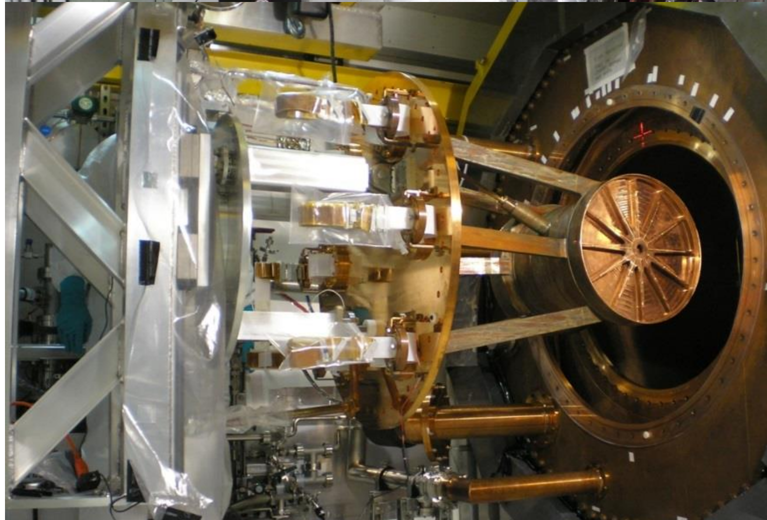
Hunting for Majorana neutrinos with nEXO



Thomas Brunner

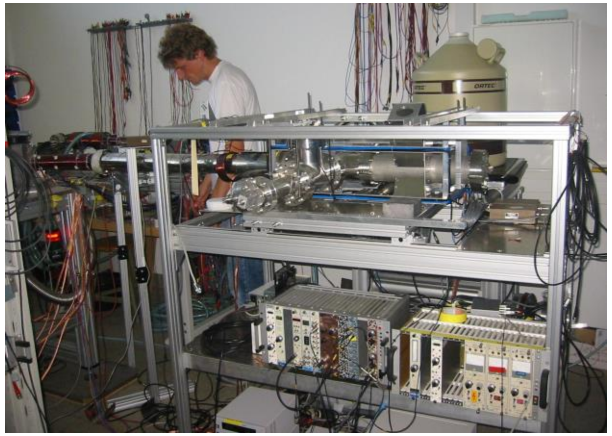
McGill University and TRIUMF

The summer particle (astro)physics workshop

May 11, 2022

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
- Parental leave for five months in 2021

(Condensed matter physics)

↓

Atomic physics

↓

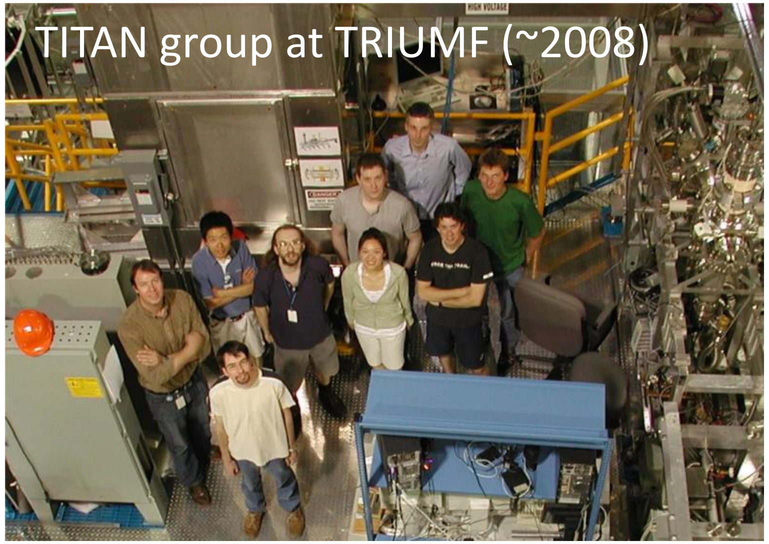
Nuclear physics
(decay spectroscopy and
mass measurements)

↓

Particle/neutrino/nuclear physics

Don’t be afraid to change fields!

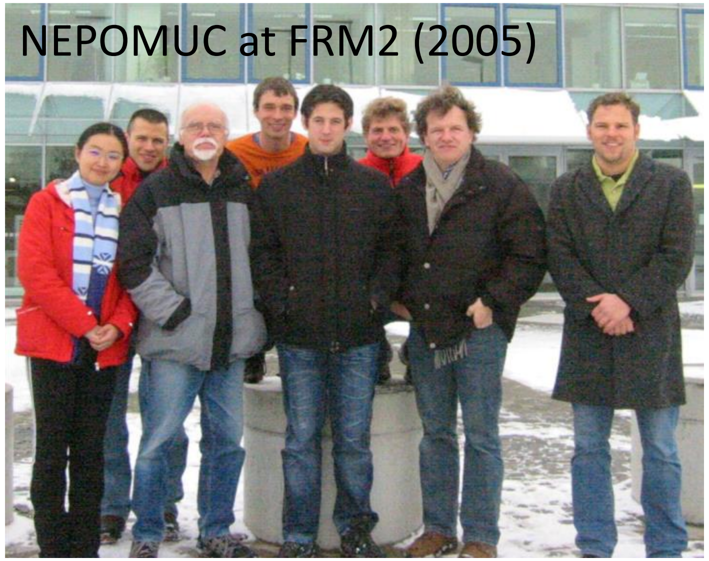
I enjoy research because of the people

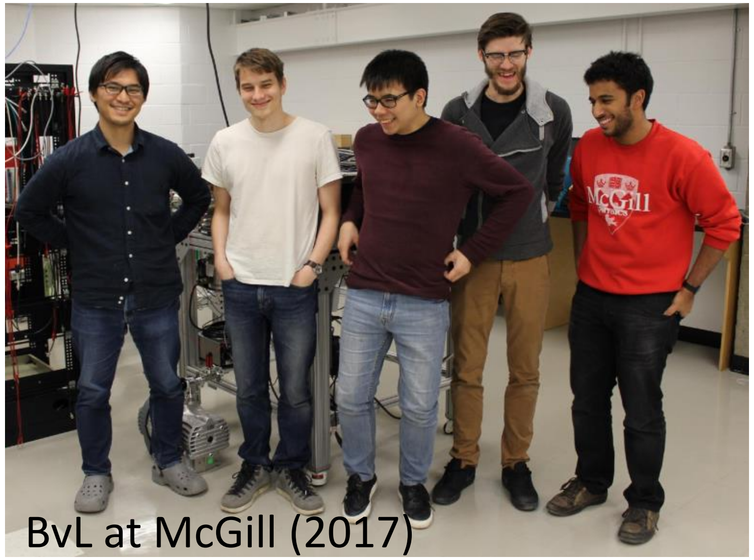

TITAN group at TRIUMF (~2008)


BvL at McGill (2021)


TRISTAN group (sabbatical 2021)


Gratta group at Stanford (2015)


NEPOMUC at FRM2 (2005)


BvL at McGill (2017)

What we hope to learn with nEXO

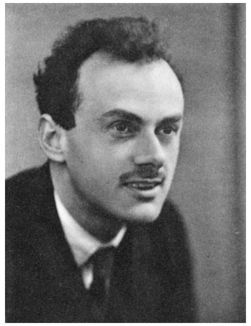
(Exactly how heavy are neutrinos?)

What is the quantum nature of the neutrino?

Quantum nature of the neutrino

“Dirac” neutrinos

$\nu \neq \bar{\nu}$



“Majorana” neutrinos

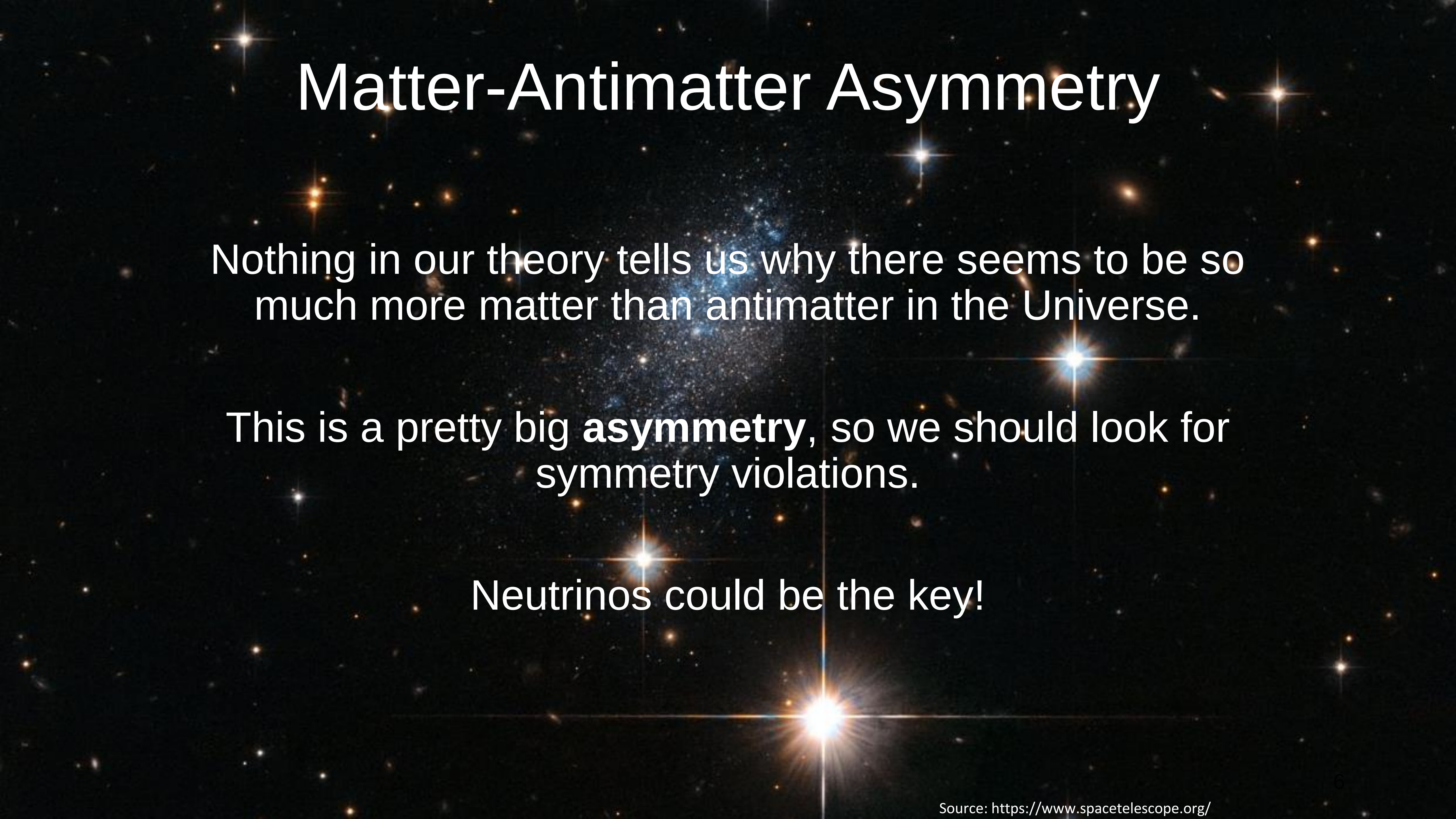
$\nu = \bar{\nu}$

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.

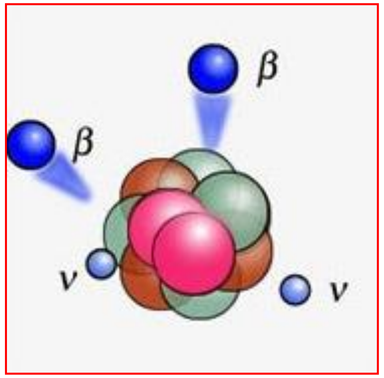
This is a pretty big **asymmetry**, so we should look for symmetry violations.

Neutrinos could be the key!

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

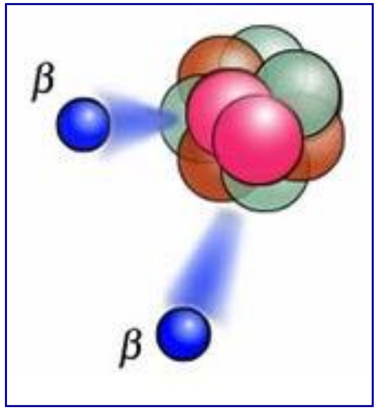
How to search for Majorana neutrinos?

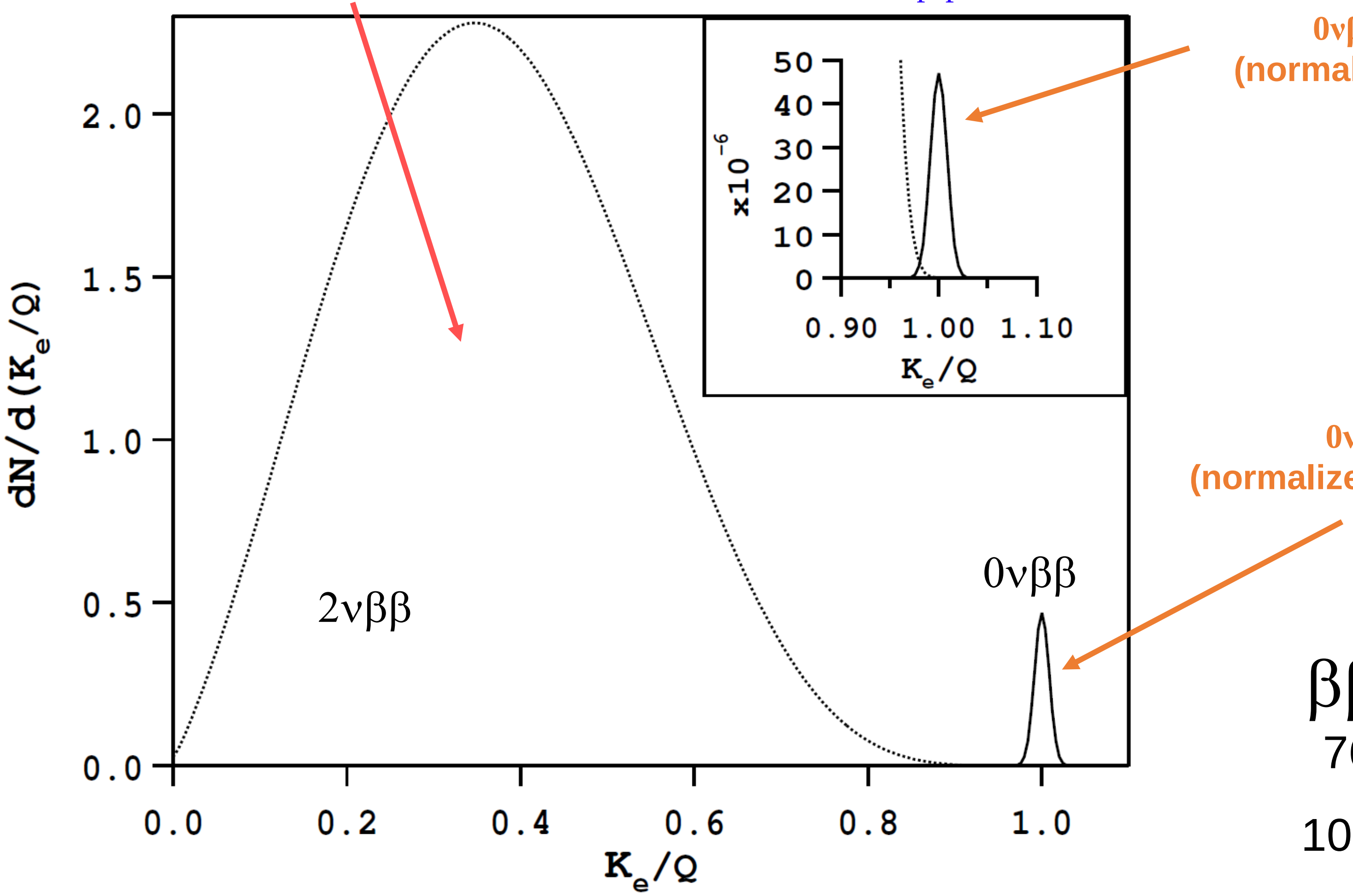
Double Beta Decay



2νββ

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





2νββ spectrum (normalized to 1)

[arXiv:hep-ph/0611243]

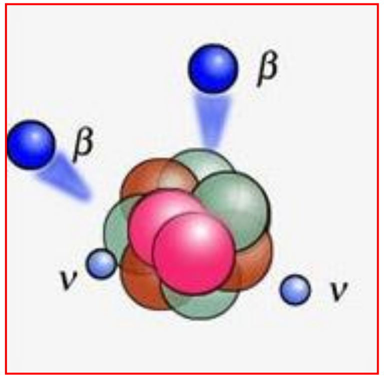
0νββ peak (normalized to 10^{-6})

0νββ peak (normalized to 10^{-2})

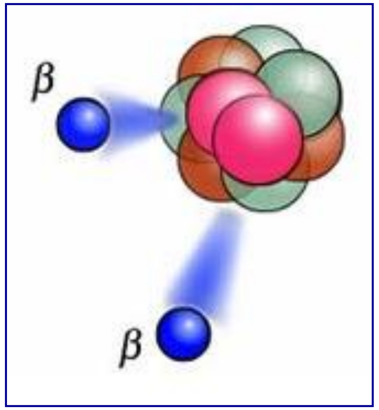
ββ isotopes:
^{76}Ge, ^{82}Se,
^{100}Mo, ^{130}Te,
^{136}Xe

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

Double Beta Decay

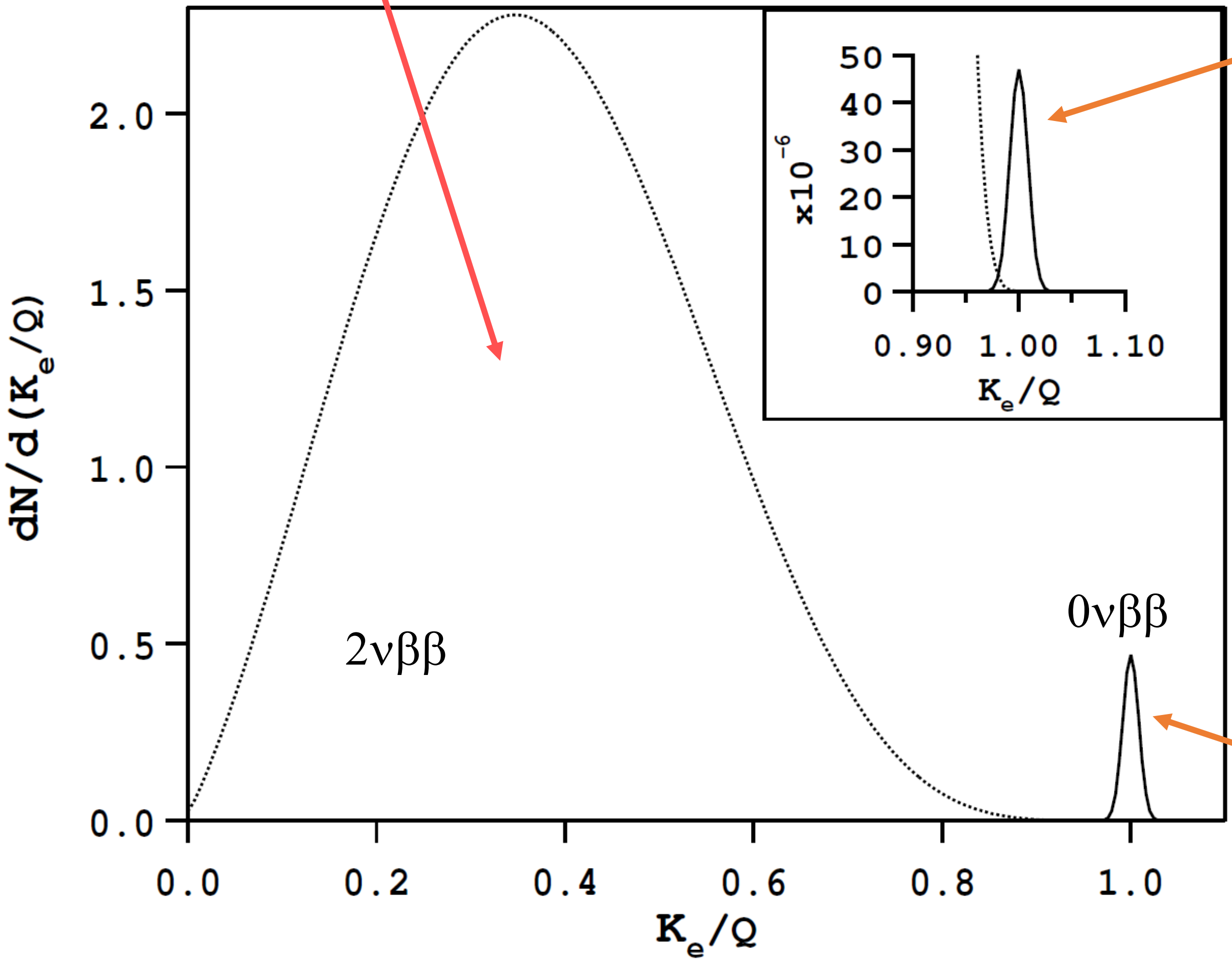


2νββ
$T_{1/2} \approx 10^{20}$ y



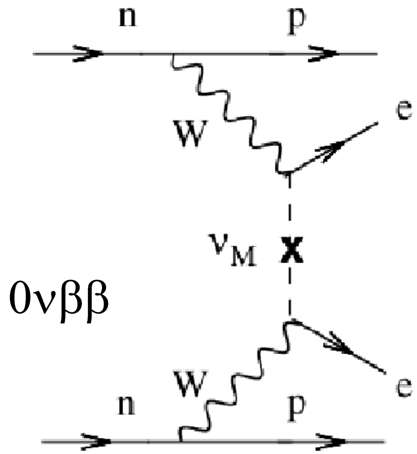
2νββ spectrum
(normalized to 1)

[arXiv:hep-ph/0611243]



0νββ peak
(normalized to 10^{-6})

0νββ peak
(normalized to 10^{-2})

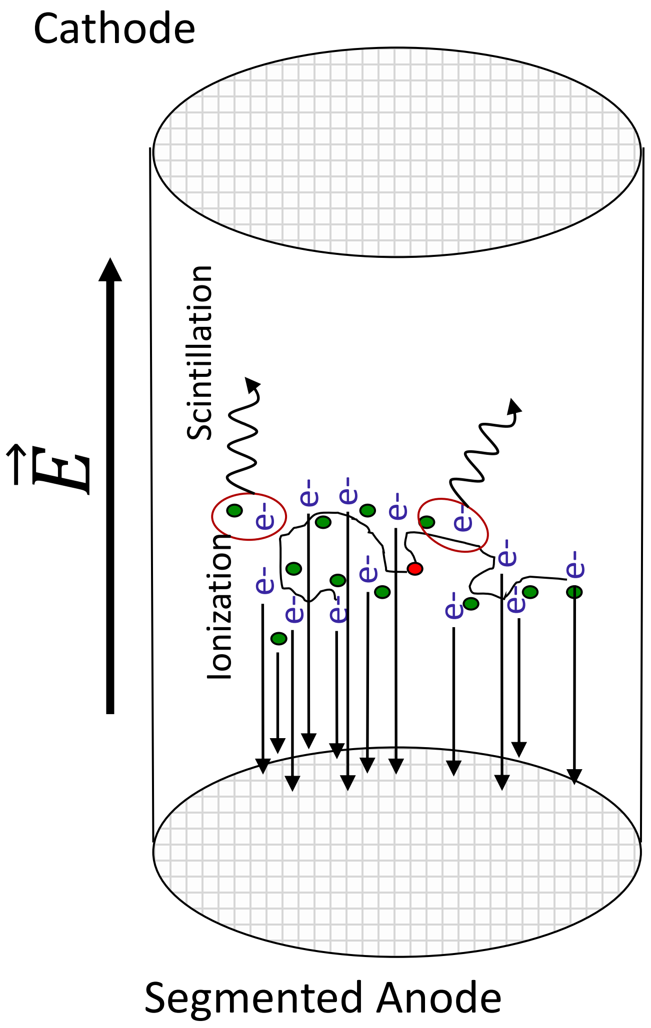


$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}\left|M^{0\nu}\right|^{2}\left\langle m_{\nu}\right\rangle^{2} \qquad \left\langle m_{\nu}\right\rangle = \left|\sum_{i} U_{ei}^{2} m_{i}\,\varepsilon_{i}\right|$$

(light neutrino exchange mechanism only)

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

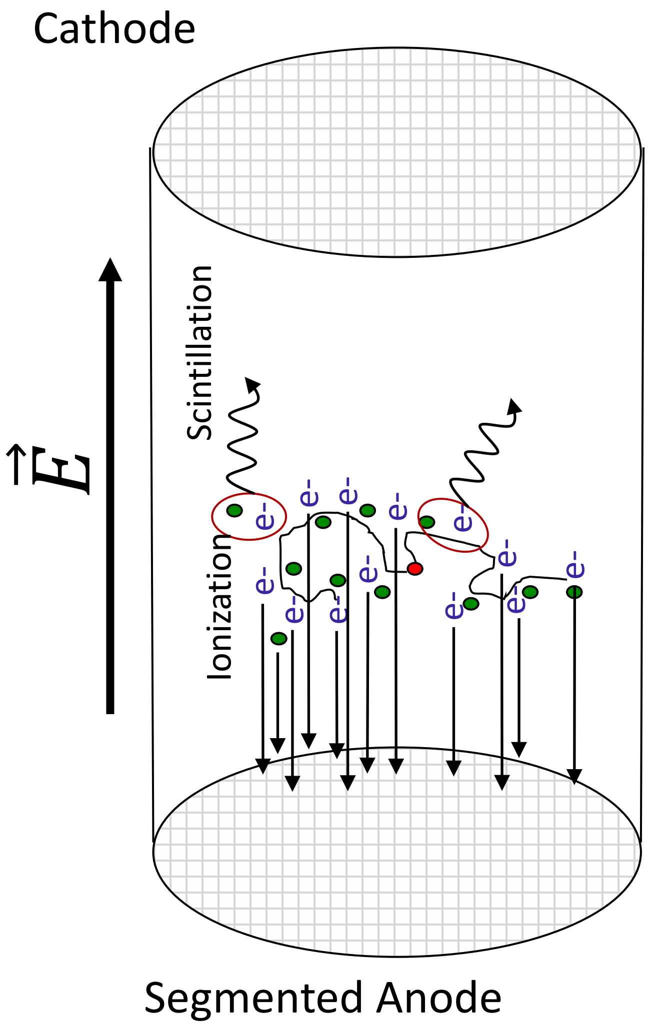
Searching for $0\nu\beta\beta$ in ^{136}Xe with liquid Xe TPC



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!

<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

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

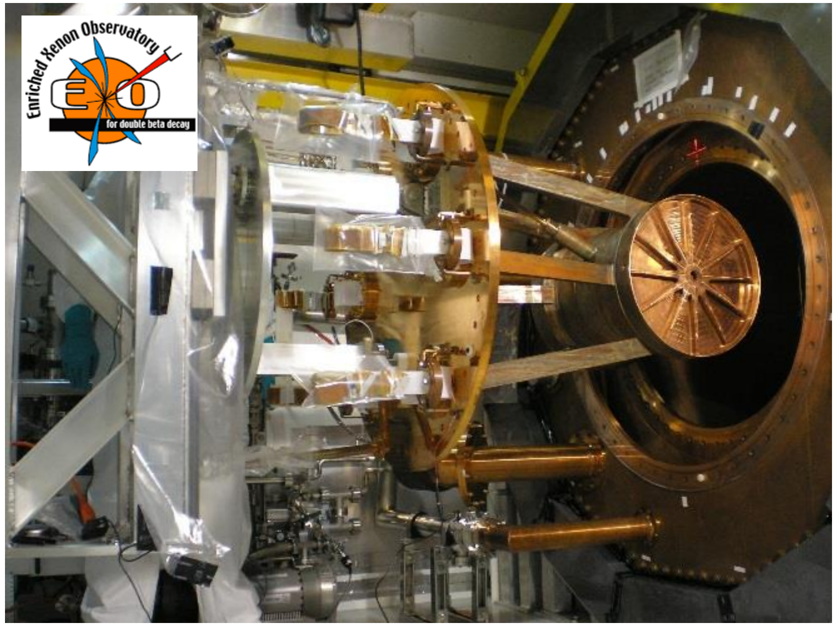
→Need:

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

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

EXO-200:

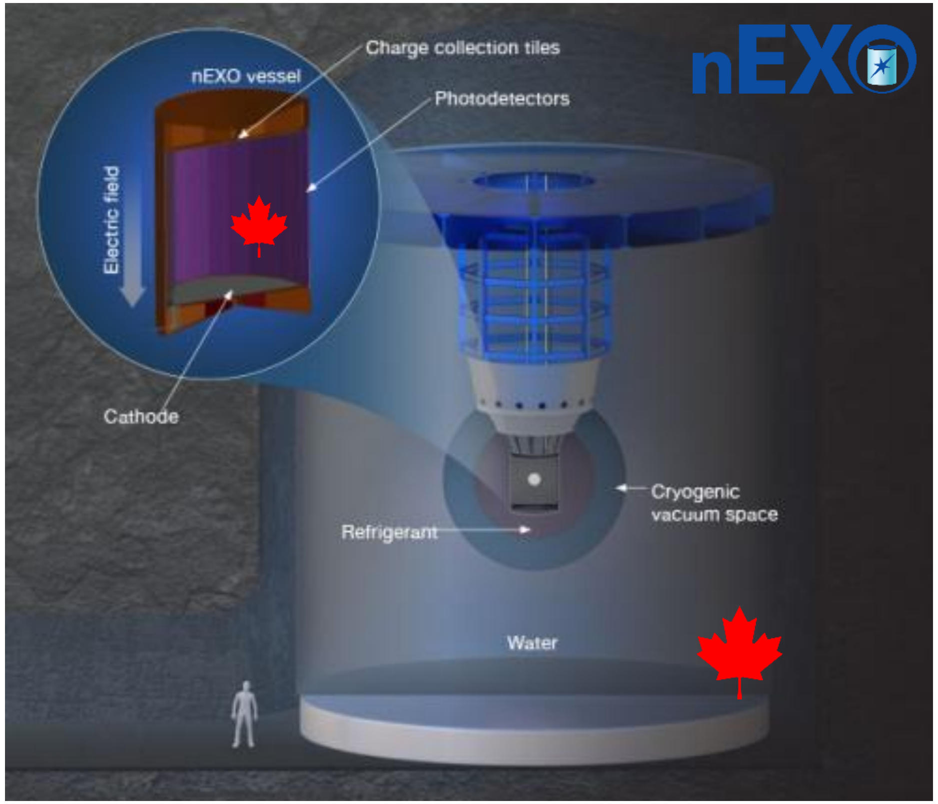
- EXO-200 first 100-kg class ββ experiment
- 200kg liquid-Xe TPC with ~80% Xe-136
- Located at the WIPP mine in NM, USA
- Decommissioned in Dec. 2018
- Analyze data from end-of-run calibration campaign
  → data will inform the detailed design of nEXO



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

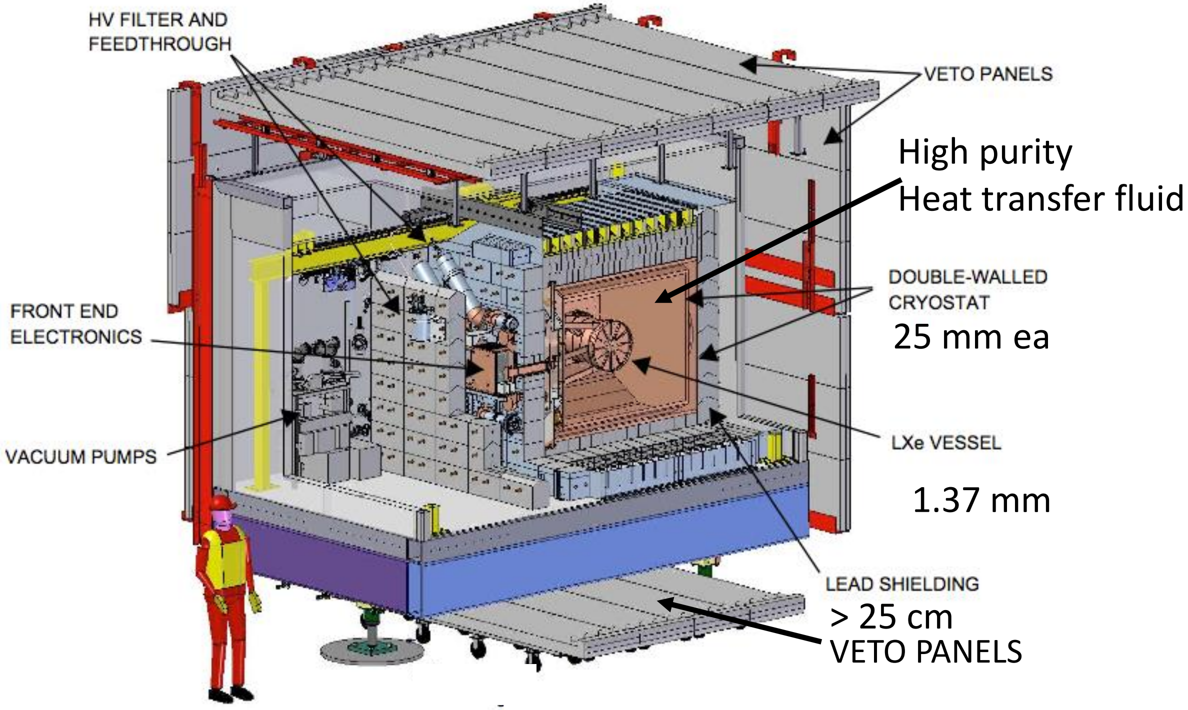
nEXO:

- Next-generation 5-ton liquid Xe TPC
- Enriched in Xe-136 at ~90%
- SNOLAB cryopit preferred location by collaboration



https://nexo.llnl.gov/

EXO-200

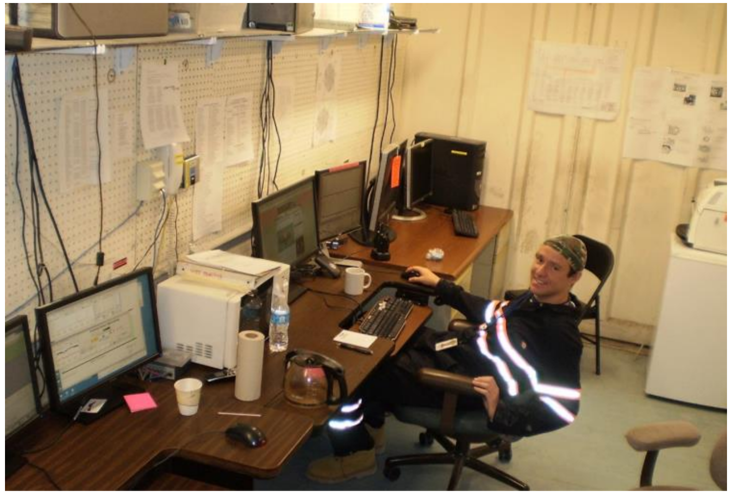


High purity
Heat transfer fluid

25 mm ea

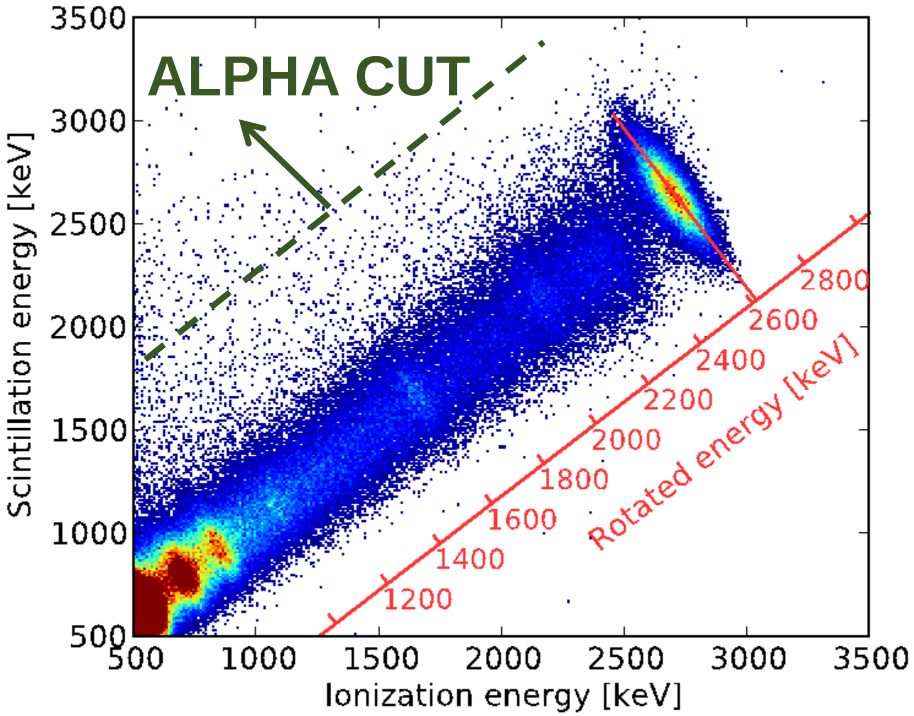
1.37 mm

> 25 cm
VETO PANELS

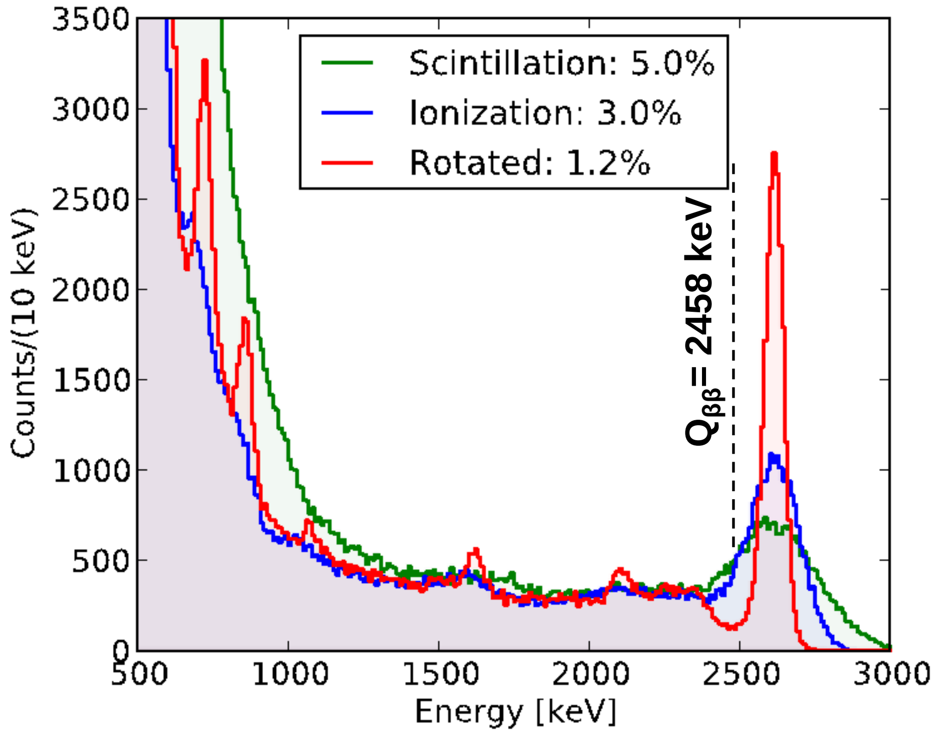


Energy measurement (EXO-200 data)

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



Reconstructed energy, ^{228}Th calibration:

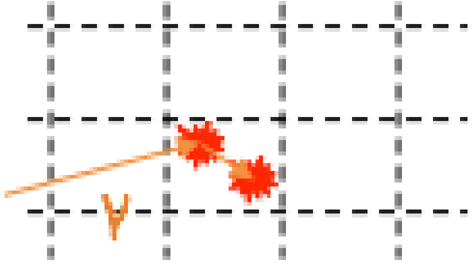


- Anticorrelation between scintillation and ionization in LXe known since early EXO R&D and now standard in LXe detectors [E.Conti et al. Phys Rev B 68 (2003) 054201]
- Rotation angle determined weekly using ^{228}Th source data, defined as angle which gives best rotated resolution
- EXO-200 has achieved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

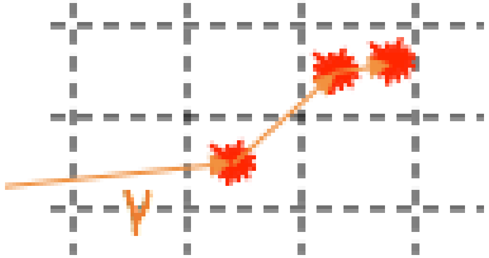
Position and multiplicity (EXO-200 data)

Allows for background measurement and reduction

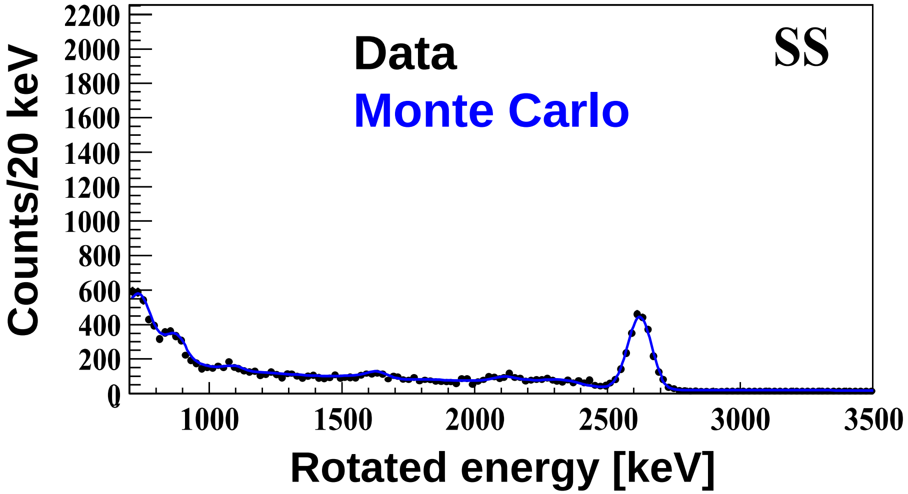
Events with **> 1** charge cluster: multi-site events (MS)
Events with **1** charge cluster: single-site events (SS)



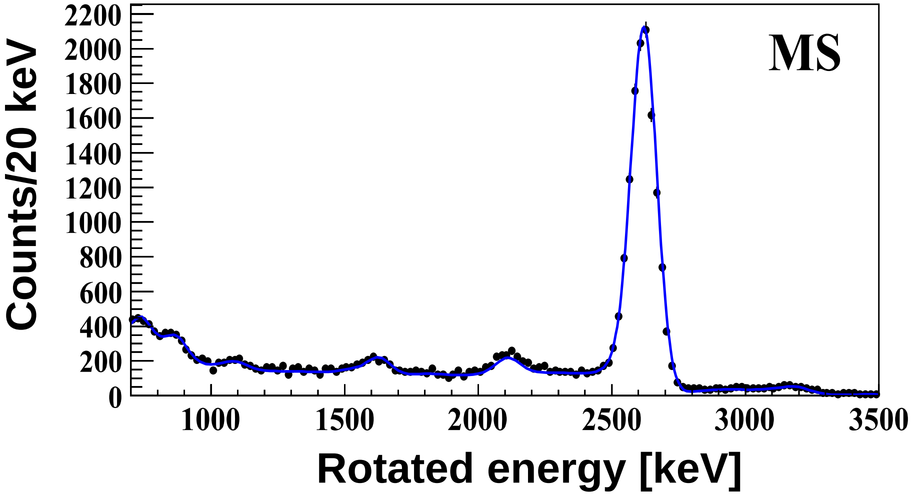
0νββ: ~90% SS
γ-rays: ~15% SS at 0νββ Q-value



^{228}Th calibration data, SS:



^{228}Th calibration data, MS:

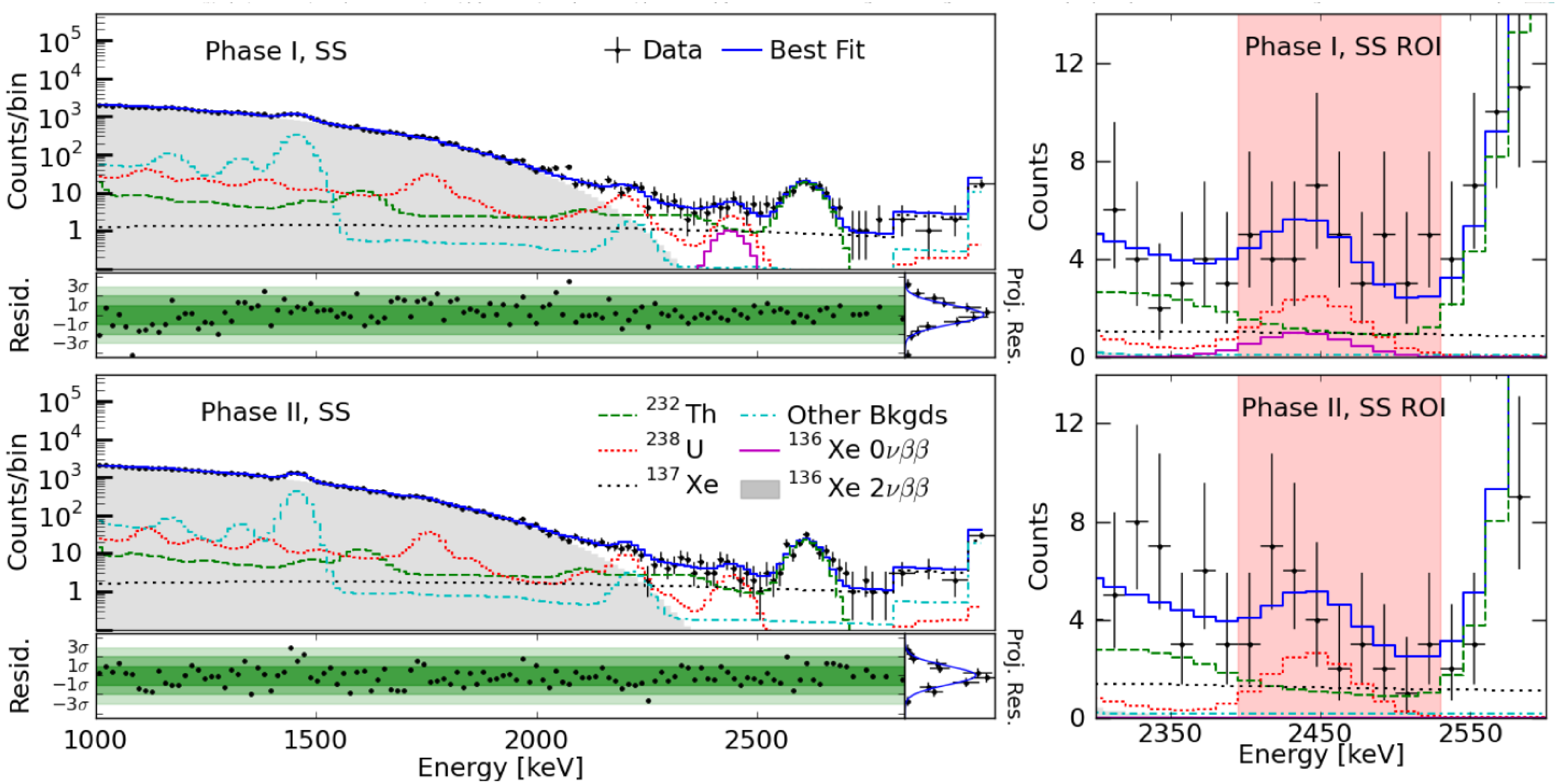


Final EXO-200 Results

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

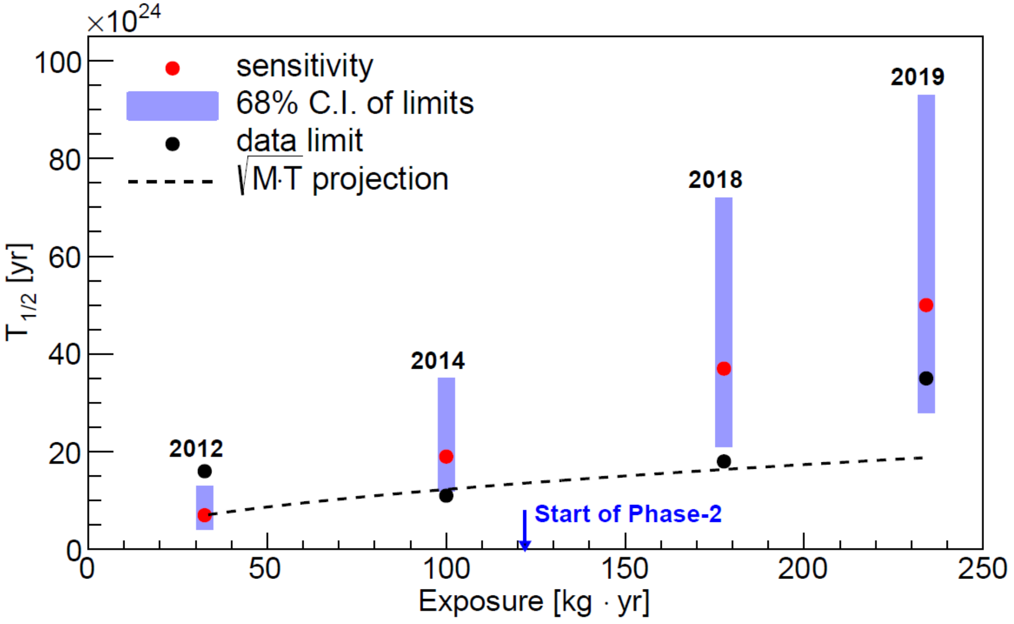
- No statistically significant 0νββ signal observed

PRL 123 (2019) 161802



EXO-200 search for 0νββ - Results

- EXO-200 demonstrated excellent background, very well predicted by the massive material characterization program and simulations → ***This is essential for nEXO design***
- Sensitivity increased linearly with exposure.



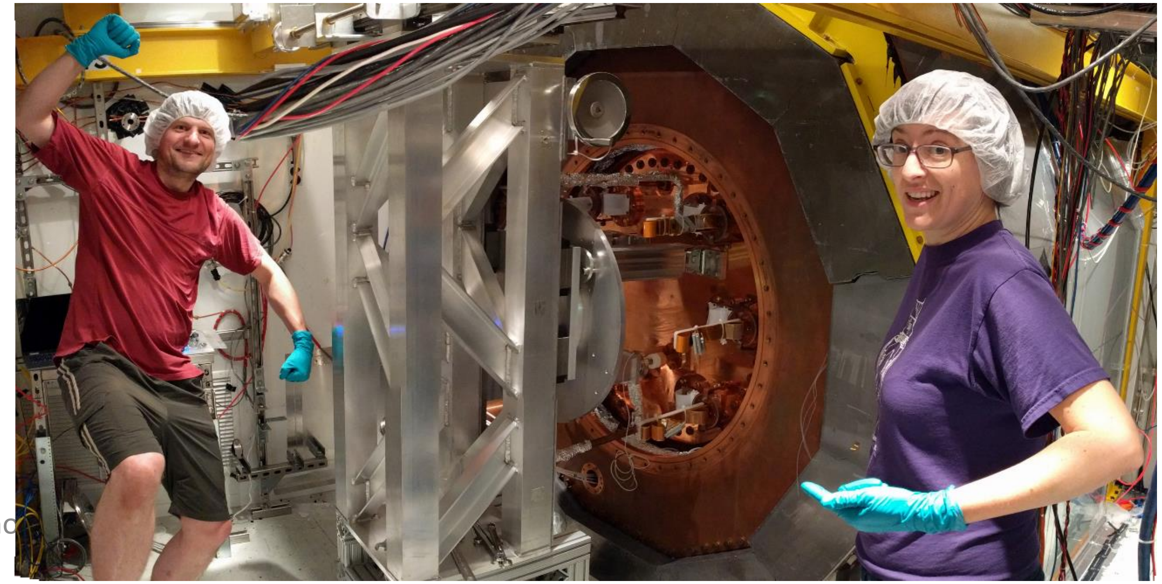
2012: Phys. Rev. Lett. 109 (2012) 032505
2014: Nature 510 (2014) 229-234
2018: Phys. Rev. Lett. 120, 072701 (2018)
2019: Phys. Rev. Lett. 123 (2019) 161802

Final result
Phase I+II: 234.1 kg yr of ^{136}Xe exposure
Limit: $T_{1/2}^{0\nu\beta\beta}$ > 3.5x10^{25} yr (90% CL)
$\langle m_{\beta\beta} \rangle$ < (93 -286) meV
Sensitivity: 5.0x10^{25} yr

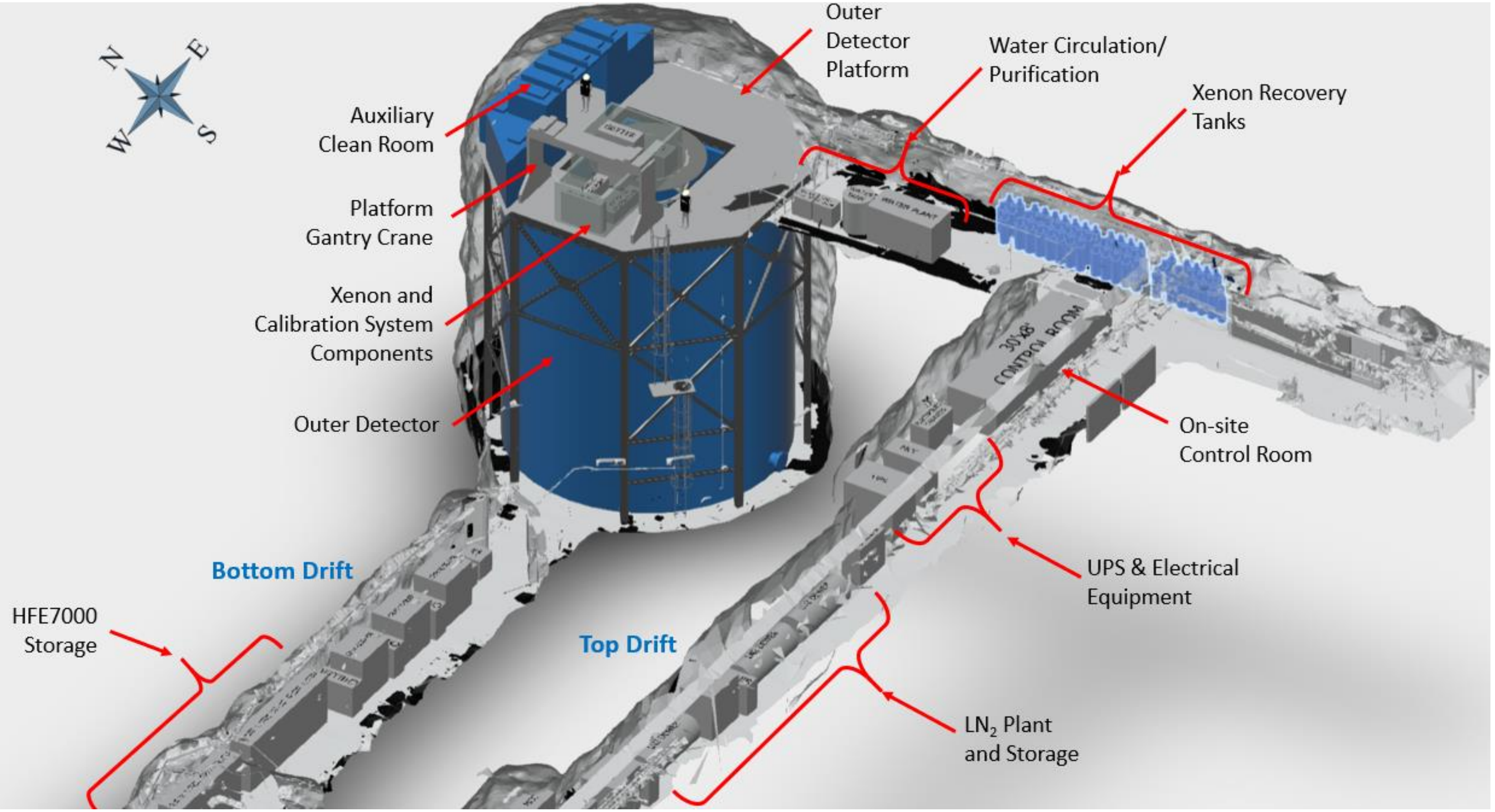
- More papers on non-ββ decay physics, background studies, and detector performance: https://www-project.slac.stanford.edu/exo/publications.html

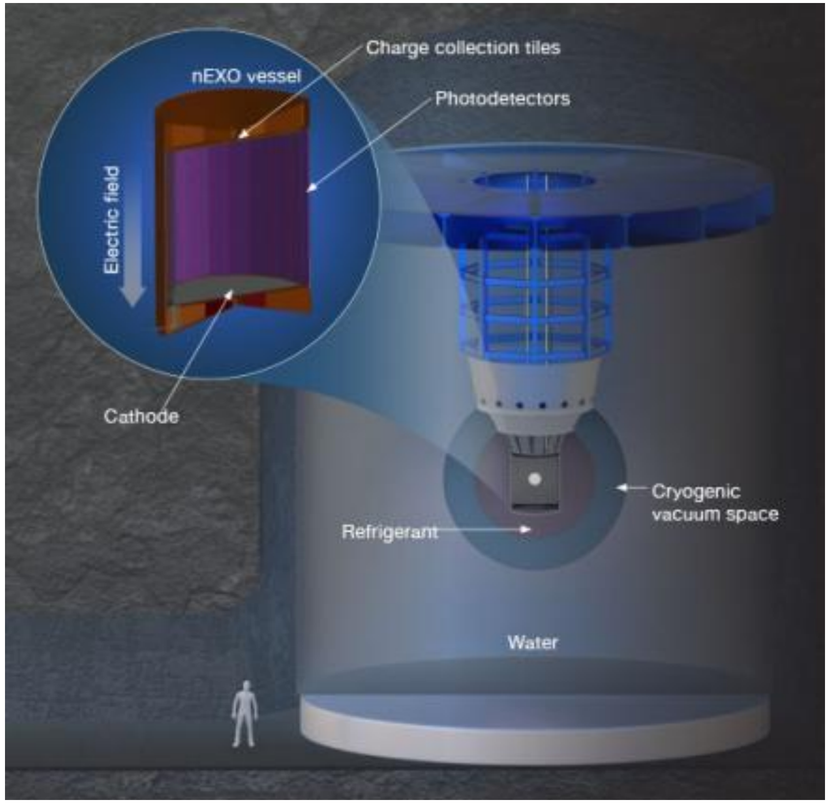
EXO-200 decommissioning

December 2018



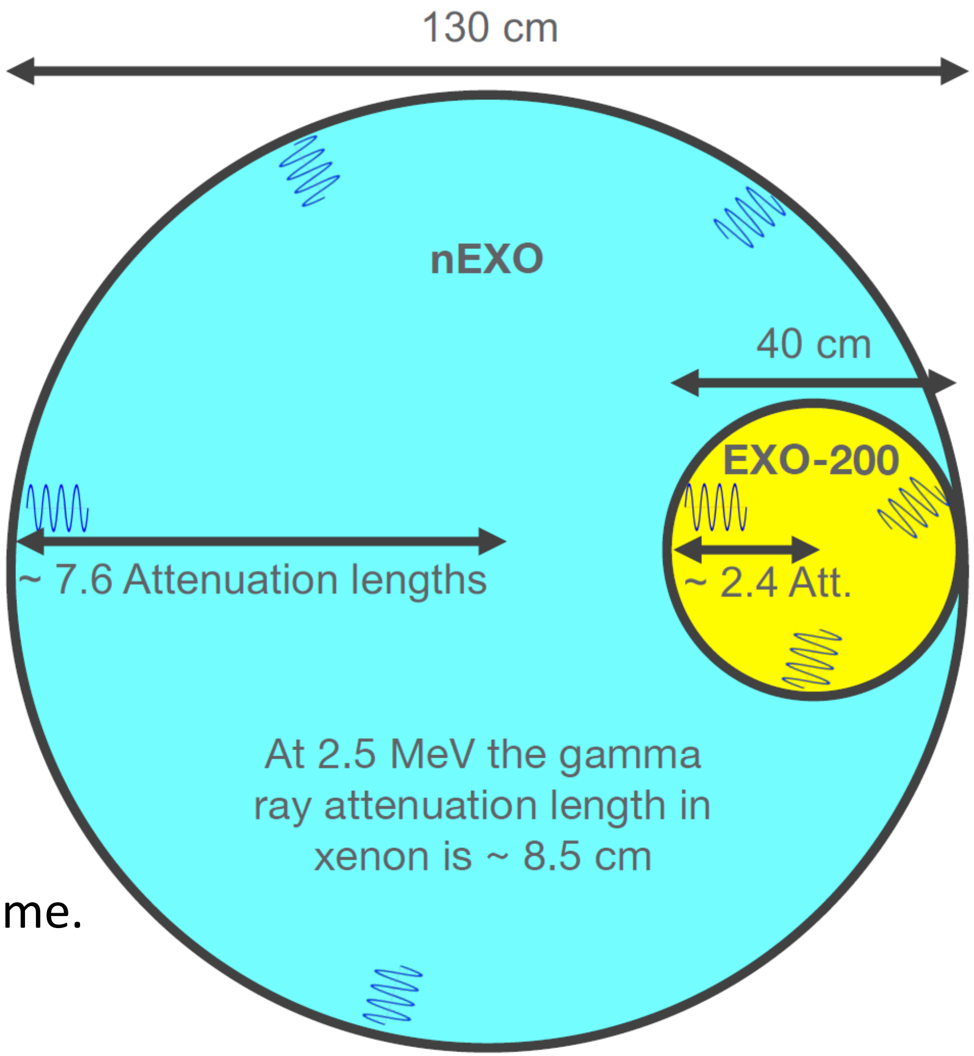
nEXO at SNOLAB





The power of a monolithic detector

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

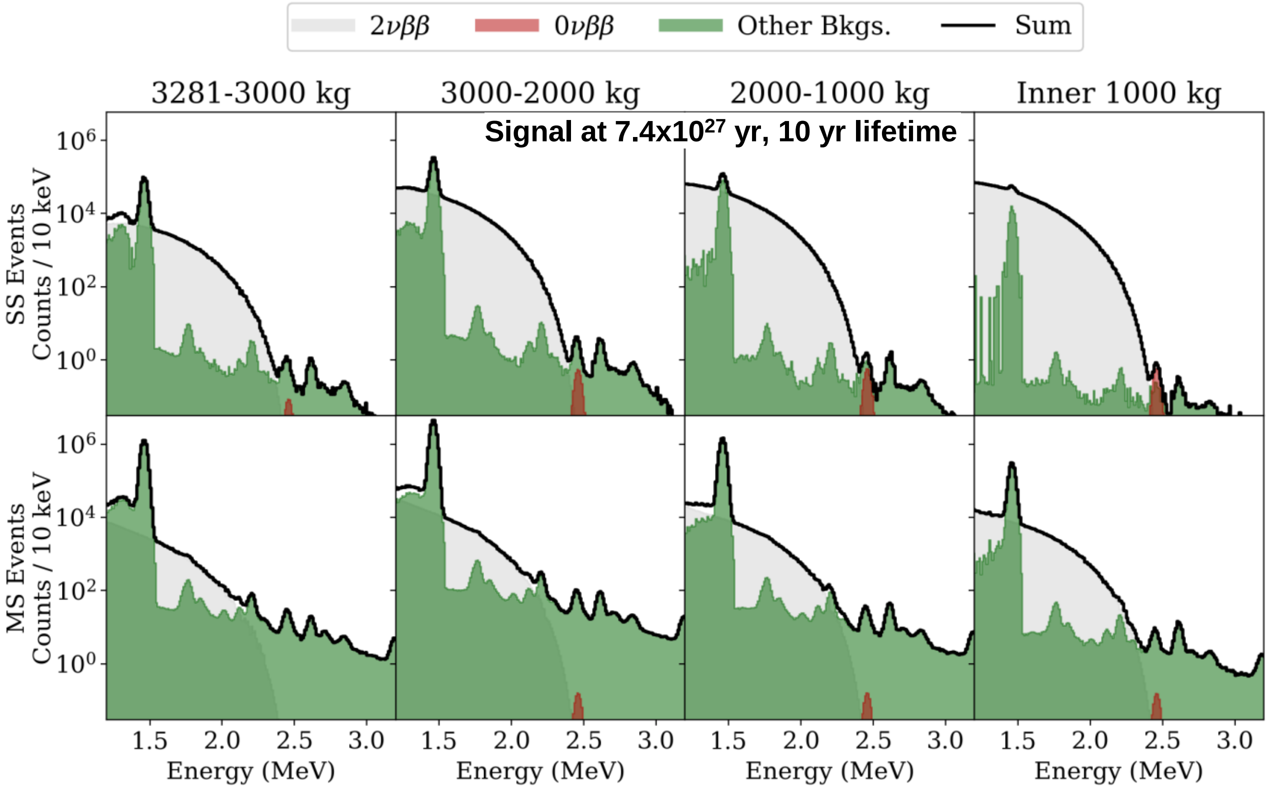


At 2.5 MeV the gamma ray attenuation length in xenon is ~ 8.5 cm

- Gamma backgrounds typically originate from the walls
  → photons Compton scatter on their way into the detector volume.
- The complete detector volume is used to identify and reject backgrounds.

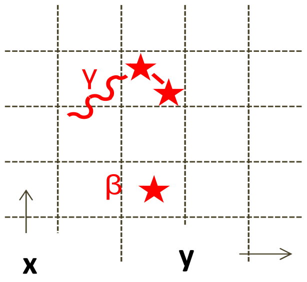
Power of the monolithic nEXO detector

Multi-parameter analysis: much more information than just energy

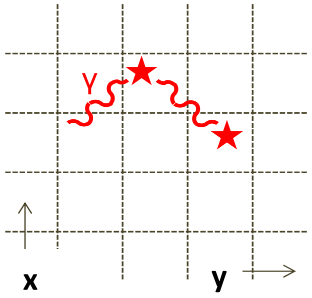


Signal at 7.4x10^{27} yr, 10 yr lifetime

Single Site Events (SS)



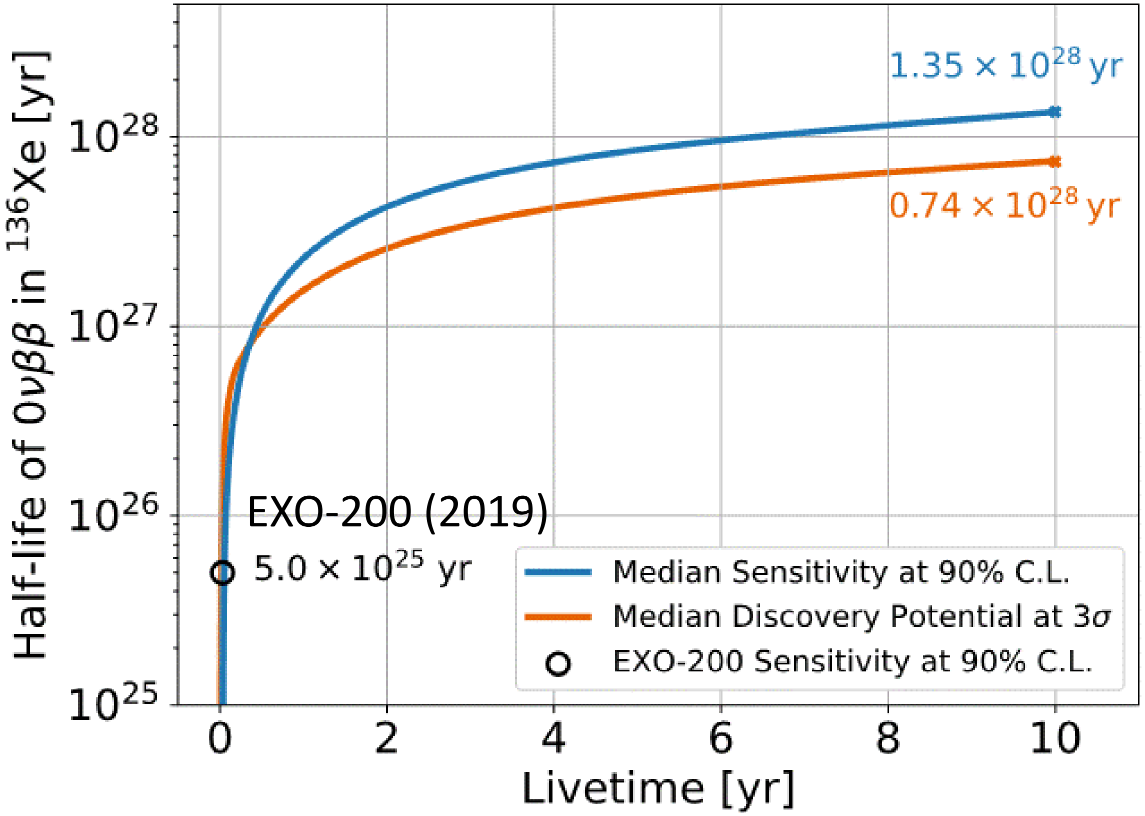
Multiple Site Events (MS)



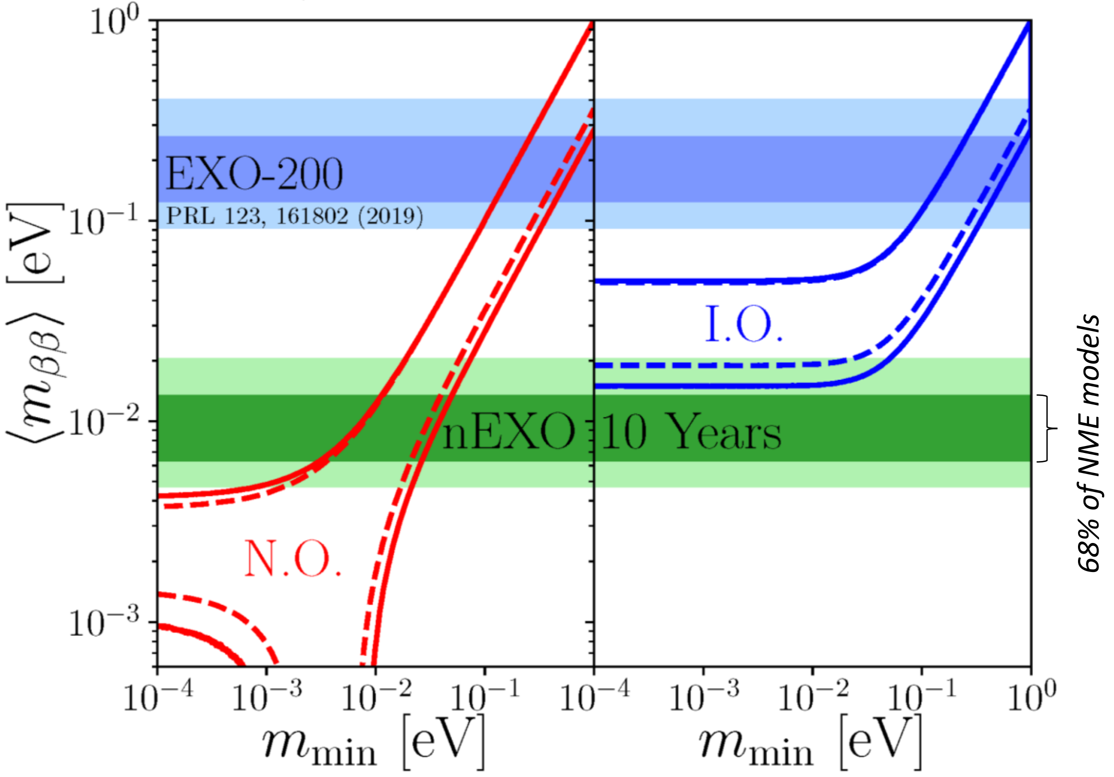
The homogeneous detector with advanced topological reconstruction has a proven track record for γ background <u>identification</u> and <u>rejection.</u>

Multi-parameter analysis makes the measurement robust also with currently unknown backgrounds.

nEXO Projected Sensitivity



Allowed parameter space and nEXO exclusion sensitivity (90% CL):



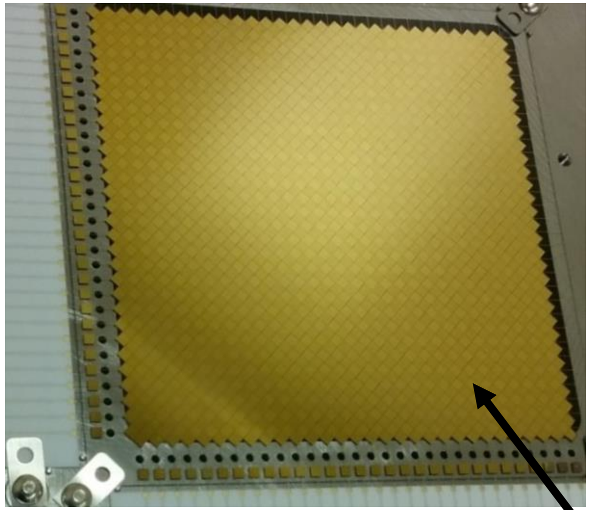
nEXO sensitivity reaches 10^{28} yr in 6.5 yr data taking

Projected sensitivity based on actual background level measurements!

arXiv:2106.16243

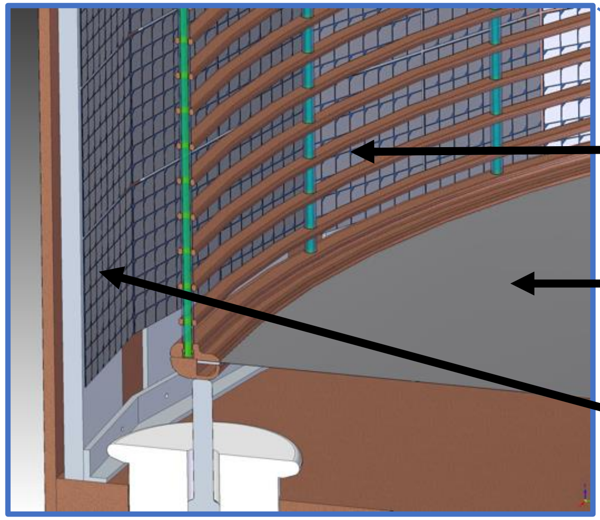
The nEXO detector

- 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.

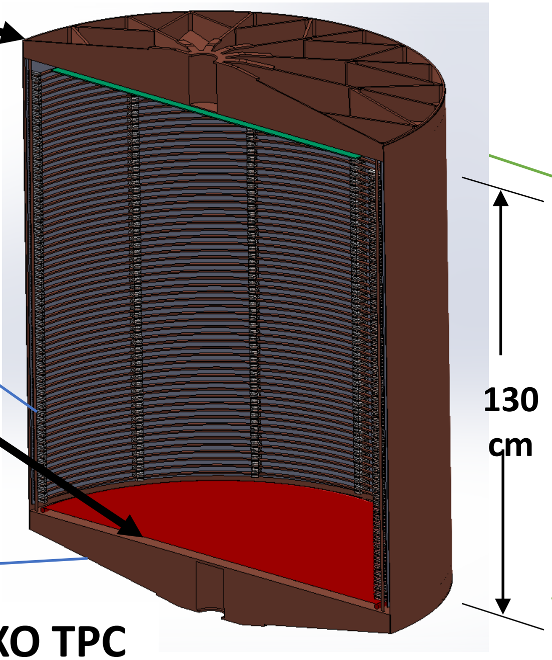
charge readout pads (anode)



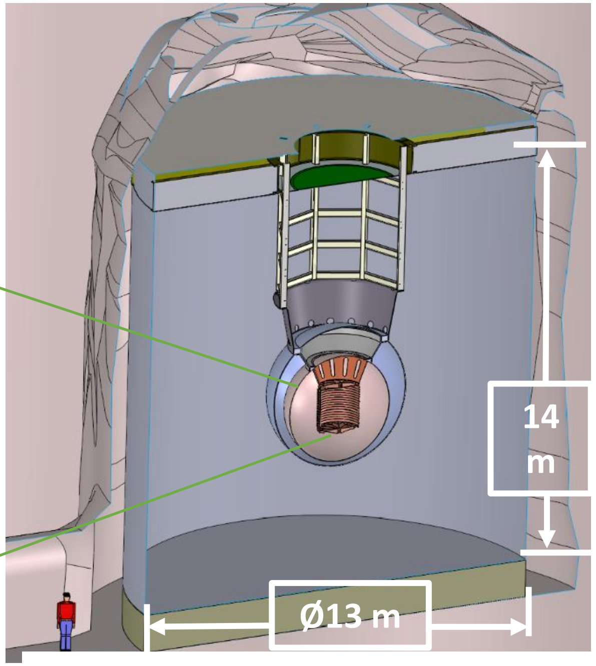
Field shaping rings

Cathode

SiPM 'staves' covering the barrel



nEXO TPC



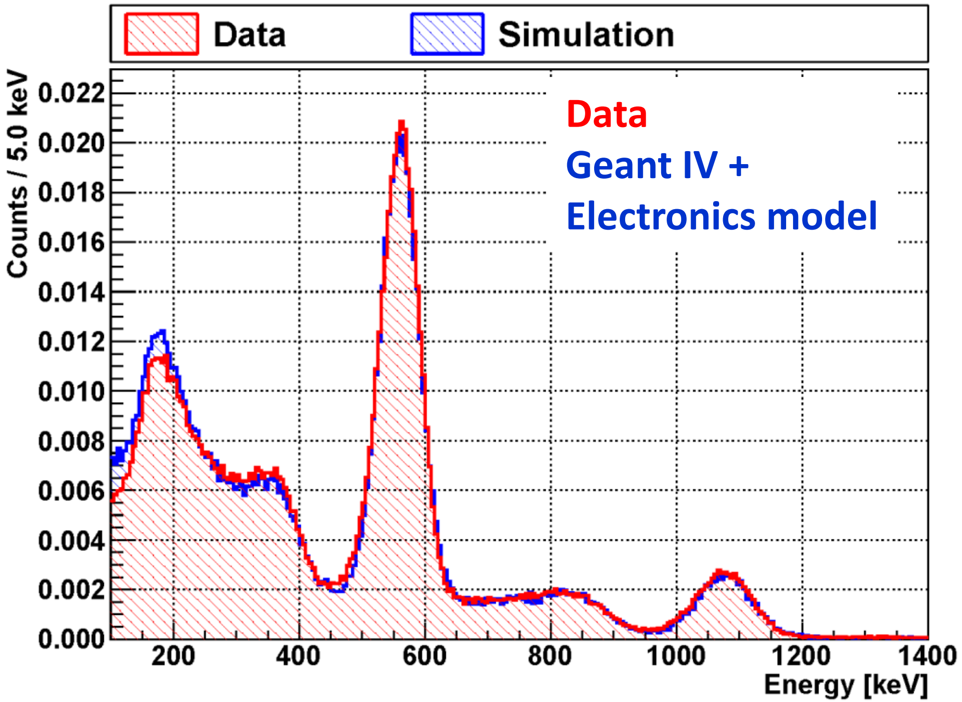
nEXO at the SNOLAB Cryopit

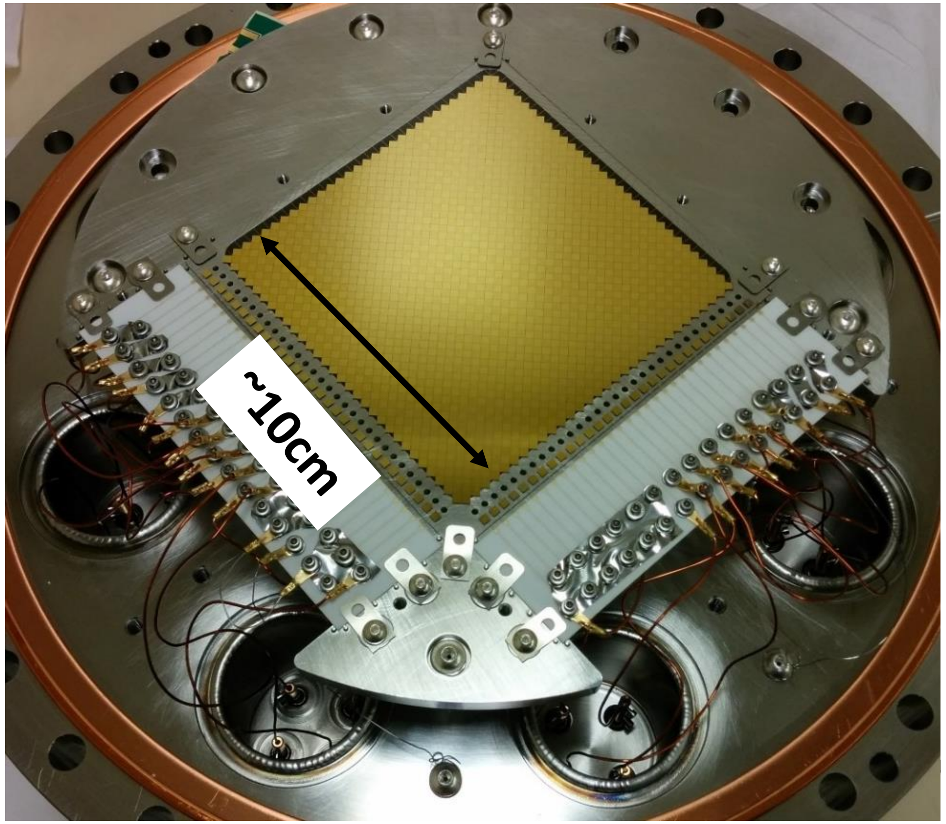
nEXO pre-CDR, arXiv:1805.11142

Charge Readout

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

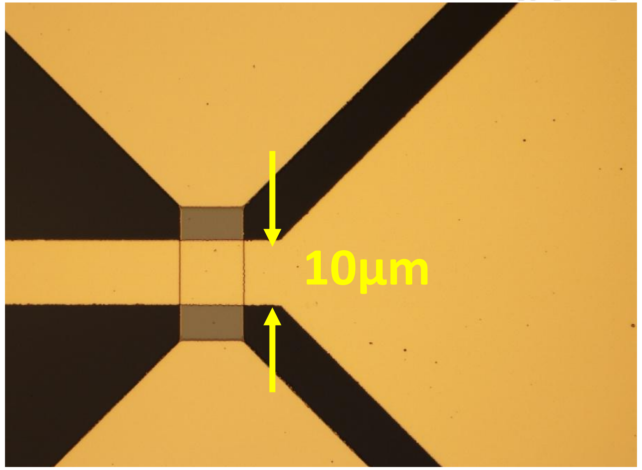
- **Self-supporting/no tension**
- **Built-on electronics (on back)**
- **Far fewer cables**
- **Ultimately more reliable, lower noise, lower activity**





Max metallization cover with min capacitance

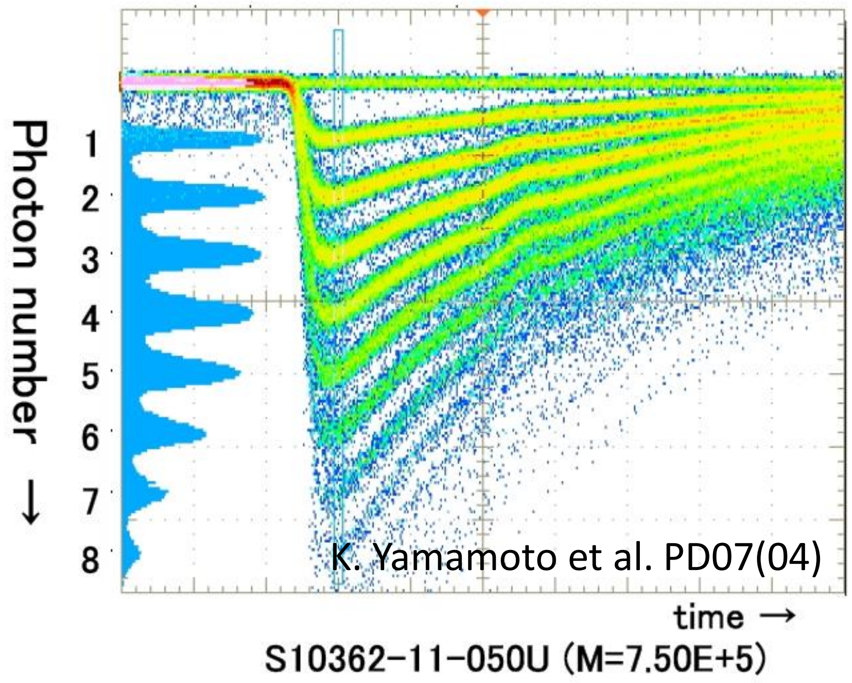
JINST 13, P01006 (2018)
arXiv 1710.05109



- 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

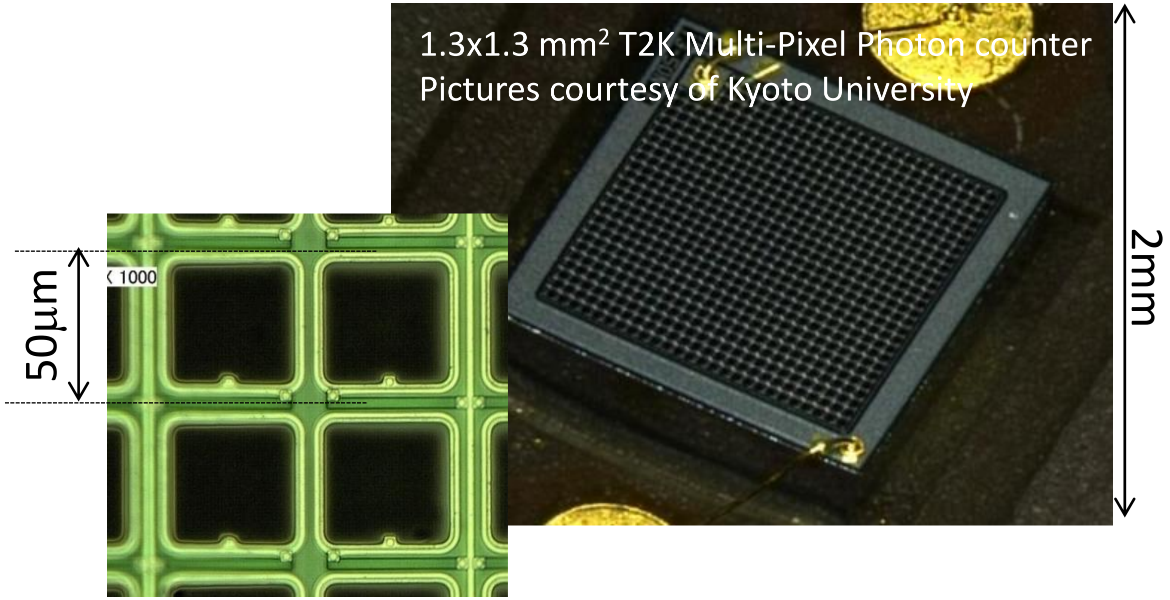
Analog SiPMs - baseline solution for nEXO

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



K. Yamamoto et al. PD07(04)

S10362-11-050U (M=7.50E+5)

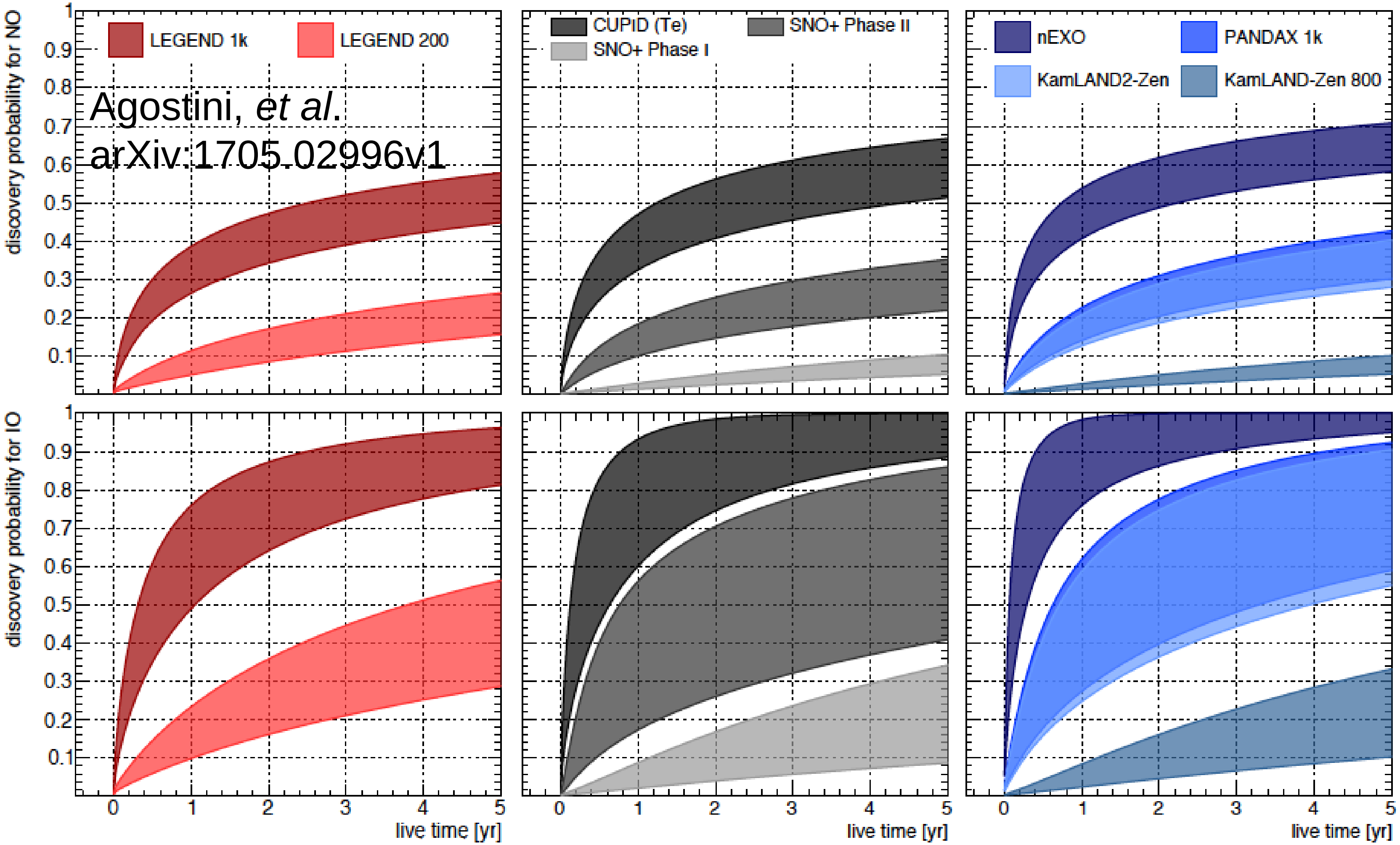


1.3x1.3 mm^2 T2K Multi-Pixel Photon counter
Pictures courtesy of Kyoto University

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 V
Dark noise rate	$< 50\ \mathrm{Hz/mm}^2$
Correlated avalanche rate	< 0.2

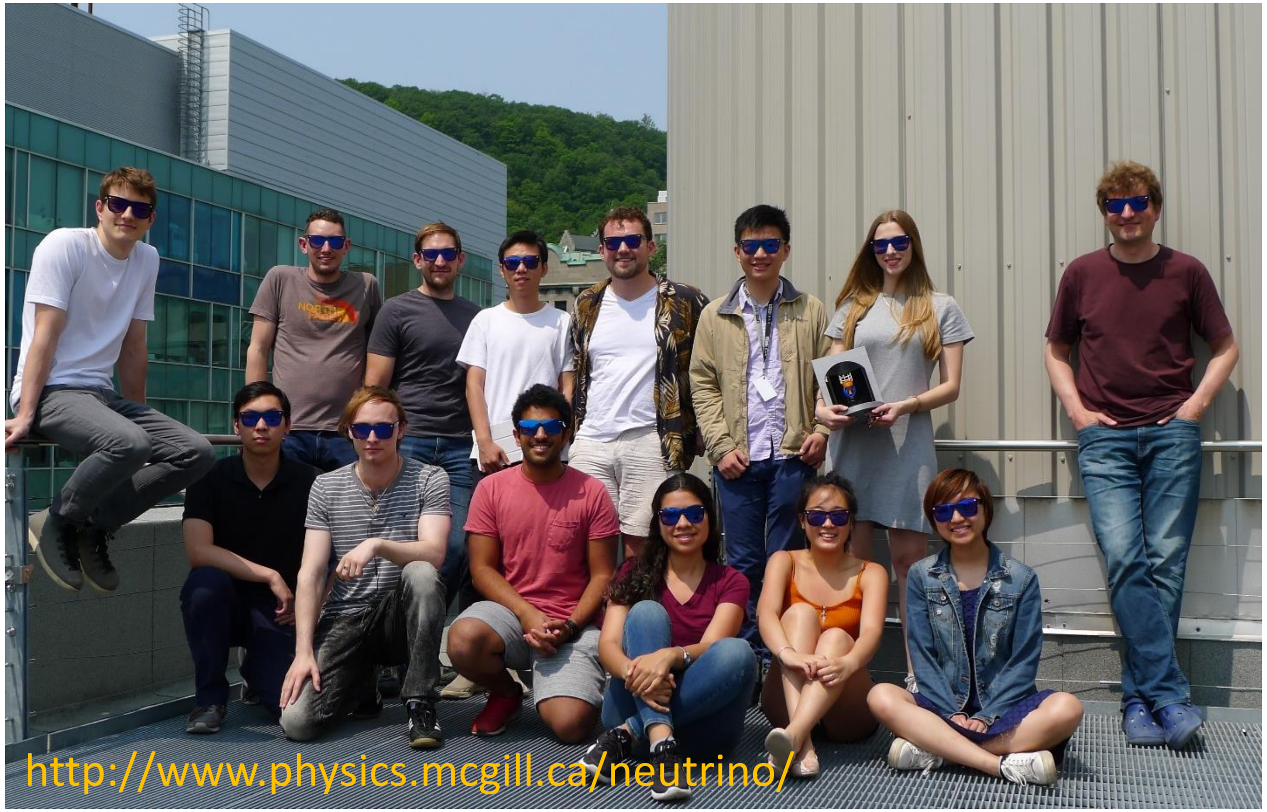
0νββ Discovery Potential



Agostini, *et al.*
arXiv:1705.02996v1

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

Join us for awesome neutrino physics!



http://www.physics.mcgill.ca/neutrino/

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California Institute of Technology, Pasadena CA, USA — P Vogel
Carleton University, Ottawa ON, Canada
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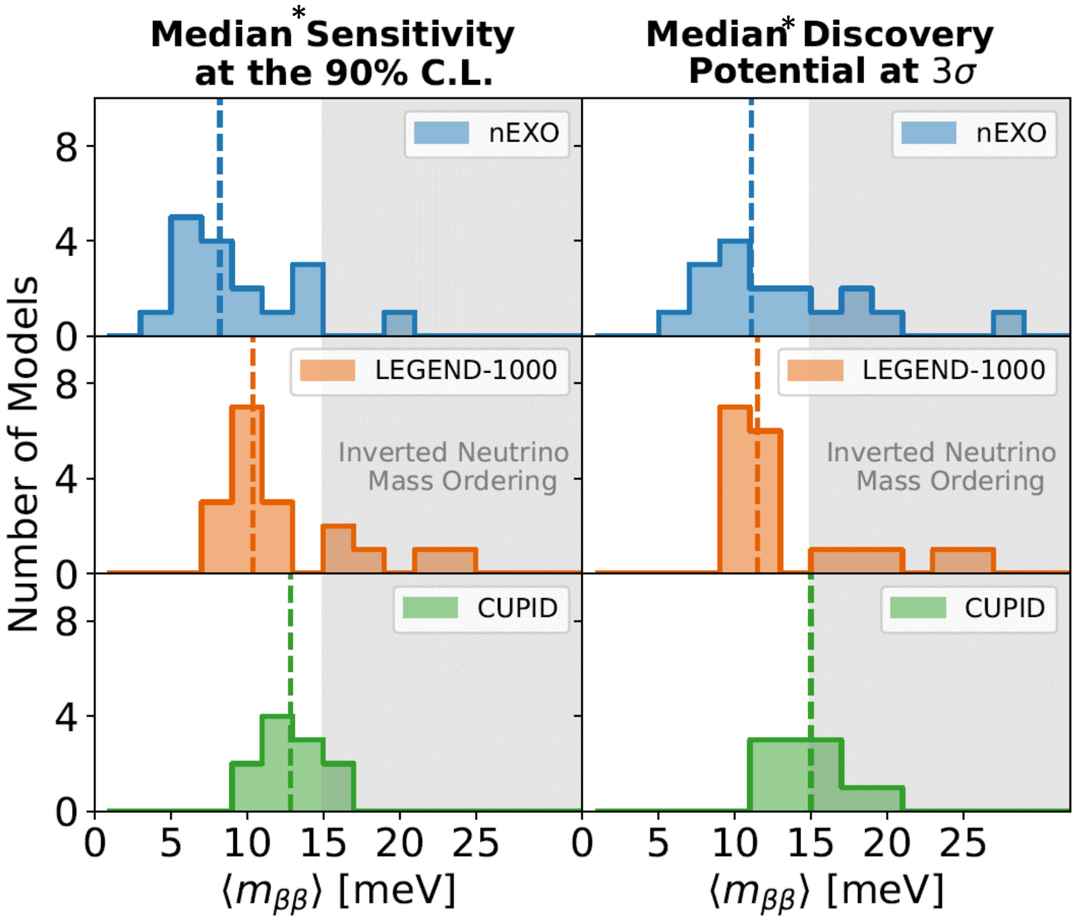
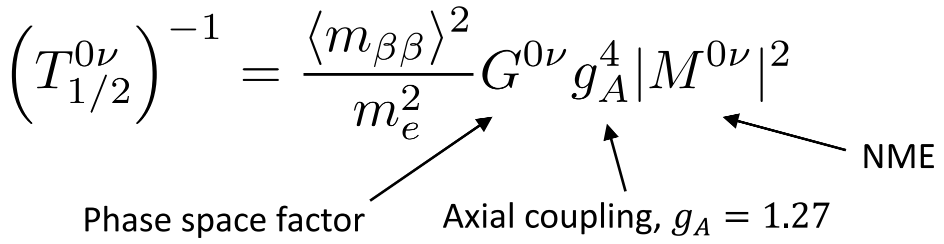
TRIUMF, Vancouver BC, Canada — J Dilling, G Gallina, R Krücken Y Lan, F Retière, M Ward
Yale University, New Haven CT, USA — A Jamil, Z Li, DC Moore, Q Xia

Backup

Comparison with other experiments



← Deeper Physics Reach —



$$\left(T_{1/2}^{0\nu}\right)^{-1} = \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2} G^{0\nu} g_A^4 |M^{0\nu}|^2$$

Phase space factor

Axial coupling, $g_A = 1.27$

NME

- 3σ discovery potential for most NME reaching beyond inverted ordering further into normal ordering

	$m_{\beta\beta}$ [meV], *(median* NME)*	
	90% excl. sens.	3σ discov. potential
nEXO	8.2	11.1
LEGEND	10.4	11.5
CUPID	12.9	15.0

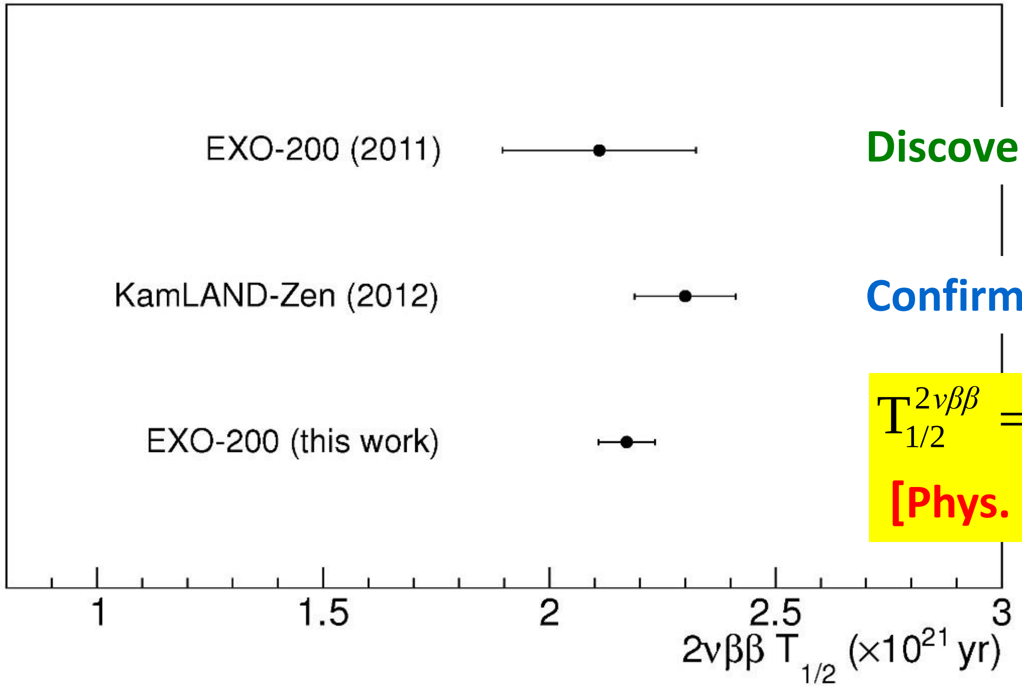
*$T_{1/2}$ values used [x10^{28} yr]:
nEXO: 1.35 (90% sens.), 0.74 (3σ discov.) [1]
LEGEND: 1.6 (90% sens.), 1.3 (3σ discov.) [2]
CUPID: 0.15 (90% sens.), 0.11 (3σ discov.) [3]

[1] nEXO collaboration, arXiv:2106.16243
[2] LEGEND pCDR, arXiv: 2107.11462
[3] CUPID pCDR, arXiv:1907.09376

*Median shown to guide the eye; NME is not a statistical value → There is only one correct NME.

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)]

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

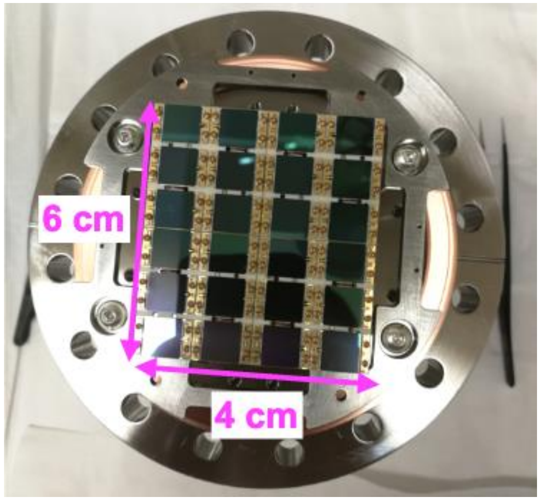
[Phys. Rev. C 89 (2014) 015502]

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

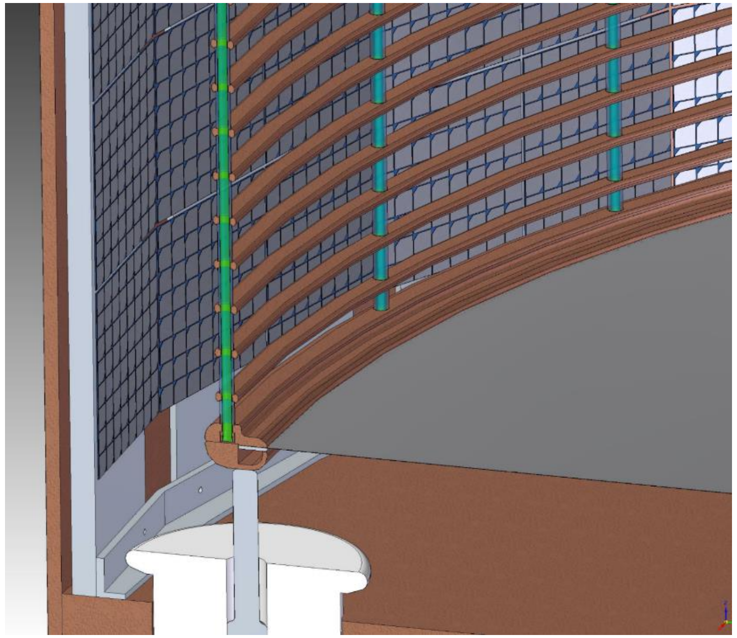
Analog SiPMs - baseline solution for nEXO

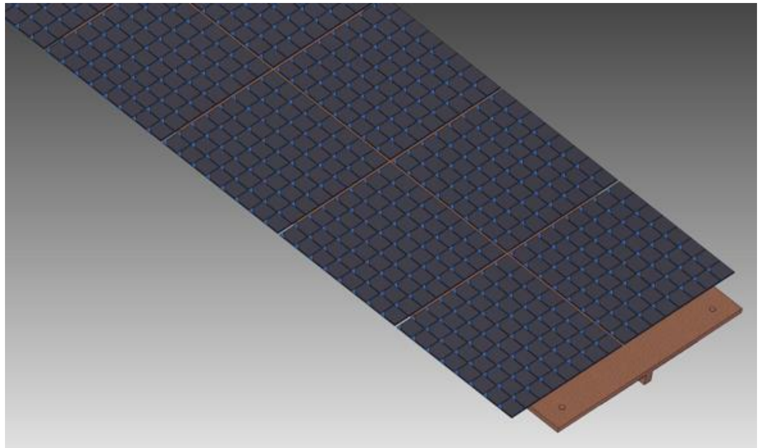
- Integrate SiPMs into ‘tiles’ (~10 x 10 cm^2).
- ASIC chip to read out tile.
- Tiles mounted on ‘stave’ (~20 x 120 cm^2).
- Staves mounted inside LXe behind field cage.

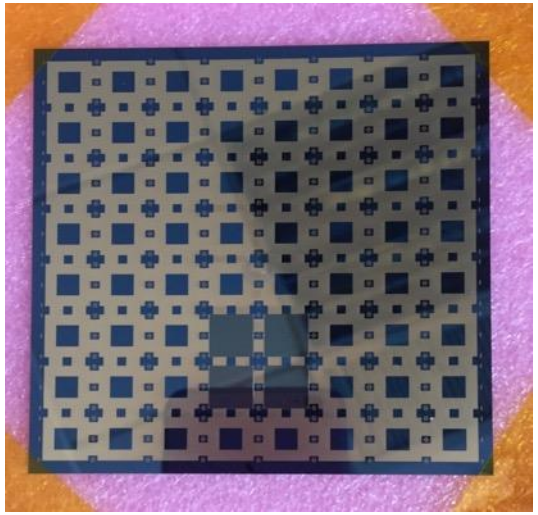
ASIC (ZENON) for SiPM readout under design (BNL)
- System on Chip
- 16 channel
- Peak detection
- Analog to digital conversion
- On-chip LDOs



Prototype SiPM Tile







Prototype silicon interposer

Conceptual design of the photo detector system underway

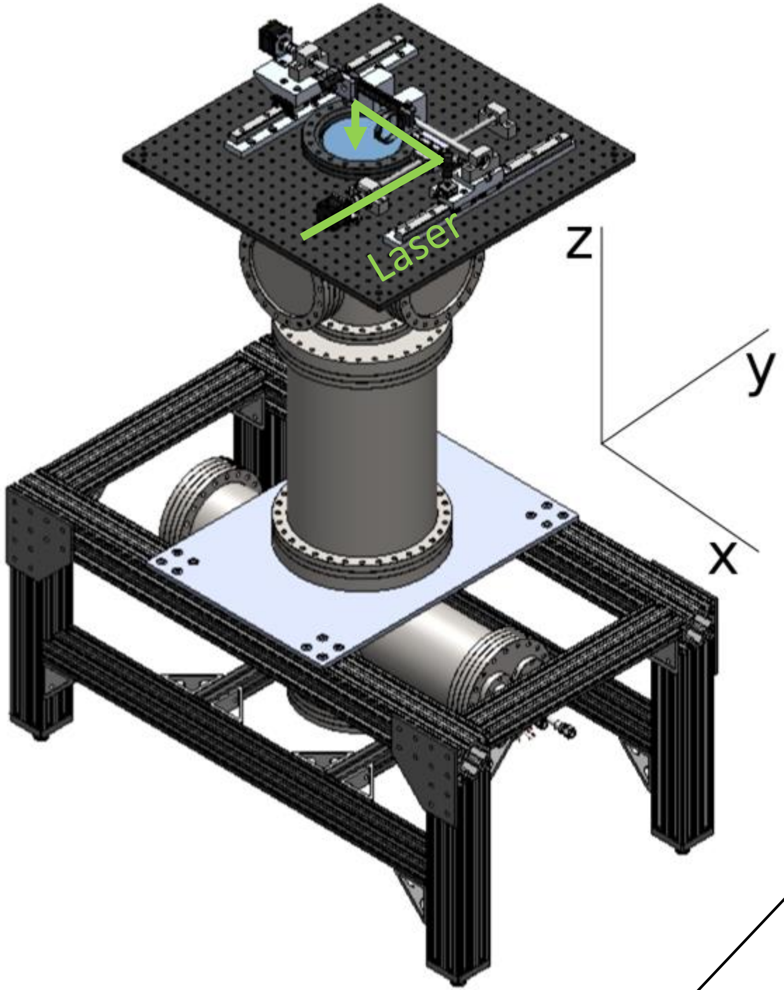
McGill Environmental Test Stand

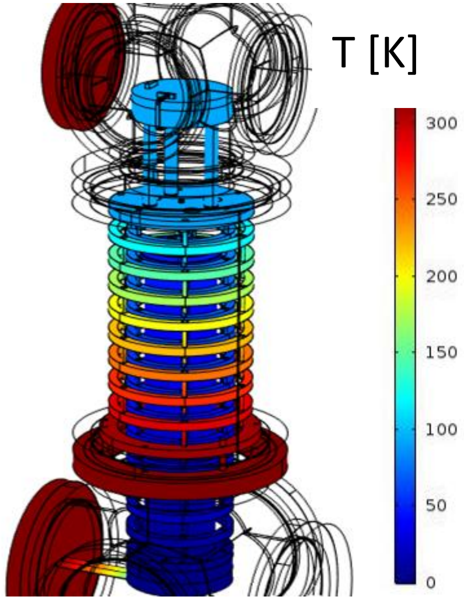
Cryostat (Liquid nitrogen powered):

- Low power [~ 1 W]
- Fast cooldown [~ 9 h]
- LXe [~ 165 K] and LAr [~ 87 K] temperatures

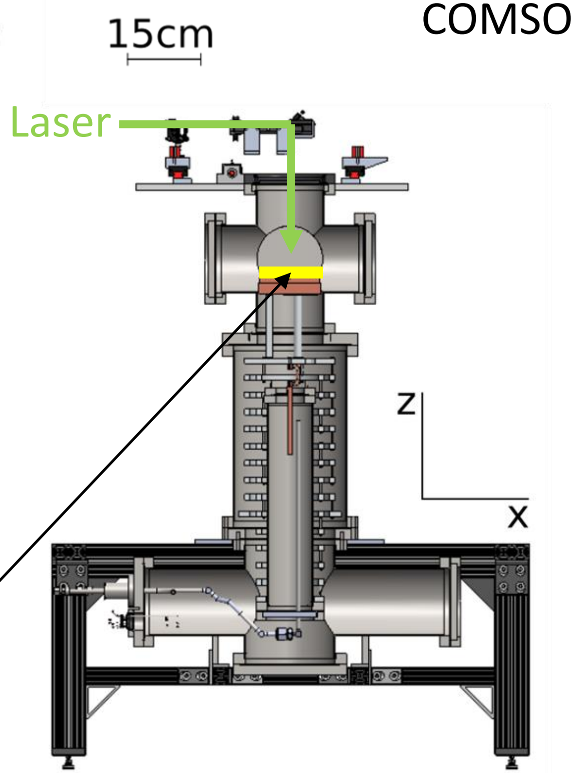
Testing Stage:

- Large area [~ 150 cm^2].
- Stable temperature.
- Easily removable top plate.
- Precision scanning across tile [~ 40 µm resolution].





COMSOL



SiPM tile

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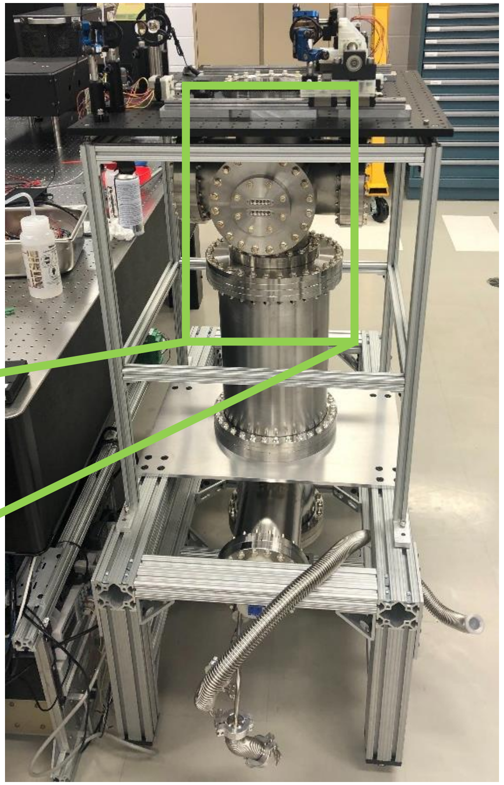
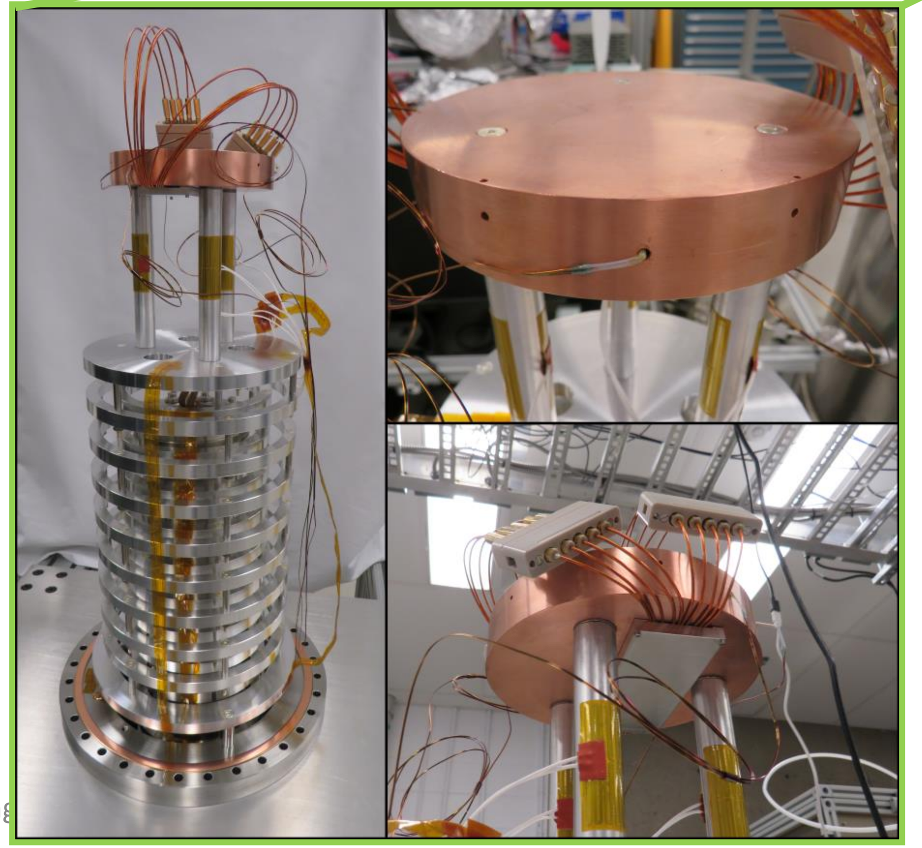
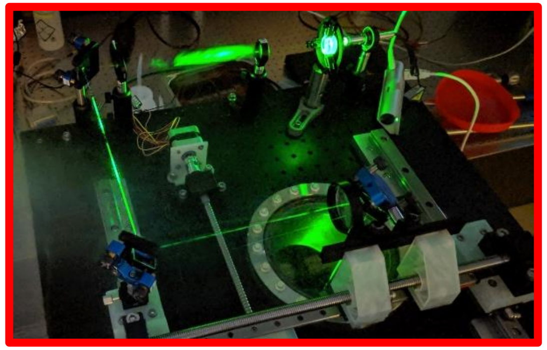
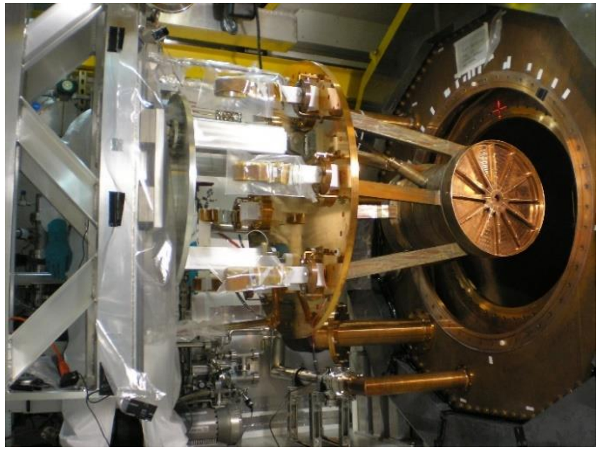


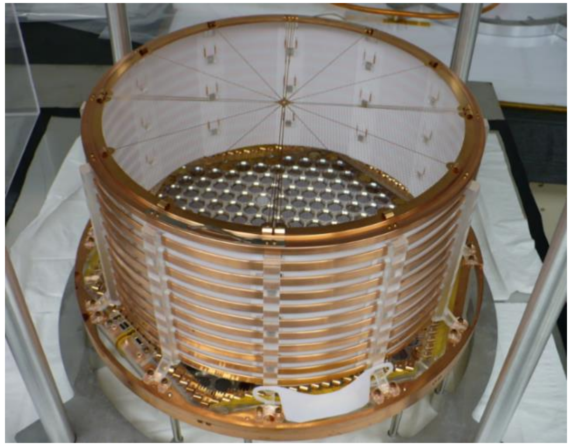


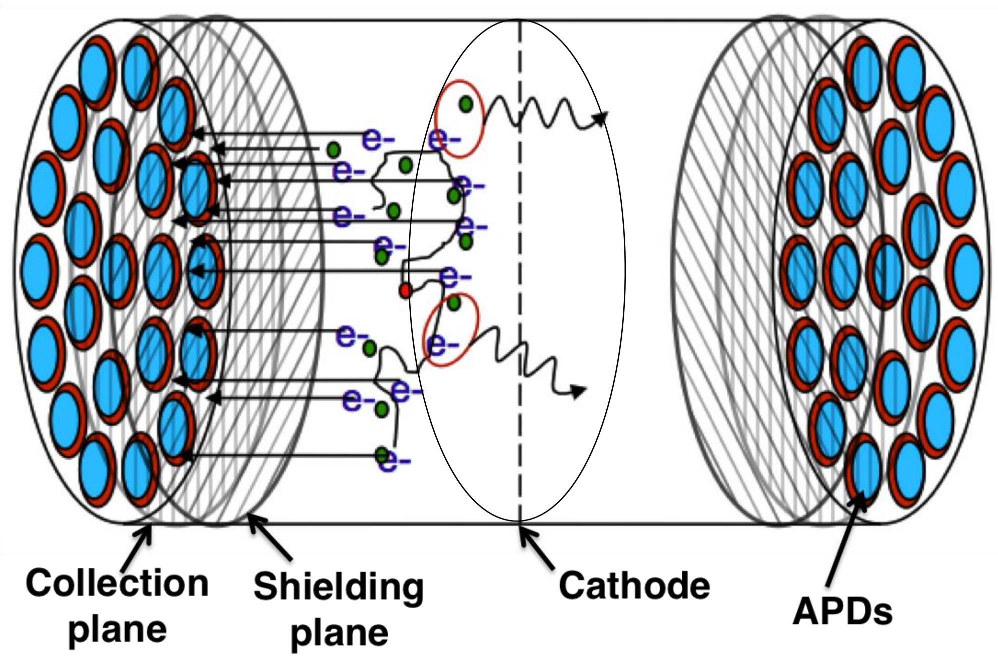


EXO-200 Detector

- EXO-200 has searched for 0νββ of ^{136}Xe to ^{136}Ba
- ~175kg Liquid Xenon (LXe) Time Projection Chamber (TPC)
- Located at Waste Isolation Pilot Plant (WIPP) in Carlsbad, NM, USA
- Two identical back to back TPCs made from radio-pure copper with transparent cathode
- Energy measured using two signals
  - Ionization signal drifted to crossed wire planes
  - Scintillation (175nm) collected by APD

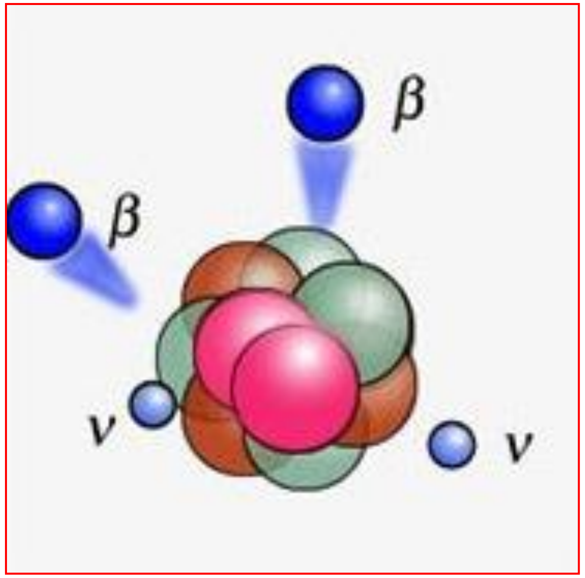


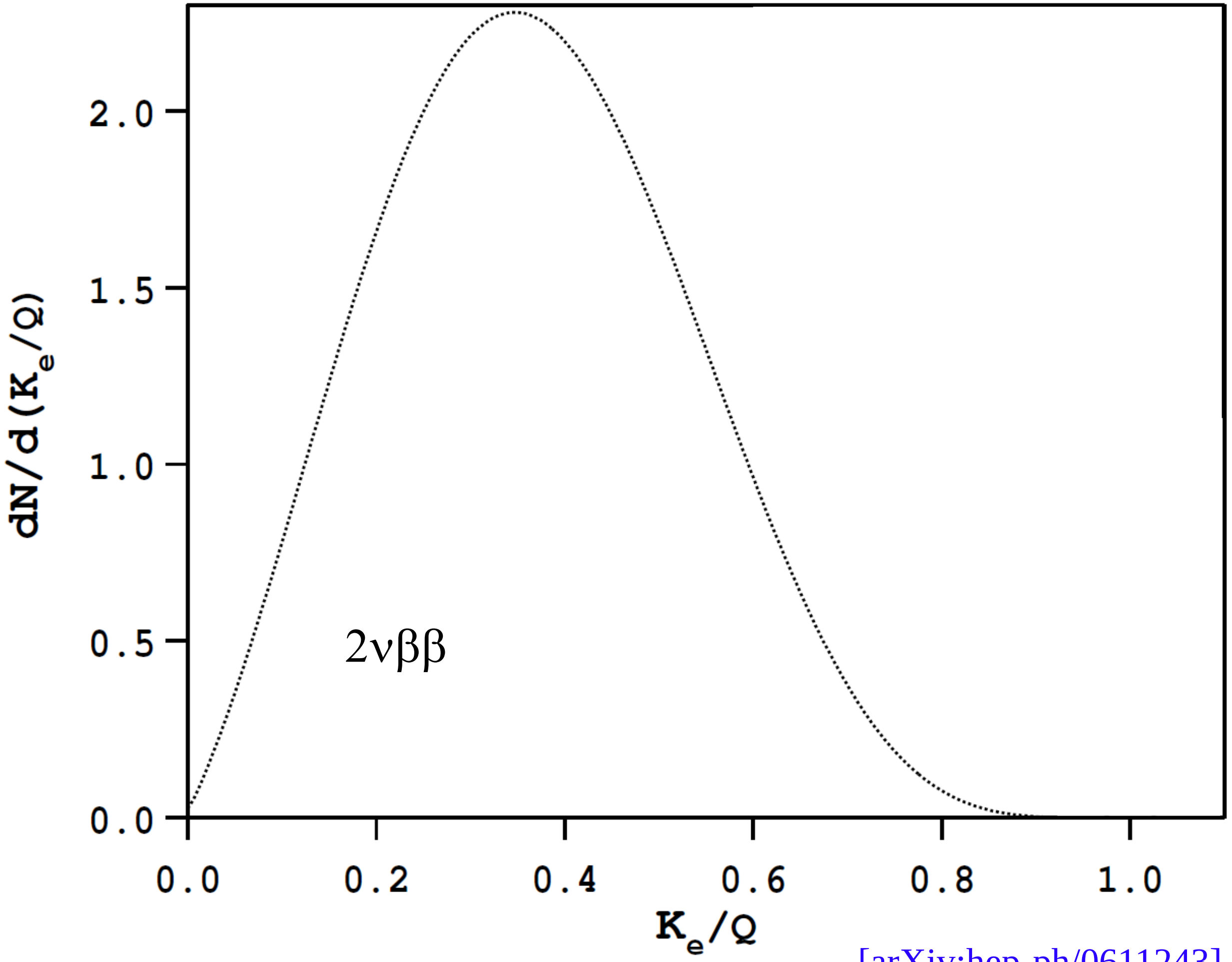




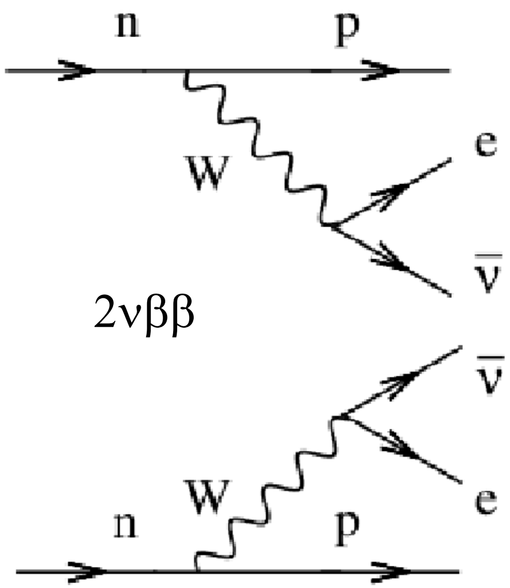
M.Goeppert-Mayer,
Phys. Rev. 48
(1935) 512

2ν Double Beta Decay





[arXiv:hep-ph/0611243]

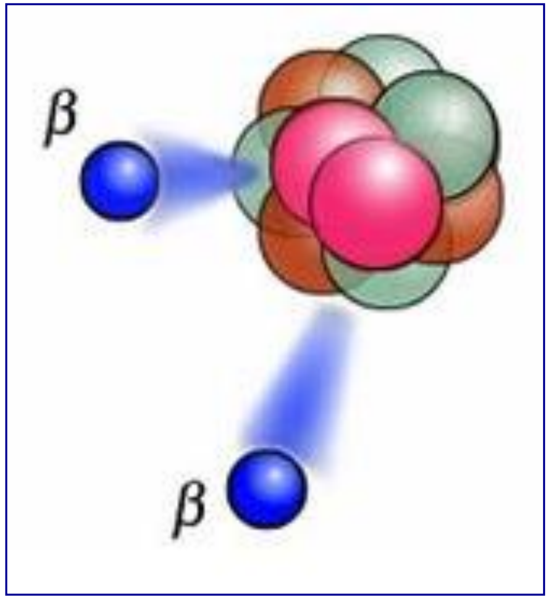


2νββ

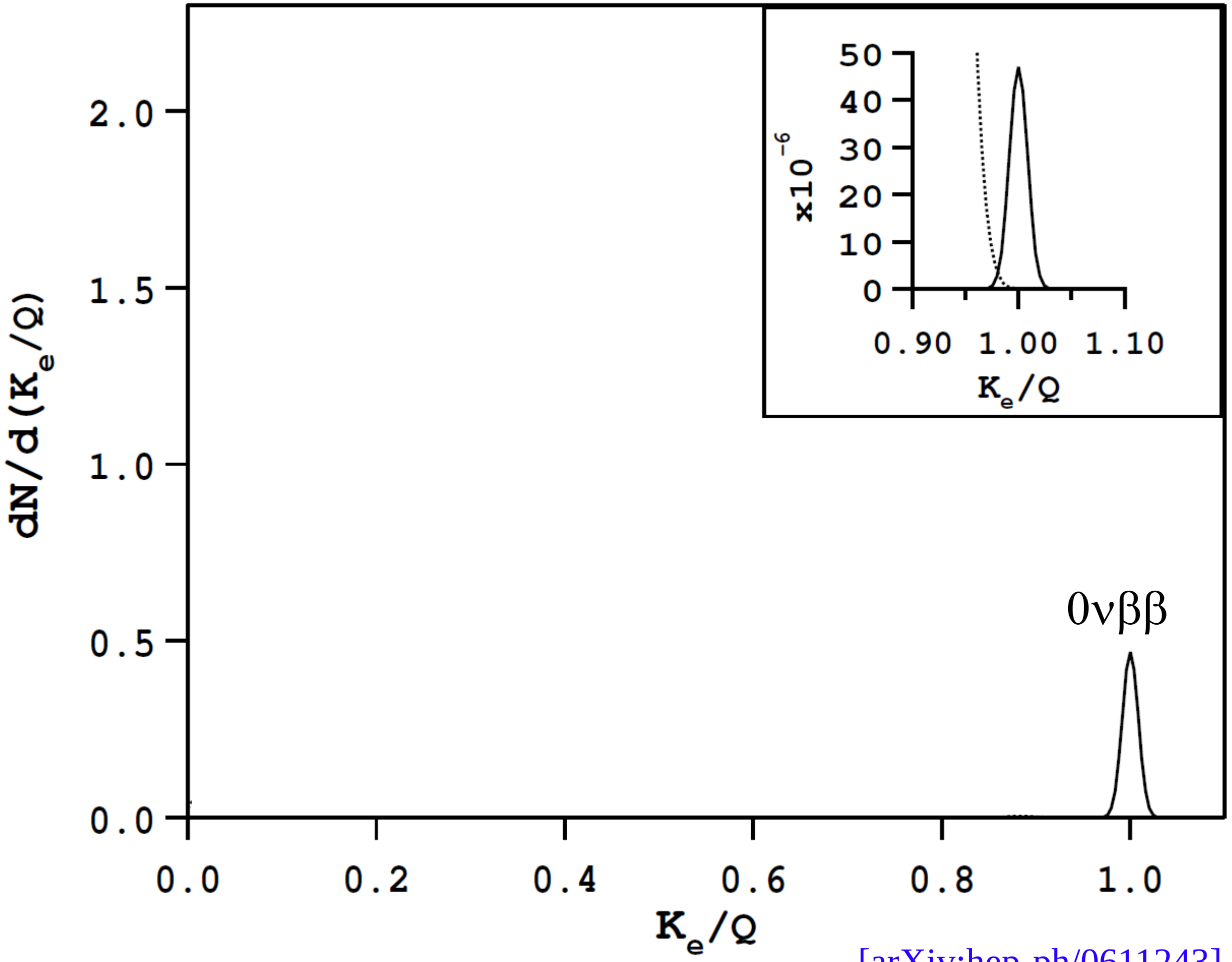
$T_{1/2} \approx 10^{20}$ y

0ν Double Beta Decay

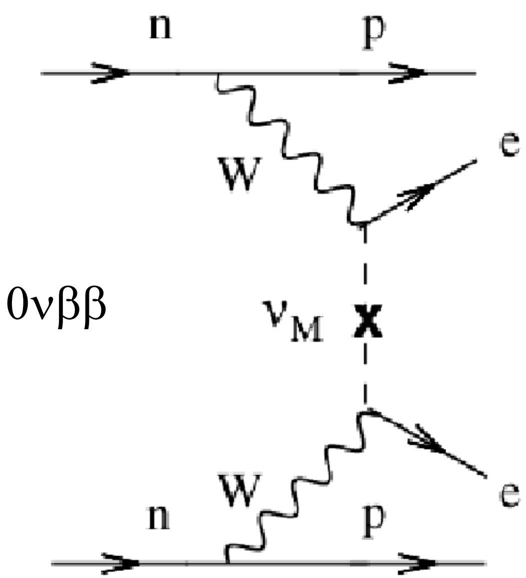

Ettore Majorana



0νββ
$T_{1/2} > 10^{25}$ y!



[arXiv:hep-ph/0611243]



0νββ – Can only happen for Majorana neutrinos!