EXO

status report

Annual DoE HEP SLAC review

Jun 13, 2007

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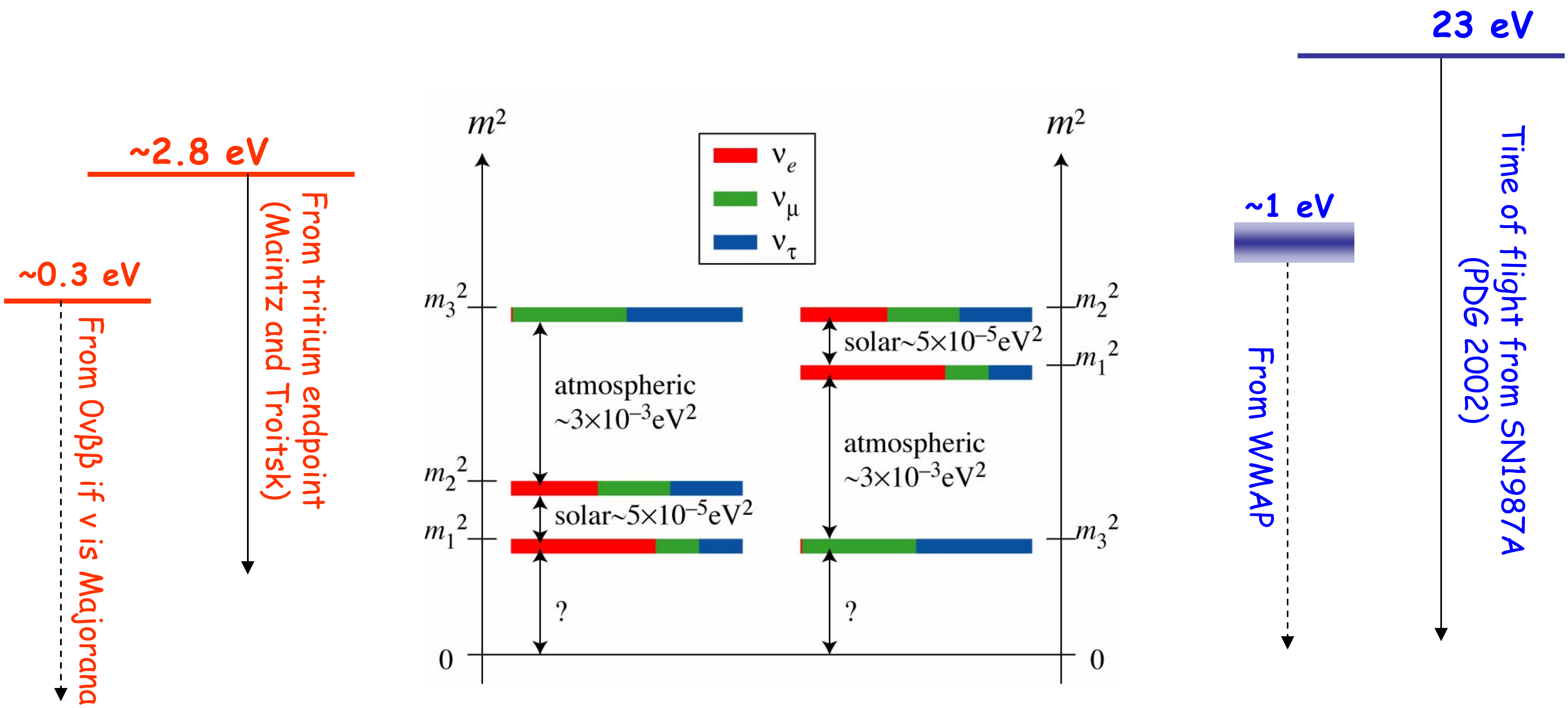
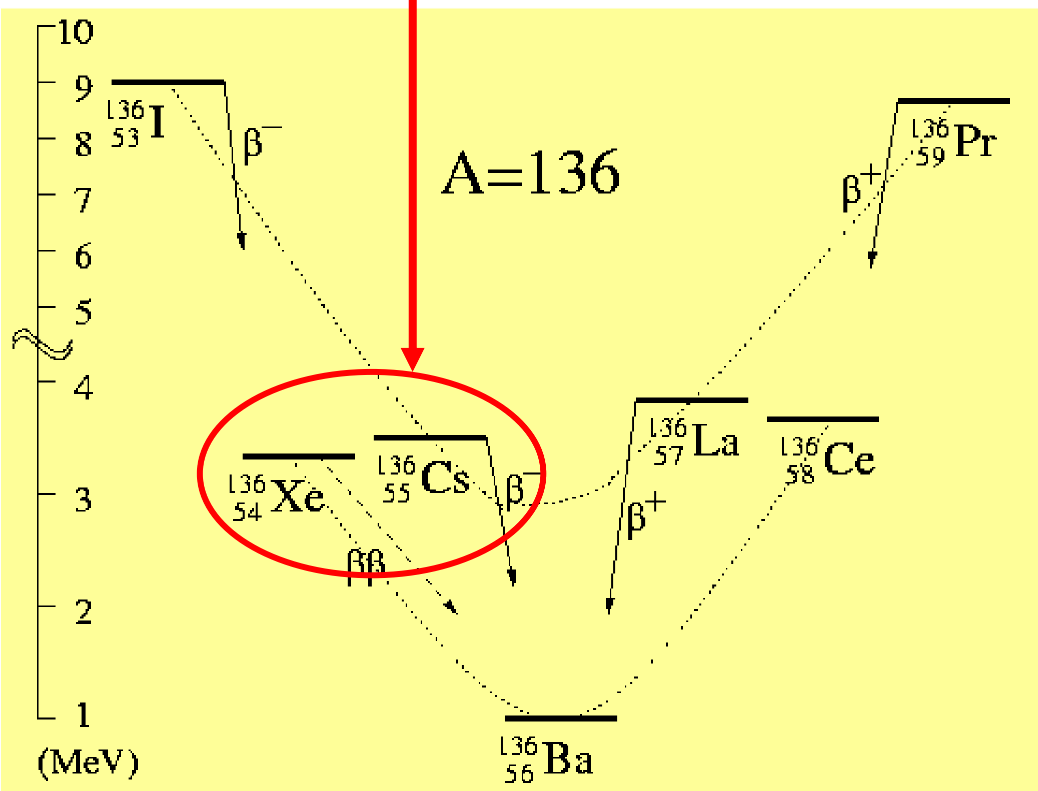
The next crucial measurement in neutrino physics:

Discovery of the neutrino mass scale



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

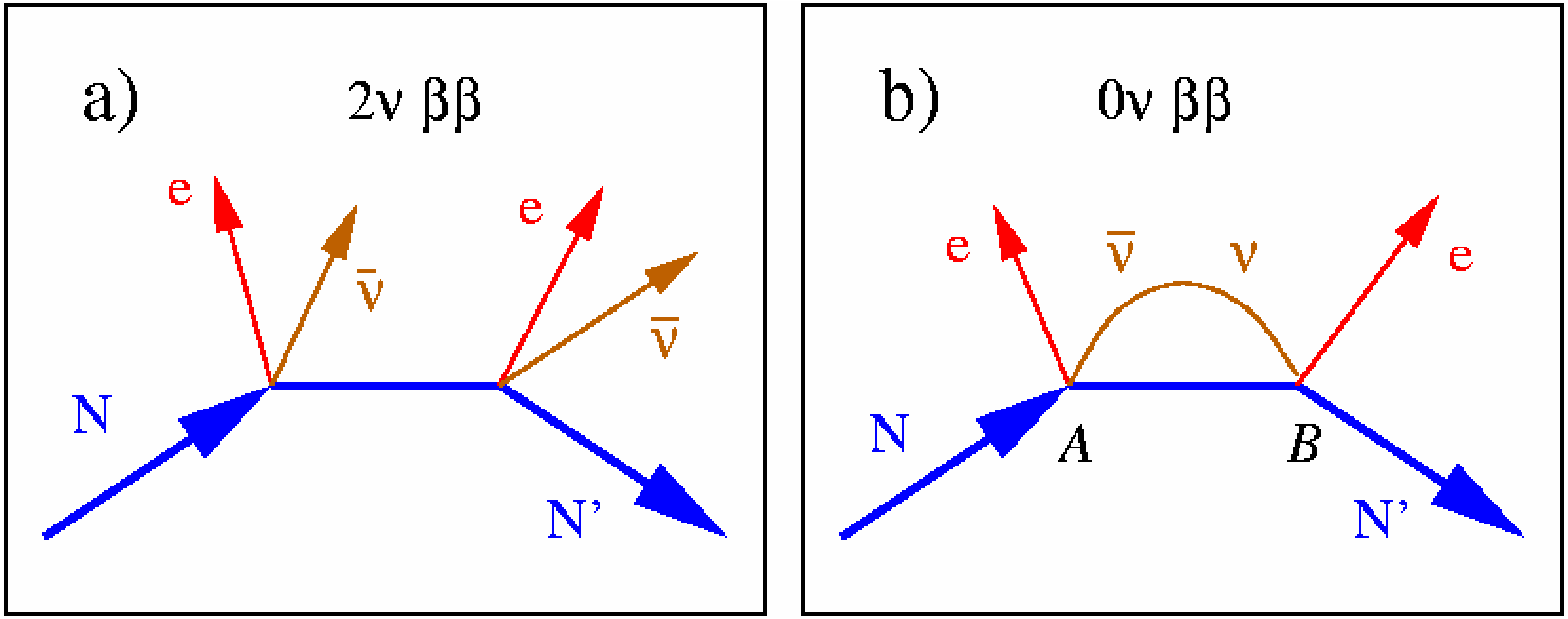
There are two varieties of $\beta\beta$ decay

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

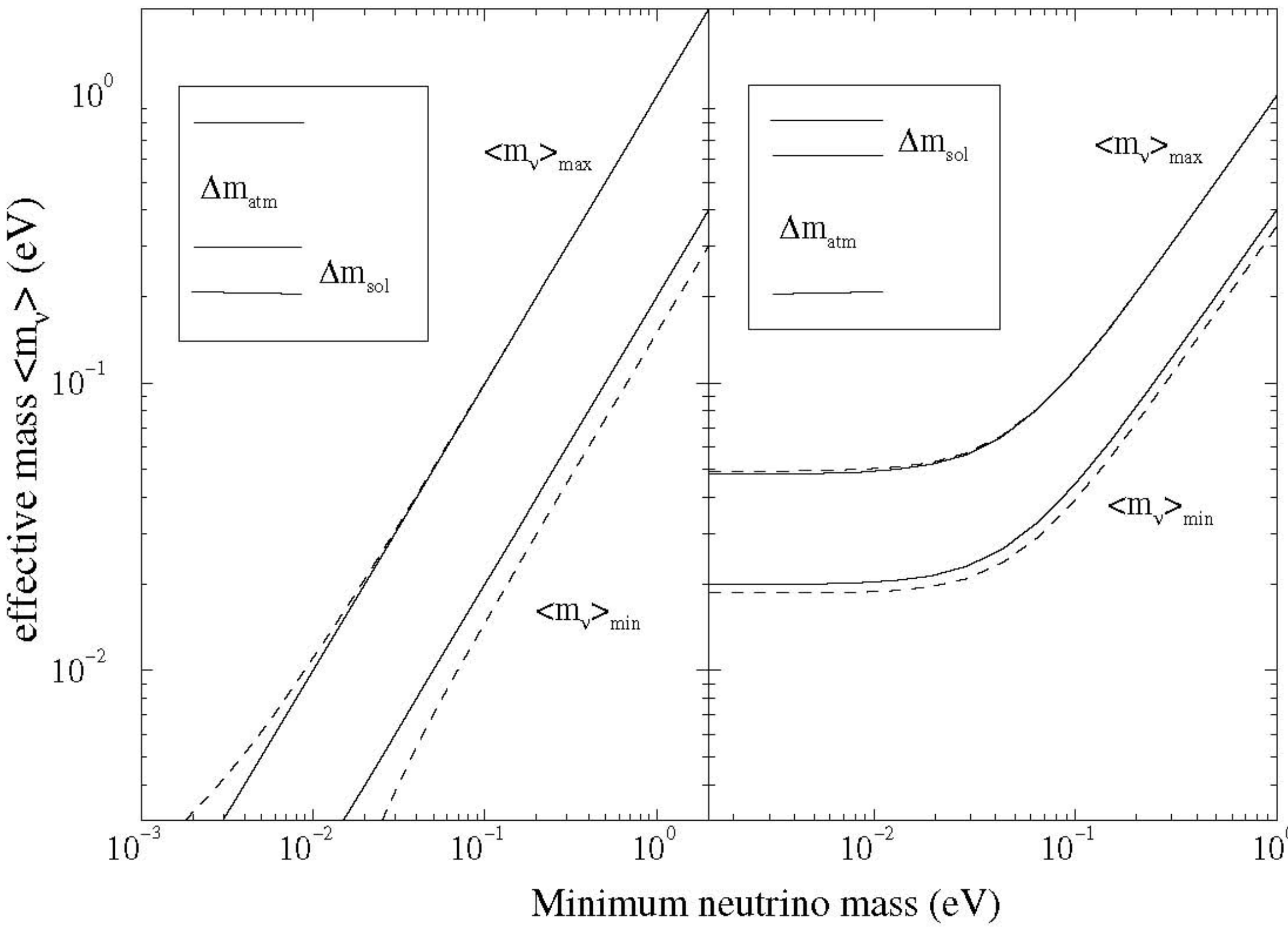
0ν mode: a hypothetical process can happen only if:

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

Since helicity has to "flip"



One can compute upper and lower bounds for <m$_\nu$> from *U* and *Δm²*



Solid lines are bounds using $\theta_{13}=0$, dashed for Chooz limit

From P.Vogel & S.Elliott Ann Rev Nucl Sci 52 (2002)

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 with ~30% accuracy

$G^{0\nu\beta\beta}$ 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)	$\langle m \rangle$ (eV)
^{48}Ca			$>1.4 \cdot 10^{22}$ (76%CL)	
^{76}Ge	Ge diode	~30	$>1.9 \cdot 10^{25}$ (90%CL)*	<0.35
^{82}Se			$>1.4 \cdot 10^{23}$ (90%CL)	
^{100}Mo			$>4.6 \cdot 10^{23}$ (90%CL)	
^{116}Cd			$>1.7 \cdot 10^{23}$ (90%CL)	
^{128}Te	TeO_2 cryo	~3	$>1.1 \cdot 10^{23}$ (90%CL)	
^{130}Te	TeO_2 cryo	~3.1	$>1.8 \cdot 10^{24}$ (90%CL)	<0.2-1.1
^{136}Xe	Xe scint	~10	$>1.2 \cdot 10^{24}$ (90%CL)	<2.9
^{150}Nd			$>1.2 \cdot 10^{21}$ (90%CL)	
^{160}Gd			$>1.3 \cdot 10^{21}$ (90%CL)	

Adapted from the PDGonline, Jun 2007

*Observation reported by part of this group, this is controversial

Alabama, Caltech, Carleton, Colorado State,
Irvine, ITEP, Laurentian, Neuchatel,
SLAC, Stanford collaboration

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 !

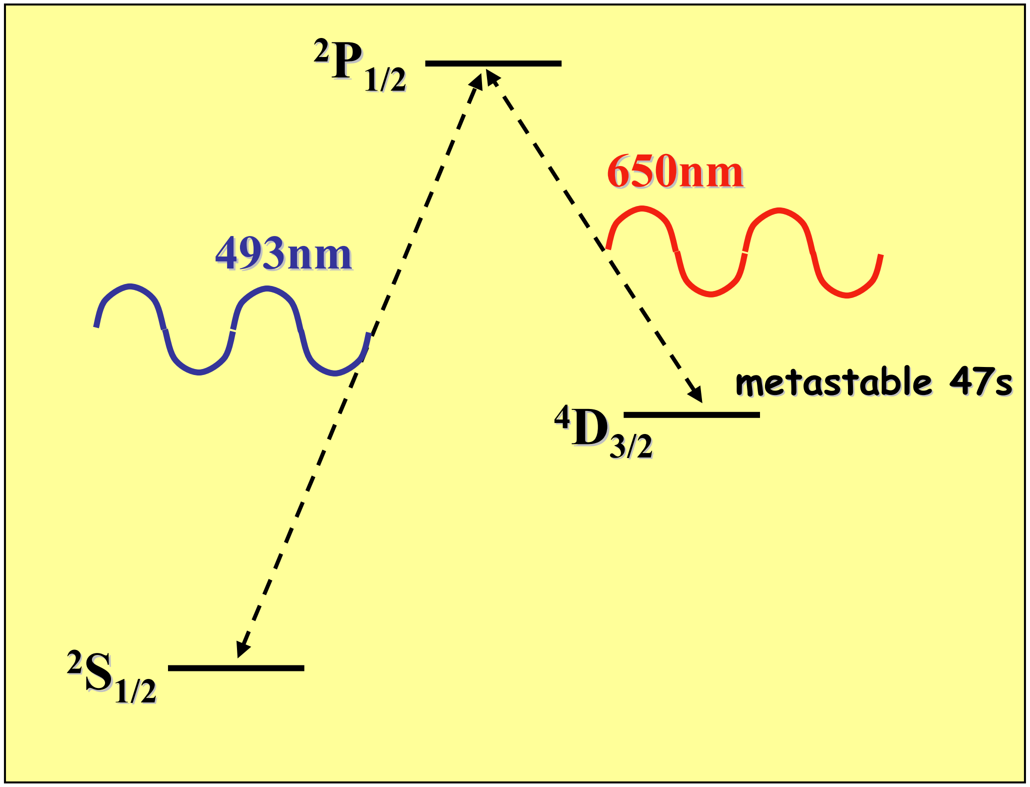
Xe is ideal for a large experiment

- 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%

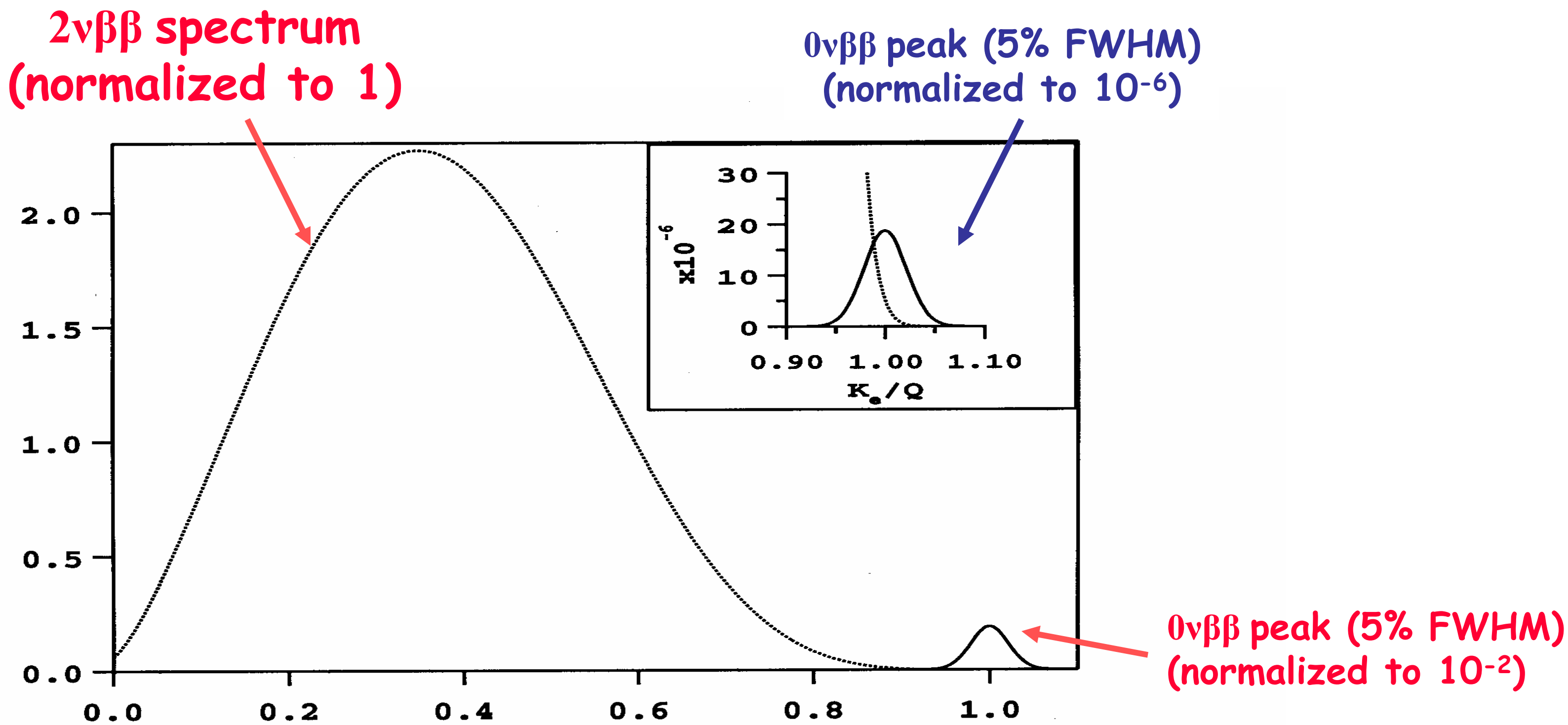
A somewhat natural scale:

- 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 $2\nu\beta\beta$ decay

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



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

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

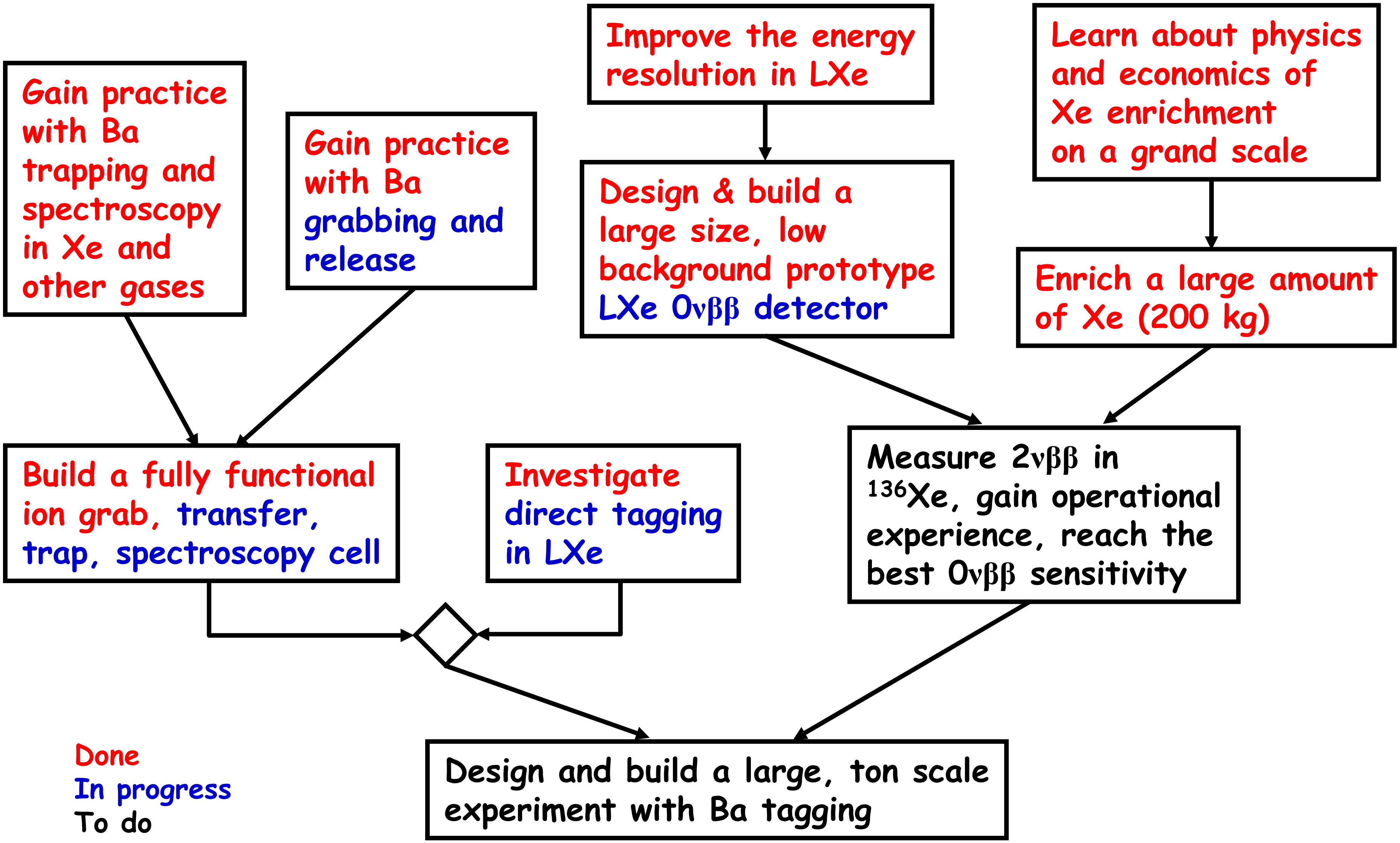
EXO neutrino effective mass sensitivity

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



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	$6.4 \cdot 10^{25}$	0.27†	0.38♦

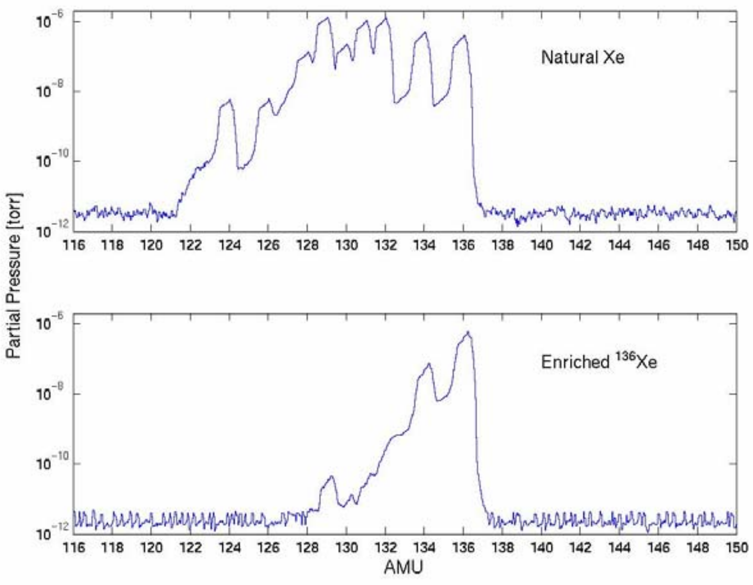
What if Klapdor's observation is correct ?

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:

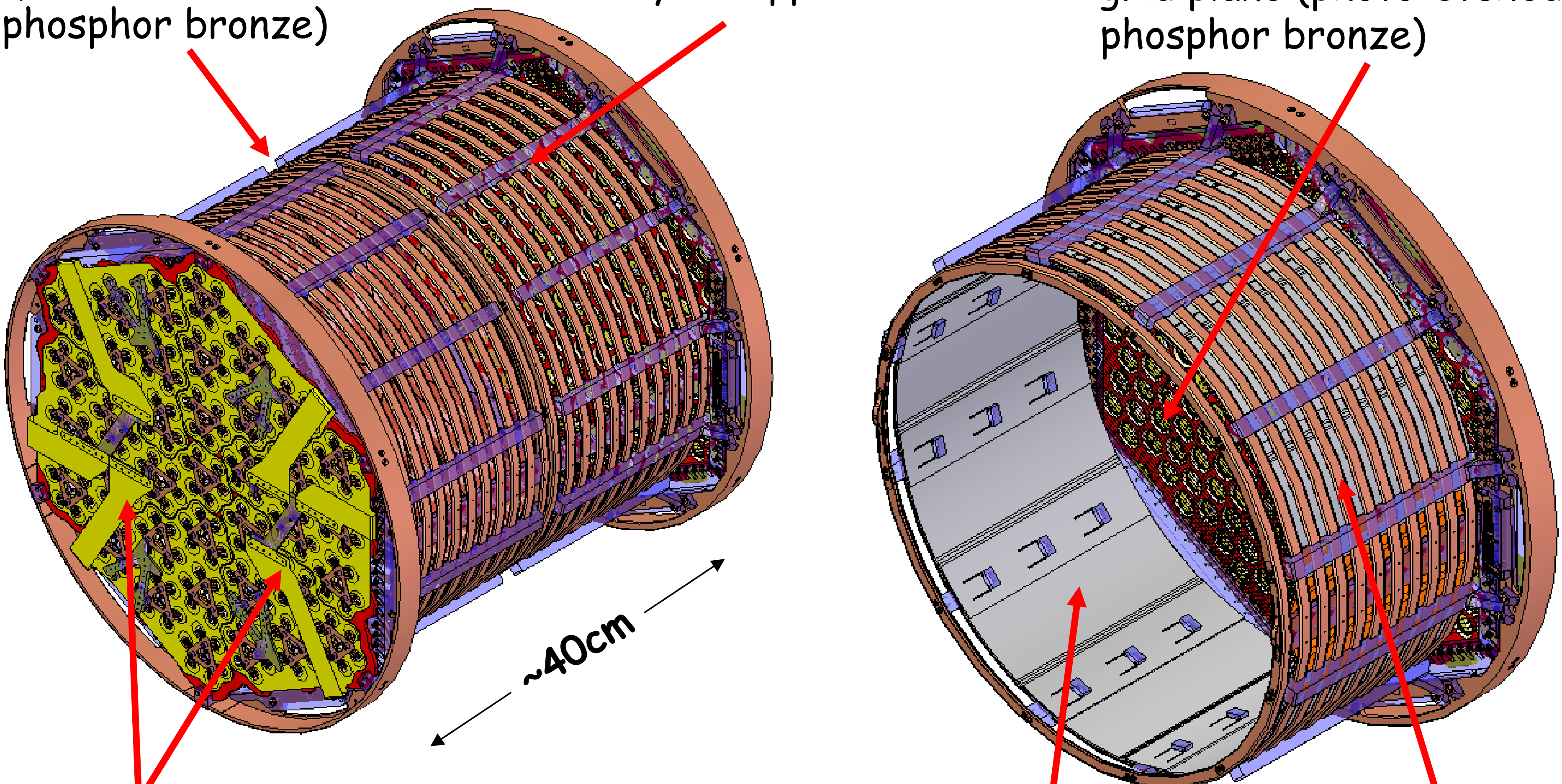
- Worst case (QRPA, upper limit) 15 events on top of 40 events bkgd → 2σ
- Best case (NSM, lower limit) 162 events on top of 40 bkgd → 11σ

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-200 LXe TPC (see P.Rowson's talk)



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)

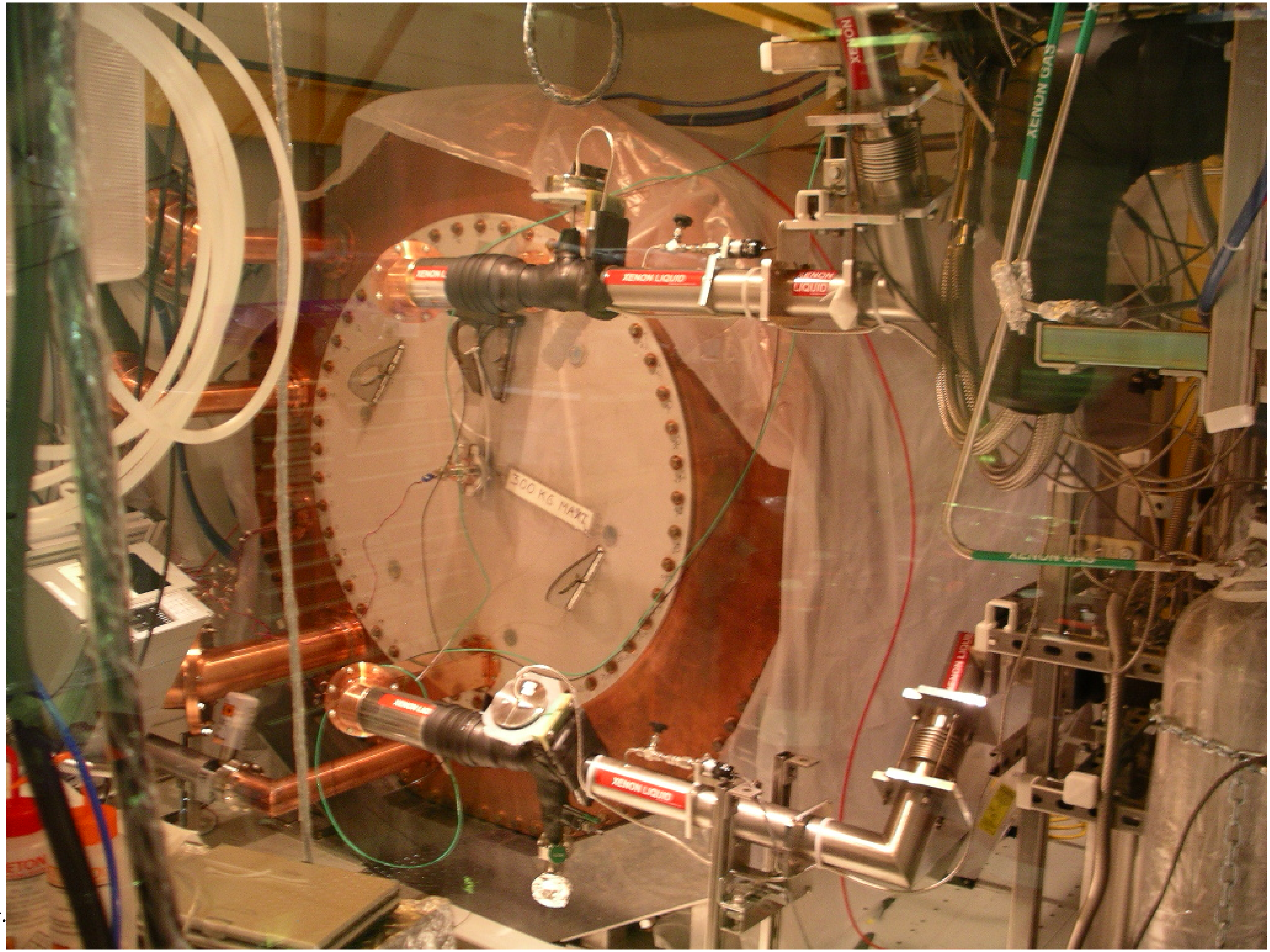
At present the database of characterized materials includes >100 entries

MC simulation of backgrounds at Alabama and Stanford/SLAC

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

Commissioning LXe cryogenics and pressure control at Stanford:

April 2007, ~30kg natural Xe



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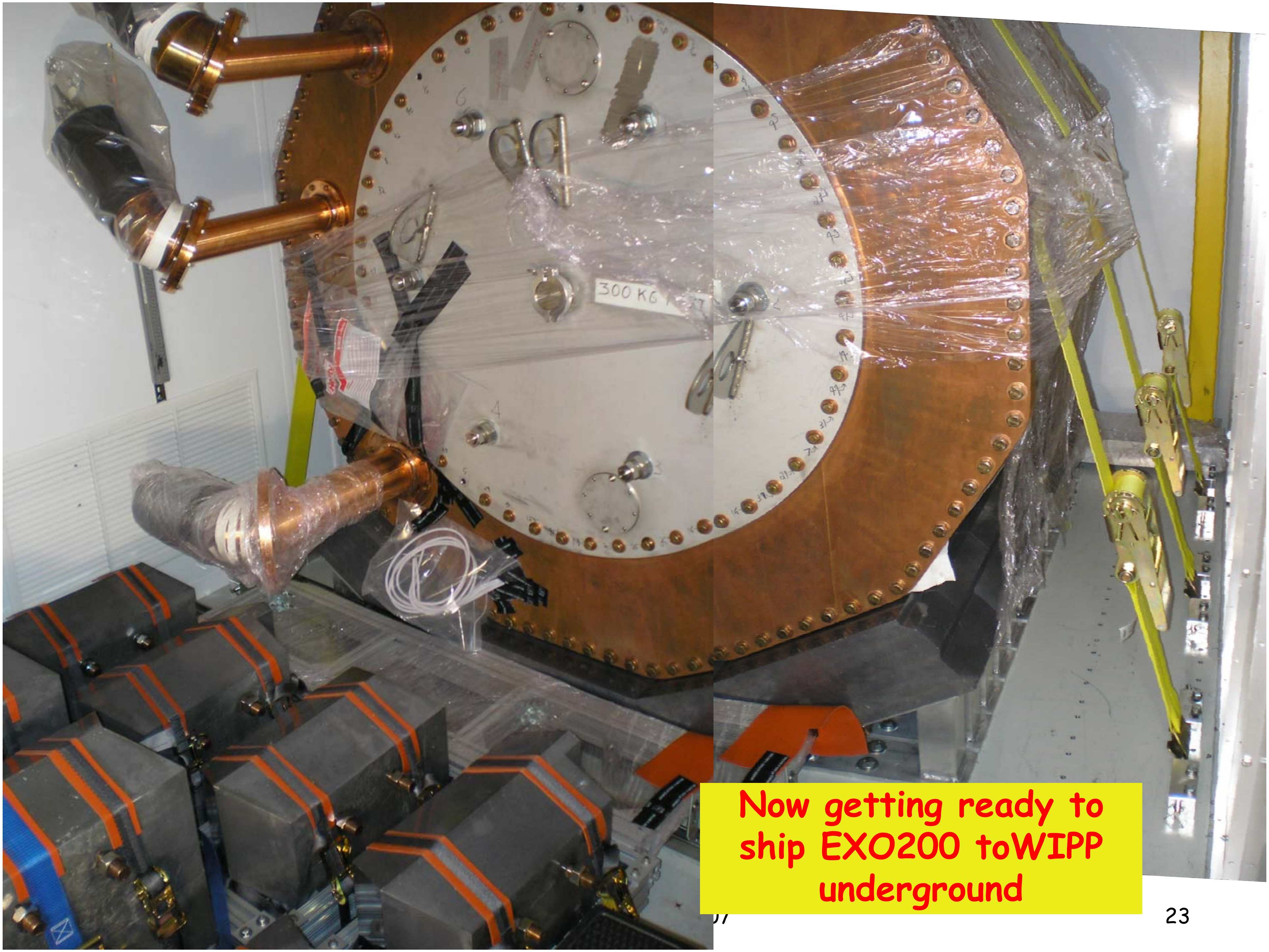
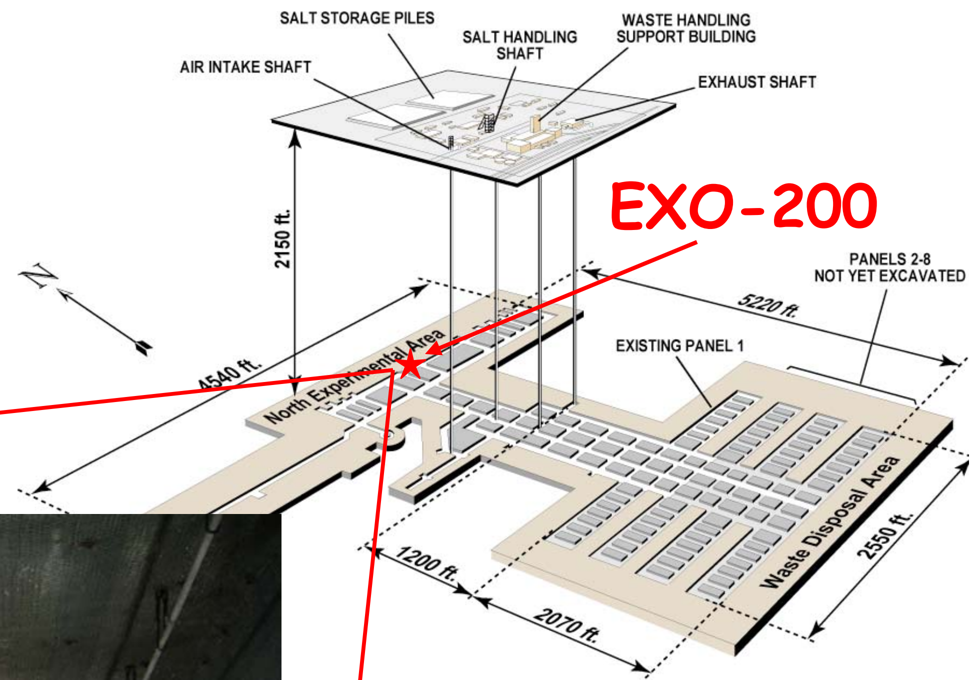


Now getting ready to ship EXO200 toWIPP underground

Now dismounting and shipping cleanroom to WIPP underground

- May 28–Jun 8 Close Mod 1
  Secure equipment
- Jun 6-11 Dismount electrical
- Jun 12-24 Dismount HVAC ←
- Jun 25-Jul 6 Decouple and weigh modules
- Jul 9-13 Float
- Jul 13-16 Ship Mod 2-6 + containers
- Jul 20 Ship Mod 1

We may ship Mod 2-6 around Jul 1, 2 weeks ahead of schedule



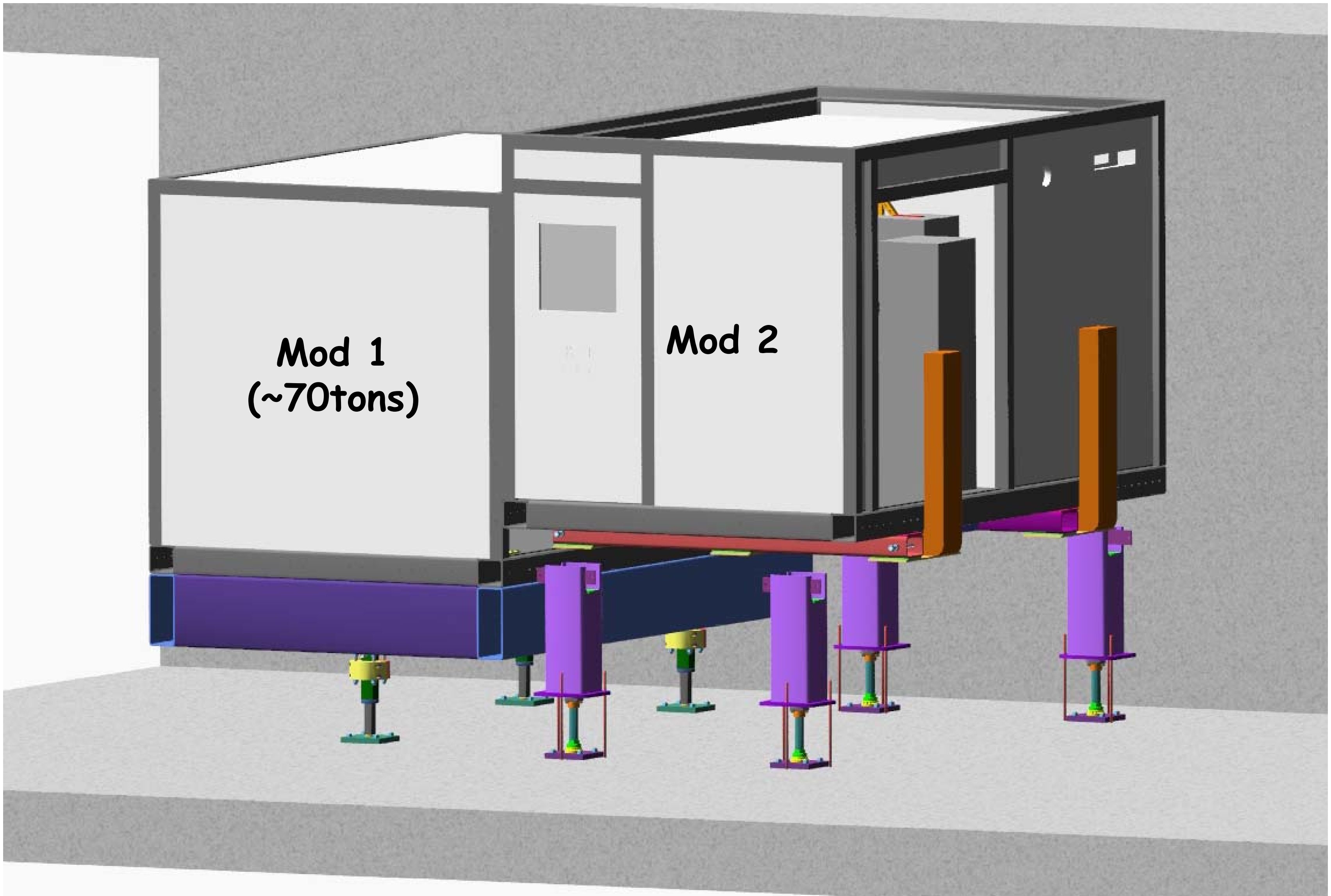
~20 EXO people have already completed the full WIPP miner training

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



Summary EXO-200 funding in k$ (US accounting used for all labor)

Institition	Type	FY02	FY03	FY04	FY05	FY06	FY07	total
DoE EM (WIPP)	labor	-	50	100	150	150	-	3,847
	M&S	950	900	297	450	800	-	
DoE HEP	labor	-	-	-	-	-	-	800
	M&S	-	-	-	300	300	200	
Stanford private	labor	-	-	-	-	-	-	450
	M&S	100	350	-	-	-	-	
SLAC	labor	-	63	269	447	290	463	2,479
	M&S	-	350	122	75	150	250	
DoE NP	labor	-	-	-	-	-	-	61
	M&S	-	9	7	22	23	-	
Alabama State	labor	-	-	-	-	-	-	122
	M&S	50	15	-	20	35	2	
Neuchatel	labor	-	-	454	454	-	-	1,176
	M&S	-	-	150	75	25	18	
NSERC Canada	labor	-	-	227	227	151	151	946
	M&S	-	-	-	50	37	103	
ITEP Moscow	labor	-	133	-	-	-	-	233
	M&S	100	-	-	-	-	-	
Total		1,200	1,870	1,626	2,270	1,961	1,187	10,114

Installation/operation cost in k$ (US accounting used for all labor)

Item	FY07	FY08	FY09	FY10
Adjustable salt foundations	50	-	-	-
Engineering	155	50	20	-
Casting/machining front lead shield	100	-	-	-
Rigging, transportation, HVAC	70	-	-	-
Complete chamber machining and welding	125	30	-	-
Cryogenic seals	15	10	-	-
Compressed/liquefied gases	-	10	5	5
Warm seals	10	-	-	-
Travel	40	50	30	30
Underground electrical hookup	50	-	-	-
Clean room supplies	25	25	15	10
Local tech	-	60	60	60
Extra UPS batteries	-	100	-	-
Extra veto HV power supply cards	-	25	-	-
Veto scintillators	-	200	-	-
Total	640*	560	130	105

* $58k paid by Neuchatel
$40k paid by NSERC,
$542 borrowed
from Stanford

Ba grabbing and tagging R&D

R&D funding from DoE-HEP, Stanford, IBM, U.Maryland and NSF *(new)*

- We have developed the atomic physics and spectroscopy techniques to achieve good quality tagging in presence of some Xe gas
- Gained experience with using He to stabilize traps and counter some of the ill effects of Xe
- Have a scheme to load a linear trap with high efficiency
- Developing a single Ba ion source in LXe for testing
- Have built a linear trap designed for high loading efficiency. Very similar to final device.
- Developing different "grabbing" techniques in parallel:
  - *Xe ice tip*
  - *Starting development of very promising RIS tip*

Continue R&D on tagging in LXe: high rewards is successful but hard

Done
In progress

EXO Ba tagging papers

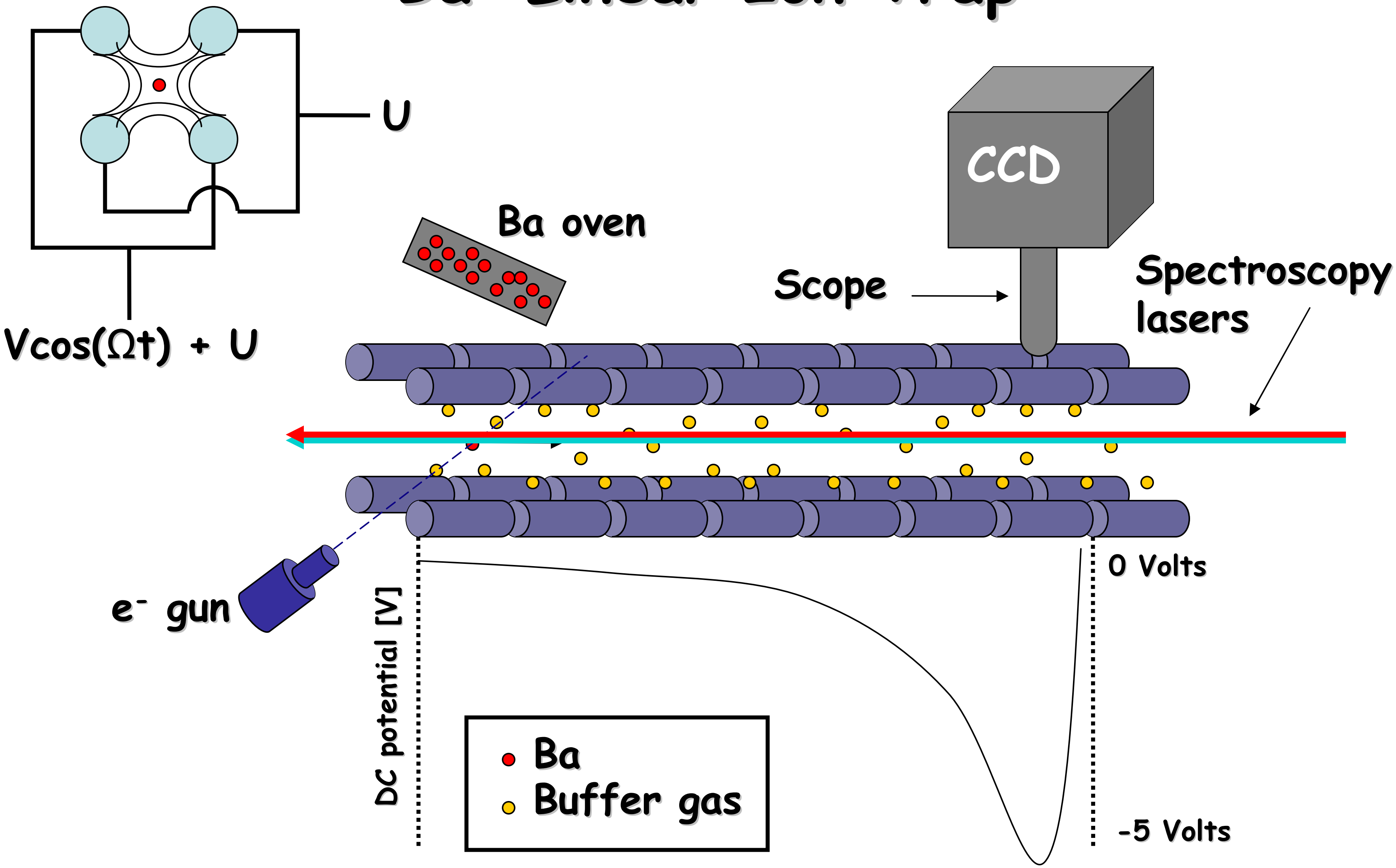
- K.Wamba et al. "Mobility of thorium ions in liquid xenon"
  Nucl. Inst. Meth. A555, 205 (2005)

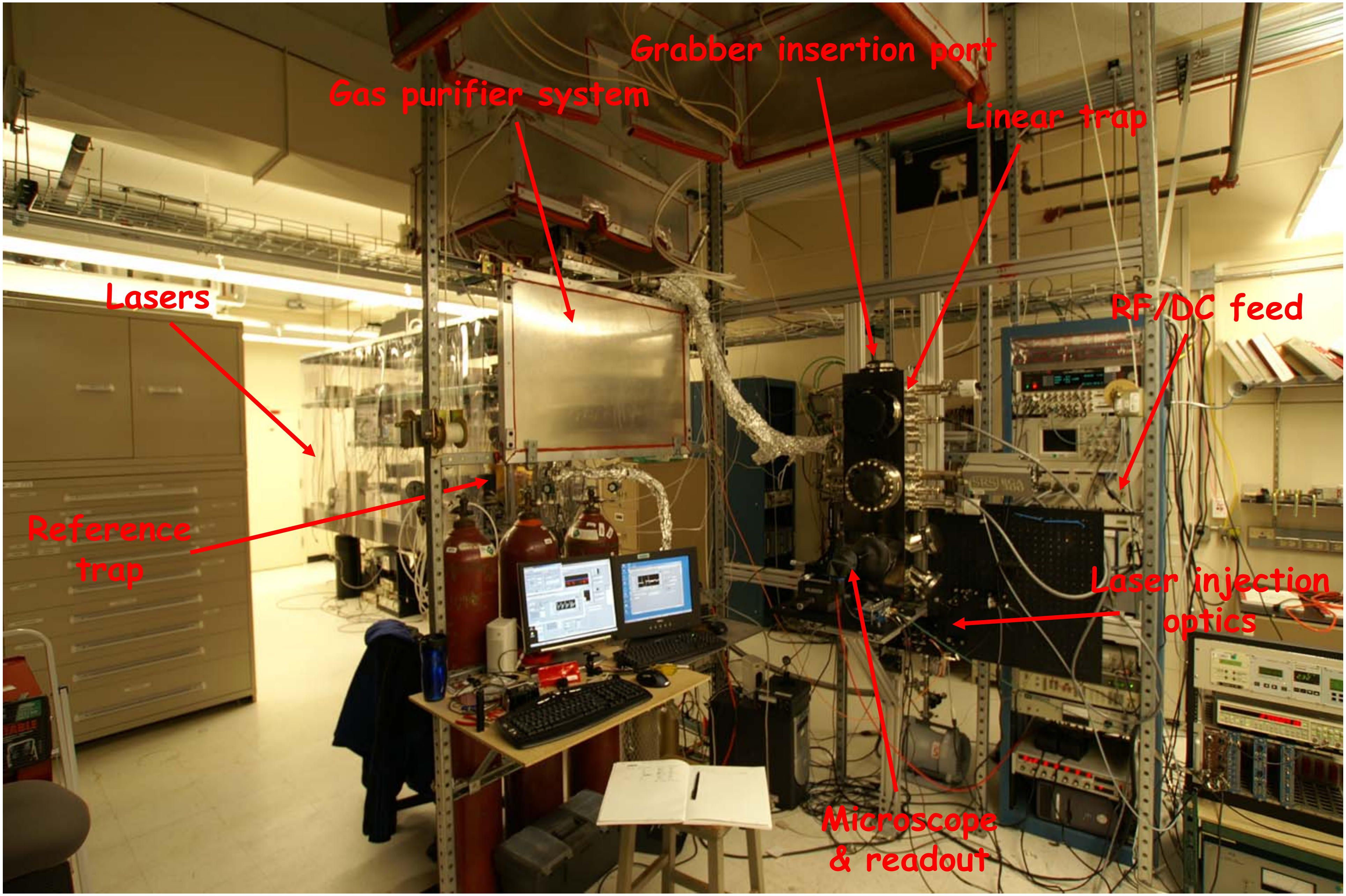
- M.Green et al. "Observation of Single Collisionally Cooled Trapped
  Ions in a Buffer Gas", arXiv:0702122 (Feb 2007),
  Submitted to Phys. Rev. A

- B.Flatt et al. "A linear RFQ ion trap for the Enriched Xenon
  Observatory", arXiv:0704.1646 (Mar 2007),
  To appear on Nucl. Inst. Meth. A

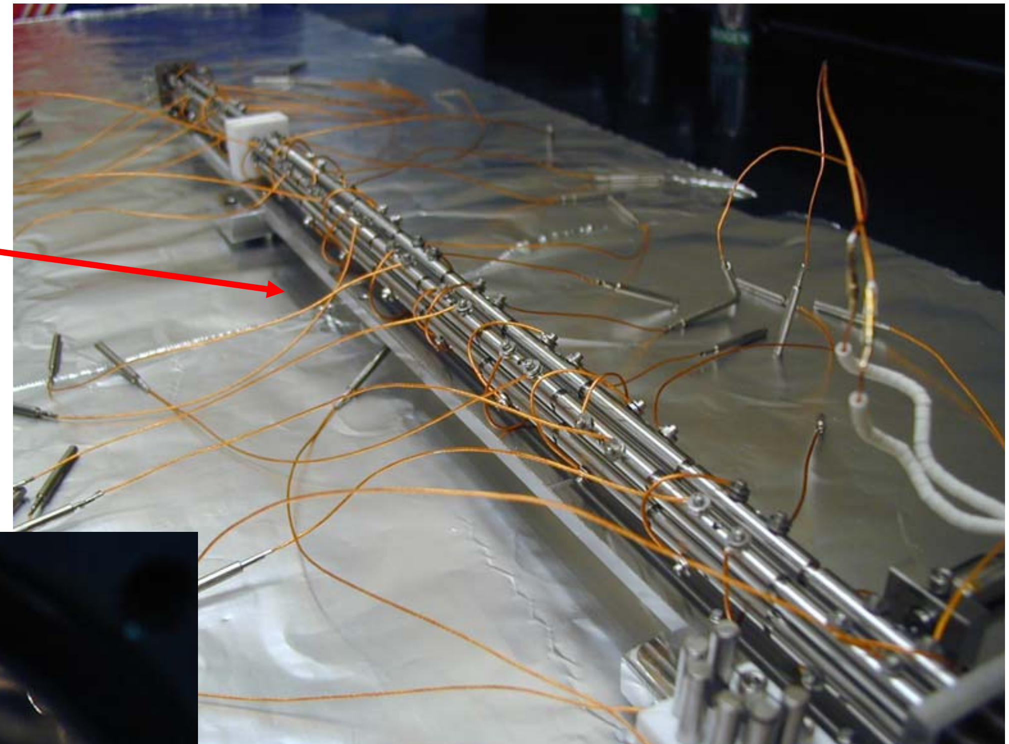
- P.Fierlinger et al. "A microfabricated sensor for thin dielectric
  layers", arXiv:0706.0540 (Jun 2007),
  Submitted to Rev. Sci. Inst.

Ba+ Linear Ion Trap



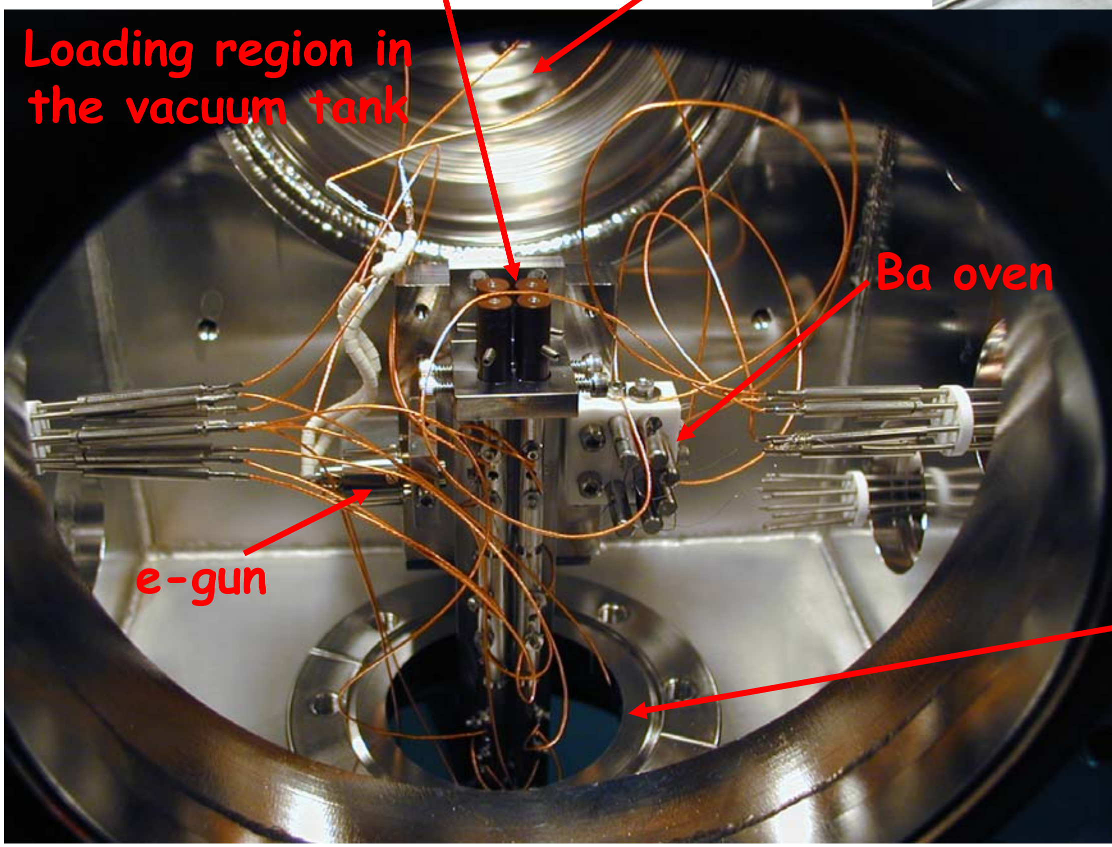

Grabber insertion port
Gas purifier system
Linear trap
Lasers
RF/DC feed
Reference trap
Laser injection optics
Microscope & readout

Electrode structure being prepared

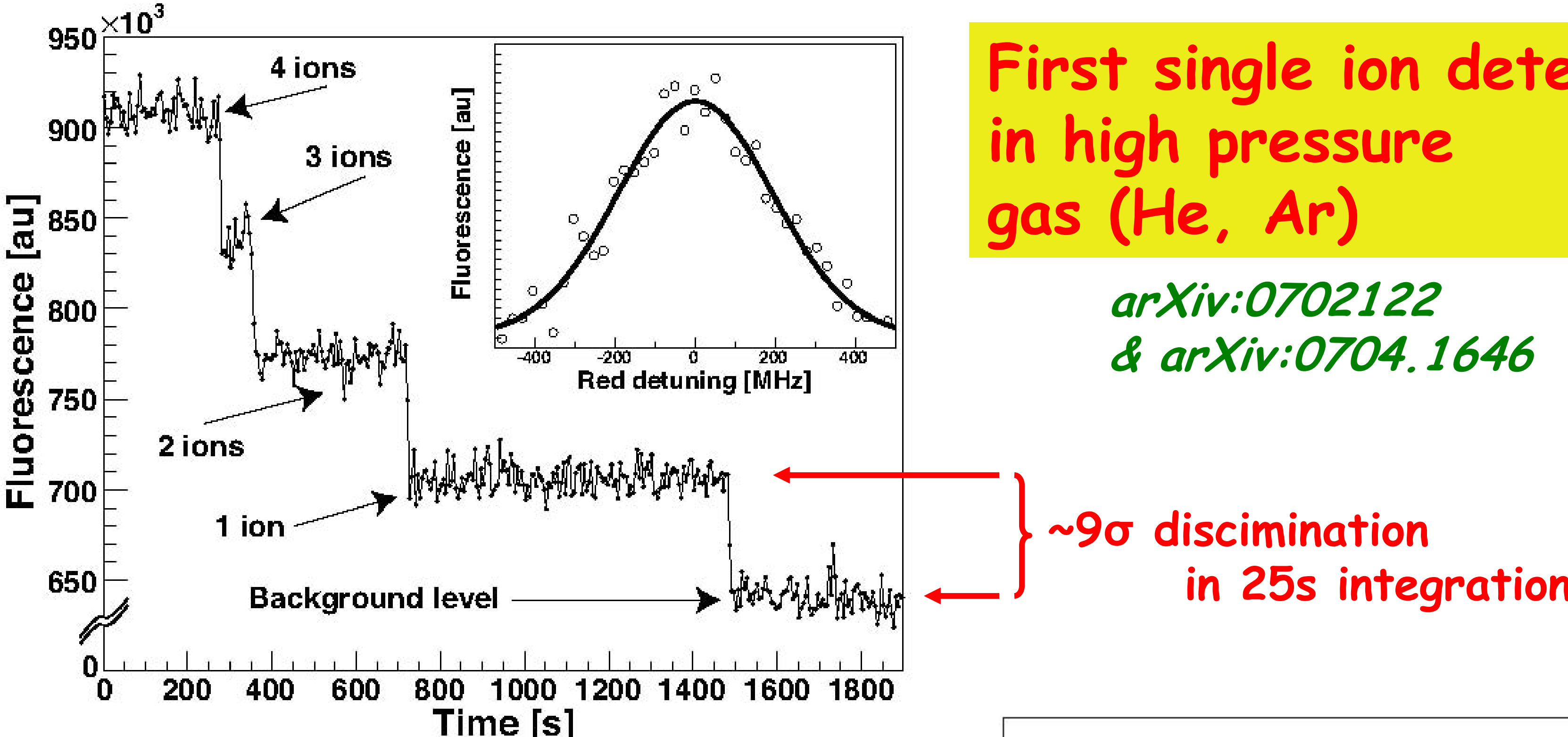


Tip loading access

Main turbo port

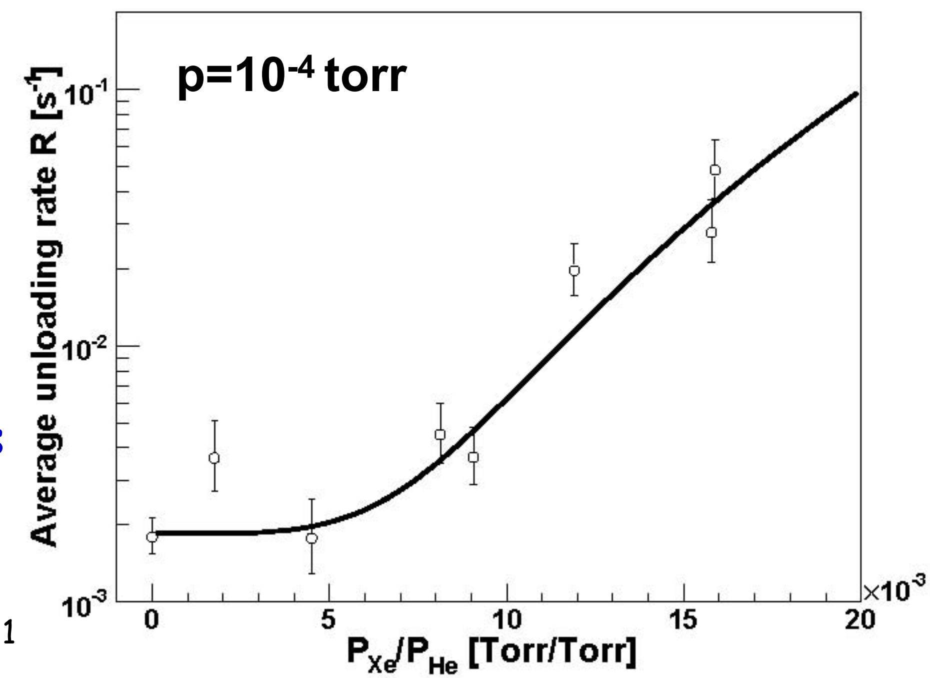


Differentially pumped aperture



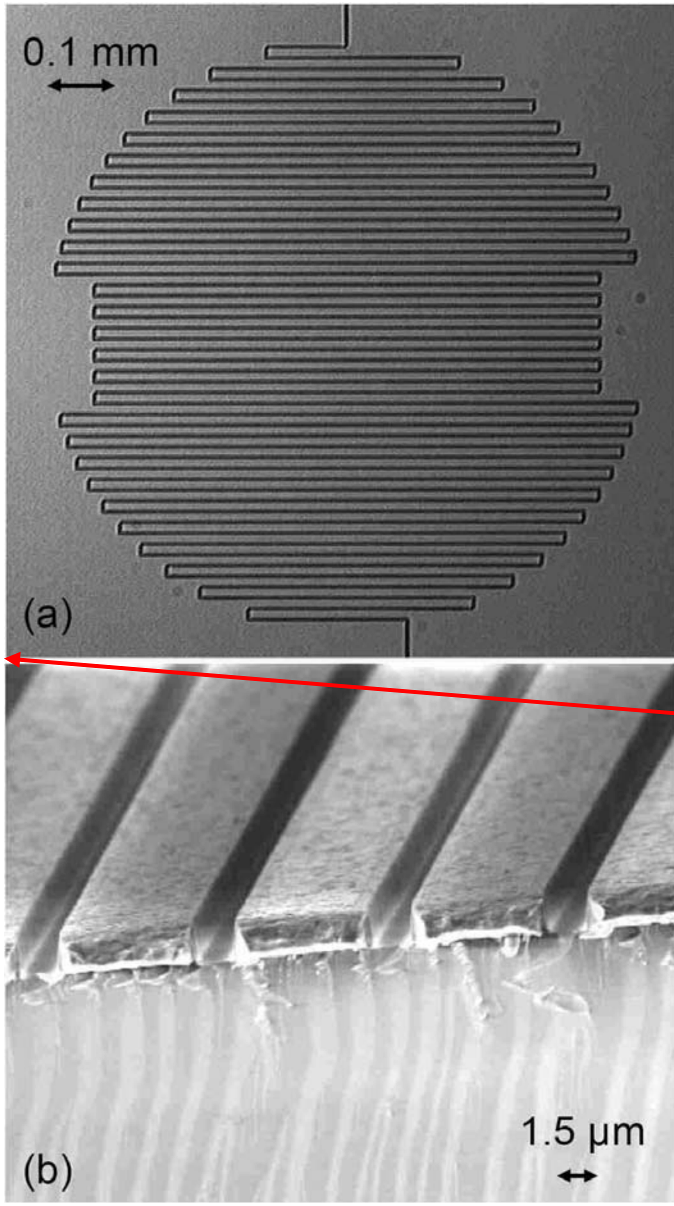
First single ion detection in high pressure gas (He, Ar)

arXiv:0702122
& arXiv:0704.1646



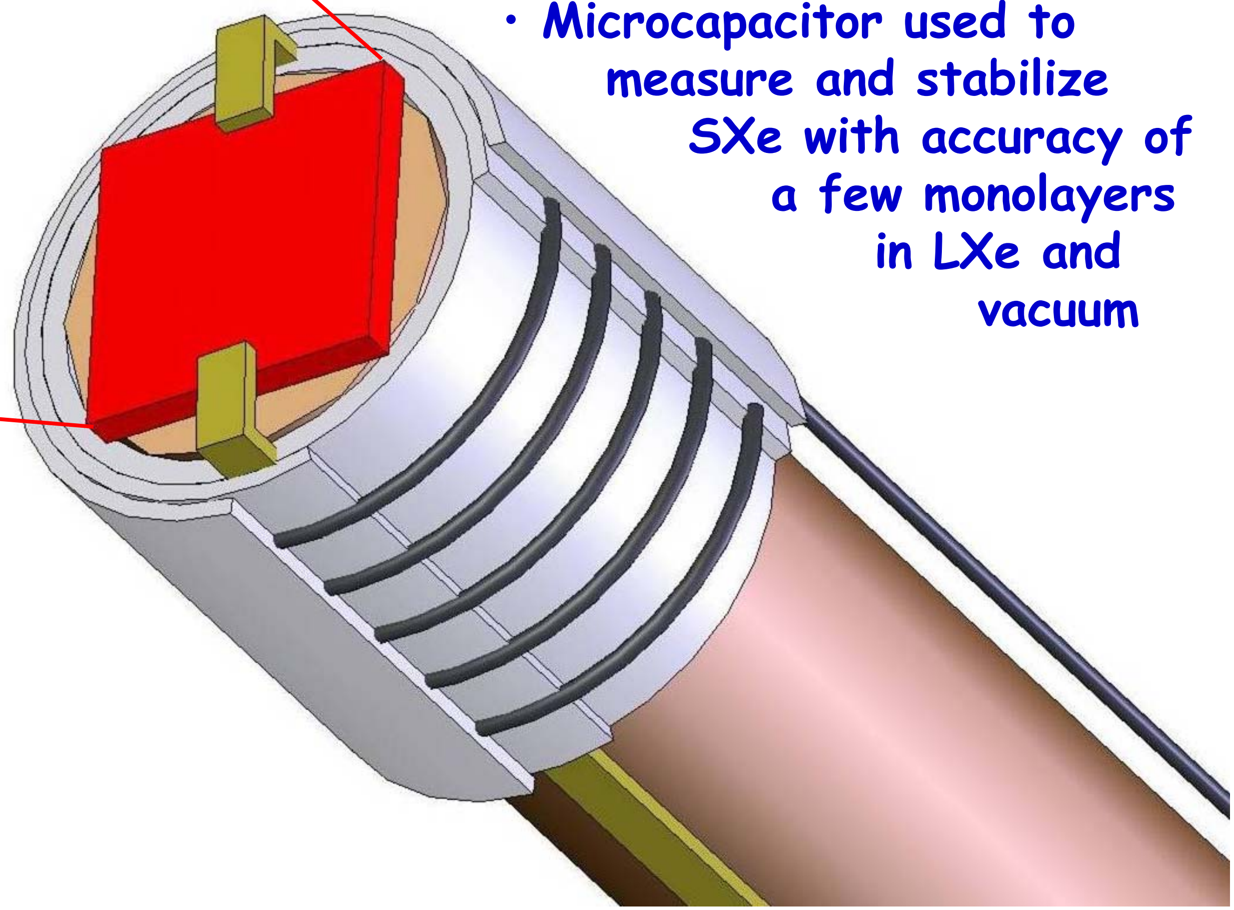
Single ion spectroscopy and identification possible in some Xe atmosphere provided He is added to the trap

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

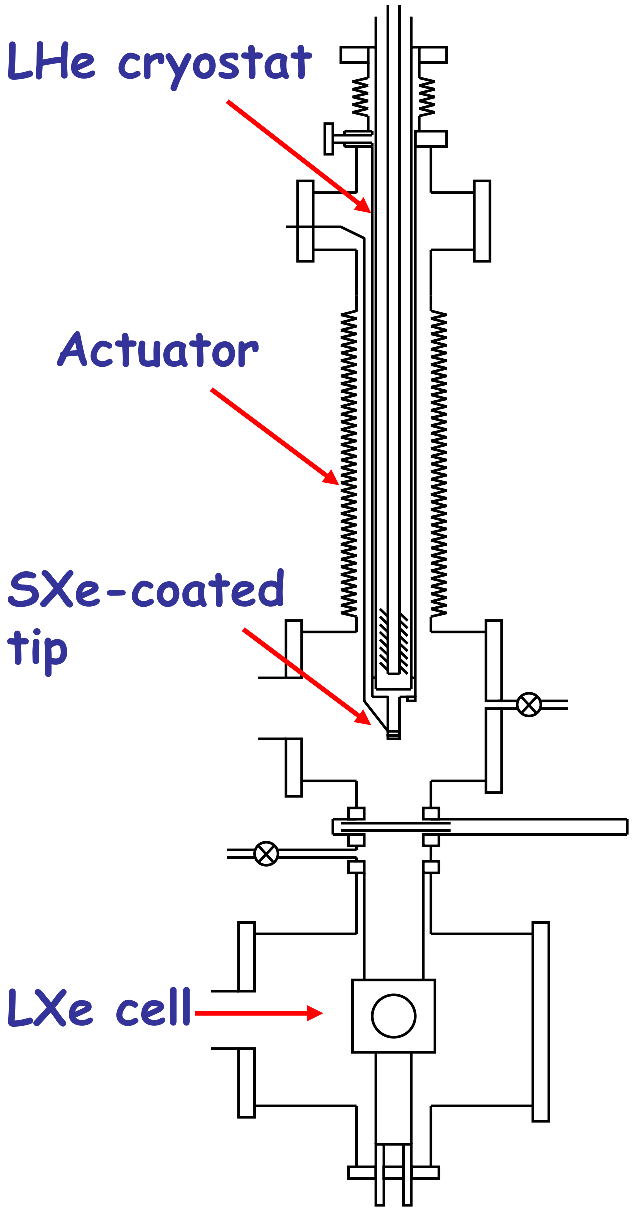


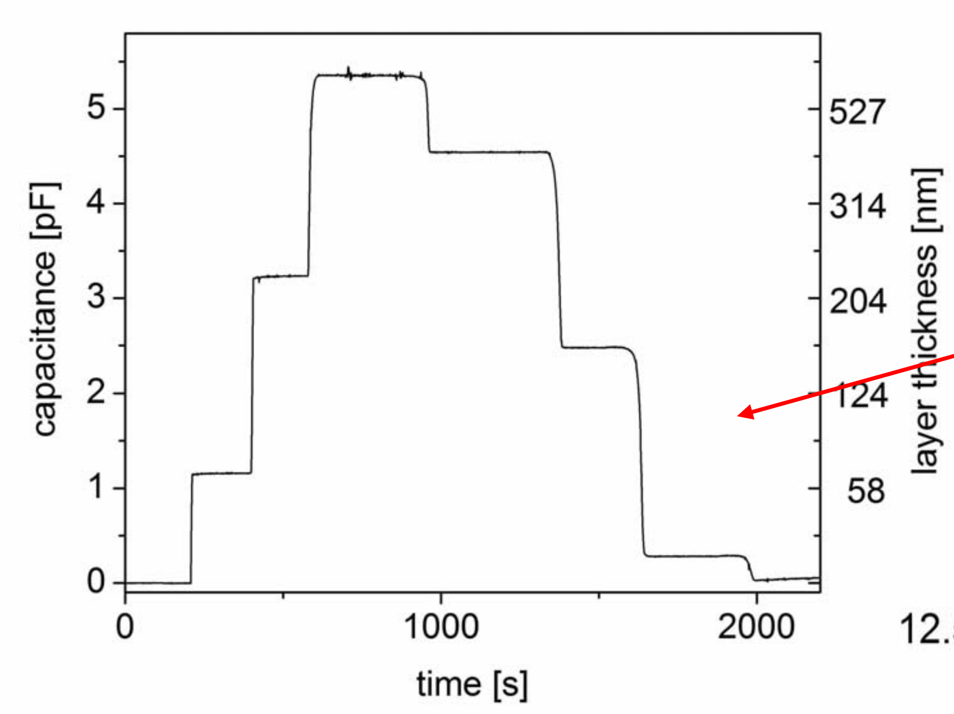
Cryogenic dipstick

- 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



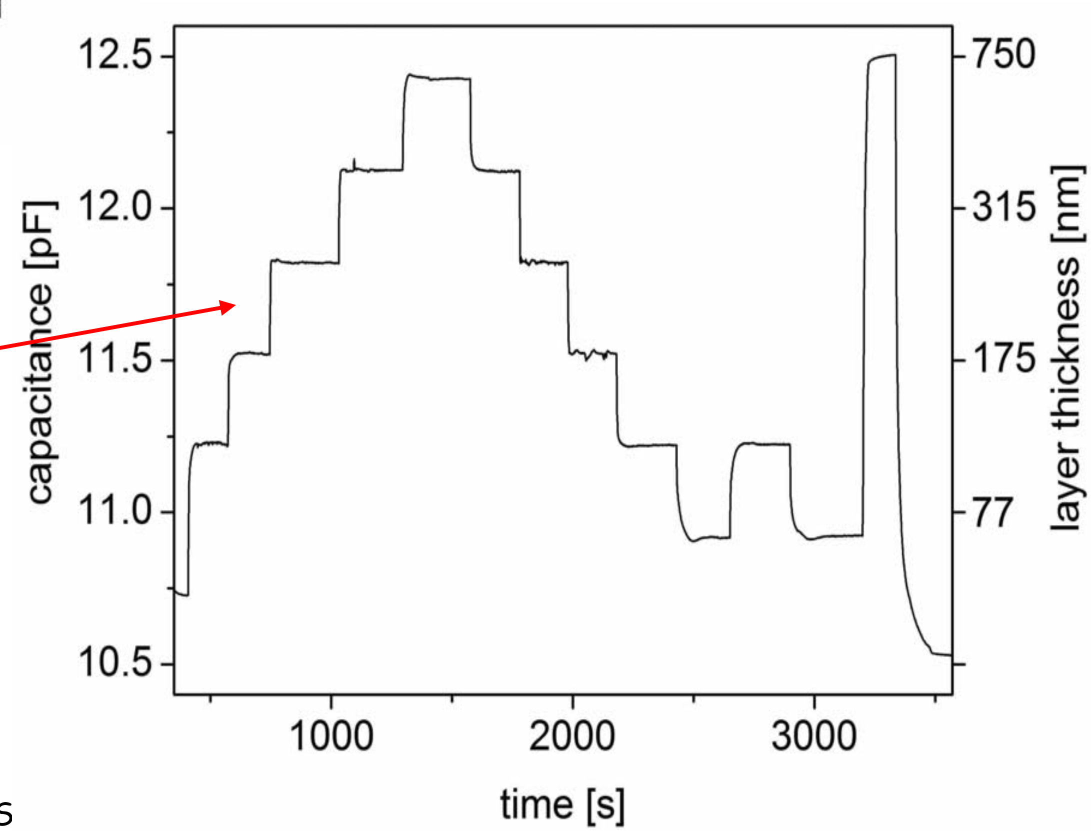
Complete setup





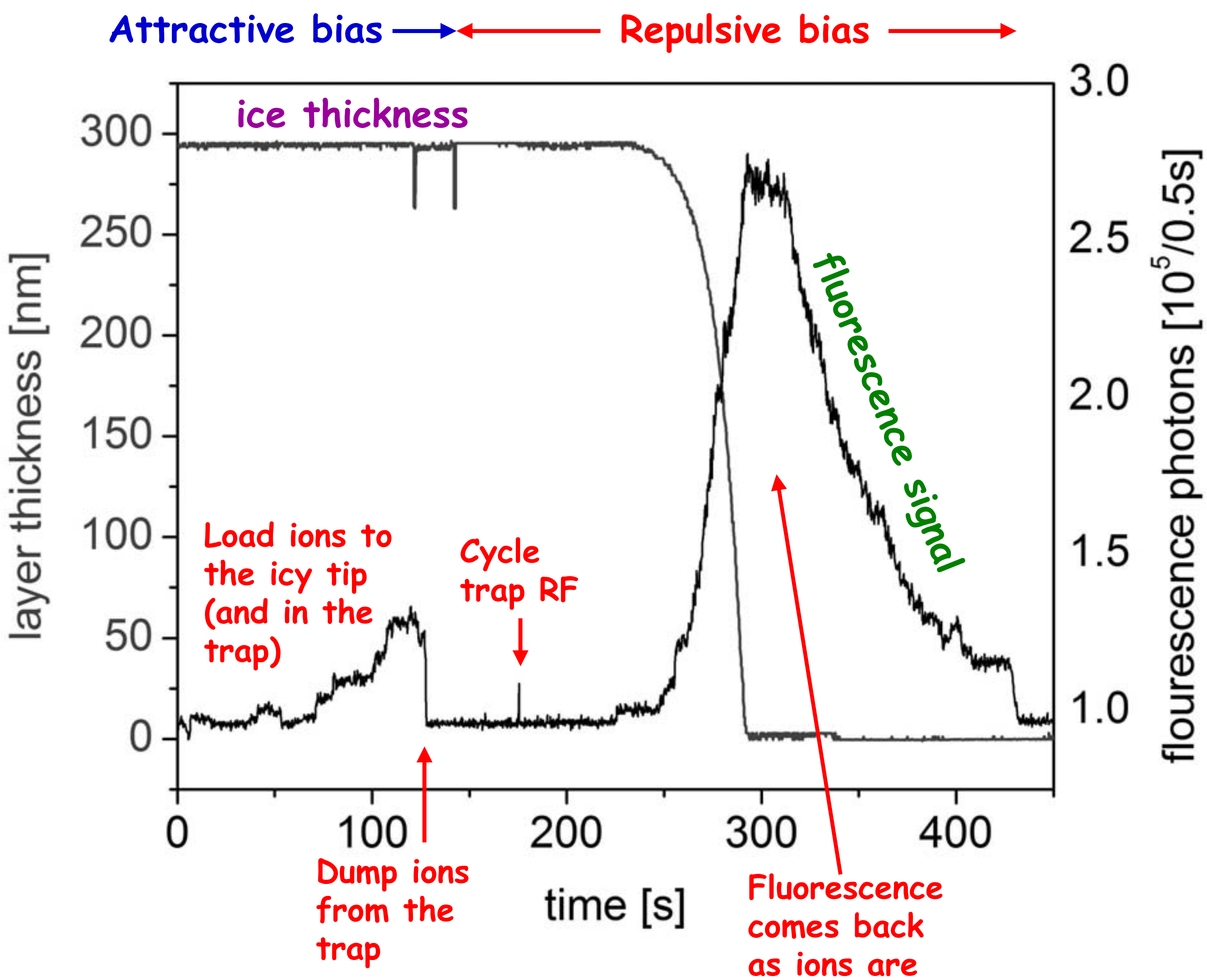
Growing SXe layers from metered amounts of GXe in the vacuum chamber

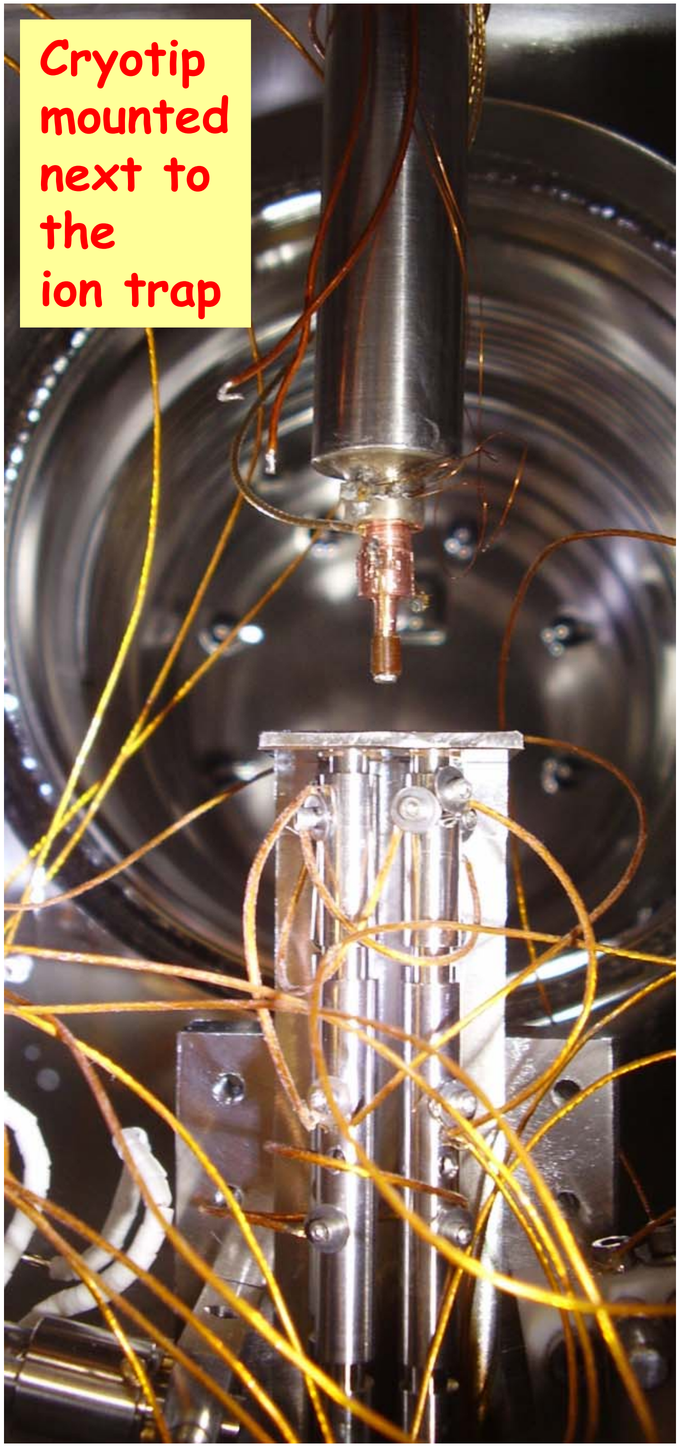
Growing and maintaining SXe layers in a LXe bath with active feedback



arXiv:0706.0540

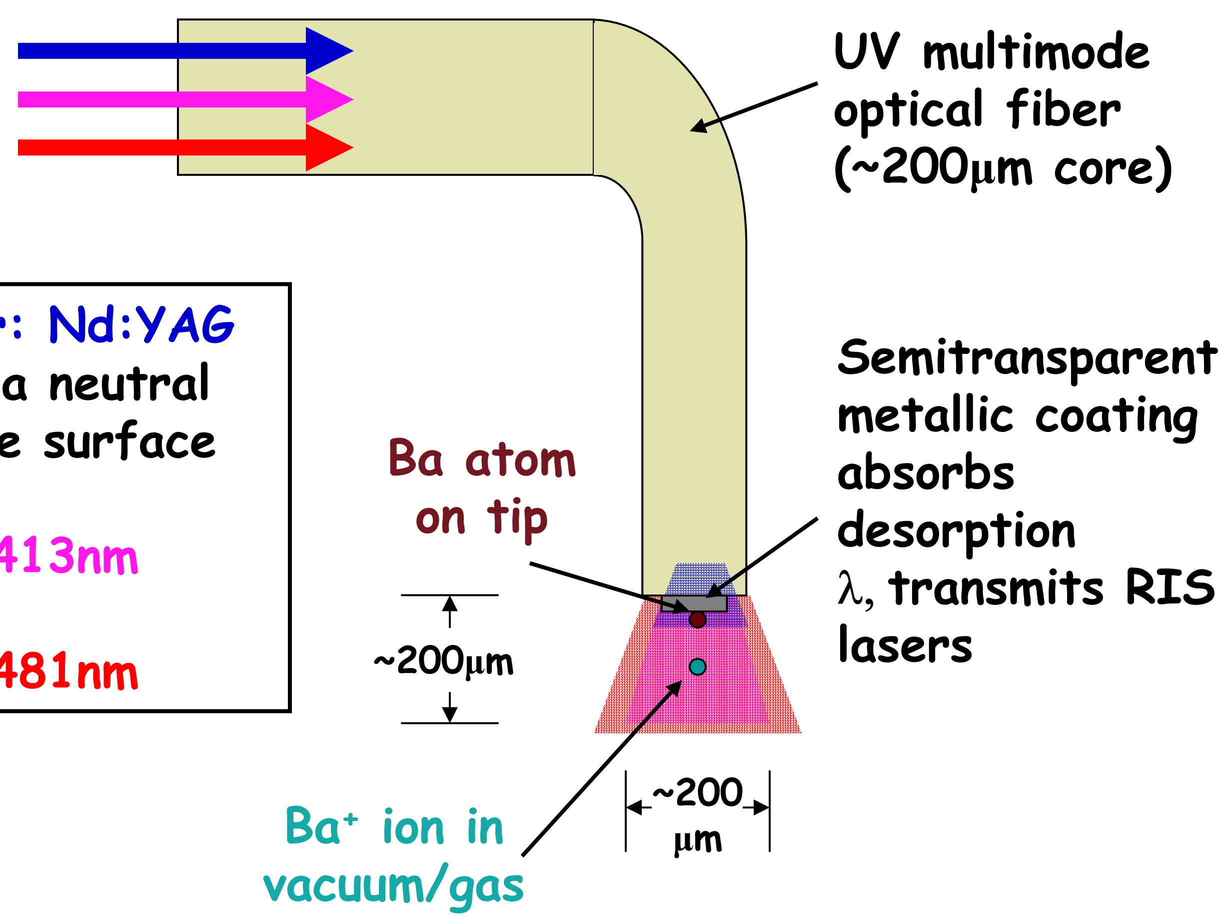
Loading the trap from a tip





Very preliminary !
Efficiency unknown

RIS tip

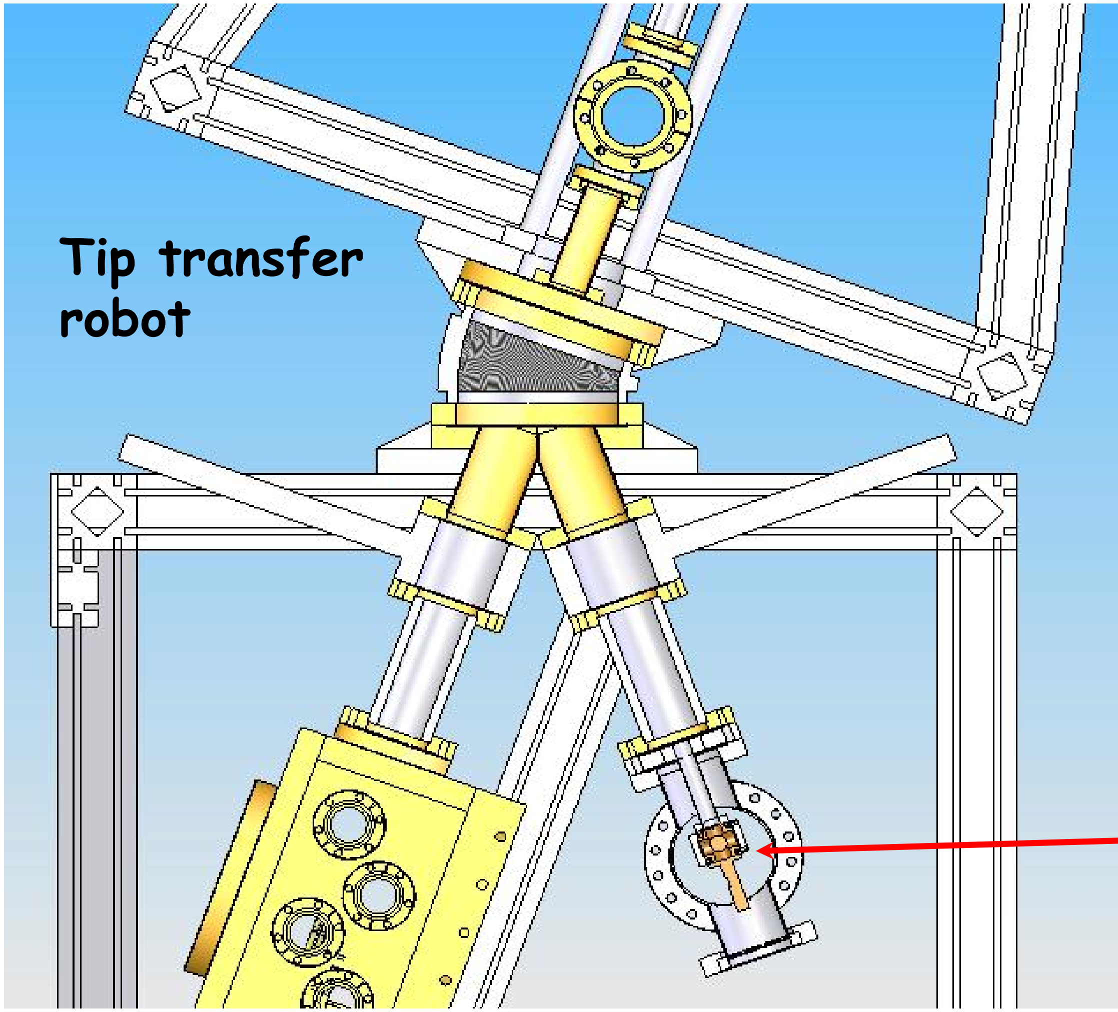


1. Pulsed desorption laser: Nd:YAG
2. ~10ns delay to allow Ba neutral atom to leave the surface
3. -Resonant step: pulsed laser @ 413nm
   -Autoionizing step: pulsed laser @ 481nm

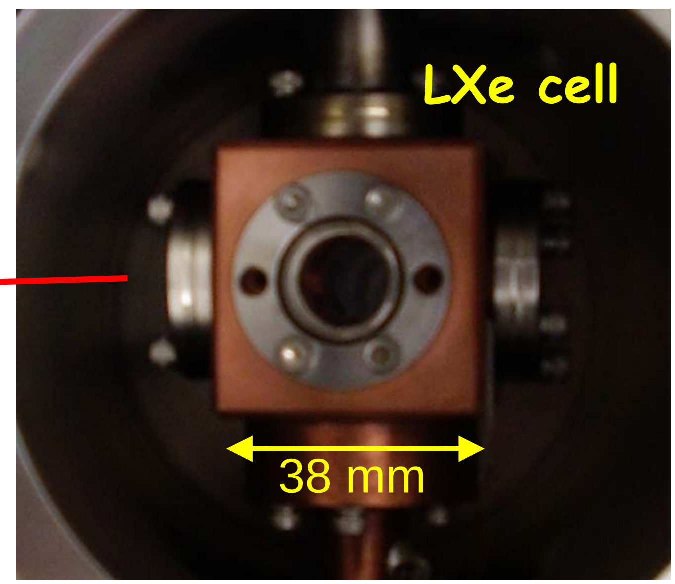
In this case *each step* can be documented to work with high efficiency in the literature !

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



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!

EXO-200 safety

WIPP managed

General WIPP training for people to gain access to the underground:

- 40hour US-MSHA training (including compromised atmosphere egress) for all collaborators who need more that minimal access (→ unescorted access to WIPP underground)
- 8hour training for escorted access for people that have a specific and sporadic need to access the EXO-200 experiment.

"EXO Project execution plan" (46 page safety analysis for EXO operations and installation at WIPP, 2006)

EXO managed

Safety committee charged with:

- Preparation of a safety analysis document from the point of view of the experiment
- Preparation of the safety training manual for all EXO collaborators

Membership: *M.Breidenbach* (SLAC, co-chair), *W.Craddock* (SLAC, cryogenics/oxygen deficiency), *G.Gratta* (Stanford, chair) *F.Jones* (SLAC, electrical safety), *F.O'Neill* (SLAC, fire/hoisting), *L.Phillips* (Stanford, radiation), *S.Pierson* (SLAC, high pressure/chemical/mechanical), *D.Sjomeling* (WIPP, mine interface)