Enriched Xenon Observatory for double beta decay

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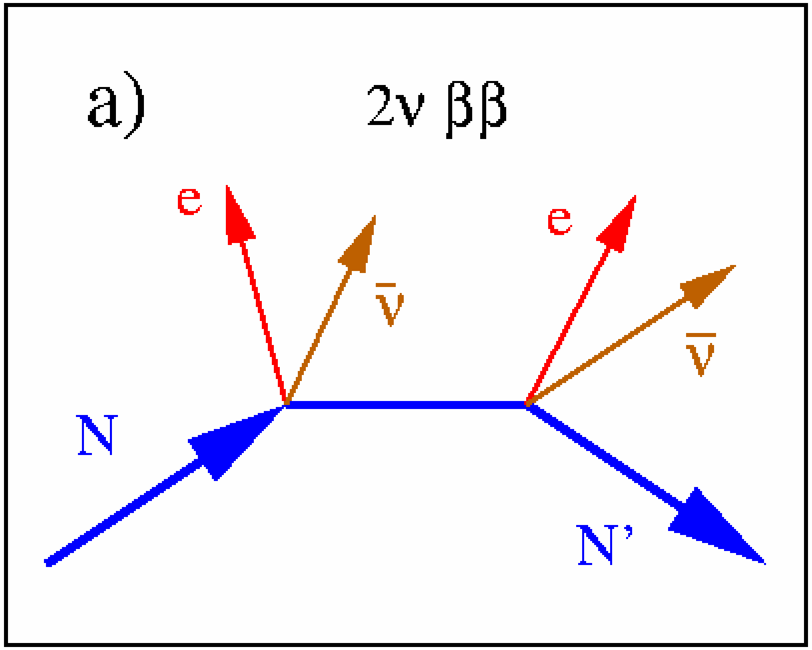
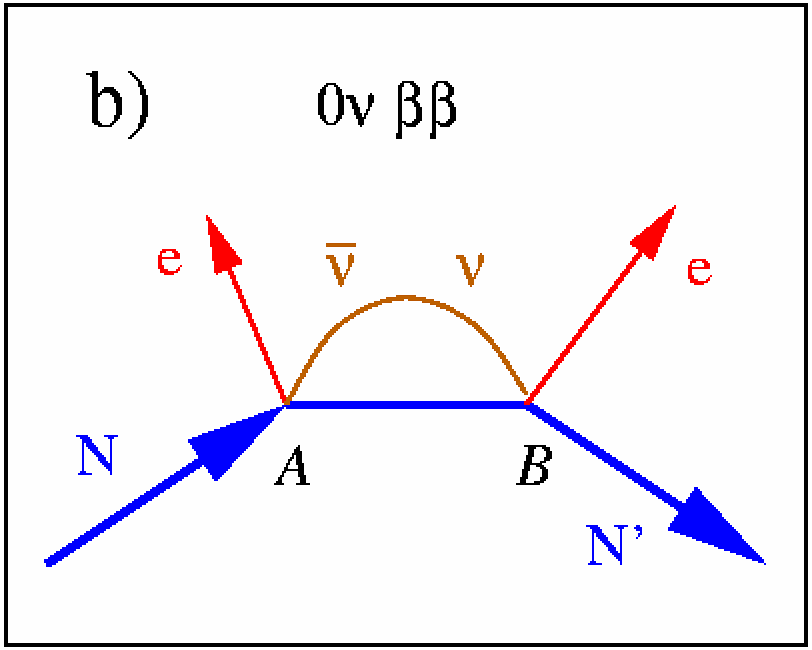
There are two varieties of ββ decay

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

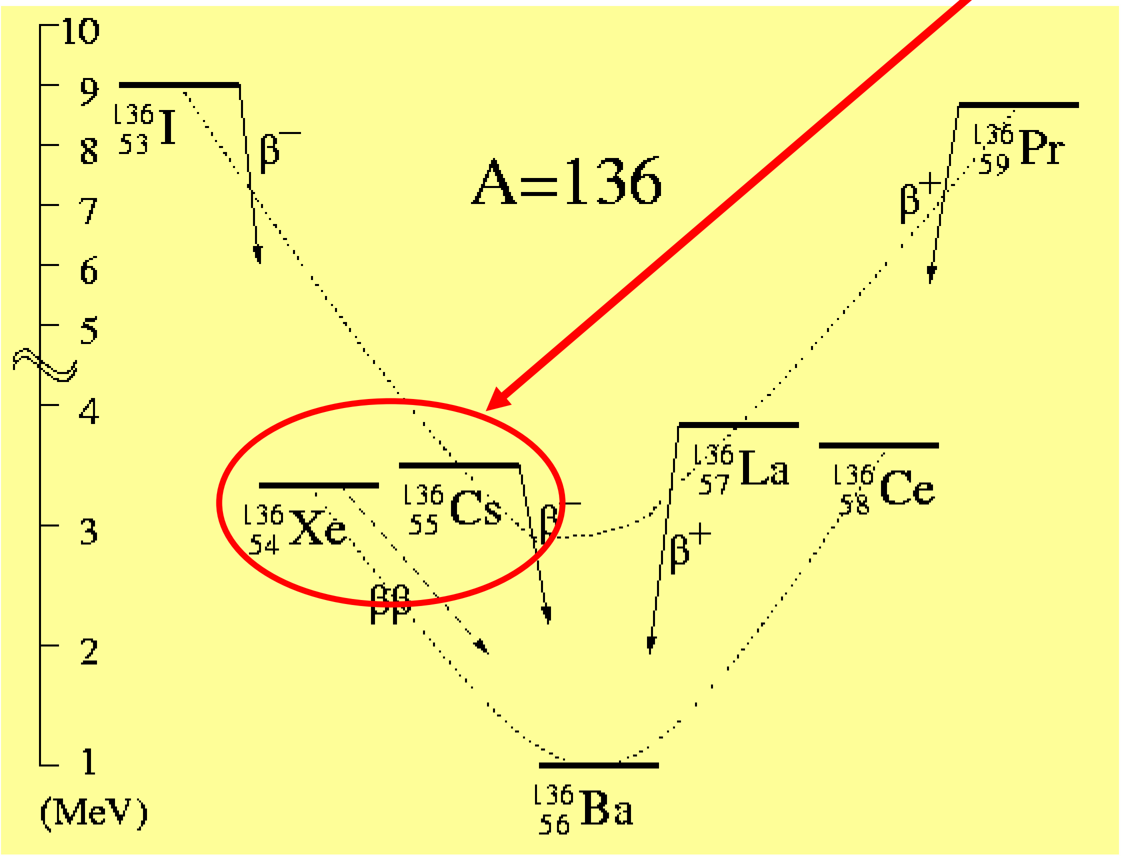
0ν mode: a hypothetical process can happen only if:
- $M_\nu \neq 0$
- $\bar{\nu} = \nu$

Since helicity has to "flip"





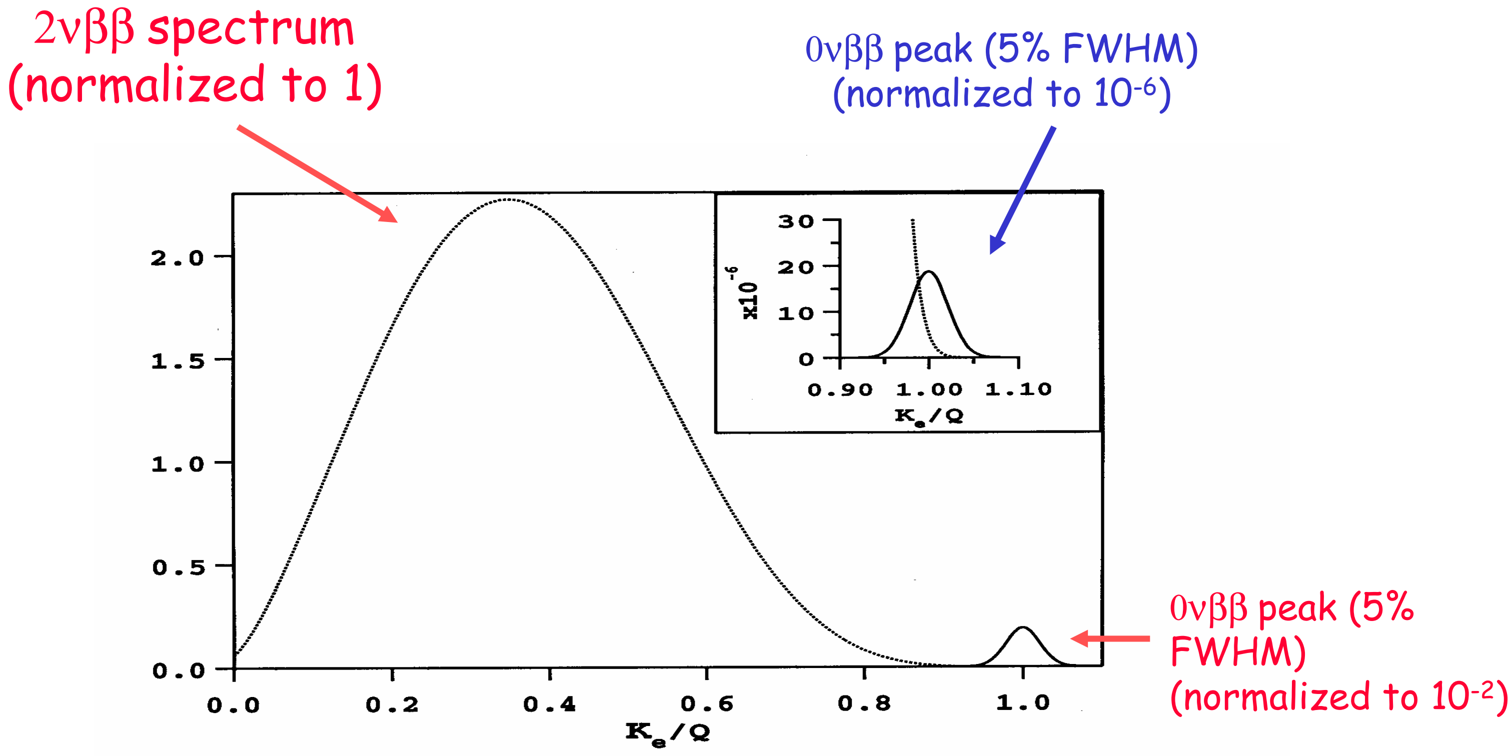
$\beta\beta$ always a second order process: only detectable if first order β decay is energetically forbidden



$2\nu\beta\beta$ has been observed in a number of cases

$0\nu\beta\beta$ has never been observed

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



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

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) QRPA	NSM
^{48}Ca			$9.5 \cdot 10^{21}$ (76%CL)		
^{76}Ge	Ge diode*	~30	$1.9 \cdot 10^{25}$ (90%CL)	0.35	1.0
^{82}Se			$2.7 \cdot 10^{22}$ (68%CL)		
^{100}Mo			$5.2 \cdot 10^{22}$ (68%CL)		
^{116}Cd			$7.0 \cdot 10^{22}$ (90%CL)		
^{130}Te	TeO_2 cryo	~1	$1.4 \cdot 10^{23}$ (90%CL)	1.1	2.6
^{136}Xe	Xe TPC	~8	$4.4 \cdot 10^{23}$ (90%CL)	1.8	5.2
^{150}Nd			$1.2 \cdot 10^{21}$ (90%CL)		

Main experimental problems

1 Very large fiducial mass (tons)

→ (except for Te) need isotopic enrichment

2 Reduce and control backgrounds in qualitatively new ways

→ bkgnd for Ge ~0.3 ev/kg yr FWHM

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

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

1 is essential

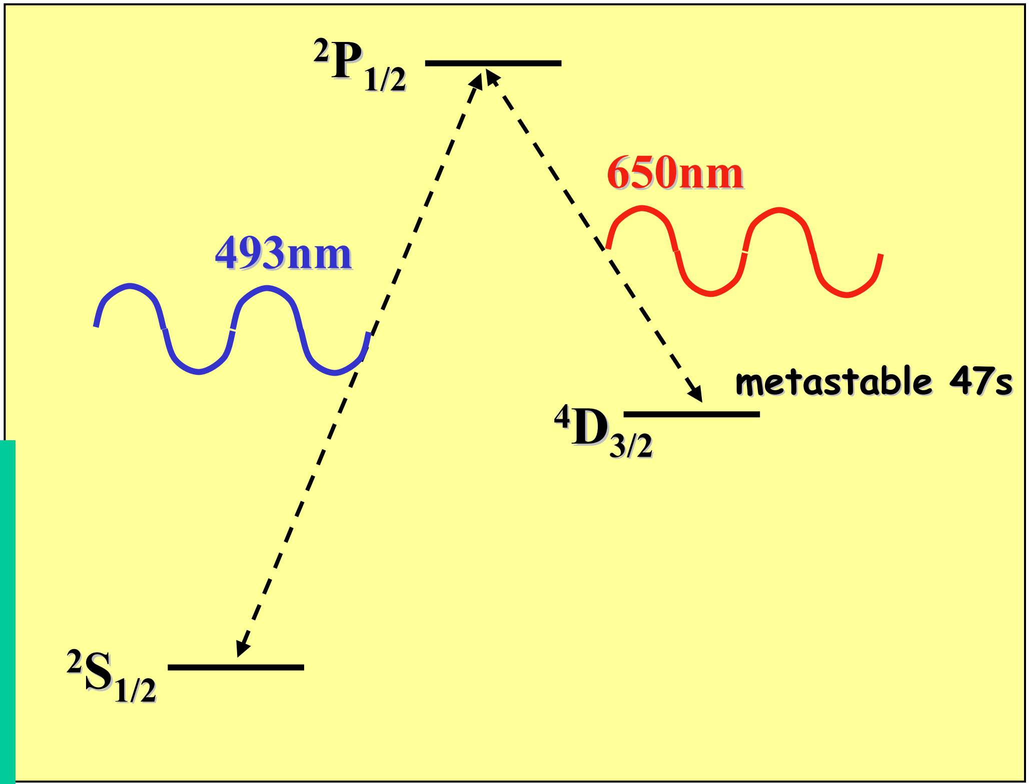
1 without 2 is a waste

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 $\propto \Delta m$. 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
- Huge background reduction

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

Energy resolution is still an all-important parameter to disentangle the $0\nu\beta\beta$ mode from $2\nu\beta\beta$

Assume an "asymptotic" fiducial mass of 10 tons of ^{136}Xe at 90%

Mainly going in light bulbs and satellite propulsion

A somewhat natural scale:

- World production of Xe is ~30 ton/yr
- Detector size
- $2*10^3$ size increase: good match to the 10^{-2} eV mass region… real chance to make an important discovery

Assuming that the Xe chamber + Ba tagging reduce to 0 all radioactive background...

Isotope	Det mass (kg)	Enrich. (%)	Eff. (%)	Measur. time (yr)	Background	$T_{1/2}^{0\nu\beta\beta}$ (yr)	$\langle m_\nu \rangle$ (eV) QRPA	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% R.Luescher et al. Phys. Lett. B434 (1998) 407
** $\sigma(E)/E$ = 2.0% (<1% observed in our test chamber)

The meV region is within reach !

~200-15 k $2\nu\beta\beta$ events/year expected in the 100 kg prototype if backgrounds are decent should be able to measure this or put the theoretical model in serious trouble

Both LXe and GXe options open:

Disadvantages:

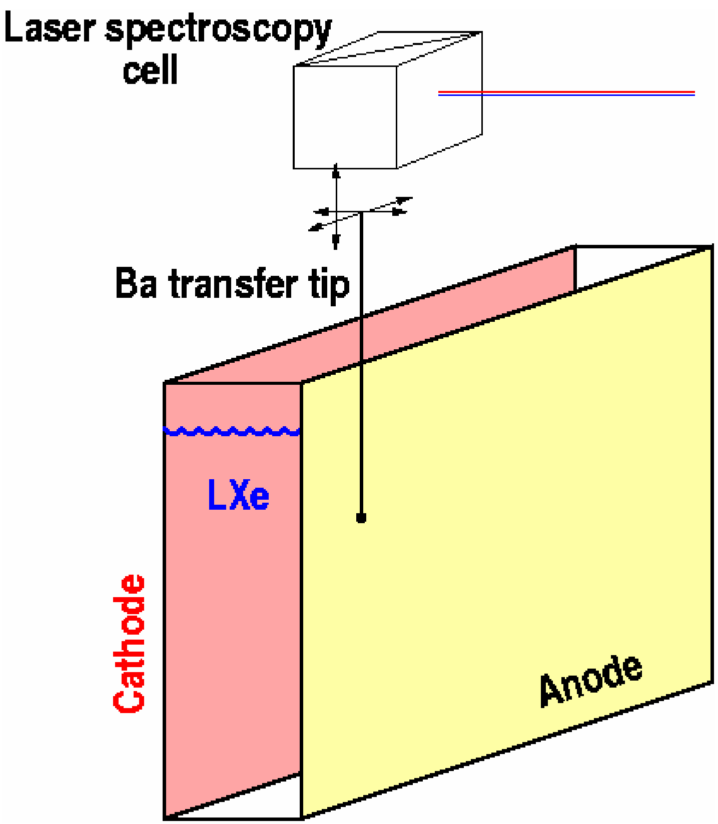
- No information from tracking
- Cannot “bring laser to the event”

Advantages:

- No high pressure
- Table top
- Ba can be analyzed at low density
- Ba^{++} neutralization easier

Unknowns:

- Is energy resolution sufficient ?
- Ba extraction with good efficiency

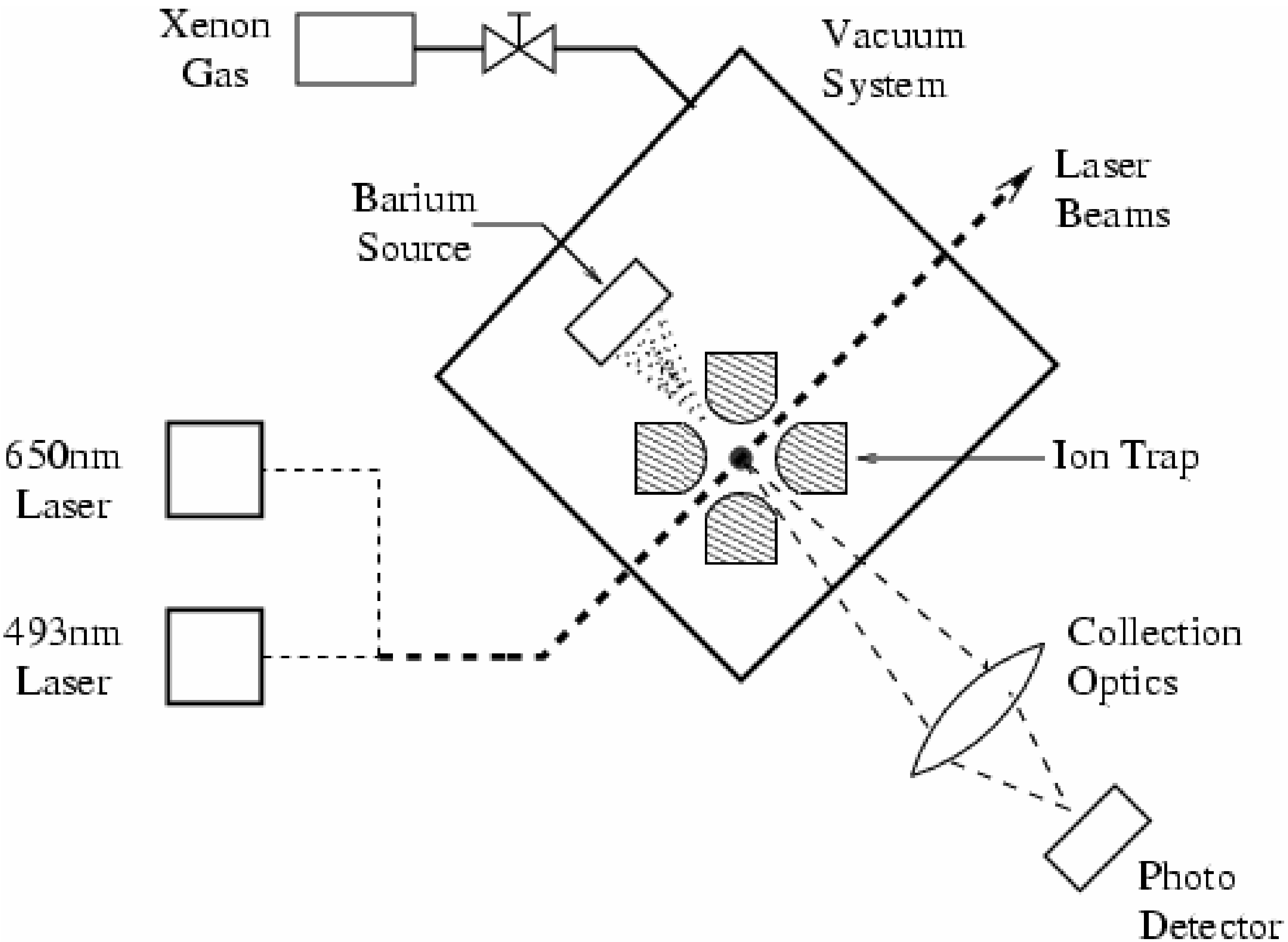


- Tip is triggered by LXe readout
- Biased – to grab and + to release
- Special care to ensure Ba release
    - Xe ice tip coating
    - Hot Ta tip
    - Atomic Force Microscope tip
- Ba analyzed in a low pressure spectroscopy cell

LXe option R&D roadmap
(GXe R&D started at ITEP and Neuchatel)

- Single ion Ba^+ tagging at different residual Xe pressures ✔
- LXe energy resolution ✔✔
- Xe purification for long e^- lifetime and radio-impurities ✔
- Ba ion lifetime and grabbing from LXe ✔
- Procurement/qualification of low background materials ✔
- Isotopic enrichment of ^{136}Xe ✔✔
- Construction/operation at WIPP of a 100 kg ^{136}Xe prototype detector ✔

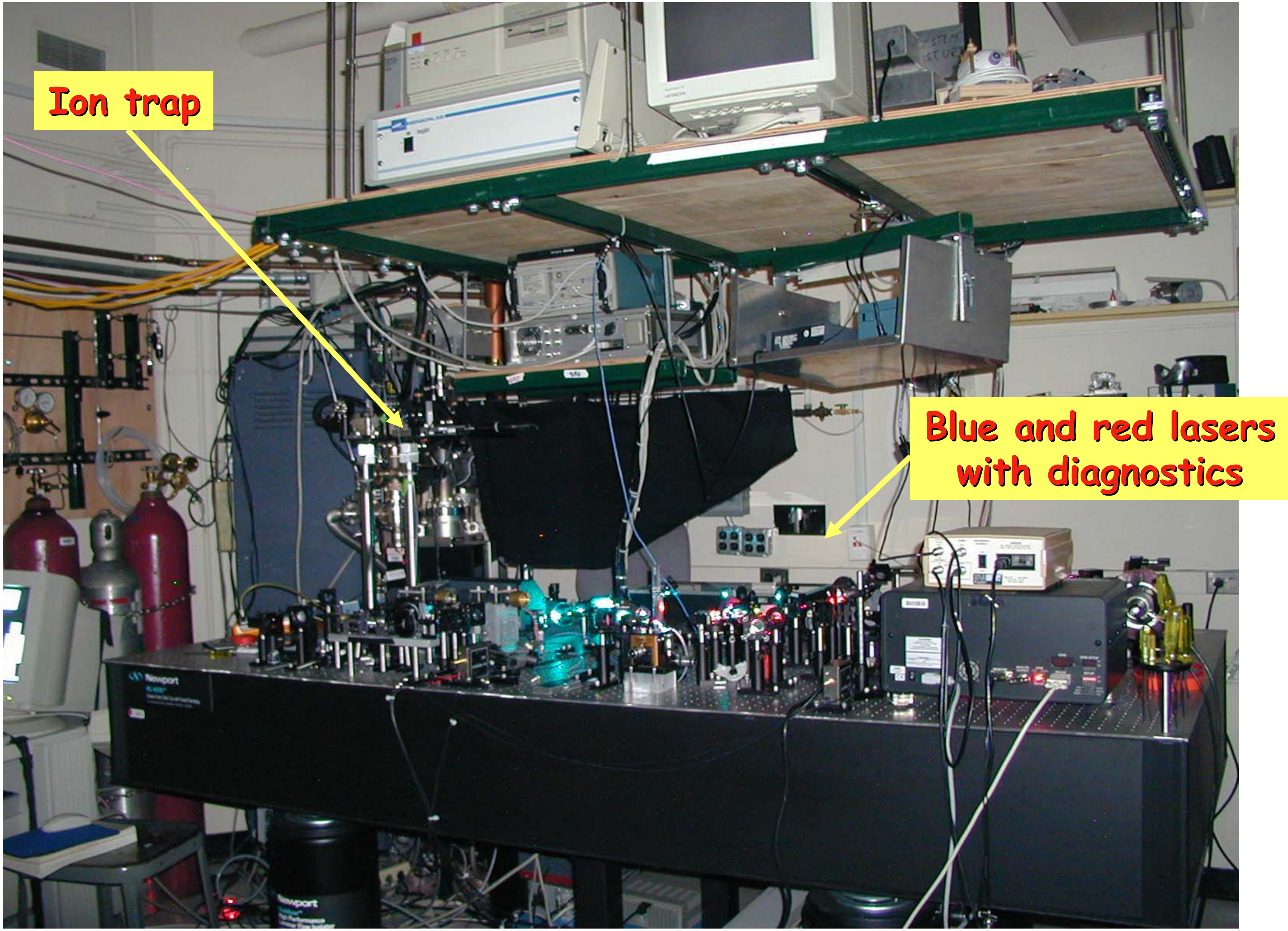
Test UHV/high pressure ion trap



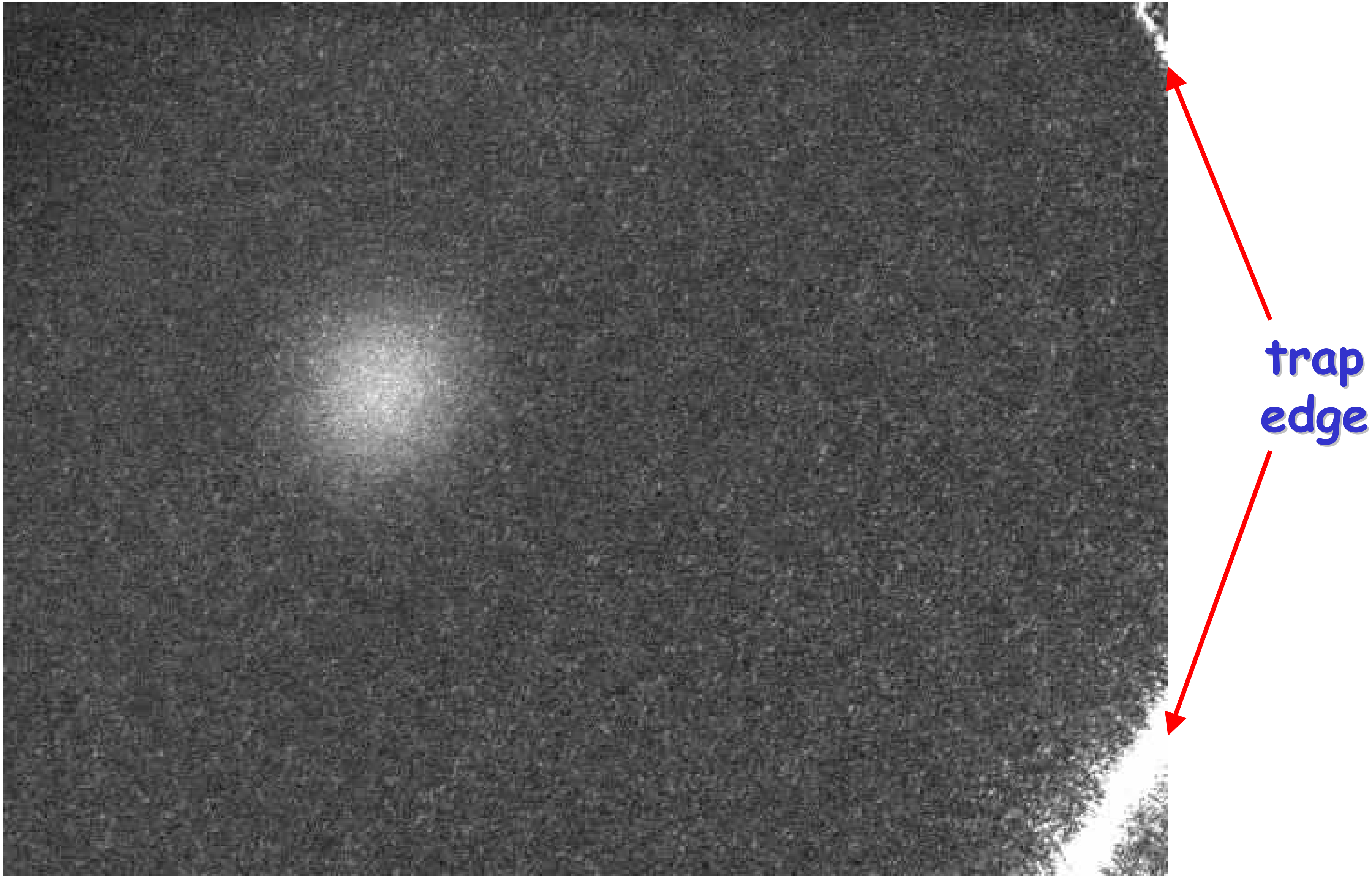
RF quadrupole trap loaded in UHV from a Ba dispenser and e-beam ionizer

Xe can be injected while observing the ions

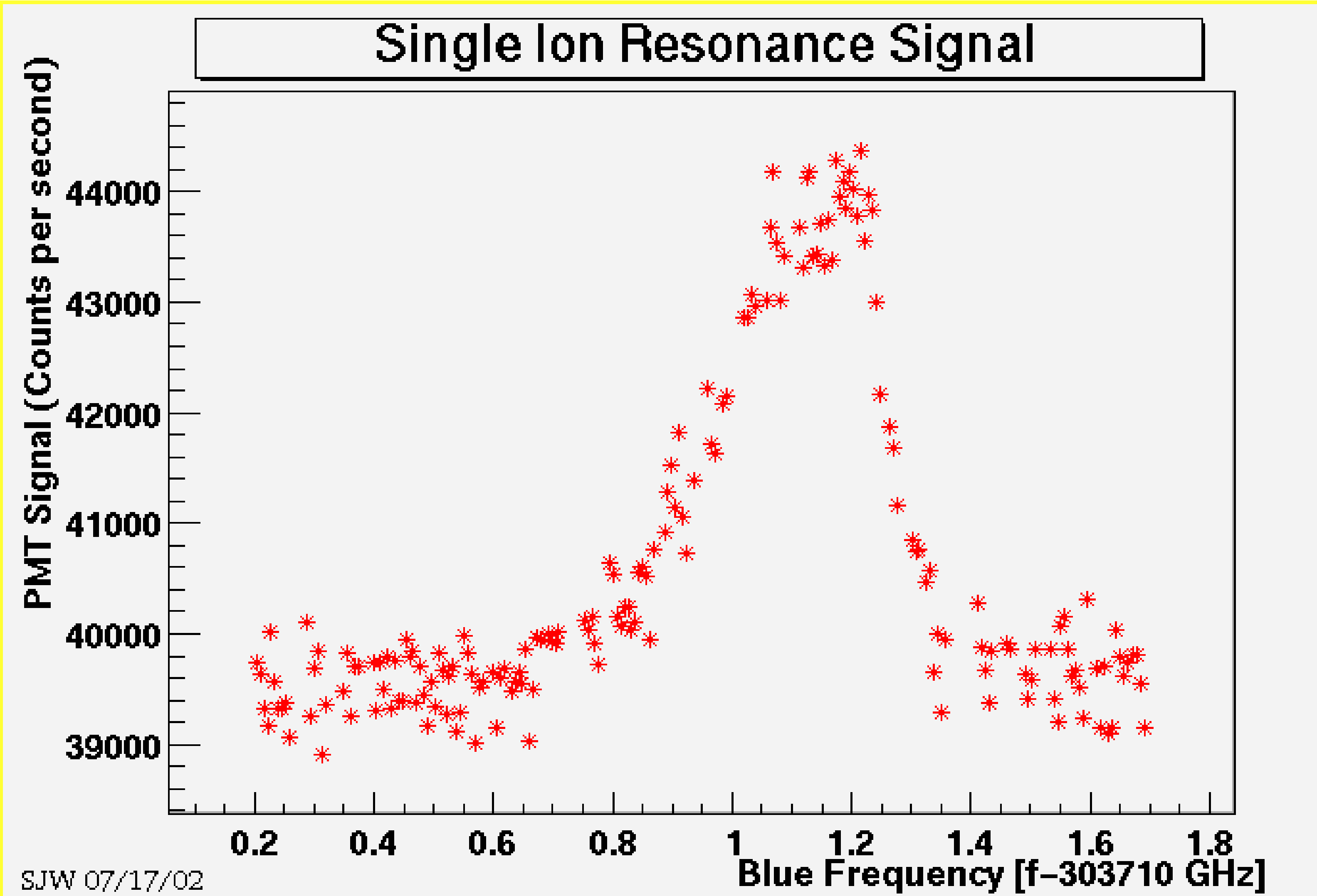
EXO spectroscopy lab



CCD image of an ion in the trap

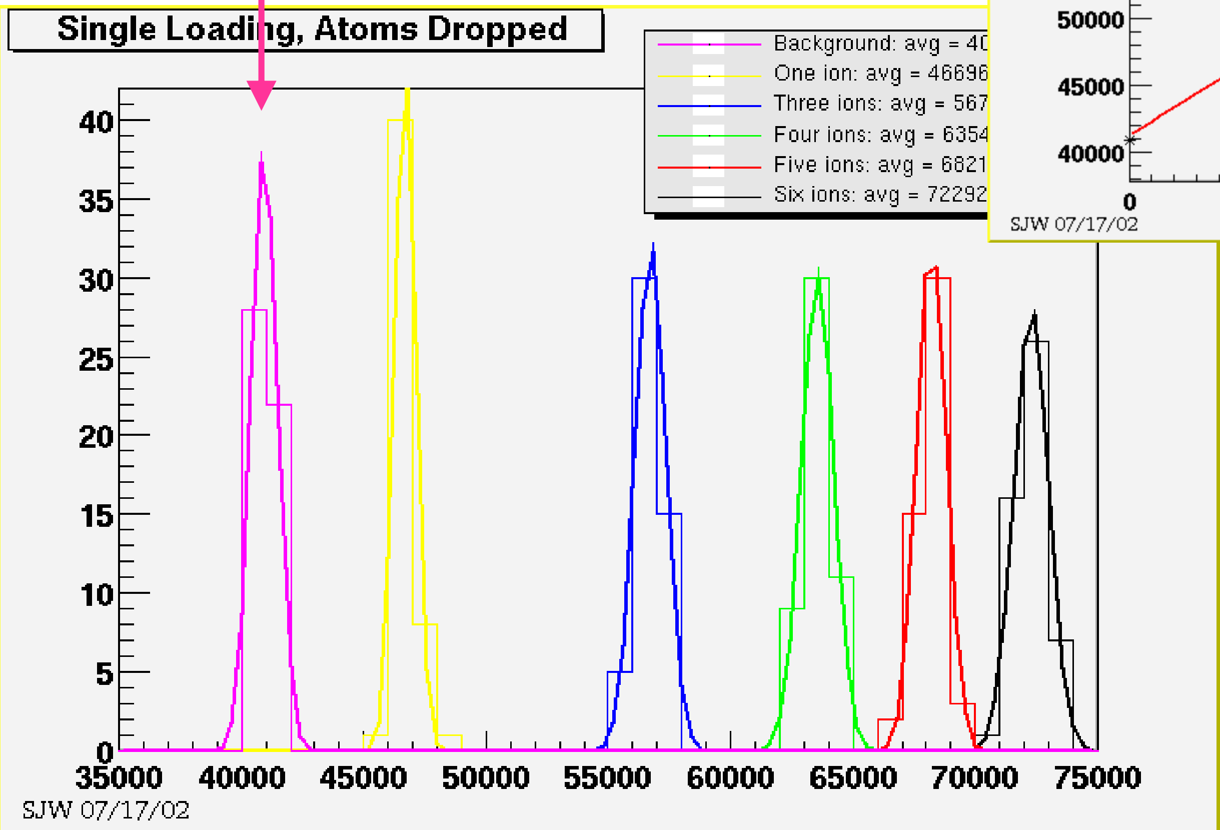


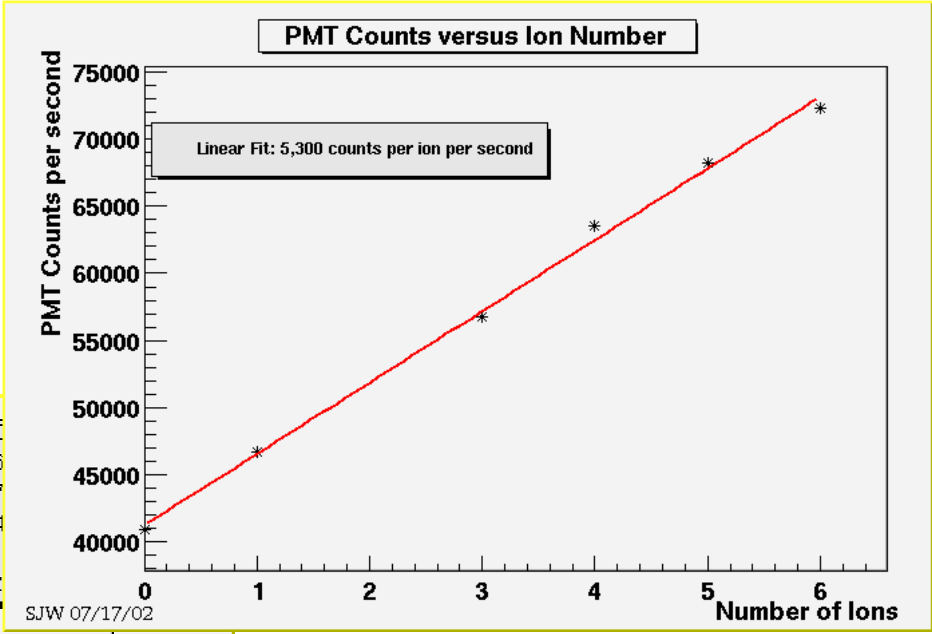
Using a PMT one can observe the signal resonance for a single ion



Indeed we are talking about single ions: one can load the trap with multiple ions and then observe the signal intensity as ions are dropped one by one…

Zero ion background

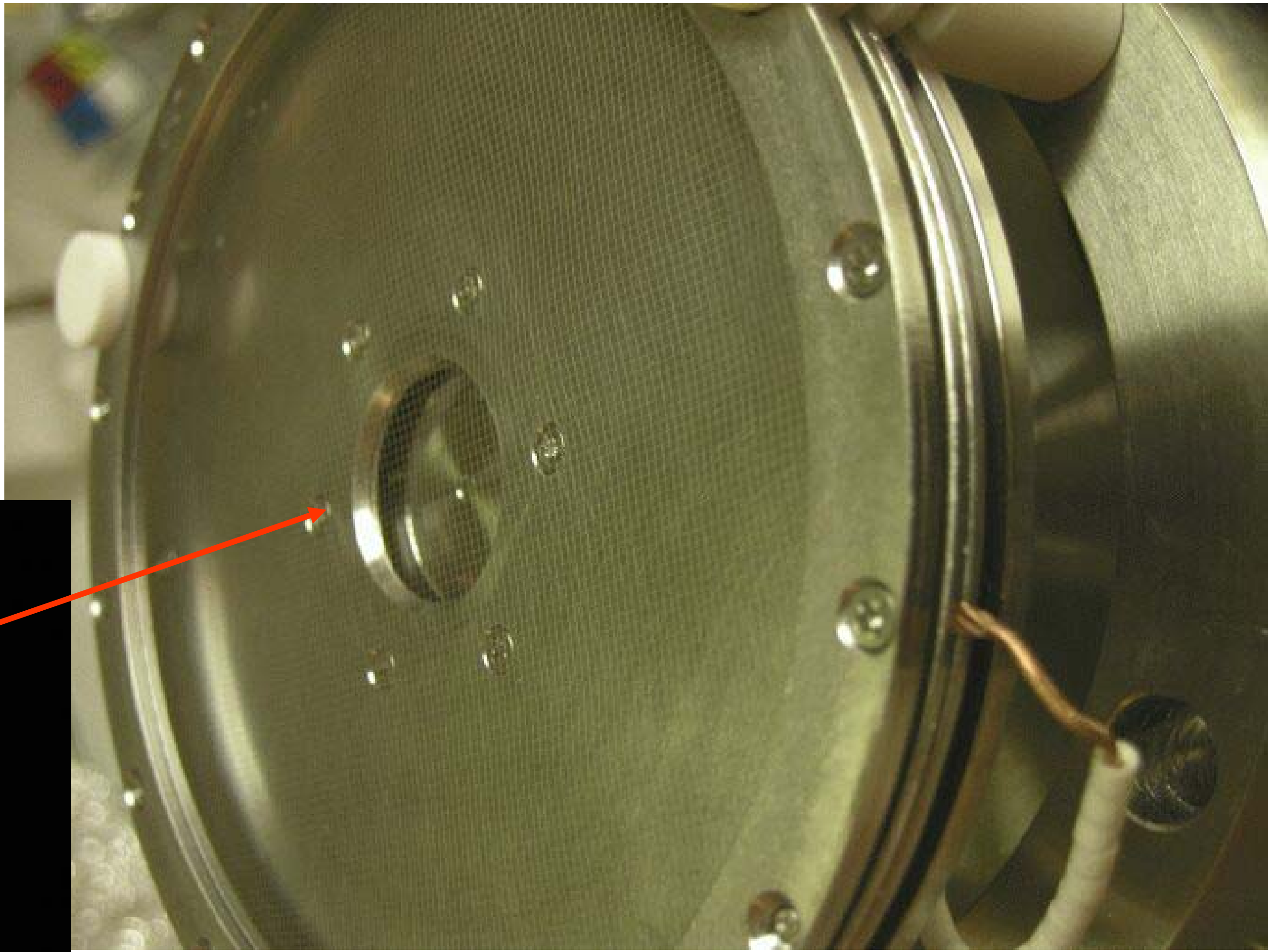


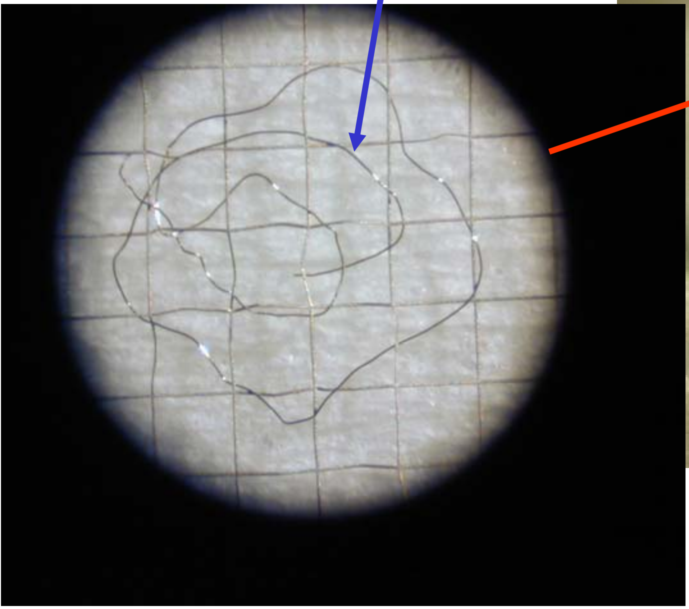


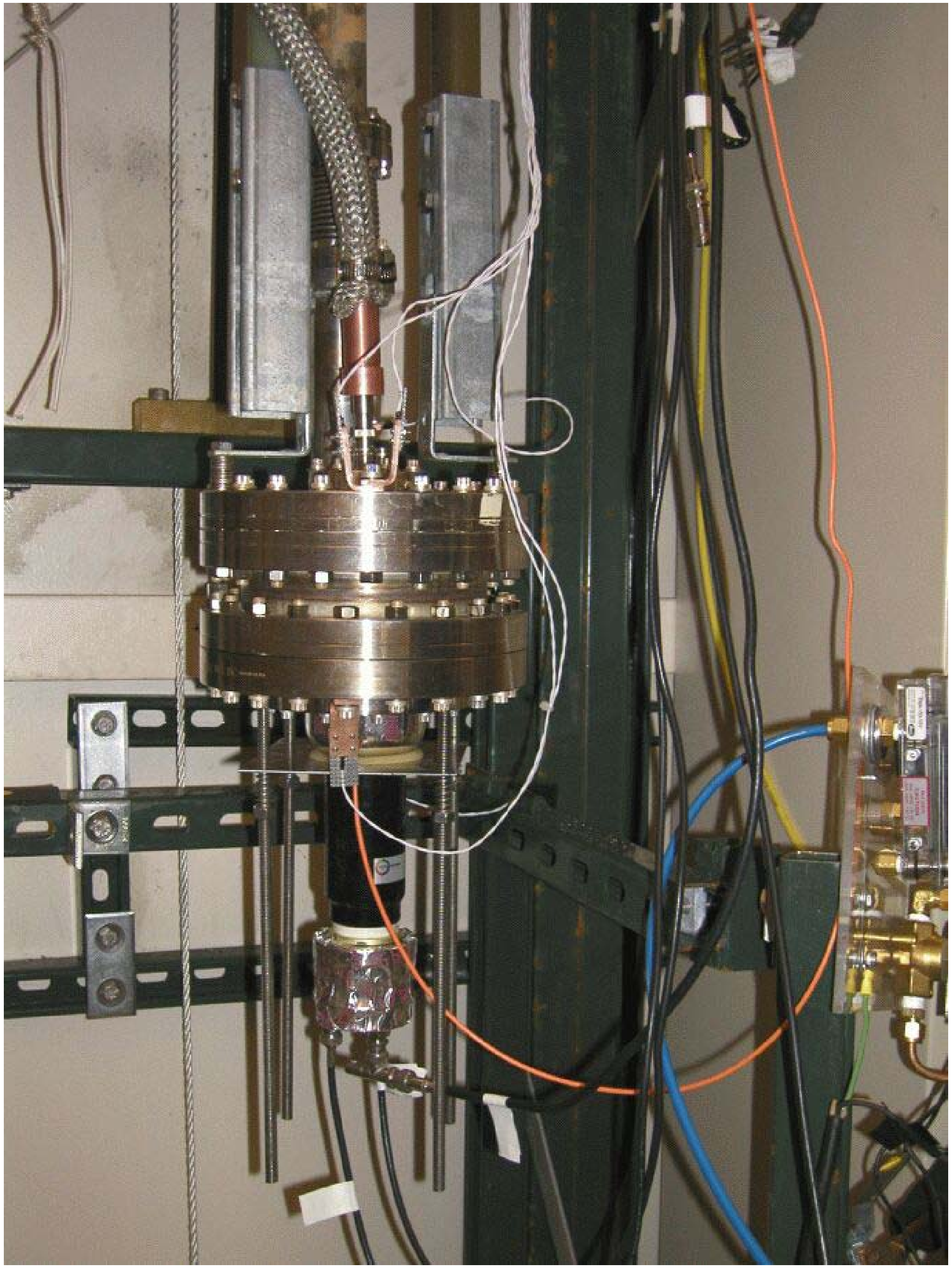
Now starting to experiment same thing in Xe atmosphere

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

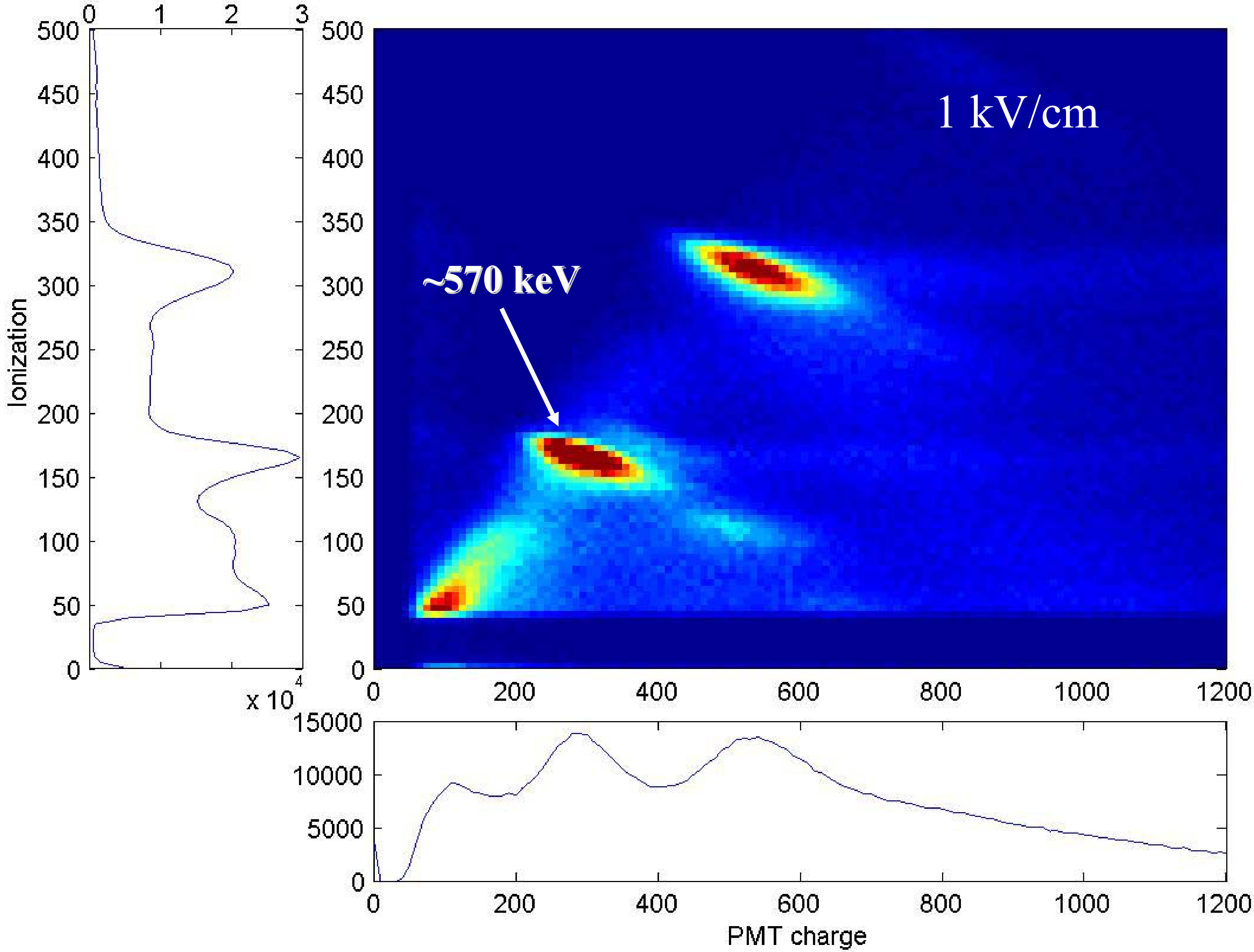
Electron/gamma source ^{208}Bi needs to be very small to avoid self shadowing (20μm plated wire)



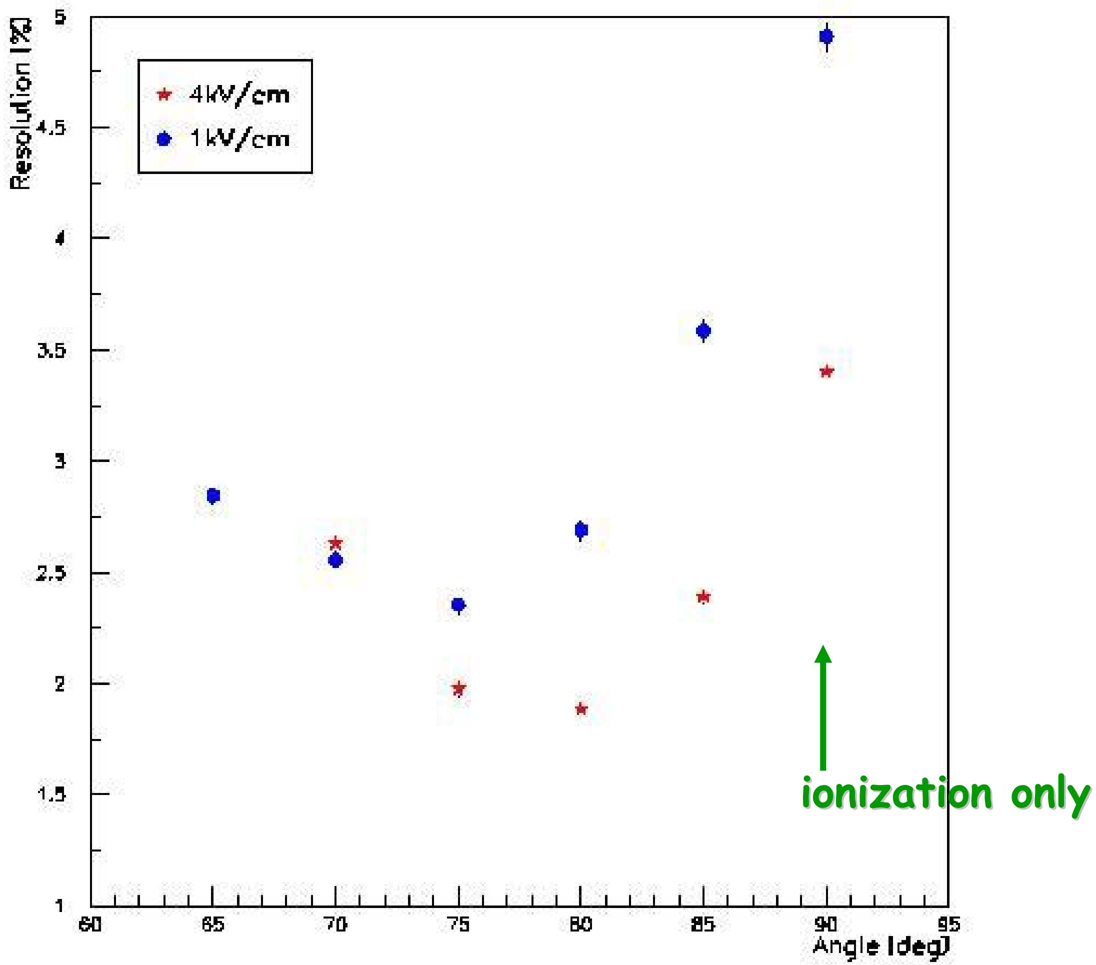




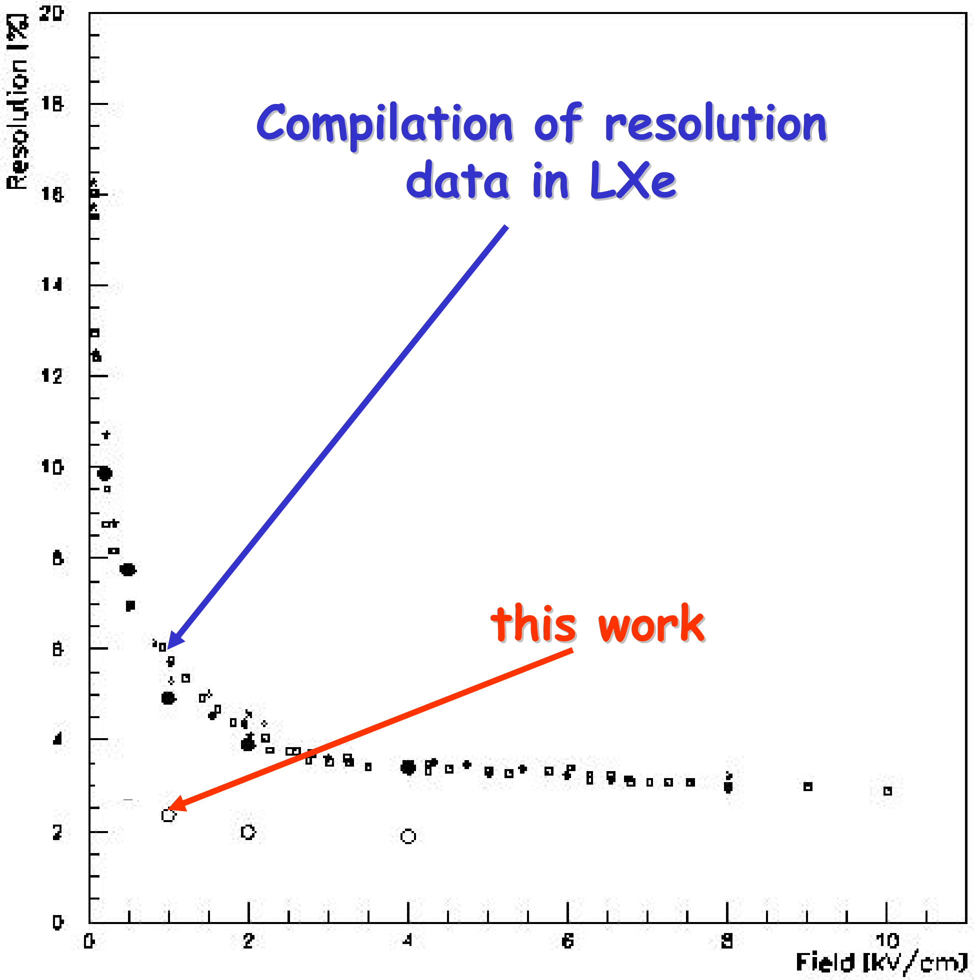
Found a clear (anti)correlation between ionization and scintillation



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

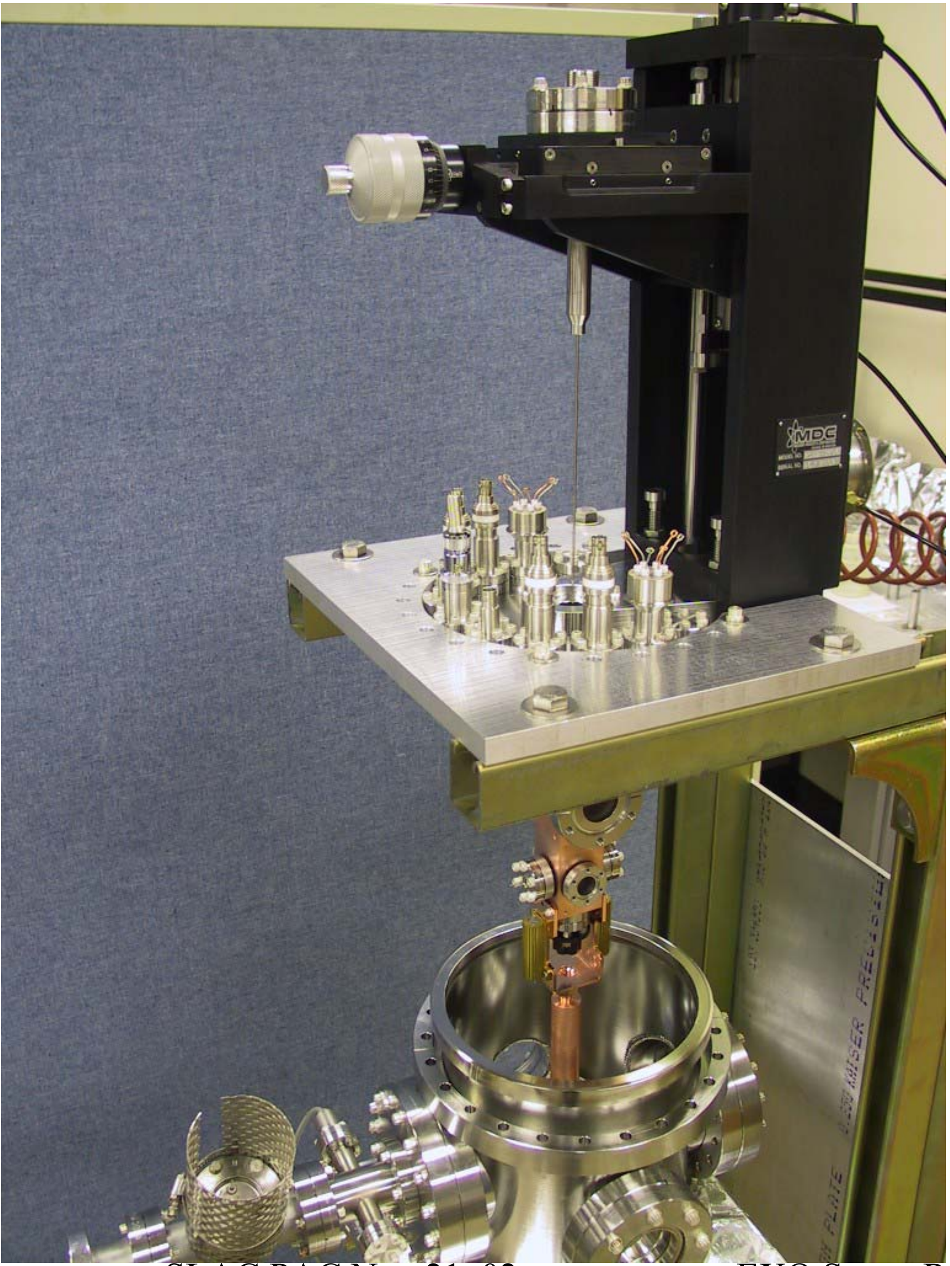


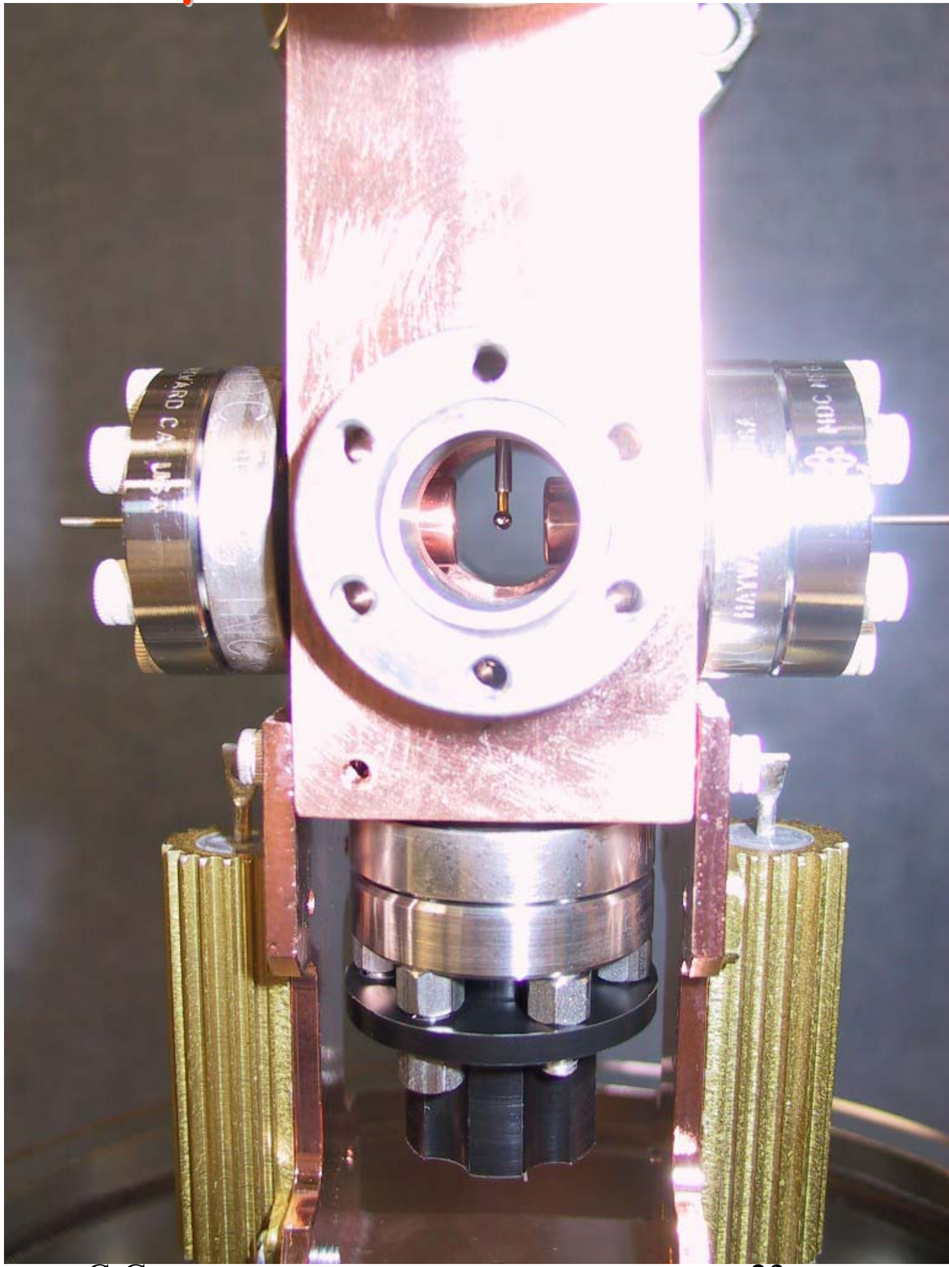
This can be used to improve the resolution in LXe and separate the 2ν from the 0ν modes



...important not only for EXO but also for industrial/medical applications where the high density of LXe make it a desirable medium

Ba extraction test system





Ion grabbing test uses a ^{222}Ra source to simulate Ba

Ba and Ra have similar chemistry

Atom	Ionization potential I (eV)	II
Sr	5.695	11.030
Ba	5.2117	10.004
Ra	5.279	10.147

Pa produced in a cyclotron
$^{230}Th + p \rightarrow {}^{230}Pa + 3n$

^{230}Pa (17.4d)

EC 91.6% → ^{230}Th (8*10^{4}yr)

8.4% β → ^{230}U (20.8d)

thin source
Th recoils out

α 5.99MeV → ^{226}Th (30.5min)

α 6.45MeV → ^{222}Ra (38s)

collect on the tip

α 6.68MeV → ^{218}Rn (35ms)

α 7.26MeV → ^{214}Po (164ms)

α 7.83MeV → ^{210}Pb (22yr)

very specific signature

^{230}U (20.8d)

α 5.99MeV

^{226}Th (30.5min)

α 6.45MeV

^{222}Ra (38s)

α 6.68MeV

^{218}Rn (35ms)

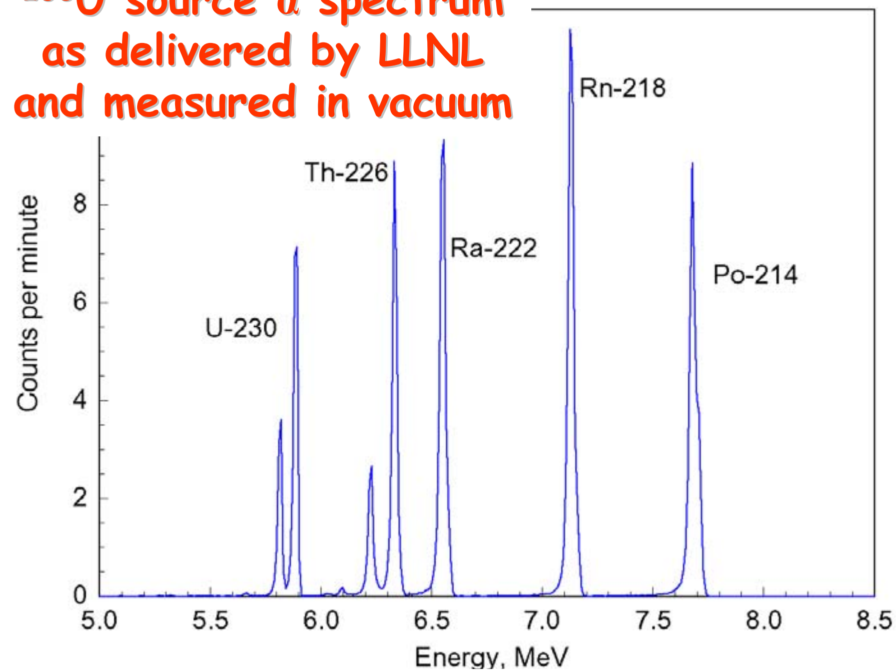
α 7.26MeV

^{214}Po (164ms)

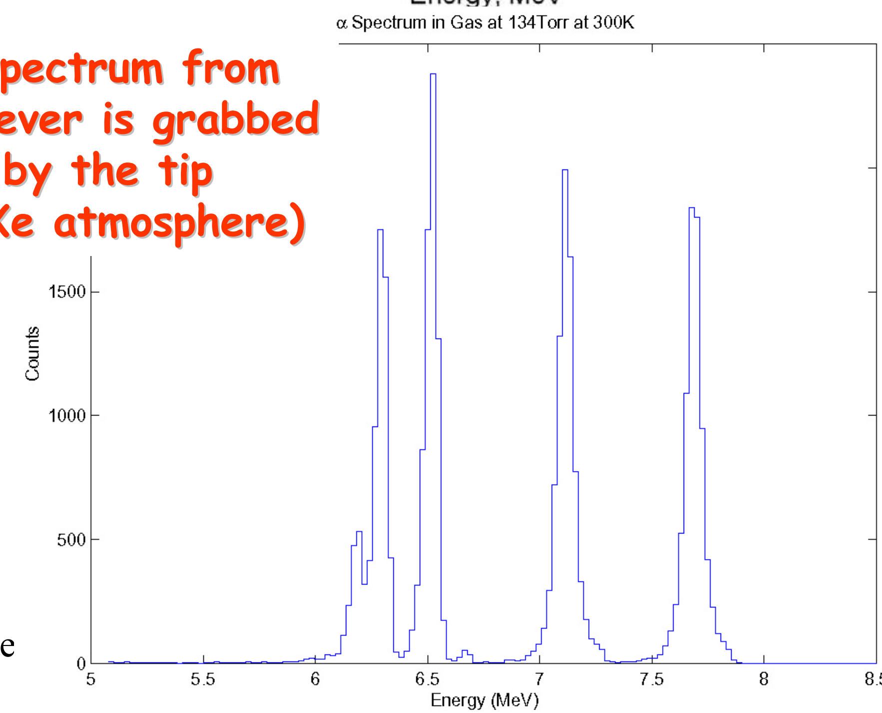
α 7.83MeV

^{210}Pb (22yr)

^{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)



Initial Ra ion grabbing successful

^{230}U (20.8d)

α 5.99MeV

^{226}Th (30.5min)

α 6.45MeV

^{222}Ra (38s)

α 6.68MeV

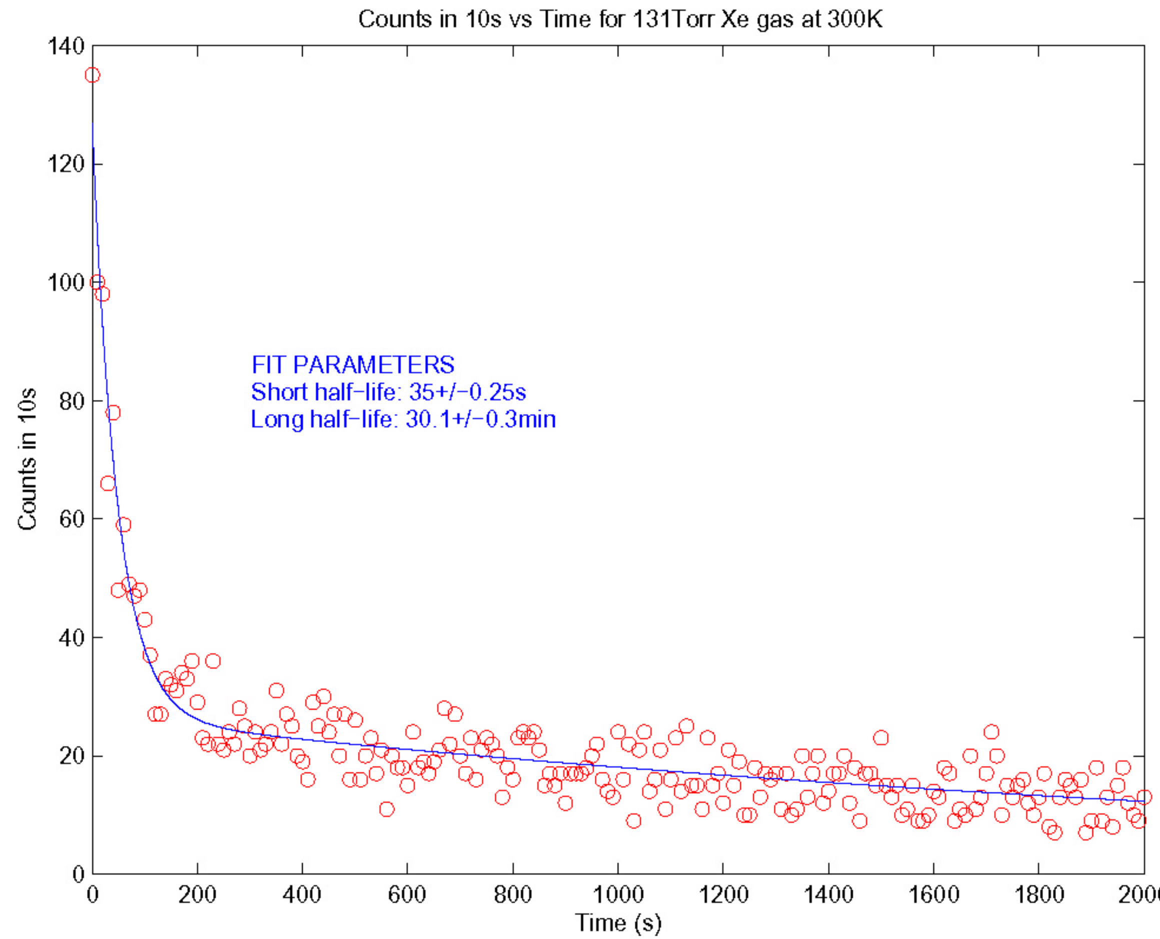
^{218}Rn (35ms)

α 7.26MeV

^{214}Po (164ms)

α 7.83MeV

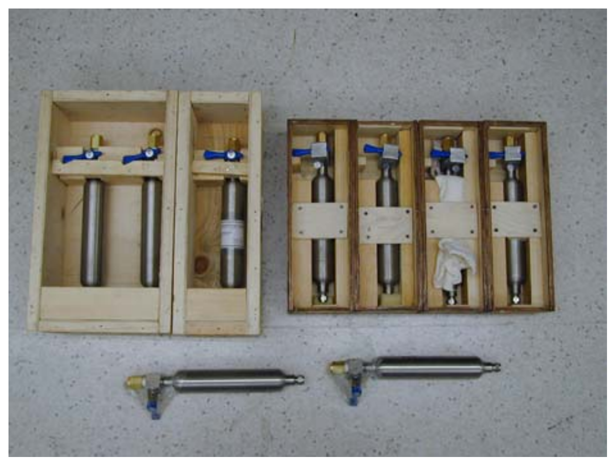
^{210}Pb (22yr)



Test enrichment

Isotope	Natl Xe	Enriched Xe
124	0.11	0.000
126	0.12	0.000
128	3.58	0.000
129	27.32	0.005
130	5.20	0.001
131	21.39	0.007
132	24.35	0.079
134	9.95	10.381
136	7.97	89.527

Russia has enough production capacity to process 100 ton Xe and extract 10 ton ^{136}Xe in 3 years



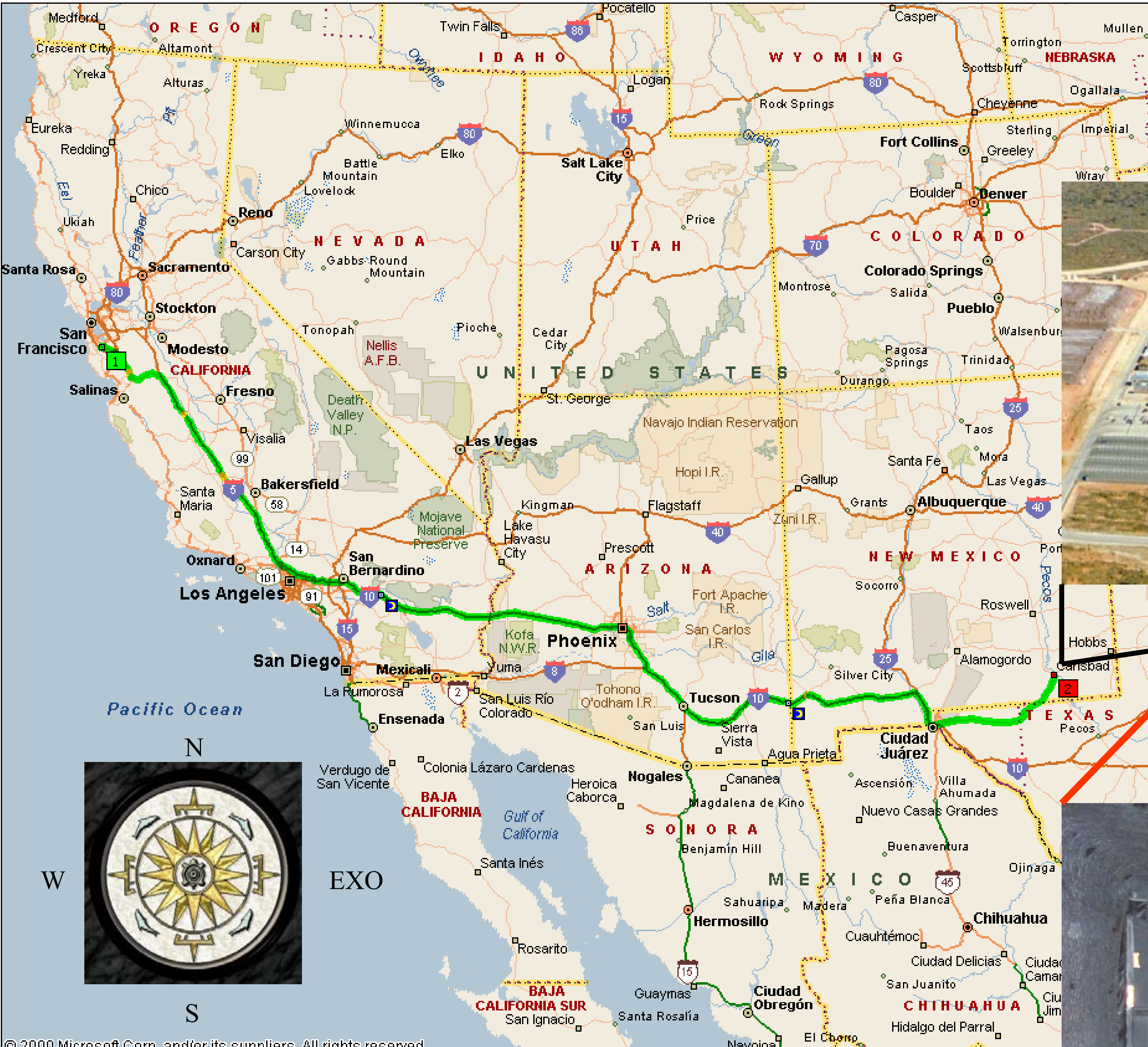
In natural sample ^{84}Kr/Xe measured to be $(4.4\pm1.5)*10^{-7}$ (as expected)

In enriched sample cannot detect Kr: ^{84}Kr/Xe $<3.4*10^{-7}$ at 90%CL

First 100 kg test production completed in Apr '02

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

Another 100 kg run started in early Oct, funded by DoE-EM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