EXO status and prospects

Jesse Wodin for the EXO collaboration

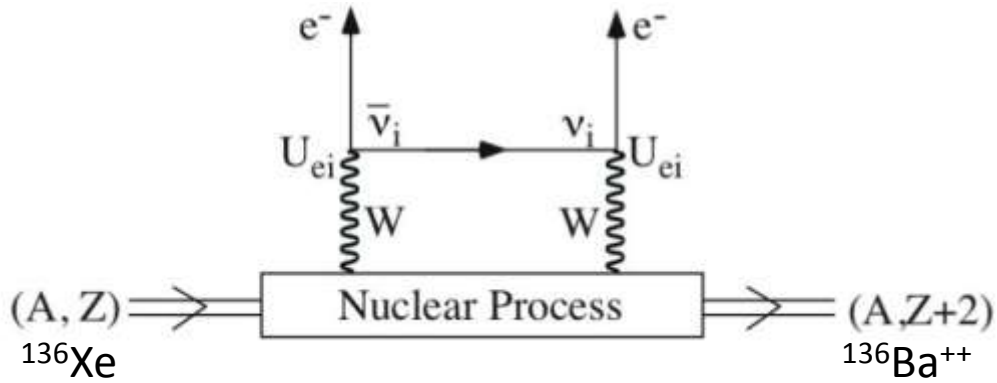
SLAC

Topics

- EXO-200 introduction and status
- Barium tagging
- Full EXO conceptual design

Neutrinoless double beta decay $0\nu\beta\beta$

Emitted ν_i is mostly right-handed, with small left handed component ~ m_i/E_ν absorbed at second vertex



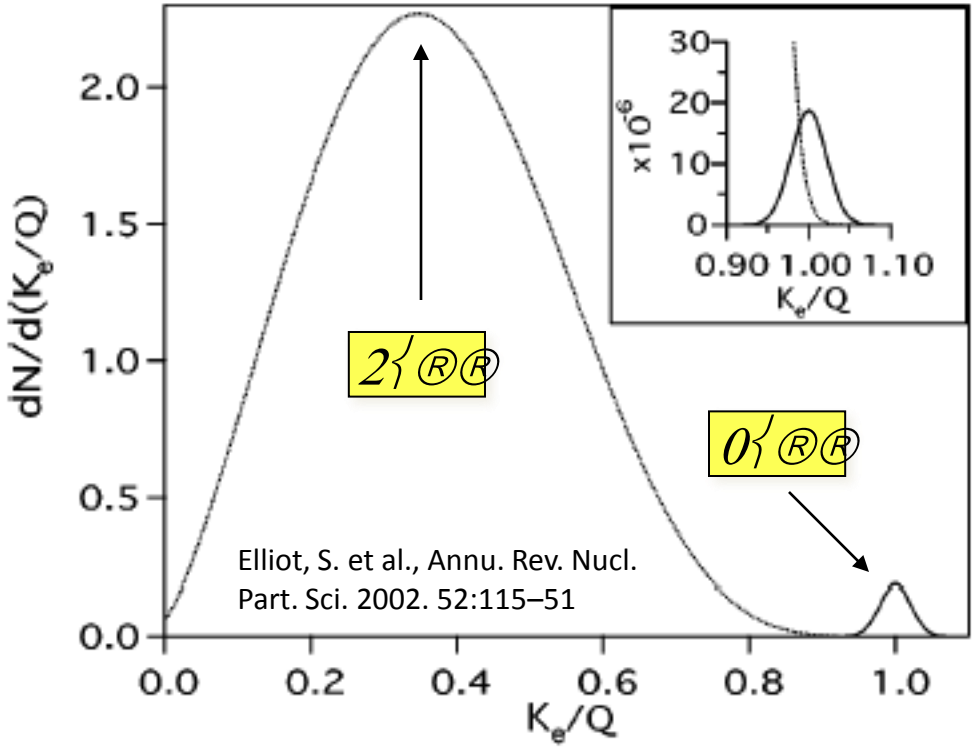
$$\left|\sum_i m_i U_{ei}^2\right| \equiv \left|\langle m_{\beta\beta}\rangle\right|$$ Effective Majorana mass is a coherent sum over mass eigenstates

$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = G_{0\nu\beta\beta}\left(Q_{\beta\beta}, Z\right)\left|M_{0\nu\beta\beta}\right|^2 \langle m_{\beta\beta}\rangle^2$$ Decay rate observed in a detector

$0\nu\beta\beta$ requires that neutrinos are ***massive Majorana particles*, *and lepton number non-conservation***

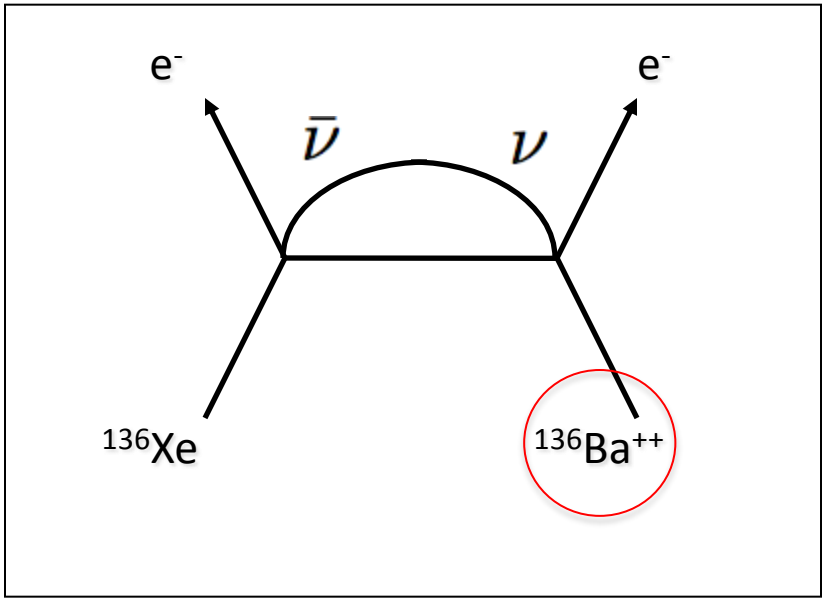
$$\bar{\nu}_i = \nu_i \qquad m_\nu \neq 0 \qquad \Delta L \neq 0$$

Experimental $\beta\beta$ observables



Energy spectrum of two emitted electrons (both $\beta\beta$ modes shown, can be distinguished with good $\Delta E/E$)

Charged daughter nucleus residing in detector after $0\nu\beta\beta$ event



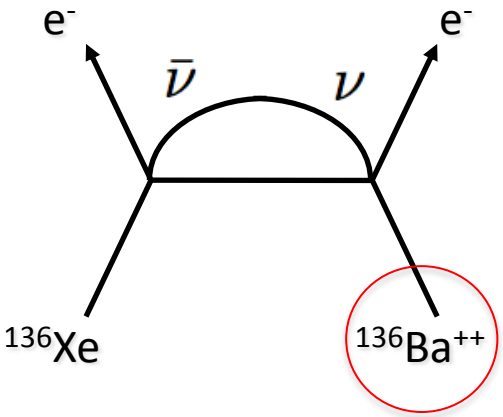
Experimental $0\nu\beta\beta$ sensitivity

$$T_{1/2}^{0\nu\beta\beta} \propto \varepsilon \frac{a}{A}\sqrt{\frac{MT}{B\Gamma}}$$

ε Efficiency
a isotopic abundance
A atomic mass
M source mass
T observation time
B background
Γ energy resolution

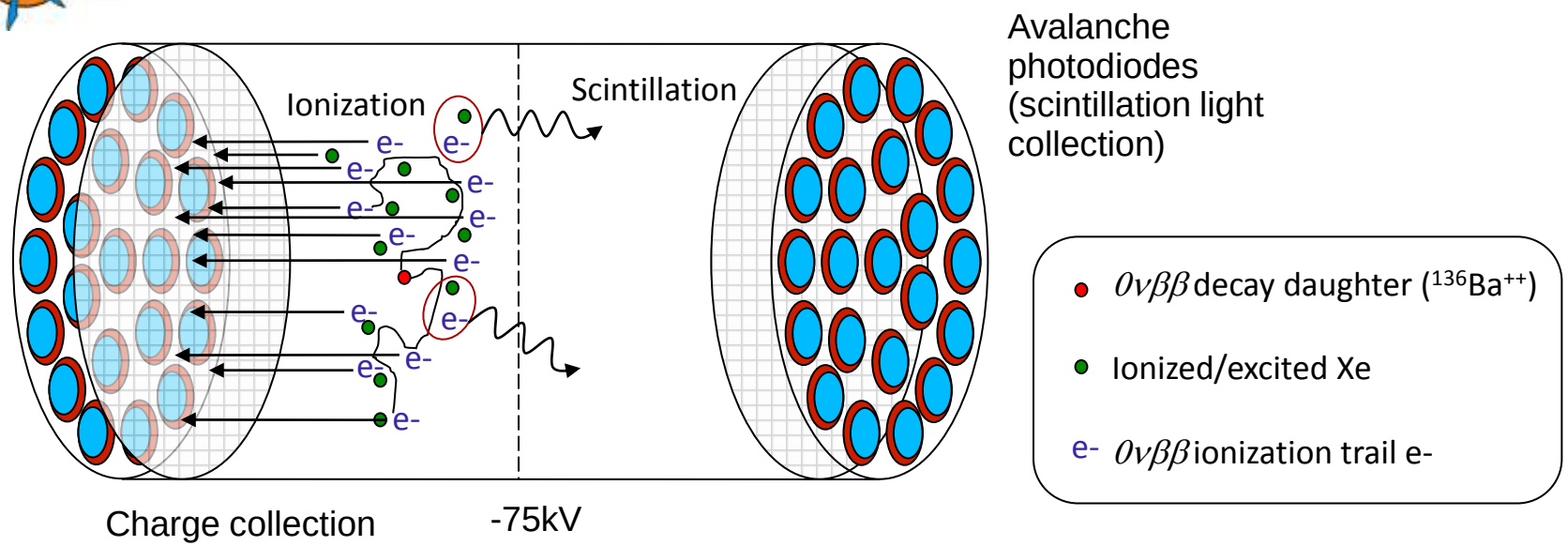
To maximize sensitivity:

- large mass
- low backgrounds
- high detection efficiency
- good energy resolution



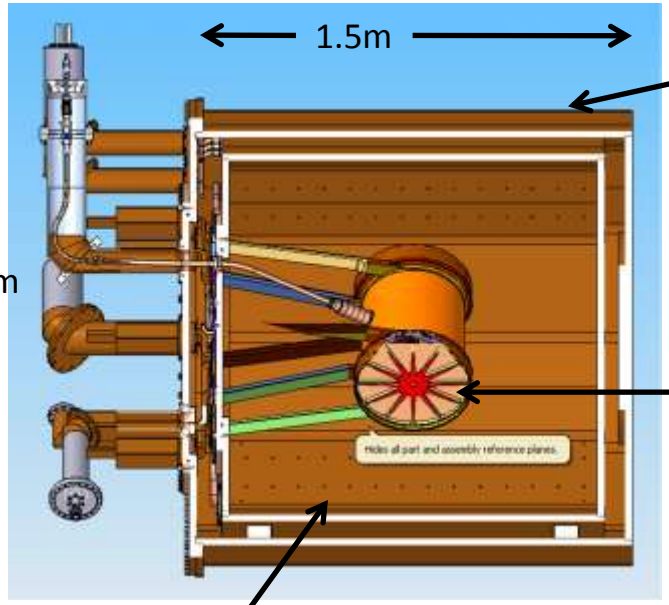
Additionally, identification of the daughter isotope would reject most sources of background and confirm $0\nu\beta\beta$ on a single event basis.

Measuring $0\nu\beta\beta$ with EXO-200



- 200kg ^{136}Xe (80% enrichment) liquid phase (-113° C), both source and detector of $0\nu\beta\beta$
- $Q_{\beta\beta}^{Xe-136}$ ~ 2.5 MeV $\beta\beta$ endpoint energy
- $0\nu\beta\beta$ electrons deposit energy as charge (slow) and scintillation (fast)
- Collect scintillation on APDs
- Collect ionization on wires -> charge preamplifiers
- Energy reconstruction, PID, from ionization+scintillation ($\Delta E/E$ = 1.4% at $Q_{\beta\beta}$)
- Event position from charge distribution and t_{SCINT}-t_{ION} (useful for Ba tagging on full EXO)

EXO-200 TPC and cryostat

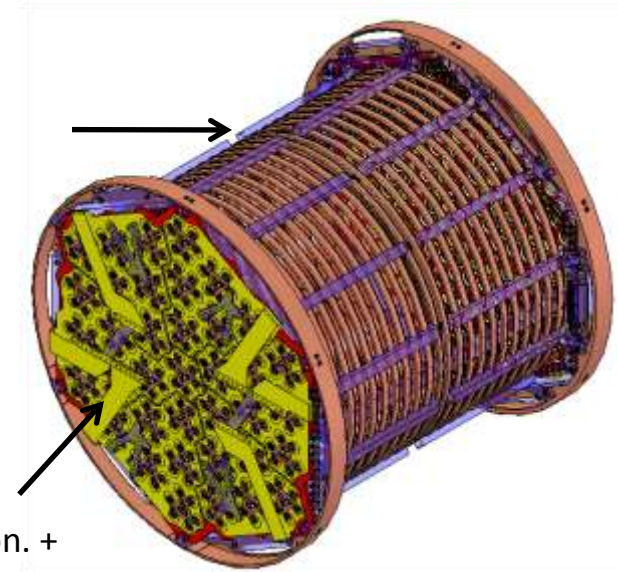


Outer cryostat

TPC

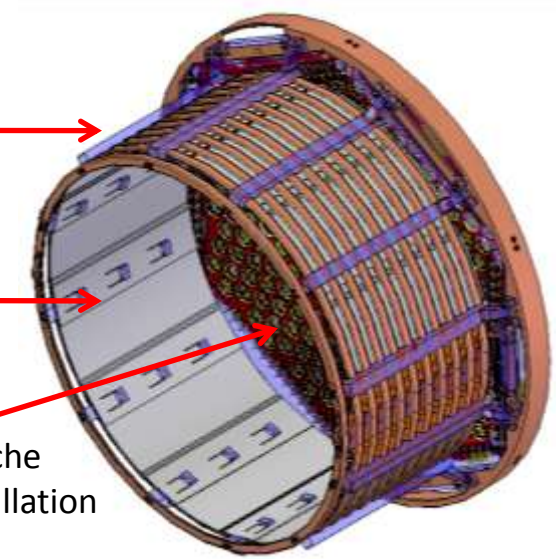
Inner cryostat filled with 50 cm HFE7000 cooling/shielding fluid (~ 1.8 g/cm^3 at 170 K)

Central HV plane (photoetched phosphor bronze)



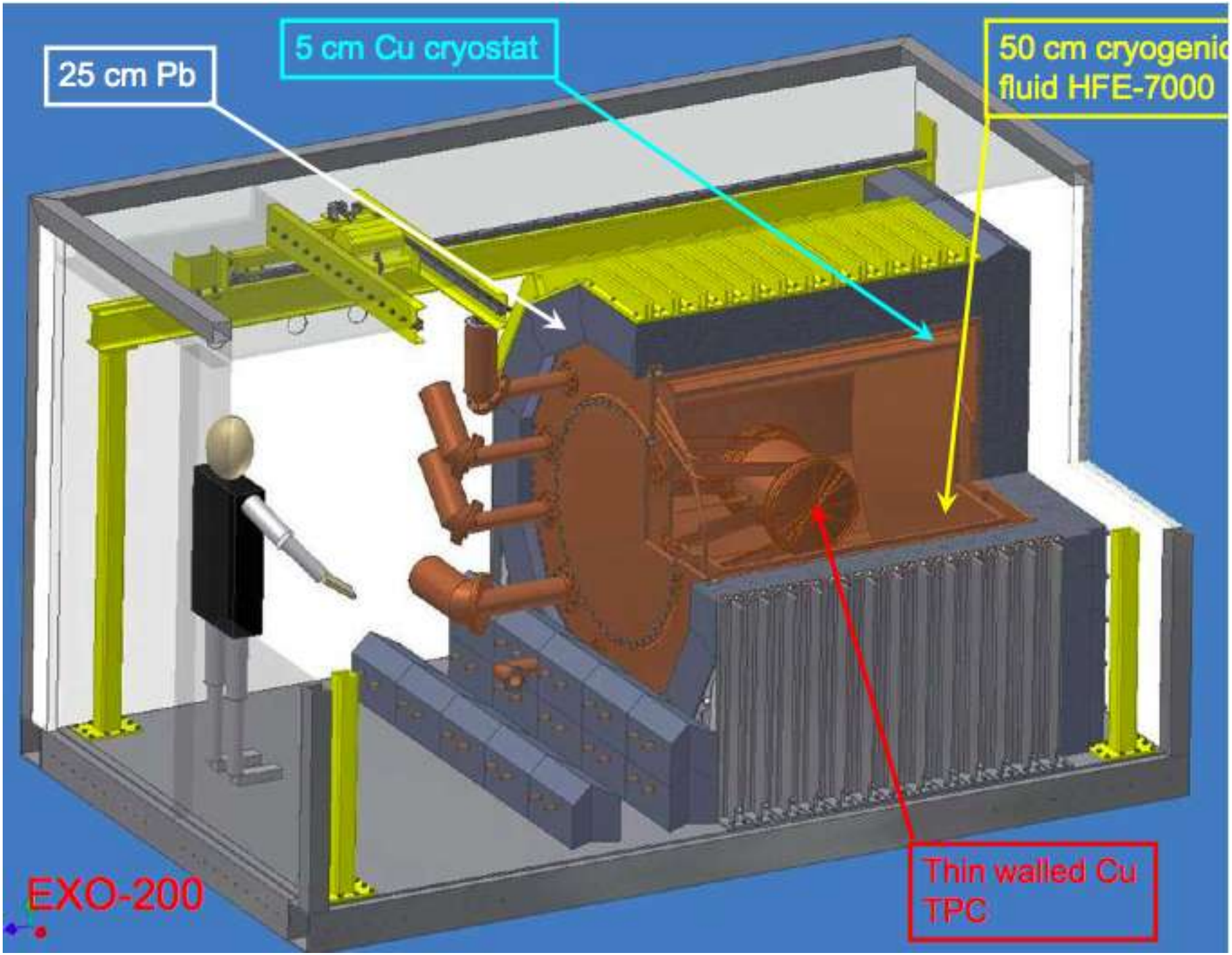
Custom kapton signal cables (ion. + scint. readout)

Acrylic supports and field shaping rings



Teflon light reflector

APD plane (avalanche photodiodes, scintillation detection)


25 cm Pb
5 cm Cu cryostat
50 cm cryogenic fluid HFE-7000
Thin walled Cu TPC
EXO-200

Shielding

- Shielding MUCH HARDER for $0\nu\beta\beta$ 2.5 MeV electromagnetic signal than for low energy nuclear recoil DM search
- *Thin walled ~ 1.4 mm thick Cu TPC* surrounded by
  - 4000kg HFE7000 (~50 cm), density ~ 1.4 g/cm^3
  - 25 cm Pb shielding on all sides
- For comparison with DM experiments, assume N-ton spherical LXe $0\nu\beta\beta$ detector, using 50% LXe for shielding

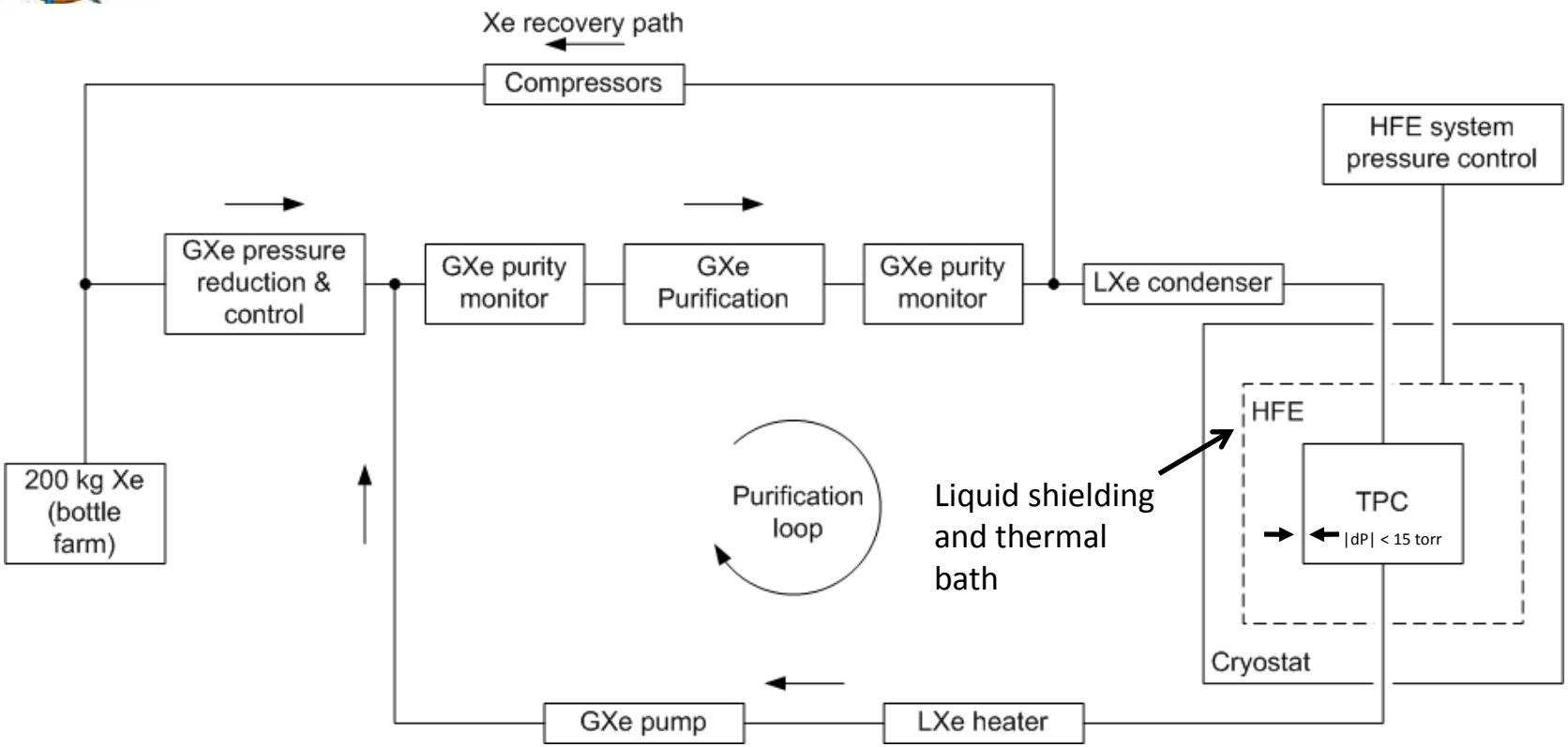
Incident γ energy	γ attenuation factor (1-ton spherical LXe)	γ attenuation factor (10-ton spherical LXe)
100 keV	36	2200
2.5 MeV	1.08	1.2

EXO-200 material screening

- Stringent requirements on K/Th/U concentrations on materials inside cryostat
- Large-scale materials testing, published in *Nucl. Instr. and Meth. A 591 (2008) 490–509*
- In particular:

Component	K 10^{-9} g/g	Th 10^{-12} g/g	U 10^{-12} g/g	^{210}Po Bq/kg
3M Novec HFE-7000, 1-methoxyheptafluoropropane	<1.08	<7.3	<6.2	
Lead shielding	<7	<1	<1	17-20
Copper	<55	<2.4	<2.9	
Acrylic	<2.3	<14	<24	
TPC grid wires	<90	47 +/- 2	320 +/- 2	

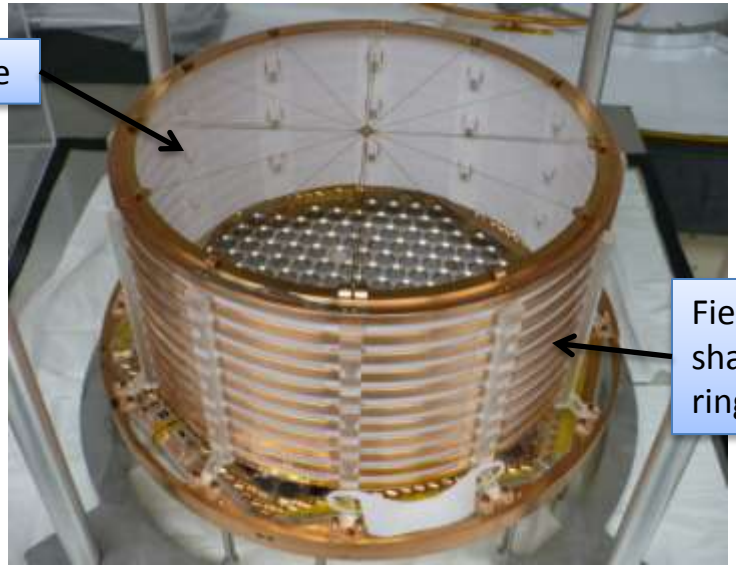
EXO-200 Xe handling system: designed around 1.4mm thin-walled TPC, constant purification



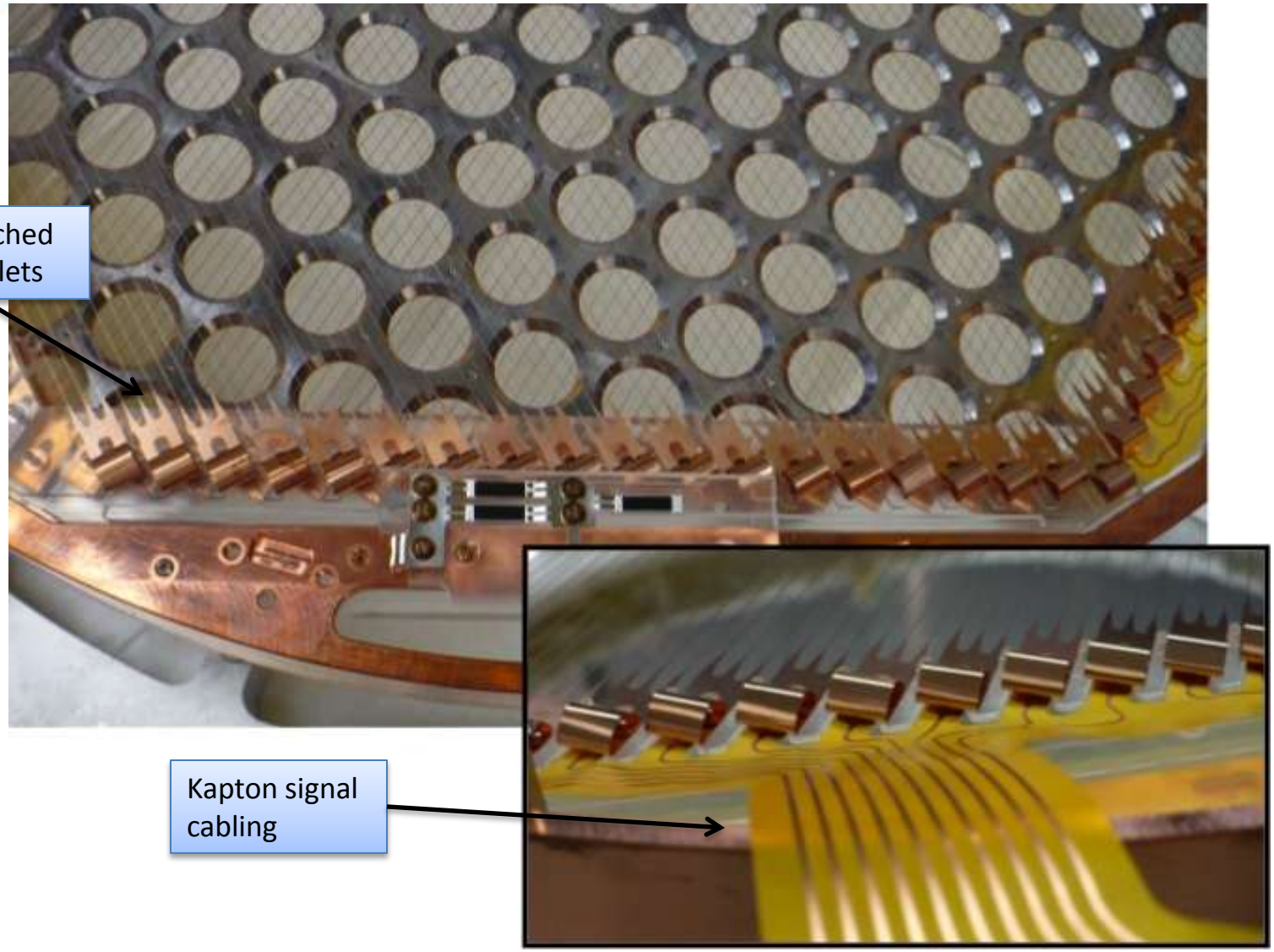
Design goals:

1. 20 SLPM circulation rate for continuous purification (uses heater, pump, condenser) while TPC full
2. Continuous purification with commercial (SAES) getters
3. Continuous purity monitoring of circulating gas (GPMs – see A. Odian's talk on Wed.)
4. Differential pressure across TPC walls $|dP| = |P_{Xe}-P_{HFE}| < 15$ torr at all times, due to thin-walled (~ 1.5mm) TPC construction (driven by radiopurity requirements)
5. Xe recovery to bottle farm with compressors
6. Triply redundant cryocooling system (3x Polycold refrigerators)

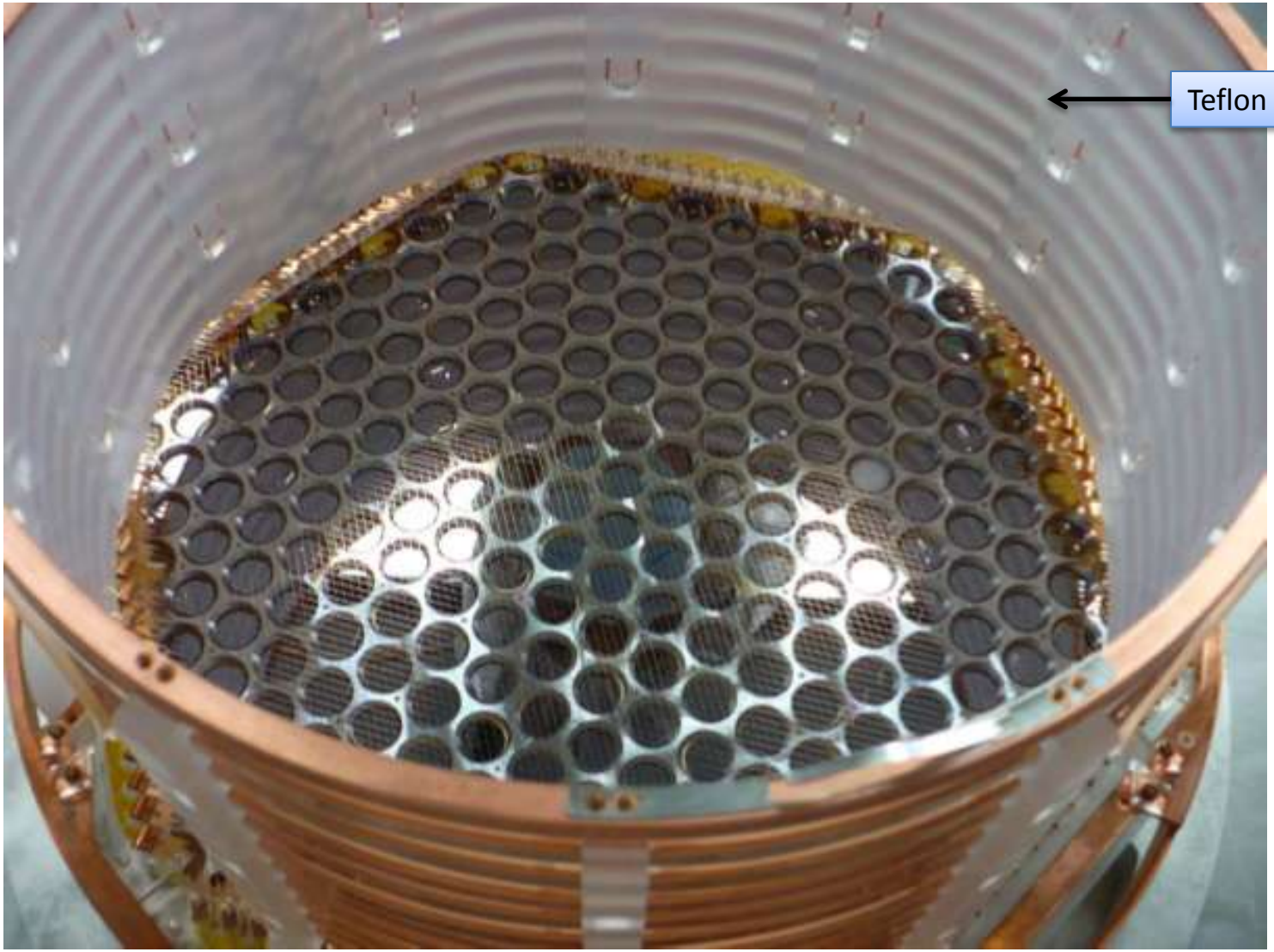
EXO-200 detector construction



EXO-200 crossed ionization collection wires



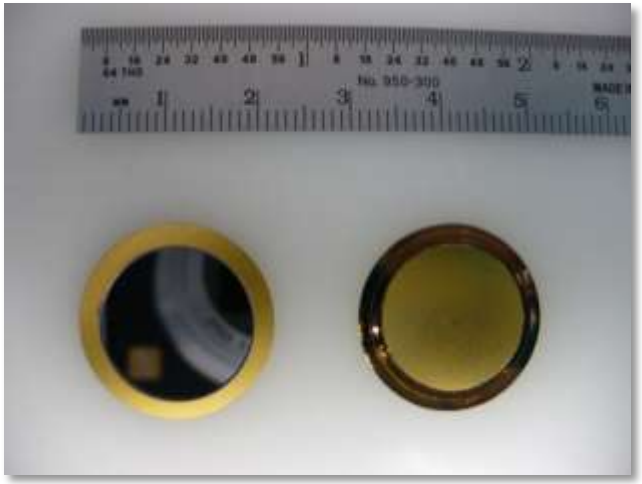
Looking into EXO-200 detector without APDs



EXO-200 LAAPD specs

- Mass ~ 0.5 g/LAAPD
- Low radioactivity construction (used bare, no window, no ceramic, EXO-supplied chemicals & metals)[a]
- QE > 1 at 175 nm (NIST)
- Gain set at 100-150
- V ~ 1500V
- $\Delta V < \pm 0.5V$
- $\Delta T < \pm 1K$ APD is the driver for temperature stability
- Leakage current cold < 1μA
- Capacitance ~ 200 pF at 1400 V
- ϕ16 mm active area per LAAPD

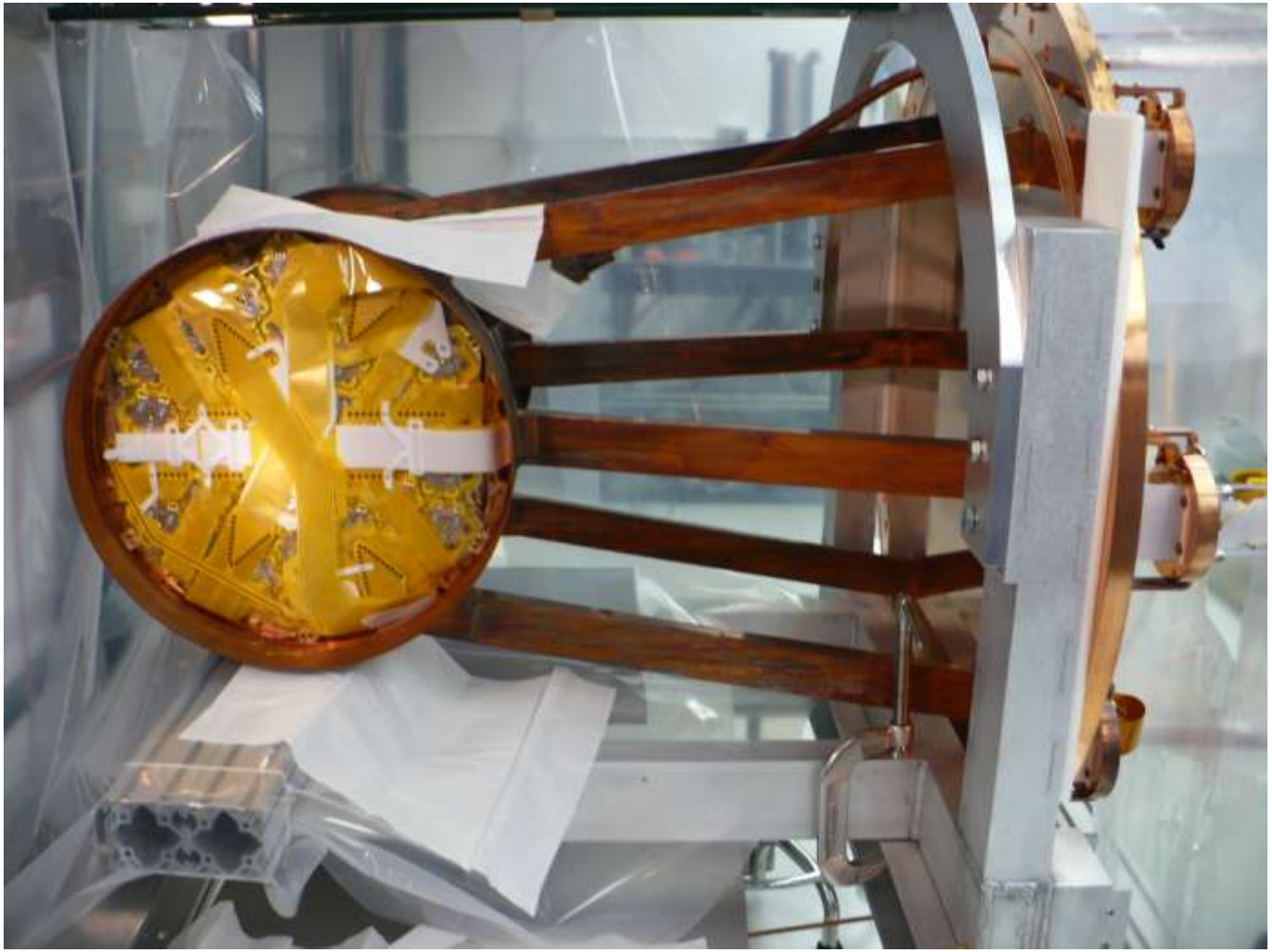
[a] D. S. Leonard, et al., Nucl. Instr. and Meth. A 591 (2008) 490-509



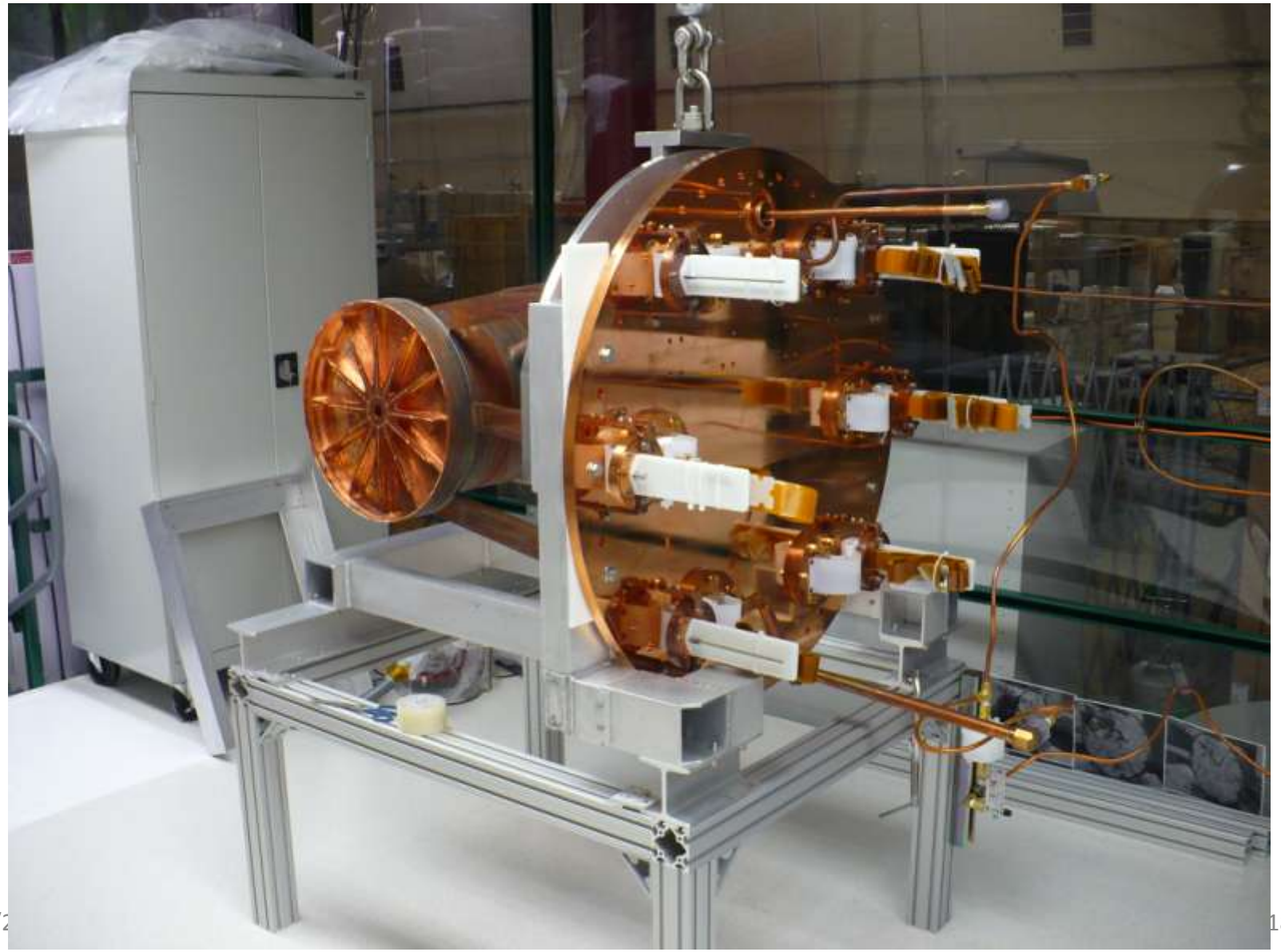
Neilson, R. et al., NIM A 608, 1 (2009)

EXO-200 APD installation

EXO-200 TPC after cable and APD installation, before final endcap welding

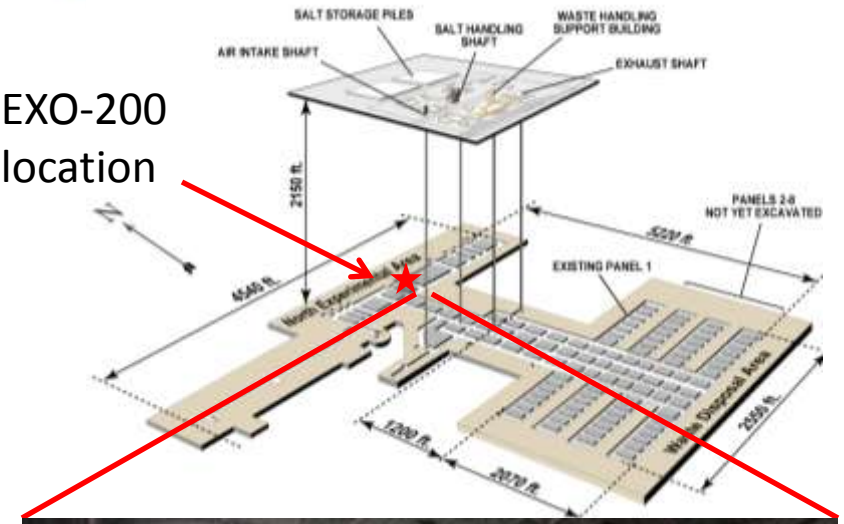


EXO-200 TPC ready for packaging at Stanford



EXO-200 installation site: WIPP

EXO-200 location



- EXO-200 installed at WIPP (Waste Isolation Pilot Plant), in Carlsbad, NM
- 1600 mwe flat overburden (2150 feet, 650 m)
- Salt mine for low-level radioactive waste storage
- Salt "rock" low activity relative to hard-rock mine

$$\Phi_\mu \sim 1.5 \times 10^5 \, yr^{-1} m^{-2} sr^{-1}$$

$$U \sim 0.048 \, ppm$$

$$Th \sim 0.25 \, ppm$$

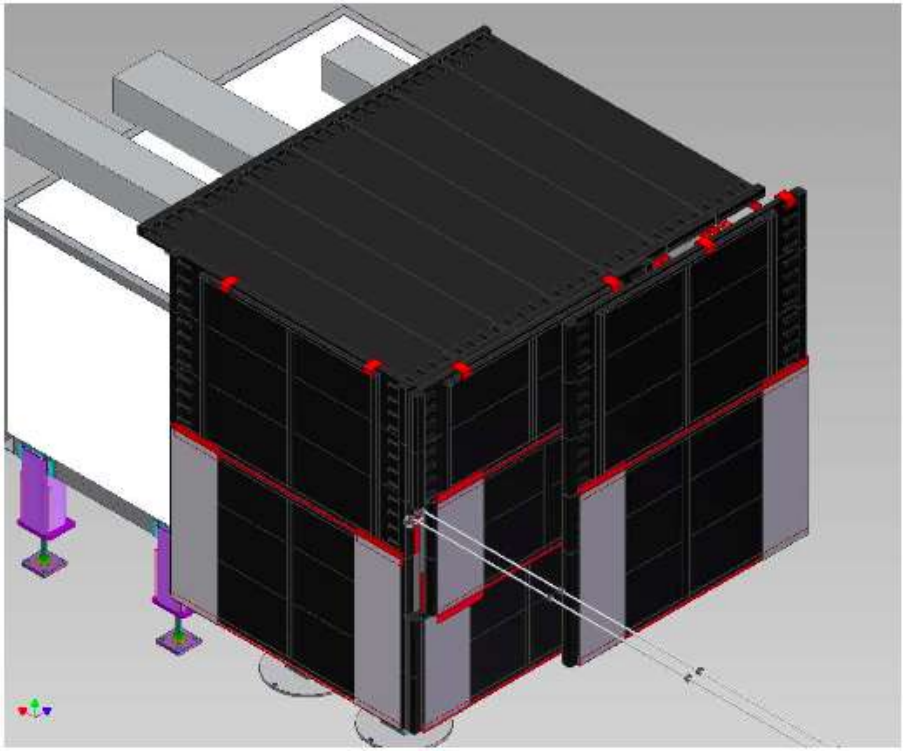
$$K \sim 480 \, ppm$$

Esch et al., arxiv:astro-ph/0408486 (2004)

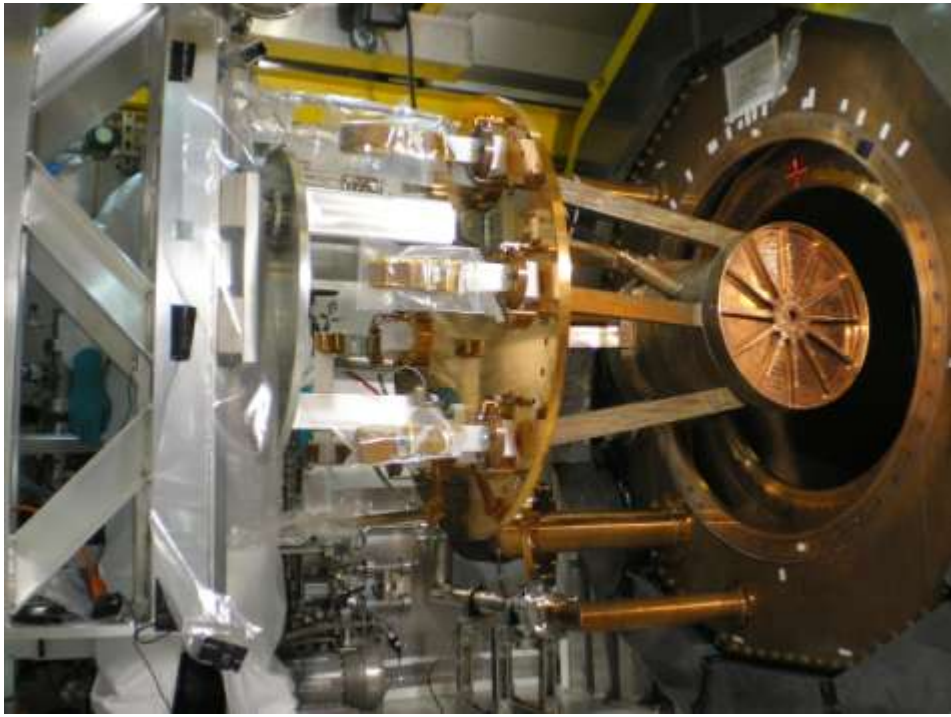
EXO-200 infrastructure

Active muon veto

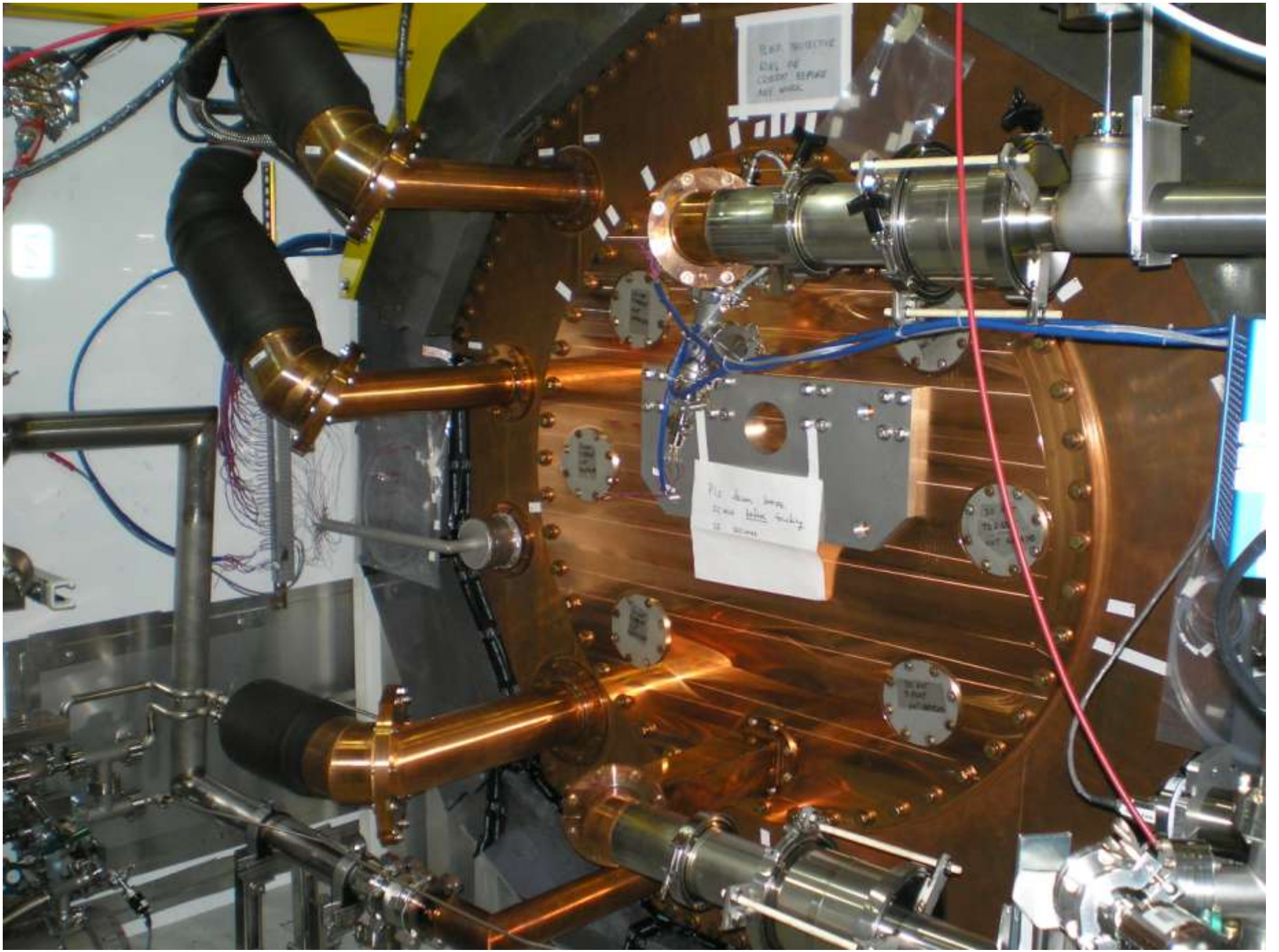
- Active muon veto system installed 2009
- Testing and integration into DAQ underway



TPC arrival & installation at WIPP



- TPC shipped from Stanford to WIPP 11/2009 in shielded container
- TPC installed in cryostat 12/2009
- LXe line re-hookup, followed by DAQ testing at WIPP
- Natural Xe run scheduled to begin late-2010



EXO-200 Majorana mass $<m_{\beta\beta}>$ sensitivity

Assumptions

1. 200 kg of ^{136}Xe, 80% enrichment
2. Low but finite radioactive background: 20 events/yr in ±2σ interval around Q=2.481 MeV
3. Negligible background from $2\nu\beta\beta$ ($T_{1/2}$ > 1x10^{22} yr, Bernabei et al.)

Case	Mass [ton]	Efficiency [%]	Run time [yr]	σ_E/E @ 2.5 MeV [%]	Radioactive background [events]	$T_{1/2}^{0\nu\beta\beta}$ [yr, 90% CL]	Neutrino majorana mass [eV]	
							QRPA	NSM
EXO-200	0.2	70	2	1.6	40	6.4x10^{25}	0.135 (1)	0.109 (2)

If Klapdor's observations are correct, EXO-200, 2-yr runtime:

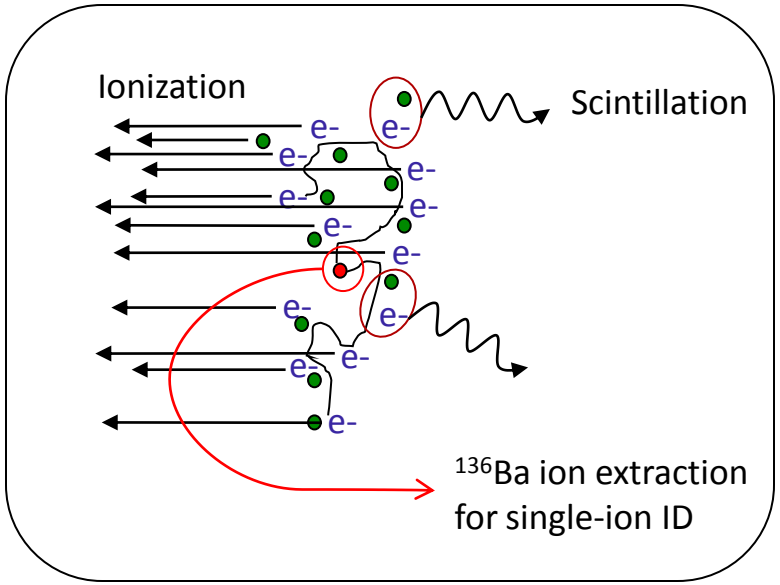
1. 46 events on top of 40 (QRPA) → 5σ measurement
2. 170 events on top of 40 (NSM) → 11.7σ measurement

(1) Simkovic et al. Phys. Rev. C79, 055501(2009) (use RQRPA and g_A = 1.25)
(2) Menendez et al., Nucl. Phys. A818, 139(2009) (use UCOM results)

Full EXO R&D

- Full EXO ~ ton scale gas or liquid TPC
- "Tagging" of $0\nu\beta\beta$ daughter nucleus ^{136}Ba ion for background rejection – R&D underway
  - Ion extraction from a TPC
  - Ion trapping
  - Ion identification with
    - Laser Induced Fluorescence (LIF)
    - Resonant ionization spectroscopy (RIS)
  - Single ion RIS
  - Others…
- GXe TPC R&D underway
  - 10 bar GXe TPC under construction
  - Test tracking, ionization+scintillation readout, $\Delta E/E$, Ba tagging interface, etc.

Full EXO $0\nu\beta\beta$ detection



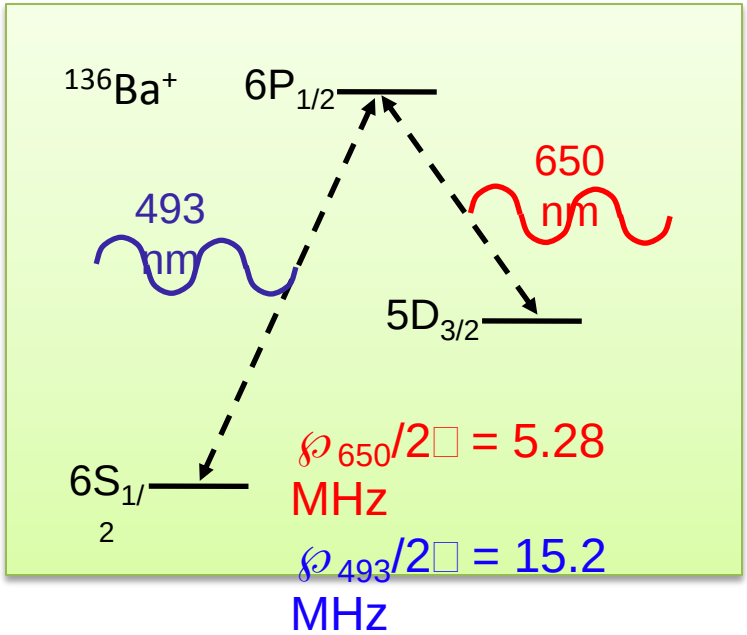
"Tagging" ^{136}Ba ion in real time may allow for rejection of all backgrounds except $2\nu\beta\beta$.

Single Ba^+ identification with Laser Induced Fluorescence

Goal: extract and ID single ^{136}Ba ions in real time from liquid or gas TPC for background rejection

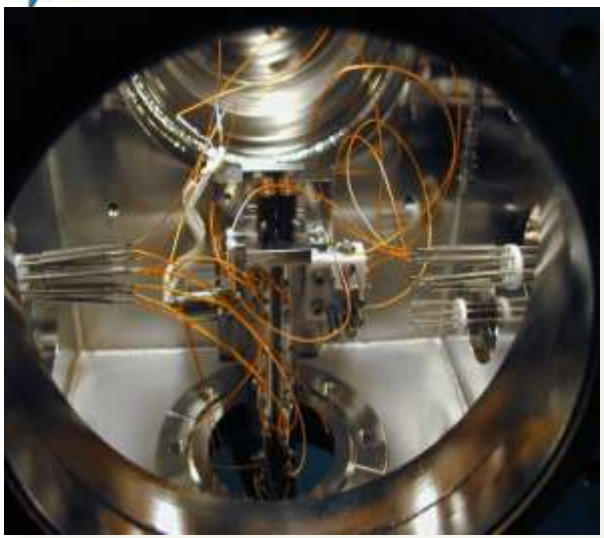
- $^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^-$
- $^{136}Ba^{++} \rightarrow {}^{136}Ba^+$ in LXe
- Isolate single ion in an ion trap
- Identification and dynamics of single Ba^+ in ion traps well studied [(1)]
- 493 nm, 650 nm lasers cycle trapped ion electronic states
- LIF ~10^7 photons/sec/ion into 4π

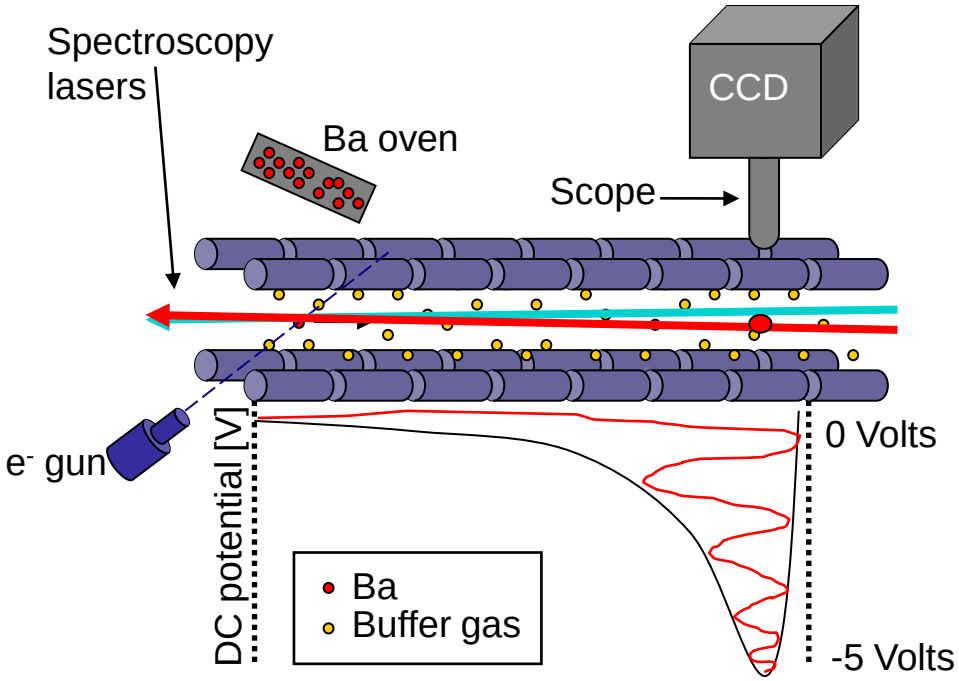
$^{136}Ba^+$ level structure

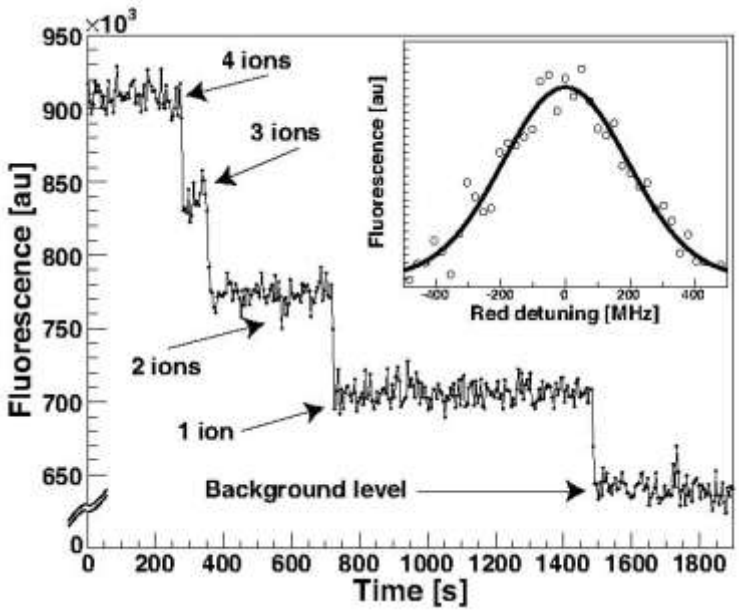


(1) H. Dehmelt et al. Phys. Rev. A 22, 1137 - 1140 (1980)

Single trapped Ba^+ in a gas-filled quadrupole ion trap



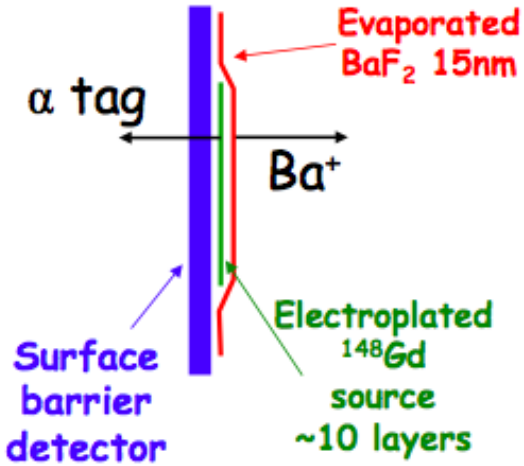




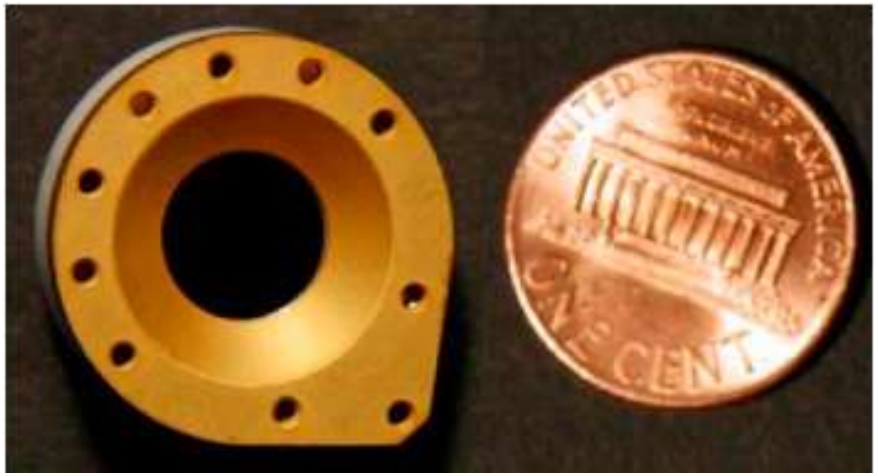
- Observed LIF of a single Ba^+ in a buffer gas filled ion trap (~ 10^{-3} torr He, some Xe)
- ~ 9σ observation at 25s storage time

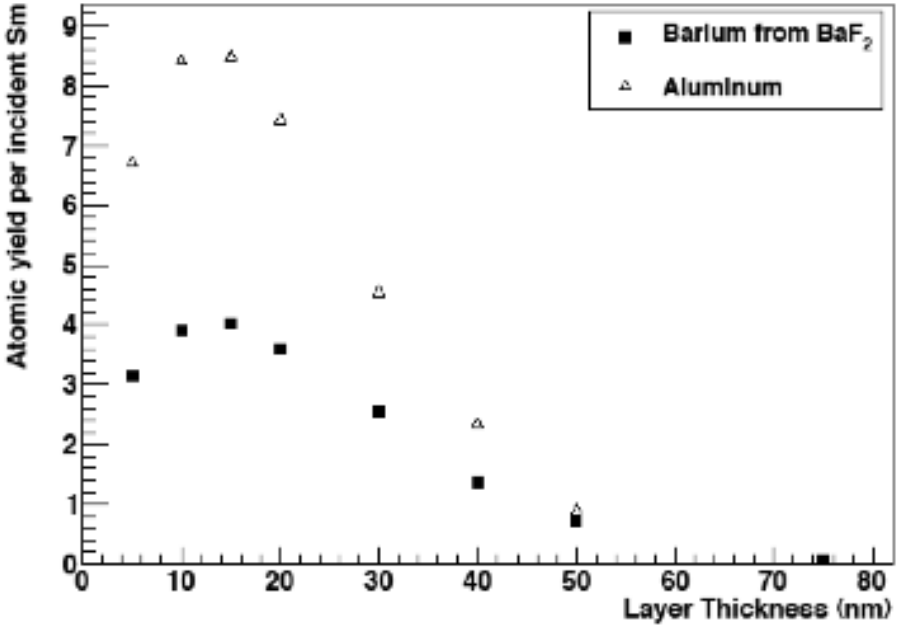
M.Green et al., Phys Rev A 76 (2007) 023404
B.Flatt et al., NIM A 578 (2007) 409

Ba^+/Ba^{++} single ion sources being developed



- Use recoils from a very thin α emitter (^{148}Gd) to dislodge Ba atoms from a carefully designed layer of BaF_2 (*arXiv:1008.3422*, accepted for publication in Rev. Sci. Instr.)
- A fraction of the Ba emitted is Ba^+
- Multiple sources under development





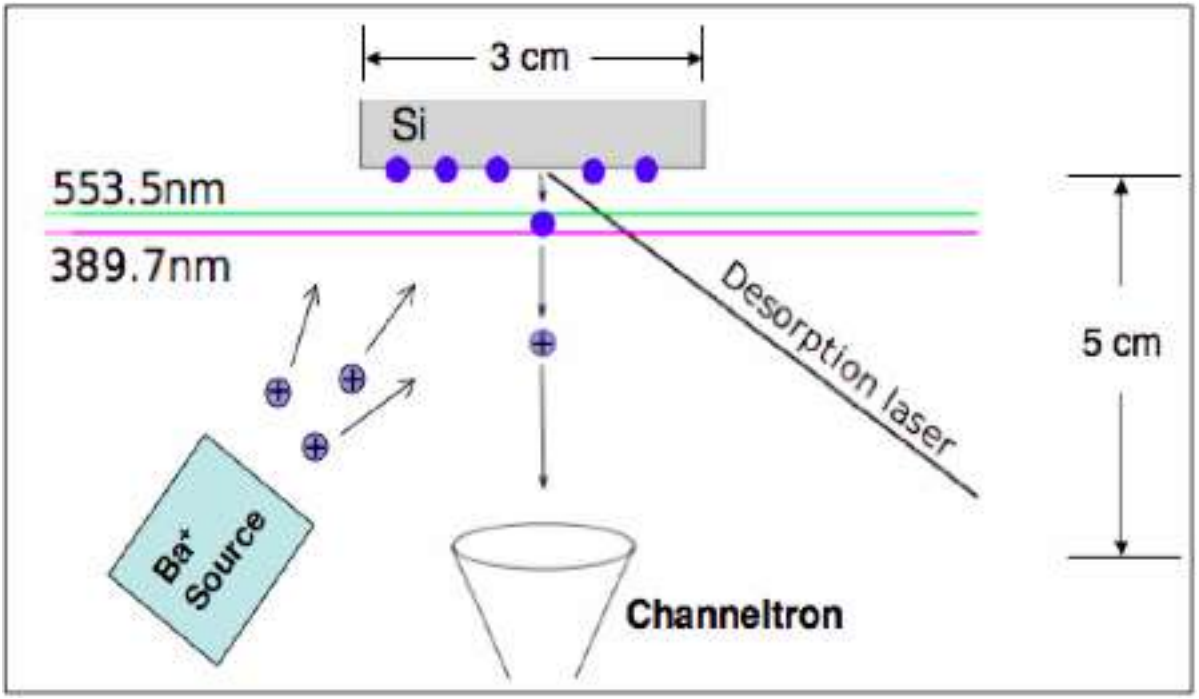
Ba transport & tagging by Resonant Ionization Spectroscopy

•Ba+ or Ba++ is electrostatically attracted (from LXe) onto a clean substrate (Si works well)

• Substrate is removed into vacuum

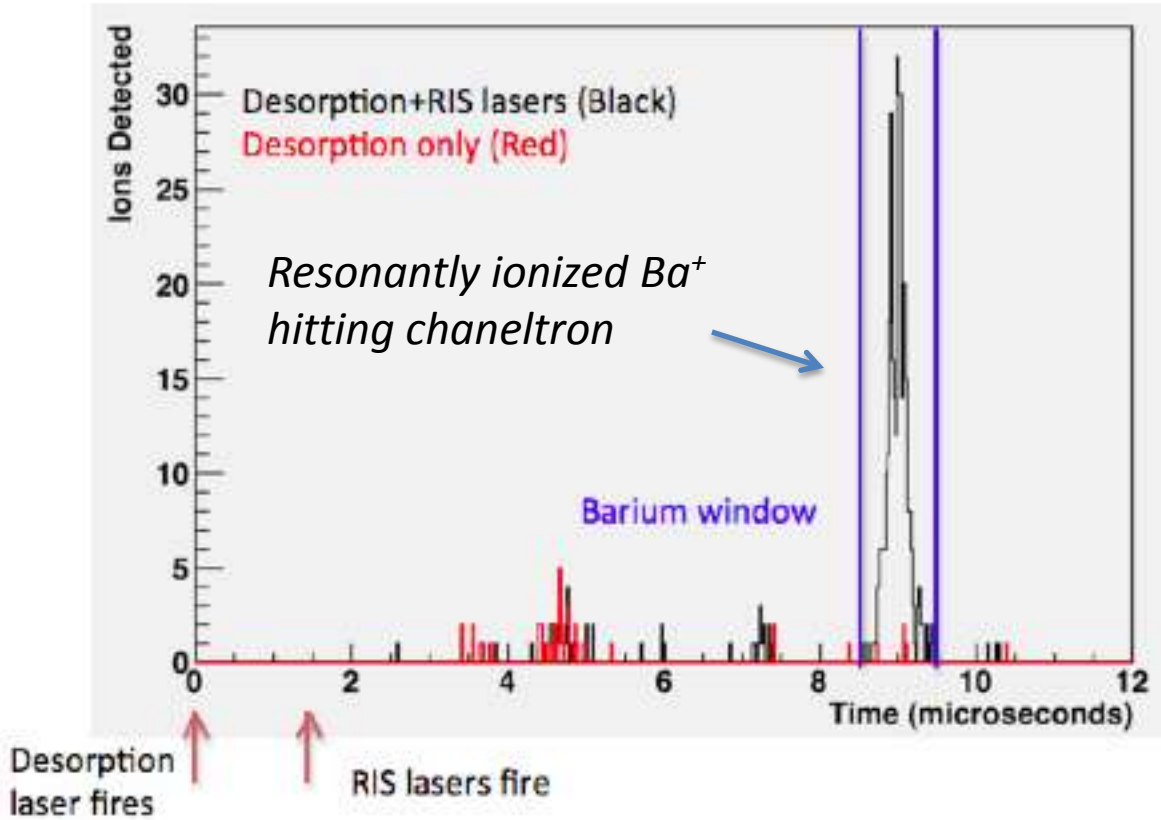
• 1064 nm YAG laser pulse desorbs Ba

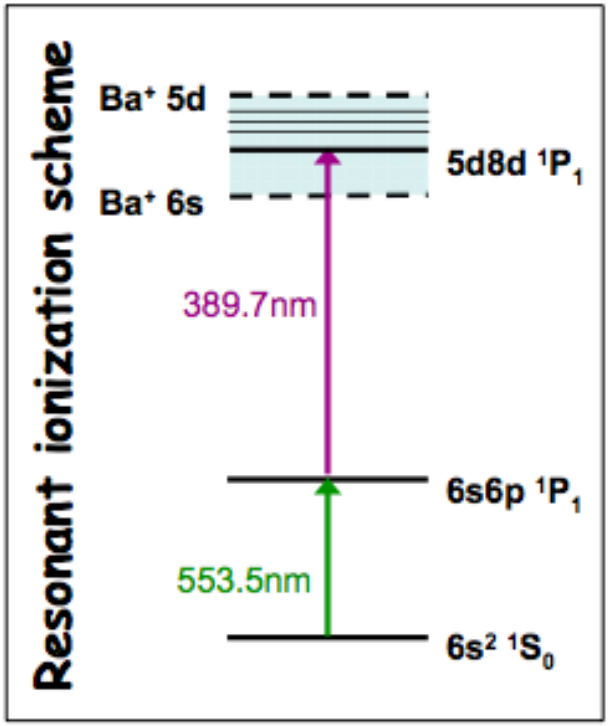
• ~ 1us later a pair of laser pulses of appropriate freq. re-ionize Ba+



• Current testing uses stationary substrate and Ba is deposited over time using the Gd-driven source (104-105 ions deposited)

TOF spectrum (data) from RIS test

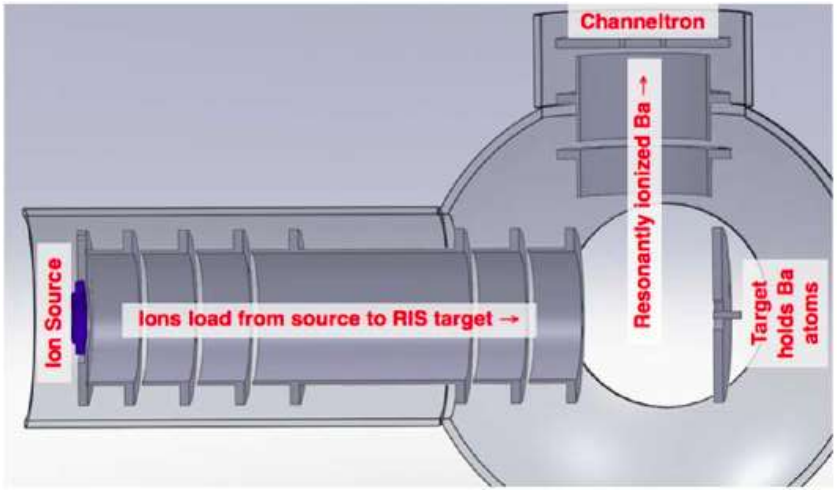


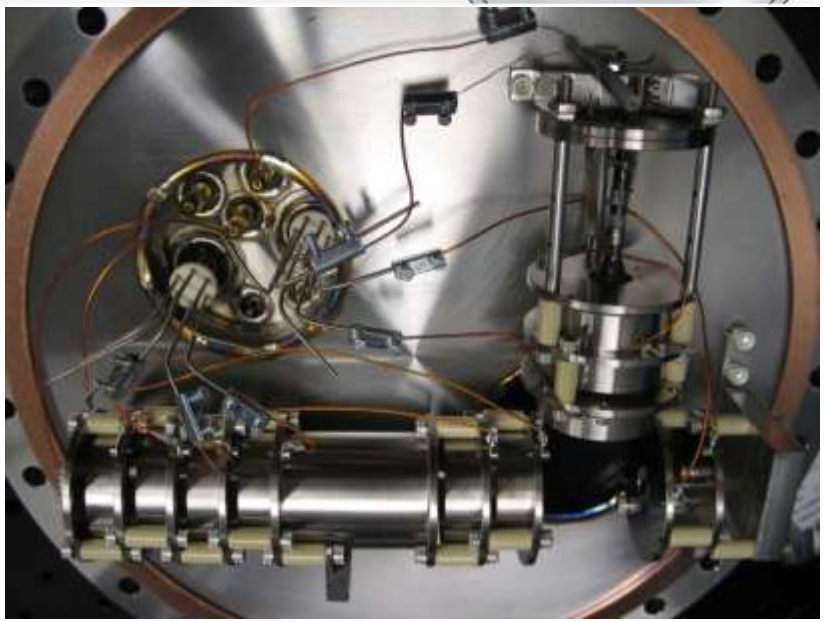


- Background already very small
- Efficiency > 10^{-3} (deposit 10^5, wait hrs., get > 100 out)
- This gives us a signal to tune on

Next step: do it one ion at a time

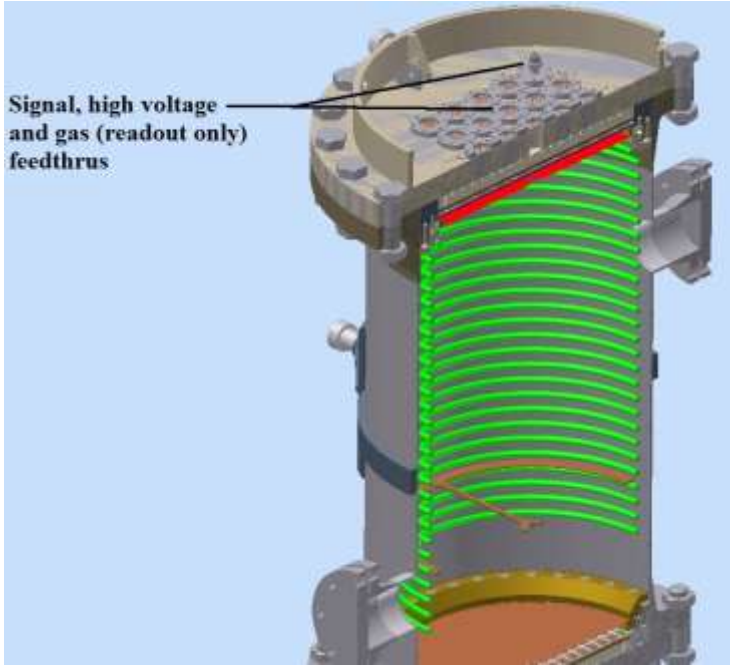
- High efficiency (~ 80%) ion optics (both injection and extraction)
- "Top hat" YAG beam (lower background)
- Only Ti and Si construction (lower background)
- Possibly no ion trap required
- *Many other Ba tagging fronts, but no time here*



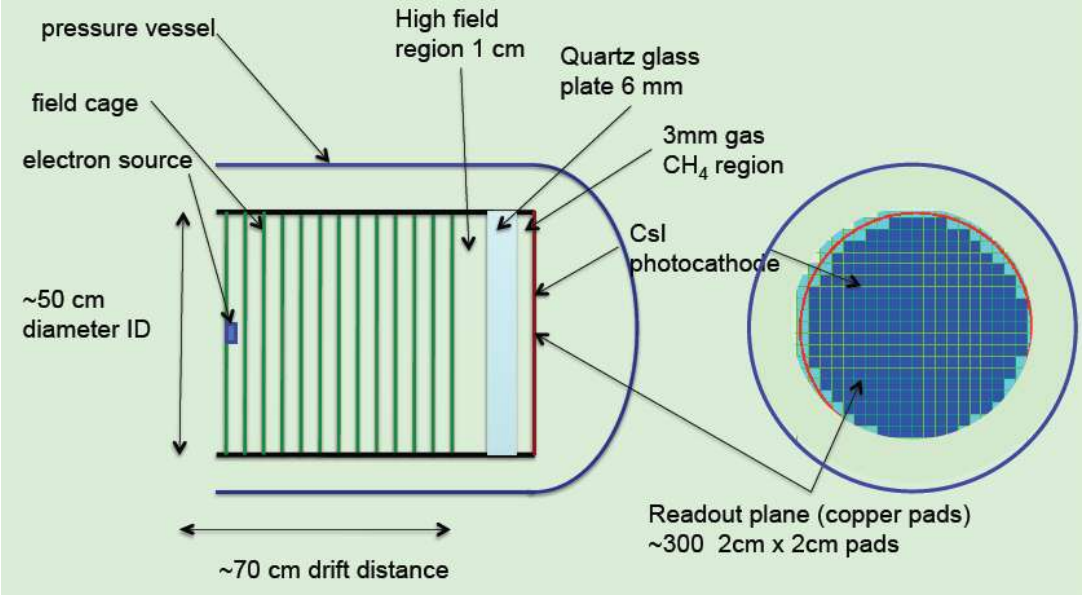


Full EXO GXe TPC R&D in progress

Goal: Test tracking, $\Delta E/E$, electronics,ionization + scintillation readout, Ba tagging interface in 1-10 bar GXe

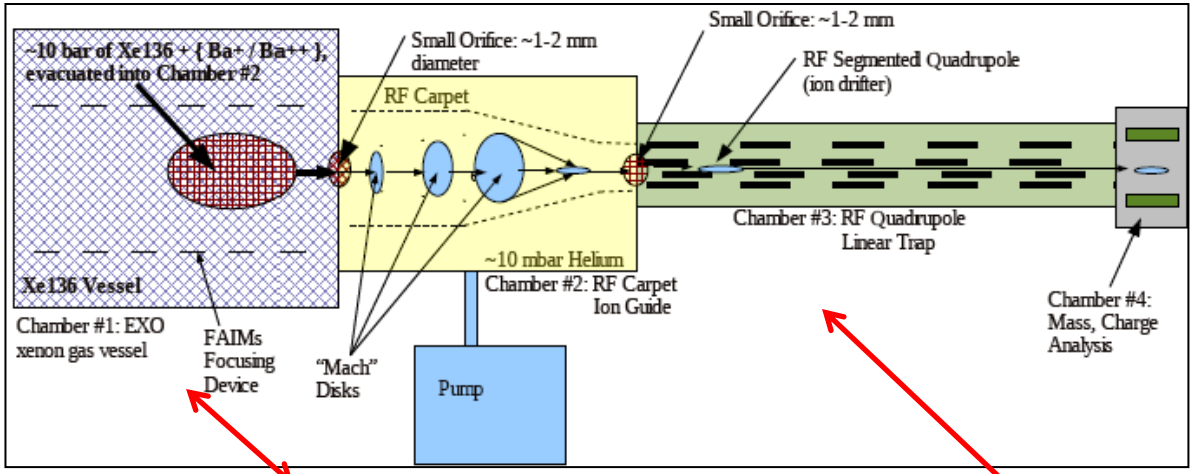


- 10 bar GXe cylindrical TPC
- 1 MeV e^- source
- Segmented readout (tracking) on both ends
- Electroluminescent gap + CsI photocathode for both charge and scintillation readout
- Replaceable endcaps for alternate charge/light readout technologies, Ba tagging interface



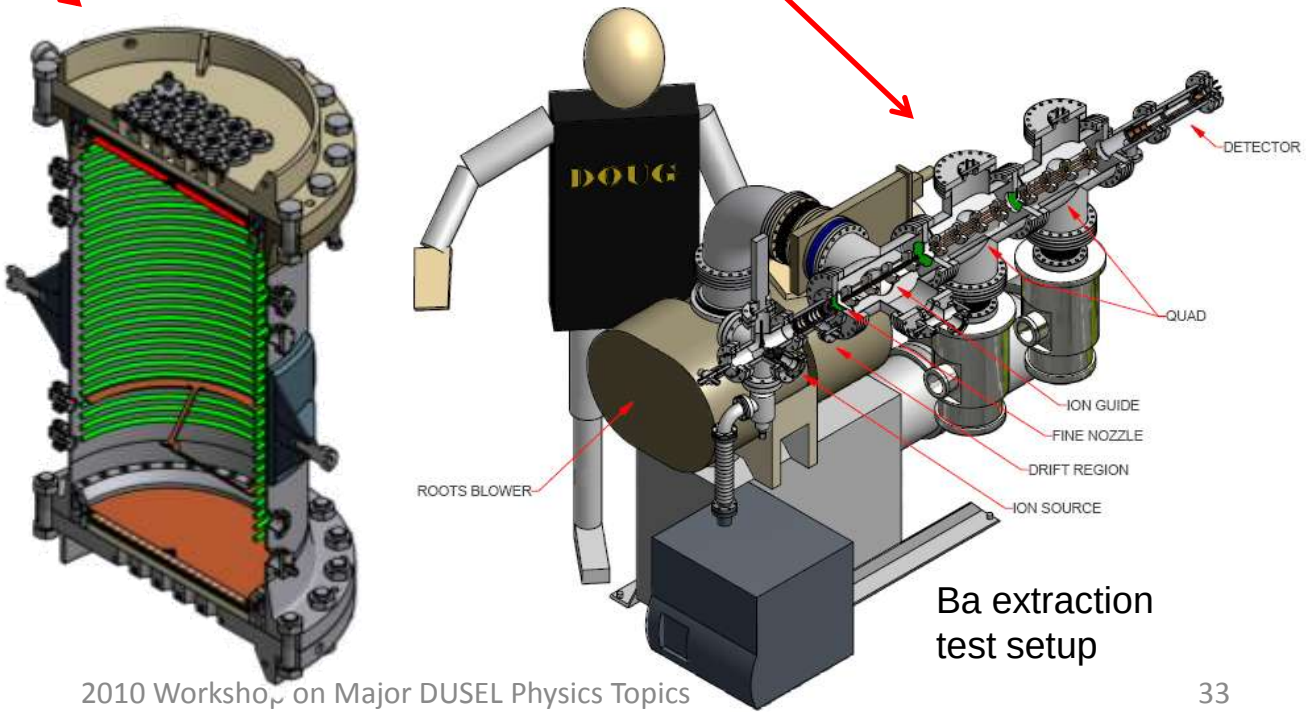
- Field cage length: 780 mm
- Field cage diameter: 535 mm

Coupling a quadrupole trap to a TPC



- Ion transport, stopping, through quadrupoles well known to heavy-ion nucl. phys.

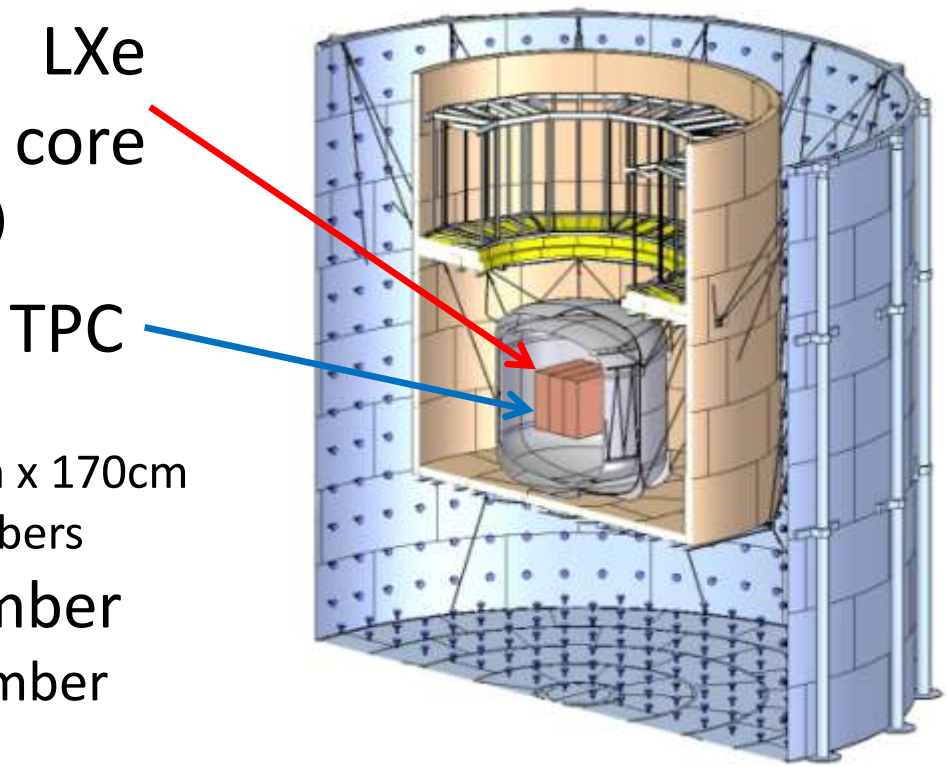
- Eventual goal is to test full pipeline efficiency for single ion extraction, ID



Ba extraction test setup

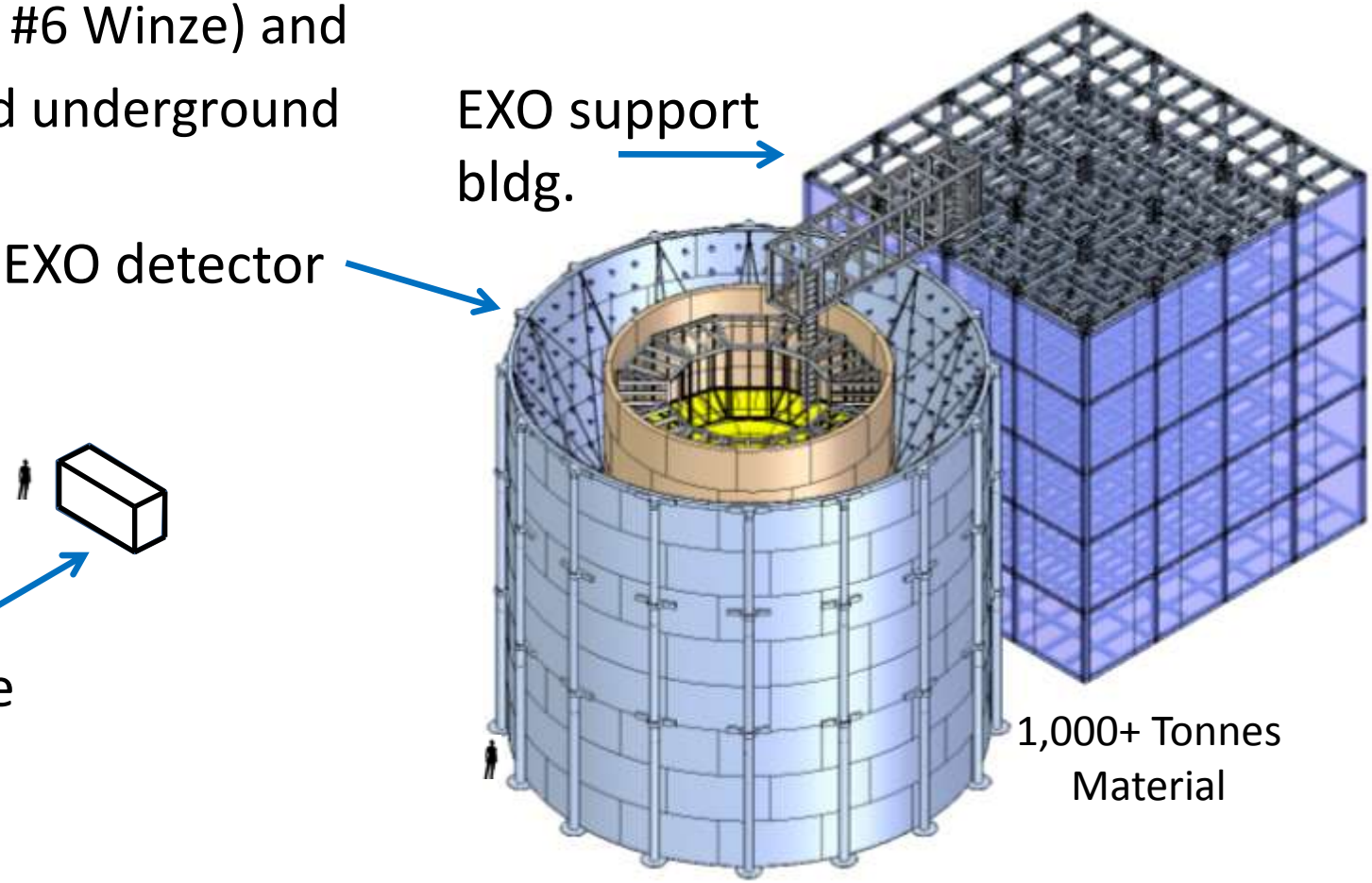
Full EXO conceptual design

- LXe core
  - Liquid Xenon (^{136}Xe)
    - Fiducial Mass = 10 Tonnes (overall geometry almost independent of fiducial mass)
    - Volume = 3,400 liters
    - Temperature = 165K
  - Cu vessel for LXe
    - Single vessel, 170cm x 160cm x 170cm
    - 3 equally sized internal chambers
- TPC – Time Projection Chamber
  - Central Cathode in each chamber
    - Max drift distance = 25cm
  - Ionization and scintillation readout
  - Coincidence measurement by identifying Ba^{++} Daughter

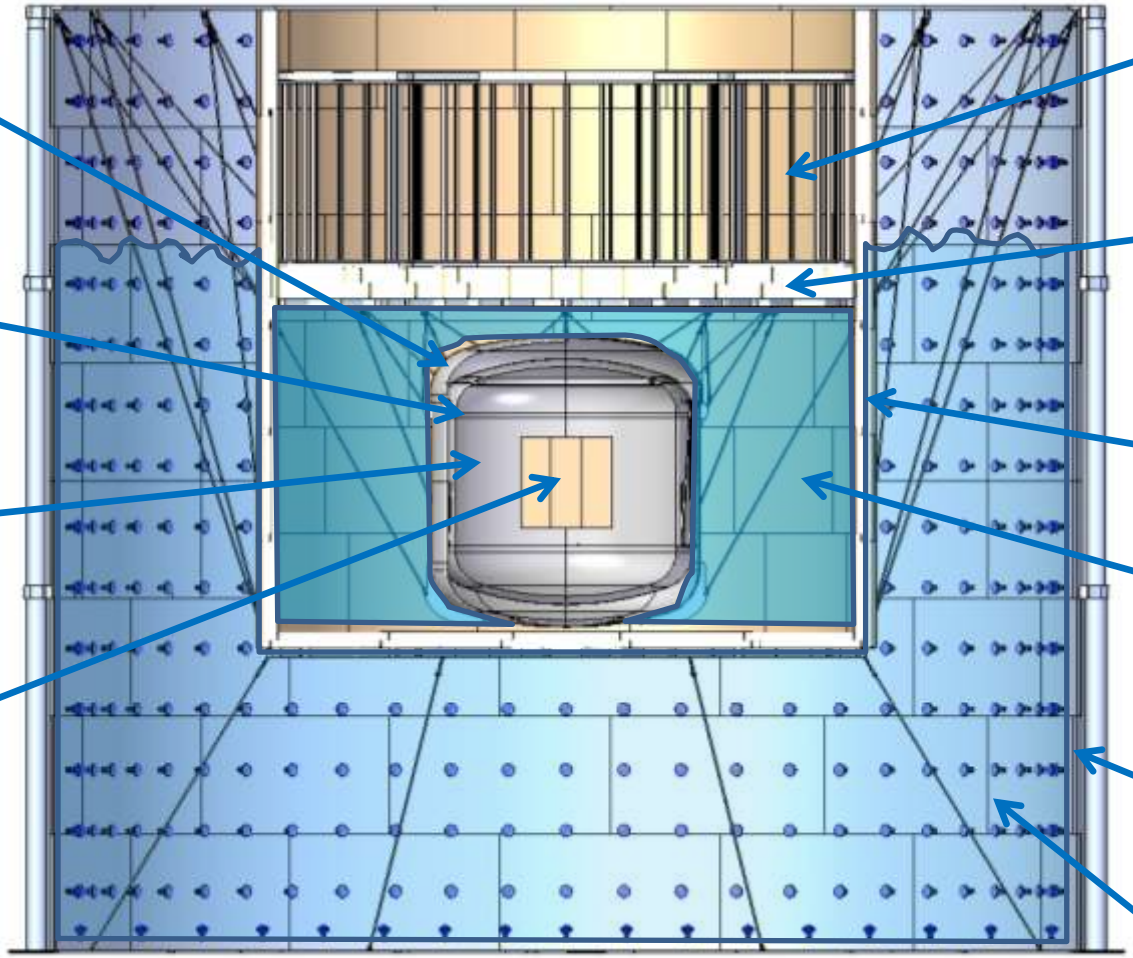


Full EXO conceptual design with shielding and infrastructure

- Because of conveyance system constraints at DUSEL, the EXO design must be made from smaller components (that fit inside the #6 Winze) and assembled underground



Full EXO TPC installation



Outer Cryo
19.1mm Ti
10Tonnes

Inner Cryo
6.35mm Ti
2Tonnes

HFE
70Tonnes

TPC
LXe/Cu
10+9Tonnes

Ba^{++} Tagging
10Tonnes

Lead Shield
0.5m Pb
430Tonnes

Inner Tank
0.25m HDPE
60Tonnes
320m^3 H_2O
320Tonnes

Outer Tank
12.7mm SS
110Tonnes
2,200m^3 H_2O
2,175Tonnes

Total Mass = ~711 Tonnes (not including H_2O)

EXO Majorana mass $<m_{\beta\beta}>$ sensitivity

Assumptions

1. ^{136}Xe, 80% enrichment
2. Intrinsic low backgrounds & Ba tagging eliminate all radioactive backgrounds
3. Energy resolution used to separate $0\nu\beta\beta$ from $2\nu\beta\beta$ modes (select 0ν events in +/- 2σ interval around 2.458 MeV endpoint)
4. $2\nu\beta\beta$ ($T_{1/2}$ > 1x10^{22} yr, Bernabei et al.)

Case	Mass [ton]	Efficiency [%]	Run time [yr]	σ_E/E @ 2.5 MeV [%]	$2\nu\beta\beta$ background [events]	$T_{1/2}^{0\nu\beta\beta}$ [yr, 90% CL]	Neutrino majorana mass [meV]	
							QRPA	NSM
Conservative	1	70	5	1.6(3)	0.5 (~1)	2.0x10^{27}	19 (1)	24 (2)
Aggressive	10	70	10	1.0(4)	0.7 (~1)	4.1x10^{28}	4.3 (1)	5.3 (2)

(1) Simkovic et al. Phys. Rev. C79, 055501(2009)) (use RQRPA and g_A = 1.25)
(2) Menendez et al., Nucl. Phys. A818, 139(2009) (use UCOM results)
(3) σ_E/E = 1.6% obtained in EXO R&D, Conti et al., Phys. Rev. B 68 (2003) 054201
(4) σ_E/E = 1.0% considered aggressive but realistic guess with large light collection

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