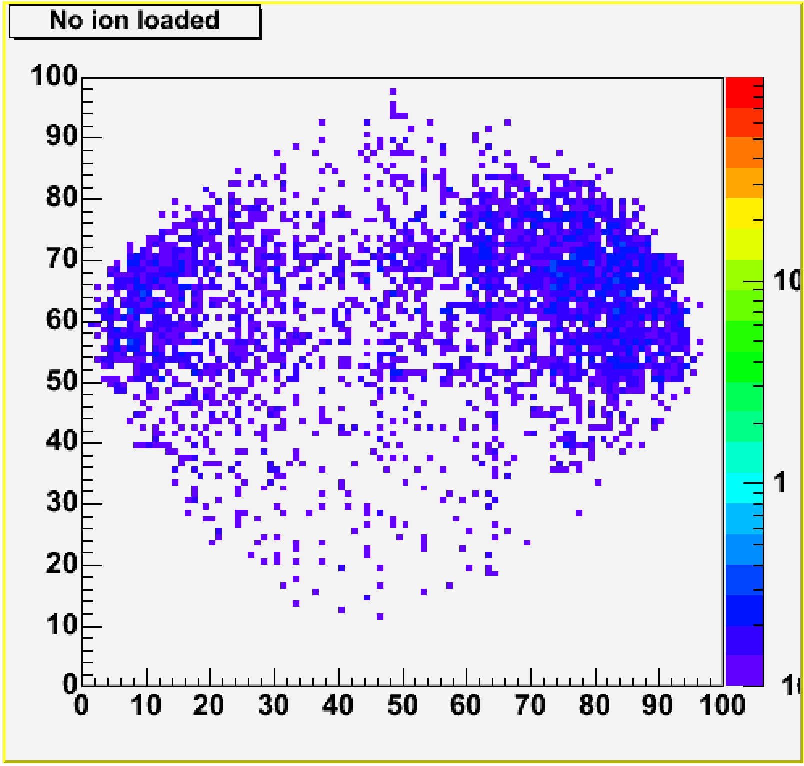


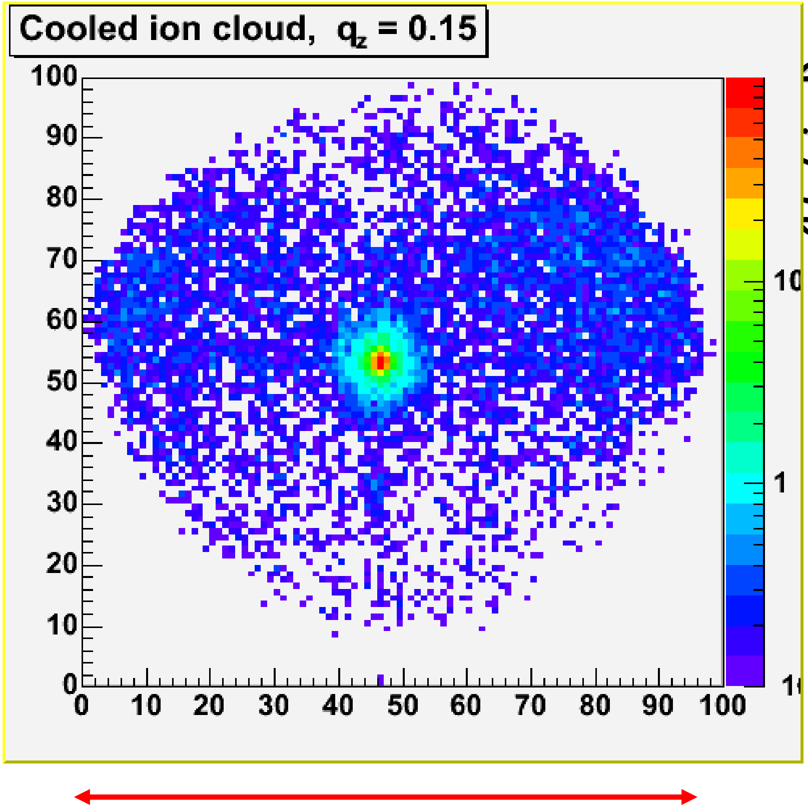
~RF applied

Ba oven

laser, Ba ionizer and detection line-of-sight through these gaps

First in vacuum: photo of a Ba ion



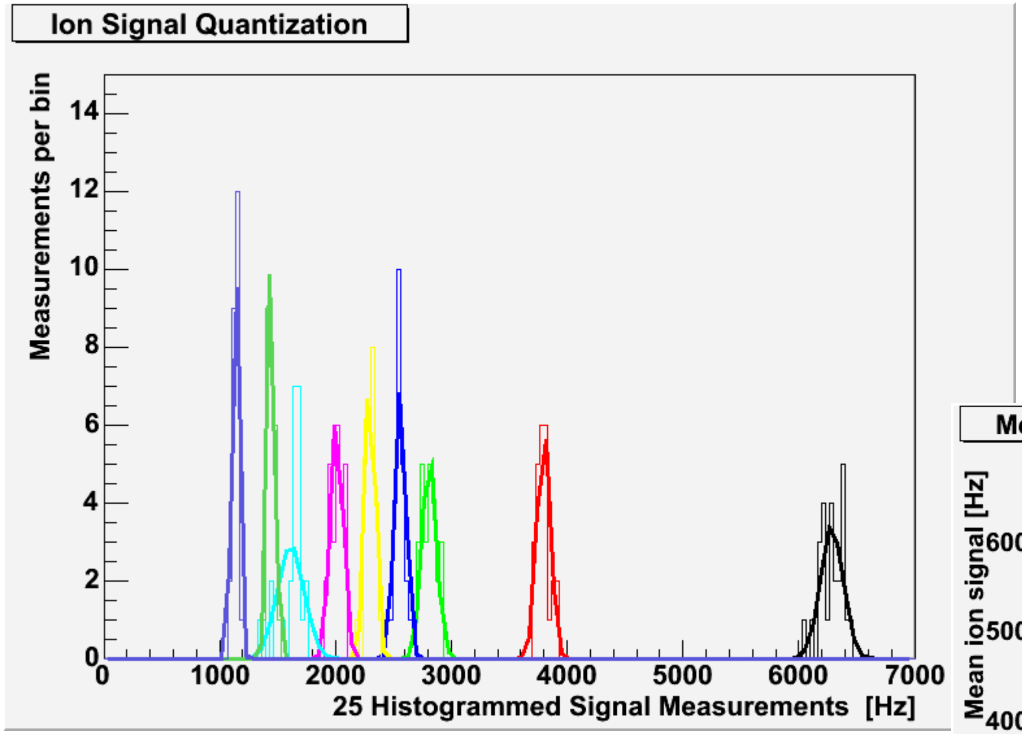


850 µm

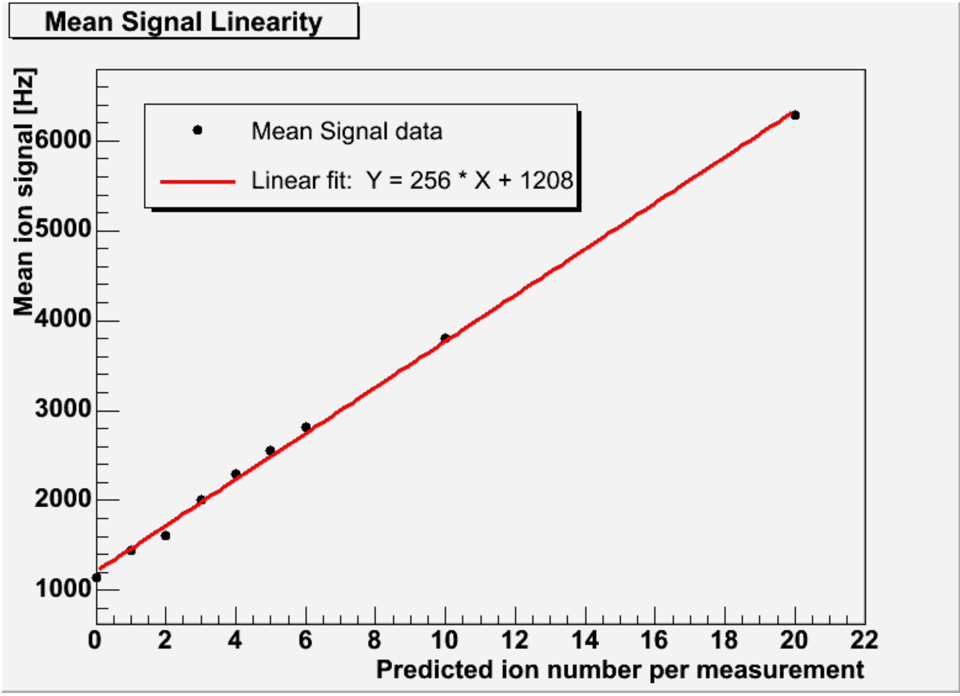
Background is obtained by turning off the red light

S/N~100 even with a CW measurement !

Millikan experiment with ions in vacuum

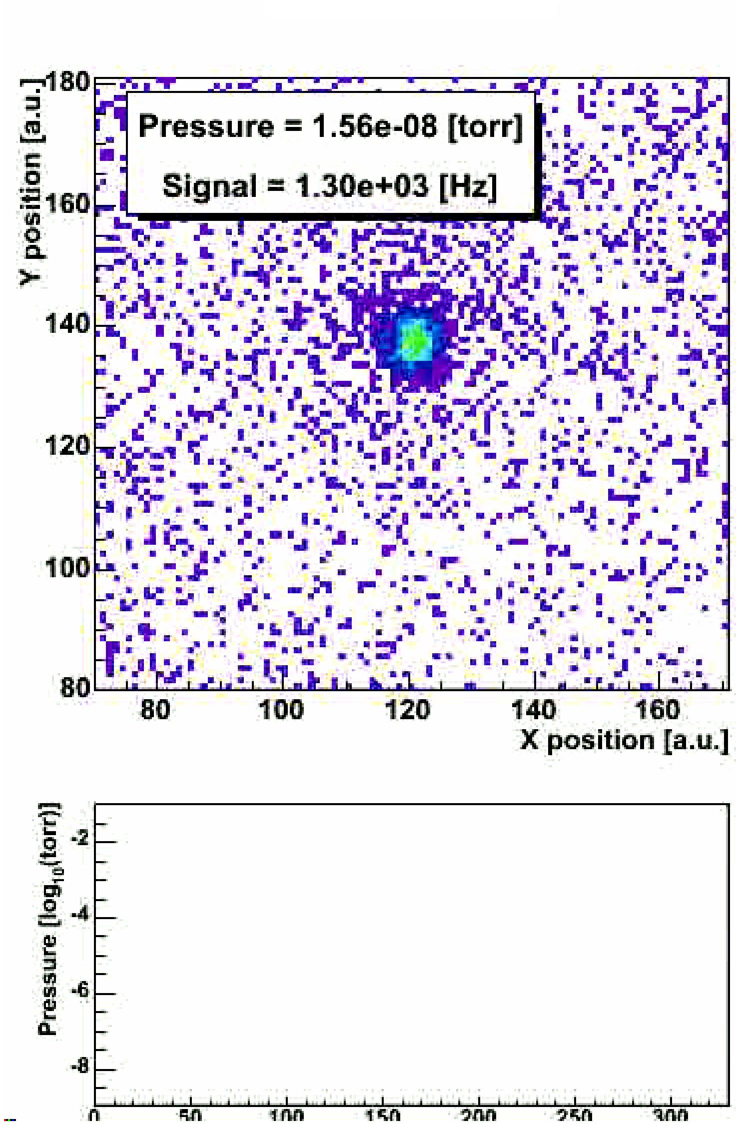


The signal amplitude is proportional to integers



Now we introduce gas

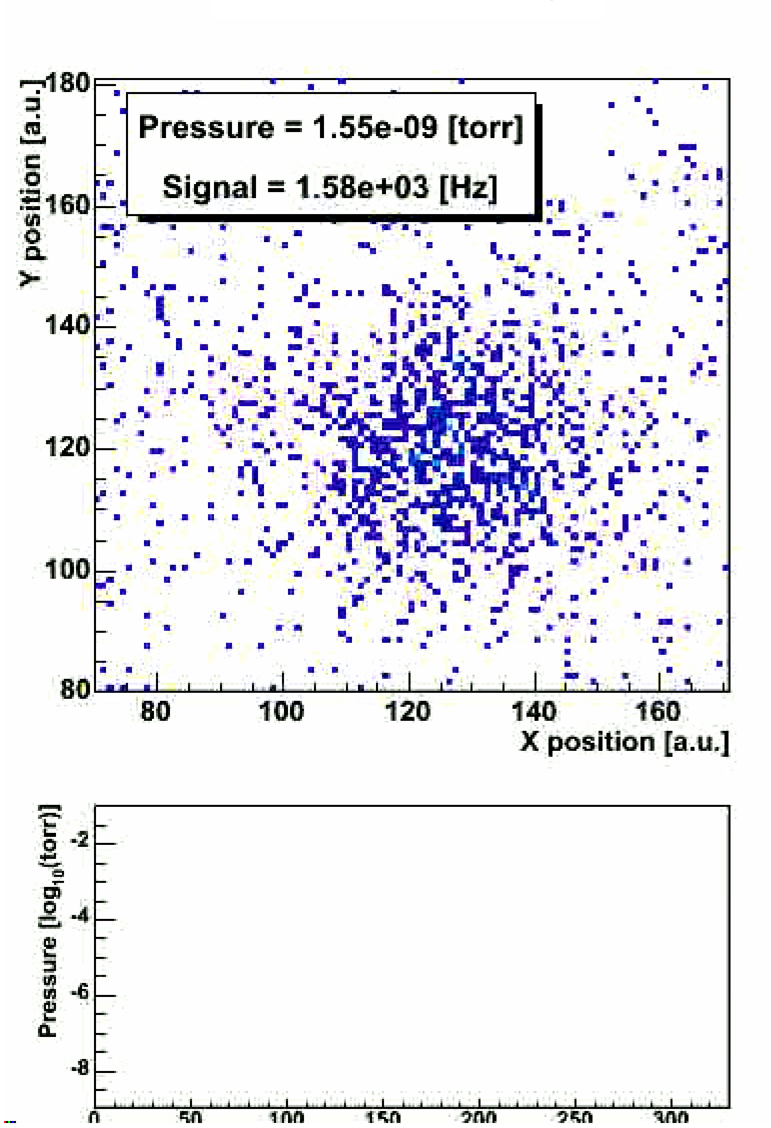
First He…



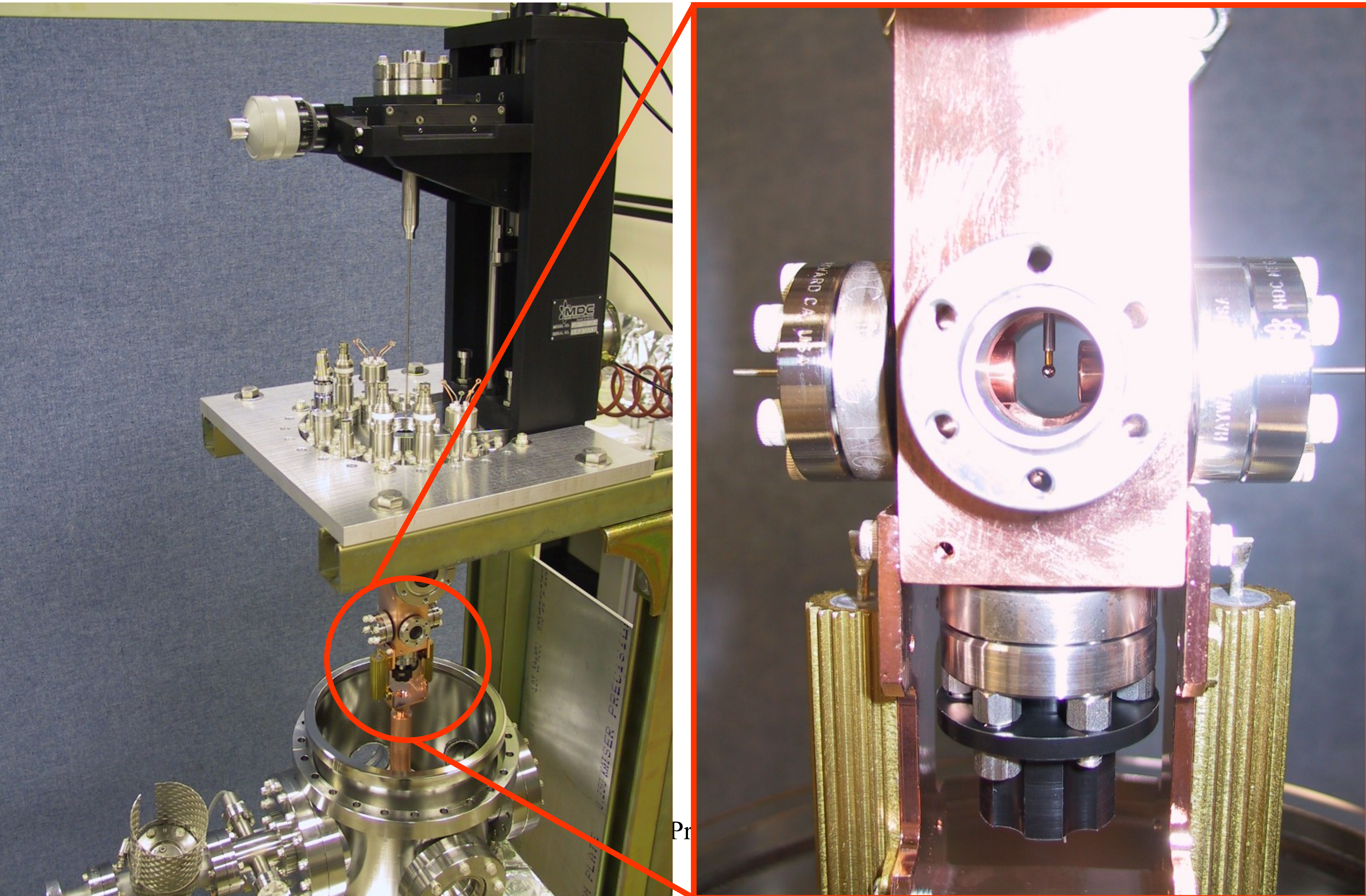
0.1 torr →

10^{-9} torr →

…and then Xe



Fishing ions in LXe



Pr

^{230}U (20.8d)

α 5.99MeV

^{226}Th (30.5min)

α 6.45MeV

^{222}Ra (38s)

α 6.68MeV

^{218}Rn (35ms)

α 7.26MeV

^{214}Po (164ms)

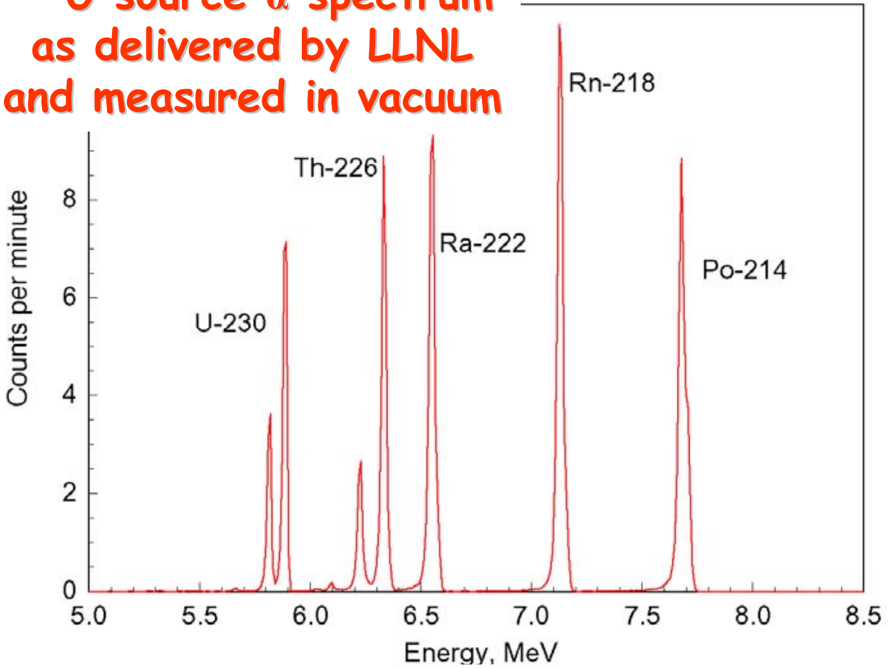
α 7.83MeV

^{210}Pb (22yr)

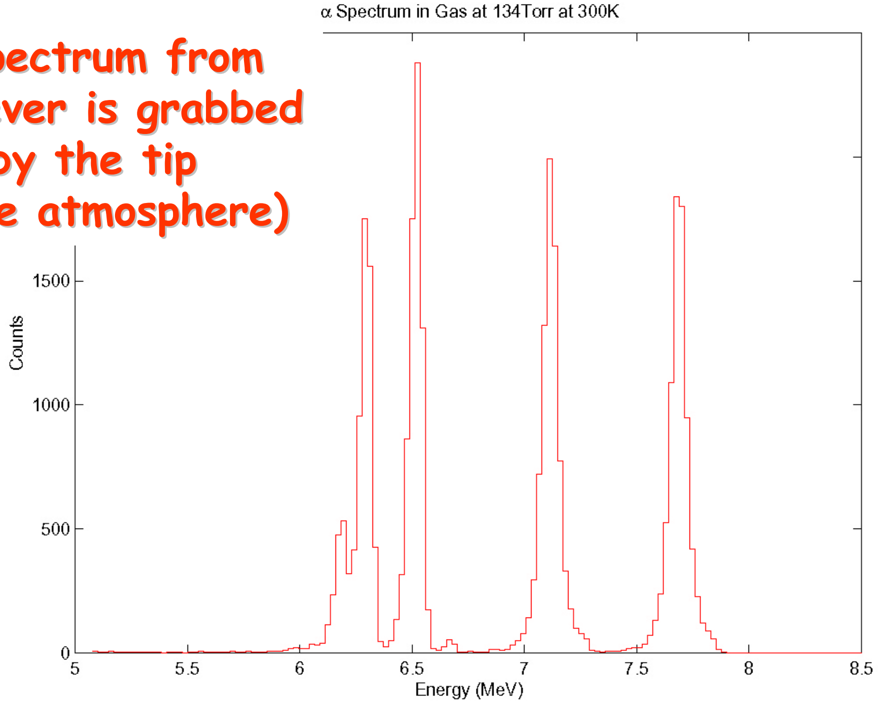
Initial Ra/Th ion grabbing successful

As expected release from a finite size metallic tip is challenging

^{230}U source α spectrum as delivered by LLNL and measured in vacuum

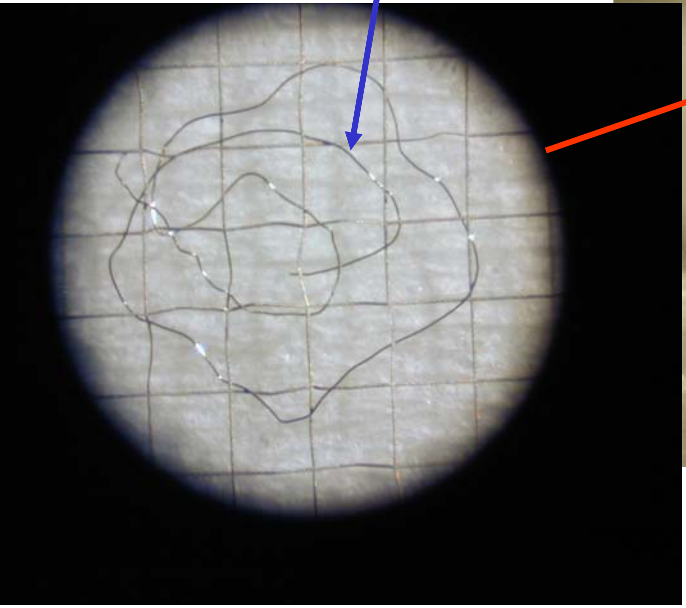


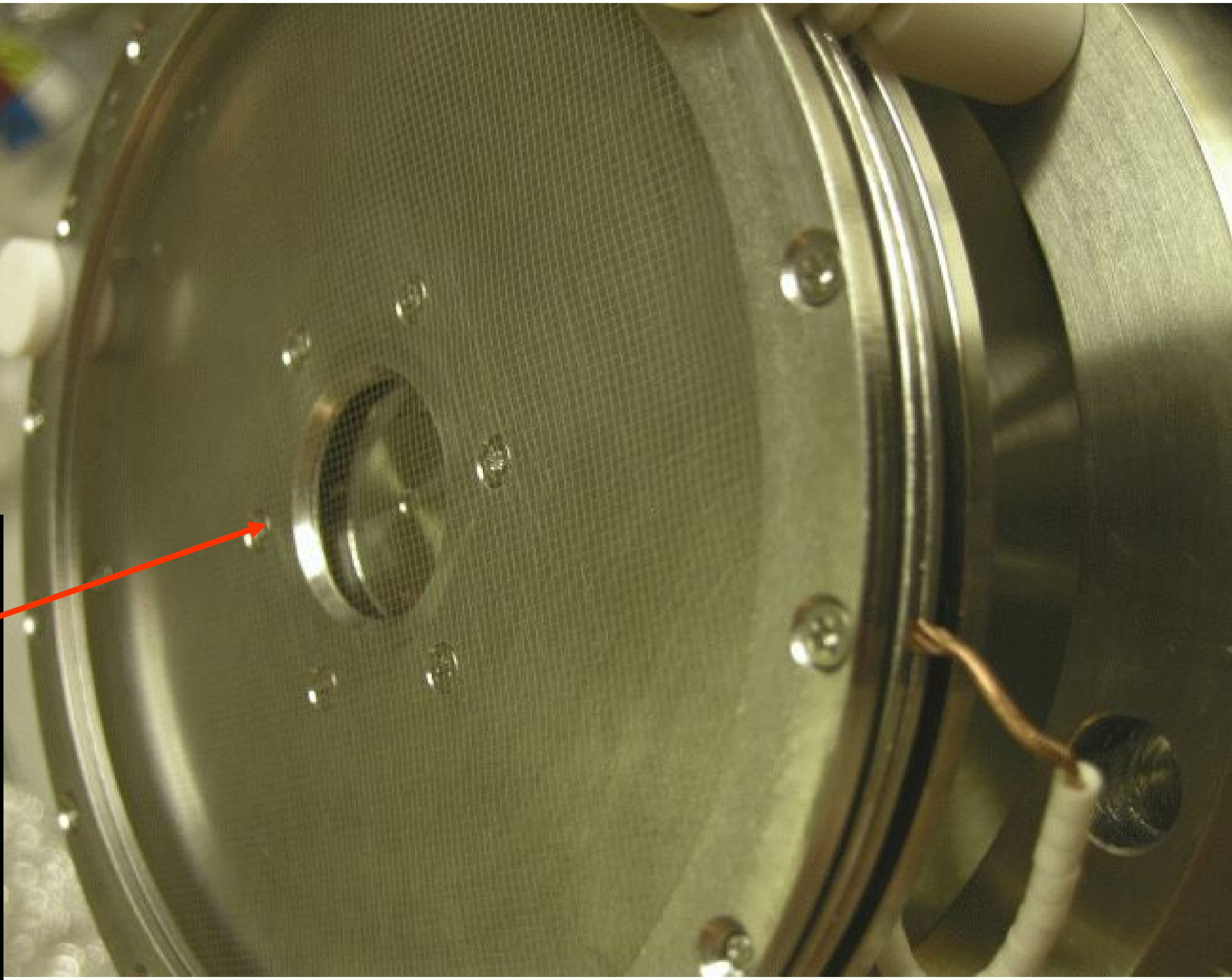
α spectrum from whatever is grabbed by the tip (in Xe atmosphere)



Pancake shaped 1liter LXe ionization chamber to test energy resolution
Good acceptance to scintillation light AND ionization

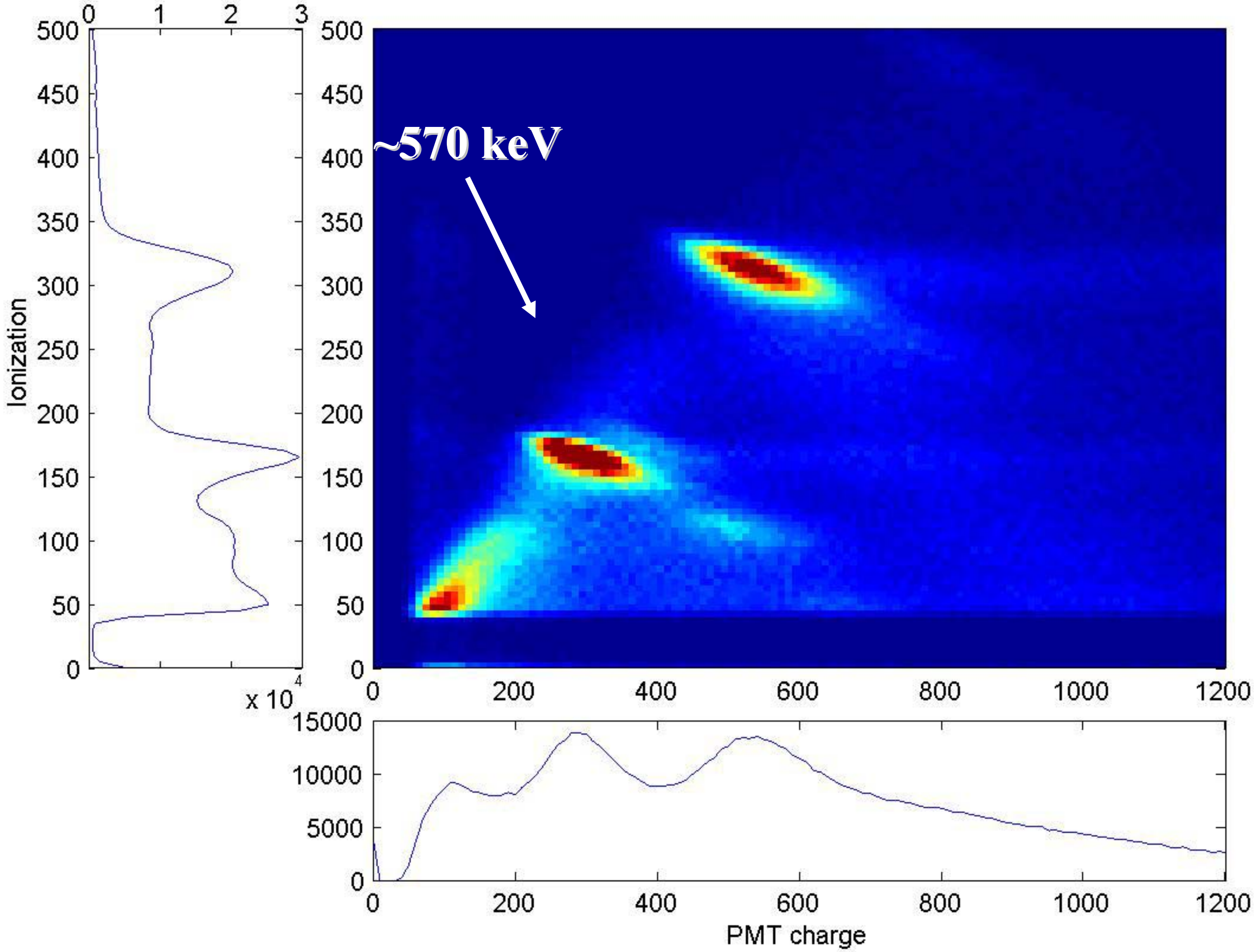
Electron/gamma source ^{208}Bi needs to be very small to avoid self shadowing (20μm plated wire)

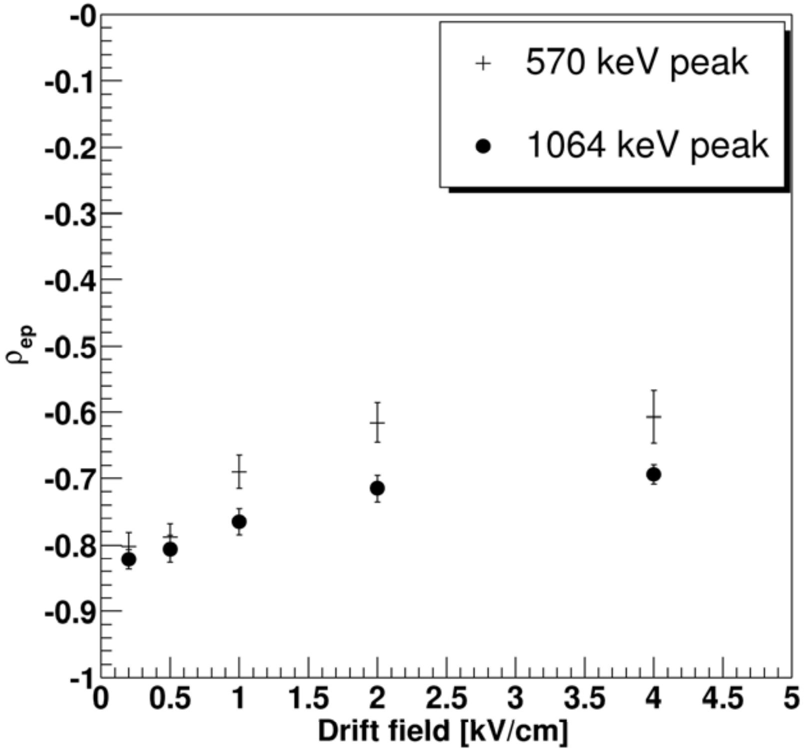




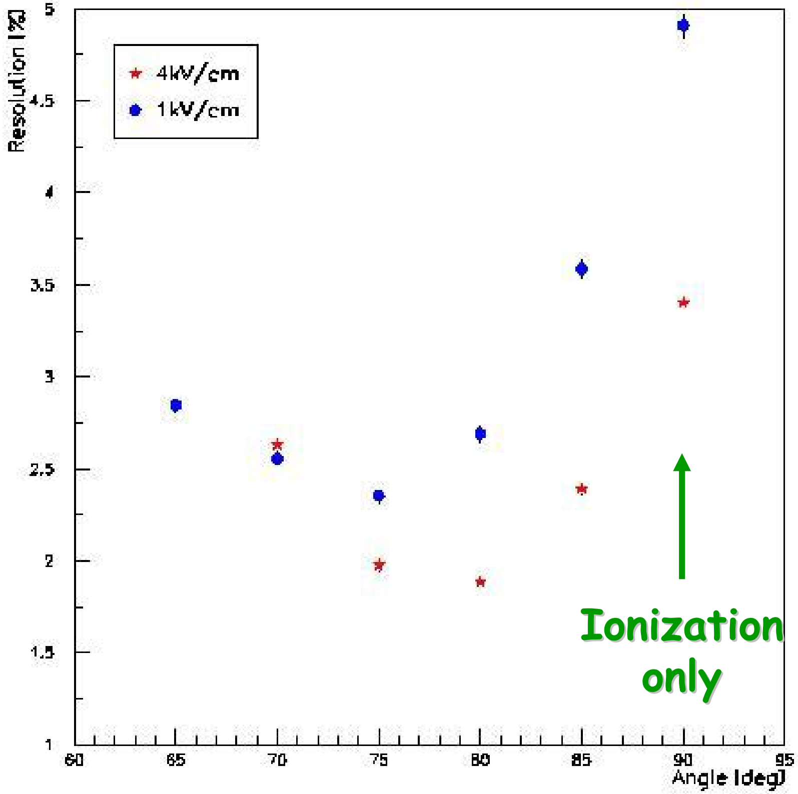
Energy resolution in LXe

Found a clear (anti)correlation between ionization and scintillation





The correlation is present at all fields



Ionization only

The best resolution is obtained by a linear combination of the scintillation and ionization signals

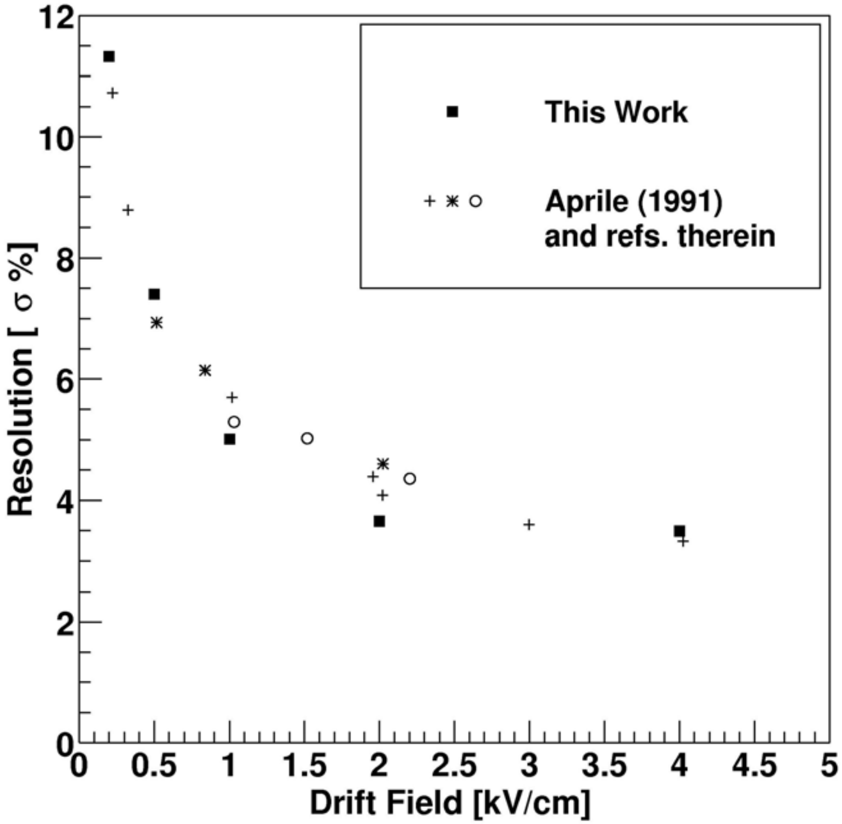
E.Conti et al. Phys Rev B 68 (2003) 054201

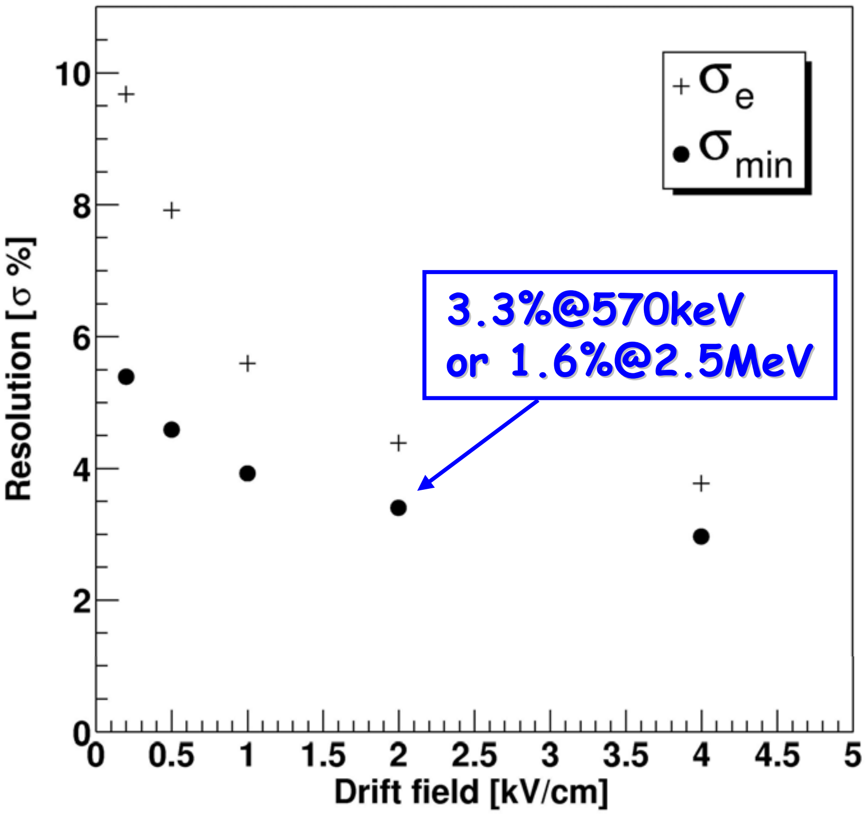
Have demonstrated that we can get sufficient energy resolution in LXe to separate the 2ν from the 0ν modes

We can do ionization measurements as well as anyone

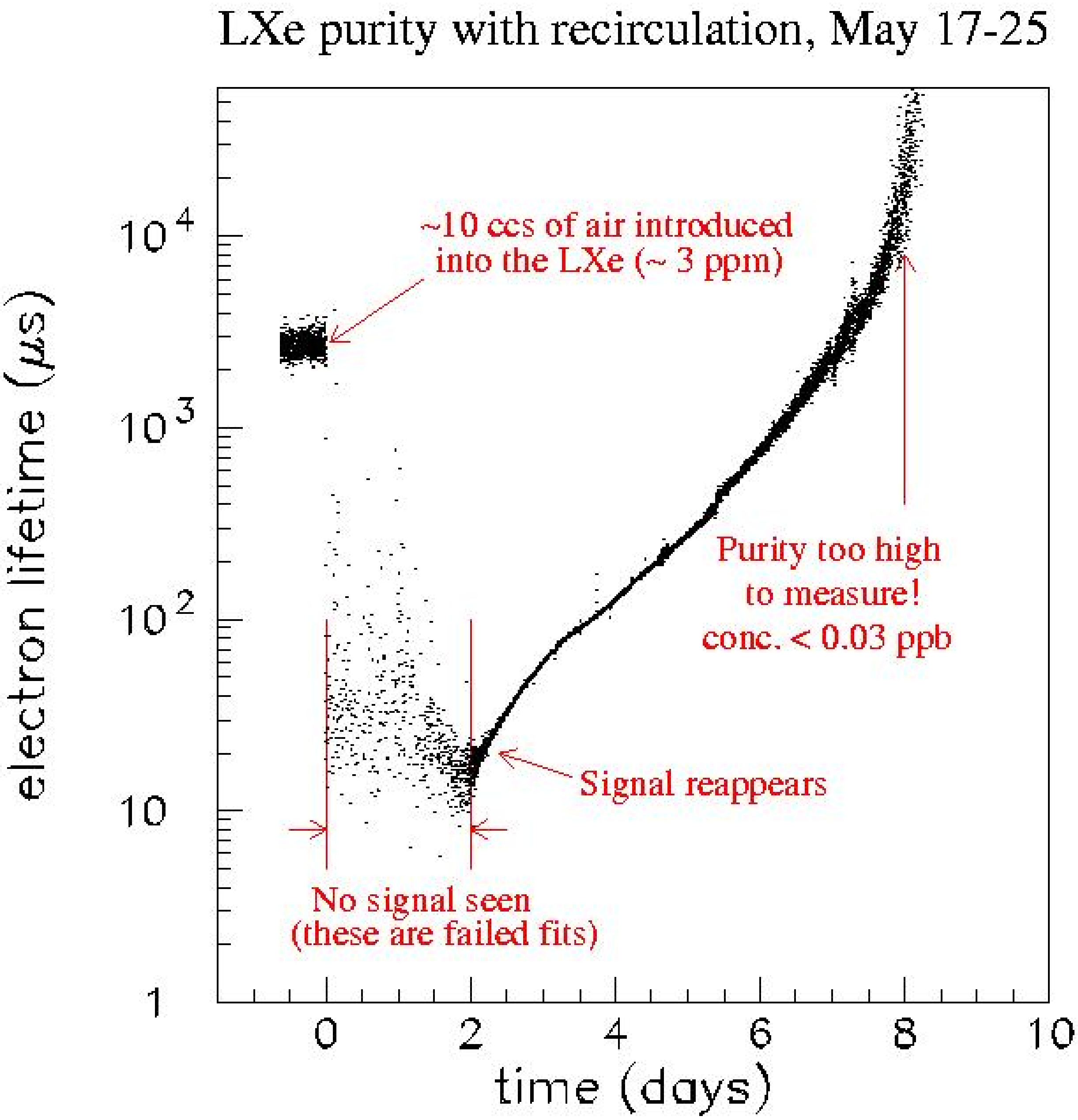
Resolutions at 570 keV

Now we turn on our new correlation technique…





3.3%@570keV
or 1.6%@2.5MeV



Keeping our Xenon clean…

200 kg prototype LXe detector

- Full test of low background LXe technology
- Largest ββ detector ever built
- No Ba tagging (being developed in parallel)
- ~60 liters enriched liquid ^{136}Xe,
  - In low background teflon vessel
  - Surrounded and shielded by ~50 cm radially low background thermal transfer fluid
  - Contained in a low background Cu double walled vacuum insulated cryostat
  - Shielded by ~ 5 cm very low background Pb
  - Further shielded by ~20 cm low background Pb
  - Located ~800 m below ground in NaCl deposit – WIPP in Carlsbad, New Mexico
- Detector is a liquid TPC with photo-detectors to provide start time and improve energy resolution of the β's.

Will measure the 2ν mode in ^{136}Xe

2νββ decay has never been observed in ^{136}Xe.
Some of the lower limits on its half life are close to (and in one case below) the theoretical expectation.

	$T_{1/2}$ (yr)	evts/year in the 200kg prototype (no efficiency applied)
Experimental limit		
Leuscher et al	$>3.6 \cdot 10^{20}$	<1.3 M
Gavriljuk et al	$>8.1 \cdot 10^{20}$	<0.6 M
Bernabei et al	$>1.0 \cdot 10^{22}$	<48 k
Theoretical prediction		
QRPA (Staudt et al) [$T_{1/2}^{max}$]	$=2.1 \cdot 10^{22}$	$=23$ k
QRPA (Vogel et al)	$=8.4 \cdot 10^{20}$	$=0.58$ M
NSM (Caurier et al)	$(=2.1 \cdot 10^{21})$	$(=0.23$ M$)$

The 200kg EXO prototype should definitely resolve this issue

EXO 200kg prototype mass sensitivity

Assumptions:

1) 200kg of Xe enriched to 80% in 136
2) σ(E)/E = 1.6% 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 ±2σ interval centered around the 2.481MeV endpoint
4) Negligible background from 2νββ ($T_{1/2}>1\cdot10^{22}$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	(NSM)
Prototype	0.2	70	2	1.6*	40	$6.4*10^{25}$	0.18	(0.53)

What if Klapdor's observation is correct ?

Central value <m>=0.44 eV, ±3σ range (0.24eV – 0.58eV)
(Phys. Lett. B 586 (2004) 198-212)

In 200kg EXO, 2yr would observe 57 events (QRPA) on top of 40 events bkgd

Using lower bound (0.24 eV) would have 17.3 signal events (and 40 bkgd),
a 2.3 σ effect

Massive materials qualification program

(Alabama, Carleton, Laurentian and Neuchatel)

Most critical are the materials for the chamber body
Very high sensitivity using NAA using MIT reactor and
U of Alabama counting/chemical processing

Material	Origin	U(ppt)	Th (ppt)	K (ppt)
Synthetic silica	BaBar DIRC (St Gobain)	<4.6	12±2	<4600
Polycarbonate	Dow Corning pellets	<6.5	<33	18000±2000
PTFE teflon	DuPont TE6472 powder	<44	<1.8	2500±800
PFA teflon	DuPont 440HP pellets	<1.8	<1.9	<900

Isotopic enrichment for a gaseous substance like Xe is most economically achieved by ultracentrifugation

Russia has enough production capacity to process 100 ton Xe and extract up to 10 ton ^{136}Xe in a finite time

This separation step that rejects the light fraction is also very effective in removing ^{85}Kr ($T_{1/2}$=10.7 yr) that is present in the atmosphere from spent fuel reprocessing

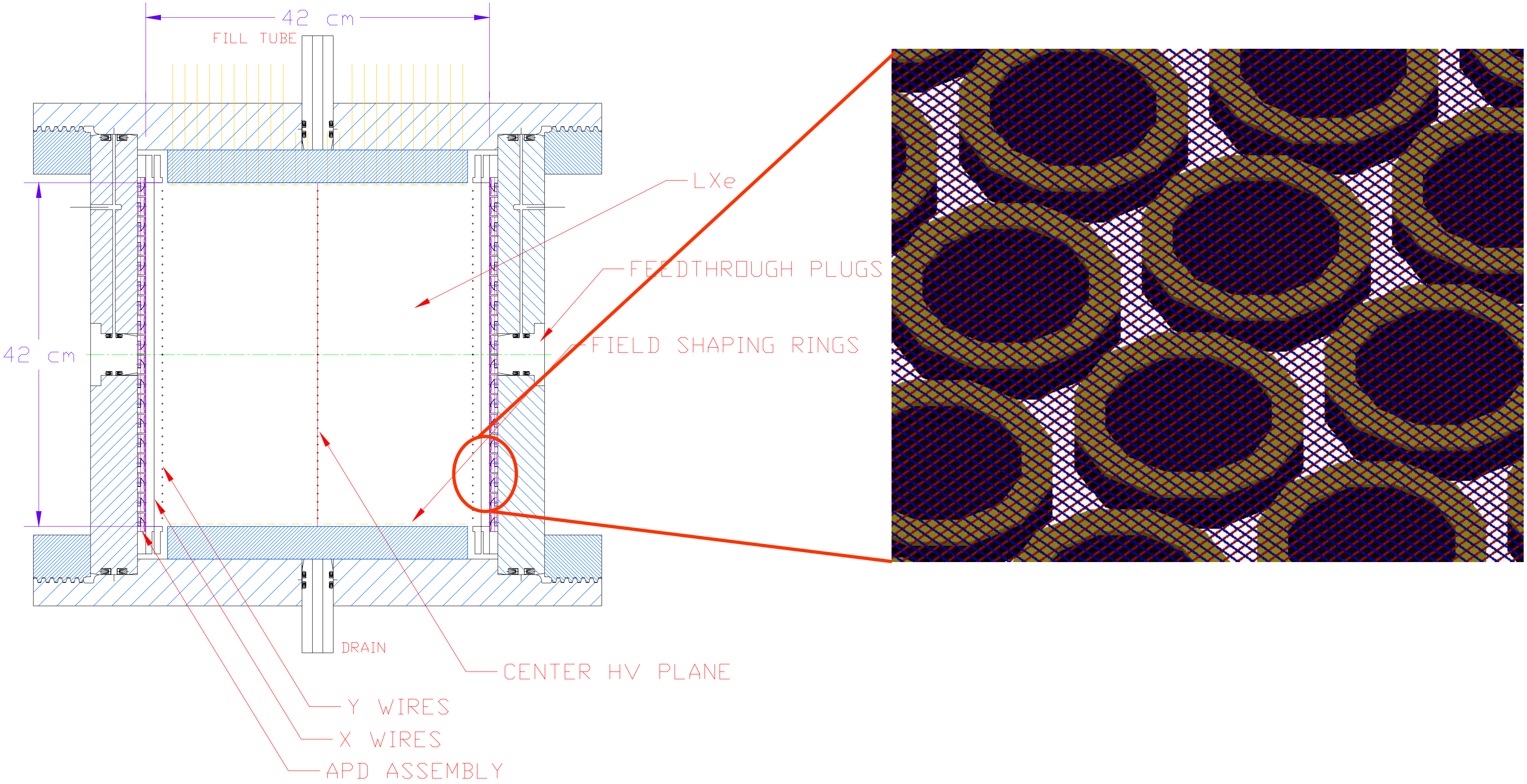
First 200 kg pilot production started in the Summer of 2001 and was successfully completed in May 2003

Funding by DoE-EM, Stanford and University of Alabama

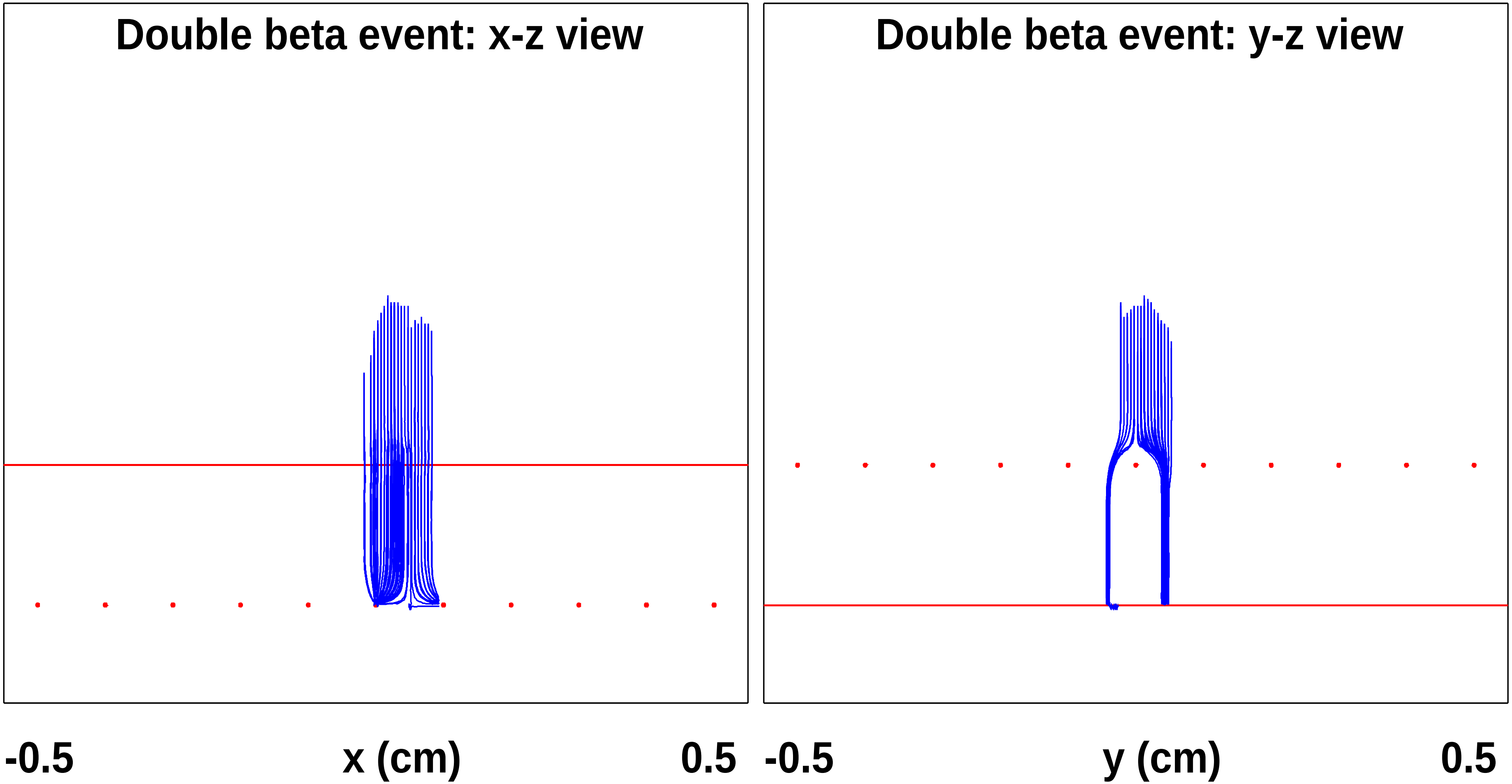
In-kind natural Xe contribution By ITEP

This is already the largest non-fissile isotope enrichment program ever entertained !

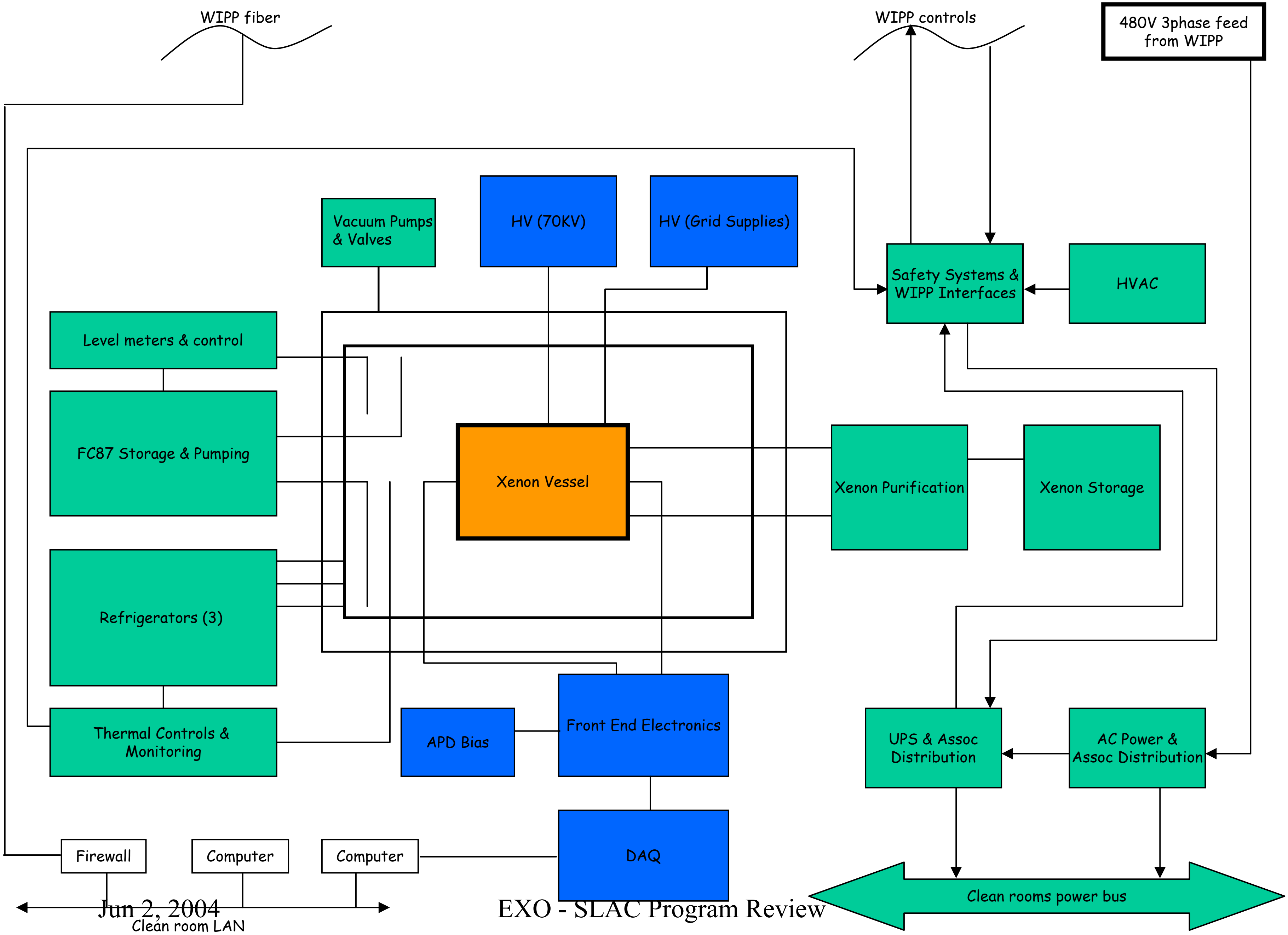
Detector


42 cm
FILL TUBE
LXe
FEEDTHROUGH PLUGS
FIELD SHAPING RINGS
42 cm
DRAIN
CENTER HV PLANE
Y WIRES
X WIRES
APD ASSEMBLY

Drift trajectories - crossed wires



EXO Prototype Simplified System Schematic

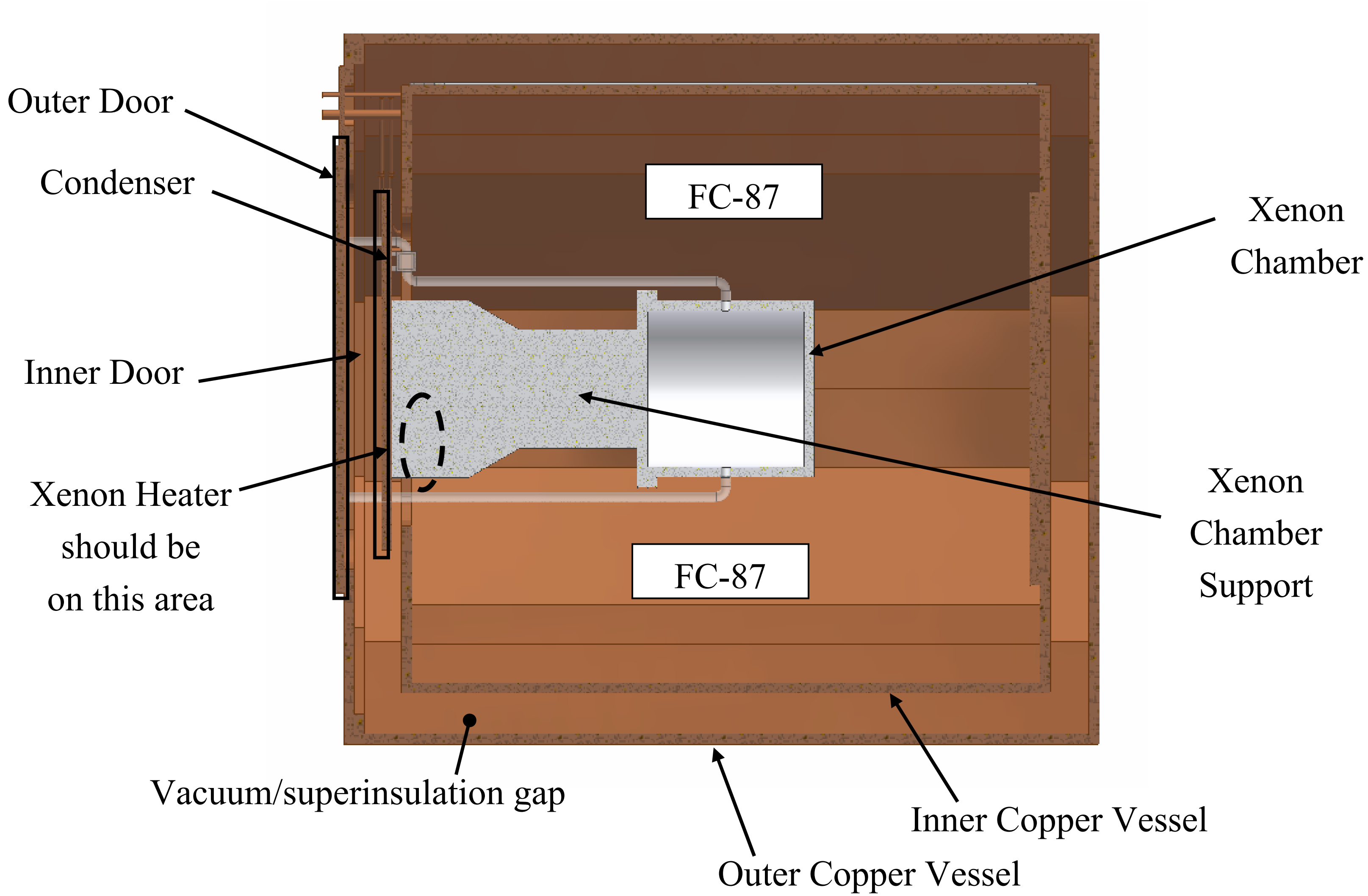


29 January 2004 MB,GG

Electronics & DAQ

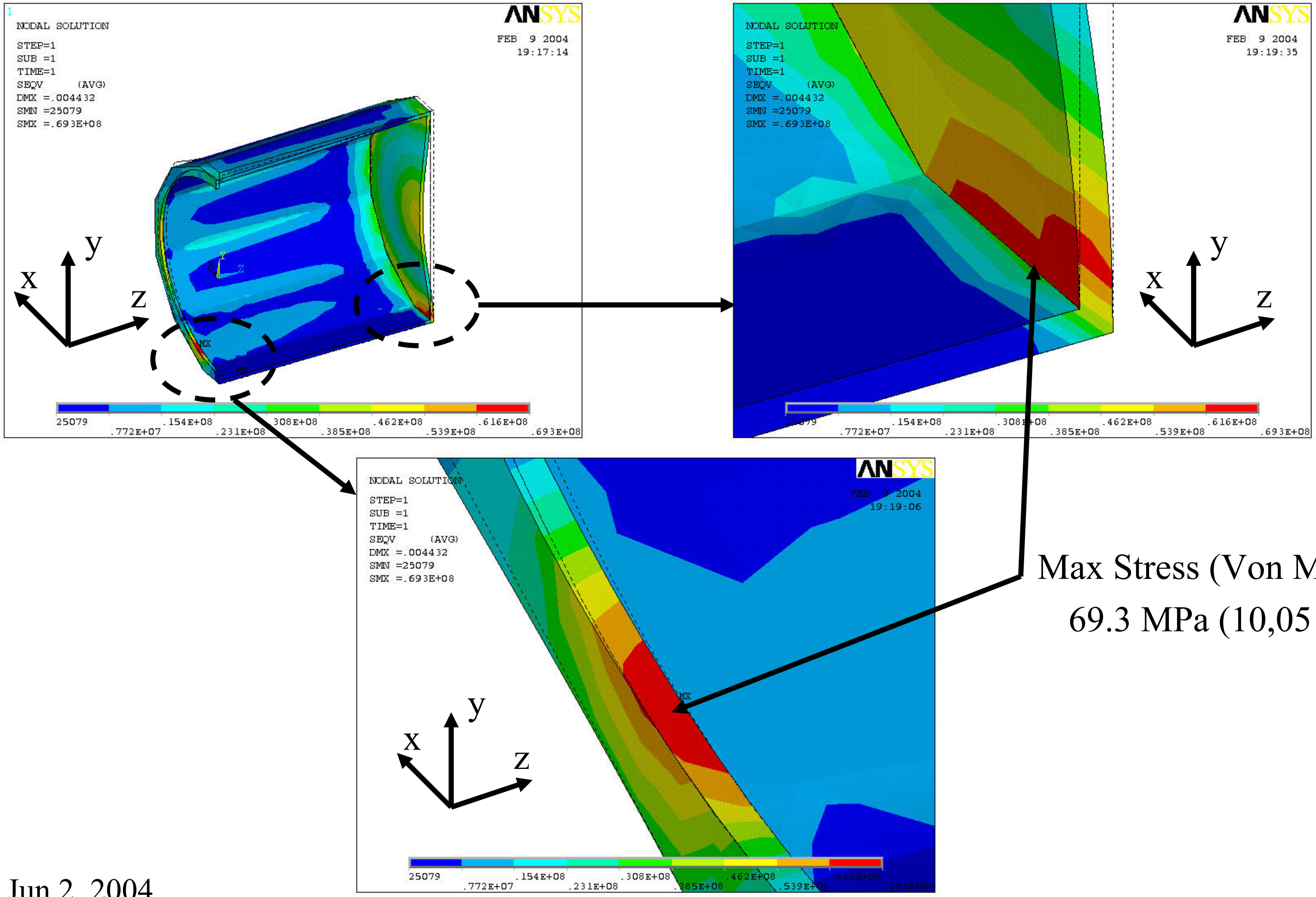
- **Signals from detector brought outside cryostat and shielding on stripline cables. Capacitance is ok.**
- **Front end for ionization and APD's is Babar charge amplifier running as simple charge integrator.**
  - **Followed by continuously running 1 MS/s ADC**
  - **32 channels are multiplexed (with trigger sums calculated on the fly) and transmitted on optical fiber to back end.**
- **~100 APD channels; ~200 ionization channels**
- **Back end is commercial PC with PCI-fiber adapter. Software is simple part of trigger and FIFO manager.**

Cryostat Cross Section



Copper Vessel Supporting its Own Weight and 50mm of Lead and Full Vacuum

Stress Plots



NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SEQV (AVG)
DMX =.004432
SMN =25079
SMX =.693E+08

FEB 9 2004
19:17:14

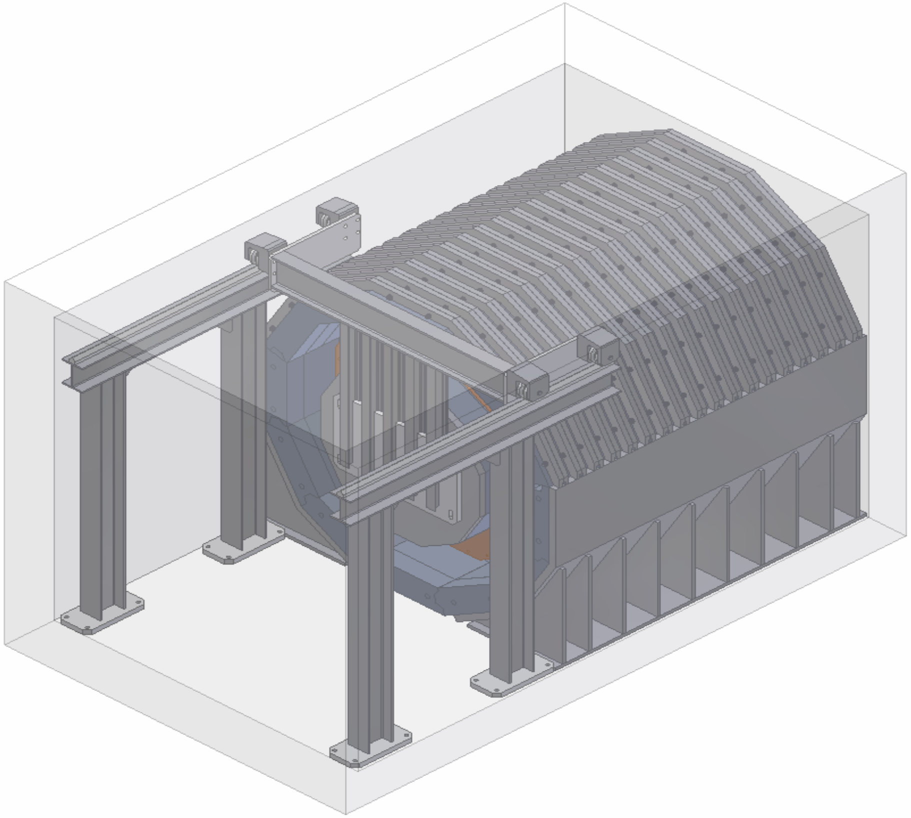
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SEQV (AVG)
DMX =.004432
SMN =25079
SMX =.693E+08

FEB 9 2004
19:19:35

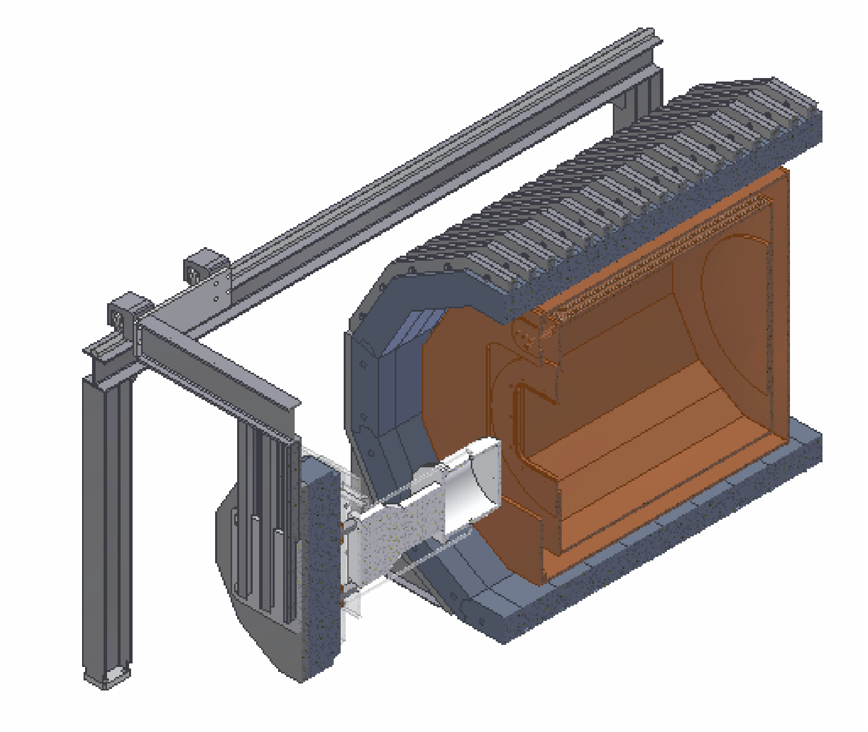
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SEQV (AVG)
DMX =.004432
SMN =25079
SMX =.693E+08

FEB 9 2004
19:19:06

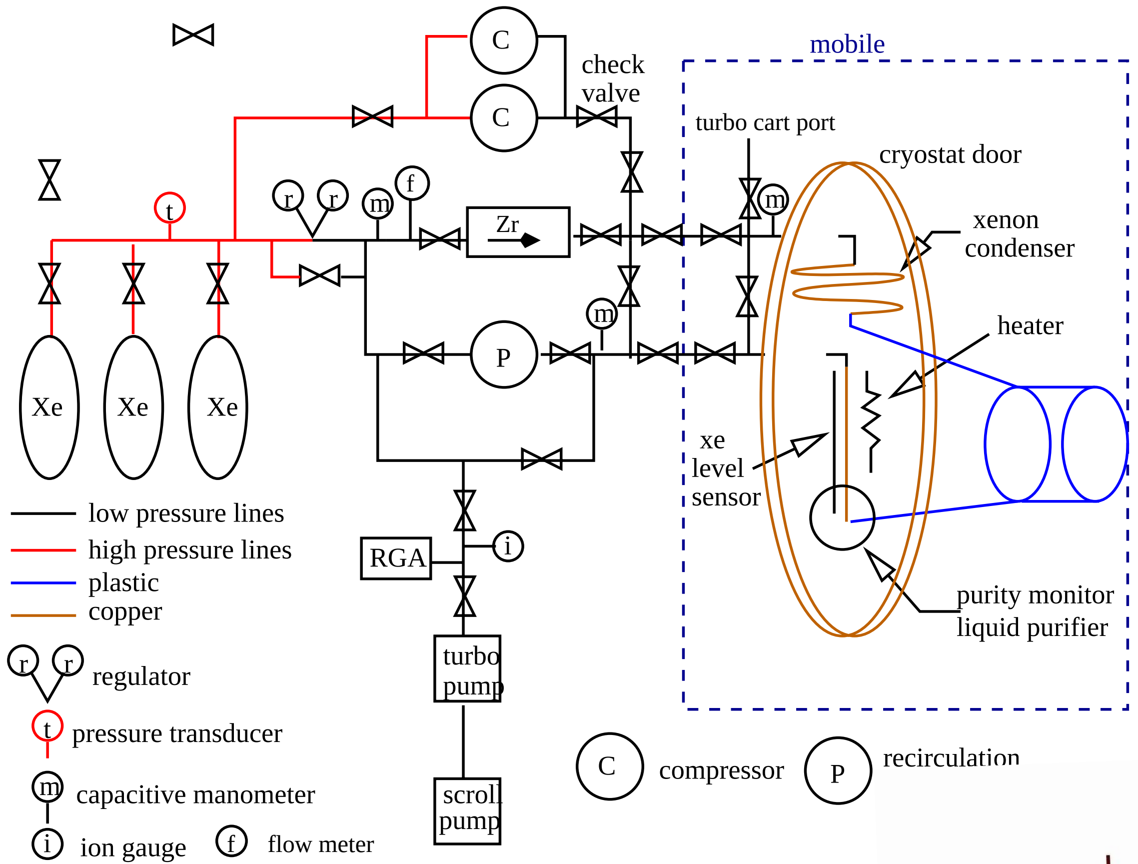
Max Stress (Von Misses) :
69.3 MPa (10,051 psi)

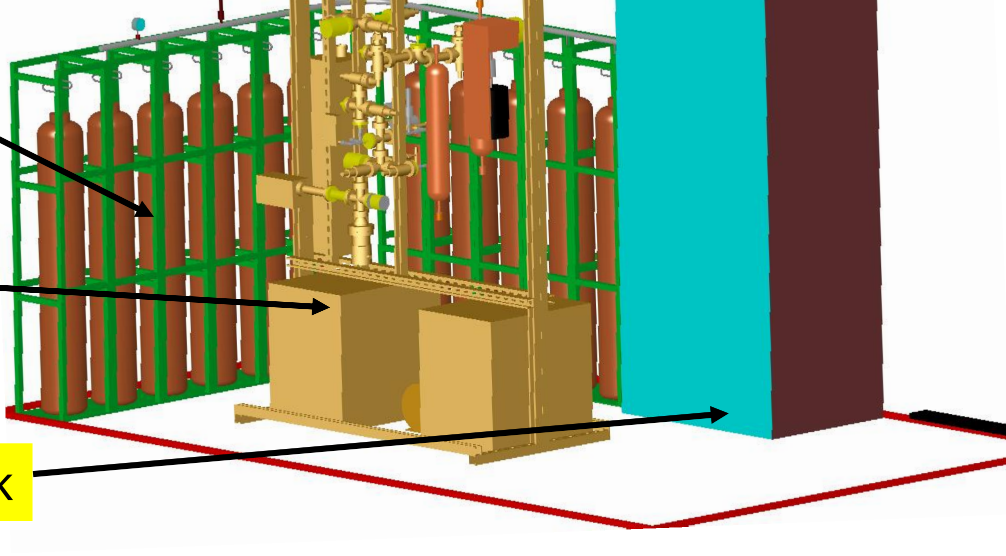


Full detector with shielding



Xenon purification and handling system



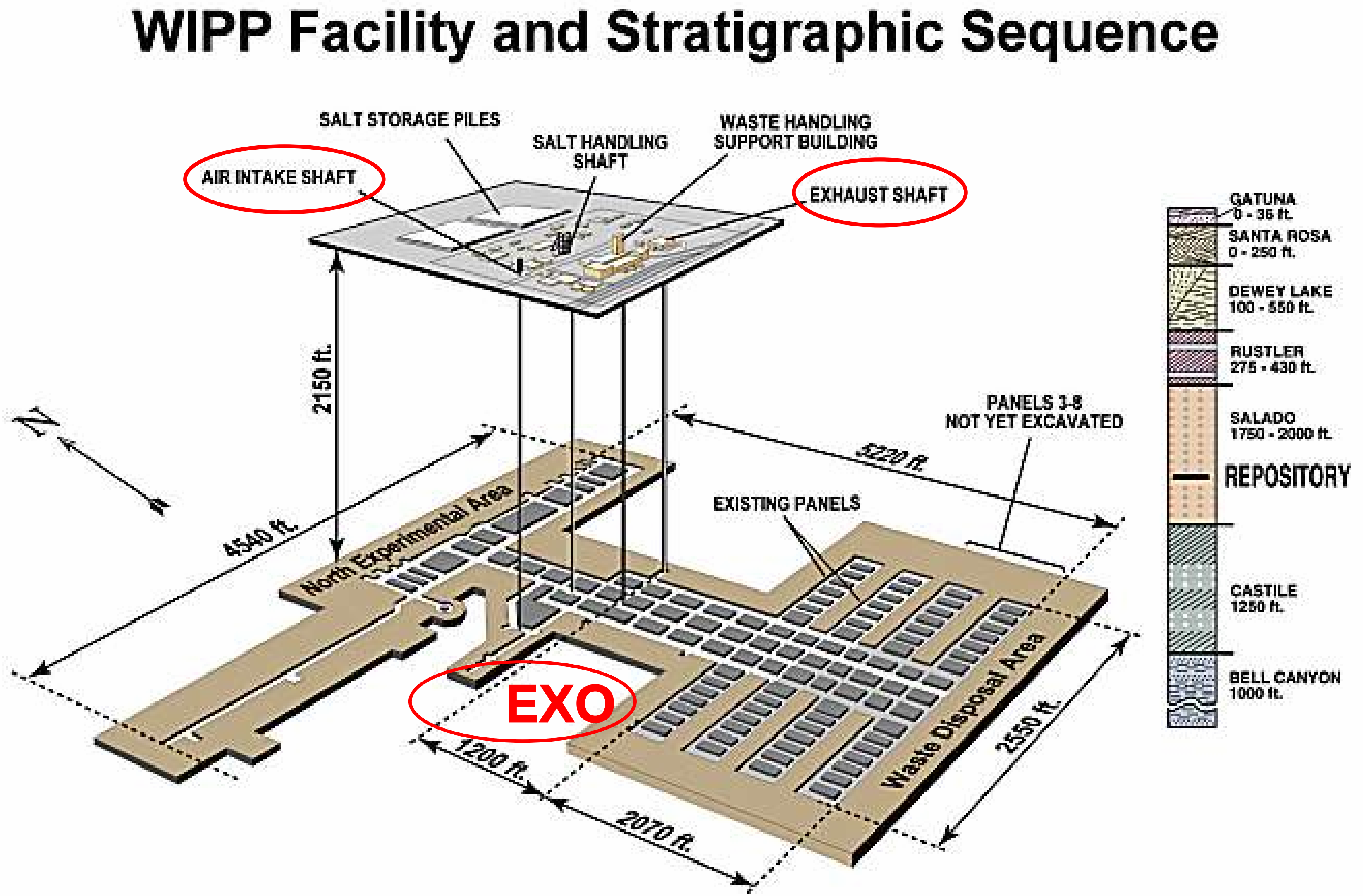


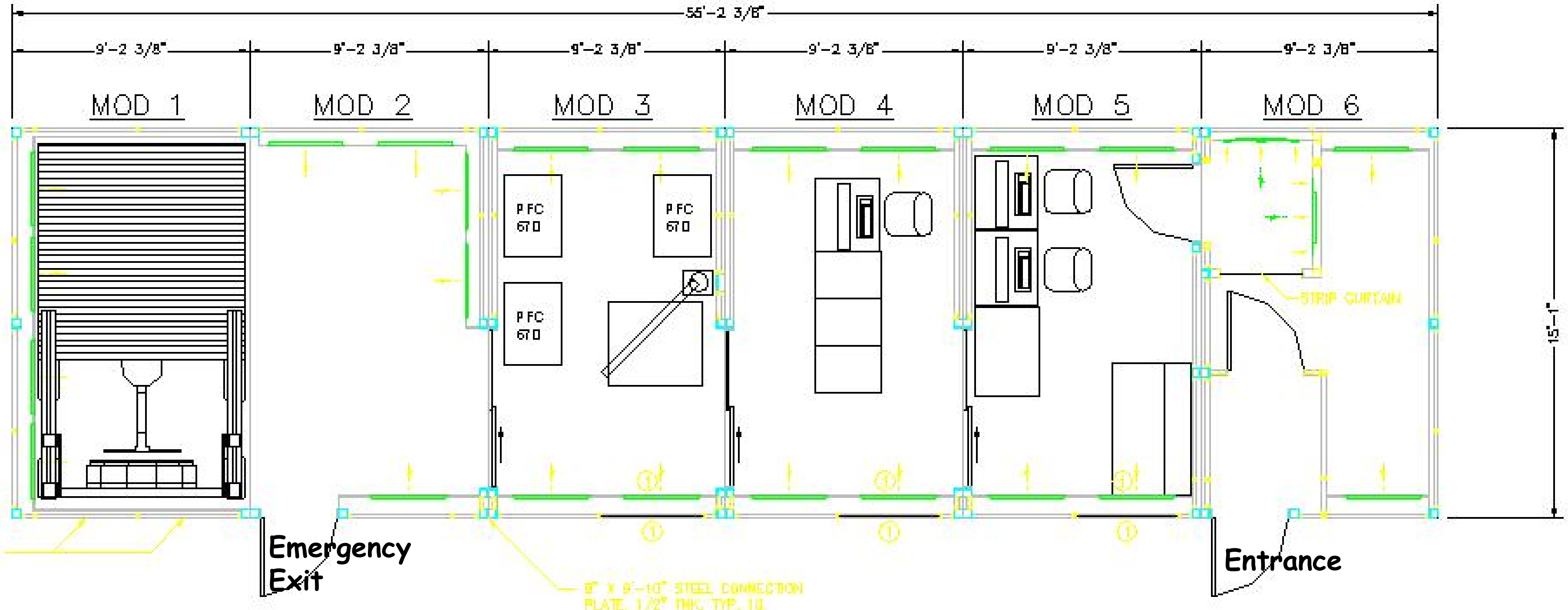
Xenon storage/recovery bottles

Purification system

Electronics rack

WIPP Schematic Overall View





Modules 1&2 in the shop

Clean Rooms construction well under way Delivery in late Jun 04

R&D: to do in '05

- Single ion Ba^+ tagging at different residual Xe pressures
- Ba ion lifetime and grabbing from LXe
- Single ion Ba tagging in directly LXe
- Construction/operation of 200 kg ^{136}Xe prototype detector
  - Gain operational experience on a large LXe detector underground
  - Measure 2ν mode in Xe
  - Have a shot at the measurement of the neutrino mass !