EXO

Status and perspectives

Giorgio Gratta
Physics Dept, Stanford

LBL, Mar 19, 2009

Our knowledge of the lepton mixing matrix

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} =$$

information on $\not{C}\!P$ is here

Neutrino factory ?

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \bullet \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \bullet \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \bullet \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha/2} & 0 \\ 0 & 0 & e^{-i\alpha/2+i\beta} \end{pmatrix}$$

Atmospheric ν
K2K
Minos et al

θ_{23}~45°

Chooz/Palo Verde
Off axis
Future reactors

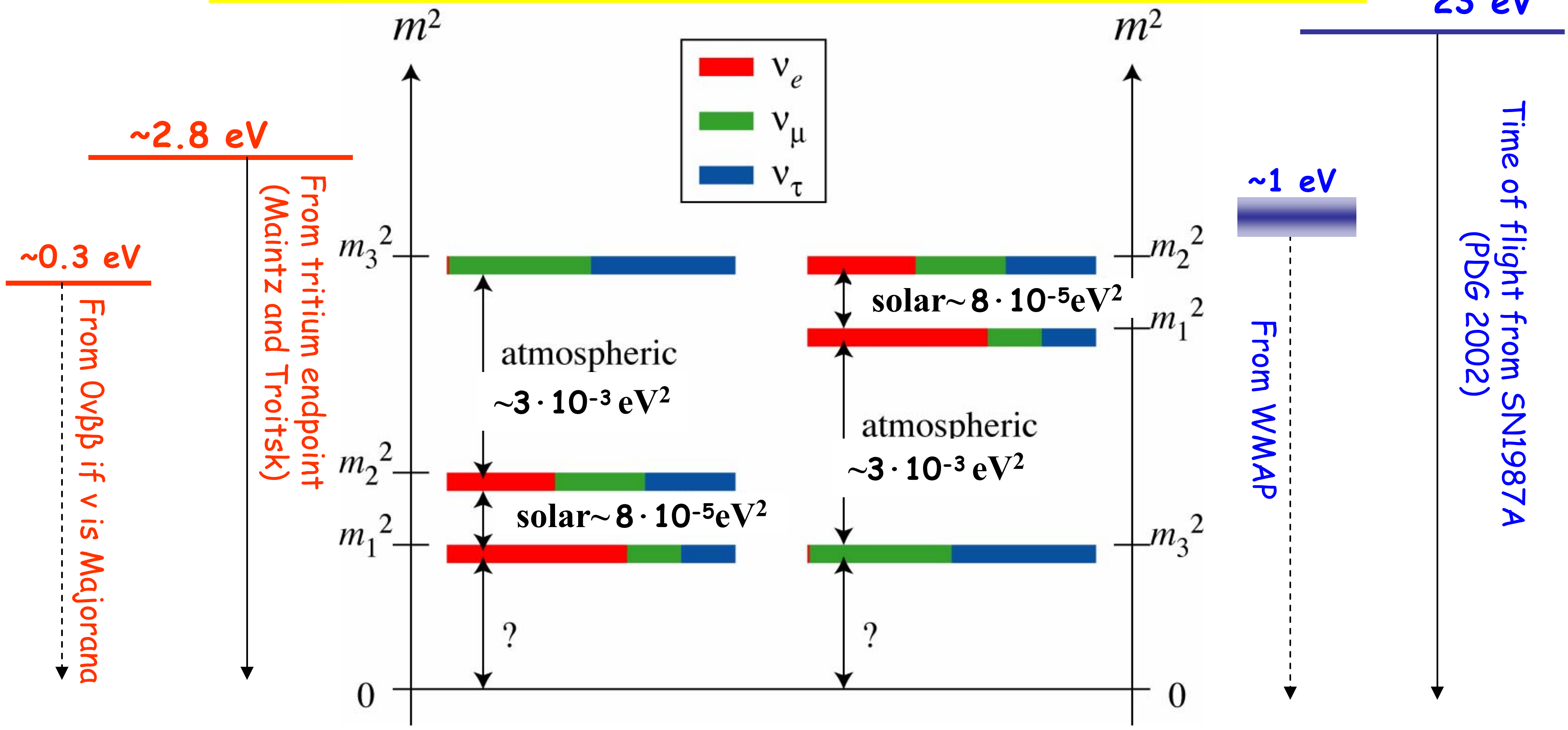
θ_{13}<7° @ 90%CL

Solar ν
KamLAND
Future solar ν exp.

θ_{12}~32°

Neutrinoless double beta decay

Our knowledge of the ν mass pattern



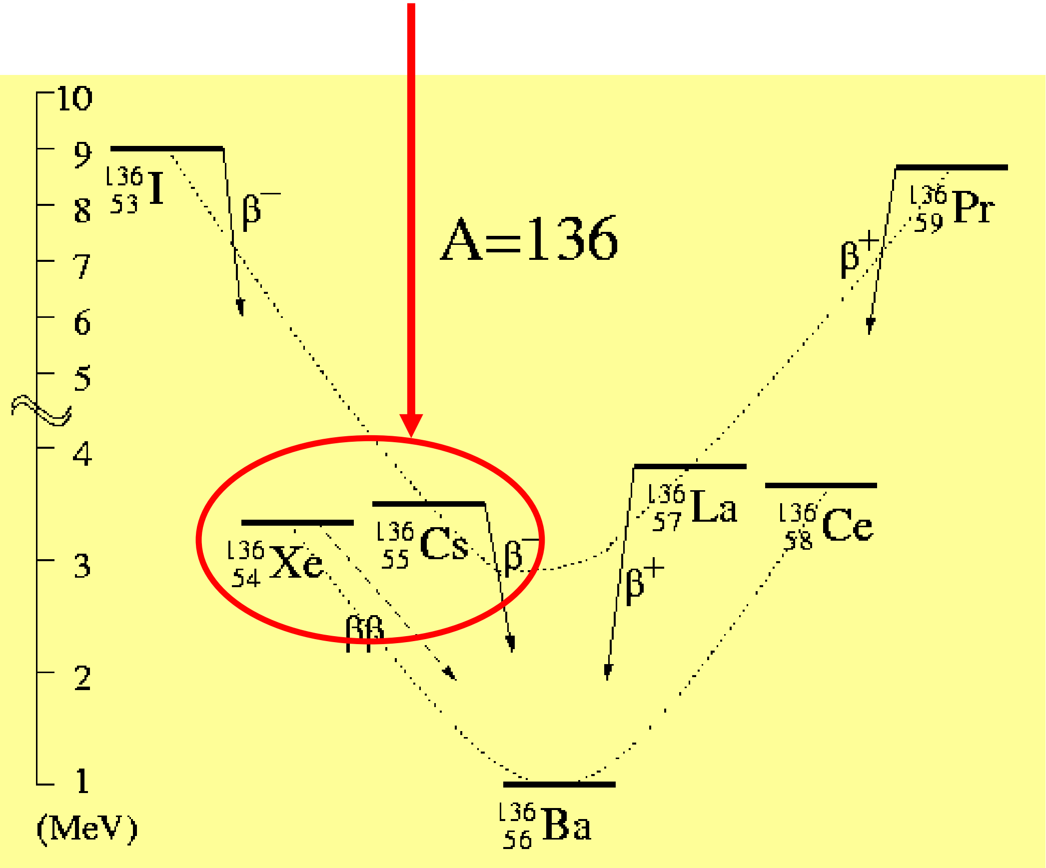
The measurement of the absolute mass scale,

θ_{13} and the choice of hierarchy

are the next big challenges in neutrino physics

Double-beta decay:

a second-order process only detectable if first order beta decay is energetically forbidden



Candidate nuclei with Q>2 MeV

Candidate	Q (MeV)	Abund. (%)
^{48}Ca→^{48}Ti	4.271	0.187
^{76}Ge→^{76}Se	2.040	7.8
^{82}Se→^{82}Kr	2.995	9.2
^{96}Zr→^{96}Mo	3.350	2.8
^{100}Mo→^{100}Ru	3.034	9.6
^{110}Pd→^{110}Cd	2.013	11.8
^{116}Cd→^{116}Sn	2.802	7.5
^{124}Sn→^{124}Te	2.228	5.64
^{130}Te→^{130}Xe	2.533	34.5
^{136}Xe→^{136}Ba	2.479	8.9
^{150}Nd→^{150}Sm	3.367	5.6

There are two varieties of ββ decay

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

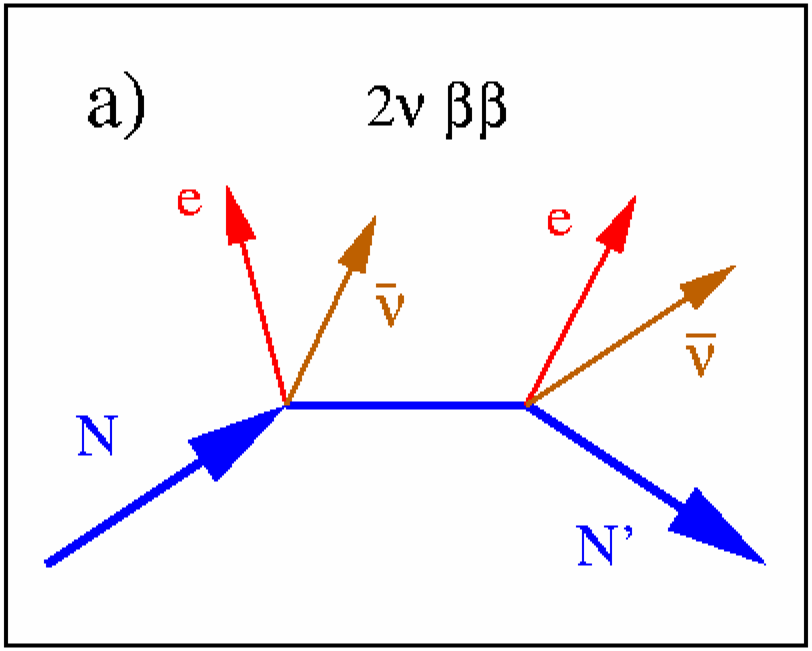
0ν mode: a hypothetical
process can happen
only if: $M_\nu \neq 0$

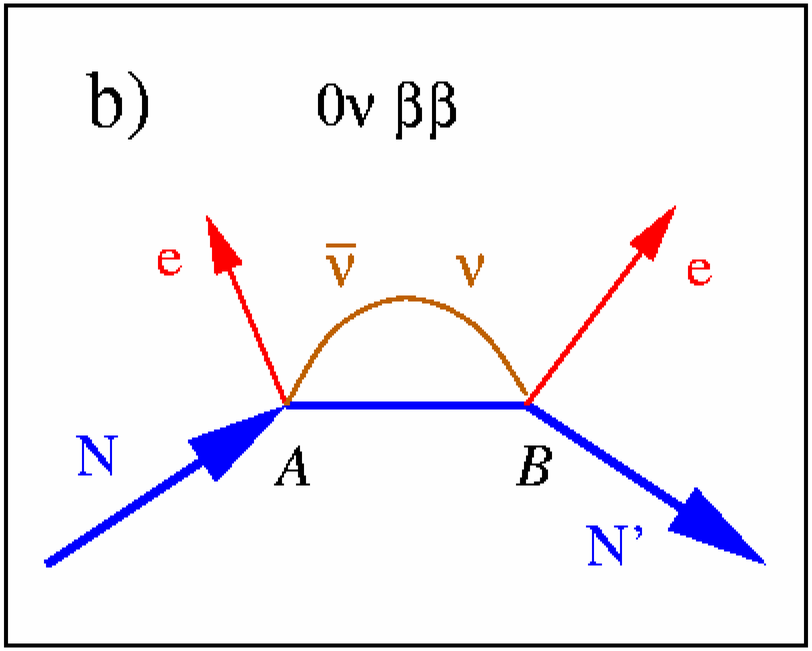
$\nu = \bar{\nu}$

$|\Delta L|=2$

$|\Delta(B-L)|=2$

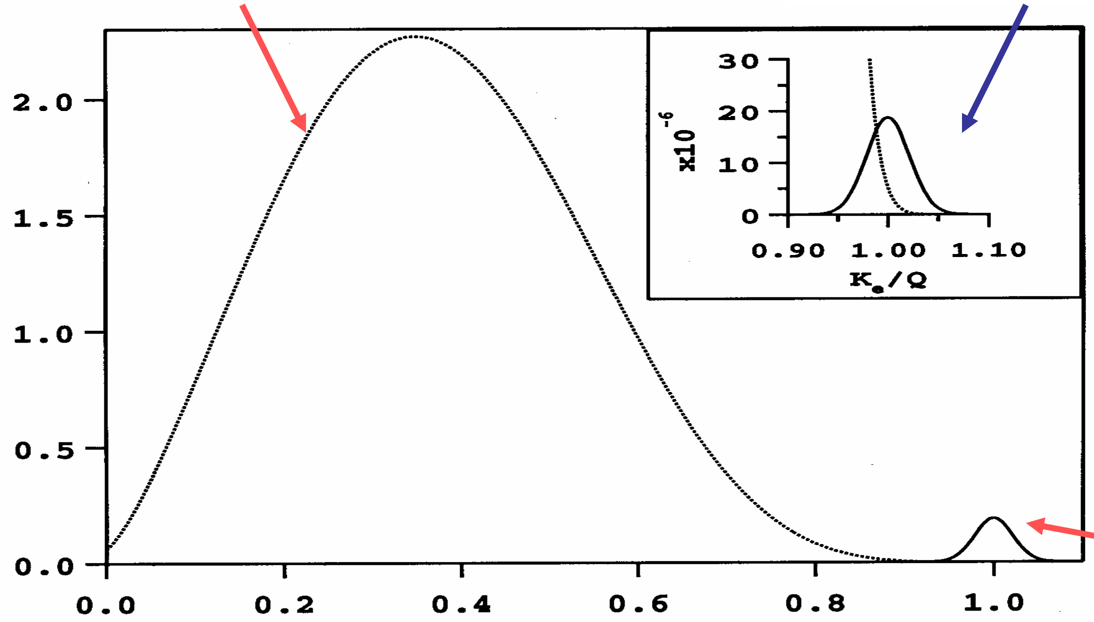
Since helicity has to "flip"





Background due to the Standard Model 2νββ decay

from S.R. Elliott and P. Vogel, Ann.Rev.Nucl.Part.Sci. **52** (2002) 115.



2νββ spectrum
(normalized to 1)

0νββ peak (5% FWHM)
(normalized to 10^{-6})

0νββ peak (5% FWHM)
(normalized to 10^{-2})

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

The two can be separated in a detector with good energy resolution

If $0\nu\beta\beta$ is due to light ν Majorana masses

$$\langle m_\nu \rangle^2 = \left(T_{1/2}^{0\nu\beta\beta}\ G^{0\nu\beta\beta}(E_0, Z)\ \left| M_{GT}^{0\nu\beta\beta} - \frac{g_V^2}{g_A^2} M_F^{0\nu\beta\beta} \right|^2 \right)^{-1}$$

$M_F^{0\nu\beta\beta}$ and $M_{GT}^{0\nu\beta\beta}$ can be calculated within particular nuclear models

$G^{0\nu\beta\beta}$ a known phasespace factor

$T_{1/2}^{0\nu\beta\beta}$ is the quantity to be measured

$$\langle m_\nu \rangle = \sum_{i=1}^{3} \left| U_{e,i} \right|^2 m_i\ \varepsilon_i$$

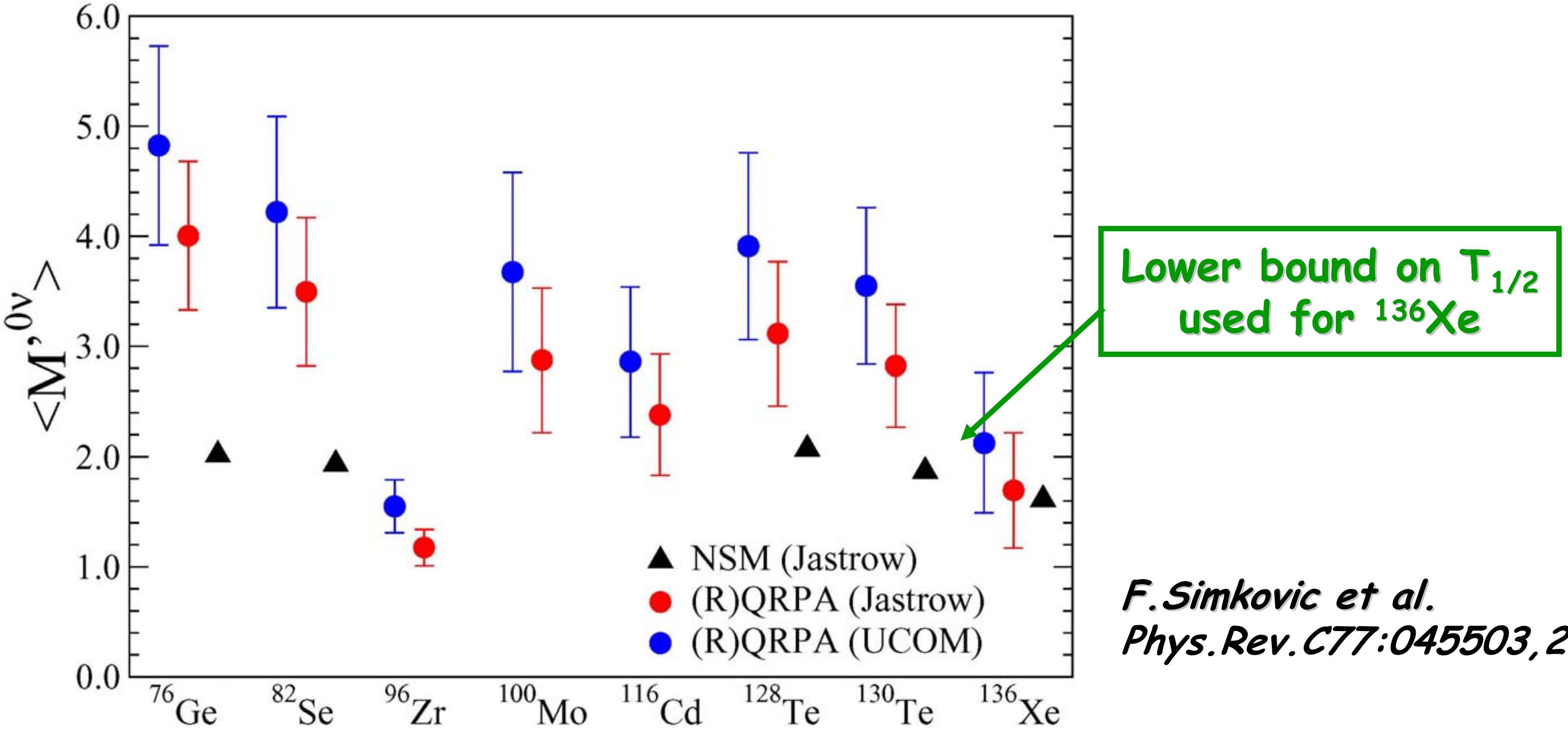
effective Majorana ν mass
($\varepsilon_i = \pm 1$ if CP is conserved)

Cancellations are possible…

Much progress made recently in accuracy of nuclear matrix elements.

(e.g. was found that main uncertainly in (R)QRPA calculations comes from the single particle space around the Fermi surface.

→ Can *use the measured $2\nu\beta\beta$ $T_{1/2}$ to make a correction.*)



Lower bound on $T_{1/2}$ used for ^{136}Xe

F.Simkovic et al.
Phys.Rev.C77:045503,2008

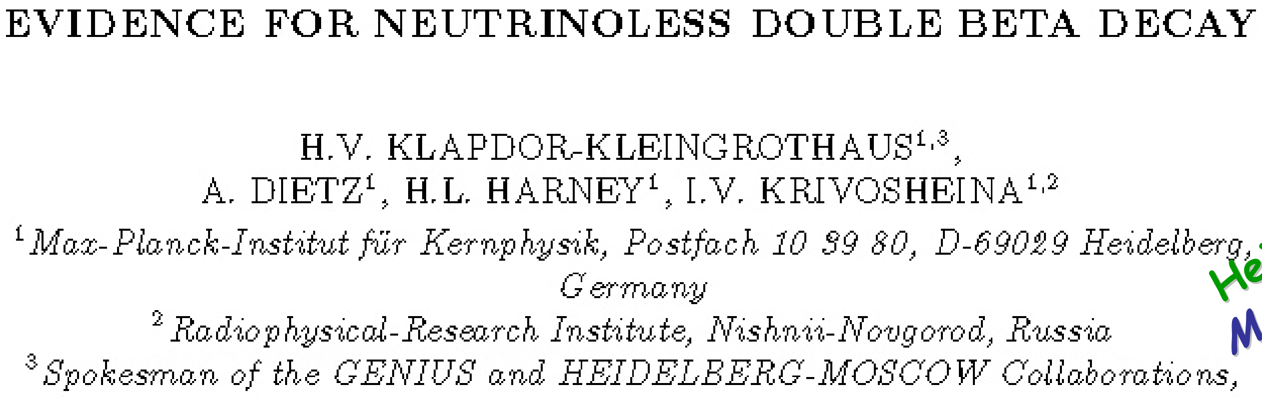
Still, if/once $0\nu\beta\beta$ decay is discovered, the $T_{1/2}$ in more than one nucleus will be needed to pin down neutrino masses

Present Limits for 0ν double beta decay

Candidate nucleus	Detector type	(kg yr)	Present $T_{1/2}^{0\nu\beta\beta}$ (yr)	<m> (eV)
^{48}Ca			$>1.4*10^{22}$ (90%CL)	
^{76}Ge	Ge diode	~47.7	$>1.9*10^{25}$ (90%CL)	<0.35*
^{82}Se			$>1*10^{23}$ (90%CL)	
^{100}Mo			$>4.6*10^{23}$ (90%CL)	
^{116}Cd			$>1.7*10^{23}$ (90%CL)	
^{128}Te	TeO_2 cryo		$>1.1*10^{23}$ (90%CL)	
^{130}Te	TeO_2 cryo	~12	$>3*10^{24}$ (90%CL)	<0.19 - 0.68
^{136}Xe	Xe scint	~4.5	$>1.2*10^{24}$ (90%CL)	<1.1 - 2.9
^{150}Nd			$>1.2*10^{21}$ (90%CL)	
^{160}Gd			$>1.3*10^{21}$ (90%CL)	

* *But also claim of signal by part of same group*

There is also a discovery claim (using ^{76}Ge)



EVIDENCE FOR NEUTRINOLESS DOUBLE BETA DECAY

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Part of the Heidelberg-Moscow collaboration

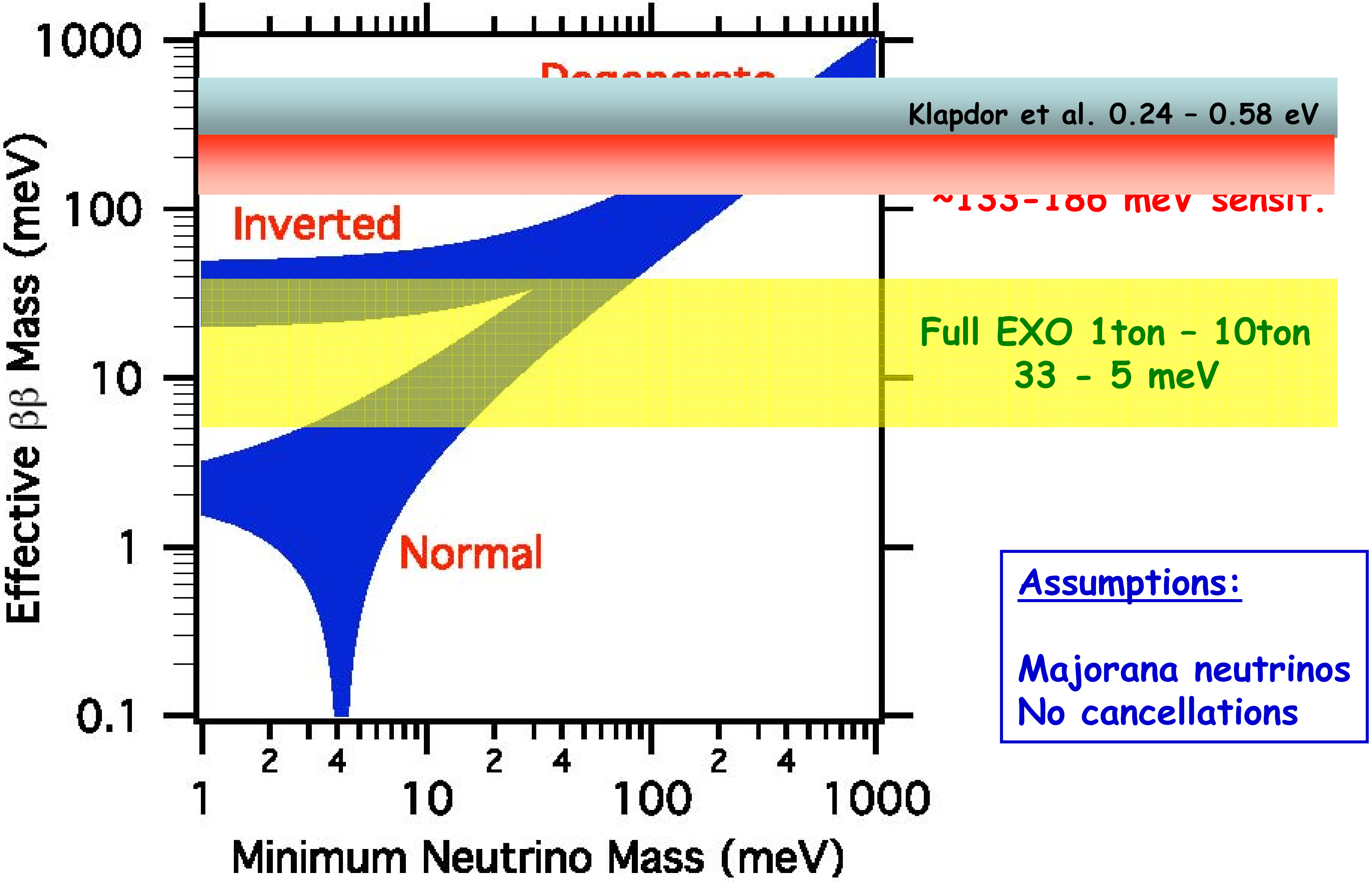
Mod. Phys Lett. A27 (2001) 2409

With the values $T_{1/2}^{0\nu\beta\beta} = 2.23^{+0.44}_{-0.31}$ $m_\nu^{eff}=0.32\pm0.03$

…but this is a controversial matter (see details in)

C.A.Aalseth Mod. Phys. Lett. A17 (2002) 1475
F.Feruglio et al. Nucl.Phys. B637 (2002) 345
Addendum-ibid. B659 (2003) 359
Yu.Zdesenko et al. Phys.Lett. B 546 (2002) 206
H.L.Harney Mod.Phys.Lett. A16 (2001) 2409
A.M.Bakalyarov et al. hep-ex/0309016
H.V.Klapdor-Kleingrouthaus et al. Phys. Lett. B 586 (2004) 198
H.V.Klapdor-Kleingrouthaus et al. Mod. Phys. Lett. 21 (2006) 1547

For the first time there is a clear opportunity to make an important discovery if one pushes the <m> sensitivity to the 0.01 - 1 eV region



Klapdor et al. 0.24 – 0.58 eV

~133-186 meV sensit.

Full EXO 1ton – 10ton
33 - 5 meV

Assumptions:

Majorana neutrinos
No cancellations

Plot from Avignone, Elliott, Engel arXiv:0708.1033 (2007)

In the last 10 years there has been a transition

1) From a few kg detectors to 100s or 1000s kg detectors
→ Think big: qualitative transition from cottage industry to large experiments

2) From "random shooting" to the knowledge that at least the inverted hierarchy will be tested

Discovering $0\nu\beta\beta$ decay:

→ Discovery of the neutrino mass scale
→ Discovery of Majorana particles
→ Discovery of lepton number violation

To reach $<m_\nu>$ ~ 10 meV very large fiducial mass (tons)
(except for Te) need massive isotopic enrichment
Need to reduce and control backgrounds in qualitatively new ways
these are the lowest background experiment ever built

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

Scaling with bkgd goes like *Nt* $\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0\nu\beta\beta}} \propto 1/(Nt)^{1/4}$

In addition a multi-parameter experiment, if feasible, would provide information for cross checks with more than one single variable, if a discovery is made.

ββ decay experiments are at the leading edge of "low background" techniques

- Final state ID: 1) "Geochemical": search for an abnormal abundance
  of (A,Z+2) in a material containing (A,Z)
  2) "Radiochemical": store in a mine some material (A,Z)
  and after some time try to find (A,Z+2) in it
  + Very specific signature
  + Large live times (particularly for 1)
  + Large masses
  - Possible only for a few isotopes (in the case of 1)
  - No distinction between 0ν, 2ν or other modes
- "Real time": ionization or scintillation is detected in the decay
  a) "Homogeneous": source=detector
  b) "Heterogeneous": source≠detector
  + Energy/some tracking available (can distinguish modes)
  + In principle universal (b)
  - Many γ backgrounds can fake signature
  - Exposure is limited by human patience

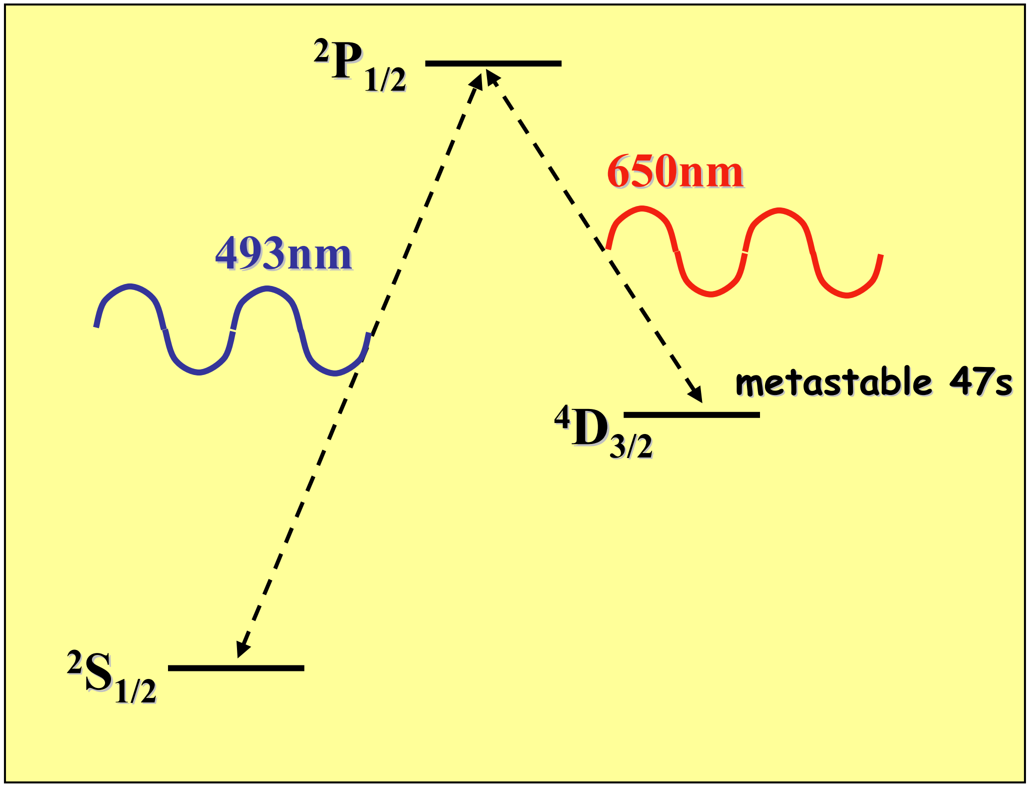
Xe is ideal for a large experiment

- 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 ~ Δm. 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
- Drastic background reduction



The Ba-tagging, added to a high resolution Xe imaging detector provides the tools to develop a background-free next-generation ββ experiment

Assume an "asymptotic" fiducial mass of 10 tons of ^{136}Xe at 80%

A somewhat natural scale:

- World production of Xe is ~40 ton/yr
- Detector size
- $2 \cdot 10^3$ size increase: good match to the 10^{-2} eV mass region

Mainly going in light bulbs, plasma displays and satellite propulsion

Enriched Xenon Observatory

for double beta decay

Enriched Xenon Observatory
EXO
for double beta decay

The EXO Collaboration

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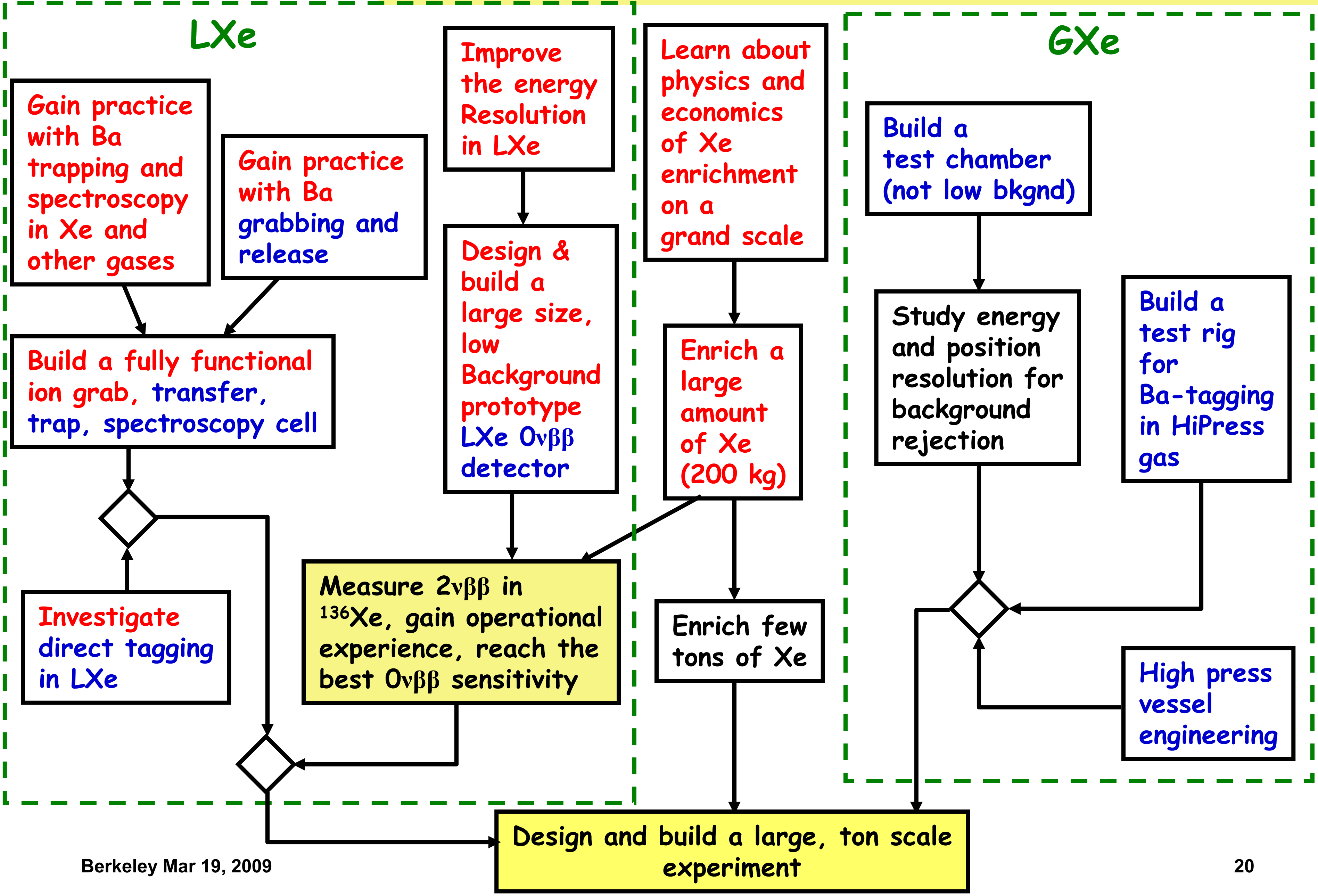
Done In progress
To do

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



LXe

Gain practice with Ba trapping and spectroscopy in Xe and other gases

Gain practice with Ba grabbing and release

Improve the energy Resolution in LXe

Design & build a large size, low Background prototype LXe $0\nu\beta\beta$ detector

Build a fully functional ion grab, transfer, trap, spectroscopy cell

Investigate direct tagging in LXe

Measure $2\nu\beta\beta$ in ^{136}Xe, gain operational experience, reach the best $0\nu\beta\beta$ sensitivity

Learn about physics and economics of Xe enrichment on a grand scale

Enrich a large amount of Xe (200 kg)

Enrich few tons of Xe

GXe

Build a test chamber (not low bkgnd)

Study energy and position resolution for background rejection

Build a test rig for Ba-tagging in HiPress gas

High press vessel engineering

Design and build a large, ton scale experiment

EXO-200kg Majorana mass sensitivity

Assumptions:

1) 200kg of Xe enriched to 80% in 136
2) σ(E)/E = 1.4% obtained in EXO R&D, Conti et al Phys Rev B 68 (2003) 054201
3) Low but finite radioactive background:
   20 events/year in the ±2σ interval centered around the 2.481MeV endpoint
4) Negligible background from 2νββ ($T_{1/2}>1\cdot10^{22}$yr R.Bernabei et al. measurement)

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	$6.4*10^{25}$	0.133†	0.186*

What if Klapdor's observation is correct ?

Central value $T_{1/2}$ (Ge) = $1.2^{+3}_{-0.5}\cdot10^{25}$, (±3σ)
(Phys. Lett. B 586 (2004) 198-212
consistently use Rodin's matrix elements for both Ge and Xe)

In 200kg EXO, 2yr:

- Worst case (QRPA, upper limit) 15 events on top of 40 events bkgd → 2σ
- Best case (NSM, lower limit) 162 events on top of 40 bkgd → 11σ

EXO-200kg Majorana mass sensitivity

Assumptions:

1) 200kg of Xe enriched to 80% in 136
2) $\sigma(E)/E$ = 1.4% obtained in EXO R&D, Conti et al Phys Rev B 68 (2003) 054201
3) Low but finite radioactive background:
   20 events/year in the $\pm 2\sigma$ interval centered around the 2.481MeV endpoint
4) Negligible background from $2\nu\beta\beta$ ($T_{1/2} > 1 \cdot 10^{22}$yr R.Bernabei et al. measurement)

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	$6.4 * 10^{25}$	0.13†	0.19*

What if Klapdor's observation is correct ?

Central value $T_{1/2}$ (Ge) = $2.23^{+0.44}_{0.31} \cdot 10^{25}$, ($\pm 3\sigma$)

In EXO-200, 2yr:

- Worst case (QRPA, upper limit) 46 events on top of 40 events bkgd → 5.0 σ
- Best case (NSM, lower limit) 170 events on top of 40 bkgd → 11.7 σ

EXO neutrino effective mass 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)	$2 \cdot 10^{27}$	24	33
Aggressive	10	70	10	1†	0.7 (use 1)	$4.1 \cdot 10^{28}$	5.3	7.3

* σ(E)/E = 1.4% 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

‡ Rodin, *et. al.*, Nucl. Phys. A 793 (2007) 213-215

\# Caurier, *et. al.*, arXiv:0709.2137v1

Status of 2ν mode in ^{136}Xe

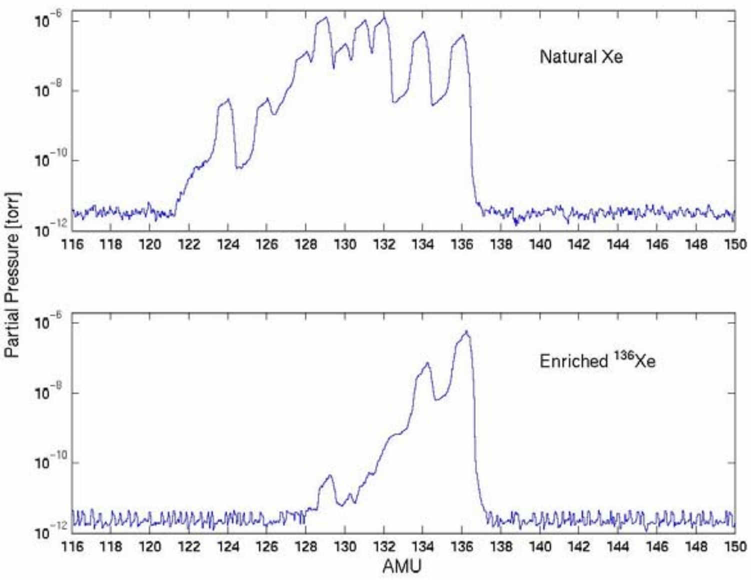
2νββ decay has never been observed in ^{136}Xe.
Some of the lower limits on its half life are close to (and in one case below) the theoretical expectation.

	$T_{1/2}$ (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 should definitely resolve this issue

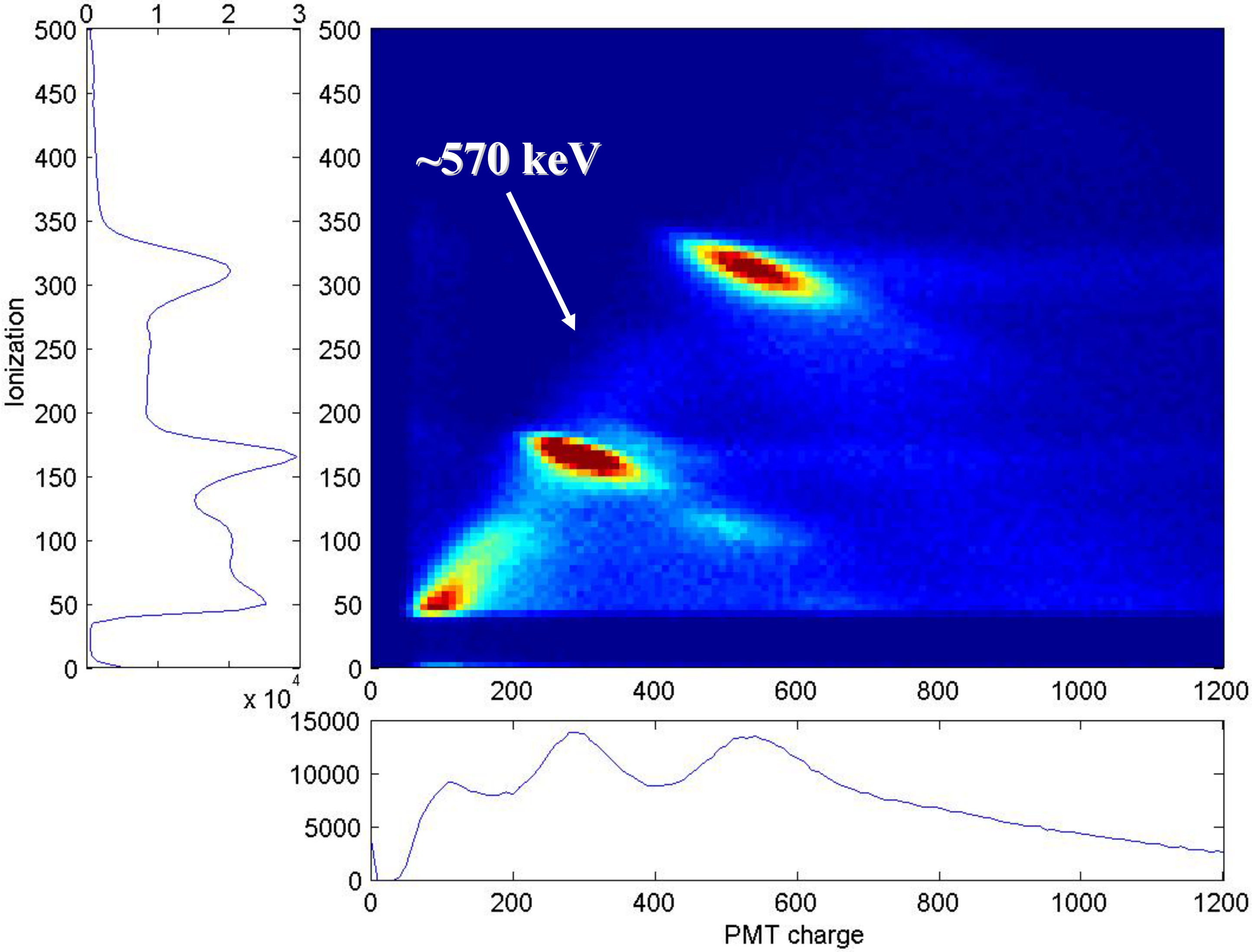
EXO-200

200 kg ^{136}Xe test production completed in spring '03 (80% enrichment)

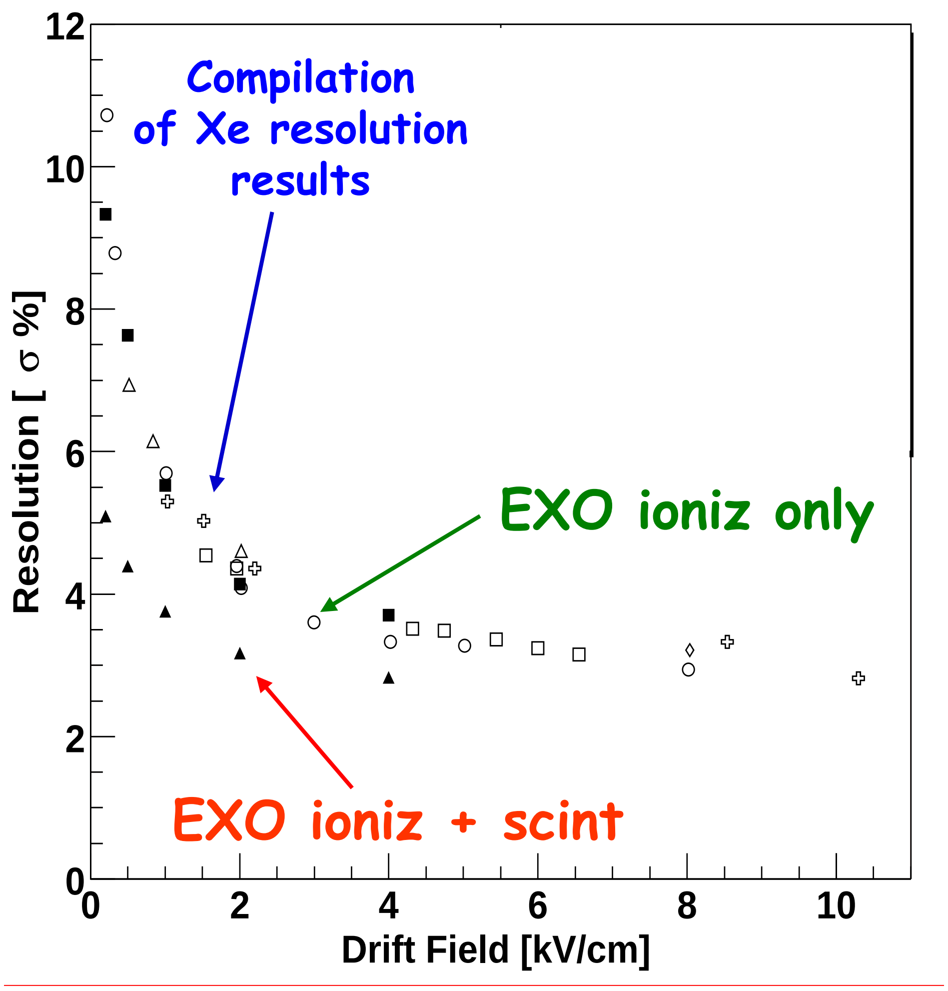


- Largest highly enriched stockpile not related to nuclear industry
- Largest sample of separated $\beta\beta$ isotope (by ~factor of 10)

EXO R&D showed the way to improved energy resolution in LXe: *Use (anti)correlations between ionization and scintillation signals*



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



Ionization alone:

$\sigma(E)/E$ = 3.8% @ 570 keV

or 1.8% @ $Q_{\beta\beta}$

Ionization & Scintillation:

$\sigma(E)/E$ = 3.0% @ 570 keV

or 1.4% @ $Q_{\beta\beta}$

(a factor of 2 better than the Gotthard TPC)

E.Conti et al.

Phys. Rev. B: 68 (2003) 054201

and by now other groups have used this [e.g. E. Aprile et al. PRB 76 (2007) 014115]

EXO-200 will collect 3-4 times as much scintillation… further improvement possible

EXO-200 TPC basics

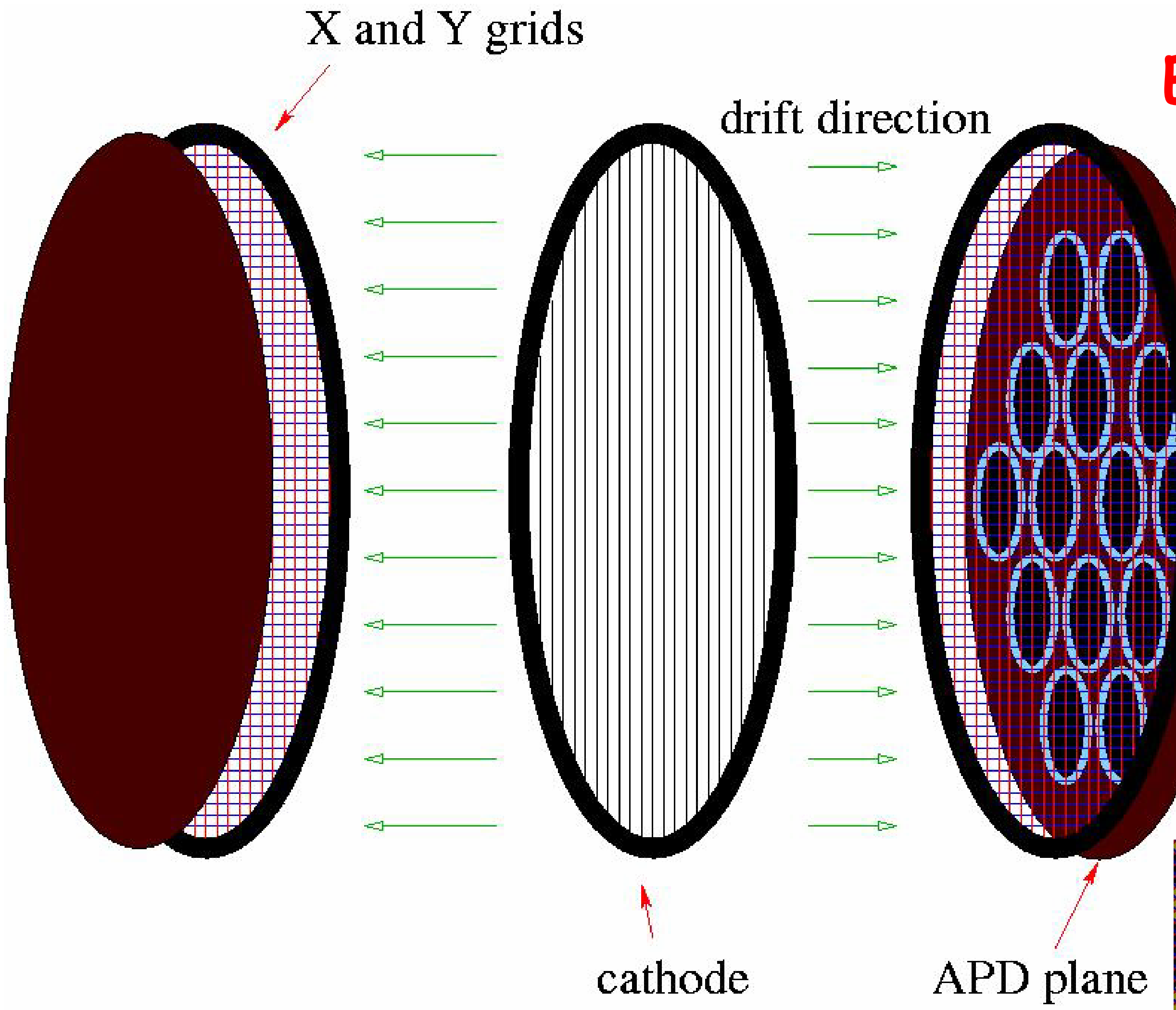
- The detector measures both the ionization electrons and the scintillation light to get best energy resolution.
  - In addition, the position of the decay is measured to get spatial distributions and (for later) the position of the Ba ion.
  - Info on event topology also important for background separation.

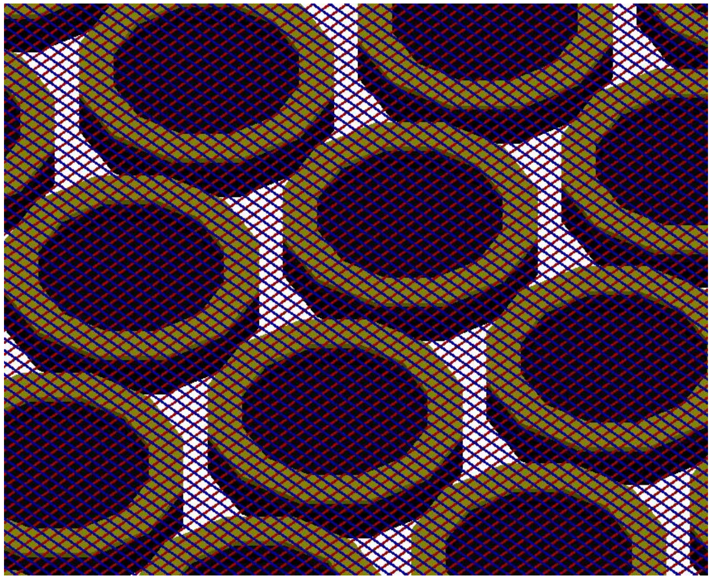
- The detector is a cylinder of ~40cm ID by ~40cm inner length.

- The cylinder is split by a cathode plane at the center so there are two symmetric drift regions. The cathode runs at negative HV.
  - Max HV is ~ 70kV (~3.5 kV/cm drift). Energy resolution improves with drift field, but there are arguments that separation of 1 vs 2 primary electrons might be better at lower fields.
    → field optimization is an important mission of EXO-200

- Readout "style":
  - Crossed wires, 100μm wires, 3mm pitch, ganged in groups of 3
    48ch x, 48ch y, total 96 ch per 1/2 detector
    (Pad readout rejected because of high channel count)

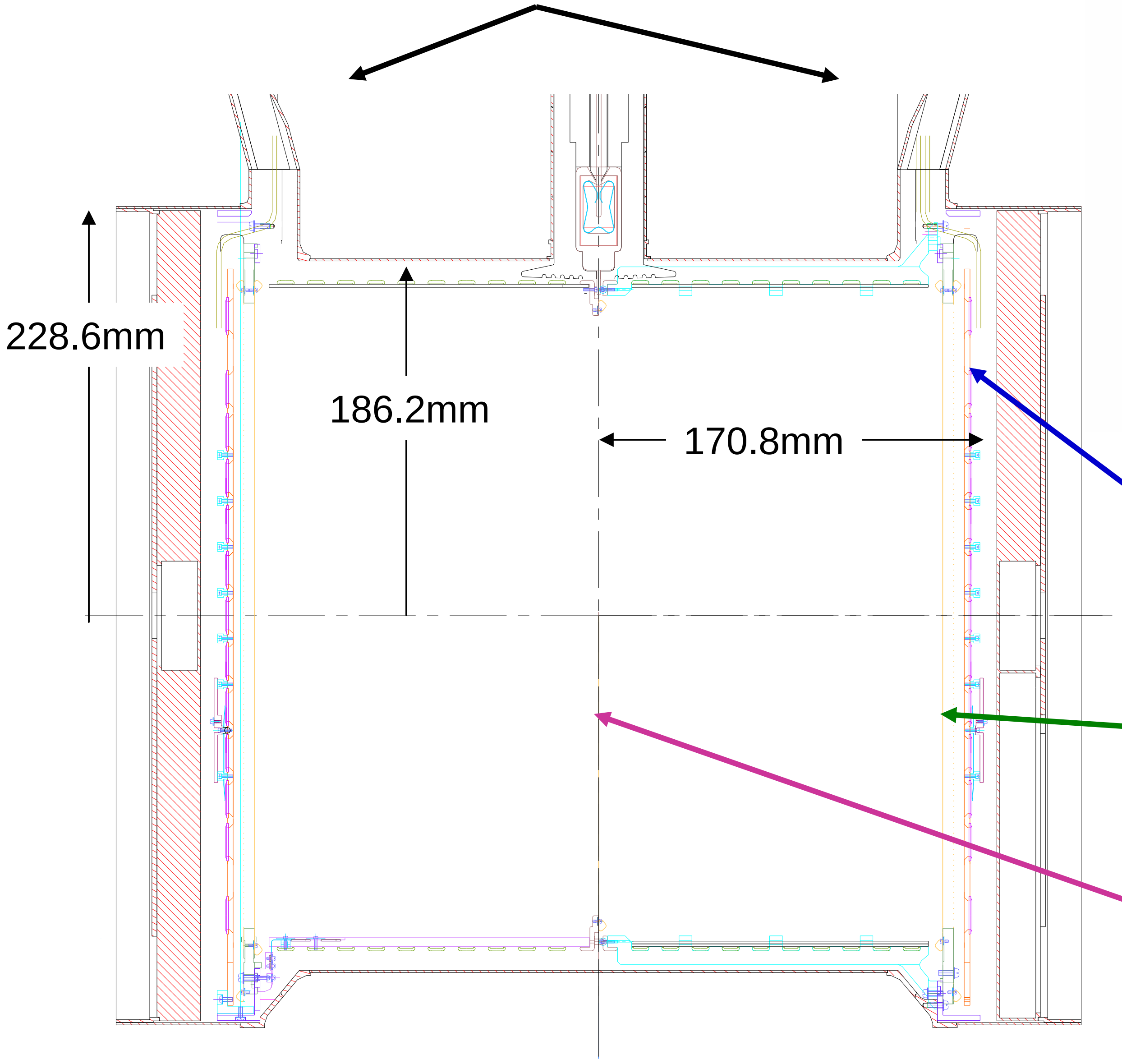
EXO-200 TPC basics

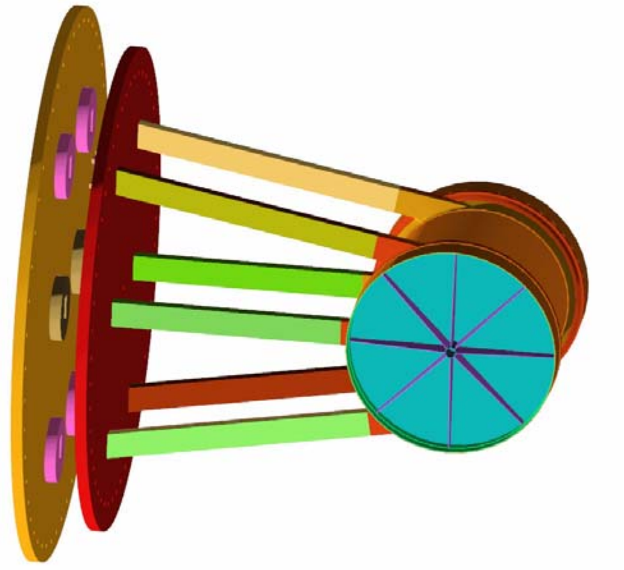




EXO chamber "hugs" the fiducial volume very closely!

Mechanical supports and cable/Xe conduits





2x300 large area
(1.6cm active diameter)
unmounted APDs

Inductive and charge
collecting wire planes

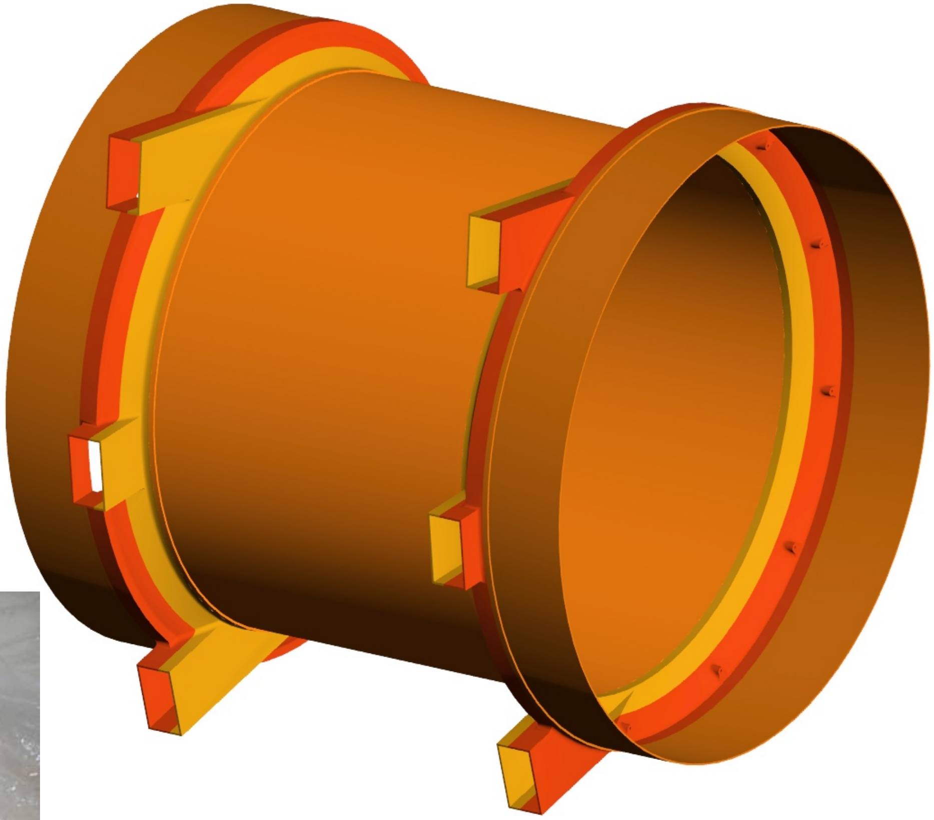
Cathode grid

Low activity copper traveled from Germany to…

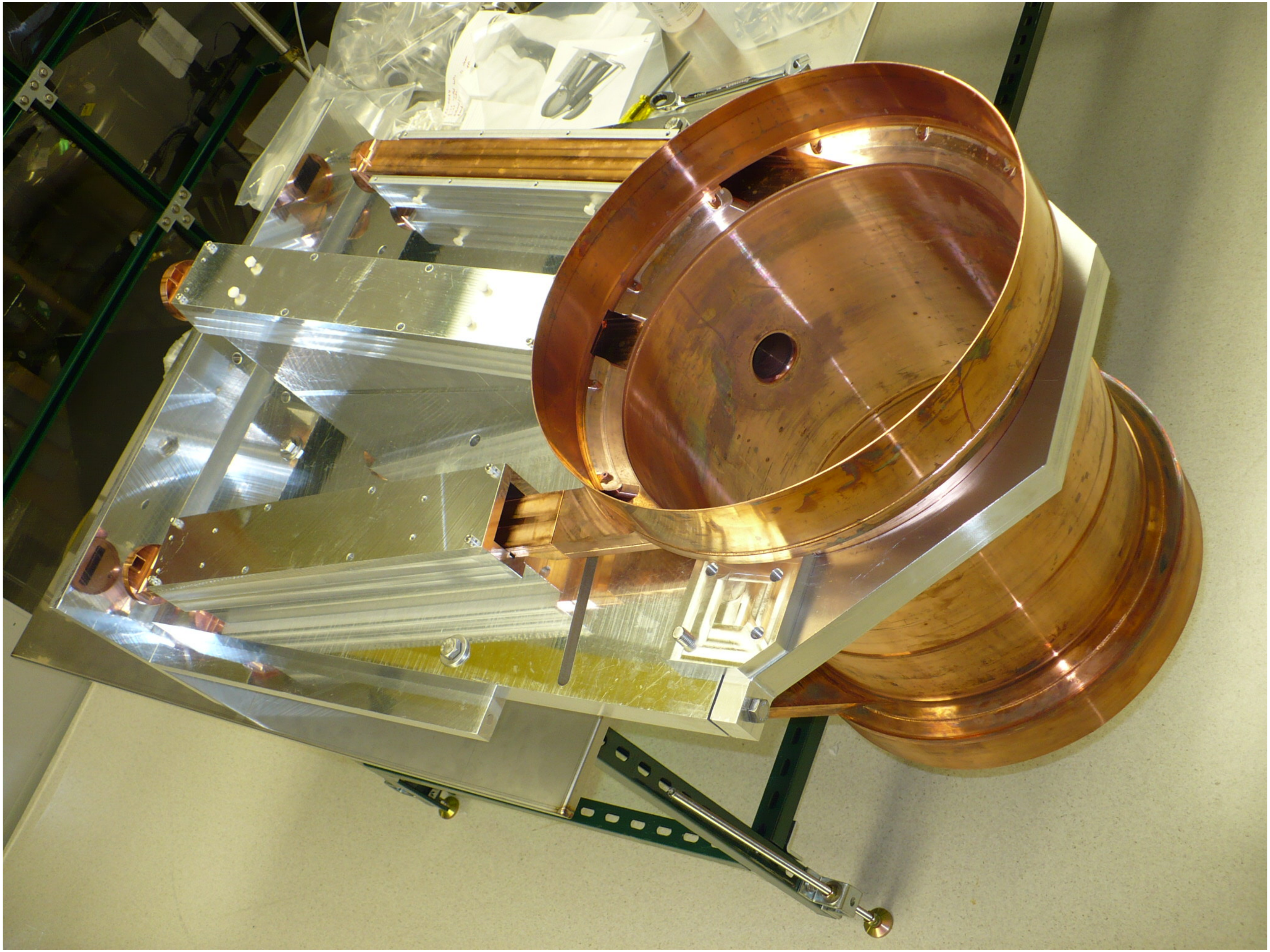
…California in a shielded container

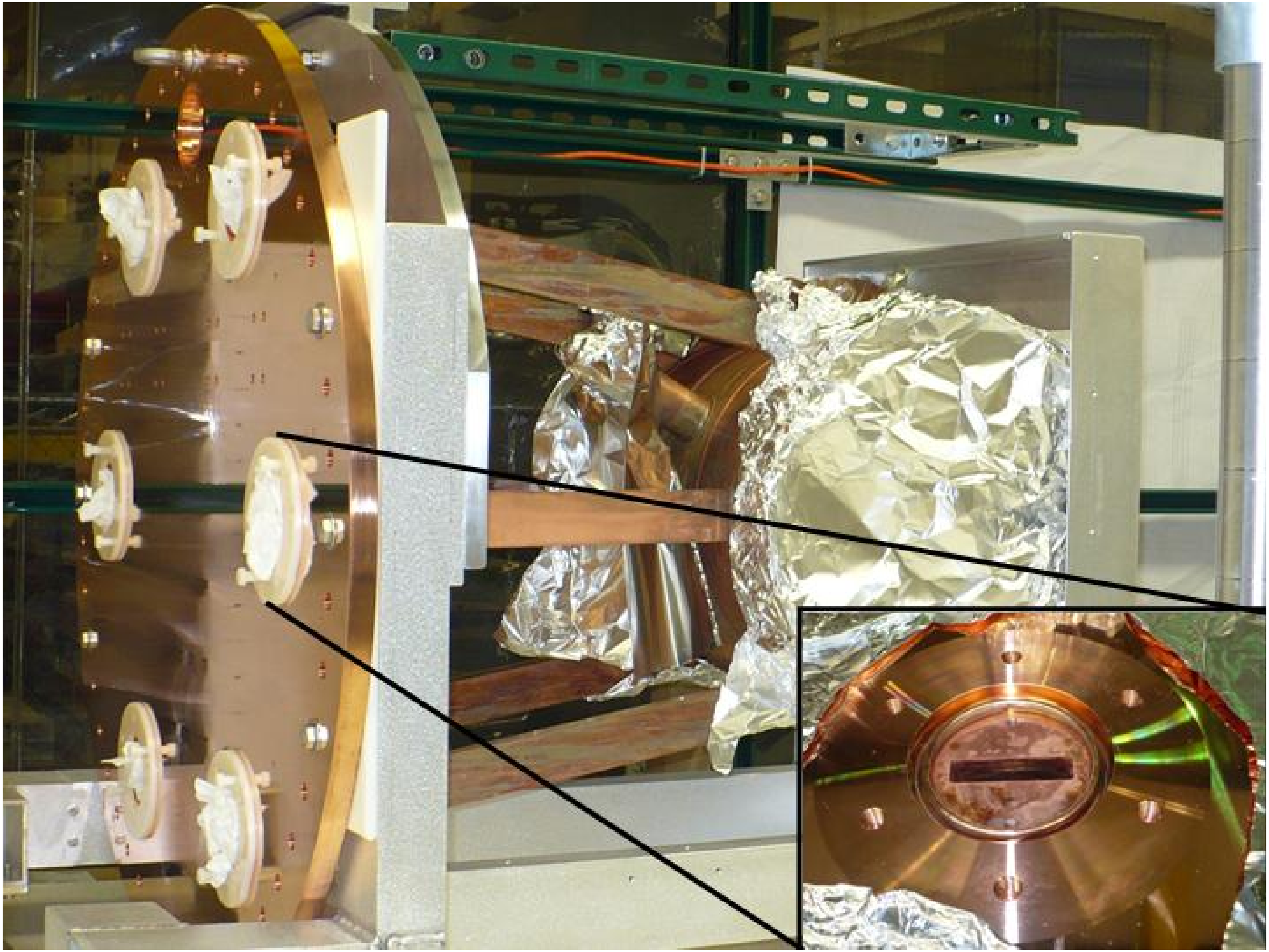
Ultra-low activity Cu vessel

- Very light (~1.5mm thin, ~15kg) to minimize materials

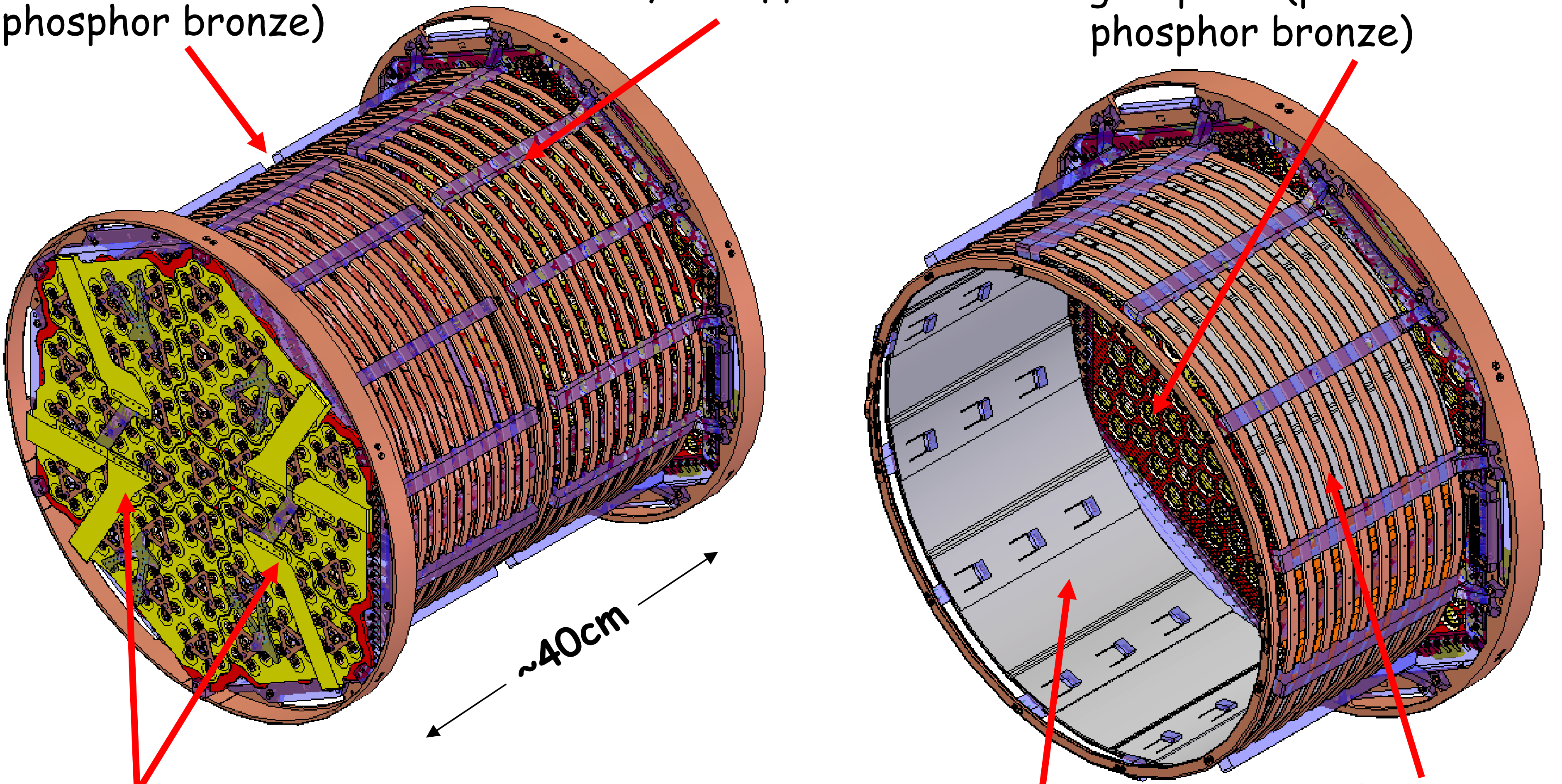


- Different parts e-beam welded together (San Leandro)
- Field TIG weld(s) to seal the vessel after assembly (TIG technology tested for radioactivity)
- All machining done by in a shop under a shallow cosmic ray shielding





EXO-200 LXe TPC field cage & readout planes



Central HV plane (photo-etched phosphor bronze)

acrylic supports

APD plane (copper) and grid plane (photo-etched phosphor bronze)

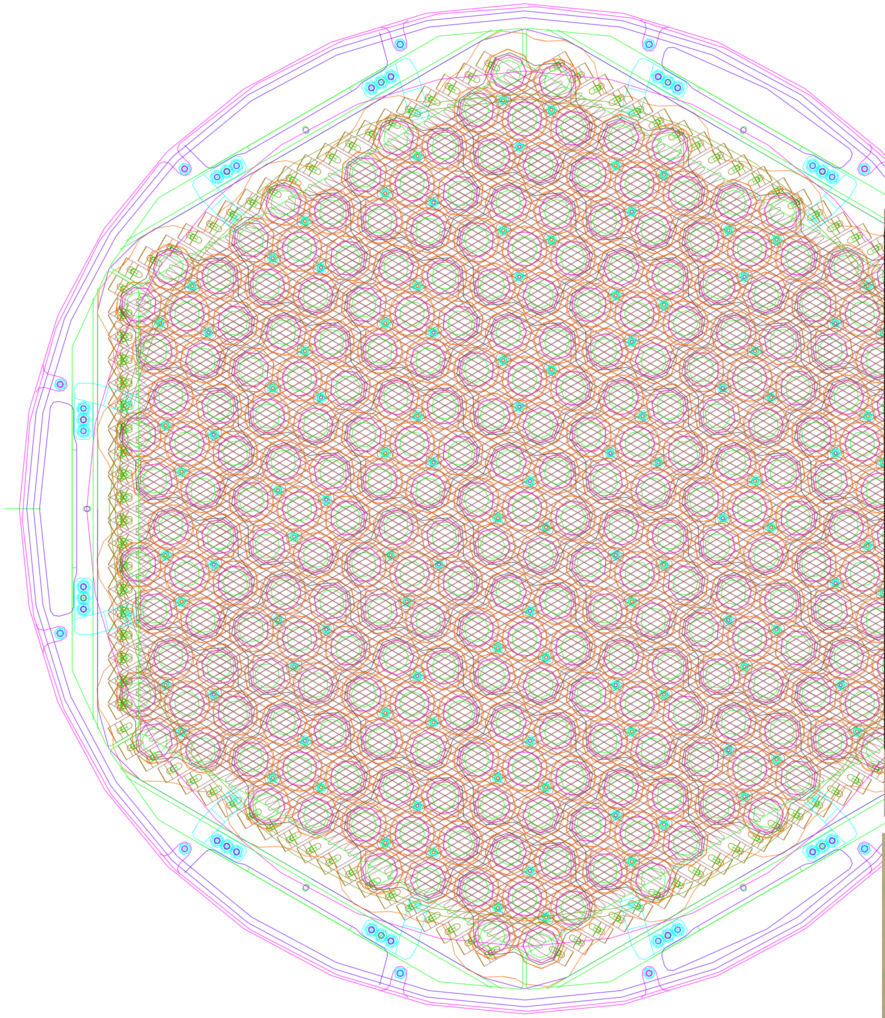
~40cm

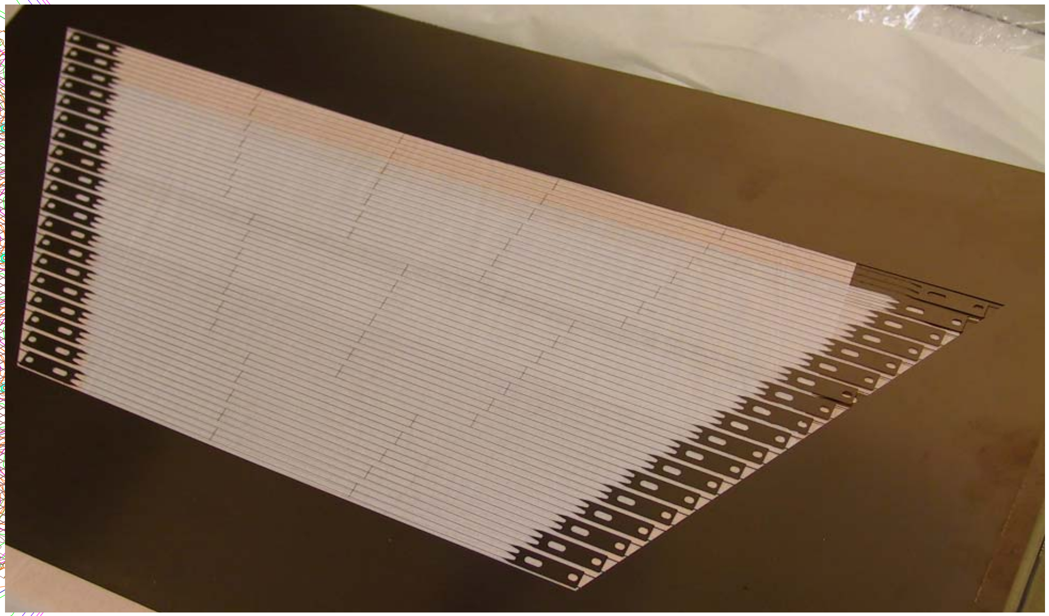
flex cables on back of APD plane

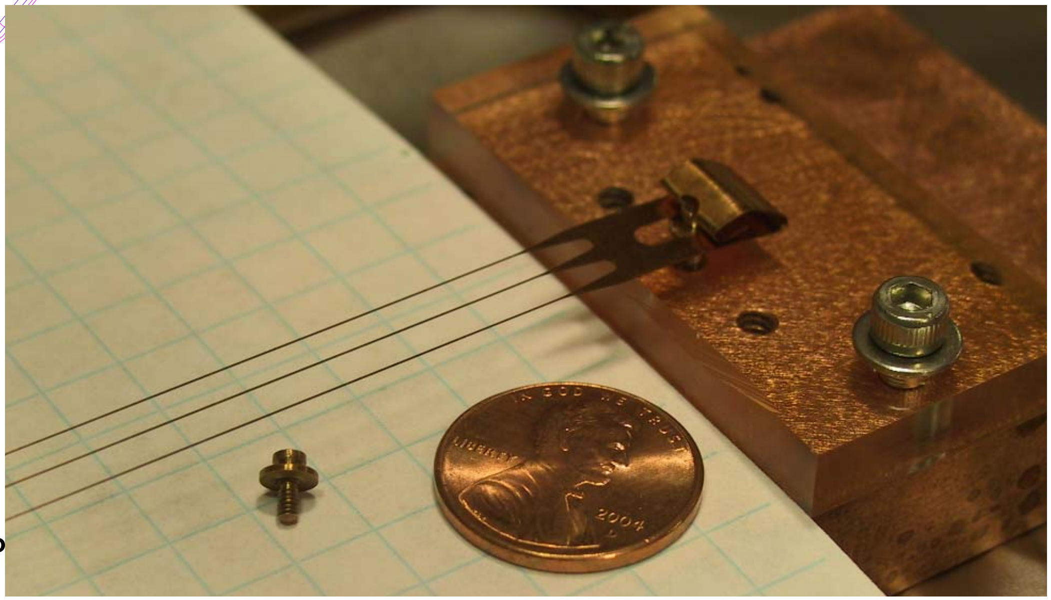
teflon light reflectors

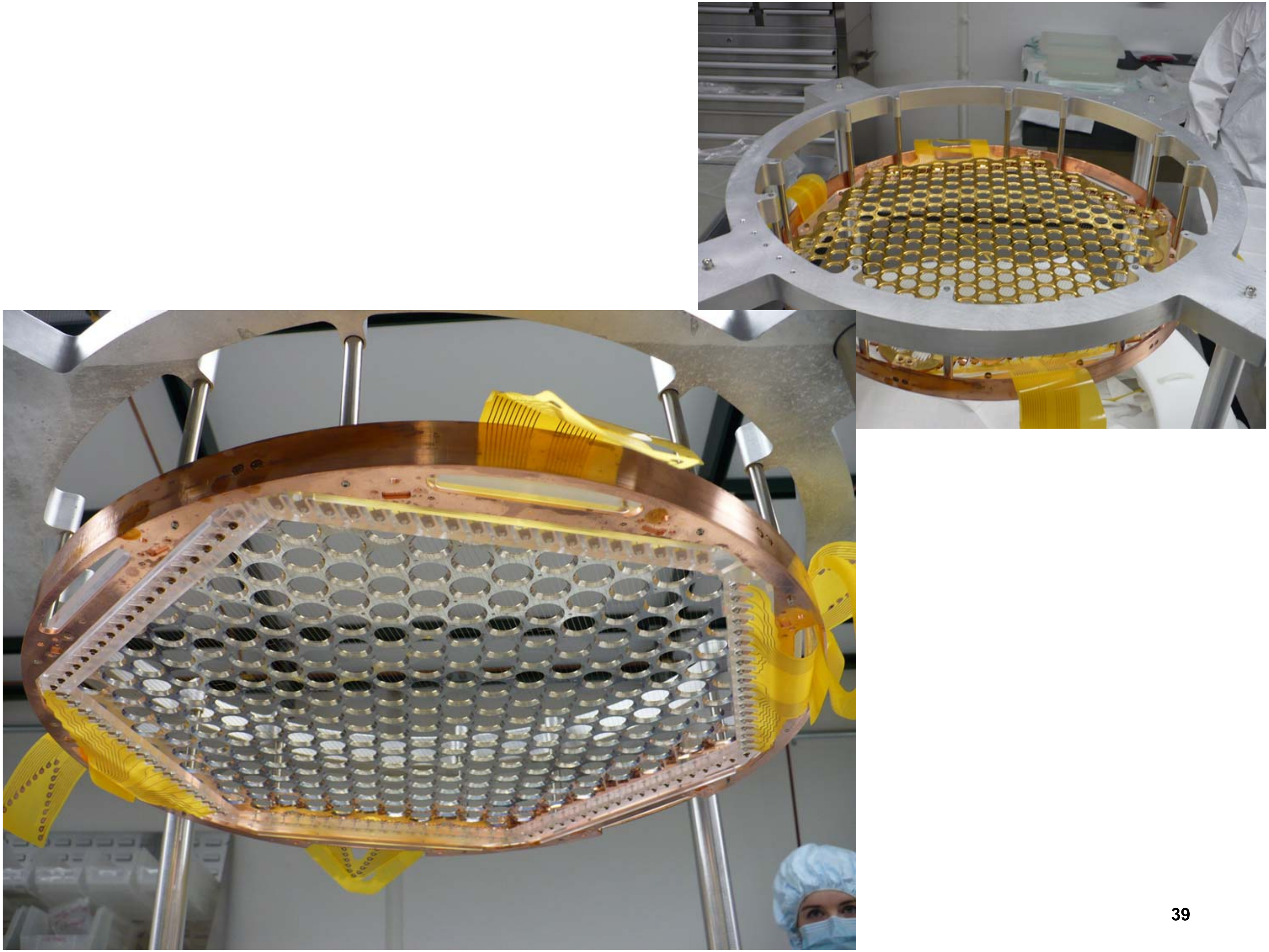
field shaping rings (copper)

One readout pancake

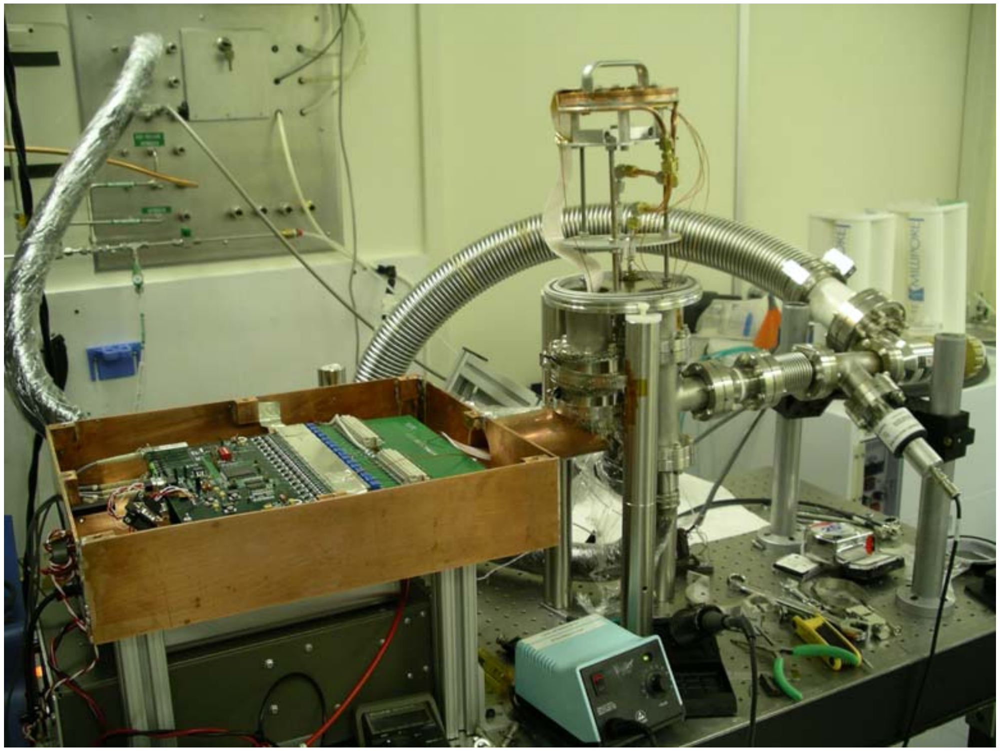








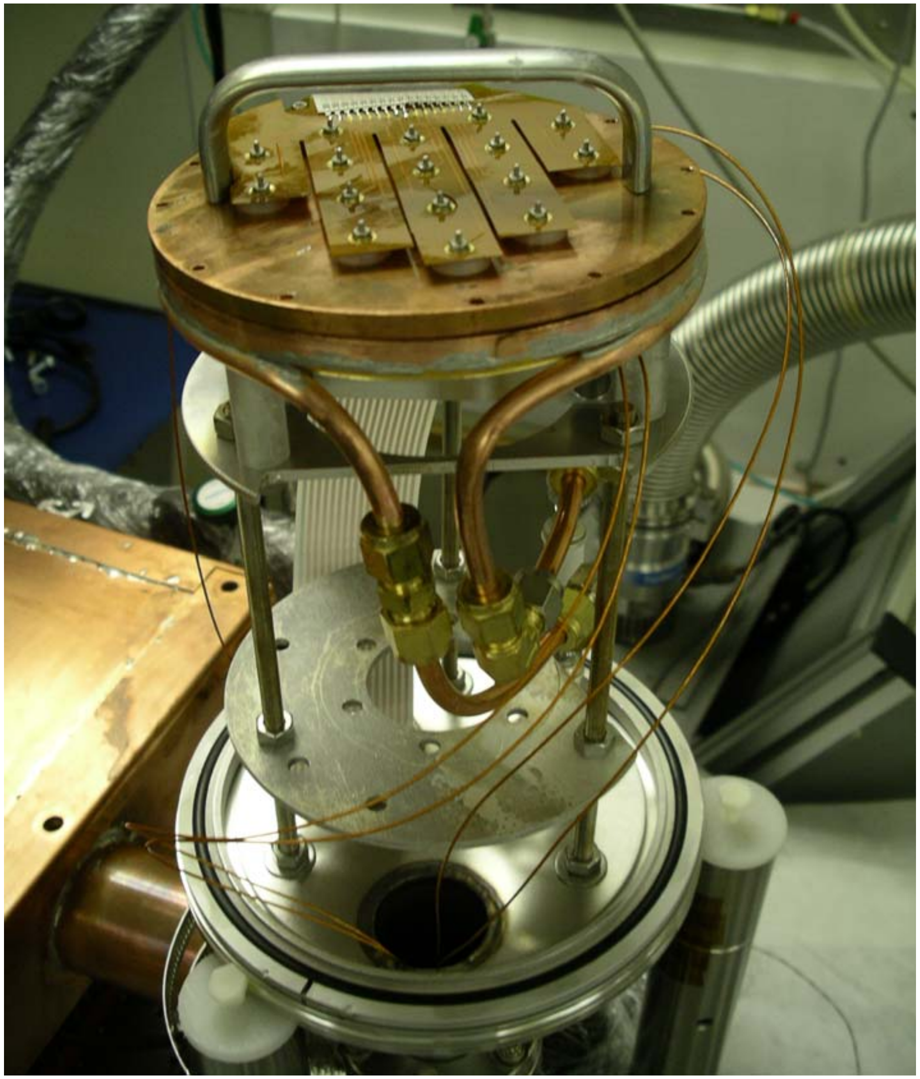
650 bare LAAPD from Advanced Photonix



~500 "Bare" LAAPD

APDs are ideal for our application:

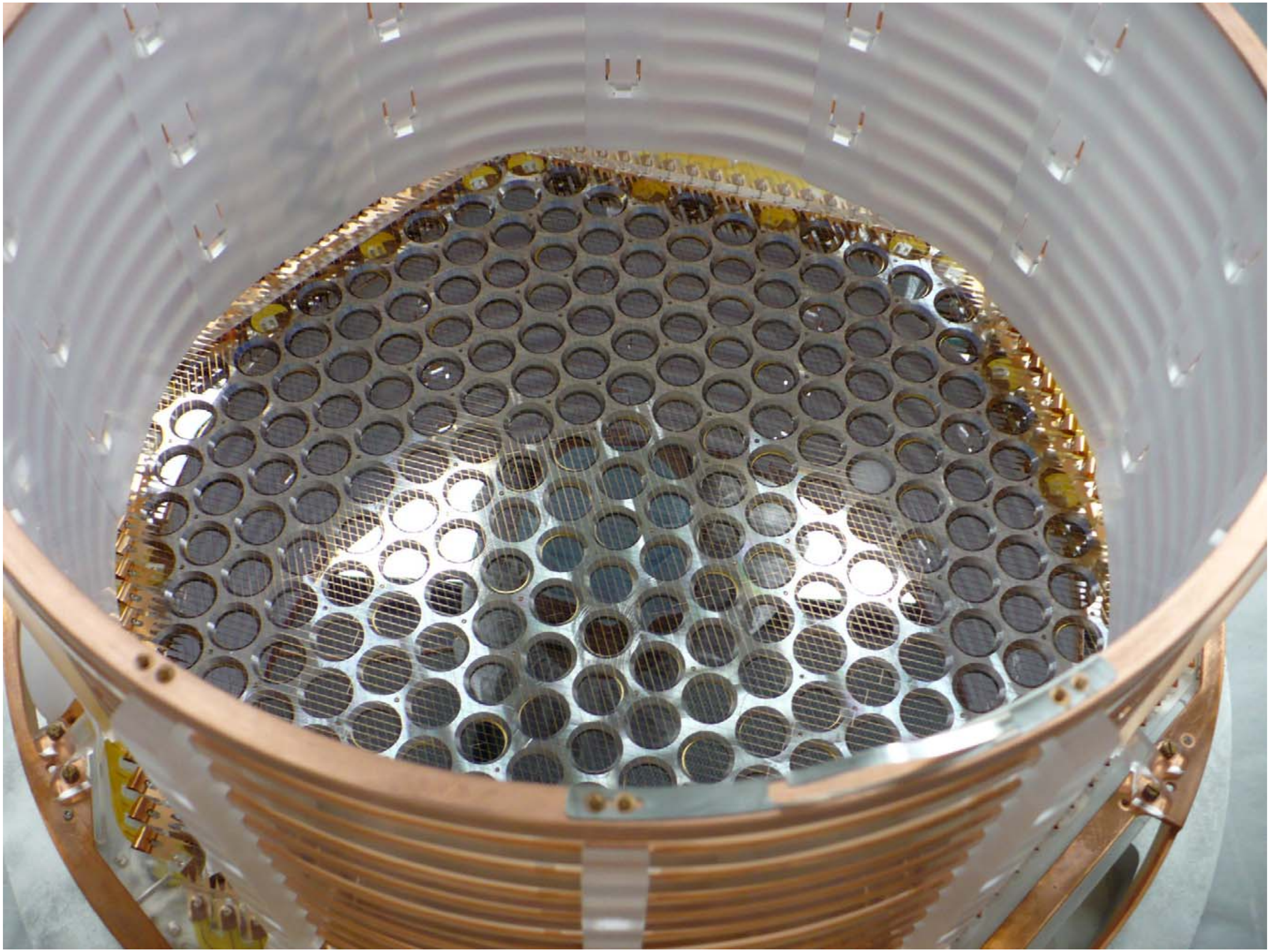
- very clean & light-weight,
- very sensitive to VUV

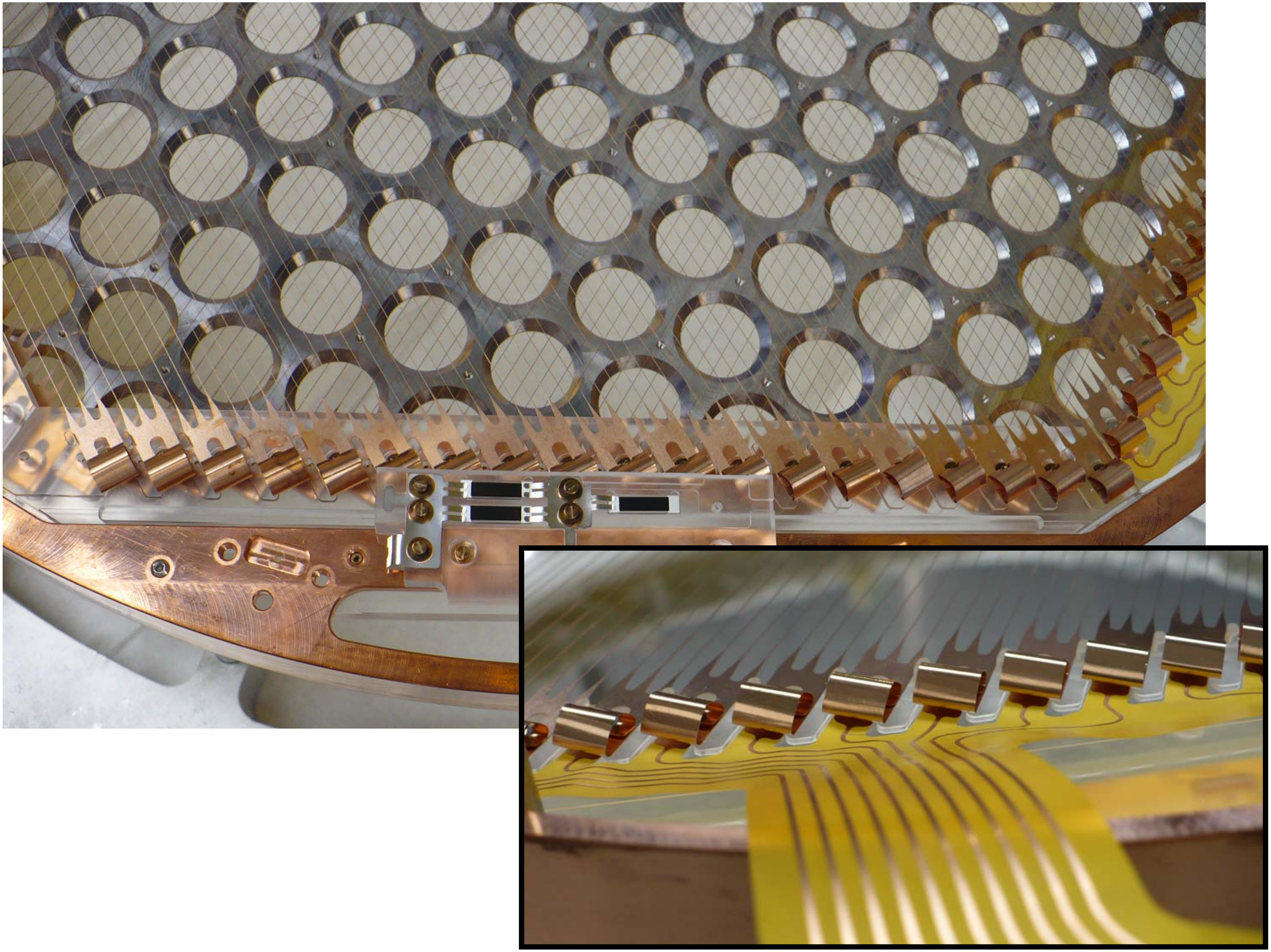


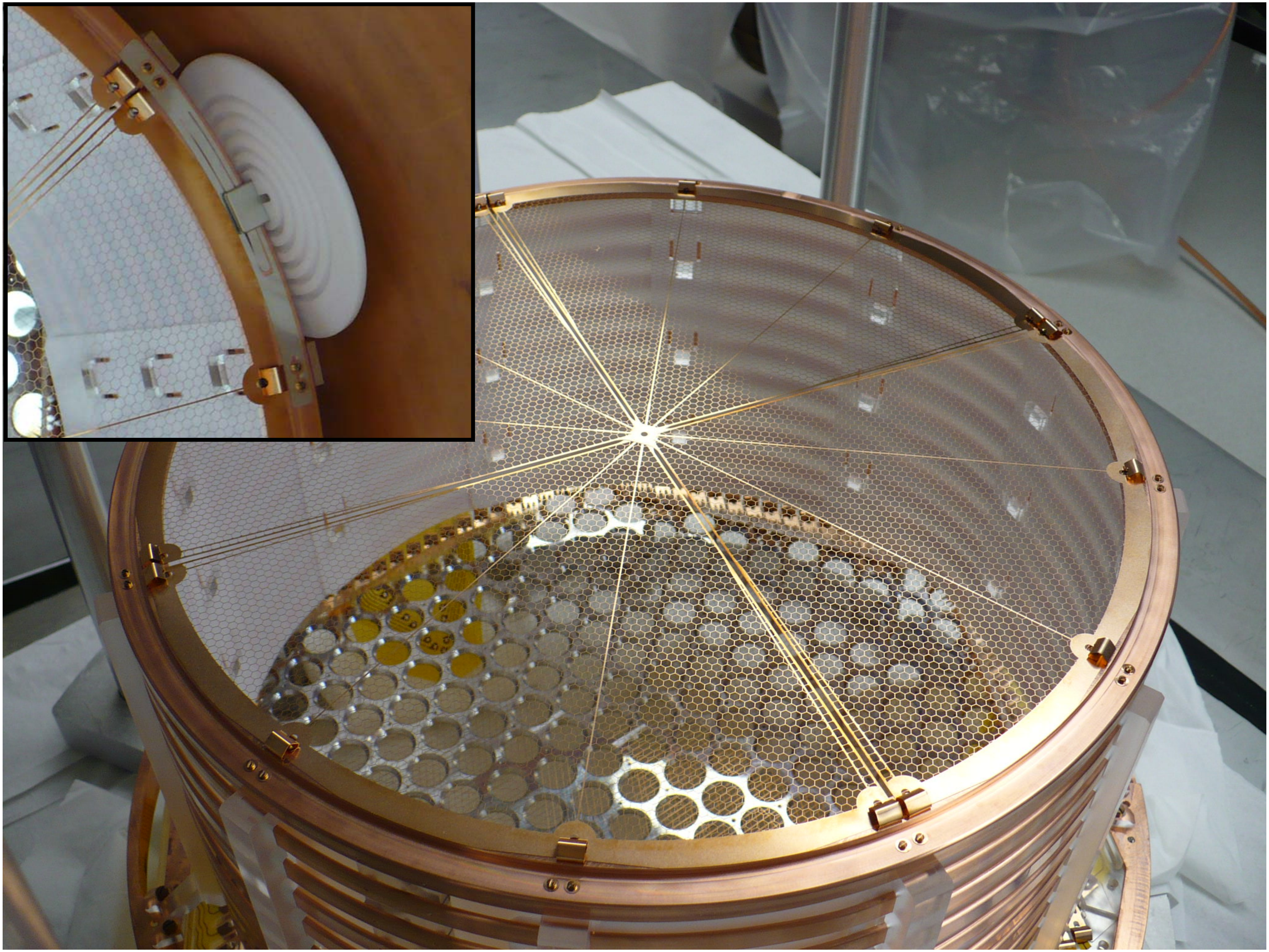
QE > 1 at 175nm

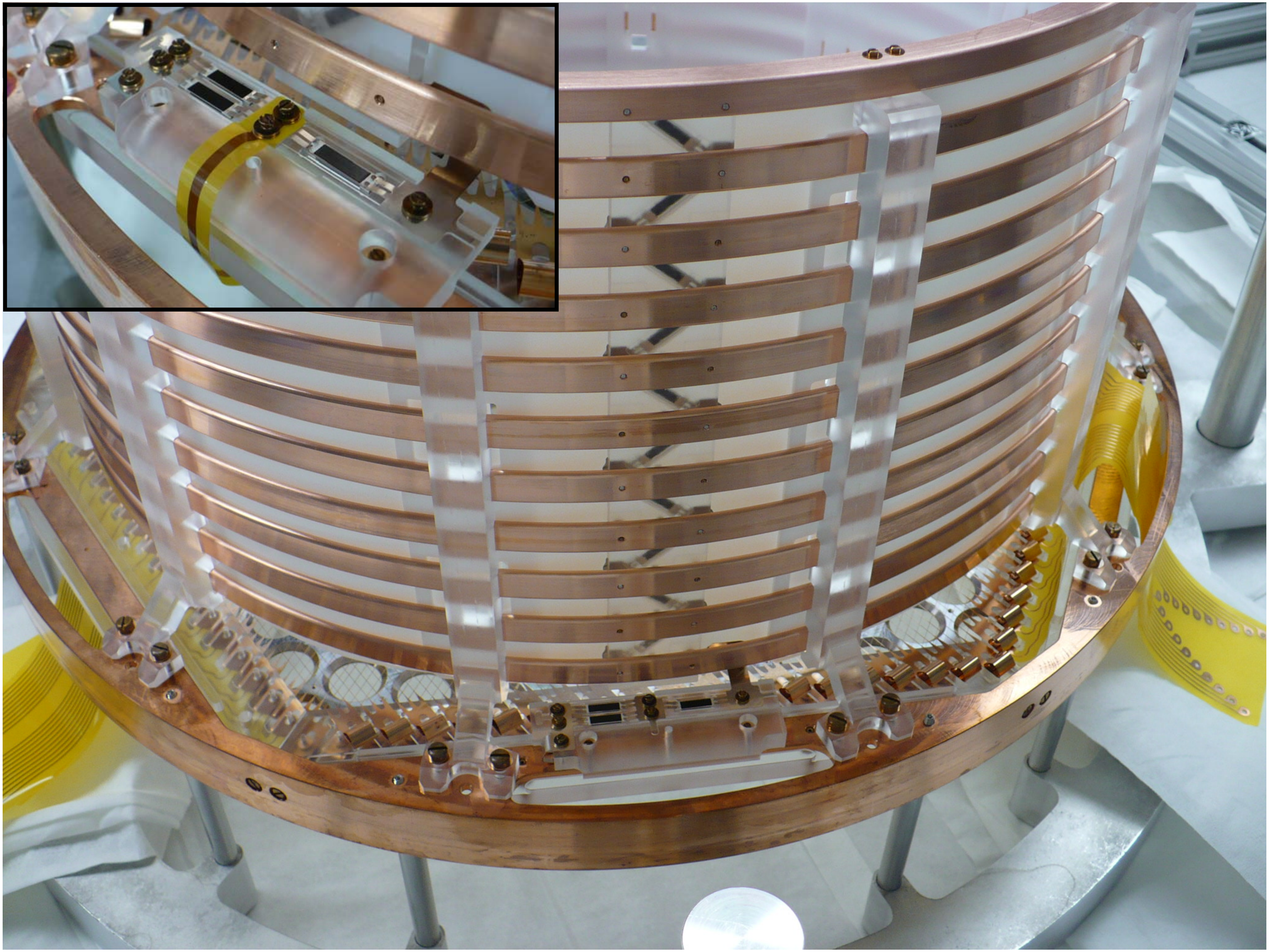
Gain set at 100-150

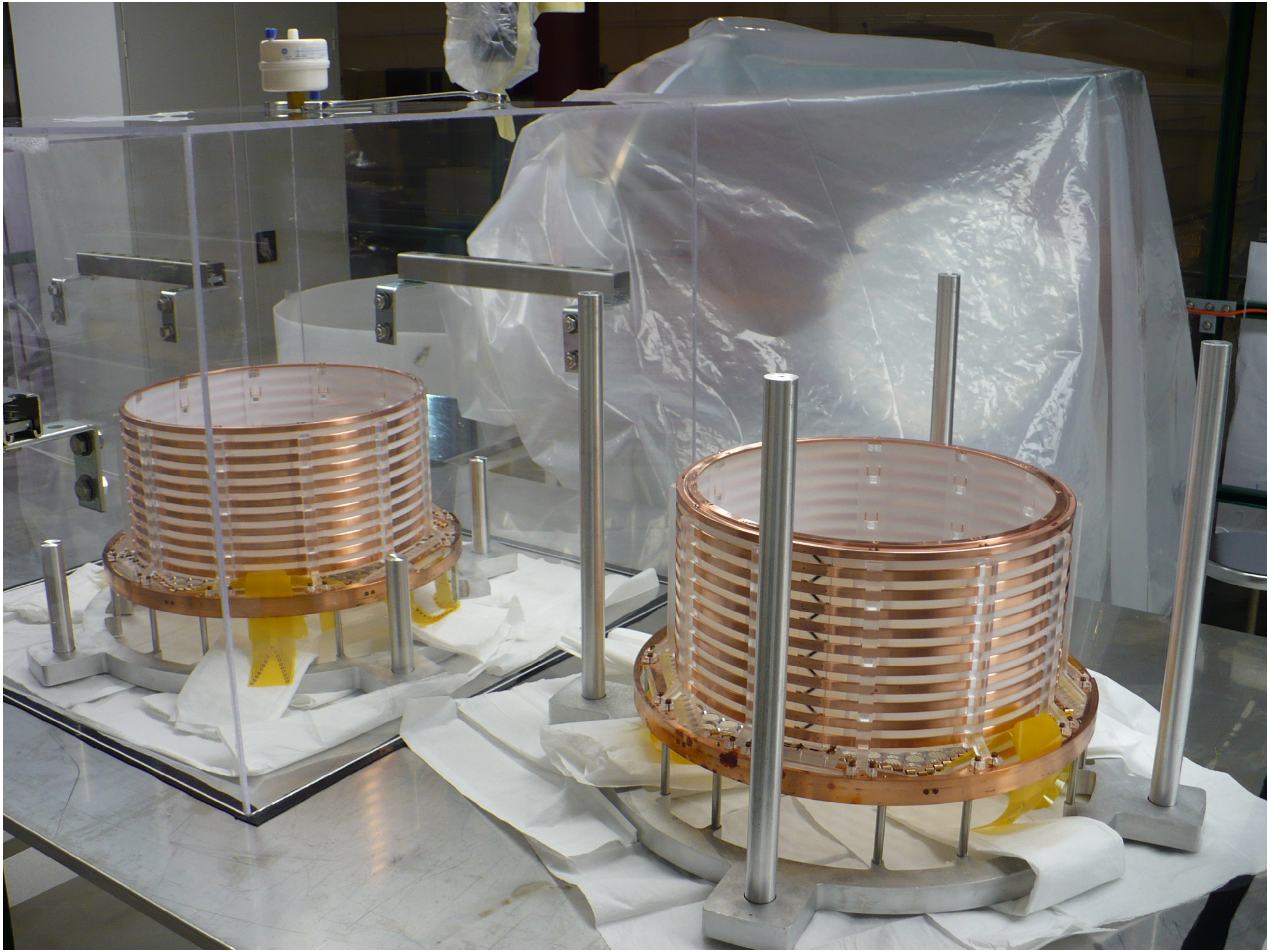
V~1500V
ΔV < ±0.5V
ΔT < ±1K APD is the driver for temperature stability
Leakage current OK cold

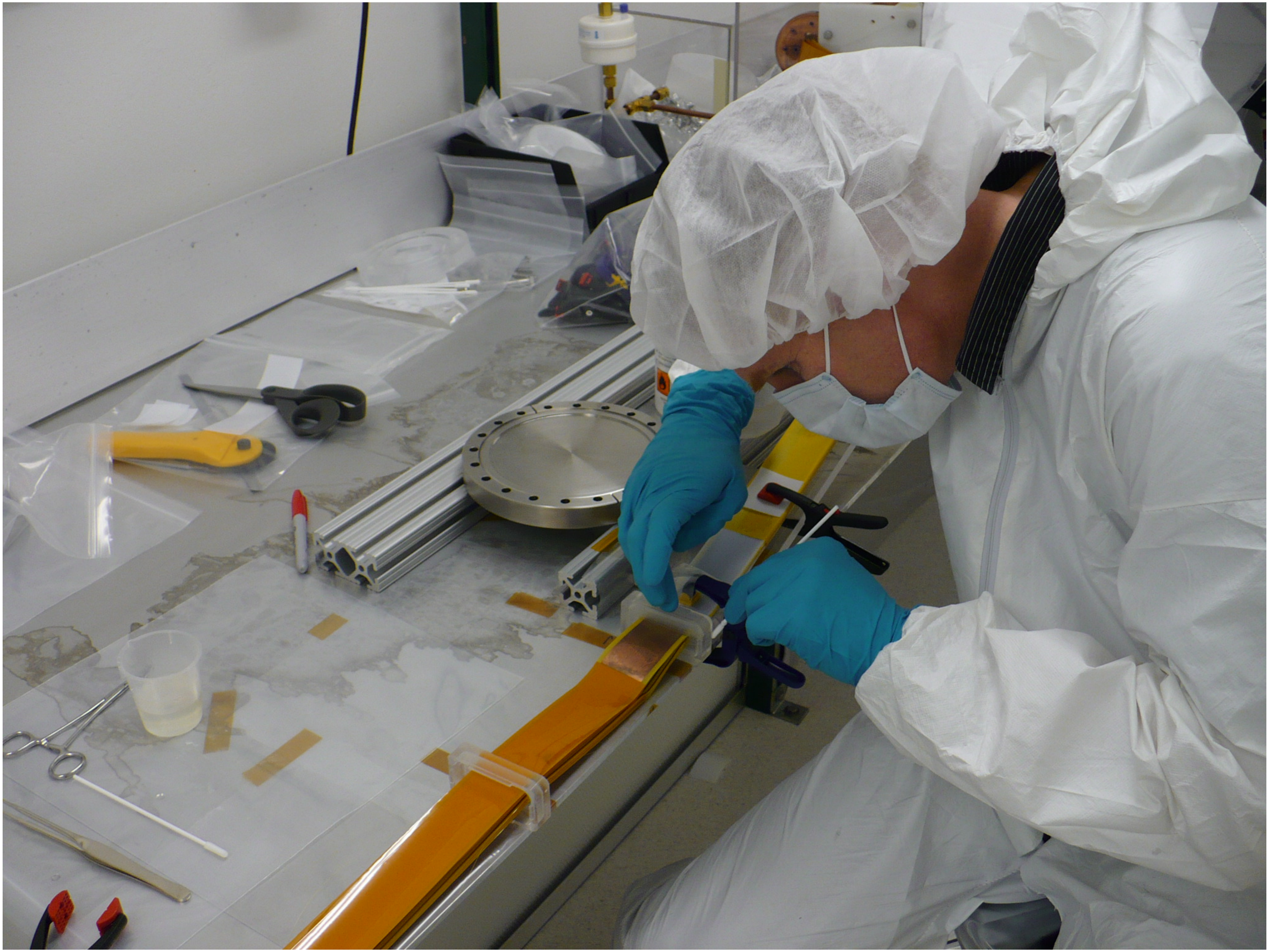


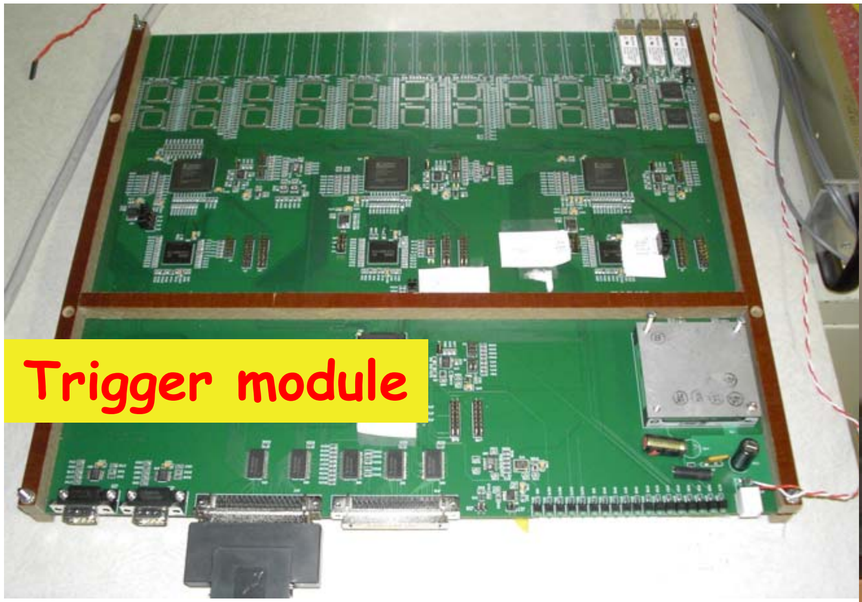




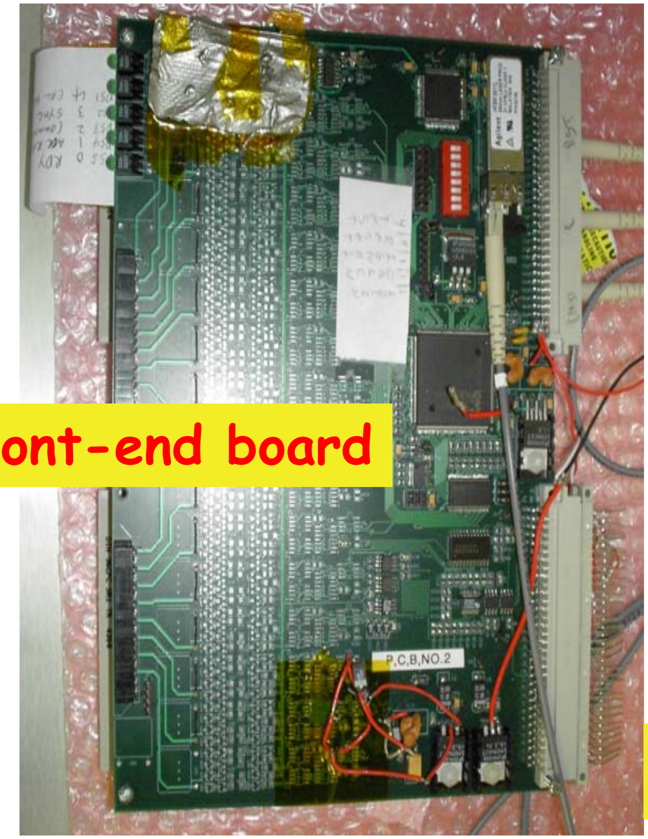




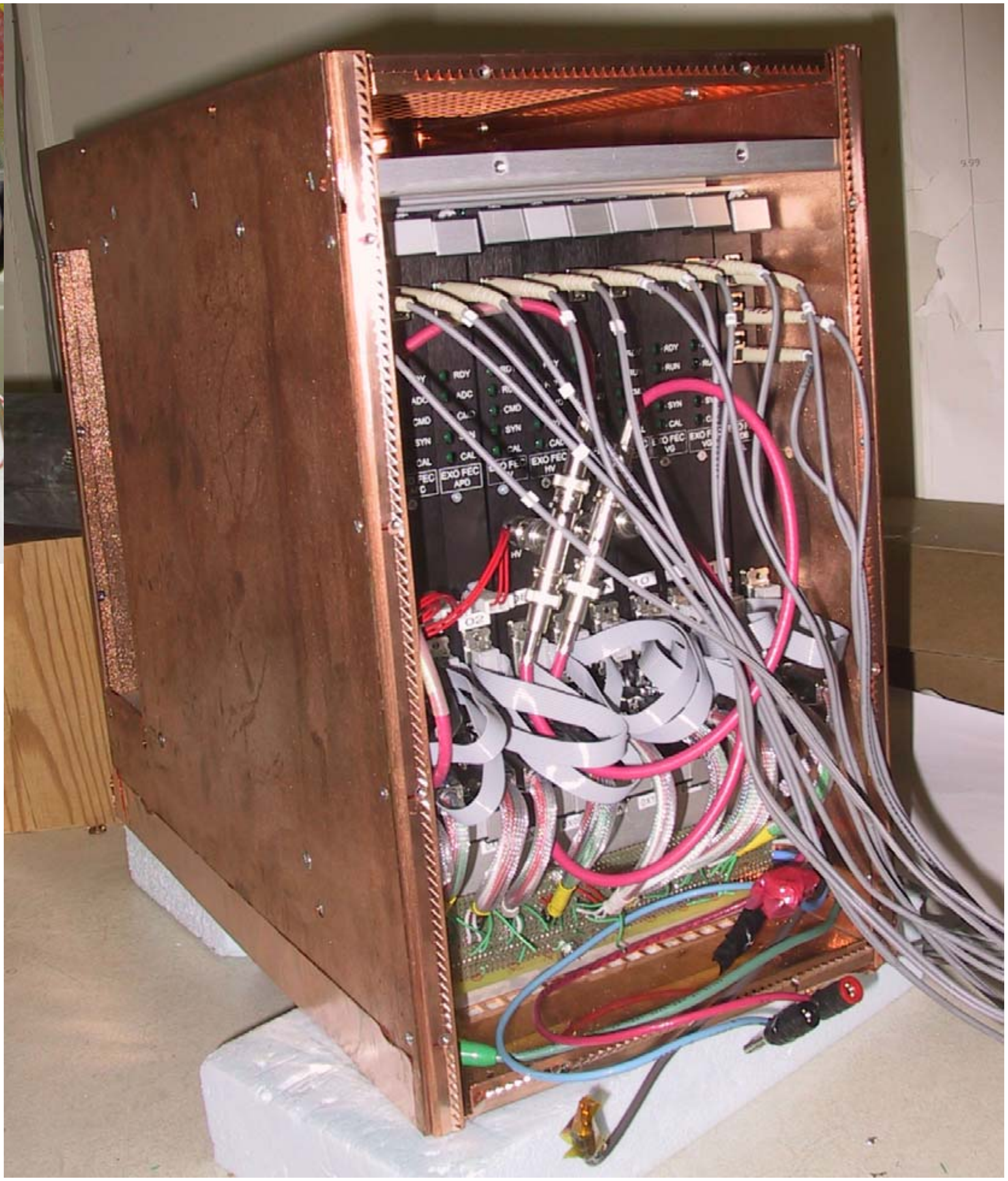




Trigger module

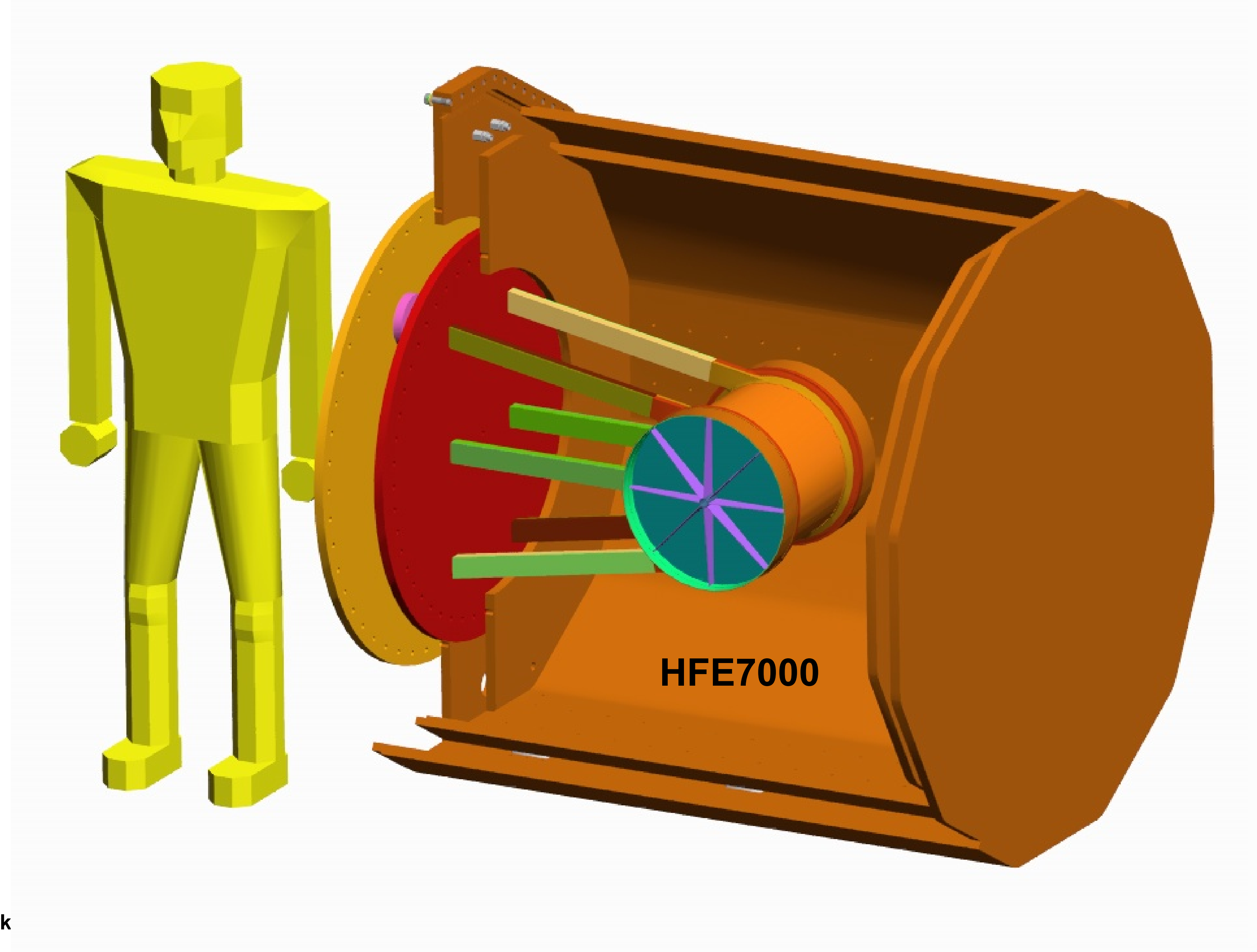


Front-end board



Electronics completed, in calibration

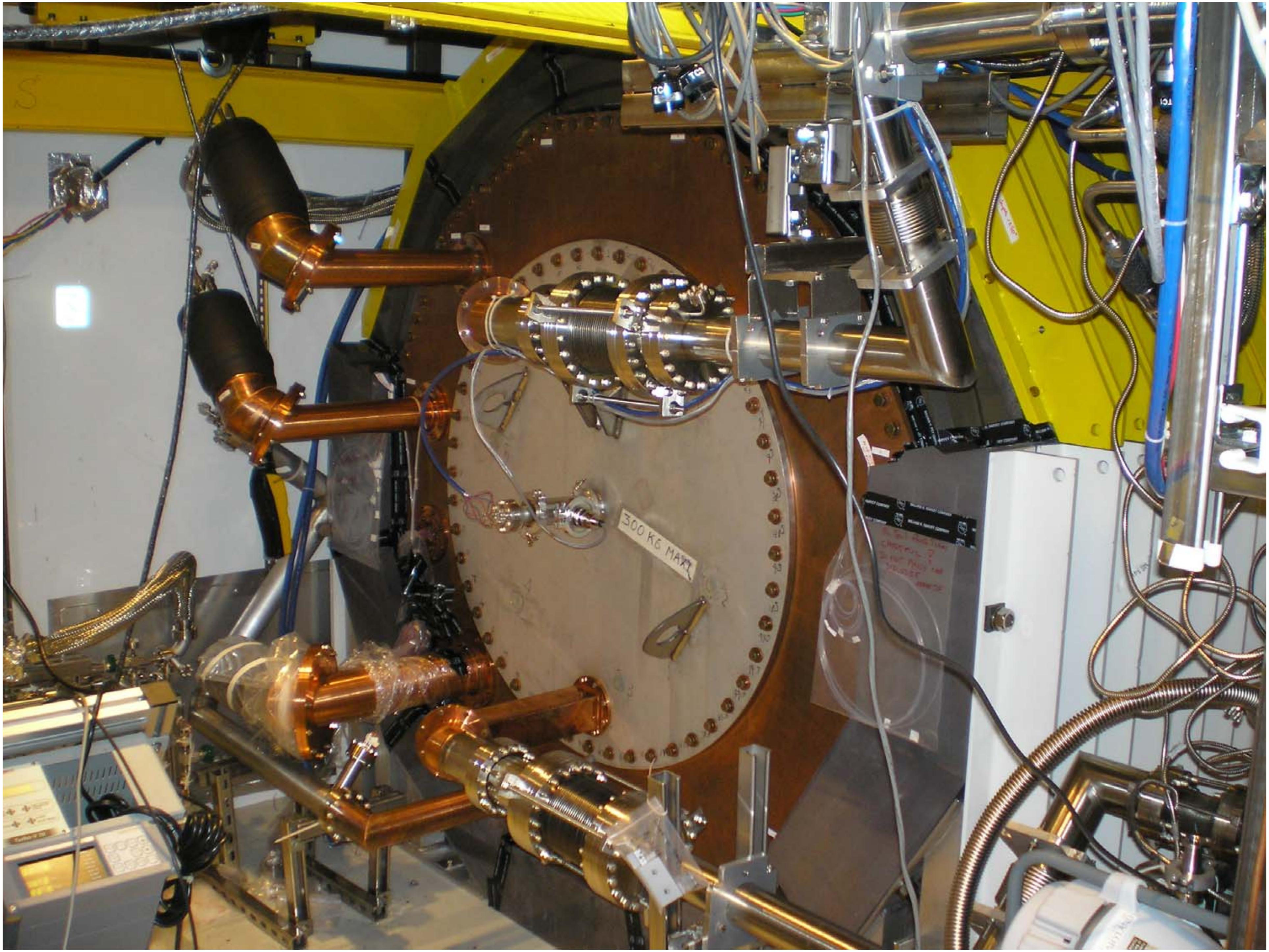
The TPC vessel sits in a low background, copper cryostat filled with ultra-clean HFE7000 refrigerant/shielding fluid



Cryostat was fabricated at SDMS (Grenoble)

Extensive use of e-beam welding to reduce radioactive contamination

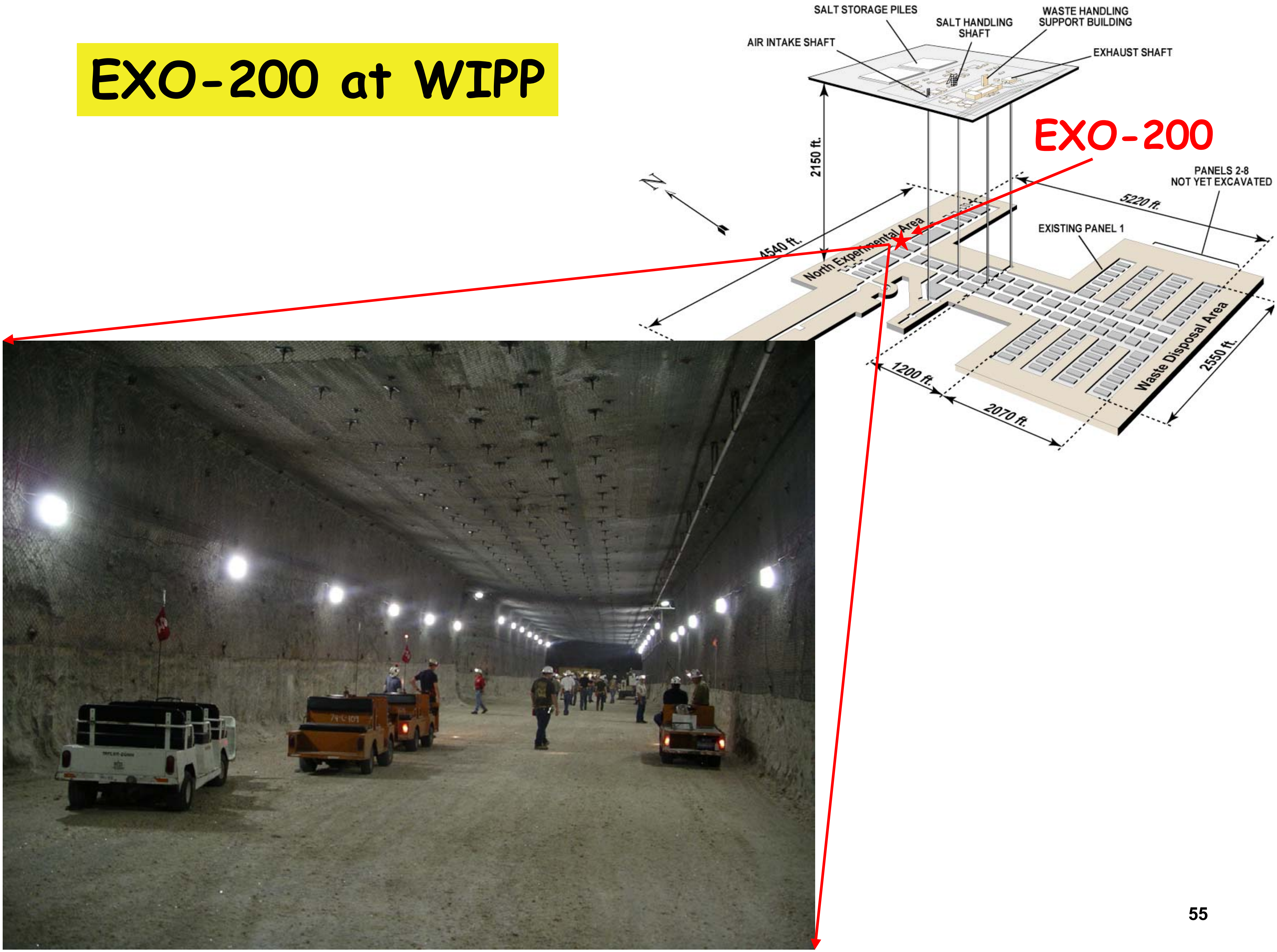
Outer vessel


300 KG MAX

Each brick is epoxy painted at the factory in Germany to reduce Pb dust and shipped to the WIPP underground site

Jul 5, 07, the first shipment (Mods 5 & 6)

EXO-200 at WIPP



Aug 22, 07, 6PM MDT

Module 1 goes underground


74-L 097

Part of the EXO-200 infrastructure at WIPP, NM

Massive effort on material radioactive qualification using:

- NAA
- Low background γ-spectroscopy
- α-counting
- Radon counting
- High sensitivity GD-MS and ICP-MS

At present the database of characterized materials includes >300 entries

MC simulation of backgrounds

The impact of every screw within the Pb shielding is evaluated before acceptance

NIM article published on the subject with entries for 225 materials [D.Leonard et al., Nucl. Inst. and Meth. A 591 3 (2008)]

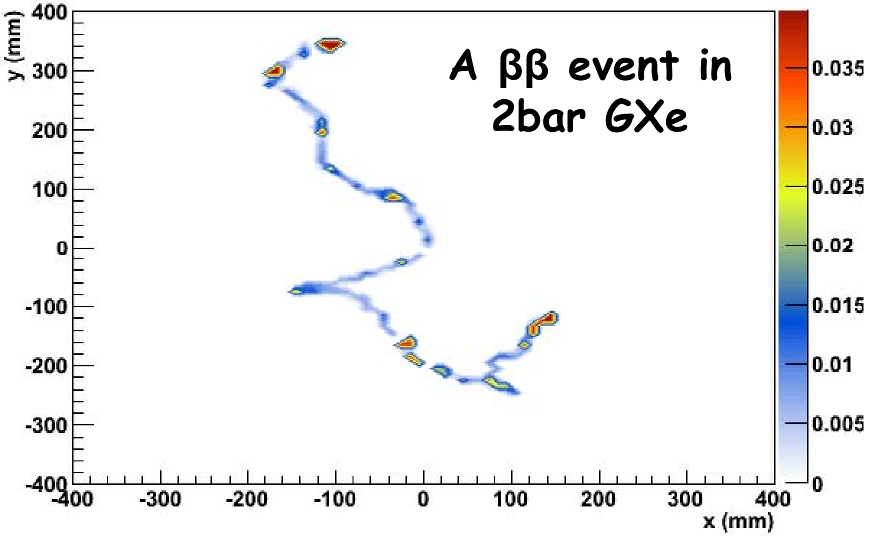
EXO Materials Testing Summary

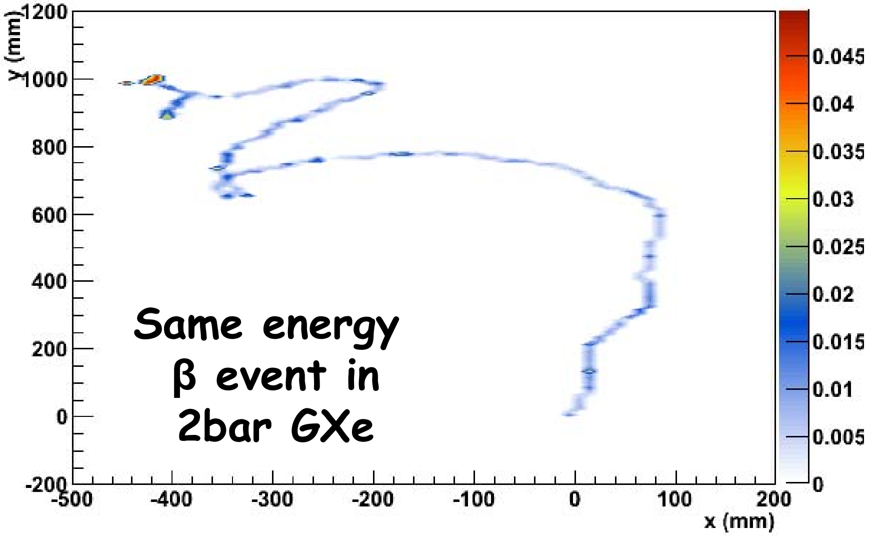
GXe R&D program

Gas Xe has the potential of providing event topology information along with very good energy resolution

How well this works depends of course on the pressure.

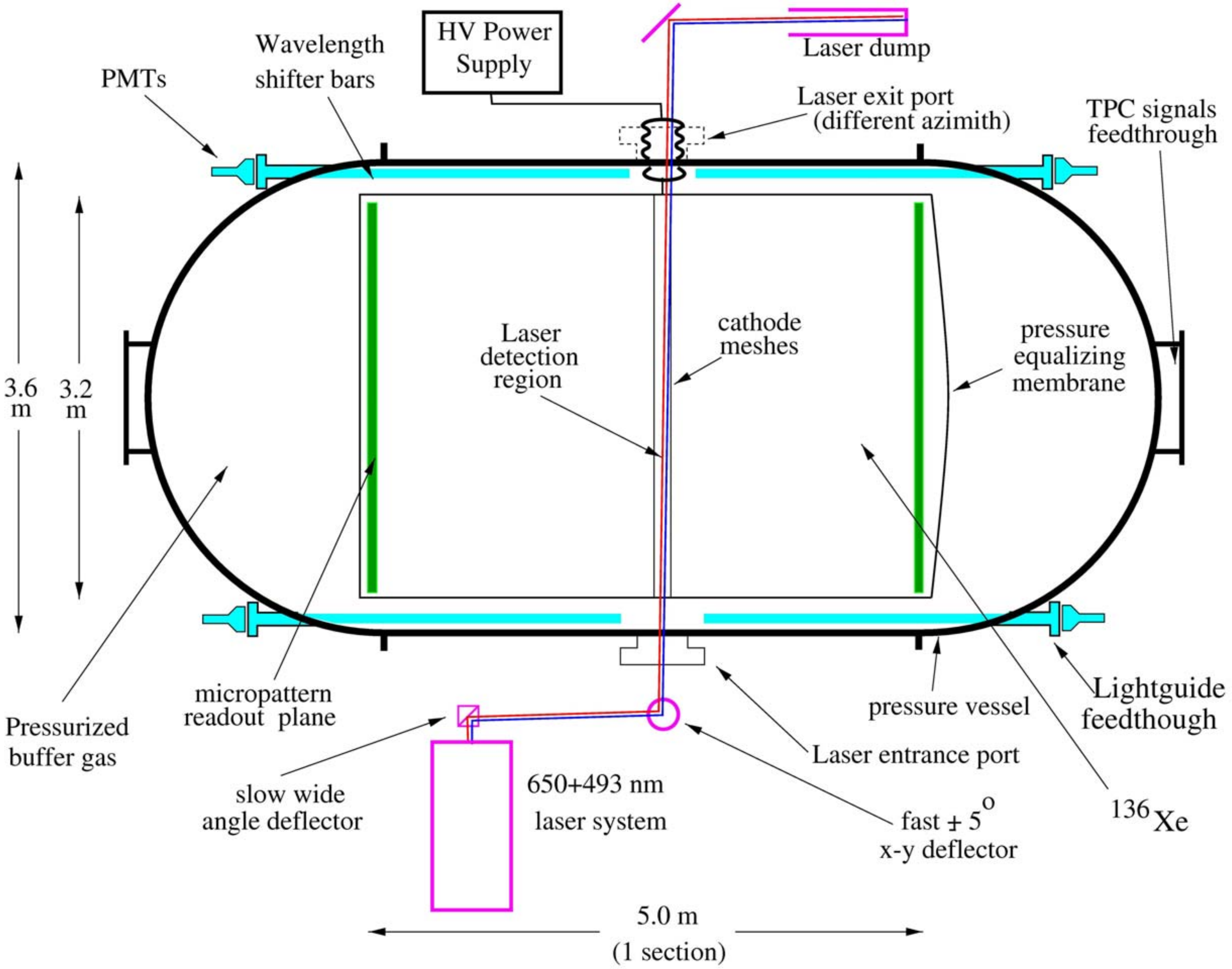
1000 kg, 0C, cylinder with 2R=L		
Pressure (atm)	Volume (m^3)	Diameter or Length (m)
1	179	6.1
2	89	4.8
5	35	3.5
10	17	2.8


A ββ event in 2bar GXe

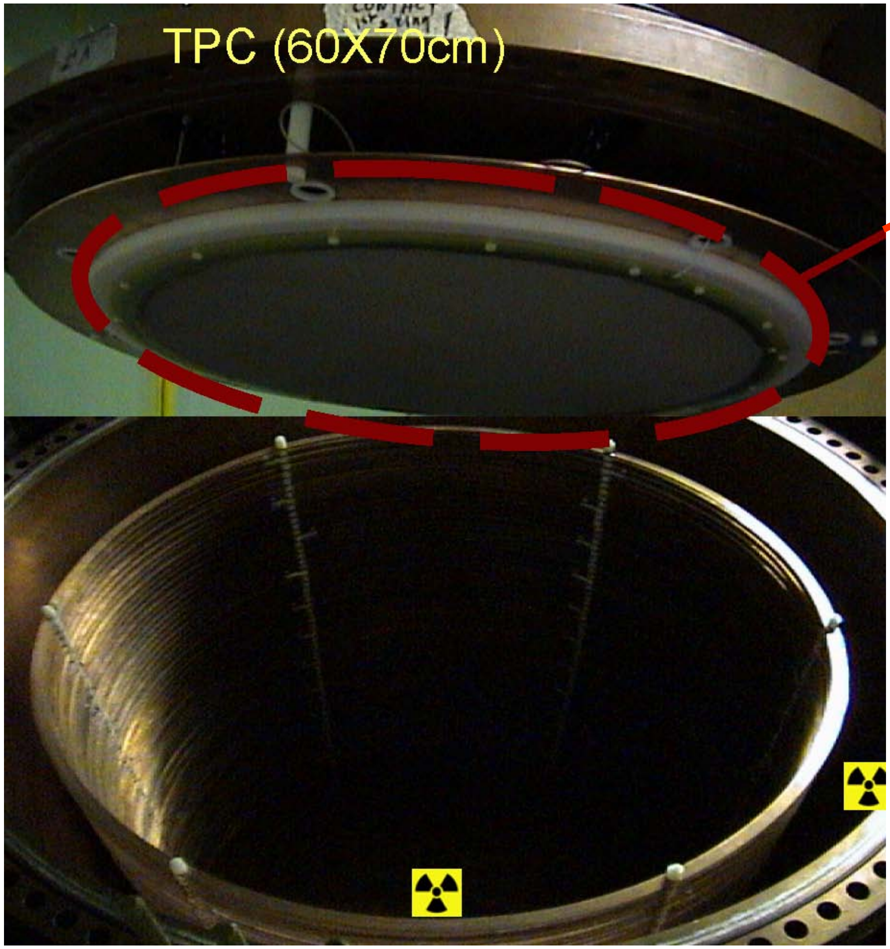

Same energy β event in 2bar GXe

First EXO concept

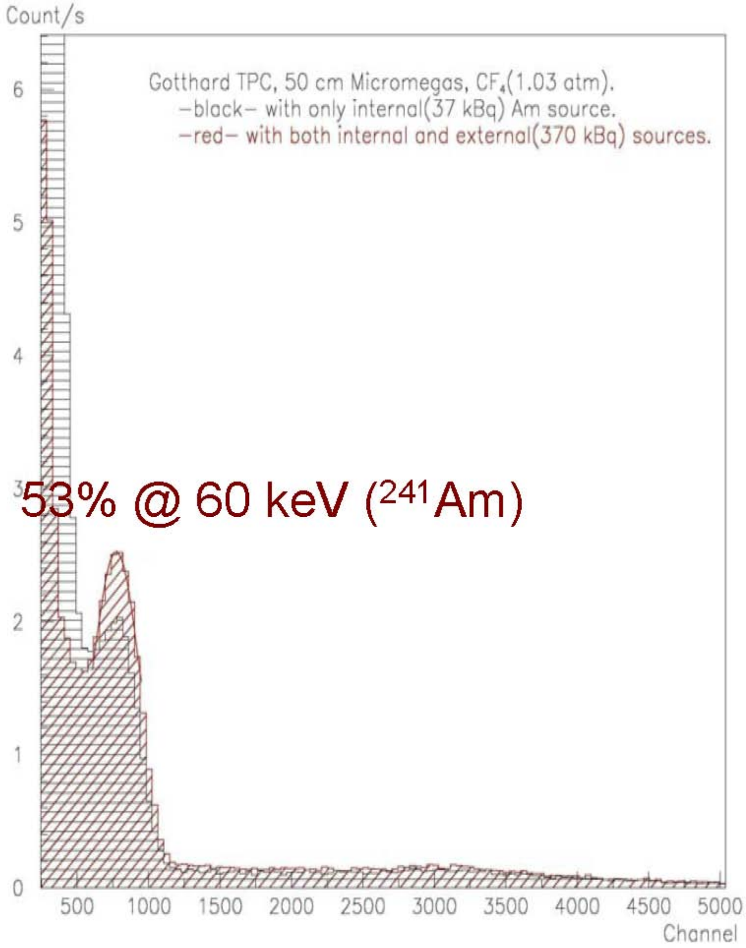
M.Danilov et al (EXO coll), Phys Lett 480 (2000) 12



Old Gotthard TPC has a new life in EXO R&D



50cm diameter micromegas

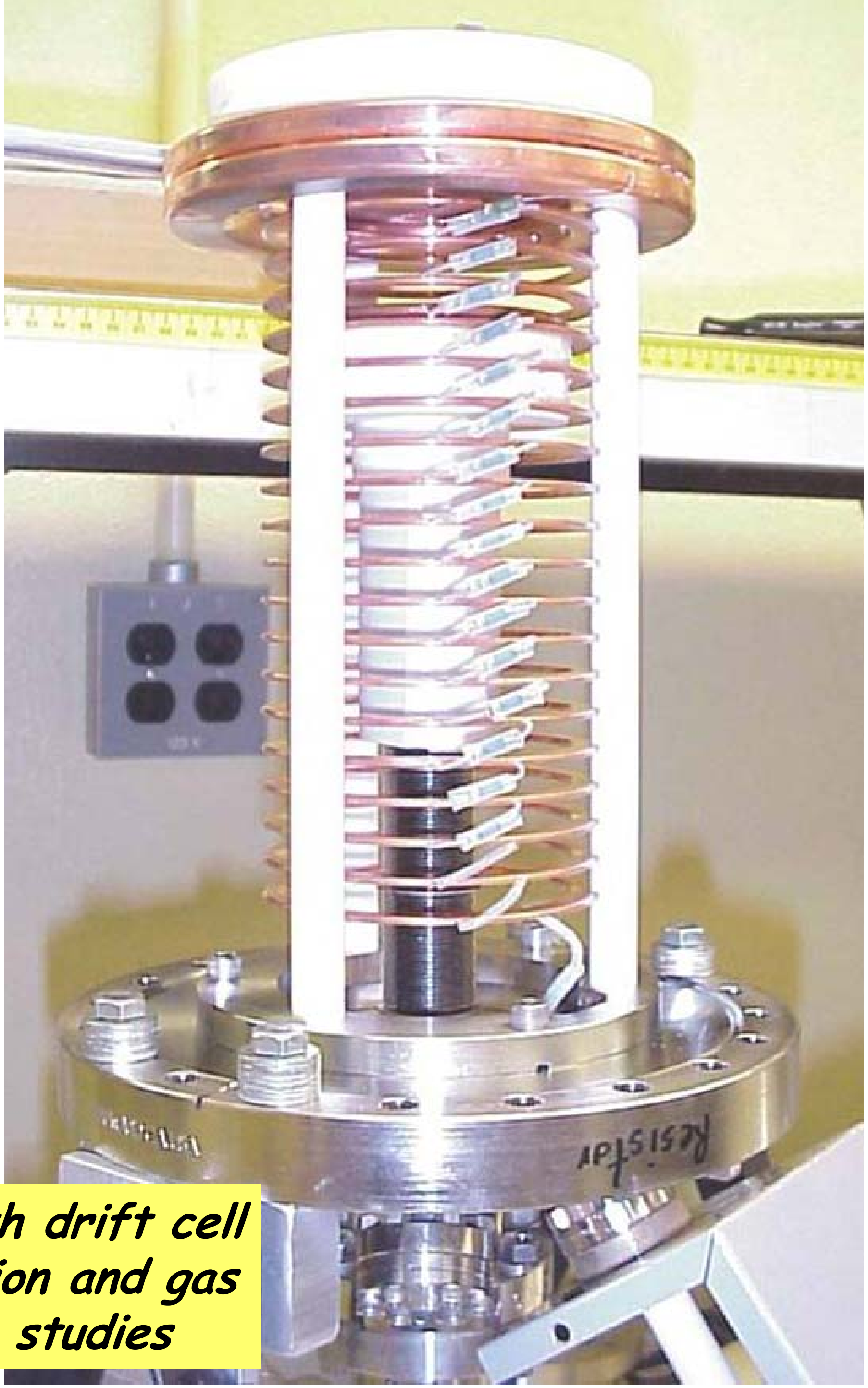


53% @ 60 keV (^{241}Am)

Conventional gain, including GEMs and Micromegas, has a number of problems for EXO:

1. Energy resolution not ideal
2. Additive quenchers likely eat up the Ba or at least add another constraint to an already challenging problem

If feasible, pure Xe option appears better suited



Variable length drift cell for resolution and gas composition studies

Next Step: build a high pressure chamber able to contain ~1MeV electrons with electroluminescent readout

This chamber will NOT be low background but will use methods that can be made low background

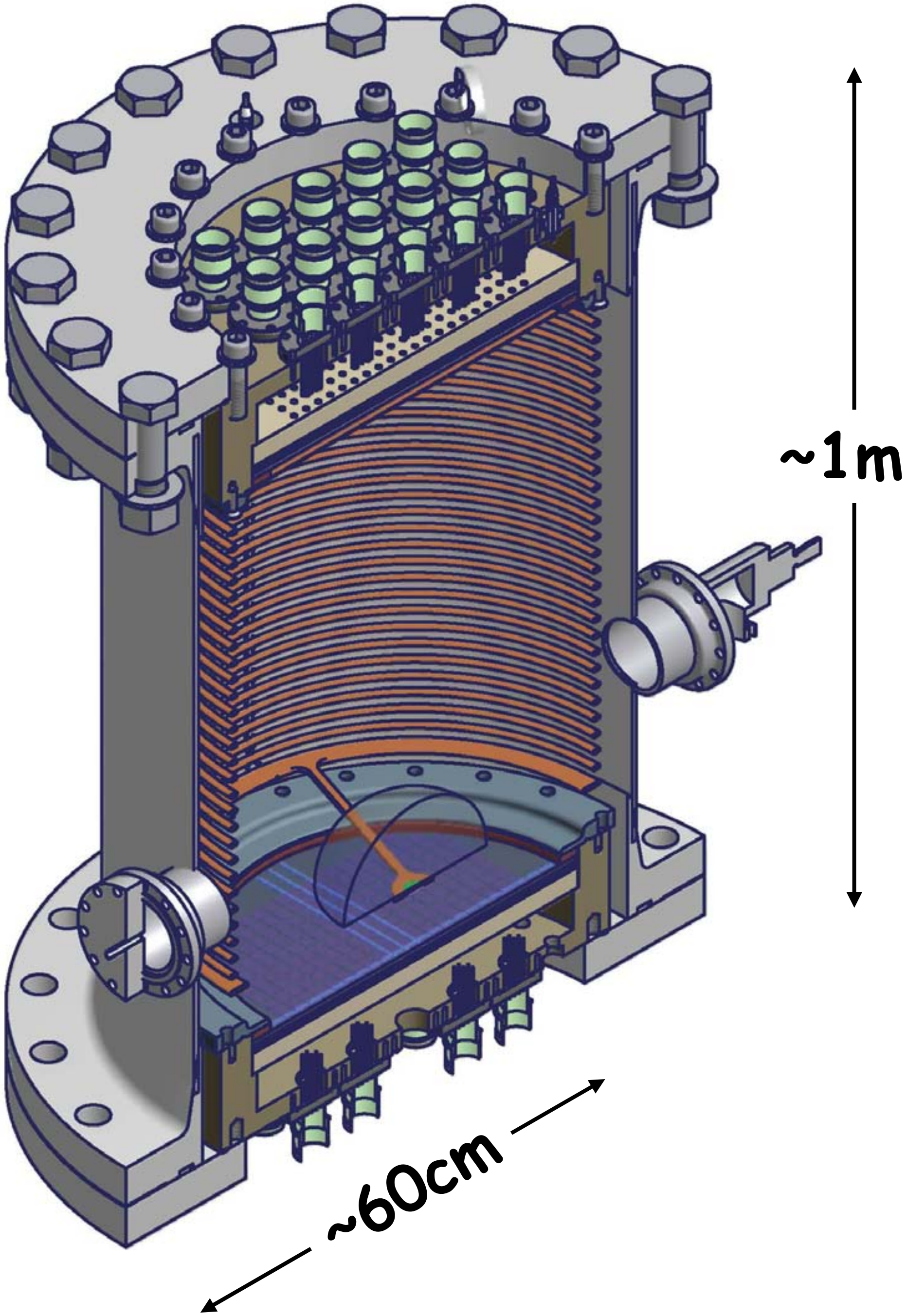
No PMTs.   Primary VUV detection option: CsI modular structure will allow the test of gaseous photocathodes (and, possibly wavelength shifting fibers or APDs)

Goals:
- Measure energy resolution for 1MeV electrons with segmented readout
- Evaluate tracking ability and background rejection at different pressures
- Study E field and readout options
- Validate the concept for a large detector

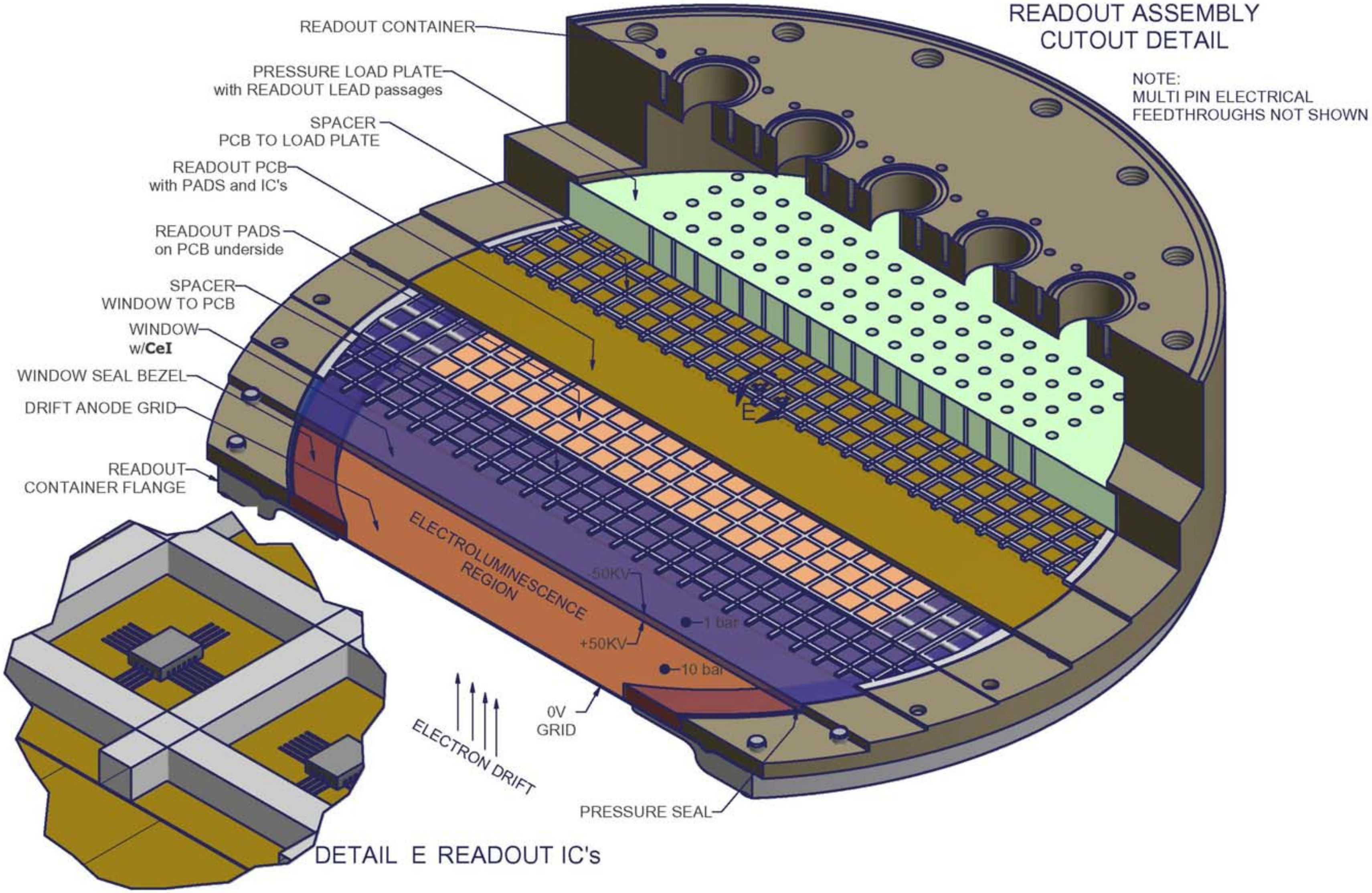
Will try to have chamber ready in summer 09 at Carleton

(although competition for personnel to start EXO-200 is harsh)

$V \sim 300$ l
$P \leq 10$atm

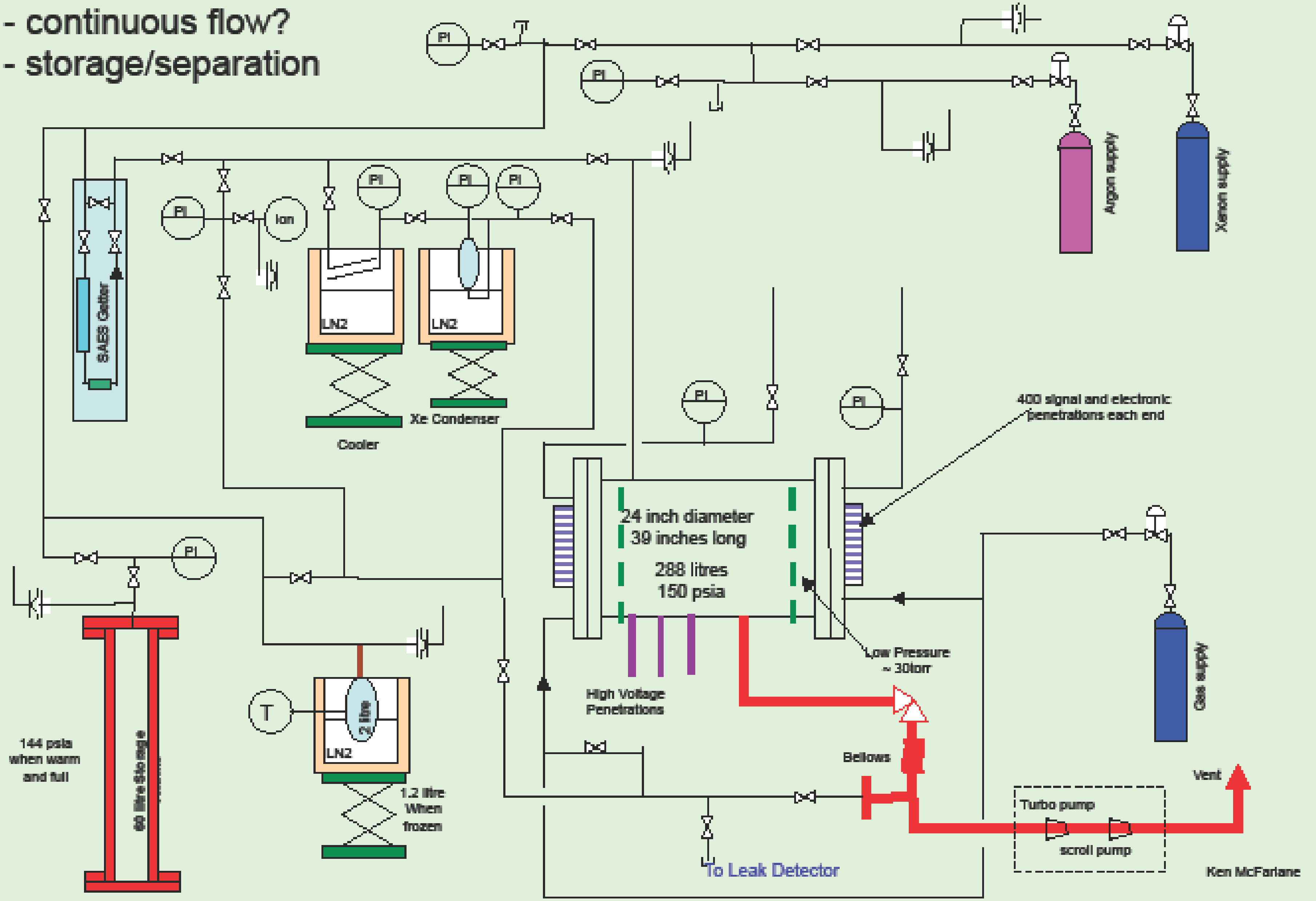


CsI readout plane



Process Systems

- purity monitor
- continuous flow?
- storage/separation



Gaseous photocathode R&D

UV flash lamp

Drift cell

Distillation system

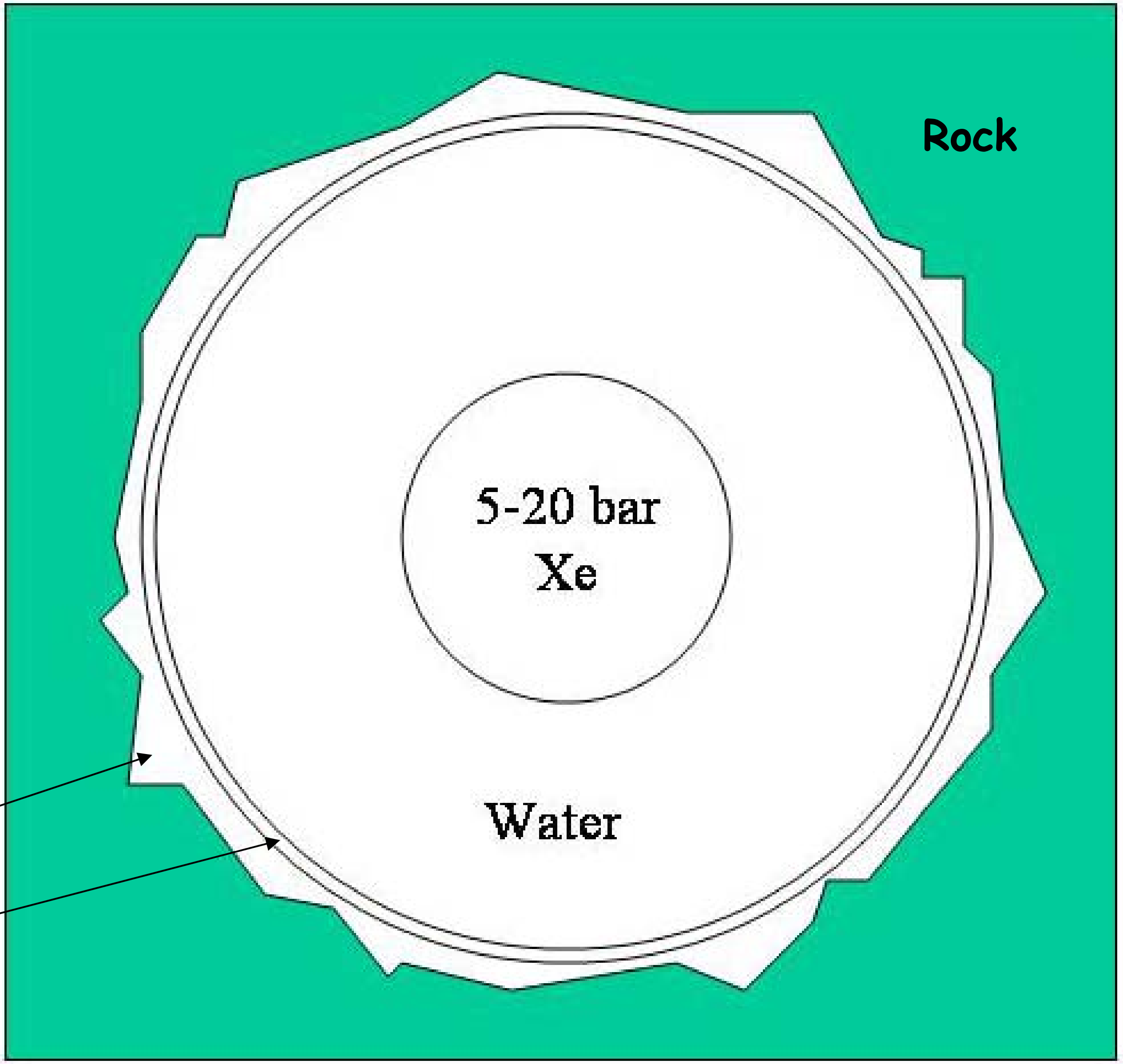
Name	Composition	Ioniz potential (eV)	Vap press at 20C (torr)
TMAE	$C_{10}H_{24}N_4$	5.4	0.35
TEA	$C_{17}H_{44}N_4$	7.5	55
exo-2-chloronorbornane	$C_7H_{11}Cl$	1.65	3.3
(S)-exo-5-norbornen-2-ylchloride	$C_7H_{19}Cl$	1.1	1.6

Ideas about pressure vessel

The pressure vessel requires substantial engineering to optimize shielding, structure, access, …

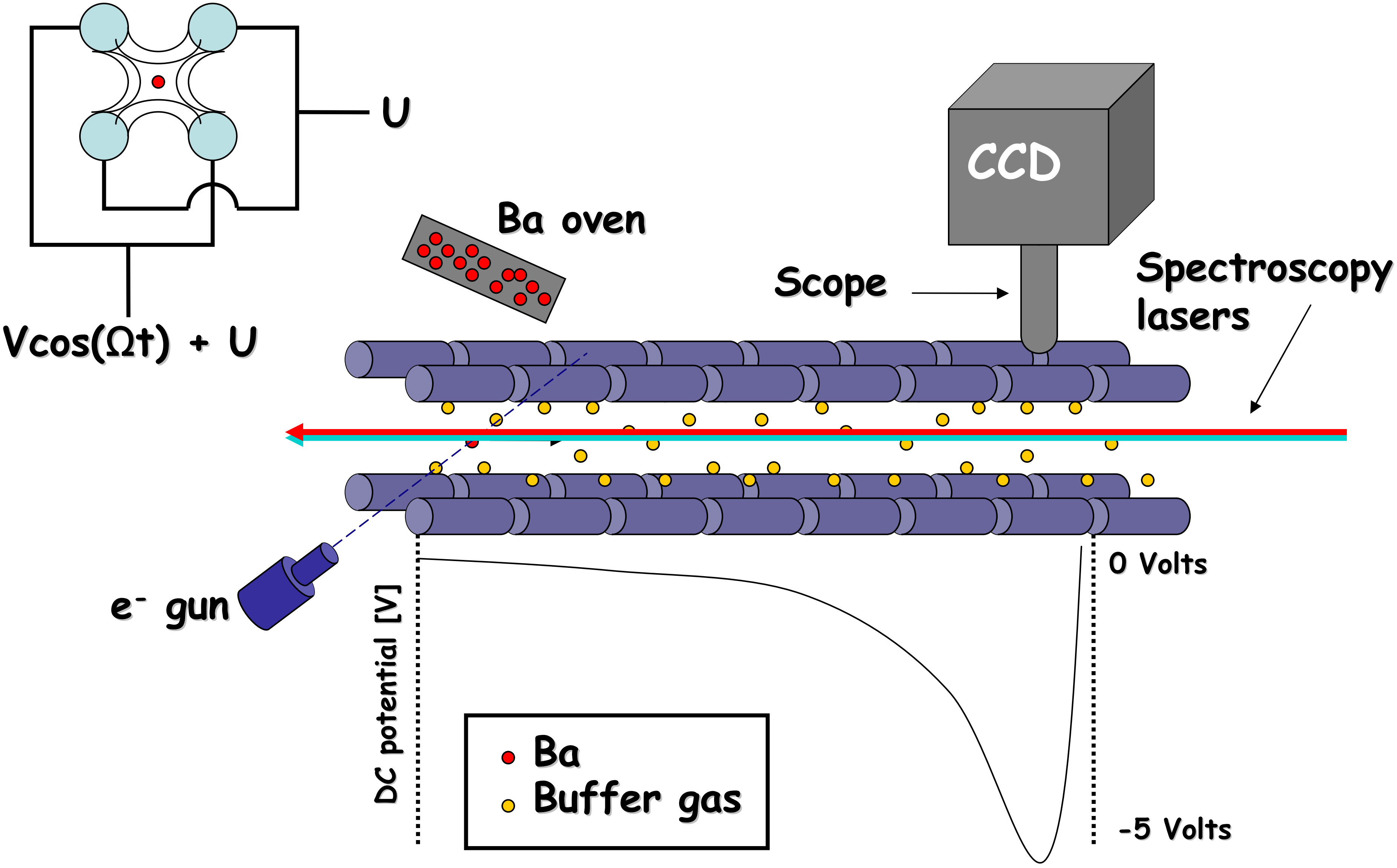
Maybe rock can support the pressure.

If a free-standing vessel is needed, does it have to be built underground? (weight, size)



Ba tagging R&D

Ba$^+$ identification in a Linear Ion Trap



U

Vcos(Ωt) + U

Ba oven

CCD

Scope

Spectroscopy lasers

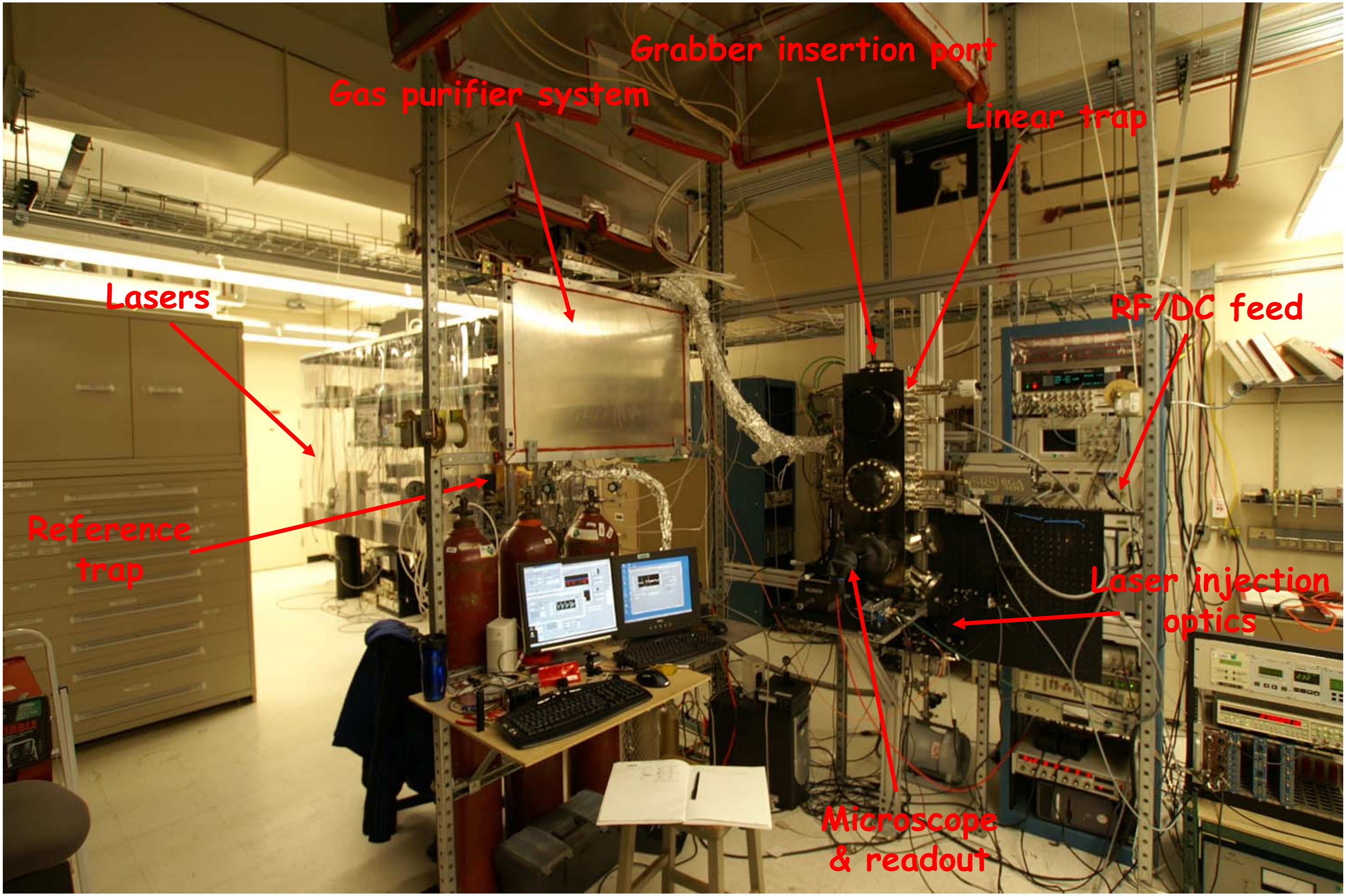
e$^-$ gun

DC potential [V]

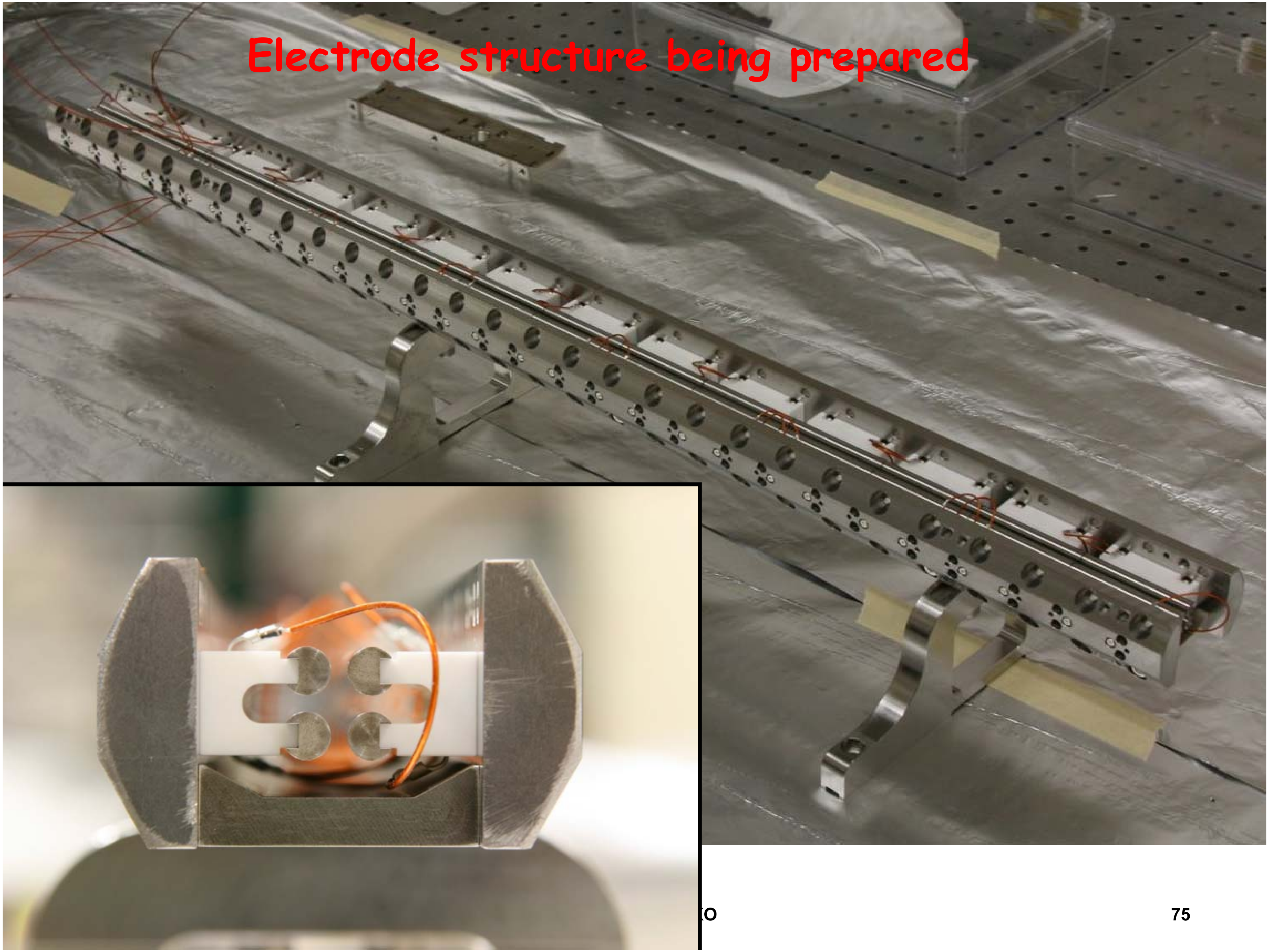
0 Volts

-5 Volts

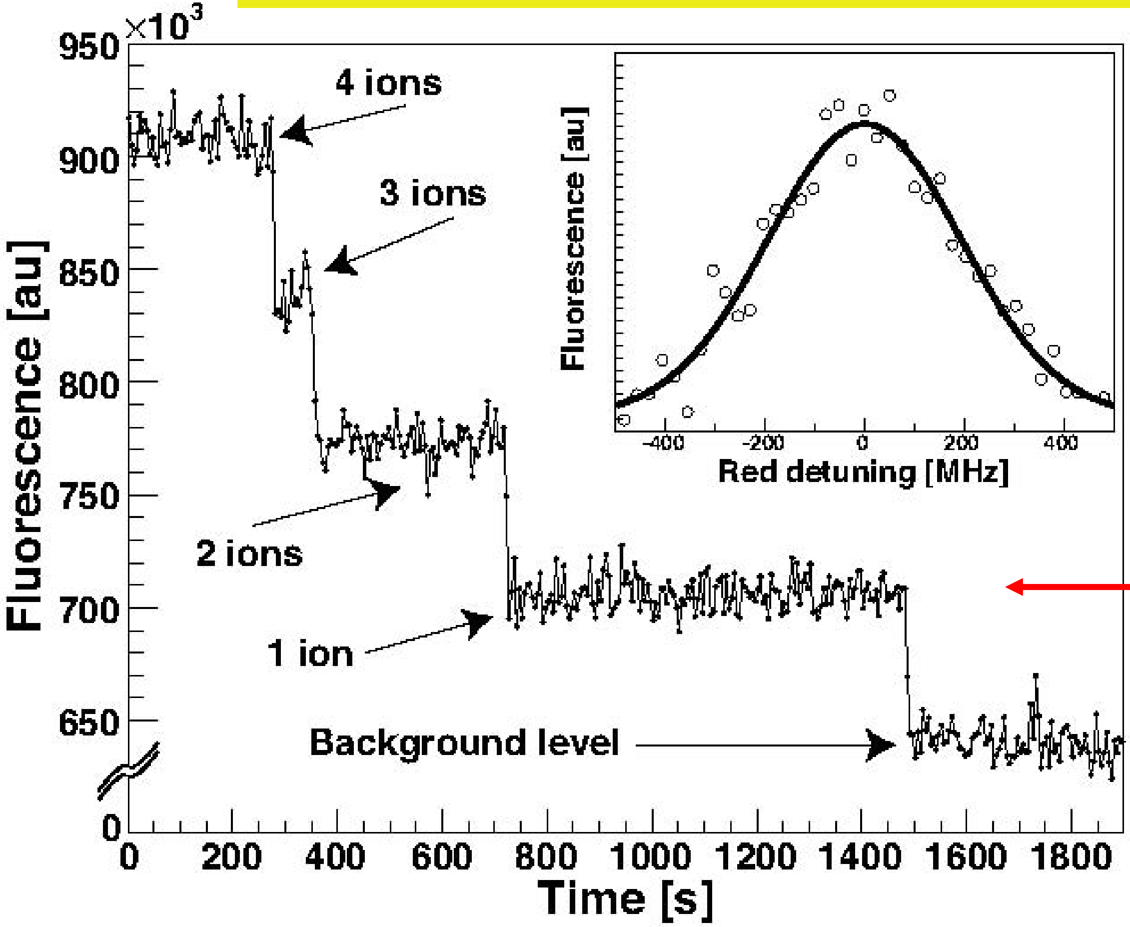
● Ba
● Buffer gas


Grabber insertion port
Gas purifier system
Linear trap
Lasers
RF/DC feed
Reference trap
Laser injection optics
Microscope & readout

Electrode structure being prepared



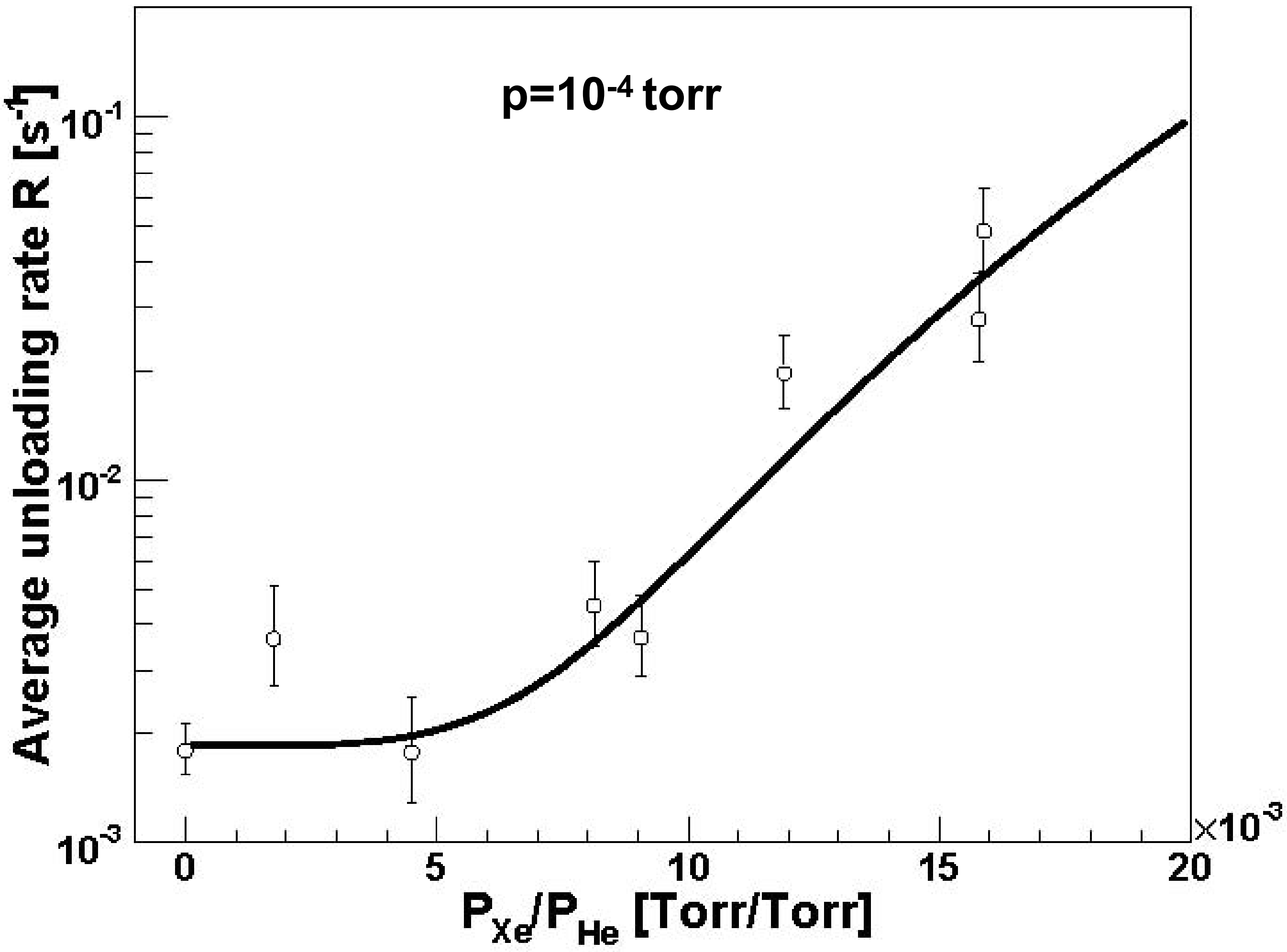
First single ion detection in high pressure gas (He, Ar)



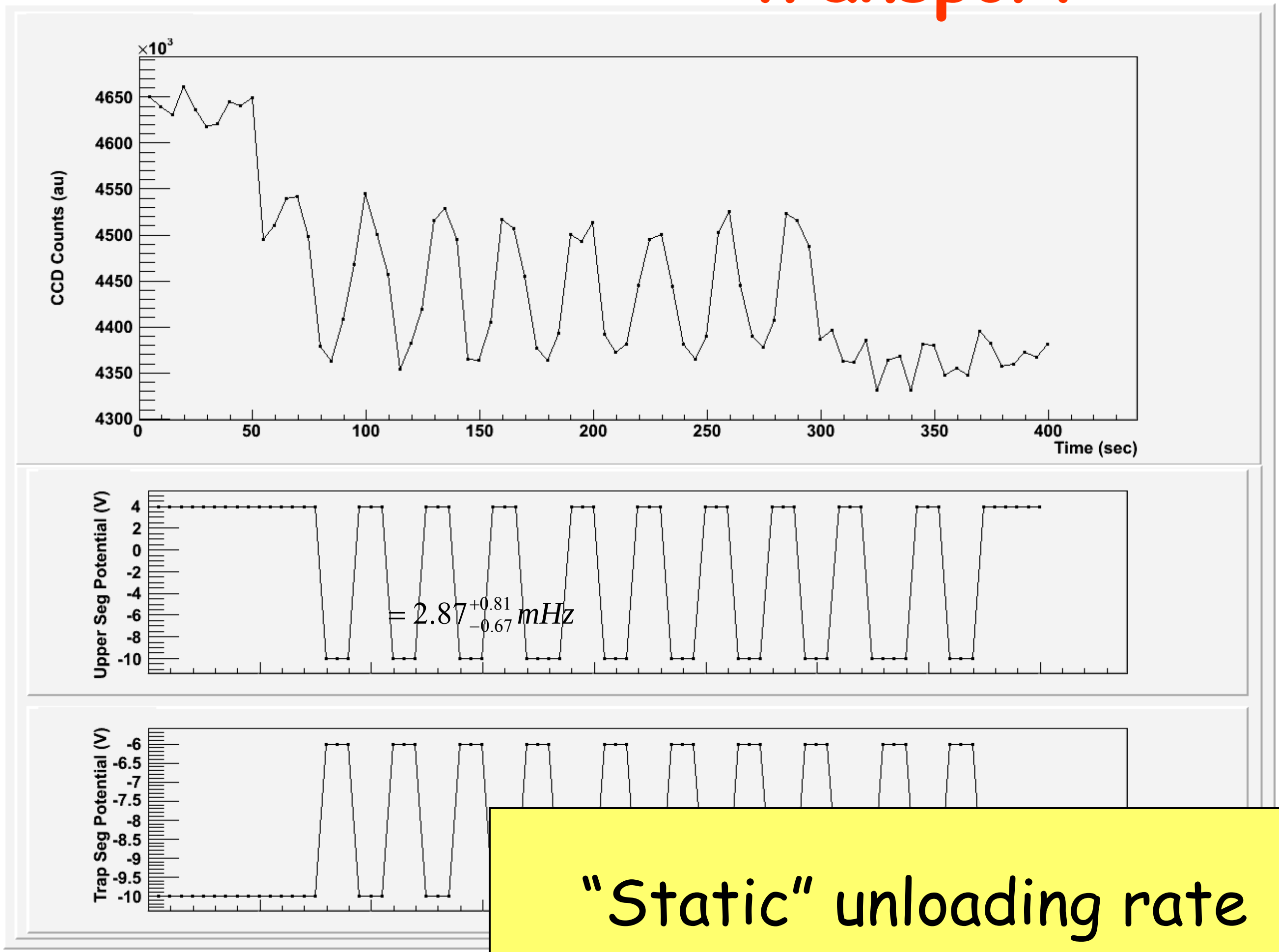
~9σ discimination
in 25s integration

M.Green et al. arXiv:0702122, Phys Rev A 76 (2007) 023404
B.Flatt et al. arXiv:0704.1646, NIM A 578 (2007) 409

Single ion spectroscopy & identification possible in some Xe atmosphere provided He is added to the trap



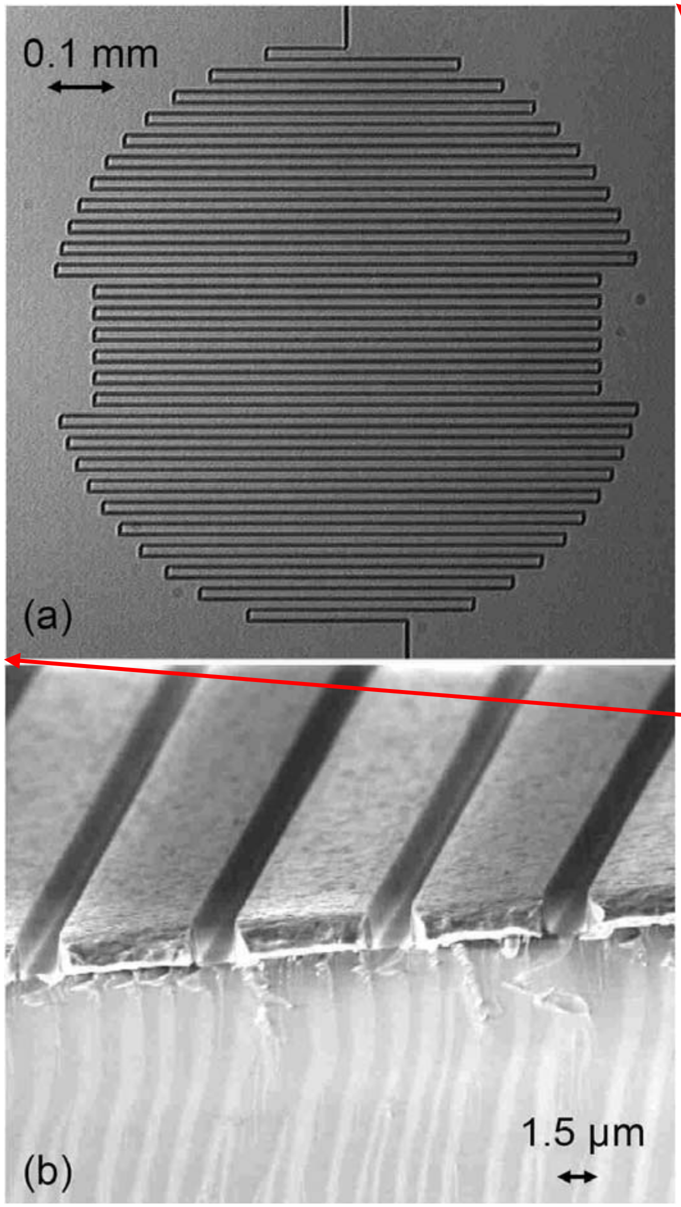
Trap also allows for very "clean" ion transport

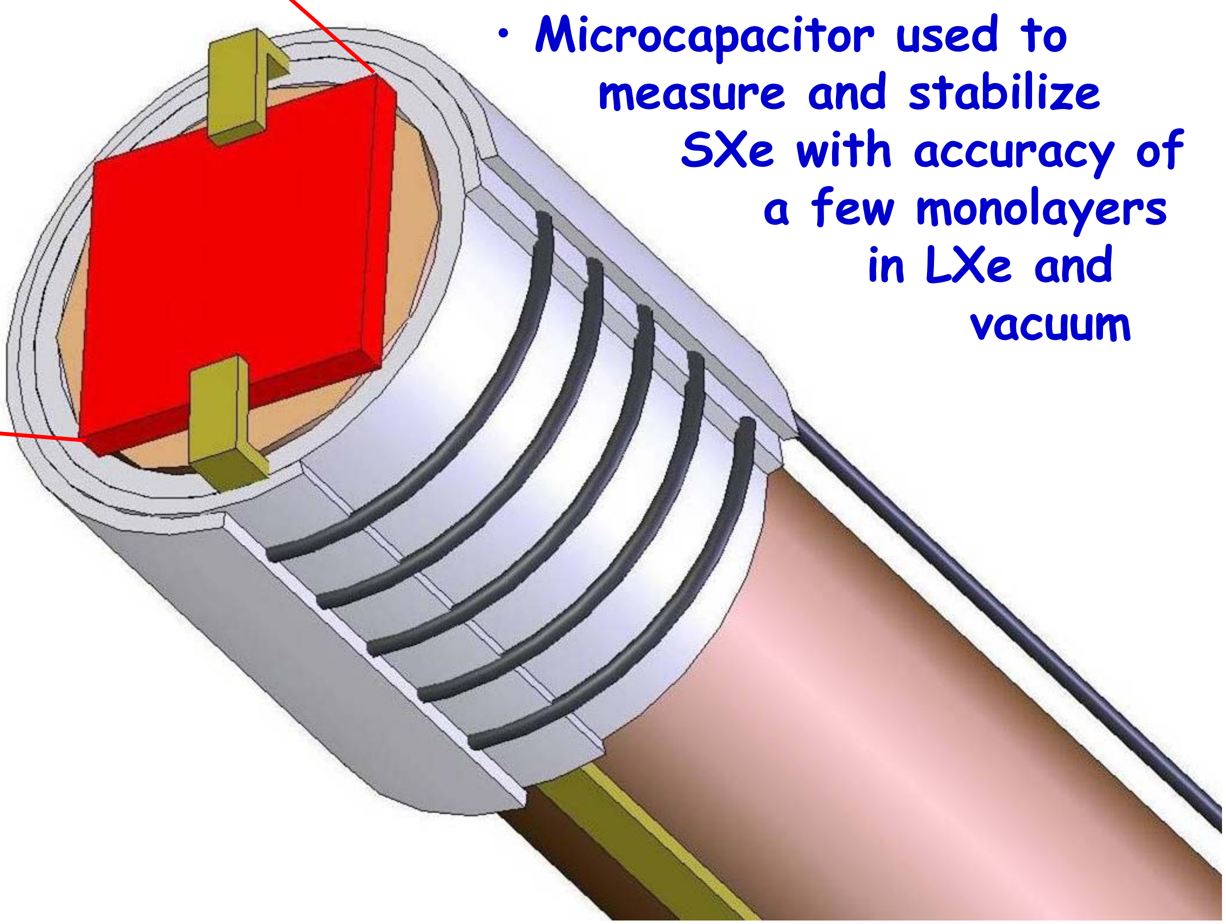


"Static" unloading rate $= 2.87^{+0.81}_{-0.67}\,mHz$

"Cycling" unloading rate $= 7.80^{+1.56}_{-2.34}\,mHz$

Remaining challenge is the efficient transfer of single Ba ions from LXe to the ion trap

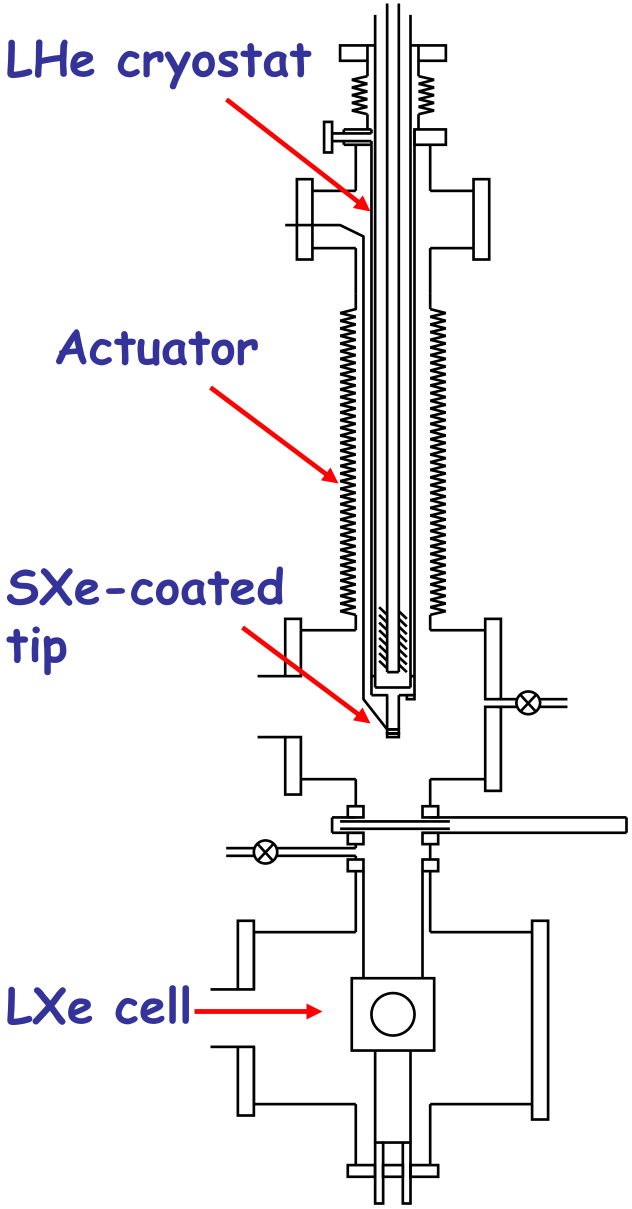




Cryogenic dipstick

- Capture ion on SXe coating
- LHe cooling (~20K) to maintain stable SXe coating in 10^{-8} torr vacuum
- Microcapacitor used to measure and stabilize SXe with accuracy of a few monolayers in LXe and vacuum

Complete setup

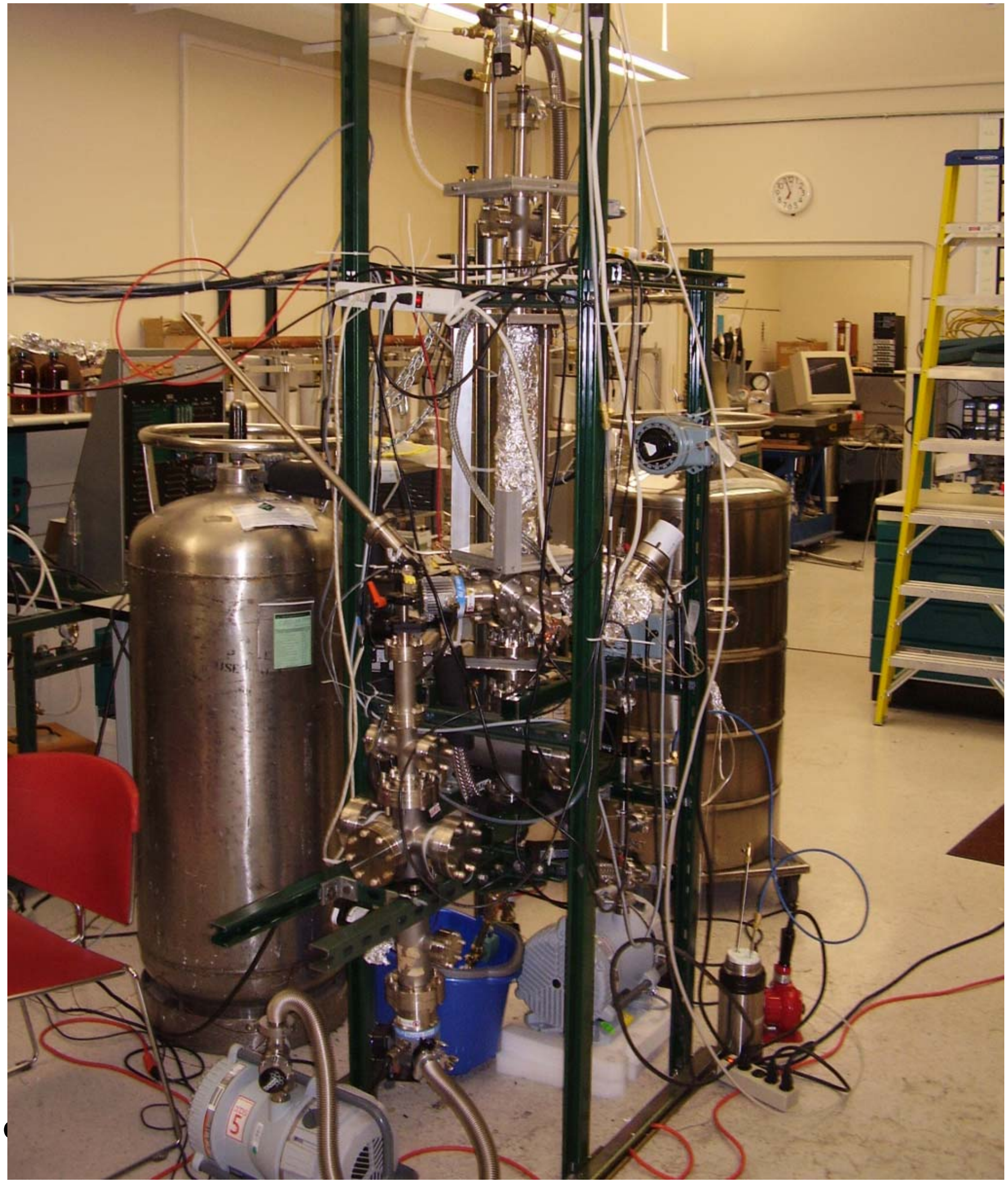


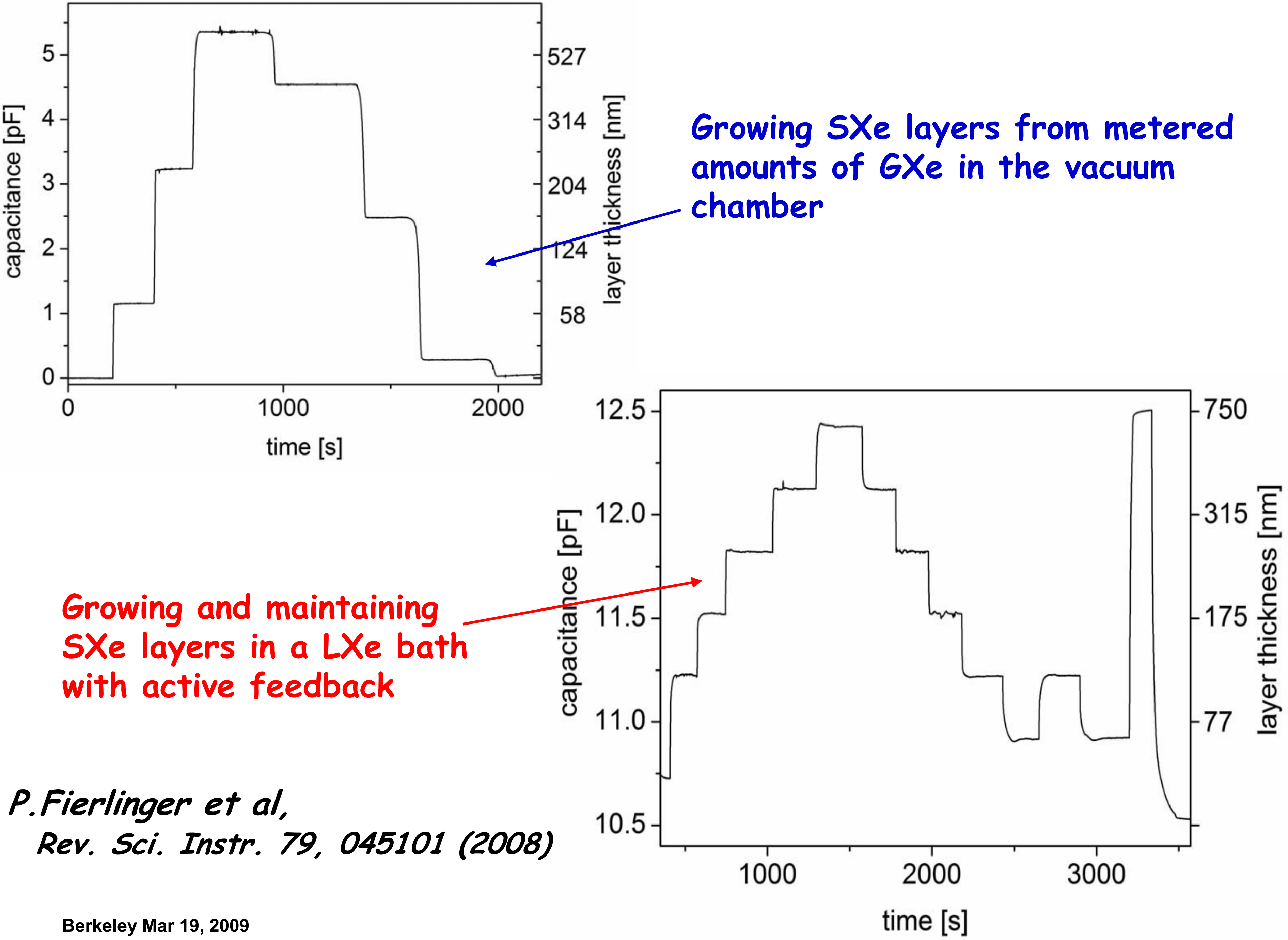
LHe cryostat

Actuator

SXe-coated tip

LXe cell





Growing SXe layers from metered amounts of GXe in the vacuum chamber

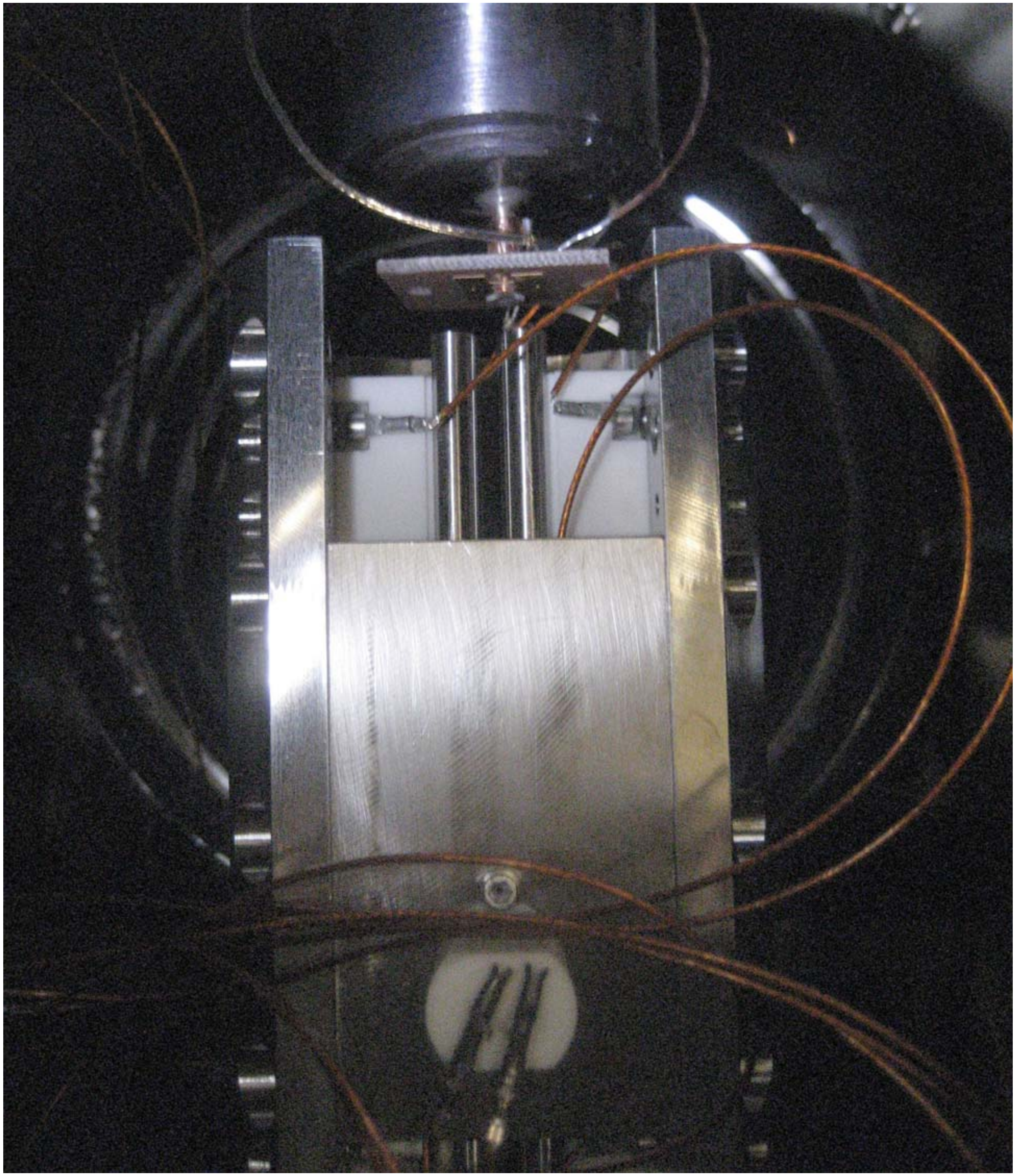
Growing and maintaining SXe layers in a LXe bath with active feedback

P.Fierlinger et al, Rev. Sci. Instr. 79, 045101 (2008)

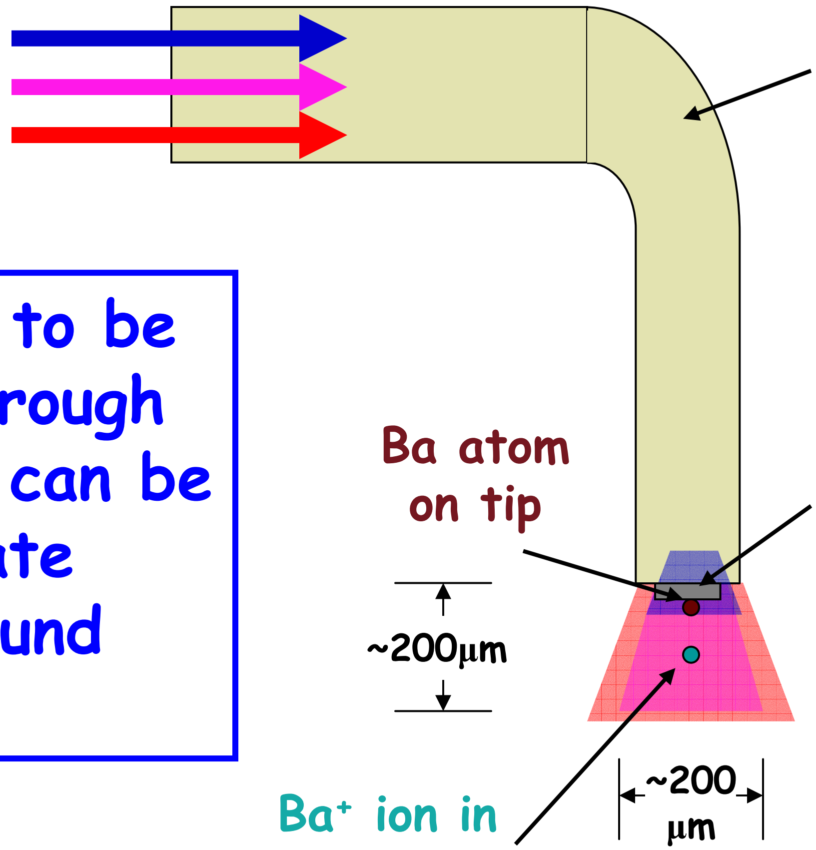
In progress…

Shoot ions from the trap onto the cryotip and back into the ion trap

Measure the product of efficiencies



An alternative way to transport the Ba ion:



UV multimode optical fiber (~200μm core)

Semitransparent metallic coating absorbs desorption λ, transmits RIS lasers

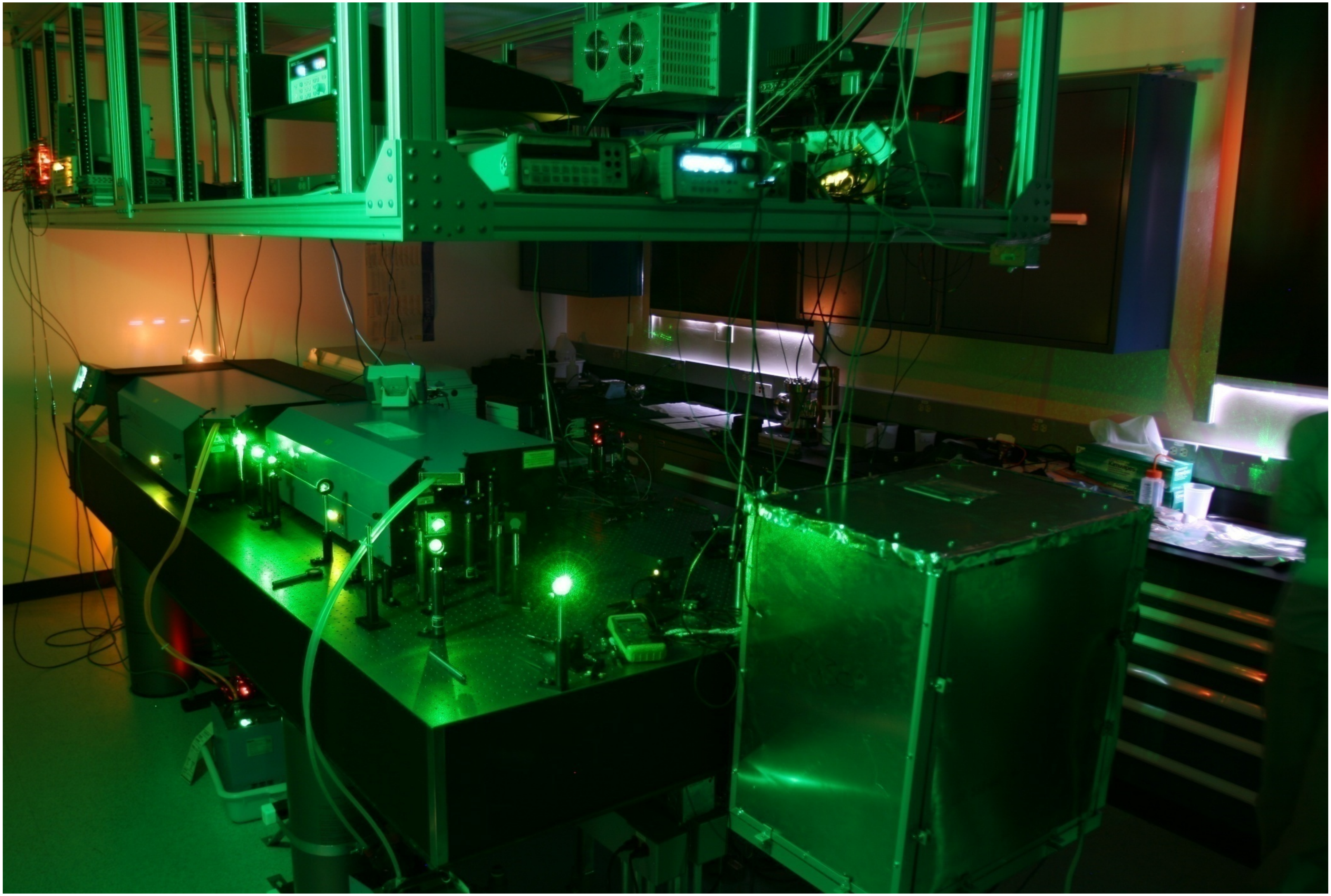
Ba atom on tip

Ba⁺ ion in vacuum/gas

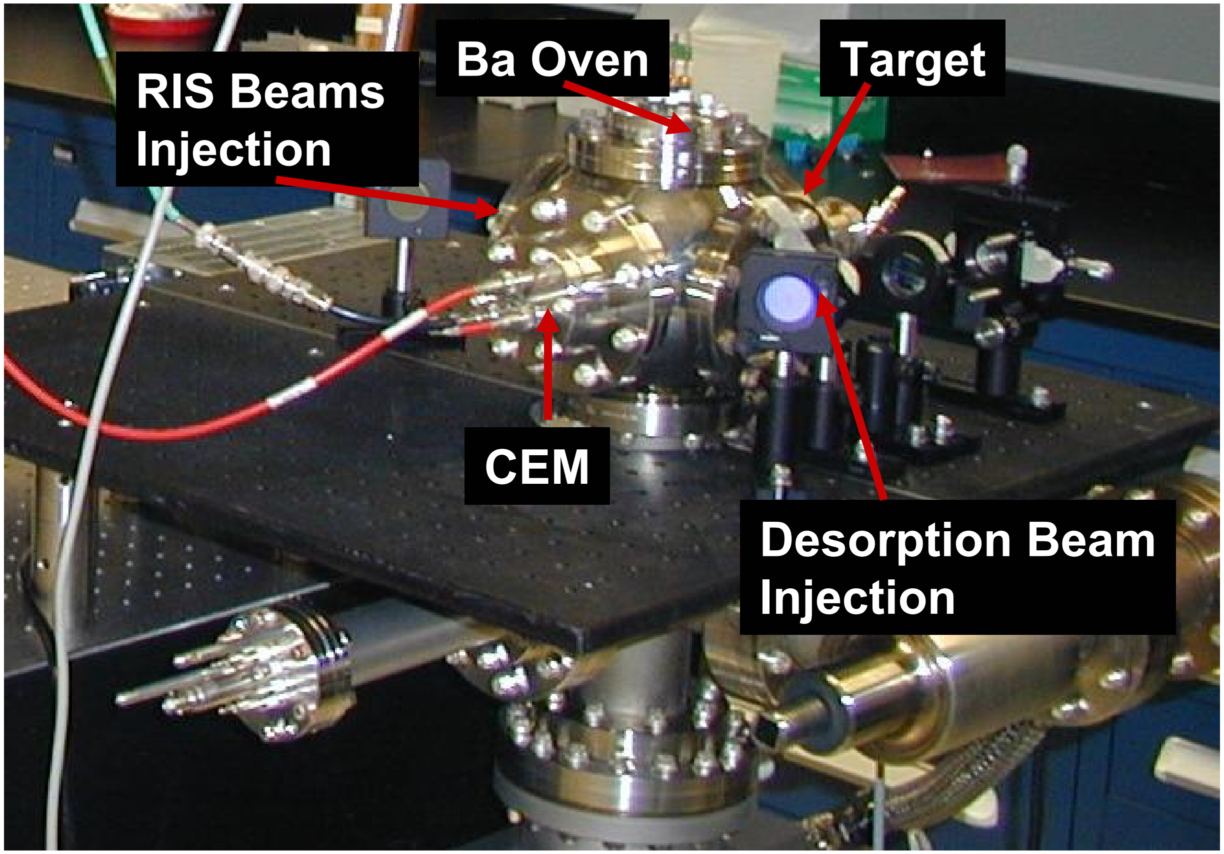
This does not have to be necessarily done through a fiber, the lasers can be shot at the substrate where the ion is bound from the "outside"

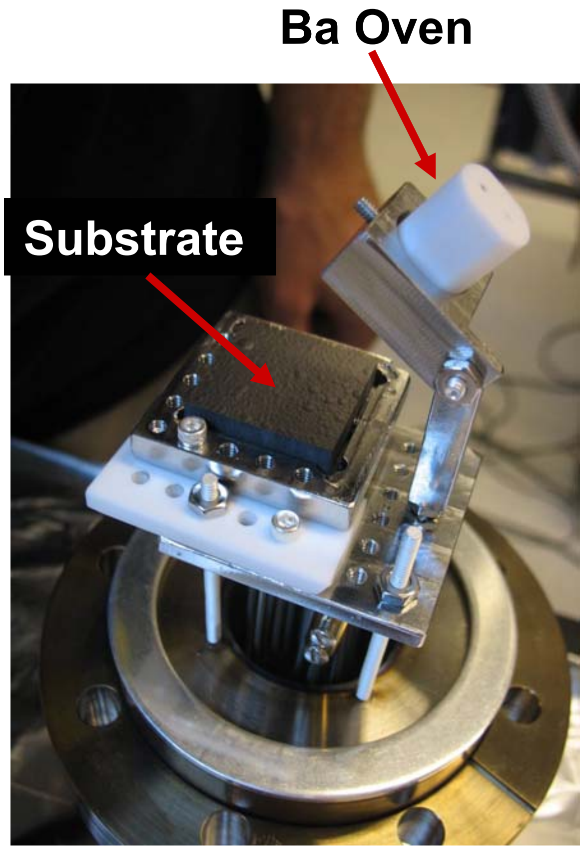
In this case *each step* can be documented to work with high efficiency in the literature !

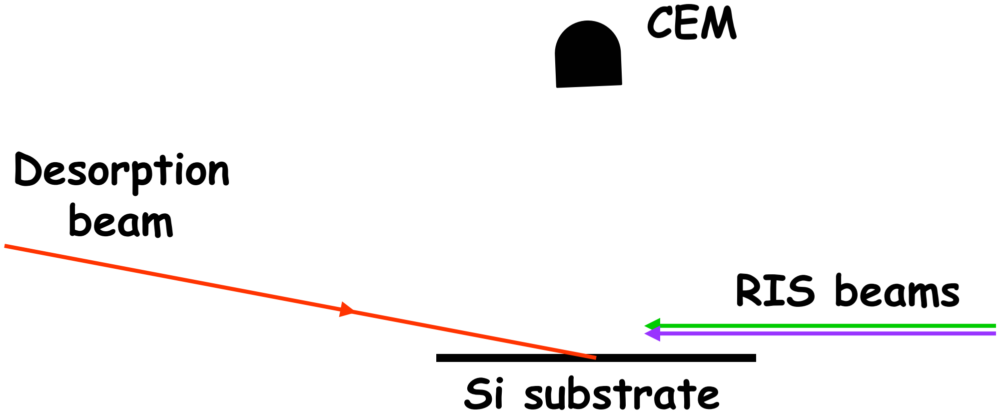
Resonant ionization spectroscopy lab



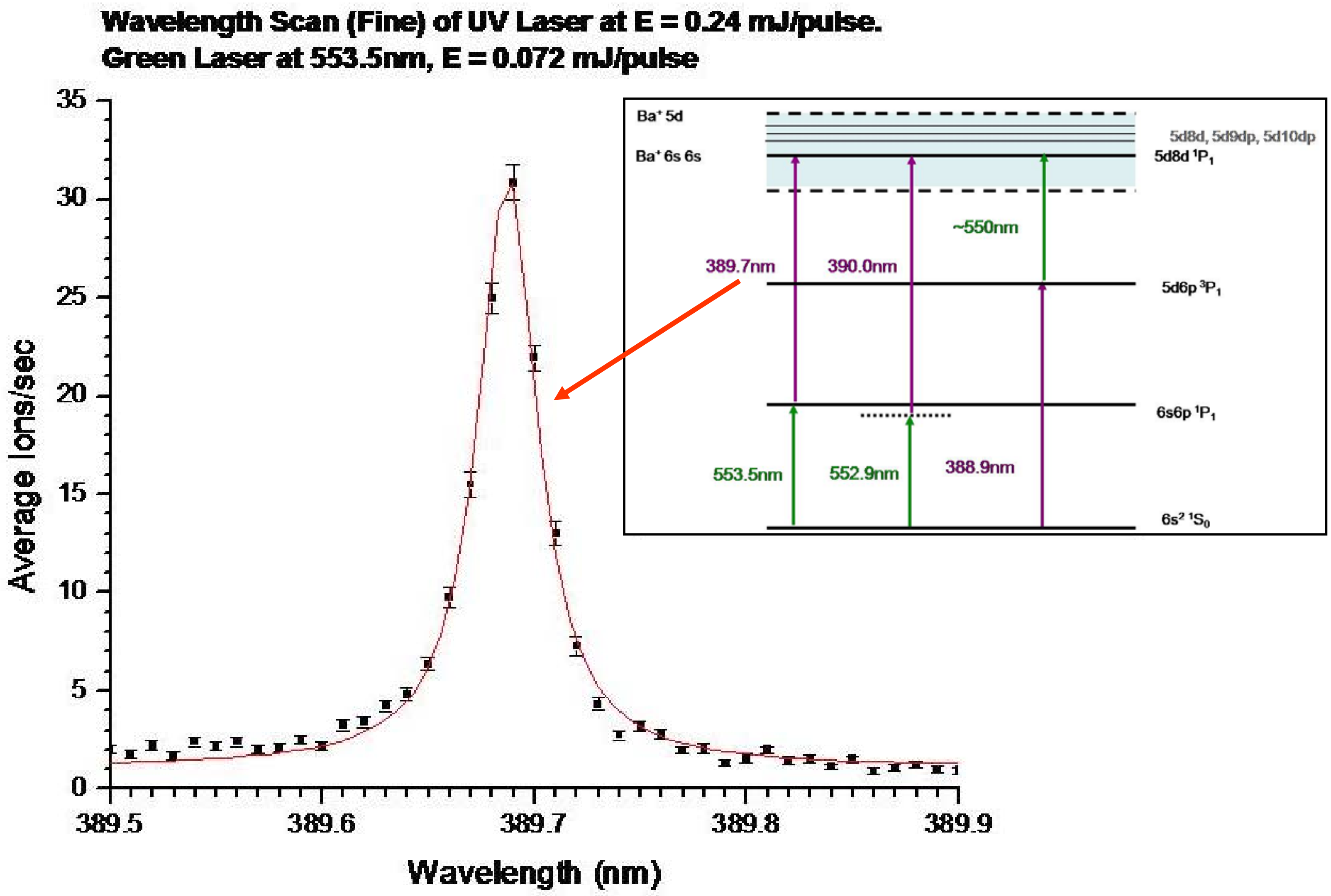
…and cell


RIS Beams Injection
Ba Oven
Target
CEM
Desorption Beam Injection

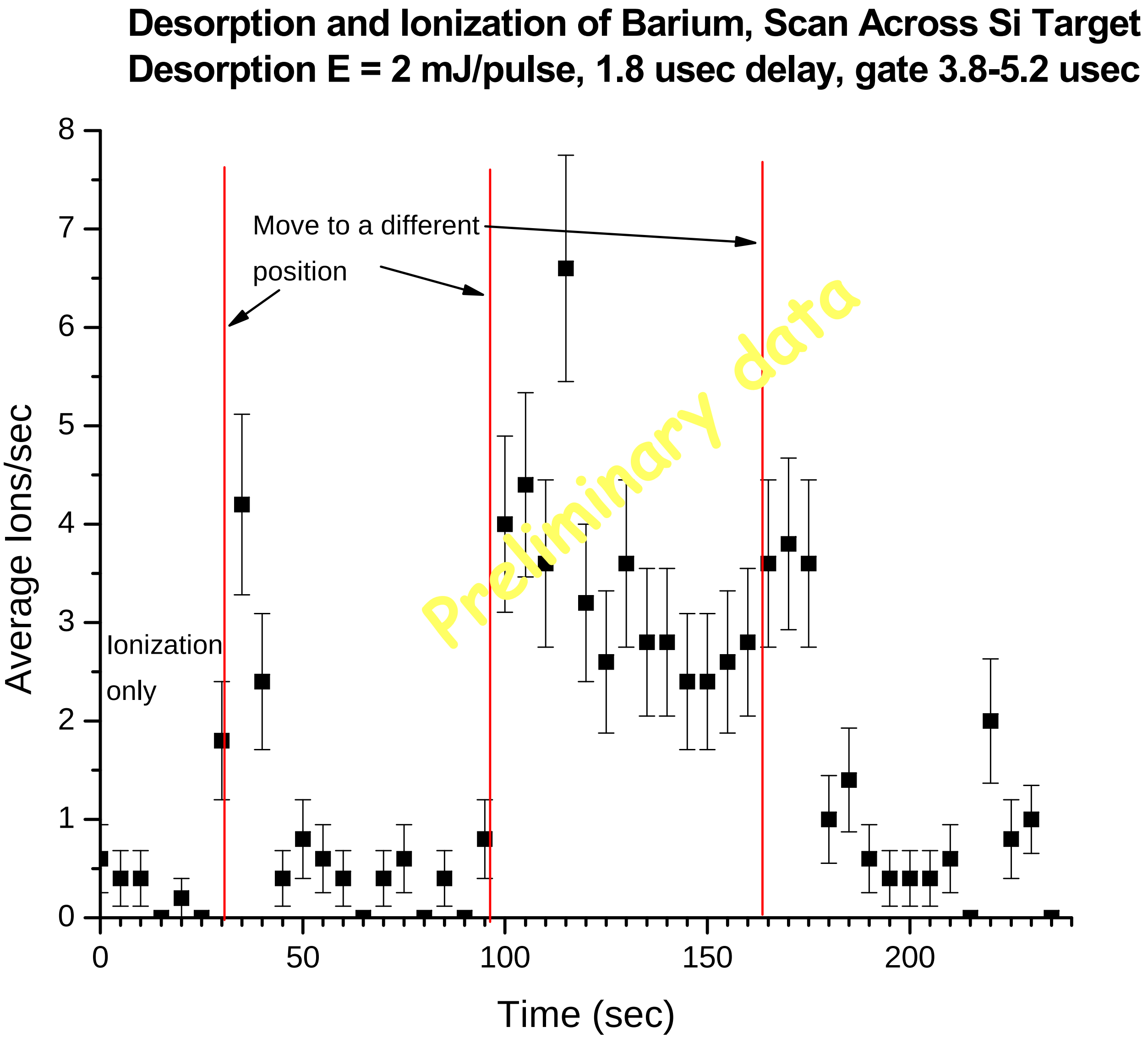

Ba Oven
Substrate


CEM
Desorption beam
RIS beams
Si substrate

RIS from Ba vapor phase: things work as they should



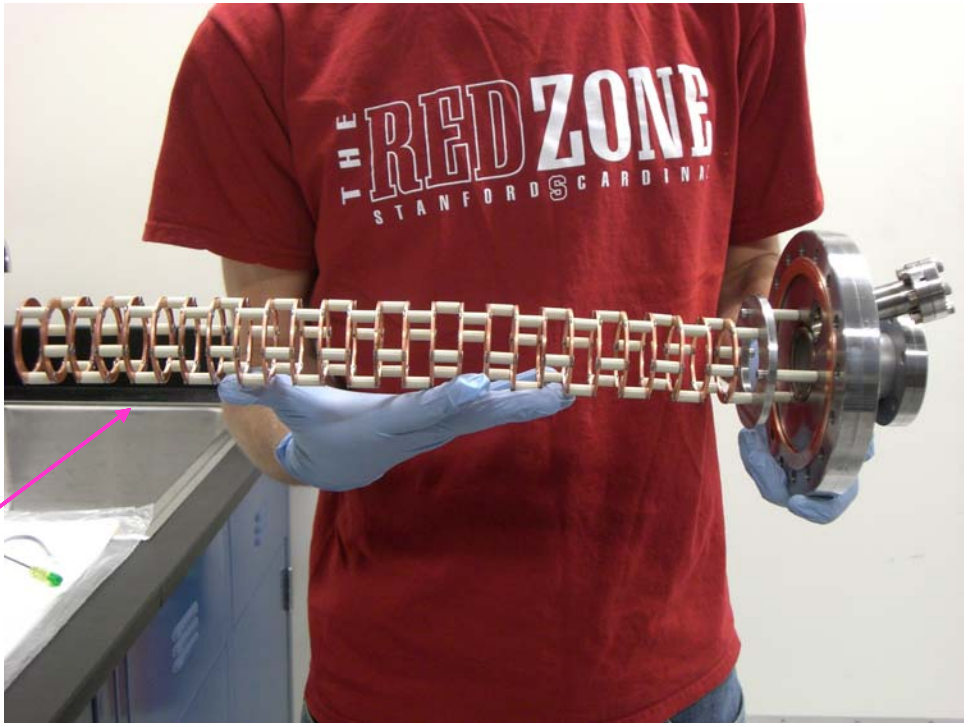
For very thin Ba coatings a few shorts remove the Ba from a particular spot. But the signal comes back elsewhere



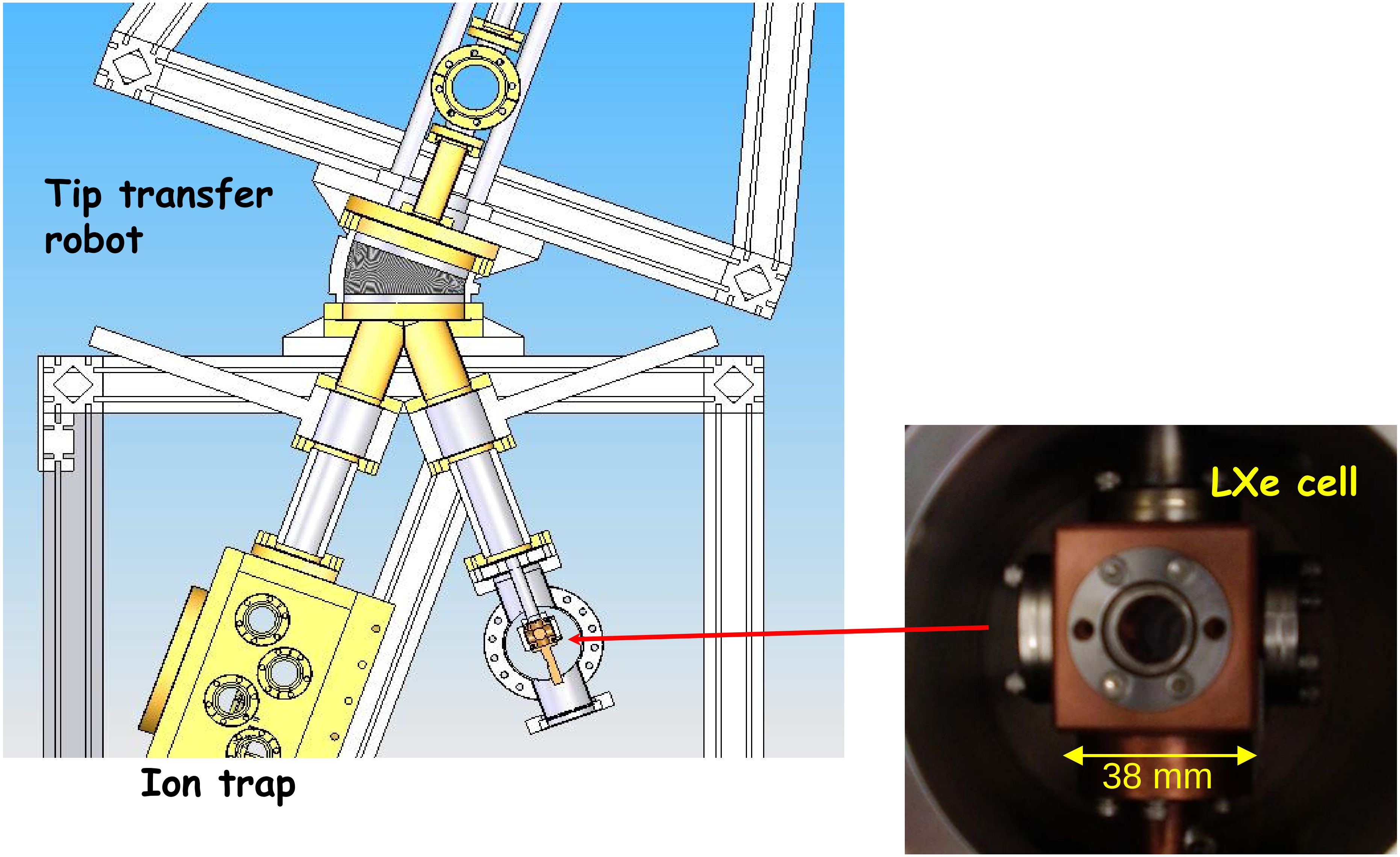
Can desorb Ba and ionize in the same shot

To do:

- Learn how to deal with the fact that few shots may "burn" all the Ba from a place (this will not be a problem with single ions!)
- Understand better ablation thresholds
- Figure out a nice way to present data
- Install TOF spectrometer
- Build a, possibly tagged, single Ba source
- Work with single ions and measure efficiency

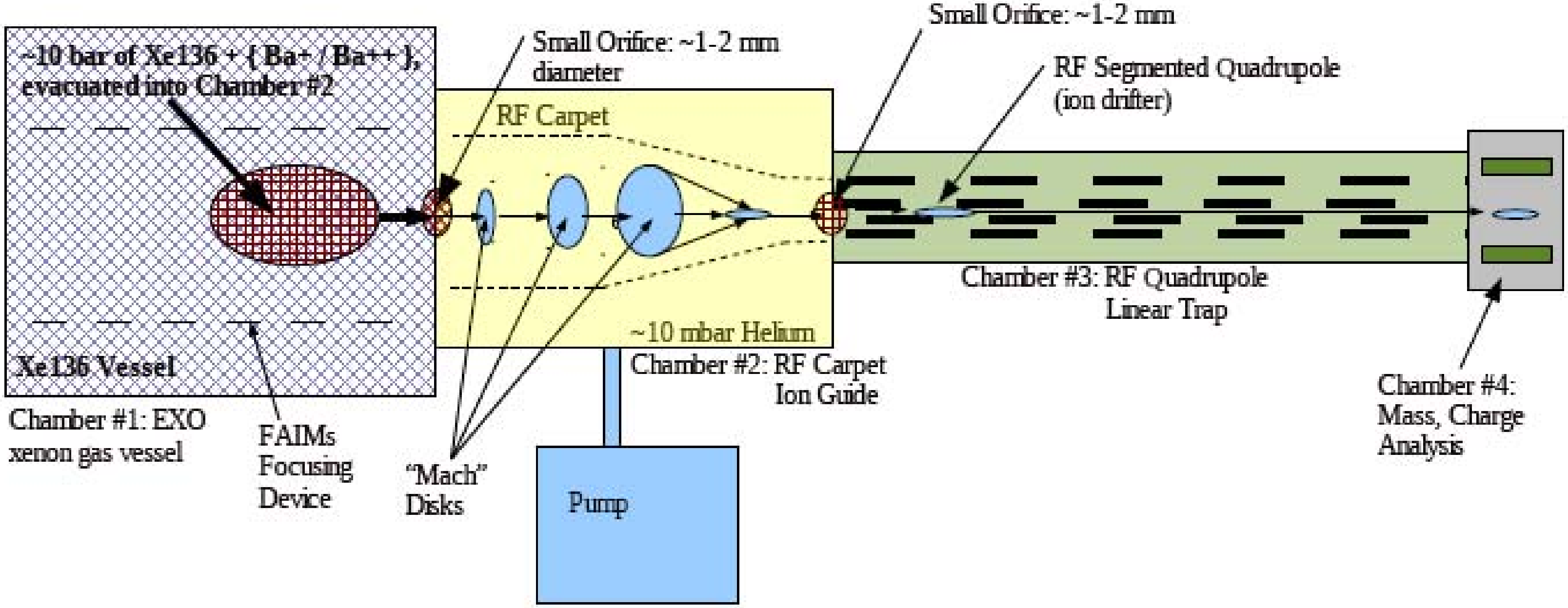


Following step:
transfer Ba-ions from LXe cell to ion trap



What about Ba tagging from a GXe detector?

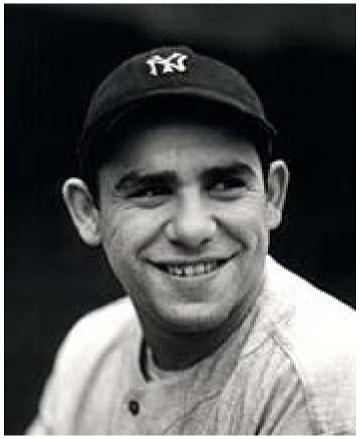
We have just started to think about this:



One may be able to borrow techniques from the radioactive ion beams community and build a chain of differentially pumped chambers, separated by nozzles, where the ion is confined by various means before reaching the identification stage in vacuum.

Plans for the future

It’s tough to make predictions…
especially about the future



Some possibilities from possible EXO-200 outcomes

Case 1: EXO-200 sees nothing, really

→ Build the largest possible EXO, with Ba tagging unless the EXO-200 background is spectacular

Go to DUSEL or to SNOlab

Start in 5 to 8 yrs from now

Case 2: EXO-200 has a 2 or 3 sigma peak at the right place

→ Build a new ~500kg chamber maybe in the same cryostat and same mine

Start in <2 after signal is seen

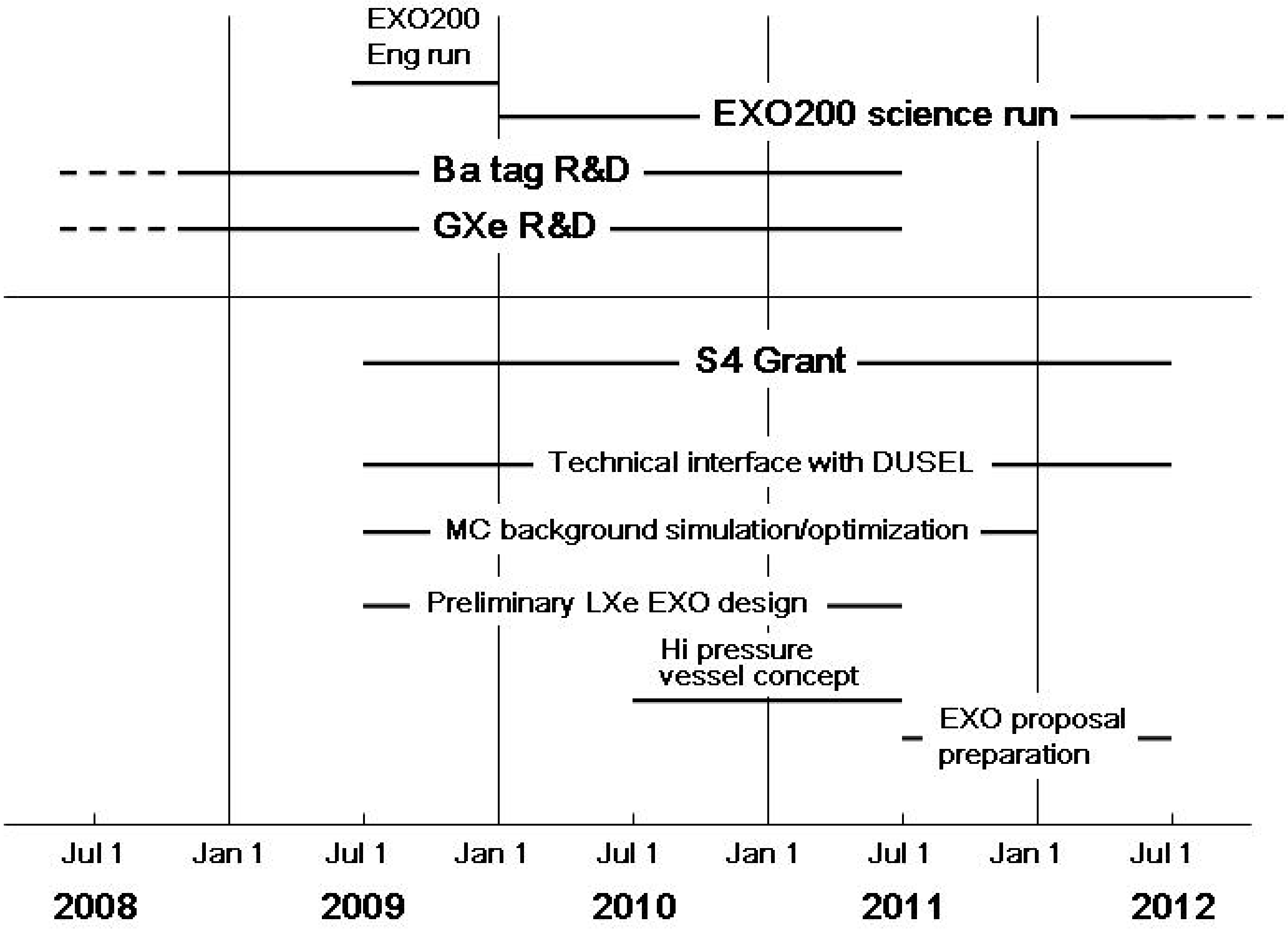
Case 3: EXO-200 has a clear signal

→ (open Champagne and) build a 1 bar GXe TPC for the very same 200kg of Xe to study angular correlations

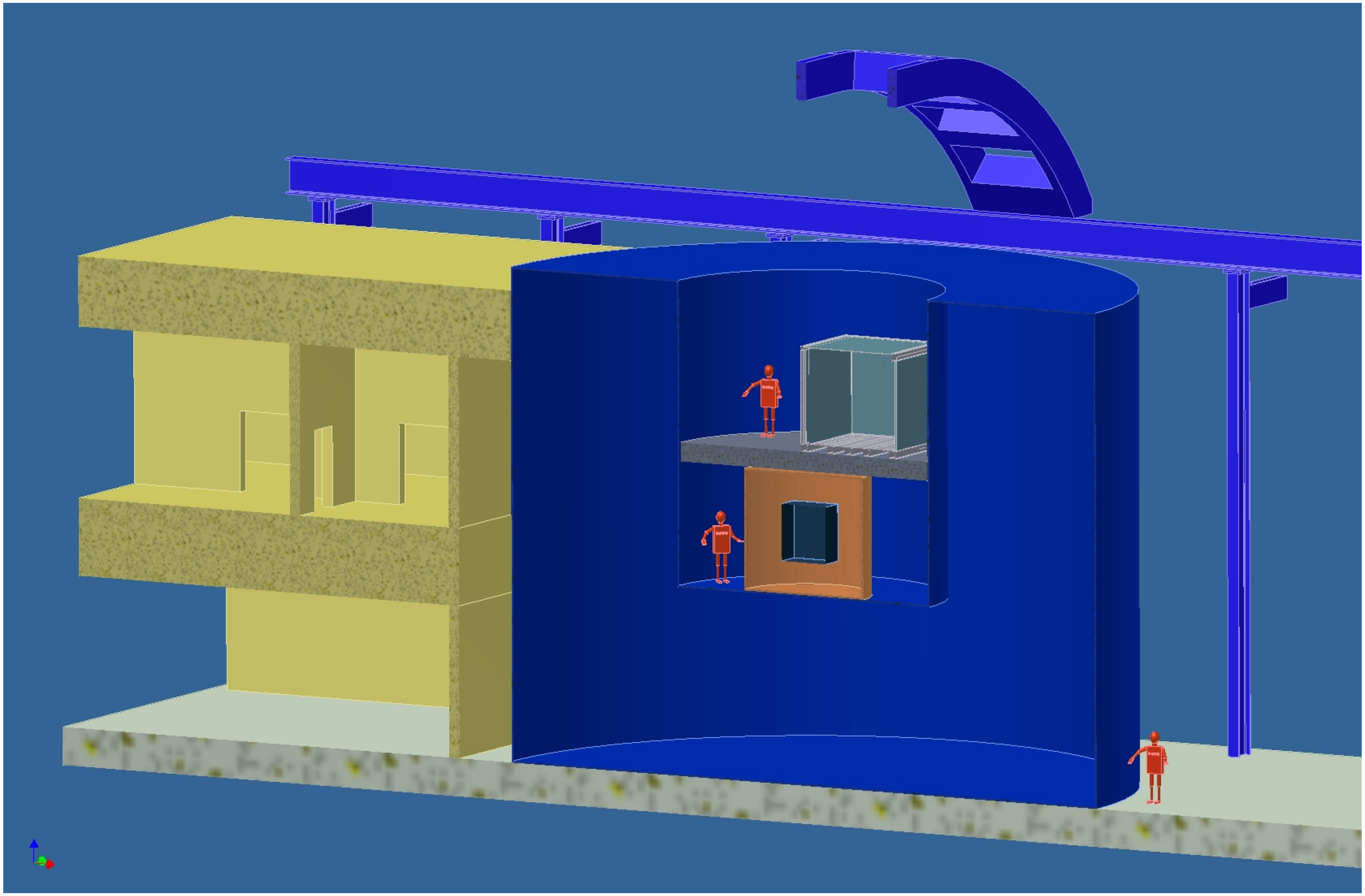
Possibly go to SNOlab

Start in 2014

How does DUSEL S4 fit in with the rest?



Outline of a LXe multi-ton EXO with Ba tagging in a DUSEL module



Conclusions

Over its glorious history neutrino physics has provided plenty of surprises and has required forays in many different areas of science and technology

EXO really belongs to this tradition!

Isotope enrichment at an unprecedented scale (for science) is a reality

Data taking is approaching for EXO-200

Ba tagging for EXO is using bag of tricks borrowed from nuclear and particle physics, *AMO* and surface science

EXO is ramping up GXe R&D to arrive to the technology decision point with all of the information needed

Enriched Xenon Observatory

for double beta decay