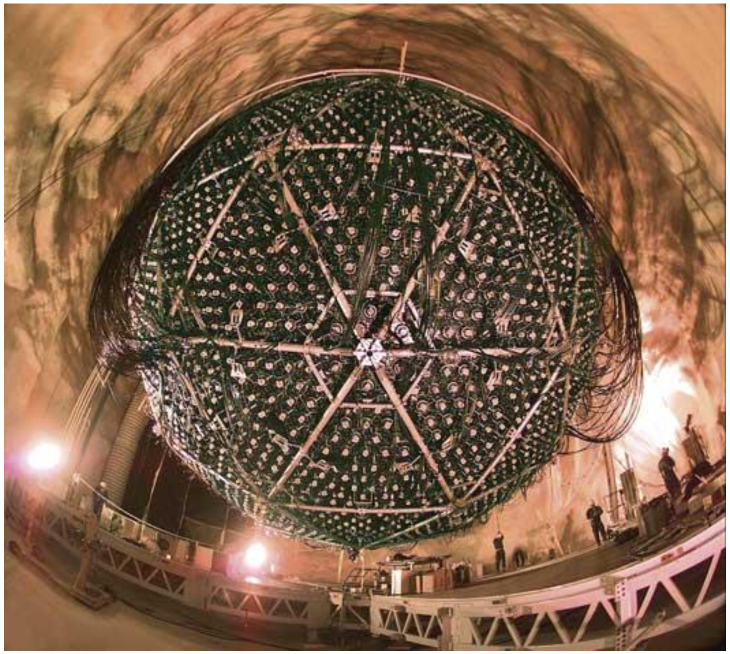
Barium-Ion Tagging for ^{136}Xe Double-Beta Decay Studies with nEXO

- Motivation for ββ search
- The EXO-200 experiment
- The nEXO project and why Ba-tagging

Thomas Brunner for the nEXO collaboration

WNPPC– February 17, 2016

Neutrino oscillations



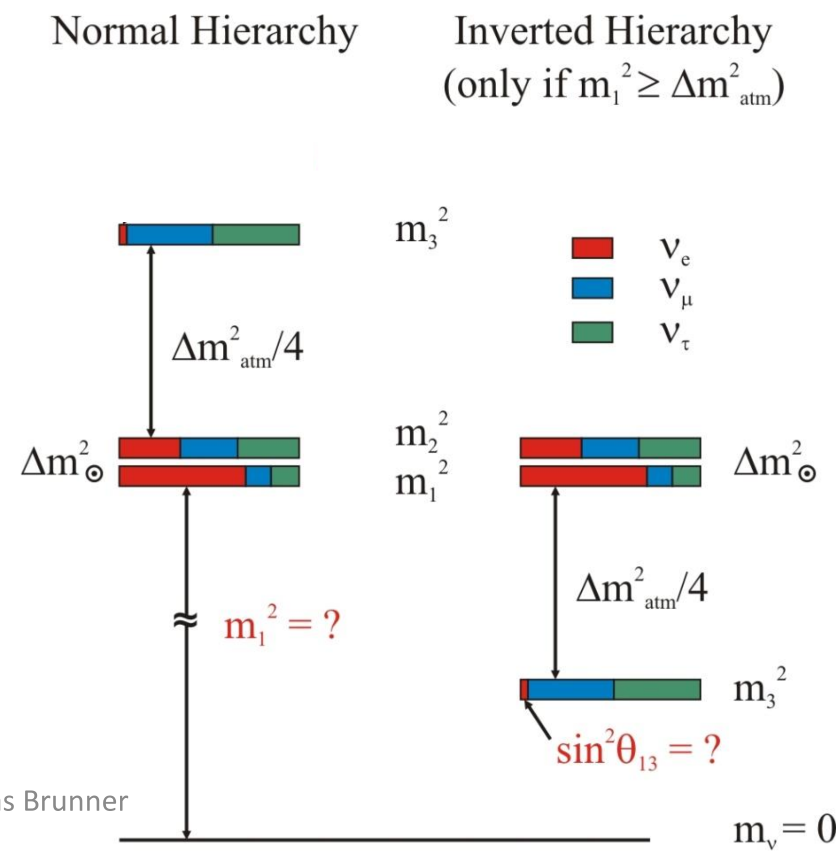
SNO, picture taken from http://www.oit.on.ca

Relative mass scale

- Indicate a neutrino mass
- Determination of mixing angle θ_{ij}
- Indicate mass hierarchy
- Determination of δm^2

Pontecorvo–Maki–Nakagawa–Sakata matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_{m1} \\ \nu_{m2} \\ \nu_{m3} \end{pmatrix}$$



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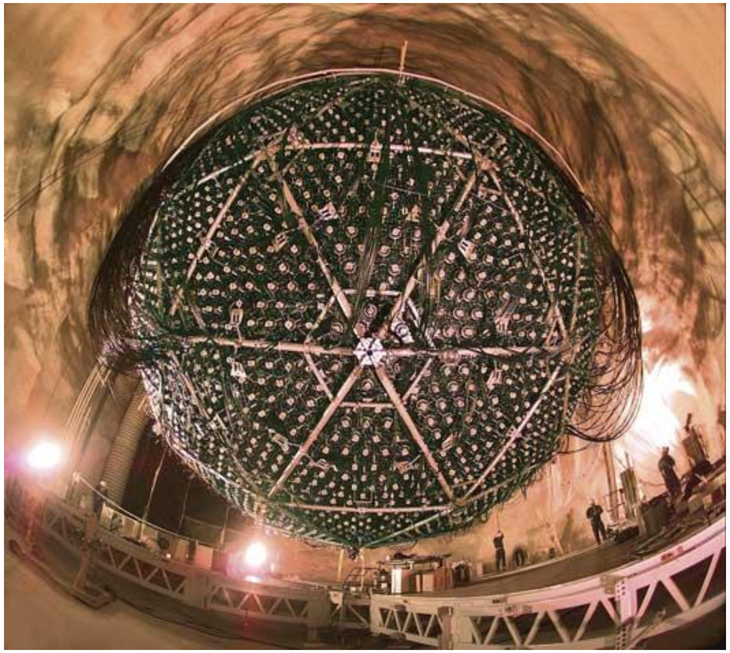

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What oscillation experiments cannot tell us about ν's

- What is the absolute mass scale
- Why is the neutrino mass so small?
- What is the nature of the ν: Dirac or Majorana?

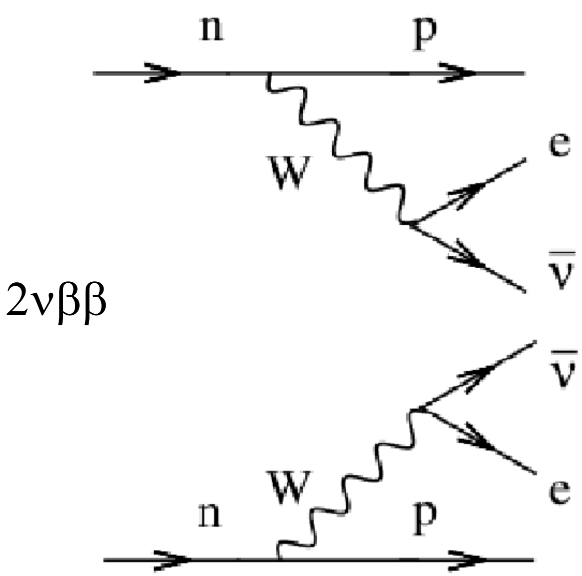
→Search for 0νββ decay

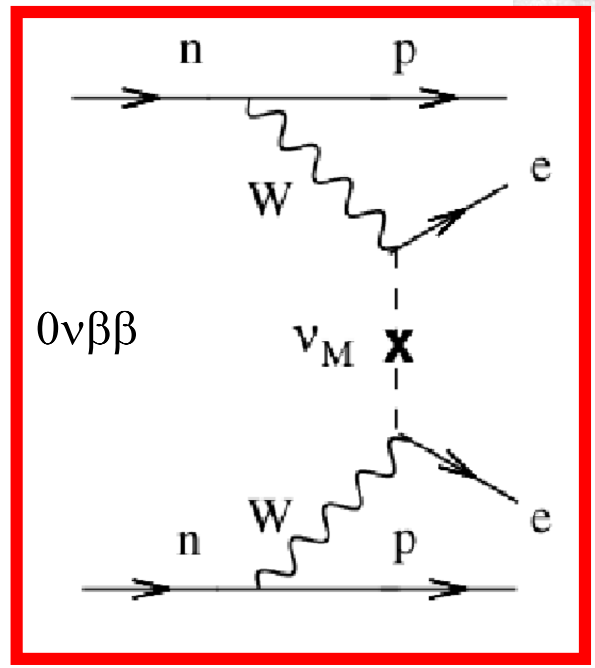
Double beta decay

M.Goeppert-Mayer, Phys. Rev. 48 (1935) 512

The most promising approach to determine the nature of the neutrino!
Lepton number is violated in this decay!

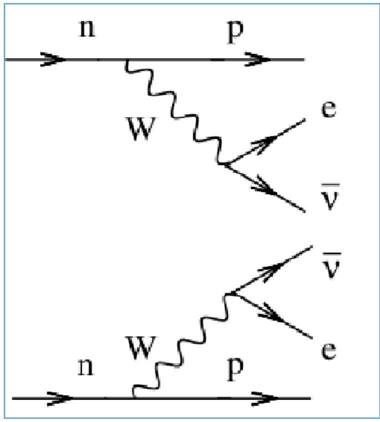
Ettore Majorana



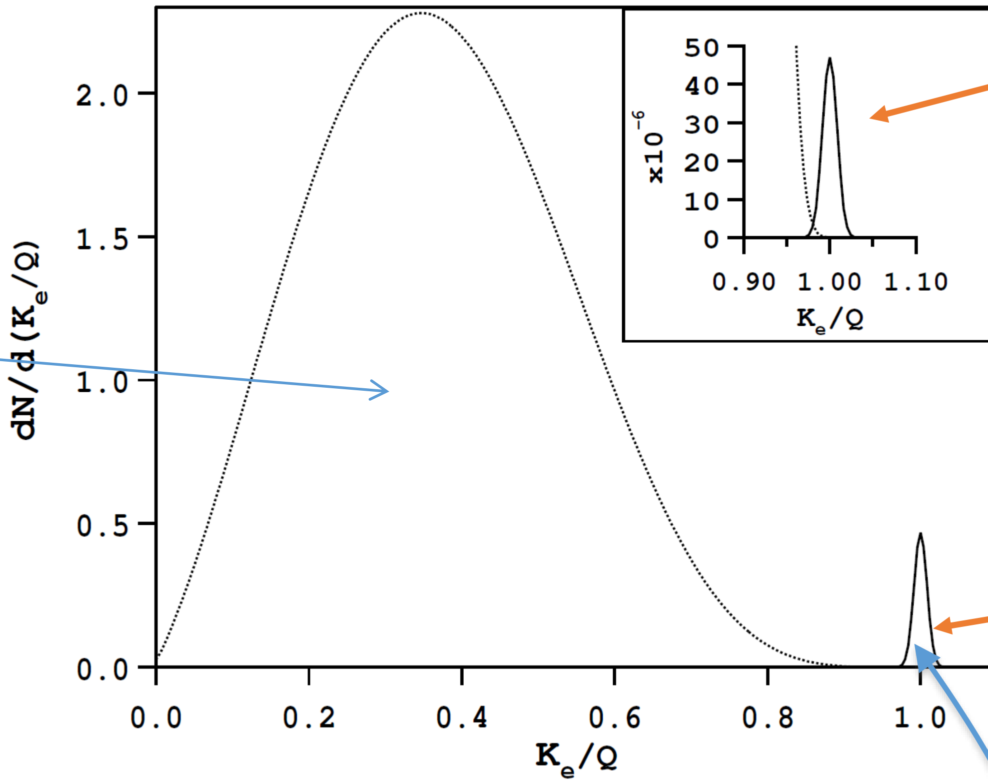


This process can only occur for a Majorana neutrino!

Neutrinoless double beta decay

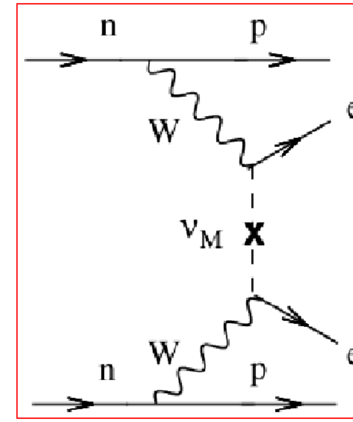


[arXiv:hep-ph/0611243]



$0\nu\beta\beta$ peak (normalized to 10^{-6})

$0\nu\beta\beta$ peak (normalized to 10^{-2})

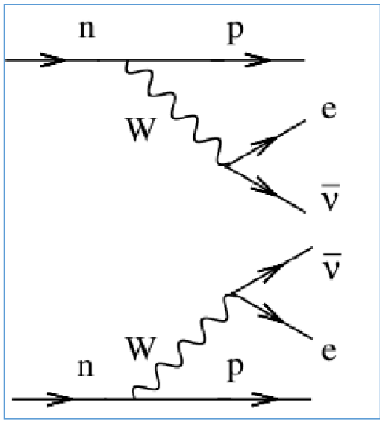


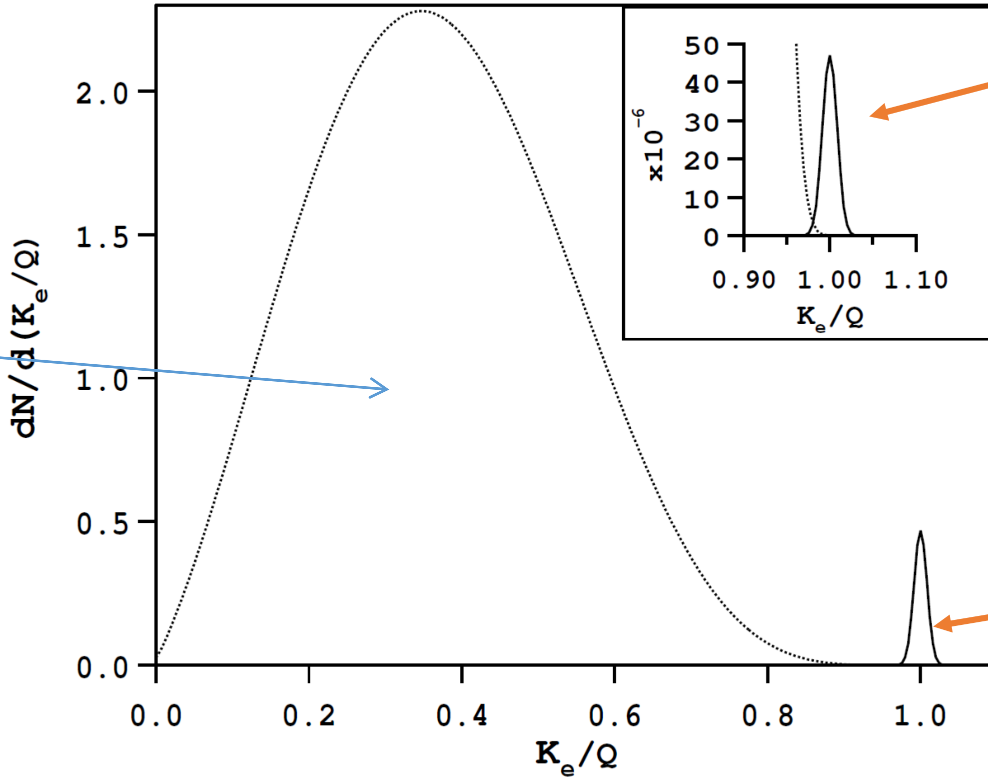
kinetic energy K_e of the two electrons in units of kinematic endpoint (Q)

Smeared by the energy resolution of the hypothetical detector

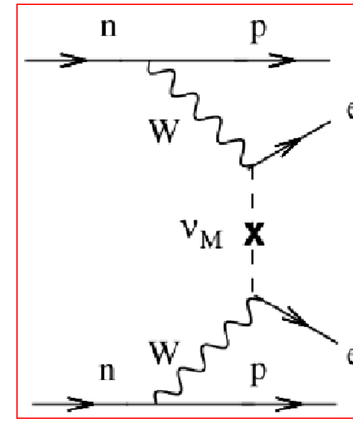
Neutrinoless double beta decay

[arXiv:hep-ph/0611243]





0νββ peak (normalized to 10^{-6})



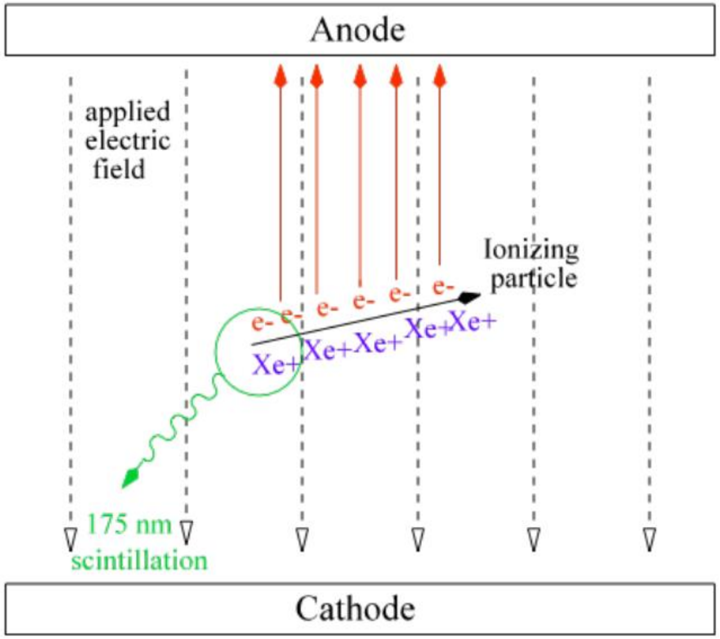
0νββ peak (normalized to 10^{-2})

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

$G^{0\nu}$ is a phase space factor
$M^{0\nu}$ is the nuclear matrix element

Effective Majorana mass: $$\langle m_\nu\rangle = \left|\sum_i U_{ei}^2 m_i \, \varepsilon_i\right|$$ (light neutrino exchange mechanism only)

Searching for $0\nu\beta\beta$ in ^{136}Xe with EXO



Liquid-Xe Time Projection Chamber

- Liquid Xe at 168K
- Cryogenic electronics in LXe
- Detection of scintillation light and secondary charges
- 2D read out of secondary charges at segmented anode
- Full 3D event reconstruction:
  1. Energy reconstruction
  2. Position reconstruction
  3. Event Multiplicity

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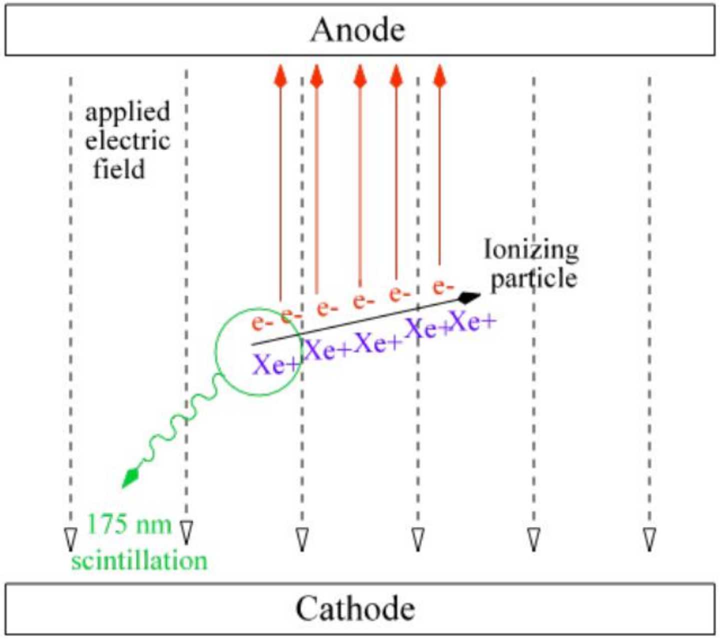

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Natural radiation decay rates

A banana	~10 decays/s
A bicycle tire	~0.3 decays/s
1 l outdoor air	~1 decay/min
100 kg of ^{136}Xe (2ν)	~1 decay/10 min

$0\nu\beta\beta$ decay	>10000 x rarer than $2\nu\beta\beta$
Age of universe	1.4 x 10^{10} years

$T_{1/2}^{0\nu} > 10^{25}$ years !!

→Need:

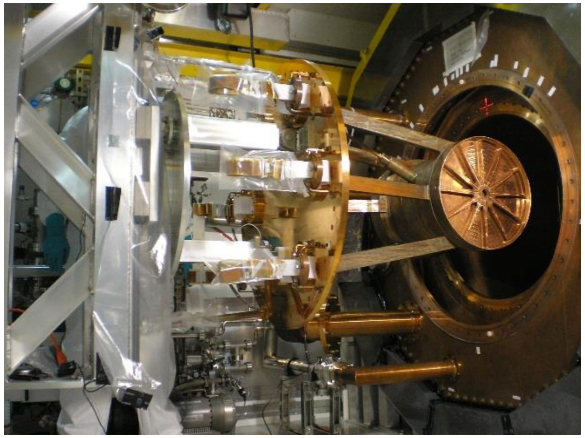
- high target mass
- high exposure
- low background rate
- good energy resolution

Advantages of ^{136}Xe

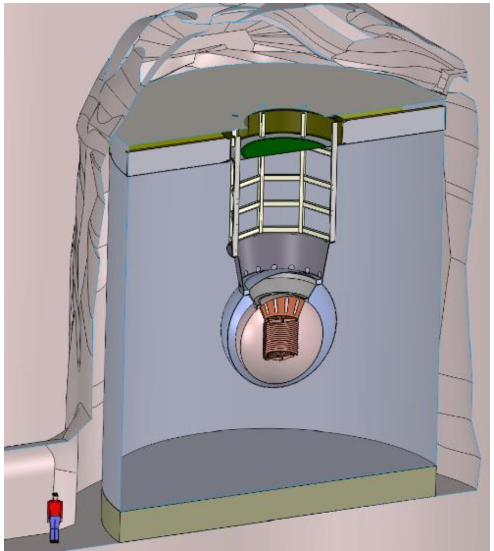
- Easy to enrich: 8.9% natural abundance but can be enriched relatively easily (better than growing crystals)
- Can be purified continuously, and reused
- High $Q_{\beta\beta}$ (2458 keV): higher than most naturally occurring backgrounds
- Minimal cosmogenic activation: no long-life radioactive isotopes
- Energy resolution: improves using scintillation and charge anti-correlation
- LXe self shielding
- Background can be potentially reduced by Ba^{++} tagging

Phased approach:

1. EXO-200: 200kg liquid-Xe TPC

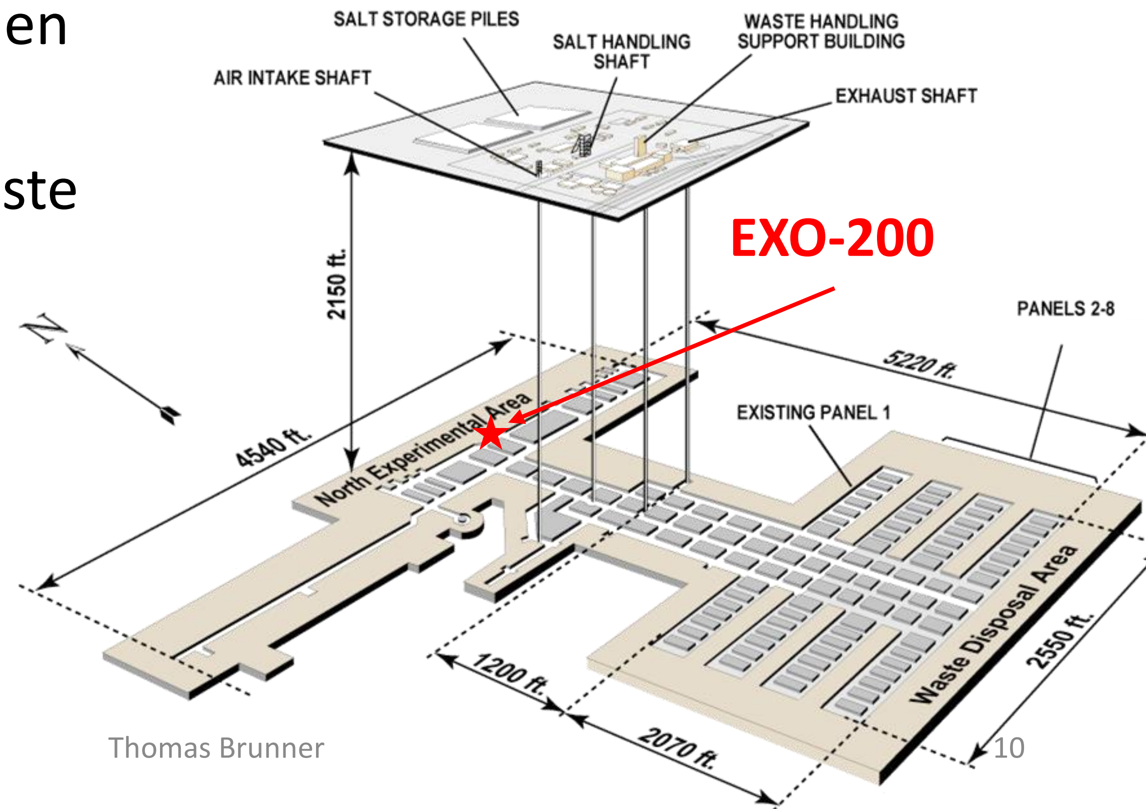


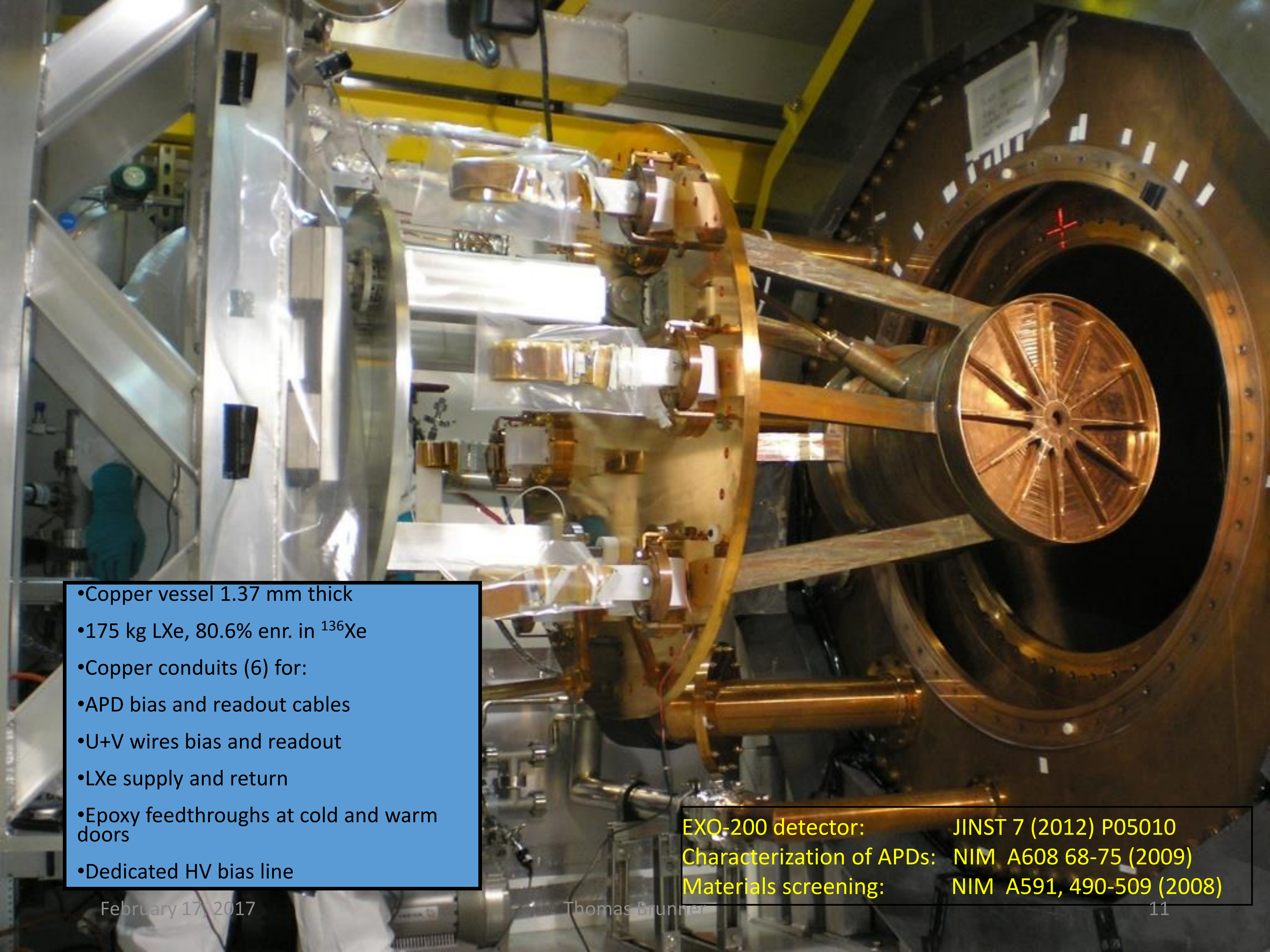
2. nEXO: 5-ton liquid Xe TPC with Ba tagging option (SNO lab cryopit)



EXO-200

- Located at the Waste Isolation Pilot Plant at 32°22’30”N 103°47’34”W (Carlsbad, NM).
- 2150 feet depth (~655m), ≈1585 mwe flat overburden
- U.S. DOE permanent repository for nuclear waste
- Low radioactivity levels:
    - U, Th <100ppb
    - Radon background < 10 Bq/m^3

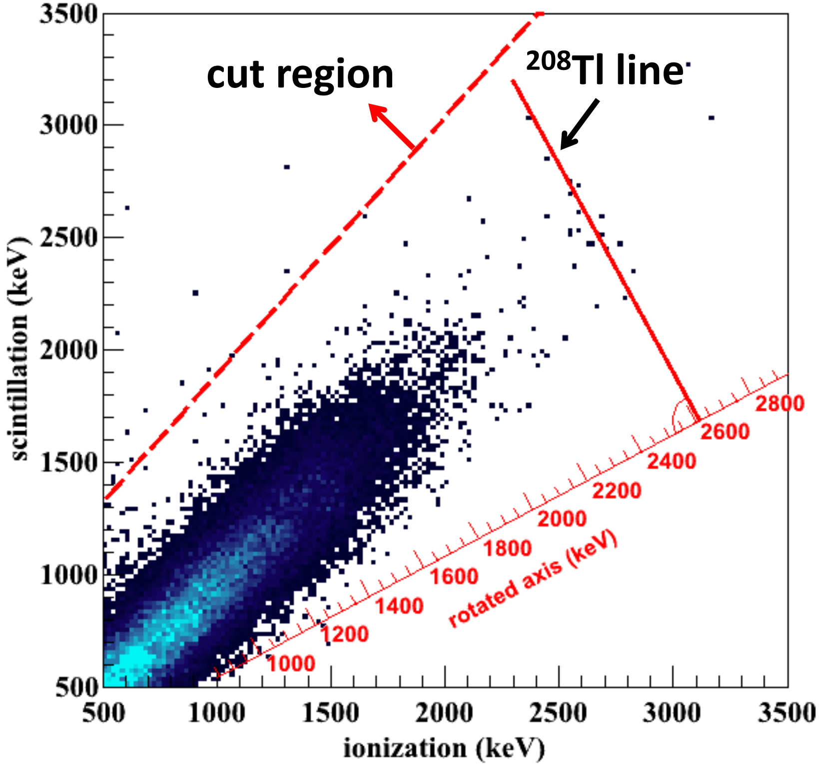


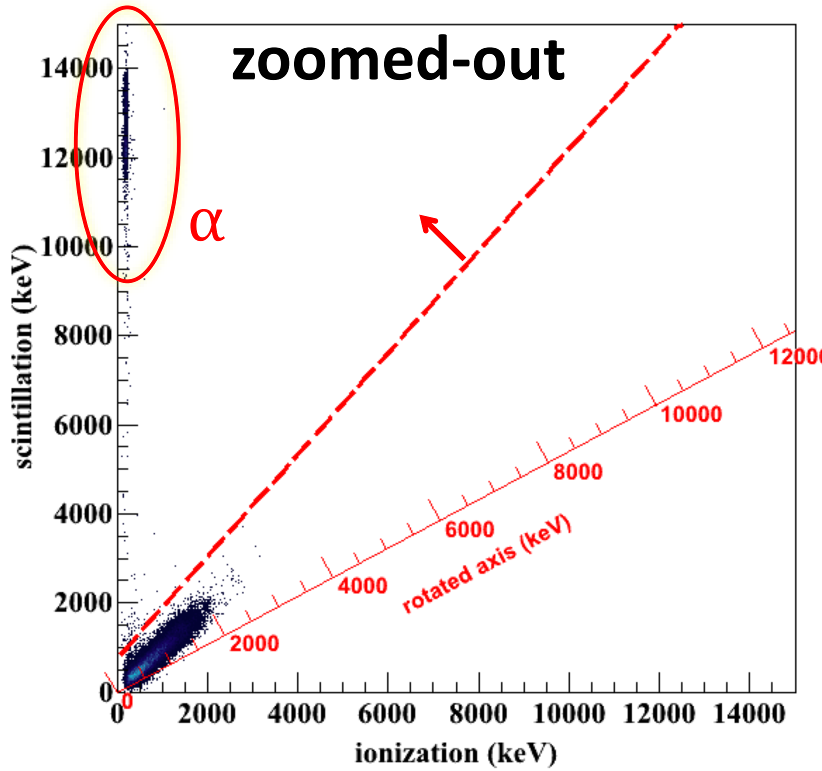


- Copper vessel 1.37 mm thick
- 175 kg LXe, 80.6% enr. in ^{136}Xe
- Copper conduits (6) for:
- APD bias and readout cables
- U+V wires bias and readout
- LXe supply and return
- Epoxy feedthroughs at cold and warm doors
- Dedicated HV bias line

EXO-200 detector:	JINST 7 (2012) P05010
Characterization of APDs:	NIM A608 68-75 (2009)
Materials screening:	NIM A591, 490-509 (2008)

Low Background 2D SS Spectrum

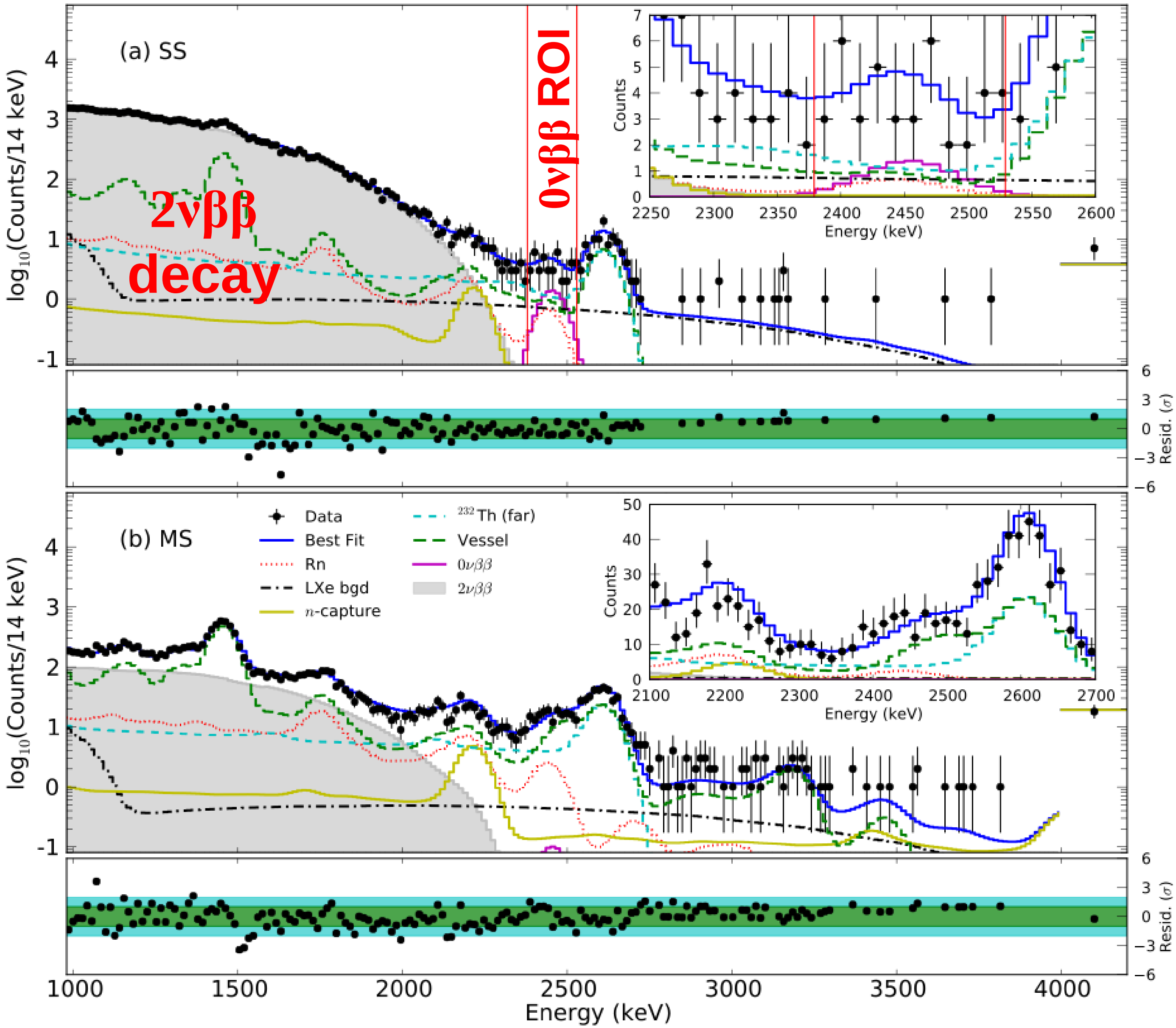




Events removed by diagonal cut:

- **α (larger ionization density → more recombination → more scintillation light)**
- **events near detector edge → not all charge is collected**

Recent 0νββ decay result



Run 2 data consists of:
Run 2a already used for PRC 2014 and PRL 2012
09/22/2011 – 04/15/2012
Runs 2b and 2c
04/16/2012 – 09/01/2013

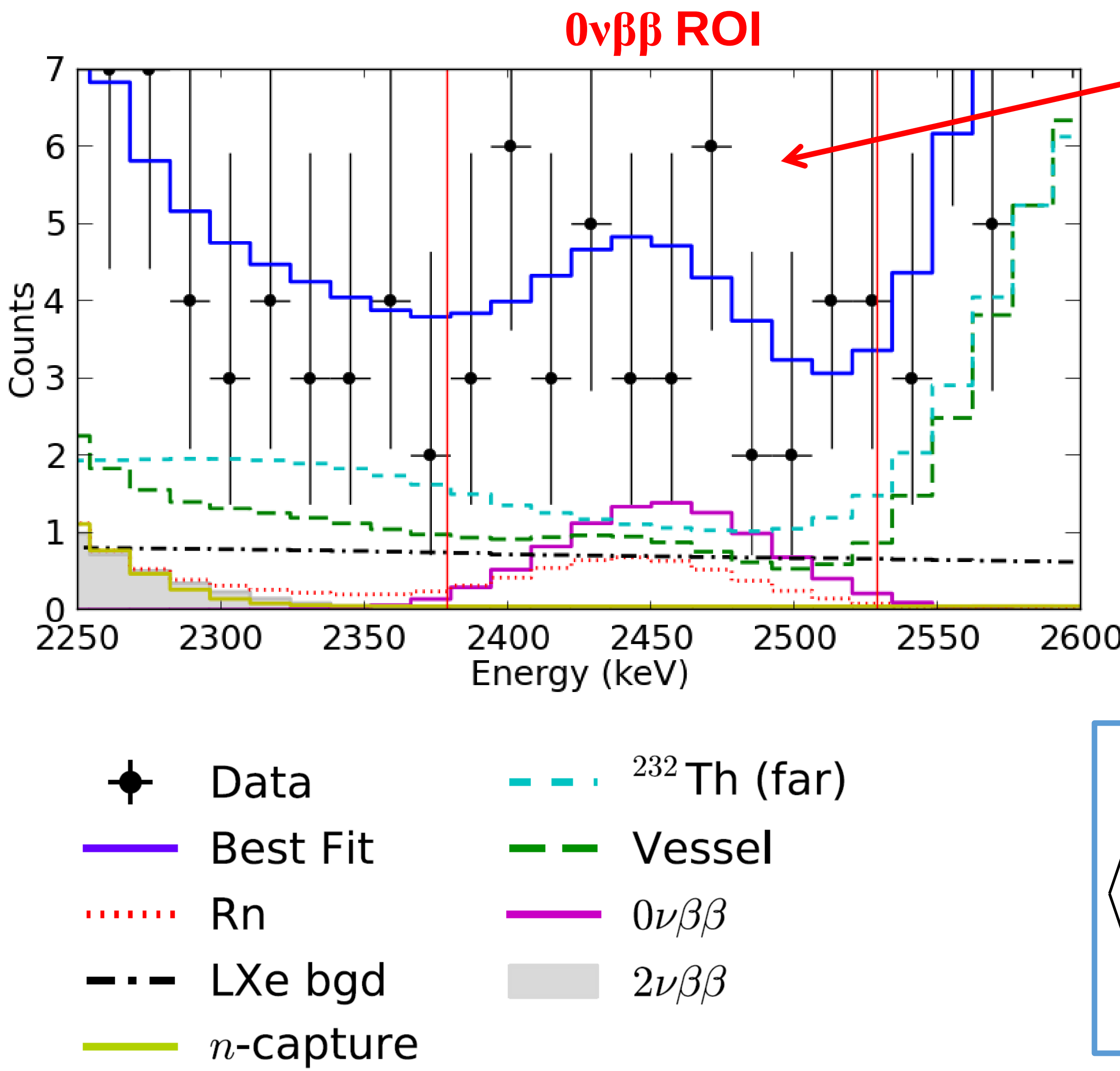
477.60+/-0.01 days of data

^{136}Xe exposure: 99.8 kg yr

Simultaneous fit to energy and standoff distance for SS and MS

Nature 510, 229 (2014)

Recent 0νββ decay result



39 counts in ±2σ ROI

Background fit in ±2σ ROI	
^{232}Th	16.0
^{238}U	8.1
^{137}Xe	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 510, 229 (2014)

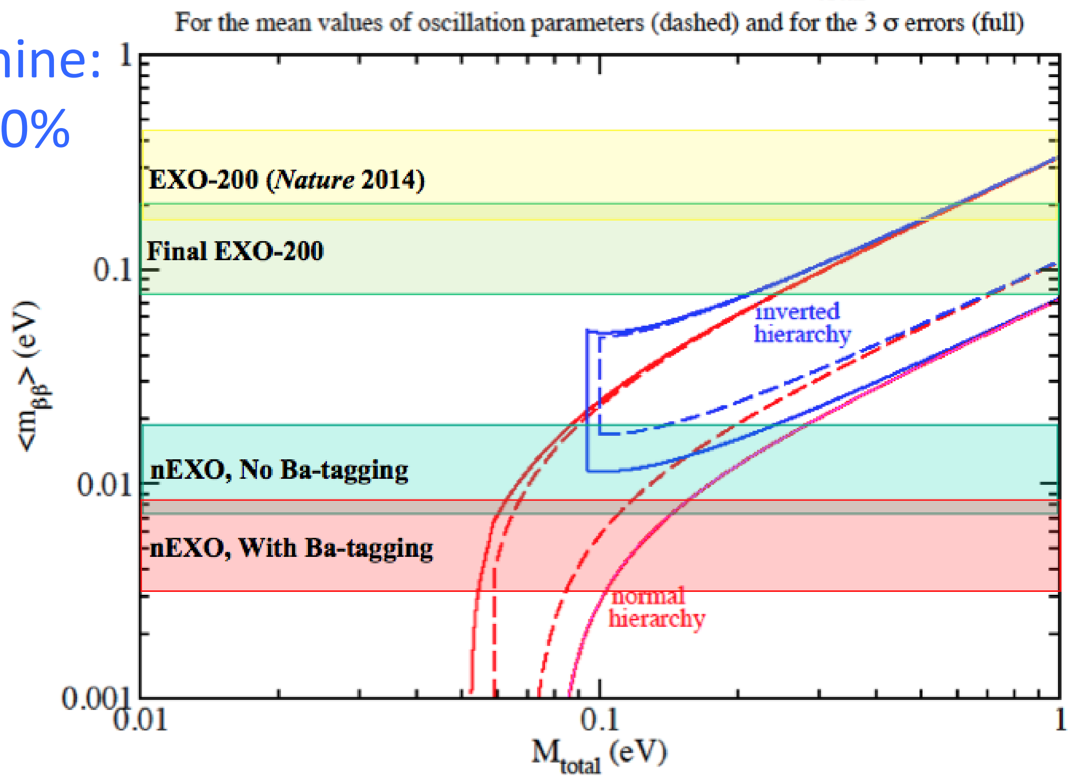
Phys. Rev. Lett. 109, 032505 (2012)

0νββ search with EXO

Multi-phase program :

- **EXO-200** – operational at WIPP mine:
  - ~175kg xenon enriched at ~80%
  - Current limit on 0νββ: 1.1 x 10^{25} years (EXO-200)
  - Continue data taking for 2 more years
  - Sensitivity: 100-200 meV

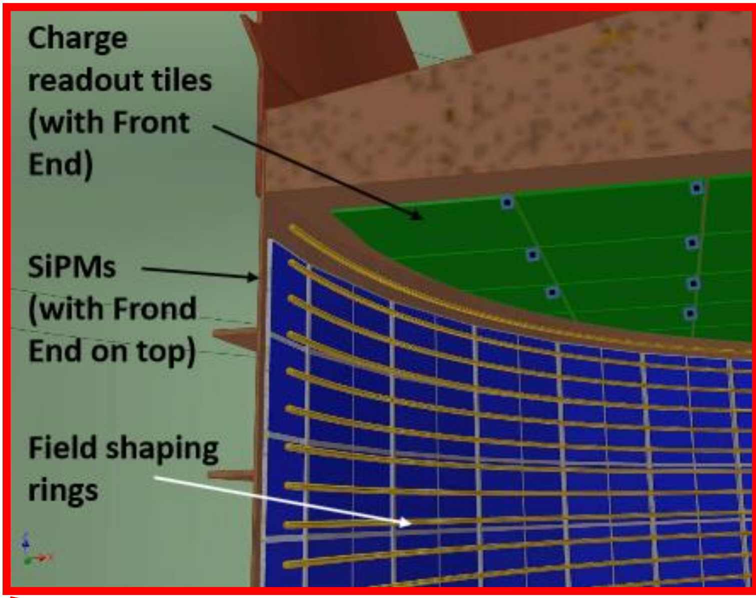
- **nEXO** - R&D underway:
  - 5T xenon enriched at ~90%
  - Sensitivity: 5-30 meV
  - Improved techniques for background suppression and possibly Ba tagging

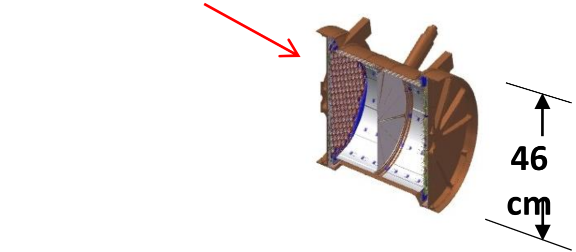


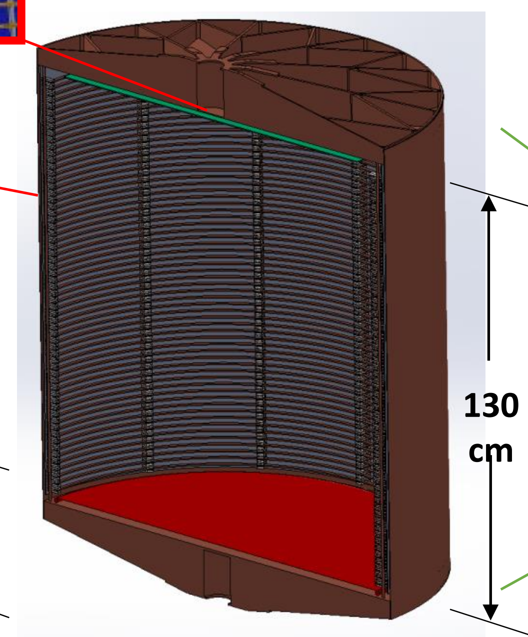
→ **Development of nEXO is well advanced**

Searching for 0νββ with nEXO

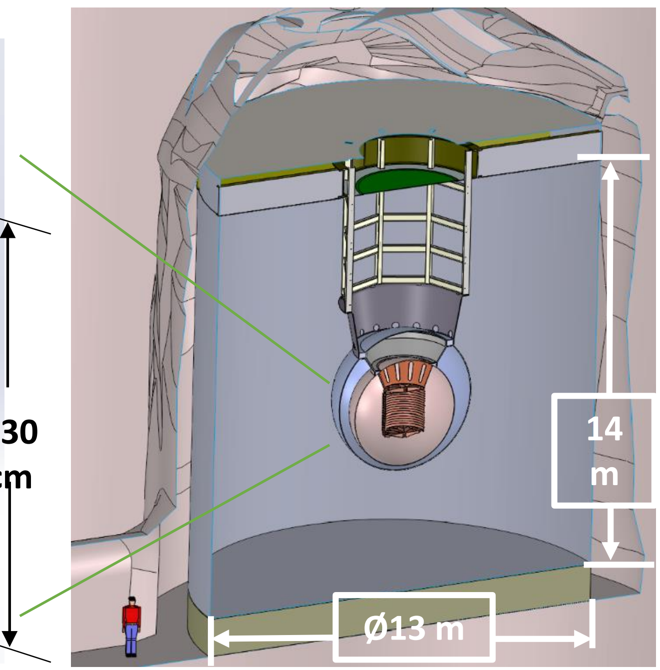
- Next-generation neutrinoless double beta decay detector
- 5 t liquid xenon TPC similar to EXO-200 (50x the size)
- Possible location in SNOLab Cryo Pit (6010 mwe)
- SiPM for light detection
- Tiles for charge read out
- 3D event reconstruction
- Required σ/E of 1% at Q-value
- Possible addition of Ba-tagging after 5 years







nEXO TPC



nEXO at the SNOlab Cryopit

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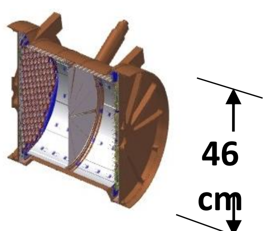
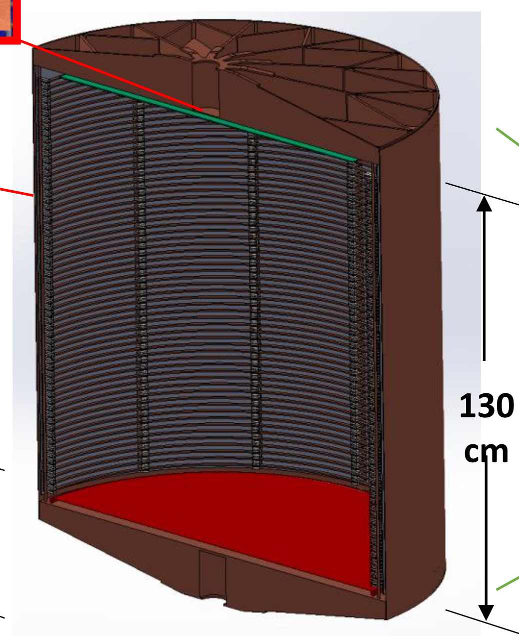
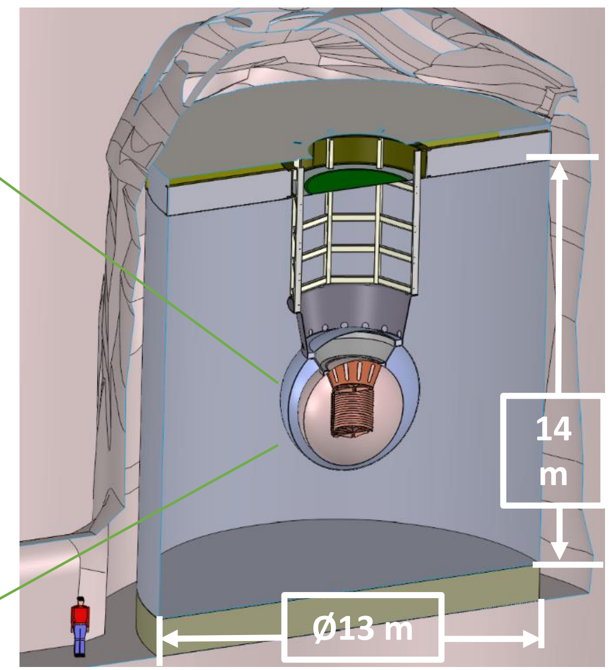
EXO-200 for size comparison



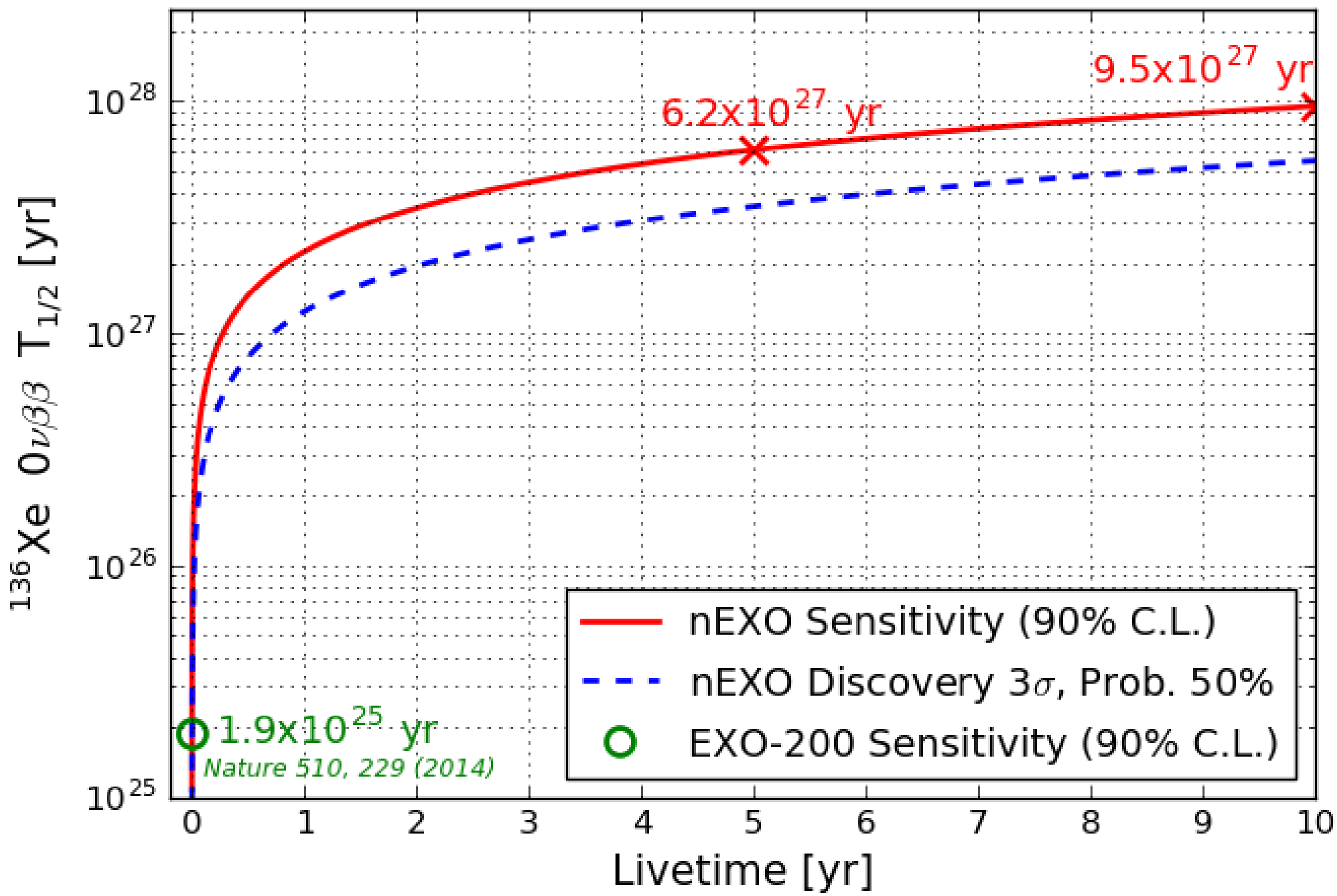


nEXO TPC



nEXO at the SNOlab Cryopit

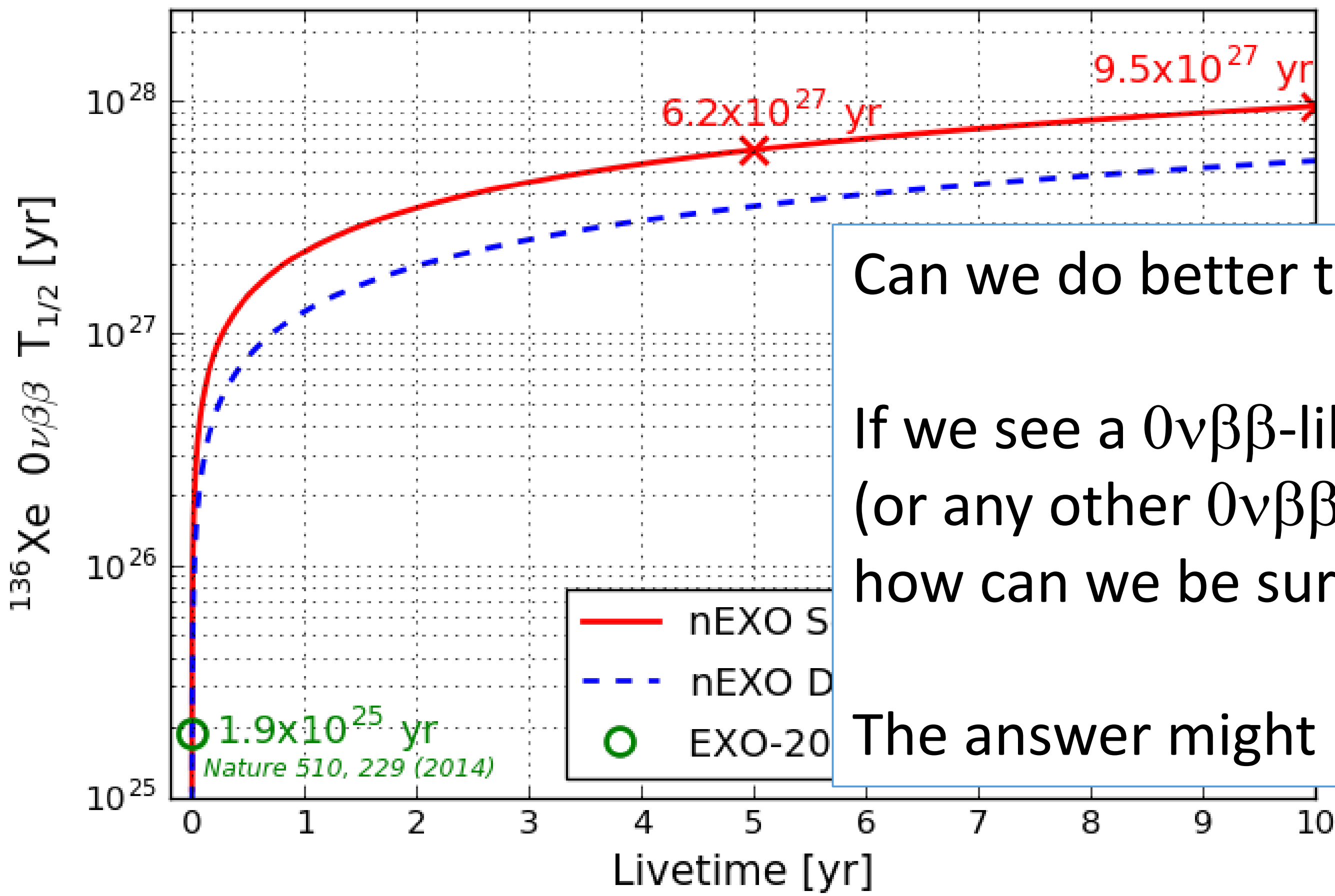
nEXO Sensitivity & Discovery Potential



Methodology:

- 3860 kg fiducial Xe
- 90% enrichment
- 1% σE/E resolution
- Realistic background projections based on measurements
- EXO200-like analysis

nEXO Sensitivity & Discovery Potential



Methodology:

- 3860 kg fiducial Xe

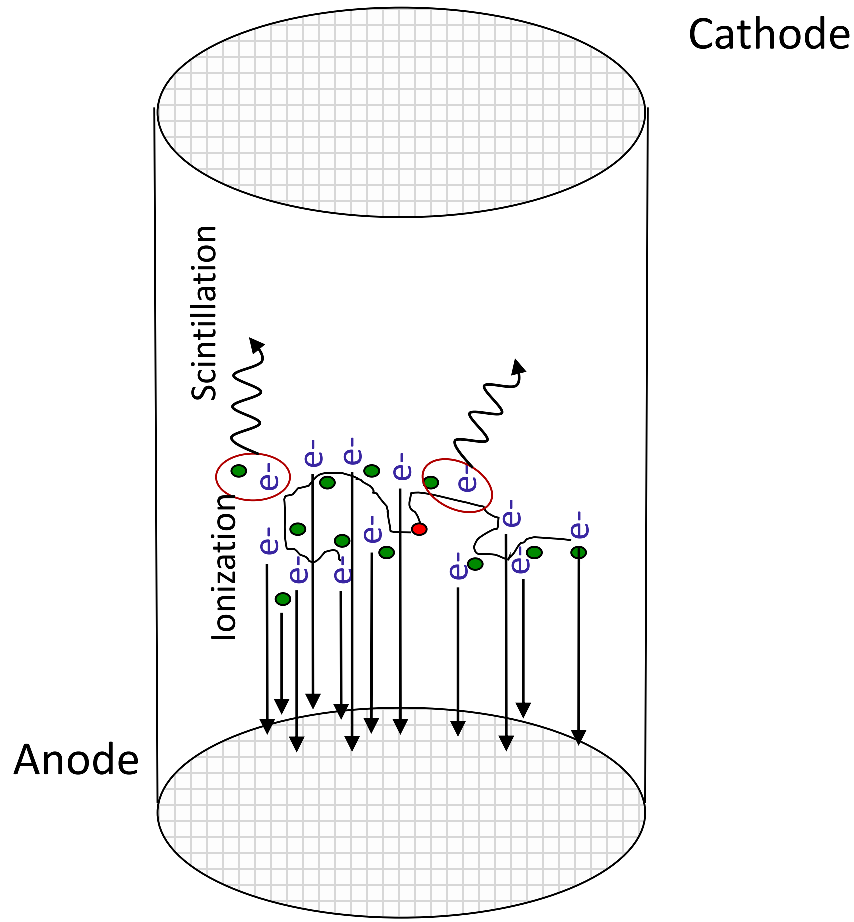
Can we do better than this?

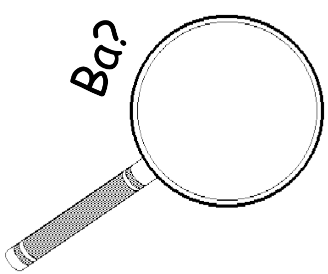
If we see a $0\nu\beta\beta$-like signal with nEXO (or any other $0\nu\beta\beta$ detector), how can we be sure it really is $0\nu\beta\beta$?

The answer might be Ba-tagging.

Ba-tagging concept

1. Localize event √
2. Is the event of interest?
   - Close to Q-value? √
   - Beta-like event?
3. Extract ion from detector volume ?
4. Identify ion: is it barium? √

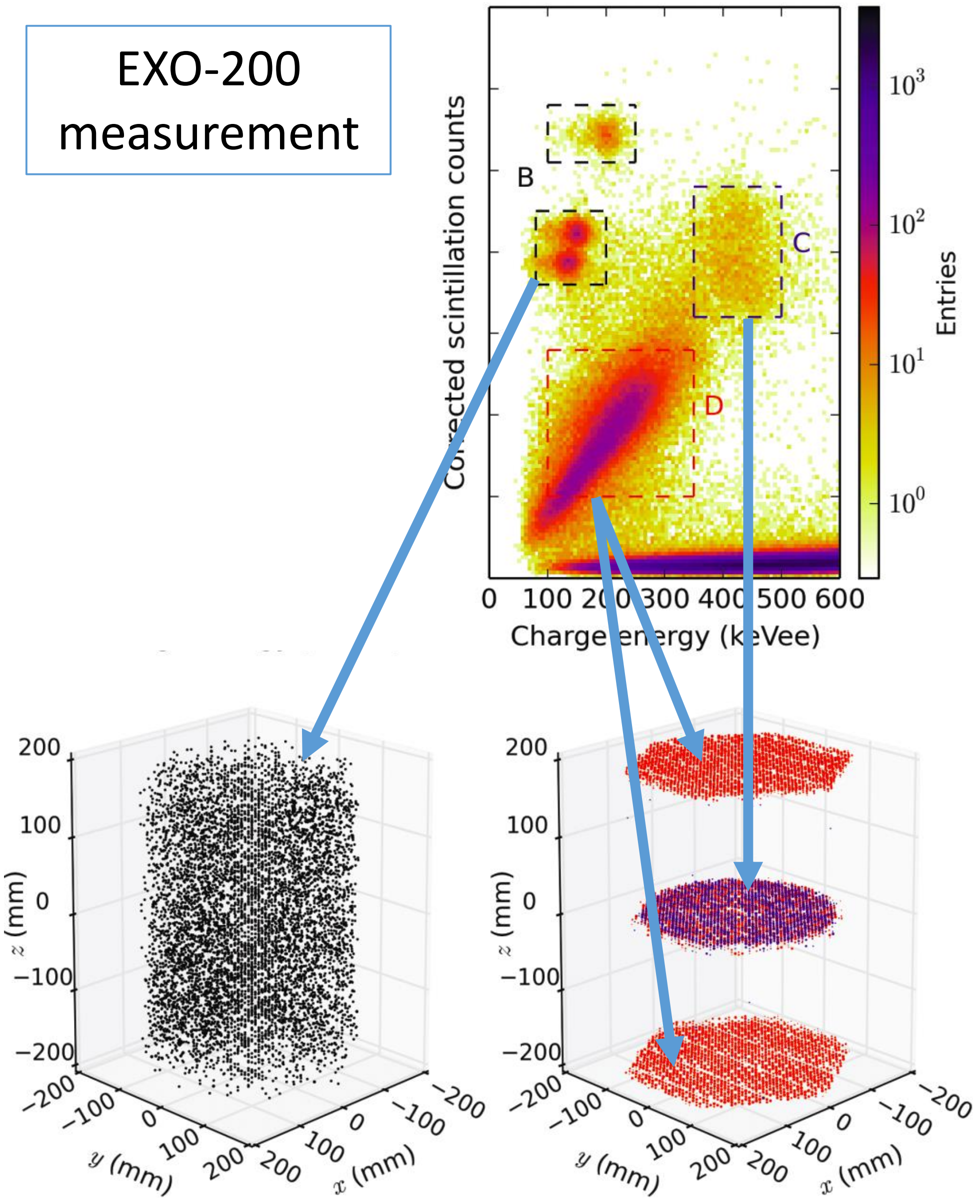


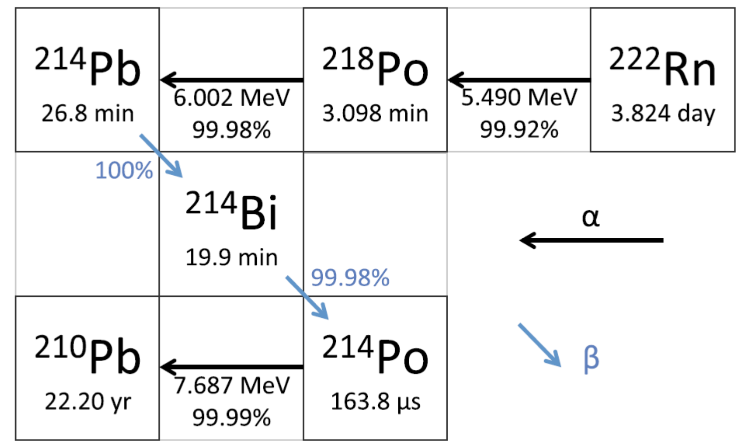


Ba tagging R&D ongoing for liquid- and gas-phase detector

Ion Fraction in LXe after α and β Decay

EXO-200 measurement





EXO-200 with drift field 380 ± 5 V/cm

Ion Fraction

^{214}Bi$^+$ from ^{214}Pb β decay: 76.4 ± 5.7%

^{218}Po$^+$ from ^{222}Rn α decay: 50.3 ± 3.0%

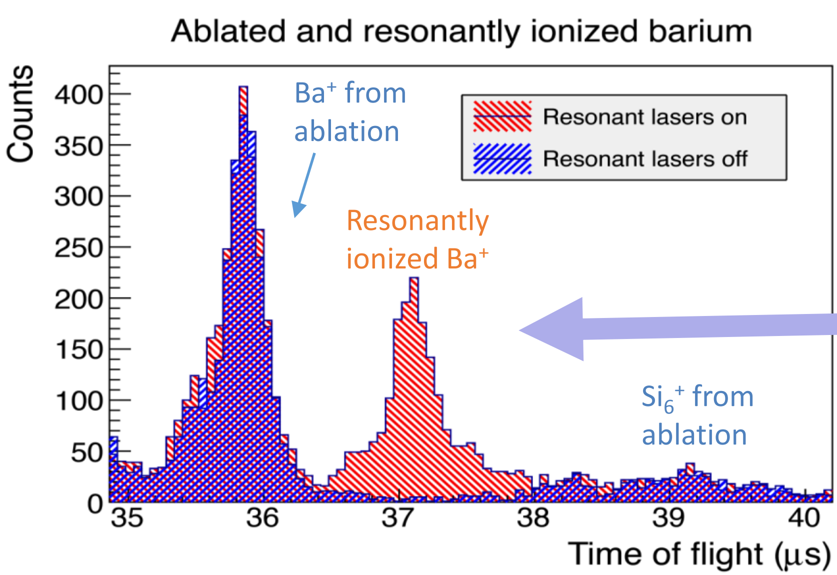
Phys. Rev. C 92(2015)045504

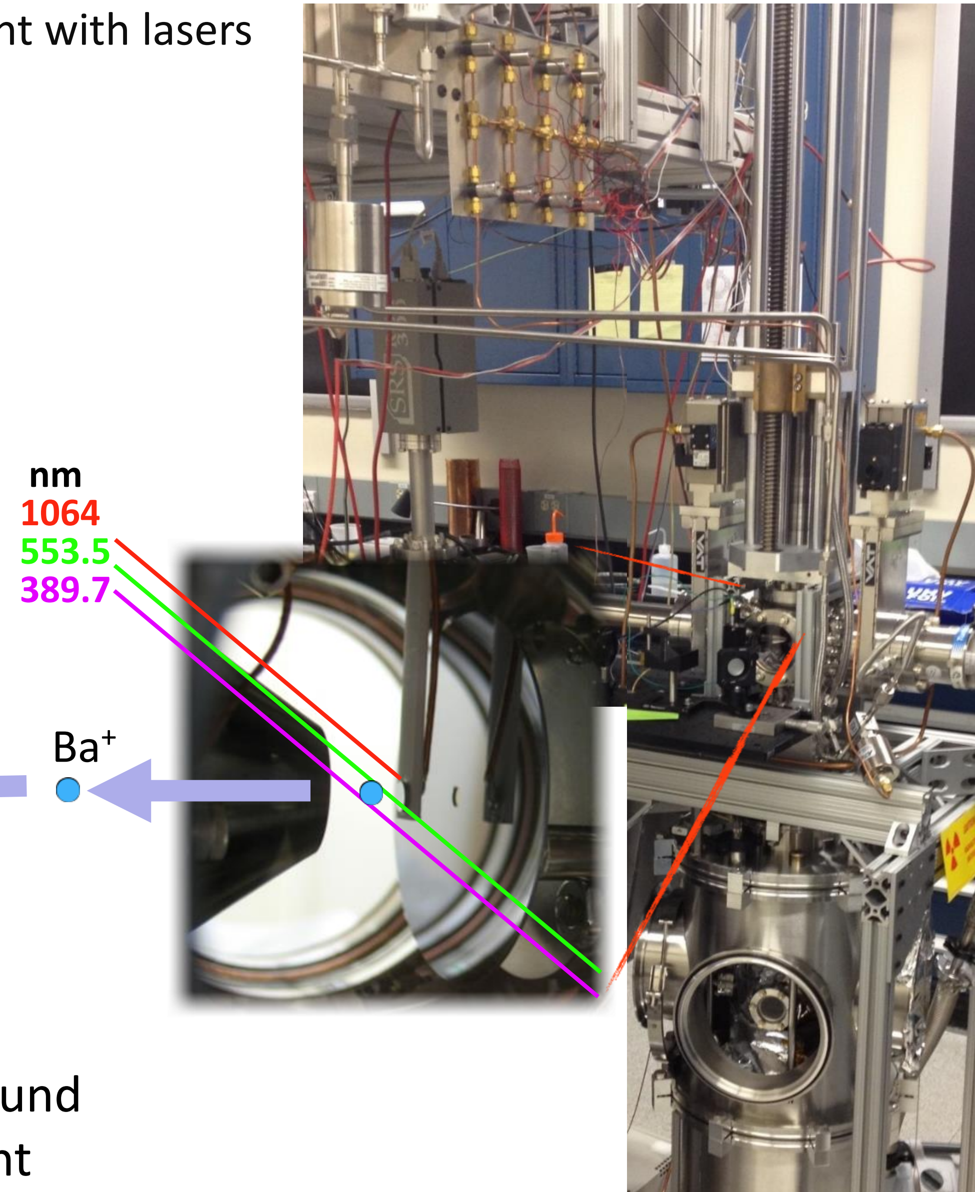
RIS Ba$^+$ tagging at Stanford

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



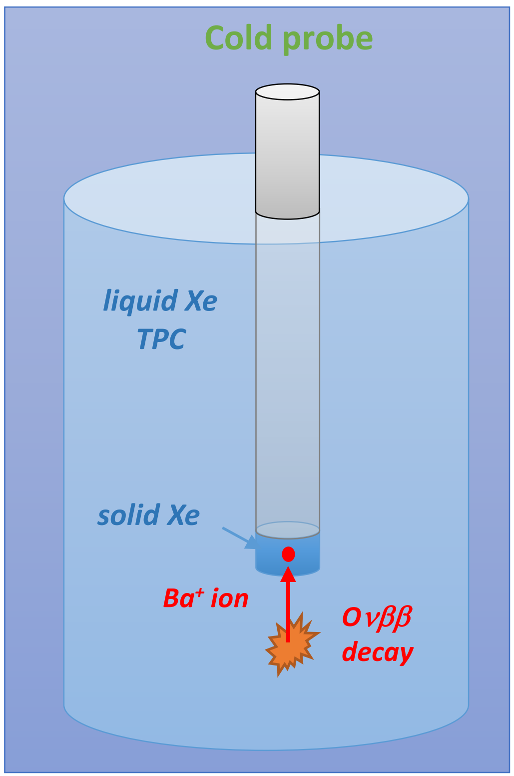


RIS and ablated Ba$^+$ as well as background ablated ions separated by time-of-flight

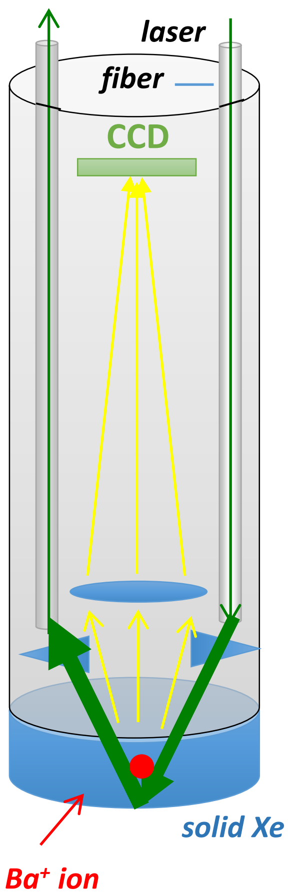
Barium tagging in solid xenon (CSU)

Tagging concept

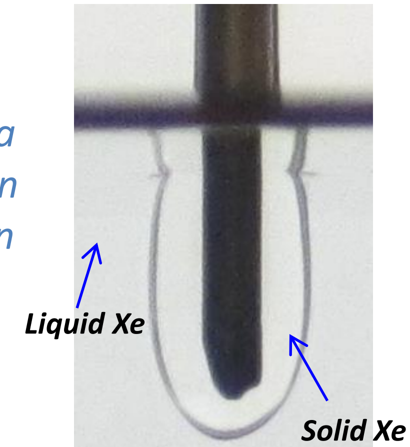
1, Capture Ba^+ daughter in solid xenon on a probe:



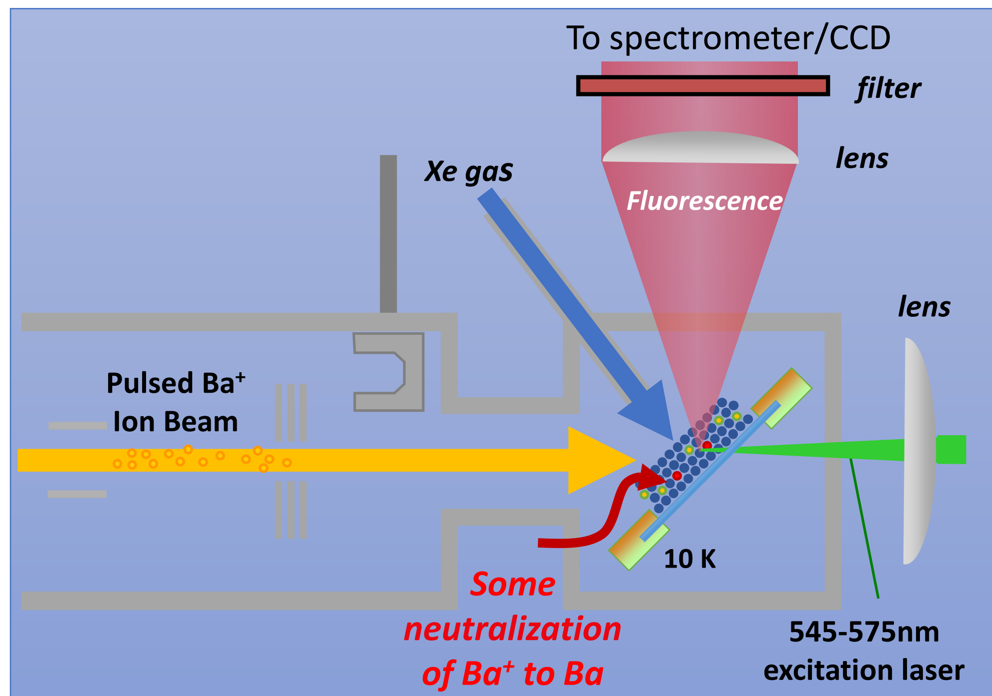
2, Detect single Ba^+ or Ba on probe by fluorescence:



Solid Xe formed on a cryoprobe in liquid xenon



Barium tagging test apparatus



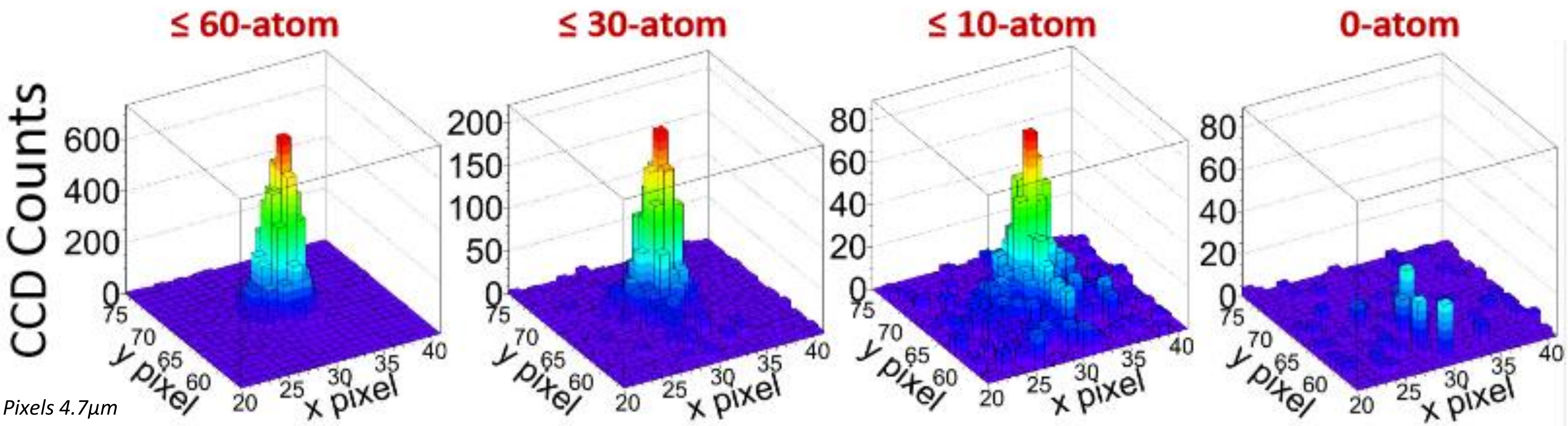
Details:
Mong et al. (nEXO collaboration), PRA 91, 022505 (2015)

Successful spectroscopy of Ba-ions in SXe (CSU)

Technique to reach small-number sensitivity:

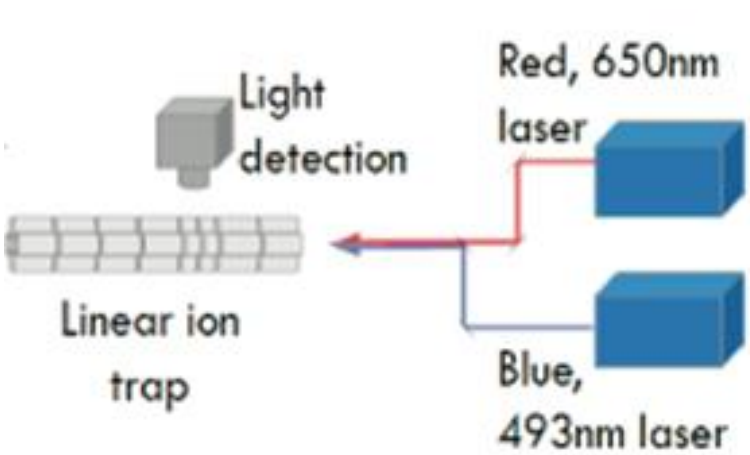
1. Focus laser down to w = 2.3μm for small viewing area
2. Pulse ion beam with varying numbers of pulses

Imaging 619nm Fluorescence
~220 cts/(atom *mW)

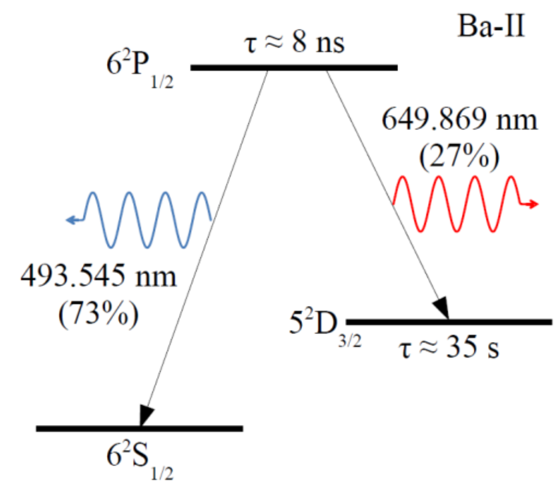


Pixels 4.7μm

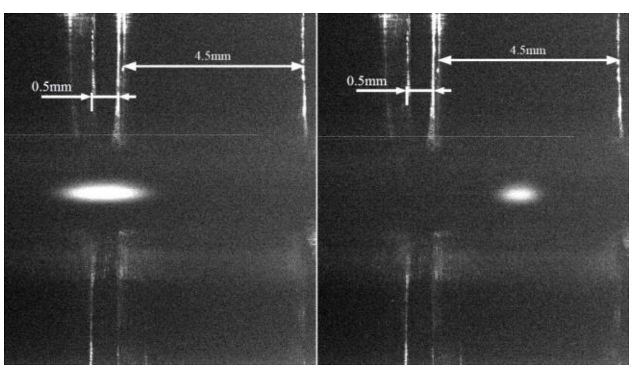
Ba ion detection & identification (Carleton)



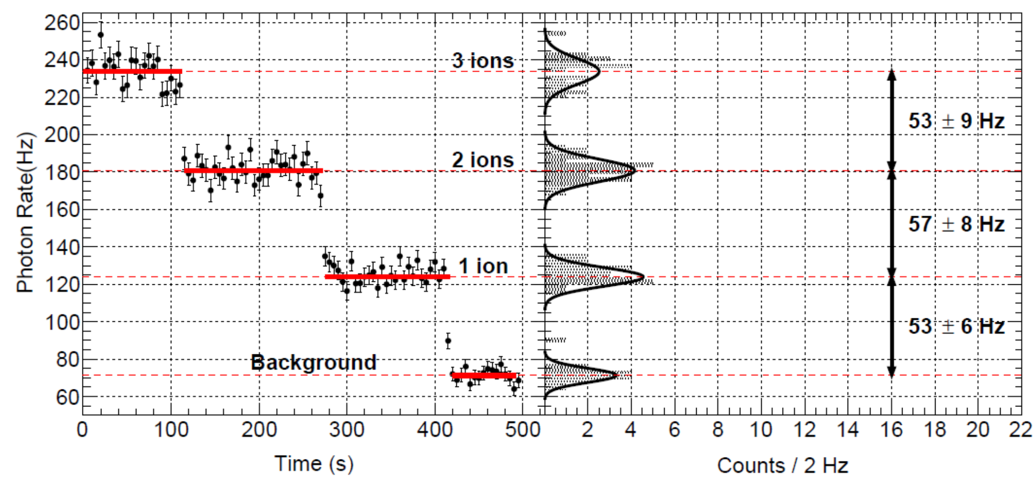
Using a relatively simple and well understood fluorescing system



Demonstrated ion cloud imaging and accurate position control

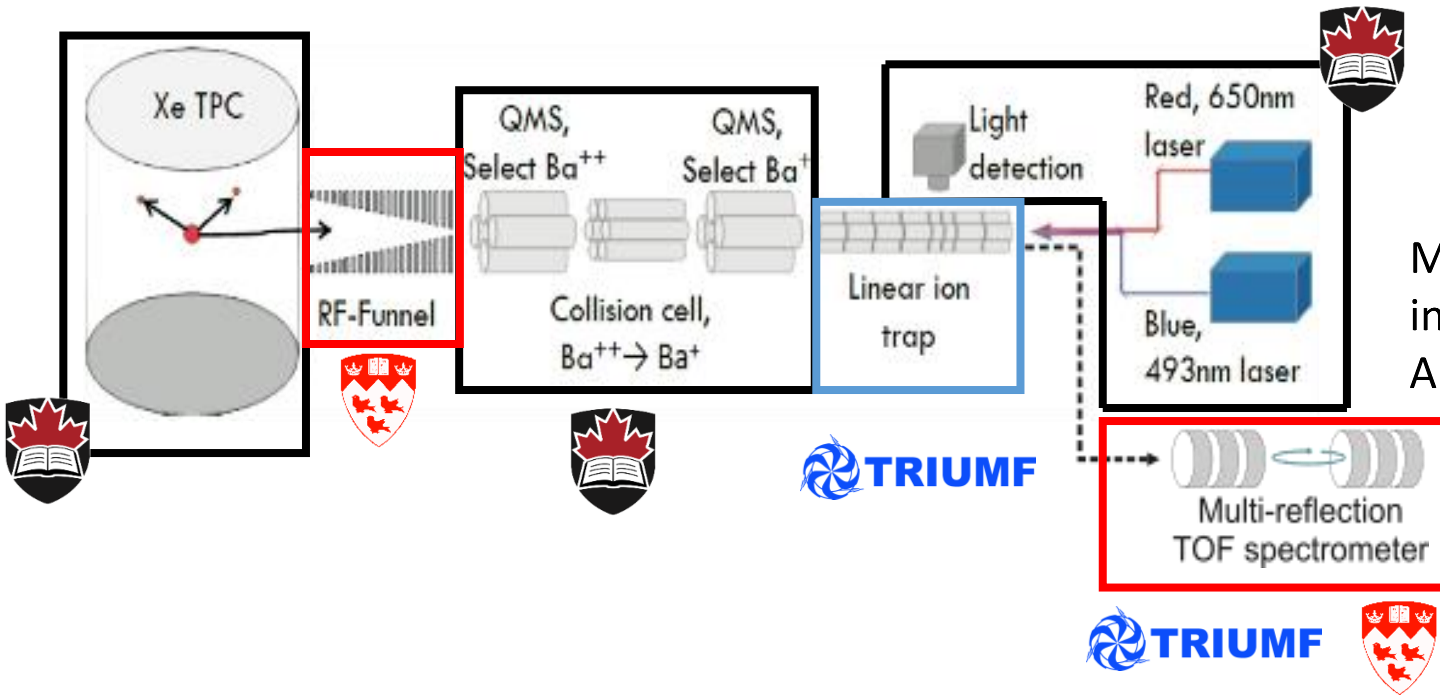


Demonstrated single ion sensitivity using intermodulation technique (background control)



Slide courtesy from R. Gornea

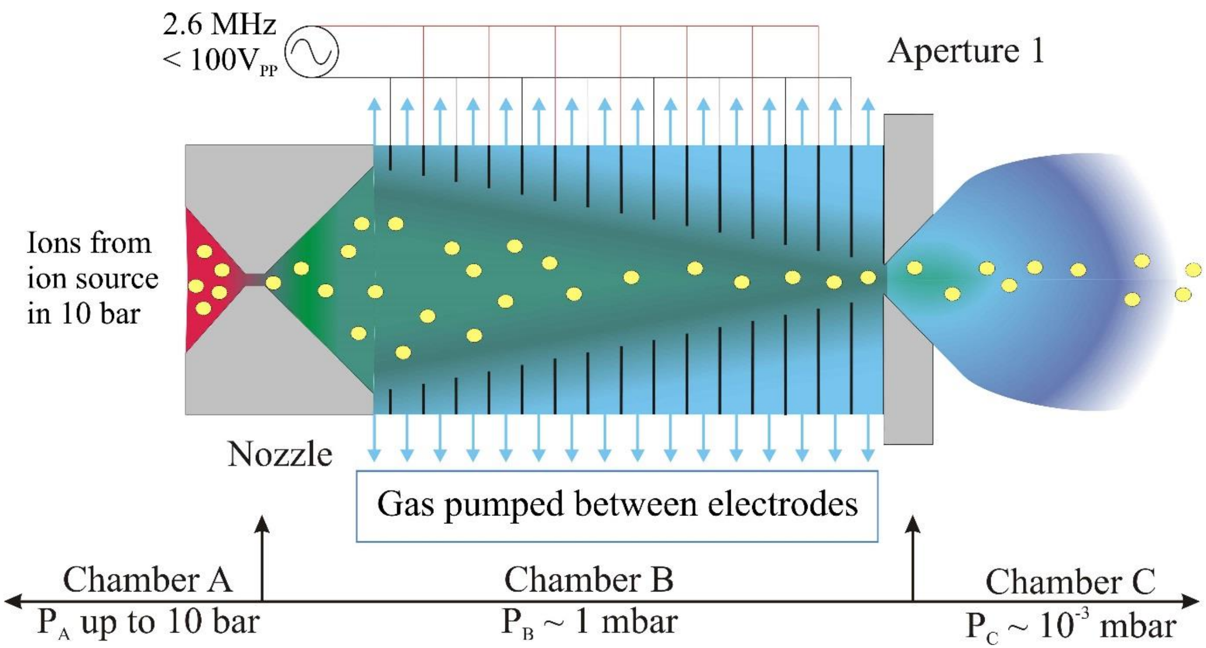
Ba-ion extraction and identification – the Canadian approach



MR-TOF introduced by A. Kwiatkowsi

- Extract $Ba^{+(+)}$ from liquid Xe TPC into a Xe gas environment
- Extract $Ba^{+(+)}$ with a Xe gas jet into a low pressure chamber
- After nozzle, pump Xe gas away and guide $Ba^{+(+)}$ to identification

RF funnel concept



RF-funnel concept:

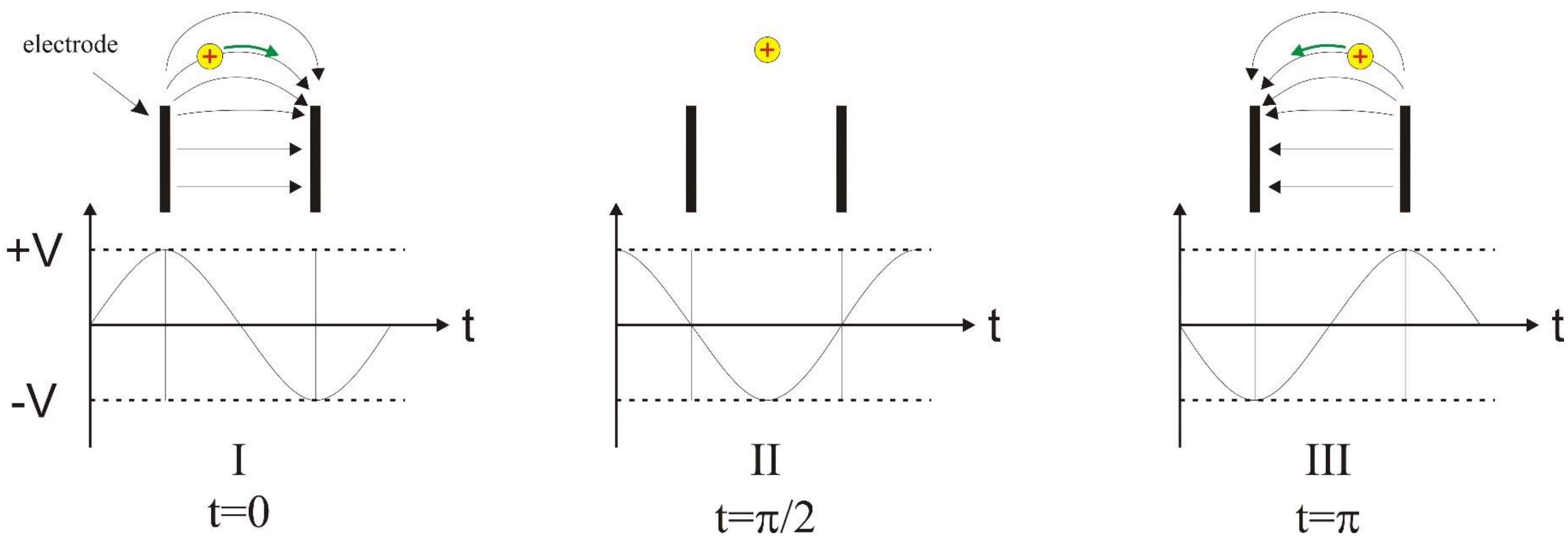
- Converging-diverging nozzle
- 2 Stacks total 301 electrodes
- RF-field applied to electrodes
- P_A = 10 bar, P_B = 1 mbar

V_{RF} = 120 V, f = 10 MHz

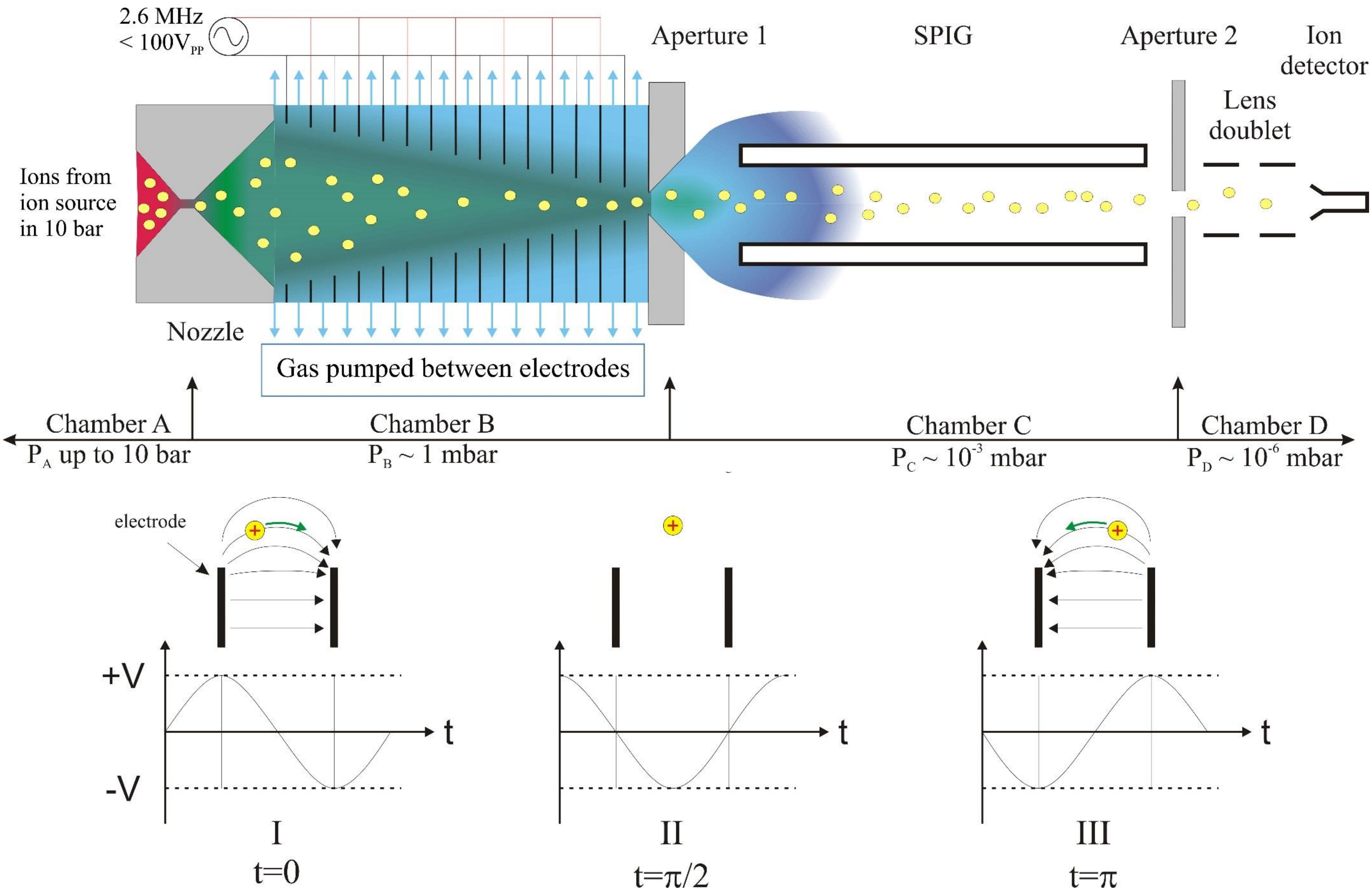
Simulated Ba^+ transmission ~95%

V_{RF} = 25V, f = 2.6 MHz

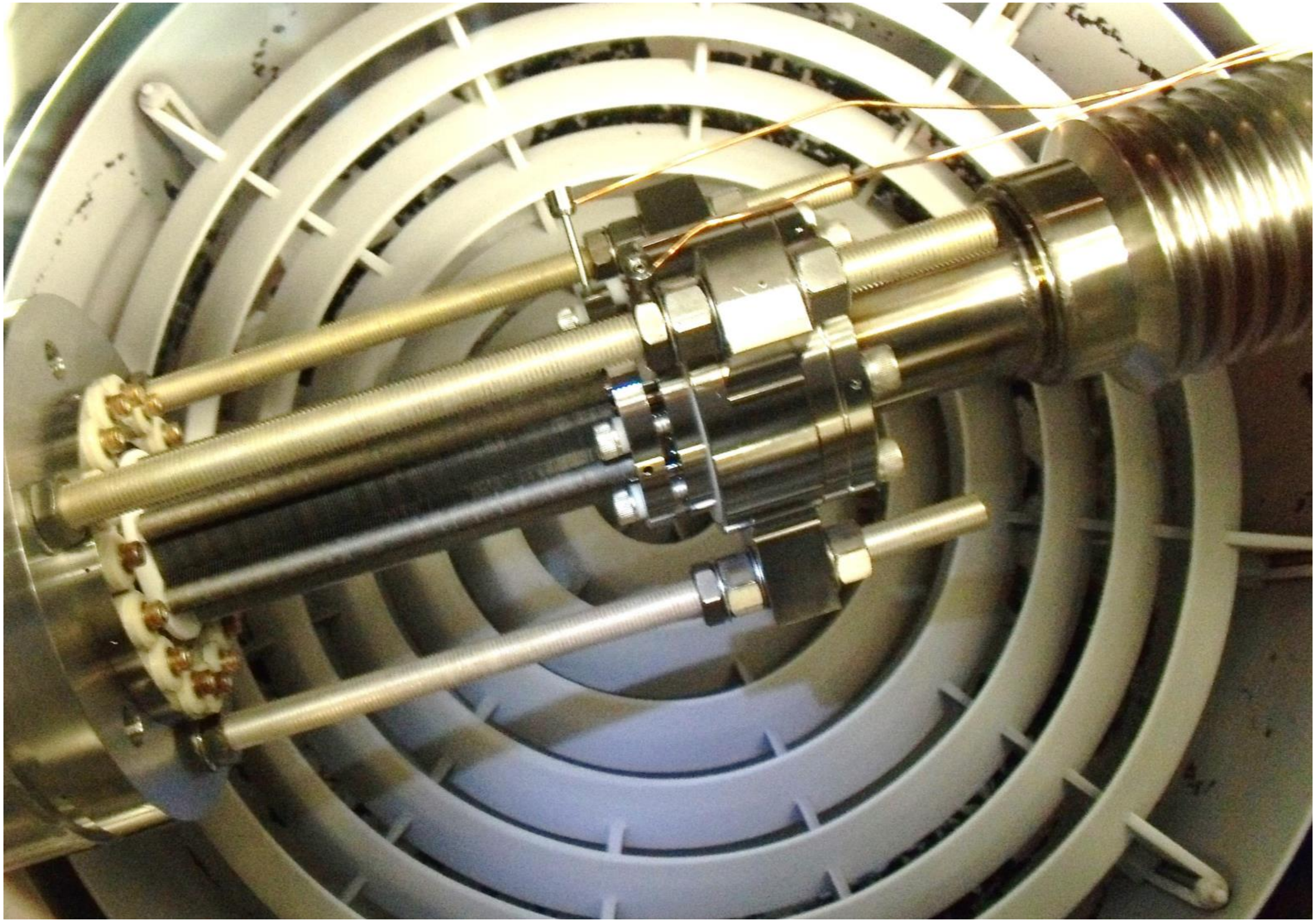
Simulated Ba^+ transmission ~72%



RF funnel concept

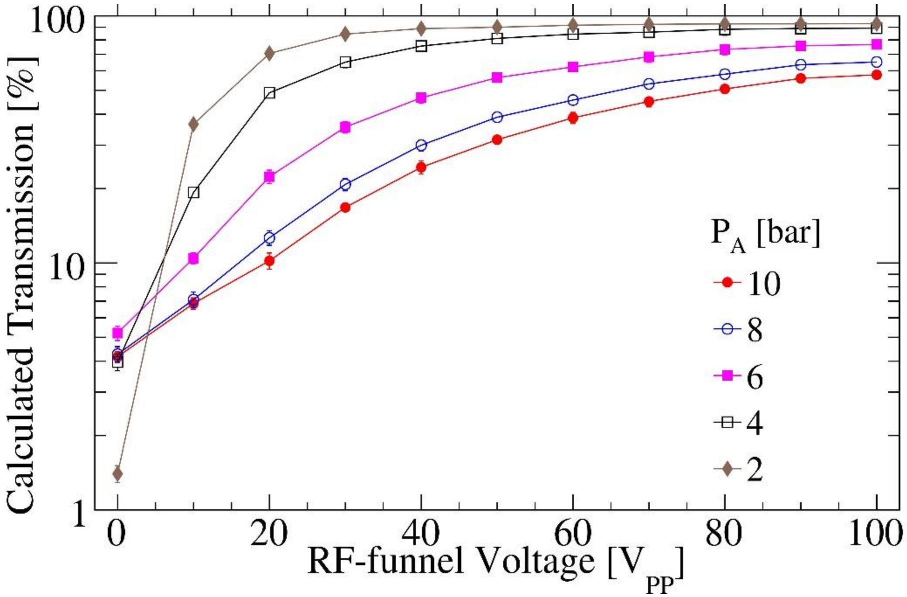


Funnel during xenon operation

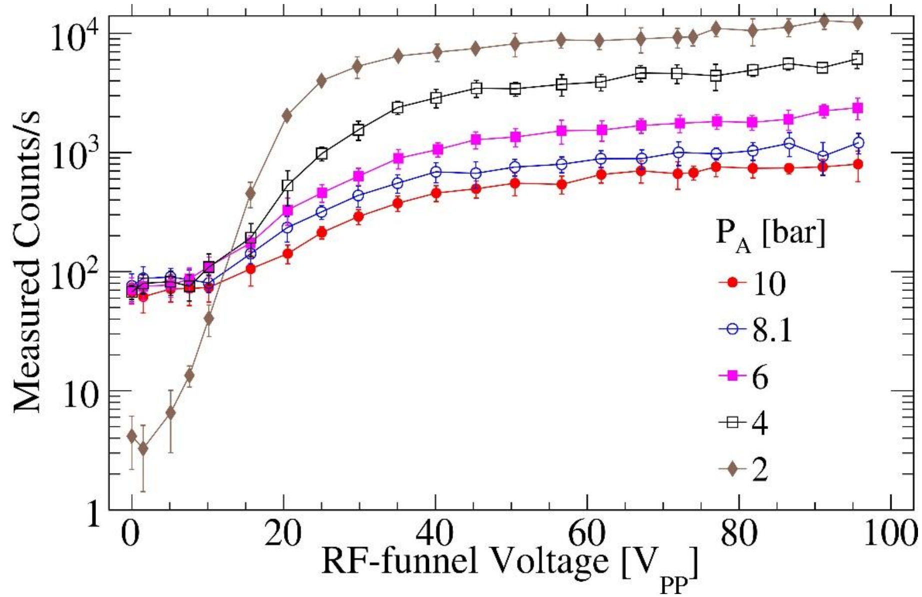


Ion extraction in xenon gas

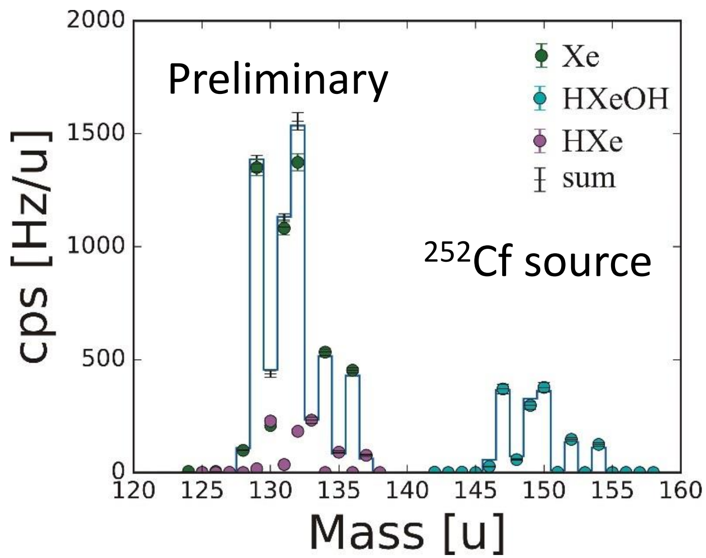
Calculation



Measurement



- General shape well reproduced
- Ion extraction up to 10 bar!
- Ba-ions not identified!
- Ion extraction efficiency unknown!



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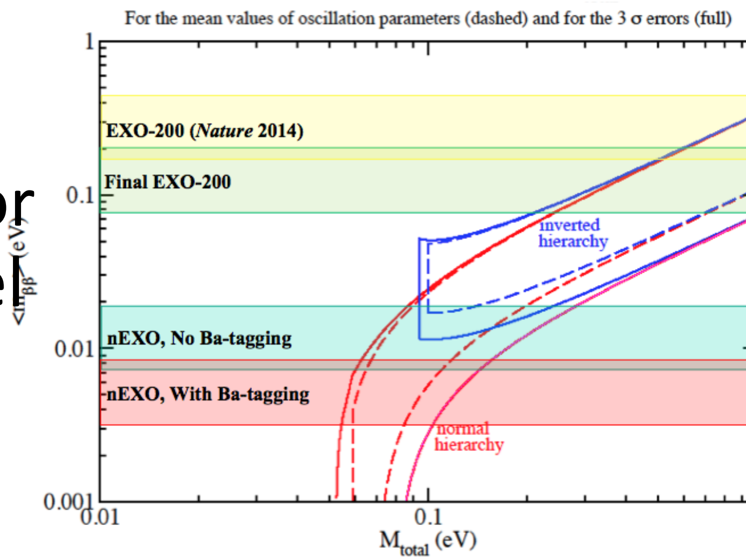
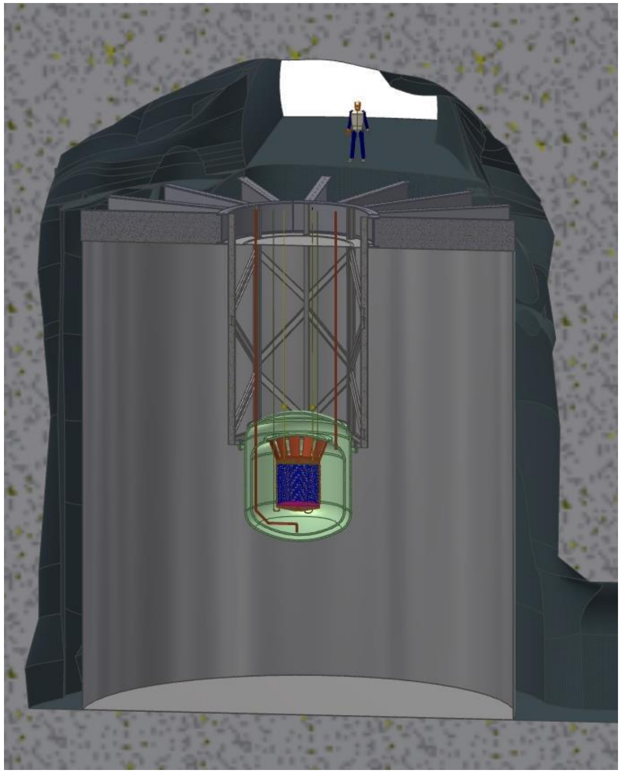
Summary & Plans

- EXO-200 and nEXO are searching for physics beyond the Standard Model
- nEXO is the next generation $0\nu\beta\beta$ experiment with 5 T isotopically enriched LXe
- The 10meV region is within reach with nEXO
- Ba-tagging will increase the sensitivity of $0\nu\beta\beta$ search
- Ba-tagging will allow verification of a possible $0\nu\beta\beta$ signal





The nEXO Collaboration

Enriched Xenon Observatory for double beta decay

Thank you for your attention

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