Searching for Majorana Neutrinos with nEXO

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on behalf of the nEXO Collaboration

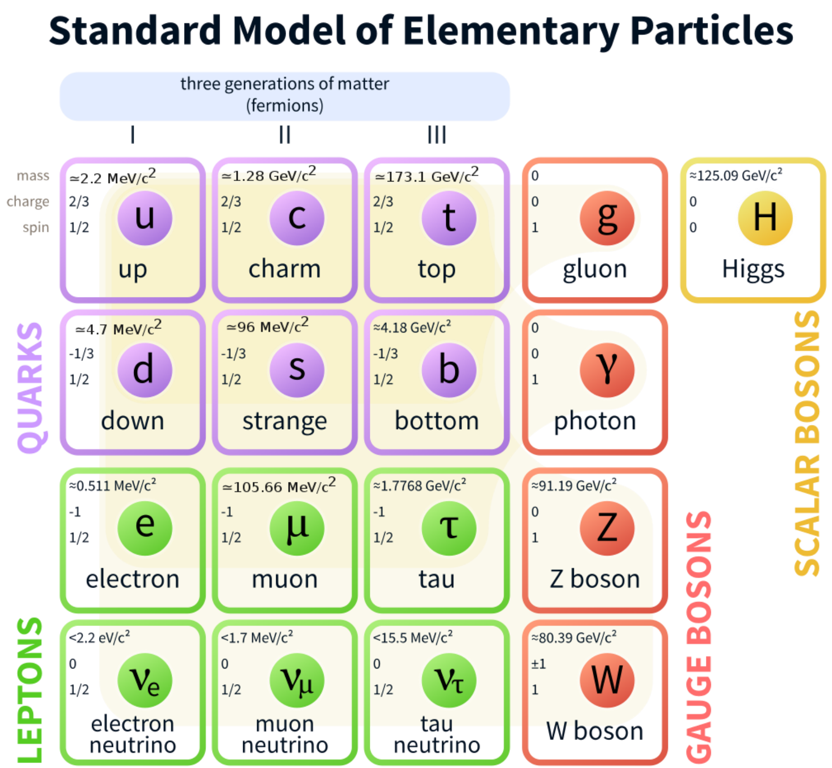
McGill University

Lake Louise Winter Institute Feb 12, 2020

Neutrinos

- Fundamental particles
- Neutral
- Weakly Interacting
- Small Mass (< 1 eV)
- Common

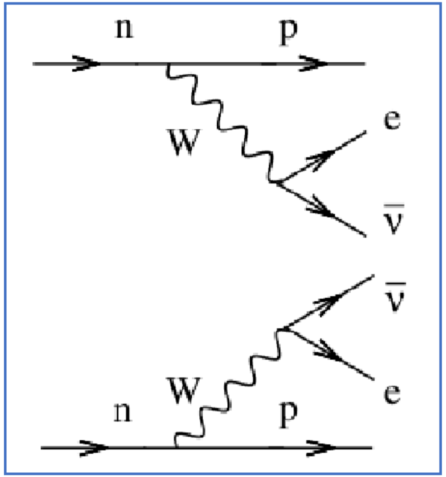
Open Questions:
- Are neutrinos their own anti-particle?
- What are the neutrino masses?
- Can neutrinos violate lepton # conservation?



Double Beta Decay

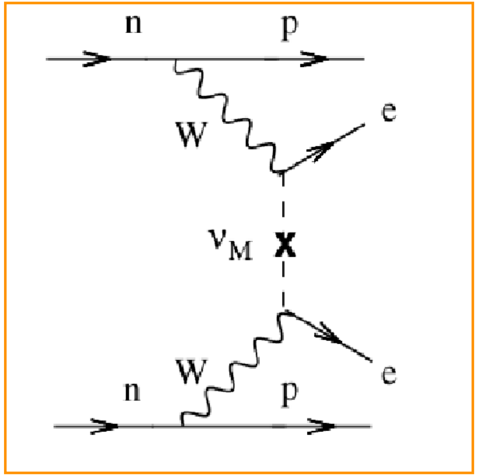
- Second-order weak nuclear process
- Observable when first-order beta decay is forbidden
- 35 2νββ nuclei have been found
  - ^{136}Xe – EXO-200, nEXO, NEXT, KL-Z
  - ^{76}Ge – Legend, GERDA, MJD
  - ^{130}Te – CUORE, SNO+

2νββ



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

0νββ



Proposed by: Ettore Majorana

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

$T_{1/2}^{0\nu}$ is the measured 0νββ half-life
$G^{0\nu}$ 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)

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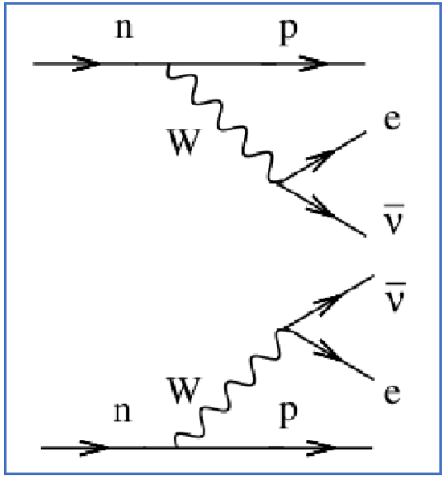
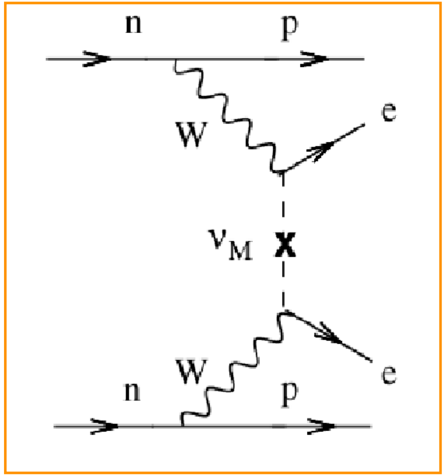
2νββ



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

0νββ

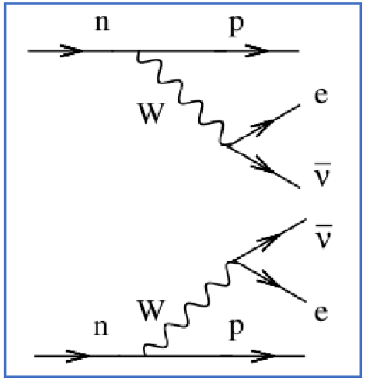


Proposed by: Ettore Majorana

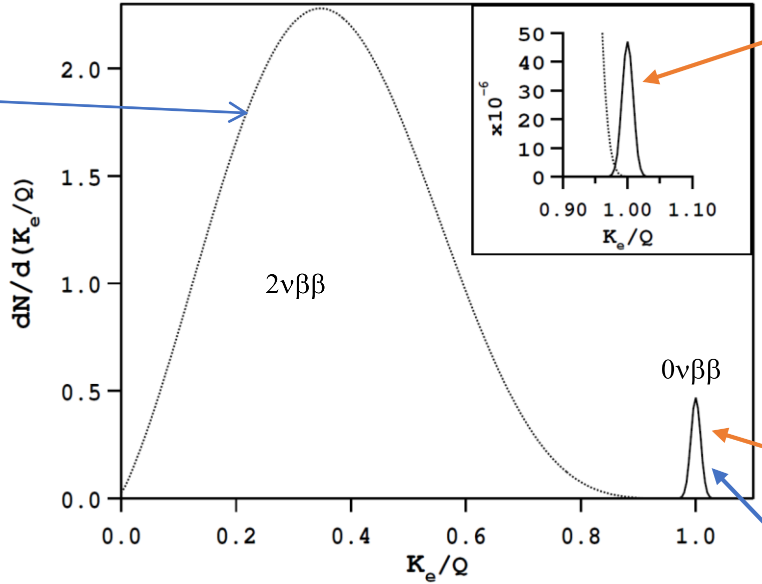
Open Questions:
- Are neutrinos their own anti-particle?
- What are the neutrino masses?
- Can neutrinos violate lepton # conservation?

Lepton # conservation violation is an important requirement for many theories that seek to explain the matter-antimatter asymmetry of the universe

Detecting Neutrinoless Double Beta Decay (0νββ)

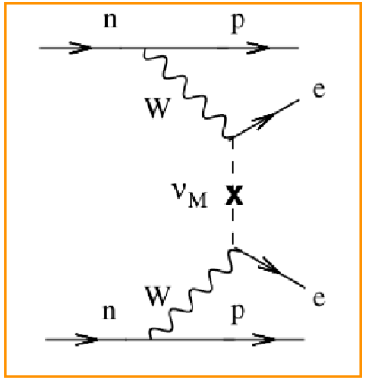


arXiv:hep-ph/0611243



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

0νββ peak (normalized to 10^{-6})



0νββ peak (normalized to 10^{-2})

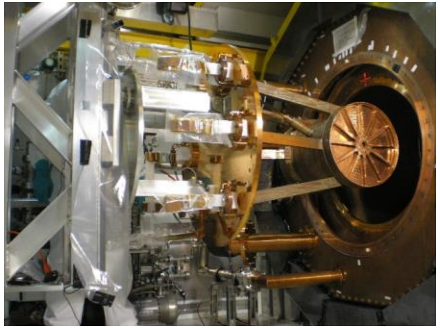
Smeared by the energy resolution of the hypothetical detector

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

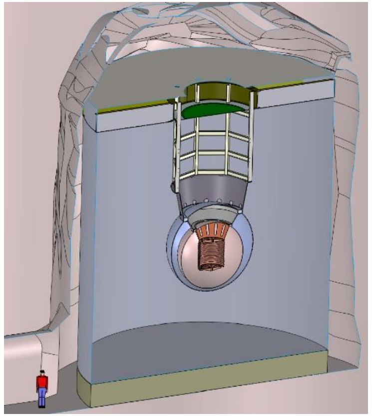
- Easy to enrich: 8.9% natural abundance but can be enriched relatively easily (better than growing crystals)
- Can be purified continuously, and reused
- High $Q_{\beta\beta}$ (2458 keV): higher than most naturally occurring backgrounds
- Minimal cosmogenic activation: no long-life radioactive isotopes
- 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**: ~175kg liquid-Xe TPC, finished 2018



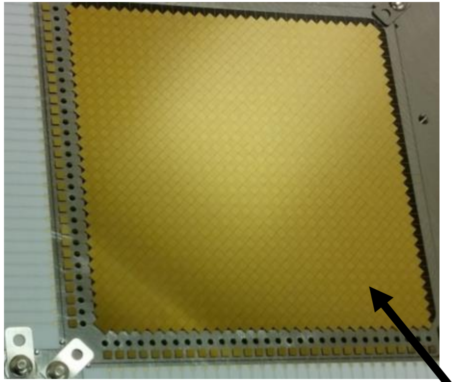
2. **nEXO**: future 5-tonne liquid Xe TPC with Ba tagging upgrade option (SNOLAB cryopit)



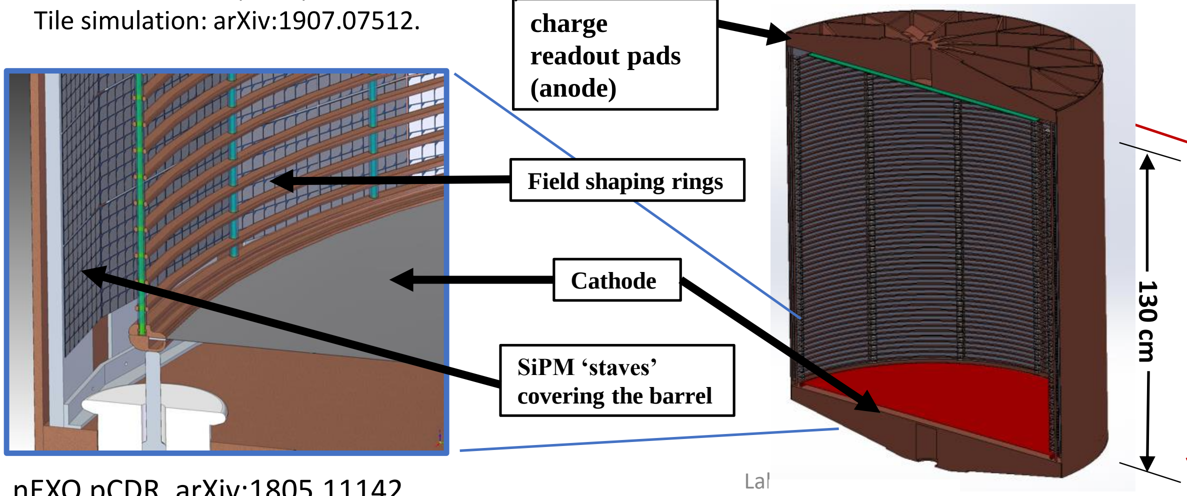
The nEXO Experiment:

Next-generation Liquid Xenon (LXe) Time Projection Chamber (TPC)

- Next-generation neutrinoless double beta decay detector
- 5 tonne liquid xenon TPC
- SiPM for 175nm scintillation light detection
- Tiles for charge read out
- 3D event reconstruction
- Combine charge and light readout. Goal → σ/E of 1% at Q-value.
- 1.7 k-tonne water shield

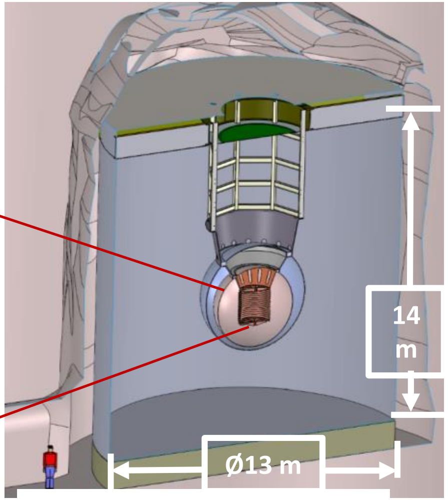


Picture: 10 x 10 cm^2 tile prototype
JINST 13, P01006 (2018)
Tile simulation: arXiv:1907.07512.



nEXO pCDR, arXiv:1805.11142

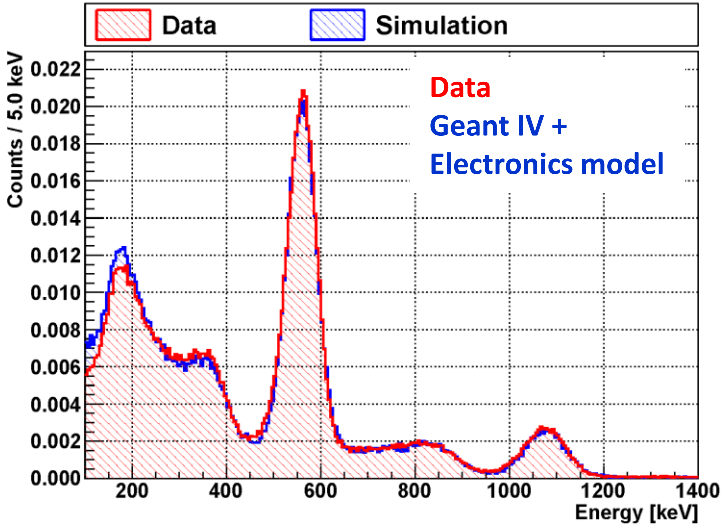
nEXO TPC



nEXO at the SNOLAB Cryopit

Charge and Light Detection in nEXO

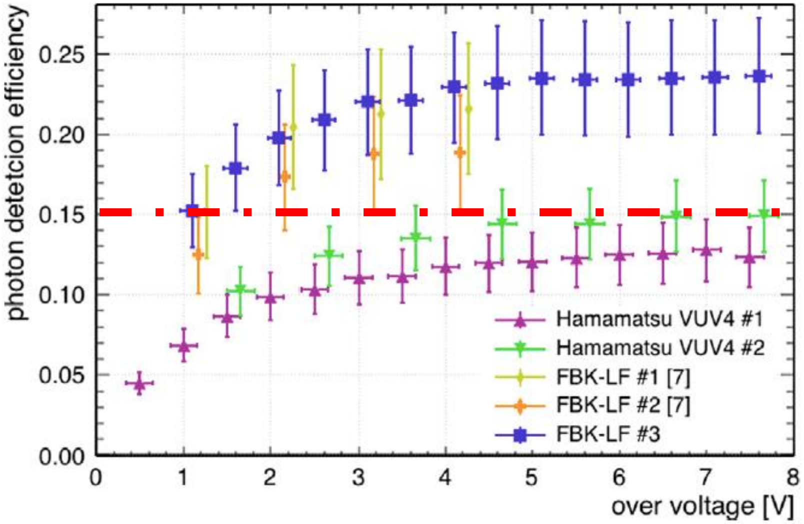
Test of Charge Tiles with ^{207}Bi Source



Metal strips deposited on low-BG dielectric substrate
Interleaved for X, Y position reconstruction
Electronics mounted to back of chip
Self-supported --> More robust than tensioned wire grid

JINST 13, P01006 (2018), arXiv 1710.05109

Photon Detection Efficiency of SiPMs

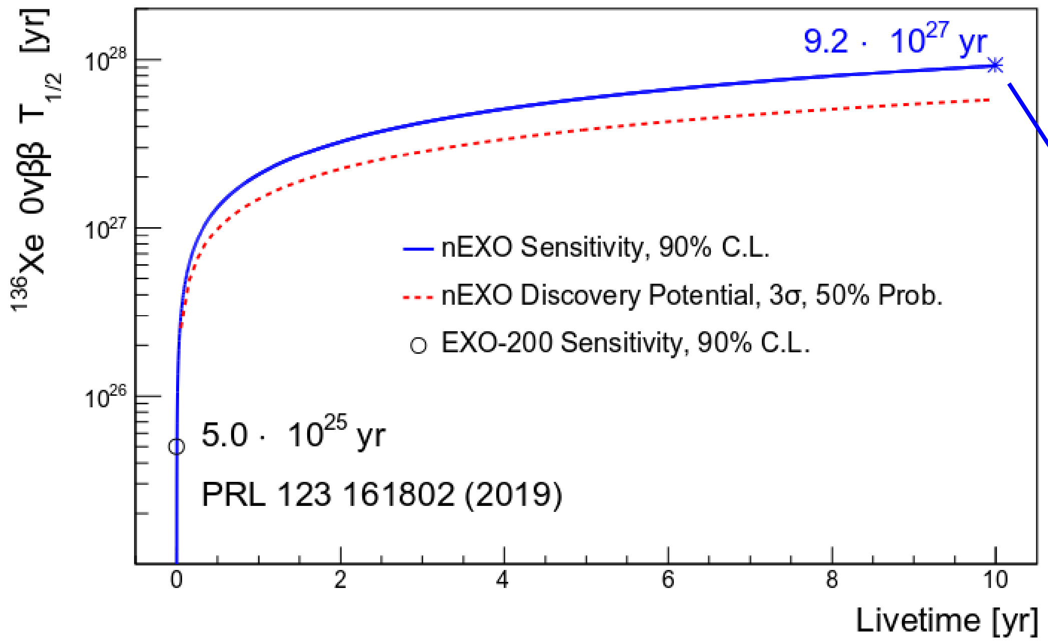


Relatively low bias requirements (30 - 80 V)
High gain (10^5 - 10^6)
Photon detection efficiency is sufficient
Low dark noise (< 50 Hz/mm^2)

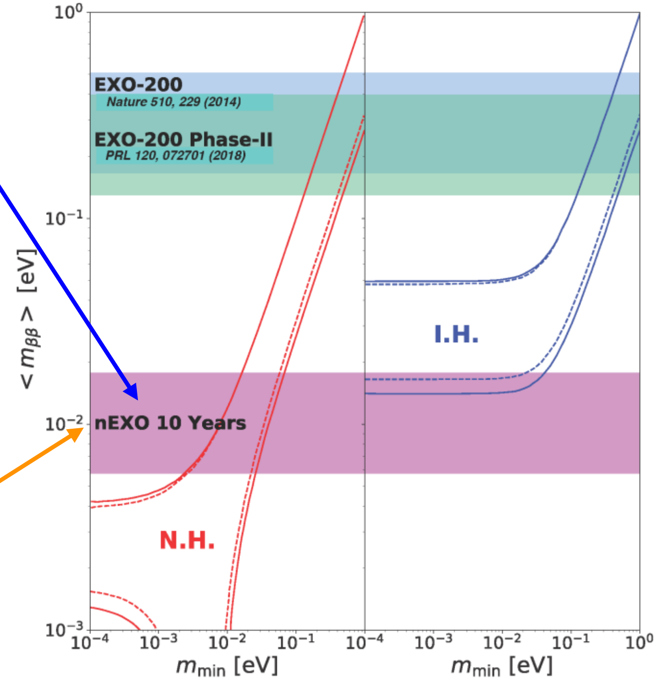
A, Jamil, et al. IEEE Trans.Nucl.Sci. 65, 2823 (2018)
G. Gallina et al. Nucl. Instrum. Meth., 940, 371 (2019)

Projected nEXO Sensitivity

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



Projected sensitivity based on actual background level measurements!



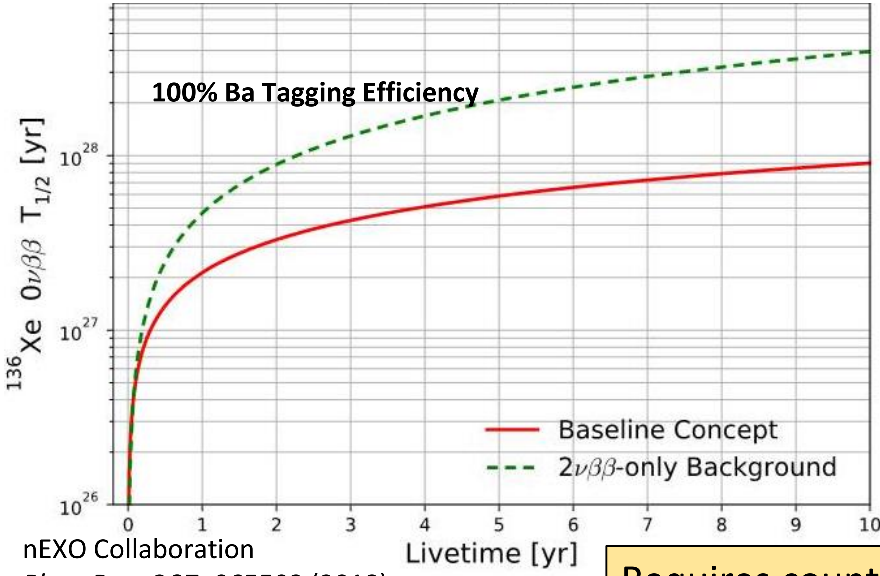
- Band is the envelope of Nuclear Matrix Element:

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)

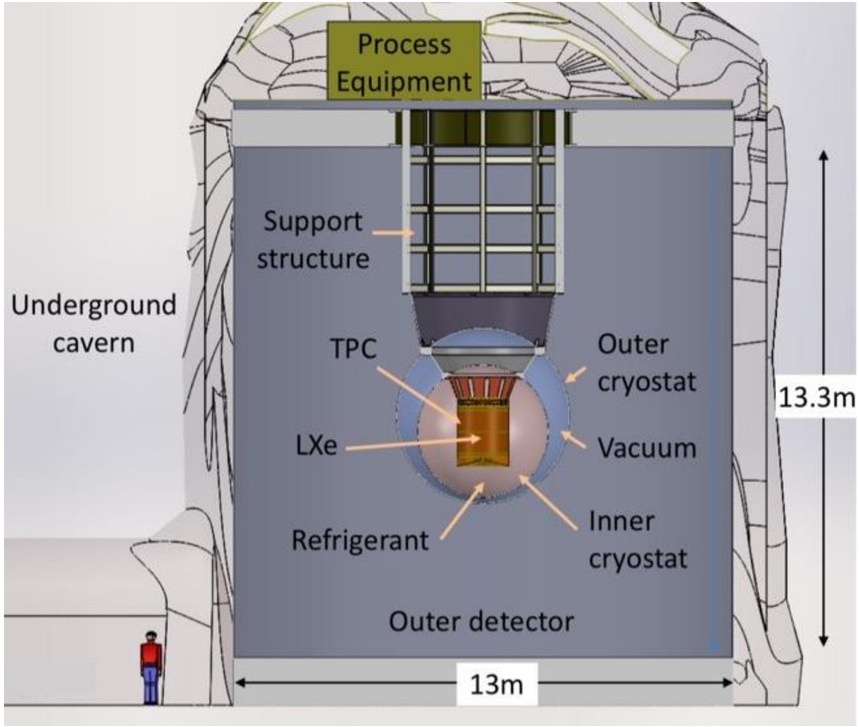
Barium Tagging Concept as an upgrade to nEXO

$$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-}$$

Barium Tagging: identify barium daughter at 0νββ decay site for **complete** background elimination



nEXO Collaboration
Phys. Rev. C **97**, 065503 (2018)



nEXO pCDR, arXiv:1805.11142

Requires counting of ***single*** Ba daughter in macroscopic amount of Xe

Barium Tagging R&D Program for nEXO

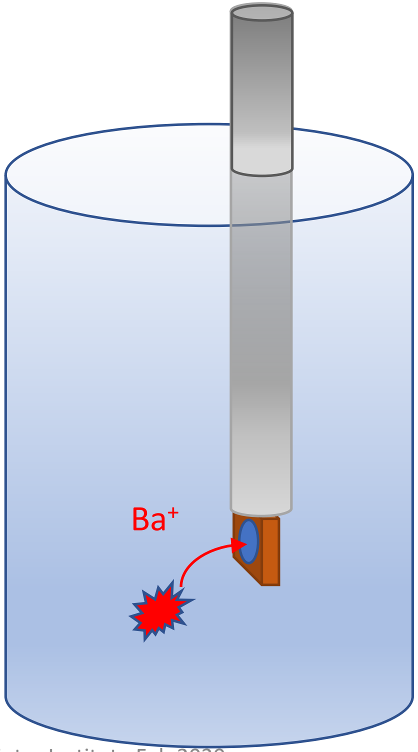
- Cryogenic probe with Fluorescence Spectroscopy in Solid Xenon
  - Colorado State University
- Extraction to Gas Phase with Ion Trapping
  - McGill and Carleton Universities and TRIUMF
- Electrically Biased probe with Resonance Ionization Spectroscopy
  - Stanford University
- Electrically Biased probe with Thermal Desorption
  - University of Illinois Urbana-Champaign @ ANL
- Electrically Biased probe with Electron Microscopy
  - Brookhaven National Lab

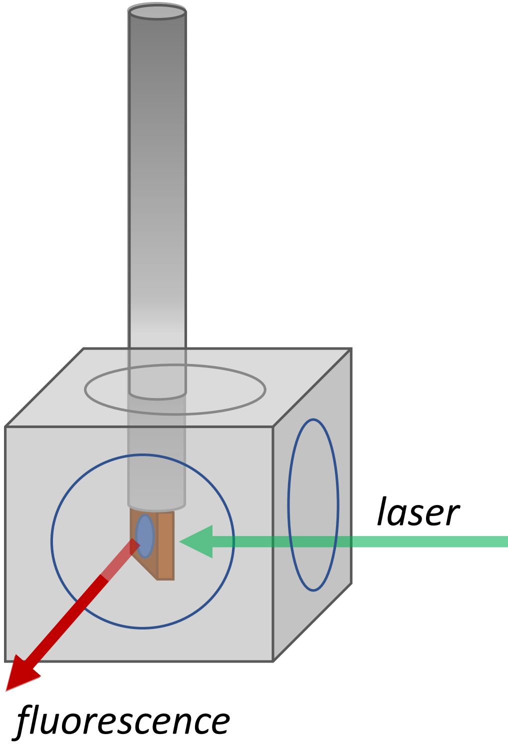
Barium Tagging in Solid Xenon

- Locate the decay position with the TPC
- Insert a cryogenic probe and trap the Ba decay daughter in solid Xe
- Extract the probe and cool further
- Tag the Ba daughter in the solid Xe via laser induced fluorescence

0 Ba → Not ββ decay

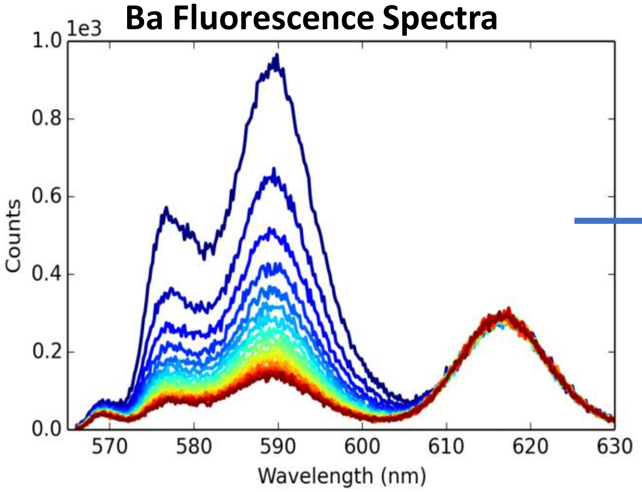
1 Ba → ββ decay



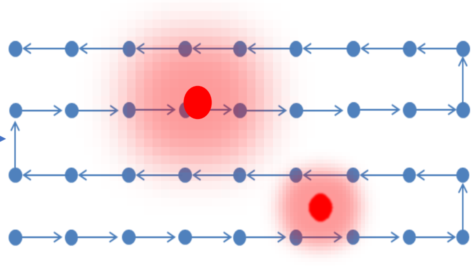


Remove probe to observation region –
Use single Ba imaging technique we have developed

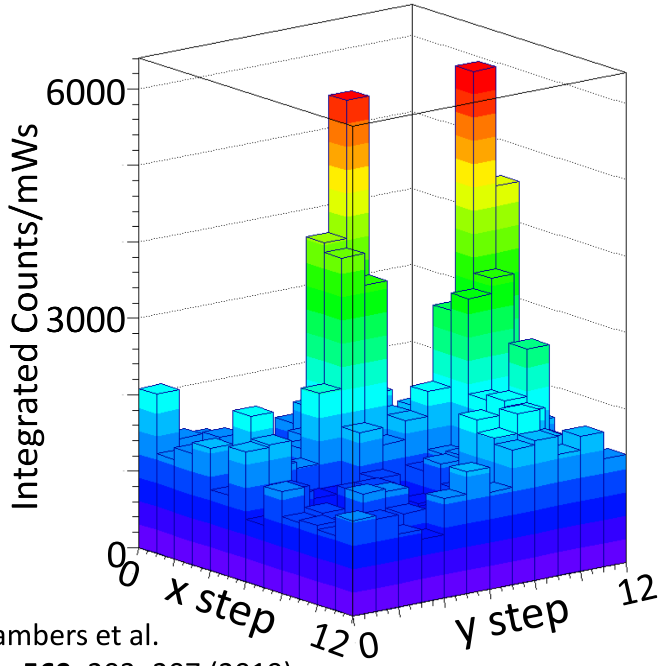
Fluorescence Images of Individual Ba Atoms in Solid Xe



B. Mong et. al, *Phys. Rev. A* **91**, 022505 (2015)



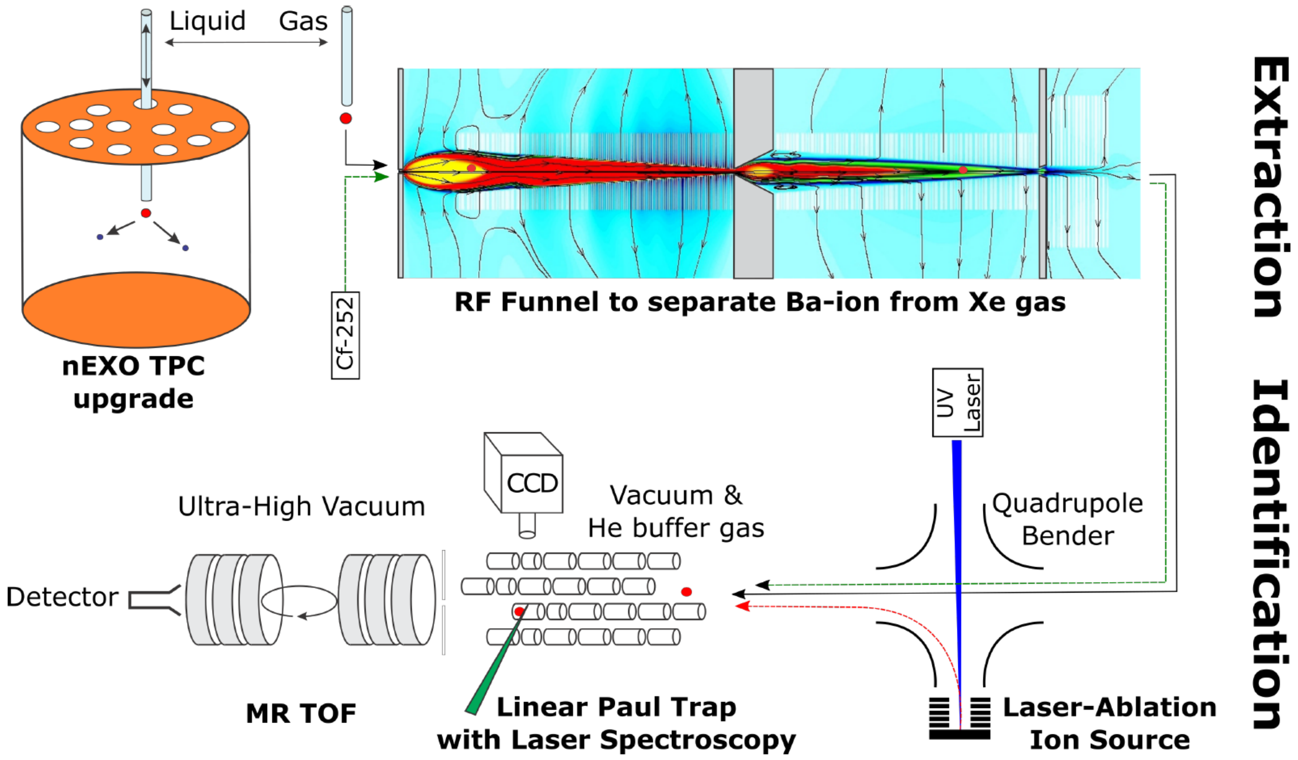
Use a focused laser to scan solid Xe sample with implanted Ba



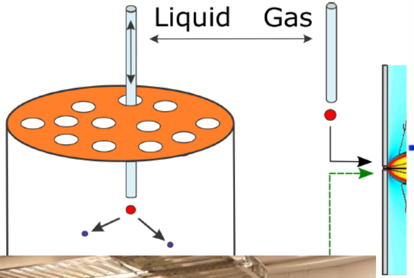
C. Chambers et al. *Nature* **569**, 203–207 (2019)

Single Ba atoms successfully imaged in solid Xe → Major breakthrough for Ba tagging!

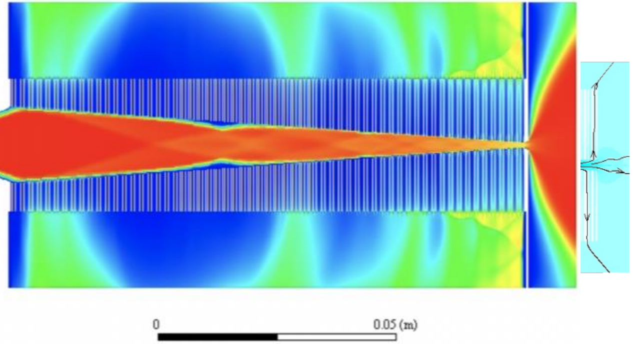
Ba Extraction and Tagging in Xe Gas



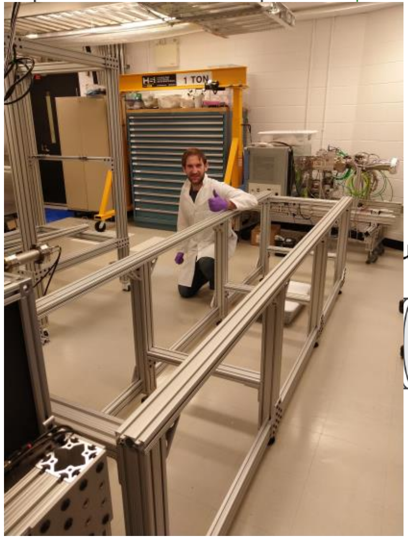
Under Development – Stay Tuned!



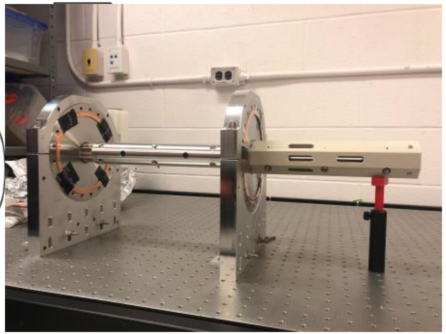
ANSYS Fluent Simulation of RF Funnel



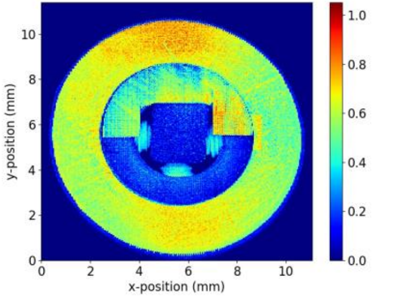
Ion trap/MR-TOF rail system



LPT being built



Multi-Metal Ion Source



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We are looking for new collaborators!

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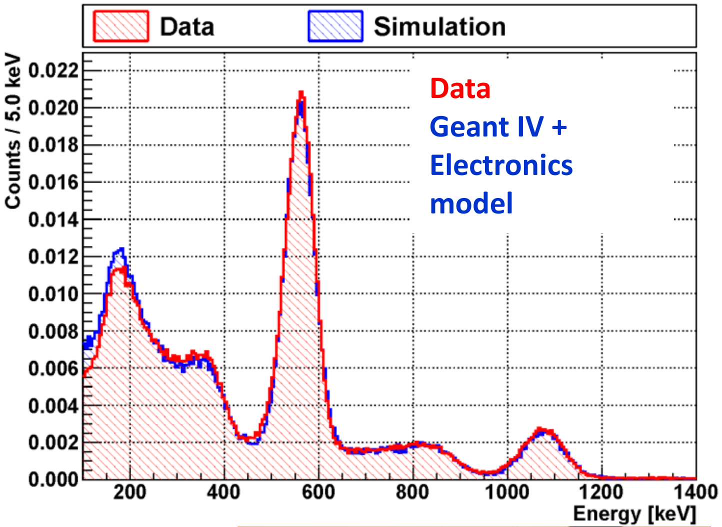
Stony Brook University, SUNY, Stony Brook NY, USA — KS Kumar
TRIUMF, Vancouver BC, Canada — J Dilling, G Gallina, R Krücken Y Lan, F Retière, M Ward
Yale University, New Haven CT, USA — A Jamil, Z Li, DC Moore, Q Xia

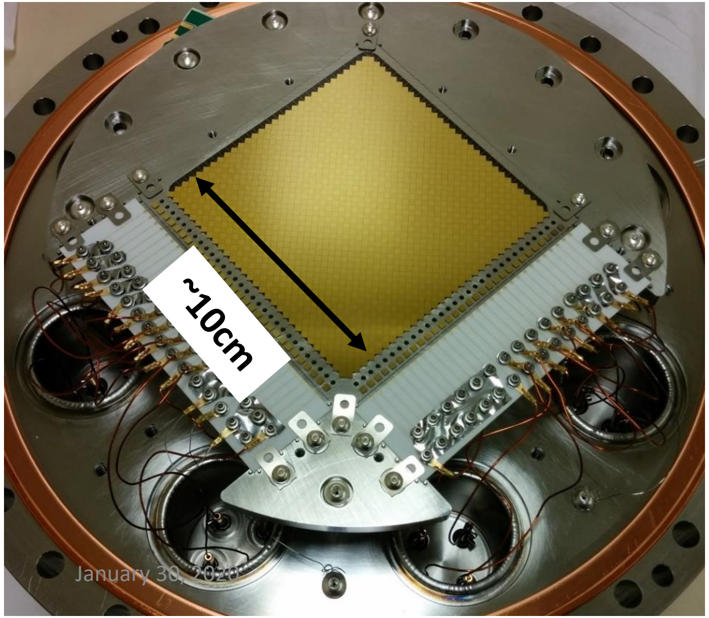
Backup

Charge Readout

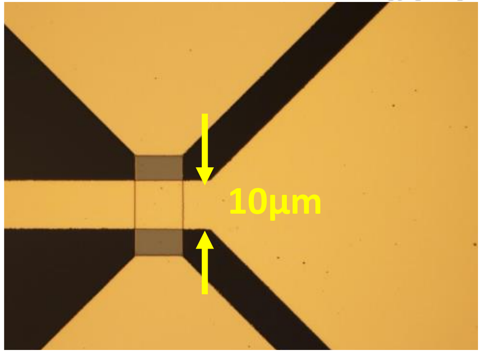
Charge will be collected on arrays of strips fabricated onto low background dielectric wafers
(low radioactivity quartz has been identified)

- 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

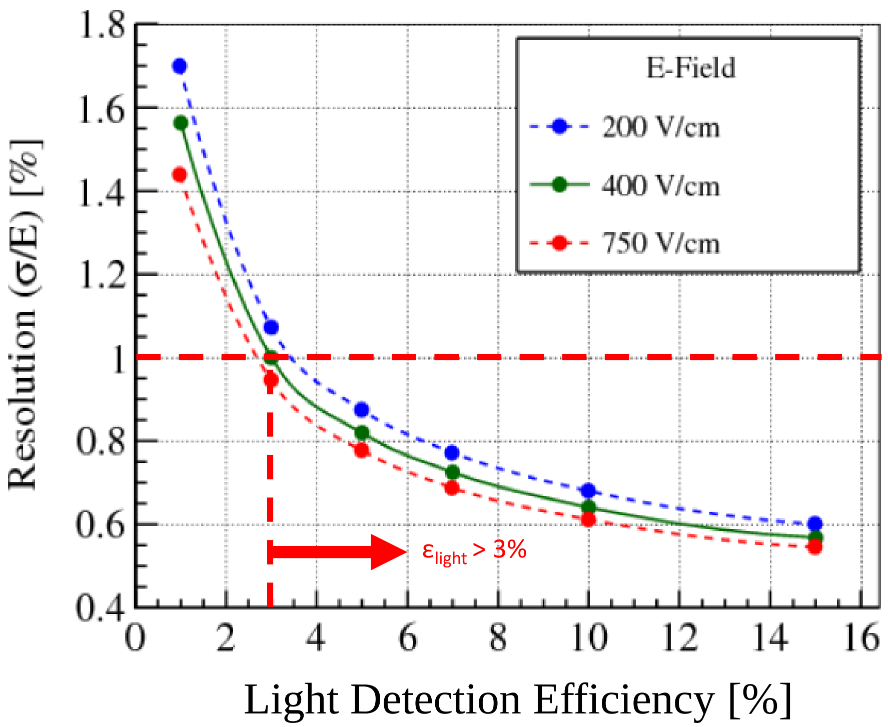
- 10 x 10cm^2 Prototype Tile
- Metallized strips on fused silica substrate
- 60 orthogonal channels (30 x 30), 3mm strip pitch
- Strip intersections isolated with SiO_2 layer

Photon Detection Efficiency Requirements

To achieve 1% energy resolution, an overall 3% photon detection efficiency is required, consisting of two parts:

- **Photon detection efficiency (PDE) of SiPM**
  - **Determined by filling factor, transmittance, quantum efficiency and trigger efficiency.**
  - **Can be measured by a standalone setup.**
- **Photon transport efficiency (PTE)**
  - **Detector geometry**
  - **Reflective electrodes in TPC**
  - **Reflectivity of SiPM**

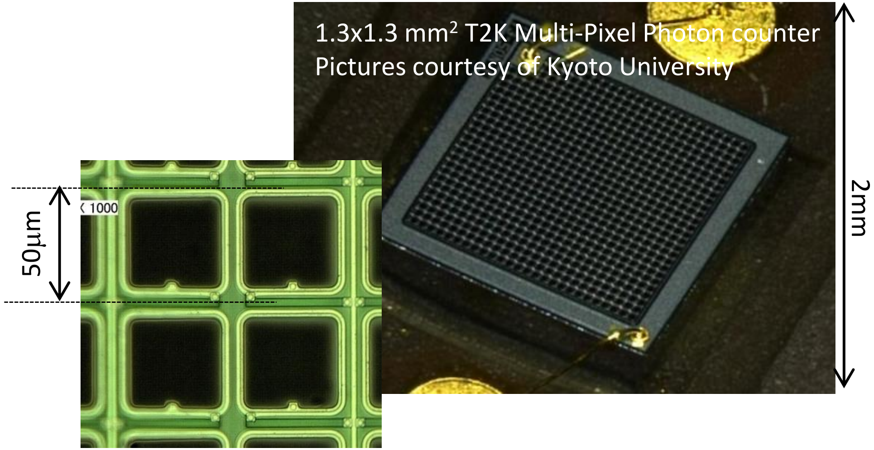
For VUV photons, more than 50% will be reflected on SiPM surface, assuming Si-SiO_2 interface.

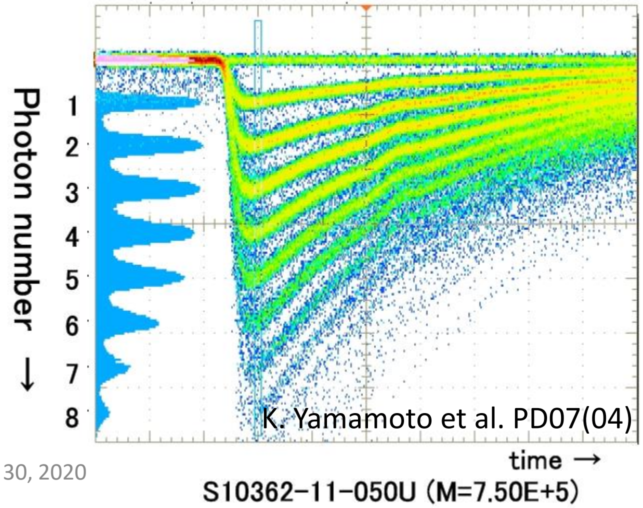


arxiv:1805.11142

Analog SiPMs - baseline solution for nEXO

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

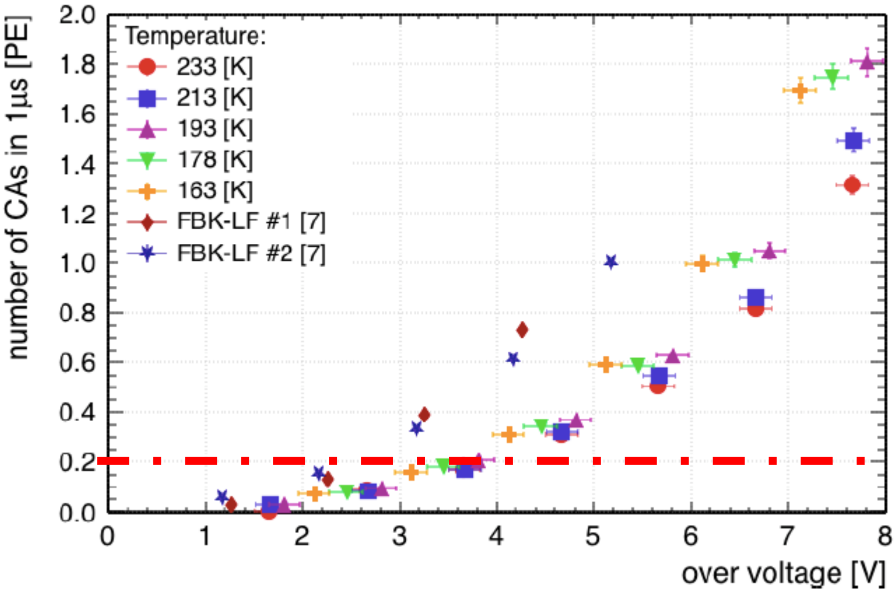


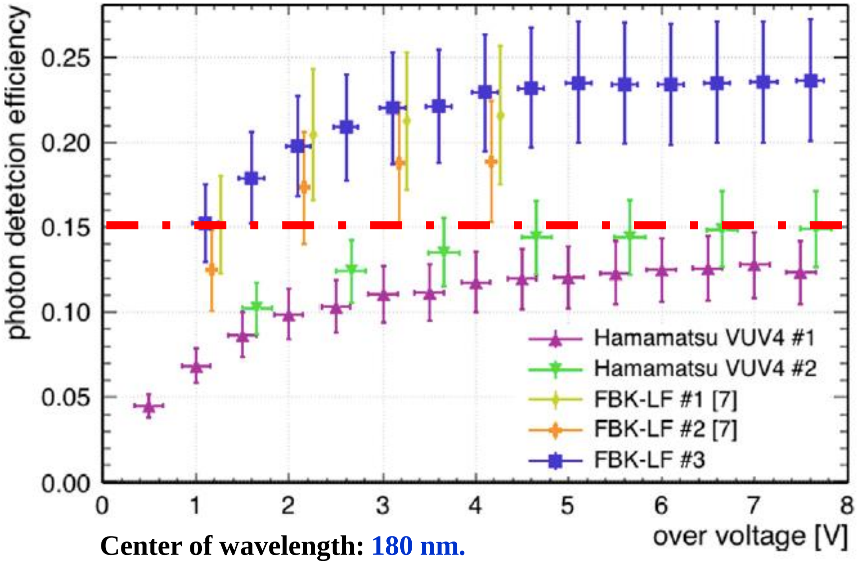


nEXO key parameters (1805.11142):

Parameter	Value
Total instrumented area	$\simeq 4.5$ 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 Hz/mm^2
Correlated avalanche rate	< 0.2

PDE Measurements





Center of wavelength: 180 nm.

A, Jamil, et al. IEEE Trans.Nucl.Sci. 65, 2823 (2018)
G. Gallina et al. Nucl. Instrum. Meth., 940, 371 (2019)

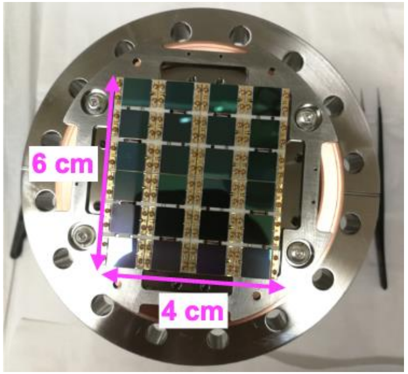
- **The uncertainty is dominated by quantum efficiency of the reference PMT.**
- **To achieve 1% energy resolution, the SiPM correlated avalanches (CA) need to be below 20%.**
- **VUV4 from Hamamatsu has low CA than FBK-VUV-LF, thus can be operated at a higher over-voltage.**
- **Dark noise rates for both type devices are comfortably below nEXO requirement of < 50Hz/mm^2.**

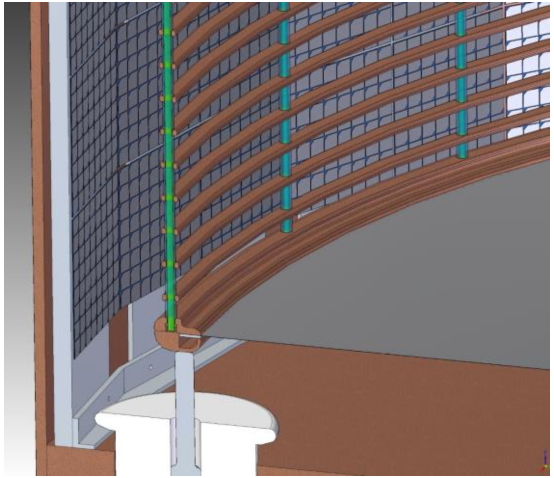
Analog SiPMs - baseline solution for nEXO

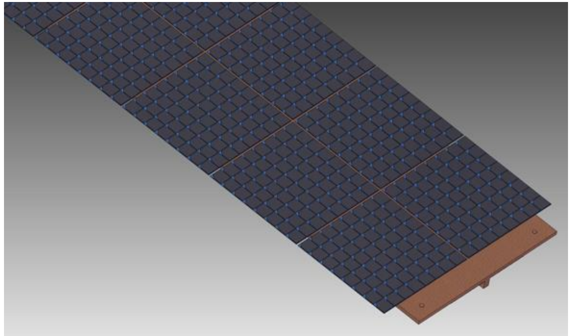
- Integrate SiPMs into ‘tiles’ (~10 x 10 cm^2).
- ASIC chip to read out tile.
- Tiles mounted on ‘stave’ (~20 x 120 cm^2).
- Staves mounted inside LXe behind field cage.

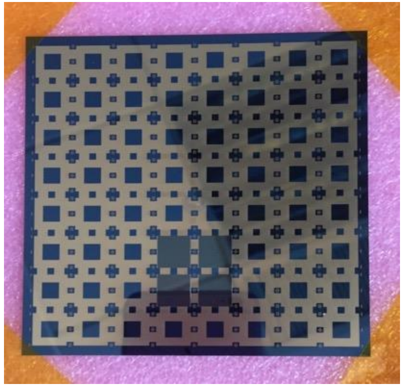
ASIC (ZENON) for SiPM readout under design (BNL)
- System on Chip
- 16 channel
- Peak detection
- Analog to digital conversion
- On-chip LDOs

Prototype SiPM Tile







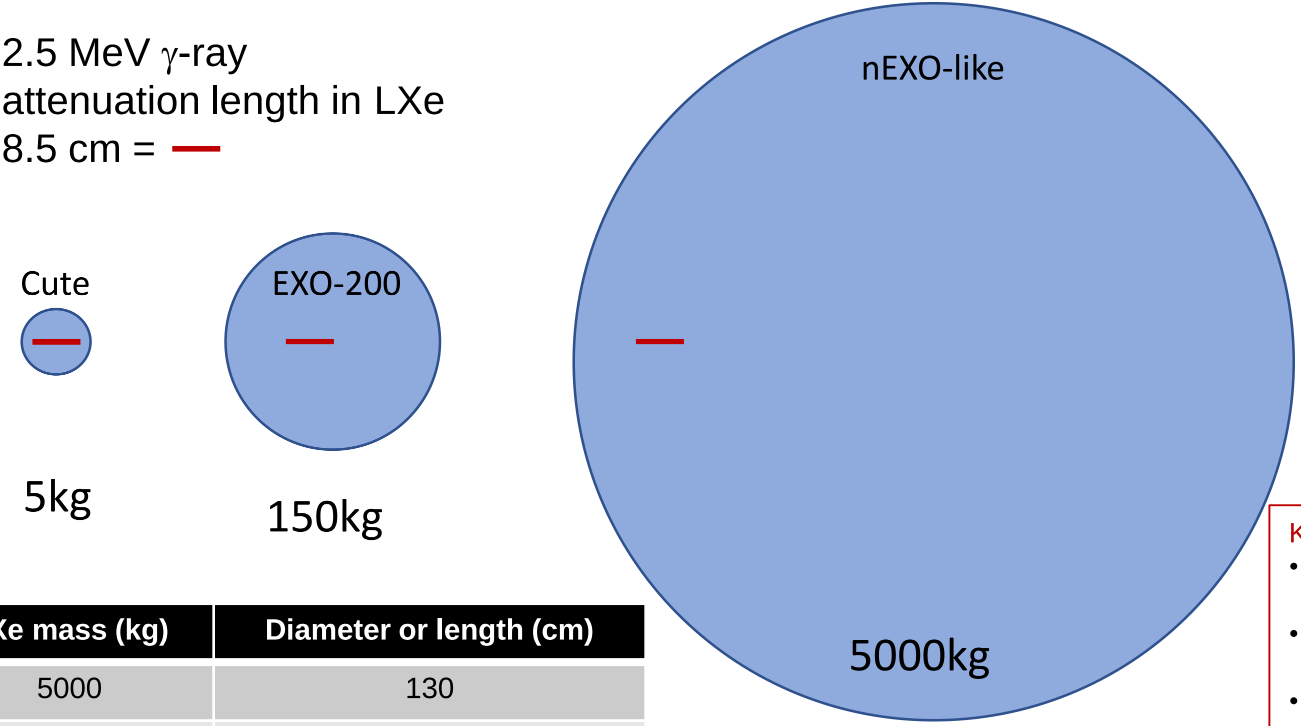


Prototype silicon interposer

Conceptual design of the photo detector system underway

Self-shielding in Monolithic Detectors

2.5 MeV γ-ray
attenuation length in LXe
8.5 cm = —

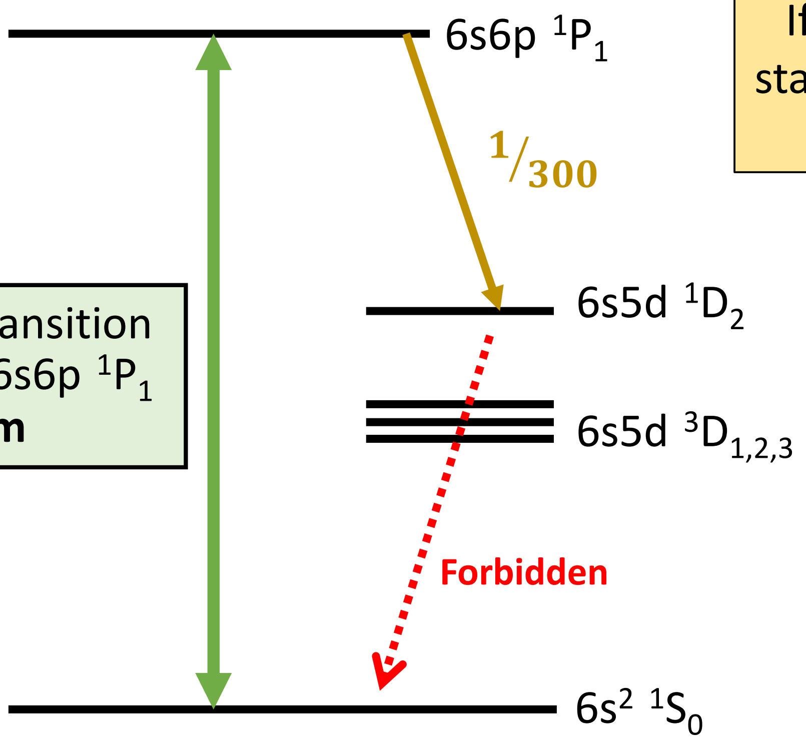


LXe mass (kg)	Diameter or length (cm)
5000	130
150	40
5	13

Key Advantages:

- The innermost LXe mostly measures **signal**
- The outermost LXe mostly measures **background**
- The overall fit knows all this (and more) very well and uses all the information available to obtain the best sensitivity

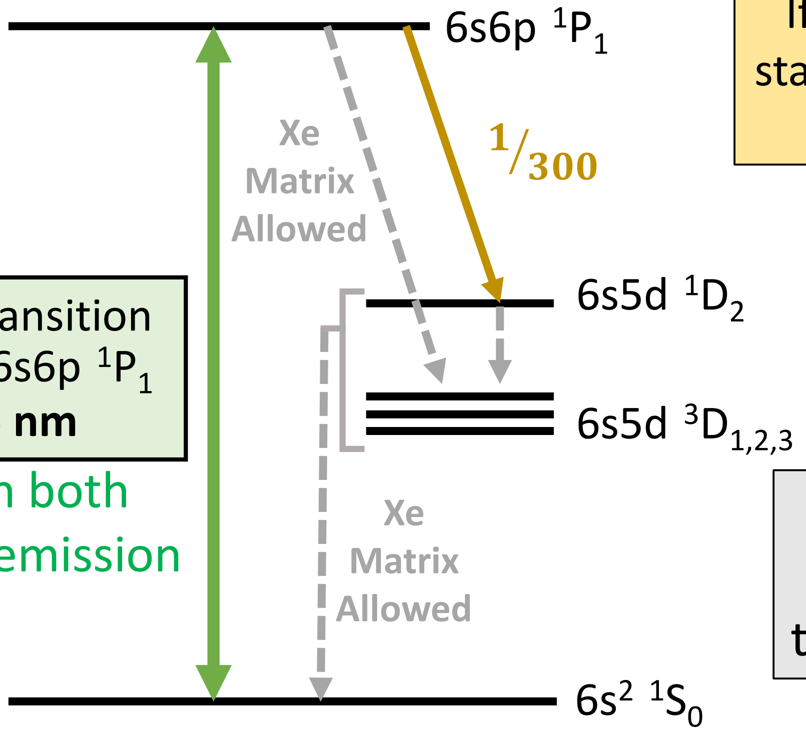
Energy Levels of Ba in Vacuum



If the electron decays to metastable state it is no longer excited by the laser
It "Turns off"

Fluorescence Transition
$6s^2\ ^1S_0 \longleftrightarrow 6s6p\ ^1P_1$
@ **553.5 nm**

Energy Levels of Ba in Solid Xe



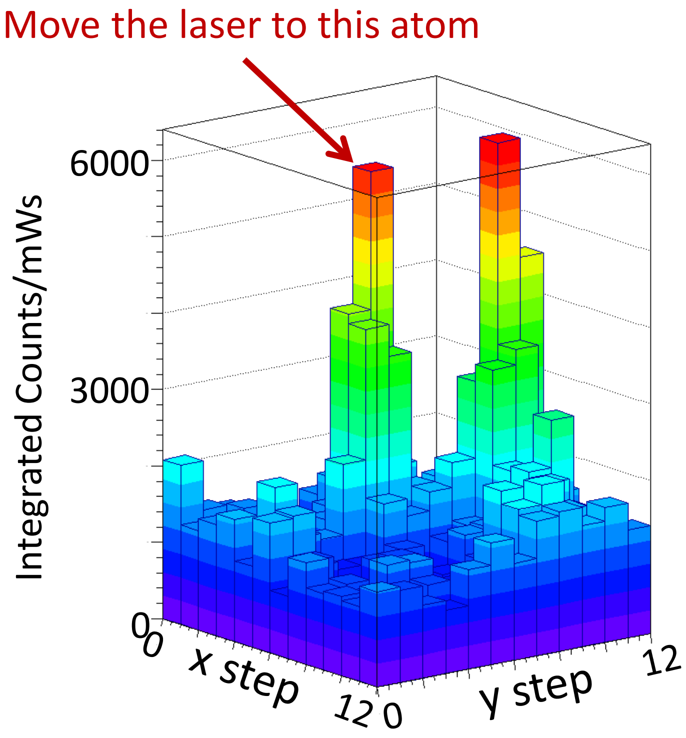
If the electron decays to metastable state it is no longer excited by the laser
It "Turns off"

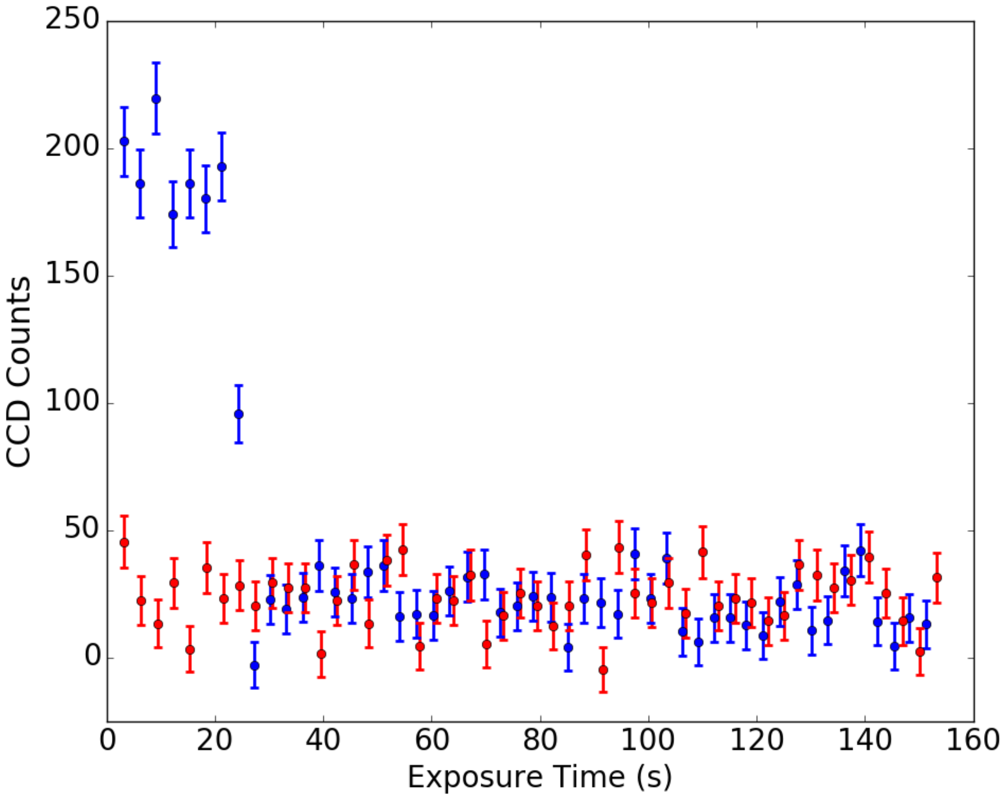
Fluorescence Transition
$6s^2\ ^1S_0 \longleftrightarrow 6s6p\ ^1P_1$
@ 545 – 585 nm

Broadened in both excitation and emission

In the solid Xe matrix, the modified potential **may allow** transitions forbidden in vacuum

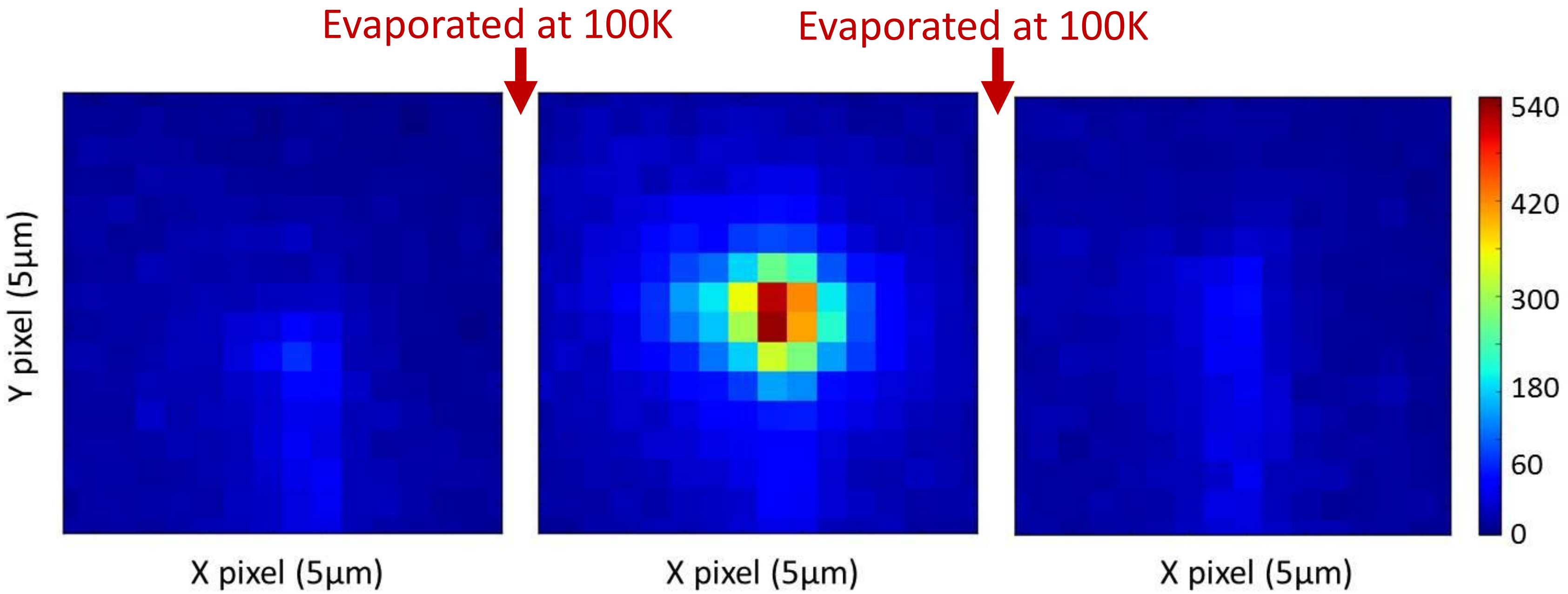
Looking at one Ba Atom





C. Chambers et al. *Nature* **569**, 203–207 (2019)

Erasing the Ba Deposit



Even after a large deposit (7000 ions) we remove detectable Ba atoms to a limit of **< 0.16%**
Thus no "history effect" interfering with subsequent deposits