Title: Ugrnd Experiments

Speakers:

Collection: TRISEP 2023

Date: June 30, 2023 - 2:30 PM

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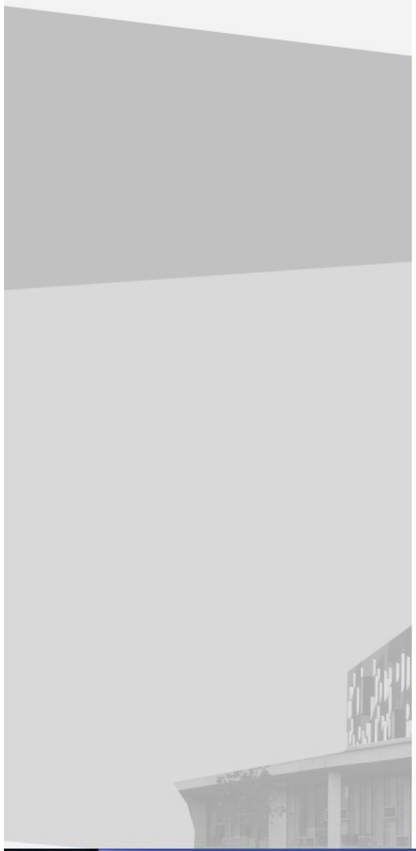
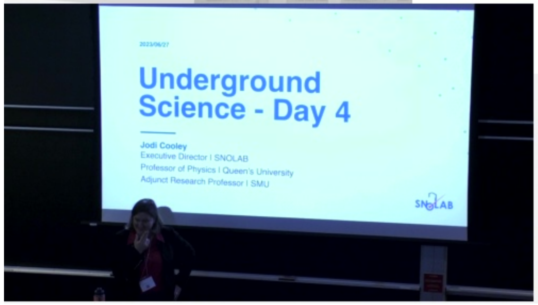


2023/06/27

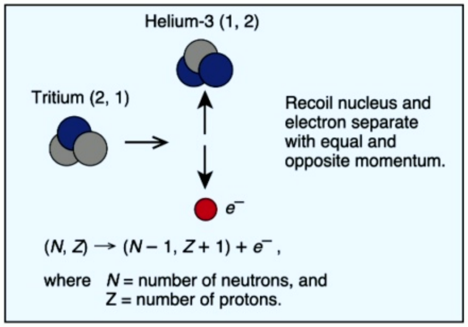
Underground Science - Day 4

Jodi Cooley
Executive Director I SNOLAB
Professor of Physics I Queen's University
Adjunct Research Professor I SMU



A Neutrino Origin Story

1930s Beta Decay



Helium-3 (1, 2)

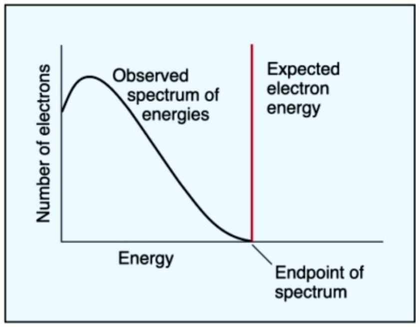
Tritium (2, 1)

Recoil nucleus and electron separate with equal and opposite momentum.

e^-

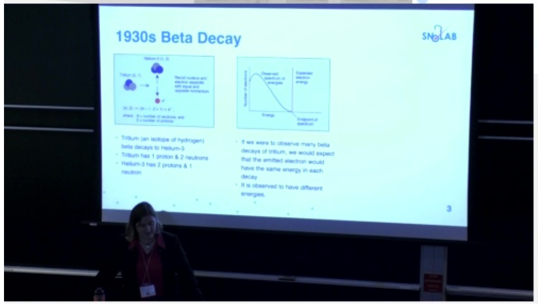
$(N, Z) \rightarrow (N-1, Z+1) + e^-$,

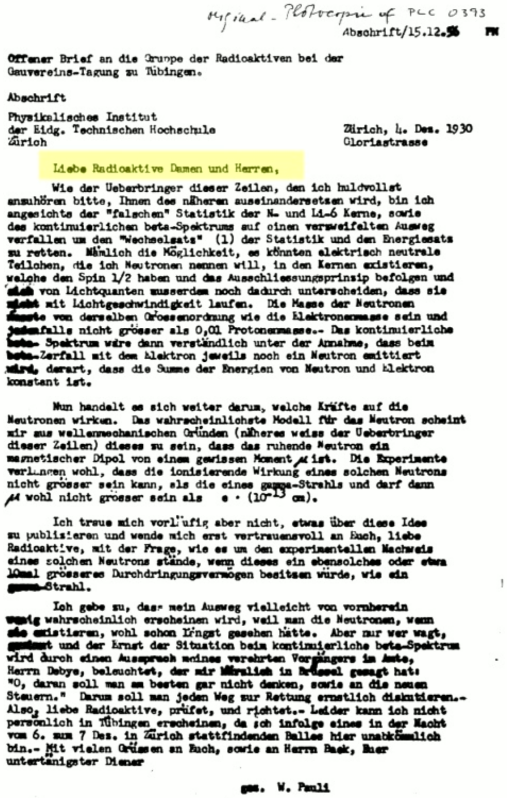
where N = number of neutrons, and
Z = number of protons.



- Tritium (an isotope of hydrogen) beta decays to Helium-3
- Tritium has 1 proton & 2 neutrons
- Helium-3 has 2 protons & 1 neutron

- If we were to observe many beta decays of tritium, we would expect that the emitted electron would have the same energy in each decay.
- It is observed to have different energies.





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Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

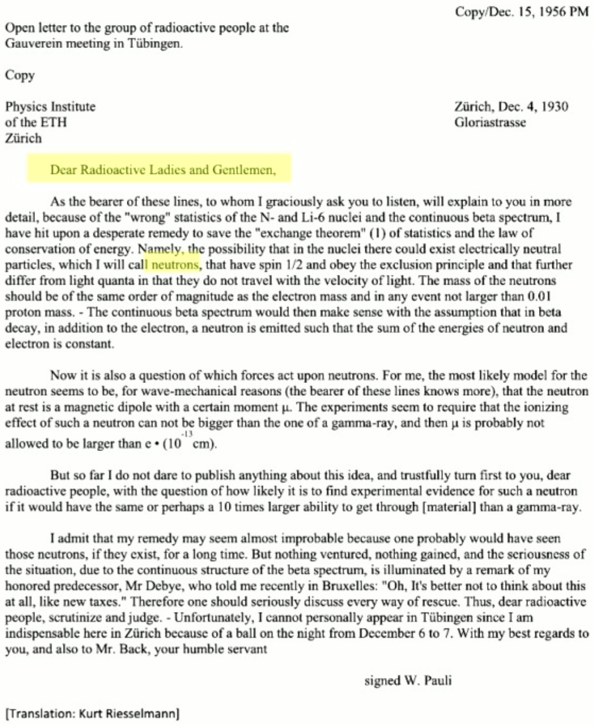
Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli



Copy/Dec. 15, 1956 PM

Open letter to the group of radioactive people at the Gauverein meeting in Tübingen.

Copy

Physics Institute
of the ETH
Zürich

Zürich, Dec. 4, 1930
Gloriastrasse

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, because of the "wrong" statistics of the N- and Li-6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and the law of conservation of energy. Namely, the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle and that further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton mass. - The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.

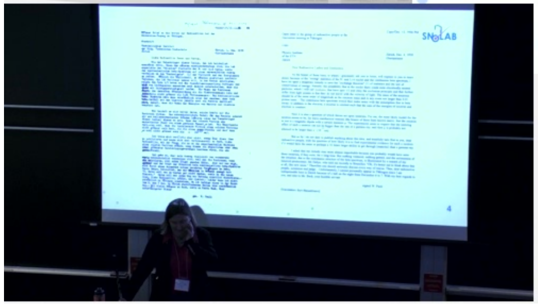
Now it is also a question of which forces act upon neutrons. For me, the most likely model for the neutron seems to be, for wave-mechanical reasons (the bearer of these lines knows more), that the neutron at rest is a magnetic dipole with a certain moment μ. The experiments seem to require that the ionizing effect of such a neutron can not be bigger than the one of a gamma-ray, and then μ is probably not allowed to be larger than $e \cdot (10^{-13}$ cm).

But so far I do not dare to publish anything about this idea, and trustfully turn first to you, dear radioactive people, with the question of how likely it is to find experimental evidence for such a neutron if it would have the same or perhaps a 10 times larger ability to get through [material] than a gamma-ray.

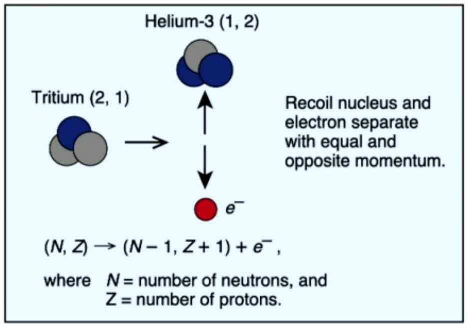
I admit that my remedy may seem almost improbable because one probably would have seen those neutrons, if they exist, for a long time. But nothing ventured, nothing gained, and the seriousness of the situation, due to the continuous structure of the beta spectrum, is illuminated by a remark of my honored predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's better not to think about this at all, like new taxes." Therefore one should seriously discuss every way of rescue. Thus, dear radioactive people, scrutinize and judge. - Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6 to 7. With my best regards to you, and also to Mr. Back, your humble servant

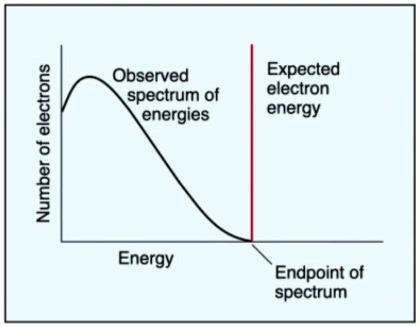
signed W. Pauli

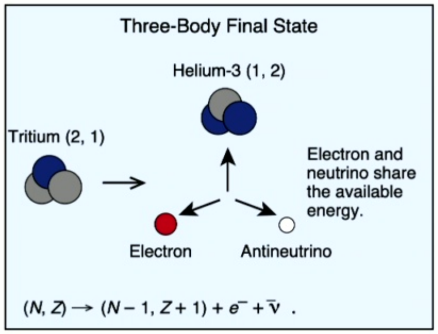
[Translation: Kurt Riesselmann]



An Origin Story: The Neutrino







- Tritium (an isotope of hydrogen) beta decays to Helium-3
- Tritium has 1 proton & 2 neutrons
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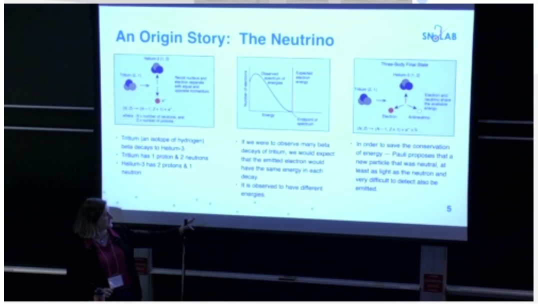
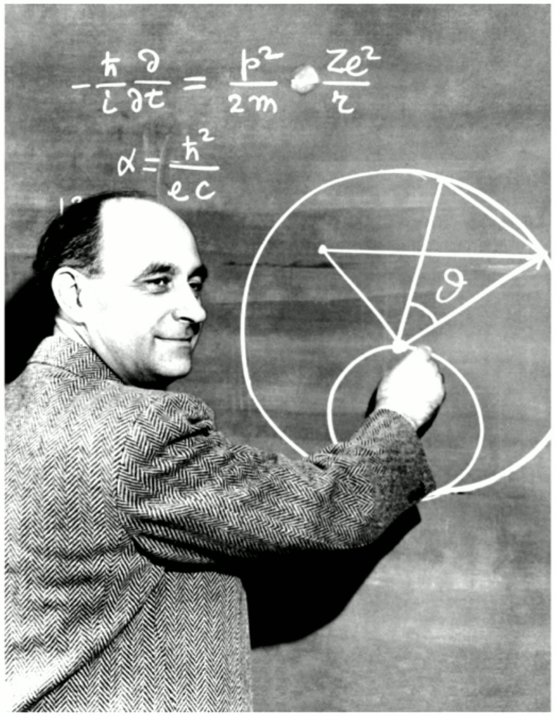
- If we were to observe many beta decays of tritium, we would expect that the emitted electron would have the same energy in each decay.
- It is observed to have different energies.

- In order to save the conservation of energy — Pauli proposes that a new particle that was neutral, at least as light as the neutron and very difficult to detect also be emitted.





AP Photo - Enrico Fermi

The Ghost Particle

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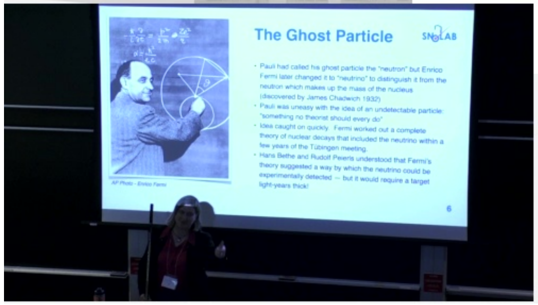
- Pauli had called his ghost particle the "neutron" but Enrico Fermi later changed it to "neutrino" to distinguish it from the neutron which makes up the mass of the nucleus (discovered by James Chadwich 1932)
- Pauli was uneasy with the idea of an undetectable particle: "something no theorist should every do"
- Idea caught on quickly. Fermi worked out a complete theory of nuclear decays that included the neutrino within a few years of the Tübingen meeting.
- Hans Bethe and Rudolf Peierls understood that Fermi's theory suggested a way by which the neutrino could be experimentally detected — but it would require a target light-years thick!



1953: Project Poltergeist

Clyde Cowan

Frederick Reines

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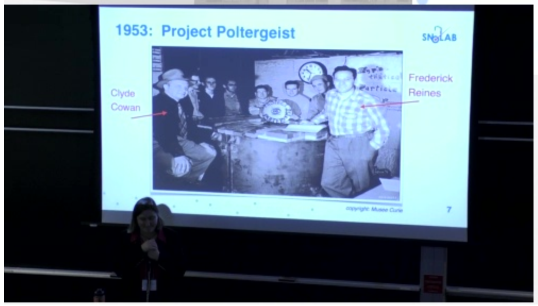
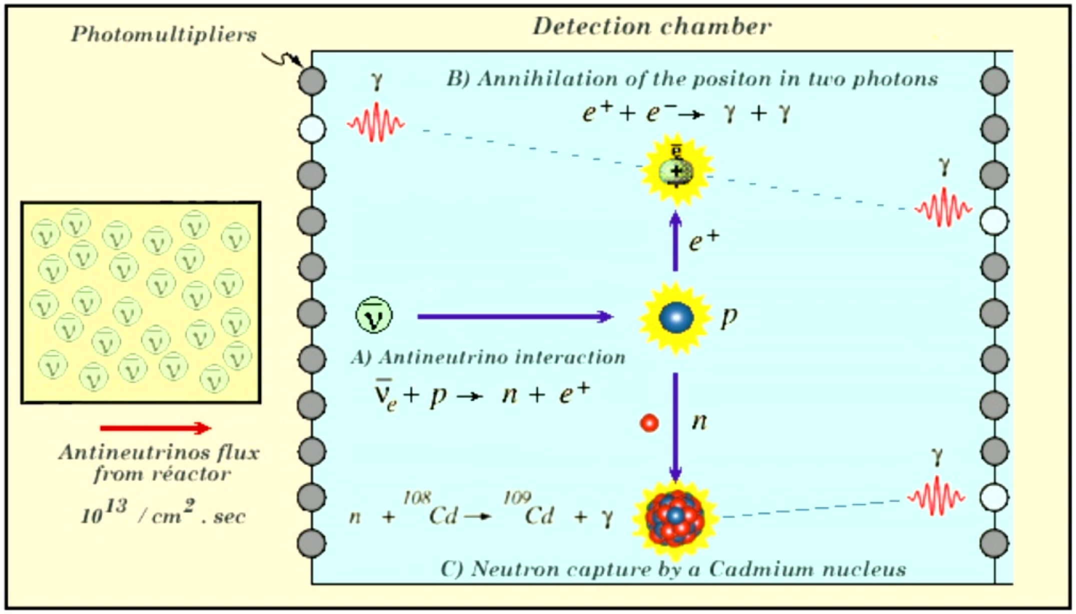


The Experiment Set-Up



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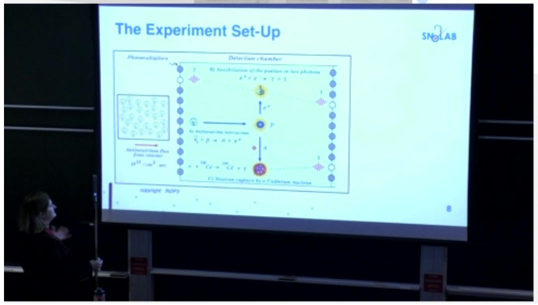
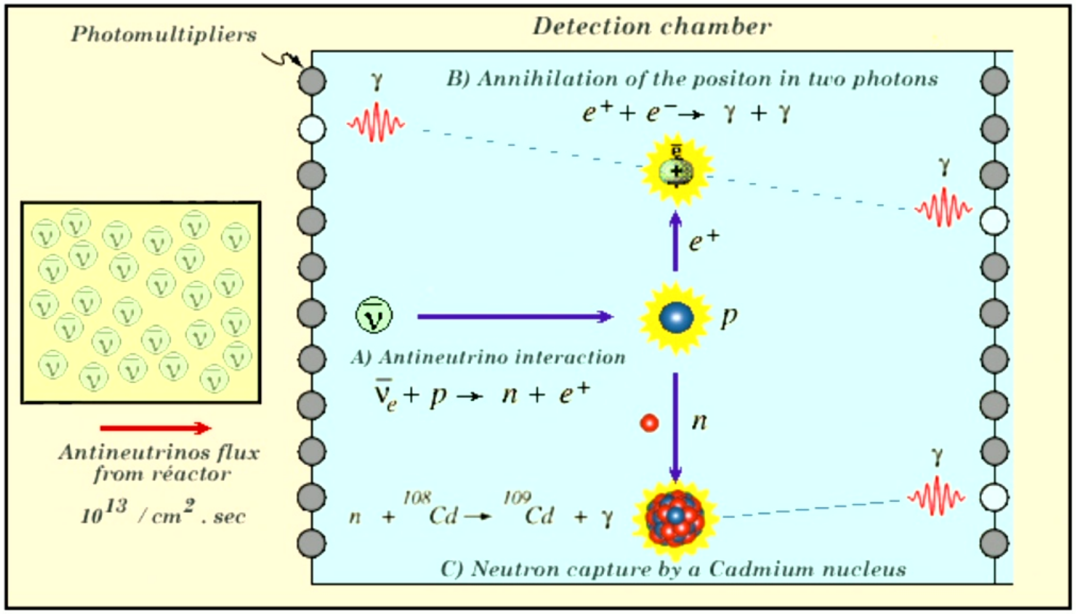


The Experiment Set-Up



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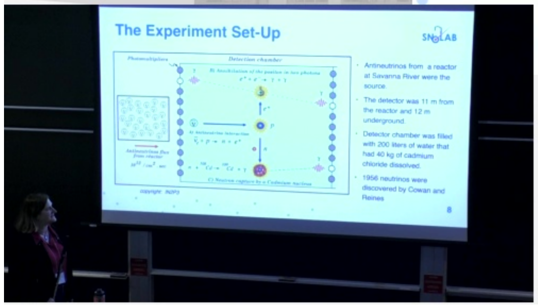
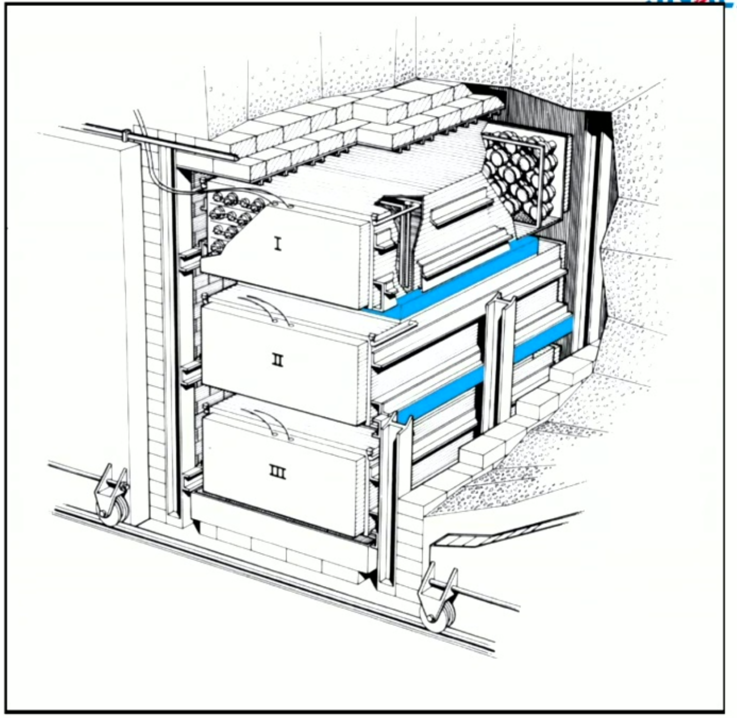
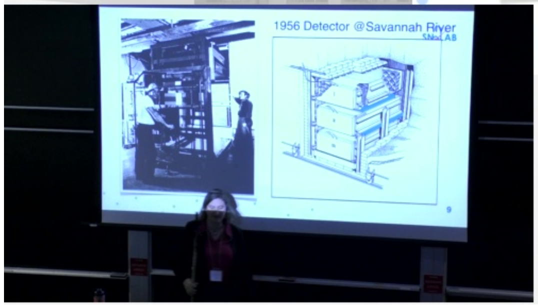
- Antineutrinos from a reactor at Savanna River were the source.
- The detector was 11 m from the reactor and 12 m underground.
- Detector chamber was filled with 200 liters of water that had 40 kg of cadmium chloride dissolved.
- 1956 neutrinos were discovered by Cowan and Reines

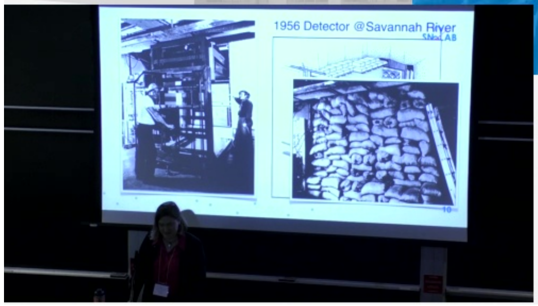


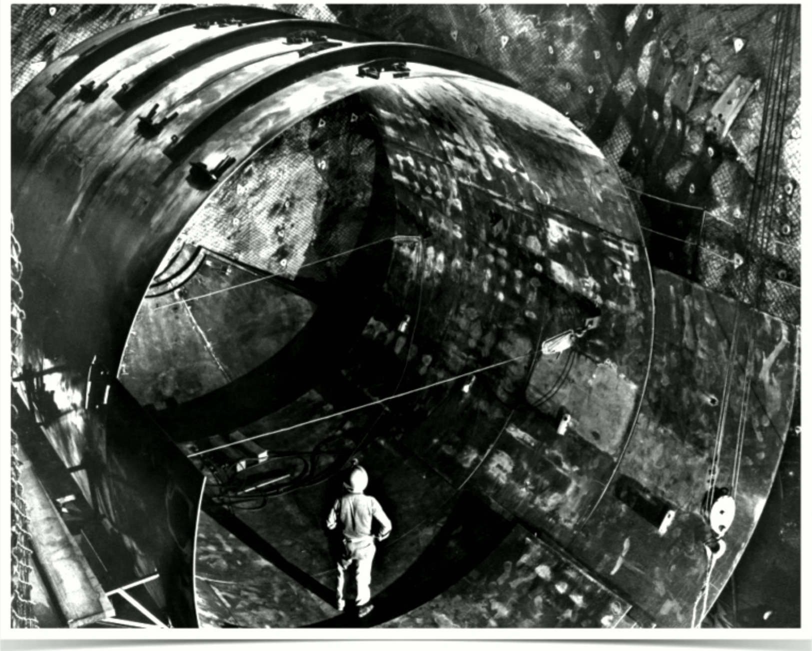
1956 Detector @Savannah River



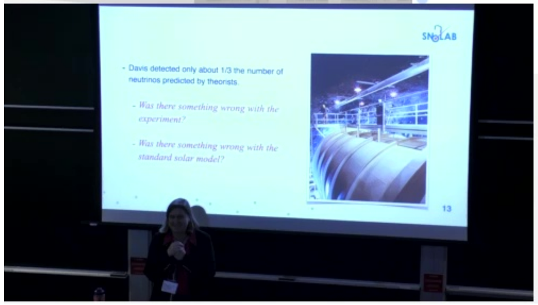


Neutrinos from the Sun

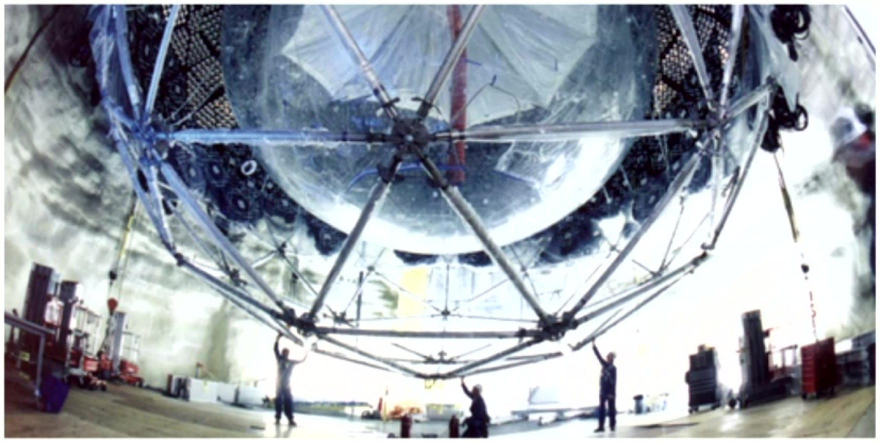




- Davis detected only about 1/3 the number of neutrinos predicted by theorists.
  - *Was there something wrong with the experiment?*
  - *Was there something wrong with the standard solar model?*



- In the 1990s the SNO experiment in Canada and the Kamiokande experiment Japan resolved the issue.
- Neutrinos came in three “flavors” — electron, muon and tau.
- Davis was only measuring the electron neutrinos produced in the sun.
- Furthermore, it was later shown that the neutrino could change its flavor as it travels through space.



The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass."

© Nobel Media AB. Photo: A. Mahmoud

Takaaki Kajita

Prize share: 1/2

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Arthur B. McDonal

Prize share: 1/2

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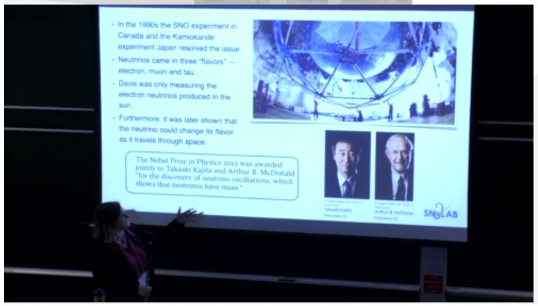
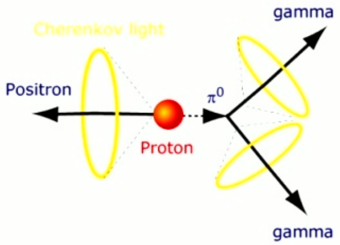
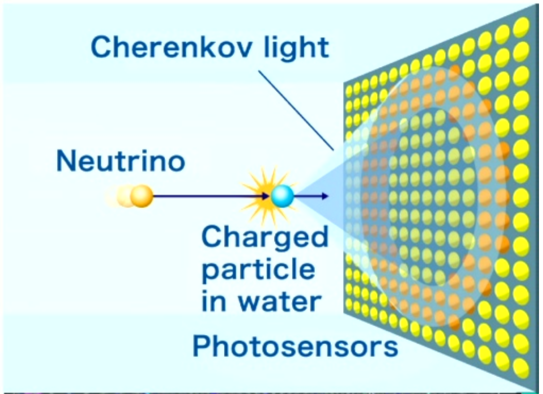
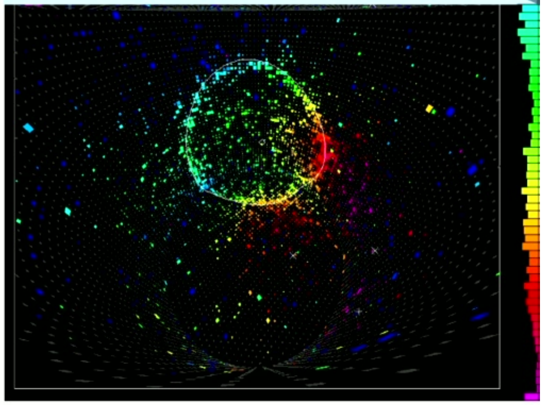


Aside:
Serendipity - Preparing for the Unexpected



- KamiokaNDE and IBM were water Cherenkov detectors designed to detect proton decay
- Realized that large cherenkov detectors would be ideal neutrino detectors
- KamiokaNDE II: Observed solar neutrinos, SN1987A (Nobel Prize: Masatoshi Koshiba)
- SNO, SuperK: Proved existence of neutrino oscillations. (Arthur McDonald and Takaaki Kajita)





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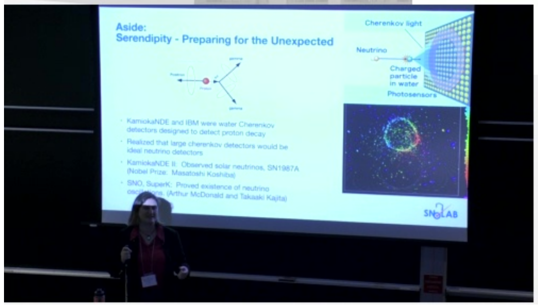
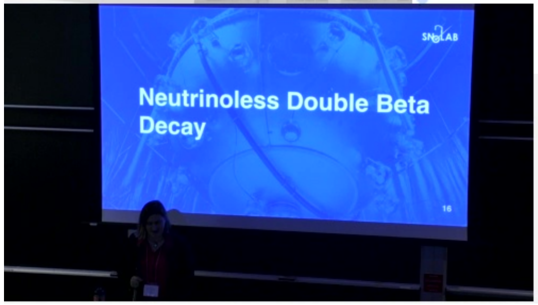


0νββ Decay References

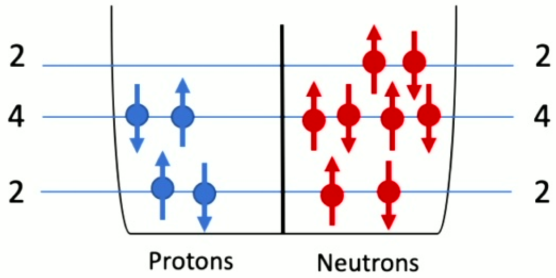
- https://www.mpi-hd.mpg.de/manitop/Neutrino/sheets/Lecture14_SS21.pdf
- https://arxiv.org/abs/2108.09364
- https://arxiv.org/pdf/0708.1033.pdf
- https://journals.aps.org/rmp/abstract/10.1103/RevModPhys.87.137

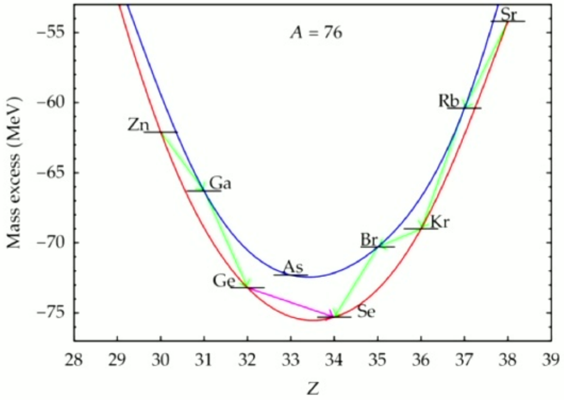


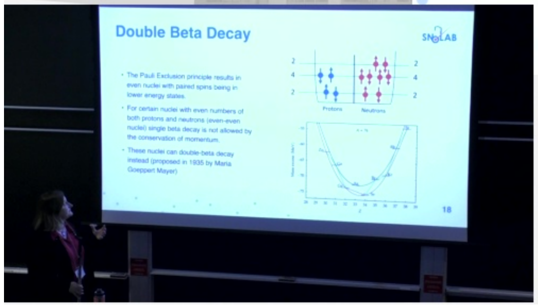
Neutrinoless Double Beta Decay

Double Beta Decay

- The Pauli Exclusion principle results in even nuclei with paired spins being in lower energy states.
- For certain nuclei with even numbers of both protons and neutrons (even-even nuclei) single beta decay is not allowed by the conservation of momentum.
- These nuclei can double-beta decay instead (proposed in 1935 by Maria Goeppert Mayer)



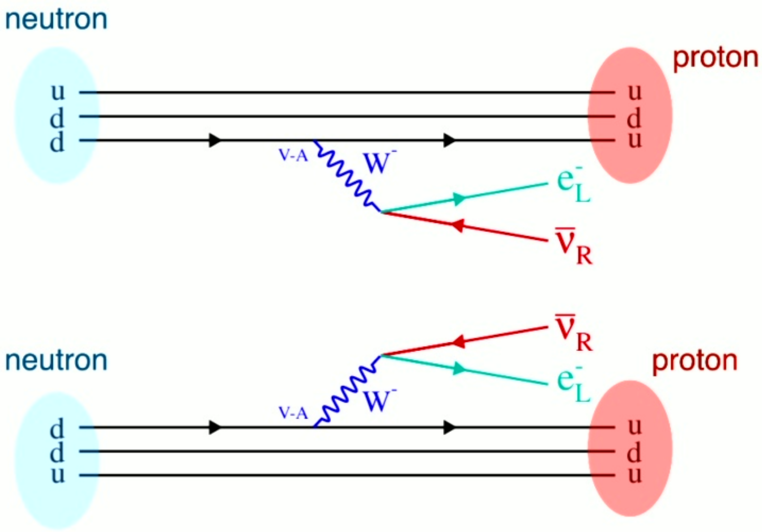


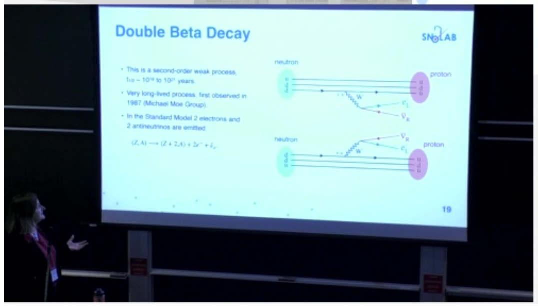


Double Beta Decay

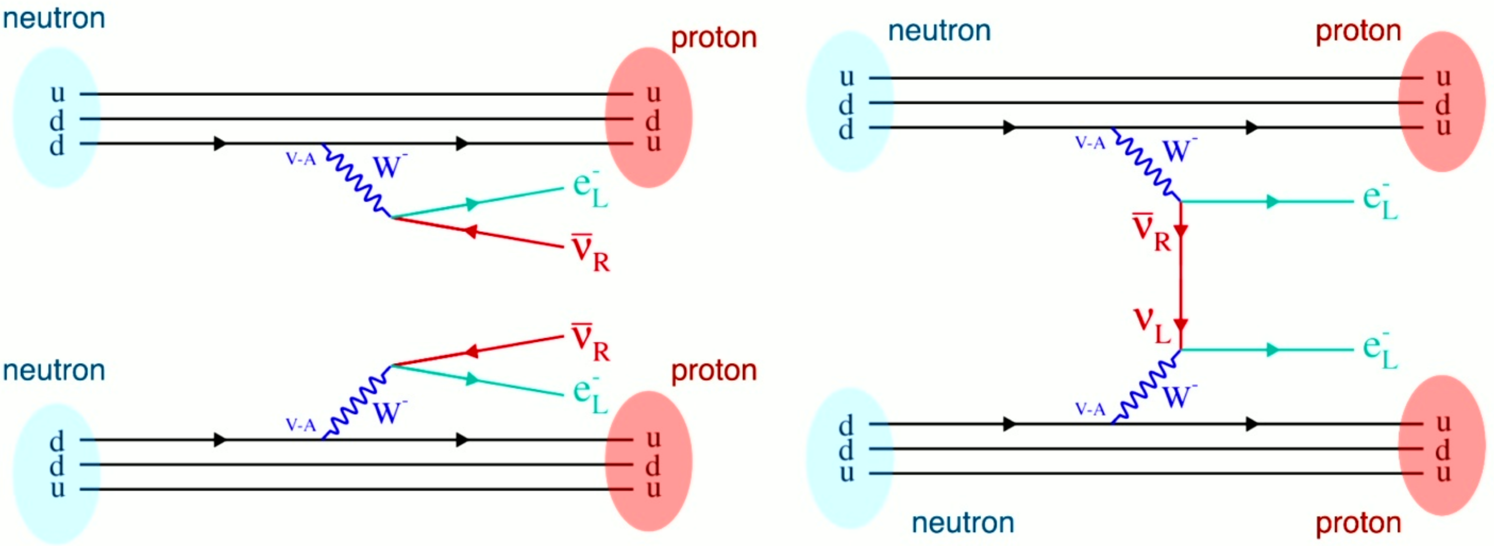
- This is a second-order weak process, $t_{1/2} \sim 10^{19}$ to 10^{21} years.
- Very long-lived process, first observed in 1987 (Michael Moe Group).
- In the Standard Model 2 electrons and 2 antineutrinos are emitted.

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

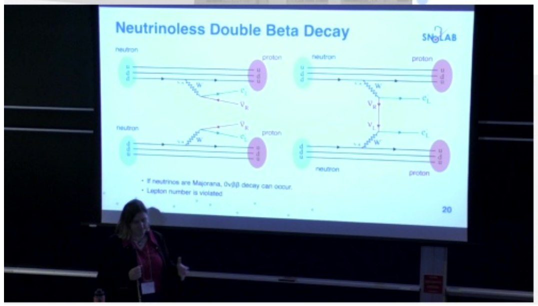




Neutrinoless Double Beta Decay

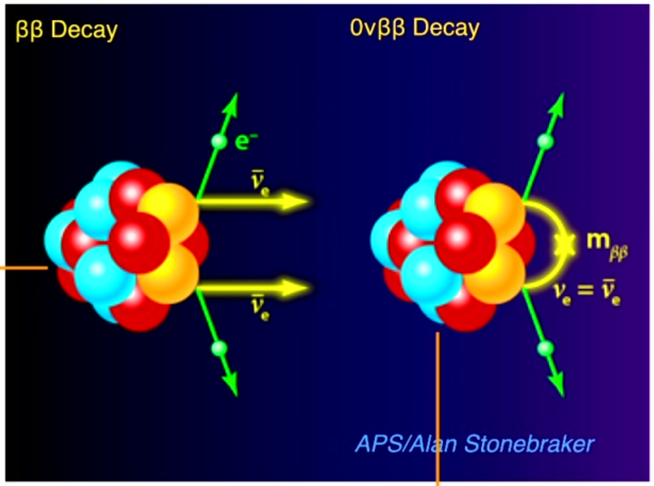


- If neutrinos are Majorana, 0νββ decay can occur.
- Lepton number is violated

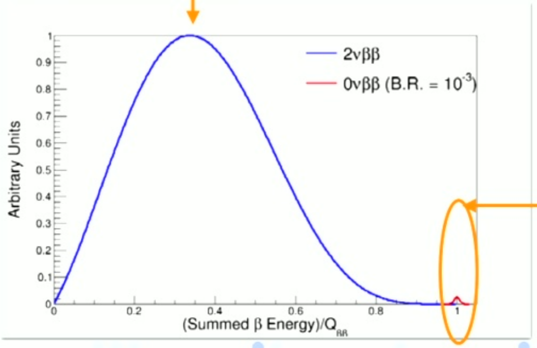


What does this look like?

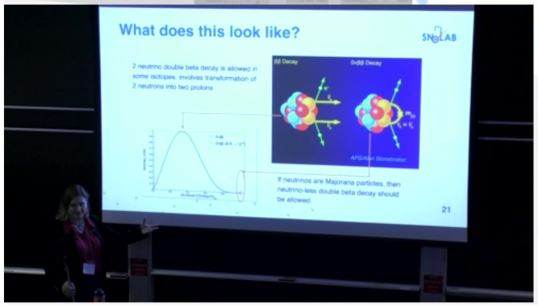
2 neutrino double beta decay is allowed in some isotopes, involves transformation of 2 neutrons into two protons



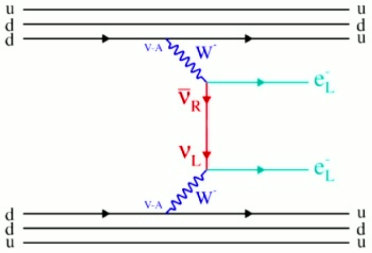
APS/Alan Stonebraker



If neutrinos are Majorana particles, then neutrino-less double beta decay should be allowed.



0νββ Decay Rates for Light Majorana Neutrino Exchange



The rate can be written as

$$\Gamma(0\nu) = T_{1/2} = (G \cdot |M_{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2)^{-1}$$

G = phase factor for 2ν emmission

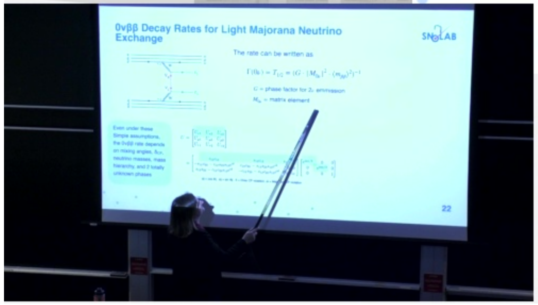
$M_{0\nu}$ = matrix element

Even under these Simple assumptions, the 0νββ rate depends on mixing angles, δ_{CP}, neutrino masses, mass hierarchy, and 2 totally unknown phases

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

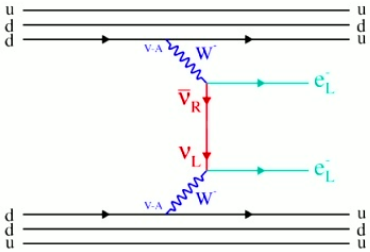
$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

cij = cos θij , sij = sin θij , δ = Dirac CP violation, αi = Majorana CP violation



0νββ Decay Rates for Light Majorana Neutrino Exchange

SNOLAB



The rate can be written as

$$\Gamma(0\nu) = T_{1/2} = (G \cdot |M_{0\nu}|^2 \cdot \boxed{\langle m_{\beta\beta}\rangle^2})^{-1}$$

G = phase factor for 2ν emmission

$M_{0\nu}$ = matrix element

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

Sensitive to the effective Majorana ν mass

Even under these Simple assumptions, the 0νββ rate depends on mixing angles, δ_{CP}, neutrino masses, mass hierarchy, and 2 totally unknown phases

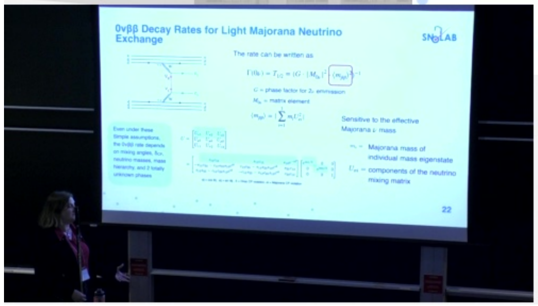
$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

cij = cos θij , sij = sin θij , δ = Dirac CP violation, αi = Majorana CP violation

m_i = Majorana mass of individual mass eigenstate

U_{ei} = components of the neutrino mixing matrix



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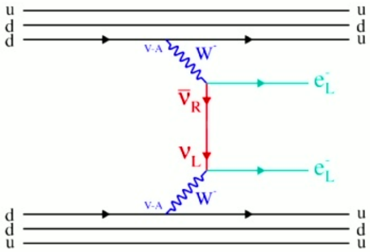

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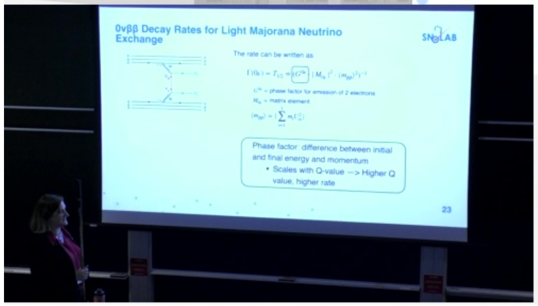
$G^{0\nu}$ = phase factor for emission of 2 electrons

$M_{0\nu}$ = matrix element

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

Phase factor: difference between initial and final energy and momentum
- Scales with Q-value —> Higher Q value, higher rate



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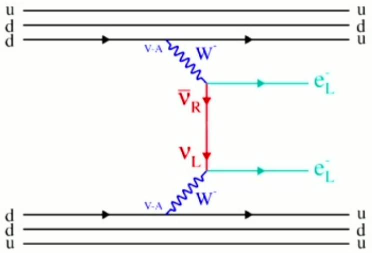

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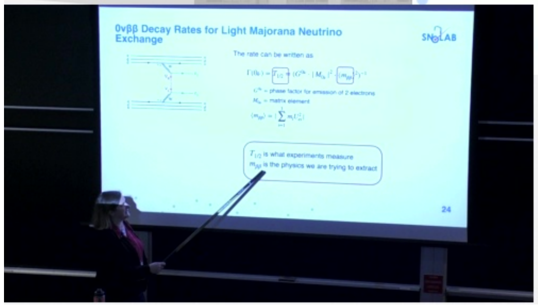
$$\langle m_{\beta\beta}\rangle = |\sum_{i=1}^{3} m_i U_{ei}^2|$$

$T_{1/2}$ is what experiments measure
$m_{\beta\beta}$ is the physics we are trying to extract



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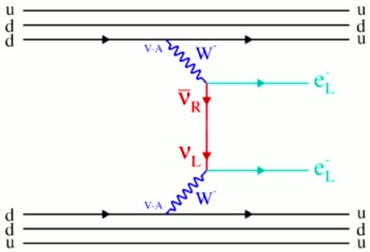

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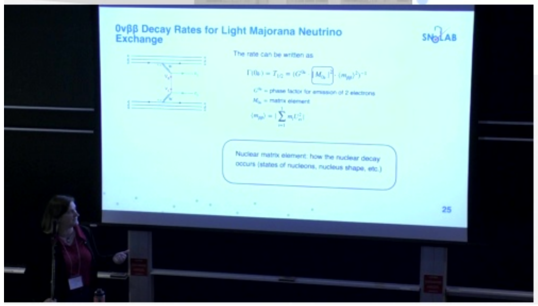
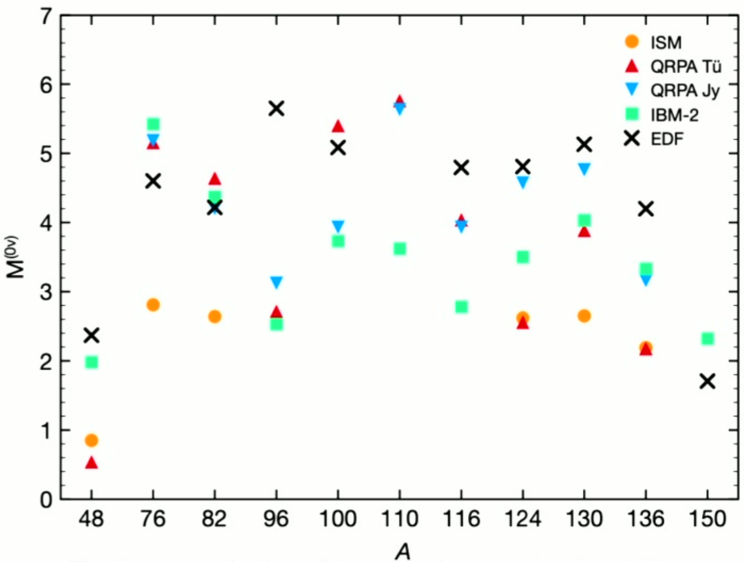
Nuclear matrix element: how the nuclear decay occurs (states of nucleons, nucleus shape, etc.)

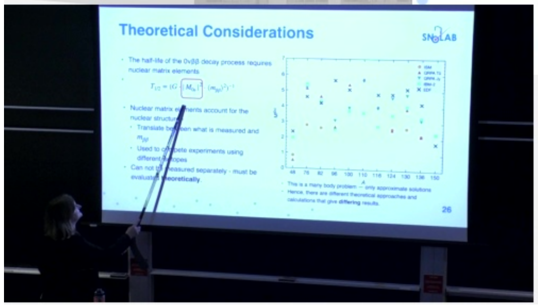


Theoretical Considerations

- The half-life of the 0νββ decay process requires nuclear matrix elements
- $$T_{1/2} = (G \cdot \boxed{|M_{0\nu}|^2} \cdot \langle m_{\beta\beta}\rangle^2)^{-1}$$
- Nuclear matrix elements account for the nuclear structure -
  - Translate between what is measured and $m_{\beta\beta}$
  - Used to compete experiments using different isotopes
- Can not be measured separately - must be evaluated **theoretically**.



- This is a many body problem — only approximate solutions
- Hence, there are different theoretical approaches and calculations that give **differing** results.

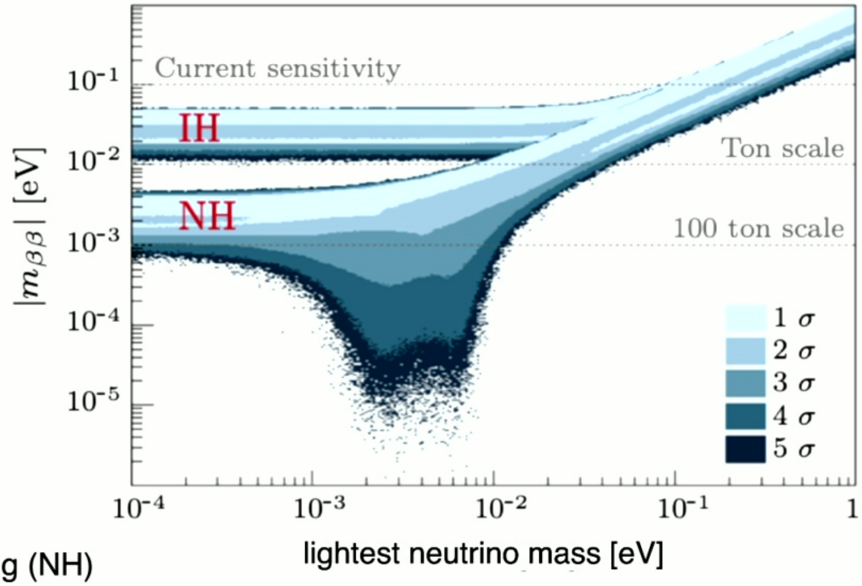


Neutrinoless Double Beta Decay

$$\Gamma(0\nu) = T_{1/2} = (G \cdot |M_{0\nu}|^2 \cdot \langle m_{\beta\beta}\rangle^2)^{-1}$$

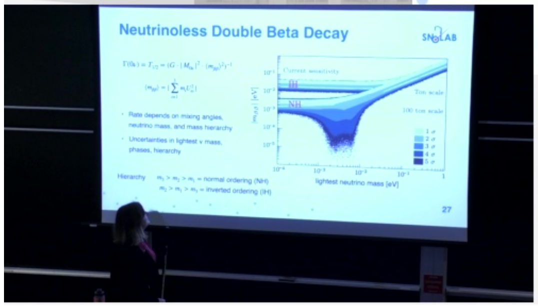
$$\langle m_{\beta\beta}\rangle = |\sum_{i=1}^{3} m_i U_{ei}^2|$$

- Rate depends on mixing angles, neutrino mass, and mass hierarchy
- Uncertainties in lightest ν mass, phases, hierarchy



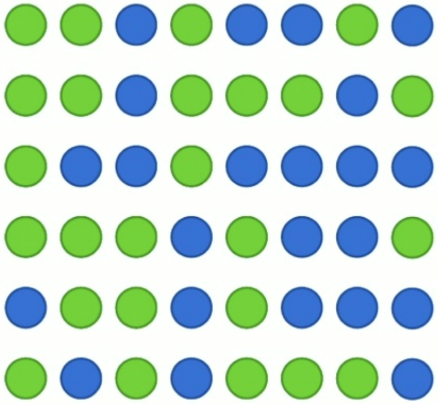
Hierarchy $m_3 > m_2 > m_1$ = normal ordering (NH)

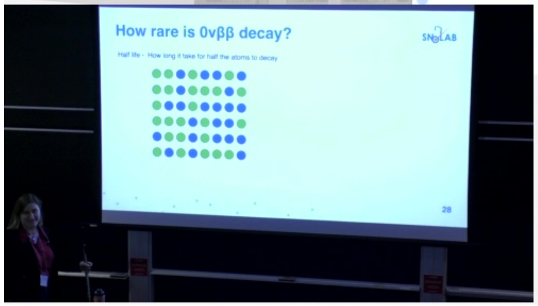
$m_2 > m_1 > m_3$ = inverted ordering (IH)



How rare is 0νββ decay?

Half life - How long it take for half the atoms to decay





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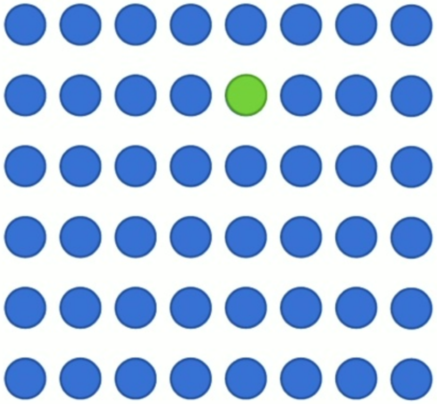


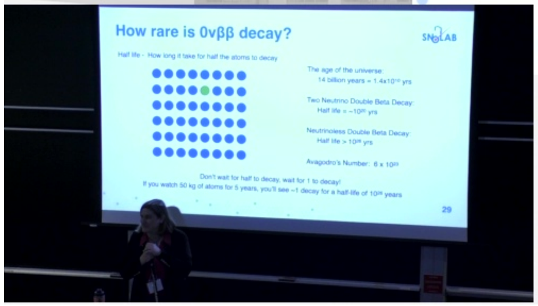
The age of the universe:
14 billion years = 1.4×10^{10} yrs

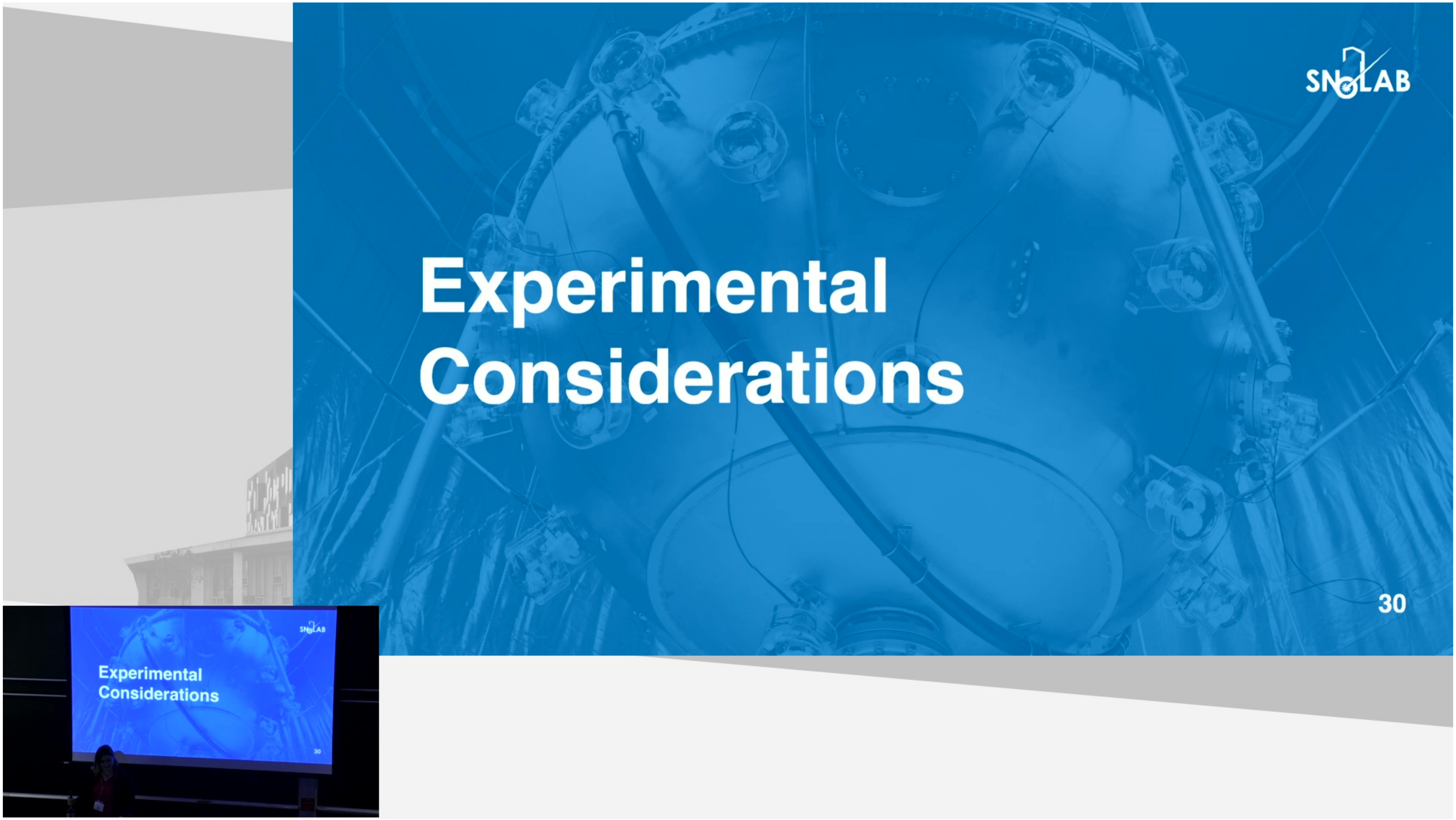
Two Neutrino Double Beta Decay:
Half life = $\sim10^{20}$ yrs

Neutrinoless Double Beta Decay:
Half life > 10^{26} yrs

Avagodro's Number: 6×10^{23}

Don't wait for half to decay, wait for 1 to decay!
If you watch 50 kg of atoms for 5 years, you'll see ~1 decay for a half-life of 10^{26} years

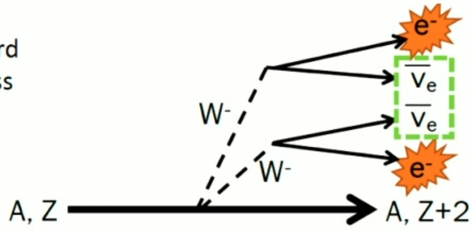




Experimental Considerations

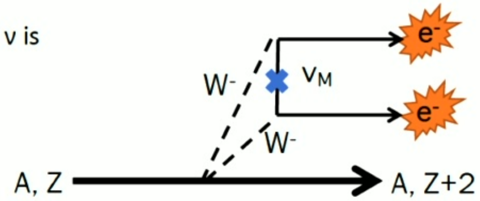
How to detect 0νββ decay

2νββ: Standard Model process



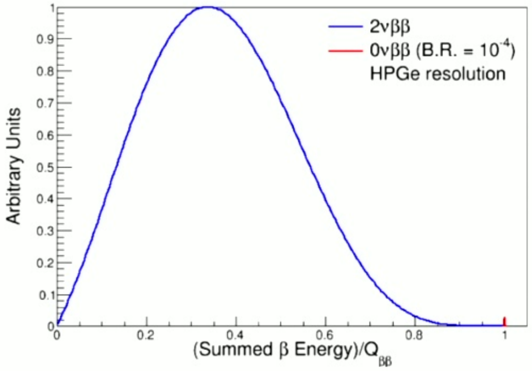
Missing energy

0νββ: Only if ν is Majorana

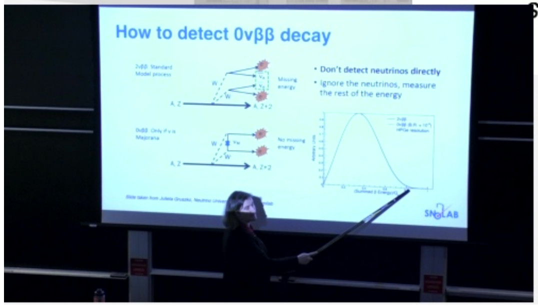


No missing energy

- **Don't detect neutrinos directly**
- Ignore the neutrinos, measure the rest of the energy

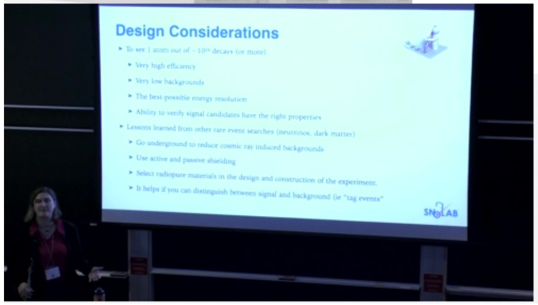


Slide taken from Julieta Gruszko, Neutrino University Series @ Fermilab

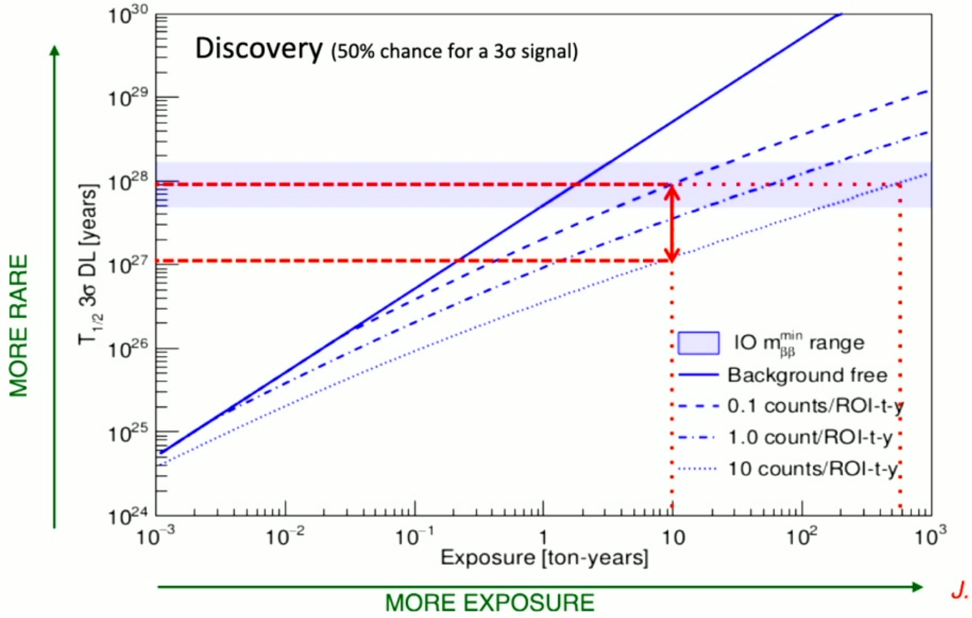


Design Considerations

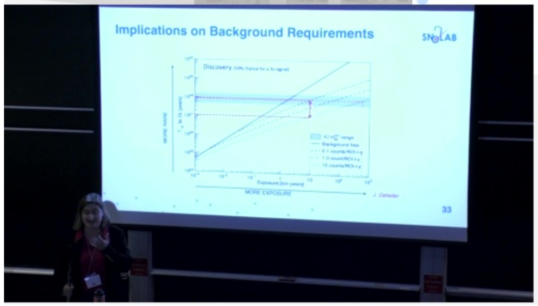
- To see 1 atom out of ~10^{26} decays (or more)
  - Very high efficiency
  - Very low backgrounds
  - The best-possible energy resolution
  - Ability to verify signal candidates have the right properties
- Lessons learned from other rare event searches (neutrinos, dark matter)
  - Go underground to reduce cosmic ray induced backgrounds
  - Use active and passive shielding
  - Select radiopure materials in the design and construction of the experiment.
  - It helps if you can distinguish between signal and background (ie "tag events"



Implications on Background Requirements



J. Detwiler



Experimental Considerations

- Two measurement techniques for measuring the electrons from the 2ββ decay
  - Spectroscopy - looking for a peak
  - Tracking - reconstructing topology
- $Q_{\beta\beta}$ values depend on the target isotope
- The number of events

$$N \propto \frac{N_A}{W} \frac{\boxed{a} \cdot \epsilon \cdot M \cdot t}{T_{1/2}}$$

N_A = Avogadro's Number

W = molar mass

a = isotope abundance

ϵ = detection efficiency

M = isotope mass

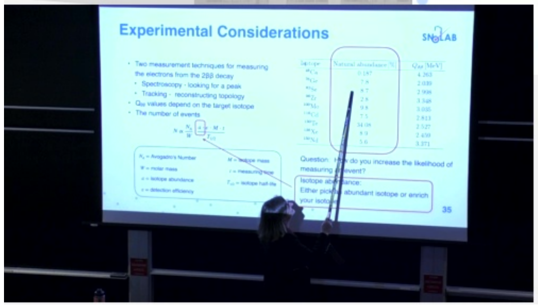
t = measuring time

$T_{1/2}$ = isotope half-life

Isotope	Natural abundance [%]	$Q_{\beta\beta}$ [MeV]
^{48}Ca	0.187	4.263
^{76}Ge	7.8	2.039
^{82}Se	8.7	2.998
^{96}Zr	2.8	3.348
^{100}Mo	9.8	3.035
^{116}Cd	7.5	2.813
^{130}Te	34.08	2.527
^{136}Xe	8.9	2.459
^{150}Nd	5.6	3.371

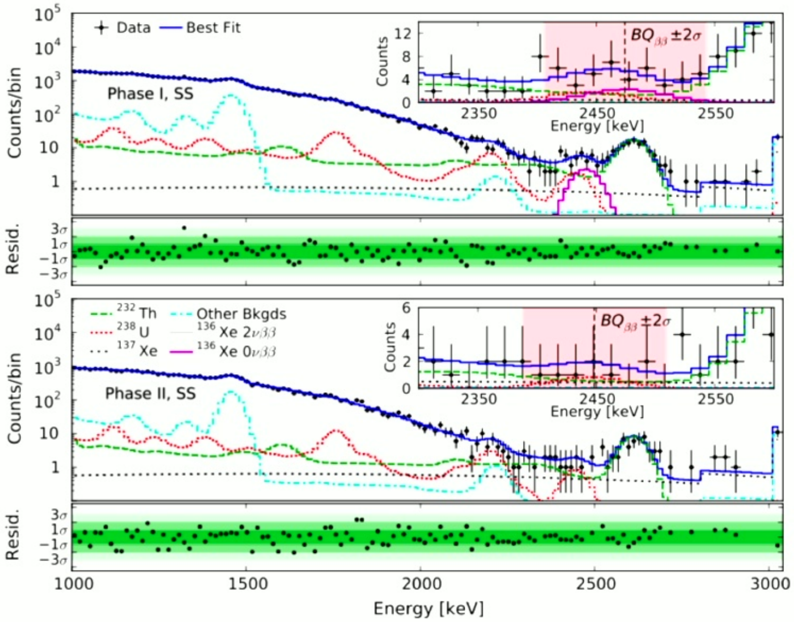
Question: How do you increase the likelihood of measuring an event?

Isotope abundance:
Either pick an abundant isotope or enrich your isotope

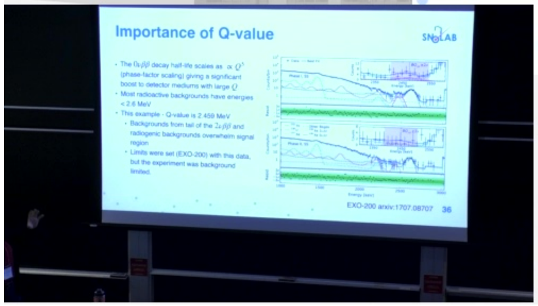


Importance of Q-value

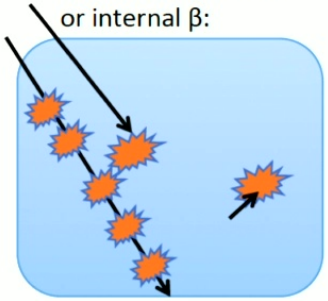
- The $0\nu\beta\beta$ decay half-life scales as $\propto Q^5$ (phase-factor scaling) giving a significant boost to detector mediums with large Q.
- Most radioactive backgrounds have energies < 2.6 MeV
- This example - Q-value is 2.459 MeV
  - Backgrounds from tail of the $2\nu\beta\beta$ and radiogenic backgrounds overwhelm signal region
  - Limits were set (EXO-200) with this data, but the experiment was background limited.

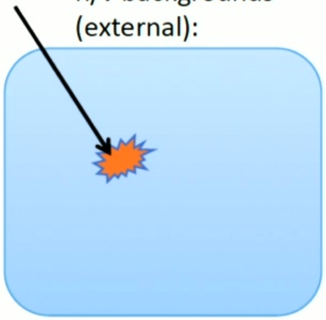


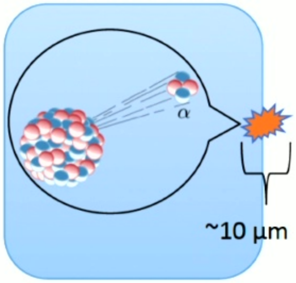
EXO-200 arxiv:1707.08707



Event Signatures

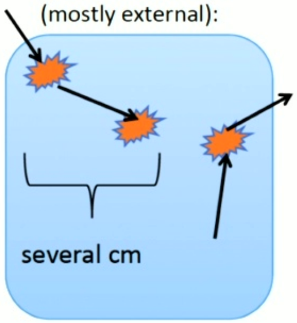

cosmic μ (external)
or internal β:

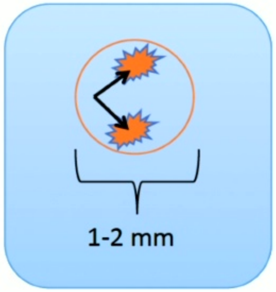

n/ν backgrounds
(external):


α backgrounds
(mostly surface events):

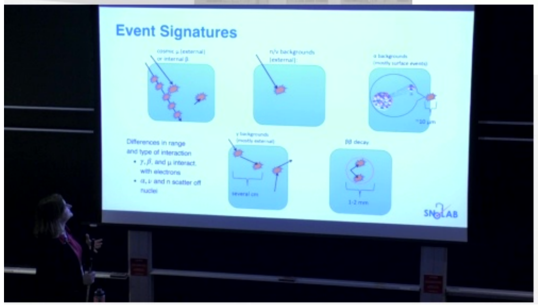
Differences in range
and type of interaction

- γ, β, and μ interact. with electrons
- α, ν and n scatter off nuclei


γ backgrounds
(mostly external):

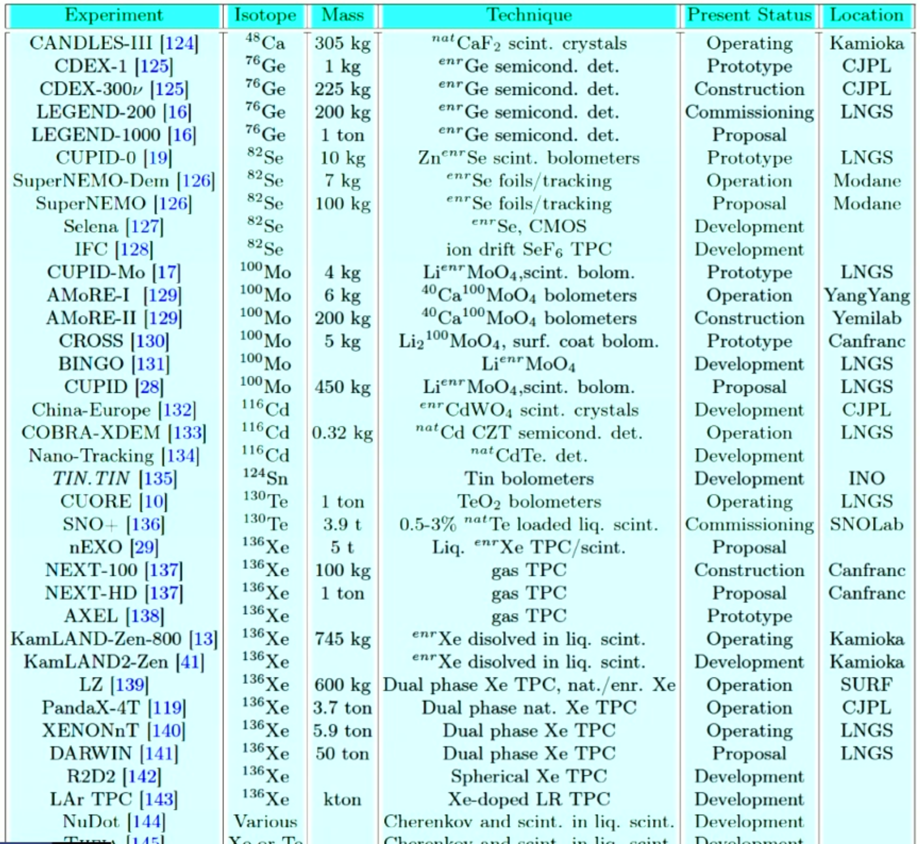

ββ decay:

SNOLAB



The Experimental Landscape (in a nutshell)

Experimental Landscape in a Nutshell

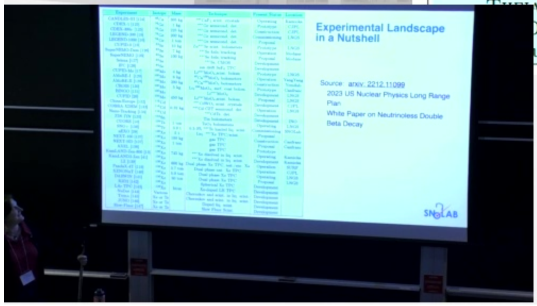


Experiment	Isotope	Mass	Technique	Present Status	Location
CANDLES-III [124]	^{48}Ca	305 kg	^{nat}CaF$_2$ scint. crystals	Operating	Kamioka
CDEX-1 [125]	^{76}Ge	1 kg	^{enr}Ge semicond. det.	Prototype	CJPL
CDEX-300ν [125]	^{76}Ge	225 kg	^{enr}Ge semicond. det.	Construction	CJPL
LEGEND-200 [16]	^{76}Ge	200 kg	^{enr}Ge semicond. det.	Commissioning	LNGS
LEGEND-1000 [16]	^{76}Ge	1 ton	^{enr}Ge semicond. det.	Proposal	
CUPID-0 [19]	^{82}Se	10 kg	Zn^{enr}Se scint. bolometers	Prototype	LNGS
SuperNEMO-Dem [126]	^{82}Se	7 kg	^{enr}Se foils/tracking	Operation	Modane
SuperNEMO [126]	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal	Modane
Selena [127]	^{82}Se		^{enr}Se, CMOS	Development	
IFC [128]	^{82}Se		ion drift SeF$_6$ TPC	Development	
CUPID-Mo [17]	^{100}Mo	4 kg	Li^{enr}MoO$_4$,scint. bolom.	Prototype	LNGS
AMoRE-I [129]	^{100}Mo	6 kg	^{40}Ca^{100}MoO$_4$ bolometers	Operation	YangYang
AMoRE-II [129]	^{100}Mo	200 kg	^{40}Ca^{100}MoO$_4$ bolometers	Construction	Yemilab
CROSS [130]	^{100}Mo	5 kg	Li$_2$^{100}MoO$_4$, surf. coat bolom.	Prototype	Canfranc
BINGO [131]	^{100}Mo		Li^{enr}MoO$_4$	Development	LNGS
CUPID [28]	^{100}Mo	450 kg	Li^{enr}MoO$_4$,scint. bolom.	Proposal	LNGS
China-Europe [132]	^{116}Cd		^{enr}CdWO$_4$ scint. crystals	Development	CJPL
COBRA-XDEM [133]	^{116}Cd	0.32 kg	^{nat}Cd CZT semicond. det.	Operation	LNGS
Nano-Tracking [134]	^{116}Cd		^{nat}CdTe. det.	Development	
TIN.TIN [135]	^{124}Sn		Tin bolometers	Development	INO
CUORE [10]	^{130}Te	1 ton	TeO$_2$ bolometers	Operating	LNGS
SNO+ [136]	^{130}Te	3.9 t	0.5-3% ^{nat}Te loaded liq. scint.	Commissioning	SNOLab
nEXO [29]	^{136}Xe	5 t	Liq. ^{enr}Xe TPC/scint.	Proposal	
NEXT-100 [137]	^{136}Xe	100 kg	gas TPC	Construction	Canfranc
NEXT-HD [137]	^{136}Xe	1 ton	gas TPC	Proposal	Canfranc
AXEL [138]	^{136}Xe		gas TPC	Prototype	
KamLAND-Zen-800 [13]	^{136}Xe	745 kg	^{enr}Xe disolved in liq. scint.	Operating	Kamioka
KamLAND2-Zen [41]	^{136}Xe		^{enr}Xe disolved in liq. scint.	Development	Kamioka
LZ [139]	^{136}Xe	600 kg	Dual phase Xe TPC, nat./enr. Xe	Operation	SURF
PandaX-4T [119]	^{136}Xe	3.7 ton	Dual phase nat. Xe TPC	Operation	CJPL
XENONnT [140]	^{136}Xe	5.9 ton	Dual phase Xe TPC	Operating	LNGS
DARWIN [141]	^{136}Xe	50 ton	Dual phase Xe TPC	Proposal	LNGS
R2D2 [142]	^{136}Xe		Spherical Xe TPC	Development	
LAr TPC [143]	^{136}Xe	kton	Xe-doped LR TPC	Development	
NuDot [144]	Various		Cherenkov and scint. in liq. scint.	Development	
[145]	Xe or Te		Cherenkov and scint. in liq. scint.	Development	
D [146]	Xe or Te		Doped liq. scint.	Development	
uor [147]	Xe or Te		Slow Fluor Scint.	Development	

Source: arxiv: 2212.11099

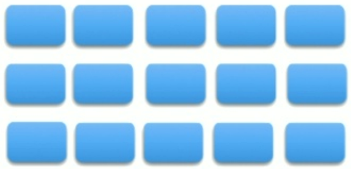
2023 US Nuclear Physics Long Range Plan

White Paper on Neutrinoless Double Beta Decay



Experimental Techniques

Granular Detectors



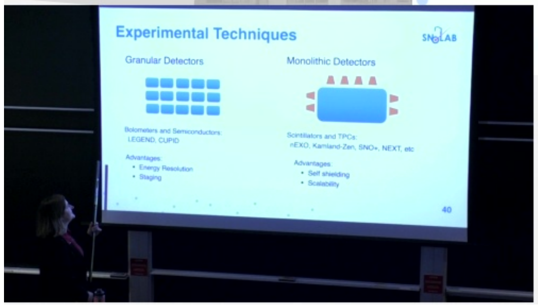
Bolometers and Semiconductors:
LEGEND, CUPID

Advantages:
- Energy Resolution
- Staging

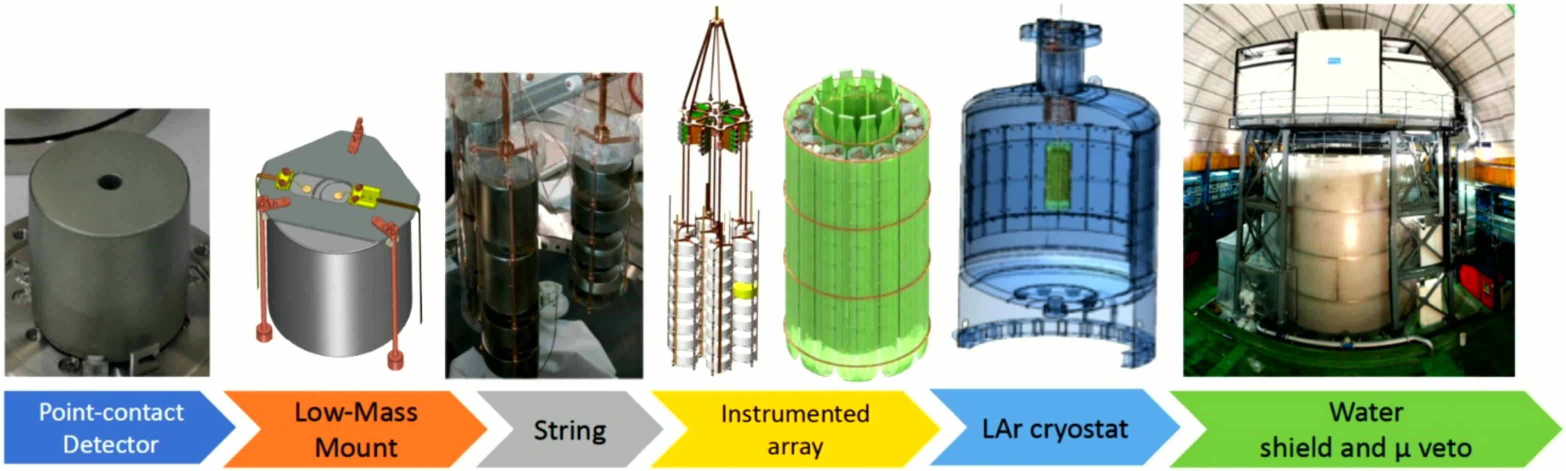
Monolithic Detectors

Scintillators and TPCs:
nEXO, Kamland-Zen, SNO+, NEXT, etc

Advantages:
- Self shielding
- Scalability



LEGEND Concept



Point-contact Detector

Low-Mass Mount

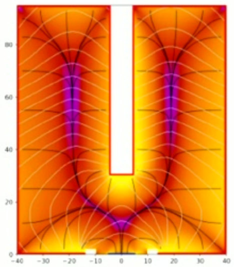
String

Instrumented array

LAr cryostat

Water shield and µ veto

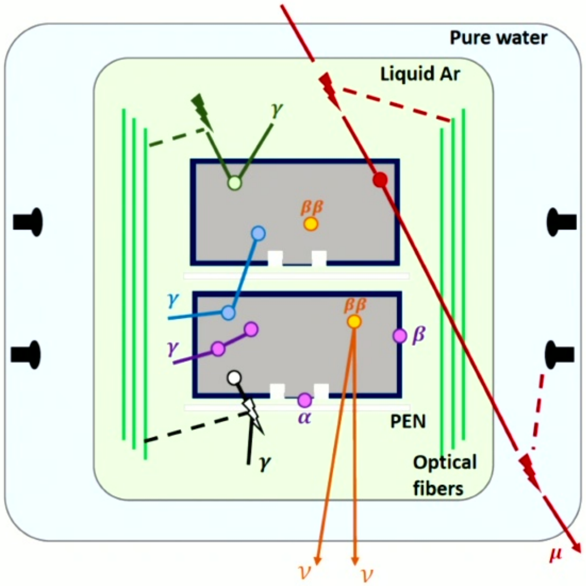
LEGEND Concept



HPGe point-contact detectors:

- Event topology and fiducialization
- Excellent (~0.1%) energy resolution

$\beta\beta$ decay signal: single energy deposition in a 1 mm³ volume



Pulse shape discrimination (PSD) for multi-site and surface α events

Ge detector anti-coincidence

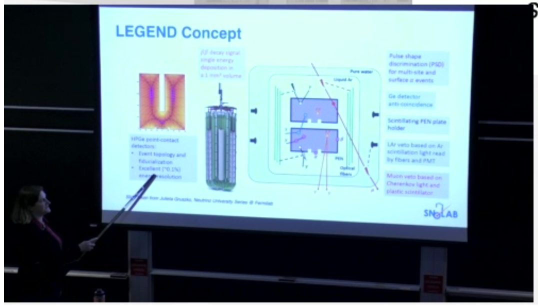
Scintillating PEN plate holder

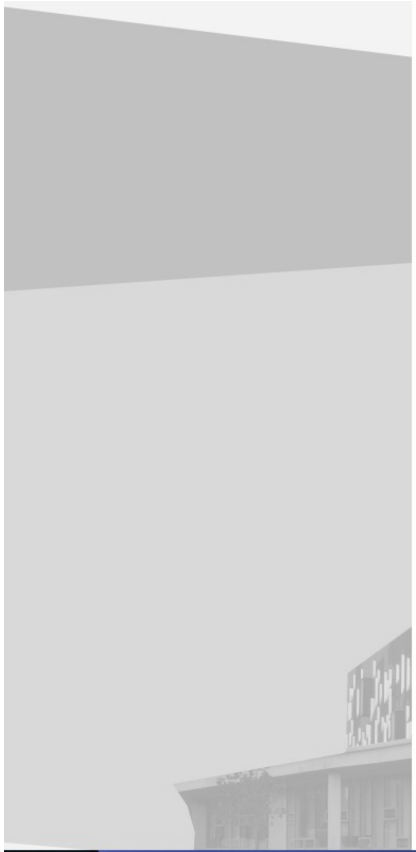
LAr veto based on Ar scintillation light read by fibers and PMT

Muon veto based on Cherenkov light and plastic scintillator

Slide taken from Julieta Gruszko, Neutrino University Series @ Fermilab

SNOLAB





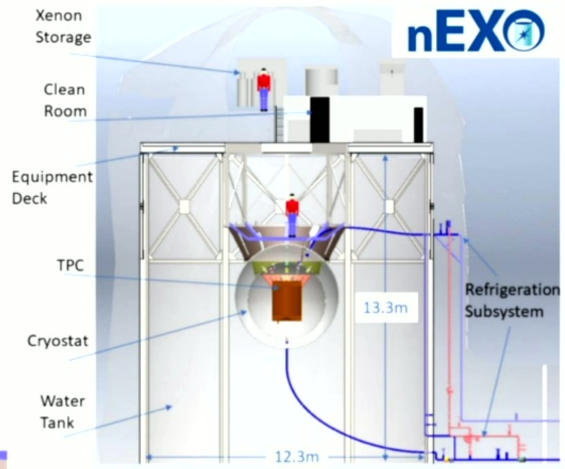
nEXO Concept

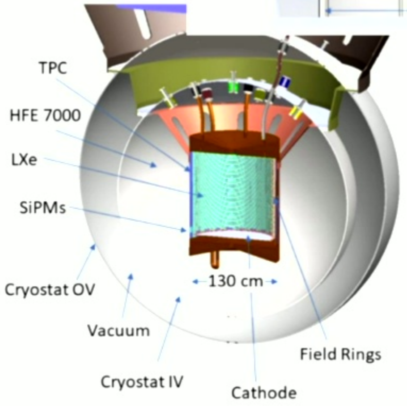
- TPC with 5000 kg of 90% enriched ^{136}Xe
  - SiPMs to collect scintillation light
  - Charge Tiles to collect ionization signal

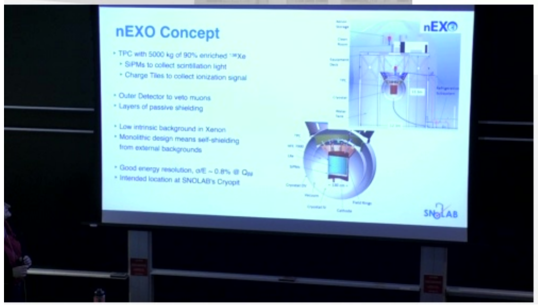
- Outer Detector to veto muons
- Layers of passive shielding

- Low intrinsic background in Xenon
- Monolithic design means self-shielding from external backgrounds

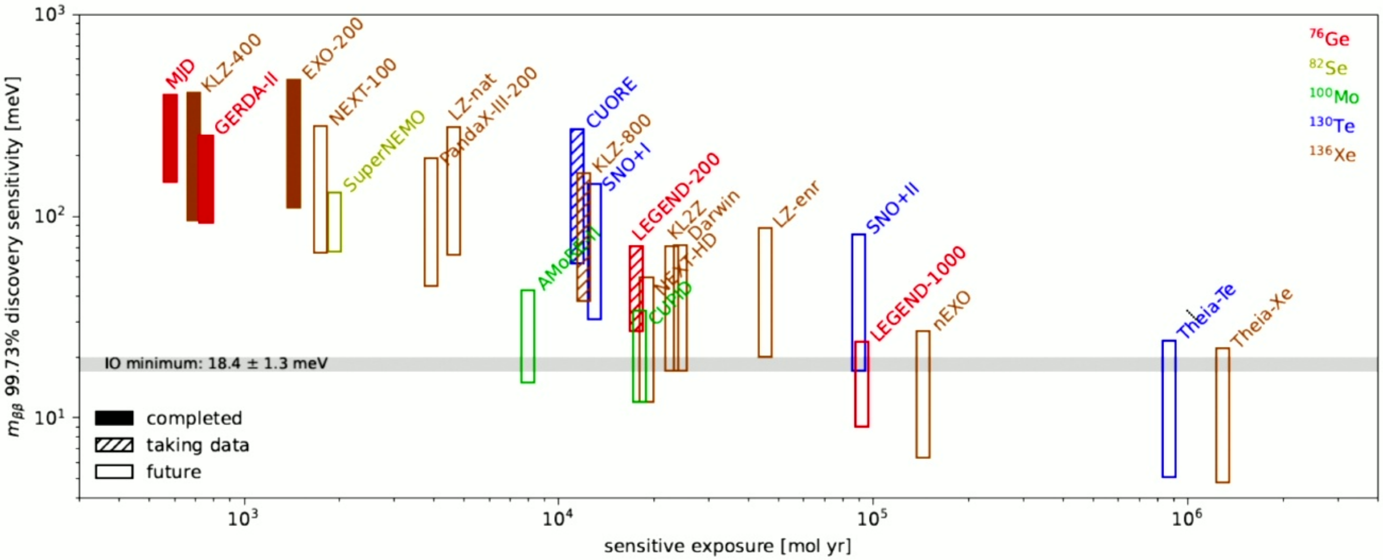
- Good energy resolution, σ/E ~ 0.8% @ $Q_{\beta\beta}$
- Intended location at SNOLAB's Cryopit

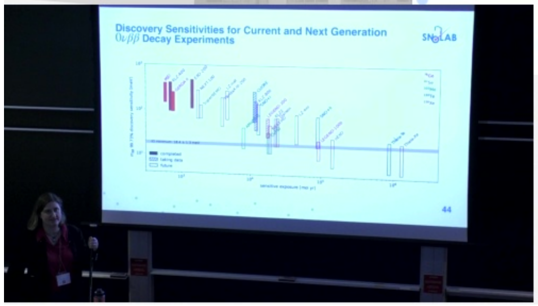






Discovery Sensitivities for Current and Next Generation $0\nu\beta\beta$ Decay Experiments





Conclusions

- There exist a very rich program of underground science that is being done here in Canada and around the world.d
- The world-wide dark matter program is expansive and the next decade will be very exciting as collaboration start reporting results from the existing generation of experiment and the next generation of experiments gets underway.
- The $0\nu\beta\beta$ decay program is very active with current and planned experiments. The planning process for a tonne-scale program using multiple isotopes is underway.
- Thank you for the interesting discussions and being a great class. I hope to see you at SNOLAB soon!