A New Approach to Double-Beta Decay :
The EXO R&D Project

P.C. Rowson, SLAC

for

Enriched Xenon Observatory
for double beta decay

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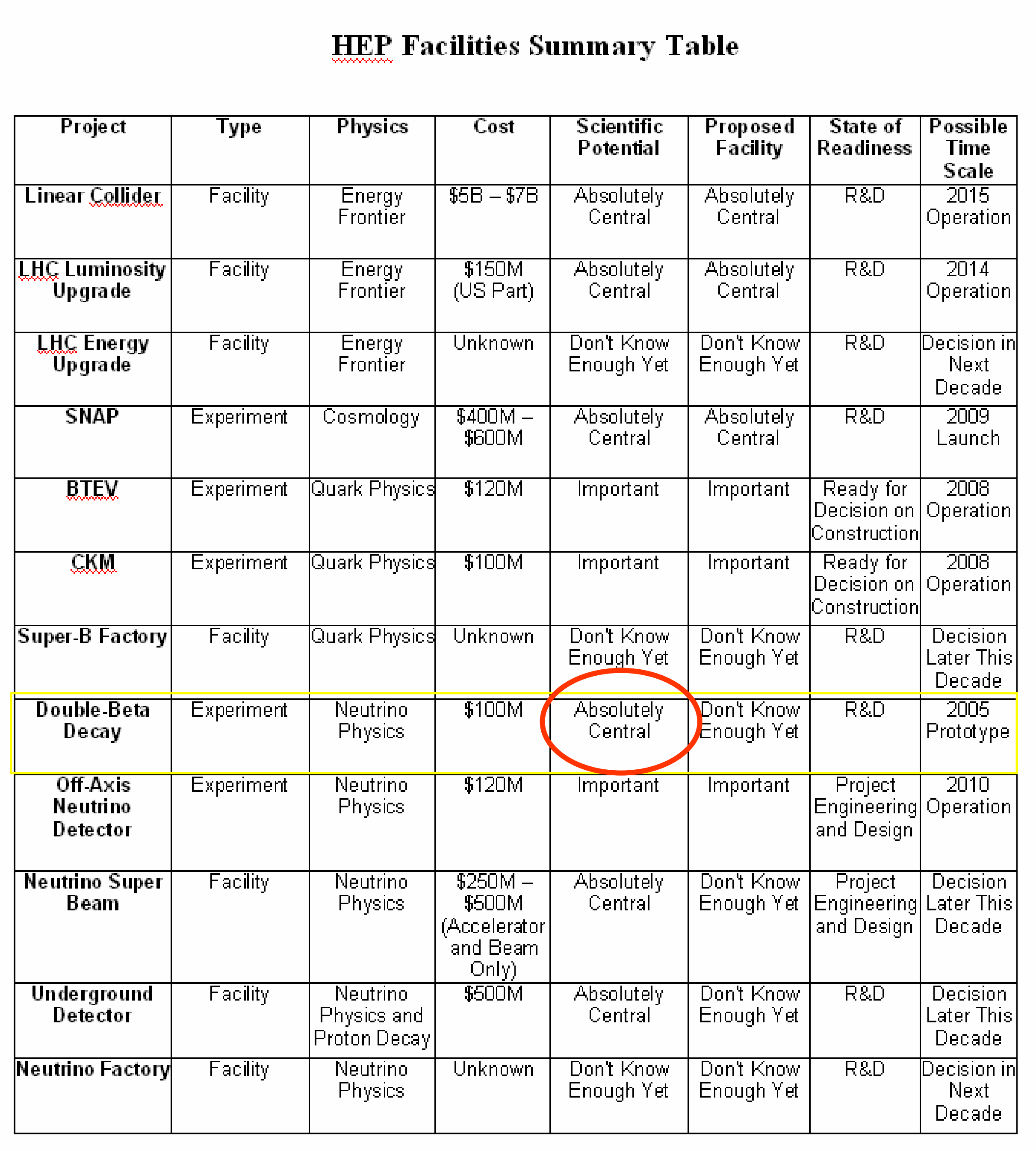
**Visitor from INFN Padova*

High-Energy Physics Facilities on the DOE Office of Science Twenty-Year Roadmap March 2003

The recei [illegible] urgh recognized the importance of the EXO scientific program…



HEP Facilities Summary Table

Project	Type	Physics	Cost	Scientific Potential	Proposed Facility	State of Readiness	Possible Time Scale
Linear Collider	Facility	Energy Frontier	\$5B – \$7B	Absolutely Central	Absolutely Central	R&D	2015 Operation
LHC Luminosity Upgrade	Facility	Energy Frontier	\$150M (US Part)	Absolutely Central	Absolutely Central	R&D	2014 Operation
LHC Energy Upgrade	Facility	Energy Frontier	Unknown	Don't Know Enough Yet	Don't Know Enough Yet	R&D	Decision in Next Decade
SNAP	Experiment	Cosmology	\$400M – \$600M	Absolutely Central	Absolutely Central	R&D	2009 Launch
BTEV	Experiment	Quark Physics	\$120M	Important	Important	Ready for Decision on Construction	2008 Operation
CKM	Experiment	Quark Physics	\$100M	Important	Important	Ready for Decision on Construction	2008 Operation
Super-B Factory	Facility	Quark Physics	Unknown	Don't Know Enough Yet	Don't Know Enough Yet	R&D	Decision Later This Decade
Double-Beta Decay	Experiment	Neutrino Physics	\$100M	Absolutely Central	Don't Know Enough Yet	R&D	2005 Prototype
Off-Axis Neutrino Detector	Experiment	Neutrino Physics	\$120M	Important	Important	Project Engineering and Design	2010 Operation
Neutrino Super Beam	Facility	Neutrino Physics	\$250M – \$500M (Accelerator and Beam Only)	Absolutely Central	Don't Know Enough Yet	Project Engineering and Design	Decision Later This Decade
Underground Detector	Facility	Neutrino Physics and Proton Decay	\$500M	Absolutely Central	Don't Know Enough Yet	R&D	Decision Later This Decade
Neutrino Factory	Facility	Neutrino Physics	Unknown	Don't Know Enough Yet	Don't Know Enough Yet	R&D	Decision in Next Decade

Nuclear Double Beta Decay

Process **a)** occurs in the Standard model.

Process b) only proceeds :

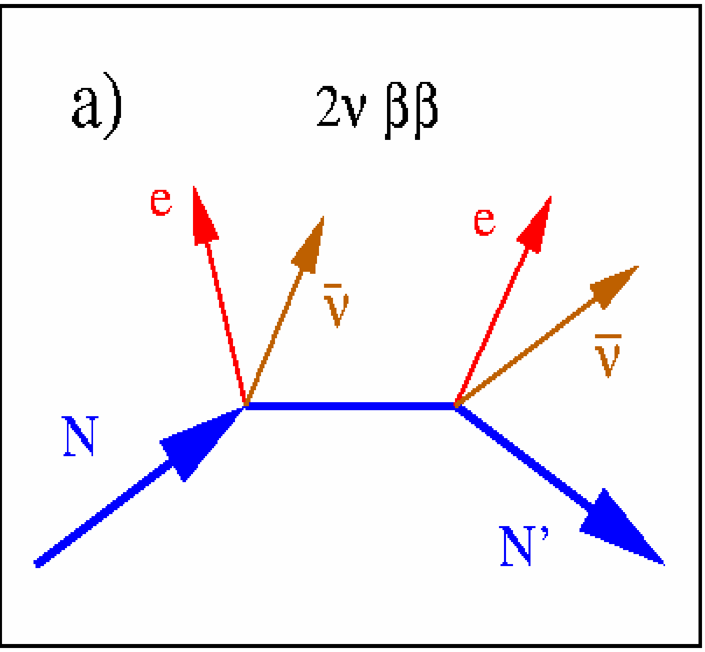
- ***If ν's are their own antiparticles (Majorana)***

AND

- ***If the ν's are massive*** (a spin flip is required to conserve angular momentum).

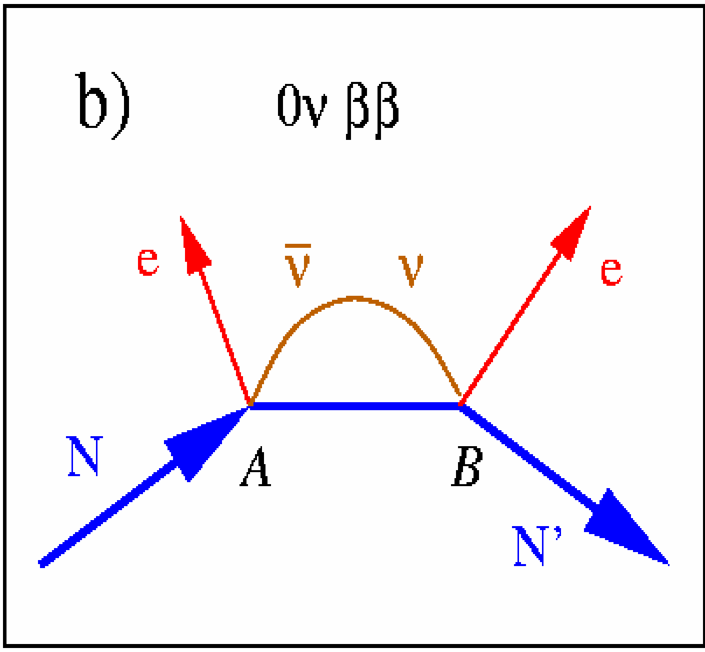
∴ For 0νββ decay, the rate ~ $\langle m \rangle^{2}$.

- ***0νββ decay does not conserve lepton number***



4-body decay

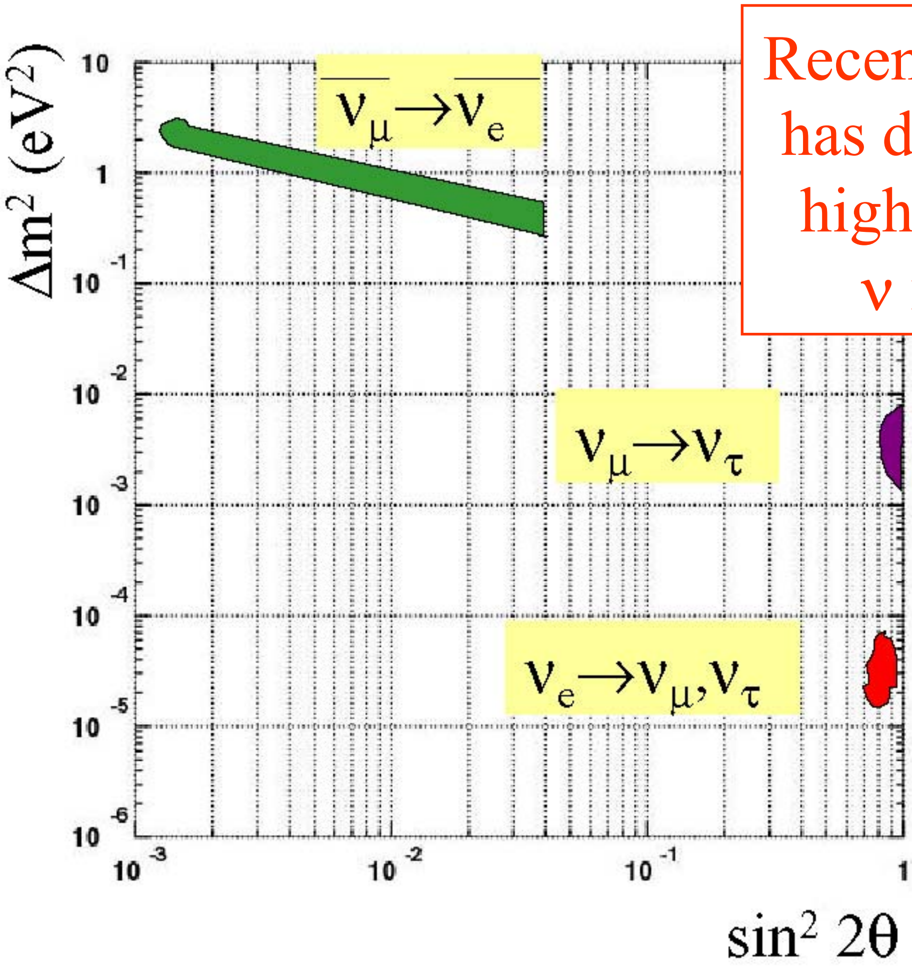
continuous spectrum for e^- energy sum



2-body decay

e^- energy sum is at the max. (Q)

A new era : the neutrino is massive



Recently, ν mixing data has demonstrated with high confidence that **ν mass is finite**.

But since only *phase differences* are observed, only *mass differences* are determined

Let $m_{ij}^2 = m_j^2 - m_i^2$
with m_3 the most splitted state, and $m_2 > m_1$.
Then, the state of affairs is roughly given by :

solar ν mass range	$\Delta m_{21}^2 \approx 10^{-5} - 10^{-4}\, eV^2$
atmospheric ν mass range	$\Delta m_{23}^2 \approx 10^{-2} - 10^{-3}\, eV^2$

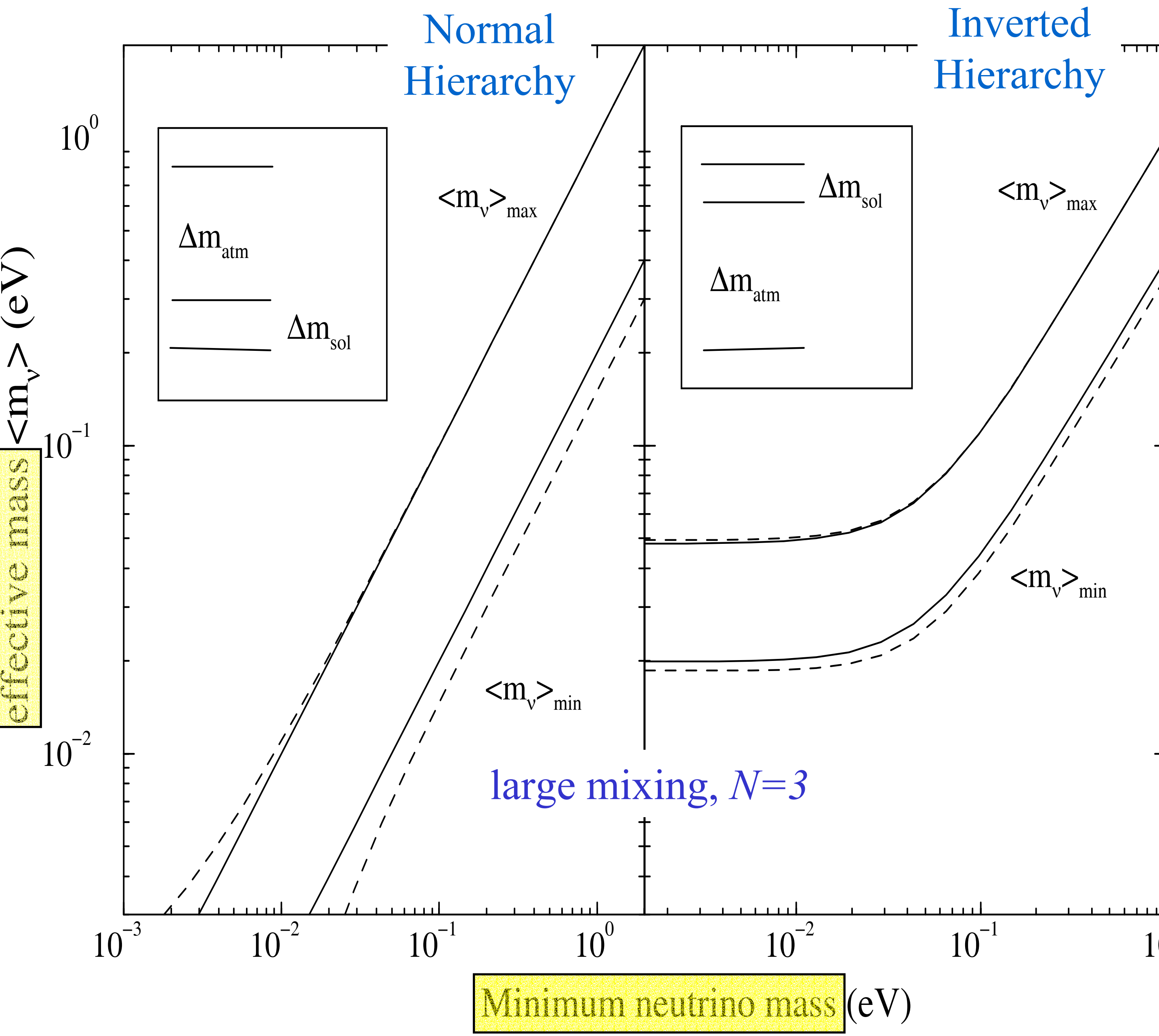
Neutrino Oscillation Results : A New Era

<m> 90% C.L. ranges from all data :

~(1 - 4 meV)$_{\textbf{normal hierarchy}}$ ~(15 - 60 meV)$_{\textbf{inverted hierarchy}}$

[for example F.Feruglio et al. CERN-TH/2002-13. Also see

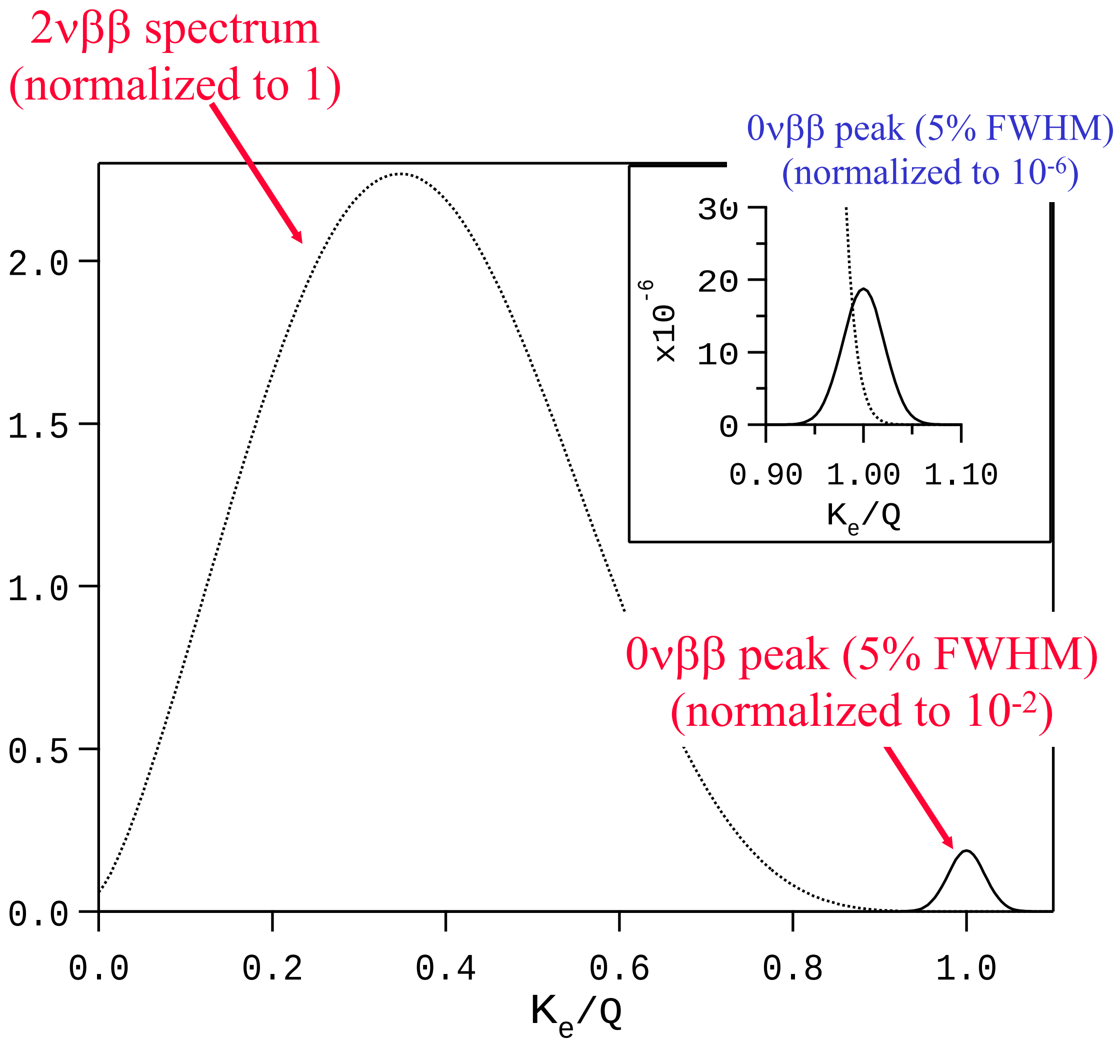
S.R. Elliott and P.Vogel, Ann.Rev.Nucl.Part.Sci. **52** (2002) 115-151. }]



Detection of $0\nu\beta\beta$ Decay

The two e^- energy sum is the primary tool

In this rare decay search, superb E resolution is essential for bkgrd. control, particularly bkgrd. due to the Standard Model $2\nu\beta\beta$ decay.



$2\nu\beta\beta$ spectrum (normalized to 1)

$0\nu\beta\beta$ peak (5% FWHM) (normalized to 10^{-6})

$0\nu\beta\beta$ peak (5% FWHM) (normalized to 10^{-2})

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

Important issue : $2\nu\beta\beta$ rate must be determined.

(A smaller $2\nu\beta\beta$: $0\nu\beta\beta$ rate ratio is experimentally favorable.)

Calculating the rates for 2ν and 0νββ

$$[T_{1/2}^{2\nu\beta\beta}]^{-1} = G^{2\nu\beta\beta}\left|M^{2\nu\beta\beta}\right|^2$$: **2ν** (typ. >10^{19} y)

Well known
phase space factors

Matrix elements calculated
from nuclear models

$$[T_{1/2}^{0\nu\beta\beta}]^{-1} = G^{0\nu\beta\beta}\left|M^{0\nu\beta\beta}\right|^2\left|\langle m\rangle\right|^2$$: **0ν** (>10^{23} y eV^2)

where …

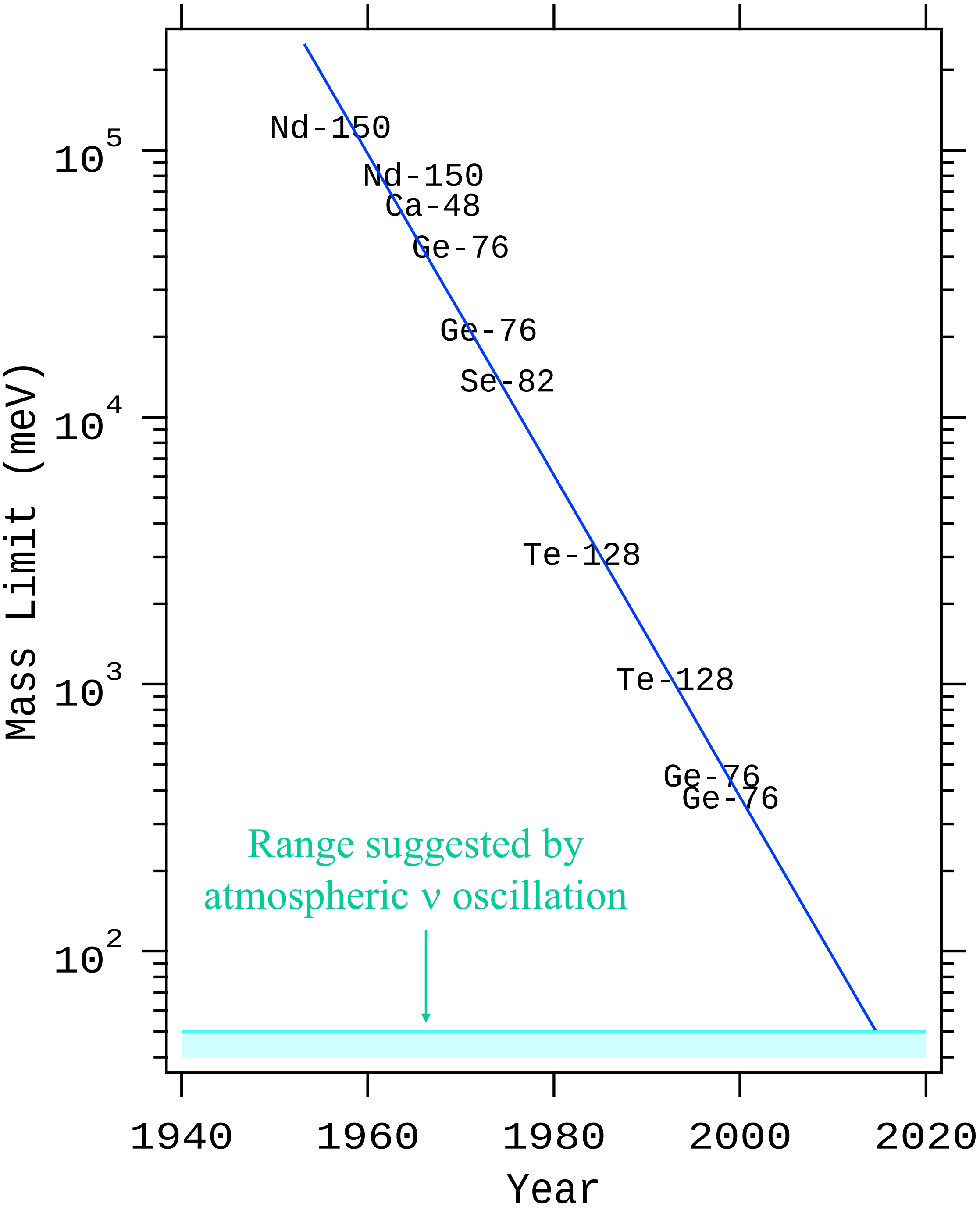
$$\langle m\rangle = m_1\left|U_{e1}\right|^2 + m_2\left|U_{e2}\right|^2 e^{i\alpha_{21}} + m_3\left|U_{e3}\right|^2 e^{i\alpha_{31}}$$

The effective mass **<m>** is a complex linear comb. of the 3 generations of mass eigenstates (and cancellations can occur).

From the present neutrino oscillation data, one can deduce, with some assumptions, that this effective mass may be in the range from below 1 meV to 100 meV or higher.

There is an opportunity to make an important discovery if one pushes the <m> sensitivity to the ~ 10 meV region

"Moore's Law" for Double Beta Decay



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

Candidate Nuclei for Double Beta Decay

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

Issues include : Q value (11th power dependence), abundance, ease of purification (chemical and isotopic), radioactivity (incl. cosmogenesis), & experimental ease of use.

Backgrounds :
The key issue in a rare event search

These arise from cosmic rays, natural radioactivity both external to and from within the apparatus (which can be induced by cosmogenesis), and lastly, Standard Model processes (2νββ decay).

With an mass of M and a time period T ⇒ an exposure MT (in, eg, ton years) …

For a bkgrd limited experiment :
(*b* is the bkgrd per unit exposure per unit energy, and δ is the energy resolution at the endpoint.)

$$\langle m_\nu \rangle \sim \left(\frac{b\delta}{MT} \right)^{1/4}$$

For a bkgrd free experiment :

$$\langle m_\nu \rangle \sim \left(\frac{1}{MT} \right)^{1/2}$$

Background control was ***the issue*** for the most sensitive experiments to date (Ge^{76}) – in particular due to internal radioactivity (eg. Ge^{68}, $t_{1/2}$ = 271 days, and activity from detector construction materials).

Active Media (calorimetric) Experiments :

$0\nu\beta\beta$ State of the Art

Experiment	$T_{1/2}^{0\nu\beta\beta}$ (yr)	kg yr	$< m >$ (eV)	
			QRPA	NSM
Ge Diode Calorimeter	$> 5.7 \times 10^{25}$	29	< 0.2	< 0.6
TeO_2 cryo calorimeter	$> 5.6 \times 10^{22}$	0.15	< 2.9	< 6.1
Xe TPC	$> 4.4 \times 10^{23}$	8	< 2.2	< 5.2

In order to significantly improve sensitivity into the interesting region (10's of milli-eV), total exposures (in kg years) must increase substantially.

But for the O(1 ton year) experiment, qualitative improvements in background control are needed.

For example, the ^{76}Ge experiment achieved backgrounds of ~0.2 events/kg yr per FWHM energy resolution window.

Factor of >1000 improvement required

Background reduction by coincidence measurement

It was recognized early on that coincident detection of the two decay electrons *and* the daughter decay species can dramatically reduce bkgrd.

One possibility would be the Observation of a γ from an excited daughter ion, but the rates compared to ground state decays are generally very small (best chance might be ^{150}Nd, but Eγ is only 30keV.)

$$\begin{tikzcd}
X \arrow[r] & (Y^{++})^{*} \arrow[d] + e^{-} + e^{-} \\
 & Y^{++} + \gamma
\end{tikzcd}$$

A more promising approach :
Barium detection from ^{136}Xe decay

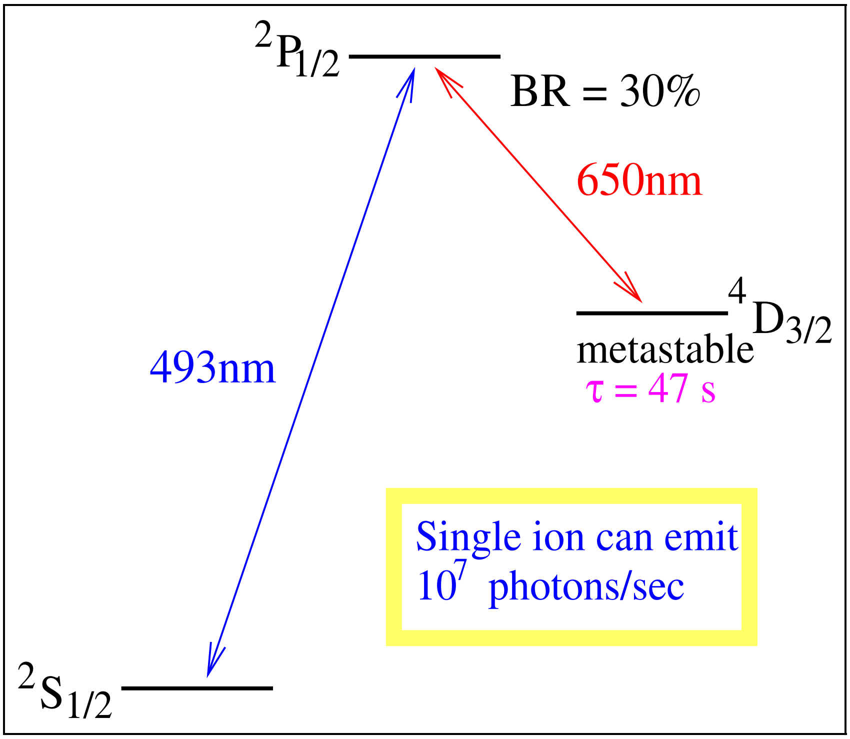
$$\begin{tikzcd}
{}^{136}\mathrm{Xe} \arrow[r] & {}^{136}\mathrm{Ba}^{++} \arrow[d] + e^{-} + e^{-} \\
 & \text{Identify event-by-event}
\end{tikzcd}$$

Described in 1991 by M. Moe (PRC, 44, R931,(1991)).

The method exploits the well-studied spectroscopy of Ba and the demonstrated sensitivity to a *single* Ba^{+} ion in an ion trap.

Event-by-Event Decay Daughter Identification

$^{136}\mathrm{Xe} \rightarrow \mathbf{^{136}Ba^{++}} + e^{-} + e^{-}$



Single ion can emit 10^7 photons/sec

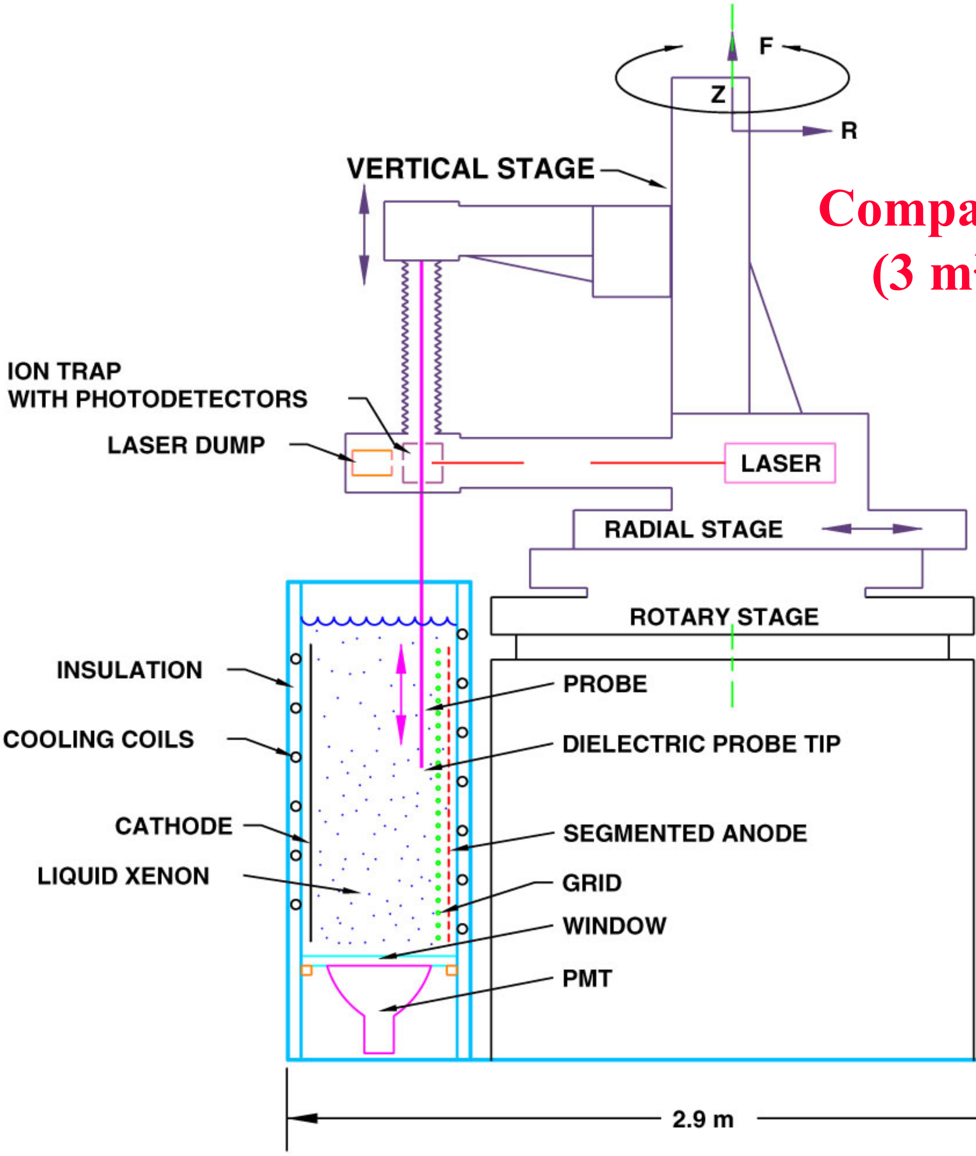
Level structure for Ba^+

Ba^{++} lines in the UV – convert ion to Ba^+or Ba.

“Shelving” into metastable D state allows for modulation of 650nm light to induce modulated 493nm emission *out of synch.* with excitation (493nm) light – improves S/N.

Isotopic shift can be resolved (eg. ^{136}Ba to ^{137}Ba)

Liquid Xenon TPC conceptual design



Compact and scalable ($3\ m^3$ for 10 tons).

The basic concept, shown here for a LXe option, is :

- Use ionization and scintillation light in the TPC to determine the event location, and to do **precise calorimetry.**

- **Extract the Barium ion** from the event location (electrostatic probe eg.)

- Deliver the Barium to a laser system for **Ba^{136} identification**.

EXO R&D

The R&D program is addressing the following issues

Xenon procurement and isotopic enrichment.

Xe^{136} natural abundance of 9% - increase to ~80%

Xenon purification.

long electron lifetimes → electronegative impurities <1ppb

Single ion Barium spectroscopy in vacuum and in Xe gas.

conversion of Ba++ to Ba+ or neutral Ba, line broadening

Sufficient energy resolution in Xenon, particularly in LXe.

incl. studies of scintillation light/ionization correlation

Barium ion “capture and release” in Xenon (LXe)

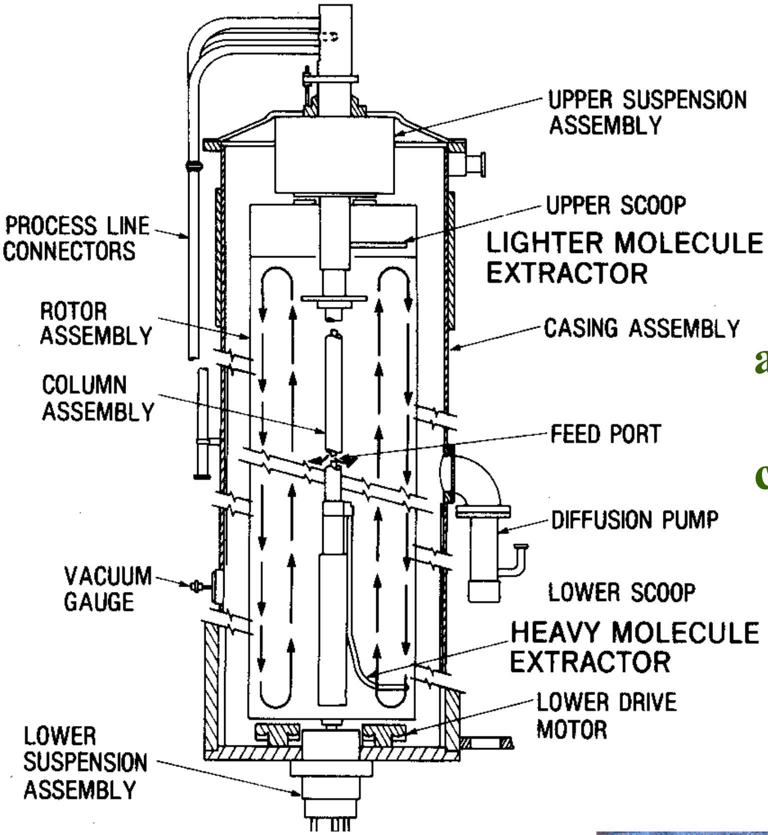
Barium ion lifetimes, mobility, charge state – in LXe

Prototyping of LXe TPC (w/o Barium identification)

all issues, incl. energy, position resolution

Testing and procurement of low background materials

Isotopic enrichment for a gaseous Xe is most economically achieved by ultracentrifugation

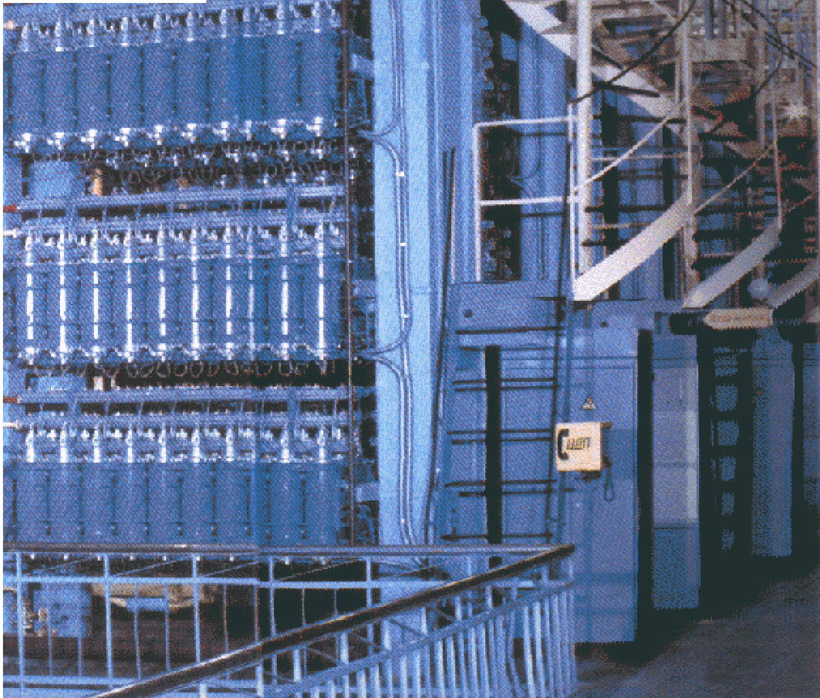


^{136}Xe, being the heaviest Xe isotope, is particularly easy to separate.

The separation step that rejects the light fraction is also very effective in removing ^{85}Kr ($T_{1/2}$=10.7 yr) that is constantly produced by fission in nuclear reactors.

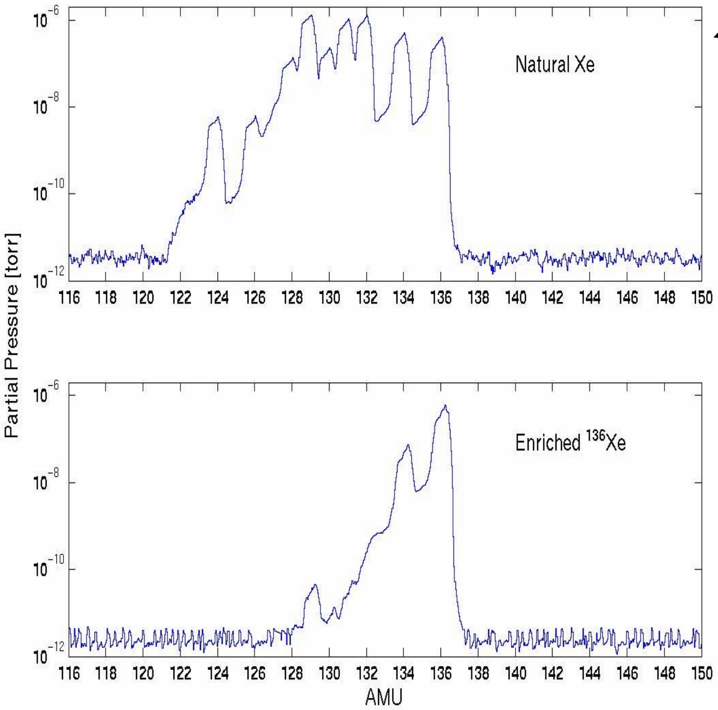
Large facilities exist In Russia – 500,000 centrifuges per plant.

We now have 100 kg of enriched Xenon, with another 100 kg due in late April.



20 STP liter sample of 90% ^{136}Xe received in June '01 from Krasnoyarsk

(Mass spectra below from RGA at Stanford)



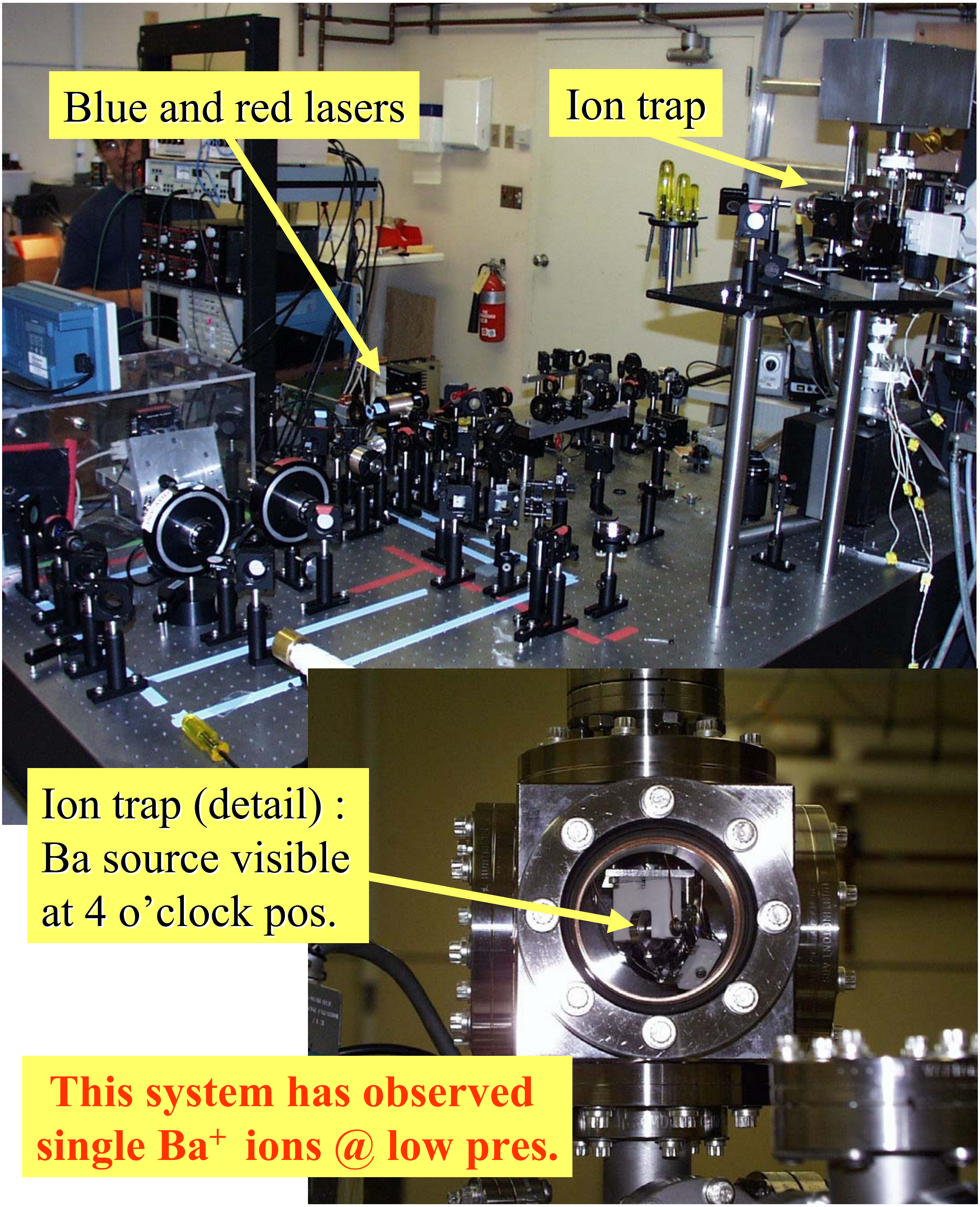
Isotope	Natl Xe	Enrch Xe
124	0.11	0.000
126	0.12	0.000
128	3.58	0.000
129	27.32	0.005
130	5.20	0.001
131	21.39	0.007
132	24.35	0.079
134	9.95	10.381
136	7.97	89.527

In natural sample ^{85}Kr/Xe measured to be $(4.4\pm1.5)*10^{-7}$ (as expected)

More sensitive measurements to be done on a better mass spectrometer

To date, we have received 200 kg of enriched Xe to be used in prototype exp. w/o Barium tag.

Spectroscopy lab at Stanford



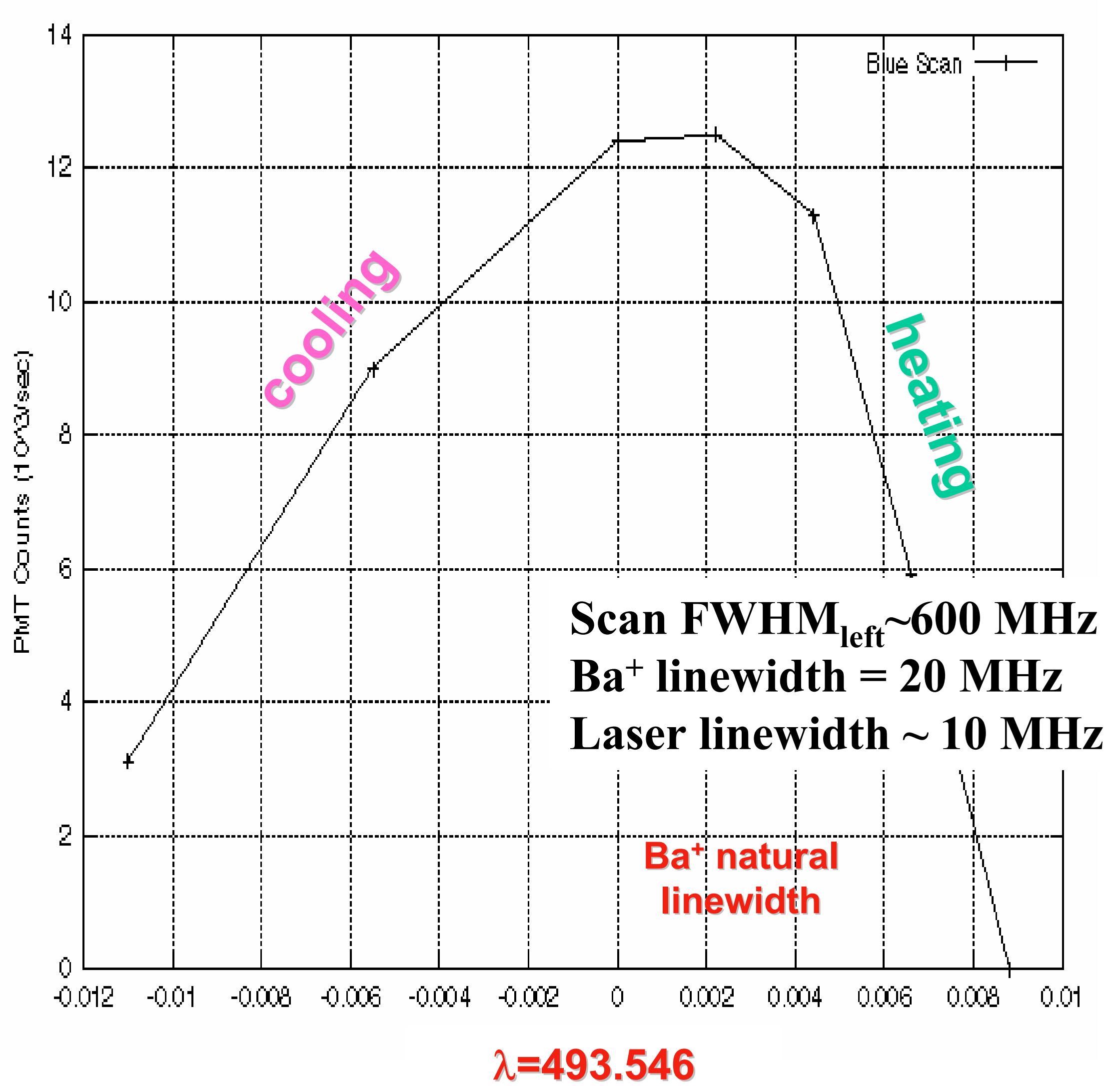
Blue and red lasers

Ion trap

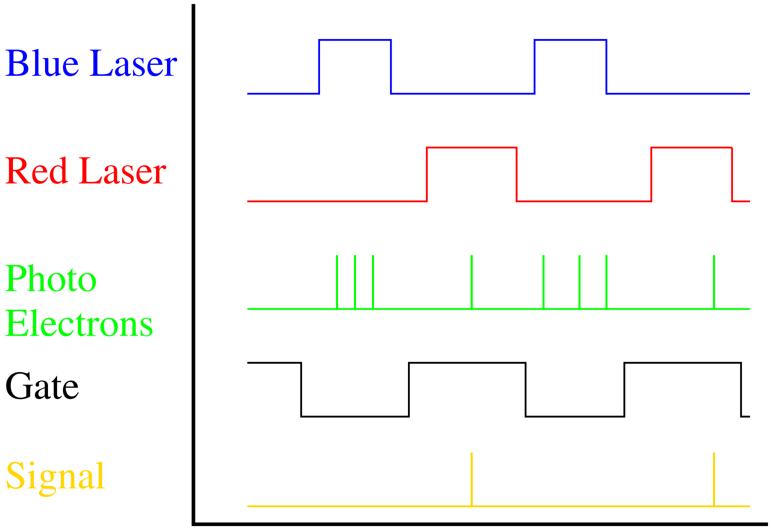
Ion trap (detail) :
Ba source visible
at 4 o’clock pos.

This system has observed
single Ba^+ ions @ low pres.

Low Background Ion Detection



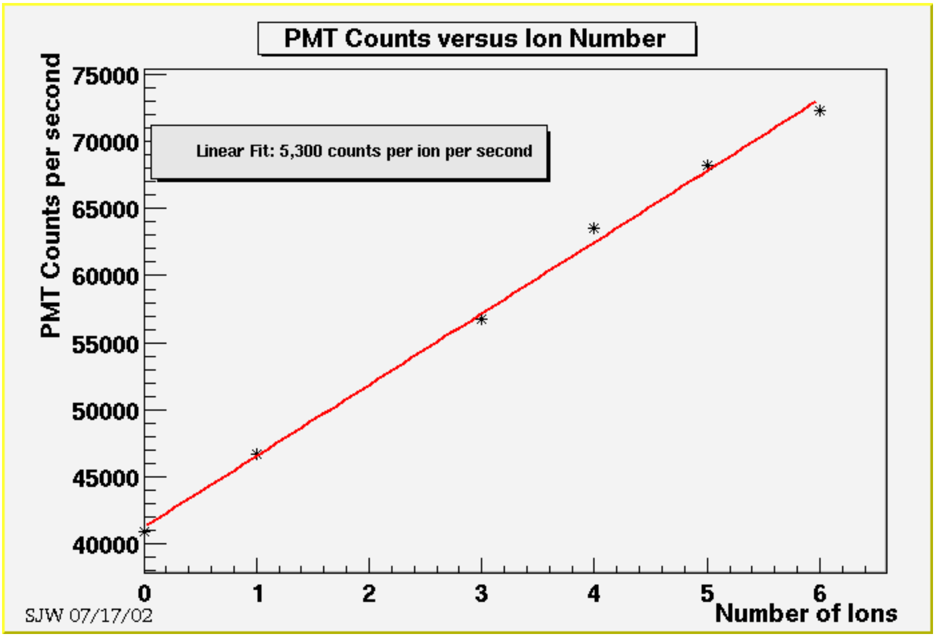
Scan FWHM$_{left}$~600 MHz (~300K)
Ba$^+$ linewidth = 20 MHz
Laser linewidth ~ 10 MHz



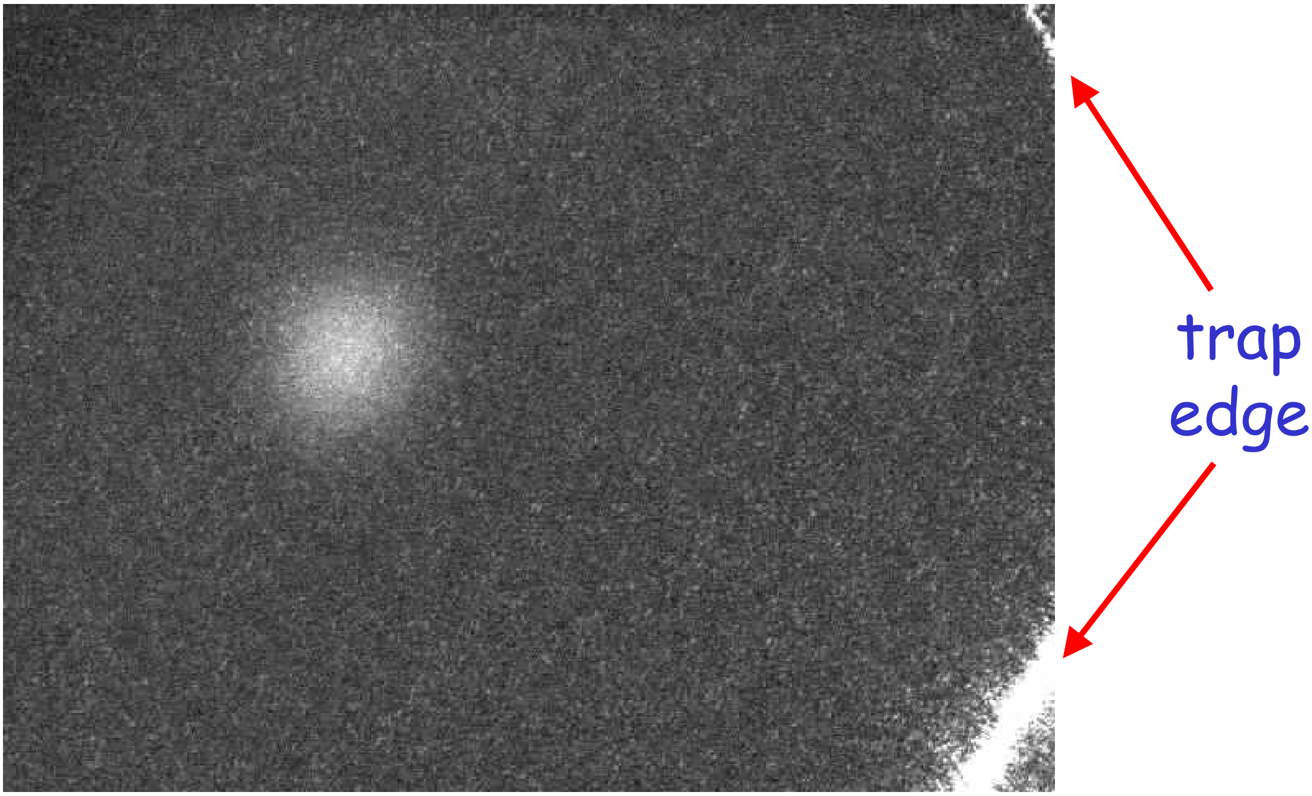
Modulation: we only look for fluorescence photons when there is no light in the chamber

For a 10 ms observation, SNR = 3.

The trap is loaded with multiple ions:
We observe the signal intensity as ions
are dropped one by one…

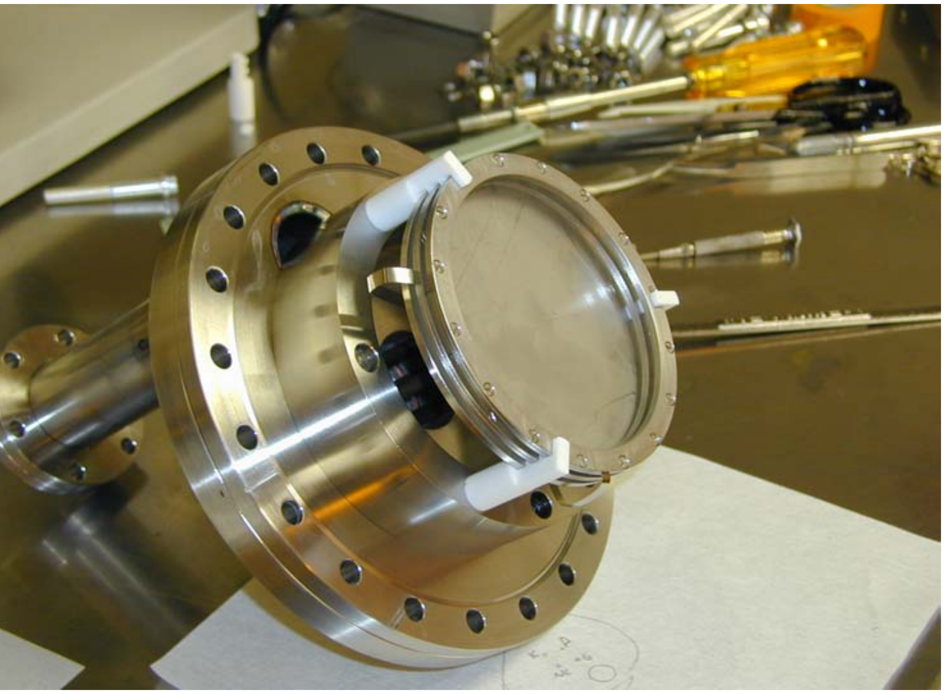


CCD image of an single ion in the trap



Stanford pancake shaped 1 liter LXe chamber to test energy resolution.

Good acceptance to scint. light AND ionization



Reconstruct energy as linear combination of ionization and scintillation signals

Longstanding speculation that correlations between the two variables help improving resolution ***[J.Seguinot et al. NIM A 354 (1995) 280]***

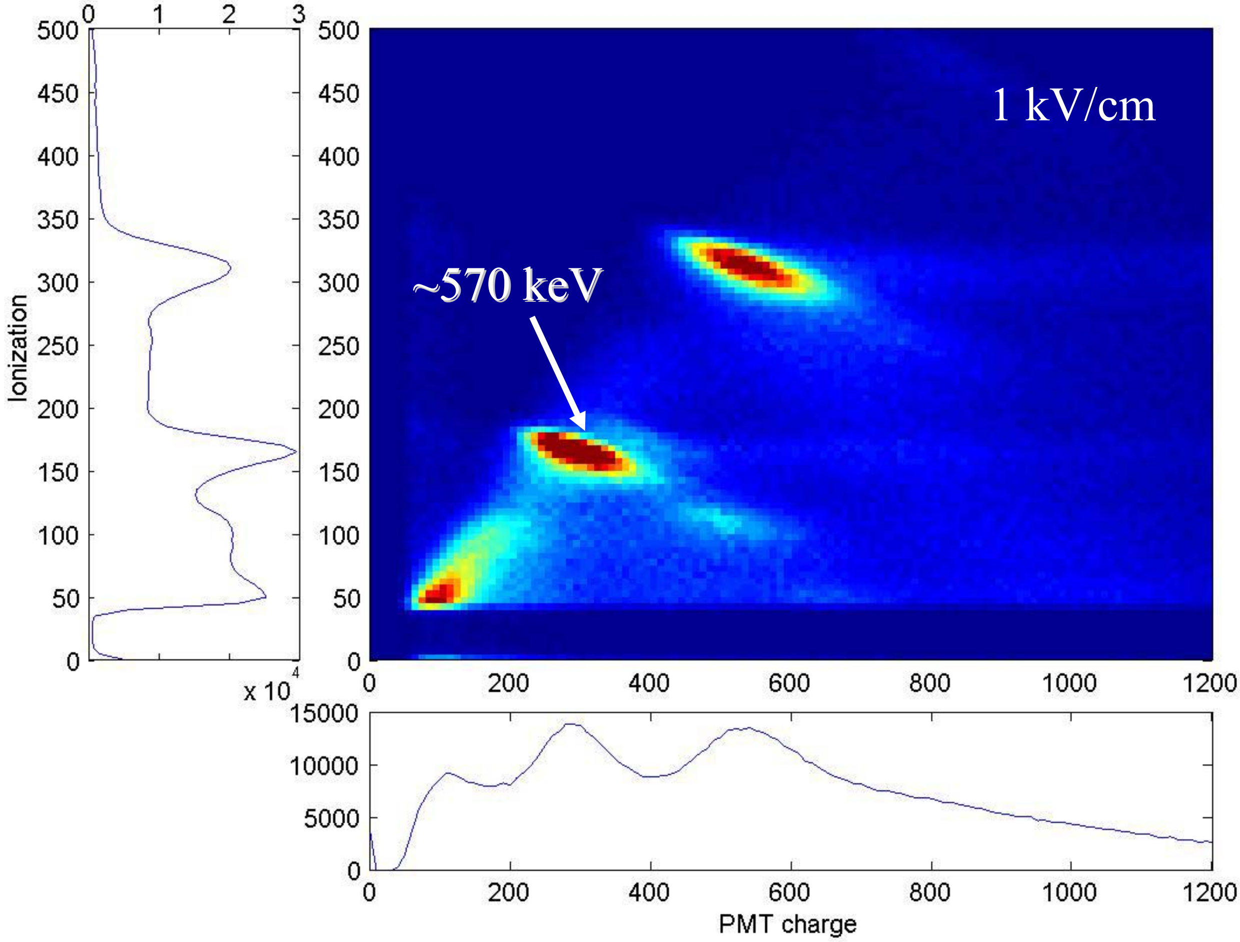
single grid device –

- cathode to grid 5.5mm
- grid to anode 1.6 mm

A ^{207}Bi source is used –
both ionization and scintillation seen.

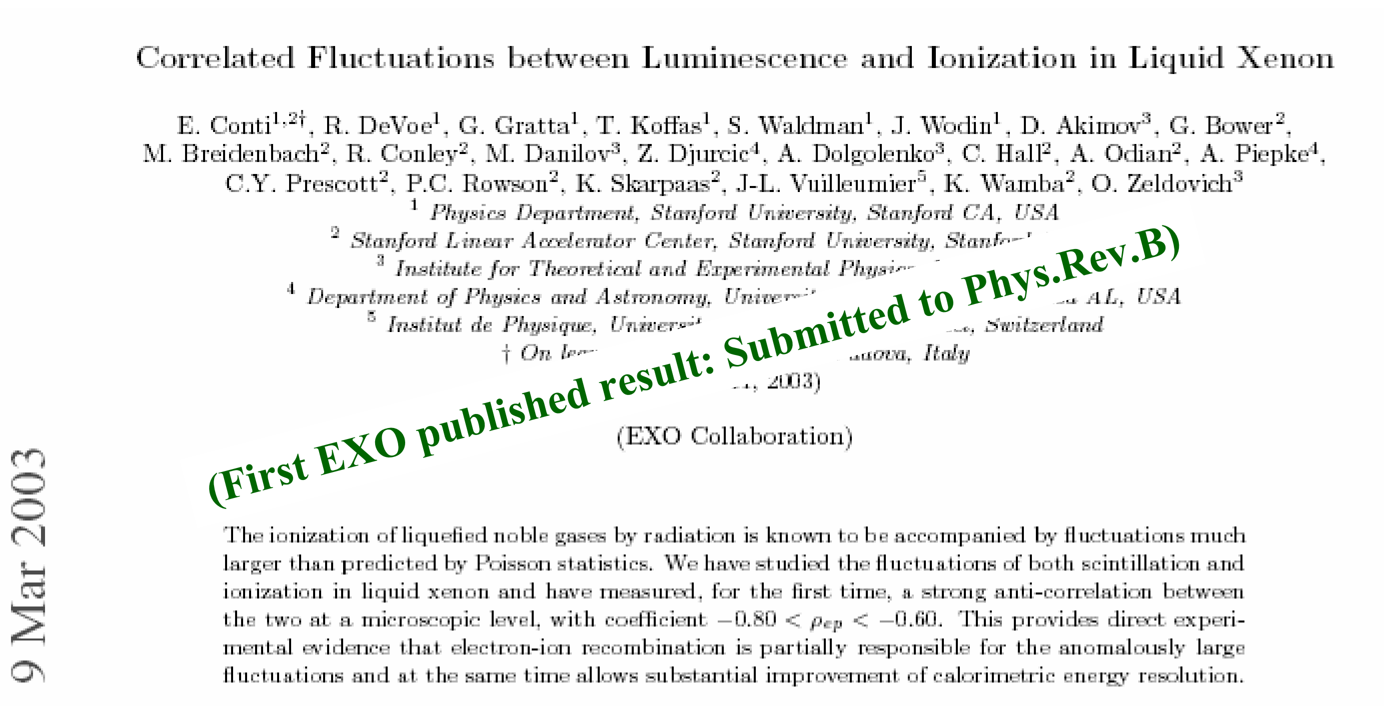
Stanford pancake shaped 1 liter LXe chamber to test energy resolution.

Preliminary results using ionization only reproduced the best resolutions seen …



Observed (noise subtracted) resolution the at 570 keV Bi peak corresponds to 2% at the 2.5 MeV endpoint. PMT resolution is not as good, but a clear anticorrelation is seen :

A linear comb. of ionization and scintillation will optimize resolution



9 Mar 2003

Correlated Fluctuations between Luminescence and Ionization in Liquid Xenon

E. Conti[1,2†], R. DeVoe[1], G. Gratta[1], T. Koffas[1], S. Waldman[1], J. Wodin[1], D. Akimov[3], G. Bower[2],
M. Breidenbach[2], R. Conley[2], M. Danilov[3], Z. Djurcic[4], A. Dolgolenko[3], C. Hall[2], A. Odian[2], A. Piepke[4],
C.Y. Prescott[2], P.C. Rowson[2], K. Skarpaas[2], J-L. Vuilleumier[5], K. Wamba[2], O. Zeldovich[3]
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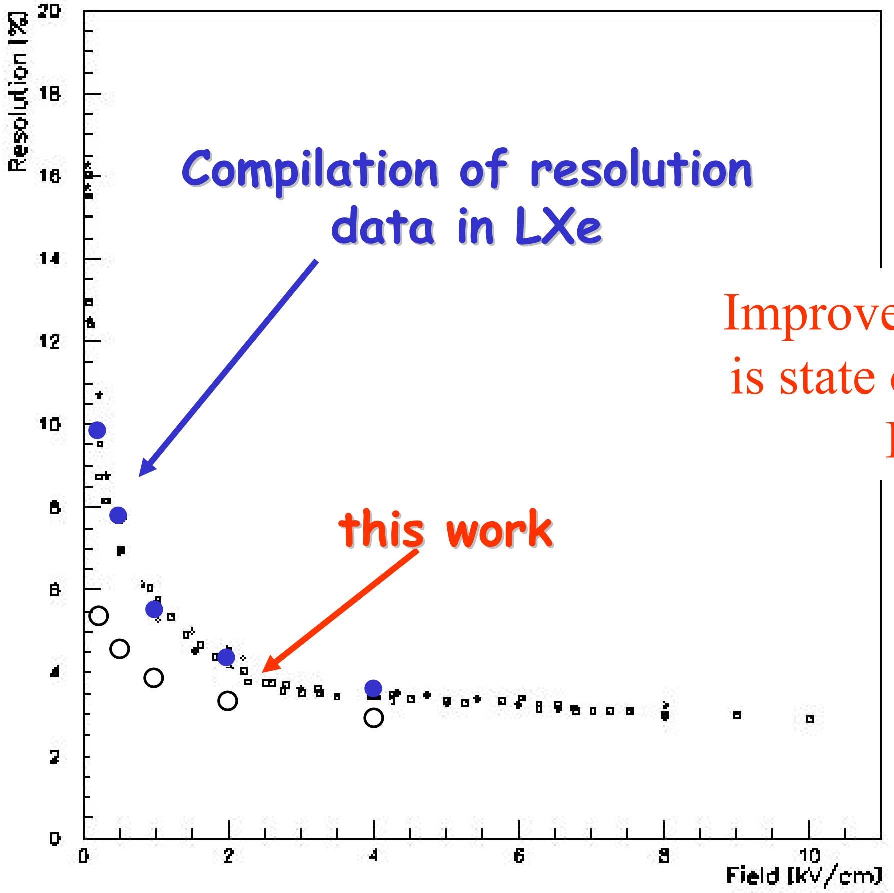
[2] *Stanford Linear Accelerator Center, Stanford University, Stanf*
[3] *Institute for Theoretical and Experimental Physic*
[4] *Department of Physics and Astronomy, Univer* *AL, USA*
[5] *Institut de Physique, Univers* *Switzerland*
† *On le* *ova, Italy*
2003)

(EXO Collaboration)

(First EXO published result: Submitted to Phys.Rev.B)

The ionization of liquefied noble gases by radiation is known to be accompanied by fluctuations much larger than predicted by Poisson statistics. We have studied the fluctuations of both scintillation and ionization in liquid xenon and have measured, for the first time, a strong anti-correlation between the two at a microscopic level, with coefficient $-0.80 < \rho_{ep} < -0.60$. This provides direct experimental evidence that electron-ion recombination is partially responsible for the anomalously large fluctuations and at the same time allows substantial improvement of calorimetric energy resolution.

Resolution is optimized by a ~(10-15)^{O} "mixing angle".



Compilation of resolution data in LXe

this work

Improved resolution is state of the art in LXe.

Barium ion extraction R&D at SLAC

Pa produced in a cyclotron → $^{230}\mathrm{Pa}$ (17.4d)

$^{230}\mathrm{Th} + p \rightarrow {}^{230}\mathrm{Pa} + 3n$

Ion capture test simulates Ba ions by using a $^{230}\mathrm{U}$ source to recoil $^{222}\mathrm{Ra}$ into the Xenon – Ba and Ra are chemically similar (ionization potentials 5.2 eV and 5.3 eV respectively).

$^{230}\mathrm{Pa}$ (17.4d)

8.4% β

$^{230}\mathrm{U}$ (20.8d)

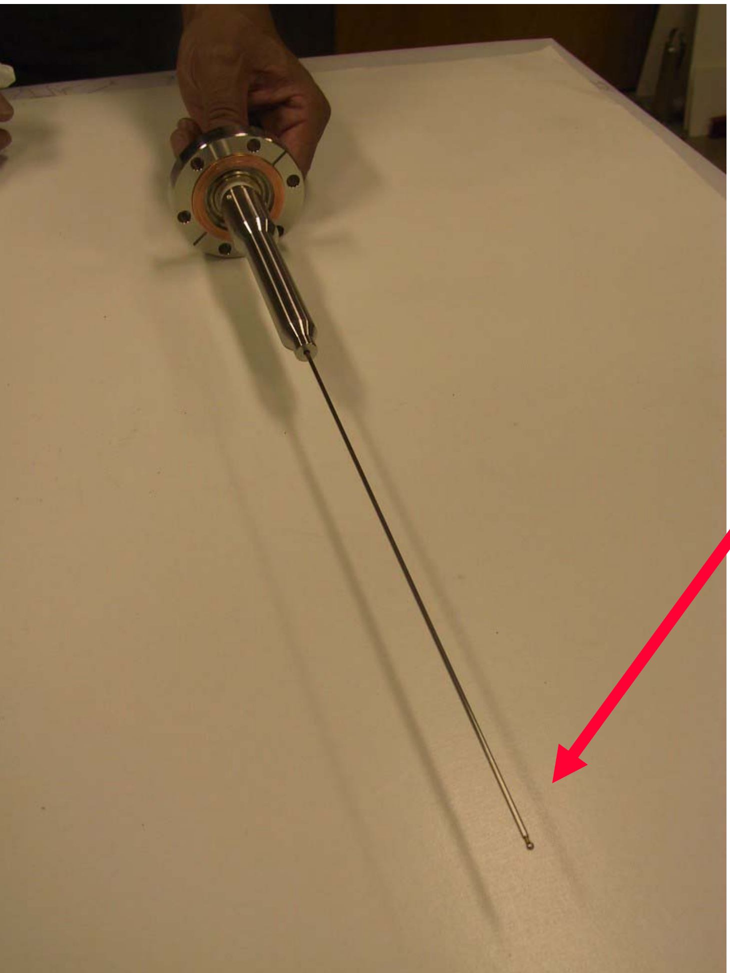
α 5.99MeV

$^{226}\mathrm{Th}$ (30.5min)

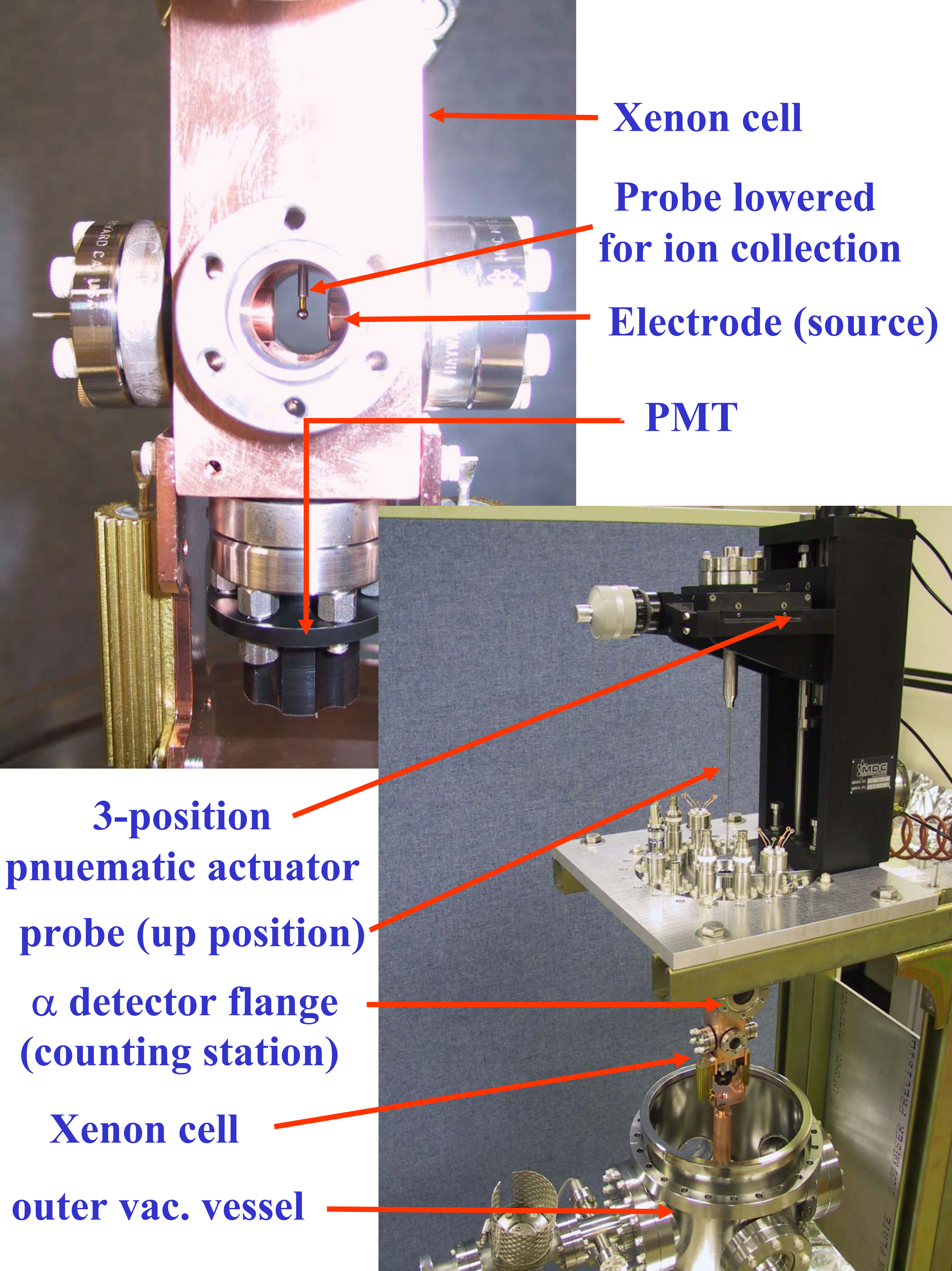
α 6.45MeV

$^{222}\mathrm{Ra}$ (38s)

3-steps of α decay



Prototype electrostatic probe – W tipped. Many variations will be tried … SEM needle, "cold finger" tip, diamond coated …



Xenon cell

Probe lowered for ion collection

Electrode (source)

PMT

3-position pnuematic actuator

probe (up position)

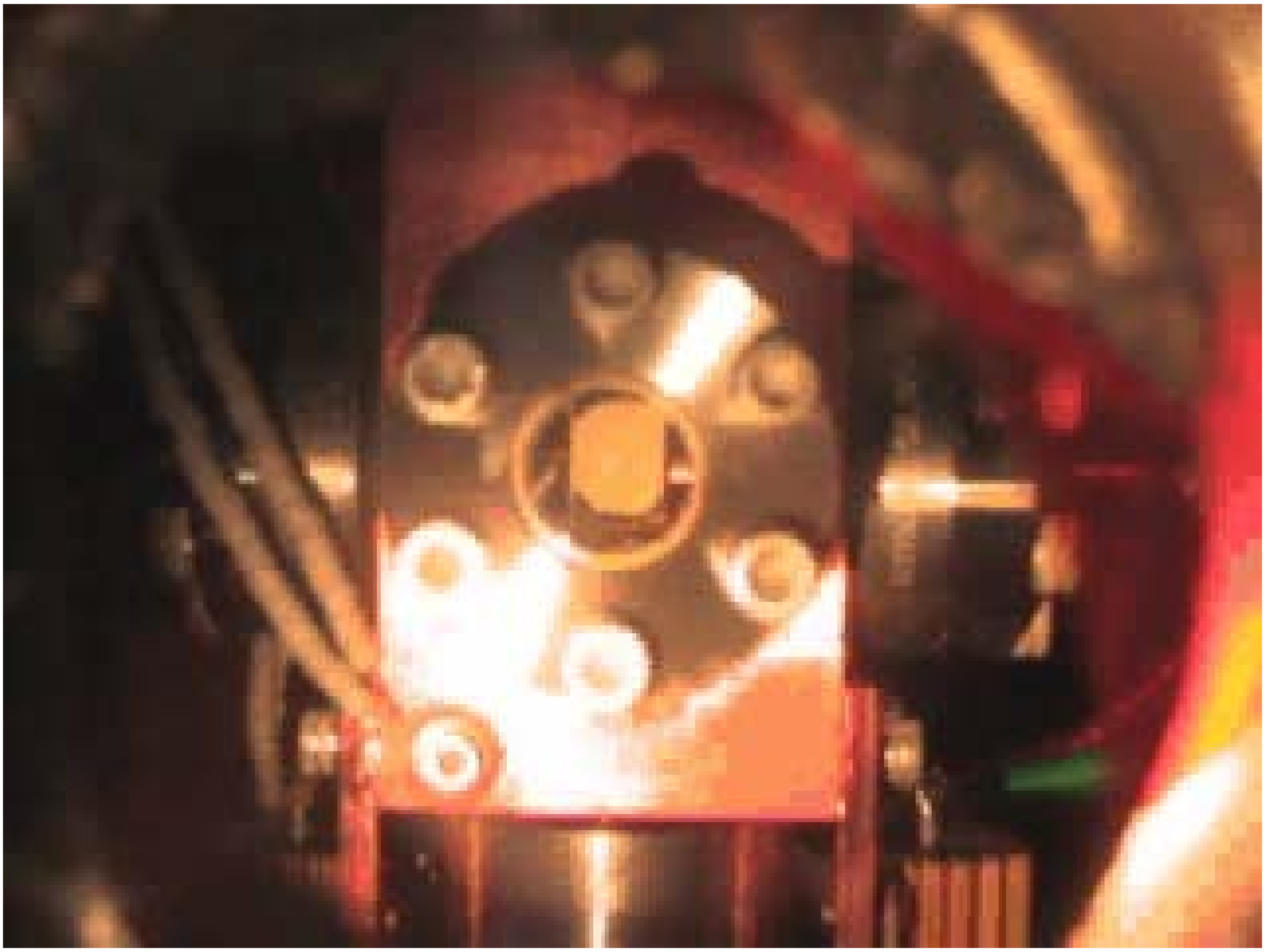
α detector flange (counting station)

Xenon cell

outer vac. vessel

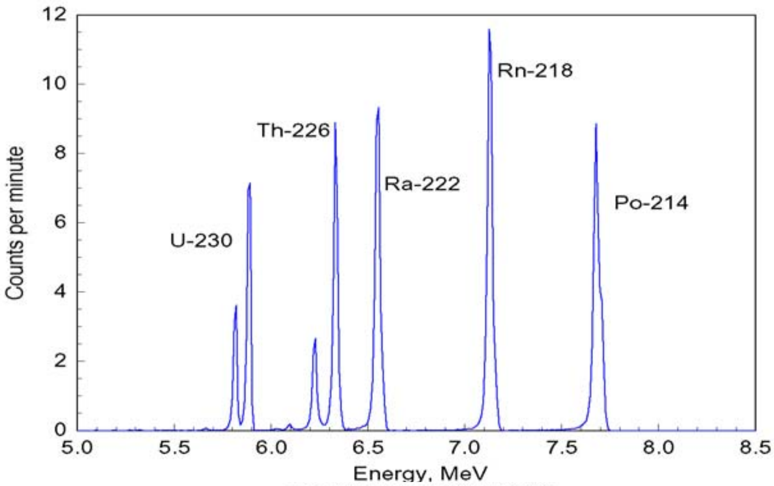
Testing the ion extraction probe

U^{230} sources have been installed, xenon has been liquified in the cell, ion capture has been demonstrated, ion mobilities have been Measured.

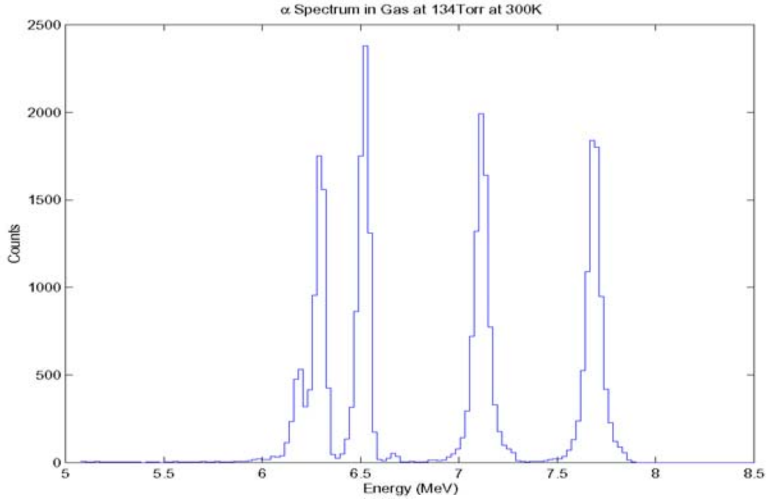


The next experiments will attempt to demonstrate ion release, and to determine efficiencies.

Ion extraction from Xe and LXe

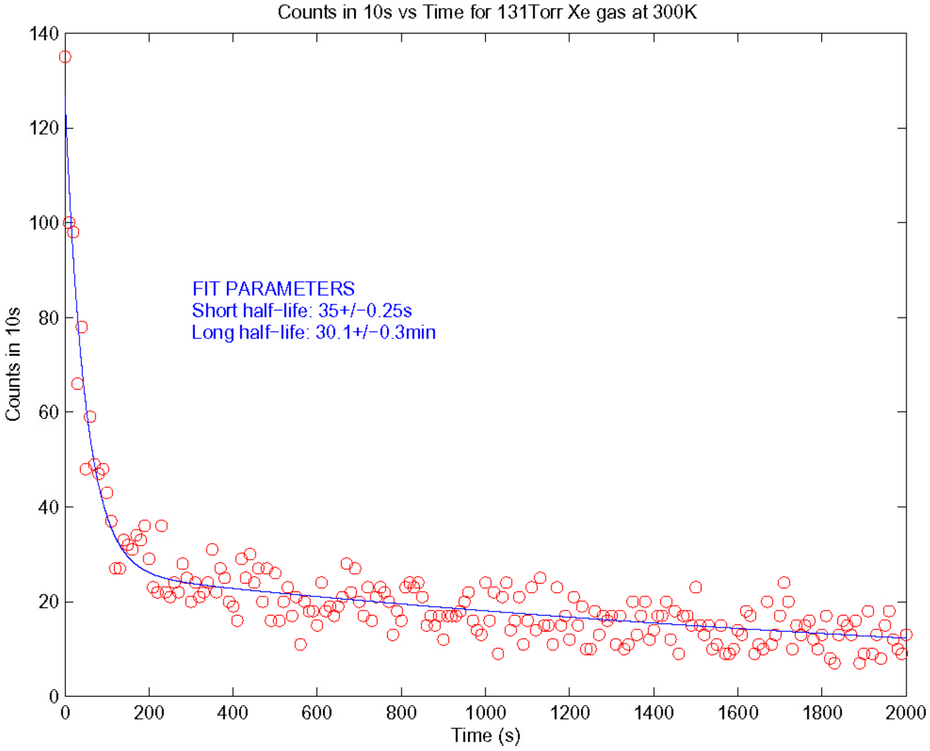


^{230}U source α spectrum as delivered by LLNL (measured in vacuum)



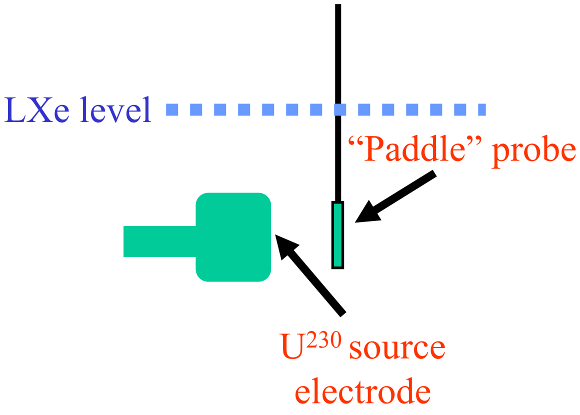
α spectrum from whatever is grabbed by the tip (in Xe atmosphere)

An additional signature from the observed Th and Ra lifetimes.



Ion mobility studies in LXe

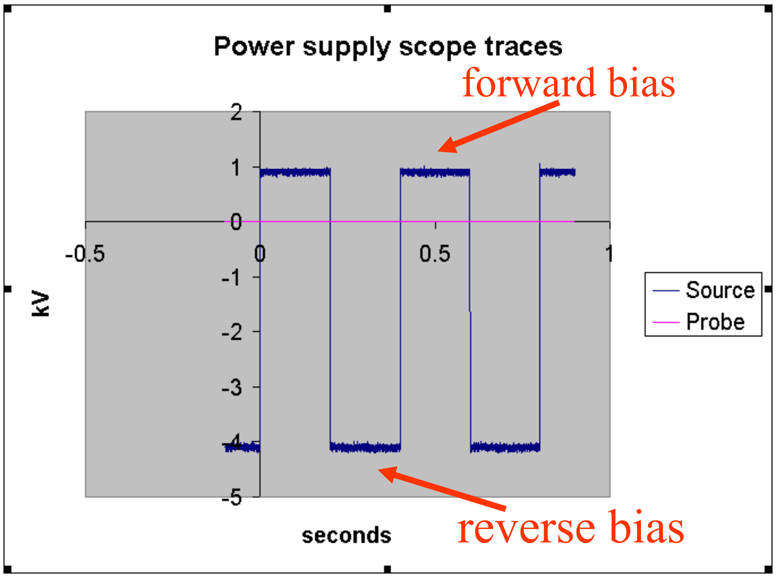
We use the probe test cell to measure ion drift speed



LXe level

"Paddle" probe

U^{230} source electrode

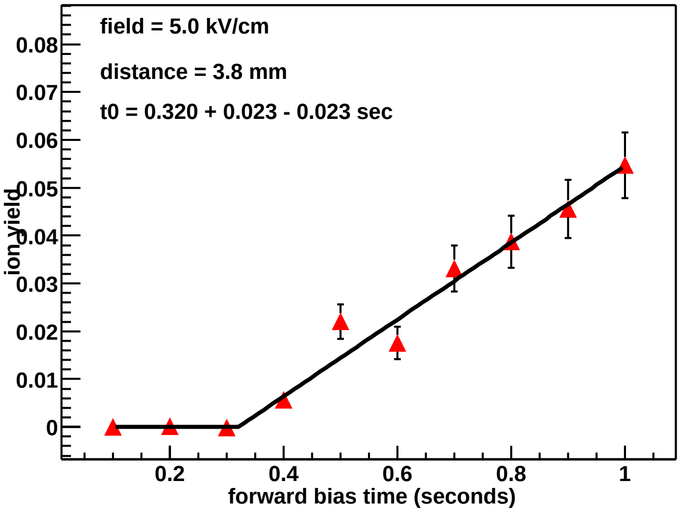


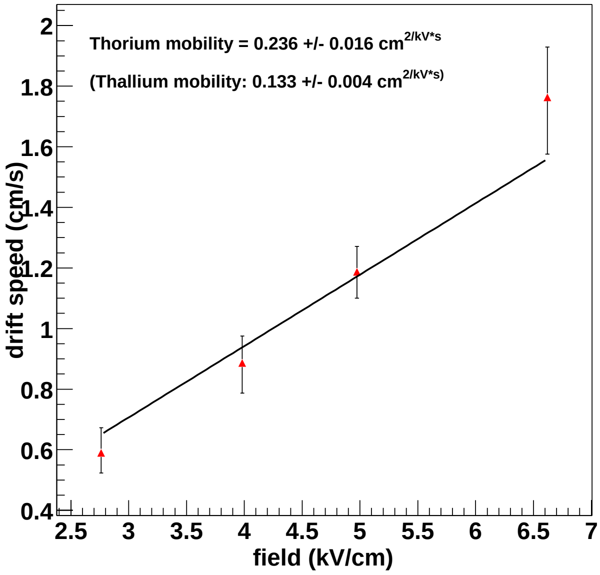
forward bias

reverse bias

Modulate the electrode voltage, and measure ion collection rate.

Data taken for various separation distances and voltage differences.



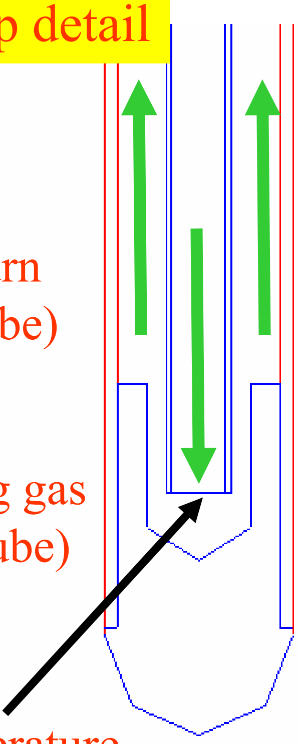


Observed mobility of 0.24±0.02 cm^2/kVs for Thorium ions compares with result for Thallium ions 0.133 cm^2/kVs.

(A.J. Walters et al. J. Phys. D: Appl. Phys. *submitted*)

Next step : Radium ions

Ion Capture "Cryo Probe" prototype



Probe tip detail

gas return
(outer tube)

incoming gas
(inner tube)

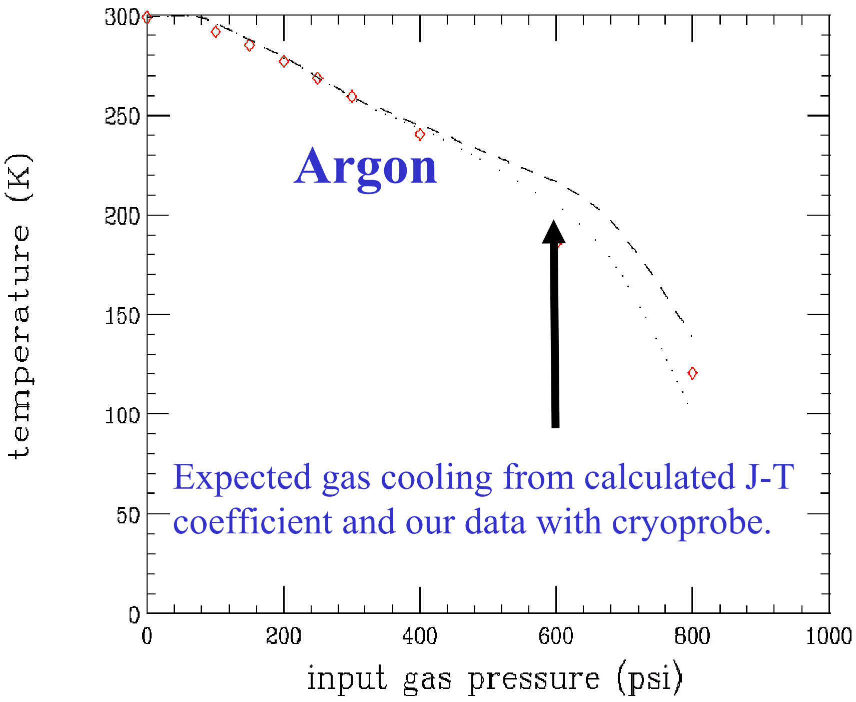
small aperature
at tube end

In order to *release* a captured ion, the electrostatic probe can be cooled such that Xe ice coats the tip. The captured ion can then be released by thawing.

Joule-Thompson cooling is used for cooling (argon gas).

An additional benefit : the Ba^+ charge state may be stable in solid and liquid xenon.

Remarkably, surgical cryoprobes seem to be ideally suited to our application. We are adapting 2.4 mm diameter probes for use in our probe test cell.



Expected gas cooling from calculated J-T coefficient and our data with cryoprobe.

Upcoming test :

See Xe ice, collect and release ions (?)

Additional R&D activities

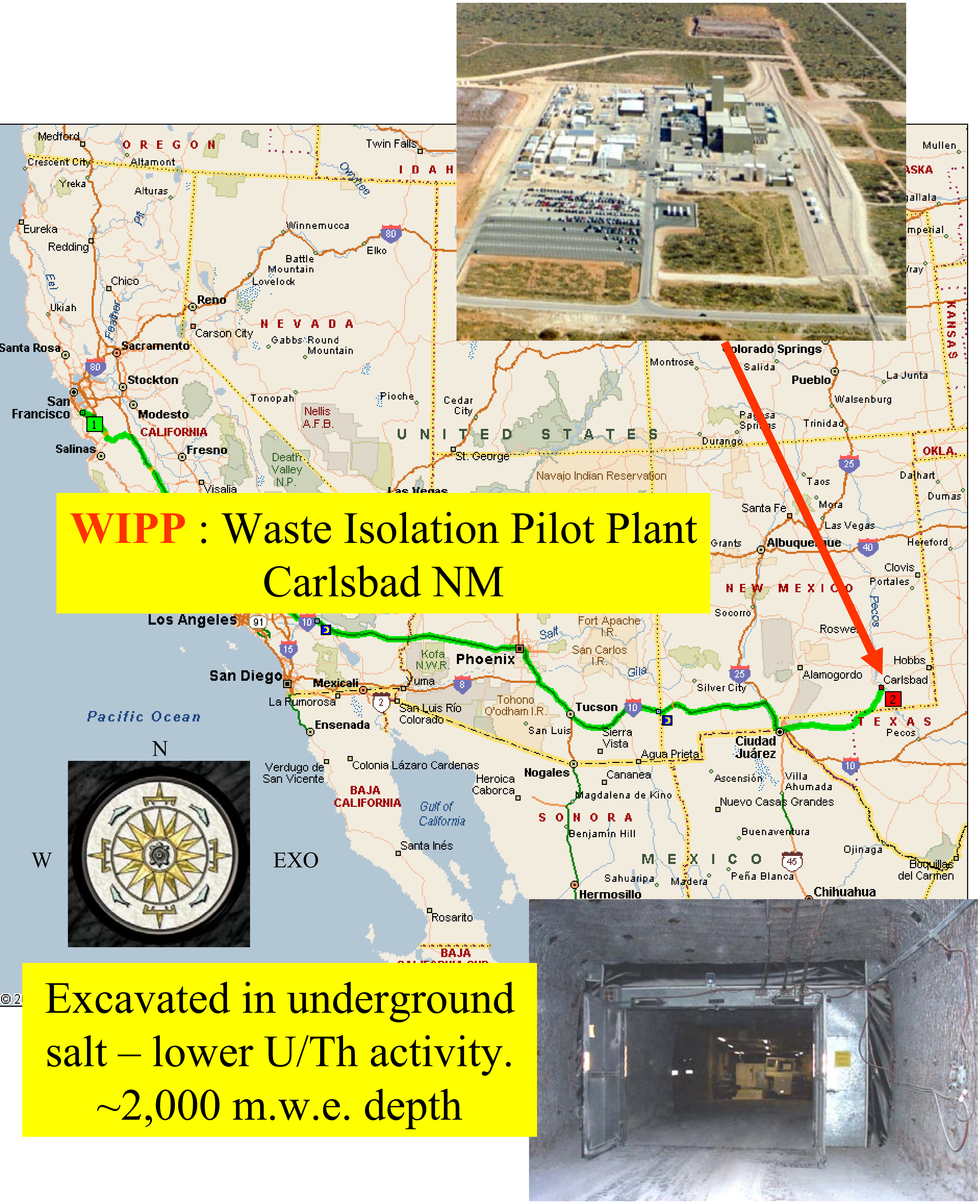
Studies of “two-phase” ionization detection
(eg. ZEPLIN collaboration – dark matter search)

- Drift ionization electrons from LXe into Xe gas, where they will produce scintillation light as they drift. *Photon statistics can be much better than primary electron statistics – a way to avoid ultra-low noise charge sensitive preamps.* Also, the total secondary light signal depends only on the voltage drop in the gas (above a pressure dependent threshold).

- Investigating the use of LAAPDs for light collection – high Q.E., low radioactivity (compared to PMTs, but noise is higher).

- Simulations of light collection efficiency underway. Test cell design underway (Stanford campus test cell adapted for preliminary studies). Secondary light has been observed.

An experimental facility for EXO

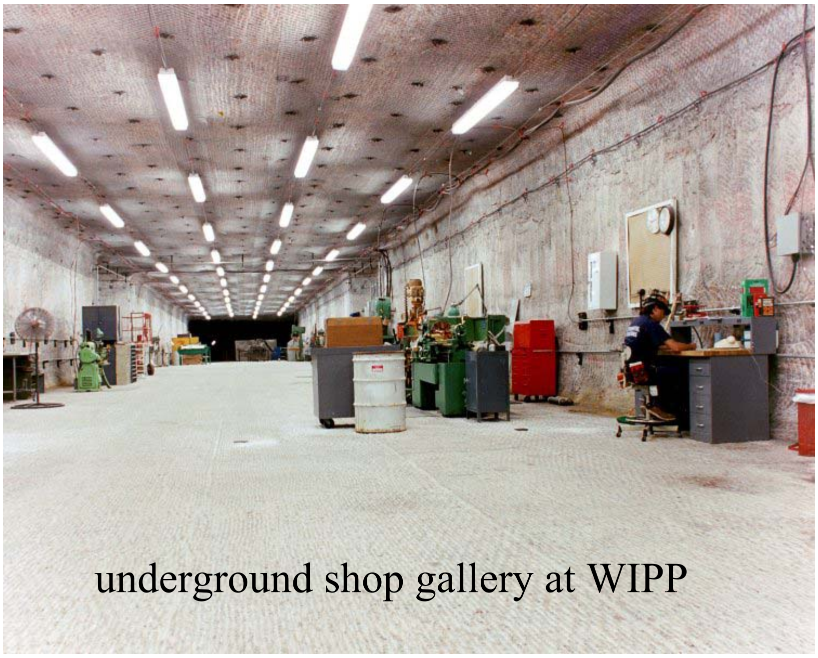


WIPP : Waste Isolation Pilot Plant
Carlsbad NM

Excavated in underground salt – lower U/Th activity. ~2,000 m.w.e. depth

Is the WIPP site essential – Are there alternatives ?

While we have focused on WIPP so far, and the site has some desirable features (low bkgrds in salt), it is not essential. Any site with > 700 m.w.e. overburden would be suitable. The deep rock mines (eg. Soudan) would be an alternative – trading off lower cosmic ray rates against higher Radon backgrounds.



underground shop gallery at WIPP

At this time we have detailed plans for the experimental area that we have been tentatively assigned. Modular rooms will be constructed as clean rooms (various grades up to class 100 for the inner detector chamber), assembly areas, and work areas. Utilities include UPS for cryogen safety.

Performance Projections

Building on previous Xe-based experiments, and using the available nuclear physics calcs.

- Assume a TPC with Ba tagging has no radioactivity background
- Use initially (a) conservative Gotthard resolution $\sigma_E = 2.8\%$, (b) $\sigma_E = 2.0\%$

Isotop	Total mass (kg)	Enr. grade (%)	Det. eff. (%)	Meas. Time (yr)	Bkgd	$T^{0\nu\beta\beta}_{1/2}$ (yr)	< m > (eV)	
							QRPA	NSM
^{76}Ge	11	86	75	2.2	0.3	1.9 10^{25}	0.35	1.0
^{136}Xe	3.3	63	22	1.5	2.5	4.4 10^{23}	2.2	5.2
^{130}Te	6.8	34	84.5	0.125	8.1	1.4 10^{23}	1.8	3.8
^{136}Xe (a)	1000	90	70	5	1.8 ev	8.3 10^{26}	0.051	0.14
^{136}Xe (b)	10,000	90	70	10	5.5 ev	1.3 10^{28}	0.013	0.037

R&D efforts are underway.
If we are successful, EXO
should reach a sensitivity of 10's of meV

EXO R&D Highlights : FY 2002 (and earlier)

Xenon purification system (for long electron drift)

Zr getter&distillation system operated, XPM sees ~1 ms lifetimes

Construction of probe test cell (for electrostatic ion capture)

metal tipped probe with or w/o dielectric coating. Am^{241} α's seen.

Production of U^{230} Radium/Thorium ion source (for test cell)

UC Davis cyclotron and LLNL radiochemist used.

Florescence laser and ion trap system constructed and operated

single Ba^{+} ion observed in trap in vacuo. S/N improved.

Energy resolution test cell constructed and operated

ionization and scintillation signals collected and correlated.

Enriched Xe^{136} obtained from Russian Minatom facilities

80% enrichment confirmed, 100 kg received, 100 kg on order

Testing and procurement of low background materials

EXO R&D Highlights : FY 2003

Xenon purity monitor upgrade

Lengthen XPM drift gap for sensitivity to >1 ms lifetimes

Probe test cell experiments : ion capture, mobility measurements

Th and Ra ions captured, Th mobility meas. “Cryo probe” prototype.

Large Area Avalanche Photodiodes testing program

LAAPDs performance in LXe tested in preparation for prototype use

Closed-loop HFE refrigerator commissioning

Cooling system alternative to LN_2 - bkgrd shielding

Energy resolution test cell observes ion./scint. correlations

Improved resolution demonstrated with ion./scint. linear combination

Florescence laser and ion trap upgrade

New lasers, new trap, improved stability. Prepare for Xe gas test.

Detailed design of WIPP experimental area layout

EXO: FY 2004 - 2005

…prototype operation

Design, construction of 100-200 kg prototype

Operating prototype 1.5-2 years from now, w/o Ba tagging.

Complete preparation of WIPP exp. area for prototype

…continuing R&D, & proceed to SLAC proposal

Demonstrate viable laser system, incl. possible Xe buffer gas.

S/N optimized, trap design suitable for ion delivery

Demonstrate viable ion capture system

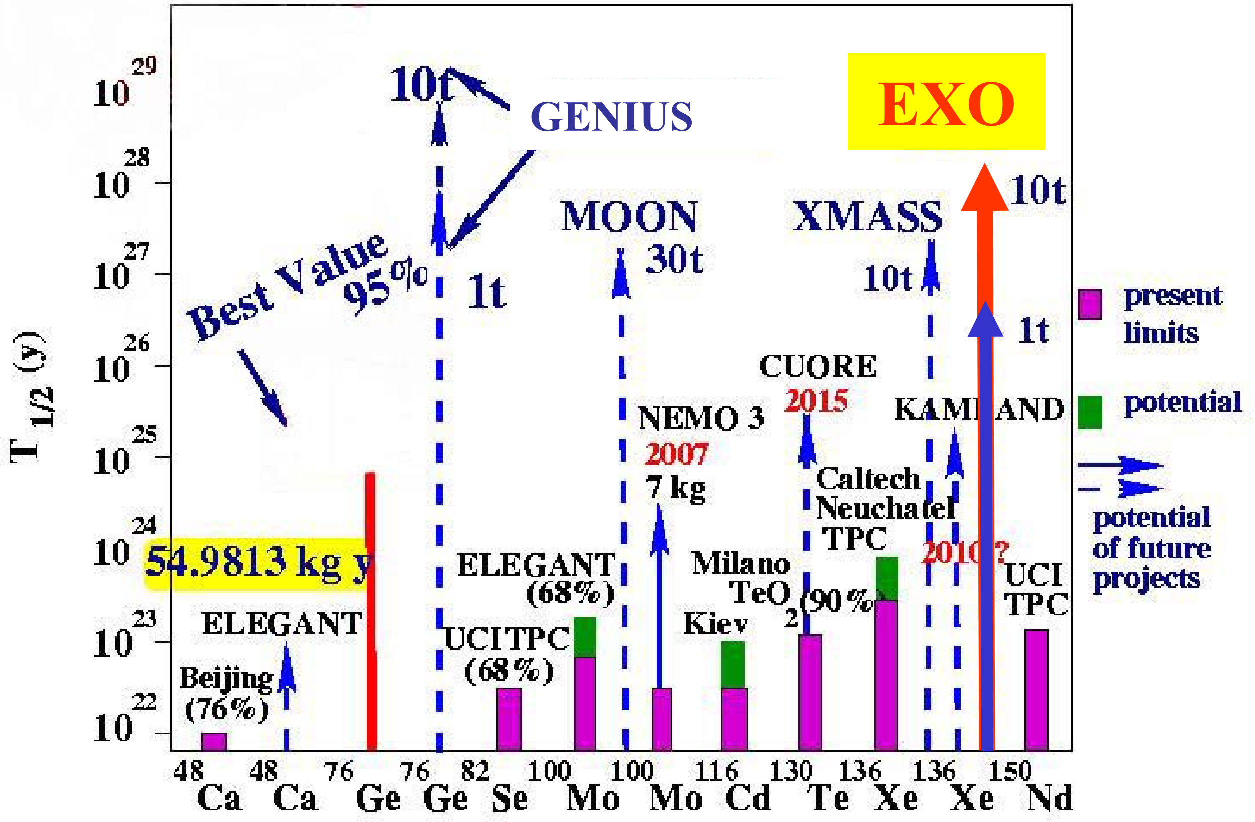
High efficiency, suitable design for large scale detector

Pending R&D results, design/build large detector

Complete system, electronics design.

Continuing xenon acquisition

Worldwide R&D Efforts
Performance Projections



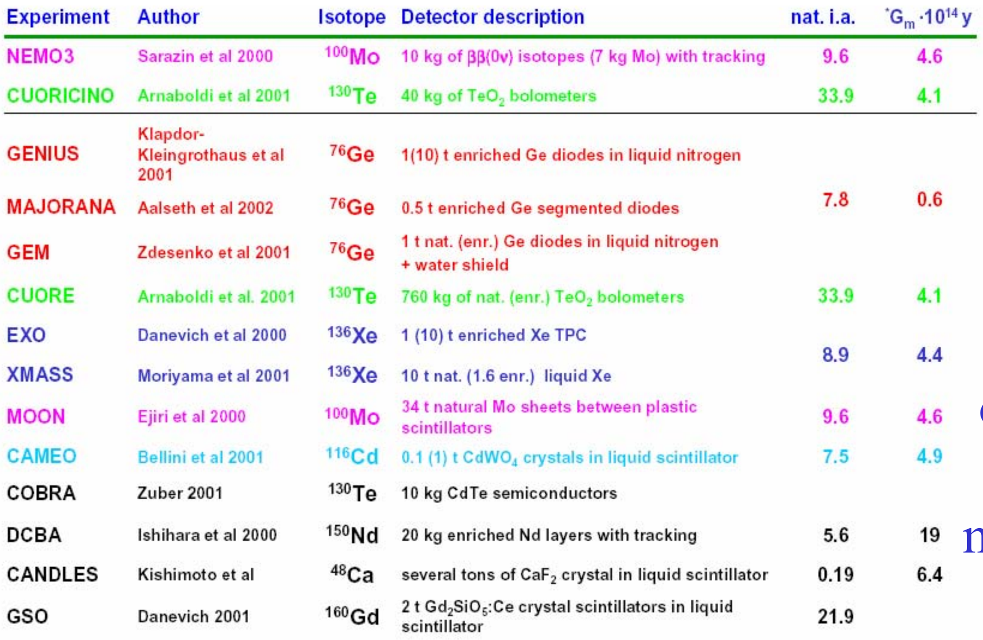
H.V. Klapdor-Kleingrothaus et al. Mod.Phys.Lett.A16(2001)2409-2420

H.V. Klapdor-Kleingrothaus "60 Years of Double Beta Decay", World Scientific (2001)

A number of "ton-class" $0\nu\beta\beta$ experiments are under study.

Due to the importance of a positive signal for Majorana neutrinos, confirmation in more than one isotope would be highly desirable.

Question : Comparison with other potential experiments ?

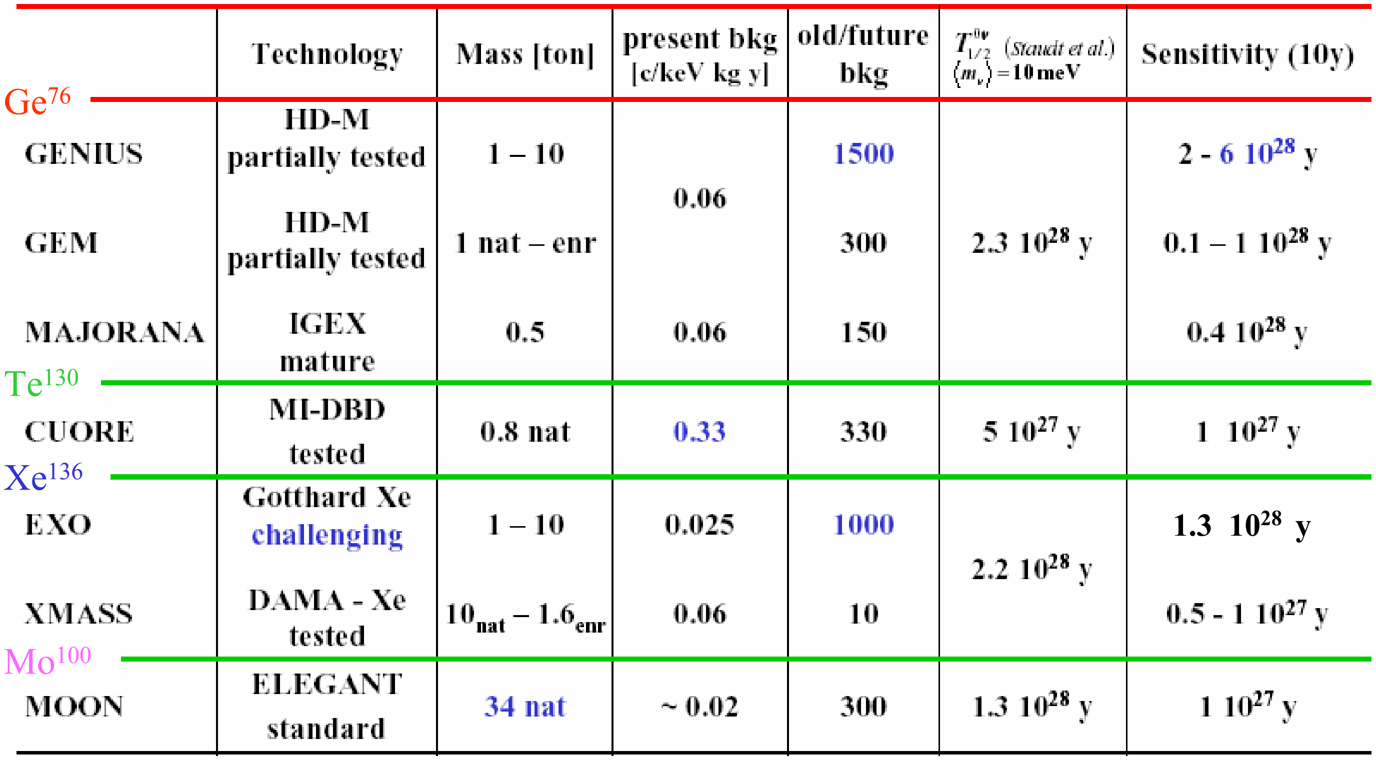


Experiment	Author	Isotope	Detector description	nat. i.a.	$^{\prime}G_m \cdot 10^{14}$ y
NEMO3	Sarazin et al 2000	^{100}Mo	10 kg of $\beta\beta(0\nu)$ isotopes (7 kg Mo) with tracking	9.6	4.6
CUORICINO	Arnaboldi et al 2001	^{130}Te	40 kg of TeO_2 bolometers	33.9	4.1
GENIUS	Klapdor-Kleingrothaus et al 2001	^{76}Ge	1(10) t enriched Ge diodes in liquid nitrogen	7.8	0.6
MAJORANA	Aalseth et al 2002	^{76}Ge	0.5 t enriched Ge segmented diodes		
GEM	Zdesenko et al 2001	^{76}Ge	1 t nat. (enr.) Ge diodes in liquid nitrogen + water shield		
CUORE	Arnaboldi et al. 2001	^{130}Te	760 kg of nat. (enr.) TeO_2 bolometers	33.9	4.1
EXO	Danevich et al 2000	^{136}Xe	1 (10) t enriched Xe TPC	8.9	4.4
XMASS	Moriyama et al 2001	^{136}Xe	10 t nat. (1.6 enr.) liquid Xe		
MOON	Ejiri et al 2000	^{100}Mo	34 t natural Mo sheets between plastic scintillators	9.6	4.6
CAMEO	Bellini et al 2001	^{116}Cd	0.1 (1) t $CdWO_4$ crystals in liquid scintillator	7.5	4.9
COBRA	Zuber 2001	^{130}Te	10 kg CdTe semiconductors		
DCBA	Ishihara et al 2000	^{150}Nd	20 kg enriched Nd layers with tracking	5.6	19
CANDLES	Kishimoto et al	^{48}Ca	several tons of CaF_2 crystal in liquid scintillator	0.19	6.4
GSO	Danevich 2001	^{160}Gd	2 t Gd_2SiO_5:Ce crystal scintillators in liquid scintillator	21.9	

The sought-for lifetimes do not differ by much from exp. to exp.

The Ge^{76} exps. offer good E resol. but nevertheless must improve bkgrd by factor >1000.

Especially for the ton scale proposals, background control is critical, and will be a limiting factor for all experiments – only EXO proposes a qualitatively different approach to bkgrnd control. Xe also has advantages for bulk enrichment/purity.



	Technology	Mass [ton]	present bkg [c/keV kg y]	old/future bkg	$T^{0\nu}_{1/2}$ (Staudt et al.) $\langle m_\nu \rangle = 10$ meV	Sensitivity (10y)
Ge^{76}						
GENIUS	HD-M partially tested	1 – 10	0.06	1500	2.3 10^{28} y	2 - 6 10^{28} y
GEM	HD-M partially tested	1 nat – enr		300		0.1 – 1 10^{28} y
MAJORANA	IGEX mature	0.5	0.06	150		0.4 10^{28} y
Te^{130}						
CUORE	MI-DBD tested	0.8 nat	0.33	330	5 10^{27} y	1 10^{27} y
Xe^{136}						
EXO	Gotthard Xe challenging	1 – 10	0.025	1000	2.2 10^{28} y	1.3 10^{28} y
XMASS	DAMA - Xe tested	$10_{nat} – 1.6_{enr}$	0.06	10		0.5 - 1 10^{27} y
Mo^{100}						
MOON	ELEGANT standard	34 nat	~ 0.02	300	1.3 10^{28} y	1 10^{27} y