New Techniques
EXO, MOON, SuperNEMO

Andreas Piepke
for the EXO Collaboration

We know that neutrinos are massive. Oscillation observed with

- Solar and reactor neutrinos

- Atmospheric and accelerator neutrinos

- LSND and MiniBooNE → still unconfirmed, perhaps at this conference…

- We don’t know how neutrinos behave under charge conservation.
  Are neutrinos Dirac or Majorana particles?

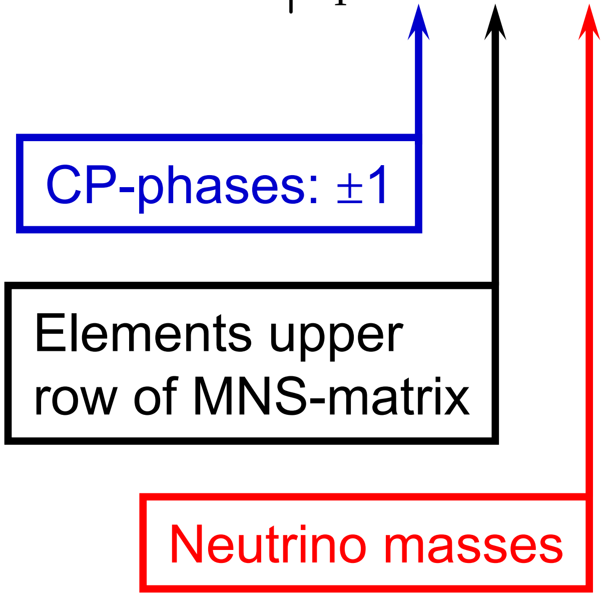
- What is the absolute neutrino mass scale?

New generation double beta decay experiments will help answer this questions.

Decay rate translates into effective Majorana mass. Requires knowledge of nuclear physics quantities.

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \cdot \left|M^{0\nu}\right|^2 \cdot \langle m_\nu \rangle^2$$

$$\langle \mathrm{m}_\nu \rangle^2 = \left| \sum_{\mathrm{i}} \eta \mathrm{U}_{\mathrm{ei}}^2 \mathrm{m}_{\mathrm{i}} \right|^2$$



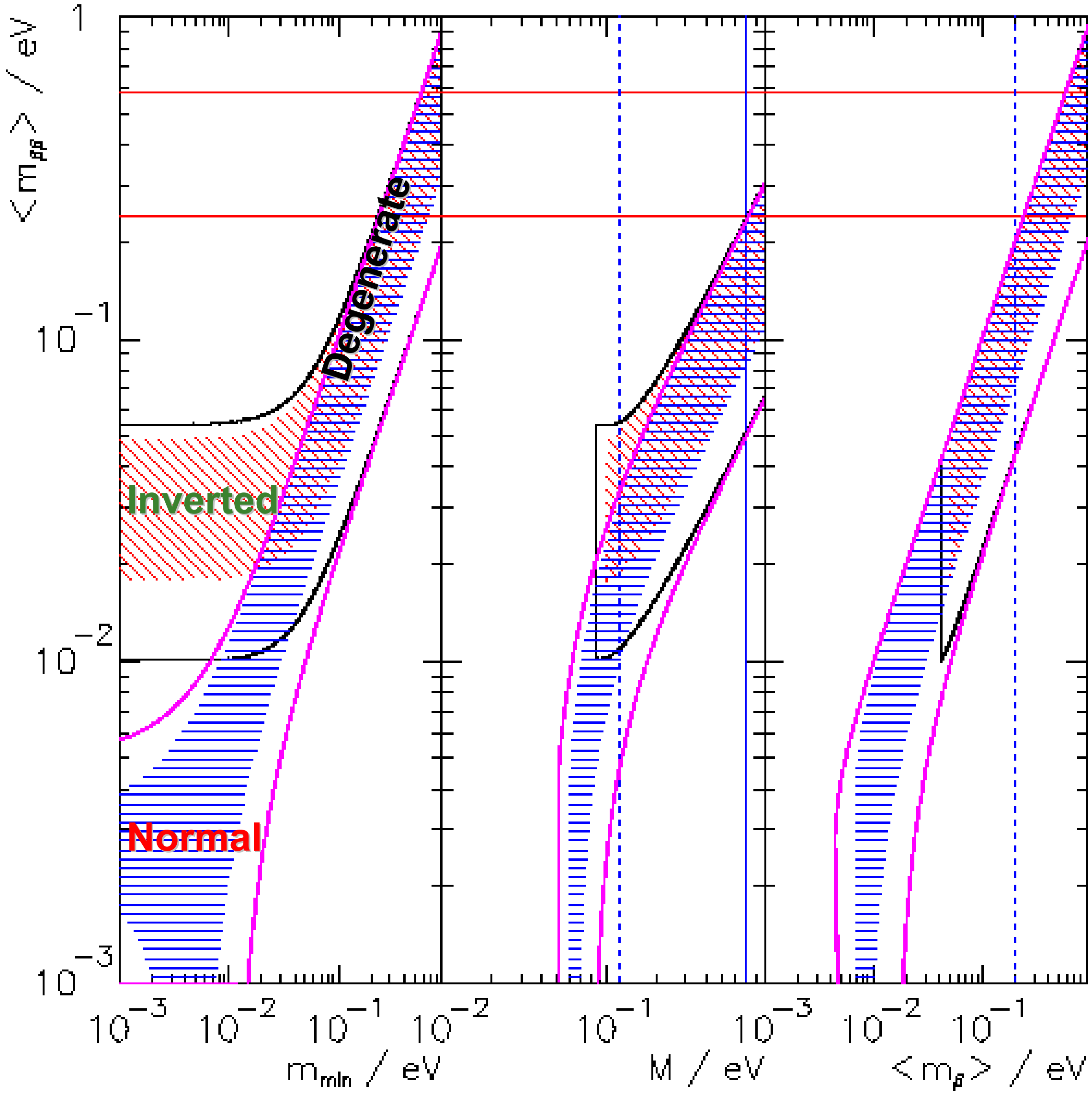
CP-phases: ±1

Elements upper row of MNS-matrix

Neutrino masses

CP-phases can lead to cancellation. But how much? Replace masses by two possible choices of minimal mass m_1 or m_3 and add knowledge of mixing and mass splitting from oscillations.

The problem to be solved:



^{76}Ge : 5.8×10^{28} y

^{100}Mo: 3.5×10^{28} y

^{136}Xe : 4.8×10^{28} y

Rodin et al. PRC68 (2003)

Talk will cover SuperNEMO, MOON and EXO, all tracking calorimeters.

I am a member of the EXO collaboration and will thus focus on this project.

Next generation experiments hope to actually observe neutrinoless double beta decay. The talk will focus on this decay mode.

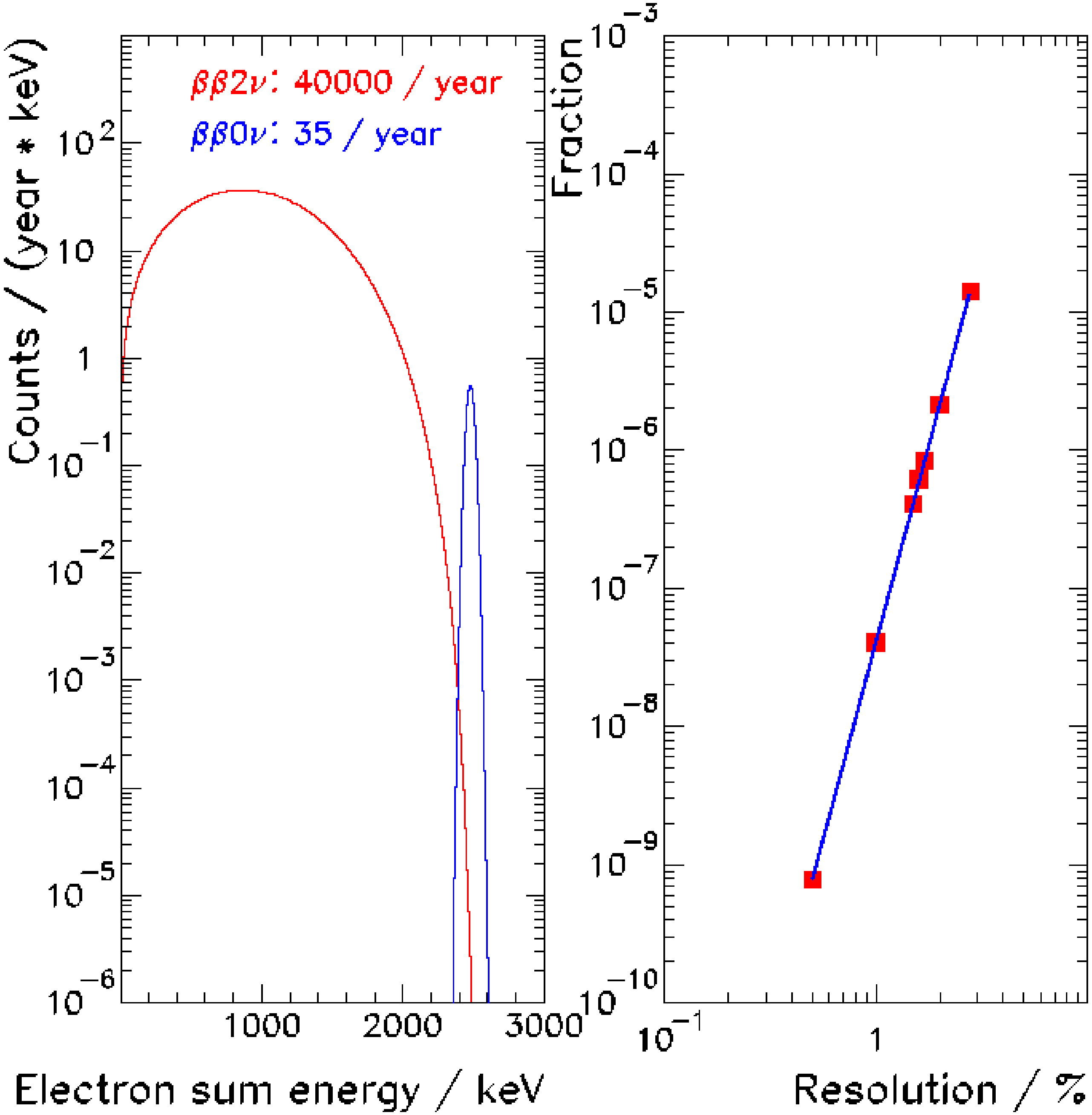
$\beta\beta0\nu$–decay: $A(Z,N) \rightarrow A(Z+2,N-2) + e^-$ has no easy to exploit experimental signature.

Given the interesting half lives of order 10^{27} to 10^{28} y, background reduction is THE problem to solve. Large source amount needed for reasonable decay rate.

Calorimetric detectors address this problem by carefully avoiding radioactivity of any kind and optimizing energy resolution. In many cases technical simplicity of the devices is a powerful advantage compared to more complex detectors.

Tracking calorimeters try to solve this problem by making background events more specific. EXO explores a novel method combining tracking with a true $\beta\beta$–tag.
Such detectors are often technically complex which makes radioactivity control difficult. Energy resolution is not as good as for pure calorimeters. $\beta\beta2\nu$–decay may become an irreducible background.

Decay modes distinguished by measurement of electron sum energy.



Left: expected spectra for 200 kg ^{136}Xe in one year.

Right: leakage of ββ2ν-events into ββ0ν–analysis interval. 5.8th power!

MOON

- Tracking calorimeter. Source ≠ Detector
- Several tons of thin (20 mg/cm^2) enriched Se or Mo foils
- Calorimetry through plastic scintillator σ=2-3% resolution
- Tracking through scintillating fibers or MWPC. Single/double track ID
- Perhaps dual purpose solar ν_e detector

Material supplied by

Hiro Ejiri

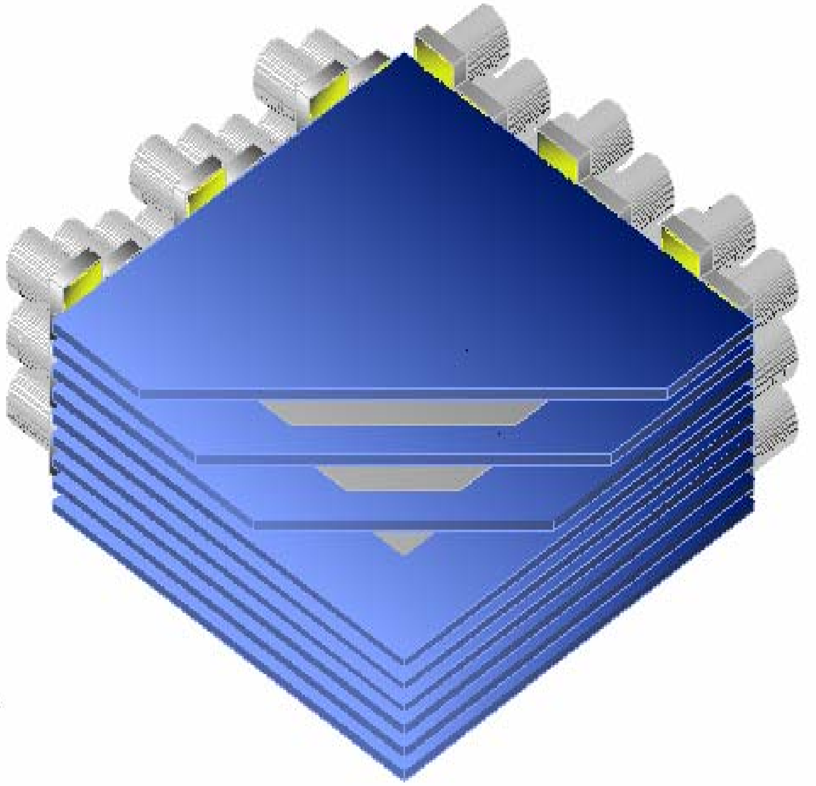
MOON : Majorana /Mo Observatory Of Neutrinos

Osaka, UW, FNAL, ICU, JINR, LANL, NIRS, Praha, Tokushima, UNC, VNIIEF.

1. Goal: m_ν~ IH 30meV for ground and excited O+.
2. Detector $\neq$ ββ source. Use one or two of ^{100}Mo, ^{82}Se, ^{150}Nd with large Q > most RI .
3. ββ tracking E_1, E_2, Θ_{12} correlations to identify ν-mass term.
4. Application to low-E solar ν

MOON detector

Multi-layer PL plates : compact & active self-shields
Position /particle ID by PL fiber or MWPC chamber
Enriched isotopes by centrifugal separation.

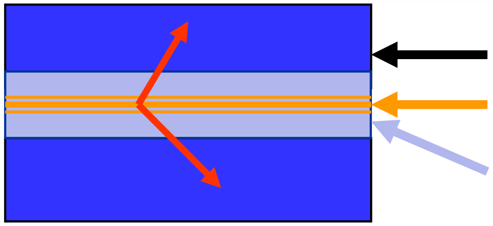


Sensitivity

- 20-40 meV for ^{100}Mo, ^{82}Se, ^{150}Nd
  with 5 year-ton and σ = 2-3 % E-resolution.

Schedule (tentative)

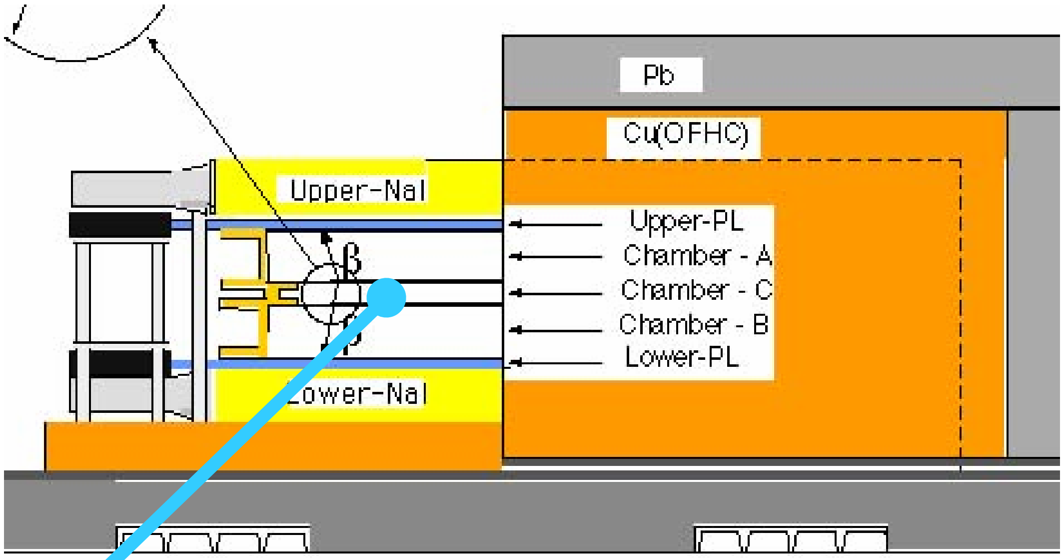
2006 Prototype MOON-1 without position
2006-2007 MOON-2 with position detector
2008 (Proposal)



PL E detector
Mo
Position detector
(PL fiber or MWPC)

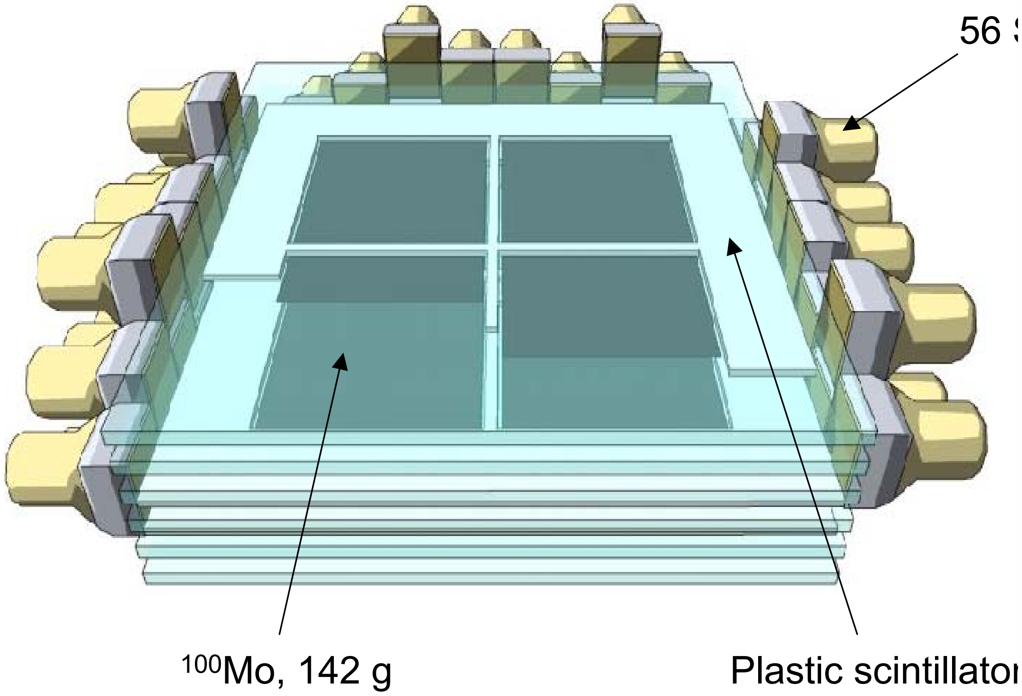
MOON-1 Proto type

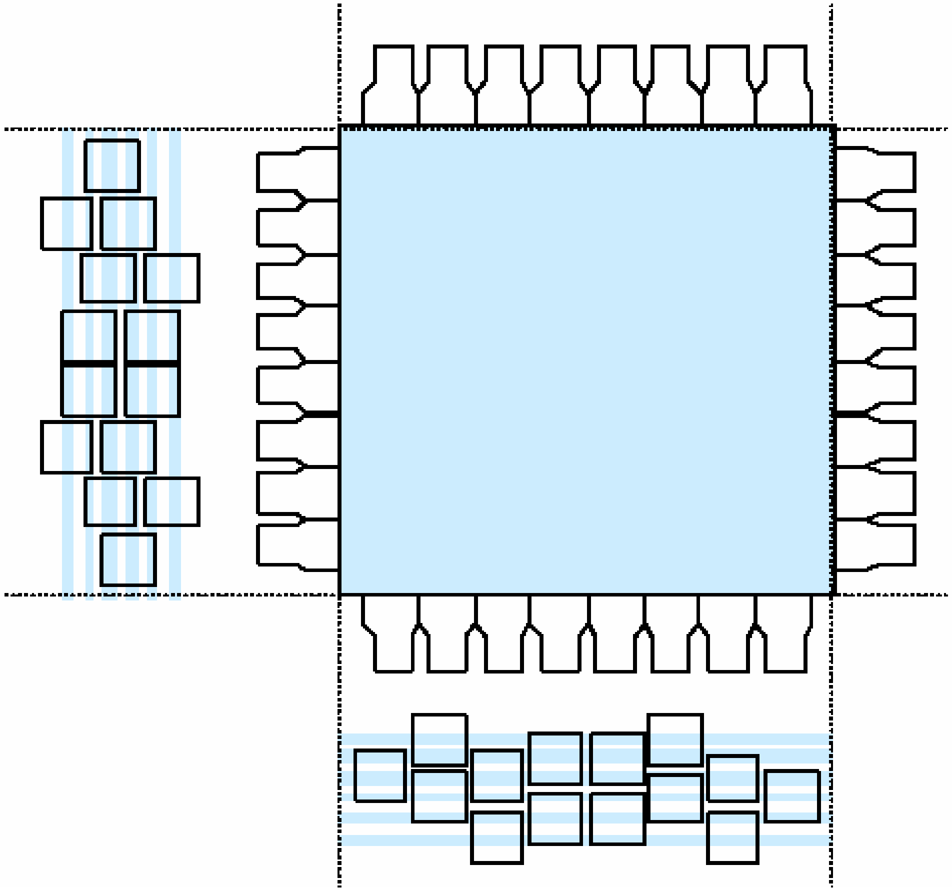
½ scale of MOON(1m ×1m)



Inside the ELEGANT V
Pb-Cu NaI shields since April 2005.

6-layers of PL 53×53×1cm³ Mo-Foil 160g @20mg/cm²×2

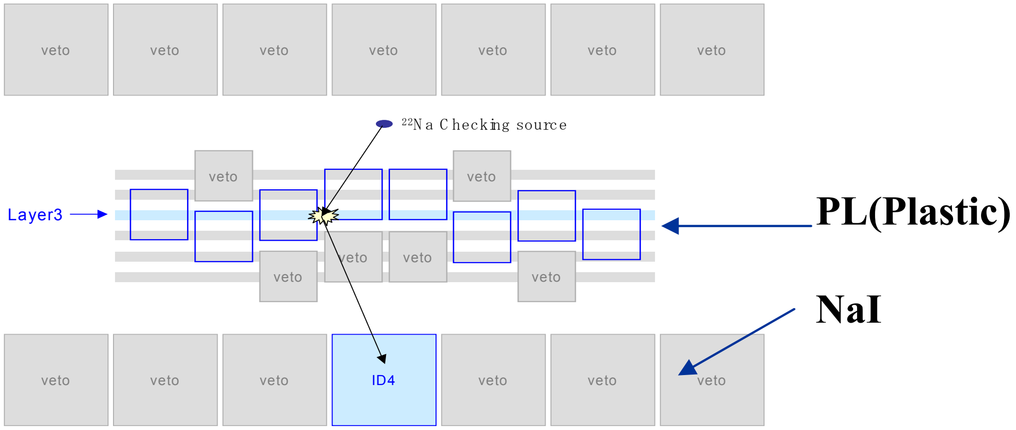




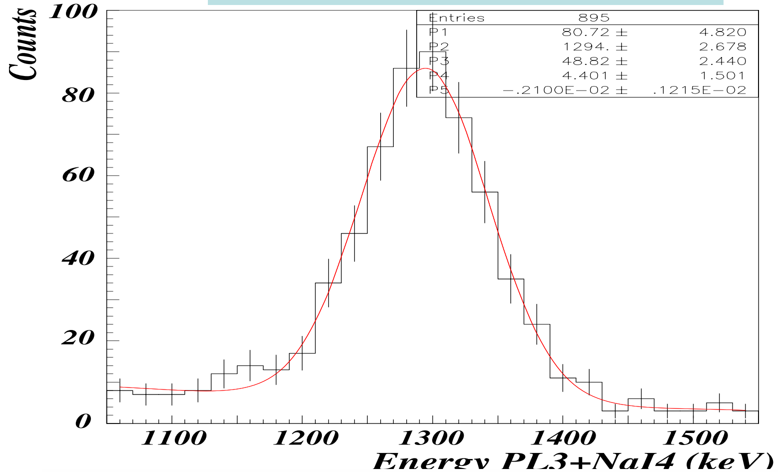
Energy Resolution

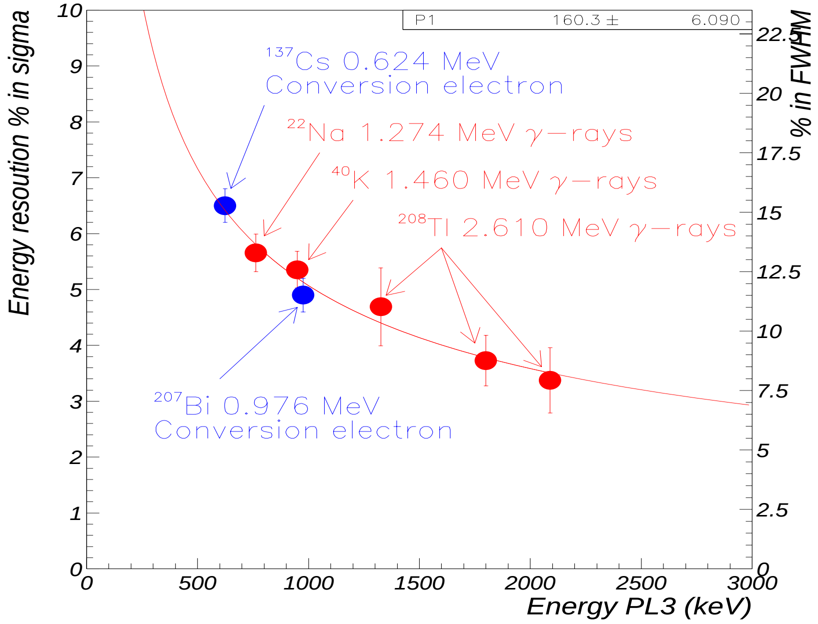
σ = 2.9±0.1 % (6.8 % in FWHM) at Q=3.034 MeV is just good for IH mass.

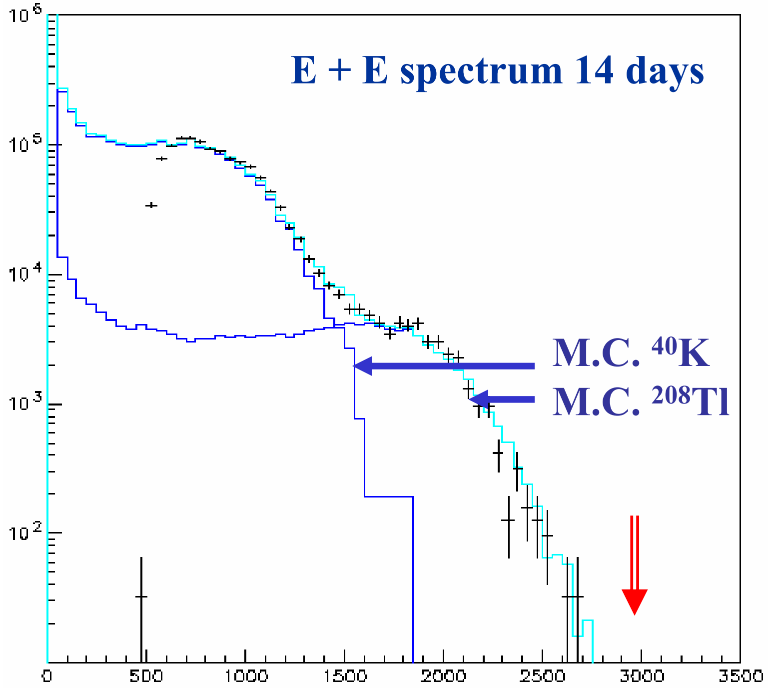
Compton-e in PL and Compton-γ in NaI



PL + NaI 1.275 σ = 3.8 %







PL Photo-electrons = 1860 MeV,

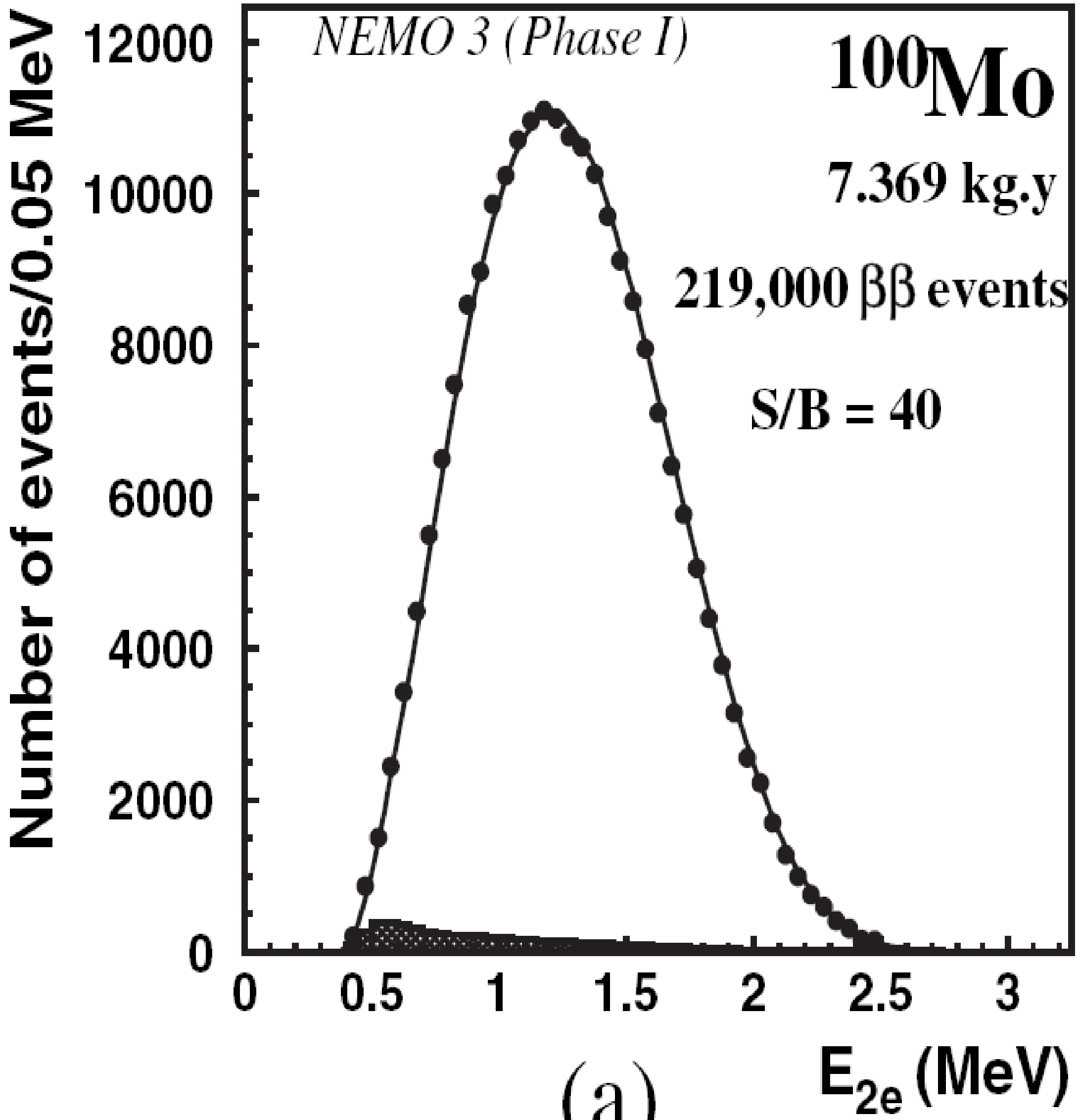
σ = 5.0±0.2 % ($E^{1/2}/E$)

< 0.8 / kg kev y with 68% CL(1.6 counts)

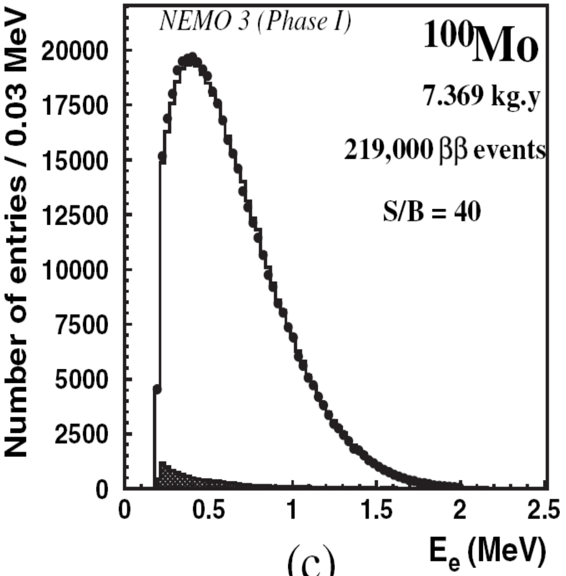
SuperNEMO

- Tracking calorimeter. Source ≠ Detector
- ~100 kg of thin (50 mg/cm^2) enriched Se or Nd foils
- Calorimetry through plastic scintillator or scintillating bar, σ≈2% resolution
- Tracking through Geiger cells. Single/double track ID

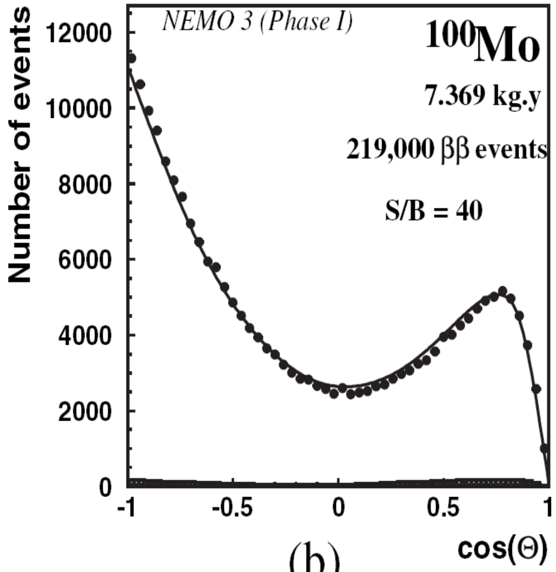
Material supplied by
Dominique Lalanne


Number of events/0.05 MeV
12000
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
3
E2e (MeV)
NEMO 3 (Phase I)
100Mo
7.369 kg.y
219,000 ββ events
S/B = 40

(a)


Number of entries / 0.03 MeV
20000
17500
15000
12500
10000
7500
5000
2500
0
0
0.5
1
1.5
2
2.5
Ee (MeV)
NEMO 3 (Phase I)
100Mo
7.369 kg.y
219,000 ββ events
S/B = 40

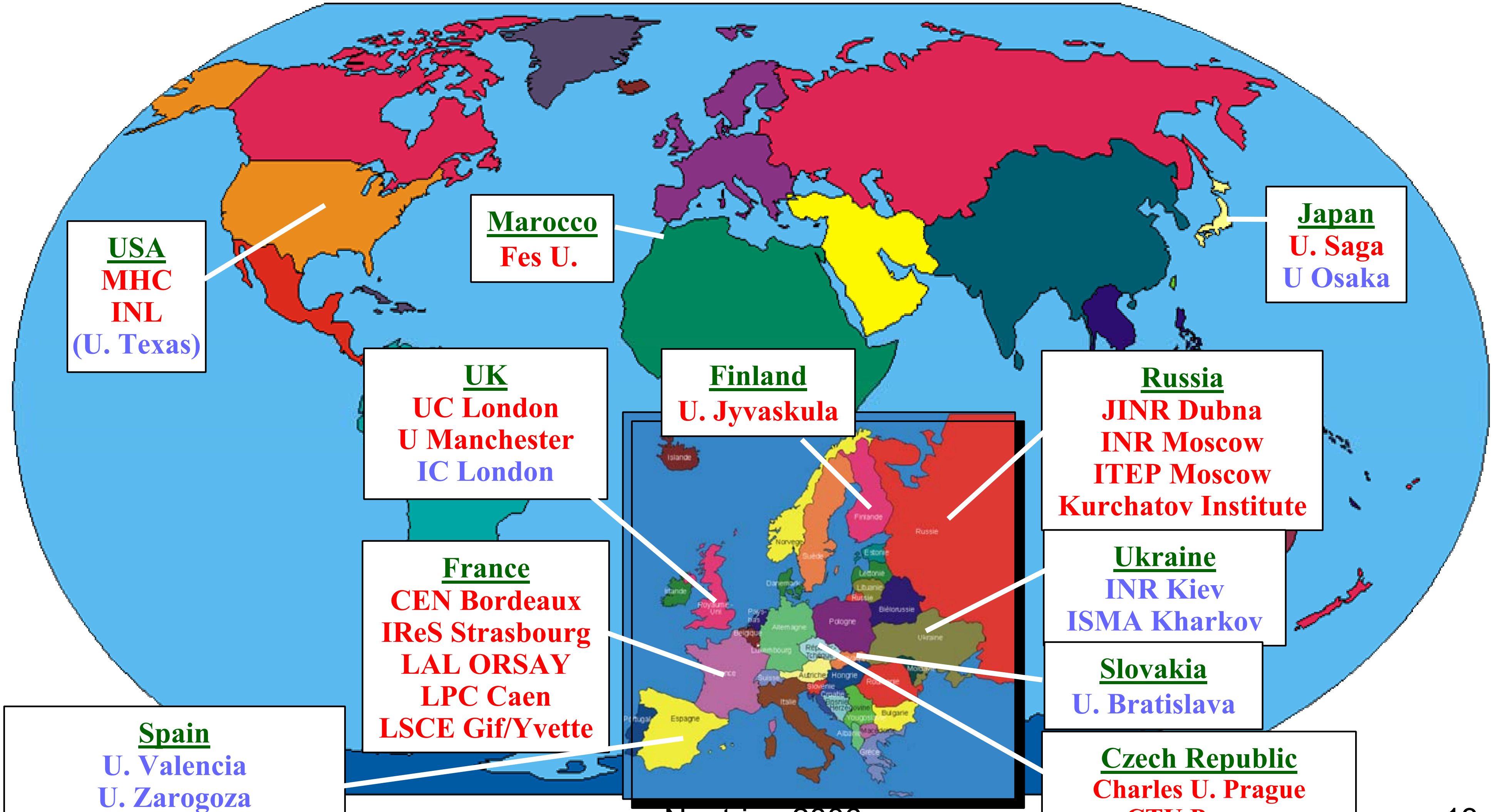
(c)


Number of events
12000
10000
8000
6000
4000
2000
0
-1
-0.5
0
0.5
1
cos(Θ)
NEMO 3 (Phase I)
100Mo
7.369 kg.y
219,000 ββ events
S/B = 40

(b)

SuperNEMO collaboration

NEMO collaboration + new labs ~ 60 physicists, 11 countries, 27 laboratories



USA
MHC
INL
(U. Texas)

Marocco
Fes U.

Japan
U. Saga
U Osaka

UK
UC London
U Manchester
IC London

Finland
U. Jyvaskula

Russia
JINR Dubna
INR Moscow
ITEP Moscow
Kurchatov Institute

France
CEN Bordeaux
IReS Strasbourg
LAL ORSAY
LPC Caen
LSCE Gif/Yvette

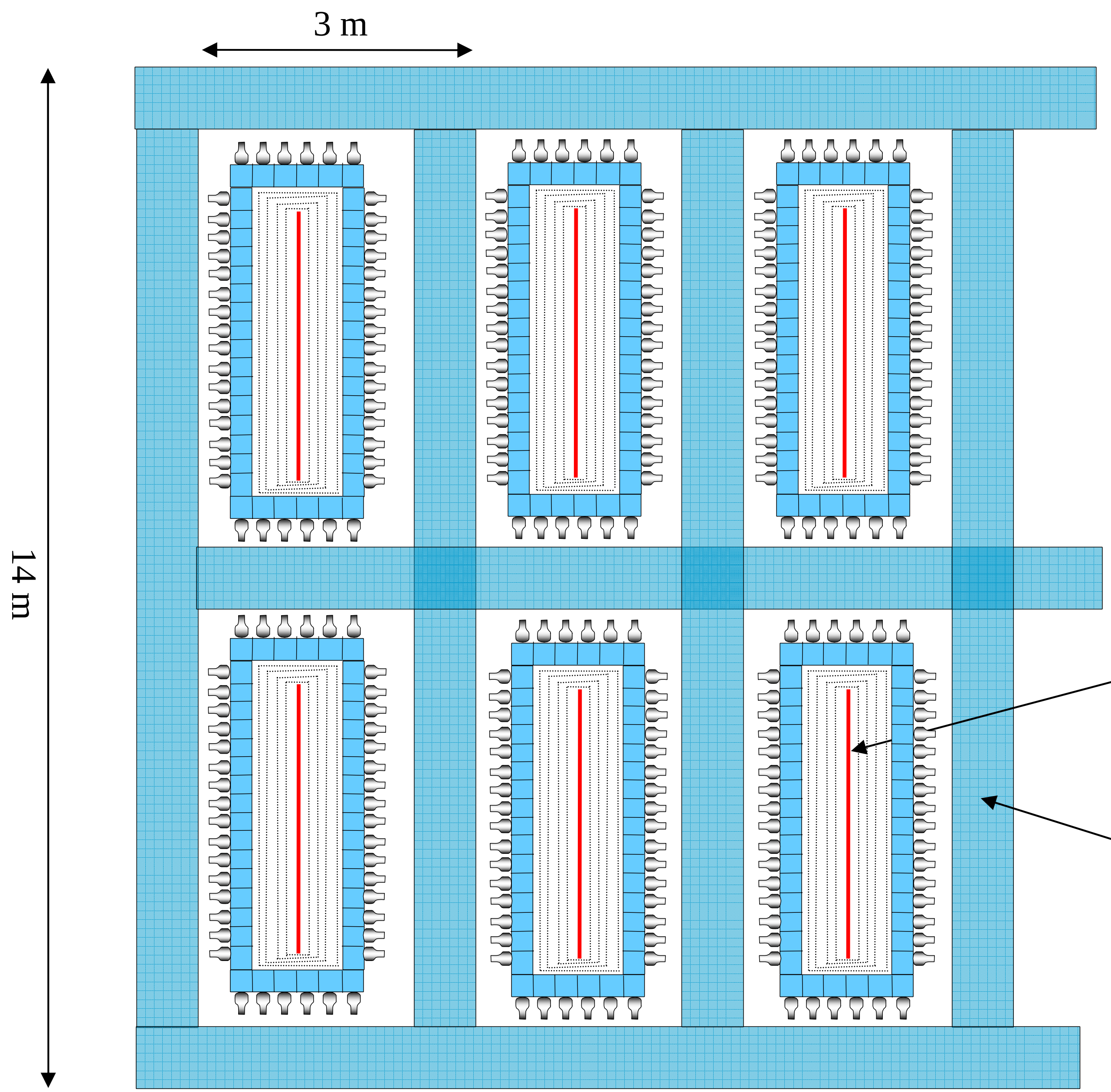
Ukraine
INR Kiev
ISMA Kharkov

Slovakia
U. Bratislava

Spain
U. Valencia
U. Zarogoza
U. Autonoma Barcelona

Czech Republic
Charles U. Prague
CTU Prague

SuperNEMO detector: possible design



Number of Modules = 20

For each module

Calorimeter : 300 to 1000 PMT's
(depending on the final design)
Resolution (FWHM) at 3MeV = 4%

Tracking : drift chamber (3000 cells in Geiger mode)

Magnetic field : 25 gauss

Source foil:
5 kg of enriched ^{150}Nd or ^{82}Se

Water shield:
2kT of water for 20 modules

ε(ββ0ν) ~ 30 %

SuperNEMO ββ source: ^{82}Se, ^{150}Nd

Goal : $T_{1/2} > 10^{26}$ y
$< m_\nu > \leq 50$ meV

$$\frac{1}{T_{0\nu}} = G_{0\nu} M_{0\nu}^2 \langle m_\nu \rangle^2$$

^{82}Se

$Q_{\beta\beta} = 2.995$ MeV

Phase space factor $G_{0\nu} = 1.08 \times 10^{-25}$ $y^{-1}eV^{-2}$

Radiopurity requirements for the ββ source

^{214}Bi < 10 μBq/kg
^{208}Tl < 2 μBq/kg
Radon < 2 μBq/m^3

$T_{2\nu} = 9 \times 10^{19}$ y

Expected background from 2β2ν = 1.4 evt/500kg.y in 200 keV (200 keV energy window at $Q_{\beta\beta}$)

Enrichment by ultracentrifugation

^{150}Nd

$Q_{\beta\beta} = 3.367$ MeV

Phase space factor $G_{0\nu} = 8.00 \times 10^{-25}$ $y^{-1}eV^{-2}$

The best choice for phase space and background

Radiopurity requirements for the ββ source

^{208}Tl < 2 μBq/kg

$T_{2\nu} = 9 \times 10^{18}$ y

Expected background from 2β2ν = 2.2 evt/500kg.y in 200 keV (200 keV energy window at $Q_{\beta\beta}$)

Enrichment by laser

EXO

Enriched Xenon Observatory

for double beta decay

D.Leonard, A.Piepke
Physics Dept, University of Alabama, Tuscaloosa AL

P.Vogel
Physics Dept Caltech, Pasadena CA

A.Bellerive, M.Bowcock, M.Dixit, C.Hargrove, D.Sinclair, V.Strickland
Carleton University, Ottawa, Canada

W.Fairbank Jr., S.Jeng, K.Hall
Colorado State University, Fort Collins CO

M.Moe
Physics Dept UC Irvine, Irvine CA

D.Akimov, A.Burenkov, M.Danilov, A.Dolgolenko, A.Kovalenko, D.Kovalenko, G.Smirnov, V.Stekhanov
ITEP Moscow, Russia

J.Farine, D.Hallman, C.Virtue
Laurentian University, Canada

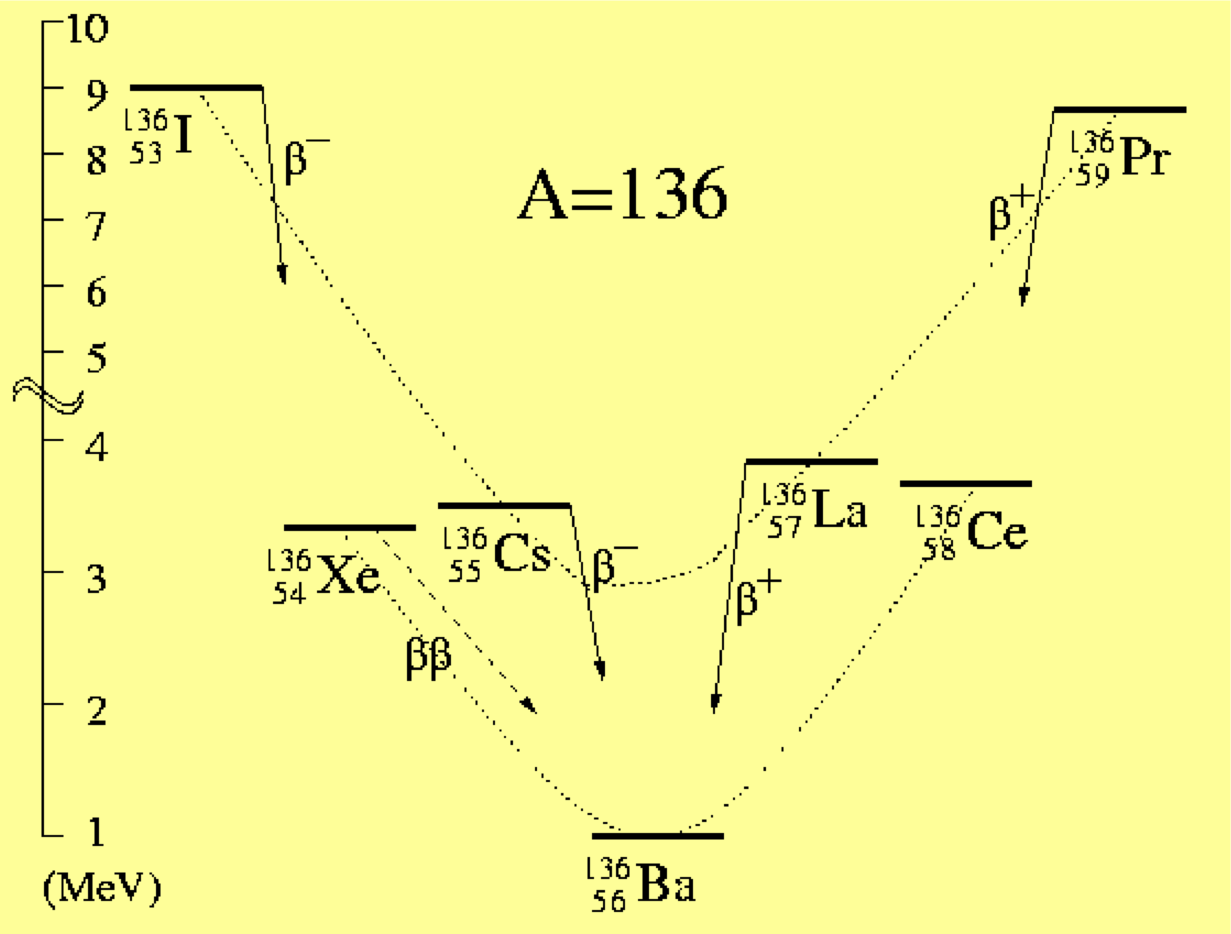
M.Hauger, F.Juget, L.Ounalli, D.Schenker, J-L.Vuilleumier, J-M.Vuilleumier, P.Weber
Physics Dept University of Neuchatel, Switzerland

M.Breidenbach, R.Conley, C.Hall, D.McKay, A.Odian, C.Prescott, P.Rowson, K.Skarpaas, K.Wamba
SLAC, Menlo Park CA

R.DeVoe, P. Fierling, B.Flatt, G.Gratta, M.Green, F.LePort, M. Montero-Diez, R.Neilson, A.Pocar, J.Wodin
Physics Dept Stanford University, Stanford CA

Why ^{136}Xe?

- Reasonable Q-value of 2 s
  measurement at FSU. M.
  to be submitted to Phys.
- Active detection mediu
  charge collection plus l
  ~50 e/keV, anti-correlat
- Isotope ^{136}Xe has reaso
- Noble gas, isotopic enri
  No chemistry needed.
- Xenon can be re-purifie or



Ionization potentials Xe: 12.130 eV, Ba^{+}: 5.212 eV, Ba^{++}: 10.004 eV
→ ββ–decay product atom remains charged → opens possibility of Ba removal and final state tagging through Ba single ion detection

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[1] XENON Collaboration data

EXO Road Map

- Goal: build 1 to 10 ton high resolution tracking TPC using enriched ^{136}Xe.
  Equip with Ba-final state tagging. → This should result in extremely small
  if not zero random background.
  Envisaged sensitivity 10 meV, covers mass range allowed for inverted hierarchy.

- Active R&D program under way. Explores the technical feasibility in phased approach.

- Detect decay and vertex in TPC using liquid Xenon

- Extract Ba ion using a charged probe. Transfer into ion trap, use laser pumping to identify single ion.

- Research on a high pressure gas TPC and in situ detection of Ba in the Xenon gas is being pursued too.

EXO Technical Preparation

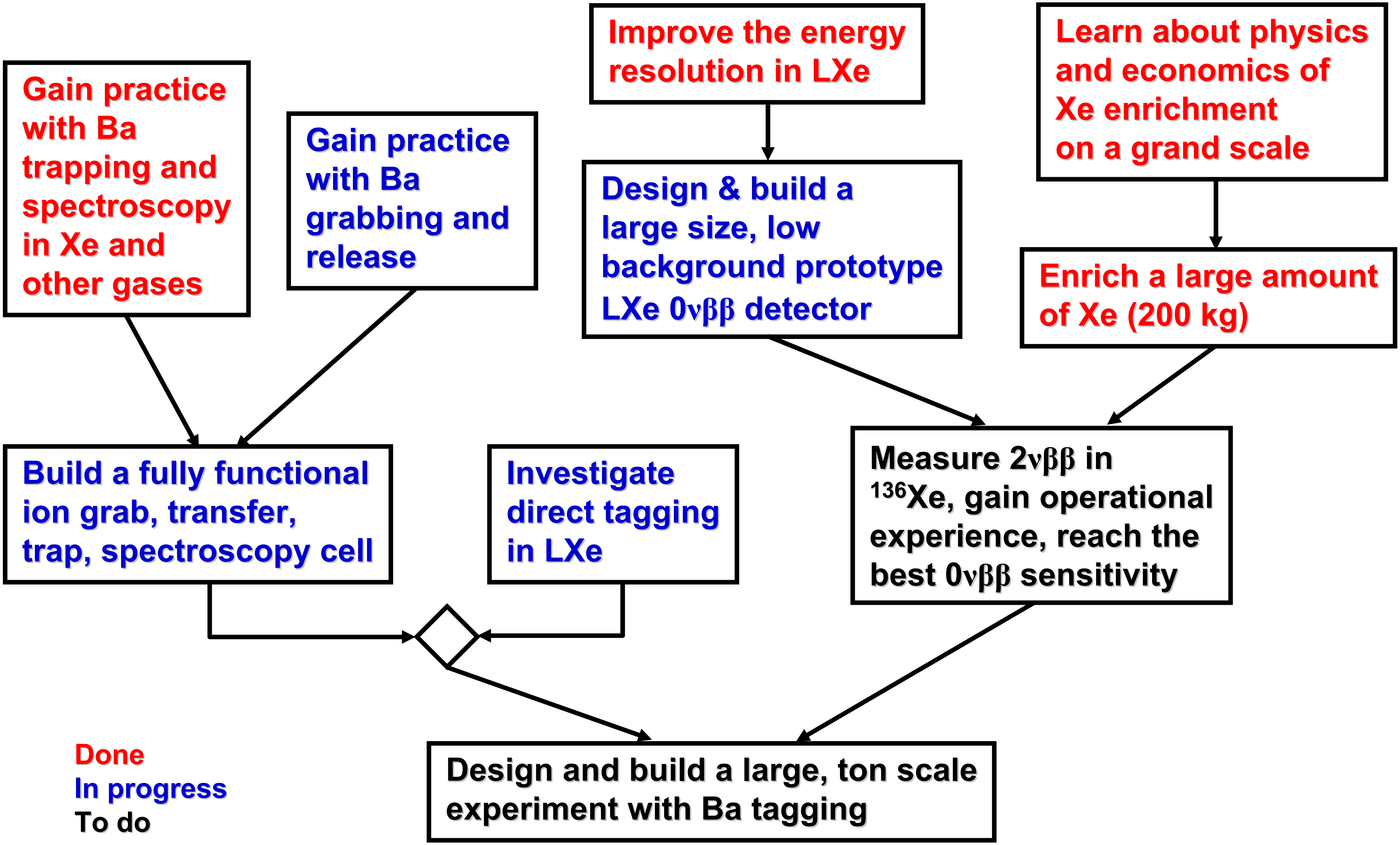
Build and operate a smaller scale TPC to demonstrate that required energy resolution and background can be achieved. Demonstrate feasibility of large scale enrichment of ^{136}Xe.

We are building detector using 200 kg enriched Xe (at hand), to be installed at WIPP, New Mexico 2006/2007.
Will demonstrate background and energy resolution.

Ba extraction, transfer and single ion detection being developed in the lab in parallel.

After successful completion of these parallel research thrusts preparation of full proposal.
In this plan proof of principle does not require the funding of a very costly large experiment up front.

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



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 0νββ detector

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

Enrich a large amount of Xe (200 kg)

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

Investigate direct tagging in LXe

Measure 2νββ in ^{136}Xe, gain operational experience, reach the best 0νββ sensitivity

Design and build a large, ton scale experiment with Ba tagging

Done
In progress
To do

EXO-200

Scientific goals:

1) **Measurement of yet unobserved $\beta\beta2\nu$ decay of ^{136}Xe. Task: $T_{1/2} > 10^{22}$ y, ~67 dcs / (d 100 kg). Important background for EXO.**

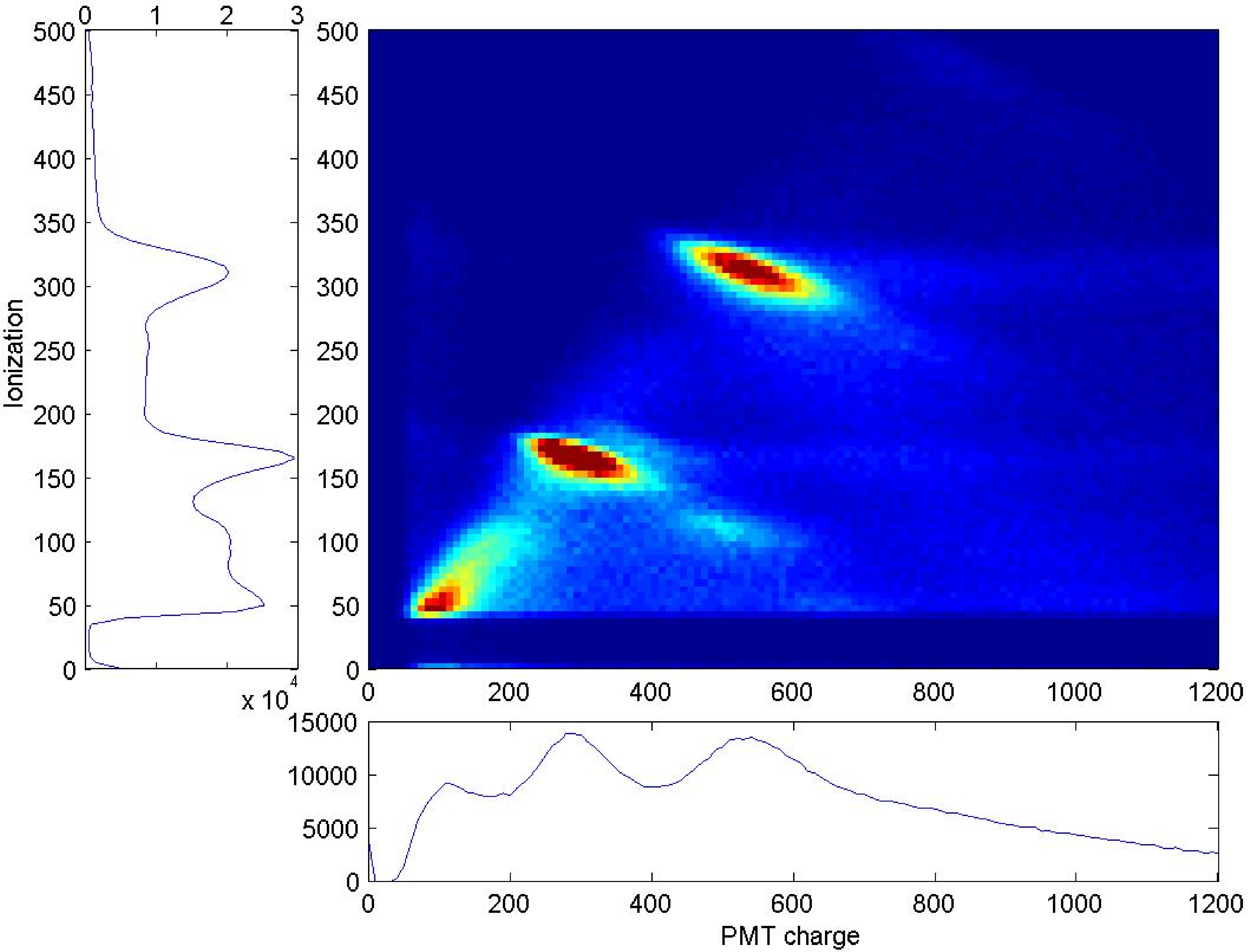
2) **Test of the Heidelberg evidence for $\beta\beta0\nu$ decay.**
   Expectation for ^{136}Xe [Ge $\pm 3\sigma$ range $(0.7\text{-}4.2)\cdot10^{25}$ y]:
   $T_{1/2} = (0.58\text{–}3.5)\cdot10^{25}$ y [Rodin et al. PRC68 (03) RQRPA] 7-43 dcs / (y 100 kg)
   $= (0.66\text{–}4.0)\cdot10^{25}$ y [Staudt et al. EPL13 (90) QRPA]
   $= (0.48\text{–}2.9)\cdot10^{25}$ y [Caurier et al. NPA654 (99) SM]

Approach:

Achieve good resolution by utilizing both ionization and scintillation and the fact that both are anti-correlated. Resolution (extrapolated from 570 keV to 2460 keV) achieved in the lab: 1.6% @$Q_{\beta\beta}$.

Build tracking liquid Xe TPC with 1 cm spatial resolution. Allows to discriminate gamma background from electron signal. Background reduction by MC: depending on proximity and type reduction factor 5-50.
Initially no Ba tagging.

Please see poster #14 by Jesse Wodin and Andrea Pocar


Ionization
PMT charge
x 10^4
0
1
2
3
500
450
400
350
300
250
200
150
100
50
0
200
400
600
800
1000
1200
15000
10000
5000

201

s

e

Massive effort on material radioactivity qualification

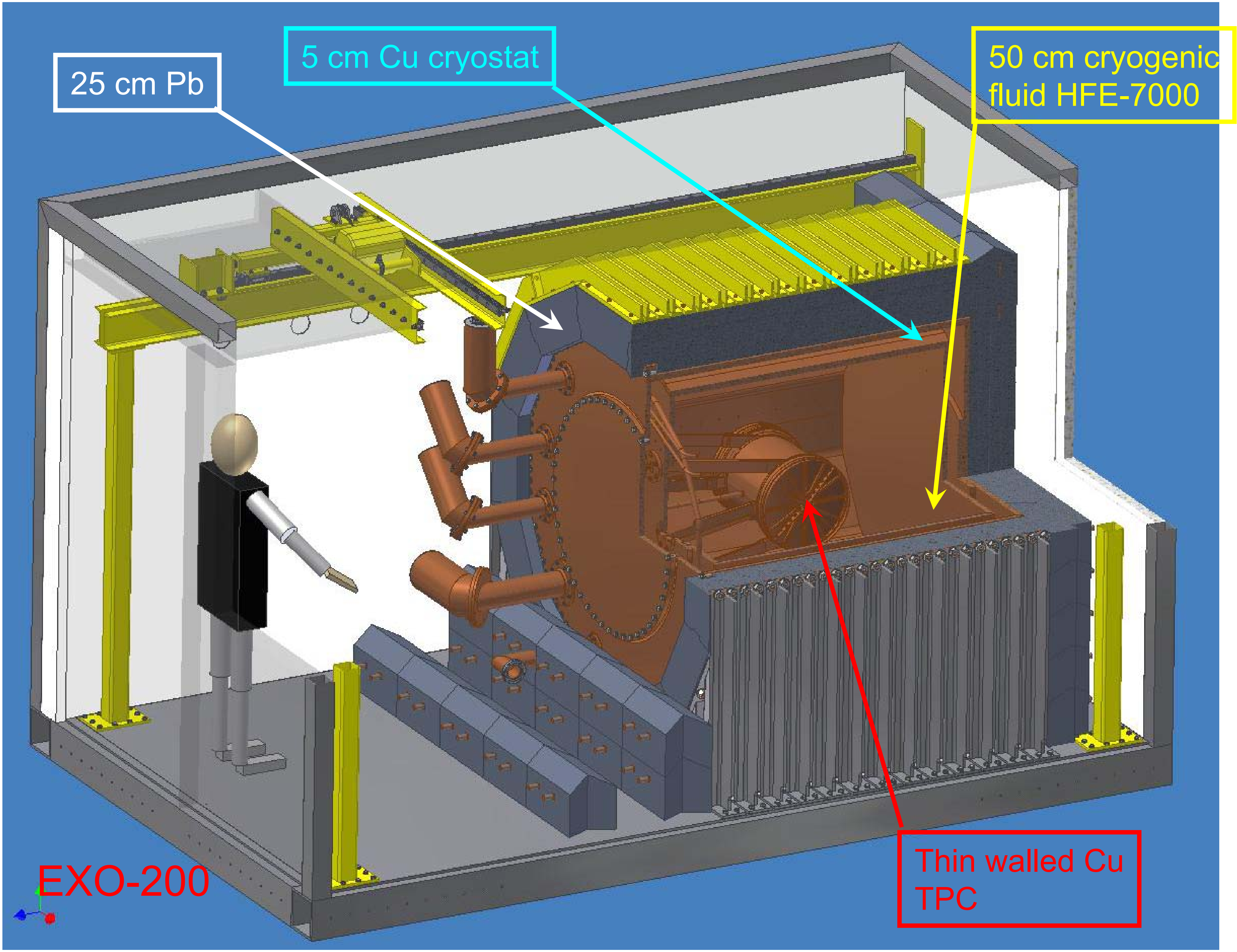
- **NAA**[a]
- **Low background γ-spectroscopy**[b]
- **α-counting**[c]
- **Radon counting**[d]
- **GD-MS and ICP-MS**[e]

Th/U Sensitivity
Teflon (TPC):
<0.3 ppt or
1 and 4 μBq/kg
Cu (TPC):
<0.8 ppt

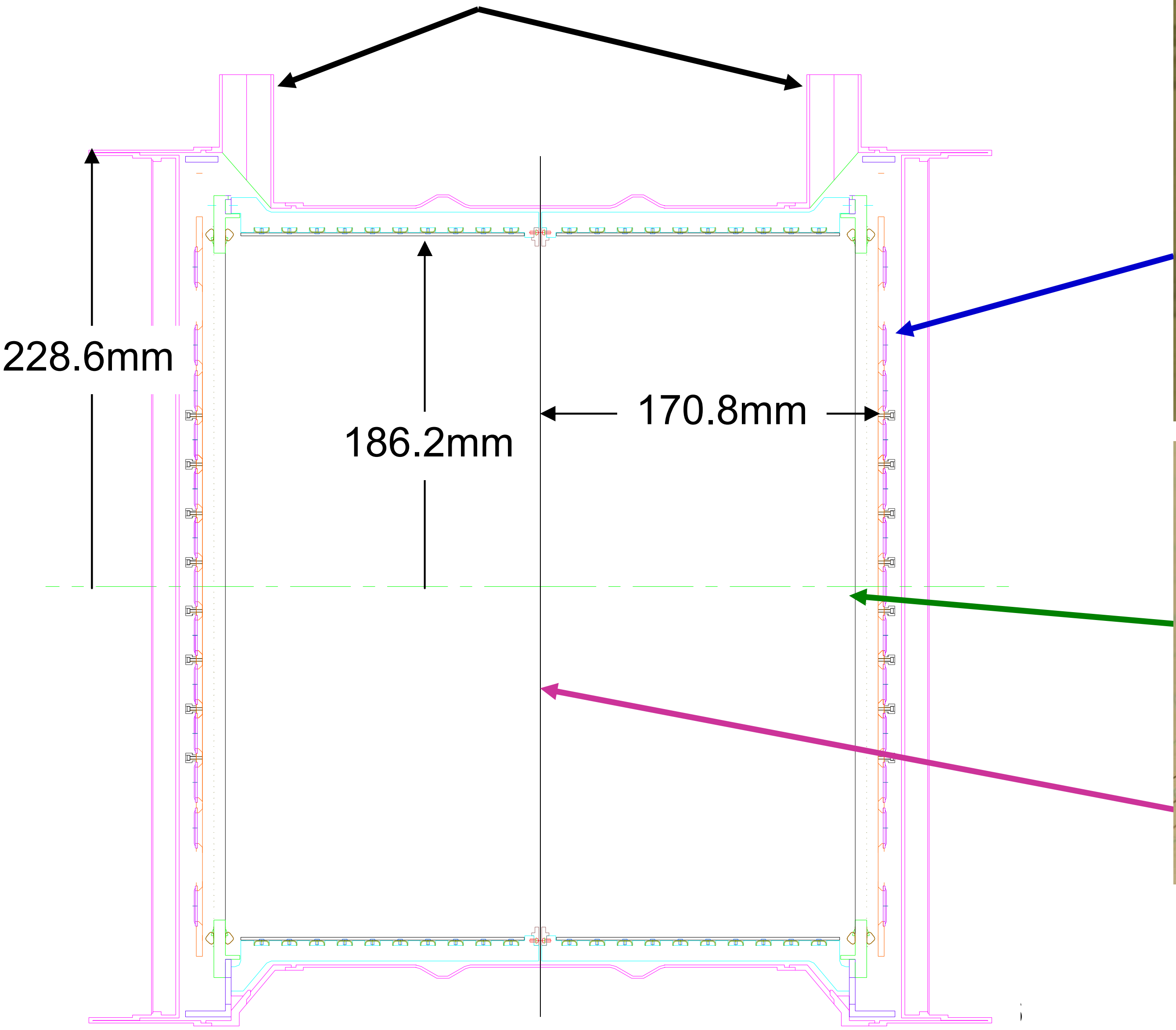
Online database for collaborators at present includes > 230 entries

MC simulation of backgrounds
Alabama & Stanford / SLAC

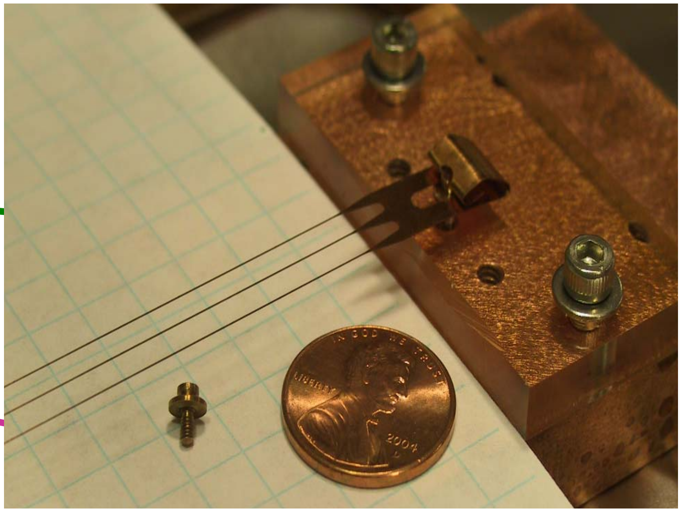
[a] Alabama using MIT reactor
[b] Neuchatel, Alabama
[c] Alabama, SLAC, Carleton
[d] Laurentian
[e] Canadian Inst. Standards


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

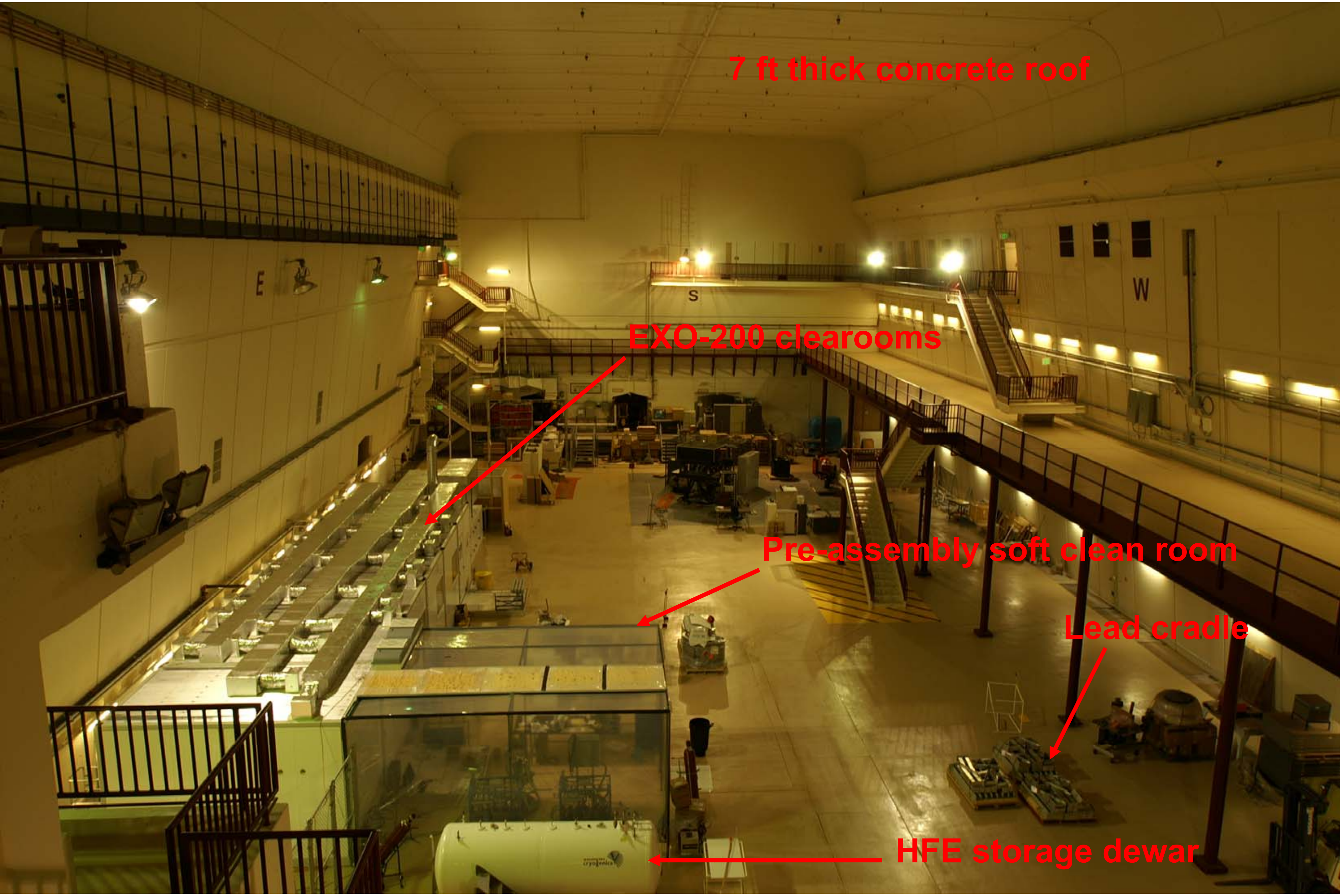
What’s inside the vessel (besides 200 kg enriched Xe)?

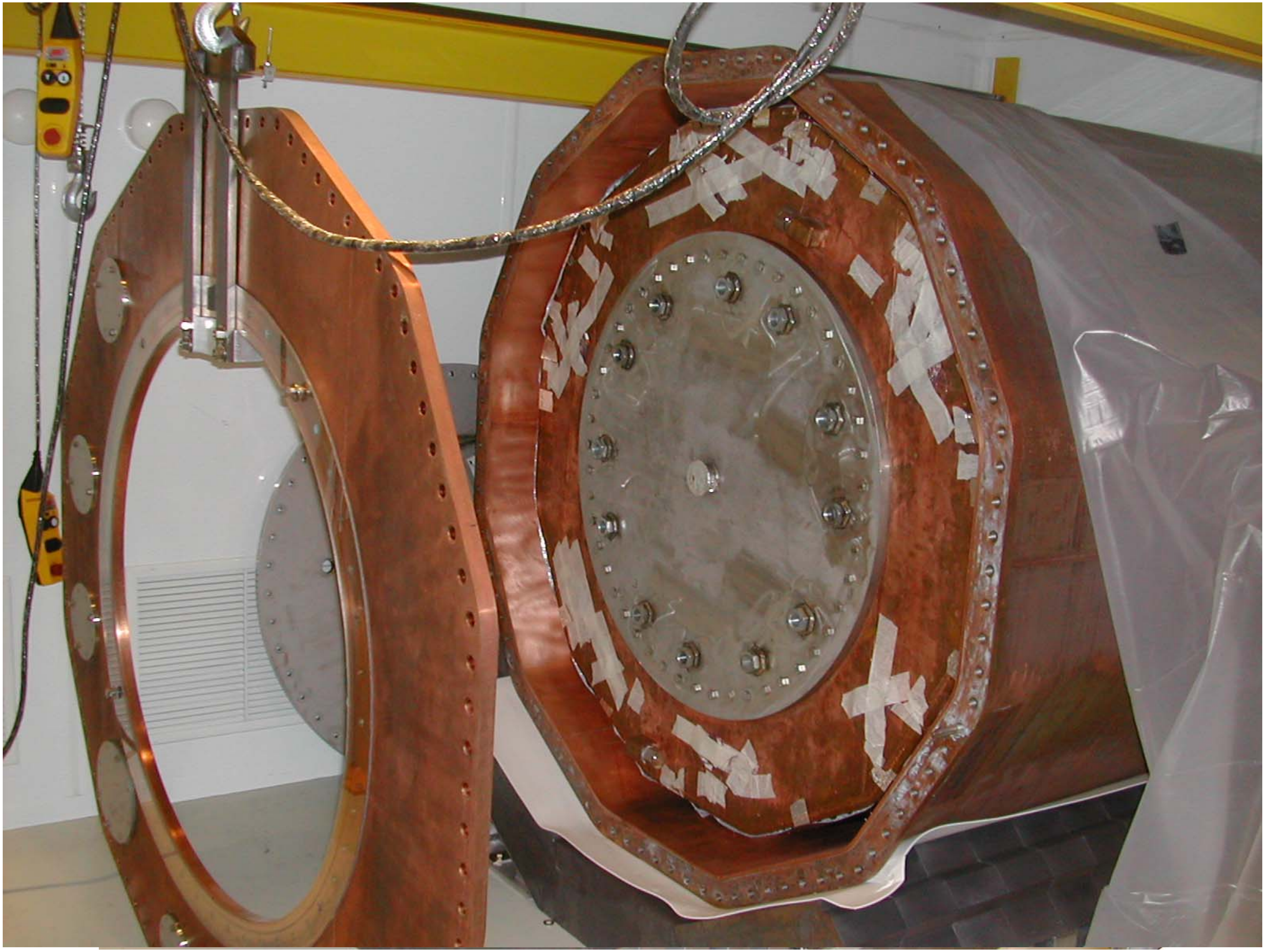


Mechanical supports and cable/Xe conduits



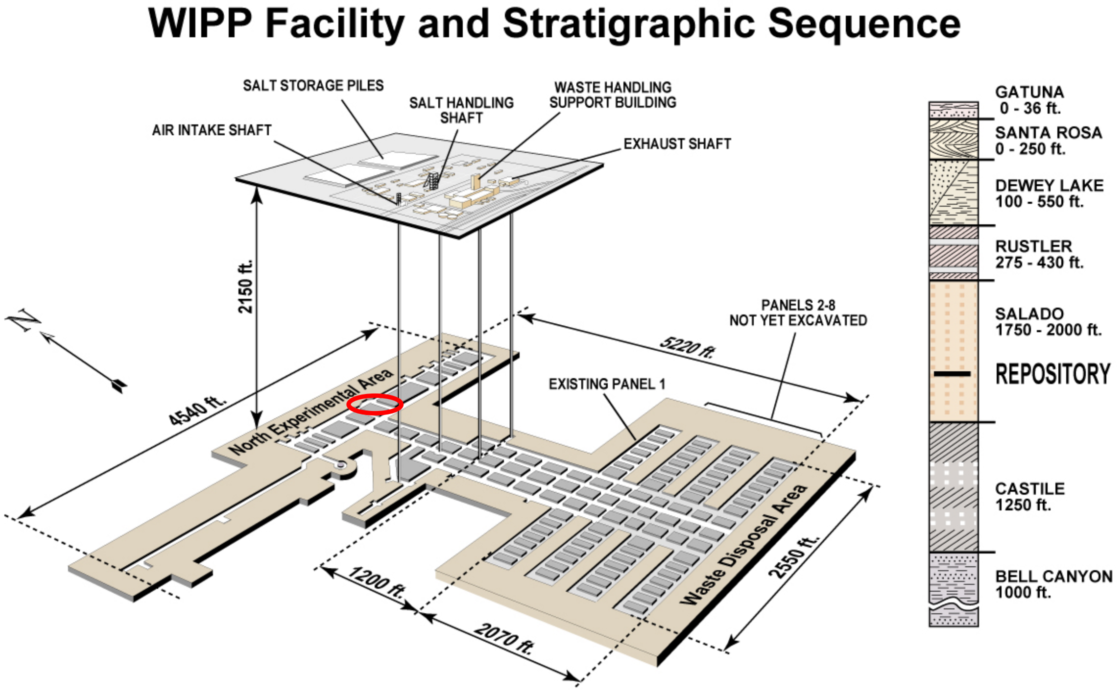
EXO-200 installation at HEPL (Stanford campus)





EXO-200 schedule

May, 2006	Pb cradle installation complete
Jun, 2006	Cryostat installed
Jul, 2006	First full cooldown
Oct, 2006	End tests at Stanford
Nov, 2006	Dismounting complete
Nov, 2006	Lower first module at WIPP
Dec, 2006	Lower last load (Pb arches) at WIPP



EXO-200 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 2.46MeV 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)	
							RQRPA	NSM
EXO-200	0.2	70	2	1.6[*]	40	6.4×10^{25}	0.27[†]	0.38[♦]

What if the Heidelberg signal is due to $\beta\beta0\nu$–decay ?

Central value $T_{1/2}$ (Ge) = $1.2^{+3}_{-0.5} \cdot 10^{25}$, ($\pm 3\sigma$) (PL B 586 (04)

In 200 kg EXO, 2 yr:

- **Worst case (RQRPA, upper limit) 19 events on top of 40 events bkgd → 2.6 σ**
- **Best case (NSM, lower limit) 159 events on top of 40 bkgd → 11.2 σ**

Barium Grabber

Three techniques being … **d**

Cryo tip: **- thin layer of** … **a metal**

- Ba ion is elec … **ice surface**

- ice is thawed … **nd Ba ion is released**

Challenge: control th … ***ic layers***

→ Close to a soluti

FE tip: **- u** … **he very tip**

- s

Challen

→ Fie … ***nstalled soon***

RIS tip: **- t** … **n at end**

- E

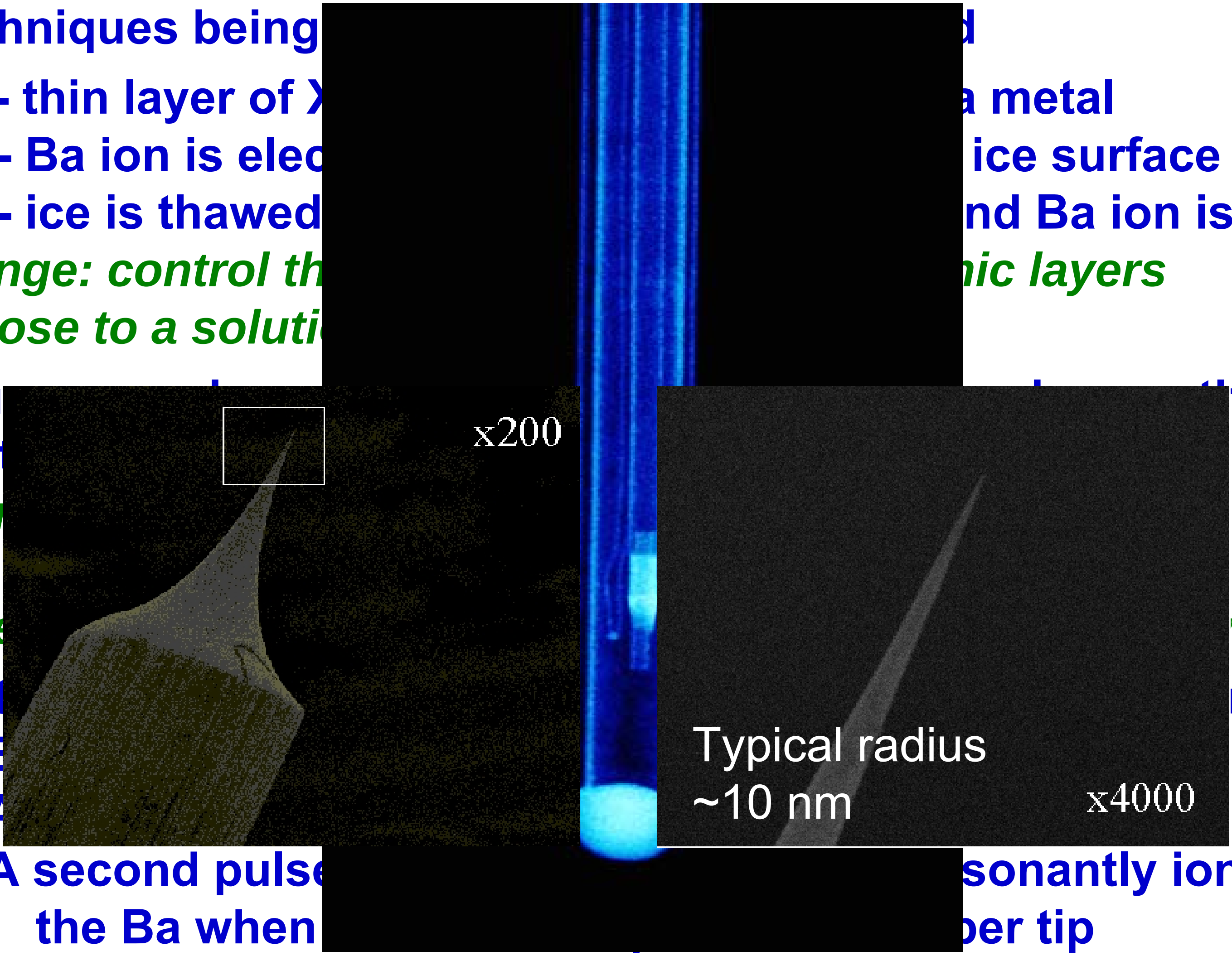
- A

- A second pulse … **sonantly ionizes**

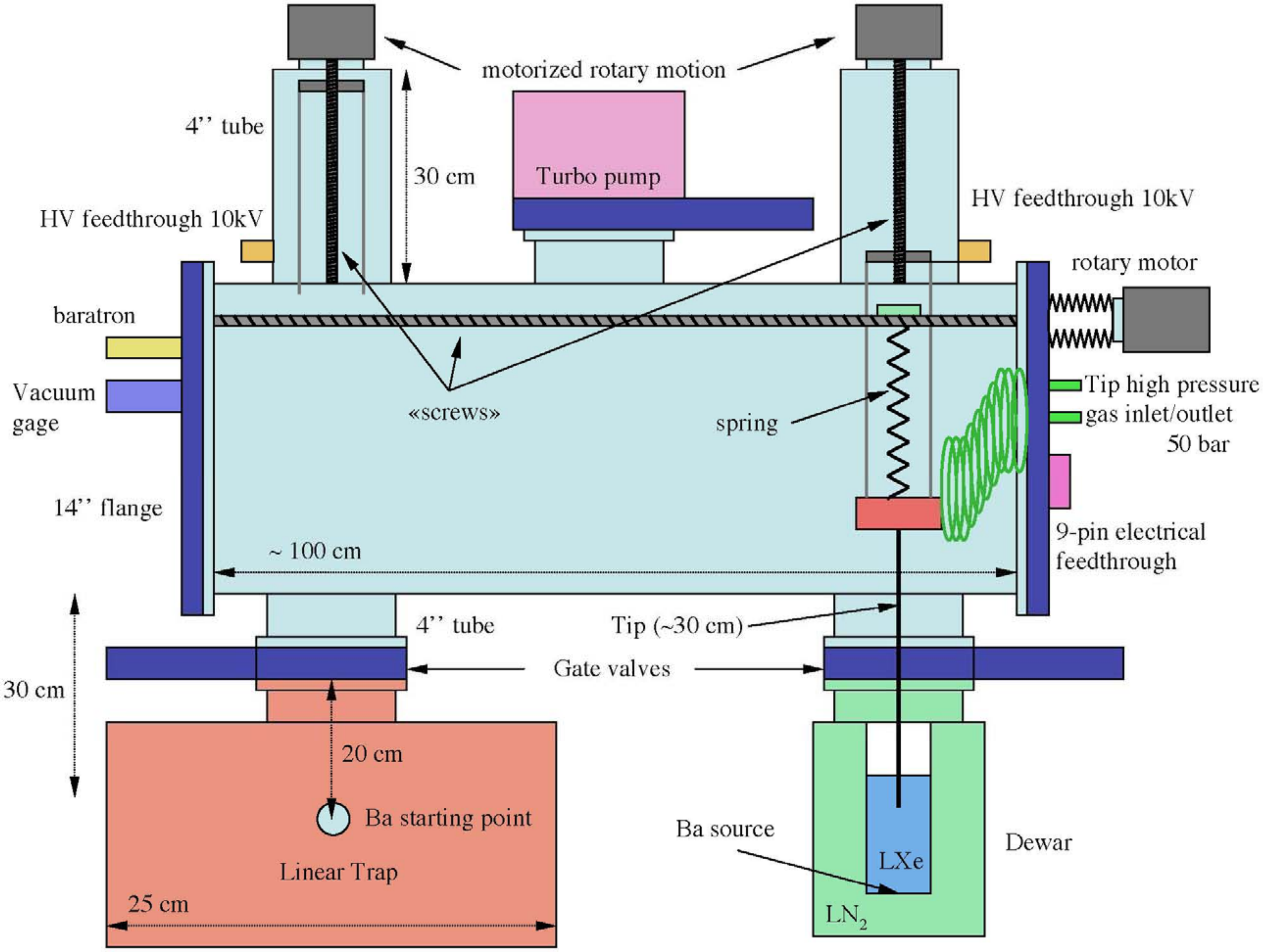
the Ba when … **per tip**

Challenge: The lasers are expensive

→ Each step demonstrated and known to work with high efficiency



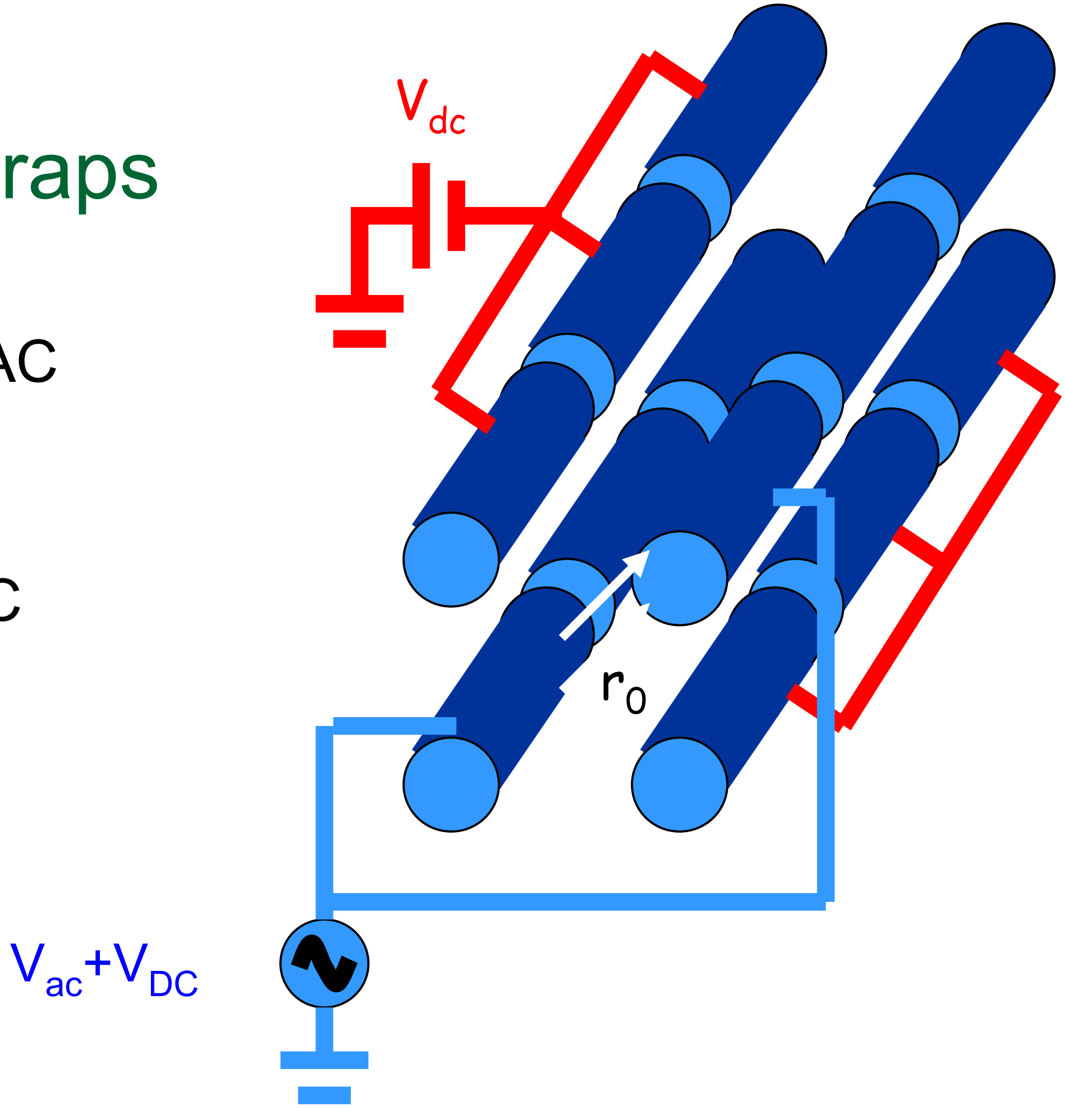
Grabber tip transfer system being built at the Univ of Neuchatel. To be installed on the Stanford linear trap in 2006



Ba single Ion Detection

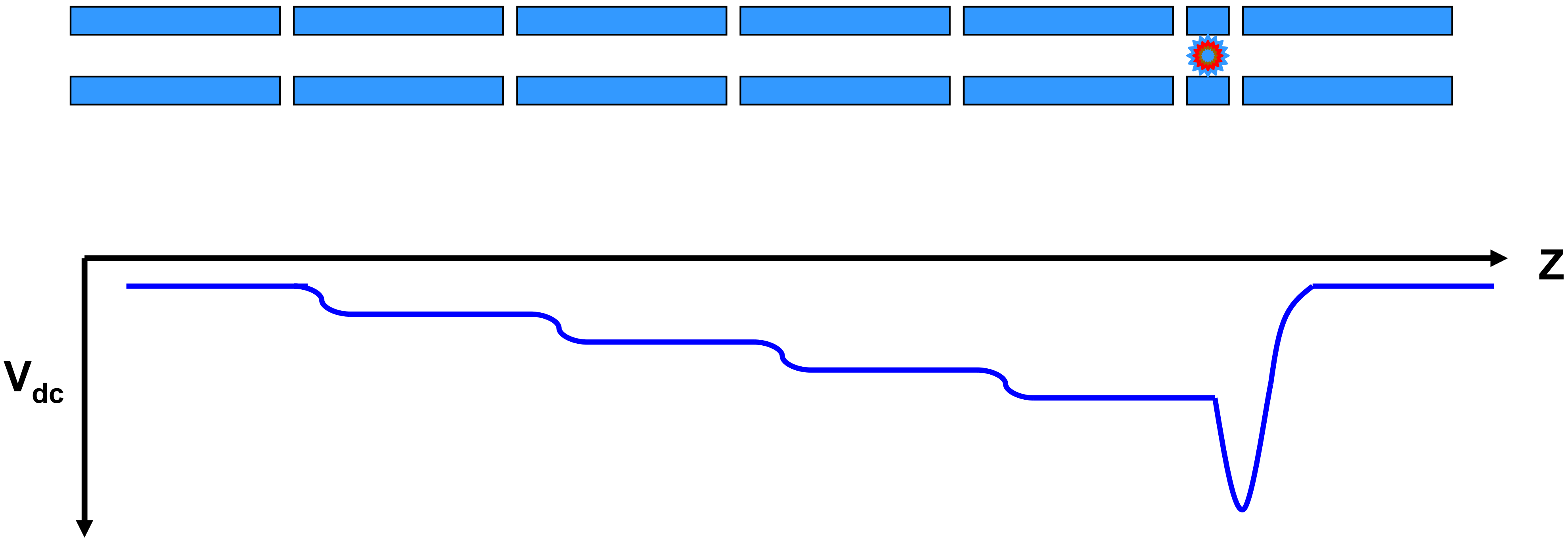
Linear Paul (RFQ) Traps

- Radial confinement from AC potential across rods.
- Axial confinement from DC potentials across rod segments.



Please see poster #20 by Matt Green and Bjorn Flatt

Linear Traps



High loading efficiency for incoming ions observed.

Ions that loaded at one end will travel to the other.

Ions can be manipulated by changing the DC potential configuration.

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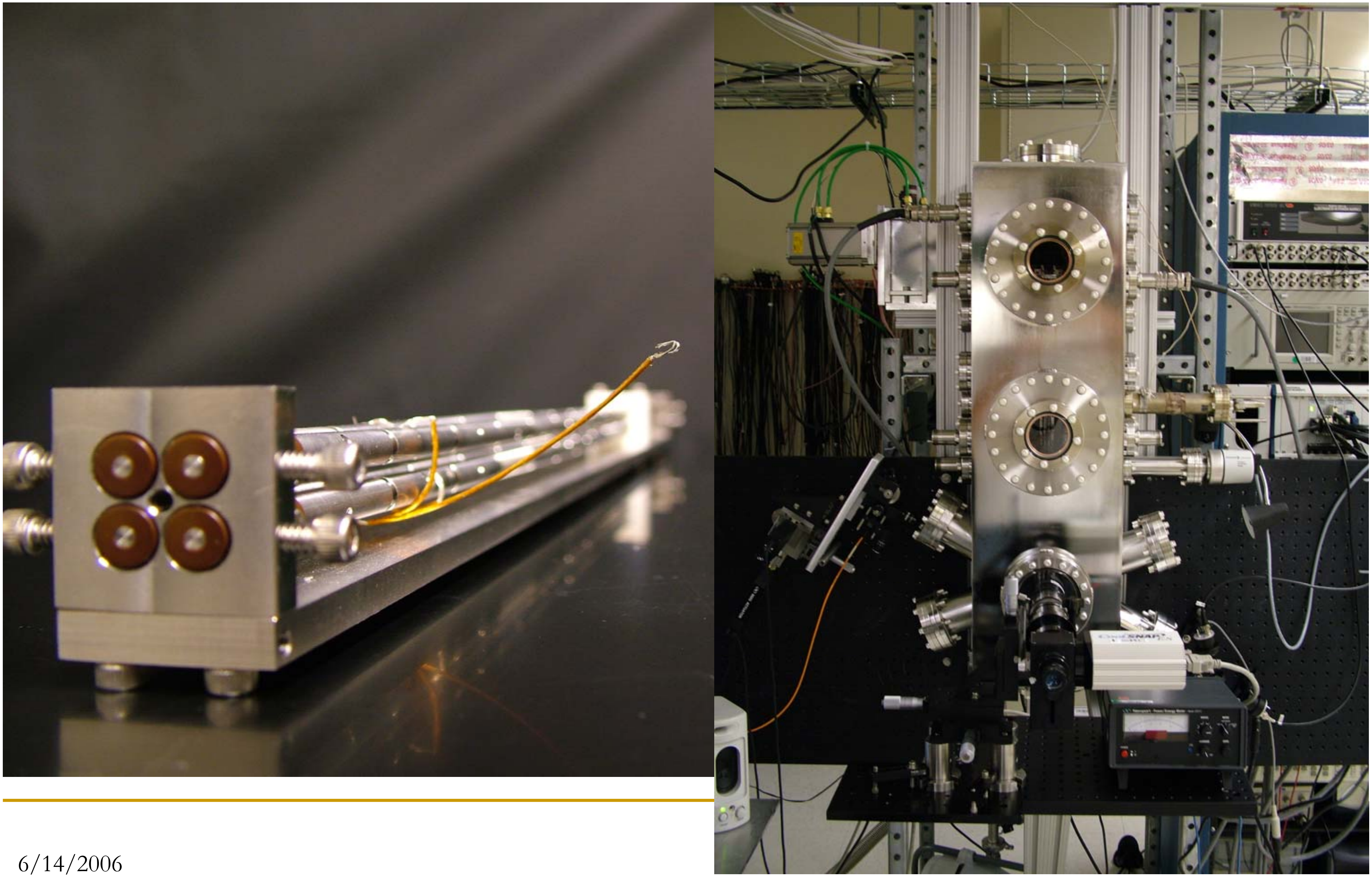
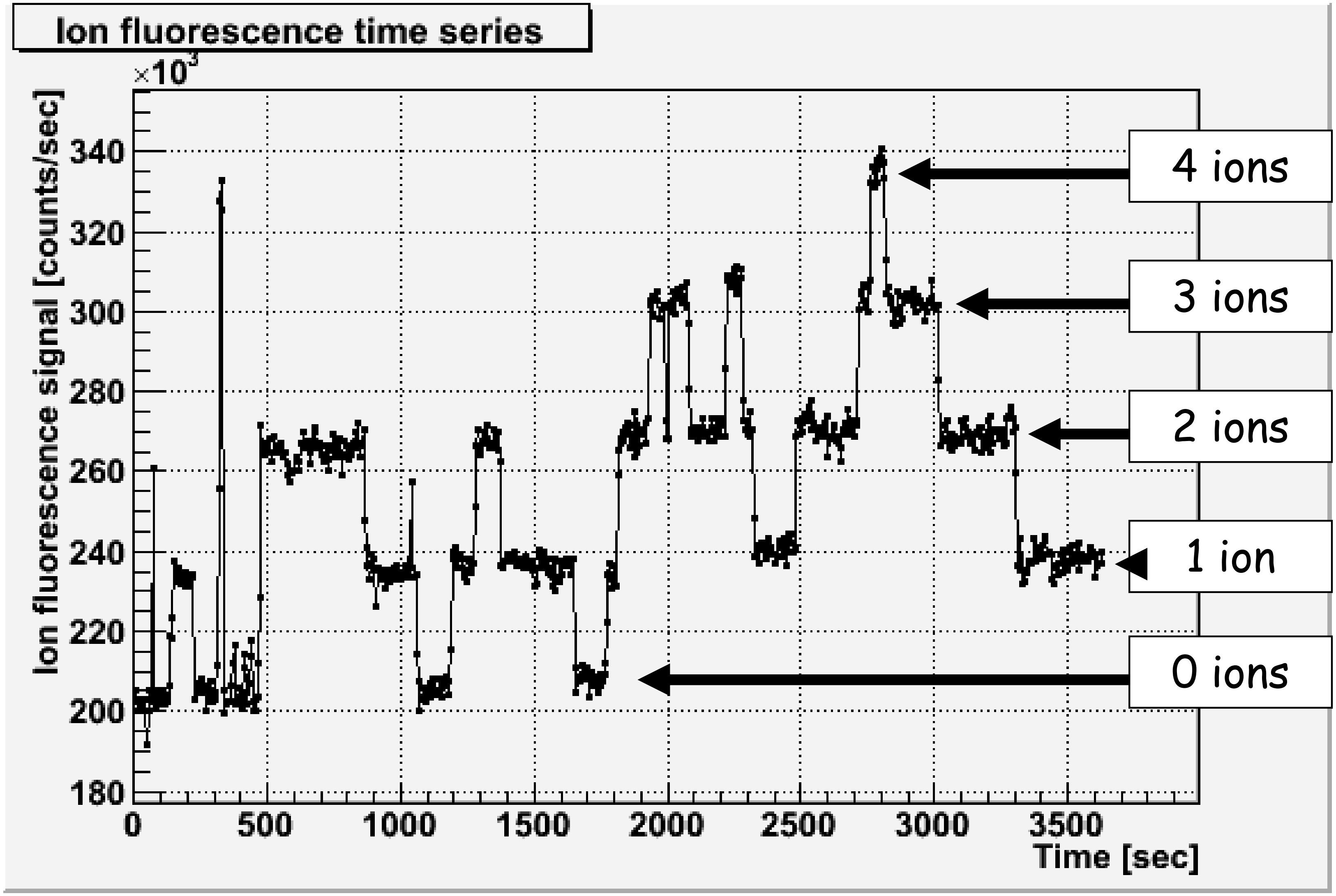
Stanford Linear Trap





Ion signal as a function of time as ions are loaded and unloaded from the linear trap. The quantized structure demonstrates our ability to detect single atoms in a buffer gas with high S/N.

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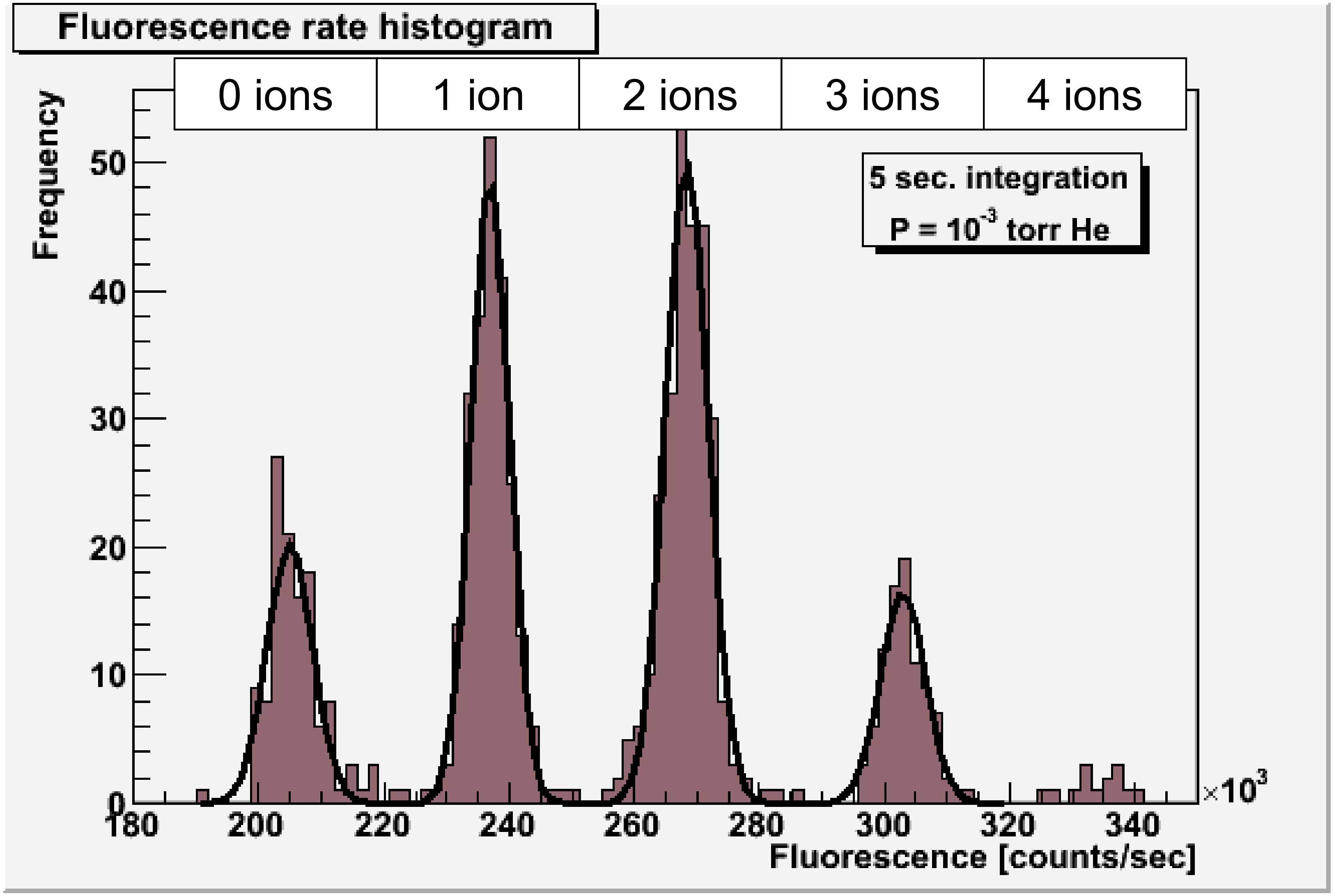

Histogram of ion fluorescence signal. With a 5 sec integration the signal from 1 ion is distinguishable from background at the 8.7σ level.

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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 2.46 MeV 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

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

[†] s(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

Conclusion

The next generation ββ–experiments hope to observe this decay.

Unambiguous evidence will be important for making a clear case that Neutrinos are Majorana particles.

To achieve this we will need experiments using different methods and different nuclides. In case of success this would give some handle on the matrix element calculations and their spread.

This goal requires both high resolution calorimetric and tracking detectors.

Several large tracking detectors are being prepared. We hope that they will help provide this unambiguous evidence utilizing their high diagnostic power.

Stay tuned! First data will come soon.