EXO

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PRESENTATION TO THE 2017 IPP AGM

KINGSTON

What is EXO

- EXO is a program searching for neutrinoless double beta decay in Xenon
- It is comprised of 3 activities
  - EXO-200 – a 200 kg detector operating at WIPP in New Mexico
  - nEXO – a proposed 5 tonne detector at SNOLAB
  - Detector Development to extend to the Normal Hierarchy
- The realization of nEXO – a major international project to be sited in Canada is the top priority of the Canadian collaboration but the other activities are very important and complementary

Canadian participation in EXO

- Carleton – Mark Boulay, Razvan Gornea, Thomas Koffas, David Sinclair
- Laurentian – Bruce Cleveland, Jacques Farine, Ubi Wichoski
- McGill – Thomas Brunner (Deputy Spokesperson)
- Sherbrooke – Serge Charlebois, Rejean Fontaine, Jean-Francois Pratte
- TRIUMF – Jens Dilling, Reiner Kruecken, Fabrice Retiere

- New collaborator since last grant
- New Institution since last grant

EXO-200

- Major successes
  - First project to detect 2-neutrino beta-beta decay of Xenon
  - Most precise measure of the rate for a 2 neutrino double beta decay
  - First project to challenge the Heidelberg-Moscow claim of observation of 0 neutrino double beta decay
  - Continues to take precision data and should produce another globally competitive result
  - Strong Candian participation in operation and analysis
  - Candian (Jacques Farine) chairs the Collaboration Board

Next Analysis for EXO-200

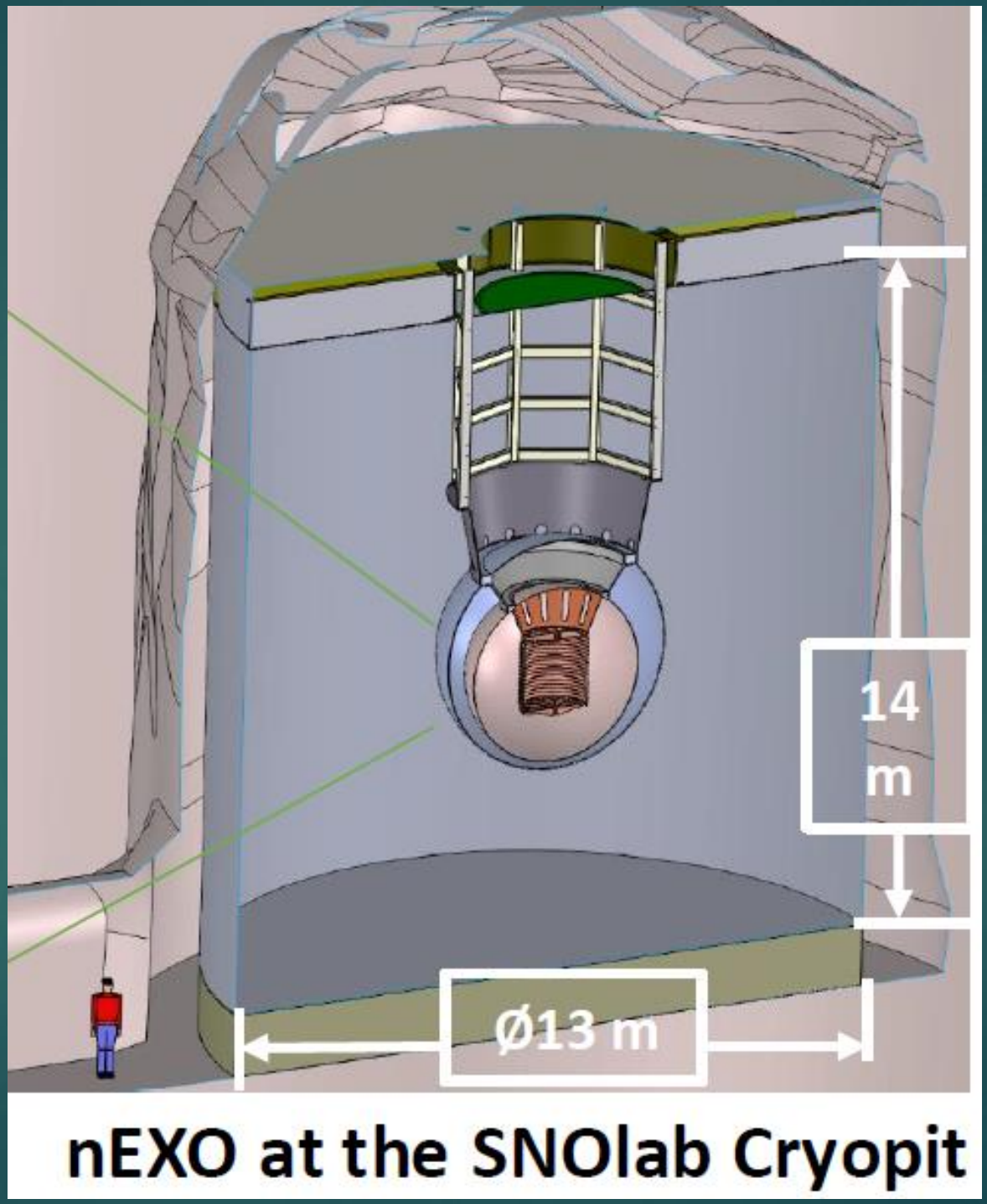
- Caio Licciardi (EXO Post doc at Carleton) will present the first analysis of the current EXO-200 run at TAUP. Caio is the co-analysis coordinator
- Main technique will be a multivariant analysis technique introduced by Thomas Koffas which forms part of the thesis of a student Warren Cree

nEXO

- Proposal being developed for submission to the US DOE ‘down select’
- Canadian leadership in light detection (Fabrice Retiere is the Manager for this activity), in Radon control (Jacques Farine is the subgroup manager) and participation in calibration and low background assay. Major role played in simulation.
- Work on concepts beyond the baseline being explored as possible enhancements to sensitivity
- Collaboration Board chaired by Canadian (David Sinclair)

nEXO

- A detector to explore the inverted hierarchy region of parameter space for neutrinoless double beta decay
- Based on the success of EXO-200
- Modify the design to improve and optimize
- Base performance predictions on a proven detector



nEXO at the SNOlab Cryopit

EXO-200 -> nEXO : Location

- EXO-200 is at WIPP
- Depth is too shallow for a larger detector
- Salt creeps!
- Lead used for shielding
- nEXO is expected to be at SNOLAB
- Negligible cosmogenic production
- Water shield kills local neutrons, gammas and is very pure

EXO-200 -> nEXO: Design Concepts

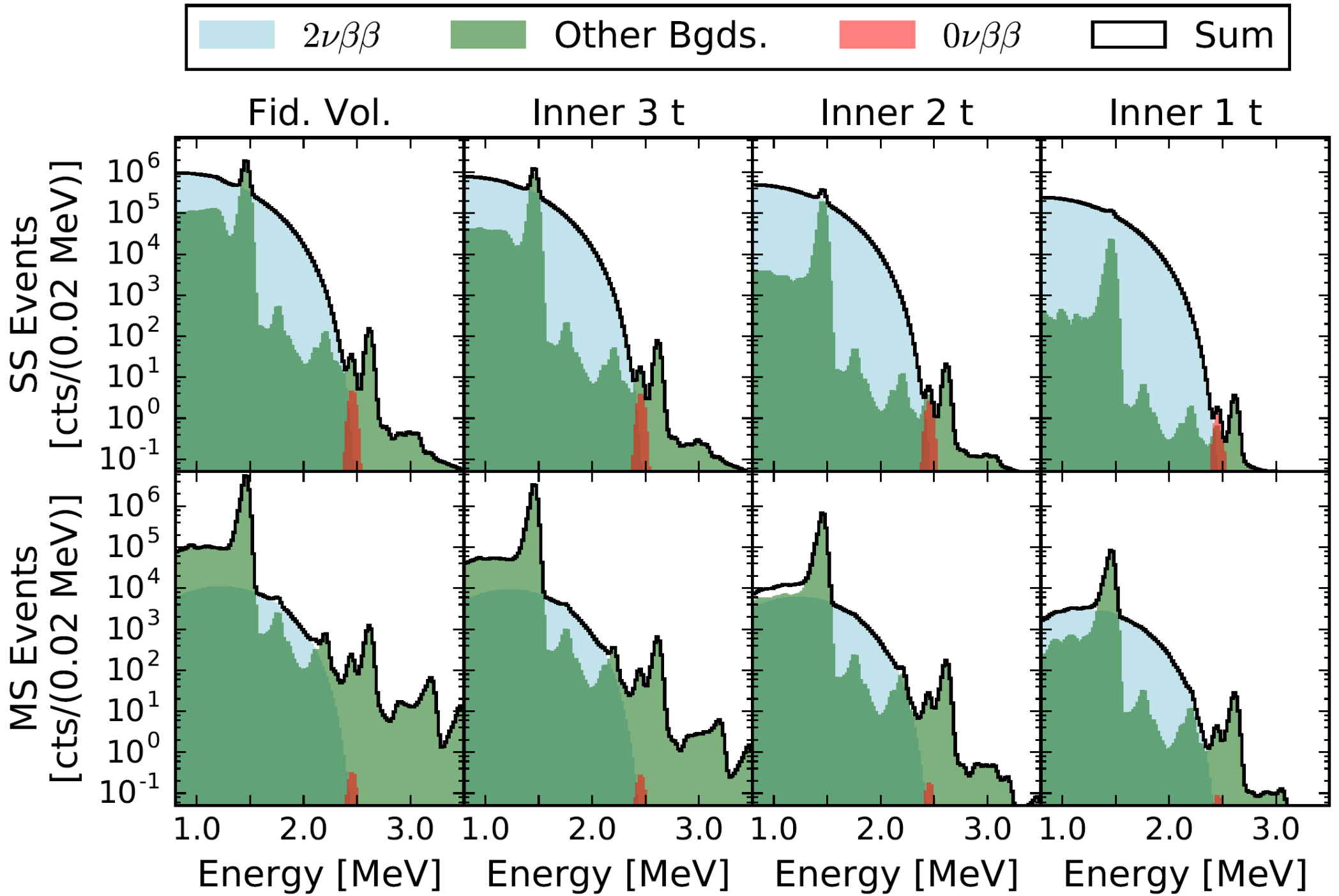
- EXO-200 has two back-to-back TPCs with central cathode
- nEXO has a single TPC with diameter = height
- This gives best, homogeneous and shielded conditions
- nEXO has much longer drift length
  - EXO-200 had excellent electron lifetime (~3 ms) but nEXO must be better
  - Eliminate plastics wherever possible
  - (EXO-200 used SNO acrylic to support the field cage and clean Teflon as a reflector to enhance photon collection. Must find fused silica or something to replace the acrylic and eliminate the Teflon)

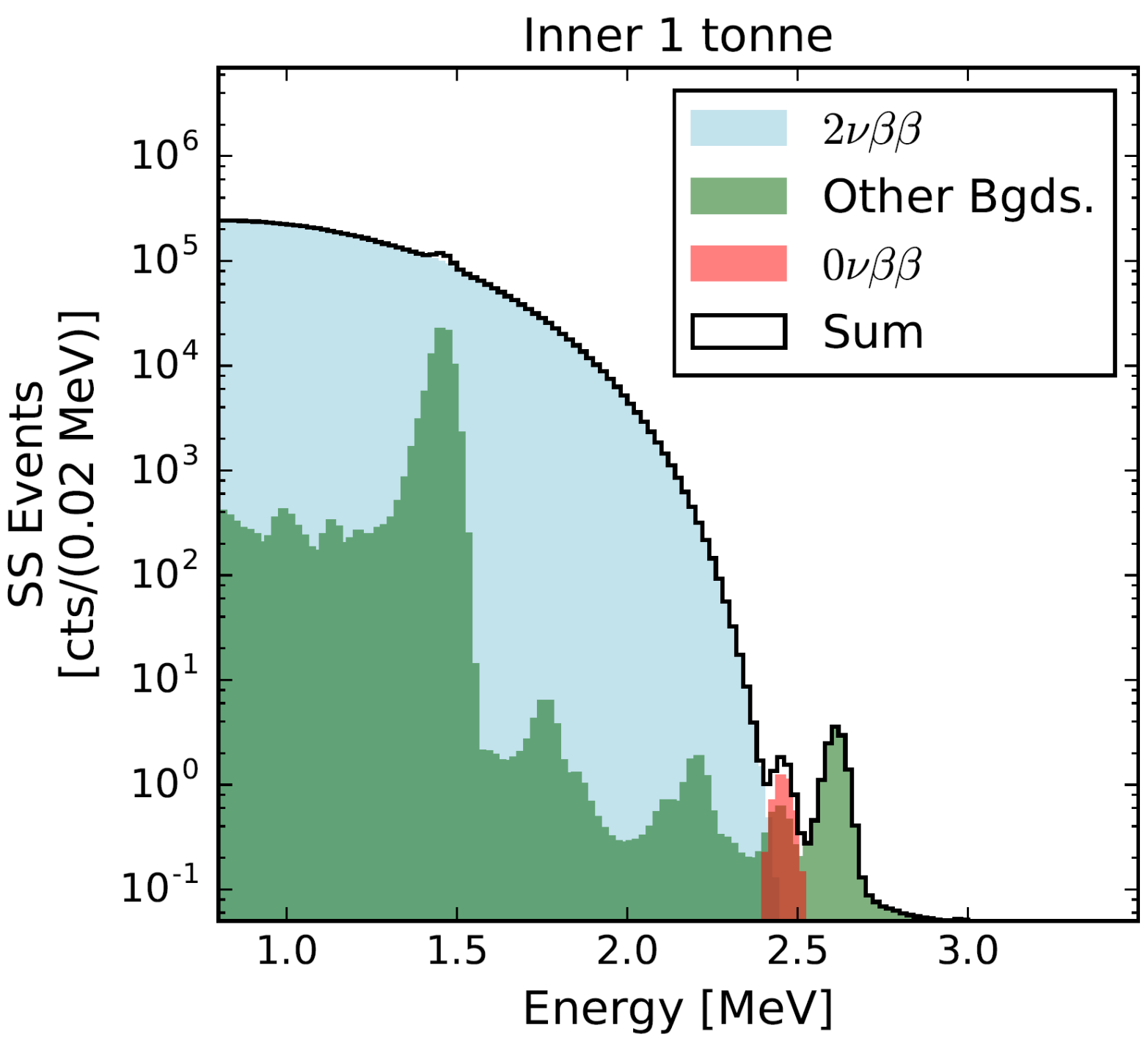
EXO-200 -> nEXO: Light Sensors

- In EXO-200 LAAPDs are used for light detection.
- The units we used are not available
- Need high voltage (~2 kV)
- Noise a problem – low gain
- nEXO -
- Use SiPMs and cover the barrel (4 m^2)
- Better light collection -> better resolution
- Need SiPMs sensitive to 172 nm light (ε> 15%)
- Need operation at -100°, Low dark noise, Low cross talk, etc.
- This is a major area of development for Canada

Expected sensitivity for nEXO

- Extensive and detailed Monte Carlo simulations have been made to estimate the sensitivity and discovery potential for nEXO
- All activity levels are based on measurement and experience with EXO-200
- Sensitivity and Discovery calculations developed in Canada

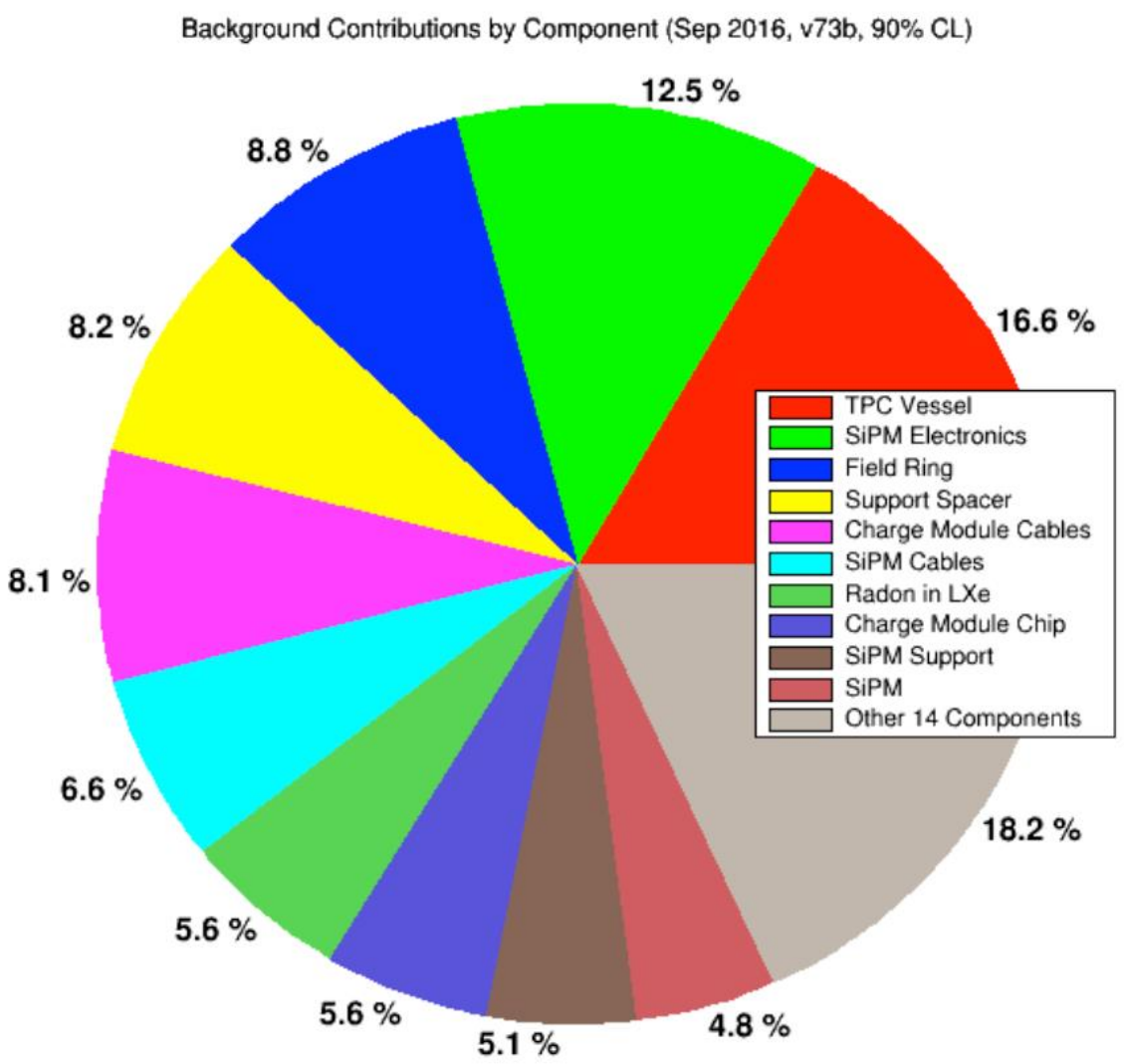

$2\nu\beta\beta$
Other Bgds.
$0\nu\beta\beta$
Sum
Fid. Vol.
Inner 3 t
Inner 2 t
Inner 1 t
SS Events [cts/(0.02 MeV)]
MS Events [cts/(0.02 MeV)]
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
1.0
2.0
3.0
Energy [MeV]

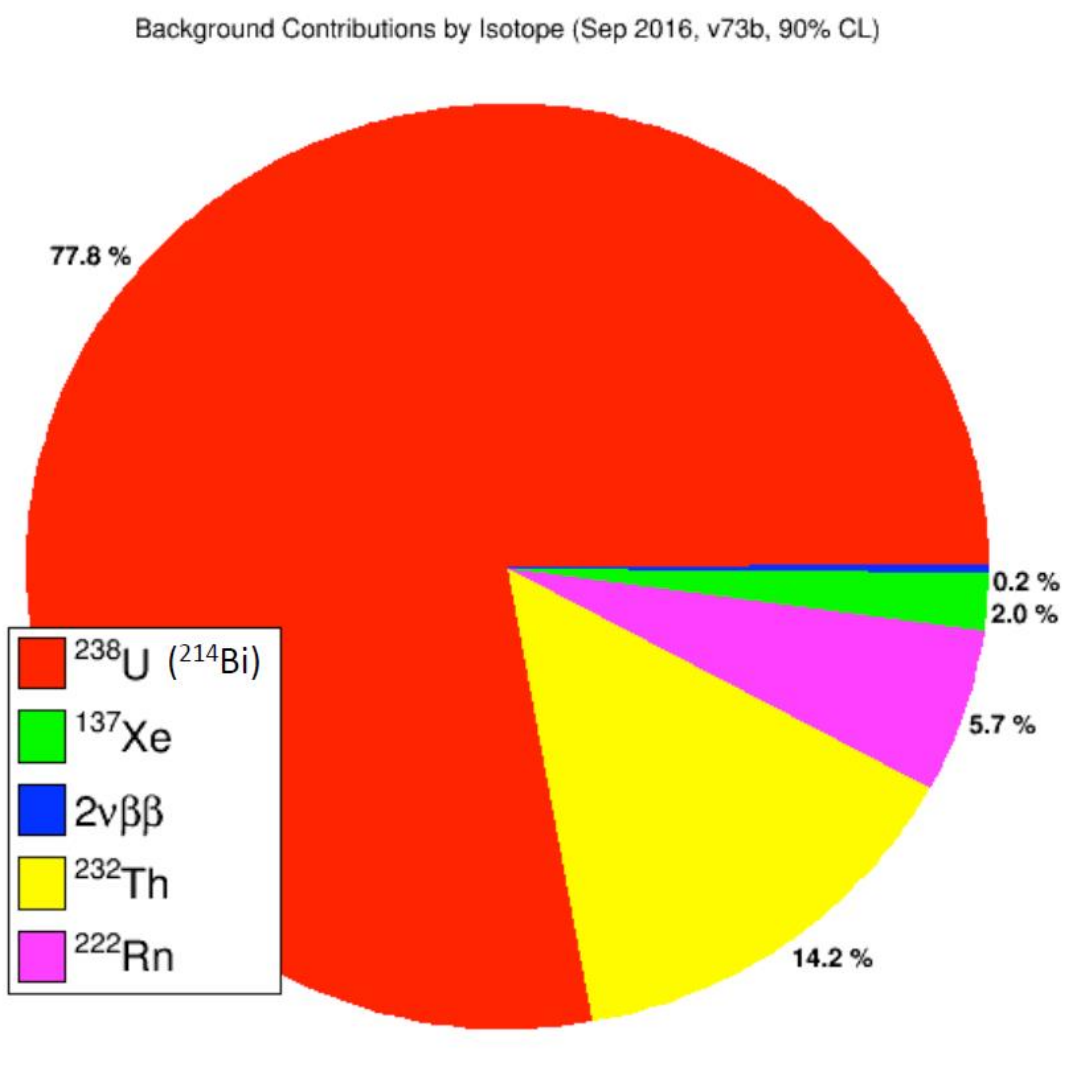


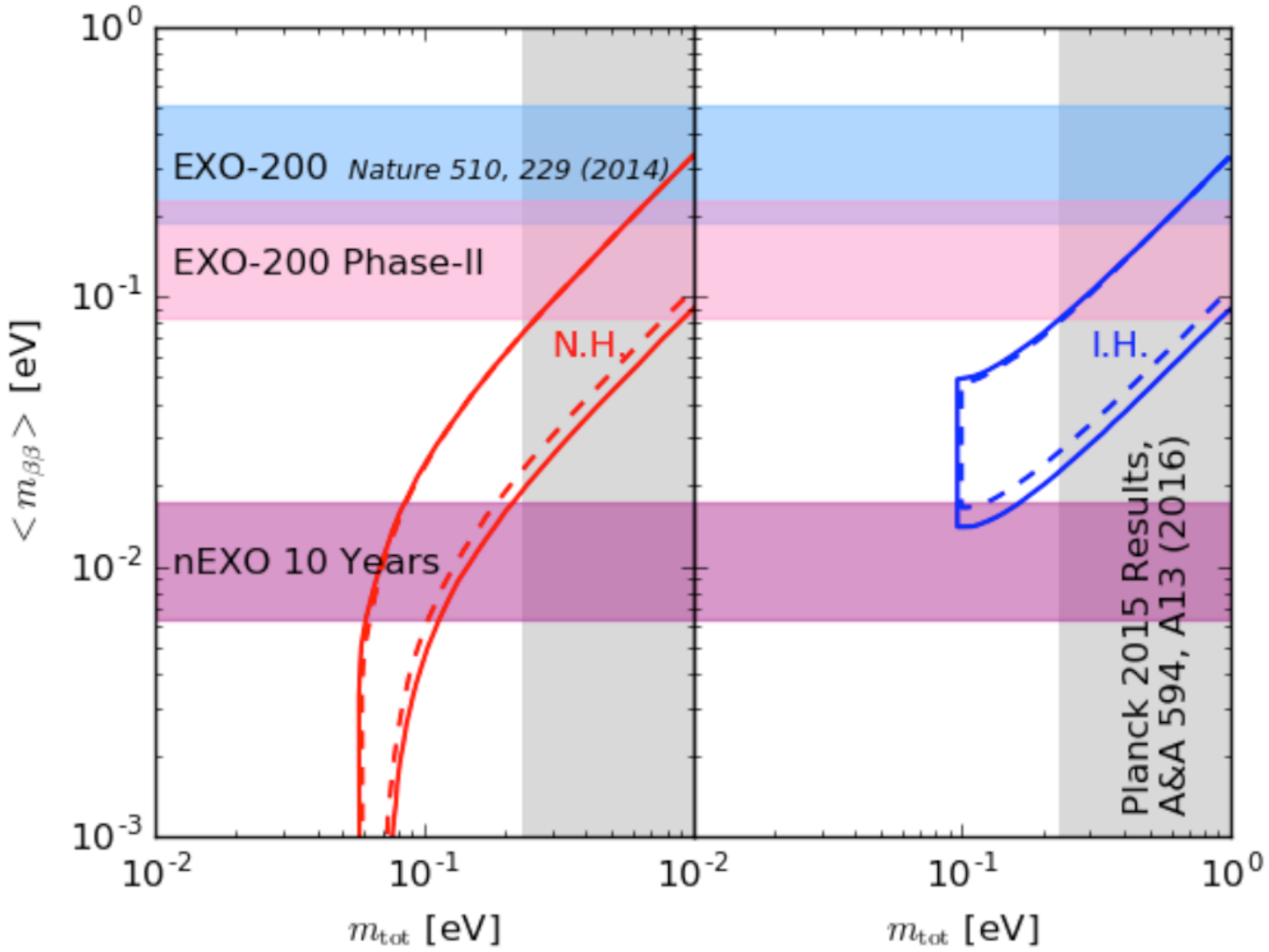
Expected data for 10 years

Discovery potential limit
5.5×10^{27}yr

Background Budgets (90% CL)

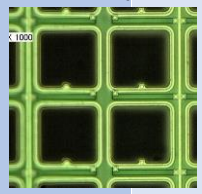
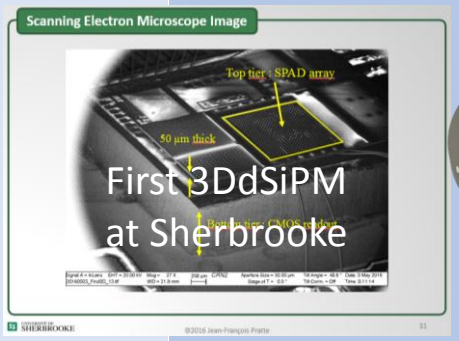
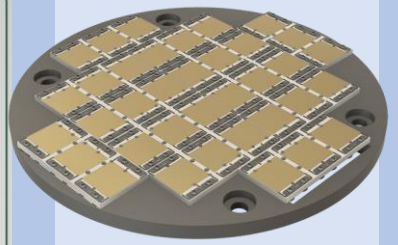
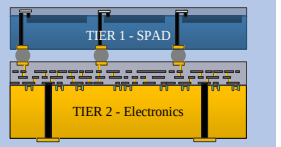
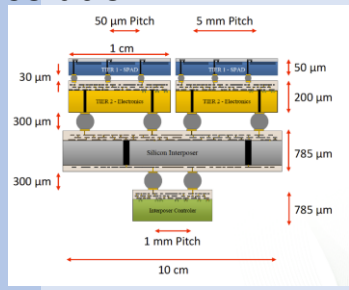
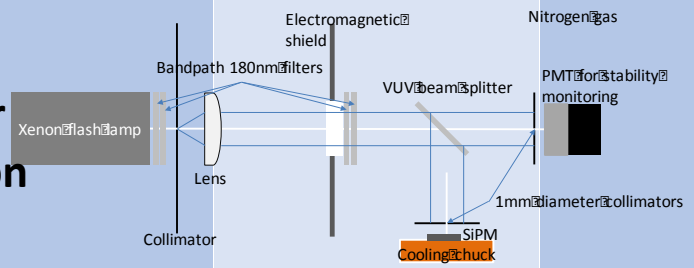
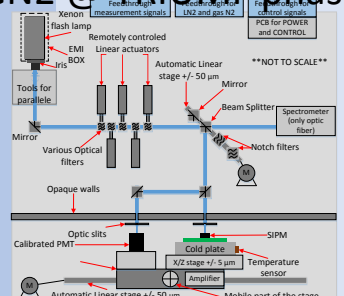
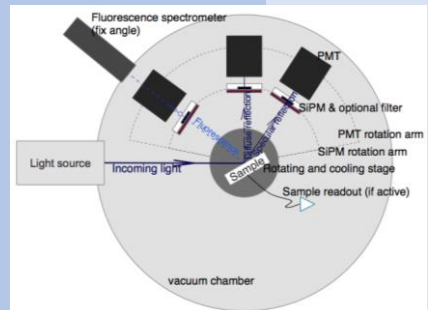





EXO-200 Nature 510, 229 (2014)
EXO-200 Phase-II
nEXO 10 Years
N.H.
I.H.
Planck 2015 Results, A&A 594, A13 (2016)
$< m_{\beta\beta} >$ [eV]
m_{tot} [eV]
m_{tot} [eV]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^{-2}
10^{-1}
10^0

The Canadian Program

nEXO photo-detector effort

	2014	2015	2016	2017	2018	2019	2020
Main milestones			Suitable SiPM identified		Final spec. for SiPM	DOE down Select	nEXO SiPM tech. select.
Photo-detector Technology	Analog SiPM for nEXO (FBK, HPK) 			36cm^2 analog SiPM (Stanford) 	3DdSiPM for nEXO 	Complete 3DdSiPM solution 	
Photo-detector Characterization	SiPM test setups In vacuum at Stanford In GN2 @ TRIUMF phase 1 		SiPM test setups In vacuum at Stanford & BNL In LXe at Erlangen, UMass In GN2 @ TRIUMF phase 2 	SiPM efficiency/reflectivity Setup (CFI) 	

Additional or related support for the development of nEXO photo-detectors

- CRFREF
  - One technician at TRIUMF working about 50% on photo-detector development for 5 to 6 years
  - One research professional at U.Sherbrooke working on 3DdSiPMs development for astro-particle physics for 3.5 years.
- CFI. “Facility for Development of Noble Liquid Detectors and Optical Readout for Subatomic Physics and Particle Astrophysics”
  - Date: applied for Oct. 2016. Award announcement: Jun. 2017,
  - PI: Mark Boulay (Carleton).
  - Amount: ~2M$ for 3DdSiPM at Sherbrooke, ~1M$ for SiPM characterization at TRIUMF, ~0.5M$ for large area SiPM at McGill
- DRDC 1. ”Enabling Single Photon imaging technologies for underwater arctic surveillance”
  - Date: applied for February 1, 2017, award announcement?
  - PI: JF Pratte, Sherbrooke
  - Amount: 6M$ (no deliverable for SAP but building highly relevant expertise)
- DRDC 2. “A broadband single photon detector for enhanced arctic air surveillance”
  - Date: applied for February 1, 2017, award announcement?
  - PI: F. Retiere, TRIUMF
  - Amount: 3M$. Need DRDC1 to be viable (no deliverable for SAP but building highly relevant expertise)
- NSERC CRD. “Input/Output Through Silicon Vias in CMOS”
  - Date: application in 2017
  - PI: S.Charlebois in partnership with Teledyne-DALSA
- Partnerships with industrials (KETEK, Hamamatsu) being investigated for 3DdSiPMs

nEXO Photo-detector group management

- Define specifications for SiPMs and passive optics (mirrored electrode)
  - TRIUMF taking over simulation effort from IHEP (Eric Woolsey, graduate student)
    - In FY2017 investigate interplay between SiPM efficiency and reflectivity
    - Investigate electrodes made of silicon
- Agree on measurement techniques for assessing specifications
- Define the photo-detector architecture up to the electronics
- Coordinate SiPM prototyping effort with manufacturers, including 3DdSiPM development
- Organize workshops at IEEE NSS to share research effort with other collaborations (DarkSide50k, CTA, MEG,…)
- Support from NSERC critical for HQP and travel

nEXO photo-detector characterization

- Setup for measuring SiPM efficiency at 175nm and assessing nuisance parameters
  - TRIUMF setup upgraded in FY2016 using NSERC and TRIUMF funds. Expected to be used until 2019
- Combined efficiency/reflectivity test setup at TRIUMF requested from CFI
  - Risk mitigation if CFI fails, contribute to exploitation of setups at U.Alabama and IHEP
    - Need travel funds
- Setup for measuring SiPM self-emission (light emitted in avalanches) at TRIUMF requested from CFI and DRDC2
  - Risk mitigation if CFI and DRDC2 fails, reuse some equipment available at U.Sherbrooke
- Overall setup operation and data analysis
  - Maintenance and upgrade by CFREF funded technician.
  - Operation and data analysis by HQPs requested from NSERC
    - Currently done by 1 Italian student paid by INFN and 1 Chinese professor on sabbatical (paid by China)
    - Postdoc critical for continuity between visitors, coop and graduate students

Large scale photo-detector plane

- Scaling up from ~1cm^2 SiPM chips to 100cm^2 module and 10,000 cm^2 staves
  - Critical effort if Canada is to build the complete photo-detector staves for nEXO
    - Will likely compete with other groups for this work package
  - Assembly and test equipment requested from CFI
    - Risk mitigation if CFI fails: short term, collaborate with US groups, long term: apply for equipment again
- Effort led by McGill
  - Electrical engineering support through CFREF - CPARC
  - HQP requested from NSERC: Ako Jamil (PhD) and undergraduate student (Soud Kharusi)

Other nEXO development

- Continuing the battle against radon ingress – monitoring and removal techniques (Laurentian)
- Calibration techniques and hardware – nEXO gains enormous advantage from self shielding but this also makes calibration with external gamma sources challenging. Simulations and new insertion hardware being developed (Laurentian)
- Explore improved spatial resolution to improve background rejection through use of 2 phase detection. Carleton funded development but now 2 students have chosen this for grad studies.

Development of new technologies

- 1) New forms of SiPM
- 2) Use of 2 phase detection techniques to reduce backgrounds
- 3) Single ion Ba tagging techniques to reduce backgrounds
- Success with these technologies could lead to a concept for detection of neutrinoless double beta decay at the normal hierarchy

Supporting the new technologies

- Funds requested from CFI for
  - (a) Development of infrastructure and testing for all aspects of SiPM application to nEXO
  - (b) A Cryogenics laboratory to be established at Carleton for developing next generation of cryogenic liquid detectors including 2 phase detection for double beta decay and dark matter
- NSERC requests separate project request for Ba tagging development – will be submitted in Fall.

3DdSiPM for nEXO

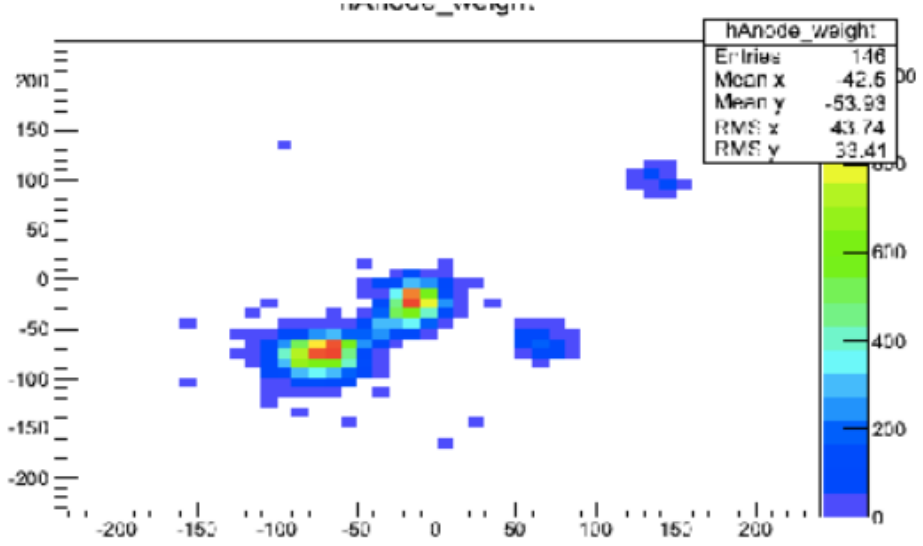
- Establishing 3DdSiPM production at Teledyne-DALSA and Sherbrooke
  - Generic effort regardless of end project
  - Fund requested from CFI and DRDC1
    - Risk mitigation if CFI and DRDC1 fails, investigating partnership with established companies (Hamamatsu, KETEK) or with new venture
- Tailoring photo-detector tier for nEXO (VUV sensitivity and cryogenic operation)
  - Design proposed in DRDC2 compatible with VUV. Could also be tested with CFI funds
    - Risk mitigation: low cost small technology demonstration test. Probably not complete sensors
  - Additional support will likely be needed from NSERC RTI (FY2018, FY2019) for investigating ultra-shallow (delta) doping and VUV anti-reflective coatings
- Tailoring electronics for nEXO (ultra-low power dissipation and moderate speed)
  - Need CFI or DRDC funds for large production though small production possible without

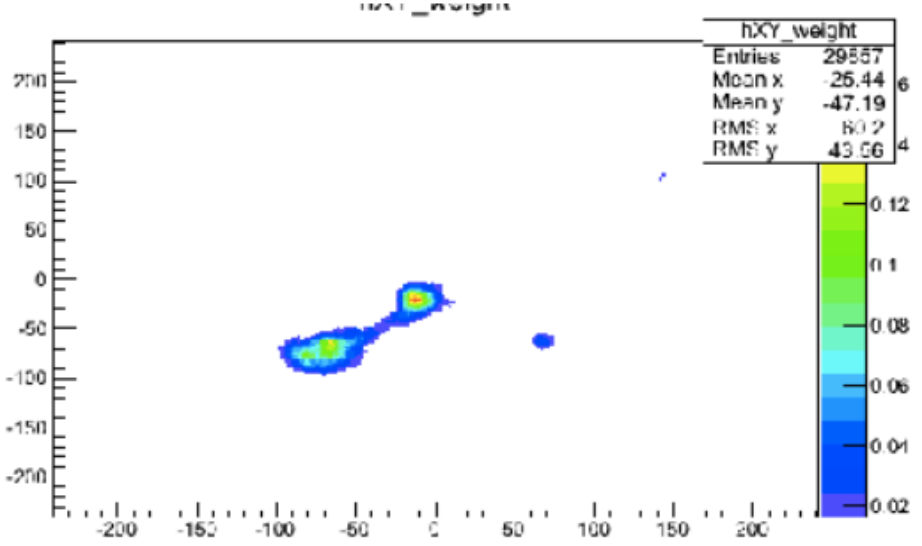
2 Phase detection

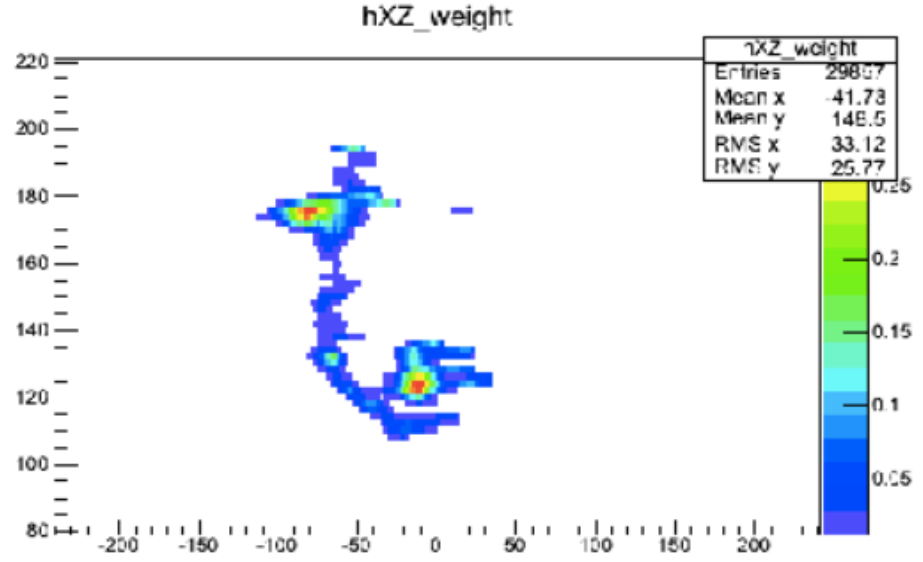
- The addition of an electroluminescence region to the nEXO detector concept, together with the use of 3D SiPM would allow much greater spatial resolution to determine the topological details of the decay events.
- This should allow substantial improvement in background rejection
- In early gas xenon detectors, requirement of 2 beta tracks reduced background by ~25

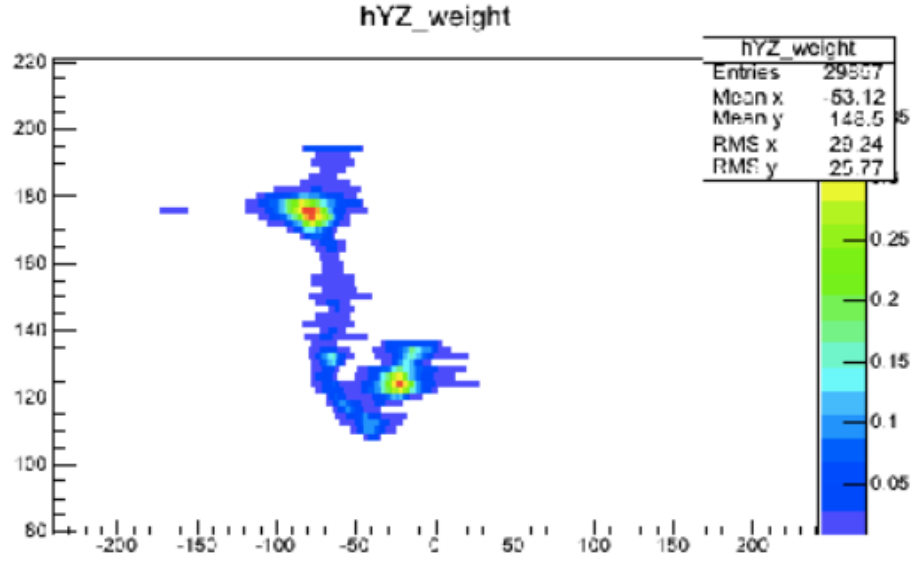
Double electrons! (Co-56 data)

(NEXT Data)







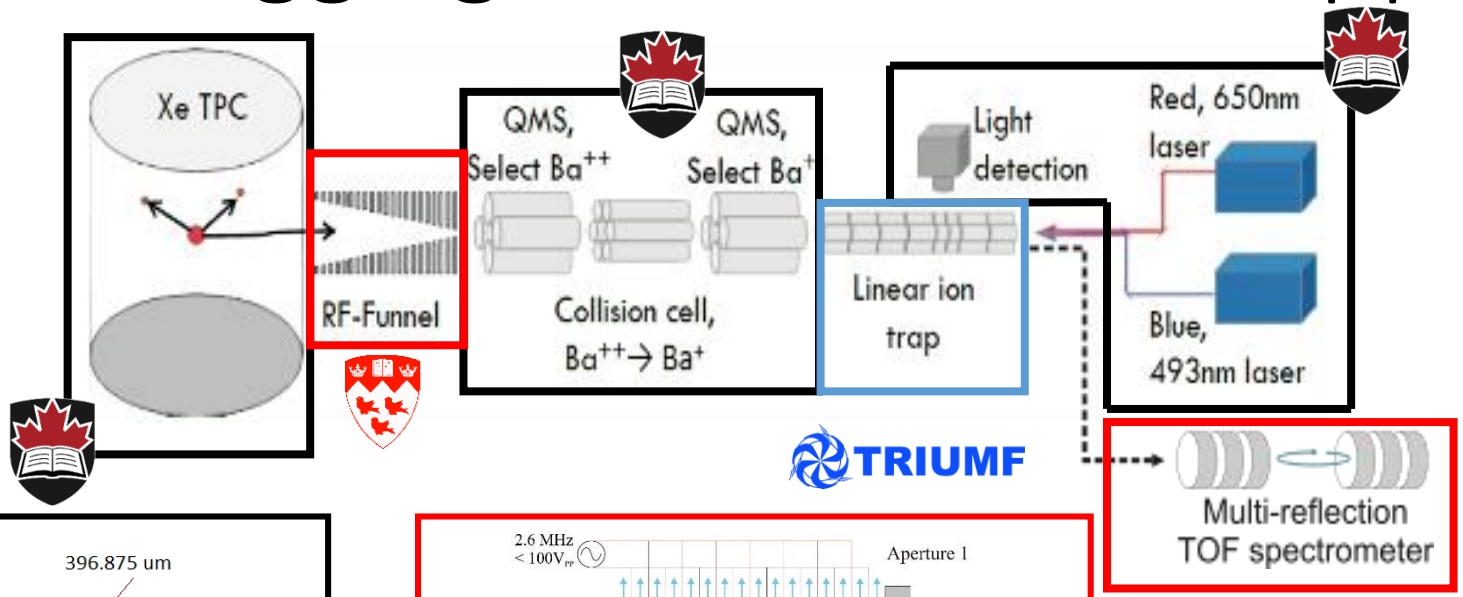


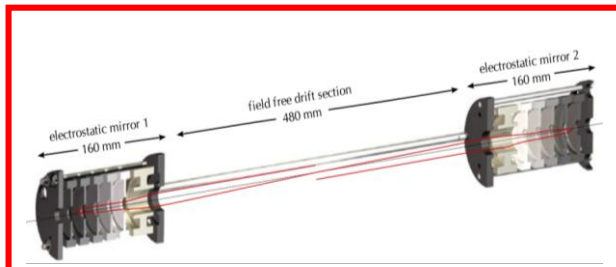
Ba-tagging

- Ba-tagging not part of the baseline design (reminder: baseline design means we can start building nEXO the day after the down select)
- But: Ba-tagging is being developed by several groups in the nEXO collaboration (Stanford, Colorado State, U. Illinois Champaign, **TRIUMF, Carleton, McGill**)
- Great progress has been made so far:
  - Three nEXO collaboration paper on Ba-tagging (the only nEXO collaboration wide paper)
- No technology identified so far that is sensitive on the 1 Ba-ion level
- Canada now concentrates Ba-tagging experts with the hires of R. Gornea and T. Brunner → great potential to solve the challenges
- Modest funding requested for preparatory activities
- Coherent Canadian approach to tackle the challenges of Ba-tagging

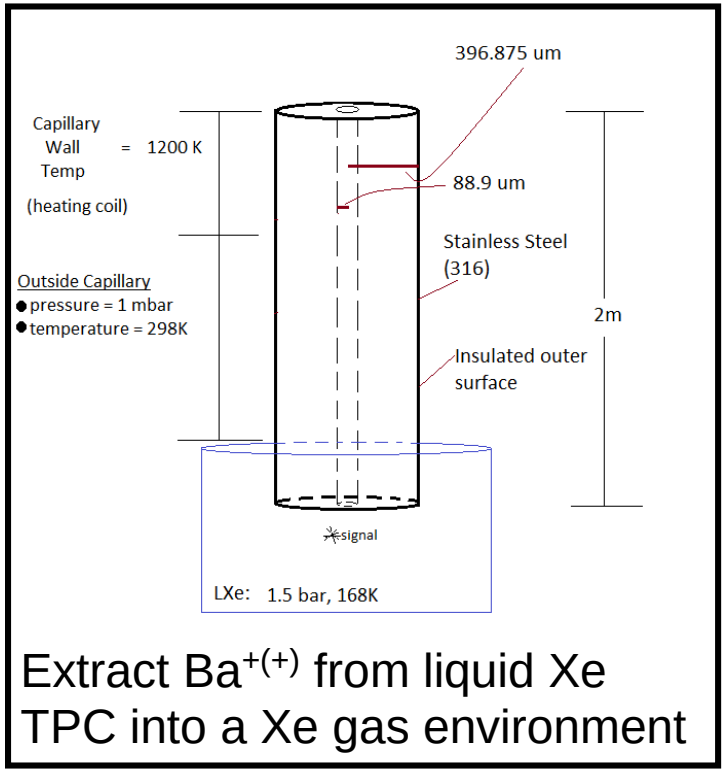
→ Ba-tagging is the only way to verify that a positive $0\nu\beta\beta$ signal is indeed from a $\beta\beta$ decay

Ba-tagging – the Canadian approach

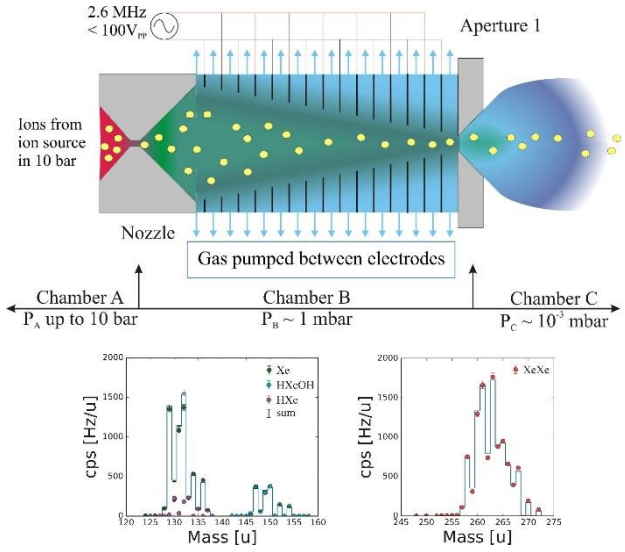




Systematic ion-extraction studies with MR TOF MS

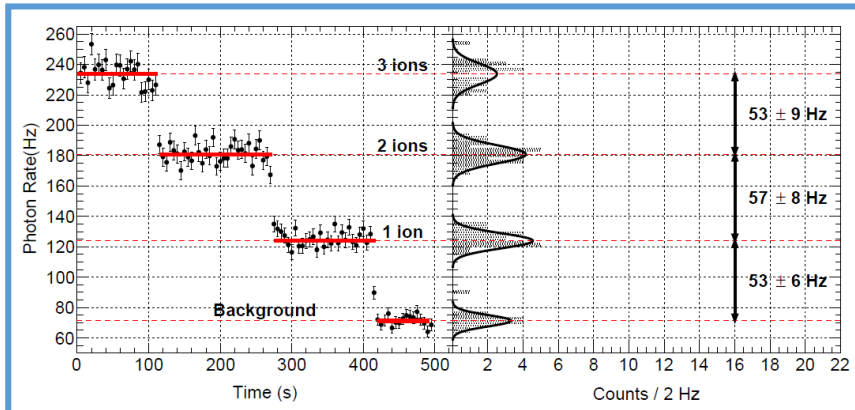


Extract $Ba^{+(+)}$ from liquid Xe TPC into a Xe gas environment



Int. J. Mass. Spectrom. 379(2015)110

Extract $Ba^{+(+)}$ with a Xe gas jet into a low pressure chamber.



Identify $Ba^{+(+)}$ with laser-fluorescence spectroscopy.

Status

- Time scale for project driven by US funding decisions
- ‘Downselect’ always 2-3 years off
- Recently R&D funding provided for preparation for Downselect
- nEXO received substantial support through this process
- Prospects for a major new double beta initiative look very good