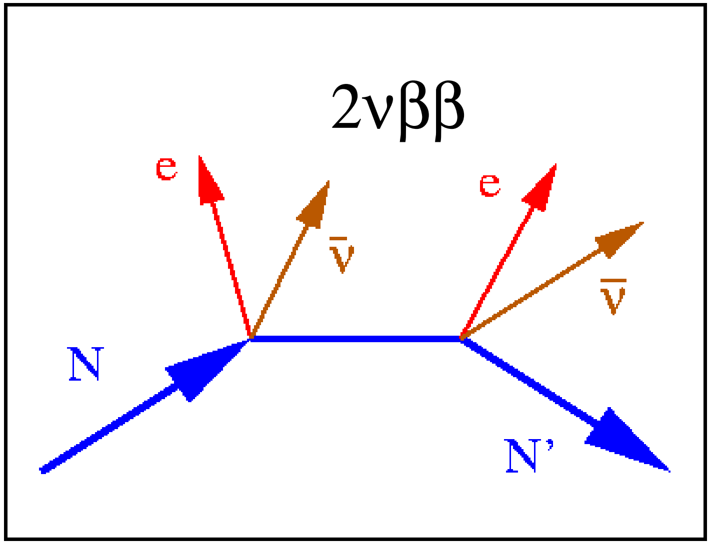
Enriched Xenon Observatory for double beta decay

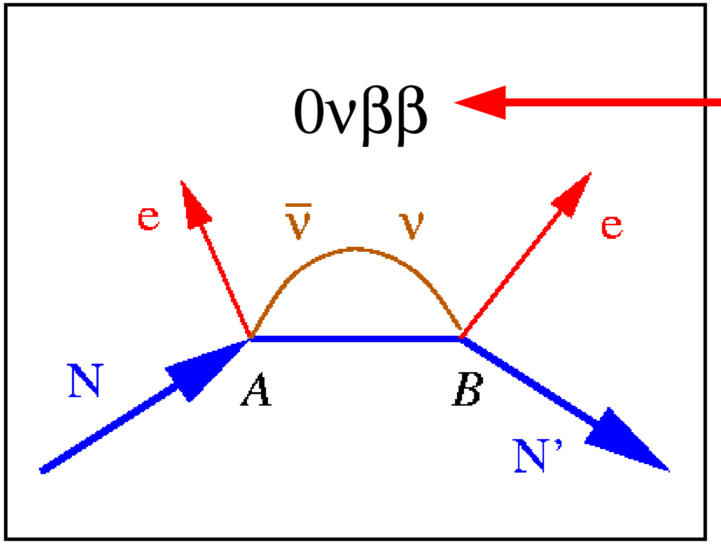
Jesse Wodin for the EXO collaboration

Z.Djurcic, A.Piepke *Physics Dept, University of Alabama*
P.Vogel *Physics Dept Caltech*
M.Moe *Physics Dept UC Irvine*
D. Akimov, M.Danilov, A.Dolgolenko, O.Zeldovich *ITEP Moscow*
J-L.Vuilleumier *Physics Dept University of Neuchatel*
G.Bower, M.Breidenbach, R.Conley, C.Hall, A.Odian, C.Prescott, P.Rowson, K.Skarpaas, K.Wamba *SLAC*
E.Conti, R.deVoe, G.Gratta, M.Green, T.Koffas, S.Waldman, J.Wodin *Physics Dept Stanford University*

more information at hep16.stanford.edu

EXO is an experiment to search for both $0\nu\beta\beta$ and $2\nu\beta\beta$ in ^{136}Xe





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

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

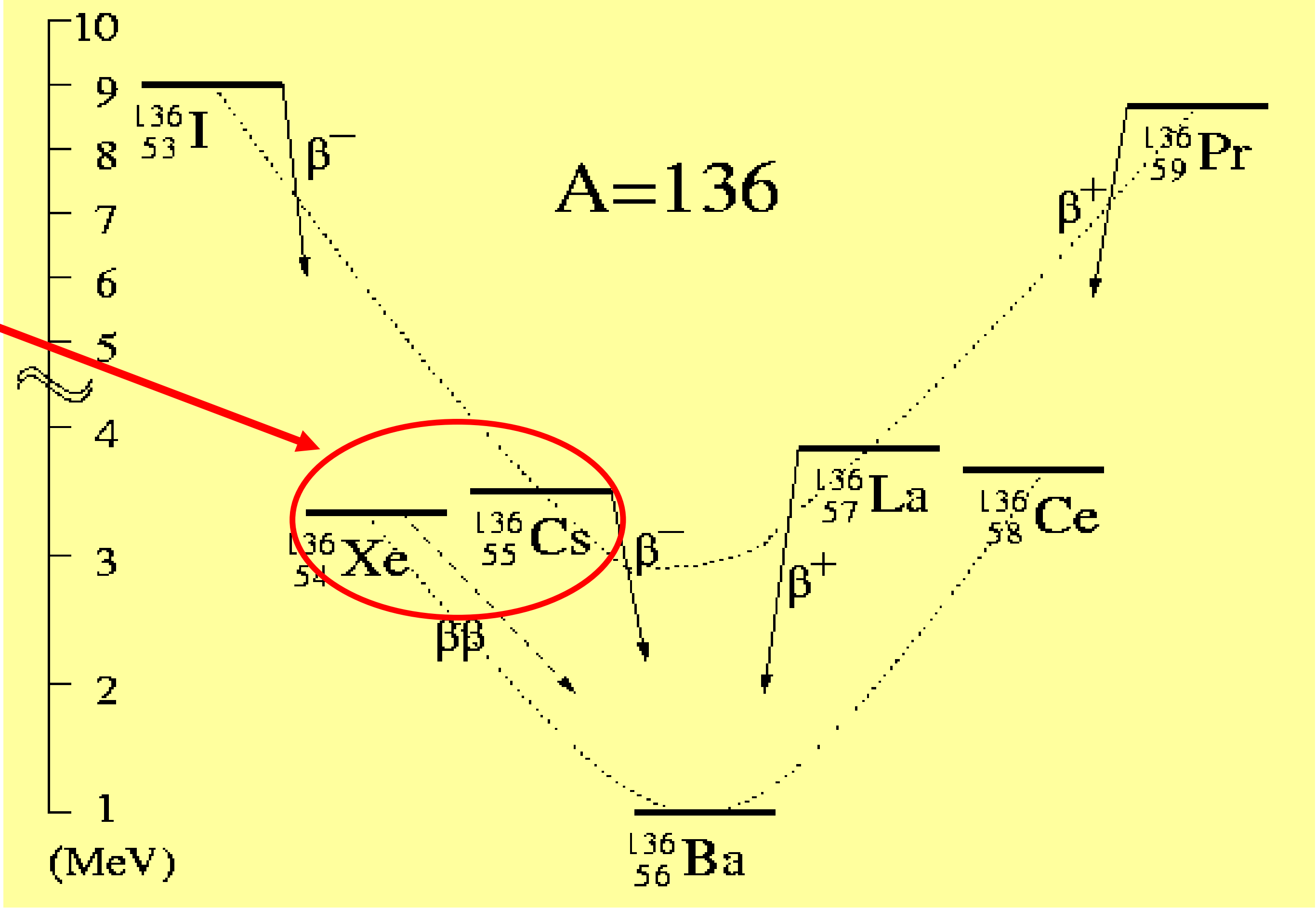
Quantity to be measured

Known phase space factor

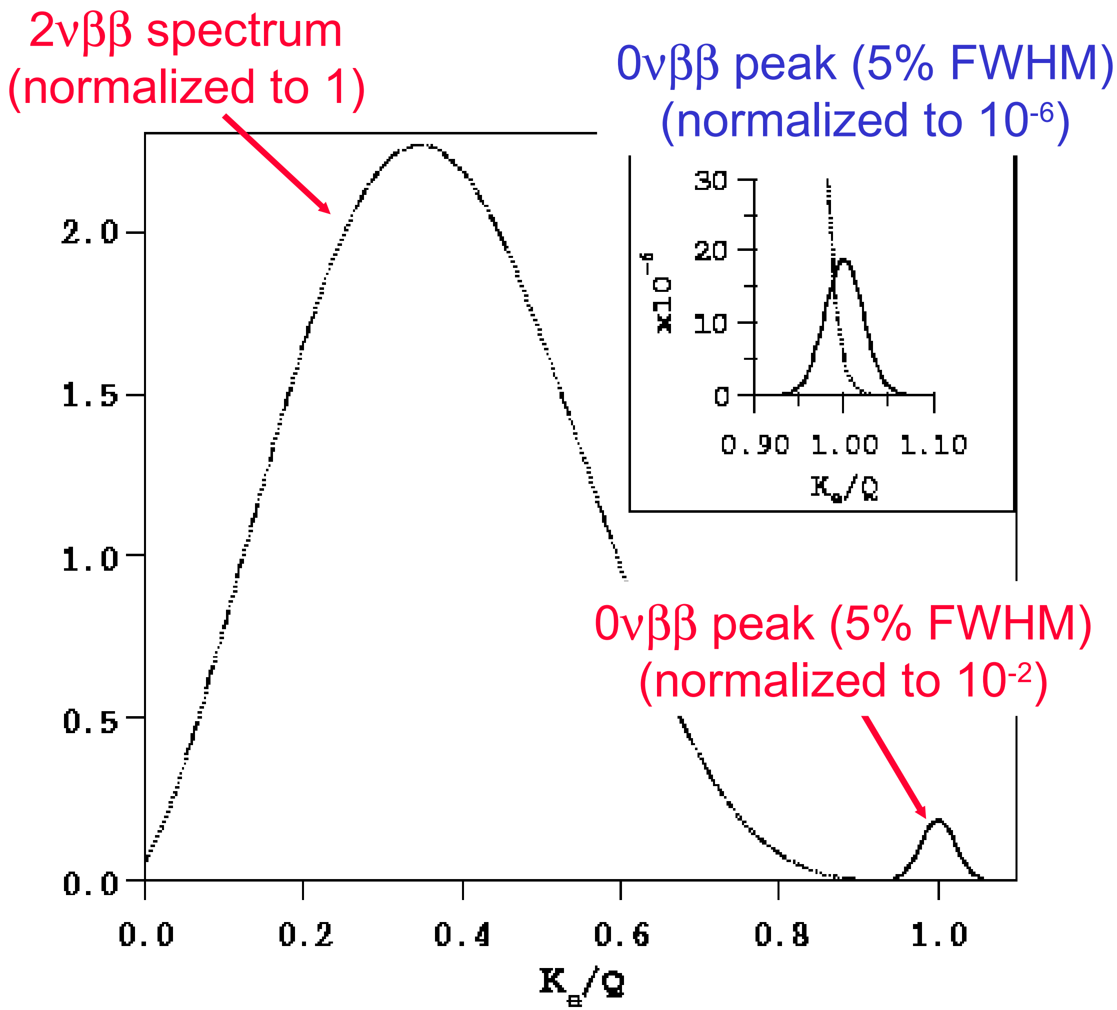
Nuclear matrix elements (hard to calculate accurately!!!)

ββ always a second order process

Only detectable if first order β decay is energetically forbidden



Measuring 0νββ over the 2νββ background



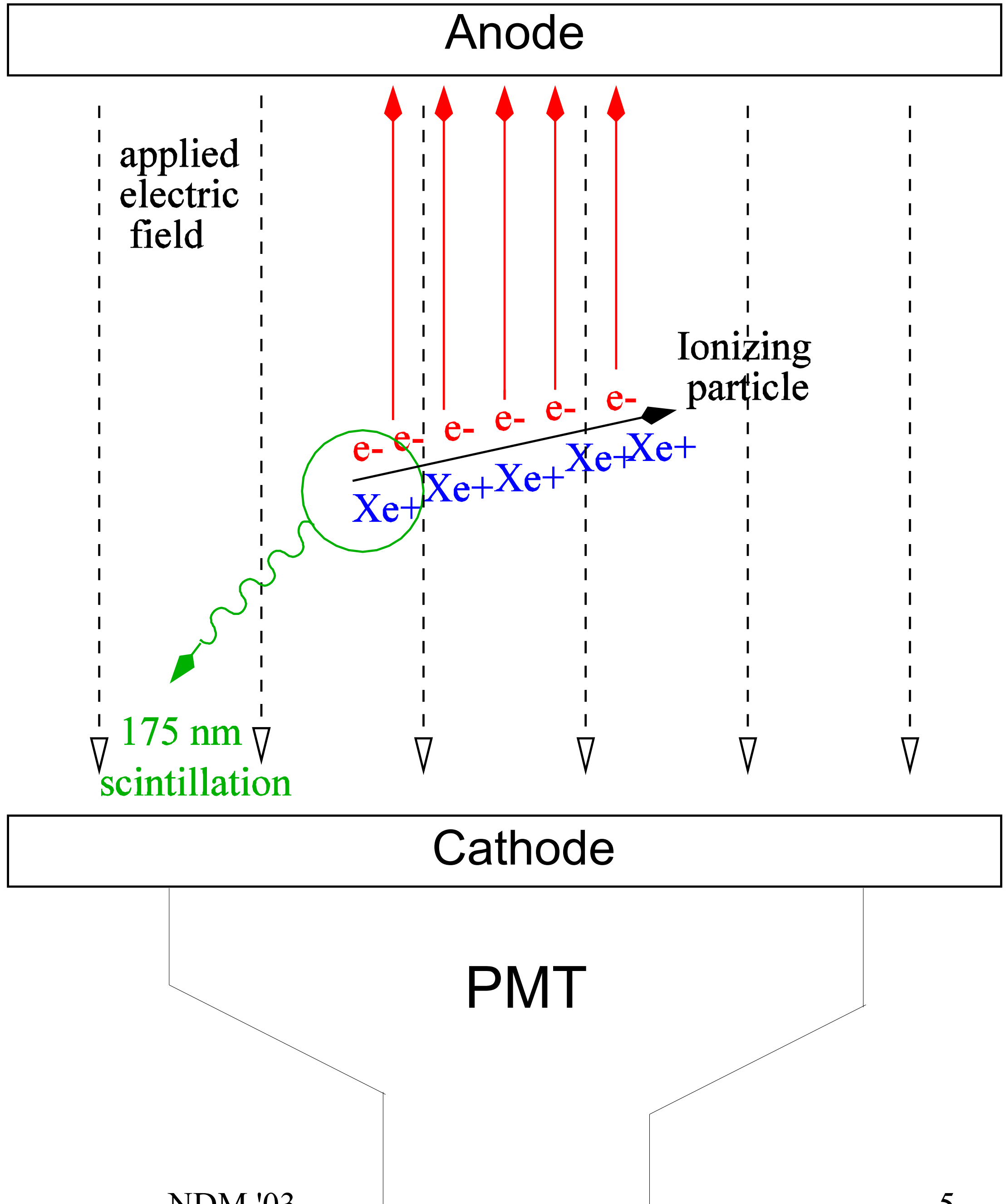
Summed electron energy in units of the kinematic endpoint (Q)

Superb energy resolution and background reduction is needed to distinguish 2νββ from 0νββ.

Xenon calorimetry

We measure the event energy by collecting the **ionization** on the anode *and* observing the **scintillation**

As the electric field is increased, the collected ionization increases and the scintillation decreases

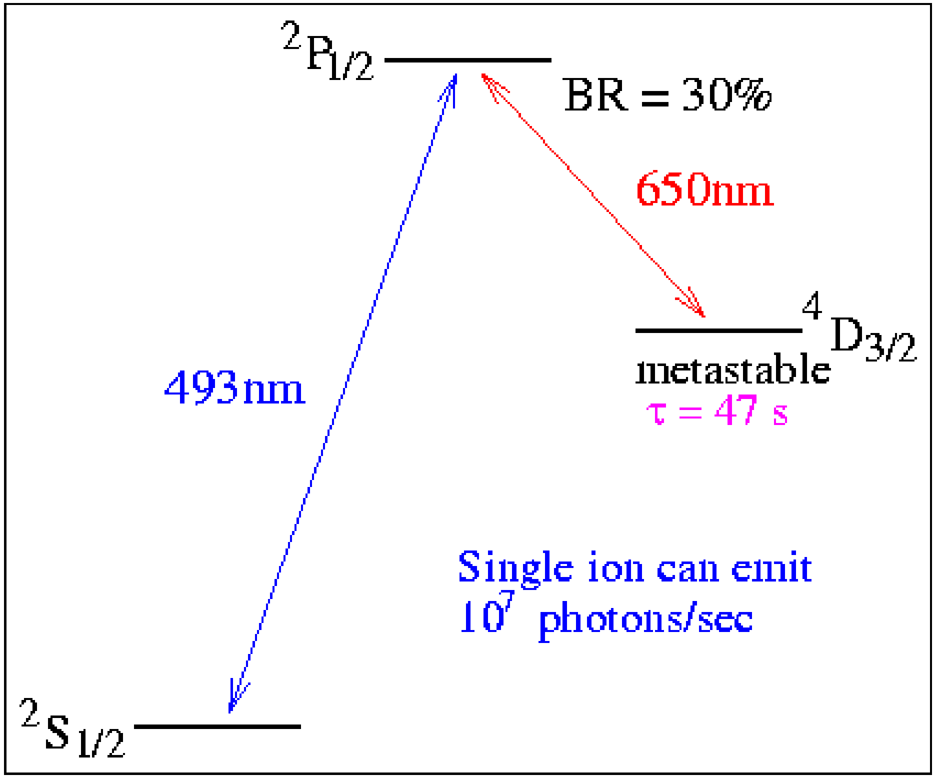


Xe offers a qualitatively new tool against background: $^{136}Xe \rightarrow {}^{136}Ba^{++} + e^- + e^-$ final state can be identified using optical spectroscopy (*M. Moe Physical Review C 44 (1991) 931*)

Ba^+ system well studied by Neuhauser, Hohenstatt, Toshek, Dehmelt 1980

Single ions can be detected from a photon rate of 10^7/s

- Important additional constraint
- Huge background reduction



Level structure for Ba^+

^{136}Xe overview

- No need to grow crystals
- No long lived isotopes to activate
- $Q_{\beta\beta}$ = 2.479 MeV (reasonable endpoint)
- Fluid can be purified *in situ*
- Noble gas enrichment relatively easy and safe
- Ba tagging can reduce external backgrounds to zero
- Fair energy resolution

Make no small plans

1. **Very large fiducial mass (tons)**

2. **Reduce and control backgrounds in qualitatively new ways**

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

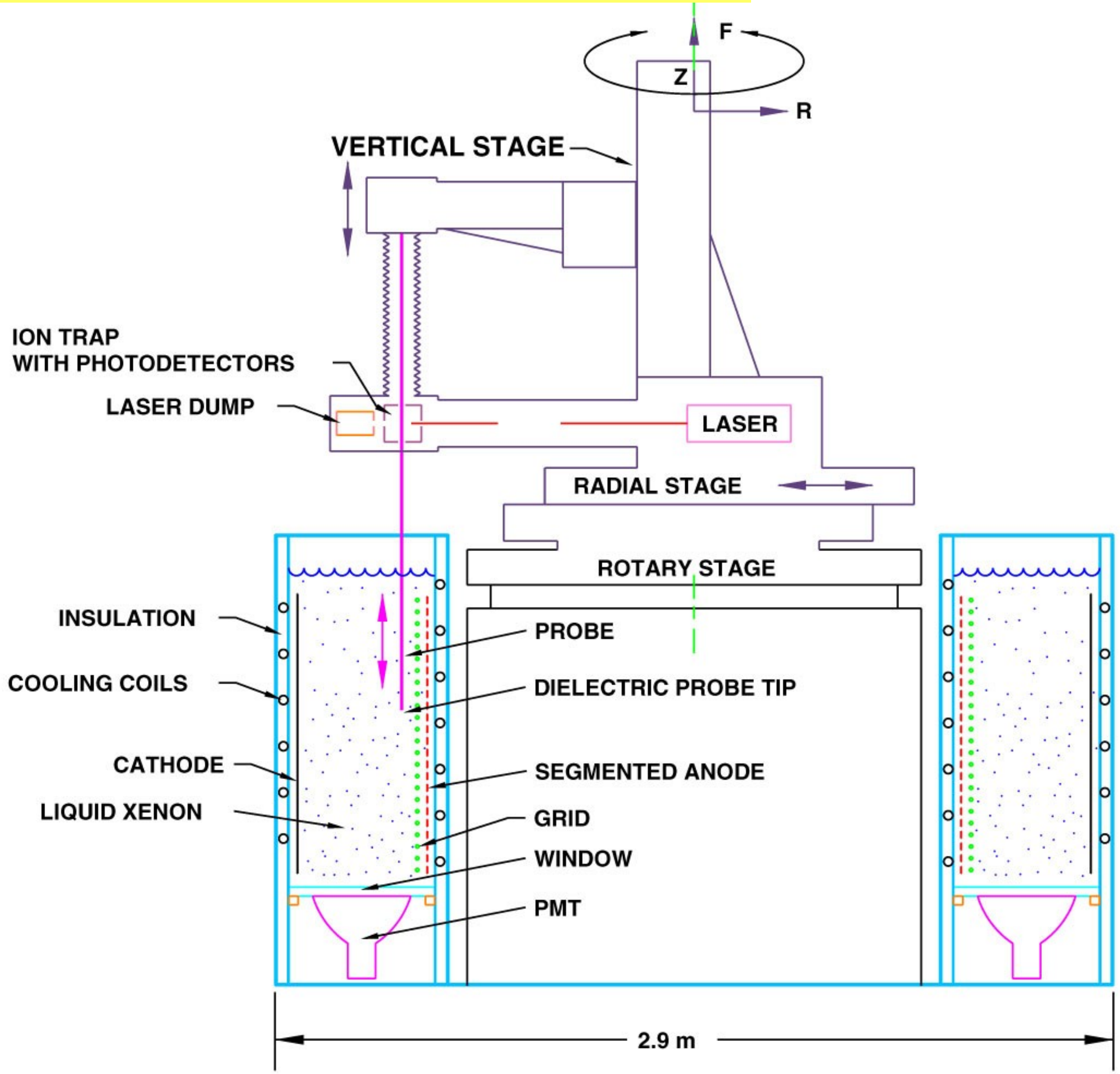
For no bkgnd $$\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0\nu\beta\beta}} \propto 1/\sqrt{Nt}$$

1 is essential

1 without 2 is a waste

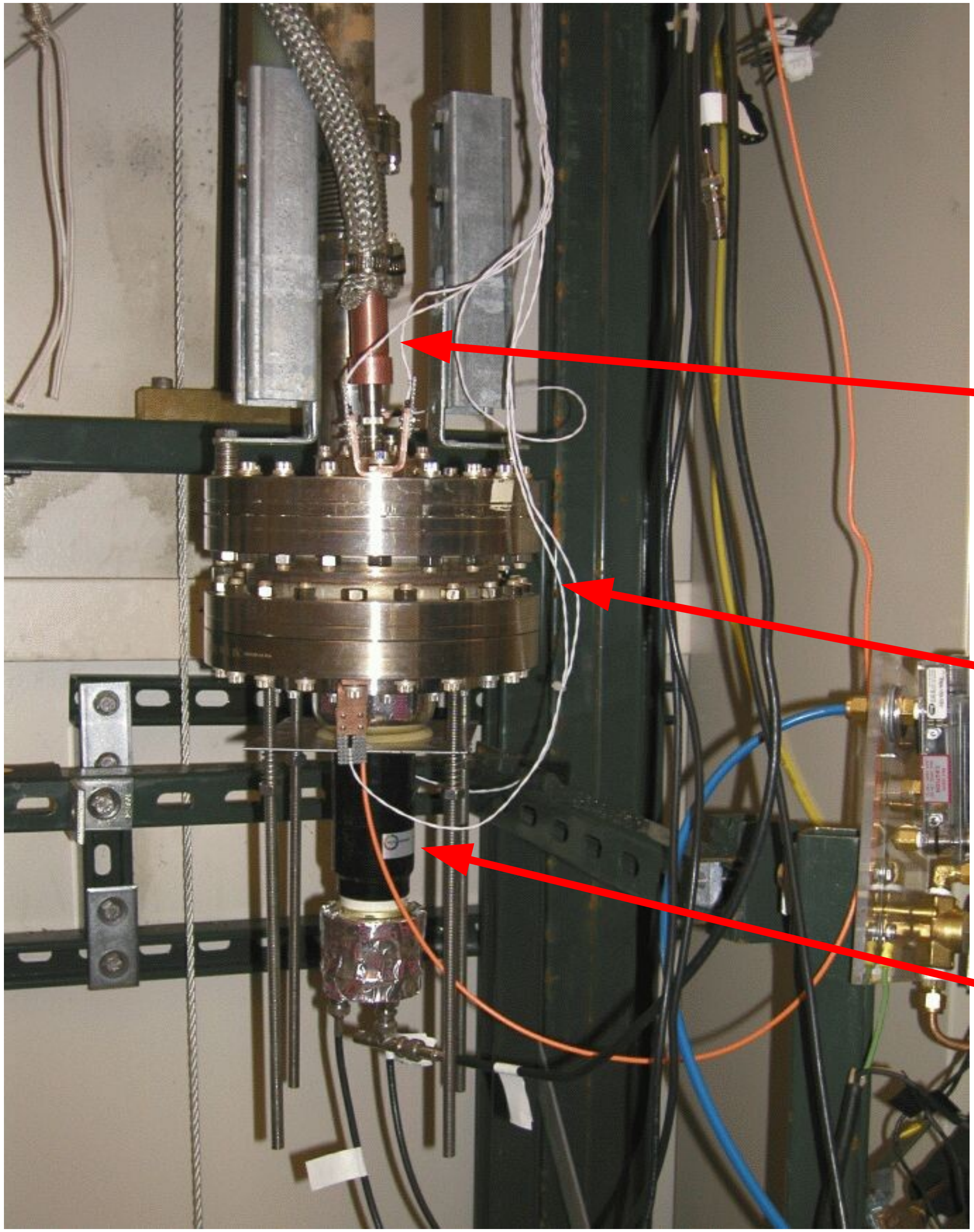
Liquid Xenon TPC conceptual design

- Use ionization and scintillation light in the TPC to determine the event location, and to do **precise calorimetry**
- **Extract the Ba ion** from the event location (electrostatic probe)
- Deliver the Ba to a laser system for **spectroscopic identification**, or possibly vice versa



EXO R&D

- **Can we achieve sufficient energy resolution in the liquid xenon?**
- **Can we extract ions from the liquid Xe with a probe?**
- **Can we release the ions from the probe?**
- **Can we perform Ba^{+} spectroscopy in a Xe buffer gas?**
- **Pilot enrichment of ^{136}Xe**
- **200kg prototype construction**
- **Gas phase R&D**



Liquid Xe chamber built for resolution studies

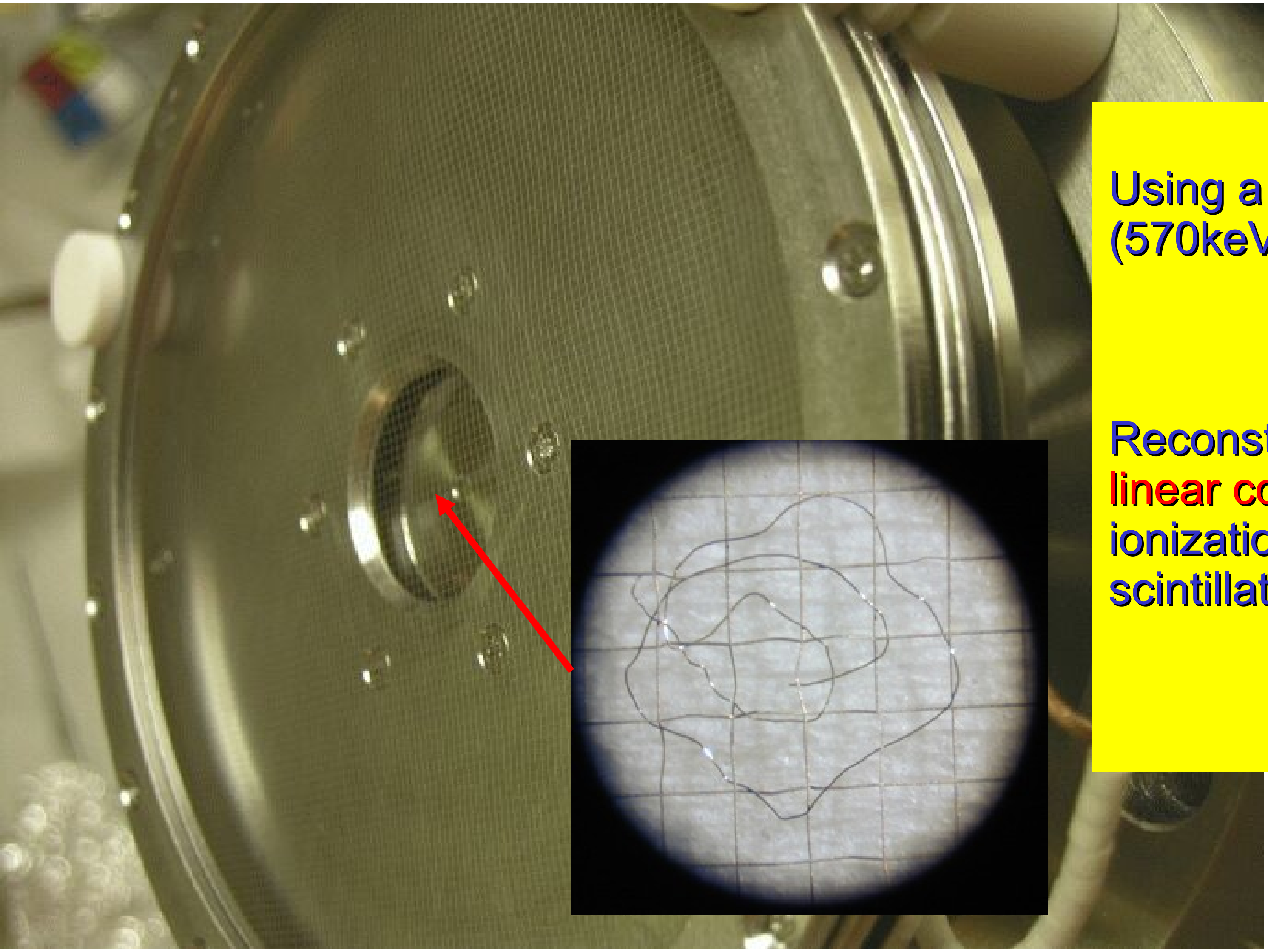
Anode readout electronics & HV feedthroughs

Stainless steel Xe vessel

PMT

Pancake shaped 1.5 liter LXe ionization chamber to test energy resolution

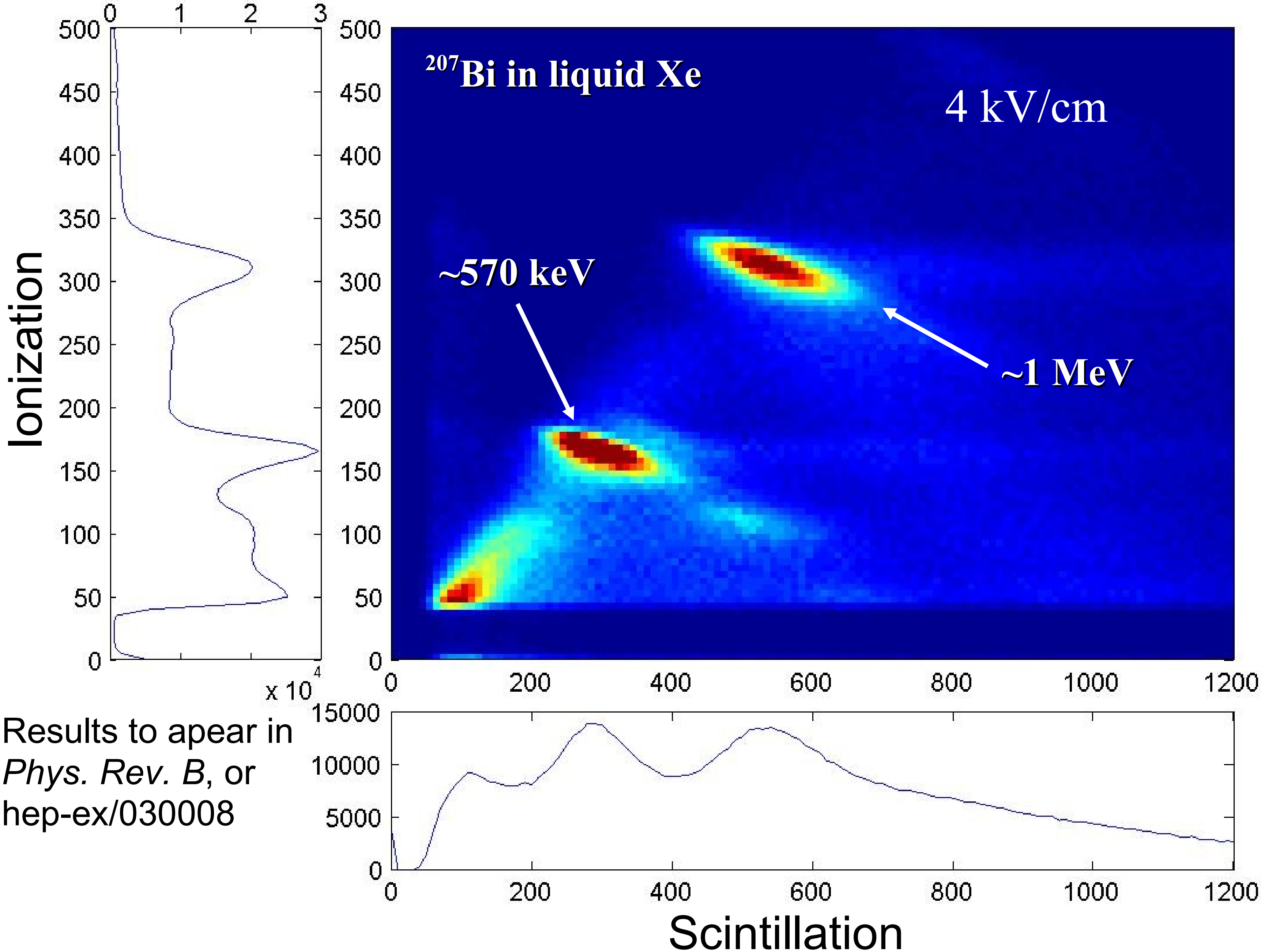
Good acceptance to scintillation light AND ionization



Using a ^{207}Bi source (570keV & 1MeV lines)

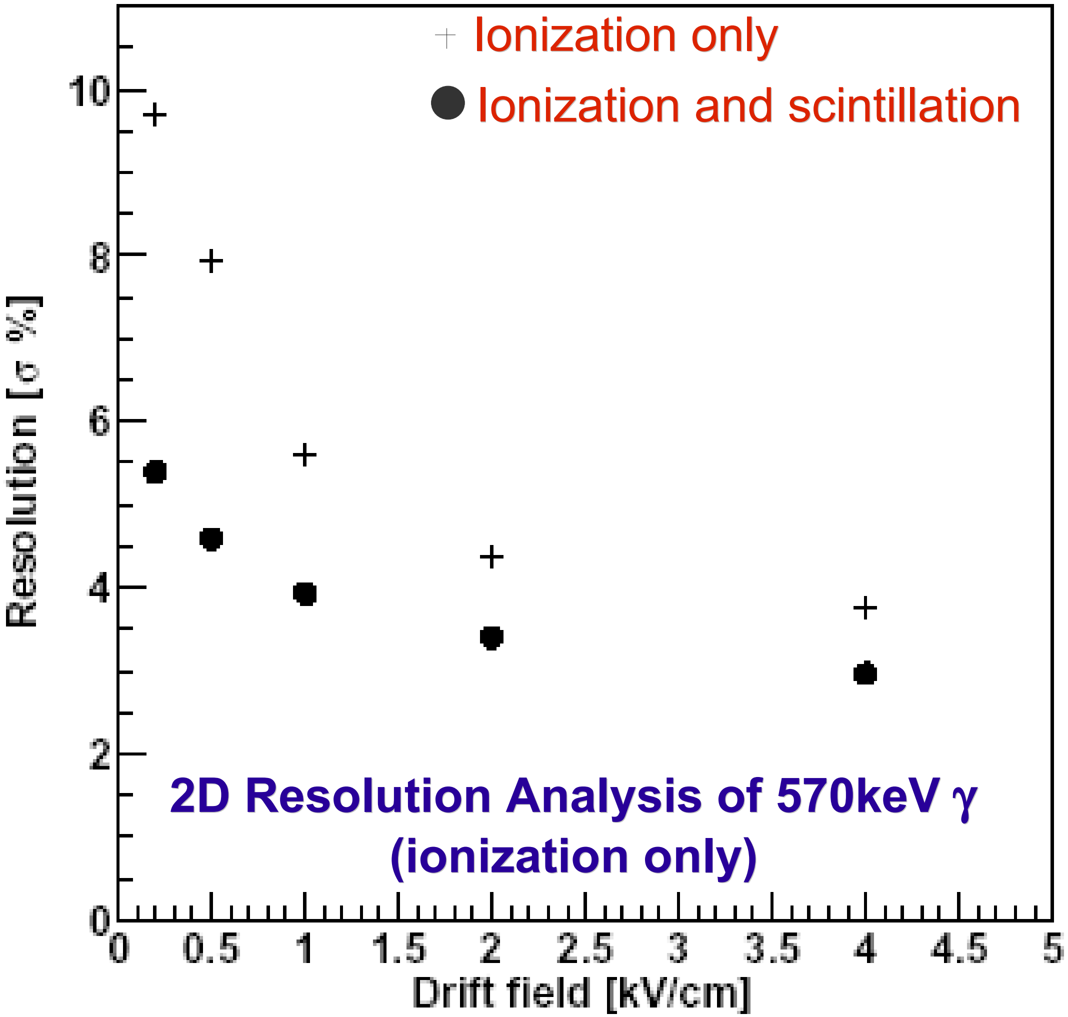
Reconstruct energy as linear combination of ionization and scintillation signals

Found anticorrelation between ionization and scintillation



Results to apear in *Phys. Rev. B*, or hep-ex/030008

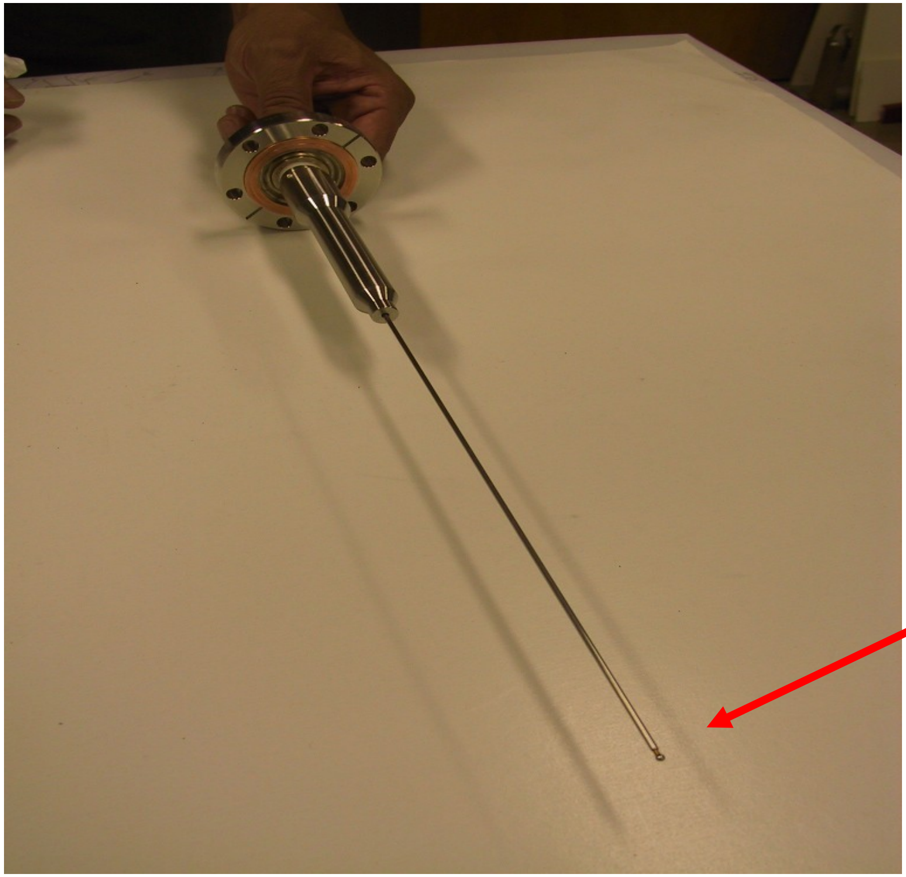
This can be used to improve the resolution in LXe and separate the 2ν from the 0ν modes



Ionization alone @ 4kV/cm:
$\sigma(E)/E$ = 4.0% @ 570 keV or 1.9% @ $Q_{\beta\beta}$

Ionization & Scintillation @ 2kV/cm:
$\sigma(E)/E$ = 3.0% @ 570 keV or 1.44% @ $Q_{\beta\beta}$

Ion grabbing test simulates Ba ions by using a ^{230}U source to recoil ^{226}Th and ^{222}Ra into the xenon



^{230}U(20.8 days)

↓ α

^{226}Th(30.5 min)

↓ α

^{222}Ra(38 sec)

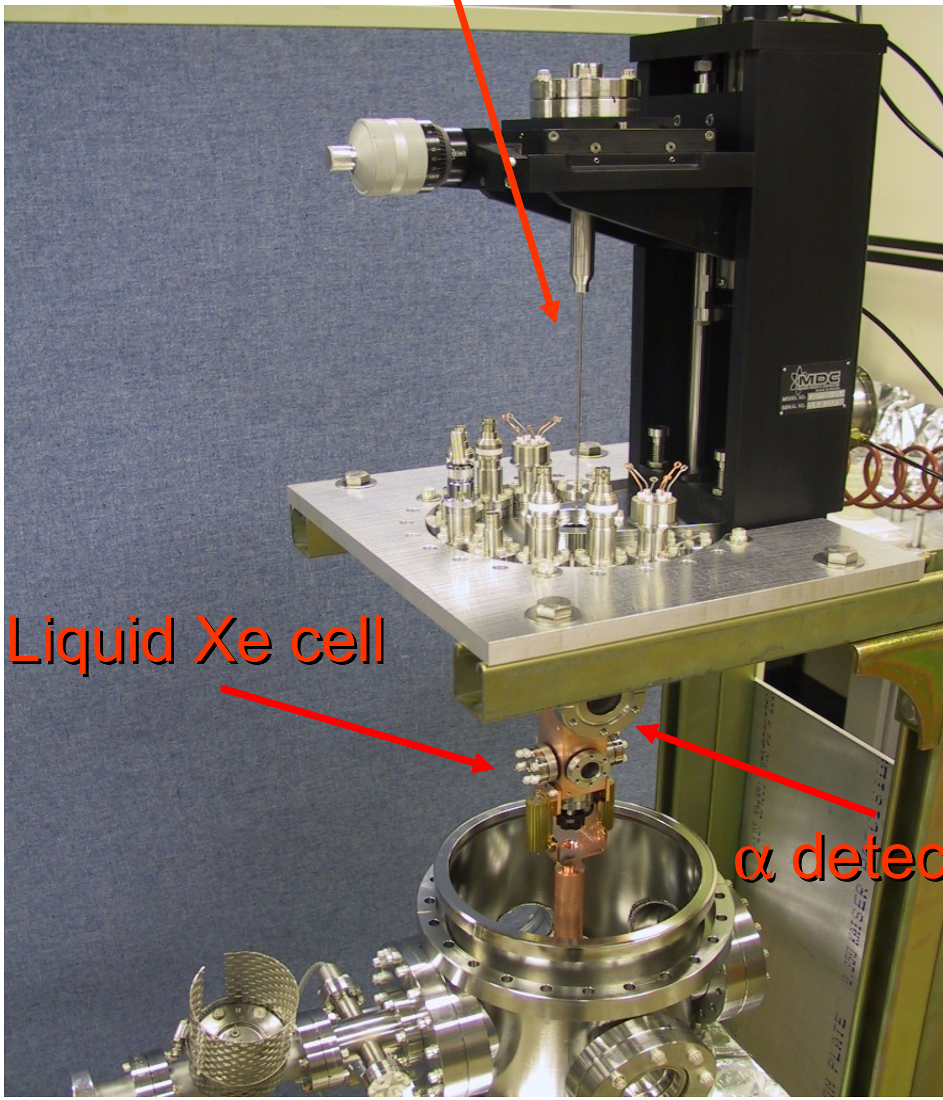
↓ α

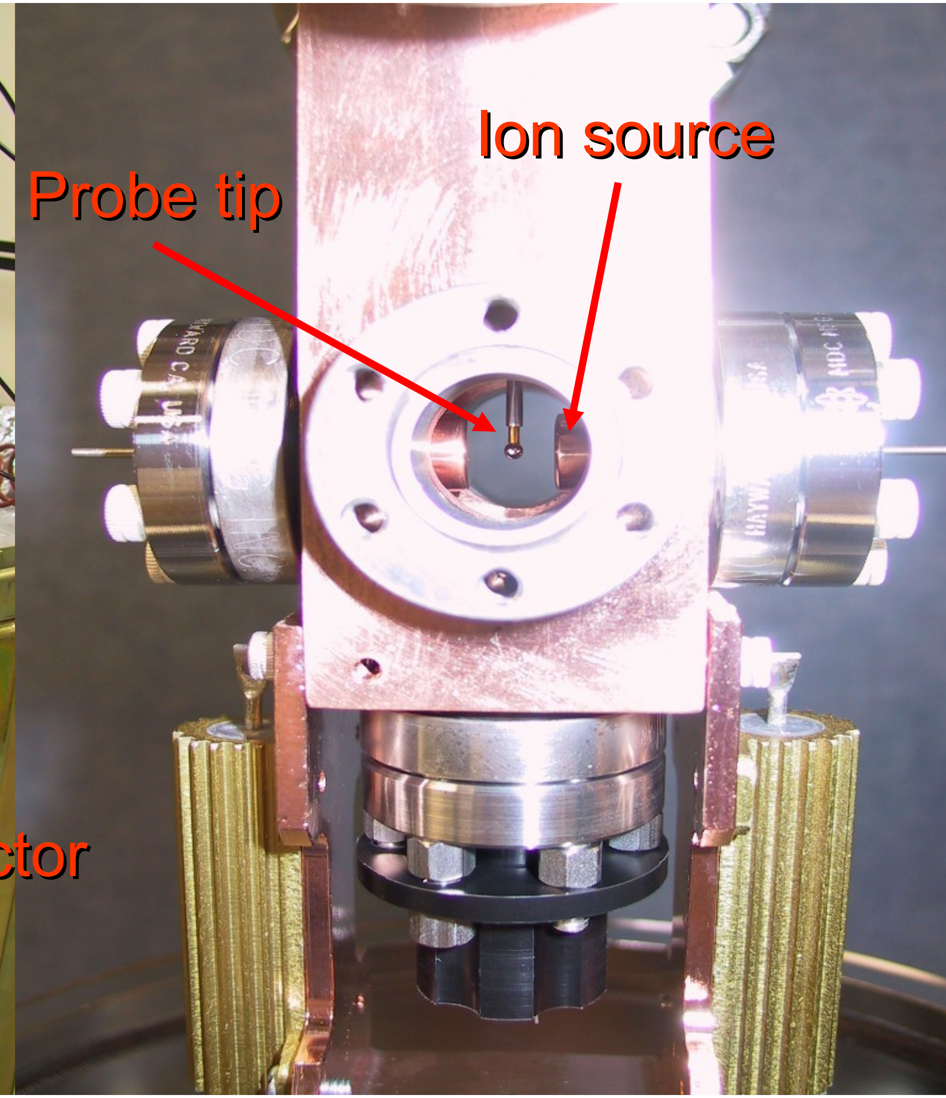
3 fast α decays

Prototype electrostatic probe picks up ^{226}Th and ^{222}Ra in LXe.
Ions are subsequently identified by their α decays.

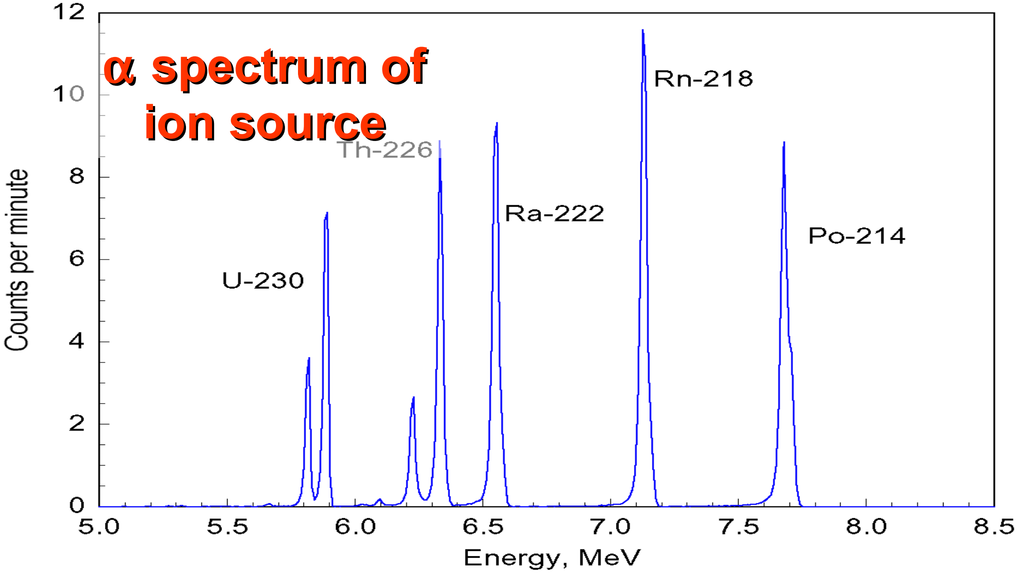
Electrostatic probe moves up and down

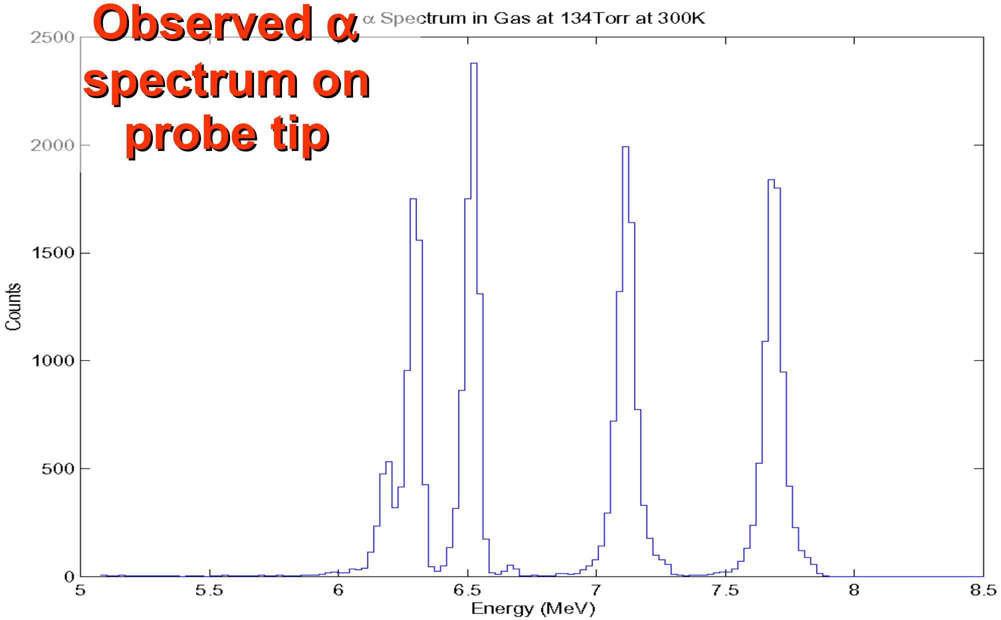
Close up of Liquid Xe cell



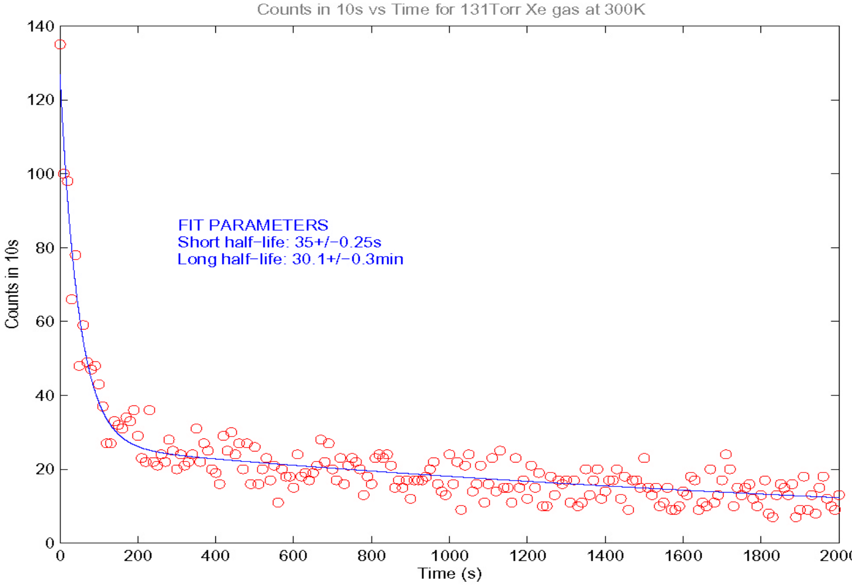


Ion grabbing in Xe (gas and liquid) works



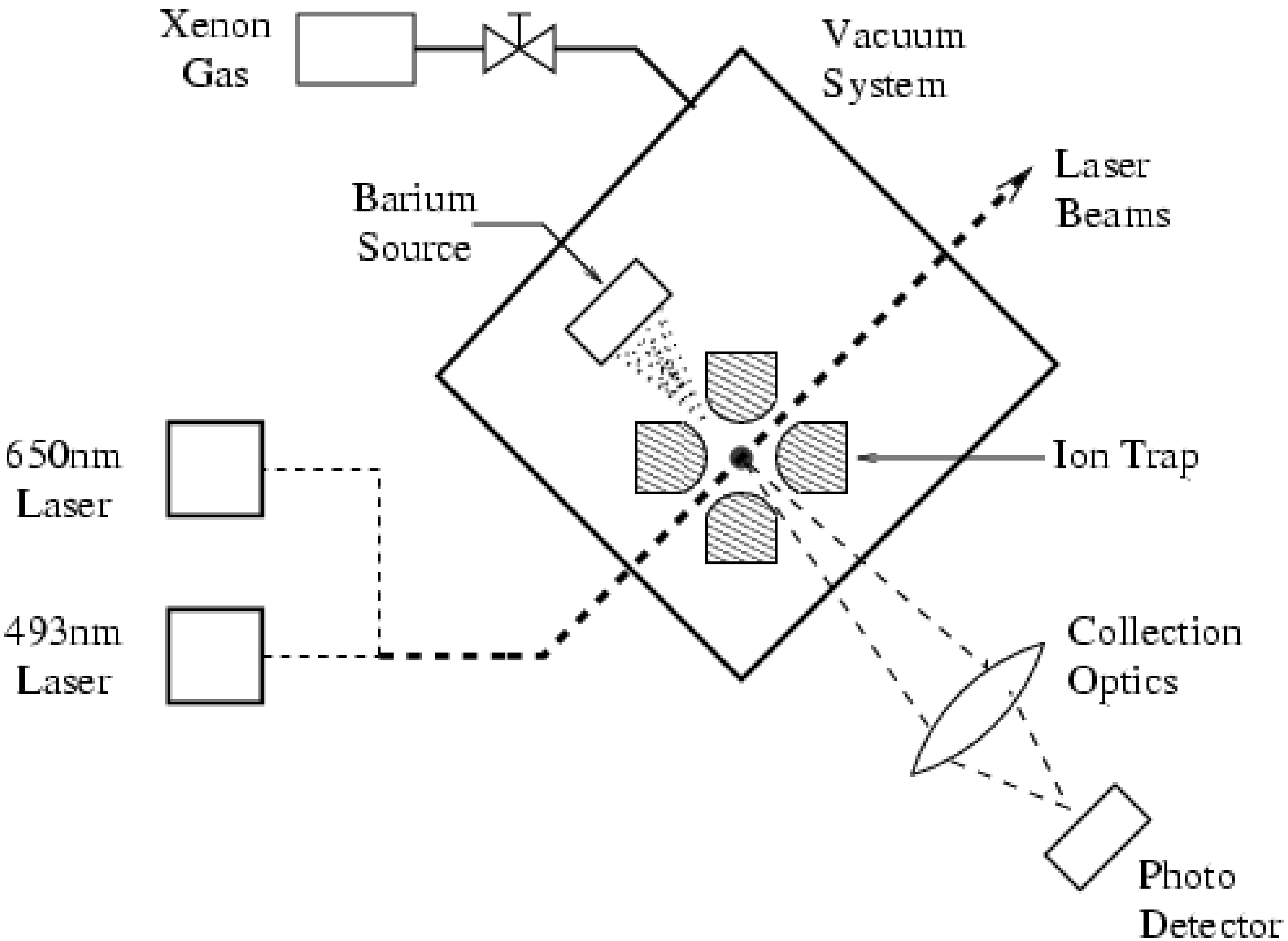


α decay lifetimes on probe tip agree with expectation for ^{226}Th and ^{222}Ra



Now measuring the ion drift velocity and studying ion release techniques

Test UHV/high pressure ion trap

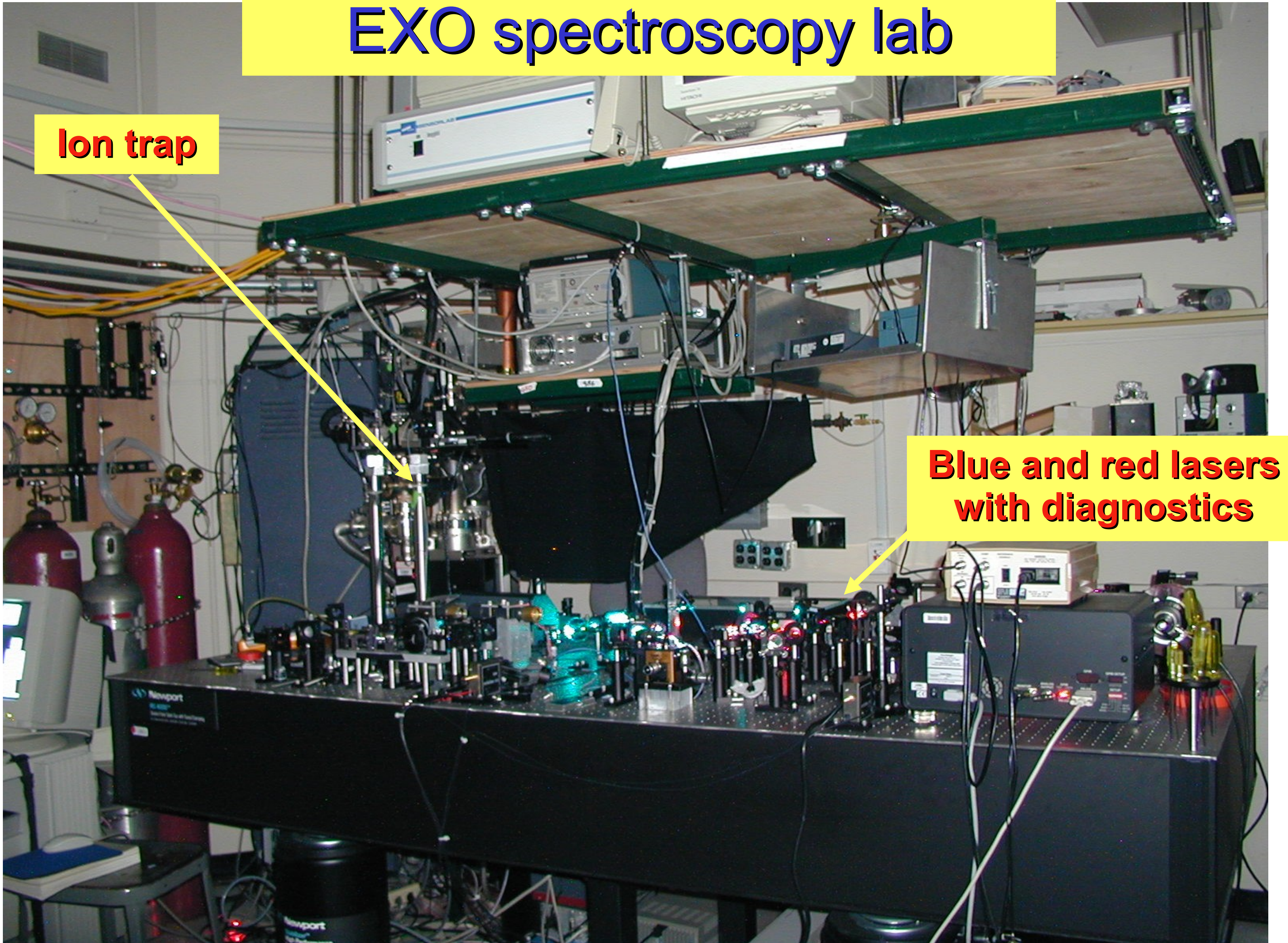


RF quadrupole trap loaded in UHV from a Ba dispenser and e^- beam ionizer

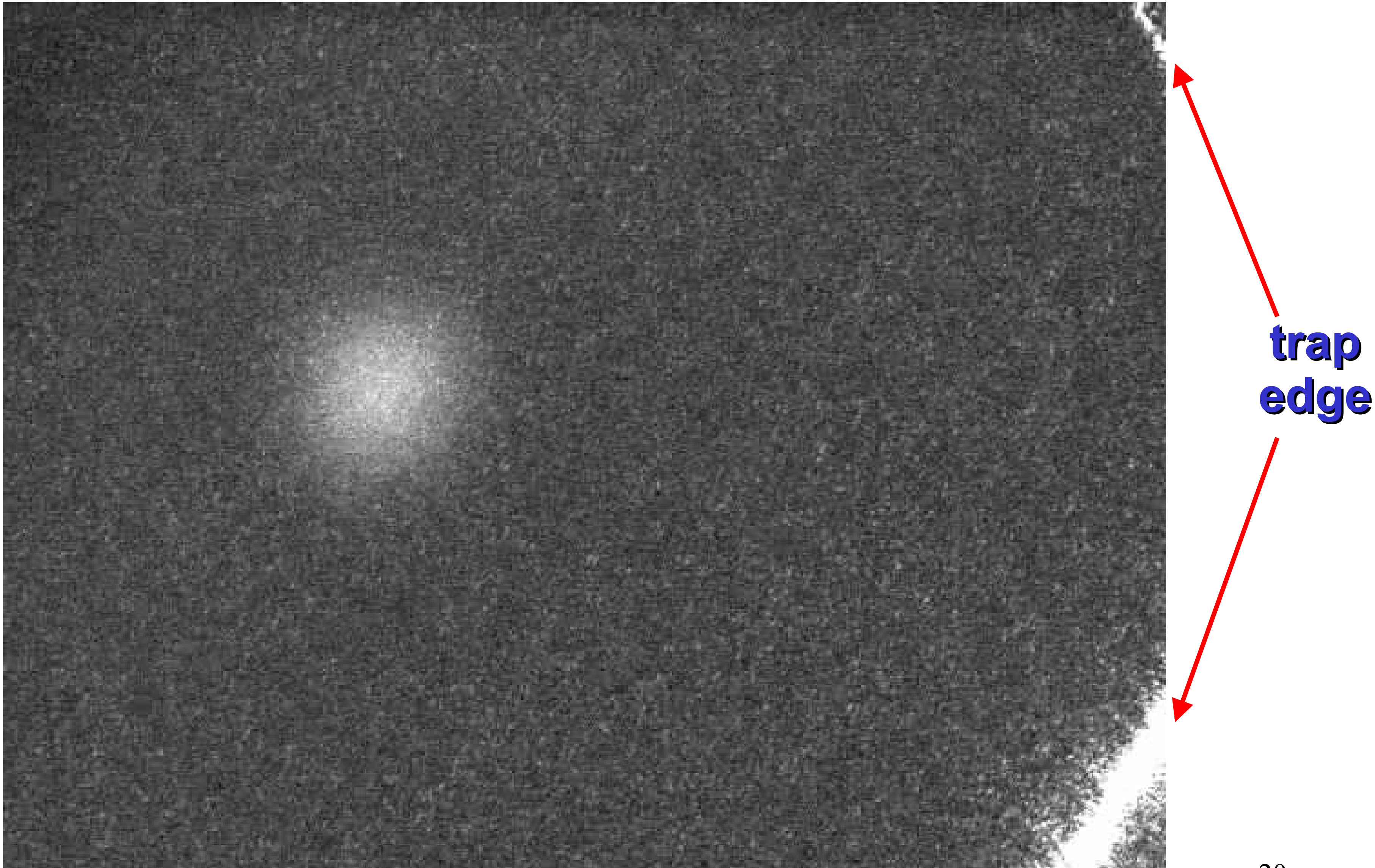
Xe can be injected while observing the ions

See if we can detect Ba^+ in Xe gas

EXO spectroscopy lab

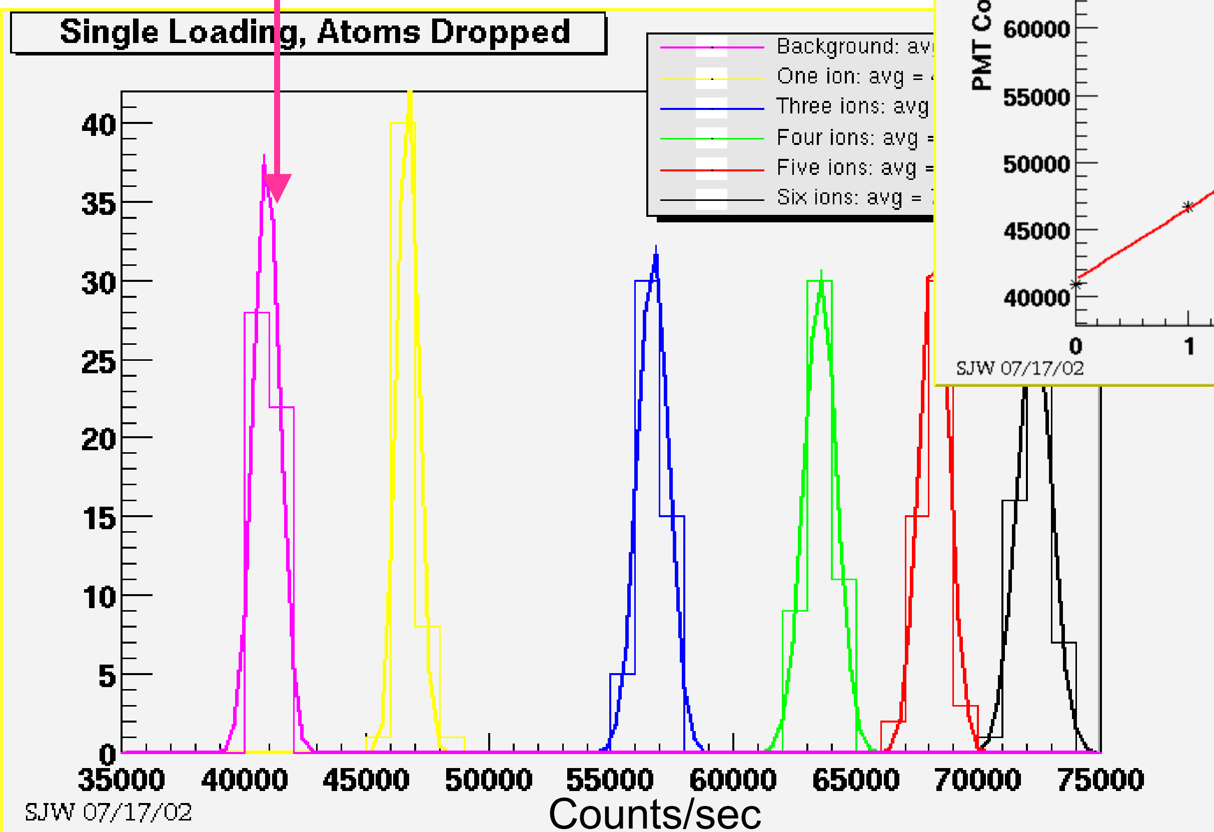


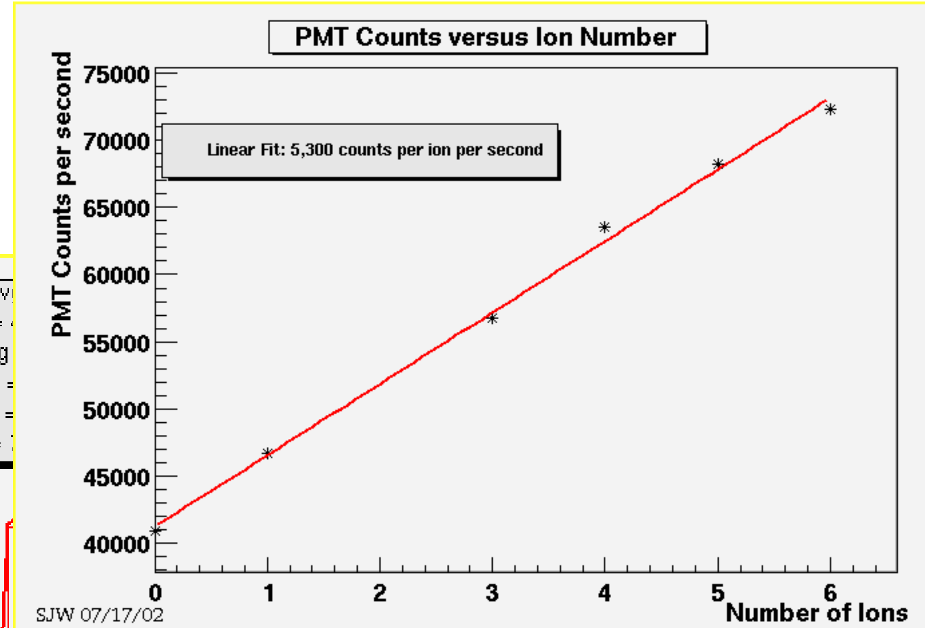
CCD image of multiple ions in the trap



Individual Ions…

Zero ion background





Now starting crucial experiments in Xe atmosphere

Some Ba^+ spectroscopy issues in Xe gas

How much P-state collisional broadening

- Ion traps usually work in **UHV** with e.m. field used to trap ions
- Ba^+ natural linewidth ~ 20MHz

Is the D state still metastable in gas?

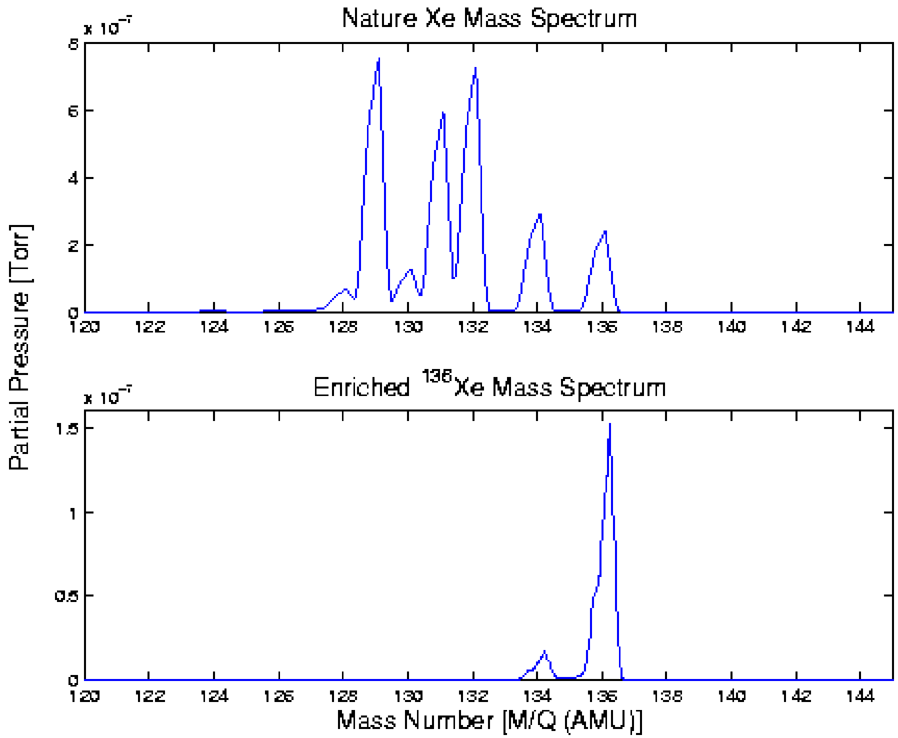
- At least we know that neutral Ba has 240ms D state in vacuum that retains same lifetime in 0.5 atm Ar *(Physical Review A 46 (1992) 2642)*

Are Ba^+ ions stable (in liquid and gas)?

- Lifetime in vacuum: forever
- Possibility of forming $(BaXe)^+$ due to high polarizability of Xe

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

First 100 kg test production completed in Apr '02



Isotope	Natl Xe	Enriched Xe
124	0.11	0.00
126	0.12	0.00
128	3.58	0.00
129	27.32	0.00
130	5.20	0.00
131	21.39	0.00
132	24.35	0.20
134	9.95	18.80
136	7.97	81.00

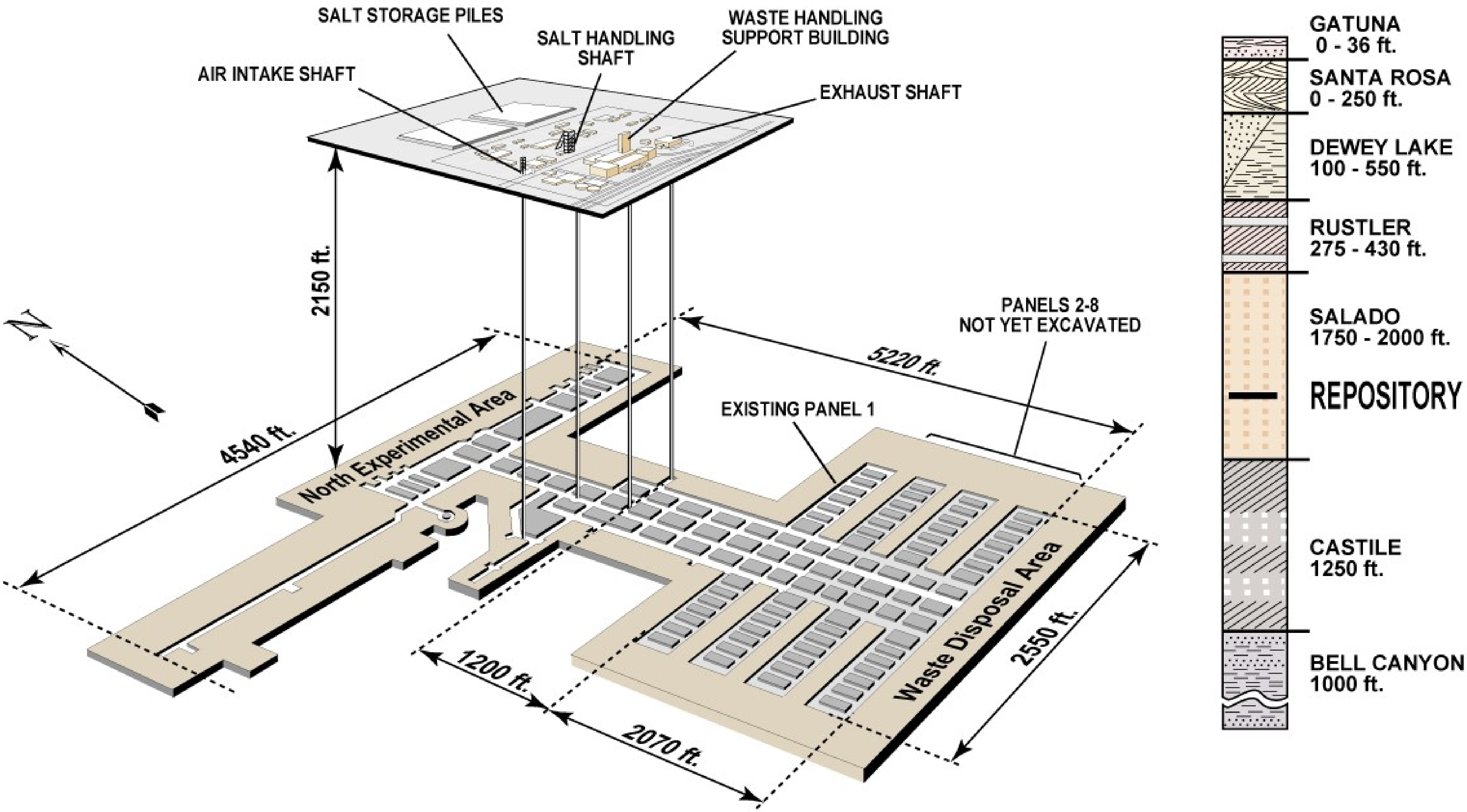
In natural sample $^{84}Kr/Xe$ measured to be $(4.4\pm1.5)\times10^{-7}$ (as expected)

In enriched sample cannot detect Kr: $^{84}Kr/Xe < 3.4\times10^{-7}$ at 90% C.L.

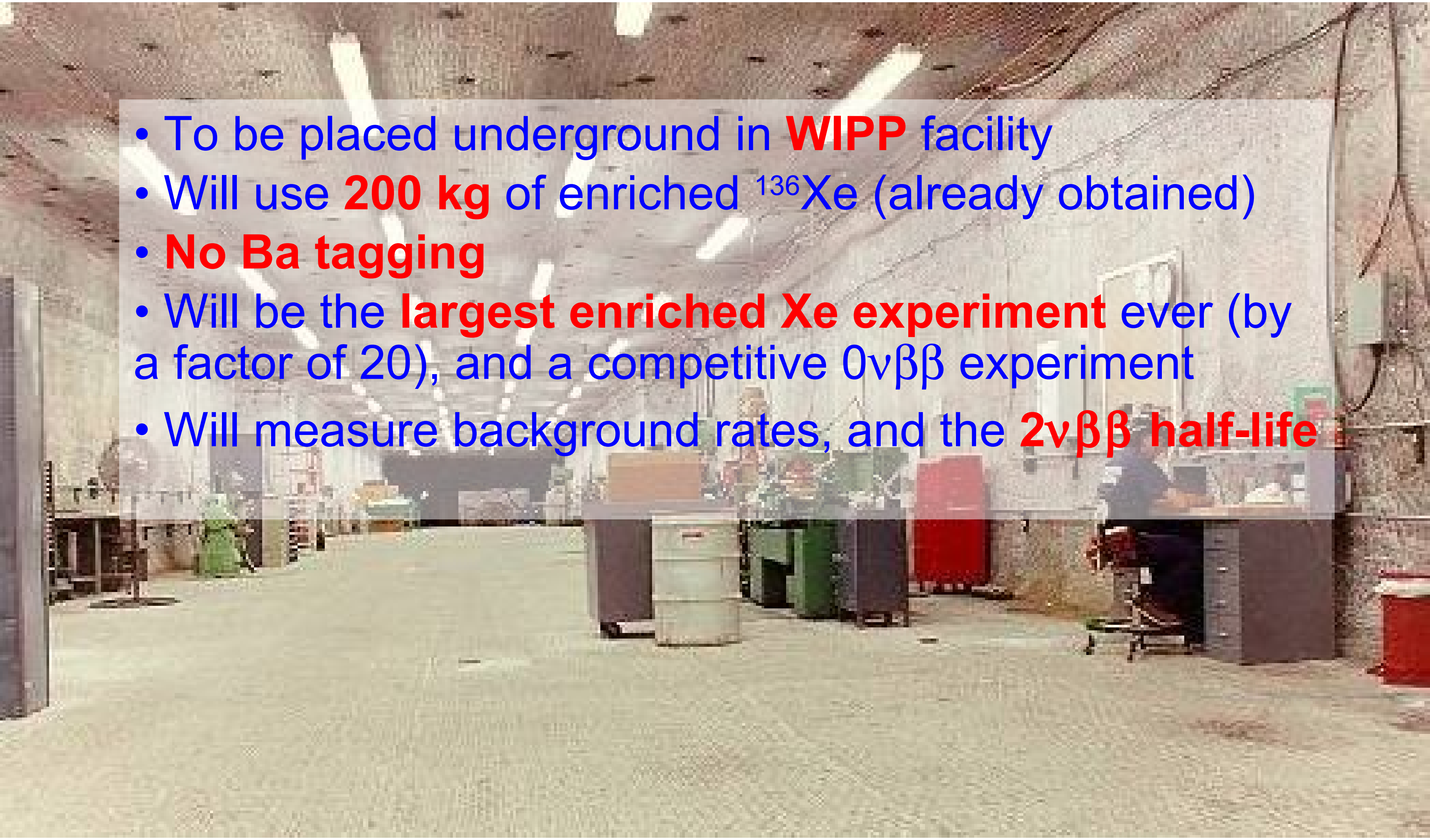
More sensitive measurements to be done on a better mass spectrometer

A 200 kg prototype detector is slated to be installed at DoE's Waste Isolation Pilot Plant (WIPP), Carlsbad NM

A salt mine to store radioactive waste…
…and perform low background physics experiments



Plans for an EXO prototype



- To be placed underground in **WIPP** facility
- Will use **200 kg** of enriched ^{136}Xe (already obtained)
- **No Ba tagging**
- Will be the **largest enriched Xe experiment** ever (by a factor of 20), and a competitive $0\nu\beta\beta$ experiment
- Will measure background rates, and the **$2\nu\beta\beta$ half-life**

Progress towards 200 kg EXO Prototype

- High Xe purity achieved (millisecond e^- drift lifetimes)
- Material testing (chemical and radiopurity) in progress
- Light collection studies underway (PMTs and APDs)
- Testing a two phase TPC
- GEANT4 simulations underway (background studies, shielding, and detector geometry optimization)
- WIPP experimental facilities under design

- **Can we achieve sufficient energy resolution in the liquid xenon? *Surpassed 2% @ $Q_{\beta\beta}$***
- **Can we extract ions from the liquid Xe with a probe? *Done!***
- **Can we release the ions from the probe? *Testing underway***
- **Can we perform Ba^+ spectroscopy in a Xe buffer gas? *Testing underway***
- **Pilot enrichment of ^{136}Xe *Done!***
- **200kg prototype construction *Currently under initial construction***
- ***Gas phase Currently under investigation***

Some projections

Assuming that the Xe chamber + Ba tagging eliminate all radioactive background...

Isotope	Det mass (kg)	Enrich. (%)	Eff. (%)	Measur. time (yr)	Background	$T_{1/2}^{0\nu\beta\beta}$ (yr)	$\langle m_n \rangle$ QRPA	(eV)
NSM								
$^{136}Xe^{*}$	1000	80	70	5	0 + 1.8 events	8.3×10^{26}	0.051	0.14
$^{136}Xe^{**}$	10000	80	70	10	0 + 5.5 events	1.3×10^{28}	0.013	0.037

$^{*}\sigma(E)/E = 2.8\%$

$^{**}\ \sigma(E)/E = 2.0\%$ *(achieved in our lab)*

Radioactivity backgrounds

$2\nu\beta\beta$ background