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DIE LUFT DER FREIHEIT WEHT
1891

Enriched Xenon Observatory

EO

for double beta decay

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DEPARTMENT OF ENERGY
UNITED STATES OF AMERICA

CALIFORNIA INSTITUTE OF TECHNOLOGY
1891

Colorado State University
Knowledge to Go Places

Laurentian UNIVERSITY•UNIVERSITÉ Laurentienne

THE UNIVERSITY OF ALABAMA
1831

Why ^{136}Xe?

Reasonable Q-value of **2457.8±0.4 keV**. Based on recent high precision mass measurement at FSU. M. Redshaw, J.McDaniel, E. Wingfield and E.G. Myers, to be submitted to Phys. Rev. C

Isotope ^{136}Xe has reasonable natural abundance 8.9%.

Noble gas, isotopic enrichment by ultra centrifugation cost effective. No chemistry needed.

- **Xenon can be re-purified during operation and moved to different detector**

- **Active detection medium in both liquid and gaseous phase. Suited for charge collection plus high yield UV scintillator (@ 3 kV/cm ~25 ph/keV, ~50 e/keV, anti-correlated[1]). No crystal growth needed.**

Ionization potentials Xe: 12.130 eV, Ba^{+}: 5.212 eV, Ba^{++}: 10.004 eV
$\beta\beta$-decay product atom remains charged. Opens possibility of Ba removal and final state tagging through Ba single ion detection

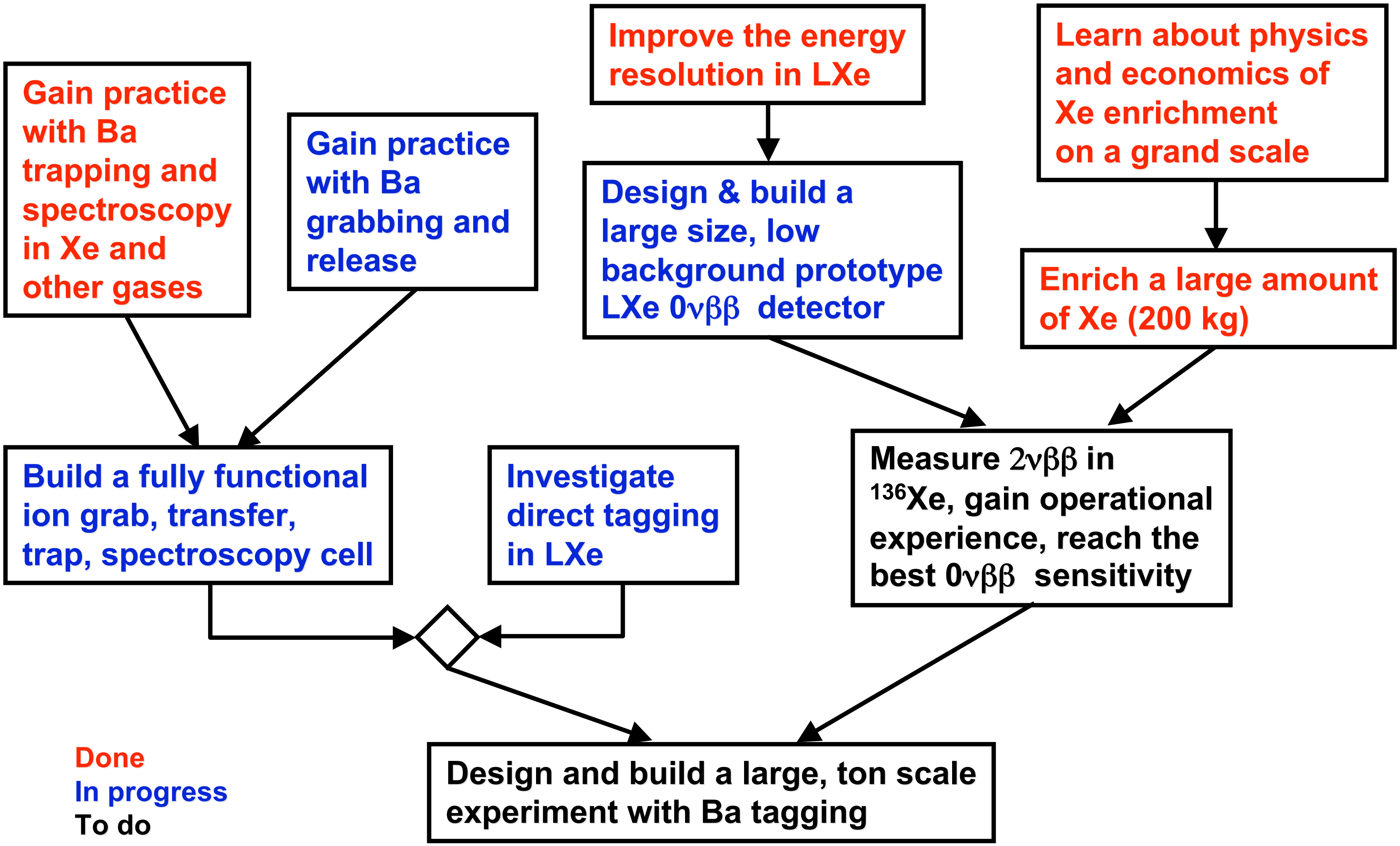
EXO Road Map

Ultimate Goal: build 1 to 10 ton high resolution tracking TPC using enriched ^{136}Xe. Equip it with Ba-final state tagging. This should result in extremely small if not zero random background. Envisaged sensitivity 10 meV, would cover mass range allowed for inverted mass hierarchy.

- Detect decay and vertex in TPC using liquid Xenon. Extract Ba ion using a charged probe. Transfer into ion trap, use laser pumping to identify single Ba ion.

- Research on a high pressure gas TPC and in situ detection of Ba in the Xenon gas is being pursued in parallel.

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



EXO-200

Scientific goals:

1) **Measurement of yet unobserved $2\nu\beta\beta$ decay of ^{136}Xe. Task: $T_{1/2} > 10^{22}$ y, ~67 dcs / (d 100 kg). Important background for EXO.**

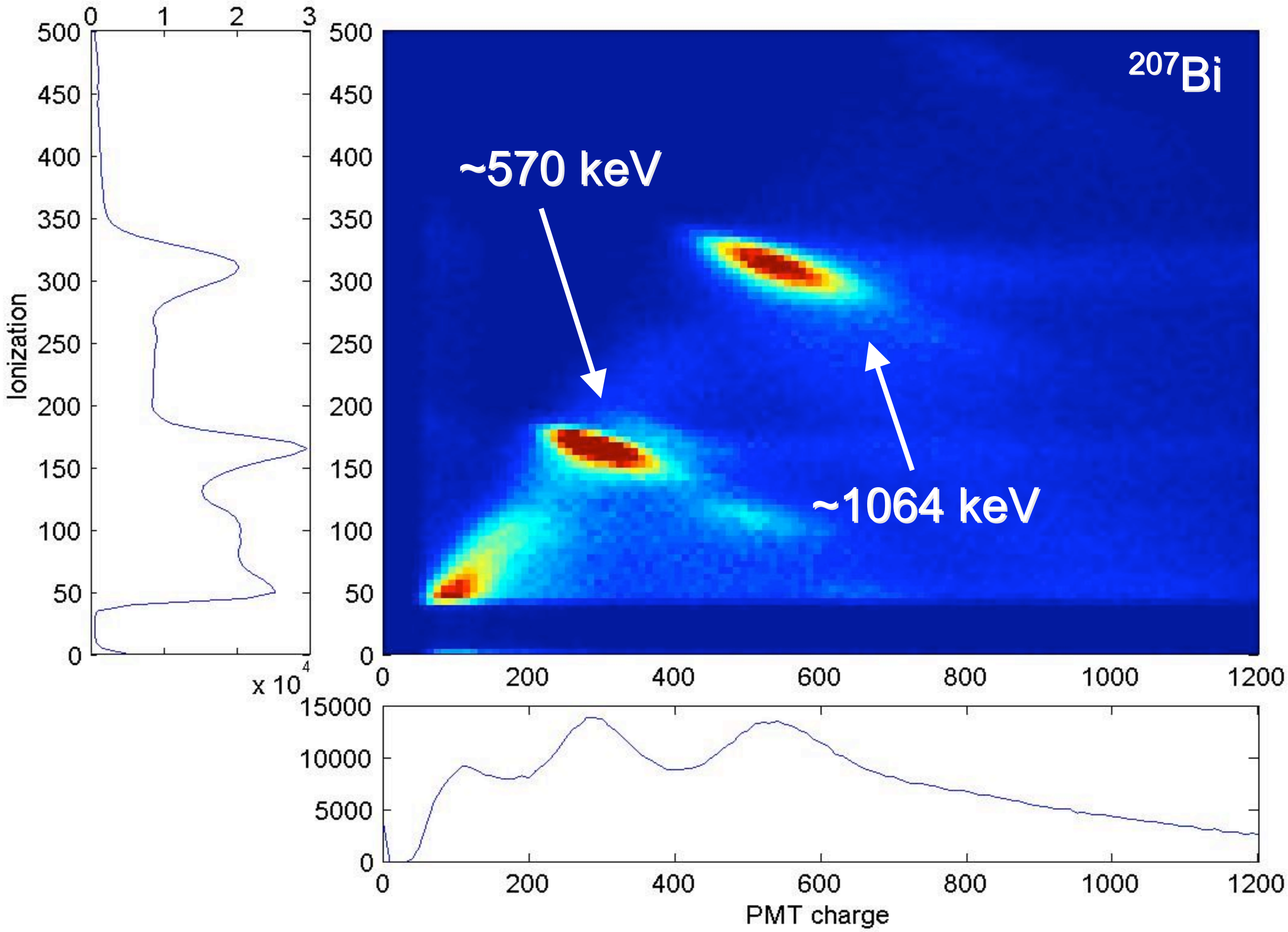
2) **Test of the Heidelberg evidence for $\beta\beta0\nu$ decay.**
   Expectation for ^{136}Xe [Ge $\pm 3\sigma$ range $(0.7\text{-}4.2)\times10^{25}$ y]:
   $T_{1/2}$ = $(0.58–3.5)\times10^{25}$ y [Rodin et al. PRC68 (03) RQRPA] 7-43 dcs / (y 100 kg)
   = $(0.66–4.0)\times10^{25}$ y [Staudt et al. EPL13 (90) QRPA]
   = $(0.48–2.9)\times10^{25}$ y [Caurier et al. NPA654 (99) SM]

Approach:

Achieve good resolution by utilizing both ionization and scintillation and the fact that both are anti-correlated. Resolution (extrapolated from 570 keV to 2460 keV) achieved in the lab: 1.6% @$Q_{\beta\beta}$.

Build tracking liquid Xe TPC with 1 cm spatial resolution. Allows to discriminate gamma background from electron signal. Background reduction by MC: depending on proximity and type reduction factor 5-50.
Initially no Ba tagging.

Use (anti) correlations between ionization and scintillation signals to improve energy resolution



Energy resolution improvement 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% @ $Q_{\beta\beta\beta}$
(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

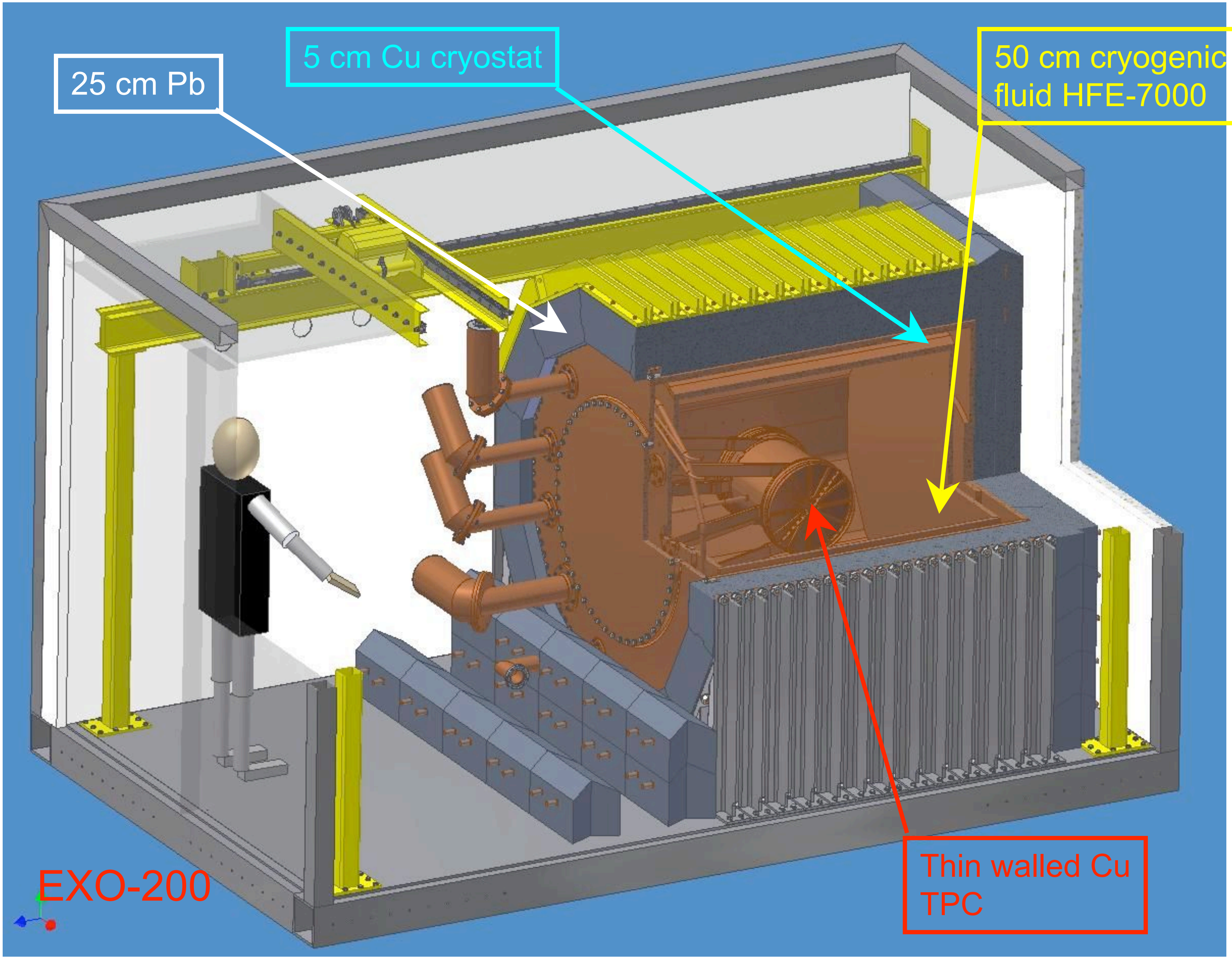
Massive effort on material radioactivity qualification

Th/U Sensitivity
Teflon (TPC):
<0.3 ppt or
1 and 4 μBq/kg
Cu (TPC):
<0.8 ppt

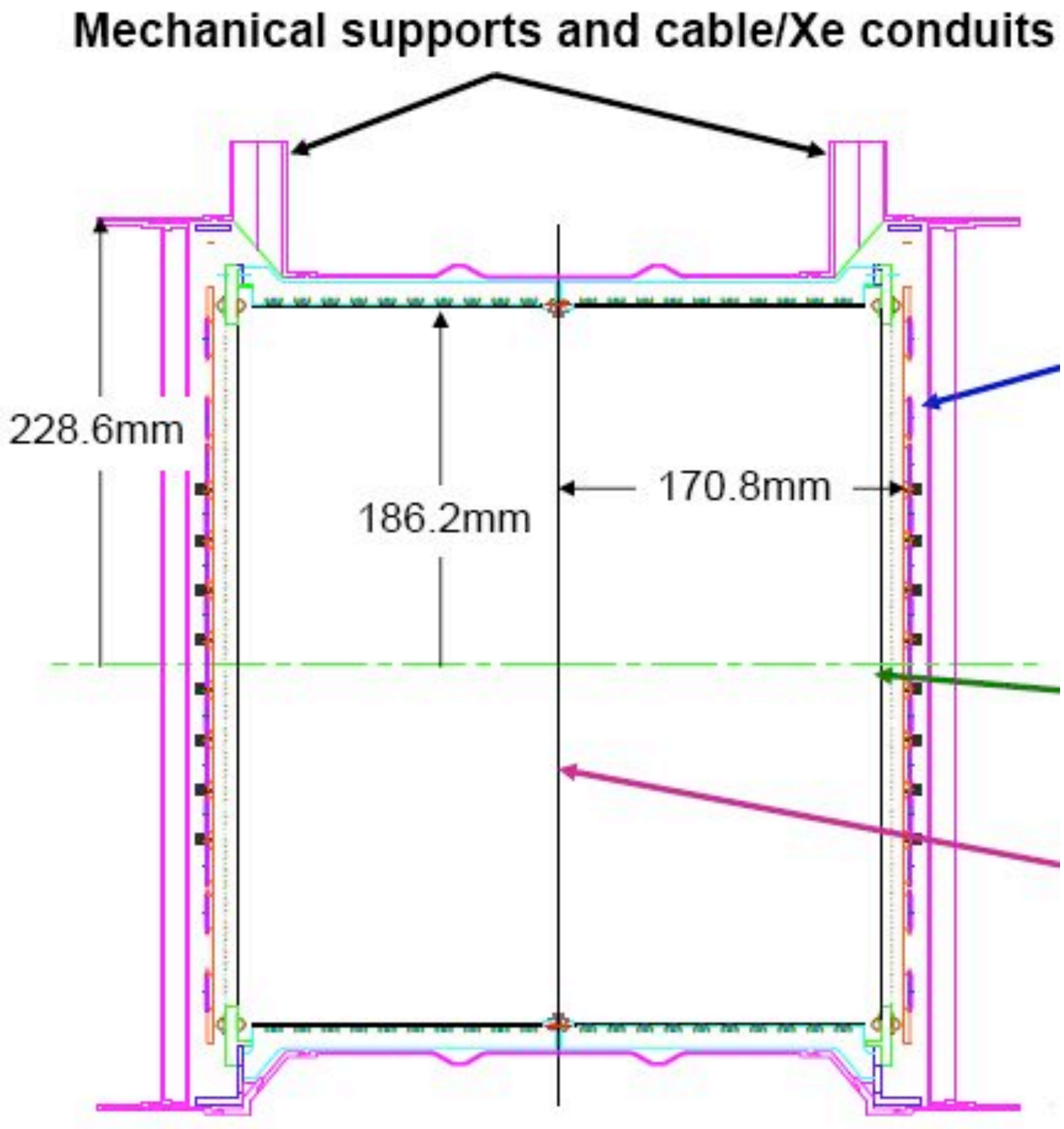
Online database for collaborators at present includes > 230 entries

MC simulation of backgrounds
Alabama & Stanford / SLAC

[a] Alabama using MIT reactor
[b] Neuchatel, Alabama
[c] Alabama, SLAC, Carleton
[d] Laurentian
[e] Canadian Inst. Standards


5 cm Cu cryostat
25 cm Pb
50 cm cryogenic fluid HFE-7000
Thin walled Cu TPC
EXO-200

What's inside the vessel (besides 200 kg enriched Xe)?



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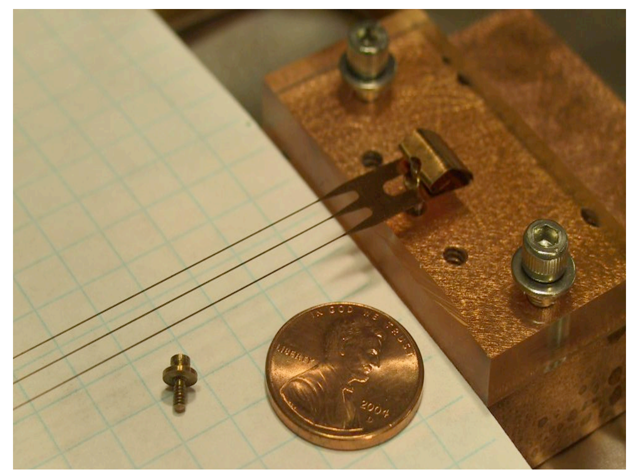
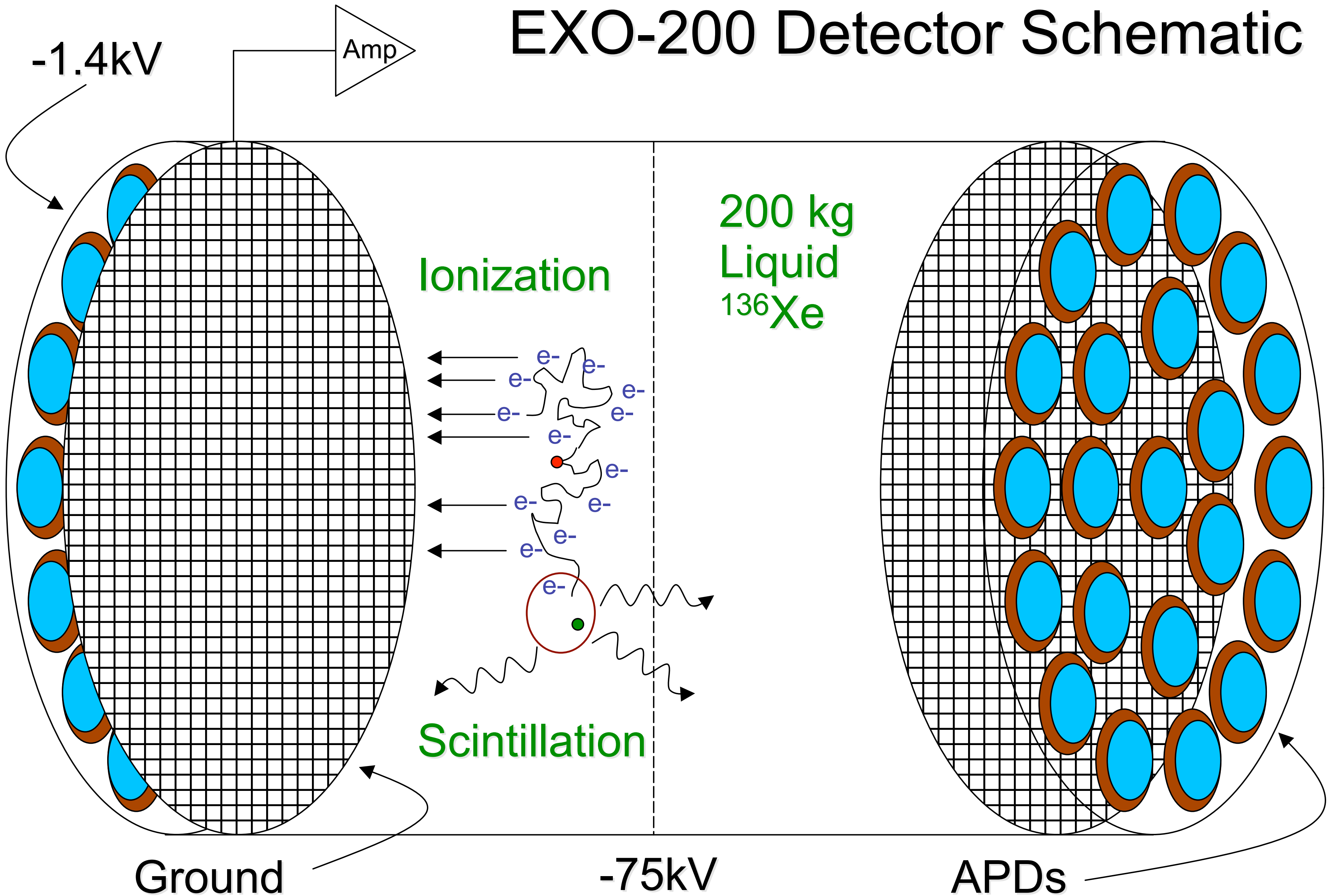
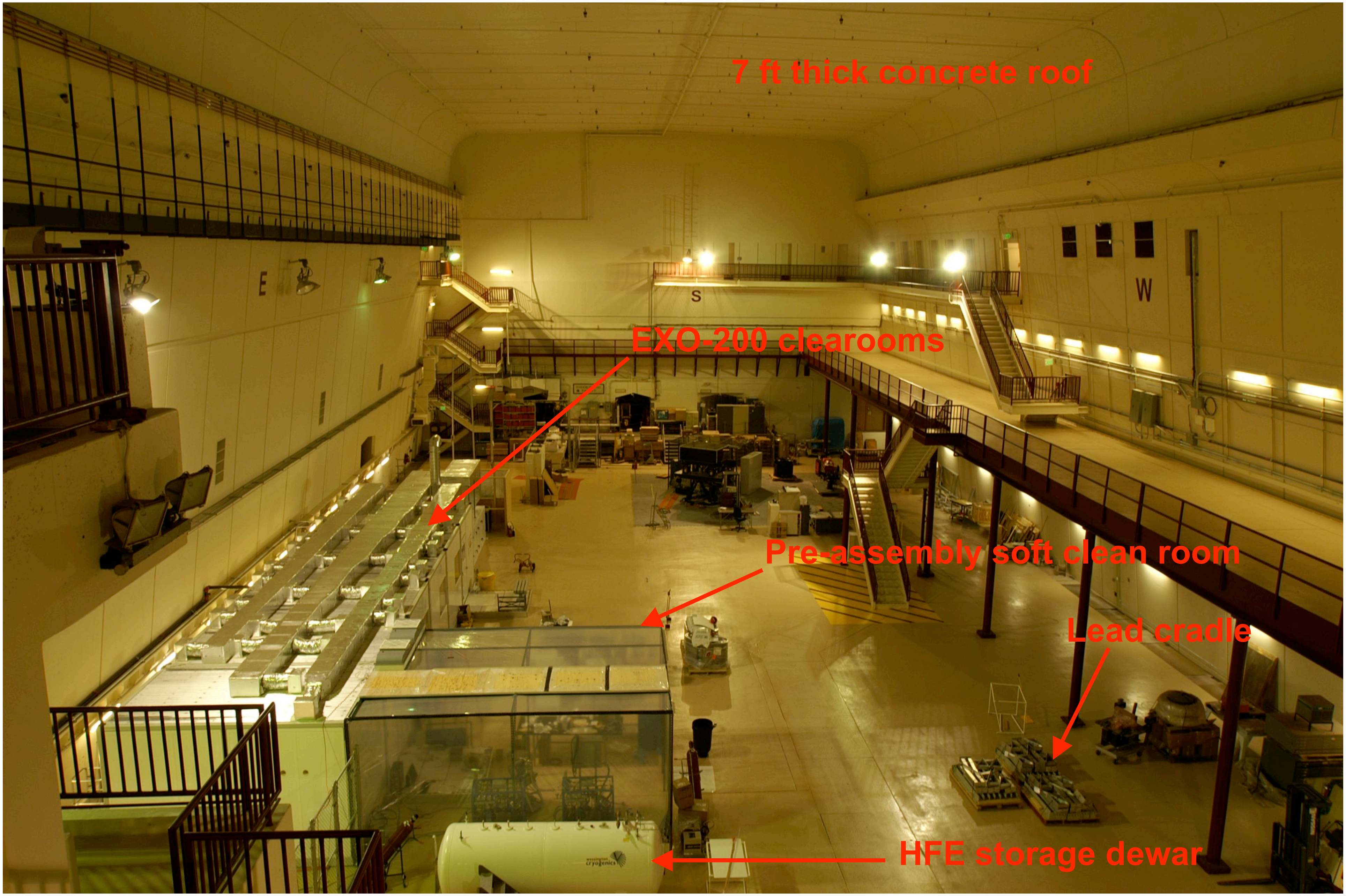


EXO-200 Detector Schematic

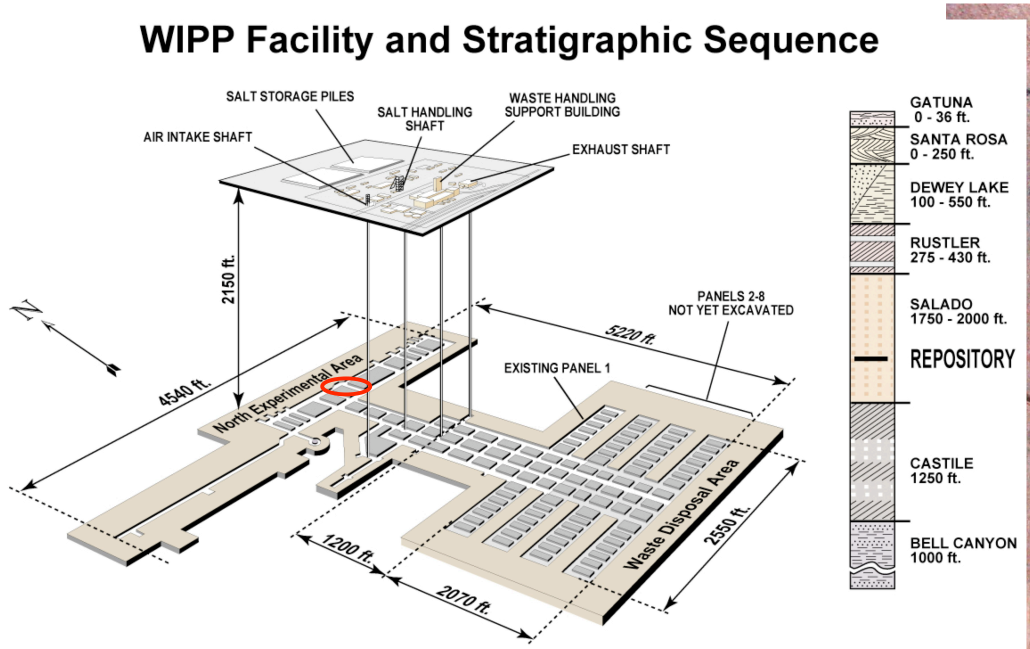


EXO-200 installation at HEPL (Stanford campus)



EXO-200 schedule

• May, 2006	Pb cradle installation complete
• Jun, 2006	Cryostat installed
• Jul, 2006	First full cooldown (delayed, happening now)
• Oct, 2006	End tests at Stanford
• Nov, 2006	Dismounting complete
• Nov, 2006	Lower first module at WIPP
• Dec, 2006	Lower last load (Pb arches) at WIPP



EXO-200 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 2457.9(0.4) keV endpoint [a]
5) Negligible background from $2\nu\beta\beta$ ($T_{1/2} > 1 \cdot 10^{22}$yr) [b]

Case	Mass (ton)	Eff. (%)	Run Time (yr)	$\sigma(E)/E$ @ 2.5MeV (%)	Radioactive Background (events)	$T_{1/2}^{0\nu\beta\beta}$ (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♦

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

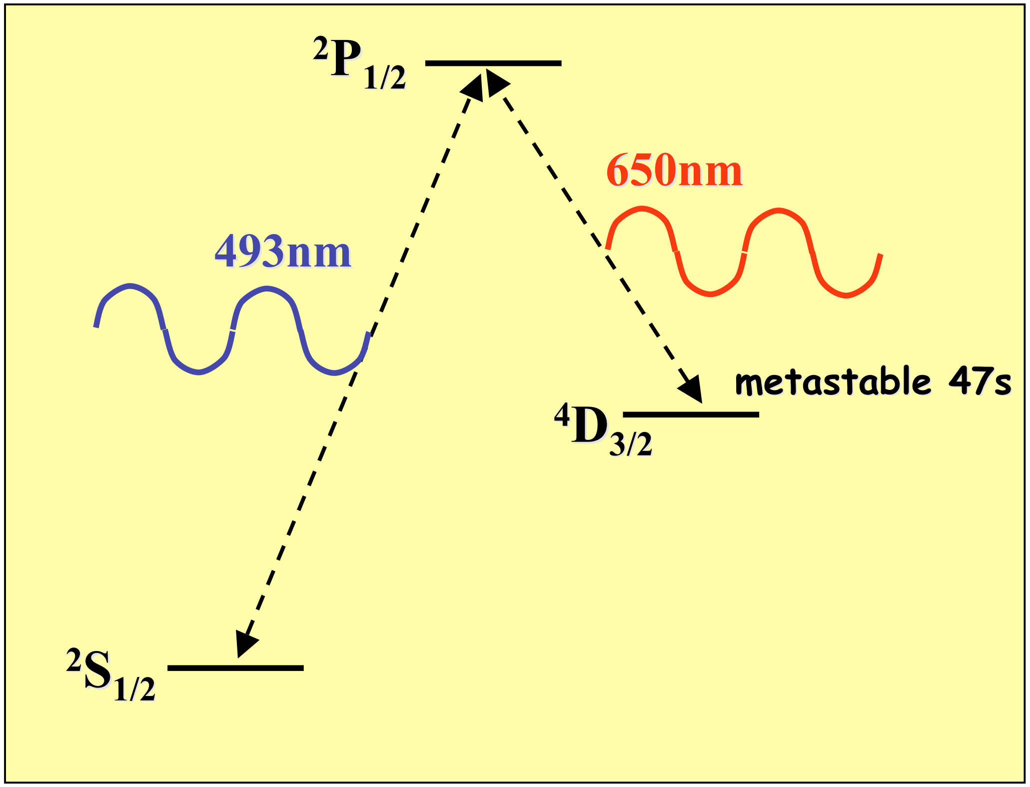
♦ Courier et al. Nucl Phys A 654 (1999) 973c

[a] M. Redshaw, J., McDaniel, E. Wingfield and E.G. Myers (Florida State Precision Penning Trap), to be submitted to Phys. Rev C.

[b] R. Bernabei et al., Phys. Lett. B 546, 23 (2002)

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

Barium Grabber

Three techniques being tested in parallel at Stanford

Cryo tip: **- thin layer of Xe-ice formed on surface of a metal**
- Ba ion is electrostatically attracted to the ice surface
- ice is thawed at the entrance of the trap and Ba ion is released

Challenge: control the ice thickness to ~100 atomic layers
→ Close to a solution

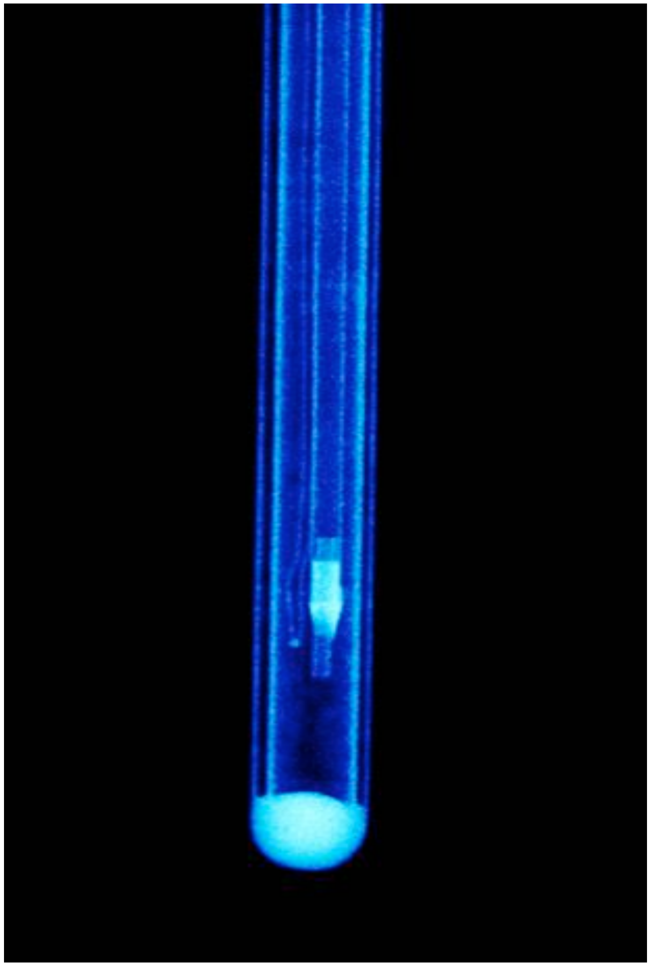
FE tip: **- use very sharp STM tip to grab ion, Ba ion lands near the very tip**
- strong positive bias field emits the ion in the trap

Challenge: - maintain tips sharp in LXe
- field emission at grabbing in LXe
→ Field emission microscope being commissioned, to be installed soon

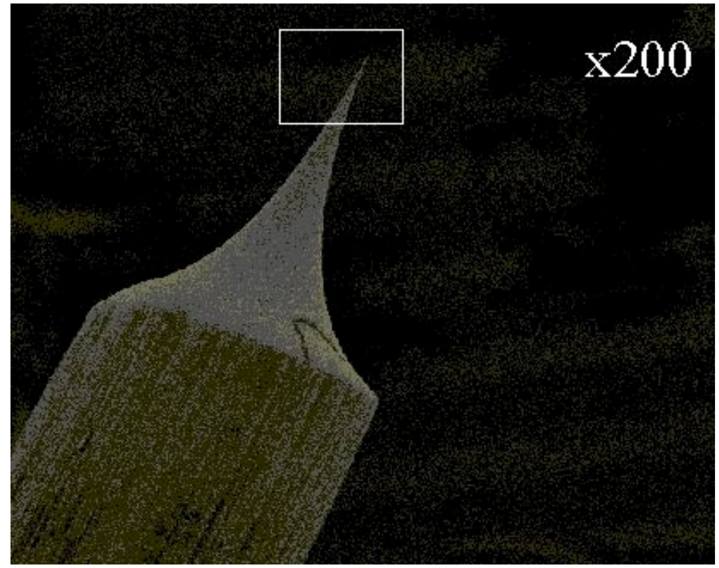
RIS tip: **- tip is a ~200 μm fiber with semitransparent metallization at end**
- Ba ion is attracted to metallization and neutralized
- A desorption laser pulse evaporates the Ba in the trap
- A second pulse (2 specific wavelengths) resonantly ionizes the Ba when it is still ~100μm from the fiber tip

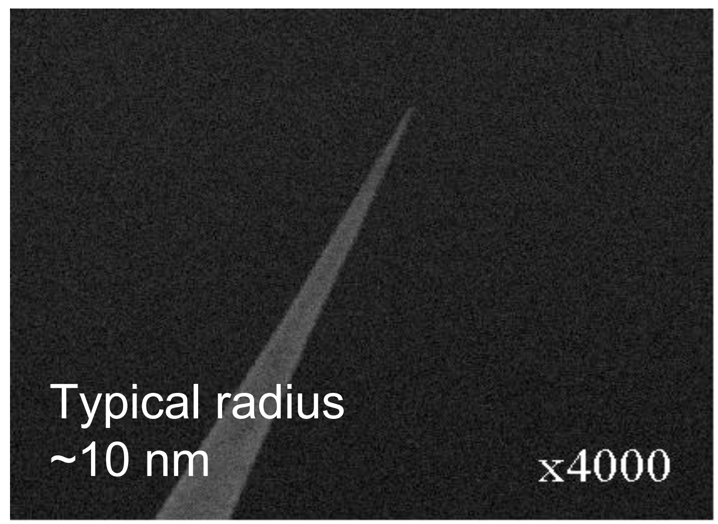
Challenge: The lasers are expensive
→ Each step demonstrated and known to work with high efficiency

Cryotip

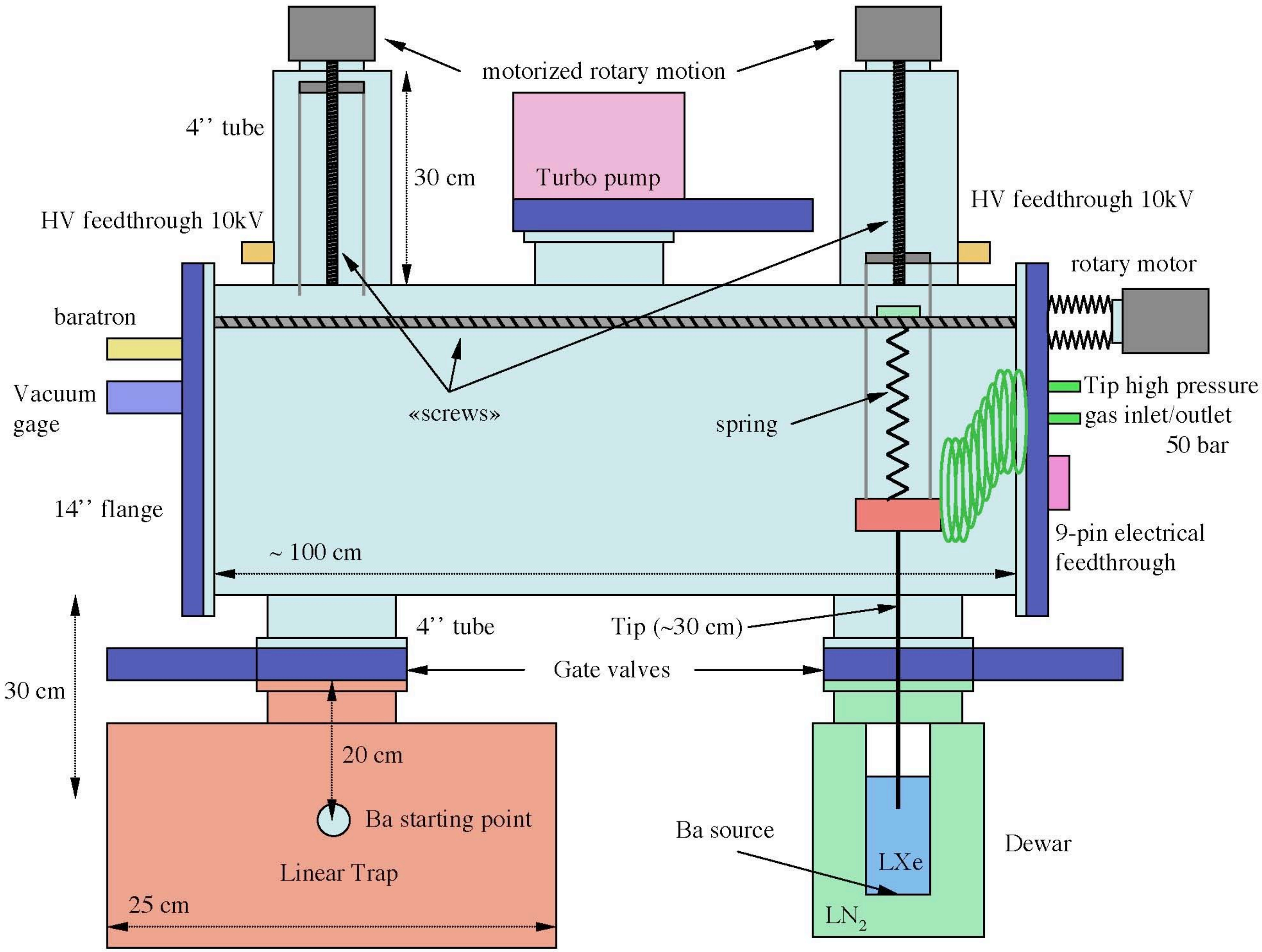


Fe-tip

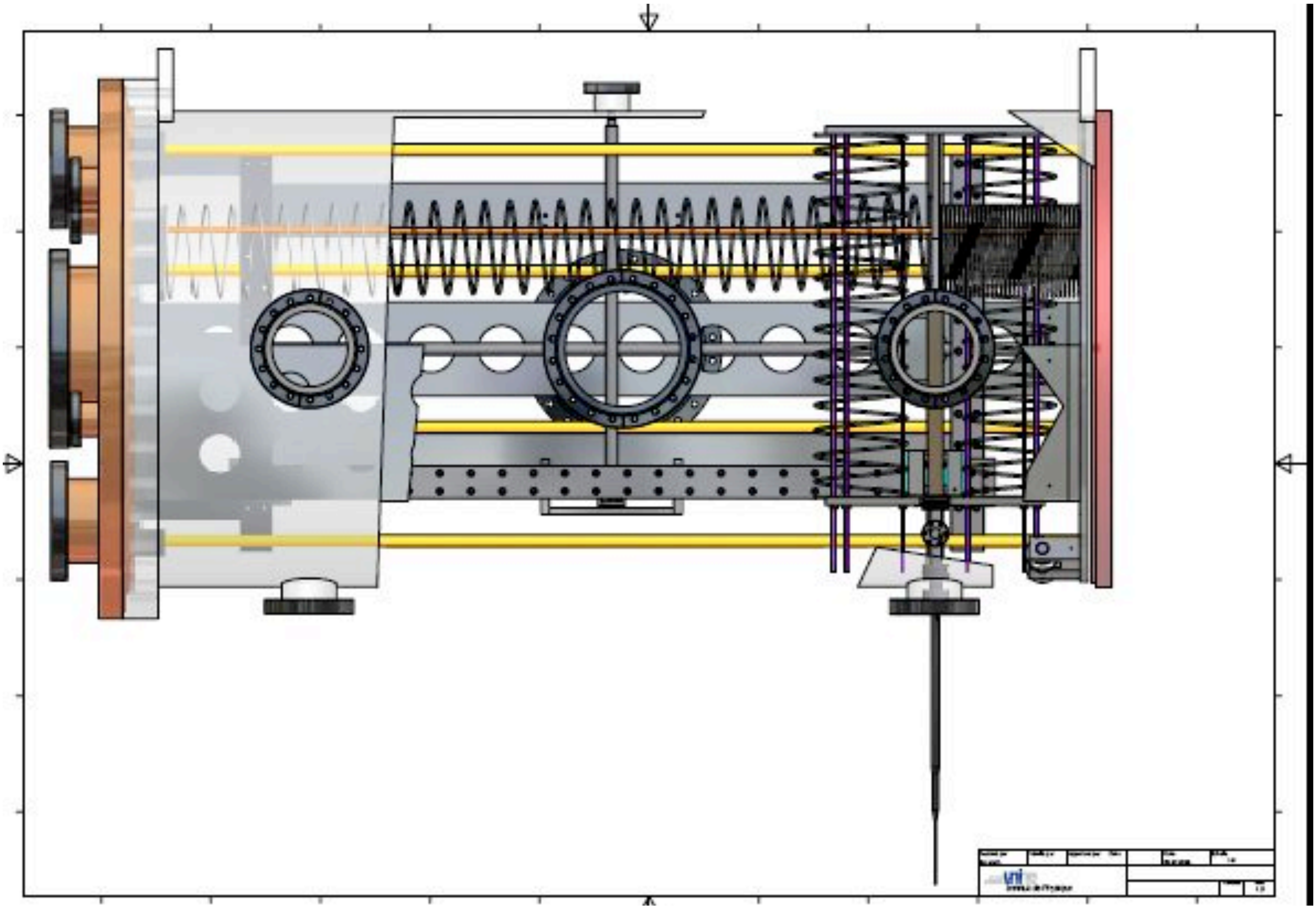




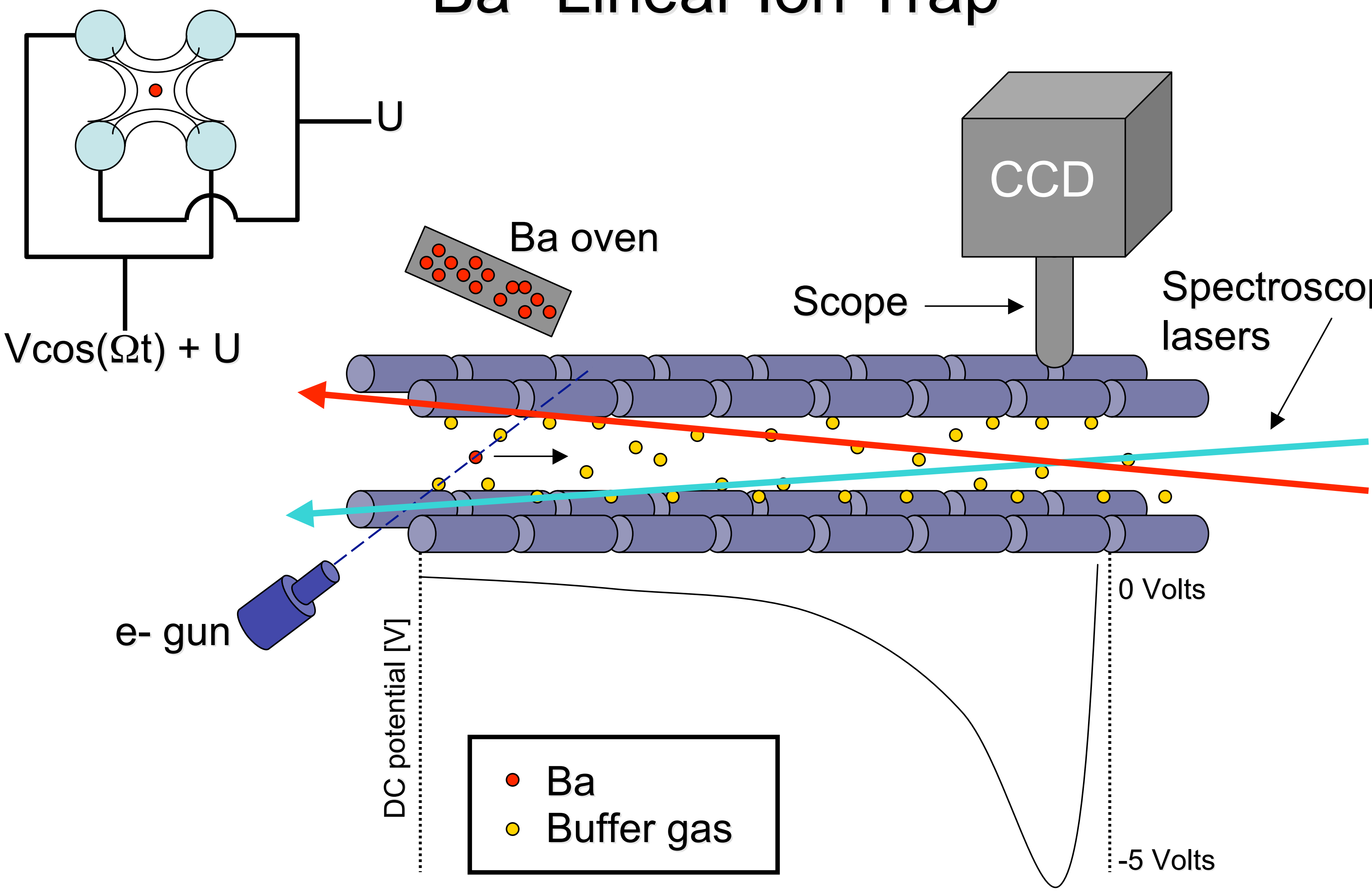
Grabber tip transfer system being built at the Univ of Neuchatel.
To be installed on the Stanford linear trap in 2006



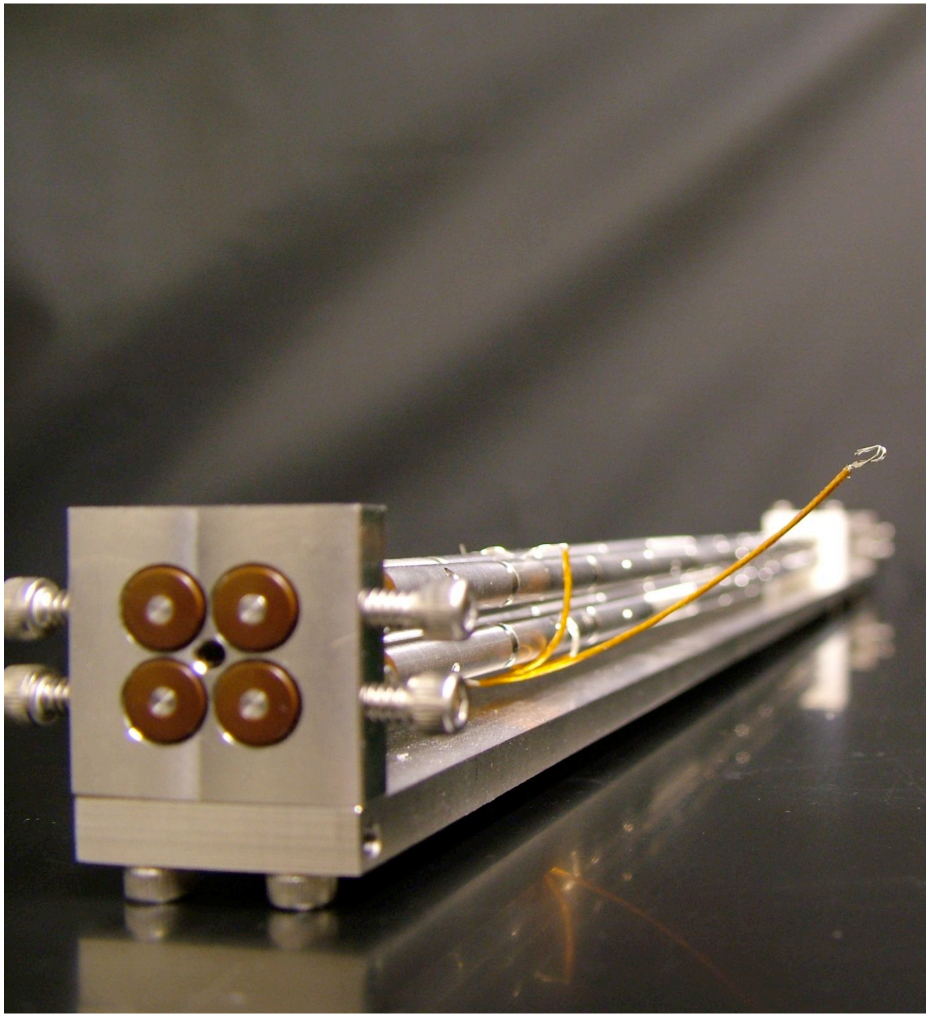
Technical drawing of the ion graber tip transfer system

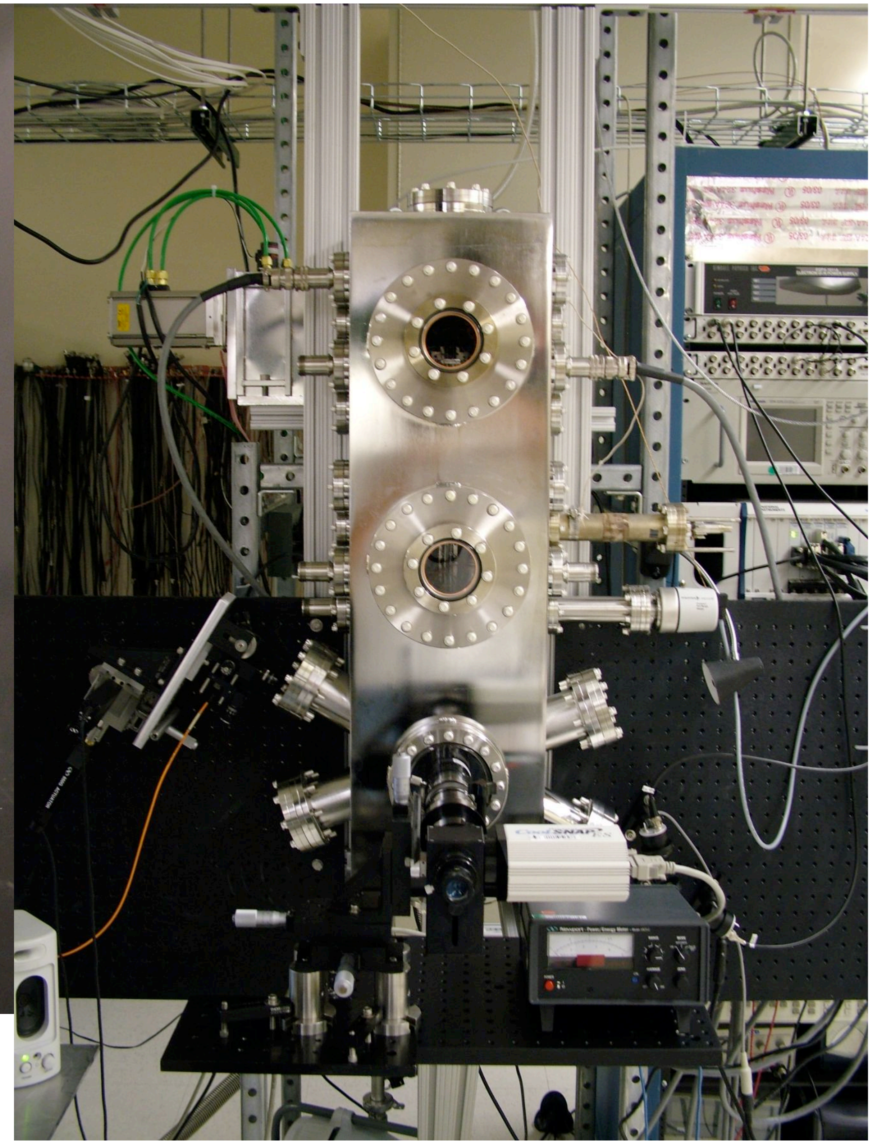


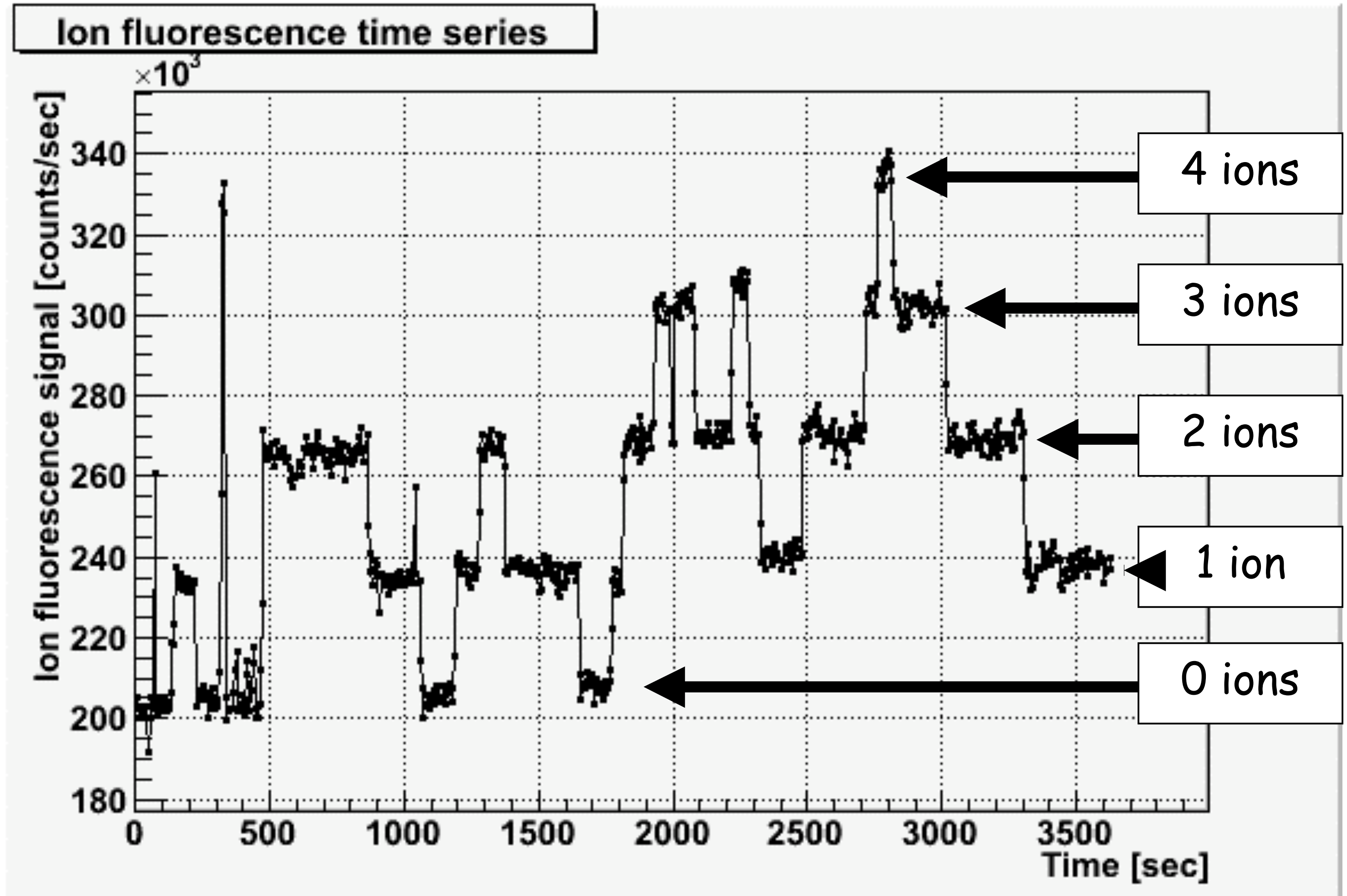
Ba$^+$ Linear Ion Trap



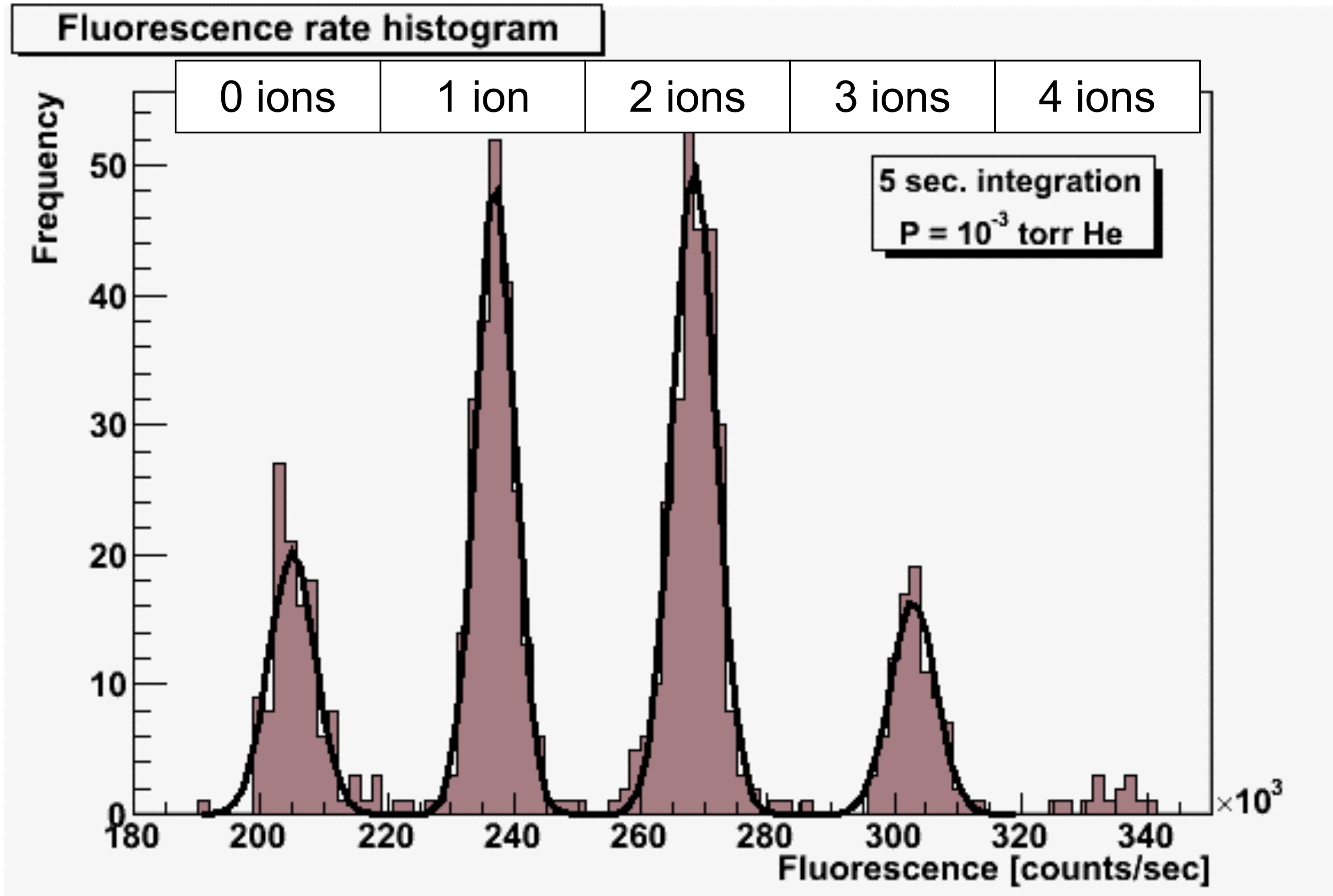
Stanford Linear Trap







Ion signal as a function of time as ions are loaded and unloaded from the linear trap. The quantized structure demonstrates our ability to detect single atoms in a buffer gas with high S/N.



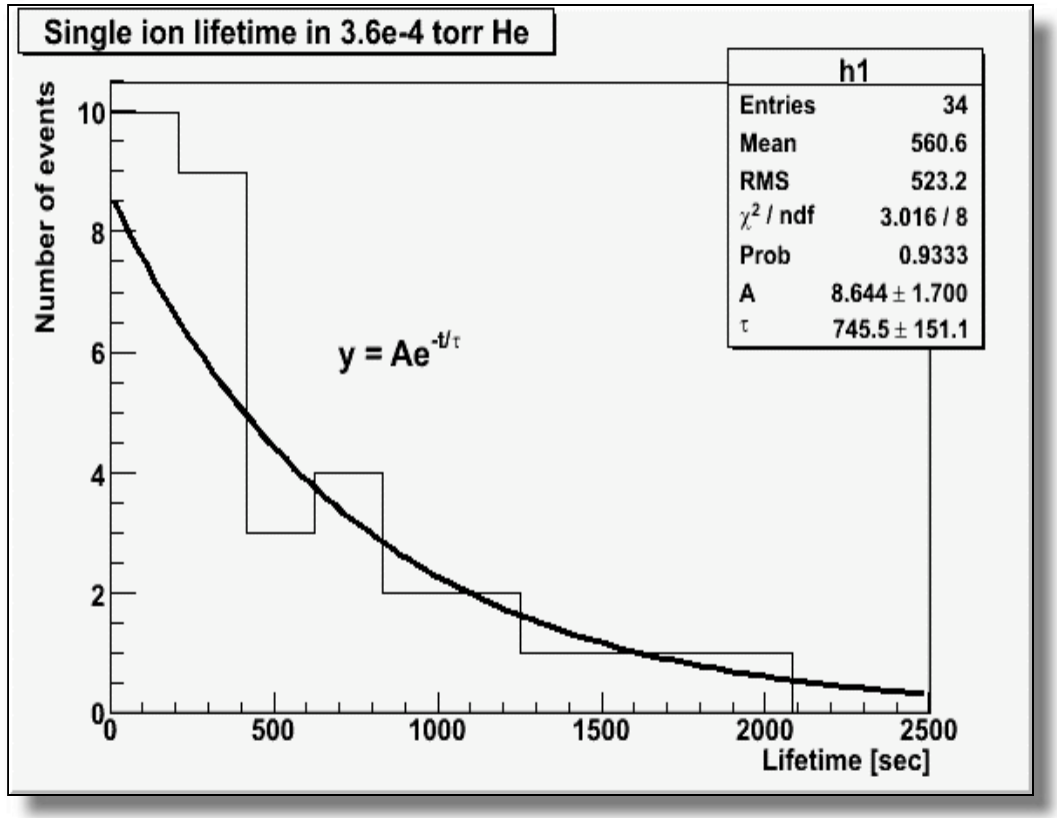
Histogram of ion fluorescence signal. With a 5 sec integration the signal from 1 ion is distinguishable from background at the 8.7σ level.

Single Ba^+ lifetime in the trap

- P_{buffer} ~ 3.6×10^{-4} torr He
- Single ion is loaded, and timed until ejection from trap
- Ion lifetimes histogrammed and fit to exponential
- Lifetime follow exponential distribution with

  τ ~ 746 ± 151 sec

  → Probably capture on impurities in trap (O_2, NO, CO_2, etc.)



3.6×10^{-4} torr He → λ_{mfp} ~ 31cm → $R_{collision}$ ~ 740 Hz → *2 ppm impurities*

EXO neutrino effective mass sensitivity

Assumptions:

1) 80% enrichment in 136
2) Intrinsic low background + Ba tagging eliminate all radioactive background
3) Energy resolution only used to separate the $0\nu\beta\beta$ from $2\nu\beta\beta$ modes:
   Select $0\nu\beta\beta$ events in a $\pm 2\sigma$ interval centered around the 2.46 MeV endpoint
4) Use for $2\nu\beta\beta$ $T_{1/2} > 1 \cdot 10^{22}$ yr (Bernabei et al. measurement)

Case	Mass (ton)	Eff. (%)	Run Time (yr)	$\sigma(E)/E$ @ 2.5MeV (%)	$2\nu\beta\beta$ Background (events)	$T_{1/2}^{0\nu\beta\beta}$ (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

* $\sigma(E)/E$ = 1.4% 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

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

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

Conclusions

EXO-200 very soon will be ready

- Largest double beta decay detector ever
- Largest amount of separated isotope (by a factor of 10) in hand
- Tie for the largest Xe detector ever…

  But we are - ultra-clean

  - enriched xenon
- First liquid bath cooled/shielded LXe detector
- First Ionization & Scintillation LXe detector
- First massive use of APDs for scintillation readout

Grabbing/release/tagging R&D in full swing in parallel

- Very interdisciplinary effort ! (AMO, condensed matter, nanoscience)
- May have broad impact on other fields
- Linear trap was brought to life in record time (Oct 05 – Feb 06)
- Will soon start Ba capture/release experiments with stationary STM tip !
- Tip transfer system being built
- Realistic cryo tip well advanced
- Would like to do R&D on RIS tip !

Full EXO will naturally emerge from these two efforts

Enriched Xenon Observatory
for double beta decay

D.Leonard, A.Piepke
Physics Dept, University of Alabama, Tuscaloosa AL

P.Vogel
Physics Dept Caltech, Pasadena CA

A.Bellerive, M.Bowcock, M.Dixit, C.Hargrove, D.Sinclair, V.Strickland
Carleton University, Ottawa, Canada

W.Fairbank Jr., S.Jeng, K.Hall
Colorado State University, Fort Collins CO

M.Moe
Physics Dept UC Irvine, Irvine CA

D.Akimov, A.Burenkov, M.Danilov, A.Dolgolenko, A.Kovalenko, D.Kovalenko, G.Smirnov, V.Stekhanov
ITEP Moscow, Russia

J.Farine, D.Hallman, C.Virtue
Laurentian University, Canada

M.Hauger, F.Juget, L.Ounalli, D.Schenker, J-L.Vuilleumier, J-M.Vuilleumier, P.Weber
Physics Dept University of Neuchatel, Switzerland

M.Breidenbach, R.Conley, C.Hall, D.McKay, A.Odian, C.Prescott, P.Rowson, K.Skarpaas, K.Wamba
SLAC, Menlo Park CA

R.DeVoe, P. Fierling, B.Flatt, G.Gratta, M.Green, F.LePort, M. Montero-Diez, R.Neilson, A.Pocar, J.Wodin
Physics Dept Stanford University, Stanford CA

EXO Technical Preparation

Build and operate a smaller scale TPC to demonstrate that required energy resolution and background can be achieved. Demonstrate feasibility of large scale enrichment of ^{136}Xe.

We are building detector using 200 kg enriched Xe (at hand), to be installed at WIPP, New Mexico 2006/2007.
Will demonstrate background and energy resolution.

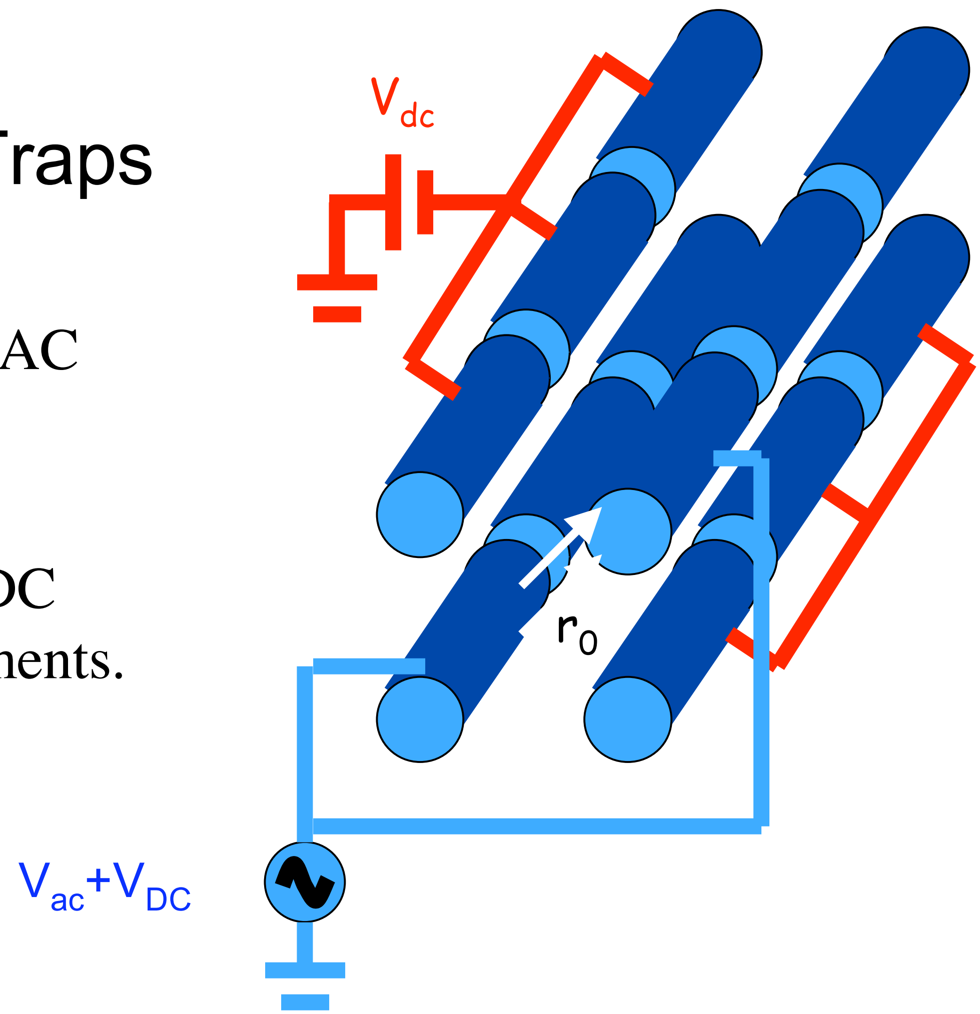
Ba extraction, transfer and single ion detection being developed in the lab in parallel.

After successful completion of these parallel research thrusts preparation of full proposal.
In this plan proof of principle does not require the funding of a very costly large experiment up front.

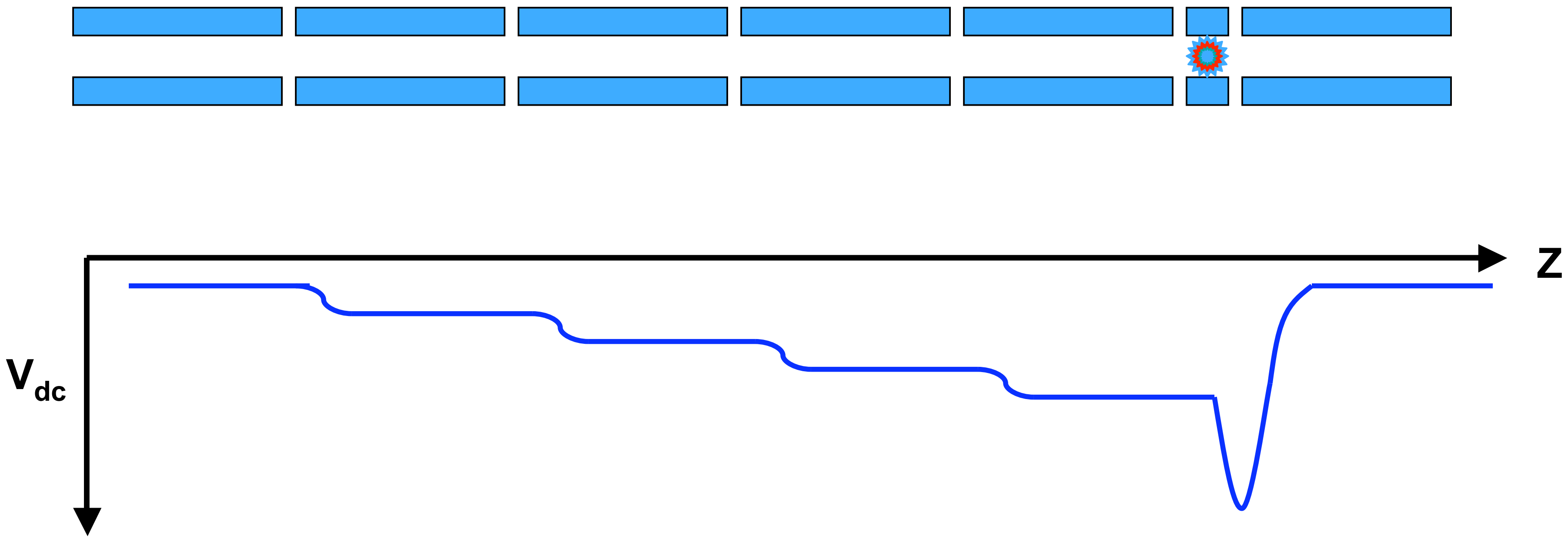
Ba single Ion Detection

Linear Paul (RFQ) Traps

- Radial confinement from AC potential across rods.
- Axial confinement from DC potentials across rod segments.



Linear Traps



High loading efficiency for incoming ions observed.

Ions that loaded at one end will travel to the other.

Ions can be manipulated by changing the DC potential configuration.