EXO

Measuring the mass of the neutrino…

one atom at the time…

INFO-07 Santa Fe, Jul 2, 2007

To reach $\langle m_\nu \rangle$ ~ 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 want a multi-parameter experiment, so that possible discovery can be backed-up by cross checks with more than one single variable

$\beta\beta$ 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

Real time is needed to discover ν masses, final state ID would substantially reduce backgrounds !

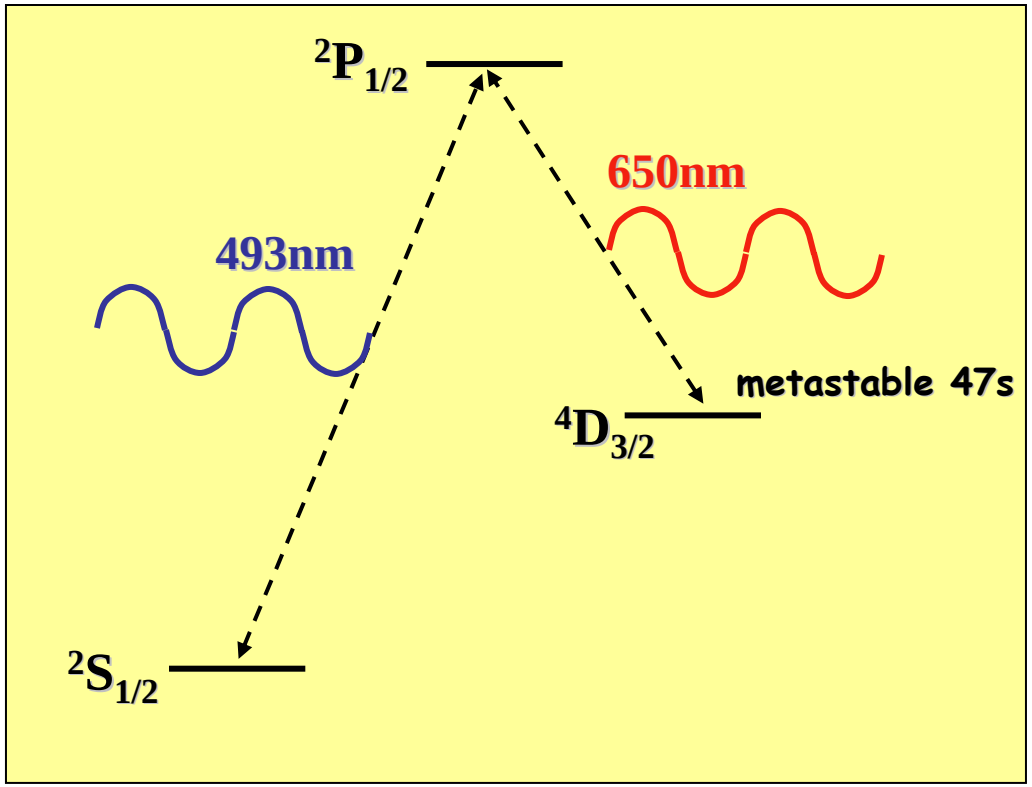
Xe is ideal for a large experiment

- 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**



The Ba-tagging, added to a high resolution Xe imaging detector provides the tools to develop a background-free next-generation ββ experiment

Assume an "asymptotic" fiducial mass of 10 tons of ^{136}Xe at 80%

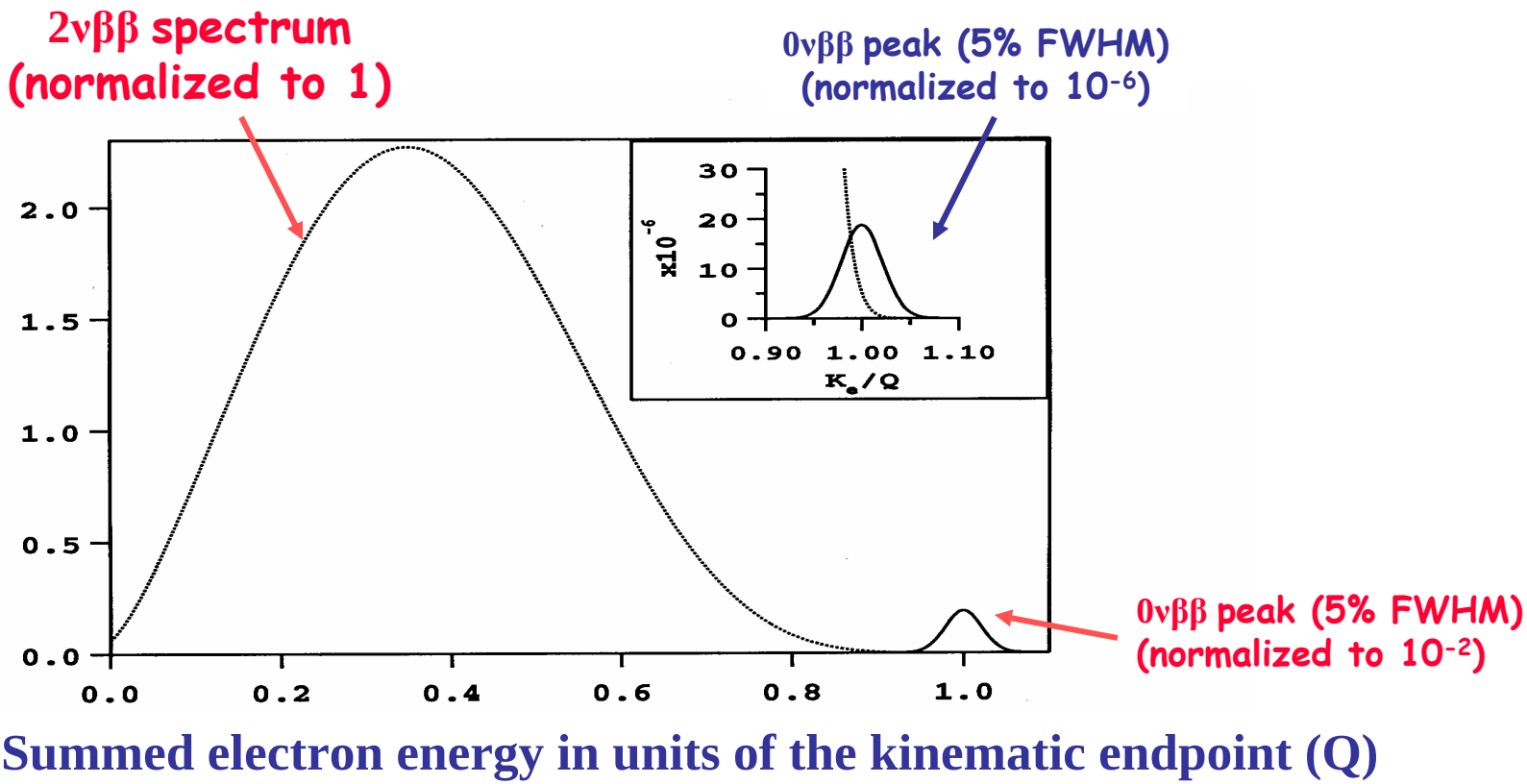
A somewhat natural scale:

- **World production of Xe is ~30 ton/yr**
- **Detector size**
- **$2 \cdot 10^3$ size increase: good match to the 10^{-2} eV mass region**

Mainly going in light bulbs and satellite propulsion

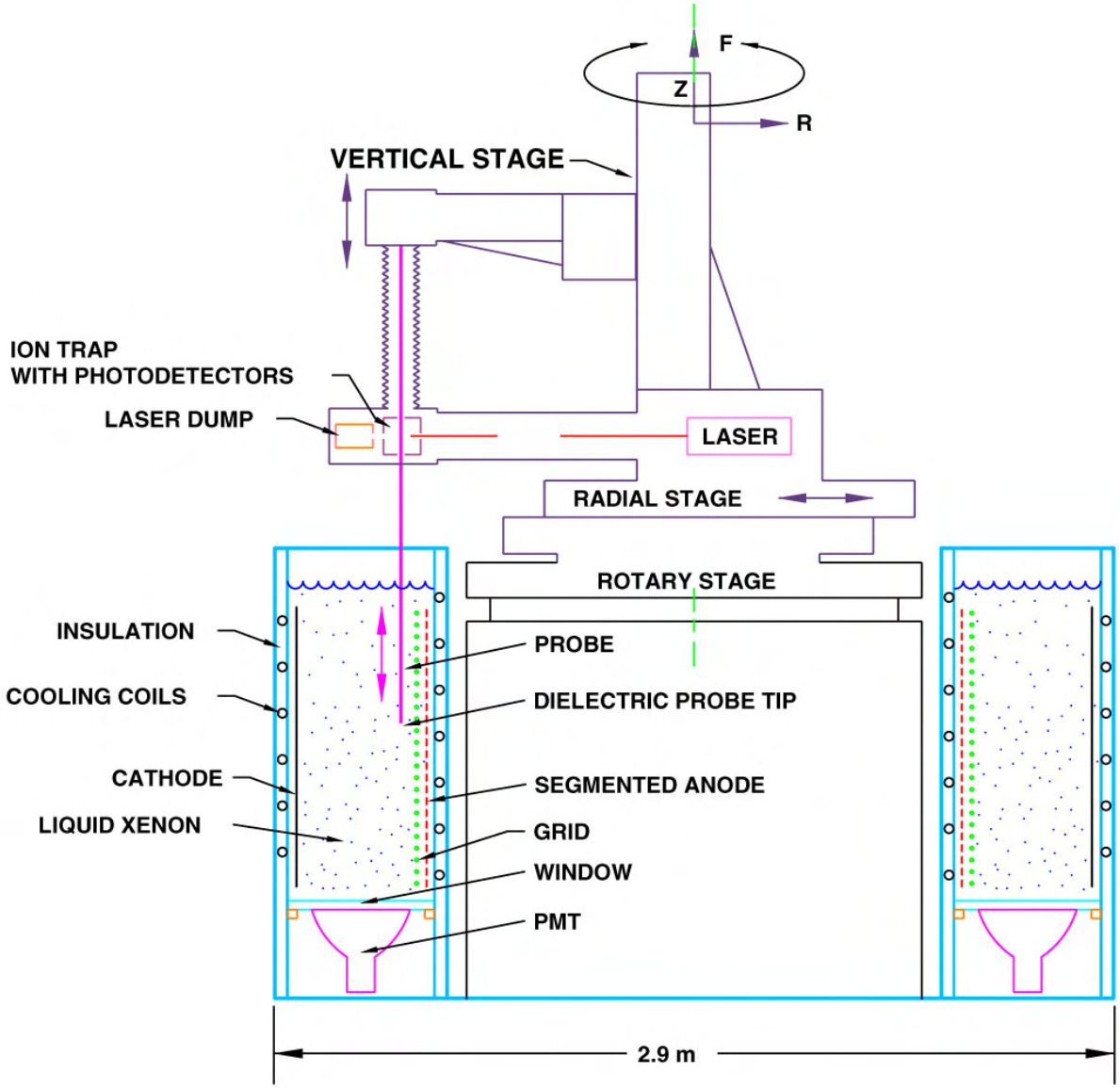
Background due to the Standard Model 2νββ decay

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

Conceptual scheme of a LXe detector with Ba extraction



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)	$2*10^{27}$	50	68
Aggressive	10	70	10	1†	0.7 (use 1)	$4.1*10^{28}$	11	15

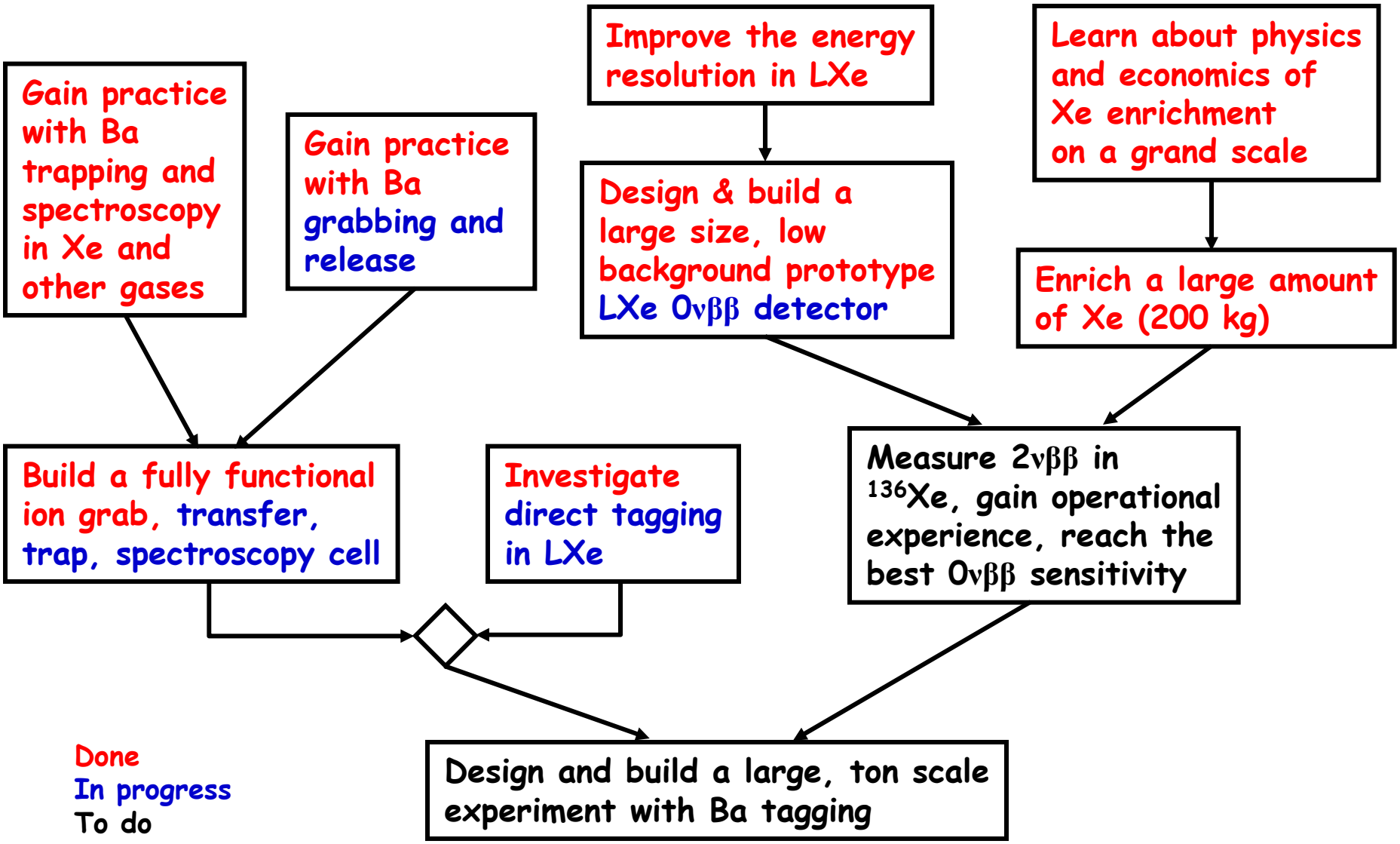
* σ(E)/E = 1.4% obtained in EXO R&D, Conti et al Phys Rev B 68 (2003) 054201

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

‡ Rodin et al Phys Rev C 68 (2003) 044302

\# Courier et al. Nucl Phys A 654 (1999) 973c

The roadmap to the background free discovery of Majorana neutrinos and the neutrino mass scale



Done
In progress
To do

EXO-200:
an intermediate detector <u>without</u> Ba tagging

- Need to test detector technology, particularly the LXe option:
  A 200 kg chamber is close to the largest Xe detector ever built and hence good training ground
- Essential to understand backgrounds from radioactivity:
  200 kg is the minimum size for which the self-shielding is important and there is negligible surface inefficiency
- Using ^{136}Xe can hope to measure the "background" $2\nu\beta\beta$ mode:
  200 kg is needed to have a chance (if do not see the mode then is really good news for the large experiment !!)
- The production logistics and quality of ^{136}Xe need to be tested:
  Need a reasonably large quantity to test production
- Already a respectable (20x) $\beta\beta$ decay experiment
- No need for Ba tagging at this scale

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	Majorana mass (eV) NSM
EXO-200	0.2	70	2	1.6*	40	$6.4 * 10^{25}$	0.27†	0.38♦

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

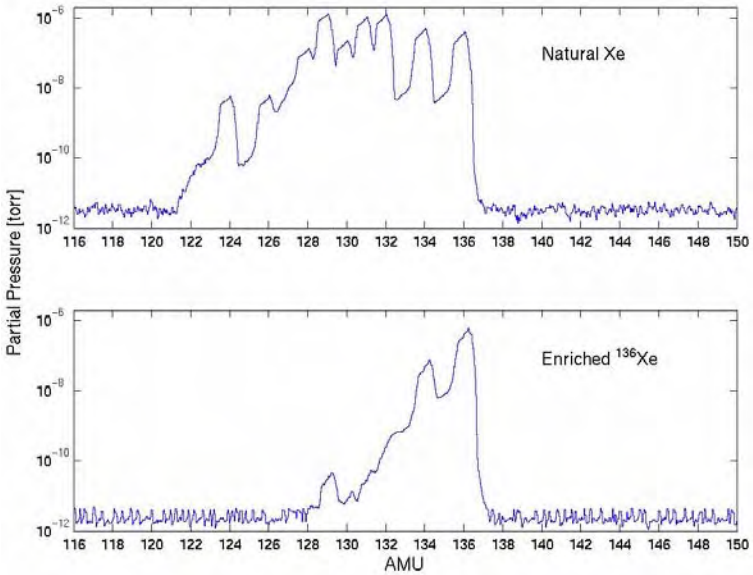
Status of 2ν mode in ^{136}Xe

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)

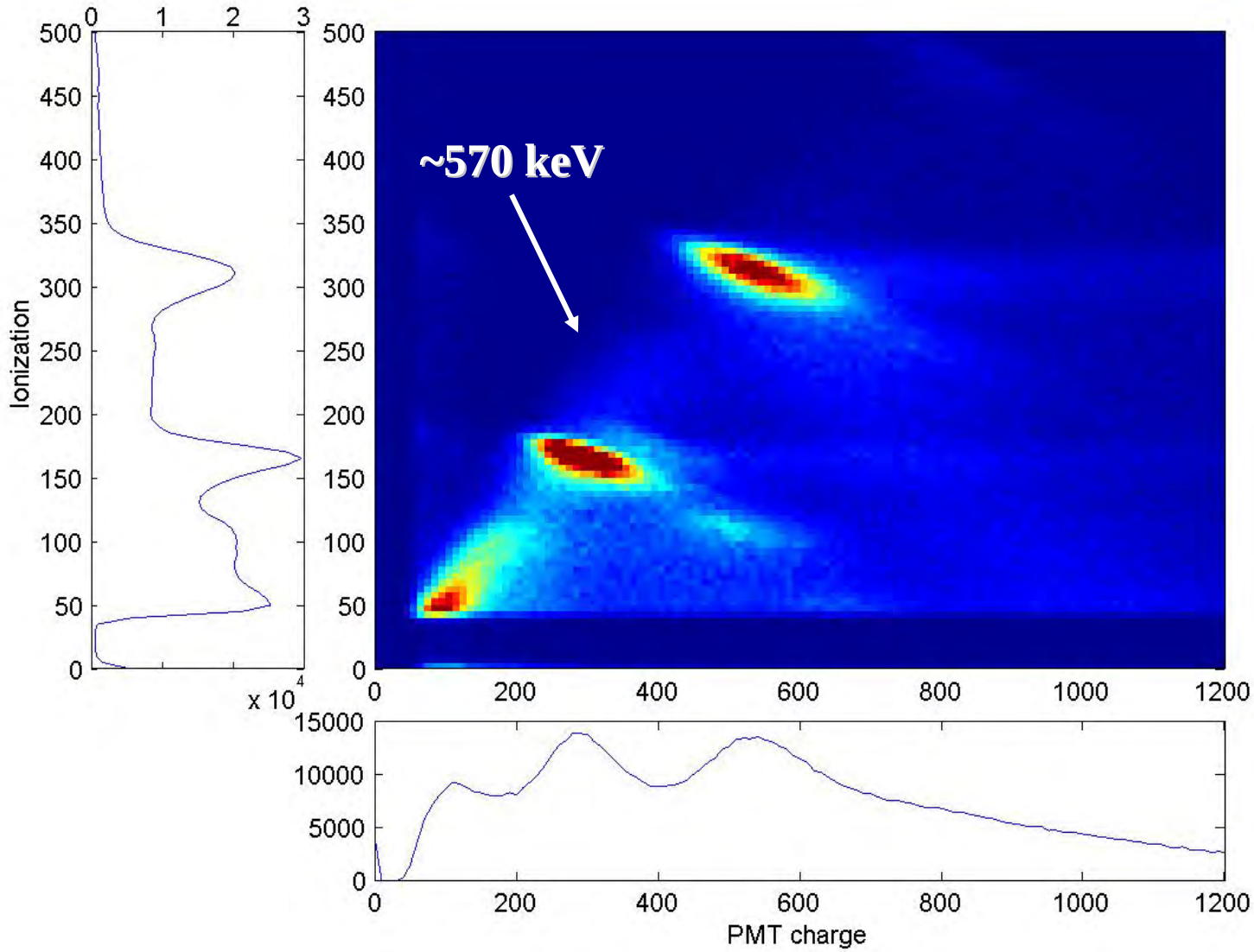
EXO-200 should definitely resolve this issue

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

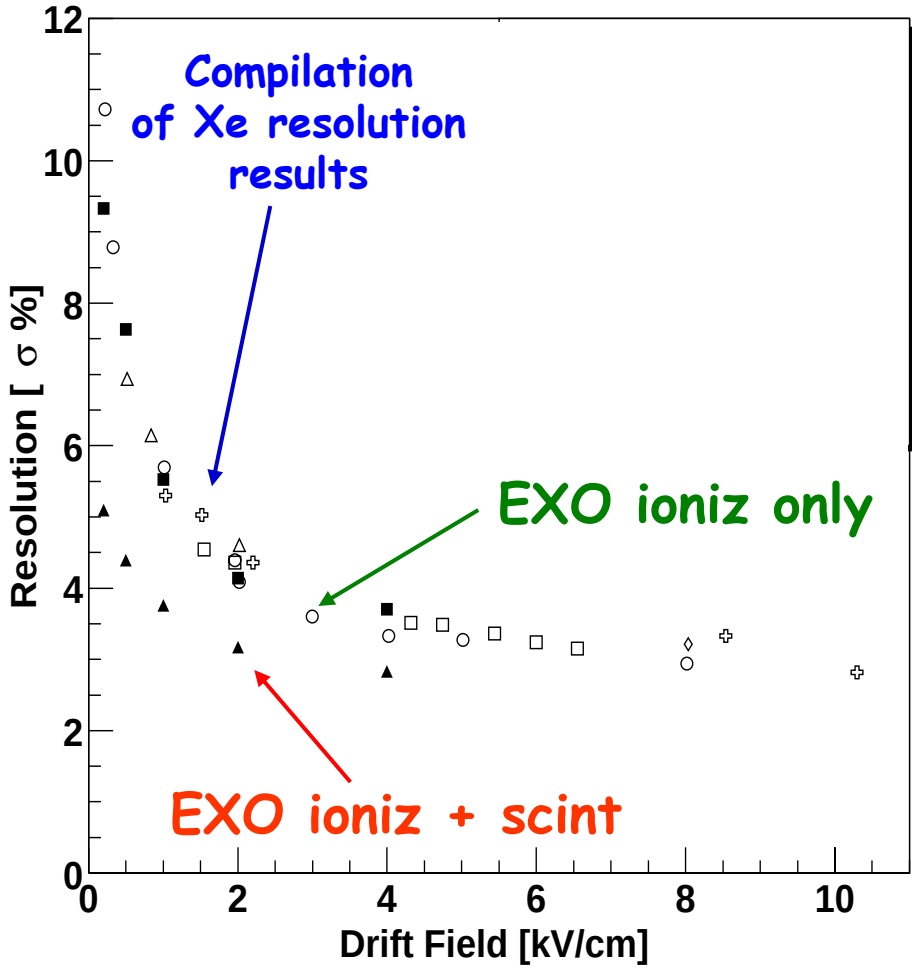


- Largest highly enriched stockpile not related to nuclear industry
- Largest sample of separated ββ isotope (by ~factor of 10)

EXO R&D showed the way to improved energy resolution in LXe: *Use (anti)correlations between ionization and scintillation signals*



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



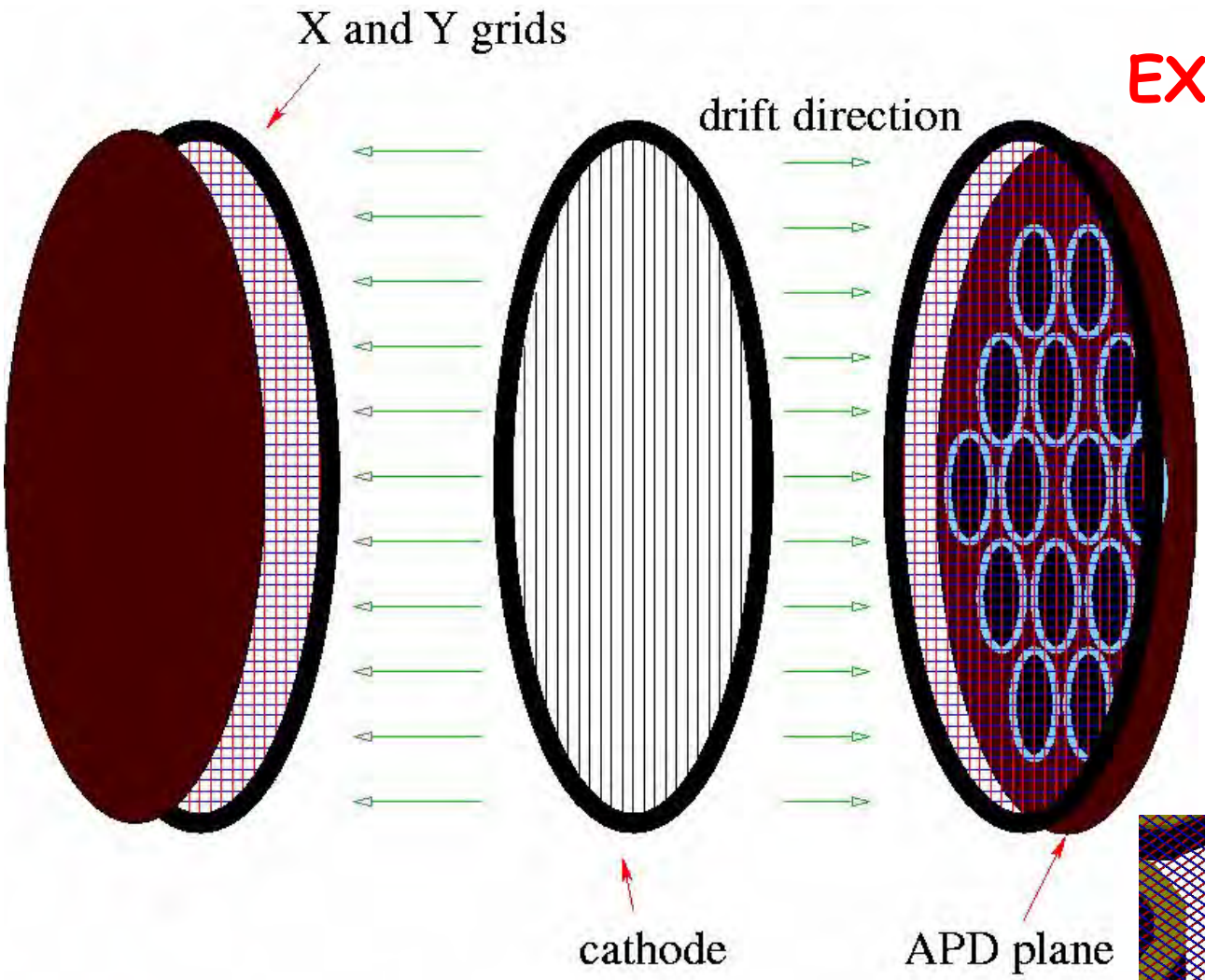
Ionization alone:
$\sigma(E)/E$ = 3.8% @ 570 keV
or 1.8% @ $Q_{\beta\beta}$

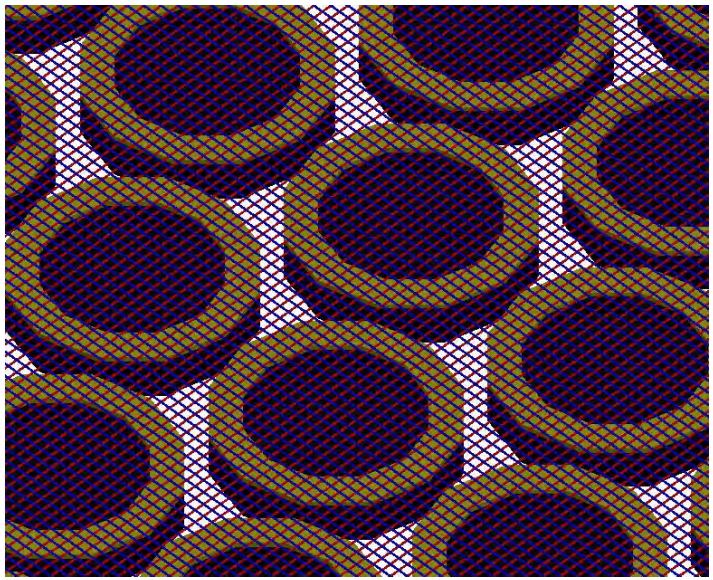
Ionization & Scintillation:
$\sigma(E)/E$ = 3.0% @ 570 keV
or 1.4% @ $Q_{\beta\beta}$
(a factor of 2 better than the Gotthard TPC)

E.Conti et al. Phys. Rev. B: 68 054201

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

EXO-200 TPC basics





EXO-200 TPC basics

- The detector measures both the ionization electrons and the scintillation light to get best energy resolution.
  - In addition, the position of the decay is measured to get spatial distributions and (for later) the position of the Ba ion.
  - Info on event topology also important for background separation.

- The detector is a cylinder of ~40cm ID by ~40cm inner length.

- The cylinder is split by a cathode plane at the center so there are two symmetric drift regions. The cathode runs at negative HV.
  - Max HV is ~ 70kV (~3.5 kV/cm drift). Energy resolution improves with drift field, but there are arguments that separation of 1 vs 2 primary electrons might be better at lower fields.
    → field optimization is an important mission of EXO-200

- Readout "style":
  - Crossed wires, 100μm wires, 3mm pitch, ganged in groups of 3
    48ch x, 48ch y, total 96 ch per 1/2 detector
    (Pad readout rejected because of high channel count)

TPC vessel technology

All-teflon vessel was developed (with a DoE SBIR), however the baseline technology under construction uses a (slightly) more conventional copper vessel

- Teflon main advantage: - ultra-low activity (the teflon variety used is possibly the lowest activity solid ever measured)
- Teflon has disadvantages: - engineering quite tricky (but this is understood by now)
  - emanations from field welds damage APDs
    (Solved by now but because of scheduling we have decided to proceed with copper in the mean time)

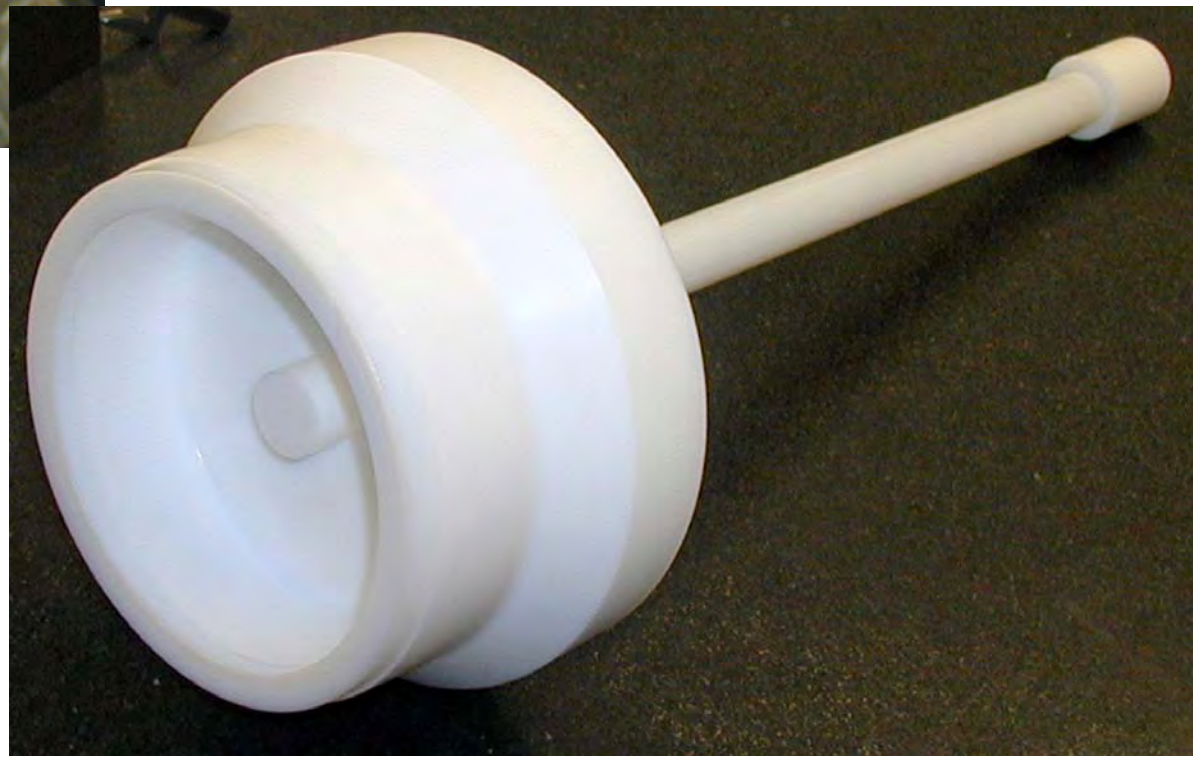
- The copper acquired for the vessel is extremely clean. However both for copper and for teflon sensitive material qualification uses indirect measurements that assume secular equilibrium in the decay chains.
  - Cu is measured using ultra-high sensitivity ICPMS (Canadian INMS)
  - Teflon is measured by NAA (MIT reactor and U of Alabama)

  Both pass our criteria assuming secular equilibrium in the U and Th chains. For a number of reasons we feel like this assumption is more likely to be ok for the case of teflon, but this is not a science…

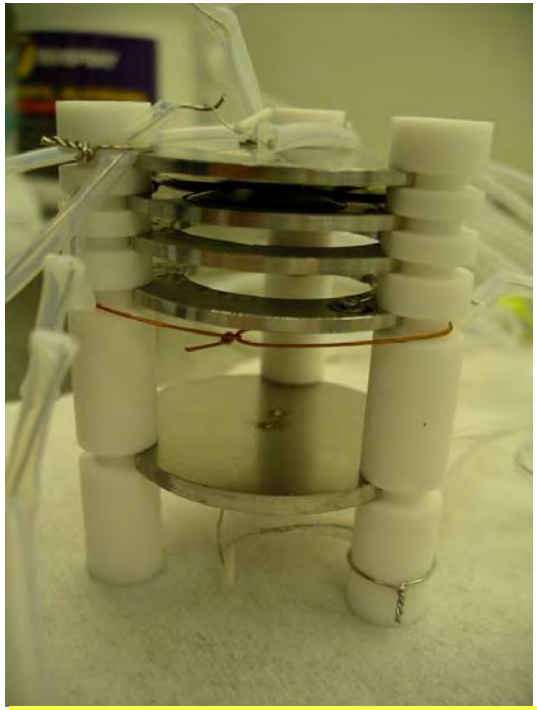
- The teflon vessel technology, once perfected, may be very valuable for other low background, cryogenic detectors.

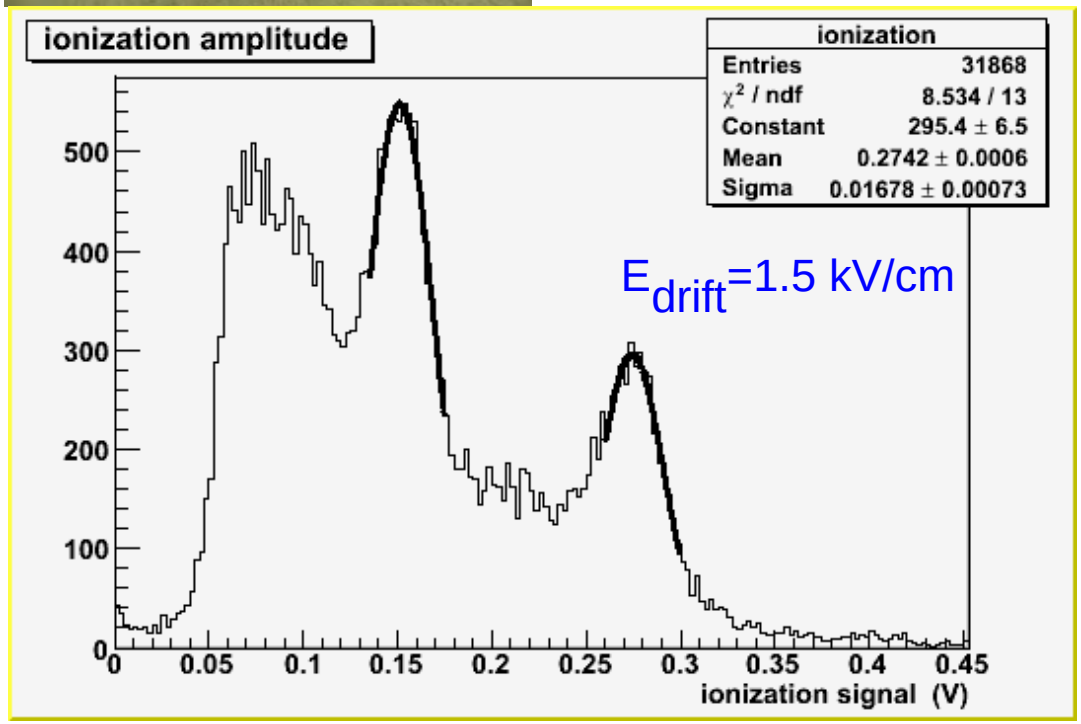
Several "all teflon" vessels built
all He-leak tested OK

- Body made out of parts sintered and fused in the oven
- Recirculation pipes preformed and welded with hot clamp
- Large seal welded with hot clamp



Fully functional all-teflon ionization detector built and operated in our lab

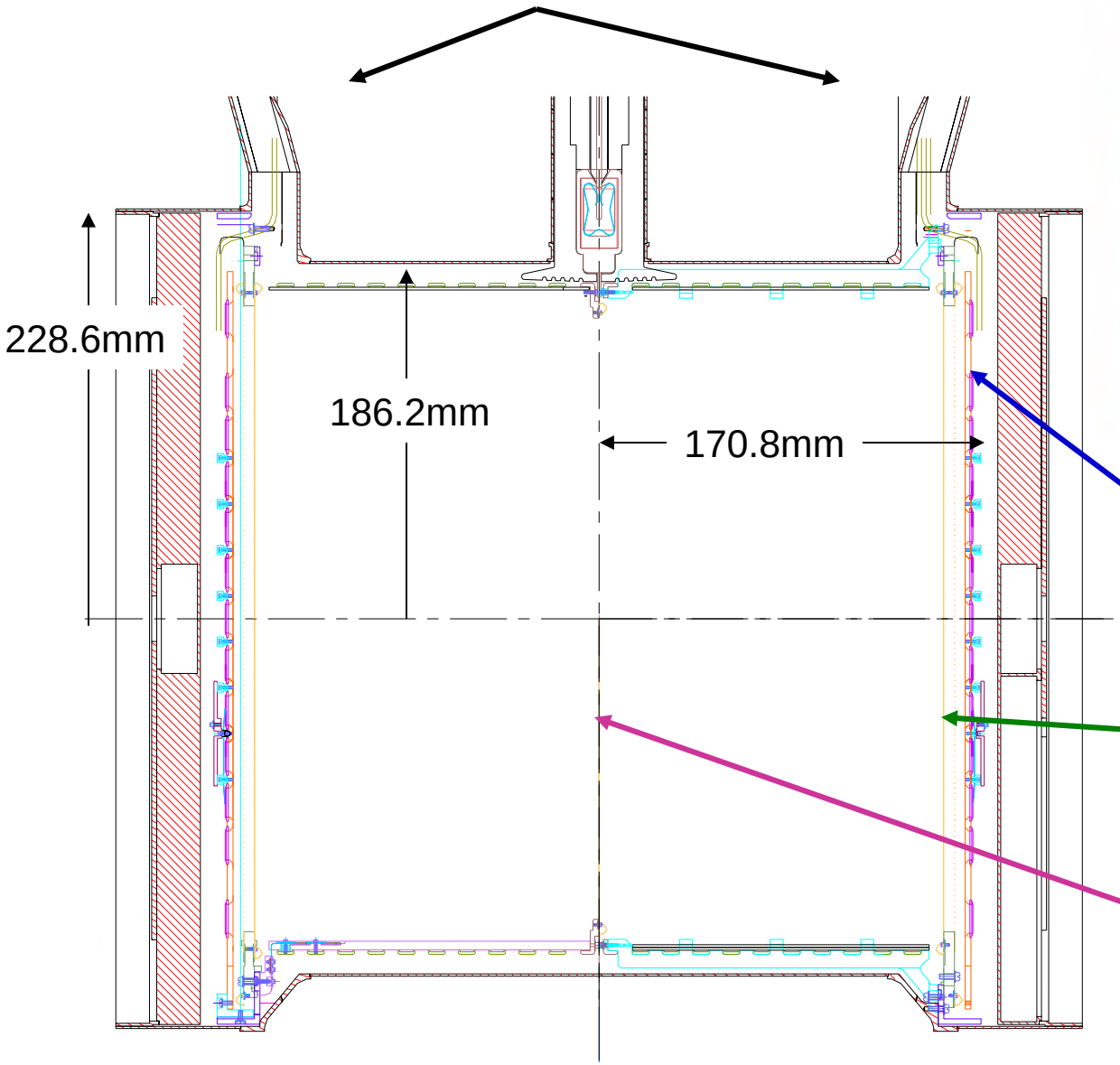


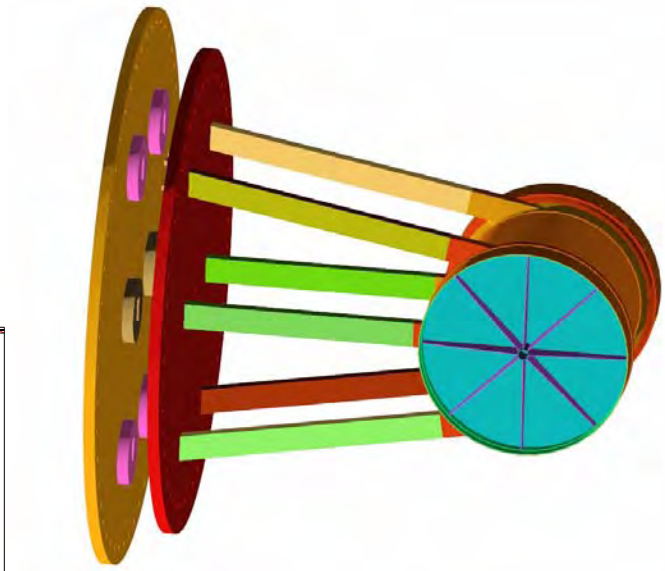


First observation of ionization and scintillation signals in a "all plastic" construction LXe Detector

F.Leport et al. arXiv:0611183v1 to appear on Nucl. Inst. Meth. A

EXO chamber "hugs" the fiducial volume very closely!





2x300 large area
(1.6cm active diameter)
unmounted APDs

Inductive and charge
collecting wire planes

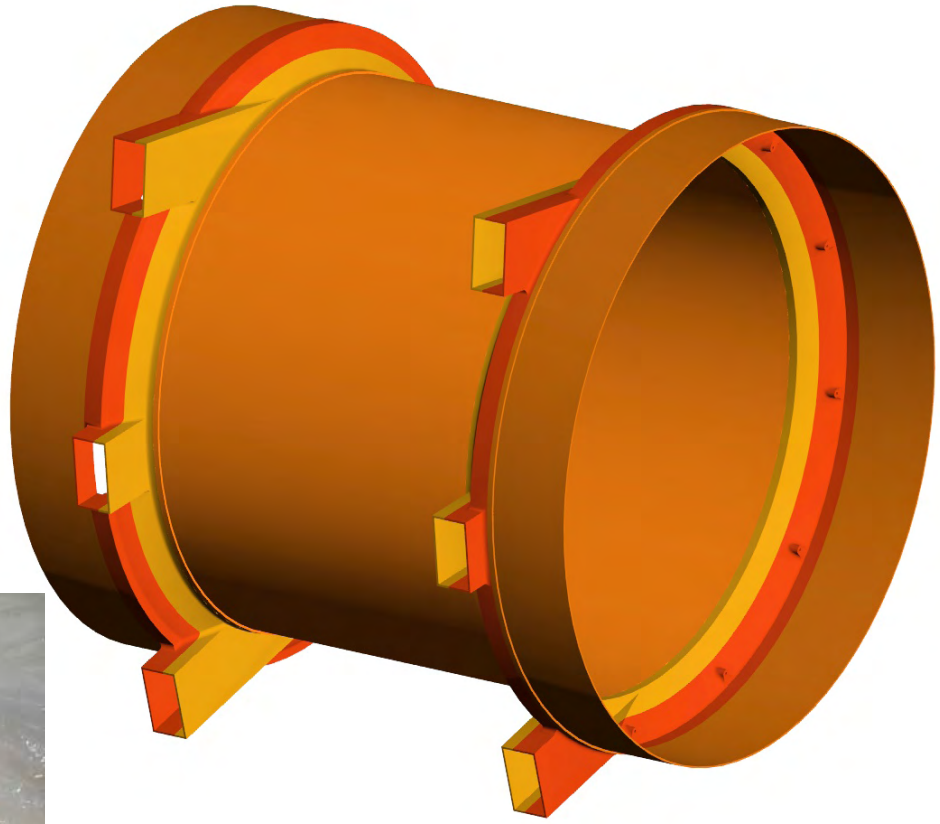
Cathode grid

Low activity copper traveled from Germany to…

…California in a shielded container

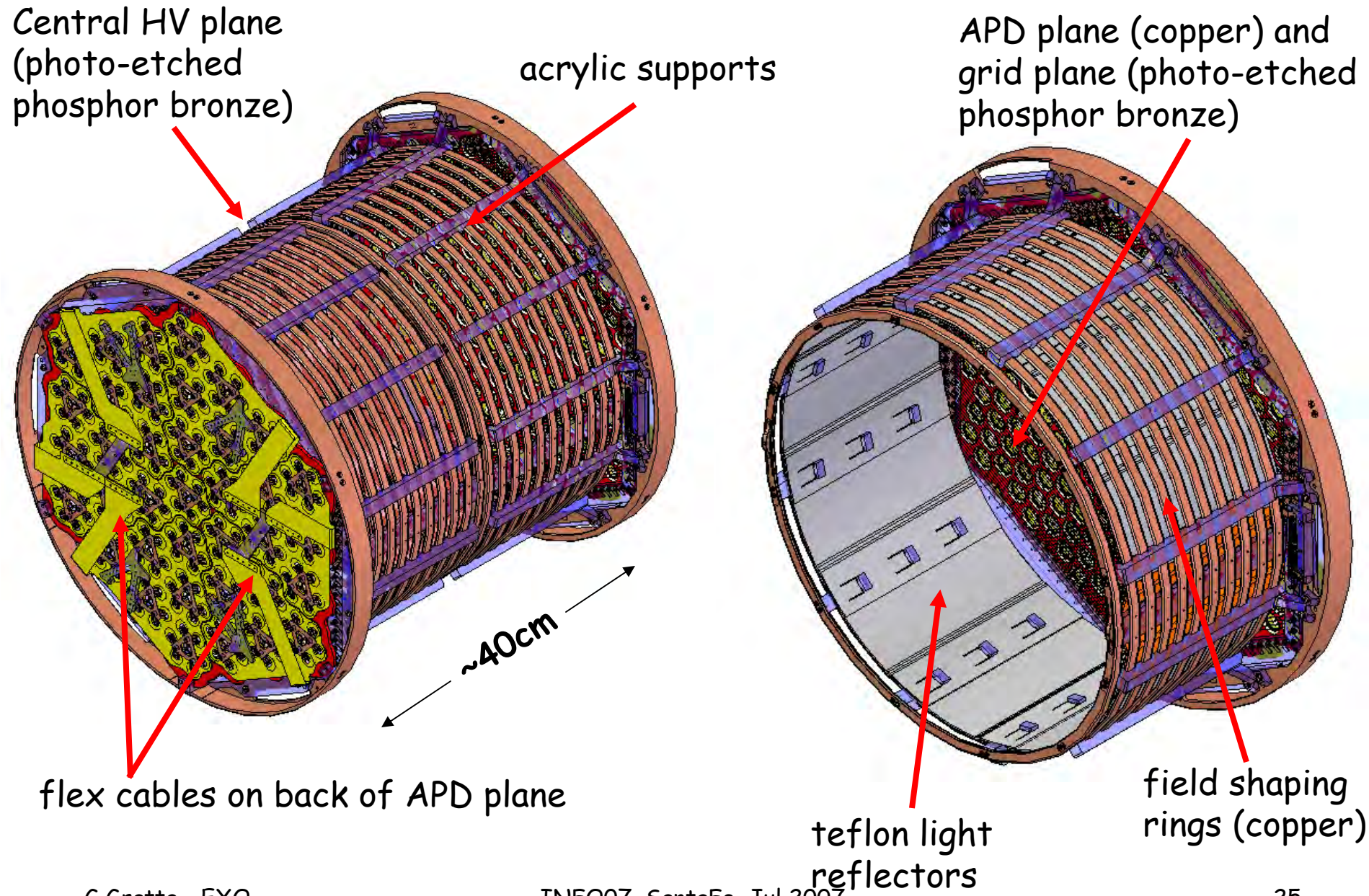
Ultra-low activity Cu vessel

- Very light (~1.5mm thin, ~15kg) to minimize materials

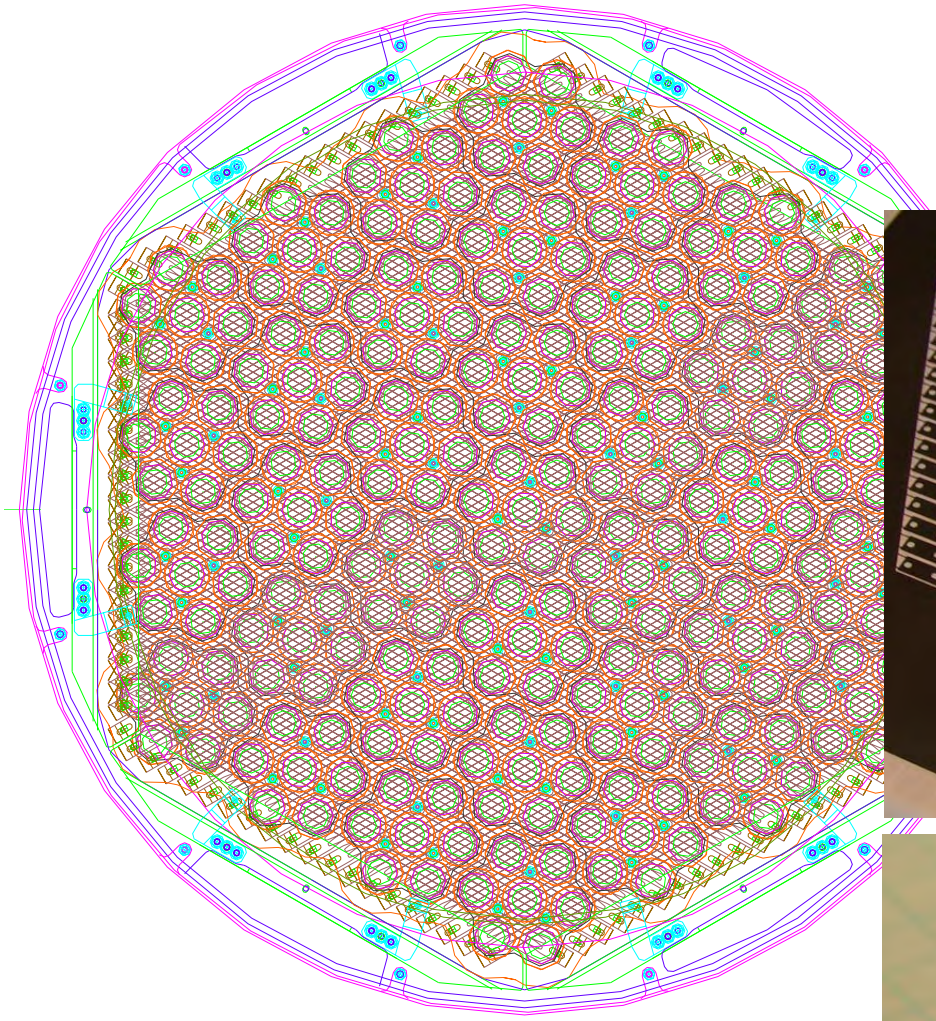


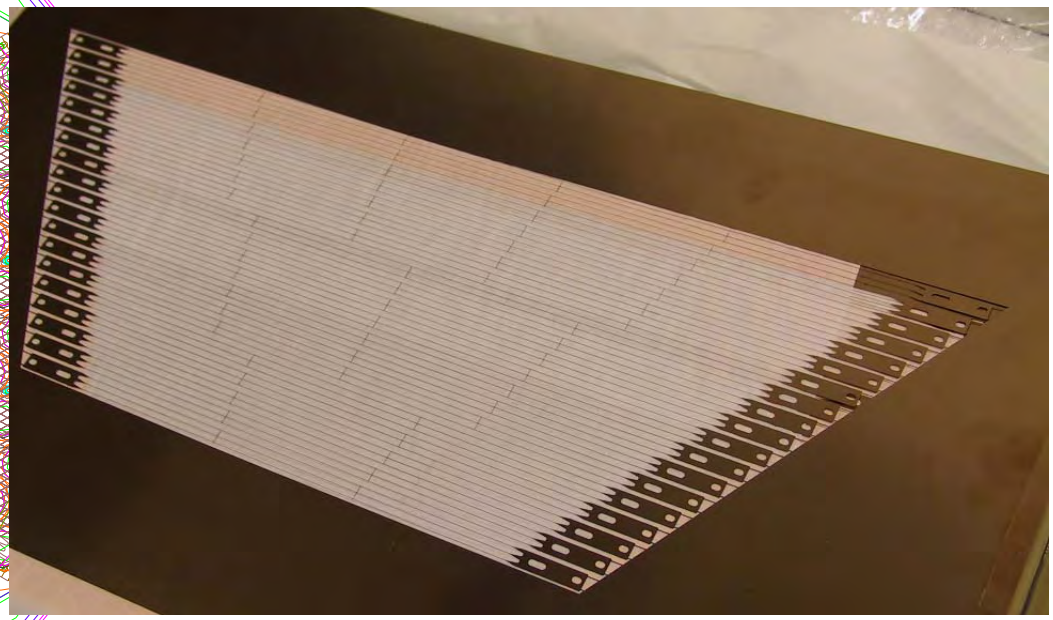
- Different parts e-beam welded together
- Field TIG weld(s) to seal the vessel after assembly (TIG technology tested for radioactivity)
- All machining done by in the CR-shielded HEPL building)

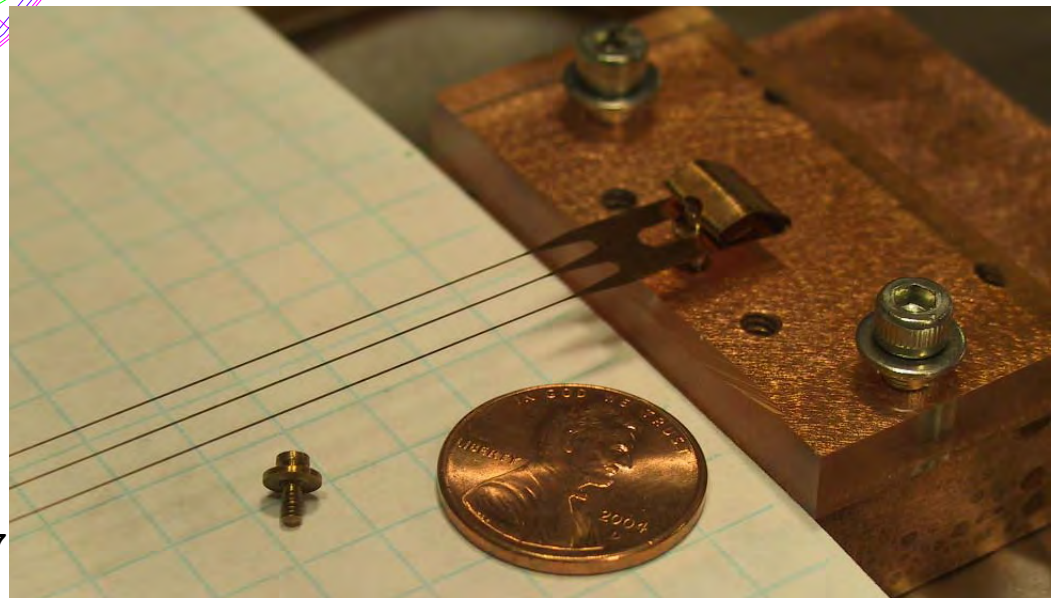
EXO-200 LXe TPC field cage & readout planes



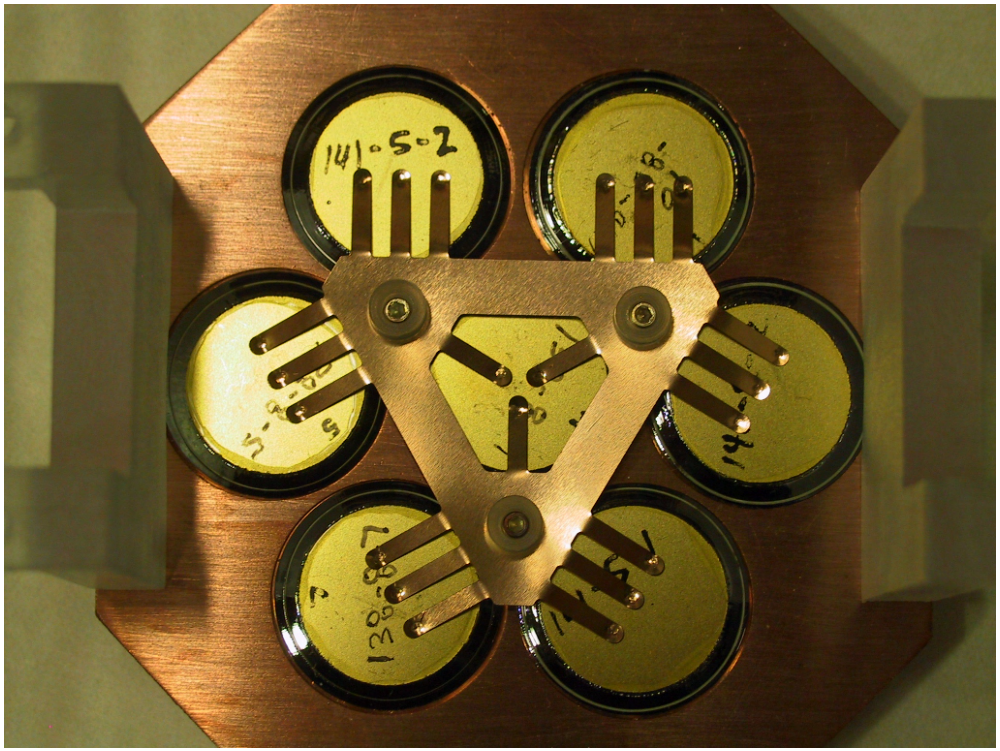
One readout pancake





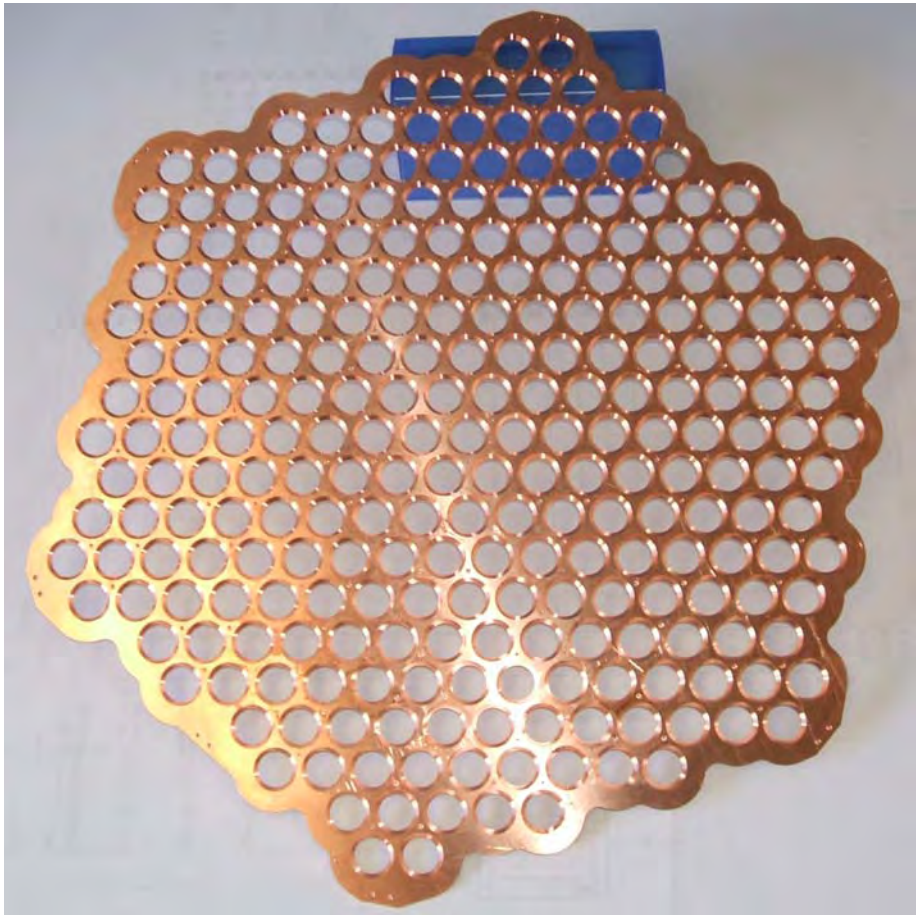


~500 "Bare" LAAPD



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

QE > 1 at 175nm



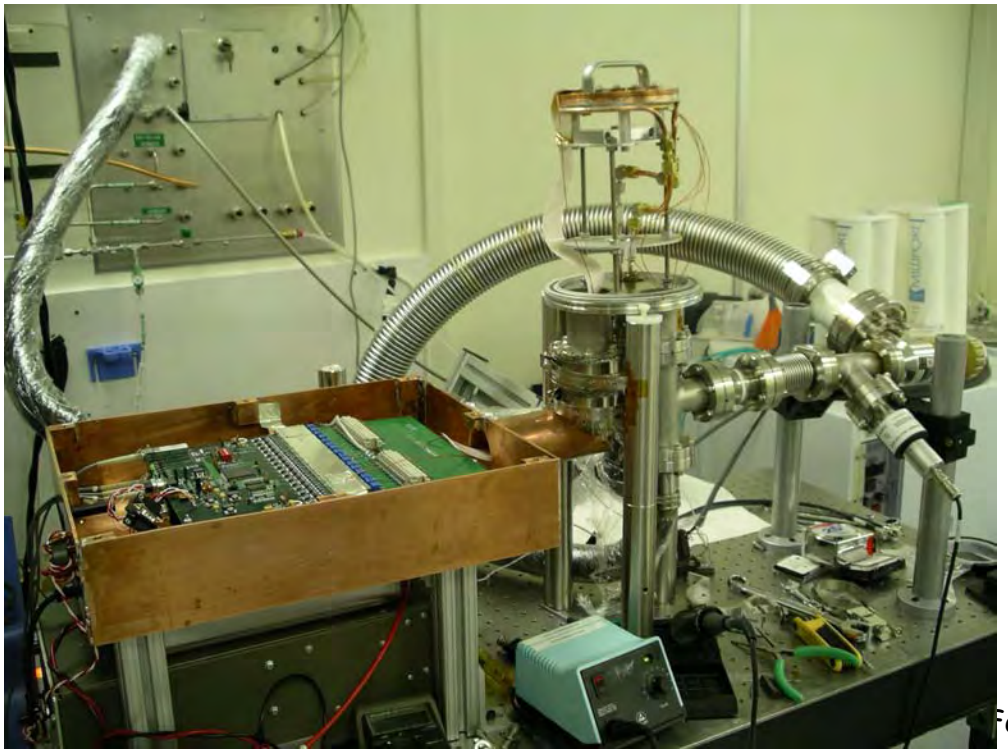
Gain set at 100-150

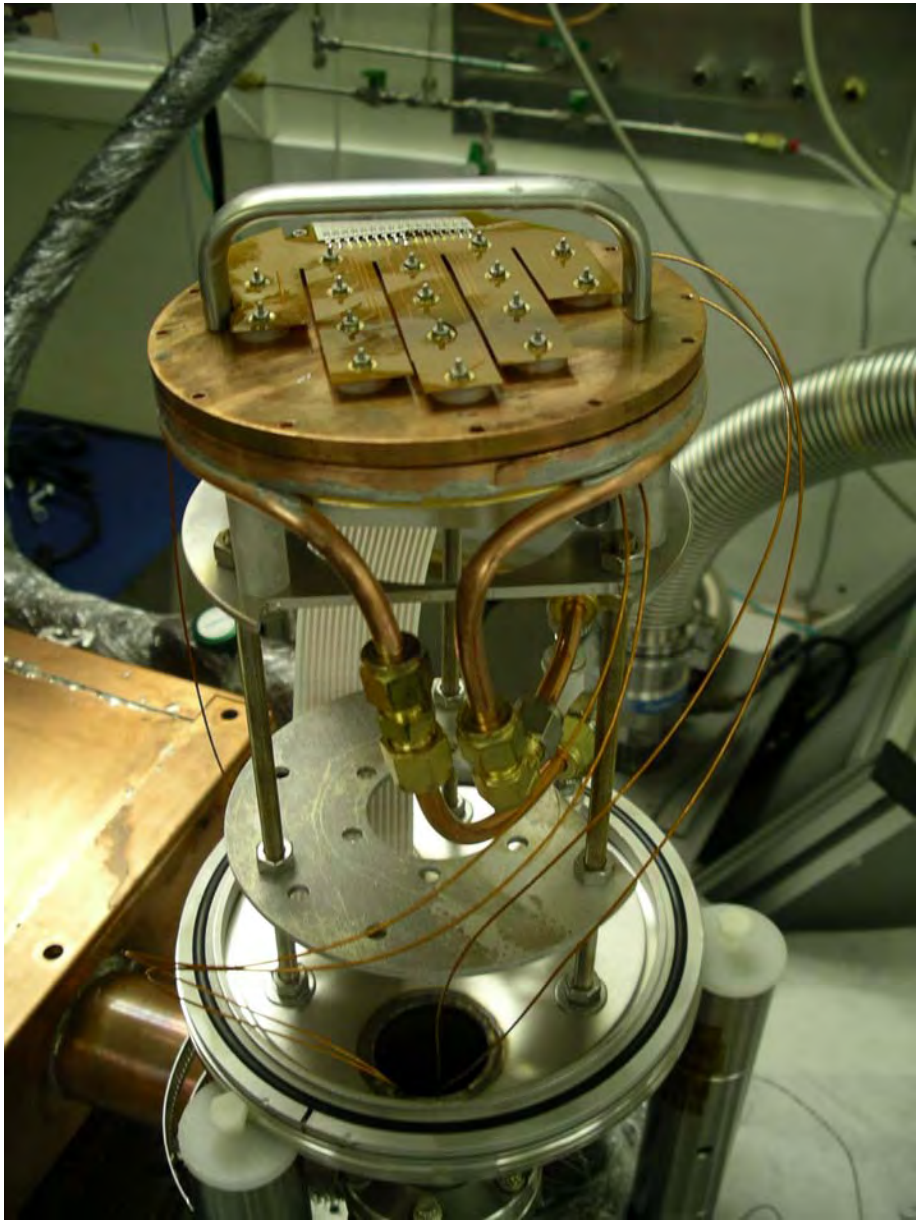
V~1500V
ΔV < ±0.5V
ΔT < ±1K APD is the driver for temperature stability
Leakage current OK cold

APD testing rig to measure
16 APDs at the time in vacuum
At -100C.

For each APD gain, leakage
current, QE will be measured

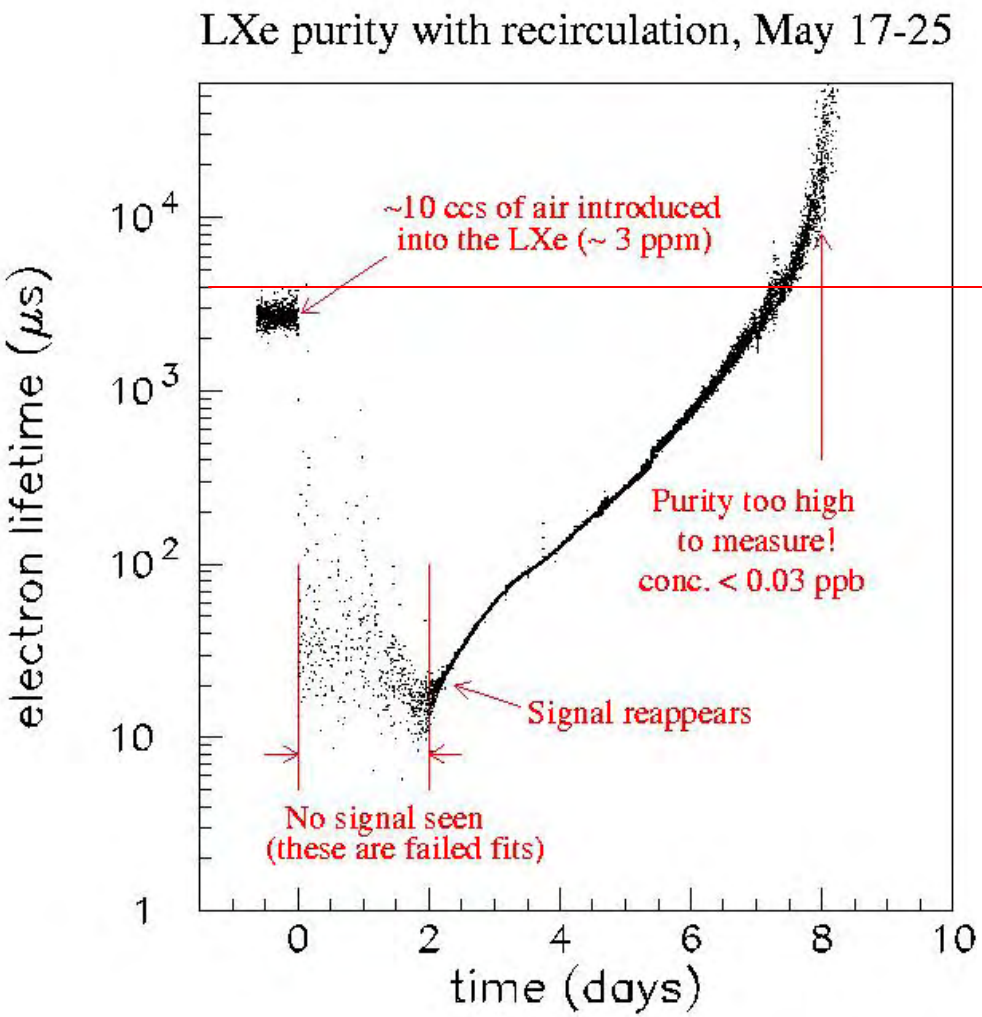
Readout using production
EXO-200 electronics (one card)





~200 APDs ready to go

Recirculation essential



EXO-200 goal

l > 400 cm

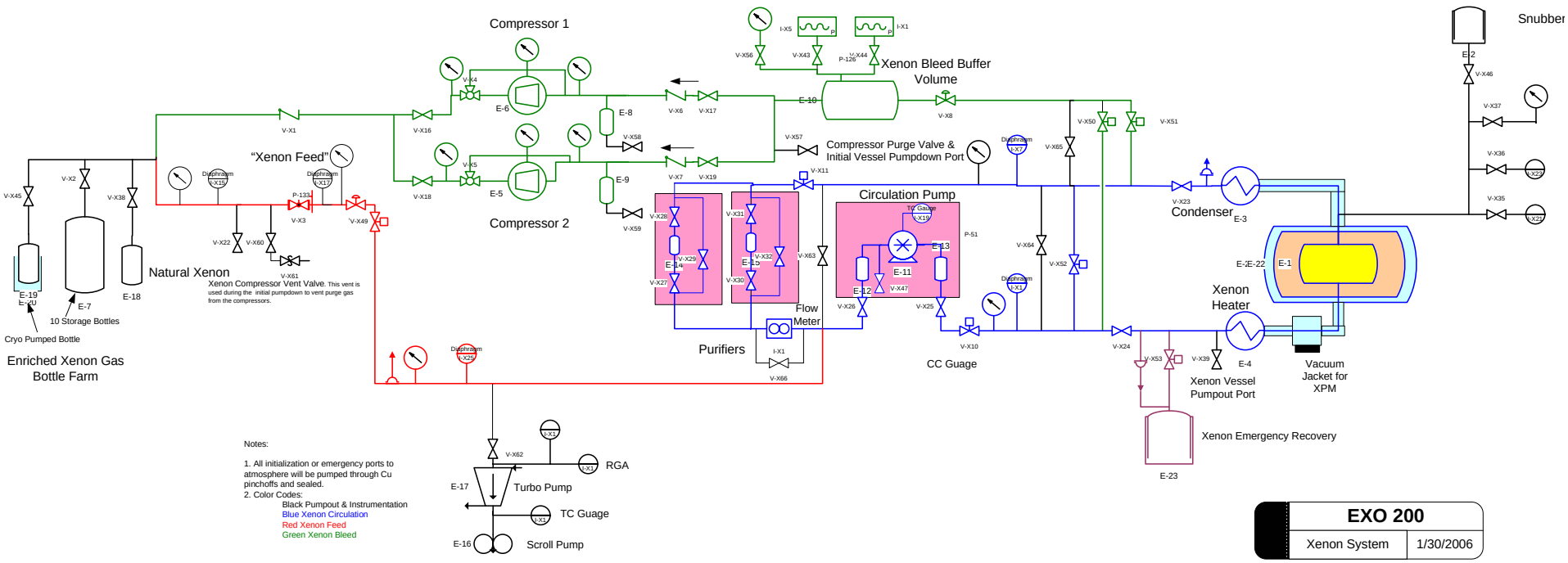
t ~ 4 ms

0.1 ppb O_2 equivalent

Conclusion: common impurities (O_2, H_2O, CO_2) efficiently removed by purifier, recirculation.

Cryogenics/fluidics

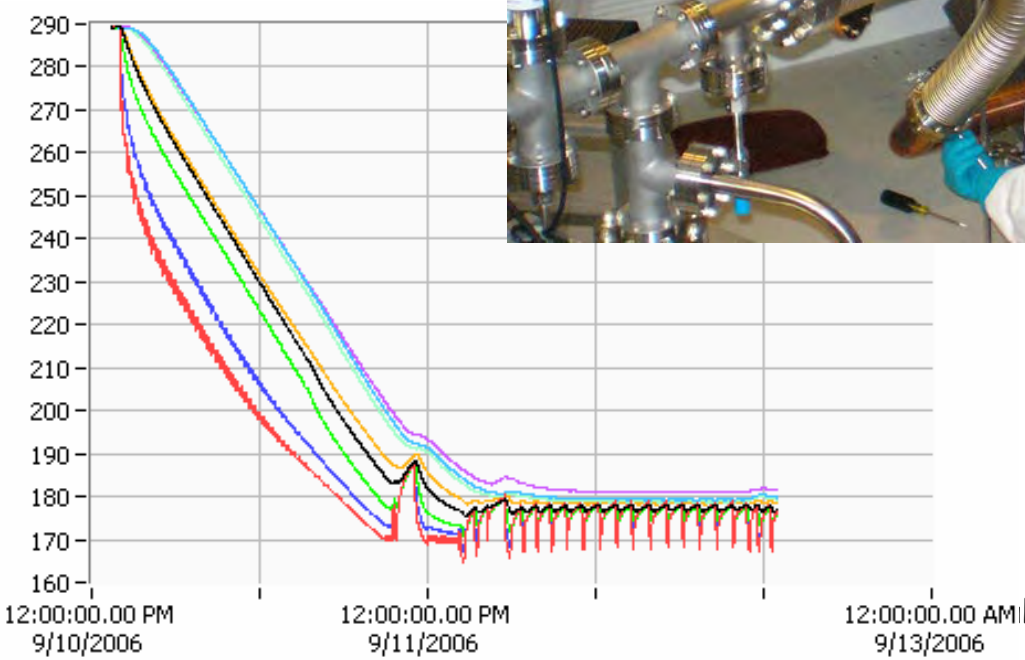
Must maintain ΔP = ±0.3 bar across the thin copper vessel



Cryostat was fabricated at SDMS (Grenoble)

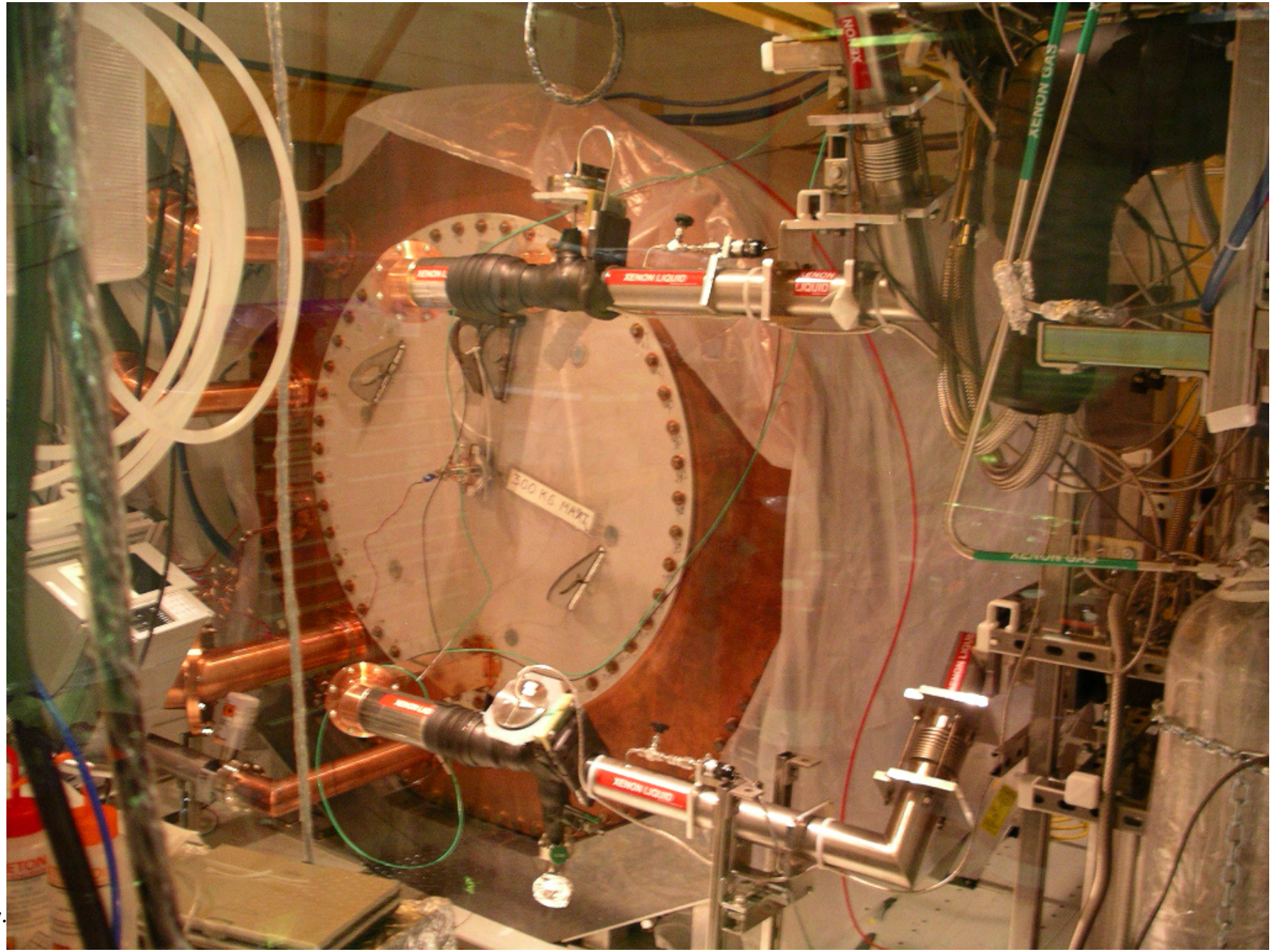
First cryostat cooldown

Sept 10-17, 2006



Commissioning LXe cryogenics and pressure control at Stanford:

April 2007, ~30kg natural Xe



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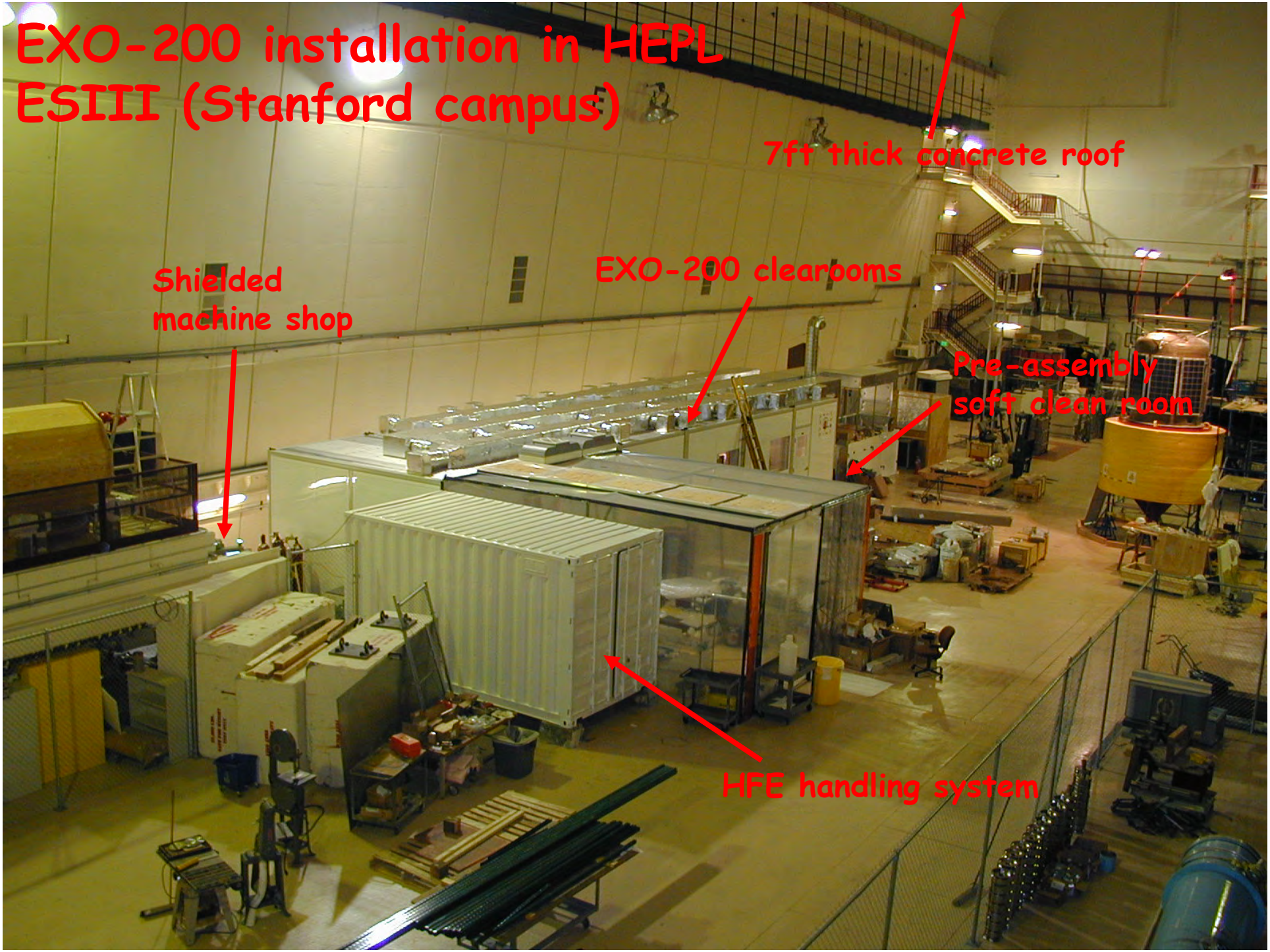

EXO-200 installation in HEPL
ESIII (Stanford campus)
7ft thick concrete roof
Shielded
machine shop
EXO-200 clearooms
Pre-assembly
soft clean room
HFE handling system

Massive effort on material radioactive qualification using:

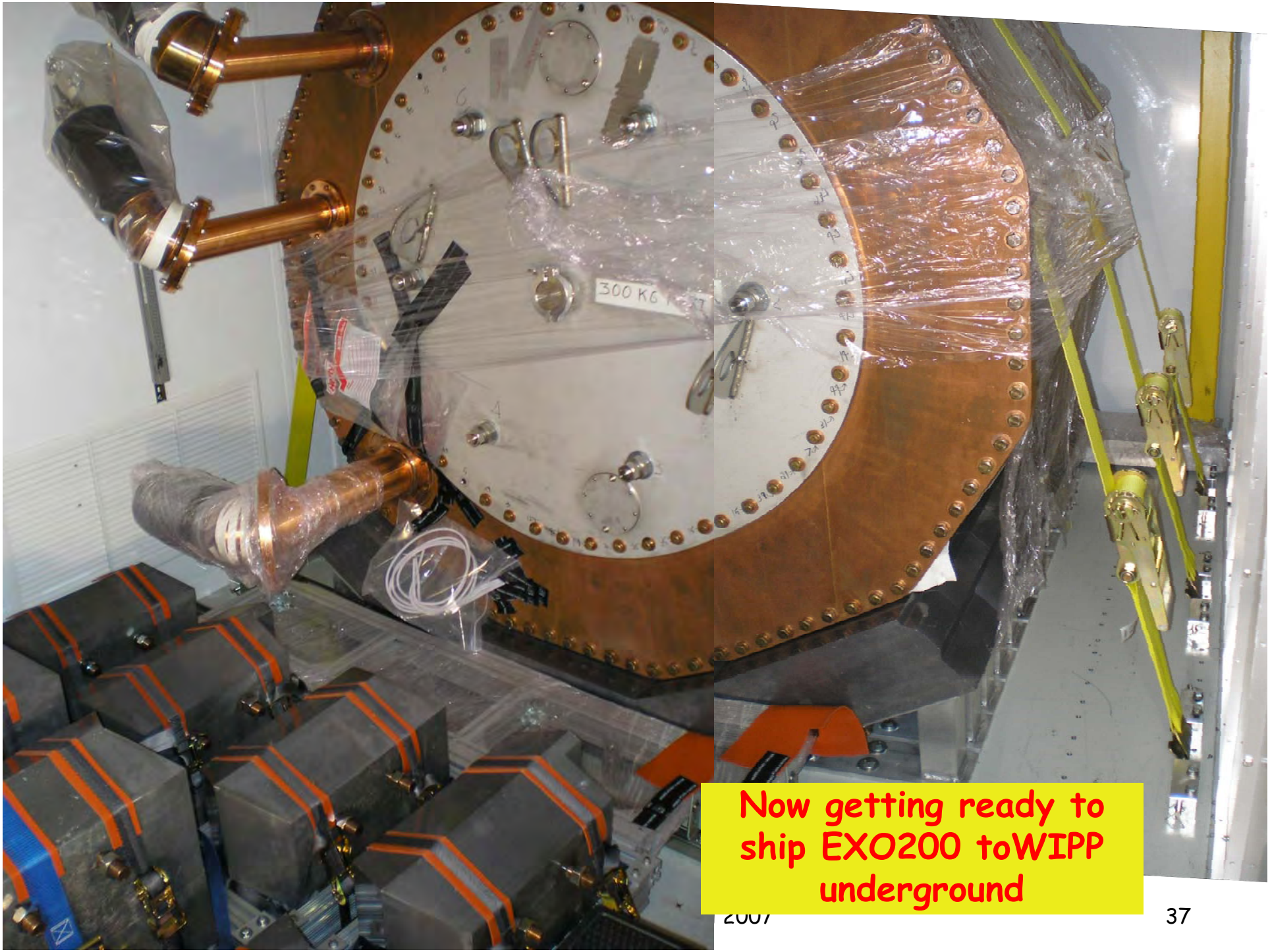
- NAA (MIT-Alabama)
- Low background γ-spectroscopy (Neuchatel, Alabama)
- α-counting (Alabama, Stanford, SLAC, Carleton)
- Radon counting (Laurentian)
- High performance GD-MS and ICP-MS (Canadian Inst. Standards)

At present the database of characterized materials includes >300 entries

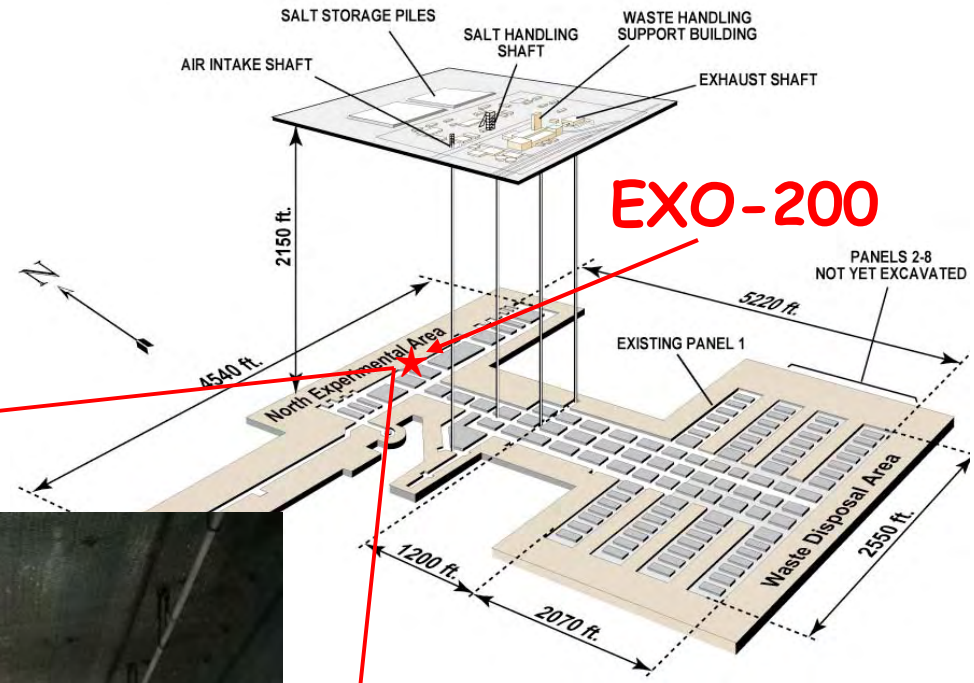
MC simulation of backgrounds at Alabama and Stanford/SLAC

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

Cleanrooms now dismounted and ready to ship to WIPP underground



Now getting ready to ship EXO200 toWIPP underground



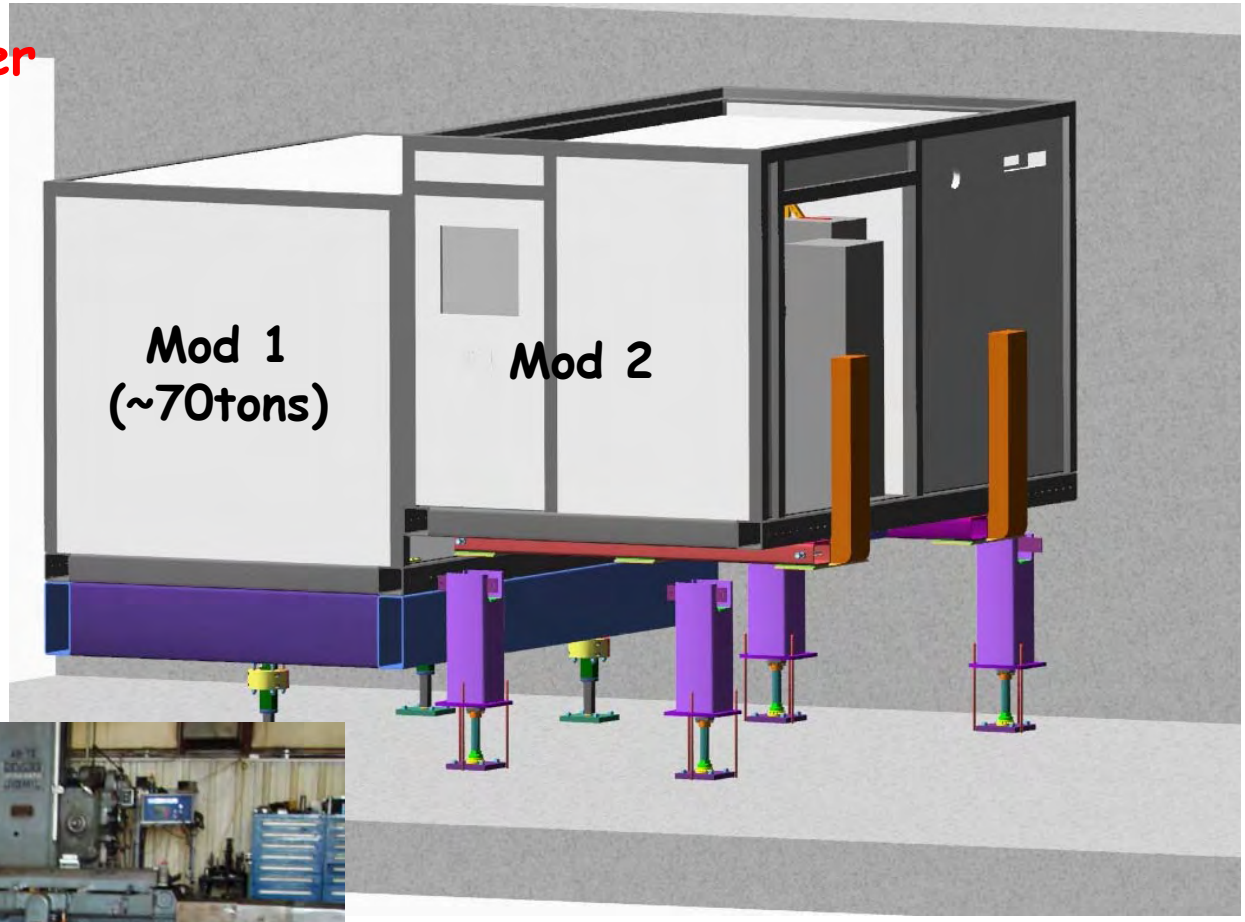
~20 EXO people have already completed the full WIPP miner training

Underground transportation at WIPP has been rehearsed

both in terms of load (~35 tons)

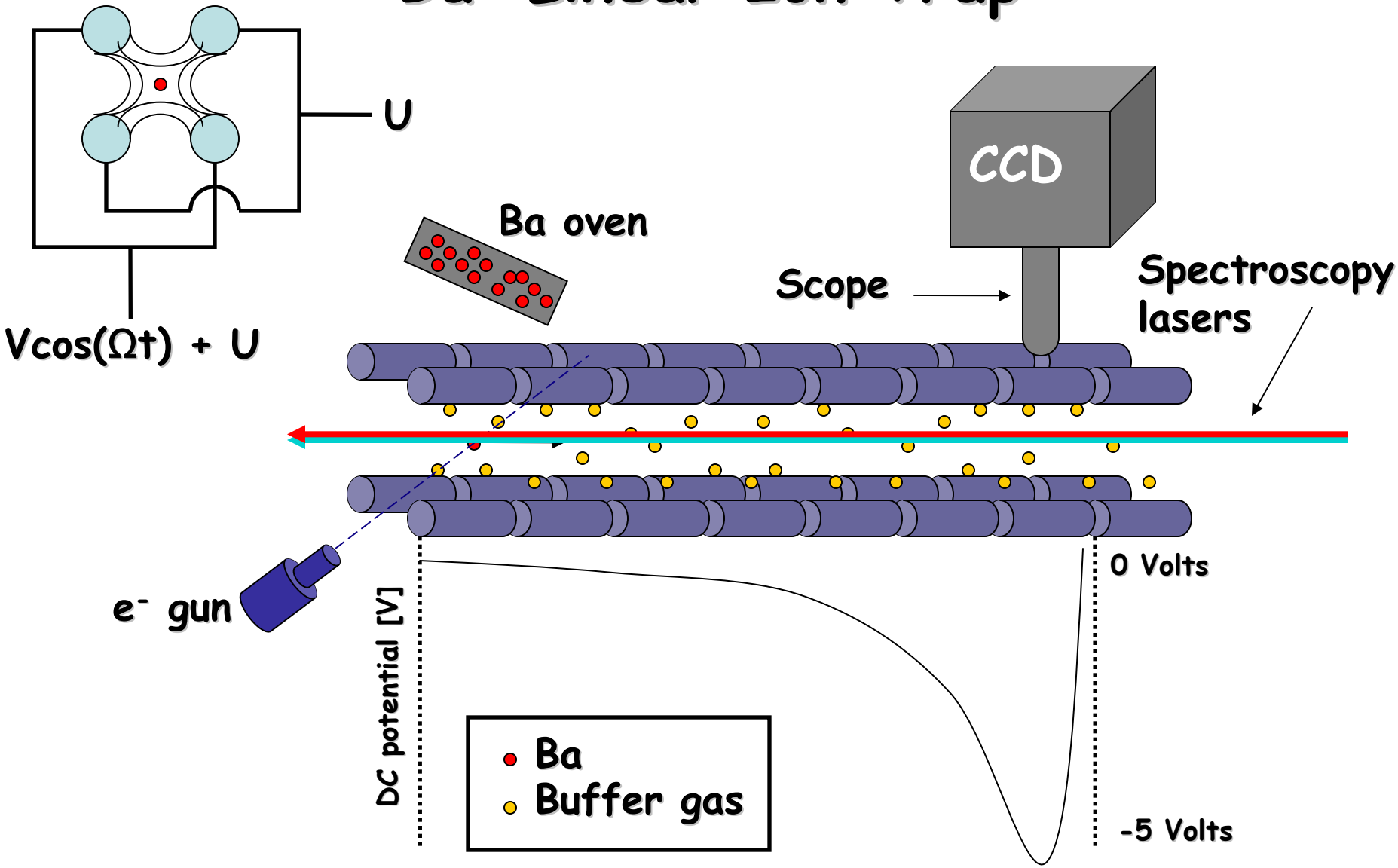
and size (our clean rooms clear the conveyance by ~1inch)

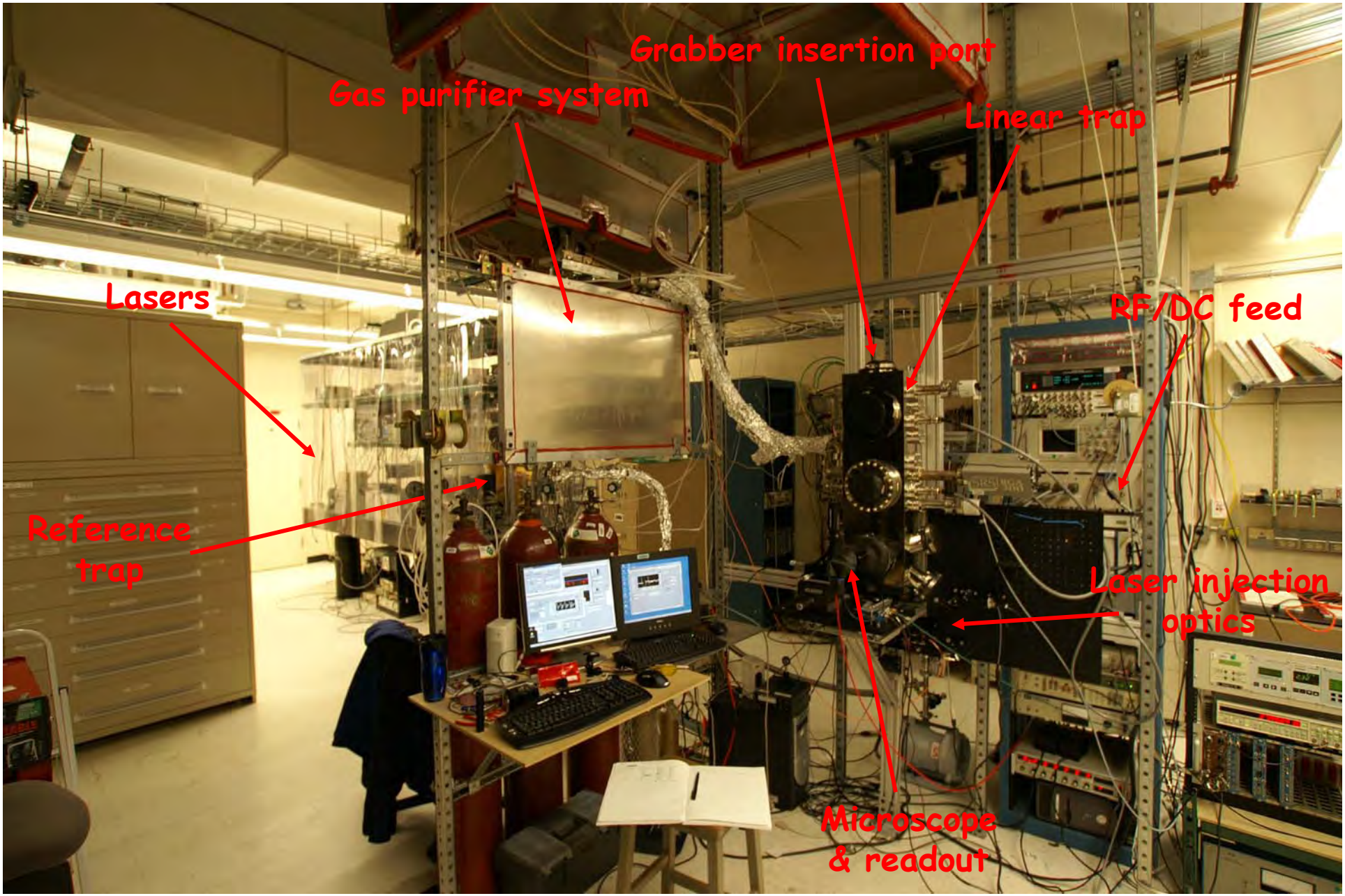
Because of salt creep over the years a system of adjustable foundations maintains the EXO-200 cleanrooms level without the need for mining



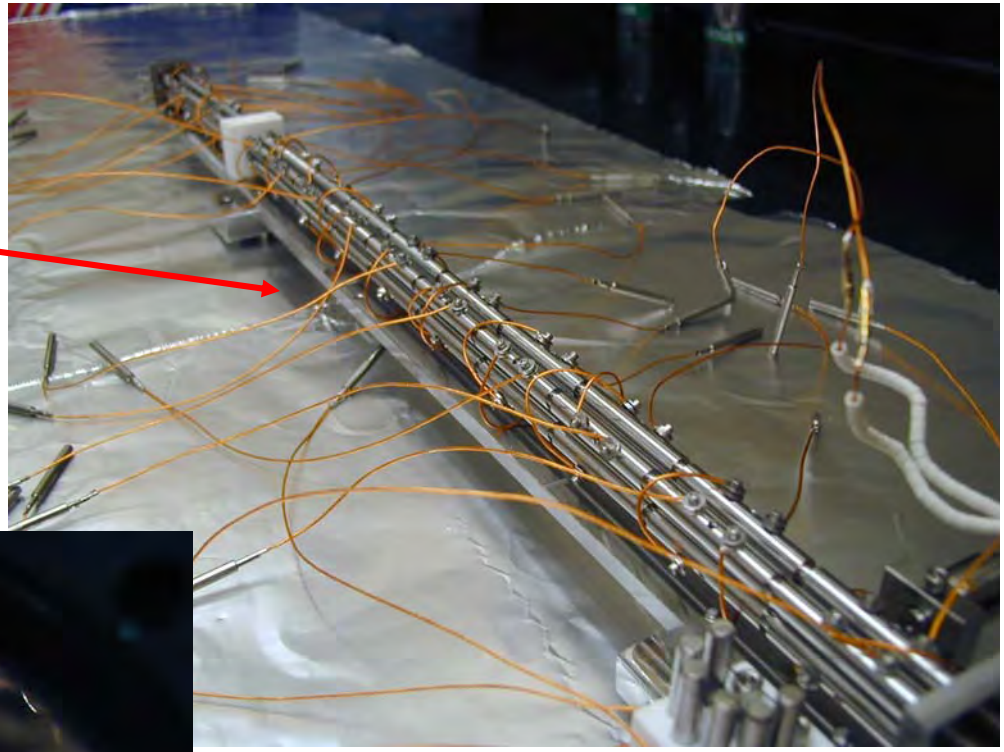
Ba tagging R&D

Ba^+ Linear Ion Trap



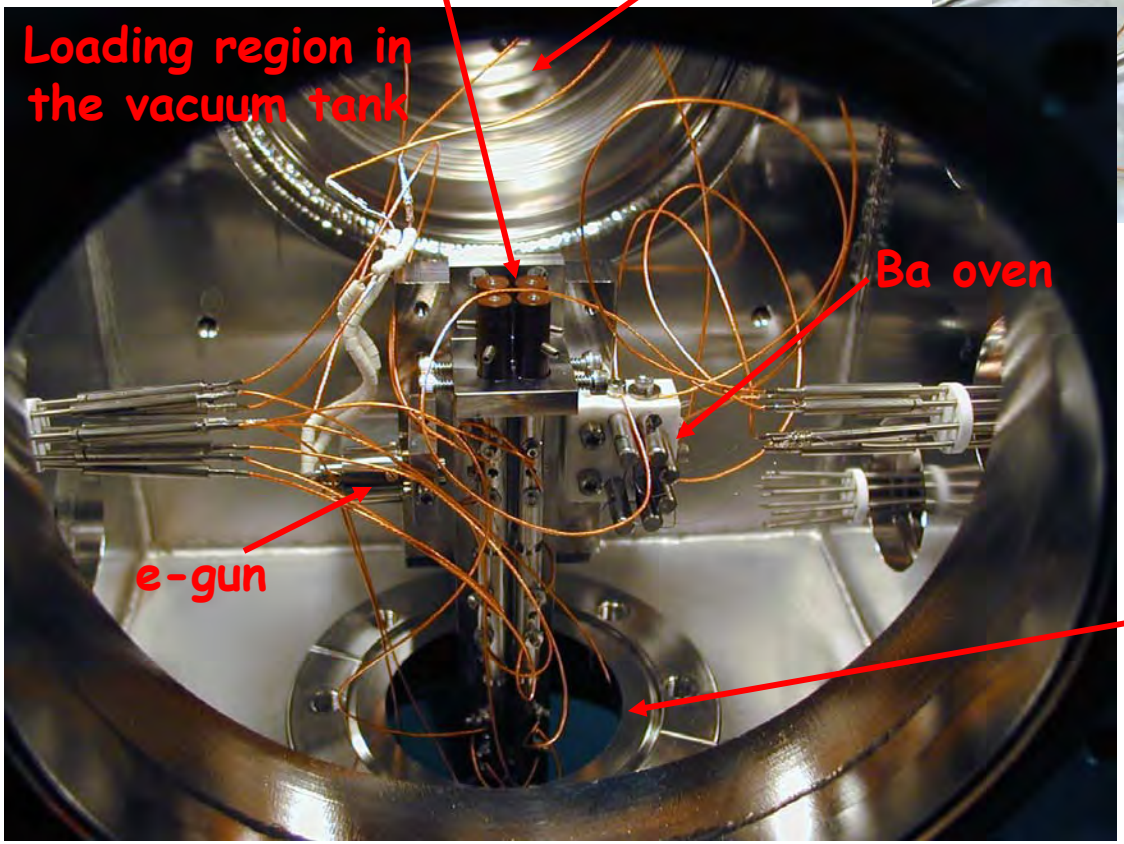

Grabber insertion port
Gas purifier system
Linear trap
Lasers
RF/DC feed
Reference trap
Laser injection optics
Microscope & readout

Electrode structure being prepared

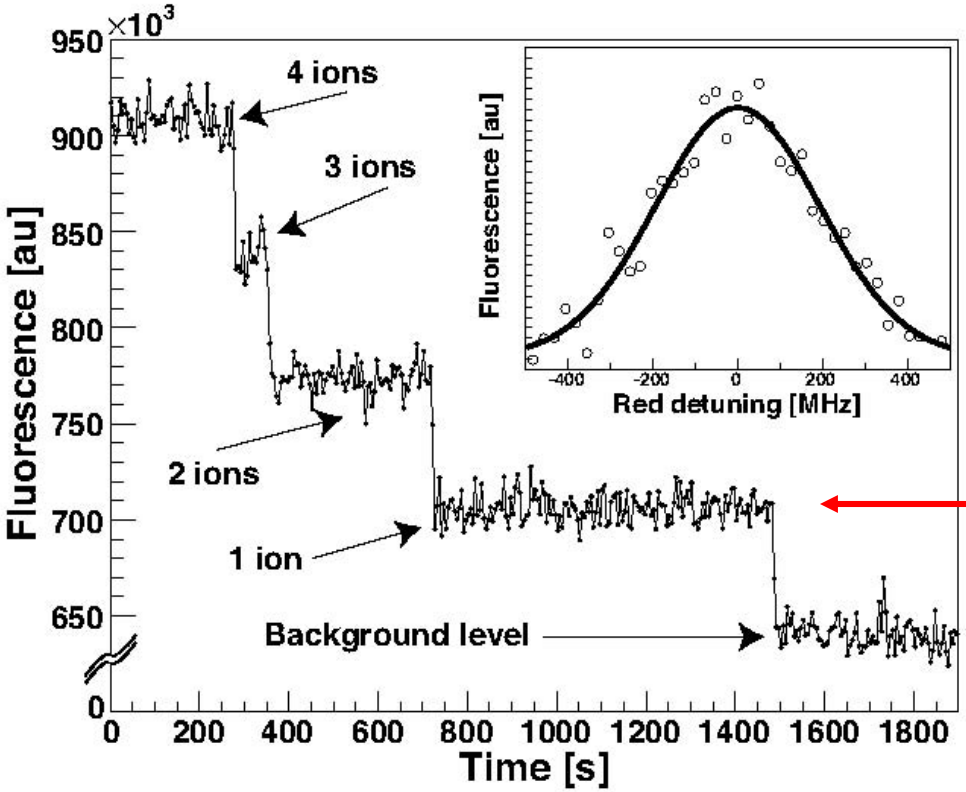


Tip loading access

Main turbo port



Differentially pumped aperture

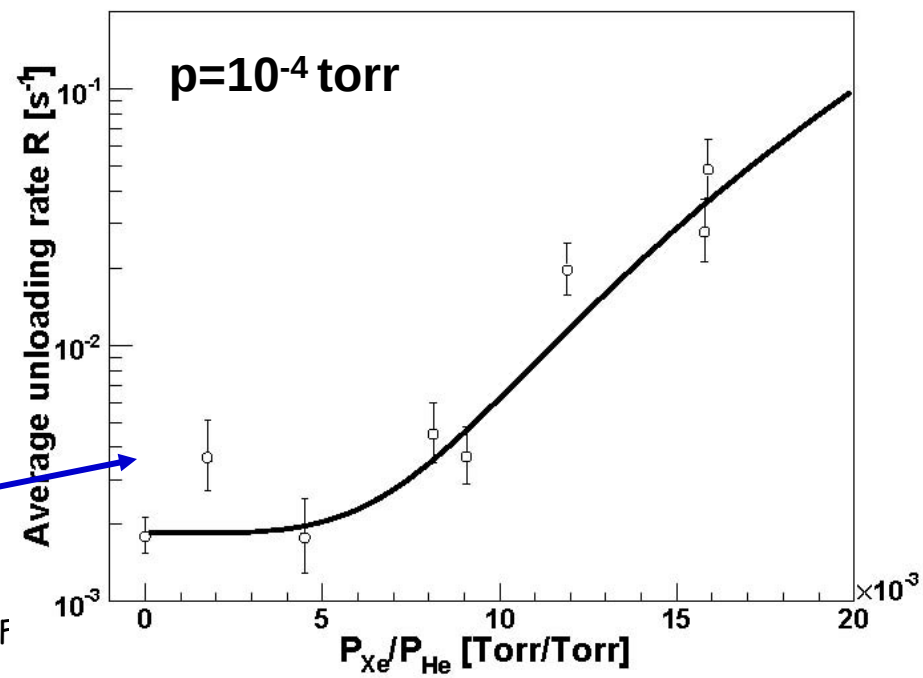


First single ion detection in high pressure gas (He, Ar)

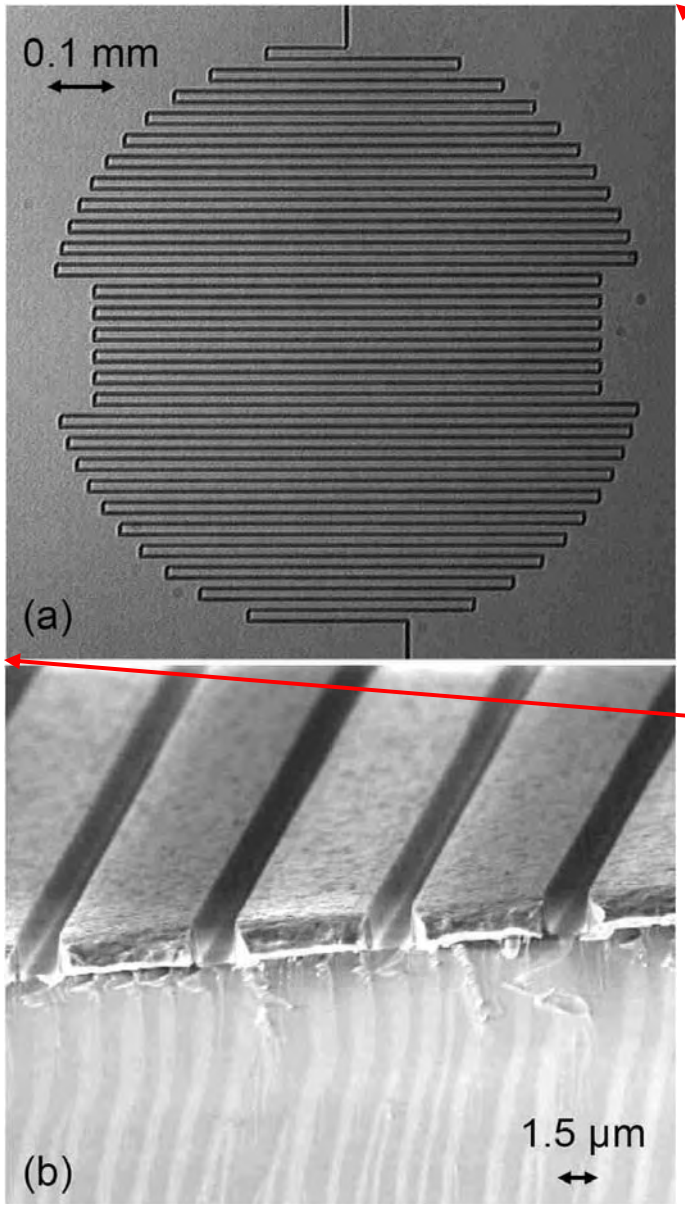
~9σ discimination in 25s integration

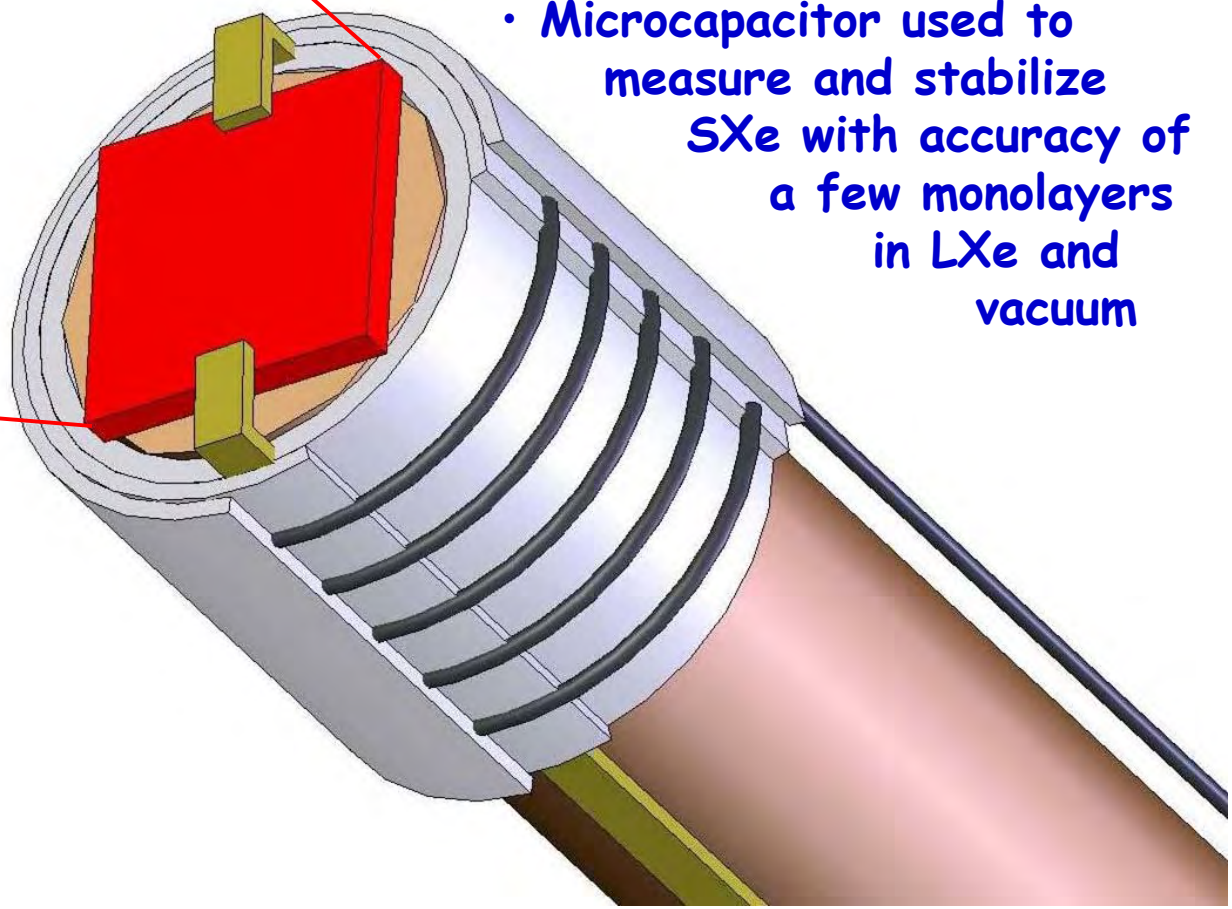
M.Green et al. arXiv:0702122, to appear in Phys Rev A
B.Flatt et al. arXiv:0704.1646 to appear in Nucl Inst and Meth A

Single ion spectroscopy & identification possible in some Xe atmosphere provided He is added to the trap



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

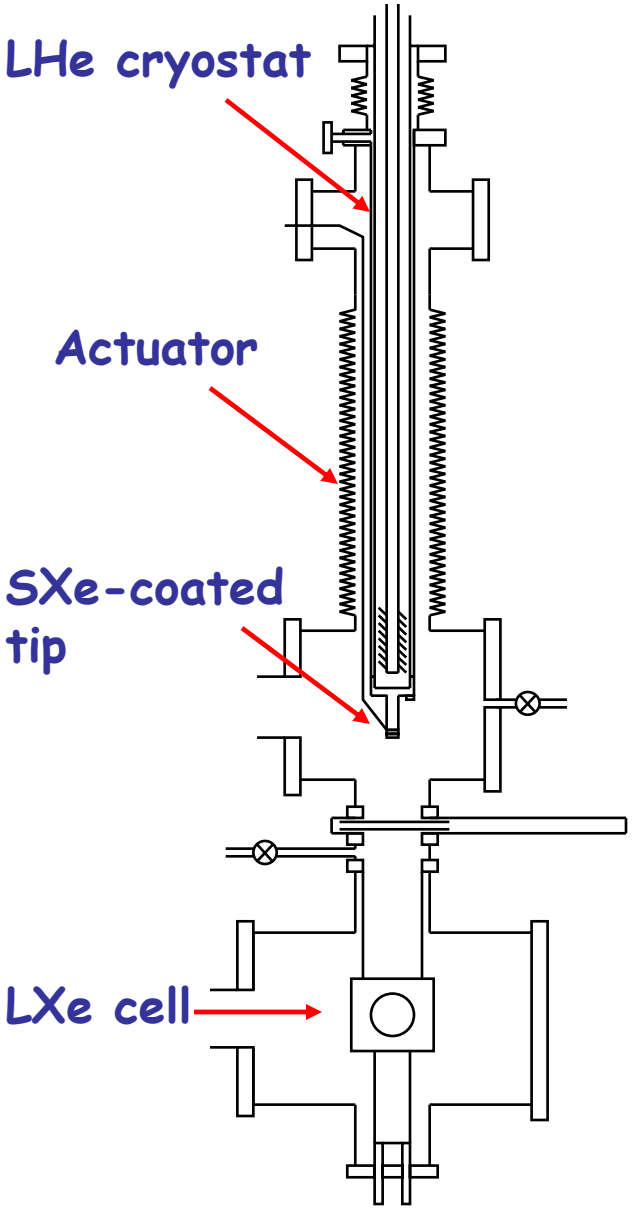


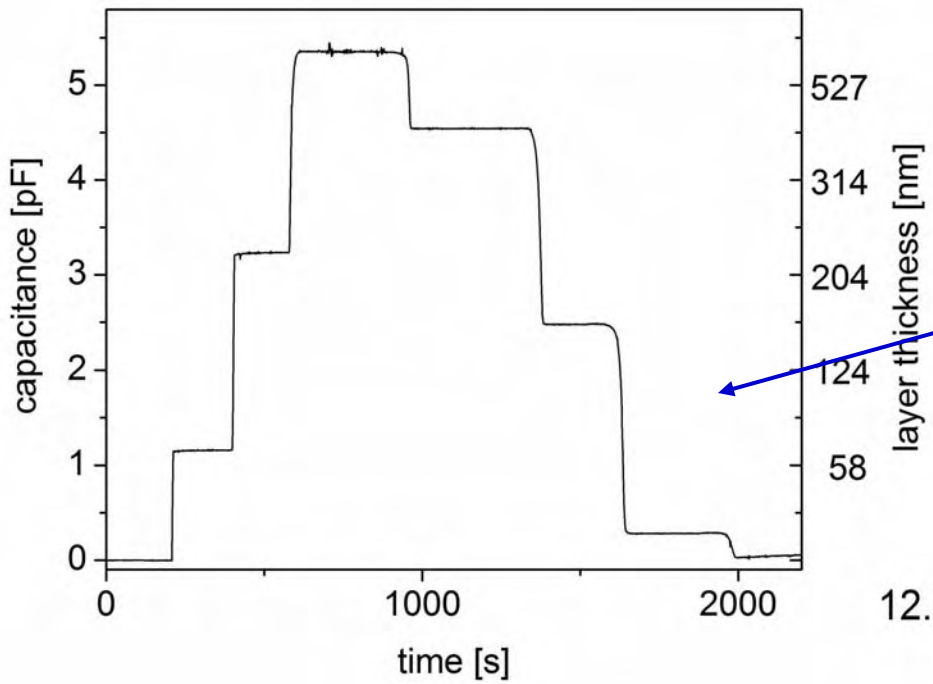


Cryogenic dipstick

- 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

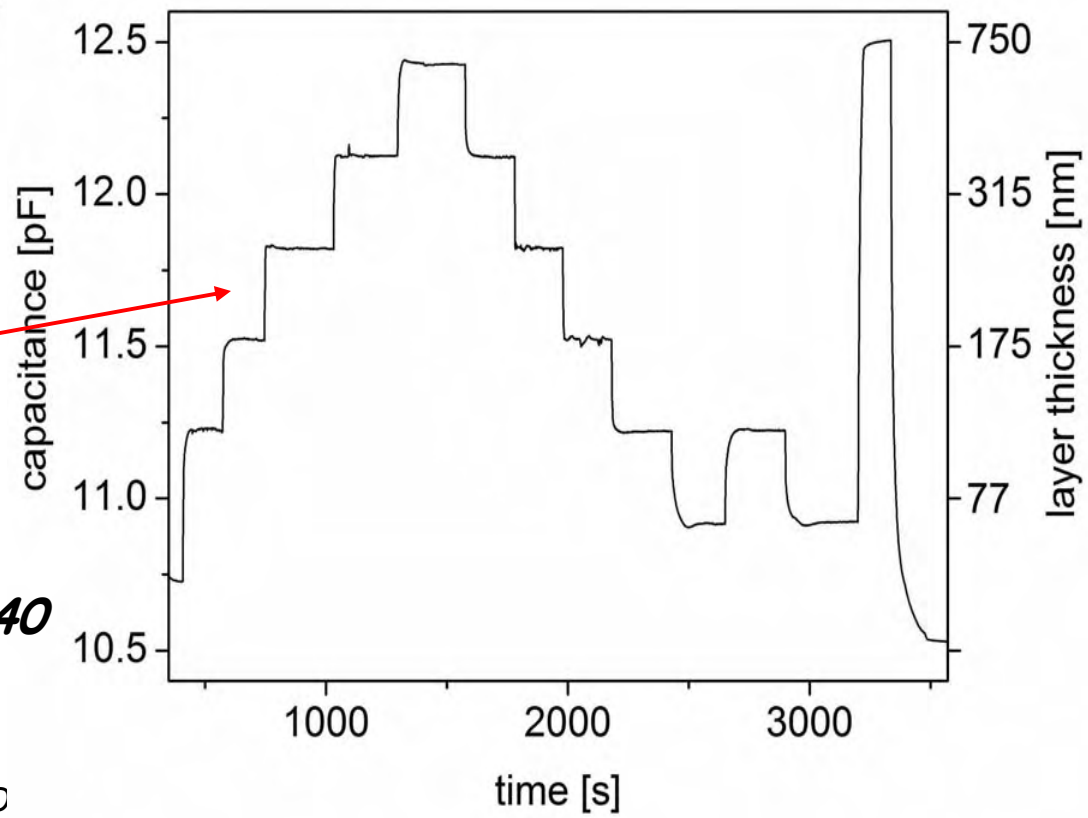
Complete setup





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

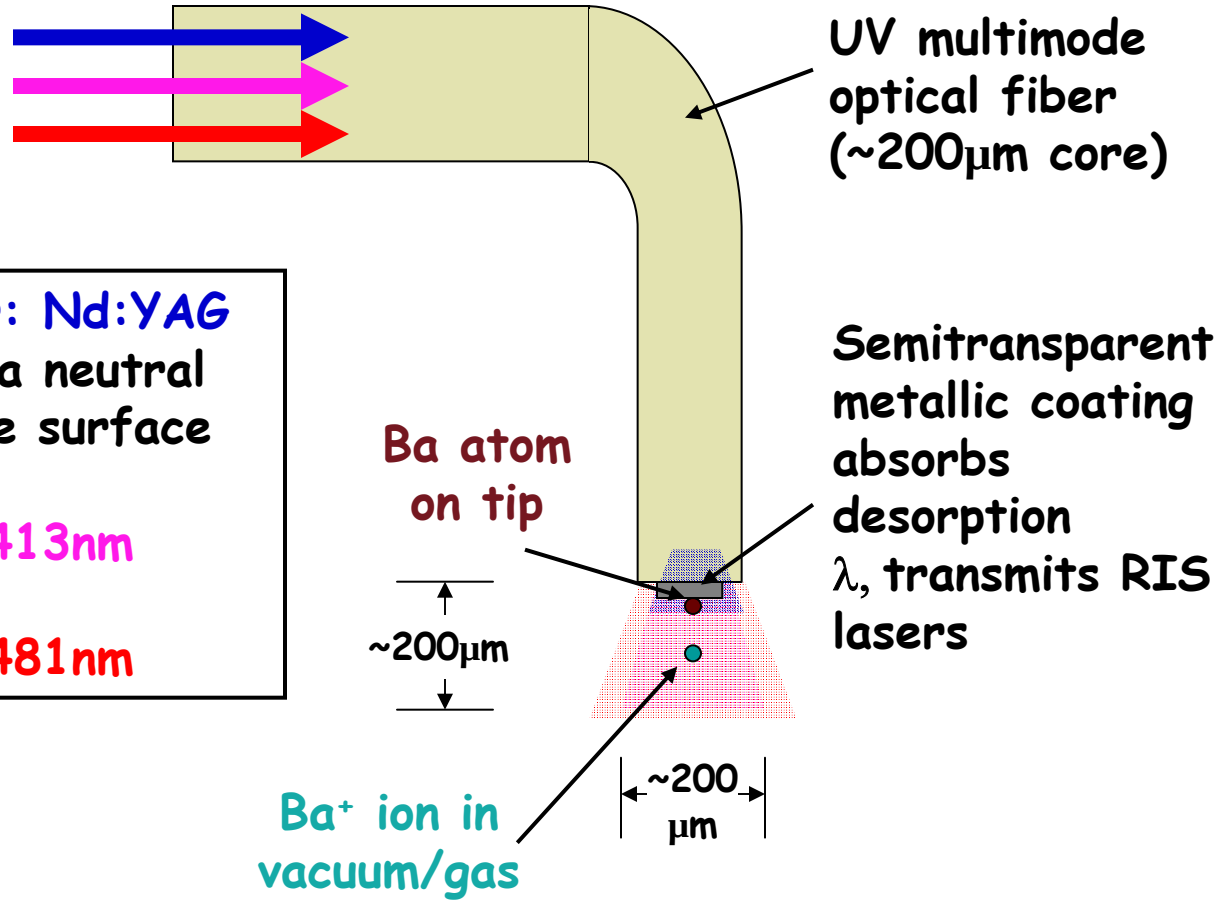
Growing and maintaining SXe layers in a LXe bath with active feedback



P.Fierlinger et al, arXiv:0706.0540 submitted to Rev. Sci. Inst.

RIS tip

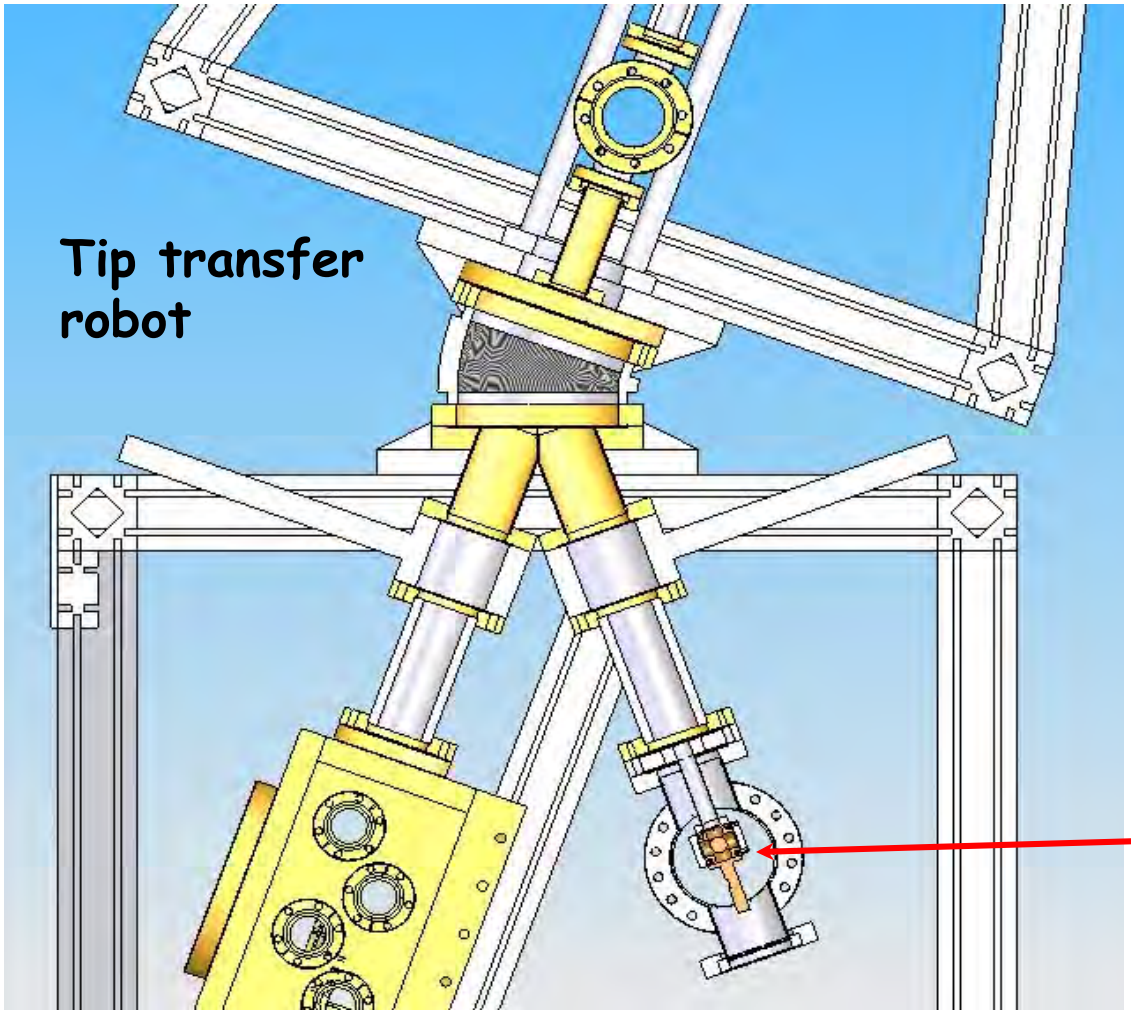
1. Pulsed desorption laser: Nd:YAG
2. ~10ns delay to allow Ba neutral atom to leave the surface
3. -Resonant step: pulsed laser @ 413nm
   -Autoionizing step: pulsed laser @ 481nm

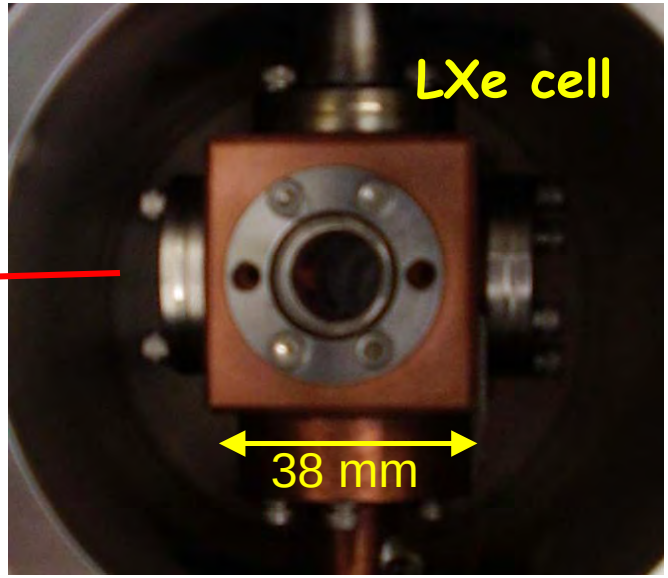


In this case *each step* can be documented to work with high efficiency in the literature !

Start investigating desorption from a vacuum window with a borrowed YAG laser.
Will soon order the RIS (dye) lasers

Next step:
transfer Ba-ions from LXe cell to ion trap





Conclusions

Over its glorious history neutrino physics has provided plenty of surprises and has required forays in many different areas of science and technology

EXO really belongs to this tradition!

Isotope enrichment at an unprecedented scale (for science) is a reality

EXO-200 is going underground!

Ba tagging for EXO is using bag of tricks borrowed from nuclear and particle physics, AMO and surface science

Stay tuned for results!

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