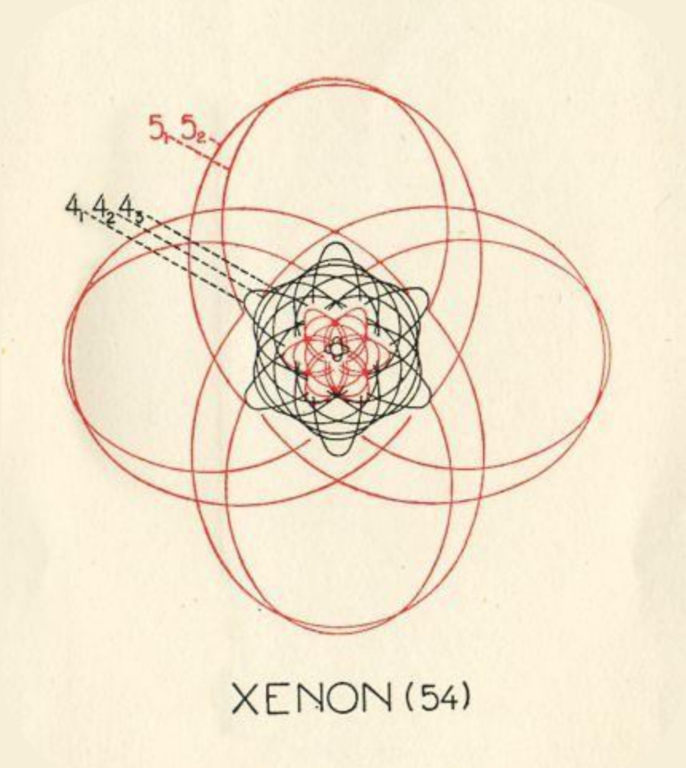
The Search for $0\nu\beta\beta$ with



Niels Bohr between physics and chemistry, Helge Kragh, Physics Today Vol. 66 Iss. 5
adapted from H. Kramers, H. Holst (1923).

Soud Al Kharusi

SNOLAB User's Meeting
June 26th 2024

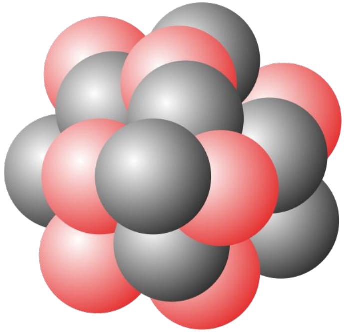
soudk@stanford.edu
https://www.soudkharusi.com/

Supervisors at McGill: Thomas Brunner & Daryl Haggard

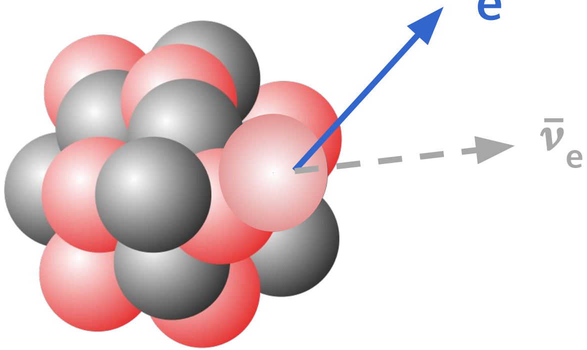
Google Slides link

Beta decay

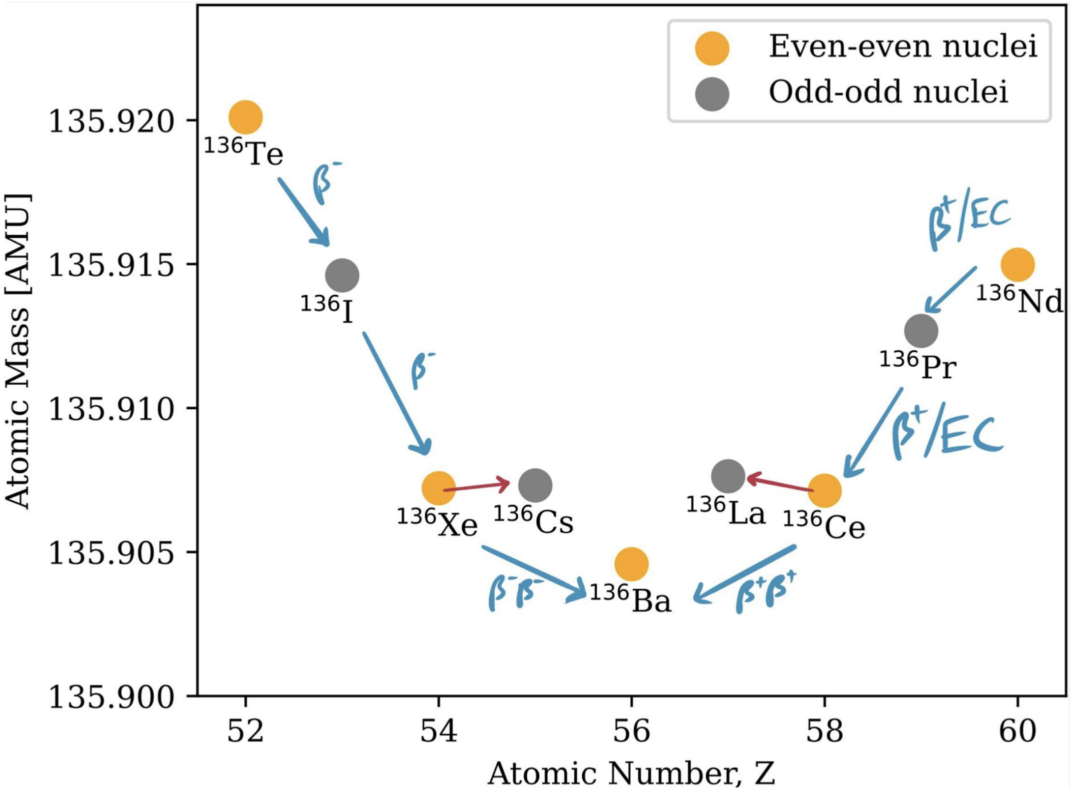
Your favourite β-unstable nucleus N = (Z, A)



Your favourite more stable nucleus N = (Z+1, A)

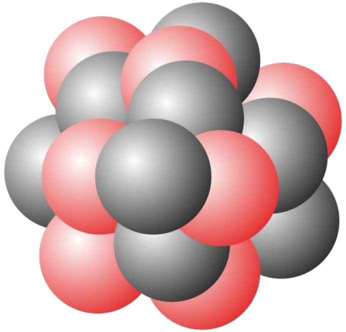


Double beta decay (2νββ)



Double beta decay ($2\nu\beta\beta$)

^{136}Xe



Double beta decay ($2\nu\beta\beta$)

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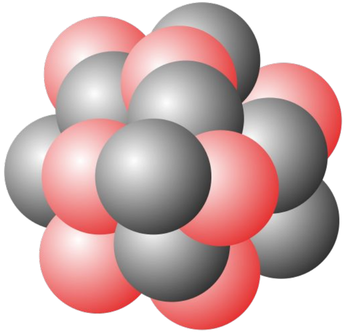
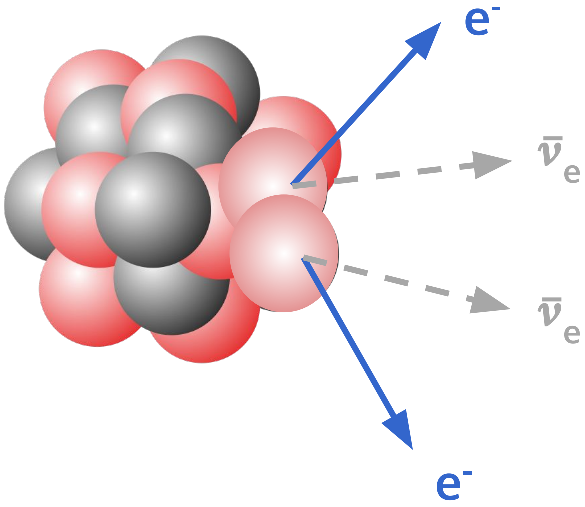
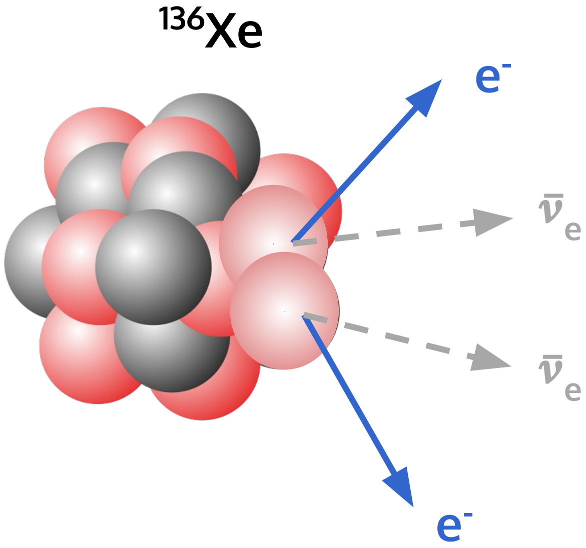


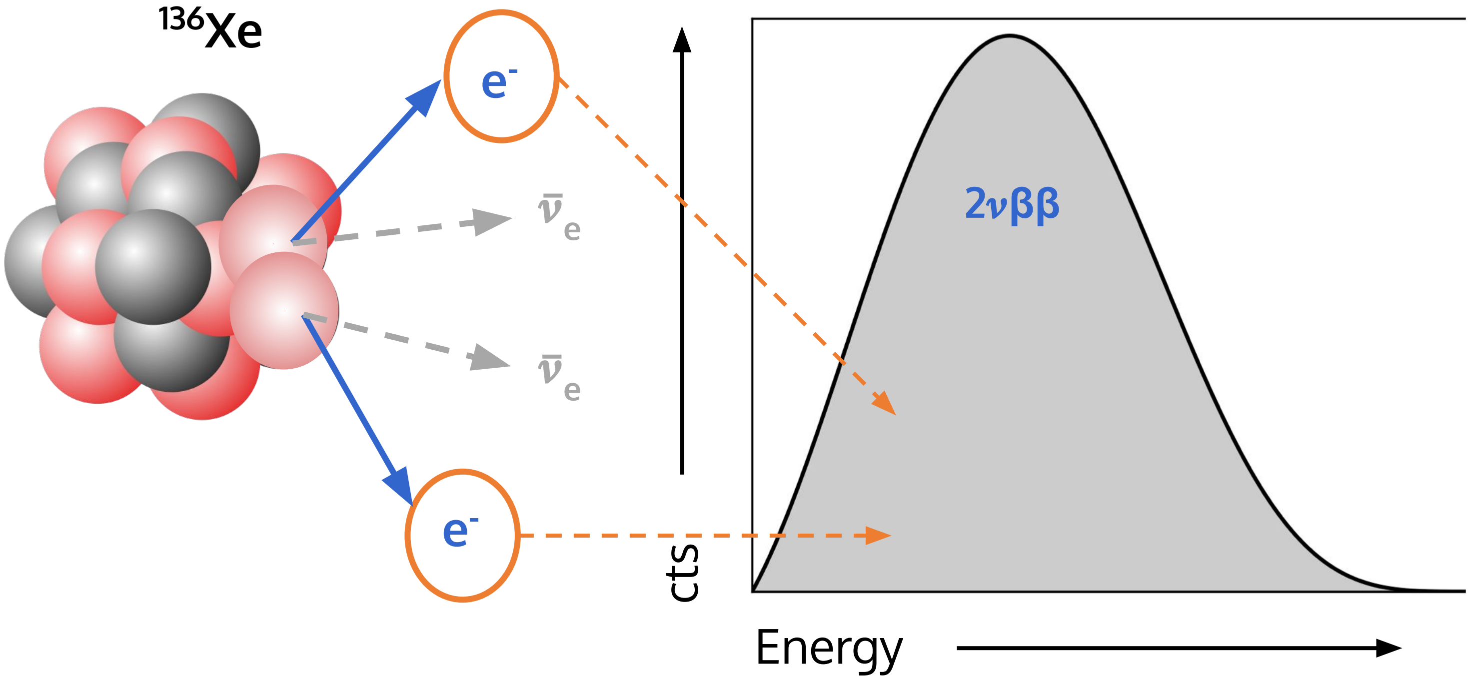


$T_{1/2}(2\nu\beta\beta) \sim 10^{21}$ years

Double beta decay (2νββ)

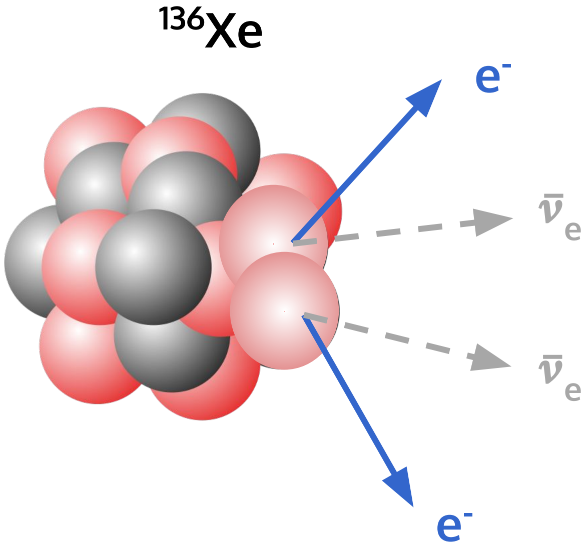


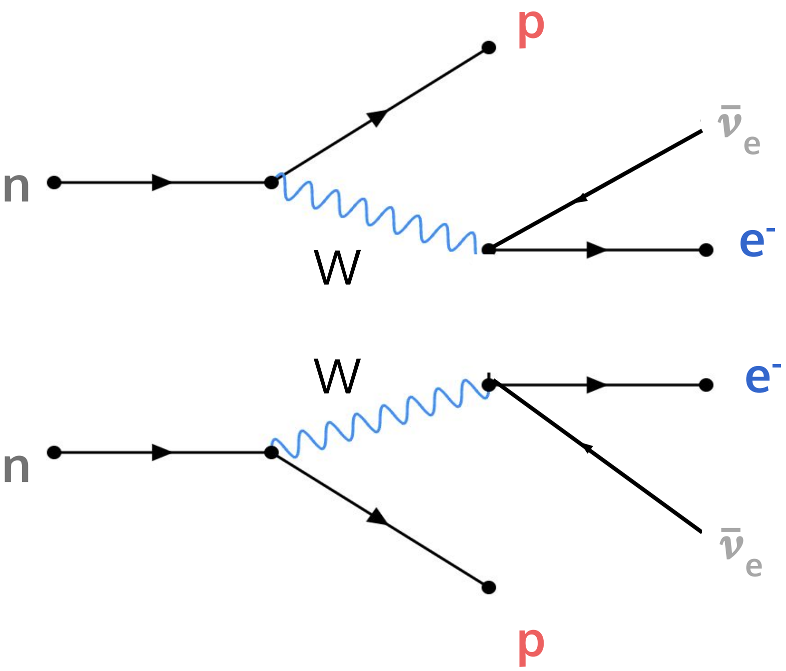
Double beta decay (2νββ)



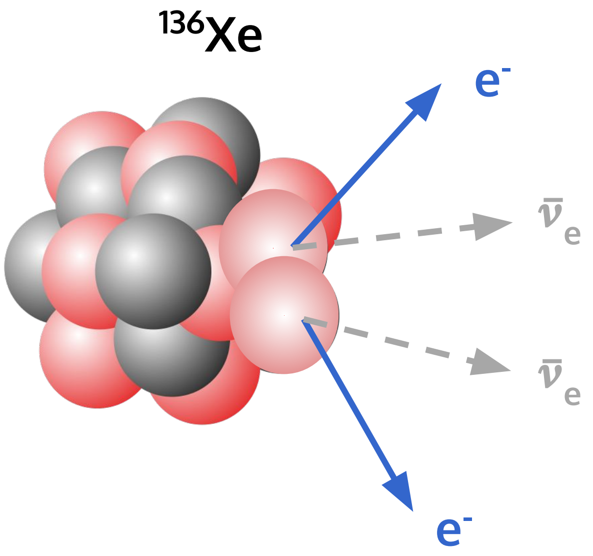
We can measure the energy of outgoing electrons!

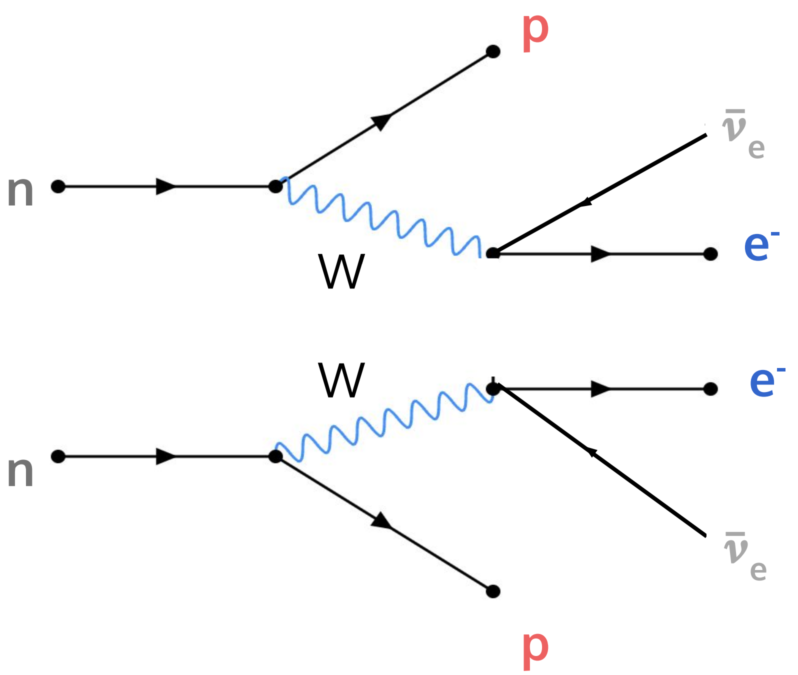
Double beta decay (2νββ)





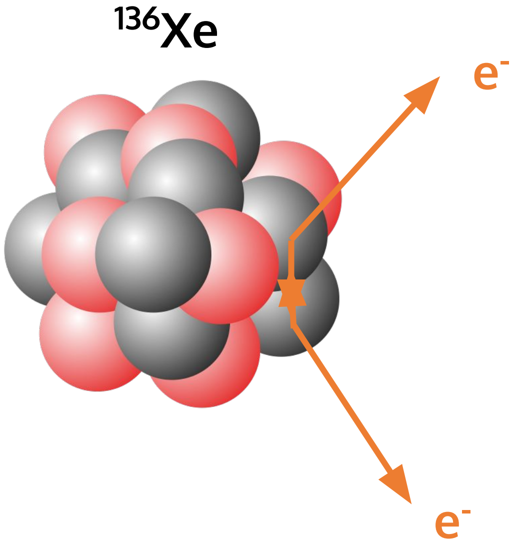
Double beta decay (2νββ)

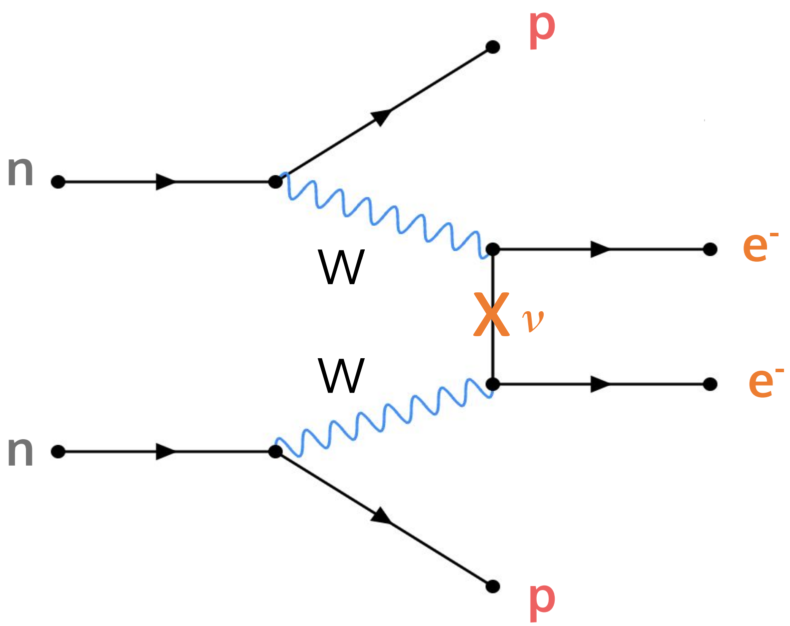




What if neutrinos were Majorana particles?

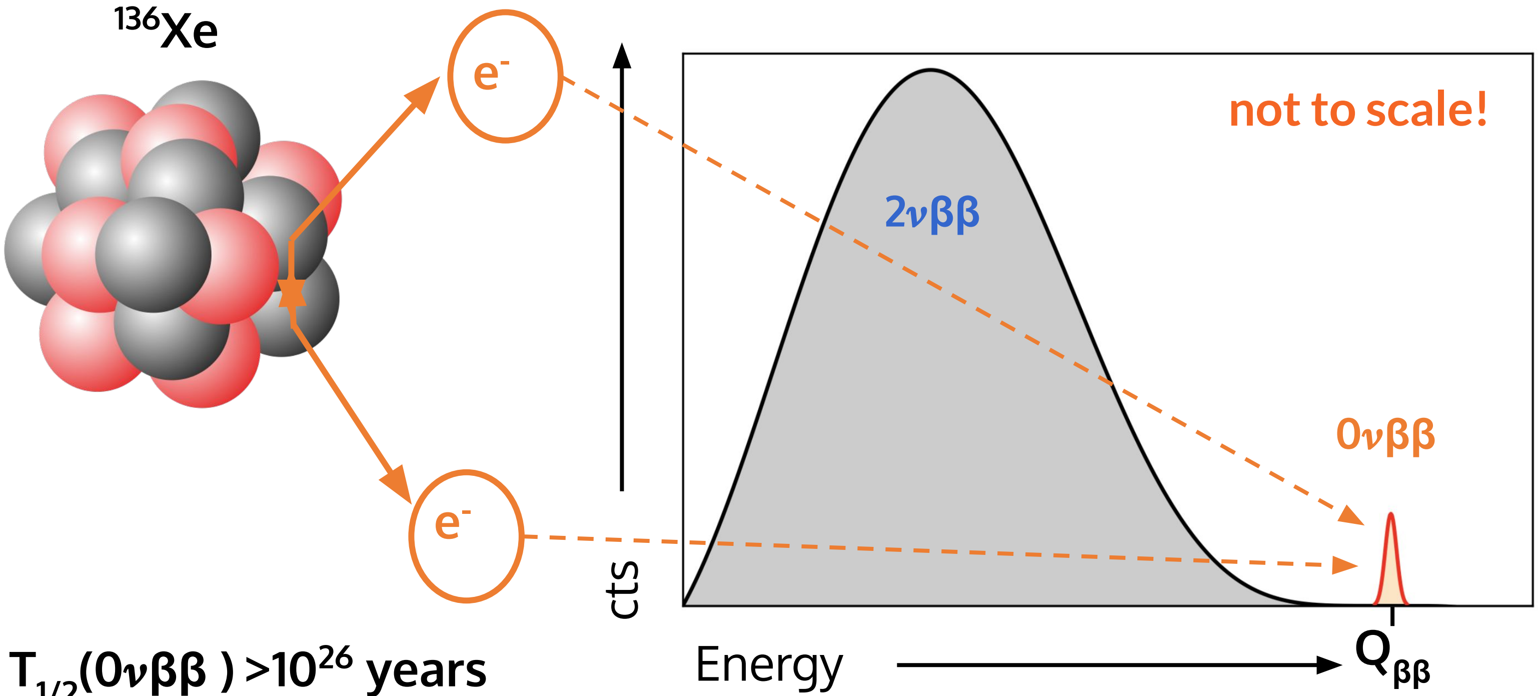
Neutrinoless double beta decay (0νββ)





If neutrinos were Majorana particles ⟶ 0νββ is possible

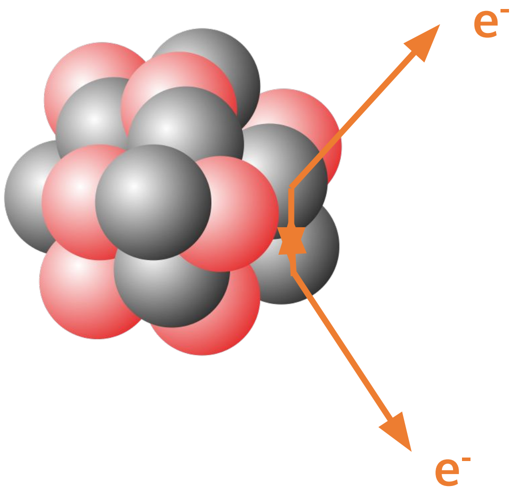
2νββ vs 0νββ

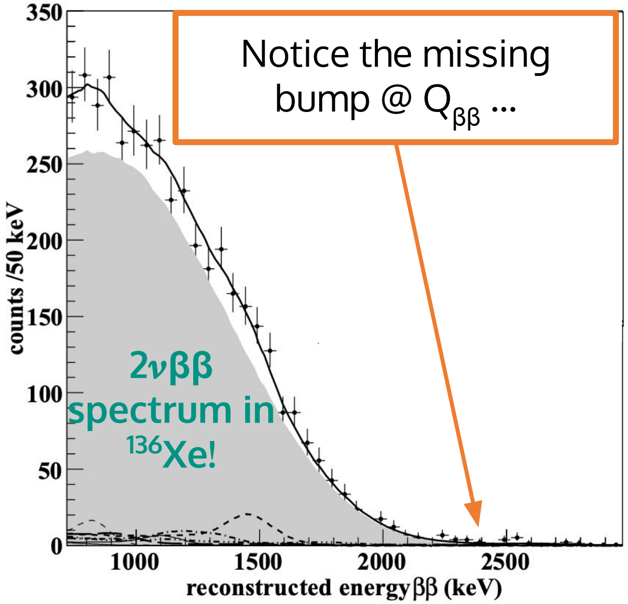


$T_{1/2}(0\nu\beta\beta) > 10^{26}$ years

[KamLAND-Zen limit (2023)](#)

2νββ vs 0νββ



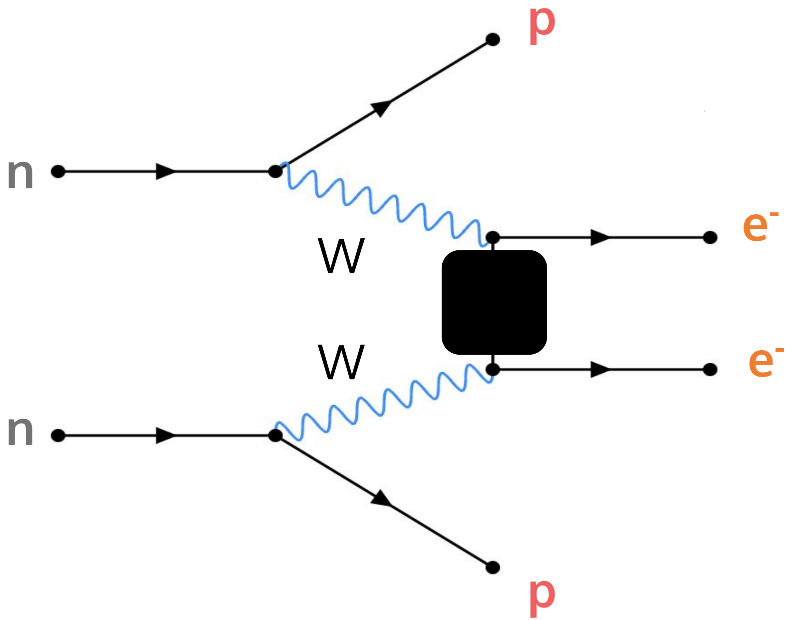


Adapted from: Ackerman, N., et al. "Observation of two-neutrino double-beta decay in Xe-136 with the EXO-200 Detector." *Phys Rev Lett* 107.21 (2011): 212501.

Does 0νββ exist?

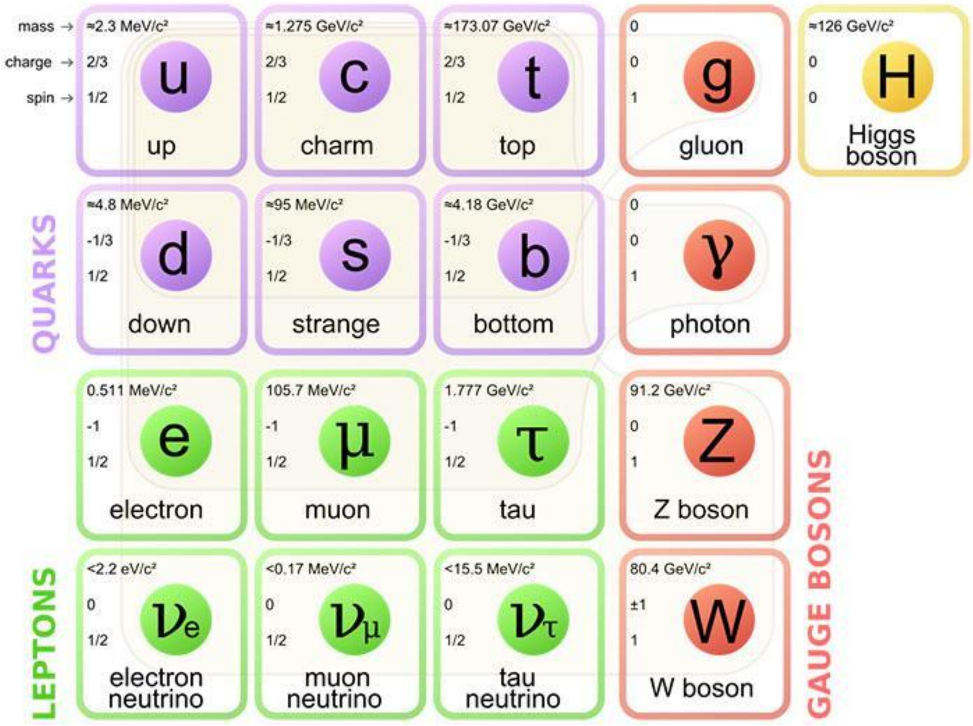
Motivation to search for 0νββ …

Particle physics community searching for physics beyond the Standard Model

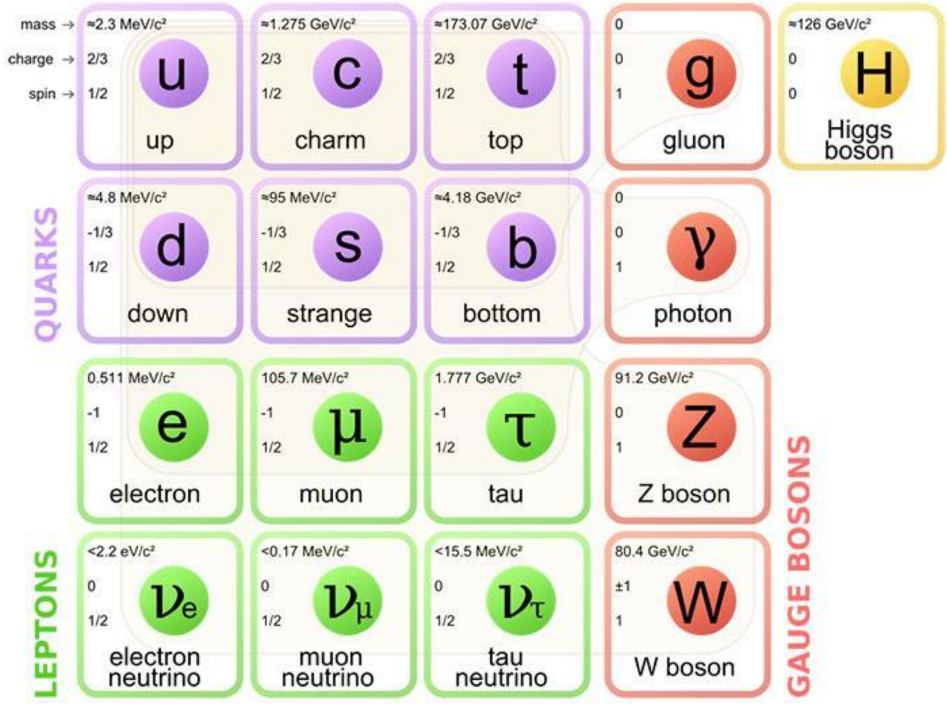


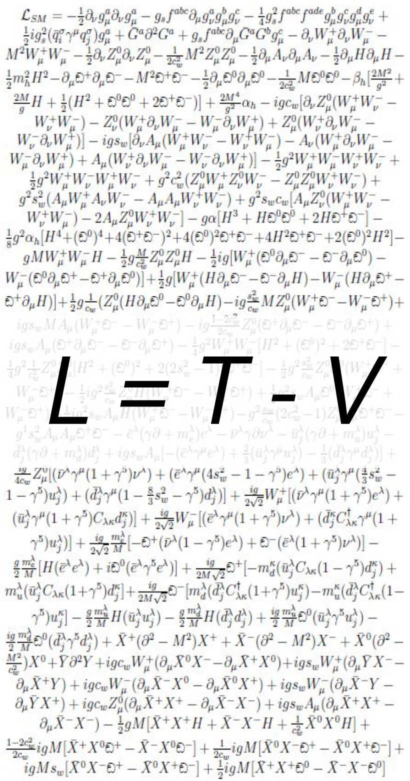
Schecter-Valle "**Black Box theorem**"
… regardless of what mechanism $0\nu\beta\beta$ proceeds by, **$0\nu\beta\beta$ always implies new physics.**

The Standard Model: Particles & Fields



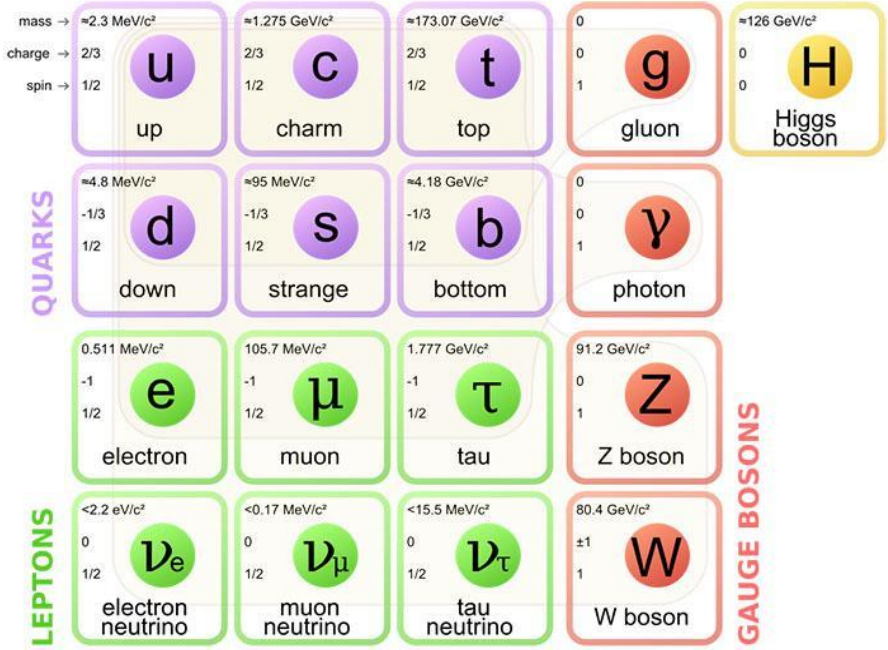
The Standard Model: Lagrangian

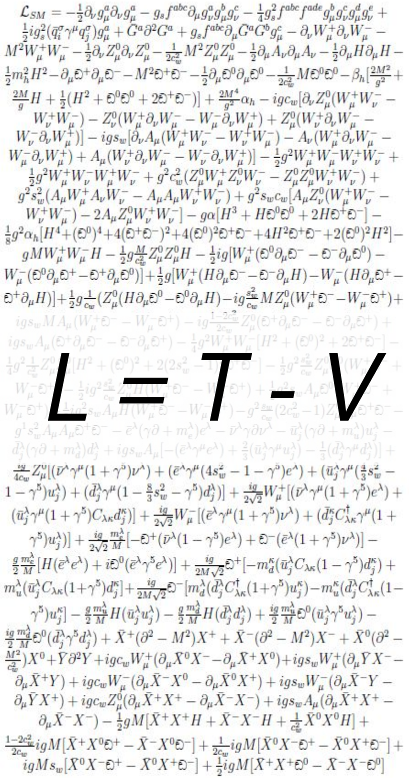




The Standard Model: Symmetries

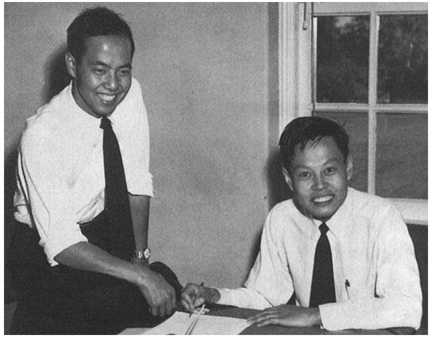
$SU(3) \times SU(2)_L \times U(1)_Y$

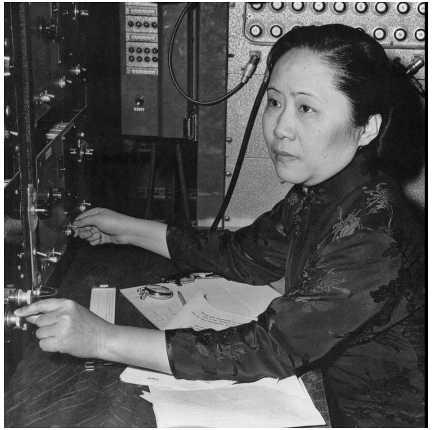




$L = T - V$

Standard Model: Electroweak Symmetry





$SU(3) \times SU(2)_L \times U(1)_Y$

Only **left handed fields feel the weak force**;
It is a parity-violating chiral theory

Parity violated ✅ thanks Dr's Lee, Yang and Wu!

Symmetries of a Lagrangian

↕

Conservation Laws

“Noether’s theorems” – thanks Dr. Emmy!

Symmetries of a Lagrangian

↕

Conservation Laws

… there is no symmetry in the SM Lagrangian protecting lepton number!

"Noether's theorems" – thanks Dr. Emmy!

The Higgs and Mass Generation

Nobel Prize in Physics 1979

Photo from the Nobel Foundation archive.
Sheldon Lee Glashow

Photo from the Nobel Foundation archive.
Abdus Salam

Photo from the Nobel Foundation archive.
Steven Weinberg

credit Royal Swedish Academy of Sciences

Nobel Prize in Physics 1999

Martinus Veltman
Professor Emeritus at the University of Michigan, Ann Arbor, USA, formerly at the University of Utrecht, Utrecht, the Netherlands.

Gerardus 't Hooft
Professor at the University of Utrecht, Utrecht, the Netherlands.

credit Royal Swedish Academy of Sciences

Nobel Prize in Physics 2013

credit: Bob the Bolder & Alexander Mahmoud

$$SU(3) \times \mathbf{SU(2)_L} \times \mathbf{U(1)_Y}$$

(lower energies)

electroweak force breaks down to electromagnetism + weak force

$$SU(3) \times U(1)_{EM}$$

The Higgs and Mass Generation

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$$SU(3) \times \mathbf{SU(2)_L \times U(1)_Y}$$

(lower energies)
electroweak force breaks down to
electromagnetism + weak force

$$SU(3) \times U(1)_{EM}$$

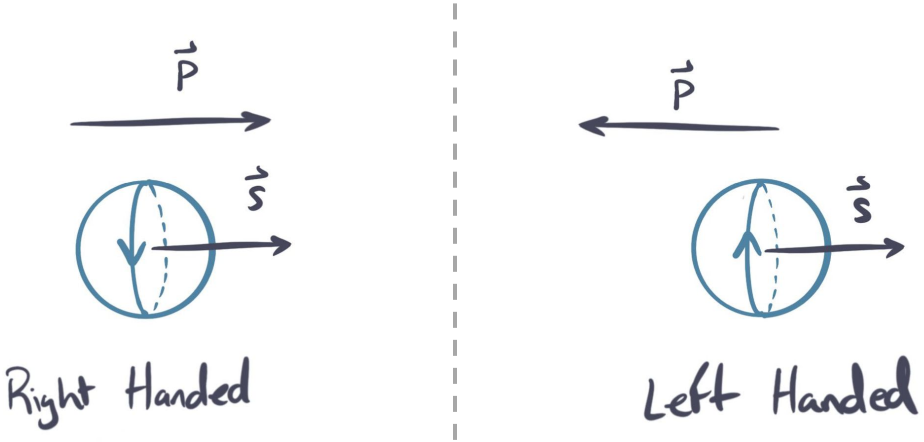
"We can glue the left- and right-chiral fields together and break the electroweak symmetry via **the Higgs mechanism…**"

" … allowing fermions to **acquire a mass**"

… and neutrinos are massless? (c. 1957-1998)

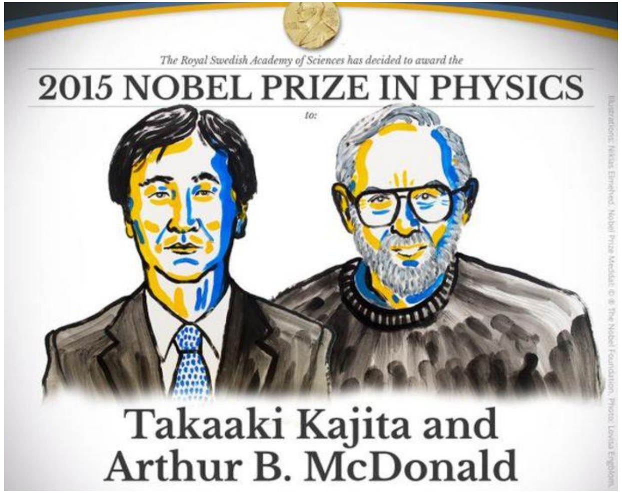
- Kinematically, neutrinos were seemingly massless
- All **neutrinos observed to be left-handed**, all **anti-neutrinos observed to be right-handed***

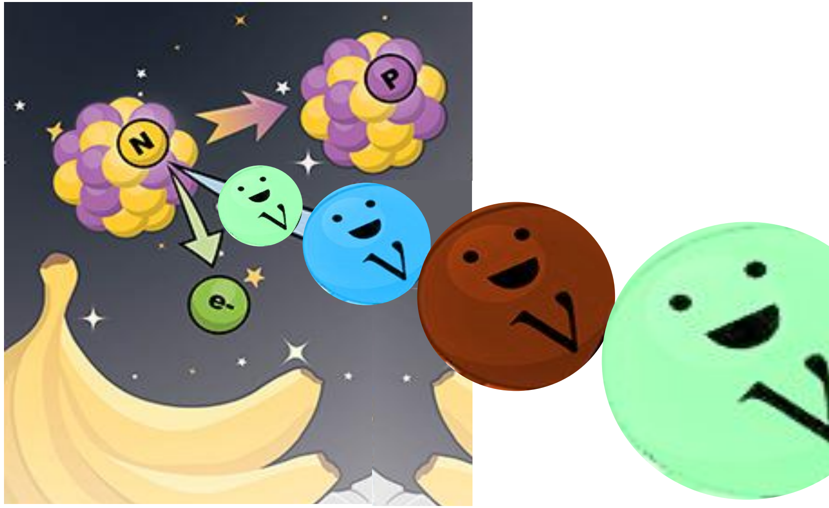
No need for RH-$\nu \longrightarrow$ **no need for additional degrees of freedom**



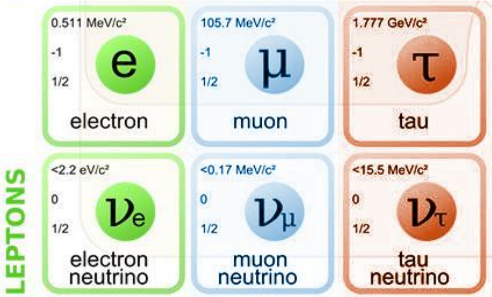
* See: "Goldhaber Experiment"

But neutrinos **must** have mass because they ~*OSCILLATE*~

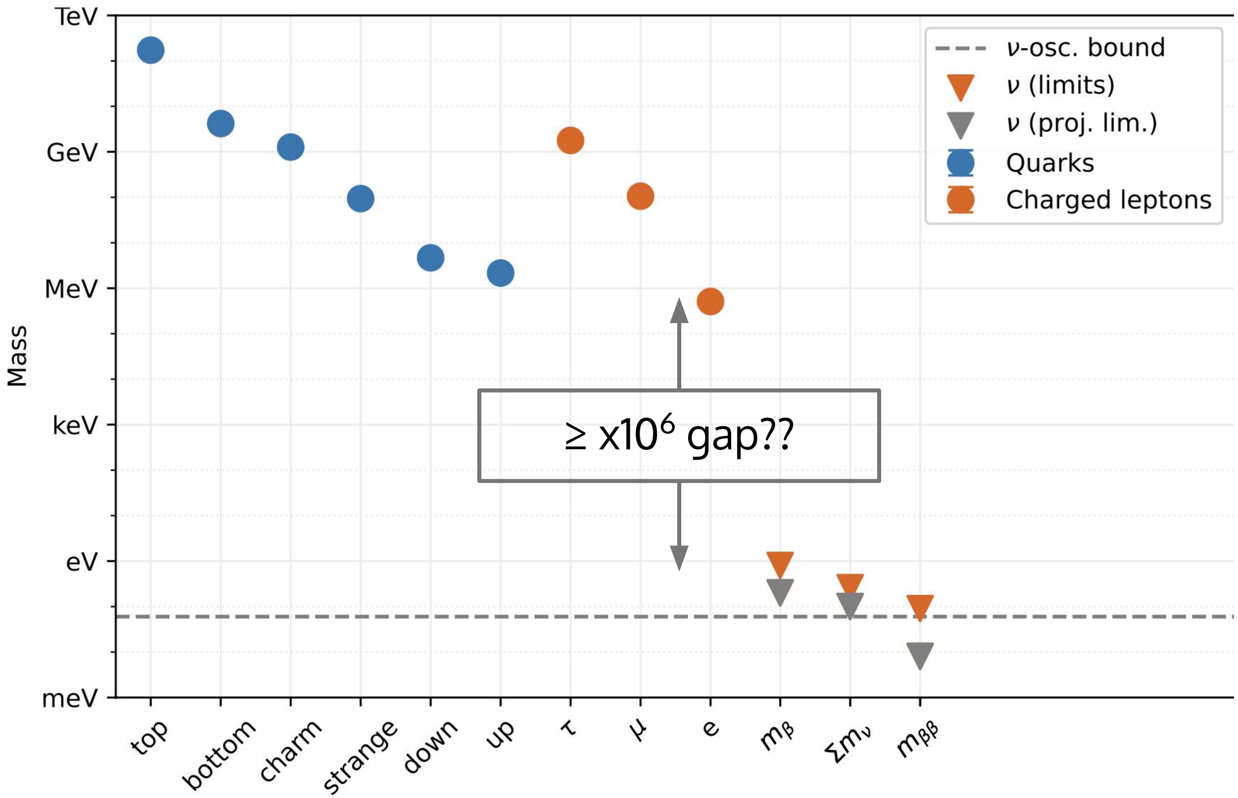




T. Bowman, BNL



How are neutrinos (ν) massive… but so much less massive than everything else?



Solutions to the neutrino mass problem

1. **Add RH-ν fields** to the Standard Model & **tune Higgs coupling to be tiny** for mass terms in the Lagrangian ($Y_c H \nu_R \nu_L$ terms)

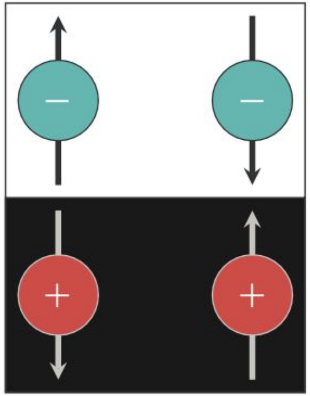
(purely Dirac particles)

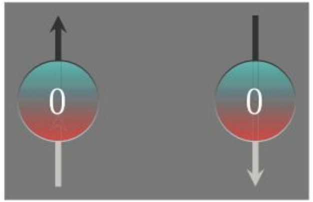
2. Keep Higgs coupling ~ 1 for ν compared to other leptons, allow for a see^{saw}

(Majorana particles)

Do Majorana neutrinos help us?

- **Lose two degrees of freedom** in the SM for Majorana neutrinos
- Weinberg operator:
- Seesaw mechanisms:
- Matter vs Antimatter?





Credit: The State of the Art of Neutrino Physics

Do Majorana neutrinos help us?

- **Lose two degrees of freedom** in the SM for Majorana neutrinos
- **Weinberg operator:** there is **one unique way** you can construct a **next-leading-order operator** in the SM **using only SM particles**. It **naturally produces Majorana neutrinos**, and **violates Lepton number**.
- **Seesaw mechanisms:**
- Matter vs Antimatter?

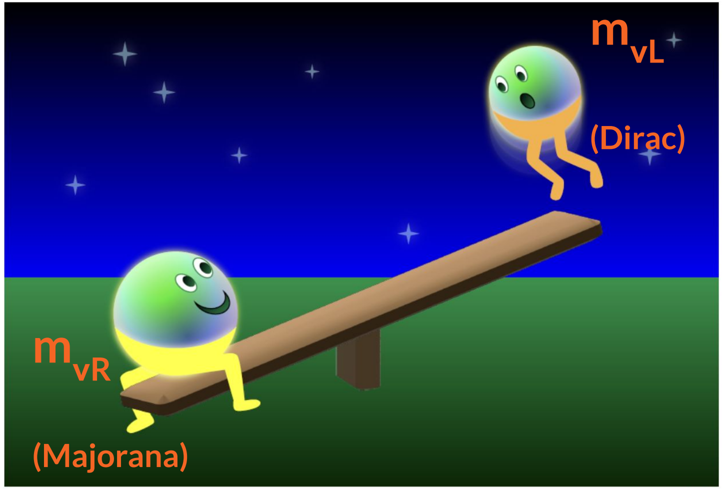
$SU(3) \times SU(2)_L \times U(1)_Y$

$$L_{Weinberg} = Y_c/\Lambda \ L_L \Phi \Phi^{\dagger} L_L$$

Λ: cutoff energy scale, need new physics

Do Majorana neutrinos help us?

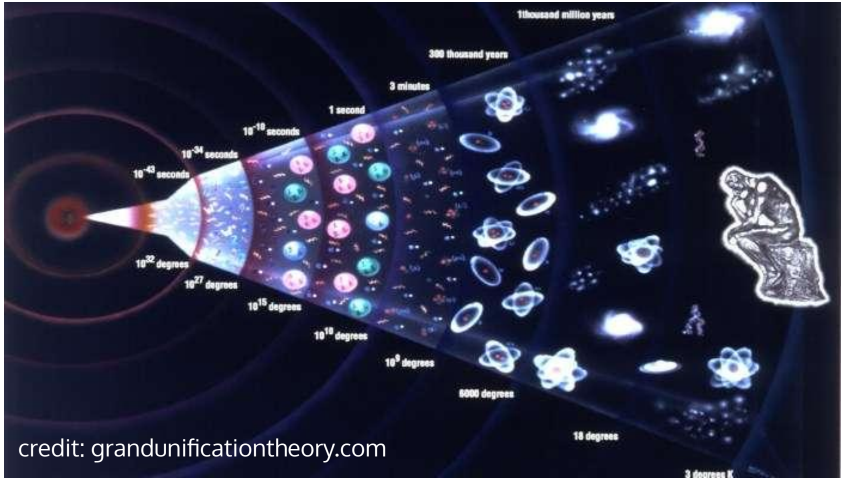
- **Lose two degrees of freedom** in the SM for Majorana neutrinos
- **Weinberg operator**
- **Seesaw mechanisms**: having masses of neutrinos be both Dirac and Majorana neutrinos give you a natural "seesaw" forcing neutrino masses to be small, even though the Higgs' vacuum expectation value is the same for all particles
- **Matter vs Antimatter?**



APS/Alan Stonebraker

Do Majorana neutrinos help us?

- **Lose two degrees of freedom** in the SM for Majorana neutrinos
- **Weinberg operator**
- **Seesaw mechanisms**
- **Matter vs Antimatter?** Maybe $\mathbf{m_{\nu R}}$ associated with Λ and are *really* heavy?
  - Possible explanation for the matter / antimatter asymmetry!! (leptogenesis)



credit: grandunificationtheory.com

Majorana neutrinos naturally give us:

lepton number non-conservation
(Weinberg operator & Schecter-Valle “theorem”)

naturally small neutrino masses
(via see$^{\text{saw}}$ mechanisms)

pathway to matter-antimatter asymmetry
(“leptogenesis”)

But how can we test these ideas?

- **Lose two degrees of freedom** in the SM for Majorana neutrinos
- **Weinberg operator**
- **Seesaw mechanisms**
- **Matter vs Antimatter?**

But how can we test these ideas?

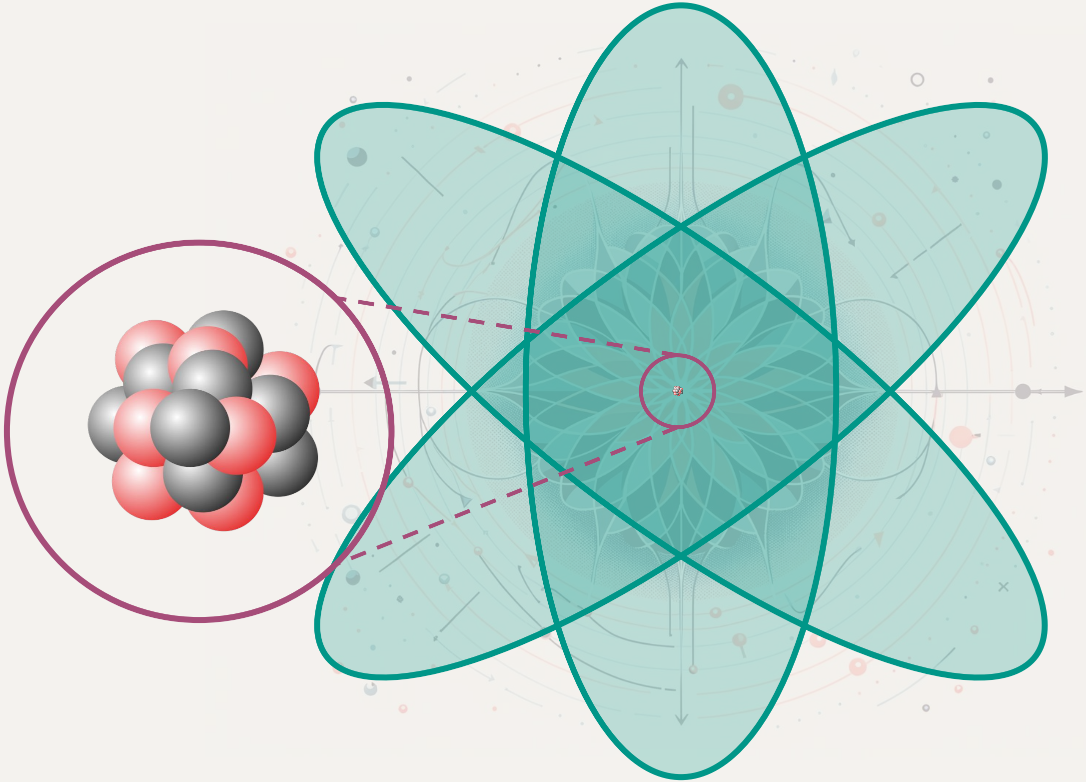
- **Lose two degrees of freedom** in the SM for Majorana neutrinos
- **Weinberg operator**
- **Seesaw mechanisms**
- **Matter vs Antimatter?**

NB: if neutrinos have masses ~meV, then Λ will be ~10^{12} TeV

LHC √s energy is ~13 TeV: **we should not expect to see *this* new physics at colliders in our lifetime!***

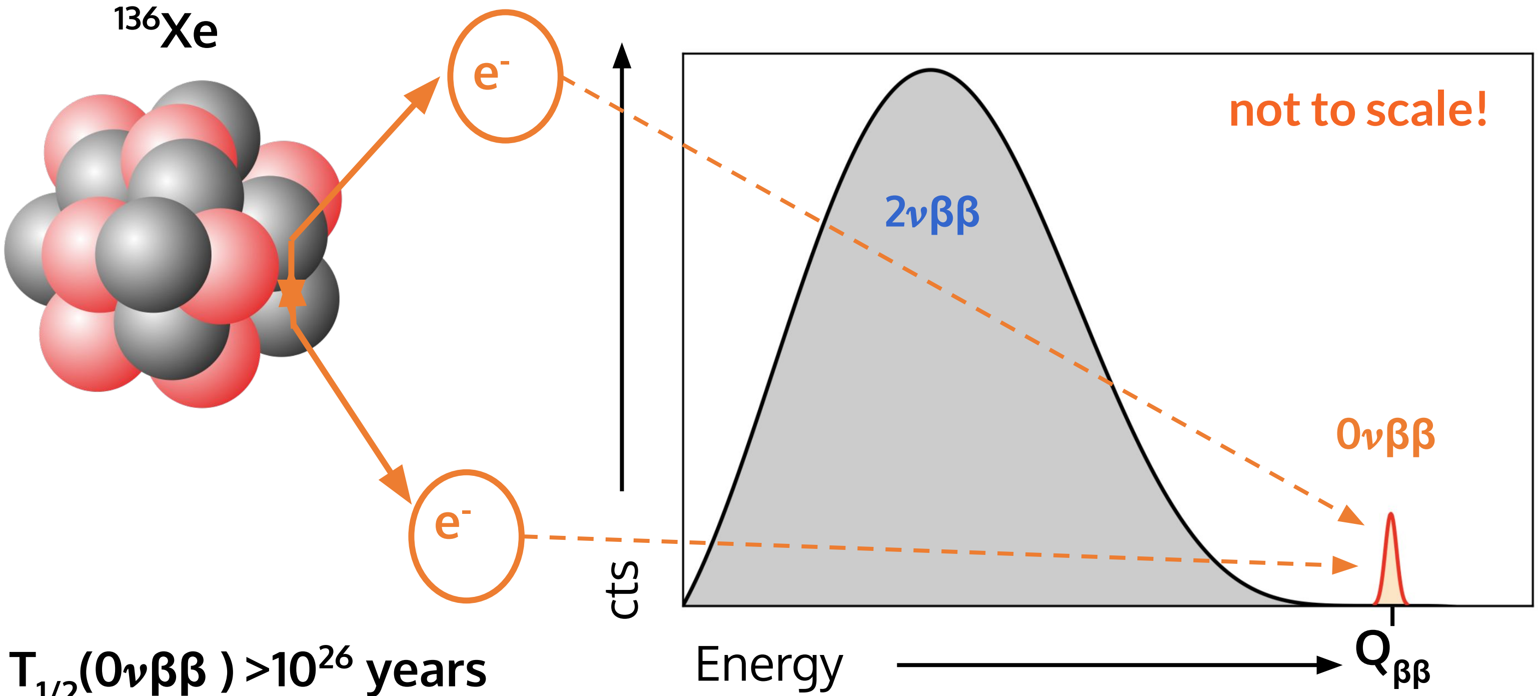
*FCC-hh √s energy is ~100 TeV

Exploring Majorana neutrinos



through the lens of an atomic nucleus

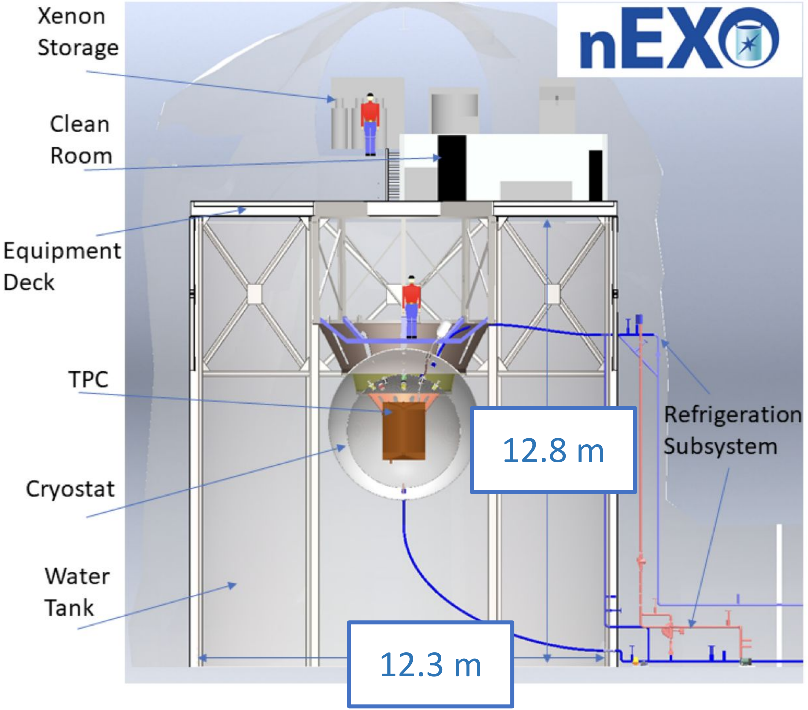
$2\nu\beta\beta$ vs $0\nu\beta\beta$



$T_{1/2}(0\nu\beta\beta) > 10^{26}$ years

The nEXO 0νββ Experiment

- 5-tonnes of LXe is **enriched to 90% in the target isotope, ^{136}Xe**
- LXe in a single-phase liquid xenon Time Projection Chamber (**LXe TPC**)
- **Surrounded by a large water tank** for radioactive shielding and **muon tagging**



[Adhikari, Govinda, et al. "nEXO: neutrinoless double beta decay search beyond 1028 year half-life sensitivity." *Journal of Physics G: Nuclear and Particle Physics* 49.1 (2021): 015104.]

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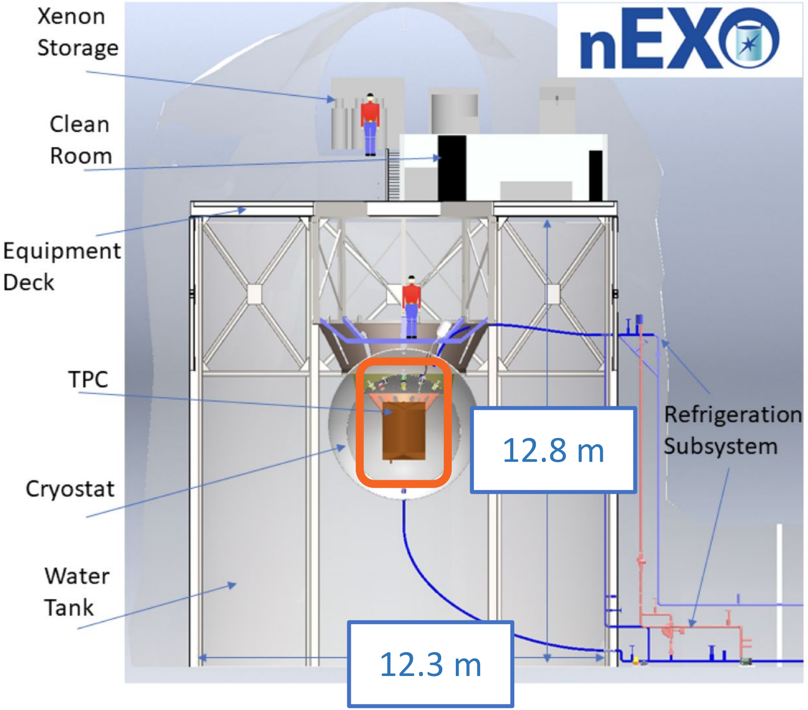

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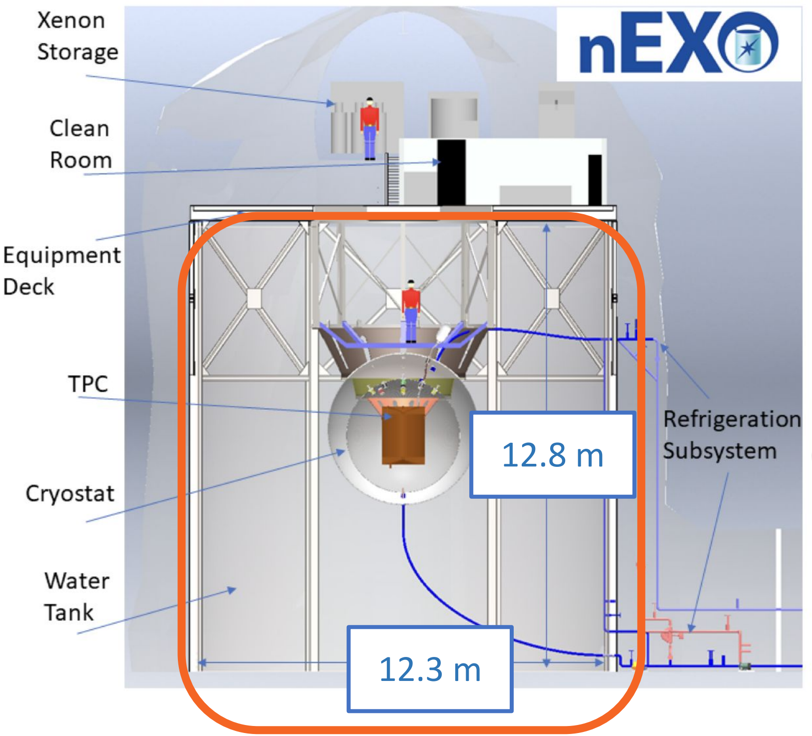

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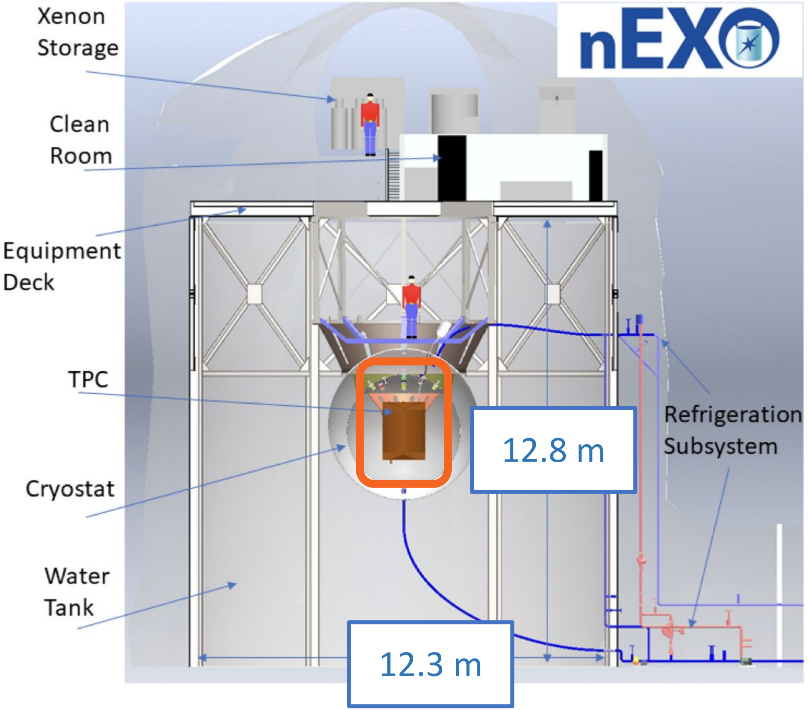

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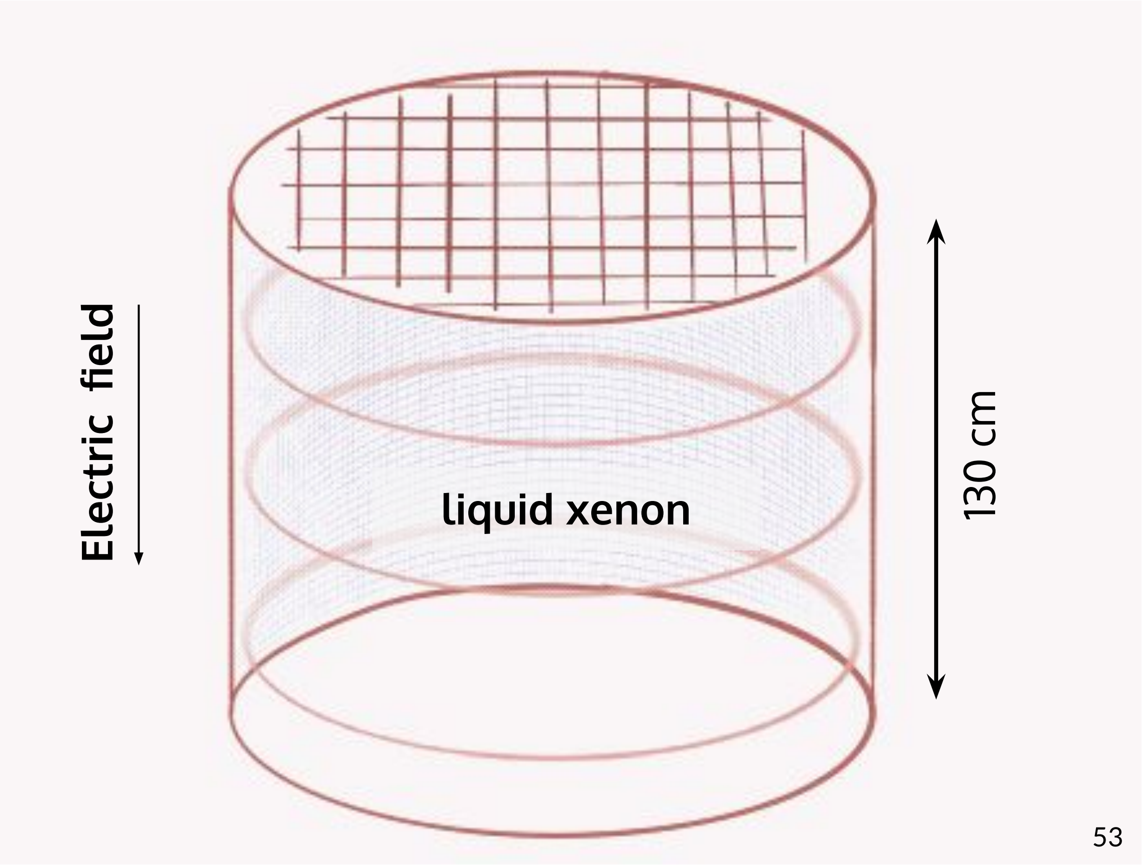
nEXO’s Time Projection Chamber (TPC)



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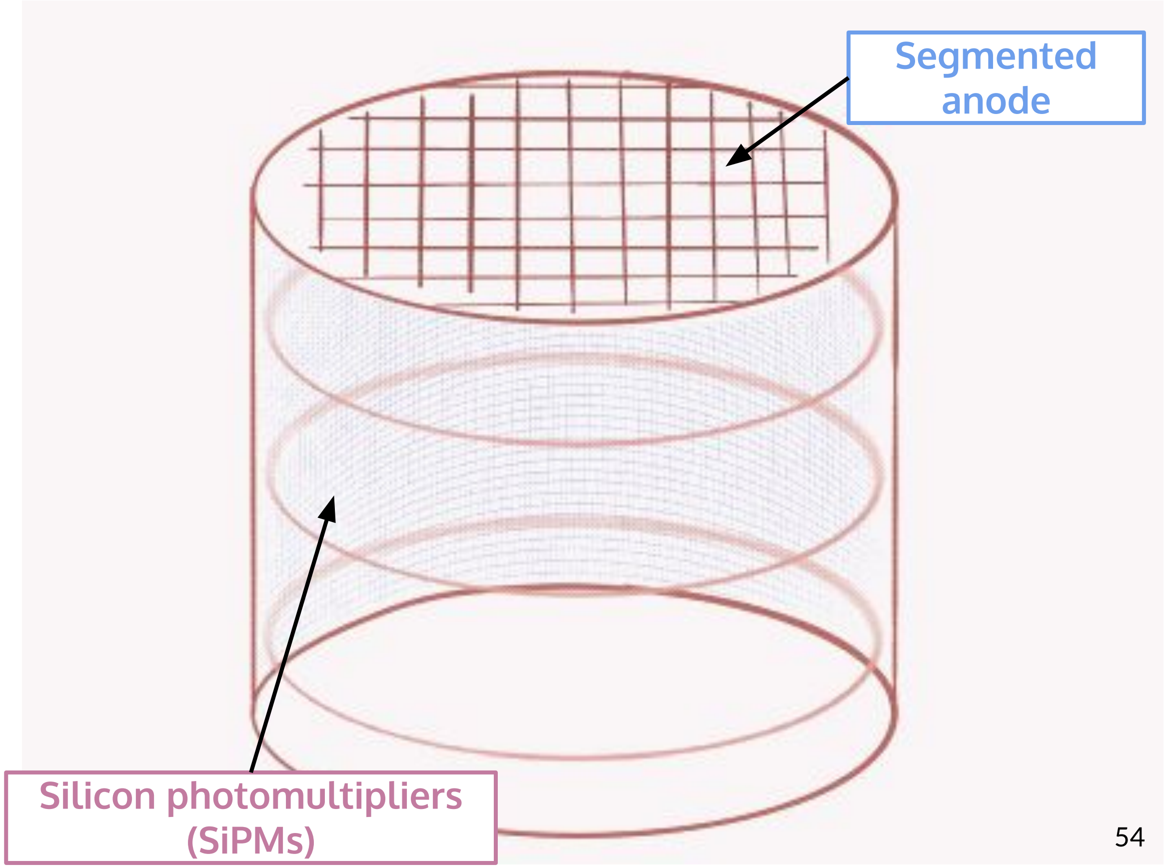
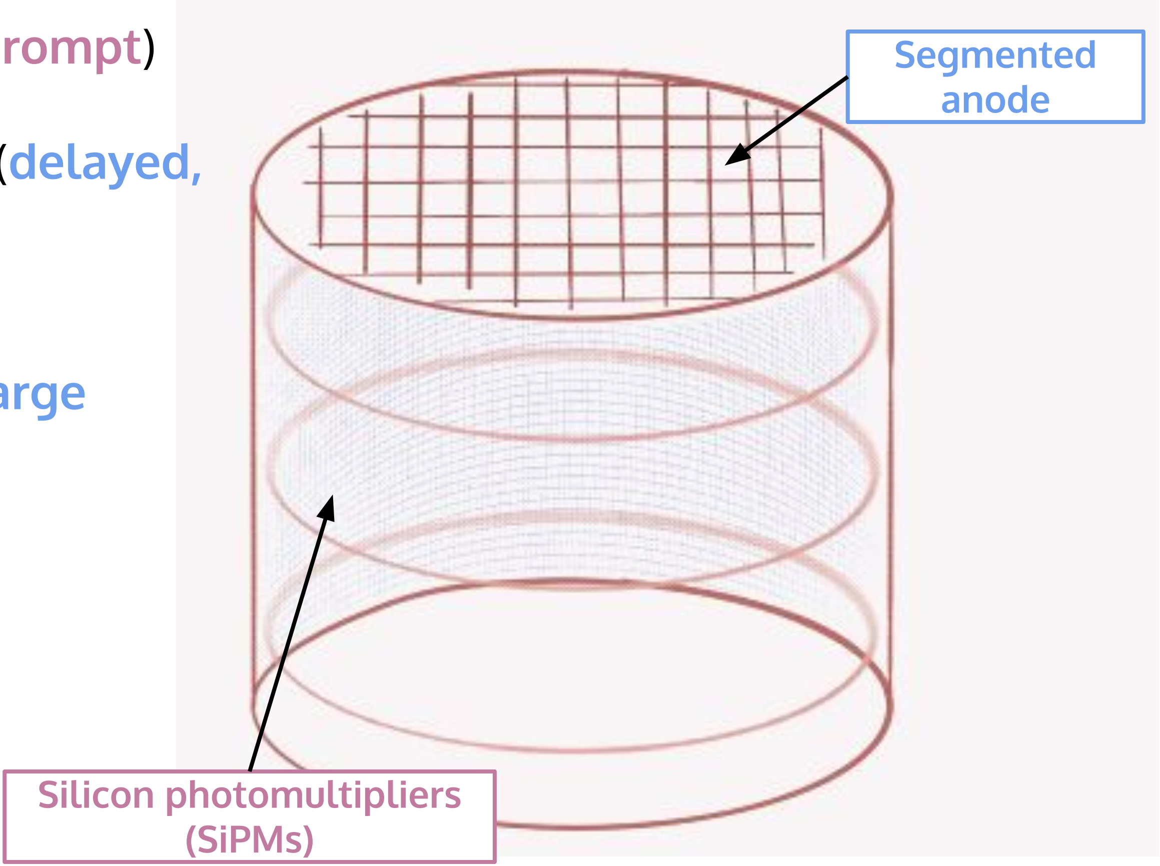


More on SiPMs in F. Retiere's talk tomorrow

nEXO's Time Projection Chamber (TPC)

1. Flash of scintillation light (prompt)
2. Ionization charge detected (delayed, provides **x-y projection**)
3. **Time difference** of light+charge readout provides **z-position**

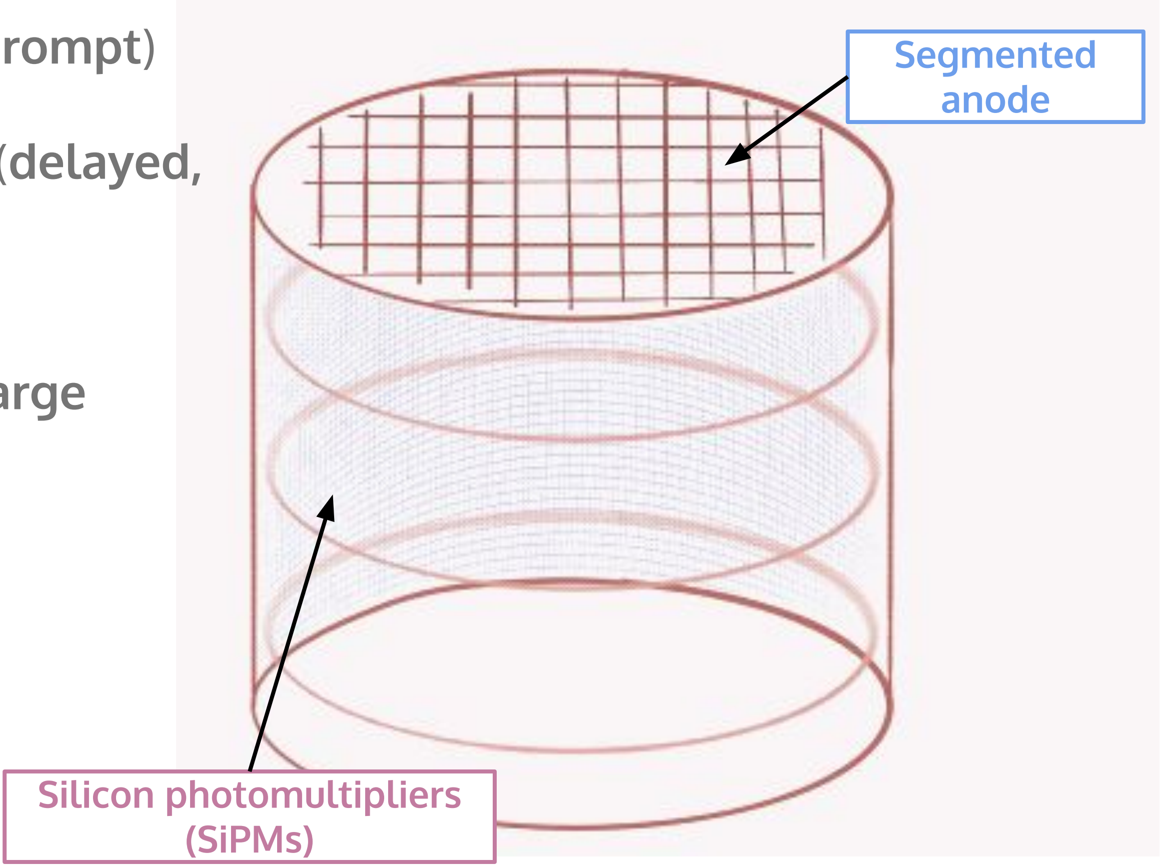


nEXO's Time Projection Chamber (TPC)

1. Flash of **scintillation light (prompt)**
2. **Ionization charge detected (delayed,** provides **x-y projection)**
3. **Time difference** of **light+charge** readout provides **z-position**

light+charge also improves energy resolution, σ_E!

Conti, E., et al. "Correlated fluctuations between luminescence and ionization in liquid xenon." *Physical Review B* 68.5 (2003): 054201.



3 high-level analysis variables separate signal from backgrounds in nEXO

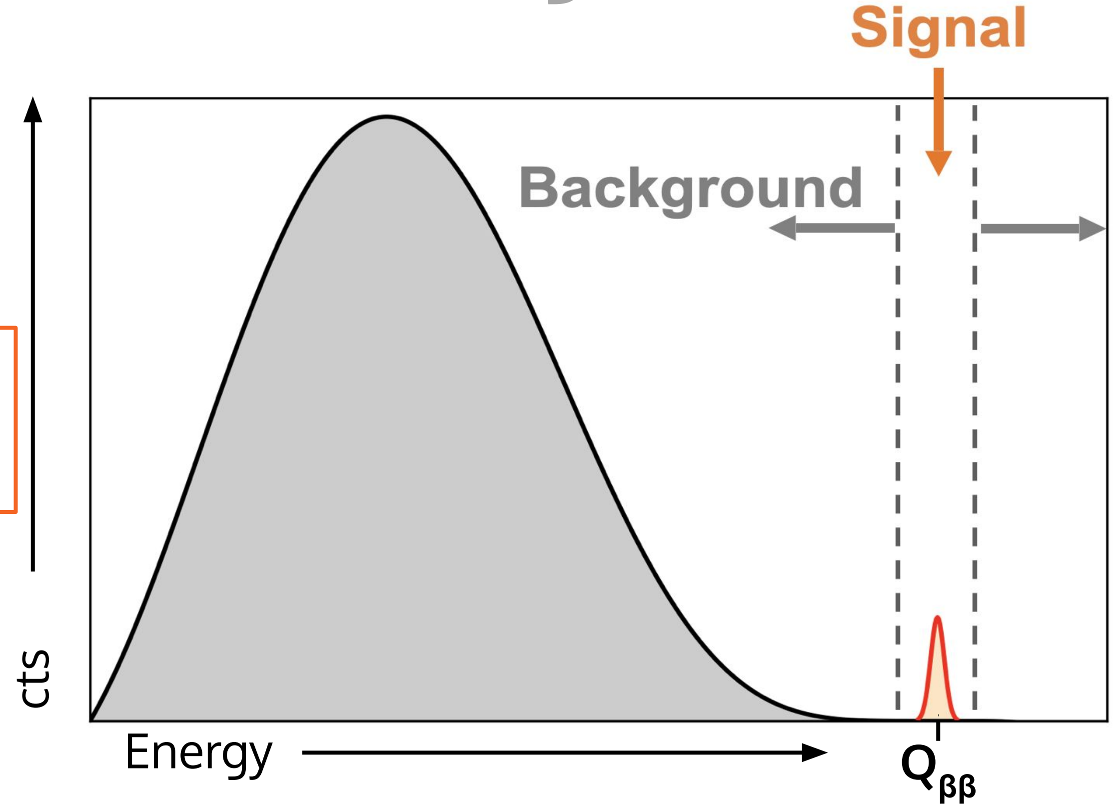
Energy, Standoff, Topology

3 high-level analysis variables separate signal from backgrounds

1. Energy

$Q_{\beta\beta}$ = 2.458 MeV

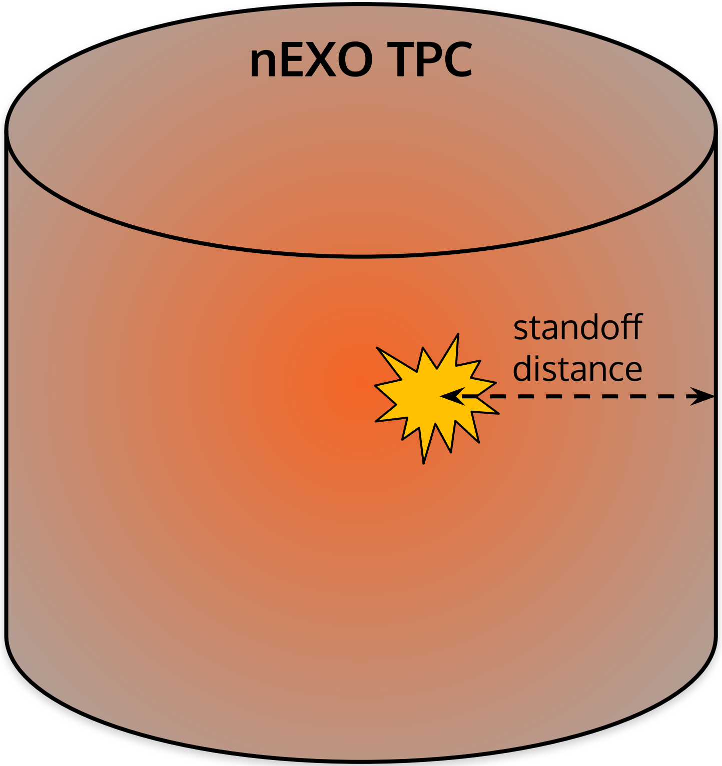
σ_E < 1%



3 high-level analysis variables separate signal from backgrounds

2. Standoff distance

Signal is homogeneous
Backgrounds are attenuated

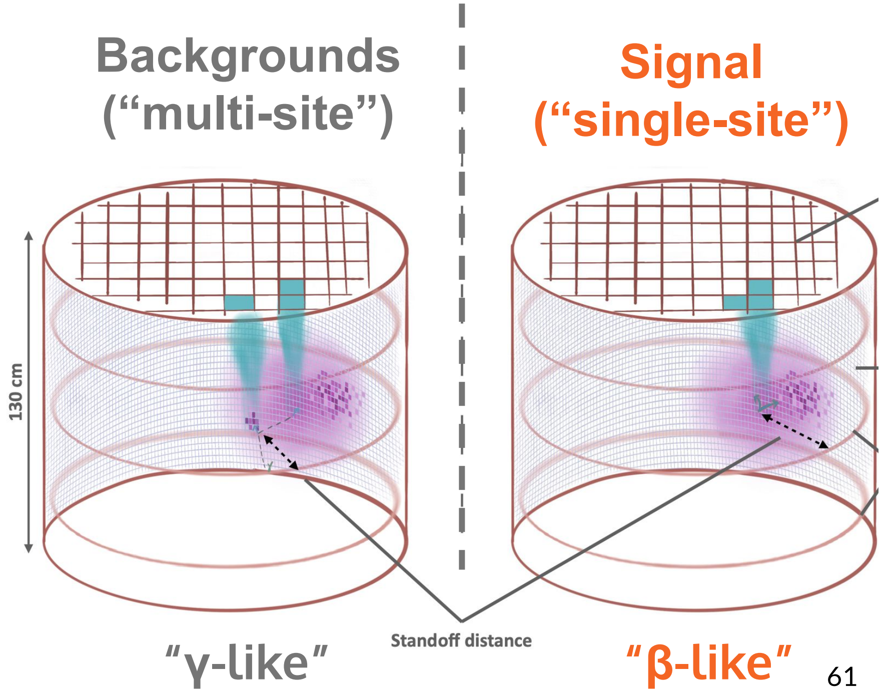


3 high-level analysis variables separate signal from backgrounds

3. Topology

Deep Neural Network (DNN) discriminator

Signal DNN score ⟶ 1
Background DNN ⟶ 0



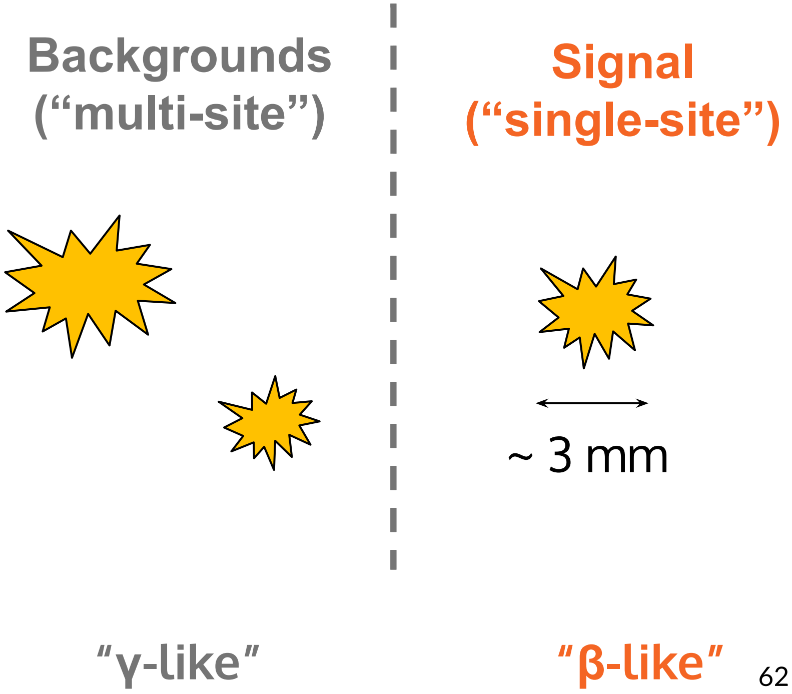
Li, Z., et al. "Simulation of charge readout with segmented tiles in nEXO." *Journal of Instrumentation* 14.09 (2019): P09020.

3 high-level analysis variables separate signal from backgrounds

3. Topology

Deep Neural Network (DNN) discriminator

Signal DNN score ⟶ 1
Background DNN ⟶ 0



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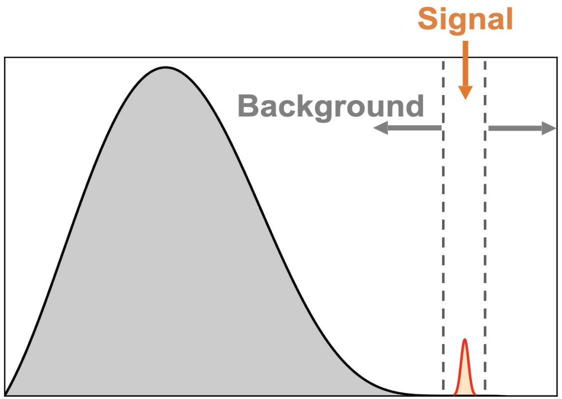
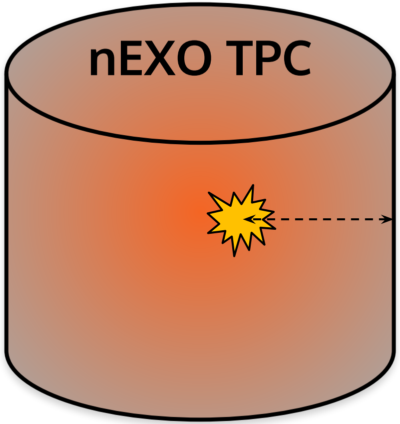
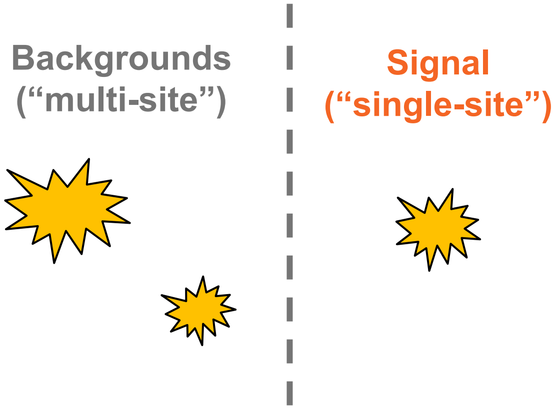
3 high-level analysis variables separate signal from backgrounds



Energy

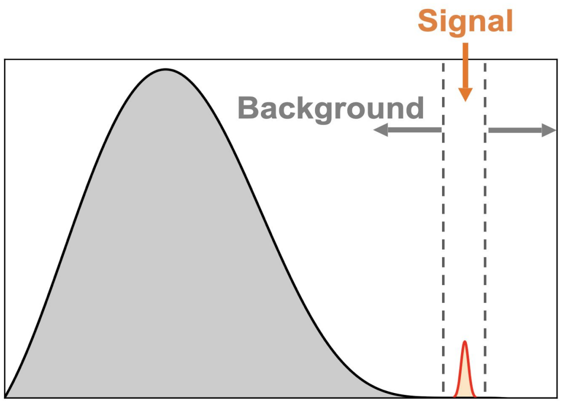


Standoff

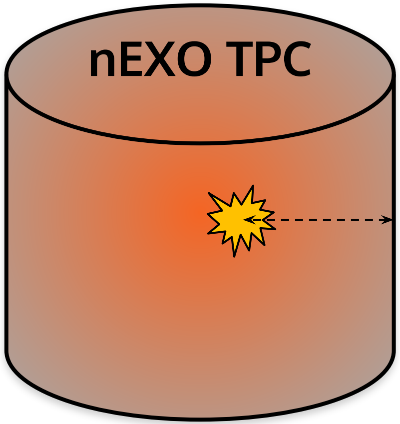


Topology

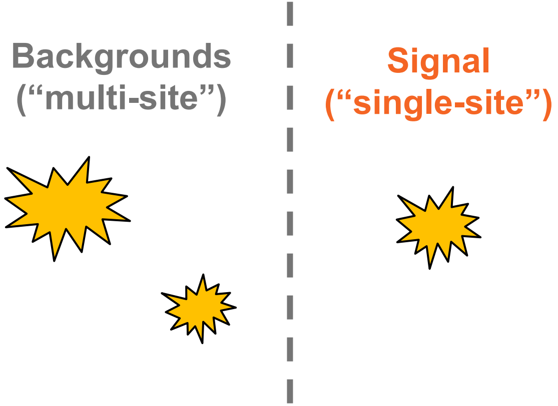
3 high-level analysis variables separate signal from backgrounds



Energy



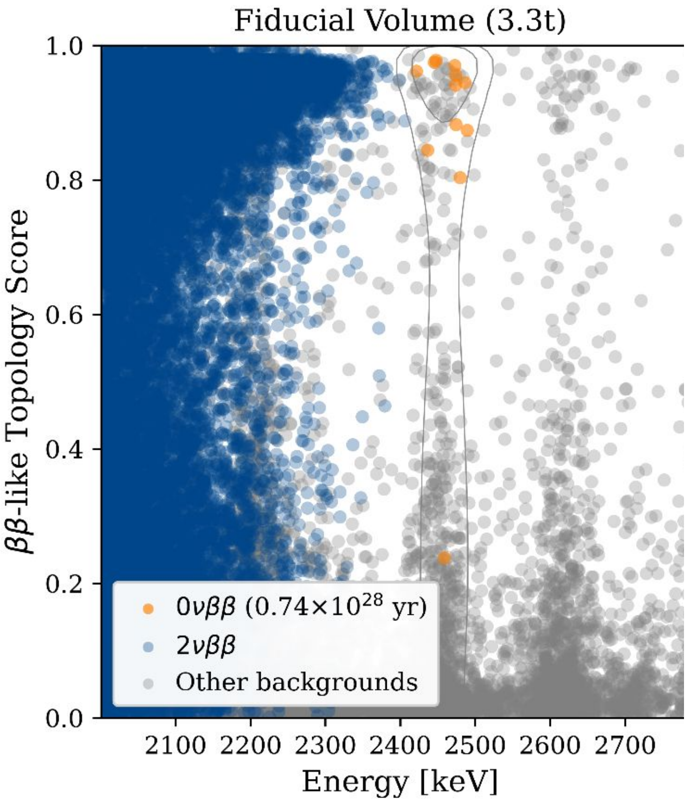
Standoff

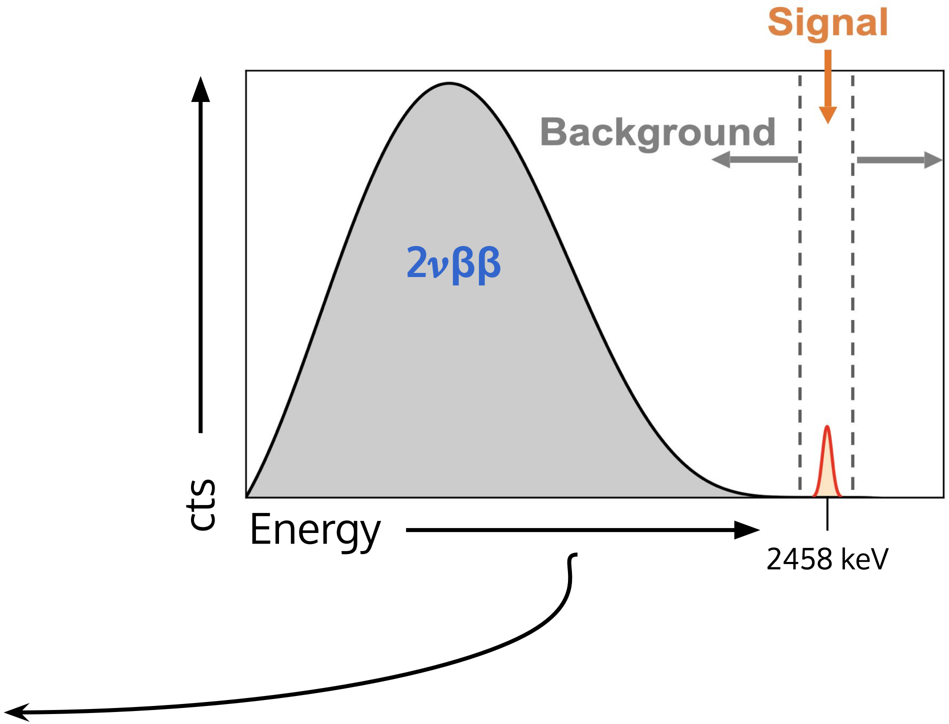


Topology

What does a nEXO dataset look like?

3D data (example 10 yr dataset)





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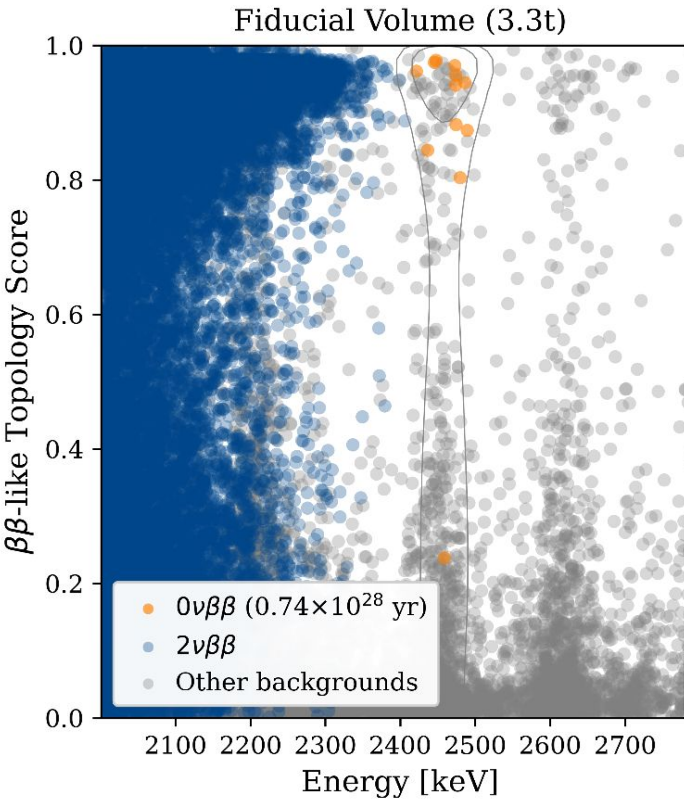

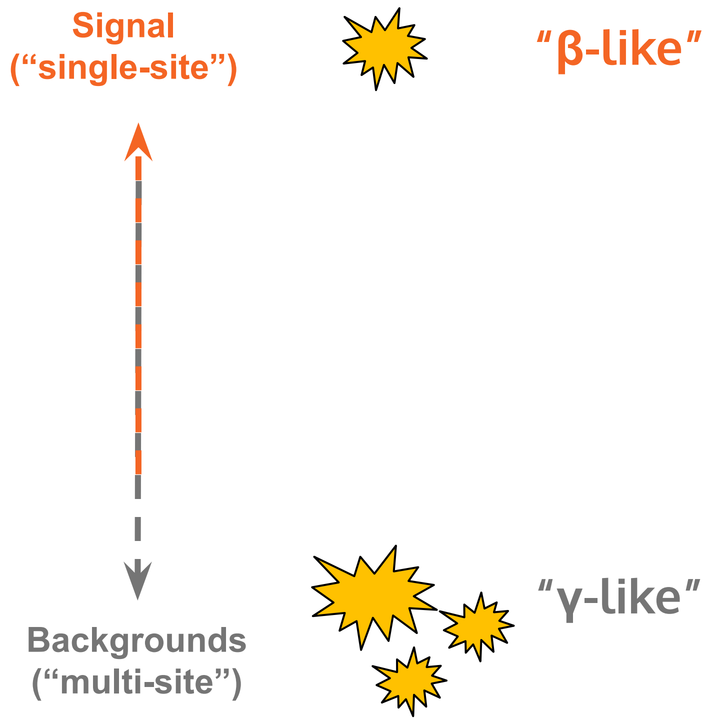

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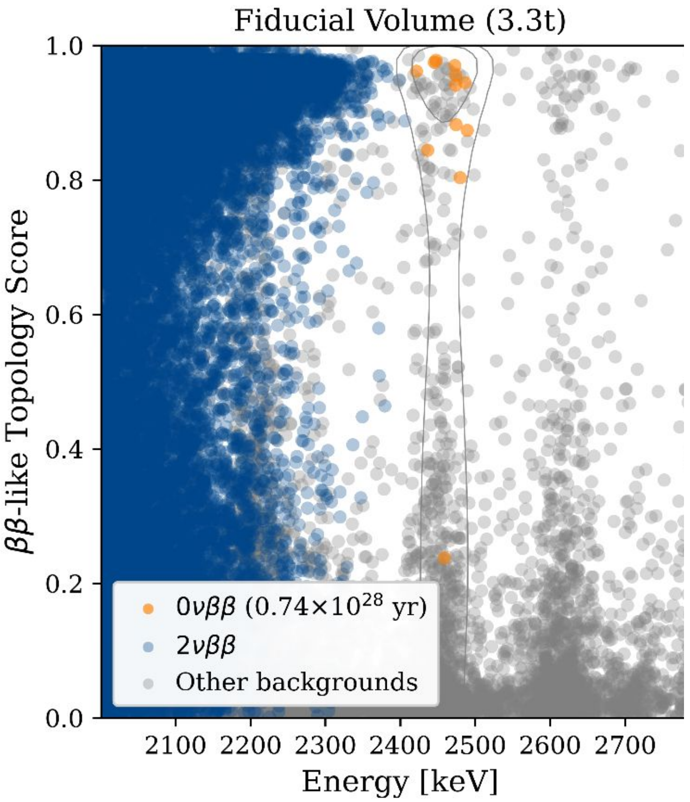

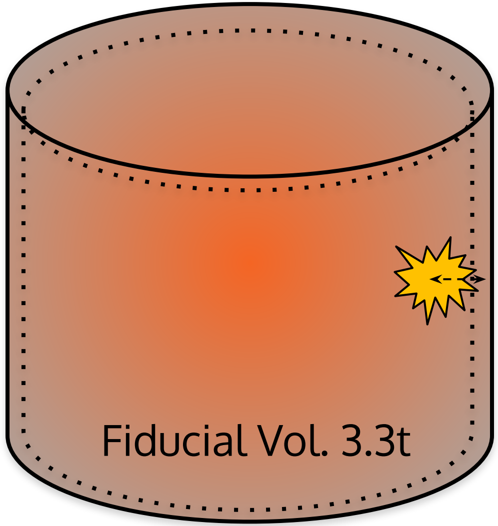

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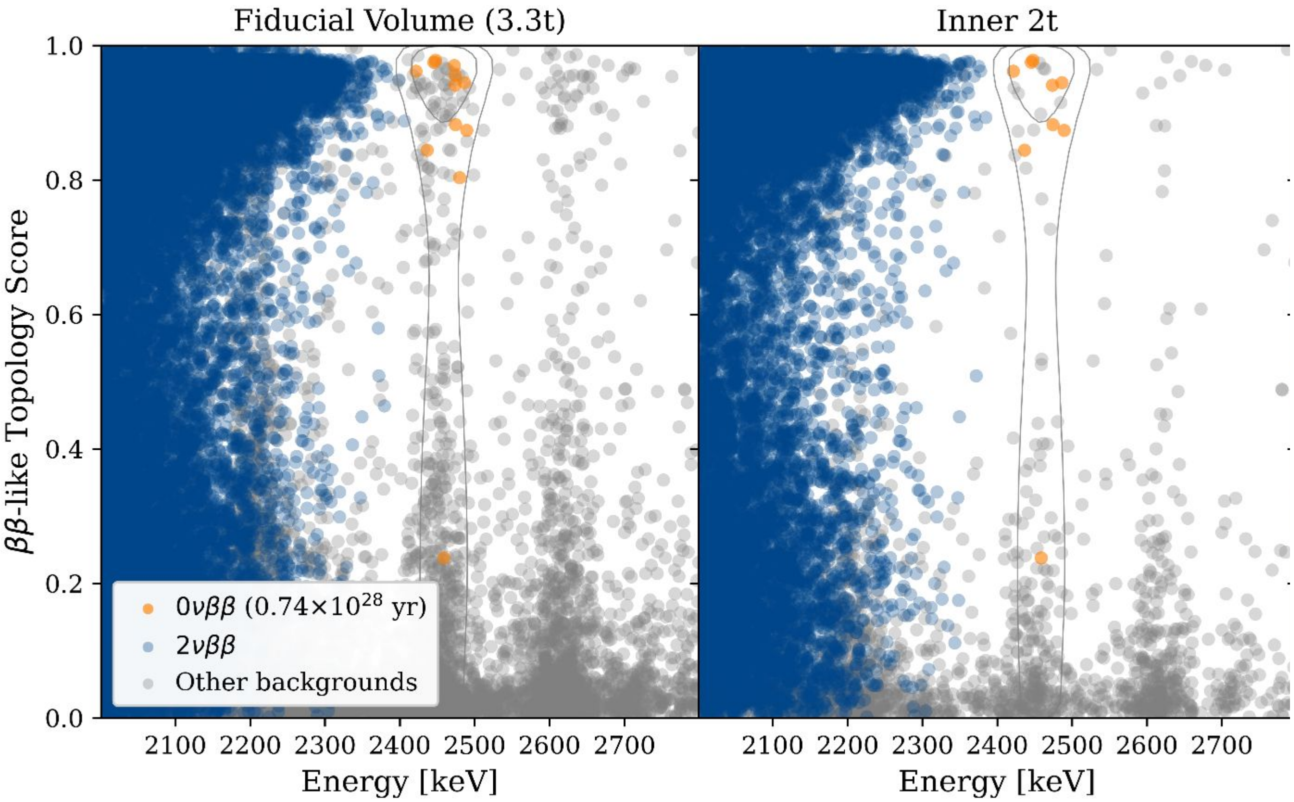
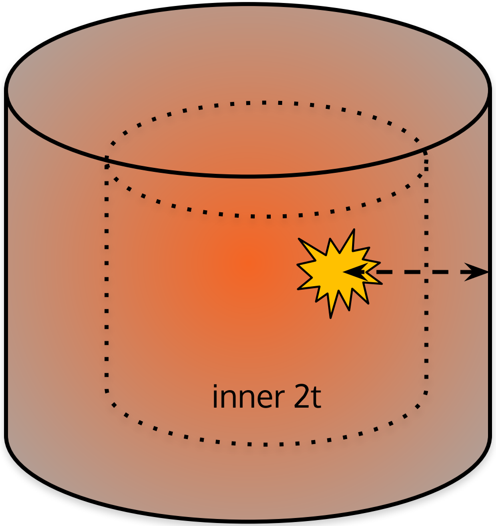
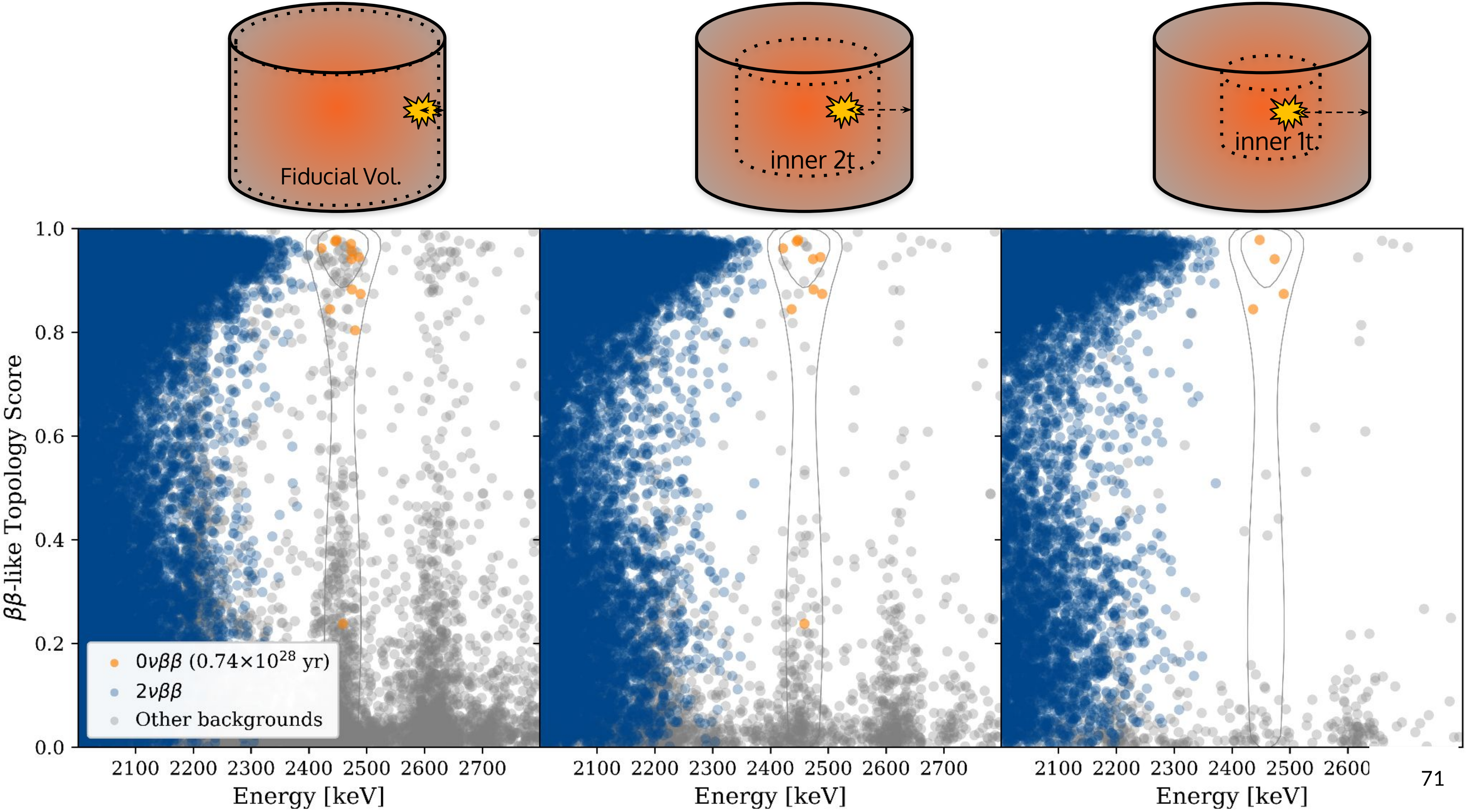
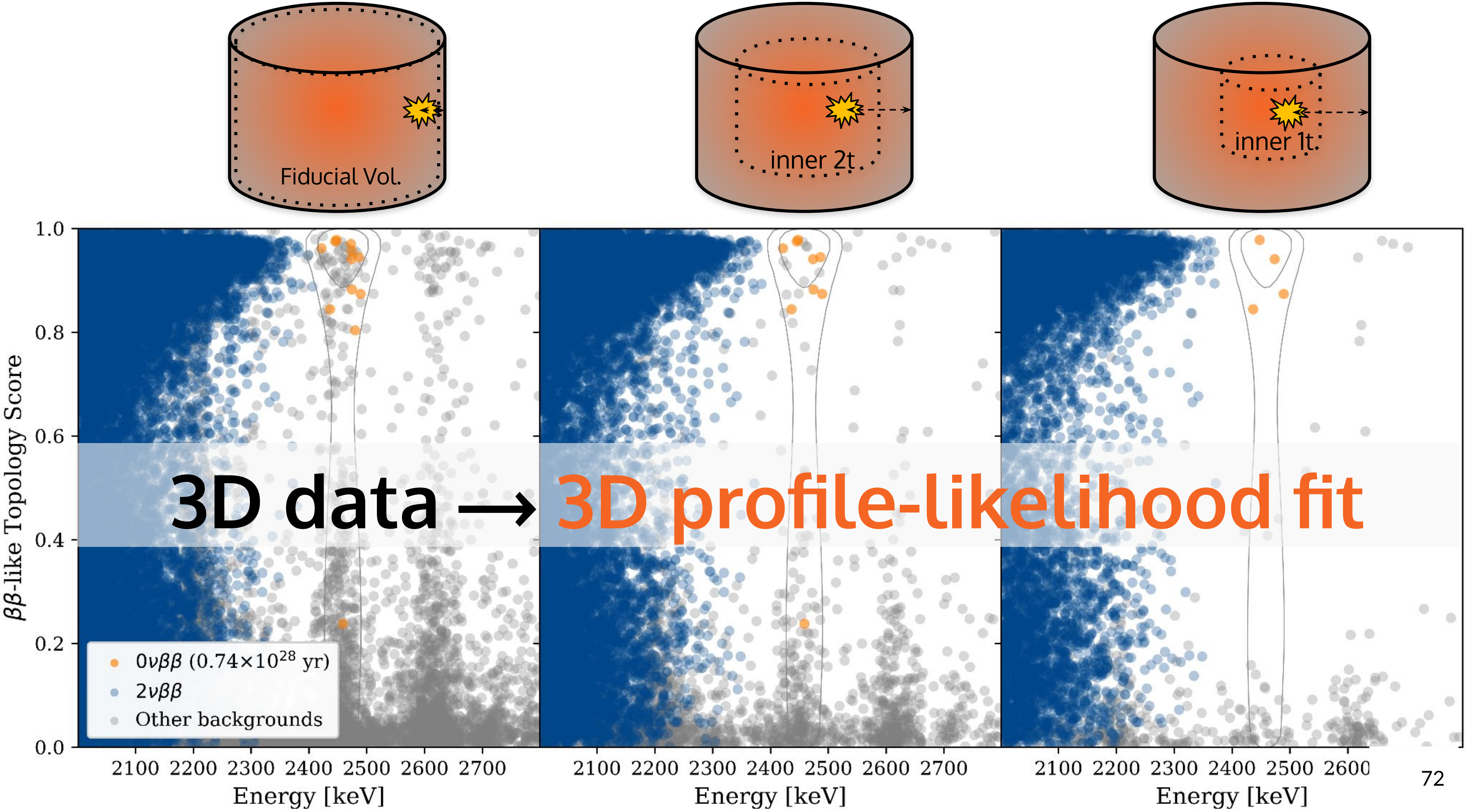




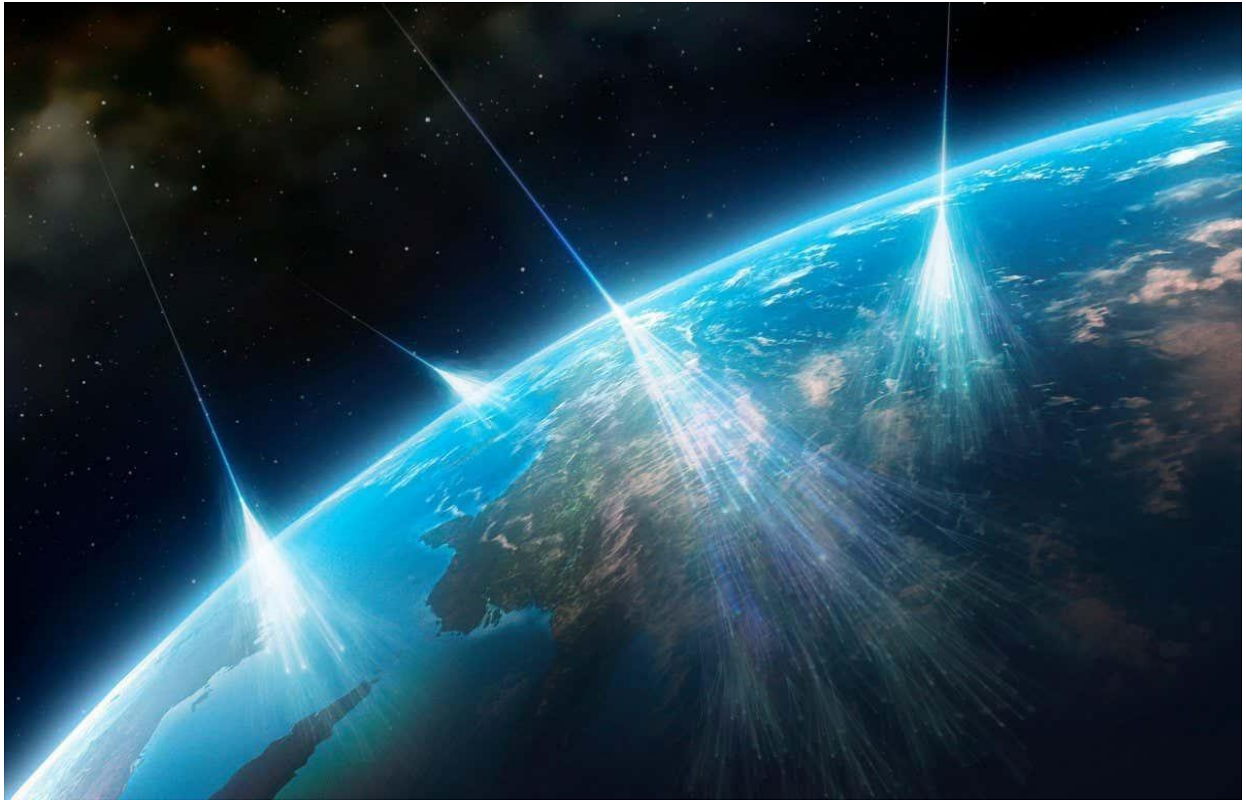


Fiducial Vol.
inner 2t
inner 1t
ββ-like Topology Score
Energy [keV]
0νββ (0.74×10^28 yr)
2νββ
Other backgrounds



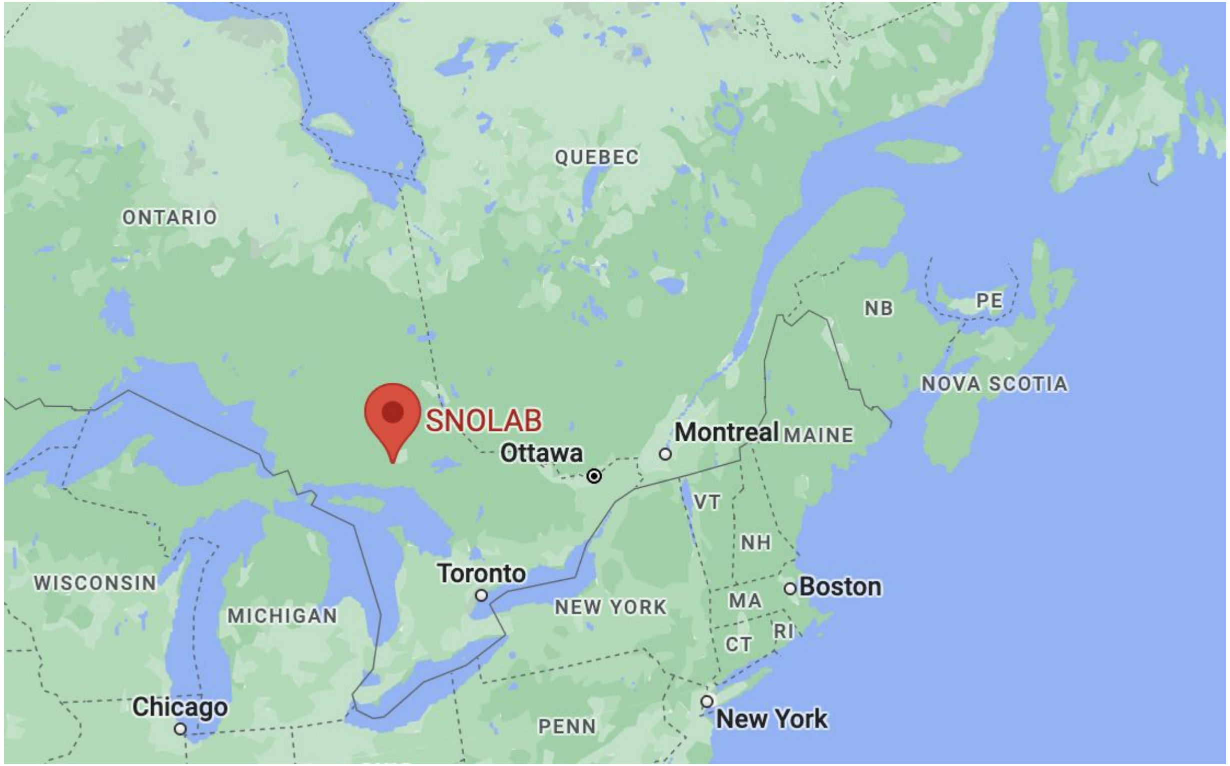
3D data ⟶ 3D profile-likelihood fit

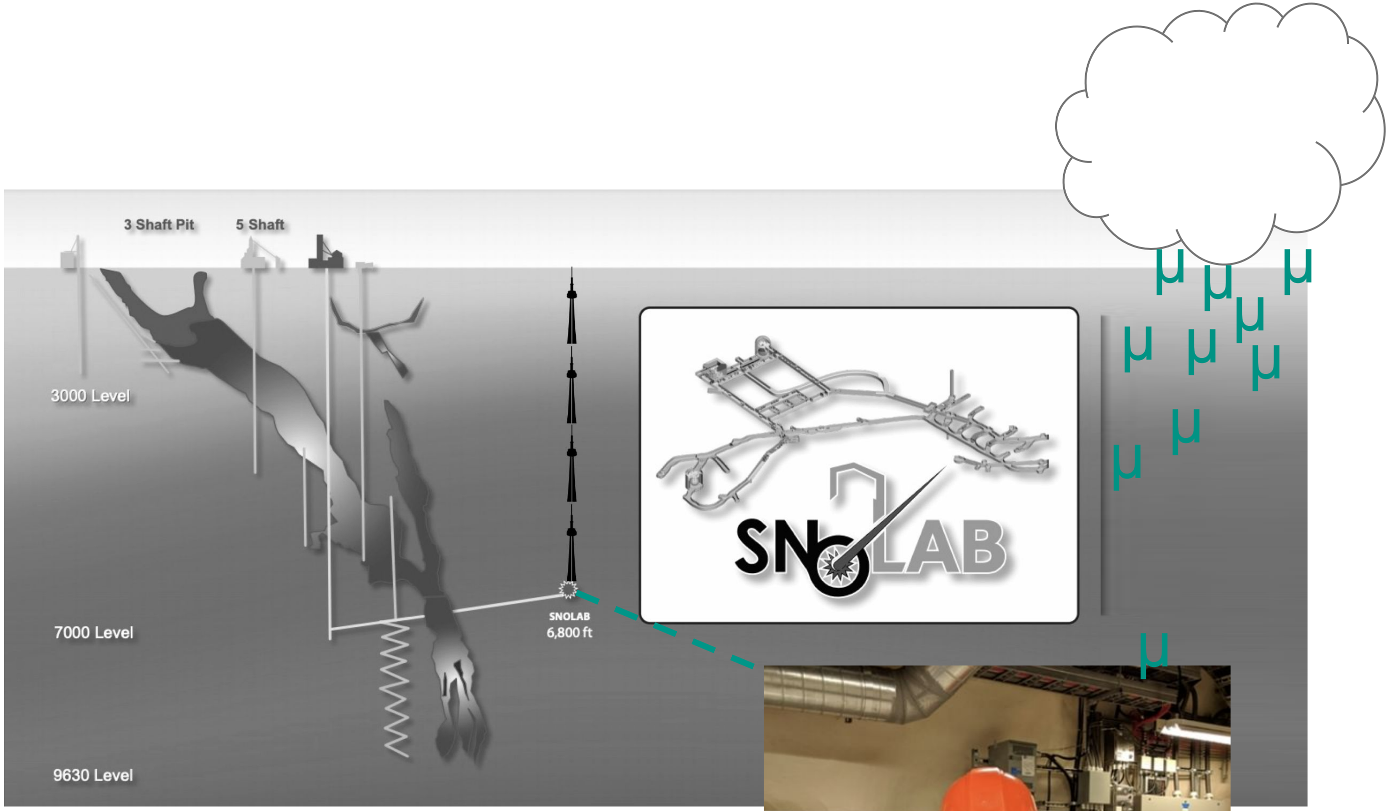
Cosmogenic Backgrounds



MARK GARLICK/SCIENCE PHOTO LIBRARY/Alamy

We shield against muons by going underground ⟶ SNOLAB

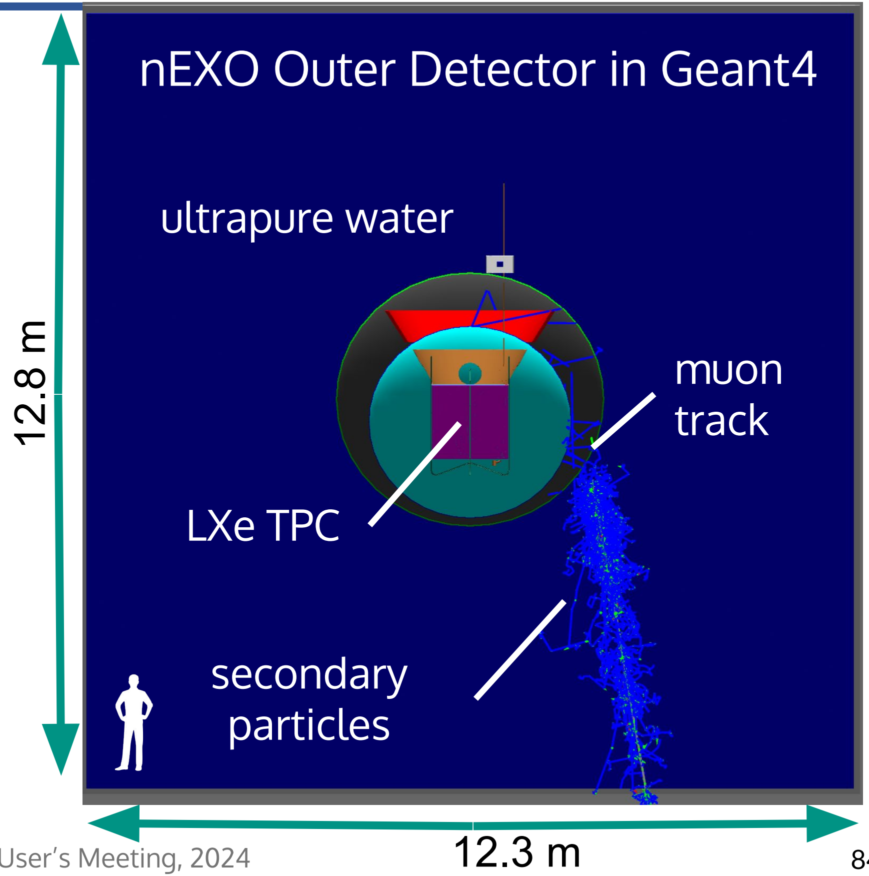




Me starting to realize what my job entails
(circa 2018)

Cosmogenic ^{137}Xe production

1. $\mu^{\pm} \rightarrow \pi^{\pm} + p + \mathbf{n} + \ldots$



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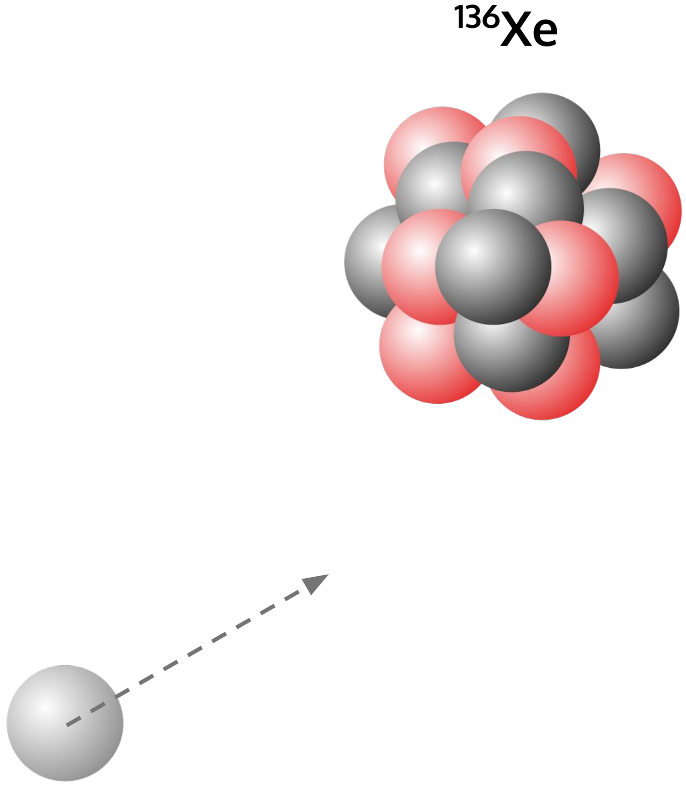
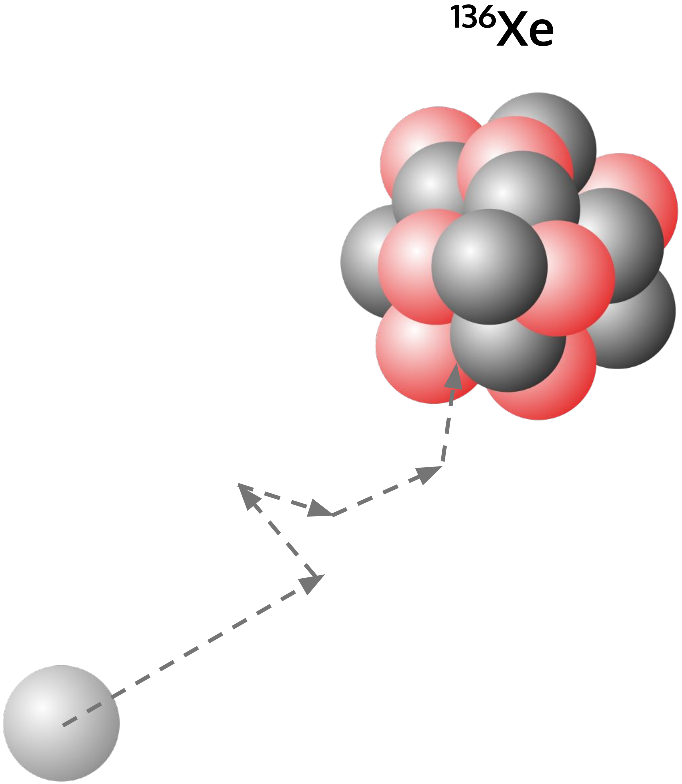


Cosmogenic ^{137}Xe production

1. $\mu^{\pm} \rightarrow \pi^{\pm} + p + \mathbf{n} + \ldots$

… neutron thermalization ~100's μs in LXe…

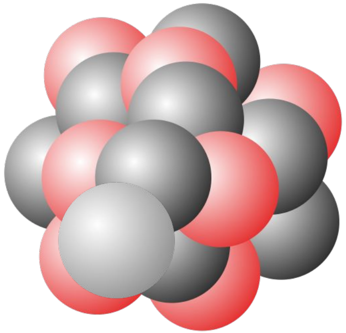


Cosmogenic ^{137}Xe production

1. $\mu^{\pm} \longrightarrow \pi^{\pm} + p + \mathbf{n} + \ldots$

… neutron thermalization ~100's μs …

2. $n + {}^{136}Xe \longrightarrow {}^{137}Xe^{*}$

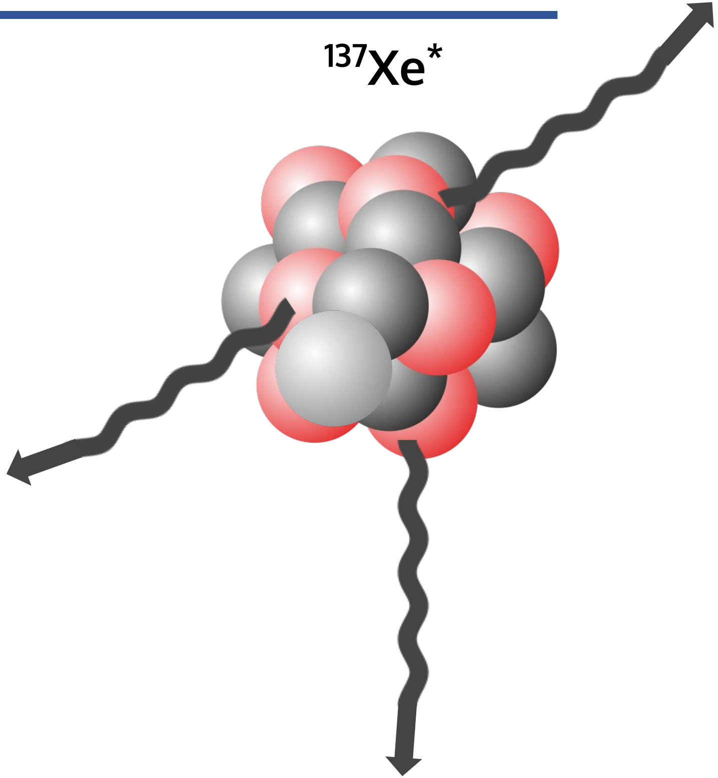


Cosmogenic ^{137}Xe production

1. $\mu^{\pm} \longrightarrow \pi^{\pm} + p + \mathbf{n} + \ldots$

... neutron thermalization ~100's μs ...

2. $n + {}^{136}Xe \longrightarrow {}^{137}Xe^{*} + \gamma$'s (4.025 MeV)



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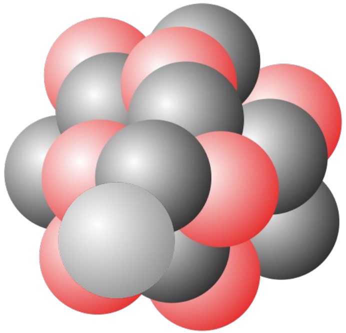
... β-decay halflife ~ 3.8 minutes



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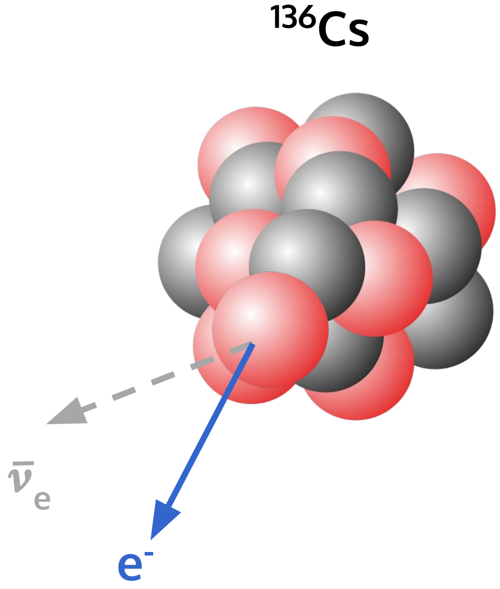
3. $^{137}Xe \longrightarrow {}^{136}Cs + \bar{\nu}_e + e^-$ (Q_β =4.17 MeV)



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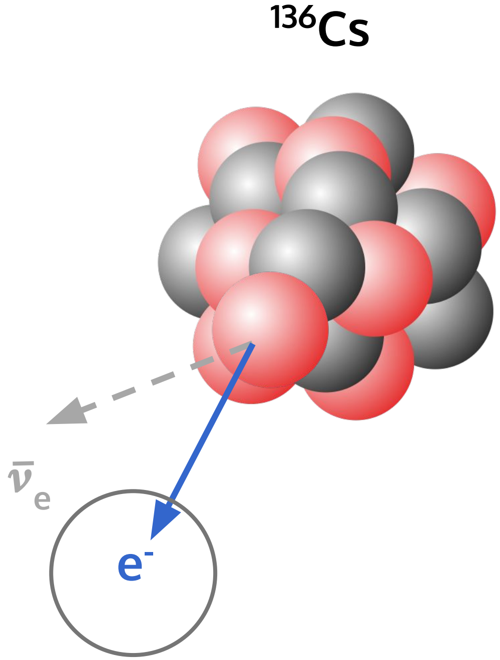
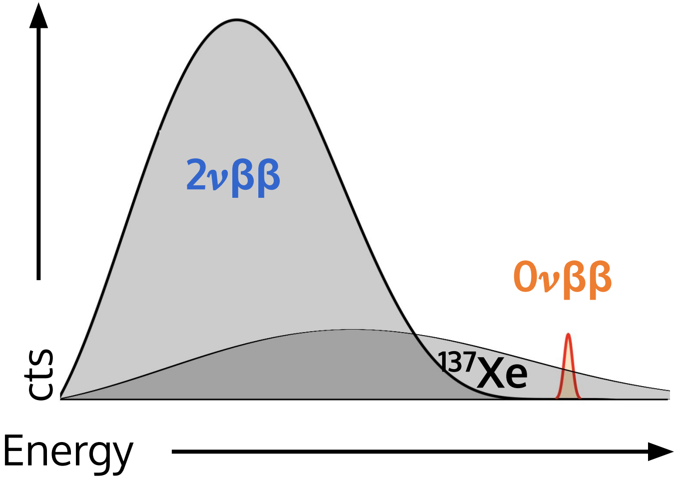
background!



β-decays of ^{137}Xe can look like 0νββ signals!



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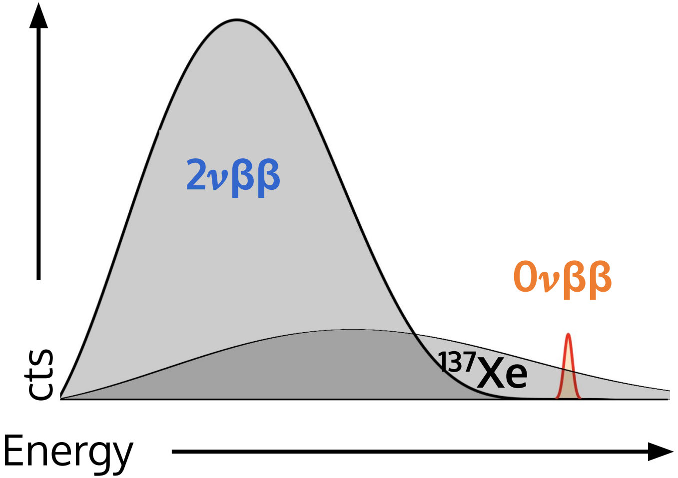

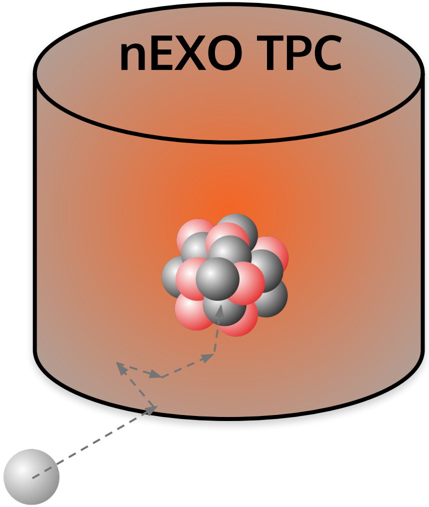

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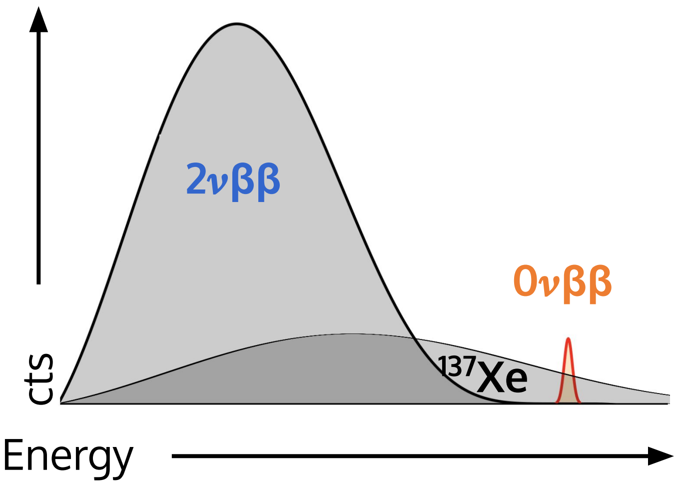
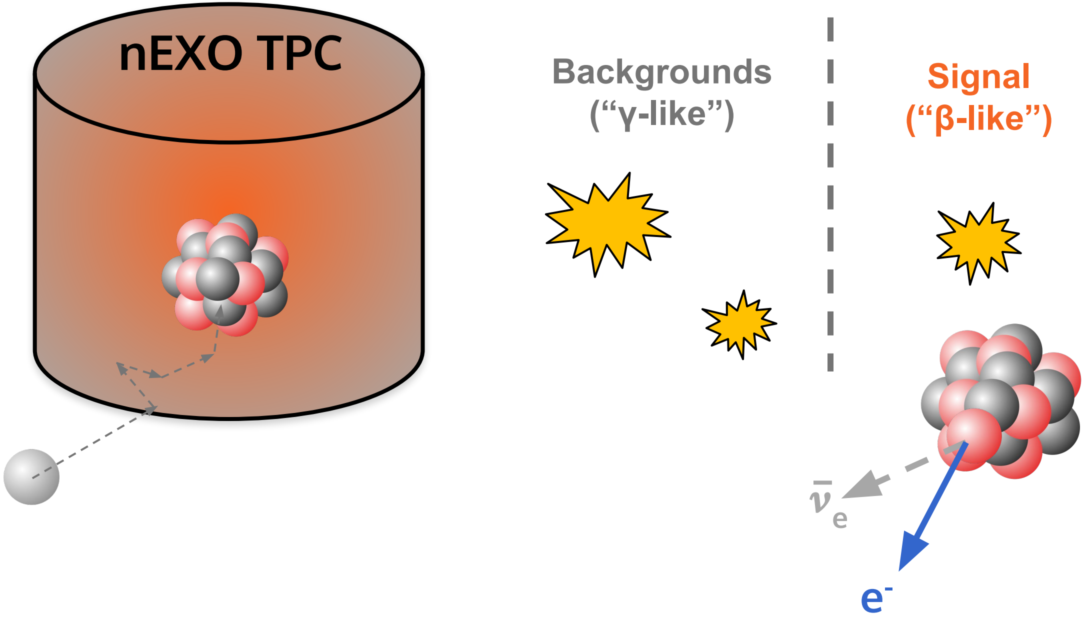
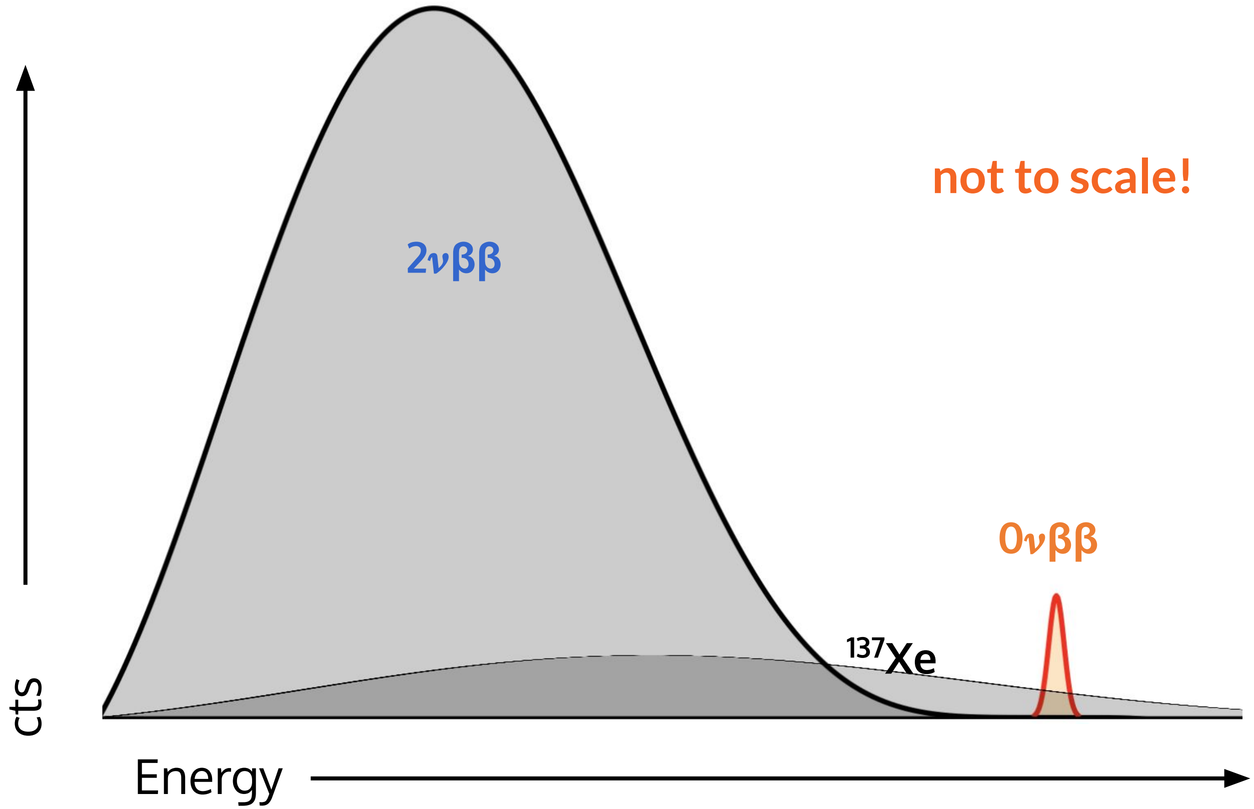




Need to quantify ^{137}Xe background rate



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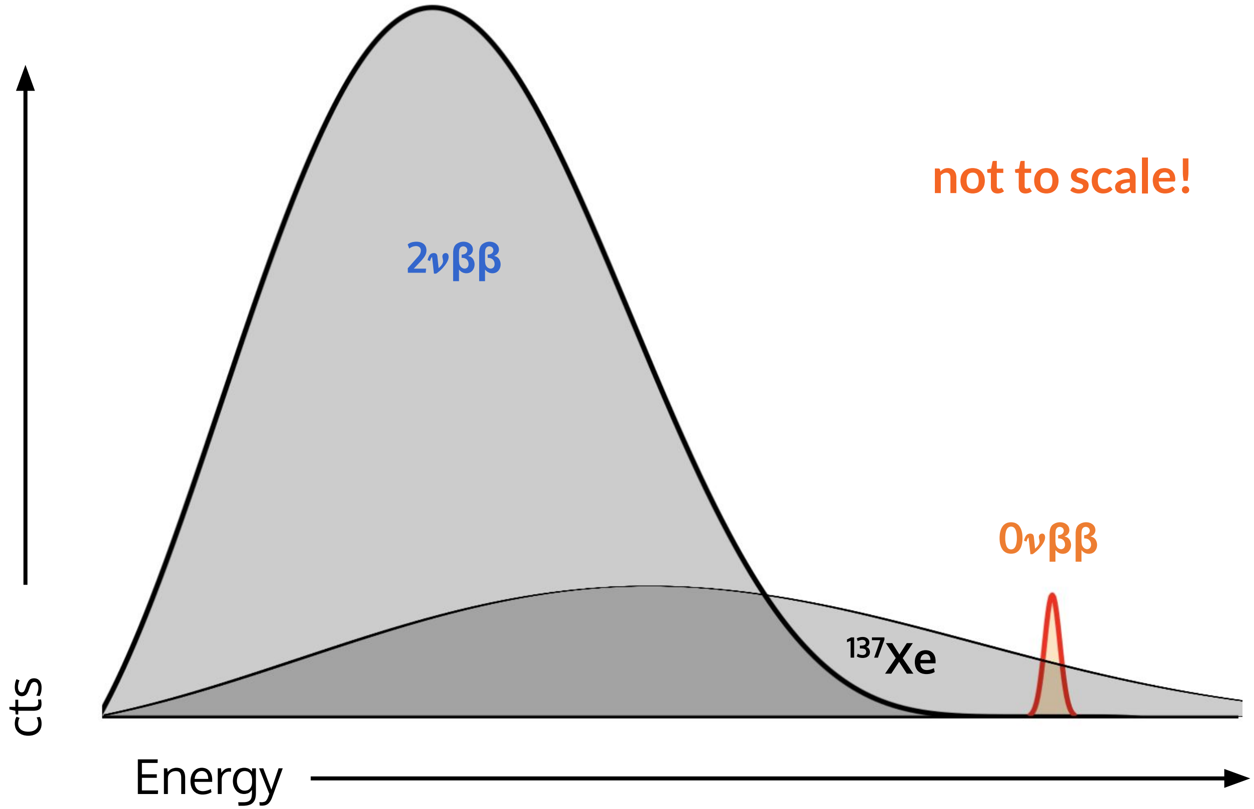

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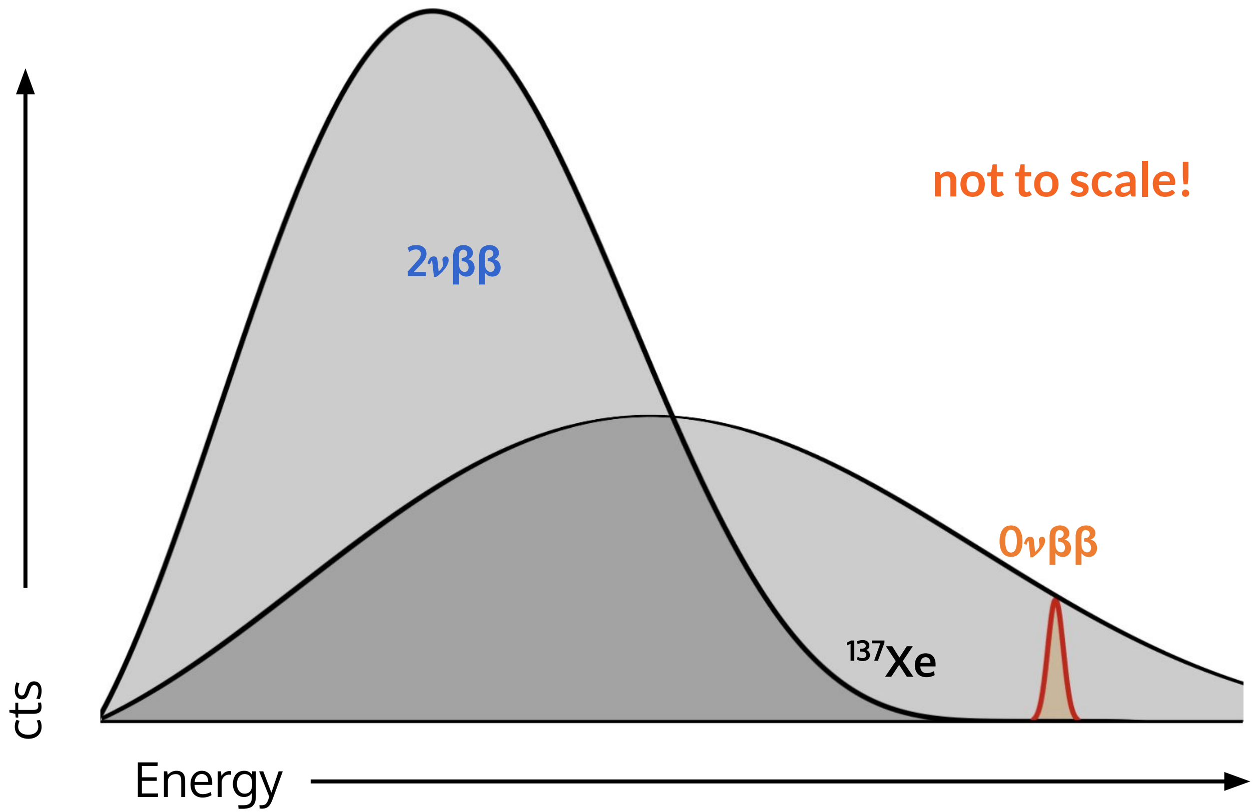
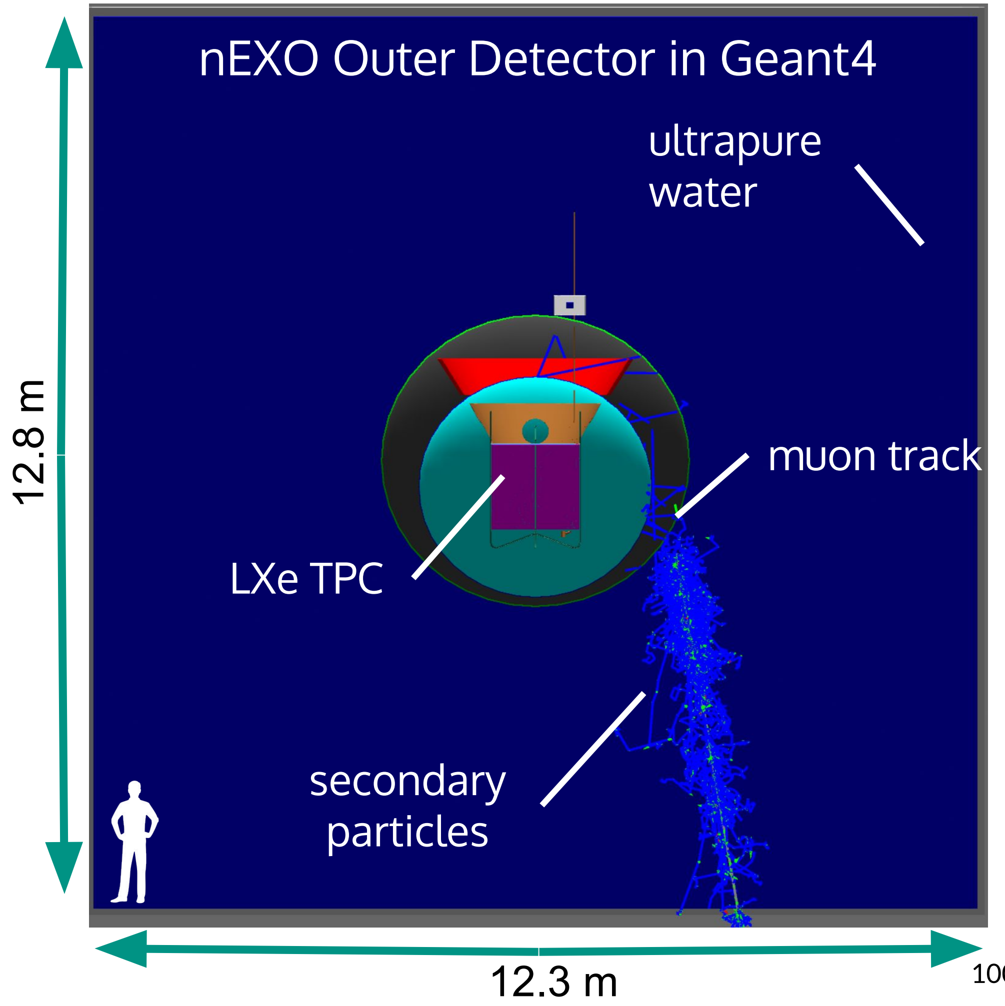
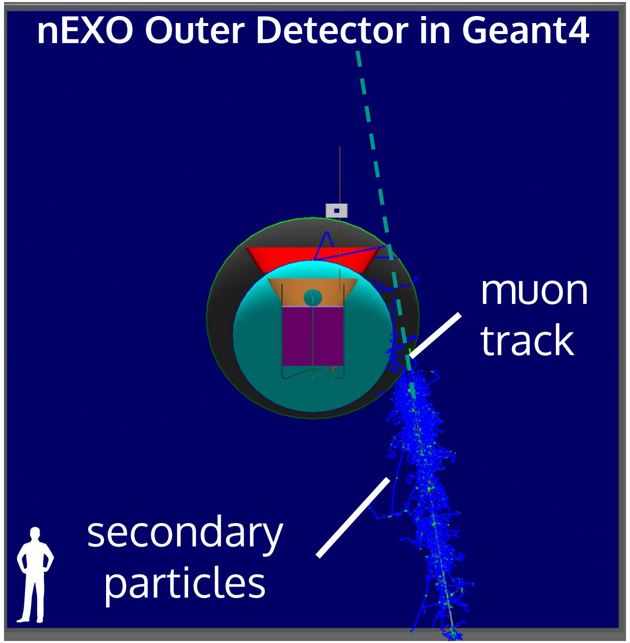
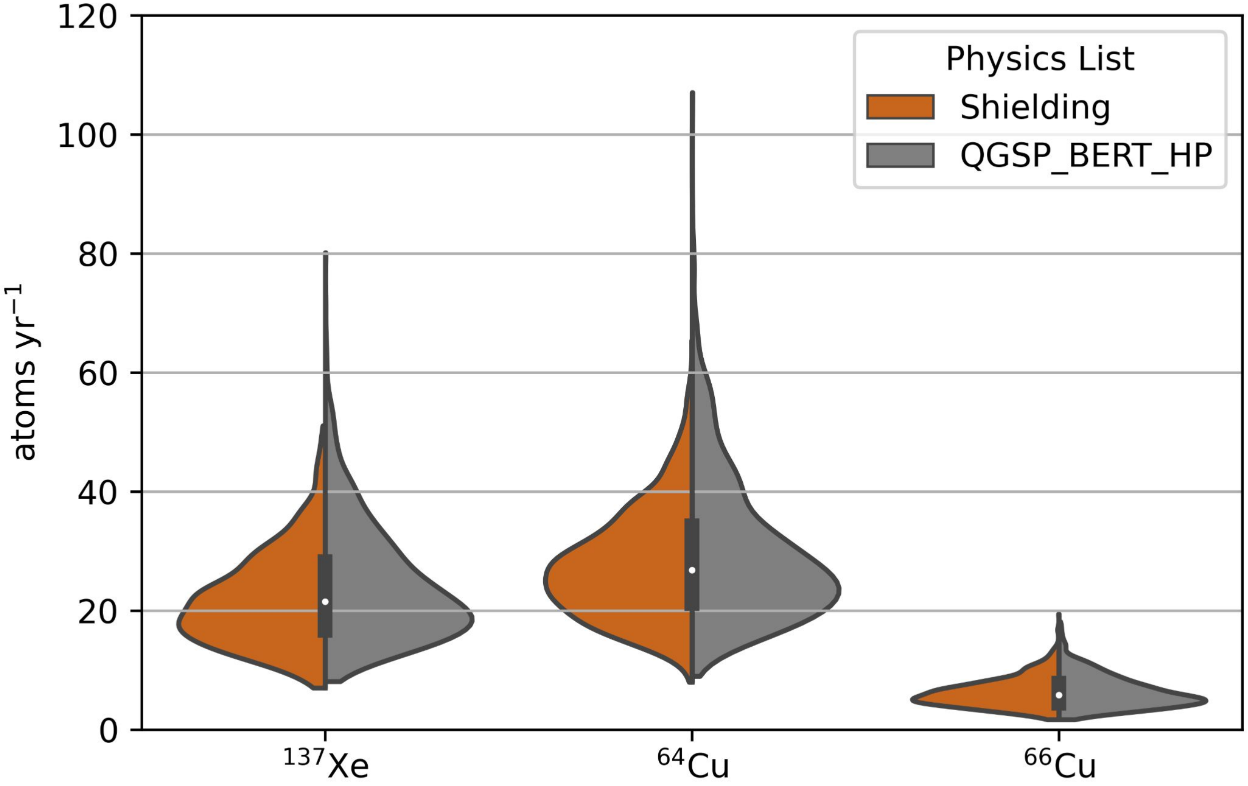


Cosmogenics Simulations



Cosmogenic activation rates

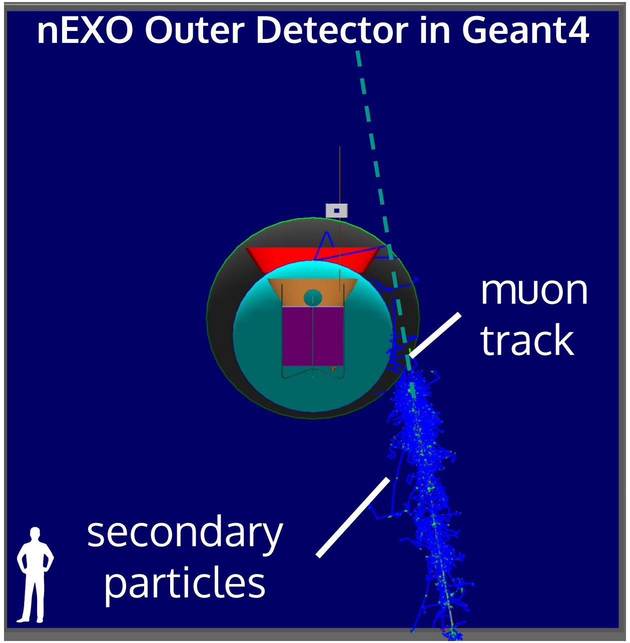




$^{136}Xe(n, \gamma)^{137}Xe$ tagging

1. $\mu^{\pm} \longrightarrow \pi^{\pm} + p + \mathbf{n} + \dots$

… neutron thermalization ~100's μs …



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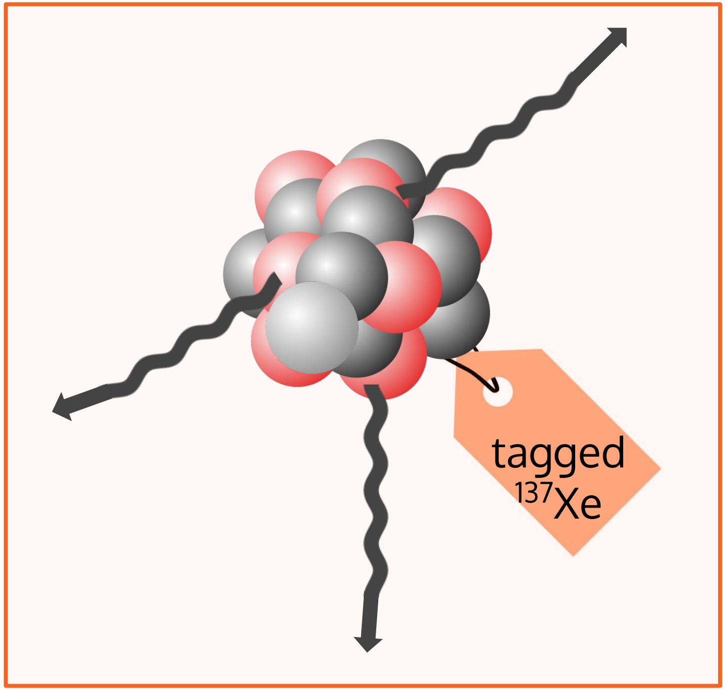
... neutron thermalization ~100's μs ...

2. $n + {}^{136}Xe \longrightarrow {}^{137}Xe^{*} + \gamma\text{'s } (4.025 \text{ MeV})$

Can we tag this?



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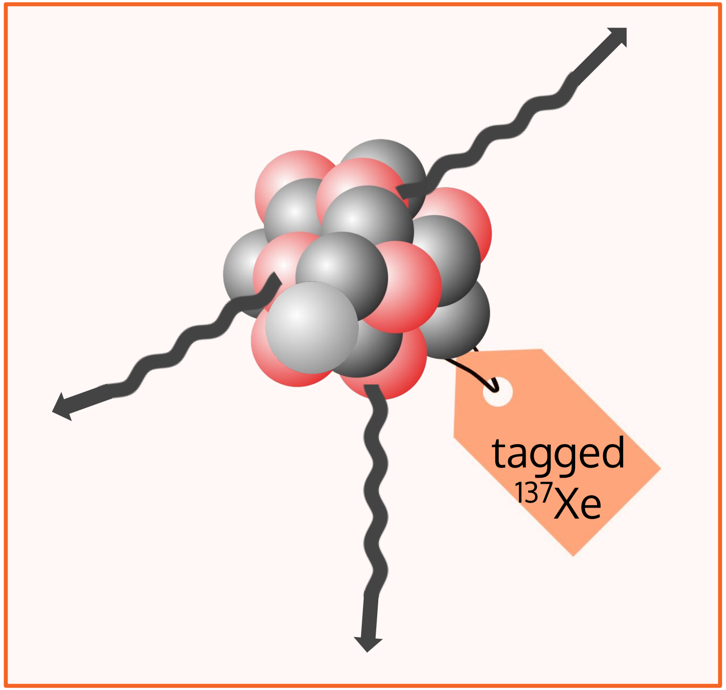
2. $n + {}^{136}Xe \rightarrow {}^{137}Xe^{*} + \gamma$'s (4.025 MeV)

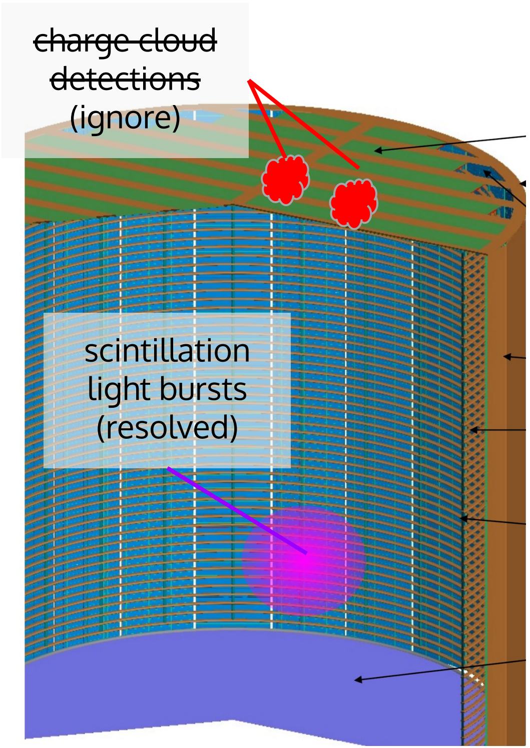
... β-decay halflife ~ 3.8 minutes

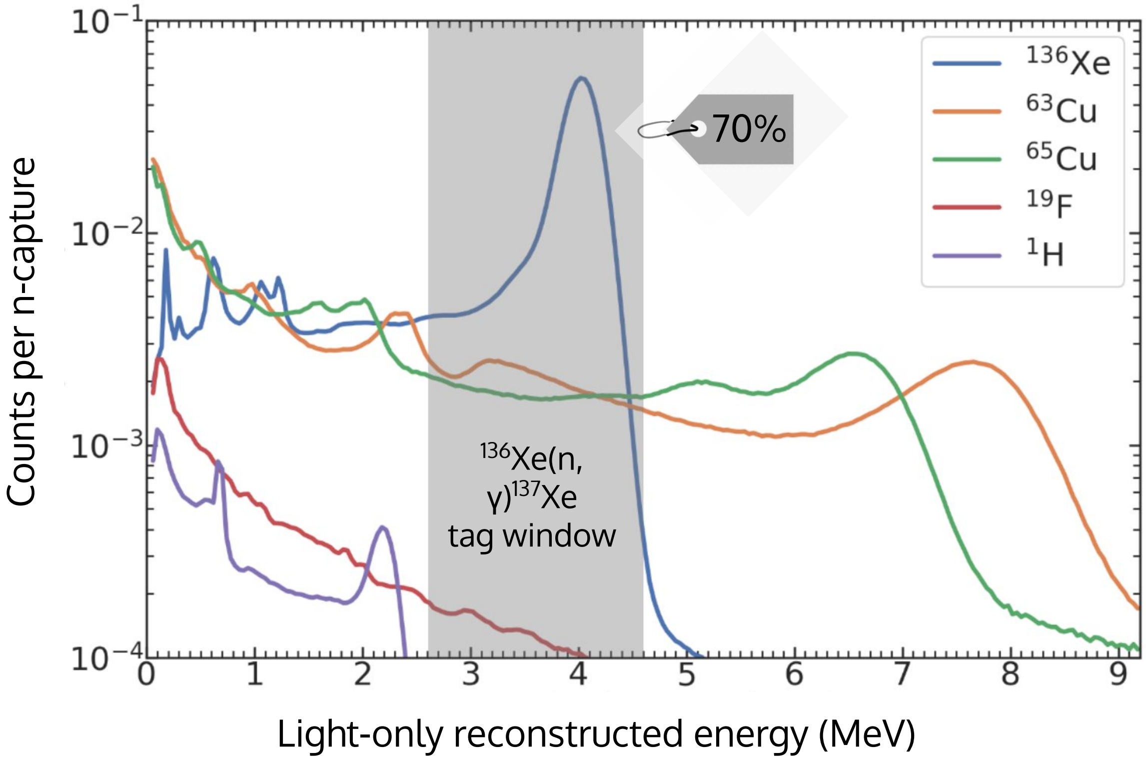
3. ${}^{137}Xe \rightarrow {}^{136}Cs + \nu_e + e^-$ (Q_β =4.17 MeV)

... and veto the following ~few half lives of ^{137}Xe from the low-background dataset?



Proposed nEXO ^{137}Xe light-only TPC tag

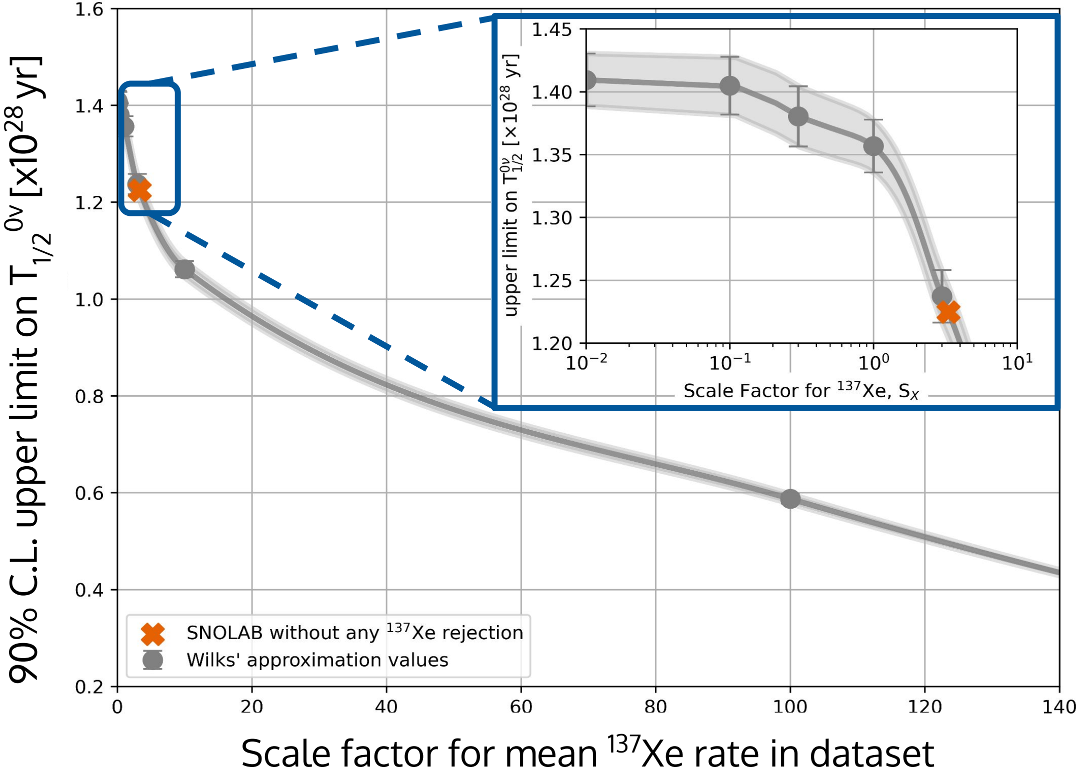




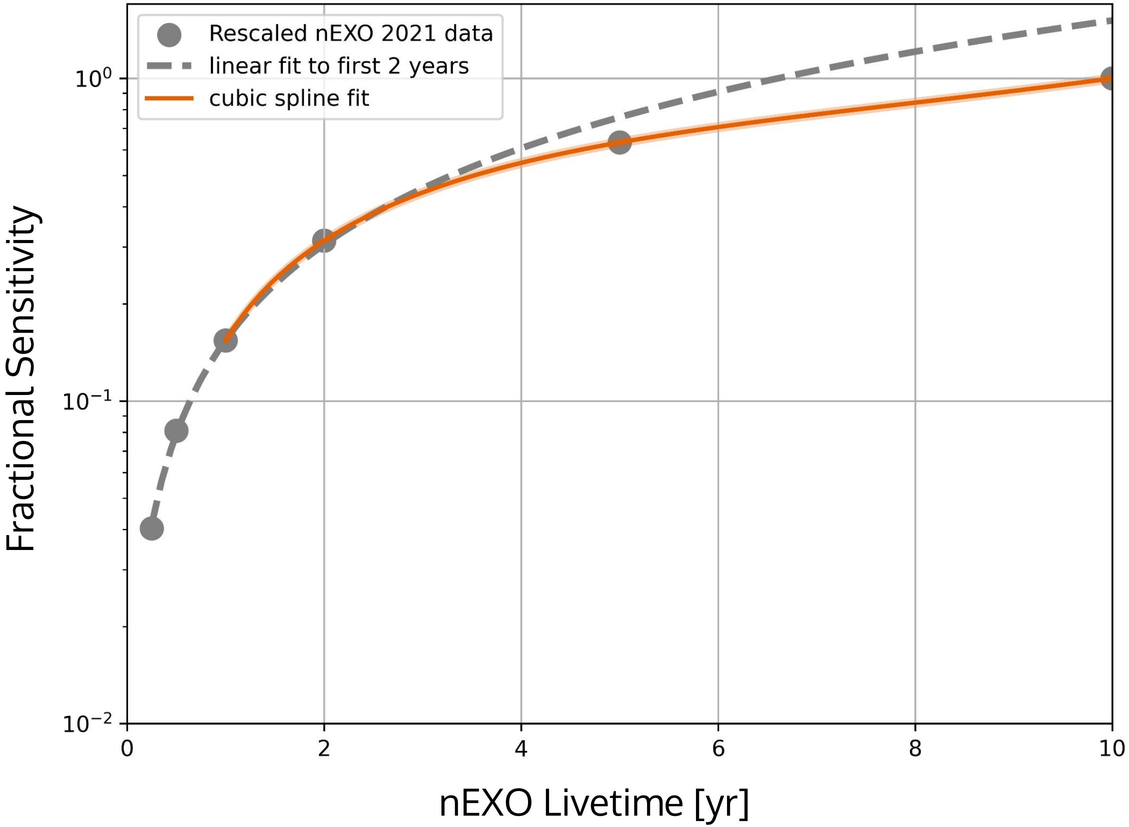
Sensitivity variation with ^{137}Xe background

Data published:

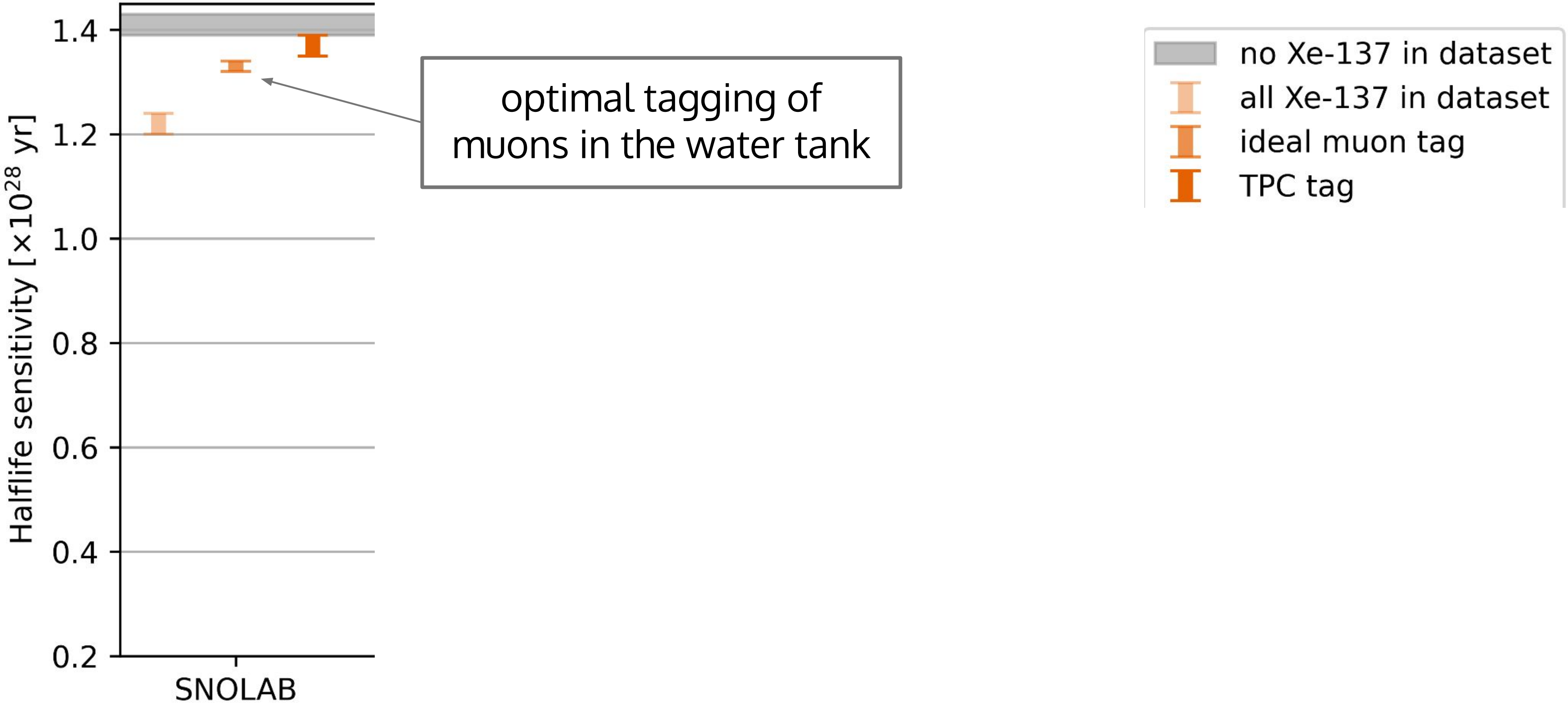
G Adhikari *et al* 2022
J. Phys. G: Nucl. Part. Phys. 49 015104
DOI 10.1088/1361-6471/ac3631



nEXO’s sensitivity scaling with livetime (exposure)

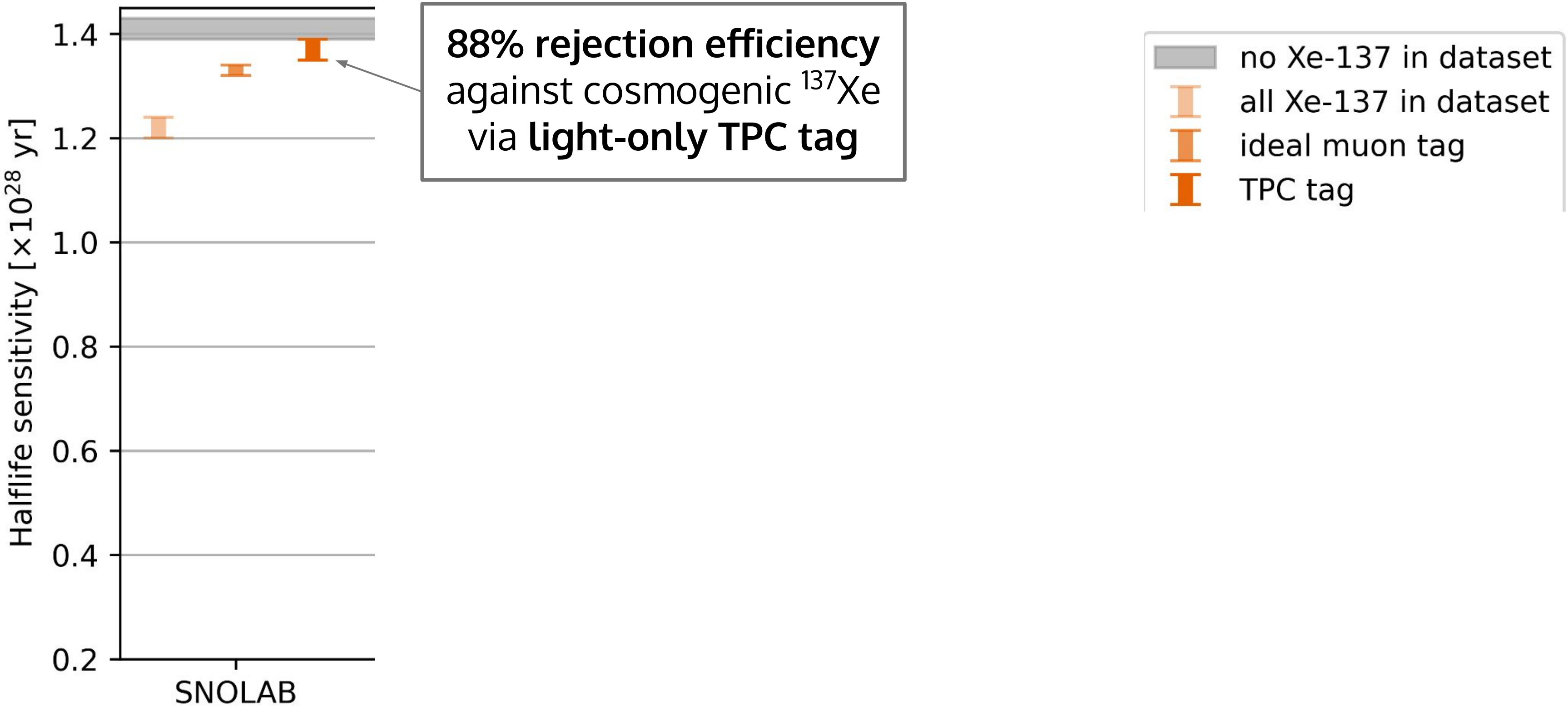


Underground site selection



(depth of 6 km w.e.)

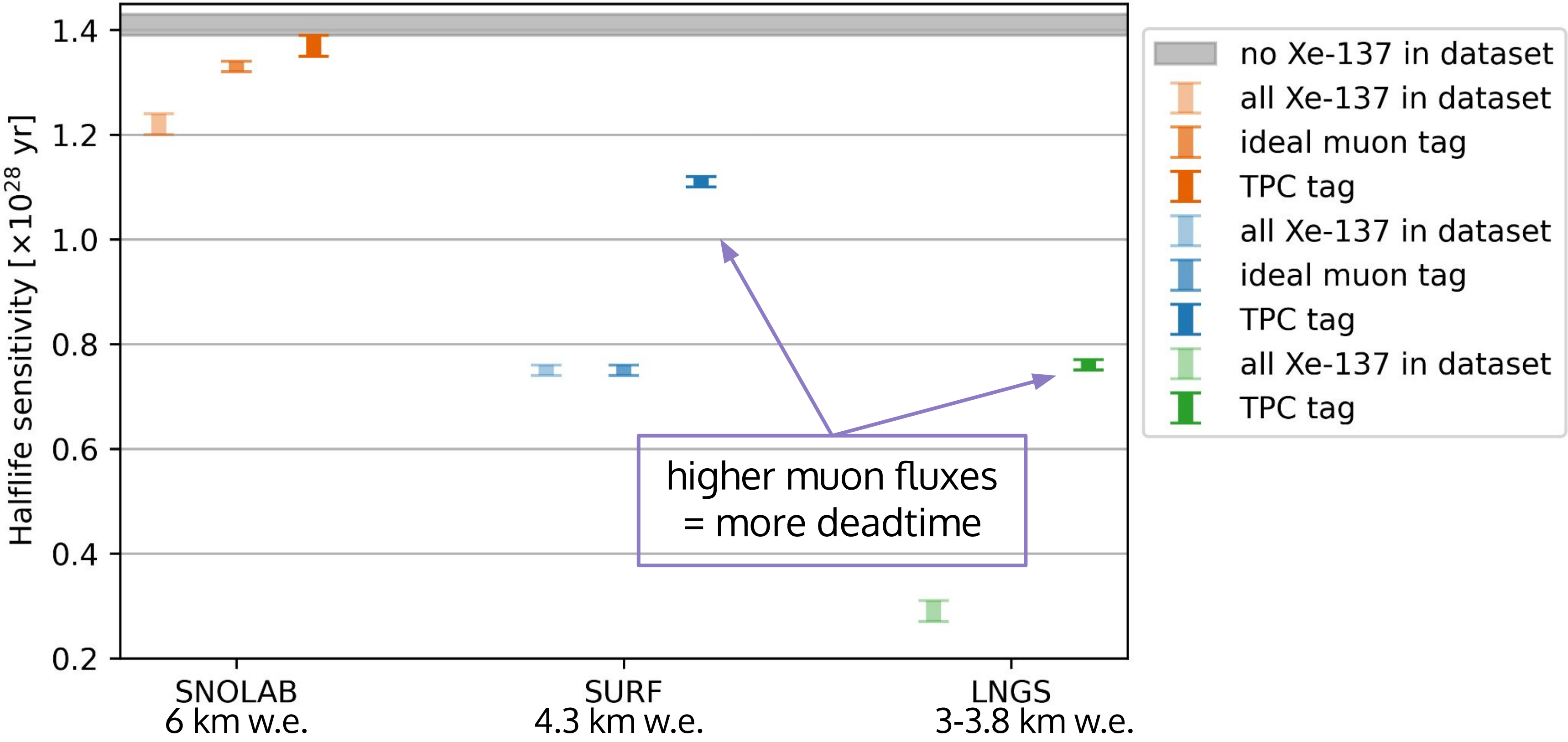
Underground site selection



(depth of 6 km w.e.)

88% rejection efficiency against cosmogenic ^{137}Xe via **light-only TPC tag**

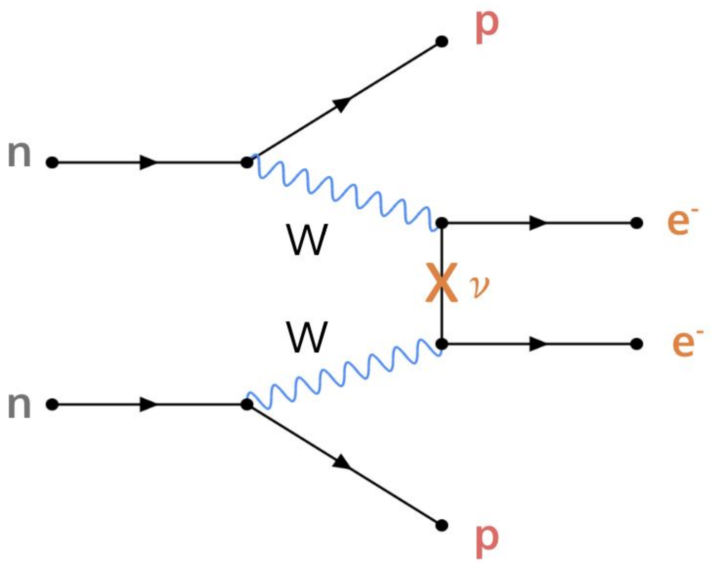
Underground site selection



nEXO Sensitivity

Neutrino Mass Measurement

- **In the paradigm of "light Majorana neutrino exchange", half lives of 0$\nu\beta\beta$ relate to an "effective Majorana mass"** of the electron neutrino **$\langle m_{\beta\beta} \rangle$**



nEXO Sensitivity

Neutrino Mass Measurement

- **In the paradigm of "light Majorana neutrino exchange", half lives of 0νββ relate to an "effective Majorana mass"** of the electron neutrino **<$m_{\beta\beta}$>**

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} \longrightarrow \langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$

The PMNS matrix relates flavour and mass eigenstates of neutrinos

nEXO Sensitivity

Neutrino Mass Measurement

- **In the paradigm of "light Majorana neutrino exchange", half lives of $0\nu\beta\beta$ relate to an "effective Majorana mass"** of the electron neutrino **$<m_{\beta\beta}>$**
- $<m_{\beta\beta}>$ is isotope-independent

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

$$(T^{0\nu}_{1/2})^{-1} \propto <m_{\beta\beta}>^2$$

nEXO Sensitivity

Neutrino Mass Measurement

- Half lives of $0\nu\beta\beta$ correspond to an effective Majorana mass of the electron neutrino $<m_{\beta\beta}>$

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

- $<m_{\beta\beta}>$ is isotope-independent
  - Depends on your choice nuclear matrix element (NME) when converting from a half life measurement to neutrino mass, NME is least constrained theoretical parameter below
  - Complex nuclear physics could change $<m_{\beta\beta}>$ estimates ⟶ **we need to search for $0\nu\beta\beta$ in multiple isotopes**

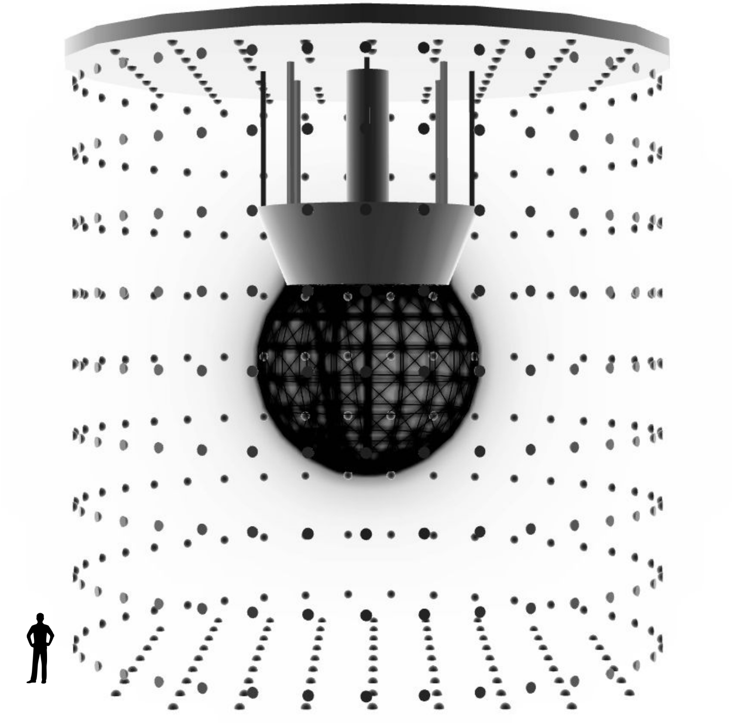
More tomorrow in [E. Caden's talk]

nEXO requires a 1.4 kt water tank to shield the xenon from neutron & γ-radiation

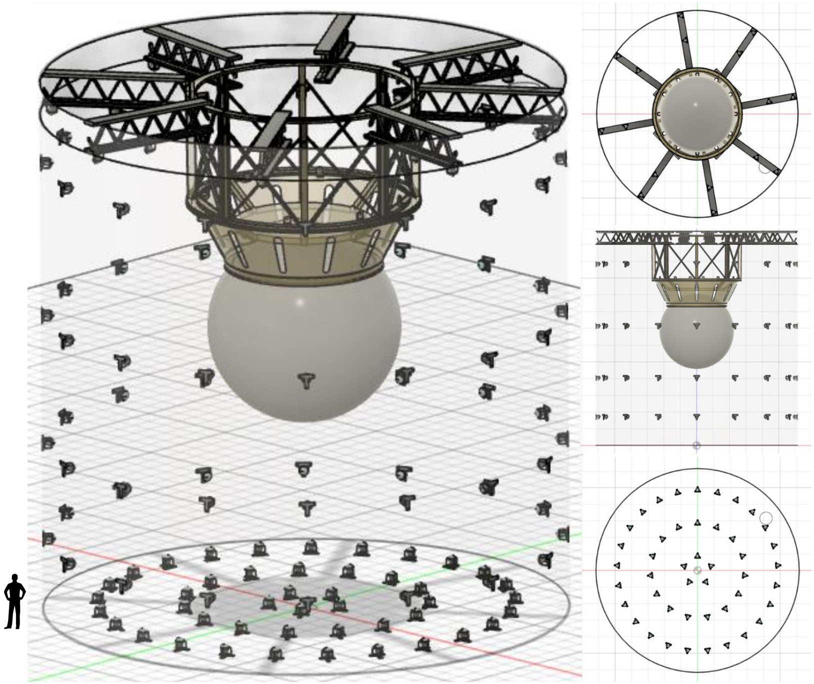
muons passing through the water will produce Cherenkov light detectable with PMTs

How many PMTs do we need & where should we place them?

water-Cherenkov Muon Veto ⟶ nEXO Outer Detector (OD)



Geant4 (CPU-based, established)



Chroma (GPU-based, first-principles)

Modelling the Outer Detector in Geant4

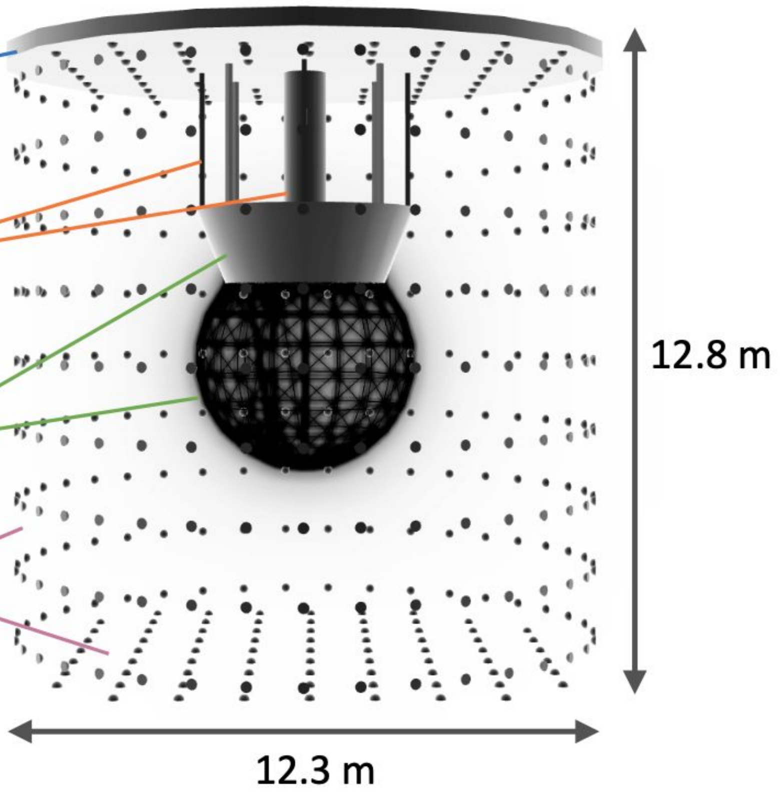
30 cm nitrogen buffer gas layer with stainless steel ceiling (40% reflective)

Stainless steel cryostat supports matching engineering designed mass (40% reflective)

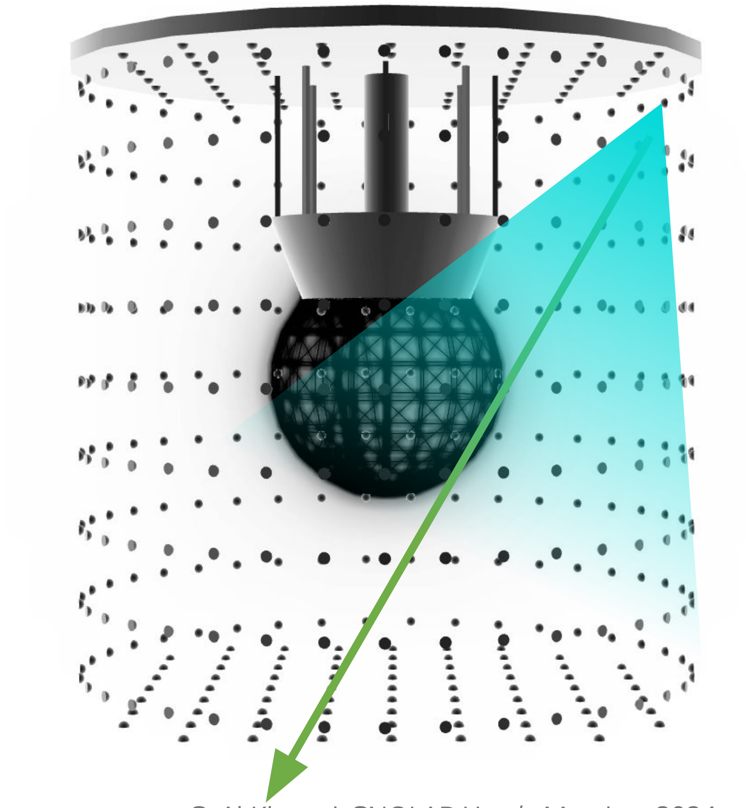
Carbon fibre cryostat surfaces (0% reflective)

Highly reflective surfaces with Tyvek coating (98% reflective)

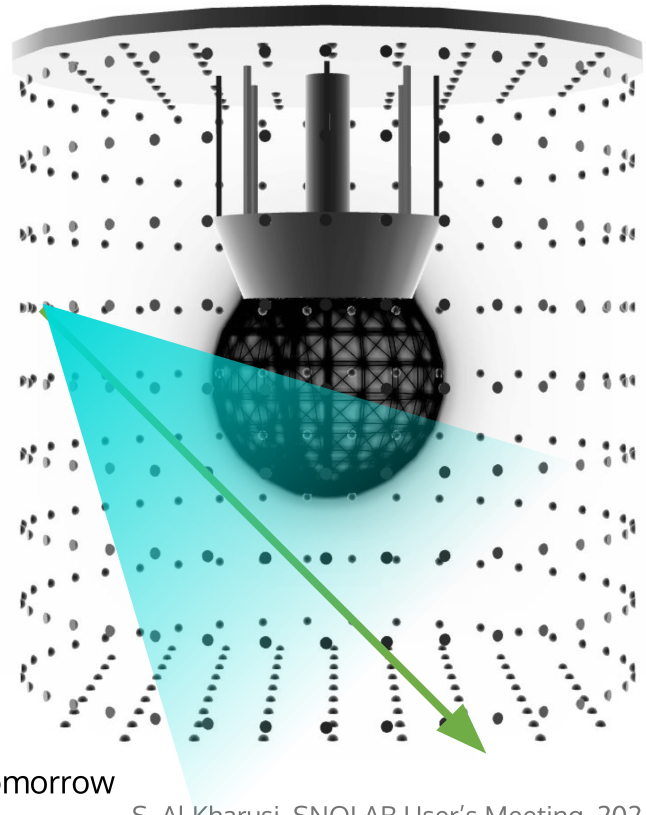
*%'s refer to reflectivity in range: 400-800 nm



Defining the muon trigger in Geant4

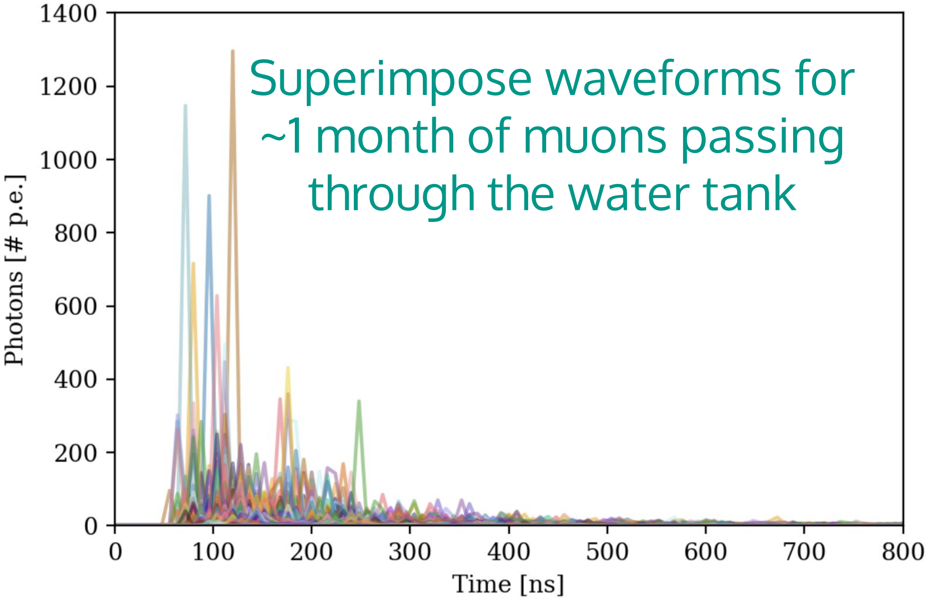


Defining the muon trigger in Geant4



More on muon flux in R. Ross' talk tomorrow

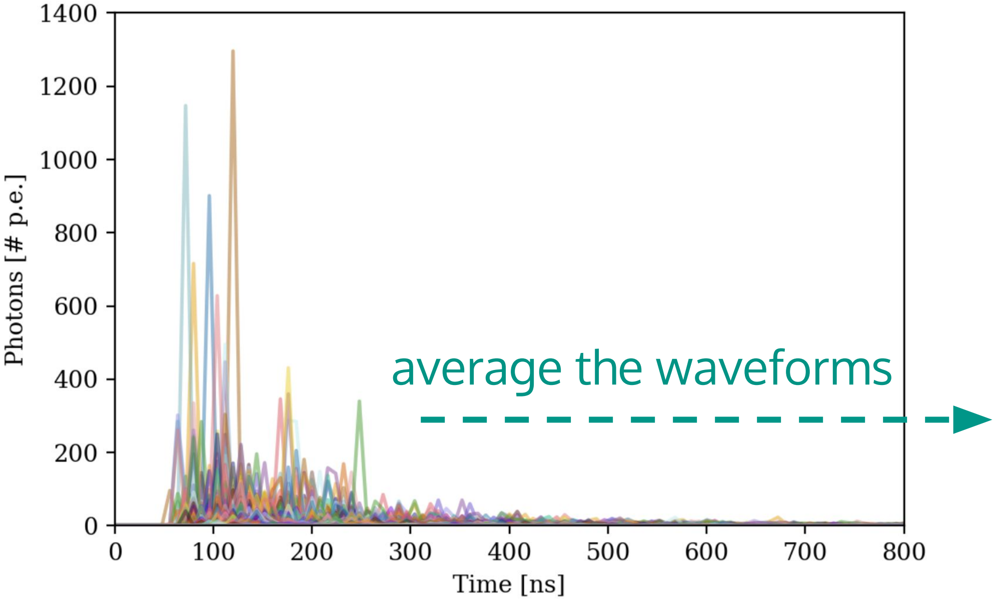
Muon trigger condition

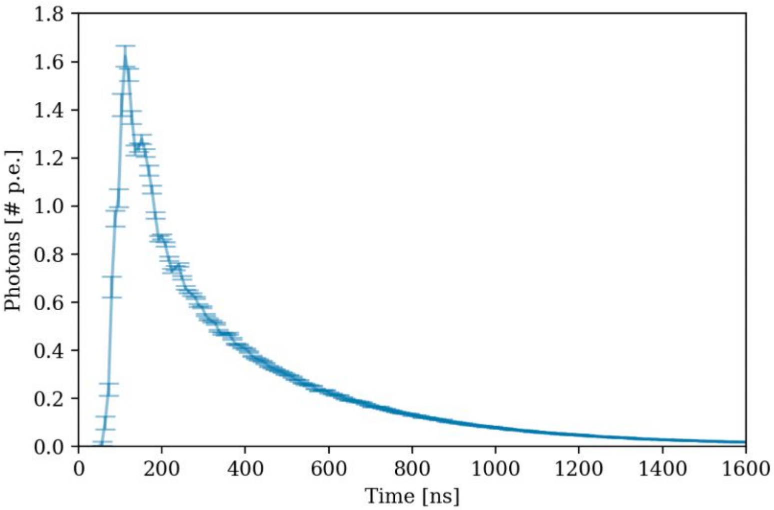


NB:

- Waveforms generated after quantum efficiency correction
- Photon hit times binned to 8 ns (CAEN VX2740 digitizer)

Muon trigger condition





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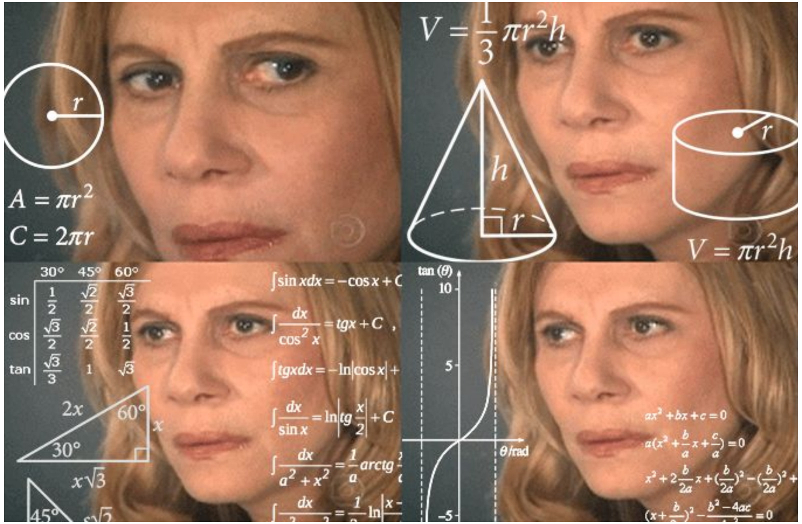
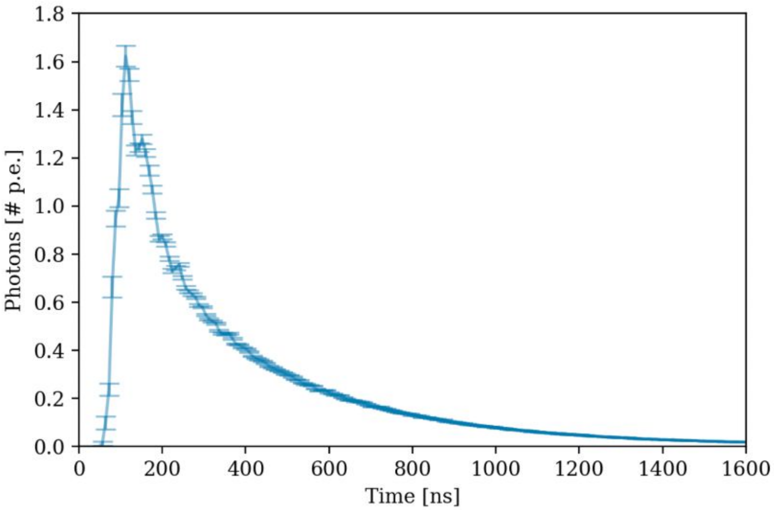
Muon trigger condition





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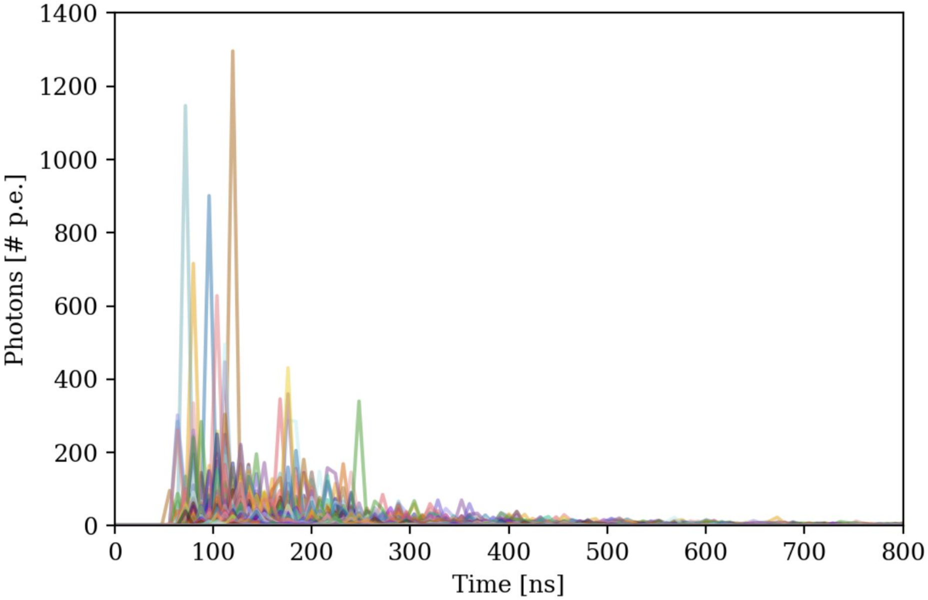
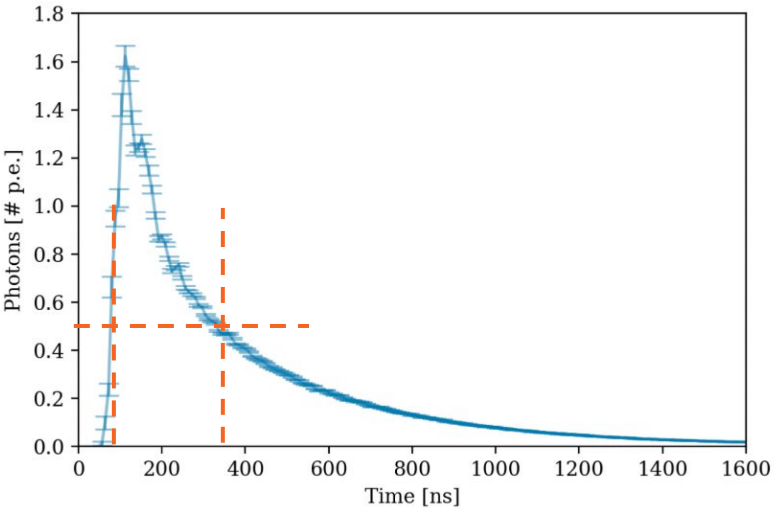
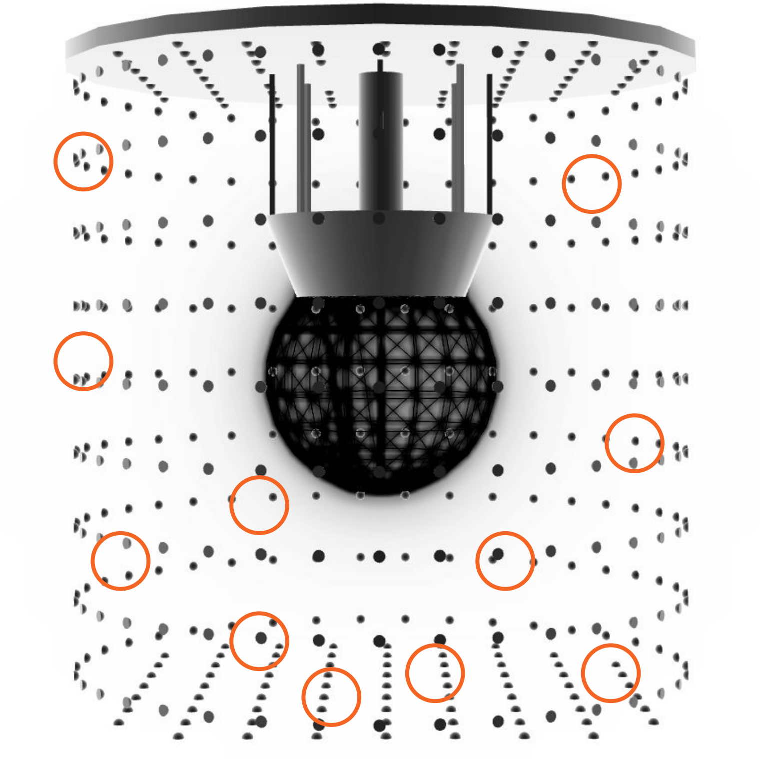
Muon trigger condition





"Trigger at the single photoelectron level in a 240 ns coincidence window"

Geant4 PMT number study

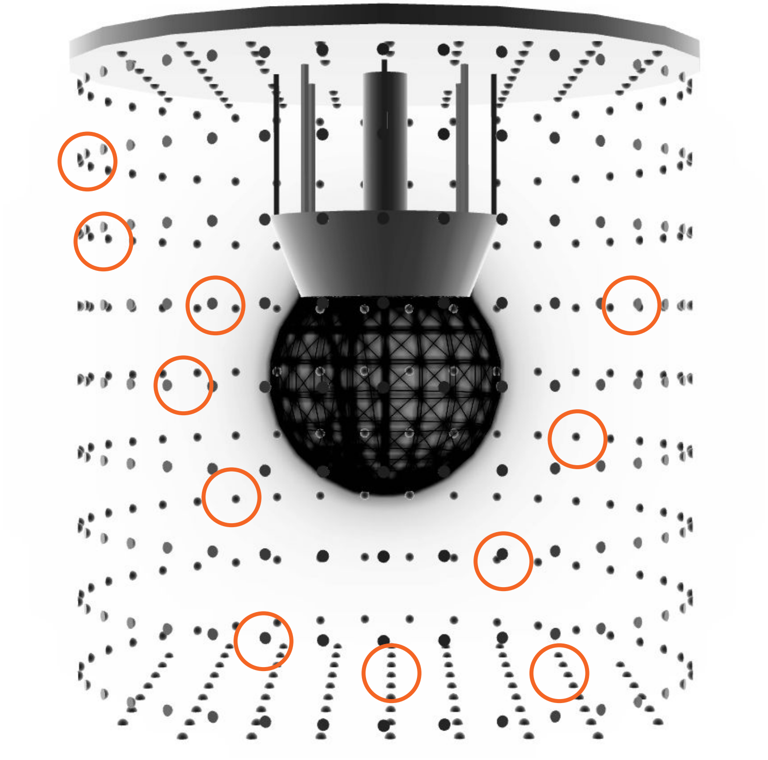


Randomly select N_{PMTs}

Analyse waveforms for 1 year of muons

Calculate muon tagging efficiency

Geant4 PMT number study



Randomly select N_{PMTs}

Analyse waveforms for 1 year of muons

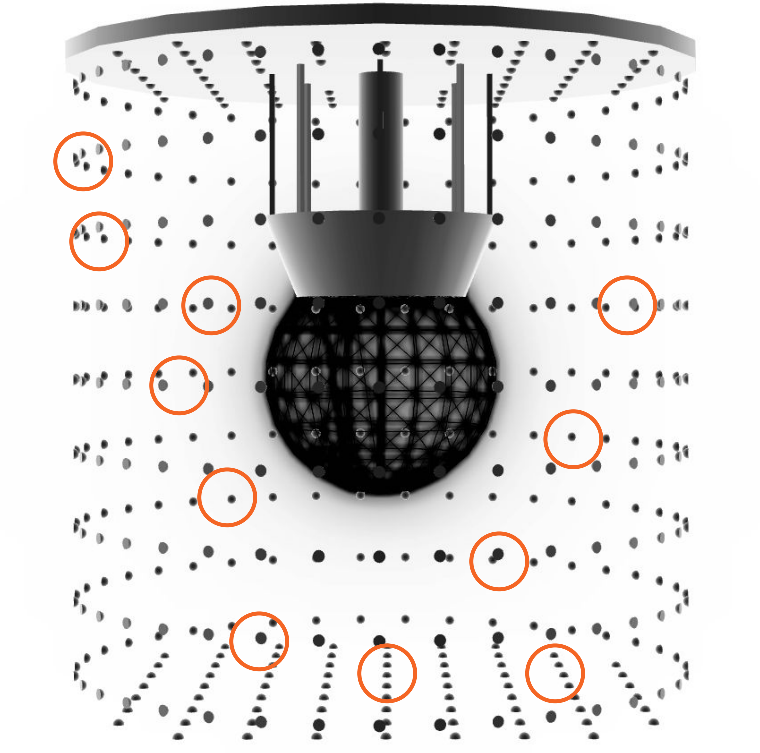
Calculate muon tagging efficiency

Choose **another** bunch of N_{PMTs}

Analyse those waveforms for the same year

Calculate muon tagging efficiency

Geant4 PMT number study



Randomly select N_{PMTs}

Analyse waveforms for 1 year of muons

Calculate muon tagging efficiency

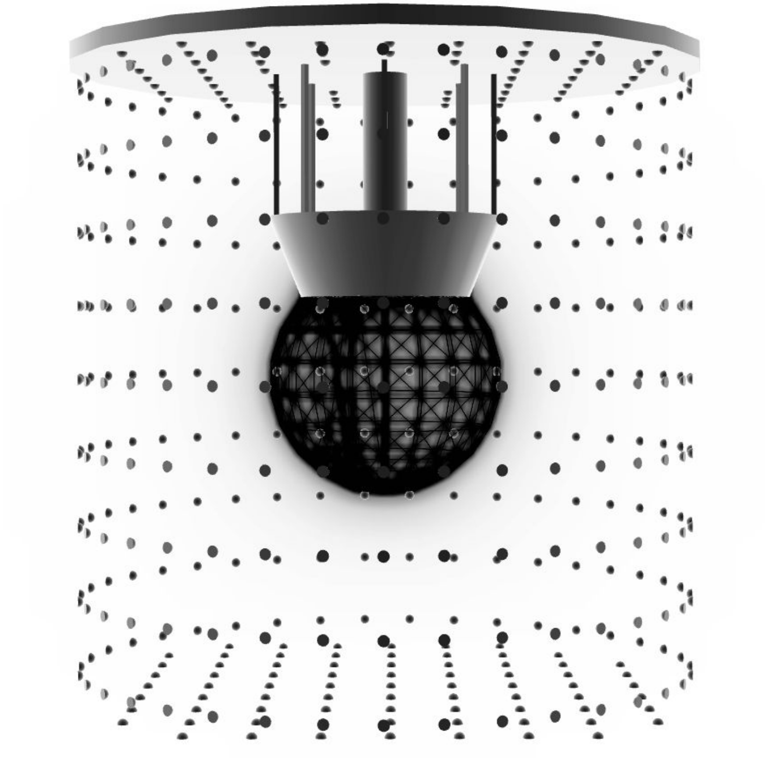
Choose **another** bunch of N_{PMTs}

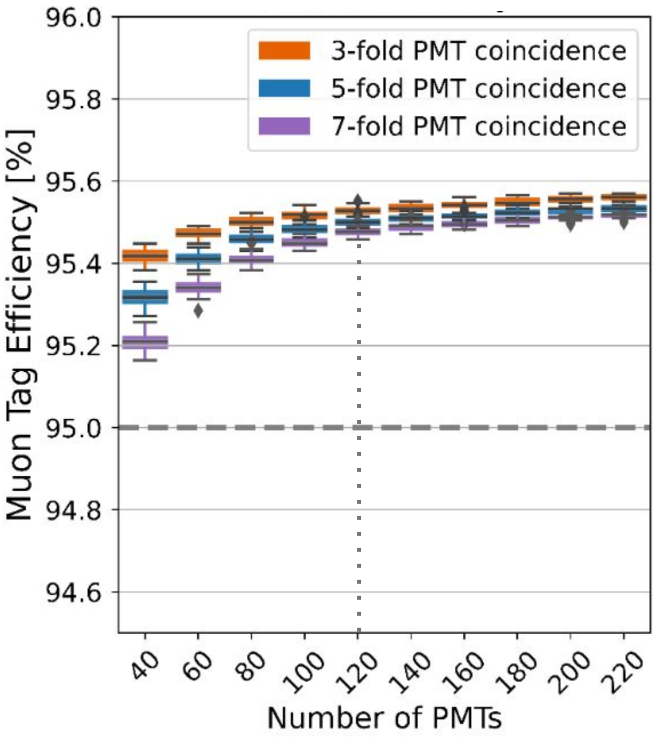
Analyse those waveforms for the same year

Calculate muon tagging efficiency

repeat this 100 times, then again for N_{PMTs} +20

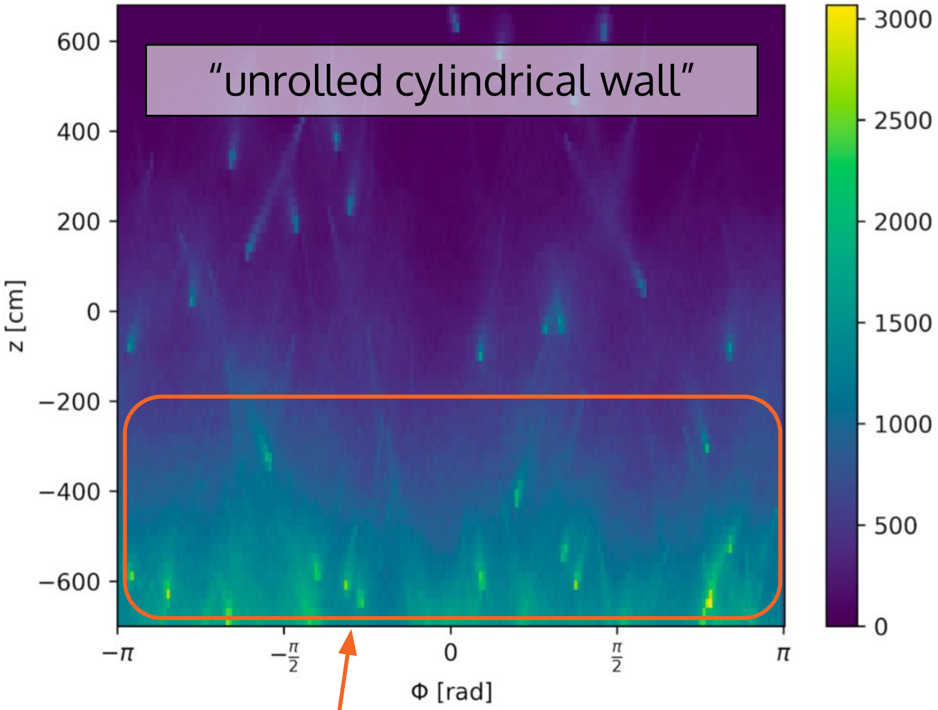
Geant4 PMT number study

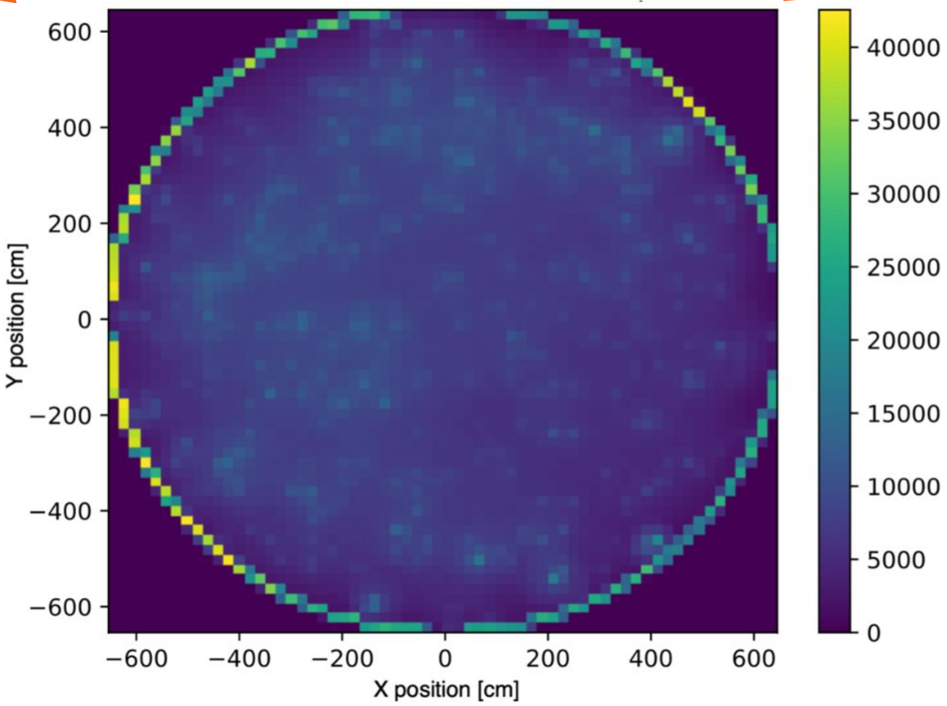




Muon light map

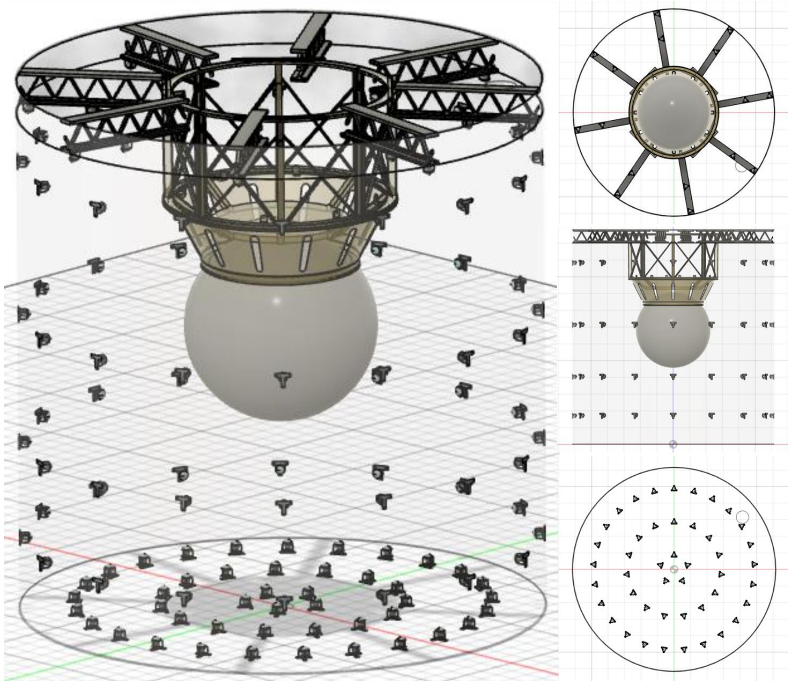
~½ the light lands on the floor



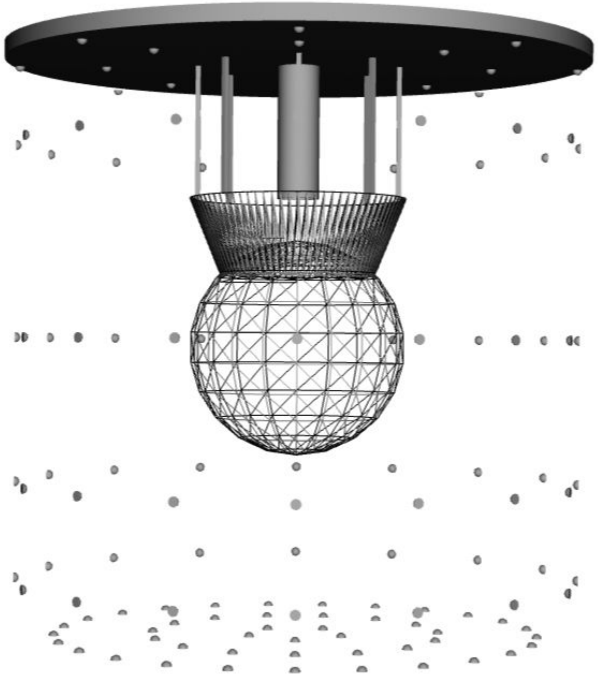


bottom ⅓ of water tank receives 40% of light

PMT layout (125 PMTs)



Chroma



Geant4

Multi-messenger astronomy is a rapidly growing field

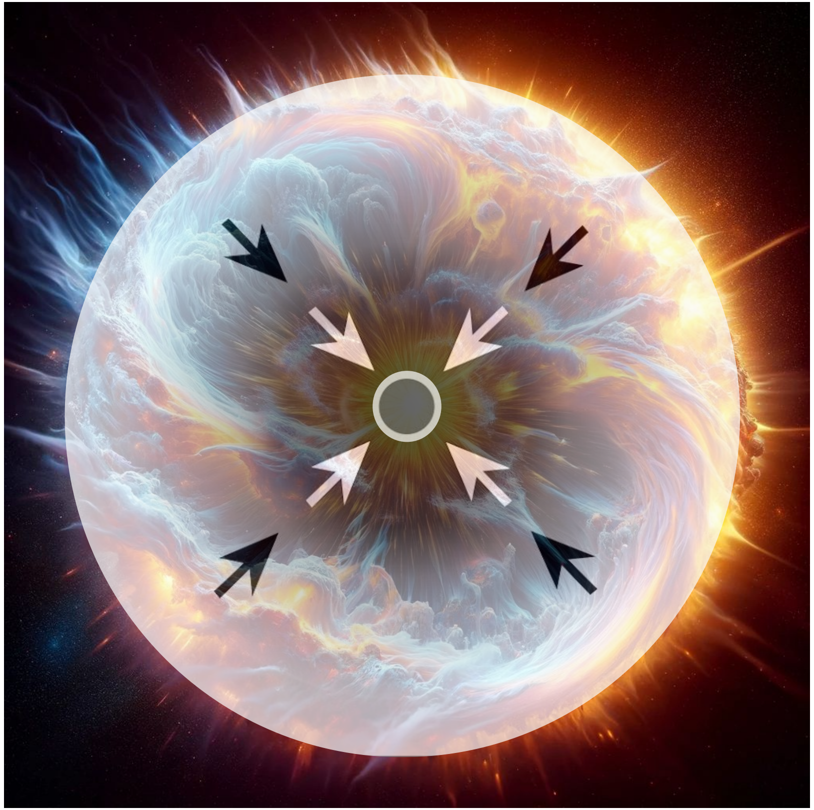
nEXO is an ultra-low background experiment optimized for MeV-scale interactions

Is nEXO sensitive to neutrinos from core-collapse supernovae?

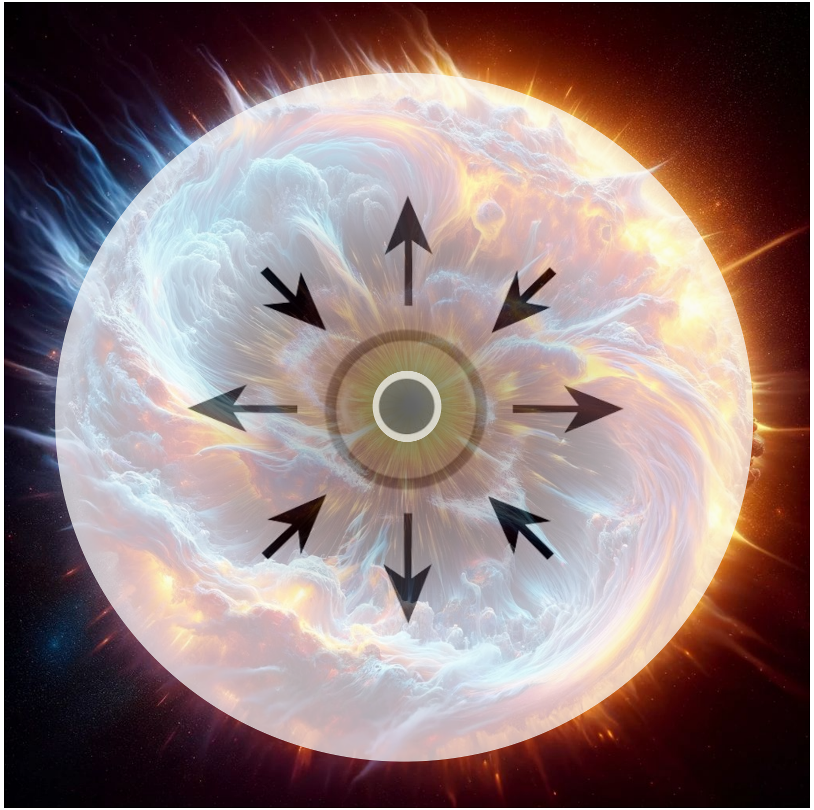
A star is ~~born~~ dying

Core-collapse supernovae (CCSN)

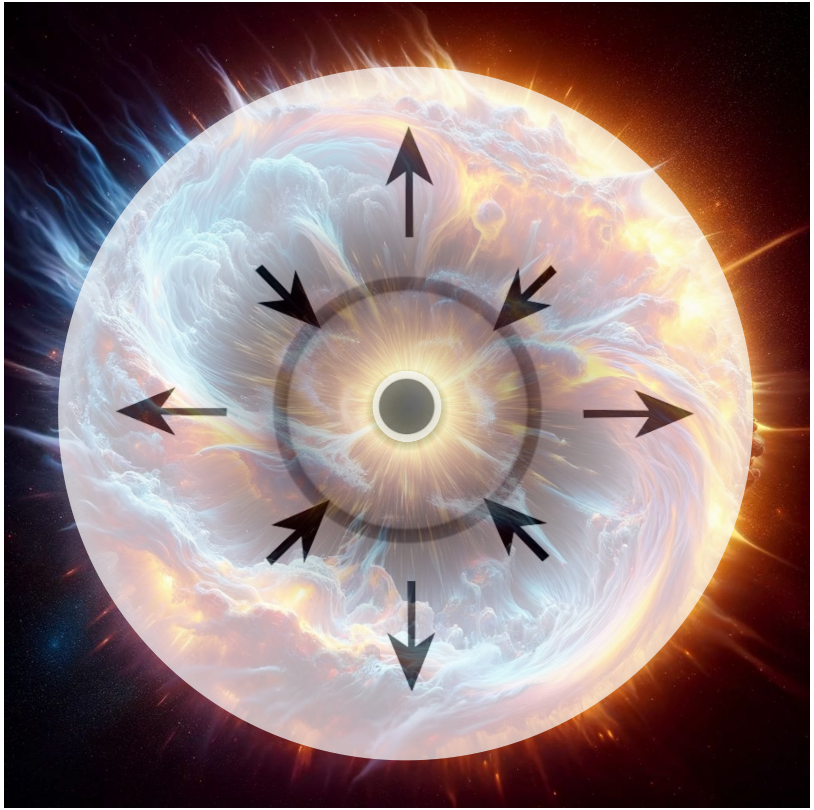
Gravitational Collapse



Infall, rebound & shock

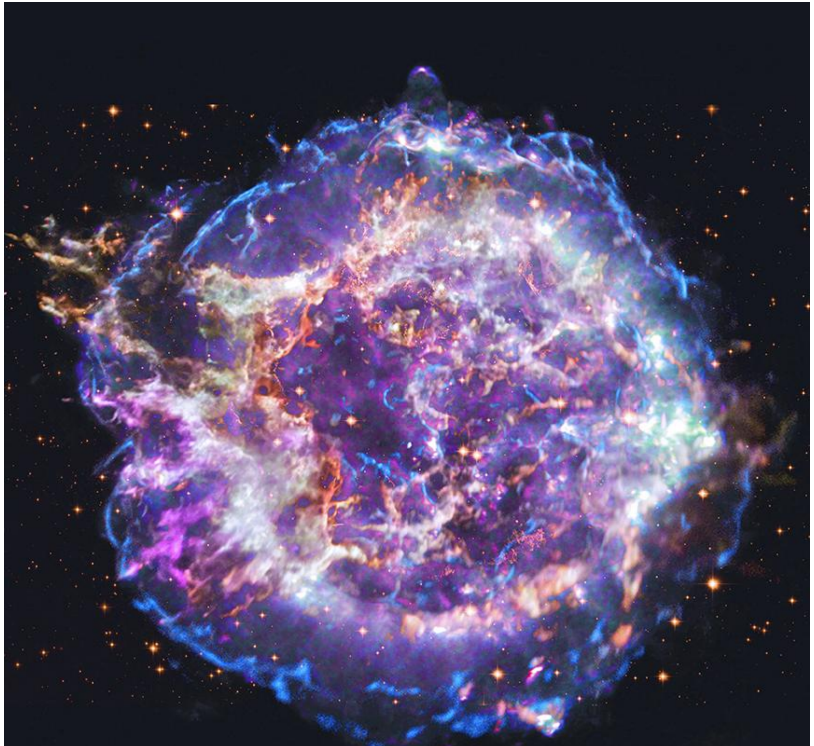


Shockwave stalling & ν's re-energizing



Shock breakout & explosion

Shock breakout & explosion

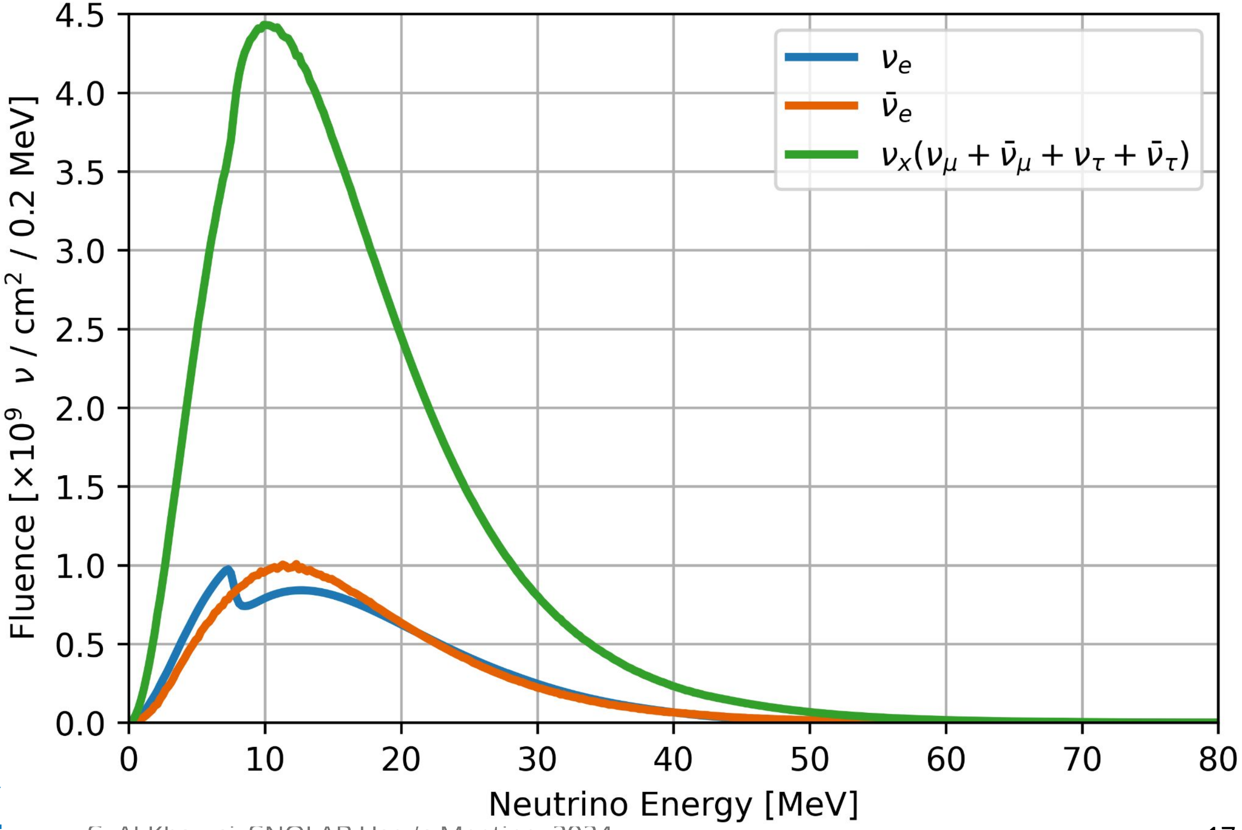


CAS-A, Chandra X-ray Observatory

SN1987A by James Webb Space Telescope

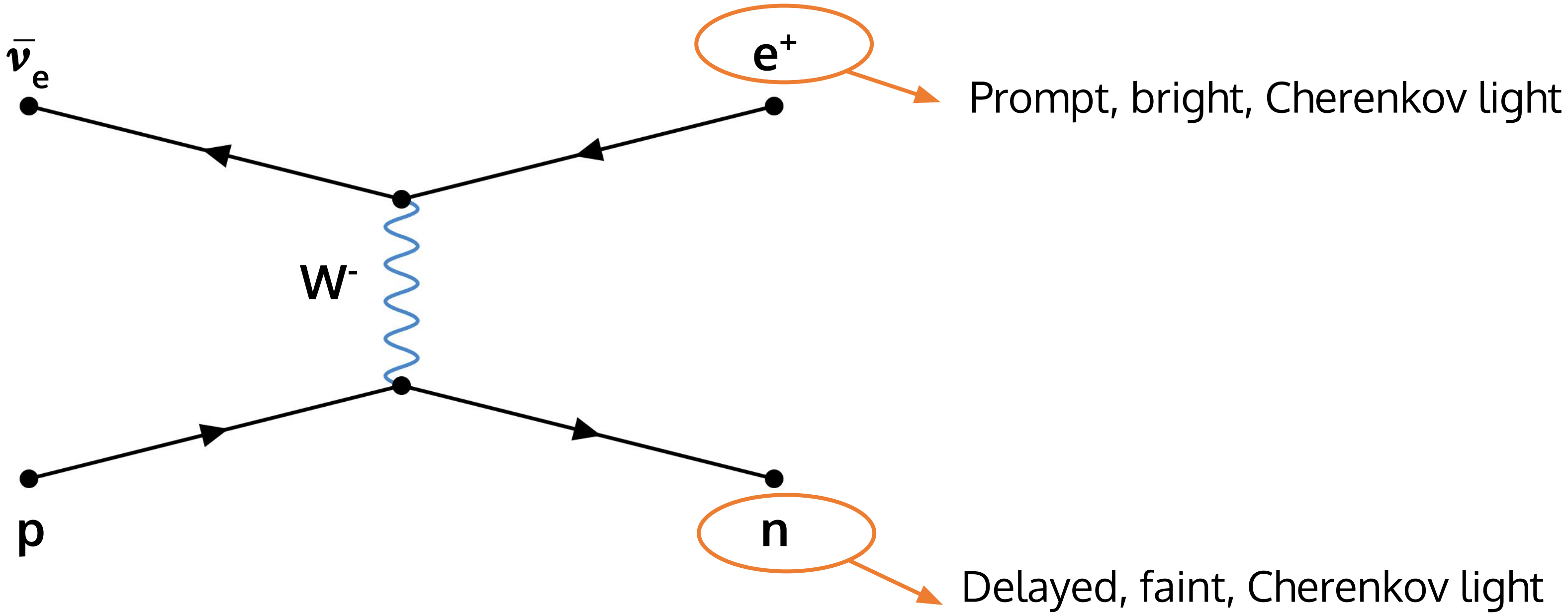
GVKM CCSN ν-Spectrum

ν-emission lasts ~10 s



For more models: SNEWPY

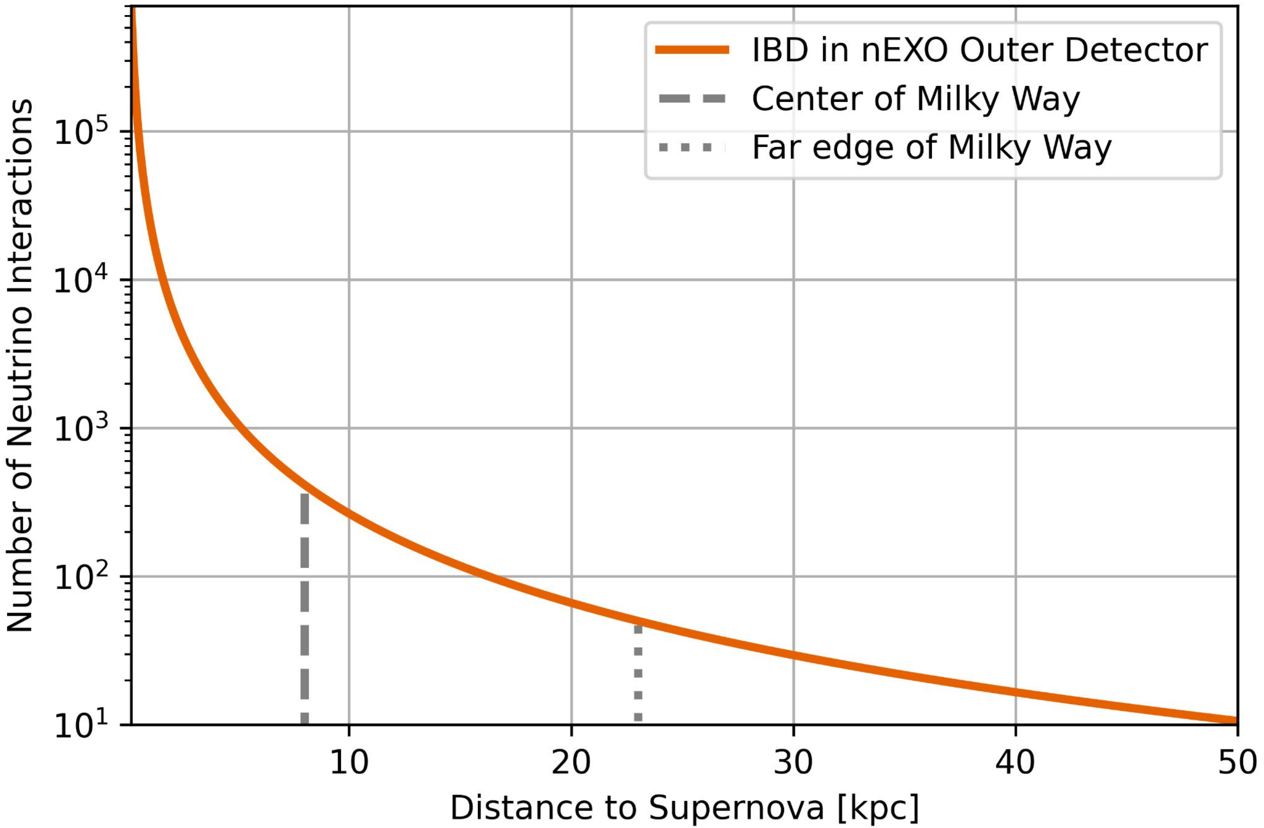
Inverse Beta Decay (IBD)



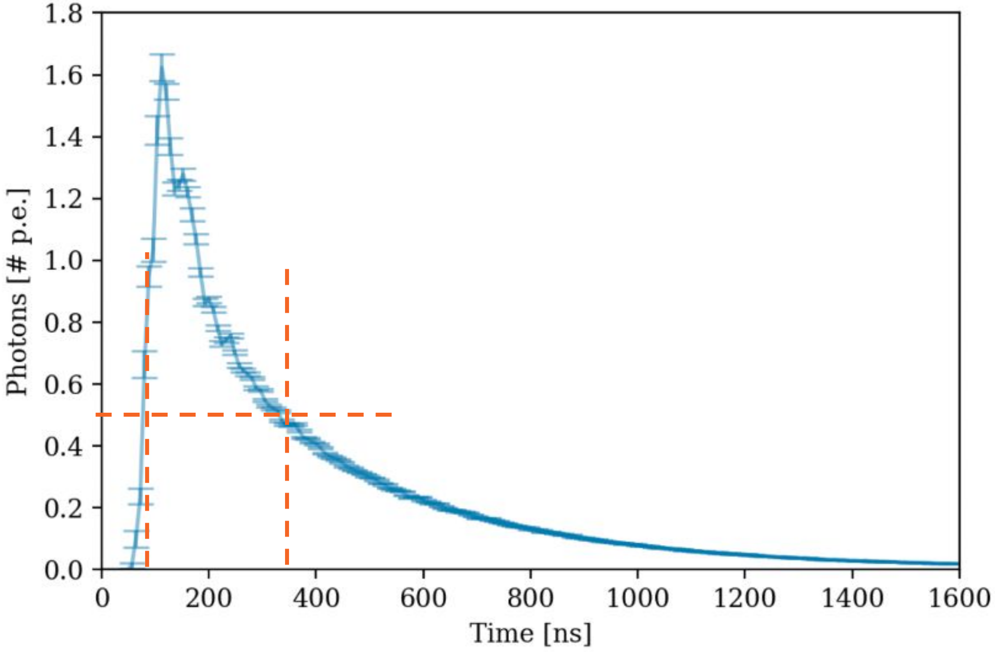
IBD event (on hydrogen in the water tank)

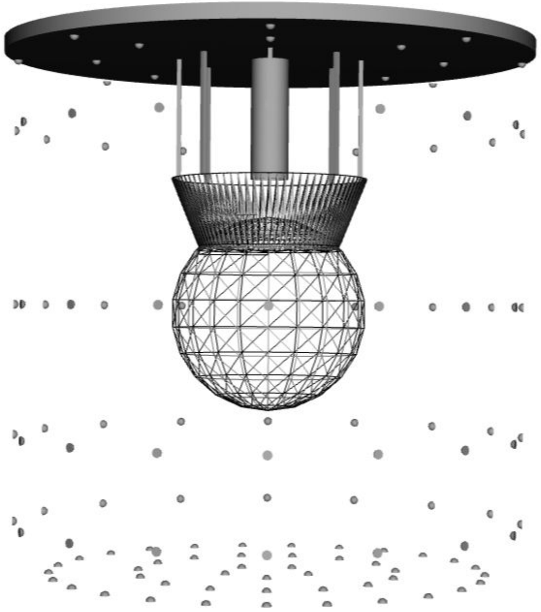
See also: S. Hedges et. al. (nEXO Collaboration) "Supernova Electron-Neutrino Interactions with Xenon in the nEXO Detector", 2024

IBD Interaction rates in the water tank



Positrons Triggering the Outer Detector

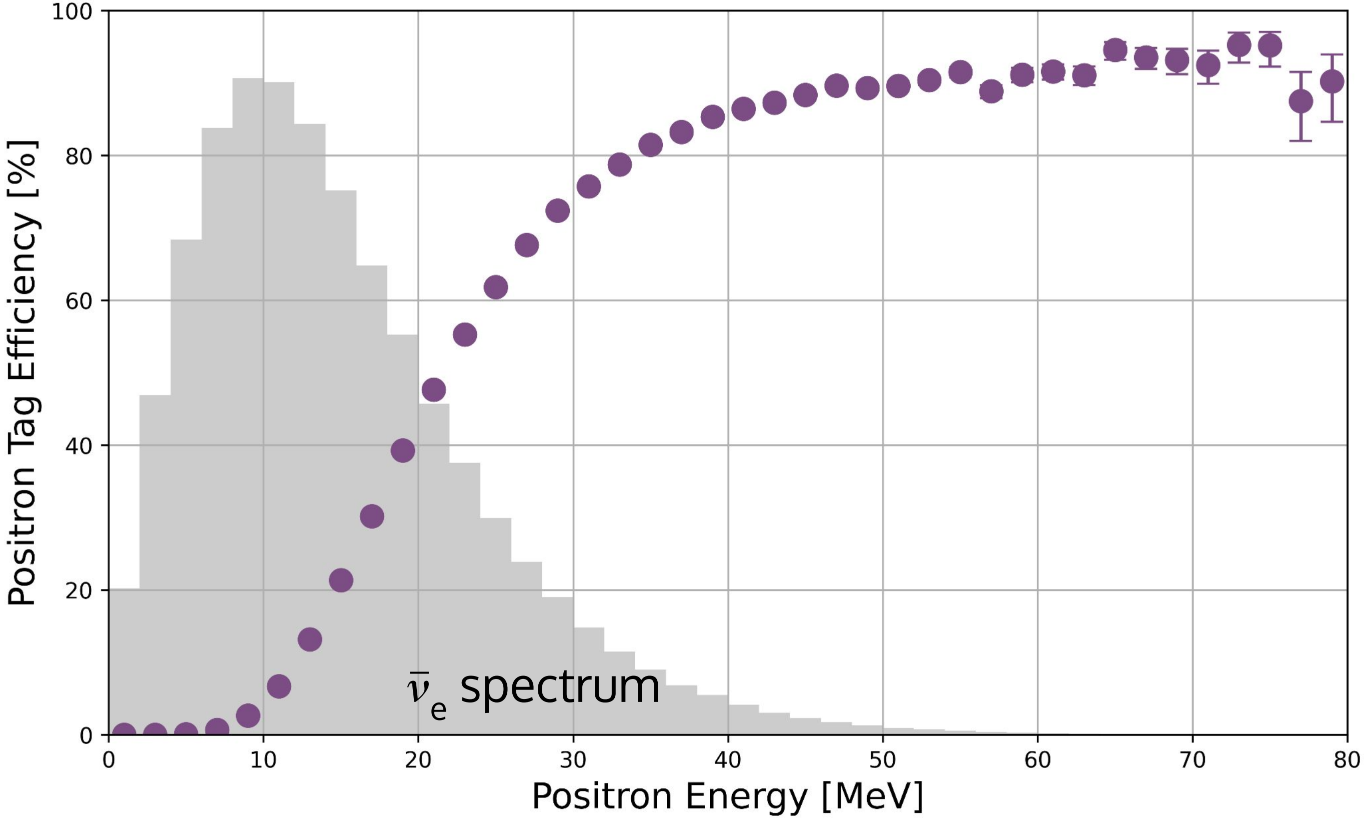




Geant4 PMT layout

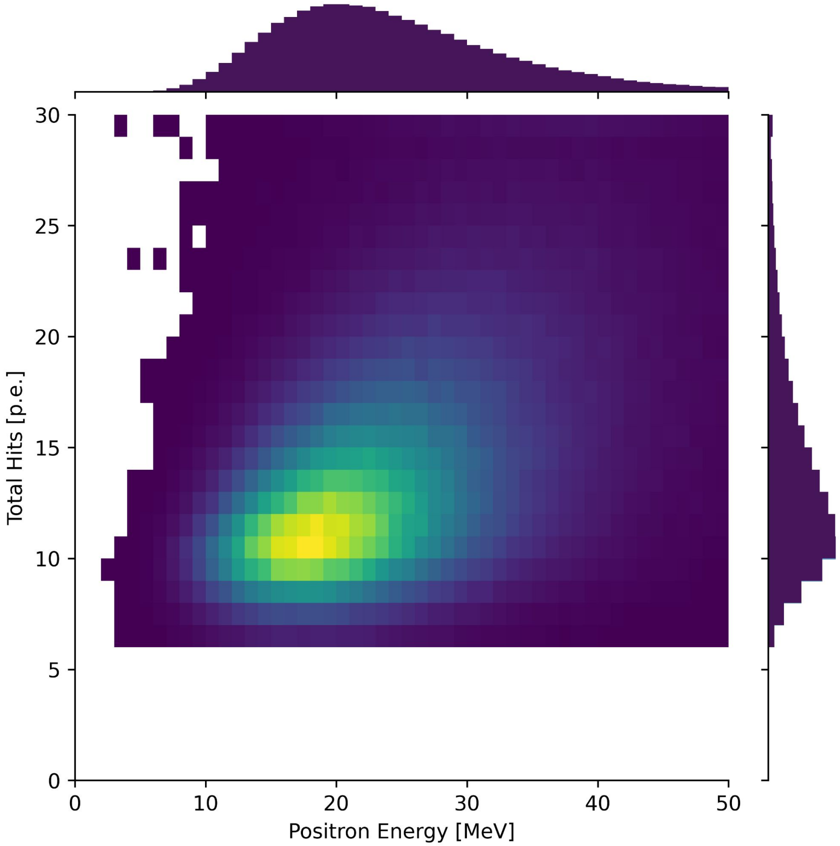
"Trigger on a 5-fold coincidence at s.p.e. level in a 240 ns window"

IBD Positron Tagging in the OD

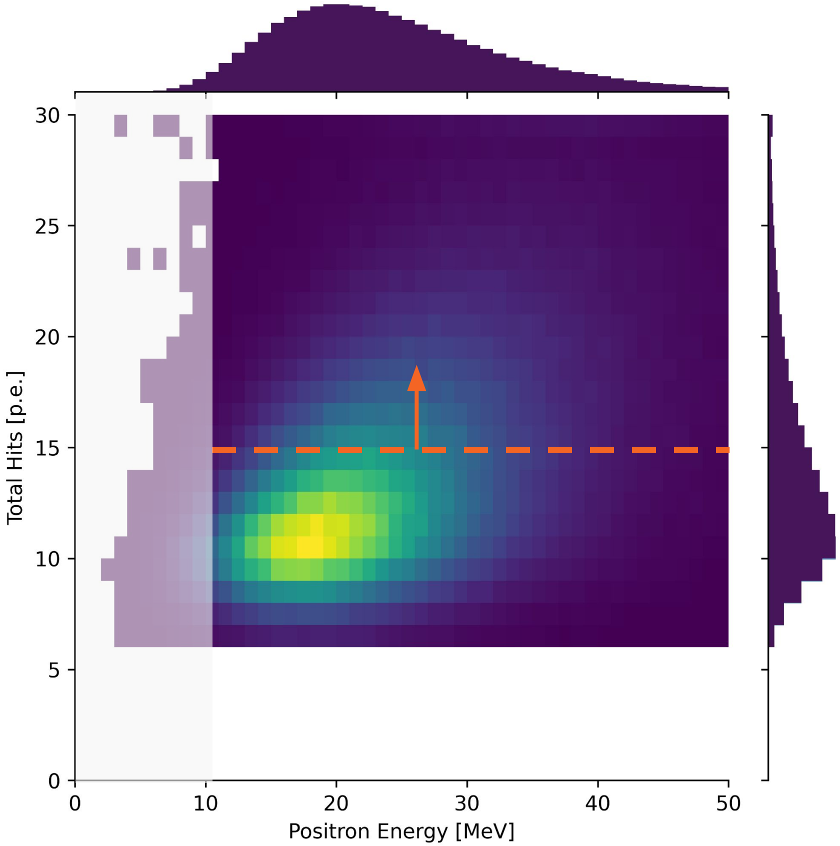


S. Al Kharusi, SNOLAB User's Meeting, 2024

Positron light yields in the Outer Detector

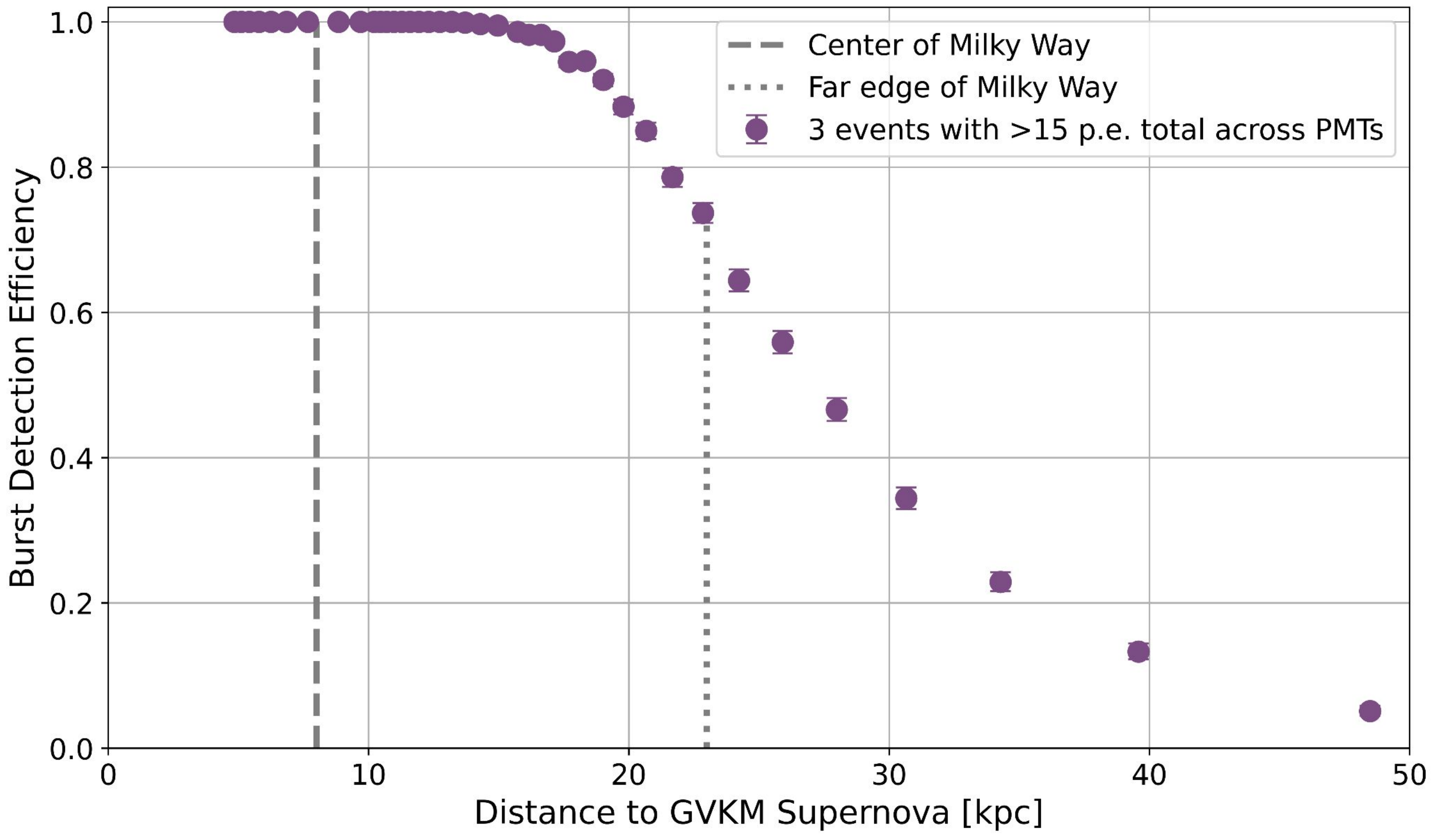


Positron light yields in the Outer Detector



"How often do we see >**3 events** in the Outer Detector, each with **>15 p.e.** within **10 seconds**?"

GVKM burst detection in Outer Detector



nEXO

Special thanks:
T. Brunner & D. Haggard

and ...

... many, many, folks in the nEXO/SNEWS collaborations & locally at McGill!

Supervisors: Thomas Brunner & Daryl Haggard

Thank you for your time!

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In Summary

Understanding the origin of neutrino masses is a deep mystery in beyond Standard Model physics

$0\nu\beta\beta$ exploits atomic nuclei to test high-energy theories that allow for neutrino masses

Cosmogenic backgrounds are mitigated in nEXO by using the TPC as a light-only gamma ray spectrometer

A water-Cherenkov muon veto validates the TPC veto and shields against radiogenic backgrounds, it is also sensitive to supernova neutrino bursts across our galaxy