Searching for neutrinoless double beta decay and nEXO

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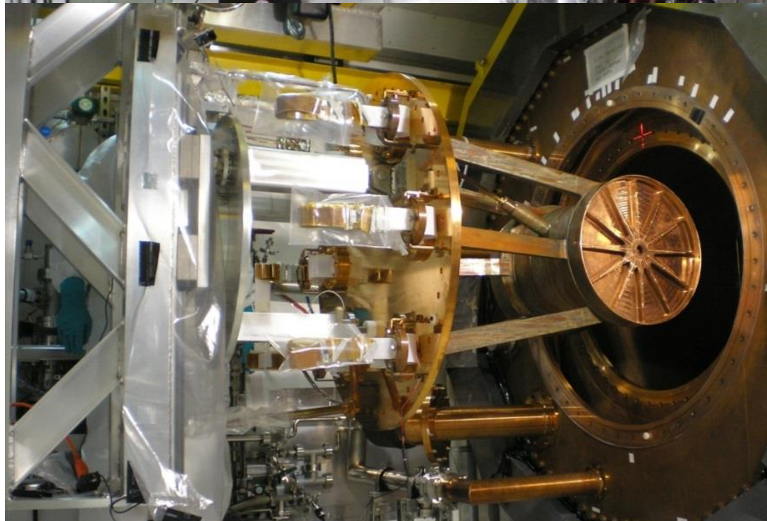
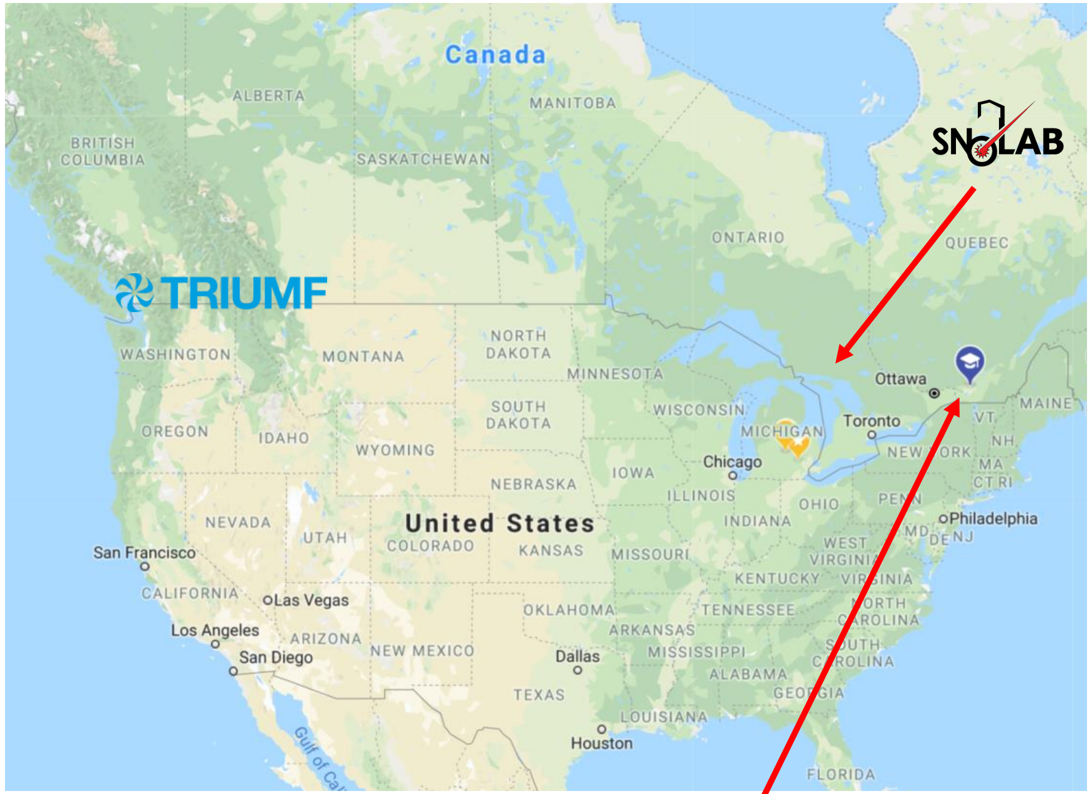


McGill University in Montreal



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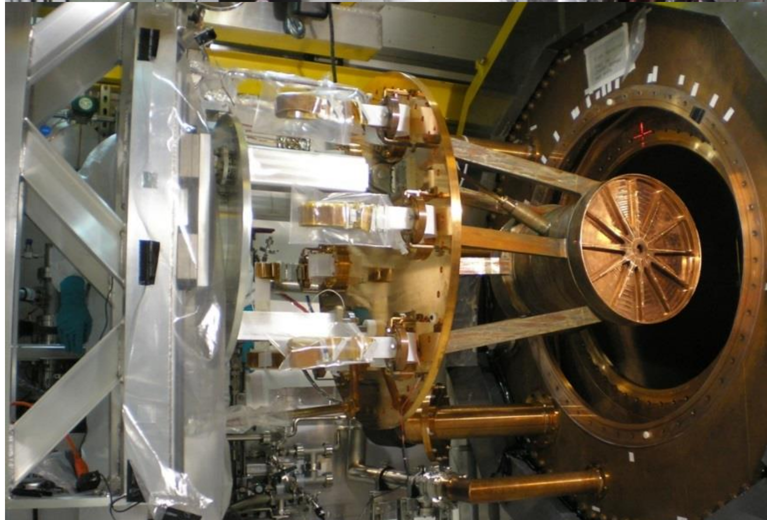
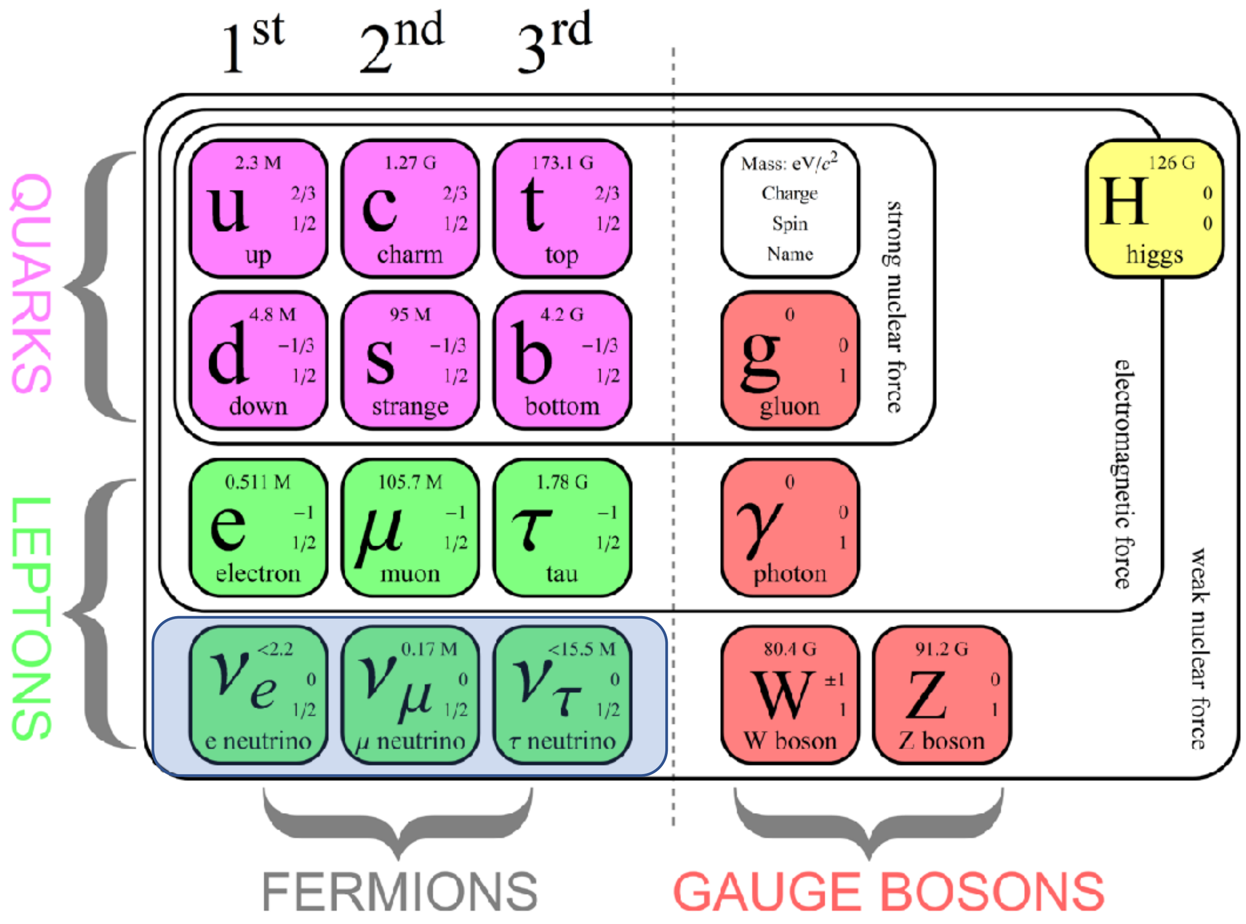
Outline

- Motivation: searching for Majorana neutrinos
- Searching for $0\nu\beta\beta$ in a liquid xenon TPC
    - The EXO-200 detector
    - The nEXO detector
    - Towards the construction of nEXO
- New technologies: beyond the nEXO baseline



Neutrinos in the Standard Model

- The Standard Model has been extremely successful in describing particle physics experiments and even predicting the existence of particles.
- Neutrinos in the SM:
  - Fundamental Spin ½ particle
  - Are Leptons
  - Only interact via the weak force
  - Electrically neutral
  - Most abundant particles with mass in the universe, yet we do not even know their mass
  - 60 billion solar neutrinos penetrate us per cm^2 every second



Some of the Big Questions in Cosmology and Particle Physics

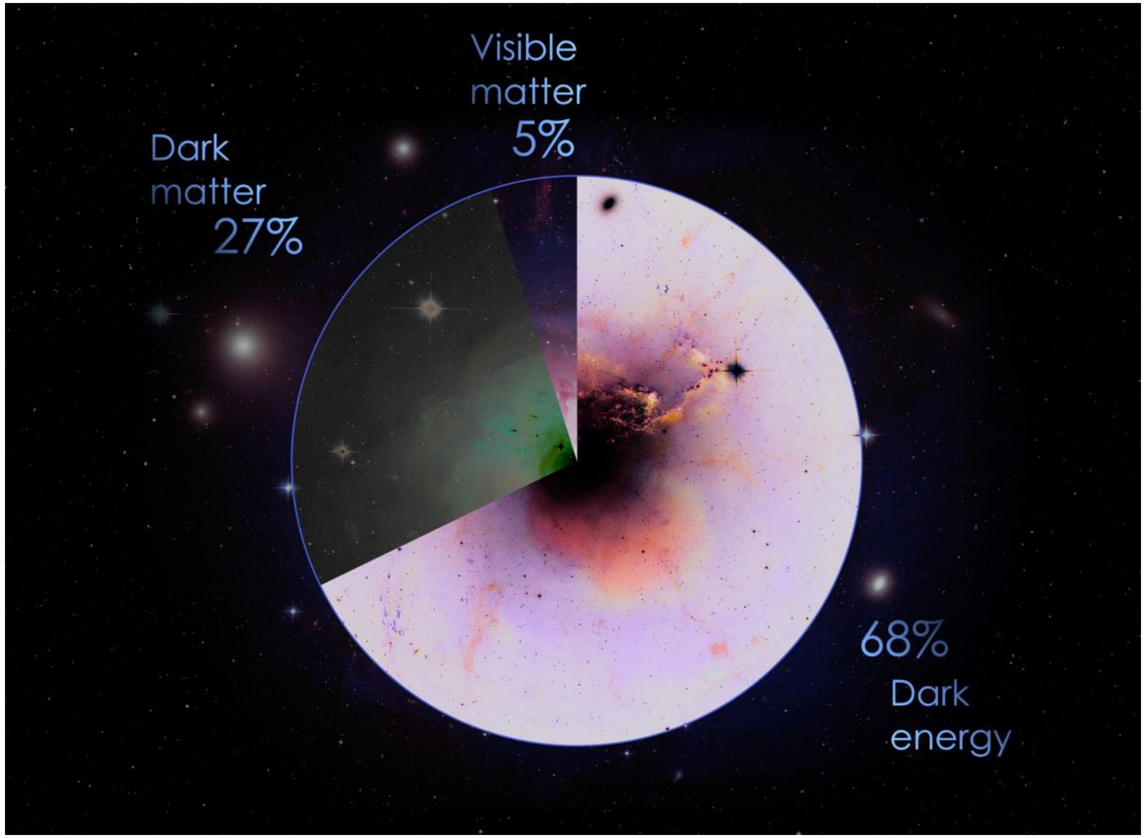


Figure: NASA

- 95% of the mass/energy density of the Universe is of as yet unknow composition
- What is Dark Energy?
- What is Dark Matter?
- Why is matter so abundant? (and dominant over anti-matter)?
- Why is gravity so weak?
- Why are neutrinos so light? (How light are neutrinos actually?)

Neutrinos may hold the key to answering some of these questions.

Neutrino mixing, mass, and 0νββ

In Quantum Mechanics there are 2 representations for our neutrinos if $m_\nu \neq 0$:

MNSP Matrix

(Maki, Nakagawa, Sakata, Pontecorvo)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_{m1} \\ \nu_{m2} \\ \nu_{m3} \end{pmatrix}$$

$$\nu_{m1}(t) = e^{-i(\boxed{E_1 t} - p_1 L)} \nu_{m1}$$
$$\nu_{m2}(t) = e^{-i(\boxed{E_2 t} - p_2 L)} \nu_{m2}$$
$$\nu_{m3}(t) = e^{-i(\boxed{E_3 t} - p_3 L)} \nu_{m3}$$

$E_i = m_i c^2$
Evolve in time with *m_i & E*

"Weak interaction eigenstate"

this is the state of definite flavor:

interactions couple to this state

"Mass eigenstate"

this is the state of definite energy:

propagation happens in this state

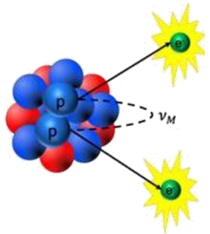
- The elements of the MNSP matrix are determined in oscillation experiments.
- Oscillation experiments can only determine Δm_{ij}^2, the squared mass difference between two eigenstates.

Measuring Neutrino Masses

Effective ββ mass

$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^{3} U_{ei}{}^2 m_i \right|$$

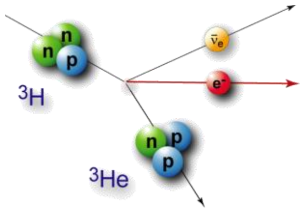
virtual ν exchange



- Majorana nature
- Upper limit: ~0.05 – 0.2 eV
- GERDA, KamLAND-ZEN, MAJORANA, LEGEND, nEXO, CUORE, CUPID, NEXT, …

m of ν_e from β endpoint

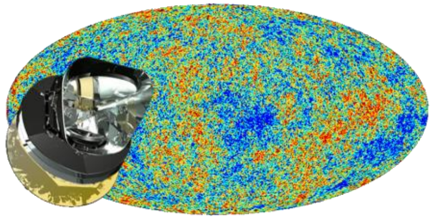
$$m_\beta = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i}$$



- Direct measurement
- Upper limit: 0.8 eV [Nature 2022]
- KATRIN, Project8, ECHo, HOLMES

Observational Cosmology

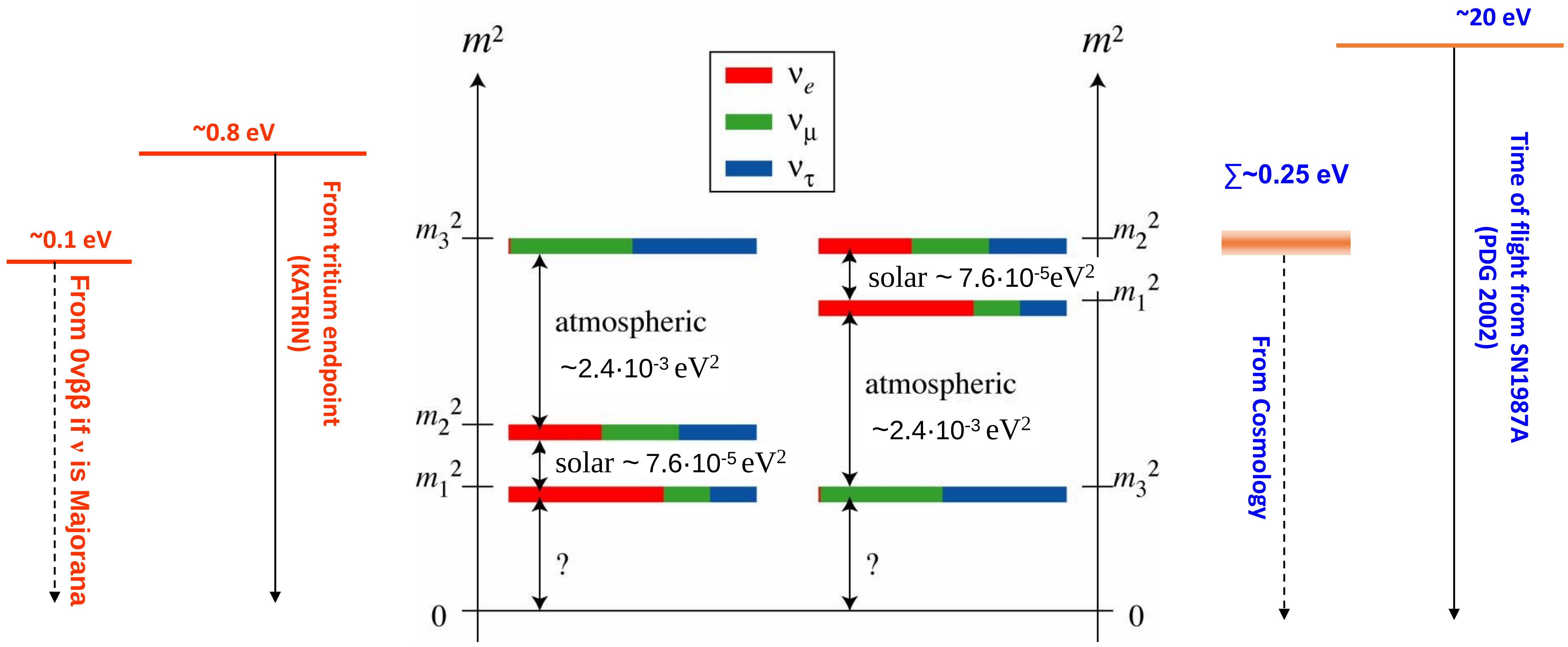
$$\sum = \sum m_i$$



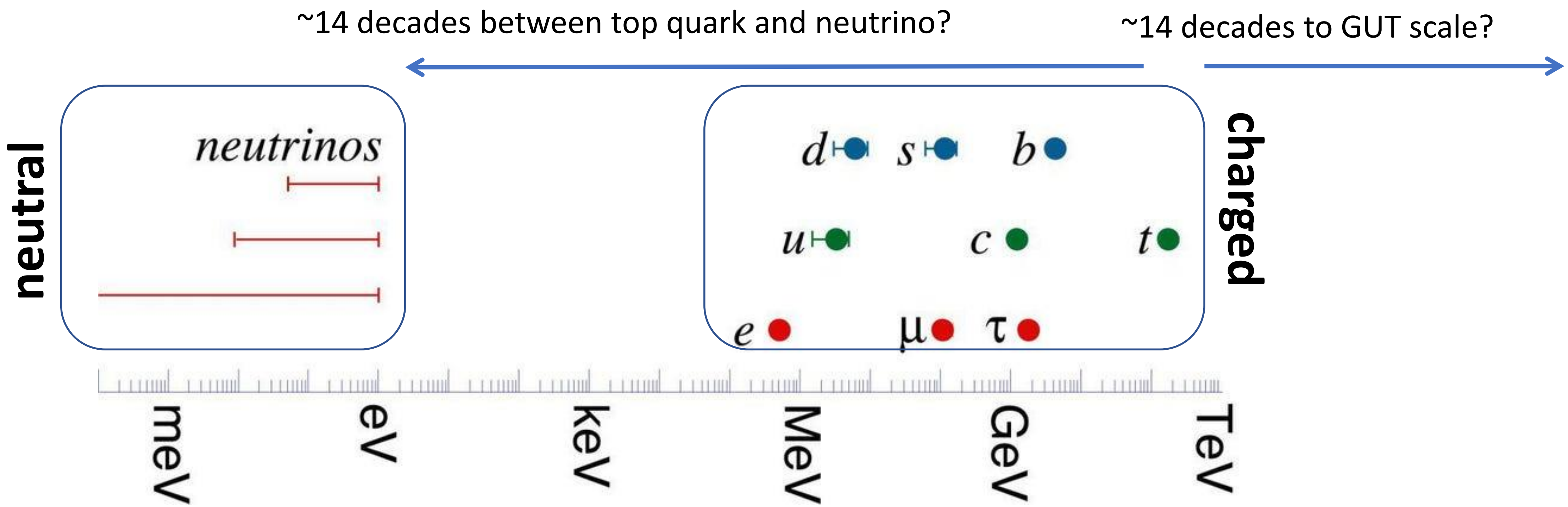
- Multi-parameter cosmological model
- Upper limit: ~0.11 – 0.54 eV*
- Planck satelite

*source: PDG 2020: Neutrinos in Cosmology

What we know about neutrinos



Spin ½ Fermion Mass spectrum

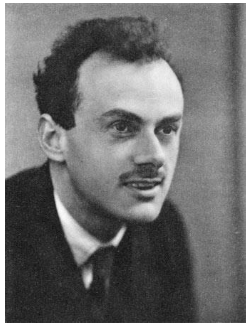


Adopted from: Hitoshi

- Neutrinos are 6 orders of magnitude lighter than the next heavy particle.
- What determines the mass scale hierarchy of elementary particles?
- Is the Higgs mechanism responsible for neutrino mass?
- Perhaps neutrinos are very different from other fermions and are Majorana particle?

Quantum Nature of the Neutrino

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



$$\nu^D = \begin{pmatrix} \nu_L \\ \bar{\nu}_L \\ \nu_R \\ \bar{\nu}_R \end{pmatrix}$$

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

$$\nu^M = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

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

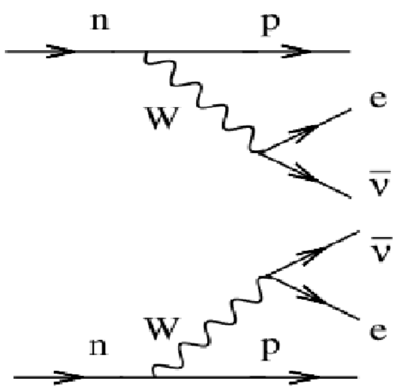
The two descriptions are distinct and distinguishable only if $m_\nu \neq 0$.

How can we determine if $\nu = \bar{\nu}$?

The answer may be neutrinoless $\beta\beta$ decay

Double Beta Decay


Maria Goeppert Mayer



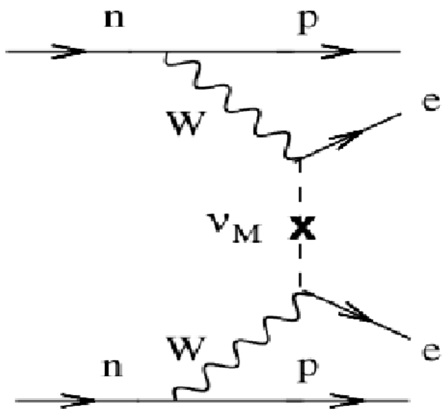
Two neutrino double beta decay

$$^{136}_{54}Xe \rightarrow ^{136}_{56}Ba^{++} + 2e^{-} + 2\bar{\nu}_e$$

1935 Maria Goeppert Mayer first proposed the idea of two neutrino double beta decay

1987 first direct observation in ^{82}Se by M. Moe


Ettore Majorana



Neutrinoless double beta decay

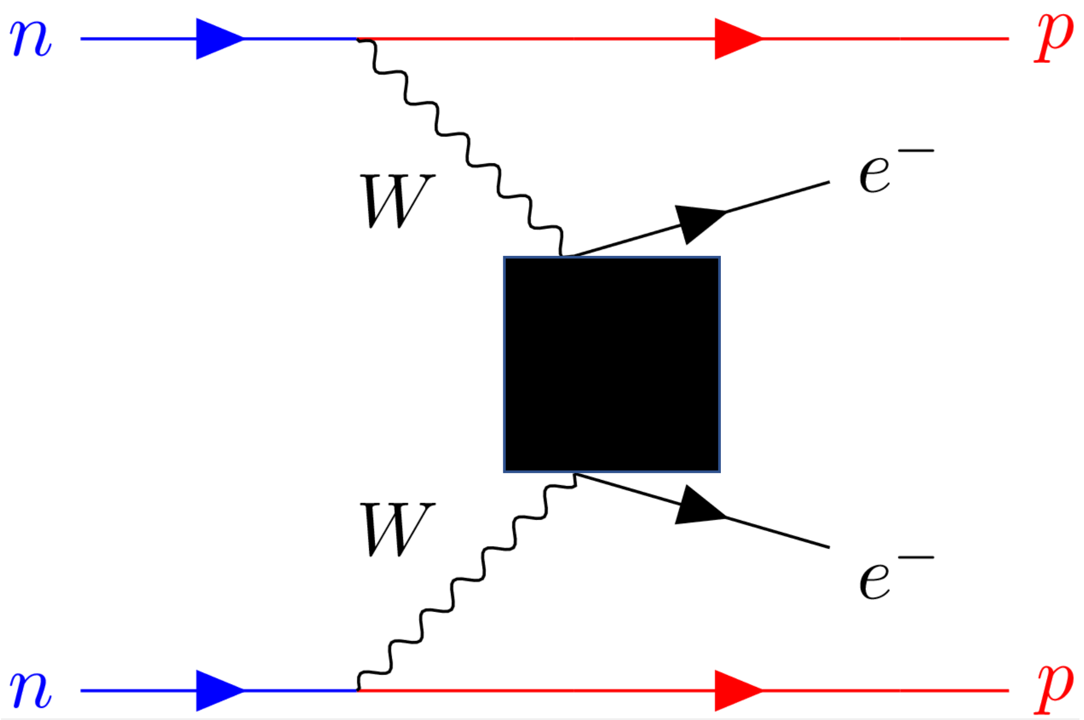
$$^{136}_{54}Xe \rightarrow ^{136}_{56}Ba^{++} + 2e^{-}$$

1937 Ettore Majorana proposed the theory of Majorana fermions

1939 Wendell Furry proposed neutrinoless double beta decay

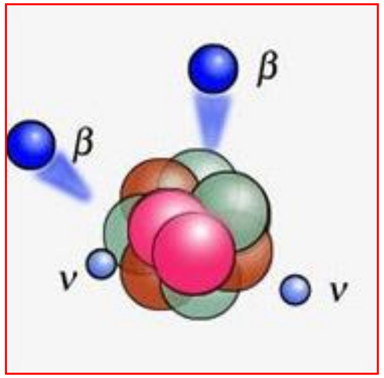
Black Box Theorem

- “Black box” theorem*: Observation of 0νββ always implies **new physics**:
  - Majorana neutrinos
  - Lepton number violation
  - Help explain observed cosmic baryon asymmetry → leptogenesis



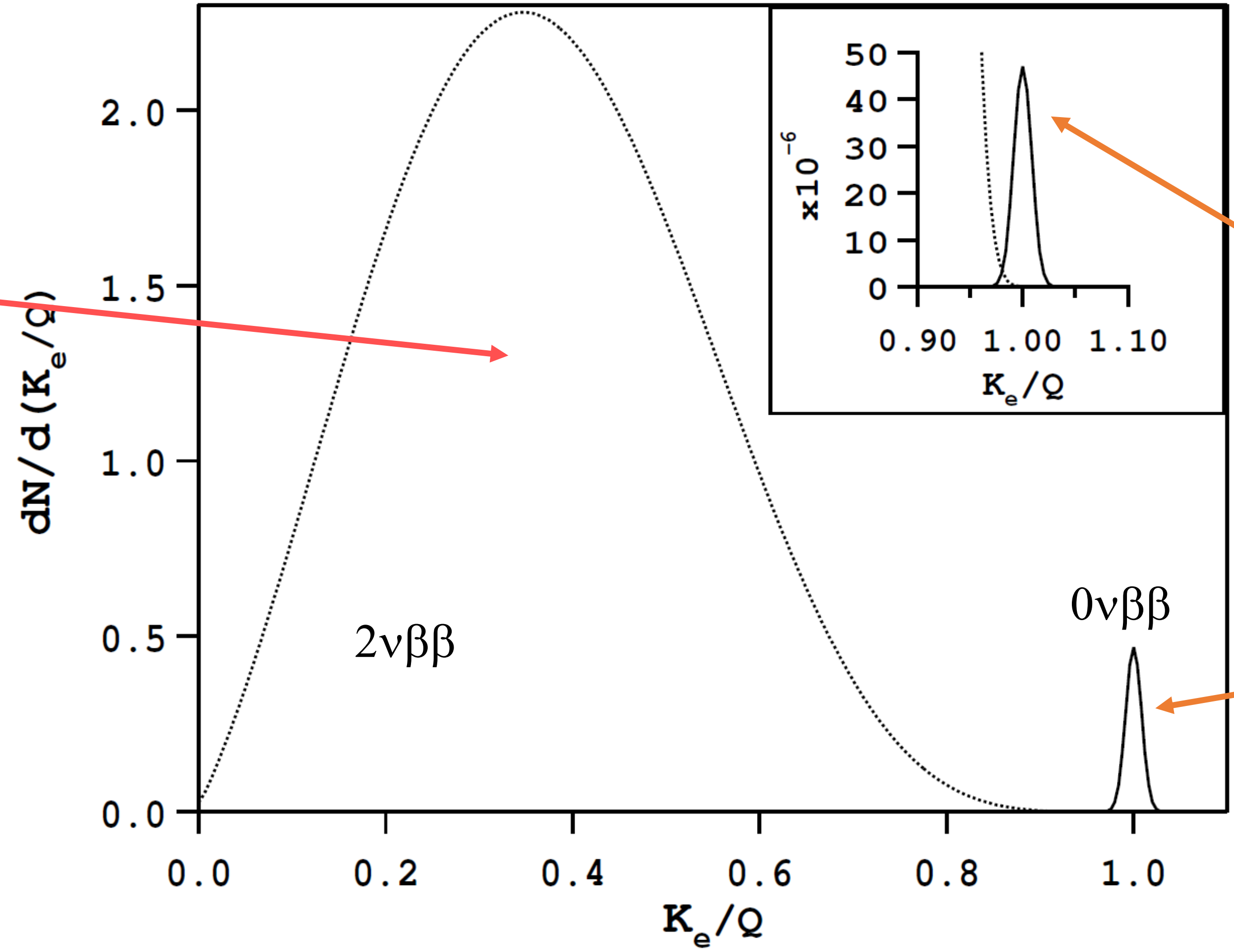
*J. Schechter, and J. W. F. Valle, Phys. Rev. D25, 2951 (1982)

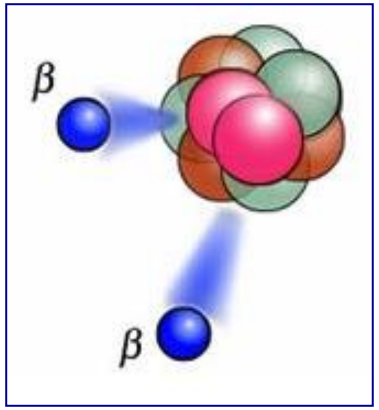
Double Beta Decay



2νββ spectrum
(normalized to 1)

[arXiv:hep-ph/0611243]



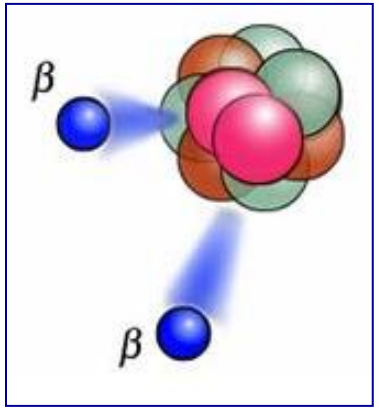


0νββ peak
(normalized to 10^{-6})

0νββ peak
(normalized to 10^{-2})

2νββ
$T_{1/2} \approx 10^{20}$ y

0νββ – Can only happen for Majorana neutrinos! $T_{1/2} > 10^{25\text{-}26}$ y!



0νββ and Neutrino Mass

Nuclear physics input

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

Phase space factor

Axial vector coupling, $g_A = 1.27$

Nuclear Matrix Element

$\langle m_{\beta\beta}\rangle$ = $\left| \sum_{i=1}^{3} U_{ei}^2 m_i e^{i\alpha_i} \right|$

Mixing matrix

mass eigenvalues

Majorana phase

Effective Majorana mass is a coherent sum of neutrino mass eigenvalues, therefore cancellations are possible…

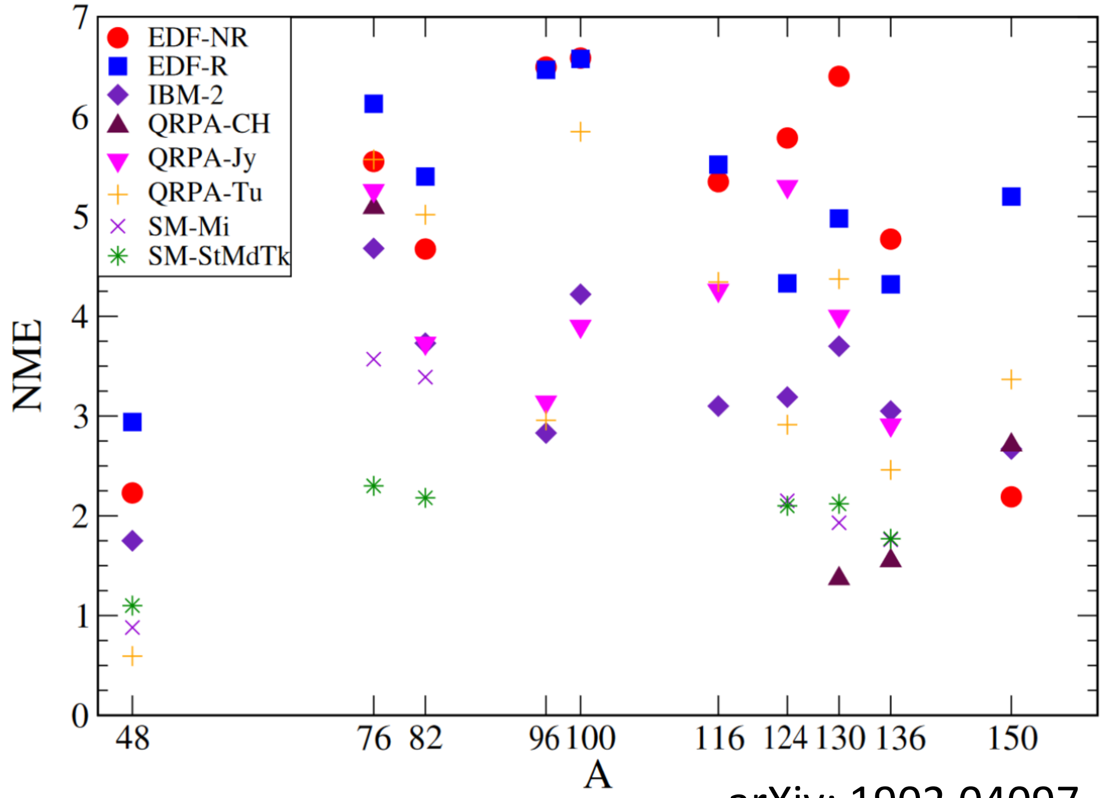
Three Caveats:

- Neutrino is a Majorana particle
- Light Majorana neutrino being the dominate decay mechanism
- Reliable calculation of matrix elements

Nuclear Matrix Element Situation

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

- Matrix element calculation is very difficult, in particular for big nuclei, which most of the $0\nu\beta\beta$ candidates are.
- Recent theoretical progress has narrowed the difference between models, but significant spread remains, difficult to estimate uncertainty.
- As a result, a particular half life results in a spread of calculated $\langle m_{\beta\beta}\rangle$.

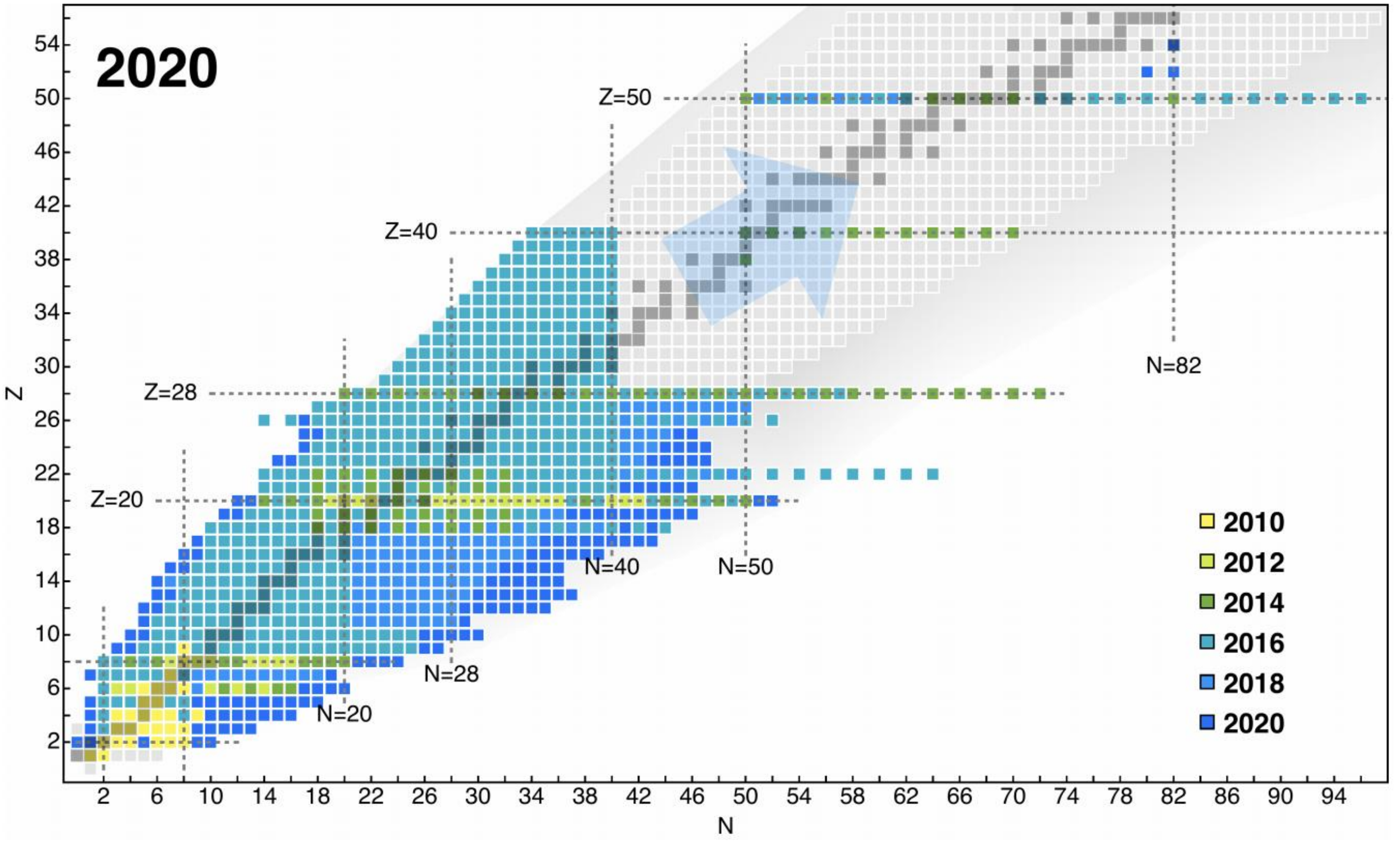


arXiv: 1902.04097

Progress in Nuclear Structure Theory

- Huge advances in nuclear theory
  - Quality and reach of *Ab initio* calculations
  - Refined chiral effective field theories and phenomenological calculations
- Hugh predictive power
  - Need to validate under extreme conditions
    (outskirts of the nuclear chart)

  →**Need of high-quality nuclear data**
  (decay properties, masses, etc.)



H. Hergert, Frontiers in Physics 8 (2020) 379

Challenges of double-β decay experiments

Sensitivity on $T_{1/2} \propto \varepsilon \cdot A \cdot \sqrt{\frac{M \cdot T}{b \cdot \Delta E}}$

ε	detection efficiency
A	isotopic abundance
M	active mass
T	exposure
b	background rate
ΔE	energy resolution

Strength of liquid-Xe ββ detectors

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

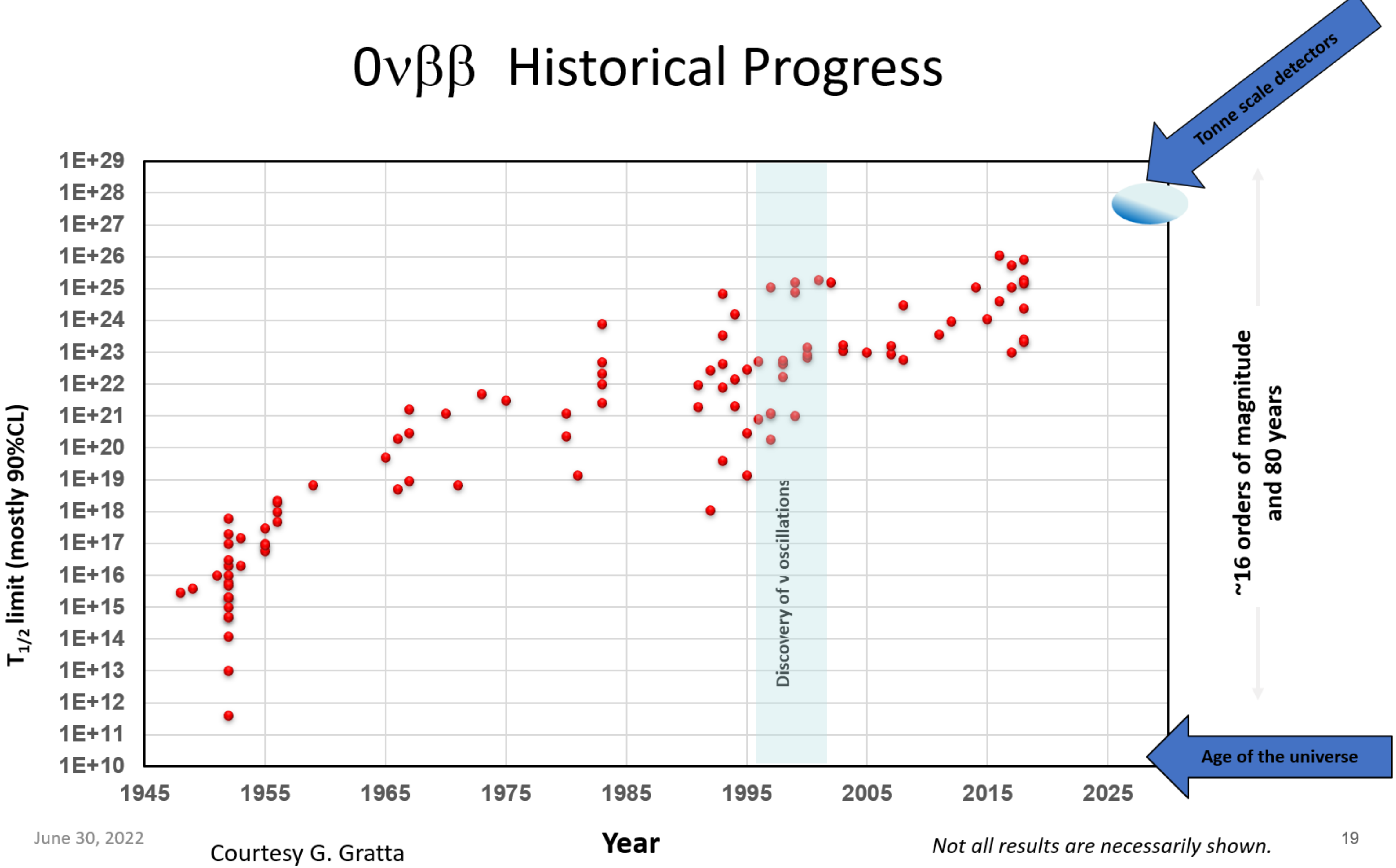
→Need:

- 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
0νββ decay	>10,000 x rarer than 2νββ
Age of universe	1.4 x 10^{10} years

$0\nu\beta\beta$ Historical Progress



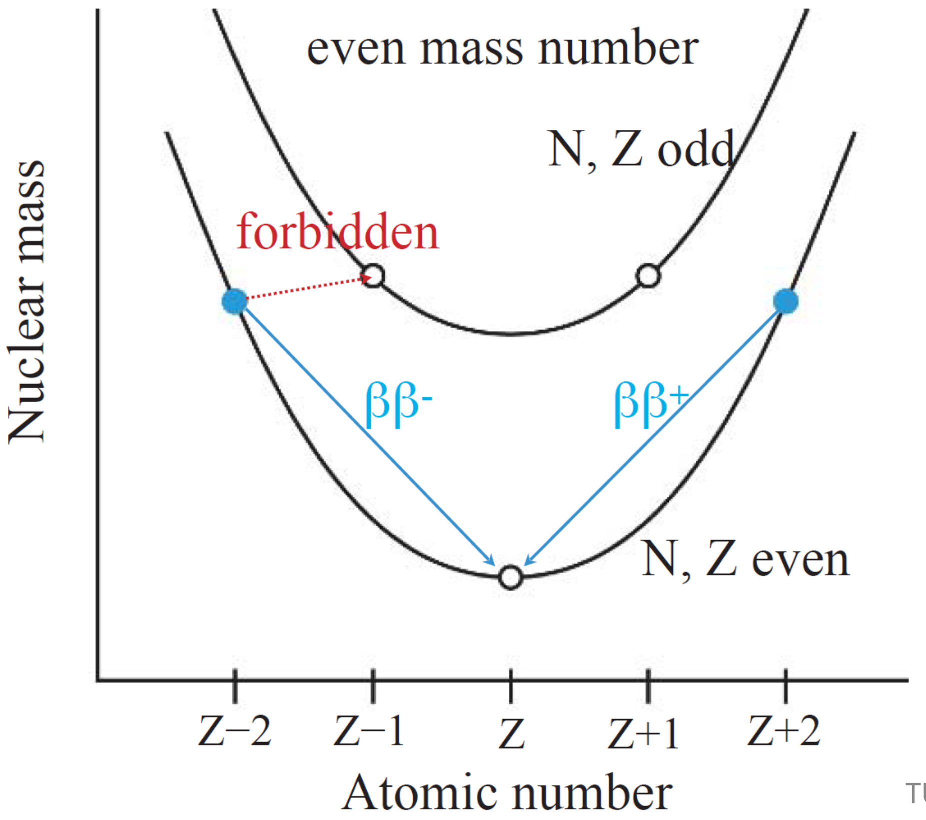
Courtesy G. Gratta

Not all results are necessarily shown.

Double Beta Decay

- Second-order weak nuclear process
- First-order beta decay is forbidden energetically or by spin
  → ββ is detectable

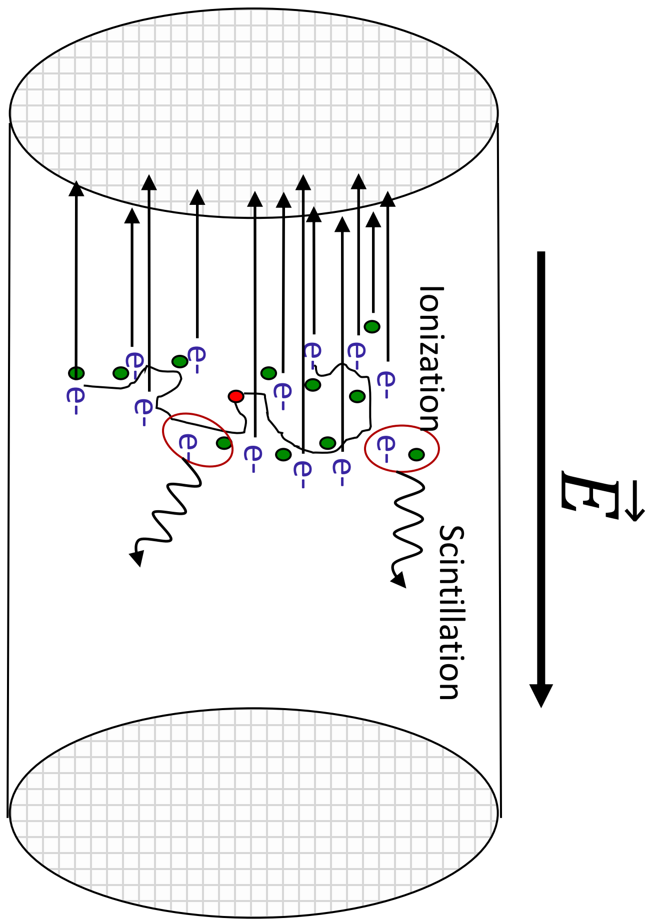
$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$$



35 2νββ nuclei found

	ββ-decay nuclei with Q > 2 MeV	Q (MeV)	Abund. (%)
	$^{48}Ca \rightarrow {}^{48}Ti$	4.271	0.187
GERDA, MJD, LEGEND	$^{76}Ge \rightarrow {}^{76}Se$	2.040	7.8
	$^{82}Se \rightarrow {}^{82}Kr$	2.995	9.2
	$^{96}Zr \rightarrow {}^{96}Ru$	3.350	2.8
CUPID	$^{100}Mo \rightarrow {}^{100}Ru$	3.034	9.7
	$^{110}Pd \rightarrow {}^{110}Cd$	2.013	11.8
	$^{116}Cd \rightarrow {}^{116}Sn$	2.802	7.5
	$^{124}Sn \rightarrow {}^{124}Te$	2.228	5.8
CUORE, SNO+	$^{130}Te \rightarrow {}^{130}Xe$	2.528	34.2
EXO-200, nEXO, KamLAND ZEN, NEXT	$^{136}Xe \rightarrow {}^{136}Ba$	2.479	8.9
	$^{150}Nd \rightarrow {}^{150}Sm$	3.367	5.6

EXO's search for $0\nu\beta\beta$ in ^{136}Xe with liquid Xe TPC

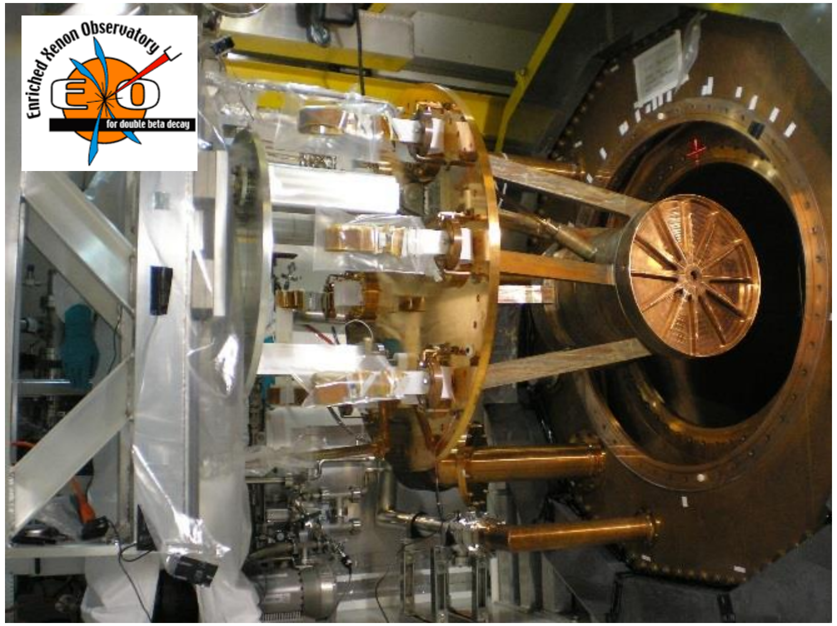


Liquid-Xe Time Projection Chamber (TPC)

- Xe is used both as the source and detection medium.
- LXe is continuously recirculated and purified.
- No long-lived cosmogenically activated Xe isotopes
- LXe TPC are well understood.
- Monolithic detector structure enables excellent background rejection capabilities.
- Multiparameter measurement from detection of scintillation light and ionization signal:
    1. Energy from combined scintillation/ionization
    2. Topology, e.g., single-site or multi-site
    3. Position distribution from 3D event reconstruction
    4. Particle identification from scintillation/ionization ratio

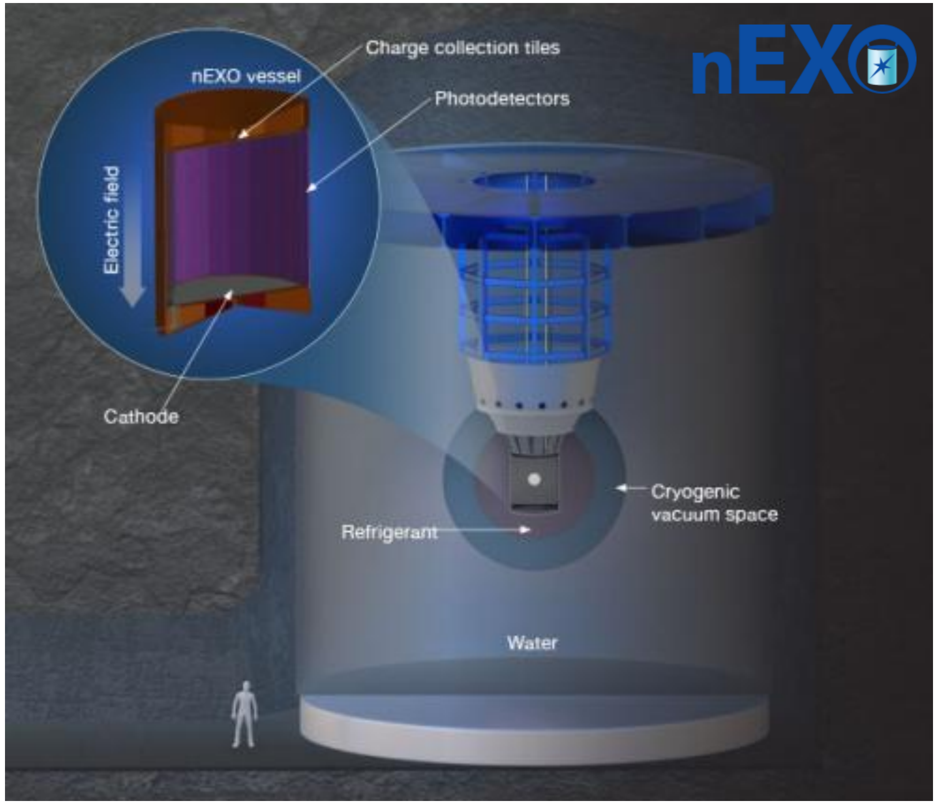
Searching for $0\nu\beta\beta$ in ^{136}Xe – a phased approach

EXO-200:
- EXO-200 first 100-kg class ββ experiment
- 175kg 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/

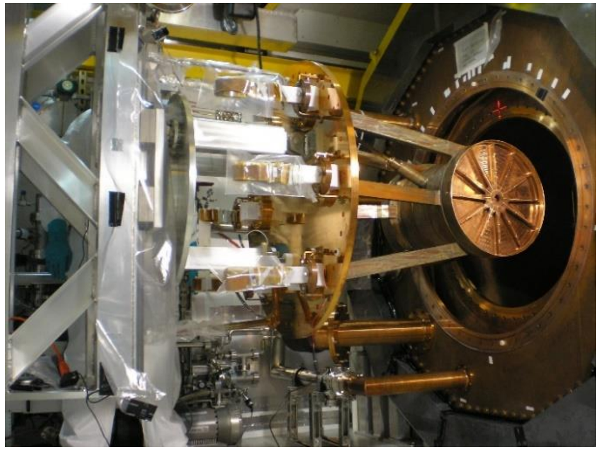
nEXO:
- 5-ton liquid Xe TPC
- Enriched in Xe-136 at ~90%
- SNOLAB cryopit preferred location by collaboration

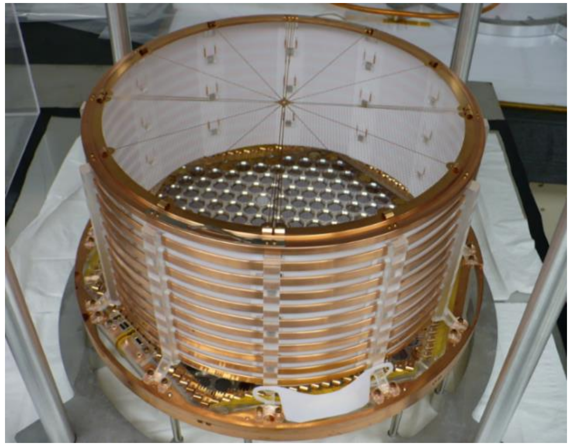


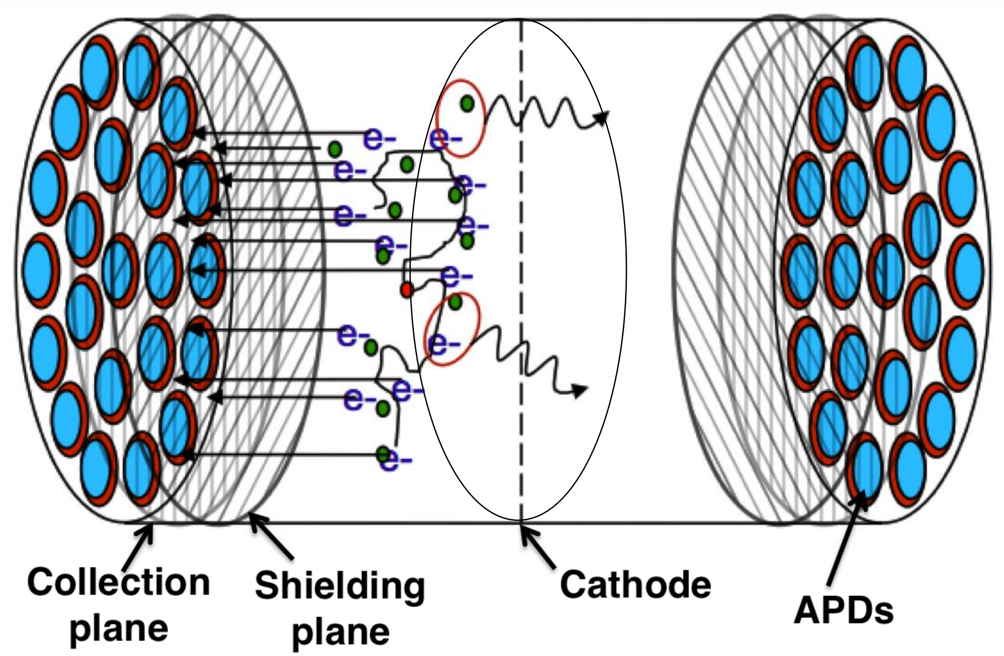
https://nexo.llnl.gov/

EXO-200 search for 0νββ - Detector

- EXO-200 was first 100-kg class ββ experiment
- Discovery of 2νββ in Xe-136 [PRL 107, 212501 (2011)]
- ~175kg Liquid Xenon (LXe) enriched at ~80% in ^{136}Xe
- Located at Waste Isolation Pilot Plant (WIPP) in Carlsbad, NM, USA until decommissioning Dec. 2018
- 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

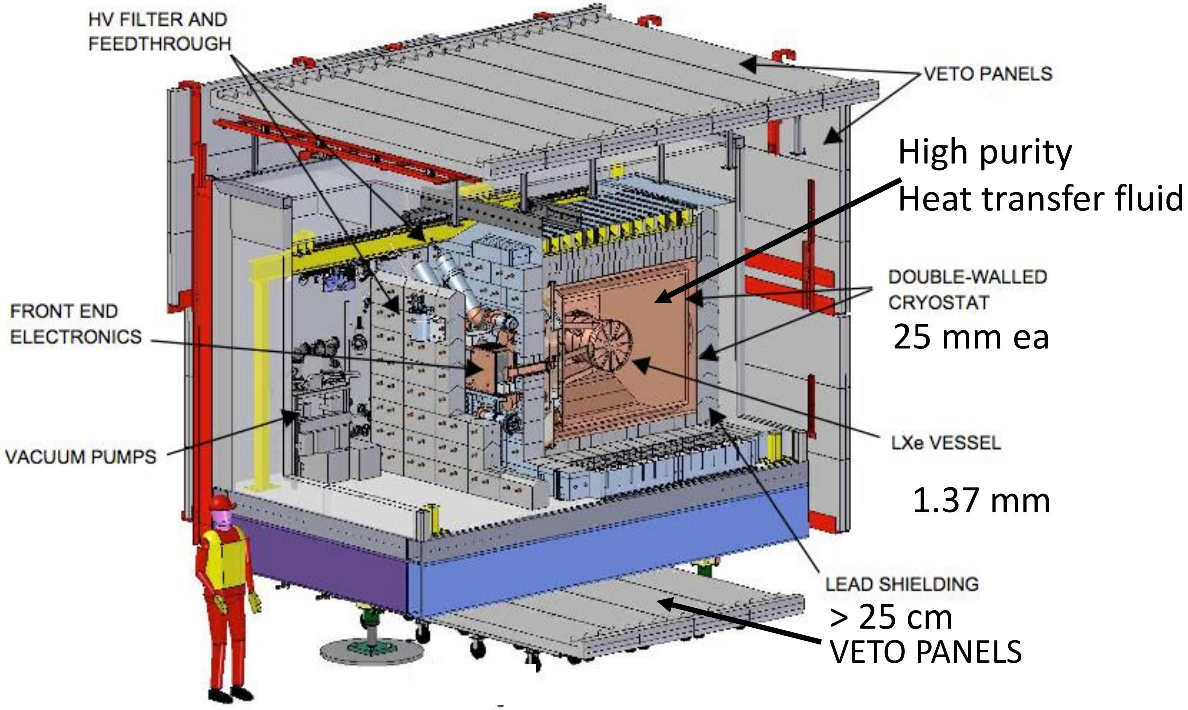


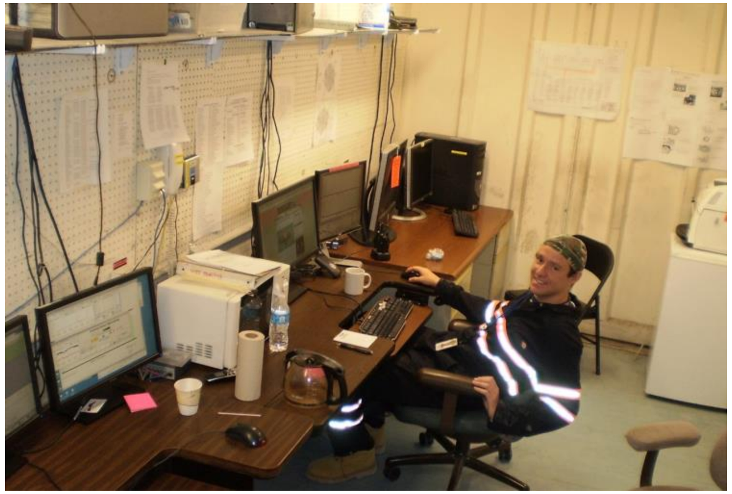




https://www-project.slac.stanford.edu/exo/

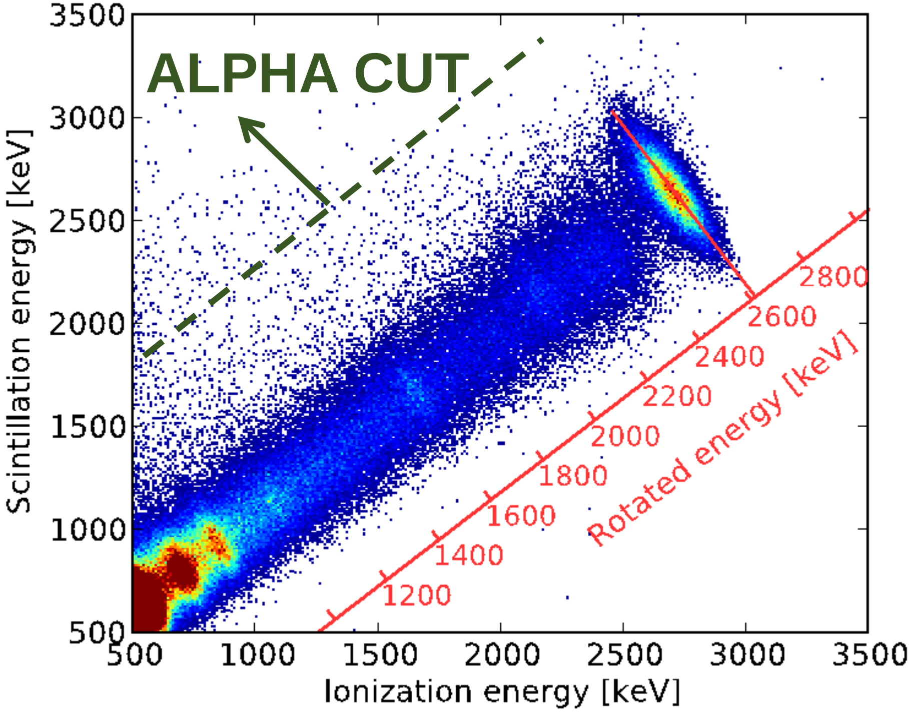
EXO-200


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



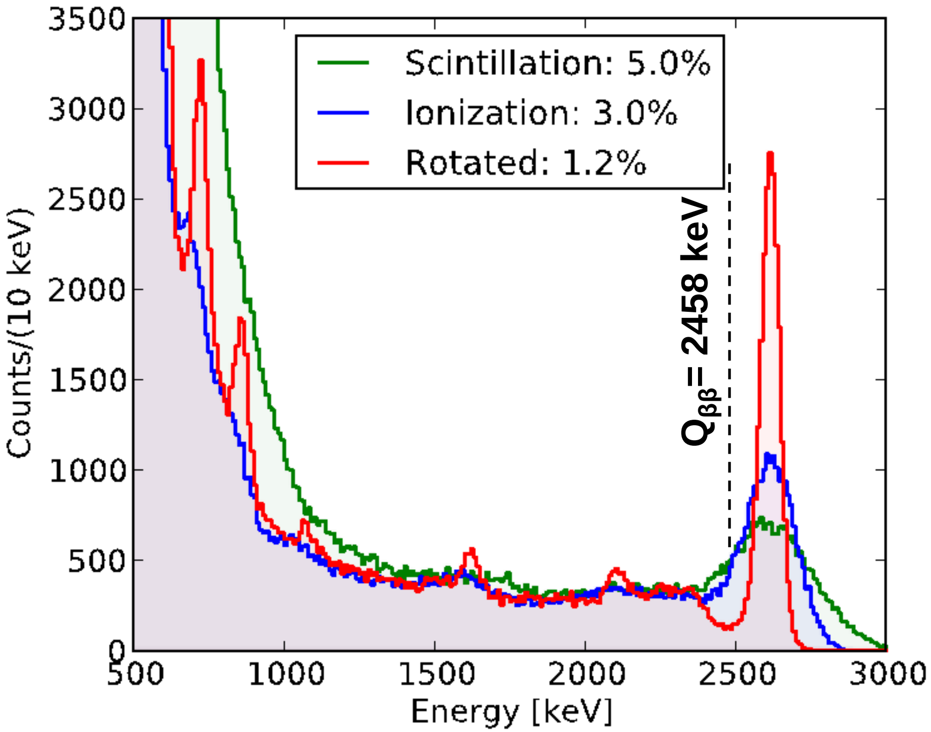
Energy measurement (EXO-200 data)

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



Rotation angle chosen to optimize energy resolution at 2615 keV

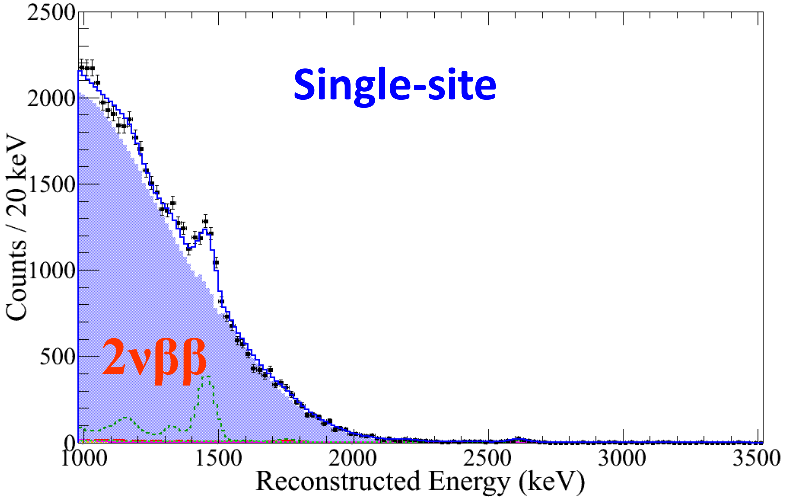
Reconstructed energy, ^{228}Th calibration:

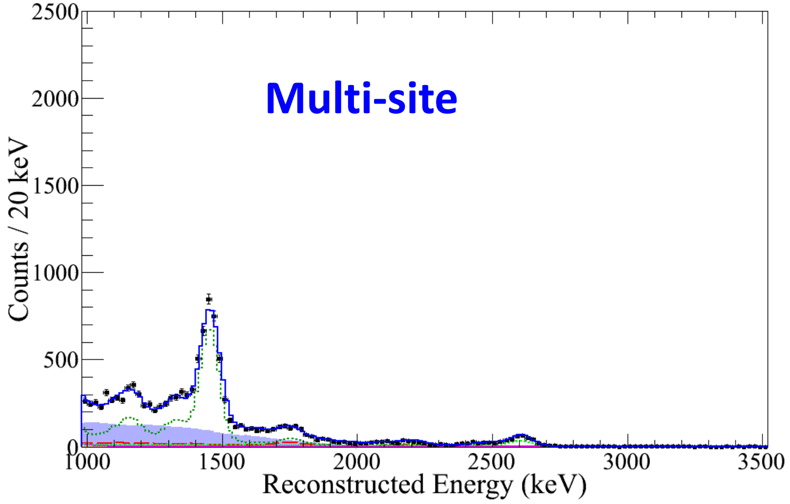


- Anticorrelation between scintillation and ionization in LXe known since early EXO R&D and now standard in LXe detectors [E.Conti et al. Phys Rev B 68 (2003) 054201]
- Rotation angle determined weekly using ^{228}Th source data, defined as angle which gives best rotated resolution
- EXO-200 has achieved ~ 1.15% (arxiv:1906.02723) energy resolution at the double-beta decay Q value in Phase II

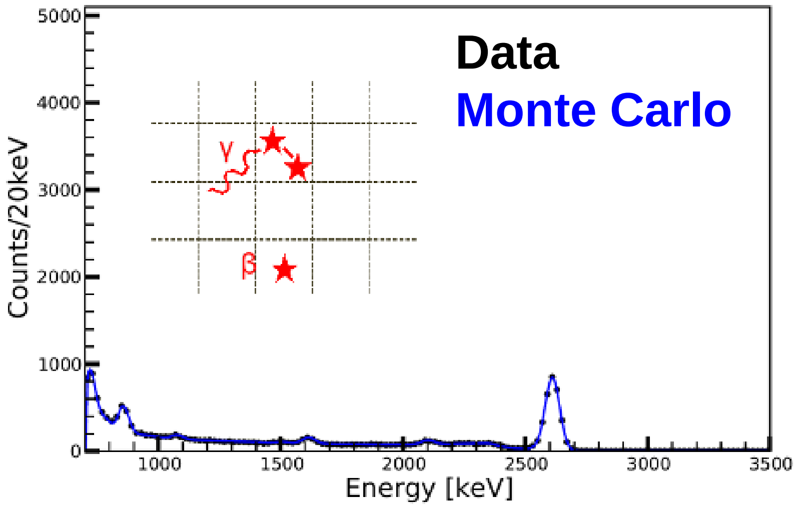
Event Position and Multiplicity (EXO-200 data)

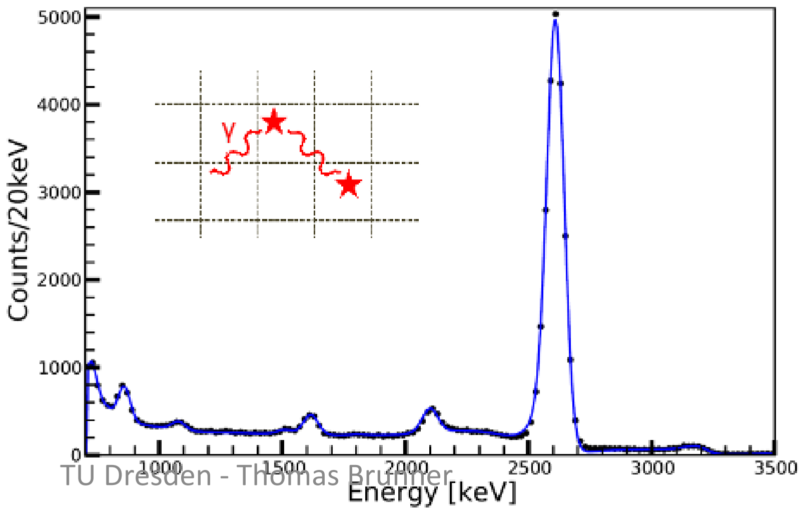
Low background data





^{228}Th calibration source





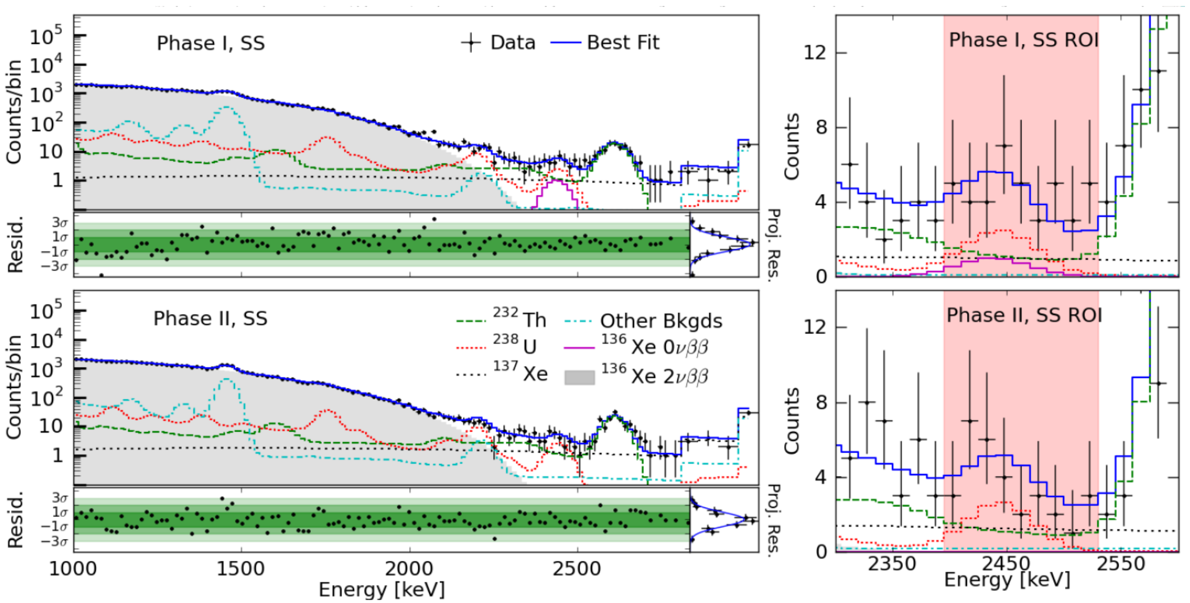
Allows for background measurement and reduction

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

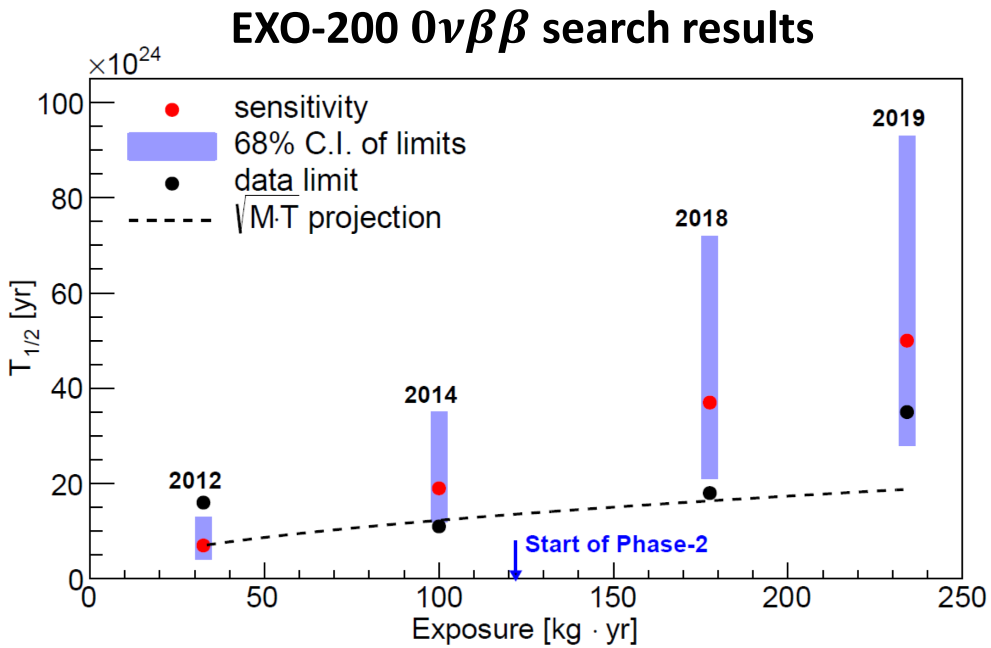
EXO-200 simulations:
$0\nu\beta\beta$: ~90% SS
γ-rays: ~15% SS at $0\nu\beta\beta$ Q-value

Final EXO-200 Result

- 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.



EXO-200 has achieved 1.15 ± 0.02% energy resolution at the Q-value.



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

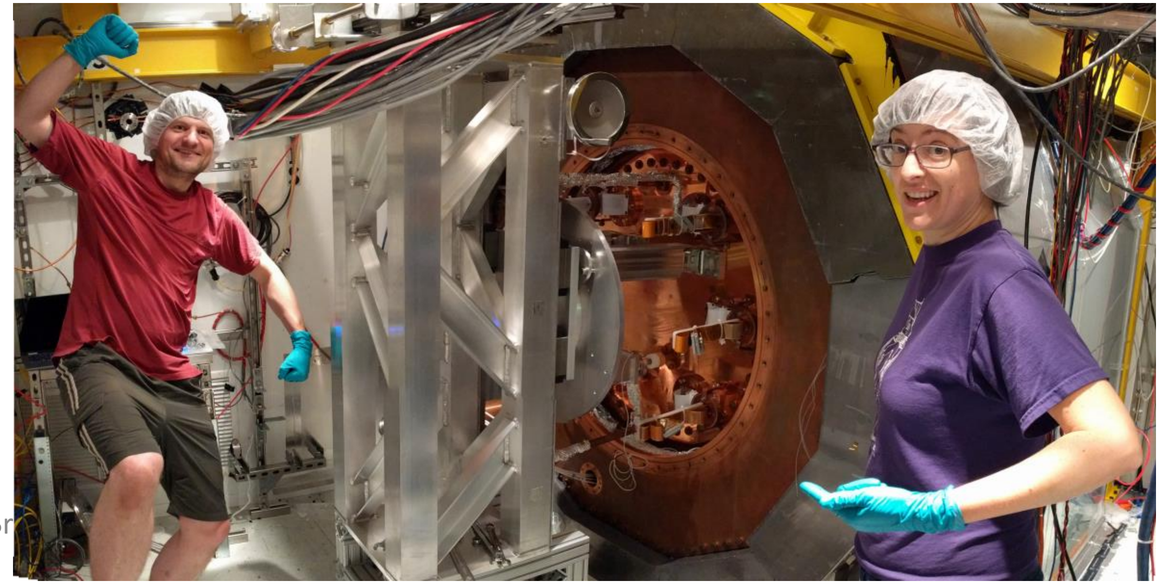
Limit $T_{1/2}^{0\nu\beta\beta}$ > 3.5 x 10^{25} yr (90% C.L.)

⟨$m_{\beta\beta}$⟩ < (93 – 286) meV

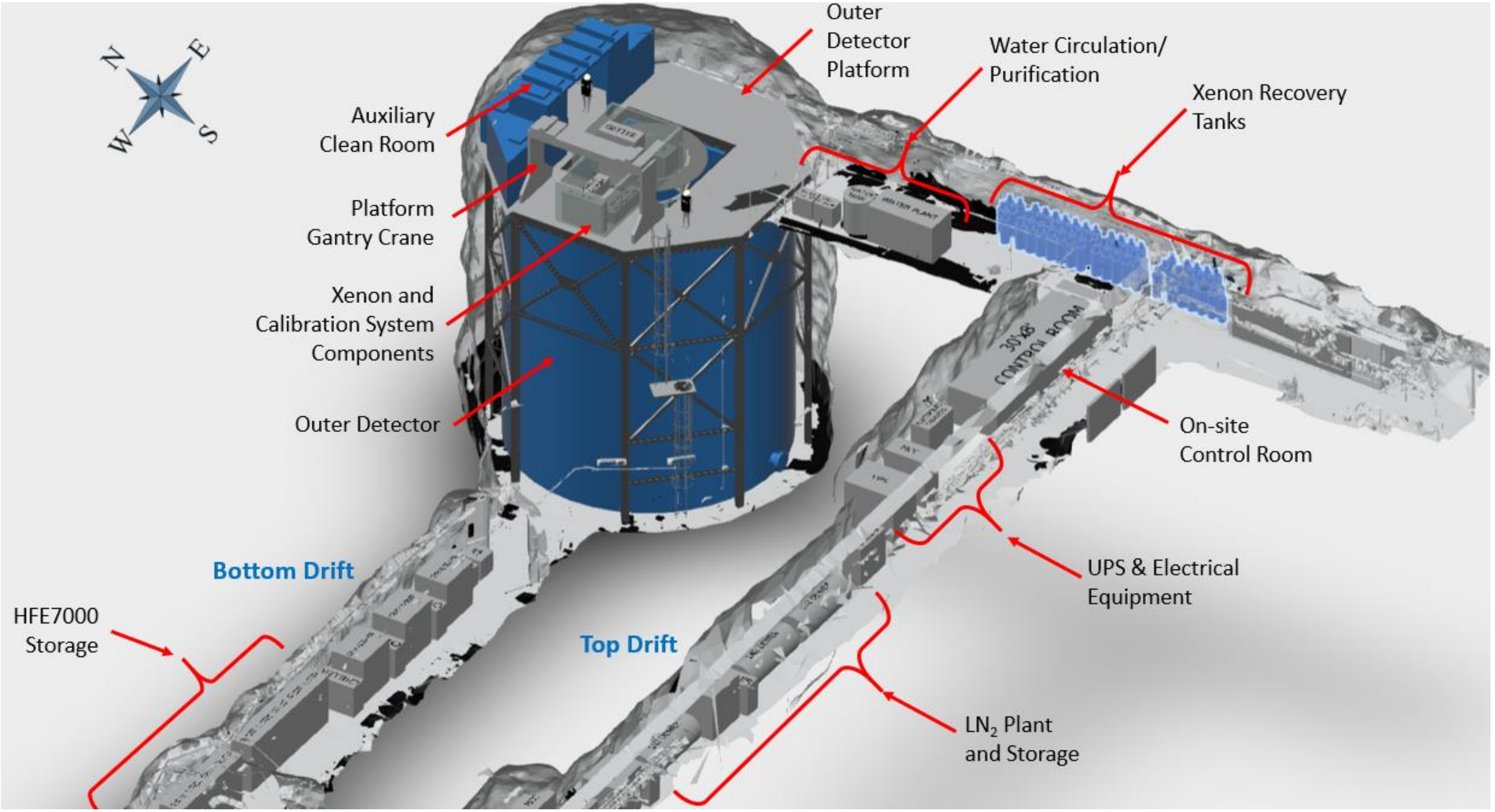
Sensitivity 5.0x10^{25} yr

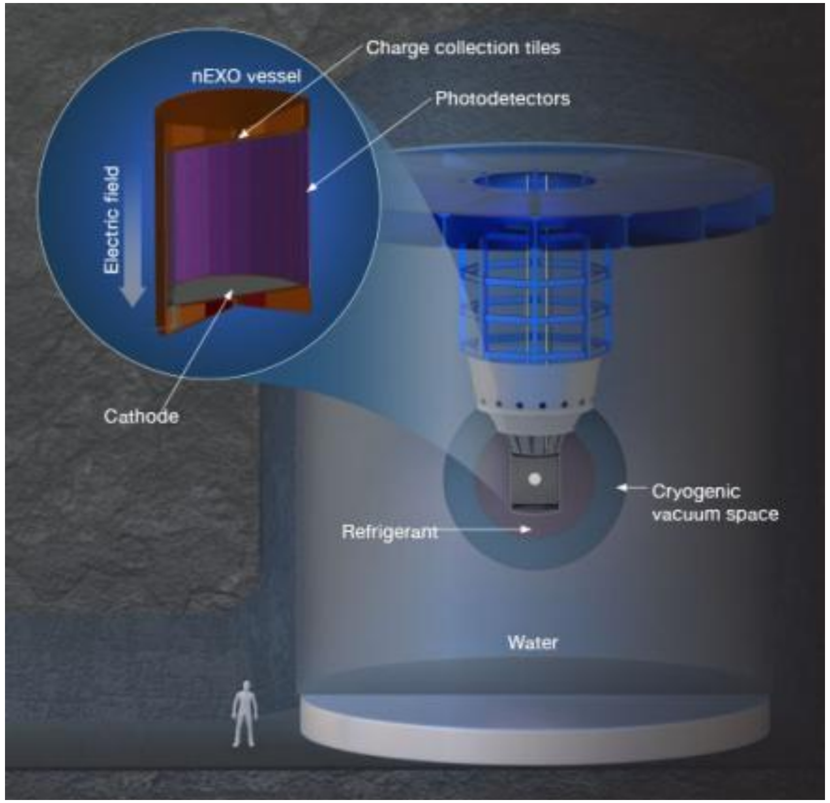
2012: Phys. Rev. Lett. 109 (2012) 032505
2014: Nature 510 (2014) 229-234
2018: Phys. Rev. Lett. 120, 072701 (2018)
2019: Phys. Rev. Lett. 123, 161802 (2019)

EXO-200 decommissioning

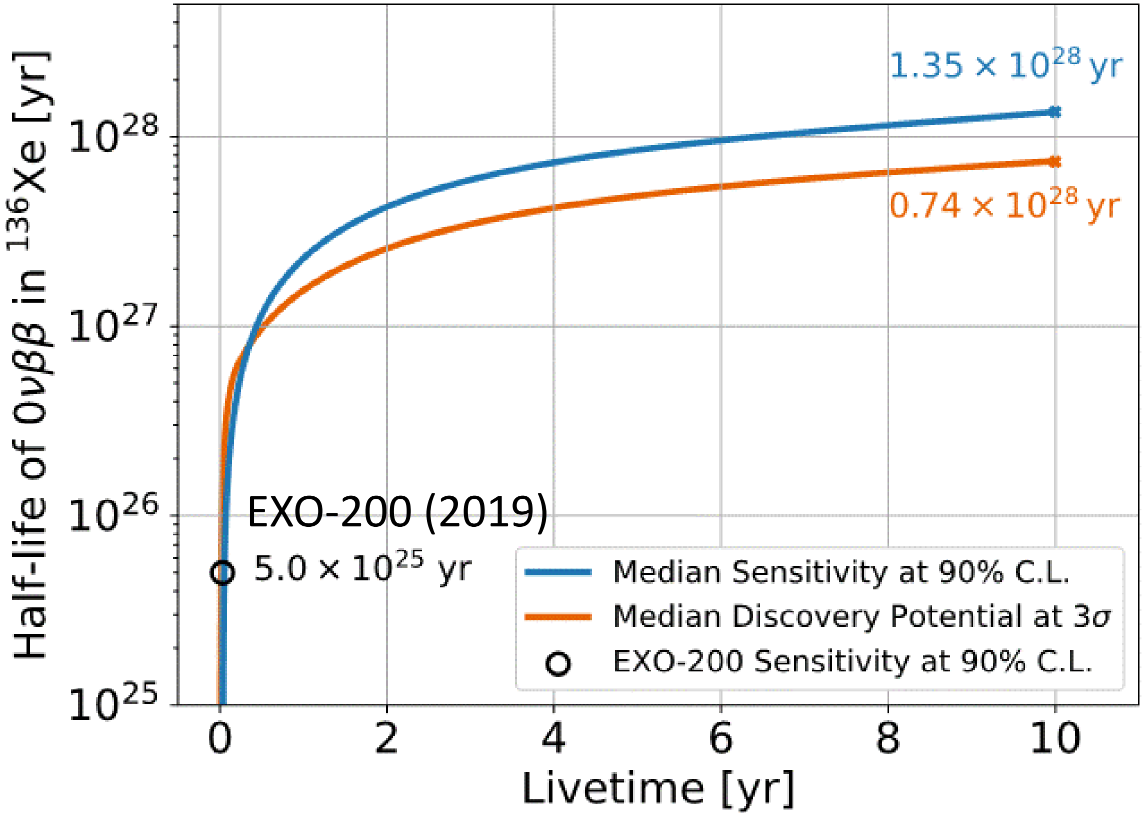


nEXO at SNOLAB

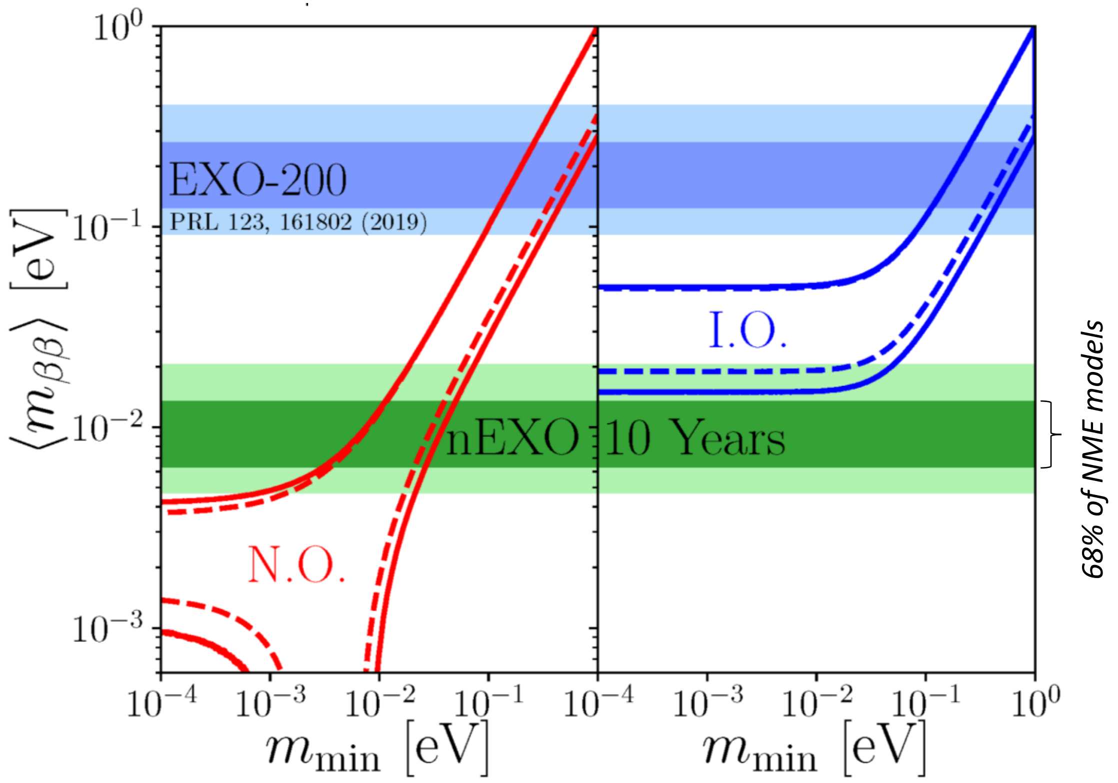




nEXO Projected Sensitivity



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

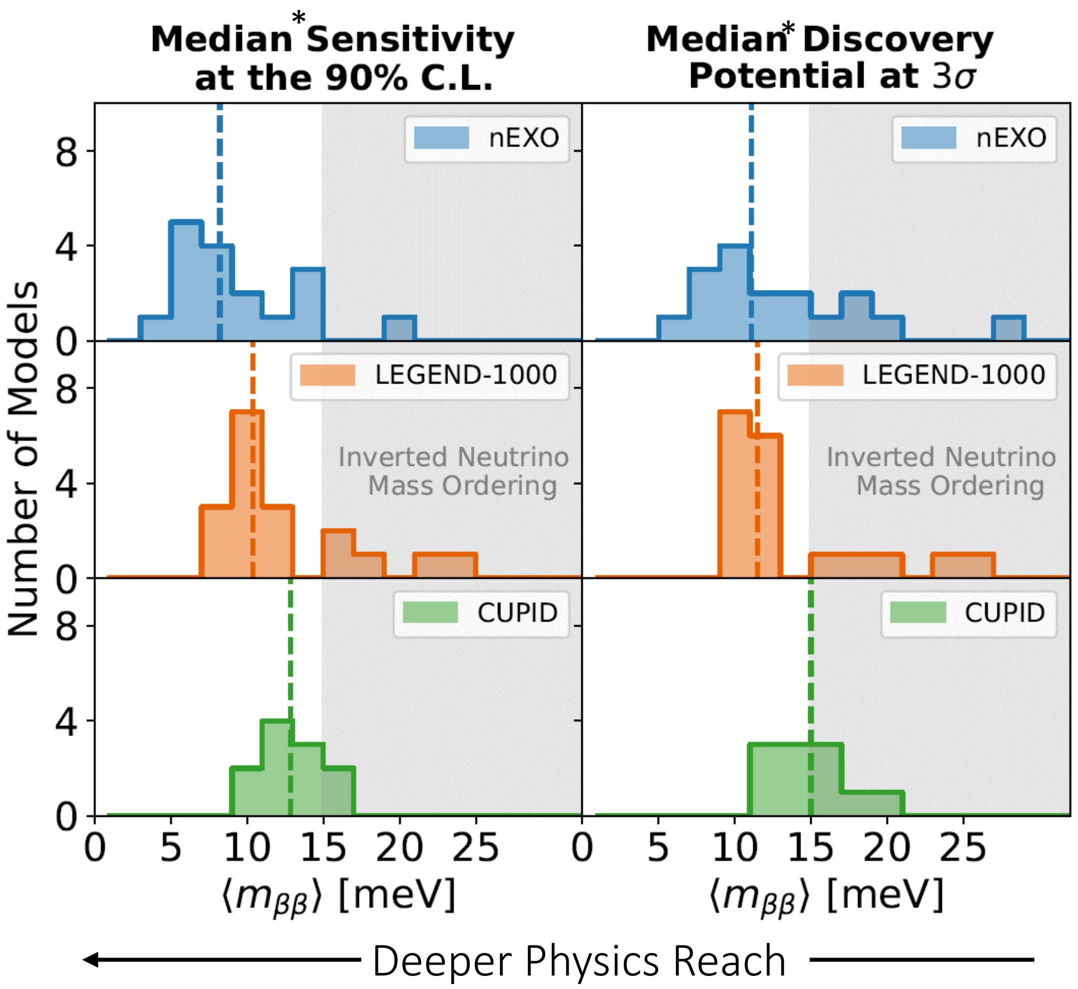


nEXO sensitivity reaches 10^{28} yr in 6.5 yr data taking

Projected sensitivity based on actual background level measurements!

arXiv:2106.16243

Comparison with other experiments



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

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

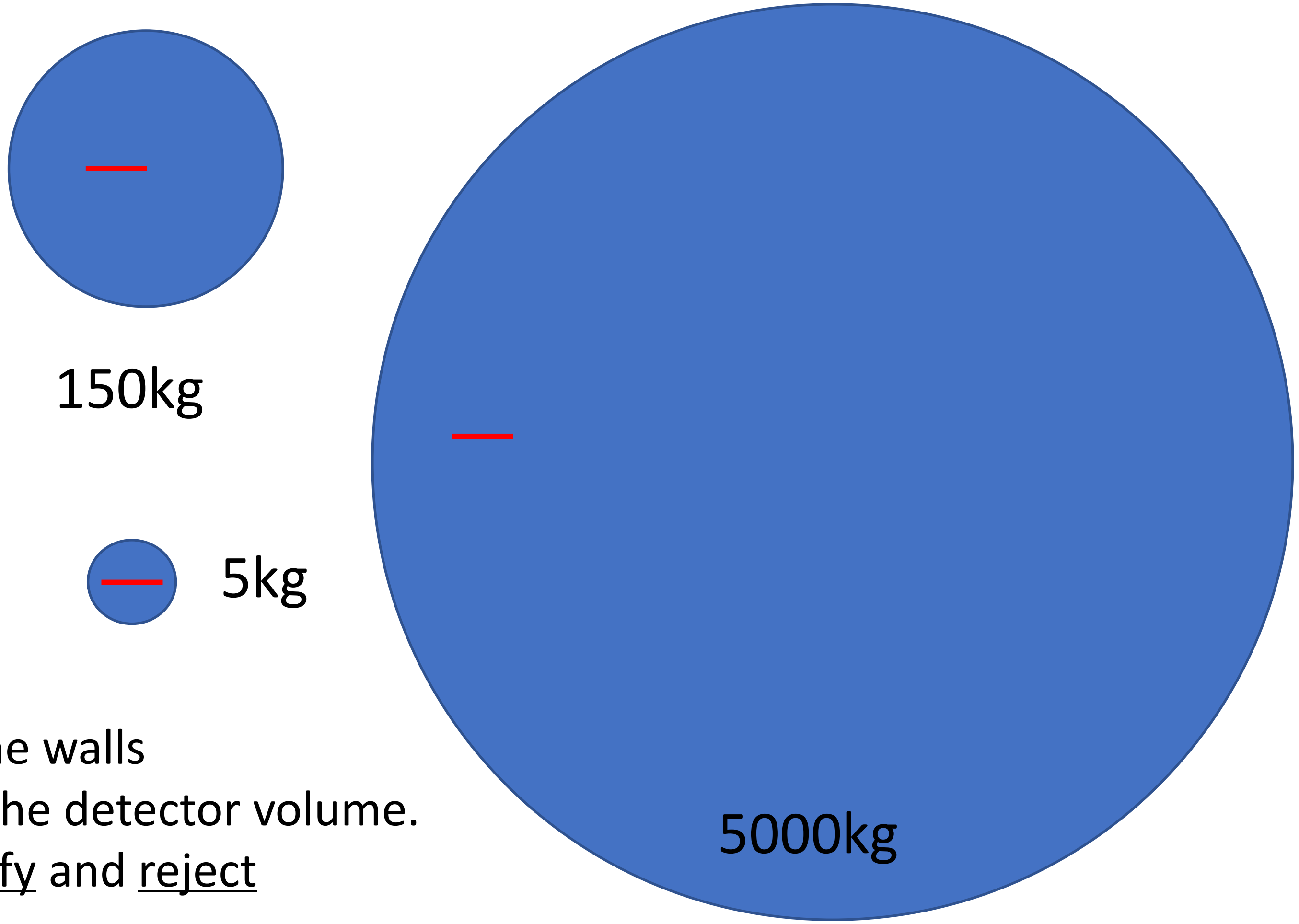
[3] CUPID pCDR, arXiv:1907.09376

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

The power of a monolithic detector

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

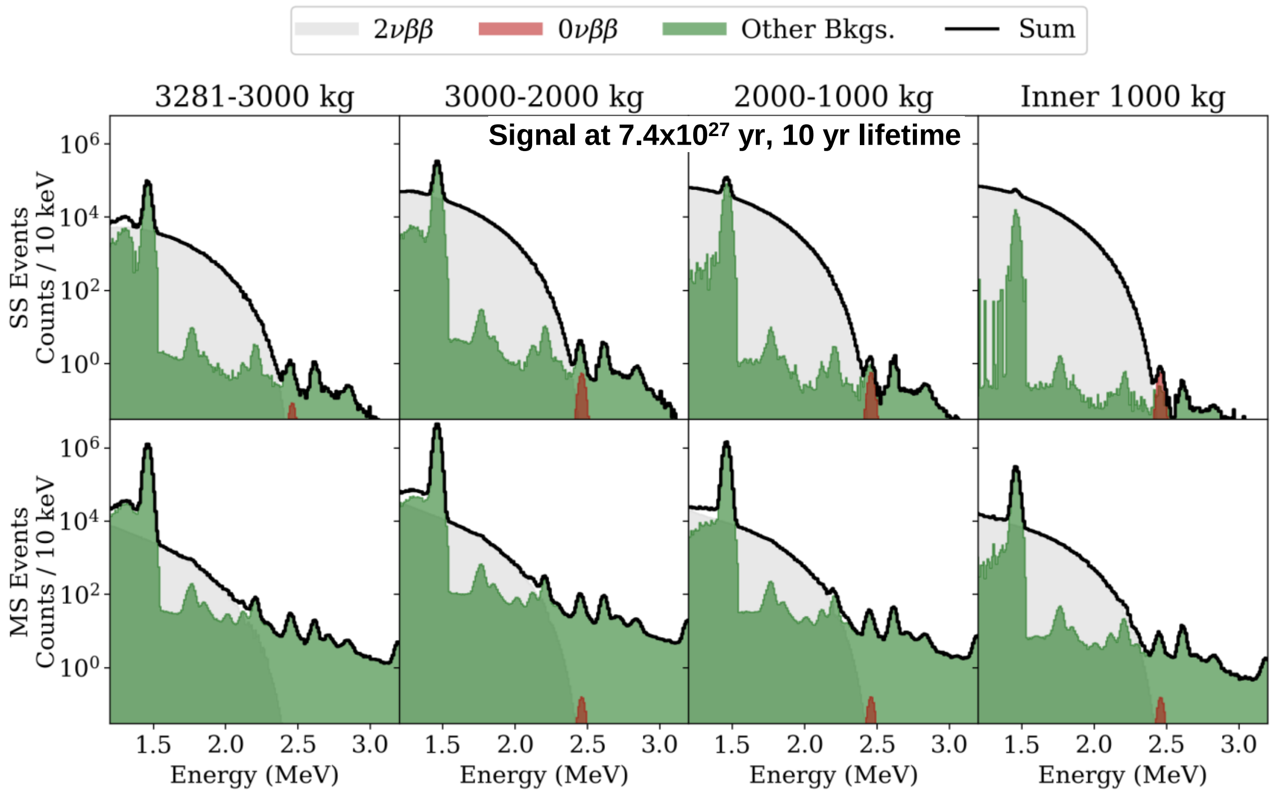
2.5 MeV γ-ray
attenuation length in LXe
8.5cm =

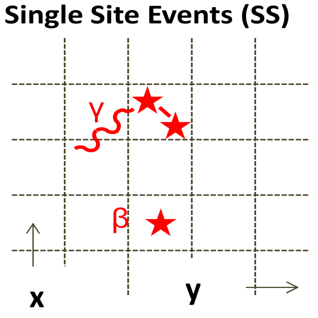


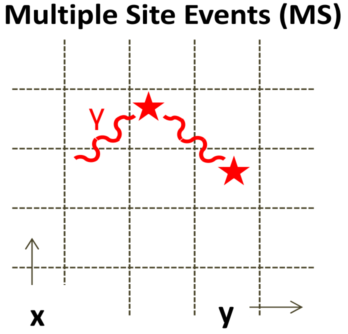
- Gamma backgrounds typically originate from the walls
  → photons Compton scatter on their way into the detector volume.
- The complete detector volume is used to <u>identify</u> and <u>reject</u> backgrounds.

Power of the monolithic nEXO detector

Multi-parameter analysis: much more information than just energy





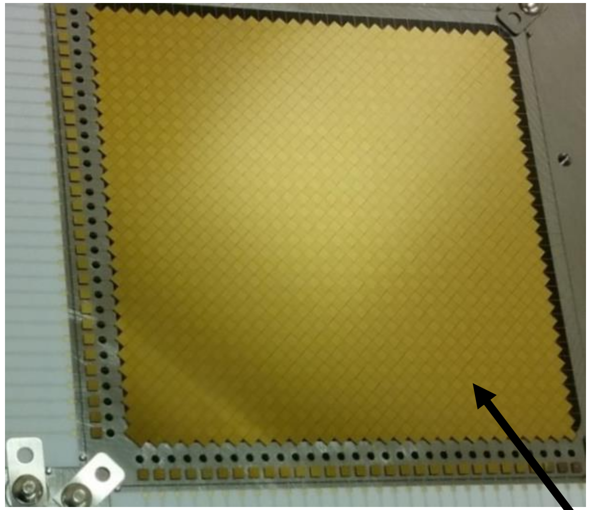


The homogeneous detector with advanced topological reconstruction has a proven track record for γ background <u>identification</u> and <u>rejection.</u>

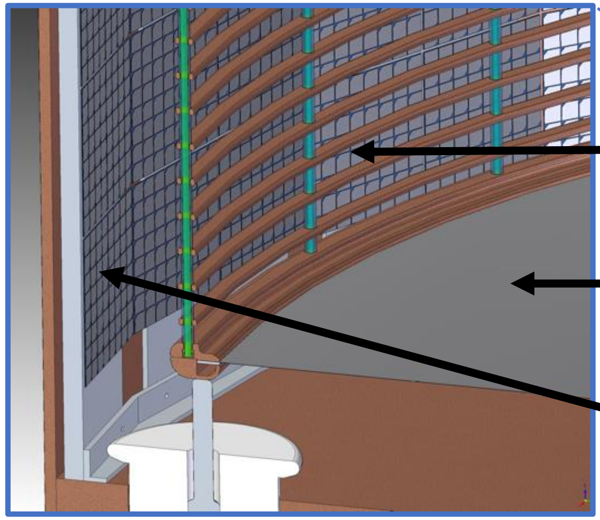
Multi-parameter analysis makes the measurement robust also with currently unknown backgrounds.

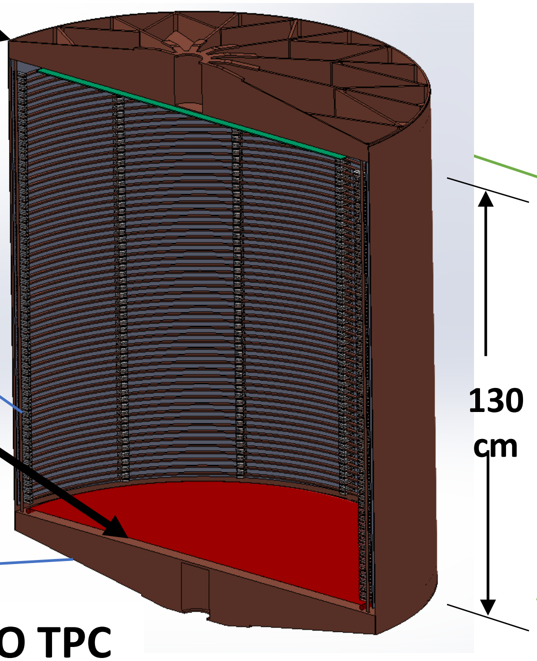
The nEXO detector

- 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 → $\sigma/E < 1\%$ at Q-value.
- 1.5 ktonnes water-Cherenkov detector for muon tagging and shielding.

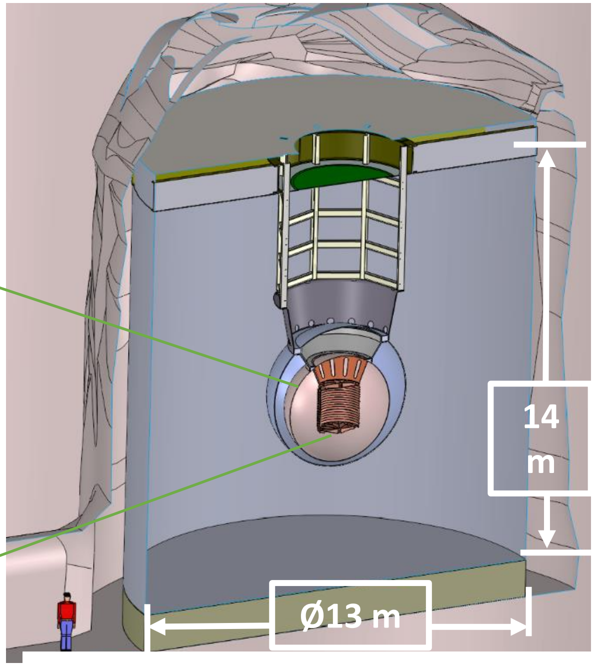


Picture: 10 x 10 cm^2 tile prototype
JINST 13, P01006 (2018)
Tile simulation: arXiv:1907.07512.





nEXO TPC



nEXO at the SNOLAB Cryopit

nEXO pre-CDR, arXiv:1805.11142

Anode Charge Readout

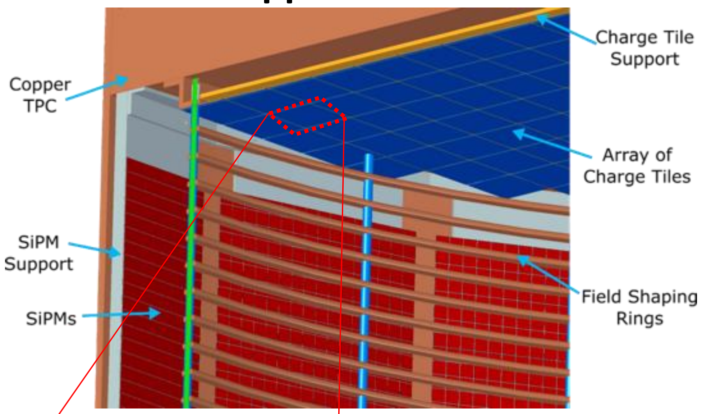
- Charge collection on tiled anode plane
- Full simulation of charge collection in nEXO used to optimize design
  - Crossed strips with no shielding grid
  - Channel pitch: 6mm
  - Tile size: 10 cm x 10 cm

Z. Li et al. (nEXO Collab) "Simulation of charge readout with segmented tiles in nEXO," JINST 14 P09020 [2019]

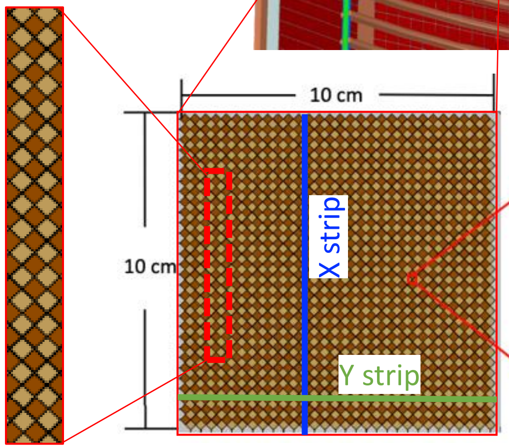
- Prototype tiles have been measured in LXe to validate simulation

M. Jewell et al. (nEXO Collab) "Characterization of an ionization readout tile for nEXO," JINST 13 P01006 [2018]

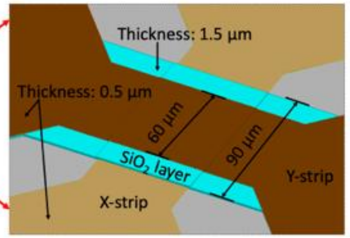
Zoom in on upper corner of TPC:



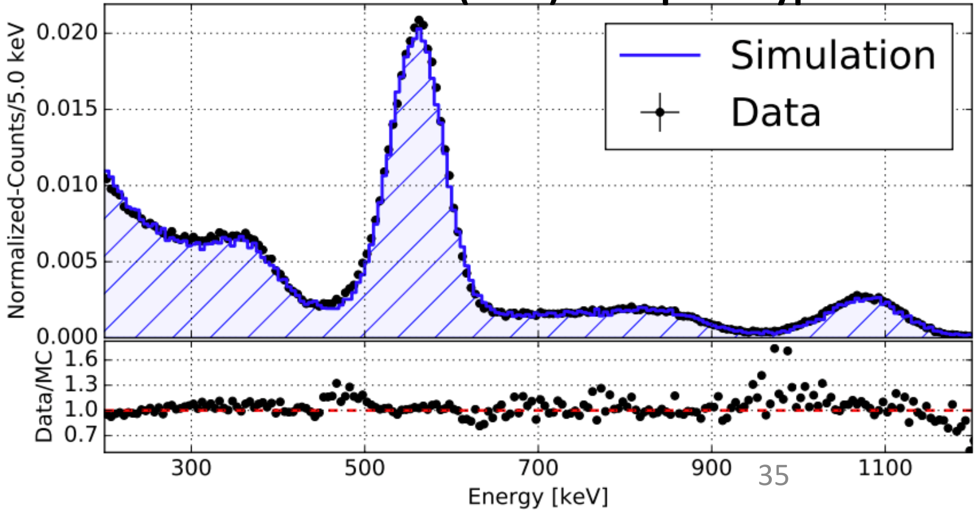
Zoom in on strip design:



X-Y strip crossing:



Source calibration (^{207}Bi) with prototype tile:

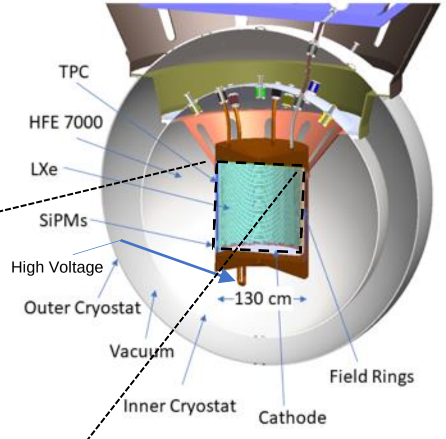


SiPMs for photon detection

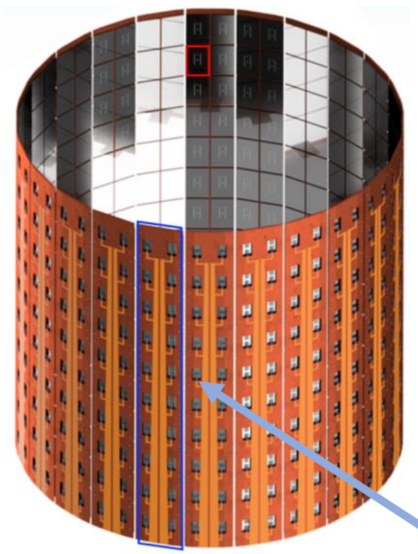
- Advantages of SiPMs for photon detection
  - Low intrinsic radioactive backgrounds
  - Improved energy resolution (SiPMs high gain)
  - Lower bias required for SiPMs (~50 V versus ~1.5 kV)
  - Devices meeting requirements demonstrated through nEXO R&D
  - Prototype SiPMs from two vendors have been tested by nEXO and meet requirements (FBK and HPK)

A. Jamil et al. (nEXO collab.) "VUV-sensitive Silicon Photomultipliers for Xenon Scintillation Light Detection in nEXO," IEEE Trans. Nucl. Sci. 65, 11 (2018)

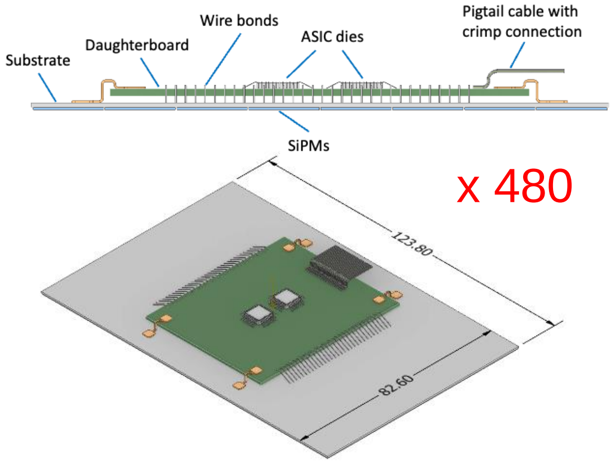
G. Gallina et al. (nEXO collab.) "Characterization of the Hamamatsu VUV4 MPPCs for nEXO," NIM A 940, 371 (2019)



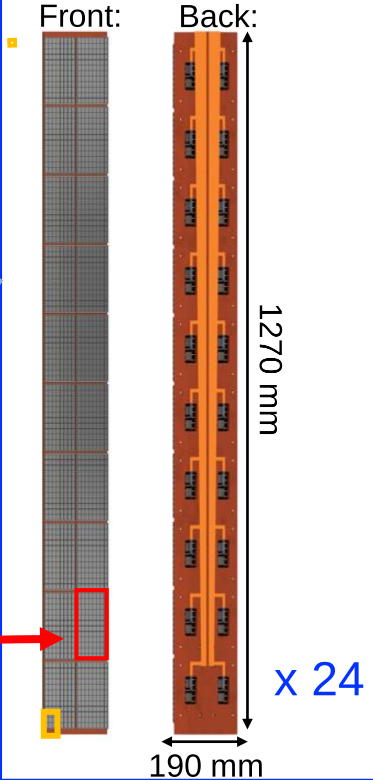
Photon detector (PD)



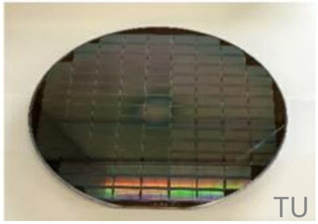
Tile module

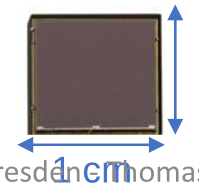


Stave



x 50,000





SiPM Devices

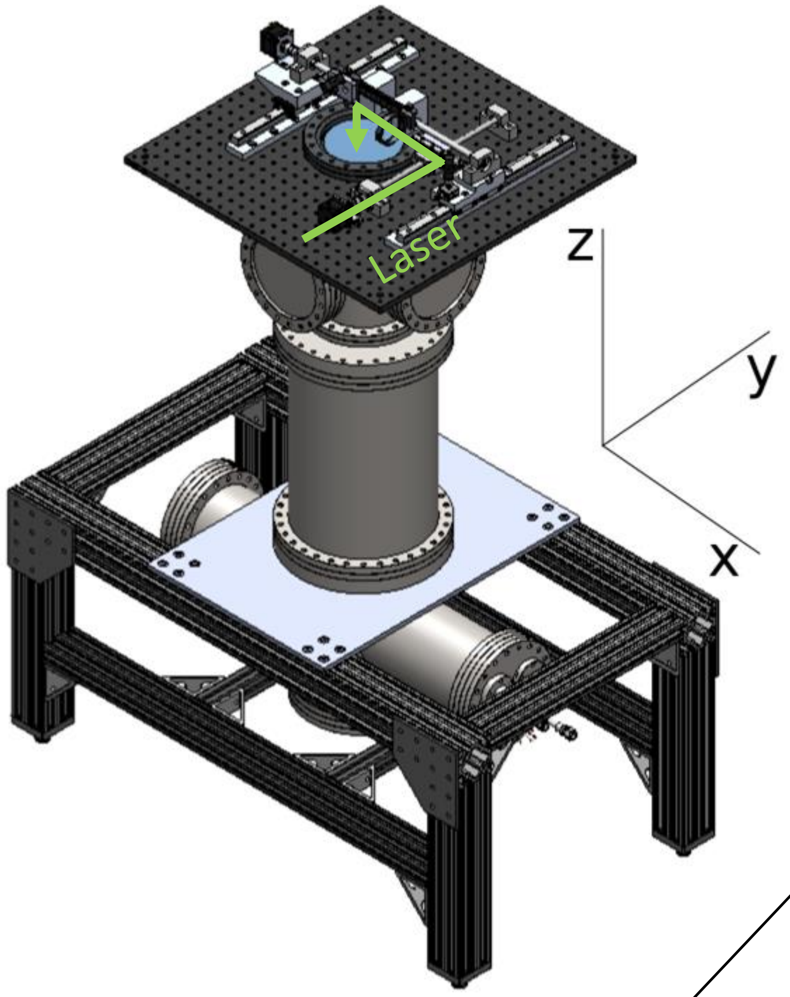
McGill Environmental Test Stand

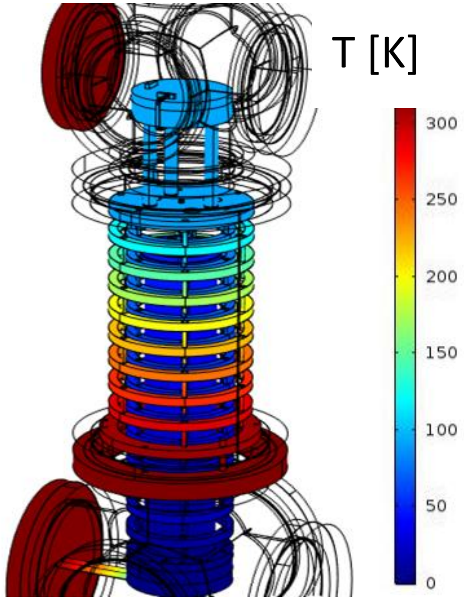
Cryostat (Liquid nitrogen powered):

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

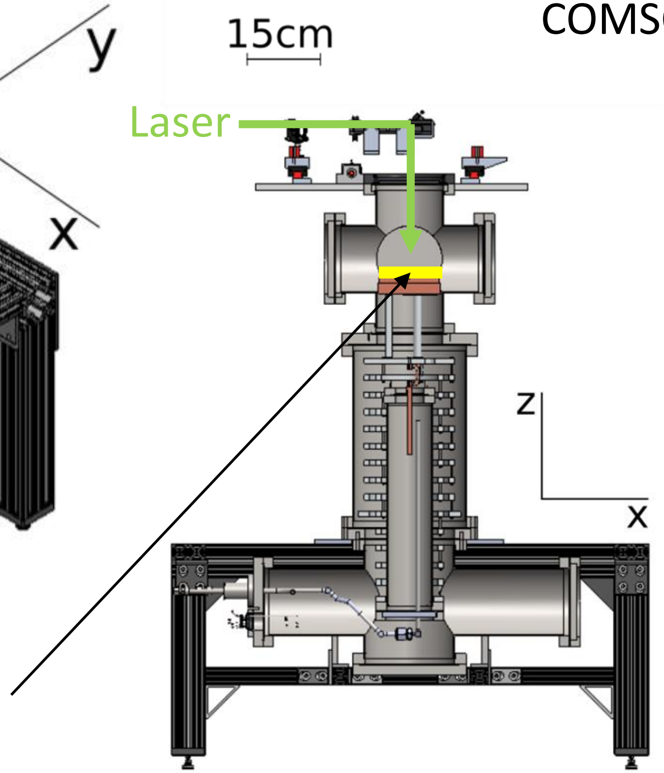
Testing Stage:

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



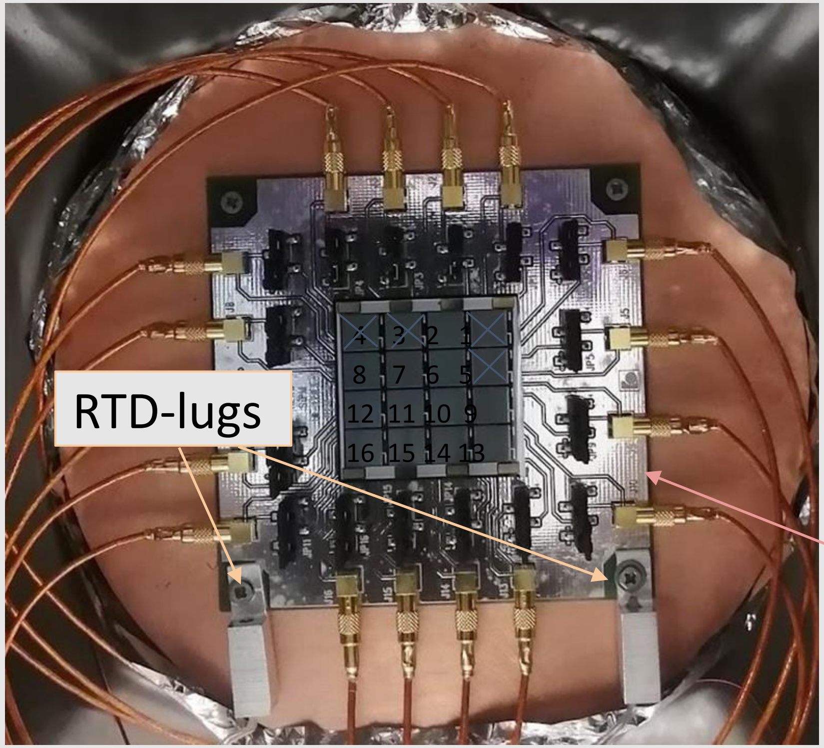


COMSOL

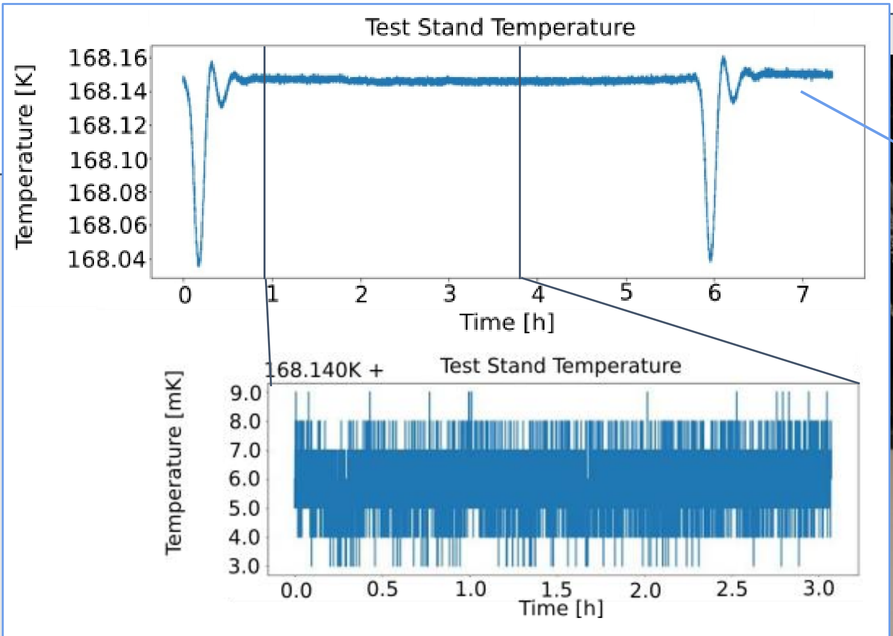


SiPM tile

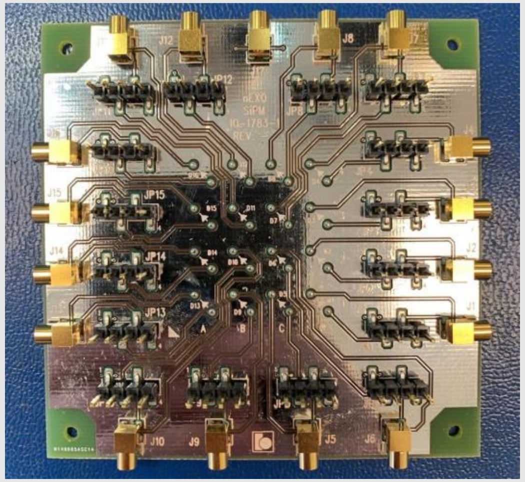
Test Setup

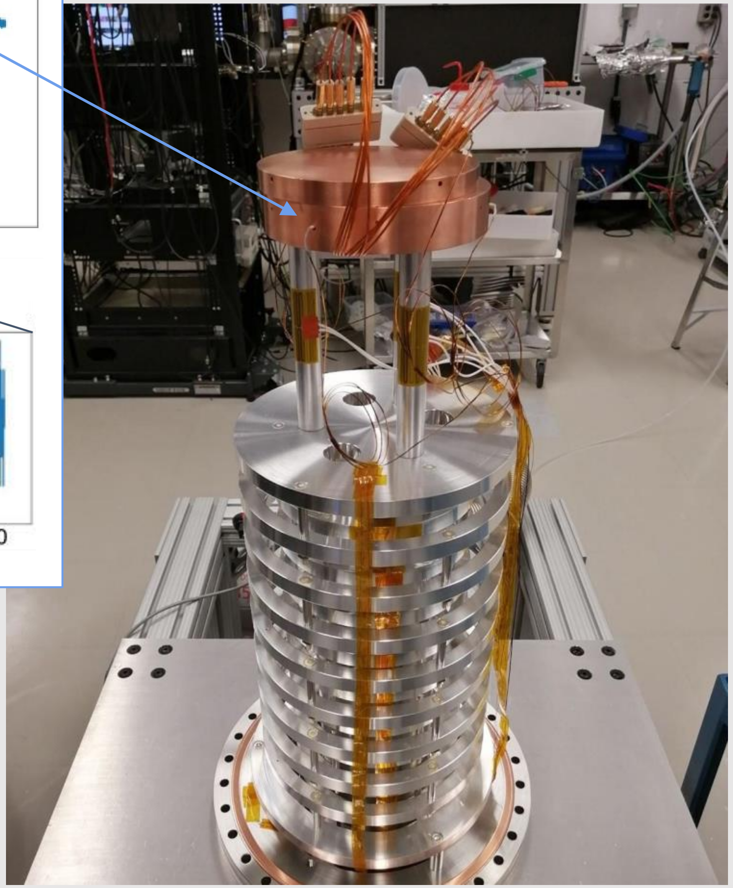


- HPK 4x4 mini tile (VUV4)
- Four dead SiPMs
- RTD-lugs fixed to mini-tile to measure temperature



PCB designed at Brookhaven National Lab





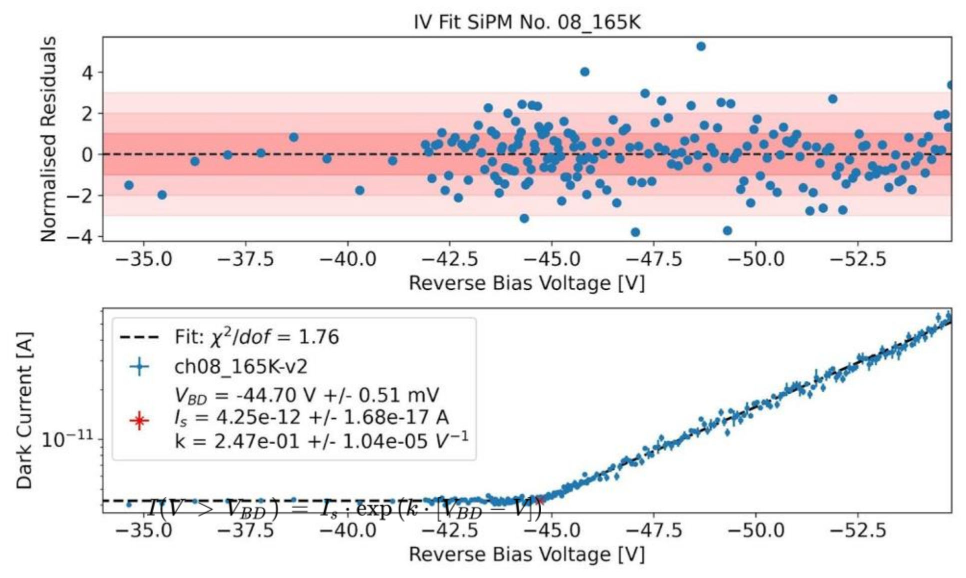
Environmental Test Stand (cryostat):

- Large surface area: A ~ 150 cm^2
- Stable operation: σ_T ~ 1 mK (3h)
- Demonstrated range: 120 - 295 K
- Turnaround time: T ~ 1 day

Slide from Lucas Darroch

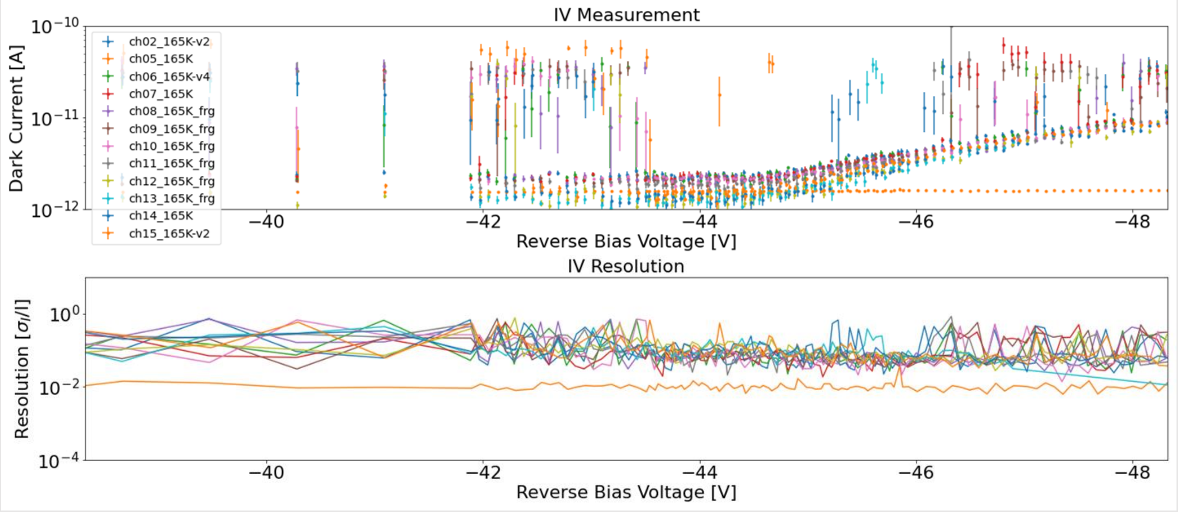
Dark Current - 165K

- Good signal resolution at pA with MUX mode B
- Runaway not observed up to 10 V overvoltage
- ~ 30 min for breakdown measurement

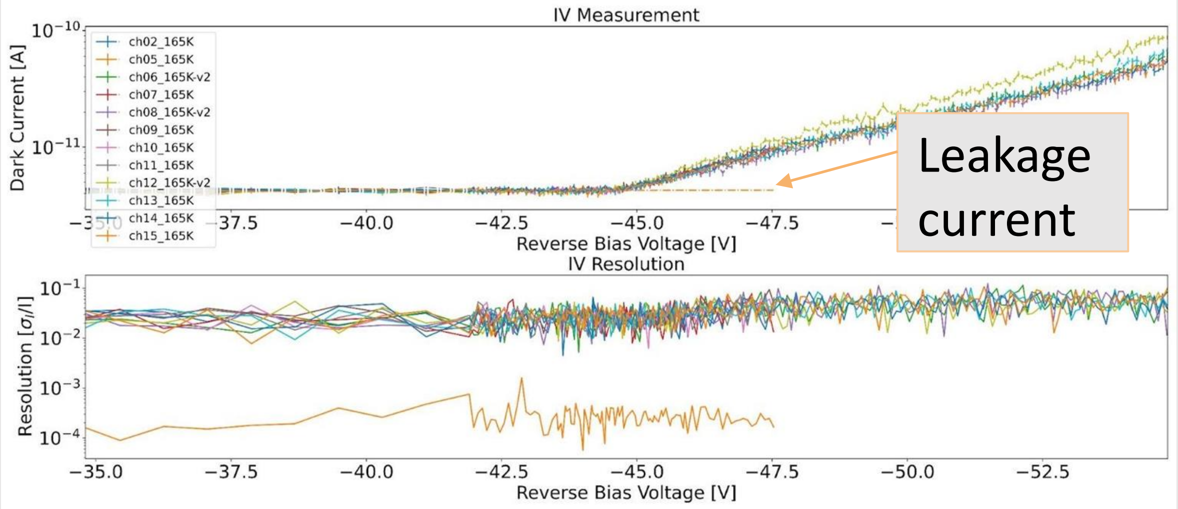


Dark IV Curve: the current increases exponentially after breakdown

MUX - Mode A



MUX - Mode B



Leakage current

Slide from Lucas Darroch

Beyond nEXO

If nEXO discovers 0νββ decay:

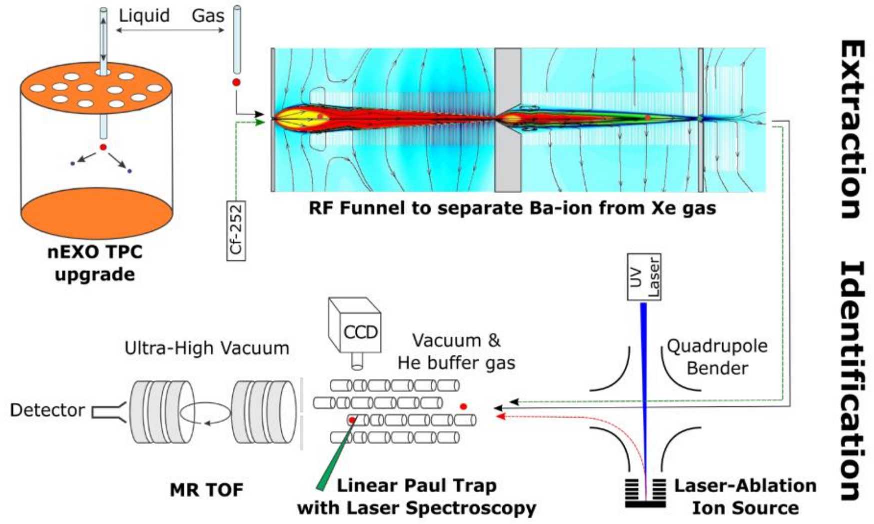
- The enriched xenon is NOT "frozen" in a particular detector.
- Should 0νββ decay be discovered by nEXO then:
  1. **Replace the enriched xenon in nEXO with natural xenon and verify disappearance of 0νββ signal.**
  2. Reused enriched Xe in a different experimental configuration to investigate the underlying physics.

If nEXO does not discover 0νββ decay:

- The advantages of the homogeneous detector keep improving with size.
- Should 0νββ decay not be discovered by nEXO, larger detectors using the same technology are plausible.
- Technologies (Ba-tagging) are being developed to further reduce backgrounds in future detector upgrades.

A clear avenue for the future is essential.

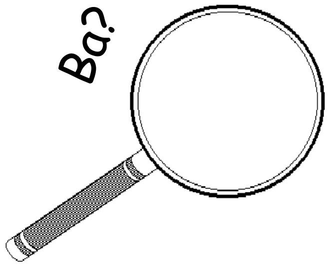
Ba-ion tagging – our Canadian approach



Pursued in collaboration between Carleton, McGill, and TRIUMF

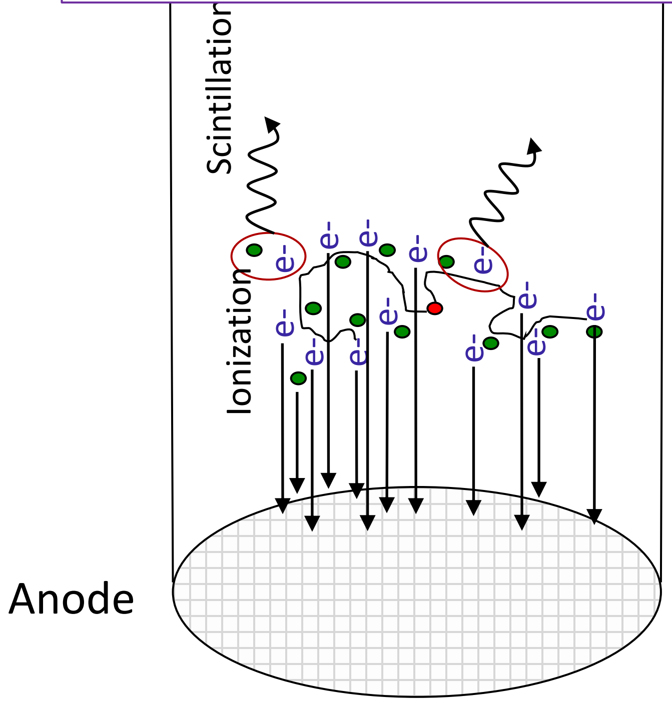
Ba-tagging concept as upgrade to nEXO

1. Is the event of interest? √
   - Close to Q-value?
   - Beta-like event?
2. Localize event √
3. Extract ion from detector volume (and separate it from Xe) ?
4. Identify ion: is it barium? √



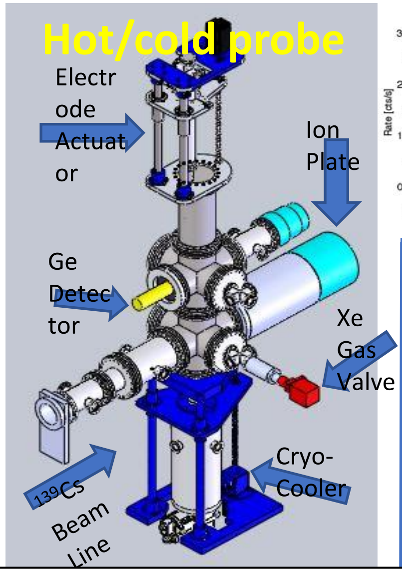
Advantages of Ba-Tagging:

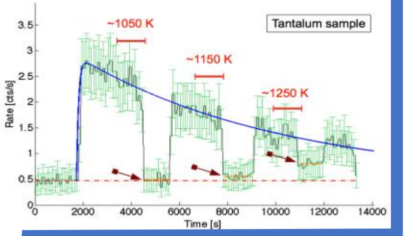
- Potential to increases nEXO's projected sensitivity by factor of 2-3
- Provides **POSTITIVE** signal of ββ decay

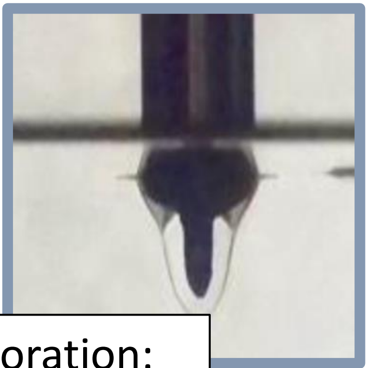


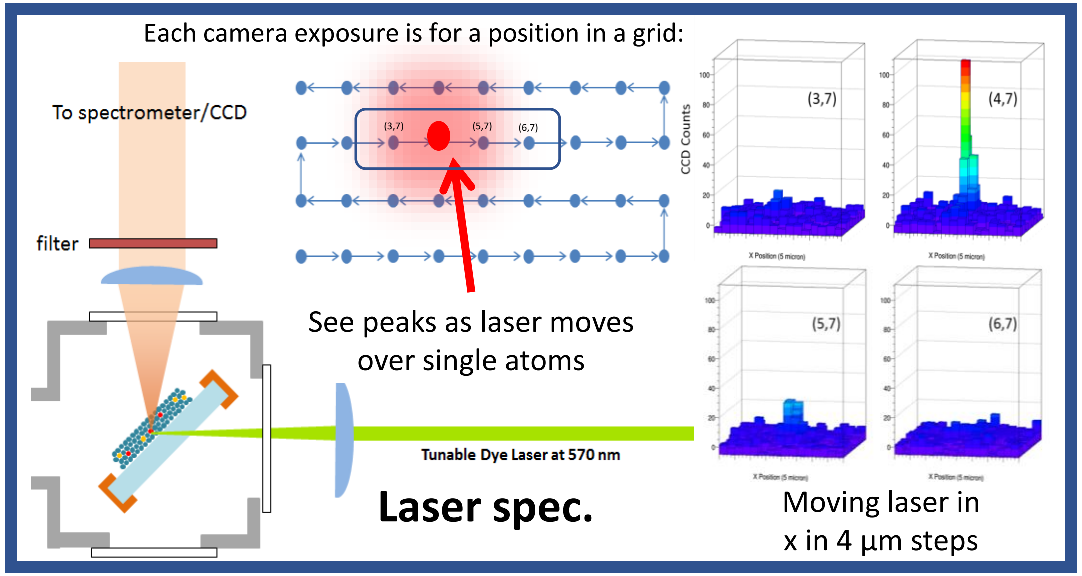
Ba tagging R&D ongoing for liquid- and gas-phase detector

Ba tagging for nEXO – a multi-facetted approach

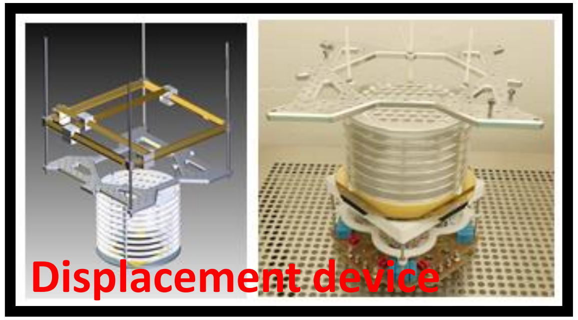


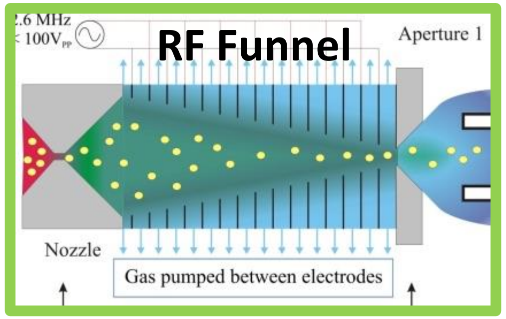


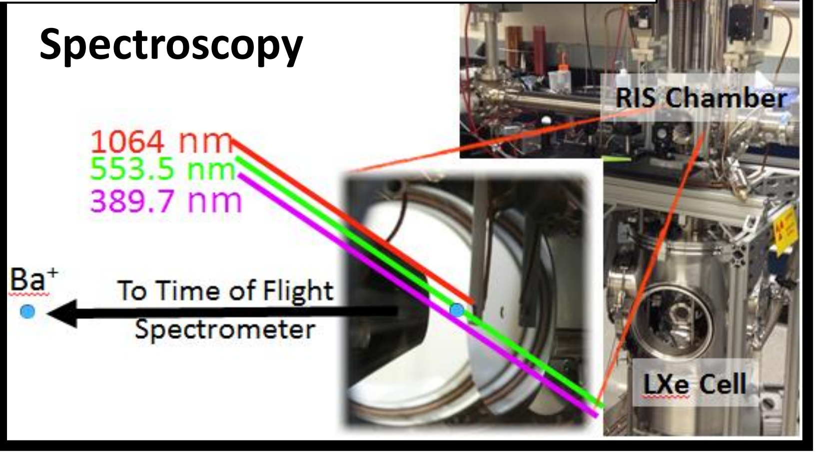




New player in town - NEXT collaboration:
Single-Molecule Fluorescence Imaging
Phys. Rev. Lett. 120, 132504 (2018)







Recent nEXO Ba-tagging publications

Imaging individual Ba atoms in solid xenon for barium tagging in nEXO
C. Chambers, et al., arXiv:1806.10694, *Nature 569, 203 (2019).*

An RF-only ion-funnel for extraction from high-pressure gases
T. Brunner, et al., Int. J. Mass Spec. 379, 110 (2015), arXiv:1412.1144.

Spectroscopy of Ba and Ba$^+$ deposits in solid xenon for barium tagging in nEXO
B. Mong, et al., Phys. Rev. A 91, 022505 (2015), arXiv:1410.2624.

An apparatus to manipulate and identify individual Ba ions from bulk liquid Xe
K. Twelker et al., Rev. Sci. Instrum. 85, 095114 (2014), arXiv:1407.0618.

Canadian Ba Extraction and Tagging Effort

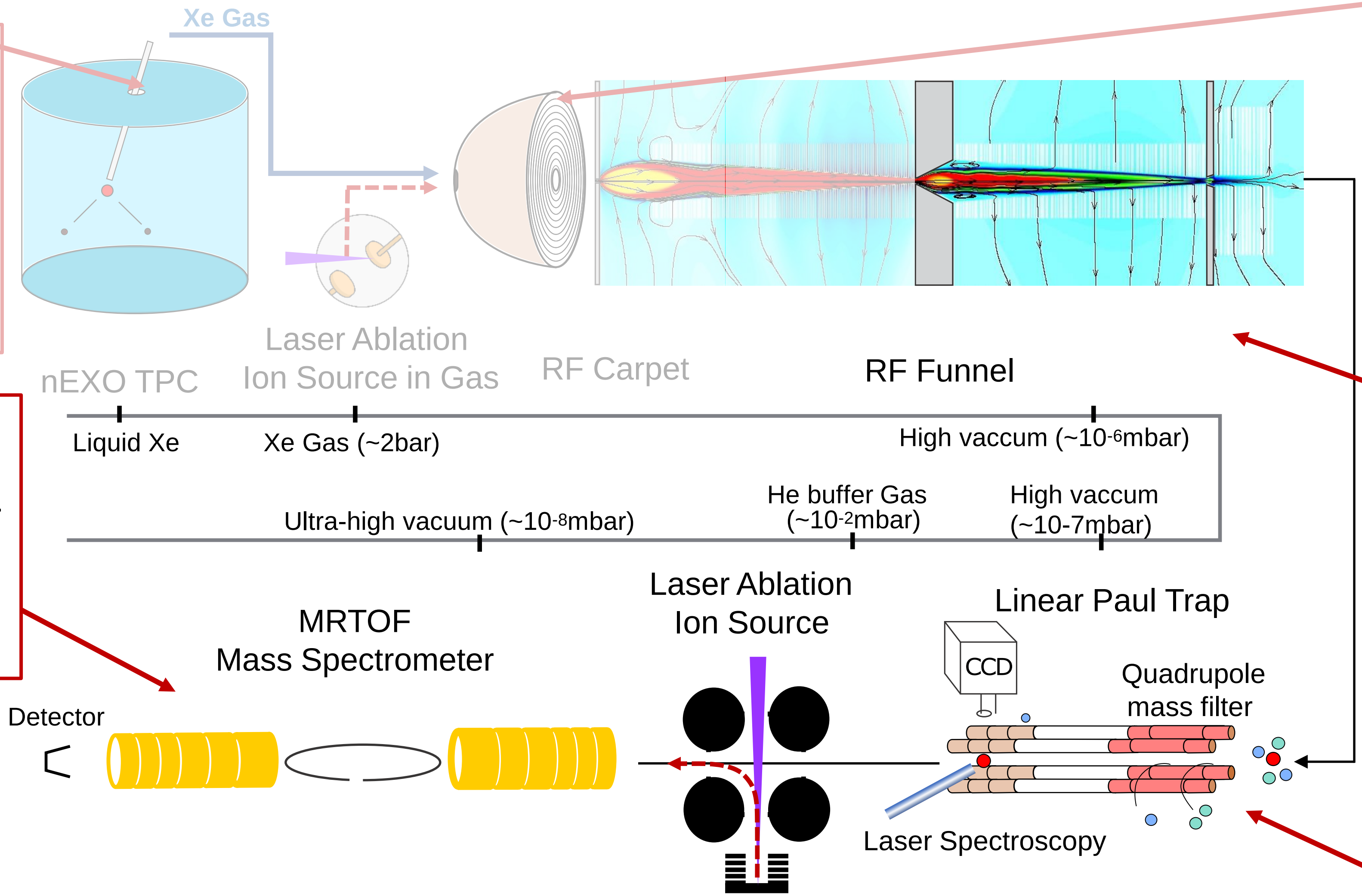
Stage1: Extraction of detector volume around the location of the decay to gas phase using a capillary tube.

Stage2: RF carpet for efficient transfer of ion from capillary to RF funnel

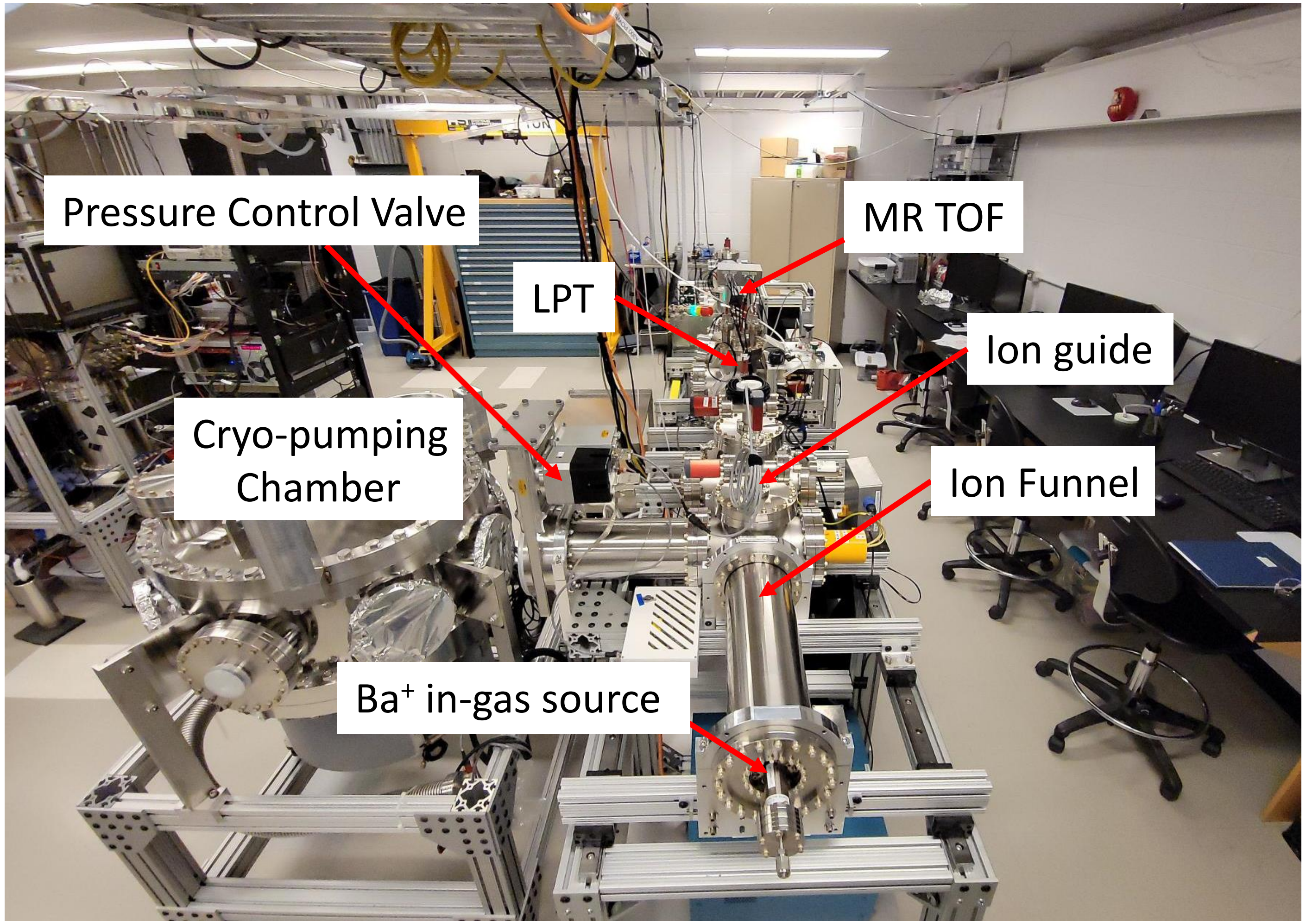
Stage3: RF funnel facilitates separation of xenon accompanying the Barium ion.

Stage4: The Linear Paul trap (LPT) for detection of barium ion via laser fluorescence spectroscopy.

Stage5: Multiple Reflection TOF Spectrometer for systematic studies and determination of ion mass.



RF Funnel Upgrade in Progress



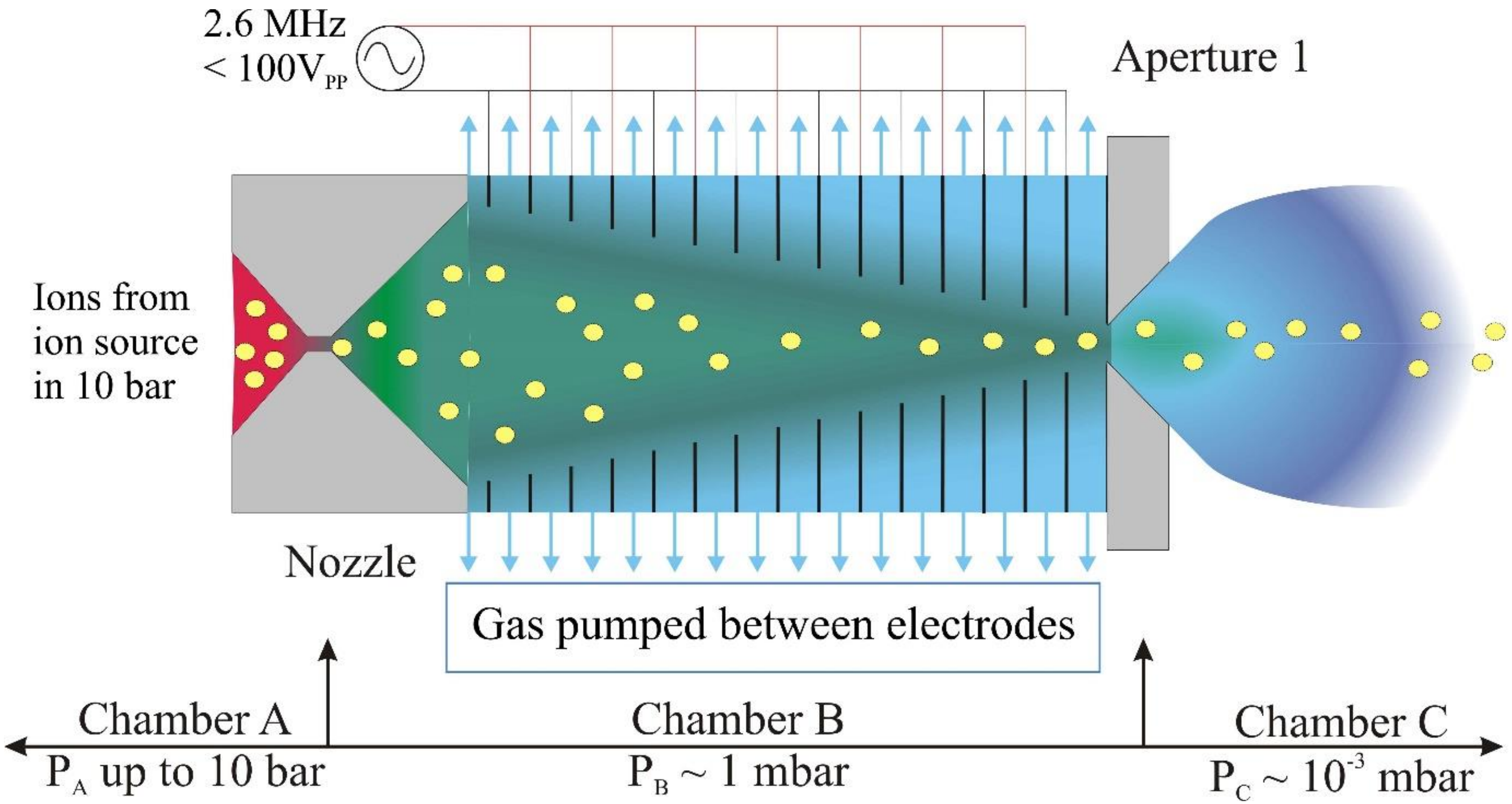
Current Status:
- Funnel transferred into new chamber
- RF electronics built and tested
- Pressure control valve installed
- Pressure readout ready

Still to do:
- Need to hook up cryo-pump chamber
- Demonstrate pressure control
- Commission with Ar gas

Unfortunately, the chip shortage has delayed many crucial parts

What is an RF-only Ion Funnel?

Device that transports ions from high pressure to high vacuum



- Supersonic nozzle at entry pushes gas and ions through the funnel
- RF potential between adjacent electrodes keeps ions radially confined
- Outside of funnel kept at low pressure (order 1 Torr)
- Gaps between electrodes allow gas to be pumped out of the funnel

Must work at high efficiency for Ba Tagging

For the RF funnel developed at Stanford University:

V_{RF} = 120 V, f = 10 MHz
Simulated Ba^+ transmission: ~95%

V_{RF} = 25V, f = 2.6 MHz
Simulated Ba^+ transmission: ~72%

The MRTOF

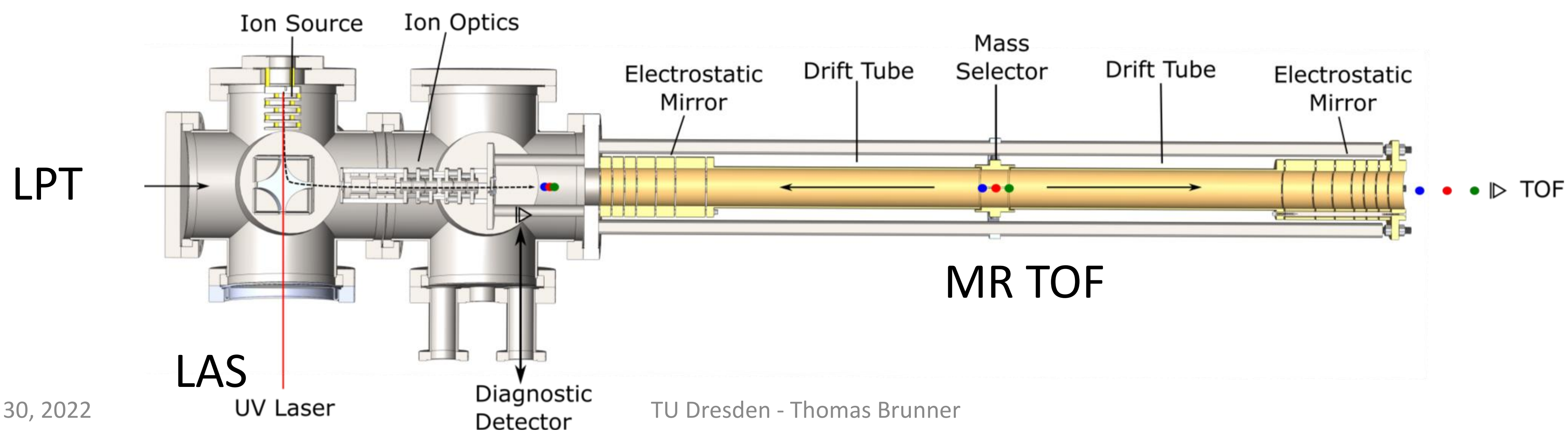
Operating Principle

- Ions accelerated by potential U gain kinetic energy $E_{kin} = z_i eU = mivi^2/2$
- Ions with different mass-to-charge separate in time, and can be resolved if $\Delta t_{ij} > \Delta t_i, \Delta t_j$
- Calculated with mass-resolving power (MRP), $R = m/\Delta m = t/(2\,\Delta t)$

^{136}Xe mass = 135.907219(8) u, ^{136}Ba mass = 135.9045759(4) u , ∴ Δm =0.0026 and $R = m/\Delta m \approx$ 52000

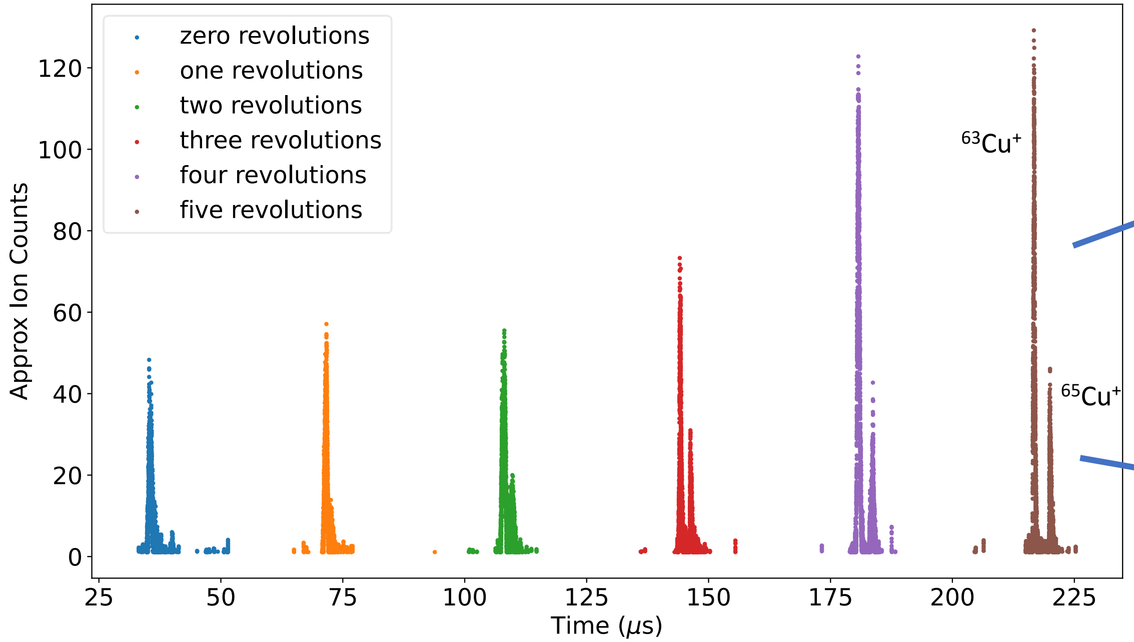
Design

- Consists of central drift-tube and 2 electrostatic mirrors formed by 6 cylindrical electrodes.
- Ions are reflected between the mirrors to dramatically increase the MRP.

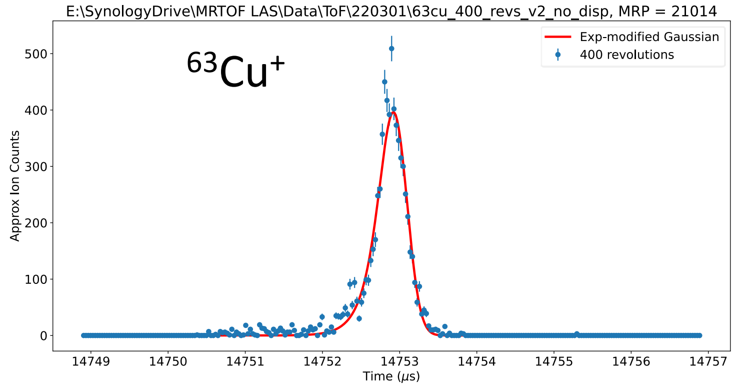


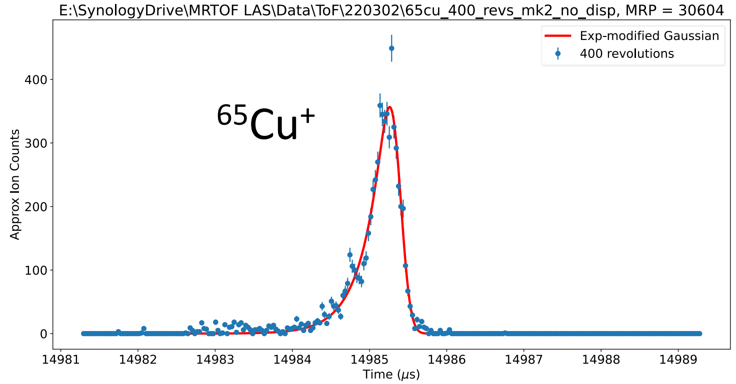
MR TOF Commissioning with Cu

Select and inject Cu into MRTOF



As revolutions increase, ToF peak splits! Cu has two stable isotopes…

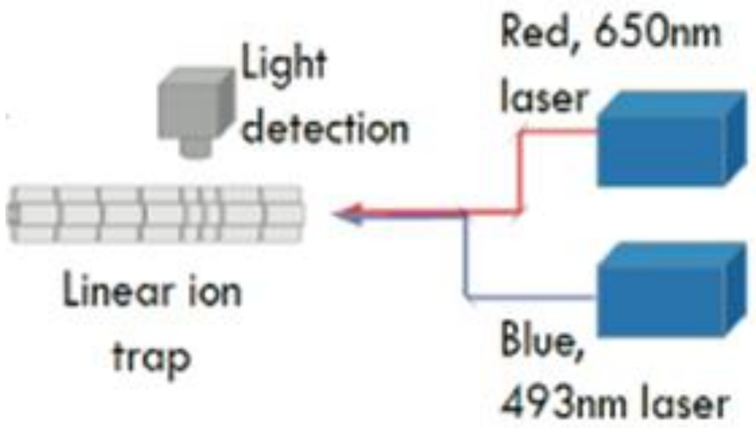




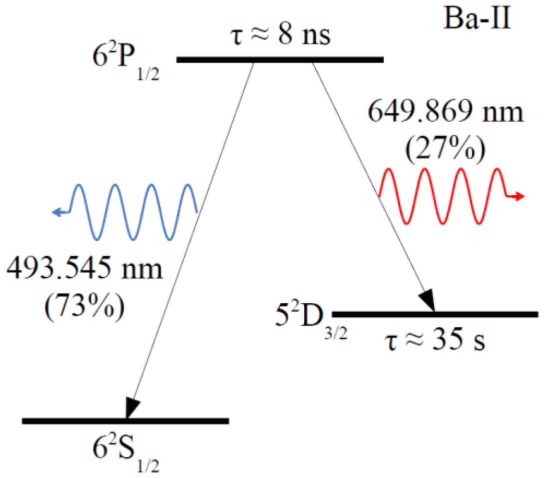
ToF extended to 15ms, for 400 revolutions: 20-30k MRP

Mass of ^{65}Cu measured as **64.9281(9) amu**, agreeing with 64.9278 amu.

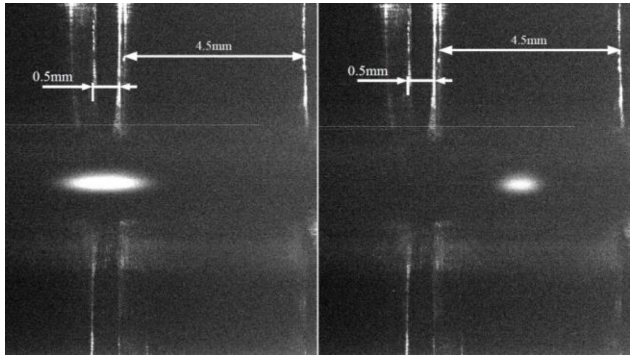
Ba ion detection & identification (Carleton)



Using a relatively simple and well understood fluorescing system

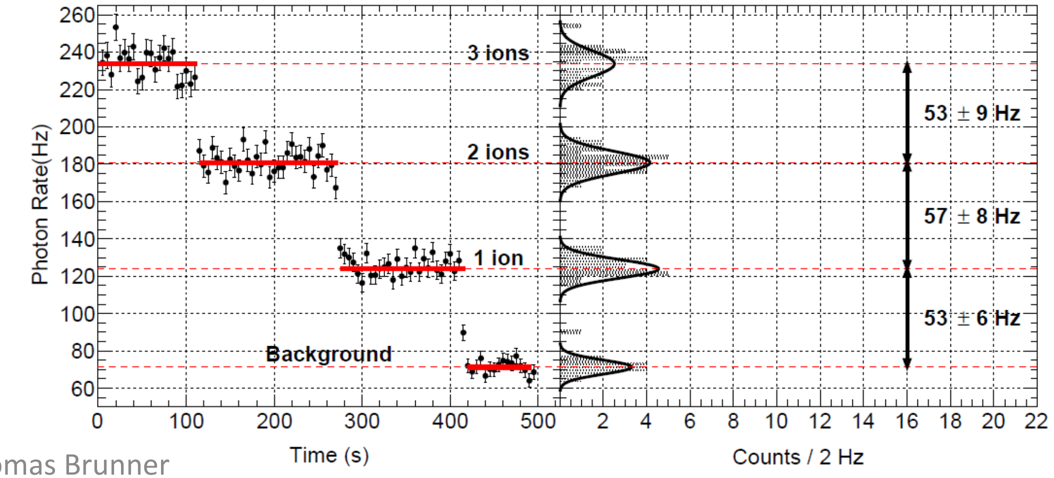


Demonstrated ion cloud imaging and accurate position control



Demonstrated by M. Green et al., Phys. Rev. A **76** 023404 (2007)

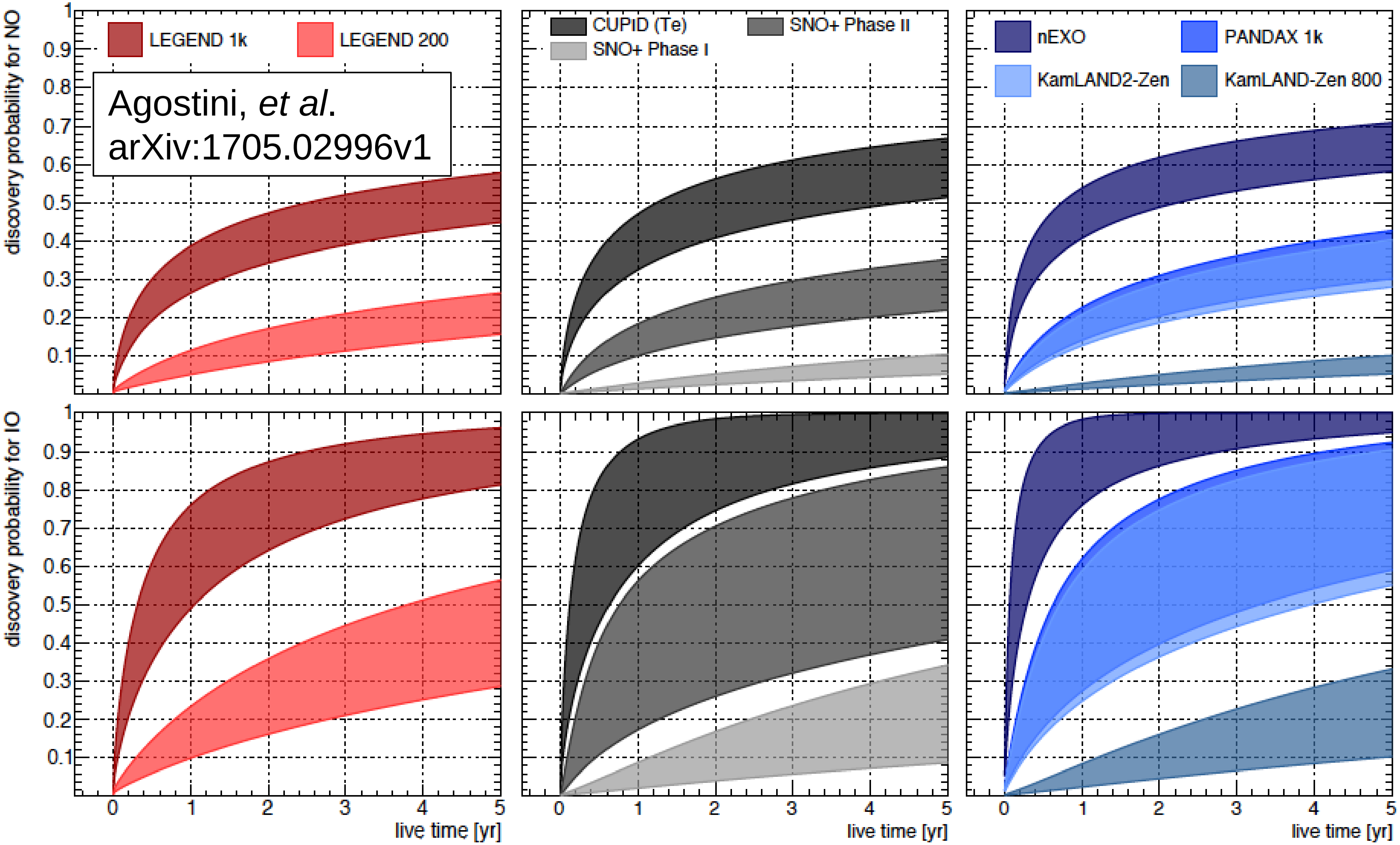
Demonstrated single ion sensitivity using intermodulation technique (background control)



Summary

- The search for $0\nu\beta\beta$ is the most promising approach to determine the quantum nature of neutrinos: Dirac versus Majorana
- Next-generation $0\nu\beta\beta$ are being designed to reach sensitivities beyond 10^{28} years (this is 10^{18} times the age of the Universe!)
- Technologies are being developed to further increase sensitivity and unambiguously identify $0\nu\beta\beta$ candidate events as true $\beta\beta$ events
- An observation of $0\nu\beta\beta$ always implies physics beyond the Standard Model, independent of the underlying process!

0νββ Discovery Potential



0νββ is the most practical way to test the Majorana nature of neutrinos.

An observation of 0νββ always implies physics beyond the Standard Model!

The nEXO collaboration