Comments on Logistics:

- Will carpool from each hotel, please leave most cars at hotels
- Meet in the hotel lobby BY 7:15
- Even if you did the computer paperwork try not to bring your computer unless
  you really have to
- Cells phones are ok
- YOU NEED AN ID (driver's license or passport)
- Please let Giorgio, Liang, Ken F, David McF, Mike H go first through security, so that
  in case of delays the presentations can start
- Very packed agenda, will strictly enforce talks timing
- Will continue through lunch, you owe US$10 to Alan Stone (thanks Alan).
  Please have exact change ready!!

The road to nEXO

Giorgio Gratta
Physics Dept, Stanford University

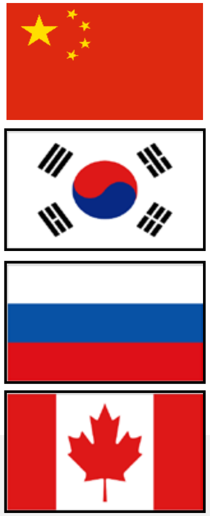
Plan for the Day:

- This talk:
  - Intro to the collaboration
  - Brief Intro to the physics, motivation of Xe and the technique
  - Summary of the technical progress to date: what the detector looks like and why
  - Intro to possible sites
- EXO-200 situation and impact on nEXO R&D (Yang + Fouts)
- nEXO R&D organization and ideas for nEXO management (D.McFarlane, Heffner, LLNL Mgrs)
- SNOlab site (Duncan [policy], Technical [K.McFarlane])
- Canadian collaborators views (Sinclair)
- nEXO R&D tasks management (House)
- nEXO R&D progress reports (all L2 managers, these are many short talks, as requested by DOE, *timing will be strictly enforced for all talks*!!)
- Summary [if required] (Gratta)

The long term vision:

- Working since 1999 on a staged approach to $0\nu\beta\beta$ decay
- "Stage 1", i.e. EXO-200 has been taking data since May 2011, producing some of the most competitive results in the field (the latest just appeared in Nature)
- EXO-200 detector performance close to design from the very beginning of data taking, and may get better in the future
- EXO-200 is also a very successful prototype for a larger, "Stage 2" detector
- "Stage 2", nEXO, is being designed as a 5 tonne $L^{enr}Xe$ detector following closely the EXO-200 layout
- nEXO is also a very flexible and cost effective detector with a clear upgrade path and the built-in capability to address possible future science scenarios making the best use of the isotopically enriched isotope.

The nEXO Collaboration



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

University of Bern, Switzerland - S. Delaquis, R. Gornea, T. Tolba, J-L. Vuilleumier

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

Carleton University, Ottawa ON, Canada - V. Basque, M. Dunford, K. Graham, R. Killick, T. Koffas, C. Licciardi, E.B. Mane, D. Sinclair

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

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

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

IHEP Beijing, People's Republic of China - G. Cao, X. Jiang, H. Li, Z. Ning, X. Sun, N. Wang, W. Wei, L. Wen, W. Wu

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

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

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, A. Der Mesrobian-Kabakian, J. Farine, B. Mong, U. Wichoski

Lawrence Livermore Nat'l Lab, Livermore CA, USA - M.Heffner, A. House

Oak Ridge Nat'l Lab, Oak Ridge TN, USA - L. Fabris, J. Newby, K. Ziock

University of Massachusetts, Amherst MA, USA - J. Dalmasson, T. Daniels, S. Feyzbakhsh, S. Johnston, A. Pocar

University of Seoul, South Korea - D.S. Leonard

SLAC National Accelerator Laboratory, Menlo Park CA, USA - K. Fouts, R. MacLellan, A. Odian, P.C. Rowson

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

Stony Brook University, Stony Brook, NY, USA - K.Kumar

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

TRIUMF, Vancouver BC, Canada – M. Constables, J. Dilling, P. Gumplinger, R. Krucken, F. Retière, V. Strickland

Collaboration composition at a glance

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

Very healthy and driven mix of

- **young and more experienced players,**
- **University groups and Nat's Labs,**
- **US and "foreign" institutions**

Unusually broad expertize in techniques, analysis, hardware, neutrino physics,…

Still growing; discussions are in progress with:

- **BNL,**
- **A number of university groups in Europe, the US and Asia**

Discovering $0\nu\beta\beta$ decay:

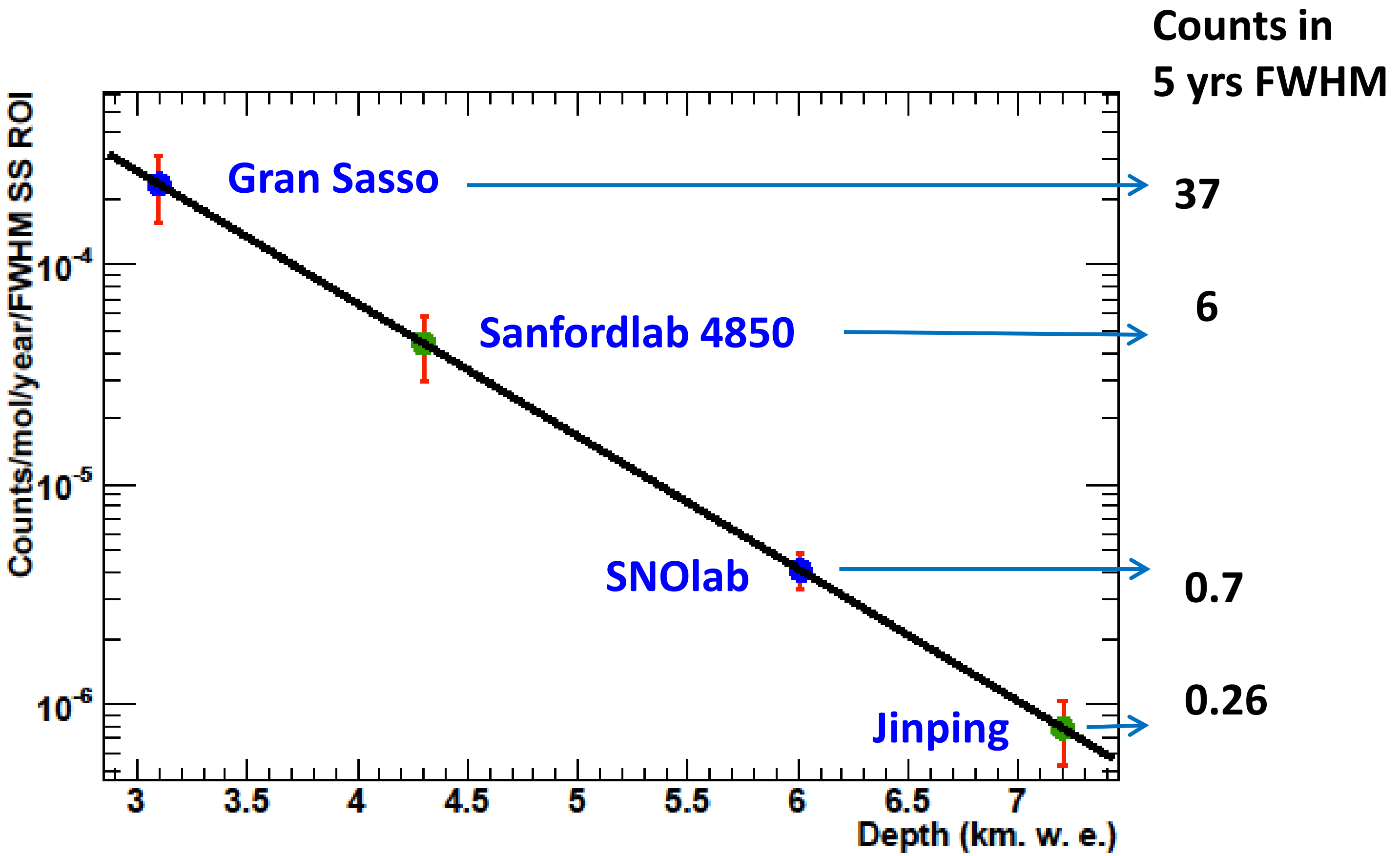
→ Discovery of the neutrino mass scale
→ Discovery of Majorana elementary particles
→ Discovery of lepton number violation

"Why wait? We have in our hands an experiment with 50% chance of making a fundamental discovery in physics, we should do it right away!"

Anon *(not a member of the collaboration)*

Physics considerations related to the choice of a site

Simulation done with muon spectrum and rate of LNGS



Conclusion:

- SNOlab and Jinping are comfortable
- SanfordLab at 4850 is probably ok
- Gran Sasso is marginal but may be ok

Other considerations related to the choice of a site

- **Gran Sasso and Jinping have horizontal access**
- **Jinping is the most remote**
  (2 hops from PEK or Shanghai + ~100min drive)
- **No science infrastructure at Jinping yet**
- **Things are moving really fast in China and the scale of the hydroelectric plant construction is staggering**
  (300km of tunnels,
  tallest dam on Earth,
  3.6GW$_{el}$ for Jinping 1)
- **There may be substantial funding in China**

➔ **Baseline is SNOlab, but other options are still on the table**

The virtues of ^{136}Xe in a large TPC

- No need to grow crystals
- Can be re-purified during the experiment
- Noble gas: easy(er) to purify
- Can be easily transferred from one detector to another depending on results and available technology
- Good (although not best) energy resolution coupled with large homogeneous and imaging detector is very powerful
- No long lived Xe isotopes to activate
- ^{136}Xe enrichment easier and cheaper:
  - *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
- ^{136}Xe can be replaced with $^{Nat'l}$Xe if a signal is observed!

Material procurement

^{136}Xe enrichment easier and cheaper:

➔ 90% enriched ^{136}Xe: ~10$/g

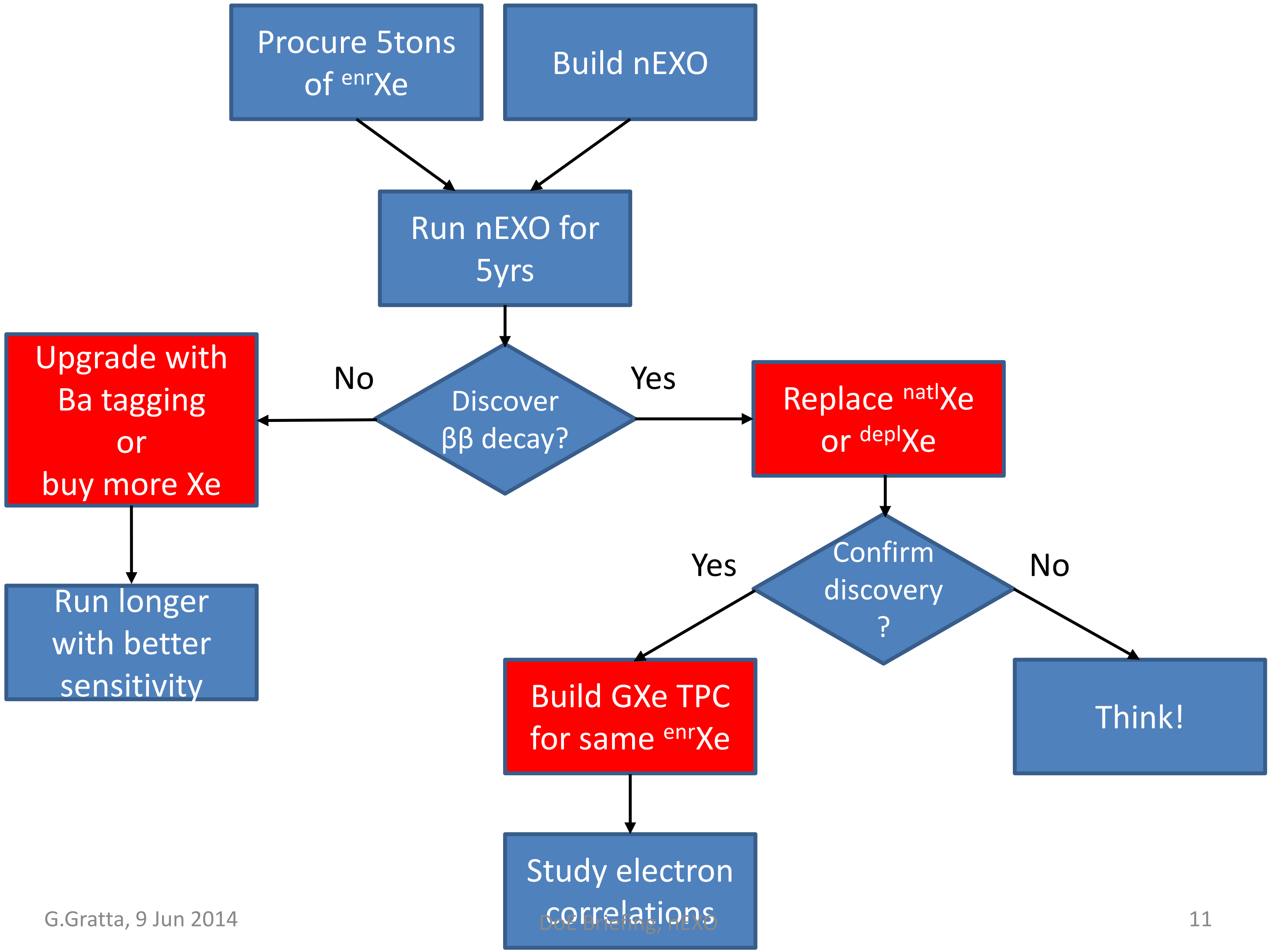
90% enriched ^{76}Ge: ~90$/g (+xtal growth)

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

Exact centrifuge capacity in Russia is classified but our contacts indicate that 5000kg in 5 years is comfortable

- ***World $^{nat'l}Xe$ production is ~40 tonnes/yr (~4000kg ^{136}Xe), however large price fluctuations are not uncommon***
- ***A large order in a hurry is not a smart way to proceed***

Flexible program based on the initial nEXO investment



A few comments on EXO-200

(see later talks by L.Yang and K.Fouts)

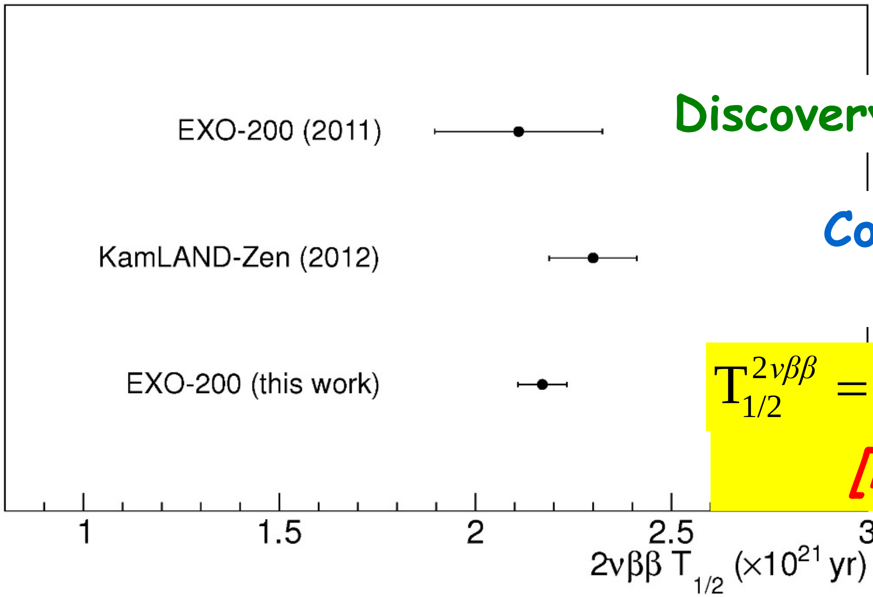
Run 1: May-Jul 2011
Run 2: Sept 2011 – Sept 2013

Feb 2014 forced stop due to WIPP's fire and radiation release

Detector upgrades for lower APD noise and Rn removal

Plan for ~3 more years of data in the new configuration
(this estimate to be refined when we start running again)

Best measured and rarest 2ν mode



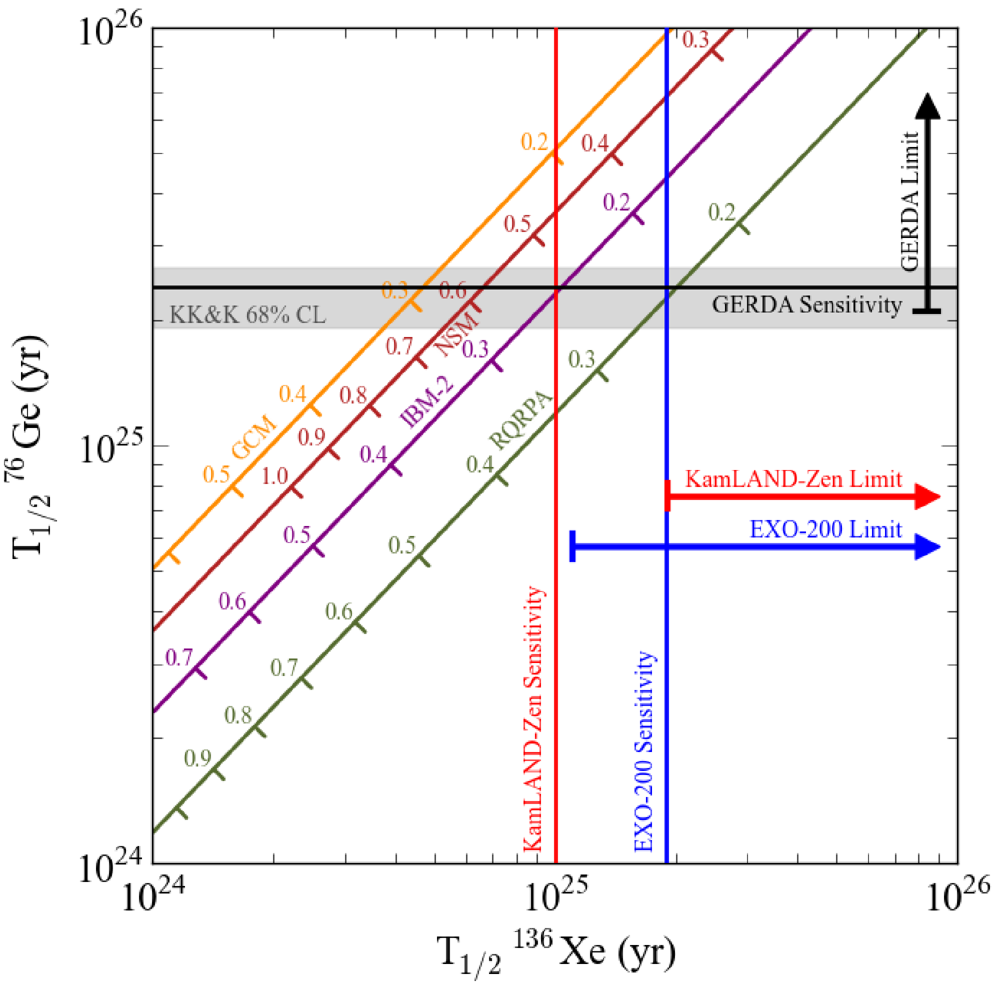
Discovery of 2ν mode *[PRL 107, 212501 (2011)]*

Confirmation by KamLAND-Zen *[PRC 85, 045504 (2012)]*

$$T_{1/2}^{2\nu\beta\beta} = \left(2.165 \pm 0.016^{\text{stat}} \pm 0.059^{\text{syst}}\right) \cdot 10^{21}\ \text{yr}$$

[Phys. Rev. C 89 (2014) 015502]

Nuclide	$T_{1/2}^{2\nu\beta\beta} \pm$ stat $\pm$ sys [y]	rel. uncert. [%]	$G^{2\nu}$ [10^{-21} y^{-1}]	$M^{2\nu}$ [MeV^{-1}]	rel. uncert. [%]	Experiment (year)
^{136}Xe	$2.165 \pm 0.016 \pm 0.059 \cdot 10^{21}$	± 2.83	1433	0.0218	± 1.4	EXO-200 (this work)
^{76}Ge	$1.84^{+0.09+0.11}_{-0.08-0.06} \cdot 10^{21}$	$^{+7.7}_{-5.4}$	48.17	0.129	$^{+3.9}_{-2.8}$	GERDA [39] (2013)
^{130}Te	$7.0 \pm 0.9 \pm 1.1 \cdot 10^{20}$	± 20.3	1529	0.0371	± 10.2	NEMO-3 [40] (2011)
^{116}Cd	$2.8 \pm 0.1 \pm 0.3 \cdot 10^{19}$	± 11.3	2764	0.138	± 5.7	NEMO-3 [41] (2010)
^{48}Ca	$4.4^{+0.5}_{-0.4} \pm 0.4 \cdot 10^{19}$	$^{+14.6}_{-12.9}$	15550	0.0464	$^{+7.3}_{-6.4}$	NEMO-3 [41] (2010)
^{96}Zr	$2.35 \pm 0.14 \pm 0.16 \cdot 10^{19}$	± 9.1	6816	0.0959	± 4.5	NEMO-3 [42](2010)
^{150}Nd	$9.11^{+0.25}_{-0.22} \pm 0.63 \cdot 10^{18}$	$^{+7.4}_{-7.3}$	36430	0.0666	$^{+3.7}_{-3.7}$	NEMO-3 [43](2009)
^{100}Mo	$7.11 \pm 0.02 \pm 0.54 \cdot 10^{18}$	± 7.6	3308	0.250	± 3.8	NEMO-3 [44](2005)
^{82}Se	$9.6 \pm 0.3 \pm 1.0 \cdot 10^{19}$	± 10.9	1596	0.0980	± 5.4	NEMO-3 [44](2005)



Papers:

J.B.Albert et al. (EXO-200)
arXiv:1402.6956 (27 Feb 2014)
Nature 12 Jun 2014 (this week!)

A. Gando et al. (KamLAND-ZEN)
PRL 110 (2013) 062502

M. Agostini et al. (GERDA)
PRL 111 (2013) 122503

Experiment	$T_{1/2}$ sensitivity	$T_{1/2}$ limit	<m> limit
EXO-200	1.9×10^{25} yr	$>1.1\times10^{25}$ yr	<190-450 meV
KamLAND-ZEN	1.0×10^{25} yr	$>1.9\times10^{25}$ yr	<150-350 meV
GERDA-I	2.4×10^{25} yr	$>2.1\times10^{25}$ yr	<200-400 meV

As communicated by WIPP's management they are on track to have us restart in the Fall (even though waste processing may be on hold for a much longer time)

EXO-200 phase II will

- **Substantially improve the sensitivity:**
  New experiments are *built* to gain the projected improvement
- **Test in the field a number of concepts that are important for nEXO design**

Q: Is there an impact of the EXO-200 restart on nEXO R&D?

A: Of course

- **Some manpower will have to go back to shifts and some people will be particularly involved with the restarting/fixing of equipment.**
- **We will produce more physics in the next two years and this is very healthy for the collaborations, especially young people**
- **nEXO will directly benefit from more EXO-200 data in the areas of**
  - **Understanding of backgrounds (need data with deradonator)**
  - **Understanding of limits of resolution (run with lower noise electronics)**
  - **HV and other "detector development" tests at the end of EXO-200 phase-2 running**

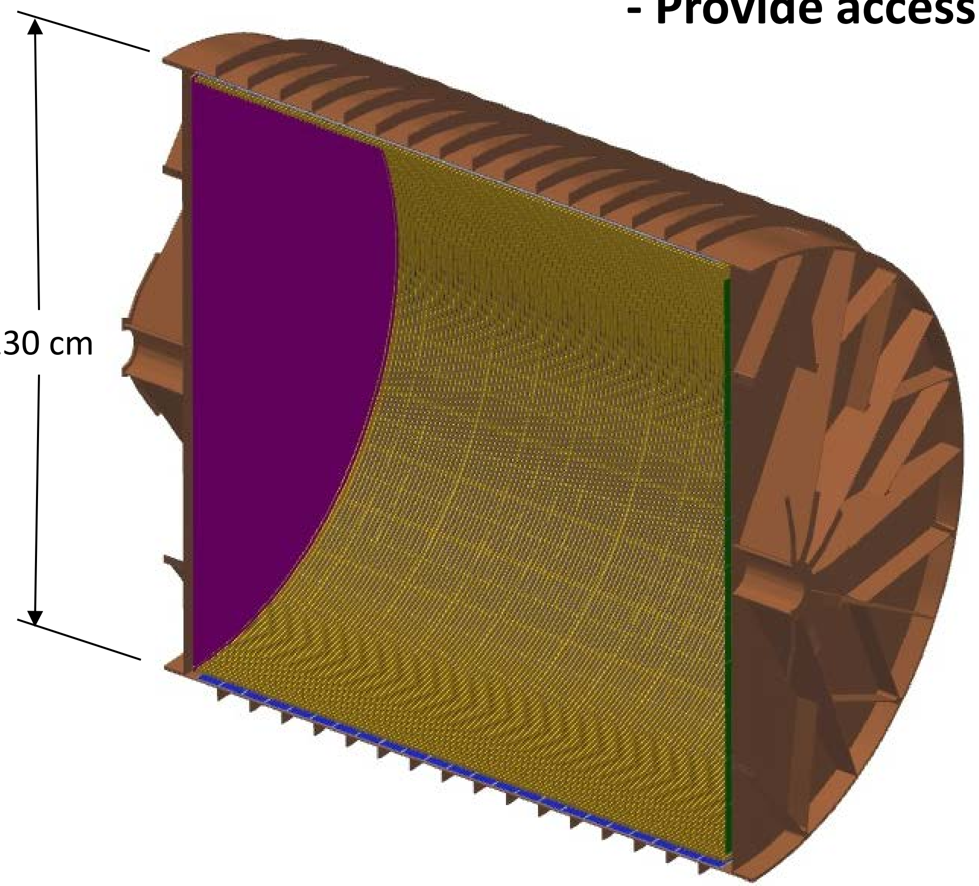
  ➔ See Liang's talk

nEXO

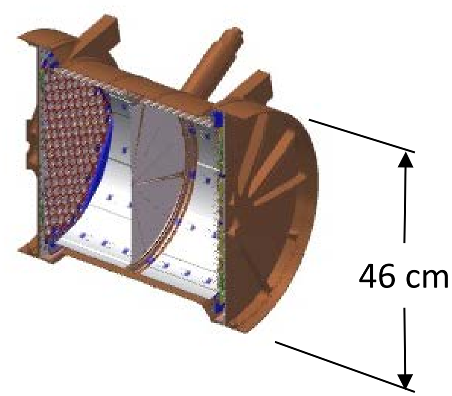
- 5 tonnes of ^{enr}Xe: entirely cover inverted hierarchy (more later)

- LXe TPC "as similar to EXO-200 as possible"

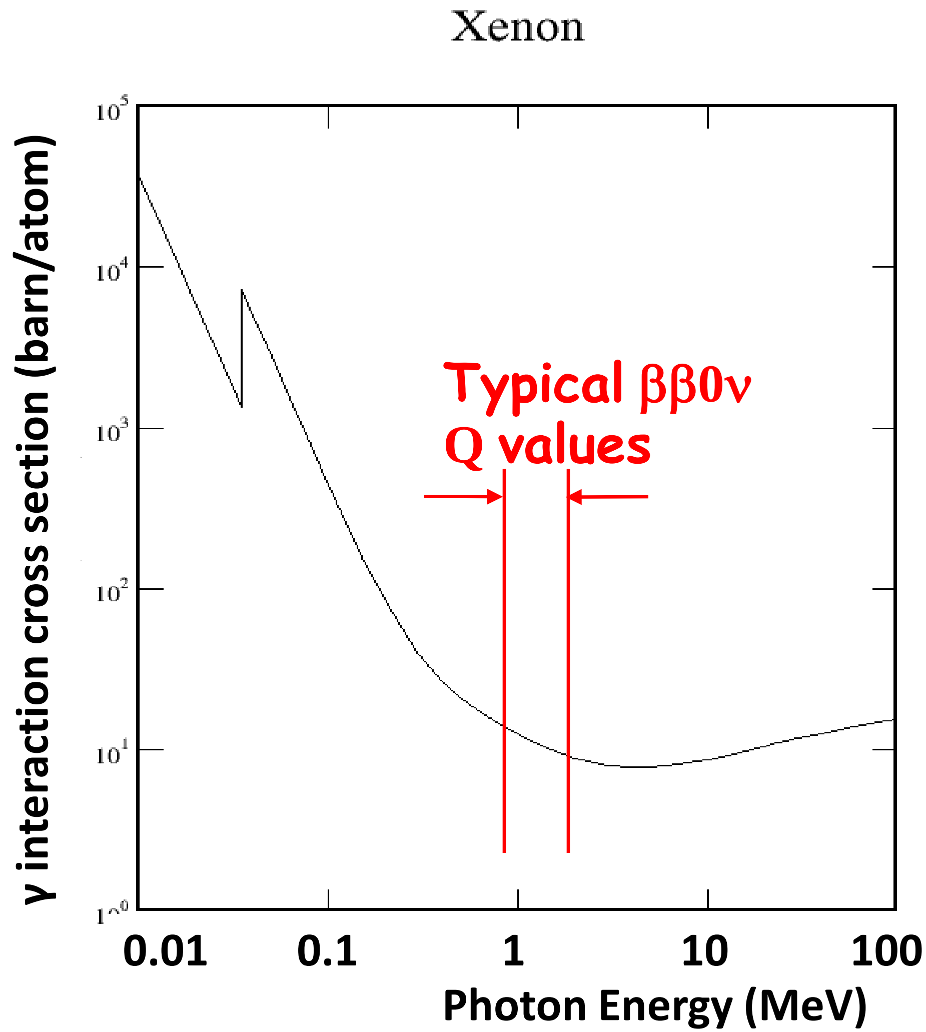
- Provide access ports for a possible later upgrade to Ba tagging



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



Photon attenuation length at a few MeV has a minimum



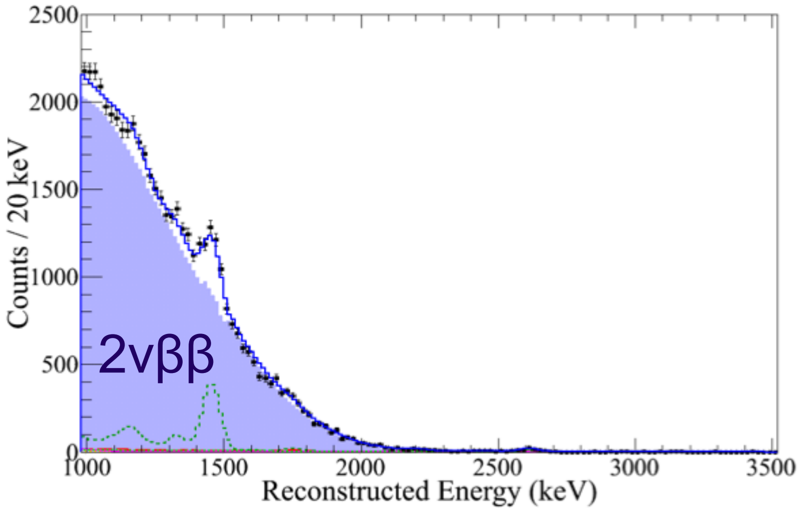
Imperative to build the detector intrinsically clean!!

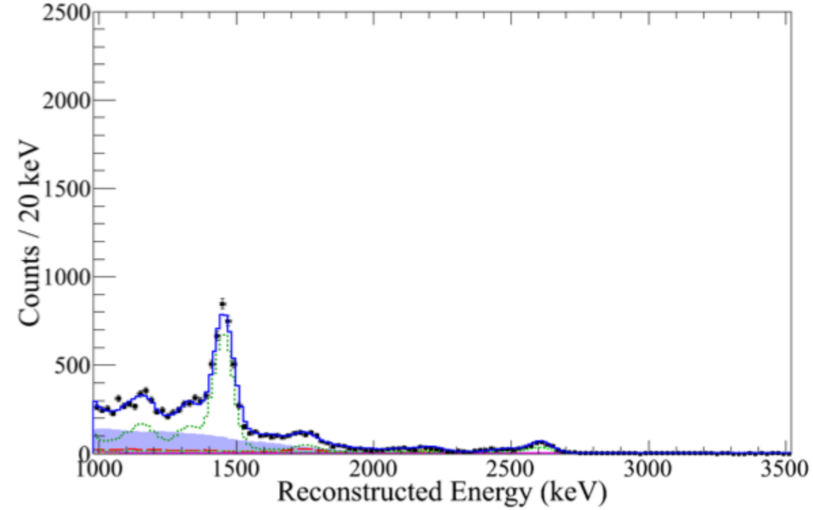
EXO-200 did this right and we need to do even better

Tracking:
an essential tool to identify and suppress backgrounds

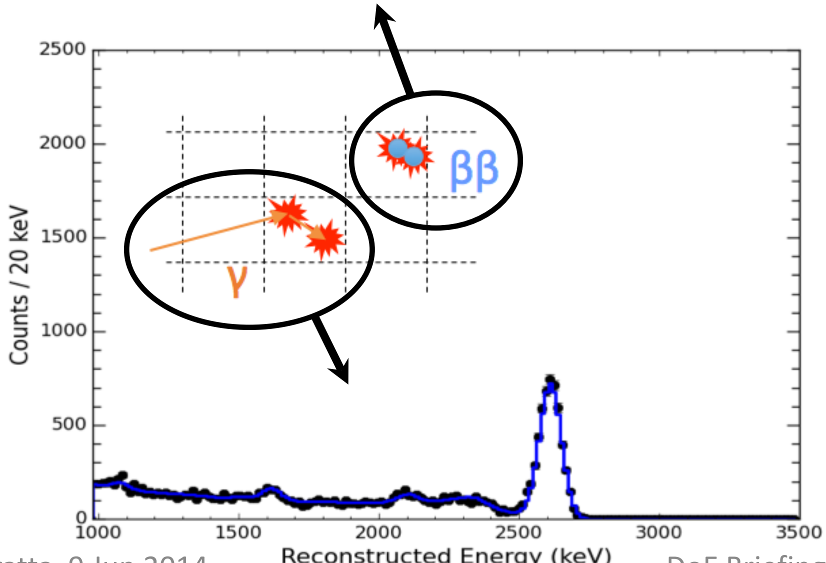
Single Site (SS) | Multiple Site (MS)

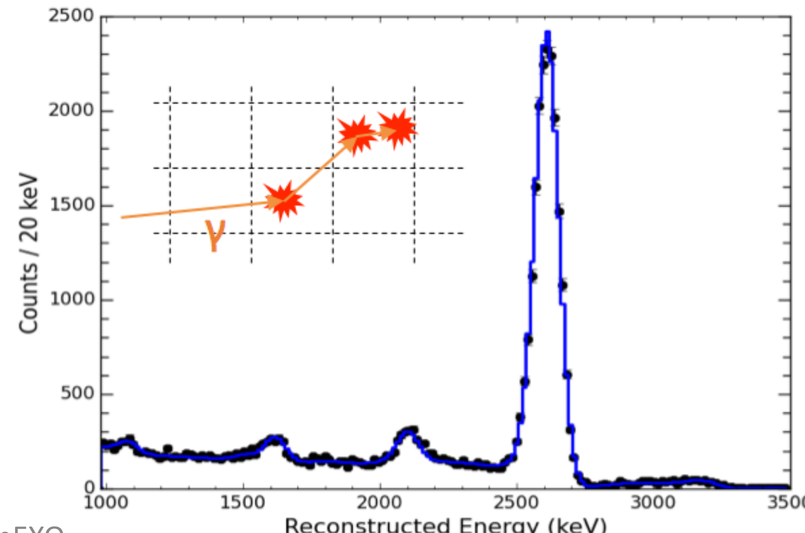
Low Background Data





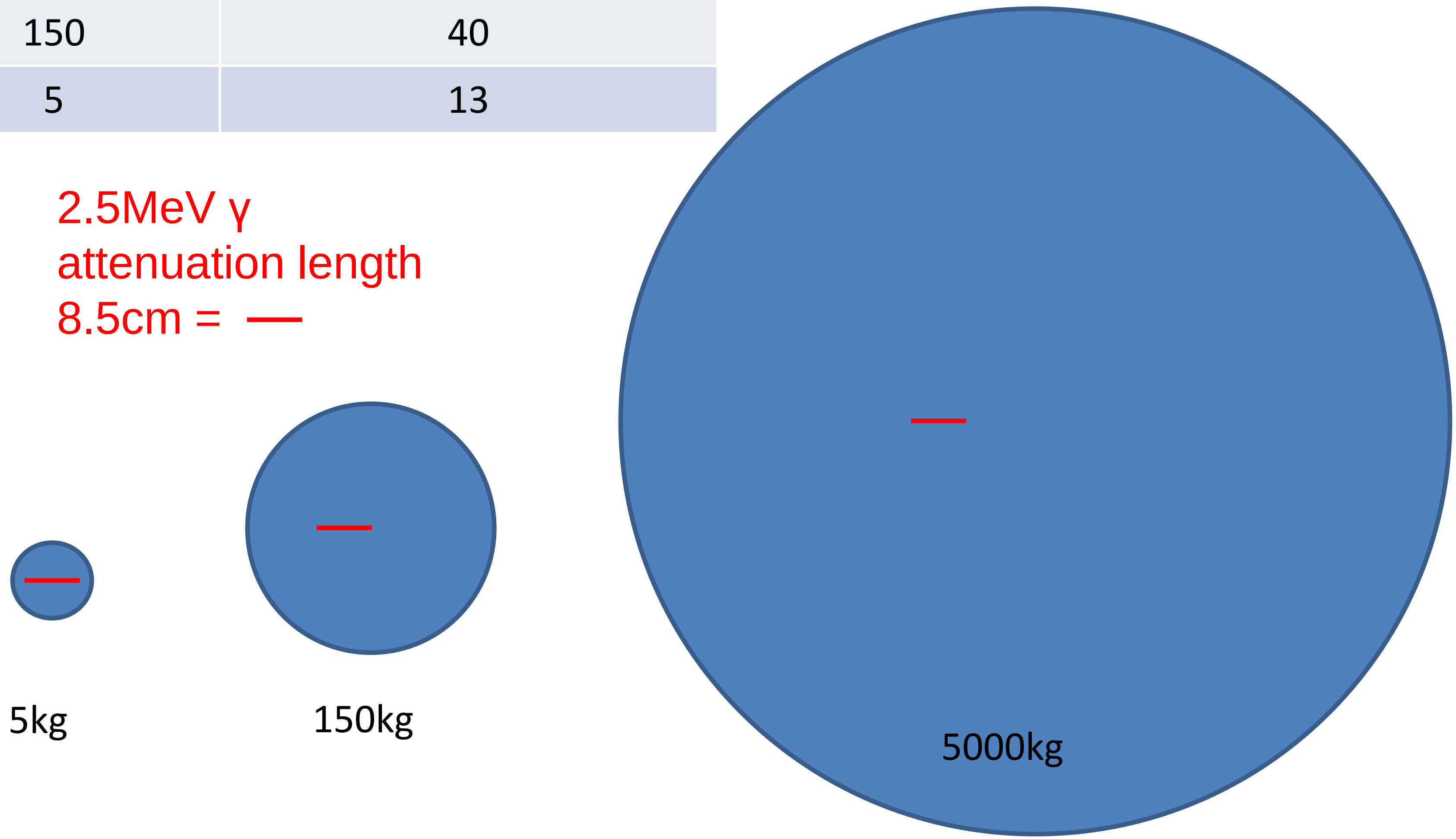
^{228}Th Calibration Source



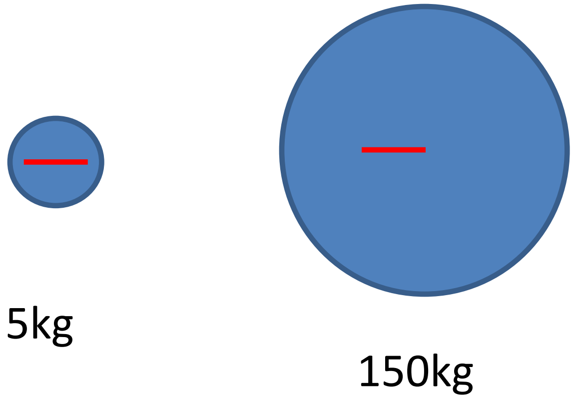


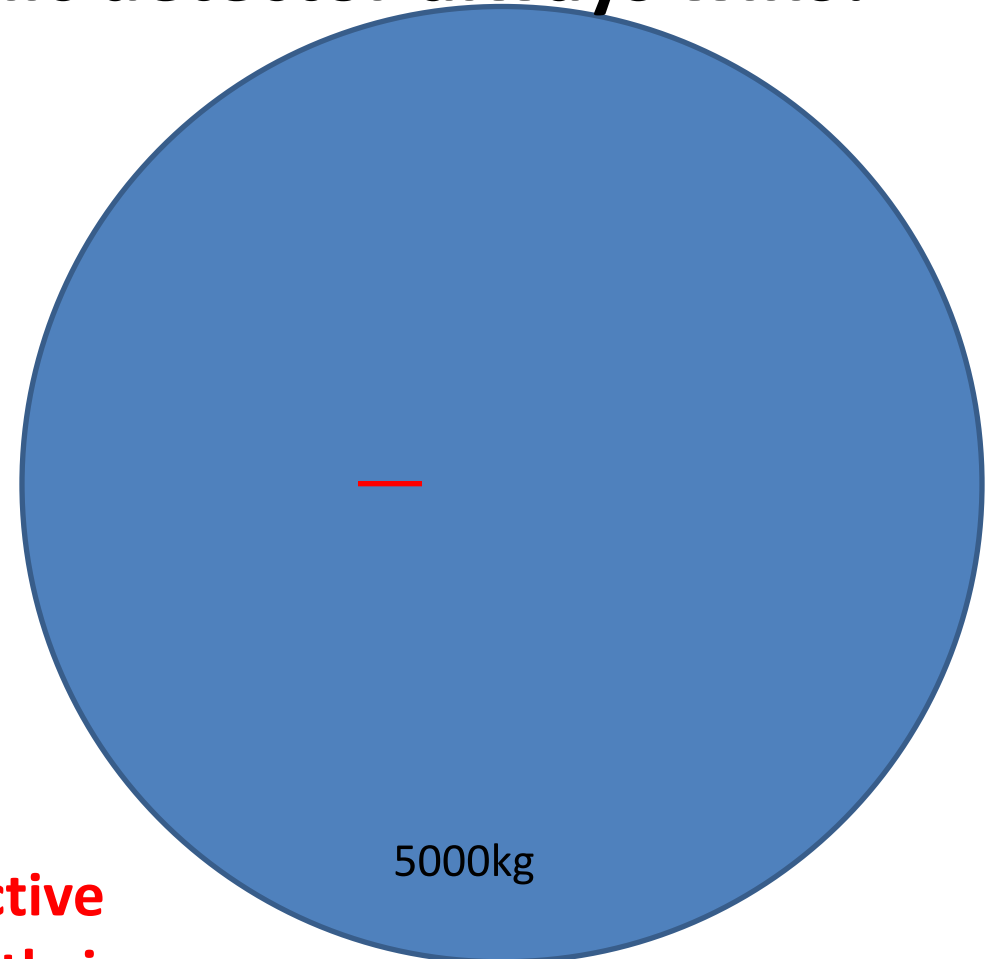
A larger, monolithic detector always wins!

LXe mass (kg)	Diameter or length (cm)
5000	130
150	40
5	13



A larger, monolithic detector always wins!





In fact, it wins twice:

1) **Self shielding becomes effective**
2) **Compton tag efficiency greatly improves**

Segmented detector for the most part can't take full advantage of these effects!

In the last year substantial progress in nEXO R&D, design and optimization:

- **Requires tight coordination between engineering, MC, radiation analysis, detector R&D**
- **Follow as closely as possible the design of EXO-200 since EXO-200 works so well**

  Only depart from this rules for good reasons:

1. ***A few things were not quite right in EXO-200***
2. ***Need to further reduce the background***
3. ***Some items don’t scale properly from 200kg to 5000kg***

   → ***Limited R&D required, low risk***

   (we know the principle works!)

There has also been substantial (but not yet conclusive) progress on the Ba tagging R&D front (NSF funded in the US)

This is essential because it is a revolutionary technique and may well be the only chance to access the normal hierarchy in the long run (<u>not just with nEXO</u>!).

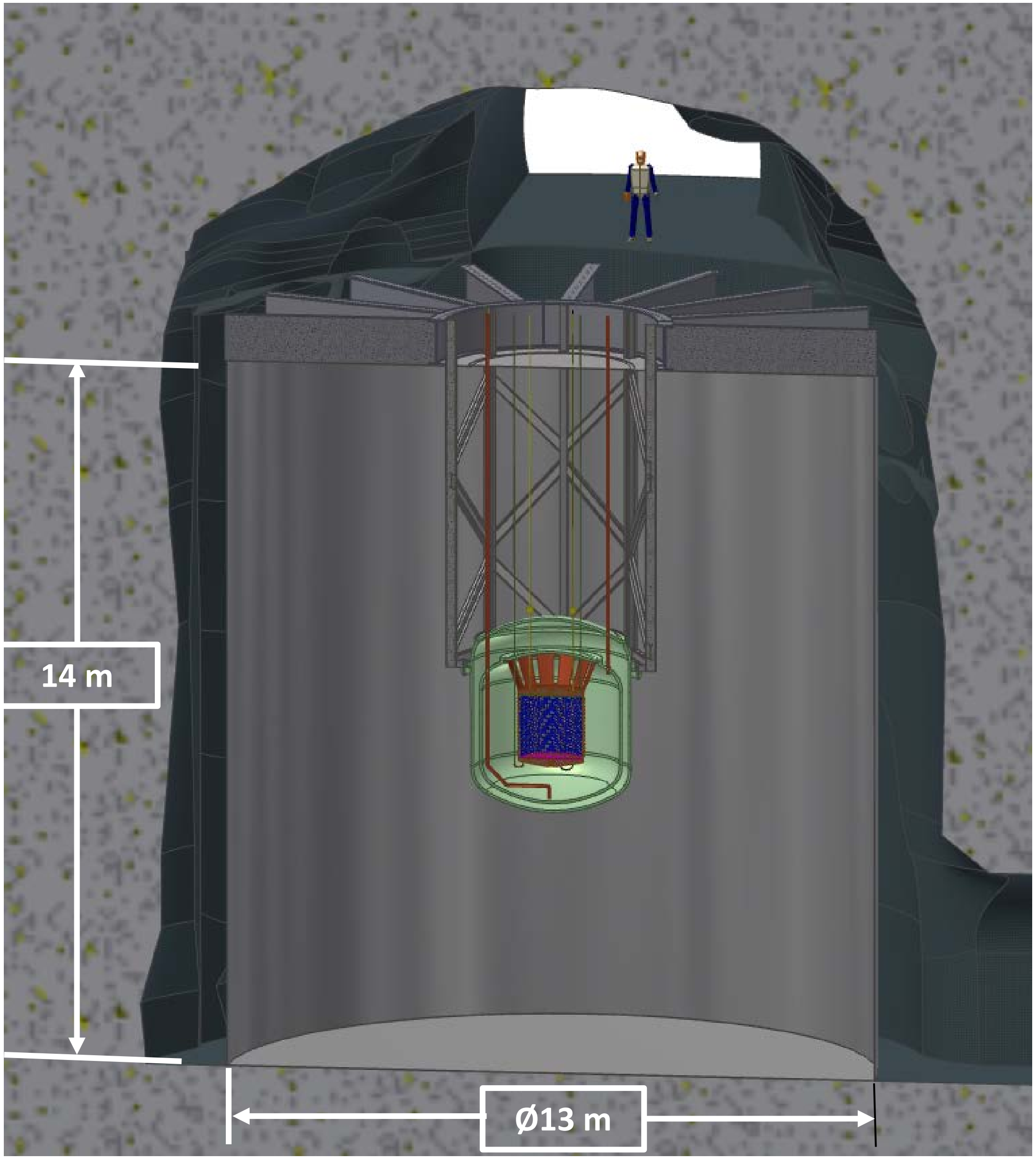
"The demands on background reduction are so stringent that modest scope demonstration projects for promising new approaches to background suppression or sensitivity enhancement should be pursued with high priority…"

From the McKeown report, p 4

Will briefly discuss this R&D today but:

Ba tagging is NOT required to reach the sensitivity to entirely cover the inverted hierarchy with nEXO!!

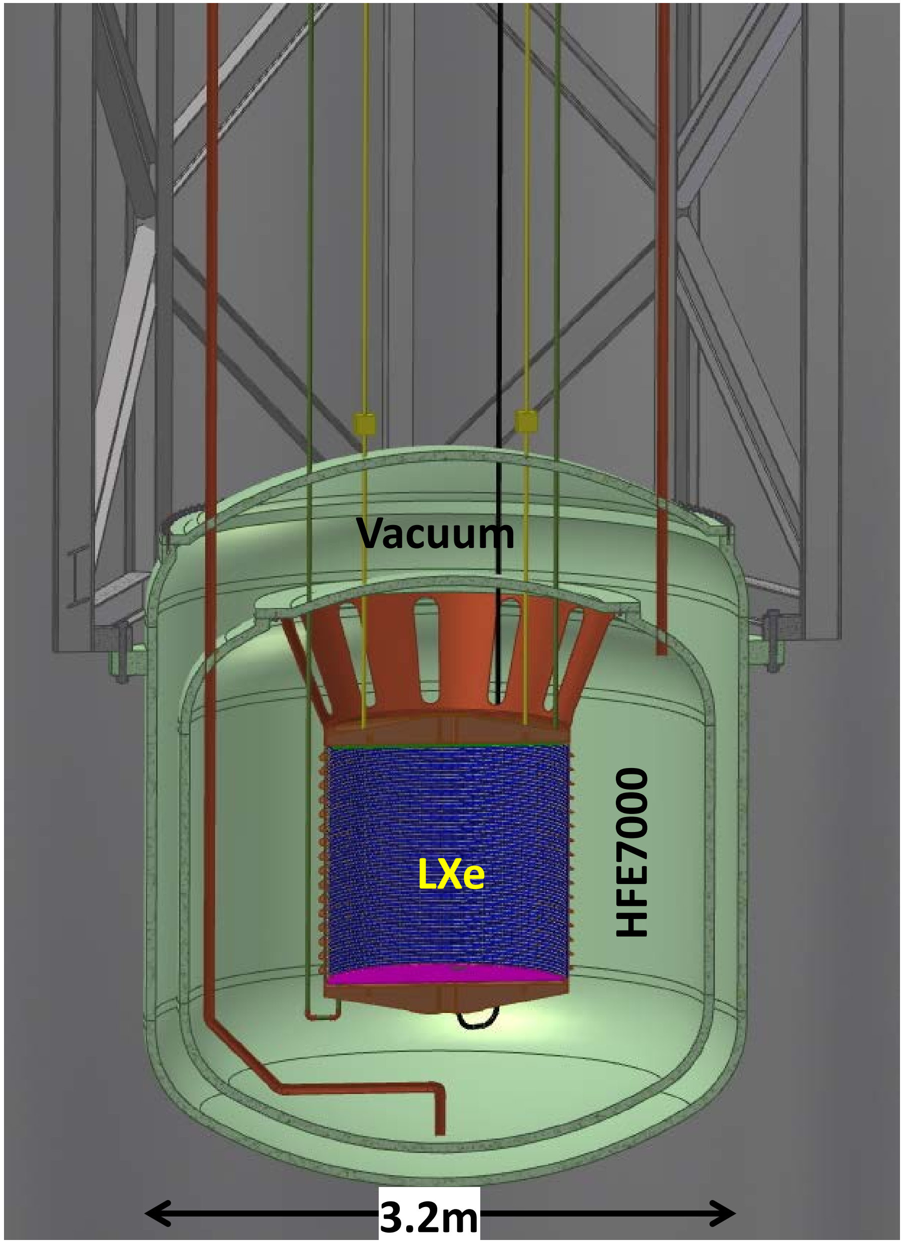
Conceptual sketch of nEXO in the SNOlab Cryopit



Decisions/detector baseline

- Instrumented water shield
  - better hermeticity
  - Easier to assemble at a deep site
  - n moderation
  - Hermetic Rn barrier
- Everything coaxial and vertical axis (obvious if space is available)
- Cryostat hanging from deck or water tank rim (seismic design)

Low background cryostat is challenging, particularly underground



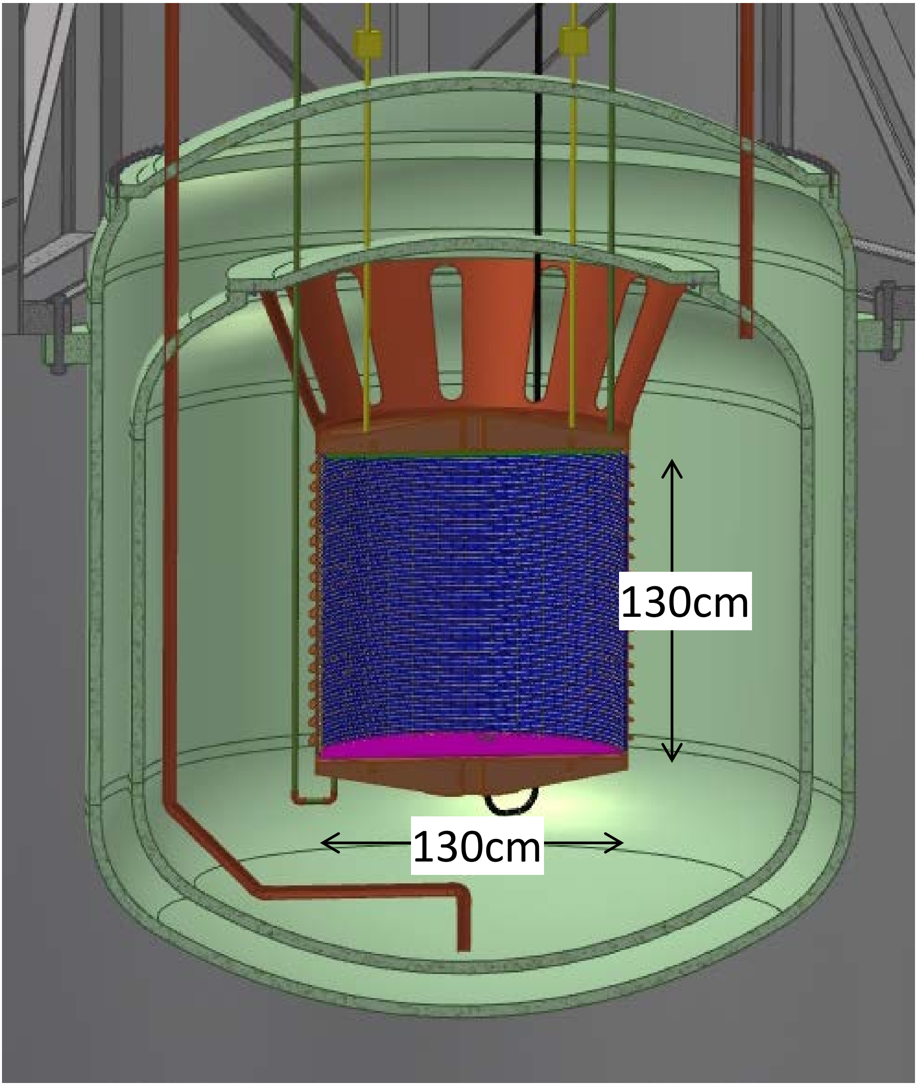
Copper construction (EXO-200) requires very substantial wall thickness to hold pressure and hydrostatic load from HFE (for the larger nEXO case this is >30 tonnes of copper).

Also requires ultra-clean welding in the underground (EXO-200 was e-beam welded in a conventional/surface shop)

Copper is the fallback solution, but we are carefully exploring the innovative solution of a graphite-composite cryostat:

- Easier to build in a clean room underground from small components
- Potentially ultra-low background if materials are carefully selected; initial measurements appear to confirm this hunch
- Possibly this will open new opportunities for other experiments in the field

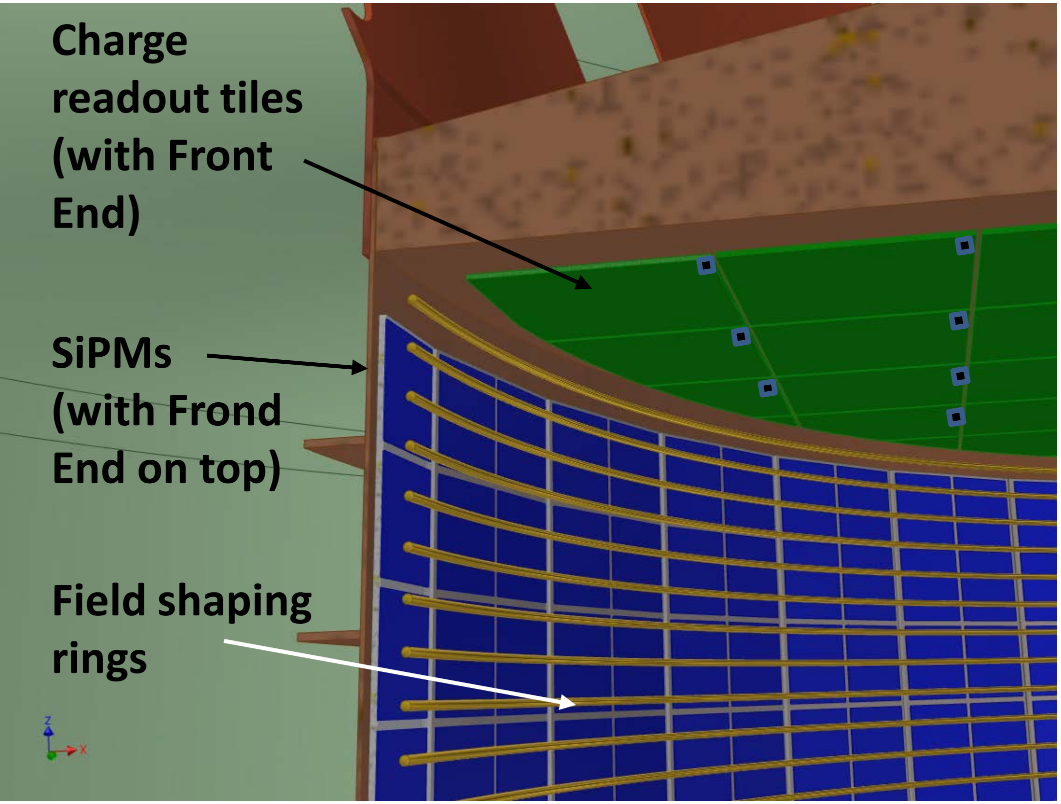
TPC vessel is larger (than EXO-200) but still copper



- **Here background requirements even more extreme**
- **Need to worry about UHV-equivalent properties**
- **Need to worry about LXe contamination**
- **Smaller and very substantially lighter than the cryostat**

→ Conservative choice is clearly copper
→ Working on even lower background copper than in EXO-200

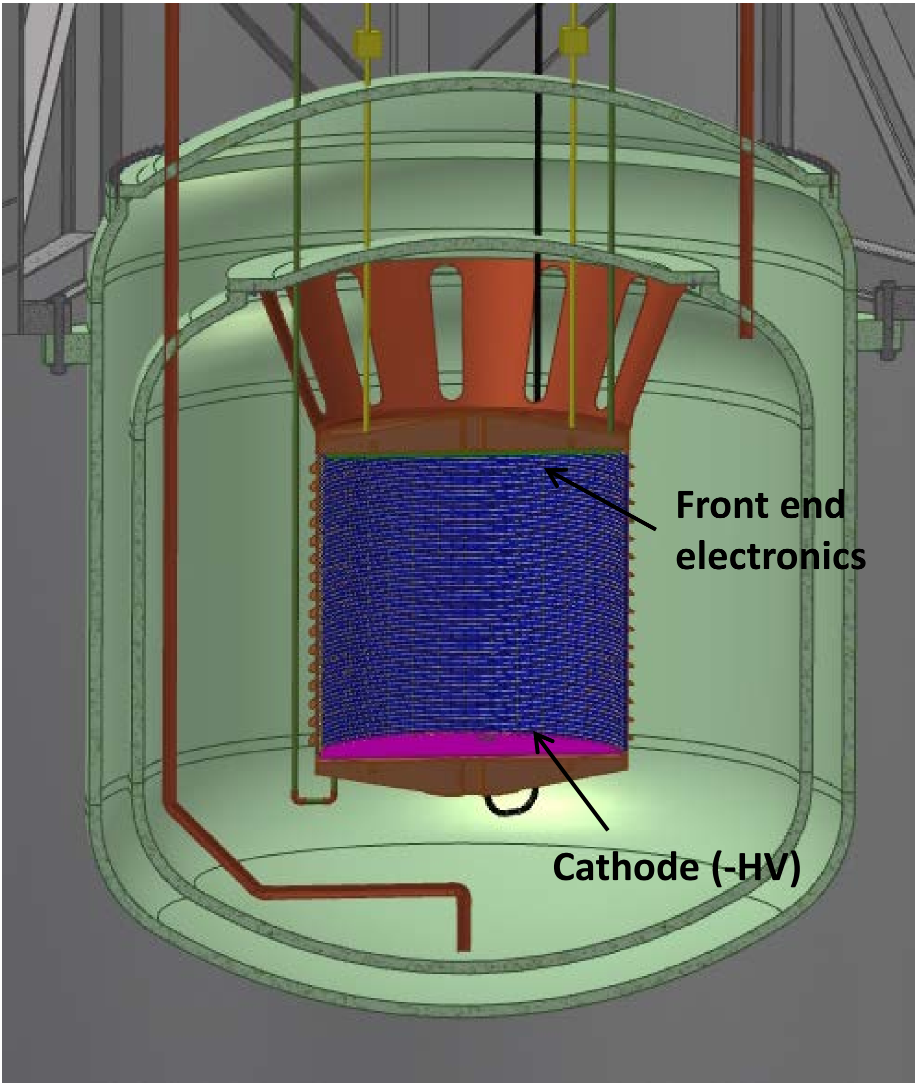
TPC configuration optimized for larger size, light collection and better photodetectors



- EXO-200 performance dominated by electronics noise. Some of this is due to non-optimal execution but internal electronics is always expected to be better in terms of noise performance
- Performance optimization requires x3 wire density
- With larger size this means 9x charge channel count + ~3m^2 of photodetectors
- Thin cables in EXO-200 were a major concern (reliability, background)

→ SiPM are more common, have higher gain, lower bias and are lighter (lower activity?)
→ Charge readout tiles provide an attractive, robust and modular alternative to strung wires
→ Custom, in-LXe frond-end/multiplexers should be a good match to tiles and SiPMs, while potentially providing lower noise, (much) fewer cables, lower activity.

TPC configured with only one drift space



- The merits of the homogeneous detector are better exploited with nothing in the middle of the TPC, where the Xe is the cleanest
- Internal electronics produces heat (capped at ~200W) that injected at the bottom of the TPC would cause substantial convection.
  ➔ readout has to be at top only.

➔ Consequences for the R&D:

- At 400V/cm (the EXO-200 field) need to hold 50kV. This is in principle not a problem except we still do not understand the EXO-200 problem.
- To get to 1% energy resolution the electron lifetime needs to be at least ~10ms. This should be relatively easy since it's generally >3ms in EXO-200 with lots of plastics. nEXO will have much less plastics and better purification.

New cryogenics and fluids handling systems

- **Cryogenics and fluids handling system will have larger capacity than EXO-200**
- **Challenging larger Xe recirculation pump being commissioned (this is unique to EXO-200/nEXO)**
- **Unlike EXO-200, nEXO will be designed with thermo-fluid/process modeling**
- **Will have pre-cleaned Xe reservoirs for feeds (more consistent purity)**

Ba-tagging R&D: lots of interesting topics,

→ *not enough time to cover all this here*

Testing several techniques

(some have been already culled)

- **Spectroscopically ID the Ba atom while on the end of an optical fiber in LXe**
- **Remove Ba atom to vacuum on a substrate, desorb and resonantly re-ionize. Count or even ID spectroscopically in a trap**
- **Eject and spectroscopically ID in a trap from a GXe TPC**

Ba-tagging R&D: lots of interesting topics,
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Testing several techniques
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- Spectroscopically ID the Ba atom while on the end of an optical fiber in LXe
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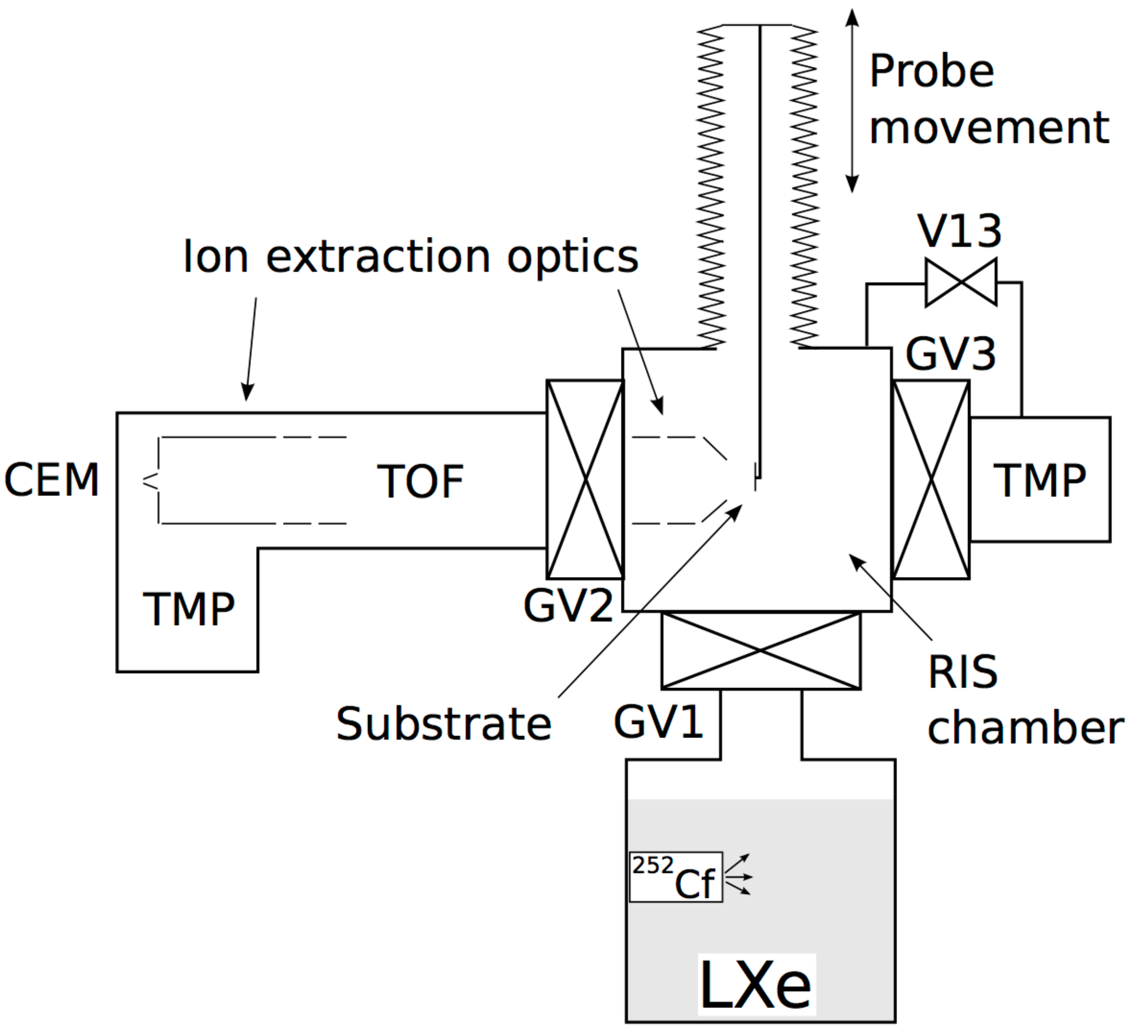
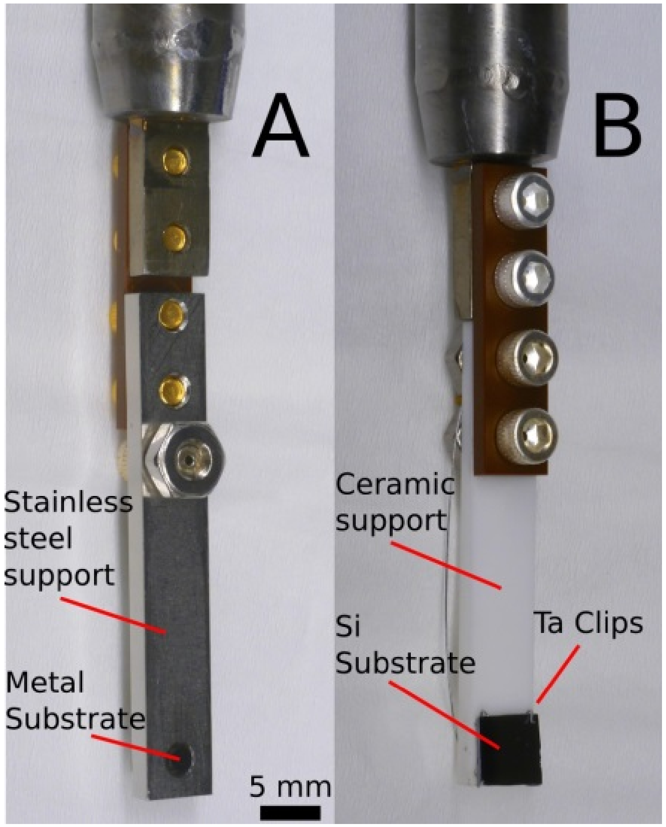
- Eject and spectroscopically ID in a trap from a GXe TPC

“realistic” system can generate Ba ions in LXe (or in vacuum), get them on a substrate, remove the substrate to vacuum and, by means of an IR and two resonantly tuned laser pulses, desorb and re-ionize the Ba.
Ions are then sucked in a TOF spectrometer.

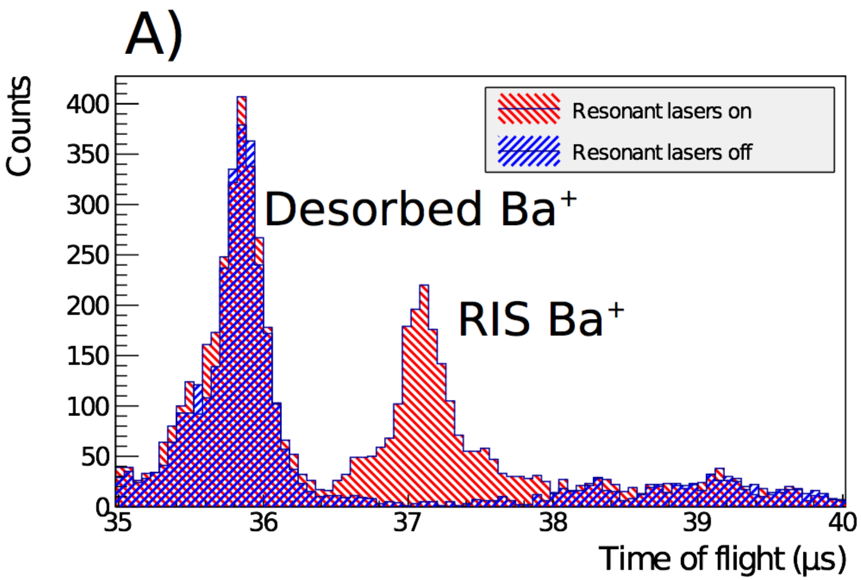
Instrumentation paper in preparation

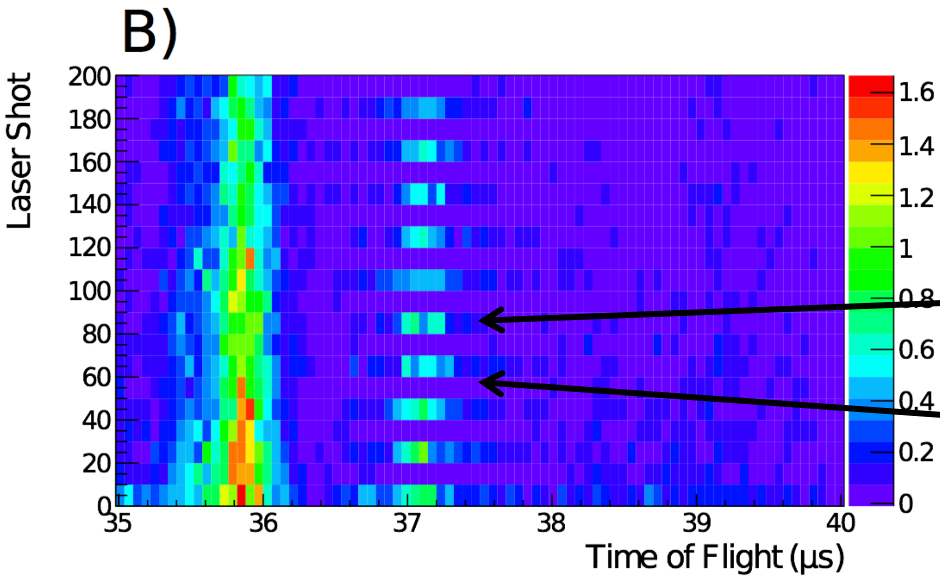




Substrate examples

Early qualitative results (loading from vacuum)

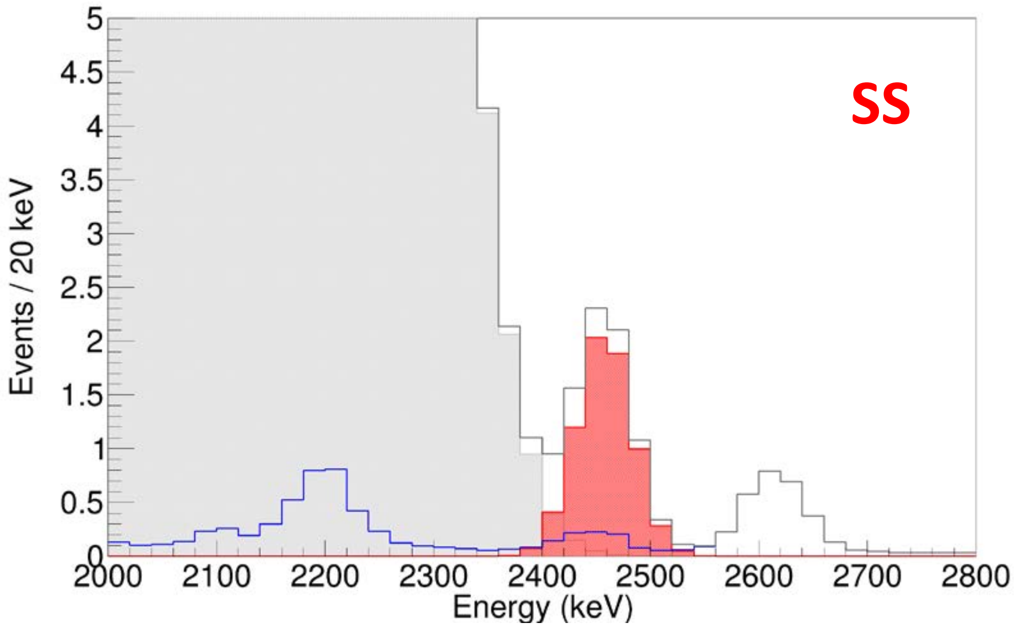




- Quantitative measurements in progress. This is quite tricky at few atoms level because the detection kills the signal (by definition)
- Lots of surface science to understand in order to optimize the detection efficiency

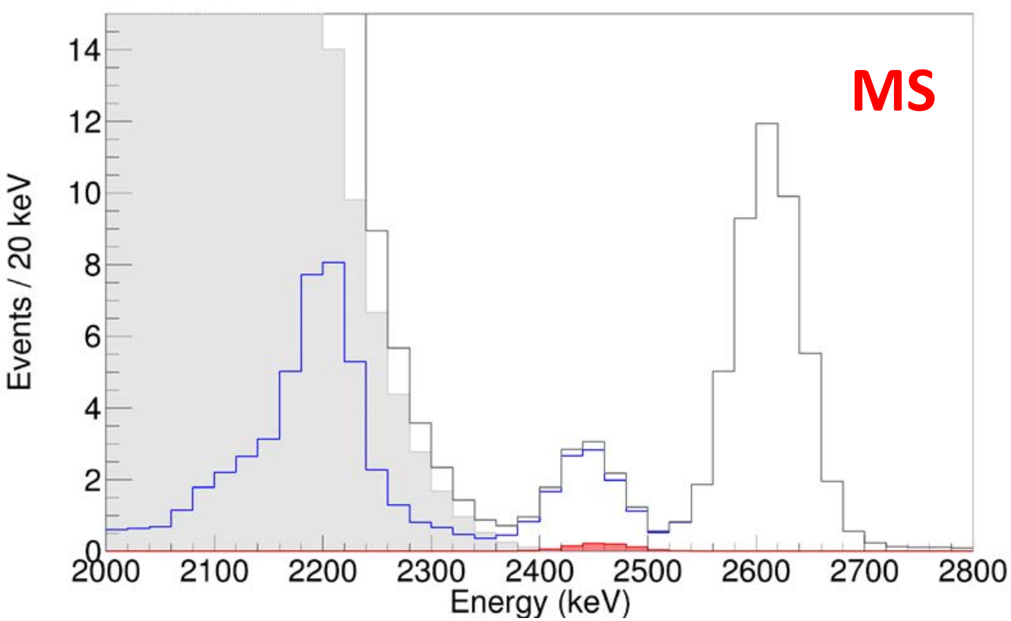
All lasers on

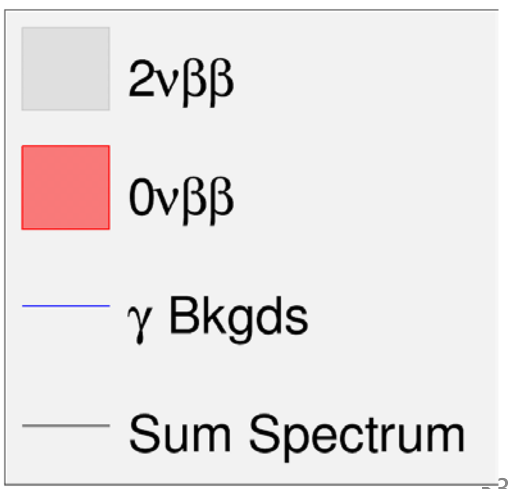
RIS lasers off

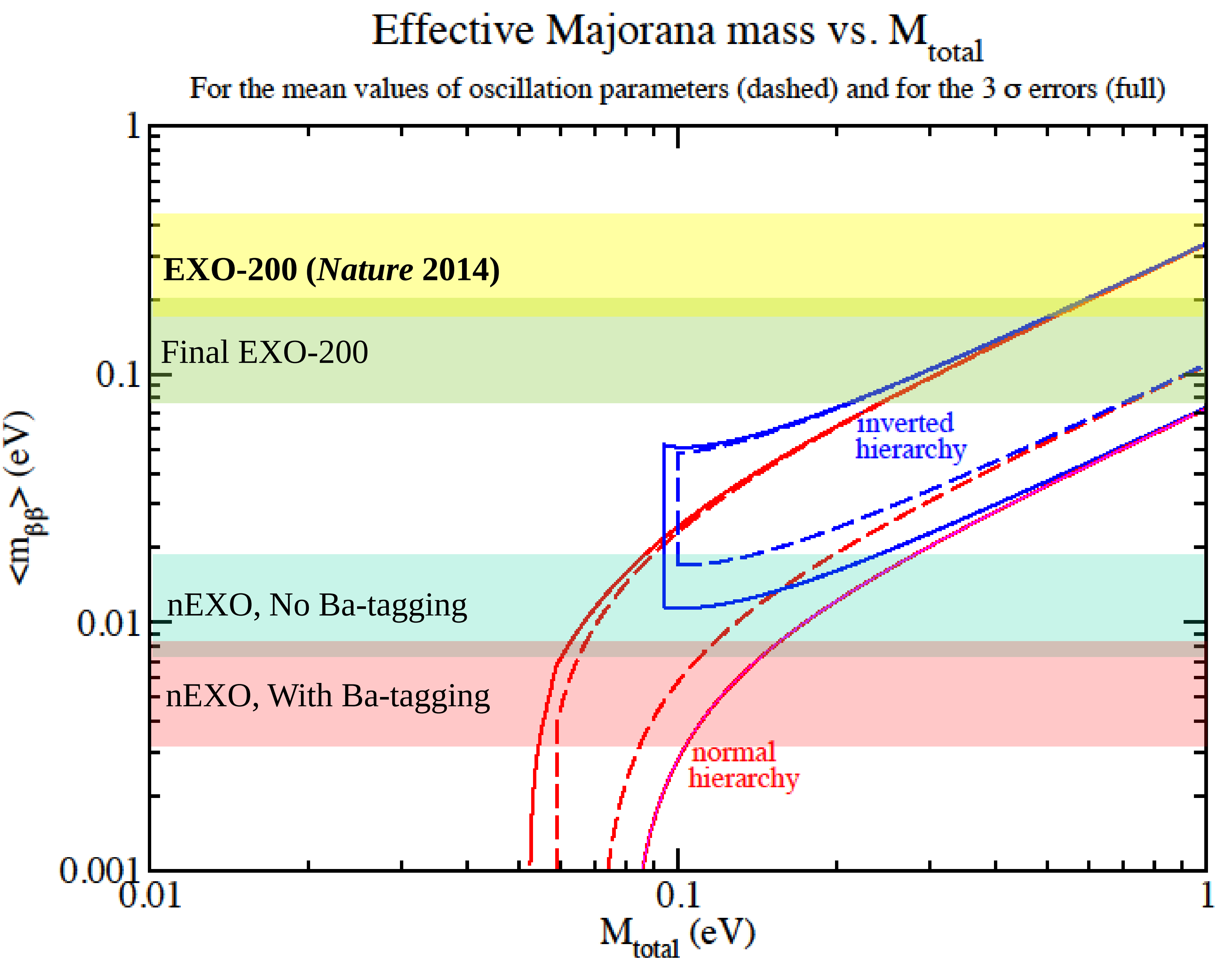


nEXO energy spectrum at the threshold of discovery: $T_{1/2}(\beta\beta)=1.8\cdot10^{27}$ yr (5yr data, *central 1 tonne*)

Note that the MS spectrum is used to ~independently measure the background







Effective Majorana mass vs. M_{total}
For the mean values of oscillation parameters (dashed) and for the 3 σ errors (full)
EXO-200 (*Nature* 2014)
Final EXO-200
nEXO, No Ba-tagging
nEXO, With Ba-tagging
inverted hierarchy
normal hierarchy
$\langle m_{\beta\beta} \rangle$ (eV)
M_{total} (eV)
1
0.1
0.01
0.001
0.01
0.1
1