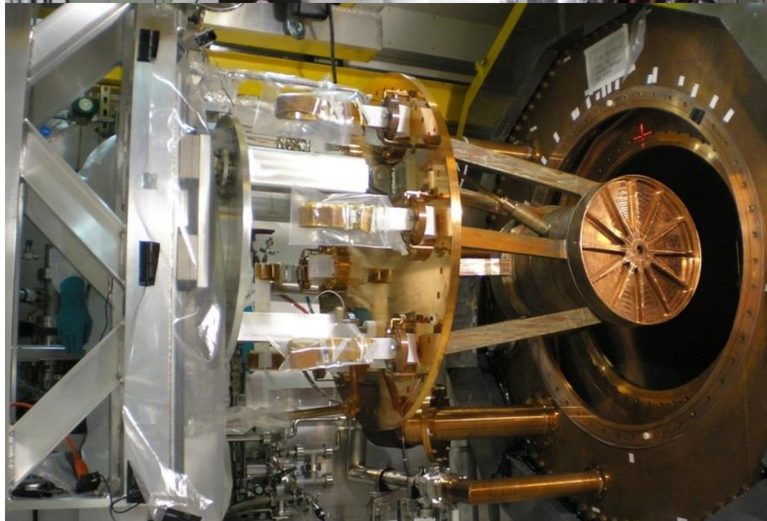
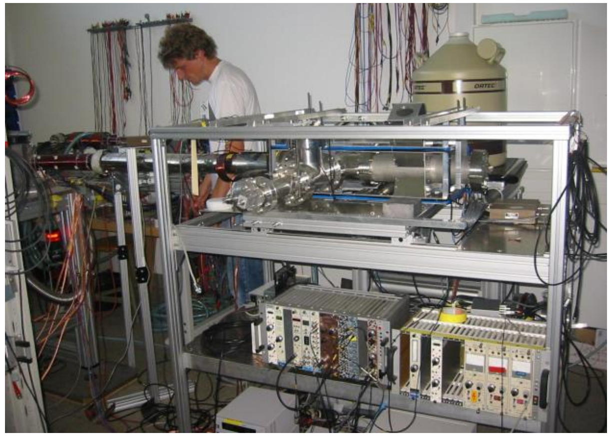
Hunting for Majorana neutrinos with nEXO

Thomas Brunner
McGill University and TRIUMF
The summer particle (astro)physics workshop
May 6, 2021
https://www.hep.physics.mcgill.ca/neutrino



My Career Path



Studied Physics at the Technical University Munich (2001 – 2011)

- Undergraduate research project
  - Programming of positron beam line in LabView
- Diploma thesis (MSc equivalent)
  - Investigation of positronium formation on cold surfaces
- PhD project, stationed at TRIUMF, Vancouver
  - In-trap decay spectroscopy with the TITAN EBIT

Post doctoral research fellow at Stanford (2011 – 2015)

- EXO-200, nEXO, and Ba-tagging

Assistant professor at McGill (2015 – 2020)

- EXO-200, nEXO, Ba-tagging, and in-trap decay spectroscopy

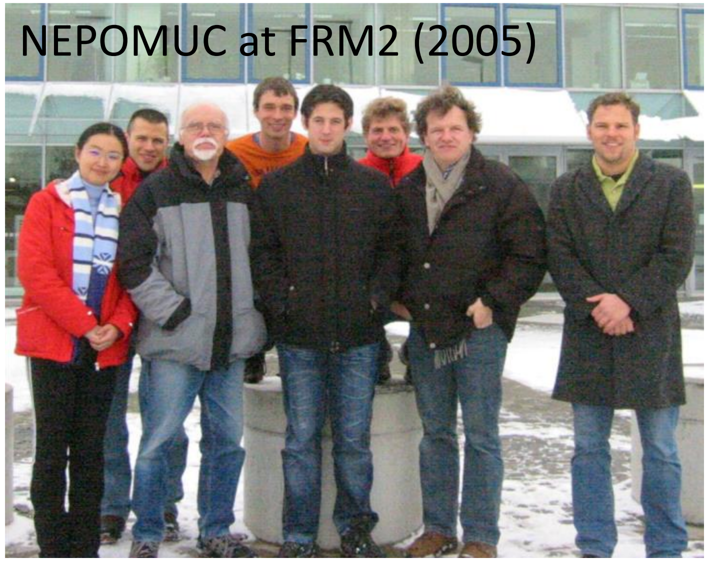
Associate professor at McGill (2020 – now)

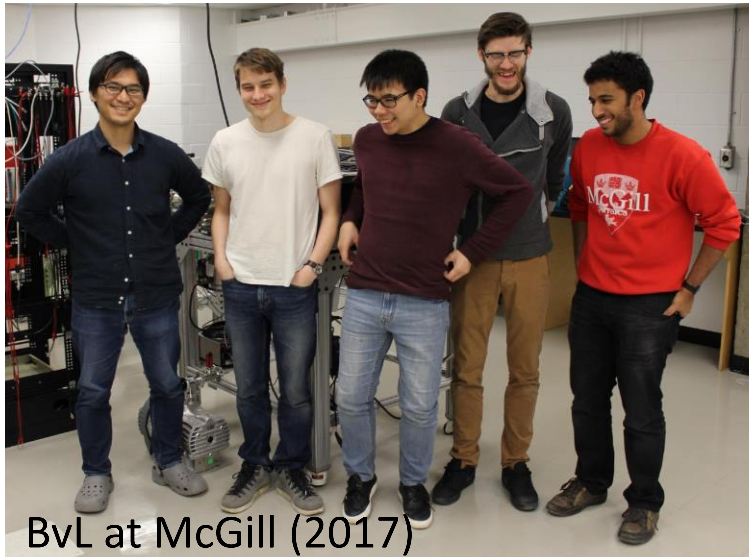
- nEXO, Ba-tagging, and in-trap decay spectroscopy

Condensed matter physics
↓
Atomic physics
↓
Nuclear physics
↓
Particle/neutrino/nuclear physics

Don’t be afraid to change fields!

I continued in research because of the people





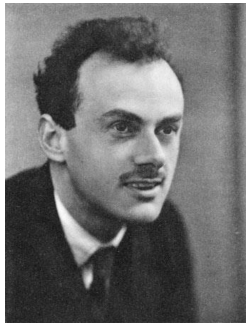
What we hope to learn with nEXO

(Exactly how heavy are neutrinos?)

What is the quantum nature of the neutrino?

Quantum nature of the neutrino

"Dirac" neutrinos $\nu \neq \bar{\nu}$



"Majorana" neutrinos $\nu = \bar{\nu}$

Lepton number violated

Which way Nature chose to proceed is an open experimental question, although Majorana neutrinos are favored by theory.

The two descriptions are distinct and distinguishable only if $m_\nu \neq 0$.

Matter-Antimatter Asymmetry

Nothing in our theory tells us why there seems to be so much more matter than antimatter in the Universe.

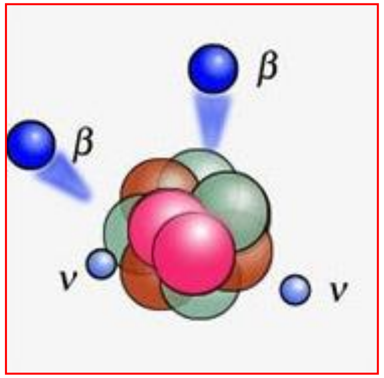
This is a pretty big **asymmetry**, so we should look for symmetry violations.

Neutrinos could be the key!

Source: https://www.spacetelescope.org/

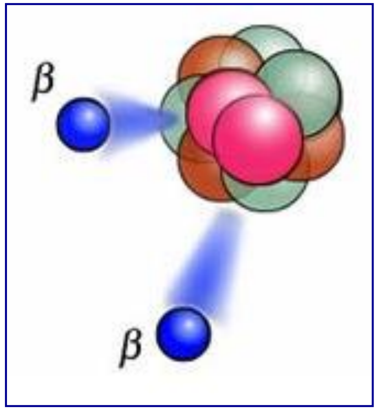
How to search for Majorana neutrinos?

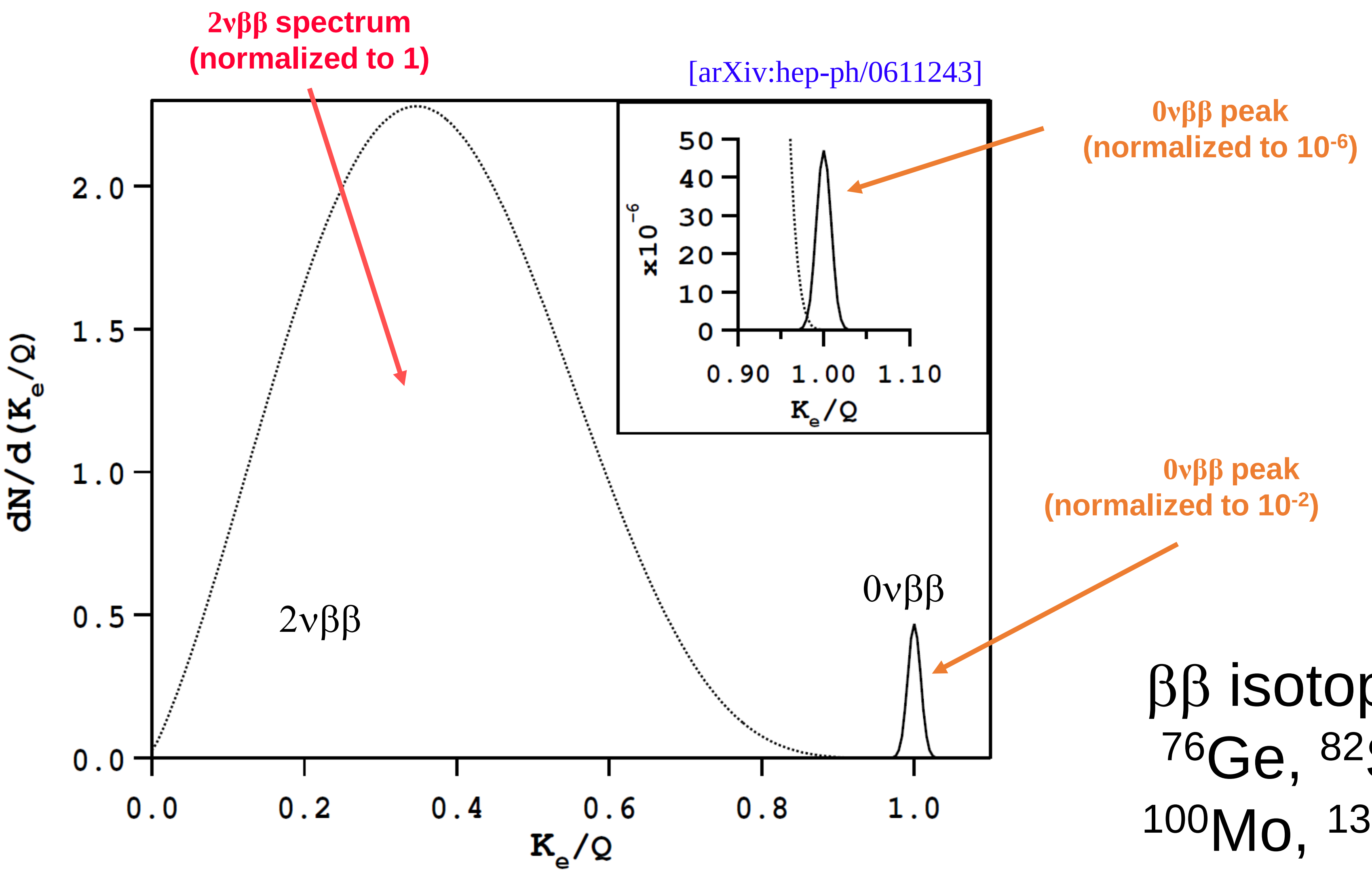
Double Beta Decay



$2\nu\beta\beta$

$T_{1/2} \approx 10^{20}$ y

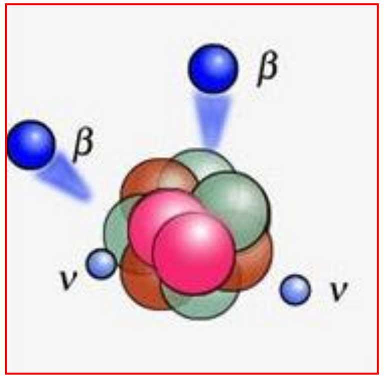




ββ isotopes:
^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te, ^{136}Xe

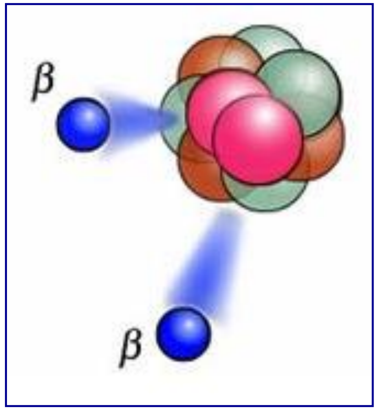
$0\nu\beta\beta$ – Can only happen for Majorana neutrinos! $T_{1/2} > 10^{25}$ y!

Double Beta Decay



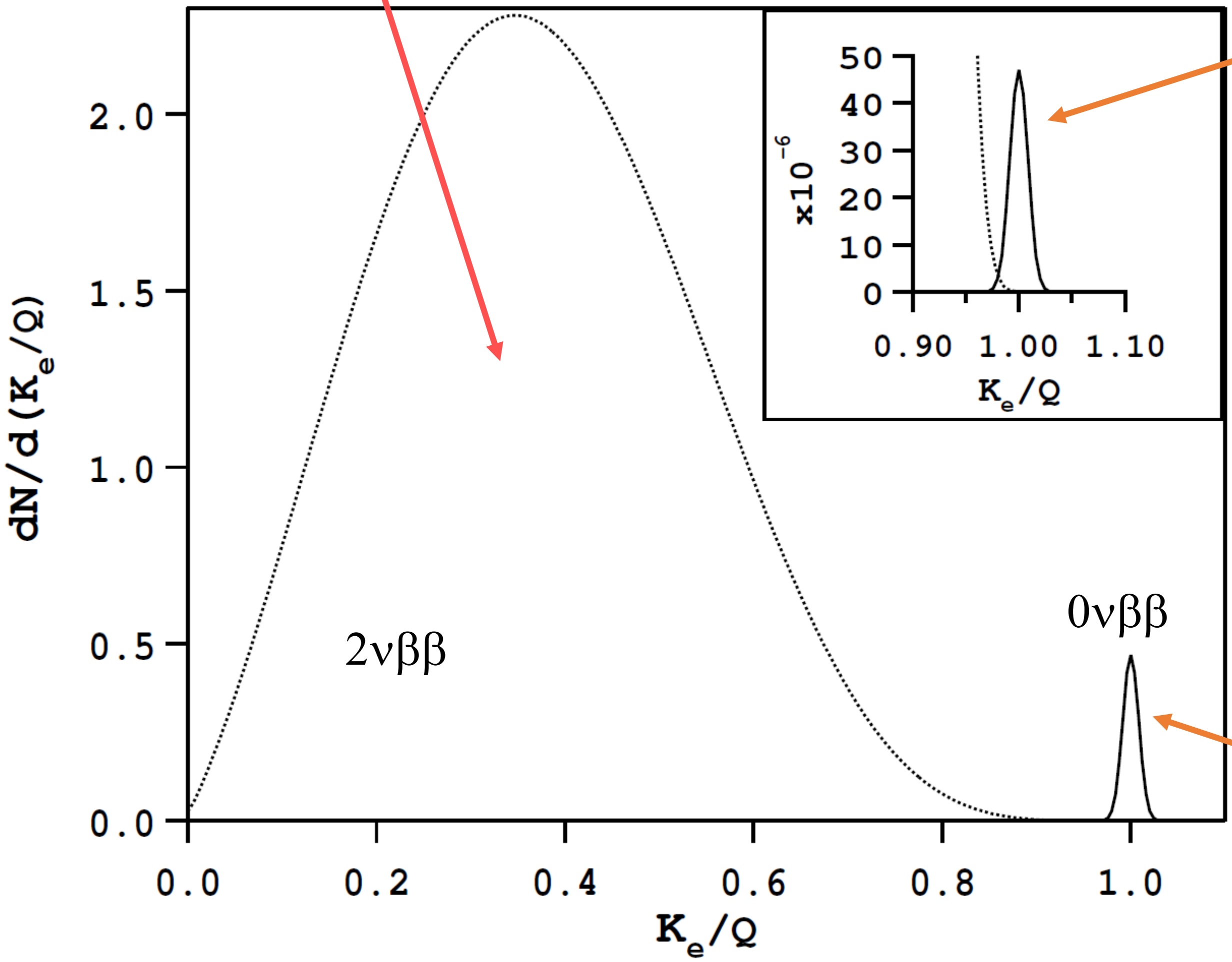
$2\nu\beta\beta$

$T_{1/2} \approx 10^{20}$ y



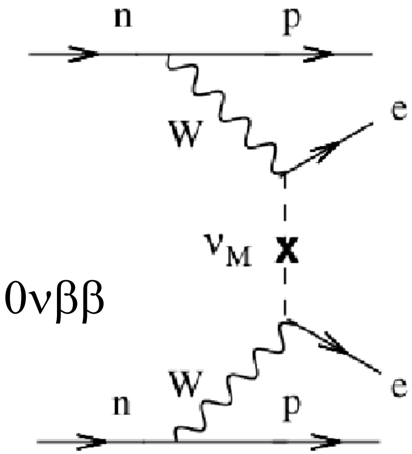
2νββ spectrum
(normalized to 1)

[arXiv:hep-ph/0611243]



0νββ peak
(normalized to 10^{-6})

0νββ peak
(normalized to 10^{-2})

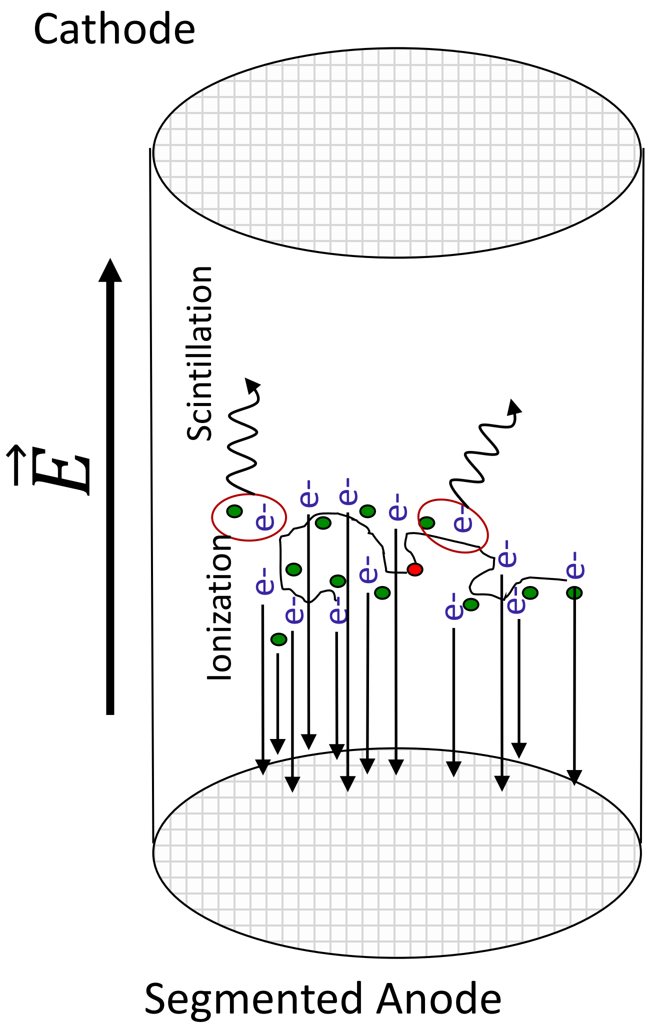


$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu} \left|M^{0\nu}\right|^2 \left\langle m_\nu \right\rangle^2 \quad \left\langle m_\nu \right\rangle = \left|\sum_i U_{ei}^2 m_i \, \varepsilon_i\right|$$

(light neutrino exchange mechanism only)

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

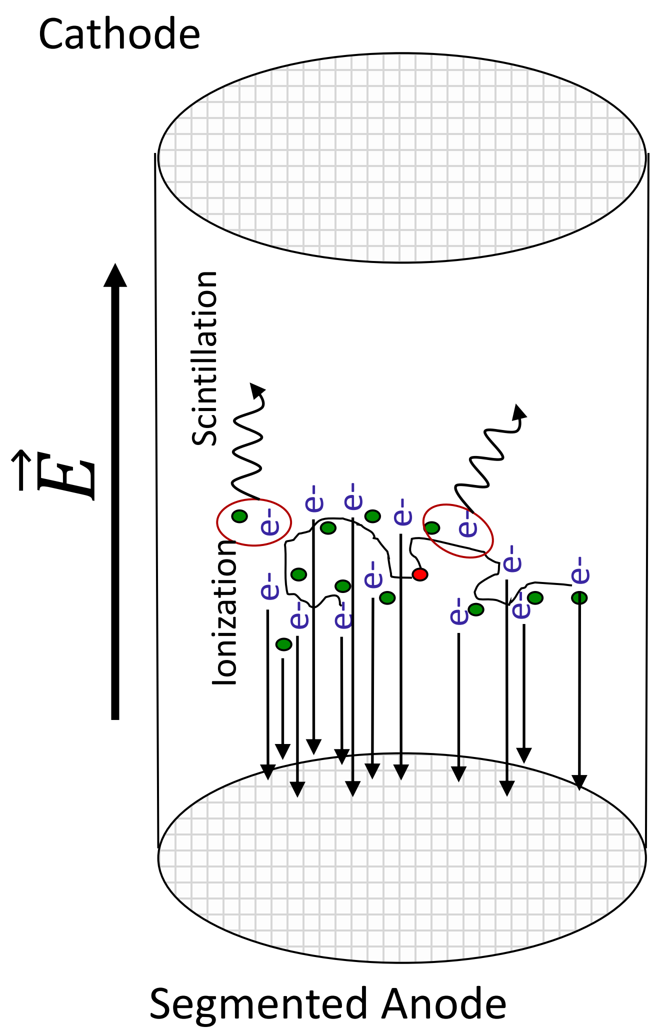
Searching for $0\nu\beta\beta$ in ^{136}Xe with liquid Xe TPC



Liquid-Xe Time Projection Chamber (TPC)

- Xe is used both as the source and detection medium.
- Monolithic detector structure, excellent background rejection capabilities.
- Cryogenic electronics in LXe (at ~168 K).
- Detection of scintillation light and secondary charges.
  - 2D read out of secondary charges at segmented anode.
  - Full 3D event reconstruction using also scintillation light:
    1. Energy reconstruction
    2. Position reconstruction
    3. Event Multiplicity

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



^{136}Xe is great to study because:

- Good $0\nu\beta\beta$ peak location.
- Easy to enrich.
- We know how to build a detector out of it!

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

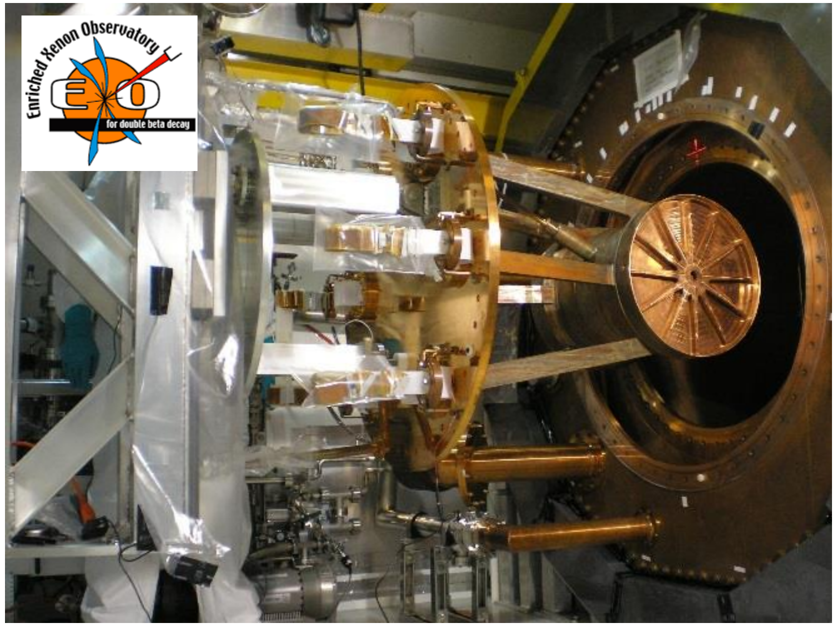
→Need:

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

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

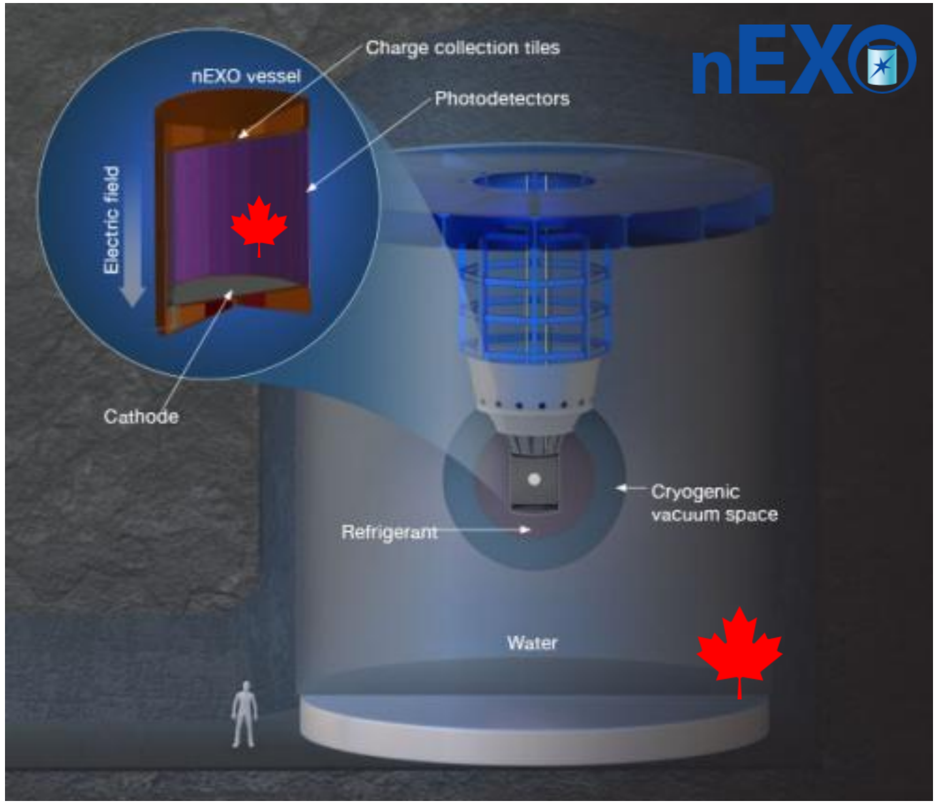
Searching for $0\nu\beta\beta$ in ^{136}Xe – a phased approach

EXO-200:
- EXO-200 first 100-kg class ββ experiment
- 200kg liquid-Xe TPC with ~80% Xe-136
- Located at the WIPP mine in NM, USA
- Decommissioned in Dec. 2018
- Analyze data from end-of-run calibration campaign
  → data will inform the detailed design of nEXO



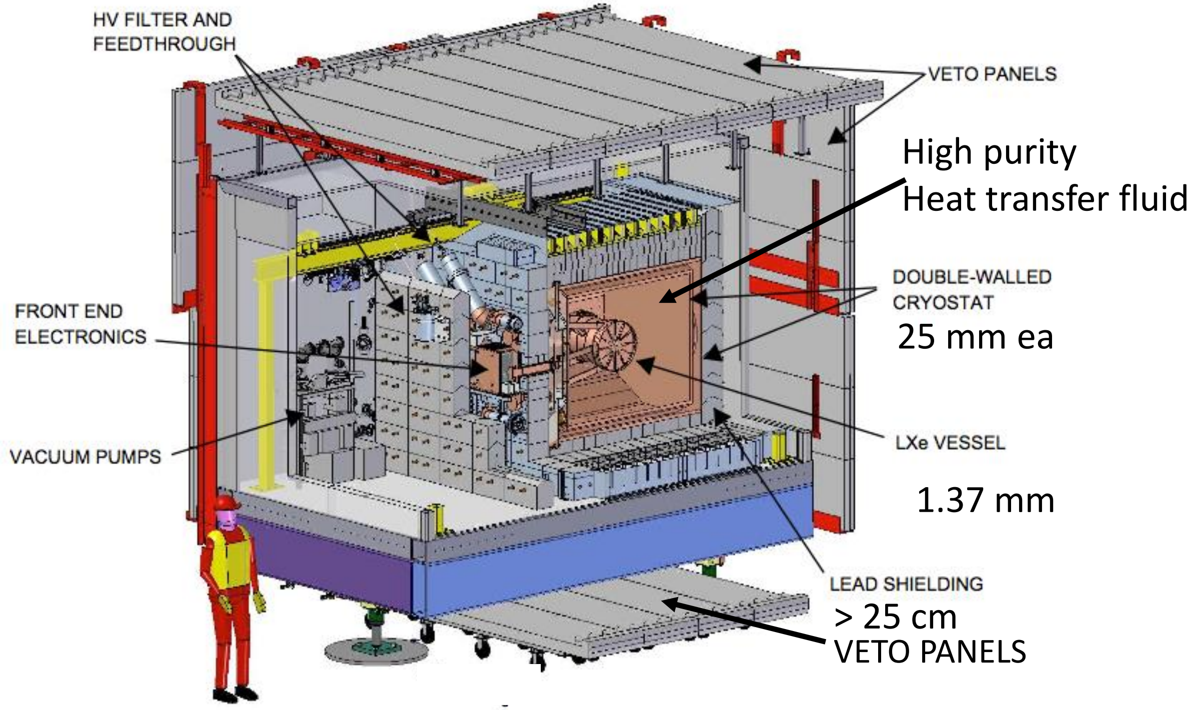
https://www-project.slac.stanford.edu/exo/

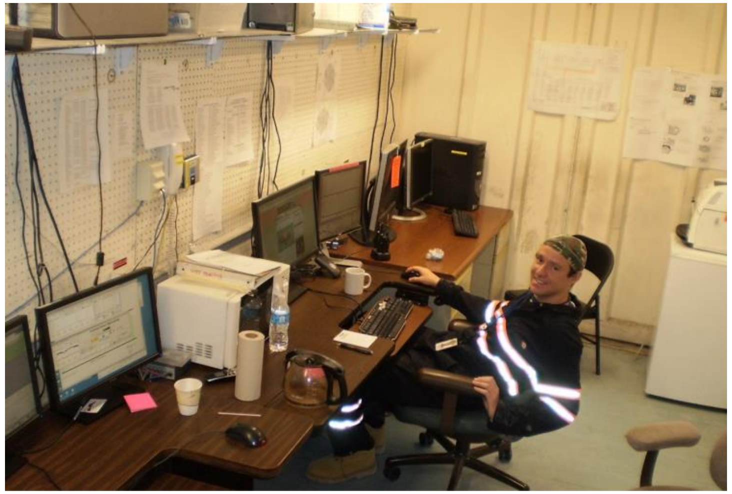
nEXO:
- future 5-ton liquid Xe TPC
- Enriched in Xe-136 at ~90%
- SNOLAB cryopit preferred location by collaboration
- Decision on funding of nEXO expected this summer!



https://nexo.llnl.gov/

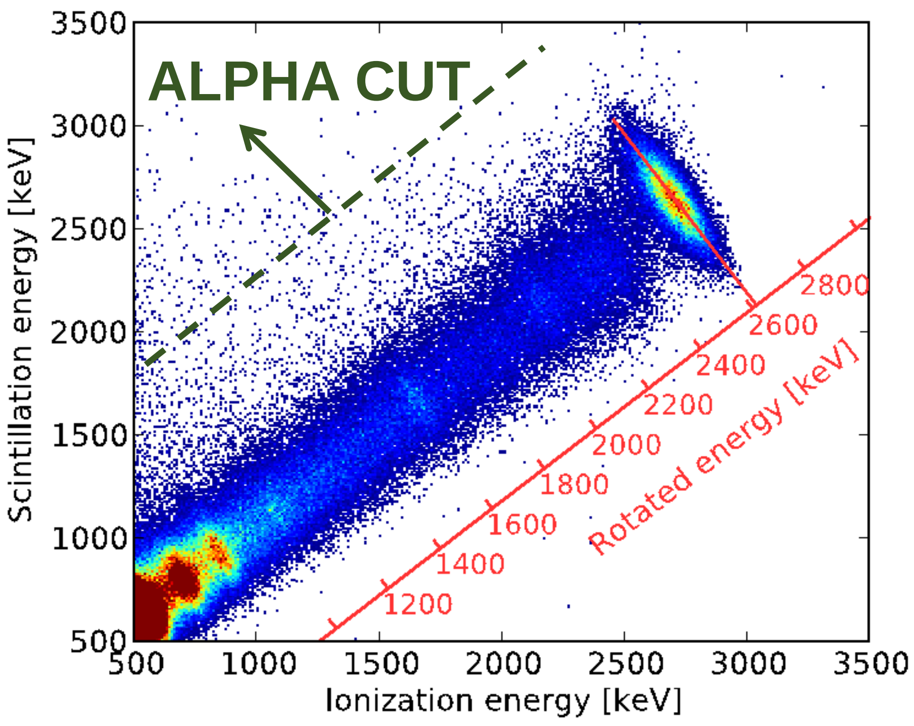
EXO-200


HV FILTER AND
FEEDTHROUGH
VETO PANELS
High purity
Heat transfer fluid
DOUBLE-WALLED
CRYOSTAT
25 mm ea
FRONT END
ELECTRONICS
VACUUM PUMPS
LXe VESSEL
1.37 mm
LEAD SHIELDING
> 25 cm
VETO PANELS

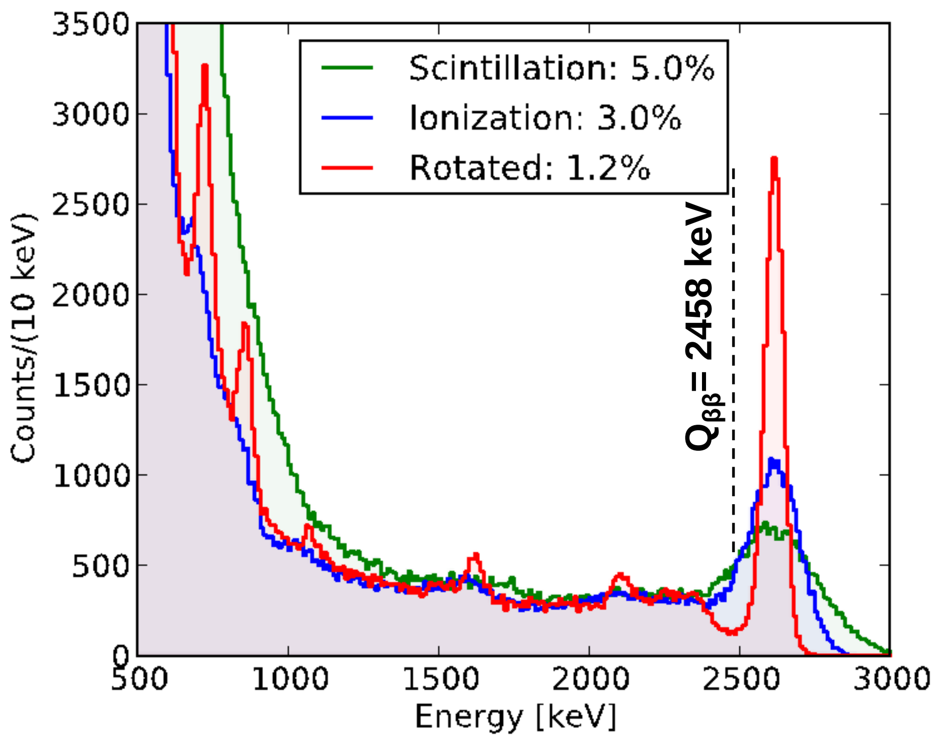


Energy measurement (EXO-200 data)

Scintillation vs. ionization, ^{228}Th calibration:



Reconstructed energy, ^{228}Th calibration:

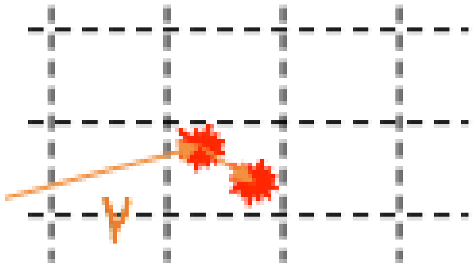


- Anticorrelation between scintillation and ionization in LXe known since early EXO R&D and now standard in LXe detectors [E.Conti et al. Phys Rev B 68 (2003) 054201]
- Rotation angle determined weekly using ^{228}Th source data, defined as angle which gives best rotated resolution
- EXO-200 has achieved ~ 1.15% (PRL123,161802(2019)) energy resolution at the ββ decay Q value in Phase II

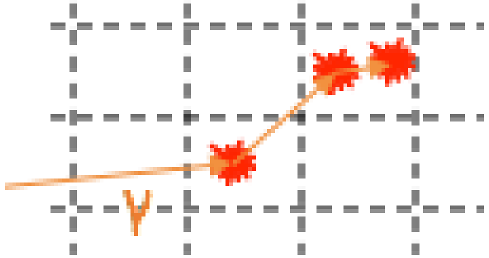
Position and multiplicity (EXO-200 data)

Allows for background measurement and reduction

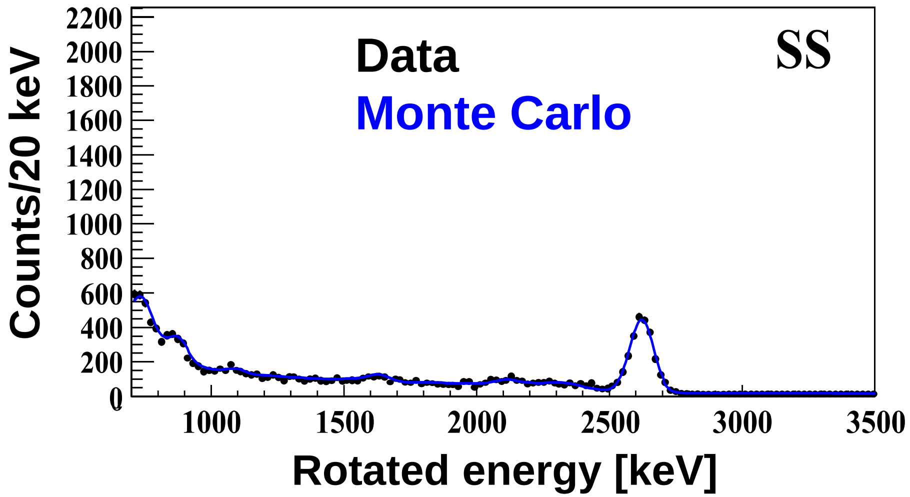
Events with **> 1** charge cluster: multi-site events (MS)
Events with **1** charge cluster: single-site events (SS)



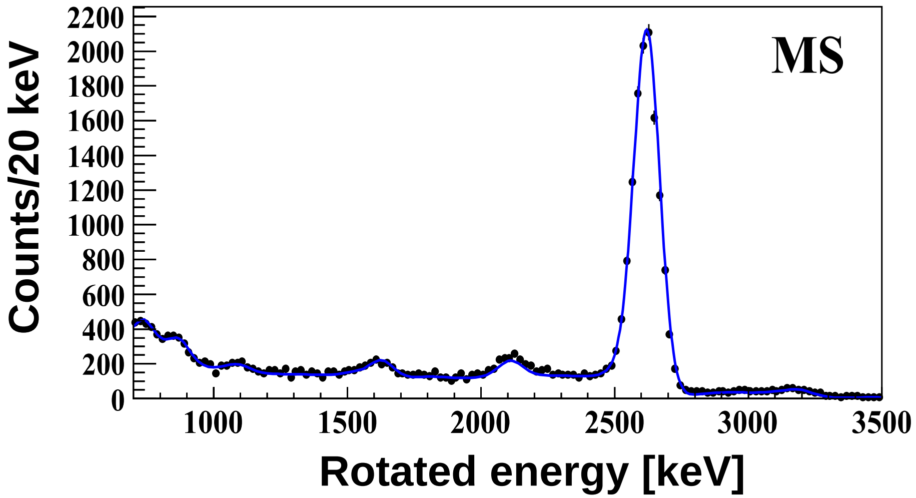
$0\nu\beta\beta$: ~90% SS
γ-rays: ~15% SS at $0\nu\beta\beta$ Q-value



^{228}Th calibration data, SS:

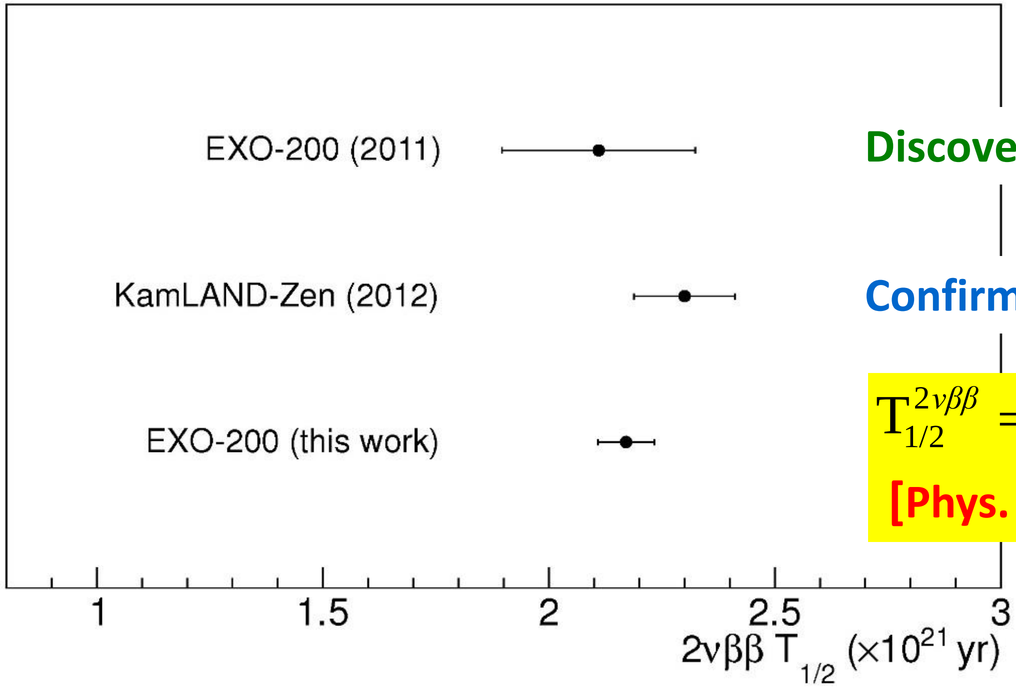


^{228}Th calibration data, MS:



EXO-200 Phase-I Results

Precision ^{136}Xe 2νββ Measurement



EXO-200 start data taking in June 2011

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

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

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

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

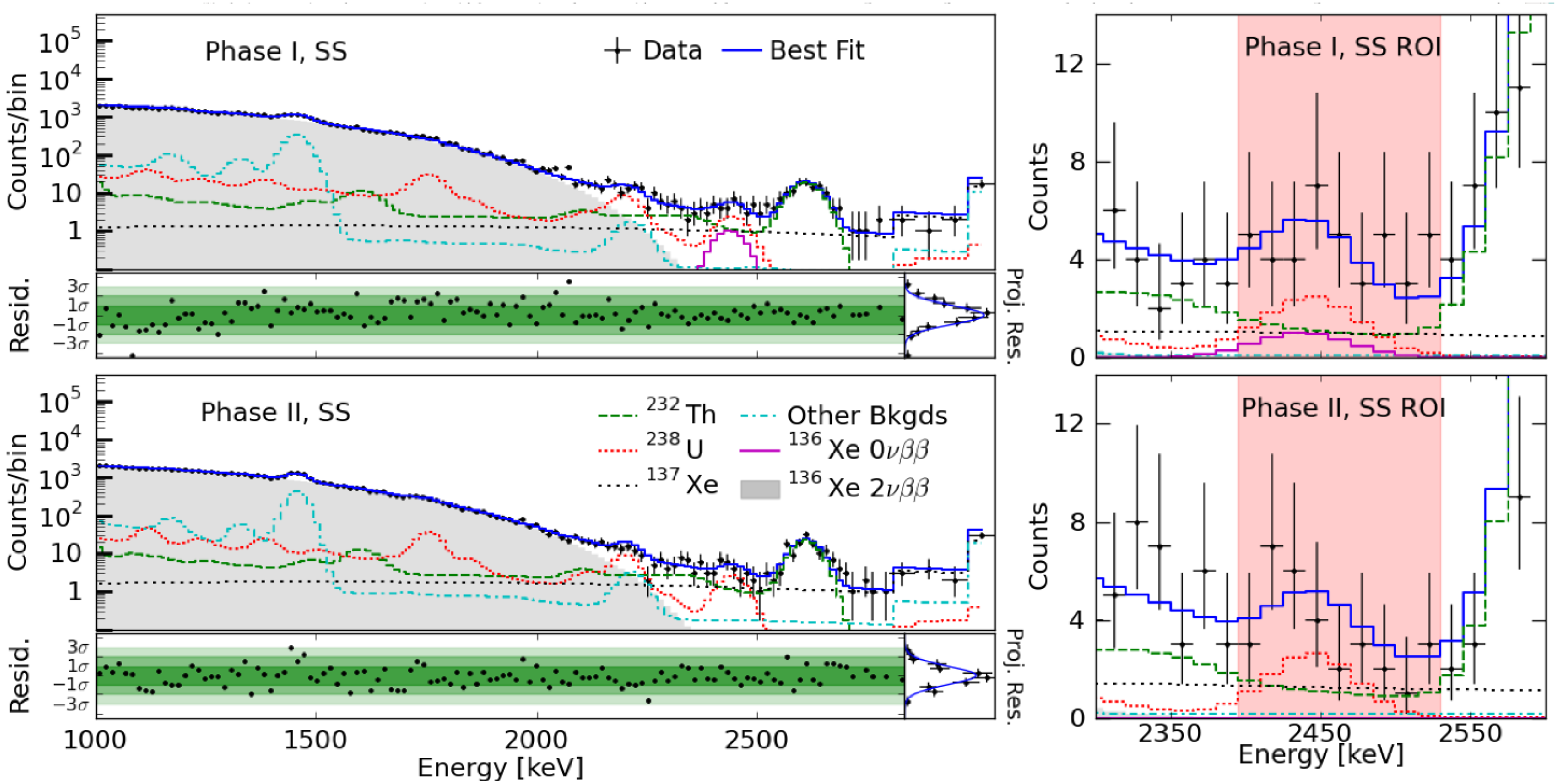
Longest and most precisely measured 2νβ⁻β⁻ half-life

Final EXO-200 Results

Slide from: M. Jewell
September, 2019
TAUP2019, Toyama, Japan

- No statistically significant $0\nu\beta\beta$ signal observed

PRL 123 (2019) 161802



Slide from: Gaosong Li
Jun 7, 2019
WIN2019, Bari, Italy

Latest EXO-200 Results

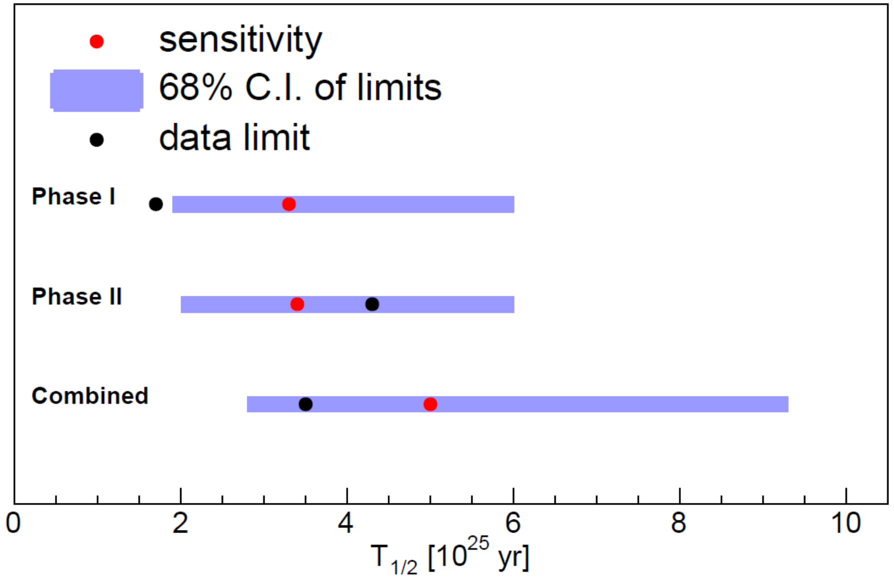
No statistical significant signal observed

Phase I+II: 234.1 kg·yr ^{136}Xe exposure

Limit $T_{1/2}^{0\nu\beta\beta}$ > 3.5 x 10^{25} yr (90% C.L.)

$\langle m_{\beta\beta}\rangle$ < (93 – 286) meV

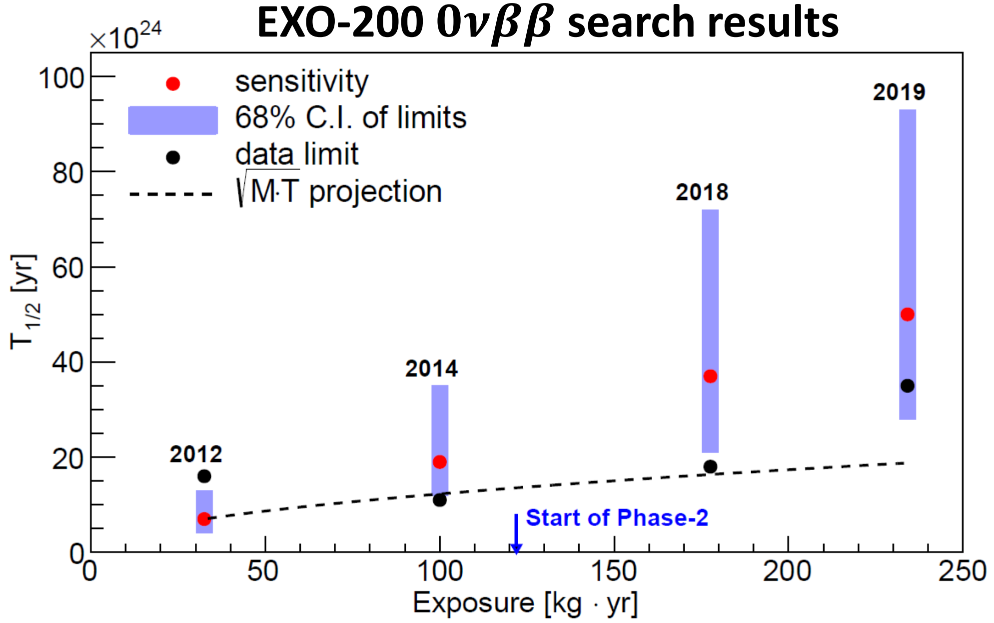
Sensitivity 5.0x10^{25} yr



Background contribution to Q $\pm 2\sigma$

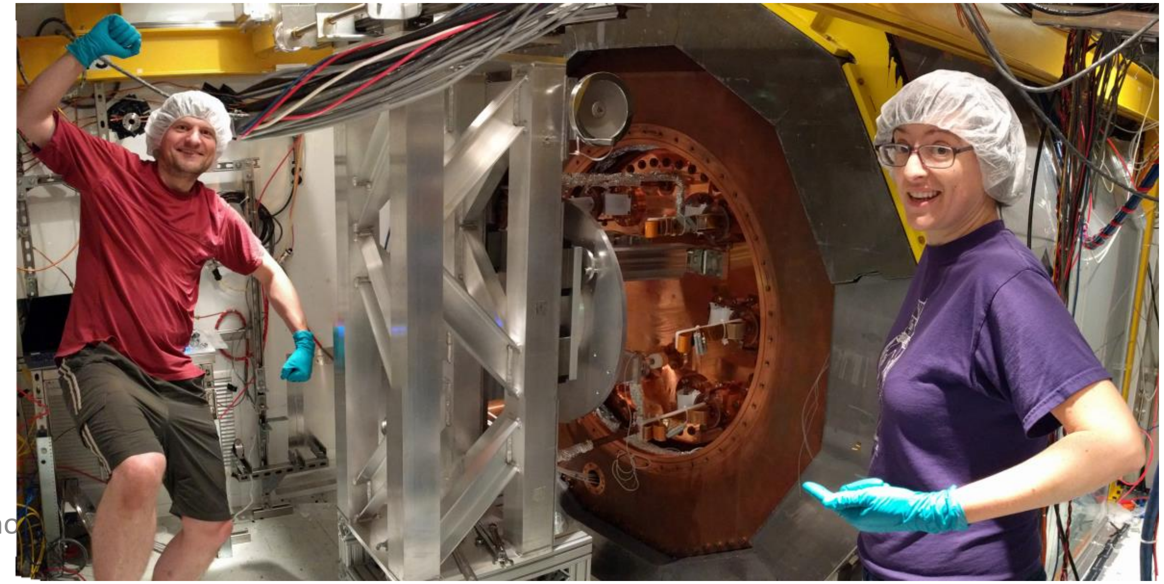
(counts)	^{238}U	^{232}Th	^{137}Xe	Total	Data
Phase I	12.6	10.0	8.7	32.3±2.3	39
Phase II	12.0	8.2	9.3	30.9±2.4	26

EXO-200 $0\nu\beta\beta$ search results



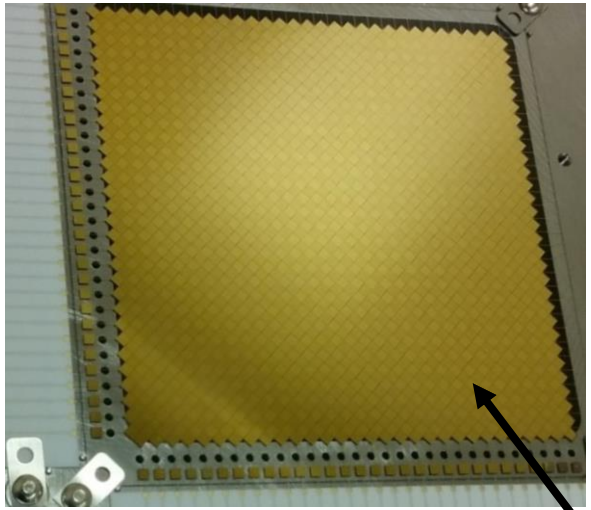
2012: Phys. Rev. Lett. 109 (2012) 032505
2014: Nature 510 (2014) 229
2018: Phys. Rev. Lett. 120 (2018) 072701
2019: PRL 123 (2019) 161802

EXO-200 decommissioning

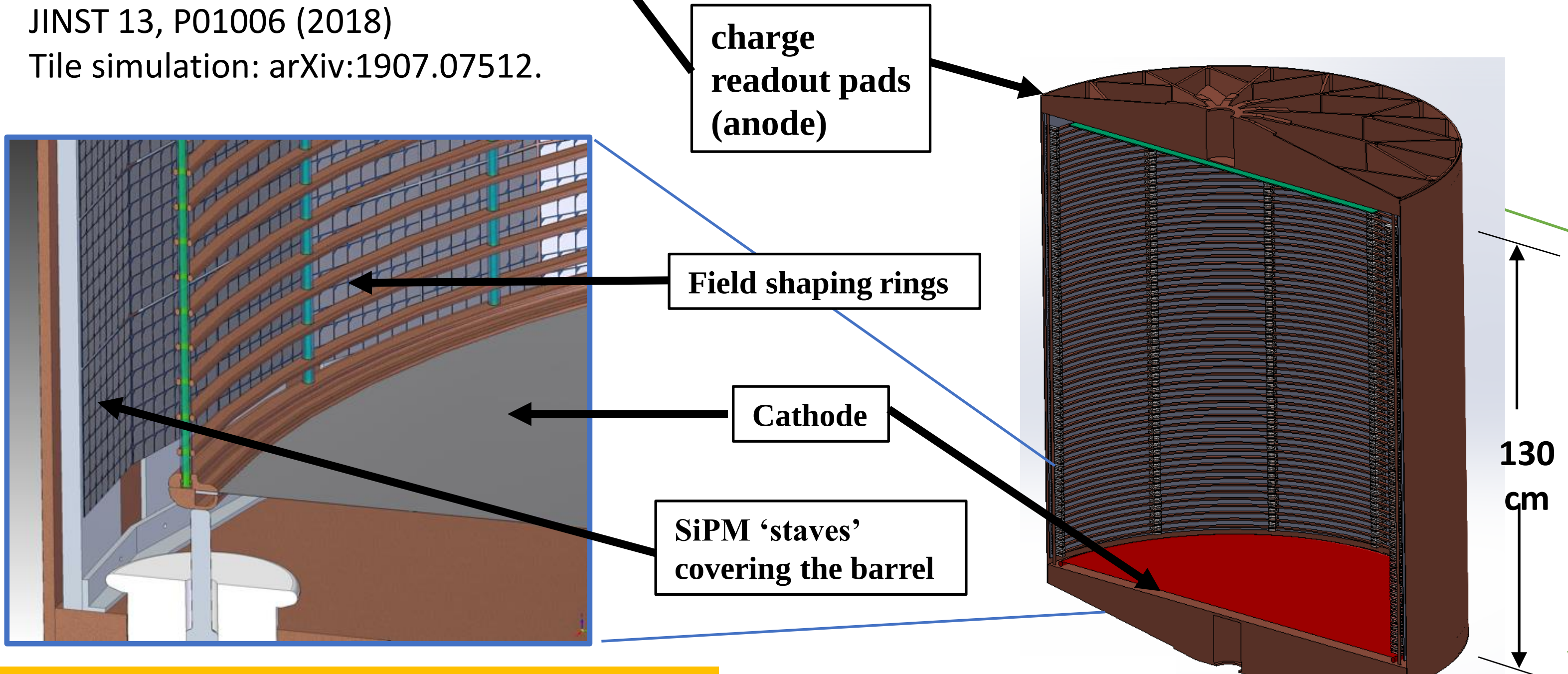


The nEXO detector

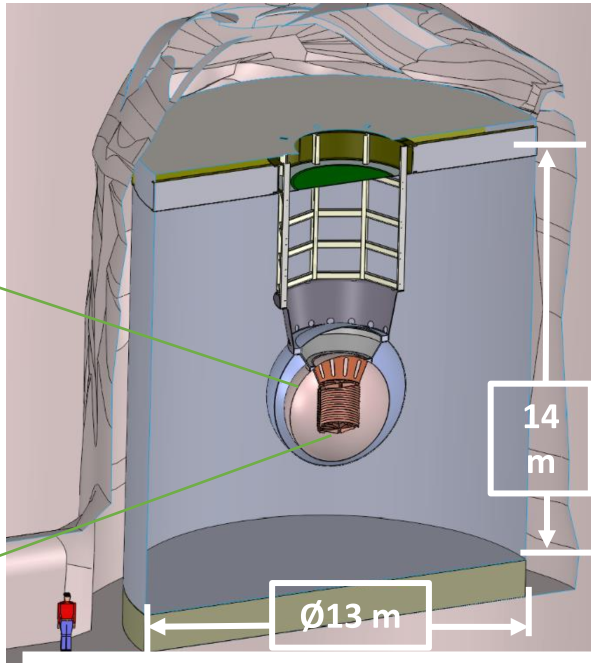
- Next-generation neutrinoless double beta decay detector.
- 5 t liquid xenon TPC similar to EXO-200.
- SiPM for 175nm scintillation light detection, ~4.5m^2 SiPM array in LXe.
- Tiles for charge read out in LXe.
- In-cold electronics inside TPC in liquid Xe.
- 3D event reconstruction.
- Combine charge and light readout. Goal → σ/E of 1% at Q-value.
- 1.5 ktonnes water-Cherenkov detector for muon tagging and shielding.



Picture: 10 x 10 cm^2 tile prototype
JINST 13, P01006 (2018)
Tile simulation: arXiv:1907.07512.



nEXO TPC



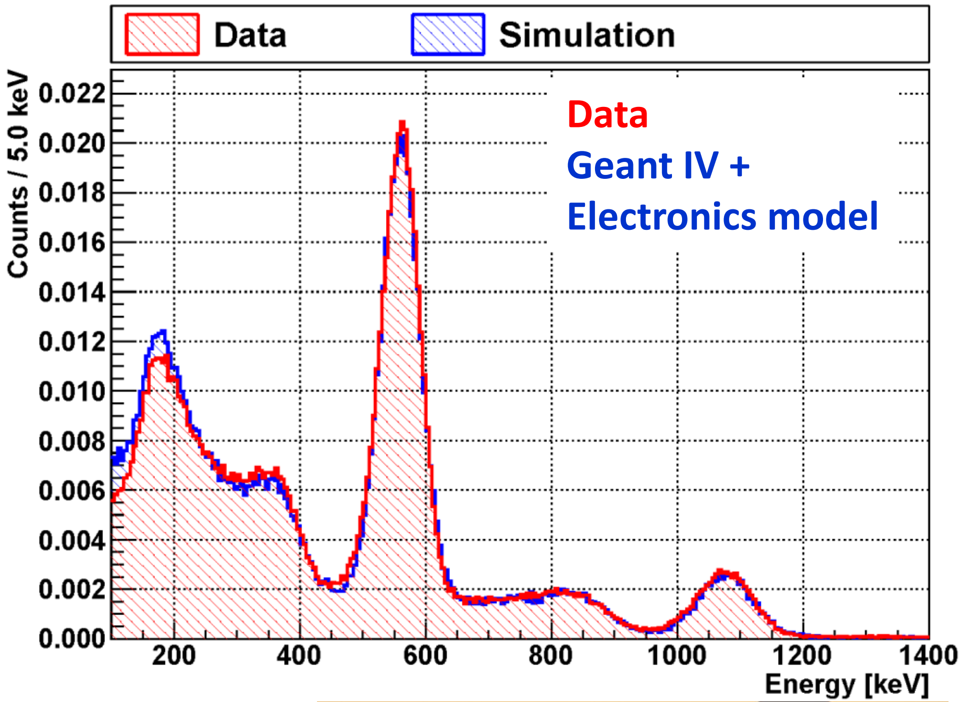
nEXO at the SNOLAB Cryopit

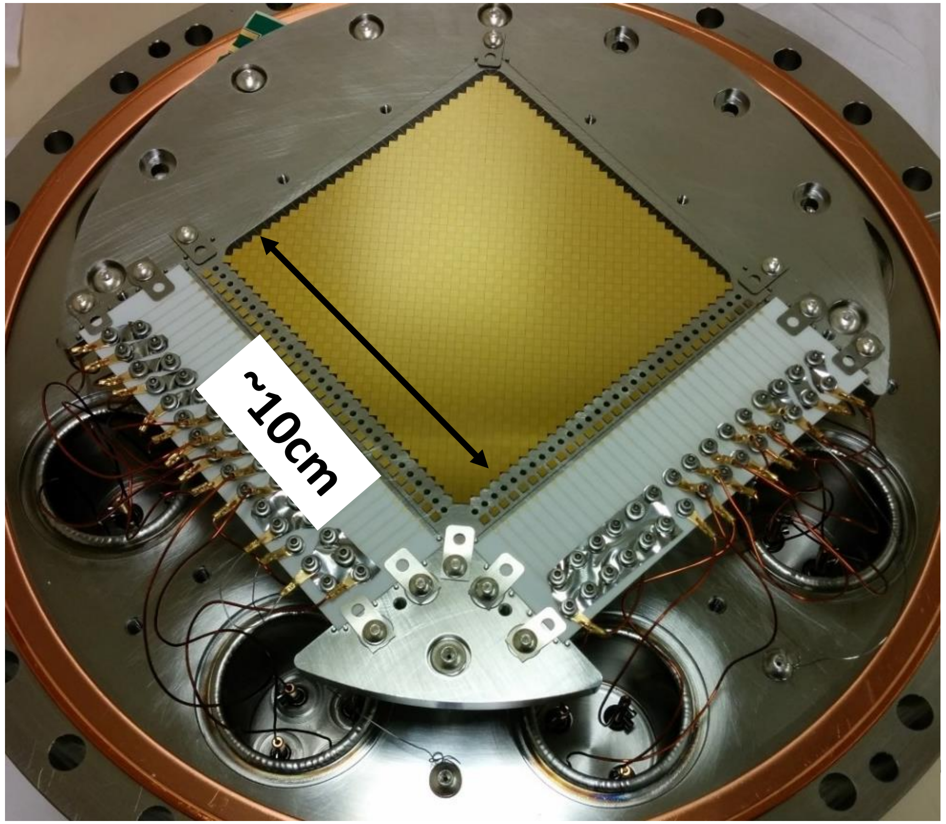
nEXO pre-CDR, arXiv:1805.11142

Charge Readout

Charge will be collected on arrays of strips fabricated onto low background dielectric wafers
(low radioactivity quartz has been identified)

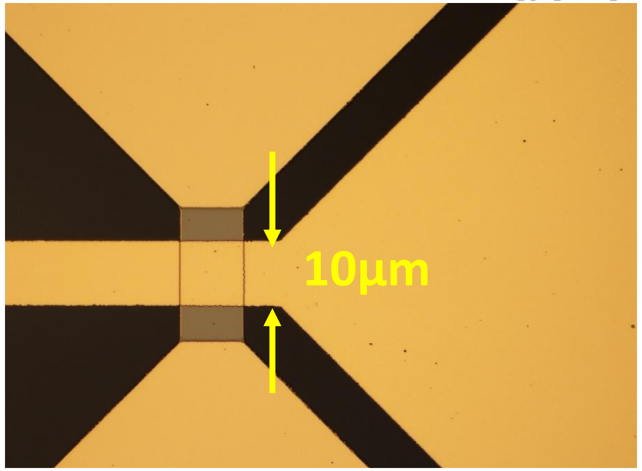
- **Self-supporting/no tension**
- **Built-on electronics (on back)**
- **Far fewer cables**
- **Ultimately more reliable, lower noise, lower activity**





Max metallization cover with min capacitance

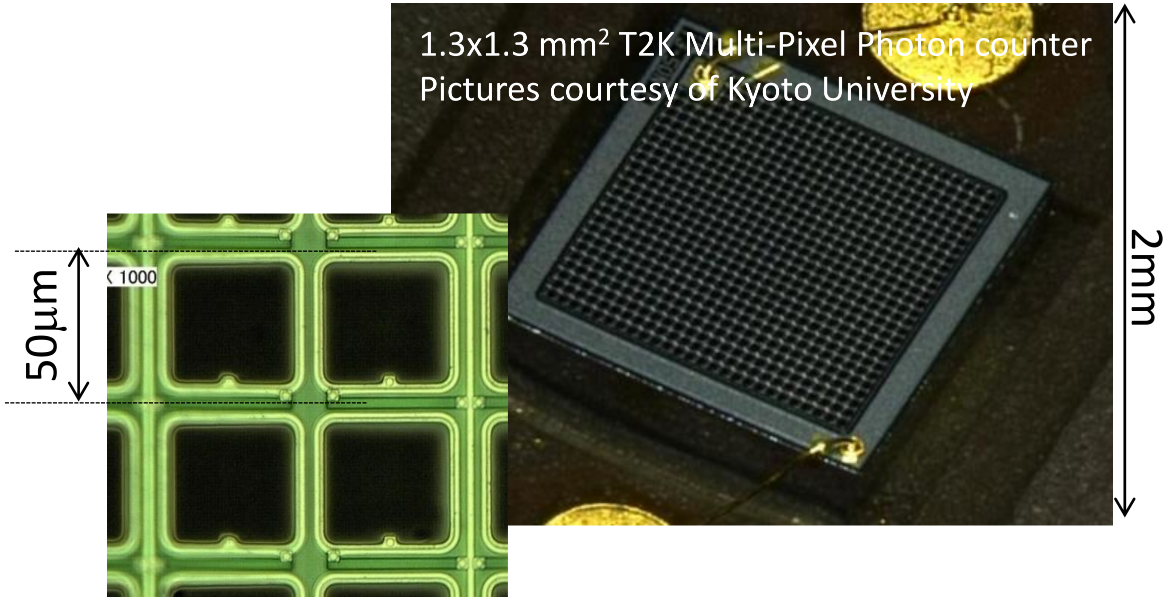
JINST 13, P01006 (2018)
arXiv 1710.05109

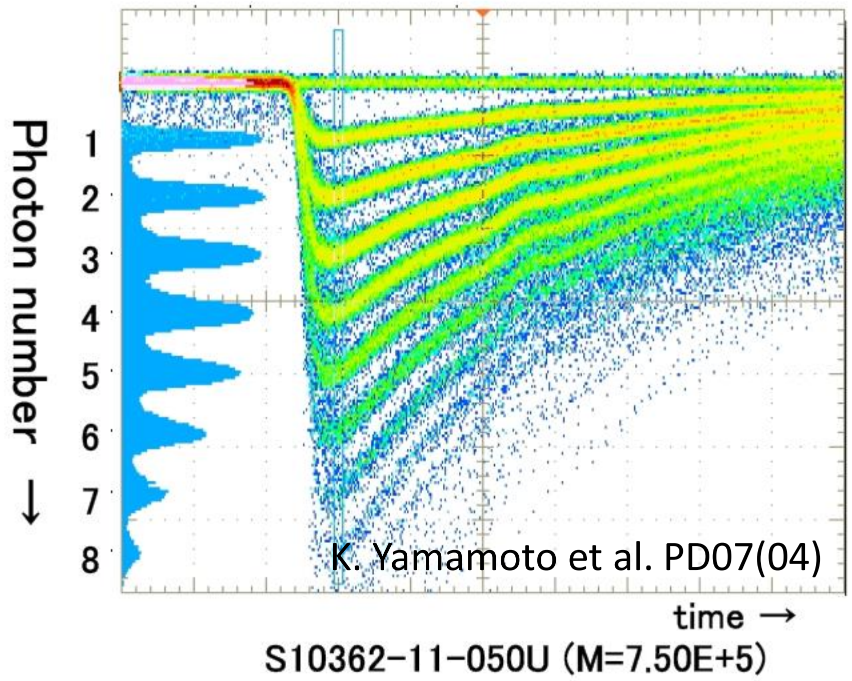


- 10 x 10cm^2 Prototype Tile
- Metallized strips on fused silica substrate
- 60 orthogonal channels (30 x 30), 3mm strip pitch
- Strip intersections isolated with SiO_2 layer

Analog SiPMs - baseline solution for nEXO

- High gain (low noise)
- Large manufacturing capabilities
- Single-photon counting possible





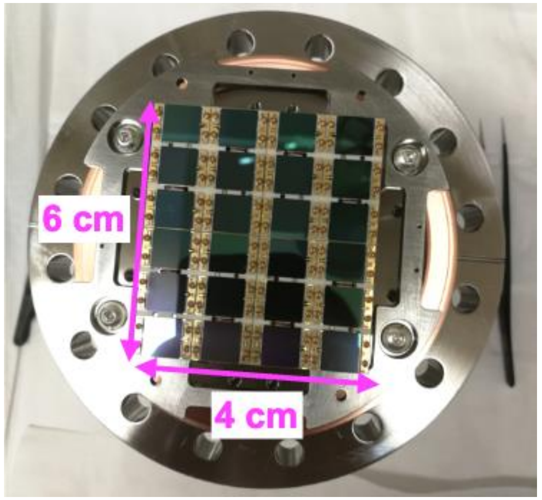
nEXO key parameters (arxiv:1805.11142):

Parameter	Value
Total instrumented area	$\simeq 4.5\ \mathrm{m}^2$
Overall light detection efficiency	$\epsilon_o > 3\ \%$
SiPM PDE (175 nm, normal incidence)	$\epsilon_{PD} > 15\ \%$
Overvoltage	$> 3\ \mathrm{V}$
Dark noise rate	$< 50\ \mathrm{Hz/mm}^2$
Correlated avalanche rate	< 0.2

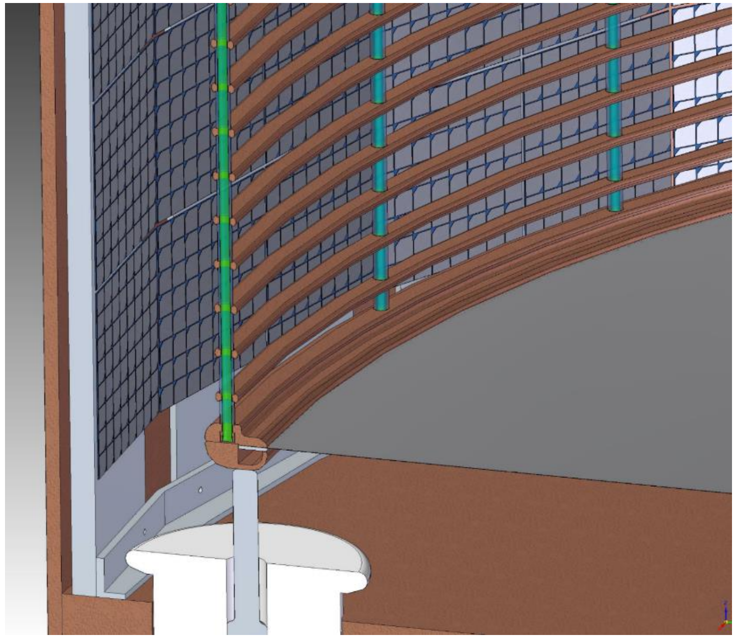
Analog SiPMs - baseline solution for nEXO

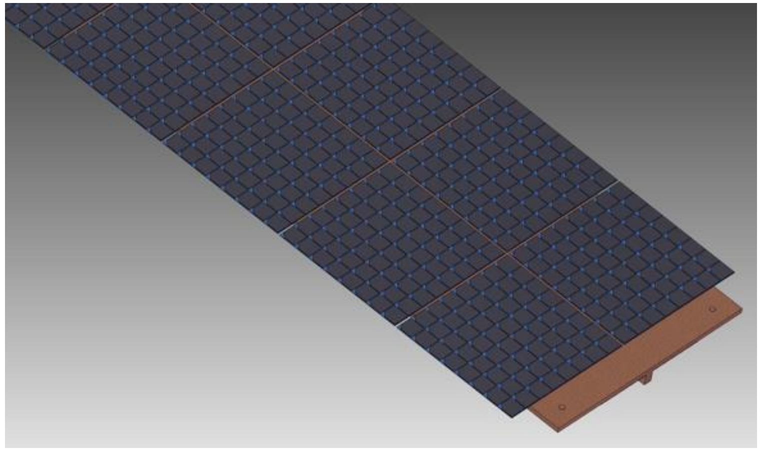
- Integrate SiPMs into 'tiles' (~10 x 10 cm^2).
- ASIC chip to read out tile.
- Tiles mounted on 'stave' (~20 x 120 cm^2).
- Staves mounted inside LXe behind field cage.

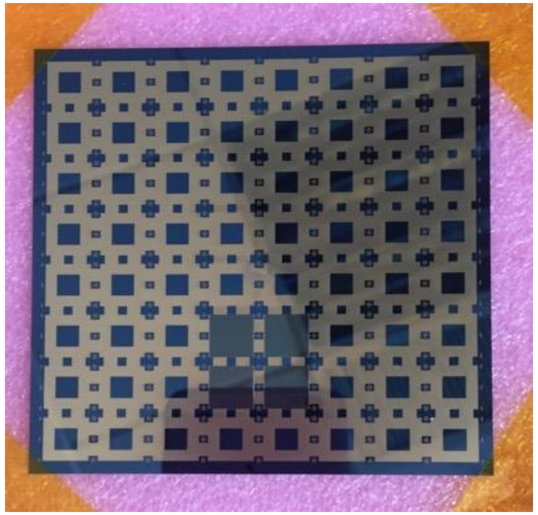
ASIC (ZENON) for SiPM readout under design (BNL)
- System on Chip
- 16 channel
- Peak detection
- Analog to digital conversion
- On-chip LDOs



Prototype SiPM Tile



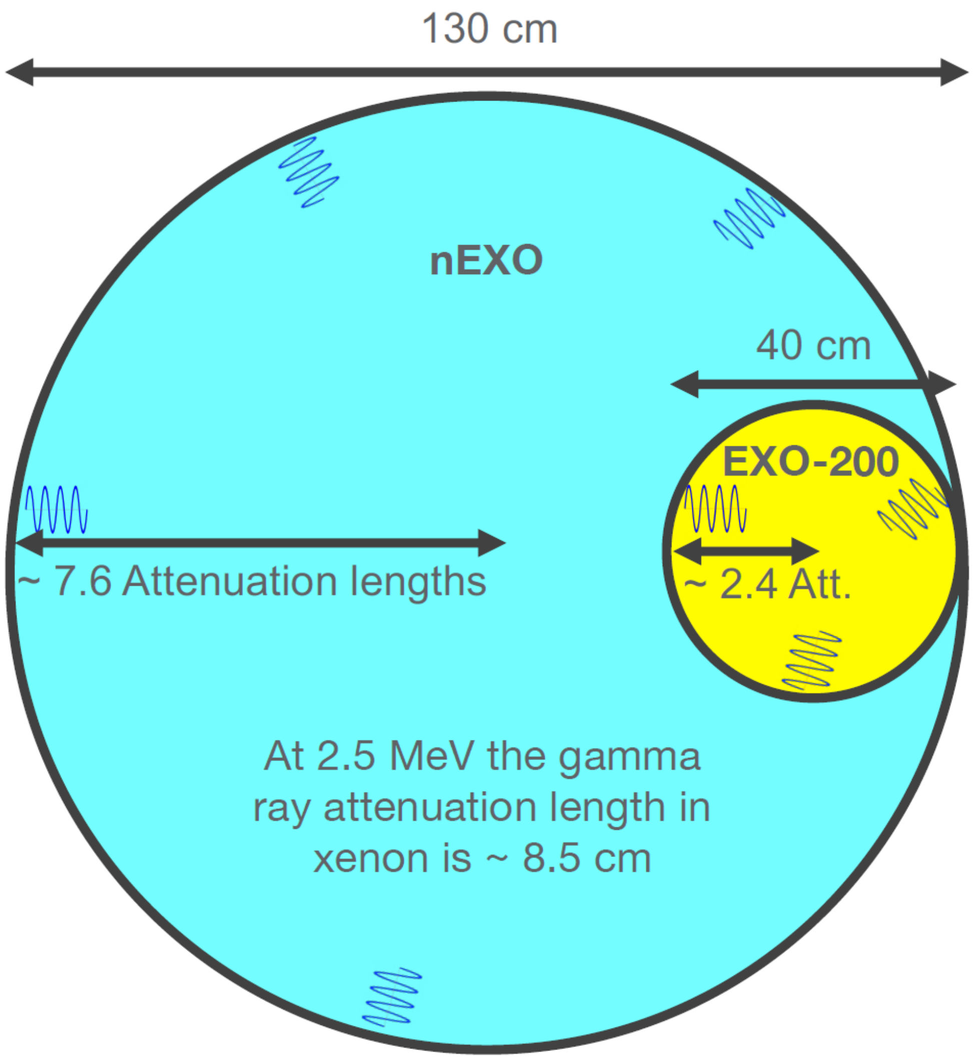




Prototype silicon interposer

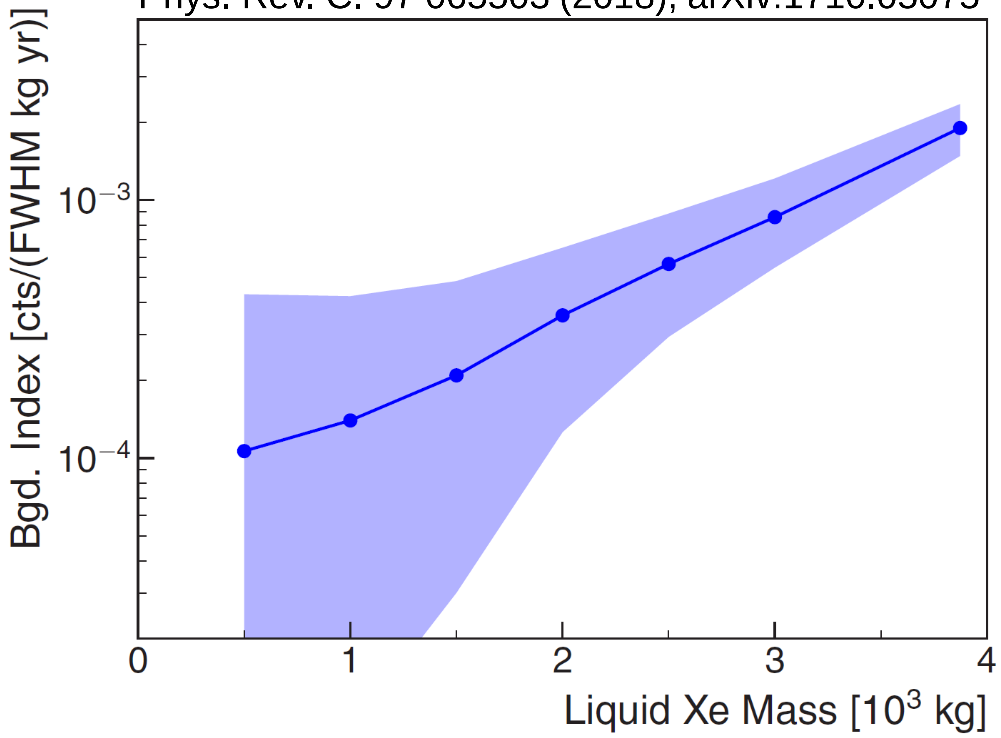
Conceptual design of the photo detector system underway

Self-shielding in monolithic detectors

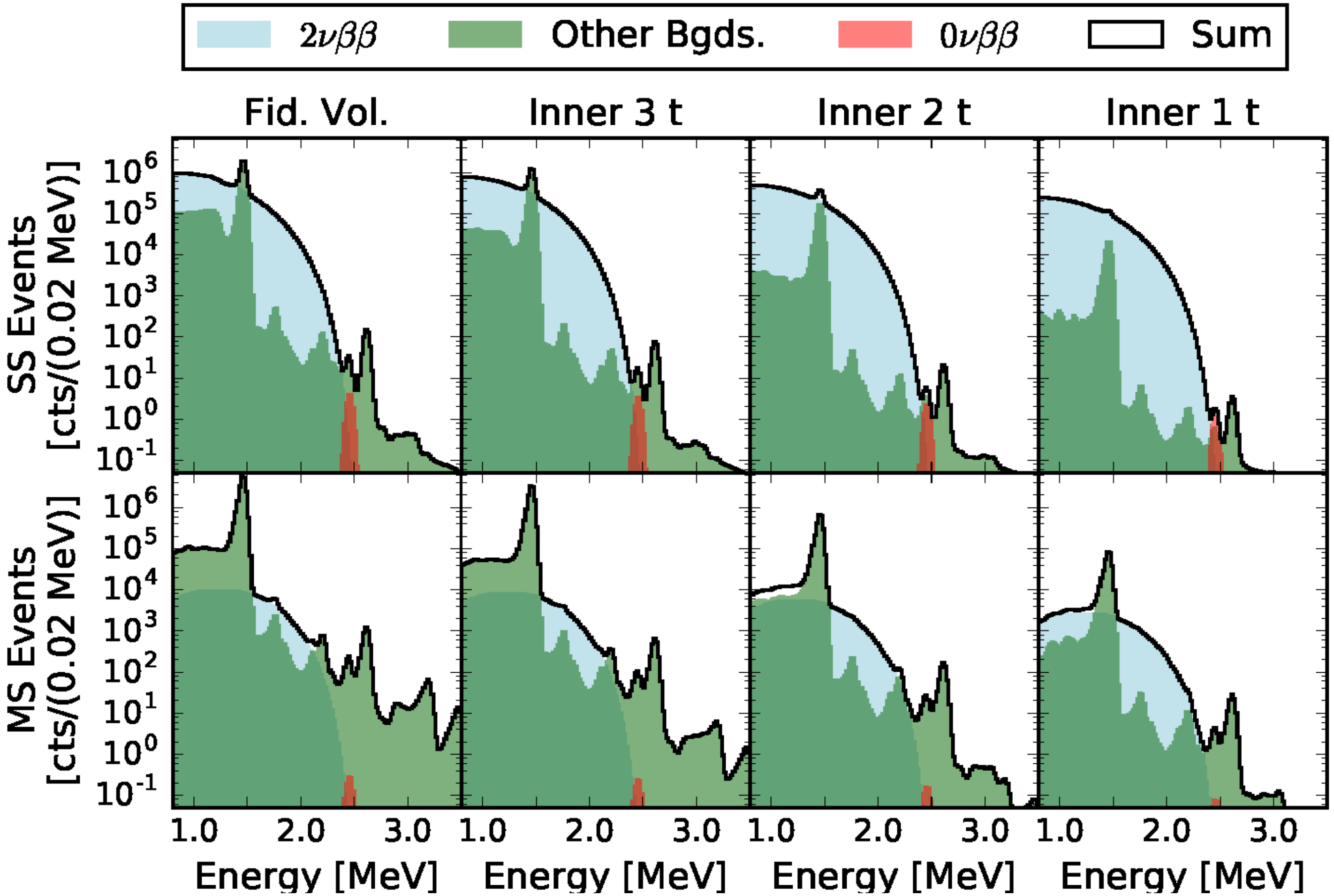


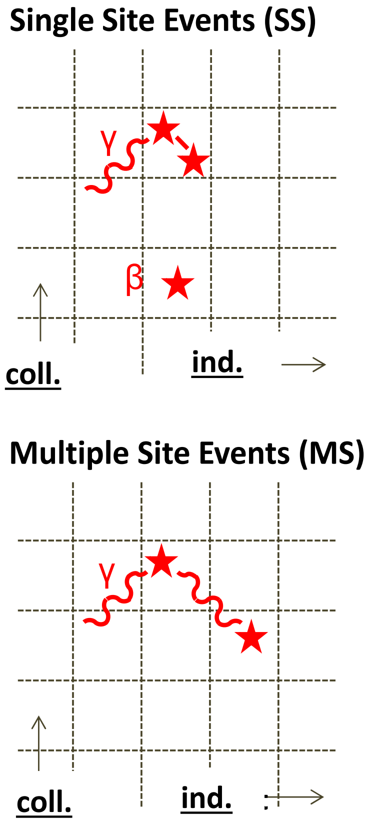
The large, monolithic volume of nEXO and high density of liquid xenon (2.9 g/cm3) is extremely beneficial to the attenuation of gamma rays coming from external materials

Phys. Rev. C. 97 065503 (2018), arXiv:1710.05075



nEXO discovery potential



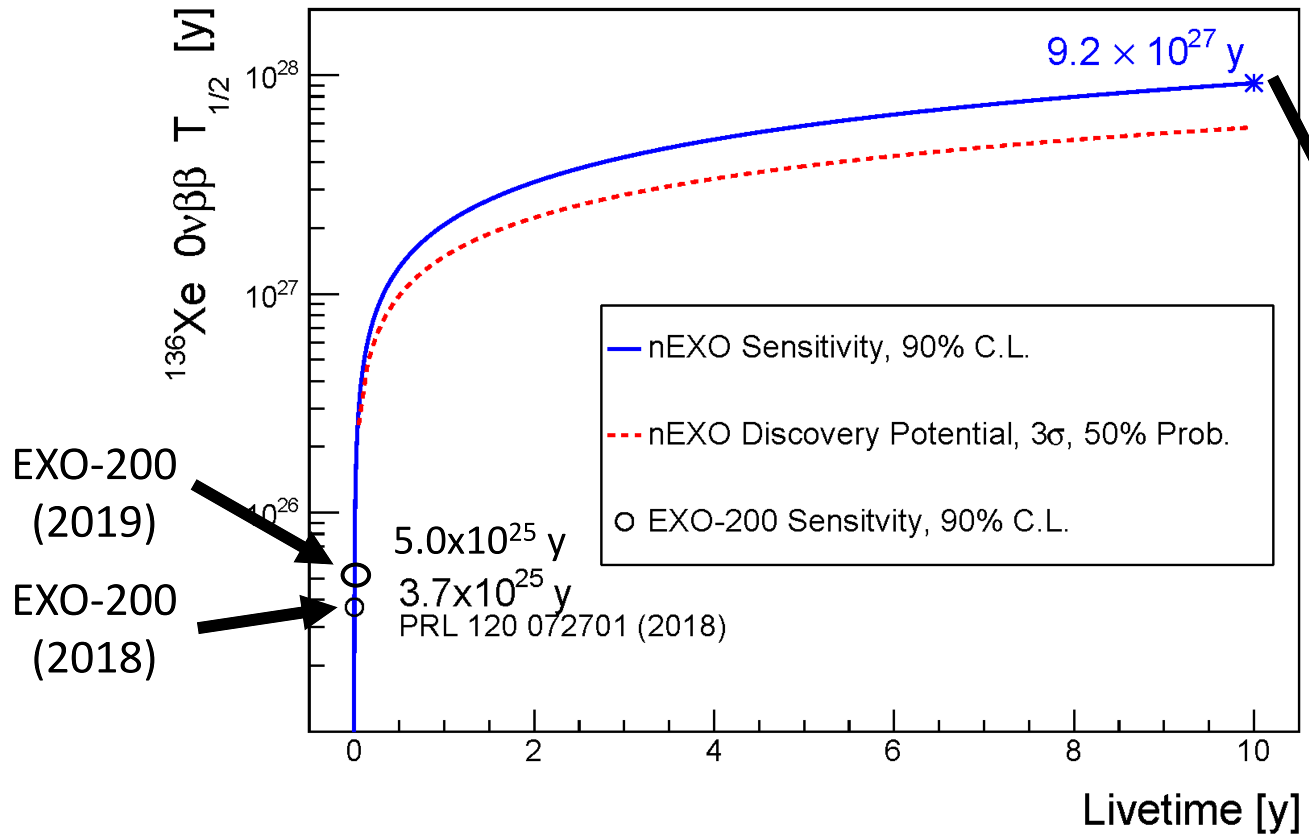


nEXO 10 year discovery potential at $T_{1/2}$=5.7x10^{27} yr (3σ)

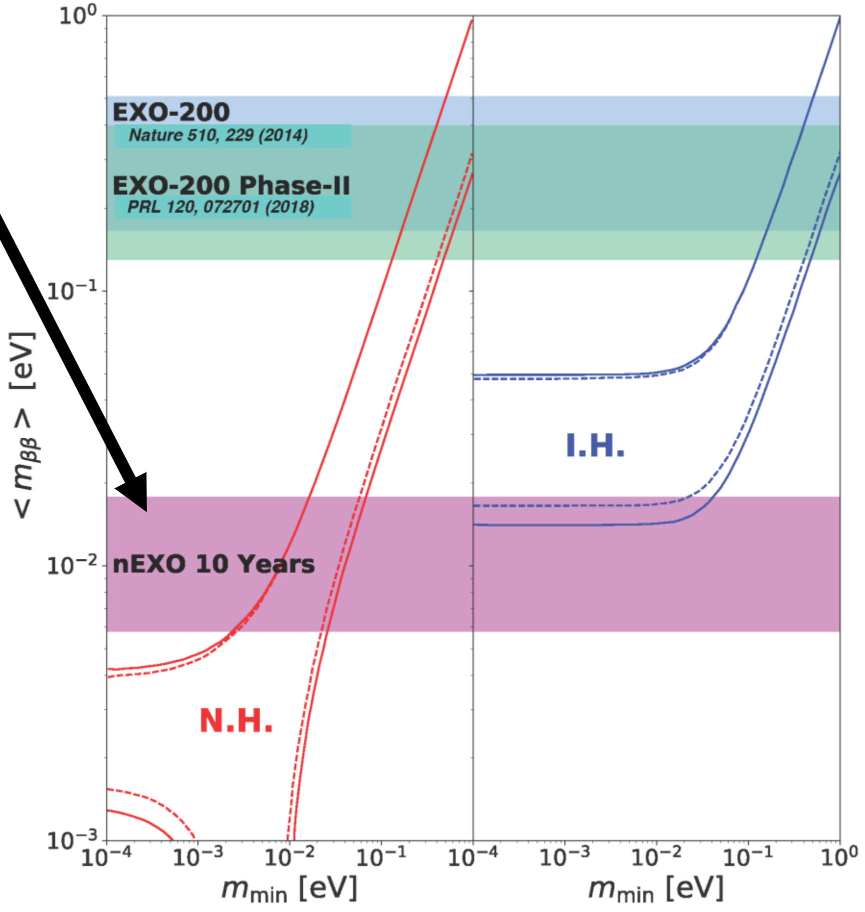
J.B. Albert et al., "Sensitivity and Discovery Potential of nEXO to Neutrinoless Double Beta Decay", Phys. Rev. C. 97 065503 (2018), arXiv:1710.05075.

Projected nEXO Sensitivity

J.B. Albert et al. Phys. Rev. C. 97 065503 (June 2018)

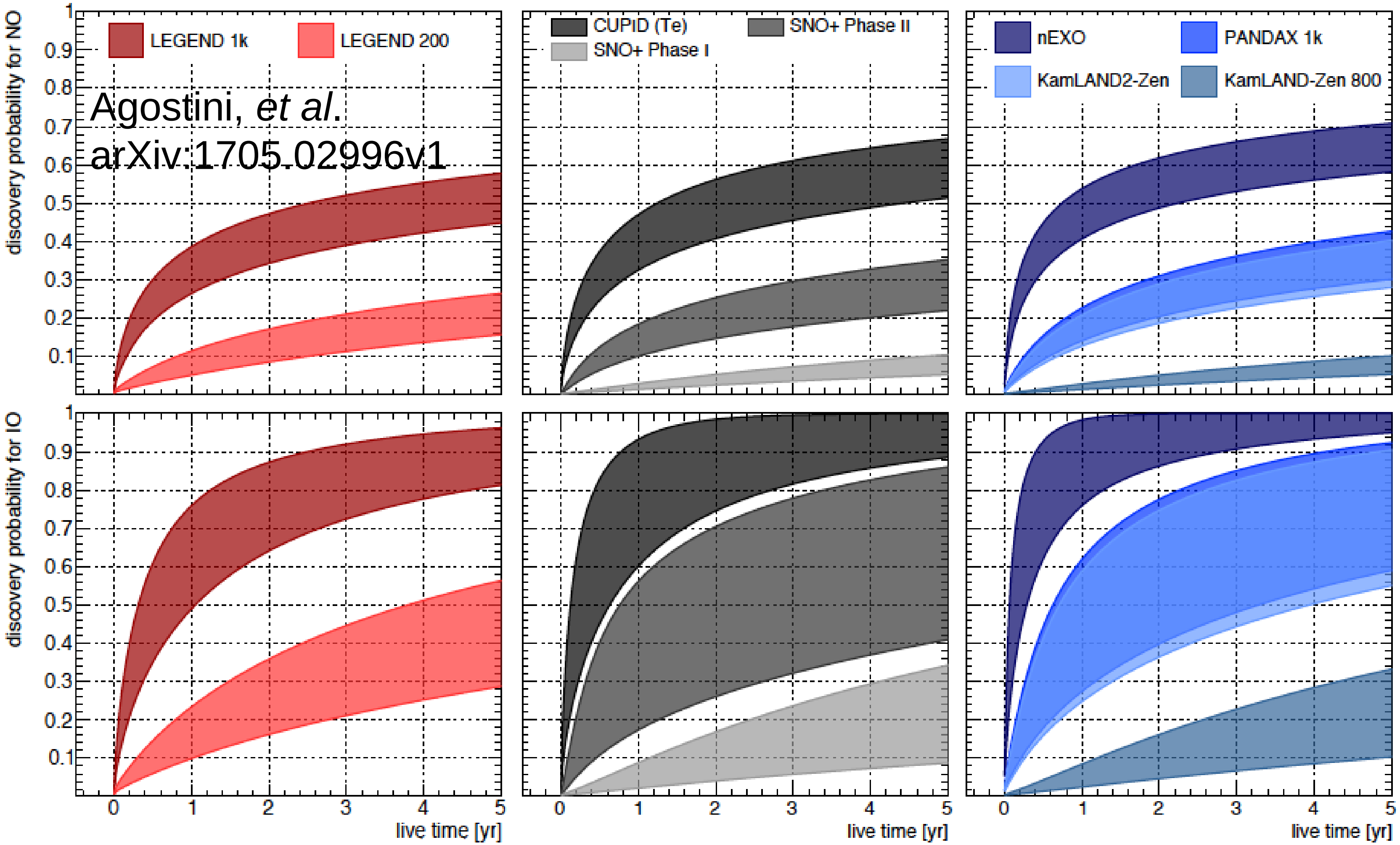


Projected sensitivity based on actual background level measurements!



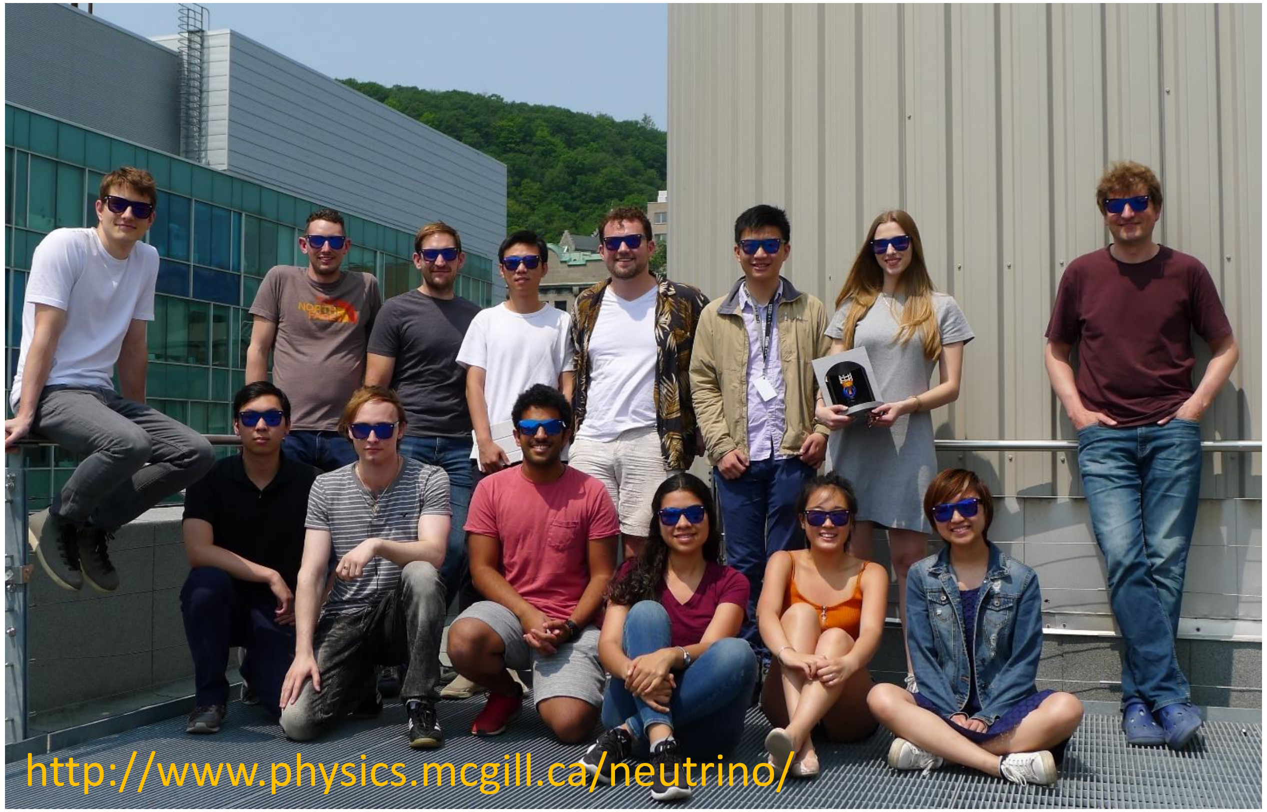
- $g_A = g_A^{free} = -1.2723$
- **Band is the envelope of NME:**
  - EDF: T.R. Rodríguez and G. Martínez-Pinedo, PRL 105, 252503 (2010)
  - ISM: J. Menendez et al., Nucl Phys A 818, 139 (2009)
  - IBM-2: J. Barea, J. Kotila, and F. Iachello, PRC 91, 034304 (2015)
  - QRPA: F. Šimkovic et al., PRC 87 045501 (2013)
  - SkyrmeQRPA: M.T. Mustonen and J. Engel PRC 87 064302 (2013)

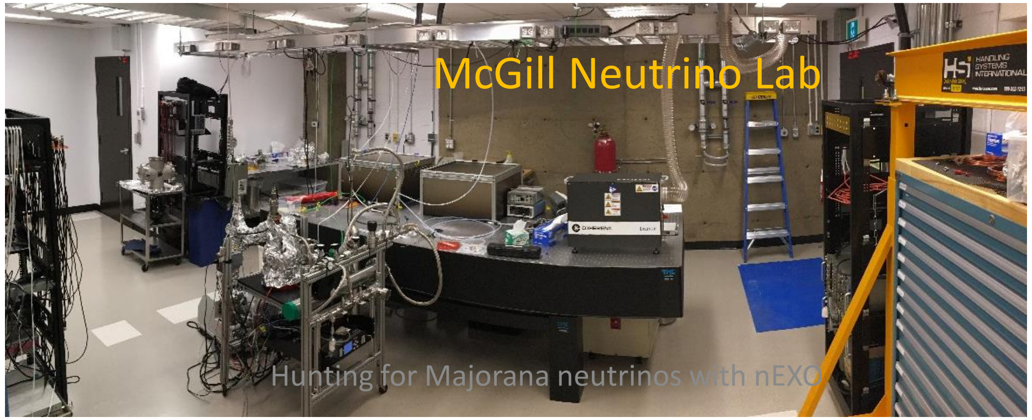
0νββ Discovery Potential



0νββ is the most practical way to test the Majorana nature of neutrinos.
An observation of 0νββ always implies 'new' physics!

Why neutrino physics is awesome!





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