Flat cables for EXO-200

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AIS-SLAC - December 10, 2008

outline

- ***EXO-200 experiment***
  - the detector
  - low background requirements
  - cable design choice

- ***flat cables for EXO-200***
  - material selection
  - details of cable design

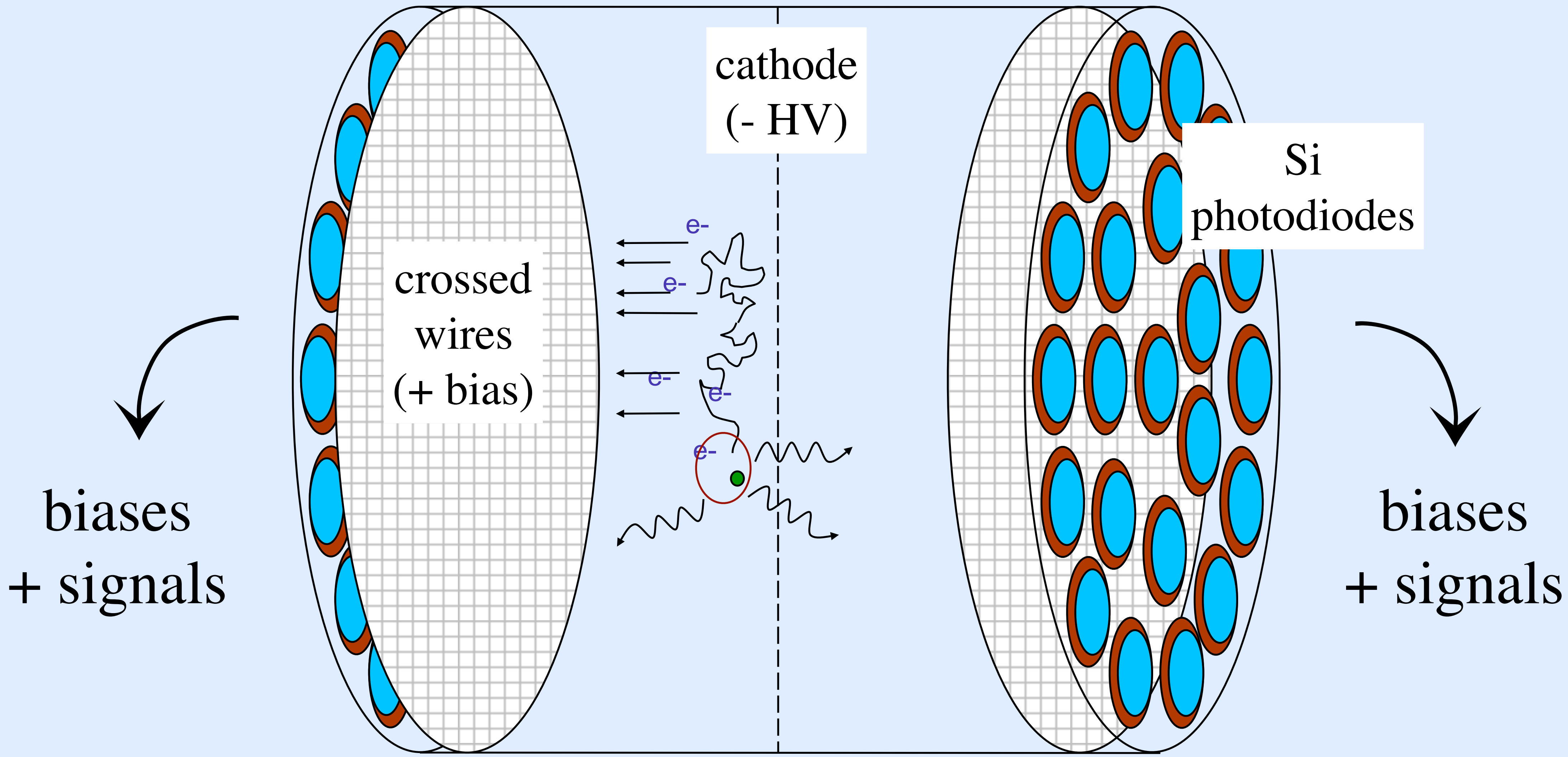
- ***flat cable fabrication and installation***
  - cable fabrication and handling
  - cable installation

- ***outlook***

EXO-200

EXO-200 is a large double beta decay experiment employing 200 kg of liquid, enriched xenon (80% ^{136}Xe) to look for neutrinoless double beta decay ($0\nu\beta\beta$) of ^{136}Xe

how: double TPC detector with scintillation light readout

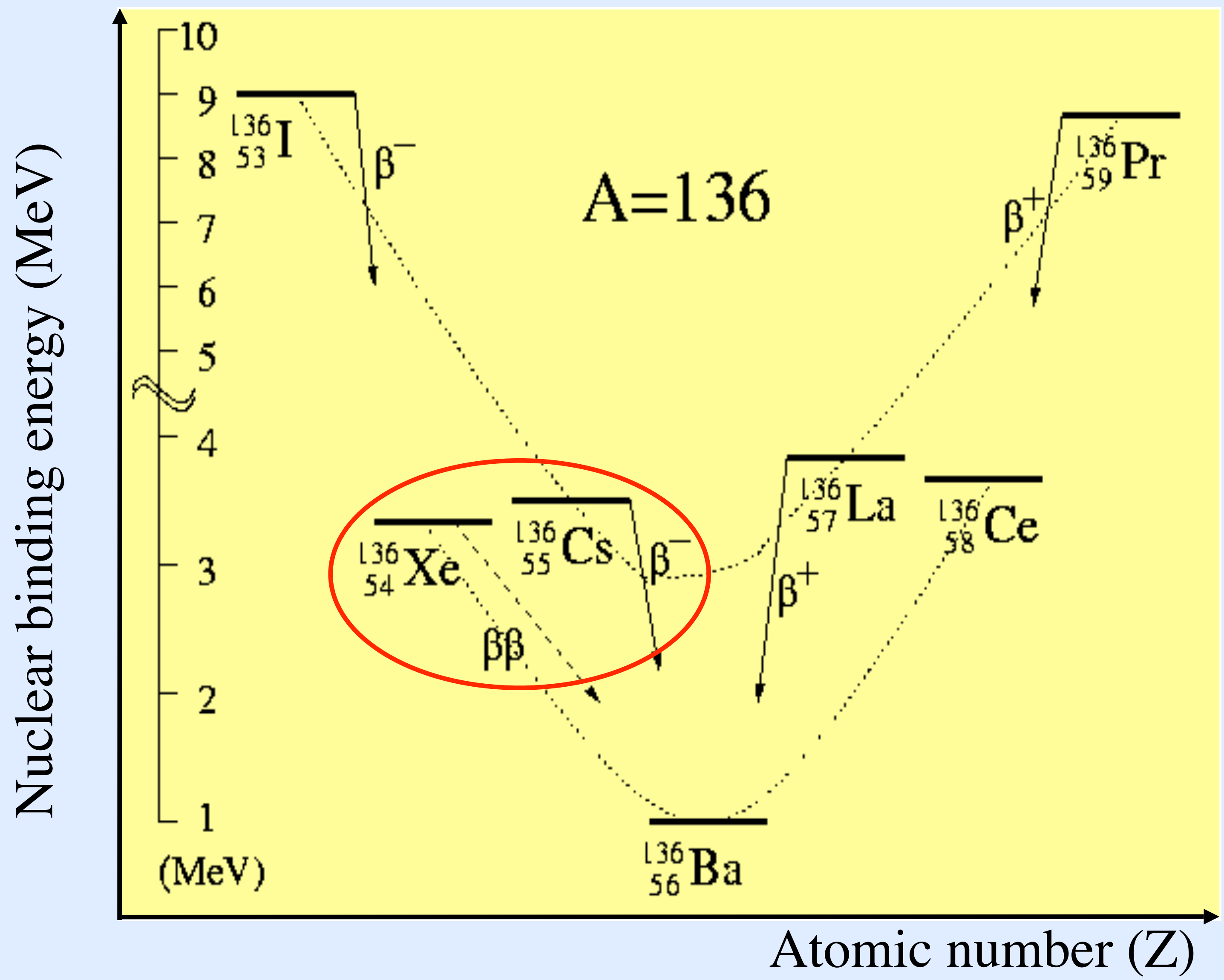


Double beta decay

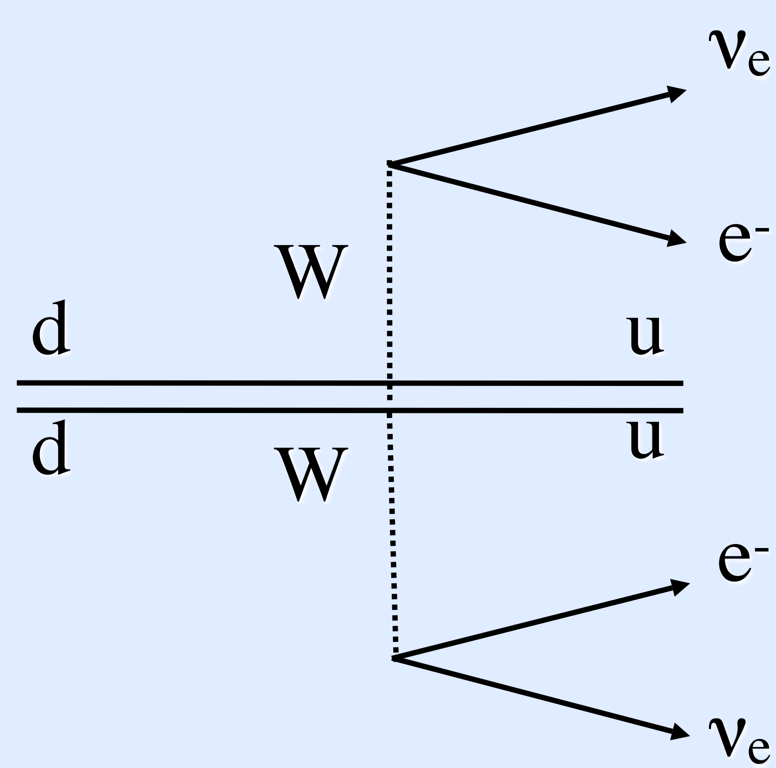
Extremely rare decay of certain nuclei, where 2 neutrons decay into 2 protons:

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

detectable in even-even nuclei when single β-decay is energetically forbidden



standard second order electro-weak process (2νββ):

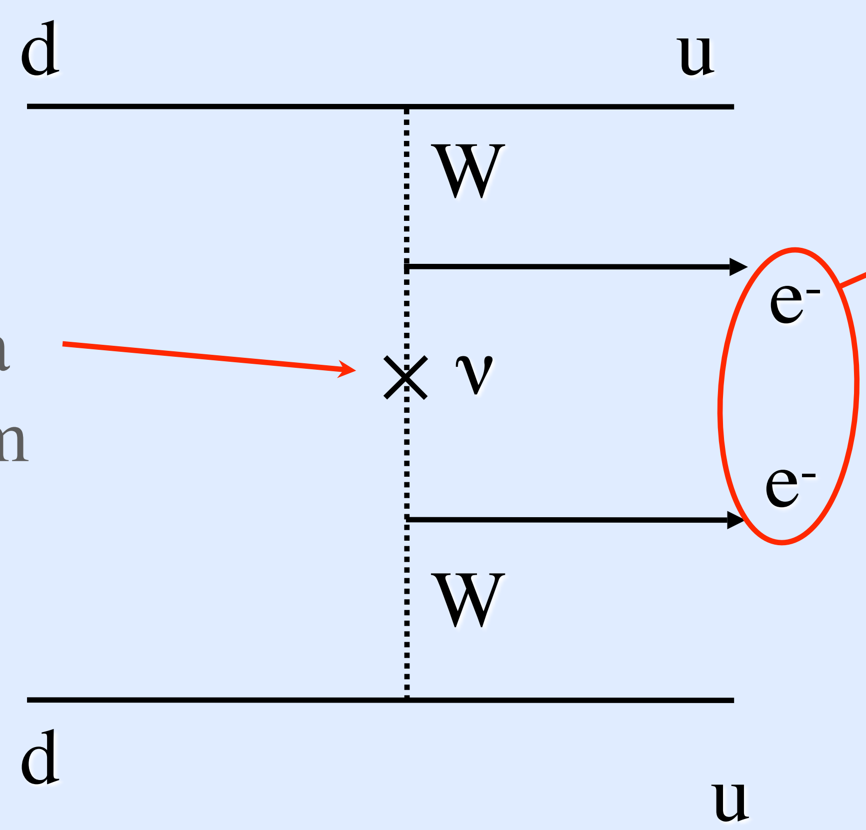


Double beta decay has not yet been observed for ^{136}Xe (lifetime limit at $\sim 10^{22}$ y)

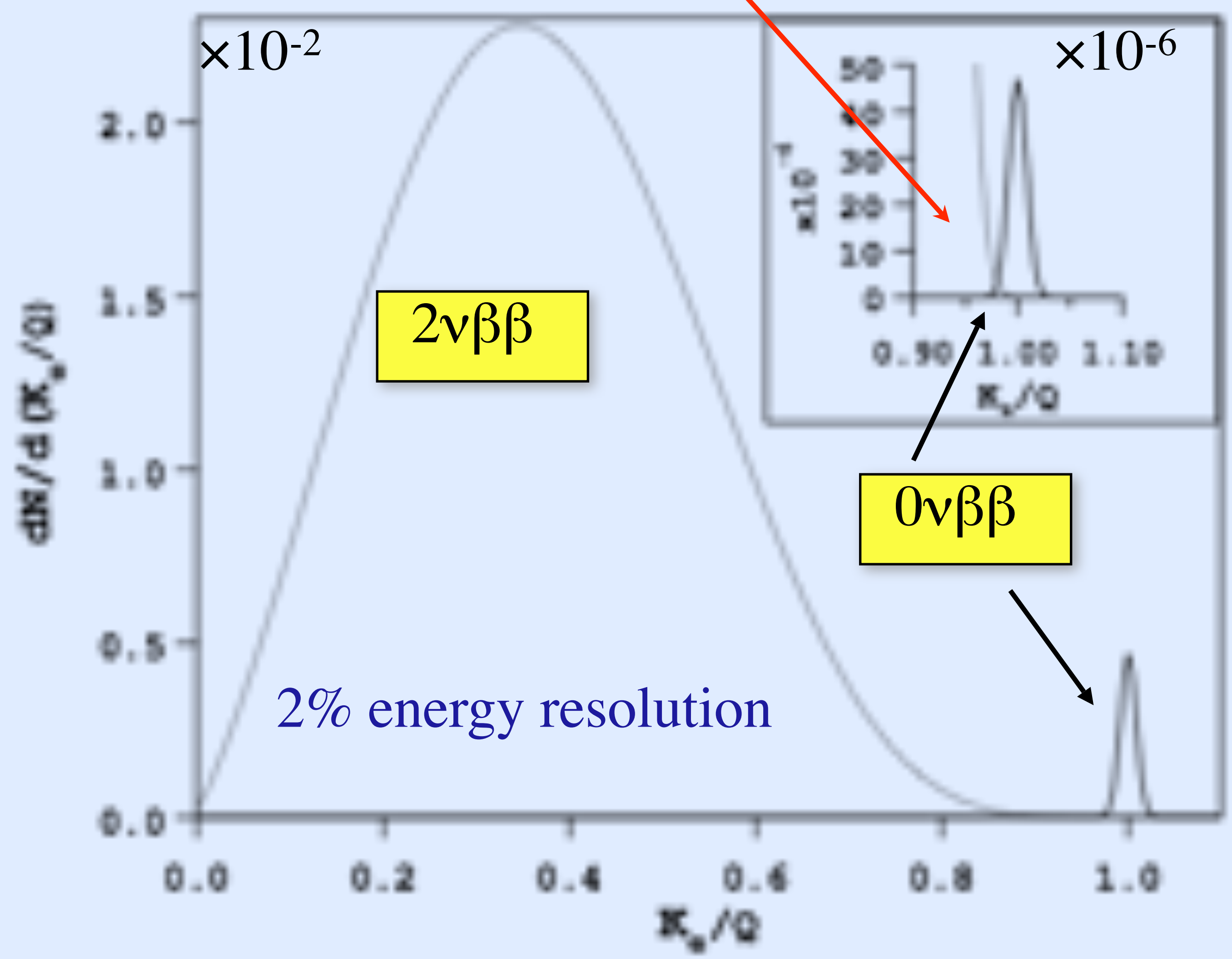
Neutrinoless double beta decay

Double β-decay without the emission of neutrinos (only 2 electrons)

effective Majorana mass term



0νββ would appear, in the 2-electron energy spectrum as a peak at the endpoint energy of the decay



not allowed in the standard model (violates lepton conservation by 2)

possible only if neutrinos are their own antiparticles

[P. Vogel, arXiv:hep-ph/0611243]

0νββ observable

event rate:
directly measured quantity

calculable phase space factor
(dependent on Q, Z)

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta}\rangle^2$$

nuclear matrix element (~1-4)
(calculated within particular nuclear models)

Majorana neutrino mass term
(can be zero):

$$\langle m_{\beta\beta}\rangle^2 = \left|\sum_i^N |U_{ei}|^2 e^{i\alpha_i} m_i\right|^2 \quad (\text{all } m_i \geqslant 0)$$

In kinematic searches of neutrino mass in β-decay:

$$\langle m_\beta\rangle^2 = \Sigma_i |U_{ei}|^2 m_i^2 > 0$$

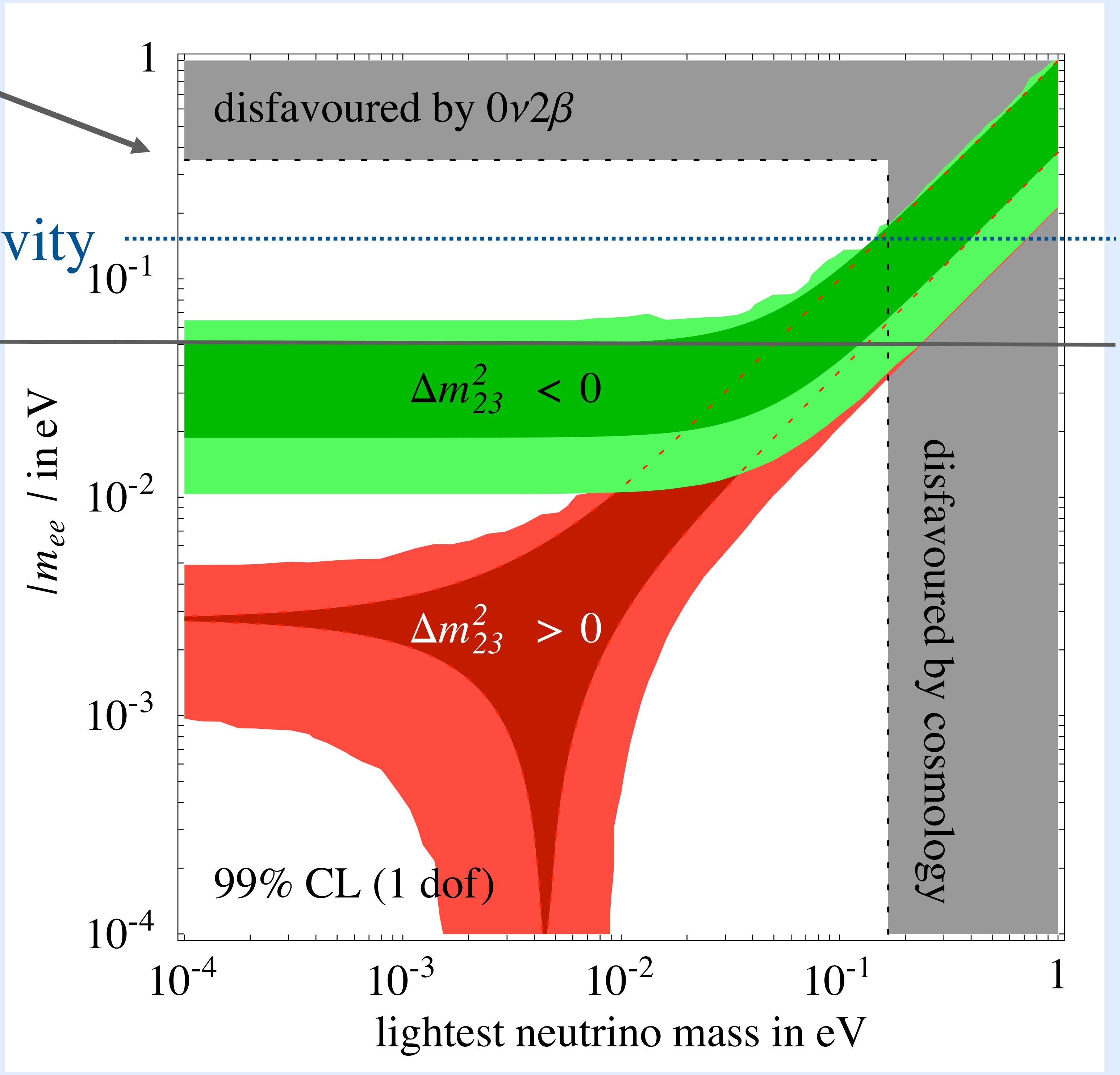
$0\nu\beta\beta$ effective neutrino mass

from neutrino oscillations:

current $0\nu\beta\beta$ sensitivity

EXO-200 expected $0\nu\beta\beta$ sensitivity

50 meV



^{76}Ge	$(2.1 - 2.6) \times 10^{27}$ y
^{82}Se	$(6.0 - 8.7) \times 10^{26}$ y
^{100}Mo	$(1.1 - 1.7) \times 10^{27}$ y
^{130}Te	$(0.7 - 1.7) \times 10^{27}$ y
^{136}Xe	$(1.5 - 5.6) \times 10^{27}$ y

[Strumia and Vissani, hep-ph/0606054]

EXO-200 event rates

- current experimental limit on $0\nu\beta\beta$ of ^{136}Xe is 10^{24} years

- 10^{25} years lifetime => in 160 kg, 71 events/year (0.2 events/day)

- double beta decay events are essentially point events in LXe

- β and γ decays inside the detector are (the main) background

In particular:

- in LXe, virtually impossible to distinguish between single and double beta events (both point-like, within the ~1 cm spatial resolution)
- γ single site Compton scattering and total absorption events are also point-like

Some of these events will fall in the double beta energy bin!

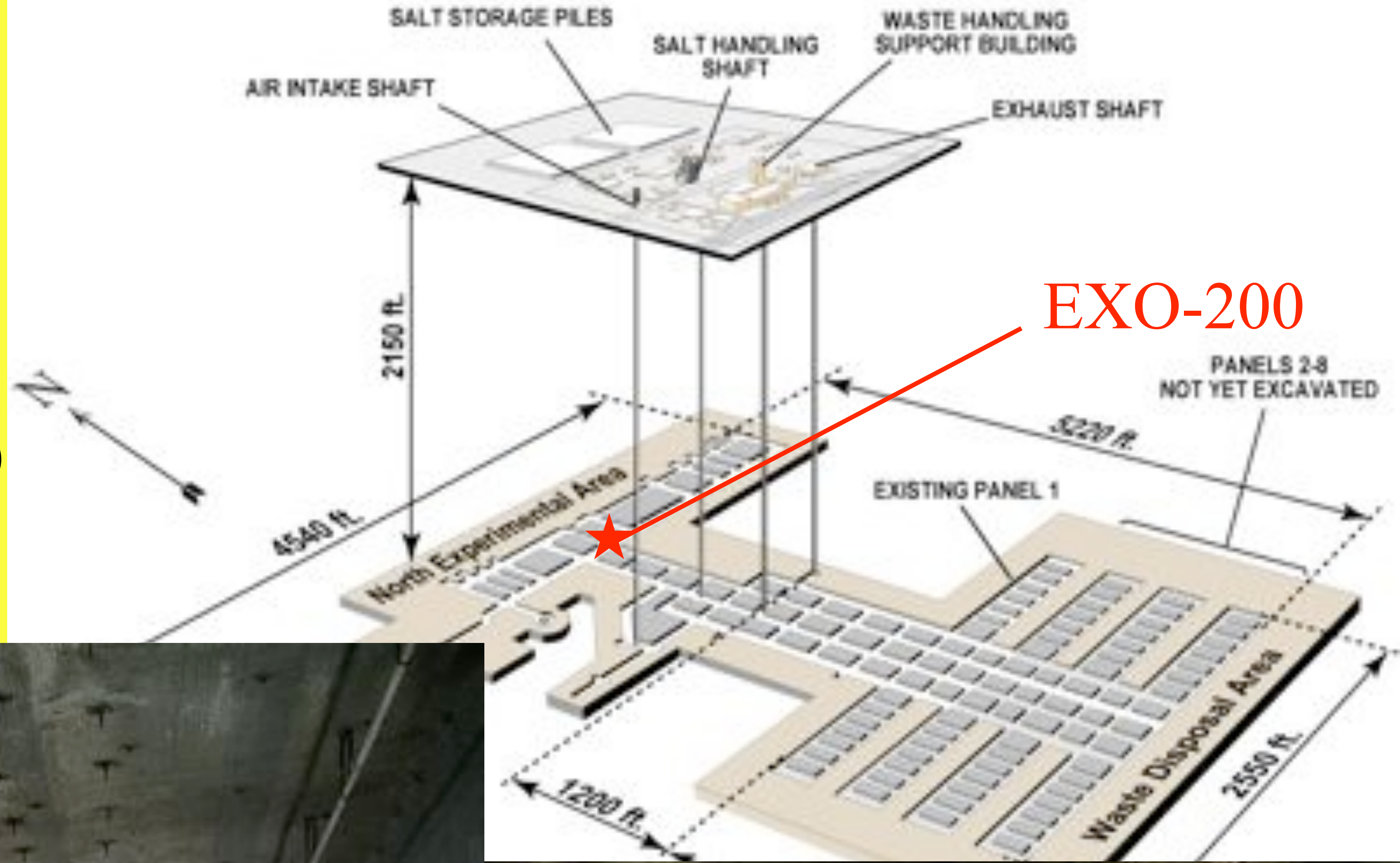
EXO-200 background suppression

- locate the experiment underground (WIPP salt mine, New Mexico)
- passive, graded shielding around the detector (Pb, Cu, thermal fluid)
- selection of clean materials for TPC, thermal bath, cryostat, Pb shield
- maximize active volume in order to maximize event rate (finite supply of enriched xenon)
- selection of events in the data with various cuts (energy resolution, fiducial volume, double site events, radon decays, ...)

muon flux at WIPP
(~ 1600 m.w.e.):

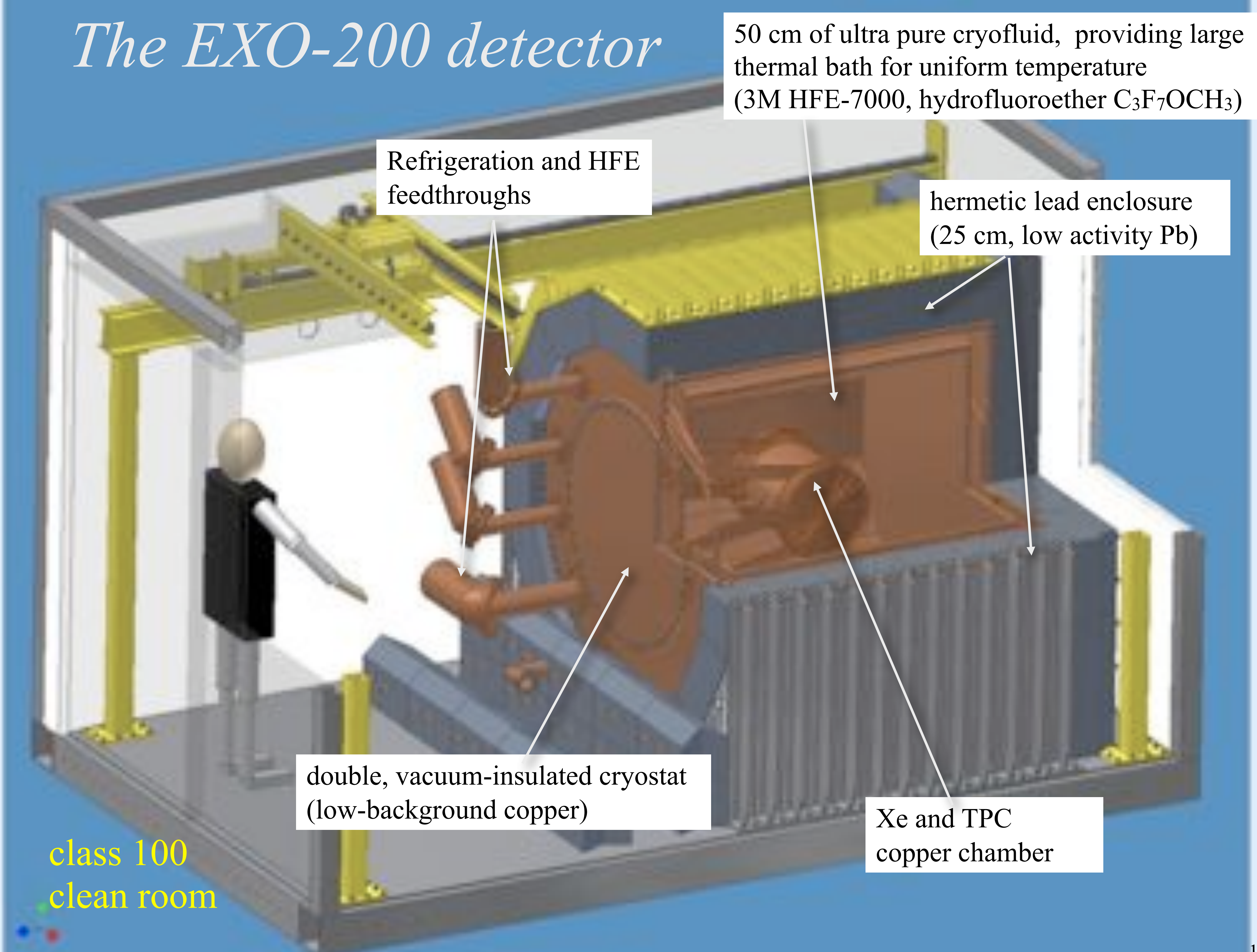
$4.77\times10^{-3}\ m^{-2}\ s^{-1}$
$(3.10\times10^{-3}\ m^{-2}\ s^{-1} sr^{-1},\ \sim15\ m^{-2}\ h^{-1})$

[Esch et al., NIM A 538 (2005) 516]



At WIPP
(October 2007)

The EXO-200 detector



EXO-200 installation underground at WIPP

system ready for re-commissioning operations

EXO-200 background rates

Example and reference for EXO-200 background needs:

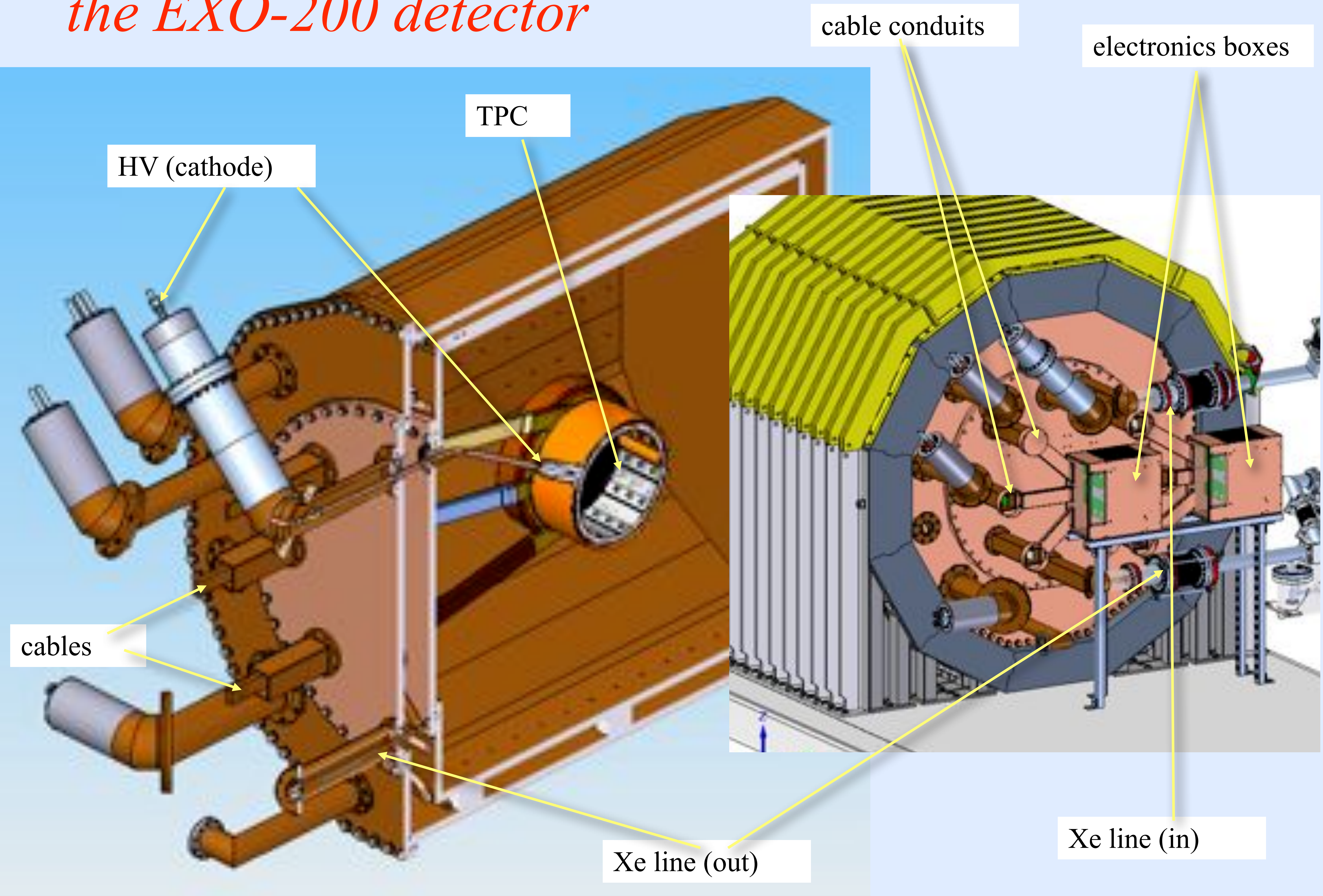
- the double cryostat is ~ 7 tons of copper
- ^{232}Th and ^{238}U intrinsic contamination is measured to be at most a few ppt (by weight)
- 1 ppt (10^{-12}) corresponds to a total ^{238}U rate of 2×10^{6} decays/y (compared to $0\nu\beta\beta$ 71 decays/y for 10^{25} years lifetime)

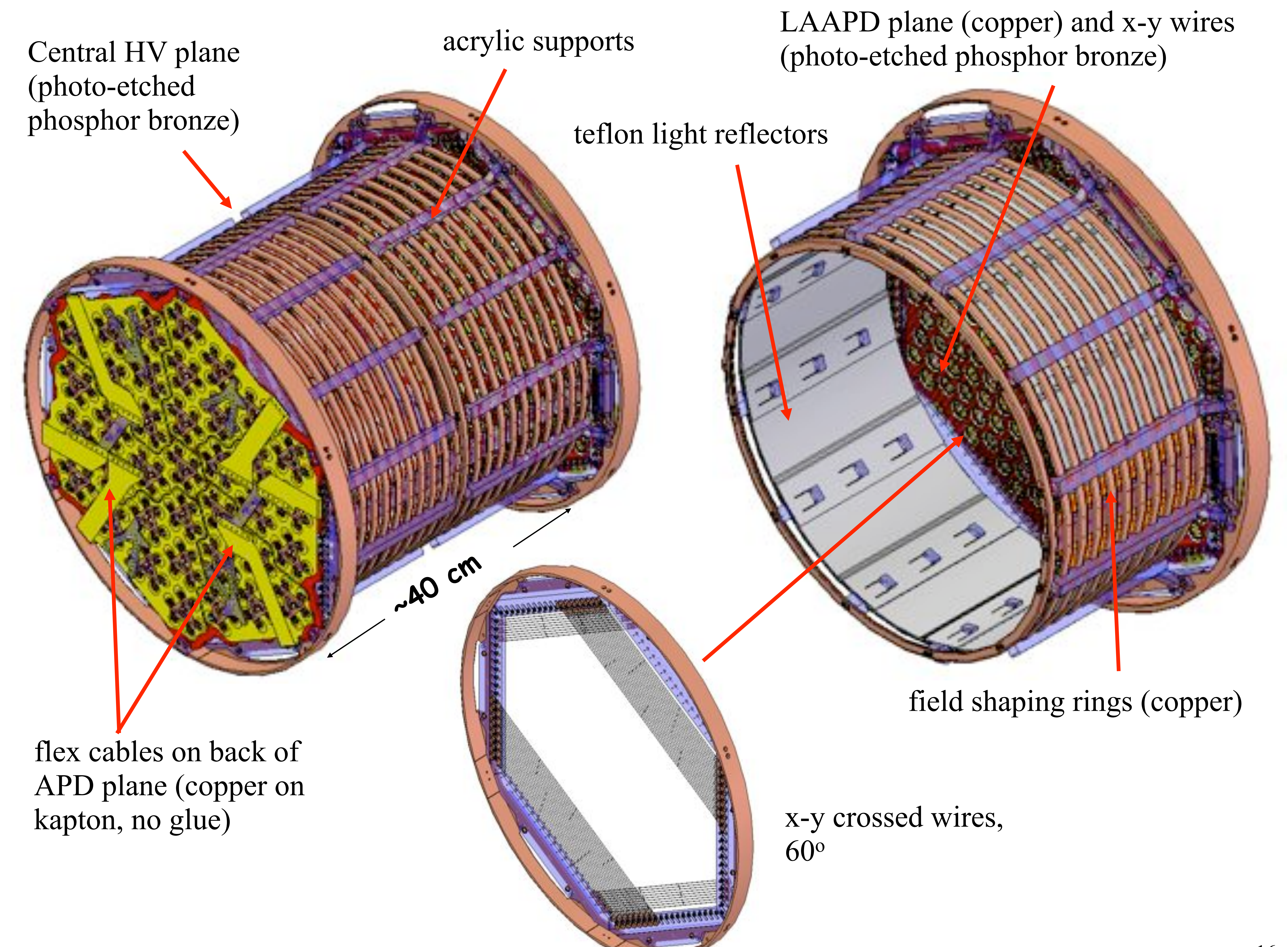
Naturally, not all U decays will generate single site events of the same energy inside the LXe .... this depends on the distance from the active region.

If there's secular equilibrium, the rate is multiplied by the number of daughters; ^{214}Bi has a 2447 keV γ ray, 1.57% branching ratio (^{136}Xe double beta Q-value is 2458 keV)

Cables are lightweight but very close to the center of the detector

the EXO-200 detector

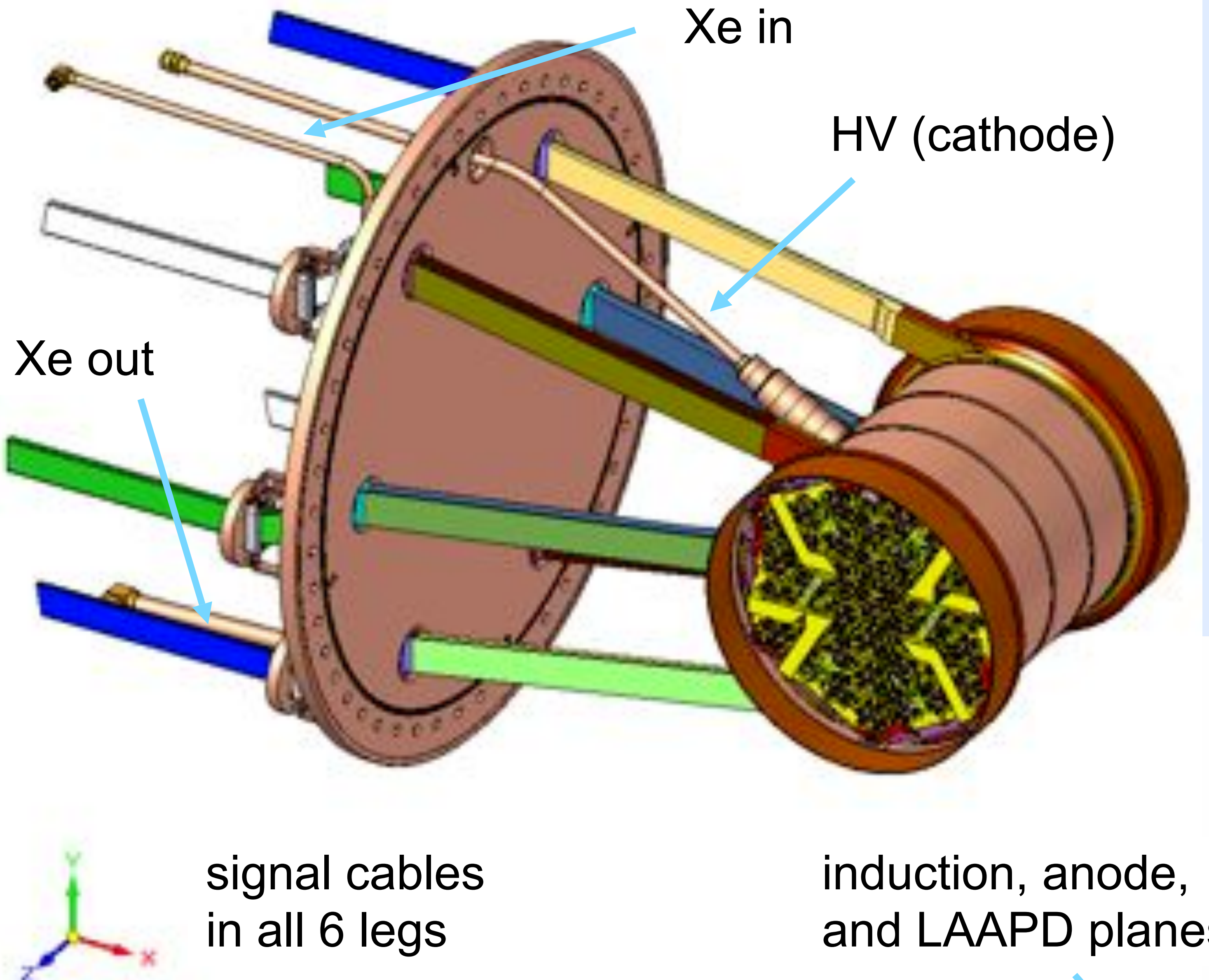


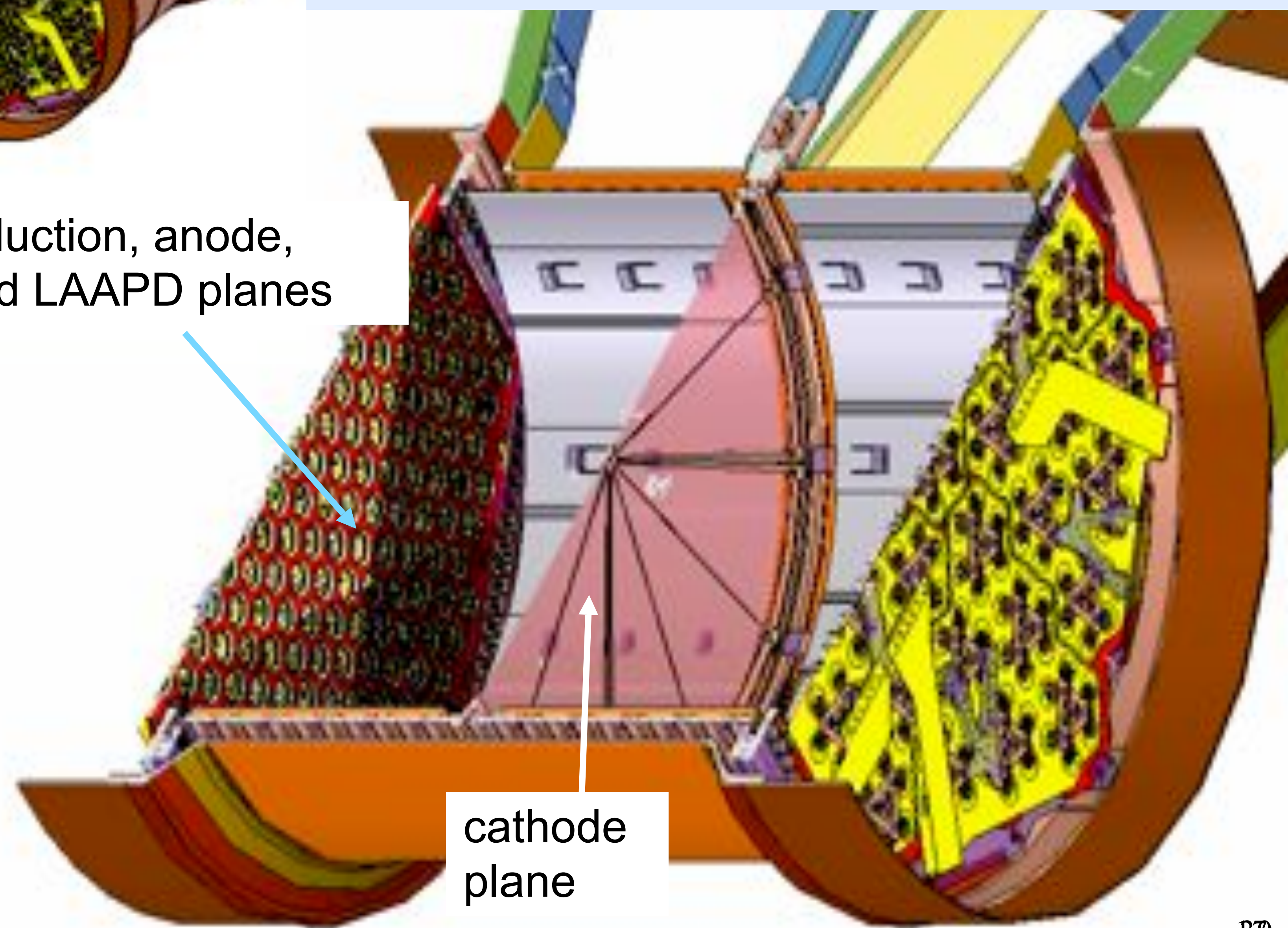

Central HV plane
(photo-etched
phosphor bronze)
acrylic supports
LAAPD plane (copper) and x-y wires
(photo-etched phosphor bronze)
teflon light reflectors
~40 cm
field shaping rings (copper)
flex cables on back of
APD plane (copper on
kapton, no glue)
x-y crossed wires,
60º

EXO-200 TPC and xenon vessel

- Xe vessel and detector made as light as possible to reduce radioactivity

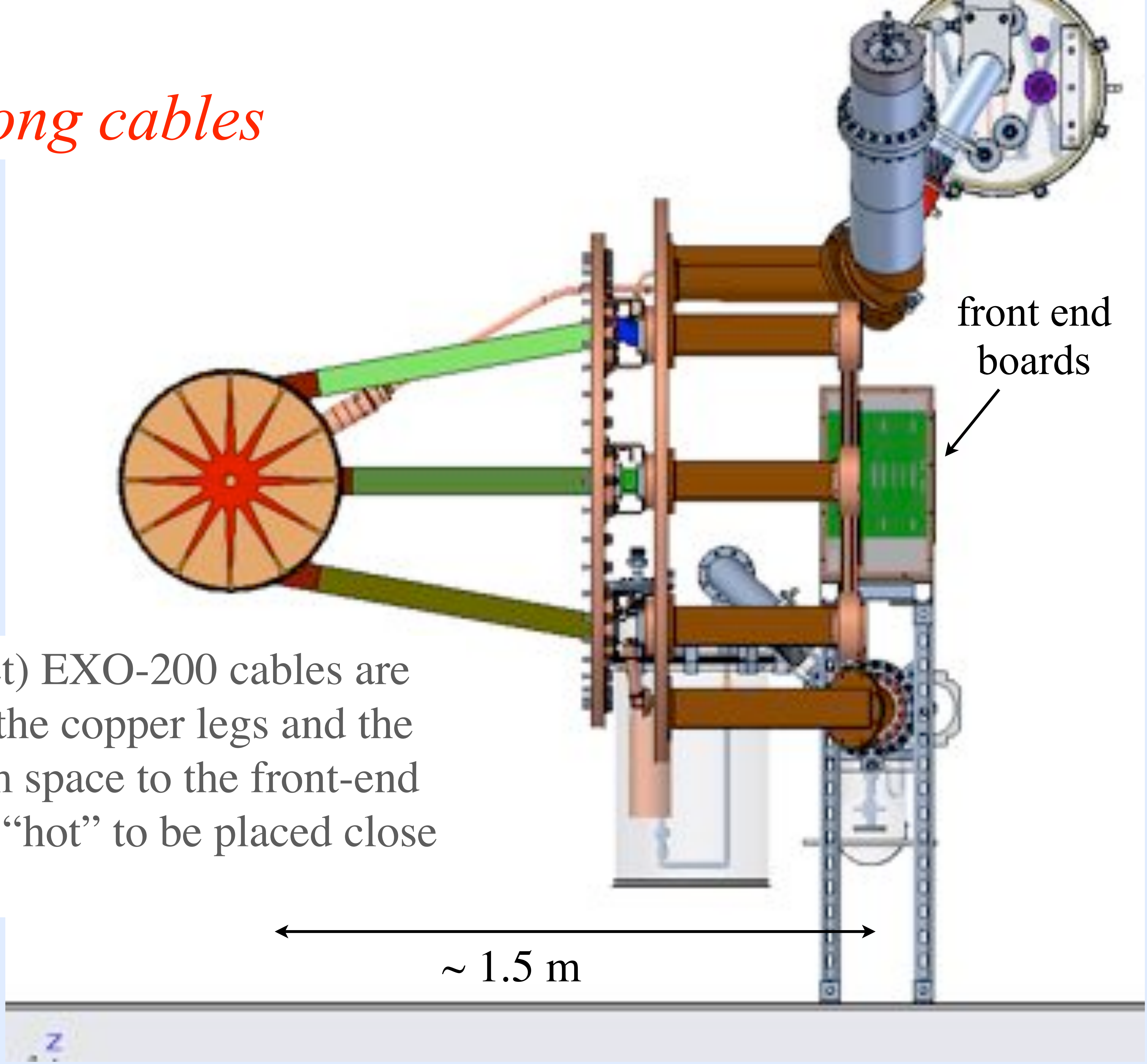
- great effort in maximizing the fiducial volume





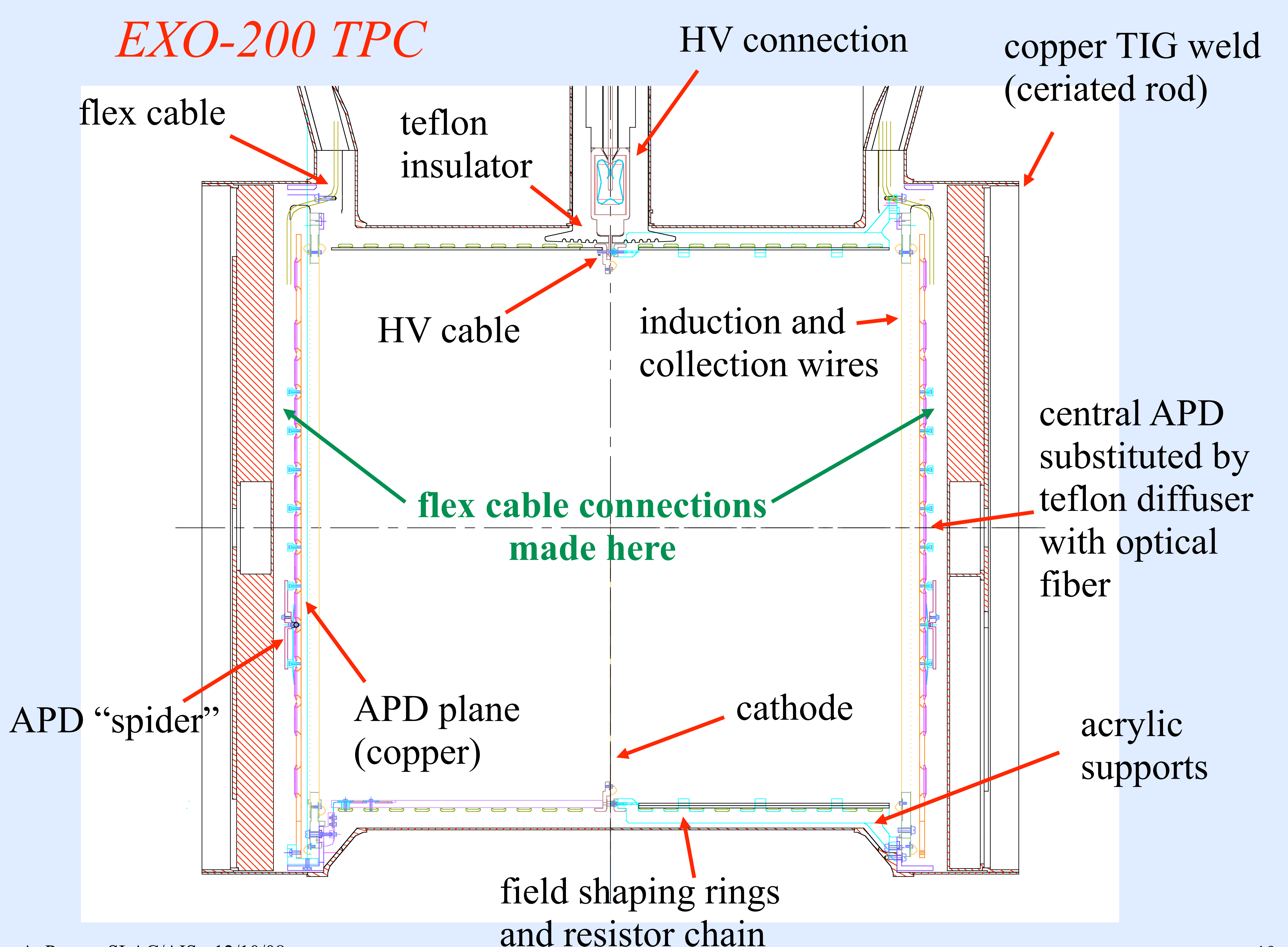
the cantilevered design was forced on us by the lack of vertical clearance at WIPP (top rather than side access would have been simpler)

EXO-200 long cables



the long (~8 feet) EXO-200 cables are routed through the copper legs and the cryostat vacuum space to the front-end electronics, too “hot” to be placed close to the detector

EXO-200 TPC



HV connection
copper TIG weld
(ceriated rod)
flex cable
teflon
insulator
HV cable
induction and
collection wires
central APD
substituted by
teflon diffuser
with optical
fiber
flex cable connections
made here
APD "spider"
APD plane
(copper)
cathode
acrylic
supports
field shaping rings
and resistor chain

EXO-200 cable design

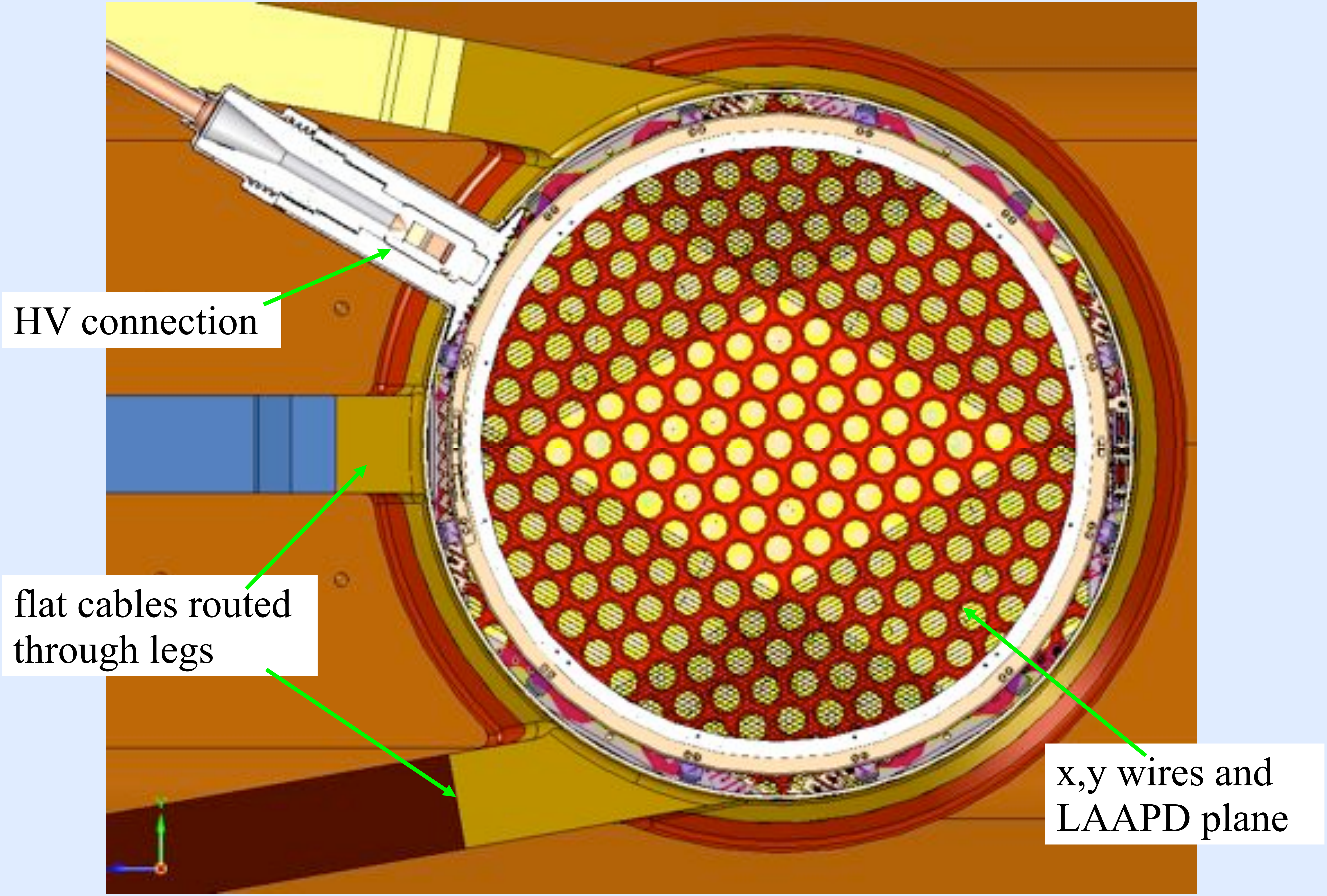
a few possibilities were considered for the EXO-200 signal cables:

- individual, twisted pairs of insulated wires (e.g. kapton-coated)
- flat, flexible cables

the choice fell on flat cables for the following reasons:

- allow access and connections in the very limited space behind wires and APD plane (dictated by the need to maximize the active xenon)
- minimize mass (higher chance of low radioactivity)
- still allow for complicated routing into the legs

EXO-200 (transverse section)



EXO-200 cathode, grid and anode

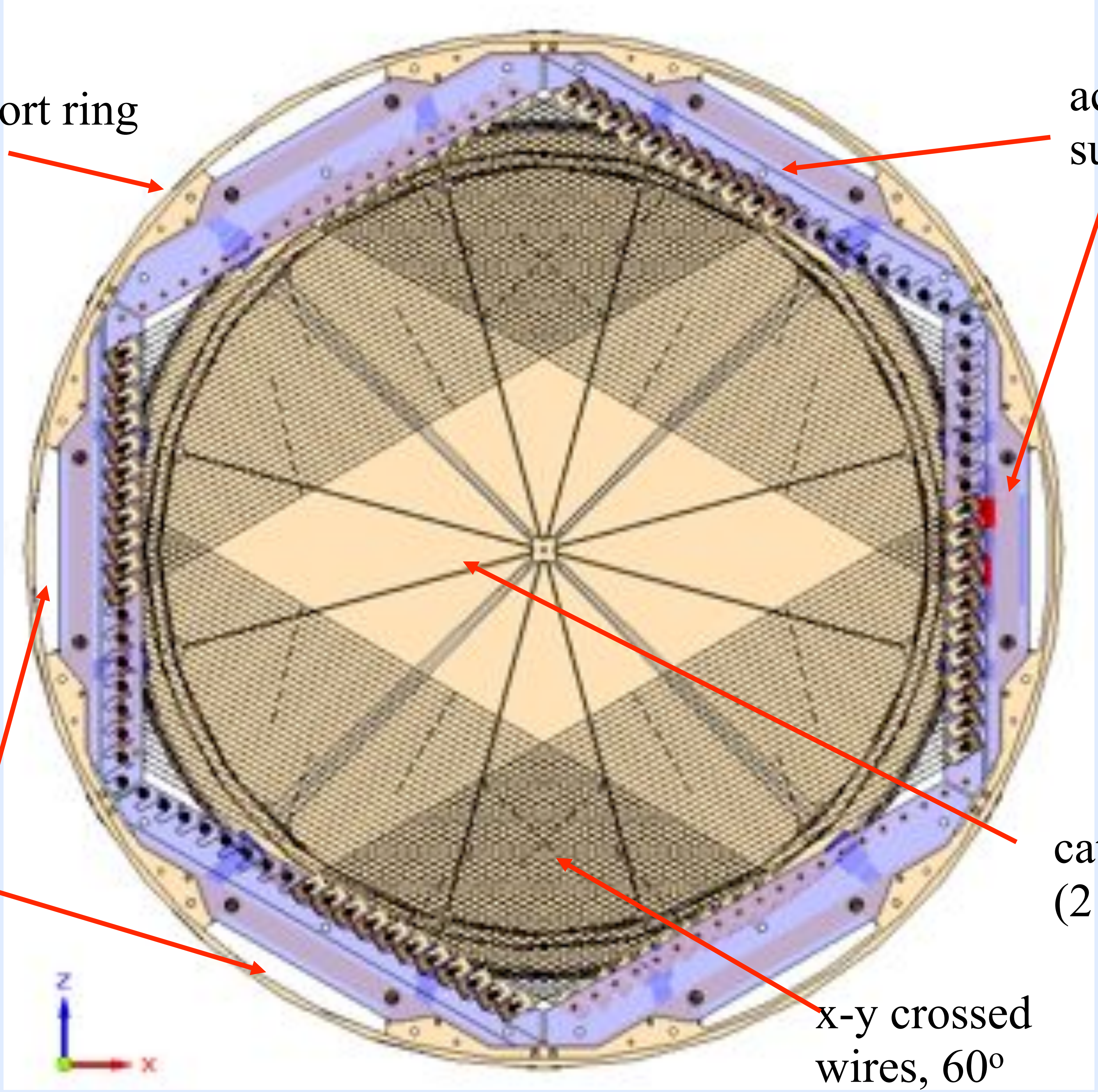
Cu support ring

acrylic wire supports

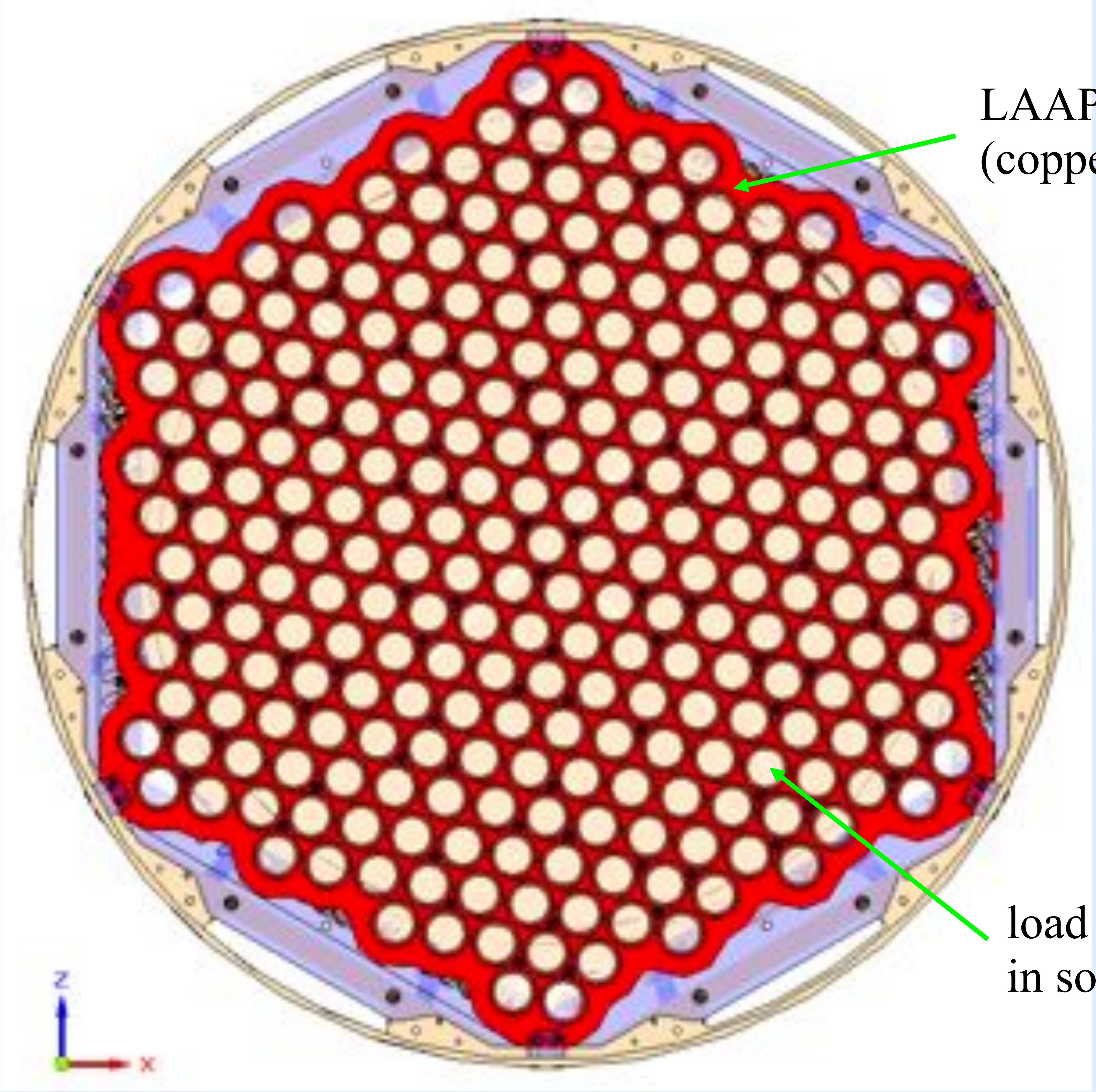
pockets for flat cables

cathode (2 “bow ties”)

x-y crossed wires, 60°



EXO-200 copper APD plane

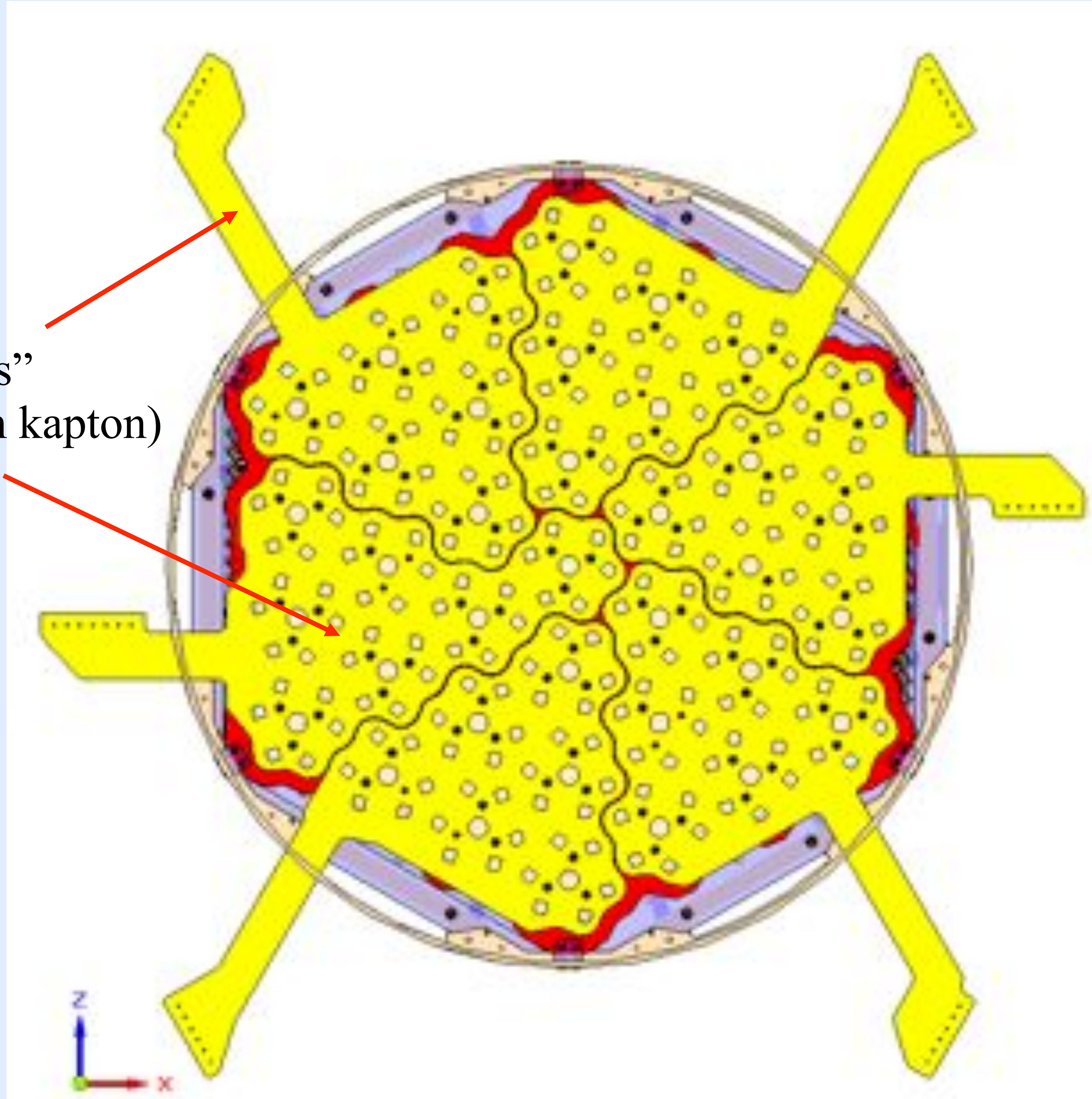


LAAPD plate (copper)

load LAAPDs in sockets

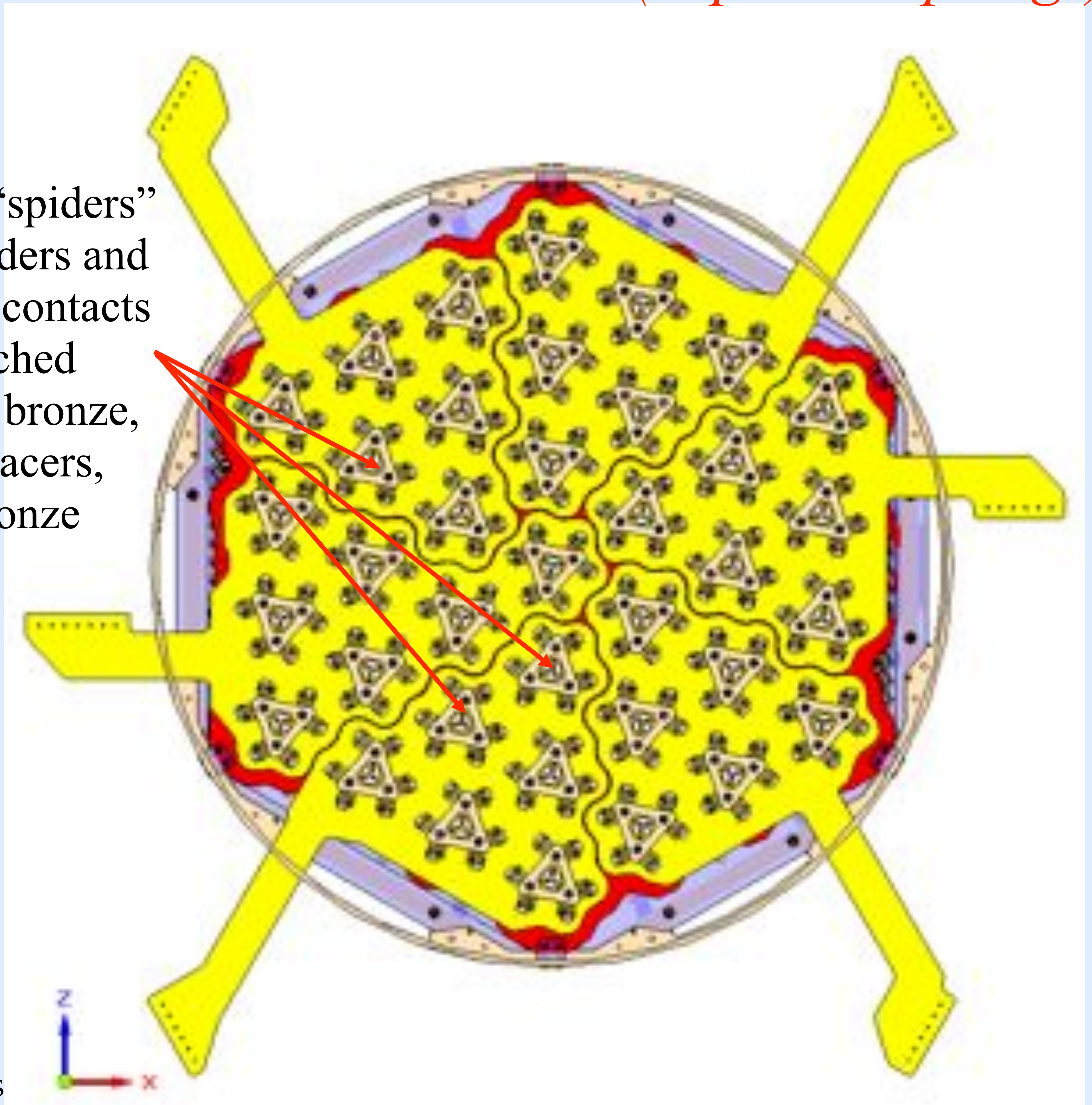
EXO-200 LAAPD connections ("pizza pies")

flat cable
"pizza pies"
(copper on kapton)



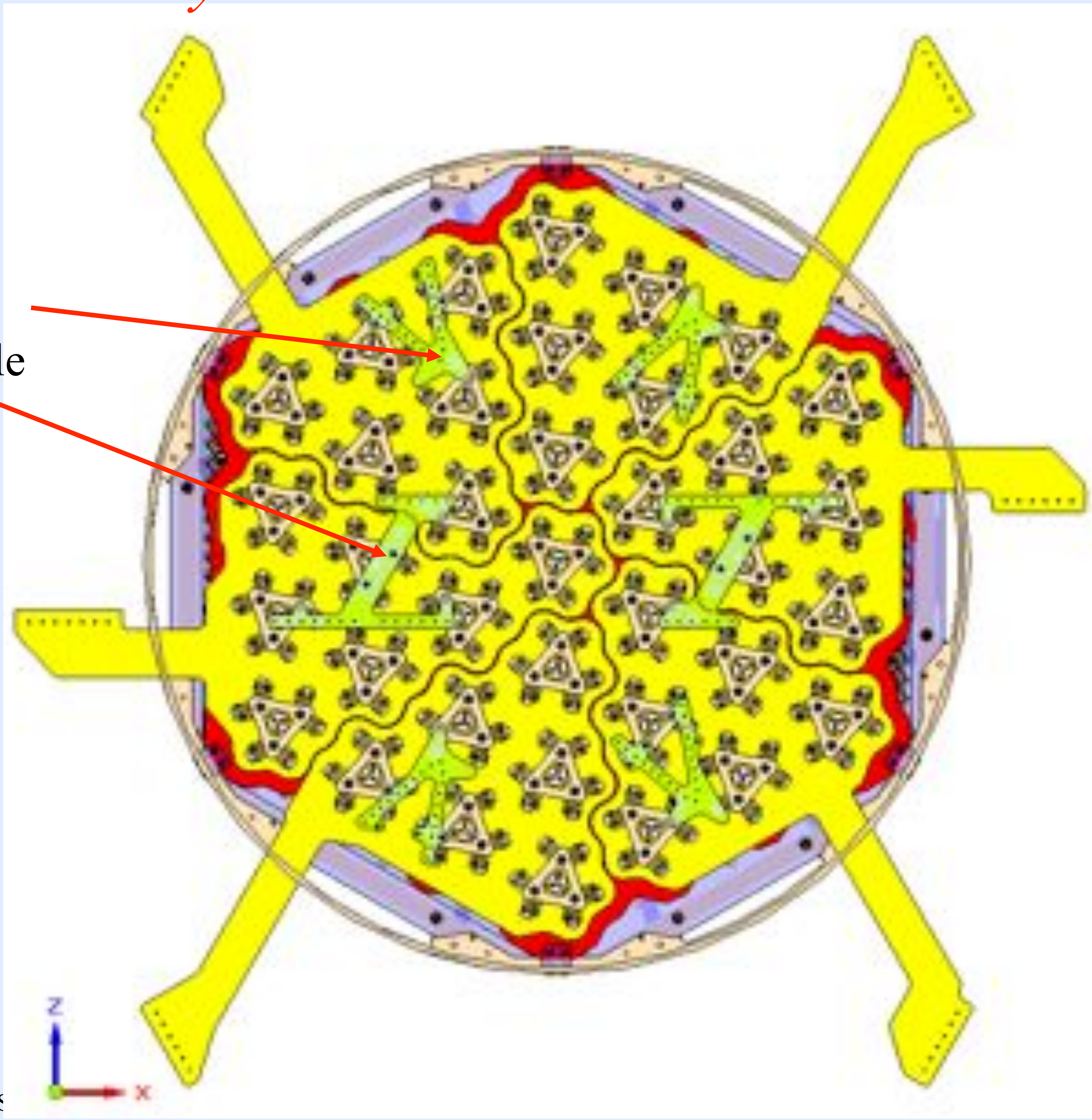
EXO-200 LAAPD contacts ("spider" springs)

LAAPD "spiders" act as holders and electrical contacts (photo-etched phosphor bronze, acrylic spacers, silicon bronze screws)

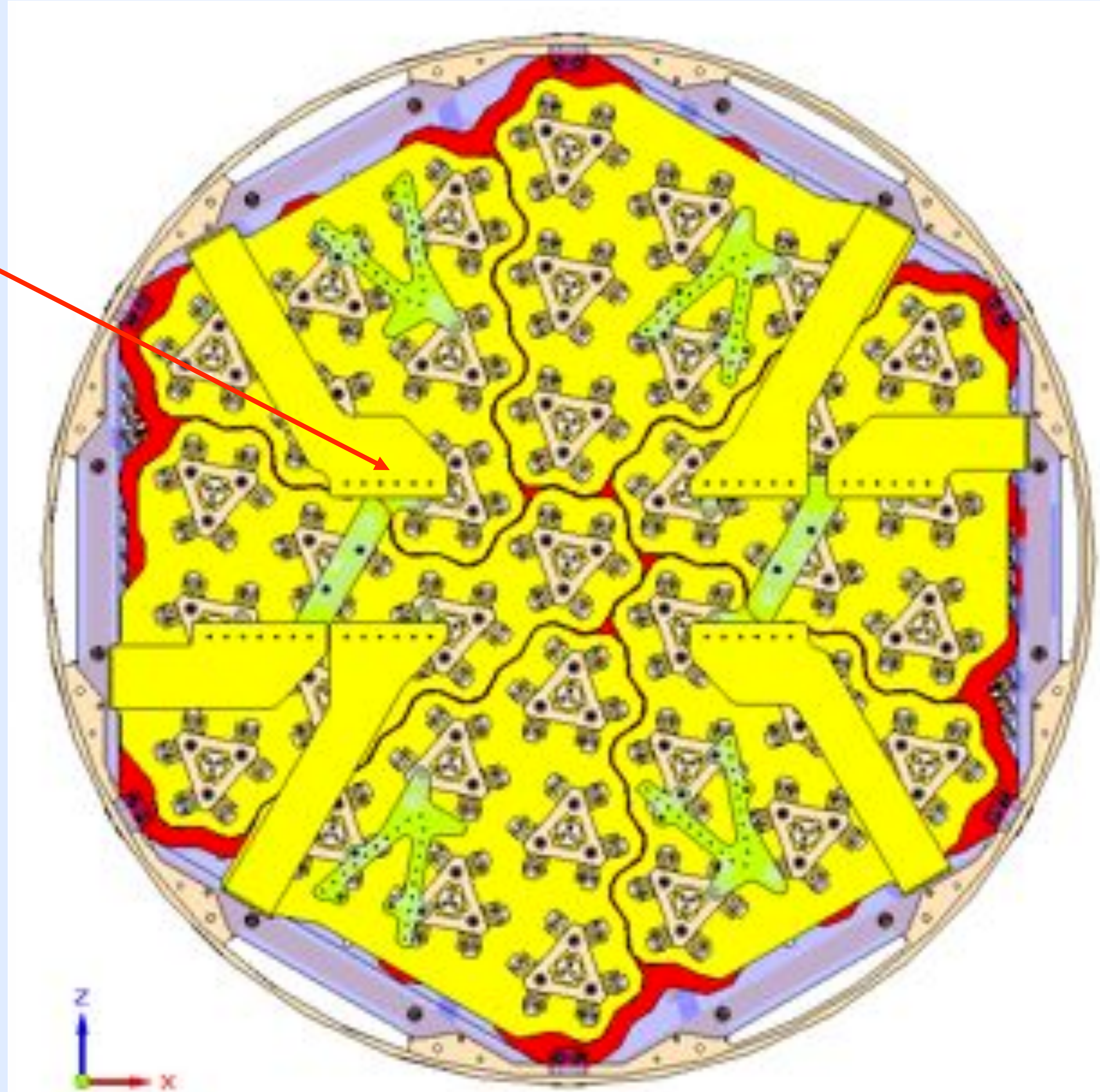


EXO-200 acrylic connectors

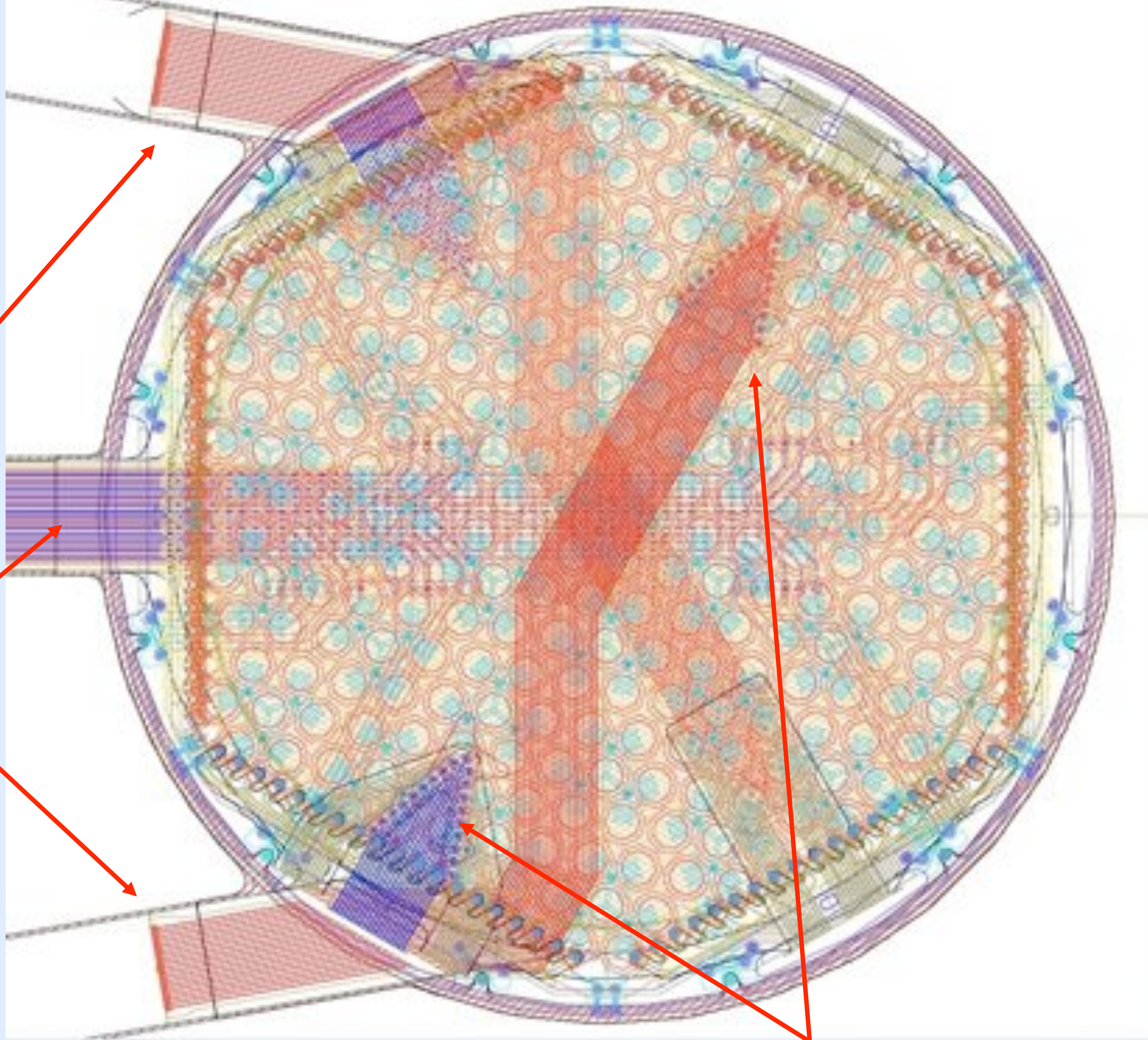
“Vee” and
“Tee” cable
supports
(acrylic)



cables folded and connected with silicon-bronze screws (acrylic backing)



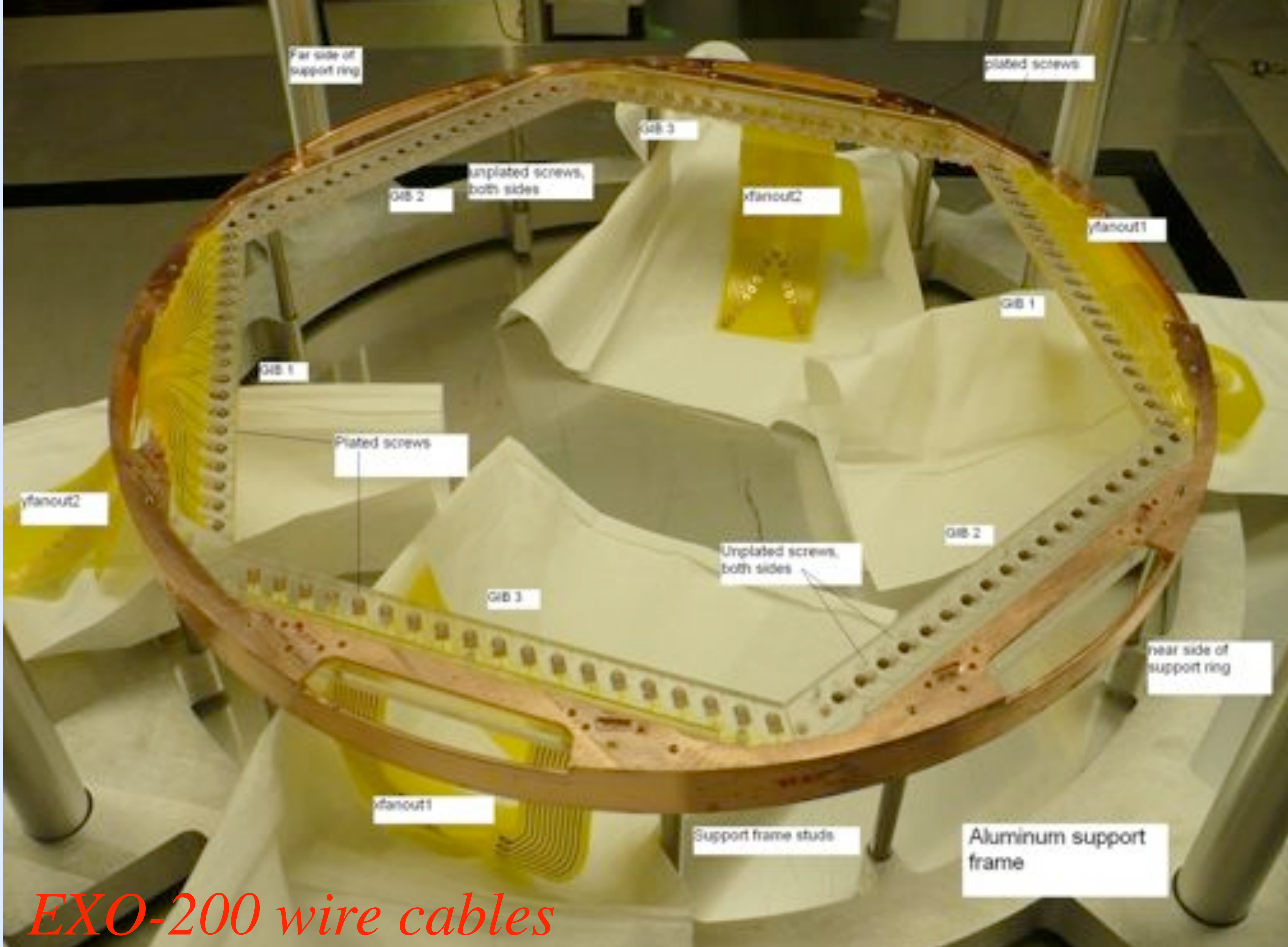
EXO-200 flat signal cables



flat cables routed through the legs

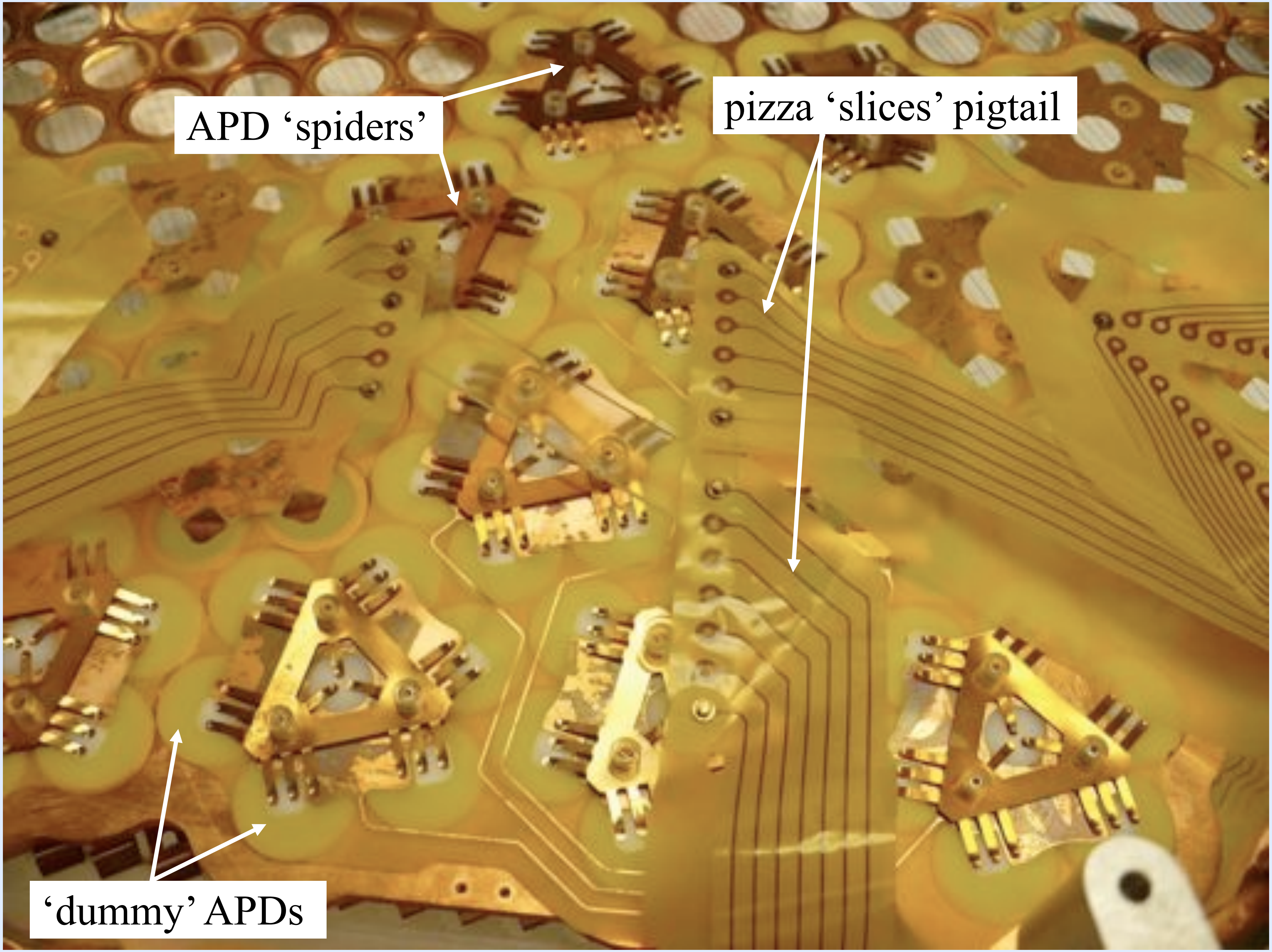
connection performed with silicon-bronze screws and spring-loaded phosphor bronze washers on acrylic backings

EXO-200 wire cables



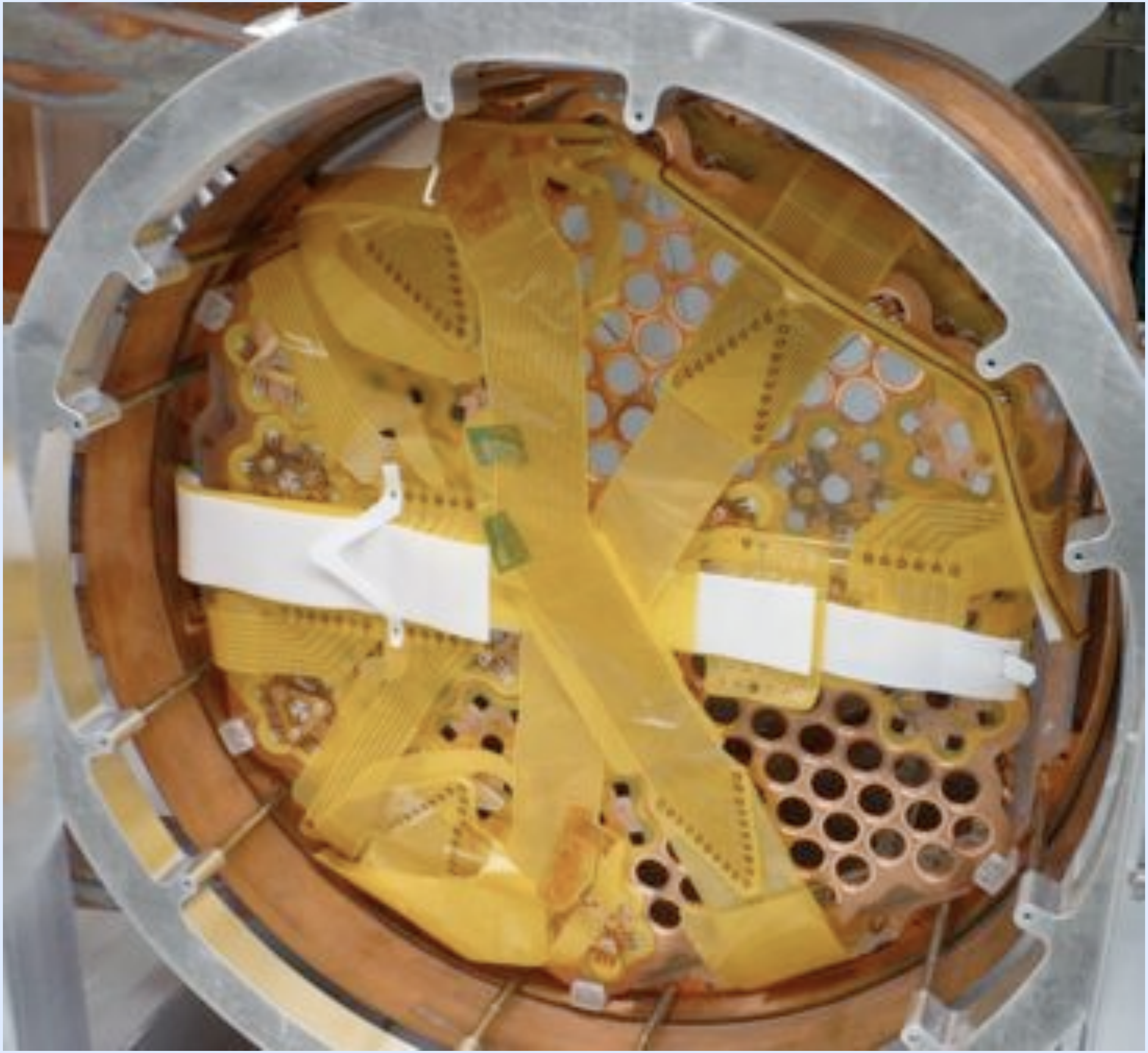
EXO-200 backplane cable connections

prototype detector



prototype detector

prototype detector



Materials qualification database

- Neutron Activation Analysis (NAA) - Alabama (MIT reactor)
- ICP-MS and GD-MS - INMS (Ottawa), commercial outfits
- Radon emanation - Laurentian (Sudbury)
- Gamma counting - Neuchâtel, Alabama
- Alpha counting - Alabama, Carleton, SLAC, Stanford
- Monte Carlo - Alabama, SLAC, Stanford, Maryland

Goals:

a) select adequate materials for EXO-200 construction
b) qualify adequate cleaning procedures for components prior to installation
c) feed data into full simulation of EXO-200 background

[EXO collaboration; D. Leonard et al., NIMA 591, 490 (2008)]

EXO Materials Testing Summary

(Status 8/31/2006)
287 entries

> 330 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,	UA, NAA	[illegible]	[illegible]	[illegible]	[illegible]

substrate selection

substrates procured from two companies, Nippon Steel and DuPont

Nippon Steel Espanex:

- glue-less 18 μm copper on 25 μm kapton (2 rolls)
- glue-less 15 μm copper on 40 μm kapton (1 roll)
- glue-less 18 μm copper on 50 μm liquid crystal (1 roll)

DuPont Pyralux:

- glue-less 18 μm copper on 25 μm kapton (1 roll)

material of choice:

Nippon Steel Espanex MC18-25-00CEM, lot G5L03-23L2

raw substrate qualification

#	Material	Method	K conc. (10^{-9} g/g)	Th conc. (10^{-12} g/g)	U conc. (10^{-12} g/g)
	Photo-etching: Cu on polyimide substrate				
101	Cu coating Nippon Steel Chemical Co., Espanex flat cable MC18-50-00CEM. Polyimide thickness: 50 μm, Cu thickness: 18 μm	ICP-MS	–	<3 (<0.05 pg/cm^2)	19 ± 2 (0.30 ± 0.03 pg/cm^2)
102	Polyimide substrate Nippon Steel Chemical Co., Espanex flat cable MC18-25-00 CEM, lot 65605-11R1. Polyimide thickness: 25 μm, Cu thickness: 18 μm	NAA[a]	<299	<1600	<1500
103	Cu coating Nippon Steel Chemical Co., Espanex flat cable MC18-25-00 CEM, lot 65605-11R1	ICP-MS	–	69 ± 3 (1.1 ± 0.05 pg/cm^2)	100 ± 3 (1.6 ± 0.04 pg/cm^2)
104	Polyimide substrate, Nippon Steel Chemical Co., Espanex flat cable, MC15-40-00 VEG. Polyimide thickness: 40 μm, Cu thickness: 15 μm	NAA[a]	107 ± 12	<450	<900
105	Cu coating, Nippon Steel Chemical Co., Espanex flat cable MC15-40-00 VEG	ICP-MS	–	135 ± 6 (1.8 ± 0.07 pg/cm^2)	67 ± 5 (0.9 ± 0.06 pg/cm^2)
106	Nippon Steel Chemical Co., Espanex flat cable MC15-40-00VEG. ^{60}Co: <0.18 mBq/kg	Ge	880 ± 120	<250	121 ± 32
107	Nippon Steel Chemical Co., Espanex flat cable MC18-25-00CEM, lot G5L03-23L2. ^{60}Co: <0.6 mBq/kg, ^{137}Cs: <1.3 mBq/kg	Ge	<146	<260	<46
108	Polyimide substrate, Nippon Steel Chemical Co., Espanex flat cable MC18-25-00CEM, lot G5C03 23L2	ICP-MS	390 ± 110 (1.4 ± 0.4 ng/cm^2)	50 ± 17 (0.54 ± 0.06 pg/cm^2)	450 ± 170 (1.6 ± 0.6 pg/cm^2)
109	Cu coating, Nippon Steel Chemical Co., Espanex flat cable MC18-25-00CEM, lot G5C03 23L2	ICP-MS	94 ± 19 (1.5 ± 0.3 ng/cm^2)	34 ± 6 (0.55 ± 0.09 pg/cm^2)	41 ± 6 (0.66 ± 0.1 pg/cm^2)
110	Nippon Steel, Espanex flat cable, MC15-40-00 VEG. Etched by Basic Electronics. ^{60}Co: <0.56 mBq/kg, ^{137}Cs: <0.63 mBq/kg	Ge	<160	<40	<97
111	Polyimide substrate Nippon Steel Espanex flat cable MC15-40-00 VEG. Etched Basic by Electronics	ICP-MS	229 ± 71 (1.3 ± 0.4 ng/cm^2)	317 ± 4 (1.8 ± 0.02 pg/cm^2)	3880 ± 120 (22 ± 0.7 pg/cm^2)
112	Cu coating Nippon Steel Espanex flat cable, MC15-40-00 VEG. Etched by Basic Electronics	ICP-MS	105 ± 23 (1.4 ± 0.3 ng/cm^2)	45 ± 4 (0.6 ± 0.05 pg/cm^2)	1720 ± 23 (23 ± 0.3 pg/cm^2)

[EXO collaboration; D. Leonard et al., NIMA 591, 490 (2008)]

flat cable production process

production proceeds as follows:

1. generate CAD drawing of desired trace pattern and contour (shape)
2. produce mask film (artwork) with desired pattern
3. drill holes (pattern and alignment) on raw sheet
4. apply photoresist on raw sheet
5. align artwork on top (Cu side) of raw sheet
6. expose photoresist
7. develop photoresist
8. etch (exposed parts harden and are NOT etched away, i.e negative artwork)
9. strip remaining photoresist off
10. 2 DI water rinses
11. isopropanol rinse
12. apply coverlayer (long cables only)
13. cut by hand
14. plasma etch (oxygen, CF_4 - small cables only)
15. place in double ziplok bag

etching options

Etchant	Etching temperature (°C)	Etch rate (μm/min)	Undercut	Dissolved copper capacity	Regeneration and metal recovery
Cupric chloride ($CuCl_2$)	50–54	25–50	Low	120–140	Copper recovery and regeneration
Ferric chloride ($FeCl_3$)	43–49	25–50	Low	40–60	Regeneration
Alkaline etchants	43–55	30–60	Lower	140–170	Copper recovery and regeneration
Hydrogen peroxide/sulphuric acid ($H_2O_2 + H_2SO_4$)	43–55	Variable	Low	50–90	Copper recovery
Ammonium persulhate [$(NH_4)_2\ S_2\ O_8$]	38–55	7	High	40–55	Copper recovery
Chromic-sulphuric acid [$CrO_3 + H_2SO_4$]	26–33	Variable	Lower	50–60	Not available

Etchant	Corrosiveness	Neutralisation and disposal problems	Toxicity	Operational cost*
Cupric chloride ($CuCl_2$)	High	Low	Medium	Low
Ferric chloride ($FeCl_3$)	High	Medium	Low	Medium
Alkaline etchants	High	Medium	Medium	High

* Include disposal cost.

[O. Cakir, J. Mat. Process. Technol. 175, 63 (2006)]

etching reaction: $CuCl_2 + Cu \rightarrow 2CuCl$

(cupric) (cuprous)

regenerating reaction: $NaClO_3 + 6HCl \rightarrow 6Cl^- + NaCl + 3H_2O$

$$CuCl + Cl^- \rightarrow CuCl_2$$

qualification of etching process

production bid included a test production for us to qualify radiologically

we worked with two firms:

- Basic Electronics
- Flexible Circuit Technologies (FlexCTech)

etching process was different: one used ferric chloride ($FeCl_3$), the other cupric chloride ($CuCl_2$)

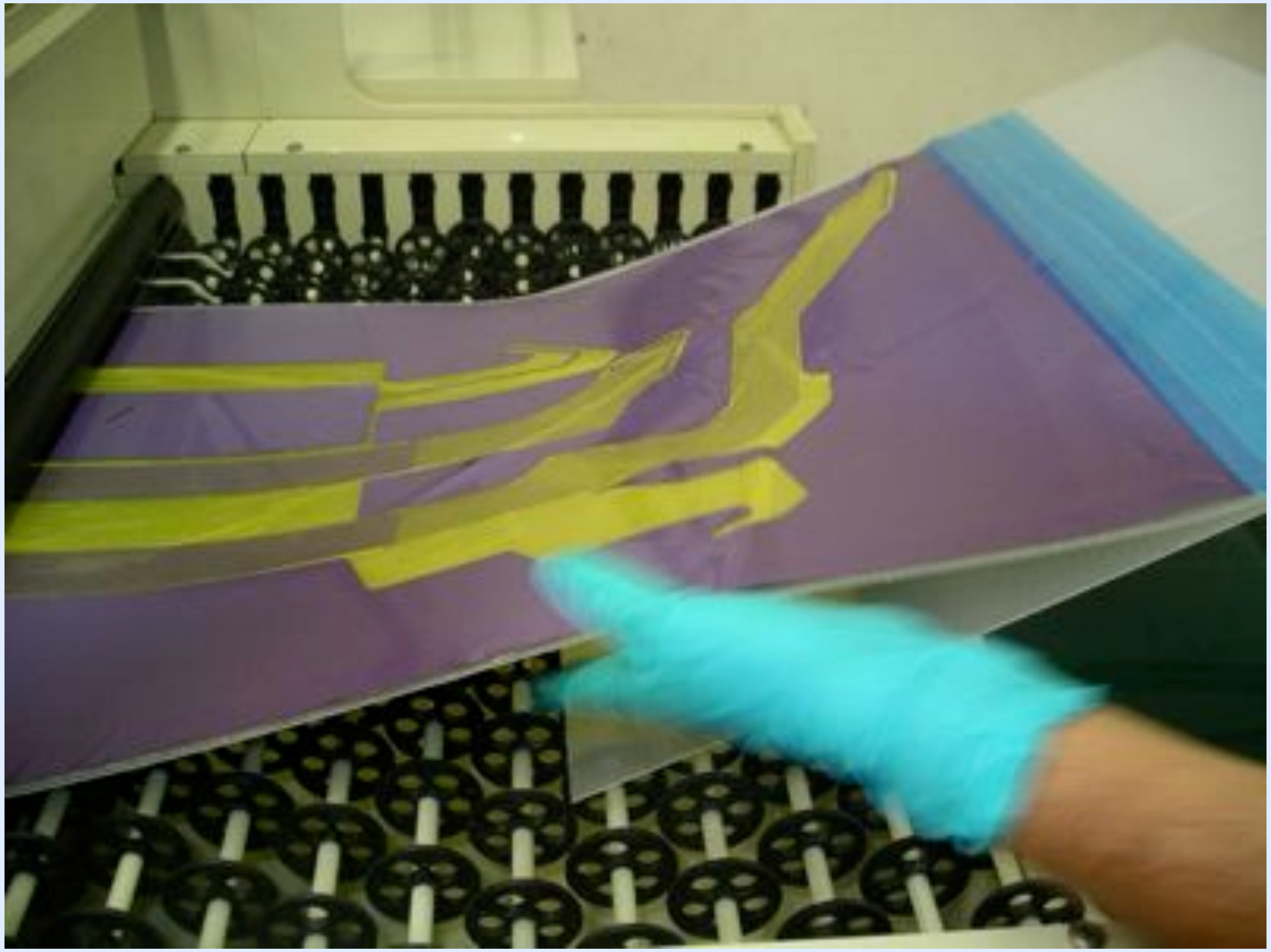
we tested samples from both companies, and both etching process added surface contamination:

- supply our own chemicals (successfully tested, but too expensive)
- require DI water and other clean practices
- clean at Stanford (tested and developed procedure)

EXO-200 flat signal cable

flat cable production performed with Flexible Circuit Technologies, at A-Flex and Pacific Image facilities in Southern California

Cutting panels, drilling
Wet chemistry (etching)
Plasma cleaning (small parts)
Cover layer, final cutting



Two people for 4 weeks on site!

- handling with gloves
- clean surfaces, tools (alcohol)
- new, clean containers
- cover parts
- use DI water
- rinse with high grade alcohol
- plasma etch small parts
- bag parts


applying photoresist


exposing long cables


developer


touch-up


etched parts


etch


photoresist stripper

the etching process


wipe down, roll up, bag


hand cut!

finished part!

flat cable installation

once back at Stanford:

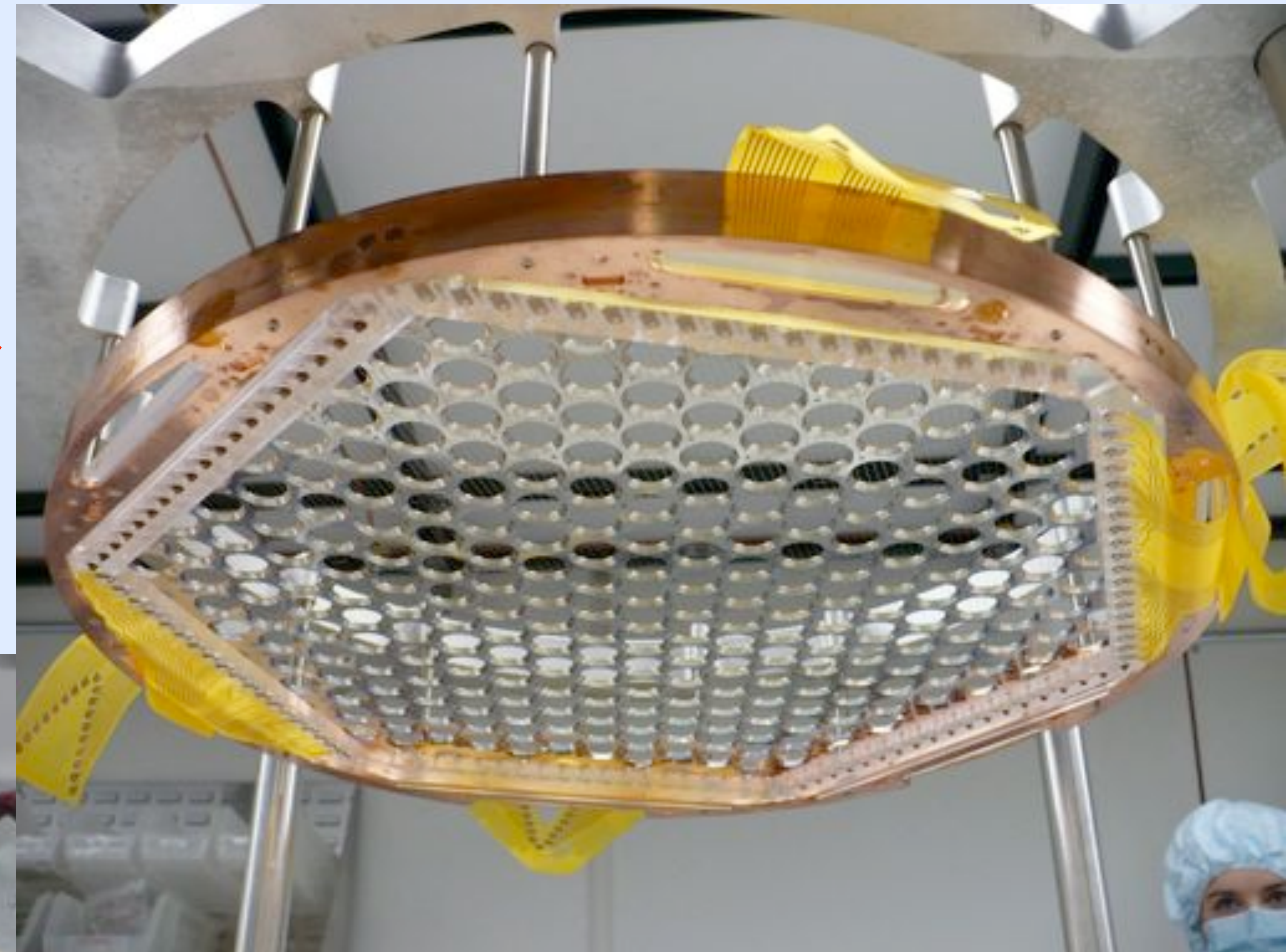
1. clean each cable (small and long) as follows
   - acetone bath and delicate wipe
   - ethanol bath and delicate wipe
   - several HCl (6% and 3%) baths, with DI water rinse in between and after, checking pH of rinse water
   - final ethanol bath

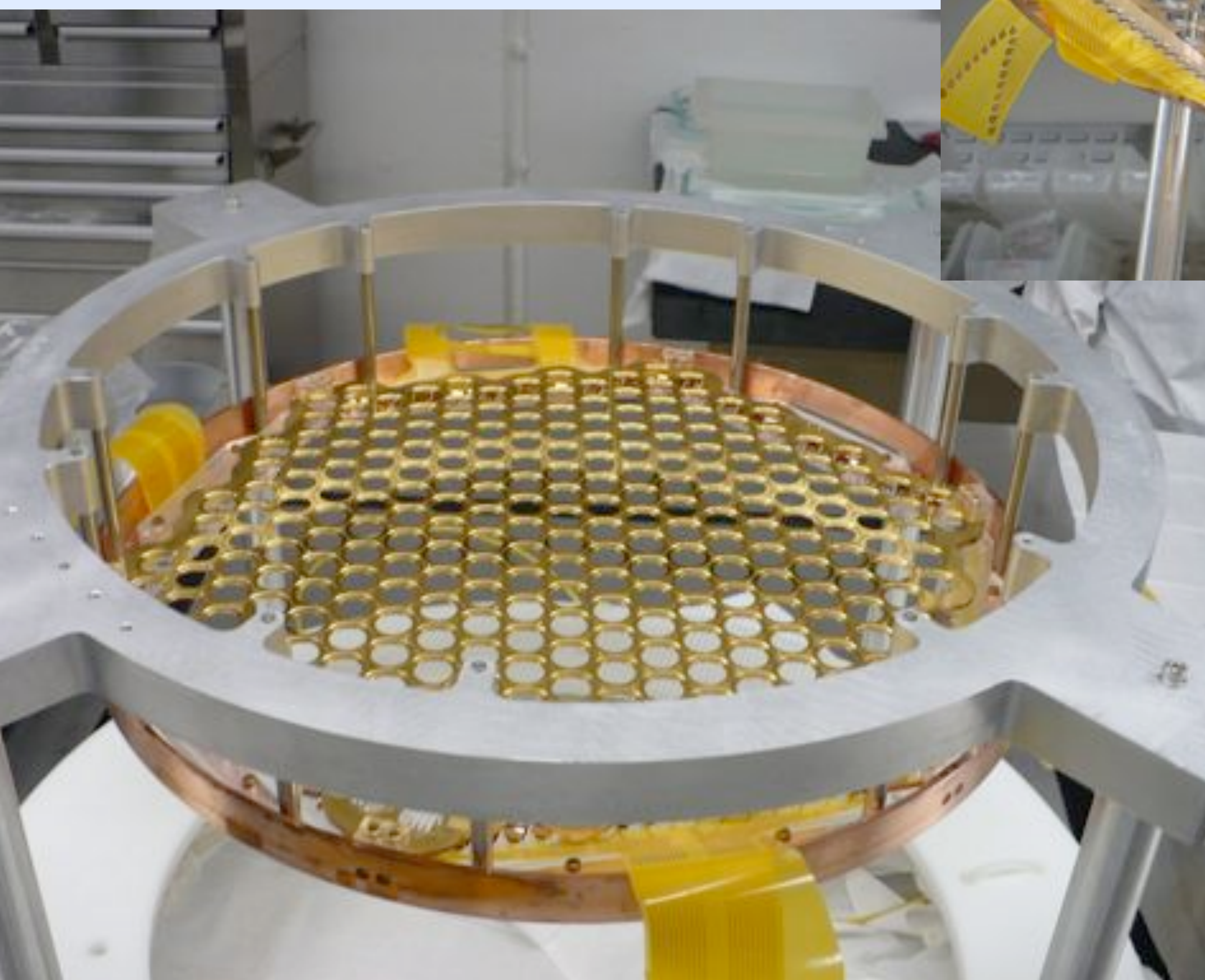
2. install small cables

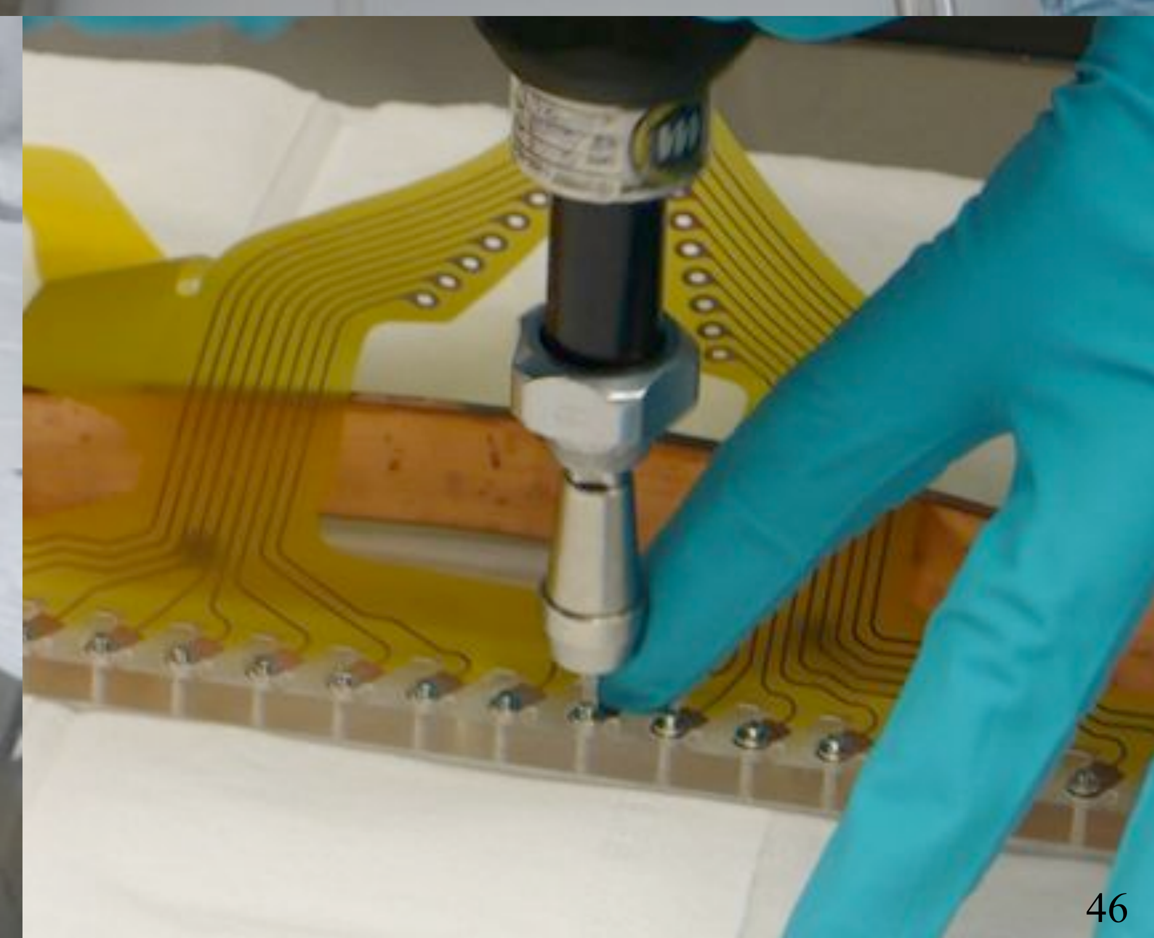
3. epoxy pot long cables in cryostat flanges

4. install long cables in legs, TPC in chamber and connect

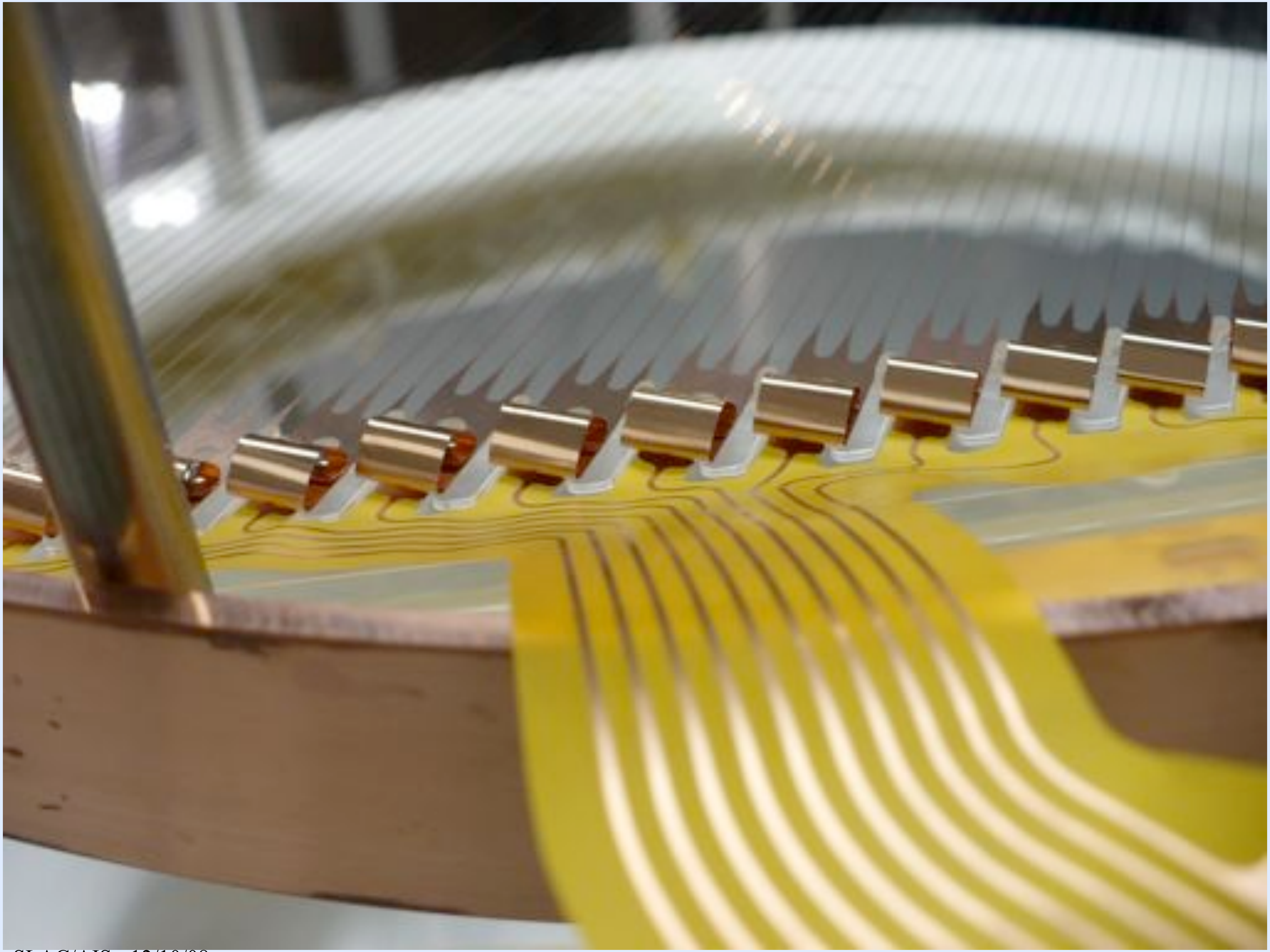
EXO-200 small wire cables installed on both halves of the TPC



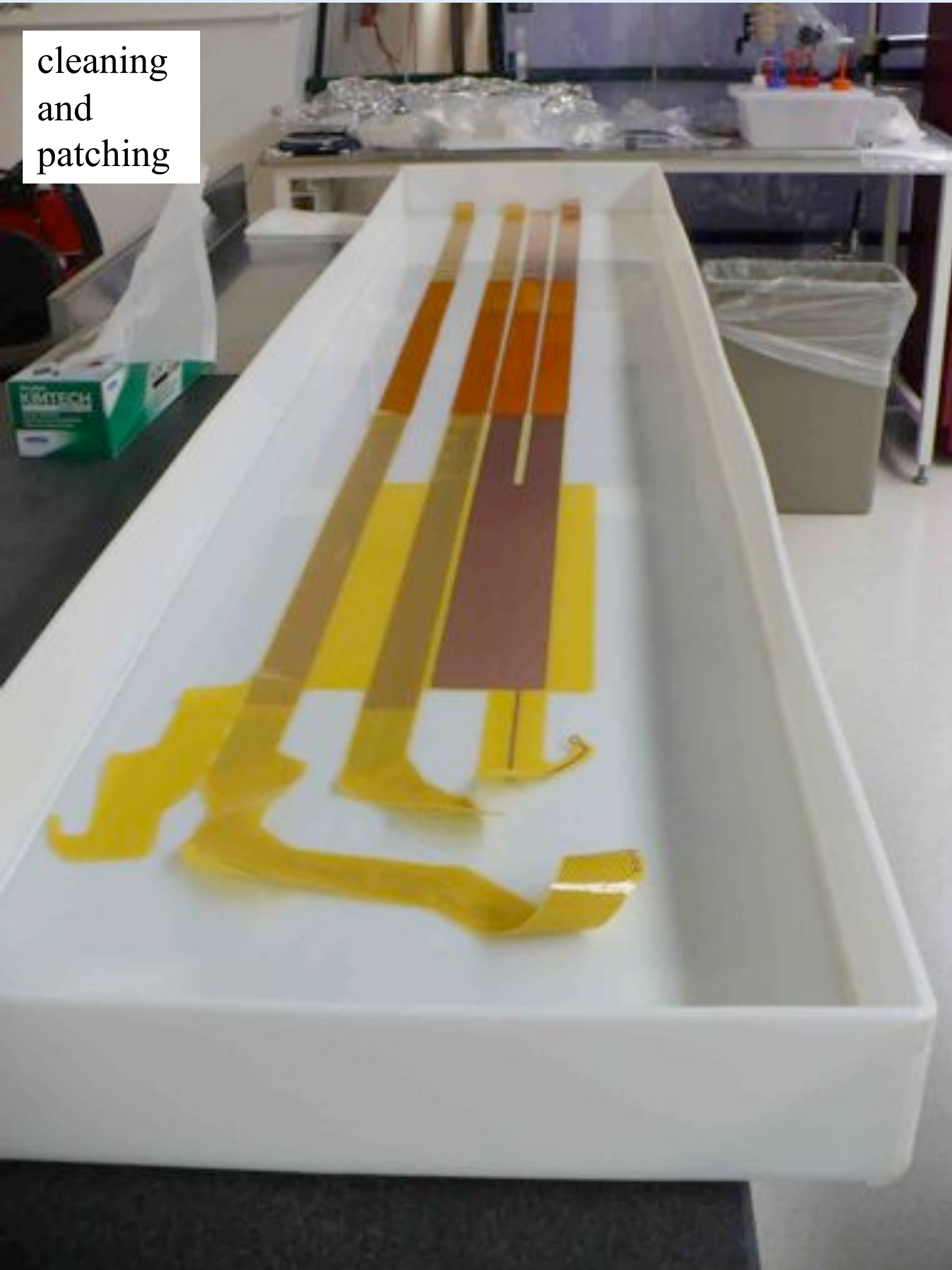




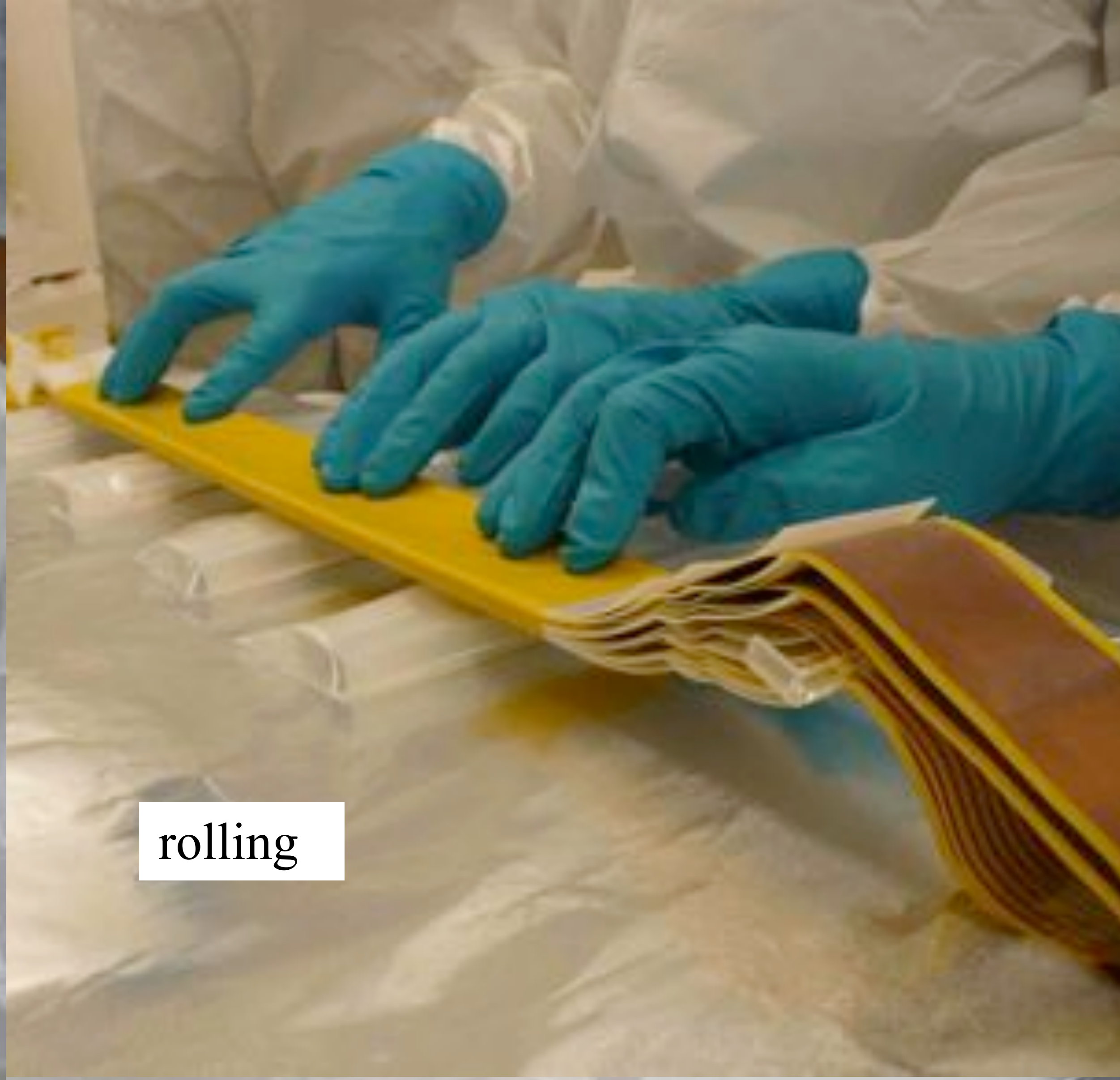
EXO-200 induction (y) wire fan-out



EXO-200 flat signal cable assembly



EXO-200 flat signal cable assembly

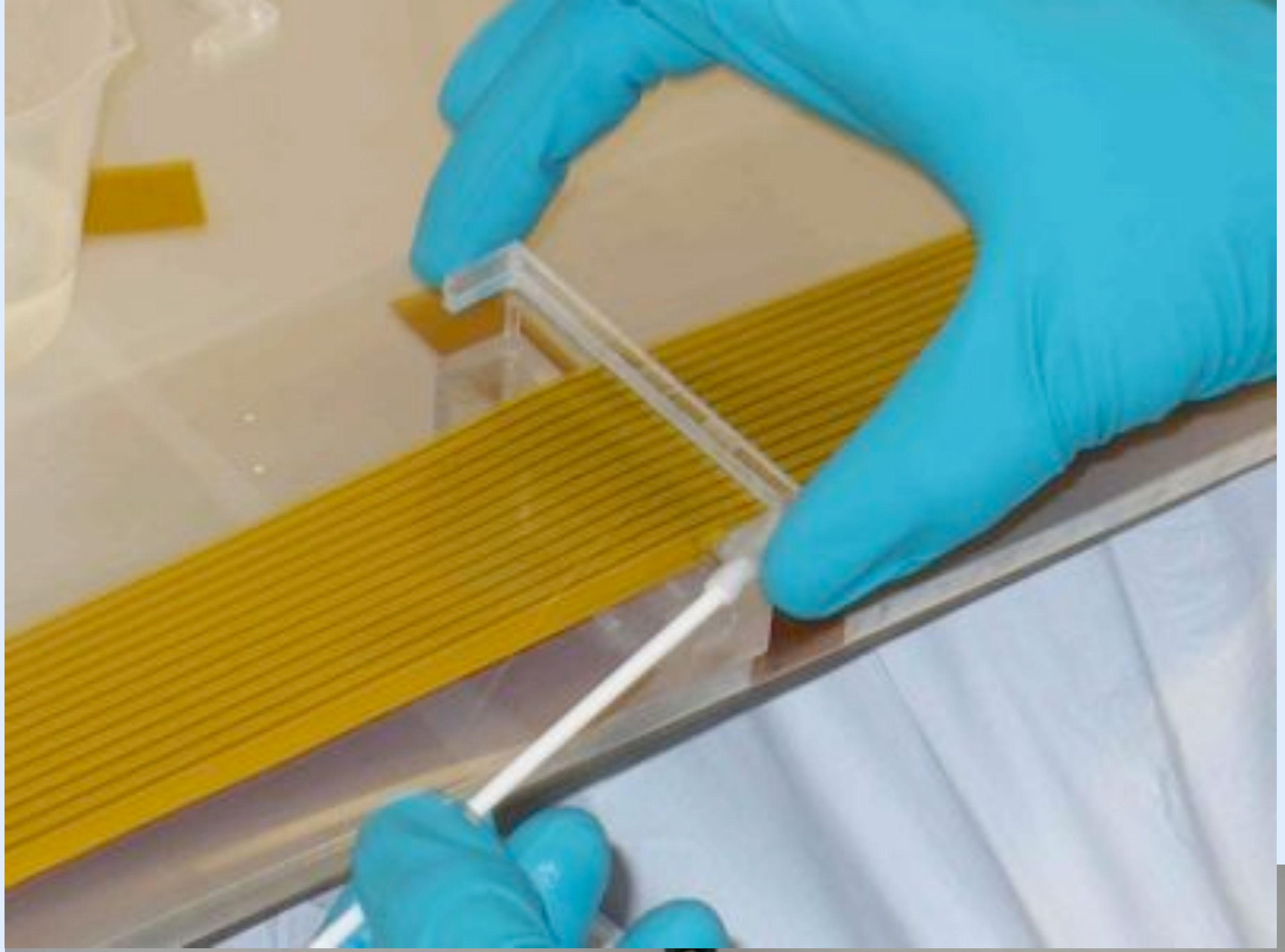


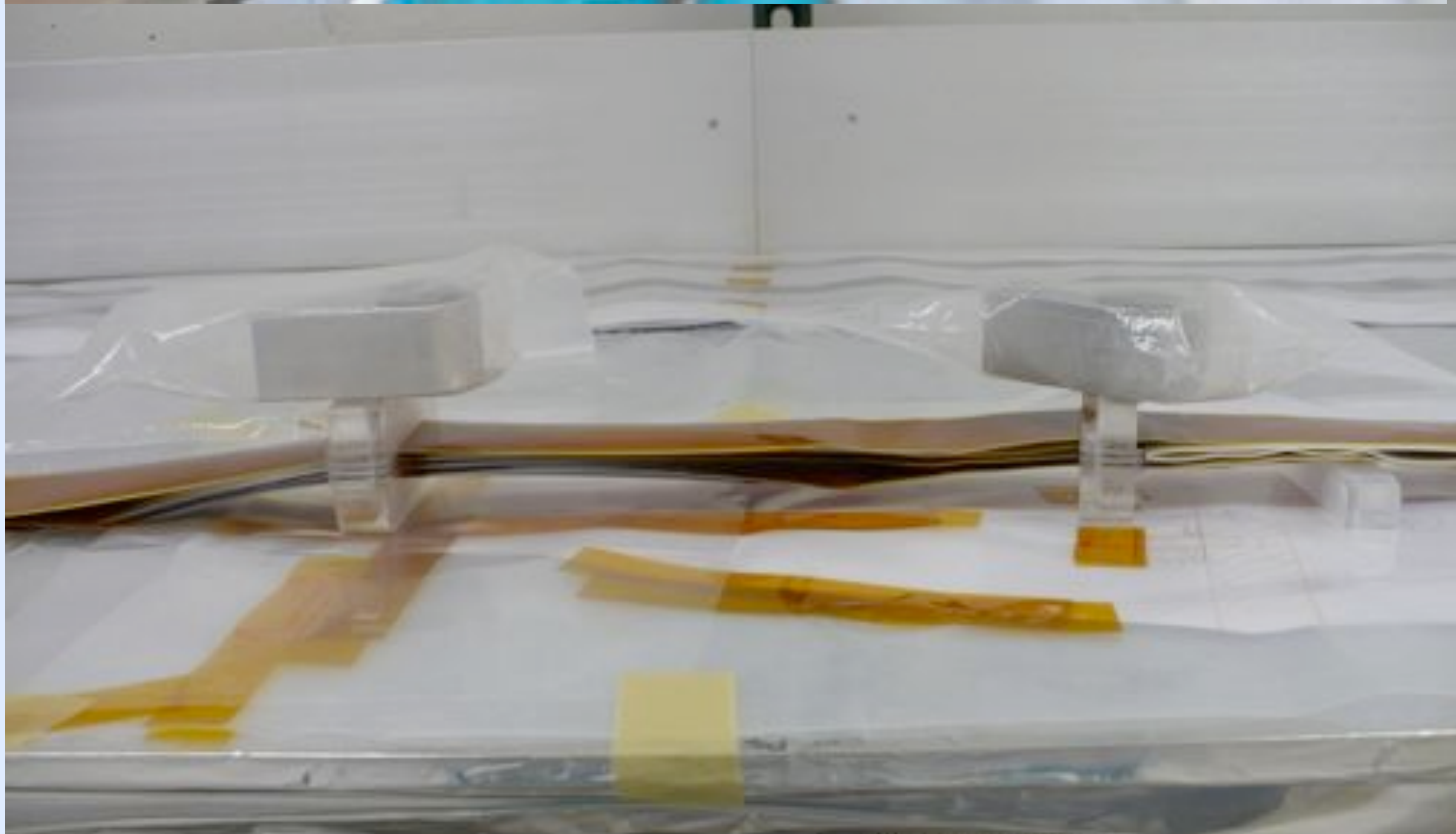
EXO-200 flat signal cable feedthroughs

after rolling, the flat cables are sealed in potted with a special cryogenic epoxy feedthrough flanges welded on the inner cryostat door

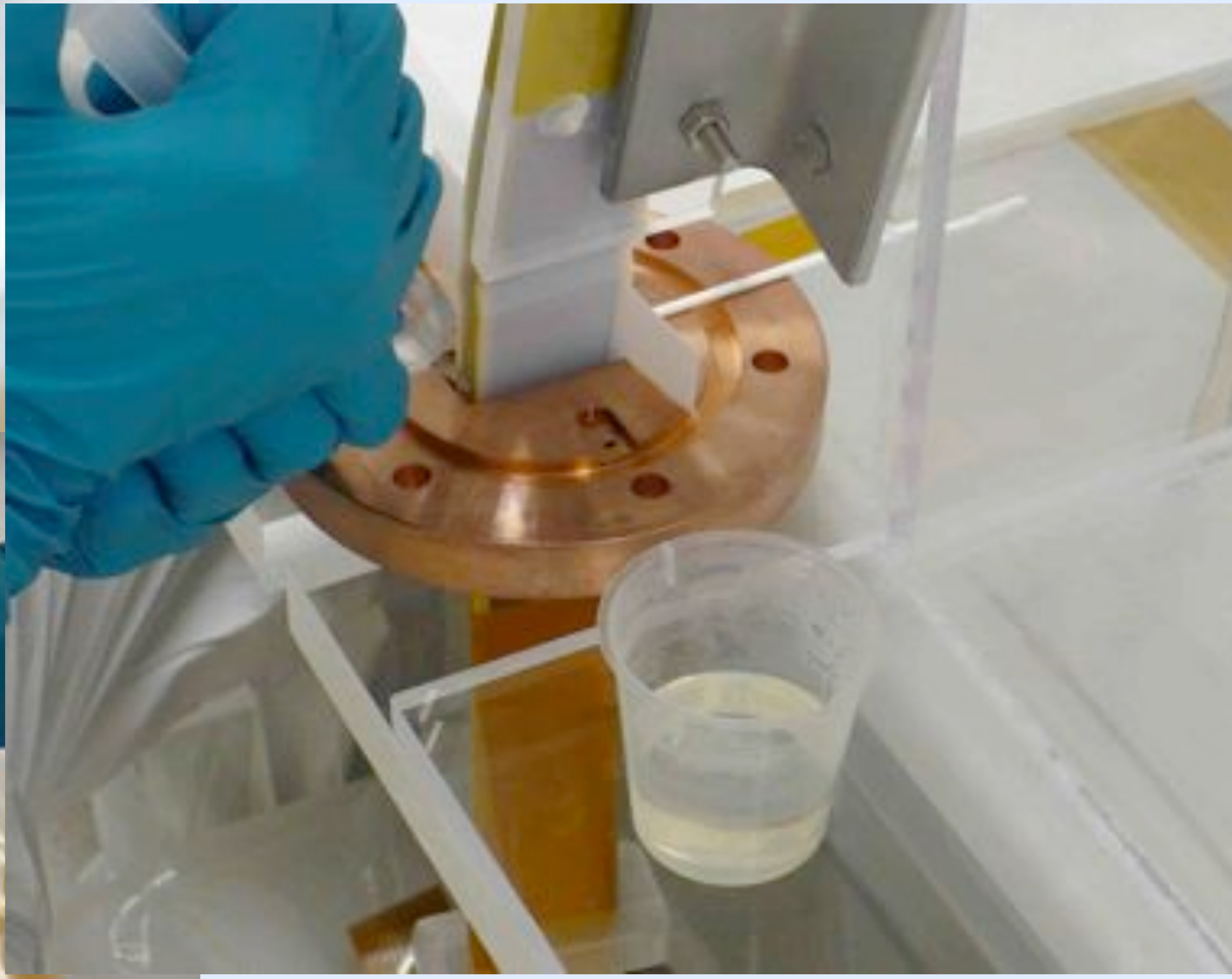
cables are first glued to acrylic fixtures, then glued to copper flanges with thin copper lips and controlled epoxy profile

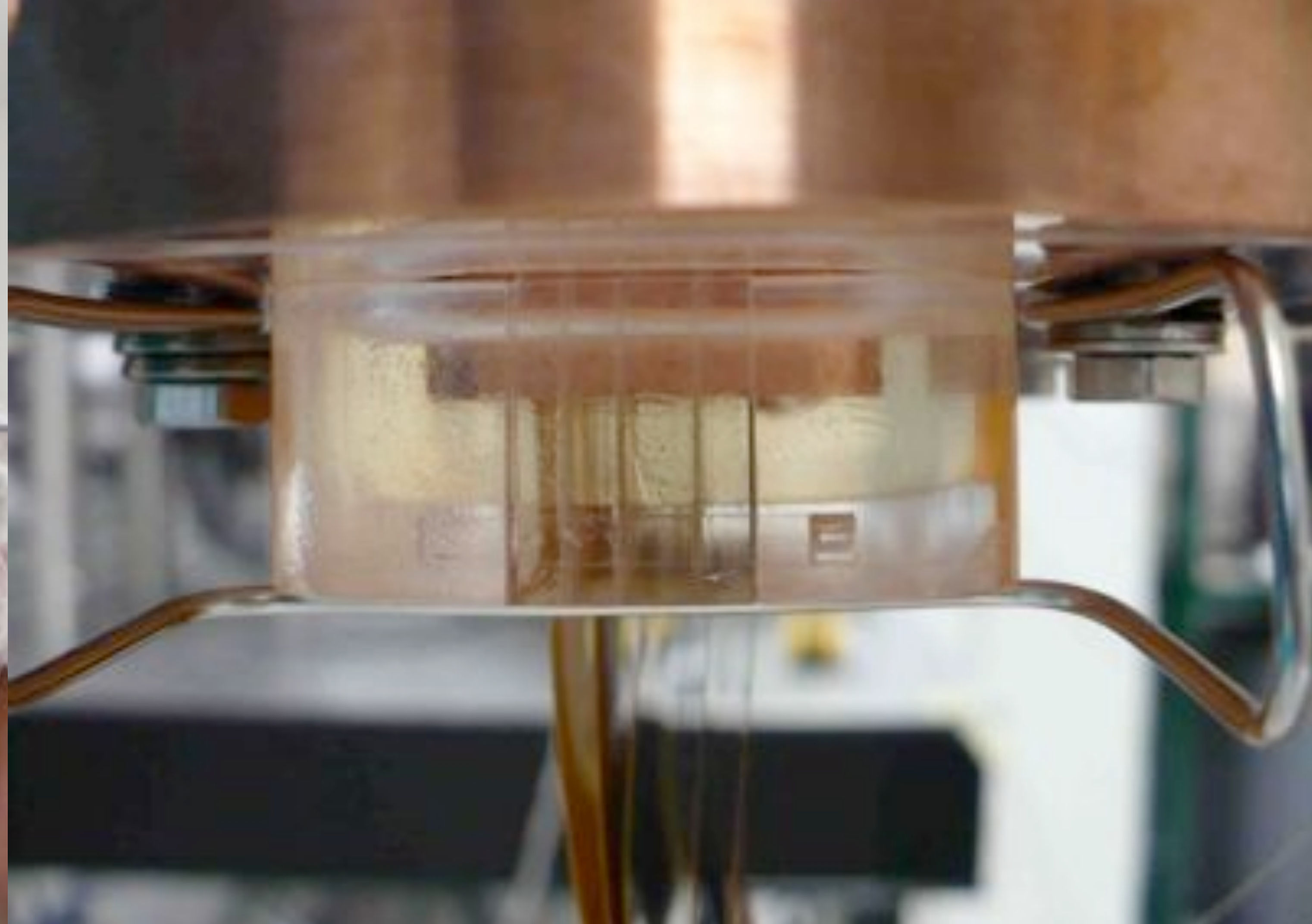
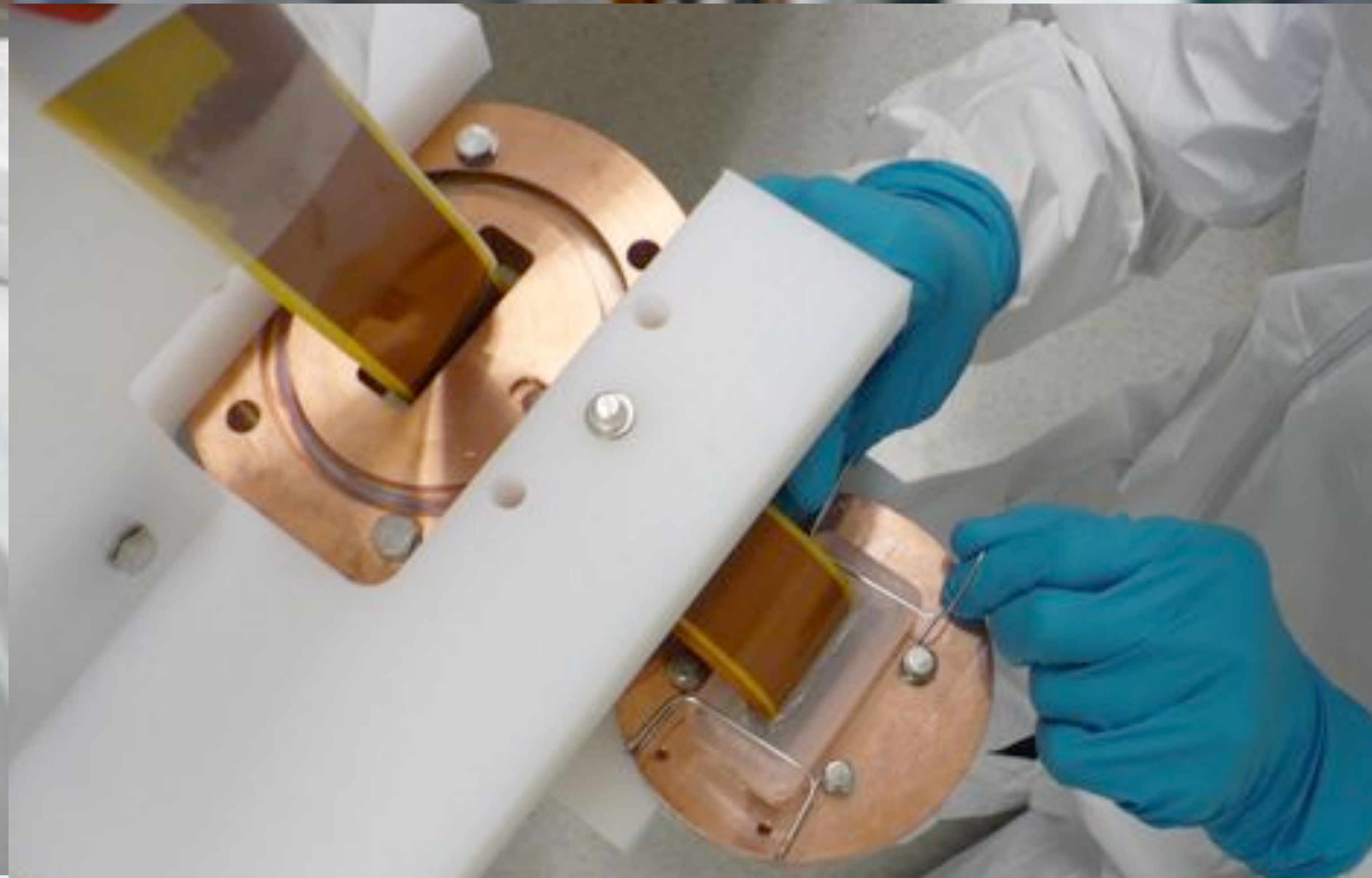
we succeeded in producing leak-tight feedthroughs and thermally cycling them several times

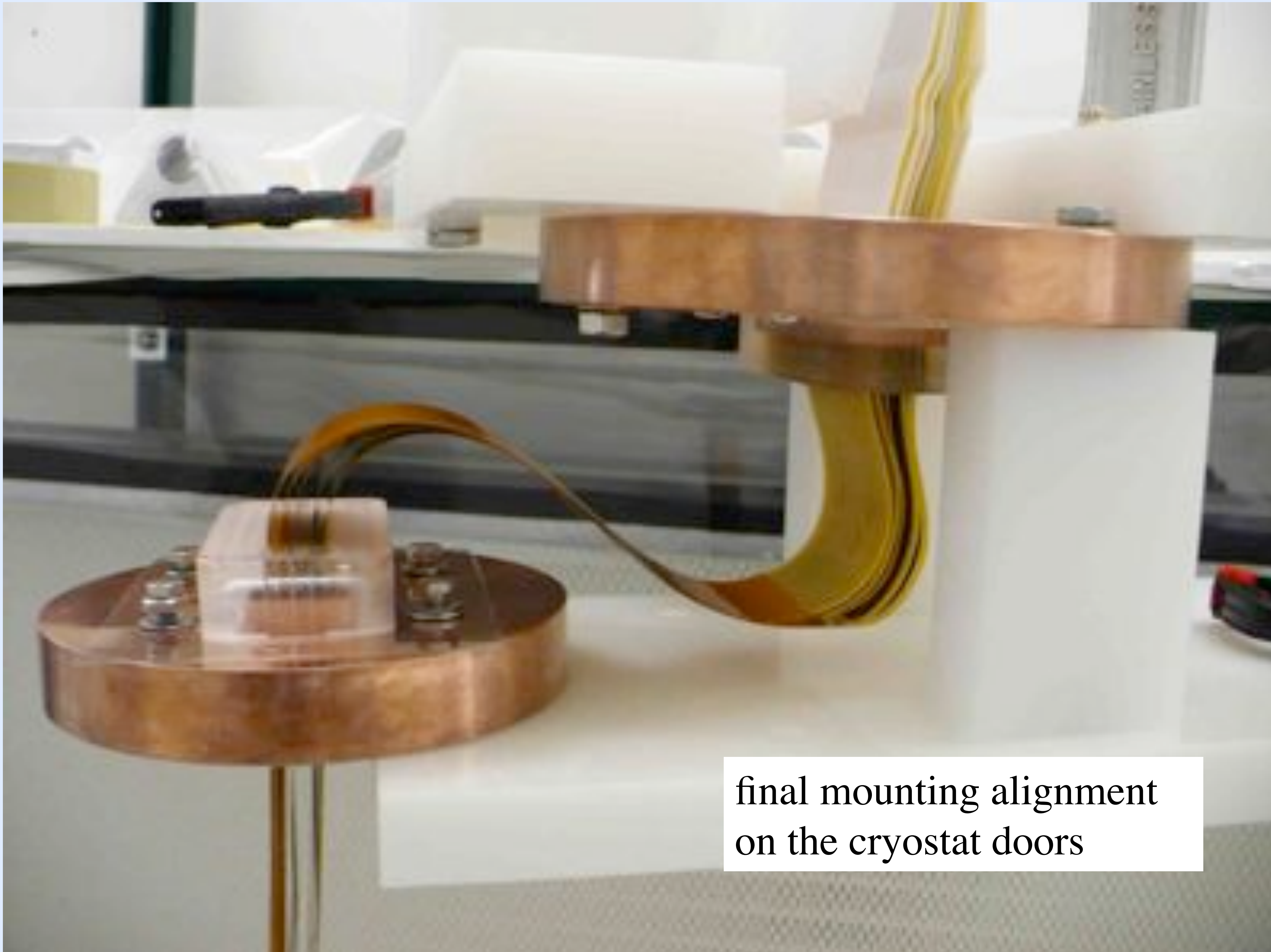




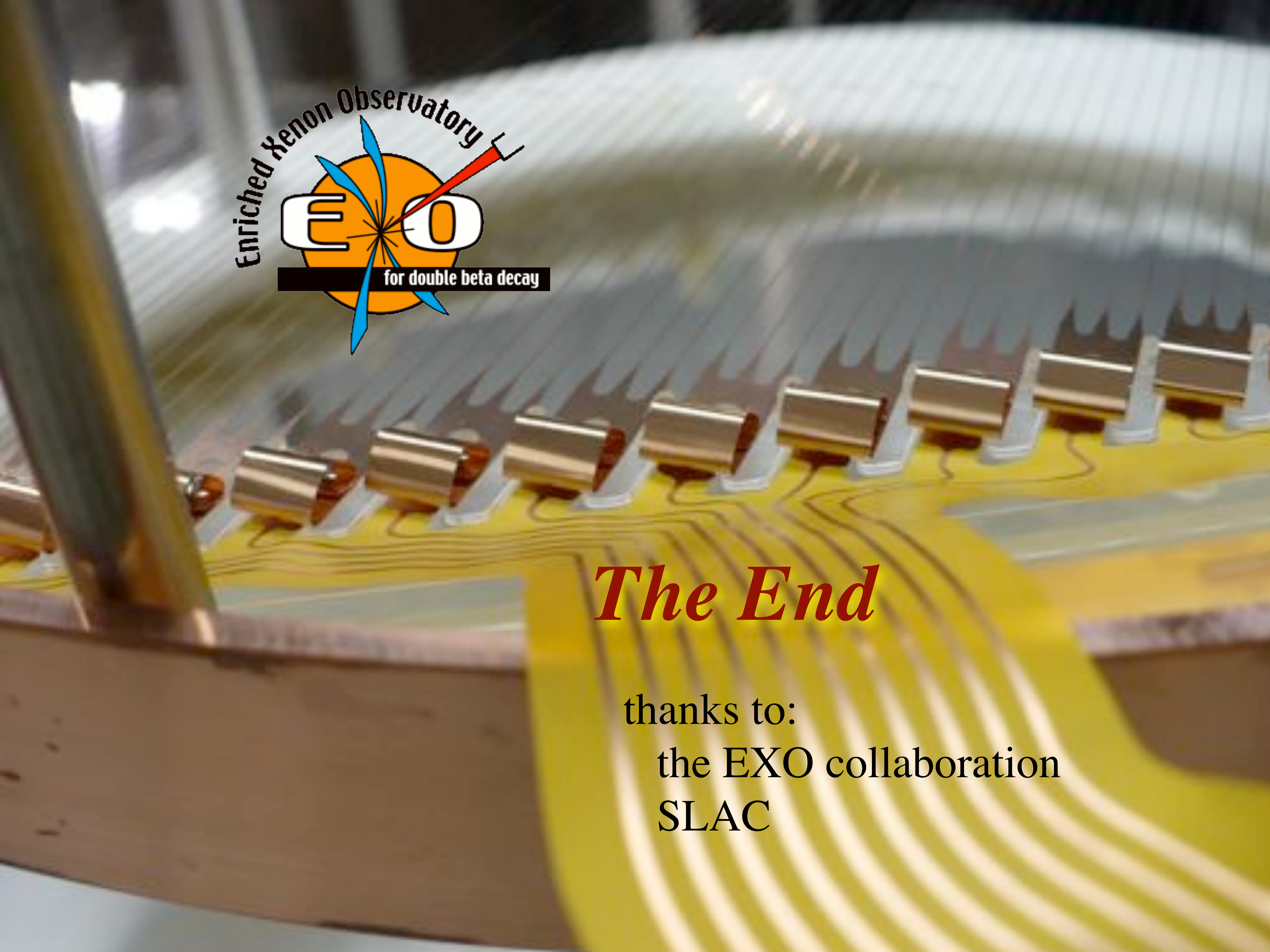
EXO-200 flat signal cable feedthroughs





final mounting alignment on the cryostat doors



Enriched Xenon Observatory

EXO

for double beta decay

The End

thanks to:

the EXO collaboration

SLAC