nEXO

Enriched Xenon Observatory

EXO

for double beta decay

EXO is a well oiled (but extremely clean!) collaboration that has been together for ~10 years and has managed to build one of the most competitive double-beta decay detectors in the world, producing results in a timely and effective way.

Most recently several new groups, including IHEP-Beijing and TRIUMF, have joined the team

The EXO Collaboration

Enriched Xenon Observatory

EXO

for double beta decay

University of Alabama, Tuscaloosa AL, USA - D. Auty, T. Didberidze, M. Hughes, A. Piepke

University of Bern, Switzerland - M. Auger, S. Delaquis, D. Franco, G. Giroux, R. Gornea, T. Tolba, J-L. Vuilleumier, M. Weber

California Institute of Technology, Pasadena CA, USA - P. Vogel

Carleton University, Ottawa ON, Canada - V. Basque, M. Dunford, K. Graham, C. Hargrove, R. Killick, T. Koffas F. Leonard, C. Licciardi, M. Rozo, D. Sinclair

Colorado State University, Fort Collins CO, USA - C. Benitez-Medina, C. Chambers, A. Craycraft, W. Fairbank, Jr., N. Kaufhold, T. Walton

Drexel University, Philadelphia PA, USA - M.J. Dolinski, M.J. Jewell, Y.H. Lin, E. Smith

Duke University, Durham NC, USA - P.S. Barbeau

University of Illinois, Urbana-Champaign IL, USA - D. Beck, J. Walton, M. Tarka, L. Yang

IHEP Beijing, People's Republic of China - G. Cao, X. Jiang, Y. Zhao

Indiana University, Bloomington IN, USA - J. Albert, S. Daugherty, T. Johnson, L.J. Kaufman

University of California, Irvine, Irvine CA, USA - M. Moe

ITEP Moscow, Russia - D. Akimov, I. Alexandrov, V. Belov, A. Burenkov, M. Danilov, A. Dolgolenko, A. Karelin, A. Kovalenko, A. Kuchenkov, V. Stekhanov, O. Zeldovich

Laurentian University, Sudbury ON, Canada - B. Cleveland, J. Farine, B. Mong, U. Wichoski

University of Maryland, College Park MD, USA - C. Davis, A. Dobi, C. Hall, S. Slutsky, Y-R. Yen

University of Massachusetts, Amherst MA, USA - T. Daniels, S. Johnston, K. Kumar, M. Lodato, C. Mackeen, K. Malone, A. Pocar, J.D. Wright

University of Seoul, South Korea - D. Leonard

SLAC National Accelerator Laboratory, Menlo Park CA, USA - M. Breidenbach, R. Conley, A. Dragone, K. Fouts, R. Herbst, S. Herrin, A. Johnson, R. MacLellan, K. Nishimura, A. Odian, C.Y. Prescott, P.C. Rowson, J.J. Russell, K. Skarpaas, M. Swift, A. Waite, M. Wittgen

Stanford University, Stanford CA, USA - J. Bonatt, T. Brunner, J. Chaves, J. Davis, R. DeVoe, D. Fudenberg, G. Gratta, S. Kravitz, D. Moore, I. Ostrovskiy, A. Rivas, A. Schubert, D. Tosi, K. Twelker, L. Wen

Technical University of Munich, Garching, Germany - W. Feldmeier, P. Fierlinger, M. Marino

TRIUMF, Vancouver BC, Canada – P.A. Amandruz, D. Bishop, J. Dilling, P. Gumplinger, R. Kruecken, C. Lim, F. Retiere, V. Strickland

The EXO Collaboration

Enriched Xenon Observatory
EXO
for double beta decay

115 collaborators (90% scientists and students, 10% engineers)
20 institutions
7 countries
3 continents

We are generally keen in growing the collaboration further (to some extent) with groups with the right expertize and interests. Indeed in the last years we accreted in part from new “EXO-generated” groups (Drexel and Duke) and in part from entirely new groups (IHEP-Beijing and TRIUMF)

Enriched Xenon Observatory
EXO
for double beta decay

Collaboration Board

Chairperson: J. Farine, Laurentian University
Makes policy decisions and rules on issues that affect the collaboration as a whole, including new collaboration members, author list decisions, etc,

P. Barbeau	Duke University
M. Breidenbach	SLAC
M. Dolinski	Drexel University
B. Fairbank	Colorado State University
J. Farine	Laurentian University
P. Fierlinger	Munich Technical University
K. Fouts	SLAC (non voting)
G. Gratta	Stanford University
C. Hall	University of Maryland
L. Kaufman	Indiana University
D. Leonard	University of Seoul
M. Moe	University of California, Irvine
A. Piepke	University of Alabama
A. Pocar	University of Massachusetts
D. Sinclair	Carleton University
P. Vogel	Caltech
J. Vuilleumier	University of Bern
L. Wen	IHEP Beijing
L. Yang	University of Illinois
O. Zeldovich	ITEP Moscow

TRIUMF membership not yet finalized

Collaboration Council

Membership is by invitation from the spokesperson
Serves as an advisory council to the spokesperson.

M. Breidenbach	SLAC
M. Dolinski	Drexel University
K. Fouts	SLAC
K. Kumar	University of Massachusetts
A. Piepke	University of Alabama
A. Pocar	University of Massachusetts
C. Prescott	SLAC
D. Sinclair	Carleton University
J. Vuilleumier	University of Bern

The EXO is funded by the following agencies:

- -DoE-HEP
- -DoE-NP
- -NSF
- -Swiss National Science Foundation
- -NSERC
- -Russian Foundation for Basic Research
- -Chinese Academy of Sciences

In the US nEXO R&D is mainly supported by DoE-HEP but with substantial contributions from the NSF and DoE-NP.

It is our understanding that when DoE will decide to fund nEXO as a project this will occur under DOE-NP, while DOE-HEP will continue supporting the science teams under their programme.

It is also expected that agencies from the other collaborating Countries will contribute to the nEXO, although negotiations on this have not started yet.

EXO: summary and plans

- Since the beginning, in 1999, the EXO collaboration has been planning a staged approach to 0νββ decay
- "Stage 1", i.e. EXO-200 is taking data, producing results and leading the charge in the field
- EXO-200 is also a (very successful) prototype for a larger, "Stage 2" detector
- "Stage 2", **nEXO**, is being designed as a

  5 tonne LXe detector

  following closely the EXO-200 layout
- Some R&D is required to address some scaling issues and non optimal EXO-200 solutions

EXO: summary and plans, cont'd

- R&D in progress to improve items that either do not scale well or were imperfectly designed in EXO-200. Expect to have a "CD1-quality" detector design by end of calendar 2015
- EXO submitted a letter of interest to locate the nEXO detector in the Cryopit at SNOlab
- From the start of construction this is likely to be a 10-15 yrs program with *unique* physics potential:
  - A conservative detector with wide reach using the well tested EXO-200 technology
  - The unique possibility of swapping the enriched Xe to Nat'l Xe in the case a discovery is made
  - A unique upgrade path to Ba tagging (of course, in this case, on a riskier path)

EXO: summary and plans, cont'd

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> ***"How exciting it would be to discover violations of either of our two surviving exact global conservation laws:***
> ***lepton number L and baryon number B!"***
> ***S.L.Glashow, arXiv:1305.5482 (2013)***
>
> …In addition 0νββ decay would discover the neutrino mass scale and a new type of Fermion: the 2-component Majorana Fermion

The central role of 0νββ decay in particle and nuclear physics was stated by many panels and committees in the last decade:

“Major Nuclear Physics Facilities for the Next Decade”, Report of the NSAC subcommittee, Mar 2013, arXiv:1212.5190;

"Report to NSAC on Implementing the 2007 Long Range Plan", Subcommittee, Jan 2013;

"Discovering the New Standard Model: Fundamental Symmetries and Neutrinos“, White paper in preparation for Tribble Subcommittee by the NP community, Aug 2012;

“Fundamental Physics at the Intensity Frontier”, Report of the Workshop held Dec 2011 in Rockville MD, arXiv:1205.2671;

“An Assessment of the Deep Underground Science and Engineering Laboratory”, Ad Hoc Committee to Assess the Science Proposed for a Deep Underground Science and Engineering Laboratory (DUSEL), US NRC (2011);

“The Frontiers of Nuclear Science, A Long Range Plan”, NSAC (2007);

“Revealing the Hidden Nature of Space and Time: Charting the Course for Elementary Particle Physics”, Comm. on Elem. Part. Phys. in the 21st Century,US NRC (2006);

“NuSAG report” Sept 2005, http://www.er.doe.gov/hep/NuSAGReport1final.pdf

“The Neutrino Matrix”, Report from the APS multi-divisional neutrino study, Nov 2004;

“SAGENAP report” Dec 13, 2004, http://www.er.doe.gov/hep/SAGENAPFINAL.pdf;

“Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century” Report of the National Academy of Sciences, 2003.

DBD experiments summary

Experiment	Isotope	Technique	Mass ββ(0v) isotope	Status
CANDLES	48Ca	305 kg of CaF2 crystals - liq. scint	0.3 kg	Construction
CARVEL	48Ca	48CaWO4 crystal scint.	~ tonne	R&D
GERDA I	76Ge	Ge diodes in LAr	18 kg	Operating
GERDA II	76Ge	Point contact Ge in LAr	18+21 kg	Construction
Majorana D	76Ge	Point contact Ge	30 kg	Construction
1TGe (GERDA +MJ)	76Ge	Best technology from GERDA and MAJORANA	~ tonne	R&D
NEMO3	100Mo/ 82Se	Foils with tracking	6.9/0.9 kg	Complete
SuperNEMO D	82Se	Foils with tracking	7 kg	Construction
SuperNEMO	82Se	Foils with tracking	100 kg	R&D
LUCIFER	82Se	ZnSe scint. bolometer	18 kg	R&D
AMoRE	100Mo	CaMoO4 scint. bolometer	50 kg	R&D
MOON	100Mo	Mo sheets	200 kg	R&D
COBRA	116Cd	CdZnTe detectors	10 kg/183 kg	R&D
CUORICINO	130Te	TeO2 Bolometer	10 kg	Complete
CUORE-0	130Te	TeO2 Bolometer	11 kg	Operating
CUORE	130Te	TeO2 Bolometer	206 kg	Construction
SNO+	130Te	0.3% Nat Te suspended in Scint	100kg	Construction
KamLAND-ZEN	136Xe	2.7% in liquid scint.	380 kg	Operating
NEXT-100	136Xe	High pressure Xe TPC	80 kg	Construction
EXO200	136Xe	Xe liquid TPC	160 kg	Operating
nEXO	136Xe	Xe liquid TPC	~ tonne	R&D
DCBA	150Nd	Nd foils & tracking chambers	20 kg	R&D

Status of ββ-decay measurements

Isotope	Experiment	$T^{2\nu}_{1/2}(10^{19}\text{ yr})$ [$\pm stat \pm syst$]	$T^{0\nu}_{1/2}(10^{24}\text{ yr})$ [90%CL]	$\langle m_{\beta\beta}\rangle$ (eV)	Background ($ton^{-1}yr^{-1}ROI^{-1}$) [$ROI \equiv \pm 2\sigma$]
^{48}Ca		$4.4 \pm 0.5 \pm 0.4$	>0.058	3.5-14.1	
^{76}Ge	HVKK et al		$22.3^{+4.4}_{-3.1}$		
^{76}Ge	GERDA	150 ± 10	>21	0.20-0.64	140
^{82}Se		$9.6 \pm 0.1 \pm 1.0$	>0.32	0.9-2.6	
^{96}Zr		$2.35 \pm 0.14 \pm 0.16$	>0.0092	4.2-15.1	
^{100}Mo		$0.716 \pm 0.001 \pm 0.054$	>1	0.33-0.95	
^{116}Cd		$2.88 \pm 0.04 \pm 0.16$	>0.17	1.3-2.4	
^{130}Te		$70 \pm 9 \pm 11$	>2.8	0.30-0.77	
^{136}Xe	EXO-200	$217.2 \pm 1.7 \pm 6.0$	>16	0.14-0.38	230
^{136}Xe	KL-Zen	$238 \pm 2 \pm 14$	>19	0.12-0.25	2000
^{150}Nd		$0.911 \pm 0.025 \pm 0.063$	>0.018	2.6-5.7	

Red: action in the last ~year

The virtues of ^{136}Xe for ββ decay

- 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 ➔ GXe R&D
- 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
- Only known case where final state identification
  appears to be not impossible
  → eliminate all non-ββ backgrounds, possibly only
  chance of getting to Normal Hierarchy
- EXO-200 has demonstrated the power of a LARGE
  and HOMOGENEOUS detector
- ^{136}Xe can be replaced with $^{\mathrm{Nat'l}}$Xe if a signal is observed!

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5 tonnes of LXe, enriched to 90%* in isotope 136

- ^{136}Xe enrichment easier and safer:

➔ 90% enriched ^{136}Xe: ~10$/g

90% enriched ^{76}Ge: ~90$/g (+xtal growth)

➔ Very top-down nEXO cost estimate: ~150M$

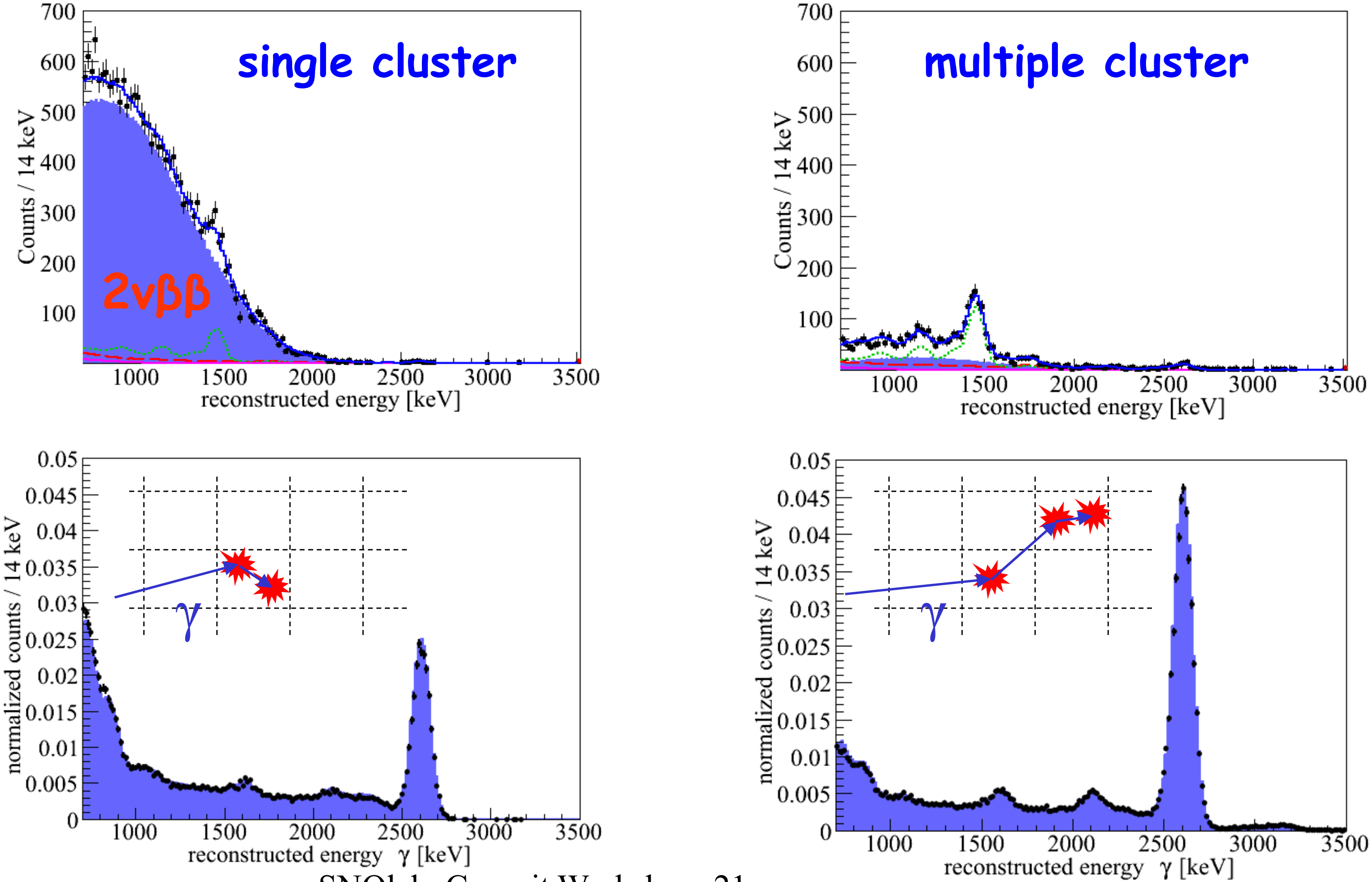
*EXO-200 uses 80% enriched Xe. It now seems customary to do 90% and it appears that there is no major cost difference

Xe is ideal for a large experiment

- EXO-200 has proven that an homogeneous TPC is ideal to suppress main backgrounds that for ßß decay is due to ~MeV γ-rays

Low background data

^{228}Th calibration source



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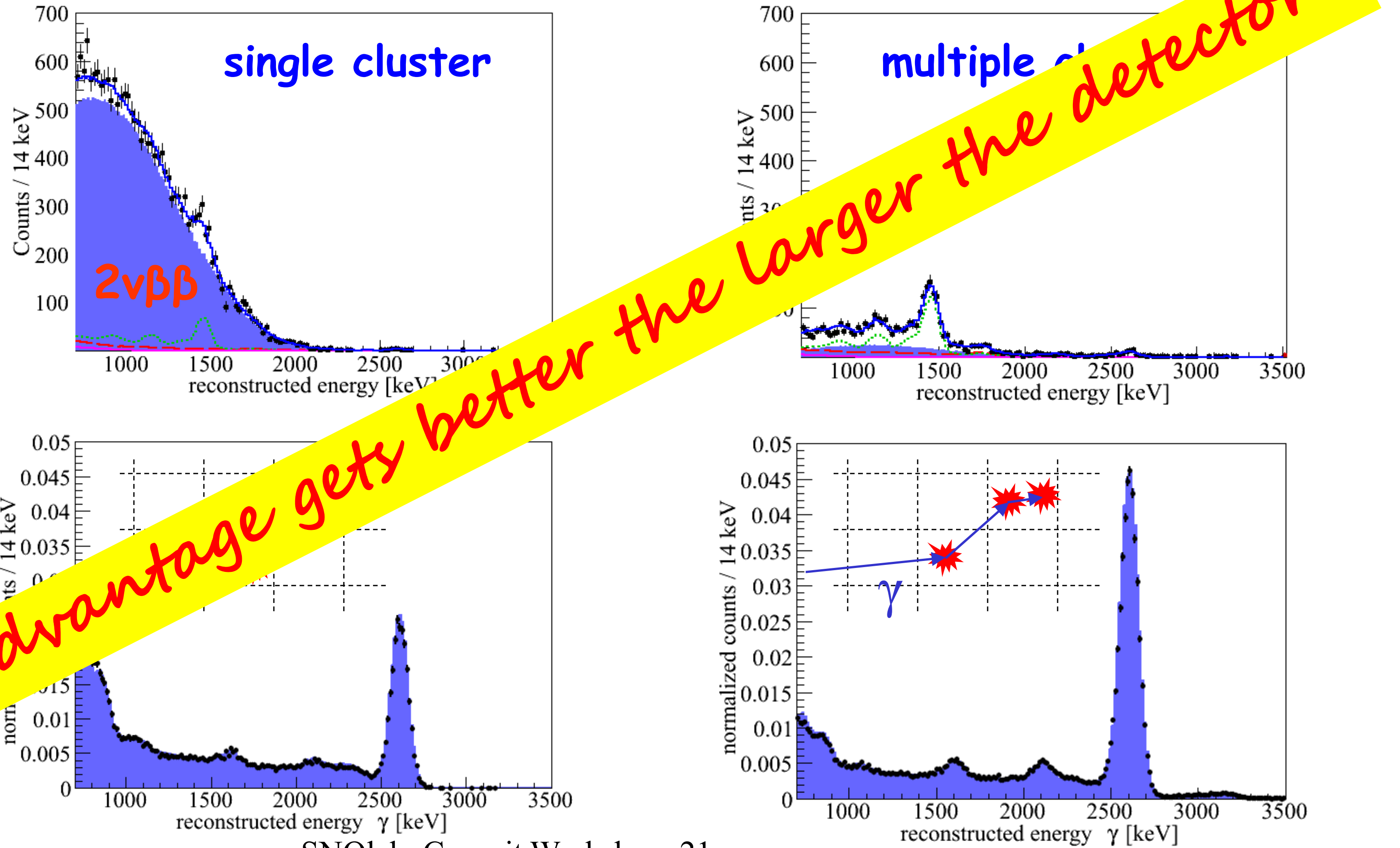
Low background data

228

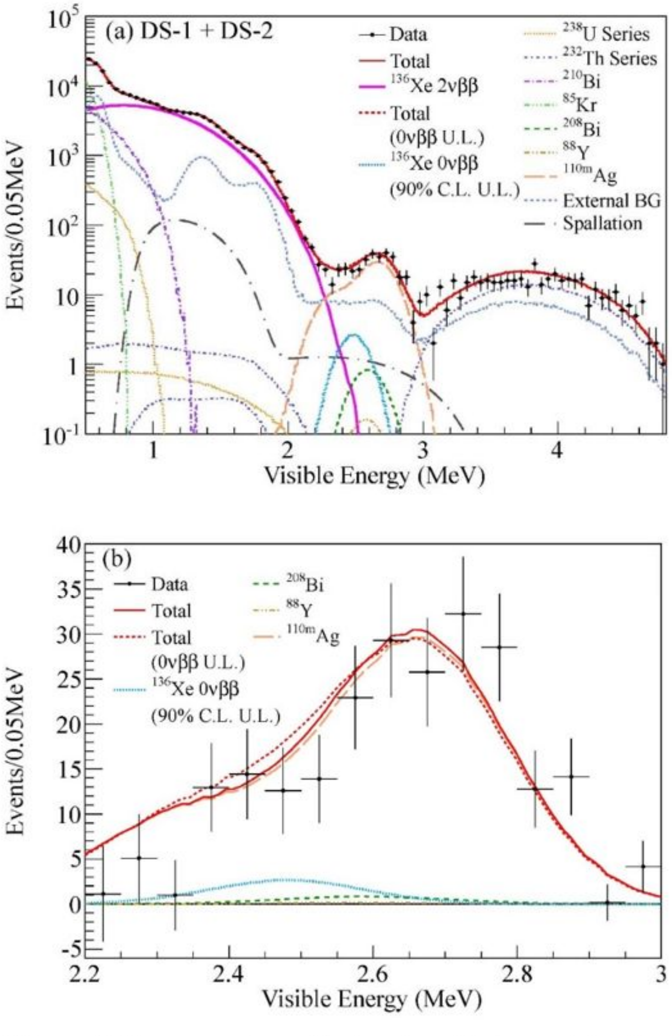
libration

ce

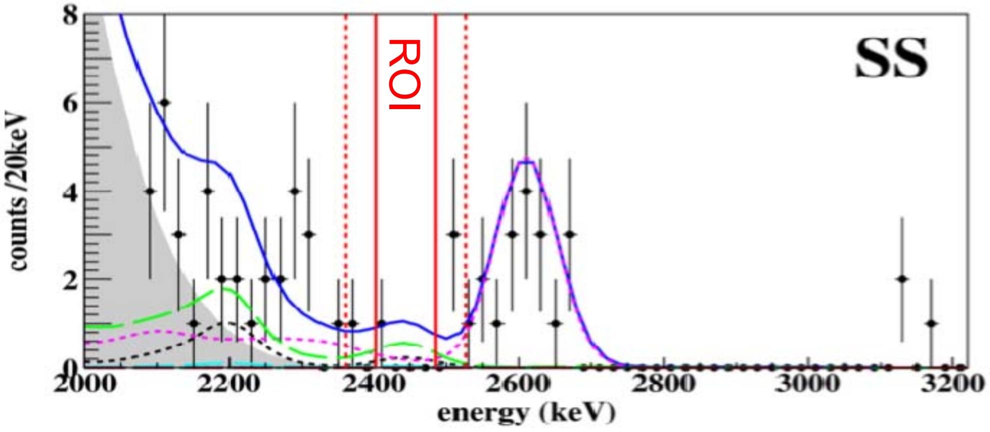


This advantage gets better the larger the detector!

Comparison between
EXO-200 (PRL 109 (2012) 032505)
KamLAND-ZEN (PRL 110 (2013) 062502)

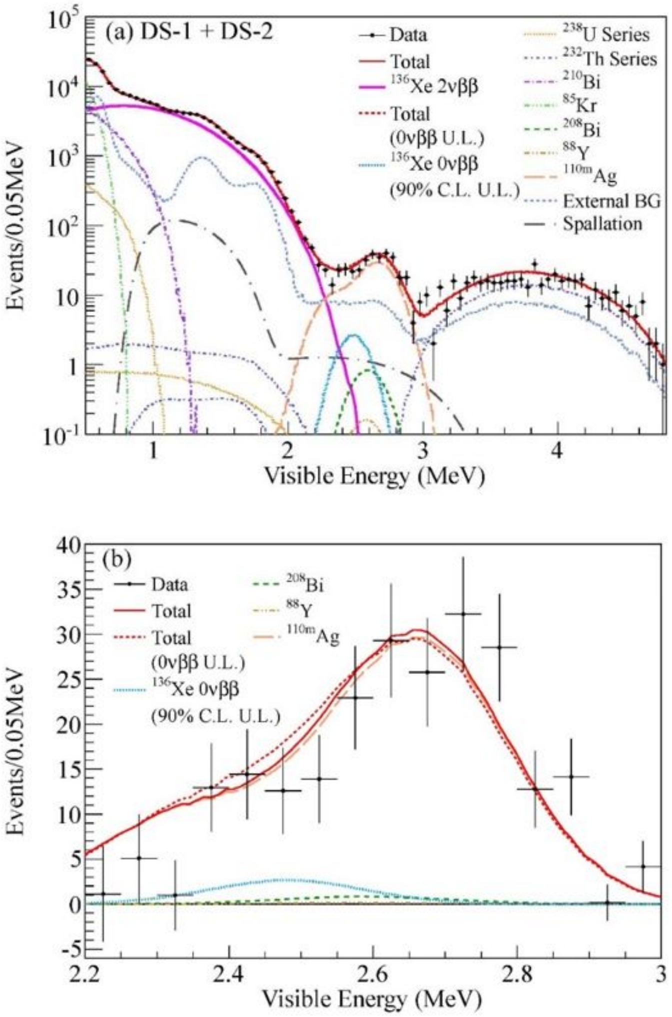


KamLAND-ZEN
2000 cts tonne^{-1}yr^{-1}ROI^{-1}



EXO-200
230 cts tonne^{-1}yr^{-1}ROI^{-1}

Comparison between
EXO-200 (PRL 109, 032505 (2012)
KamLAND-ZEN (PRL 110 (2013) 062502)



KamLAND-ZEN
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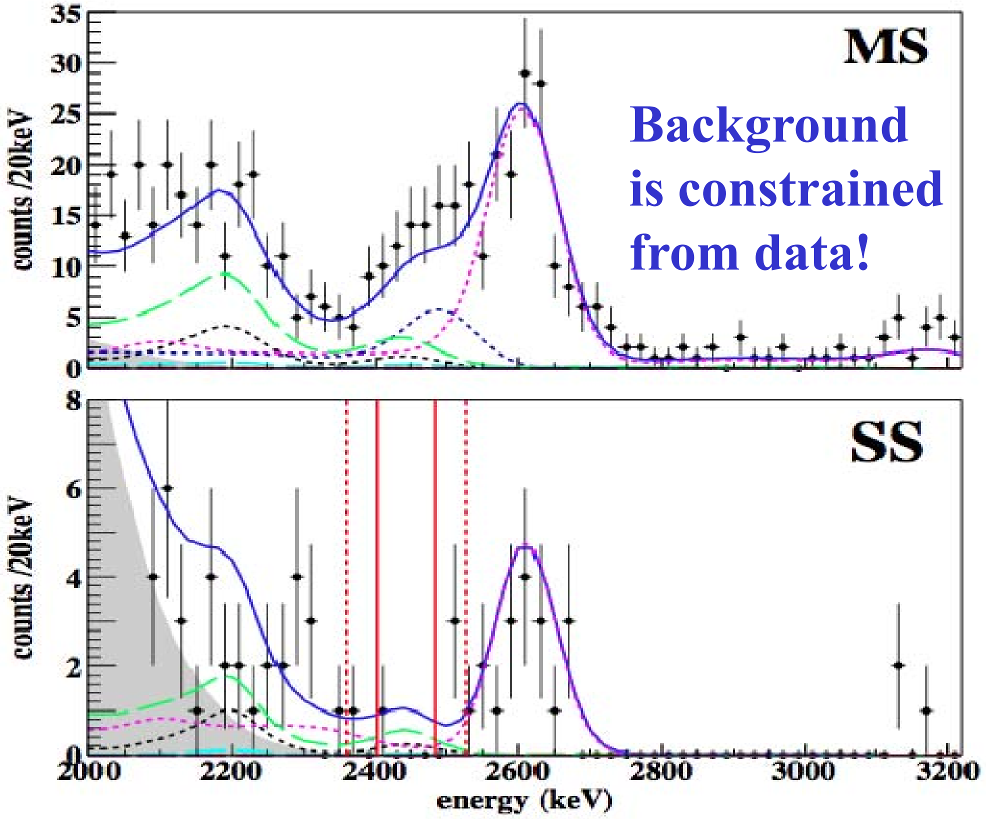

Background is constrained from data!

EXO-200
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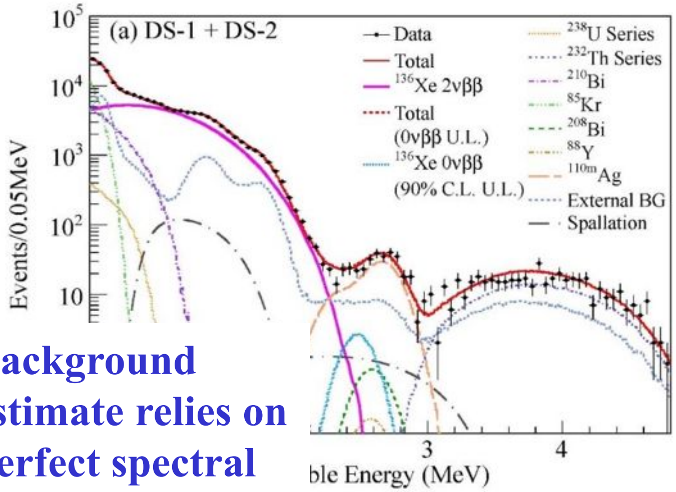
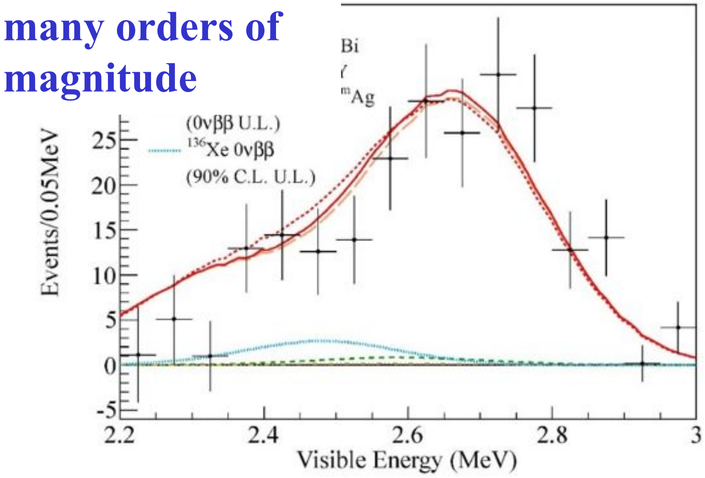


Background estimate relies on perfect spectral knowledge over many orders of magnitude



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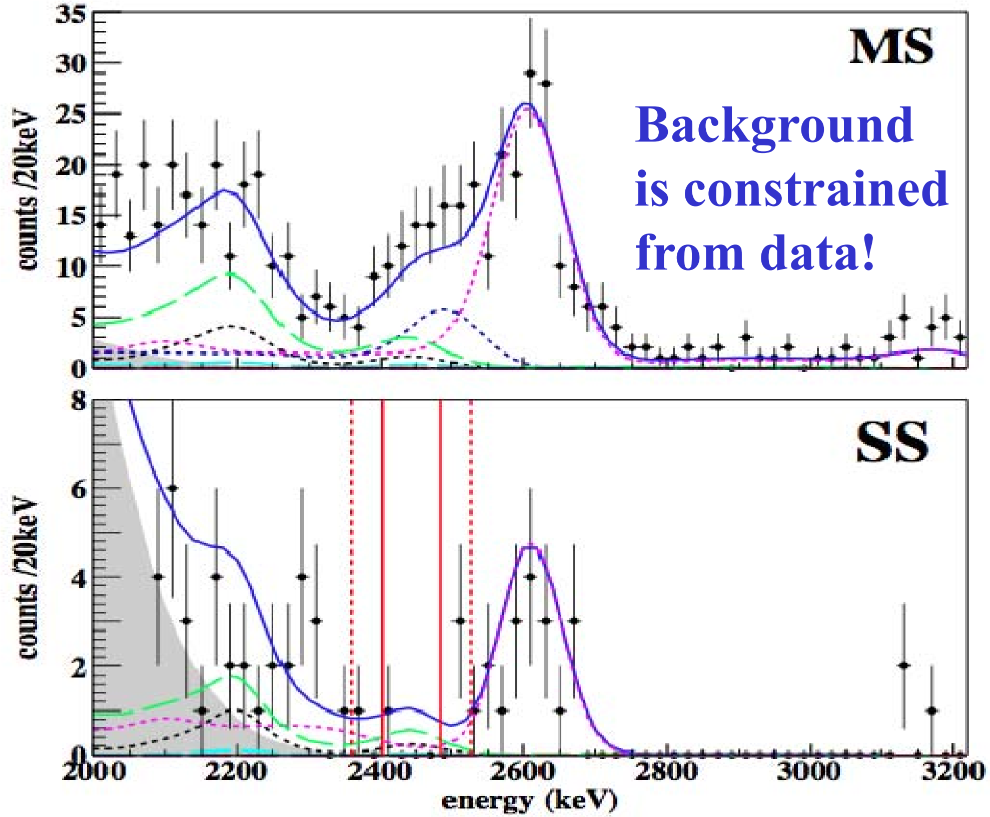

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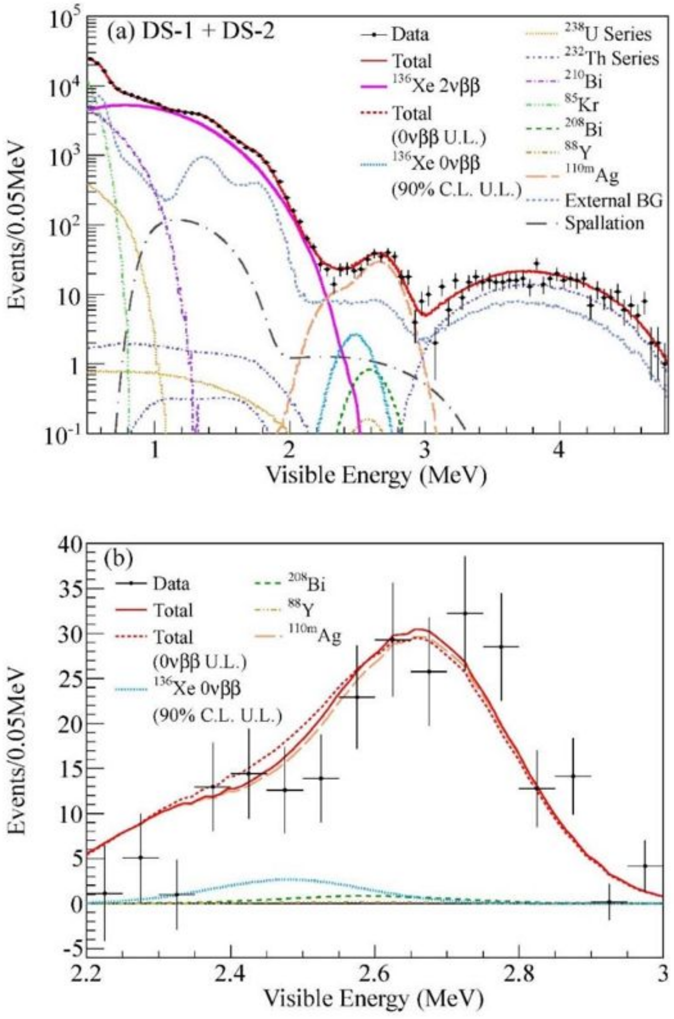

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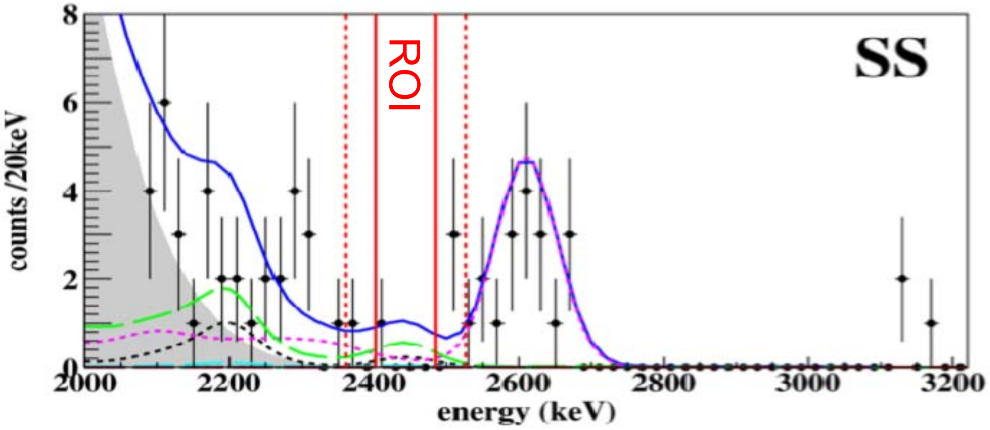


EXO-200
230 cts tonne^{-1}yr^{-1}ROI^{-1}

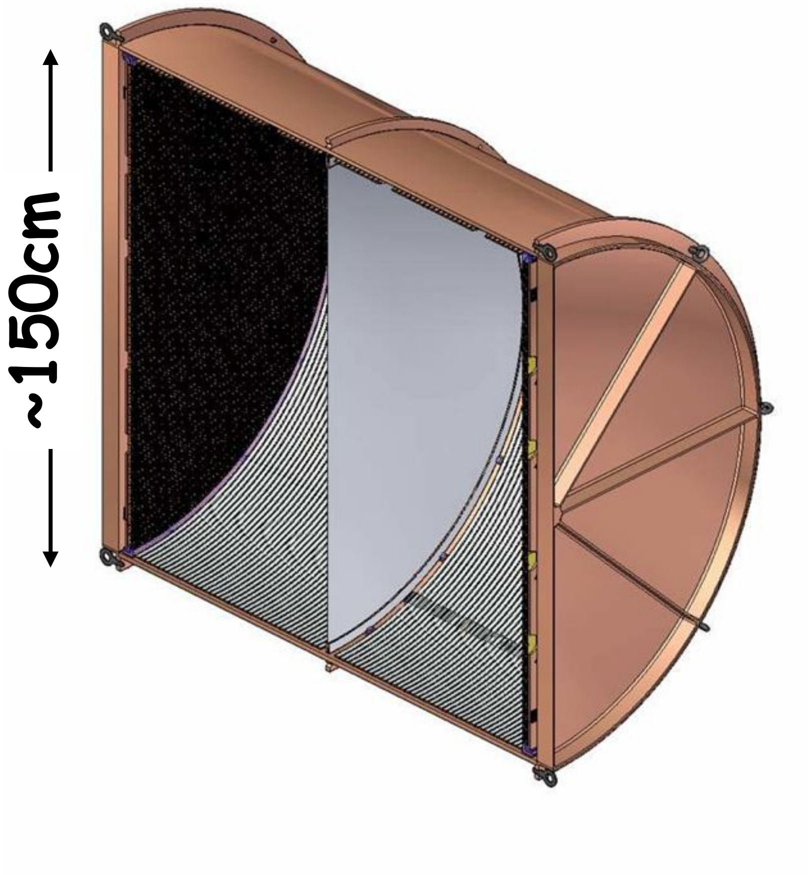
My conclusion:

- LiqScint detectors are appealing as they can “easily” handle large masses
- But unless the backgrounds can be drastically reduced they are not discovery tools

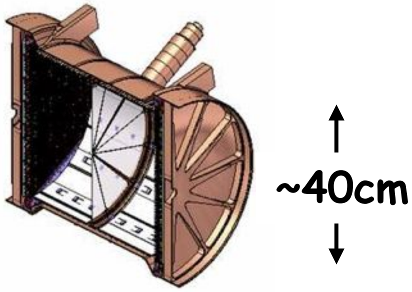
Also: the cts tonne^{-1}yr^{-1} ROI^{-1} is not entirely fair for EXO because there is discriminating power in the SS/MS and the event location.

nEXO

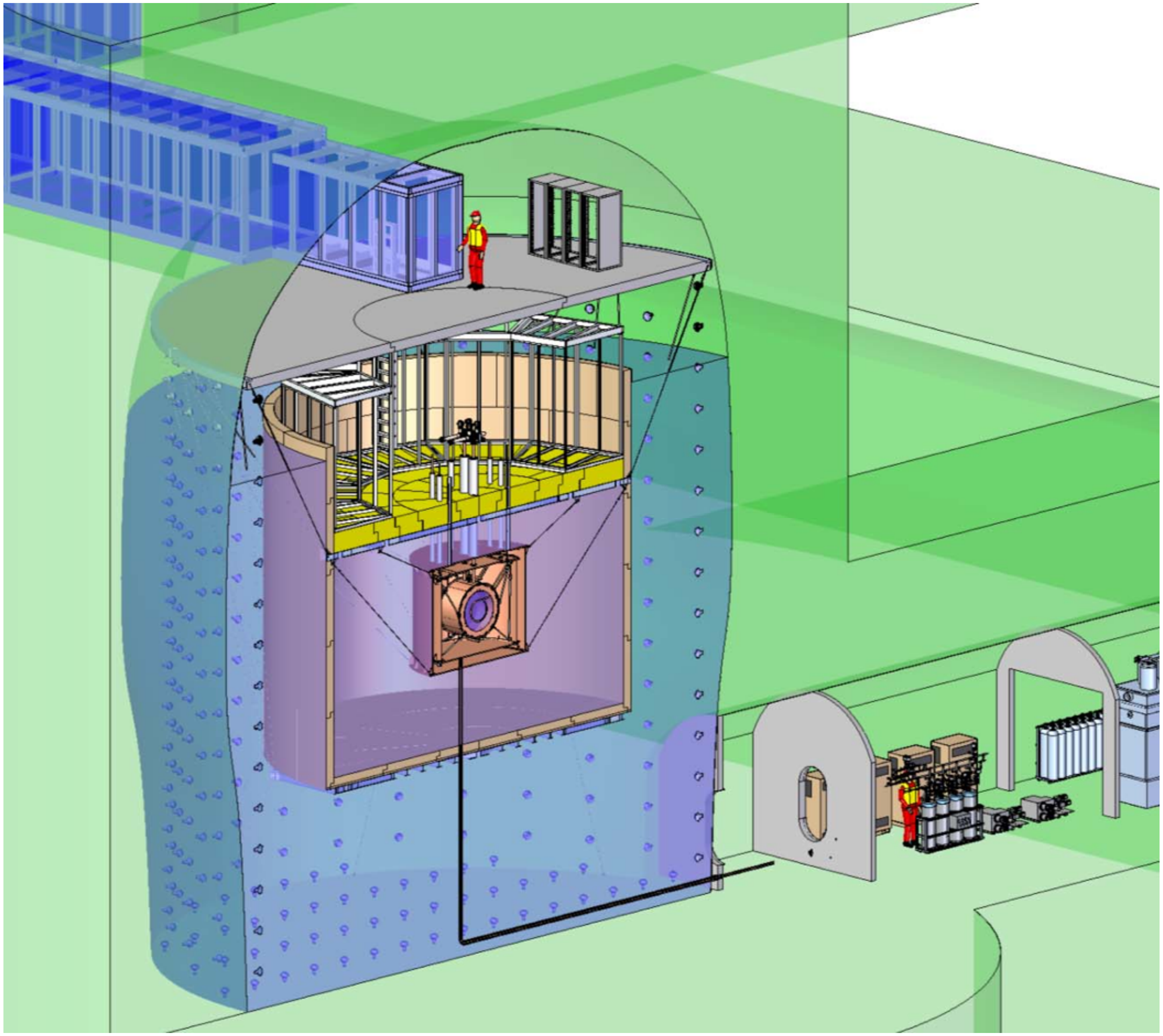
- 5 tonne: entirely cover inverted hierarchy
- LXe TPC "as similar to EXO-200 as possible"
- Provide access ports for a possible later upgrade to Ba tagging



➔ *A unique combination of conservative and aggressive design with important upgrade paths as desirable for a large experiment*



Sketch of nEXO in the SNOlab Cryopit



On-going nEXO R&D program involves many institutions (red items discussed in more detail)

Site-specific engineering (SNOlab)

Detector Conceptual engineering (SLAC)

Electrostatics and fluid mech sim. (Bern)

High Voltage Stability (SLAC)

Charge readout simulation (Umass)

Control system and thermodynamic simulation (Drexel)

Counter-flow heat exchanger (U Illinois UC)

Cosmogenic/neutron background studies (Indiana)

Simulation coordination (Carleton)

Electronics test in LXe (U Illinois UC)

100kg LXe test setup (Bern)

Photodetector (TRIUMF, Stanford, Umass)

Xe recirculation pump (IHEP Beijing/Stanford)

Cryogenic engineering

Cold electronics and charge readout (SLAC/Stanford)

Study of calibration techniques (Laurentian)

LXe (chemical) purity diagnostics (Drexel)

Radon trap (Laurentian)

Veto counter electronics (IHEP Beijing)

Ba tagging (Carleton, CSU, Stanford, TRIUMF)

Project Management (SLAC)

In addition we have re-started the very successful material characterization program

Radioactivity screening coord. **(Alabama):** Was one of the reasons of EXO-200 success and needs to be maintained

Neutron activation analysis **(Alabama):** Most sensitive technique; only requires small samples; some materials can't be processed

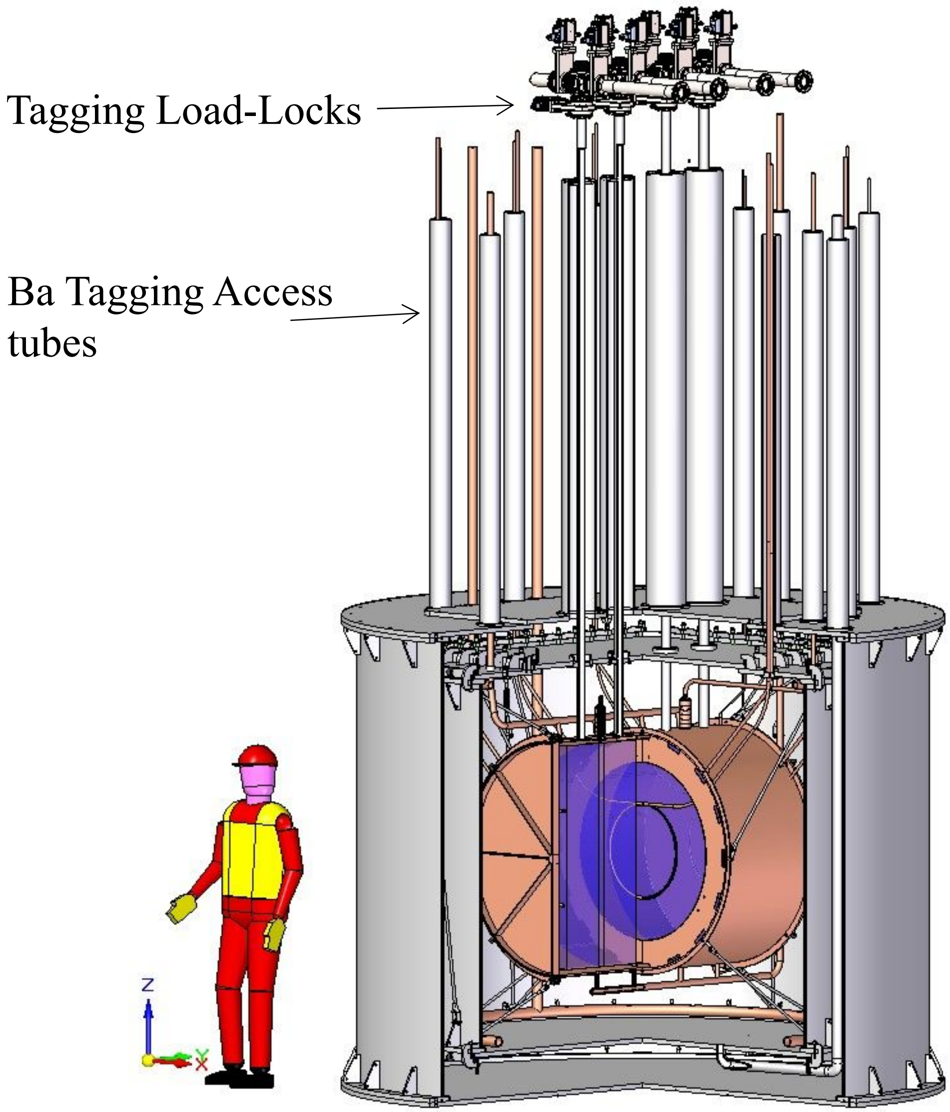
Direct counting **(Bern, Alabama):** Not particularly sensitive; only non-destructive technique, needs large samples, never impossible

ICPMS **(Seoul):** May replace or complement NAA in some cases; was key for screening (NRC Ottawa) for EXO-200

Rn emanation counting **(Laurentian):** Several high sensitivity dedicated counters. Connection with SNOlab.

➔ From EXO-200 experience expect to have to test hundreds of samples.

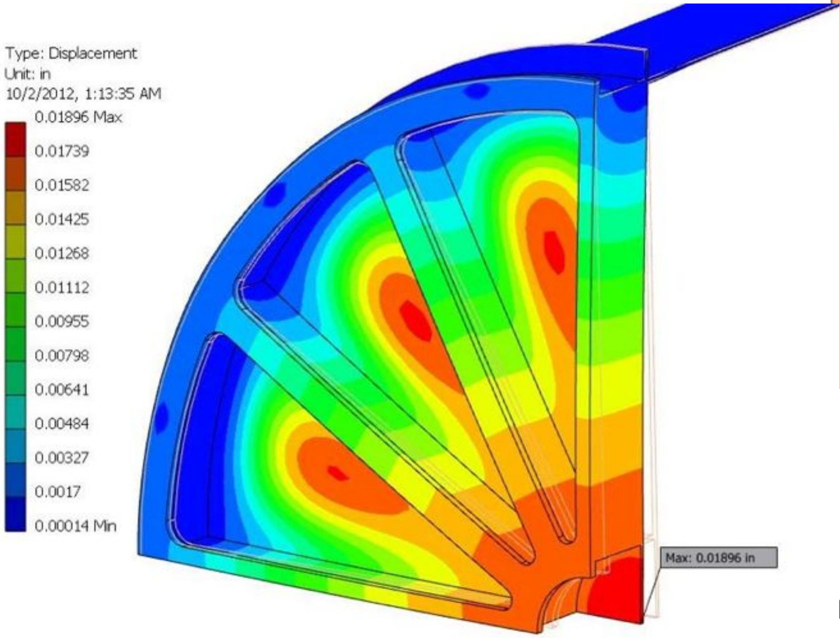
Cryostat with Ba tagging ports



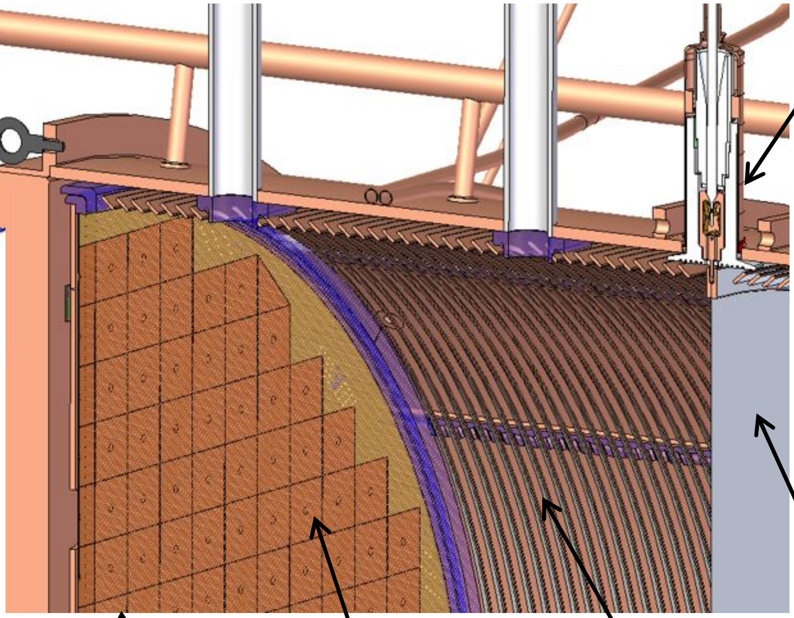
There is lots of experience (not all positive!) on LXe cryogenics that is already being used to conceptually design nEXO's subsystems

This has to happen together with the simulation effort (and, indeed, the cryostat here is probably too small -see later-)

TPC



Initial TPC endplate FEA



HV feedthrough

Cathode

Wire planes

SiPM's

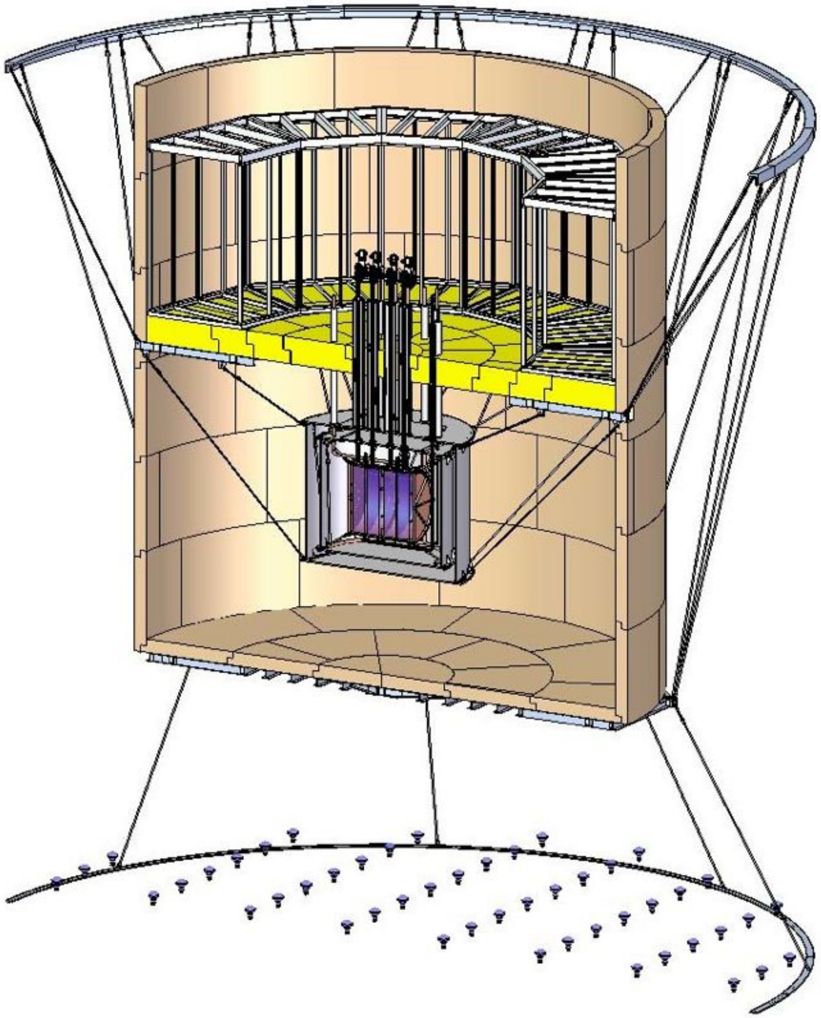
Field shaping rings

Cable Support Scheme; Ba tagging area

Present ideas include a secondary water tank that can be pumped dry for ease of access and a thin Pb shielding on top to reduce the length of penetrations for the Ba tagging system.

This assembly hangs from cables.

Other schemes are under consideration

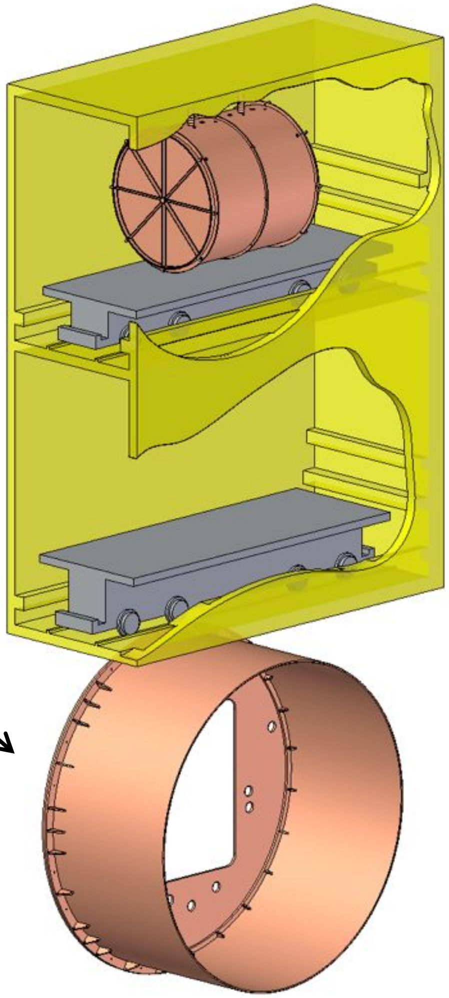


More site-specific work just started and will need SNOlab engineering help

- The TPC fits in the cage
- ½ Cryostat fits under the cage (but *this* cryostat is too small)

➔ The TPC may need to be fabricated UG: probably need clean shop with ebeam welder near Cryopit

➔ Looking into alternatives to a large cryostat



Interesting alternative:
"conductive" insulation and shielding using acrylic blocks

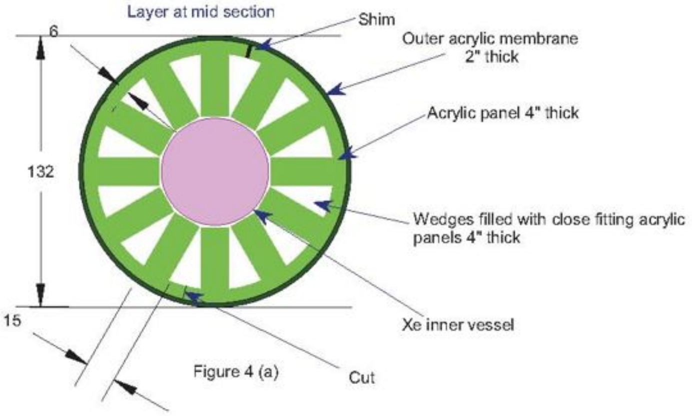
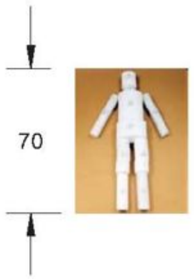
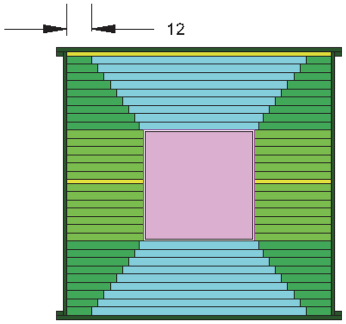

Layer of Scintillator Filled Acrylic

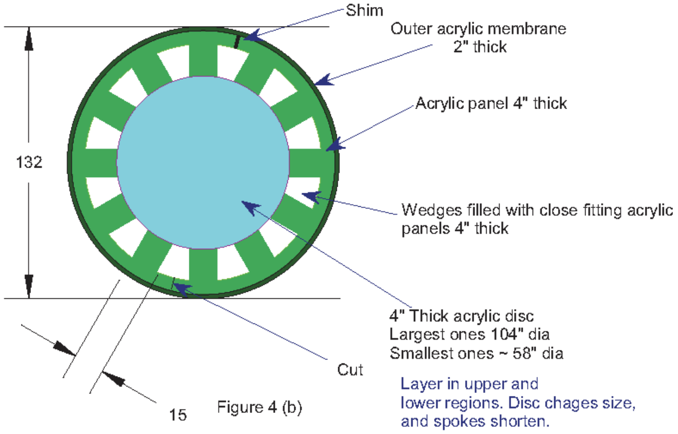
Figure 4 (a)


Acrylic Blocks Stacking Option



Elevation

Figure 4 (c)


Layer of Scintillator Filled Acrylic Above or Below Xe Detector

Layer in upper and lower regions. Disc chages size, and spokes shorten.

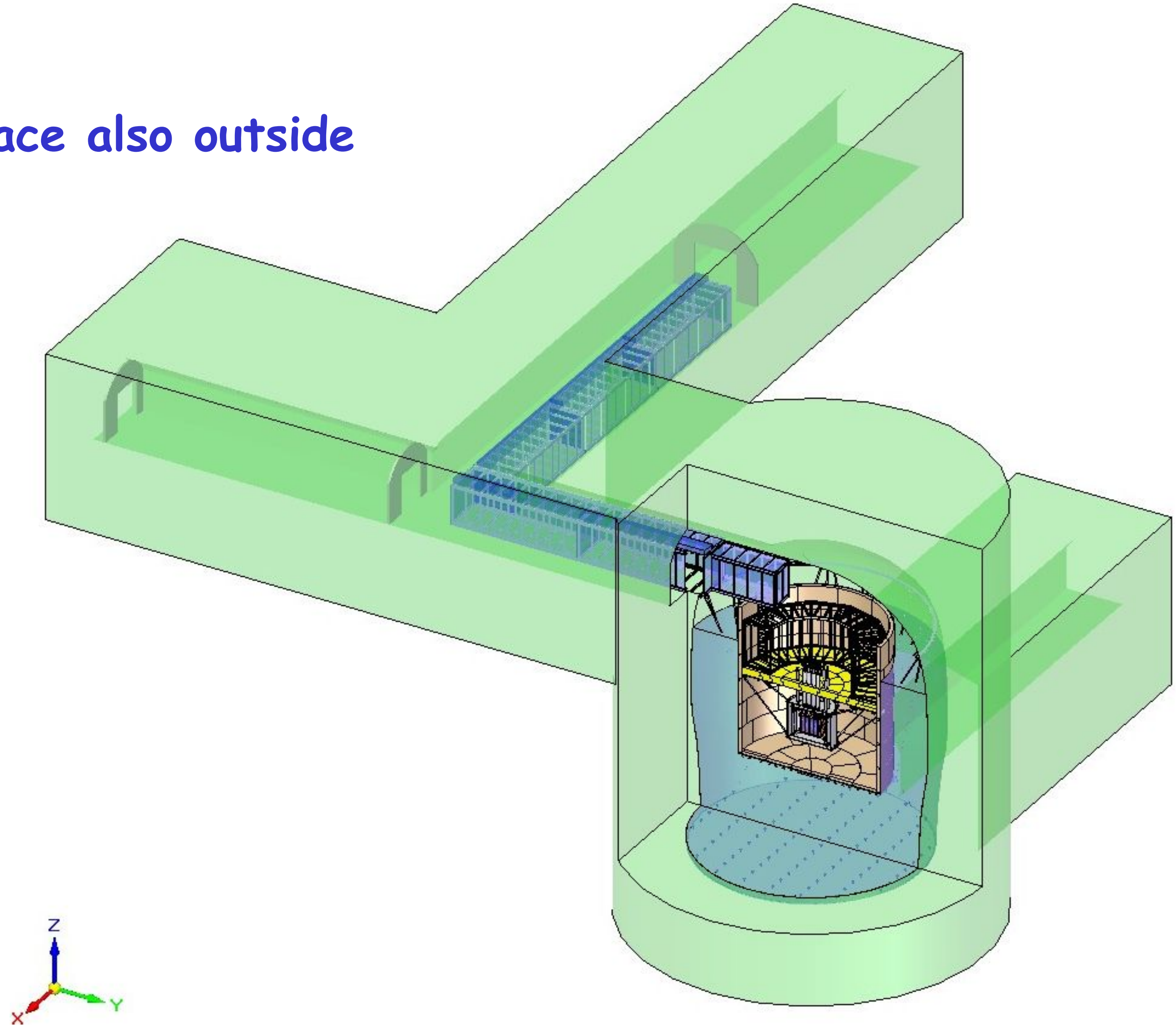
Figure 4 (b)

Heat load is 400W, nothing crazy. But many of us like the Xe to be in good thermal contact with the HFE7000 fluid (safety and removal of electronics heat)

Maybe the winner is a hybrid with inner HFE and acrylic insulation, both in an acrylic vessel at room temperature

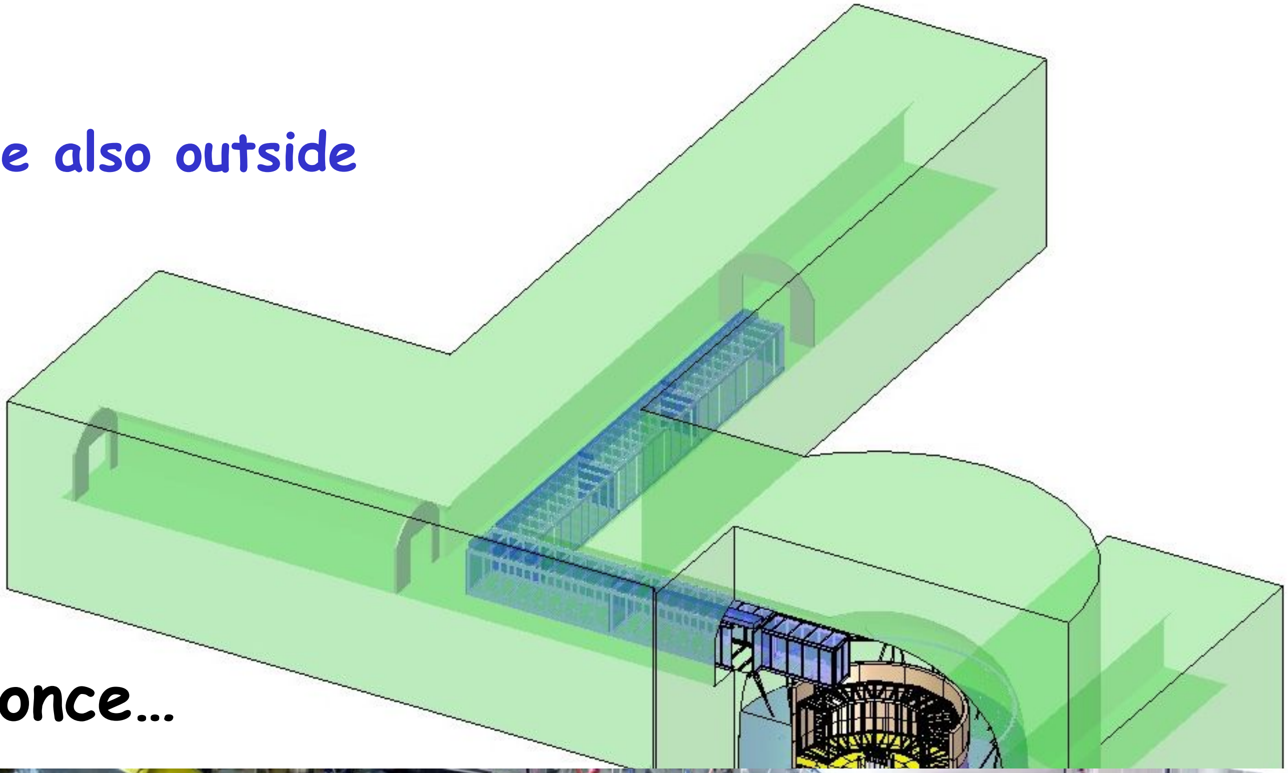
Infrastructure footprint

nEXO will require infrastructure space also outside of the Cryopit

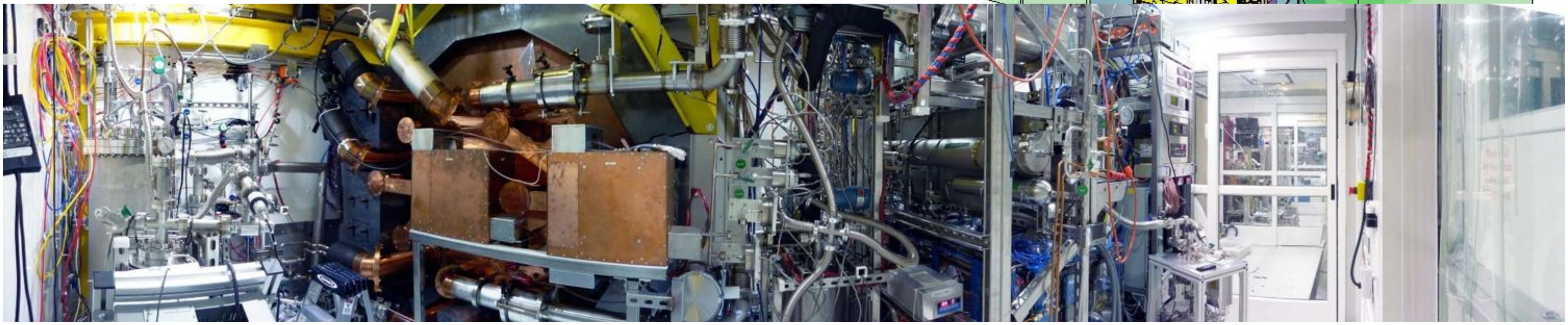


Infrastructure footprint

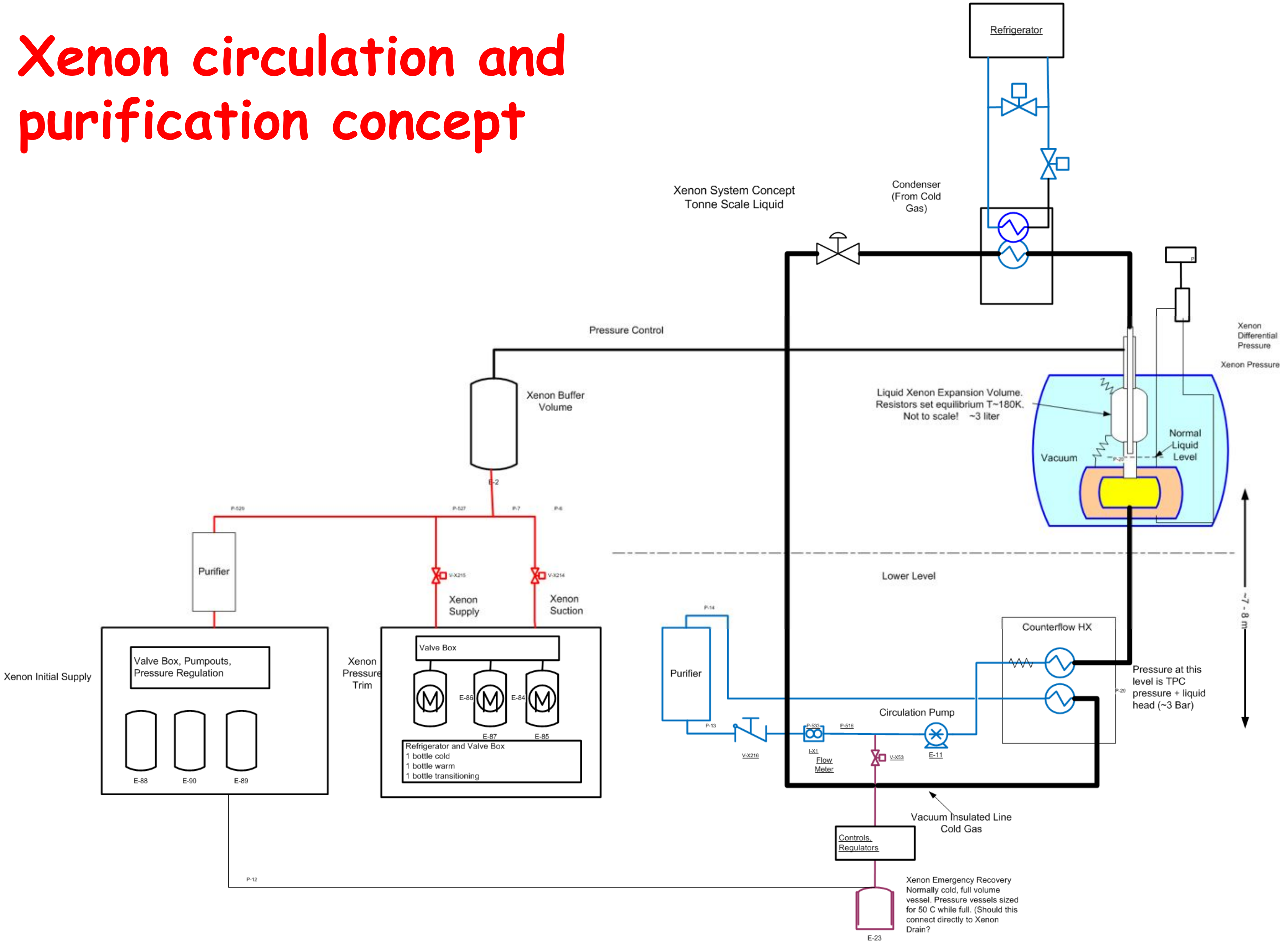
nEXO will require infrastructure space also outside of the Cryopit



…this was fun, once…



Xenon circulation and purification concept



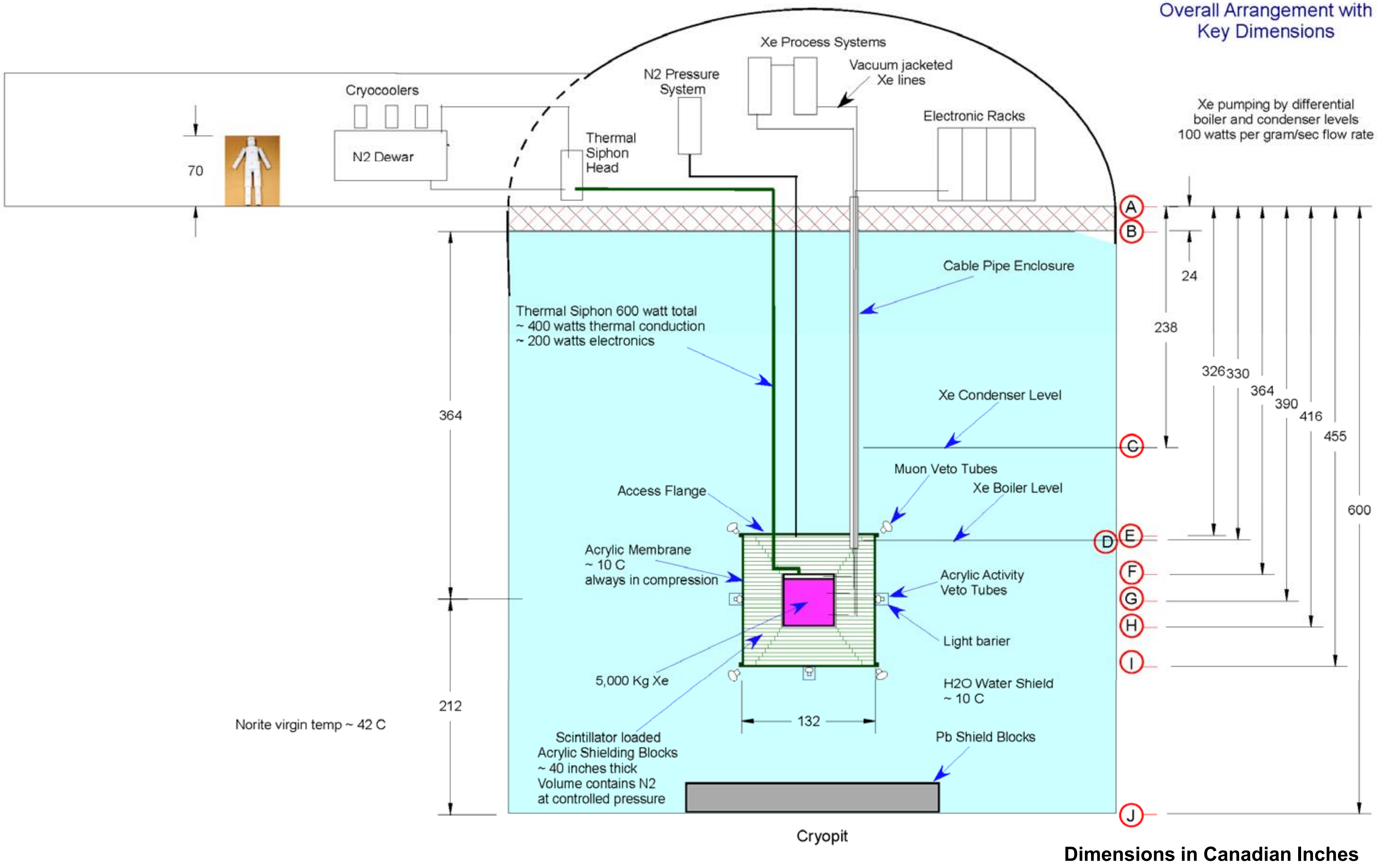
Liquid Xenon Expansion Volume.
Resistors set equilibrium T~180K.
Not to scale! ~3 liter

Pressure at this level is TPC pressure + liquid head (~3 Bar)

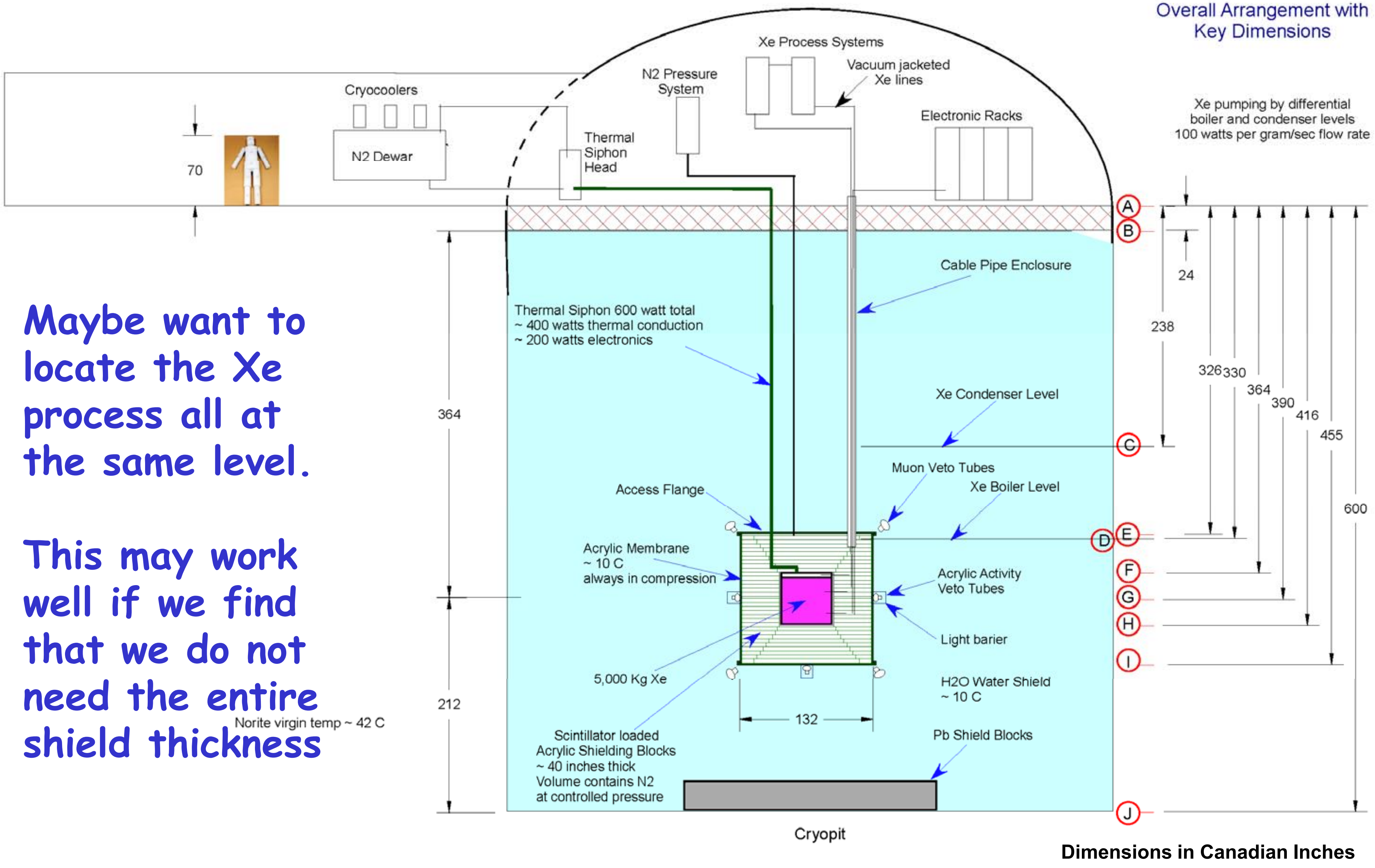
Vacuum Insulated Line
Cold Gas

Xenon Emergency Recovery
Normally cold, full volume vessel. Pressure vessels sized for 50 C while full. (Should this connect directly to Xenon Drain?

Different concept with acrylic insulation and Xe on top



Different concept with acrylic insulation and Xe on top



Maybe want to locate the Xe process all at the same level.

This may work well if we find that we do not need the entire shield thickness

Facility requirements

(quantitative figures available)

- Power and cooling
- Networking
- Some uninterruptable power to support cryogenics operations, controls and communications
- LN2 *(need both but design can trade capacity of one for the other. We need help to understand and freeze this)*
- UG machine shop, some e-beam welding desirable to essential
- Shielding water
- Chemical etch of surfaces

HV R&D

EXO-200 has had HV problem since the first engineering run in 2010.

- First fill could hold 15kV and run at 10kV
- Second (science) fill could hold 12kV and have been running at 8kV since.

This does not appreciably affect the physics performance but is a concern for nEXO where substantially higher voltage is required for the same field.

The problem appears as noise on the HV feed, accompanied by light and charge collected in the detector.

Goal: reproduce/understand/resolve the EXO200 HV issues

- **Phase I :** *Test fundamental LXe HV issues, small parts*

  Small (~400cc) LXe HV testing apparatus

  Tests have been underway since early April 2013

- **Phase II :** *Test full scale parts, long-term effects*

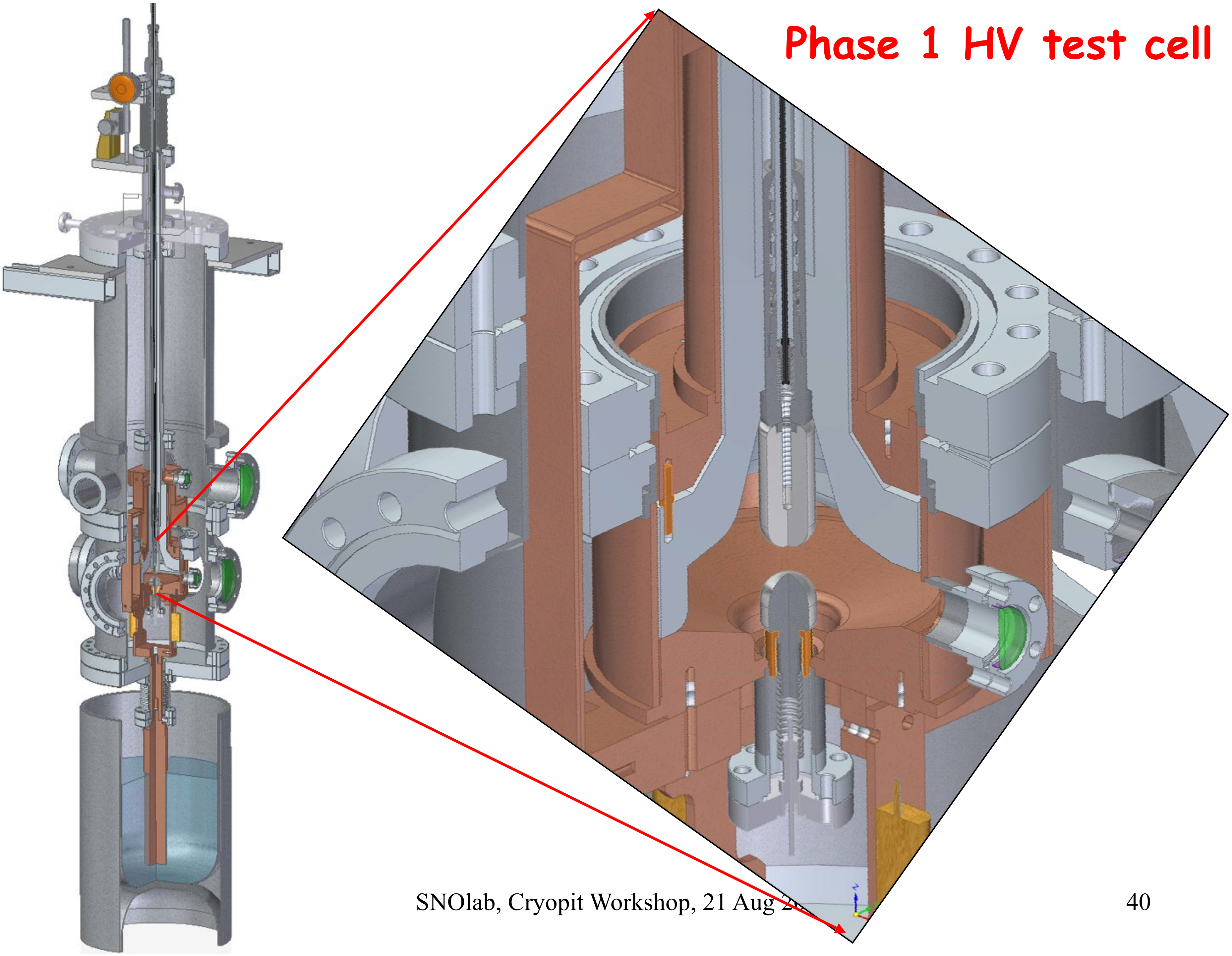
  Medium sized setup (~5 liter) setup

  Stanford cold electronics test stand could be used.

- **Phase III :** *Test prototype solutions*

  Large scale tests maybe required to validate final design

Phase 1 HV test cell



Undesirable features of LAAPDs

- Single vendor for bare LAAPDs (Advanced Photonix)
- Low gain (G~200, the electronics noise in the LAAPD channel presently dominated E res in EXO-200)
- Complex 2-wafer sandwich devices (expensive and relatively heavy –more activity)
- Poor packing fraction (circular and have substantial non-active ring)
- 1500V bias
- Large (dG/G)/dT ~ 5%/K
- Large (dG/G)/(dV/V) ~ 15

In addition the collection area is

EXO-200: 0.1m^2 nEXO: 2-5m^2

EXO-200 TPC Assembled

1500V bias distributed from here

In LXe electronics would sit here and take less space than the cables

SiPMs are better in a number of ways

- Widely used (but see later)
- Large gain (10^5-10^6)
- Plain single wafer devices (cheaper and for the same quality materials get lower activity)
- Square (or any shape), better packing fraction
- 30V bias
- Lower (dG/G)/dT ~ 0.6%/K
- Lower (dG/G)/(dV/V) ~ 0.3

But SiPMs are not perfect either

- In most cases not sensitive to VUV
- Small (large devices have problems of yield)

Large number of suppliers. Working with three of them:

- FBK (Italy)
  - Semiprivate research institute related to INFN
  - Large productions of Si devices for LHC and AMS
  - Very flexible
  - Claim to have process to obtain high QE@175nm
  - We have ordered a test run of 175nm devices that should also address the issue of device size and yield

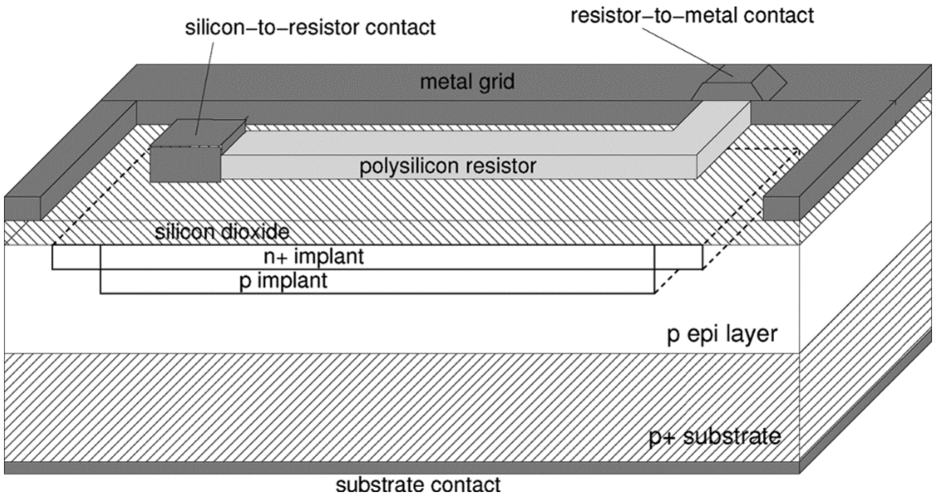
- Hamamatsu (Japan)
  - Have VUV sensitive device
  - Initially unwilling to sell bare devices
  - However in new discussions this may be negotiable
  - Will soon get samples (both electrical and for NAA)

- Fraunhofer Institute (Germany)
  - Just received devices to test for radioactivity

FBK devices

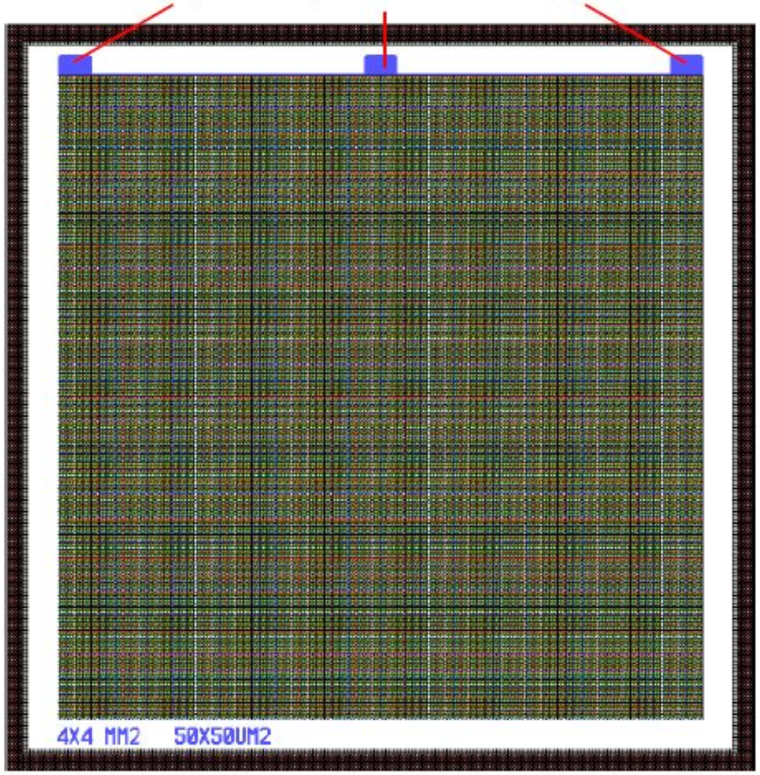
Several “standard” devices in hand:

- Substrate: ~4 μm epi layer
- Junction is created by Arsenic implantation (100 nm from top silicon surface)
- Breakdown voltage fixed by further Boron implantation
- 50 or 100 μm cells, up to 4x4mm^2 pixel size
- Gain is given by ~capacitance of a cell and the bias voltage: ~7x10^5

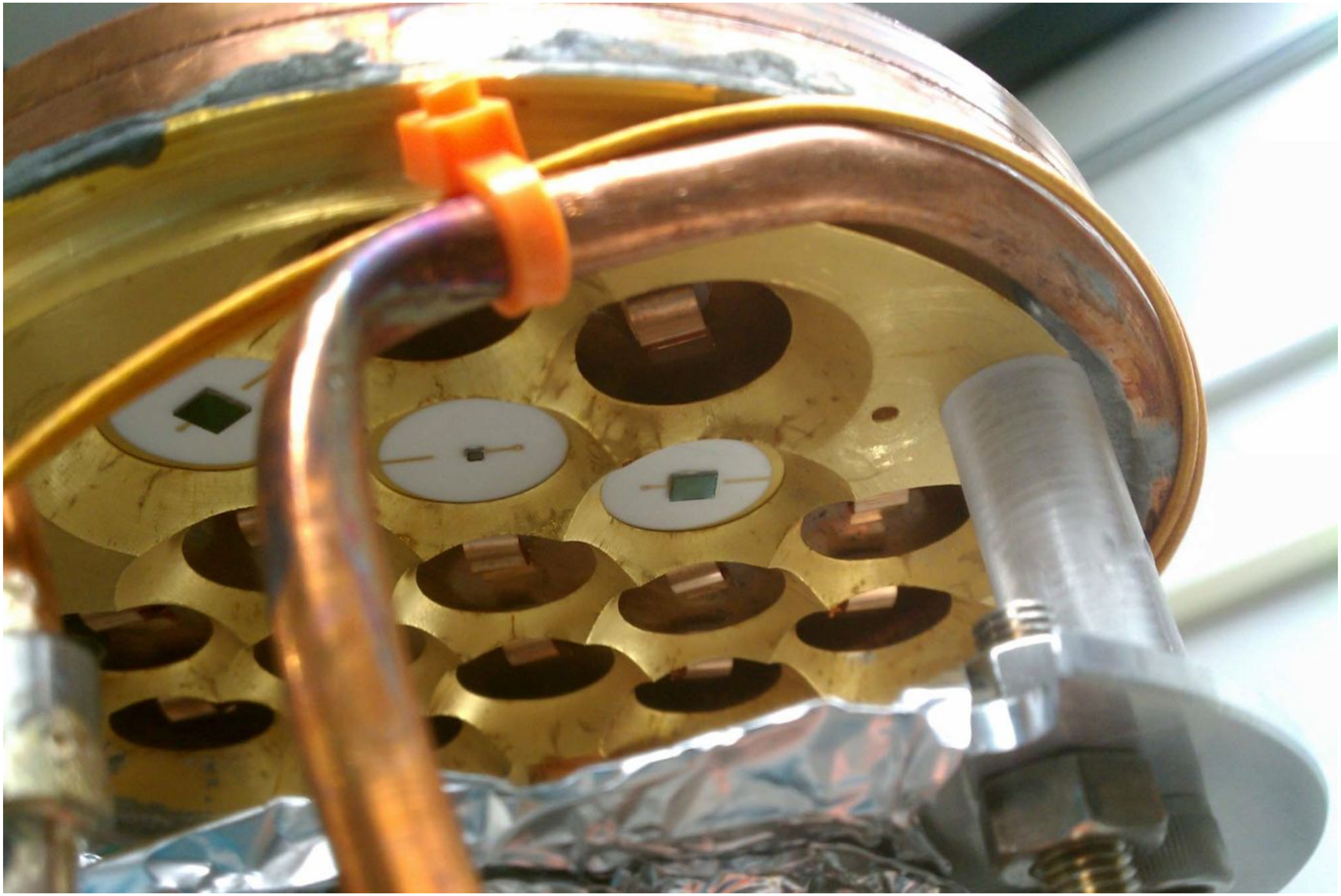


4x4 chip size: ~4.5x4.5mm^2

3 (equivalent) cathode bonding pads

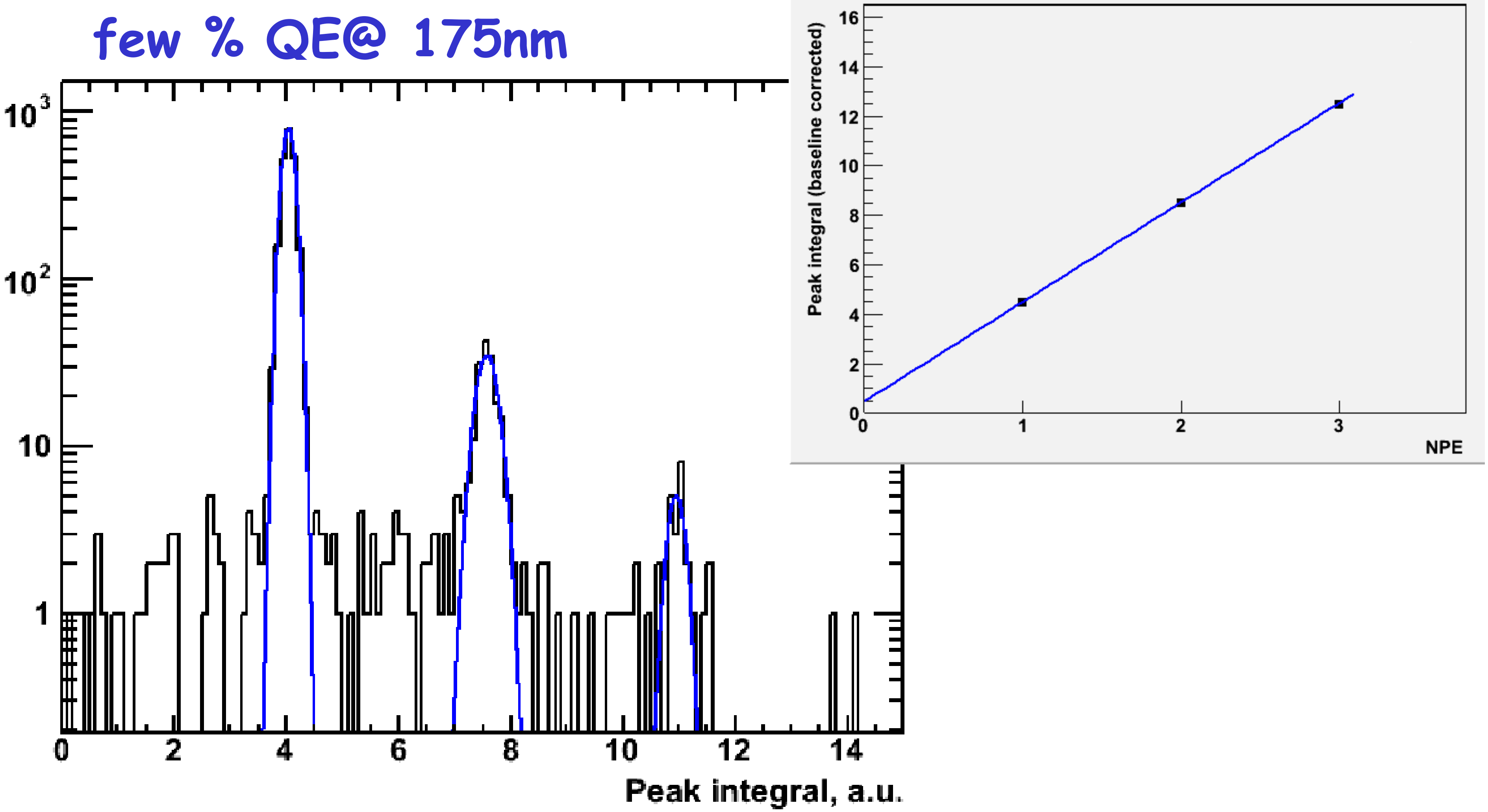


SiPMs mounted on a ceramic "LAAPD interface" into the cryogenic LAAPD tester at Stanford

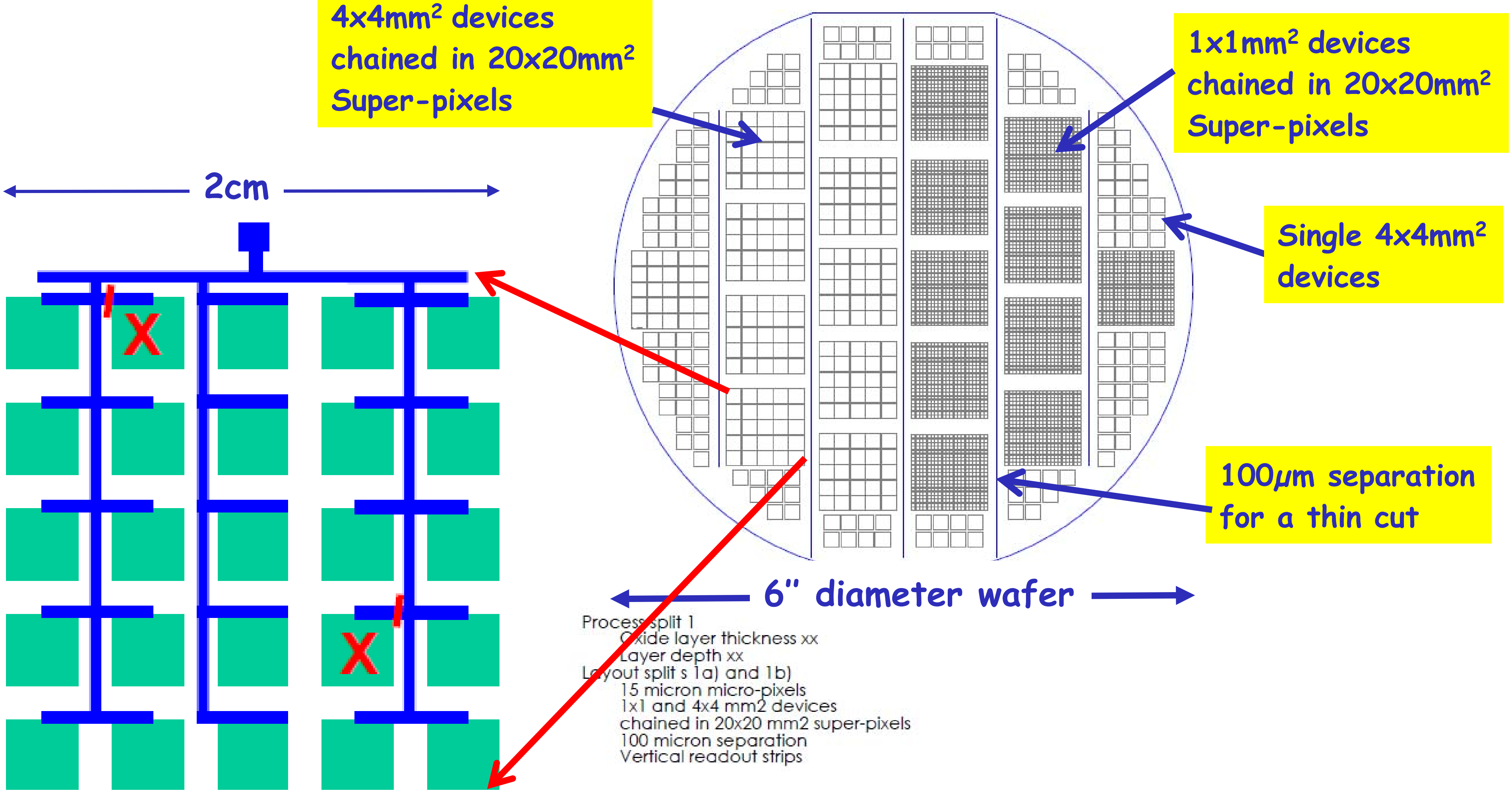


Can easily resolve individual photoelectrons (LAAPDs can't do this)

Off the shelf devices:
few % QE@ 175nm



1st FBK test run in progress



4x4mm^2 devices chained in 20x20mm^2 Super-pixels

1x1mm^2 devices chained in 20x20mm^2 Super-pixels

Single 4x4mm^2 devices

100μm separation for a thin cut

6" diameter wafer

Process split 1
Oxide layer thickness xx
Layer depth xx
Layout split s 1a) and 1b)
15 micron micro-pixels
1x1 and 4x4 mm2 devices
chained in 20x20 mm2 super-pixels
100 micron separation
Vertical readout strips

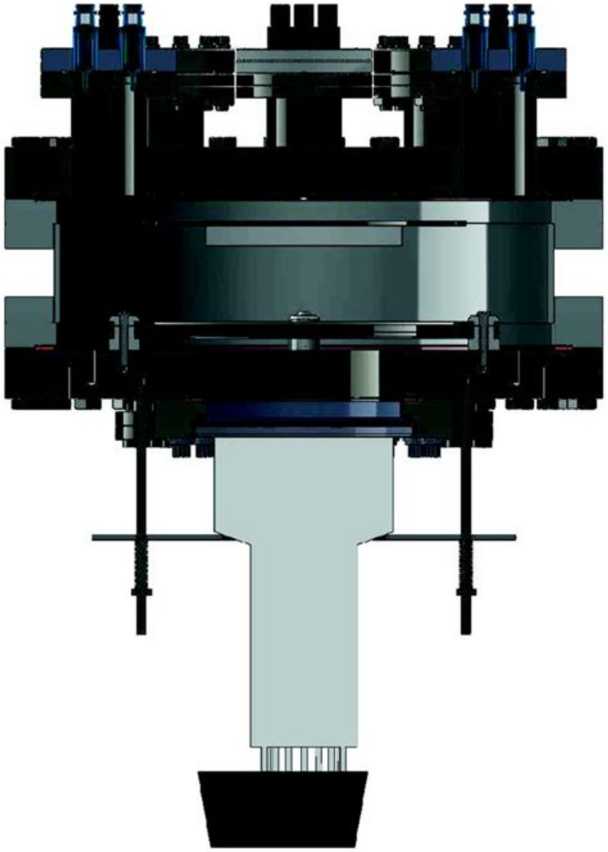
Trick to produce large area devices getting around the issues of yield

Charge readout in nEXO will have 3mm readout pitch (is 9mm in EXO-200) to optimally take advantage of Compton multiplicity tagging

Prefer to have the two grids at the same potential. Developing two techniques:

- Weaved grid
- Supported strips (probably on quartz)

15kg LXe test cell under construction for this purpose



Cold electronics

(some old problems, some new problems…)

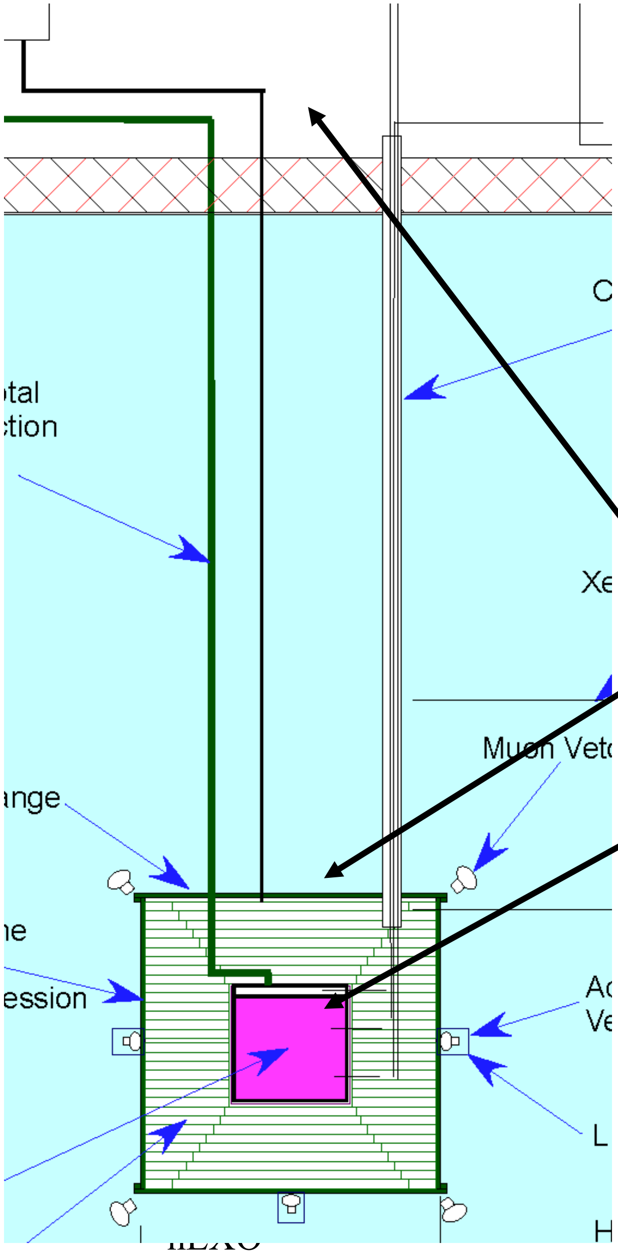
- Charge readout channels >10^3

- Light readout channels ~10^4 (~10^3 digitizer channels)

- Eliminate (most of) the cables
  - ➔ Reliability, ease of clean assembly
- Lower intrinsic noise
  - ➔ Eliminate cable capacitance
- Lower microphonic noise
  - ➔ In EXO-200 some microphonic noise is produced by vibrating cables with HV (not a major problem)
- Lower radioactivity
  - ➔ Suspect that EXO-200 flat cables are a substantial contributor to the (low) background

Noise budget for electronics at different locations

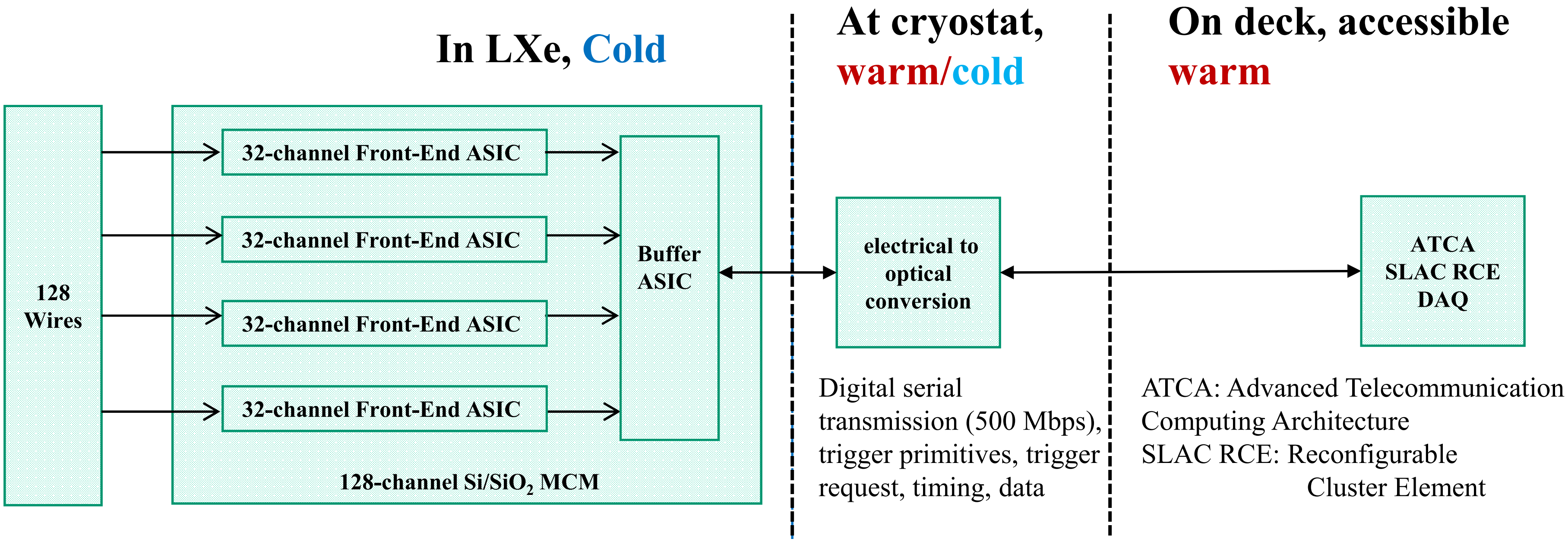
(here assuming EXO-200-style wires)



Location	Cable length (m)	Total cap (pF)	Intrinsic Noise (e)	Charge collect. Threshold (keV)	Induction Threshold (keV)
In lab (warm)	8	600	1500	225	750
At cryostat (warm/cold)	2	150	500	75	250
Inside TPC (cold)	~0	40	200	38	125

EXO-200

Electronics system block diagram

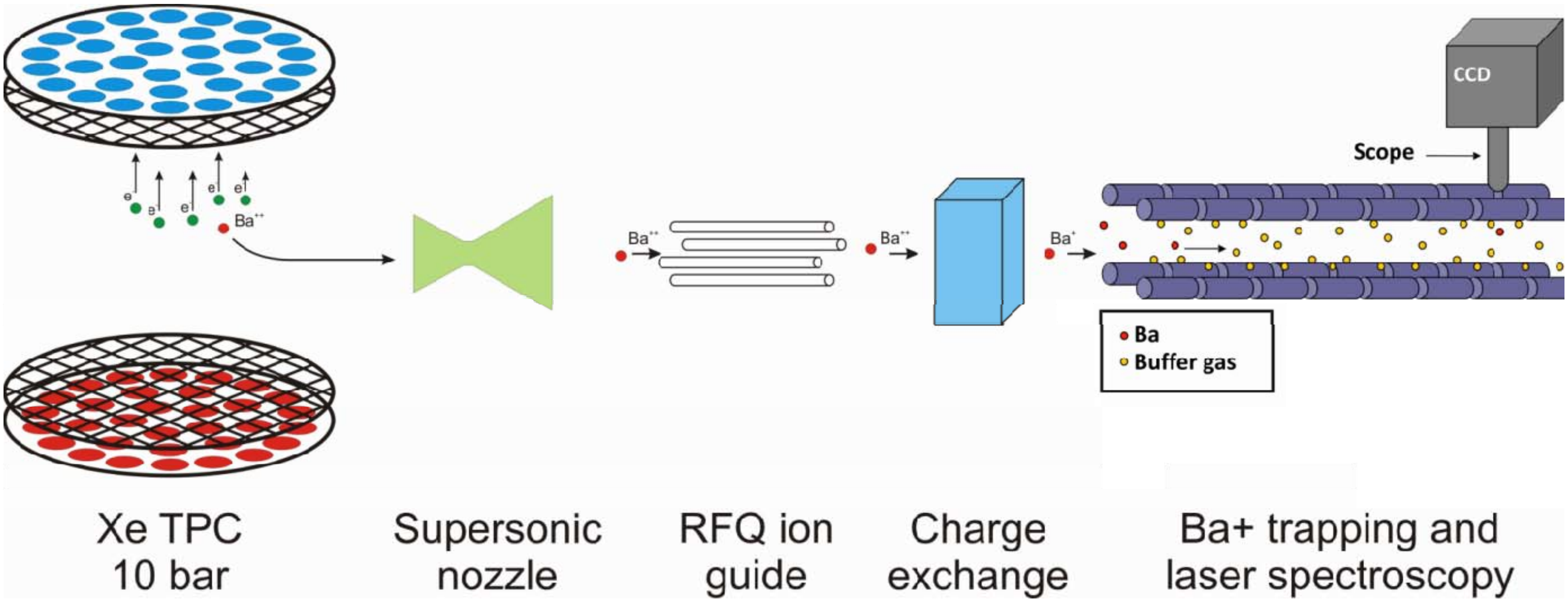


Digital serial transmission (500 Mbps), trigger primitives, trigger request, timing, data

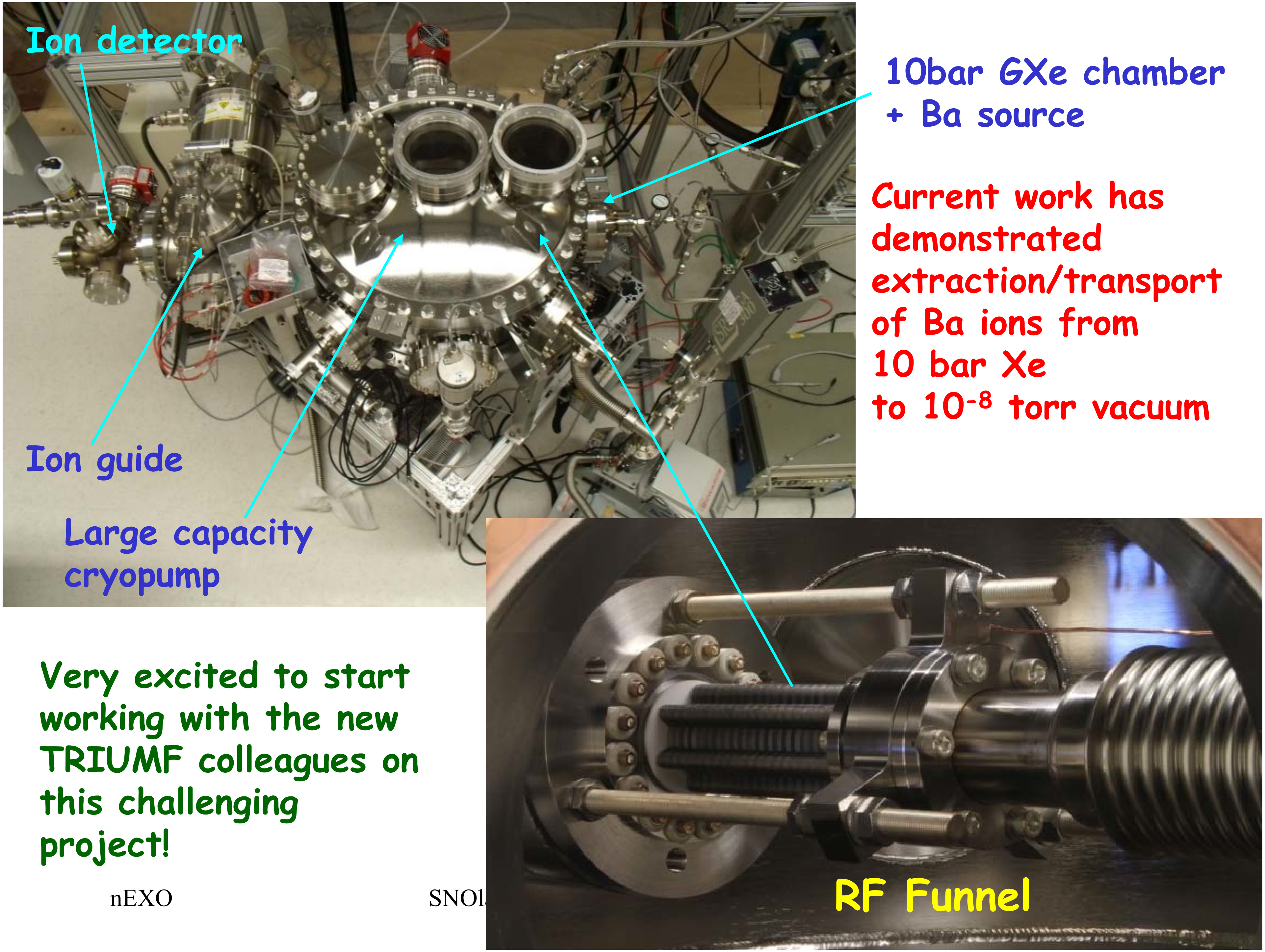
ATCA: Advanced Telecommunication Computing Architecture
SLAC RCE: Reconfigurable Cluster Element

- **Components in LXe**
  - Front-End (FE) ASIC (for 32 channels, mixed-signal)
  - Buffer ASIC (for 128 channels, digital)
  - Si/SiO$_2$ MCM (128-channel Multi-Chip Module, holds 4 FE ASICs and 1 Buffer ASIC)
  - Ultra-low background
- **Electrical-to-optical conversion at cryostat**
  - Ground isolation (no ground-loops, digital DAQ isolation), longer distance comm.
- **SLAC ATCA RCE DAQ system**
  - Used or to be used for LCLS, HPS, LSST, LHC ATLAS CSC, LBNE, Darkside, etc
  - See backup slides for more details

Tagging from Gas Xenon *(actually not nEXO)*



- Extract Ba^{++} from TPC by shaping E-field
- Guide into vacuum
- Convert Ba^{++} to Ba^{+} *[J.Phys. Conf. Ser. 309(2011)12005]*
- Identify via laser spectroscopy *[Phys.Rev.A 76, 023404 (2007)]*



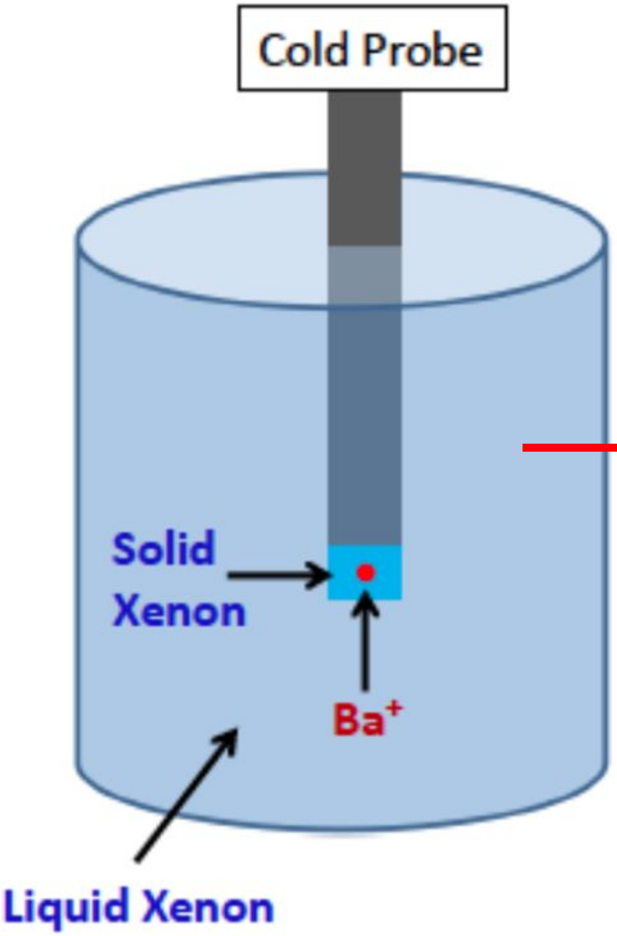
Current work has demonstrated extraction/transport of Ba ions from 10 bar Xe to 10^{-8} torr vacuum

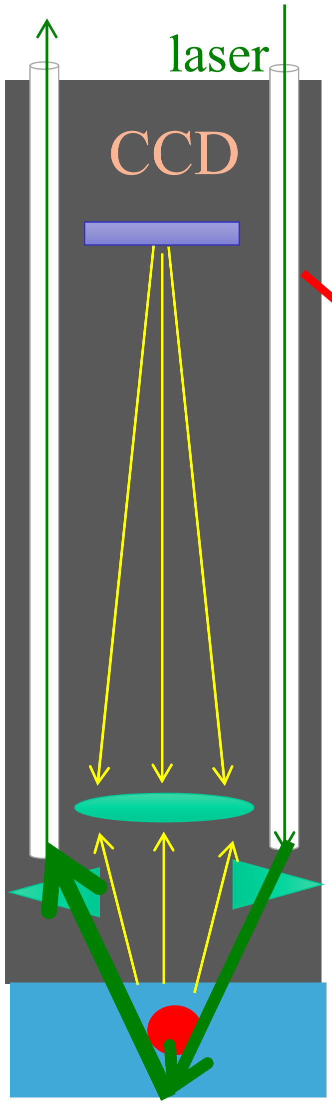
Very excited to start working with the new TRIUMF colleagues on this challenging project!

Direct Ba Tagging in LXe

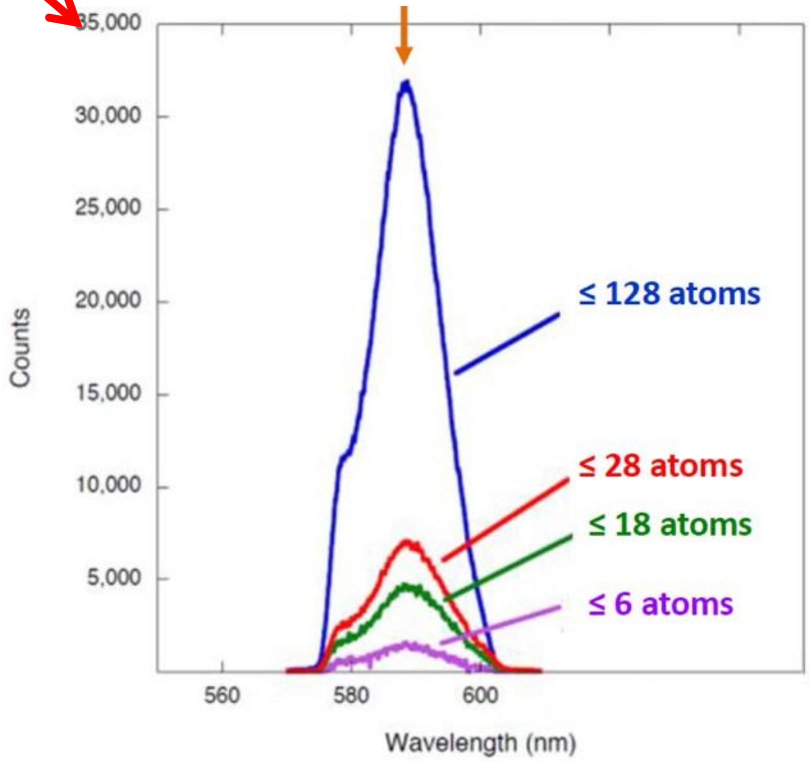
Trap barium daughter ion in SXe on a cooled probe

Detect single ion or atom on the probe with laser-induced fluorescence

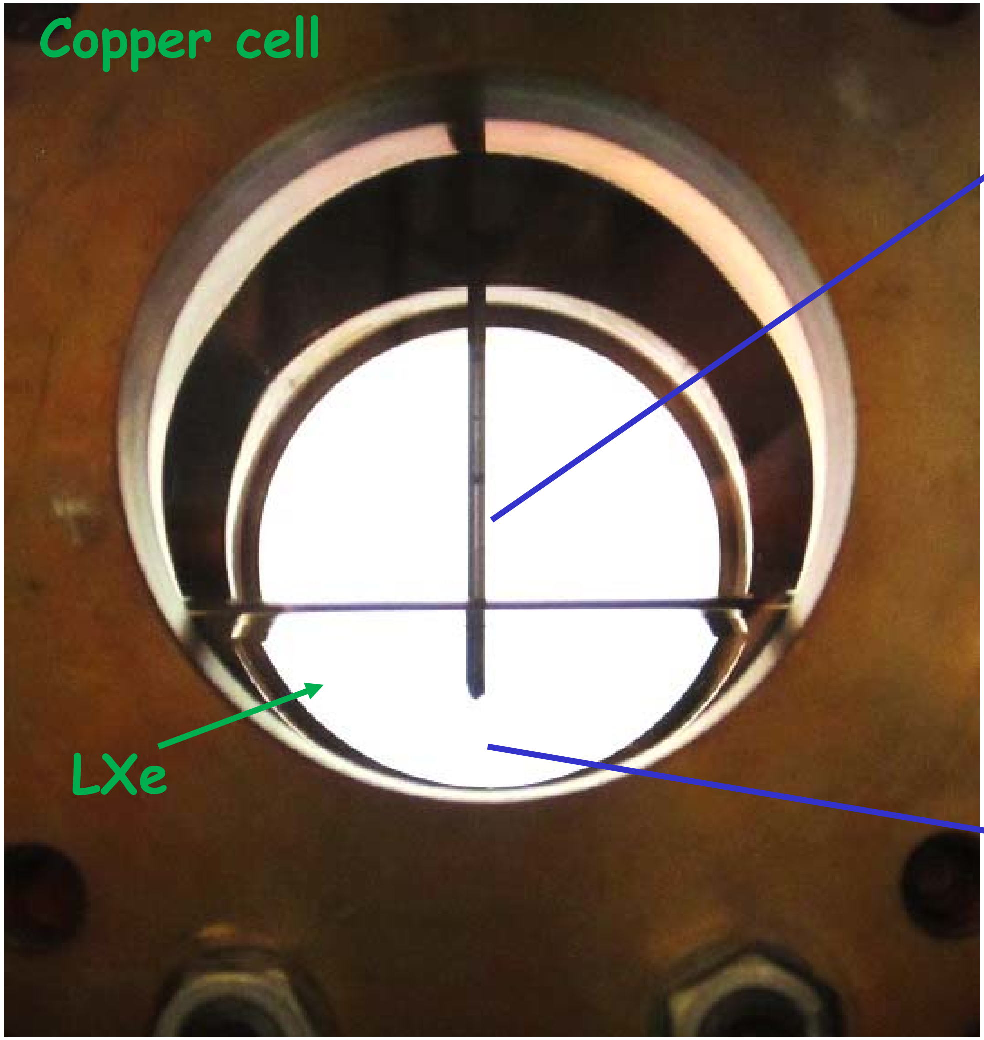


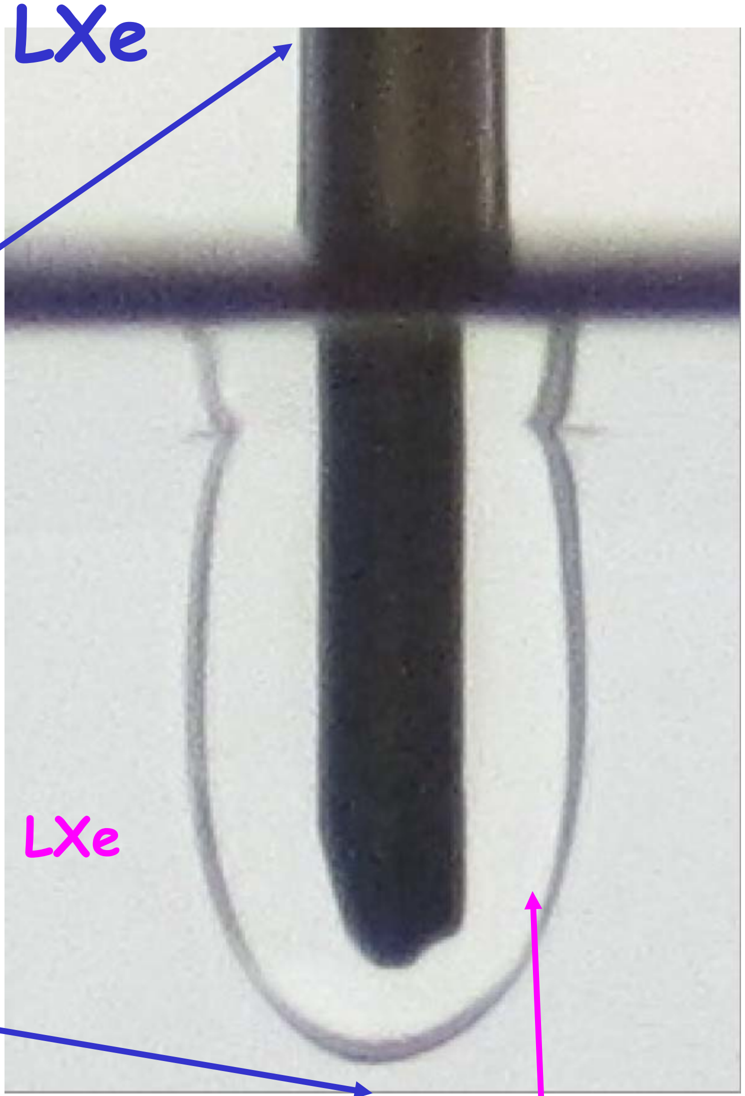


Fluorescence peak of Ba in SXe after excitation w/ 558 nm laser

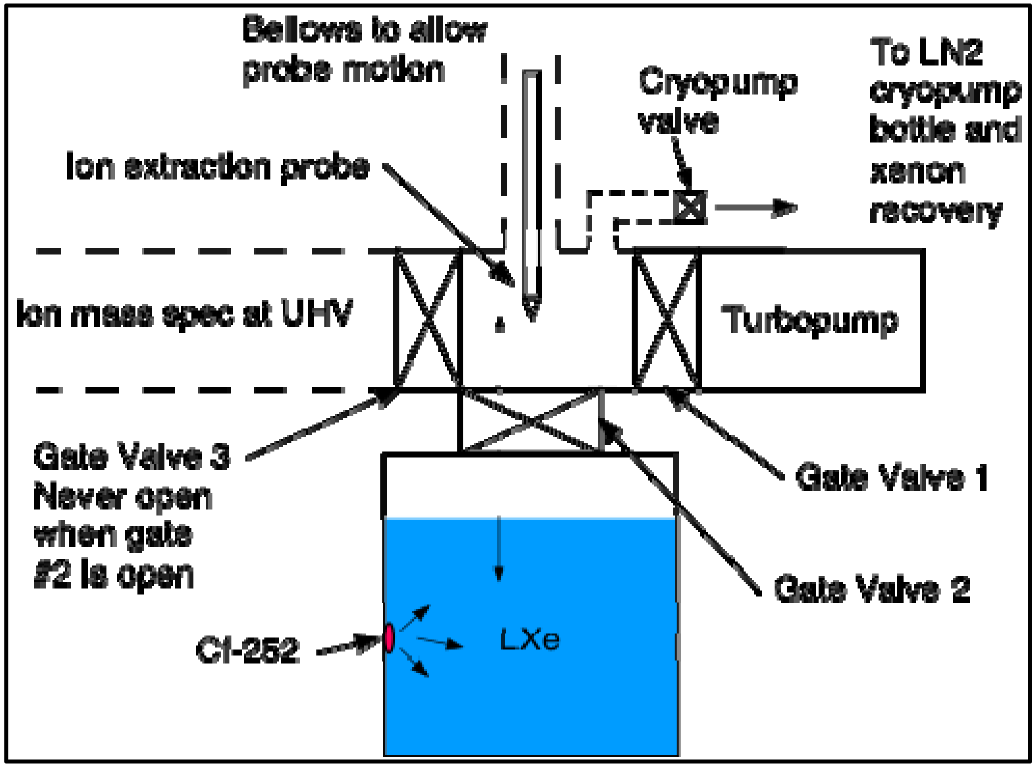


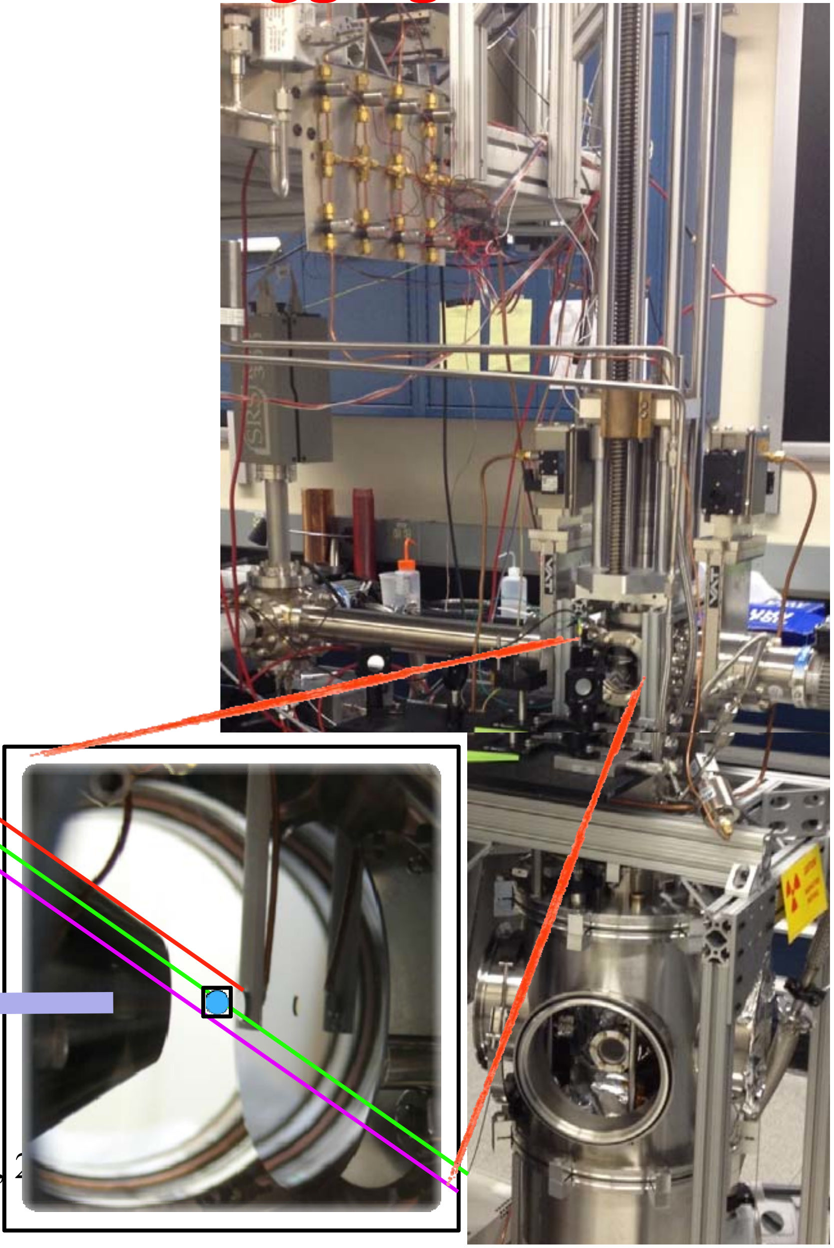
First generation cryoprobe in LXe





Ba removal from LXe and tagging in vacuum



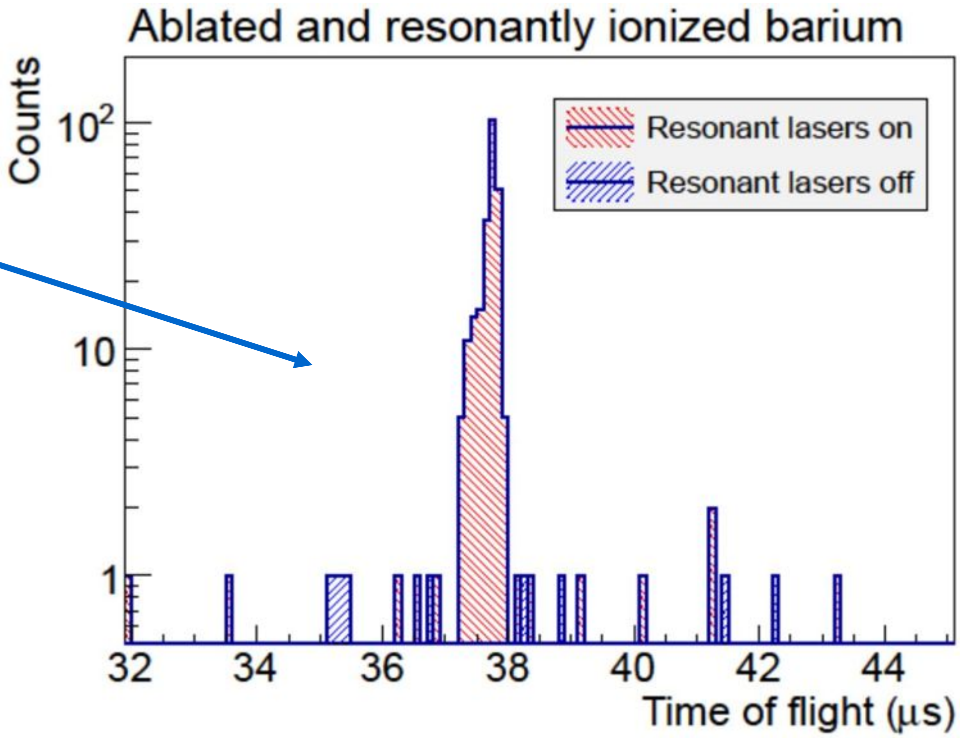


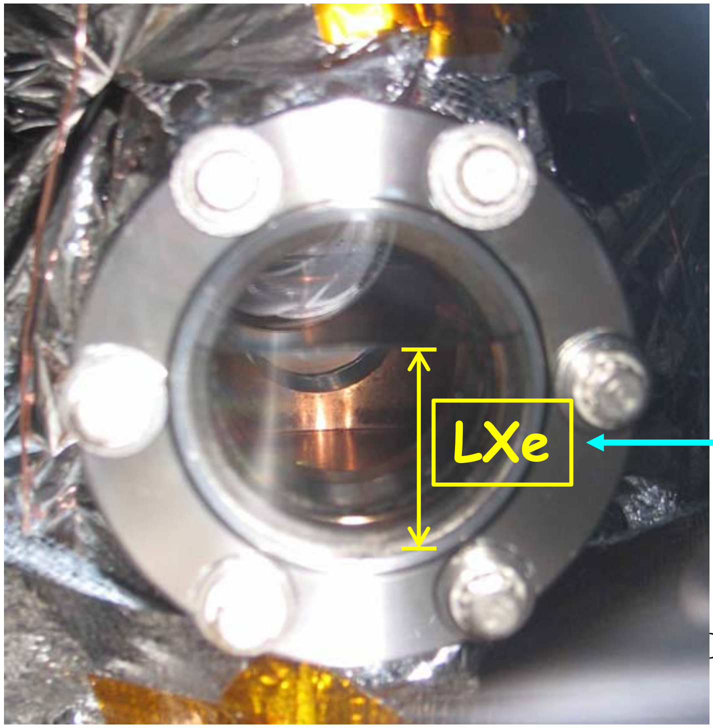
1064 nm
553.5 nm
389.7 nm

Ba^+

To Time of Flight Spectrometer

- Proper choice of material and surface prep ➔ signal with almost no background
- Ideal conditions + luck: >5% efficiency from deposition to detection





Next:

- Continued work on improving repeatability, efficiency
- Start operating in LXe

From the closeout of DoE panel review of nEXO R&D (Germantown 12 Jul 2013)

from the Charge (Standard HEP Merit Review Criteria)

"We welcome all of your comments, but we are also willing to stipulate that the well-established EXO scientific team would rate highly on these points."

Is the scope of the R&D appropriate for success?

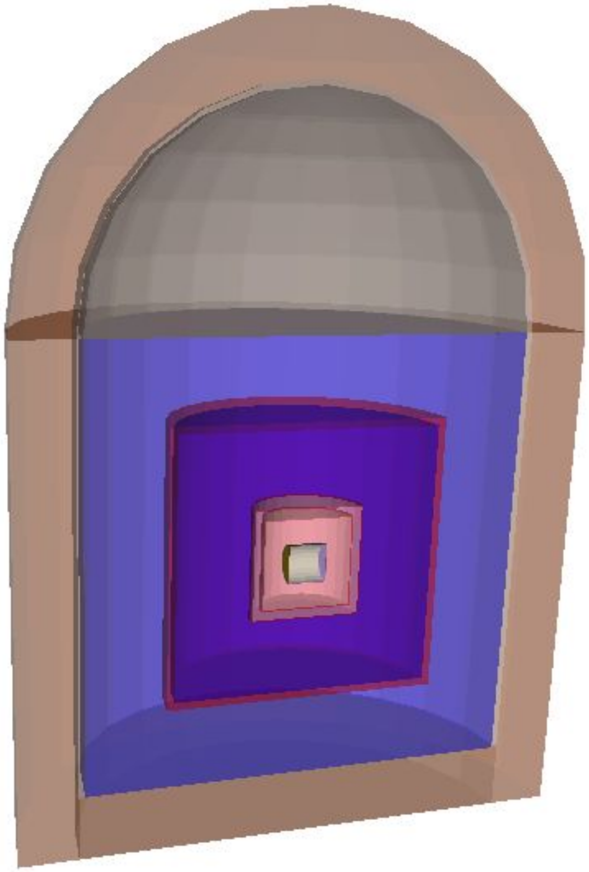
"Comments:

1. *The successful completion of the nEXO R&D program, and additional R&D at other institutions, will put the EXO collaboration in a position to be able to build a ton-scale double beta decay experiment.*
2. *Given the interest worldwide in the neutrino mass hierarchy which may be unfolding over the next 5 years, it really is important that the momentum be kept at a high level to pursue this program in a timely way."*

Rest of comments on specific topics very positive

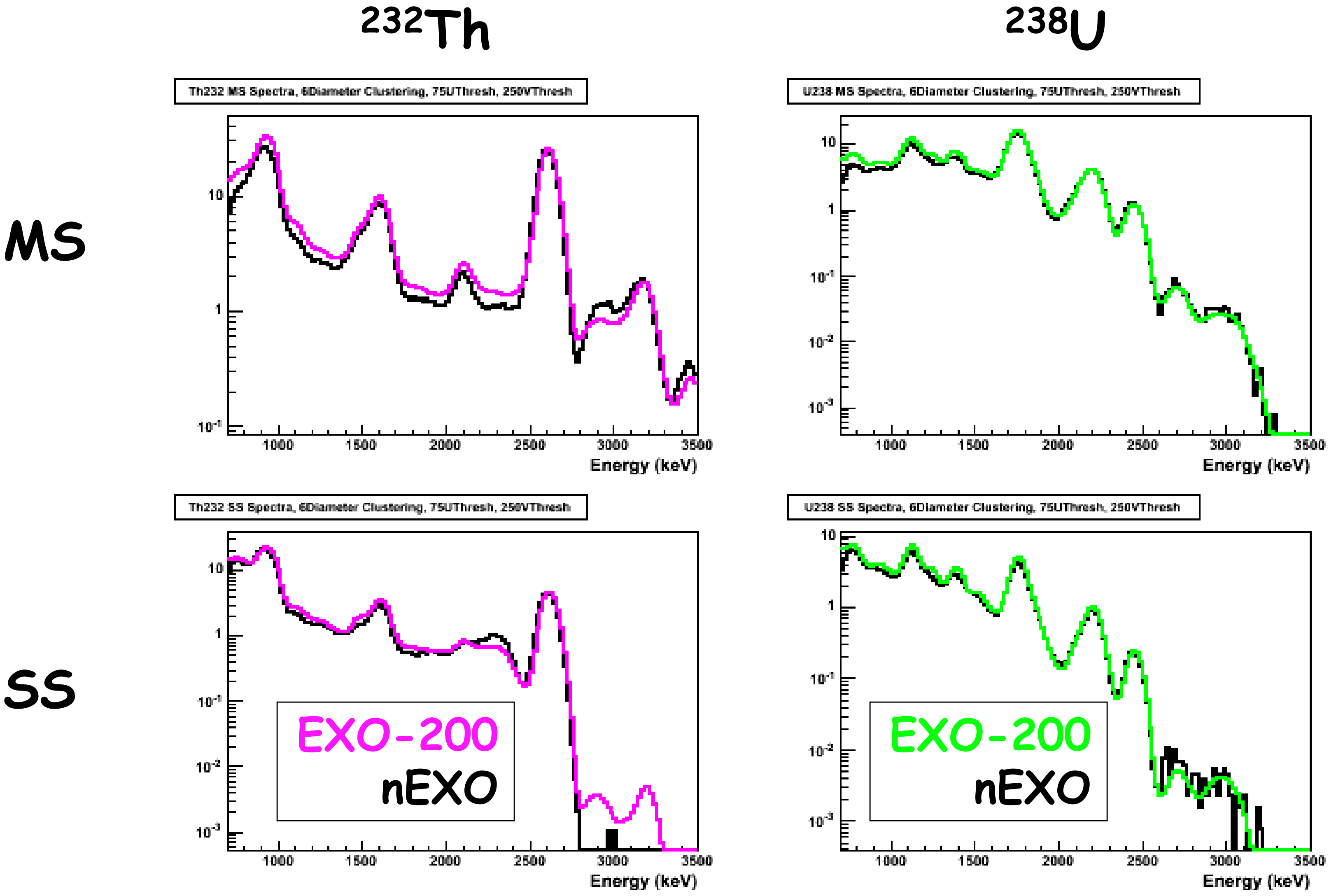
➔ Report is available to the EAC and SNOlab Director upon request

nEXO Simulation and Sensitivity

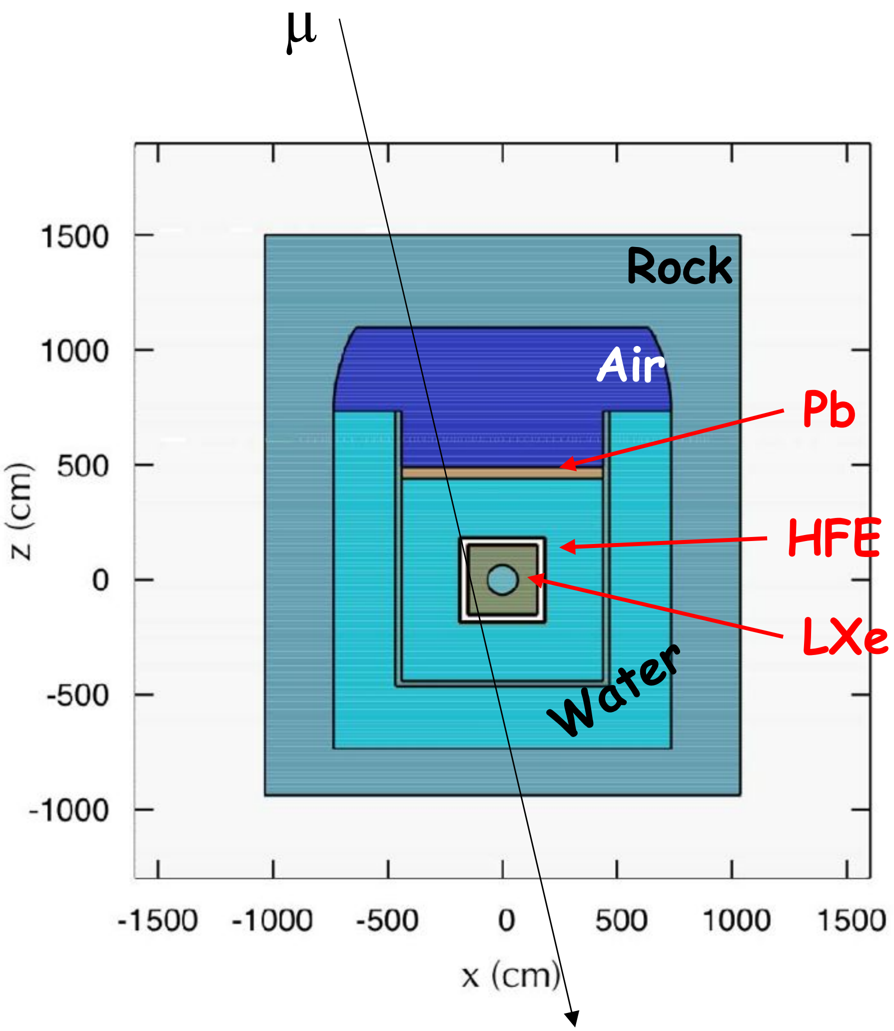


- Geant4 simulation for γ bkgnd
- Includes all major components of nEXO, as known now
- Cryopit full of water, detector centered
- σ_E = 1.5% *(this is conservative)*
- e-γ discrim. 2x that of EXO-200 *(3x finer pitch & lower threshold)*
- Scale material amounts and use EXO-200 material contaminations except where new numbers are available *(e.g. copper)*
- Short term work to be done:
  - Iterate for shielding thickness
  - Add LXe/readout physics *(confirm or modify discrimination power)*
  - Insert new figures for material radioactivity as they become available

The relatively crude model can reproduce reasonably well the better EXO-200 reconstruction if asked…



Neutrons are simulated using FLUKA, with a slightly simplified geometry



Main background from n capture on ^{136}Xe

$$^{136}Xe + n \rightarrow {}^{137}Xe$$

$$\hookrightarrow {}^{137}Cs + \overline{\nu_e} + e^-$$

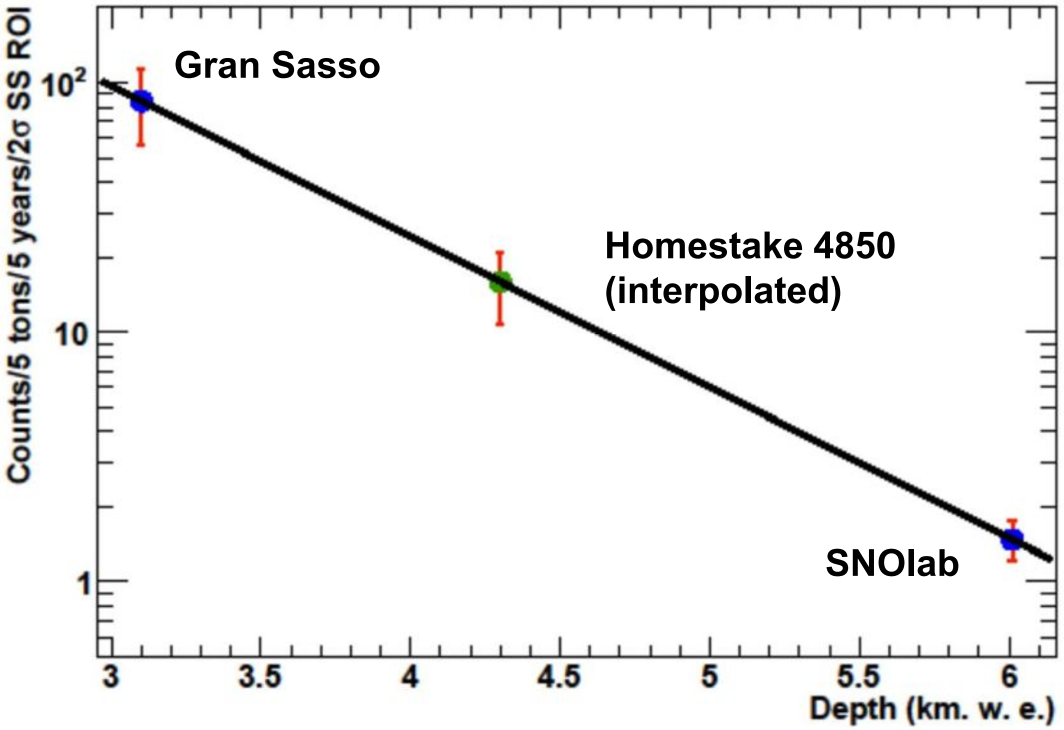
$T_{1/2}$=3.8min, Q=4.2MeV

$$\Rightarrow 1.5\ \frac{cts}{5yr\ 5ton\ \pm 2\sigma ROI}$$

Backgrounds from prompt n and n from rock activity are greatly attenuated by the large water shield and negligible

How important is the depth for this cosmogenic background?

Simulation done with muon spectrum and rate of LNGS



Background substantially higher, but we are studying various tags, including coinc. between μ veto and ^{136}Xe(n,γ) signal (~15min veto).
➔ Looks promising but not ready yet (and useful for SNOlab too).

Other n backgrounds

- Prompt events following a muon
- Neutrons from rock radioactivity

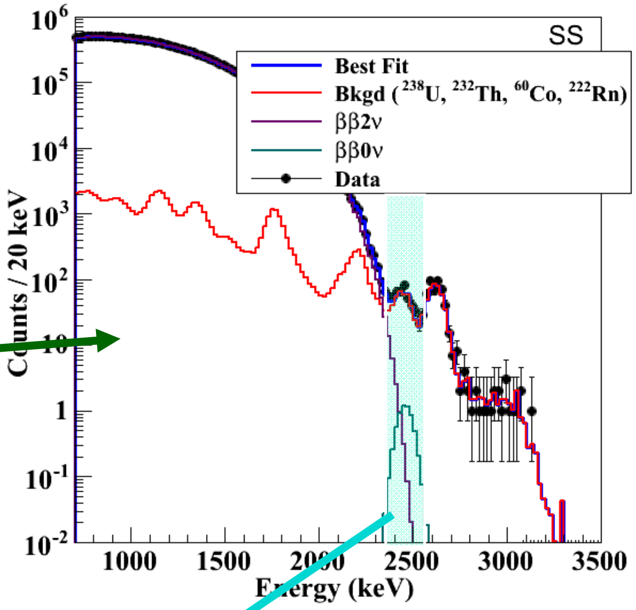
very strongly suppressed by the large water shield and give a negligible contribution (→ we may reduce the shield!)

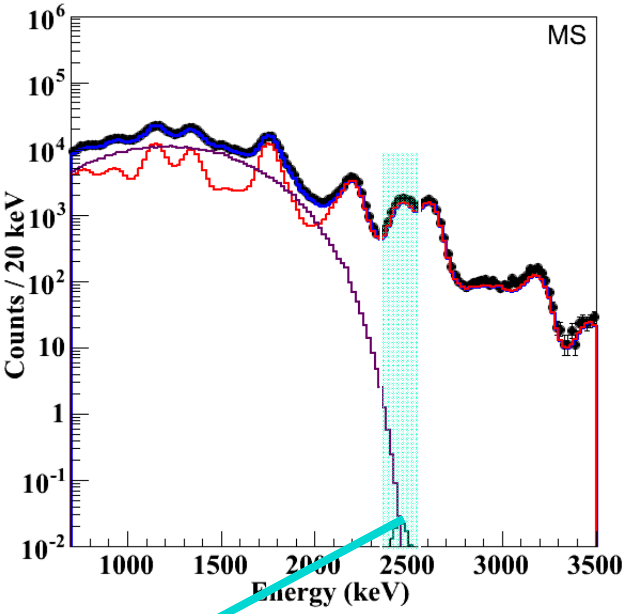
Neutrino backgrounds

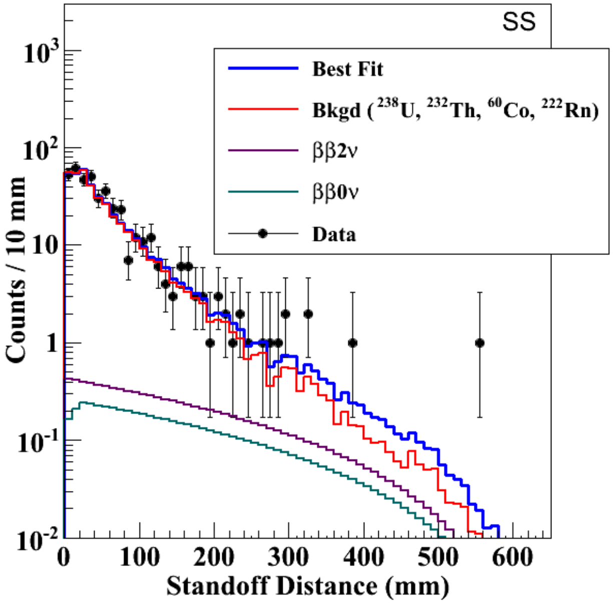
Not included yet in the sensitivity calculations

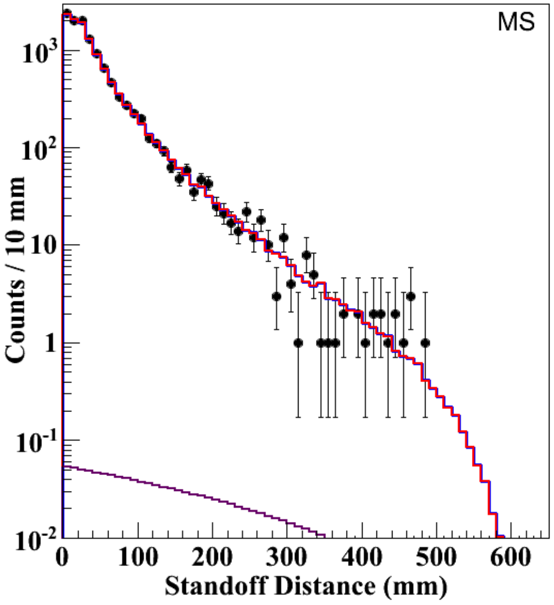
Source	Process	cts 5ton 5yr 2σROI	Comments
Solar ^{8}B	$^{136}Xe + \nu_e \rightarrow {}^{136}Cs + e^-$	1.2	
	$e^- + \nu_e \rightarrow e^- + \nu_e$	1.2	
Solar ^{7}Be, pep	$^{136}Xe + \nu_e \rightarrow {}^{136}Cs + e^-$ $\Lsh\ {}^{136}Ba + \overline{\nu_e} + e^- + \gamma s$	0.15	γs essential for rejection
ν_{Atm}	Many	<0.1	
ν_{React}, ν_{Geo}	Elastic scattering + $^{136}Xe + \overline{\nu_e} \rightarrow {}^{136}I + e^+$	<0.2	
	Total	<4.6	

Like for EXO-200 data the fit to 0v, 2v and background uses energy and standoff separately for SS/MS.

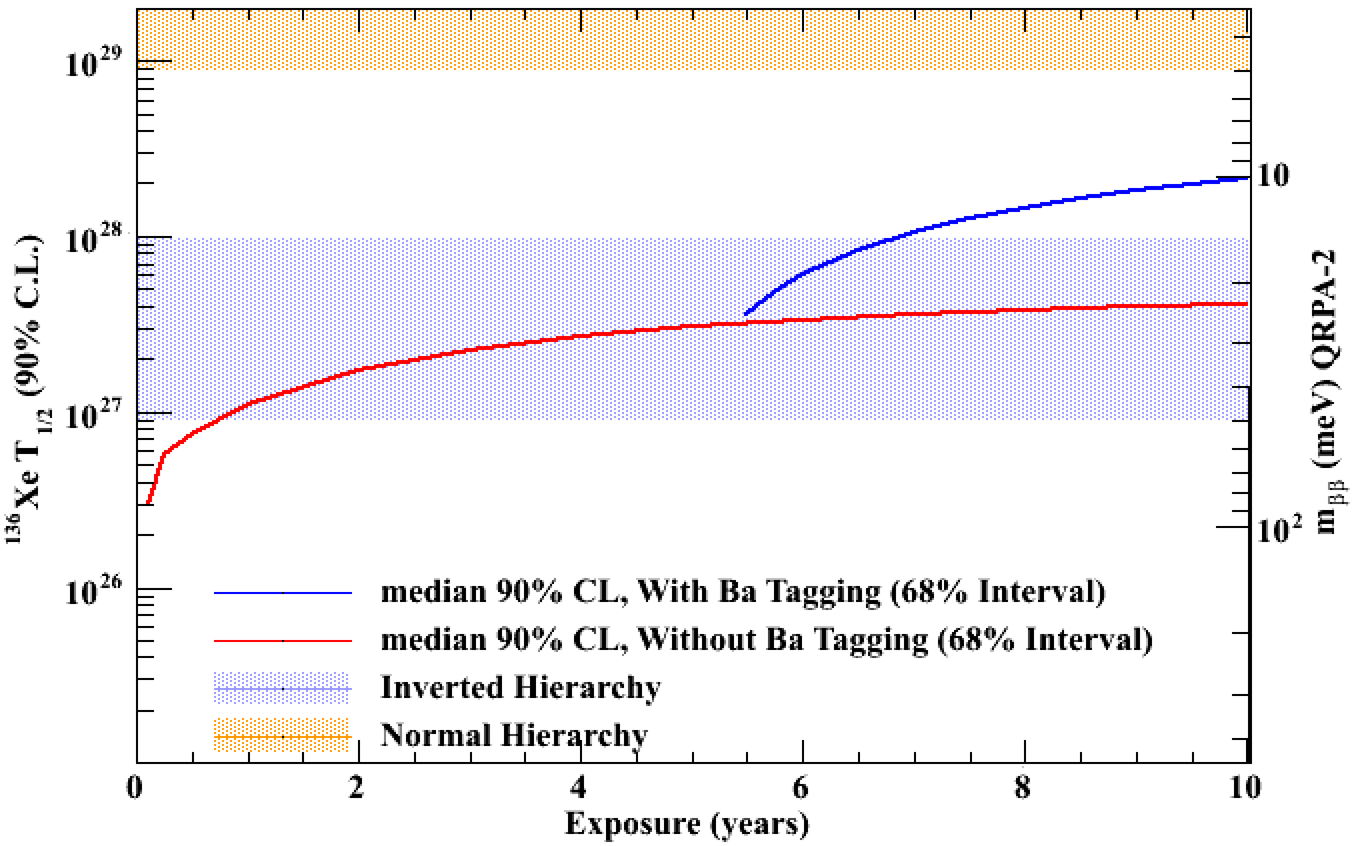




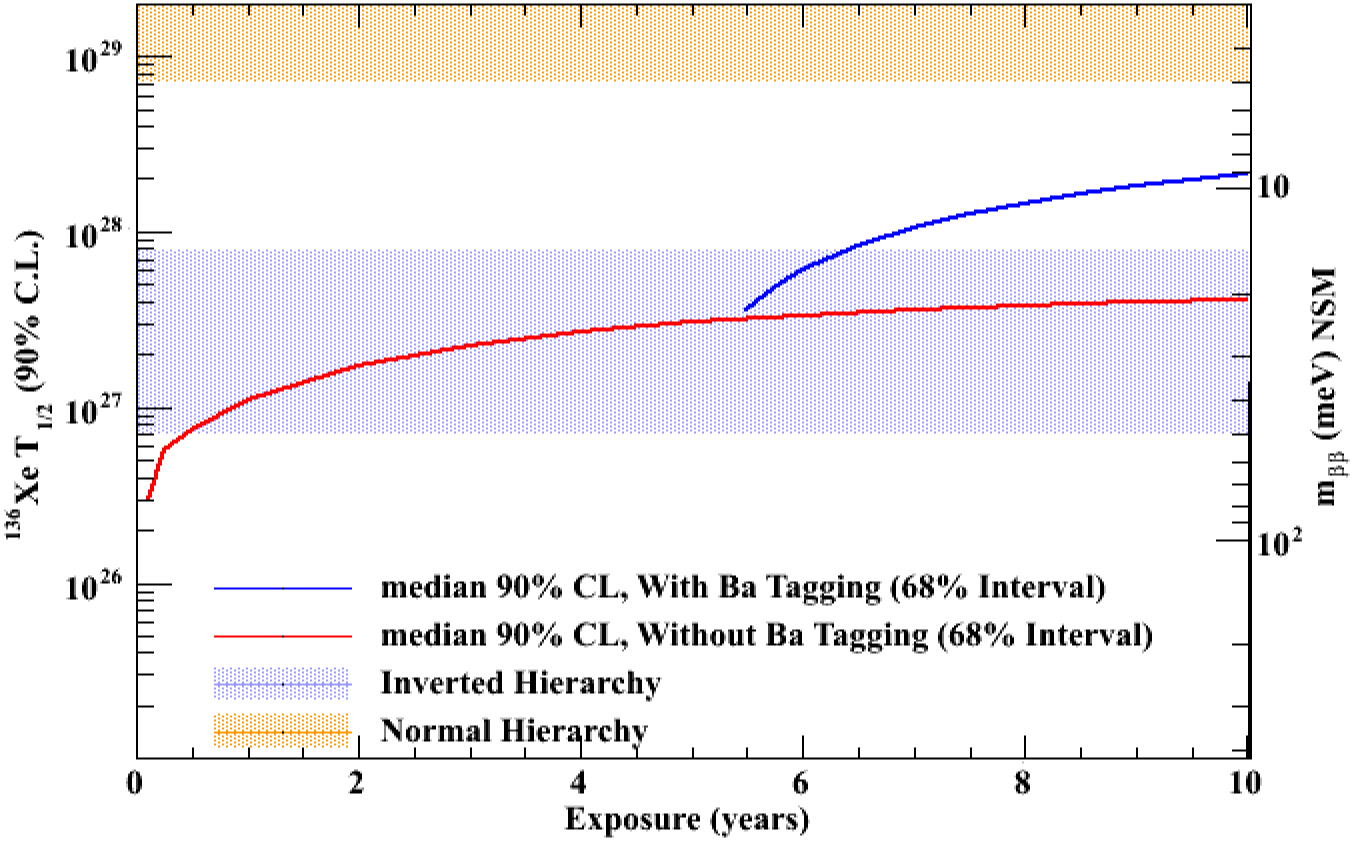




Sensitivity



Sensitivity



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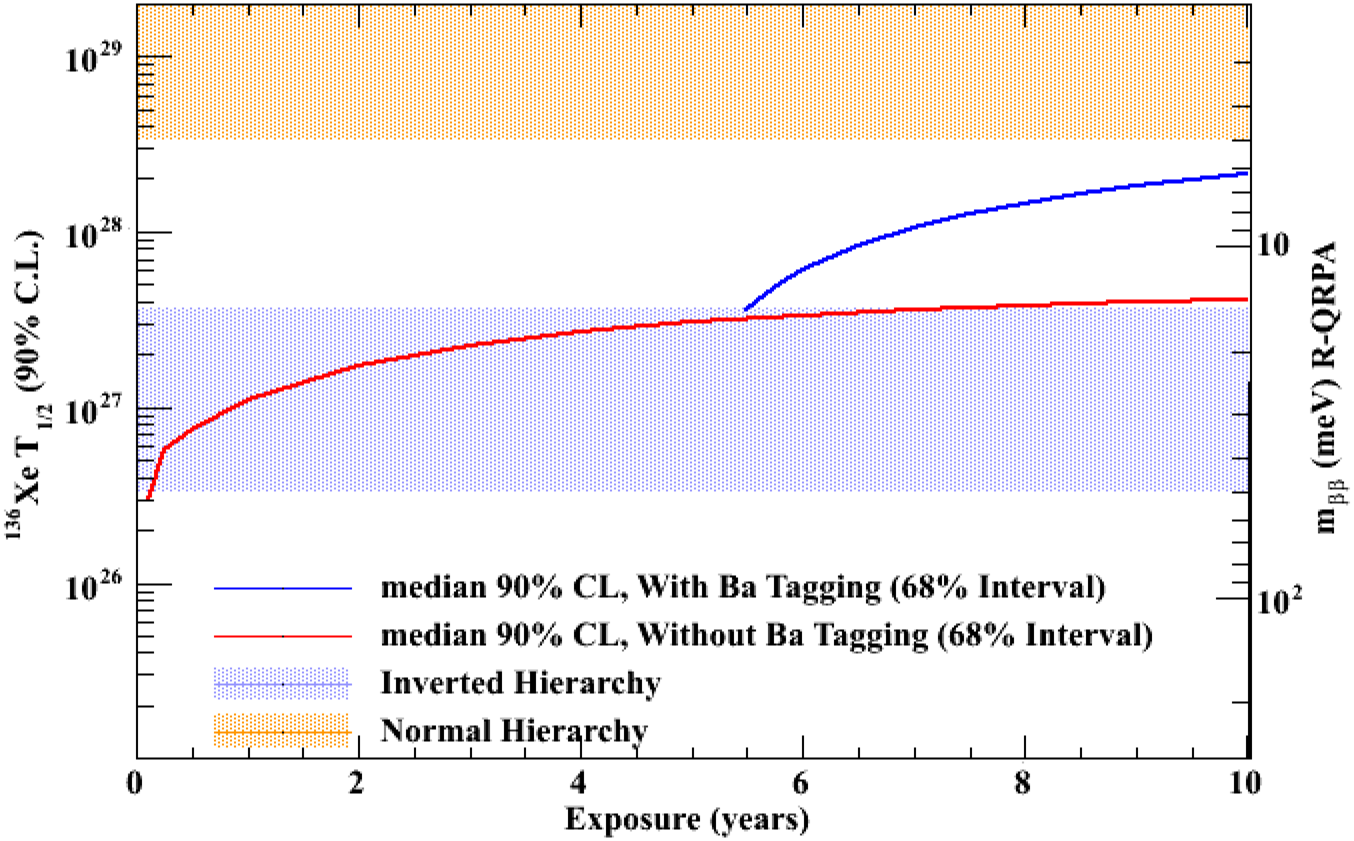

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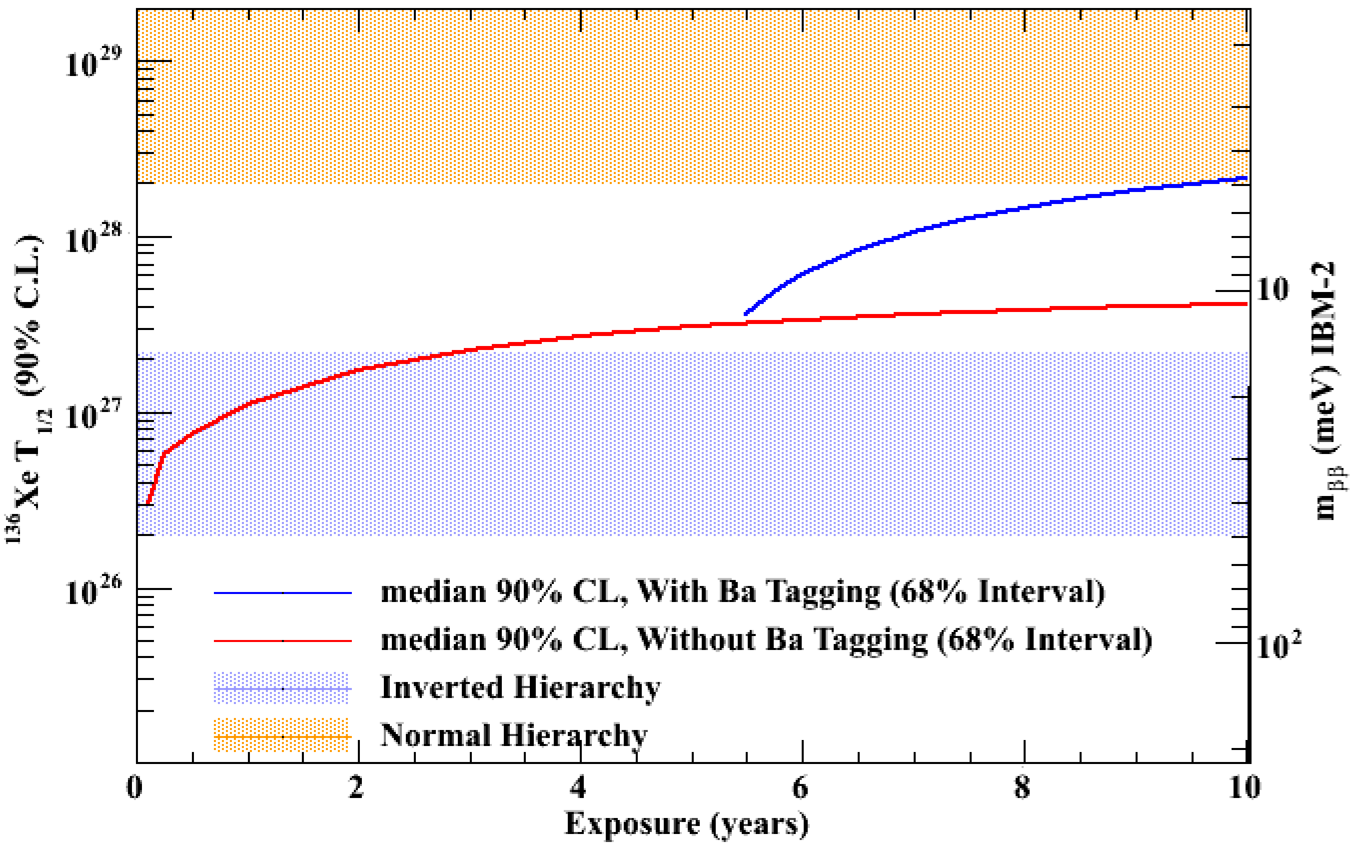
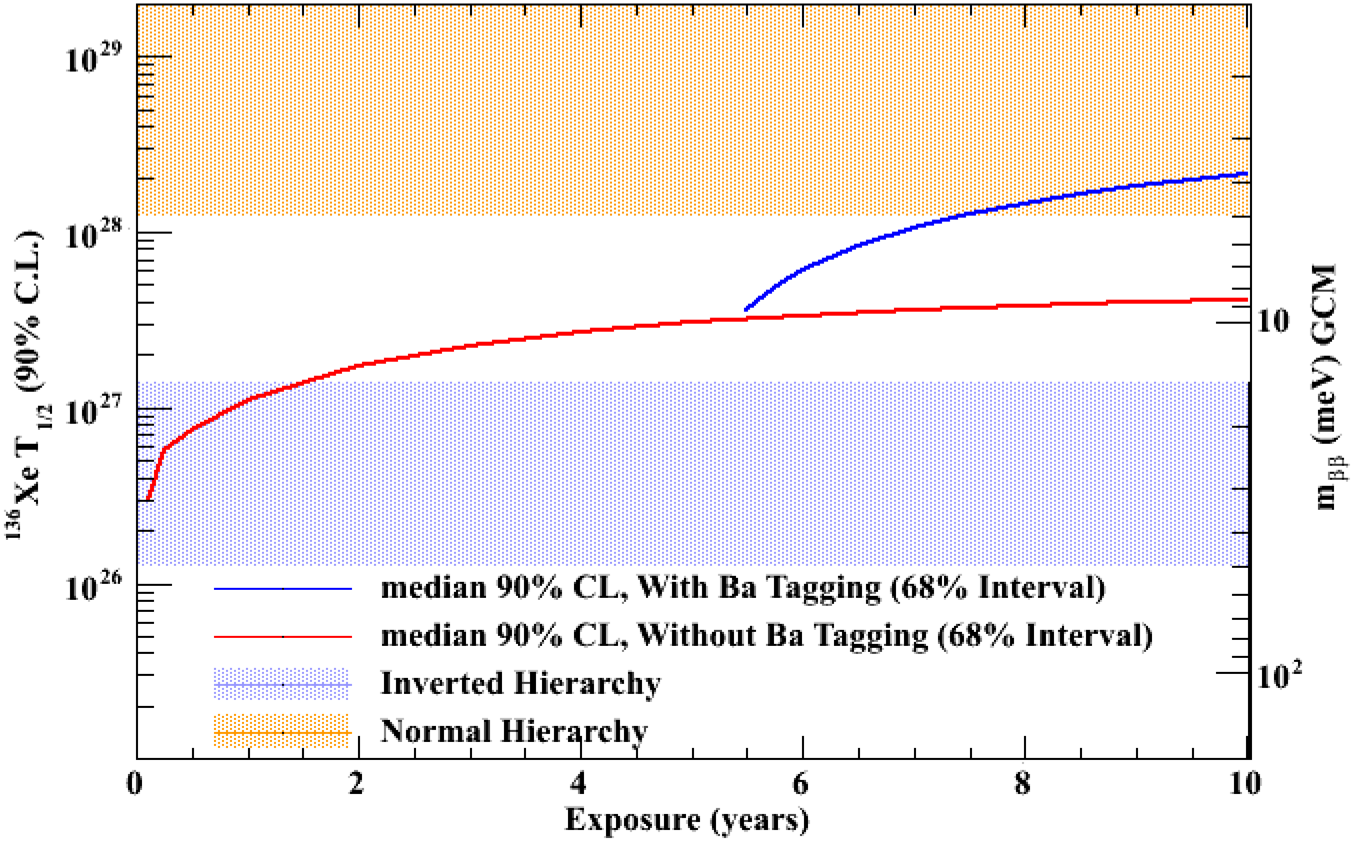
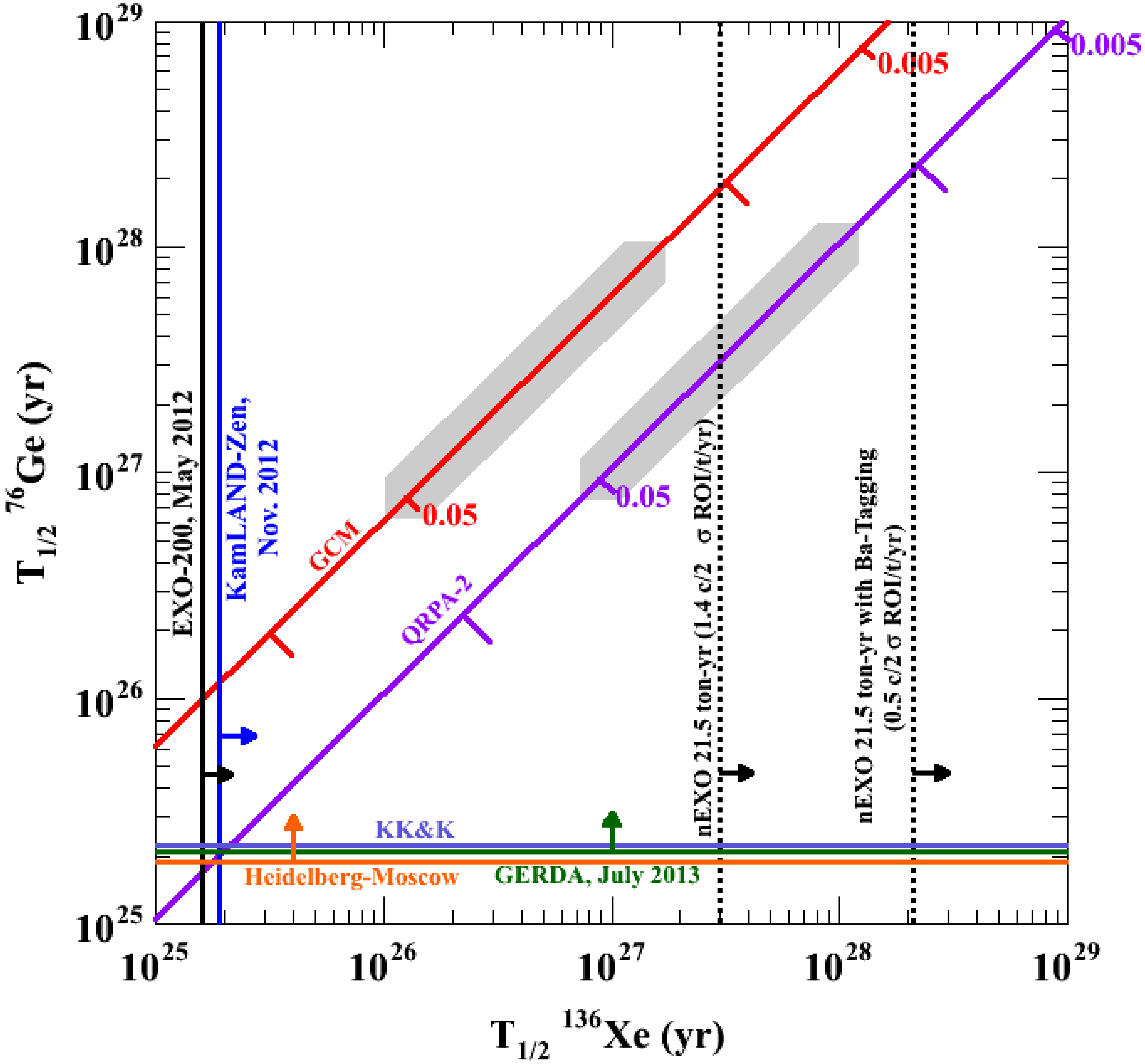


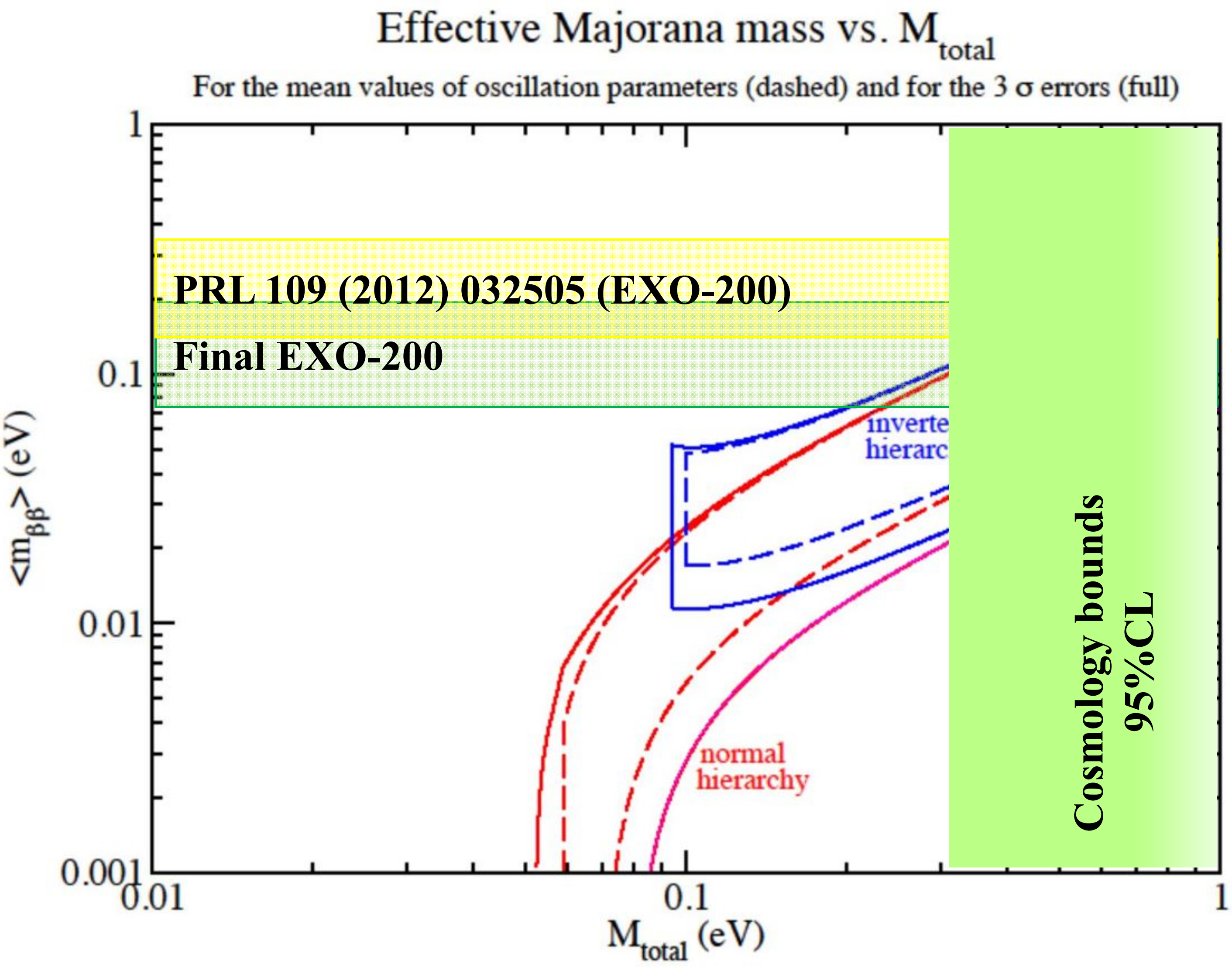
Sensitivity





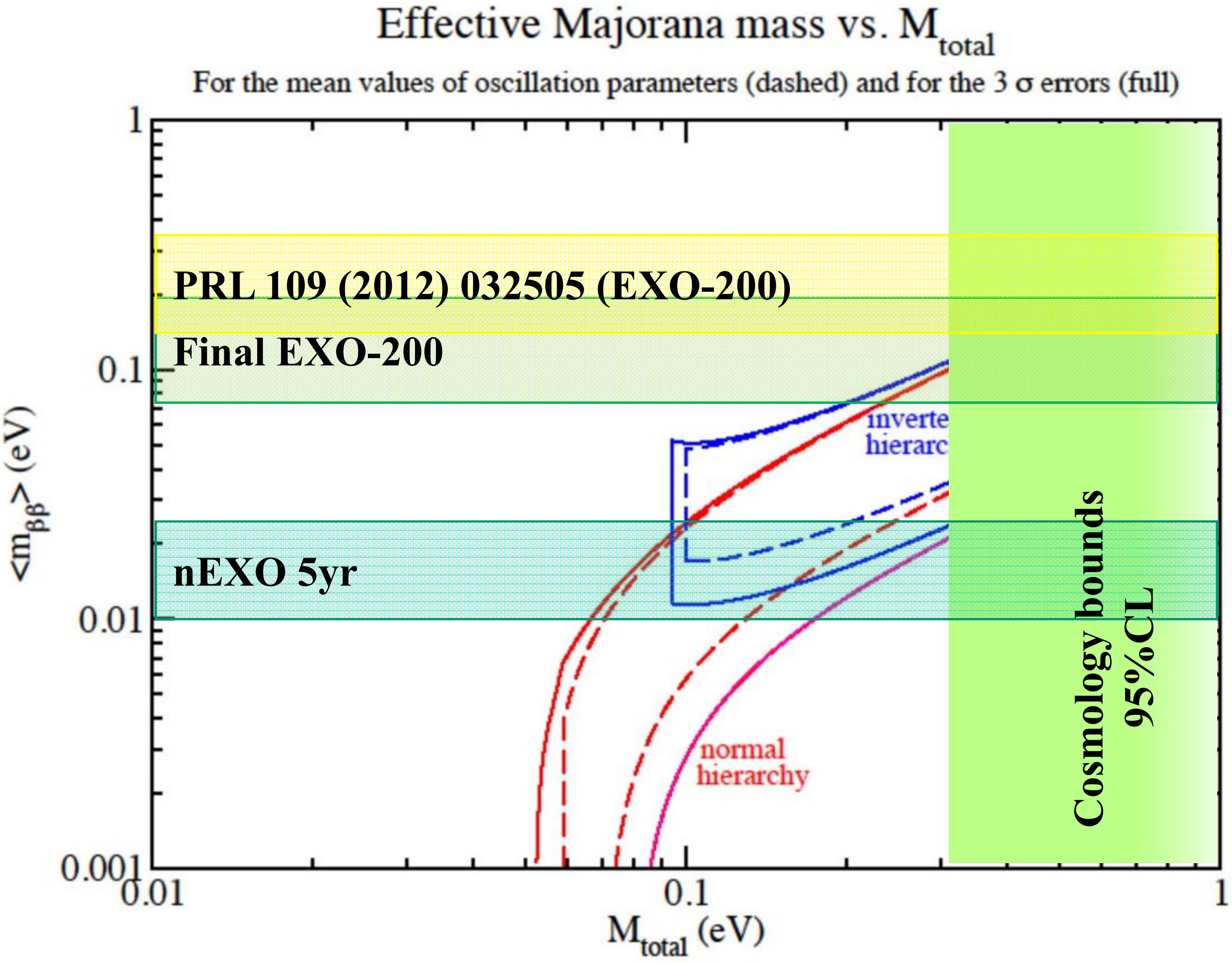
10^{29}
10^{28}
10^{27}
10^{26}
10^{25}
$T_{1/2}$ ^{76}Ge (yr)
EXO-200, May 2012
KamLAND-Zen, Nov. 2012
GCM
0.05
0.005
QRPA-2
0.05
0.005
nEXO 21.5 ton-yr (1.4 c/2 σ ROI/t/yr)
nEXO 21.5 ton-yr with Ba-Tagging (0.5 c/2 σ ROI/t/yr)
KK&K
Heidelberg-Moscow
GERDA, July 2013
10^{25}
10^{26}
10^{27}
10^{28}
10^{29}
$T_{1/2}$ ^{136}Xe (yr)

Constraints on neutrino masses



n

Constraints on neutrino masses



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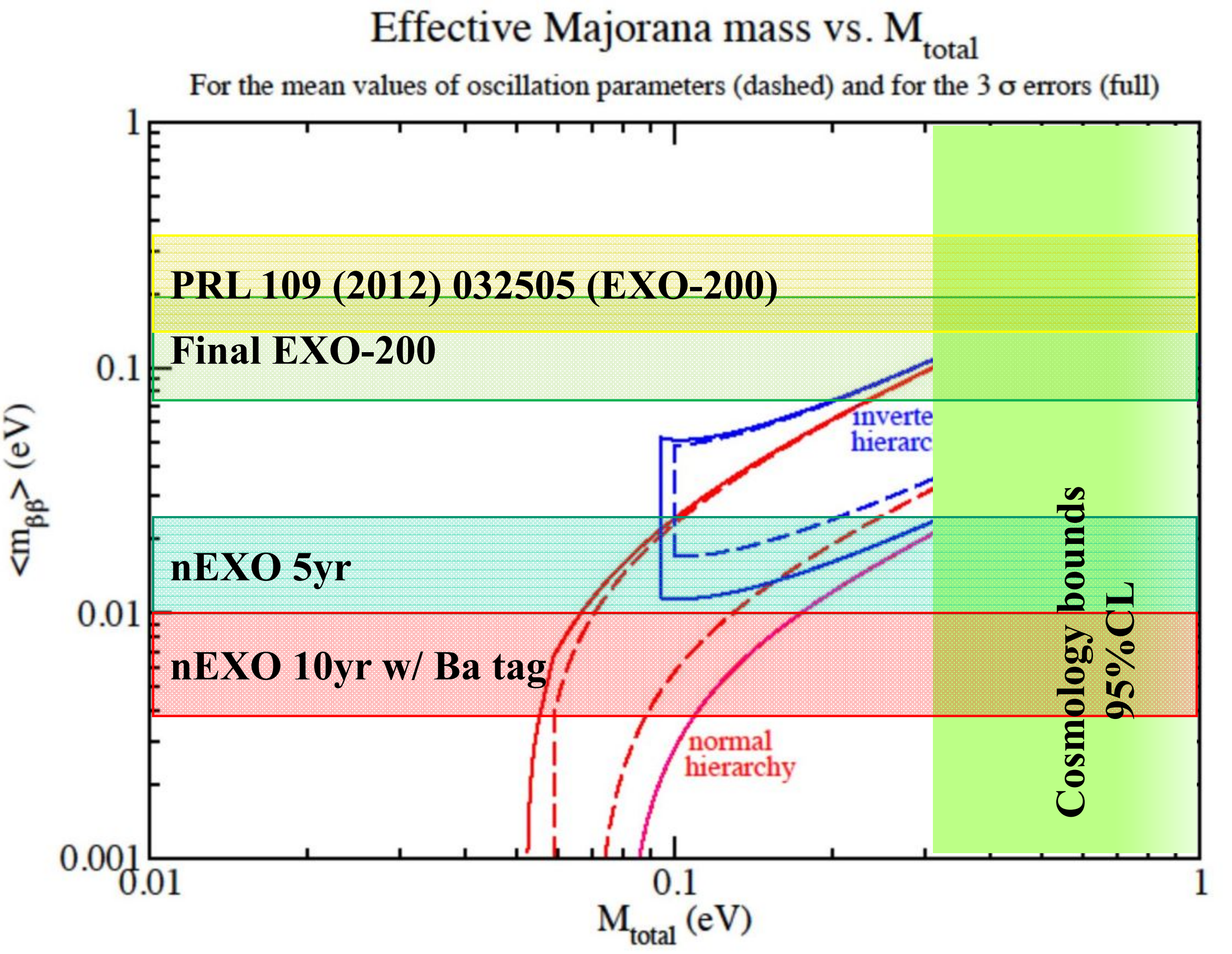
Constraints on neutrino masses



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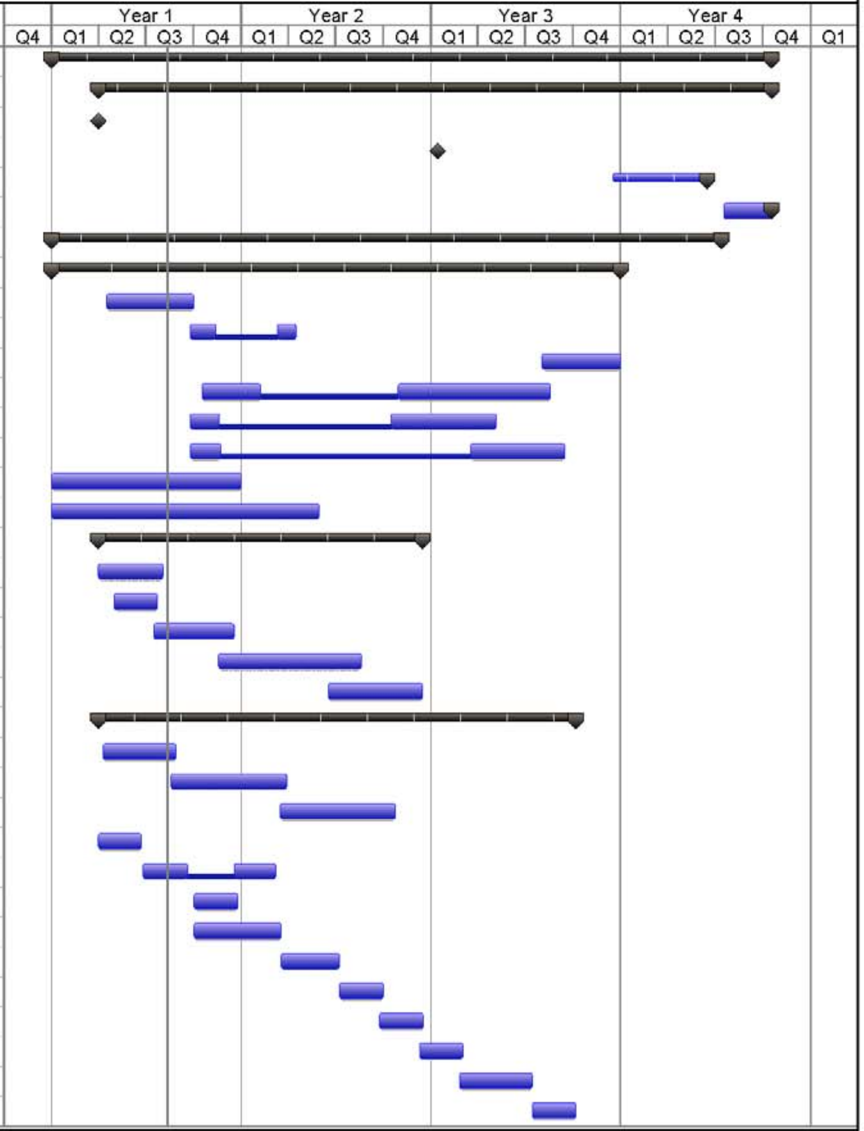
nEXO R & D

Timeline

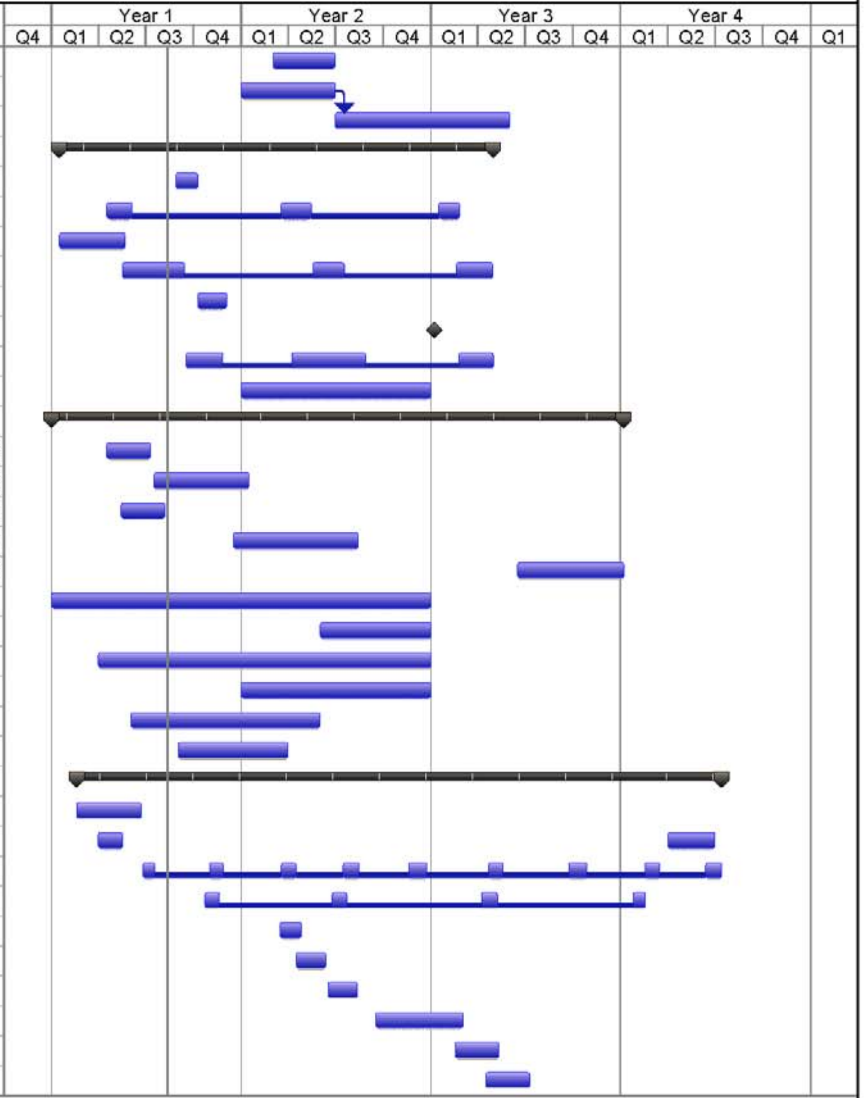
ID	Task Name	Institution
1	**nEXO R&D Plan**	
2	**Milestone**	
3	nEXO R&D Proposal to DOE	
4	nEXO Location DECISION	
5	First Draft CDR	
6	nEXO Funding DECISION (CD1)	
7	**nEXO R&D Tasks**	
8	**Conceptual Engineering Design**	
9	Create nEXO CAD model	SLAC
10	Refine liquid model	SLAC
11	nEXO Model Update	SLAC
12	Study site implications	SLAC
13	Support cost modeling	SLAC
14	Support scheduling activities	SLAC
15	Calibration Plan and Technique	Laurentian
16	Radon Trap Design	Laurentian
17	**High Voltage Stability in LXe**	
18	Design/fab test stand	SLAC
19	Design/fab simple geometry sample	SLAC
20	Perform HV tests of simple geom	SLAC
21	Design/fab more complex geom	SLAC
22	Perform HV tests of complex geom	SLAC
23	**Cold Electronics and Charge Readout**	
24	Charge readout design trades	All
25	Charge readout design prototype	SLAC
26	Charge readout testing	SLAC
27	Spec and channel count decisions	SLAC
28	Electronic Components Radiopurity testing	Alabama
29	CMOS transistor characterization at 170K	SLAC
30	ASIC design/fab/test	SLAC
31	Si "Circuit Board" Design & Fab	SLAC
32	Interconnect development	SLAC
33	Optical Powering development	SLAC
34	External power	SLAC
35	Thermal management	SLAC
36	Electronics testing warm/cold	SLAC/UIUC



nEXO R & D

Timeline

ID	Task Name	Institution
37	Veto Electronics	IHEP Beijing
38	Build cold electronics test rig	UIUC
39	Test cold electronics	UIUC
40	**Photodetector selection**	
41	Develop Photodetector Test Stand	Stanford
42	Procure SiPMs for testing	Stanford
43	APD vendor survey/evaluation	Stanford
44	Test Si PMs	Stanford
45	Test APDs	Stanford
46	Decision on prefered Photodetector technology	Stanford
47	Radiopurity Testing of PDs	Alabama
48	Testing of photodetectors in Xenon	Umass
49	**Detector Simulations**	
50	Choose common simulation tools	SLAC/Stanford
51	Develop simple detector geometric models	SLAC/Stanford
52	Assemble materials database	SLAC/Stanford
53	Run initial engineering model geometries	SLAC/Stanford
54	Run refined engineering geometries	SLAC/Stanford
55	Radon Counting	Laurentian
56	Veto Simulation	Alabama
57	ICP-MS testing	Seoul
58	Xe Purity and trace analysis	Drexel
59	Thermodynamic Simulation	Drexel
60	SPICE simulation of charge readout	Umass
61	**Project Management**	
62	Review collaboration capabilities	SLAC
63	Develop MOU's for Collaborators	SLAC
64	Follow R&D tasks & report progress	SLAC
65	Perform R&D reviews	SLAC
66	Develop draft Project plan	SLAC
67	Develop full WBS dictionary	SLAC
68	Develop initial cost models	SLAC
69	Develop WBS based cost models	SLAC
70	Build draft Project schedule (MS Proj)	SLAC
71	Resource load schedule	SLAC



Notional time schedule