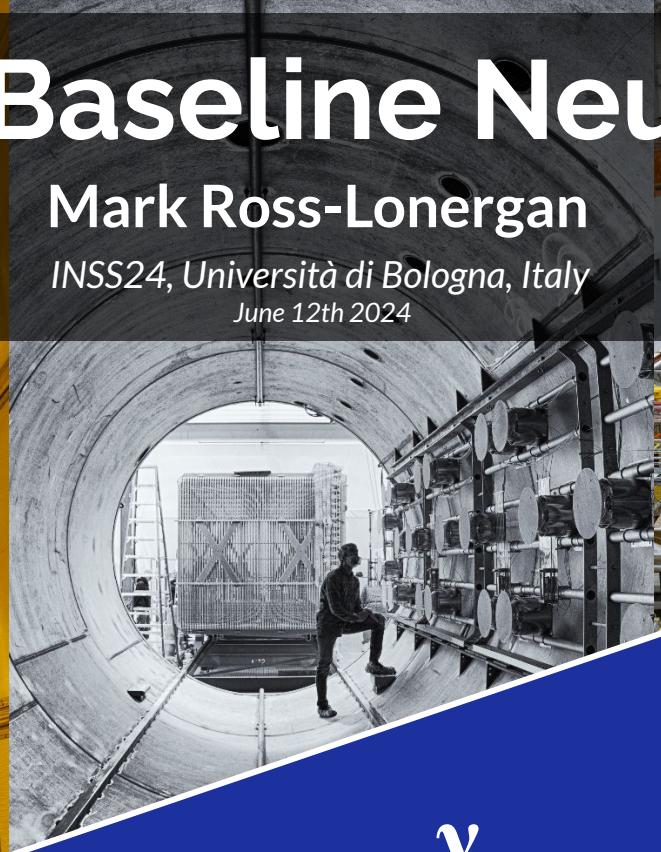
Short-Baseline Neutrinos

Mark Ross-Lonergan

INSS24, Università di Bologna, Italy

June 12th 2024



Los Alamos NATIONAL LABORATORY

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Short Baseline Neutrinos?

"Short" Dictionary Definition

Short *noun*
- *knee-length trousers*

Short *verb*
- *to sell a stock in expectation of a fall in prices*

Short *adjective*
- *Describe flaky pastry*

Short *adjective*
- limited in distance

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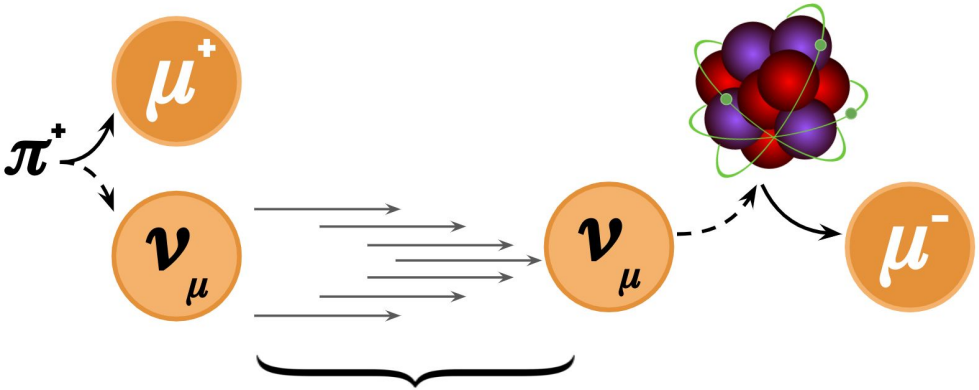

Let neutrinos propagate over some **distance L**

Short Baseline Neutrinos?

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Flavor States **Mixing Matrix** **Mass States**

$$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

Mass Difference: $m_2^2 - m_1^2$

Mixing angle

$$P_{\nu_\mu\to\nu_e}(E_\nu, L) \approx \underbrace{\sin^2(2\theta)}_{\text{Amplitude}} \underbrace{\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)}_{\text{Frequency}}.$$

Distance, or Baseline, L

Short, Relative to what?

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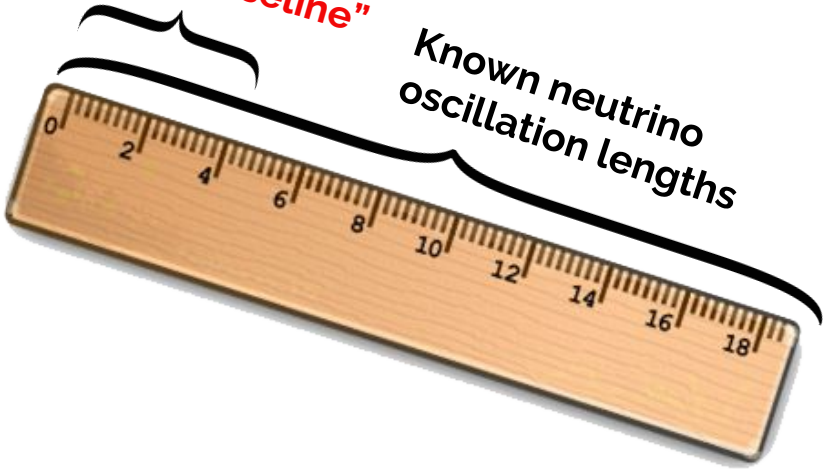

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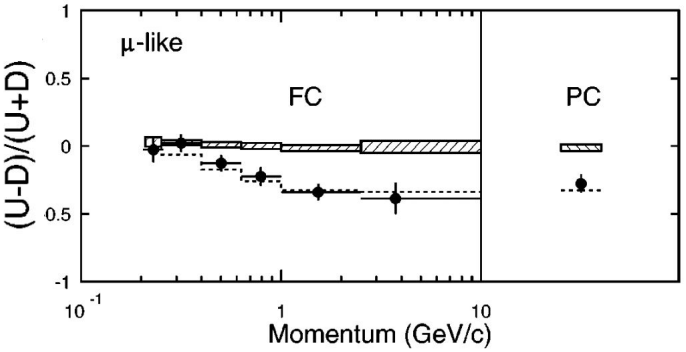
Distance, or Baseline, L

Super-Kamiokande 1998

Evidence for Oscillation of Atmospheric Neutrinos
Phys. Rev. Lett. 81, 1562



SNO 2001/2002

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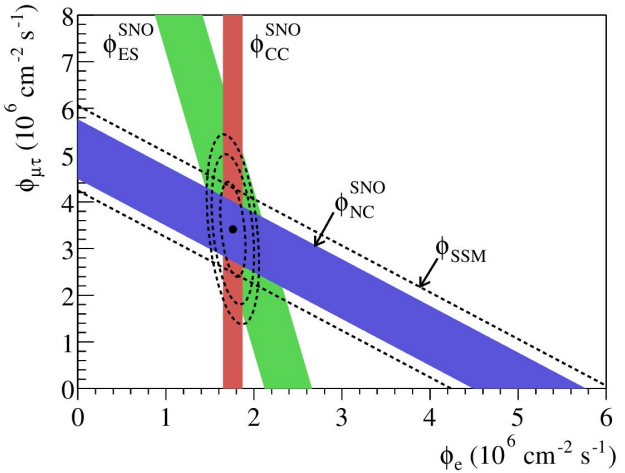

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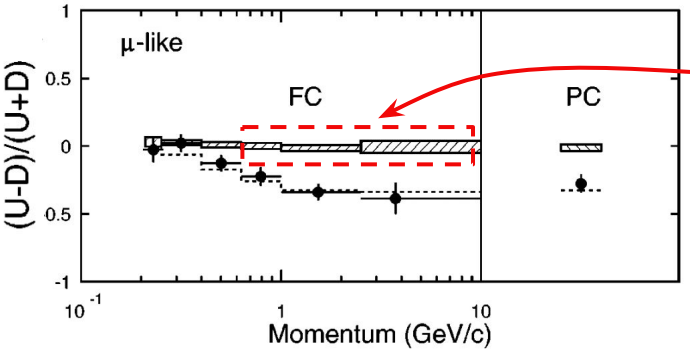

Expectation **no oscillations**

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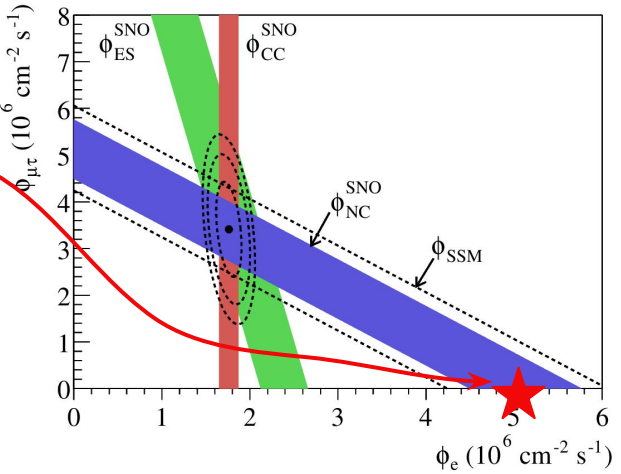

Neutrino Oscillation

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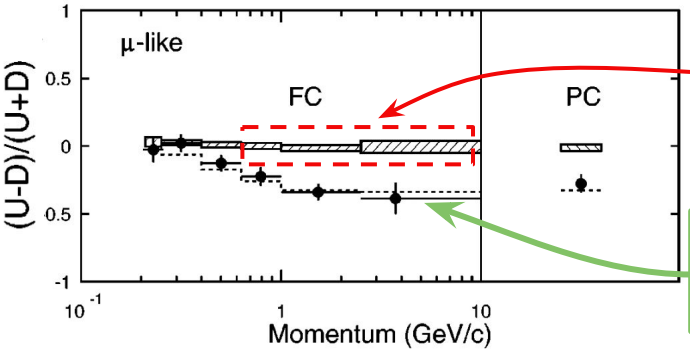

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What was observed!

"The data are consistent with two-flavor oscillations $\nu_\mu \rightarrow \nu_\tau$"

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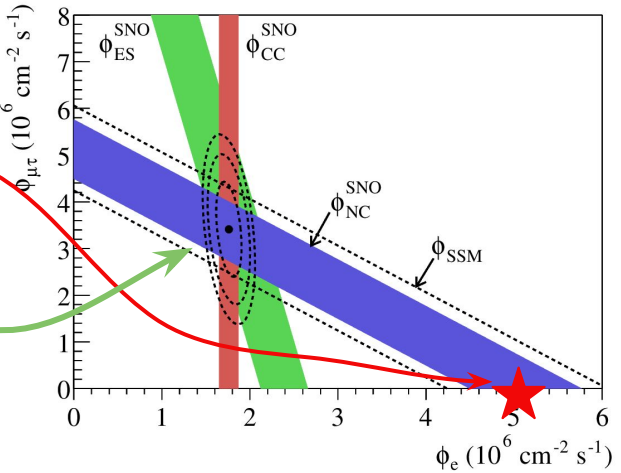

"...strong evidence for flavor transformation consistent with neutrino oscillations"

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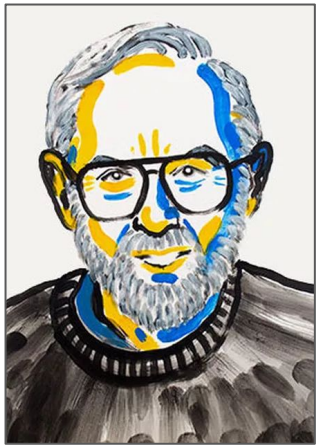
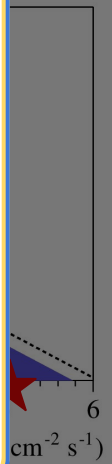
*"for the discovery of **neutrino oscillations**, which **shows that neutrinos have mass**"*



Takaaki Kajita

Arthur B. McDonald



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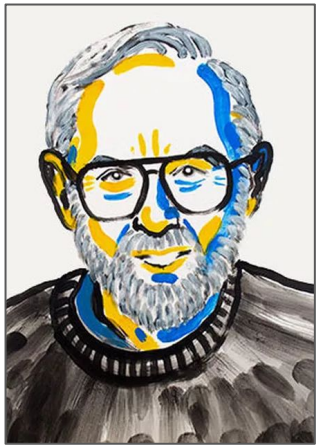

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Mixing angle ≠ 0

$\Delta m^2 \neq 0$

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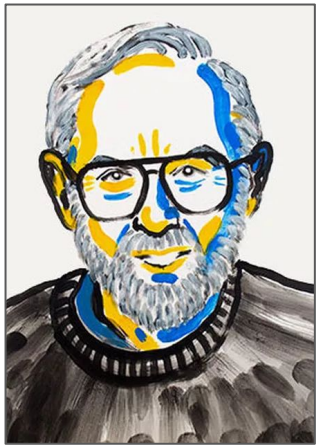

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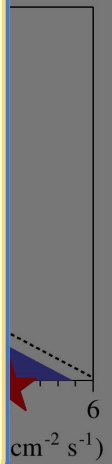

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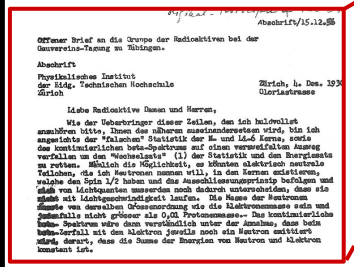
Neutrinos a ‘recent’ history

1930→1956
Hypothetical Era



Abschrift/15.12.

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

Abschrift

Physikalisches Institut
der Kdg. Technischen Hochschule
Zürich

Zürich, b. Dez. 19
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 Grössenordnung 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 den Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

“Dear Radioactive Ladies and Gentlemen,”

Liebe Radioaktive Damen und Herren,

Pauli predicts “neutrinos”

1930

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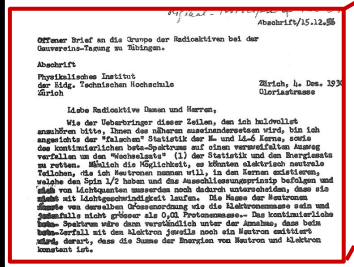

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Zürich, 6. Dez. 193
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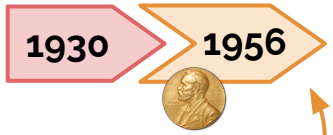

Reines and Cowan Discover ν_e
"Project Poltergeist"

PROPERTIES OF THE NEUTRINO

Spin : $1/2\hbar$.
Mass : < 1/500 electron mass, if any.
Charge : 0.
Magnetic moment : $< 10^{-9}$ Bohr magneton

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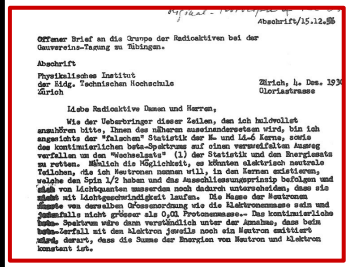

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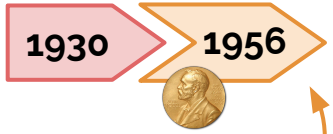

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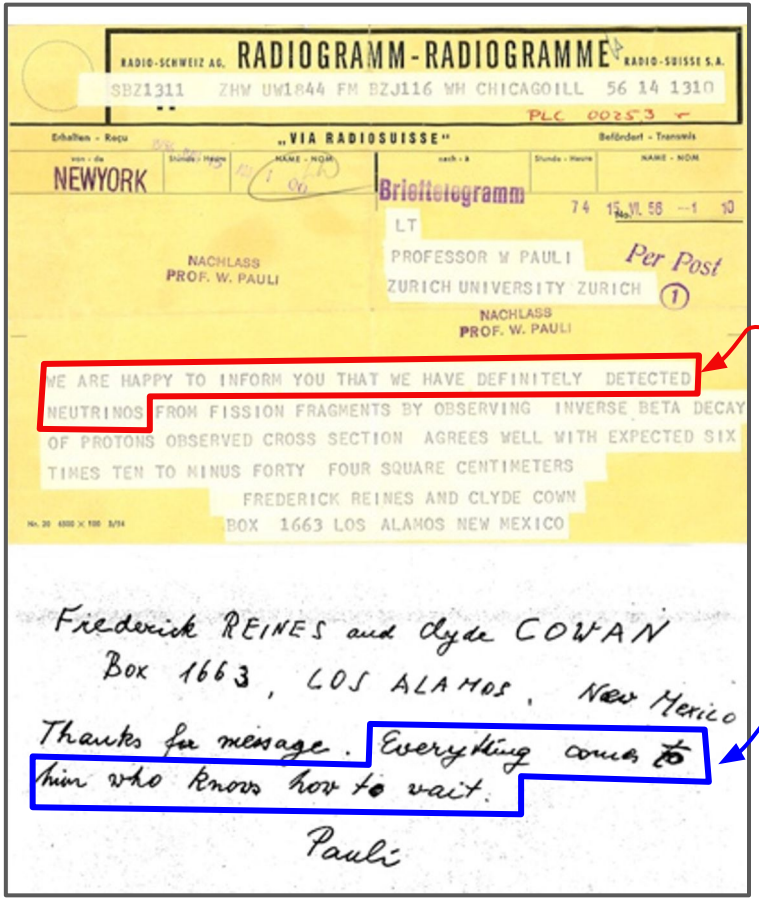

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PROFESSOR W PAULI
ZURICH UNIVERSITY ZURICH (1)

Per Post

NACHLASS
PROF. W. PAULI

NACHLASS
PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN
BOX 1663 LOS ALAMOS NEW MEXICO

Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico

Thanks for message. Everything comes to him who knows how to wait.

Pauli

"We are happy to inform you we have definitely detected neutrinos"
Reines & Cowan

"Everything comes to him who knows how to wait"
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Neutrinos a 'recent' history

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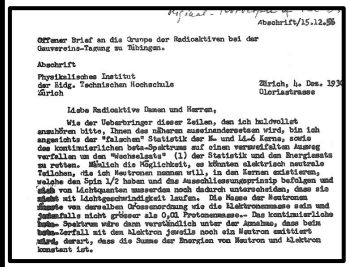
Hypothetical Era

1956→2002
Discovery Era



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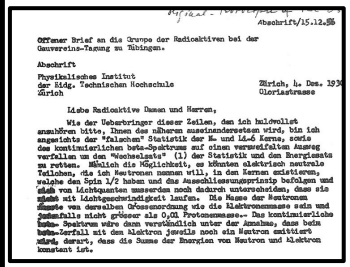

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Solar neutrinos discovered by Davis → MSW effect

ν_τ discovered at DONUT

1930 1956 1962 1968 1998 2000 2002

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Evidence for atmospheric neutrino oscillation at Super-Kamiokande

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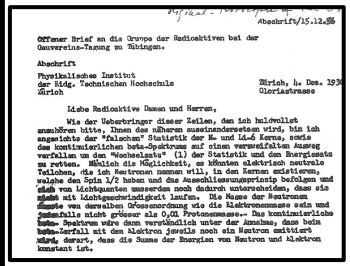

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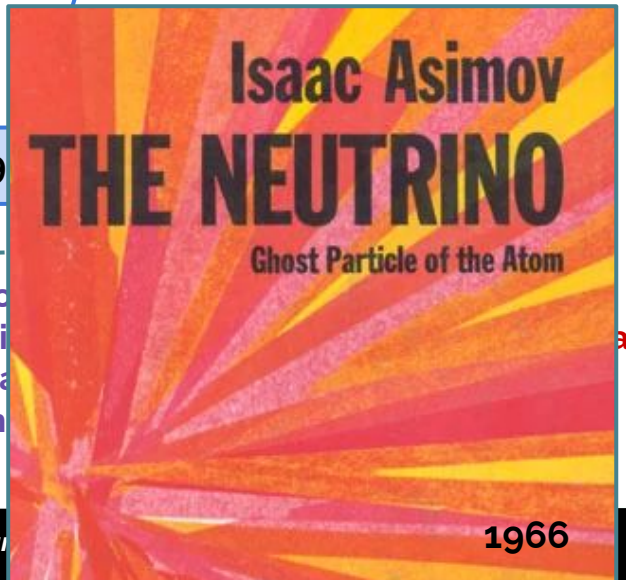

Neutrinos a 'recent' history

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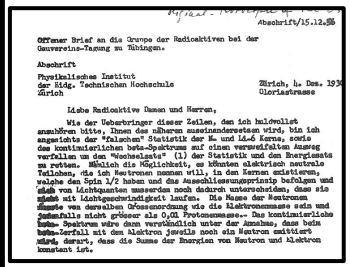
Discovery Era

2002→now
Oscillation Era

Recent: *Precision!*
Rapid development!



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

Abschrift

Physikalisches Institut
der Kdg. Technischen Hochschule
Zürich

Zürich, b. Dez. 19
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 Grössenordnung 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 den Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Pauli predicts "neutrinos"

Lederman, Schwartz & Steinberger discover ν_μ

Solar neutrinos discovered by Davis → MSW effect

ν_τ discovered at DONUT

KamLAND (Anti-Neutrino osc)

Daya-Bay (Measured θ_{13})

1930 → 1956 → 1962 → 1968 → 1998 → 2000 → 2002 → ? ?

Reines and Cowan Discover ν_e "Project Poltergeist"

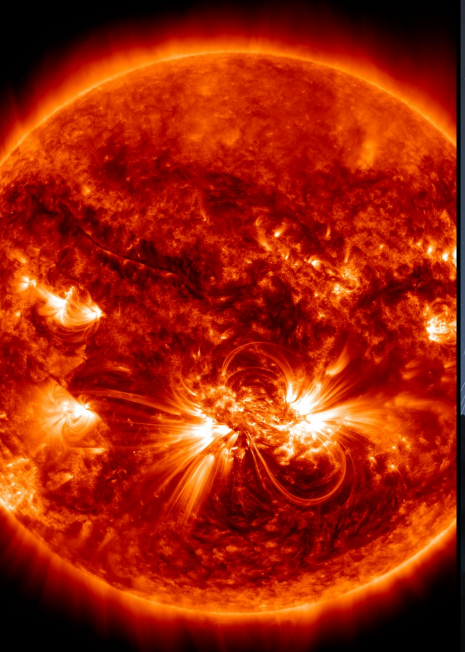
Evidence for atmospheric neutrino oscillation at Super-Kamiokande

Evidence for solar neutrino oscillation at SNO

OPERA ($\nu_\mu \rightarrow \nu_\tau$ osc)

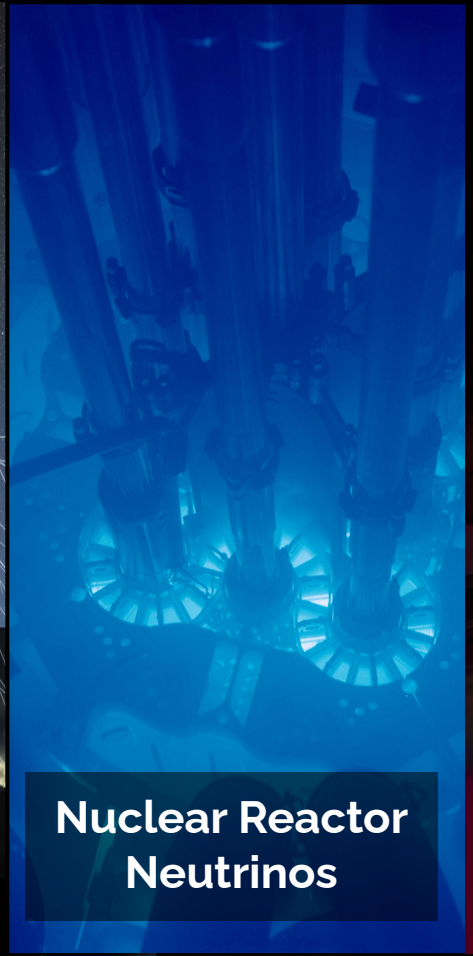
T2K & NOvA (Long Baseline Osc)

Neutrinos Sources

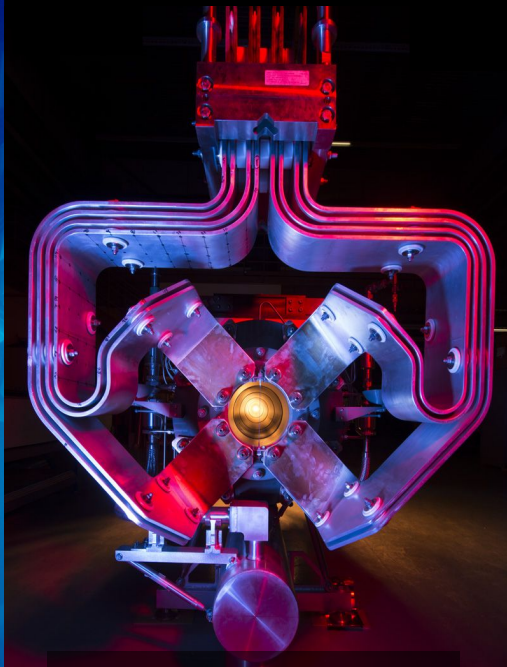


Solar Neutrinos

Atmospheric Neutrinos

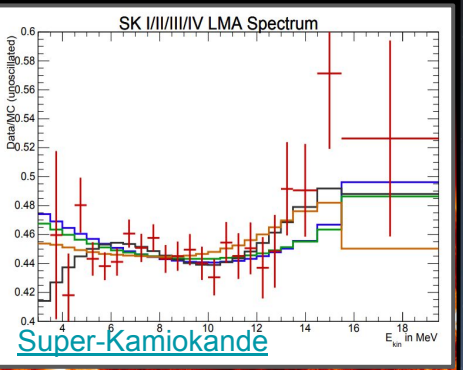


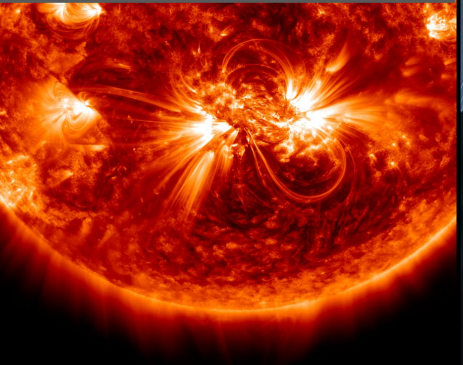
Nuclear Reactor Neutrinos



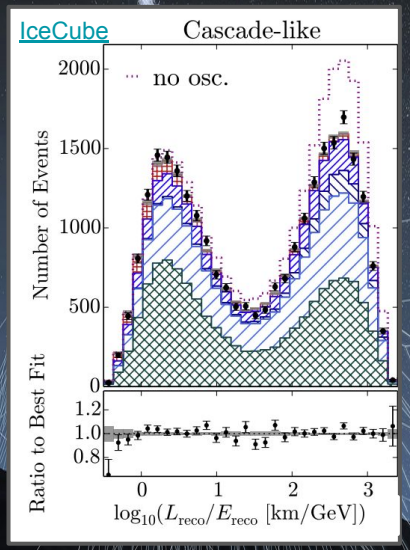
Accelerator Neutrinos

Neutrinos Sources

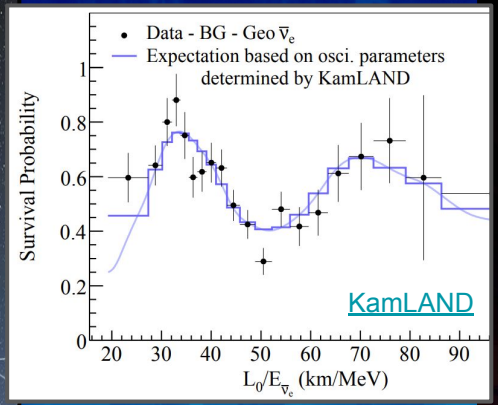




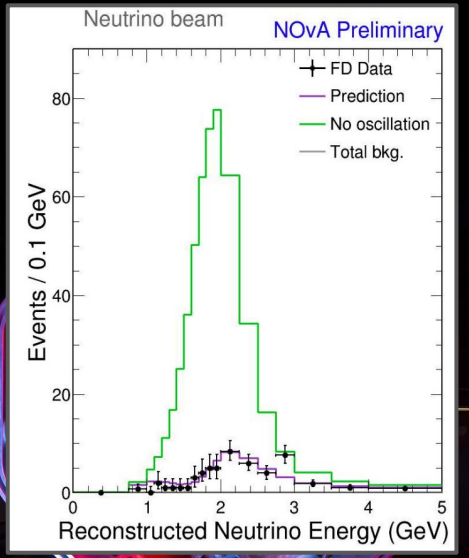
Solar Neutrinos



Atmospheric Neutrinos

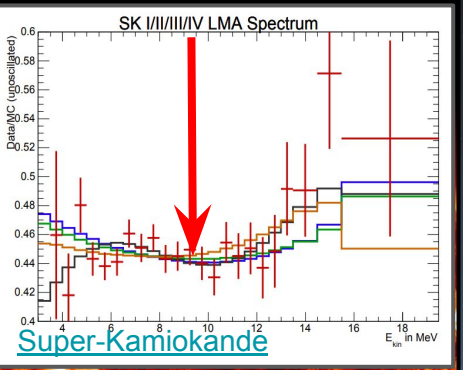


Nuclear Reactor Neutrinos



Accelerator Neutrinos

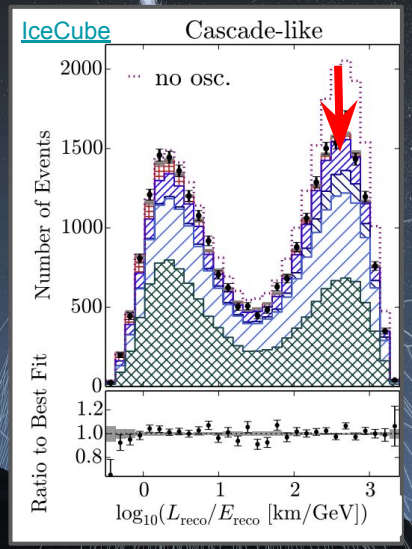
Neutrinos Sources



Super-Kamiokande

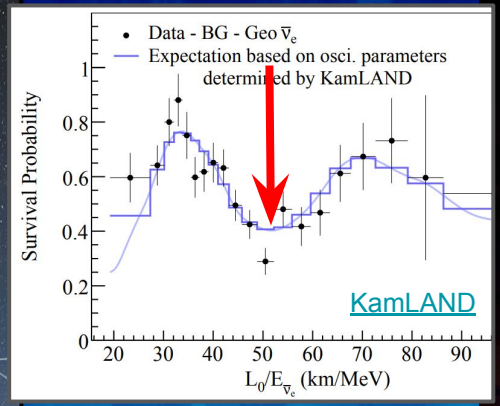
MSW driven

Solar Neutrinos



L/E ~ 300 km/GeV

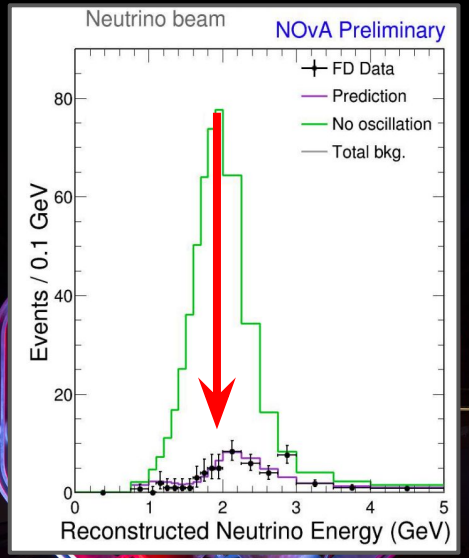
Atmospheric Neutrinos



KamLAND

L/E ~ 50,000 km/GeV

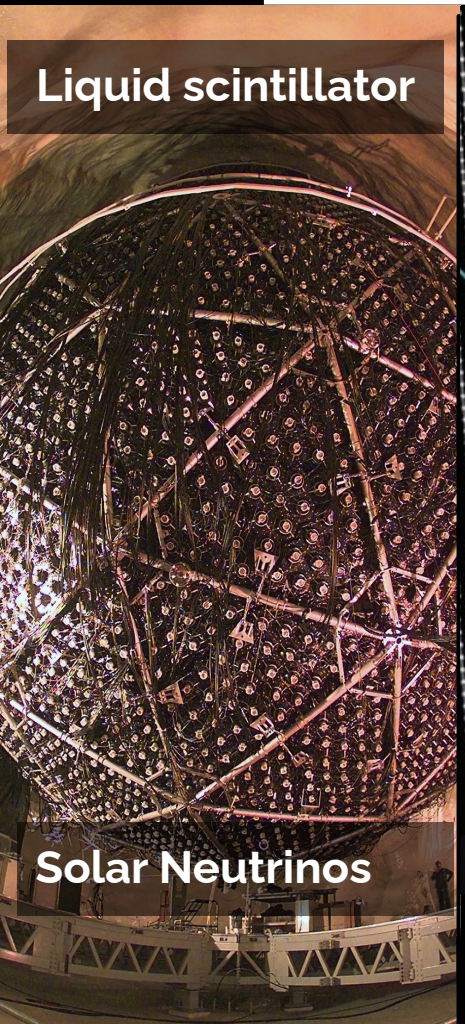
Nuclear Reactor Neutrinos

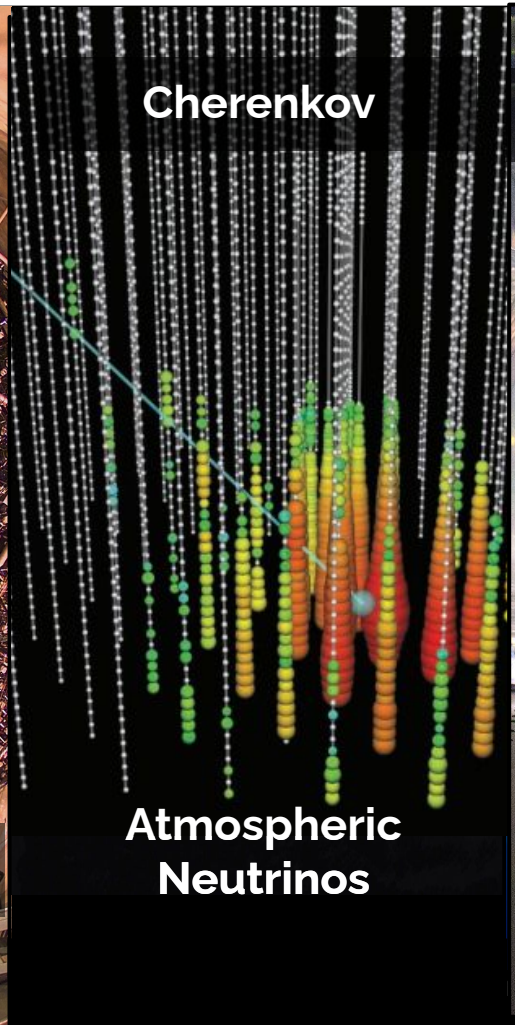


L/E ~ 150 km/GeV

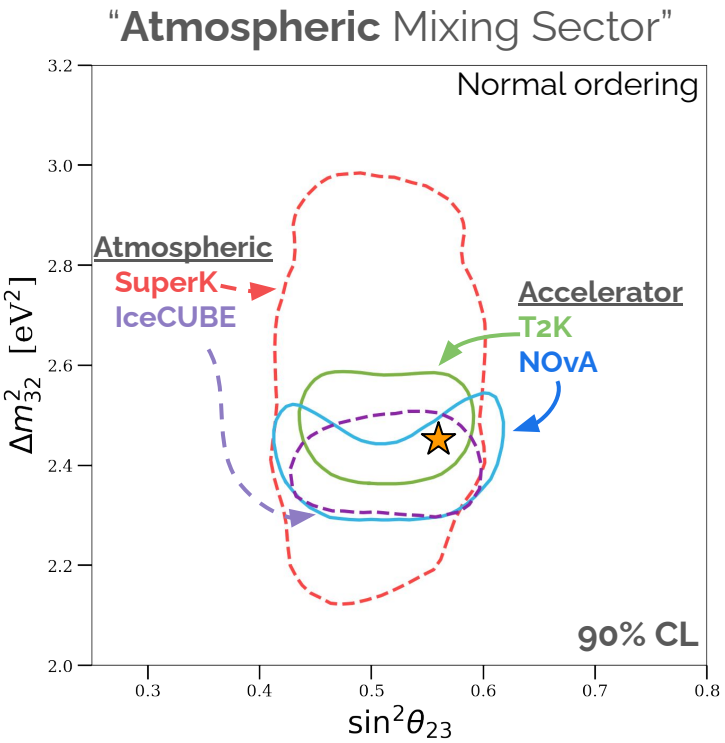
Accelerator Neutrinos

Neutrinos Detector Technologies



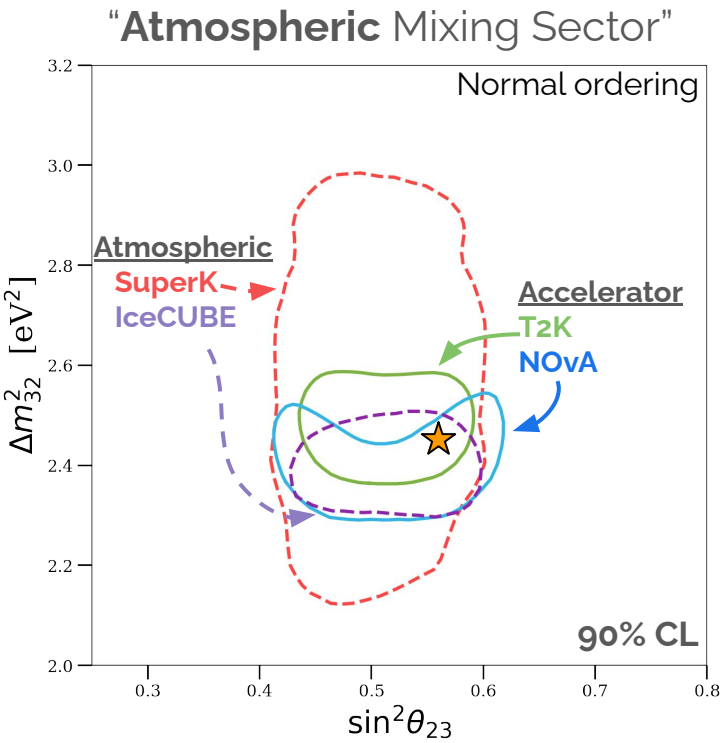


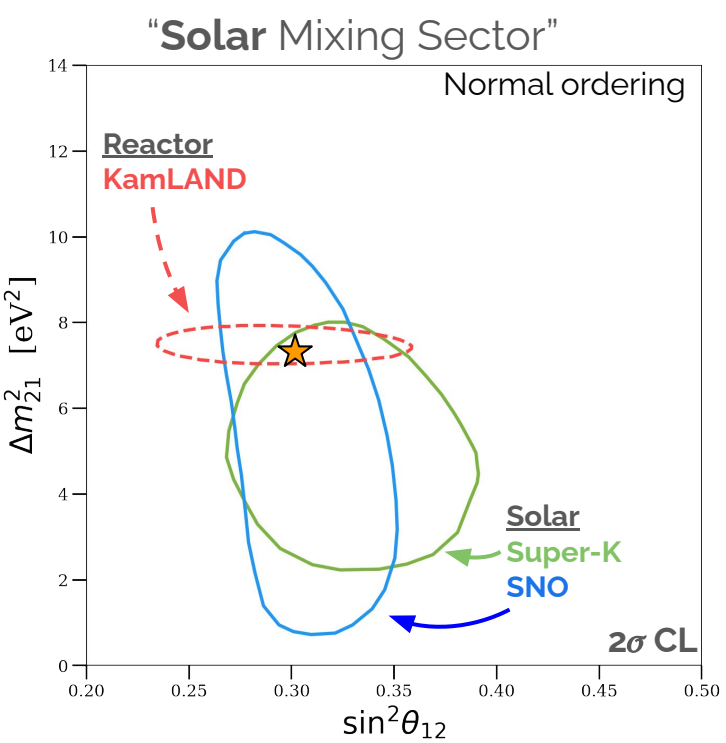
Stitched together in a surprisingly coherent way!



$$\Delta m^2_{32} = 2.5 \times 10^{-3} \mathrm{eV}^2$$

Stitched together in a surprisingly coherent way!

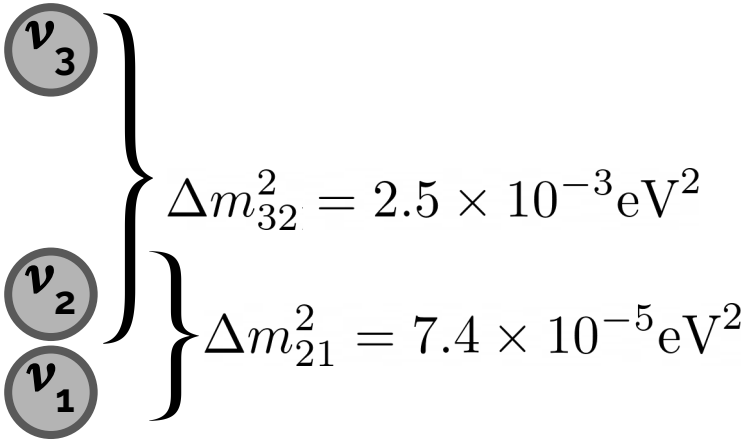


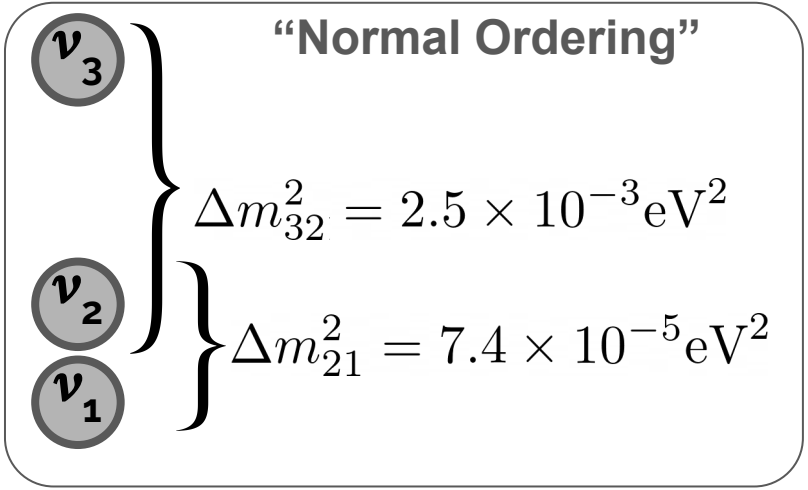


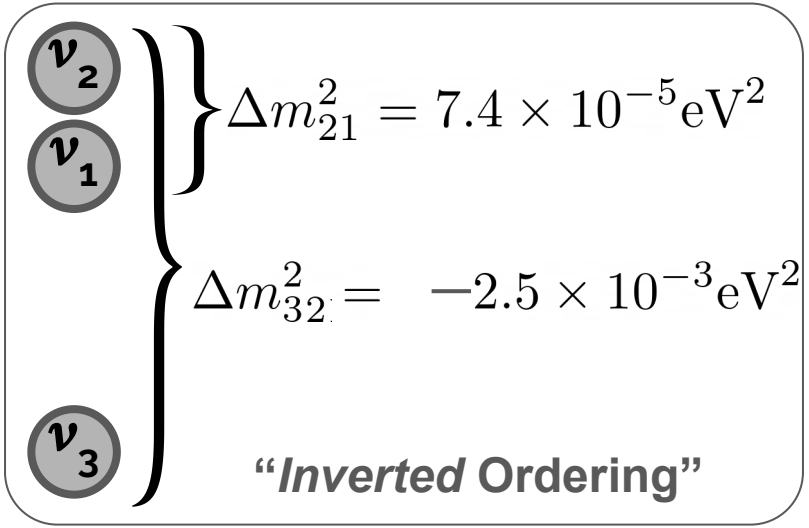
$$\Delta m^2_{32} = 2.5 \times 10^{-3}\text{eV}^2$$

$$\Delta m^2_{21} = 7.4 \times 10^{-5}\text{eV}^2$$

three flavor neutrino paradigm







$$\left|\Delta m^2_{32}\right| = 2.5 \times 10^{-3} eV^2$$

What's the **sign** of Δm^2_{32}?
The "Mass Ordering" problem

$c_{ij} = \cos(\theta_{ij})$
$s_{ij} = \sin(\theta_{ij})$

$$U_{\text{PMNS}} = \overbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}^{\text{Neutrino Mixing Matrix}} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric Sector}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix}}_{\text{Reactor Sector}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar Sector}}$$

$$\theta_{23} \approx 45^\circ \qquad \theta_{12} \approx 34^\circ$$

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$\theta_{23} \approx 45^\circ$

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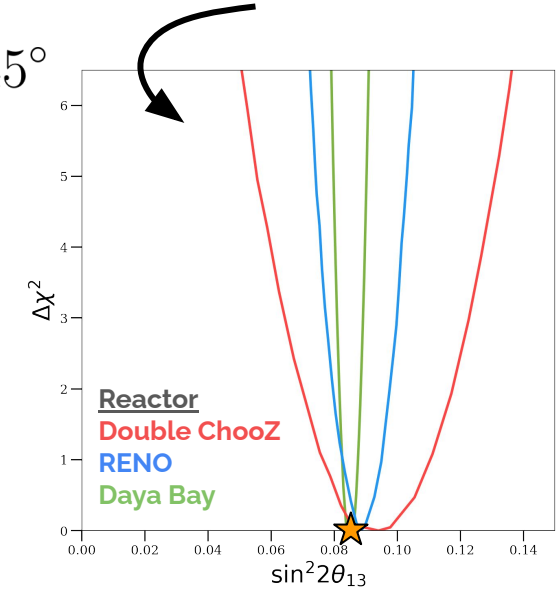

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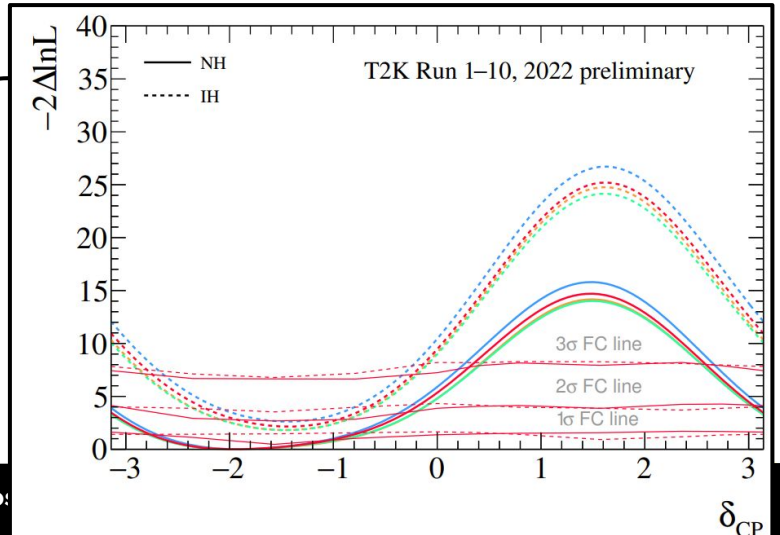
$\delta_{CP} \approx$?? $\theta_{23} \approx 45°$ $\theta_{13} \approx 8.5°$ $\theta_{12} \approx 34°$

Exciting hints at T2K!



Three remaining oscillation questions

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$\delta_{CP} \approx ??$ $\quad \theta_{23} \approx 45^\circ$ $\quad \theta_{13} \approx 8.5^\circ$ $\quad \theta_{12} \approx 34^\circ$

Is there **CP violation** in neutrino sector (do neutrinos and antineutrinos behave differently?)

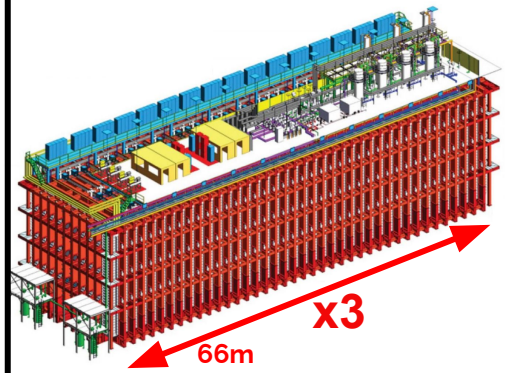
What's the **octant** of of θ_{23}? Measured with $\sin^2(2\theta_{23})$

$$\left|\Delta m^2_{32}\right| = 2.5 \times 10^{-3} eV^2$$

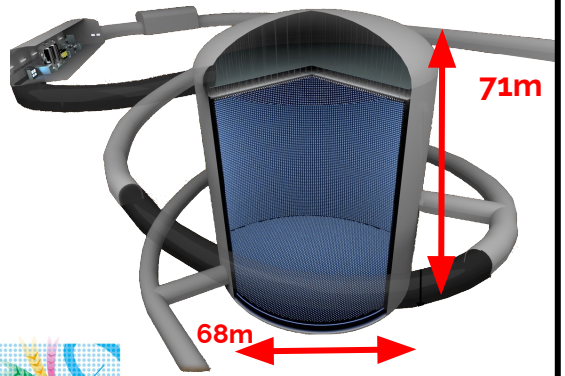
What's the **sign** of Δm^2_{32}? The "Mass Ordering" problem

Experiments probing the 3ν paradigm

DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT



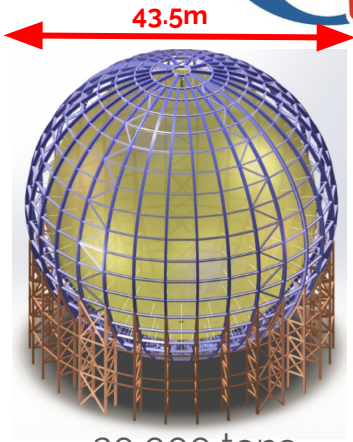
~30,000 tons Liquid Argon



Hyper-Kamiokande

260,000 tons Ultra Pure water

JUNO



20,000 tons liquid scintillator

See lectures by E. Lisi, J. Maricic, F. Di Lodovico, A. Weber ..etc, for more on these experiments and **many, many more**

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What's the value of δ_{CP} ? Is there **CP violation** in neutrino sector

$\theta_{23} \approx 45°$

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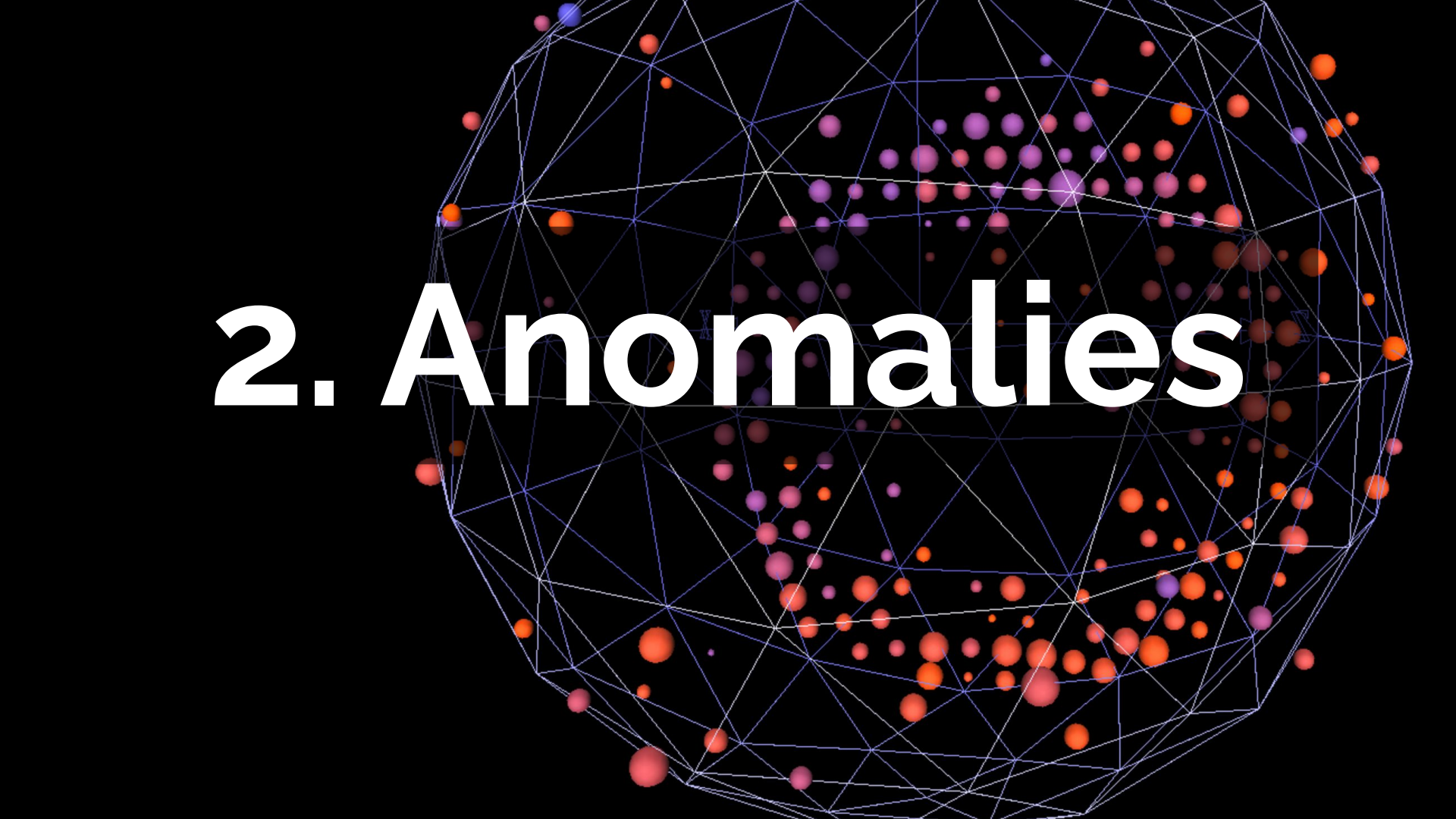
The "Mass Ordering" problem


2. Anomalies

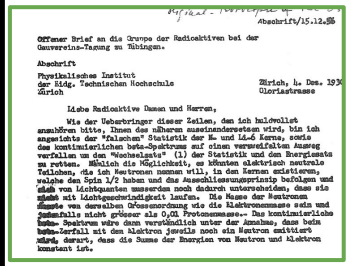
There is something anomalous happening...

There is something anomalous happening at short-baselines

There is something anomalous happening at short-baselines

1930→1956
Hypothetical Era

1956→2002
Discovery Era



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Solar neutrinos discovered by Davis, leading to discovery of MSW effect

ν_τ discovered at DONUT

1930 → 1956 → 1962 → 1968 → 1998 → 2000 → 2002

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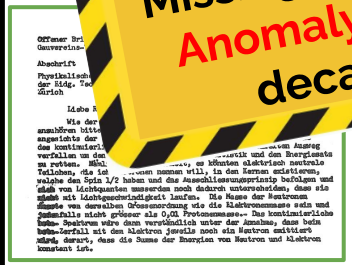
First evidence for atmospheric neutrino oscillation at Super-Kamiokande

Evidence for solar neutrino oscillation at SNO

There is something anomalous happening at short baselines



ATTENTION
Missing Energy
Anomaly in β
decay

Pauli predicts
"neutrinos"

1930

ATTENTION
Solar Neutrino
Anomaly

Solar neutri
discovered by Davis,
leading to discovery of
MSW effect

1968

1998

2002

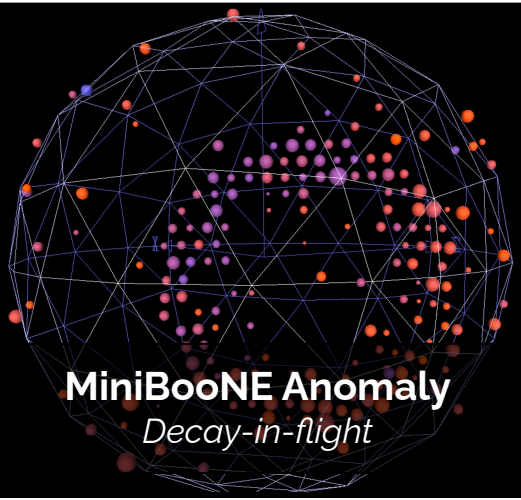
First eviden
atmospheri
oscillation a
Super-Kami

ATTENTION
Atmospheric
Neutrino
Anomaly

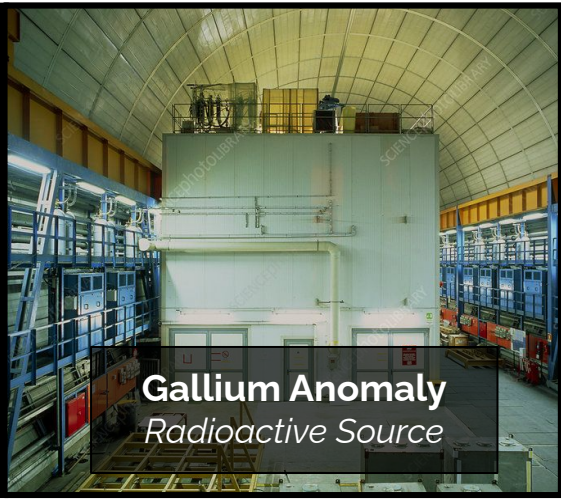
or solar
scillation at

The Short Baseline Anomalies

LSND Anomaly
Decay-at-rest

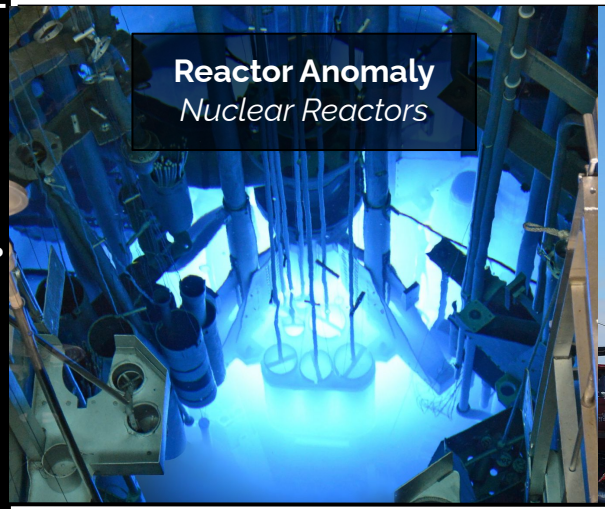


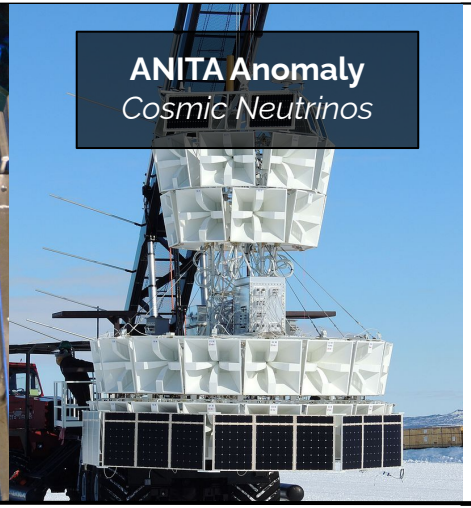
MiniBooNE Anomaly
Decay-in-flight

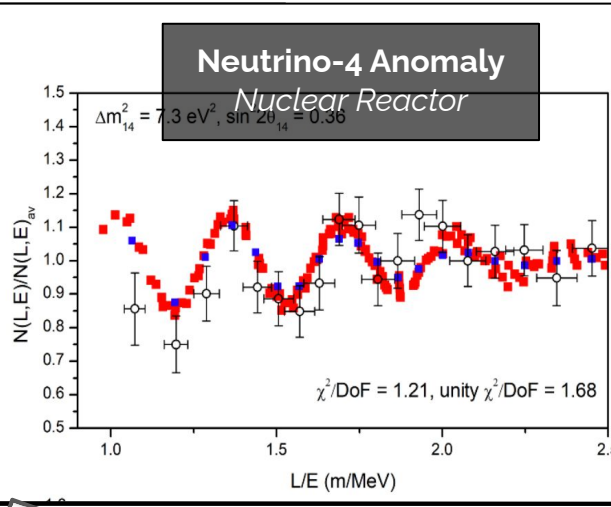


Gallium Anomaly
Radioactive Source

... + More Neutrino Anomalies







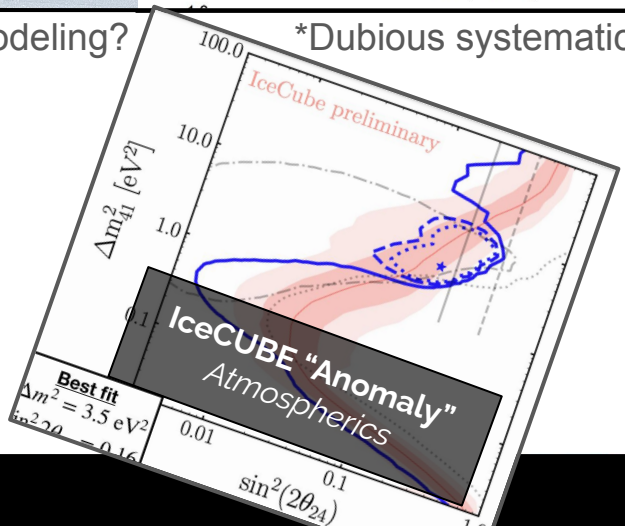
*no longer anomaly with new fluxes?

*Complex Ice modeling?

*Dubious systematics?

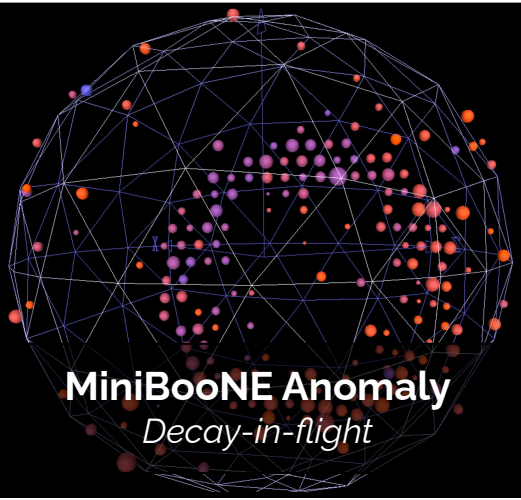
Not today!

P. Coloma touched base on some of these in her lecture last week

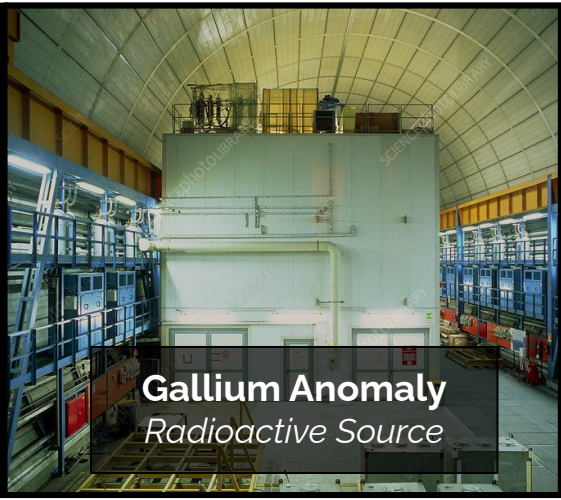


The Short Baseline Anomalies

LSND Anomaly
Decay-at-rest



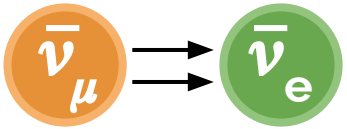
MiniBooNE Anomaly
Decay-in-flight



Gallium Anomaly
Radioactive Source

LSND (Liquid Scintillator Neutrino Detector)

LSND used a beam of $\overline{\nu}_\mu$, from **muon decay-at-rest**, to search for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ appearance oscillations



Protons $\rightarrow \pi^+$ (DAR) $\rightarrow \mu^+$ (DAR)

$\hookrightarrow e^+ + \nu_e + \overline{\nu}_\mu$

Extremely Pure!

Protons $\rightarrow \pi^- \rightarrow \cdots \rightarrow \overline{\nu}_e$

Highly suppressed through pion capture on heavy nuclei

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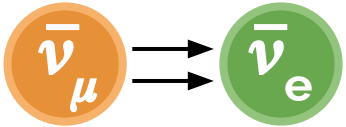

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Highly suppressed through pion capture on heavy nuclei

Oscillated anti-electron neutrinos detected by inverse beta decay, with **coincidence e⁺ and 2.2 MeV gamma**

$$\bar{\nu}_e + p \rightarrow e^+ + n \hookrightarrow n + p \rightarrow d + \gamma\ (2.2\ \text{MeV})$$

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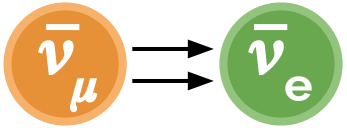
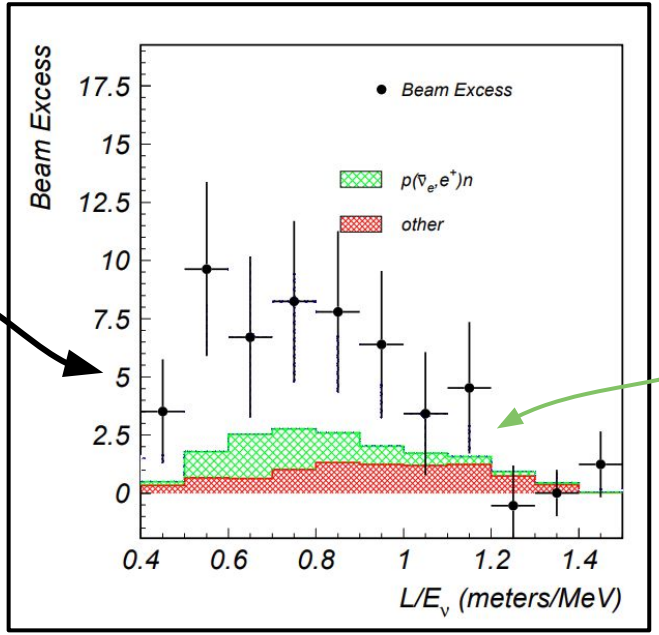


Observed a **3.8σ** significance excess



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LSND (Liquid Scintillator Neutrino Detector)

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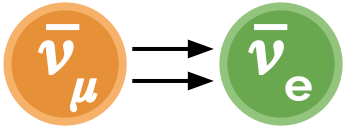
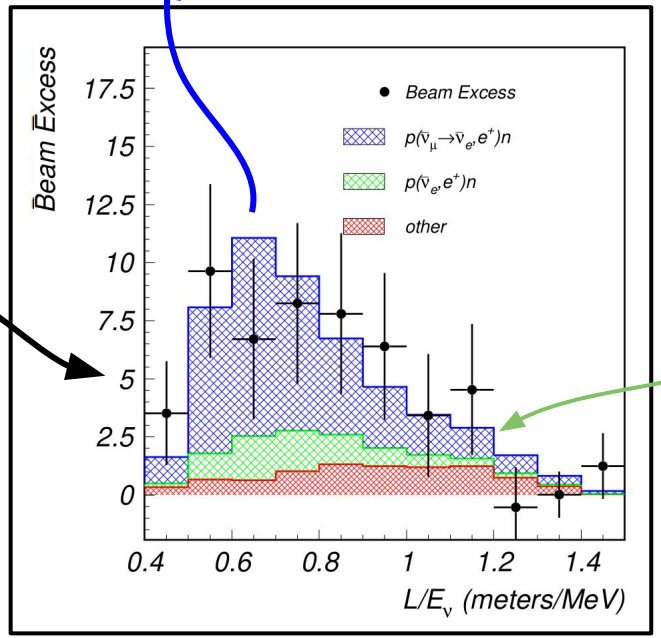
If interpreted as oscillations,
best fit $\Delta m^2 \sim 1eV^2$





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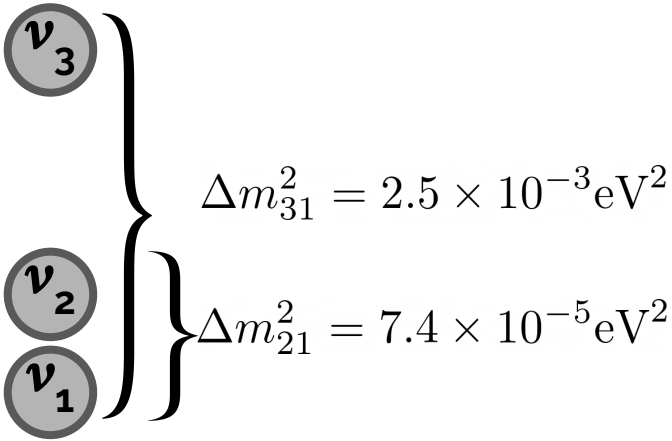
This does **not line up** with the global **"three neutrino paradigm"** picture



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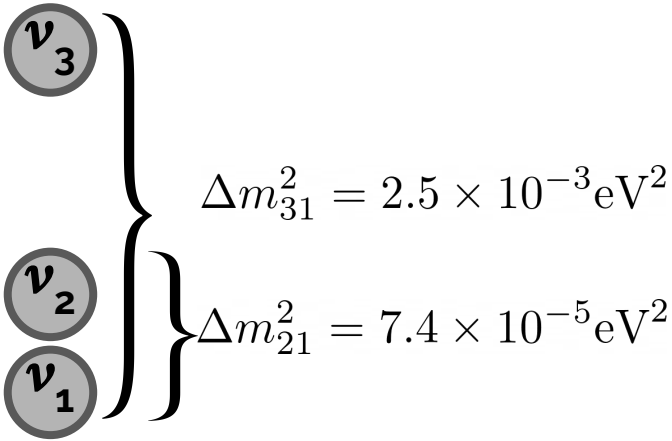
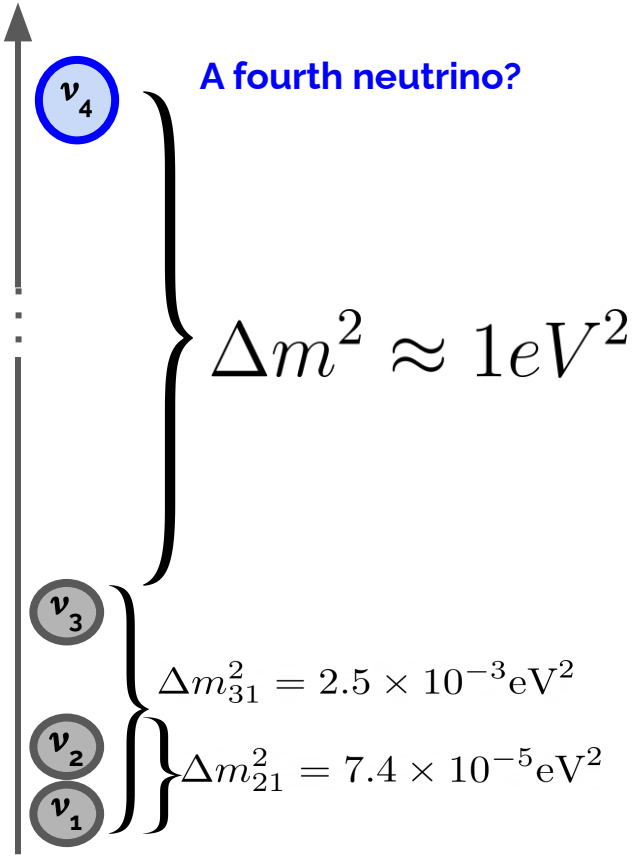


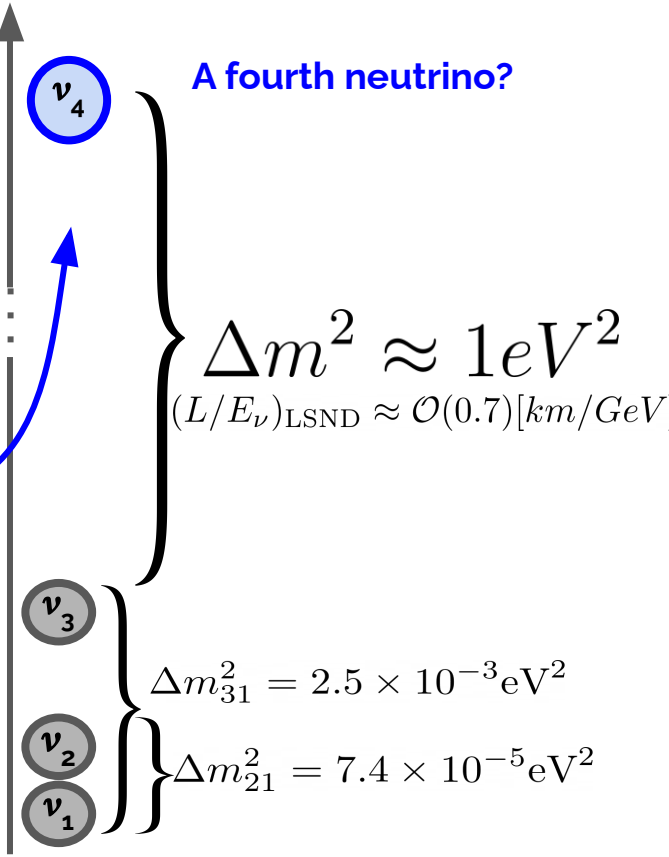


Another Definition : Short Baseline Oscillations

$$P_{\nu_\mu \to \nu_e}(E_\nu, L) = \sin^2(2\theta) \underbrace{\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)}_{\mathcal{O}(1)}.$$

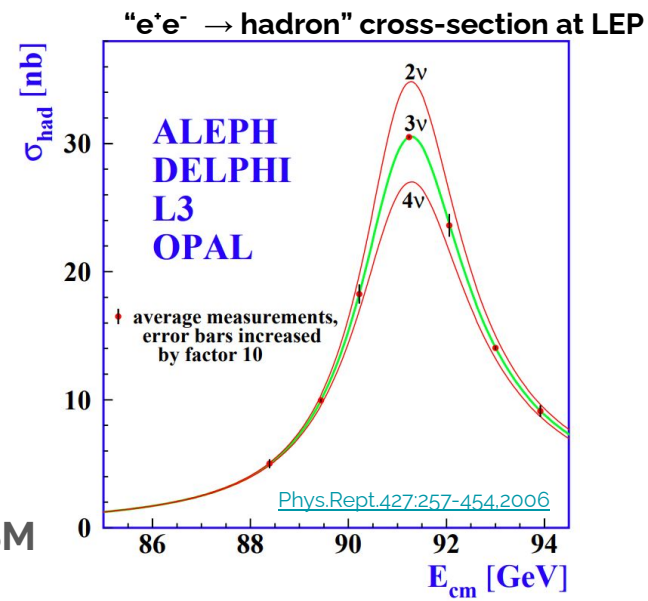
$$\Delta m^2_{31} = 2.5 \times 10^{-3} eV^2 \quad \Rightarrow \quad L/E_\nu \approx 500 \quad [km/GeV]$$
$$\Delta m^2_{21} = 7.4 \times 10^{-5} eV^2 \quad \Rightarrow \quad L/E_\nu \approx 17,000 \quad [km/GeV]$$

$$(L/E_\nu)_{\mathrm{SBL}} << \mathcal{O}(500) \quad [km/GeV]$$
$$\Delta m^2_{SBL} >> 10^{-3} eV^2$$



A 4th Neutrino? … a Sterile Neutrino

Precision measurement at LEP shows only three (light) neutrinos feel the weak force

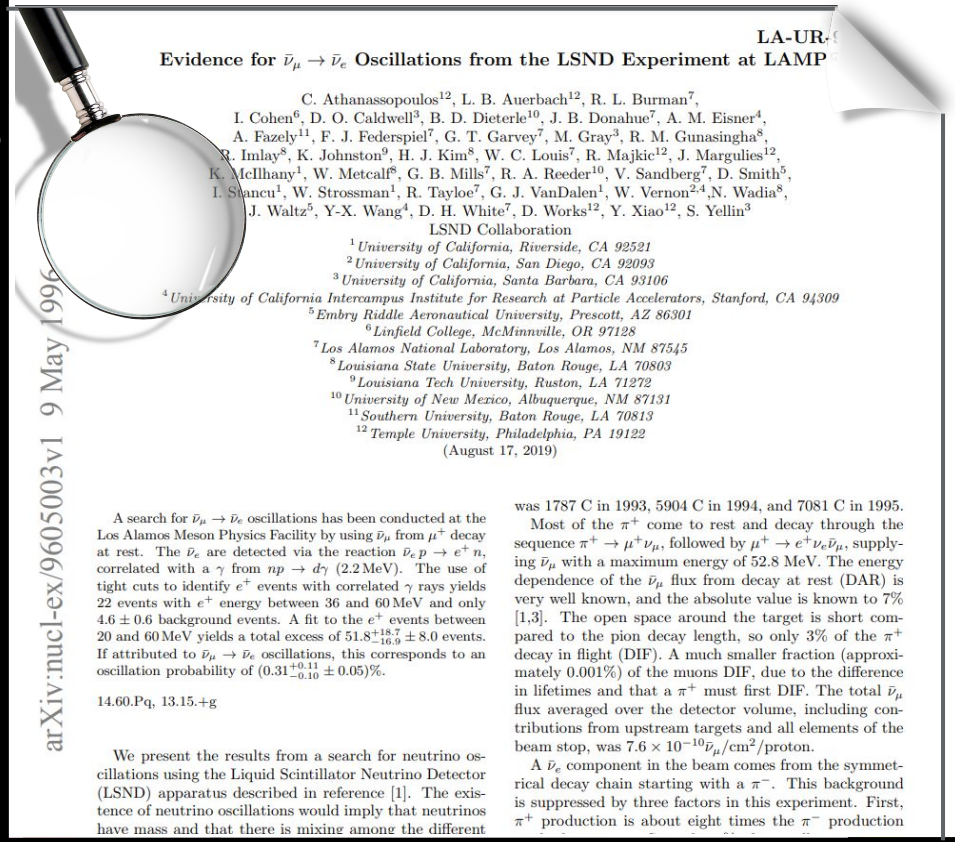


An **O(1 eV) scale** neutrino must be "**sterile**"

*I.e a fermion with **no charge under the Standard Model***

Incredibly generic extension to SM

LSND Historical Context



LA-UR-

Evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$ Oscillations from the LSND Experiment at LAMP

C. Athanassopoulos[12], L. B. Auerbach[12], R. L. Burman[7], I. Cohen[6], D. O. Caldwell[3], B. D. Dieterle[10], J. B. Donahue[7], A. M. Eisner[4], A. Fazely[11], F. J. Federspiel[7], G. T. Garvey[7], M. Gray[3], R. M. Gunasingha[8], R. Imlay[8], K. Johnston[9], H. J. Kim[8], W. C. Louis[7], R. Majkic[12], J. Margulies[12], K. McIlhany[1], W. Metcalf[8], G. B. Mills[7], R. A. Reeder[10], V. Sandberg[7], D. Smith[5], I. Stancu[1], W. Strossman[1], R. Tayloe[7], G. J. VanDalen[1], W. Vernon[2,4], N. Wadia[8], J. Waltz[5], Y-X. Wang[4], D. H. White[7], D. Works[12], Y. Xiao[12], S. Yellin[3]

LSND Collaboration

[1] *University of California, Riverside, CA 92521*
[2] *University of California, San Diego, CA 92093*
[3] *University of California, Santa Barbara, CA 93106*
[4] *University of California Intercampus Institute for Research at Particle Accelerators, Stanford, CA 94309*
[5] *Embry Riddle Aeronautical University, Prescott, AZ 86301*
[6] *Linfield College, McMinnville, OR 97128*
[7] *Los Alamos National Laboratory, Los Alamos, NM 87545*
[8] *Louisiana State University, Baton Rouge, LA 70803*
[9] *Louisiana Tech University, Ruston, LA 71272*
[10] *University of New Mexico, Albuquerque, NM 87131*
[11] *Southern University, Baton Rouge, LA 70813*
[12] *Temple University, Philadelphia, PA 19122*

(August 17, 2019)

A search for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations has been conducted at the Los Alamos Meson Physics Facility by using $\bar{\nu}_\mu$ from μ^+ decay at rest. The $\bar{\nu}_e$ are detected via the reaction $\bar{\nu}_e p \to e^+ n$, correlated with a γ from $np \to d\gamma$ (2.2 MeV). The use of tight cuts to identify e^+ events with correlated γ rays yields 22 events with e^+ energy between 36 and 60 MeV and only 4.6 ± 0.6 background events. A fit to the e^+ events between 20 and 60 MeV yields a total excess of $51.8^{+18.7}_{-16.9} \pm 8.0$ events. If attributed to $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations, this corresponds to an oscillation probability of $(0.31^{+0.11}_{-0.10} \pm 0.05)\%$.

14.60.Pq, 13.15.+g

We present the results from a search for neutrino oscillations using the Liquid Scintillator Neutrino Detector (LSND) apparatus described in reference [1]. The existence of neutrino oscillations would imply that neutrinos have mass and that there is mixing among the different

was 1787 C in 1993, 5904 C in 1994, and 7081 C in 1995.

Most of the π^+ come to rest and decay through the sequence $\pi^+ \to \mu^+ \nu_\mu$, followed by $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$, supplying $\bar{\nu}_\mu$ with a maximum energy of 52.8 MeV. The energy dependence of the $\bar{\nu}_\mu$ flux from decay at rest (DAR) is very well known, and the absolute value is known to 7% [1,3]. The open space around the target is short compared to the pion decay length, so only 3% of the π^+ decay in flight (DIF). A much smaller fraction (approximately 0.001%) of the muons DIF, due to the difference in lifetimes and that a π^+ must first DIF. The total $\bar{\nu}_\mu$ flux averaged over the detector volume, including contributions from upstream targets and all elements of the beam stop, was $7.6 \times 10^{-10} \bar{\nu}_\mu/\mathrm{cm}^2/\mathrm{proton}$.

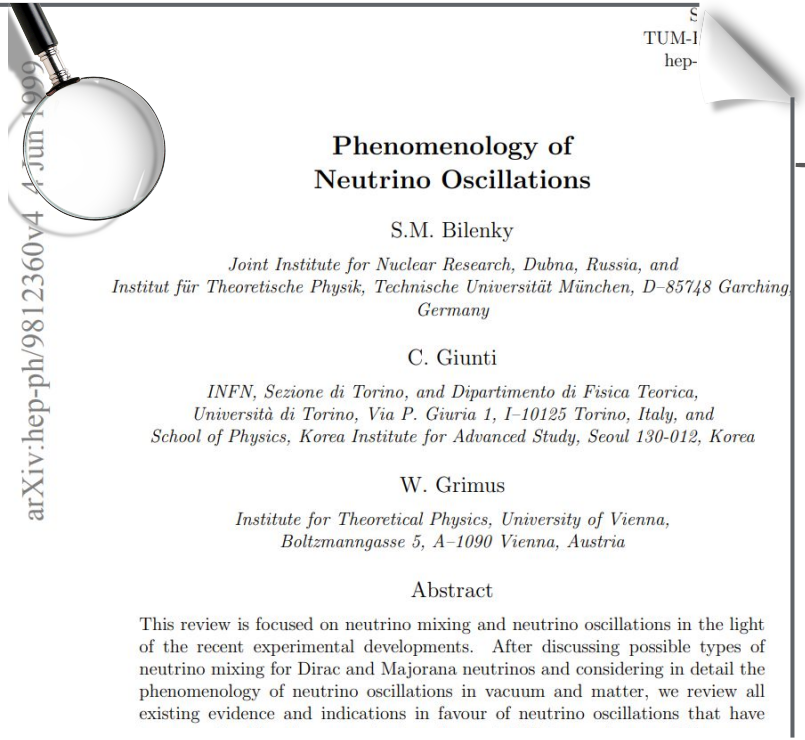
A $\bar{\nu}_e$ component in the beam comes from the symmetrical decay chain starting with a π^-. This background is suppressed by three factors in this experiment. First, π^+ production is about eight times the π^- production

LSND first results came out in **1996** there was **No mention of "sterile" neutrino whatsoever**.

At this point, **while there was compelling evidence building for solar and atmospheric oscillations,** the 3ν paradigm was by **no means taken for granted** by entire HEP community

Historical Context

Three years later, after Super-K's atmospheric results, **the picture as we know it started to form**



TUM-I
hep-

Phenomenology of Neutrino Oscillations

S.M. Bilenky

Joint Institute for Nuclear Research, Dubna, Russia, and Institut für Theoretische Physik, Technische Universität München, D–85748 Garching, Germany

C. Giunti

INFN, Sezione di Torino, and Dipartimento di Fisica Teorica, Università di Torino, Via P. Giuria 1, I–10125 Torino, Italy, and School of Physics, Korea Institute for Advanced Study, Seoul 130-012, Korea

W. Grimus

Institute for Theoretical Physics, University of Vienna, Boltzmanngasse 5, A–1090 Vienna, Austria

Abstract

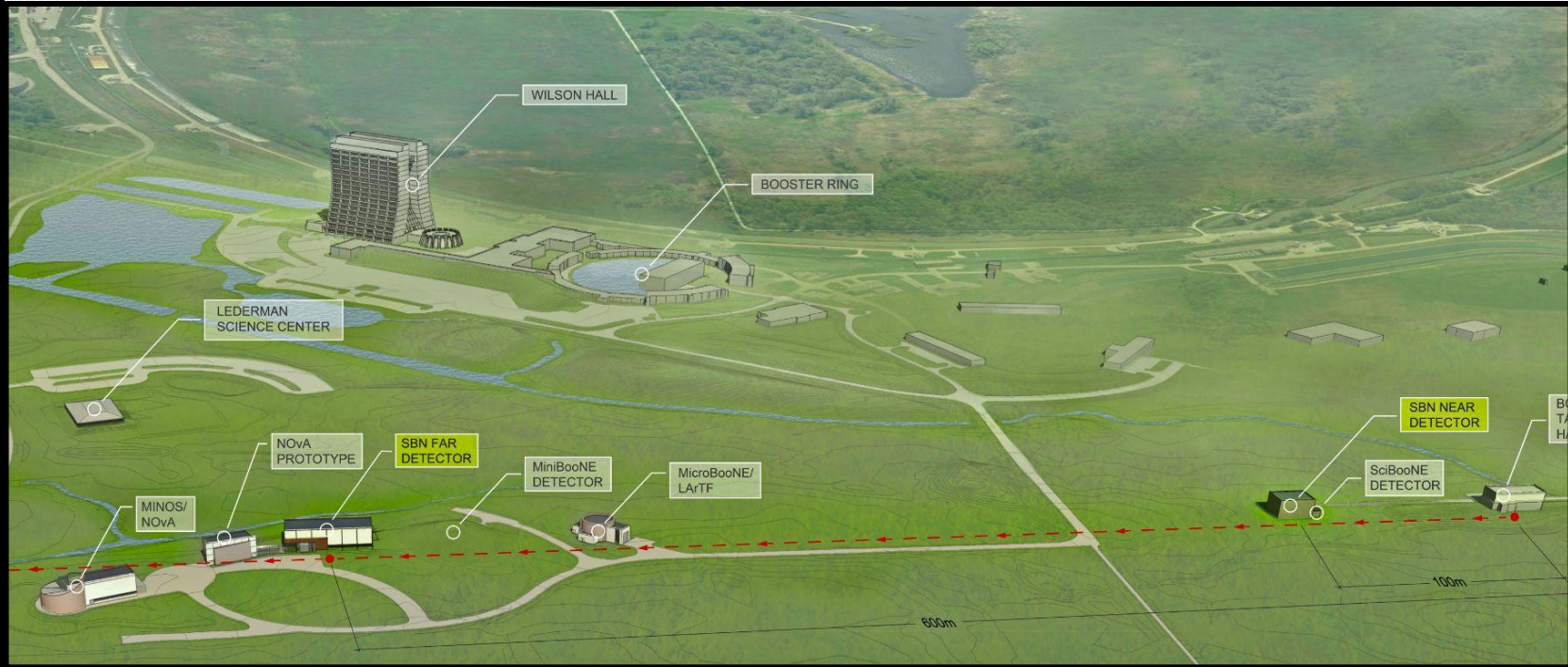
This review is focused on neutrino mixing and neutrino oscillations in the light of the recent experimental developments. After discussing possible types of neutrino mixing for Dirac and Majorana neutrinos and considering in detail the phenomenology of neutrino oscillations in vacuum and matter, we review all existing evidence and indications in favour of neutrino oscillations that have

*"..we would like to finish this section by **emphasizing the importance** of the results obtained in the **LSND experiment for neutrino physics**."*

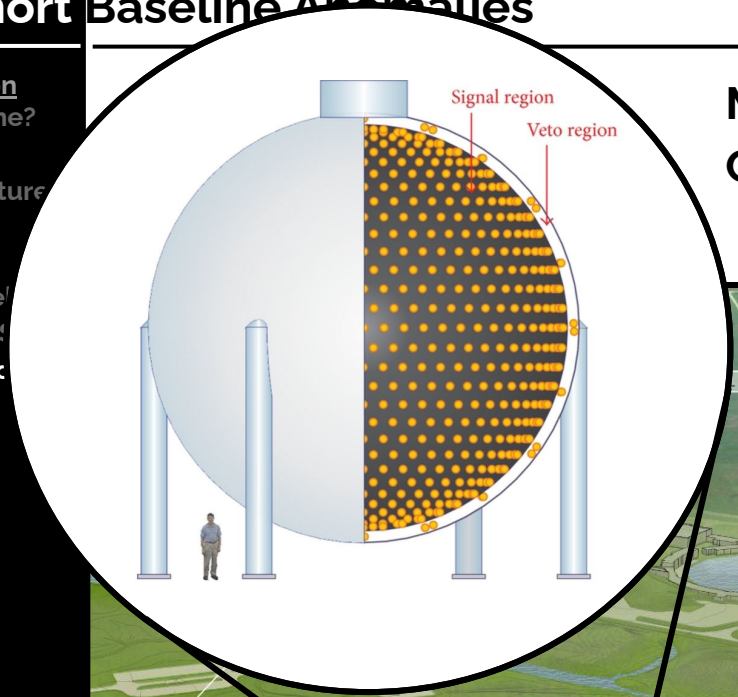
*" ..taken together with the **indications in favour of solar and atmospheric** neutrino oscillations require the **existence of at least one sterile neutrino"***

The Short Baseline Anomalies

Fermilab



The Short Baseline Anomalies



MiniBooNE was an 800 ton **Mineral Oil Cherenkov detector**

Marcol 7 Light Mineral Oil
Less dense than water
~0.85 gm/cm^3

Long hydrocarbon chains

CH_2 targets

The Short Baseline Anomalies

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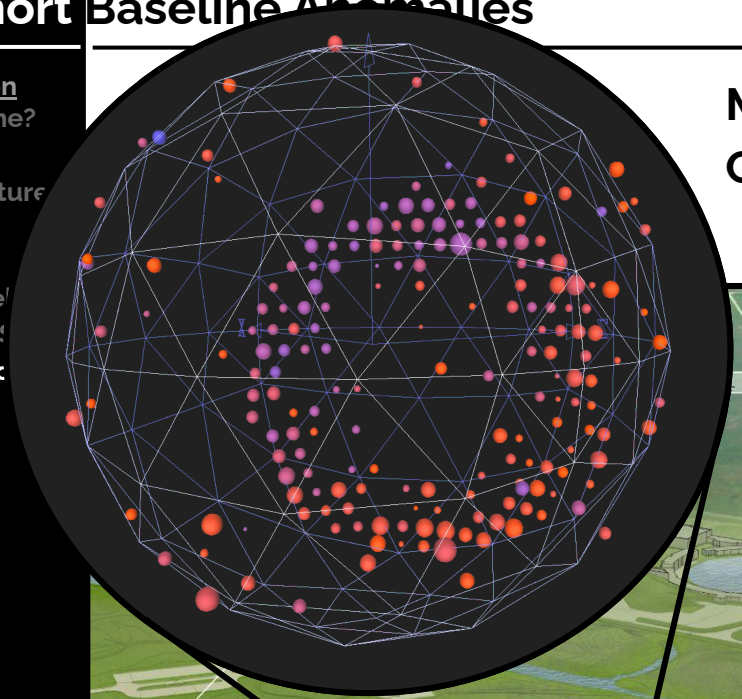

Marcol 7 Light Mineral Oil

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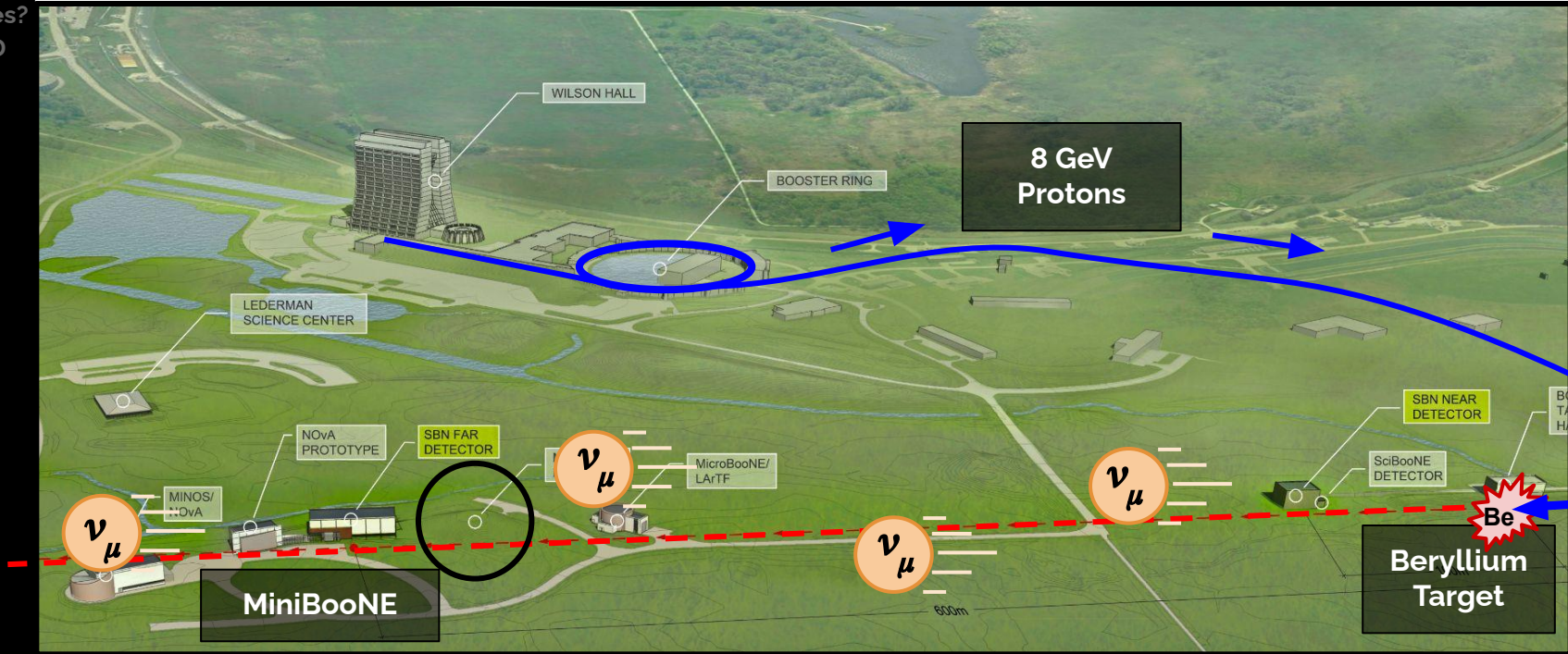
Booster Neutrino Beam (BNB)

Vast majority of neutrinos produced by **pion decay-in-flight**



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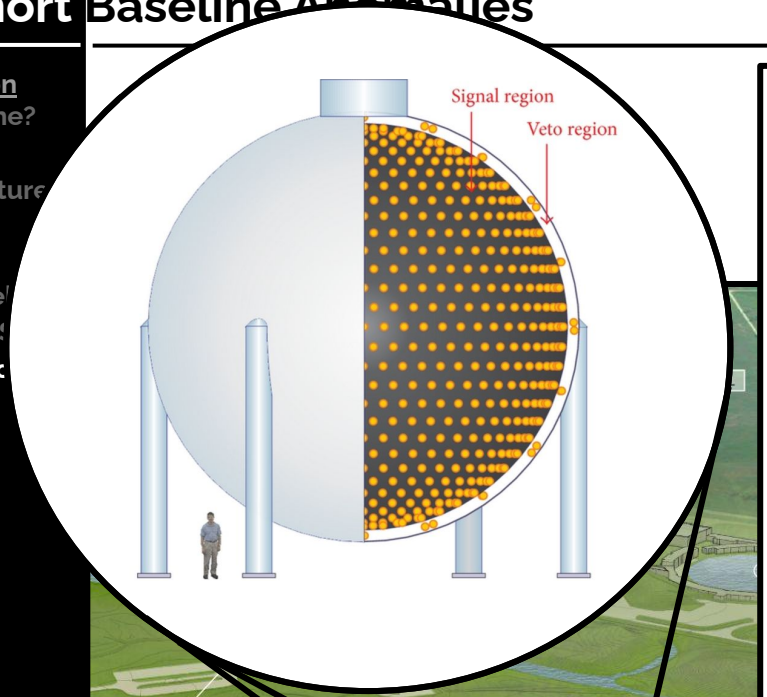
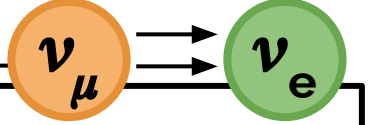


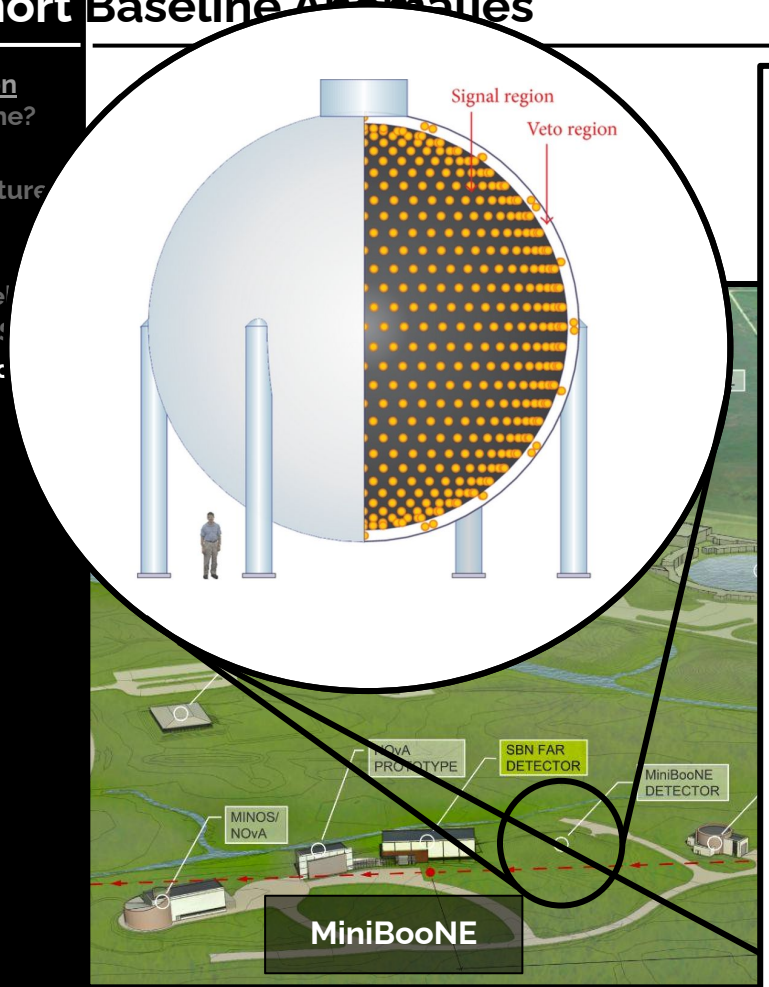


Idea: Search for $\nu_\mu \rightarrow \nu_e$ **appearance** at different E and L, but similar L/E

LSND: $\frac{L}{\langle E_\nu \rangle} = \frac{30m}{45MeV} \approx 0.667$

MiniBooNE: $\frac{L}{\langle E_\nu \rangle} = \frac{540m}{800MeV} \approx 0.675$

The Short Baseline Anomalies



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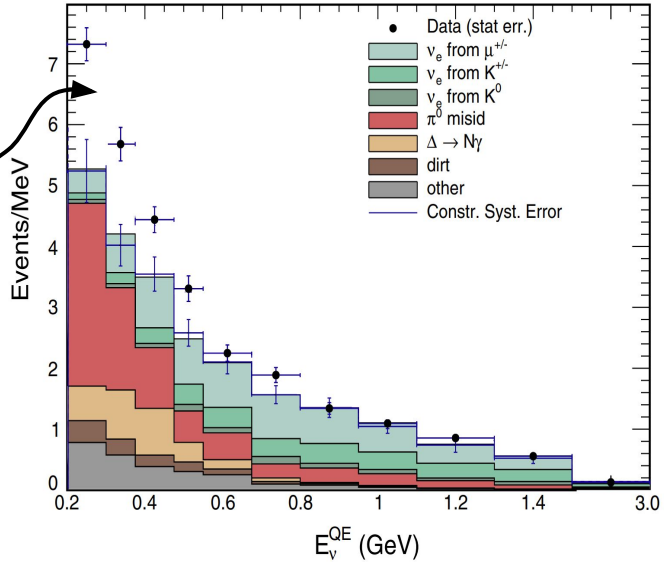

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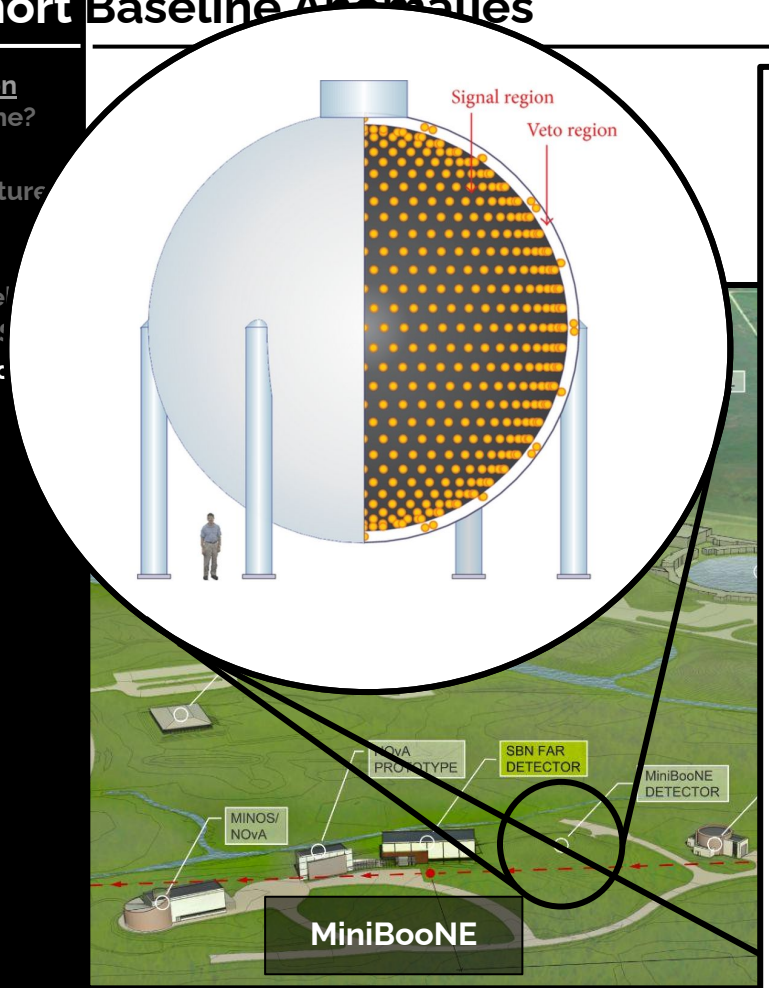

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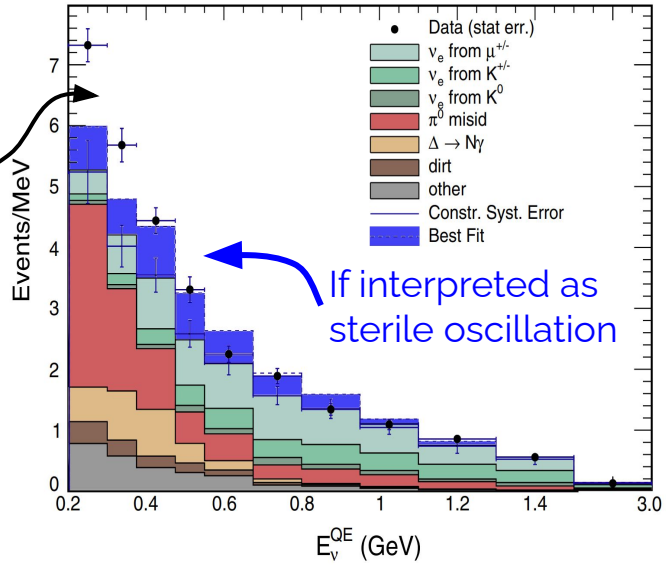
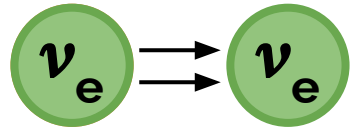
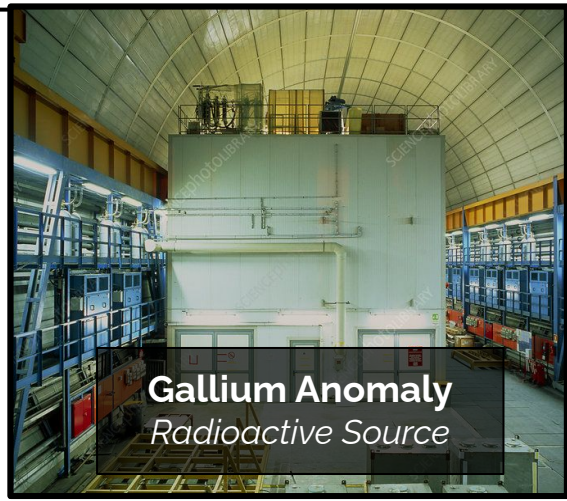


Looking for neutrinos from radioactive ^{51}Cr and ^{37}Ar sources in two experiments **SAGE** and **GALLEX**.

Recently replicated by the **BEST experiment** (PhysRevLett.128.232501 (2022))

Sensitive to $\nu_e \rightarrow \nu_e$ **disappearance oscillations**





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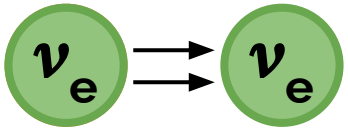

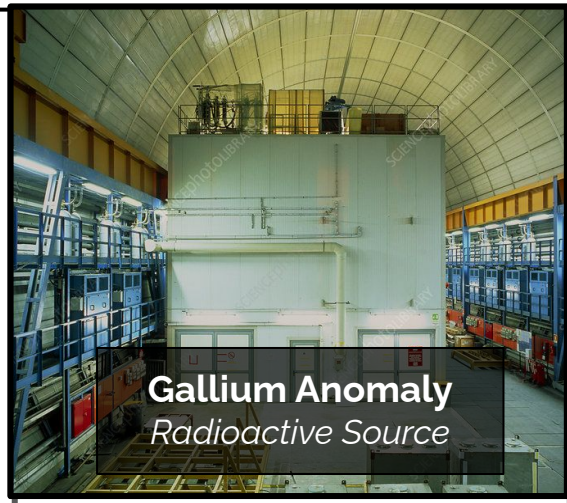

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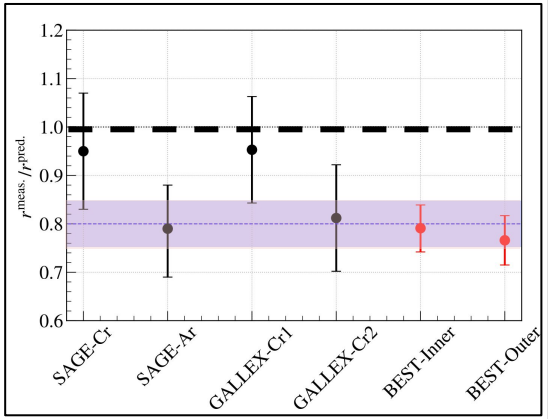

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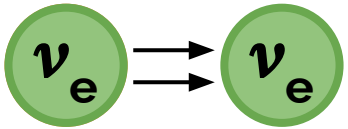

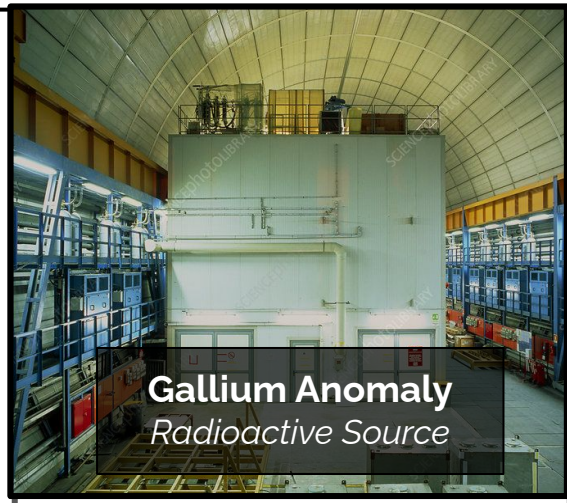

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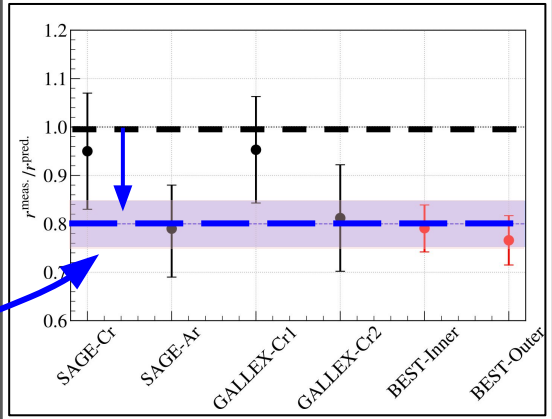
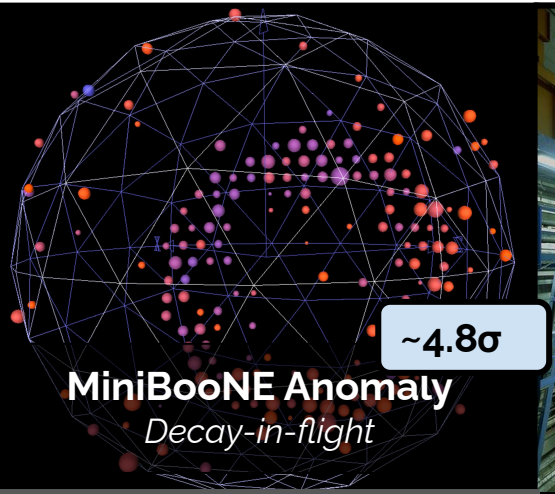


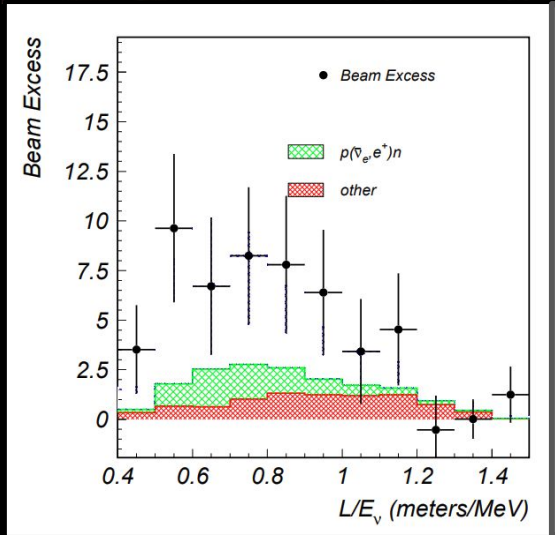
If interpreted as sterile oscillation

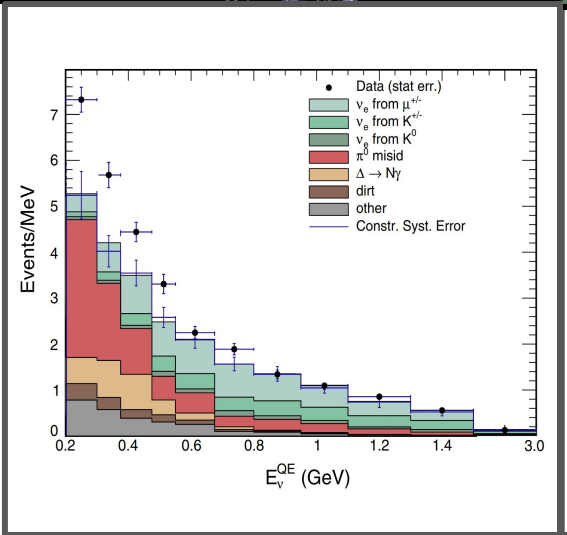
The Short Baseline Anomalies

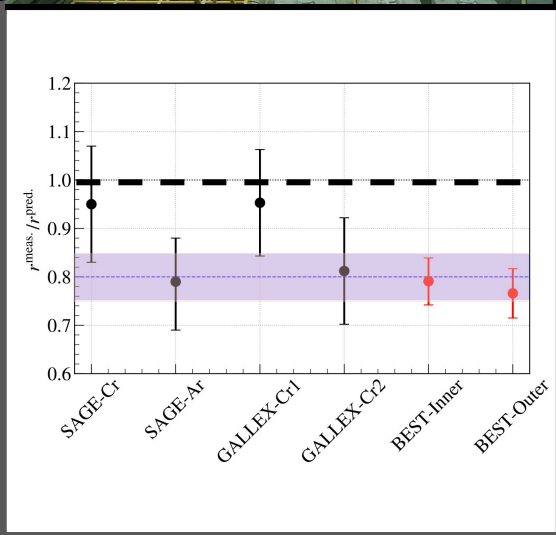
1. Introduction
Short-Baseline?
Brief History
Global 3ν Picture

2. Anomalies
At Short Baselines?
Began with LSND
Enter MiniBooNE









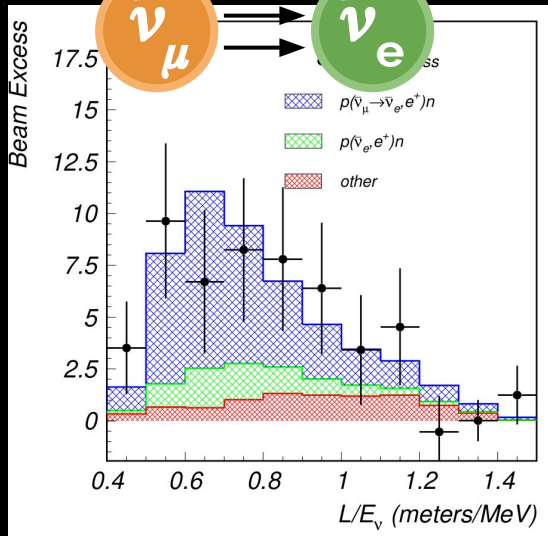
The Short Baseline Anomalies

All *individually* consistent with neutrino oscillations with a mass difference **$\Delta m^2 \sim O(1\ eV^2)$**

~3.8σ

LSND Anomaly
Decay-at-rest

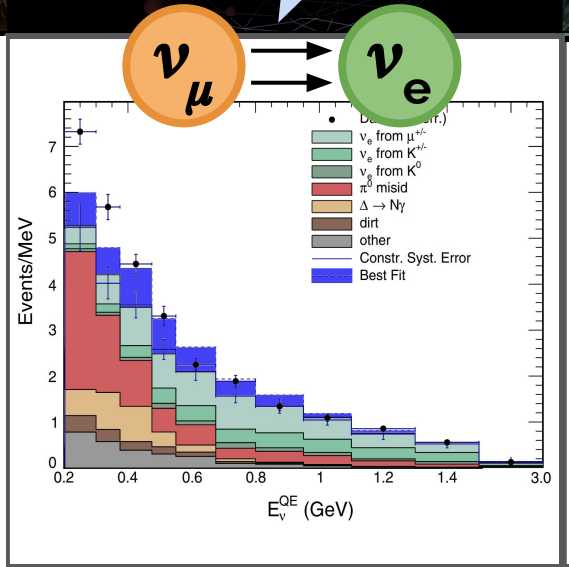
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



~4.8σ

MiniBooNE Anomaly
Decay-in-flight

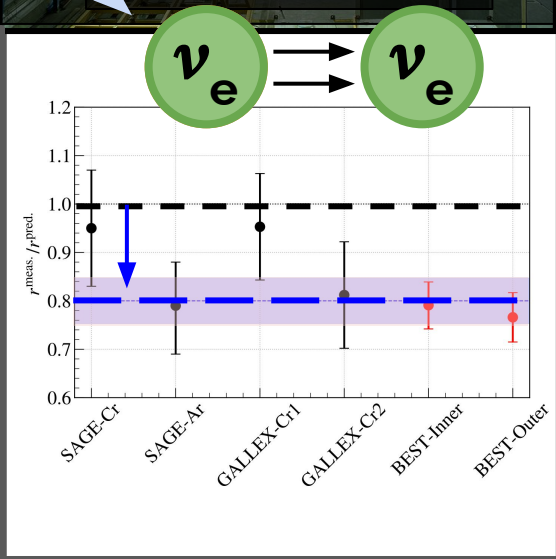
$\nu_\mu \rightarrow \nu_e$



~4.0σ

Gallium Anomaly
Radioactive Source

$\nu_e \rightarrow \nu_e$



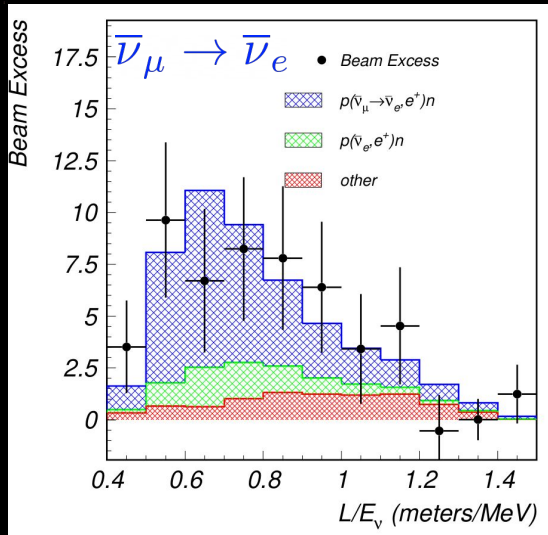
Why the debate?

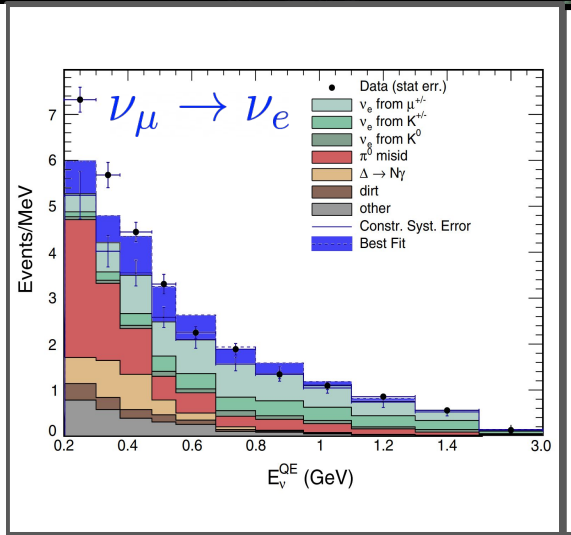
Multiple independent anomalous signals consistent with a 4th eV scale neutrino..
Why is there still debate? Where's the  ?

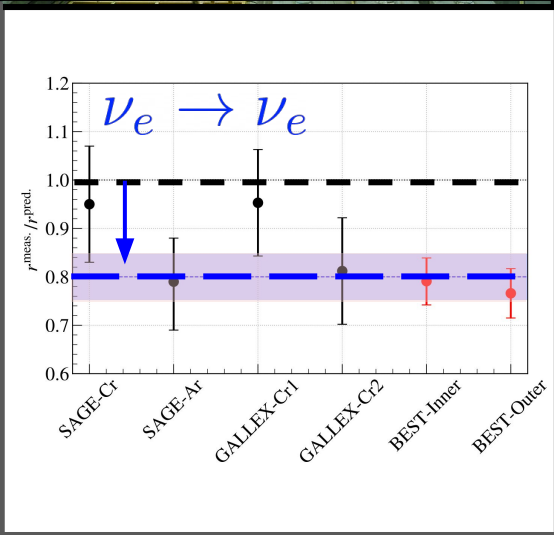
LSND Anomaly *Decay-at-rest* ~3.8σ

MiniBooNE Anomaly *Decay-in-flight* ~4.8σ

Gallium Anomaly *Radioactive Source* ~4.0σ







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LSND Anomaly ~3.8σ
Decay-at-rest

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Decay-in-flight

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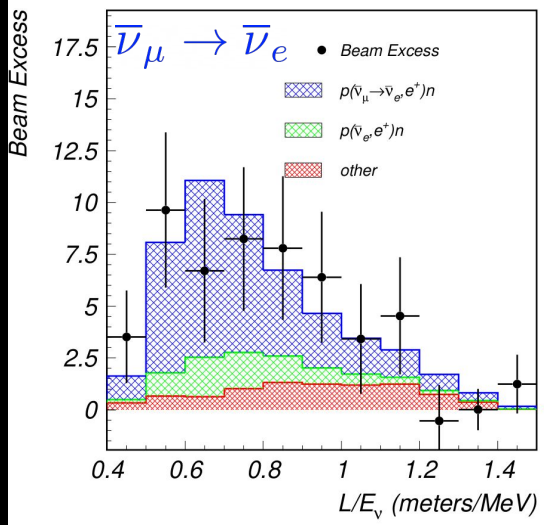
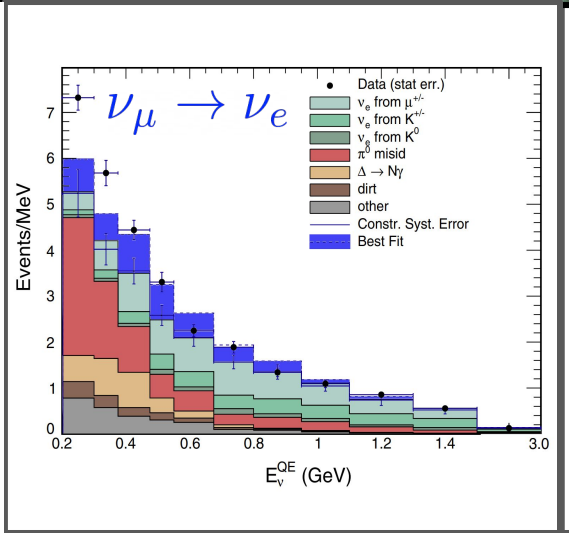
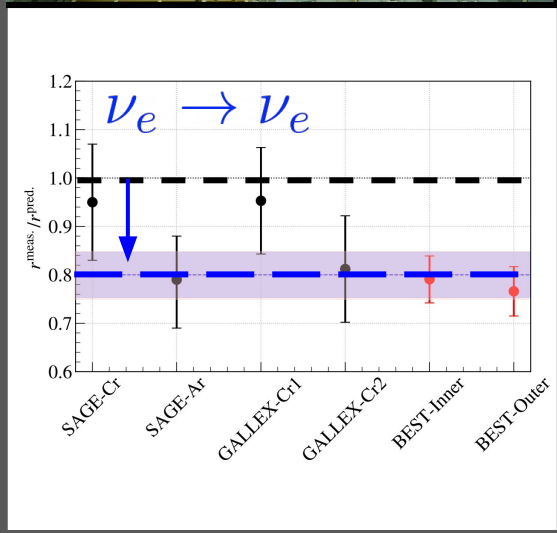
Radioactive Source

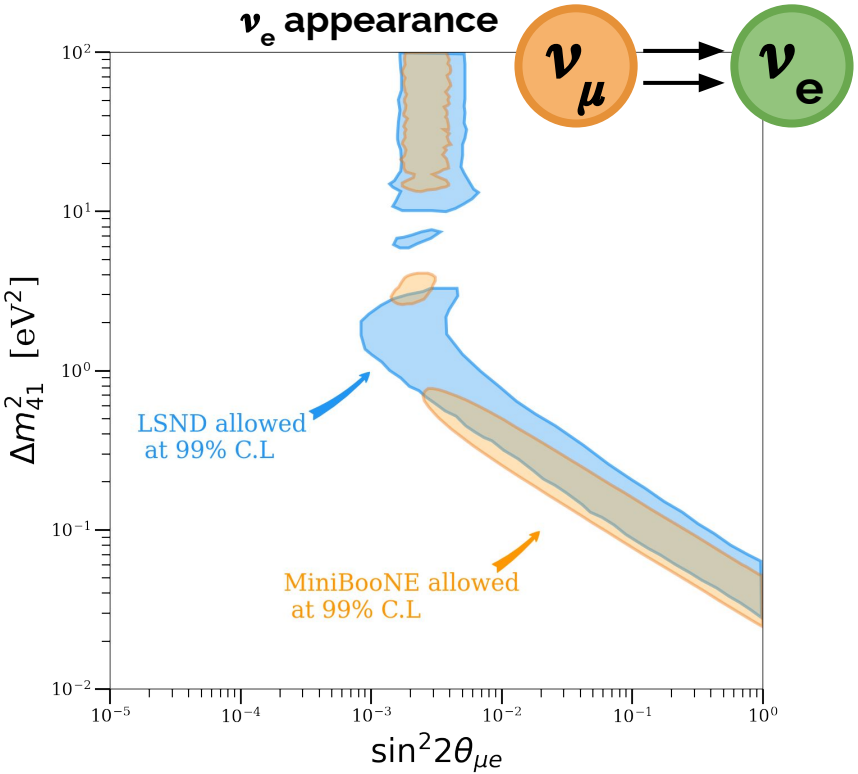






Why the debate? (I) Massive Tension in global "3+1" data

$$P(\nu_\mu \to \nu_e) \simeq 4\,|U_{\mu 4}|^2\,|U_{e4}|^2 \sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right)$$



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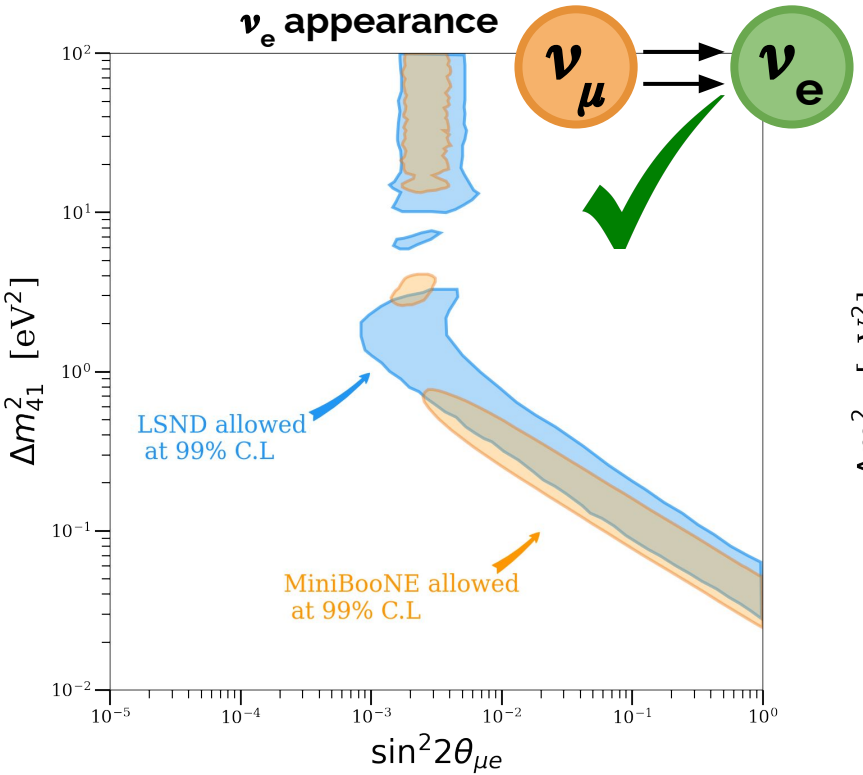

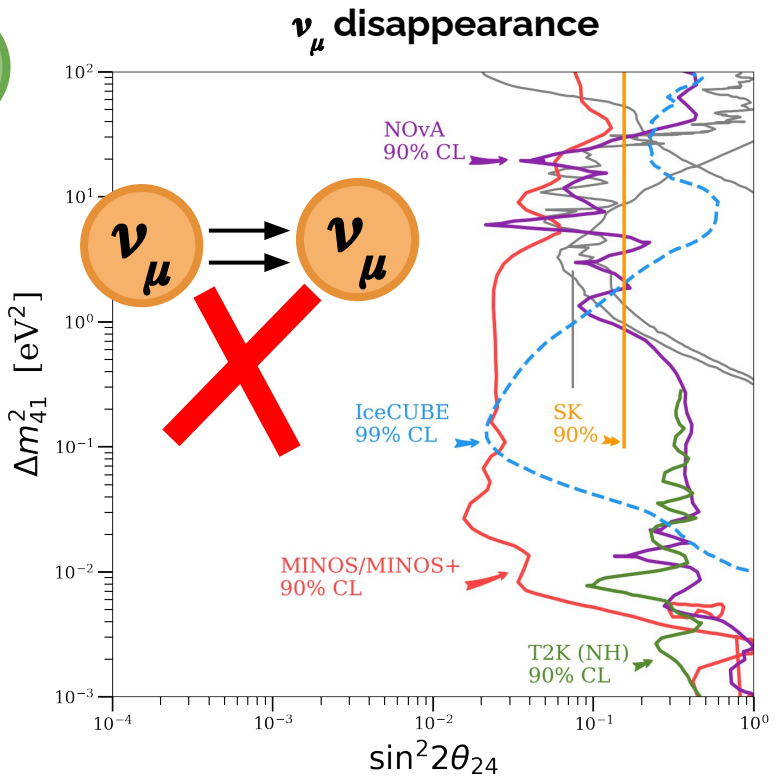

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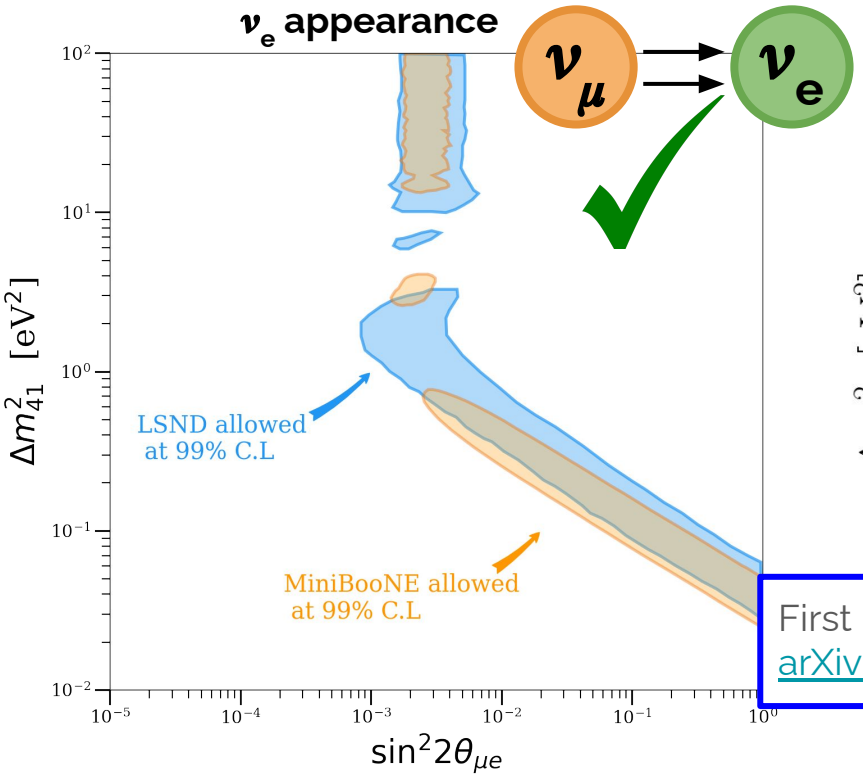

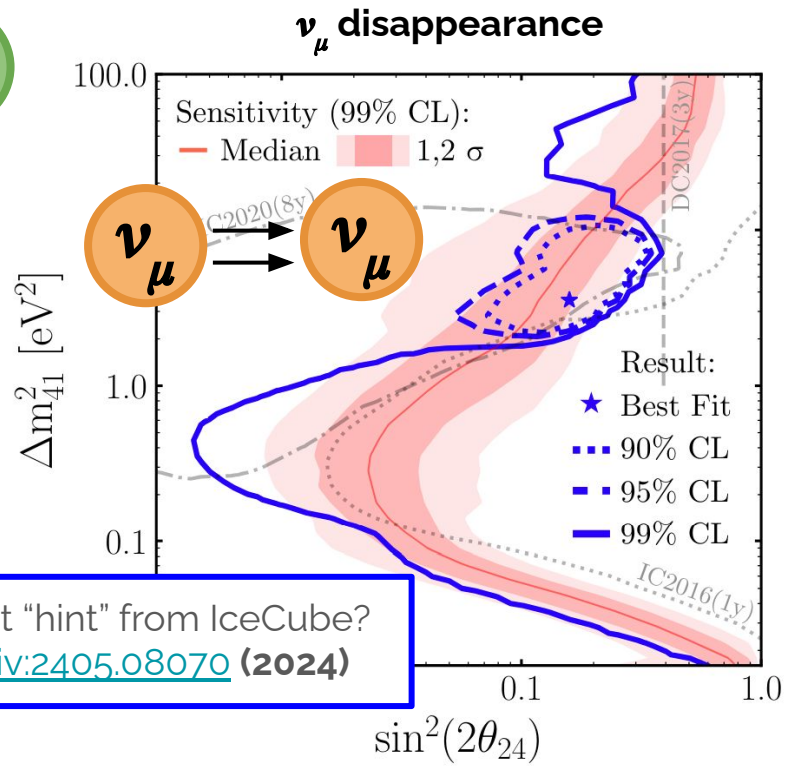

First "hint" from IceCube?
arXiv:2405.08070 **(2024)**

$$P(\nu_\mu \to \nu_e) \simeq 4\,|U_{\mu 4}|^2\,|U_{e4}|^2 \sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right)$$

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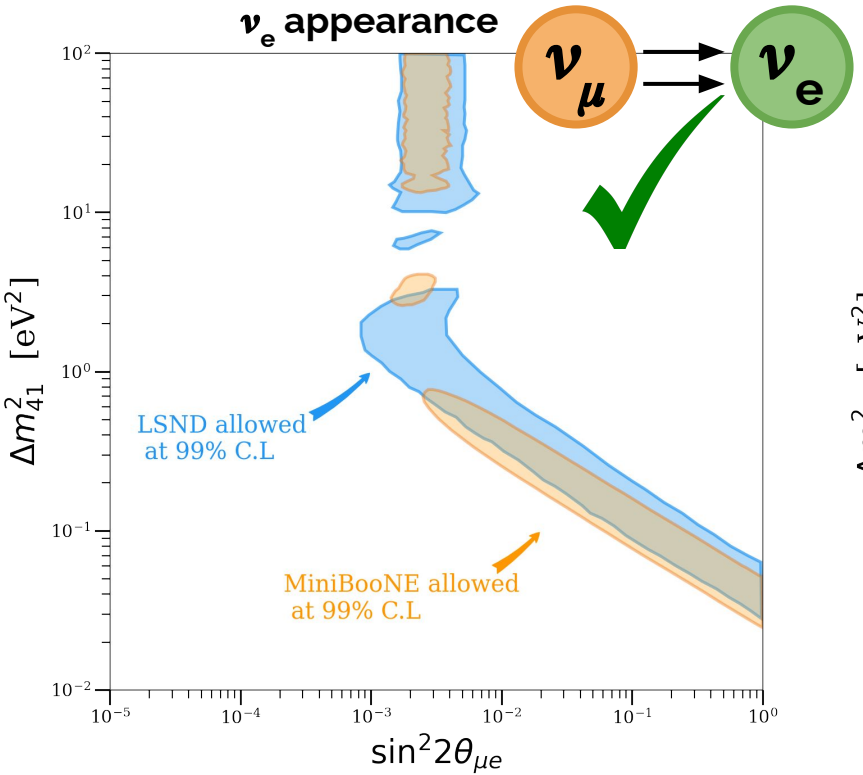
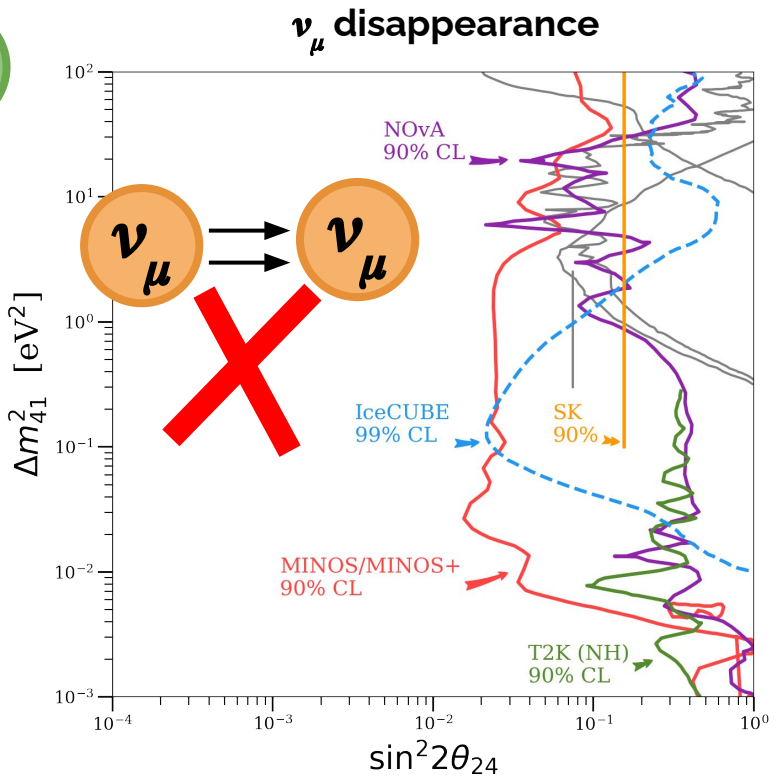
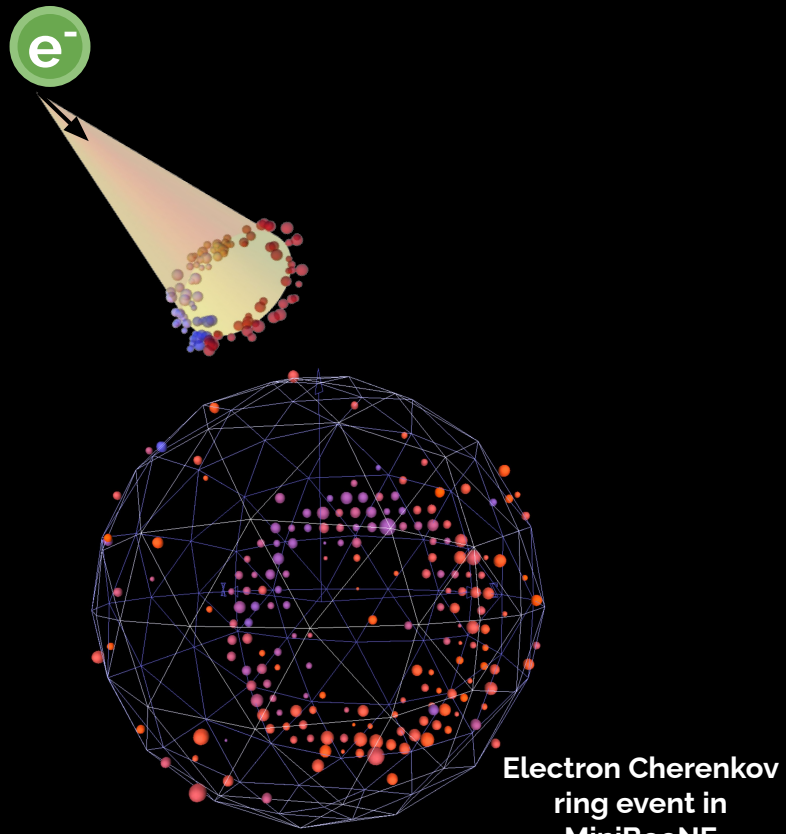
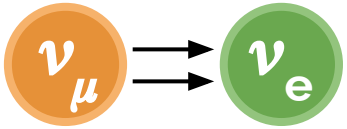




Why the debate? (II) MiniBooNE may not be as it seems

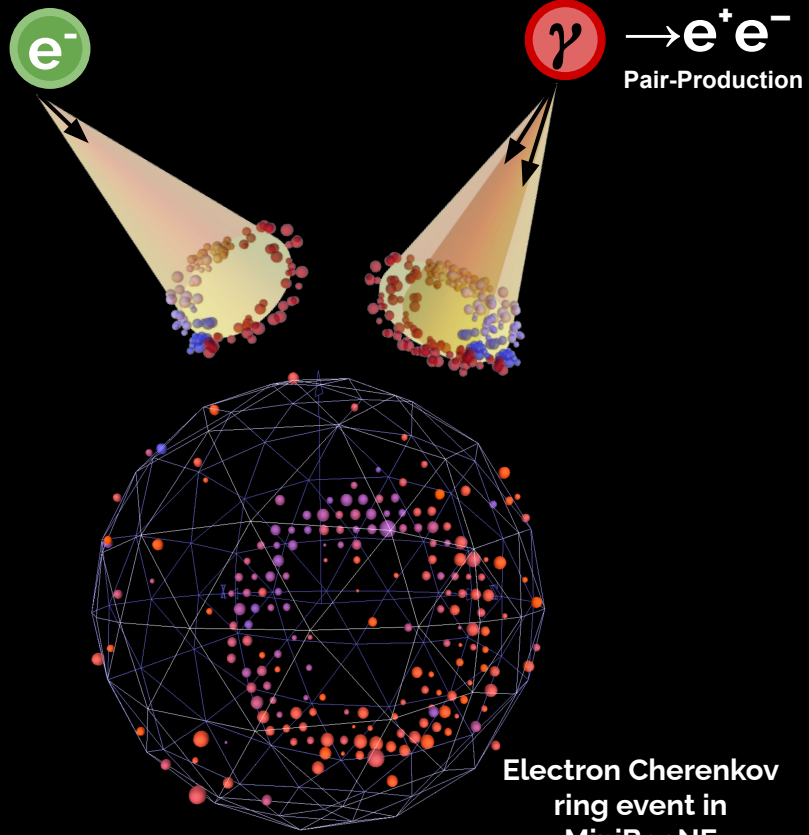


Electron Cherenkov ring event in MiniBooNE



If truly electrons, strong evidence for $\nu_\mu \rightarrow \nu_e$ and sterile neutrino oscillations

Why the debate? (II) MiniBooNE may not be as it seems



Electron Cherenkov ring event in MiniBooNE

MiniBooNE couldn't separate true **electrons** from background **photons**

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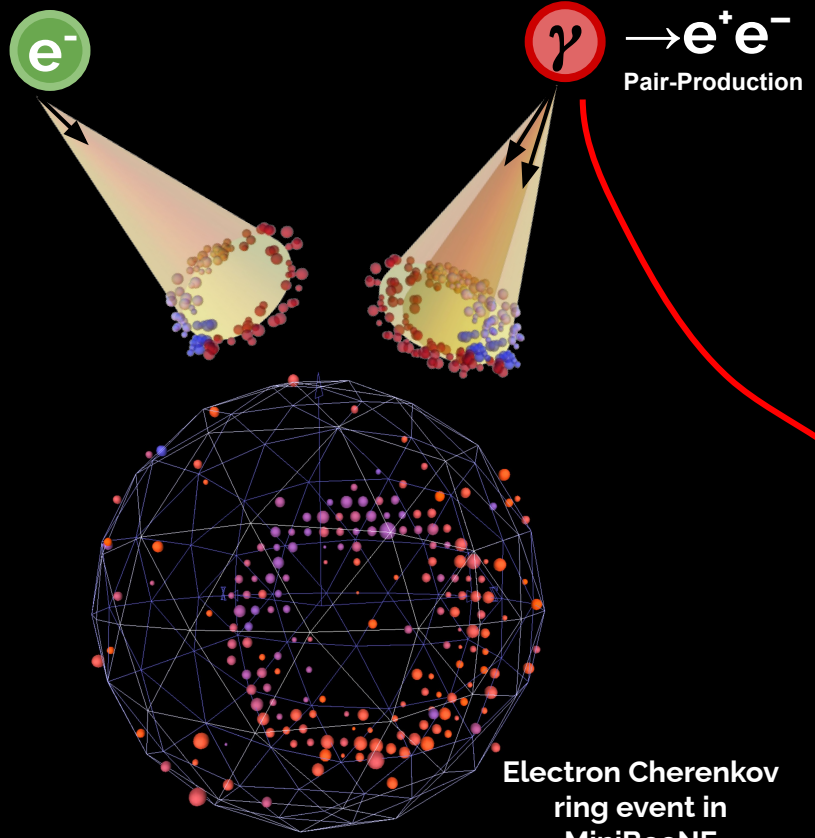

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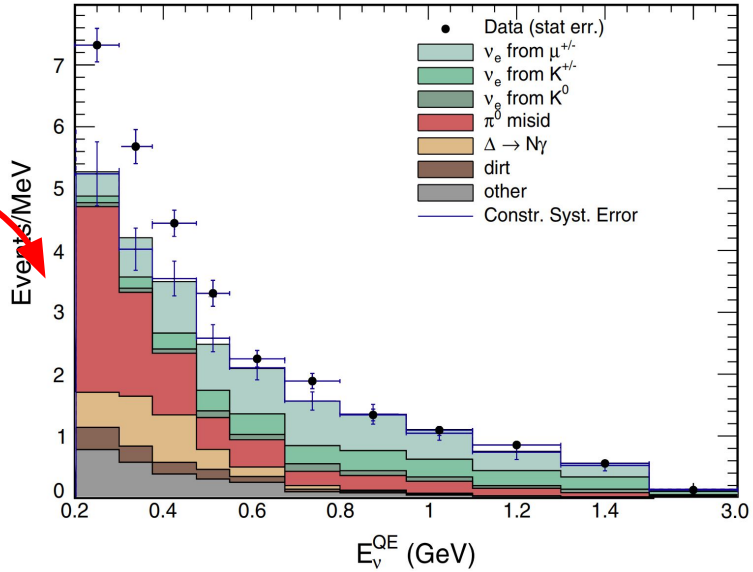
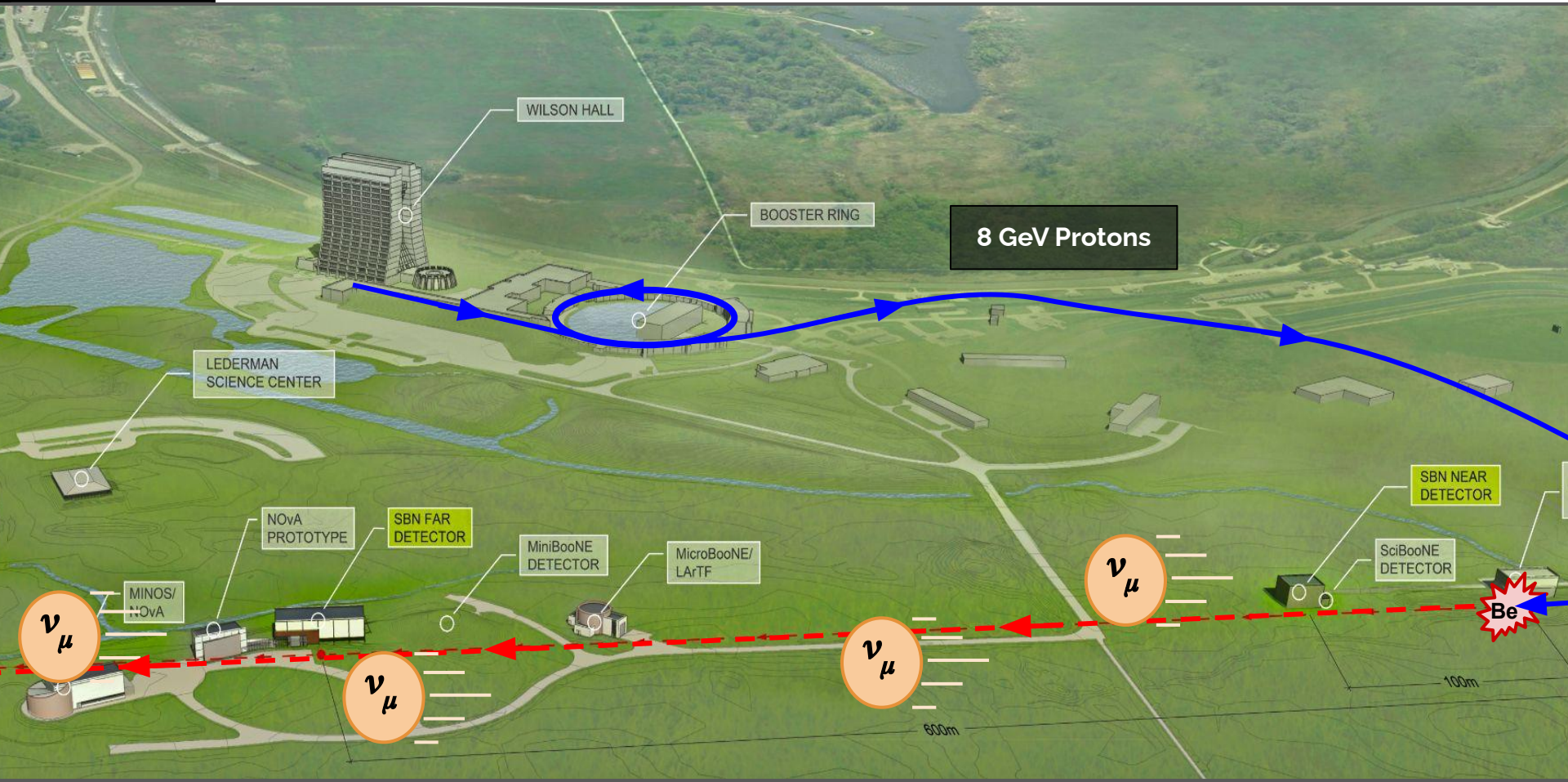
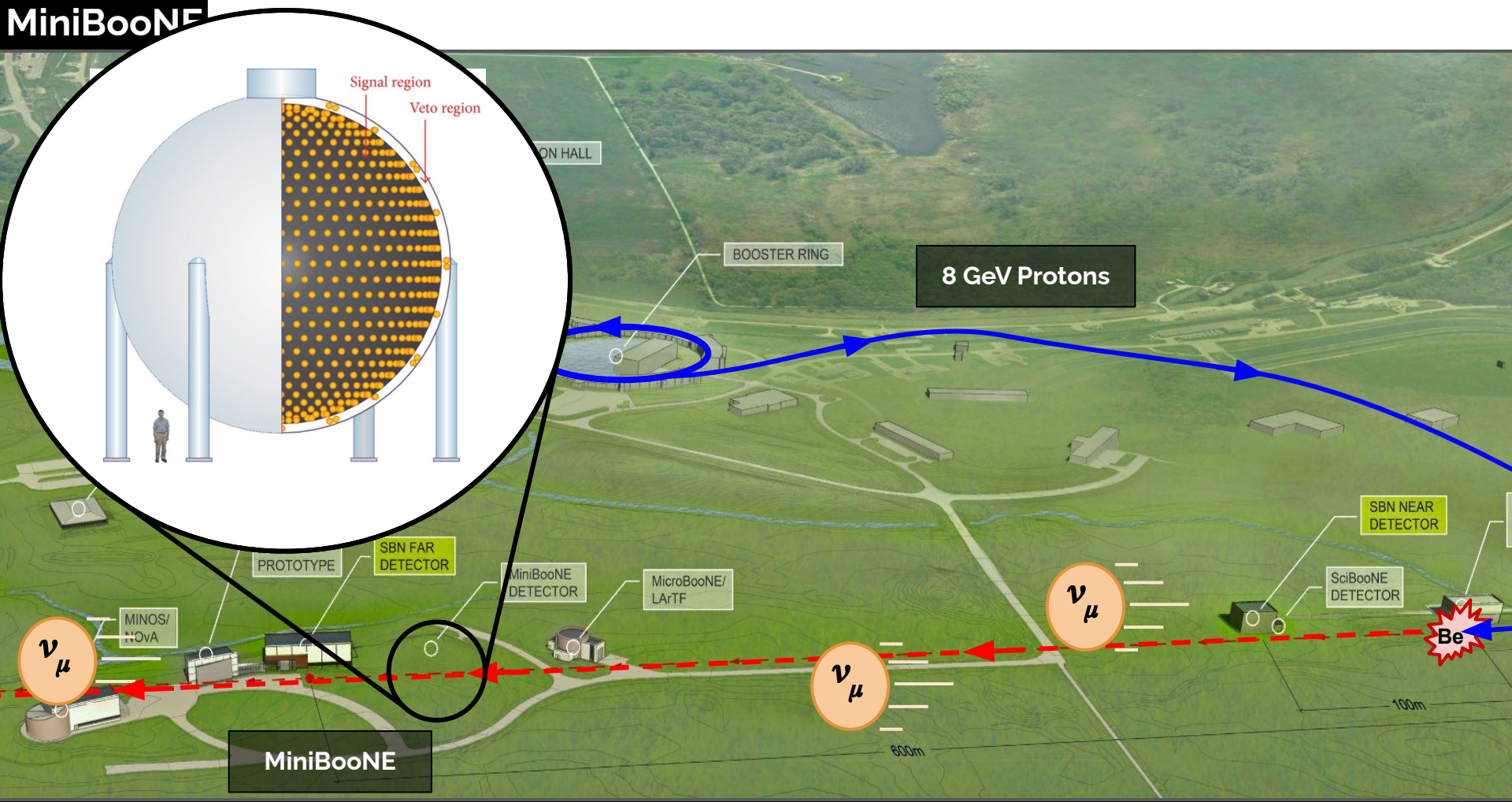
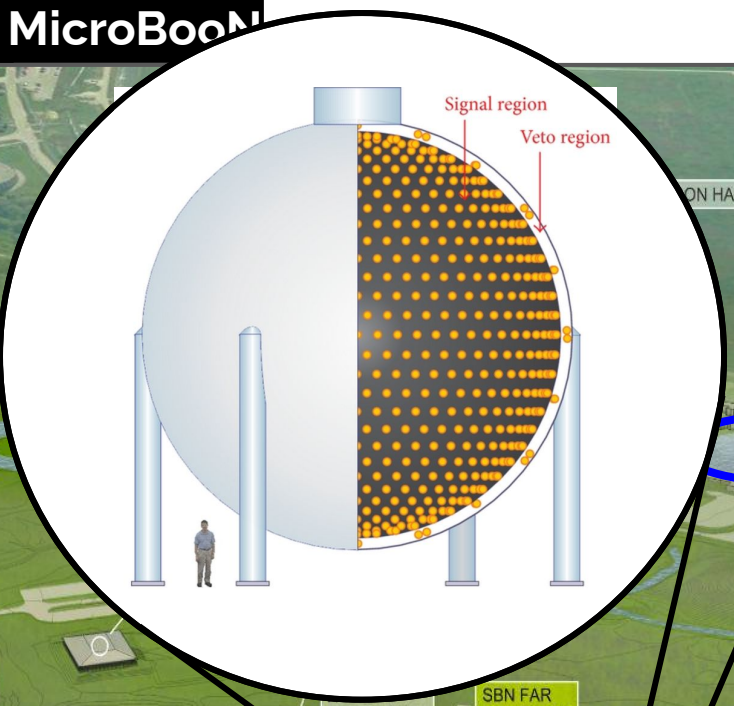


We need an experiment to set things straight!

Fermilab's Booster Neutrino Beam




Signal region
Veto region
ON HALL
BOOSTER RING
8 GeV Protons
PROTOTYPE
SBN FAR DETECTOR
MiniBooNE DETECTOR
MicroBooNE/ LArTF
MINOS/ NOvA
SBN NEAR DETECTOR
SciBooNE DETECTOR
Be
100m
600m
MiniBooNE



The MicroBooNE Cryostat

MicroBooNE

MicroBooNE is a **Liquid Argon Time Projection Chamber** (**LArTPC**) neutrino detector built at Fermilab to investigate the MiniBooNE anomaly

TPC being moved inside cryostat

MicroBooNE

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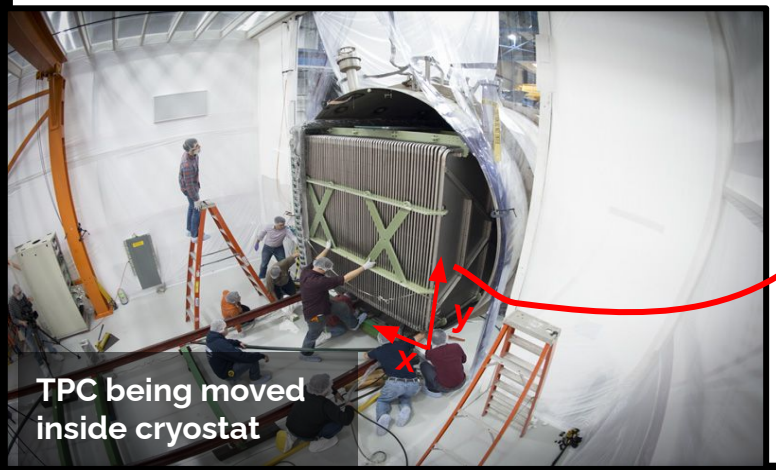

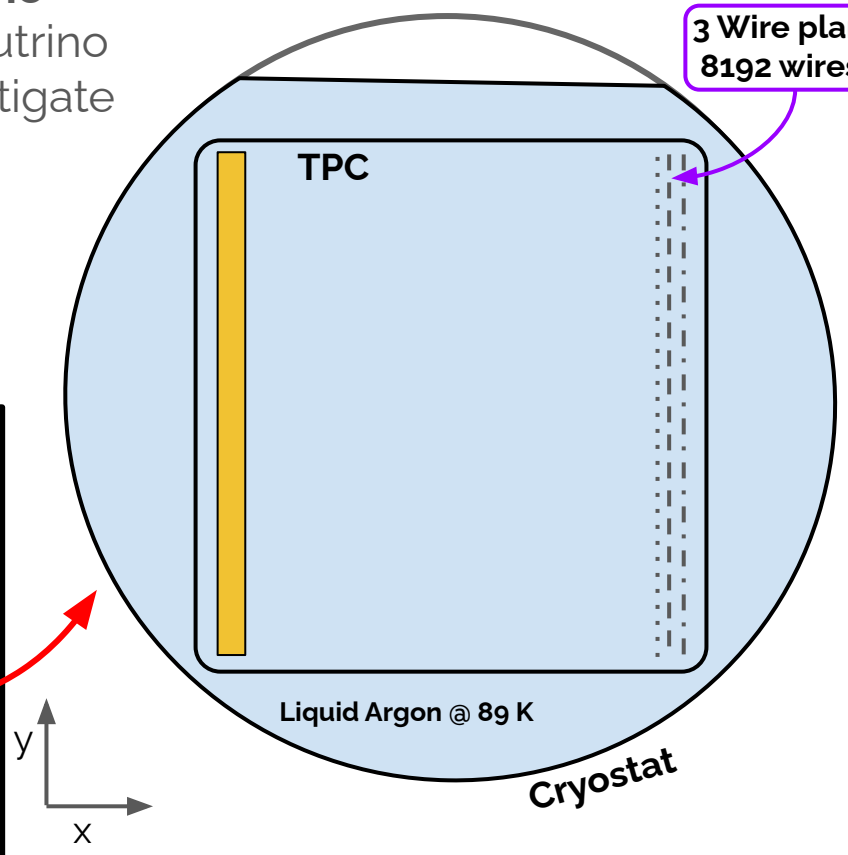

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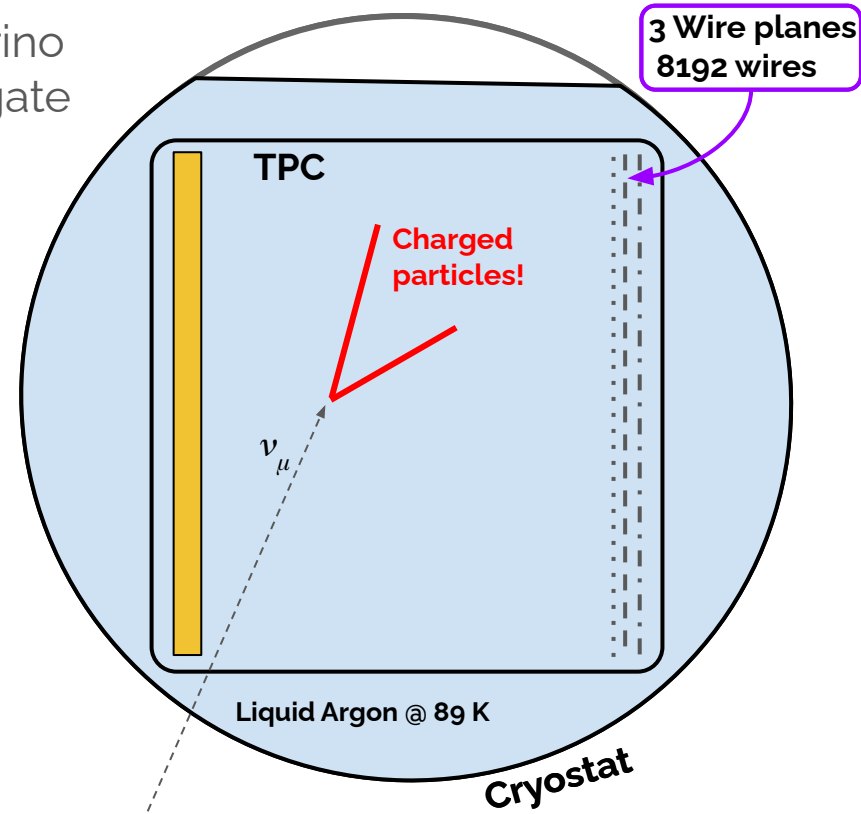

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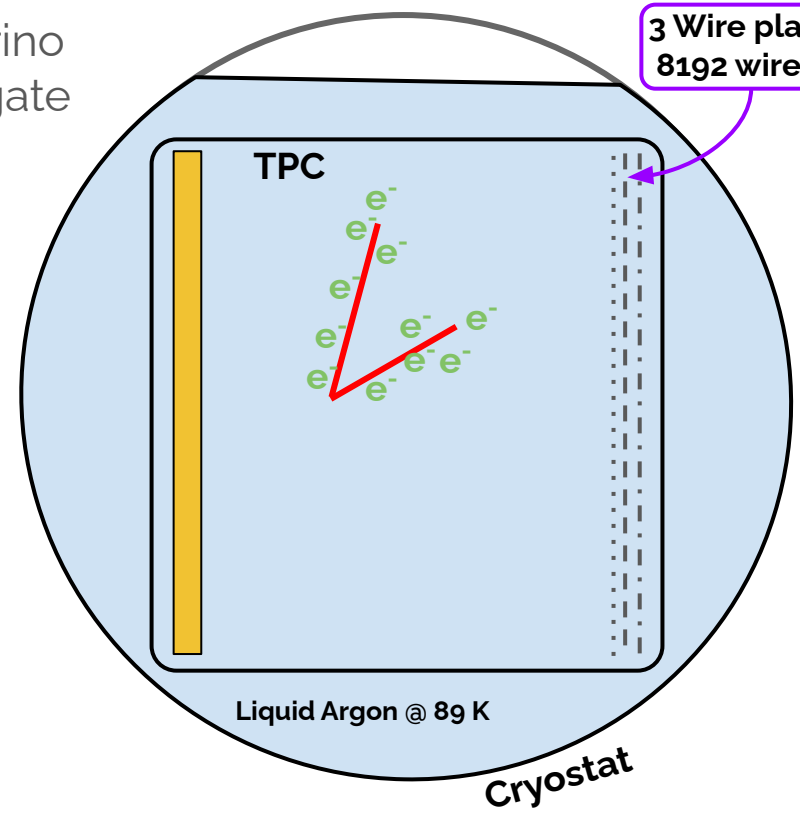

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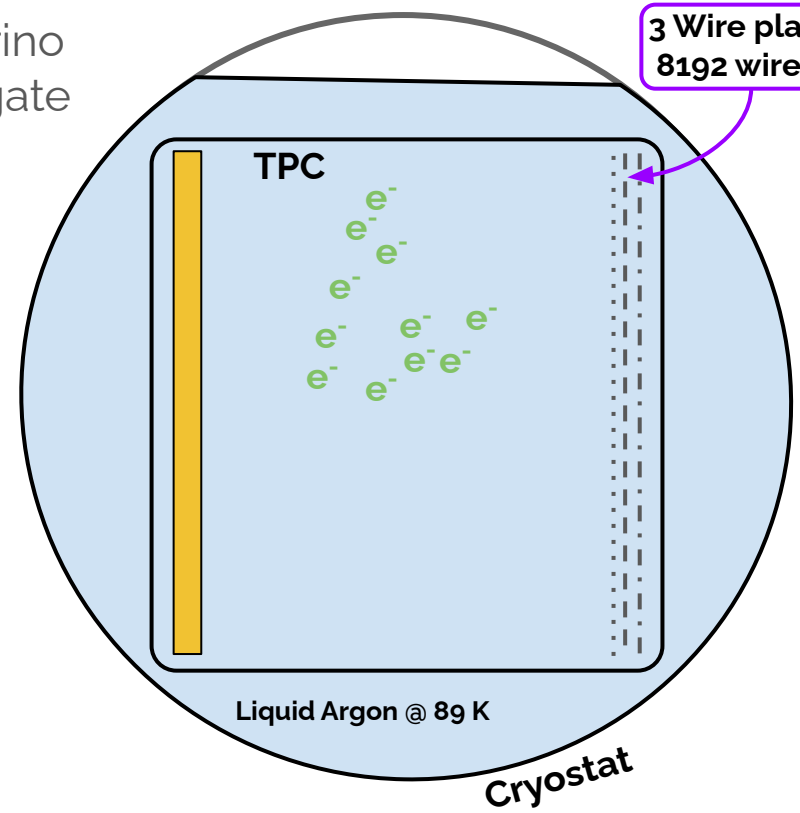
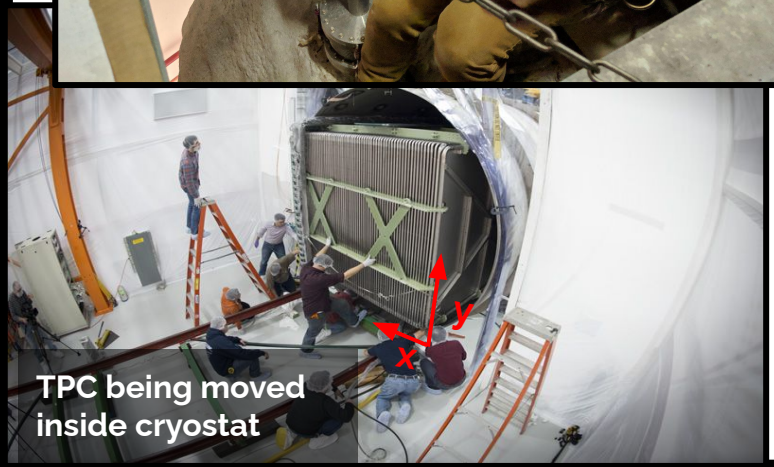
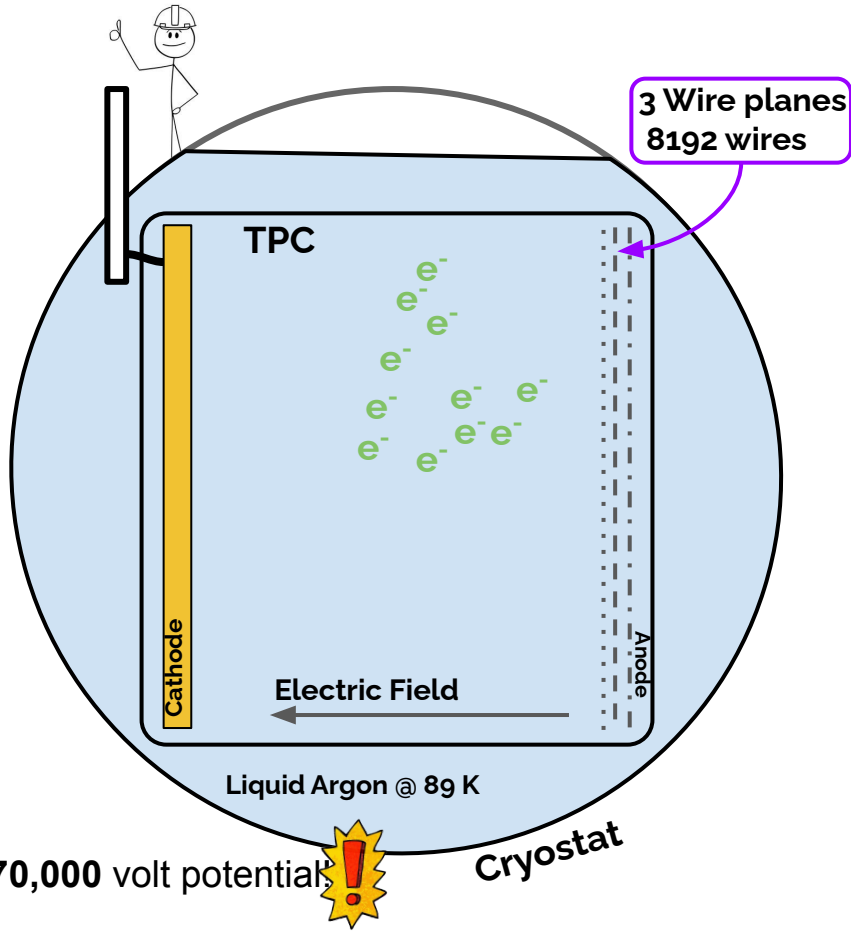


Enter MicroBooNE





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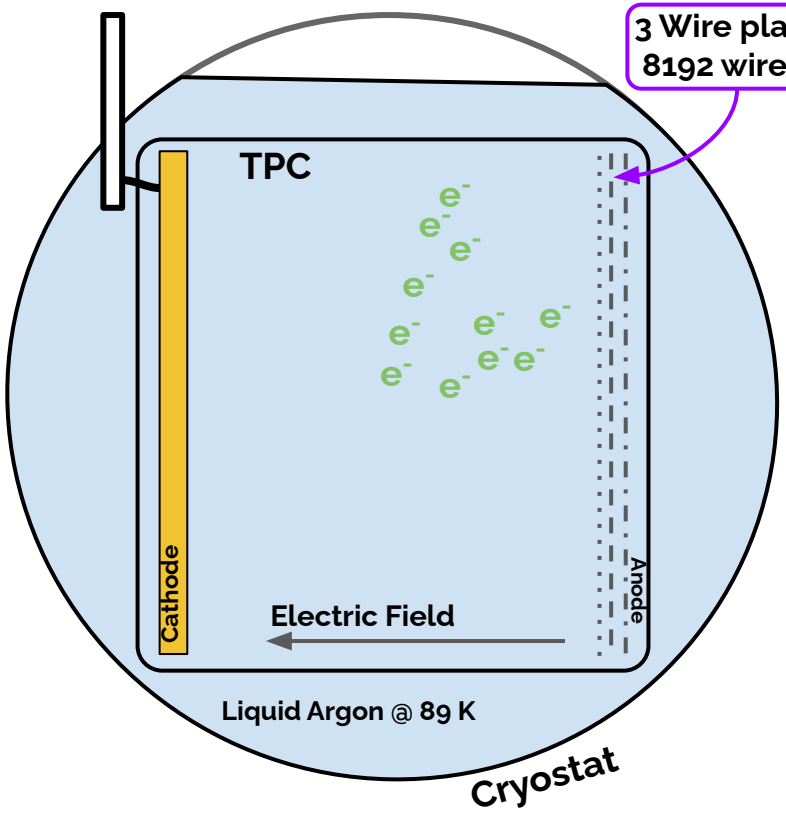

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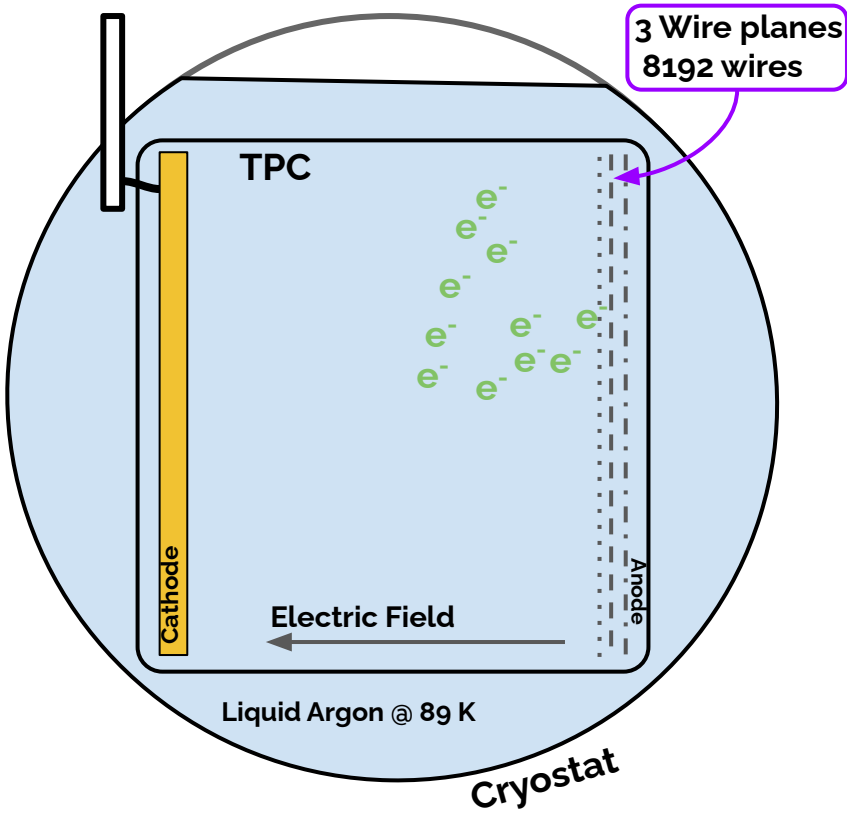

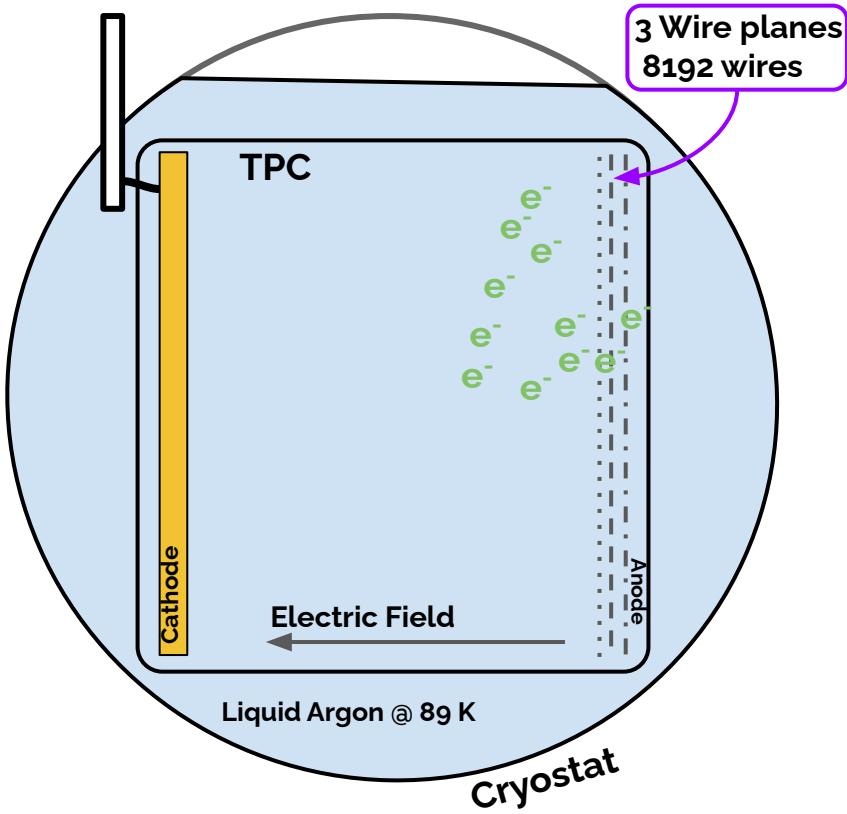

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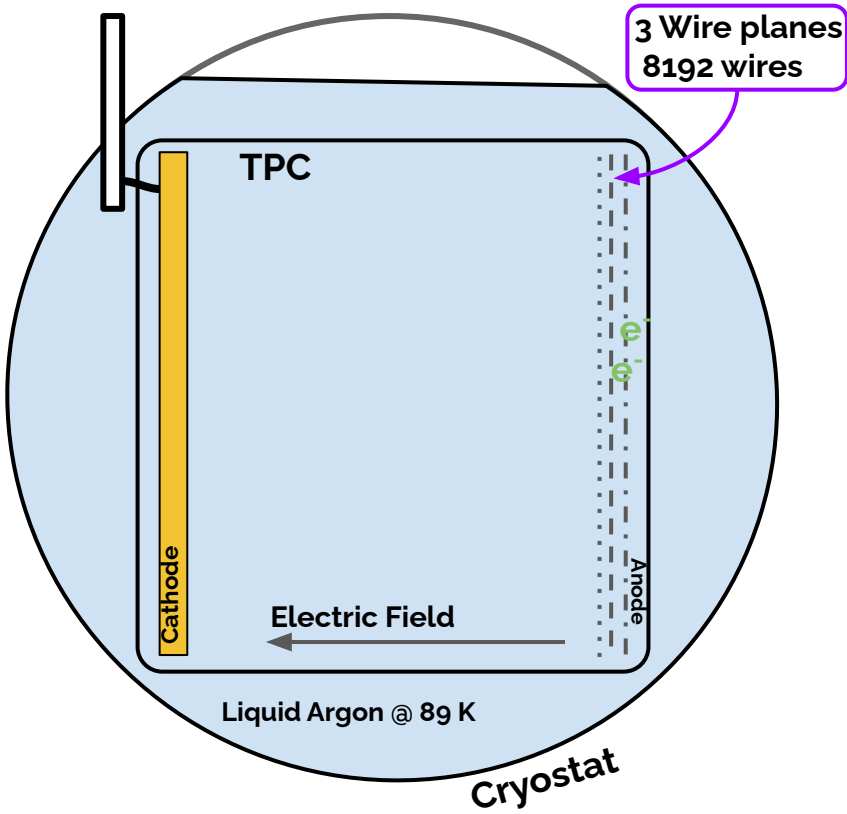

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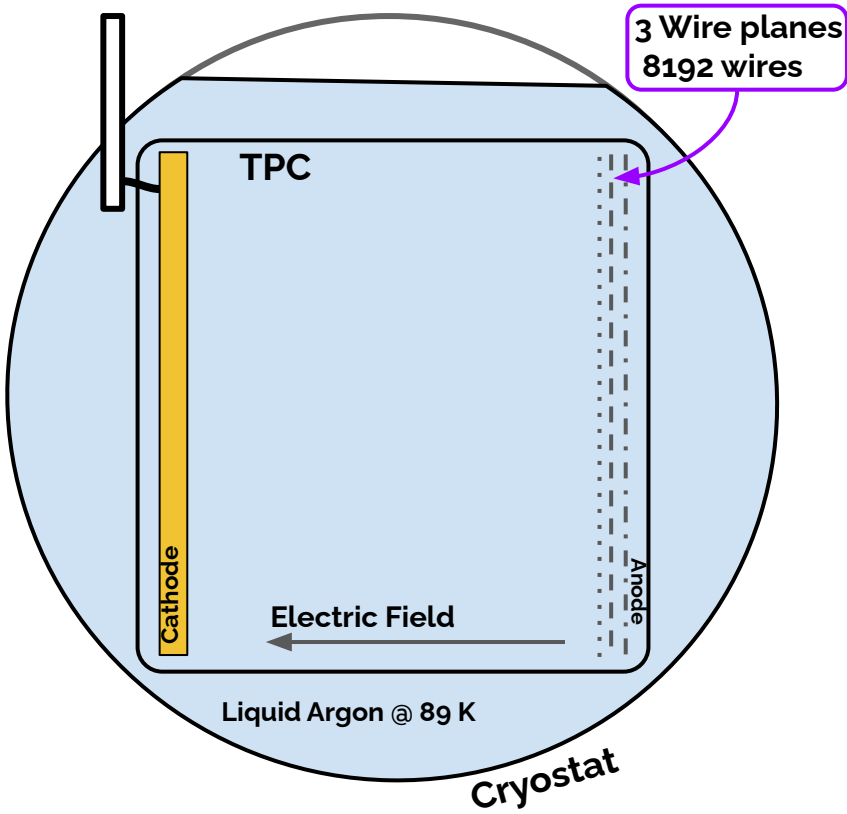
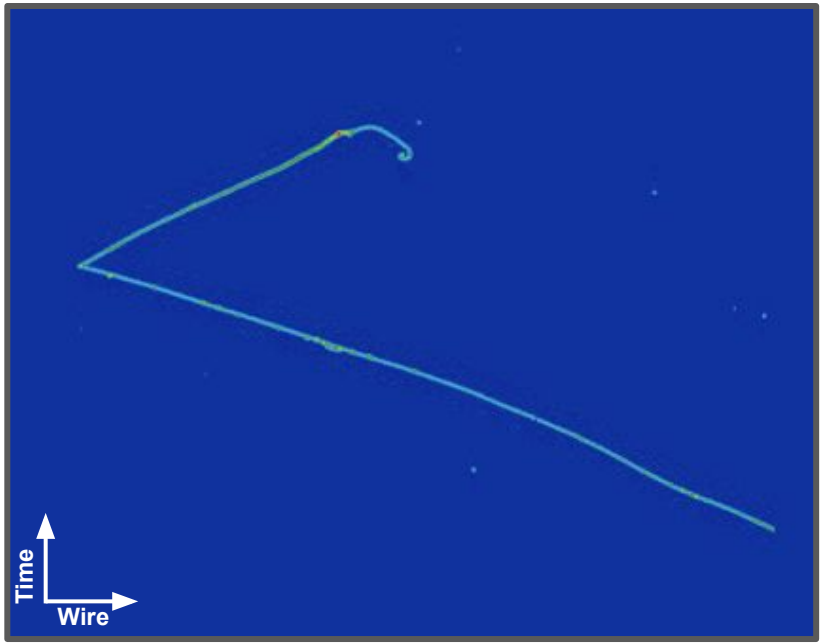
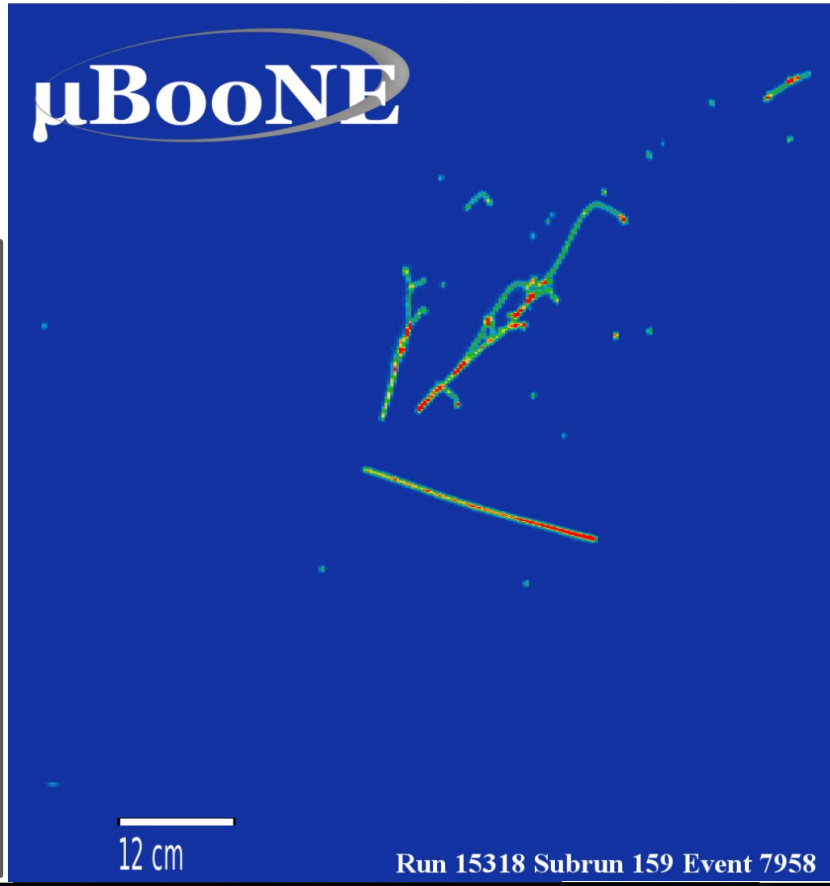


Beautiful, High Precision Neutrino Images

Like a **digital bubble chamber**, but with added calorimetry: The **color scale** shows the **amount of deposited charge**





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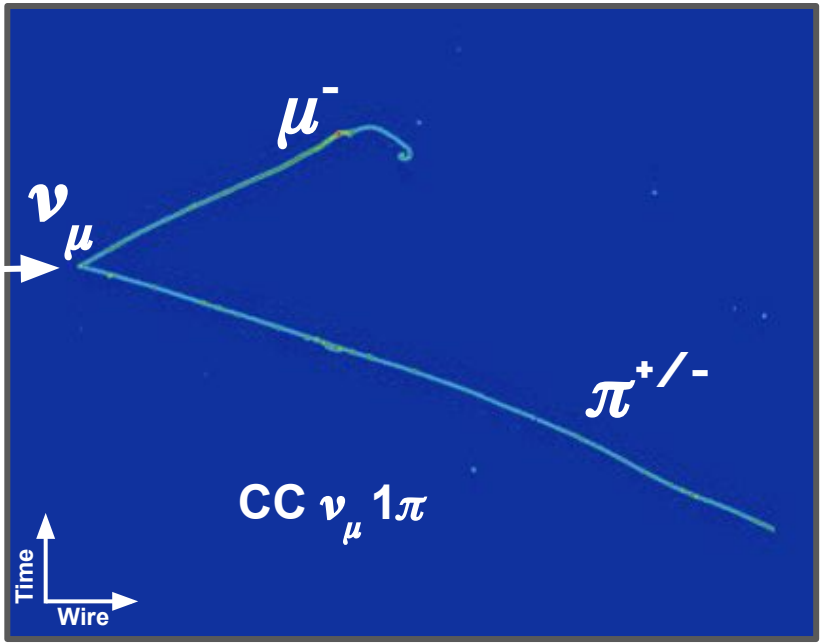
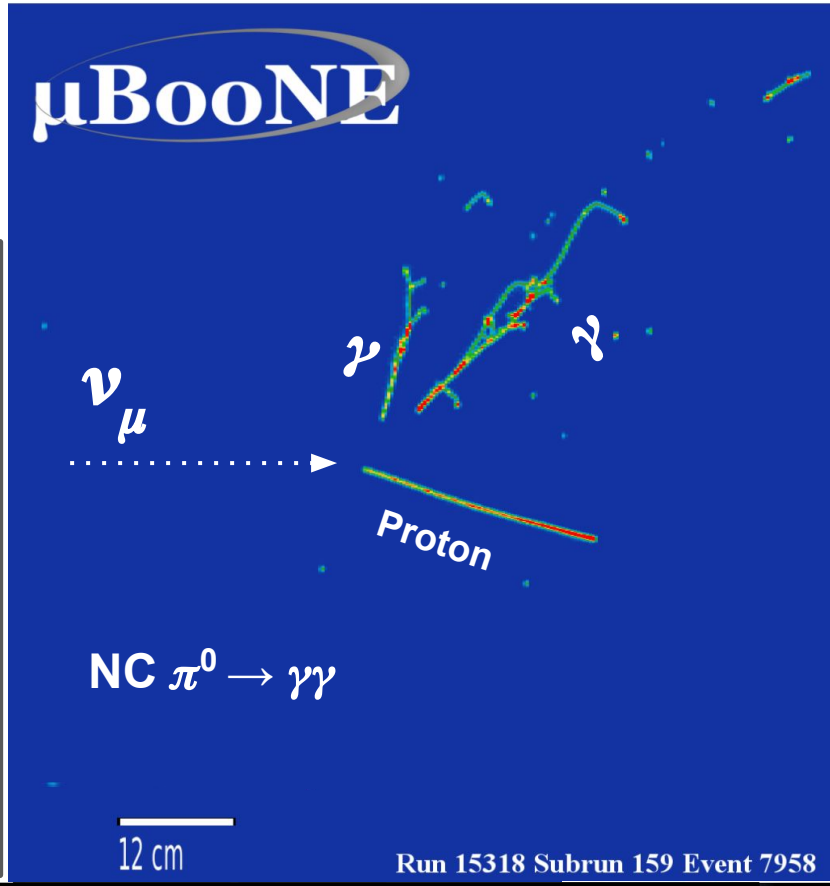
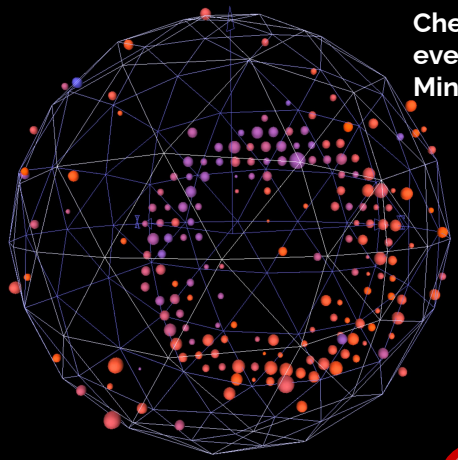




Electrons or Photons?



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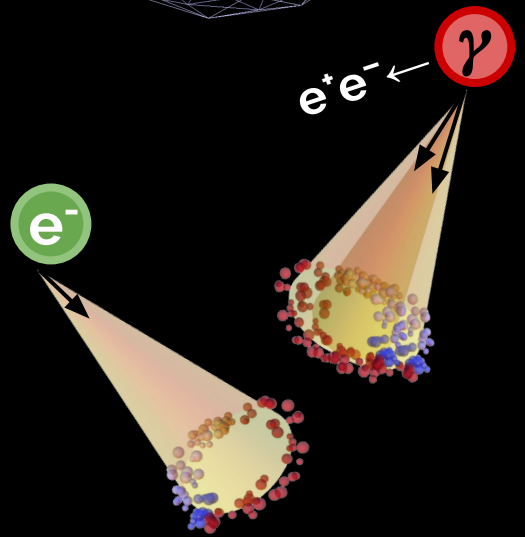

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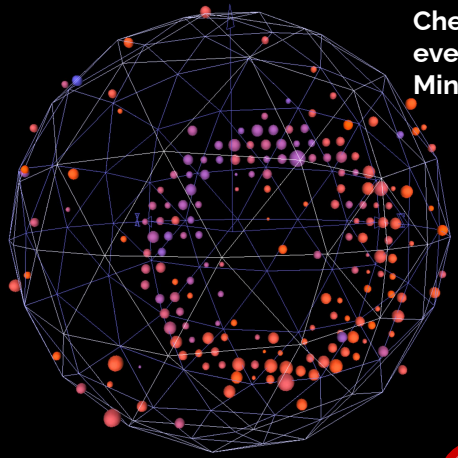

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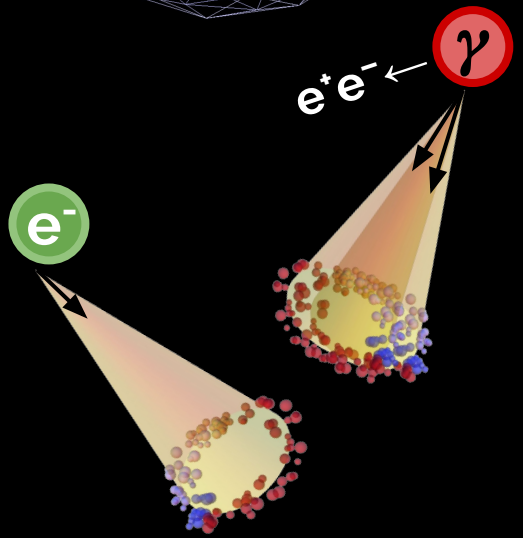
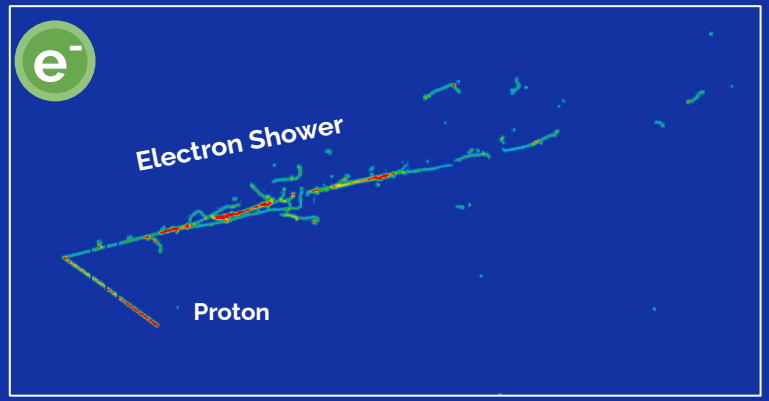
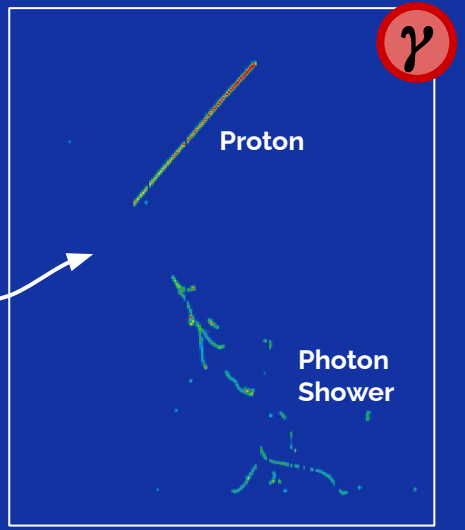


Electron + 1 proton event



Strong
photon ↔ electron
separation

Smoking gun
"gap"

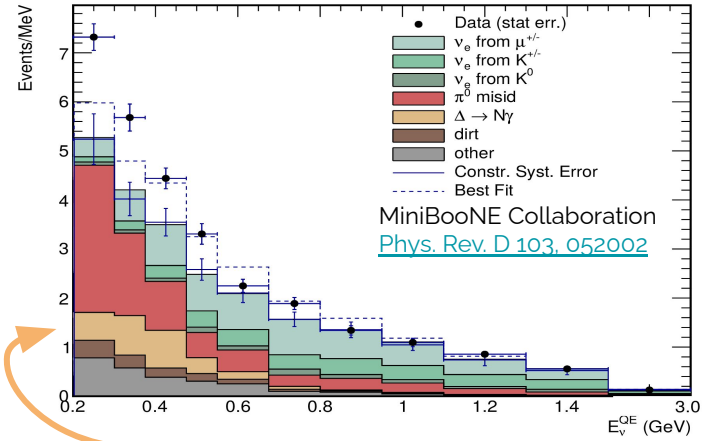


Photon + 1 proton event

MicroBooNE's first photon search

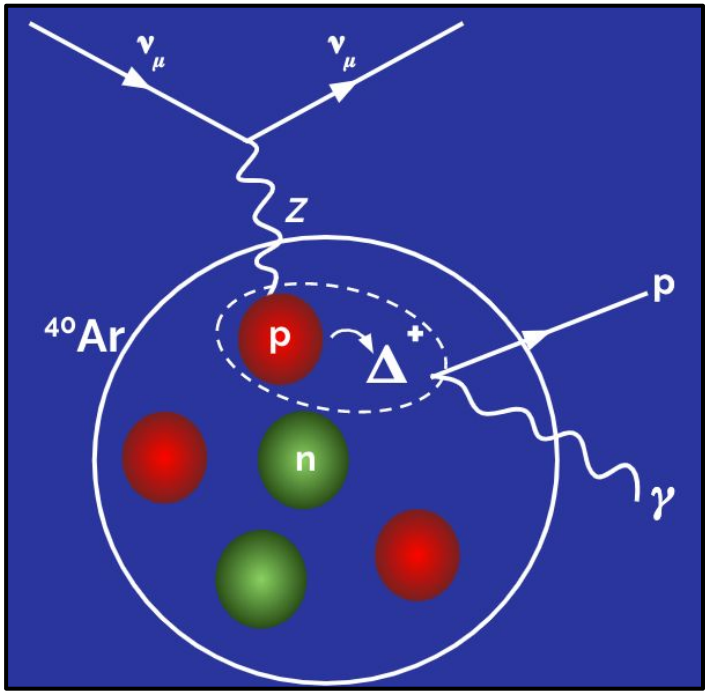
MicroBooNE's **primary aim** was to discover if the excess in MiniBooNE was **electrons** or **photons**.

First results focused on the extremely rare and unmeasured standard model process, **neutrino induced neutral current Δ radiative decay (NC Δ→Nγ)**

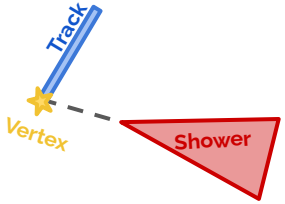


Only needs to be **~3.18 times higher than predicted** in order to **explain the MiniBooNE anomaly**

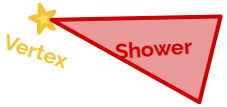
NC Δ→Nγ



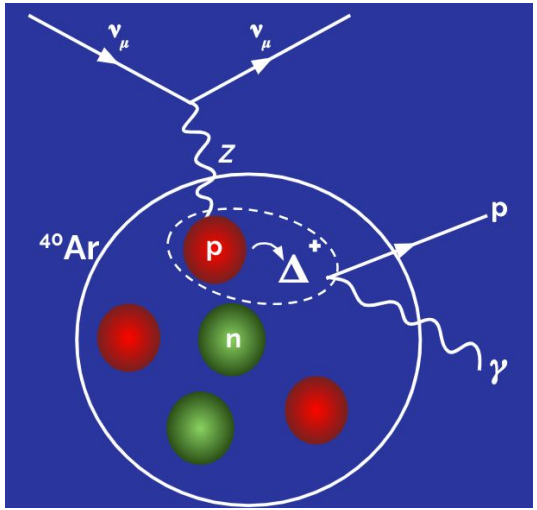
MicroBooNE's first photon search

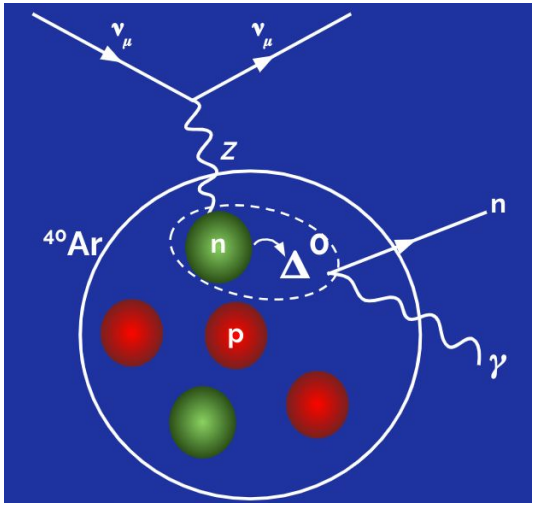


1γ1p

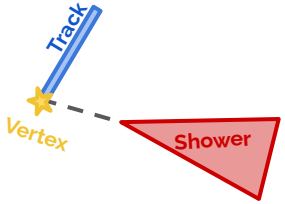


1γ0p

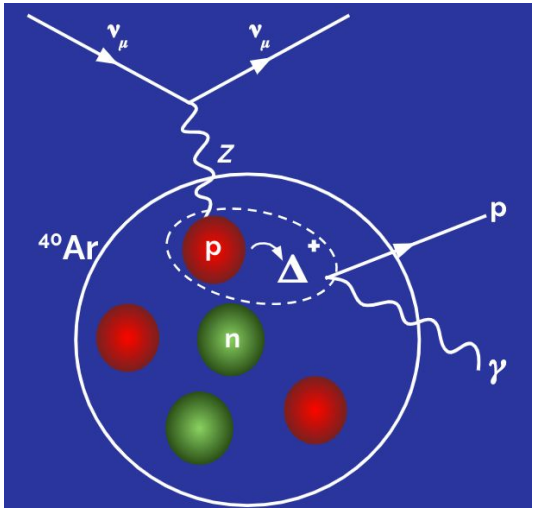




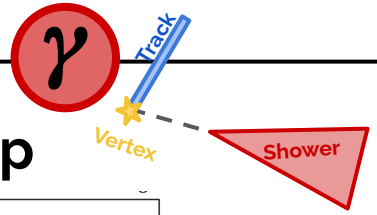
MicroBooNE's first photon search



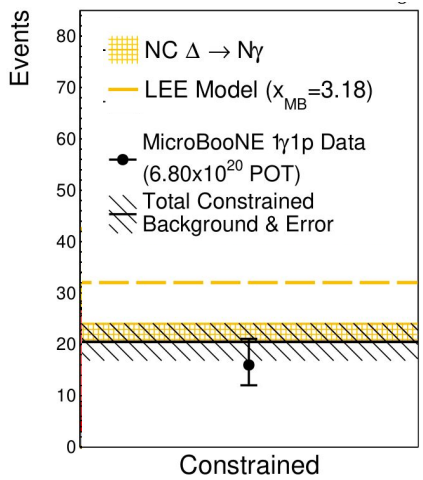
1γ1p



MicroBooNE's first photon search



1γ1p

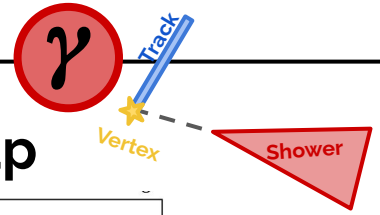


1γ1p	
Unconstr. bkgd.	27.0 ± 8.1
Constr. bkgd.	20.5 ± 3.6
NC $\Delta \rightarrow N\gamma$	+ 4.88
LEE ($x_{\mathrm{MB}} = 3.18$)	+ 15.5

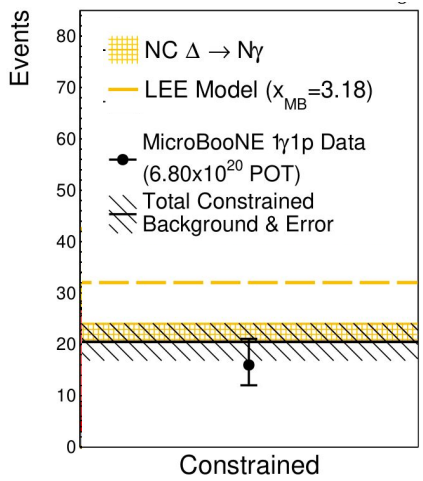
16
Data Events
Observed

MicroBooNE Phys.Rev.Lett. 128 (2022) 11, 111801

MicroBooNE's first photon search



1γ1p



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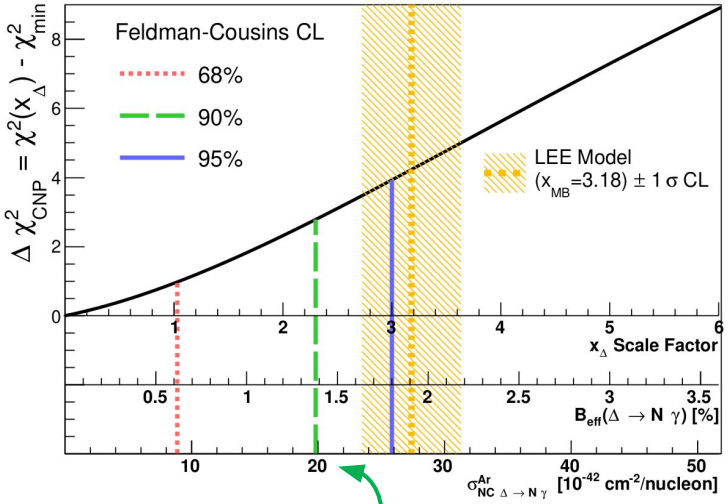
16
Data Events
Observed

- **No evidence** for an enhanced rate of single-photons from **NC Δ→Nγ decay**
- Disfavors NC Δ→Nγ backgrounds as a sole source of the MiniBooNE excess at **94.8% C.L**

MicroBooNE Phys.Rev.Lett. 128 (2022) 11, 111801

MicroBooNE's first photon search

MicroBooNE Phys.Rev.Lett. 128 (2022) 11, 111801



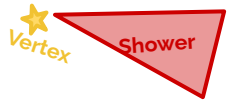
Resulting bound

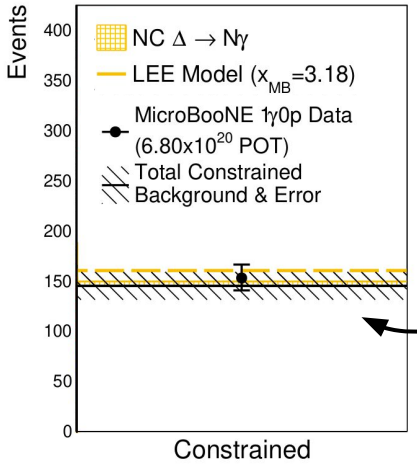
$$\sigma^{\mathrm{Ar}}_{\Delta\to N\gamma} < 19.8\times10^{-42}\ [\mathrm{cm}^{-2}/\mathrm{nucleon}],\ \text{at } 90\%\ \mathrm{CL}$$

- **No evidence** for an enhanced rate of single-photons from **NC $\Delta\to N\gamma$ decay**
- Disfavors NC $\Delta\to N\gamma$ backgrounds as a sole source of the MiniBooNE excess at **94.8% C.L**

MicroBooNE's first photon search

1γ0p

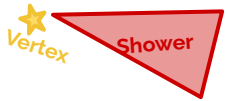


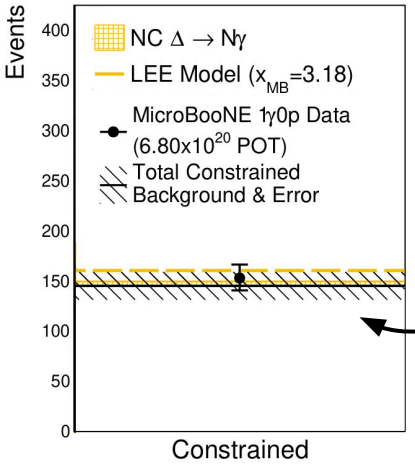


Very little sensitivity in the zero-proton sample

MicroBooNE's first photon search

1γ0p





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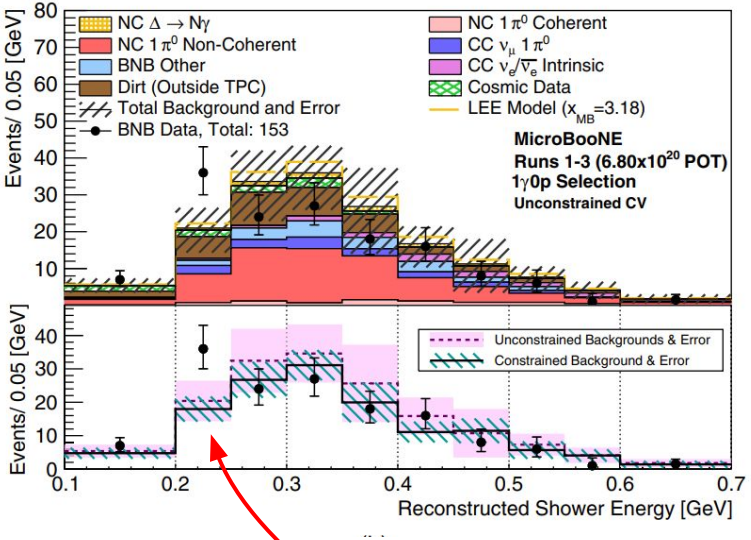
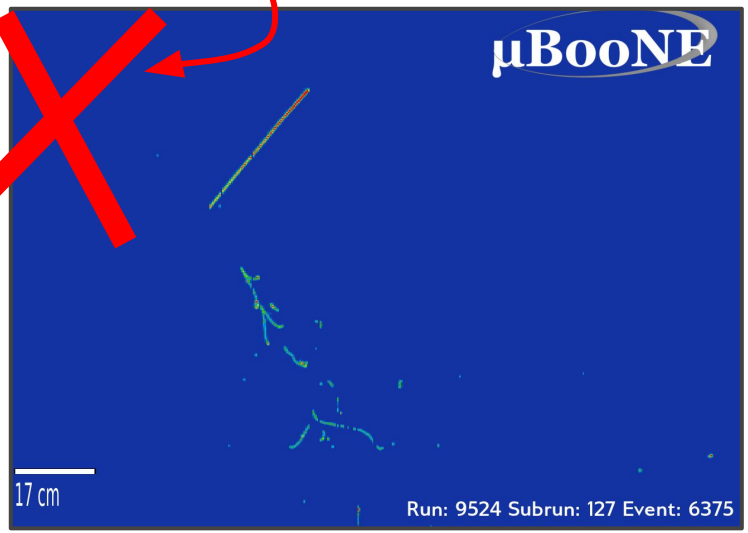


In fact mild (local 2.7σ) excess at lower energy in the **1γ0p** selection

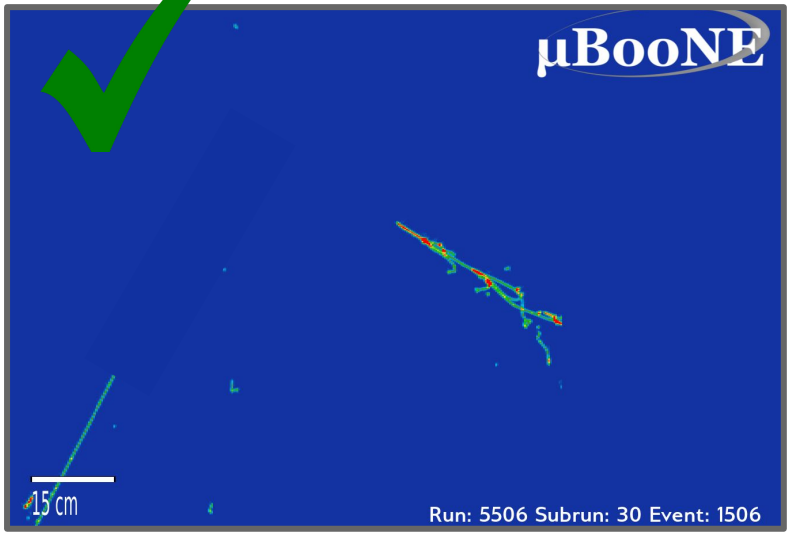
MicroBooNE's first photon search

1γ1p



Ruled out as MiniBooNE explanation!

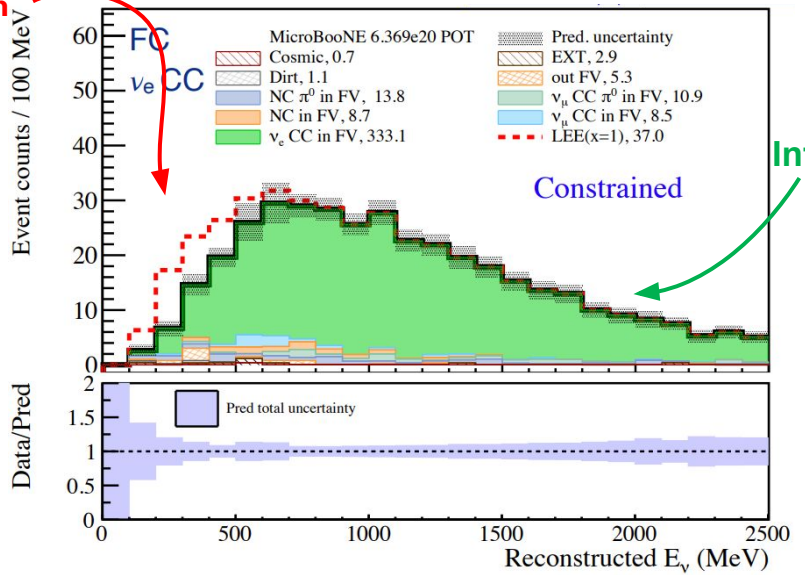
1γ0p



Still Allowed!

MicroBooNE's first electron search

What would be expected to see if MiniBooNE was solely due to increased ν_e in the beam



Intrinsic ν_e in the beam

MicroBooNE's first electron search

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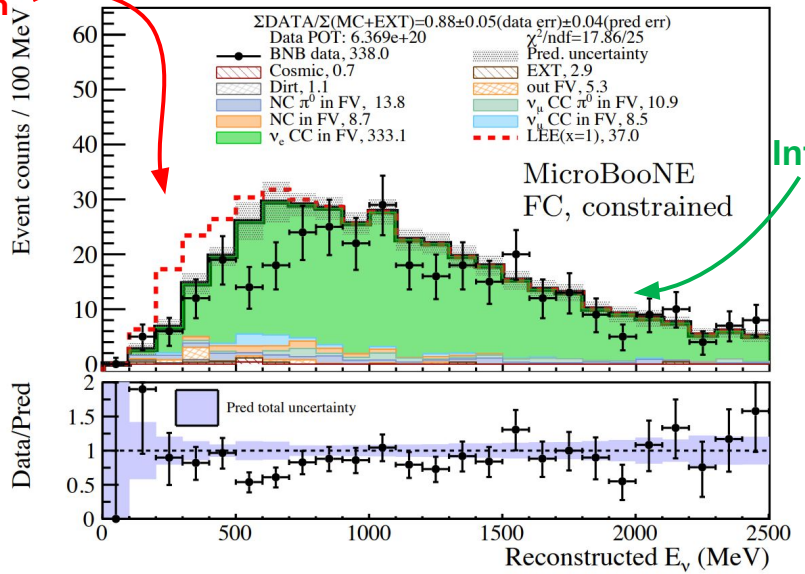

Intrinsic ν_e in the beam

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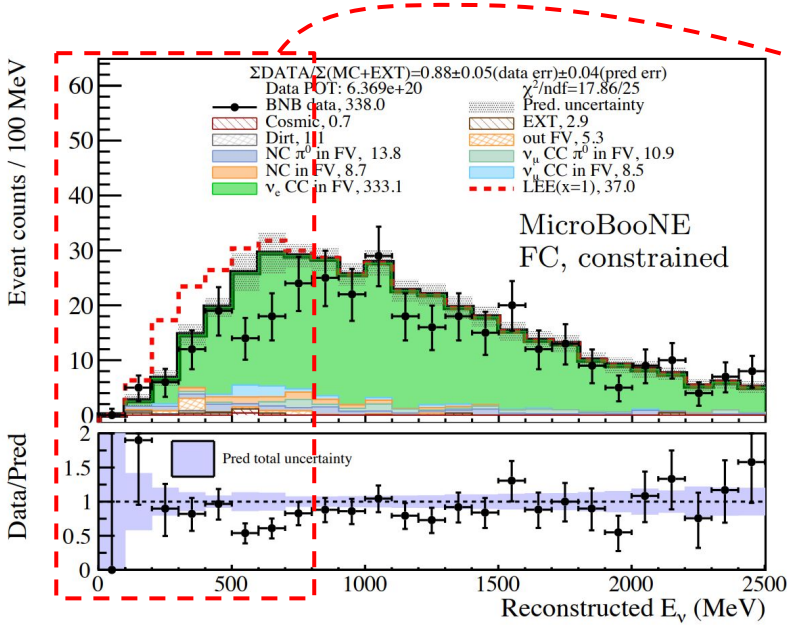
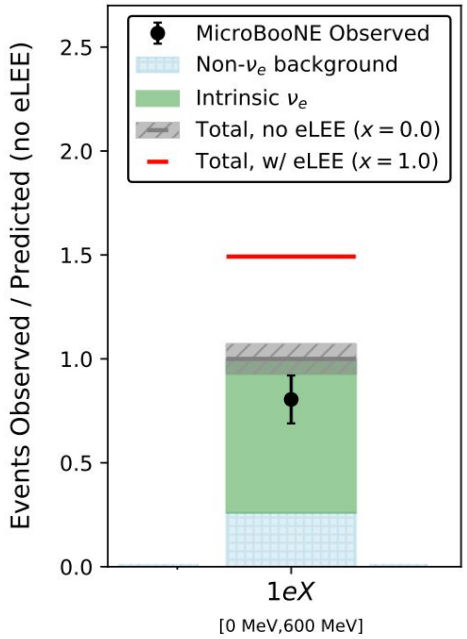


Electron excess of same scale as MiniBooNE is **rejected at > 95% CL**

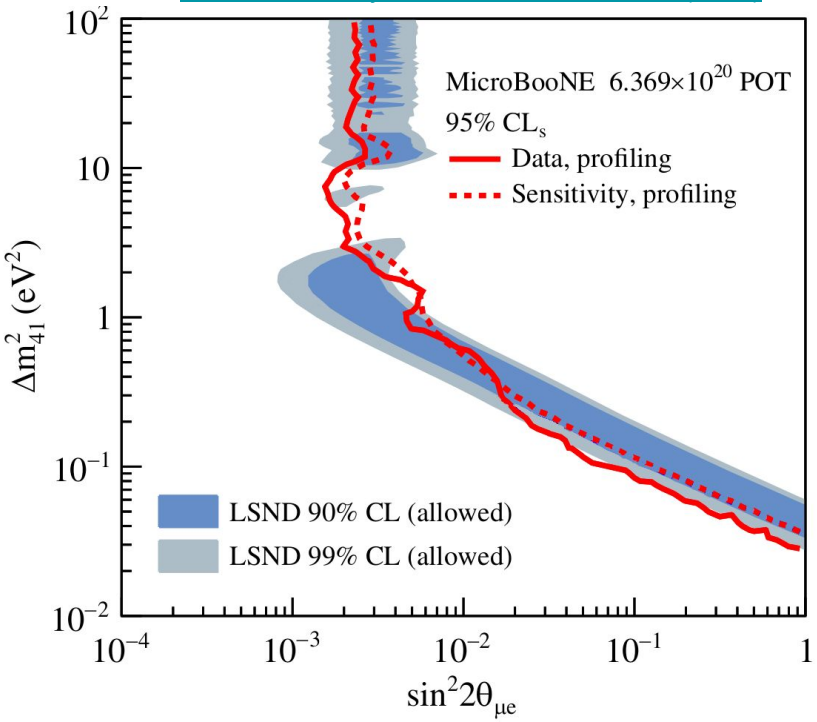
MicroBooNE PhysRevLett.128.241801



Overall mild deficit observed, not excess

MicroBooNE's sterile oscillation result

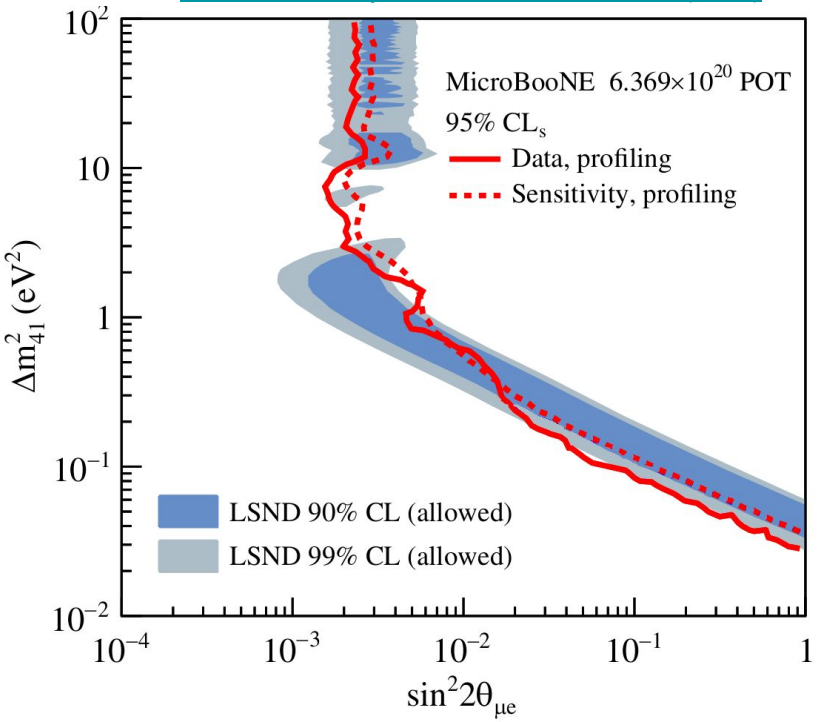
MicroBooNE Phys. Rev. Lett. 130, 011801 (2023)



Transform **CC inclusive ν_e** selection into a direct sterile neutrino search

MicroBooNE's sterile oscillation result

MicroBooNE Phys. Rev. Lett. 130, 011801 (2023)



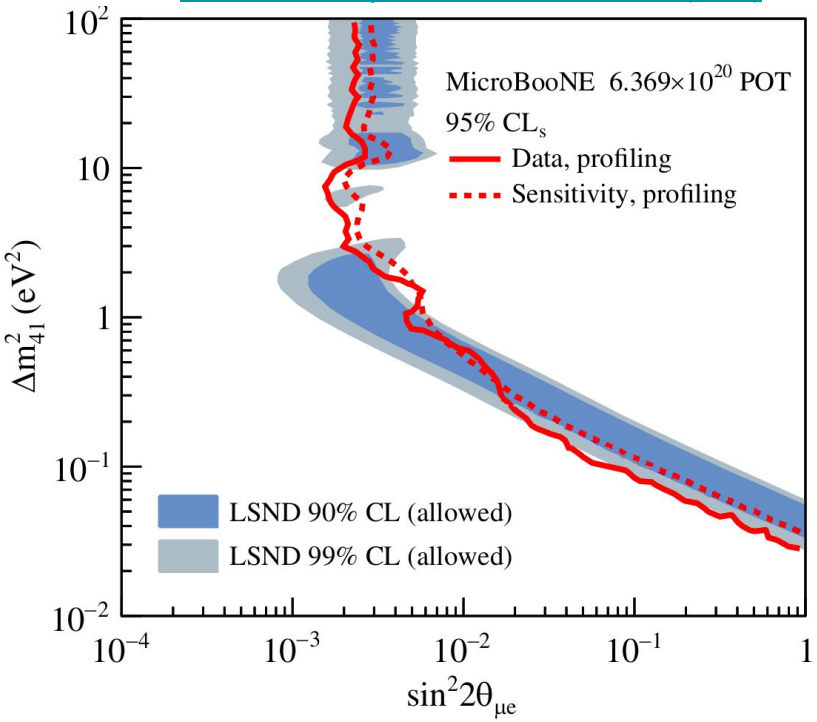
Transform **CC inclusive ν_e** selection into a direct sterile neutrino search

MicroBooNE sees no evidence of oscillations

However, the result is **not enough to fully rule out MiniBooNE and LSND** sterile explanations

MicroBooNE's sterile oscillation result

MicroBooNE Phys. Rev. Lett. 130, 011801 (2023)



"It appears that the sterile neutrino is not real."

Forbes

New Measurement Rules Out Sterile Neutrinos

Don Lincoln Contributor
I cover the physics of nothing, everything, and the stuff in between.

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Oct 27, 2021, 03:51pm EDT

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MicroBooNE's sterile oscillation result

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Science

Neutrino result heralds new chapter in physics

27 October 2021

"The search failed to find the particle, known as the sterile neutrino."

"It appears that the sterile neutrino is not real."

Forbes

New Measurement Rules Out Sterile Neutrinos

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MicroBooNE's sterile oscillation result

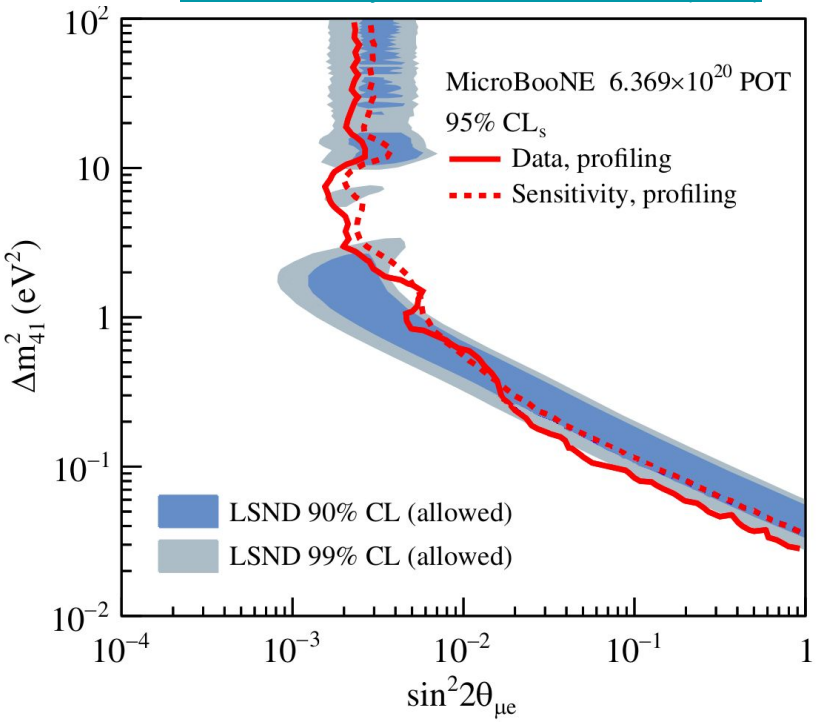
~~*"The search failed to find the particle, known as the sterile neutrino."*~~

"The search succeeded in not finding the sterile neutrino"

"It appears that the sterile neutrino is not real."

MicroBooNE's sterile oscillation result

MicroBooNE Phys. Rev. Lett. 130, 011801 (2023)



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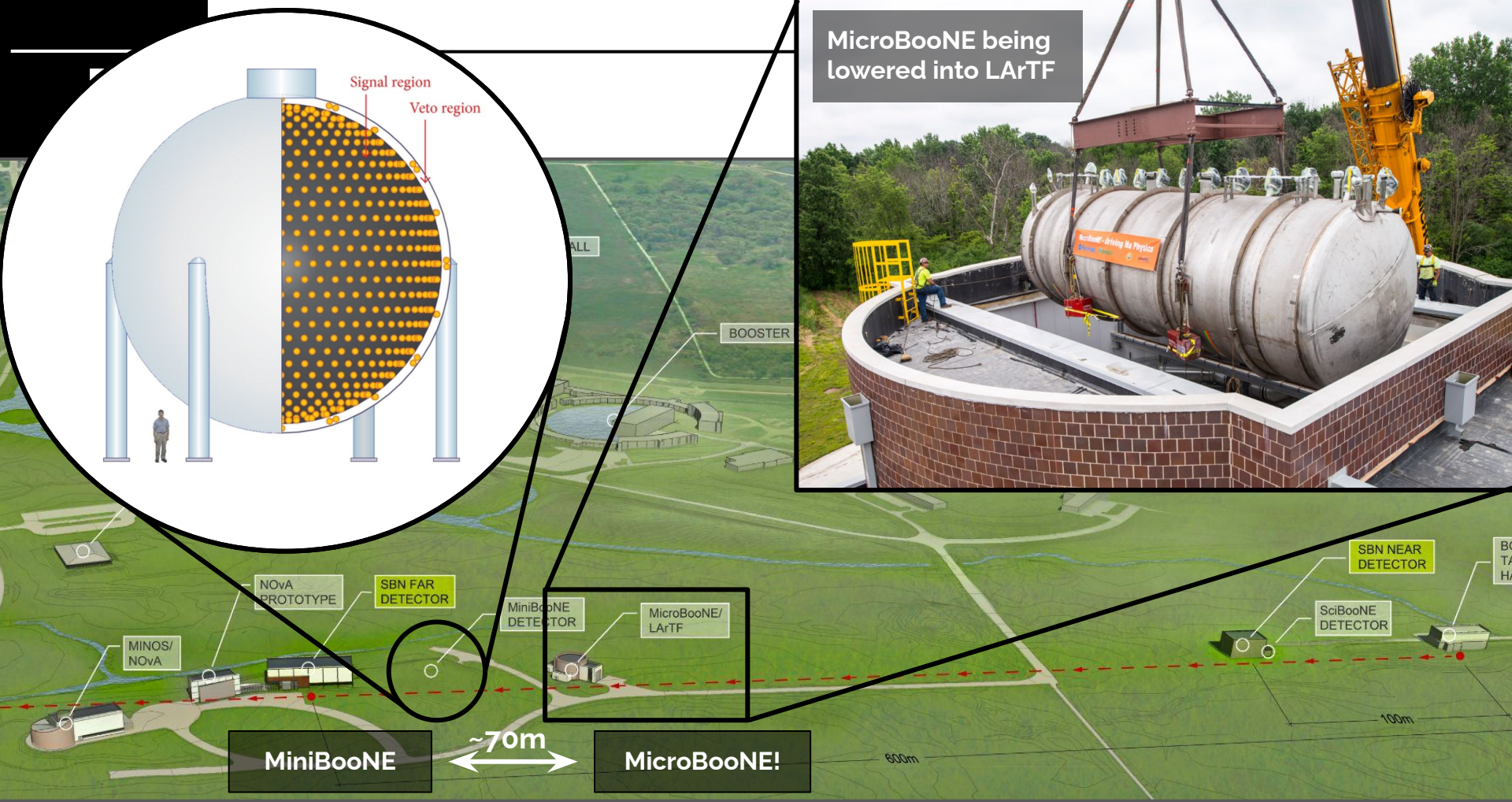
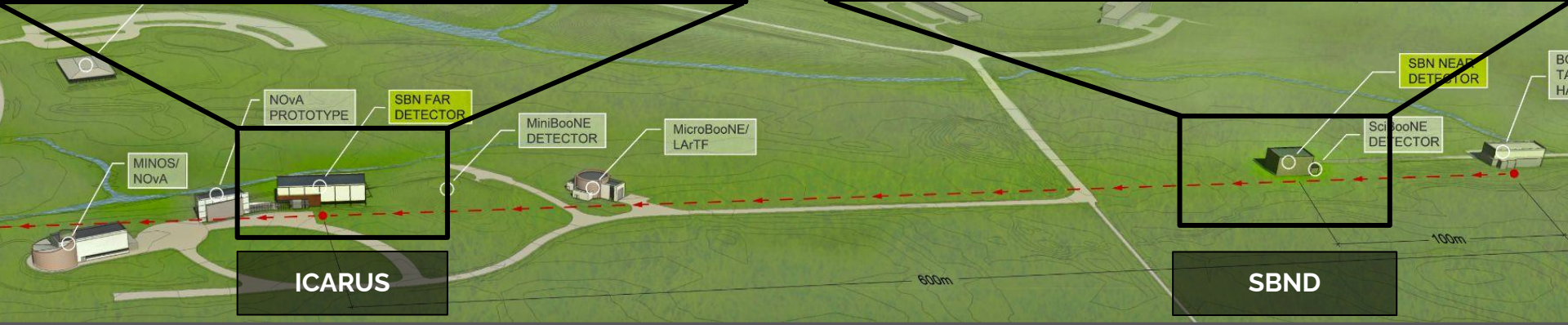
4. The SBN Programme

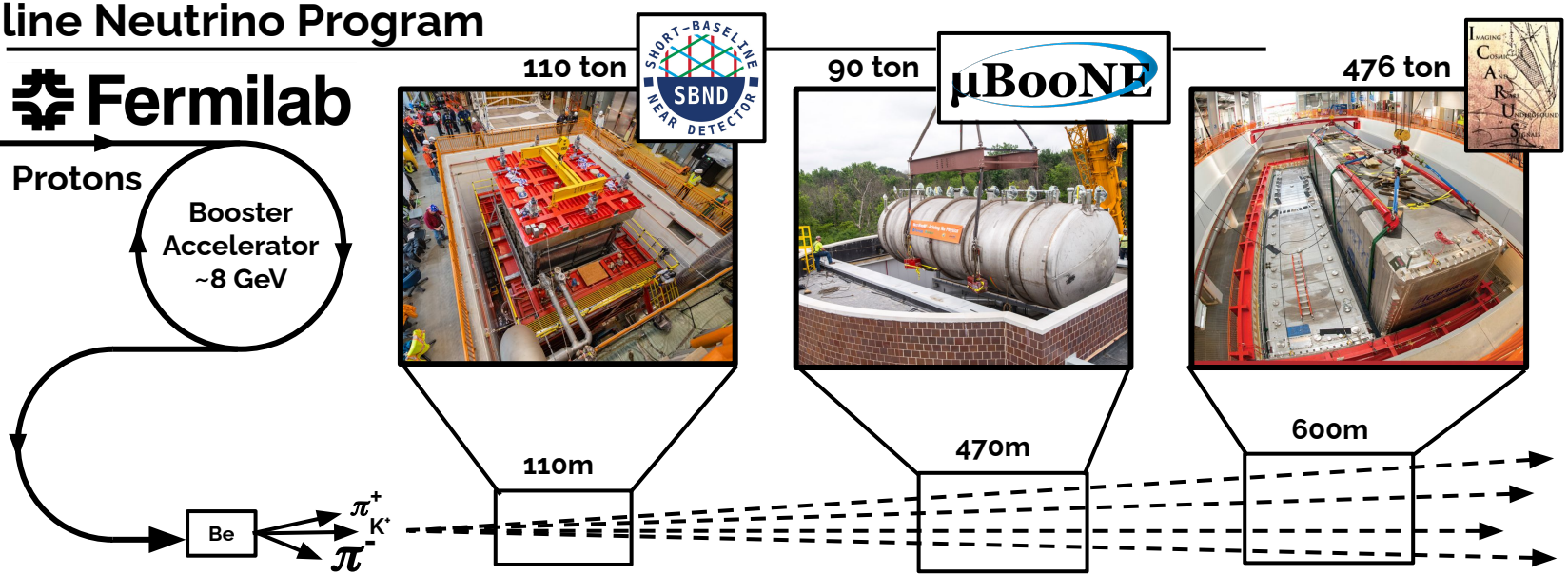

Signal region
Veto region
MicroBooNE being lowered into LArTF
BOOSTER
NOvA PROTOTYPE
SBN FAR DETECTOR
MiniBooNE DETECTOR
MicroBooNE/ LArTF
MINOS/ NOvA
SBN NEAR DETECTOR
SciBooNE DETECTOR
100m
600m
MiniBooNE
~70m
MicroBooNE!

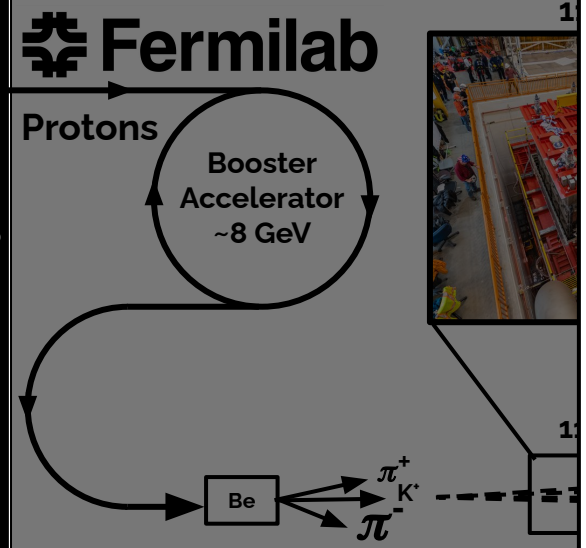
ICARUS TPC's being Installed at Fermilab

The SBND TPC being installed

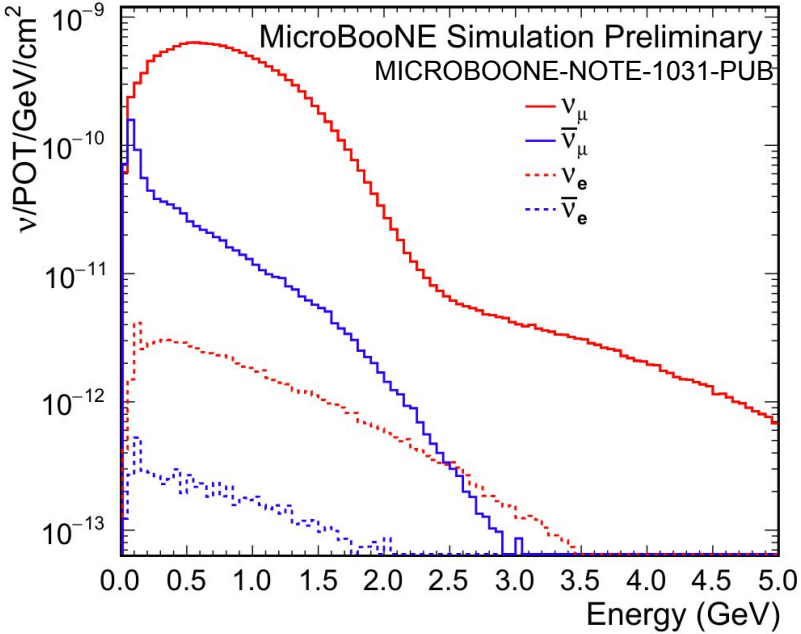


Short-Baseline Neutrino Program





Booster Neutrino Beam Flux at MicroBooNE

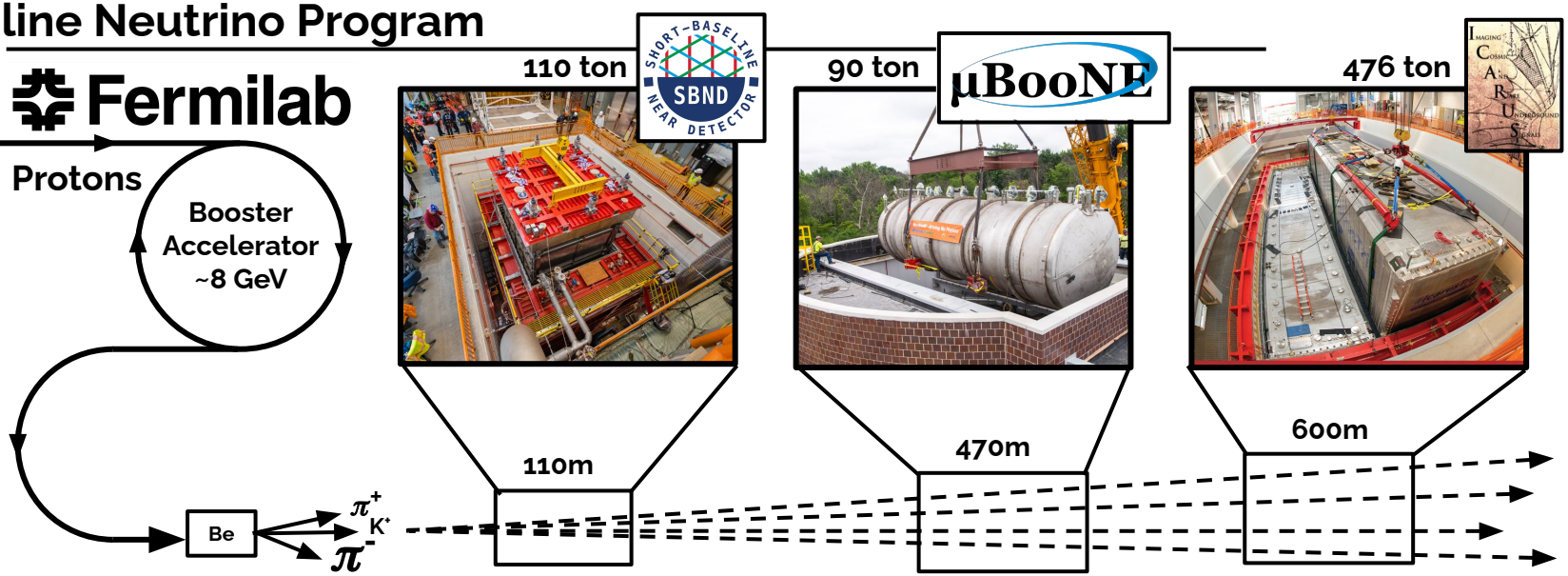


99.5% ν_μ & anti-ν_μ

0.5% ν_e & anti-ν_e

Mean Energy ~**800 MeV**

Short-Baseline Neutrino Program



Short-Baseline Neutrino Program

Fermilab

Protons

Booster Accelerator ~8 GeV

Main Injector ~120 GeV Protons

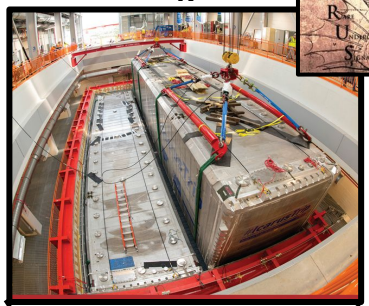
Be

π^+ K^+ π^-

110 ton

90 ton

476 ton



110m

470m

600m

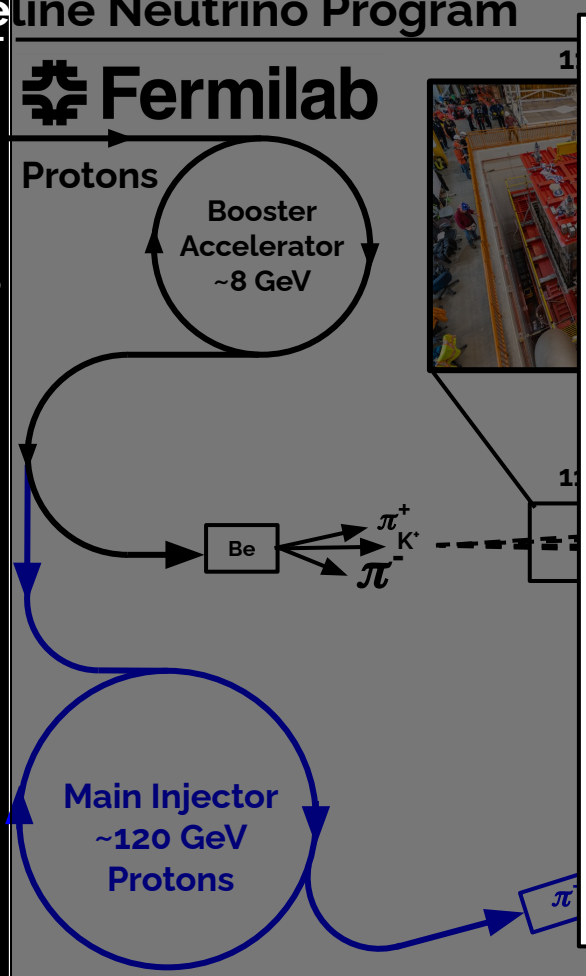
NuMI @ MicroBooNE
8.0° off-axis
680m

NuMI @ ICARUS
5.7° off-axis
800m

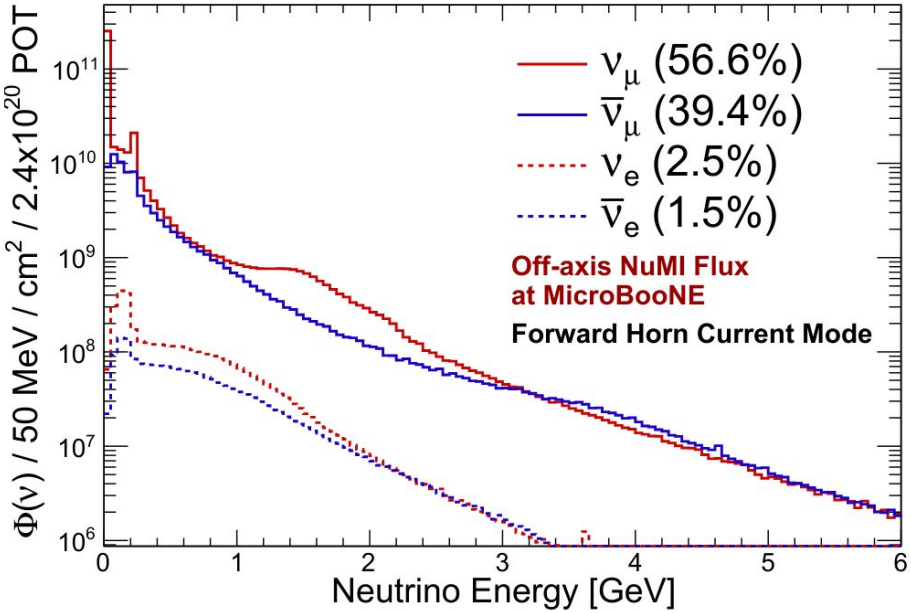
π^+ K^+ π^-

NuMI Beam

SBN Program:
3 LArTPC detectors sitting in 2 neutrino beams



NuMI Beam Flux off-axis at MicroBooNE



Extremely peaked at low energy

MicroBooNE, https://arxiv.org/pdf/2101.04228

Fermilab

Protons

Booster Accelerator ~8 GeV

Be

π^+ K^+ π^-

90 ton

μBooNE

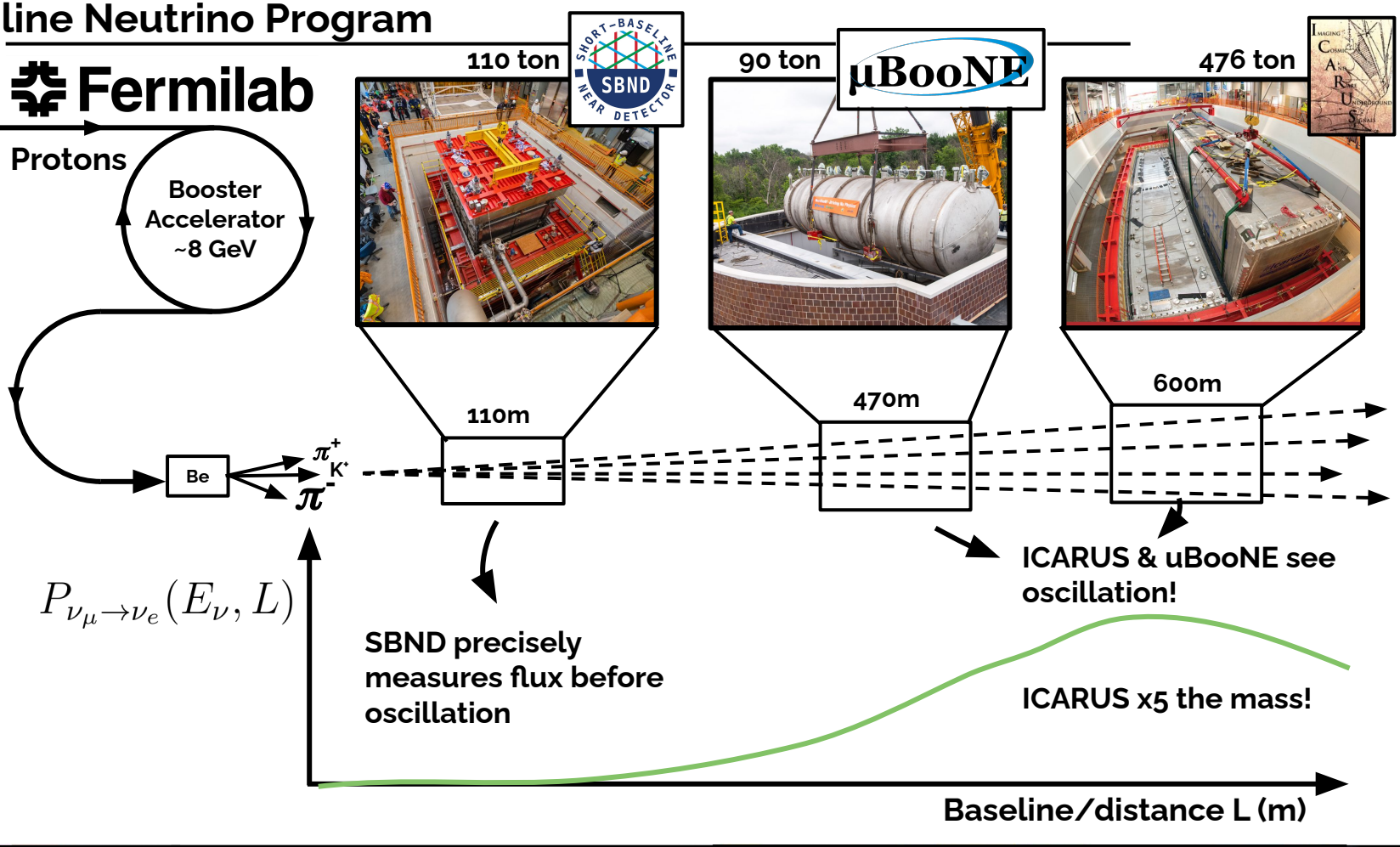
470m

uBooNE looks for oscillation

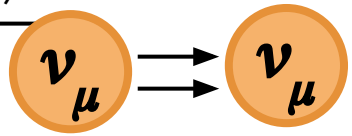
$P_{\nu_\mu \to \nu_e}(E_\nu, L)$

Baseline/distance L (m)

Short-Baseline Neutrino Program

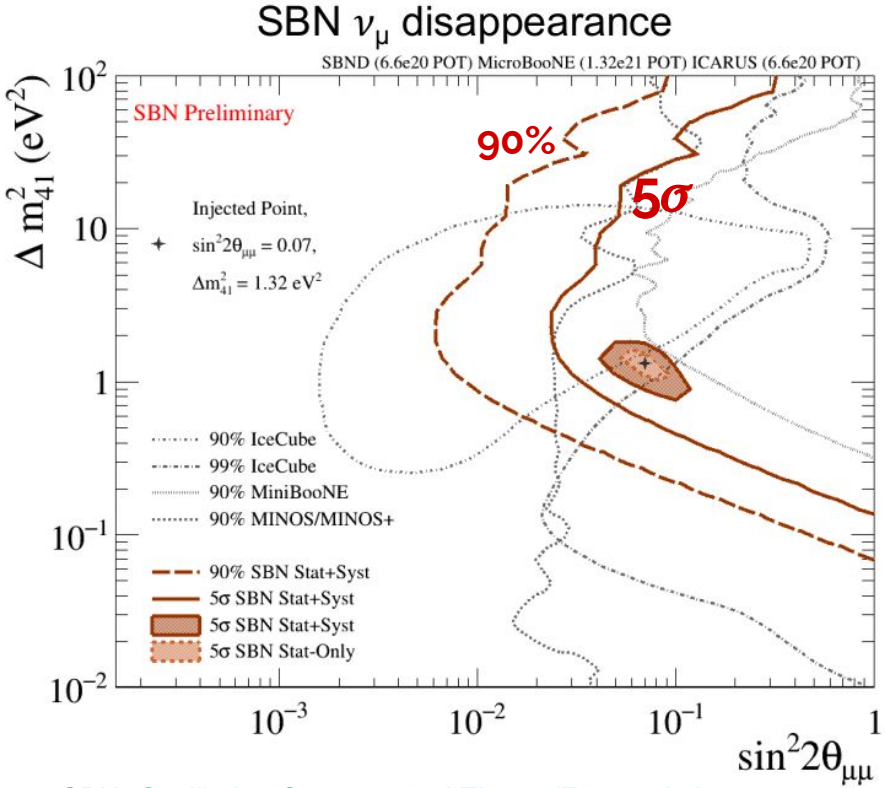


Muon Neutrino Disappearance Sensitivities (BNB only)



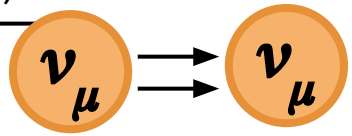
SBND will observe over **5 million charged current ν_μ** events

Extremely strong sensitivity to steriles in mass region favourable to LSND and MiniBooNE



SBN: Oscillation Strategy, 2nd Theory/Exp workshop

Muon Neutrino Disappearance Sensitivities (BNB only)



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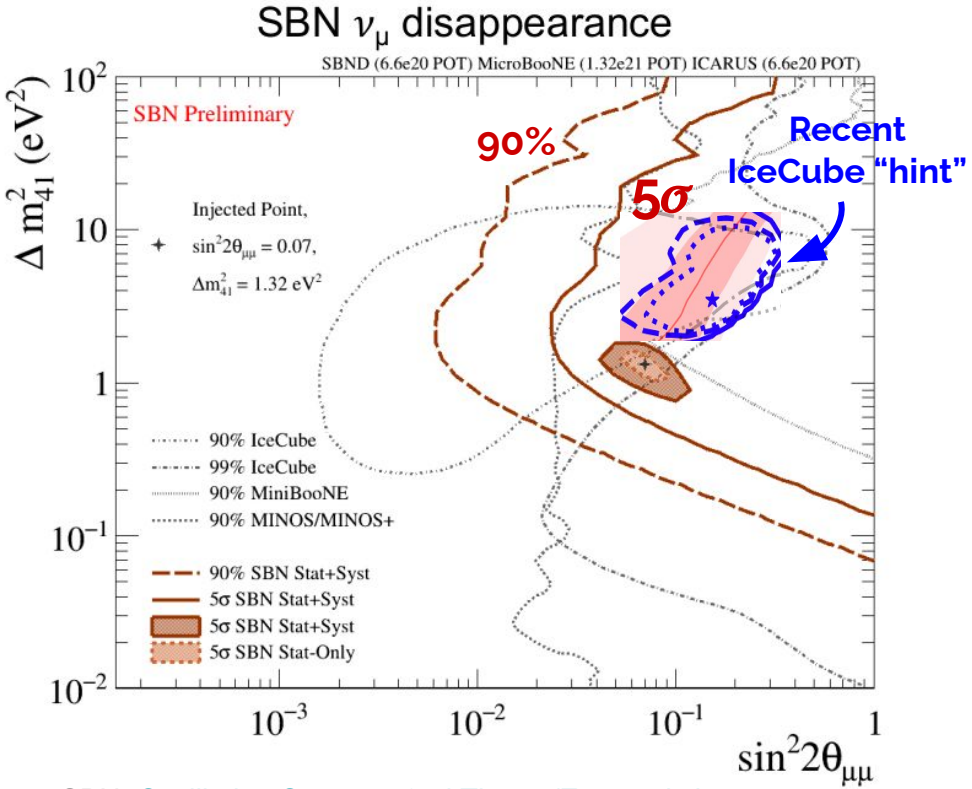
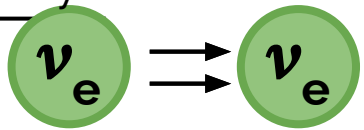


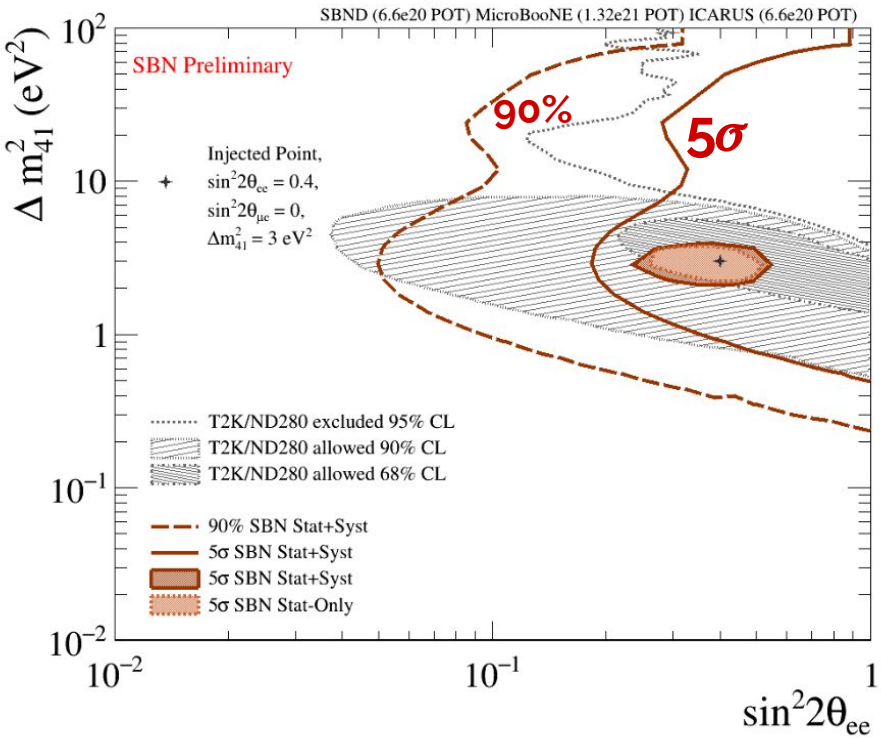
SBN: Oscillation Strategy, 2nd Theory/Exp workshop

Electron Neutrino Disappearance Sensitivities (BNB only)



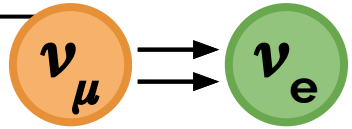
- SBND will also see over **35,000 intrinsic ν_e** in 6.6e20 POT.
- Allows for a direct accelerator based ν_e disappearance search, **complementary to both reactor and radioactive source ν_e disappearance experiments**
- **ICARUS will also see many intrinsic intrinsic ν_e from NuMI** and will be able to perform a stand alone search quickly!

SBN ν_e disappearance only



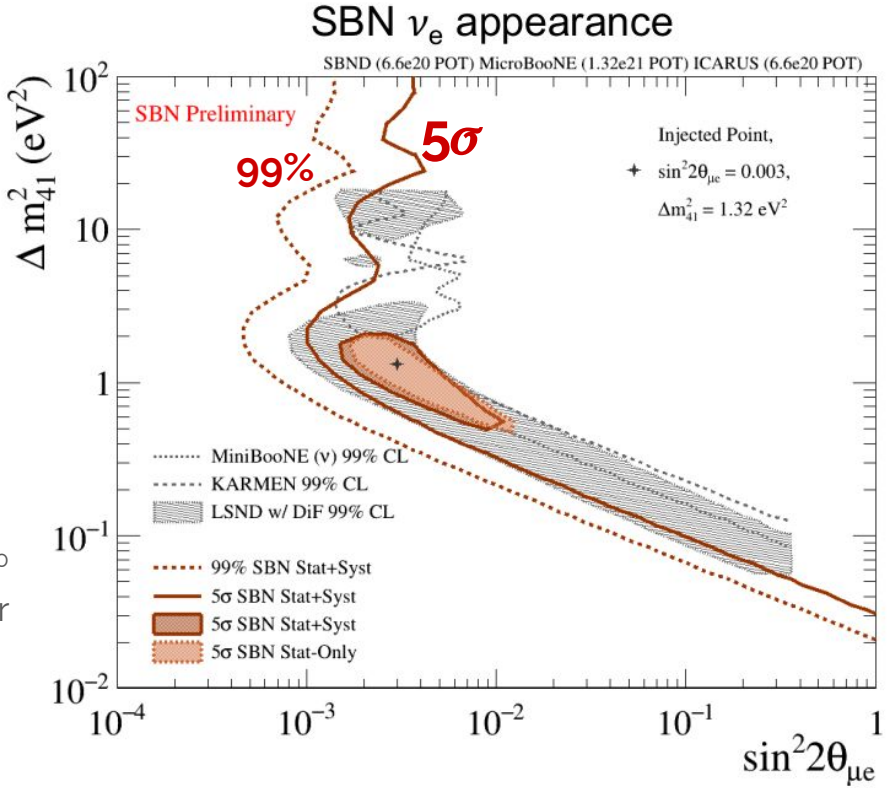
SBN: Oscillation Strategy, 2nd Theory/Exp workshop

Electron Neutrino Appearance Sensitivities (BNB only)



SBN will be able to cover:

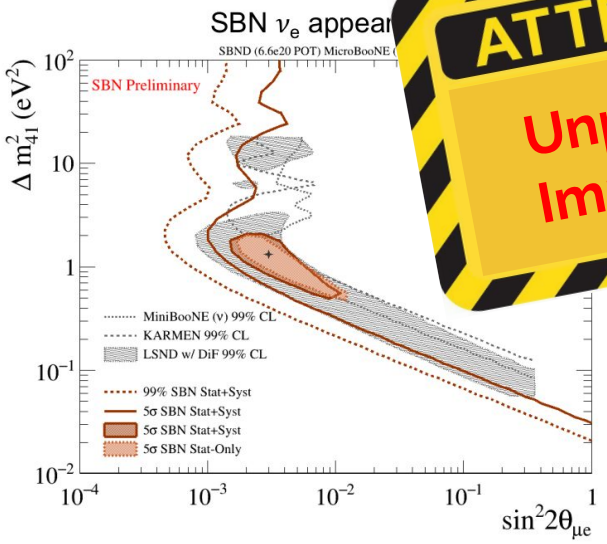
- Entire LSND and MiniBooNE anomalous regions at **>99% CL**
- **Best Fits being covered at >5σ**



These were calculated assuming 6.6x10^{20} POT for ICARUS, but current estimates for running until 2027 means **ICARUS may have close to x3 this amount**

SBN: Oscillation Strategy, 2nd Theory/Exp workshop

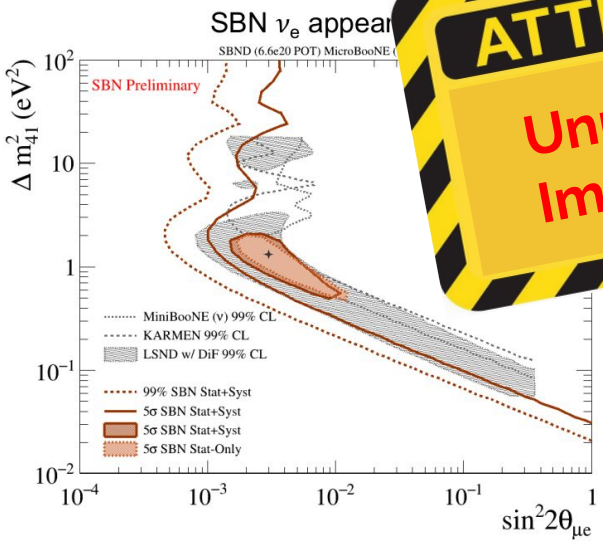
Unphysical!



Cannot have **appearance-only** without associated **disappearance**!

$$P(\nu_\mu \to \nu_e) \simeq 4\,|U_{\mu 4}|^2\,|U_{e4}|^2 \sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right) \neq 0$$

Unphysical!



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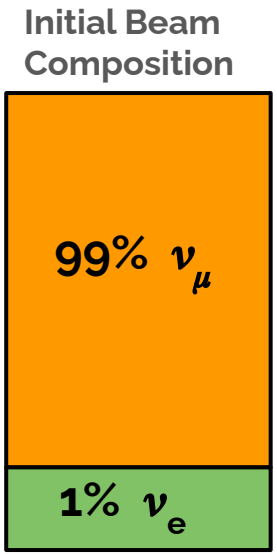
$$P(\nu_\mu \to \nu_e) \simeq 4|U_{\mu 4}|^2|U_{e4}|^2 \sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right) \neq 0$$

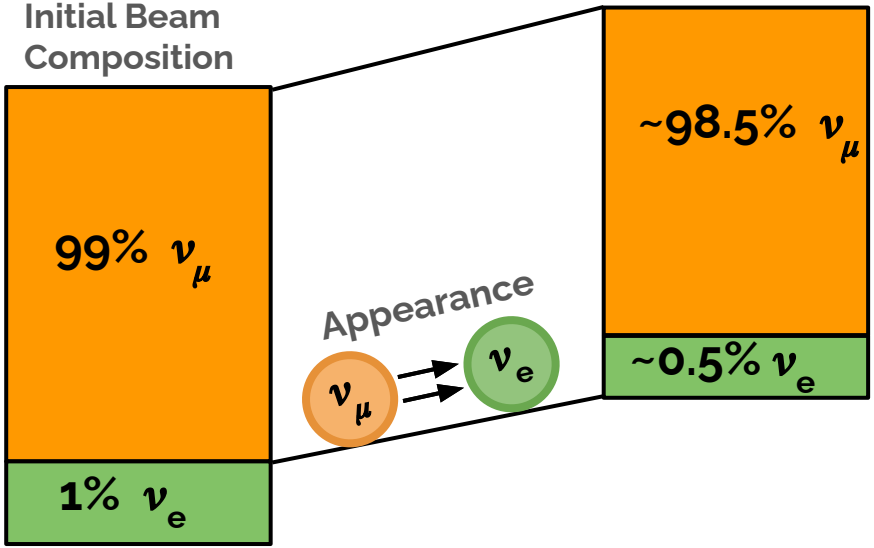
$$\neq 0 \quad \neq 0$$

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4|U_{\mu 4}|^2\left(1 - |U_{\mu 4}|^2\right) \sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right) \neq 0$$

$$P(\nu_e \to \nu_e) \simeq= 1 - 4|U_{e4}|^2\left(1 - |U_{e4}|^2\right) \sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right) \neq 0$$

Degeneracy between appearance and disappearance in a true 3+1 scenario





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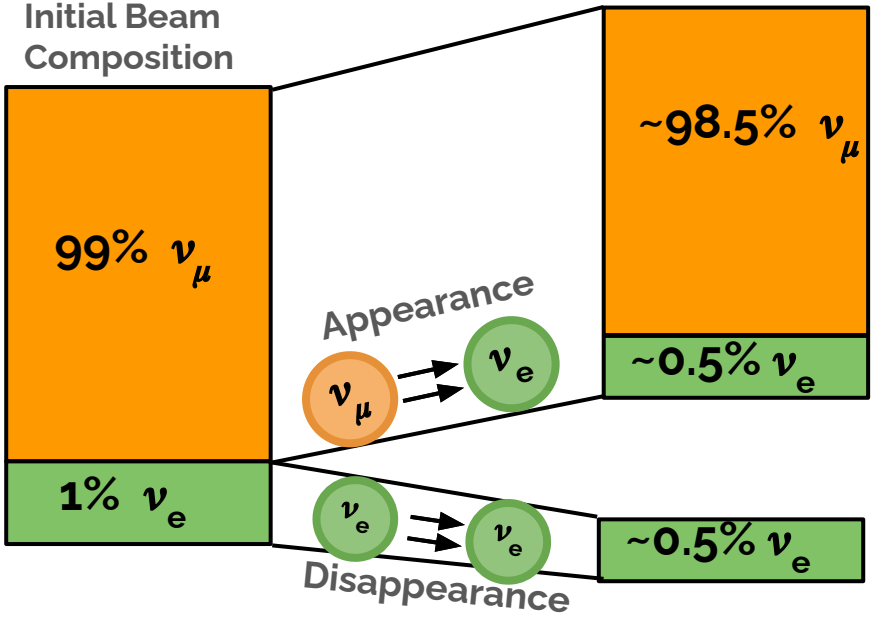
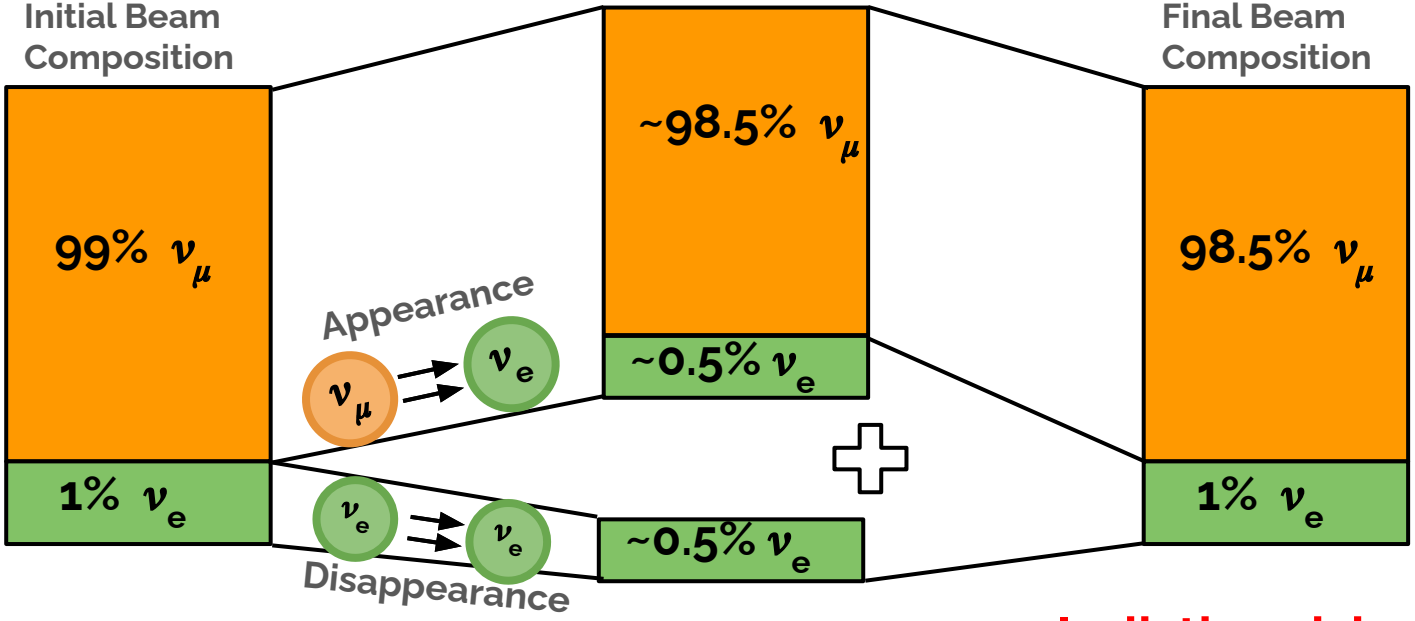


$$P(\nu_\mu \to \nu_e) \simeq 4\,|U_{\mu 4}|^2\,|U_{e4}|^2 \sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right)$$

$$P(\nu_e \to \nu_e) \simeq= 1 - 4\,|U_{e4}|^2\left(1 - |U_{e4}|^2\right) \sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right)$$



Indistinguishable!

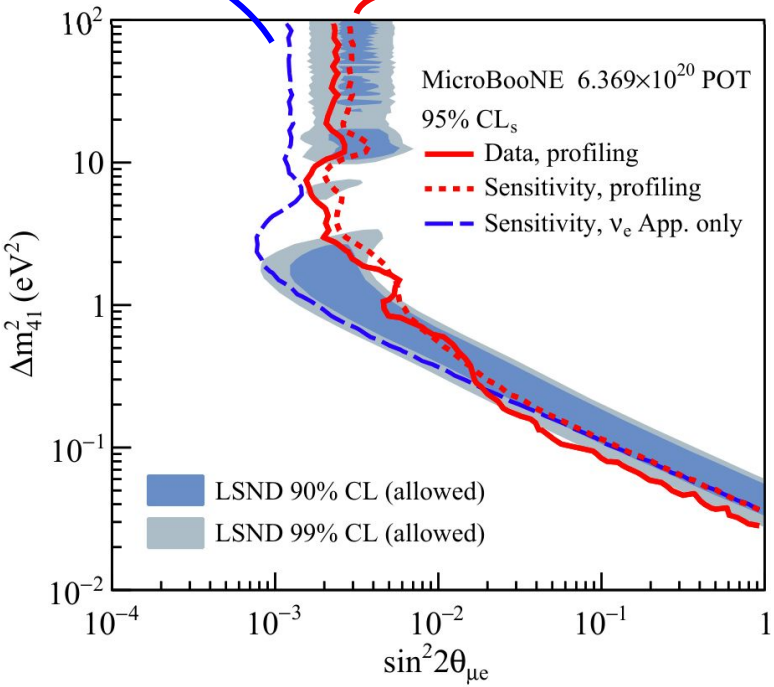
$$P(\nu_\mu \to \nu_e) \simeq 4\,|U_{\mu 4}|^2\,|U_{e4}|^2 \sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right)$$

$$P(\nu_e \to \nu_e) \simeq= 1 - 4\,|U_{e4}|^2\left(1 - |U_{e4}|^2\right) \sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right)$$

Degeneracy in MicroBooNE's Results

Unphysical "Appearance Only".

Proper "3+1" combined appearance/disappearance



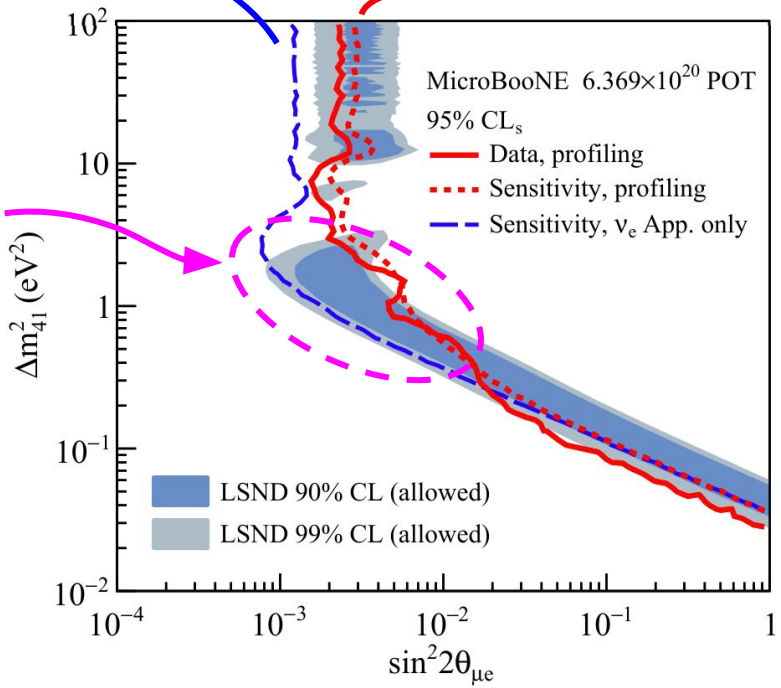
MicroBooNE, Phys. Rev. Lett. 130, 011801 (2023)

Degeneracy in MicroBooNE's Results

Unphysical "Appearance Only".

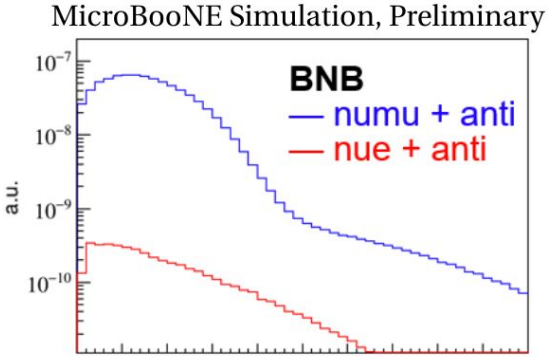
Proper "3+1" combined appearance/disappearance

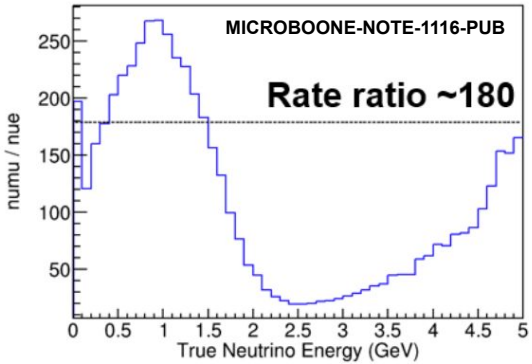
Region of degeneracy, where appearance and disappearance cancel



MicroBooNE, Phys. Rev. Lett. 130, 011801 (2023)

Degeneracy due to ν_μ / ν_e ratio

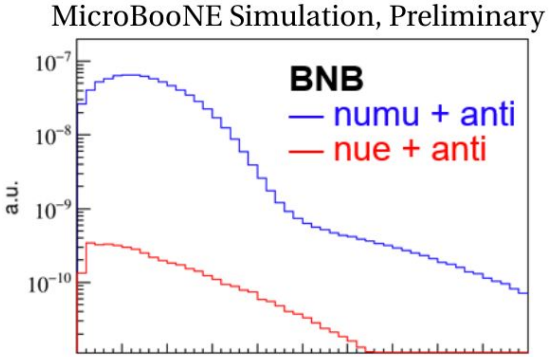




99.5% ν_μ & anti-ν_μ

0.5% ν_e & anti-ν_e

Degeneracy due to ν_μ/ν_e ratio



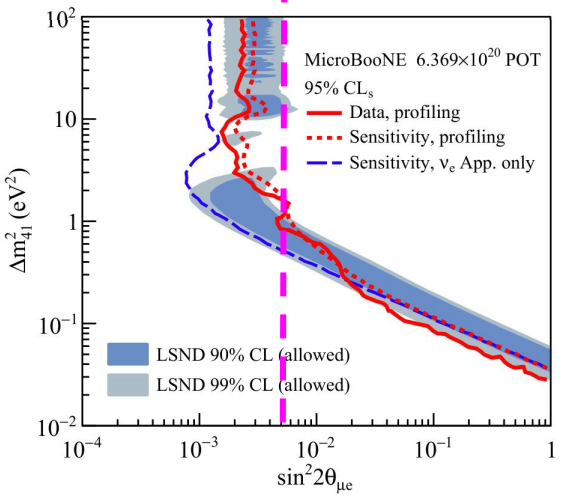
99.5% ν_μ & anti-ν_μ

0.5% ν_e & anti-ν_e

$$N_{\nu_e} = N_{\text{intrinsic } \nu_e} \cdot P_{\nu_e \to \nu_e} + N_{\text{intrinsic } \nu_\mu} \cdot P_{\nu_\mu \to \nu_e}$$

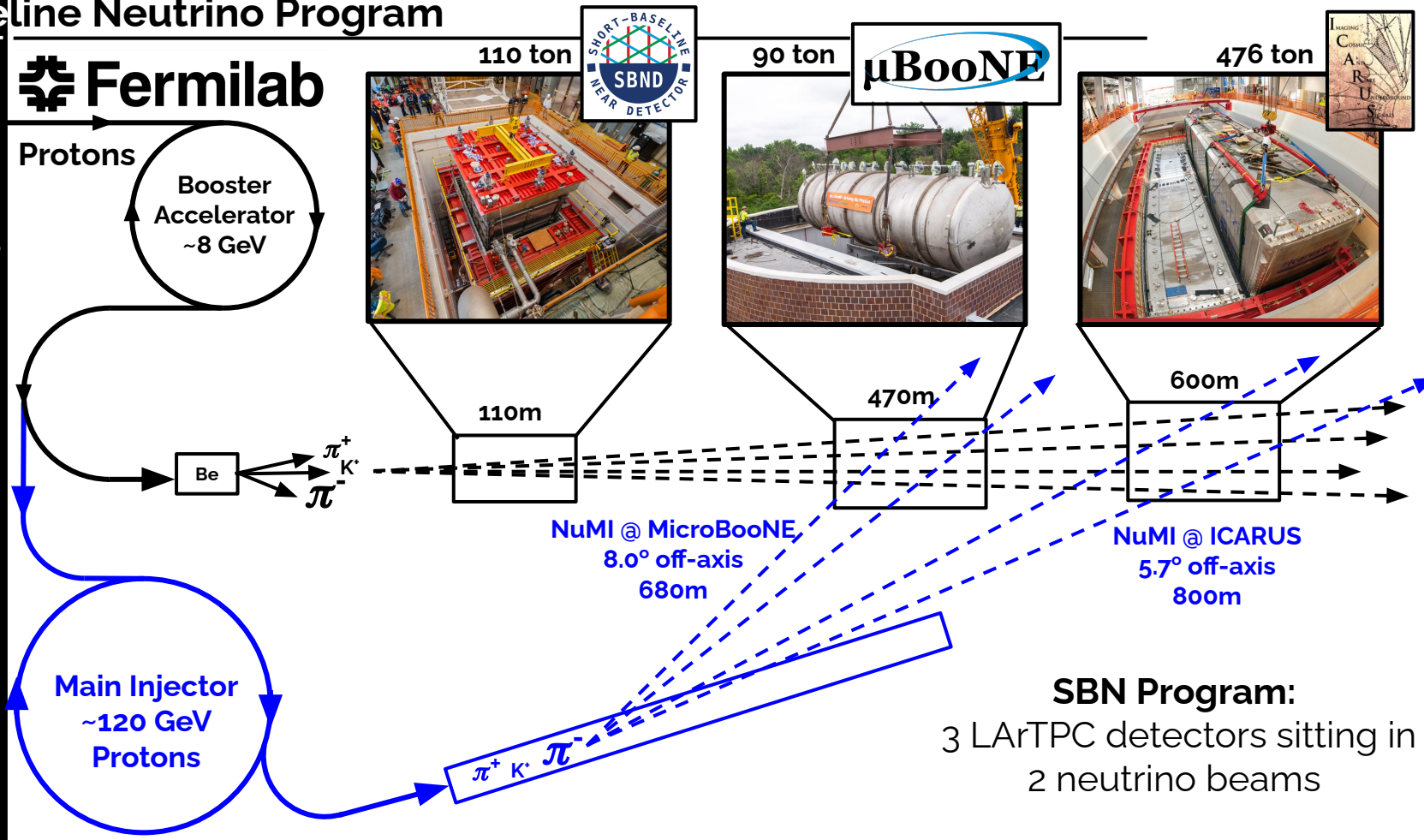
$$= N_{\text{intrinsic } \nu_e} \cdot \left[1 + (R_{\nu_\mu/\nu_e} \cdot \sin^2\theta_{24} - 1) \cdot \sin^2 2\theta_{14} \cdot \sin^2 \Delta_{41}\right]$$

$$\sin^2\theta_{24} = \frac{1}{R_{\nu_\mu/\nu_e}} \approx 0.005$$



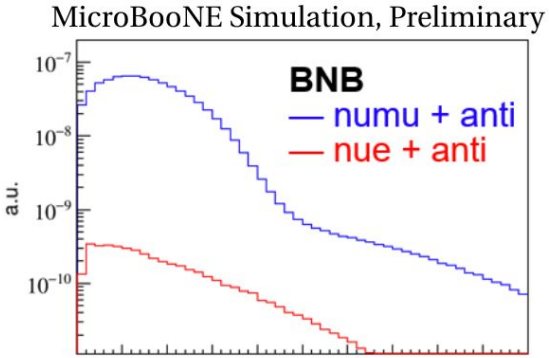
$\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2\theta_{24}$

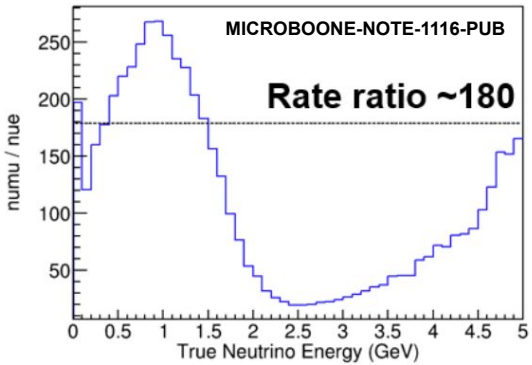
Short-Baseline Neutrino Program



SBN Program:
3 LArTPC detectors sitting in 2 neutrino beams

Breaking with the NuMI Beam



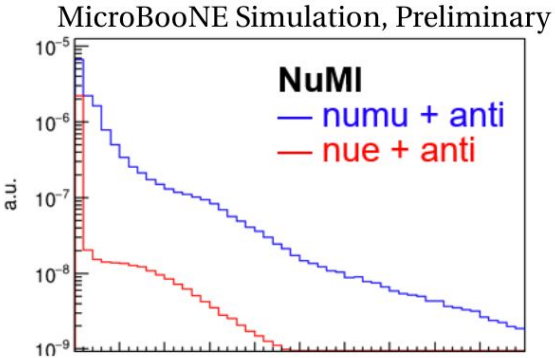


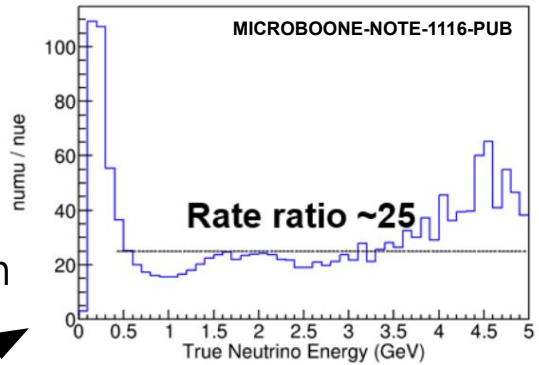
99.5% ν_μ & anti-ν_μ

0.5% ν_e & anti-ν_e

NuMI has ~x8

times more ν_e relative to ν_μ in its beam composition





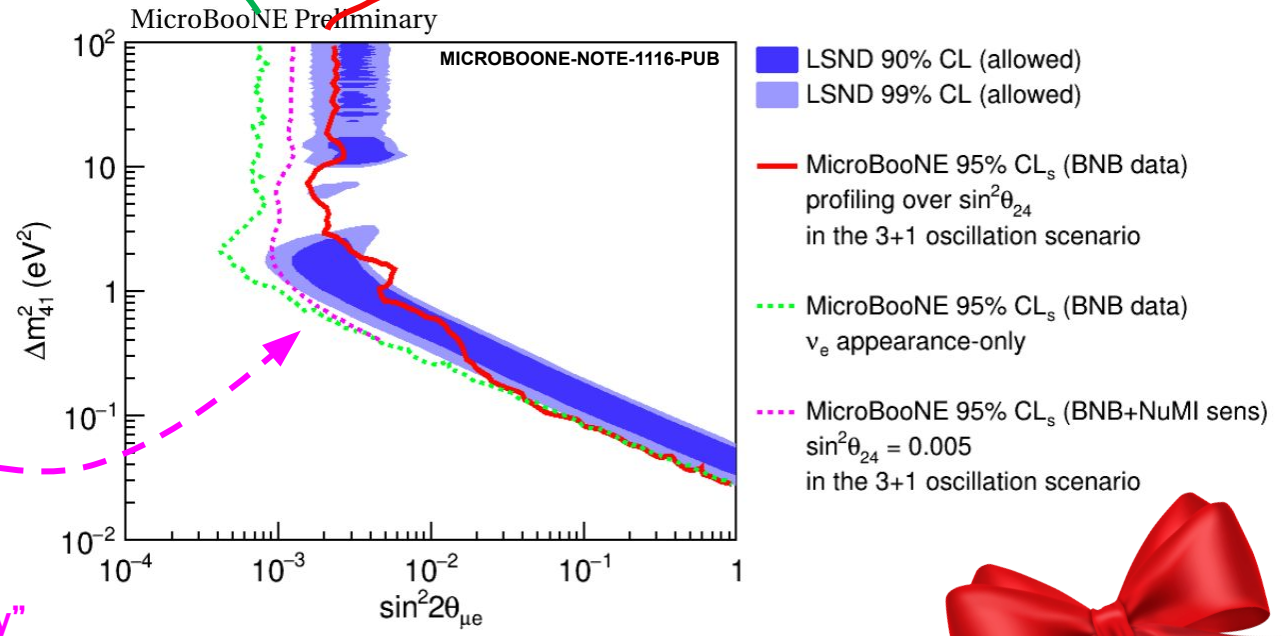
96% ν_μ & anti-ν_μ

4.0% ν_e & anti-ν_e

Effect of NuMI on MicroBooNE's Sensitivity

Unphysical "Appearance Only".

Proper "3+1" combined appearance/disappearance



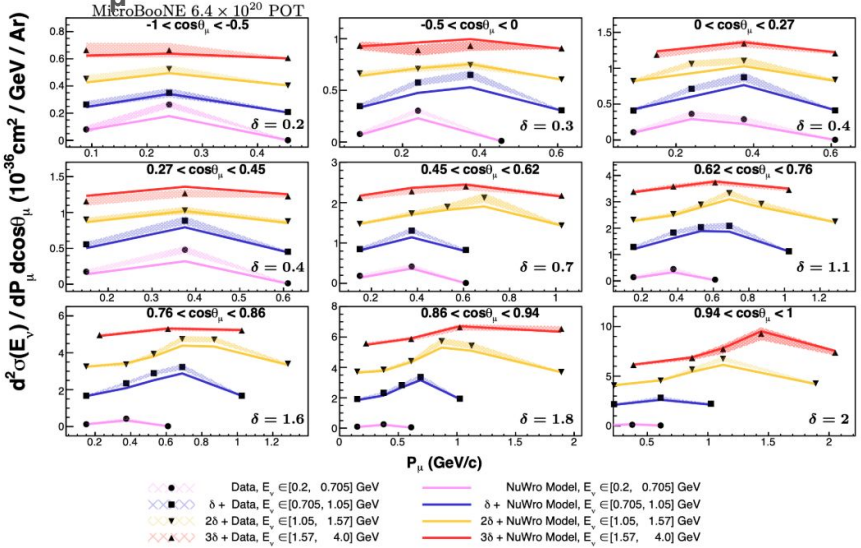
Addition of NuMI breaks the degeneracy!

Allows full 3+1 to get very close to "appearance only"

Not just anomaly hunting, Cross-Section measurement

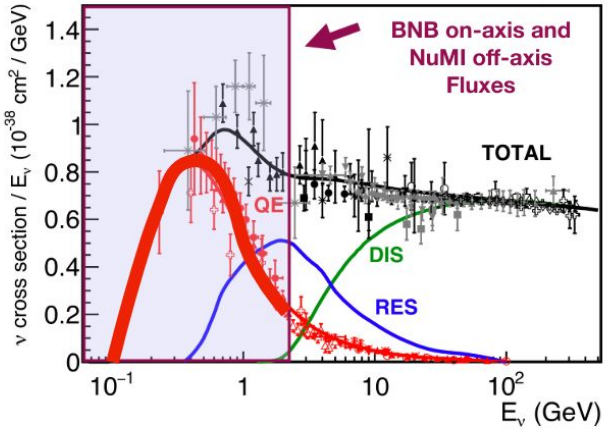
Liquid Argon is one of the important nuclear targets of the future.
The SBN program aims to **improve our understanding of ν-Ar interactions.**

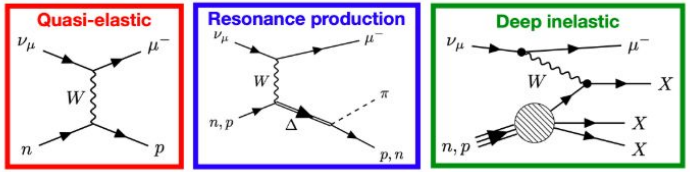
3D ν_μ CC Inclusive Cross Section Results



MicroBooNE: https://arxiv.org/abs/2307.06413

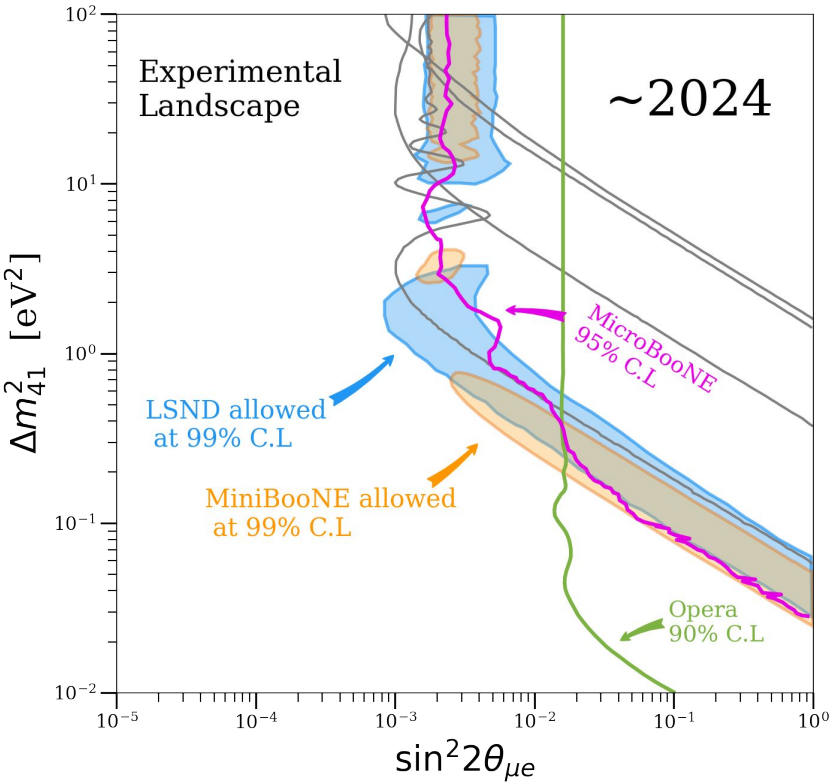
Rev. Mod. Phys. 84, 1307 (2012)





MicroBooNE already has 22 published cross-section papers, and **SBND/ICARUS will dwarf this in the long run**

do we *currently* stand on eV scale sterile



1. eV sterile neutrinos as solution for MiniBooNE and LSND are **not ruled out**

2. **MicroBooNE's results** combined with **extreme tension in global picture** has led to "***disfavor***" of eV sterile neutrino in community*

3. While we **100% need to close the box** on the eV sterile question,
   - And **SBN, with its dual beams, will do this…**
   - We also need to **look outside the box..**

*my opinion entirely!

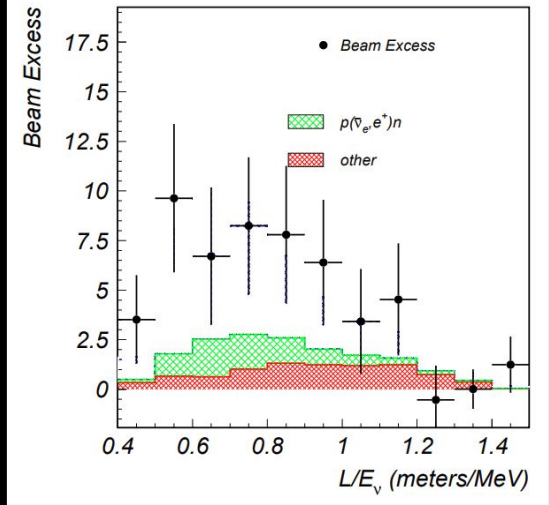
Anomalies still need explanations!

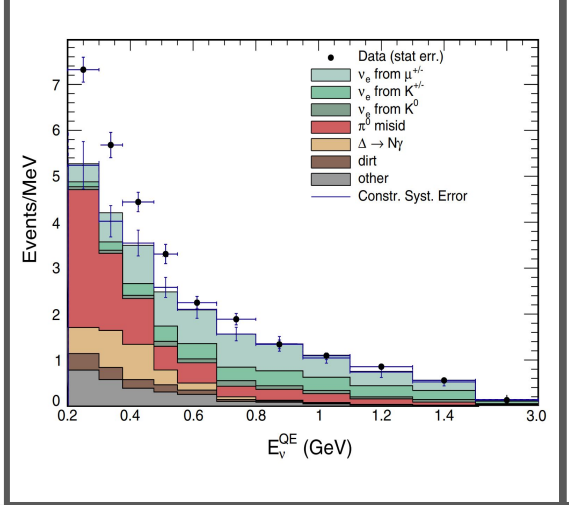
If a model fails to explain the data throw out the model, not the data.

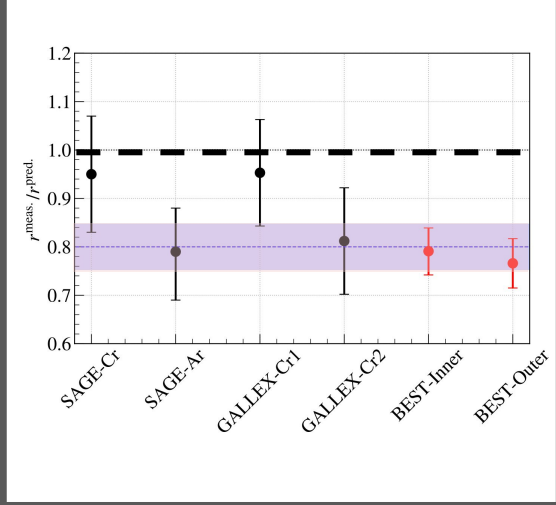
LSND Anomaly ~3.8σ
Decay-at-rest

MiniBooNE Anomaly ~4.8σ
Decay-in-flight

Gallium Anomaly ~4.0σ
Radioactive Source

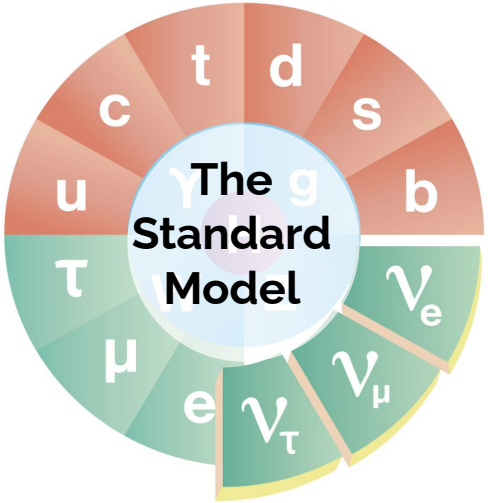






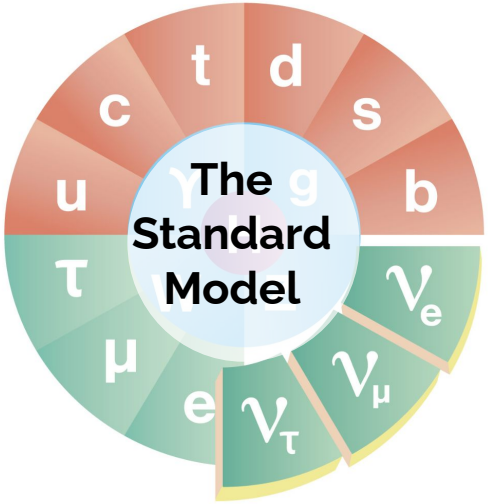

5. The Dark Sector

Welcome to the Dark Sector



"Dark Matter"

Welcome to the Dark Sector

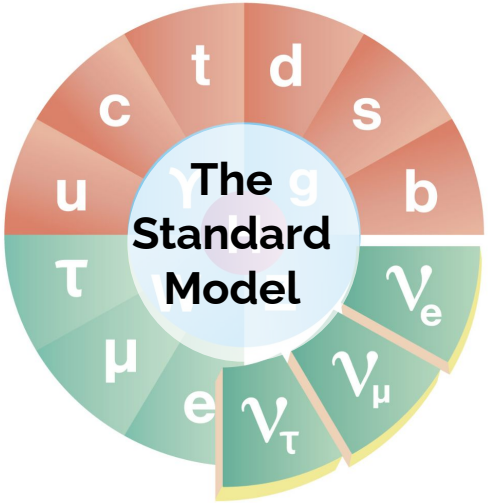


- Plethora of particles
- Three forces $U(1)_Y \times SU(2)_L \times SU(3)_C$
- Forms complex composite structures, hadrons, mesons..etc..
- Forms complex atoms & molecules (chemistry)

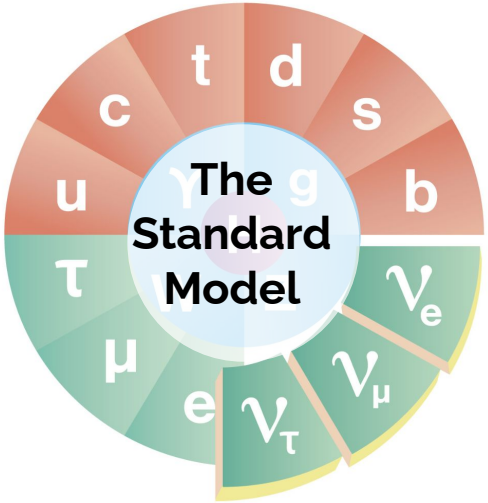
"Dark Matter"

- "Just" Dark Matter

Welcome to the Dark Sector

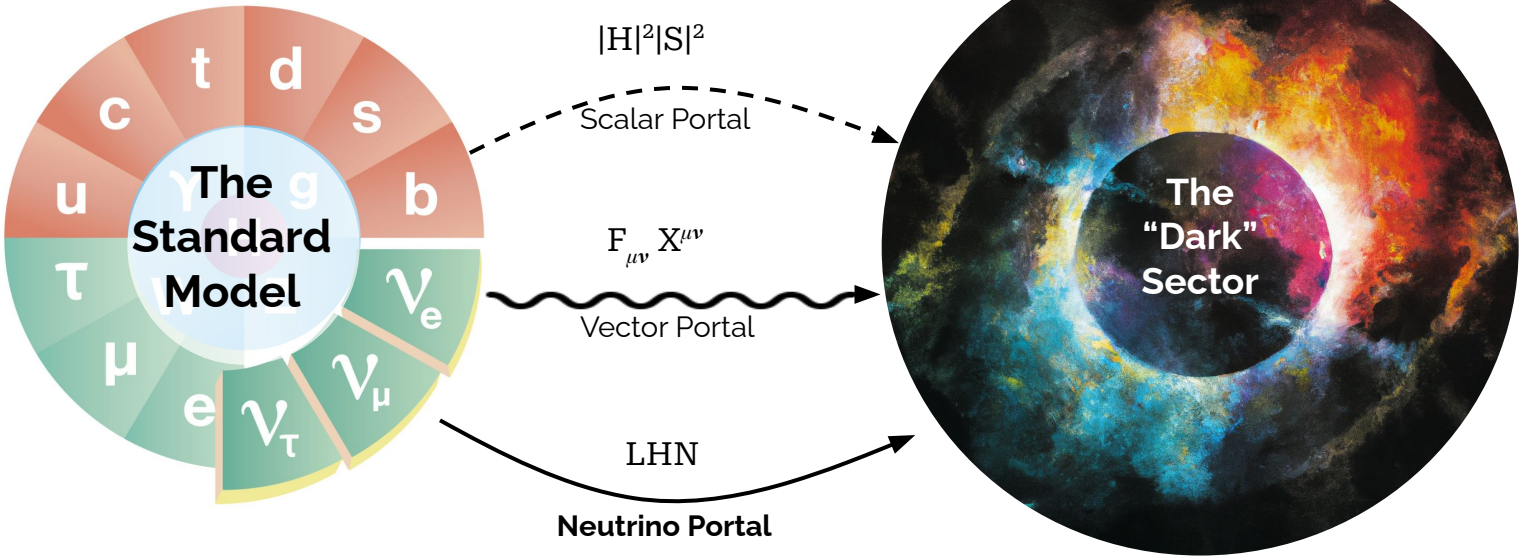


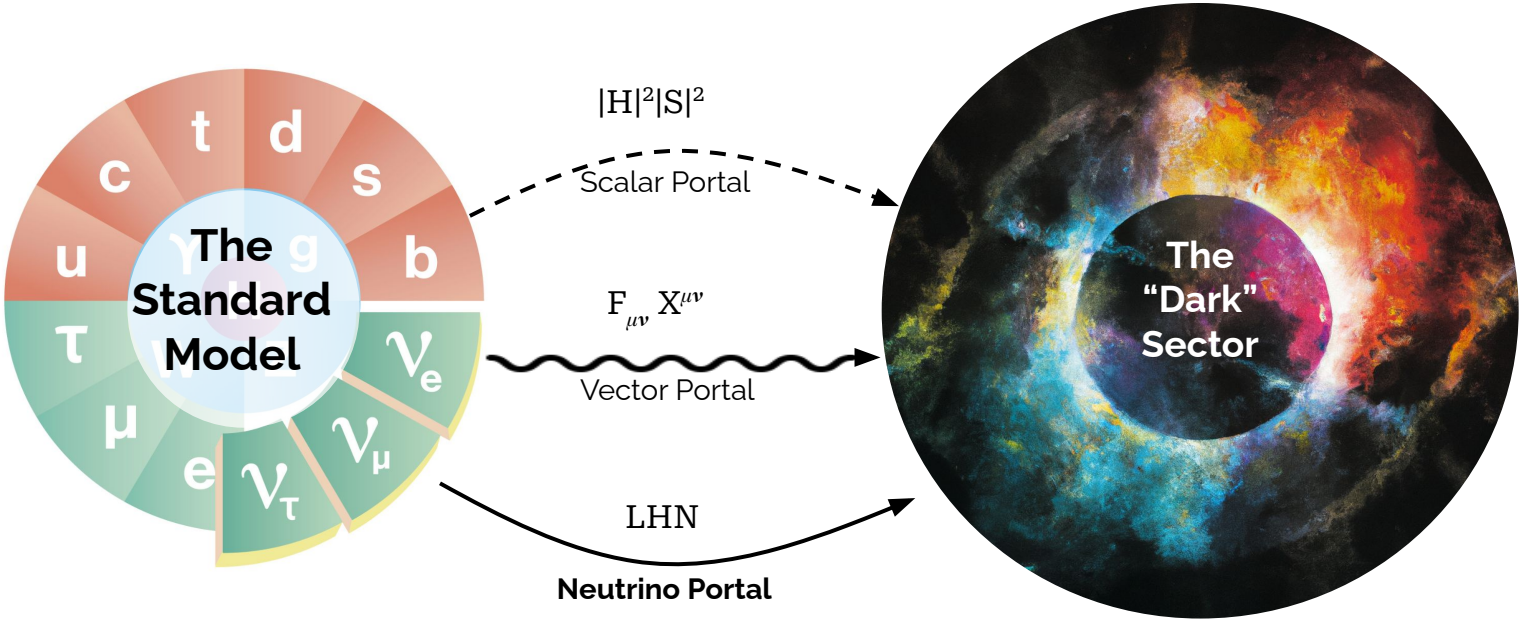
Welcome to the Dark Sector



- Rich particle content
  - Dark matter candidate (s)
  - Sterile Neutrinos .. + more
- New Forces and Interactions
- Potentially complex phenomenology

Neutrinos as a portal to the Dark Sector



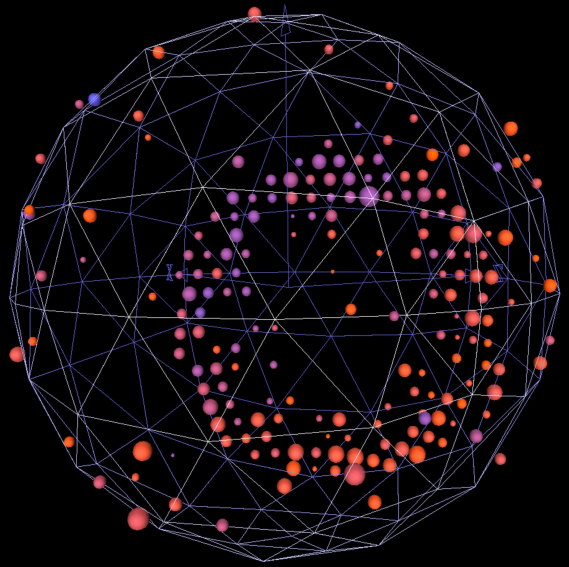


Why is this useful?

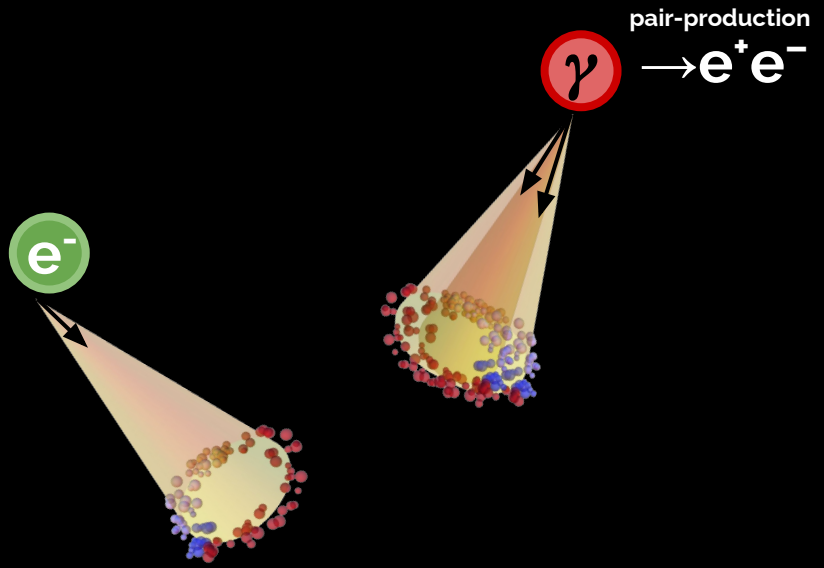
- *Low level:* To explain the anomalies ***without*** violating other null bounds
- *High Level*: The discovery of **a dark sector**, potentially containing **theorized dark matter** would be groundbreaking!

See **F. Sala's lectures for details!**

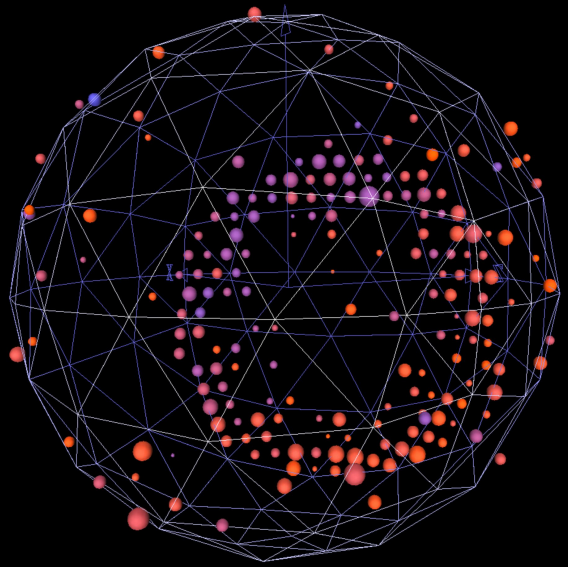
Motivation from MiniBooNE: Electrons, Photons ....



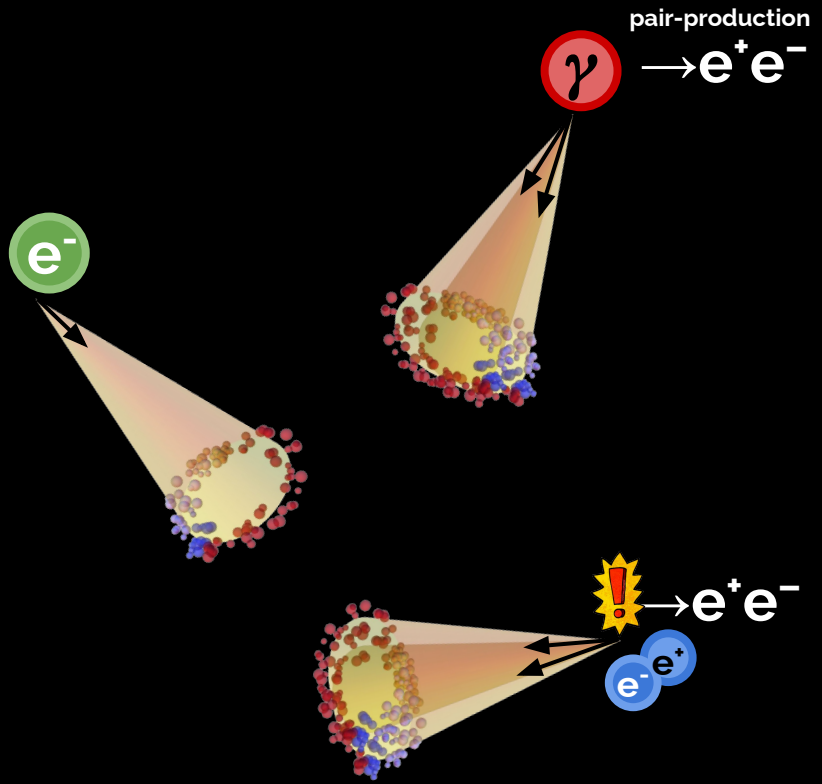
Electron Cherenkov ring event in MiniBooNE



Motivation from MiniBooNE: Electrons, Photons or e^+e^- pairs



Electron Cherenkov ring event in MiniBooNE



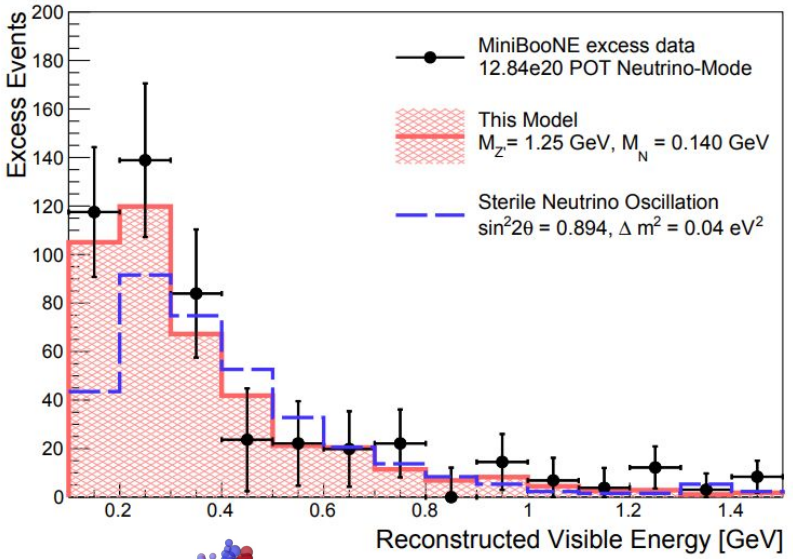
One such proposal of a **"dark sector" e^+e^- signal** as a plausible MiniBooNE explanation

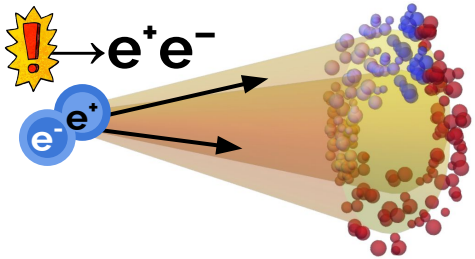
Provided the e+e- pair is

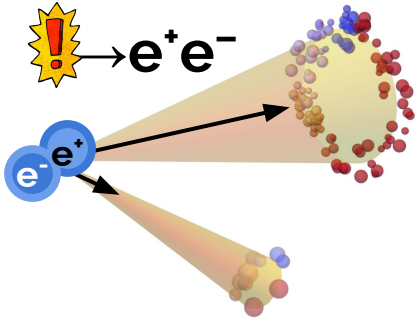
(a) Sufficiently Overlapping

(b) Asymmetric enough

P.Ballett, S.Pascoli, M. RL (2018) PhysRevD.99.071701



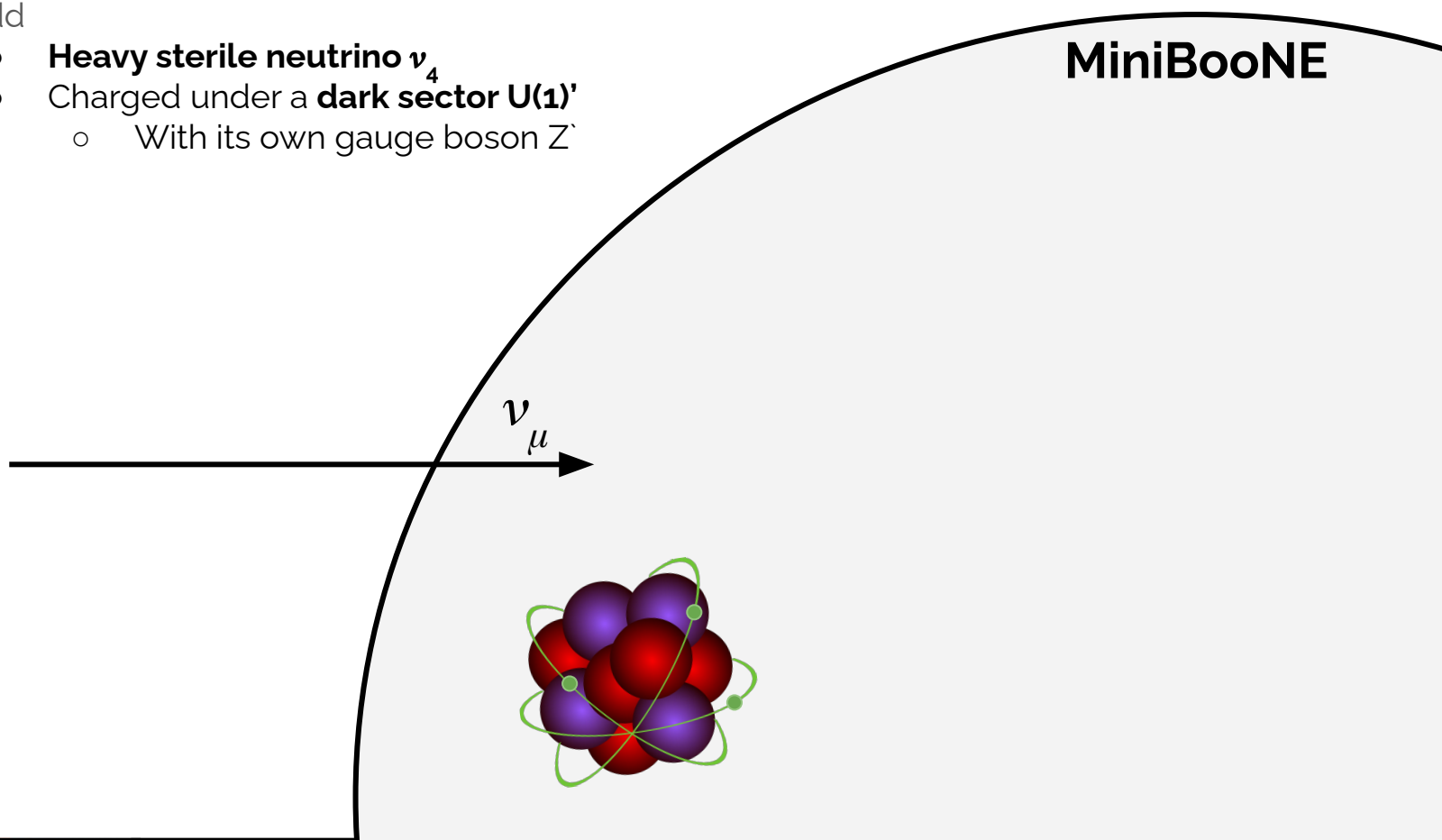




Generating e^+e^- pairs

Add

- **Heavy sterile neutrino ν_4**
- Charged under a **dark sector U(1)'**
  - With its own gauge boson Z`



Generating e^+e^- pairs

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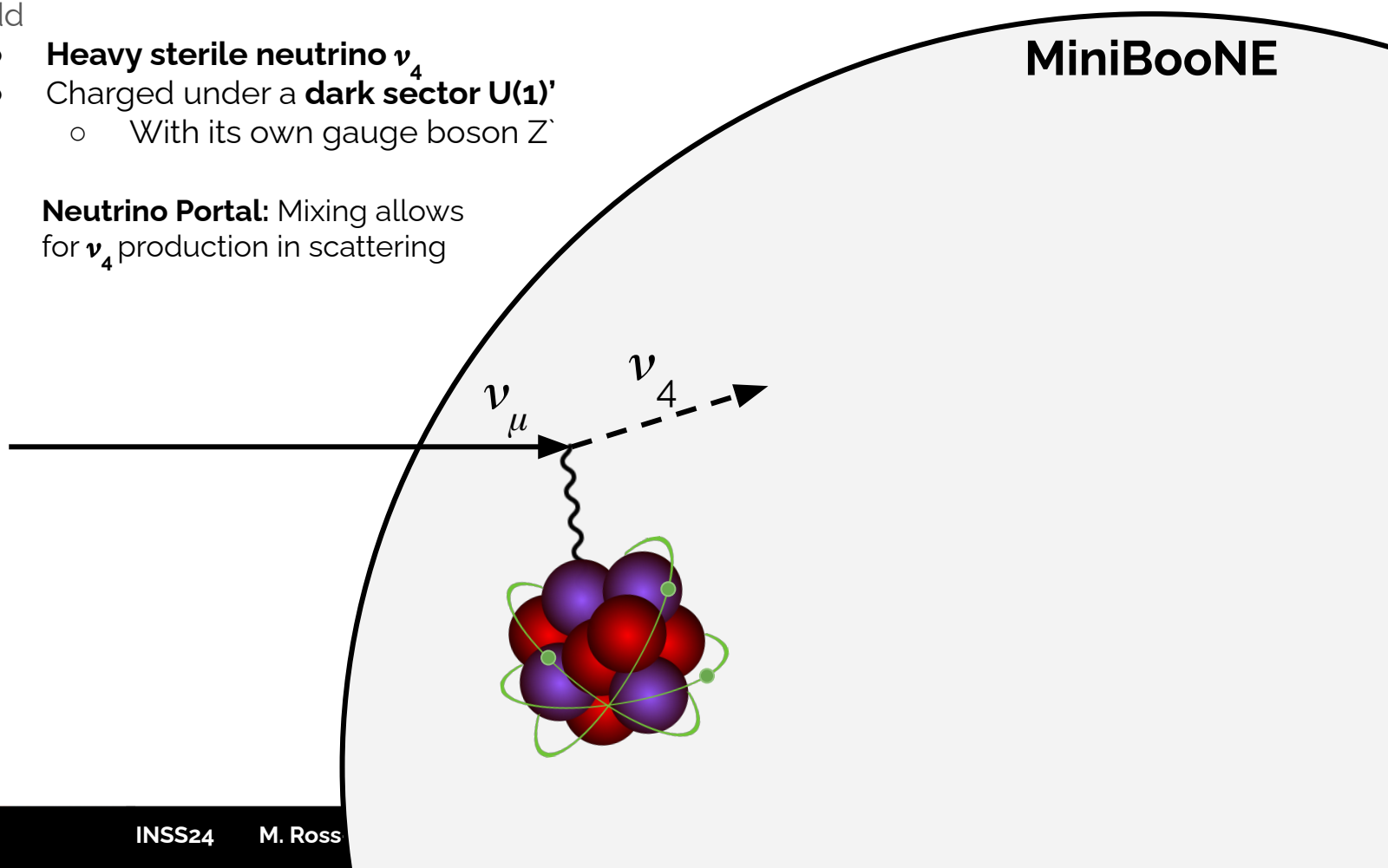
- **Neutrino Portal:** Mixing allows for ν_4 production in scattering

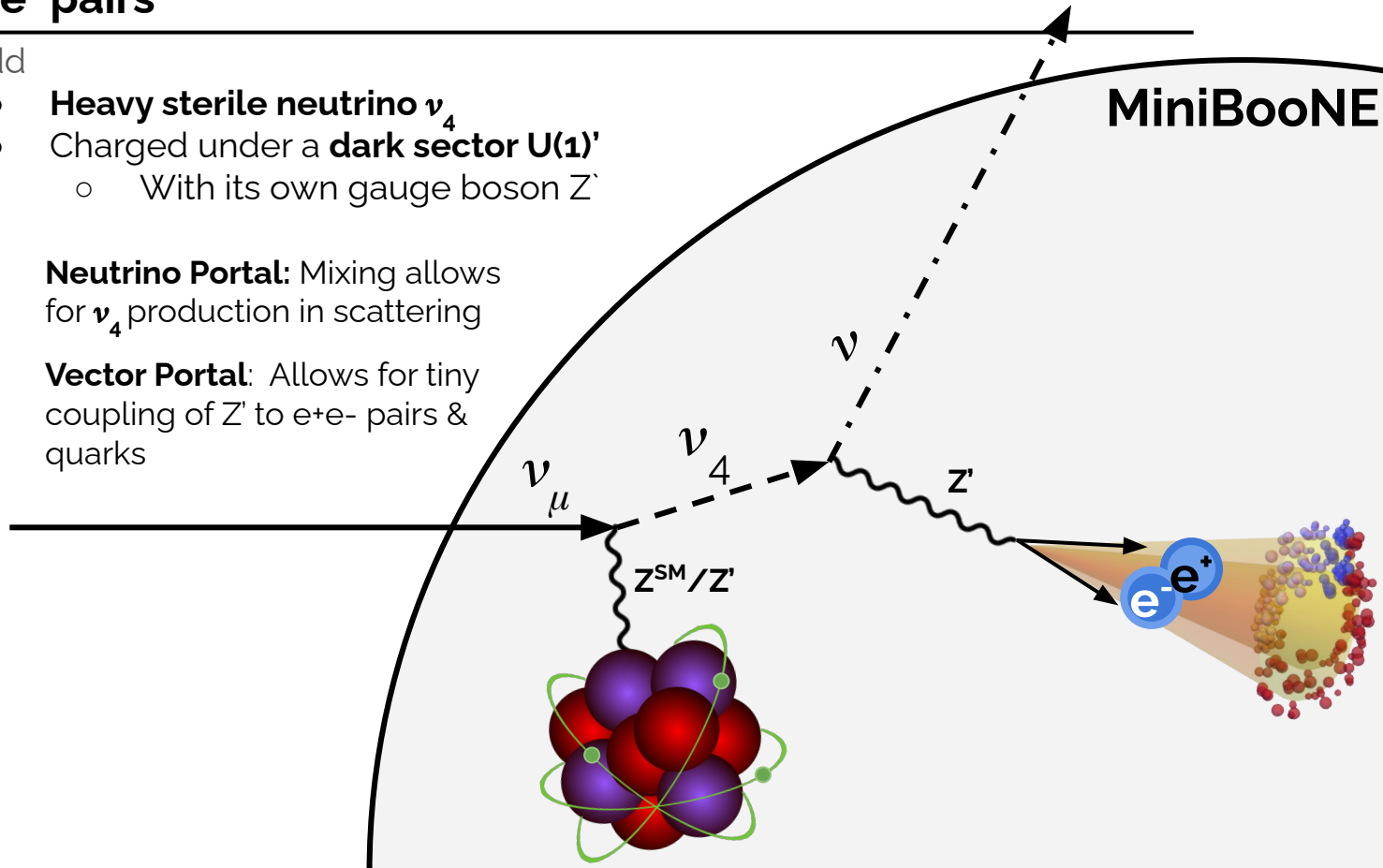


Generating e^+e^- pairs

Add

- **Heavy sterile neutrino ν_4**
- Charged under a **dark sector U(1)'**
  - With its own gauge boson Z`

- **Neutrino Portal:** Mixing allows for ν_4 production in scattering
- **Vector Portal**: Allows for tiny coupling of Z' to e+e- pairs & quarks



Explosion in the theoretical landscape

Category	Model	Signature	Anomalies		References
			LSND	MiniBooNE	
Flavor transitions Secs. 3.1.1-3.1.3, 3.1.5	(3+1) oscillations	oscillations	✓	✓	Reviews and global fits [93, 103, 105, 106]
	(3+1) w/ invisible sterile decay	oscillations w/ ν_4 invisible decay	✓	✓	[151, 155]
	(3+1) w/ sterile decay	$\nu_4 \to \phi\nu_e$	✓	✓	[159–162, 270]
Matter effects Secs. 3.1.4, 3.1.7	(3+1) w/ anomalous matter effects	$\nu_\mu \to \nu_e$ via matter effects	✓	✓	[143, 147, 271–273]
	(3+1) w/ quasi-sterile neutrinos	$\nu_\mu \to \nu_e$ w/ resonant ν_s matter effects	✓	✓	[148]
Flavor violation Sec. 3.1.6	Lepton-flavor-violating μ decays	$\mu^+ \to e^+\nu_\alpha\overline{\nu_e}$	✓	✗	[174, 175, 274]
	neutrino-flavor-changing bremsstrahlung	$\nu_\mu A \to e\phi A$	✓	✓	[275]
Decays in flight Sec. 3.2.3	Transition magnetic mom., heavy ν decay	$N \to \nu\gamma$	✗	✓	[207]
	Dark sector heavy neutrino decay	$N \to \nu(X \to e^+e^-)$ or $N \to \nu(X \to \gamma\gamma)$	✗	✓	[208]
Neutrino Scattering Secs. 3.2.1, 3.2.2	neutrino-induced upscattering	$\nu A \to NA$, $N \to \nu e^+e^-$ or $N \to \nu\gamma\gamma$	✓	✓	[205, 206, 209–216]
	neutrino dipole upscattering	$\nu A \to NA$, $N \to \nu\gamma$	✓	✓	[40, 185, 187, 188, 190, 193, 233, 276]
Dark Matter Scattering Sec. 3.2.4	dark particle-induced upscattering	γ or e^+e^-	✗	✓	[217]
	dark particle-induced inverse Primakoff	γ	✓	✓	[217]

"Standard" 3+1 light oscillation sterile model

Table modified from Snowmass White Paper on Light Sterile Neutrino Searches and Related Phenomenology

Explosion in the theoretical landscape

Category	Model	Signature	Anomalies		References
			LSND	MiniBooNE	
Flavor transitions Secs. 3.1.1-3.1.3, 3.1.5	(3+1) oscillations	oscillations	✓	✓	Reviews and global fits [93, 103, 105, 106]
	(3+1) w/ invisible sterile decay	oscillations w/ ν_4 invisible decay	✓	✓	[151–155]
	(3+1) w/ sterile decay	$\nu_4 \to \phi\nu_e$	✓	✓	[159–162, 270]
Matter effects Secs. 3.1.4, 3.1.7	(3+1) w/ anomalous matter effects	$\nu_\mu \to \nu_e$ via matter effects	✓	✓	[143, 147, 271–273]
	(3+1) w/ quasi-sterile neutrinos	$\nu_\mu \to \nu_e$ w/ resonant ν_s matter effects	✓	✓	[148]
Flavor violation Sec. 3.1.6	Lepton-flavor-violating μ decays	$\mu^+ \to e^+\nu_a\overline{\nu_e}$	✓	✗	[174, 175, 274]
	neutrino-flavor-changing bremsstrahlung	$\nu_\mu A \to e\phi A$	✓	✓	[275]
Decays in flight Sec. 3.2.3	Transition magnetic mom., heavy ν decay	$N \to \nu\gamma$	✗	✓	[207]
	Dark sector heavy neutrino decay	$N \to \nu(X \to e^+e^-)$ or $N \to \nu(X \to \gamma\gamma)$	✗	✓	[208]
Neutrino Scattering Secs. 3.2.1, 3.2.2	neutrino-induced upscattering	$\nu A \to NA$, $N \to \nu e^+e^-$ or $N \to \nu\gamma\gamma$	✓	✓	[205, 206, 209–216]
	neutrino dipole upscattering	$\nu A \to NA$, $N \to \nu\gamma$	✓	✓	[40, 185, 187, 188, 190, 193, 233, 276]
Dark Matter Scattering Sec. 3.2.4	dark particle-induced upscattering	γ or e^+e^-	✗	✓	[217]
	dark particle-induced inverse Primakoff	γ	✓	✓	[217]

25+ dark-sector models in last 5 years

Table modified from Snowmass White Paper on Light Sterile Neutrino Searches and Related Phenomenology

Explosion in the theoretical landscape

Category	Model	Signature	Anomalies		References
			LSND	MiniBooNE	
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	(3+1) w/ invisible sterile decay	$\nu_\mu \to \nu_e$ oscillations w/ ν_4 invisible decay	✓	✓	[151–155]
	(3+1) w/ sterile decay	$\nu_\mu \to \nu_e$ oscillations w/ ν_4 decay	✓	✓	[159–162, 270]
Matter effects Secs. 3.1.4, 3.1.7	(3+1) w/ anomalous matter effects	$\nu_\mu \to \nu_e$ via matter effects	✓	✓	[143, 147, 271–273]
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	Dark sector heavy neutrino decay	$\nu \to e^- e^+ \nu$, $\nu(X \to \gamma\gamma)$	✗	✓	[208]
Neutrino Scattering Secs. 3.2.1, 3.2.2	neutrino-induced upscattering	$N \to \nu\gamma$, $N \to \nu e^- e^+$	✓	✓	[205, 206, 209–216]
	neutrino dipole upscattering	$\nu \to N\gamma$, $\nu e^- \to N e^- e^+$	✓	✓	[40, 185, 187, 188, 190, 193, 233, 276]
Dark Matter Scattering Sec. 3.2.4	dark particle-induced upscattering	$\chi e^- \to \chi e^- e^+$	✗	✓	[217]
	dark particle-induced inverse Primakoff	$\chi \to \chi\gamma$	✓	✓	[217]

Table modified from Snowmass White Paper on Light Sterile Neutrino Searches and Related Phenomenology

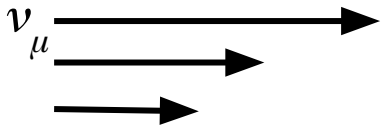
25+ dark-sector models in last 5 years

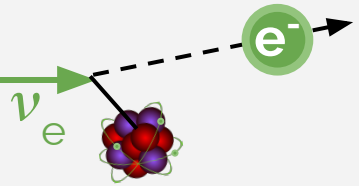
Incredibly rich and varied phenomenology containing

- Electron signals
- Photon signals
- Di-Photon signals
- e+e- signals

Dark Sector Phenomenology at SBL

Flavor changing: "3+1" Neutrino Oscillations $\Delta m^2 \sim eV^2$





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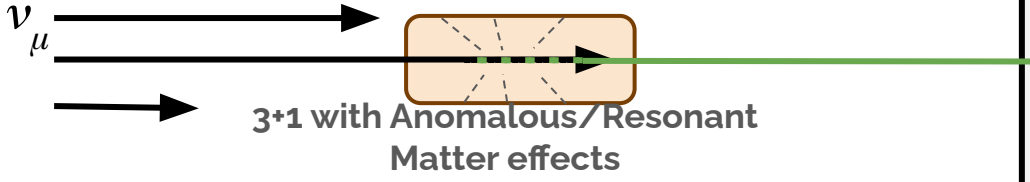
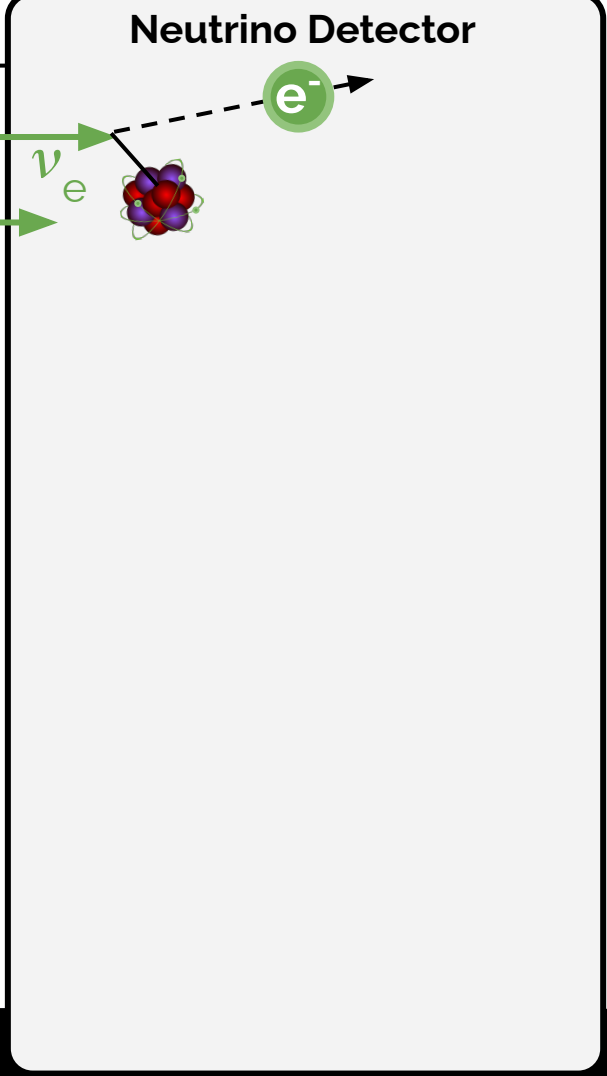




Dark Sector Phenomenology at SBL

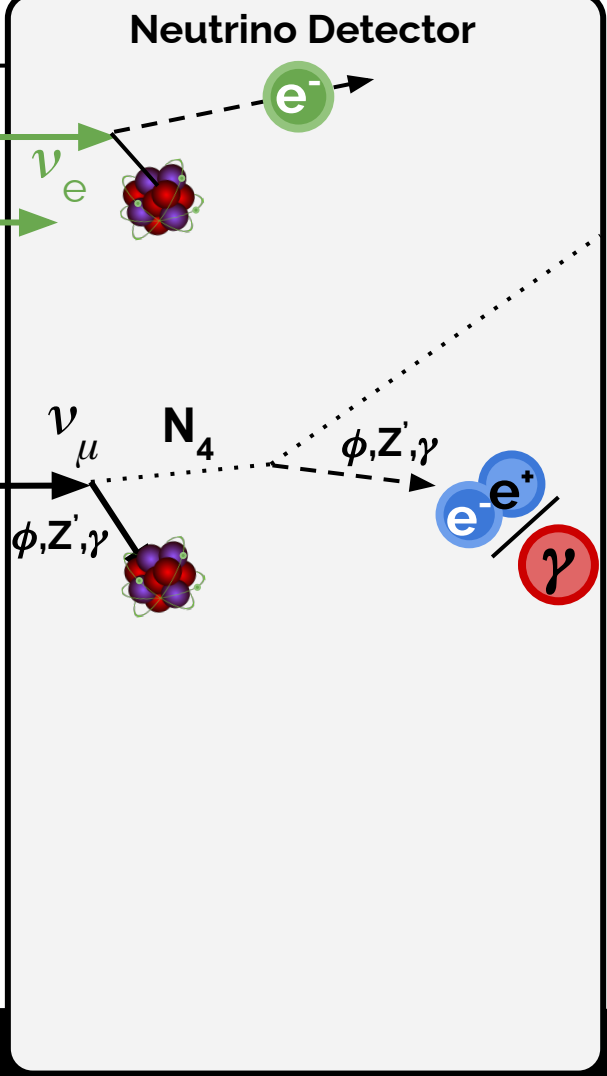
Flavor changing: "3+1" Neutrino Oscillations $\Delta m^2 \sim eV^2$

ν_μ

3+1 with Anomalous/Resonant Matter effects

ν_μ **Neutrino induced upscattering**

"Dark Neutrinos "



Dark Sector Phenomenology at SBL

Flavor changing: "3+1" Neutrino Oscillations $\Delta m^2 \sim eV^2$

ν_μ

3+1 with Anomalous/Resonant Matter effects

ν_e

Neutrino induced upscattering

ν_μ

"Dark Neutrinos "

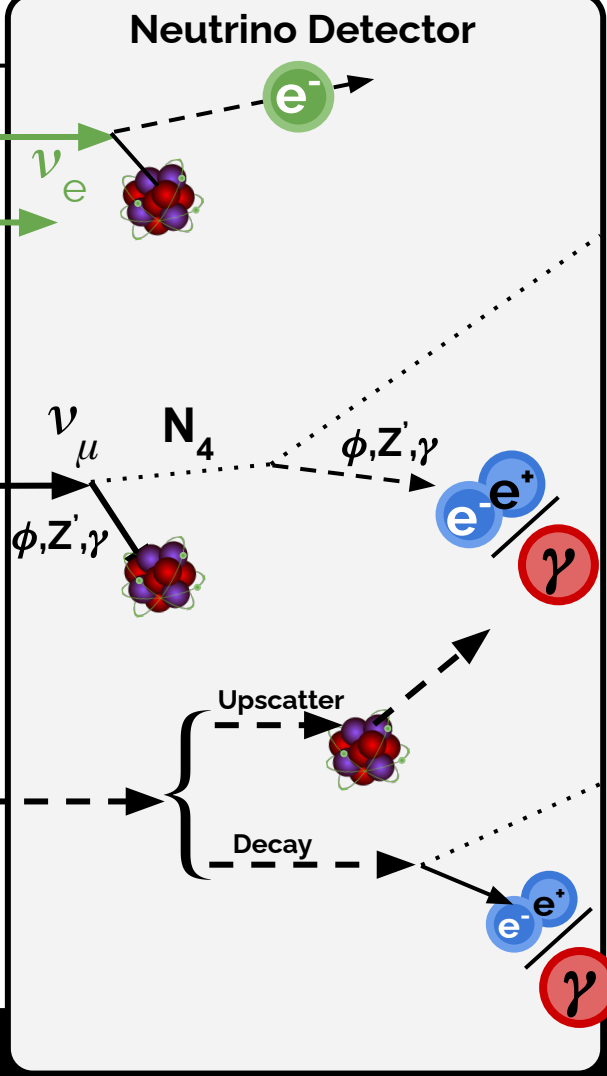
Decay Pipe

$\pi^{\pm} K^{\pm} \pi^0$

ϕ, V, χ, N_4

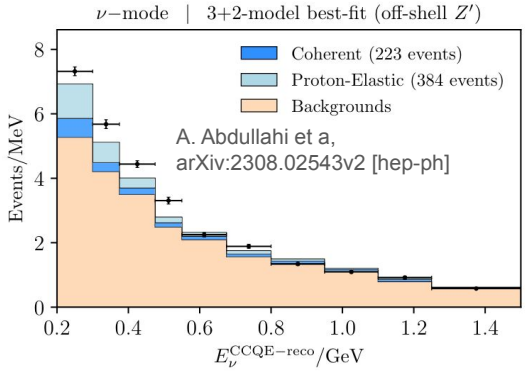
Exotic Production in Beam

"Light dark matter/ Heavy neutral leptons"

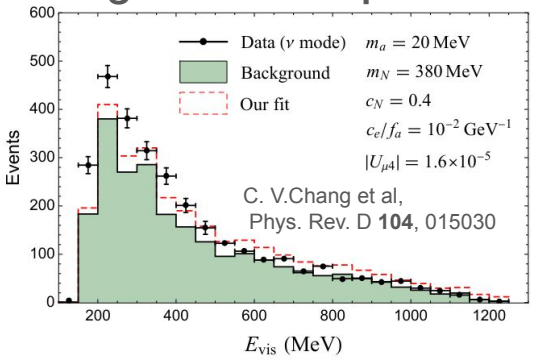


Explosion in the theoretical landscape: MiniBooNE explanations

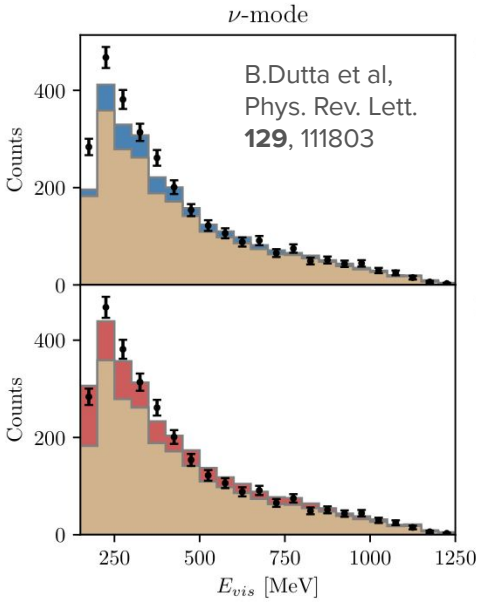
Broad class of upscattering, both on and off shell Z'



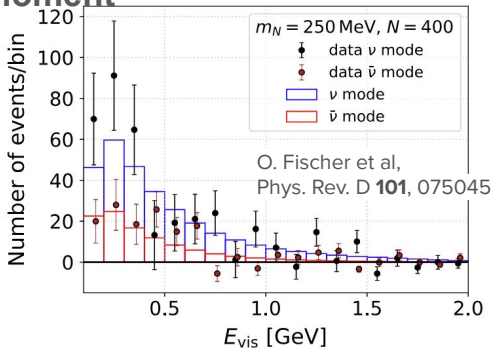
Light axion-like particles



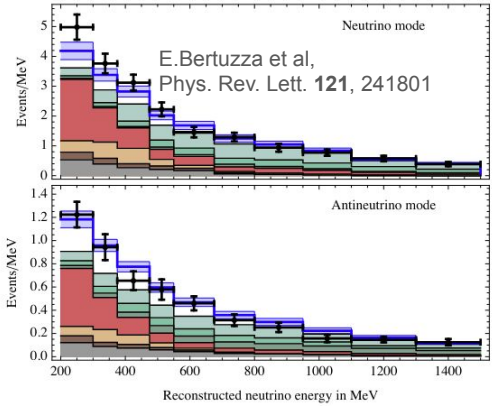
Light Dark Matter and Scalar Primakoff



NHL with transmission magnetic moment

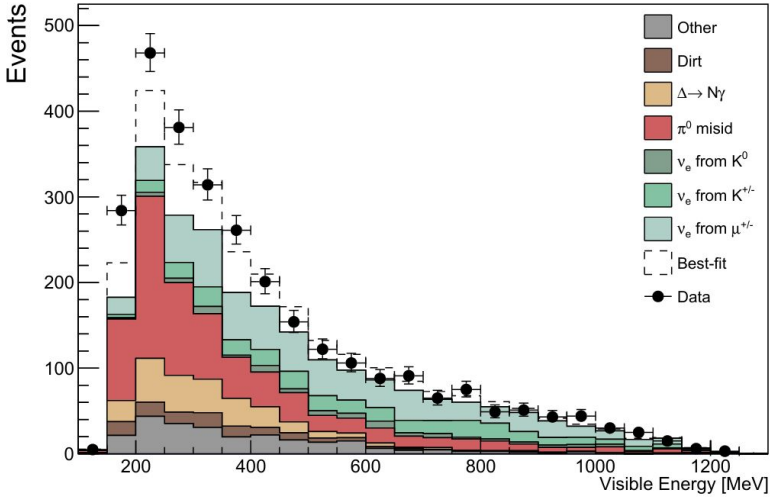


Dark Neutrino upscatter w/ light Z'



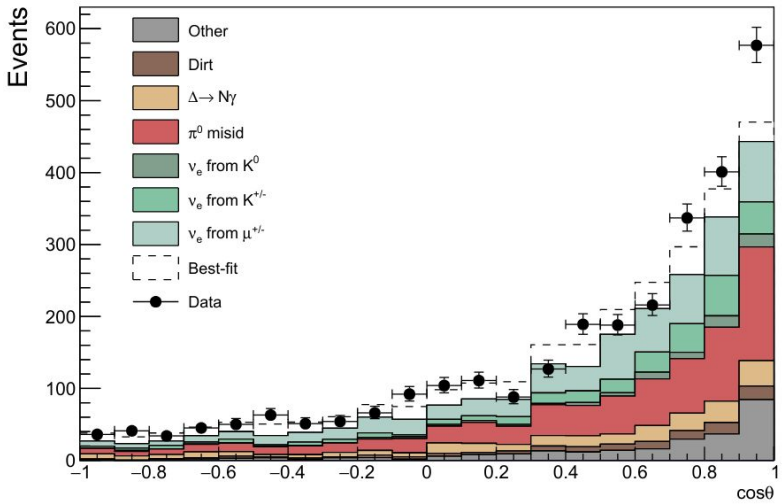
theory? Anatomy of an Anomaly in MiniBooNE (I)

Visible Energy



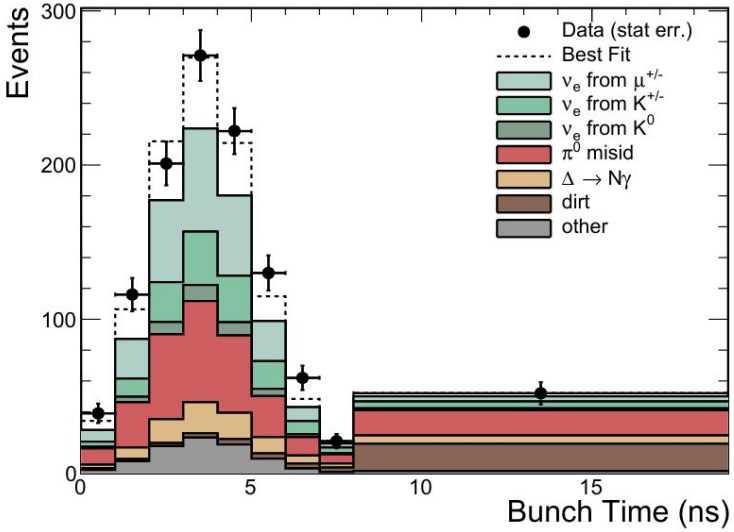
~Easy

Angle relative to Neutrino Beam



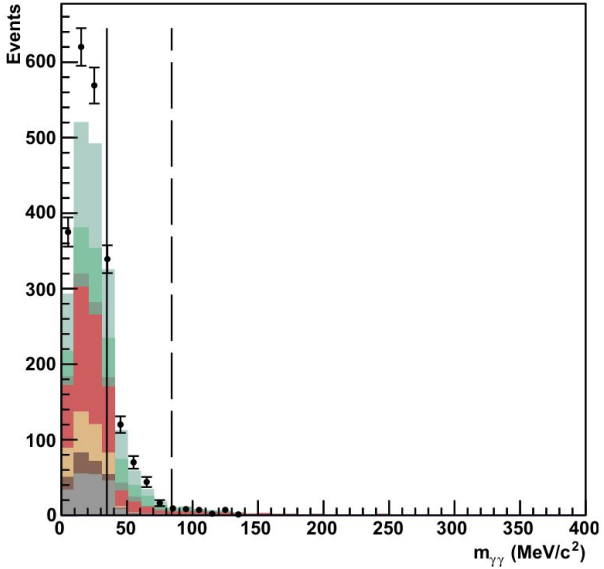
~Quite Difficult

Beam Timing



In time with the neutrino spills, I.e can't be due to very heavy particles traveling from target

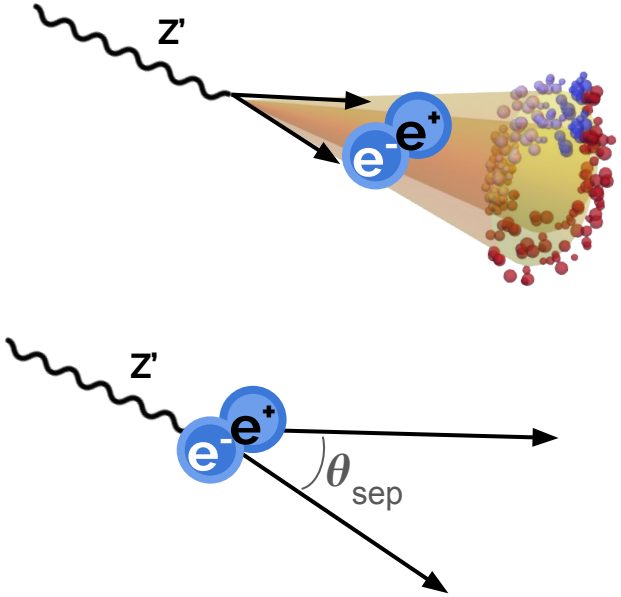
Invariant Mass of di-photon system

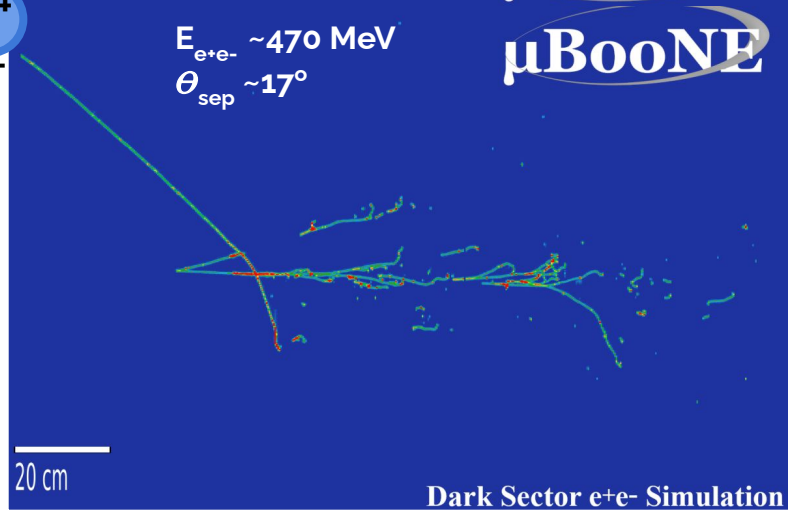


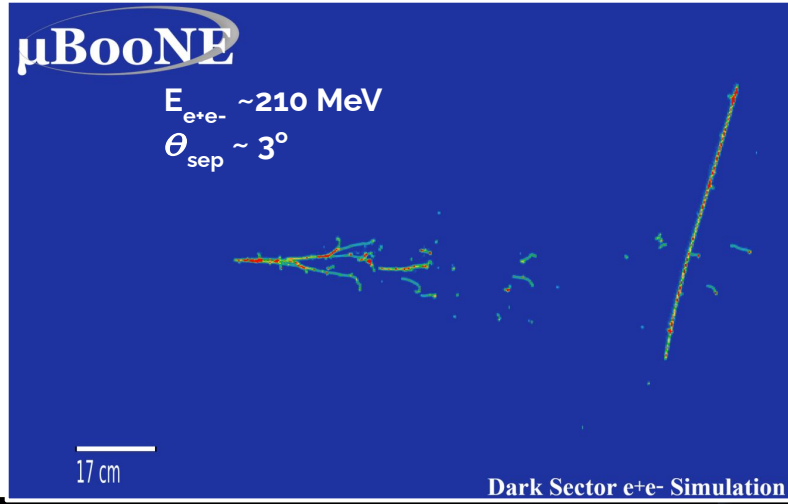
If it is two photon-like rings, invariant mass <= 50 MeV

LArTPC's targeting dark-sector e+e- pairs

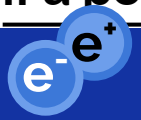
LArTPC technology used at the SBN is the perfect place to probe these models as an explanation for the MiniBooNE Anomaly

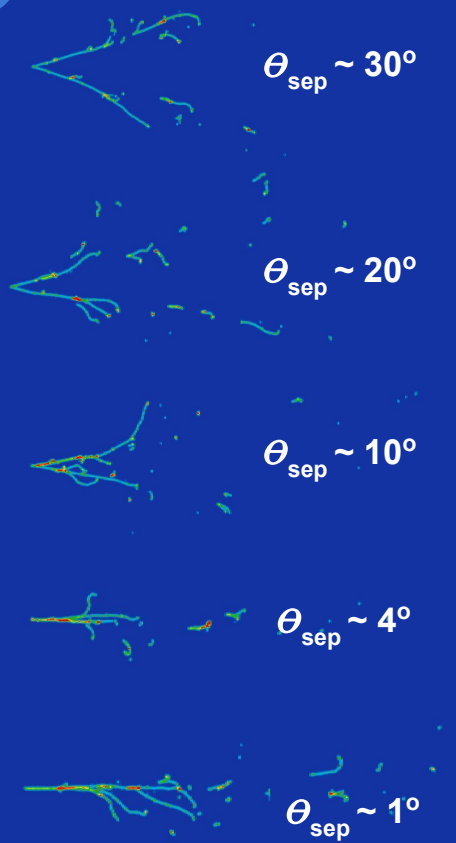






What if a positive signal is observed in a search?

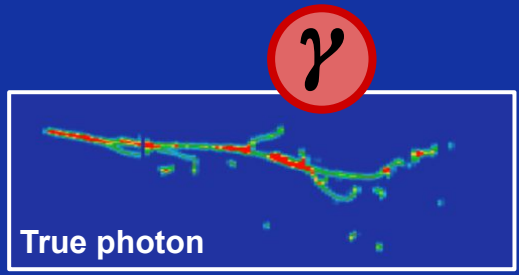




Very little in the Standard Model that produces e+e- pairs with wide (> 5°) opening angles at O(100 MeV) energies

Observation would be a smoking gun signature of BSM physics!

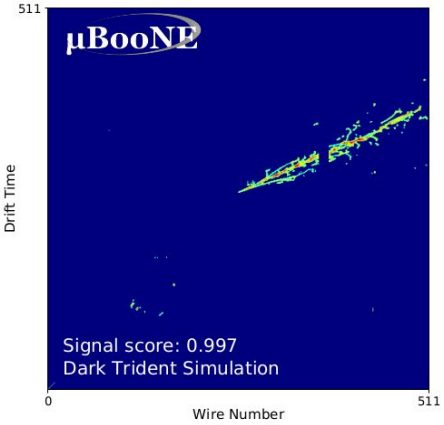
Where can we stop telling the difference?



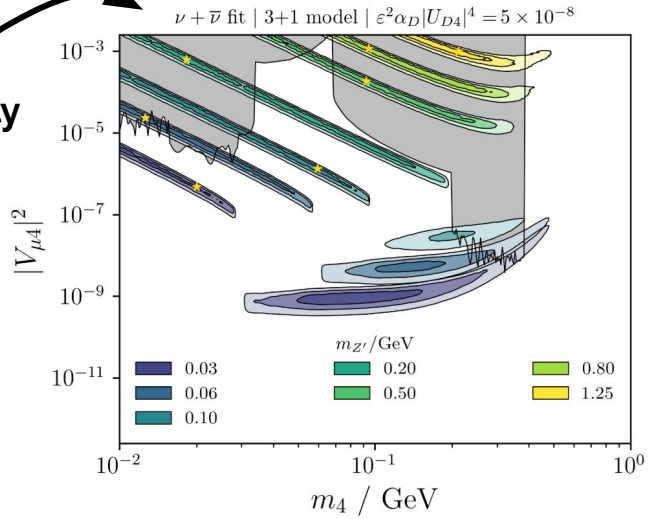
e+e- Searches

Building on the first generation photon searches, **MicroBooNE has several analyses targeting e+e- final states.**

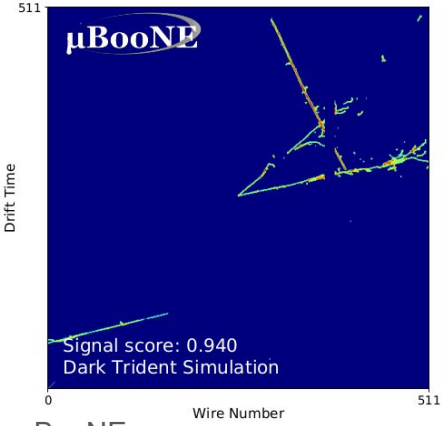
Dark-trident searches using the MicroBooNE detector and NuMI Beam



Targeting phase space that can explain the MiniBooNE anomaly

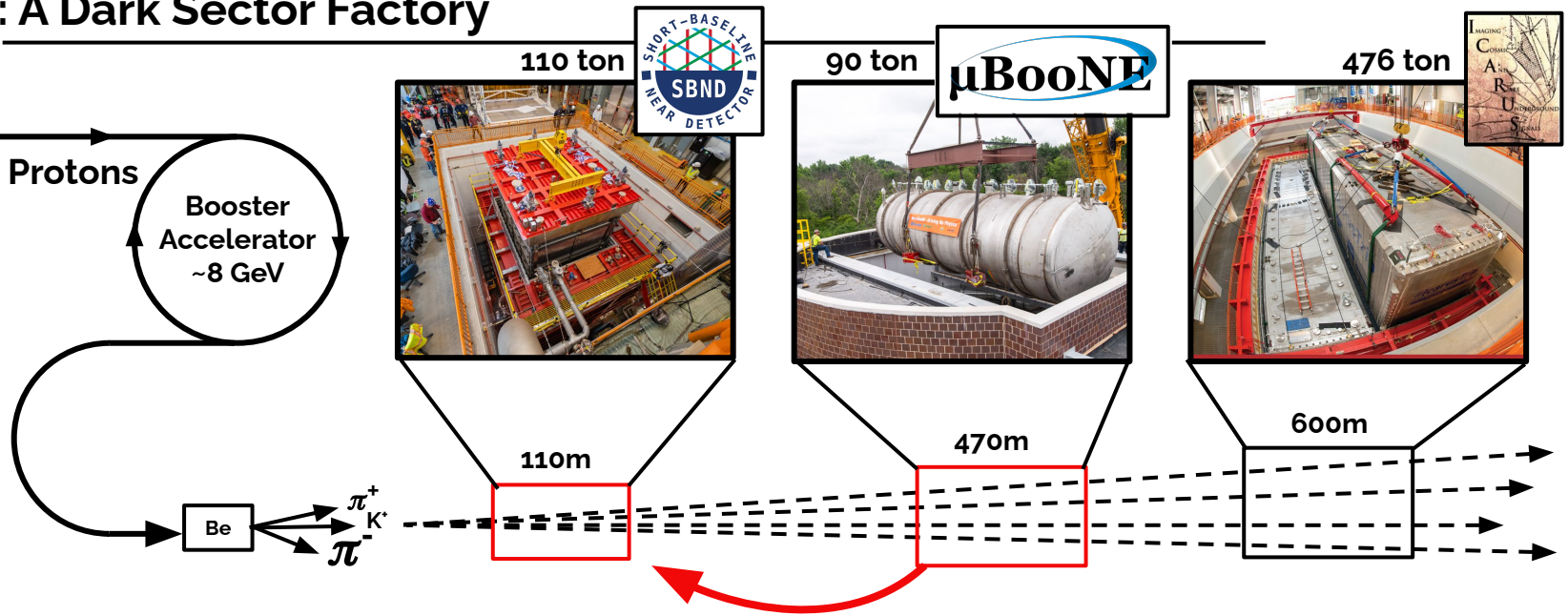


Based on:
A. Abdullahi, J. Hoefken Zink, M. Hostert, D. Massaro, S. Pascoli
arXiv:2308.02543 [hep-ph]



MicroBooNE
Phys.Rev.Lett. 132 (2024) 24, 241801

SBND : A Dark Sector Factory



A lot of dark sector physics is **not oscillatory** or L/E dependent

$$\propto \frac{1}{R^2}$$

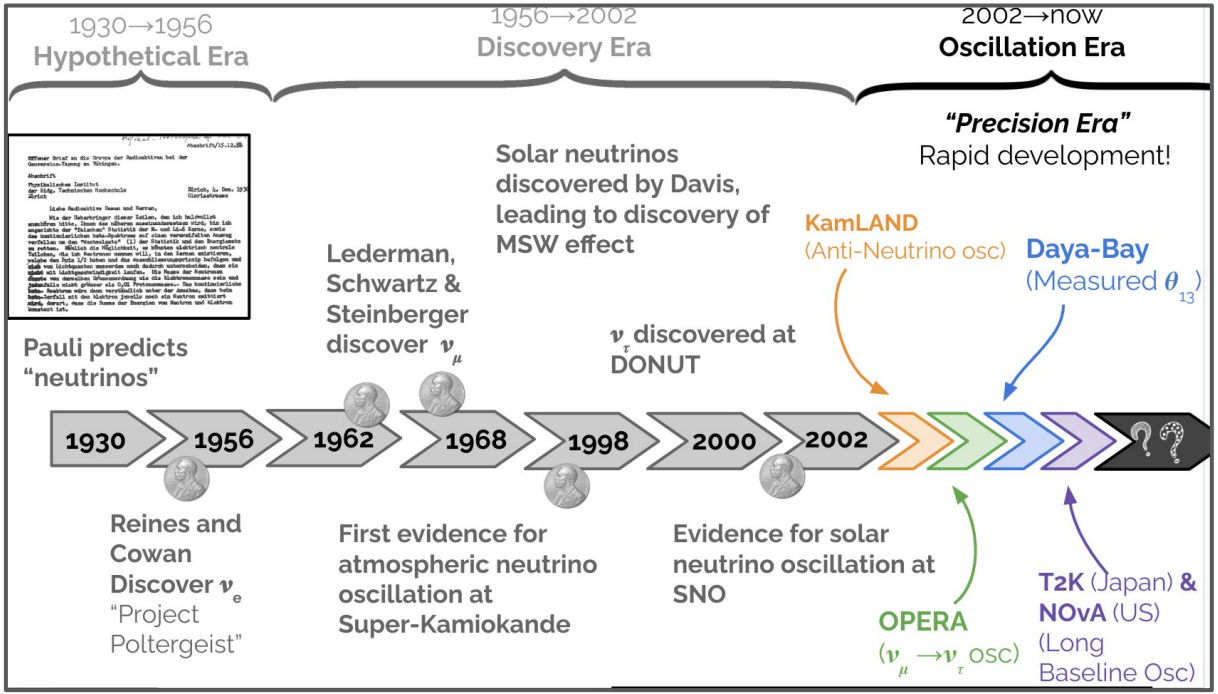
$$\frac{R^2_{uB}}{R^2_{SBND}} \approx \frac{470^2}{110^2} \approx 18$$

Huge Rate increase!

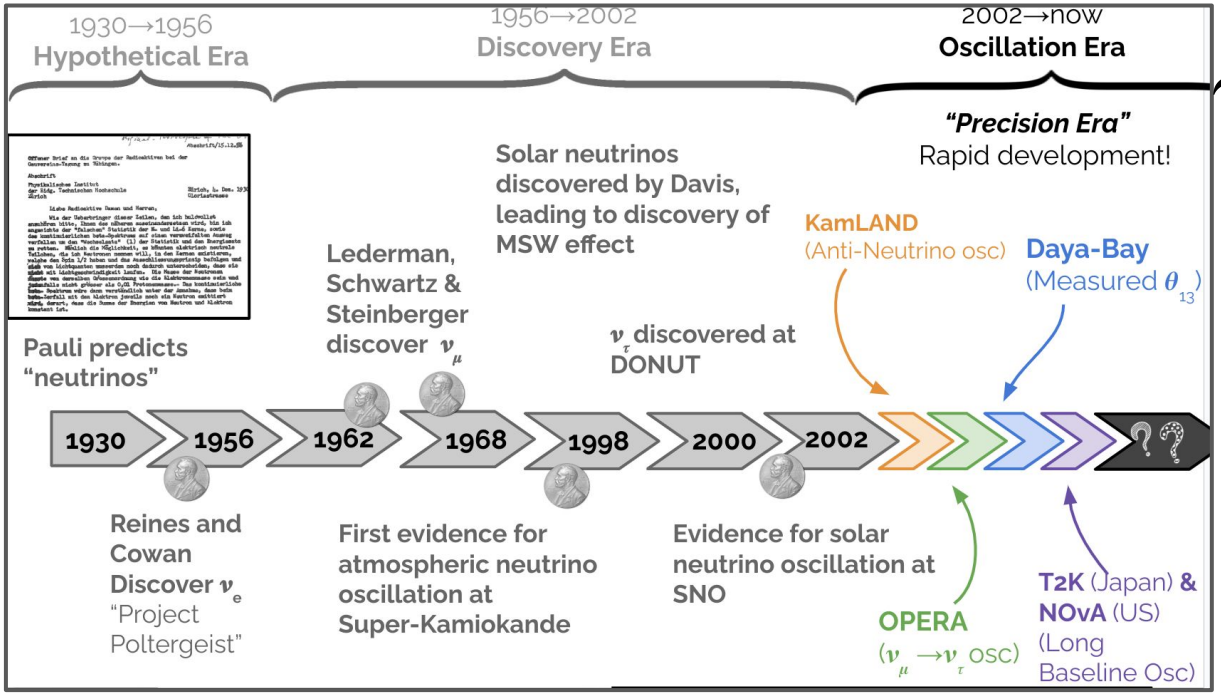
SBND will collect more data in **3 months** than MicroBooNE did in **5 years**!

6. Conclusions

Conclusions I



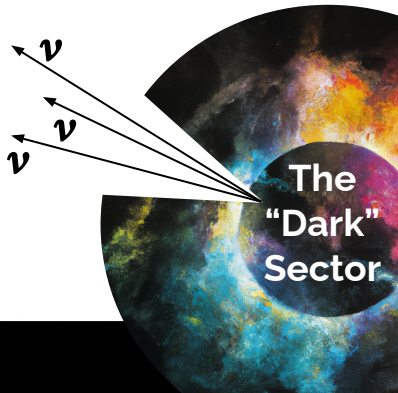
Conclusions I



Now→ Future

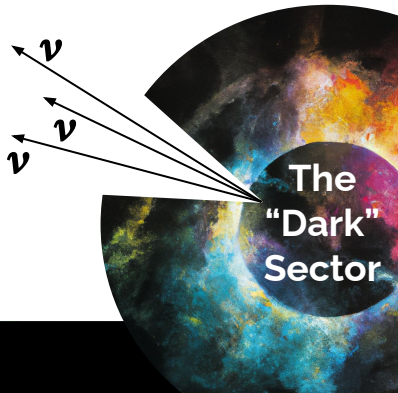
"Portal Era"

- **Access to increasingly high precision neutrino data**
- **Neutrinos as a tool**, or a *probe*, to **unlock new physics**



Conclusions II

- The 3-ν paradigm fits most global data astoundingly well
- But **persistent anomalies** still hint at something happening at **short-baselines** outside our understanding
  - *Regardless of your personal opinion of "light eV scale sterile neutrinos" the anomalies themselves remain unexplained!*
  - *Big Picture:* ***Let data point the way****!*



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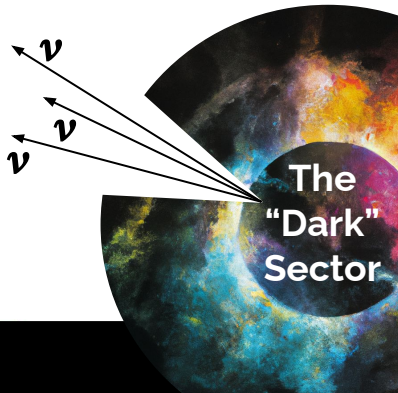
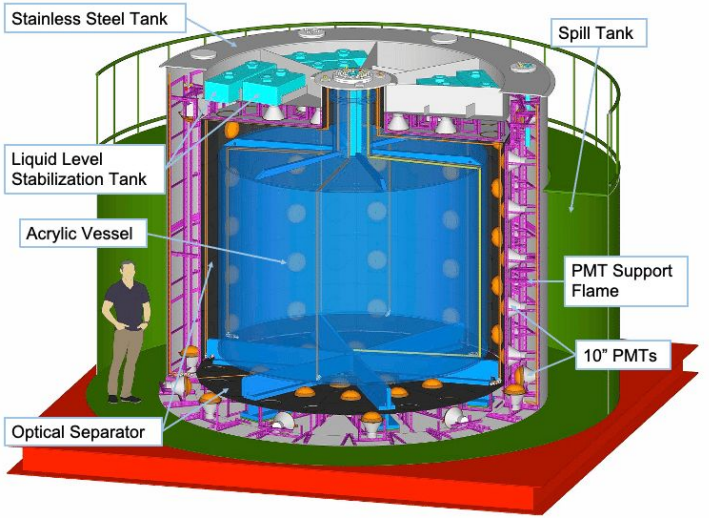
  - *Regardless of your personal opinion of "light eV scale sterile neutrinos" the anomalies themselves remain unexplained!*
  - *Big Picture: **Let data point the way**!*
- **MicroBooNE**, using **LArTPC technology**, has already **ruled out many possibilities** with first **photon** and **electron** searches, and has shown were capable of probing a vast array of possible explanations including *Dark Sector* ***e+e- results***
- **The full SBN program ,** with **three detectors** across **two neutrino beams** will prove invaluable as we probe deeper into the anomalies and the dark sector




Thank You!

JSNS² (**J**-PARC **S**terile **N**eutrino **S**earch at the **J**-PARC **S**pallation **N**eutron **S**ource)

- JSNS² provides a **clean** and **direct test** of the LSND anomaly.
- Uses the **same neutrino source** (pion decay-at-rest) , **same target**, and **same detection principle** (Inverse-beta-decay) as LSND.



JSNS² (**J**-PARC **S**terile **N**eutrino **S**earch at the **J**-PARC **S**pallation **N**eutron **S**ource)

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1st Phase: JSNS² [1310.1347]

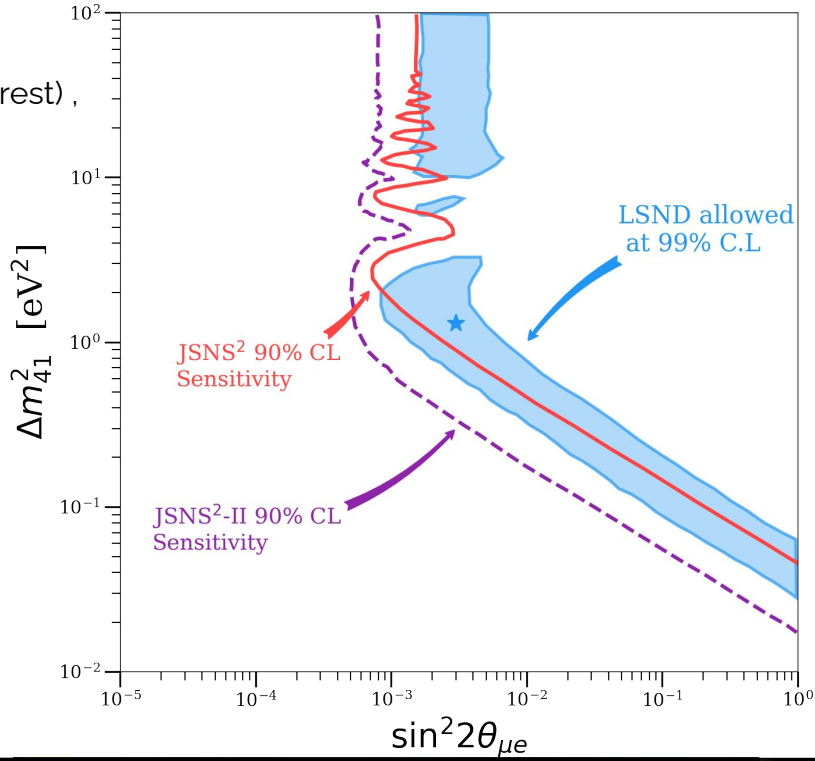
- Commissioned 2020, First physics data in 2021,
- Expect first results in 2023!

2nd Phase: JSNS²-II [2012.10807[

Upgrade to **two detectors**, Has been granted stage-2 approval

- Near@24m (17 tons, 120 10'' PMTs
- Far @ 28m (32 tons, 220 10'' PMTs)

Expected data taking in late 2023.



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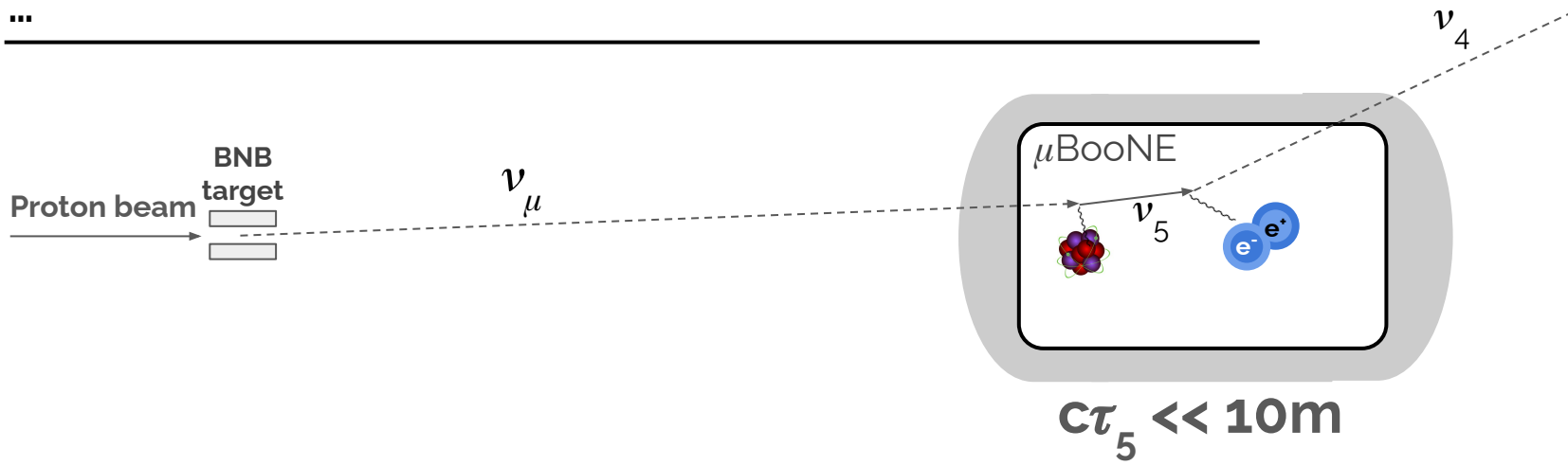

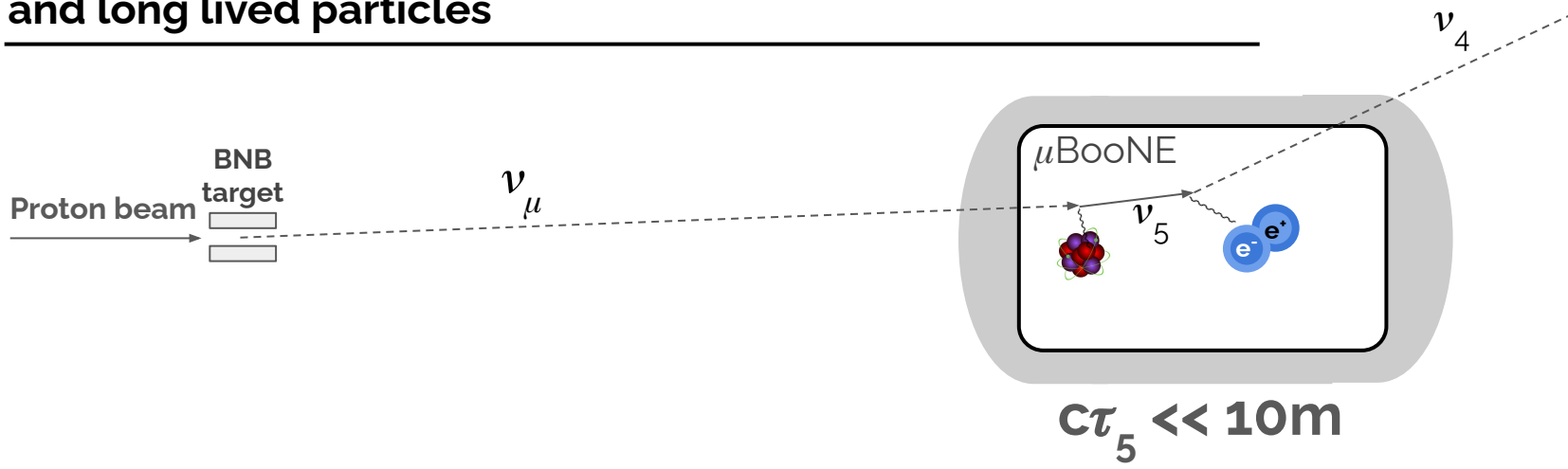

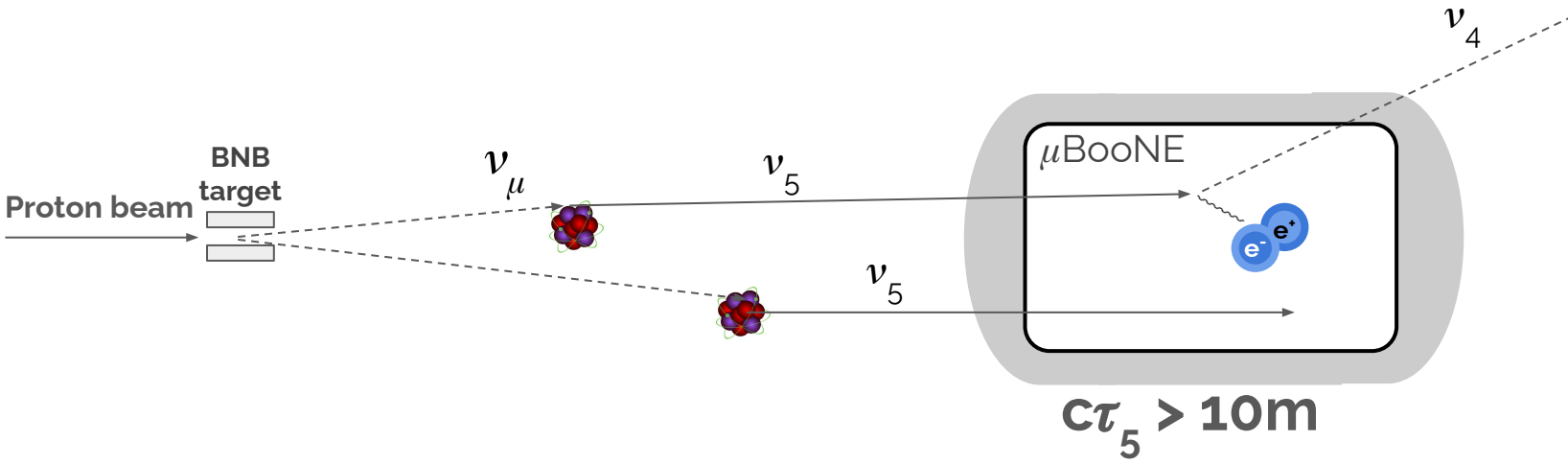

NuMi @ MicroBooNE