The EXO Search for Neutrinoless Double Beta Decay

Kevin Graham - Carleton University

for the EXO Collaboration

DBD14 Workshop Hawaii October 7, 2014

The EXO-200 Collaboration

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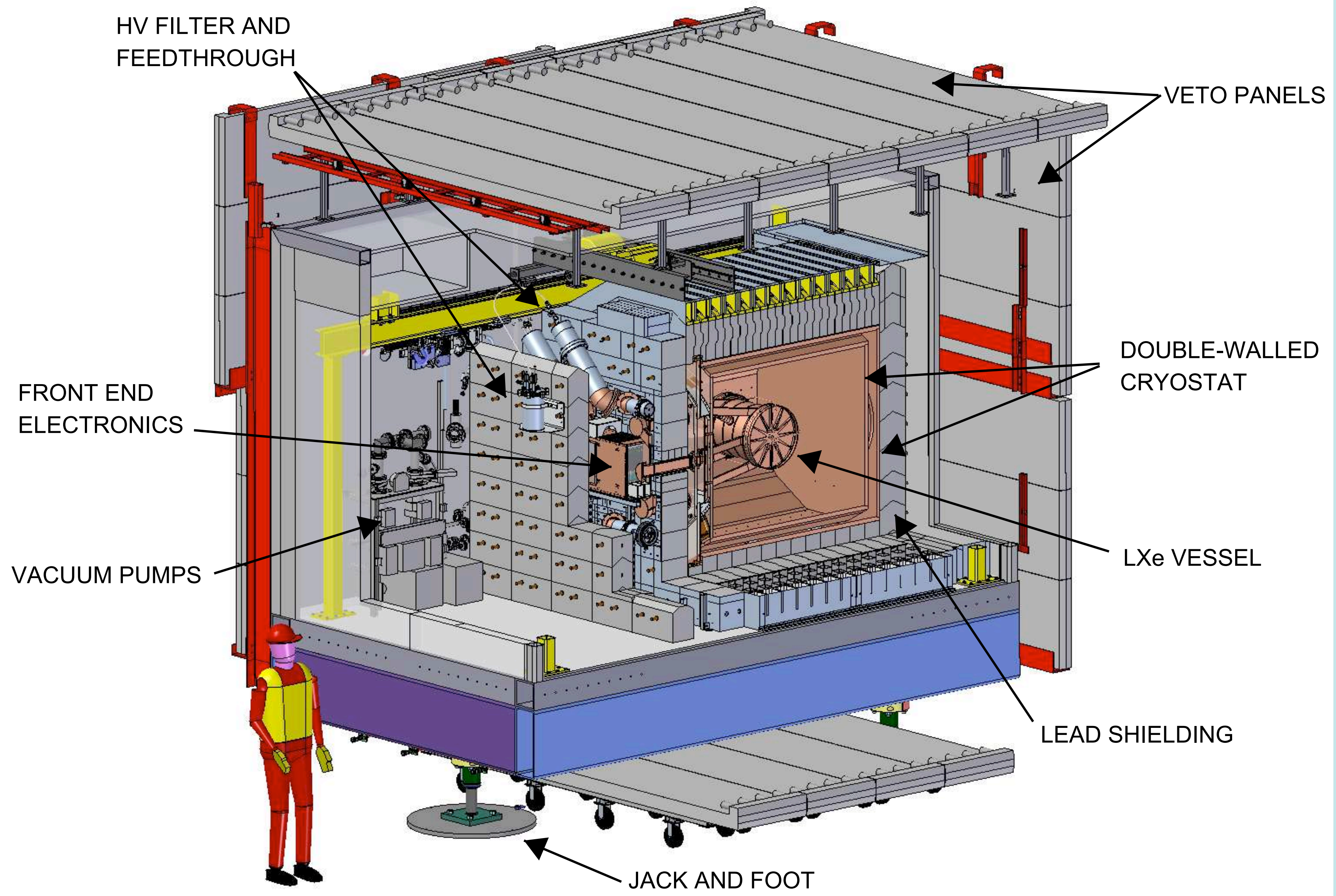
TRIUMF, Vancouver BC, Canada – J. Dilling, R. Krucken, F. Retière, V. Strickland

EXO Program

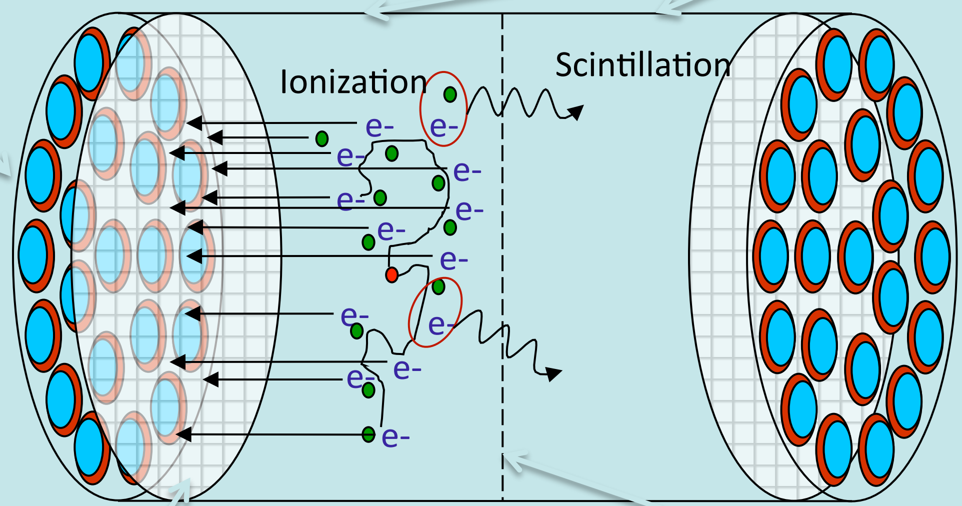
- EXO-200
  - what's happening at WIPP
  - upgrade electronics and install de-radonator
  - continue physics for ~2 years
  - update $0\nu\beta\beta$ analysis and complete other physics searches
- nEXO
  - developing next generation 5-tonne detector
  - liquid-phase with improved detector response
  - sensitivity to inverted hierarchy
- Barium tagging
  - continuing to pursue both gas and liquid phase options
  - laser spectroscopic tag suitable for either case

EXO-200 at WIPP

EXO-200 Detector

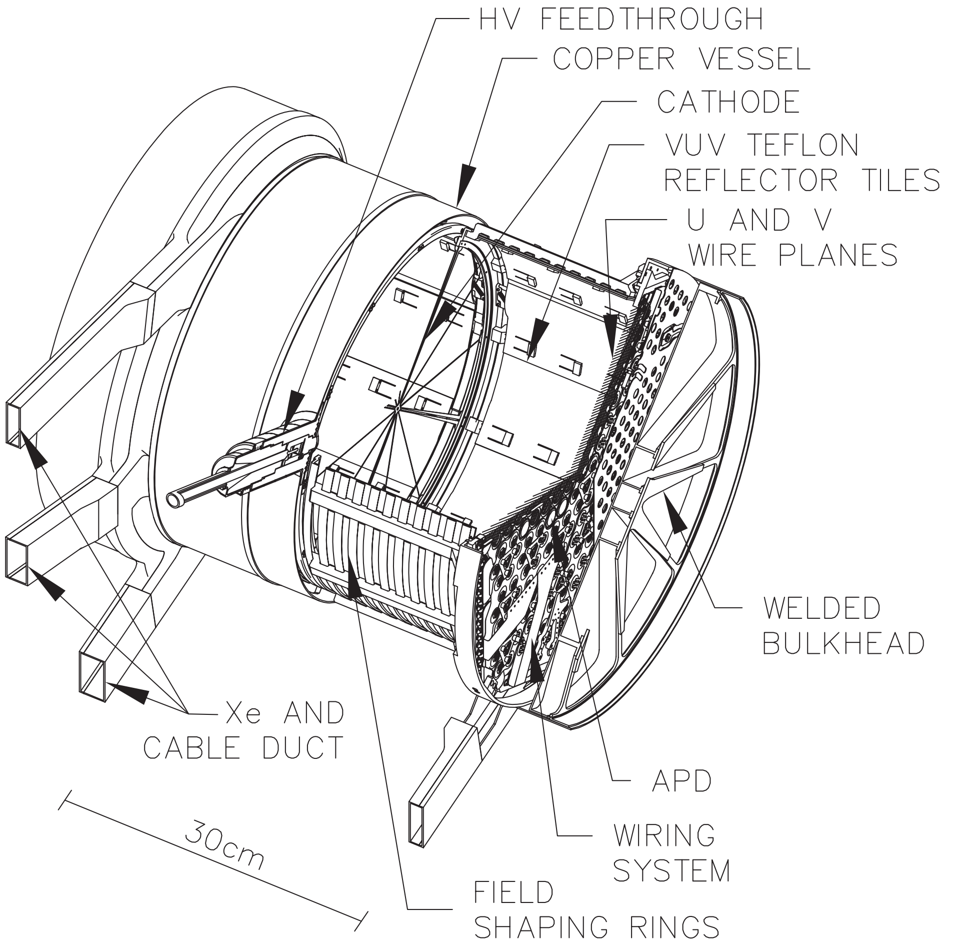


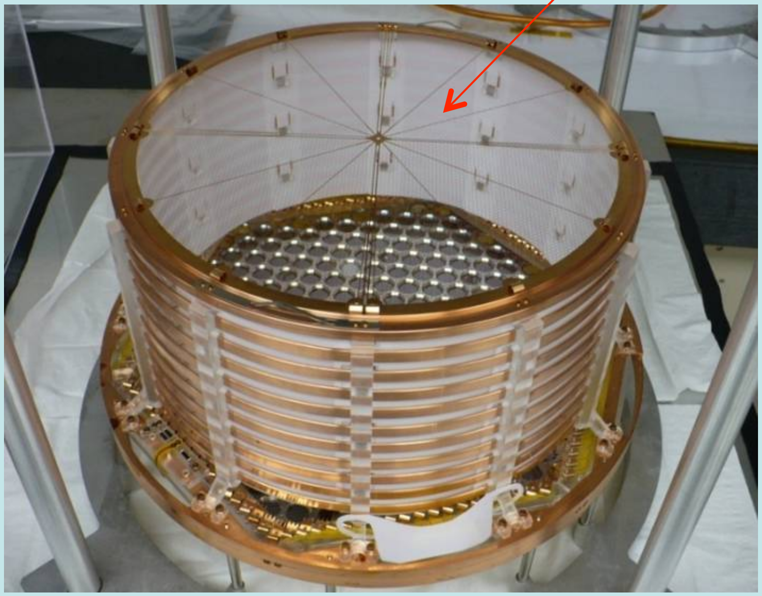
EXO200: Liquid Xenon (~200 kg) Time Projection Chamber

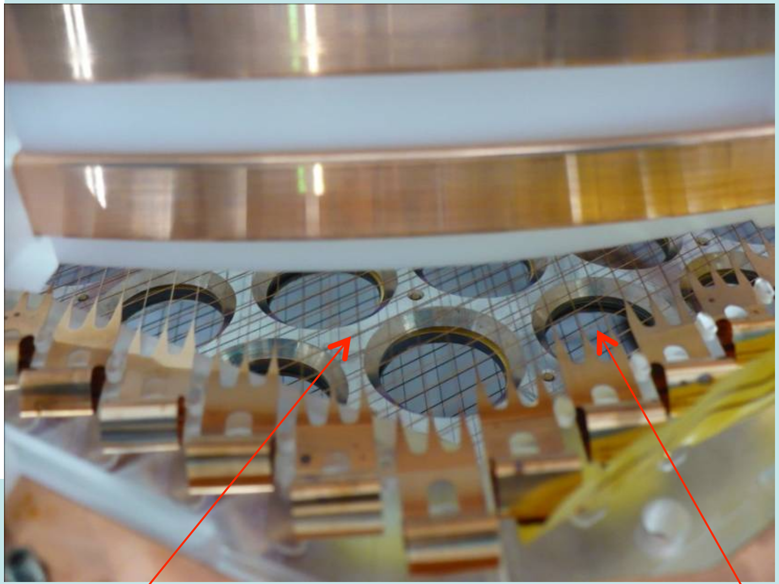


- Measure both ionization (wires) and scintillation (APDs)
- Event energy from the combination of ionization and scintillation
- reject some gamma backgrounds because Compton scattering results in multiple energy deposits

Detector Construction





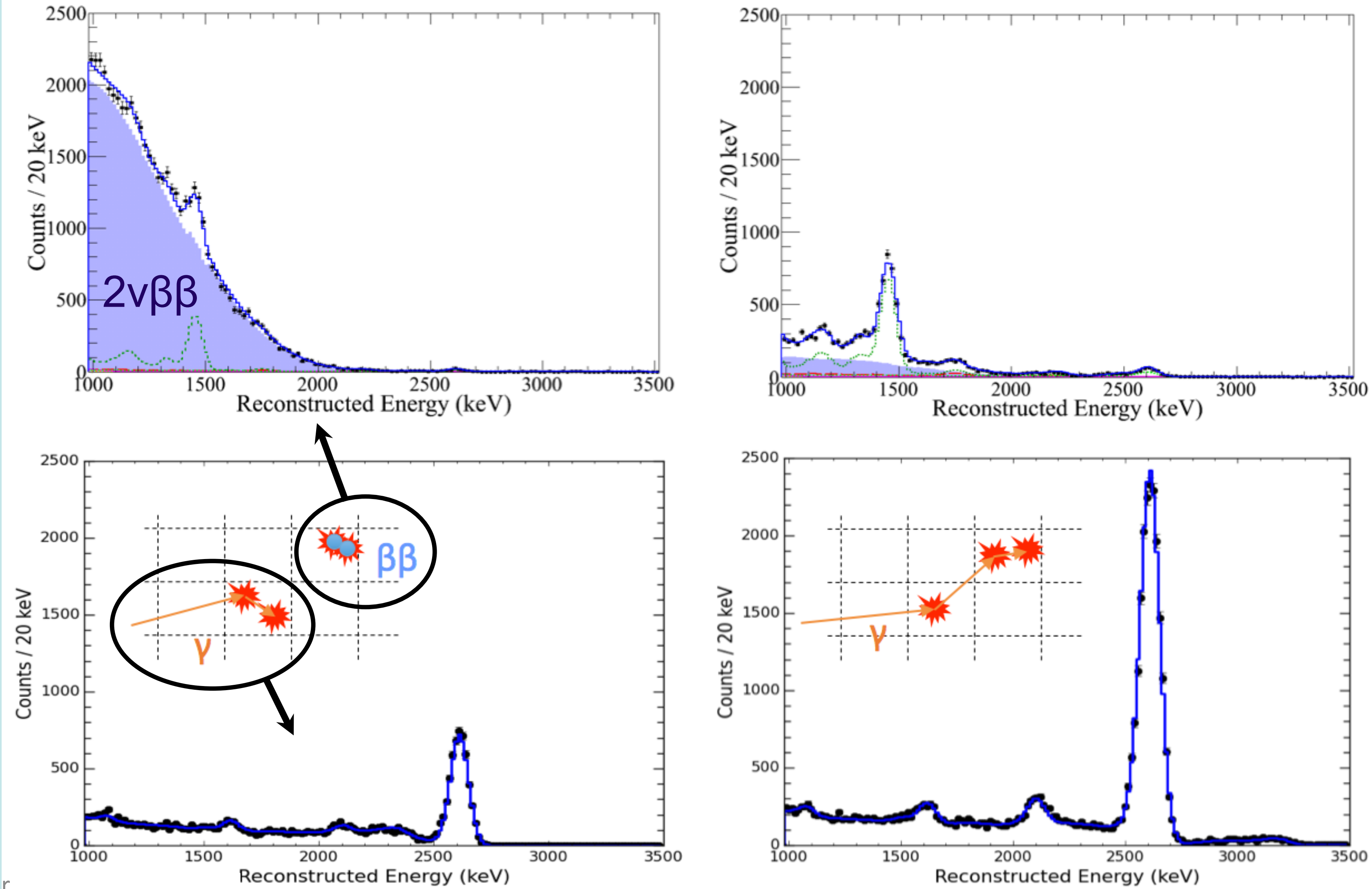


Background Rejection

Single Site (SS) | Multiple Site (MS)

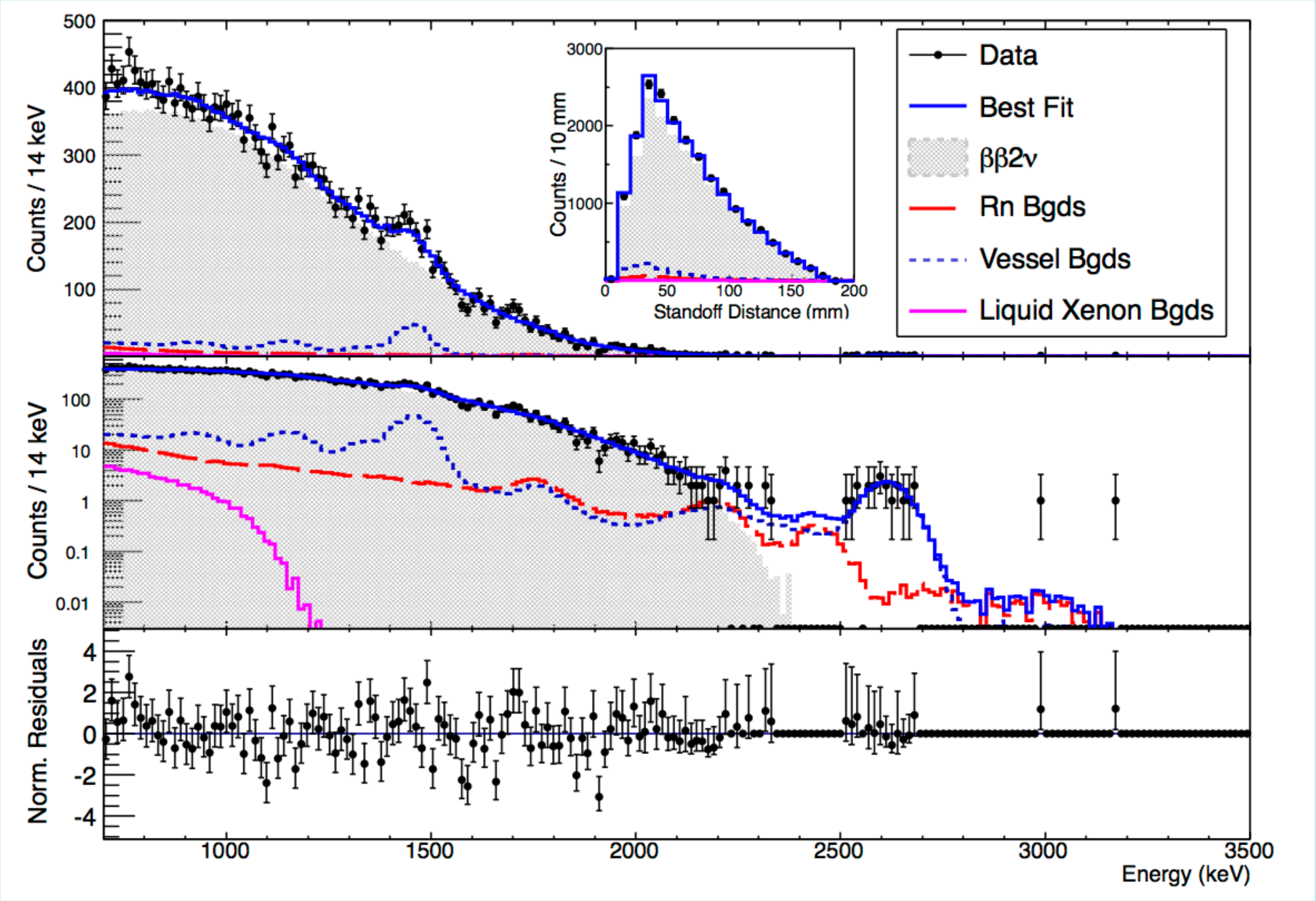
Low Background Data

^{228}Th Calibration Source



2νββ Update Paper

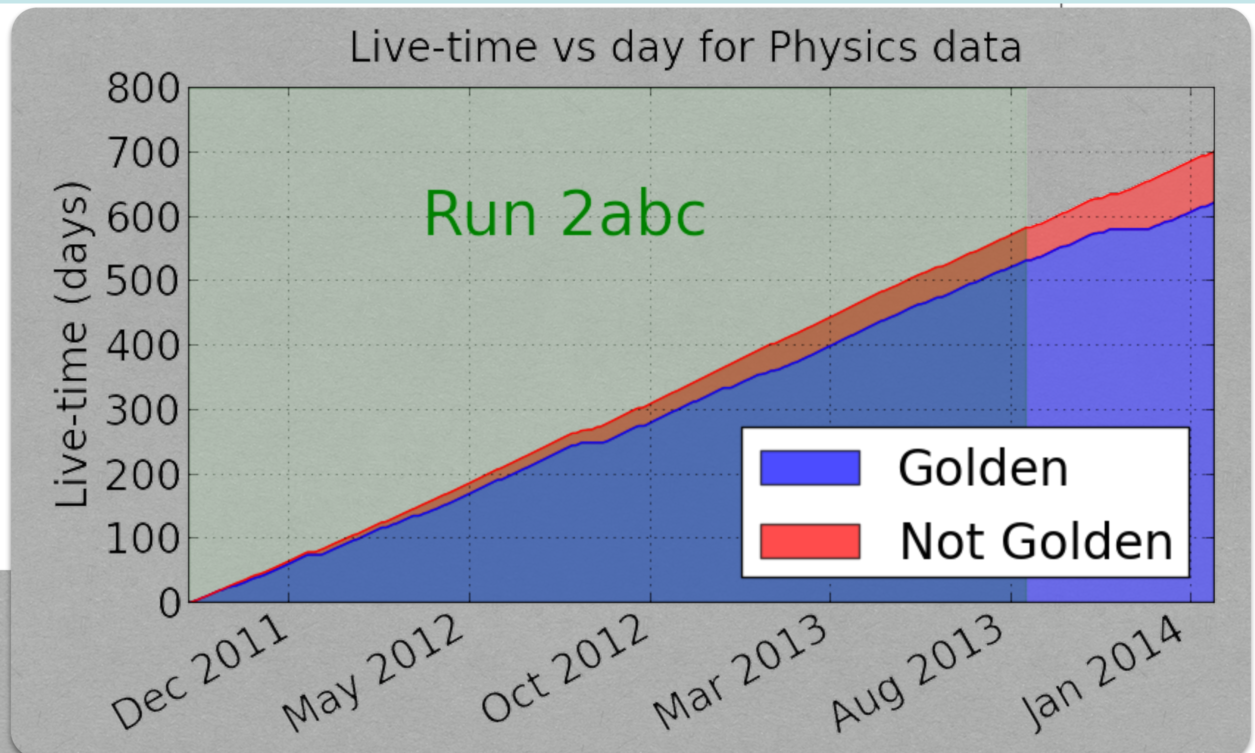
2νββ $T_{1/2} = (2.165 \pm 0.016\ \text{stat} \pm 0.059\ \text{sys}) \times 10^{21}$ yr

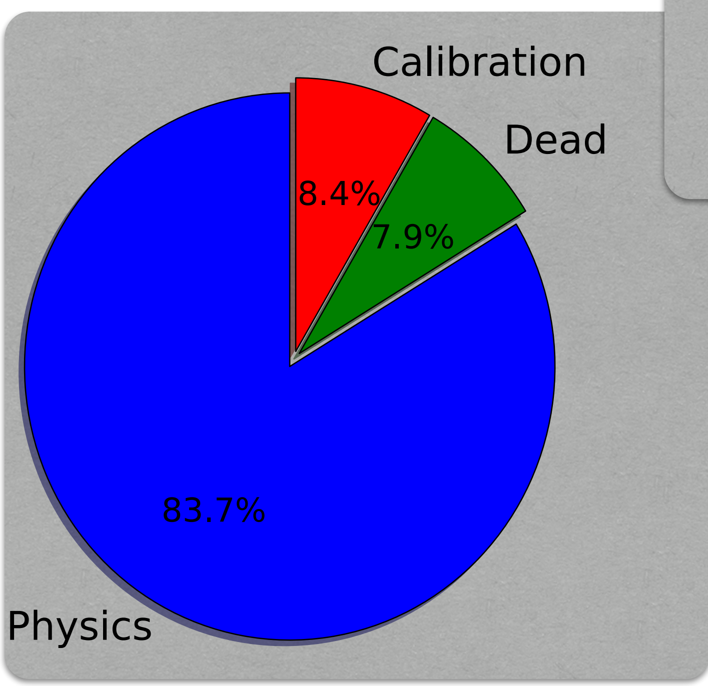


Updated 0νββ Dataset

nature

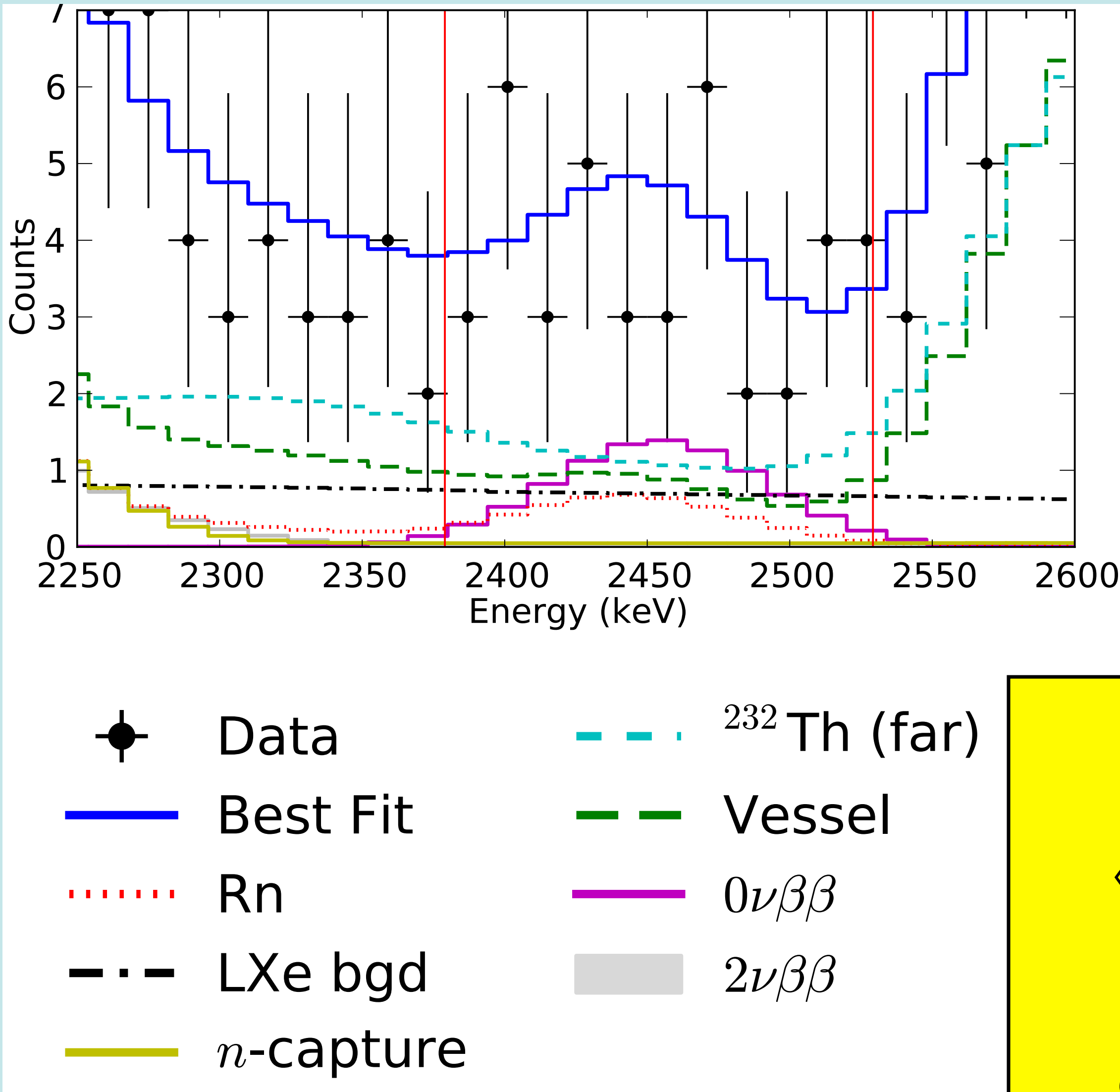
(12 June 2014, online 4 June)
doi:10.1038/nature13432





Accumulation of "Golden" data
447.60 ± 0.01 days livetime
(100 kg·yr, 736 mol·yr ^{136}Xe exposure)
(6 Oct 2011- 1 Sep 2013)

0νββ Search Update



Backgrounds in ± 2σ ROI	
Th-228 chain	16.0
U-232 chain	8.1
Xe-137	7.0
Total	**31.1 ± 3.8**

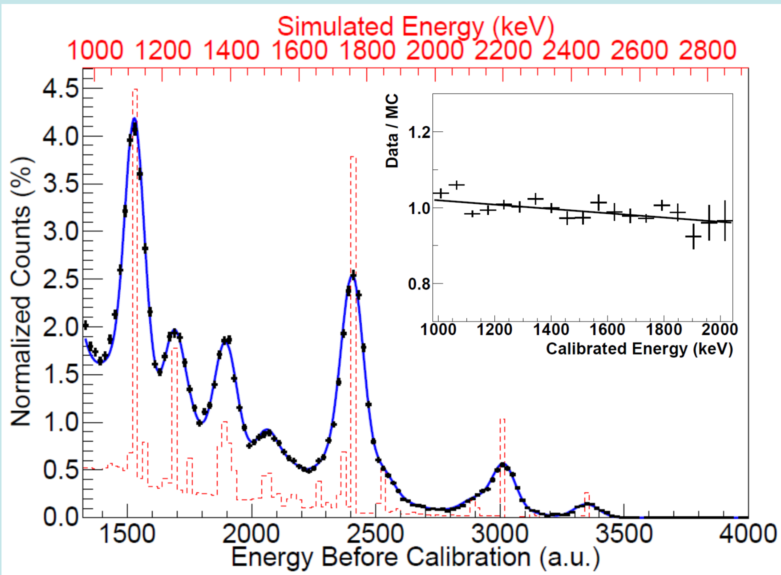
From profile likelihood:

$T_{1/2}^{0\nu\beta\beta} > 1.1 \cdot 10^{25}$ yr
$\langle m_{\beta\beta} \rangle < 190 - 450$ meV
(90% C.L.)

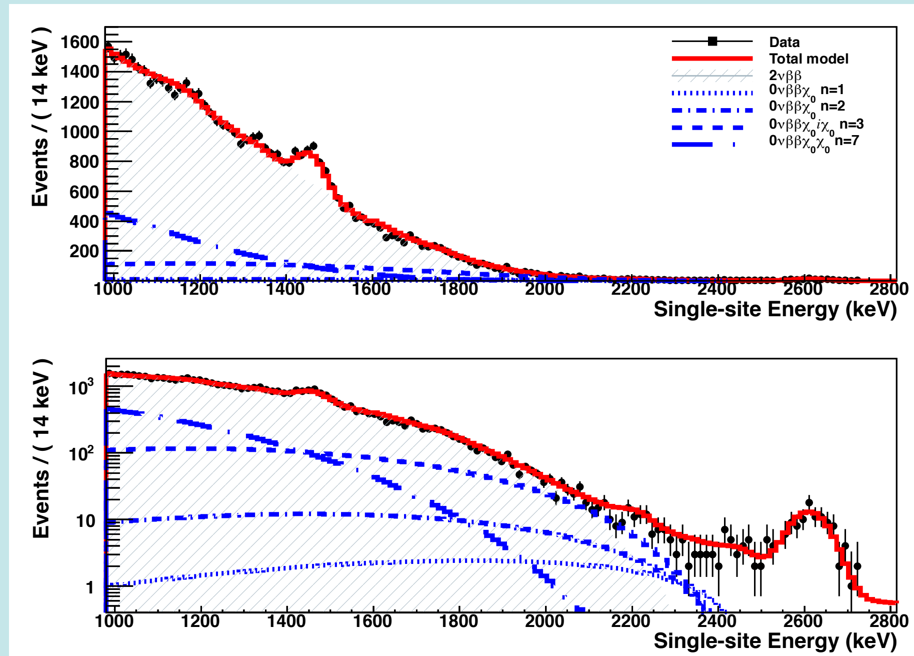
***Nature* (2014)**
doi:10.1038/nature13432

Search for Majoron-emitting Modes

^{222}Ra Calibration Data



Low Background Data



No Evidence for Majoron Modes

arXiv:1409.6829v1

Decay mode	Spectral index, n	Model types	$T_{1/2}$, yr	$\lvert\langle g_{ee}^{M}\rangle\rvert$
$0\nu\beta\beta\chi_0$	1	IB, IC, IIB	$>\mathbf{1.2\cdot10^{24}}$	$<\mathbf{(0.8\text{-}1.7)\cdot10^{-5}}$
$0\nu\beta\beta\chi_0$	2	"Bulk"	$>\mathbf{2.5\cdot10^{23}}$	–
$0\nu\beta\beta\chi_0\chi_0$	3	ID, IE, IID	$>\mathbf{2.7\cdot10^{22}}$	$<\mathbf{(0.6\text{-}5.5)}$
$0\nu\beta\beta\chi_0$	3	IIC, IIF	$>\mathbf{2.7\cdot10^{22}}$	$<\mathbf{0.06}$
$0\nu\beta\beta\chi_0\chi_0$	7	IIE	$>\mathbf{6.1\cdot10^{21}}$	$<\mathbf{(0.5\text{-}4.7)}$

WIPP Update

- fire underground stopped access
- radiation warning

- EXO remotely recovered the high-pressure xenon into bottles and was safely warmed up
- placed detector in ‘standby’ mode
- limited access has resumed
- no major external-to-cleanroom difficulties
- continue process of evaluating situation and hopefully prepare for re-start

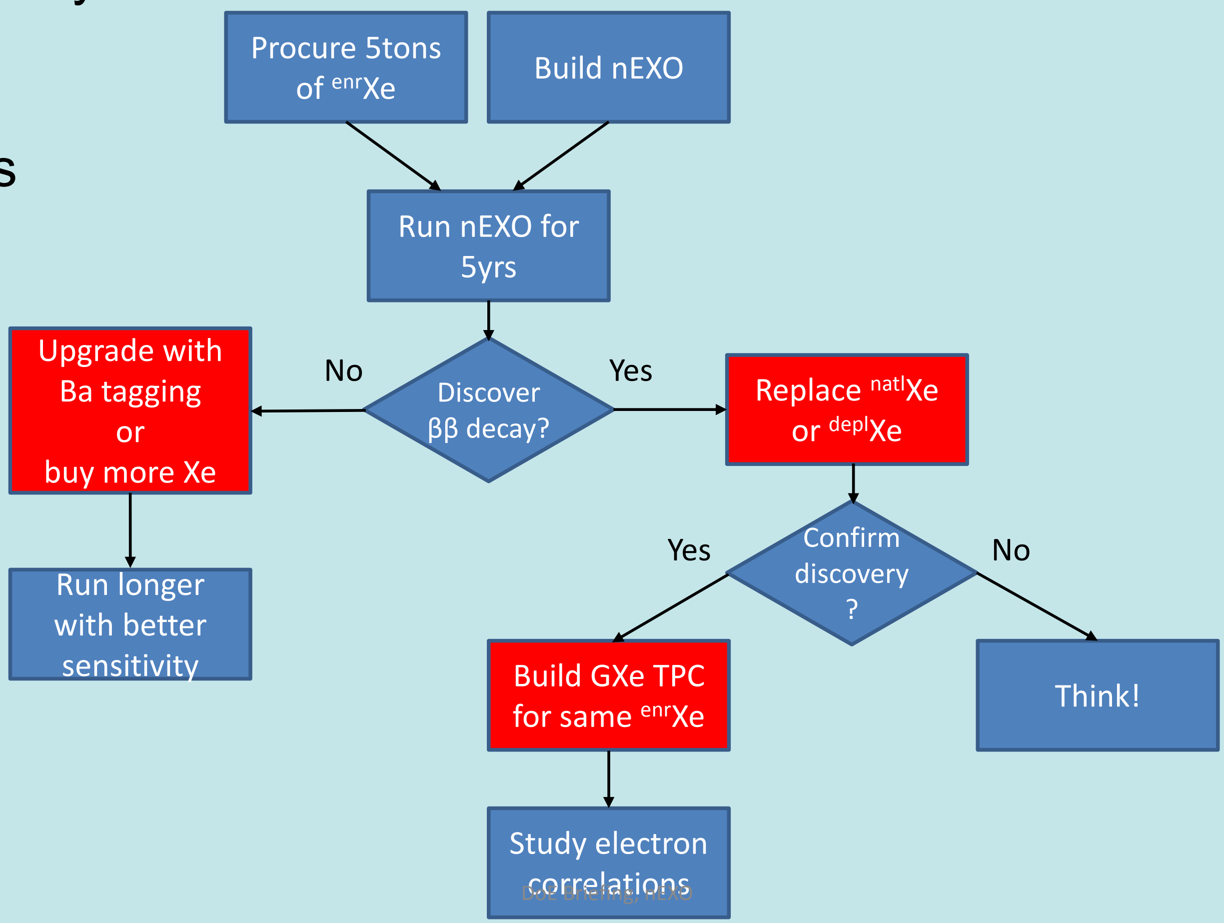
- de-radonator installed before incidents
- ready with initial electronics upgrade boards…relatively quick to do complete upgrade when possible

nEXO Plan

- develop 5-tonne TPC with single drift volume…learn from EXO-200
- improve energy resolution and background rejection
- ‘upgrade’ light detection, charge readout, and electronics
- move to dedicated facility

- growing collaboration
  some recent additions
  include:

BNL
Duke
IHEP Bejing
LLNL
ORNL
South Dakota
Stony Brook
TRIUMF



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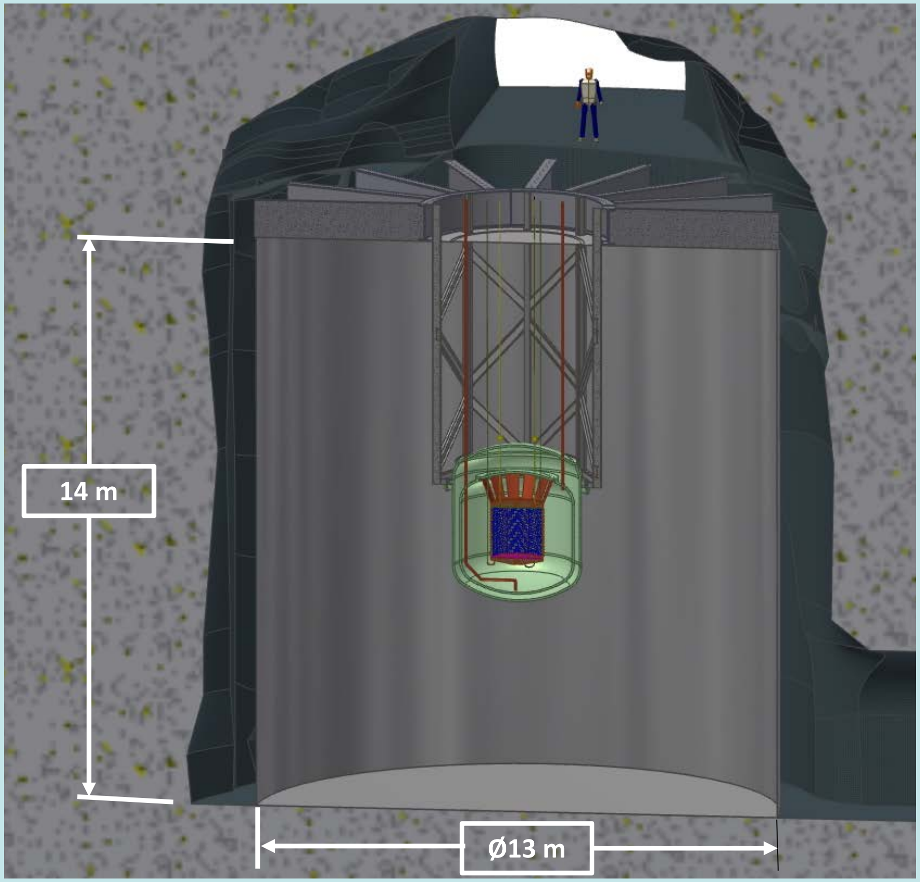
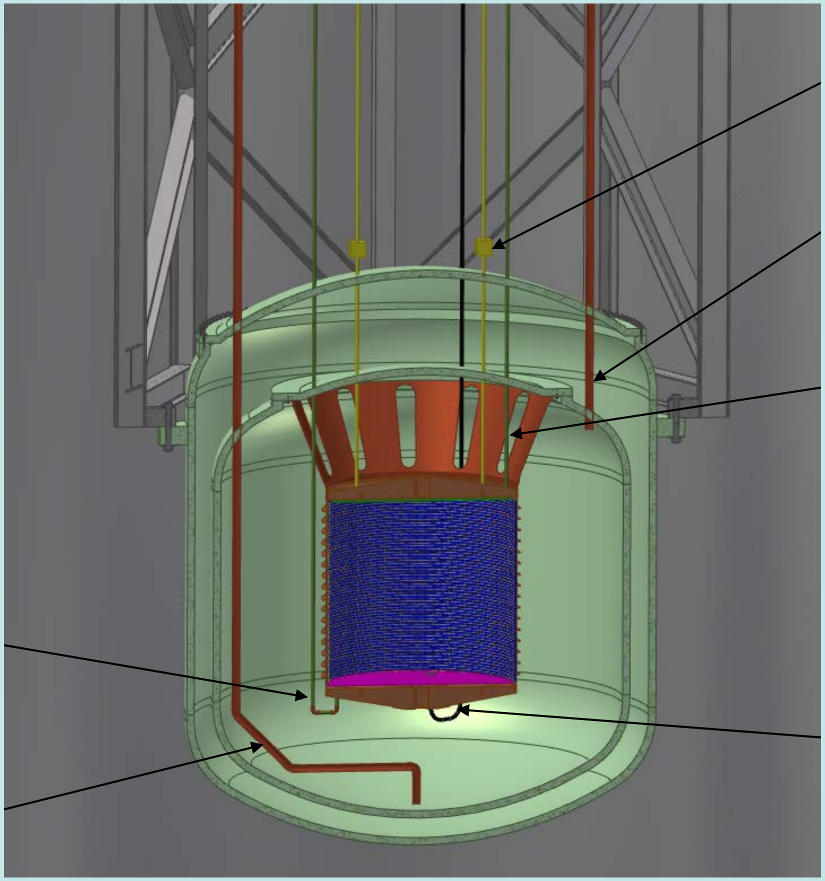
TRIUMF, Vancouver BC, Canada – J. Dilling, P. Gumplinger, R. Krücken, F. Retière, V. Strickland

nEXO Detector Concept

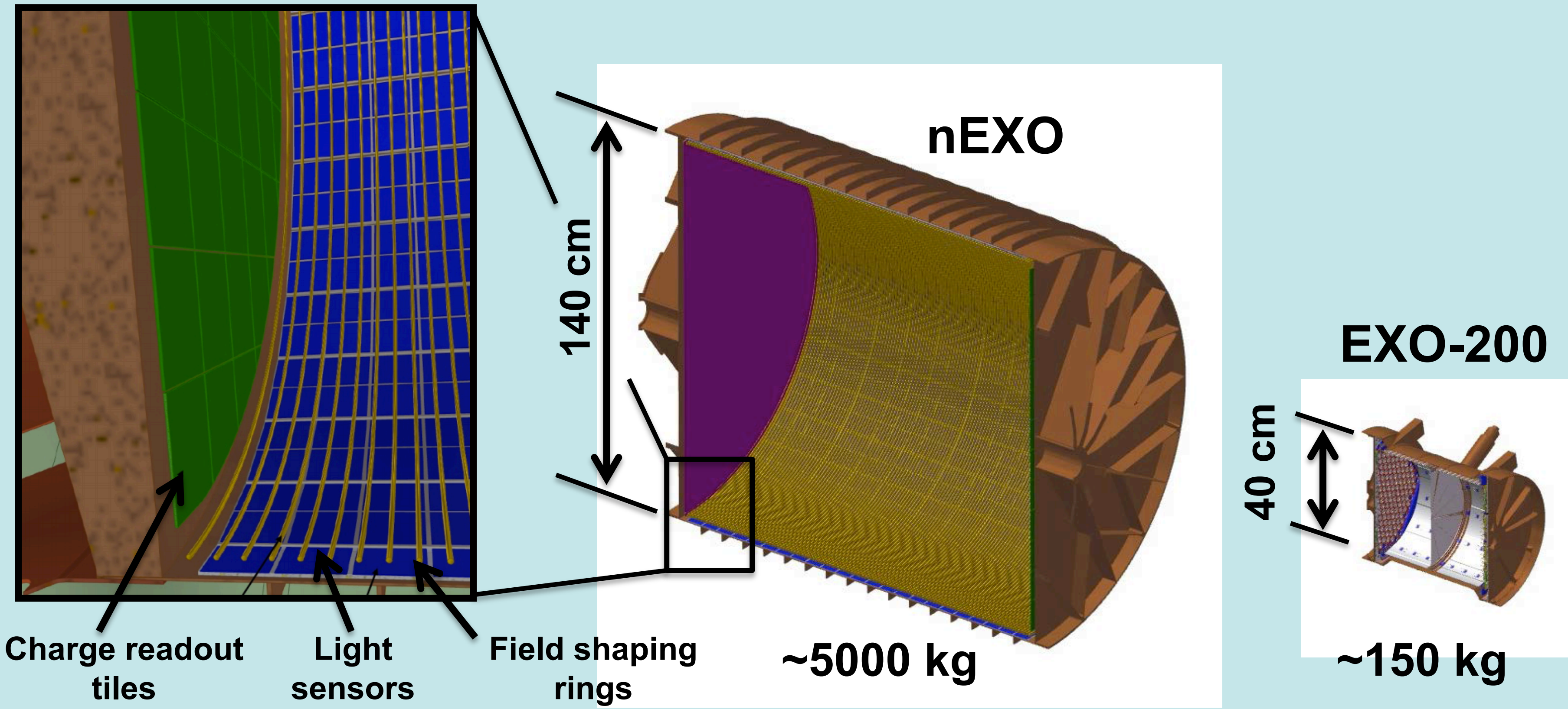
- follow success of EXO-200 with key detector improvements
  - reduced electronics noise
  - improved energy resolution (~1%) (improved light coverage)
  - finer charge readout granularity (better multi-site ID)
  - increased self-shielding (very low backgrounds in central region)





TPC concept

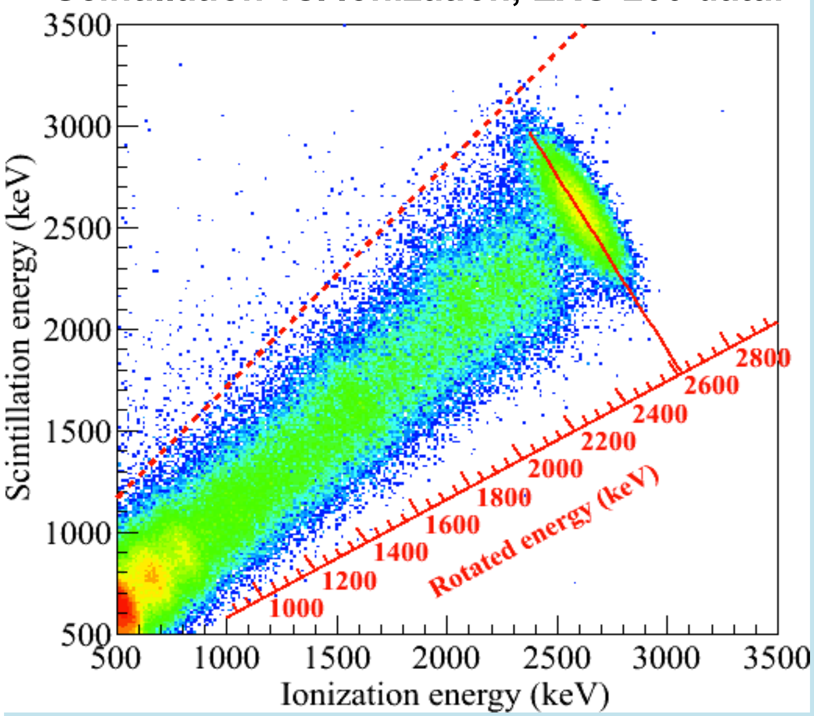
- maximize ‘clean’ volume with all components at edges…self-shielding
- proof-of-principle demonstrated with EXO-200
- large reduction in backgrounds at centre for nEXO…detailed measurement of background from outer portions



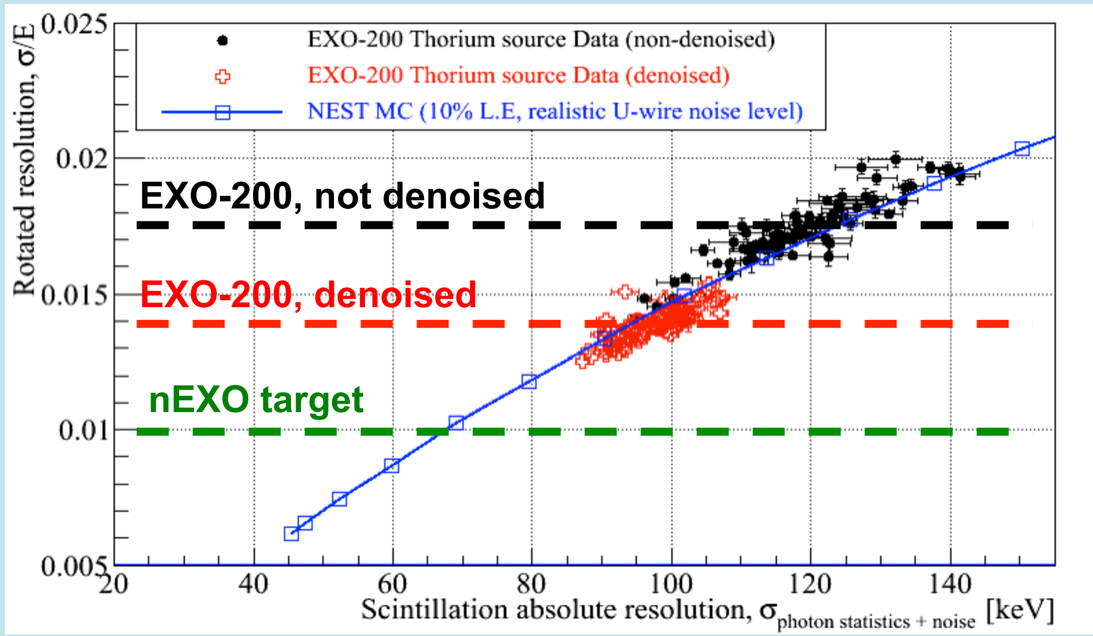
Energy resolution

- Require $\sigma_E/E < 1\%$ at $Q_{\beta\beta}$ (30 keV FWHM), which requires measuring both charge and light with minimal readout noise
- Have demonstrated 1.4% resolution in EXO-200, simulations indicate that 1% resolution is attainable with improved readout electronics for light sensors
- Planned upgrades to EXO-200 electronics should also achieve 1% resolution

Scintillation vs. Ionization, EXO-200 data:



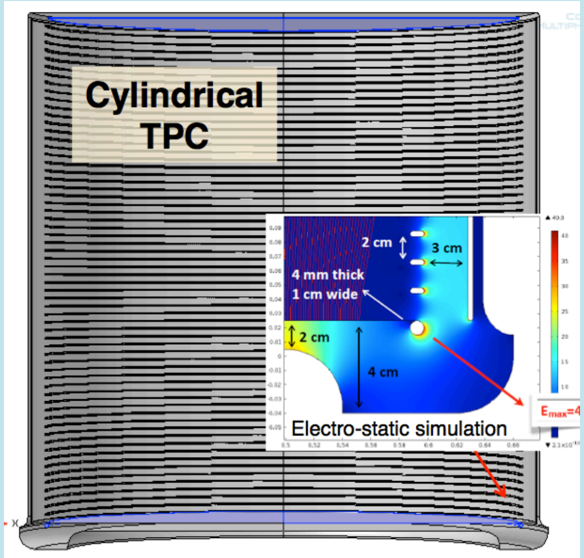
Simulated rotated resolution vs. readout noise:



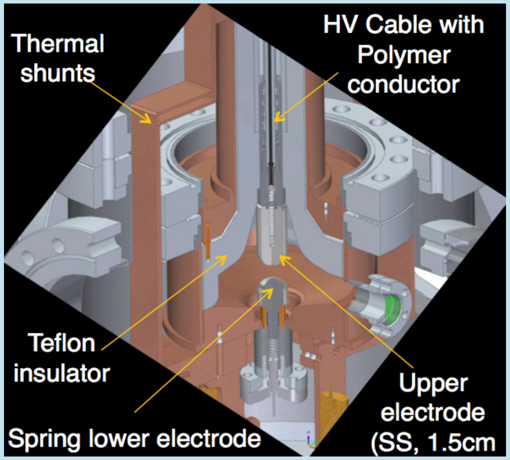
R&D

- R&D is in progress for several detector components:
  - Field cage design and electrostatic simulations
  - High voltage testing and prototyping
  - Characterization of light detectors (Silicon Photo Multipliers)
  - Design and testing of charge readout tiles

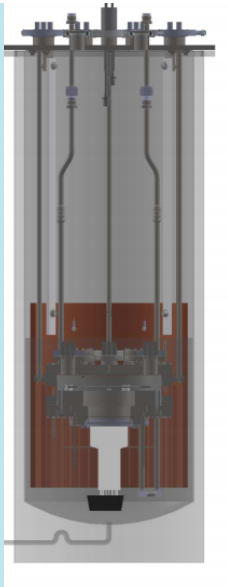
TPC E-field simulations:



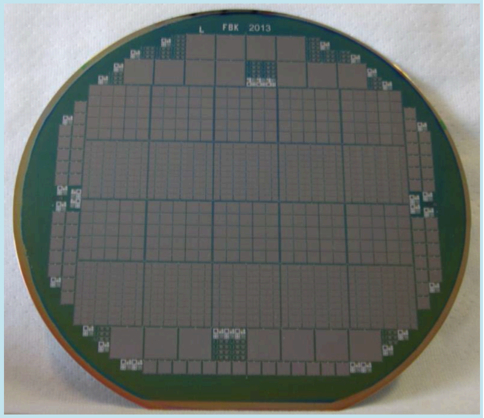
HV testing setup:



Charge readout LXe test cell:



SiPMs:



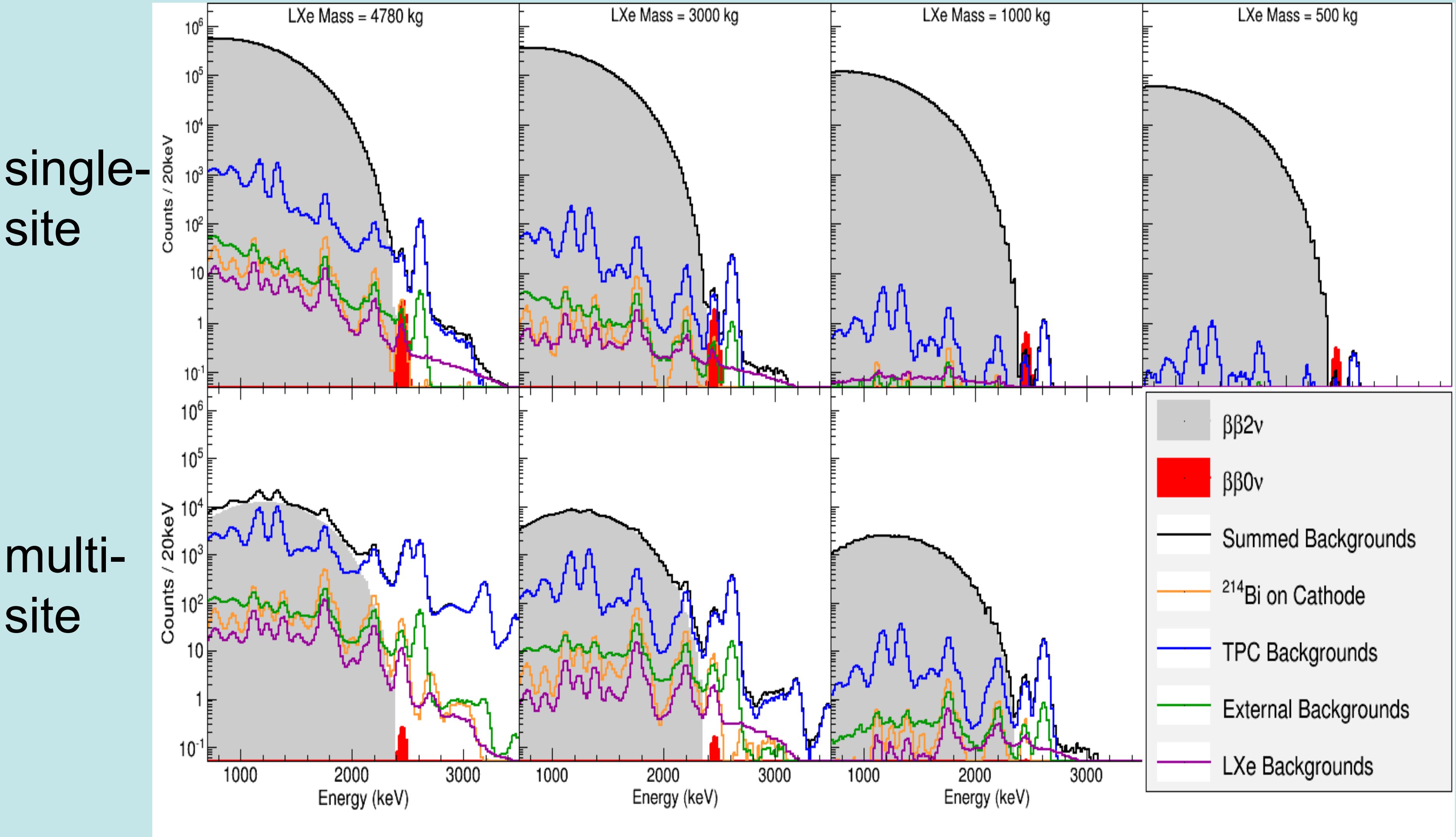
nEXO MC Simulation

- Assume measured activities for all detector materials (**JINST 7 (2012) P05010)**
- Have compared to EXO-200 data to confirm validity of these assumptions
- Measured background rate from EXO-200 is $\boldsymbol{B_{EXO\text{-}200}}$ **= 151 ± 19 ROI^{-1} ton^{-1} yr^{-1}**,
  (ROI = $Q_{\beta\beta}$ ± 0.5·FWHM) *Nature **510**, 229 (2014), arXiv:1402.6956*
- Agrees with predicted nEXO rate in outer 16.2 cm for same assumptions
- The following improvements over EXO-200 are assumed:
  - Improved energy resolution ($\sigma/Q_{\beta\beta}$ = 0.01) (light collection + reduced noise)
  - Improved SS/MS discrimination (finer charge collection pitch)
  - Cu activity from improved sensitivity radio assay
  - Reduced ^{137}Xe rate at SNOLAB
  - Reduced ^{222}Rn density, longer time window in ^{214}Bi-^{214}Po coincidence cut

- Total nEXO background prediction in outer 16.2 cm: $\boldsymbol{B_{nEXO}}$ **= 3.7 ROI^{-1} ton^{-1} yr^{-1}**
- Improvements give reduction of ~40x in background in background index relative to EXO-200

nEXO MC Simulations

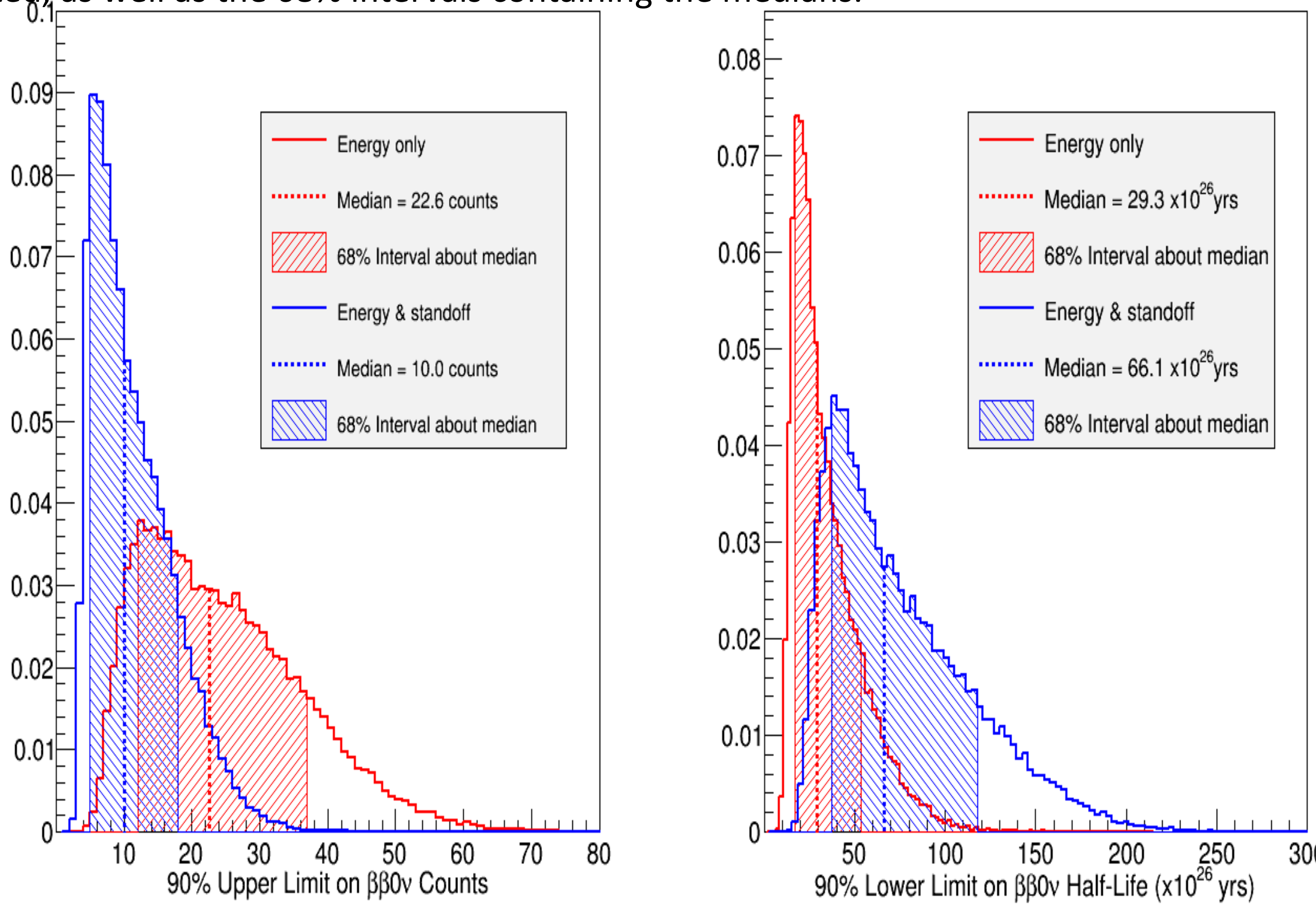
- extensive GEANT4 simulations are being carried out to optimize nEXO
- reject backgrounds with: 1) multiplicity 2) self-shielding 3) energy spectrum
- use a multi-dimensional fit to optimize information use



5 years exposure   0νββ counts corresponding to $T_{1/2}=6.6\cdot10^{27}$ yr

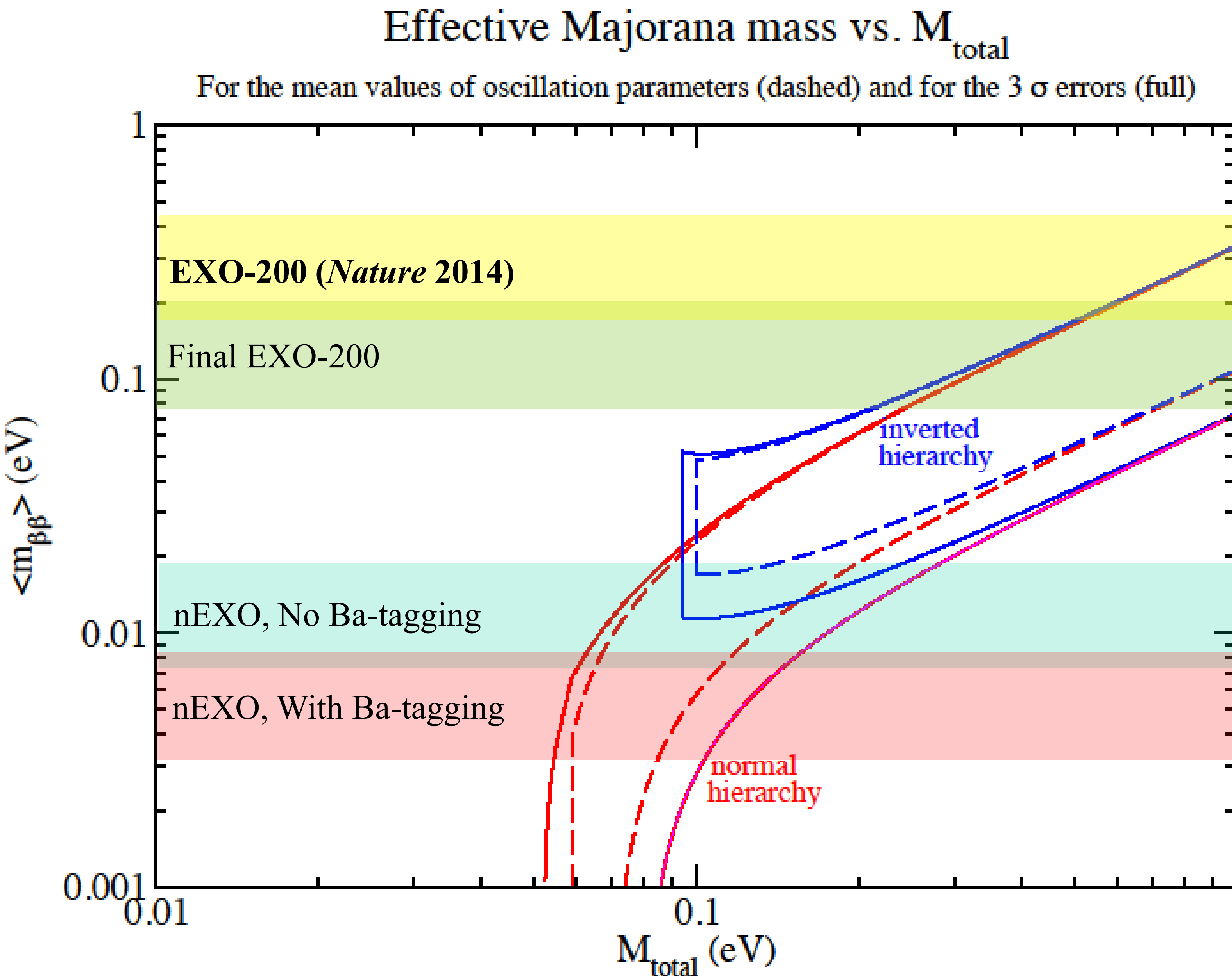
The distributions of the 90% UL (LL) on the $0\nu\beta\beta$ counts (half-life) for 5 yr exposure using an energy-only analysis, and energy + position (standoff-distance) analysis. The limits were produced by generating and fitting simulated datasets according to the background model. The median of the distributions (the sensitivity) is indicated, as well as the 68% intervals containing the medians.

Using standoff distance has an equivalent effect on sensitivity as a 4 times reduction in background! (For a background-limited experiment).



Left: The distributions of the 90% UL on the number of $0\nu\beta\beta$ counts in 5 yrs for the energy-only (red), and energy + standoff-distance (blue) analyses. **Right:** The distributions of the 90% LL on the bb0n half-life attained using the energy-only (red), and energy + standoff-distance (blue) analyses.

nEXO Sensitivity



Ba Tagging

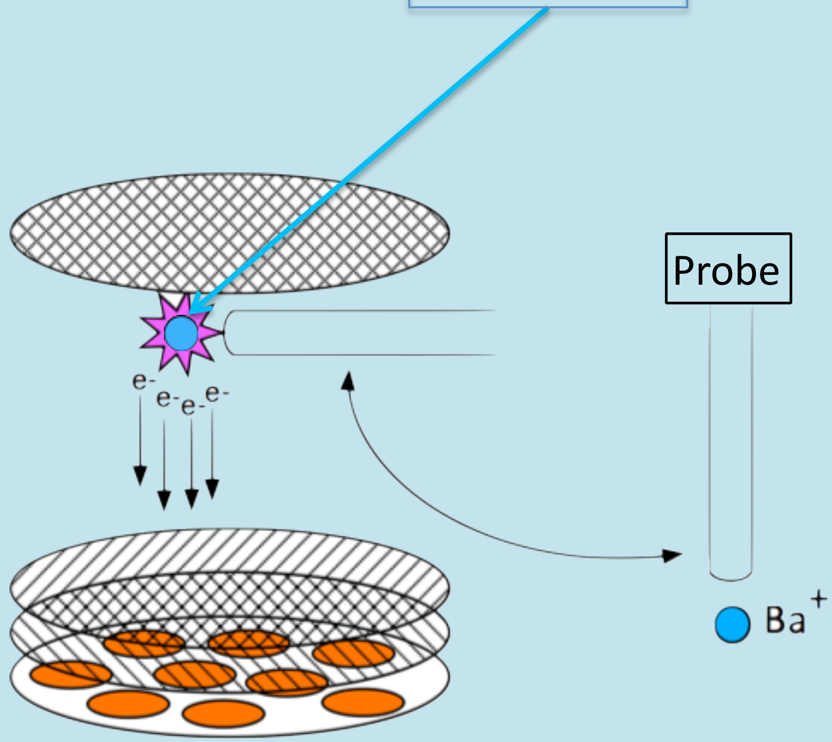
- liquid xenon detector
  - insert probe into detector to capture barium ion
  - retract probe and
    - release Ba into gas: RIS
    - keep frozen to probe: fluorescence

- high-pressure gaseous xenon detector
  - steer ion to nozzle with EM fields
  - extract through RF-funnel to lower pressure
  - charge exchange if necessary and transport to trap (under vacuum)
  - laser spectroscopy

Tagging from Liquid

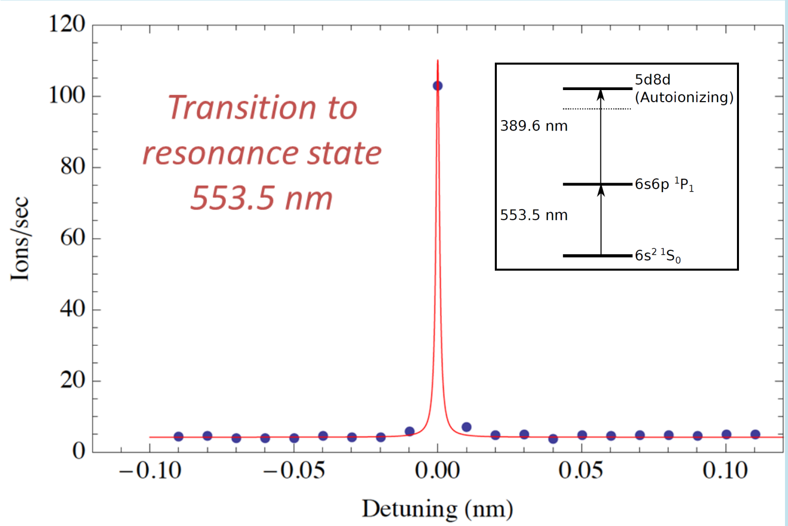
$$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^-$$

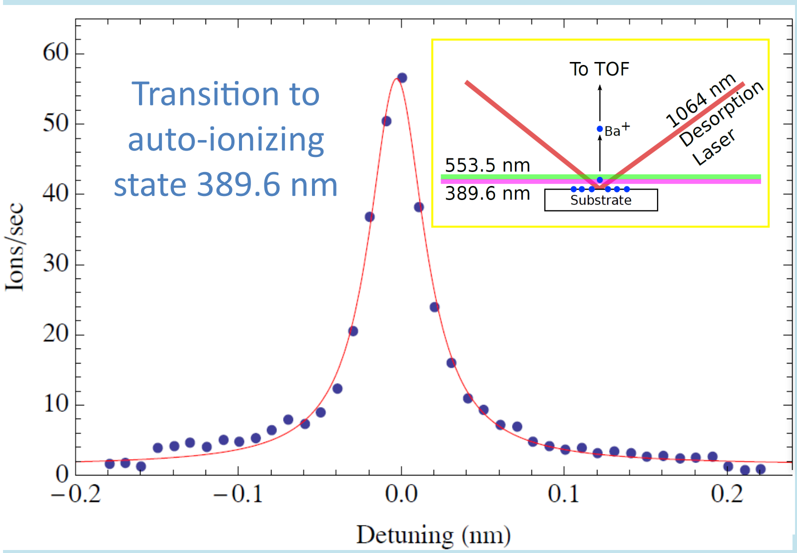
1. Detect and localize decay (like in EXO-200)
2. Send probe in to region of decay
3. Confine the Ba^+ on probe
4. Remove the probe
5. Identify the barium

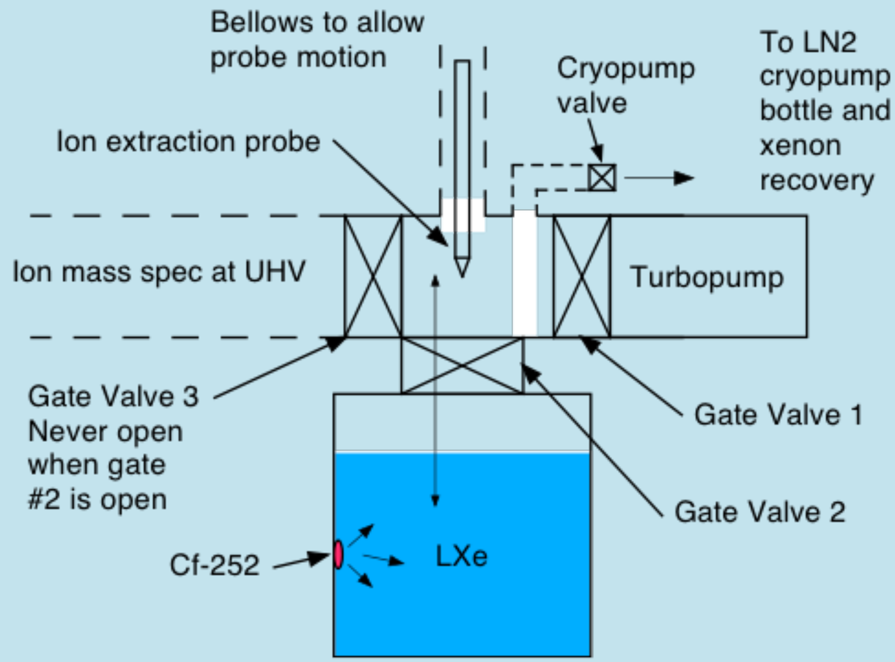


Investigated at Stanford, Colorado State U., U. of Illinois, Technical University Munich, U. Bern

Ba⁺ tagging by Resonance Ionization







Rev.Sci.Instrum. 85 (2014) 095114

Concept:

RIS - selective ionization of only one element with lasers

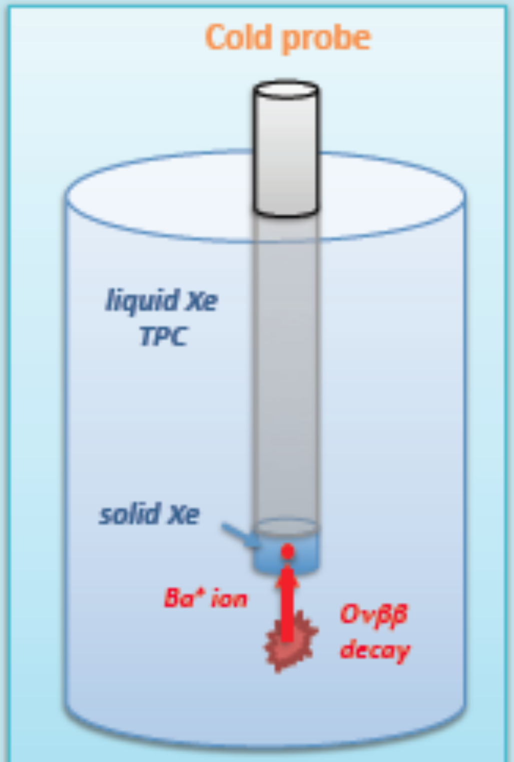
- Move probe close to Ba^+ ion in LXe
- Attach Ba^+ ion to probe
- Move probe out of LXe
- Laser-ablate Ba atom from probe
- Laser-ionize Ba^+ by RIS
- Accelerate Ba^+ ions and identify by TOF

Barium tagging in solid xenon (CSU)

Tagging concept

1, Capture Ba^+ daughter in solid xenon on a probe:

2. Image single Ba^+ or Ba on probe by fluorescence



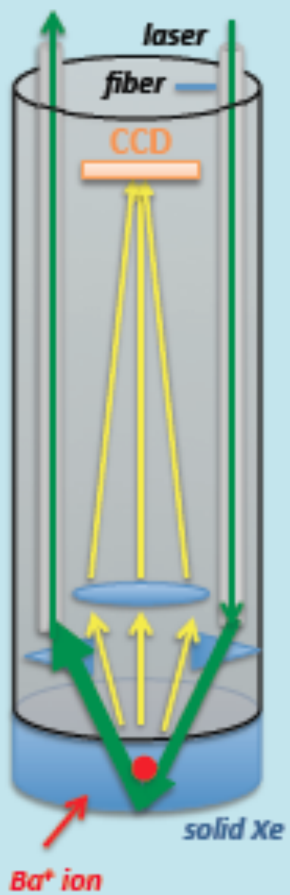
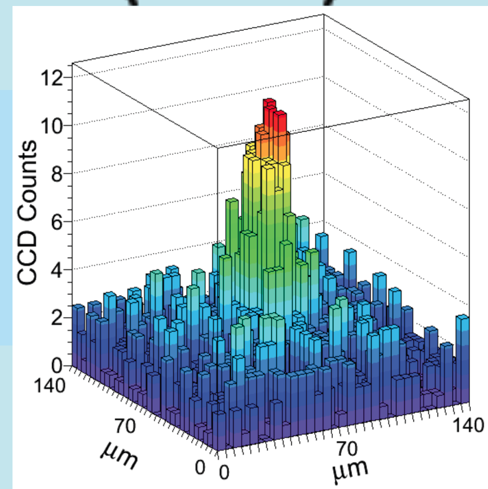
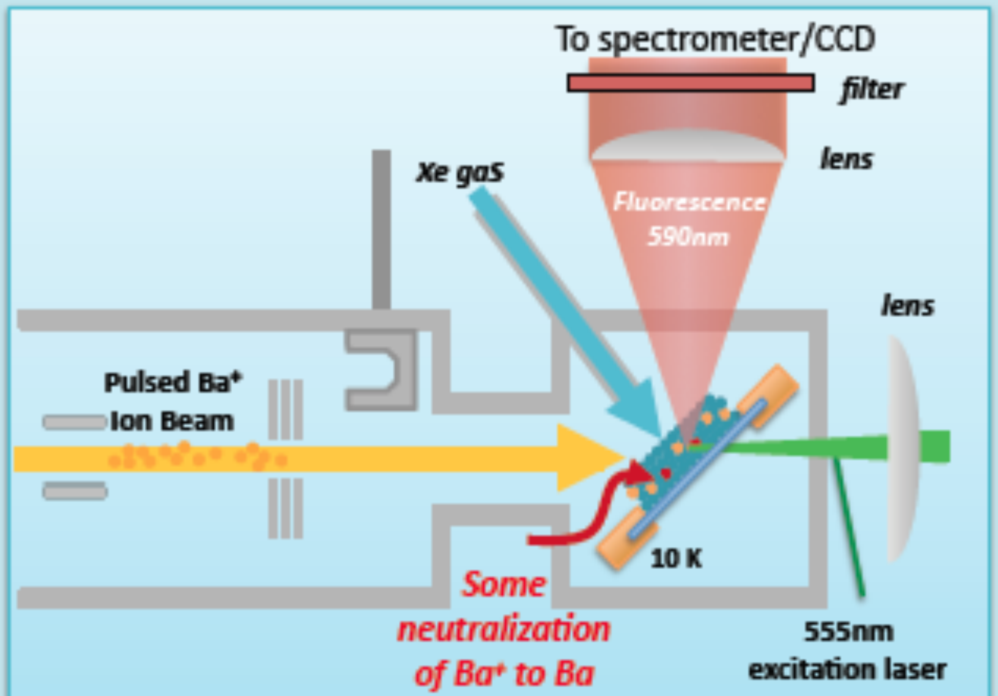


Image of ≤10^4 Ba atoms in a focused laser beam from a deposit of 10^4 Ba^+ ions in solid xenon.

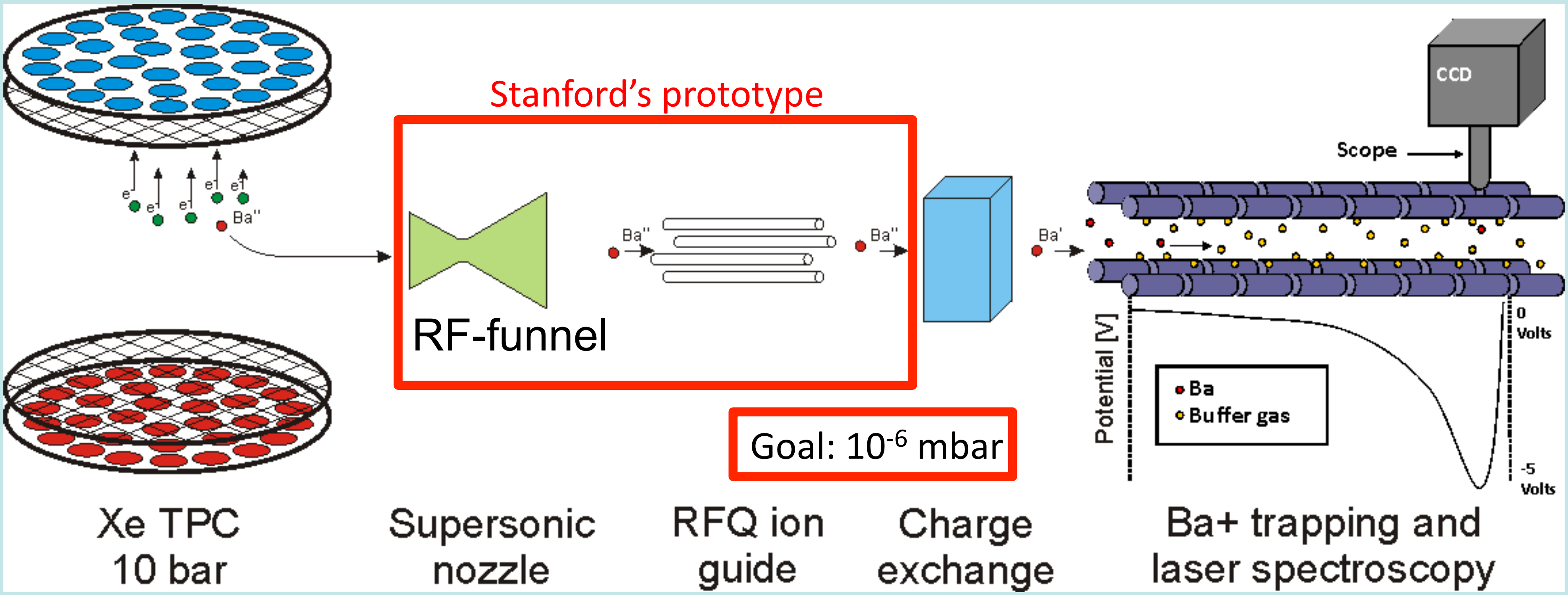


Barium tagging test apparatus



General Concept of Ba^{++} Tagging in gas

- Guide Ba^{++} in high pressure Xe inside the TPC (10 bar) to a nozzle
- Extract Ba^{++} with a Xe gas jet into a low pressure chamber
- After nozzle, pump Xe gas away and guide Ba^{++} to identification



Nucl.Instrum.Meth. B317 (2013) 473-475

Summary

– EXO200 has been a tremendous success
– many physics and technical publications
– two accidents at WIPP…now have limited access
– aim for ~2 additional years of livetime with upgrades
– additional R&D operation for nEXO possible beyond that

– nEXO design development and R&D well underway
– follow EXO-200 success and make key improvements
– aim to build a detector with discovery potential to bottom of inverted hierarchy region

– Ba tagging developments continue
– ultimately need to measure single atom efficiencies