nEXO: The Next Genergation Double-Beta Decay Experiment

Motivation

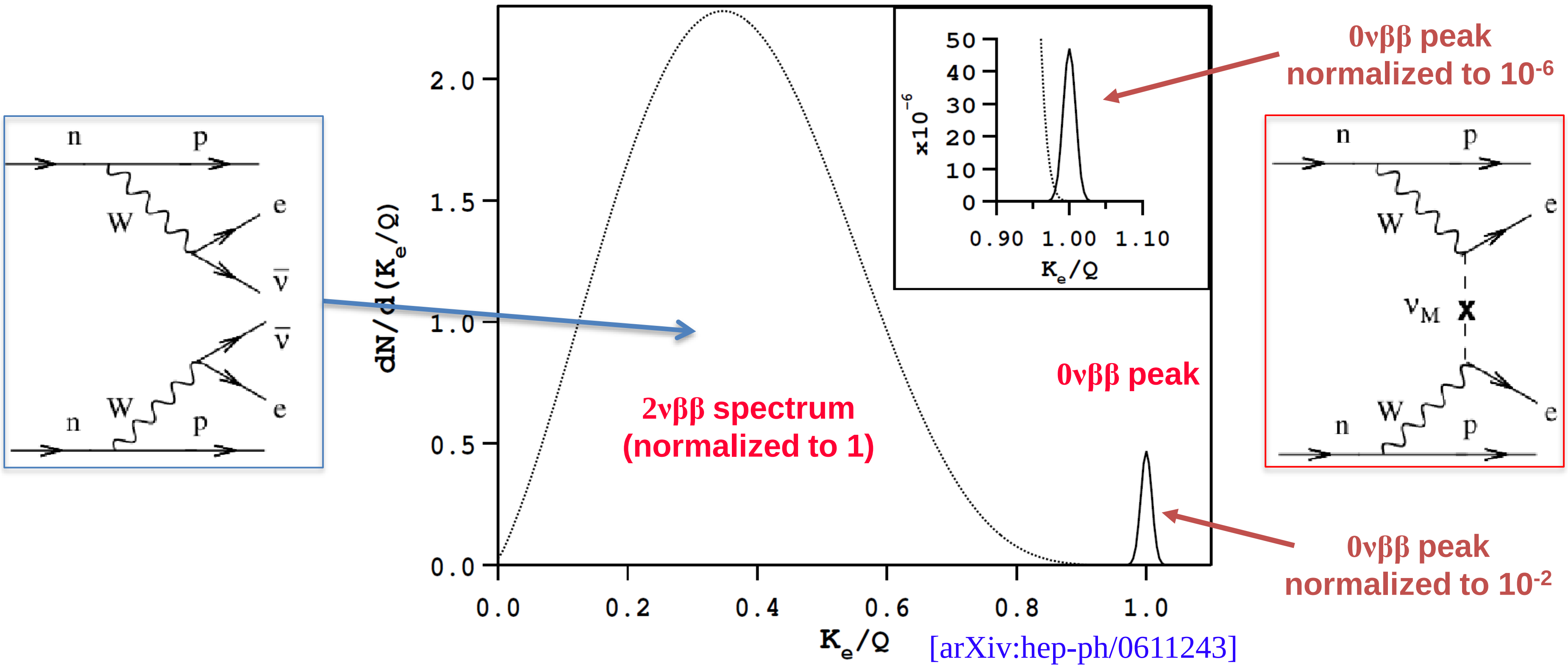
Technique

The nEXO detector

Thomas Brunner for the nEXO collaboration

TRIUMF Science Week – July 13, 2017

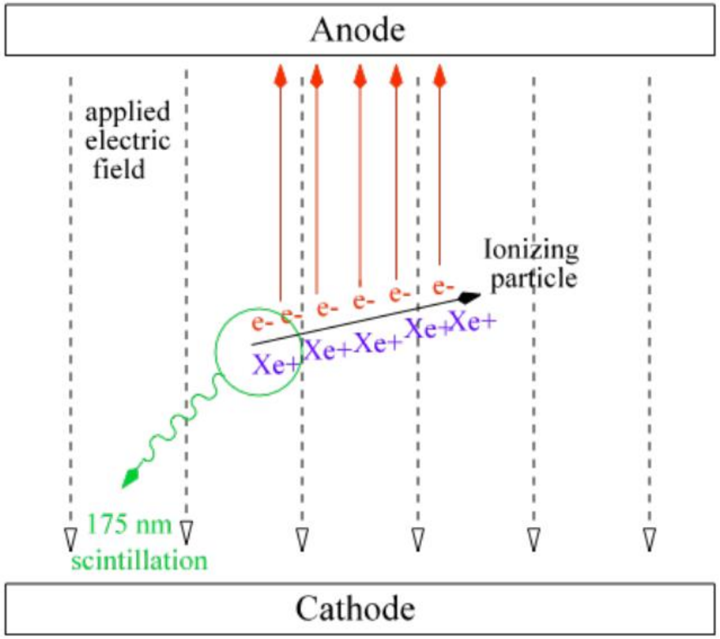
Why search for 0νββ?



An observation would violate Lepton number conservation!

- What is the absolute mass scale? How heavy is the neutrino?
- Why is the neutrino mass so small?
- Why are we living in matter-dominated universe?
- What is the nature of the ν: Dirac or Majorana?

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

<u>Natural radiation decay rates</u>

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
- Very good understanding of BGND
- good energy resolution

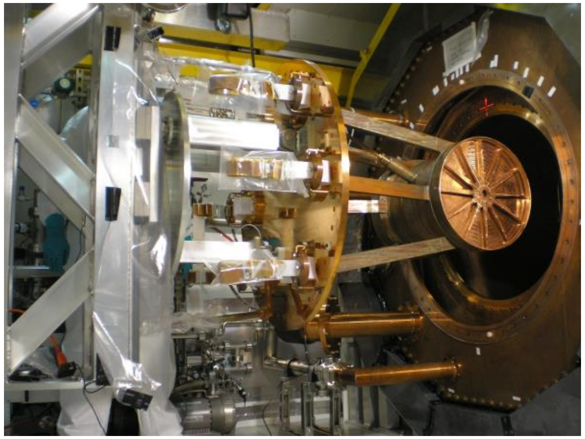
EXO– Enriched Xenon Observatory

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

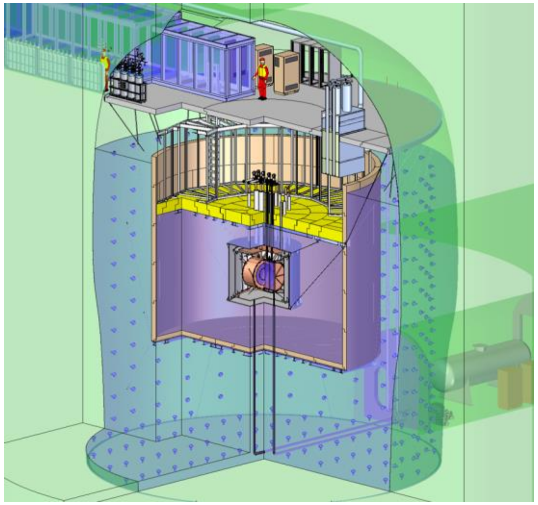
- Easy to enrich: 8.9% natural abundance but can be enriched relatively easily
- Can be purified continuously, and reused
- High $Q_{\beta\beta}$ (2458 keV): higher than most naturally occurring backgrounds
- Minimal cosmogenic activation: no long-life radioactive isotopes
- Energy resolution: improves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

Phased approach:

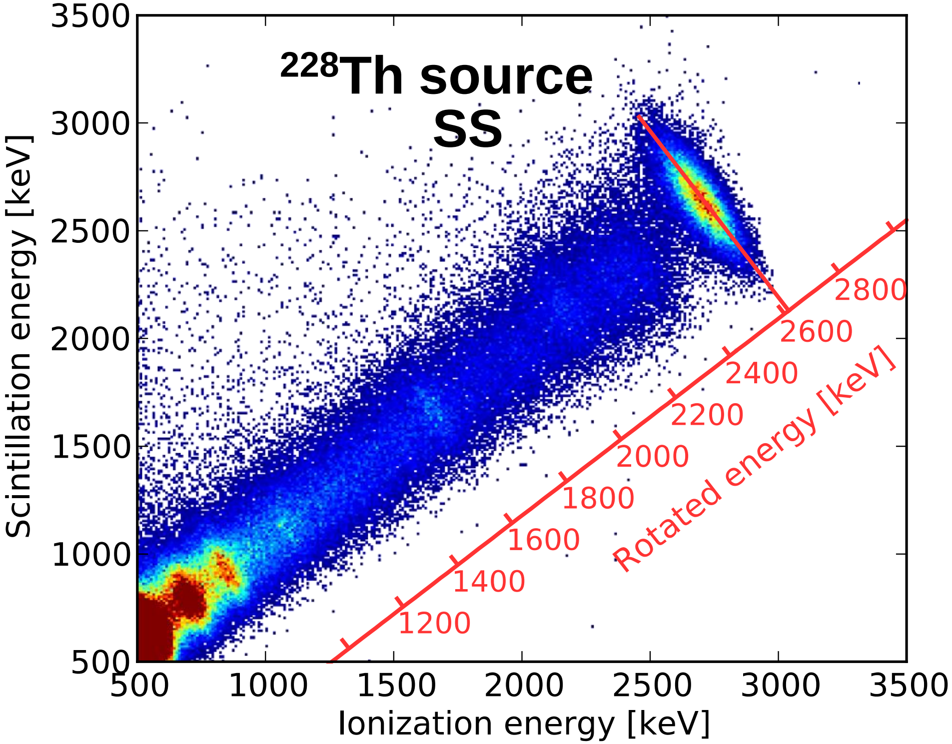
1. EXO-200: 200kg liquid-Xe TPC



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



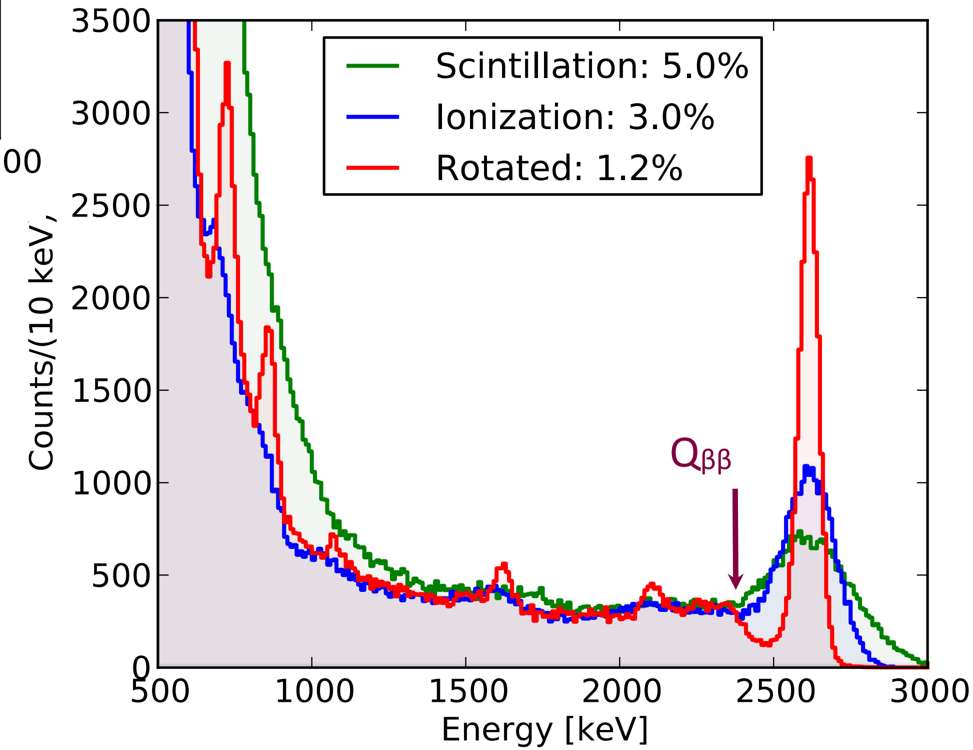
Detector Energy Resolution



Combining Ionization and Scintillation energy to enhance energy resolution

Anticorrelation between scintillation and ionization in LXe known since early EXO R&D

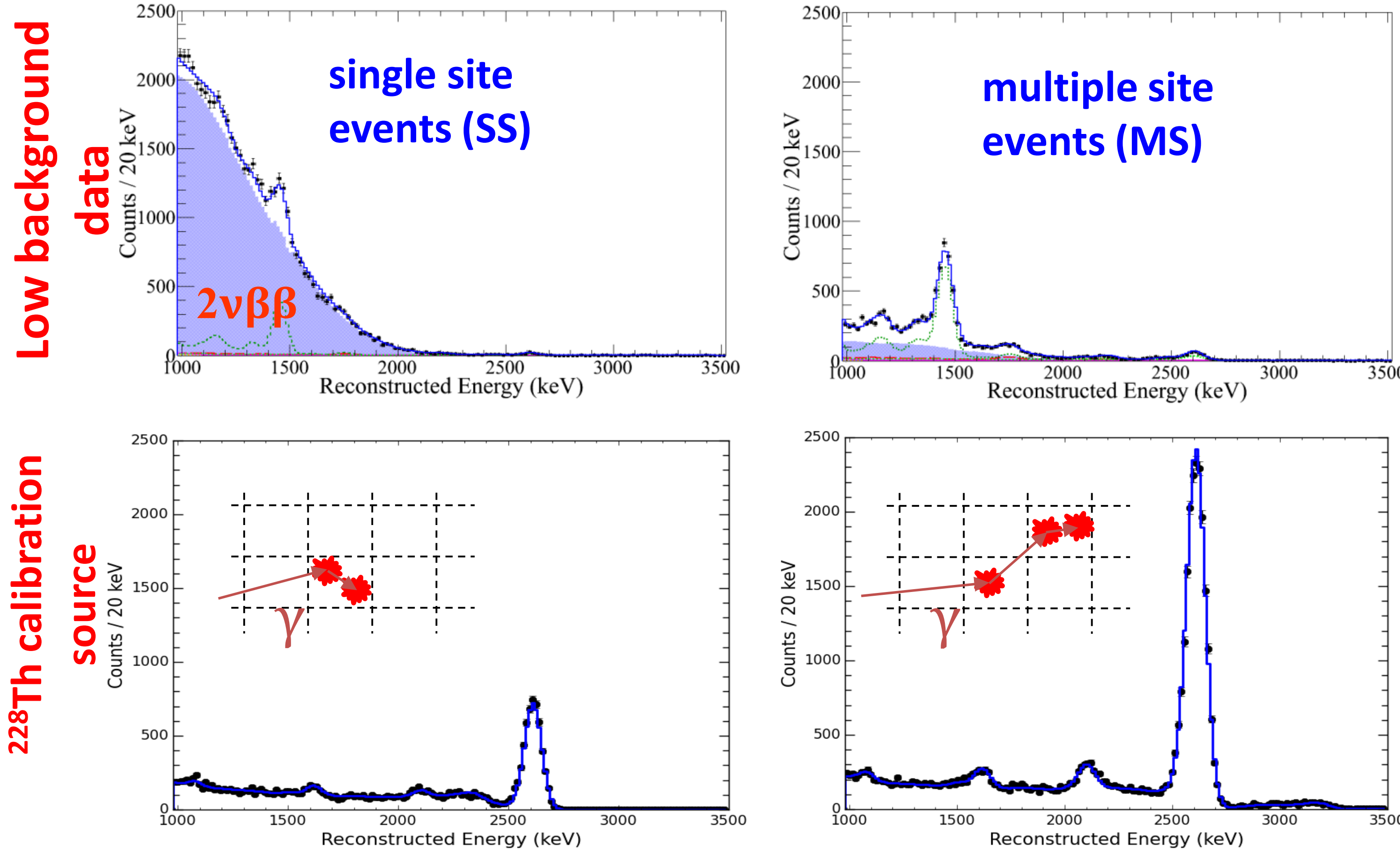
(E.Conti et al. Phys Rev B 68 (2003) 054201)



EXO-200 has achieved ~ 1.25% energy resolution at the Q value.

nEXO will reach resolution < 1%, sufficient to suppress background from 2νββ.

Topological Event Information



- **TPC allows the rejection of gamma backgrounds because Compton scattering results in multiple energy deposits.**
- **SS/MS discrimination is a powerful tool not only for background rejection, but also for signal discovery.**

EXO-200 $(0\nu)\beta\beta$ search

2011 First measurement of $2\nu\beta\beta$ in ^{136}Xe [PRL 107, 212501 (2011)]

2012 First $0\nu\beta\beta$ result, best $m_{\beta\beta}$ limit [PRL 109, 032505 (2012)]

2013 Most precisely measured $2\nu\beta\beta$ rate — and the lowest
→slowest process ever directly measured in nature! [PRC 89, 015502 (2014)]

2014 Improved sensitivity to $m_{\beta\beta}$ [Nature 510, 229 (2014)]

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

$T_{1/2}^{0\nu\beta\beta} > 1.1 \times 10^{25}$ yr @ 90% C.L.

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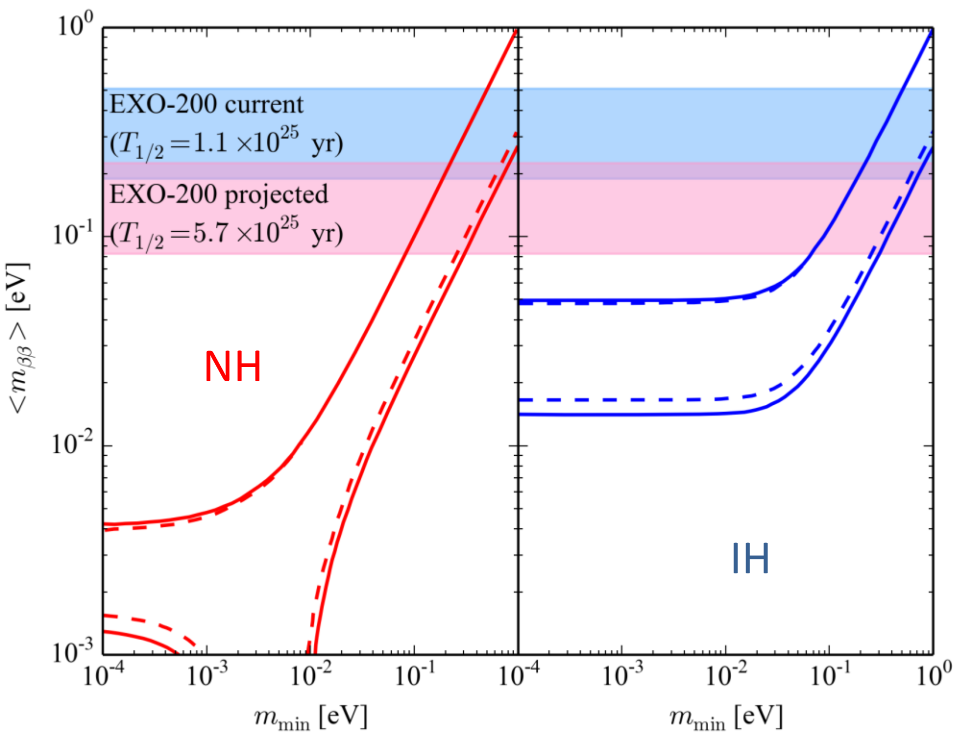


$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2\left\langle m_\nu\right\rangle^2$$

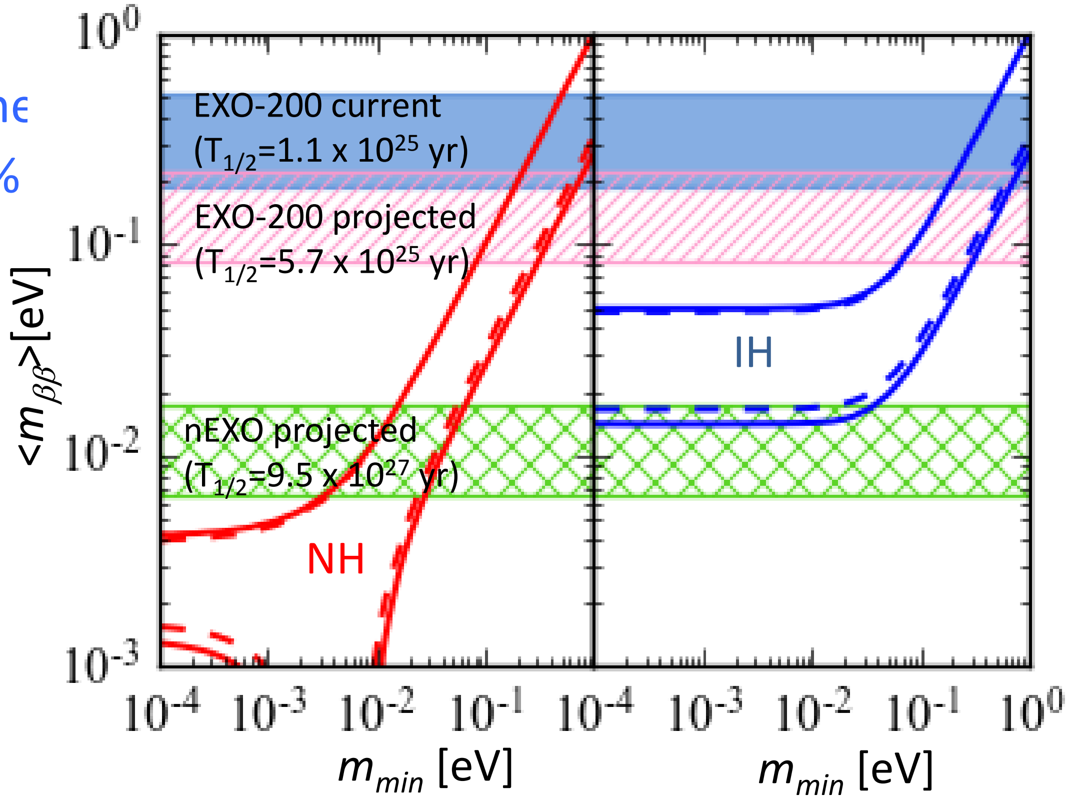
Assuming light neutrino exchange mechanism
$G^{0\nu}$ phase-space factor
$M^{0\nu}$ matrix element

0νββ search with EXO

Multi-phase program :

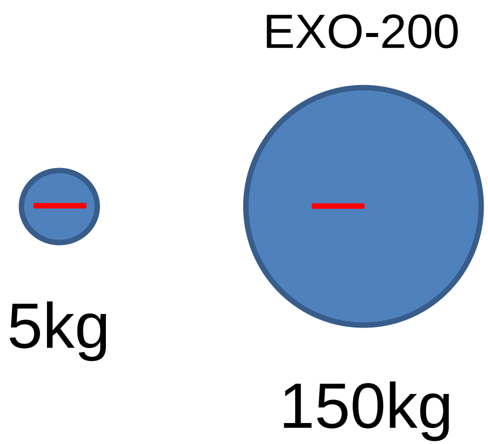
- **EXO-200** – operational at WIPP mine
  - ~175kg xenon enriched at ~80%
  - Current limit on 0νββ: 1.1 x 10^{25} years (EXO-200)
  - Continue data taking for 2 more years
  - Sensitivity: 100-200 meV

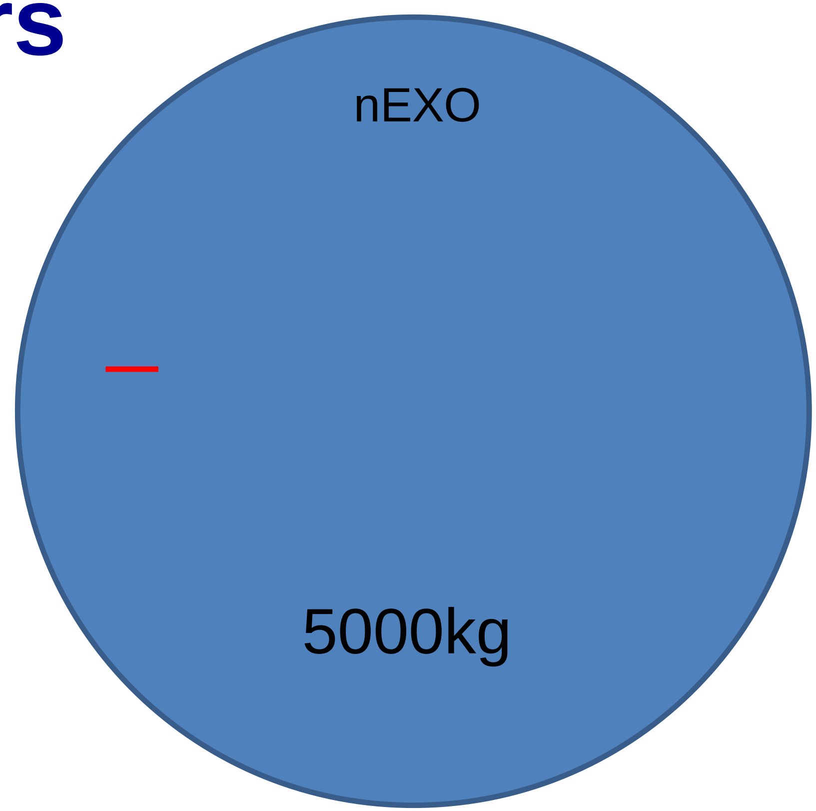
- **nEXO** - R&D underway:
  - 5T xenon enriched at ~90%
  - Sensitivity: 5-30 meV
  - Improved techniques for background suppression and possibly Ba tagging



→ **Development of nEXO is well advanced**

Monolithic Detectors





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

2.5MeV gamma ray attenuation length 8.5 cm = —

Monolithic detector is essential for background rejection:

- **Rejection of surface background**
- **Outer volume precisely measures background contribution**
  → detailed knowledge of BGND contributions to 0νββ search
- **Inner fiducial volume extremely clean**

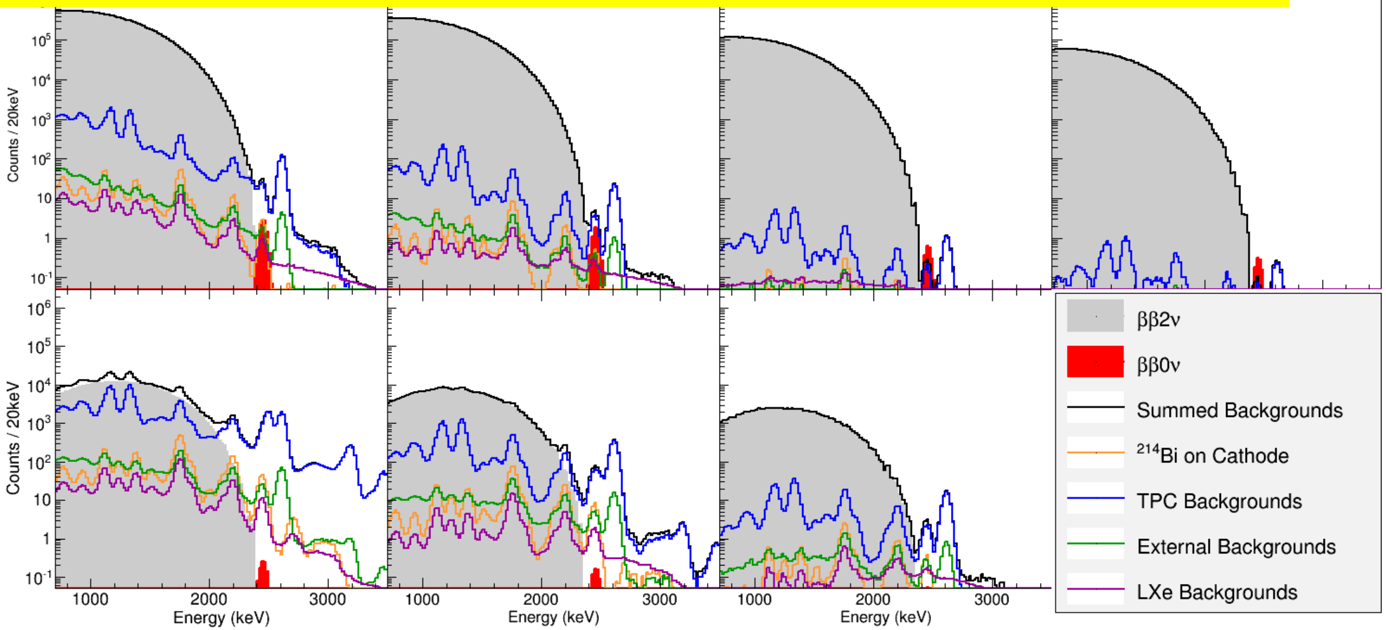
The role of the standoff distance in background identification and suppression

Example: nEXO, 5 yr data, 0νββ @ $T_{1/2}=6.6\times10^{27}$ yr, projected backgrounds from subsets of the total volume

Fid. LXe Mass = 4780kg 3000kg 1000kg 500kg

SS

MS

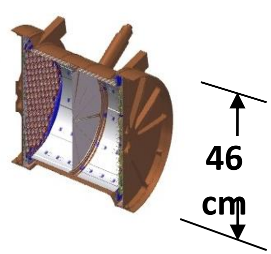


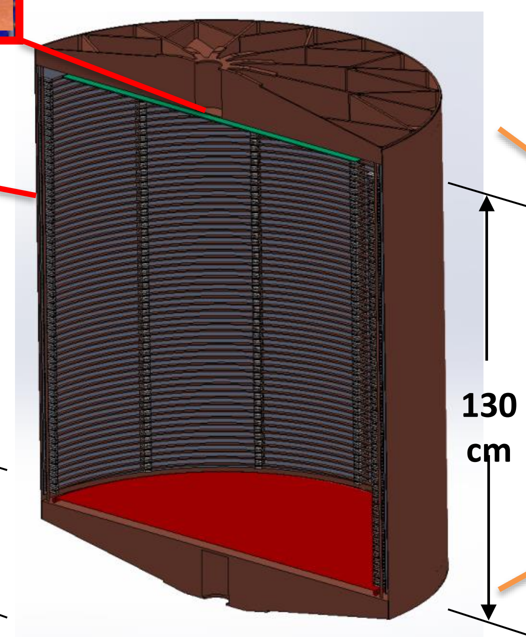
The fit gets to see all this information and use it in the optimal way

Searching for 0νββ with nEXO

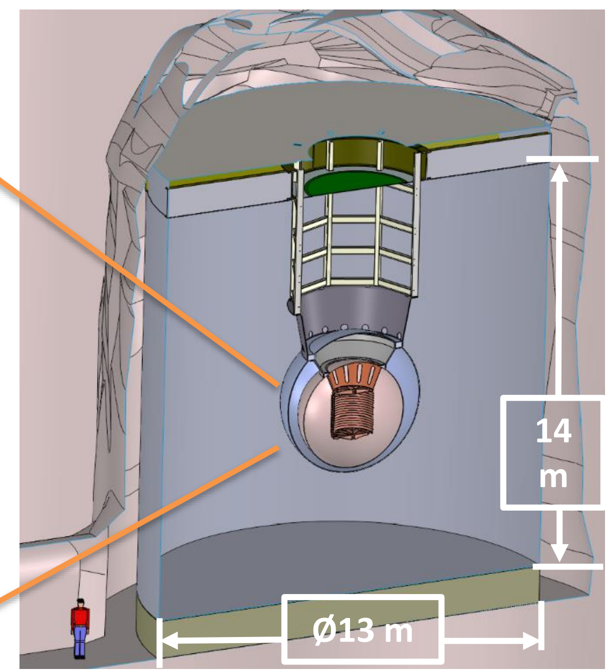
- Next-generation neutrinoless double beta decay detector
- 5 t liquid xenon TPC similar to EXO-200 (50x the size)
- Possible location in SNOLab Cryo Pit (6010 mwe)
- SiPM for light detection
- Tiles for charge read out
- 3D event reconstruction
- Required σ/E of 1% at Q-value
- Possible addition of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

EXO-200 for size comparison





nEXO TPC

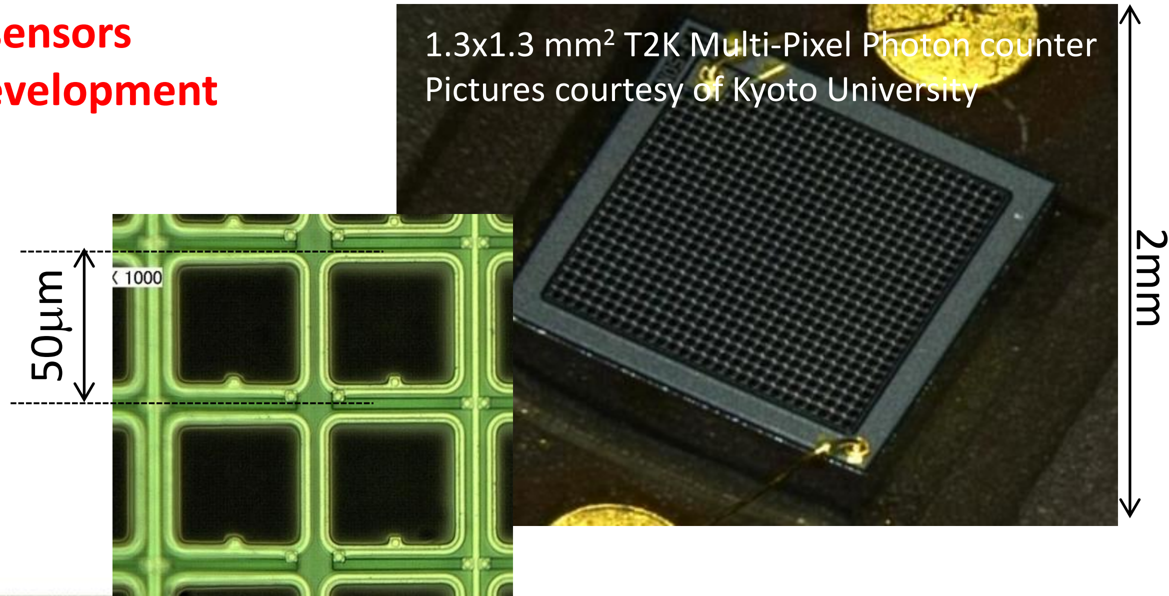


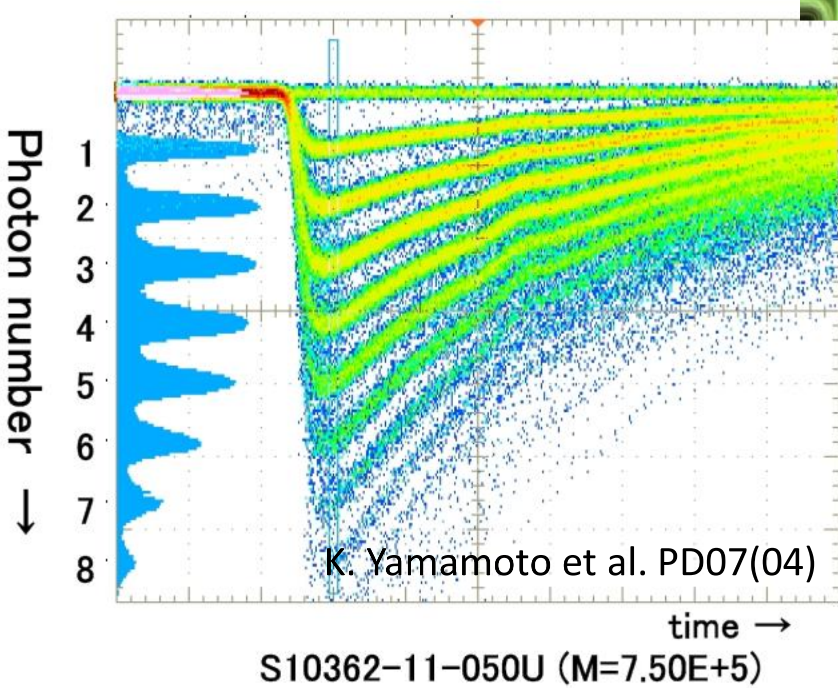
nEXO at the SNOlab Cryopit

Analog SiPMs - baseline solution for nEXO

F. Retiere L2 manager for photon sensors
Canadian CFI proposal for SiPM development

- High gain (low noise)
- Large manufacturing capabilities
- But efficiency and radioactivity need work

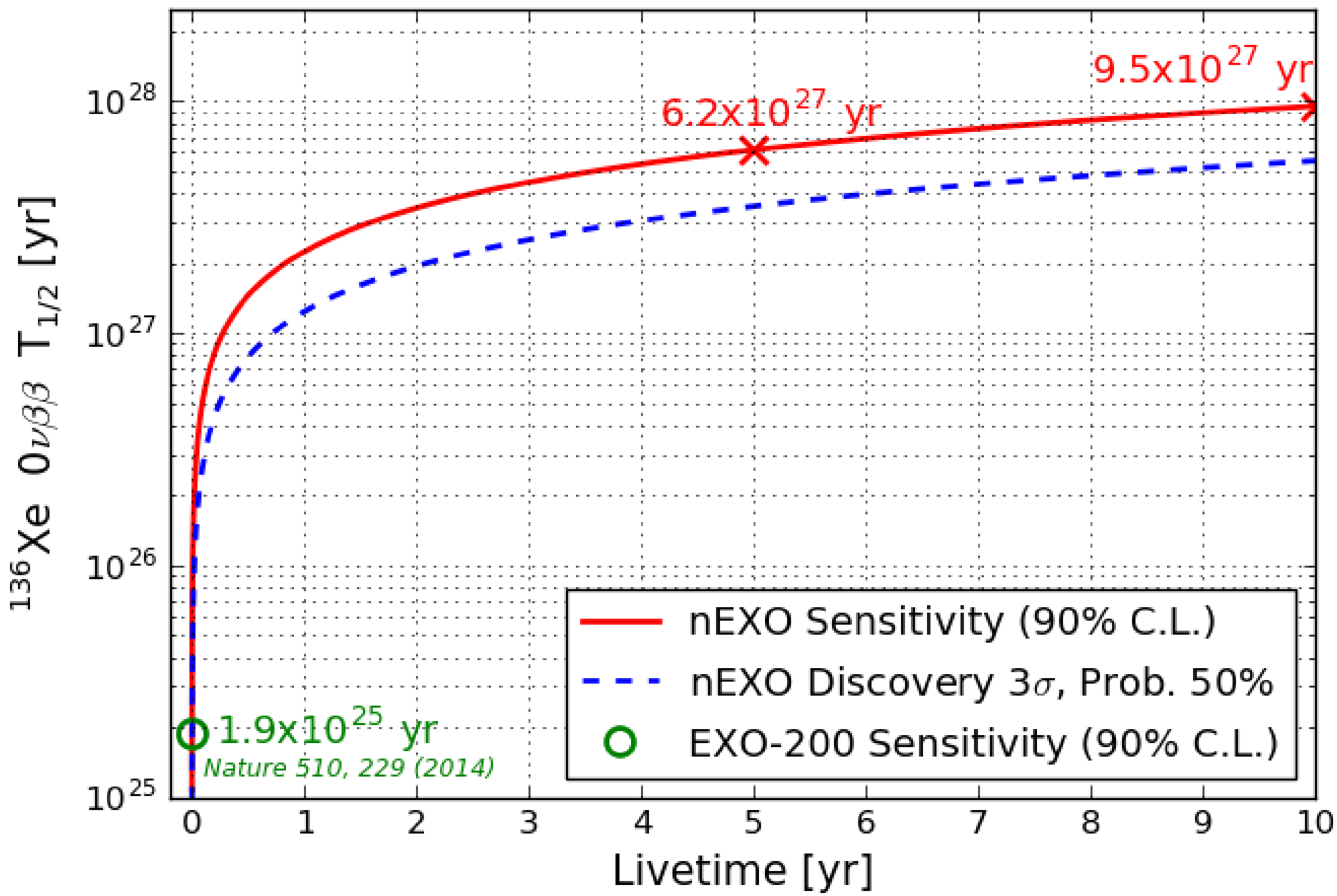




Requirements:

- High gain ⇒ negligible electronics noise
- Efficiency at 175nm > 15%
- Correlated avalanche rate < 20%
- Dark noise rate < $50 Hz/mm^2$
- ^{238}U and ^{232}Th content < 0.1 and $1 nBq/cm^2$

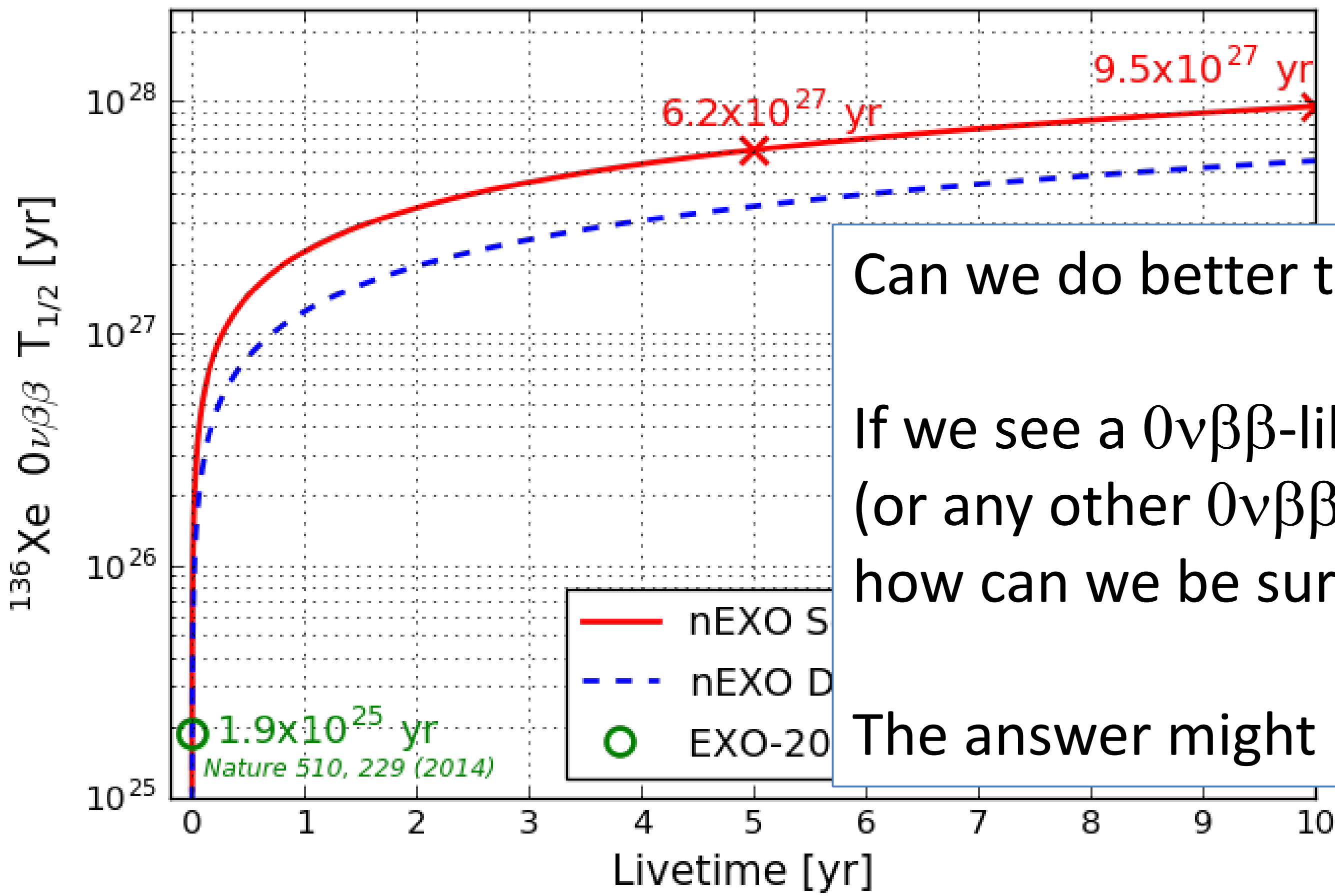
nEXO Sensitivity & Discovery Potential



Methodology:

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

nEXO Sensitivity & Discovery Potential



Methodology:

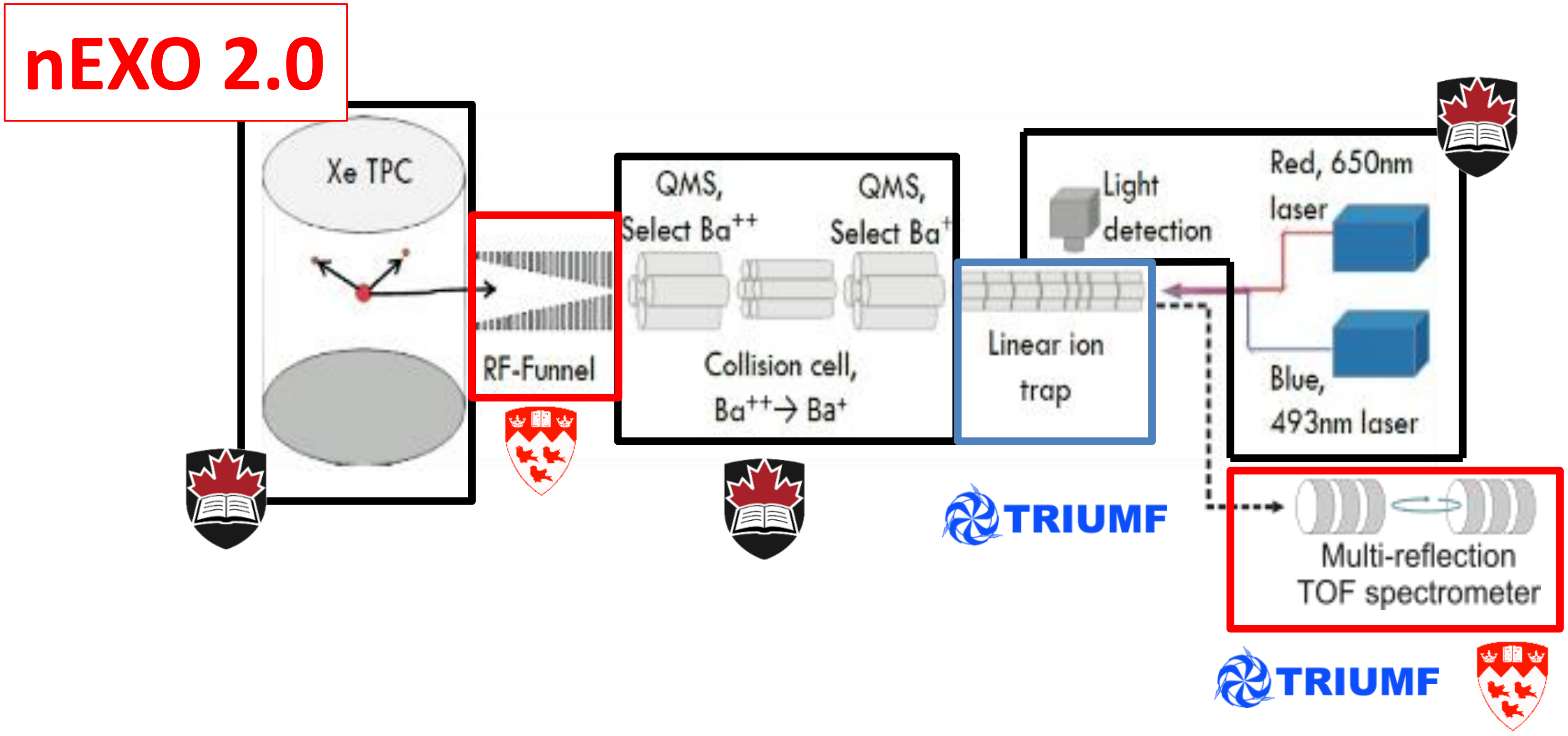
- 3860 kg fiducial Xe

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 $0\nu\beta\beta$?

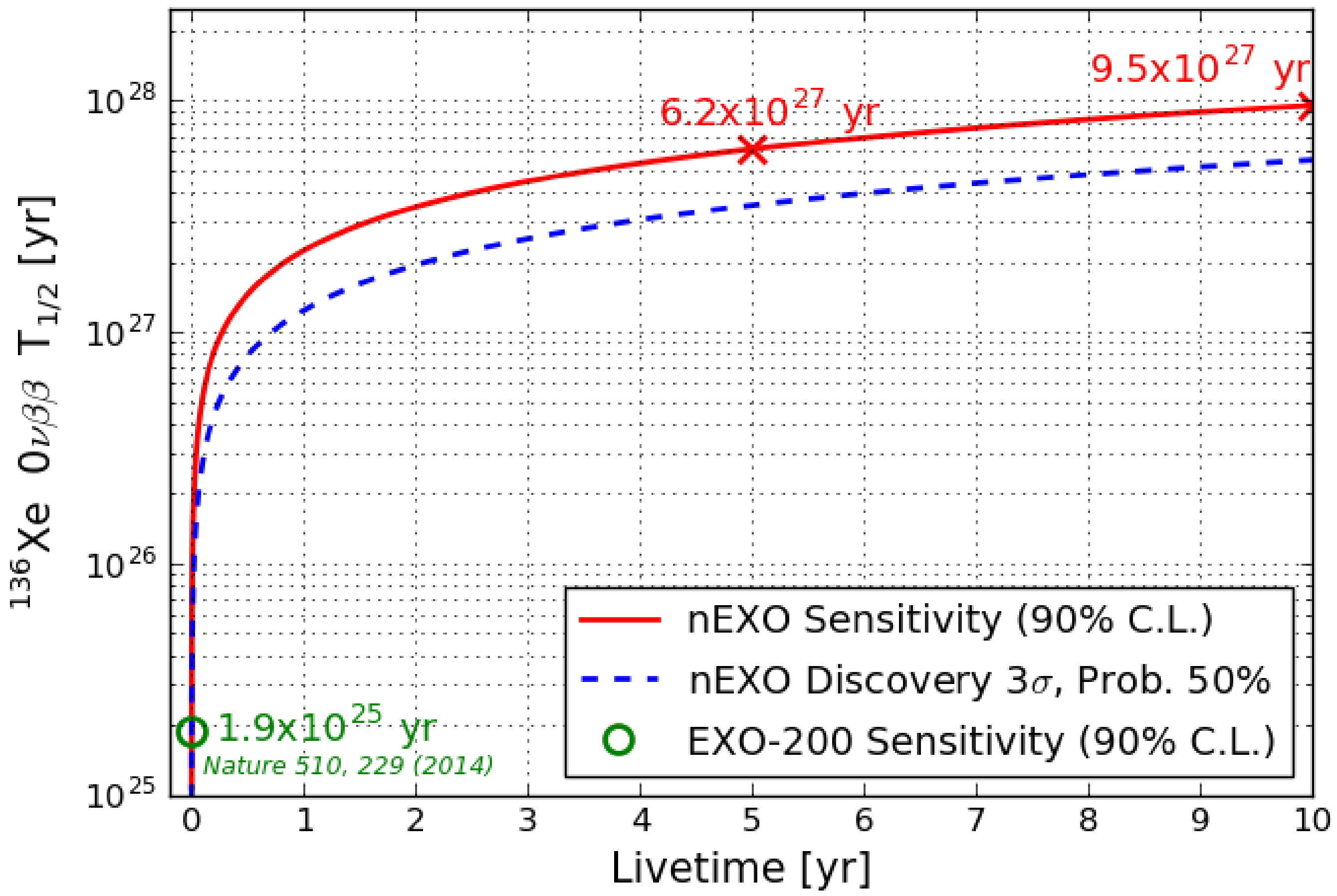
The answer might be Ba-tagging.

Ba-ion extraction and identification – the Canadian approach



- 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

nEXO Sensitivity & Discovery Potential



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- EXO200-like analysis

- nEXO based on successful EXO-200 concept
- nEXO is an exciting experiment to further push the search for 'new physics'
- nEXO may answer the question if the neutrino is a Majorana particle
- Strong Canadian contribution to nEXO photon sensor and calibration developments; and development of advanced low background techniques

The nEXO Collaboration

Enriched Xenon Observatory for double beta decay

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Technical University of Munich, Garching, Germany — P Fierlinger, M Marino
TRIUMF, Vancouver BC, Canada — J Dilling, P Gumplinger, R Krücken, Y Lan, F Retière, V Strickland
Yale University, New Haven CT, USA — D Moore

V. Varentsov

Enriched Xenon Observatory for double beta decay

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Duke University, Durham N
University of Erlangen-Nure
IBS Center for Underground
IHEP Beijing, People's Repu
IME Beijing, People's Repub
ITEP Moscow, Russia — V B
University of Illinois, Urbana
Indiana University, Bloomin
University of California, Irvi
Laurentian University, Sudb
Lawrence Livermore Nation
University of Massachusetts
McGill University, Montreal
Oak Ridge National Laborat
Pacific Northwest National
Rensselaer Polytechnic Insti
Université de Sherbrooke —
SLAC National Accelerator L
University of South Dakota,
Stanford University, Stanfor
Stony Brook University, SUN
Technical University of Munich, Garching, Germany — P Fierlinger, M Marino
TRIUMF, Vancouver BC, Canada — J Dilling, P Gumplinger, R Krücken, Y Lan, F Retière, V Strickland
Yale University, New Haven CT, USA — D Moore

Thanks to my Canadian collaborators:

Carleton University

Laurentian University

McGill University

Universite de Sherbrooke

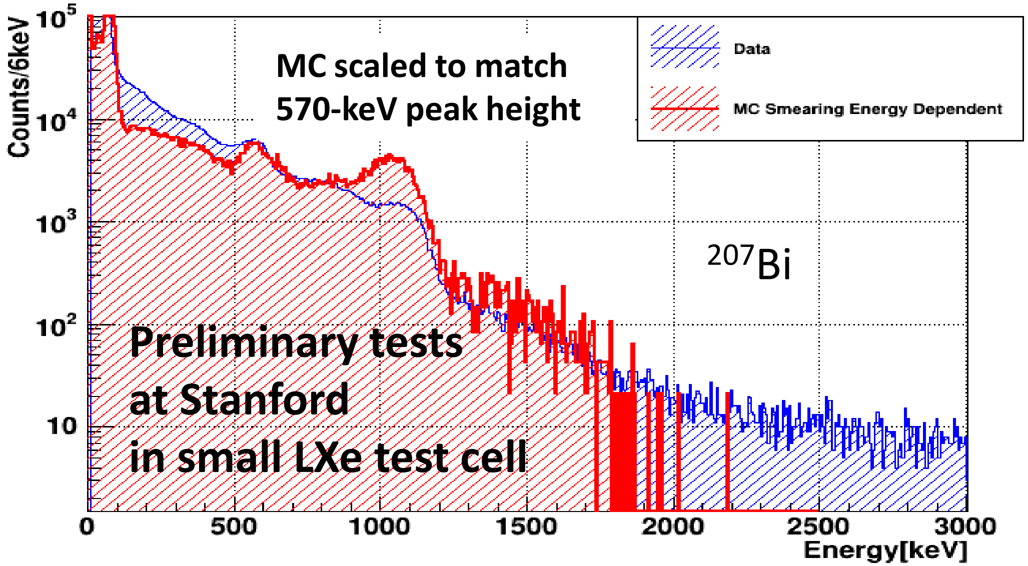
TRIUMF

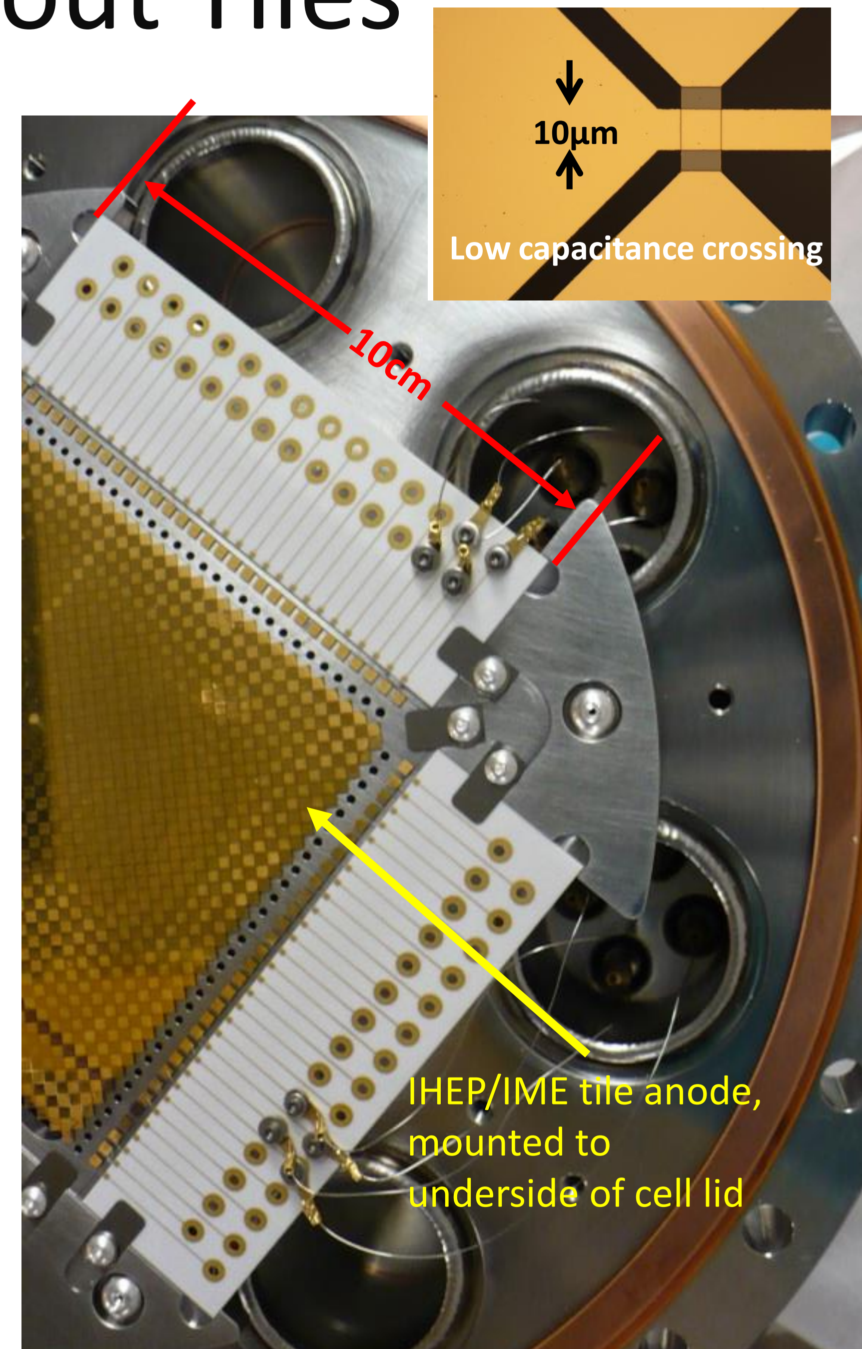
V. Varentsov

Backup slides

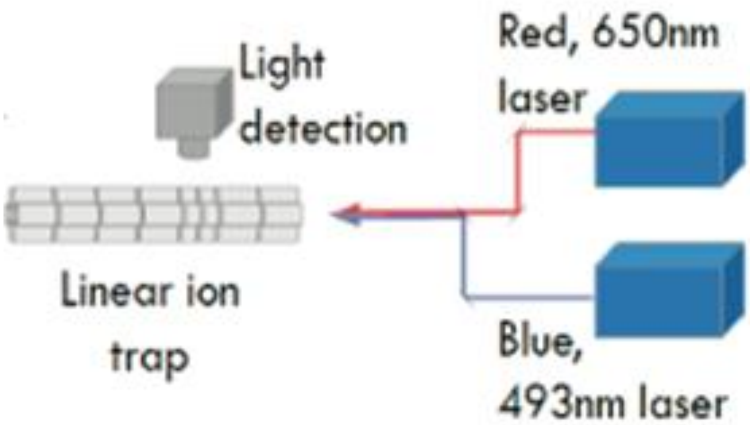
Charge Readout Tiles

- EXO-200 used wires for charge-readout
- Produced by IHEP/IME; functional testing in LXe in the US.
- 10 x 10cm^2 Prototype Tile
- Metallized strips on fused silica substrate
- 60 orthogonal channels (30 x 30)
- 3mm strip pitch
- Strip intersections isolated with SiO_2 layer
- Currently testing in LXe with a ^{207}Bi source

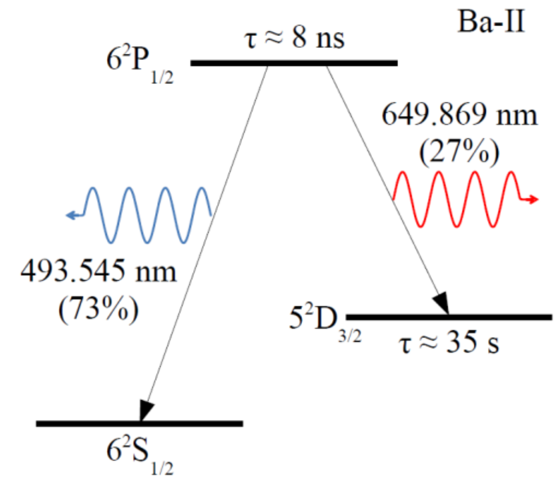




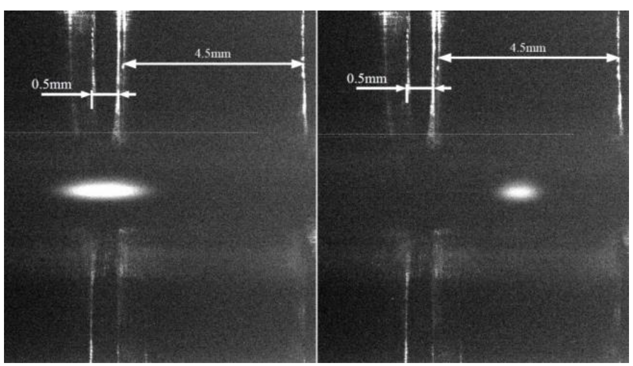
Ba ion detection & identification (Carleton)



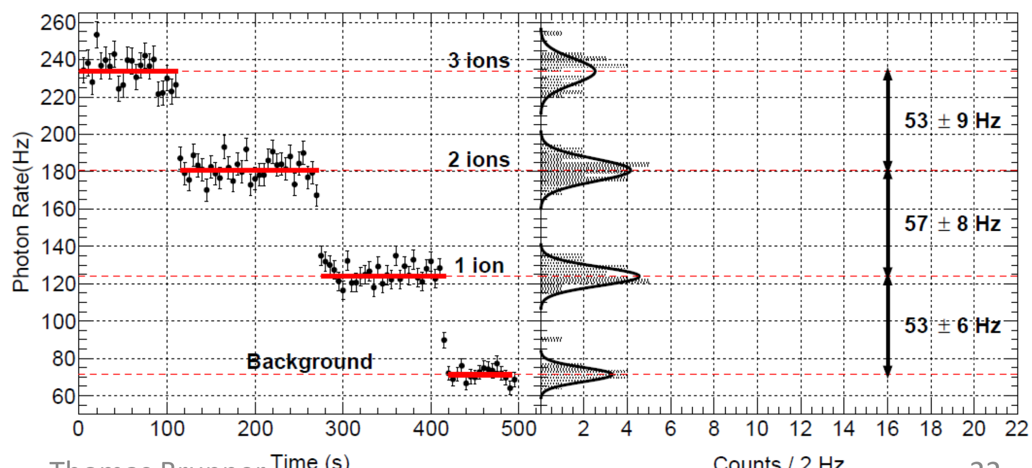
Using a relatively simple and well understood fluorescing system



Demonstrated ion cloud imaging and accurate position control

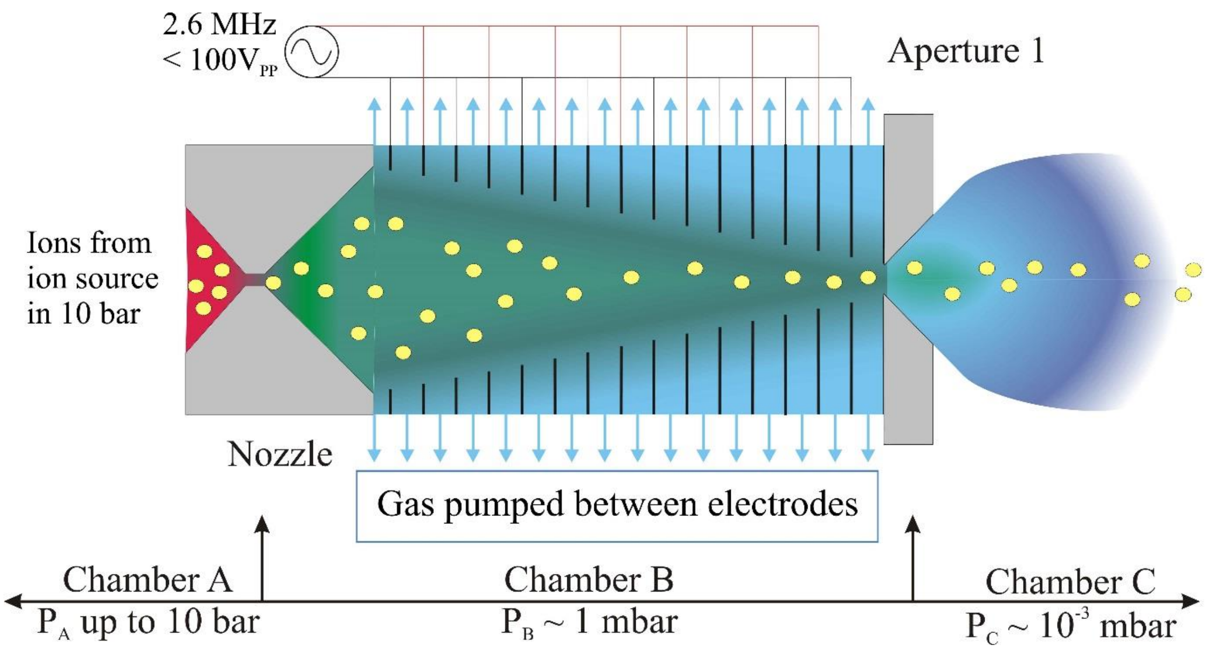


Demonstrated single ion sensitivity using intermodulation technique (background control)



Slide courtesy from R. Gornea

RF funnel concept



RF-funnel concept:

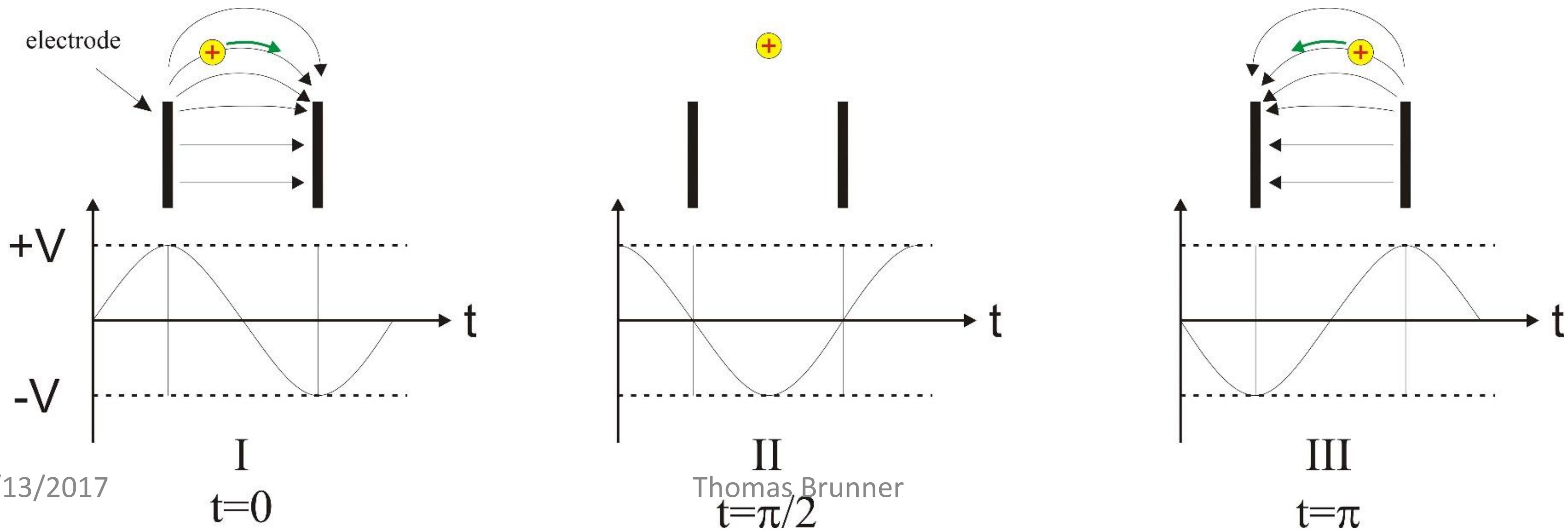
- Converging-diverging nozzle
- 2 Stacks total 301 electrodes
- RF-field applied to electrodes
- P_A = 10 bar, P_B = 1 mbar

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

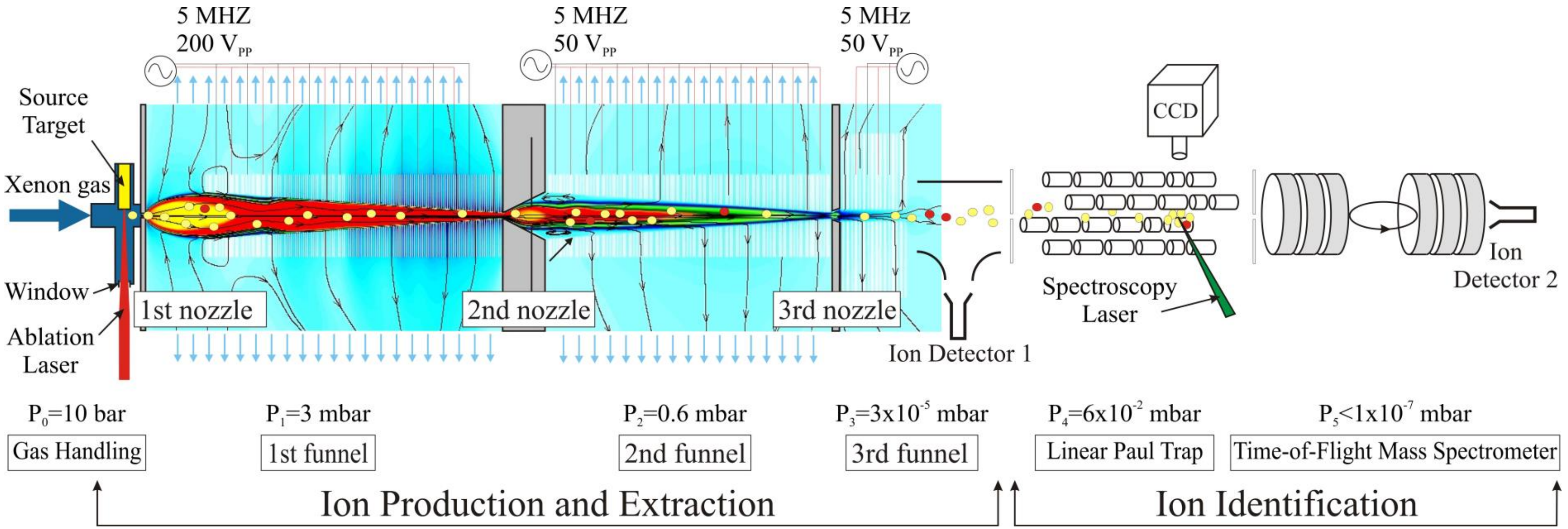
Simulated Ba^+ transmission ~95%

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

Simulated Ba^+ transmission ~72%



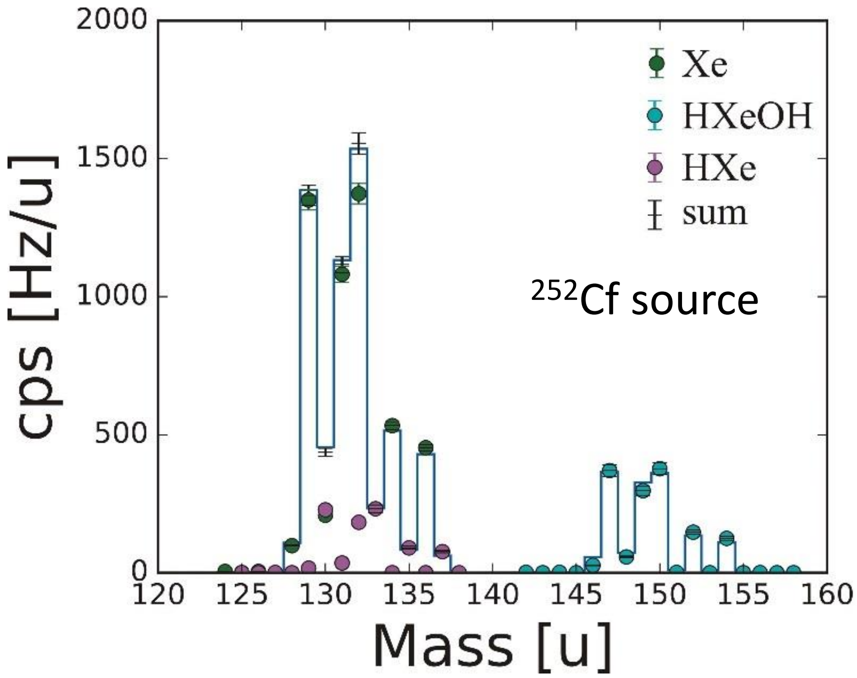
RF-funnel development

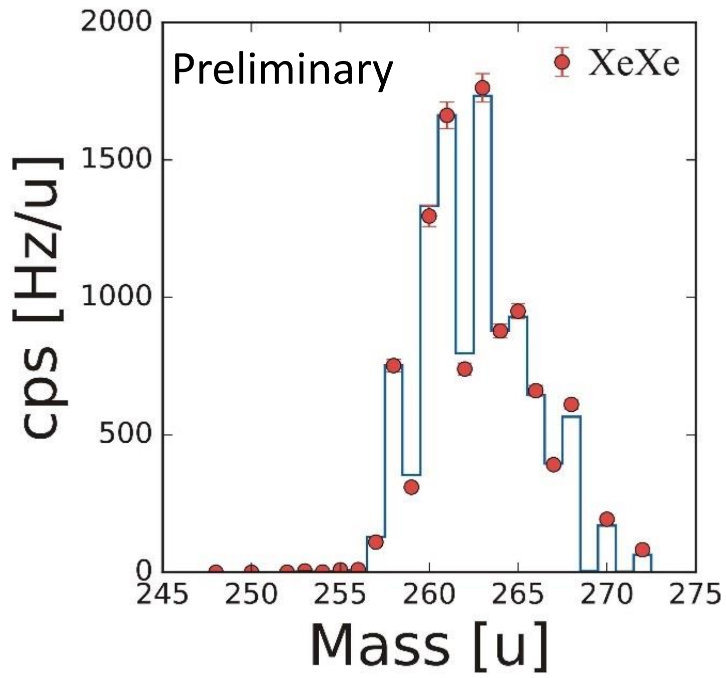


- Development of an improved ion-extraction system in Canada (McGill, TRIUMF, Carleton)
- Laser-ablation ion source in high pressure Xe gas
- Double (triple) RF funnel for improved operation → improved pumping
- Ba^{+}-ion identification through laser-fluorescence spectroscopy
- Ion identification via time-of-flight mass spectrometry

Ion extraction in xenon gas

Spectra of ions extracted from 2.1 bar Xe





- Ions extracted up to 10 bar!
- Gd-148 and Cf-252 ion sources used
- Ions extracted from Ar, Kr, and Xe

- Ba-ions not identified!
- Fission products not identified!
- Ion extraction efficiency unknown!