the Enriched Xenon Observatory for double-beta decay

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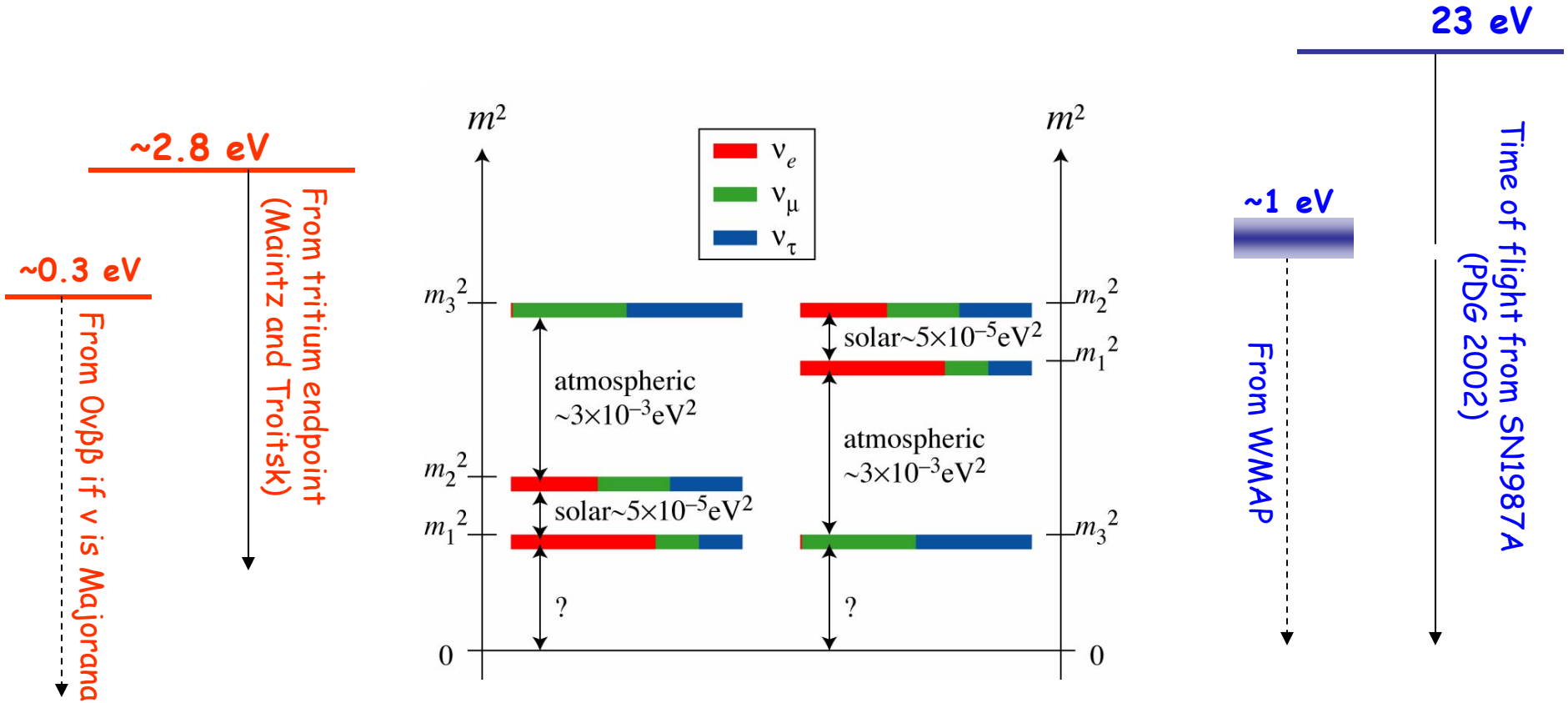
The most important question in neutrino physics:
Neutrino mass scale



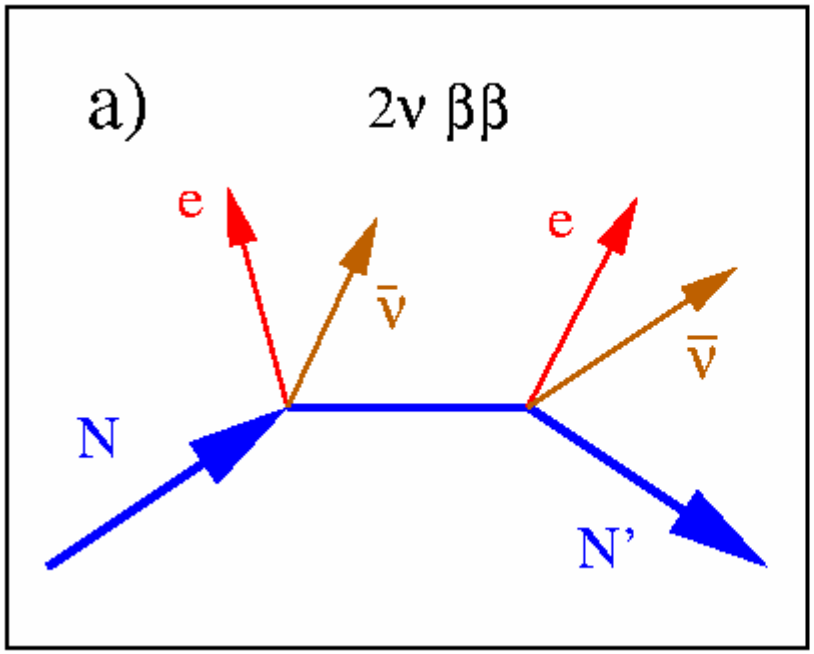
There are two varieties of ββ decay

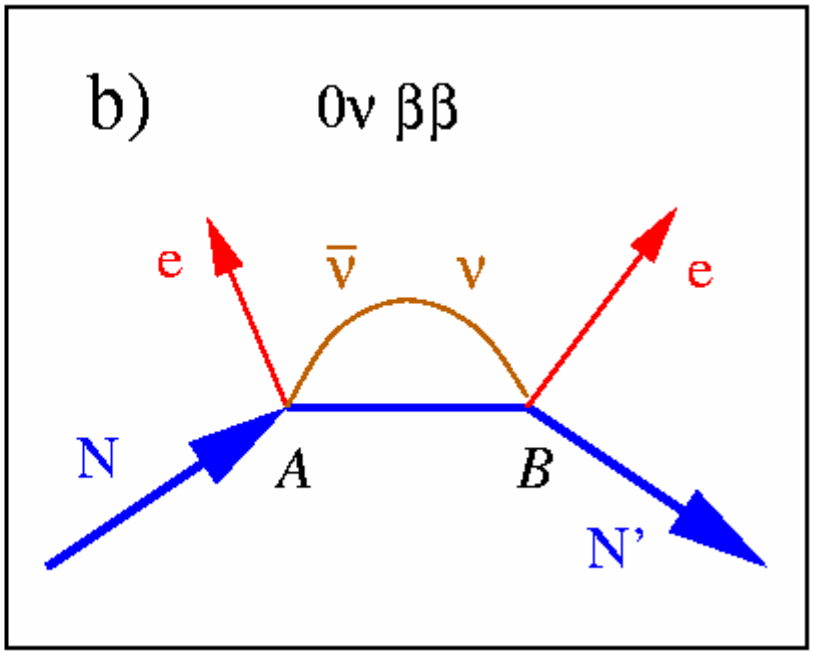
2ν mode: a conventional 2nd order process in nuclear physics

0ν mode: a hypothetical process can happen only if:

- $M_\nu \neq 0$
- $\overline{\nu} = \nu$

Since helicity has to "flip"

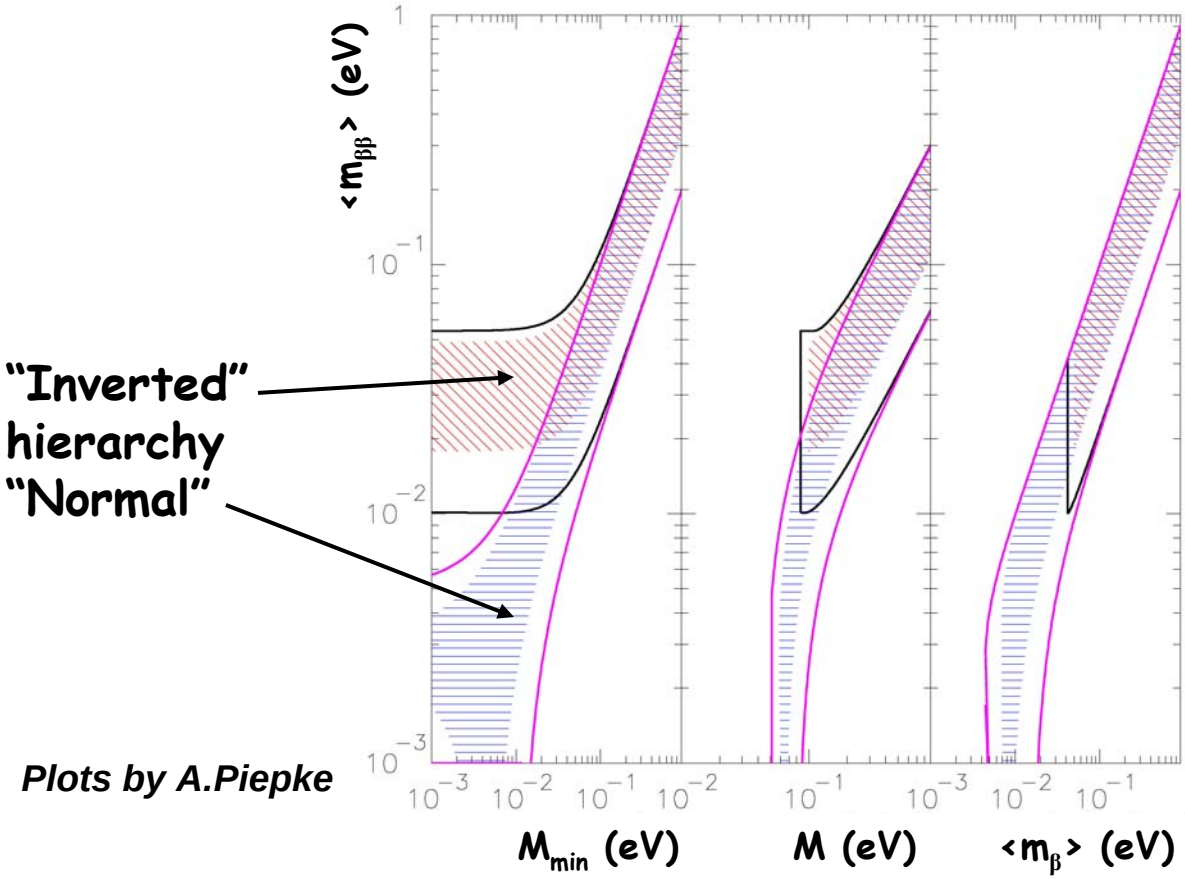




Discovering neutrino-less double-beta:

→ Discovery of the neutrino mass scale

→ Discovery of Majorana particles



Plots by A.Piepke

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

Need to shift gear and build a truly unambiguous, background free experiment !

To reach $\langle m_\nu \rangle$ ~ 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 want a multi-parameter experiment, so that possible discovery can be backed-up by cross checks with more than one single variable

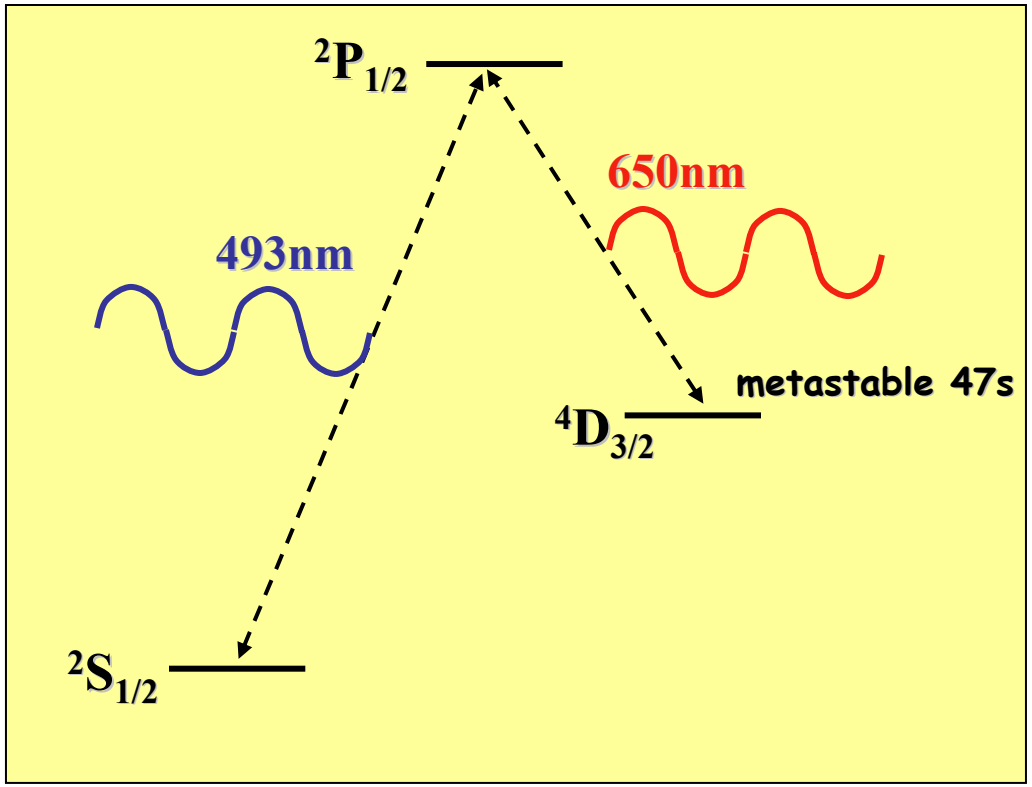
Xe is ideal for a large experiment

- 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

Energy resolution is still an all-important parameter to disentangle the 0νββ mode from 2νββ

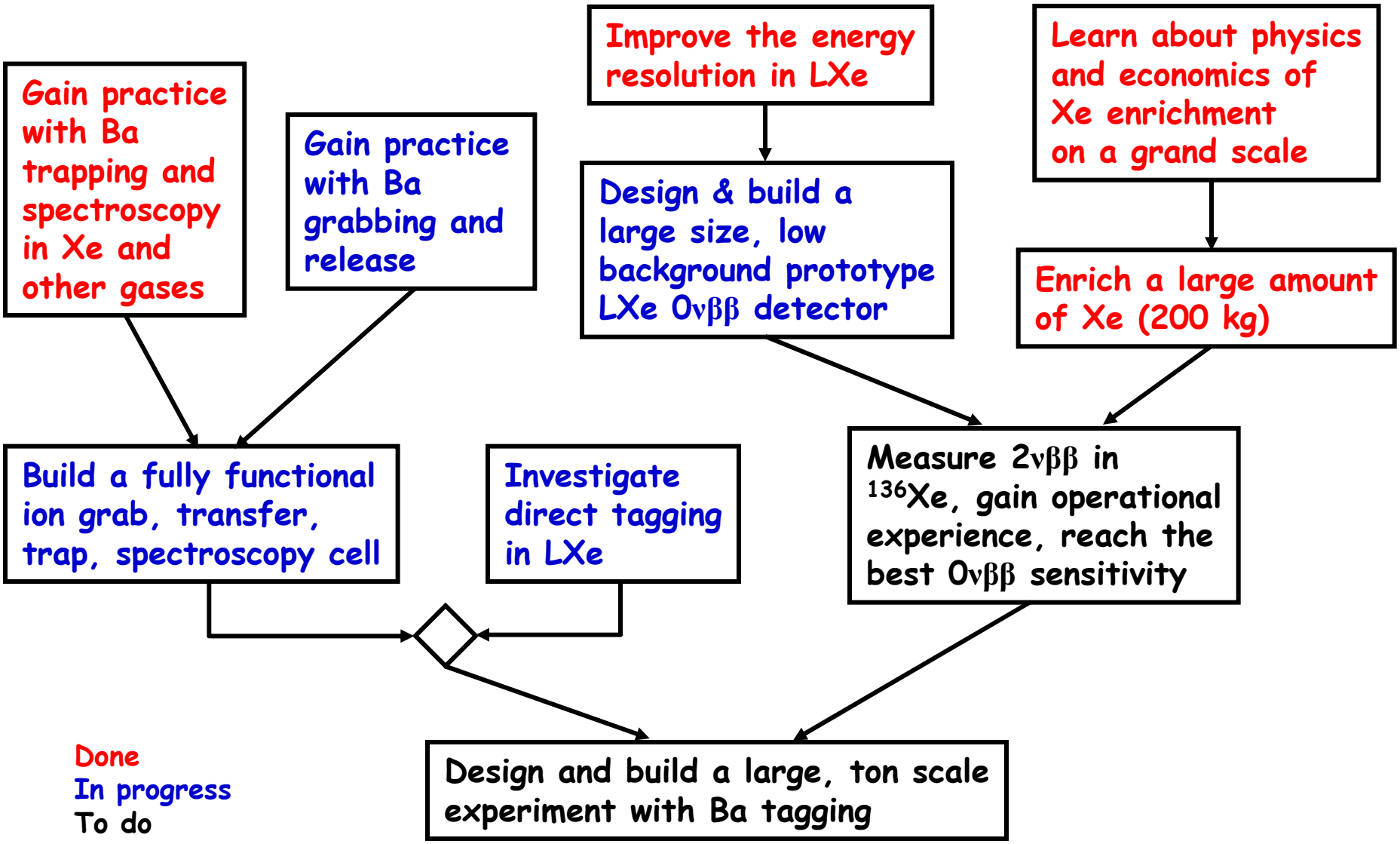
Assume an "asymptotic" fiducial mass of 10 tons of ^{136}Xe at 80%

A somewhat natural scale:

- World production of Xe is ~30 ton/yr
- Detector size
- $2 \cdot 10^3$ size increase: good match to the 10^{-2} eV mass region

Mainly going in light bulbs and satellite propulsion

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



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)	$2*10^{27}$	50	68
Aggressive	10	70	10	1†	0.7 (use 1)	$4.1*10^{28}$	11	15

* 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 Phys Rev C 68 (2003) 044302

Courier et al. Nucl Phys A 654 (1999) 973c

EXO-200:
an intermediate detector without Ba tagging

- Need to test detector technology, particularly the LXe option:
  A 200 kg chamber is close to the largest Xe detector ever built and hence good training ground
- Essential to understand backgrounds from radioactivity:
  200 kg is the minimum size for which the self-shielding is important and there is negligible surface inefficiency
- Using ^{136}Xe can hope to measure the "background" $2\nu\beta\beta$ mode:
  200 kg is needed to have a chance (if do not see the mode then is really good news for the large experiment !!)
- The production logistics and quality of ^{136}Xe need to be tested:
  Need a reasonably large quantity to test production
- Already a respectable (20x) $\beta\beta$ decay experiment
- No need for Ba tagging at this scale

Fully funded

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 ($T_{1/2} > 1 \cdot 10^{22}$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
Prototype	0.2	70	2	1.6*	40	$6.4*10^{25}$	0.27†	0.38♦

What if Klapdor's observation is correct ?

Central value $T_{1/2}$ (Ge) = $1.2^{+3}_{-0.5} \cdot 10^{25}$, (±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

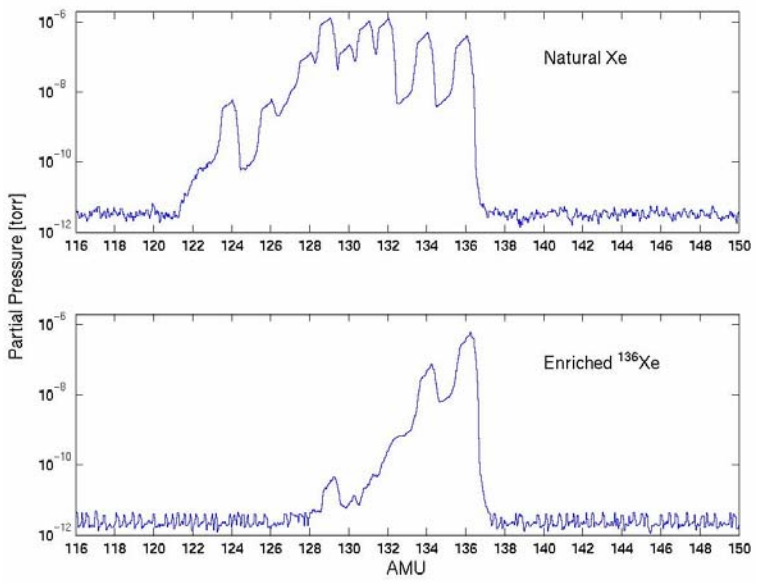
Status of 2ν mode in ^{136}Xe

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

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 ββ isotope (by ~factor of 10)

EXO-200 TPC basics

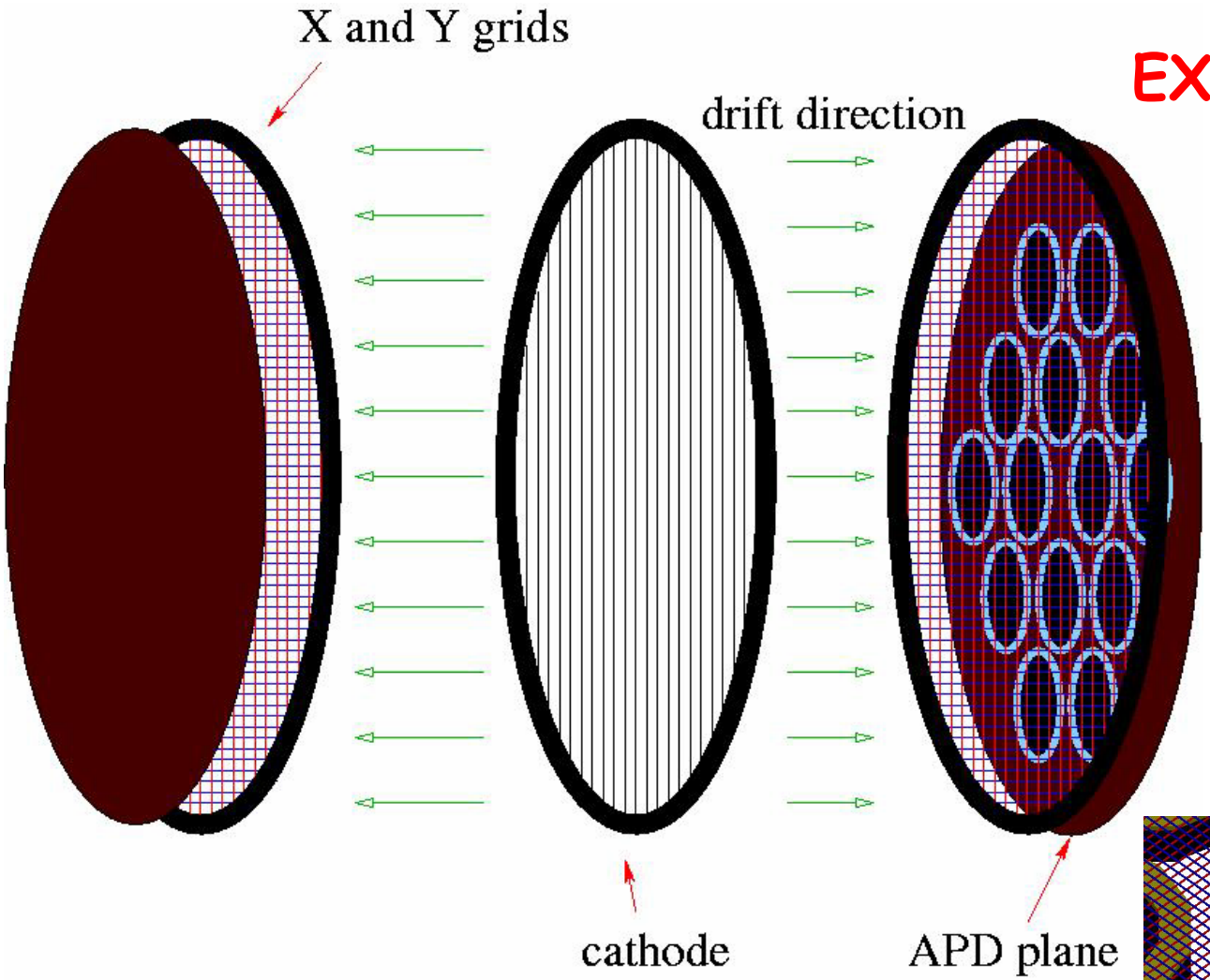
- The detector measures both the ionization electrons and the scintillation light to get best energy resolution.
  - In addition, the position of the decay is measured to get spatial distributions and (for later) the position of the Ba ion.
  - Info on event topology also important for background separation.

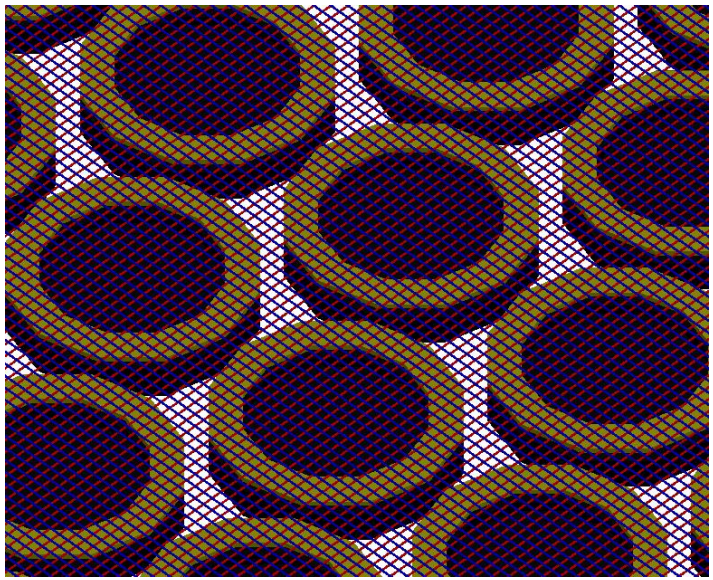
- The detector is a cylinder of ~40cm ID by ~40cm inner length.

- 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

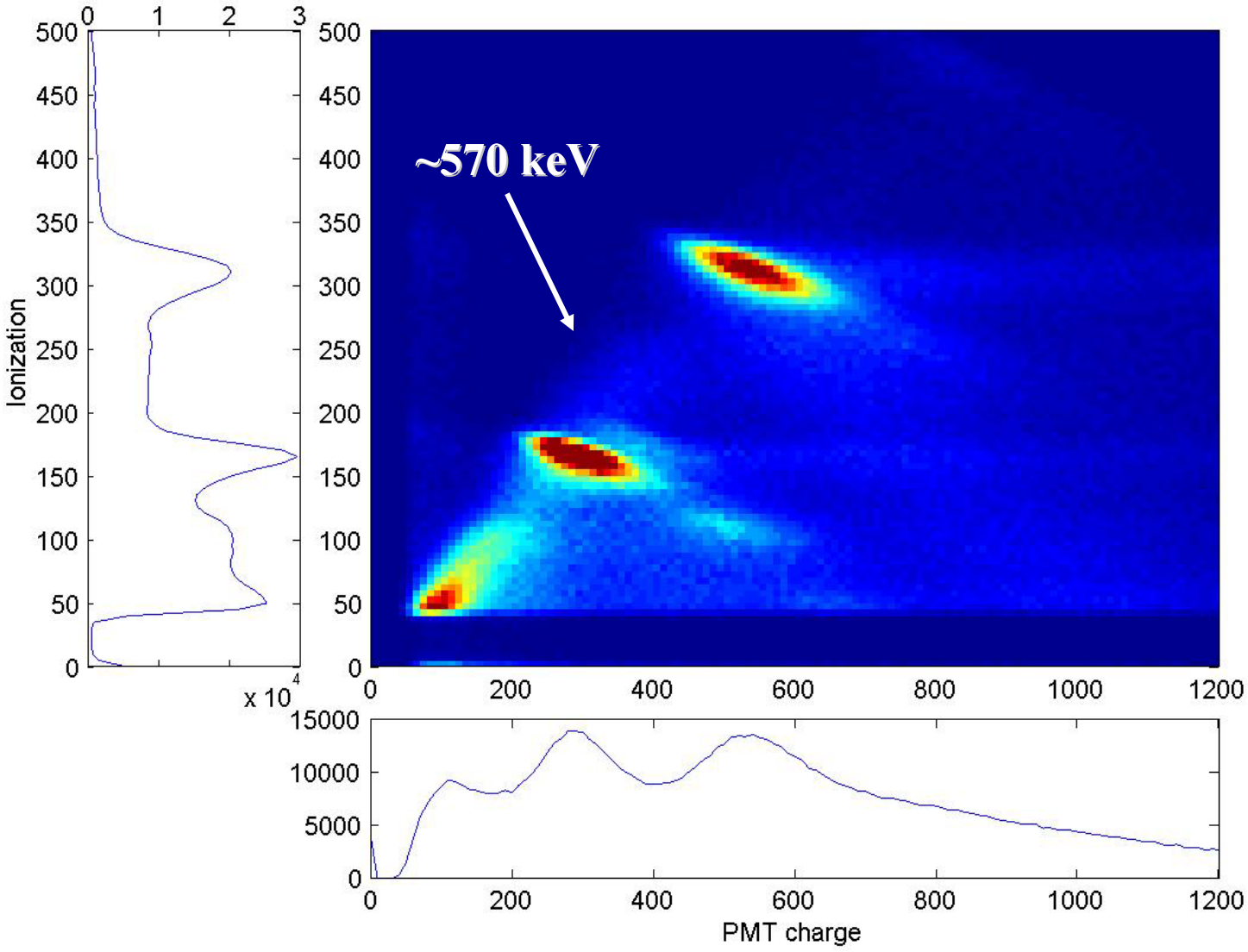
- Readout "style":
  - Crossed wires, 100μm wires, 3mm pitch, ganged in groups of 3
    48ch x, 48ch y, total 96 ch per 1/2 detector
    (Pad readout rejected because of high channel count)

EXO-200 TPC basics

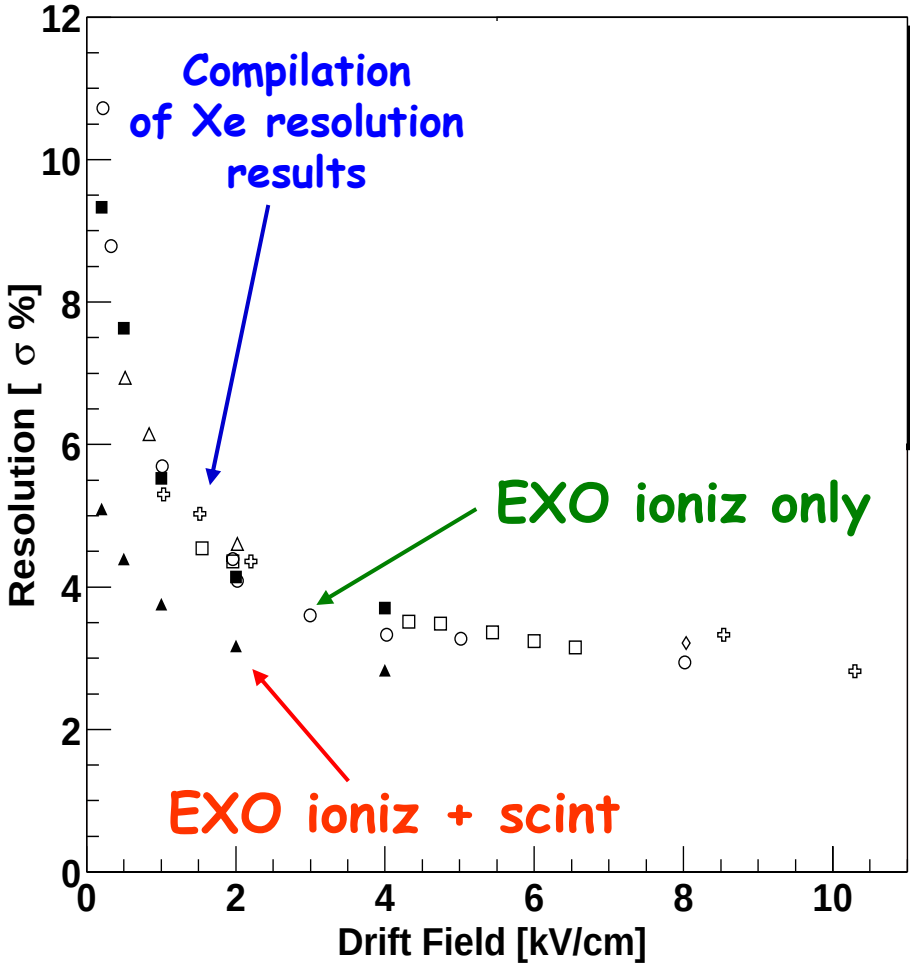




EXO R&D showed the way to improved energy resolution in LXe: *Use (anti)correlations between ionization and scintillation signals*



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



Ionization alone:
σ(E)/E = 3.8% @ 570 keV
or 1.8% @ $Q_{\beta\beta}$

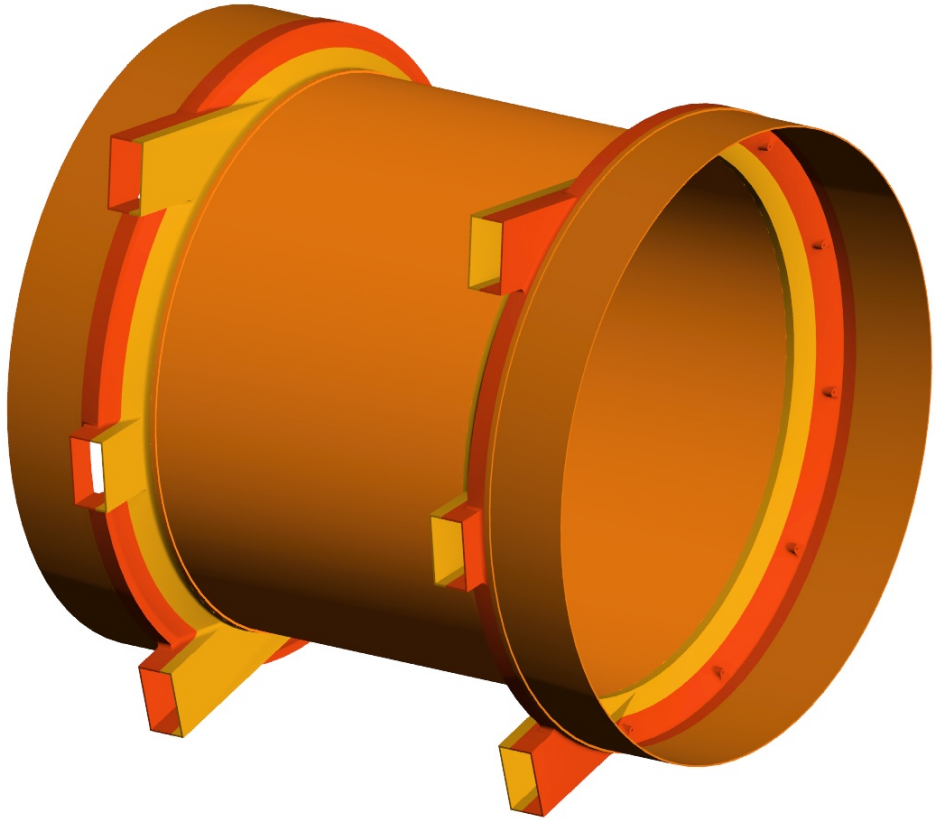
Ionization & Scintillation:
σ(E)/E = 3.0% @ 570 keV
or 1.4% @ $Q_{\beta\beta}$
(a factor of 2 better than the Gotthard TPC)

E.Conti et al. Phys. Rev. B: 68 054201

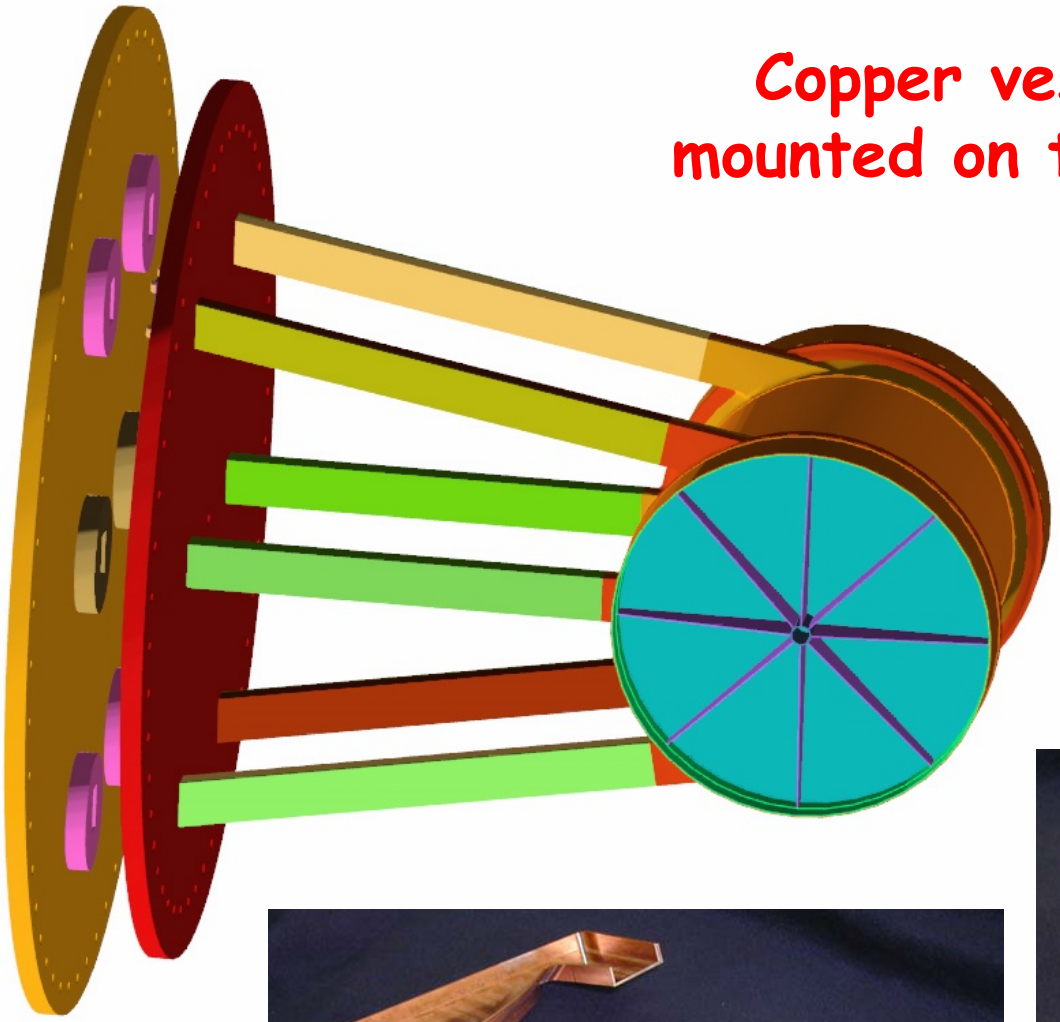
EXO-200 will collect 3-4 times as much scintillation… further improvement possible

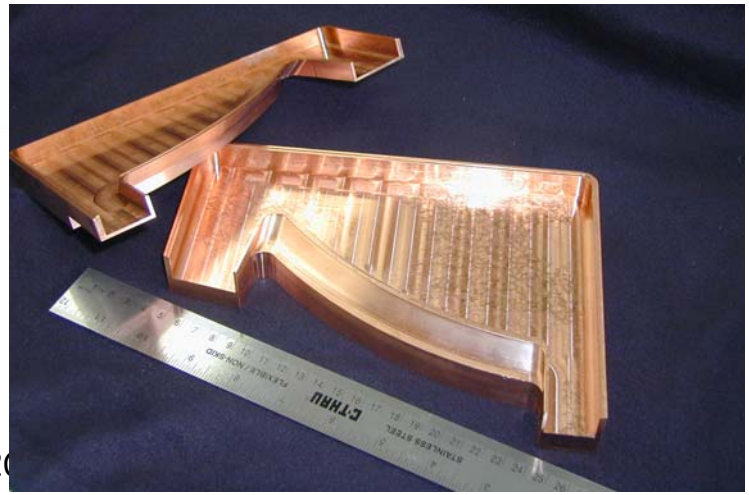
Ultra-low activity Cu vessel

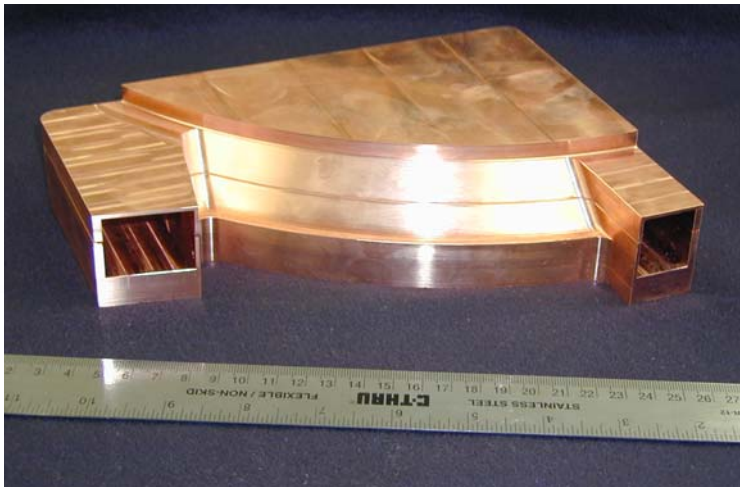
- Very light (~1.5mm thin, ~15kg) to minimize materials
- Best copper (already purchased in Germany)
- Different parts e-beam welded together
- Field TIG weld(s) to seal the vessel after assembly (TIG technology tested for radioactivity)
- All machining done by the Stanford Physics shop in the HEPL building (CR shielding)
- Test parts already built



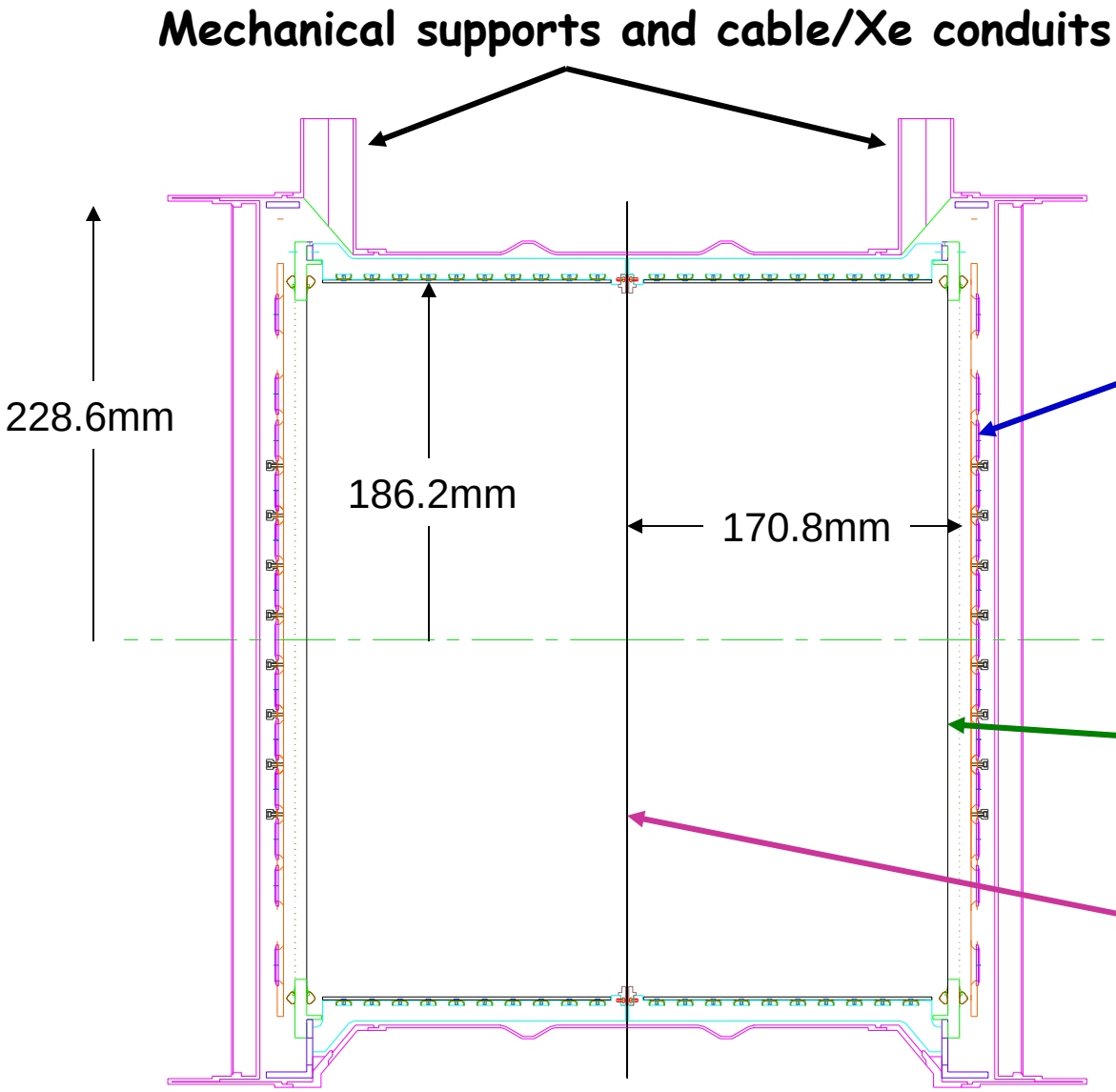
Copper vessel with services mounted on the cryostat flanges







What's inside the vessel ?

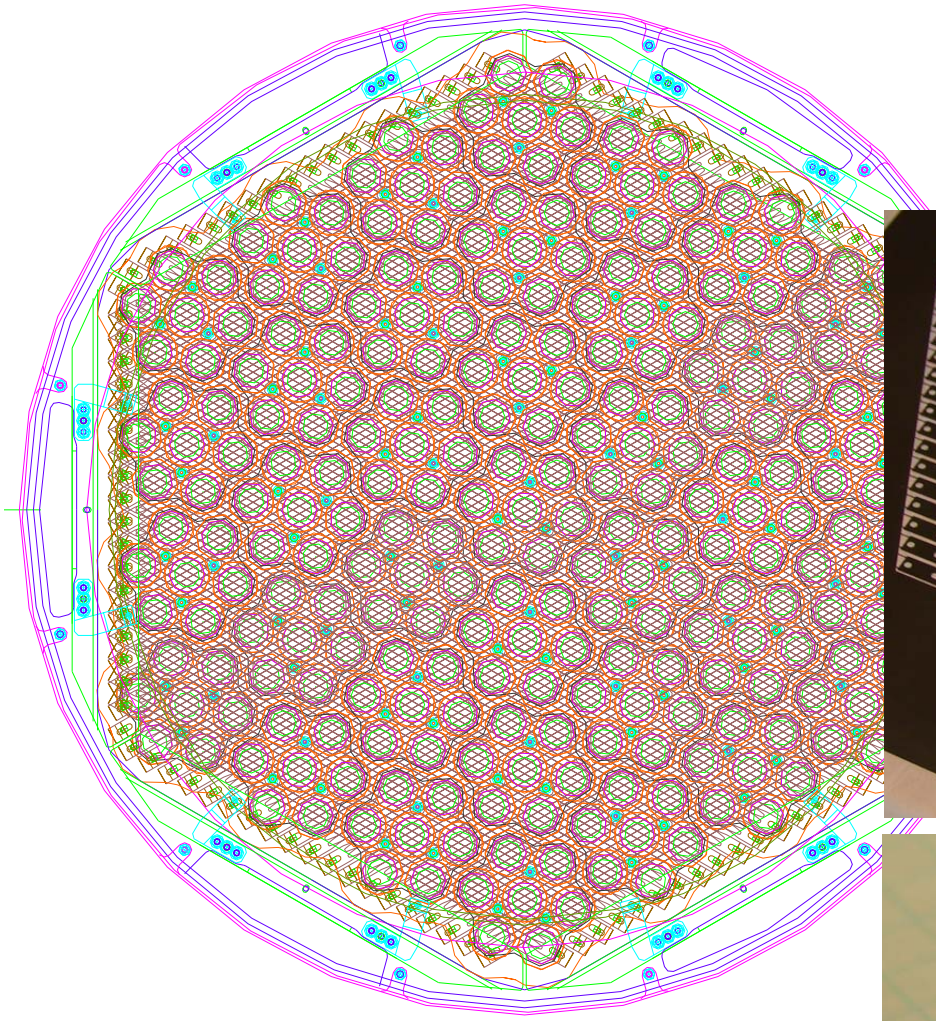


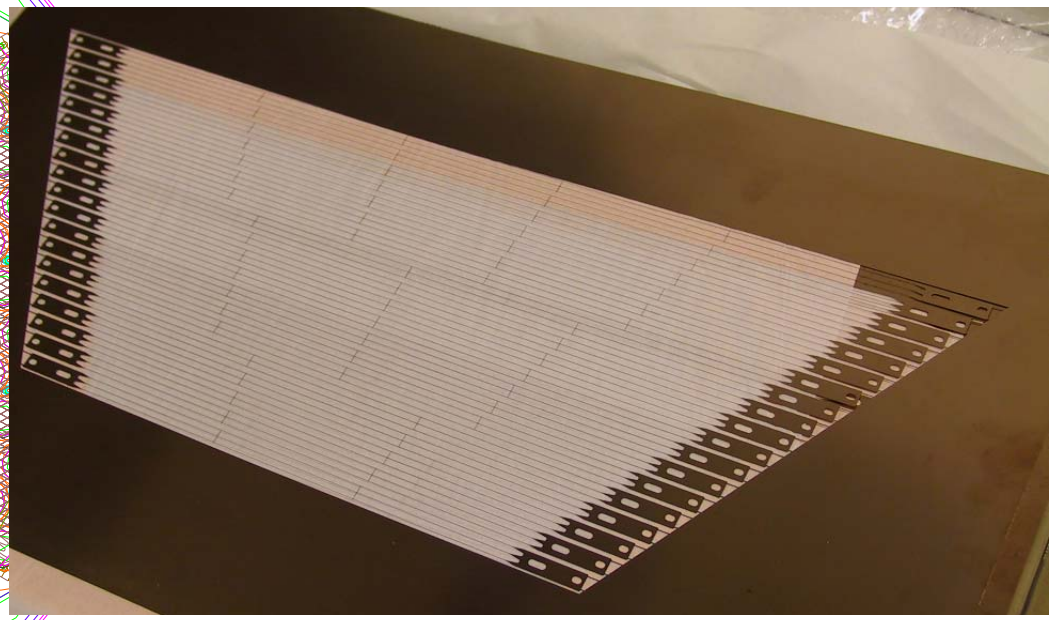
2x300 large area (1.6cm active diameter) unmounted APDs [first massive use of bare APDs for VUV detection]

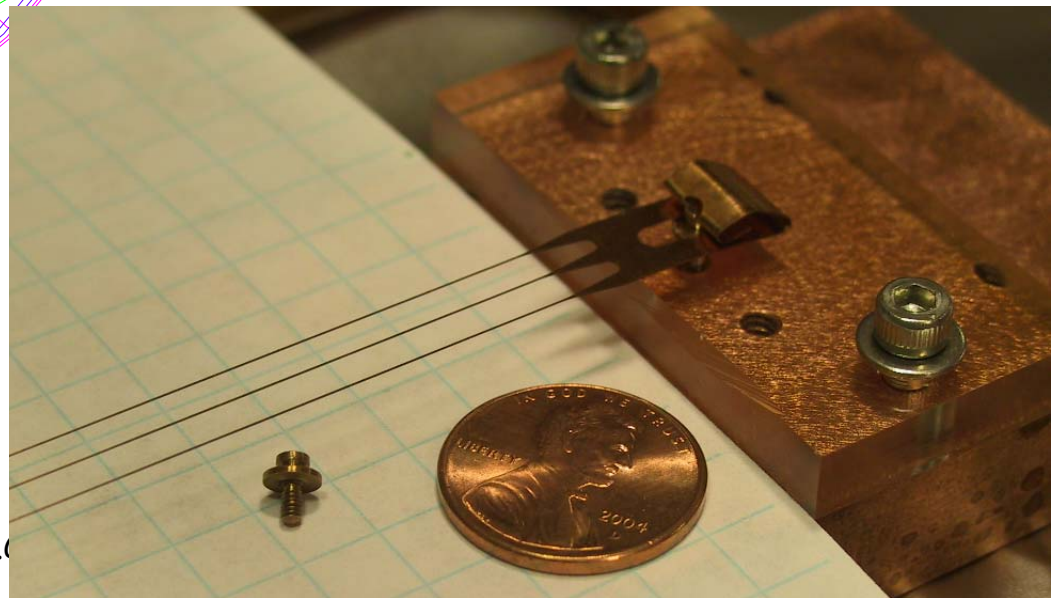
Inductive and charge collecting wire planes

Cathode grid

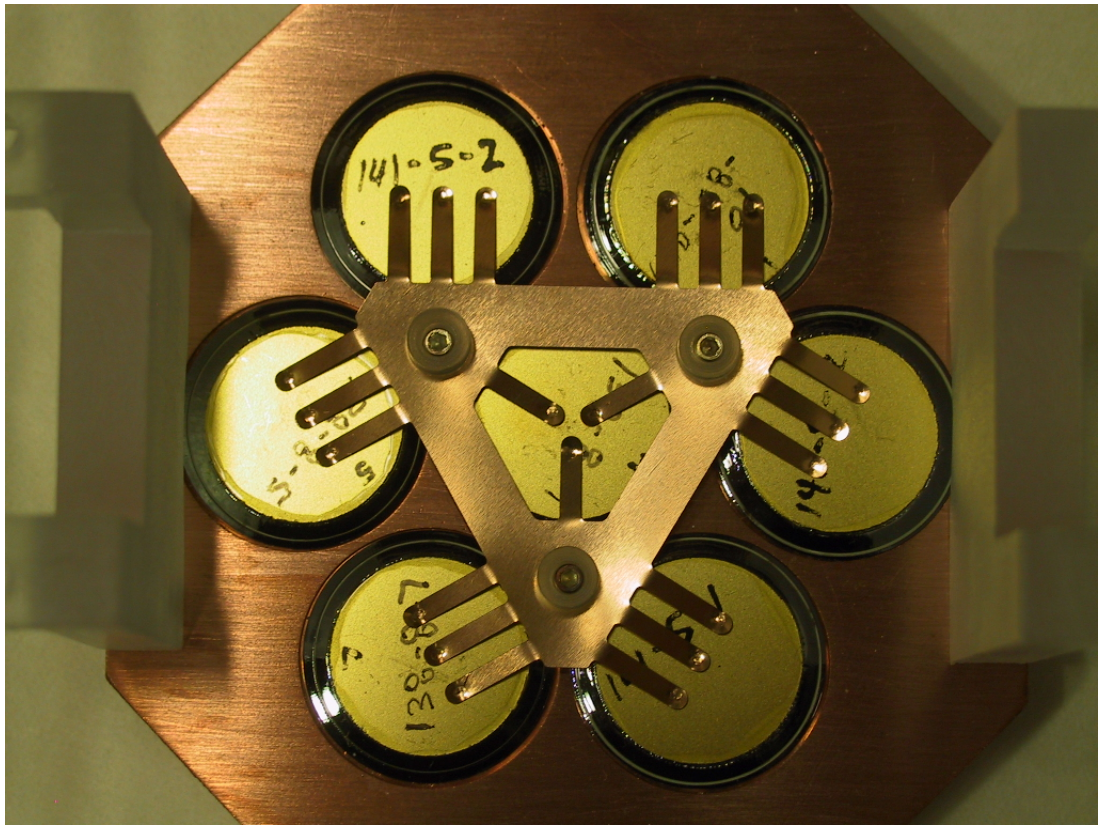
One readout pancake







Bare LAAPD from Advanced Photonix



APDs are ideal for our application:
- very clean & light-weight,
- very sensitive to VUV

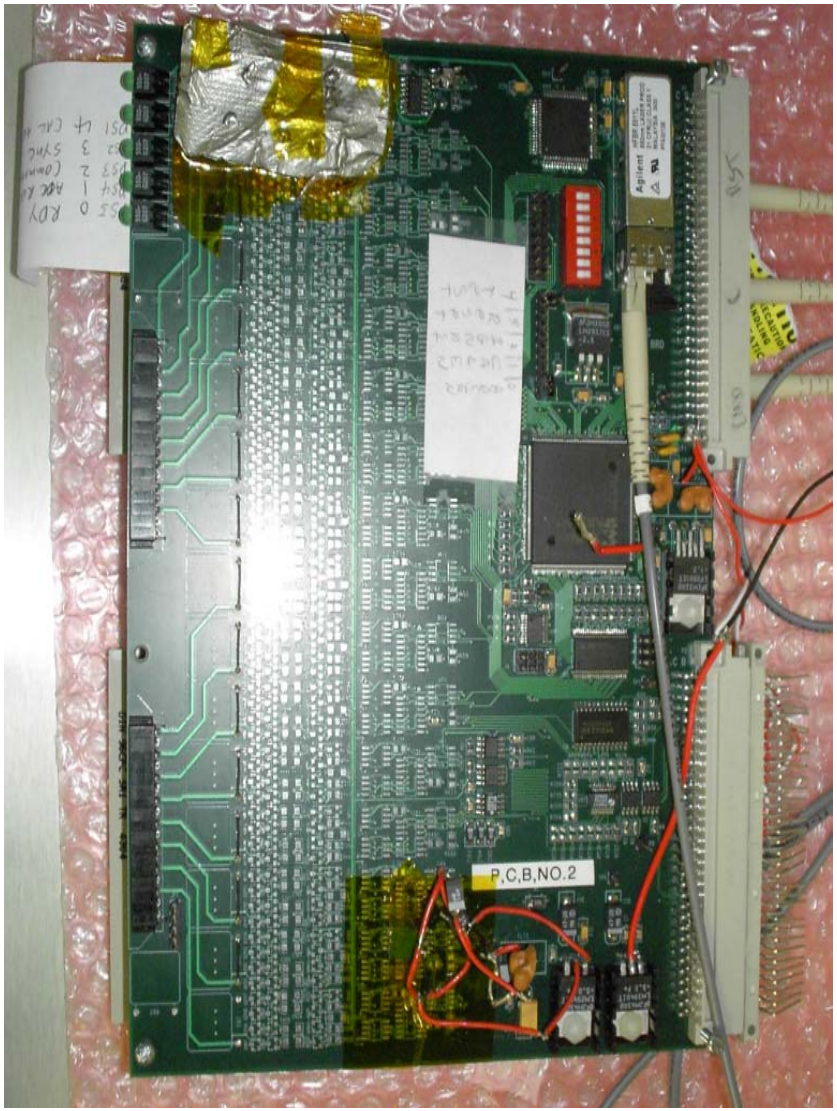
QE > 1 at 175nm

Gain set at 100-150

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

APDs ordered:
- pre-delivery (20ea) in hand
- monthly deliveries
- 600ea by Summer 2006

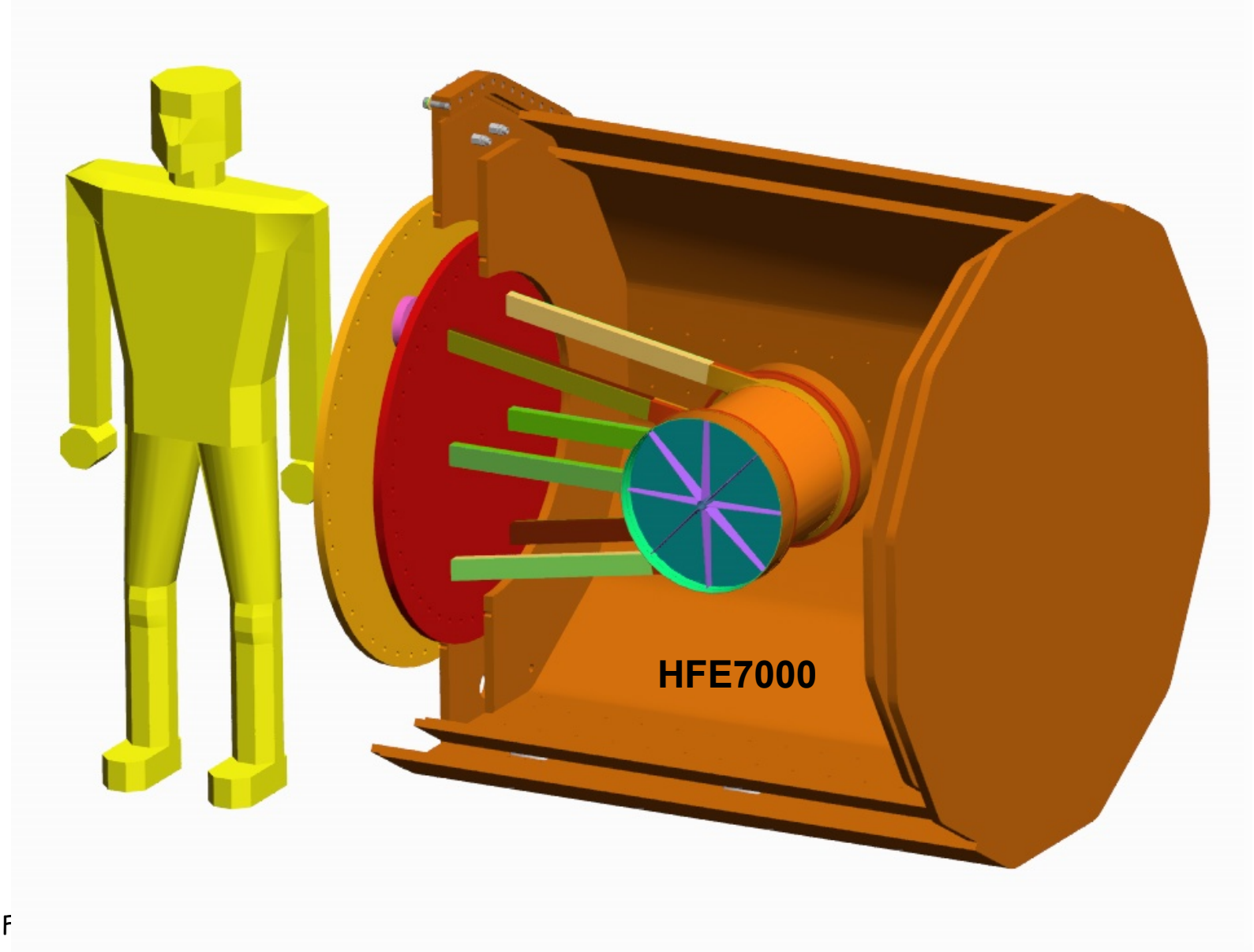
Electronics in production



Front-end board

Trigger module

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

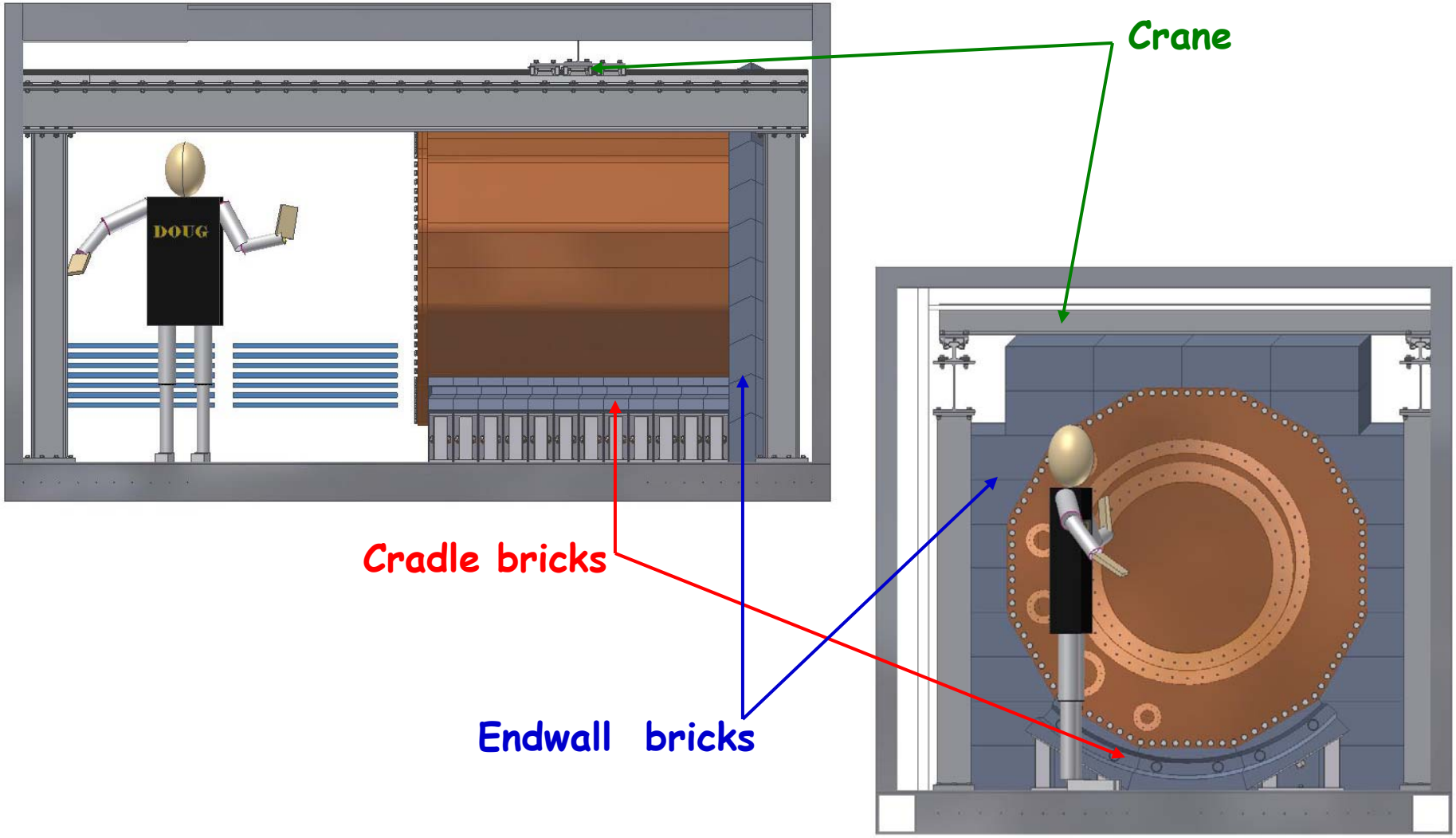


Cryostat was fabricated at SDMS (Grenoble)

Extensive use of e-beam welding to reduce radioactive contamination

Already in the US, traveling from NY to Stanford (via surface because of activation)

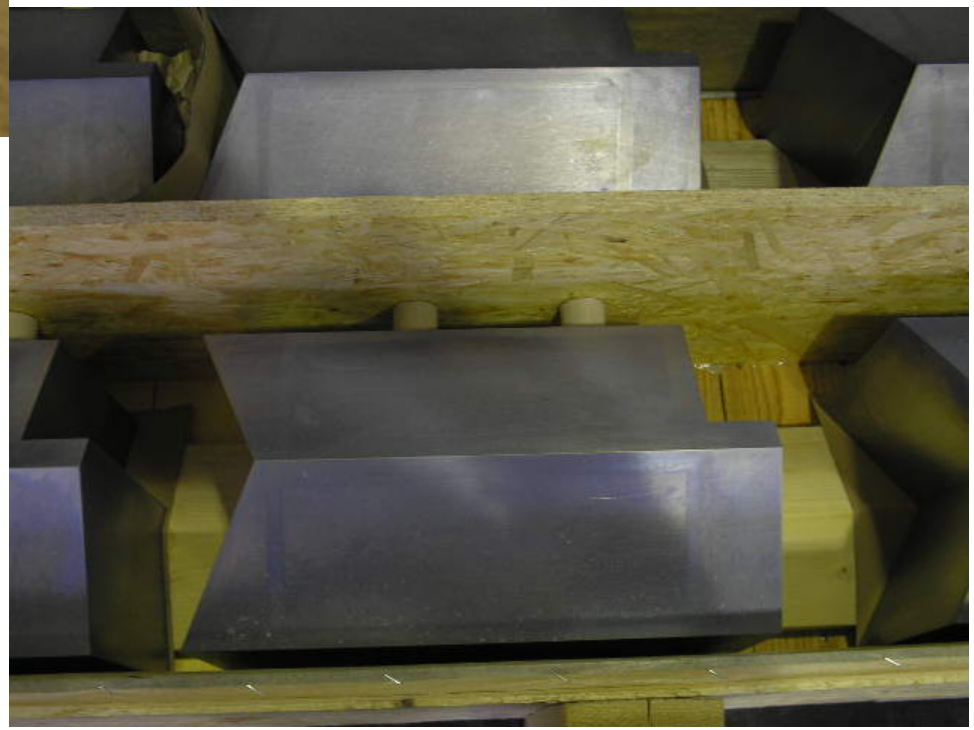
Lead Shielding



Each brick is epoxy painted to reduce Pb dust during operations

Cradle and rear Pb have been test assembled at Goslar and are now in transit to Stanford

Top "arches" and front Pb are only required later. Now in production.



Rear bricks ready for shipment

Massive effort on material radioactive qualification using:

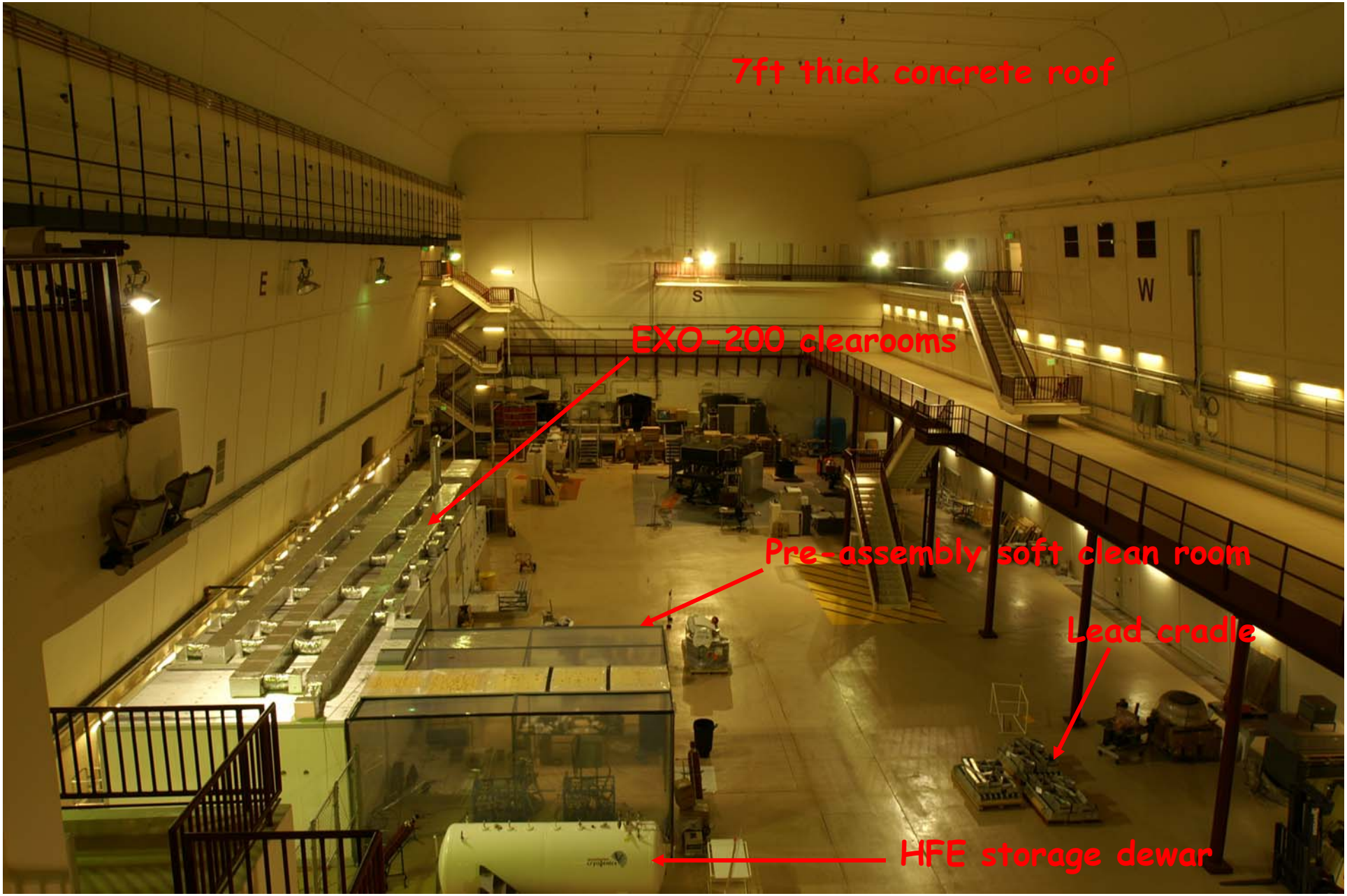
- NAA (MIT-Alabama)
- Low background γ-spectroscopy (Neuchatel, Alabama)
- α-counting (Alabama, Stanford, SLAC, Carleton)
- Radon counting (Laurentian)
- High performance GD-MS and ICP-MS (Canadian Inst. Standards)

At present the database of characterized materials
includes >100 entries

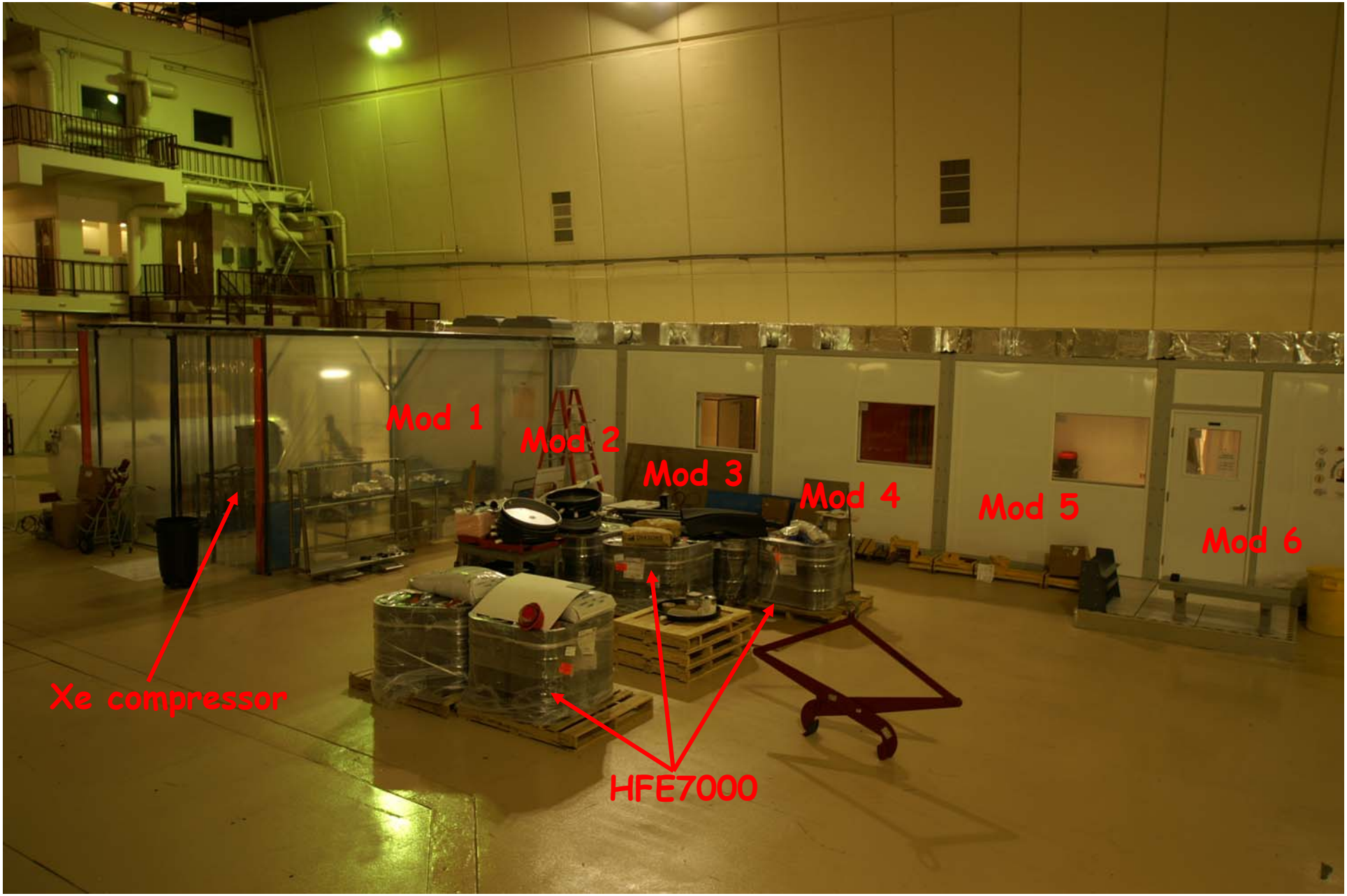
MC simulation of backgrounds at Alabama and Stanford/SLAC

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

EXO-200 installation at HEPL (Stanford campus)

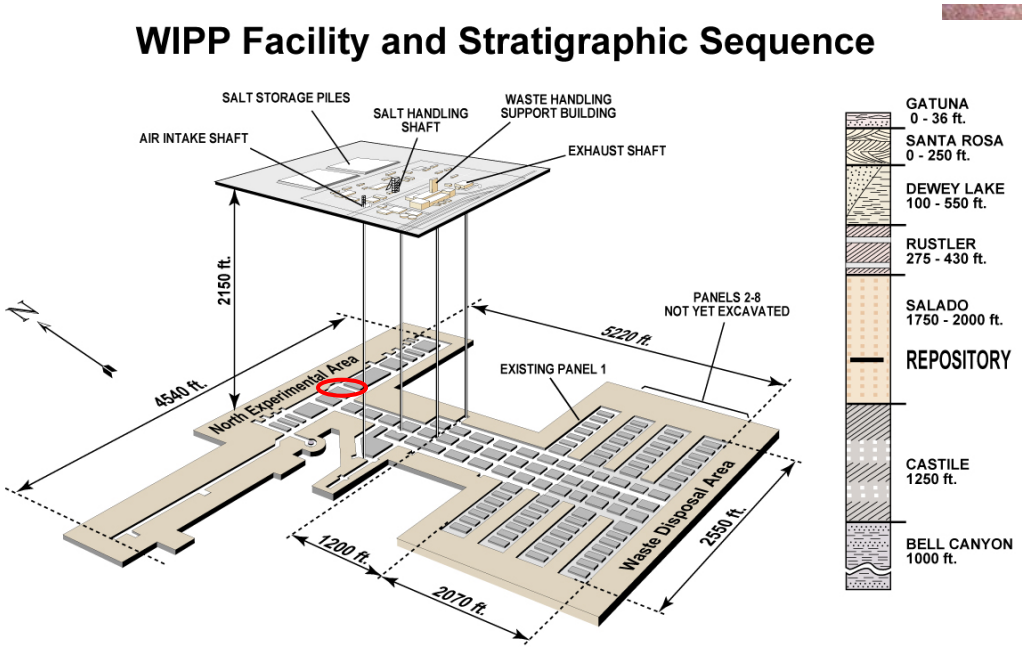


EXO-200 installation at HEPL (Stanford campus)



Milestones from the EXO-200 schedule

- Apr 19, 2006 — Start Pb cradle installation
- Jun 15, 2006 — First full cooldown
- Oct 20, 2006 — End tests at Stanford
- Nov 14, 2006 — Dismounting complete
- Nov 20, 2006 — Lower first module at WIPP
- Dec 8, 2006 — Lower last load (Pb arches) at WIPP

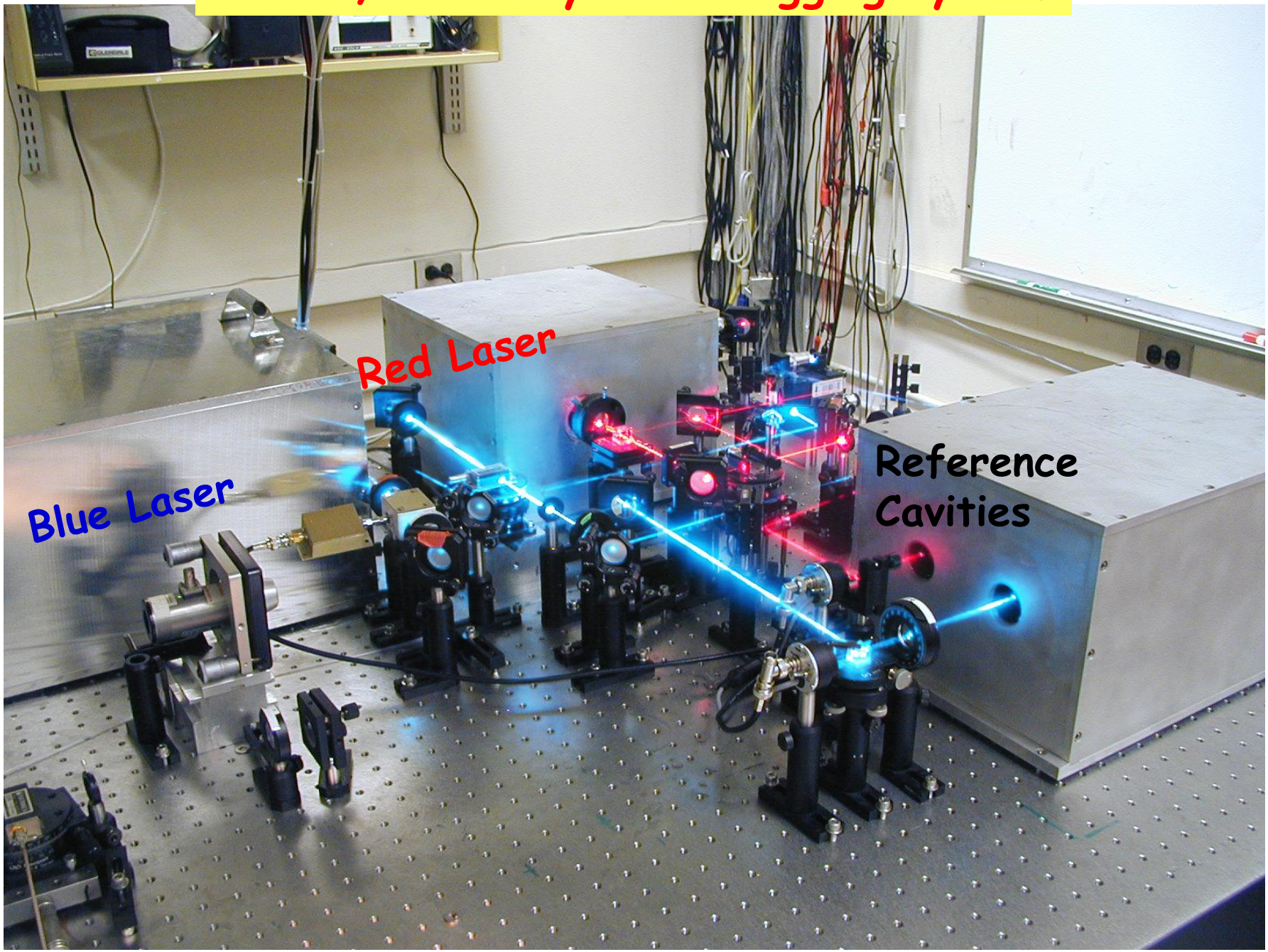


Plan for Ba grabbing and tagging R&D

- We have developed the atomic physics and spectroscopy techniques to achieve good quality tagging in presence of some Xe gas
- Gained experience with using He to stabilize traps and counter some of the ill effects of Xe
- Have a scheme to load a linear trap with high efficiency
- Developing a single Ba ion source for testing
- Have built a linear trap designed for high loading efficiency. Very similar to final device.
- Developing two different "grabbing" techniques in parallel:
  - *Xe ice tip*
  - *Field emission tip*
- Could start development of very promising RIS tip but this is unfunded
- Continue R&D on tagging in LXe: high rewards is successful but hard

Done
In progress

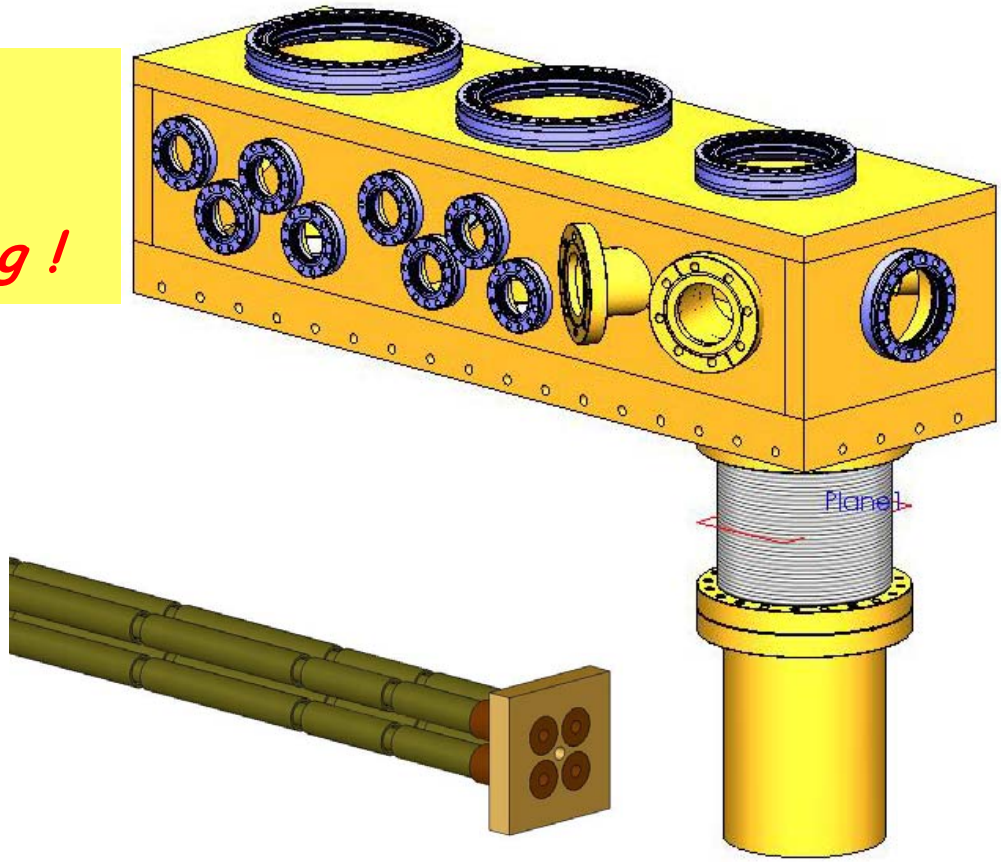
Stable, turn-key laser tagging system



RFQ linear trap

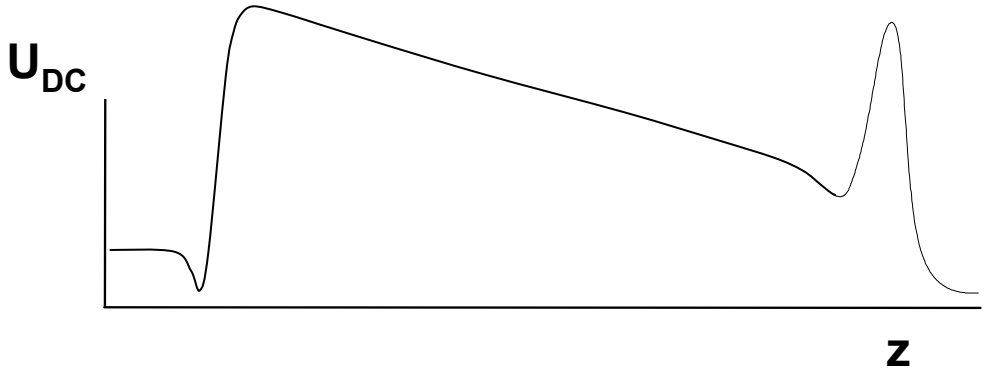
Grabbing/releasing with Ba^+

This is built like the final thing !

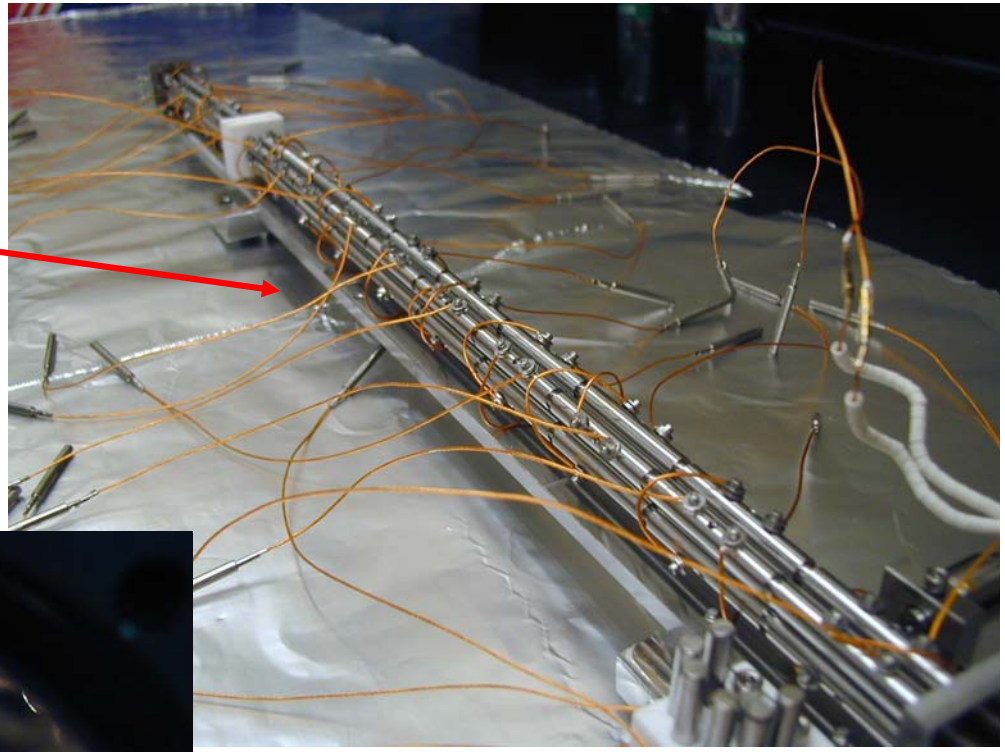


Electrostatic z-field, RF xy field

- *High loading efficiency*
- *Longitudinal gas (He/Ar) cooling*
- *length: 600 mm (~15 segments)*
- *$r_{electrode}$: 20mm, shorter in the trapping region*
- *Can load from tip in Xe/He atmosphere and move ion in laser spectroscopy region*
- *Can "shoot" ion from trap to "grabber probe"*
- *Can load/trap with residual Xe pressure (differentially pumped in different z regions)*

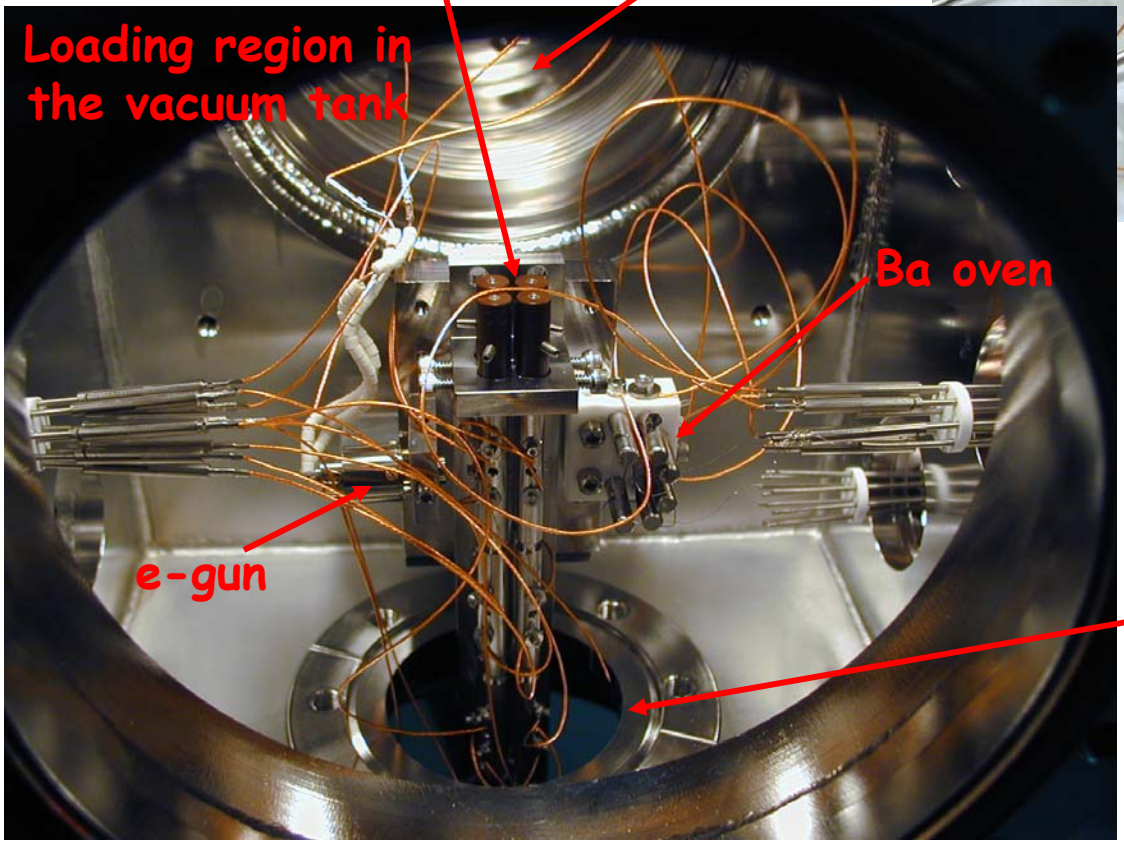


Electrode structure being prepared

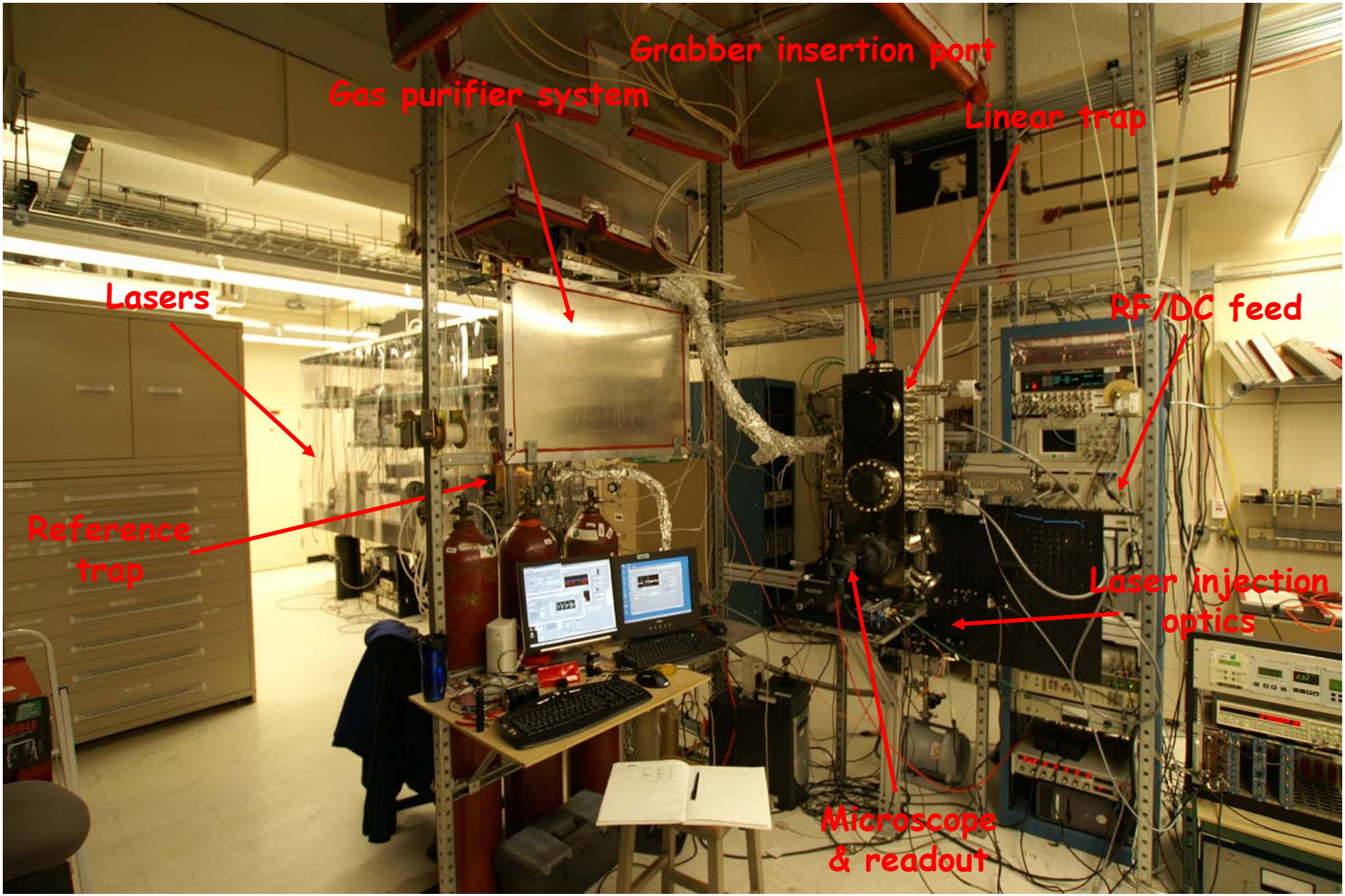


Tip loading access

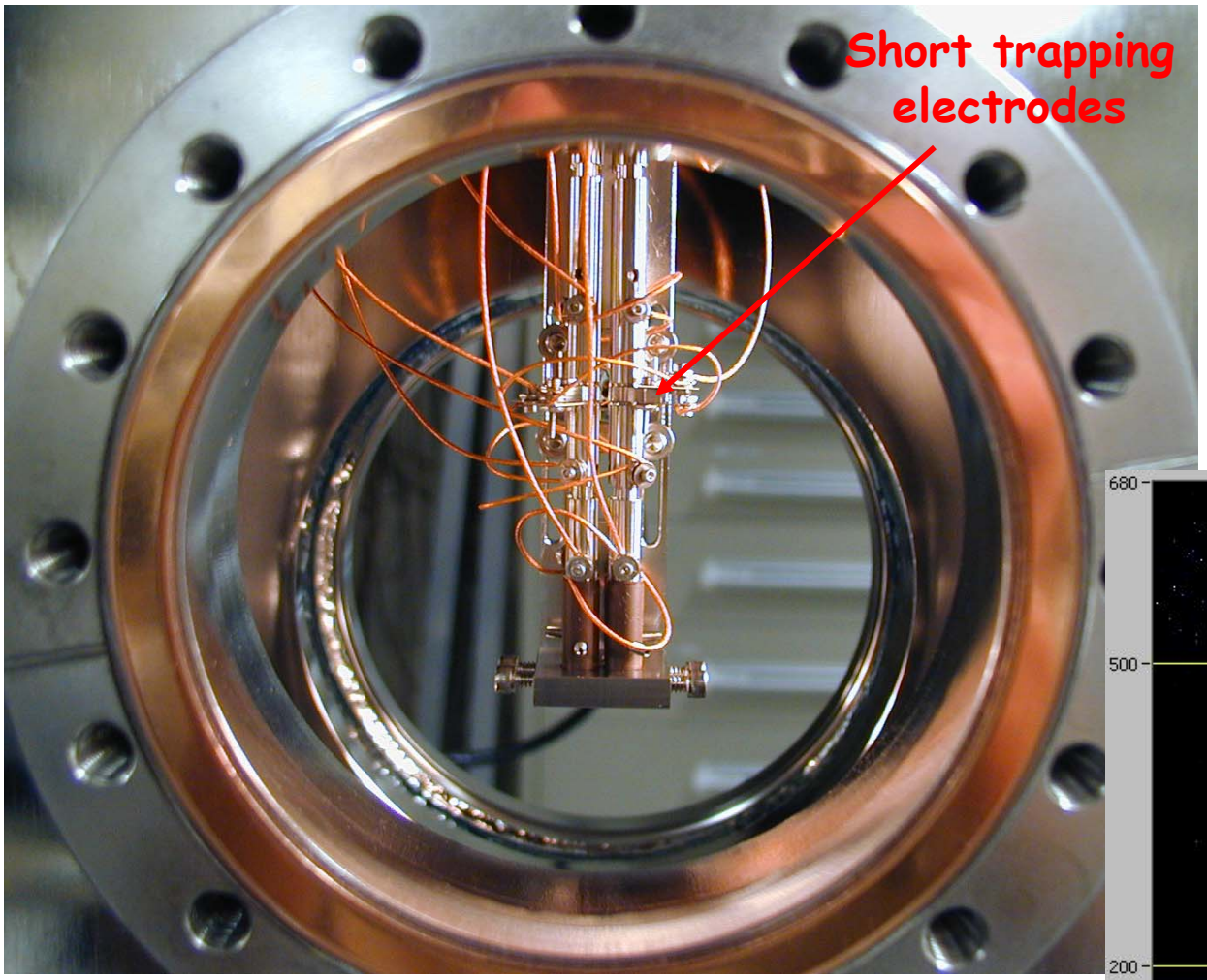
Main turbo port

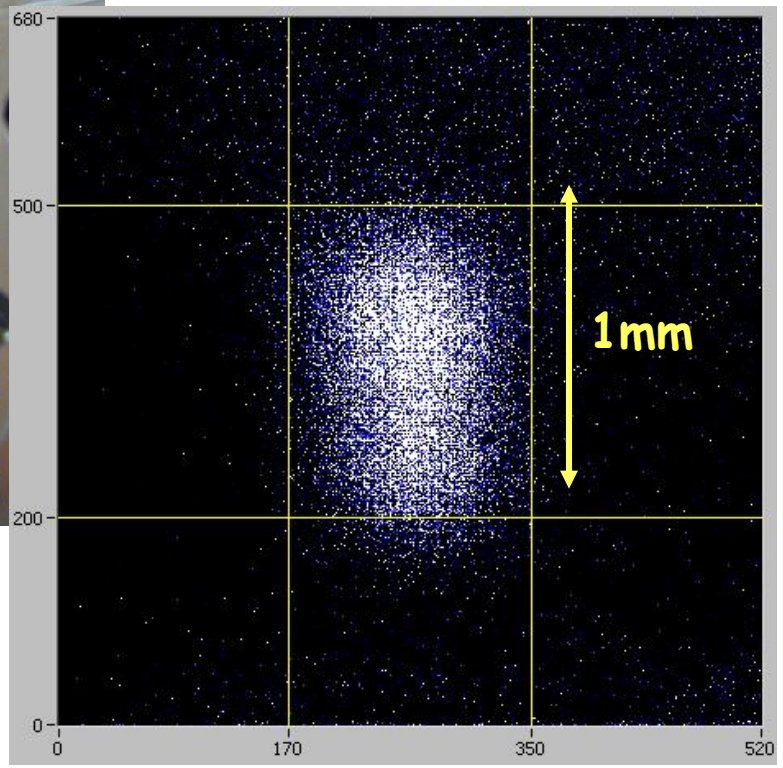


Differentially pumped aperture

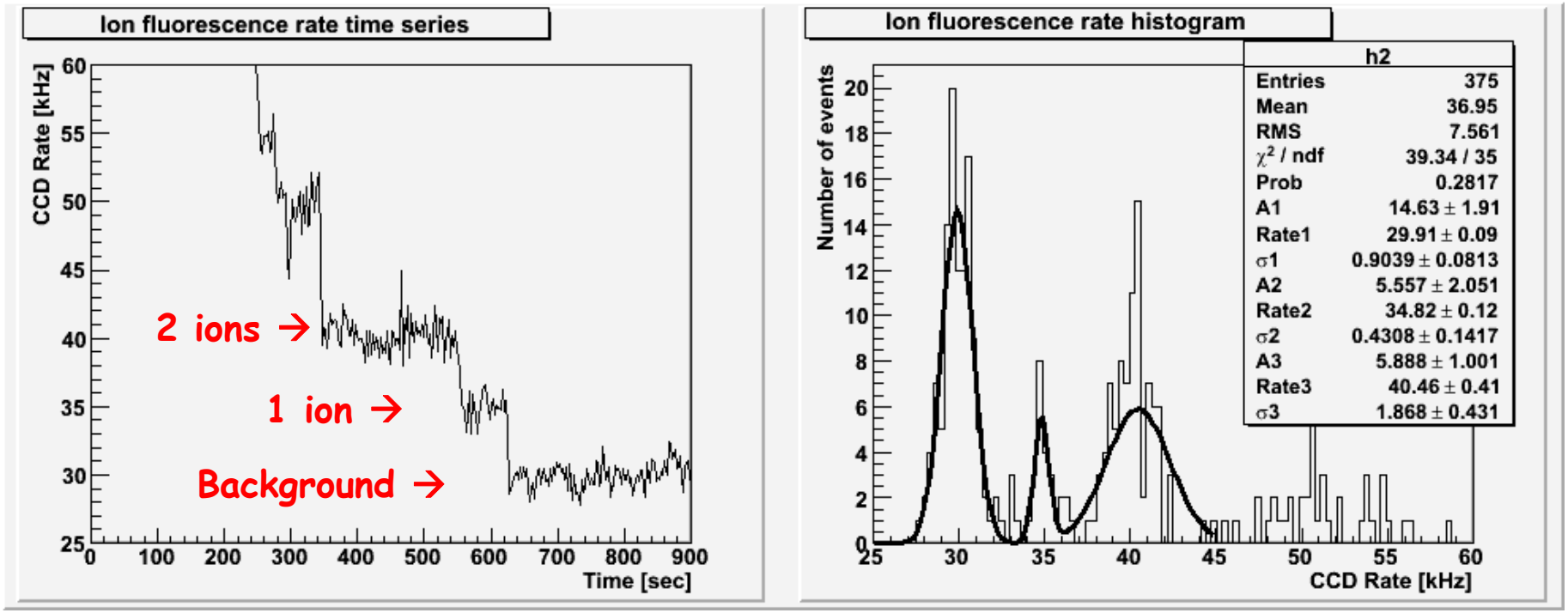

Grabber insertion port
Gas purifier system
Linear trap
Lasers
RF/DC feed
Reference trap
Laser injection optics
Microscope & readout

Trapping/spectroscopy region





Our trap is capable of single ion measurements



Grabber tip

Three techniques should be tested in parallel at Stanford
(2 postdocs + 2 grad students and 2 undergraduates)

- **Cryo tip:** - a thin layer of Xe-ice is formed on the surface of a metal
  - the Ba ion is electrostatically attracted to the ice surface
  - ice is thawed at the entrance of the trap and Ba ion is released

  Challenge: control the ice thickness to a few to ~100 atomic layers

  → Very close to a solution !
- **FE tip:** - use a very sharp STM tip to grab the ion
  - Ba ion lands near the very tip
  - A strong positive bias field emits the ion in the trap

  Challenge: - maintain the tips sharp in LXe

  - field emission at grabbing in LXe

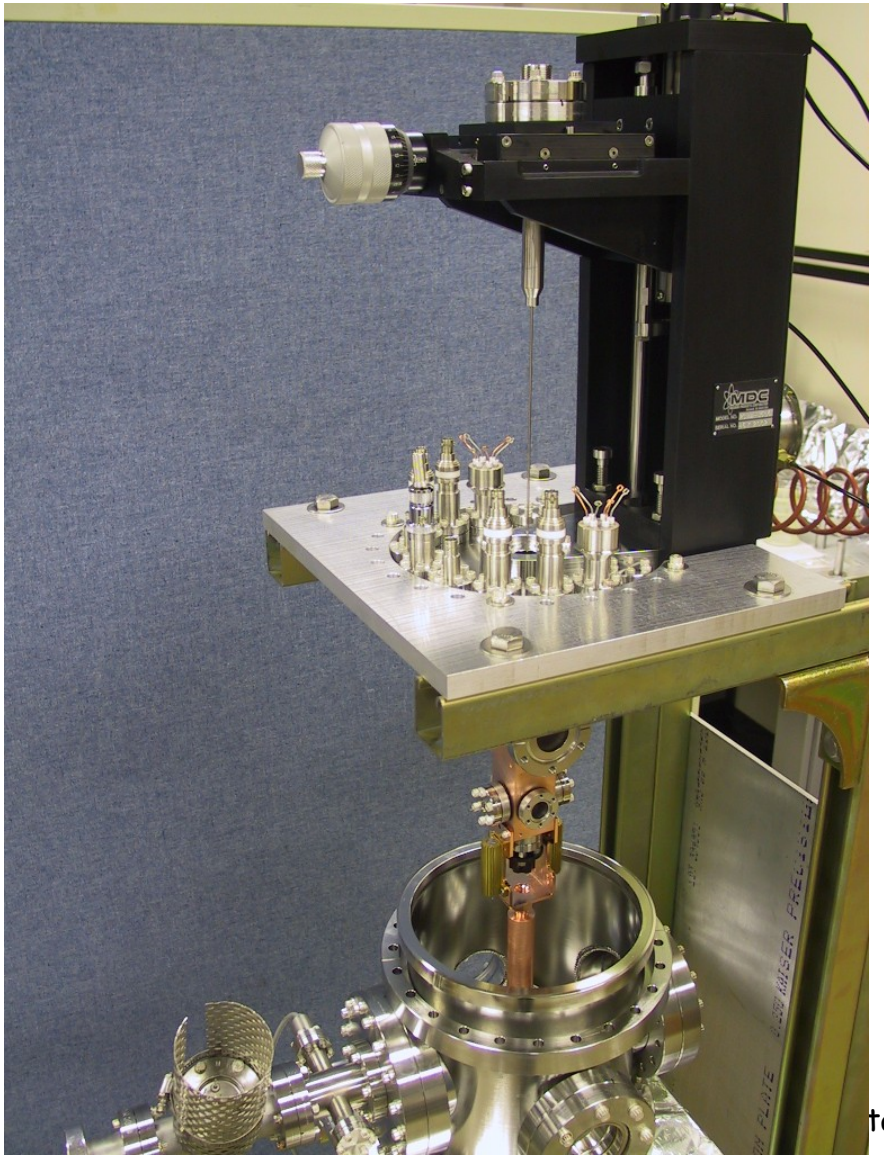
  → Field emission microscope being commissioned

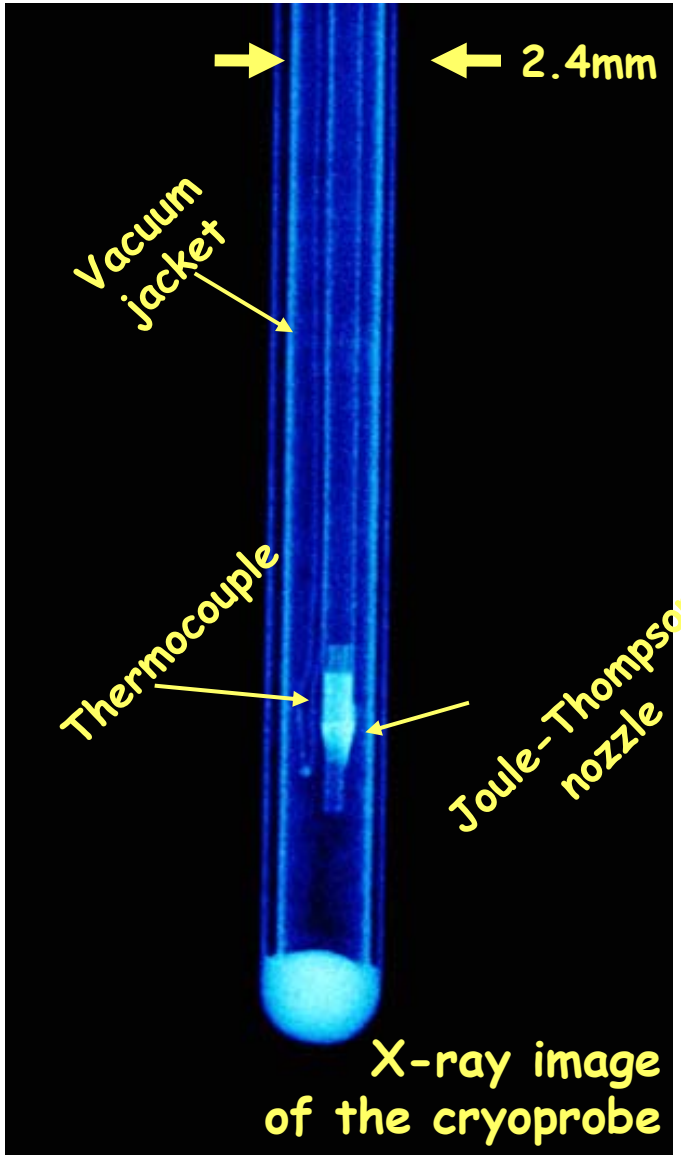
  To be installed in the ion trap soon !
- **RIS tip:** - tip is a ~200μm fiber with a semitransparent metallization at end
  - Ba ion is attracted to metallization and neutralized
  - A desorption laser pulse evaporates the Ba in the trap
  - A second pulse (2 specific wavelengths) resonantly ionizes the Ba when it is still ~100μm from the fiber tip

  Challenge: Funding ! The lasers are expensive

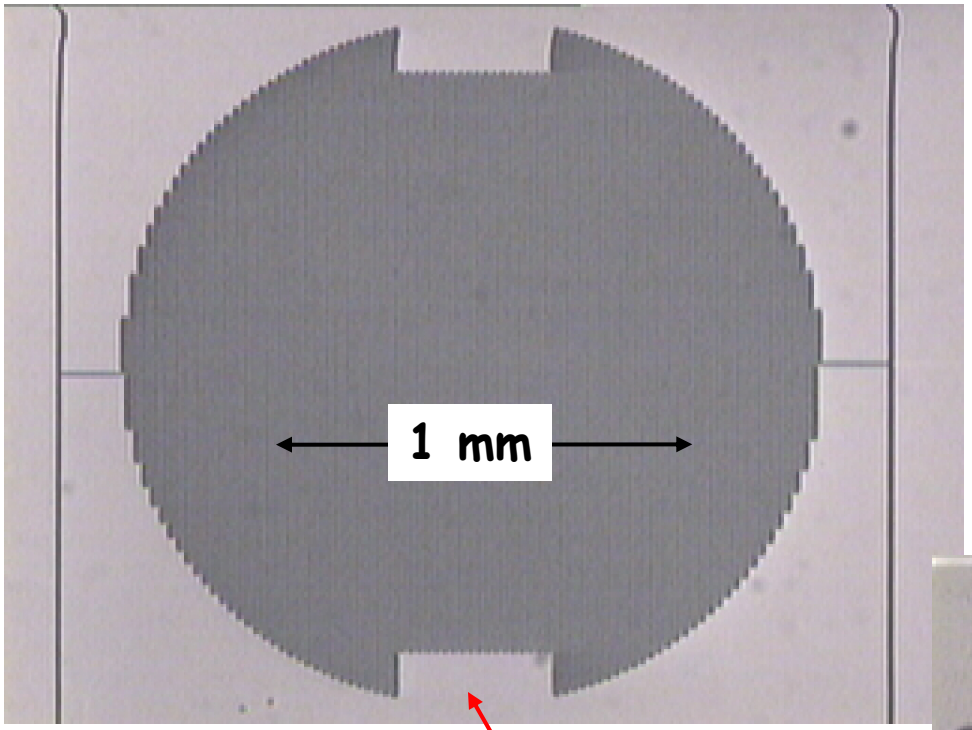
  → In this case each step has been demonstrated and is known to work with high efficiency !!

Prehistory:
R&D on grabbing/release uses Ra (chemistry ~ Ba) and α-counting



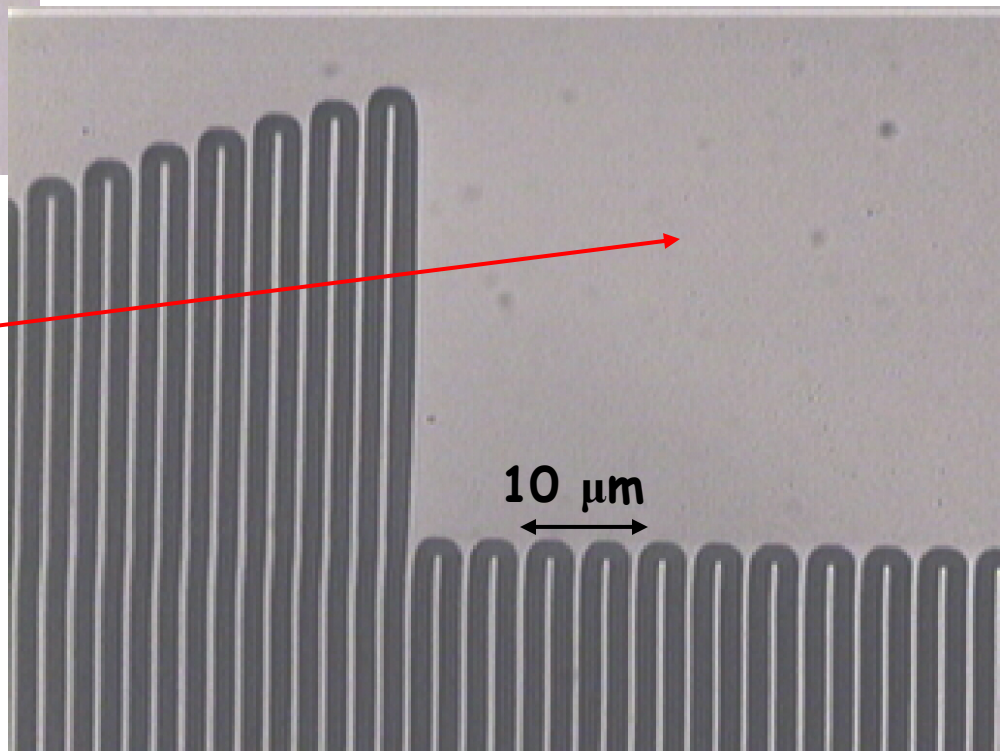


How to control the ice thickness while in the LXe ?



Build a microcapacitor on the tip and detect the chance in ε_r between liquid and solid Xe

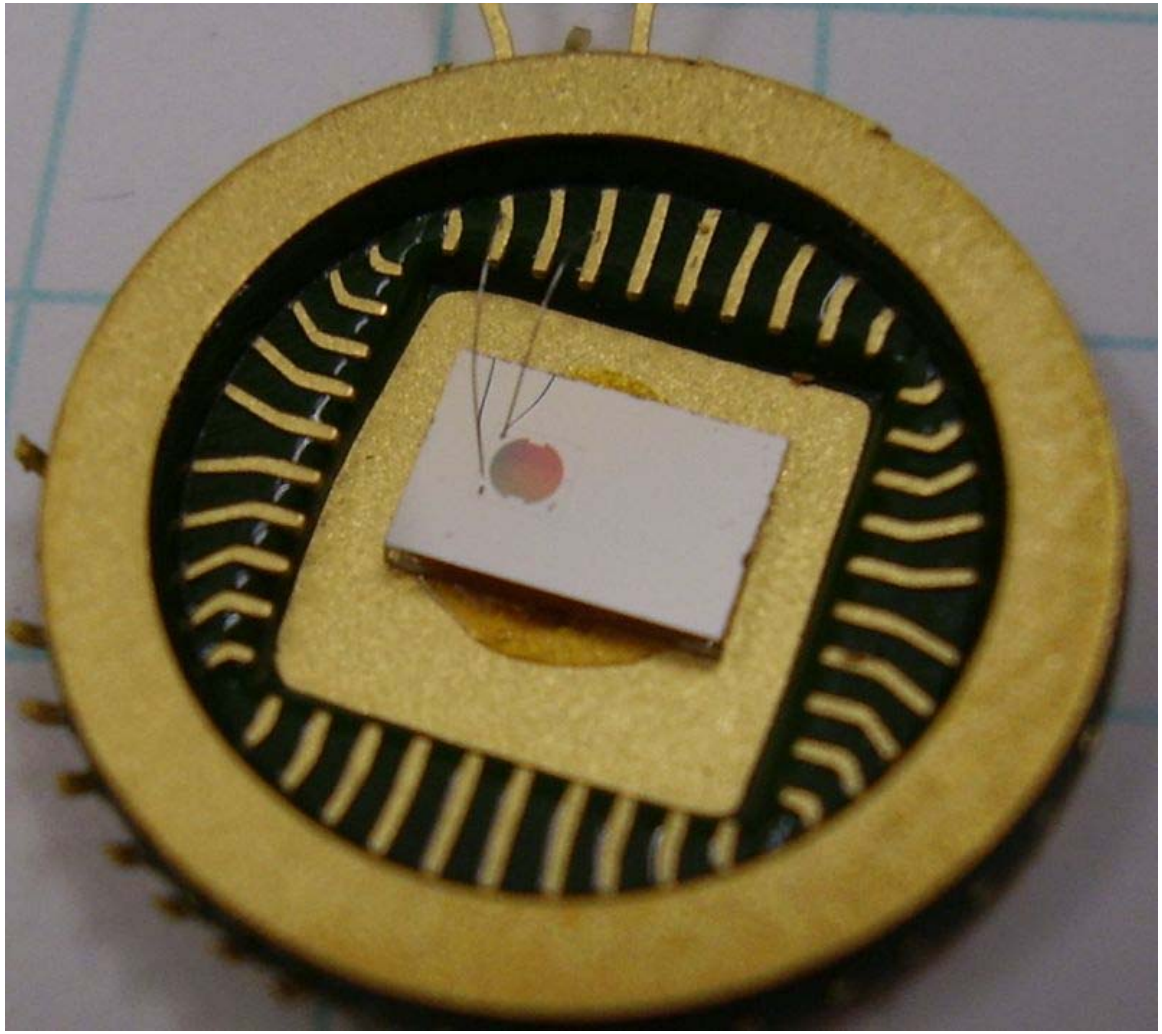
Bonding pads



First device built at CIS and just tested

C=15pF (in good agreement with simulation)

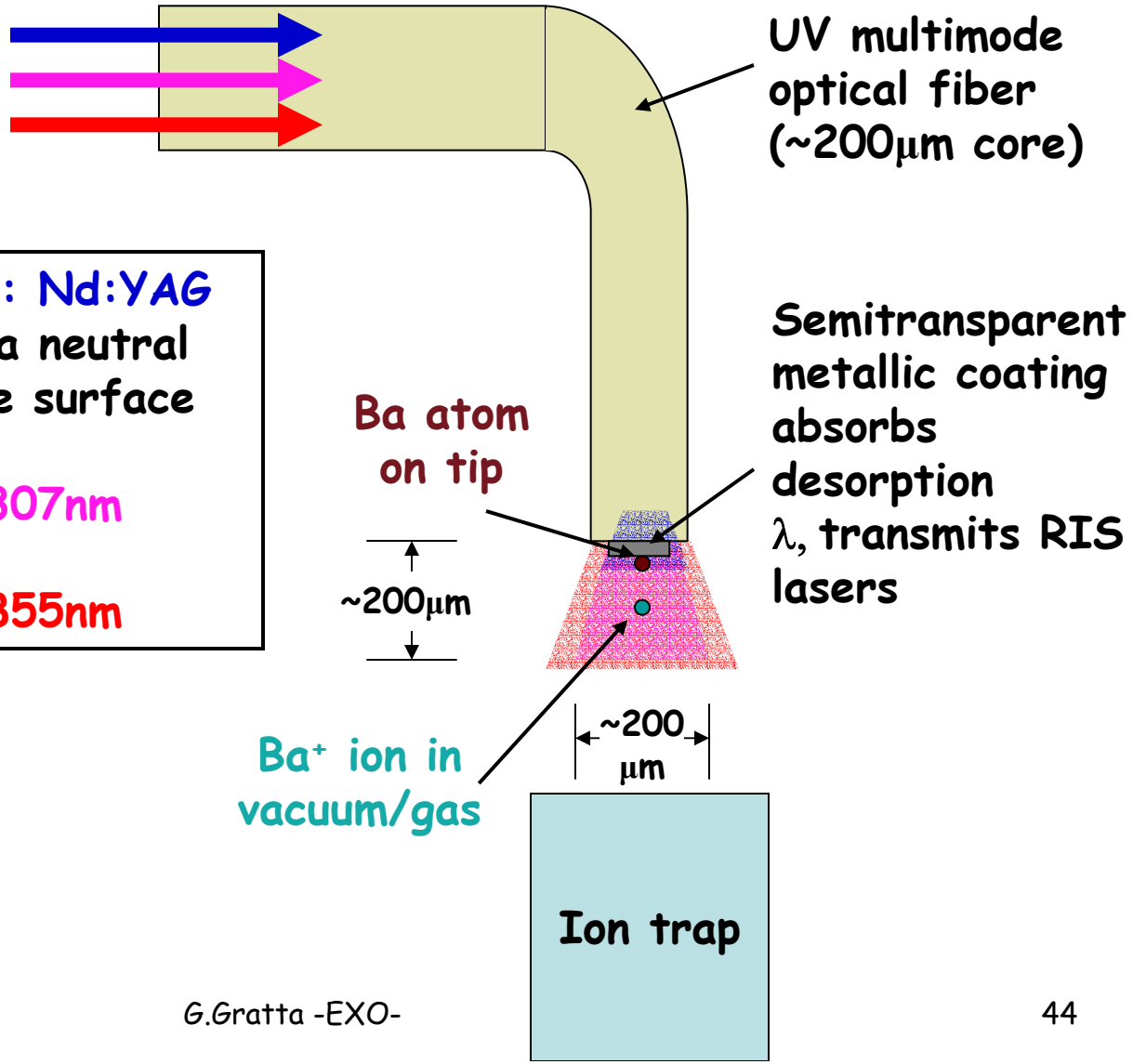
Preliminary sensitivity < 10nm



Already have a commercial JT micro-cooler. Should be able to test the full system in LXe very soon

Resonant Ionization Spectroscopy (RIS) tip for EXO

1. Pulsed desorption laser: Nd:YAG
2. ~10ns delay to allow Ba neutral atom to leave the surface
3. -Resonant step: pulsed laser @ 307nm
   -Autoionizing step: pulsed laser @ 855nm



Step 1: laser desorption

(a) Evaporation: I~10^6-10^8 W/cm^2 produces mainly neutral atoms

or

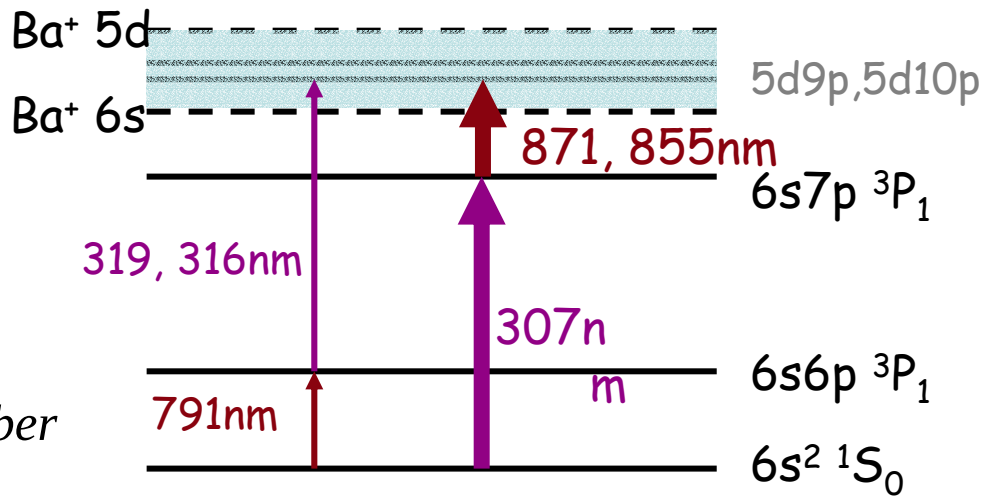
(b) Desorption induced by electronic transitions (DIET)

- Alkali atoms are bound on surfaces mainly as + ions (will is work for Ba ?)
- Absorption inside metal near surface creates a hot electron.
- Electron diffuses to the surface.
- Electron recombines with alkali+ ion.
- Larger alkali atom is pushed away from surface

Step 2: resonant ionization

$$\sigma_{autoionize} = 1000\,Mb = 1x10^{-15}\,cm^2$$

$$E_{sat} = (h\nu)\frac{A}{\sigma_{autoionize}} = 70nJ \;\; for\; 200\mu m \;\; fiber$$



A possible scenario

Desorption: >4000 pulses at 3μJ each ~5eV (250nm)?

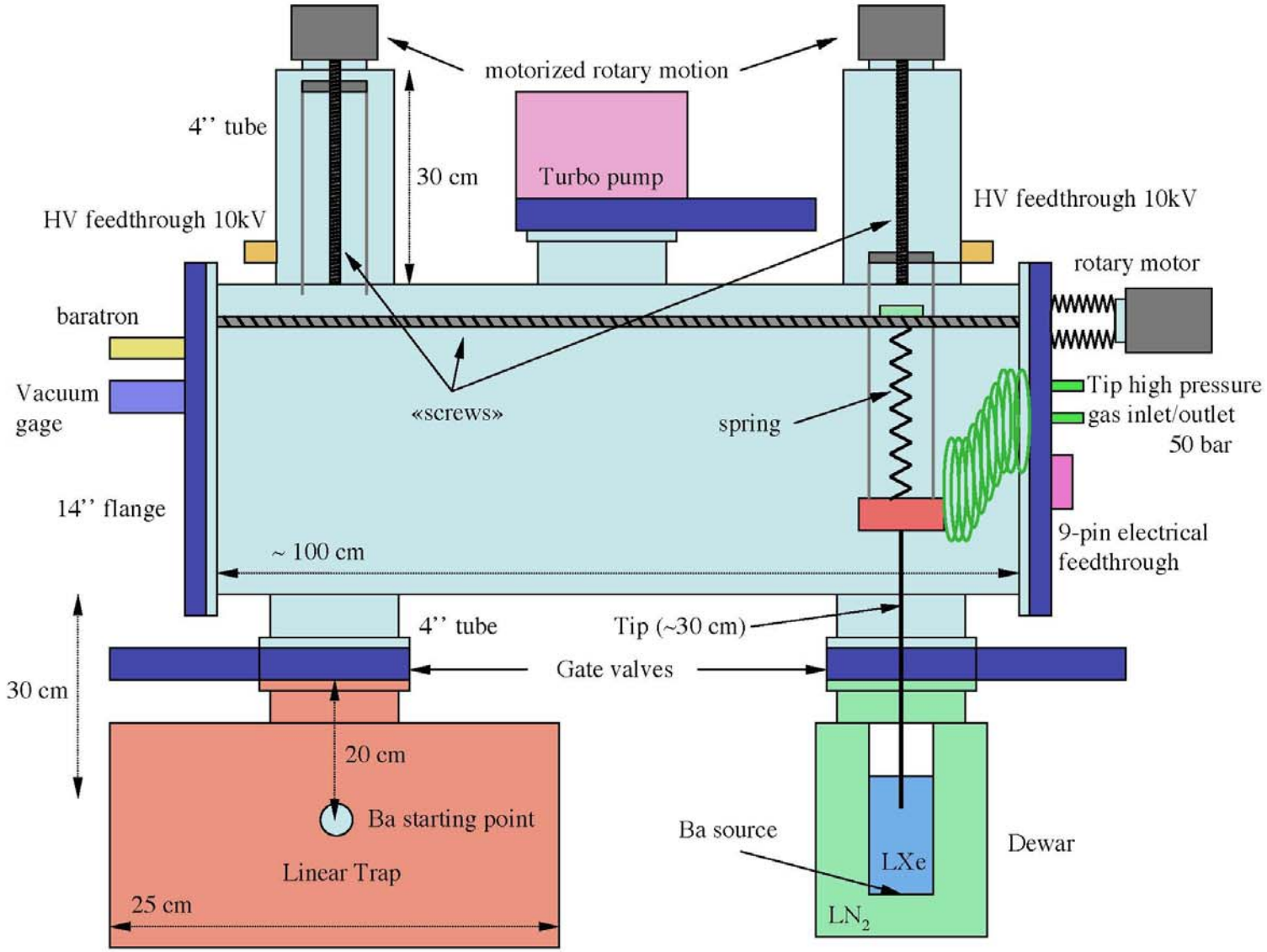
Resonance step: >4000 pulses at >0.7nJ each (307nm)
delayed by 10-30ns ($\Delta\nu$=0.3cm^{-1})

Autoionization step: >400 pulses at >70nJ each (871nm)
delayed by10-30ns.

Efficiency of order 50% is obtained in feeding a mass spectrometer from a meteorite surface using RIS

Looks very promising !
To start as soon as funding is available

Grabber tip transfer system being built at the Univ of Neuchatel. To be installed on the Stanford linear trap in the Summer 06



Plan for calibrating Ba tagging in EXO

On the Bench:

- "ping-pong" in the linear trap: -load and tag single Ba ion
  -use trap to shoot ion at FE tip
  -verify that no ion is in the trap
  -release ion and tag

  This measures the product $\eta_{tip_loading} \times \eta_{release} < \eta_{release}$
- Repeat with other types of tips (no moving parts yet)
- Assemble Neuchatel transfer device at Stanford
- Produce Ba^{+} from ^{137}Cs decays in LXe and grab, transfer, tag (with the best of the tip technologies available)

  This measures the efficiency of the entire chain of events

  It will be the "proof" that the technique is working

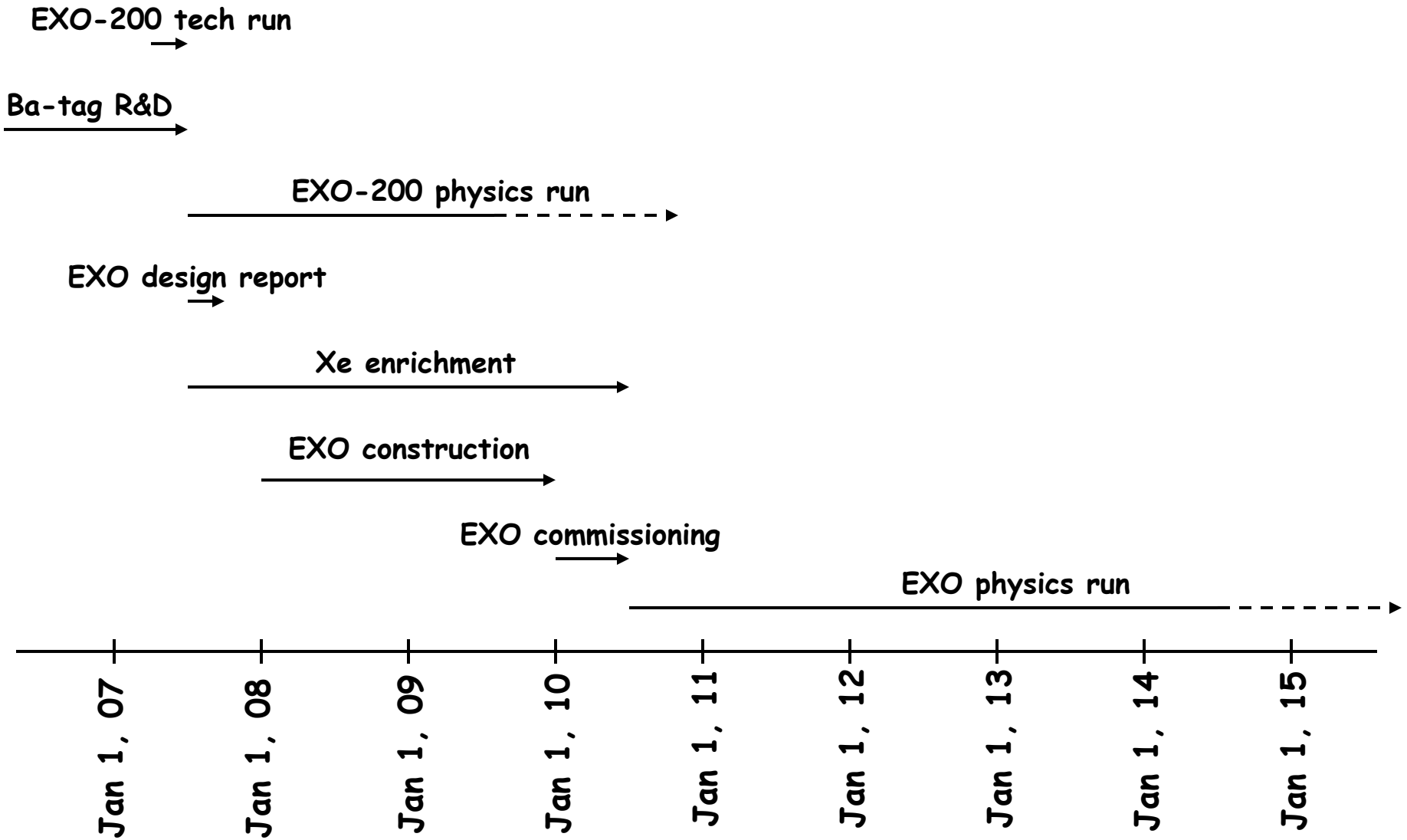
In EXO:

- Prescale $2\nu\beta\beta$ events and grab them to measure real efficiency

  This will provide the tagging efficiency for EXO papers
- Sample the LXe at random with the tagging device

  This will provide the tagging background for EXO papers

EXO timeline



Clearly too early to properly cost the full detector, however…

The 200kg enrichment program has provided us with a precise estimate for the bulk of the cost: isotopic enrichment

	$/g_{enriched}$
Enrichment from nat'l to 80 ^{136}Xe	5.5
Nat'l Xe feedstock	1.0
Depleted fraction restocking & repurification + shipment, insurance, etc	2.0
Total	8.5

A very crude, order-of-magnitude cost for the full EXO experiment:

	Crude cost estimate (M$)	
	1ton version	10ton version
^{136}Xe	8.5	85
Detector	20	20
Total	28.5	105
<m> sensitivity (QRPA, many caveats)	50meV	11meV

Conclusions

EXO-200 very soon will be ready

- Largest double beta decay detector ever
- Largest amount of separated isotope (by a factor of 10) in hand
- Tie for the largest Xe detector ever…

  But we are - ultra-clean
  - enriched xenon
- First liquid bath cooled/shielded LXe detector
- First Ionization & Scintillation LXe detector
- First massive use of APDs for scintillation readout

Grabbing/release/tagging R&D in full swing <u>in parallel</u>

- Very interdisciplinary effort ! (AMO, condensed matter, nanoscience)
- May have broad impact on other fields
- Linear trap was brought to life in record time (Oct 05 – Feb 06)
- Will soon start Ba capture/release experiments with stationary STM tip !
- Tip transfer system being built
- Realistic cryo tip well advanced
- Would like to do R&D on RIS tip !

Full EXO will naturally emerge from these two efforts