The Enriched Xenon Observatory for double beta decay

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Overview

- Neutrinoless double beta decay
- EXO concept
- The EXO-200 detector
- Barium ion identification

Double beta decay and EXO

Extremely rare decay of some nuclei:

$$(A, Z) \rightarrow (A, Z\text{-}2) + 2e^{-} \; (+\, 2\nu_e)$$

For EXO: $^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Ba}^{++} + 2e^{-} \; (+\, 2\nu_e)$

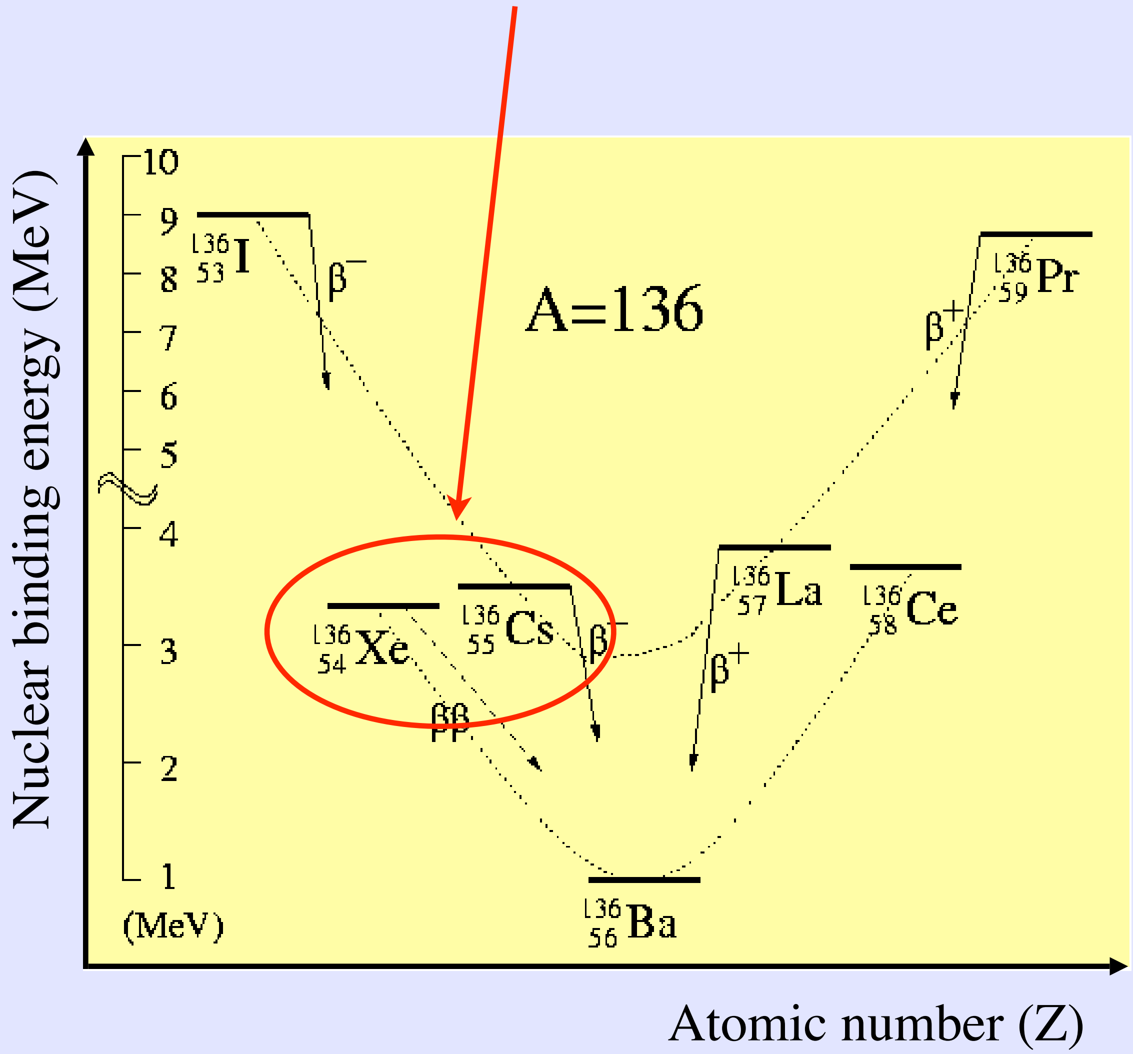
positively identify daughter via optical spectroscopy of Ba^{+}

detect the 2 electrons (ionization + scintillation in xenon detector)

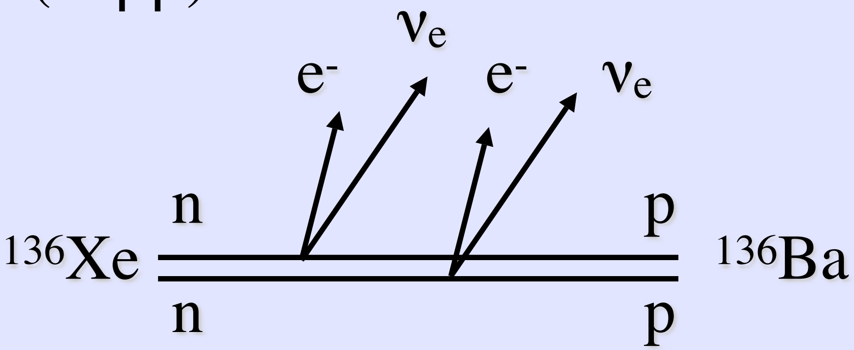
[M. Moe, Phys. Rev. C 44 (1991) R931]

Double beta decay

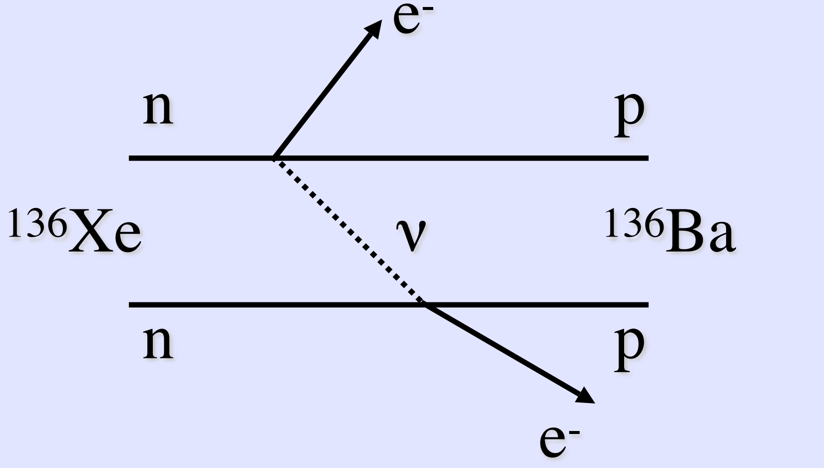
a second-order process detectable when single β-decay is energetically forbidden (even-even nuclei)



standard electroweak process ($2\nu\beta\beta$):

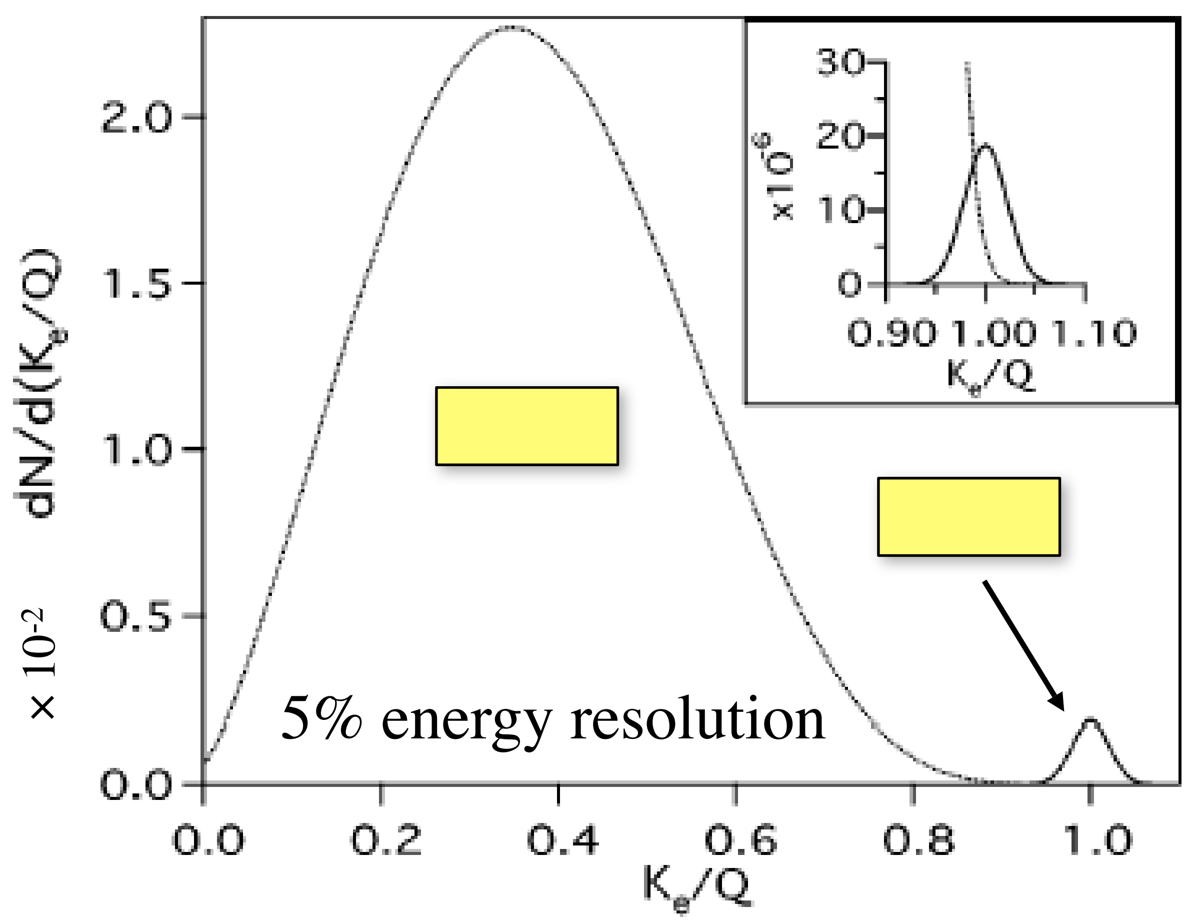


neutrinoless process ($0\nu\beta\beta$, $\Delta L=2$):



Observable for EXO

In the ideal case of perfectly efficient detection of the both the electrons and the Ba daughter, the only background to $0\nu\beta\beta$ is the spillage from the $2\nu\beta\beta$ channel due to finite energy resolution



5% energy resolution

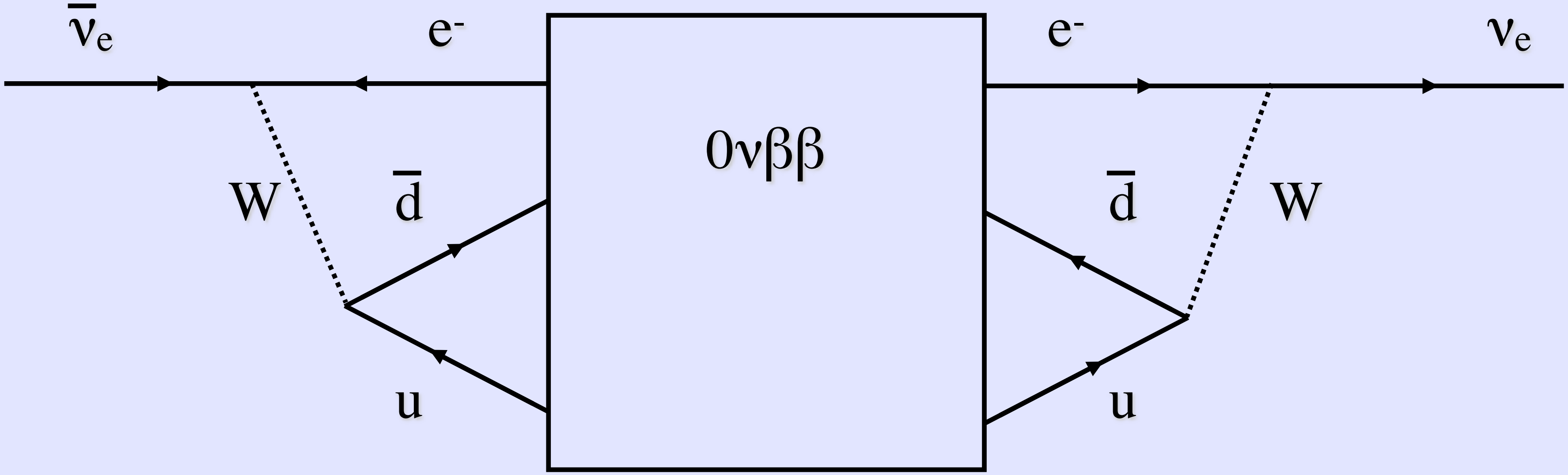
for gaussian profiles, leakage of $2\nu\beta\beta$ events into $0\nu\beta\beta$ peak goes like the 5.8th power of the energy resolution.

[Elliot and Vogel, Ann. Rev. Nucl. Part. Sci. 52 (2002) 115]

Majorana neutrinos

Neutrinoless double beta decay can only occur if neutrinos are their own antiparticles ($\nu = \bar{\nu}$):

[Schechter and Valle, Phys. Rev. D 25 (1982) 2951]



Neutrinoless double beta decay ⇒ neutrinos are Majorana particles regardless of the underlying mechanism

Why double beta decay?

If observed, neutrinoless double beta decay is the sign of new physics (although not completely unexpected new physics)

- Are neutrinos Majorana particles?
- What is the absolute mass scale of neutrinos?
- Other mechanisms?   (complementary to other experiments)

Massive neutrinos

We know neutrinos oscillate between weak eigenstates, which happens because their weak and energy (mass) eigenstates do not coincide (i.e. the 3 mass eigenstates cannot be all zero):

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} \, |\nu_i\rangle$$

From oscillation experiments (solar, atmospheric, reactor, accelerator) we know only the **mass differences** between neutrino mass states:

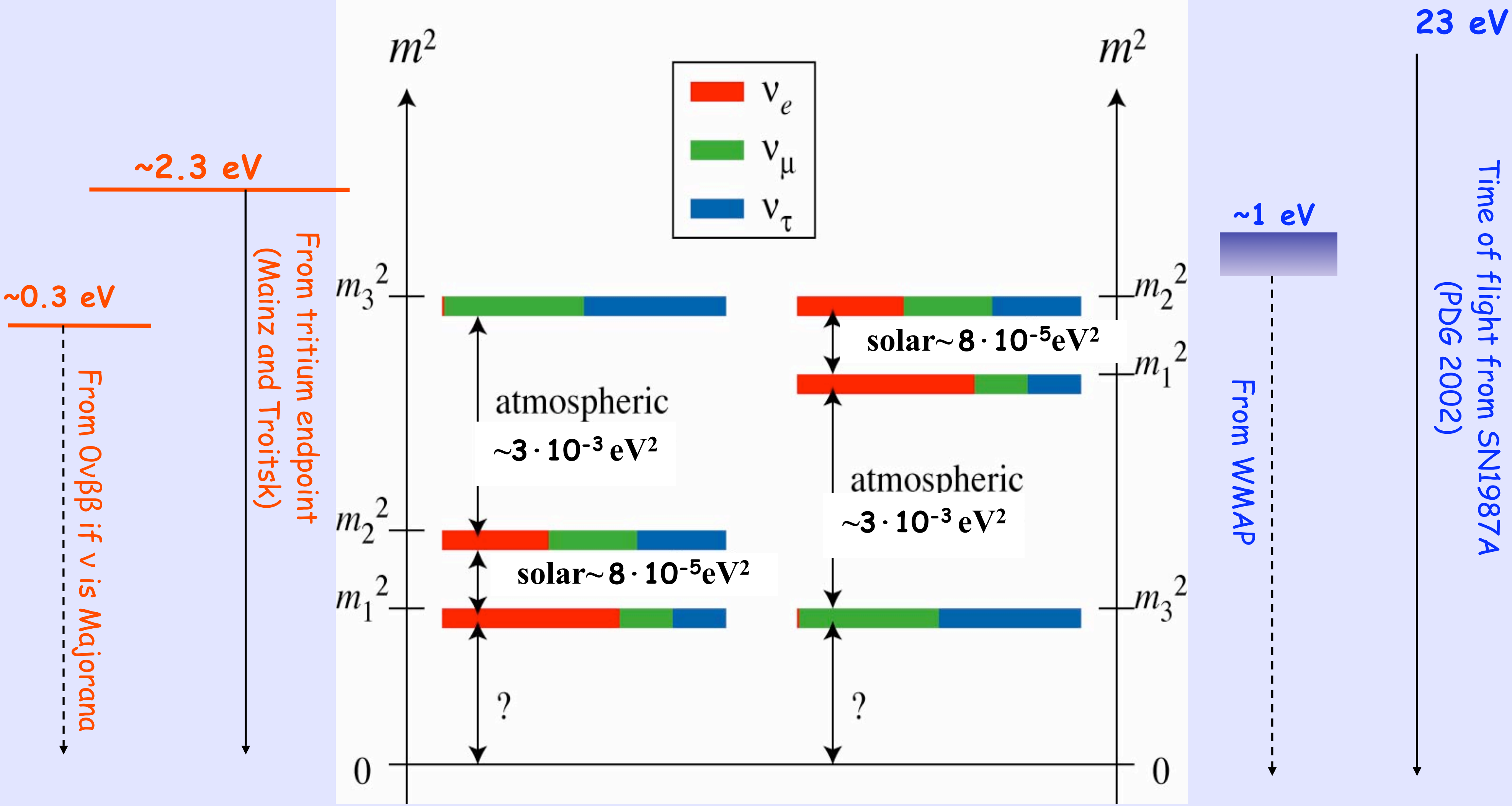
$\Delta m^2_{12} \sim 8\times10^{-5}$ eV^2
$\tan^2\vartheta_{12} \sim 0.4$ (LMA-MSW)
(solar neutrino experiments, KamLAND)

$\Delta m^2_{23} \sim 3\times10^{-3}$ eV^2
$\sin^2\vartheta_{23} > 0.9$
(SuperK + Kamiokande, K2K, MINOS)

$\Delta m^2 \sim 1$ eV^2
$\sin^2\vartheta \sim 3\times10^{-3}$
(LSND, miniBooNE?)

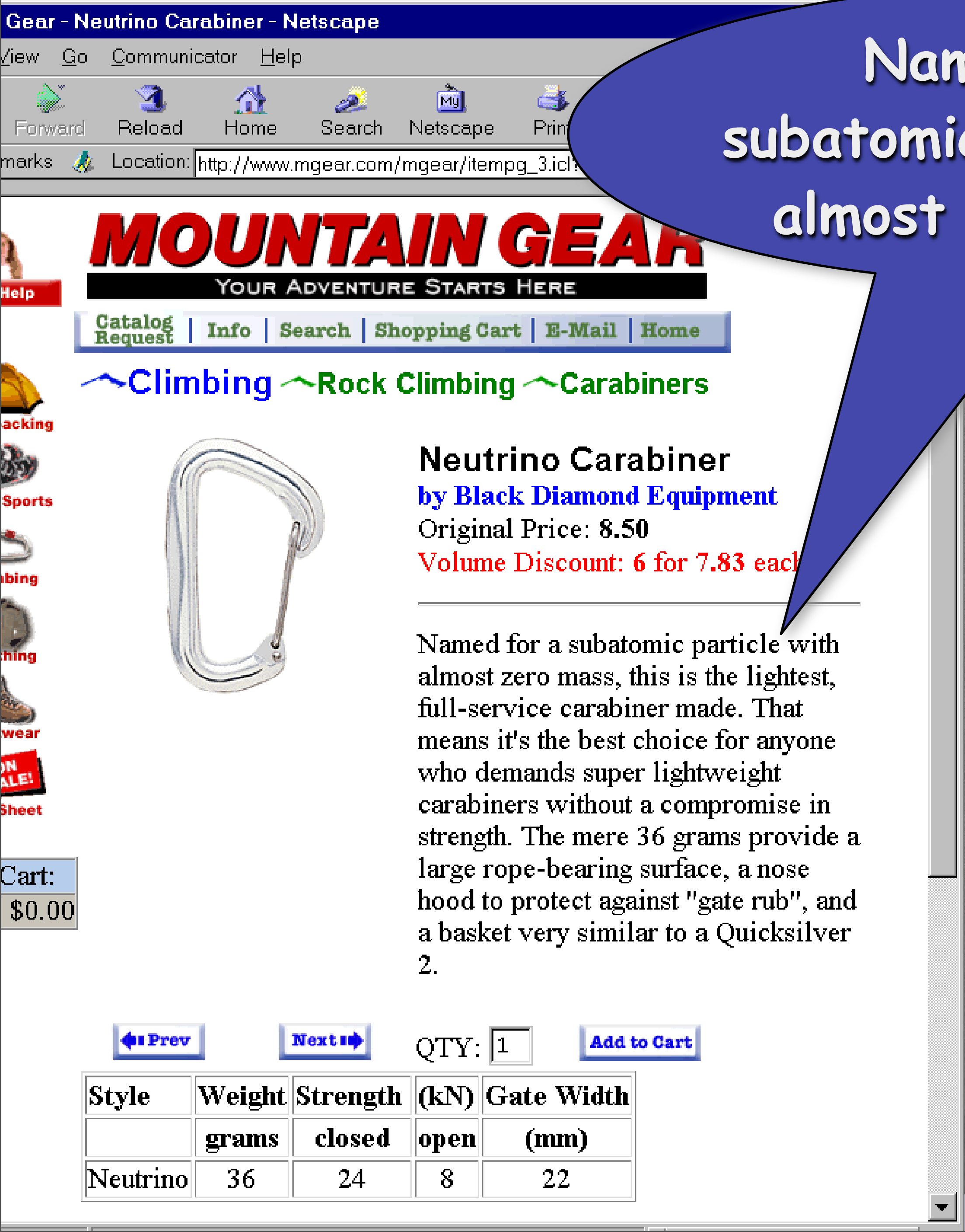
Neutrino masses

We don’t know if neutrino masses are degenerate (all very different from zero) and whether their hierarchy is direct or inverted



Neutrinos save lives!

Named for a subatomic particle with almost zero mass …



Climbing Rock Climbing Carabiners

Neutrino Carabiner

by Black Diamond Equipment

Original Price: **8.50**

Volume Discount: **6** for **7.83** each

Named for a subatomic particle with almost zero mass, this is the lightest, full-service carabiner made. That means it's the best choice for anyone who demands super lightweight carabiners without a compromise in strength. The mere 36 grams provide a large rope-bearing surface, a nose hood to protect against "gate rub", and a basket very similar to a Quicksilver 2.

QTY: 1

Style	**Weight**	**Strength**	**(kN)**	**Gate Width**
	grams	**closed**	**open**	**(mm)**
Neutrino	36	24	8	22

Double beta decay rate

$$\langle m_{\beta\beta} \rangle = \left(T_{1/2}^{0\nu\beta\beta} G^{0\nu\beta\beta}(Q,Z) \left| M_{nucl} \right|^2 \right)^{-1/2}$$

M_{nucl} can be calculated within particular nuclear models (~ O(1))

$G^{0\nu\beta\beta}(Q,Z)$ a known phase space factor

$T_{1/2}^{0\nu\beta\beta}$ is the measured quantity [Hz]

$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^{3} U_{ei}^2 m_i e^{i\alpha_i} \right|$$

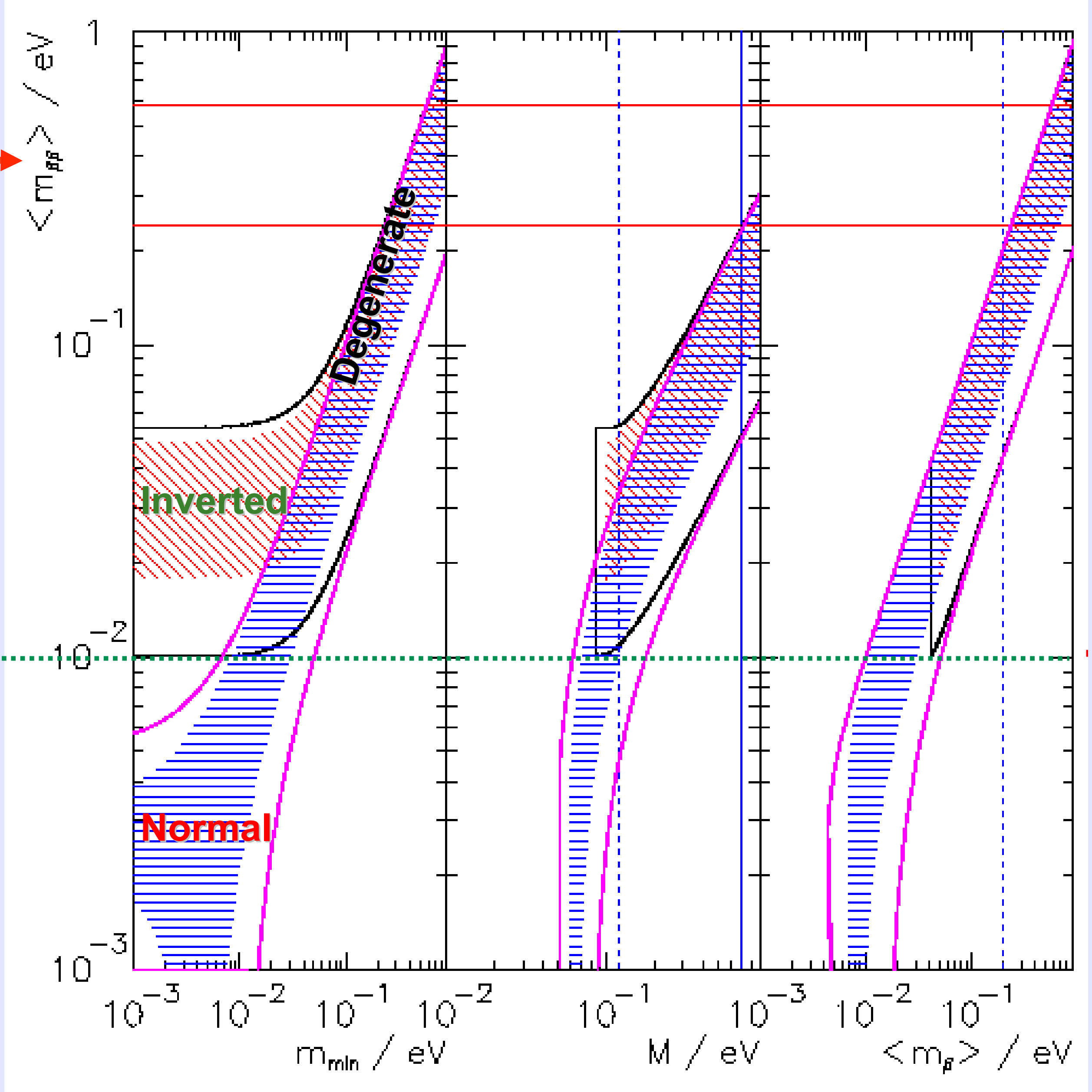
effective Majorana ν mass
(ϵ_i = ±1 if CP is conserved)

For reference, in direct kinematic searches of neutrino mass in β-decay:

$$\langle m_\beta \rangle^2 = \Sigma_i |U_{ei}|^2 m_i^2$$

Double beta decay effective neutrino mass

where we stand →



^{76}Ge: 5.8 × 10^{28} years

^{100}Mo: 5.8 × 10^{28} years

^{136}Xe: 4.8 × 10^{28} years

[Rodin et al., Phys. Rev. C, 68 (2003)]

Double beta decay candidate isotopes

Candidate	Q (MeV)	Abundance (%)
$^{48}\mathrm{Ca} \rightarrow {}^{48}\mathrm{Ti}$	4.271	0.187
$^{76}\mathrm{Ge} \rightarrow {}^{76}\mathrm{Se}$	2.040	7.8
$^{82}\mathrm{Se} \rightarrow {}^{82}\mathrm{Kr}$	2.995	9.2
$^{96}\mathrm{Zr} \rightarrow {}^{96}\mathrm{Mo}$	3.350	2.8
$^{100}\mathrm{Mo} \rightarrow {}^{100}\mathrm{Ru}$	3.034	9.6
$^{110}\mathrm{Pd} \rightarrow {}^{110}\mathrm{Cd}$	2.013	11.8
$^{116}\mathrm{Cd} \rightarrow {}^{116}\mathrm{Sn}$	2.802	7.5
$^{124}\mathrm{Sn} \rightarrow {}^{124}\mathrm{Te}$	2.228	5.64
$^{130}\mathrm{Te} \rightarrow {}^{130}\mathrm{Xe}$	2.533	34.5
$^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Ba}$	2.459	8.9
$^{150}\mathrm{Nd} \rightarrow {}^{150}\mathrm{Sm}$	3.367	5.6

$Q > 2$ MeV:

- above most natural radioactive backgrounds
- higher rates
- need isotopic enrichment for all cases (except ^{130}Te)

Current limits on 0νββ

Candidate nucleus	Detector type	(kg yr)	Present $T_{1/2}^{0\nu\beta\beta}$ (yr)	<m> (eV)
^{48}Ca			$>9.5*10^{21}$ (76%CL)	(Phys. Lett. B 586 (2004) 198)
^{76}Ge	Ge diode	~30	$>1.9*10^{25}$ (90%CL)	$<0.39^{+0.17}_{-0.28}$
^{82}Se			$>9.5*10^{21}$ (90%CL)	
^{100}Mo			$>5.5*10^{22}$ (90%CL)	
^{116}Cd			$>7.0*10^{22}$ (90%CL)	
^{128}Te	TeO_2 cryo	~3	$>1.1*10^{23}$ (90%CL)	
^{130}Te	TeO_2 cryo	~3	$>2.1*10^{23}$ (90%CL)	<1.1 - 2.6
^{136}Xe	Xe scint	~10	$>1.2*10^{24}$ (90%CL)	<2.9
^{150}Nd			$>1.2*10^{21}$ (90%CL)	
^{160}Gd			$>1.3*10^{21}$ (90%CL)	

Adapted from the Particle Data Group 2003

EXO strategy

Goal: ton-scale enriched Xe (80% ^{136}Xe) time projection chamber (TPC) with scintillation light collection and ^{136}Ba^{+} identification (possibility unique to ^{136}Xe)

Phased approach:

- EXO-200 "prototype" detector (200 kg of enriched xenon, 80% ^{136}Xe, no Ba tagging)
- Ba identification R&D as a parallel effort
- merge into one proposal

EXO-200

EXO-200 is a LXe TPC with scintillation light readout that employes 200 kg of enriched xenon (80% ^{136}Xe)

→ EXO-200 has no $^{136}Ba^{+}$ identification ←

Goals:

- look for 0νββ decay of ^{136}Xe with competitive sensitivity and test backgrounds of large LXe detector at ~2000 m.w.e. depth ($T^{0\nu}_{1/2} > 6 \times 10^{25}$ y, current limit: $T^{0\nu}_{1/2} > 1.2 \times 10^{24}$ y)
- measure the standard 2νββ decay of ^{136}Xe ($Q = 2457.8 \pm 0.4$ keV) and measure its lifetime (best upper limit to date: $T^{2\nu}_{1/2} > 1 \times 10^{22}$ y)

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

- test LXe technology and enrichment on a large scale
- test TPC components, light readout (518 LAAPDs), and radioactivity of materials, xenon handling and purification

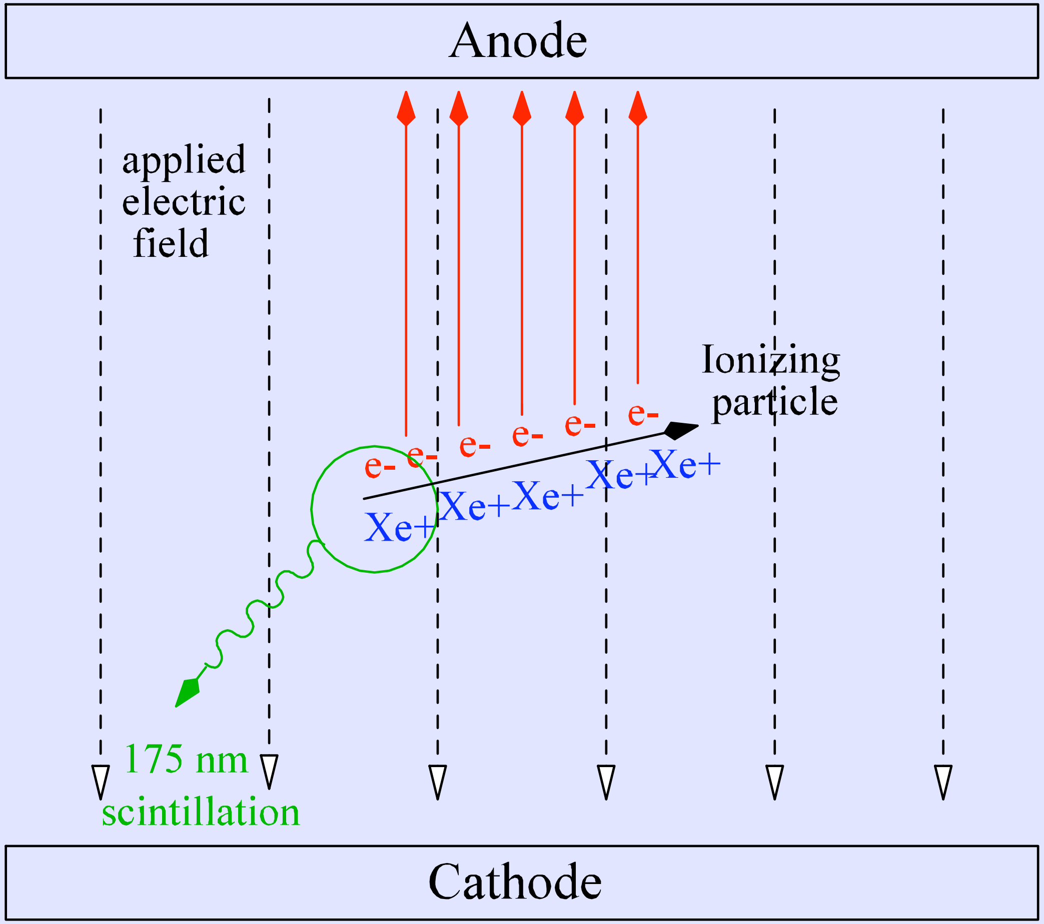
$2\nu\beta\beta$ event rate

$2\nu\beta\beta$ decay has never been observed in ^{136}Xe. Some of the lower limits on its half life are close to (and in one case below) the theoretical expectation.

	$T_{1/2}$ (yr)	evts/year in the 200kg prototype (no efficiency applied)
Experimental limit		
Leuscher et al	$>3.6 \cdot 10^{20}$	<1.3 M
Gavriljuk et al	$>8.1 \cdot 10^{20}$	<0.6 M
Bernabei et al	$>1.0 \cdot 10^{22}$	<48 k
Theoretical prediction		
QRPA (Staudt et al.) [$T_{1/2}^{max}$]	$=2.1 \cdot 10^{22}$	=23 k
QRPA (Vogel et al.)	$=8.4 \cdot 10^{20}$	=0.58 M
NSM (Caurier et al.)	$=2.1 \cdot 10^{21}$	=0.23 M

EXO-200 is very well positioned to solve this issue
(67 decays/day/100 kg)

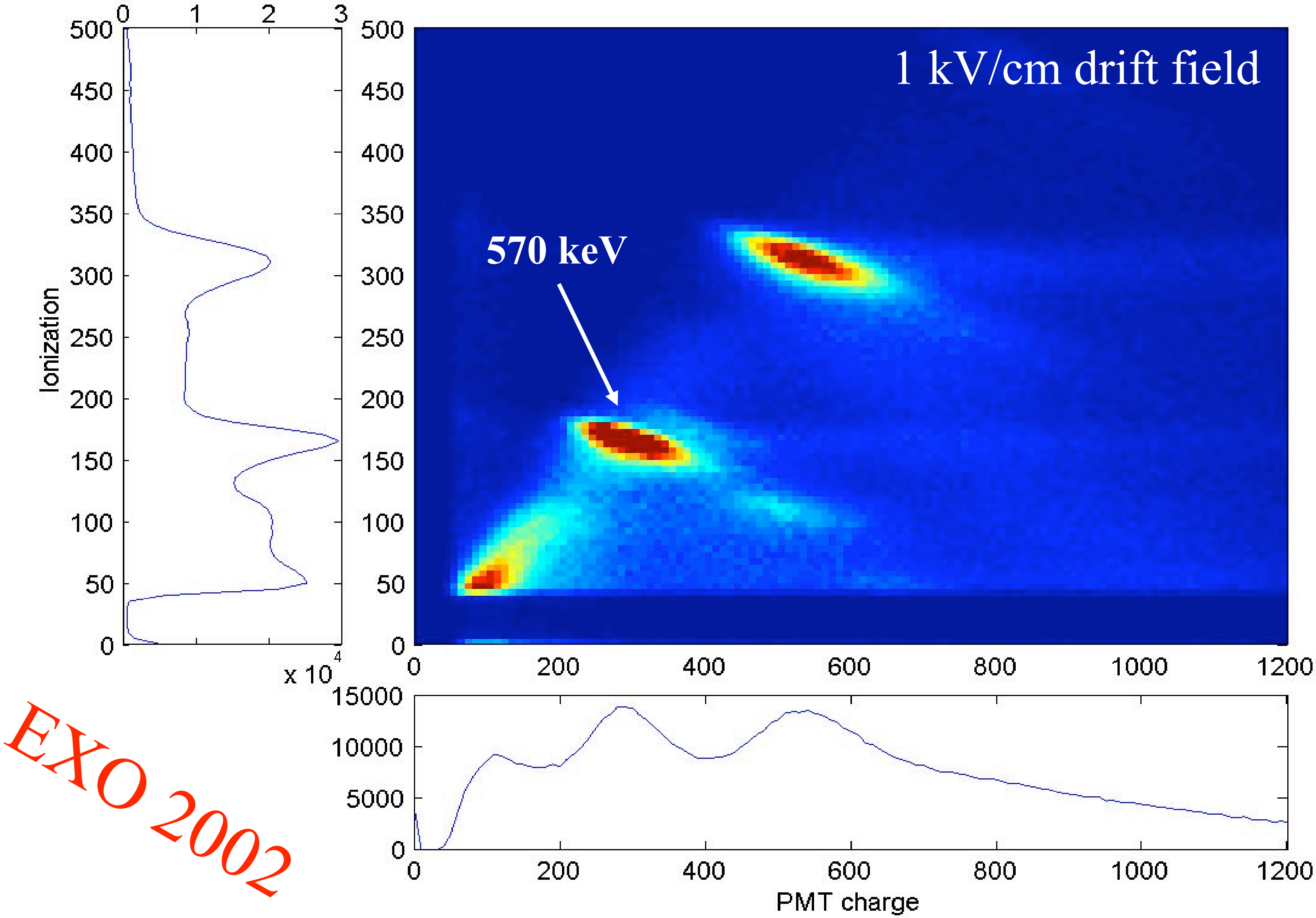
Dual readout: ionization and scintillation



The position of the event is reconstructed with two sets of wires at the anode (x-y) and the drift time (z). The position is important for external background identification and, in the future, for Ba ion identification

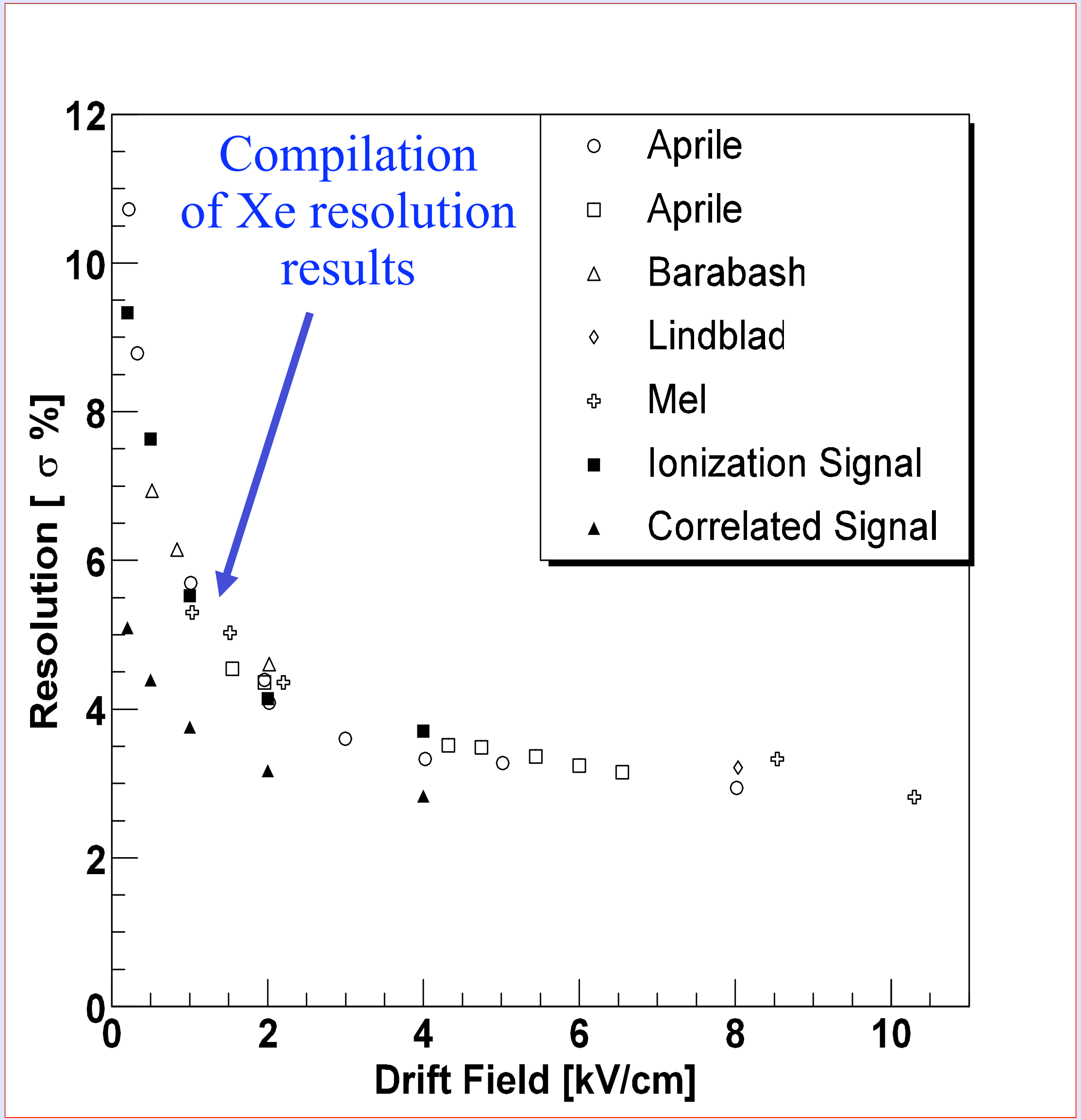
The event energy is measured by collecting the ionization charge on the anode and/or the amplitude of the scintillation light pulse (used as t=0 reference for the z drift).

Data show microscopic anticorrelation between inonization and scintillation



EXO 2002

Anti-correlated ionization and scintillation improves the energy resolution in LXe



[E. Conti et al., Phys. Rev. B: **68** 054201]

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% @ $Q_{\beta\beta}$

(twice as good as most recent xenon ββ0ν experiment)

EXO-200 will collect 3-4 times as much scintillation... possibly giving further improvement (one of the main technical tasks to be addressed)

Resolution improvement is very important to separate the 0νββ and 2νββ modes

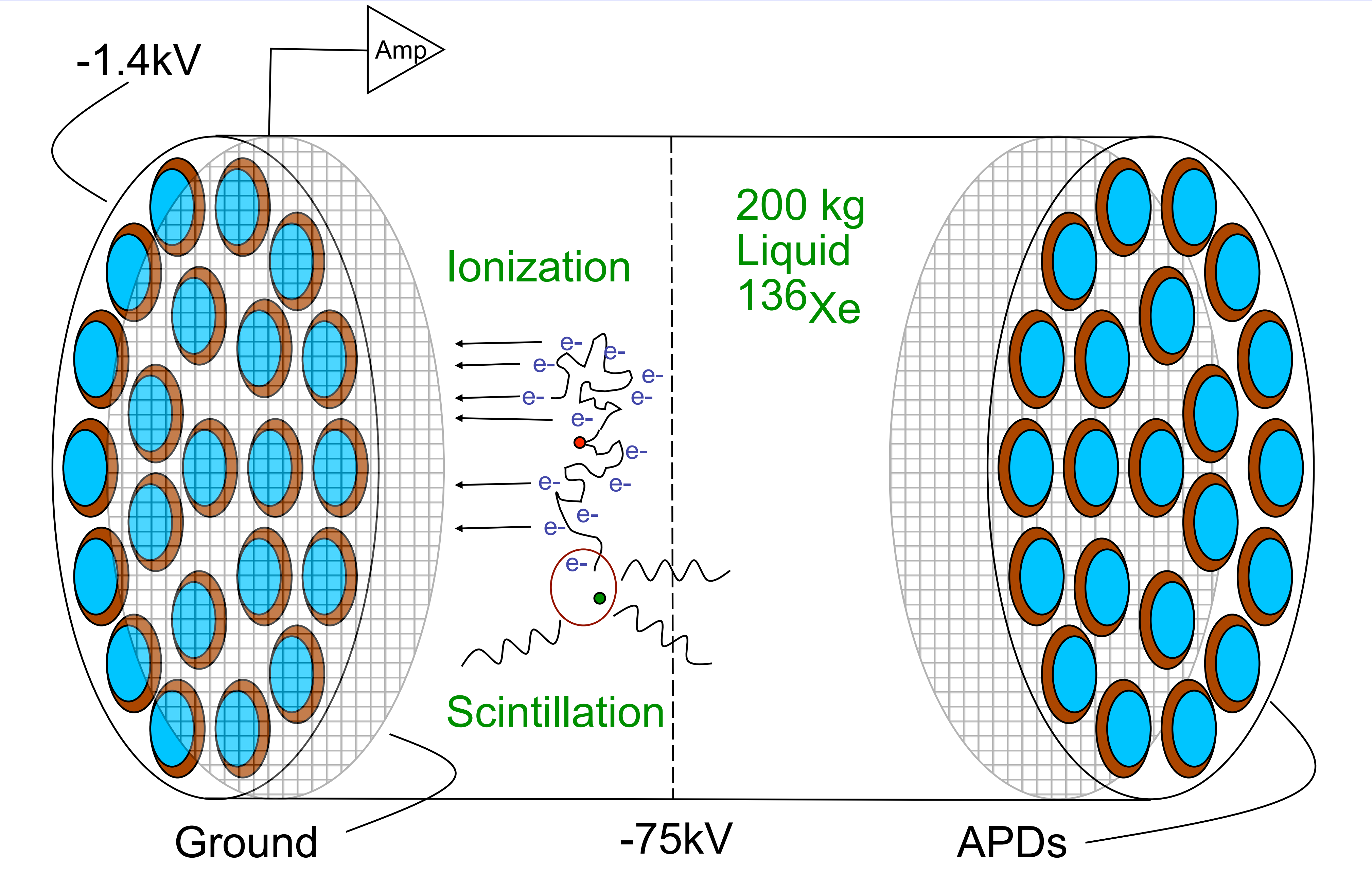
The EXO-200 TPC

- Two symmetric drift regions (16.5 cm long) along the cylinder axis, defined by a central cathode plane running at negative high voltage
    - max high voltage is 70 kV (3.5 kV/cm drift field); energy resolution improves with drift field, but possibly lower fields will allow for a better separation between events with 1 and 2 electrons (optimization is part of EXO-200's goals)
    - two sets of crossed anode wires (3 mm pitch, 100µm diameter) at each end of the cylinder, read out in groups of 3 (48 × 48 channels), for a total of 96 channels per ½ detector

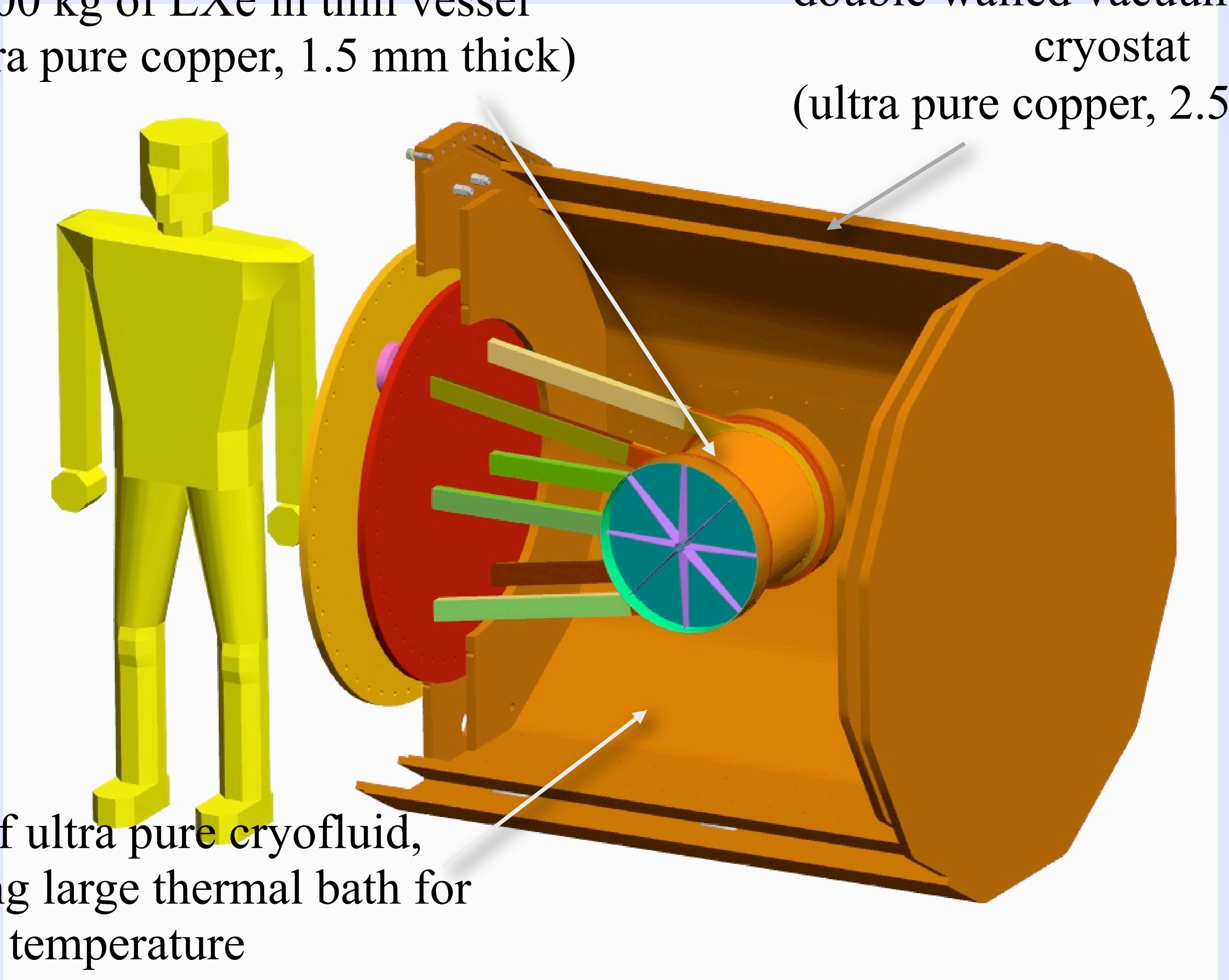
- 259 Large Area Avalache Photodiodes (LAAPDs) at each end of the cylinder, behind the anode wires (90% light transmission)
    - ”bare” devices, DUV sensitive (QE ~ 1 @ 175 nm)

- y-position given by induction signal on shielding grid.
  x-position and energy given by charge collection grid.
  APD array observes prompt scintillation to measure drift time and improve energy resolution.

EXO-200 detector schematic



The EXO-200 detector

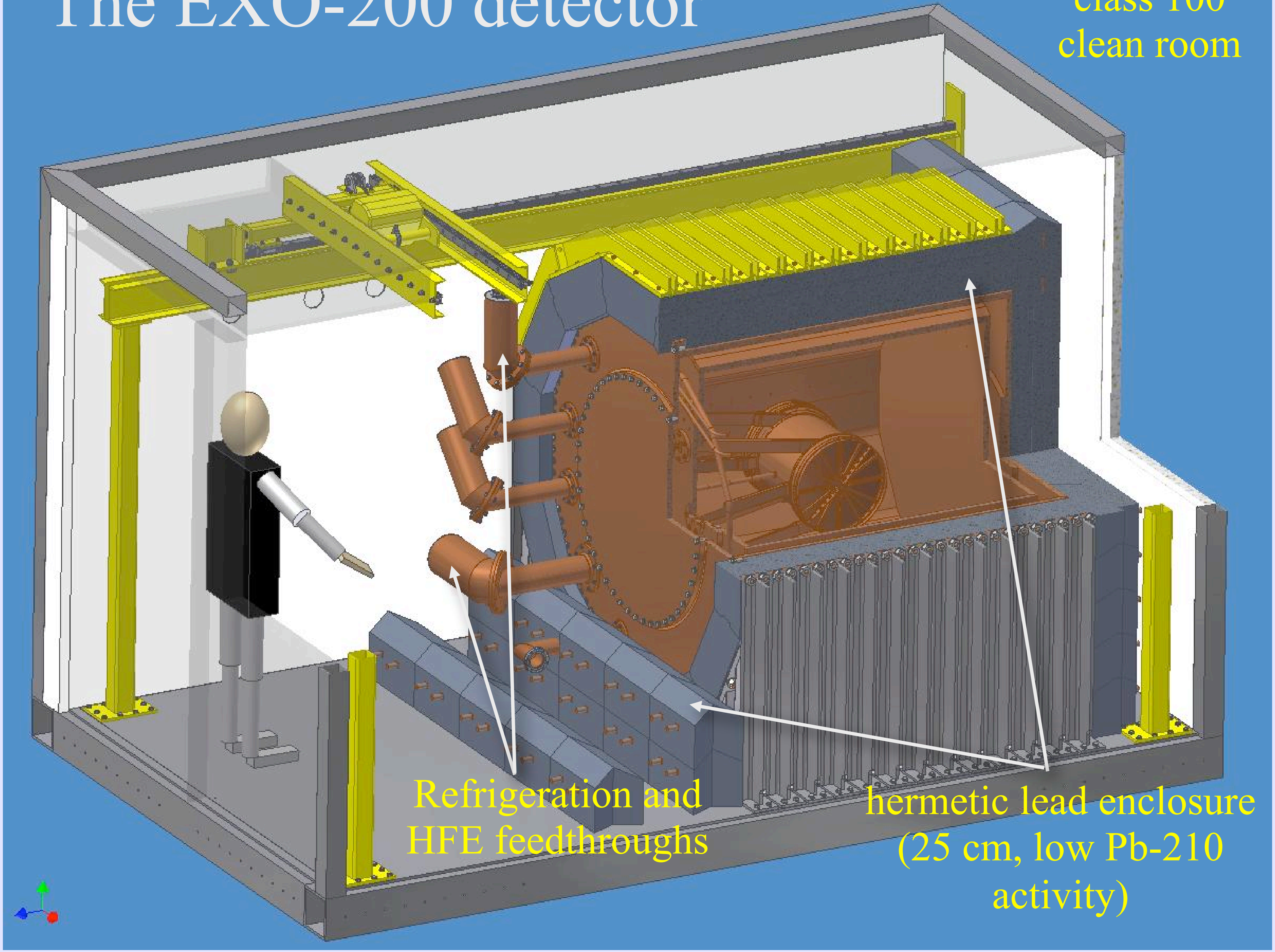


200 kg of LXe in thin vessel
(ultra pure copper, 1.5 mm thick)

double walled vacuum insulated cryostat
(ultra pure copper, 2.5 cm thick)

50 cm of ultra pure cryofluid, providing large thermal bath for uniform temperature
(3M HFE-7000, hydrofluoroether $C_3F_7OCH_3$)

The EXO-200 detector

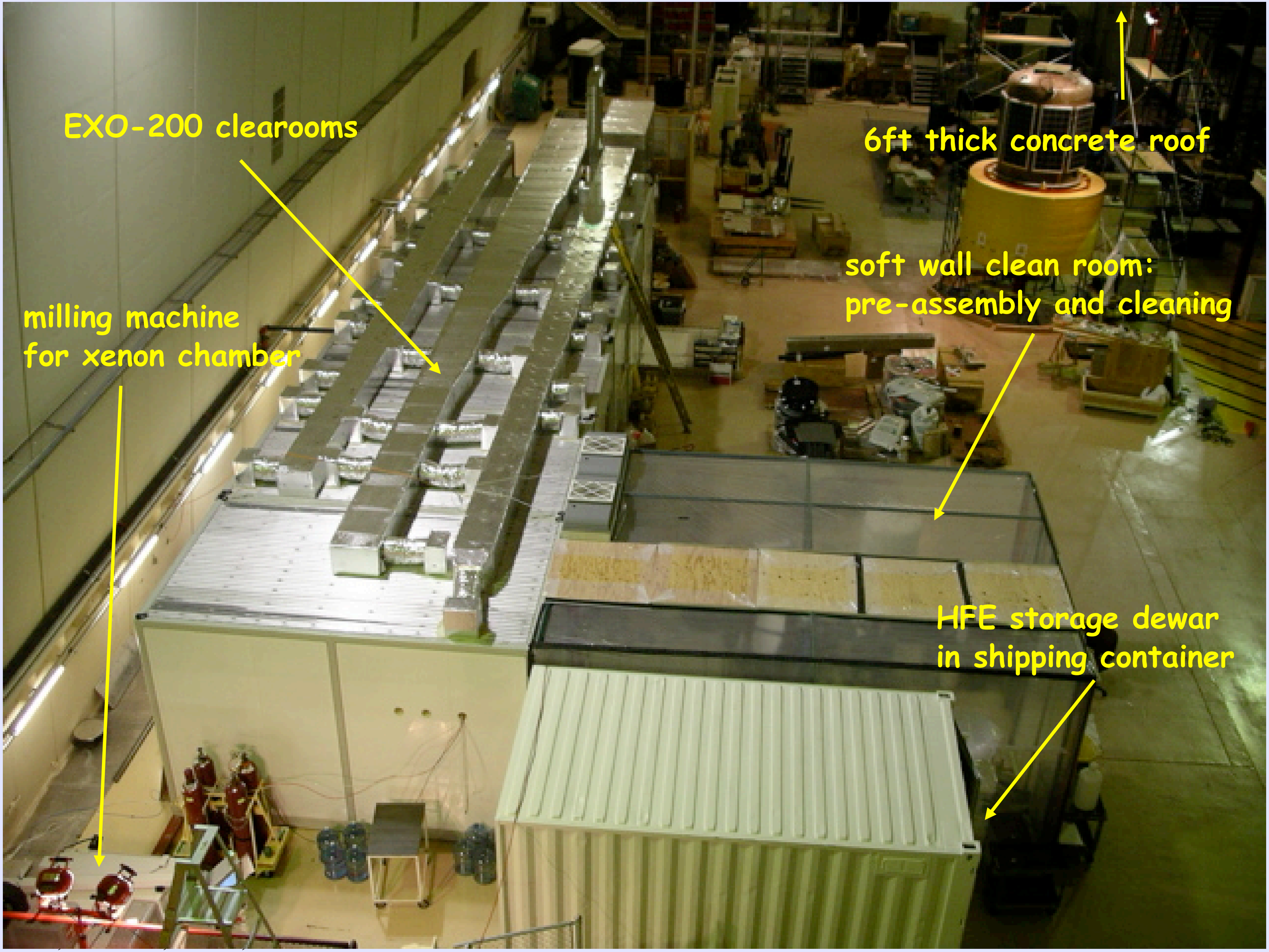


class 100 clean room

Refrigeration and HFE feedthroughs

hermetic lead enclosure (25 cm, low Pb-210 activity)

The EXO-200 modular clean rooms



EXO-200 clearooms

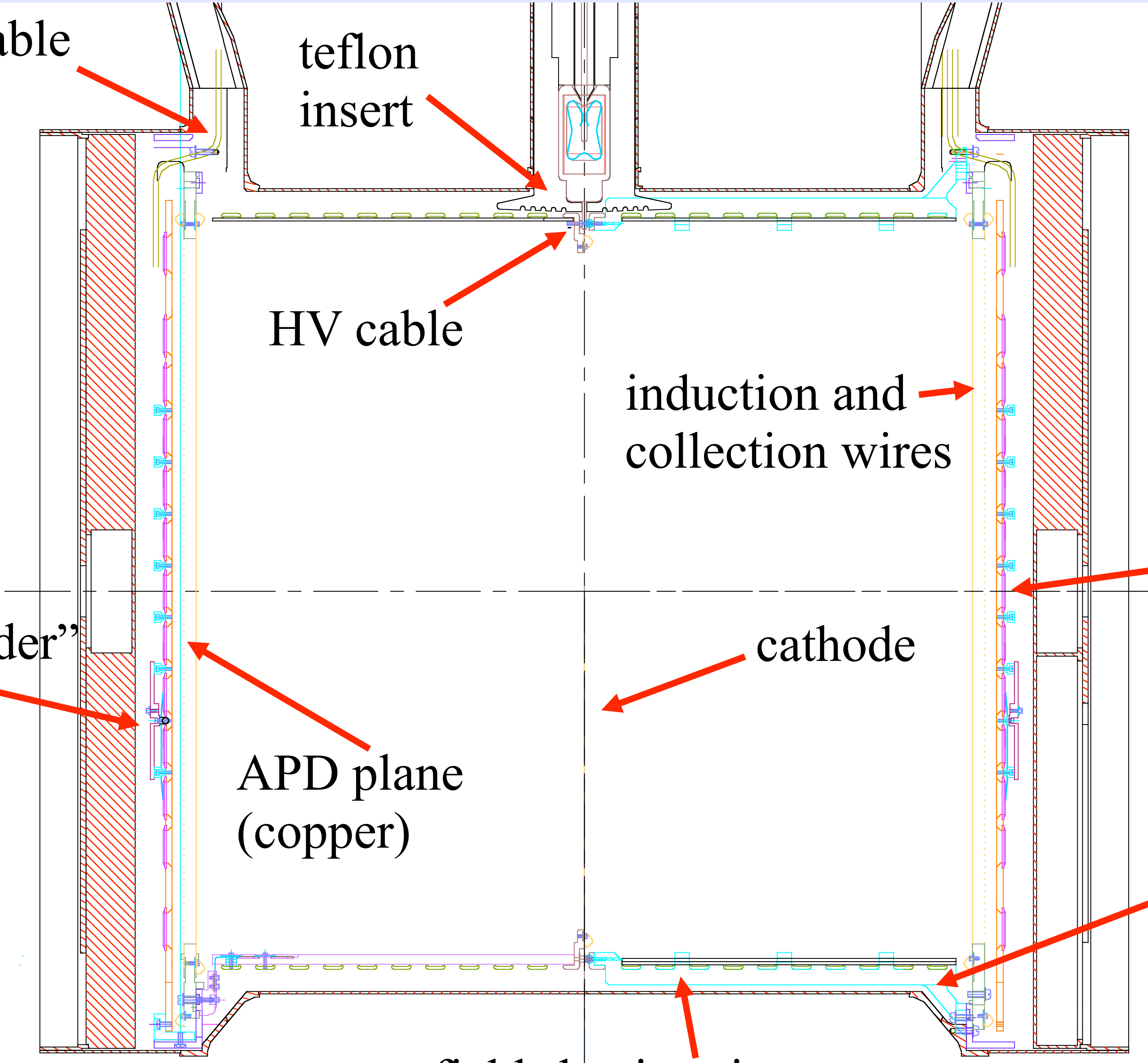
6ft thick concrete roof

soft wall clean room:
pre-assembly and cleaning

milling machine
for xenon chamber

HFE storage dewar
in shipping container

EXO-200 TPC



flex cable

teflon insert

copper TIG weld (ceriated rod)

HV cable

induction and collection wires

central APD substituted by teflon diffuser with optical fiber

APD “spider”

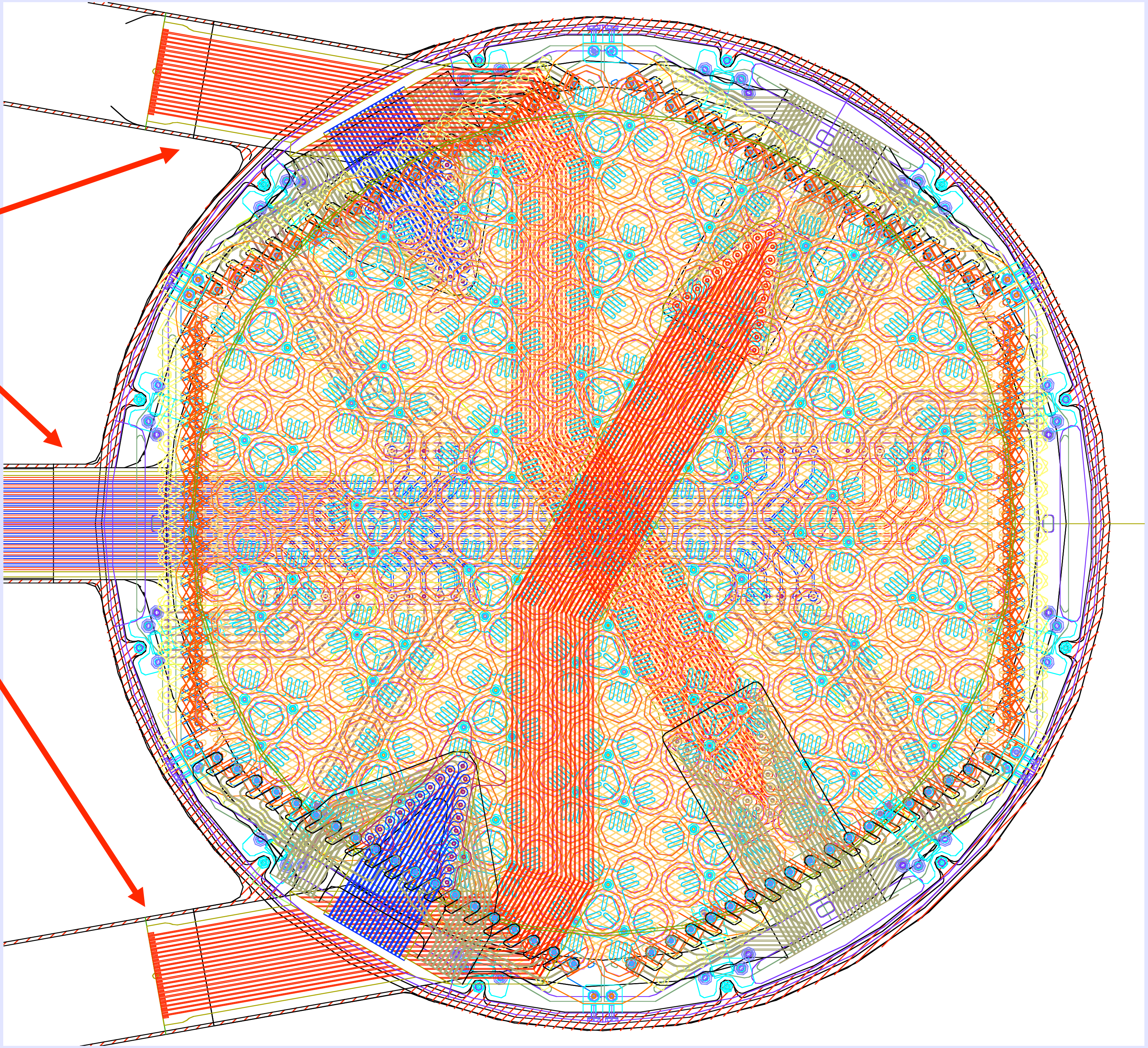
cathode

APD plane (copper)

acrylic supports

field shaping rings and resistor chain

EXO-200 TPC



stripline cables routed through the legs

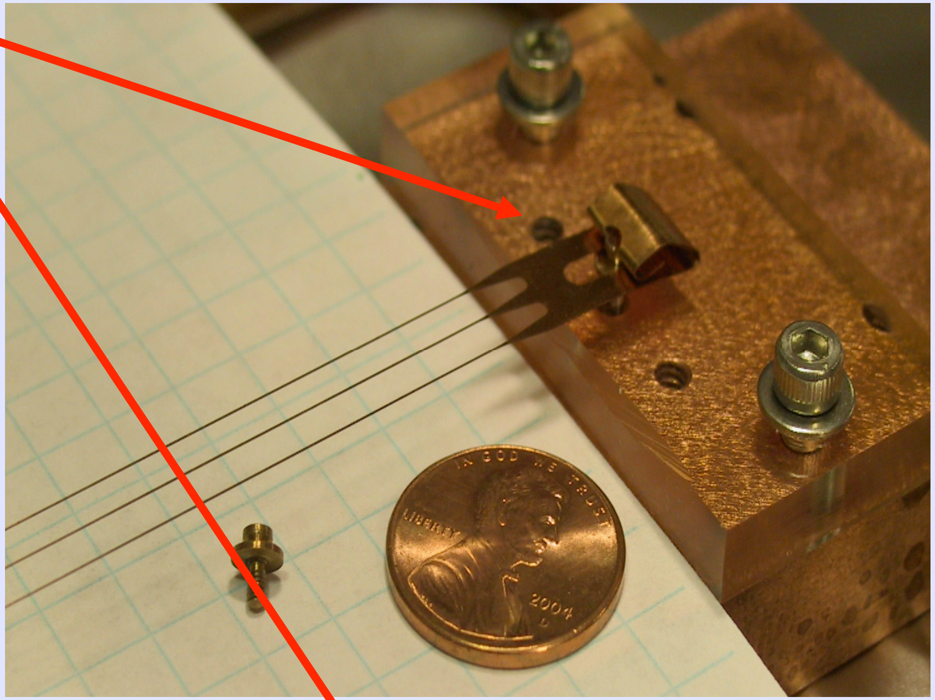
EXO-200 TPC

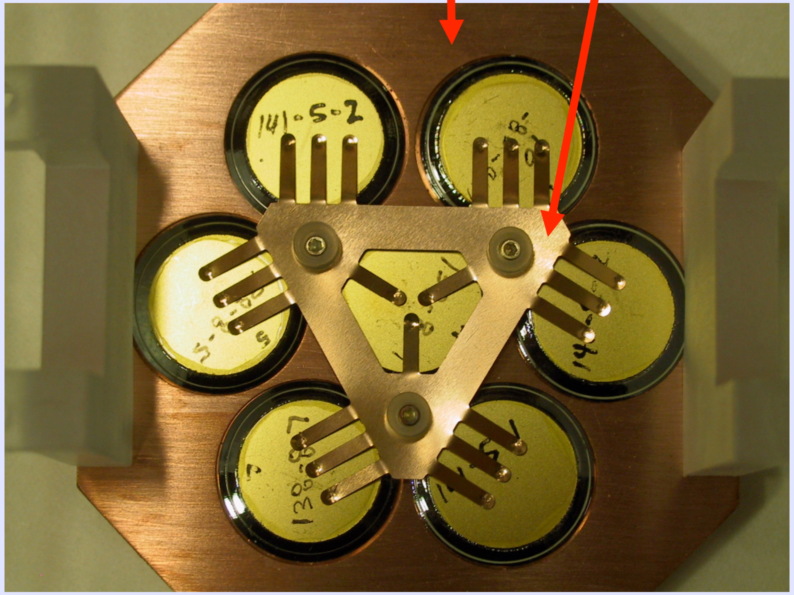
TPC fully designed, including:

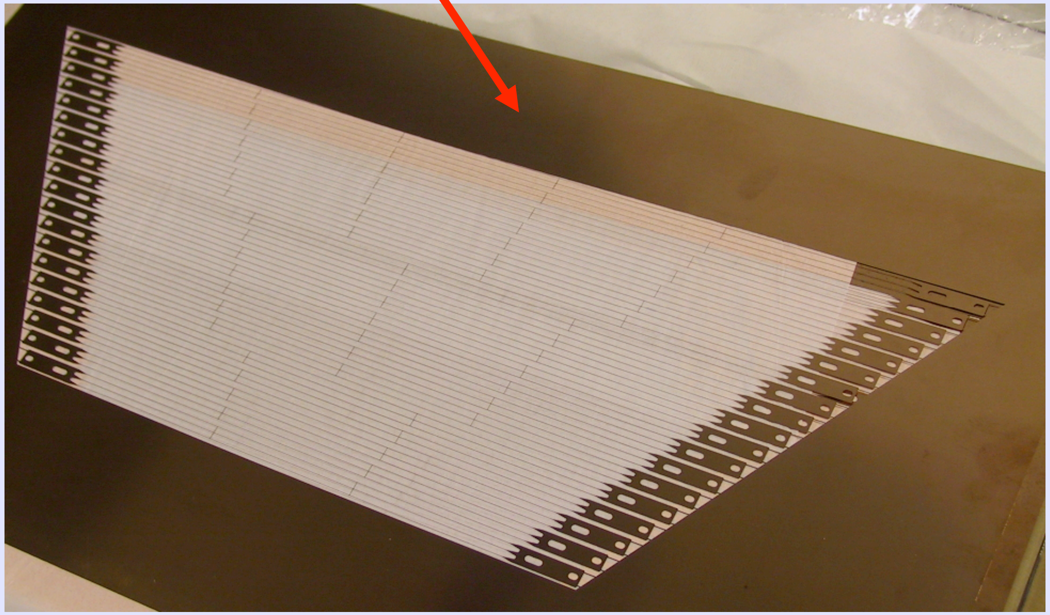
- photoetched wires (3 wires / channel)
- photoetched cathode plane
- photoetched “spider” holders for APDs
- APD plane (groups of 7)
- teflon reflector (from DuPont TE-6472)
- field grading resistor chain
- stripline cable layout and connection scheme

Approved material at hand for:

- photoetched parts (produced)
- resistors, silicon bronze screws, epoxy
- teflon reflectors, stripline cables

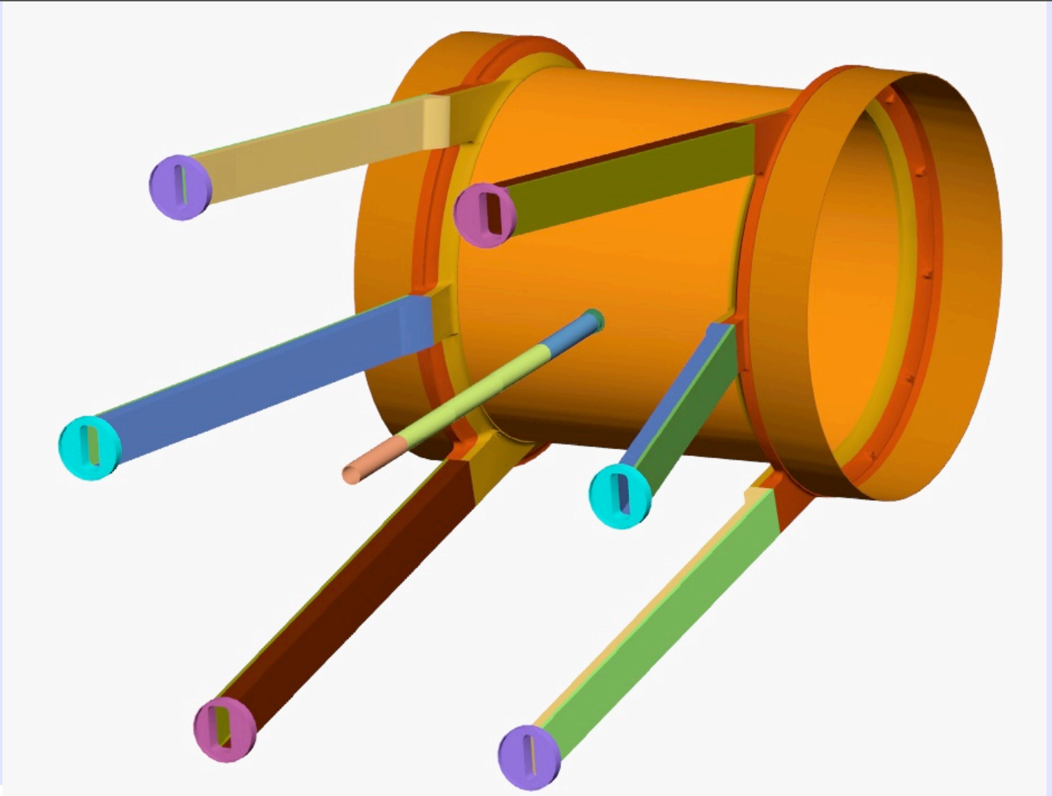


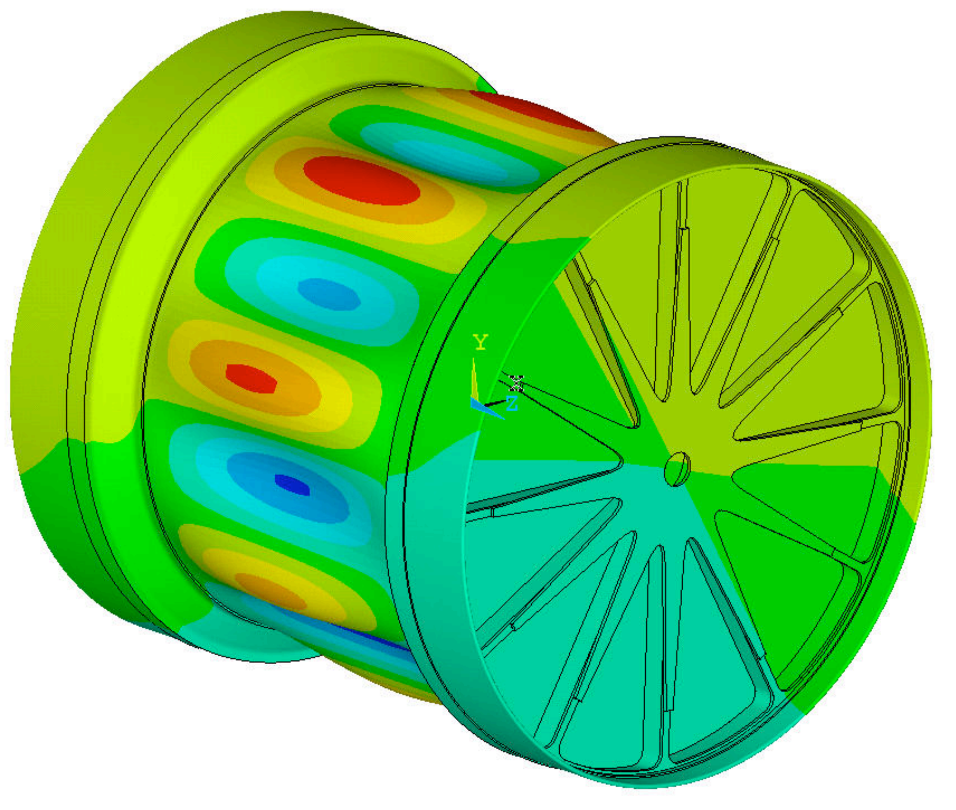


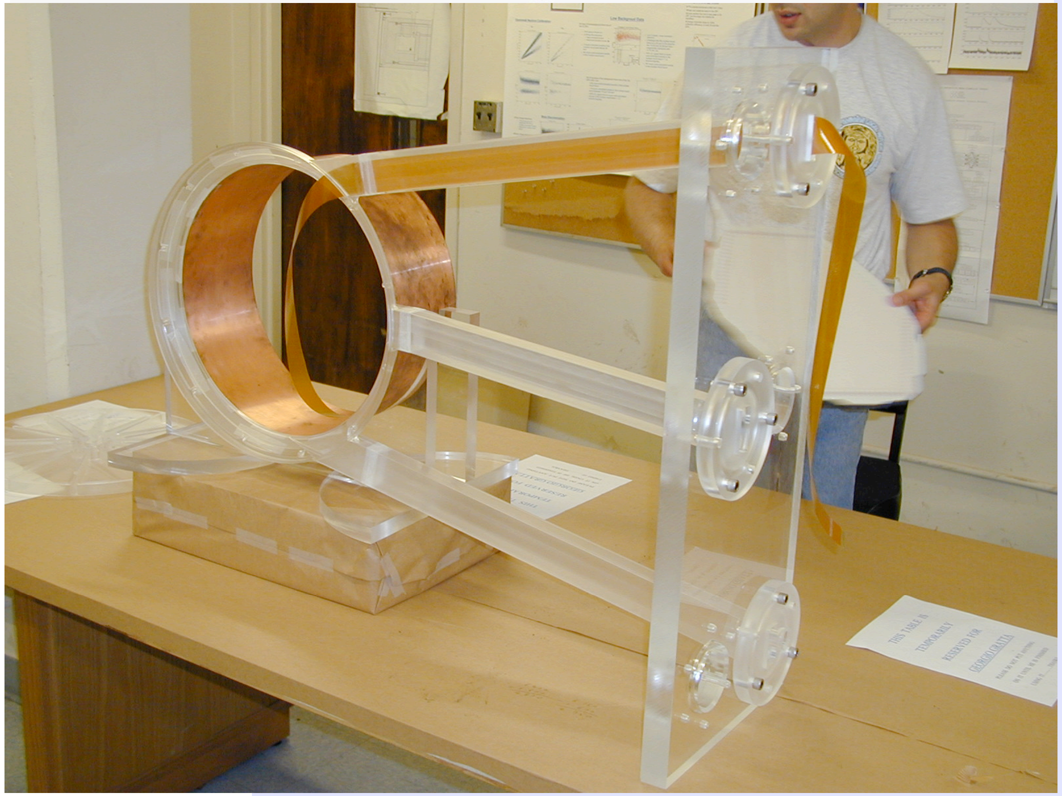


EXO-200 xenon vessel

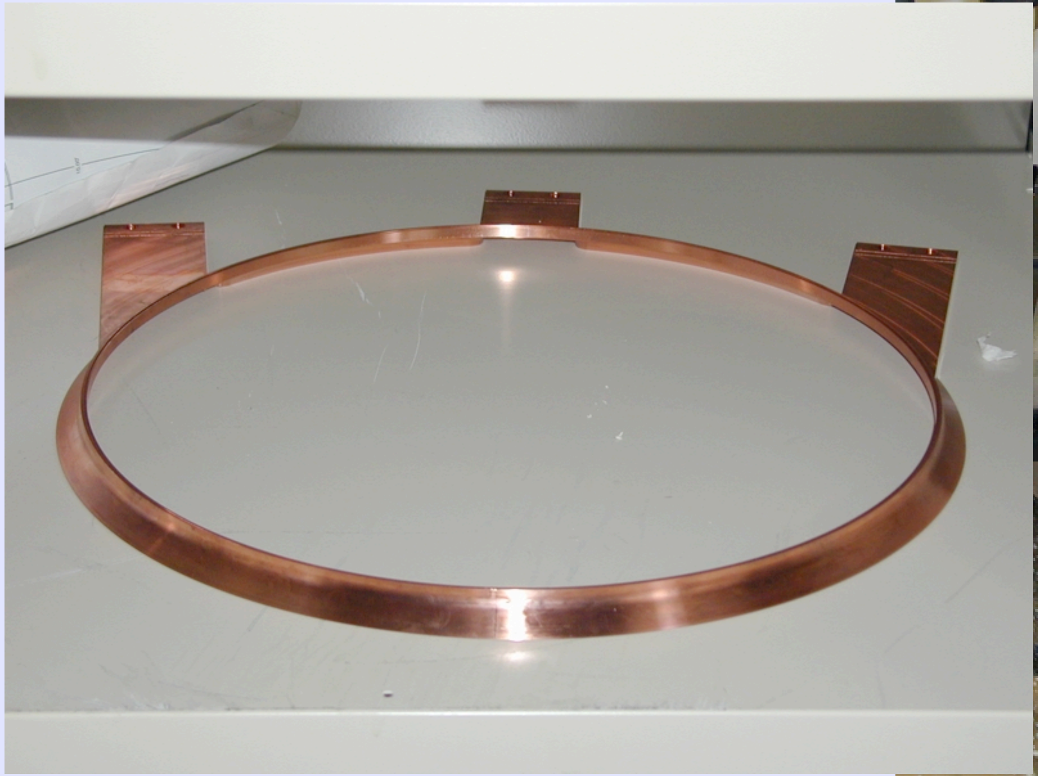
- drawings and FEA structural analysis complete
- full scale model of half detector with legs produced
- all machining performed in ES3 at Stanford (2 m concrete)
- e-beam welding performed in East Bay - 1 day exposure

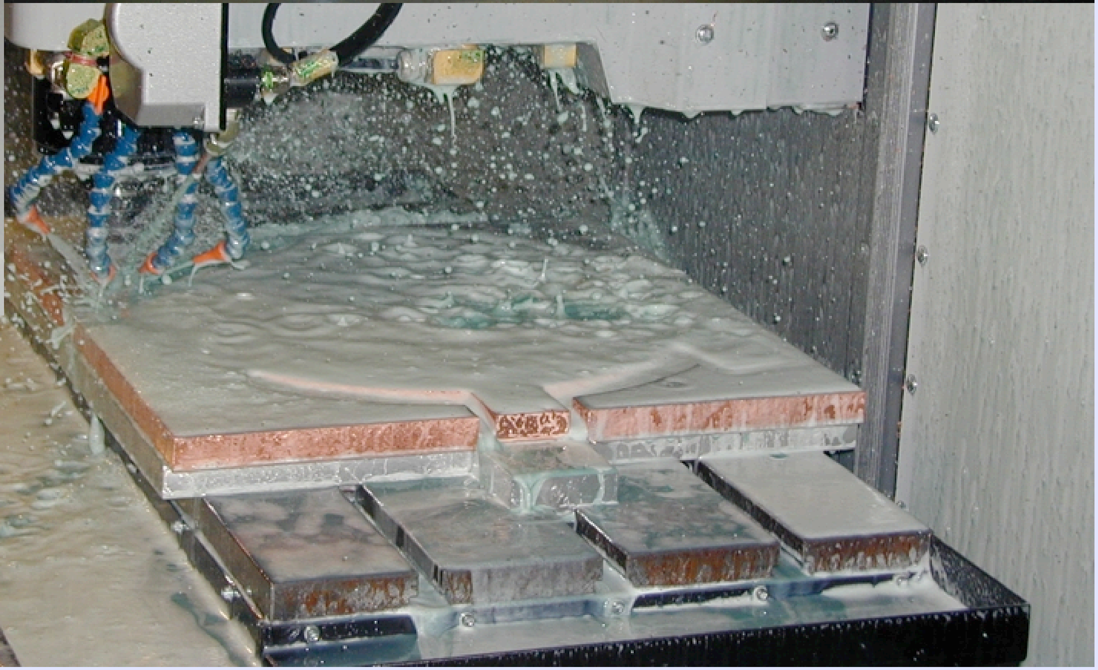






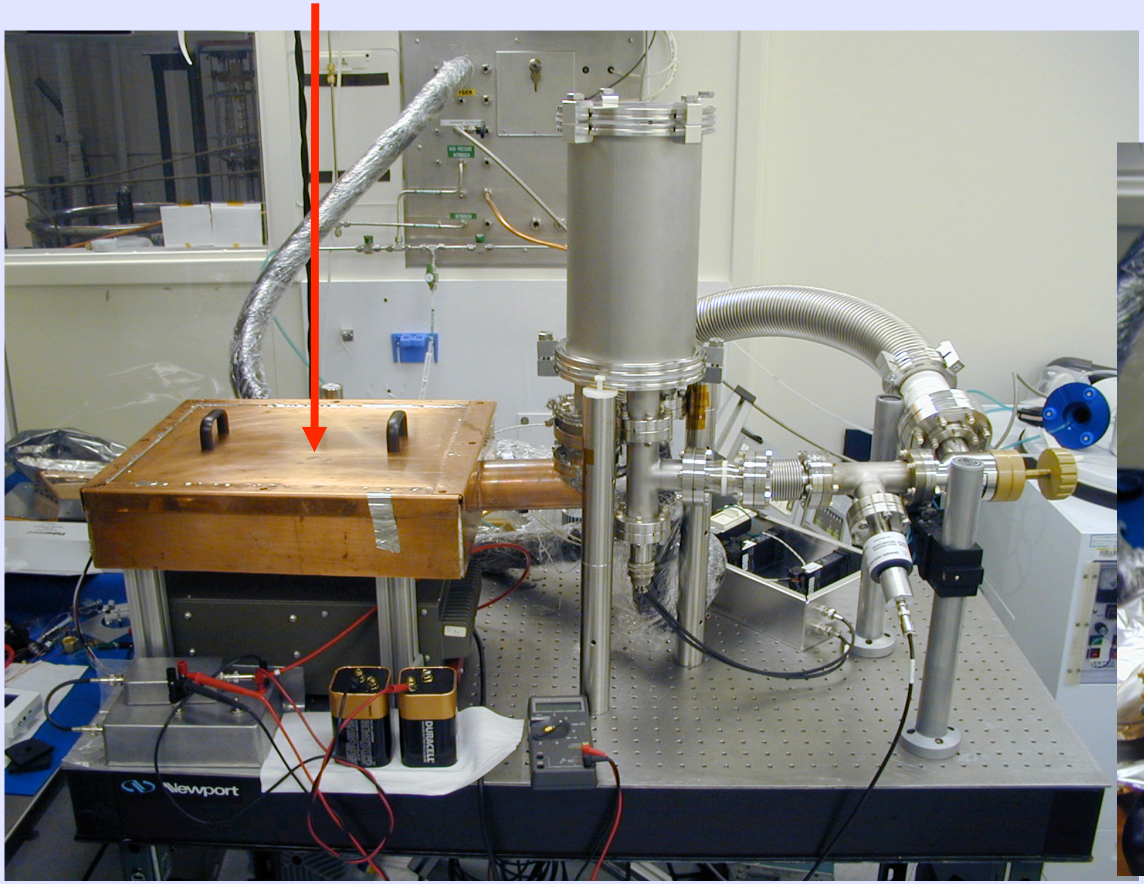
EXO-200 xenon vessel machining

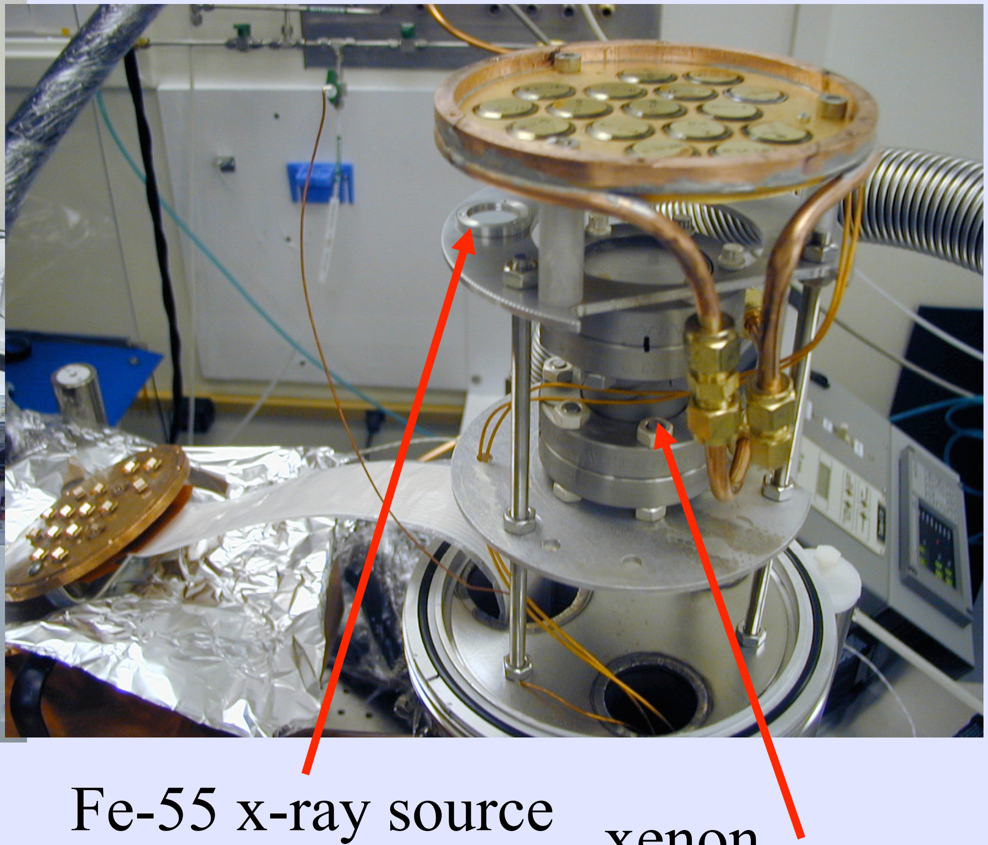




- machining of parts has begun last week

LAAPD testing rig

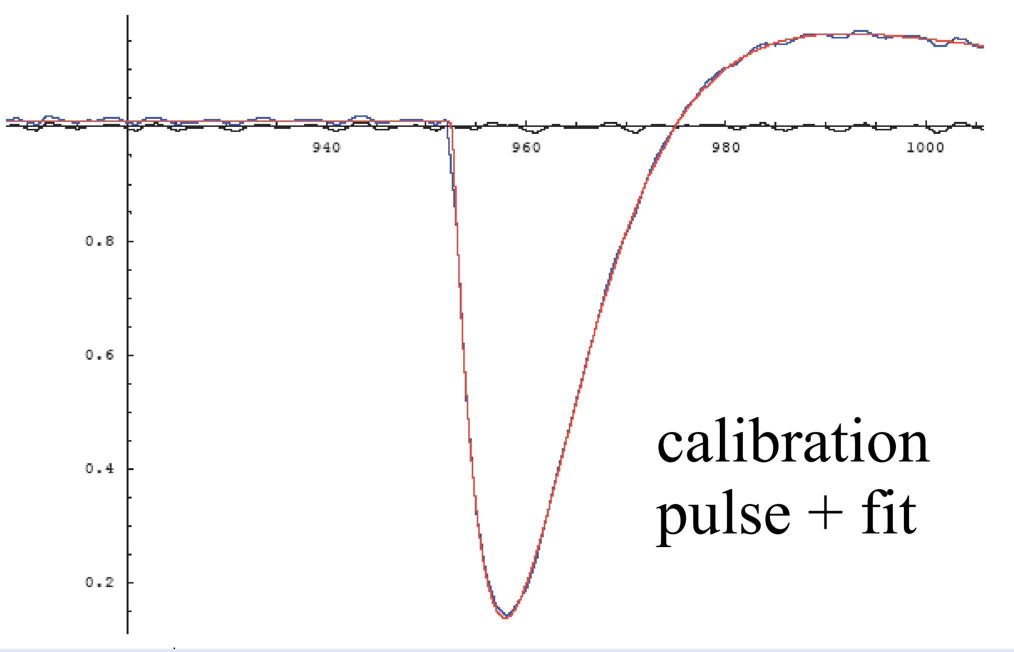




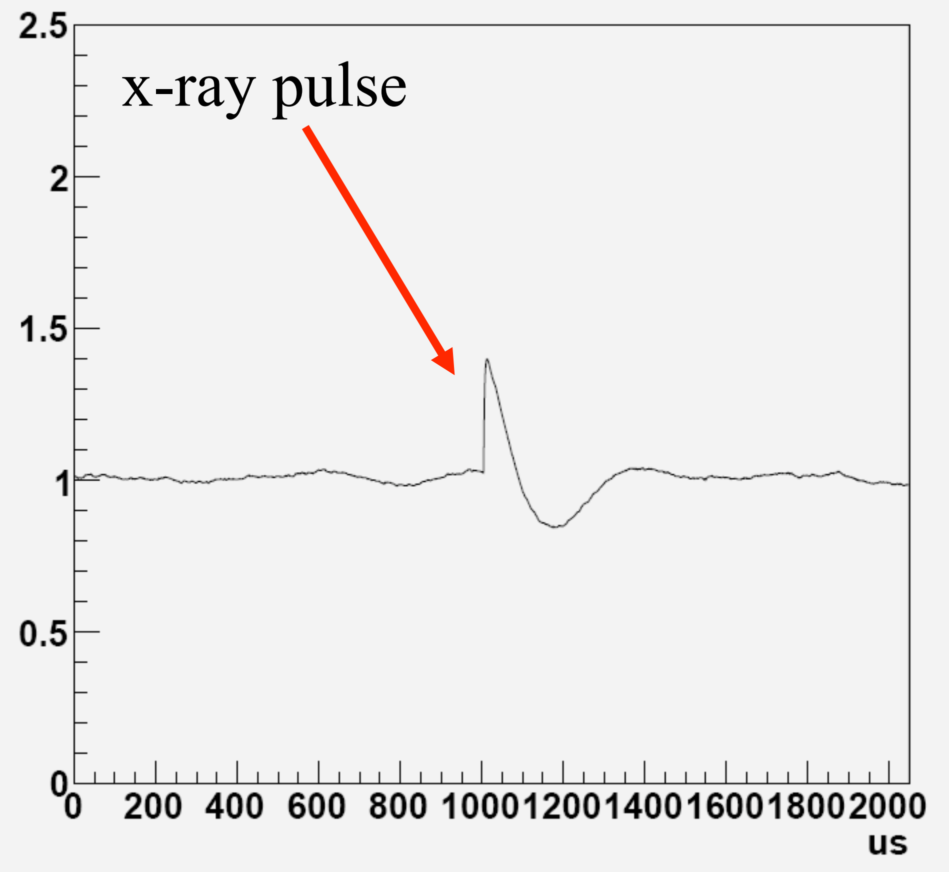
- LAAPDs stored in dry box
- First batch of 8 APDs tested and accepted last week
- 50-90 more will be received tomorrow for testing
- read out with EXO-200 electronics

LAAPD testing: data

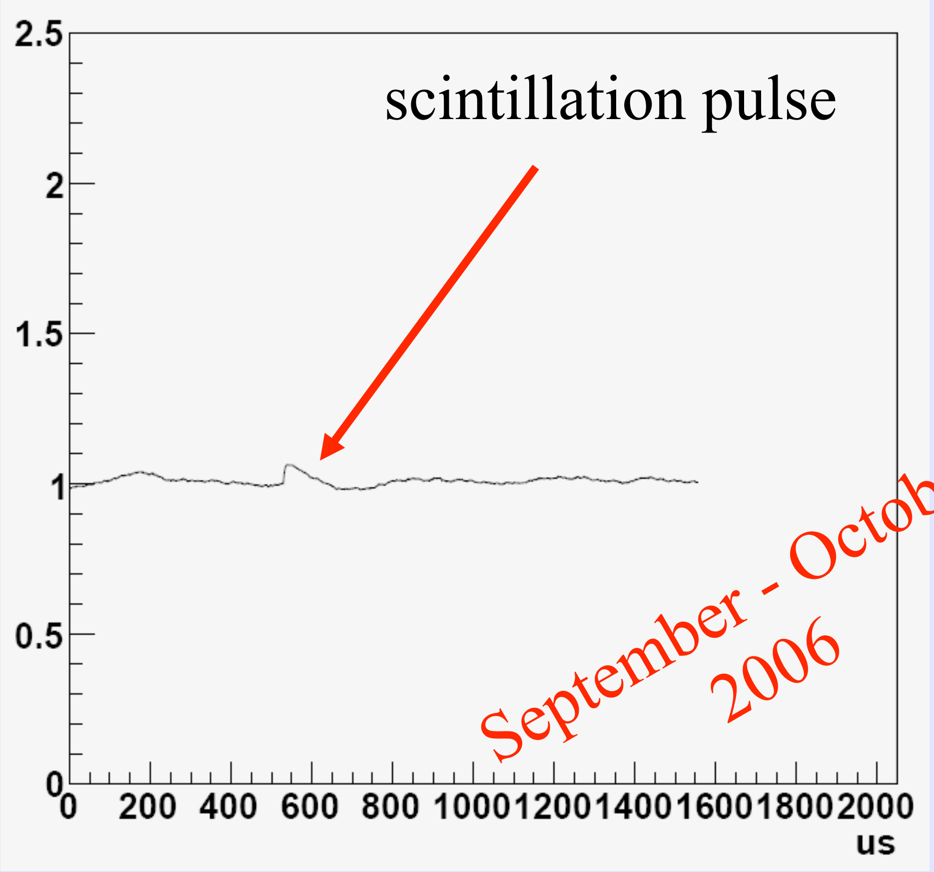
- Setup allowed thorough testing and calibration of the EXO-200 electronics
- software developed for LAAPD DAQ is also good for EXO-200 analysis
- LAAPDs are now in production



calibration pulse + fit



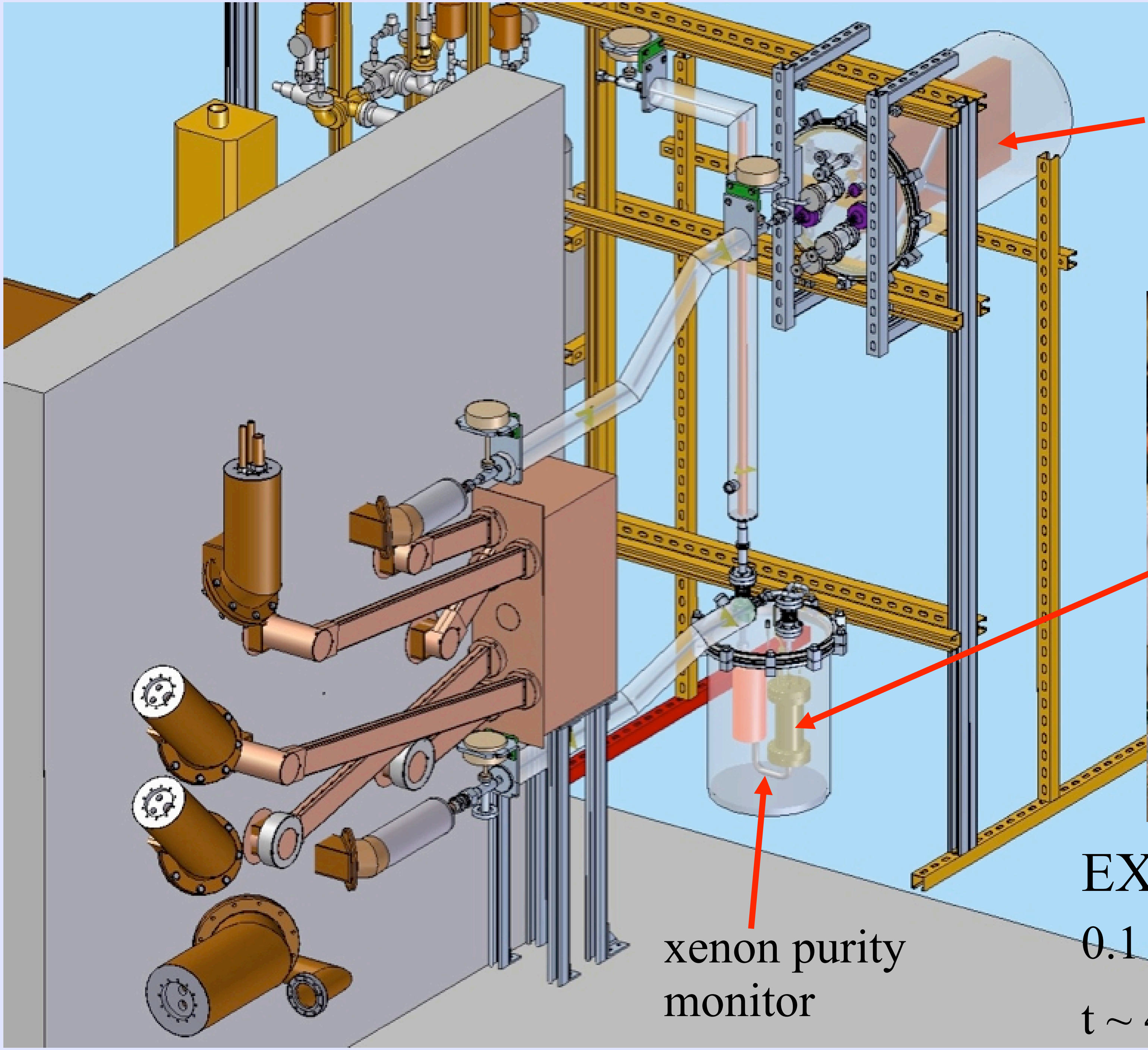
x-ray pulse



scintillation pulse

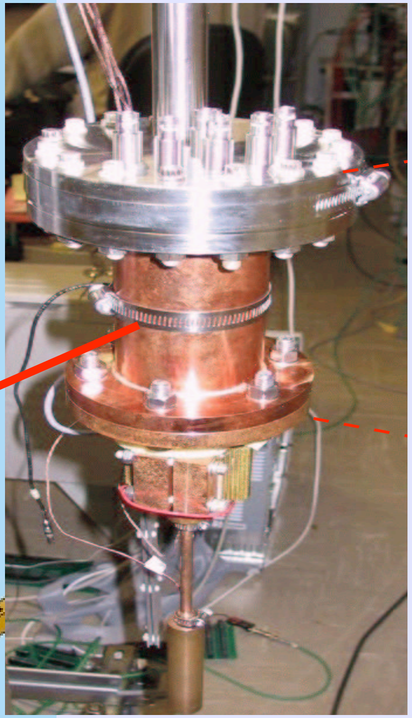
September - October 2006

EXO-200 installation: xenon handling system 2



xenon condenser

xenon purity monitor



EXO-200 goal:

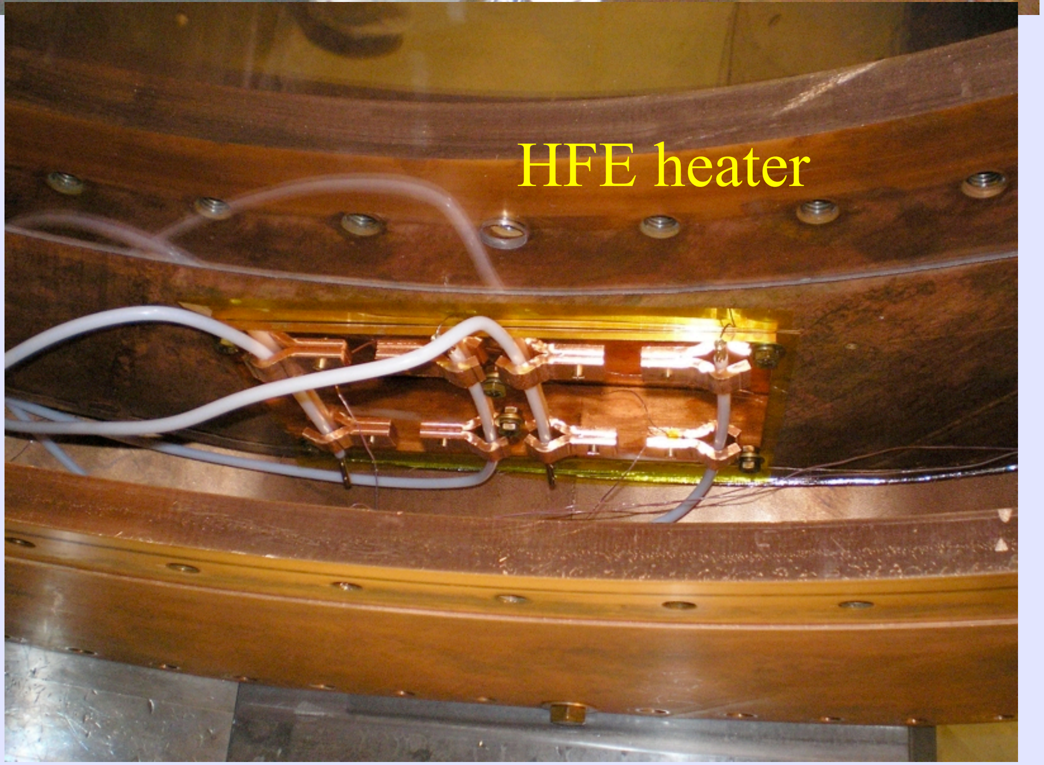
0.1 ppb O_2 equivalent

t ~ 4 ms (electrons)

EXO-200 installation: cryostat instrumentation

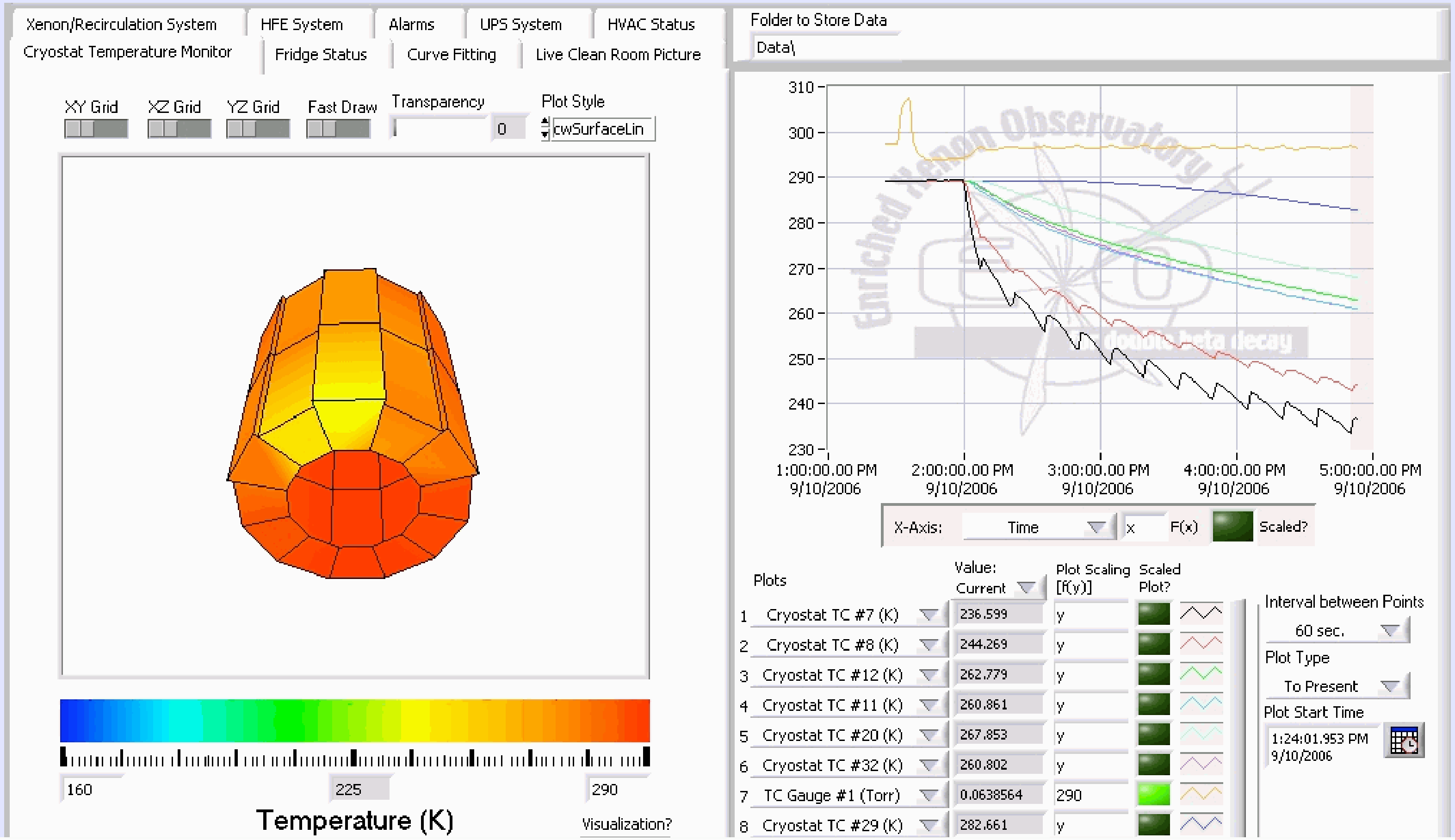
thermocouple wire epoxy potted feed through

cryostat during first cooldown and leak checking



HFE heater

EXO-200 installation: first cooldown test



Folder to Store Data: Data\

Transparency: 0

Plot Style: cwSurfaceLin

X-Axis: Time x

	Plots	Value: Current	Plot Scaling [f(y)]	Scaled Plot?
1	Cryostat TC #7 (K)	236.599	y	
2	Cryostat TC #8 (K)	244.269	y	
3	Cryostat TC #12 (K)	262.779	y	
4	Cryostat TC #11 (K)	260.861	y	
5	Cryostat TC #20 (K)	267.853	y	
6	Cryostat TC #32 (K)	260.802	y	
7	TC Gauge #1 (Torr)	0.0638564	290	
8	Cryostat TC #29 (K)	282.661	y	

Interval between Points: 60 sec.

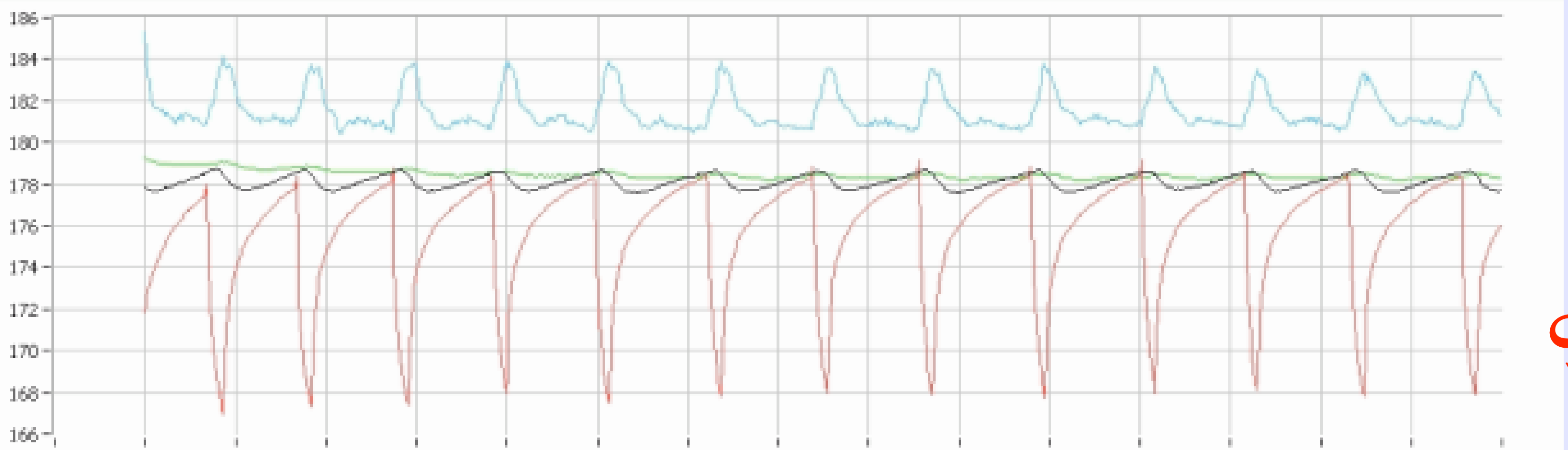
Plot Type: To Present

Plot Start Time: 1:24:01.953 PM 9/10/2006

used one refrigerator

no particular problem keeping the detector at -100 C (LXe temperature)

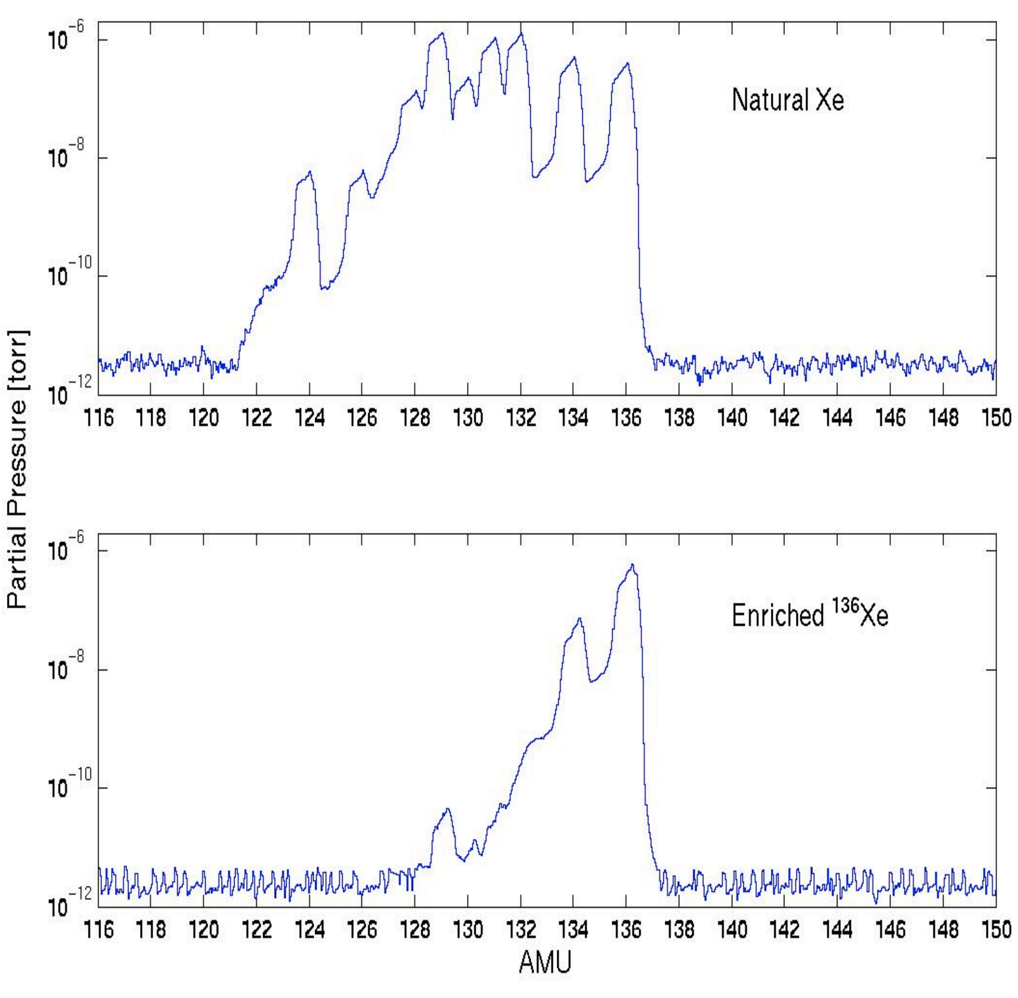
successfully tested control system



September 2006


Xe plumbing
HFE plumbing
Rn emanation chamber

^{136}Xe stockpile at Stanford



200 kg of xenon enriched to 80% in ^{136}Xe : the most isotope possession by any ββ collaboration

Trace radioactivity measurements

the material qualification campaign included:

1) new copper purchase for xenon vessel
2) etching procedures for wires and stripline cables
3) gold and metal analysis for APD production
4) silicon and phosphor bronze for TPC components
5) certification of cleaning and etching procedures of EXO-200 parts performed locally (acid etching in dedicated clean room at Stanford)
6) cryogenic epoxy
7) high voltage cable
8) APD wafers
9) Pb shielding selection

Goals:
a) material selection for EXO-200
b) most complete possible radioactivity budget to use as input of Monte Carlo simulation of backgrounds

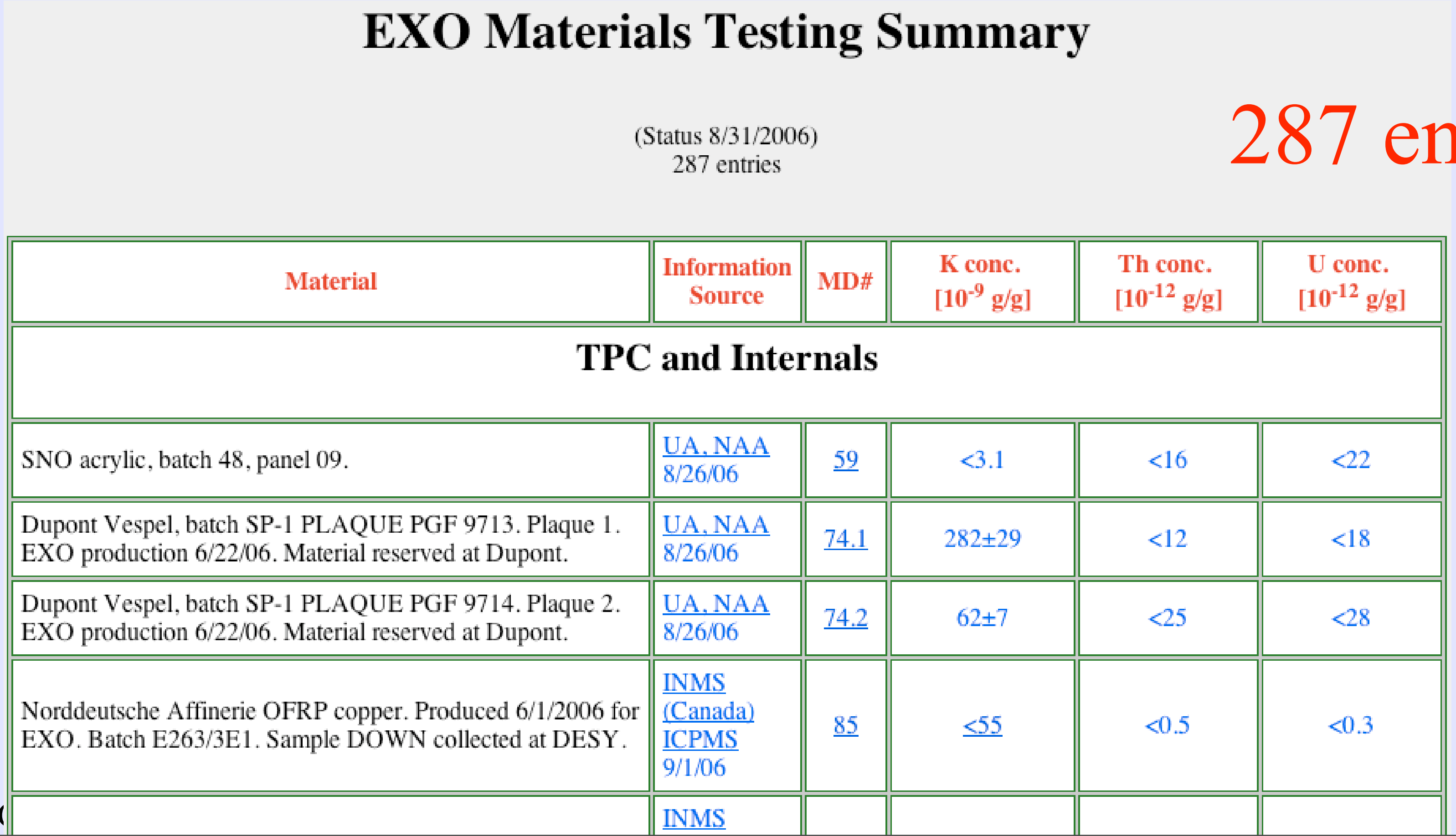
Main γ (external) backgrounds

- γ line (2449 keV) from ^{214}Bi decay (^{238}U and ^{222}Rn)
- γ line (2615 keV) from ^{208}Tl decay (^{232}Th)
- γ line (1.4 MeV) from ^{40}K
- ^{60}Co: 1.1 + 1.3 MeV simultaneous γ's
- other γ lines in ^{238}U and ^{232}Th chains
- other cosmogenics of Cu

Materials qualification database

- Neutron Activation Analysis (NAA) - Alabama (MIT reactor)
- ICP-MS and GD-MS - INMS (Ottawa)
- Radon emanation - Laurentian (Sudbury)
- Gamma counting - Neuchatel, Alabama
- Alpha counting - Alabama, Carleton, SLAC, Stanford

287 entries



EXO Materials Testing Summary

(Status 8/31/2006)
287 entries

Material	Information Source	MD#	K conc. [10^{-9} g/g]	Th conc. [10^{-12} g/g]	U conc. [10^{-12} g/g]
TPC and Internals					
SNO acrylic, batch 48, panel 09.	UA, NAA 8/26/06	59	<3.1	<16	<22
Dupont Vespel, batch SP-1 PLAQUE PGF 9713. Plaque 1. EXO production 6/22/06. Material reserved at Dupont.	UA, NAA 8/26/06	74.1	282±29	<12	<18
Dupont Vespel, batch SP-1 PLAQUE PGF 9714. Plaque 2. EXO production 6/22/06. Material reserved at Dupont.	UA, NAA 8/26/06	74.2	62±7	<25	<28
Norddeutsche Affinerie OFRP copper. Produced 6/1/2006 for EXO. Batch E263/3E1. Sample DOWN collected at DESY.	INMS (Canada) ICPMS 9/1/06	85	<55	<0.5	<0.3
	INMS				

Copper shielding

- First chamber being built with leftover copper from cryostat production; this was surface shipped to Stanford and stored in ES3 (2 meters of concrete overburden).

- Cryostat copper stored in a bunker during production at SDMS, Grenoble

- 8 more tons of copper purchased and rolled in Germany; copper was stored at DESY bunker before rolling. It will be shipped to Stanford at the end of the month in a concrete shielded container (which will be used for chipping the chamber+TPC to WIPP)


June-September 2006

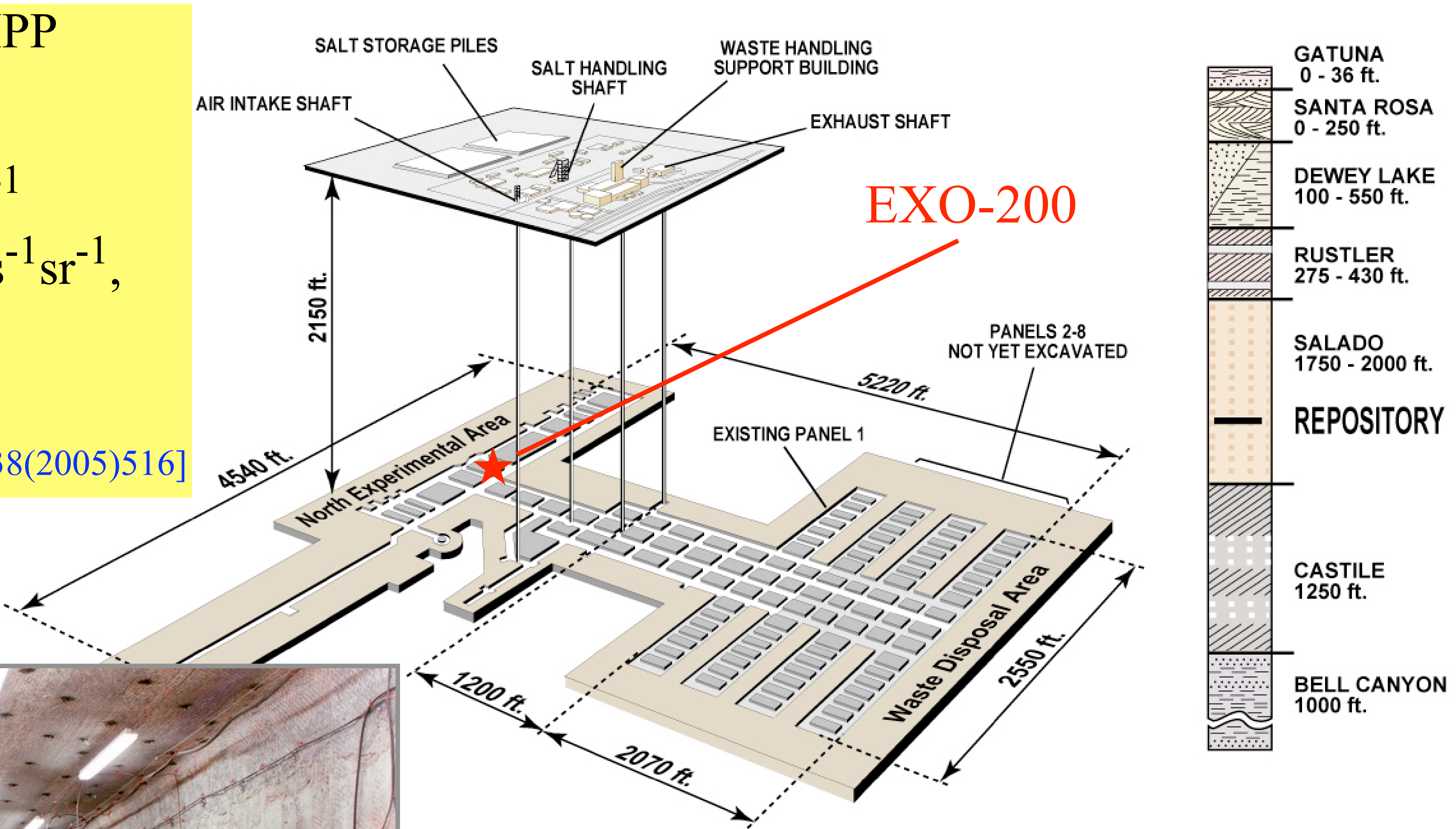
September 2006

WIPP Facility and Stratigraphic Sequence

muon flux at WIPP
(~ 1700 m.w.e.):

4.77×10^{-3} $\mathrm{m^{-2}\,s^{-1}}$
(3.10×10^{-3} $\mathrm{m^{-2}\,s^{-1}sr^{-1}}$,
~15 $\mathrm{m^{-2}\,h^{-1}}$)

[E.-I.Esch et al.,
Nucl. Instr. Meth. A 538(2005)516]



EXO-200

underground at WIPP

EXO 200 kg prototype is being assembled and commissioned at Stanford, then the six clean rooms will be shipped to WIPP (May 2007)

EXO-200 sensitivity

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‡	(NSM#)
EXO-200	0.2	70	2	1.6*	40	6.4×10^{25}	0.18	(0.53)

* σ(E)/E = 1.4% obtained in EXO R&D, E.Conti et al. Phys Rev B 68 (2003) 054201

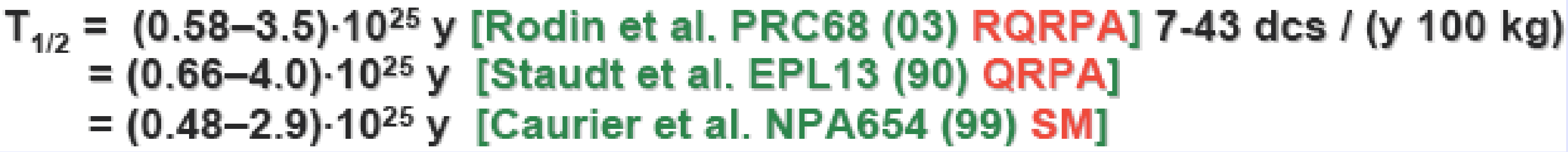
‡ QRPA: A.Staudt et al. Europhys. Lett.13 (1990) 31; Phys. Lett. B268 (1991) 312

NSM: E.Caurier et al. Phys Rev Lett 77 (1996) 1954

Improves current limits on ^{136}Xe by one order-of-magnitude

Discovery claim in Ge-76 (Phys. Lett. B 586 (2004) 198): $(0.7\text{-}4.2)\times 10^{25}$y, ±3σ range

Xe-136:



$T_{1/2}$ = $(0.58–3.5)\cdot 10^{25}$ y [Rodin et al. PRC68 (03) RQRPA] 7-43 dcs / (y 100 kg)
= $(0.66–4.0)\cdot 10^{25}$ y [Staudt et al. EPL13 (90) QRPA]
= $(0.48–2.9)\cdot 10^{25}$ y [Caurier et al. NPA654 (99) SM]

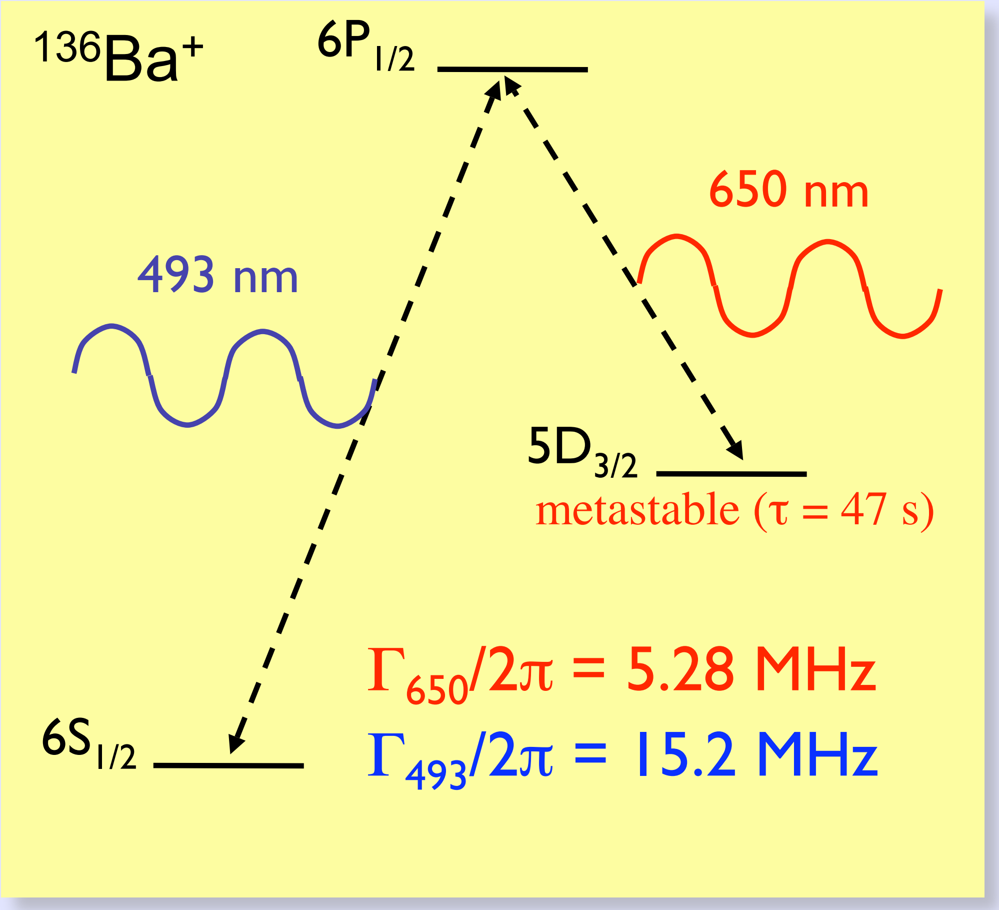
Single Ba ion detection

Daughter identified by optical spectroscopy of Ba^+, well studied in ion traps for more than 25 years

[Neuhauser, Hohenstatt, Toshek, Dehmelt, Phys. Rev. A 22 (1980) 1137]

- very specific signature
- Cycling 493/650 nm transitions gives a fluorescence rate of ~10^7 Hz (in vacuum)

bright!



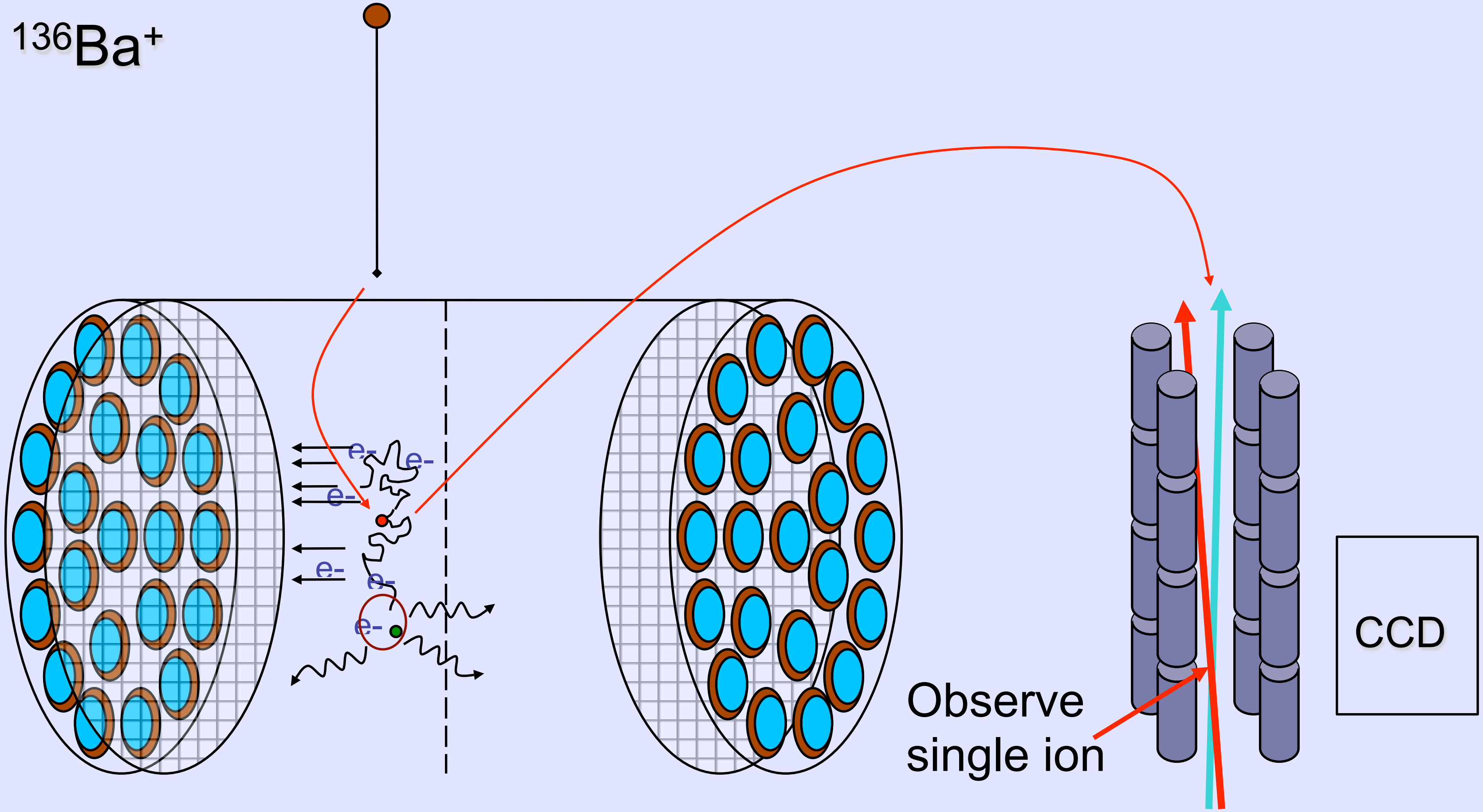
metastable (τ = 47 s)

$\Gamma_{650}/2\pi = 5.28$ MHz

$\Gamma_{493}/2\pi = 15.2$ MHz

Ba identification strategies

- grab from Xe bath, release in a trap, and identify it



- in situ detection:
    - in LXe: Bill Fairbank at Colorado State University
    - in GXe: David Sinclair at Carleton University and SNOLab

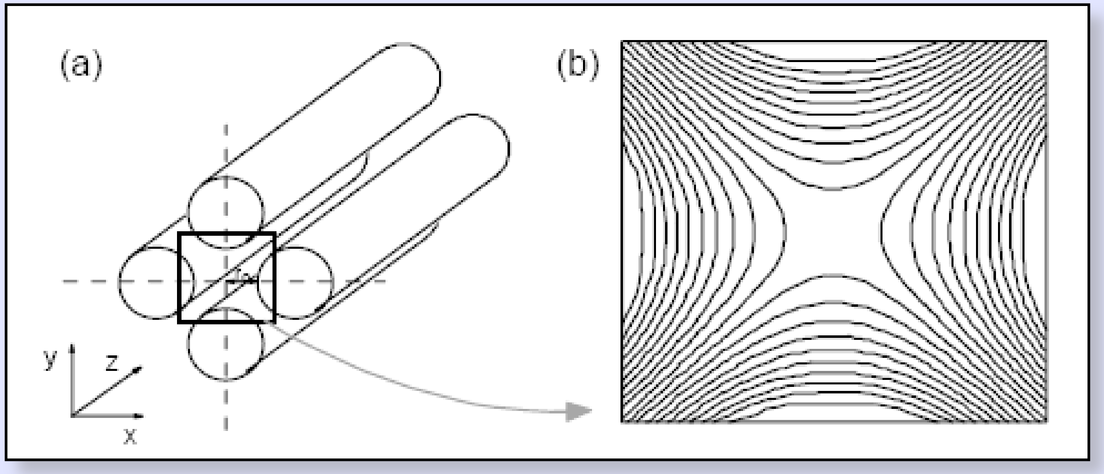
Ba tagging requirements

We need to be able to:

- Identify a single $^{136}Ba^{+}$ ion
- Inject an ion into a trap from an external source
- Trap with high overall efficiency
- Trap in the presence of some Xe

Single Ba ion trapping

Build an AC quadrupole potential:



$$\Phi = \frac{\varphi_0}{2}\left(1 + \frac{x^2 - y^2}{r_0^2}\right)$$

$$\varphi_0 = U_{DC} + V_{RF}\cos\Omega t$$

longitudinal trapping

radial trapping

write: $\vec{F} = q\vec{E} = m\vec{a}$

$$m\begin{pmatrix} \ddot{x} \\ \ddot{y} \end{pmatrix} = \begin{pmatrix} -\frac{e\varphi_0}{r_0^2}x \\ +\frac{e\varphi_0}{r_0^2}y \end{pmatrix}$$

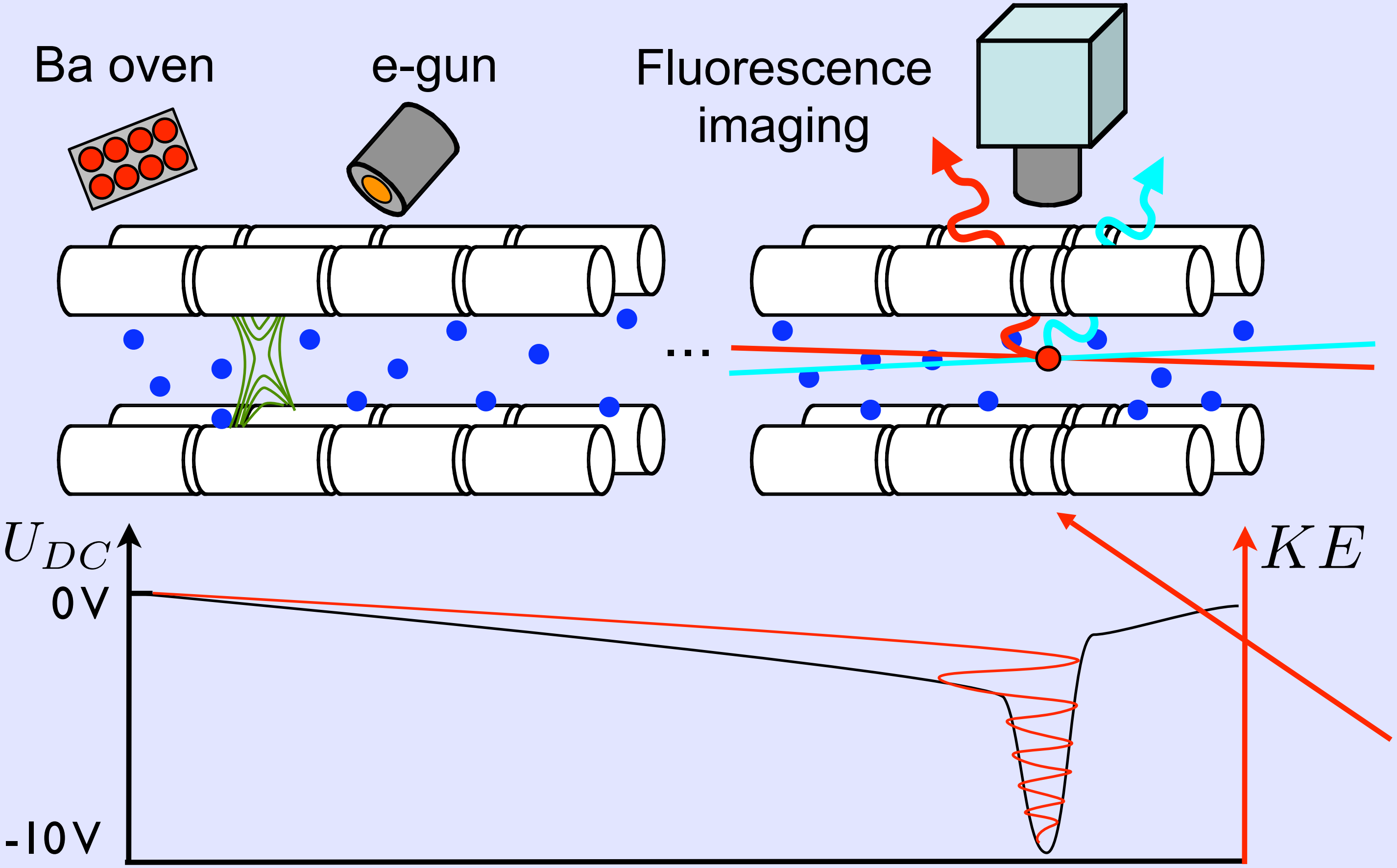
trap parameters:

$$V_{RF} = 150V_{pk}, \quad f = 1.1\text{MHz}$$

$$U_{DC} = 10V$$

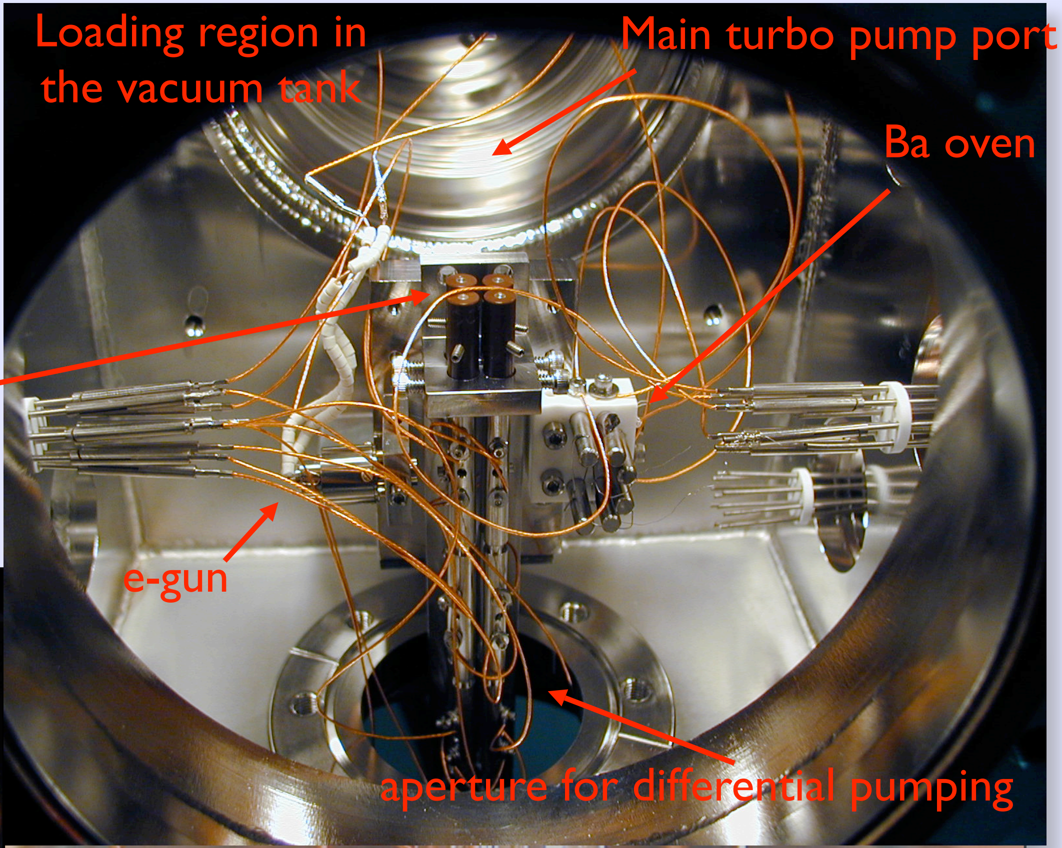
Single Ba ion trapping

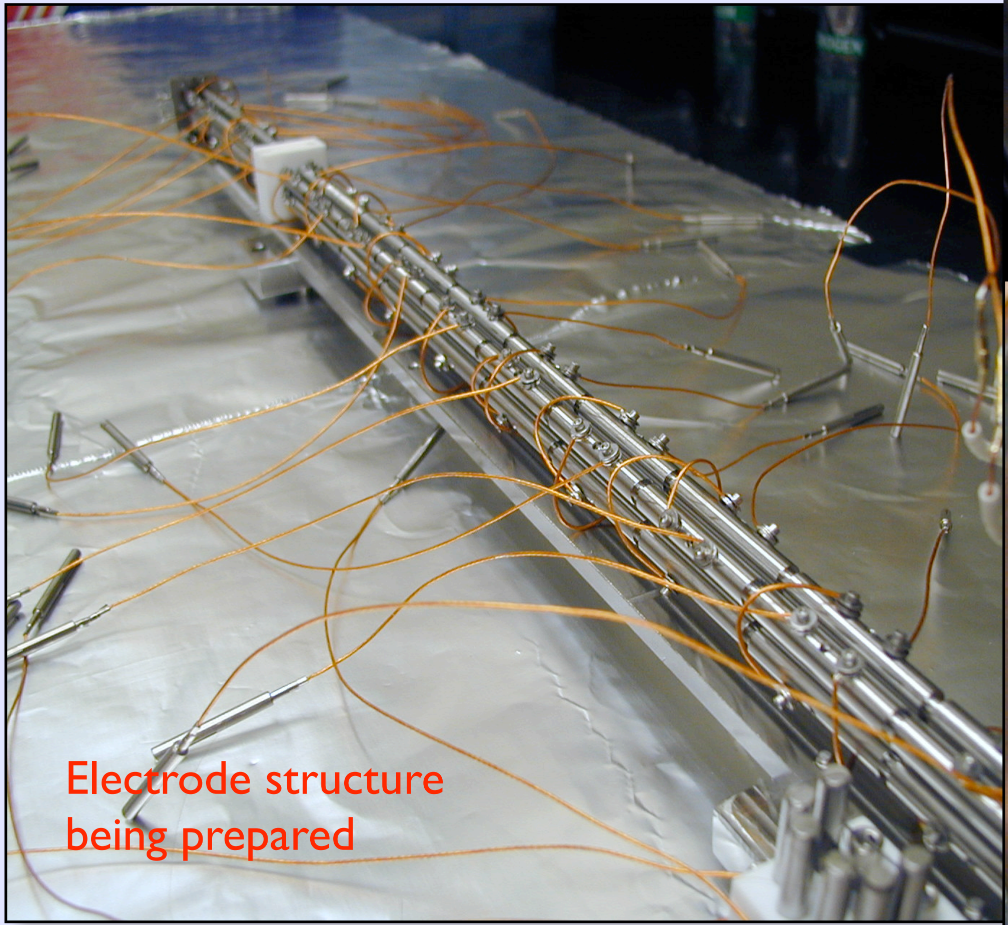
Multiply by 16, and add a buffer gas to cool down the ions injected at one end of the trap into a DC minimum

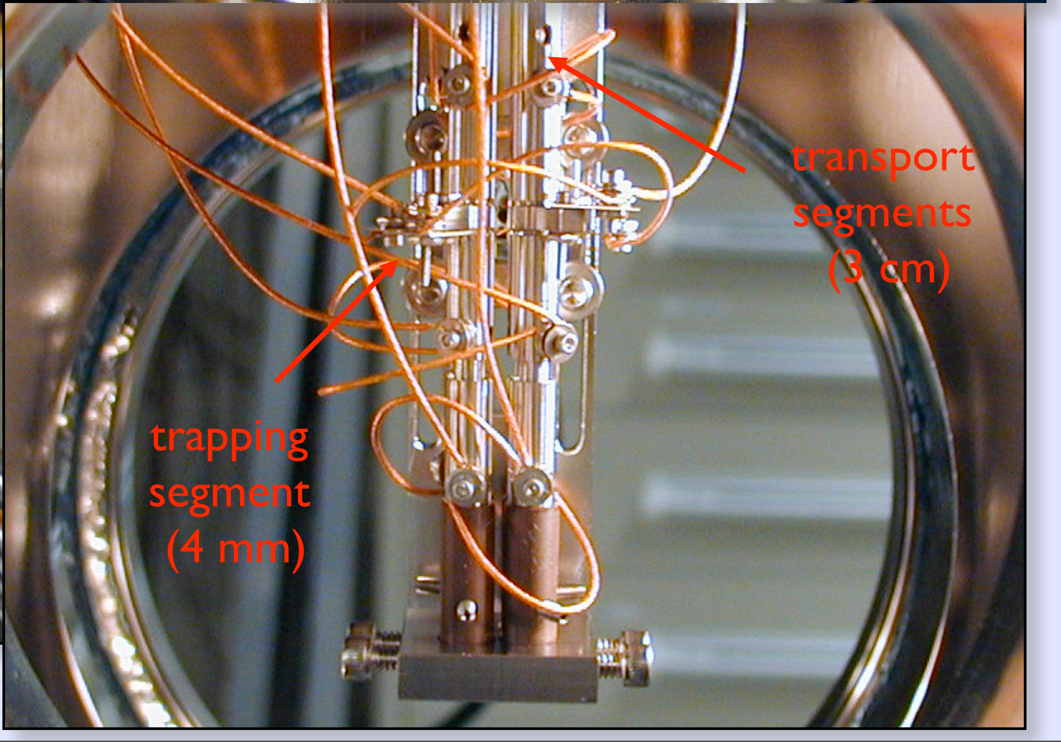


short longitudinal trapping segment

Linear ion trap at Stanford

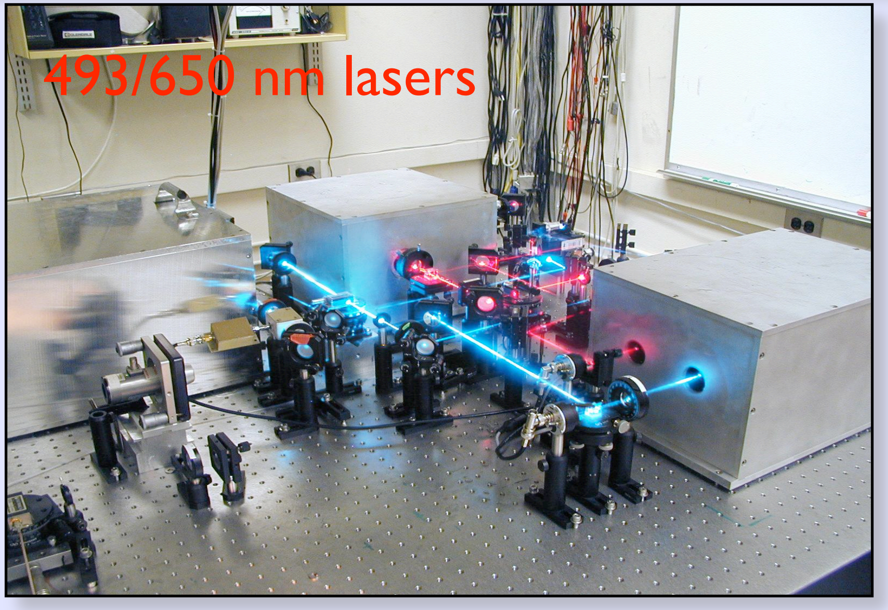




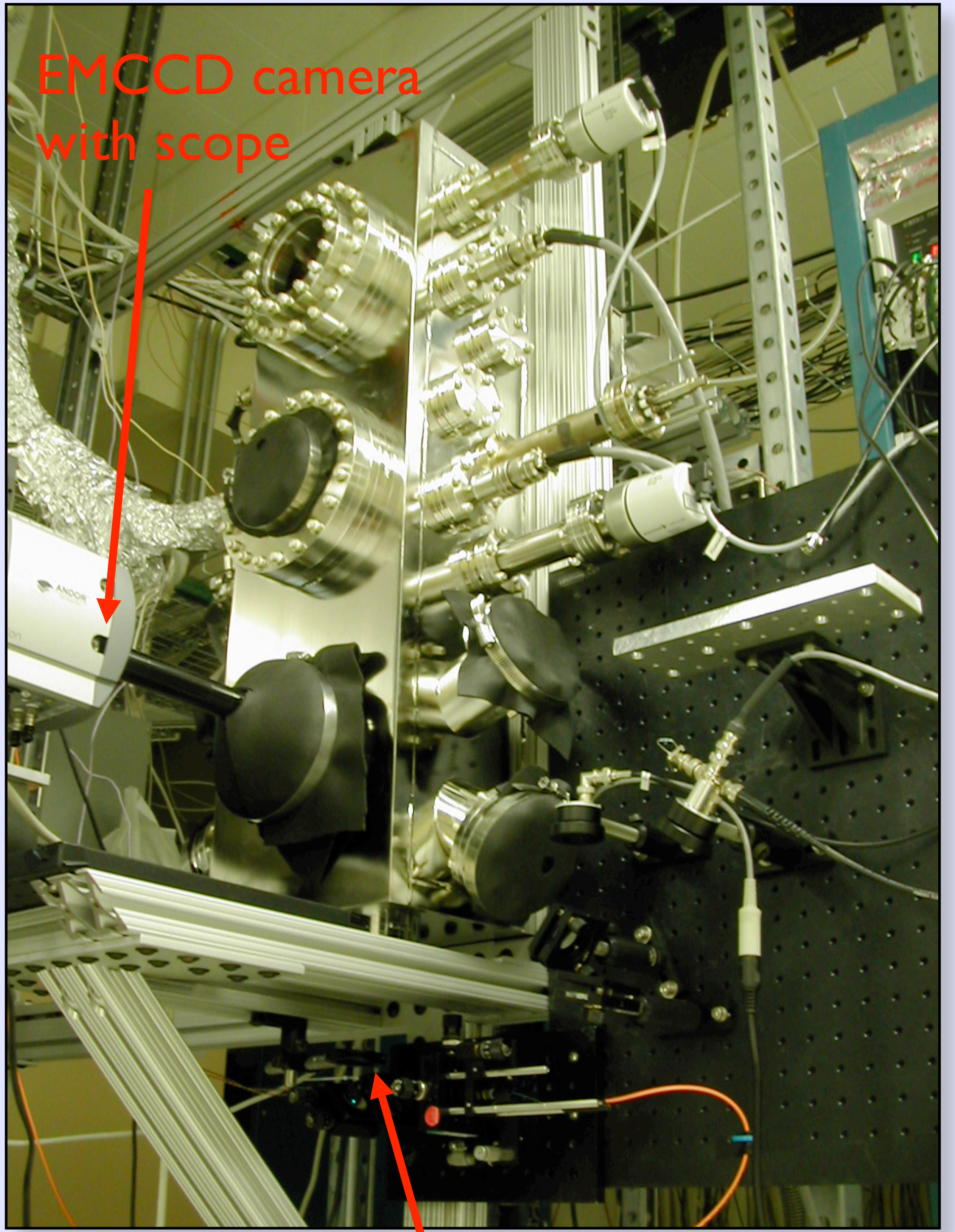


Linear ion trap at Stanford 2

Buffer gas purification/ injection system



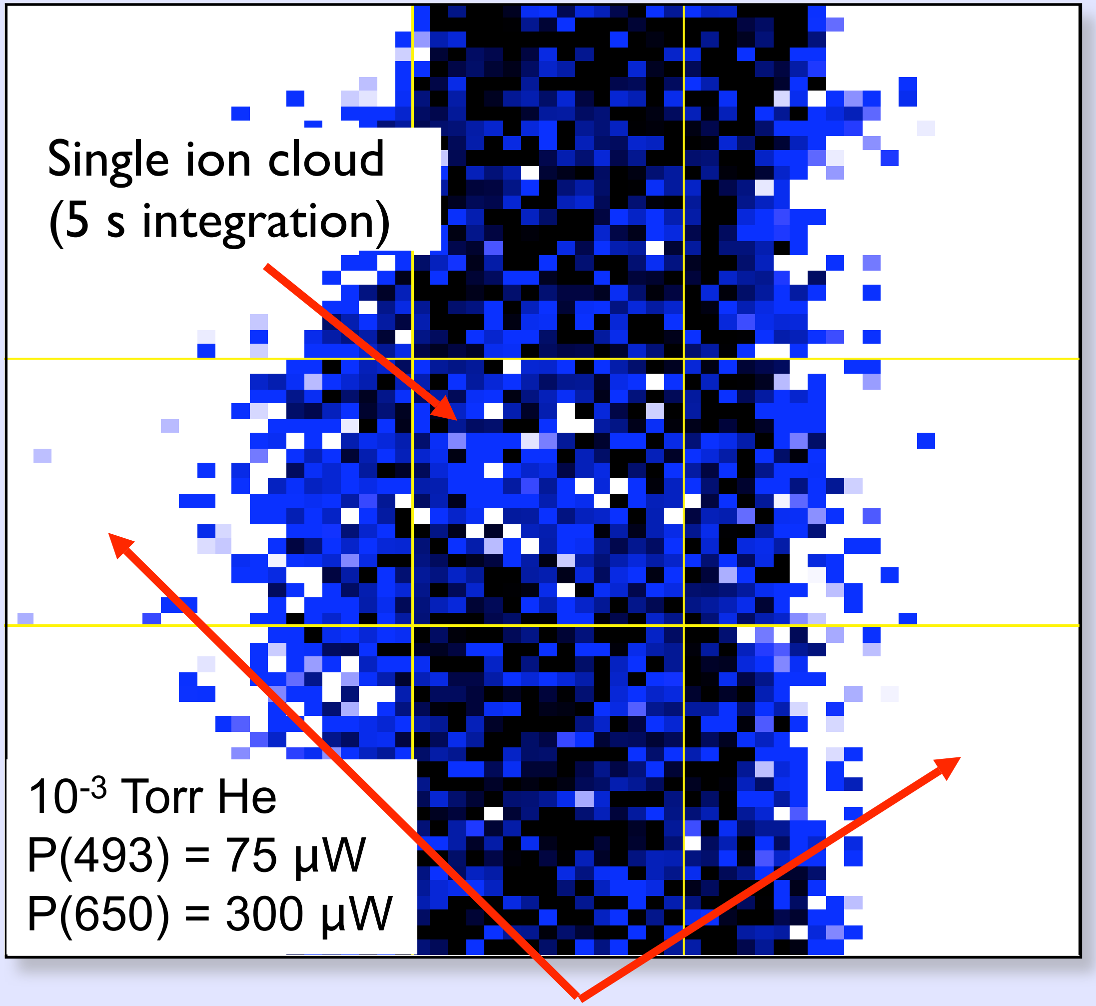
493/650 nm lasers



EMCCD camera with scope

Input optics (493 nm, 650 nm beams on single fiber)

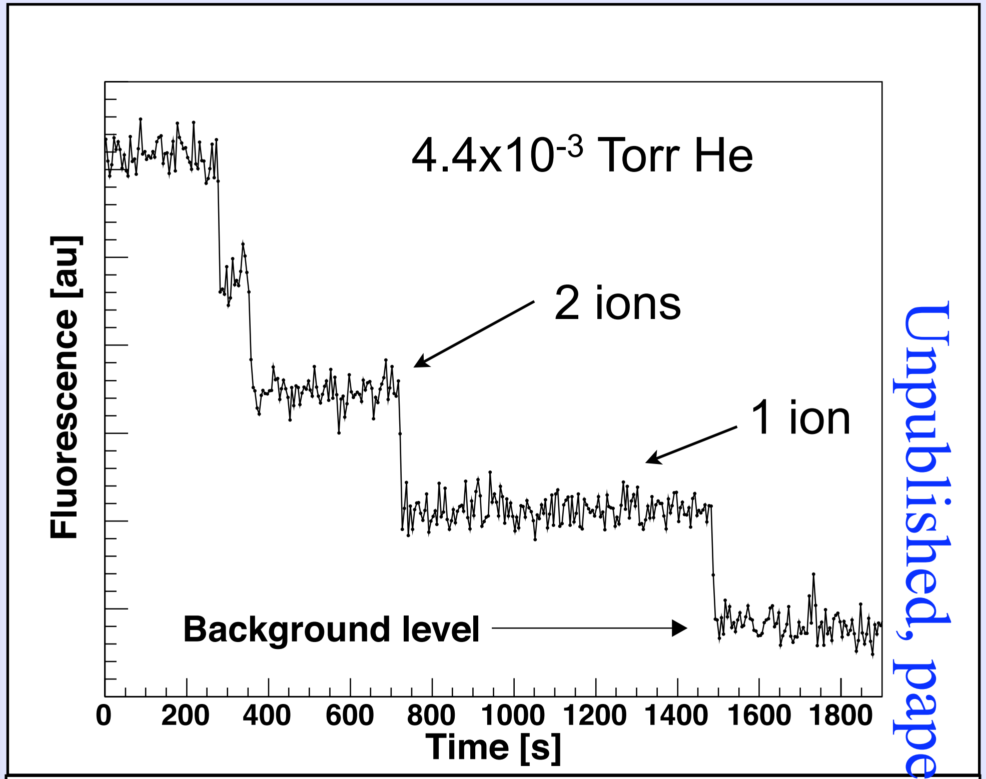
Single ion detection in buffer gas

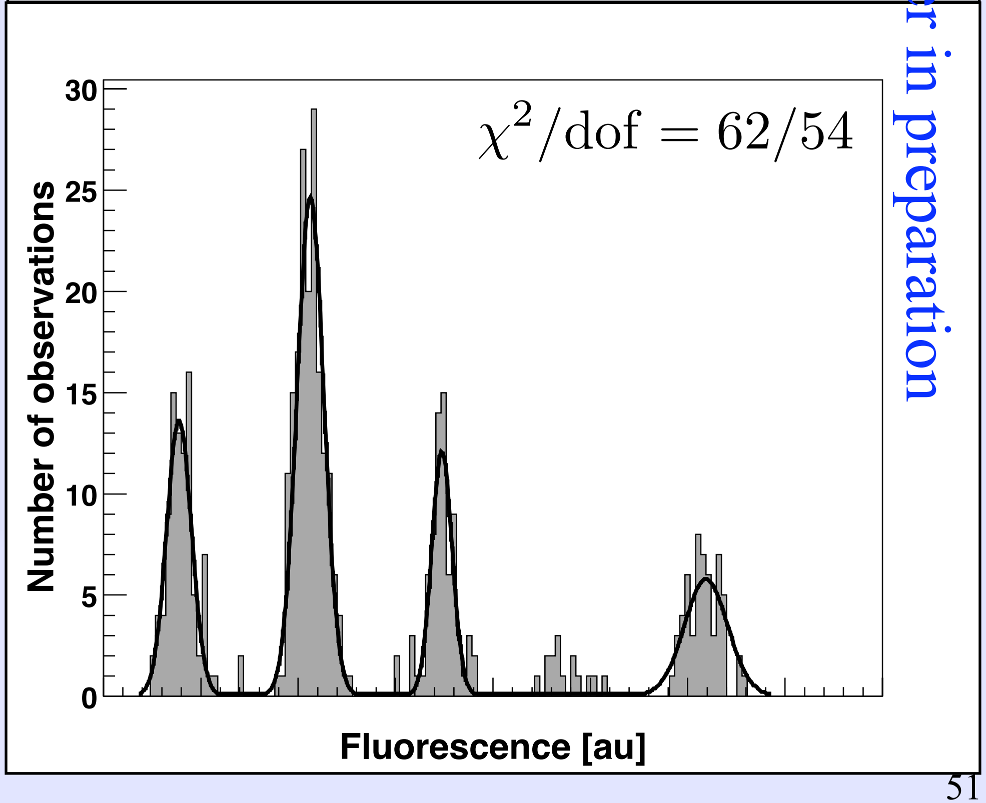


Single ion cloud
(5 s integration)

10^{-3} Torr He
P(493) = 75 μW
P(650) = 300 μW

Electrodes glowing from scattered laser light



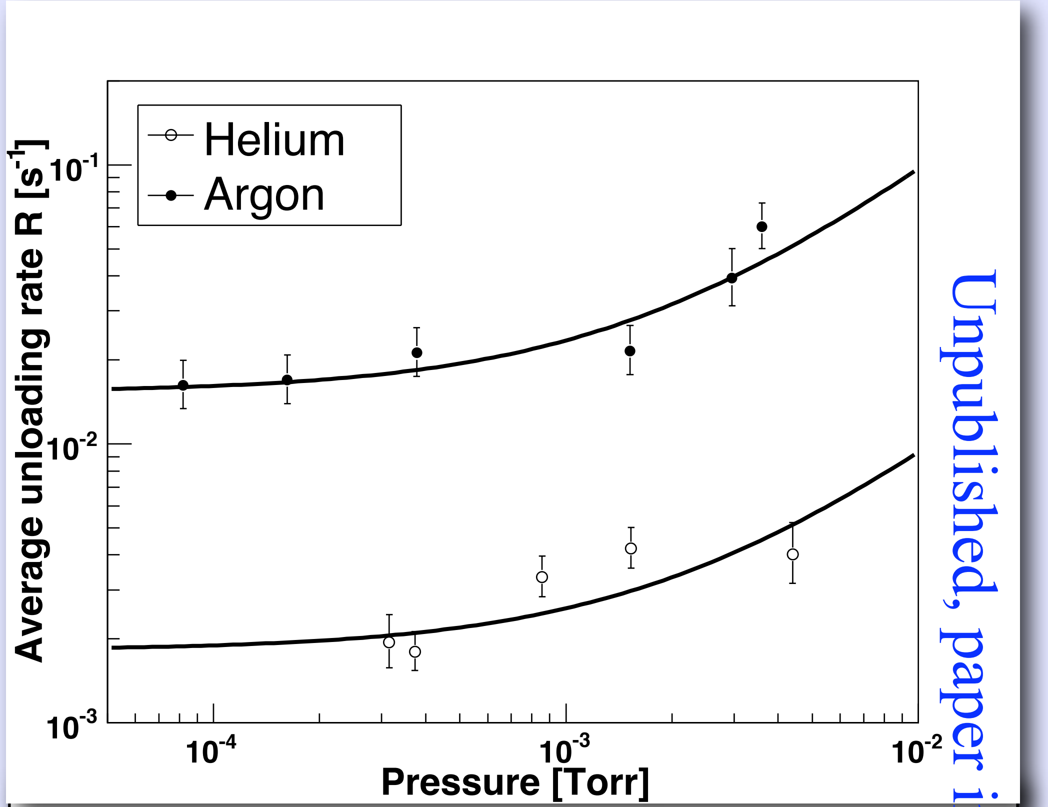


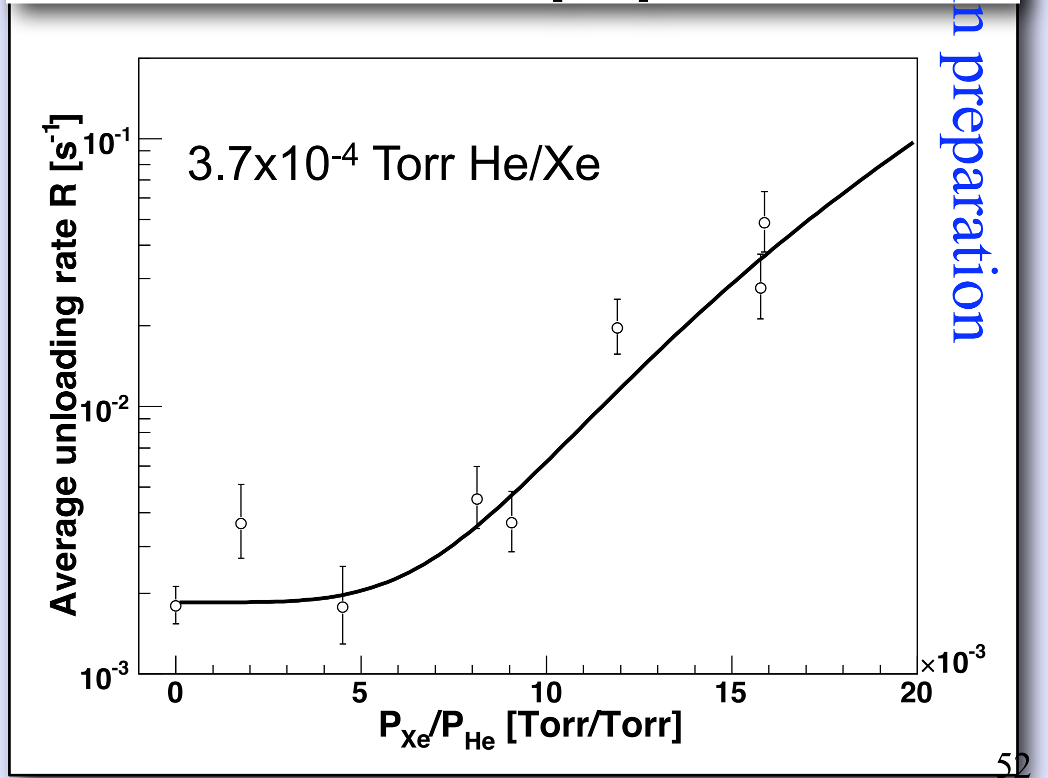
Unpublished, paper in preparation

Single ion lifetime in buffer gas

single Ba$^+$ ions live:
~ 5 min in He
~ 1 min in Ar

should operate at < 5 ×10^{-3} Xe/He concentrations (Xe can unload Ba$^+$ with few collisions)





Unpublished, paper in preparation

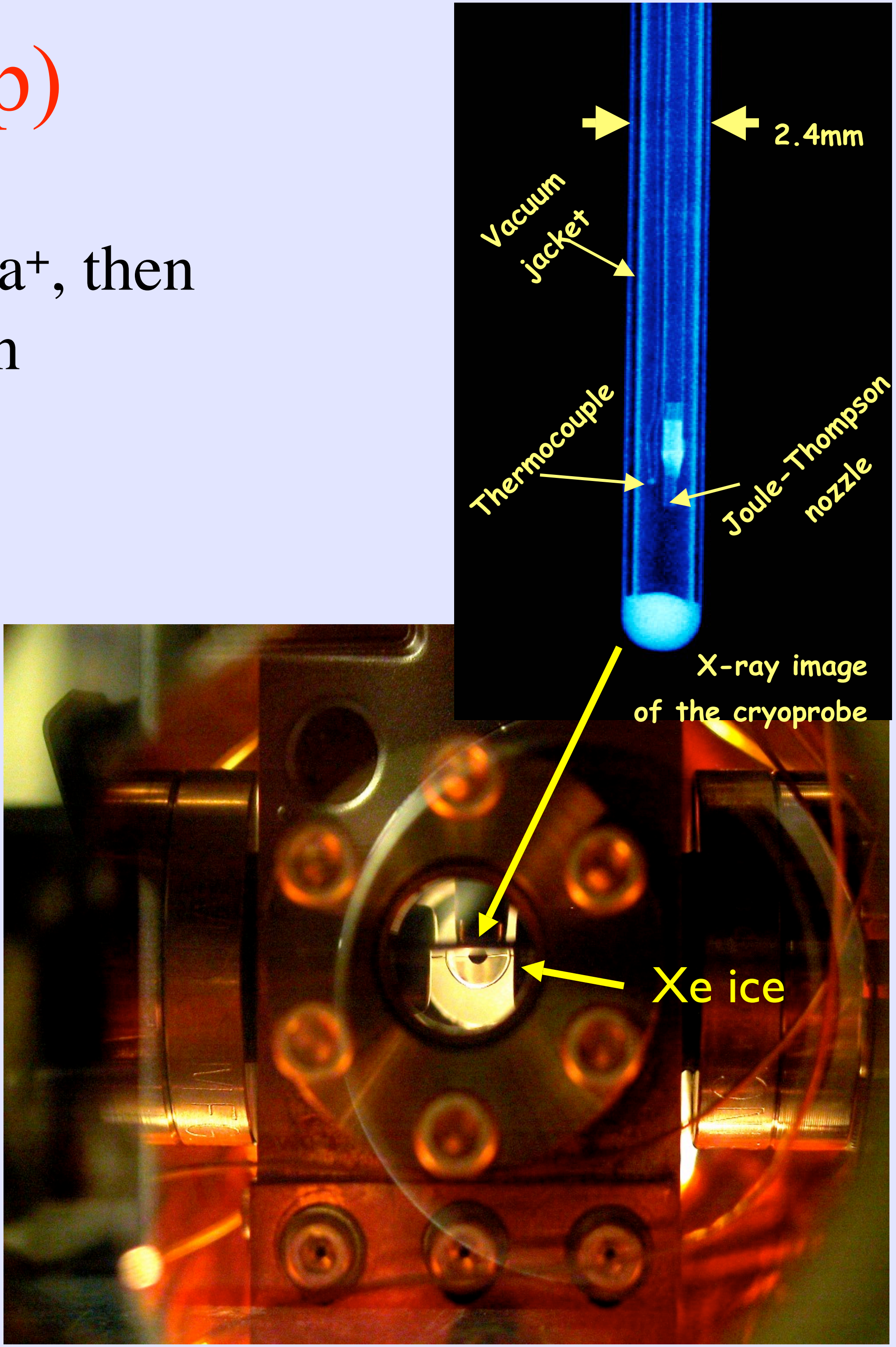
Ba ion grabbing tips

- Cold tip: freeze Ba^+ in Xe ice, then sublimate and release inside trap
- Resonant ionization tip: attract Ba^+ to metalized fiber optic tip, then desorb and ionize with laser pulses inside trap
- Hot tip: attract Ba^+ to metal tip, then desorb inside trap by heating
- Field emission tip: attract Ba^+ to extremely sharp metal tip, then desorb inside trap

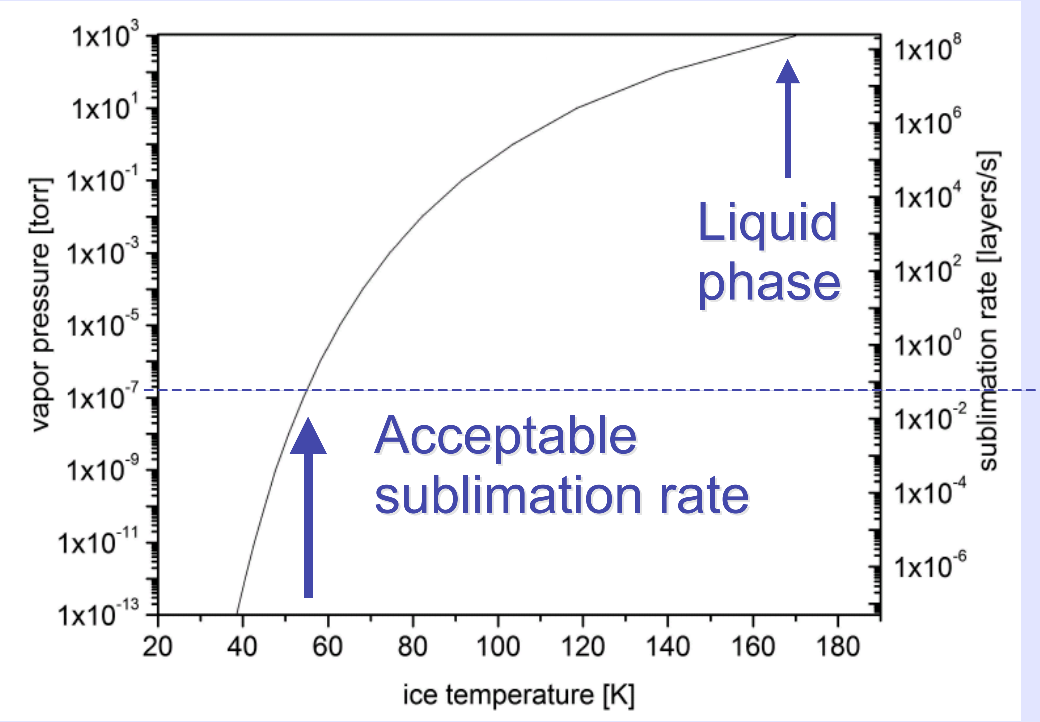
Cold ion tip (cryo-tip)

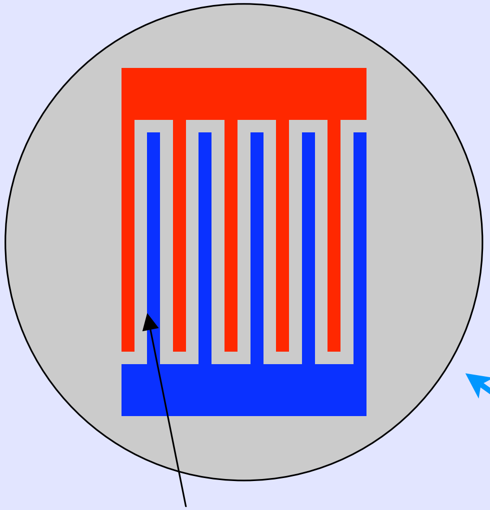
Concept: freeze Xe ice around Ba$^+$, then release inside trap by sublimation

- demonstrated ability to capture and release Th$^+$ and Ra$^+$ ions
- need to control ice formation and melting to preserve the ion and minimize Xe inside the trap (thin Xe ice layer)



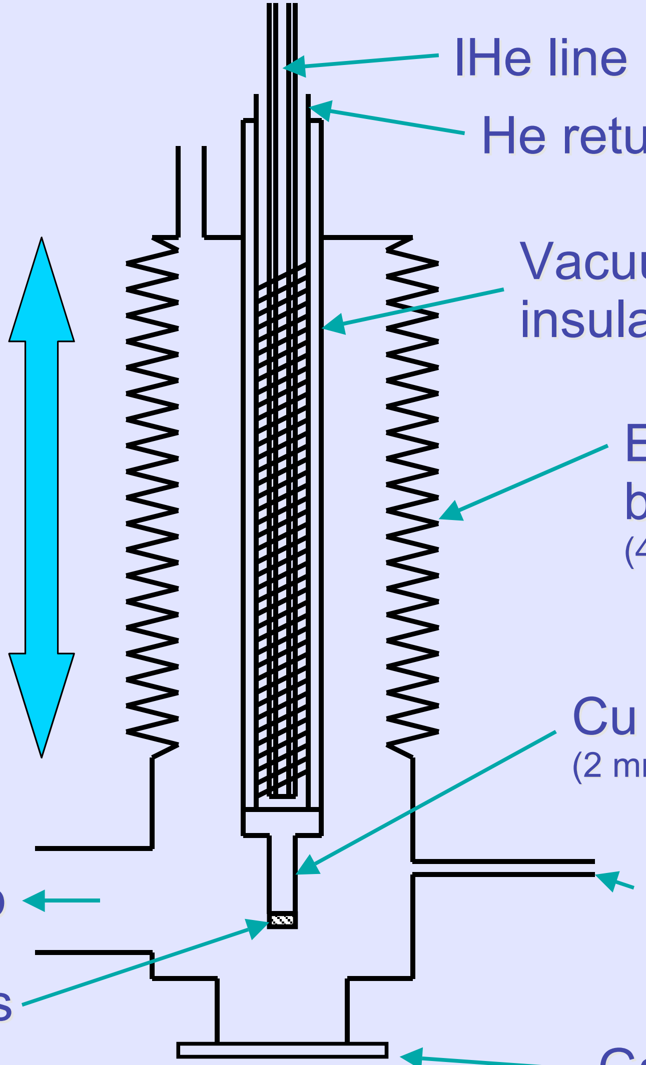
Capacitive cryo-tip





‘fingers’ for dielectric ice-thickness measurement:

ε_r(Xe,liquid) = 1.88
ε_r(Xe,solid) = 2.25



lHe line

He return

Vacuum insulation

Edge welded bellows
(400mm travel)

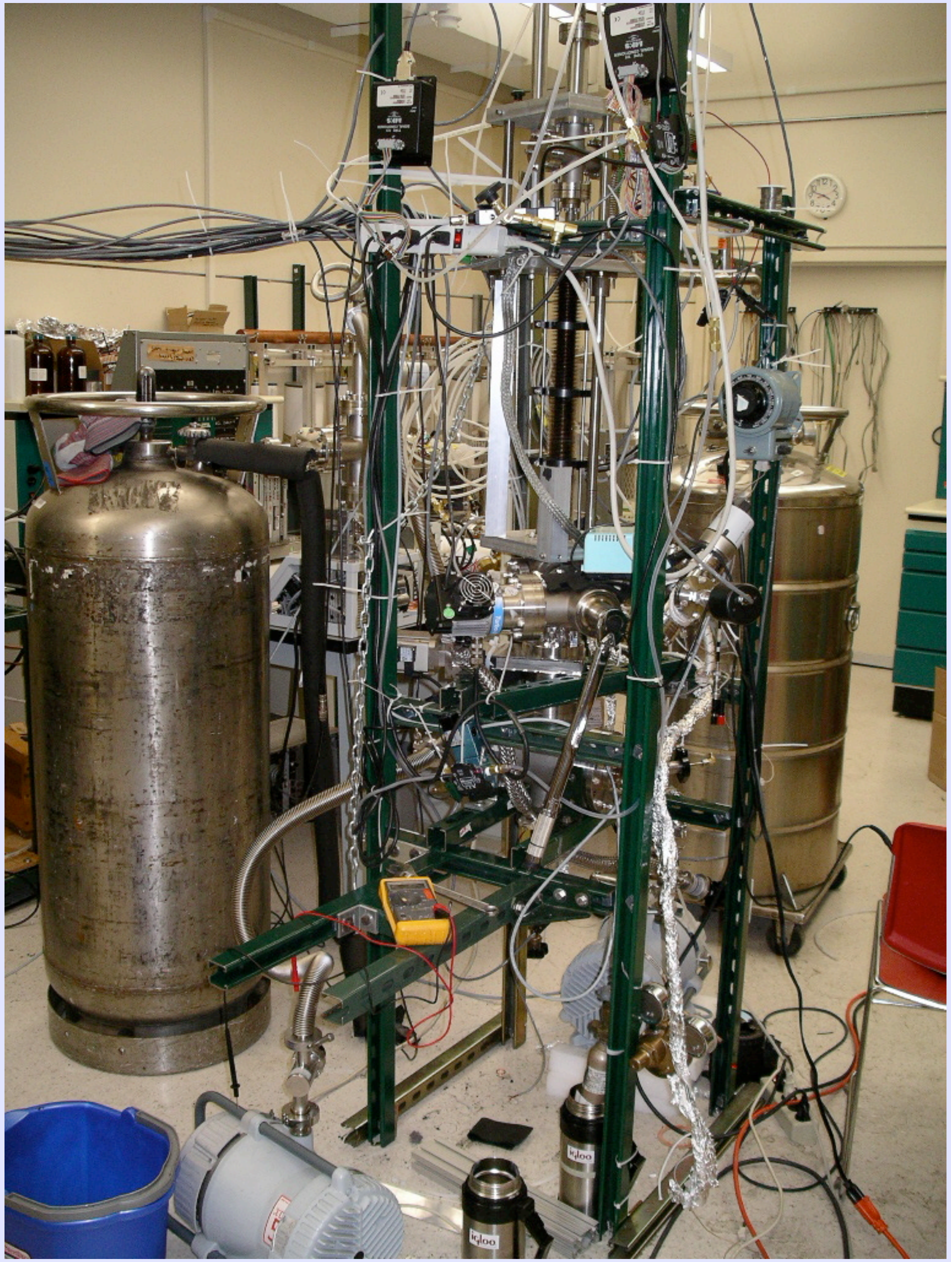
Cu cold-finger
(2 mm diameter)

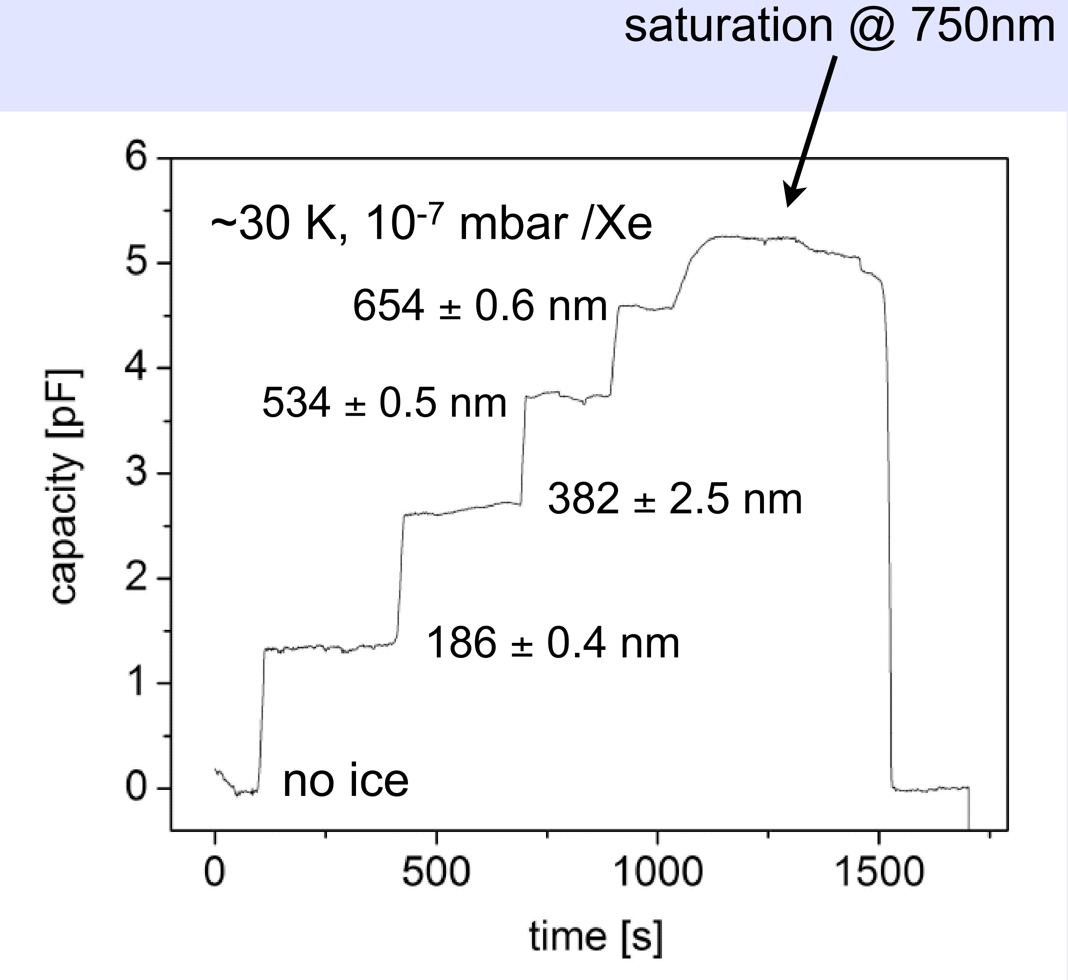
Turbo pump

Ice thickness sensor

Gate valve

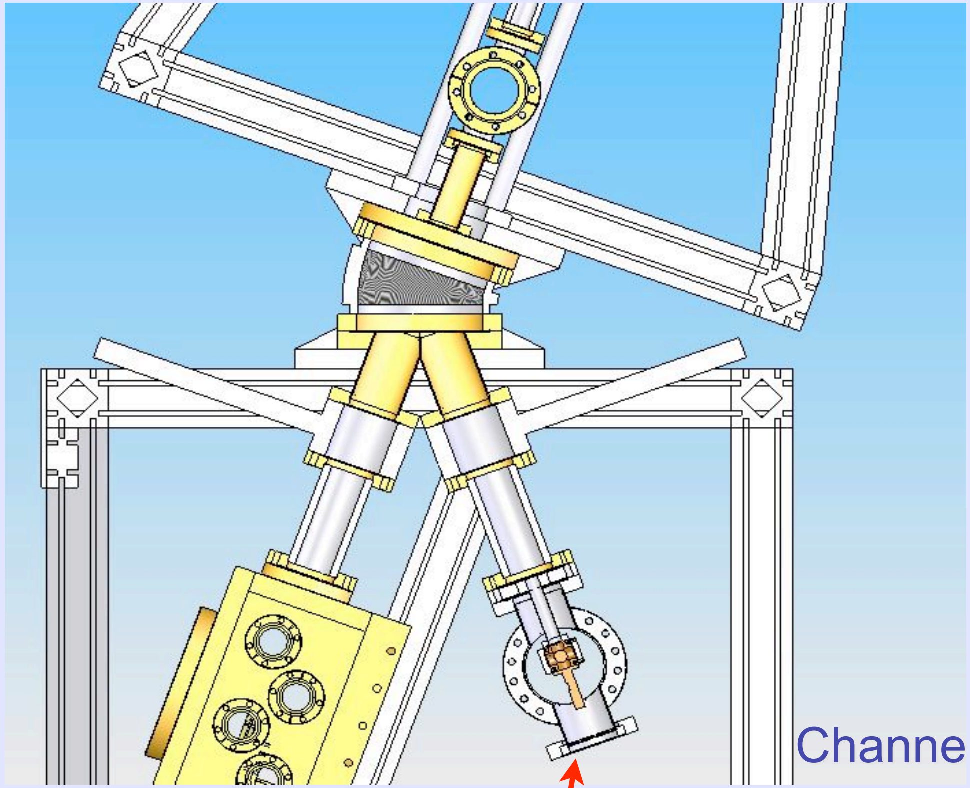
Thin Xe ice with capacitive cryo-tip

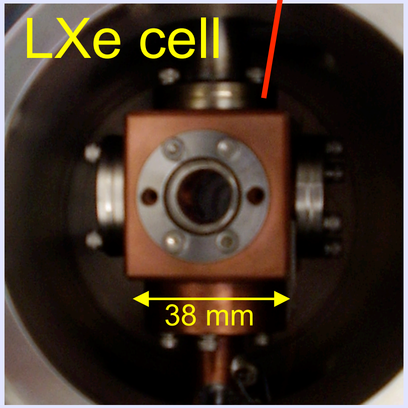


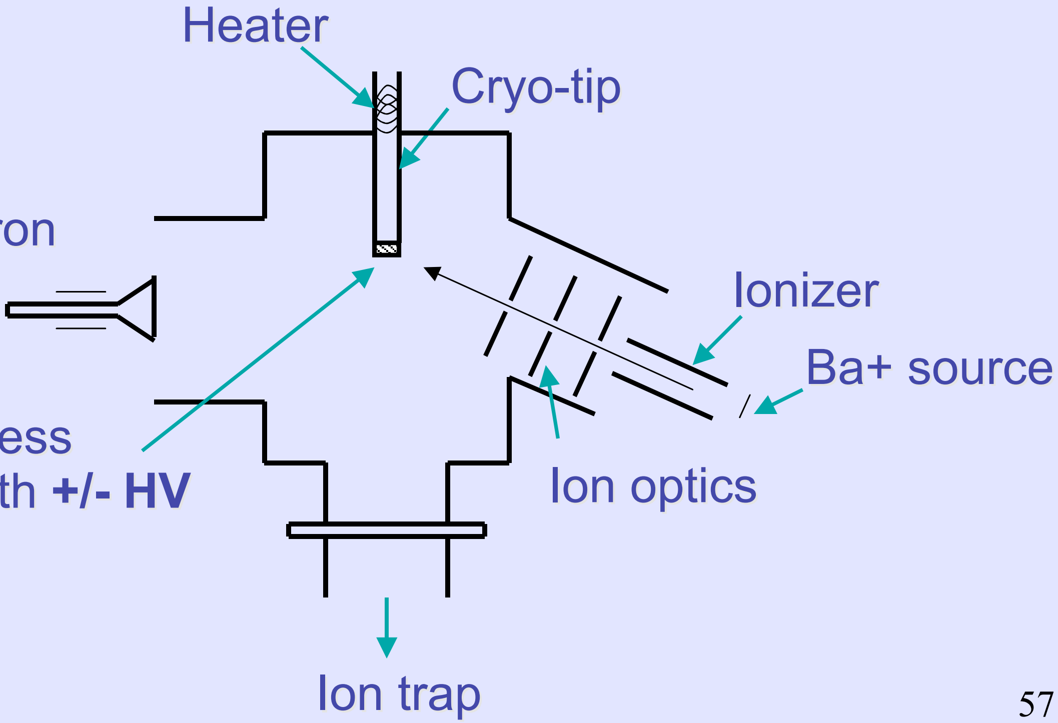


In progress / to come

- Freeze Ba$^+$ from a source on thin Xe ice
- Interface cryo-tip with linear ion trap







Main challenges

- Understanding efficiency of Ba^+ transfer from LXe bath into ion trap
- Understand ionic state of Ba in LXe (with ionization cloud following 2β decay), on tip, and after release

Towards a ton-scale EXO detector

- grabbing setup in large LXe bath (spatial resolution)
- need low trigger rate (~ 1/hour): ultra low background is still mandatory
- use 2ν channel for calibration
- energy resolution becomes the limiting factor: work as hard as possible to improve it
- consider all Ba-producing sources, if any

EXO projected 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 $T_{1/2} > 1 \cdot 10^{22}$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}	33	(95)
Aggressive	10	70	10	1[†]	0.7 (use 1)	4.1×10^{28}	7.3	(21)

[*] σ(E)/E = 1.6% 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

[‡] QRPA: A.Staudt et al. Europhys. Lett.13 (1990) 31; Phys. Lett. B268 (1991) 312

[#] NSM: E.Caurier et al. Phys Rev Lett 77 (1996) 1954

Conclusions

- the ^{136}Xe/^{136}Ba system is very attractive for measuring neutrinoless double beta decay virtually without background other than the 2ν channel

- EXO-200 is well under way: it will likely measure the lifetime of the 2νββ decay of ^{136}Xe, measure (if neutrino masses are degenerate) or set competitive limit for 0νββ of ^{136}Xe, and provide invaluable input for a larger EXO detector (backgrounds, technical solutions, materials, Xe purity in large detectors)

- Ba^{+} identification scheme is well defined, and a grabbing sequence is currently being developed

- A ton-scale EXO detector could be realized in a not-so-far future

Enriched Xenon Observatory

EXO

for double beta decay

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