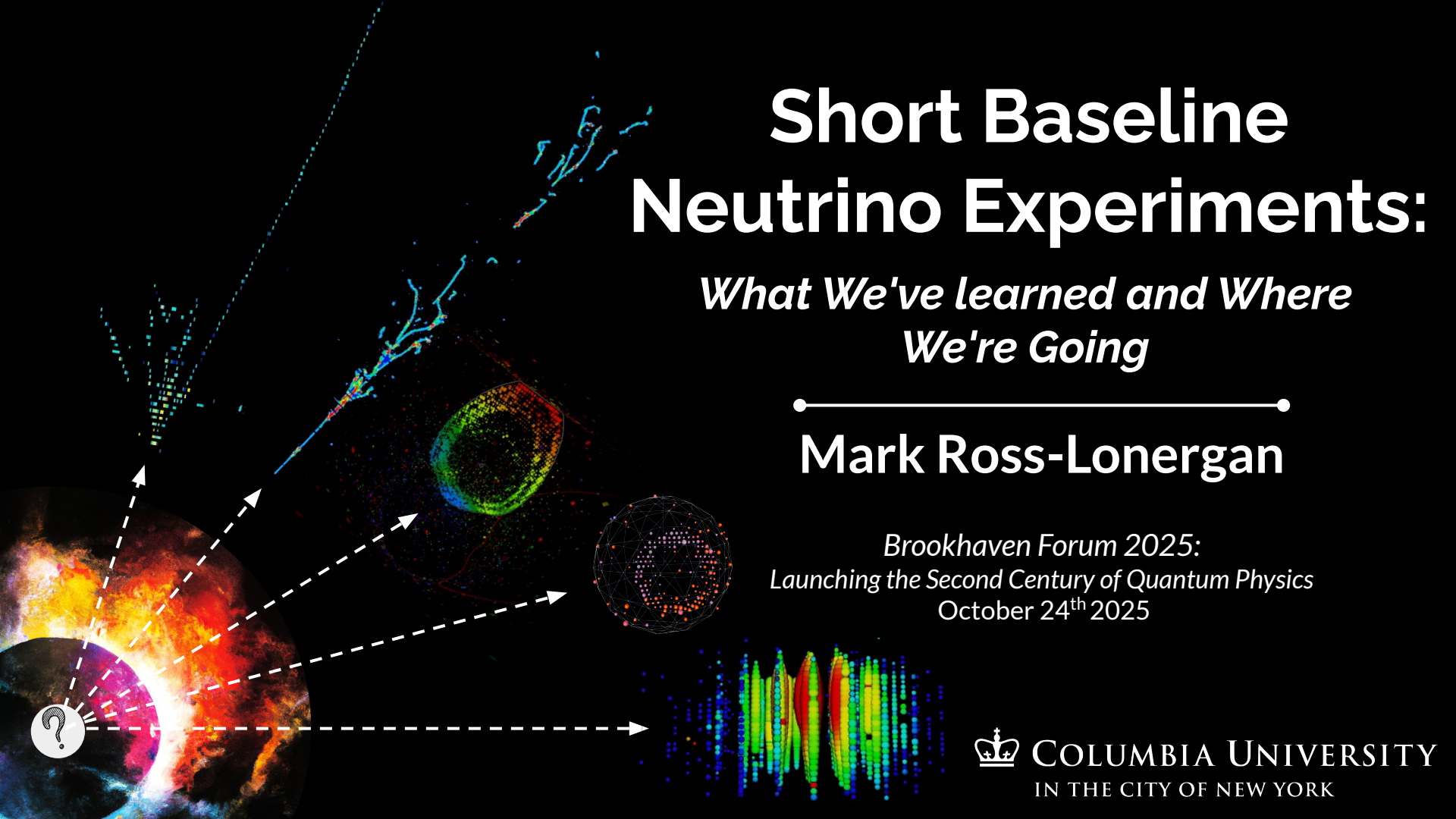


The background of the slide is a dark space filled with various scientific visualizations. On the left, a bright, fiery celestial body, possibly a supernova or a black hole, is shown with a white circle containing a question mark. Dashed white arrows radiate from this circle towards the right. In the upper left, there are blue and green particle tracks. In the center, there's a green, textured sphere. To its right is a wireframe sphere with orange dots. At the bottom right, there's a colorful, multi-layered structure resembling a particle detector or a complex data visualization.

Short Baseline Neutrino Experiments:

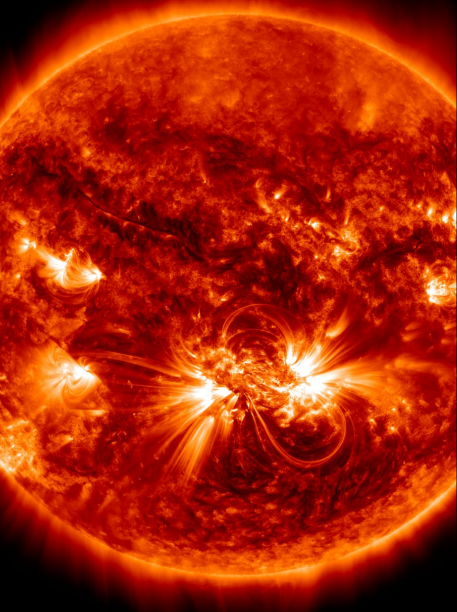
*What We've learned and Where
We're Going*

Mark Ross-Lonergan

*Brookhaven Forum 2025:
Launching the Second Century of Quantum Physics
October 24th 2025*

 **COLUMBIA UNIVERSITY**
IN THE CITY OF NEW YORK

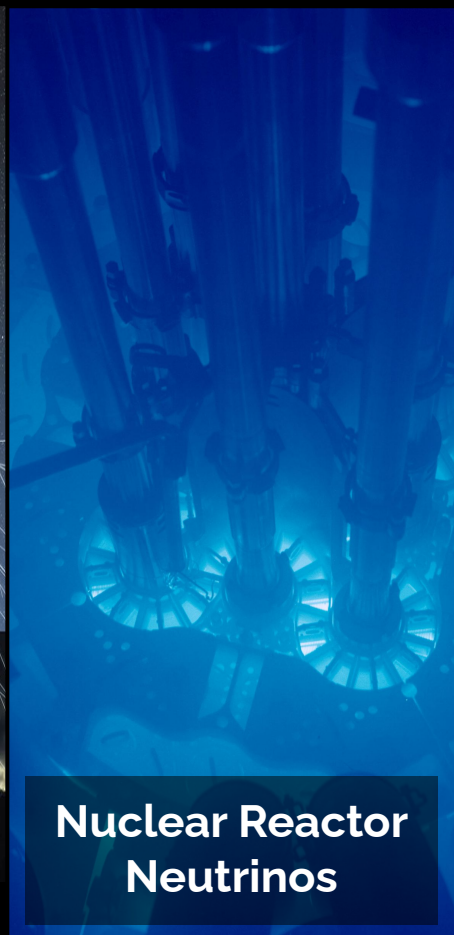
Neutrinos From Many Sources



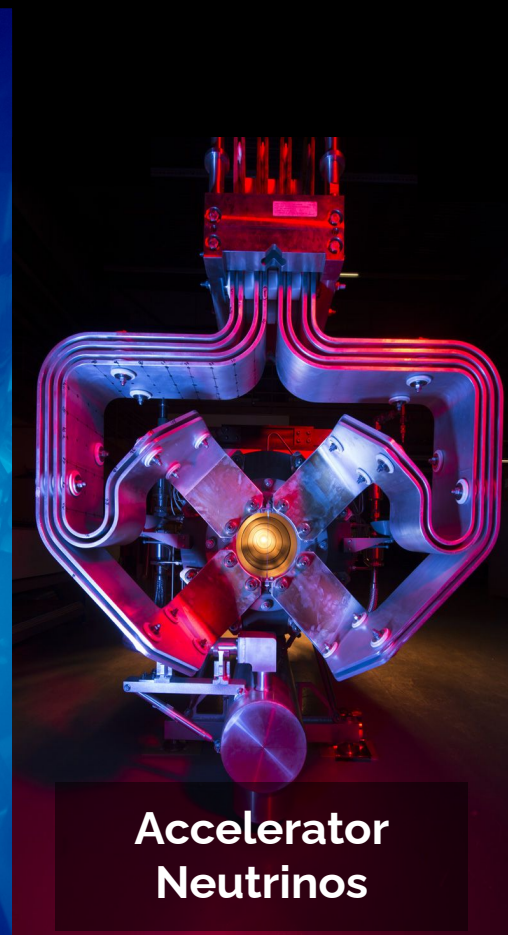
Solar Neutrinos



Atmospheric Neutrinos

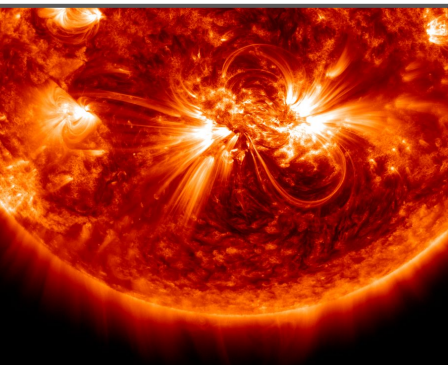
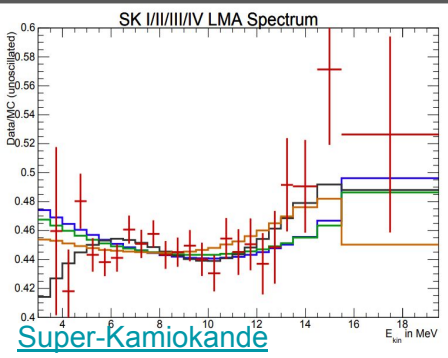


Nuclear Reactor Neutrinos

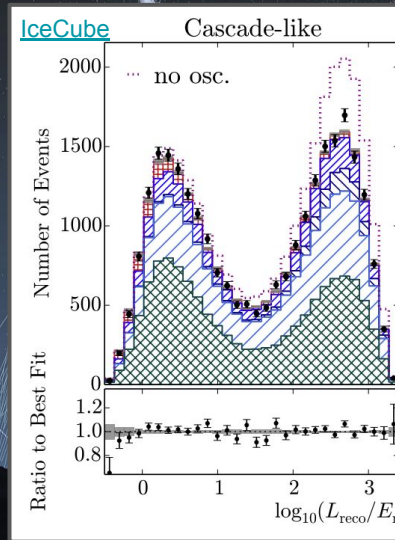


Accelerator Neutrinos

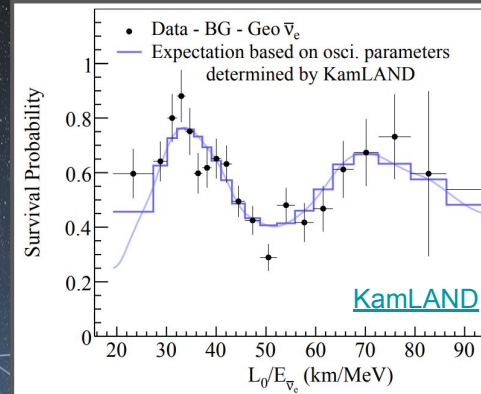
Neutrinos From Many Sources



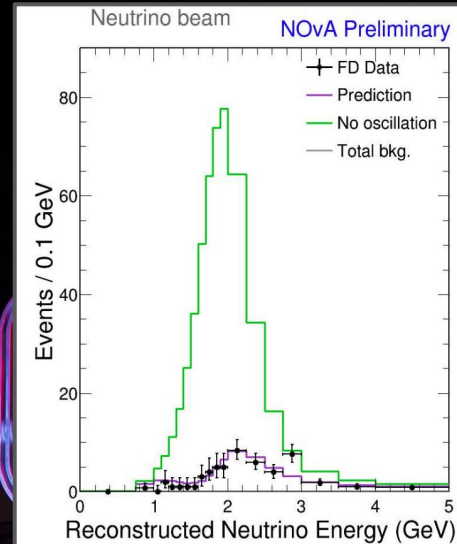
Solar Neutrinos



Atmospheric Neutrinos

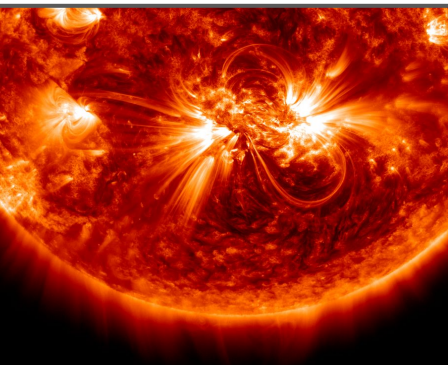
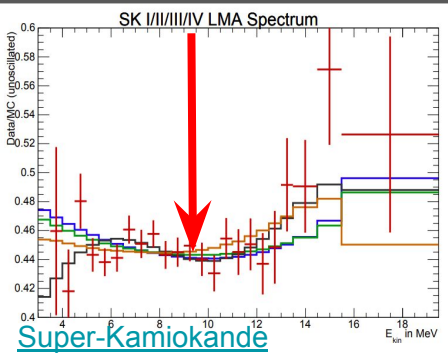


Nuclear Reactor Neutrinos

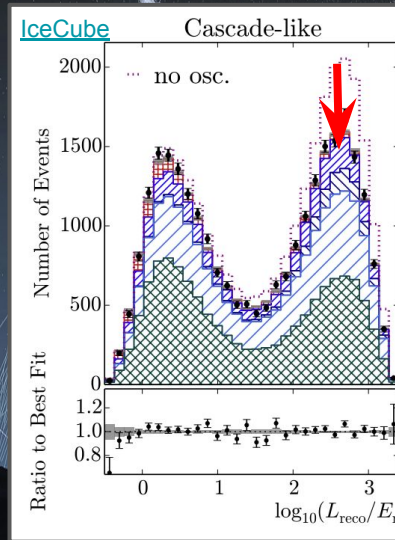


Accelerator Neutrinos

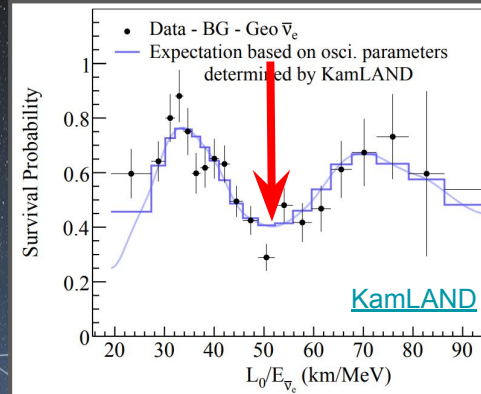
Neutrinos Oscillating From Many Sources



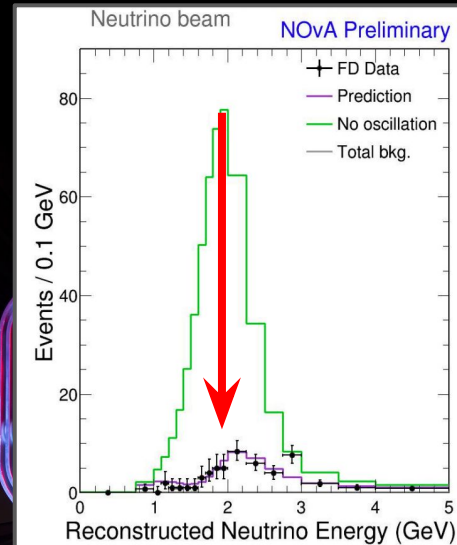
Solar Neutrinos



Atmospheric Neutrinos



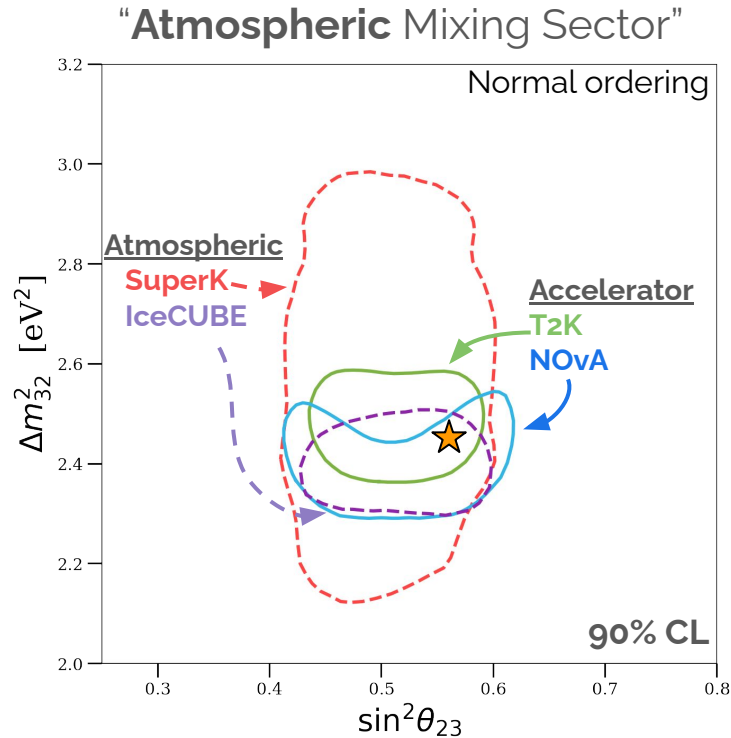
Nuclear Reactor Neutrinos



Accelerator Neutrinos

Stitches together in a surprisingly coherent way!

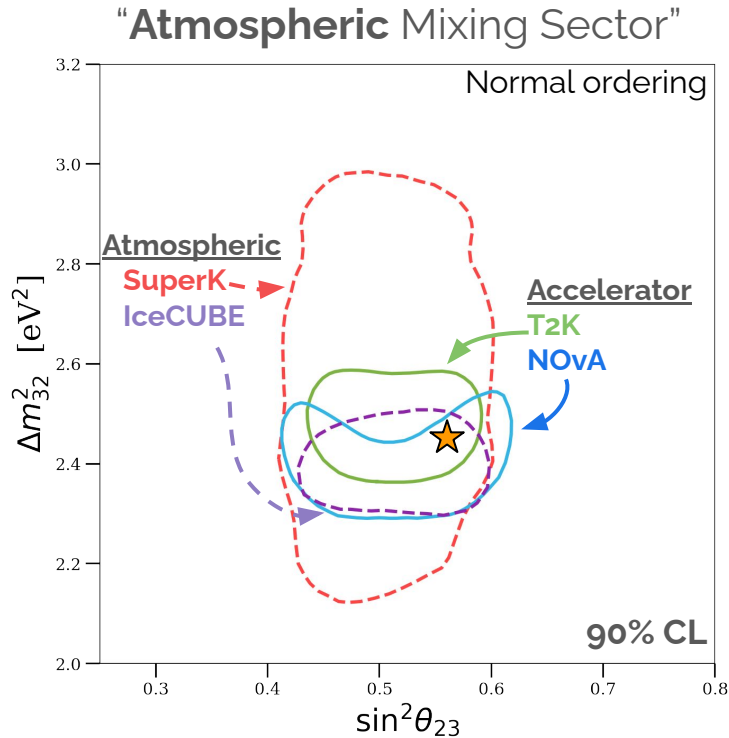
1. Introduction 3 ν Paradigm



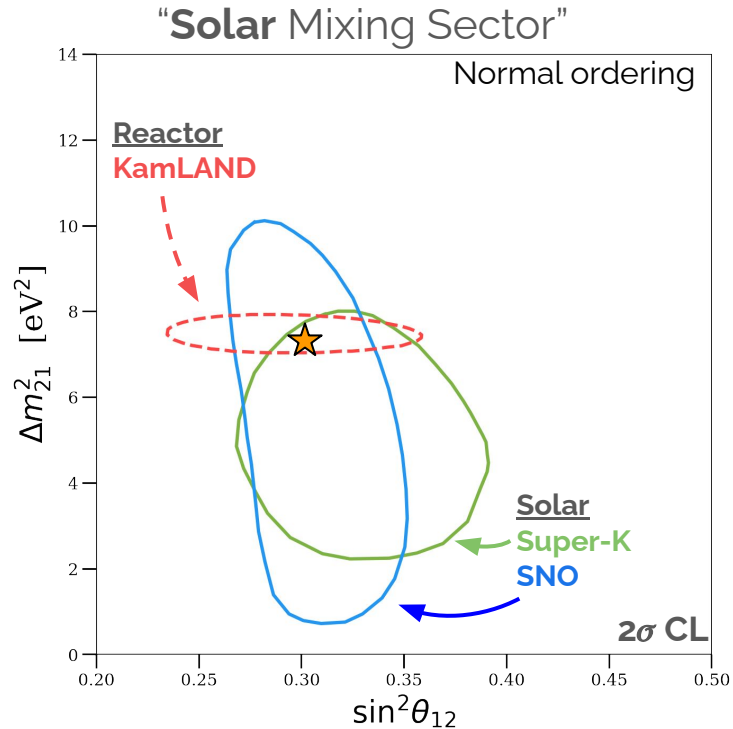
$$\Delta m^2_{32} = 2.5 \times 10^{-3} \text{eV}^2$$

Stitches together in a surprisingly coherent way!

1. Introduction 3 ν Paradigm



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



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

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

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

1. Introduction 3ν Paradigm

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

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

$$\theta_{12} \approx 34^\circ$$

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

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

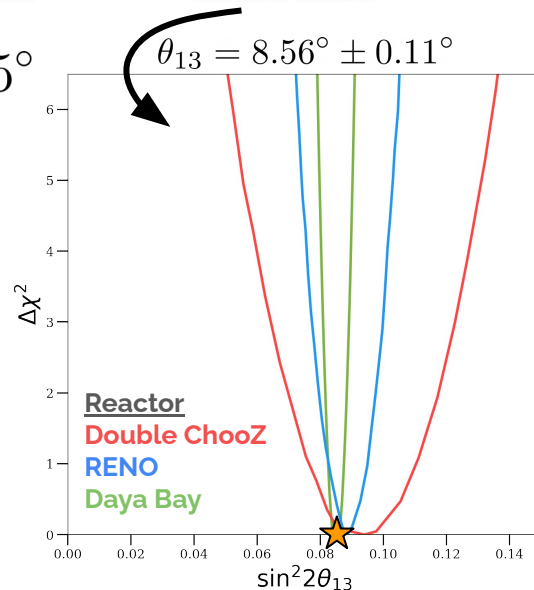
1. Introduction 3ν Paradigm

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

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

$$\theta_{13} = 8.56^\circ \pm 0.11^\circ$$

$$\theta_{12} \approx 34^\circ$$



Some remaining questions? Of course

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

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

1. Introduction 3ν Paradigm

Neutrino Mixing Matrix

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

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

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

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

$$\delta_{CP} \approx ?$$

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

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

Some remaining questions? .. we have plans!

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

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

Neutrino Mixing Matrix

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

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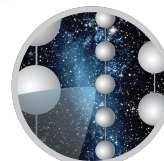
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The "**Mass Ordering**" problem

DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT



Hyper-Kamiokande



ICECUBE
Upgrade

+ Many more!

Three Neutrino Paradigm! Success!

1. Introduction 3ν Paradigm

Neutrino Mixing Matrix

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

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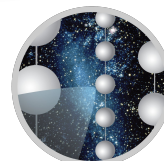
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DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT



Hyper-Kamiokande



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+ Many more!

Anomalies: Backbone of Neutrino Physics

1. Introduction
3 ν Paradigm
How we got here

1930→1956
Hypothetical Era



1930

Anomalies: Backbone of Neutrino Physics

1. Introduction
3v Paradigm
How we got here

1930→1956

Hypothetical Era

"Dear Radioactive Ladies and Gentlemen,"

Liebe Radioaktive Damen und Herren,

Offener Brief an die Gruppe der Radioaktiven bei der
Universitäts-Tagung in Röhlingen.
Abschrift
Physikalisches Institut
der Hög. Technischen Hochschule
Zürich
Liebe Radioaktive Damen und Herren,
Wie der Überbringer dieser Zeilen, den ich herzlichst
anrufen bitte, Ihnen das salbete auseinanderzusetzen wird, bin ich
angelehnt der "Falschen" Statistik der β - und α -Strahlung, sowie
des kontinuierlichen beta-Spektrums auf einen vermeintlichen Ausweg
verfallen um den "Wendekreis" (1) der Statistik und den Energieaus-
satz zu retten. Mithin die Möglichkeit, es könnten elektrisch neutrale
Teilchen, die ich Neutronen nennen will, in den Fernen existieren,
welche den Spin $1/2$ haben und das Ausschließungsprinzip befolgen und
sich von Lichtgeschwindigkeit unterscheiden, denn sie
gehen mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen
dürfte von derselben Größenordnung wie die Elektronenmasse sein und
sicherfalls nicht größer als $0,01$ Protonenmasse. Das kontinuierliche
beta-Spektrum wäre dann verständlich unter der Annahme, dass beim
beta-Verfall mit den Elektronen jeweils noch ein Neutron emittiert
wird, damit, dass die Summe der Energien von Neutron und Elektron
konstant ist.

Pauli predicts
"neutrinos"

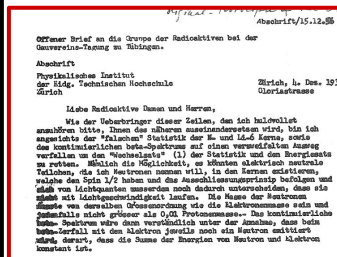
1930

Anomalies: Backbone of Neutrino Physics

1. Introduction 3 ν Paradigm How we got here

1930→1956

Hypothetical Era



"Dear Radioactive Ladies and Gentlemen,"

Liebe Radioaktive Damen und Herren,

Pauli predicts "neutrinos"

1930



- Neutrinos played a pivotal role in first century of Quantum Physics and will continue to do so in the second!
- Lets get planning for **2030**, a **Century of Neutrino Physics!**

Anomalies: Backbone of Neutrino Physics

1. Introduction 3 ν Paradigm How we got here

1930→1956

Hypothetical Era

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verfallen um den "Wundergeist" (1) der Statistik und den Burgen
zu reiten. Nämlich die Möglichkeit, es könnten elektrisch neutrale
Teilchen, die ich Neutrinos nennen will, in den Fermi-Strahlung
versteckt sein. Diese Teilchen haben die Spin $1/2$ und das Ausschließungsprinzip befolgen und
sich von Lichtgeschwindigkeit unterscheiden. Die Masse der Neutrinos
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 β -Zerfall mit den Elektronen jeweils noch ein Neutrino emittiert
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"Dear Radioactive Ladies and Gentlemen,"
Liebe Radioaktive Damen und Herren,

Pauli predicts
"neutrinos"

1930

1956



Reines and
Cowan
Discover ν_e
"Project
Poltergeist"



PROPERTIES OF THE NEUTRINO

Spin : $1/2\hbar$.

Mass : $< 1/500$ electron mass, if any.

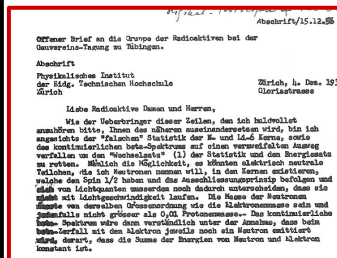
Charge : 0.

Magnetic moment : $< 10^{-8}$ Bohr magneton

Anomalies: Backbone of Neutrino Physics

1. Introduction 3v Paradigm How we got here

1930→1956 Hypothetical Era

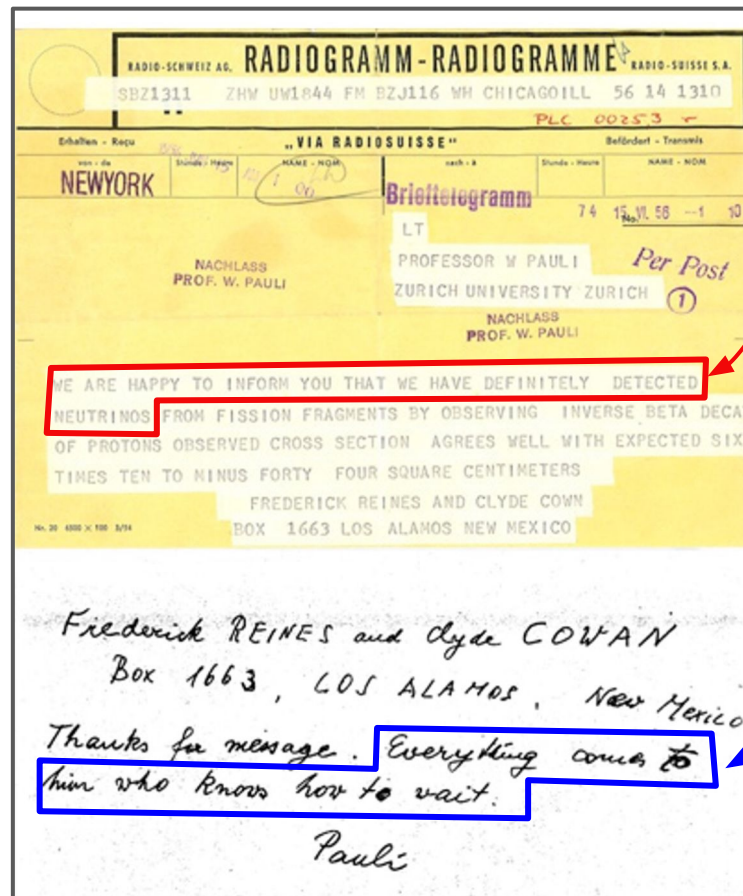


Pauli predicts “neutrinos”

1930

1956

Reines and
Cowan
Discover ν_e
“Project
Poltergeist”



“We are happy to
inform you we have
definitely detected
neutrinos”

Reines & Cowan

“Everything comes to
him who knows how
to wait”

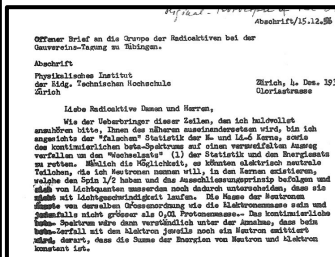
Pauli

Anomalies: Backbone of Neutrino Physics

1. Introduction 3 ν Paradigm How we got here

1930→1956
Hypothetical Era

1956→2002
Discovery Era



Lederman,
Schwartz &
Steinberger
discover ν_μ

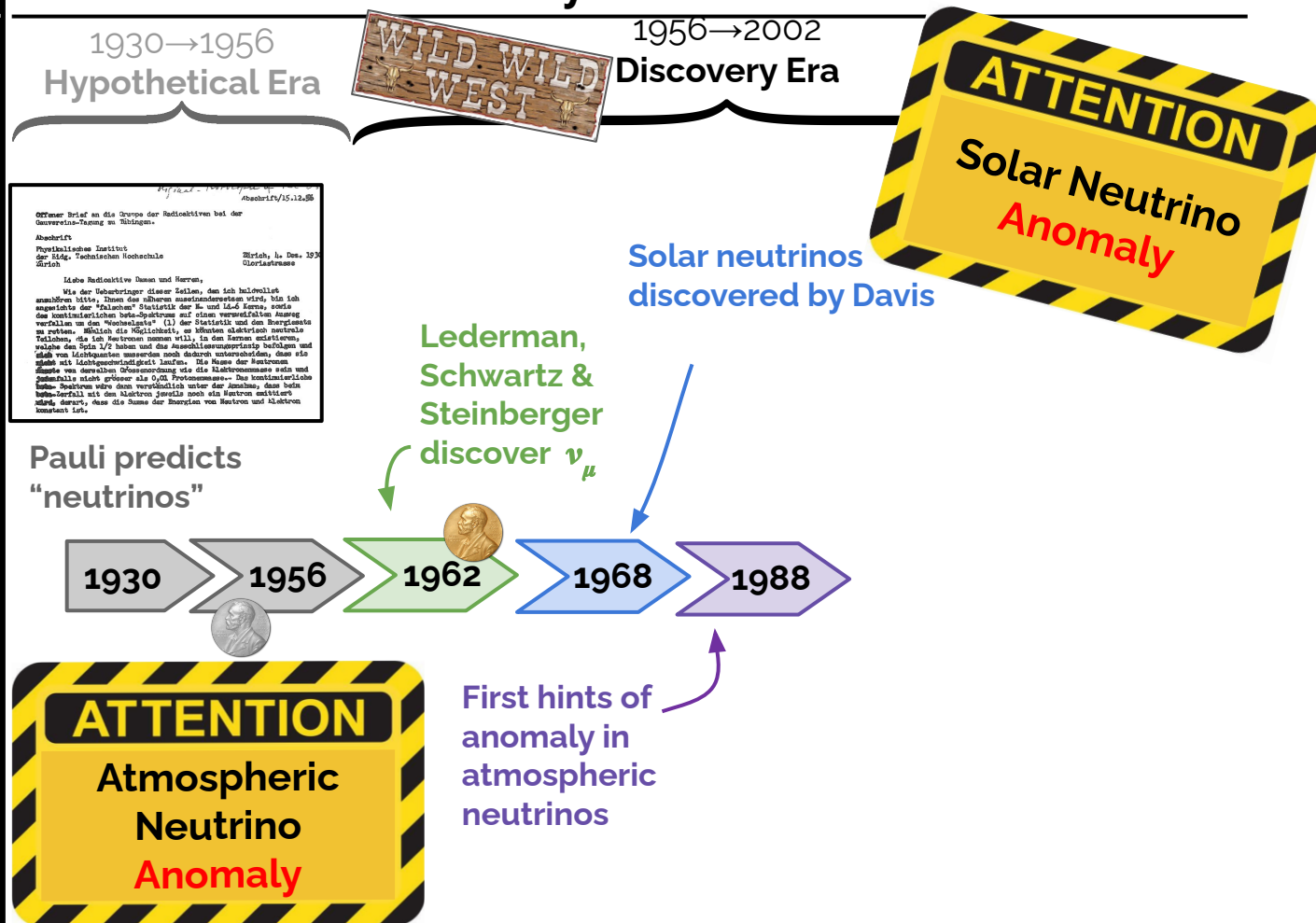
Pauli predicts
"neutrinos"



Reines and
Cowan
Discover ν_e
"Project
Poltergeist"

Anomalies: Backbone of Neutrino Physics

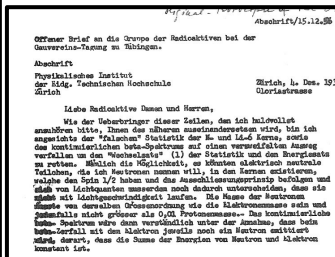
1. Introduction 3 ν Paradigm How we got here



Anomalies: Backbone of Neutrino Physics

1. Introduction 3^v Paradigm How we got here

1930→1956
Hypothetical Era



Pauli predicts
“neutrinos”

1930

1956



ATTENTION

Atmospheric
Neutrino
Anomaly



1956→2002
Discovery Era

Solar neutrinos
discovered by Davis

Lederman,
Schubert, et al.



NEUTRINO MOMENTS, MASSES AND CUSTODIAL SU(2) SYMMETRY *

Howard GEORGI and Michael LUKE

Lyman Laboratory of Physics, Harvard University, Cambridge, MA 02138, USA

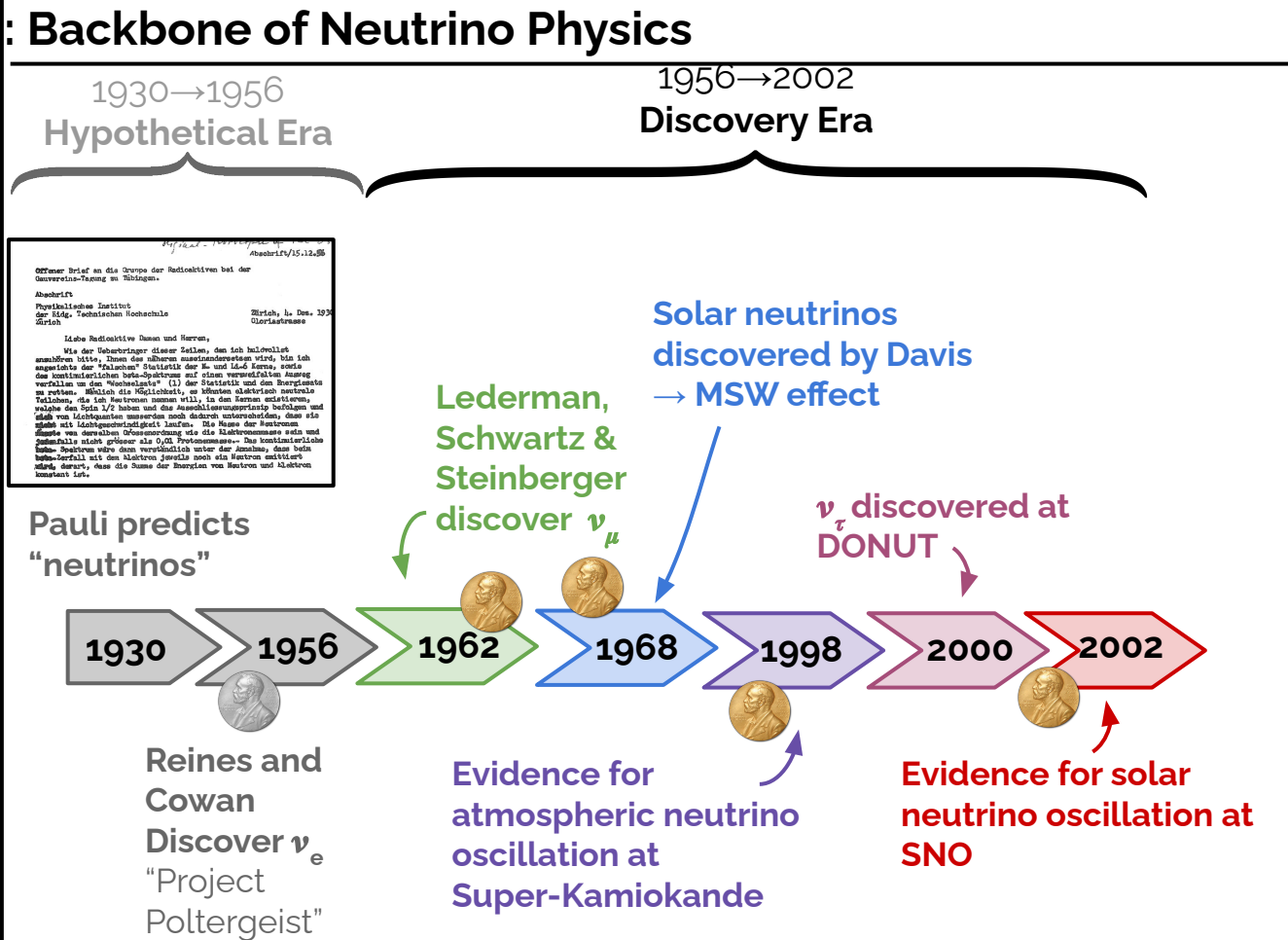
Received 17 April 1990

1. The problem

Most likely, the solar neutrino problem [1] has nothing whatever to do with particle physics. It is a great triumph that astrophysicists are able to predict the number of B^8 neutrinos coming from the sun as well as they do, to within a factor of 2 or 3 [2]. However, one aspect of the solar neutrino data, the apparent modulation of the flux of solar neutrinos with the sun-spot cycle, is certainly

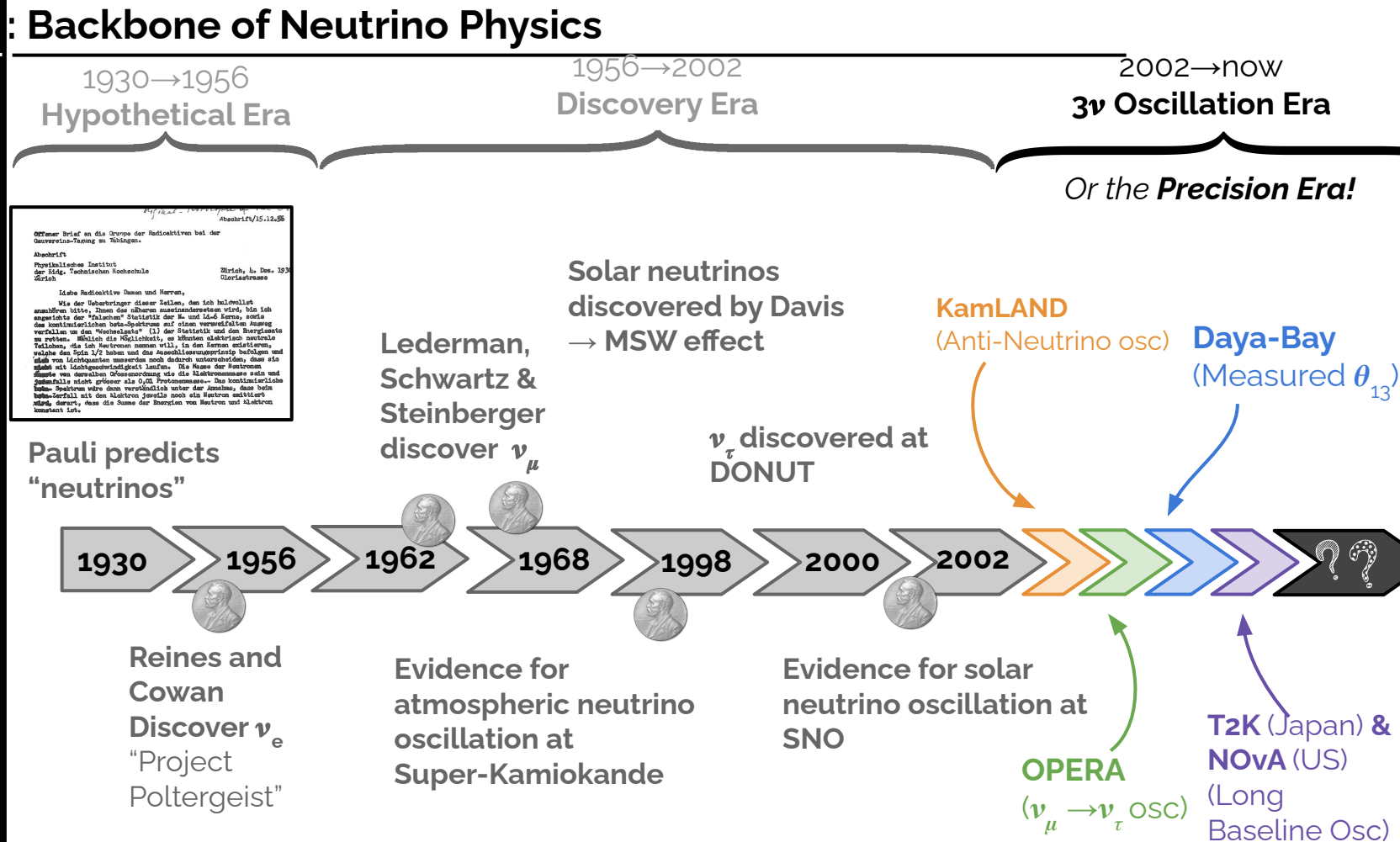
Anomalies: Backbone of Neutrino Physics

1. Introduction 3 ν Paradigm How we got here



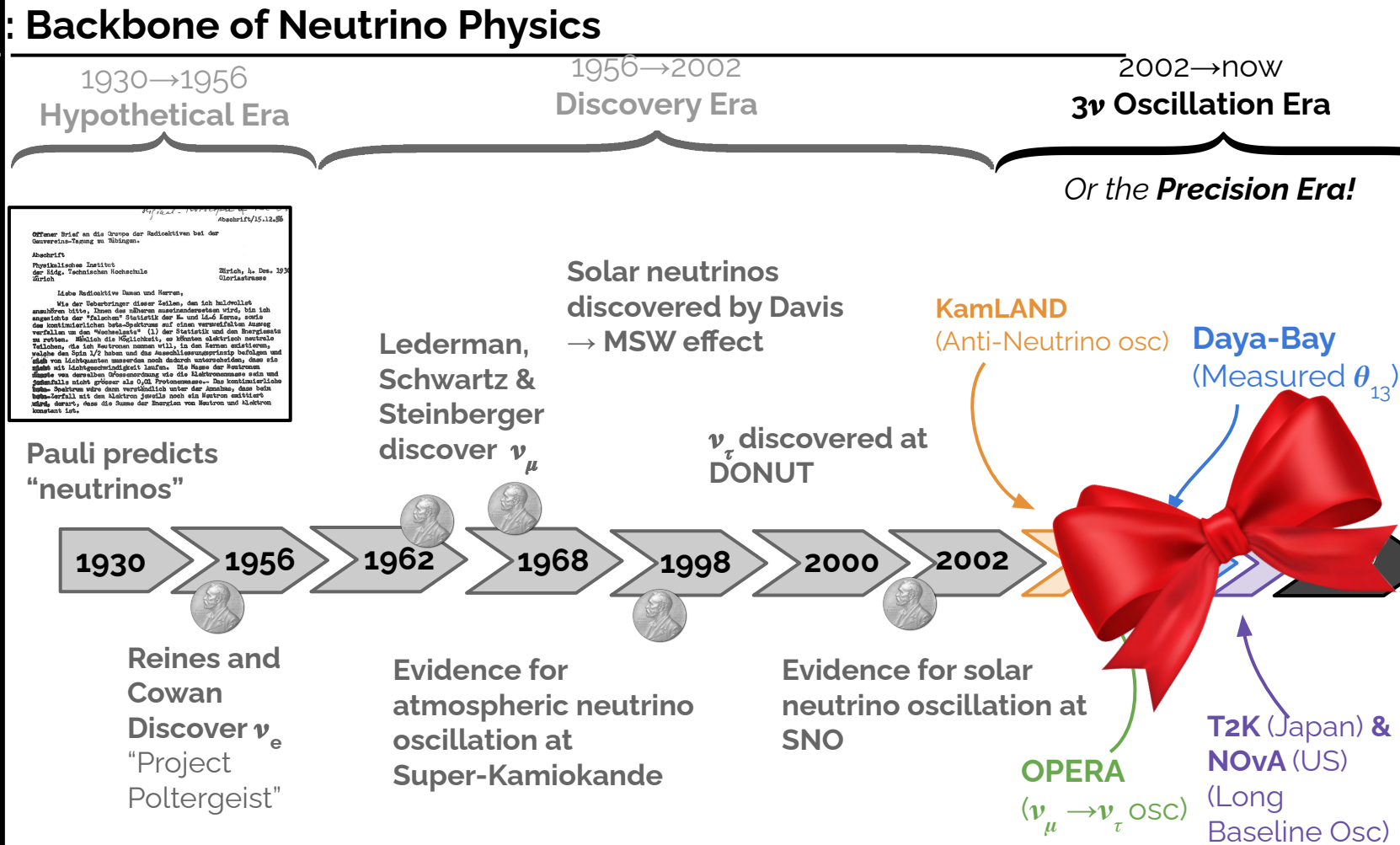
Anomalies: Backbone of Neutrino Physics

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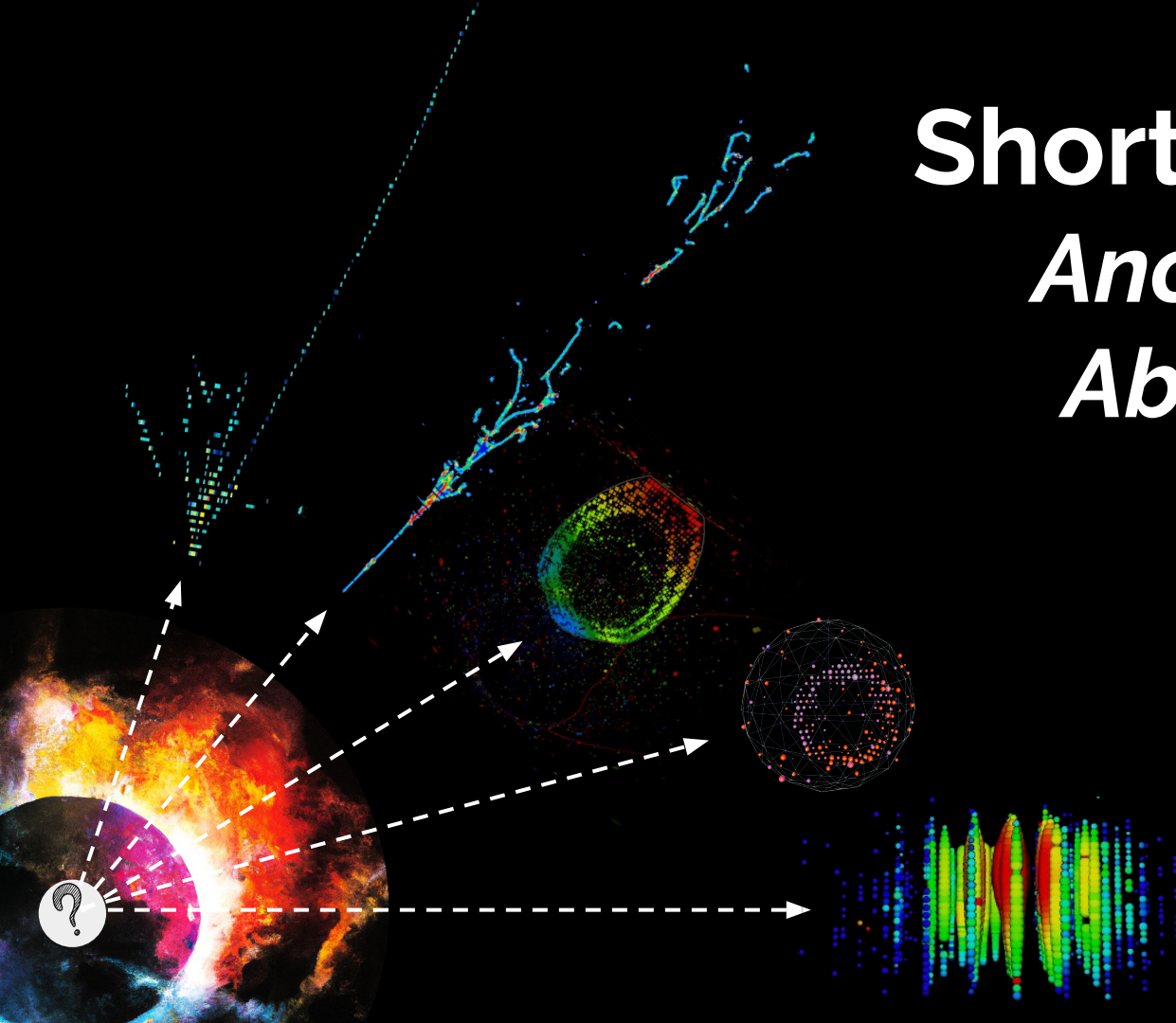


Anomalies: Backbone of Neutrino Physics

1. Introduction 3 ν Paradigm How we got here

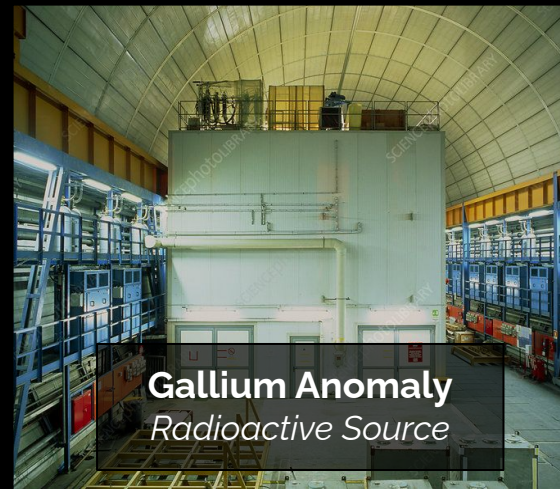
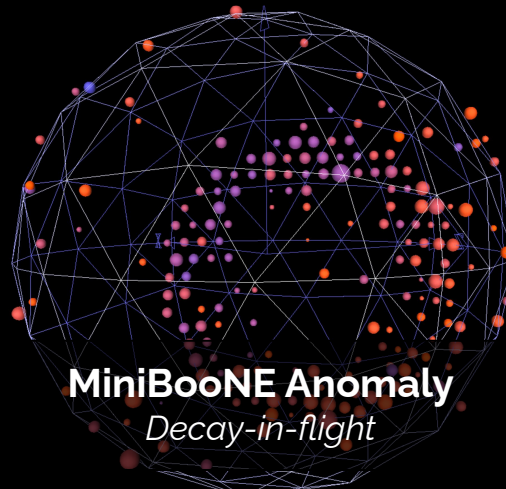


Short Baselines: *Anomalies in Abundance*



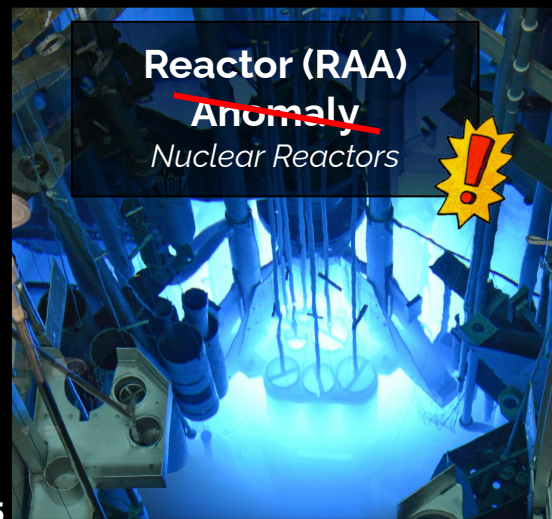
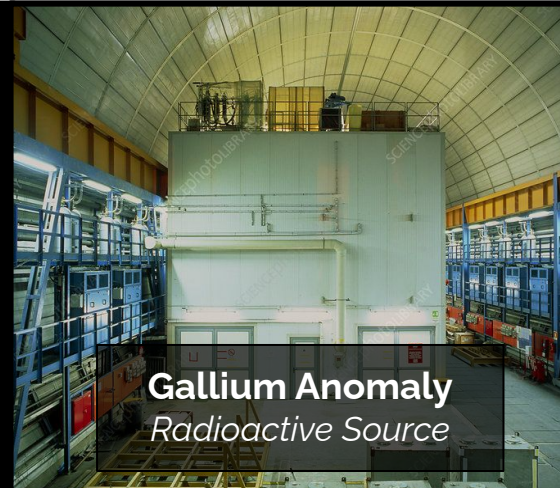
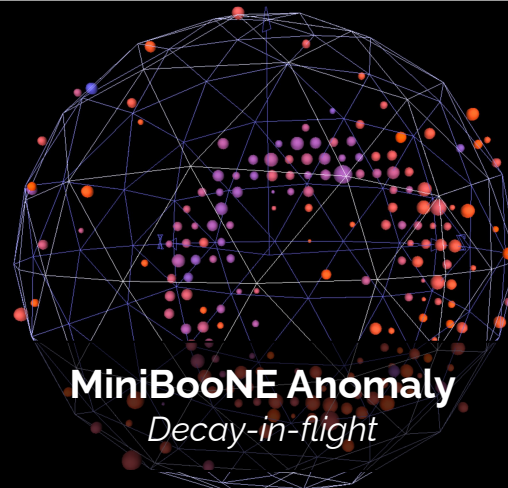
The Short Baseline Anomalies

1. Introduction
3 ν Paradigm
How we got here
2. Short-Baselines
Anomalies



The Short Baseline Anomalies

1. Introduction
3 ν Paradigm
How we got here
2. Short-Baselines
Anomalies



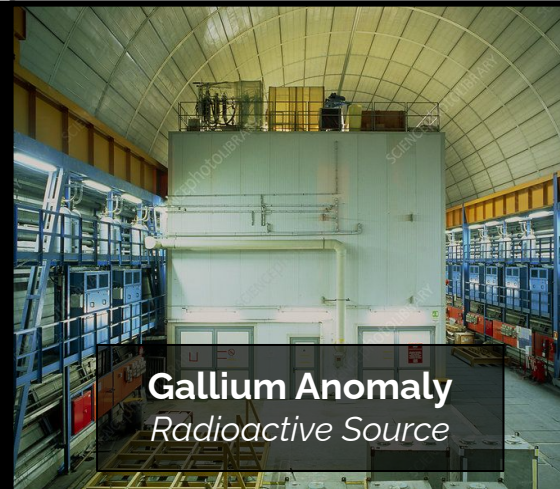
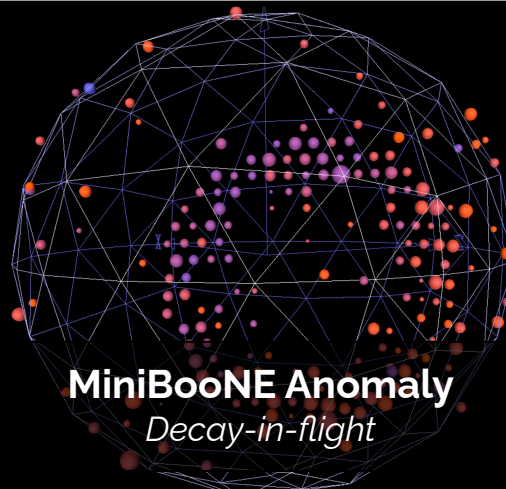
**No longer an
anomaly with
modern flux
calculations!**

←
Won't mention again.

The Short Baseline Anomalies

1. Introduction
3 ν Paradigm
How we got here

2. Short-Baselines
Anomalies



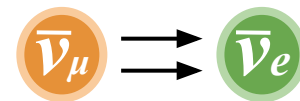
The LSND Anomaly

1. Introduction
3 ν Paradigm
How we got here

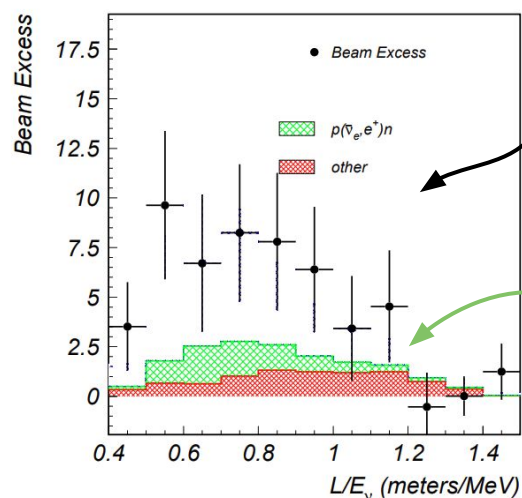
2. Short-Baselines
Anomalies



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



Observed a **3.8 σ** significance excess



Background ν_e contamination was at the level of **0.078%**

The MiniBooNE Anomaly

1. Introduction

3 ν Paradigm

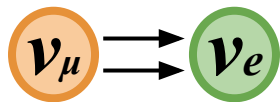
How we got here

2. Short-Baselines

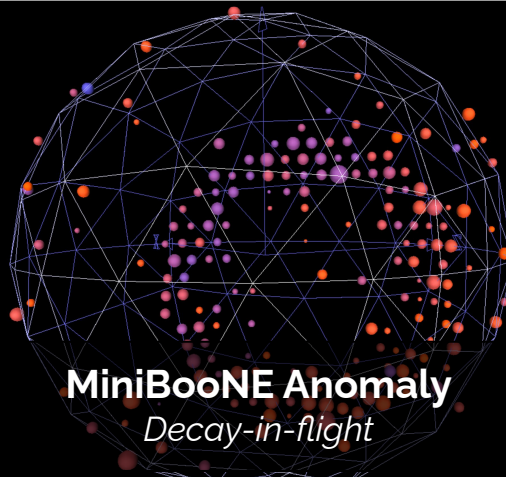
Anomalies

MiniBooNE was an 800 ton
Cherenkov detector

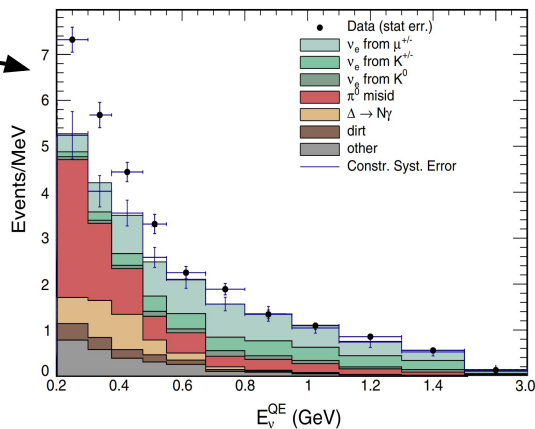
$\nu_\mu \rightarrow \nu_e$ appearance
oscillations using neutrinos
from **meson decay-in-flight**
at the Booster Neutrino
Beam (BNB) at **Fermilab**



Observed a **4.8 σ**
significance excess



MiniBooNE Anomaly
Decay-in-flight

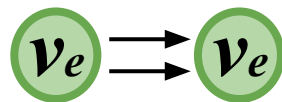


The Gallium Anomaly

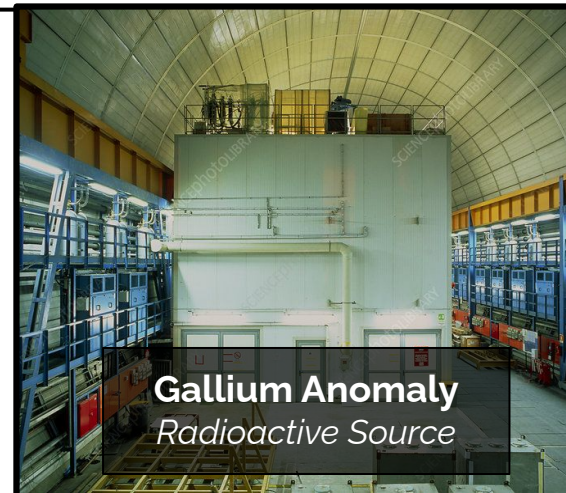
1. Introduction
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How we got here
2. Short-Baselines
Anomalies

Looking for neutrinos from radioactive ^{51}Cr and ^{37}Ar sources in two experiments **SAGE** and **GALLEX** circa 1999.

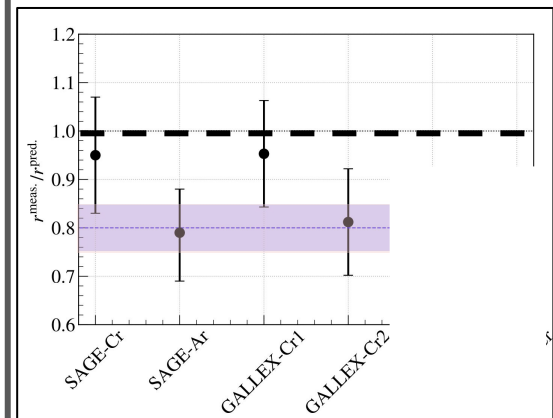
Sensitive to $\nu_e \rightarrow \nu_e$ disappearance oscillations



Observed a $\sim 2.5\sigma$ significance deficit



Gallium Anomaly
Radioactive Source



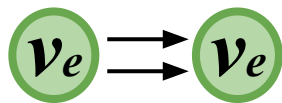
The Gallium Anomaly

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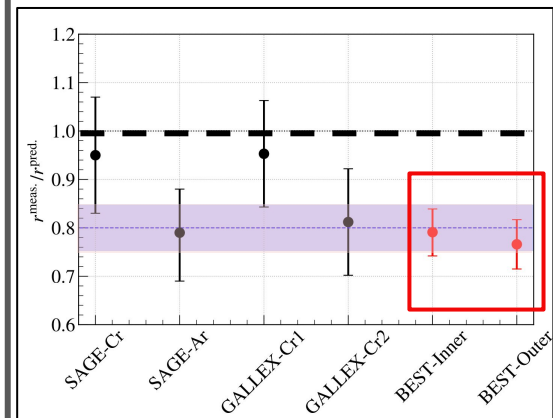
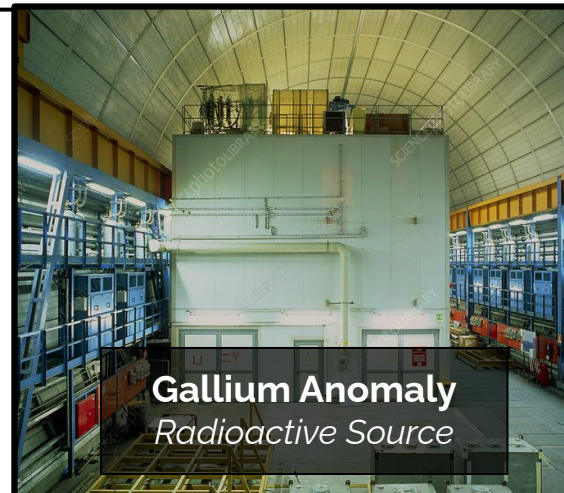
Looking for neutrinos from radioactive ^{51}Cr and ^{37}Ar sources in two experiments **SAGE** and **GALLEX** circa 1999.

Recently replicated by the **BEST** experiment
([PhysRevLett.128.232501](https://arxiv.org/abs/2205.08801) (2022))

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



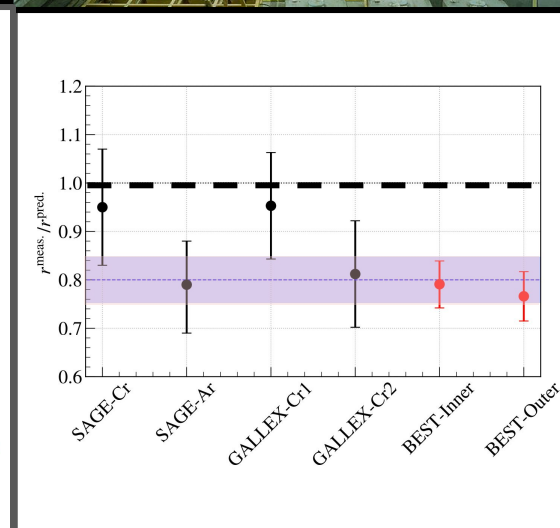
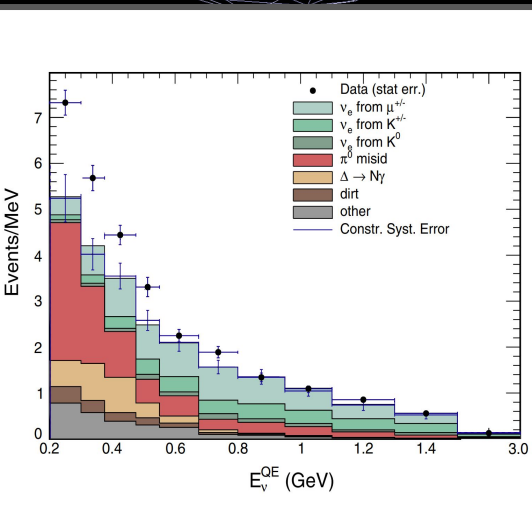
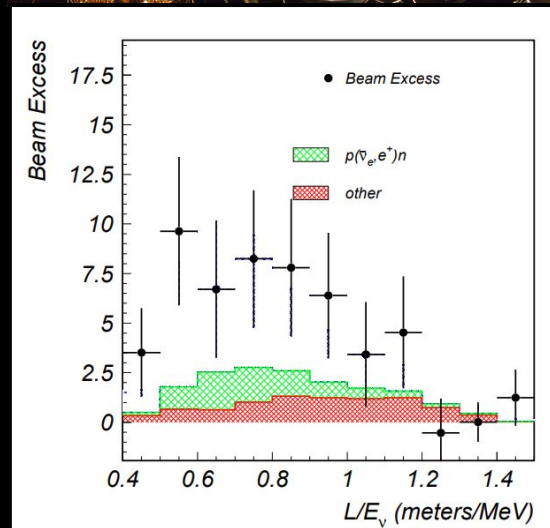
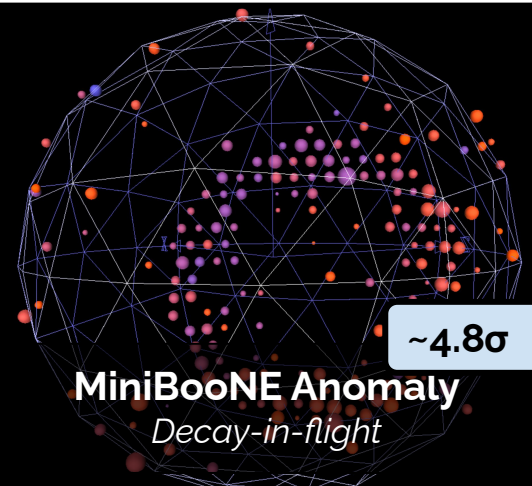
Observed a **$\sim 4.0\sigma$**
significance deficit



The Short-Baseline Anomalies

1. Introduction
3 ν Paradigm
How we got here

2. Short-Baselines
Anomalies

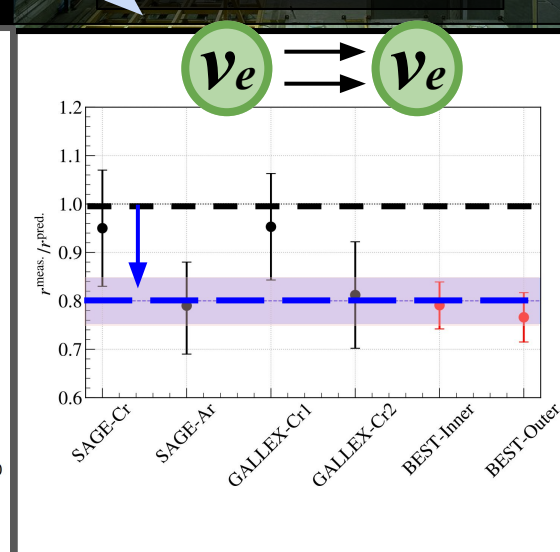
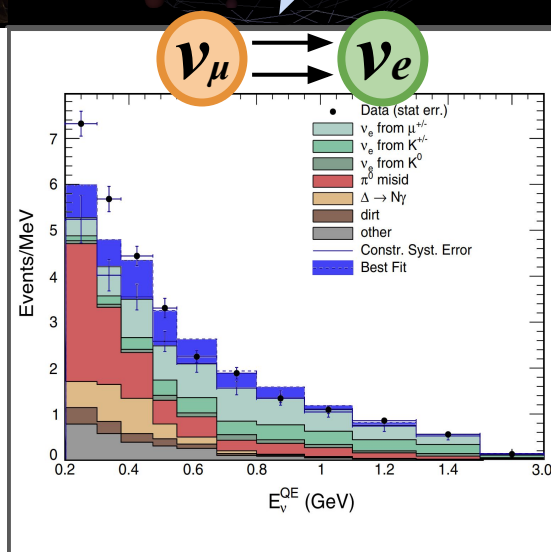
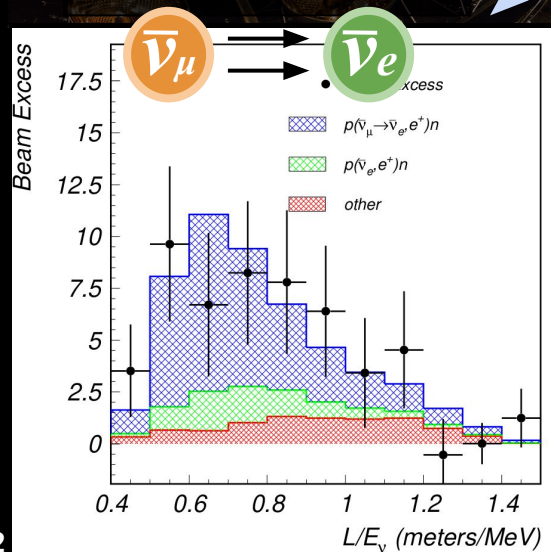
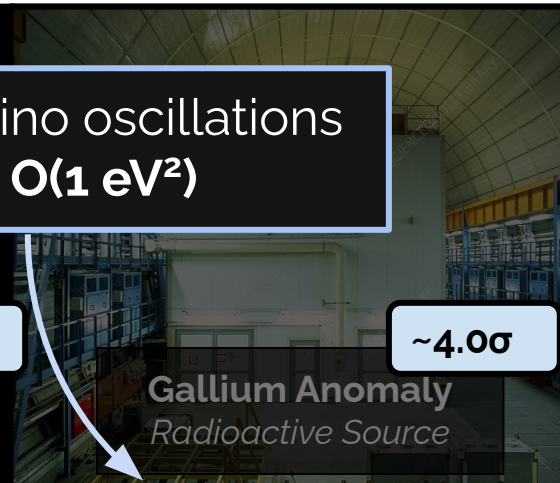
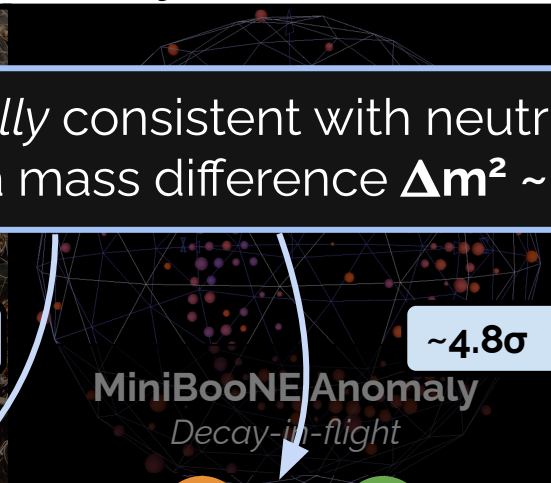


The Short-Baseline Anomalies, discovery of a New Neutrino?

1. Introduction
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2. Short-Baselines
Anomalies

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



A Sterile Neutrino?

1. Introduction

3 ν Paradigm

How we got here

2. Short-Baselines

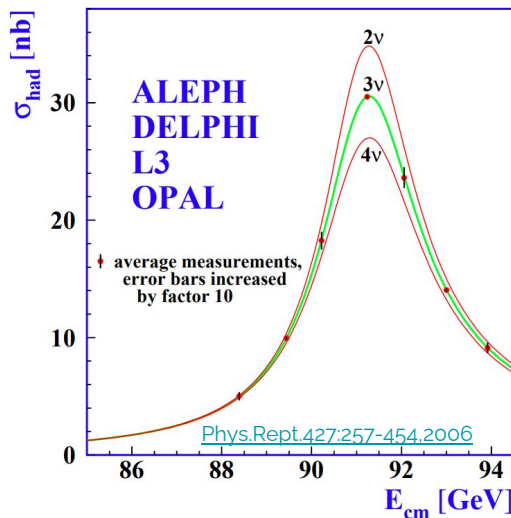
Anomalies

Sterile Neutrinos

Mass difference $\Delta m^2 \sim \mathcal{O}(1 \text{ eV}^2)$

This does **not line up** with the global "**3 neutrino paradigm**" picture and LEP electroweak precision data

"e⁺e⁻ → hadron" cross-section at LEP



$$\Delta m^2 \approx 1 \text{ eV}^2$$

ν_4

Need a 4th "sterile" neutrino

⋮

ν_3

3 Neutrino Paradigm

ν_2

ν_1

$$\Delta m_{31}^2 = 2.5 \times 10^{-3} \text{ eV}^2$$

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



1. Introduction

3ν Paradigm

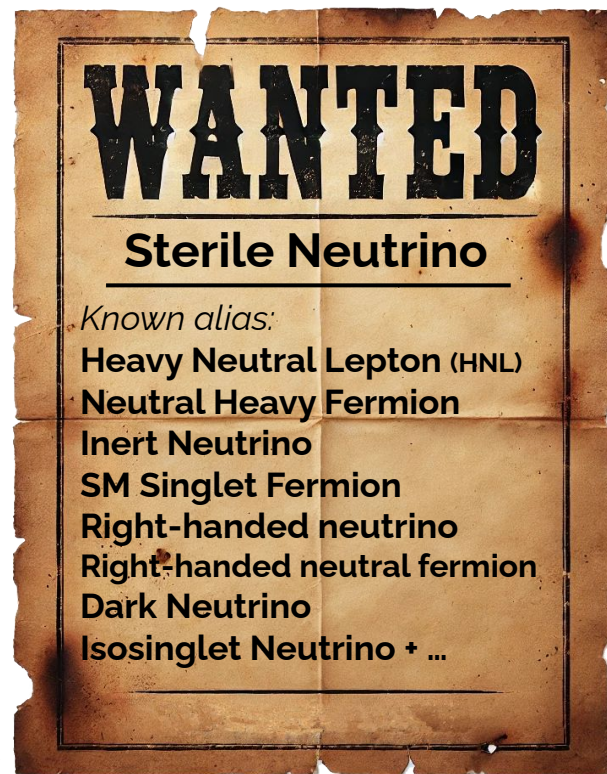
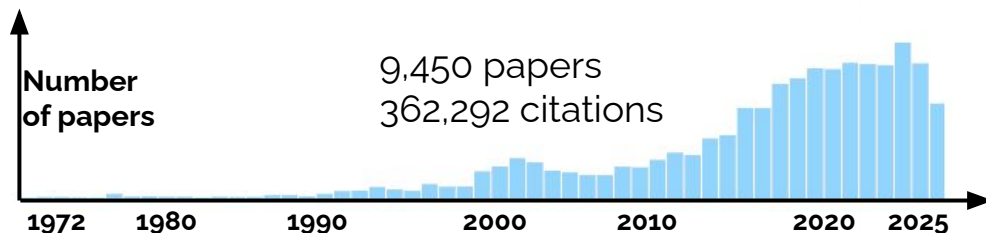
How we got here

2. Short-Baselines

Anomalies

Sterile Neutrinos

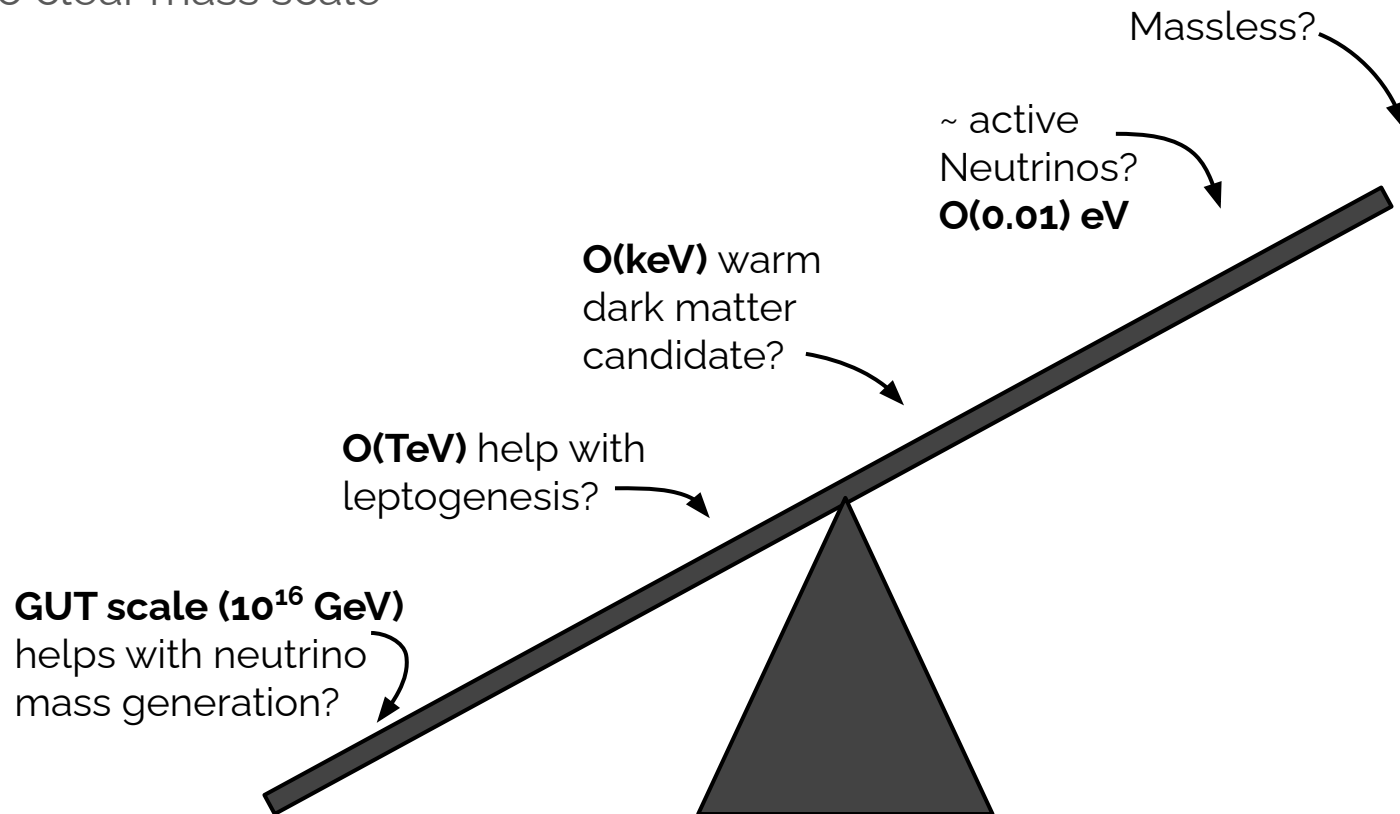
- Any SM-singlet fermions carrying no standard model charge can be called a “**sterile neutrino**”
- Extremely generic** extension. Any new theory that contains a fermion that has no SM charge can mix with our SM neutrinos
 - Gives neutrino sector a **unique probe** into the unknown*



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Anomalies
Sterile Neutrinos

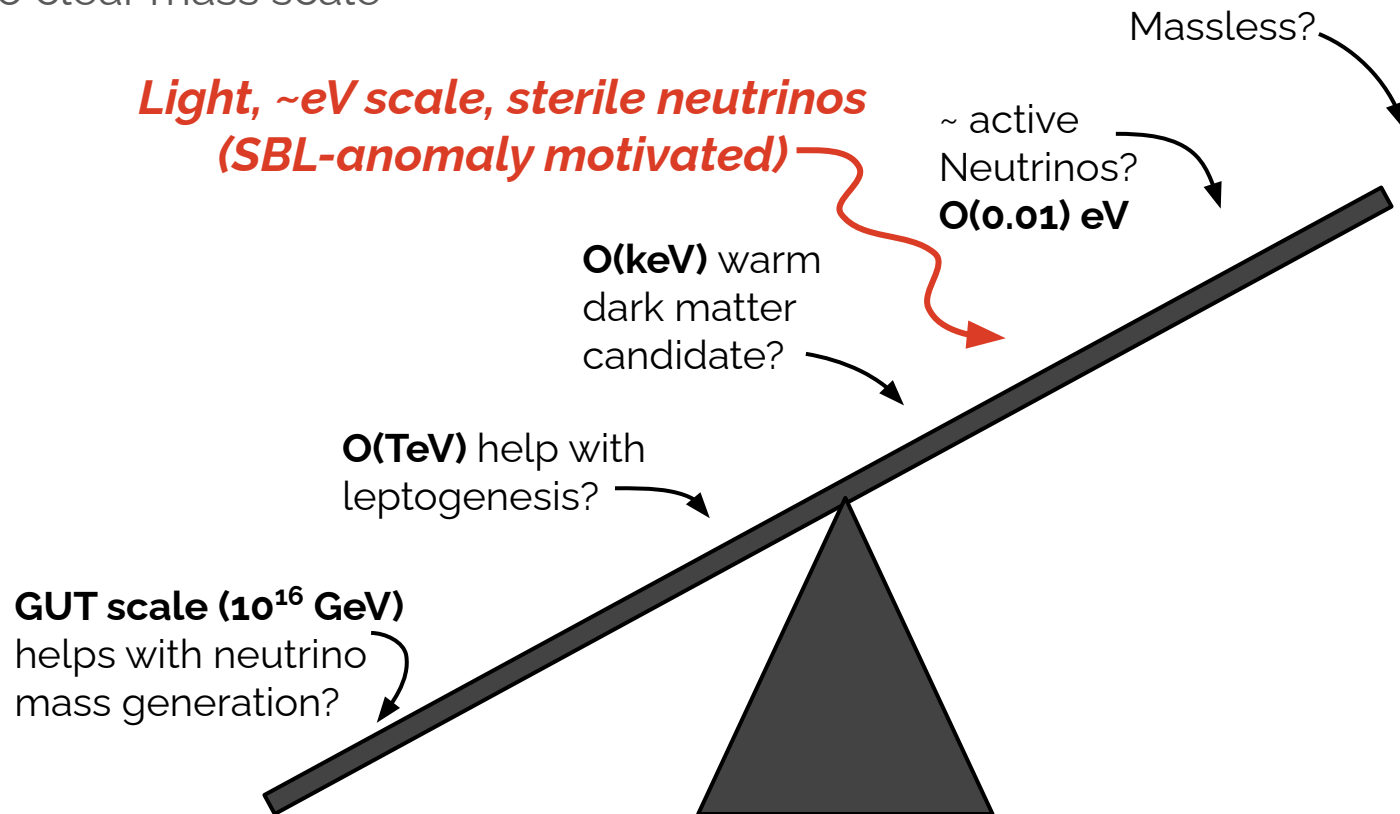
Lots of theories and applications,
a priori no clear mass scale



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Sterile Neutrinos

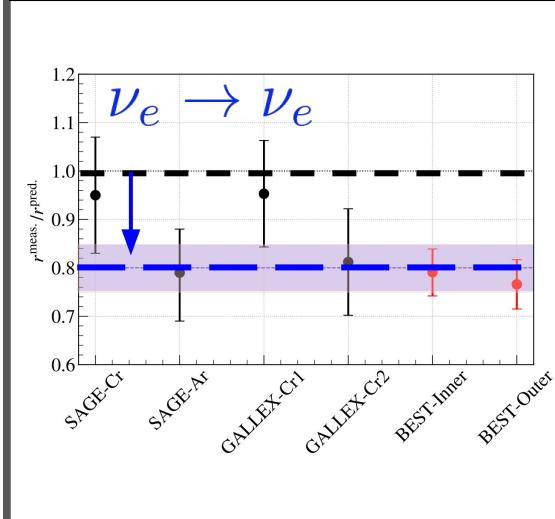
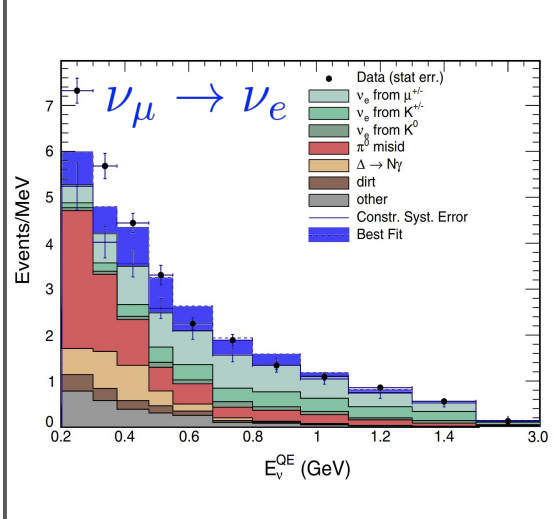
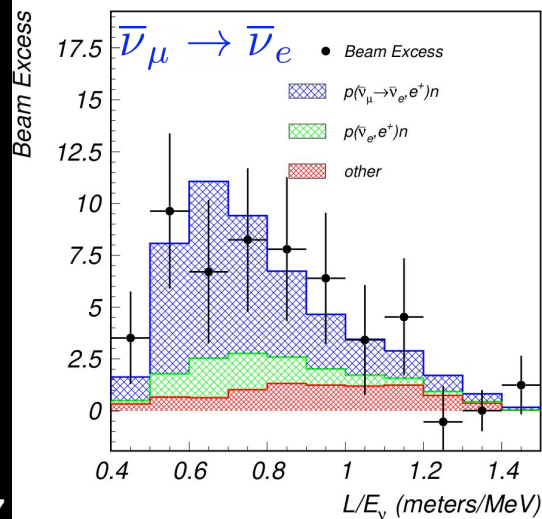
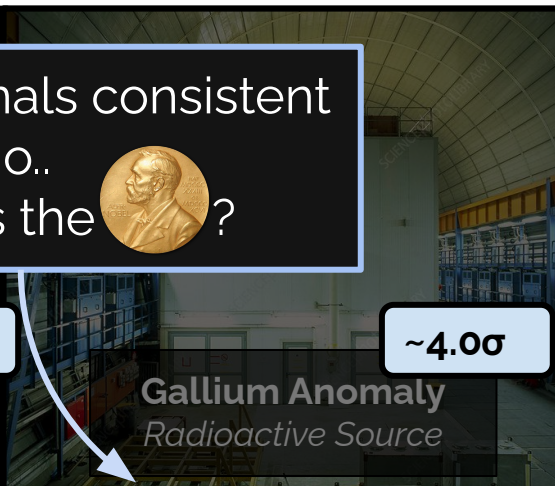
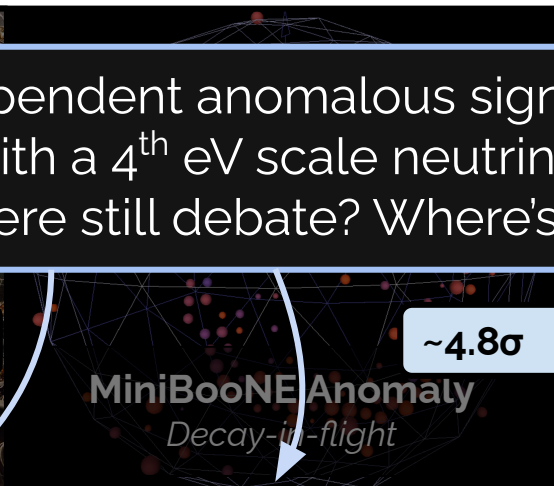
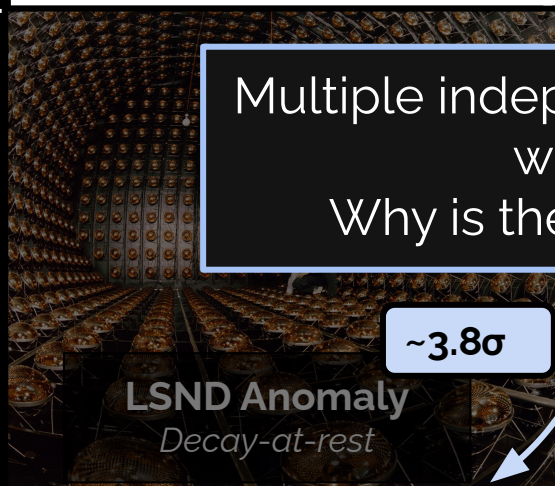
Lots of theories and applications,
a priori no clear mass scale



1. Introduction
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 Anomalies
 Sterile Neutrinos

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



The Short-Baseline Anomalies, discovery of a Sterile Neutrino?

1. Introduction
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Anomalies
Sterile Neutrinos

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

$\sim 3.8\sigma$

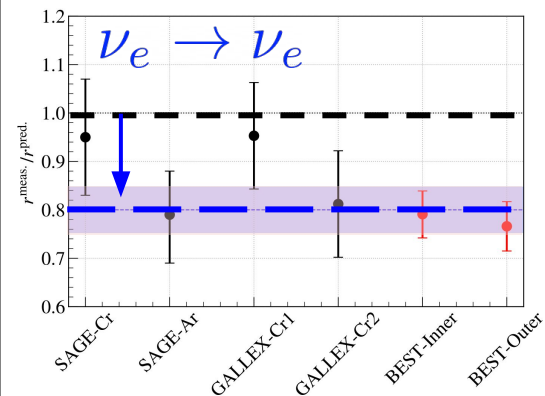
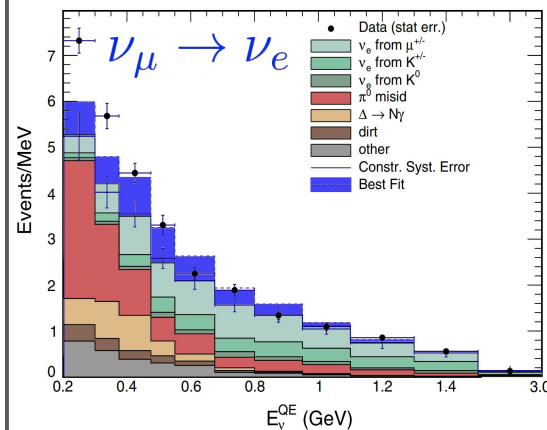
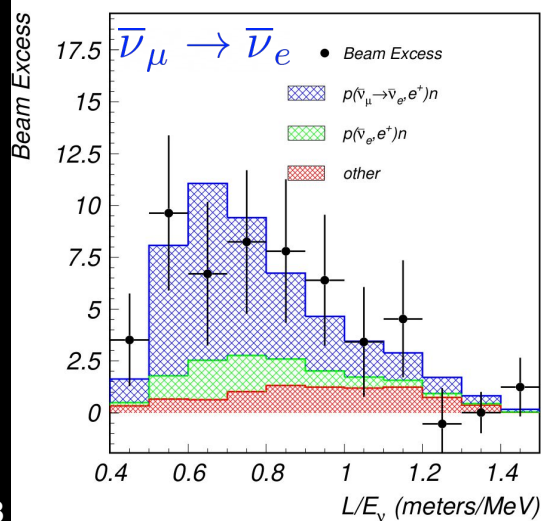
LSND Anomaly
Decay-at-rest

$\sim 4.8\sigma$

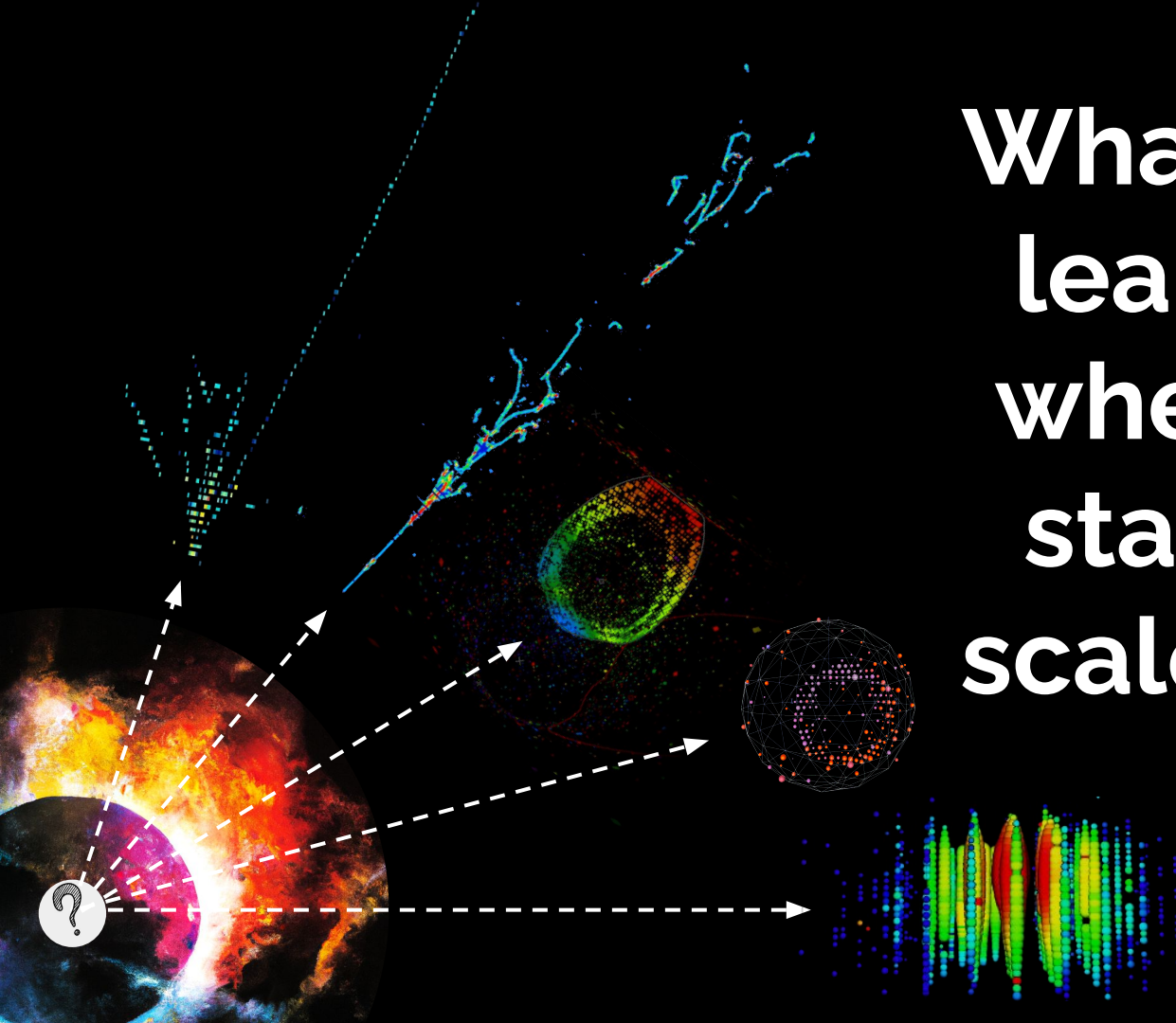
MiniBooNE Anomaly
Decay-in-flight

$\sim 4.0\sigma$

Gallium Anomaly
Radioactive Source



**What have we
learned and
where do we
stand on eV
scale steriles?**

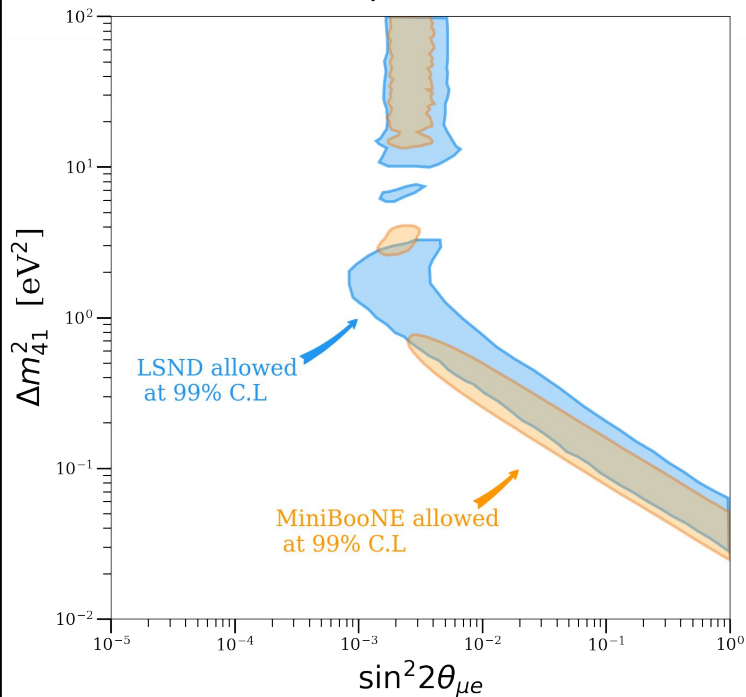


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3. Where We Stand
 $\nu_\mu \rightarrow \nu_e$ Results

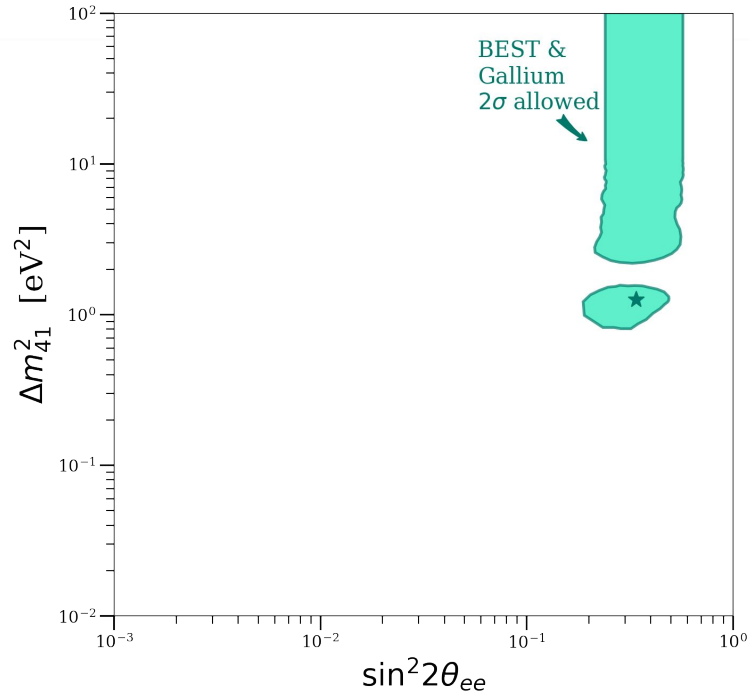
$$\nu_\mu \rightarrow \nu_e$$



Positive Hints

- LSND
- MiniBooNE

$$\nu_e \rightarrow \nu_e$$



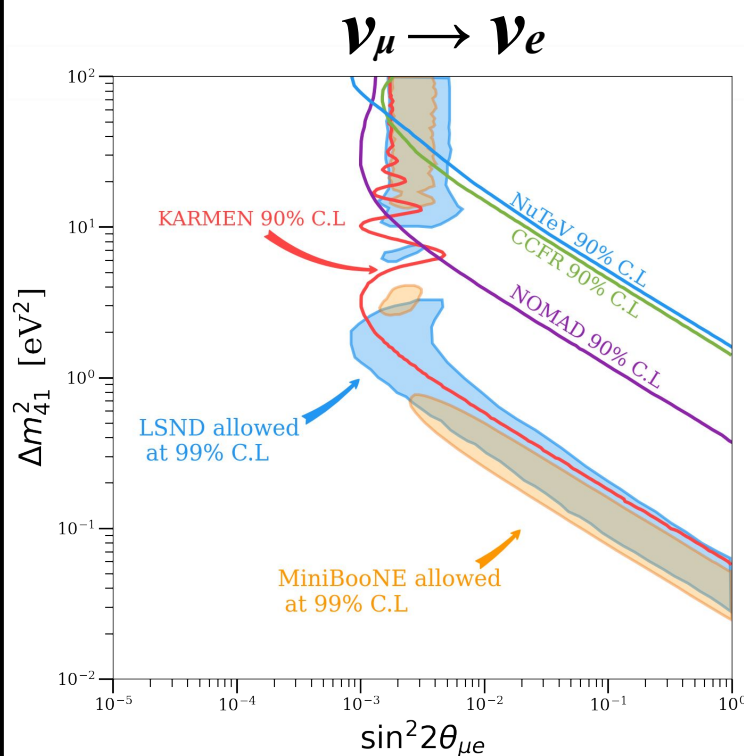
Positive Hints

- Gallium

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Positive Hints

- LSND
- MiniBooNE

Null Results

- KARMEN
- CCFR
- NuTeV
- NOMAD

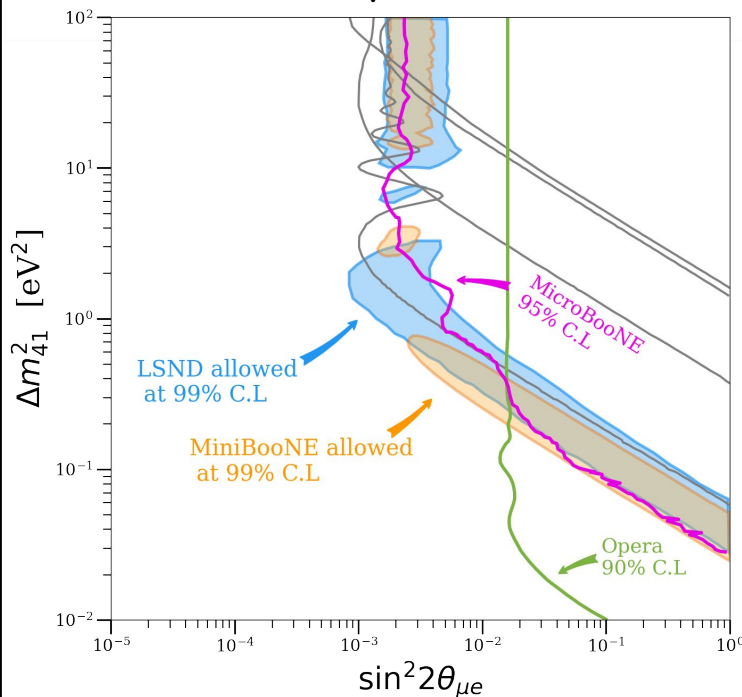
- **CCFR [1984] @ Fermilab**
 - Phys.Rev.Lett.52:10.1103, 1984
- **KARMEN [2002] @ RAL (UK)**
 - Phys.Rev.D65:112001,2002
- **NuTeV [2002] @ Fermilab**
 - Phys.Rev.Lett.89:011804,2002
- **NOMAD [2003] @ CERN**
 - Phys.Lett.B570:19-31,2003
 - ***"This result excludes the LSND allowed region of oscillation parameters with $\Delta m^2 > 10 \text{ eV}^2$ "***

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$$\nu_\mu \rightarrow \nu_e$$



Positive Hints

- LSND
- MiniBooNE

Null Results

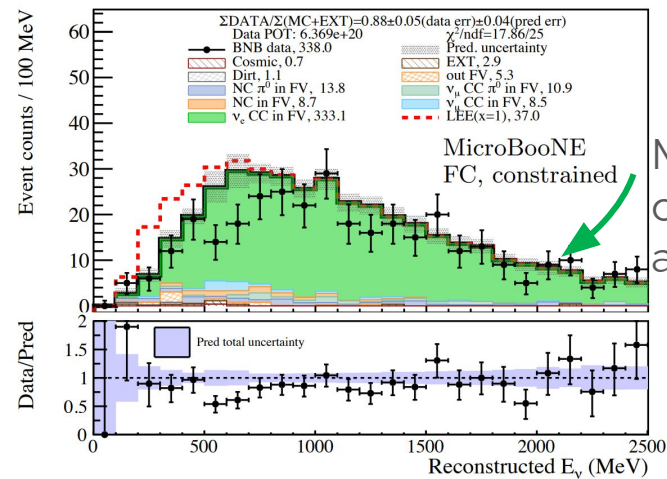
- KARMEN
- CCFR
- NuTeV
- NOMAD
- OPERA
- MicroBooNE

• OPERA [2019] @ Gran Sasso

- Phys. Rev. D 100, 051301 (2019)
- Very long baseline, 730 km, oscillations average out for LSND/MiniBooNE regions

• MicroBooNE [2023] @ Fermilab

- Phys. Rev. Lett. 130, 011801 (2023)
- Same beamline as MiniBooNE!

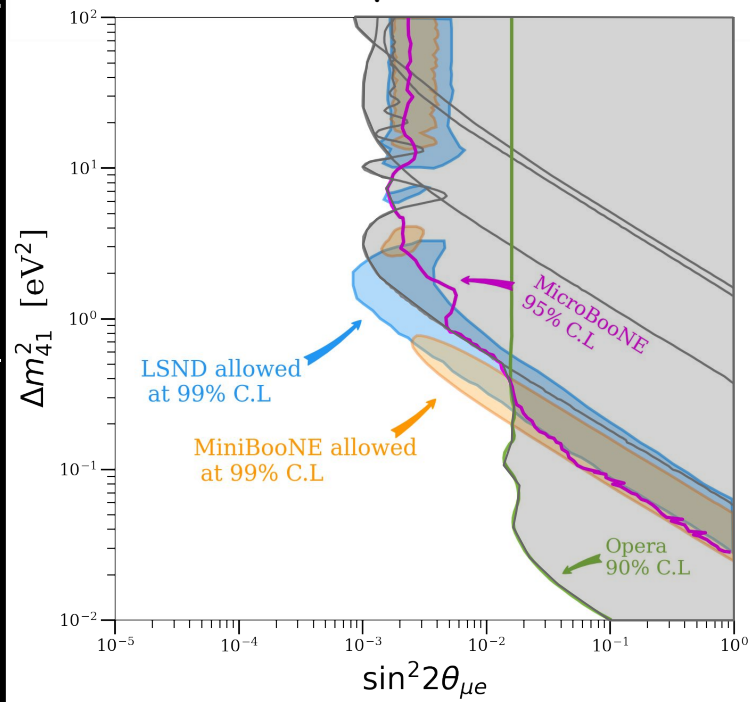


Mild deficit
 observed
 actually

Null $e \rightarrow e$

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 ν_e Disappearance

$\nu_\mu \rightarrow \nu_e$



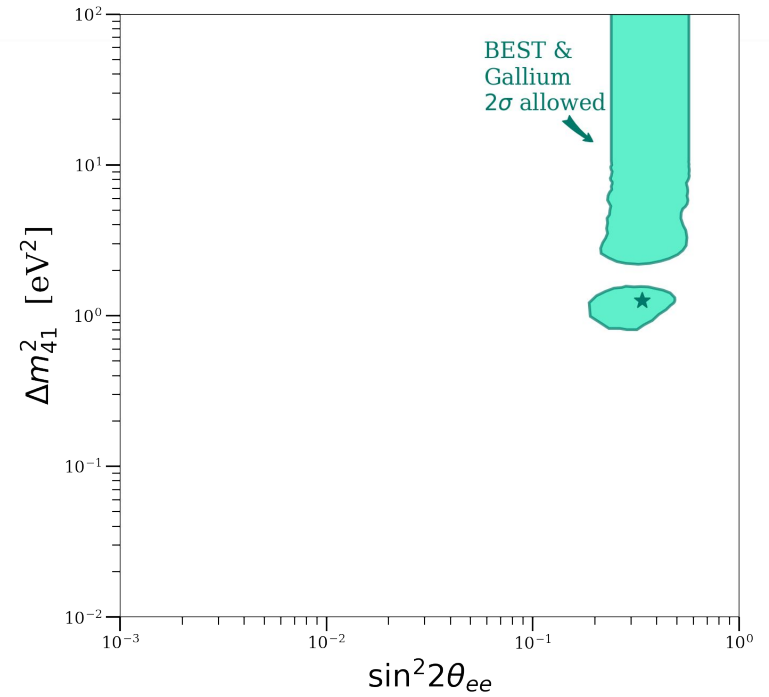
Positive Hints

- LSND
- MiniBooNE

Null Results

- KARMEN
- CCFR
- NuTeV
- NOMAD
- OPERA
- MicroBooNE

$\nu_e \rightarrow \nu_e$



Positive Hints

- Gallium

Null Results

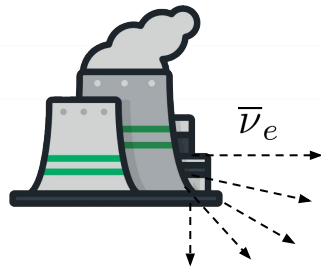
Null $e \rightarrow e$

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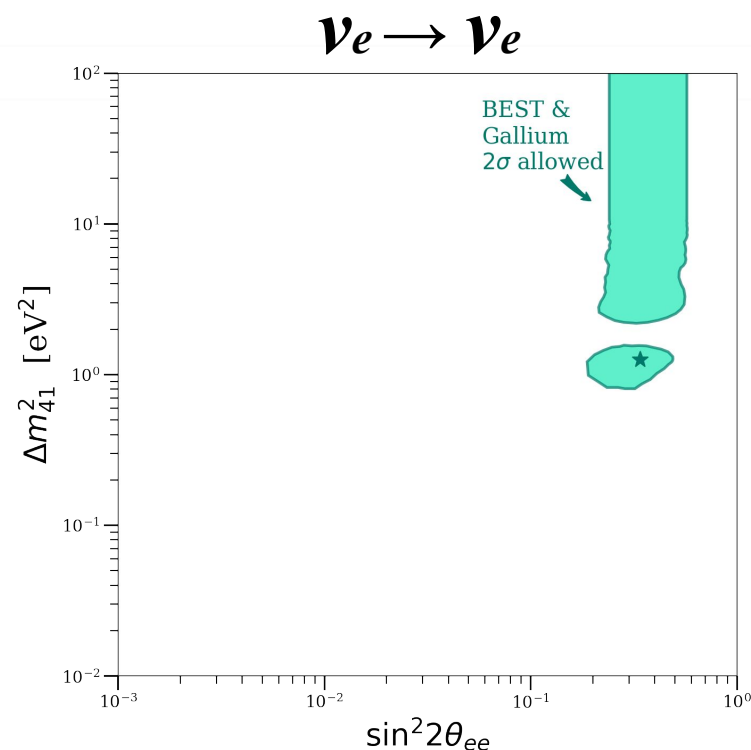
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Three strategies to see short-baseline reactor oscillations:



Positive Hints

- Gallium

Null Results

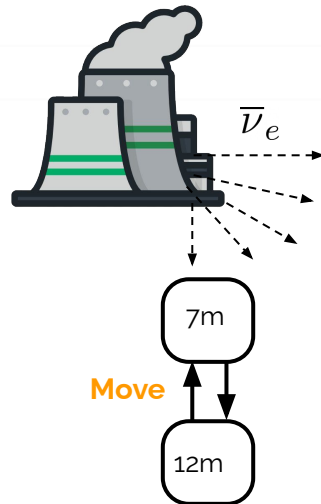
Null $e \rightarrow e$

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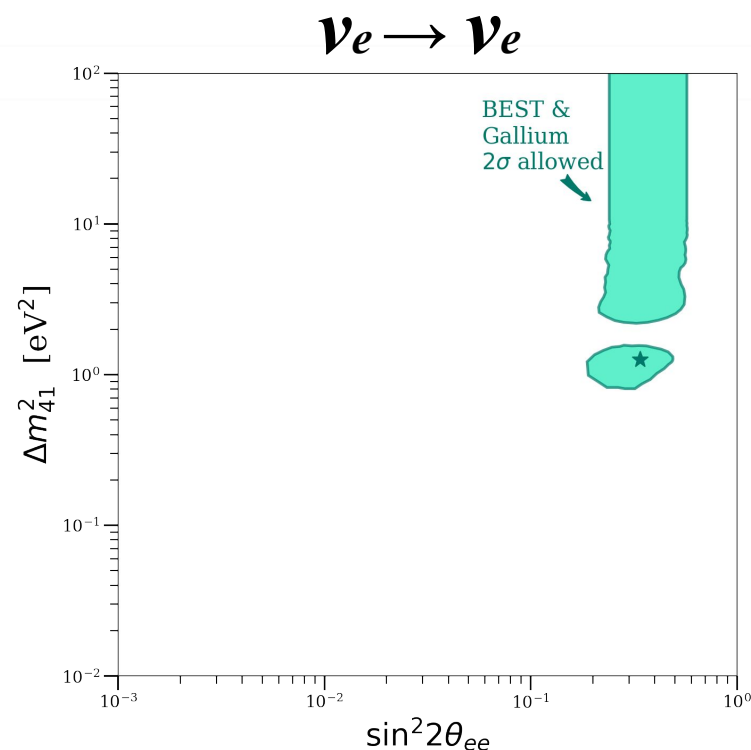
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 ν_e Disappearance



Three strategies to see short-baseline reactor oscillations:

- **Move** the whole detector to various average baselines



Positive Hints

- Gallium

Null Results

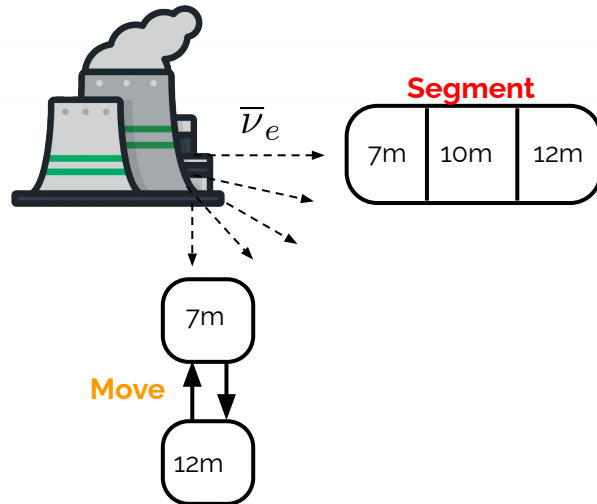
Null $e \rightarrow e$

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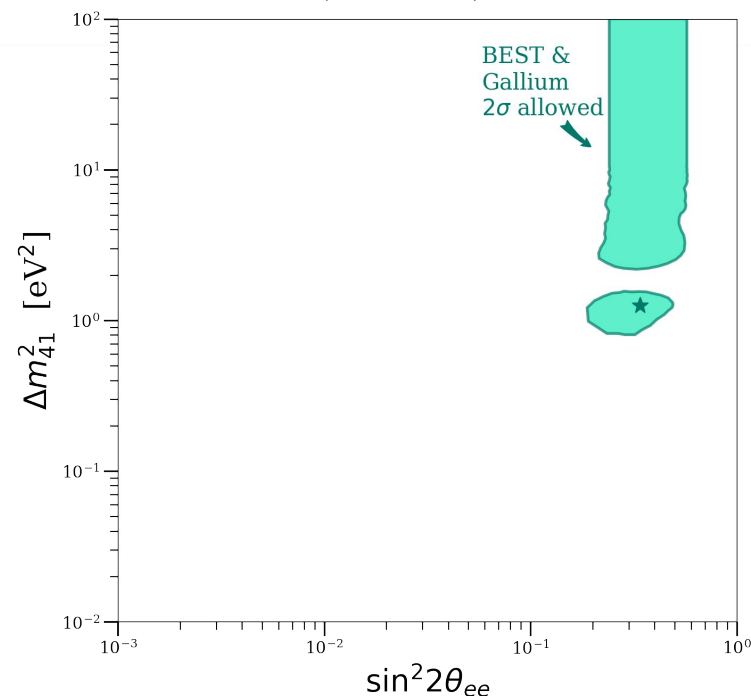
$\nu_\mu \rightarrow \nu_e$ Results
 ν_e Disappearance



Three strategies to see short-baseline reactor oscillations:

- **Move** the whole detector to various average baselines
- **Segment** a single detector to measure $\bar{\nu}_e$ rate at different average baseline.

$\nu_e \rightarrow \nu_e$



Positive Hints

- Gallium

Null Results

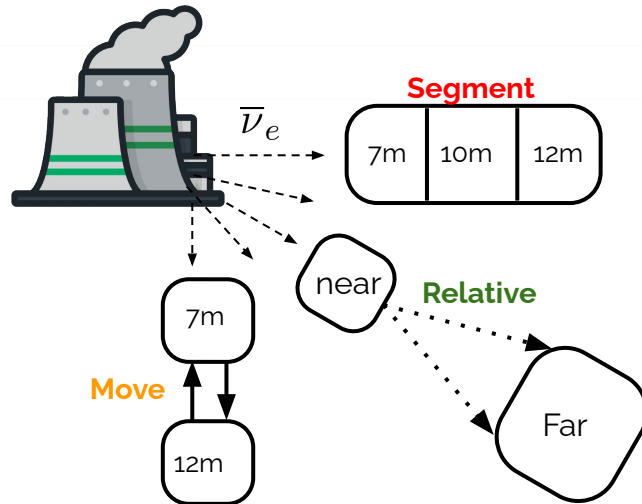
Null $e \rightarrow e$

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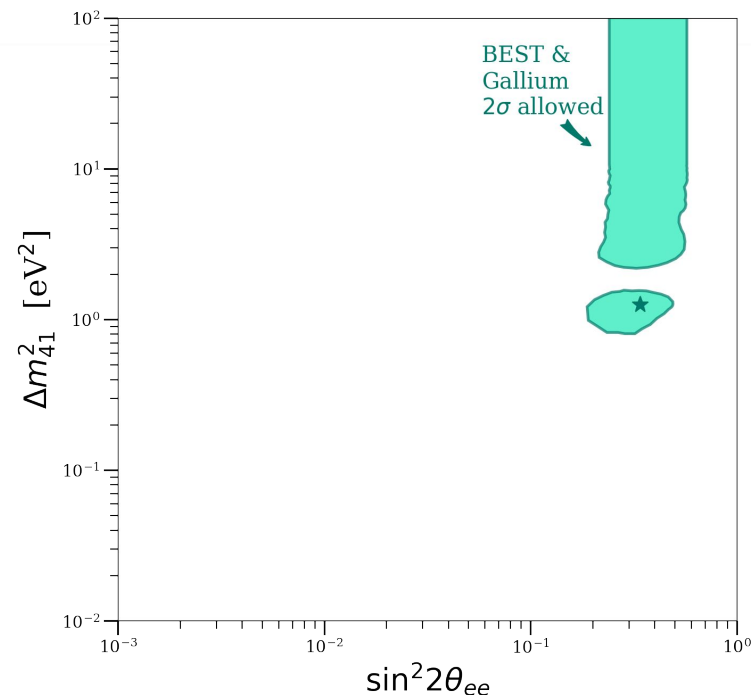
$\nu_\mu \rightarrow \nu_e$ Results
 ν_e Disappearance



Three strategies to see short-baseline reactor oscillations:

- **Move** the whole detector to various average baselines
- **Segment** a single detector to measure $\bar{\nu}_e$ rate at different average baseline.
- Calculate **relative** between near and far detector so absolute flux and reactor modelling isn't important

$\nu_e \rightarrow \nu_e$



Positive Hints

- Gallium

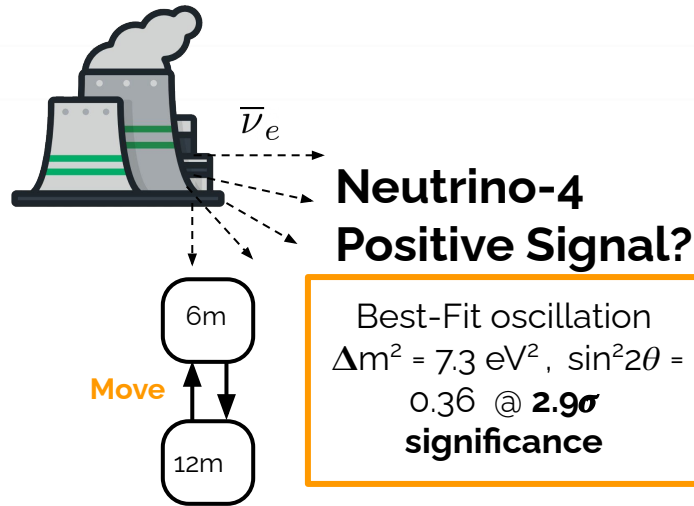
Null Results

Neutrino-4

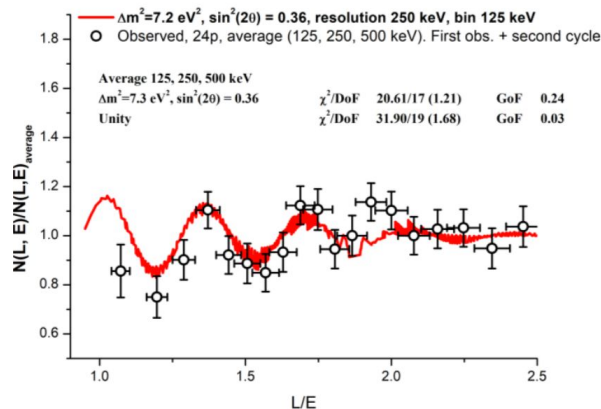
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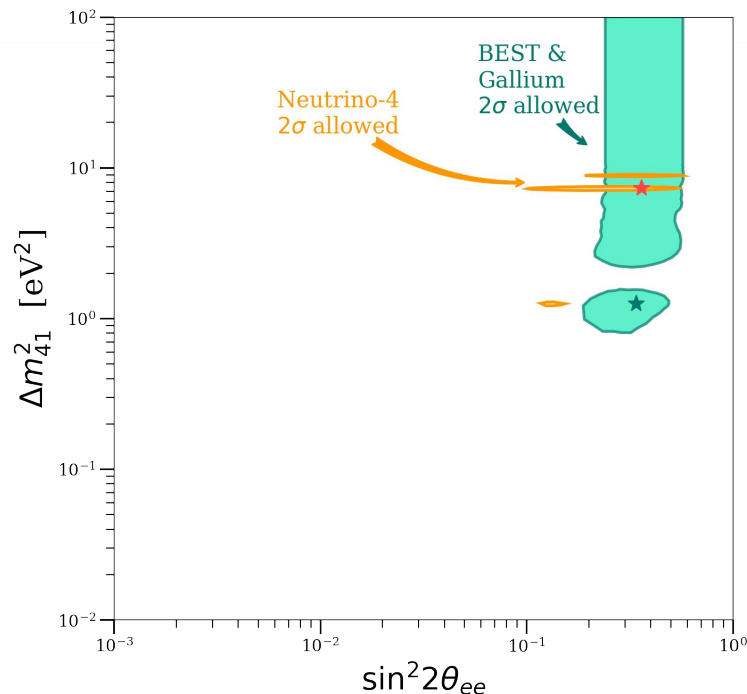
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 $\nu_e \rightarrow \nu_e$ Results
 ν_μ
 ν_e Disappearance



- Commercial reactor, 100 MW_{th} in Russia
- 334 days reactor on data



$\nu_e \rightarrow \nu_e$



Positive Hints

Null Results

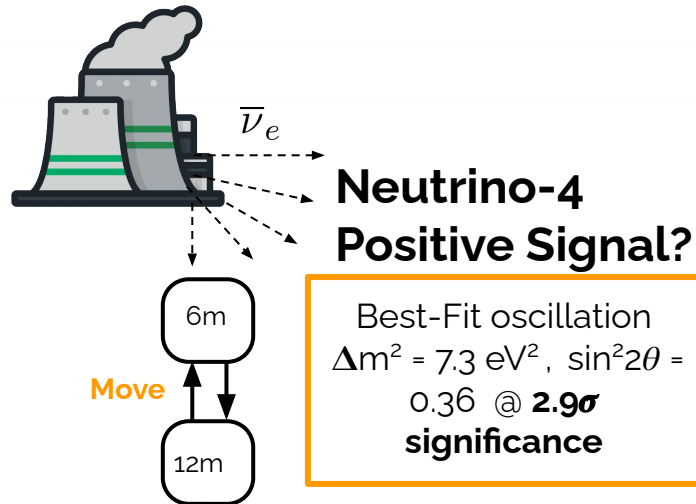
- Gallium
- **Neutrino 4?**

Neutrino-4

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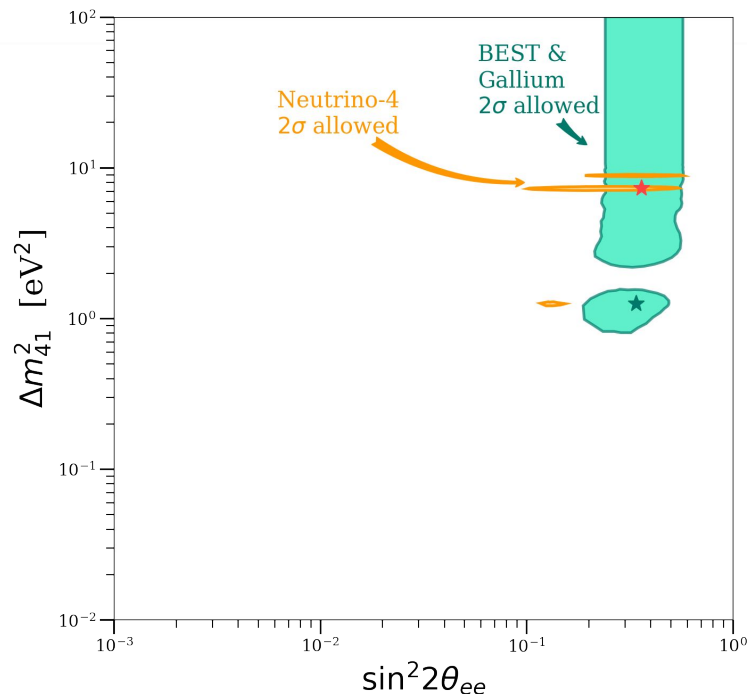


Several questions have been raised by community so far, including the **effects of the statistical approach used**, and impact of **systematics** and **expected backgrounds**

- H. Almazán et al, [arXiv:2006.13147](https://arxiv.org/abs/2006.13147)
- C. Giunti et al [j.physletb.2021.136214](https://arxiv.org/abs/2021.136214)

“Therefore, we conclude that the claimed Neutrino-4 indication in favor of short-baseline neutrino oscillations with very large mixing is rather doubtful.”

$\nu_e \rightarrow \nu_e$



Positive Hints

- Gallium
- **Neutrino 4?**

Null Results

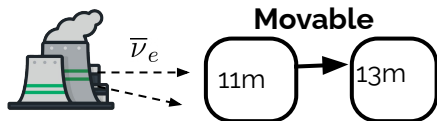
Neutrino4: [PhysRevD.104.032003](https://arxiv.org/abs/PhysRevD.104.032003)

Null Reactor Results

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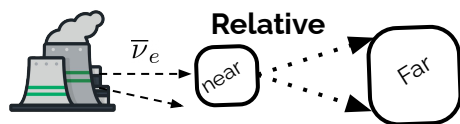
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 $\nu_\mu \rightarrow \nu_e$ Results
 ν_e Disappearance



DANSS, Movable detector in Russia,
[Phys.Lett.B 787\(2018\)56-63](#)

Detector position changed frequently, **2-3 times a week**, in order to reduce systematic effects.

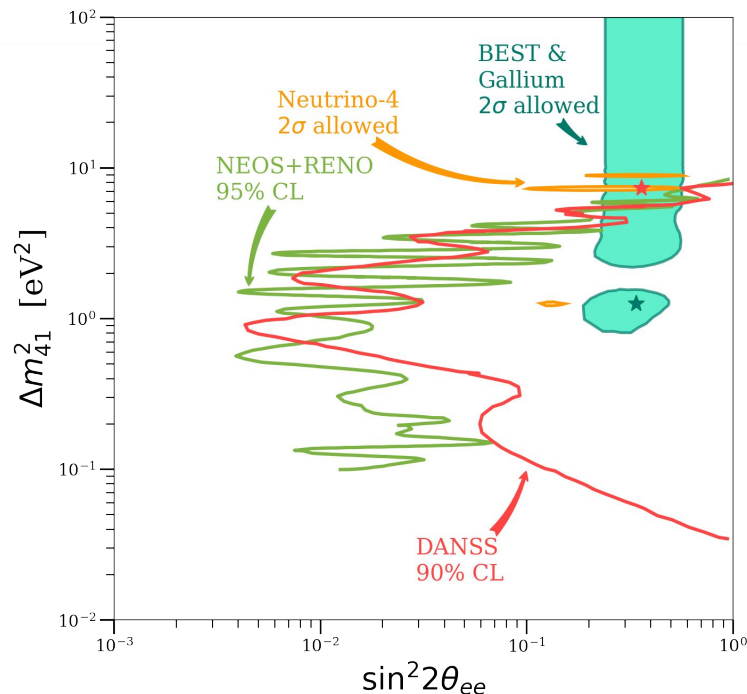


NEOS+RENO, relative 419 m RENO and 24m NEOS detectors in Korea
[Phys. Rev. D 105, L111101 \(2022\)](#)

2,509 days and 180 days of data taken in the RENO and NEOS, respectively

Need to get closer to reactors!

$\nu_e \rightarrow \nu_e$



Positive Hints

- Gallium
- Neutrino 4

Null Results

- DANSS
- NEOS+RENO

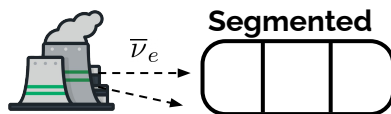
Null Reactor Results

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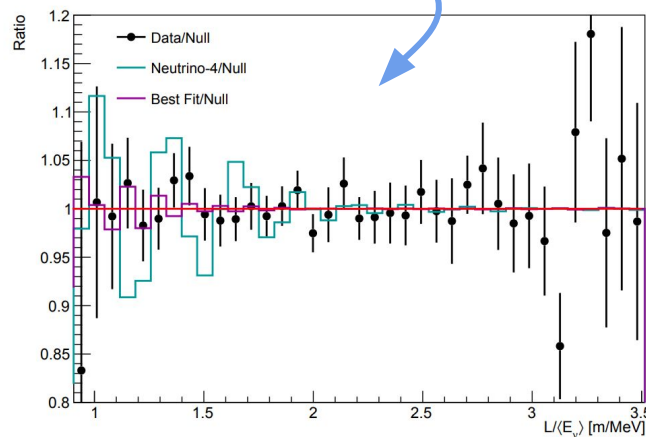


STEREO (ILL, Grenoble, France)

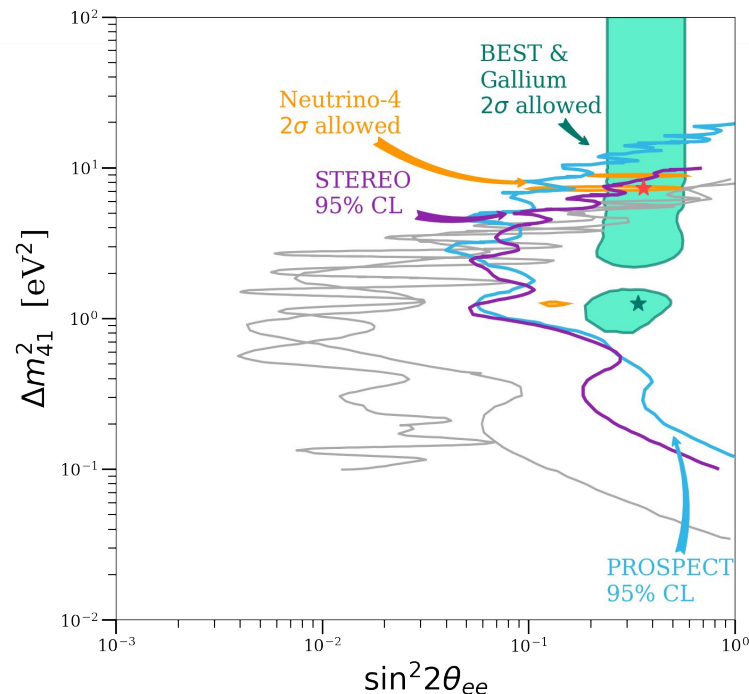
- [Nature 613, 257–261 \(2023\)](#)
- 334 days reactor on data, 58.3 MW_{th}
- **9.4 to 11.1 m Baselines**

PROSPECT (Oak Ridge National Lab, USA)

- [arXiv:2406.10408 \[hep-ex\] \(2024\)](#)
- 96 days reactor on data, 85 MW_{th}
- **7-9 m Baselines**



$\nu_e \rightarrow \nu_e$



Positive Hints

- Gallium
- Neutrino 4

Null Results

- DANSS
- NEOS+RENO
- STEREO
- PROSPECT-I

KATRIN Attacking from different angle

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How we got here

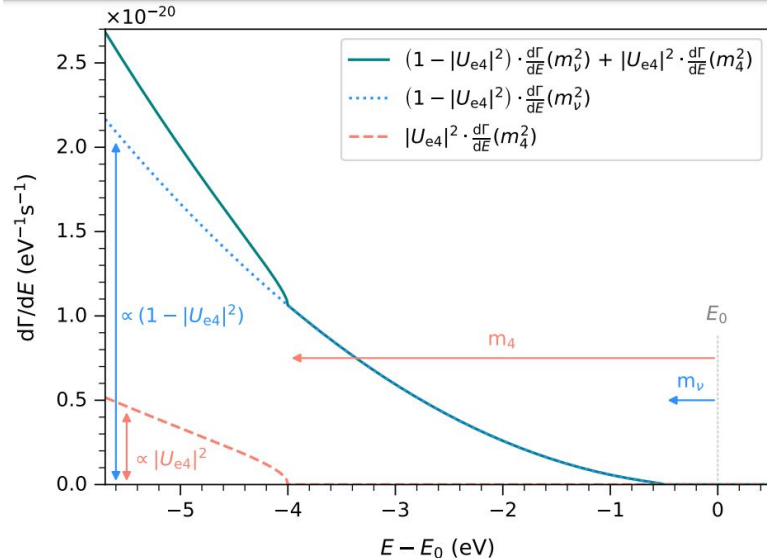
2. Short-Baselines
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3. Where We Stand
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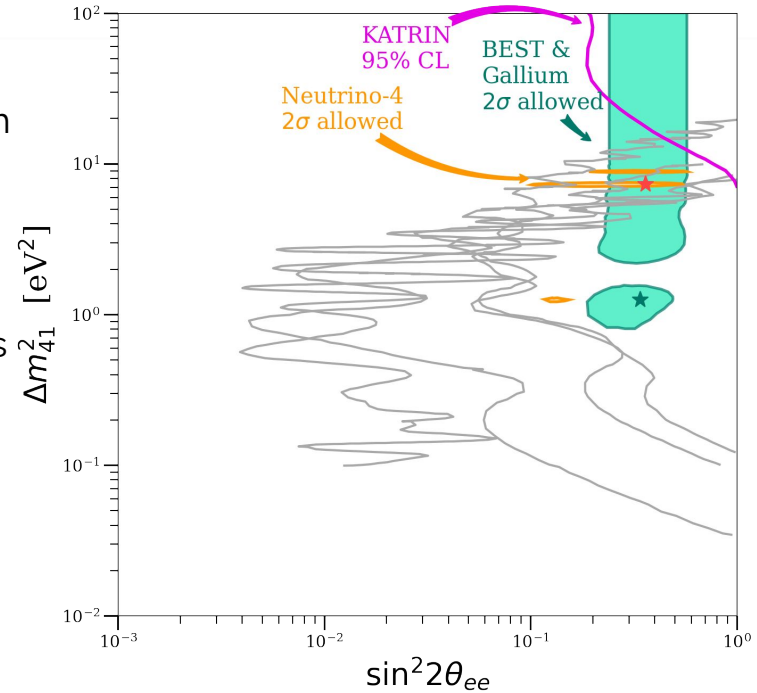
KATRIN in Karlsruhe Germany

Designed to determine the **neutrino mass** from kinematic measurements of the **β -decay of tritium** [PhysRevD.105.072004 \(2022\)](#)

Unique! KATRIN is the only ongoing laboratory experiment to be sensitive to relevant solutions at large Δm^2 values!



$\nu_e \rightarrow \nu_e$



Positive Hints

- Gallium
- Neutrino 4

Null Results

- DANSS
- NEOS+RENO
- STEREO
- PROSPECT-I
- KATRIN

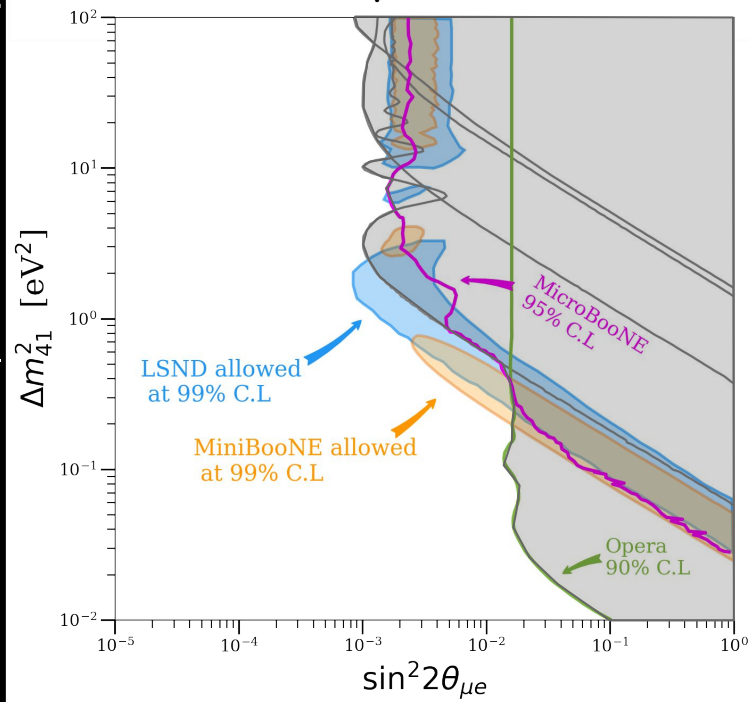
Null $e \rightarrow e$

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3. Where We Stand
 $\nu_\mu \rightarrow \nu_e$ Results
 ν_e Disappearance

$$\nu_\mu \rightarrow \nu_e$$



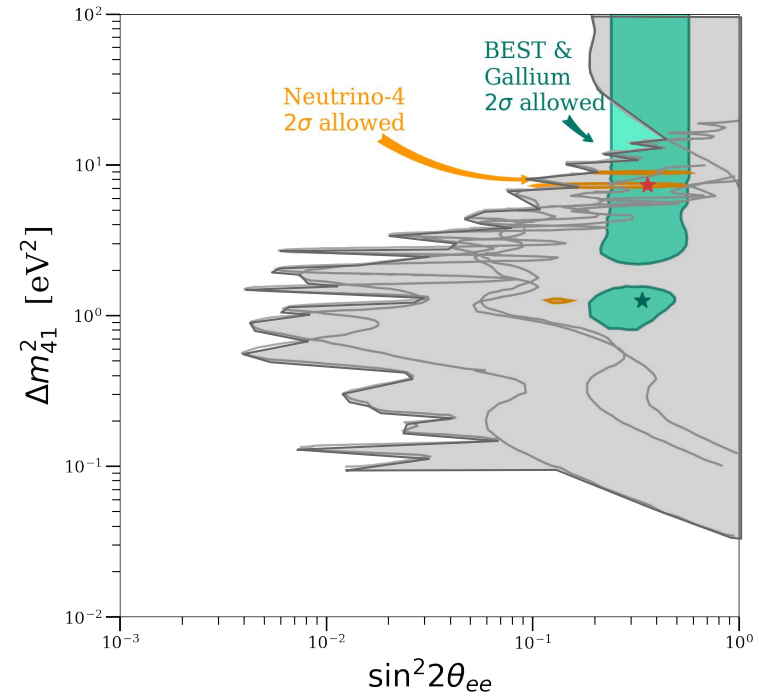
Positive Hints

- LSND
- MiniBooNE

Null Results

- KARMEN
- CCFR
- NuTeV
- NOMAD
- OPERA
- MicroBooNE

$$\nu_e \rightarrow \nu_e$$



Positive Hints

- Gallium
- Neutrino 4

Null Results

- DANSS
- NEOS+RENO
- STEREO
- PROSPECT-I
- KATRIN

Consistent 3+1?

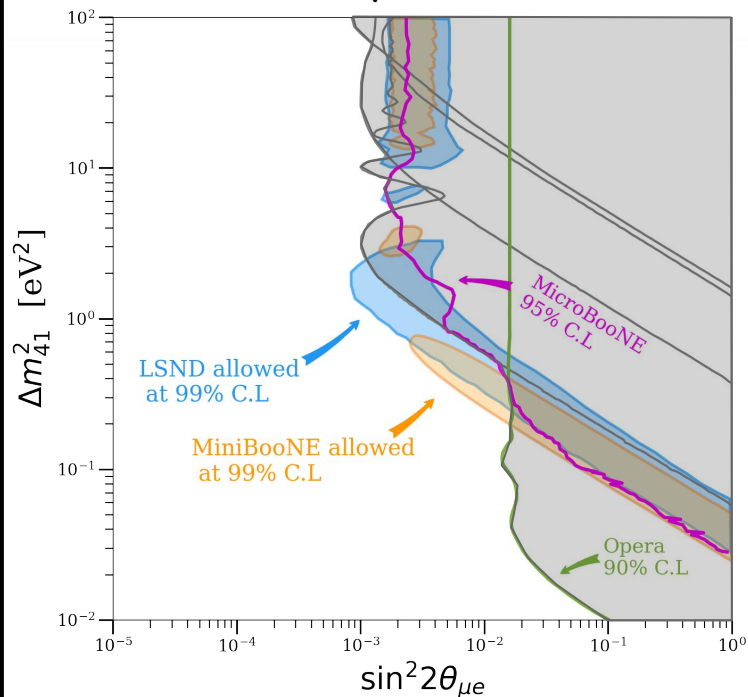
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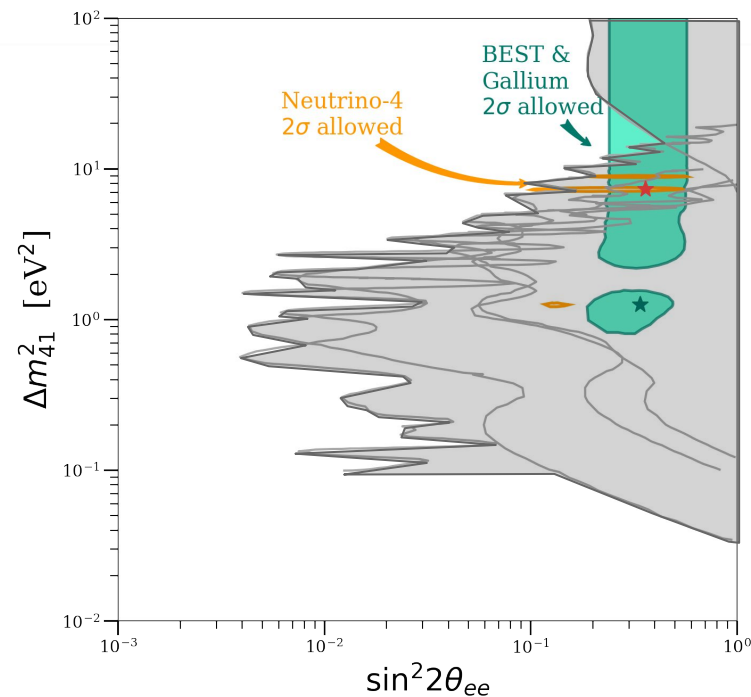
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$\nu_\mu \rightarrow \nu_e$



$\nu_e \rightarrow \nu_e$



$$P(\nu_\mu \rightarrow \nu_e) \simeq 4|U_{\mu 4}|^2 \boxed{|U_{e 4}|^2} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E_\nu} \right)$$

$$P(\nu_e \rightarrow \nu_e) \simeq \boxed{1 - 4|U_{e 4}|^2(1 - |U_{e 4}|^2)} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E_\nu} \right)$$

Consistent 3+1?

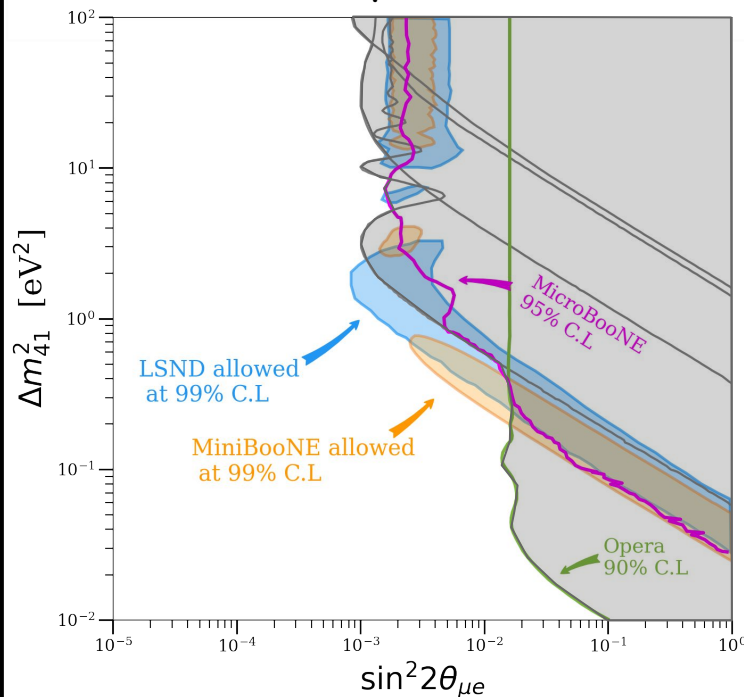
1. [Introduction](#)
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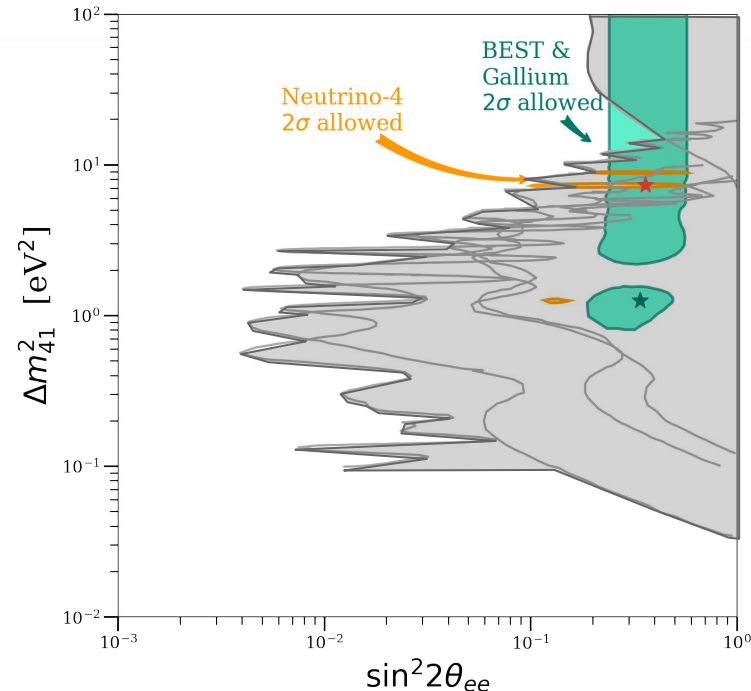
3. [Where We Stand](#)

$\nu_\mu \rightarrow \nu_e$ Results
 ν_e Disappearance

$\nu_\mu \rightarrow \nu_e$



$\nu_e \rightarrow \nu_e$



$$P(\nu_\mu \rightarrow \nu_e) \simeq 4 \boxed{|U_{\mu 4}|^2} \boxed{|U_{e 4}|^2} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E_\nu} \right)$$

$$P(\nu_e \rightarrow \nu_e) \simeq \boxed{1 - 4|U_{e 4}|^2(1 - |U_{e 4}|^2)} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E_\nu} \right)$$

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq \boxed{1 - 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E_\nu} \right)$$

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ν_μ Disappearance

- **CCFR [1984] @ Fermilab**

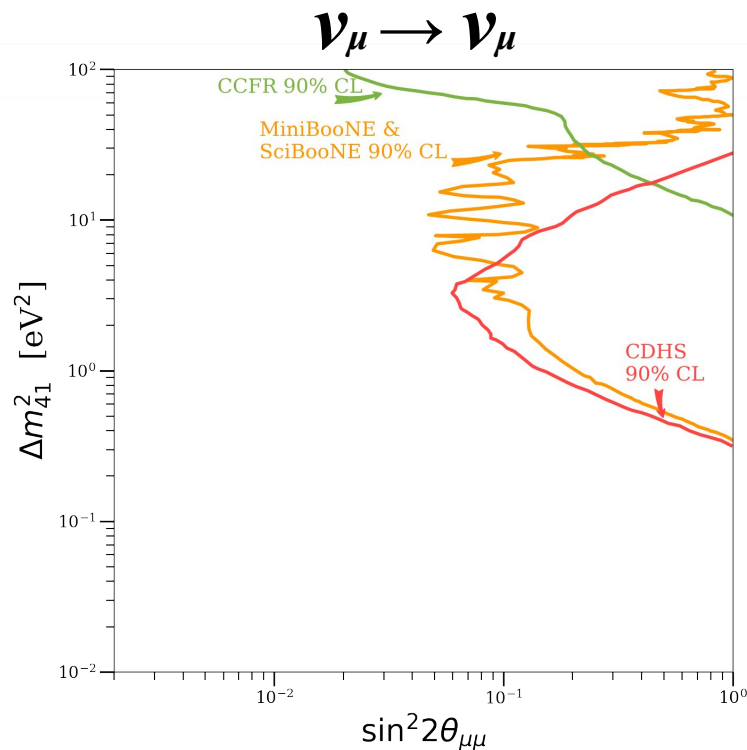
- PhysRevLett.52.10.1103, 1984

- **CDHS [1984] @ CERN**

- PhysRevLett.52.10.1103, 1984

- **MiniBooNE & SciBooNE [2011] @ Fermilab**

- Phys. Rev. D 85, 032007 (2012)



Positive Hints

Null Results

- CCFR
- CDHS
- MiniBooNE

Null $\mu \rightarrow \mu$

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ν_μ Disappearance

ν_μ Disappearance

● Super-Kamiokande

- Phys. Rev. D 91, 052019

Atmos
 ν

● T2K [2019]

- Phys. Rev. D 99, 071103

Off-axis
LBL

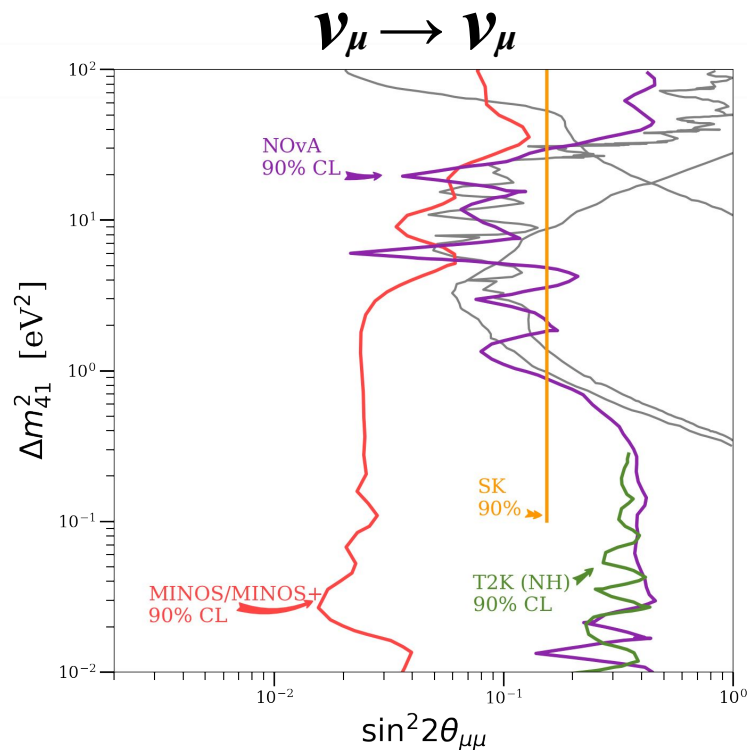
● NOvA [2024]

- arXiv 2409.04553

● MINOS/MINOS+

- Phys. Rev. Lett. 122, 091803

On-Axis
LBL



*"No muon disappearance ever observed
from huge variety of experiments!
Contradiction to MiniBooNE & LSND!"*

Me, early 2024

Positive Hints

Null Results

- CCFR
- CDHS
- MiniBooNE
- Super-K
- T2K
- NOvA
- MINOS

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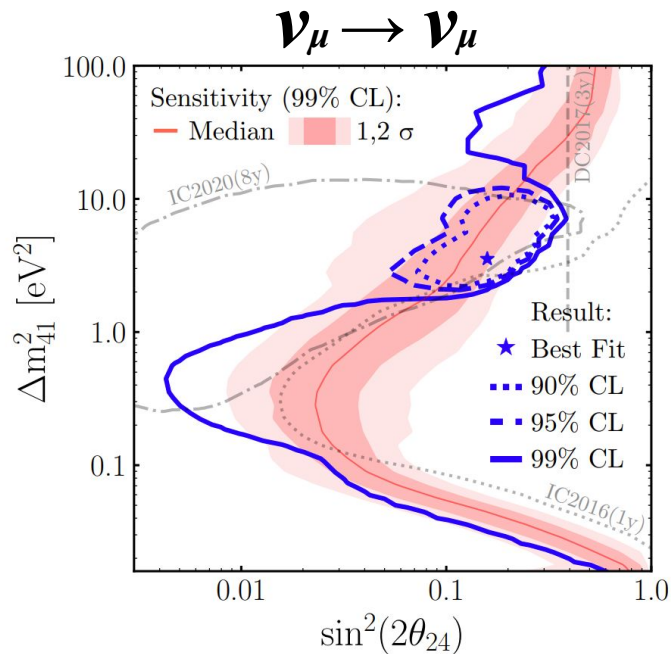
Sterile Neutrinos

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$\nu_\mu \rightarrow \nu_e$ Results

ν_e Disappearance

ν_μ Disappearance



Recent IceCube atmospheric result has closed contour at the 95% C.L. [arXiv:2405.08070 \[hep-ex\]](https://arxiv.org/abs/2405.08070)

*"This probability, corresponding to a significance of **2.2 σ** , does **not constitute evidence** for the existence of an eV scale sterile neutrino."*

... But it is the first ever **hint** in the muon sector

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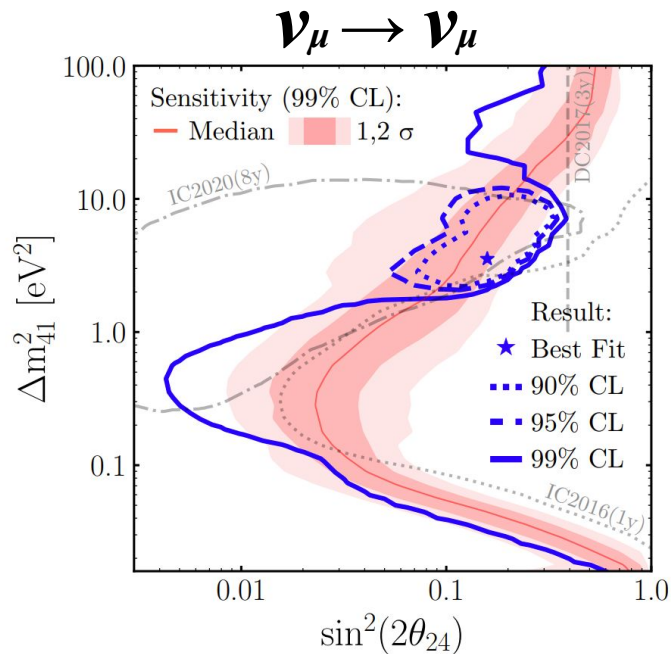
3. Where We Stand

$\nu_\mu \rightarrow \nu_e$ Results

ν_μ Disappearance

ν_e Disappearance

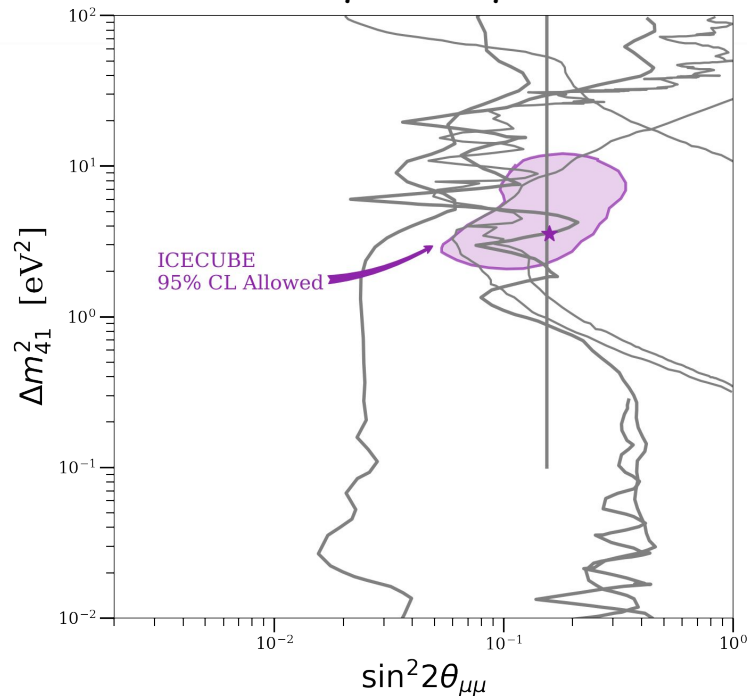
ν_μ Disappearance



"This probability, corresponding to a significance of **2.2σ**, does **not constitute evidence** for the existence of an eV scale sterile neutrino."

... But it is the first ever **hint** in the muon sector

$$\nu_\mu \rightarrow \nu_\mu$$



Positive Hints

- IceCube

Null Results

- CCFR
- CDHS
- MiniBooNE
- Super-K
- T2K
- NOvA
- MINOS

Where we Stand?

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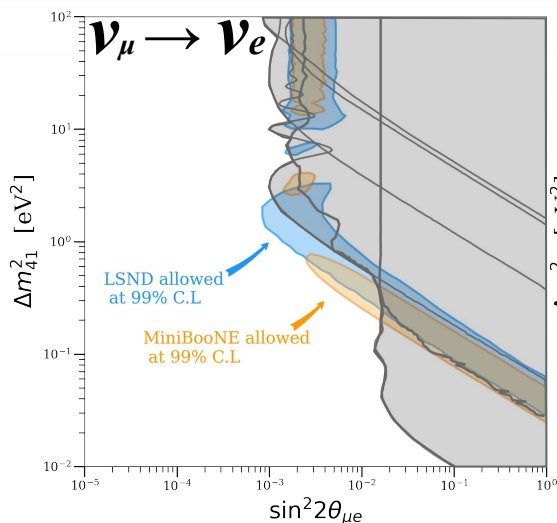
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ν_μ Disappearance

ν_e Disappearance

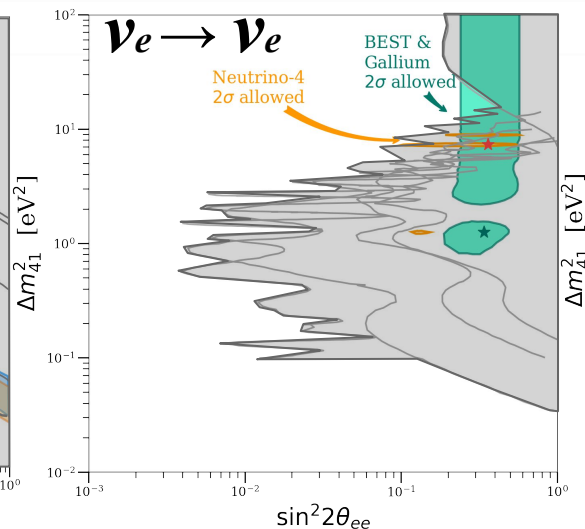


Positive Hints

- LSND
- MiniBooNE

Null Results

- Karmen
- NuTeV
- CCFR
- NOMAD
- OPERA
- MicroBooNE

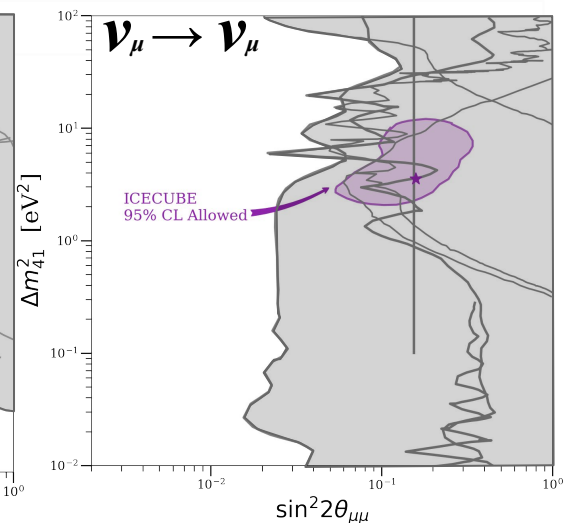


Positive Hints

- Gallium
- Neutrino-4

Null Results

- NEOS+RENO
- DANSS
- PROSPECT
- STEREO
- KATRIN



Positive Hints

- IceCube

Null Results

- MiniBooNE
- CDHS
- CCFR
- T2K
- NoVA
- MINOS
- Super-K

The Elephant in the Room...

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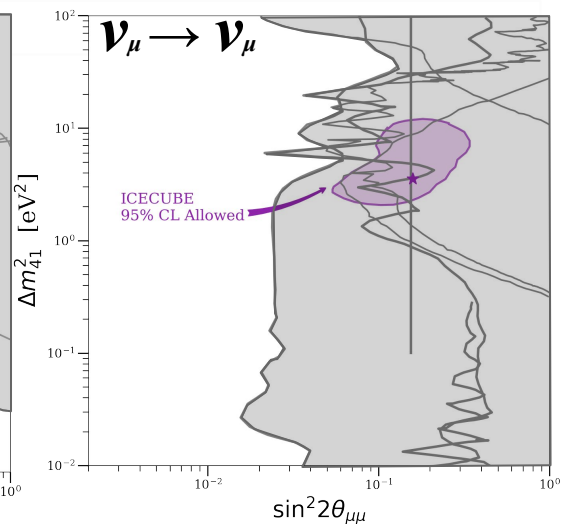
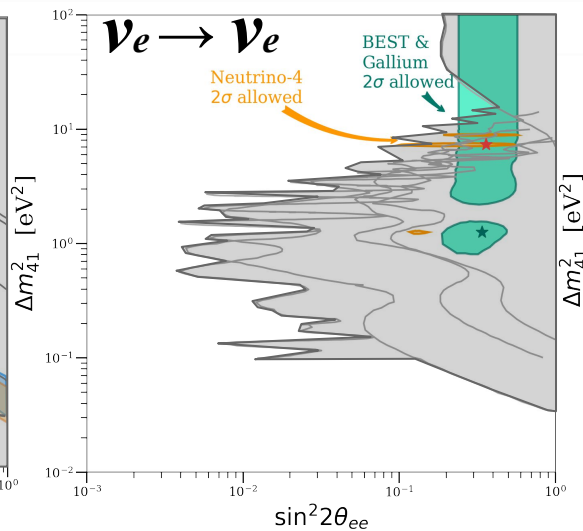
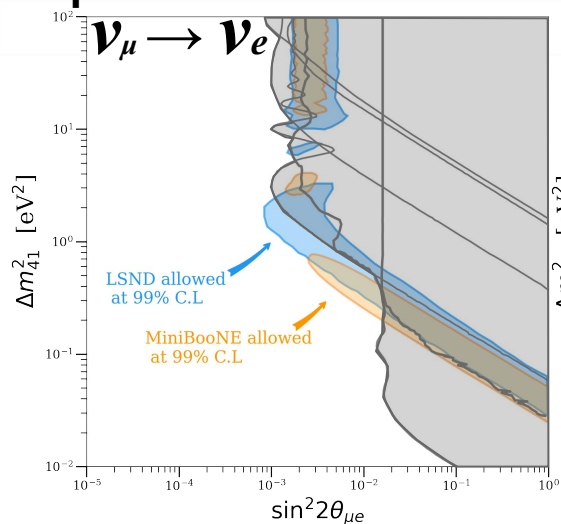
Sterile Neutrinos

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$\nu_\mu \rightarrow \nu_e$ Results

ν_e Disappearance

ν_μ Disappearance



The Elephant in the Room... Cosmological Bounds

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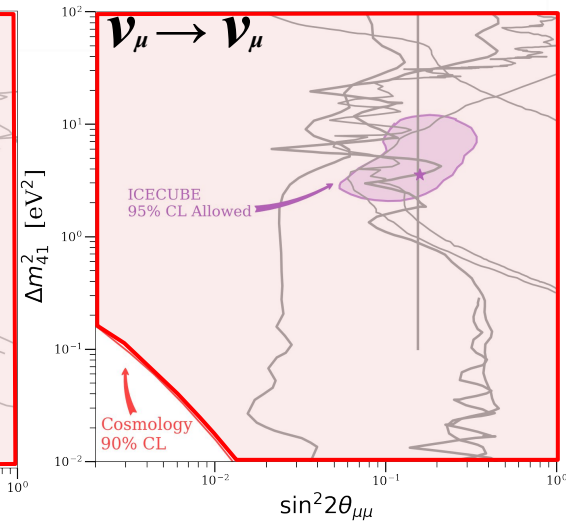
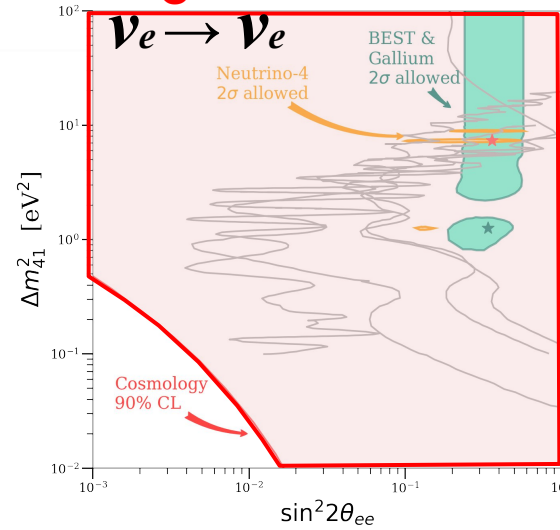
ν_e Disappearance

ν_μ Disappearance

Cosmology

HUGE tension

between
cosmological
bounds and *vanilla*
3+1 short-baseline
steriles



S. Hagstotz et al, [PhysRevD.104.123524](#)

The Elephant in the Room... **Cosmological Bounds**

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ν_μ Disappearance

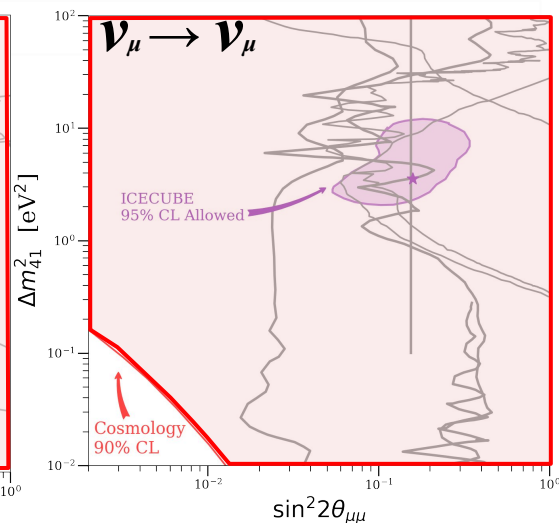
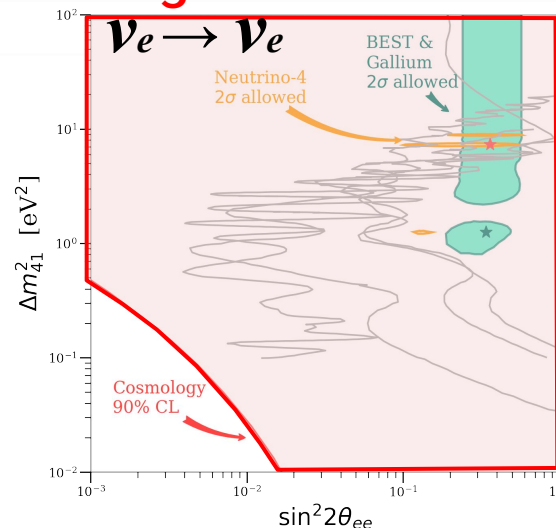
ν_e Disappearance

ν_μ Disappearance

Cosmology

HUGE tension

between
cosmological
bounds and **vanilla**
**3+1 short-baseline
steriles**



Energy density of **Relativistic Neutrinos**

S. Hagstotz et al, [PhysRevD.104.123524](#)

$$N_{\text{eff}}^\nu = \frac{8}{7} \left(\frac{11}{4} \right)^{4/3} \frac{\rho_\nu}{\rho_\gamma}$$

Energy density of **Photons**

$$N_{\text{eff}} = 2.99 \pm 0.17 \text{ (CMB+lens+BAO) } \text{ [Plank2018](#) }$$

**Can this be avoided? Is this
dependent on specific models
of Λ CDM?**

**Possibly, but you have to add
more new physics! It's no longer a
simple vanilla "3+1" model**

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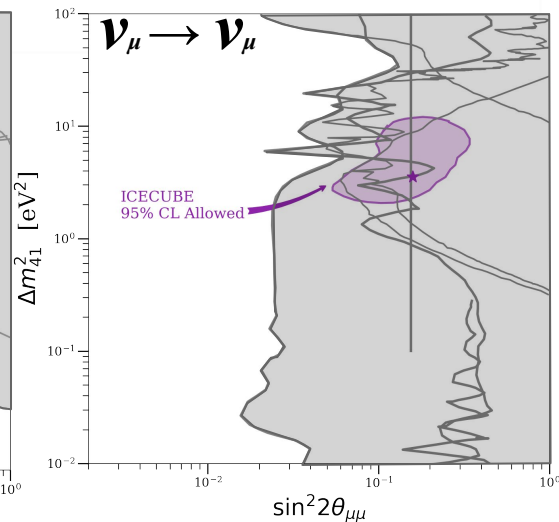
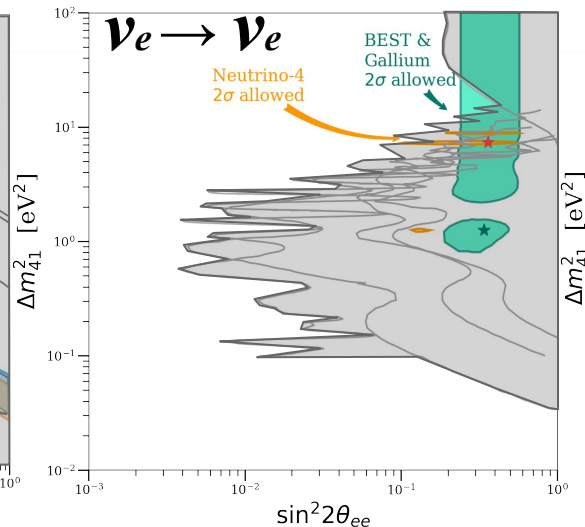
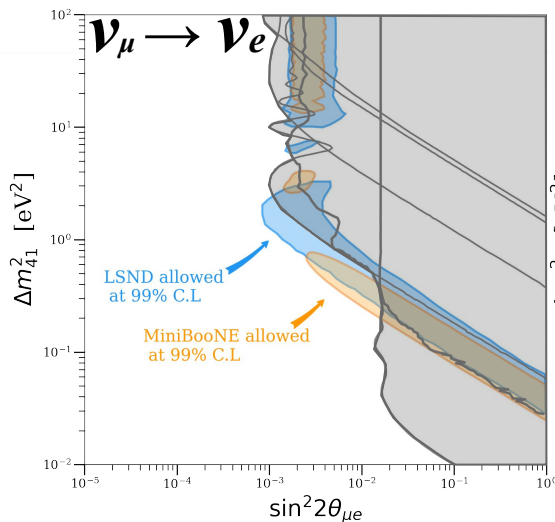
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$\nu_\mu \rightarrow \nu_e$ Results

ν_e Disappearance

ν_μ Disappearance

Cosmology



- There is **EXTREME tension** in global data for a “vanilla 3+1 sterile neutrino”
 - It's been that way for a long time, and is NOT getting better
 - Gets ***much worse*** with **cosmology** included
- Vanilla **3+1 sterile neutrino has not been a viable solution for a long time.**
- While we need to close the box on eV sterile explanation, we also need to **look outside the box..**

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New Ideas

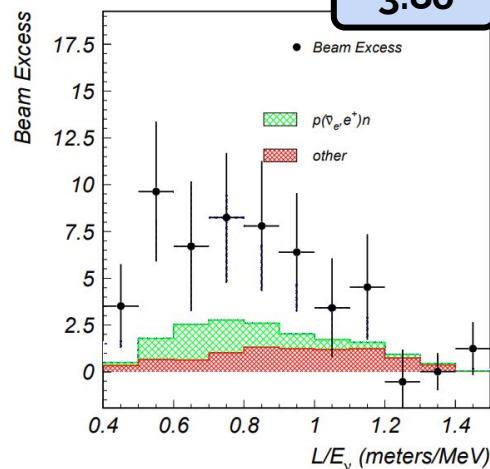
If a model fails to explain the data
throw out the model, not the data.

If not eV² scale sterile neutrinos, then what?

LSND Anomaly

Decay-at-rest

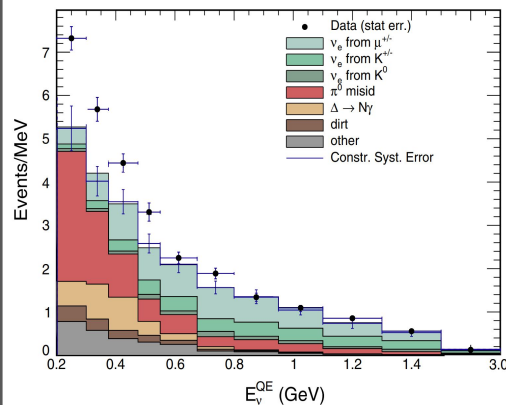
~3.8 σ



MiniBooNE Anomaly

Decay-in-flight

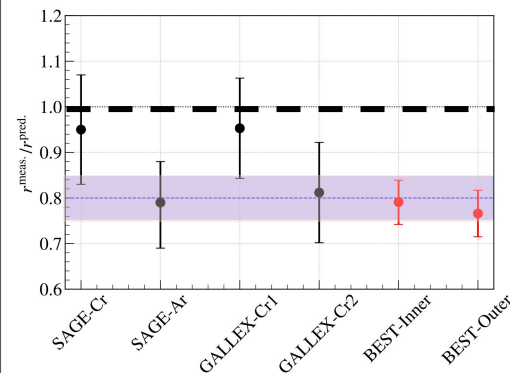
~4.8 σ



Gallium Anomaly

Radioactive Source

~4.0 σ



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ν_μ Disappearance

ν_μ Cosmology

New Ideas

Additions/Modifications to light sterile neutrino oscillations* I.e $3+1$ + something else

- **$3+2$** and **$3+3$** (more light steriles)
 - C. Giunti *et al* Phys.Rev.D 84 (2011) 9, 073008
- **$3+1$ + Non-Standard interactions** (NSI)
 - J. Liao *et al* Phys.Rev.D 99 (2019) 1, 015016
- **$3+1$ + Decay**
 - Z.Moss *et al* Phys.Rev.D 97, (2018) 055017
- **$3+1$ + Decoherence**
 - C.A. Argüelles *et al* C.Phys. Rev. D 107 (2023), 036004
- **$3+1$ + Resonance Matter Effects**
 - D.Alves *et al* JHEP08 (2022) 034

Lots of effort in this direction, to **keep the core $3+1$ light oscillating sterile neutrino model** and modify slightly to **help reduce global tension**

*Just a few references, many many more

Decouple Anomalies

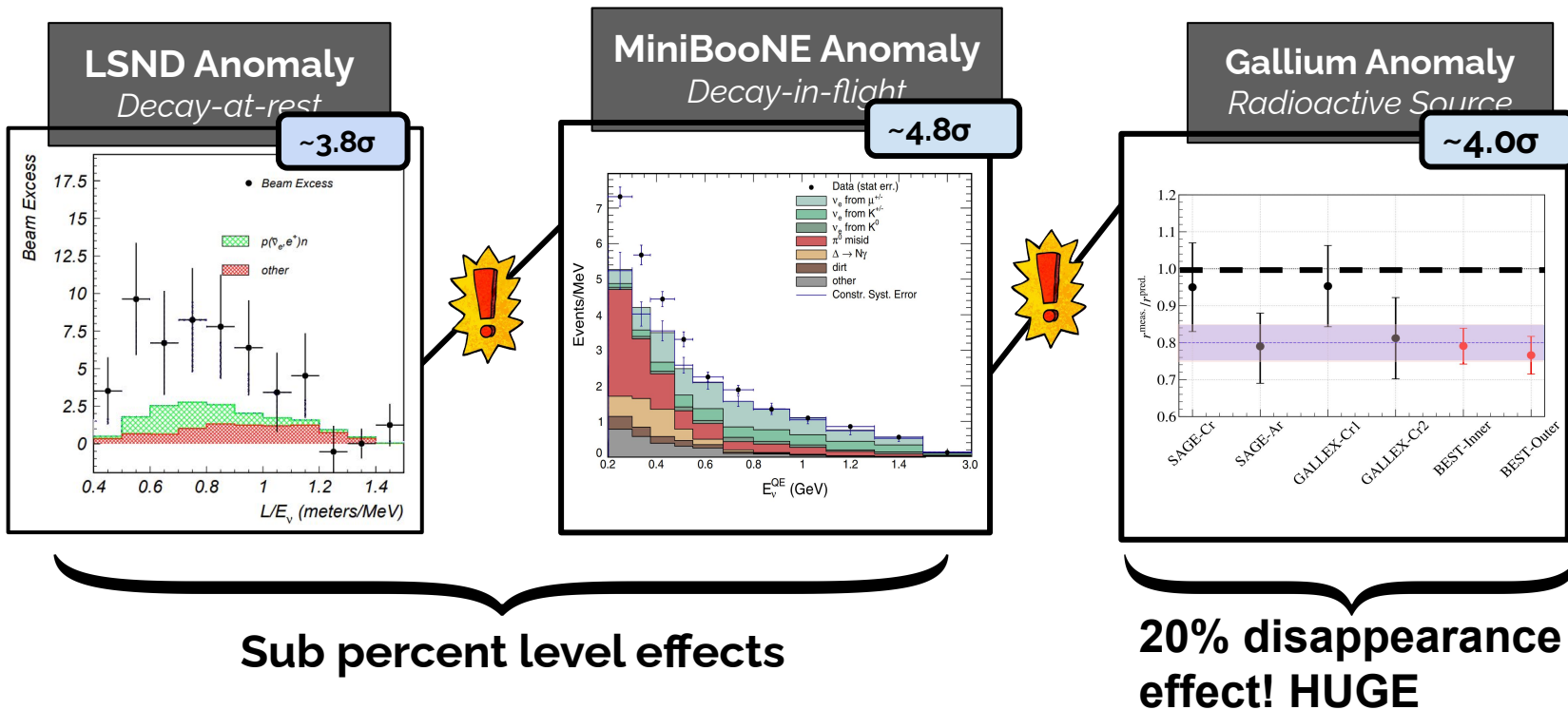
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 ν_μ Disappearance
 ν_μ Cosmology
New Ideas

If they are not all related, very little evidence for *oscillations*



Decouple Anomalies

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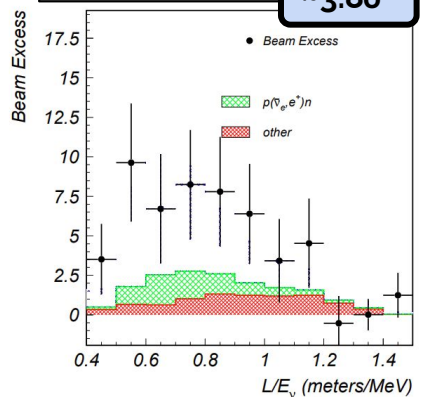
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 ν_e Disappearance
 ν_μ Disappearance
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New Ideas

If they are not all related, very little evidence for *oscillations*

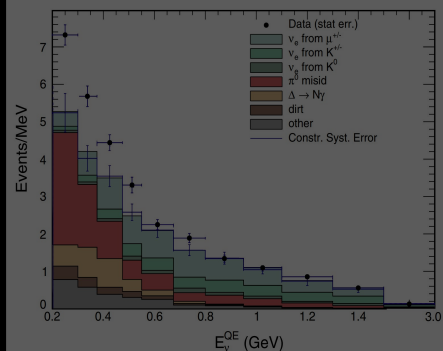
LSND Anomaly *Decay-at-rest*

$\sim 3.8\sigma$



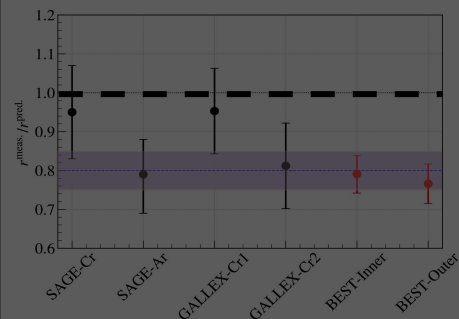
MiniBooNE Anomaly *Decay-in-flight*

$\sim 4.8\sigma$



Gallium Anomaly *Radioactive Source*

$\sim 4.0\sigma$



Sub percent level effects

20% disappearance
effect! HUGE

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ν_μ Disappearance

ν_μ Cosmology

New Ideas

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

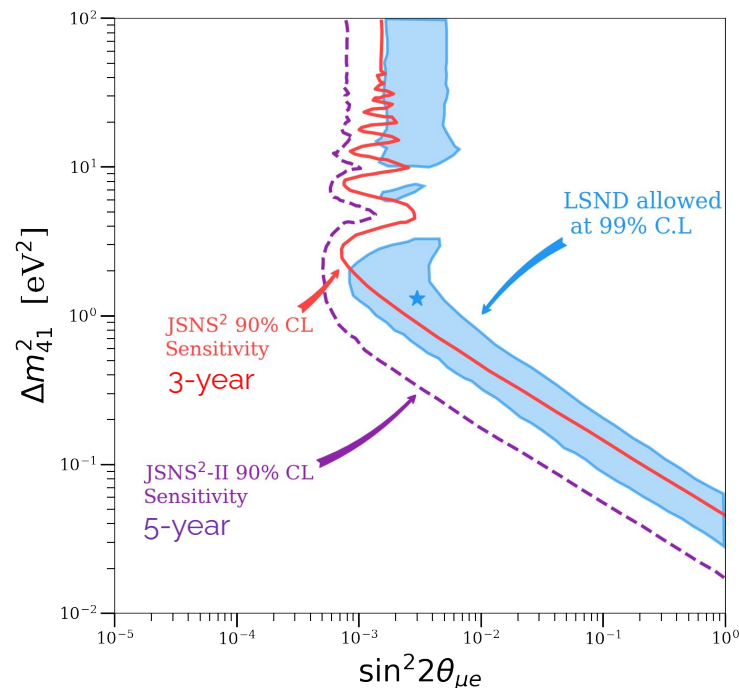
1st Phase: JSNS² [[1310.1347](#)]

- Single Detector. Commissioned 2020,
- Physics run 2021-2024 with 4.85×10^{22} POT collected [[2412.18509](#)]

2nd Phase: JSNS²-II [[2012.10807](#)]

Upgrade to **two detectors**, Second, far detector being constructed

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



Decouple Anomalies

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ν_e Disappearance

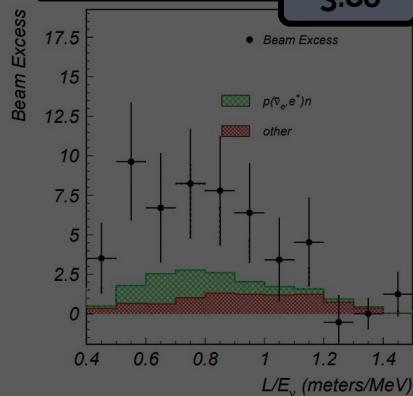
ν_μ Cosmology

New Ideas

LSND Anomaly

Decay-at-rest

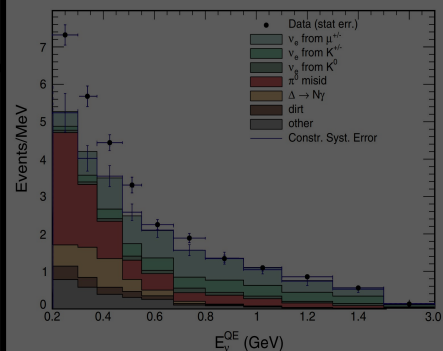
$\sim 3.8\sigma$



MiniBooNE Anomaly

Decay-in-flight

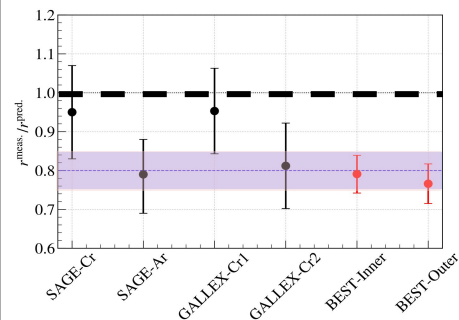
$\sim 4.8\sigma$



Gallium Anomaly

Radioactive Source

$\sim 4.0\sigma$



Sub percent level effects

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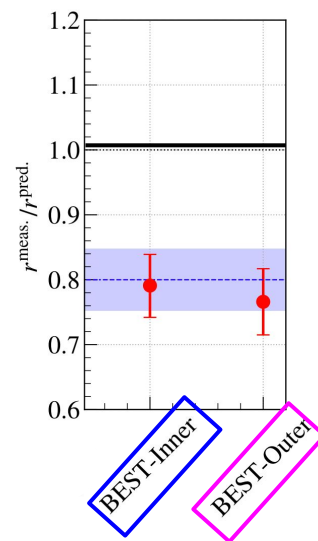
ν_e Disappearance

ν_μ Disappearance

Cosmology

New Ideas

- BEST **was** the new testing ground for this decades old anomaly
- BEST result is **extremely compelling**, the **anomaly is confirmed** but sterile origin is NOT confirmed



BEST designed as a two-distance oscillation experiment from the start **Inner** and **Outer** volumes

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ν_μ Disappearance

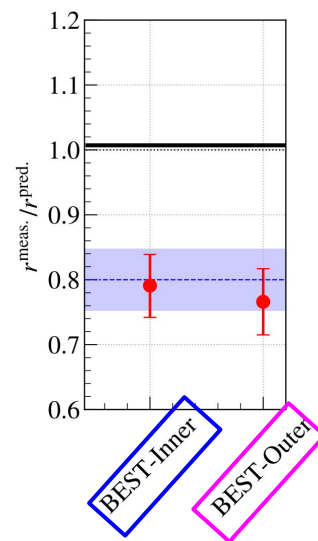
ν_e Disappearance

ν_μ Cosmology

New Ideas

- BEST **was** the new testing ground for this decades old anomaly
- BEST result is **extremely compelling**, the **anomaly is confirmed** but sterile origin is NOT confirmed
 - ***Might be the most robust neutrino anomaly right now***

If it is indeed due to new physics its **very hard** to explain a **~20% effect in the electron sector** while remaining consistent with global experiments



BEST designed as a two-distance oscillation experiment from the start **Inner** and **Outer** volumes

Decouple Anomalies

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ν_e Disappearance

ν_μ Disappearance

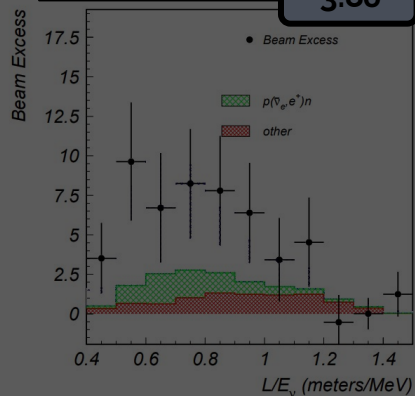
ν Cosmology

New Ideas

LSND Anomaly

Decay-at-rest

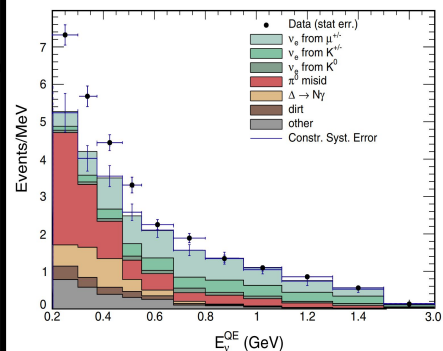
$\sim 3.8\sigma$



MiniBooNE Anomaly

Decay-in-flight

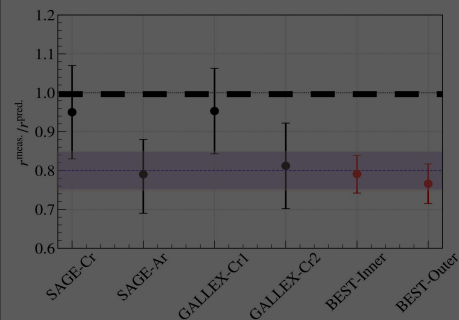
$\sim 4.8\sigma$



Gallium Anomaly

Radioactive Source

$\sim 4.0\sigma$



Sub percent level effects

20% disappearance effect! HUGE

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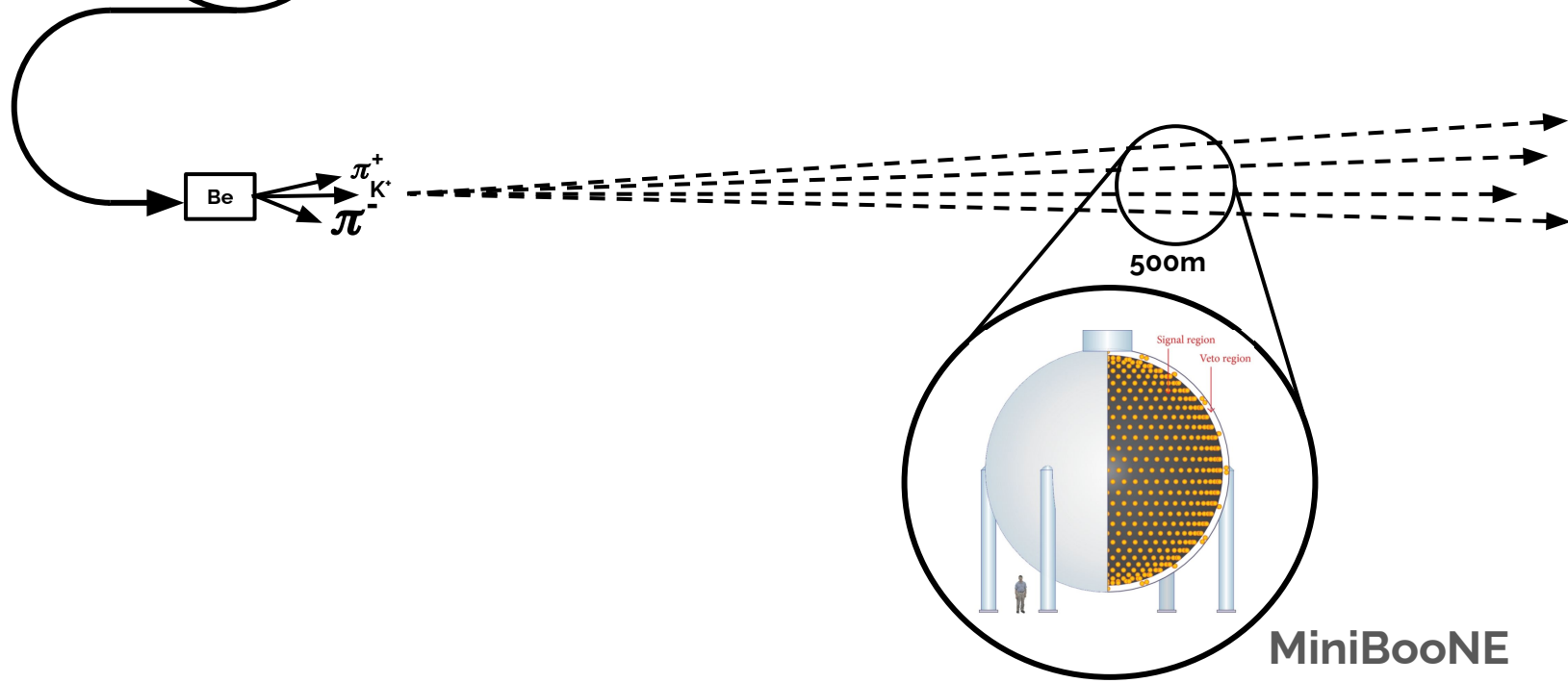
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New Ideas



Protons

Booster
Accelerator
~8 GeV



The SBN Program

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$\nu \rightarrow \nu_e$ Results
 ν_μ Disappearance
 ν_e Disappearance
 ν_μ Disappearance
Cosmology
New Ideas

 **Fermilab**

Protons

Booster
Accelerator
~8 GeV

110 ton



90 ton





476 ton



110m

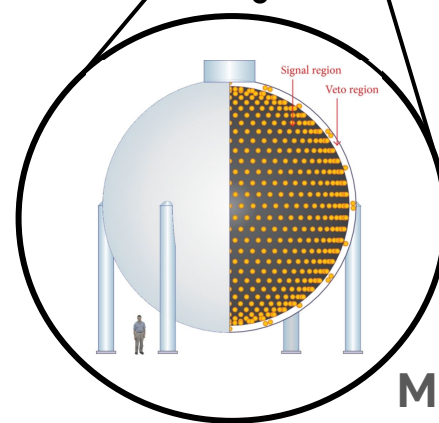
470m

600m

500m

Be

π^+
 π^-
 K^+



MiniBooNE

Motivation from MiniBooNE: **Electrons**

1. Introduction

3ν Paradigm

How we got here

2. Short-Baselines

Anomalies

Sterile Neutrinos

3. Where We Stand

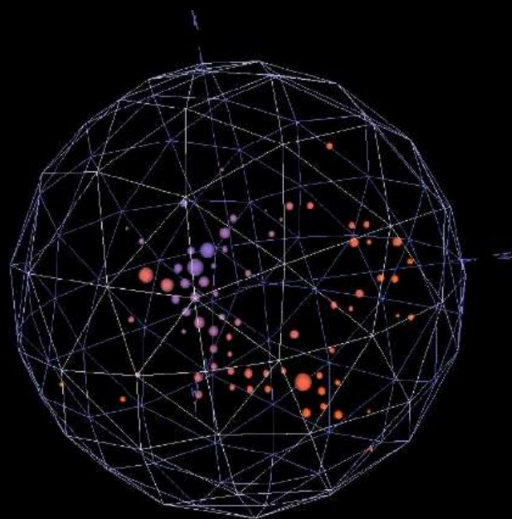
$\nu \rightarrow \nu_e$ Results

ν_μ Disappearance

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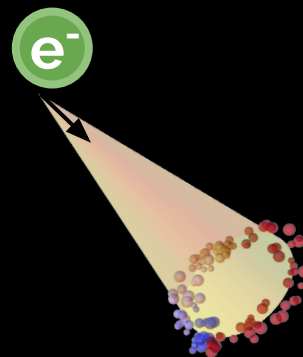
ν_μ Cosmology

New Ideas



Cherenkov ring event
in MiniBooNE

MiniBooNE couldn't separate
electrons from



Motivation from MiniBooNE: **Electrons**, **Photons**

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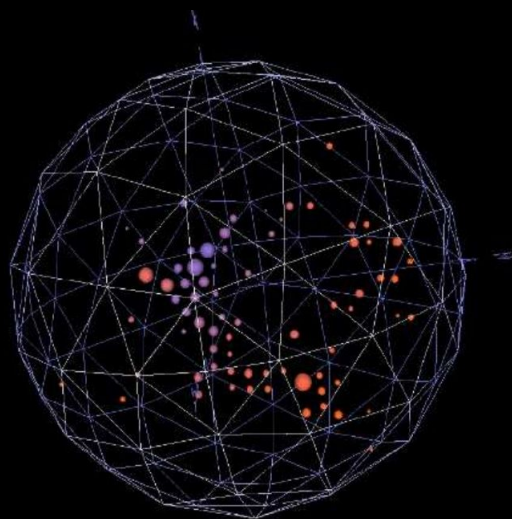
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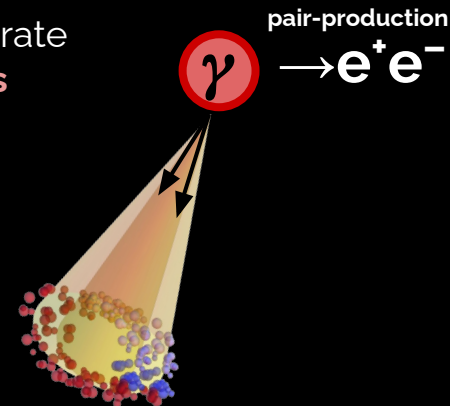
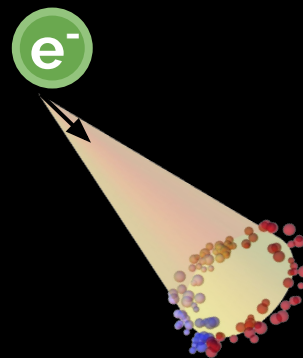
ν_μ Cosmology

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Cherenkov ring event
in MiniBooNE

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



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

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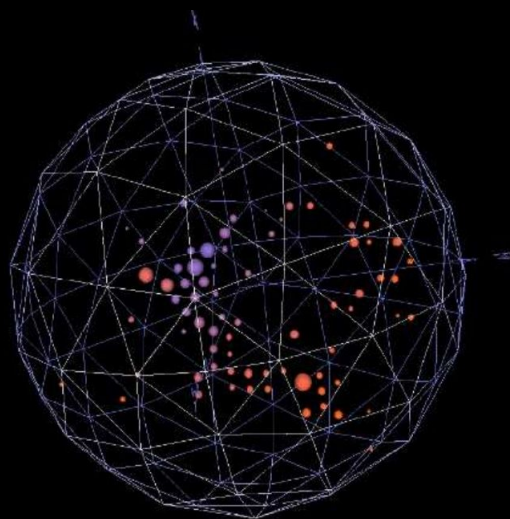
$\nu \rightarrow \nu_e$ Results

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ν_e Disappearance

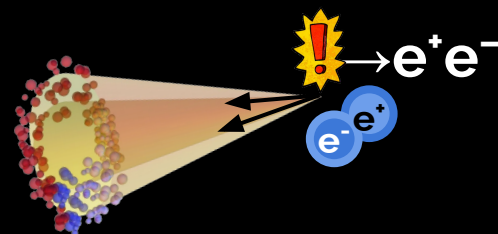
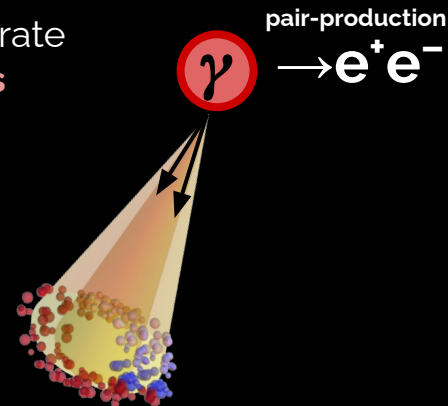
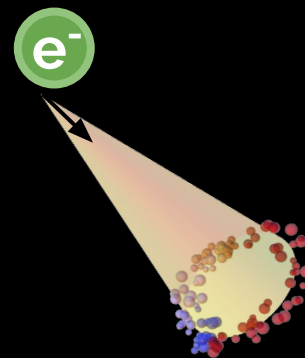
ν_μ Cosmology

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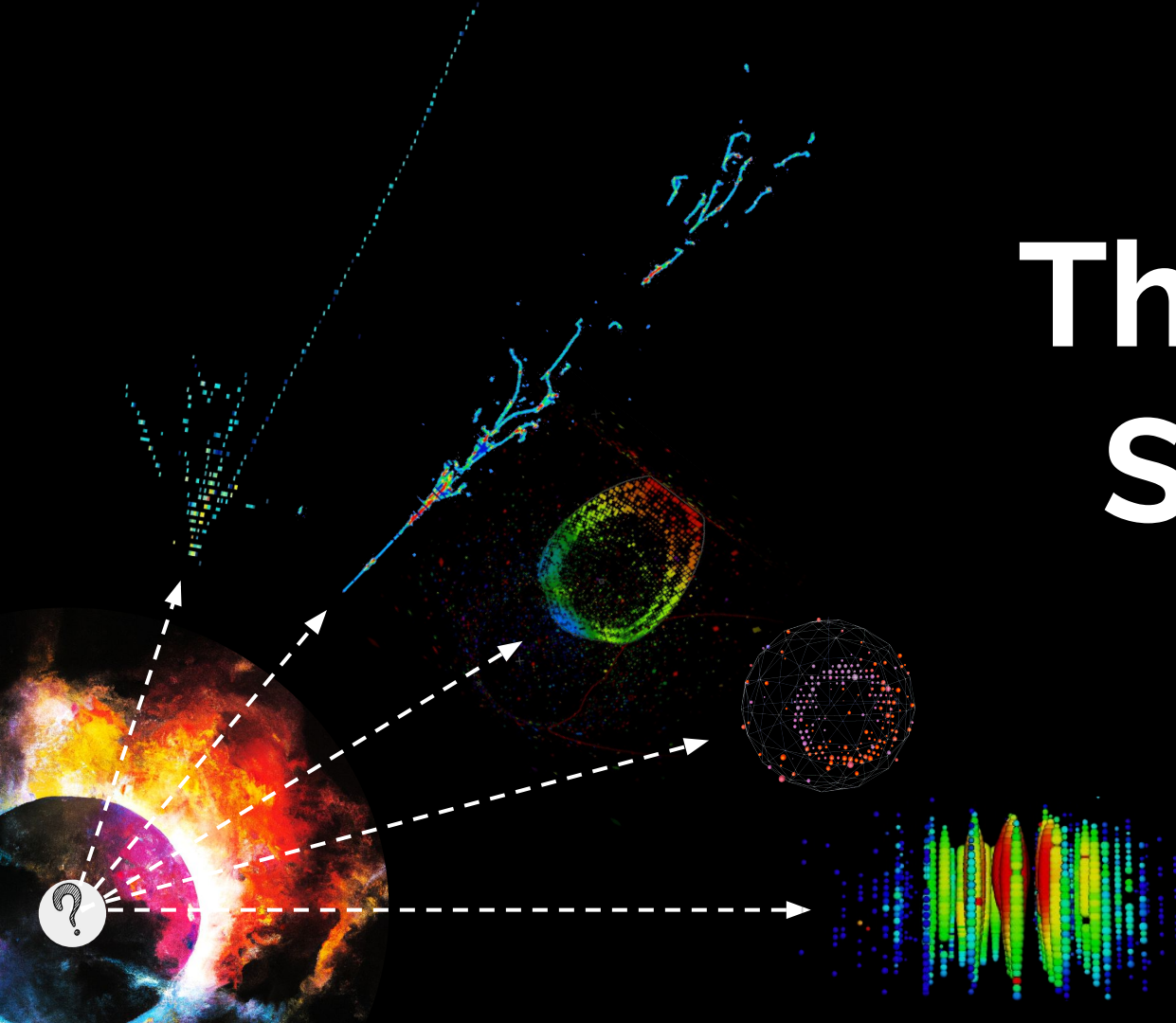


Cherenkov ring event
in MiniBooNE

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



The Dark Sector



Quick Note on MiniBooNE/Anomaly “motivation” of BSM/Dark Sector Physics

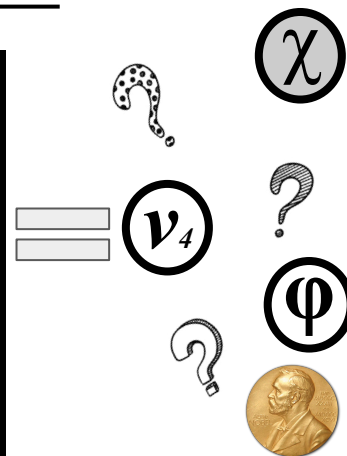
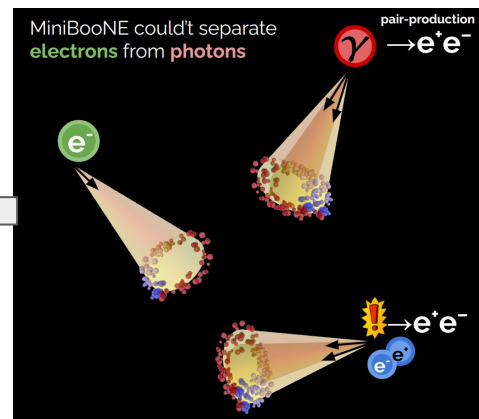
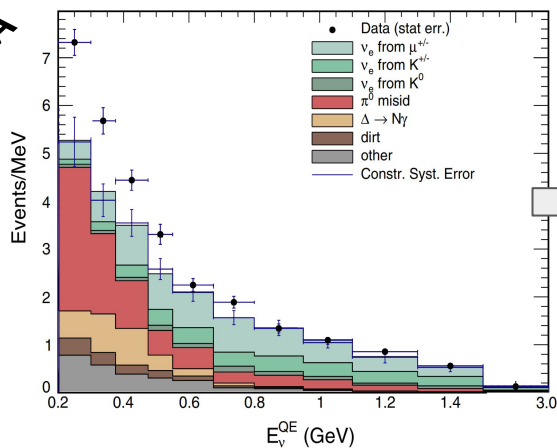
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Quick Note on MiniBooNE/Anomaly “motivation” of BSM/Dark Sector Physics

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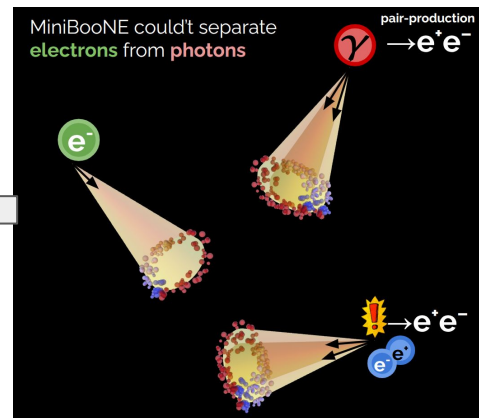
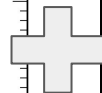
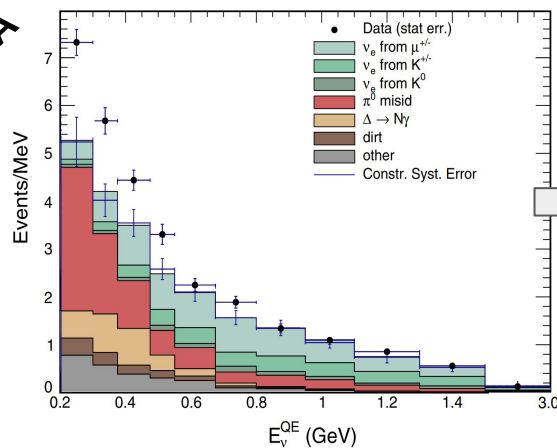
ν_e Disappearance

ν_μ Cosmology

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Physicist A

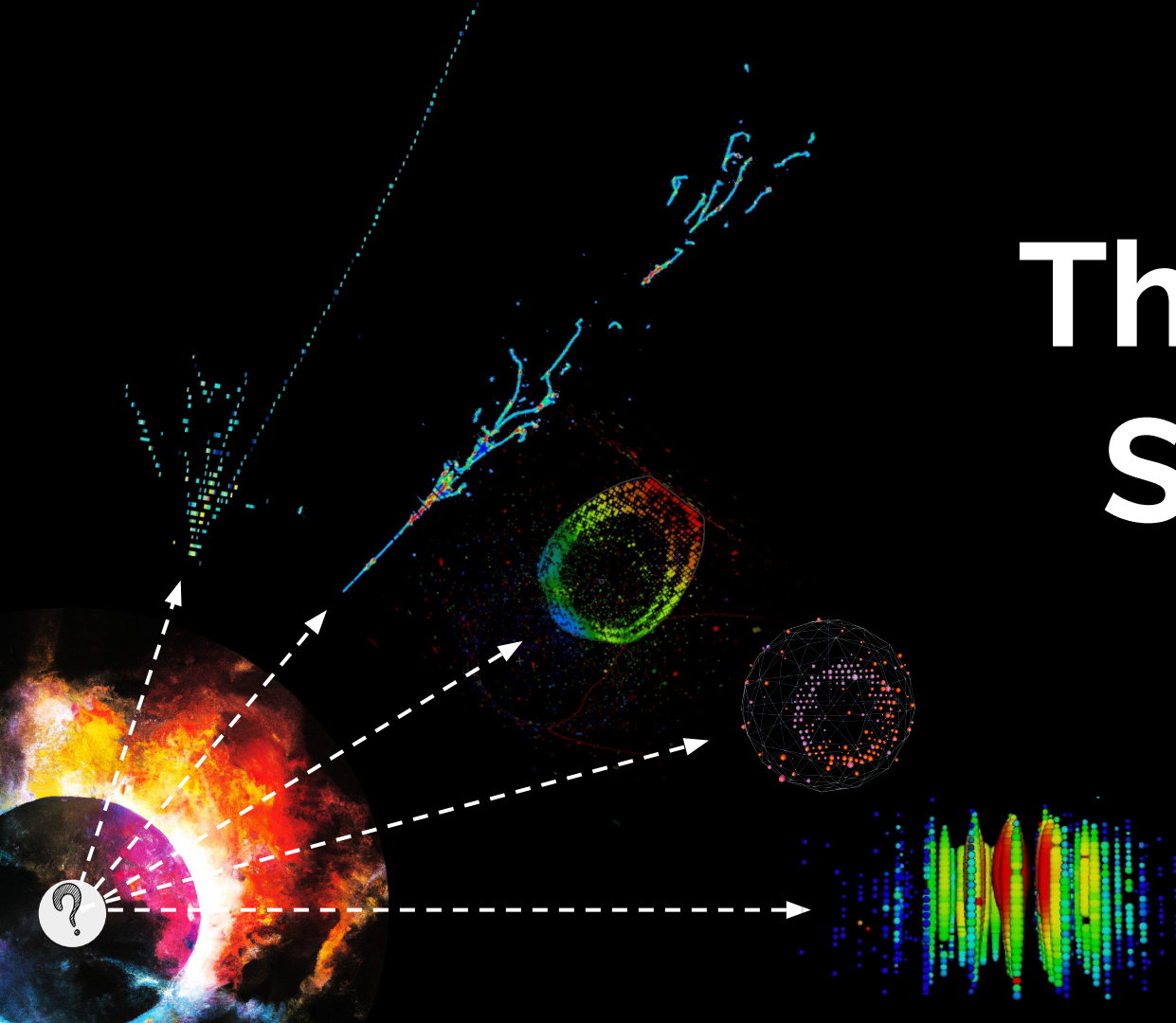


Physicist B

“I’m tired of hearing about
short-baseline anomalies”

“I don’t believe the
MiniBooNE excess is real..”

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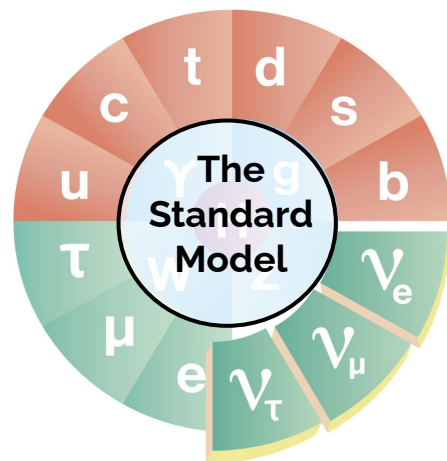
ν_μ Disappearance

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“Dark Matter”



- Plethora of particles
- Three forces
- Forms complex composite structures, hadrons, mesons..etc..
- Forms complex atoms & molecules (chemistry)

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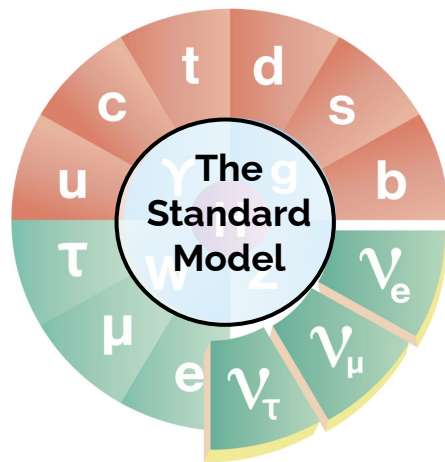
ν_e Disappearance

ν_μ Disappearance

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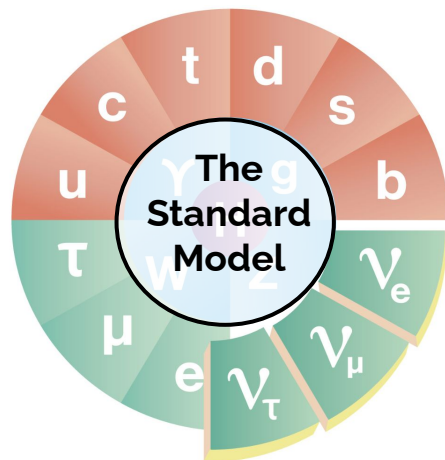
ν_μ Disappearance

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ν_μ Cosmology

New Ideas

4. The Dark Sector



- Plethora of particles
- Three forces
- Forms complex composite structures, hadrons, mesons..etc..
- Forms complex atoms & molecules (chemistry)

- Rich particle content
 - Dark matter candidate(s)
 - Sterile Neutrinos
 - Axions
 - New Scalar Bosons
 - +
 - New Forces and Interactions
 - New dark gauge bosons
- } Rich & Complex phenomenology

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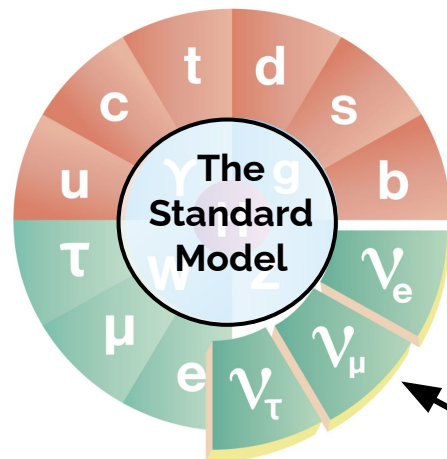
ν_e Disappearance

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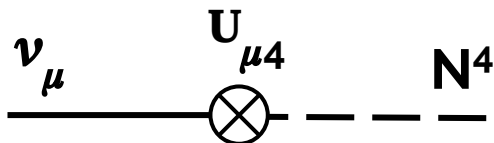
Neutrino Portal



Neutrino Portal

$$\mathcal{L} \supset -y^\alpha L_\alpha H N + \text{h.c.}$$

Couples **active**
neutrinos with
sterile neutrinos



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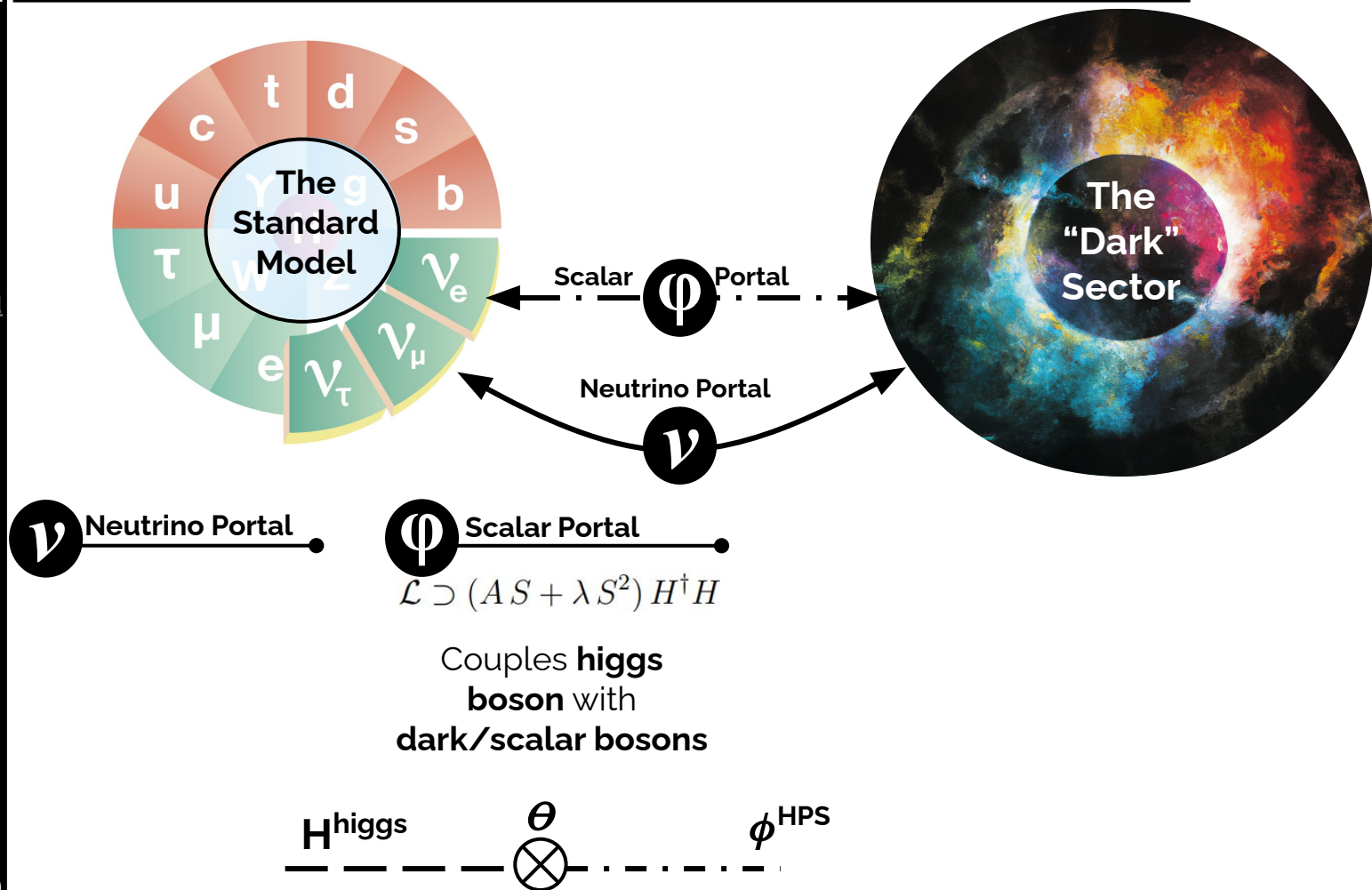
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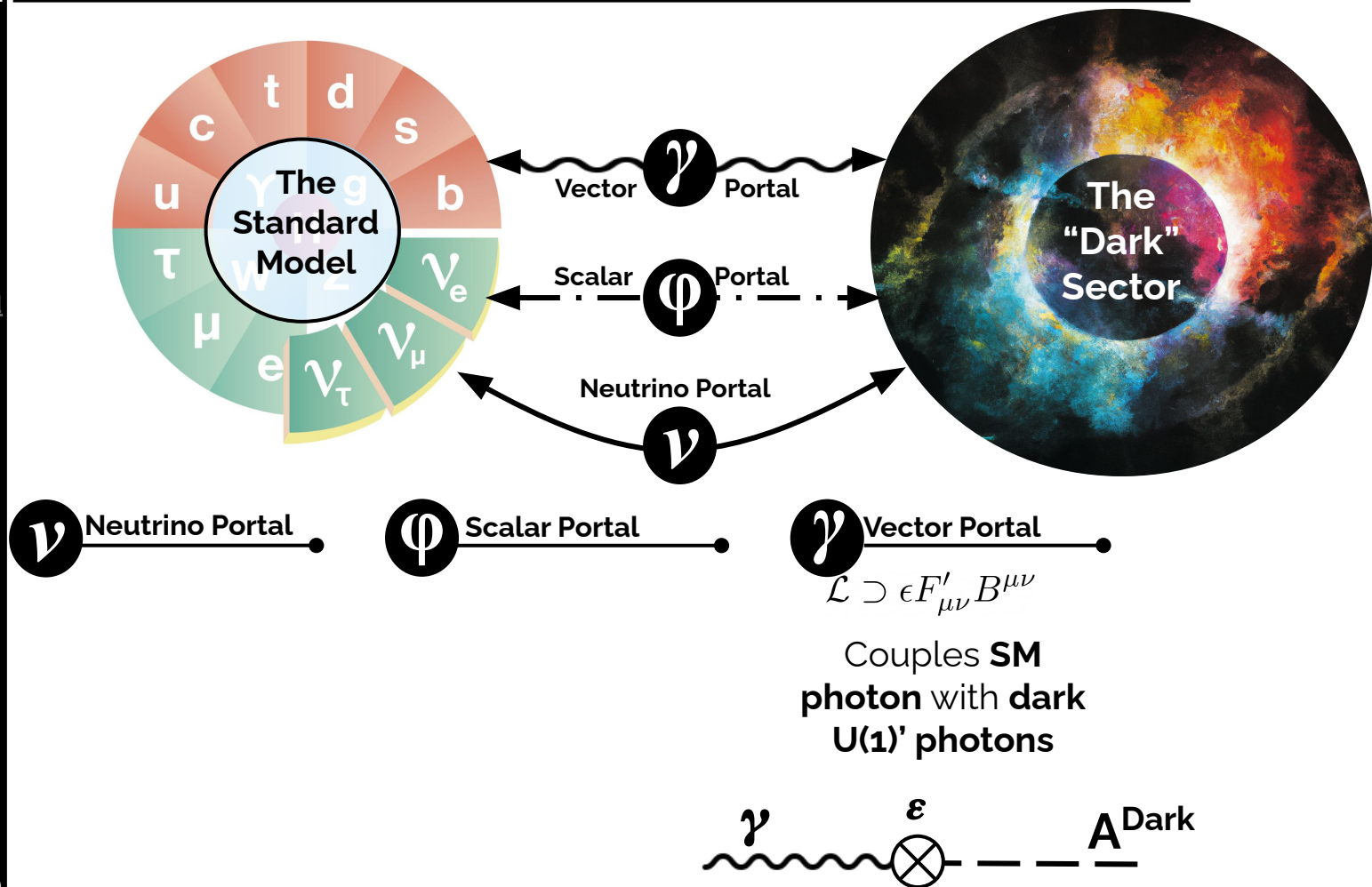
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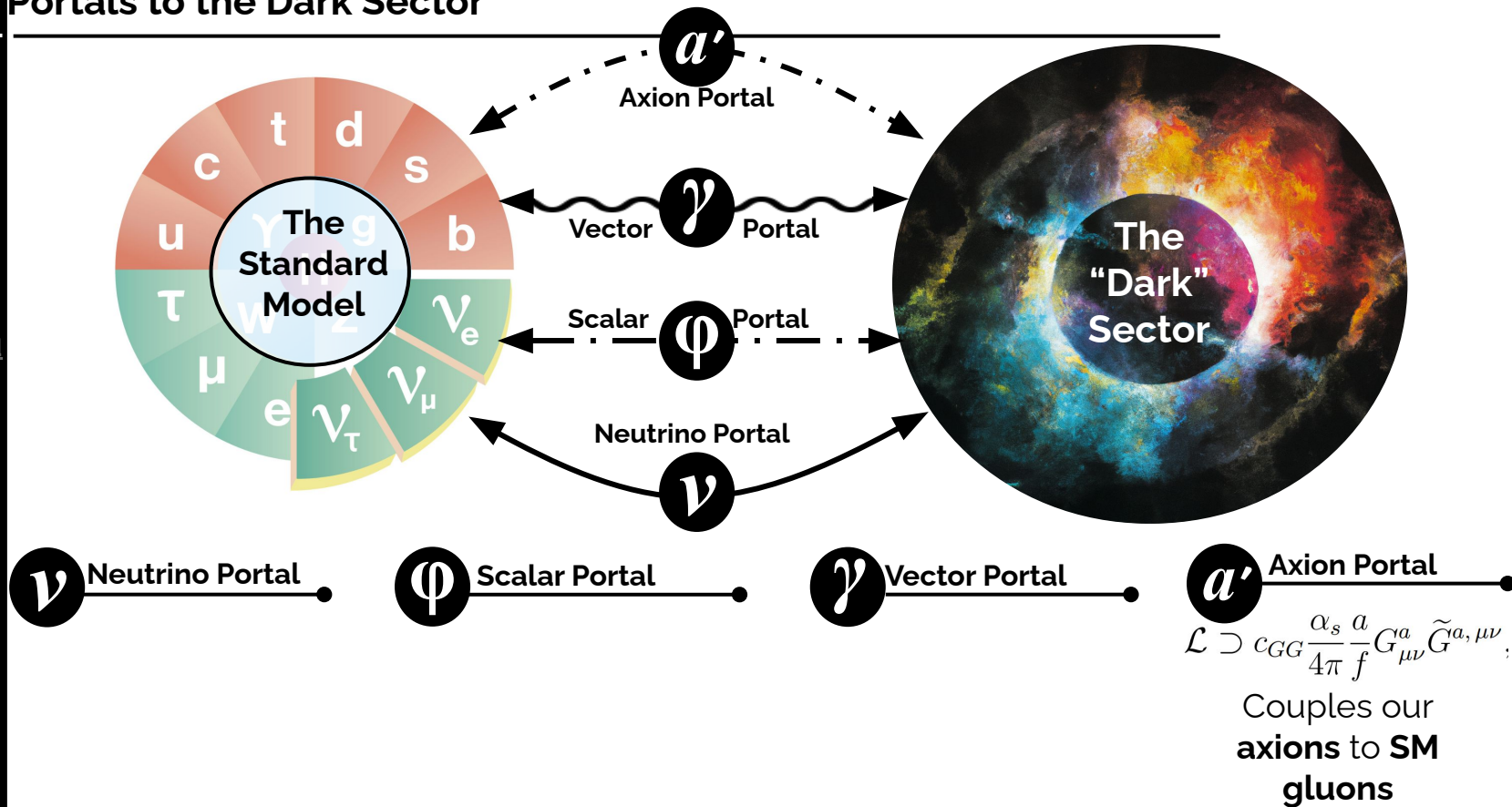
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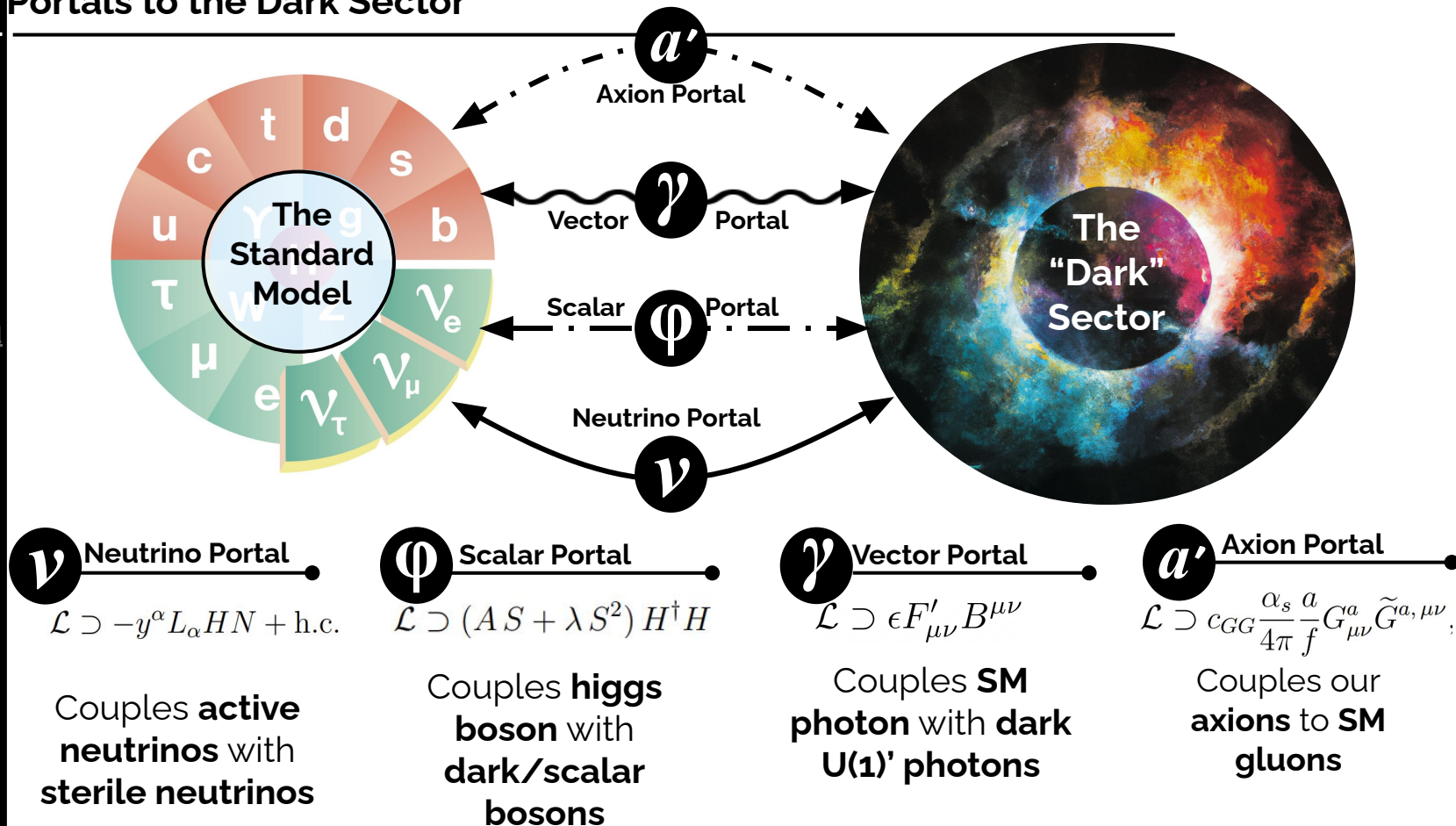
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Huge amount of phenomenology associated with these portals at short-baselines!

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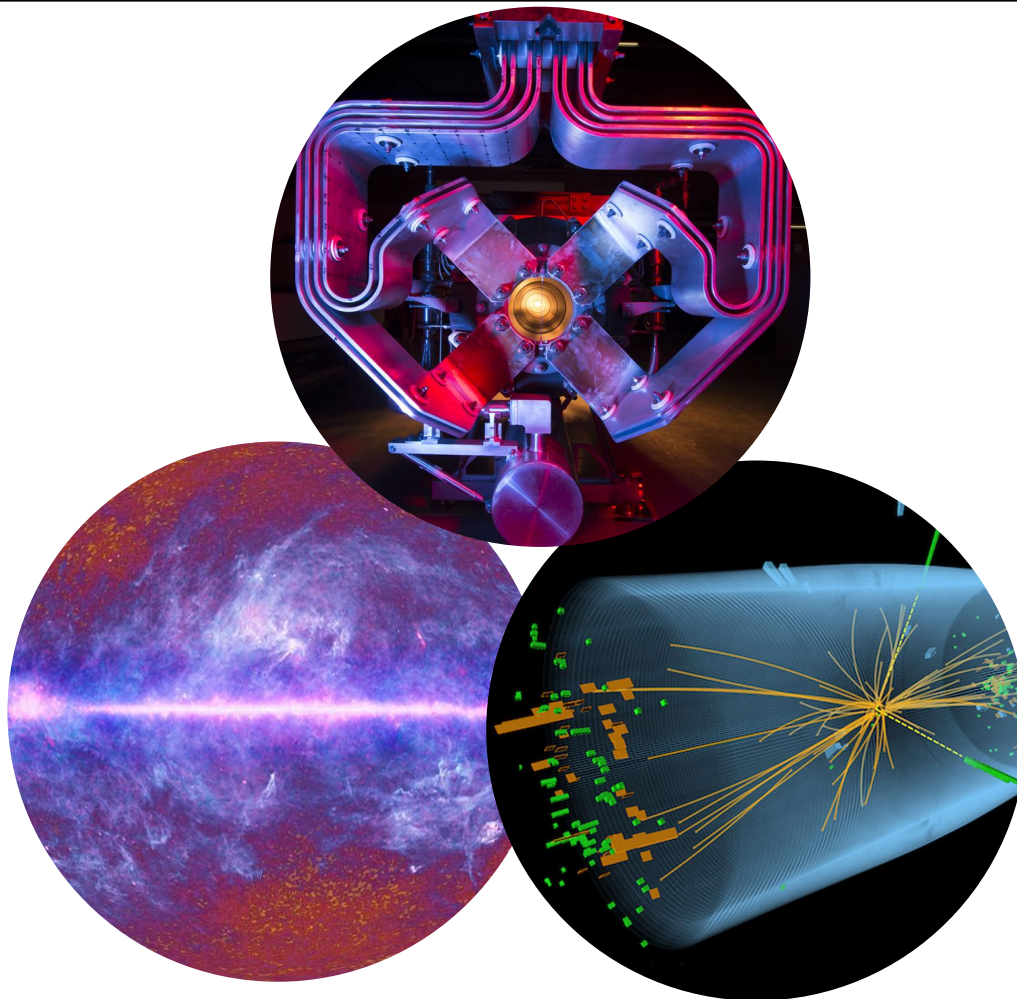
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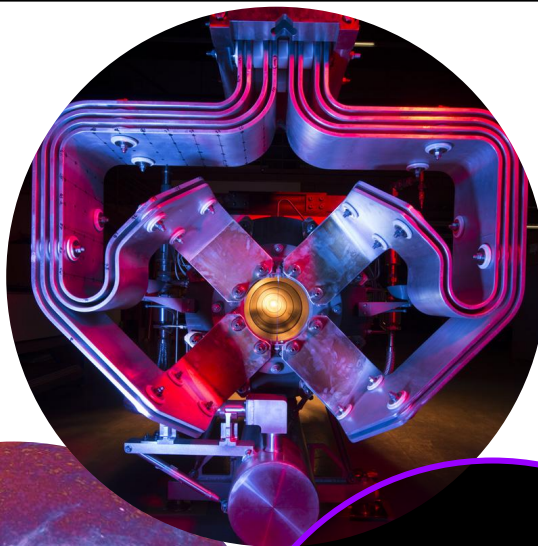
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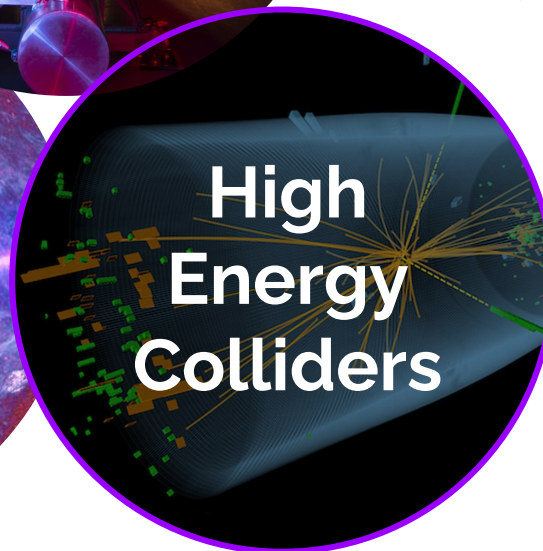
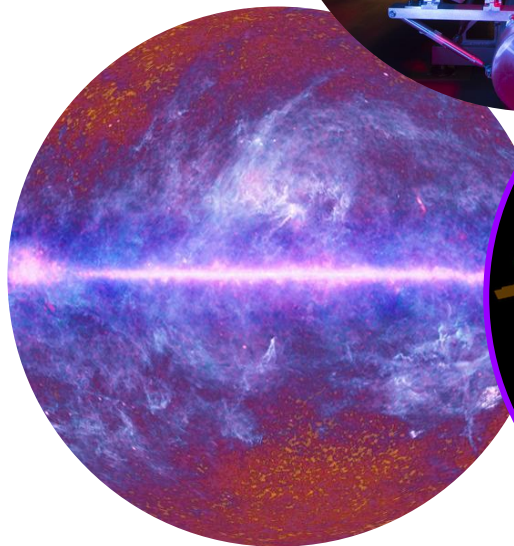
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ATLAS: JHEP 03 (2021) 243

CMS: arXiv:2405.13778 (2024)

FASER: arXiv:2410.10363 (2025)



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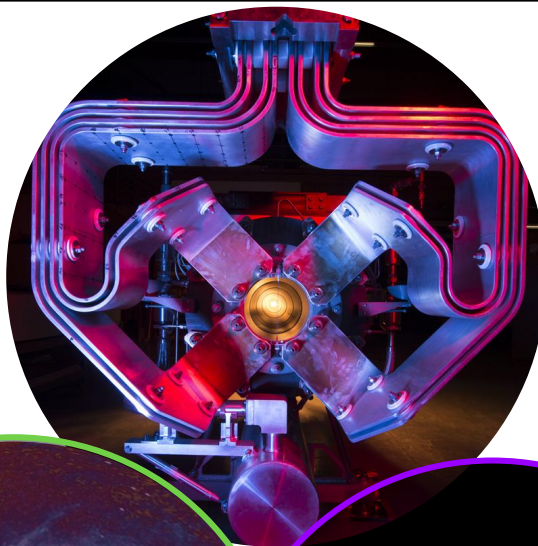
N. Sabti *et al* JCAP11(2020)056

A. Caputo *et al*

Phys. Rev. D 104 (2021) 095029

A. Boyarsky *et al*

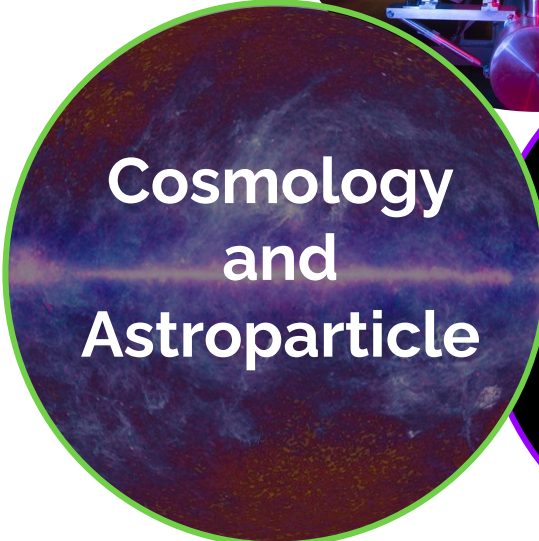
Phys. Rev. D 104, 023517 (2021)



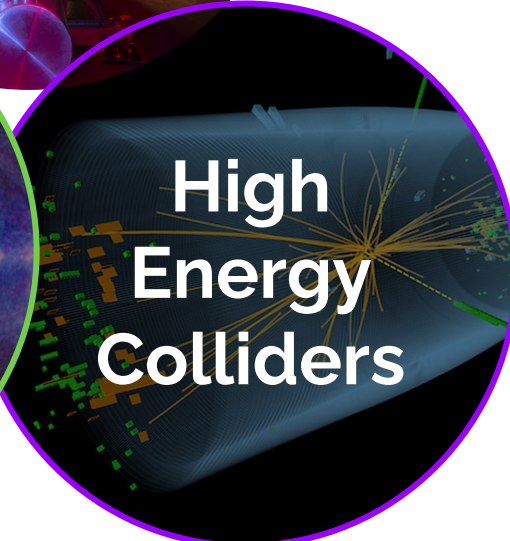
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Cosmology
and
Astroparticle



High
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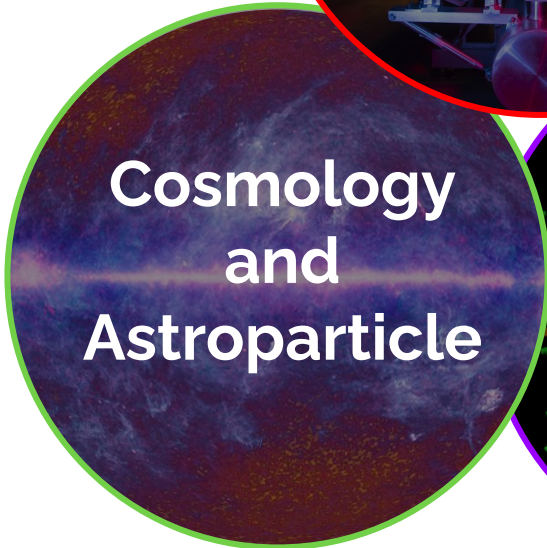


Accelerator
Neutrinos

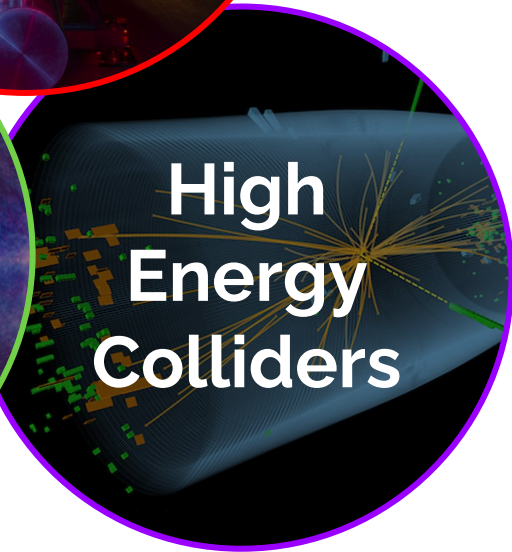
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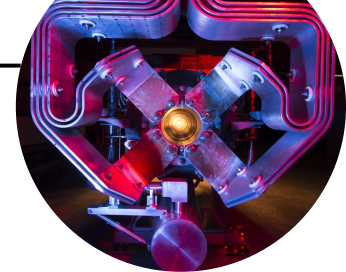
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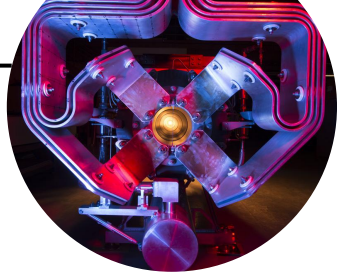
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Natural place to search

1. Impressive **increase in neutrino beam intensity** over past decades



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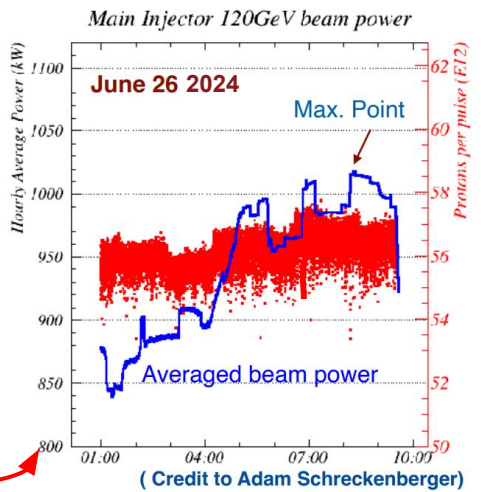
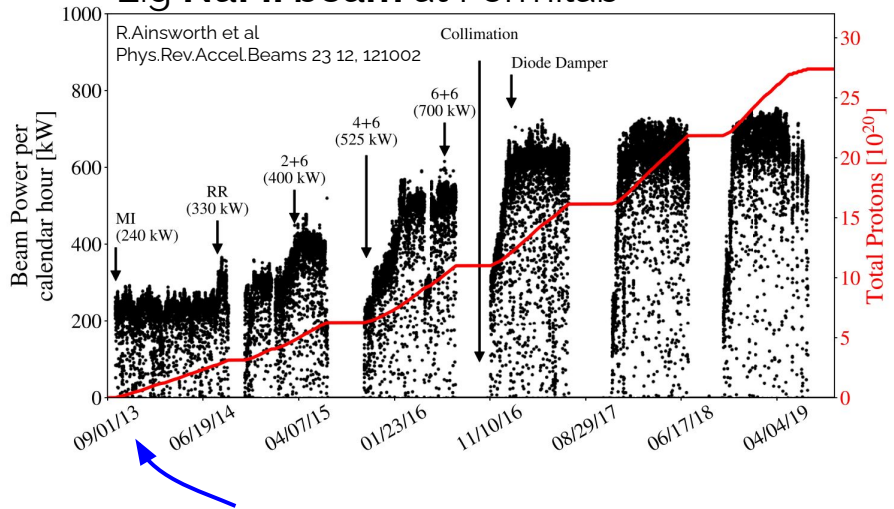
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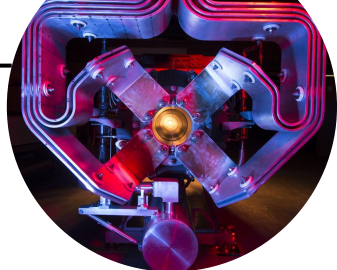
Natural place to search

- 1. Impressive **increase in neutrino beam intensity** over past decades

E.g NuMI beam at Fermilab



From **240 kW (2013)** to successful **1.018 MW (2024)** tests in just over a decade



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Natural place to search

- 1. Impressive **increase in neutrino beam intensity** over past decades

Future beam upgrades of **1.3MW for Hyper-K**

DUNE (Phase 1) to start with a **1.2MW beam** with upgrade paths for Phase II including

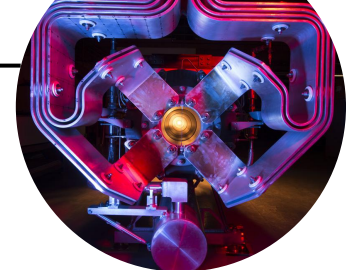
- **ACE-MIRT** (Main Injector Ramp and Targetry upgrade): Beam power to **2.0MW**
- **ACE-BR** (Booster Replacement): Beam power to **2.4MW**

Parameter	PIP-II Booster	ICD-2	BSR v1	BSR v2
Linac Energy	0.8 GeV	2 GeV	2 GeV	
Minimum Linac Current	2 mA	2 mA	2 mA	5 mA
GeV-scale Accumulator Ring	Optional	Optional	Required	Optional
RCS Energy	8 GeV	8 GeV	8 GeV	
RCS Intensity	6.5 e12	26 e12	37 e12	
RCS Circumference	474.2 m	553.2 m	570 m	
RCS Rep. Rate	20 Hz	10 Hz	20 Hz	
Number of Batches	12	6	5	
Accumulation Technique	Slip-stacking	Conventional	Conventional	
8 GeV Accumulation	Recycler	Recycler	Main Injector	
Available RCS Power	80 kW	170 kW	750 kW	
Main Injector Intensity	80 e12	156 e12	185 e12	
Main Injector Cycle Time	1.2 s	1.2 s	1.4 s	
Main Injector Power (120 GeV)	1.2 MW	2.4 MW	2.4 MW	
Upgraded Main Injector Power		3.3 MW	4.0 MW	

Further upgrade paths as high as **4.0MW** have been investigated

R. Ainsworth et al. [An Upgrade Path for the Fermilab Accelerator Complex](#)

J. Eldred et al. [Design Considerations for Fermilab Multi-MW Proton Facility in the DUNE/LBNF era](#)



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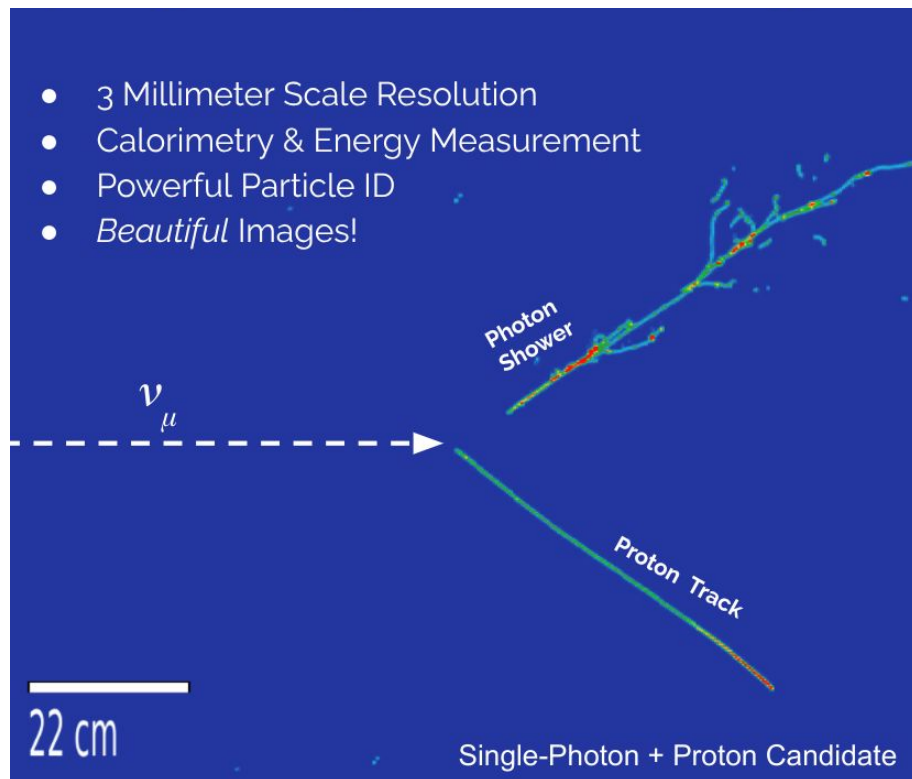
Minimal Portals

Accelerator Probes

Natural place to search

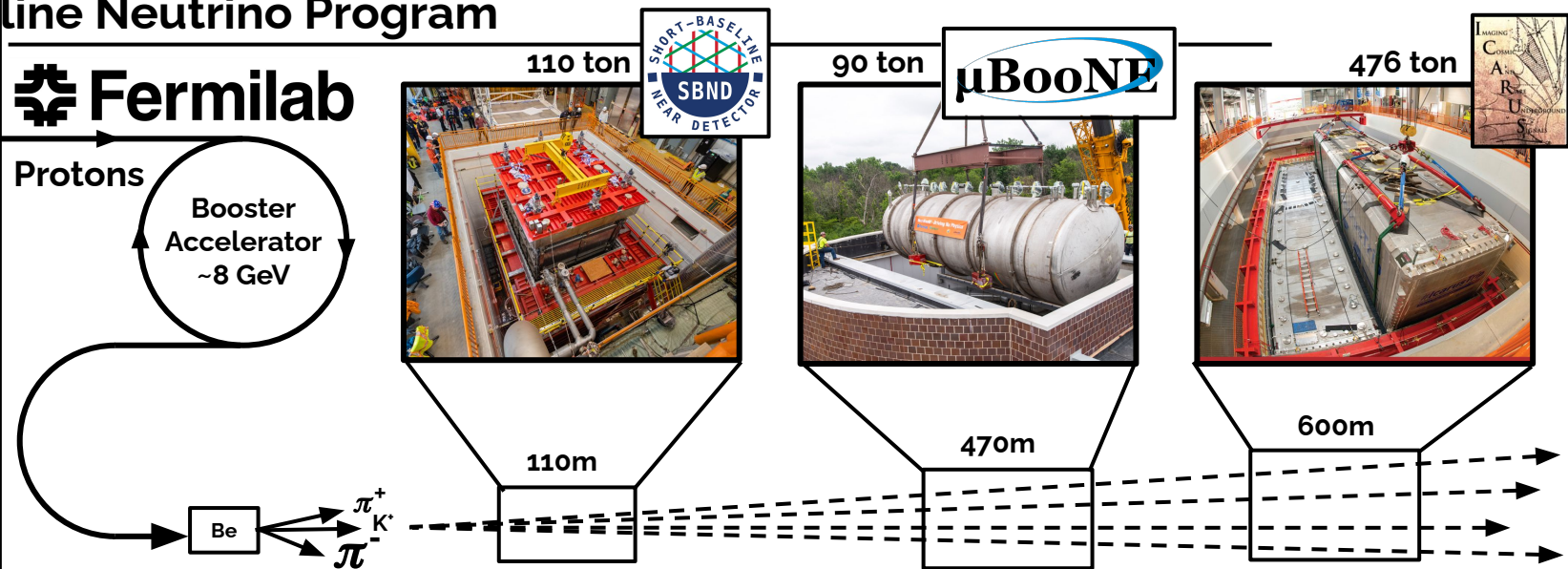
1. Impressive **increase in neutrino beam intensity** over past decades
2. High precision, multi purpose **neutrino detector technology** being employed

Eg, The Liquid Argon Time Projection Chamber (**LArTPC**) detector technology used at the **Short-Baseline Neutrino Program at Fermilab**



Short-Baseline Neutrino Program

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Accelerator Probes



Dual Beam Experiments



Protons

Booster
Accelerator
~8 GeV

Be

π^+
 π^-
 π^0
 K^+
 K^-

Main Injector
~120 GeV
Protons

π^+ π^- π^0
 K^+ K^-

NuMI Beam

90 ton

μ BooNE

470m

NuMI @ MicroBooNE
8.0° off-axis
680m

476 ton

600m

NuMI @ ICARUS
5.7° off-axis
800m



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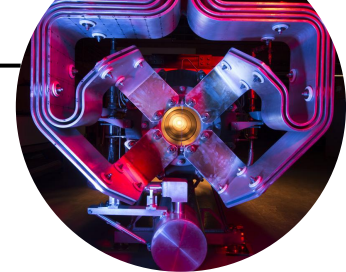
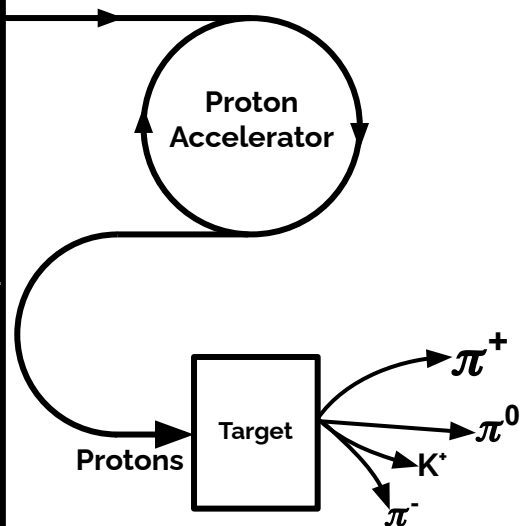
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Accelerator Neutrinos

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ν_μ Disappearance

ν_e Disappearance

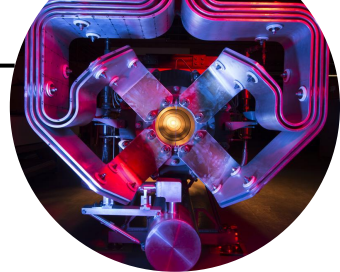
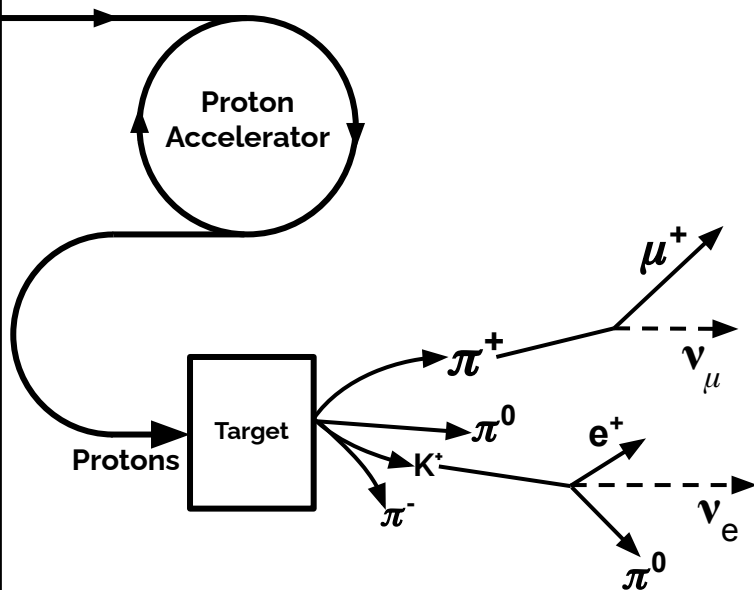
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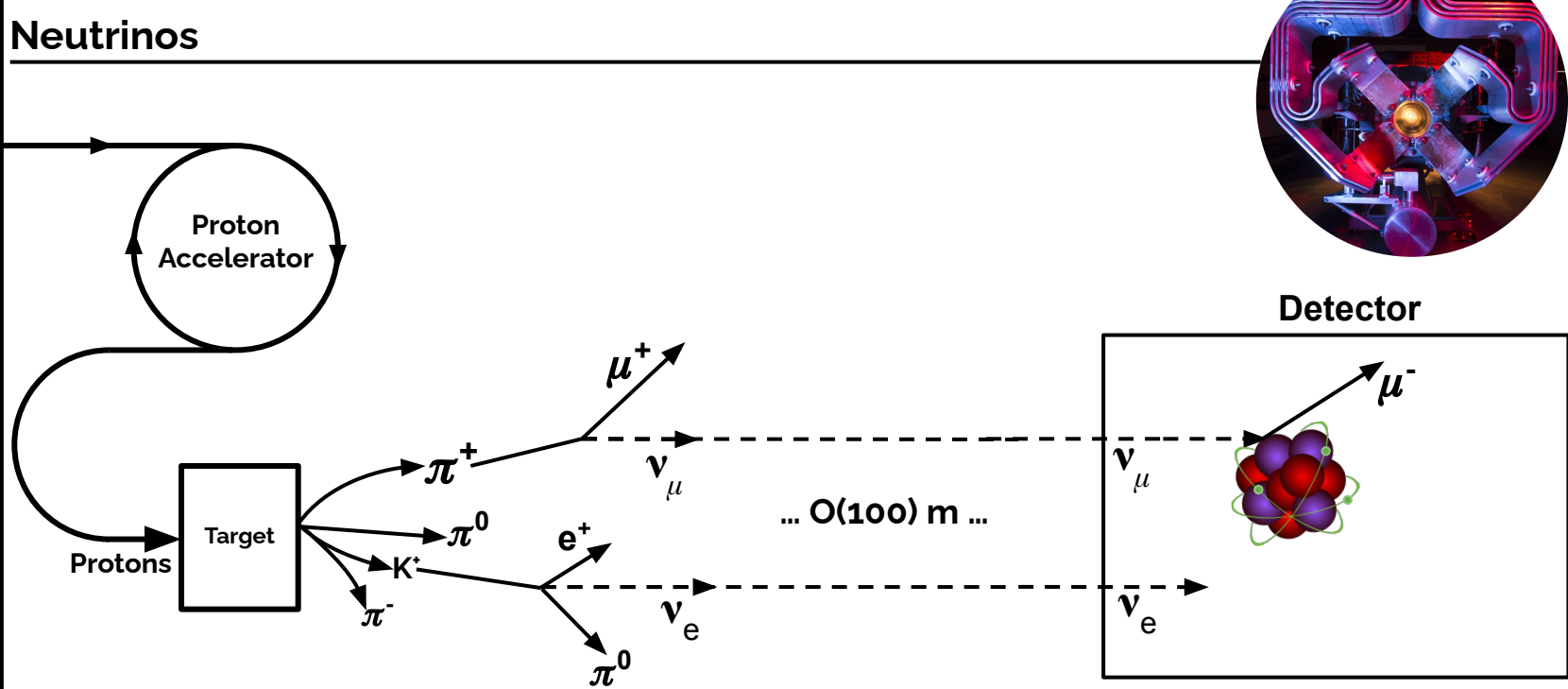
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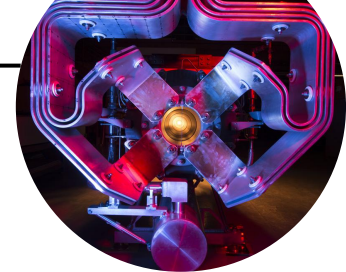
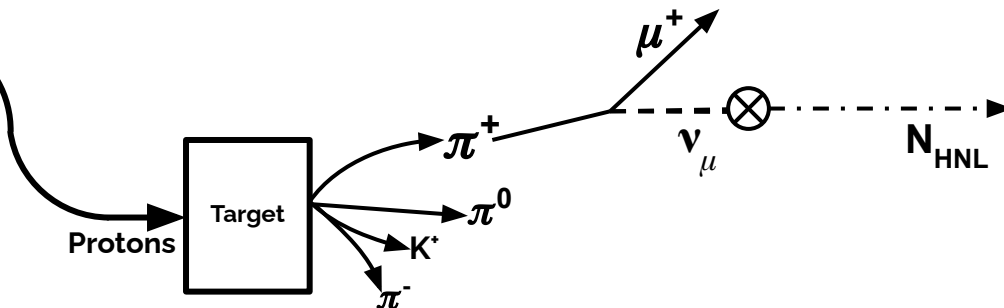
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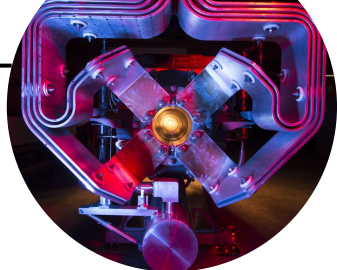
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Dark Sector Production in the beam



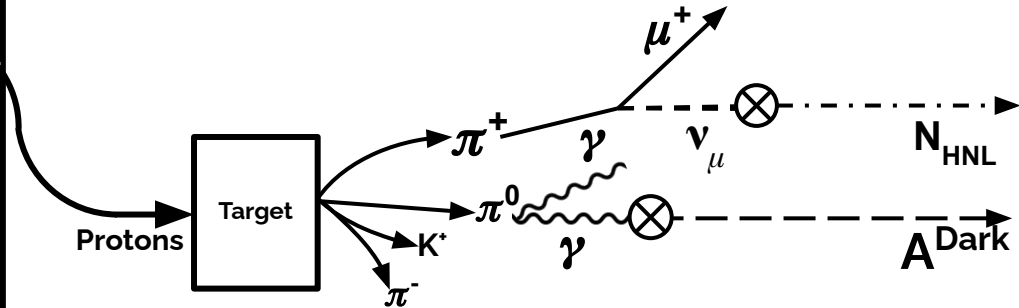
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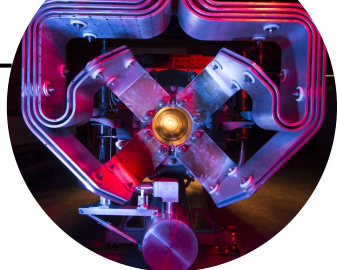
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-  Neutrino Portal $\bullet N_{\text{HNL}}$
-  Vector Portal $\bullet A^{\text{Dark}}$



Dark Sector Production in the beam



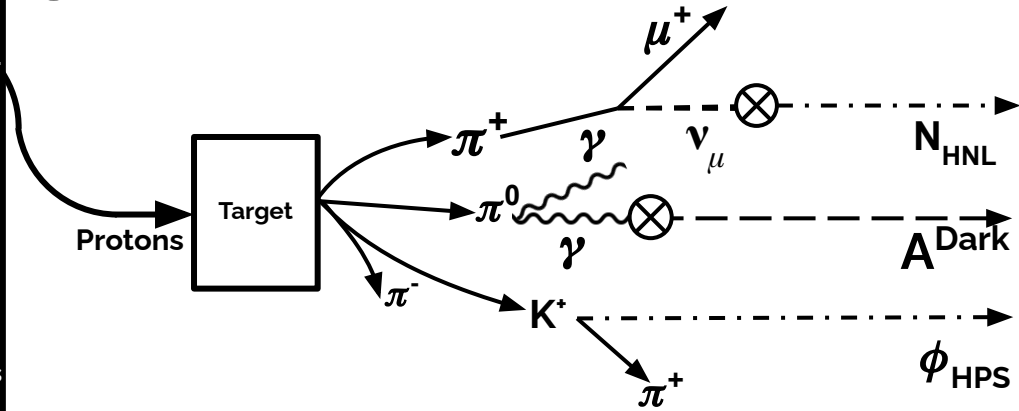
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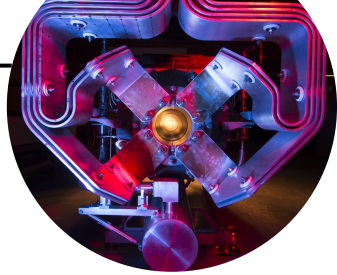
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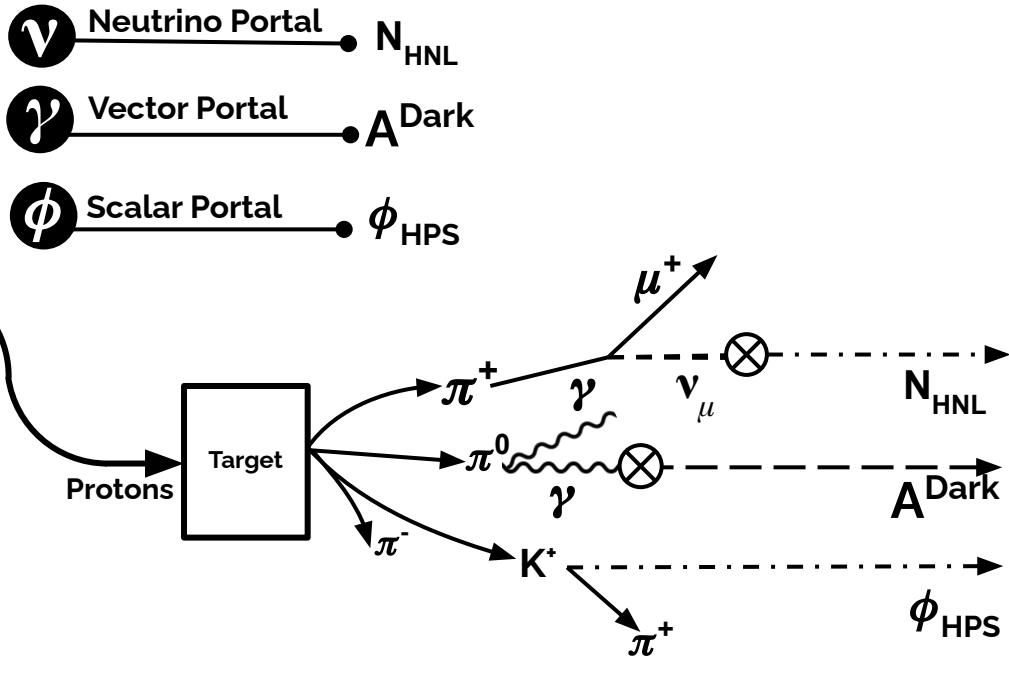
-  Neutrino Portal $\bullet N_{\text{HNL}}$
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-  Scalar Portal $\bullet \phi_{\text{HPS}}$



Dark Sector Production in the beam



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All neutrino beams are **Dark Sector particle beams, for free**

Detection of Dark Sector Particles

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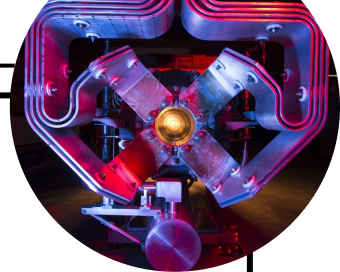
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Neutrino Portal

N_{HNL}

Neutrino Detector



Detection of Dark Sector Particles: Decays

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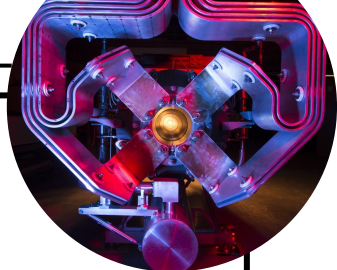
Neutrino Portal

N_{HNL}

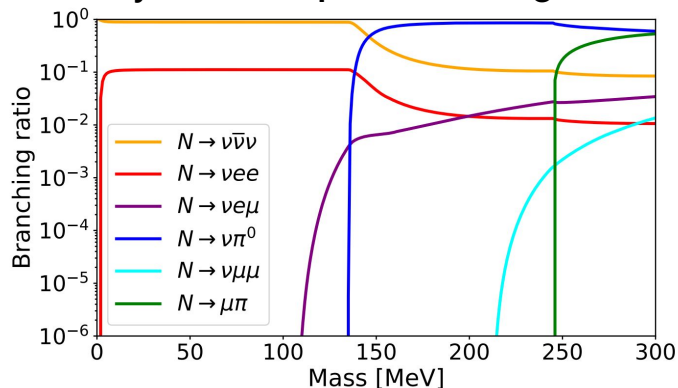
Neutrino Detector

ν_μ

π^0



Heavy Neutral Lepton Branching Ratio



MicroBooNE Collaboration

arXiv:2501.08052 [hep-ex] 2025

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Neutrino Portal

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ν_μ

π^0

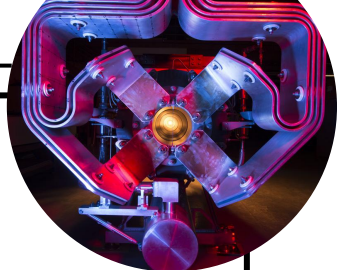
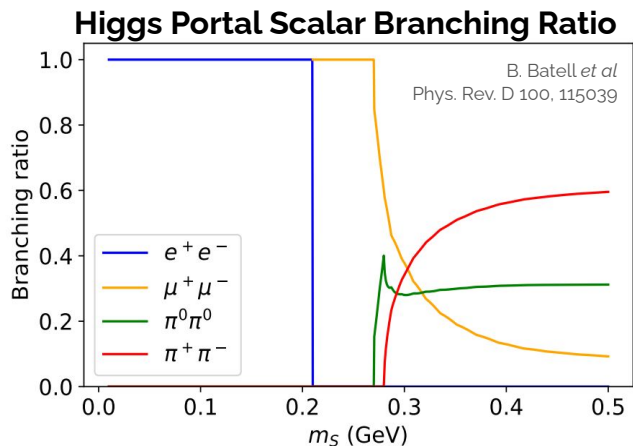


Scalar Portal

ϕ_{HPS}

μ^+

μ^-



Detection of Dark Sector Particles: Decays

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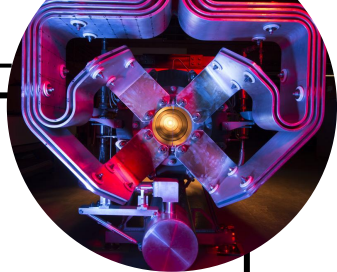
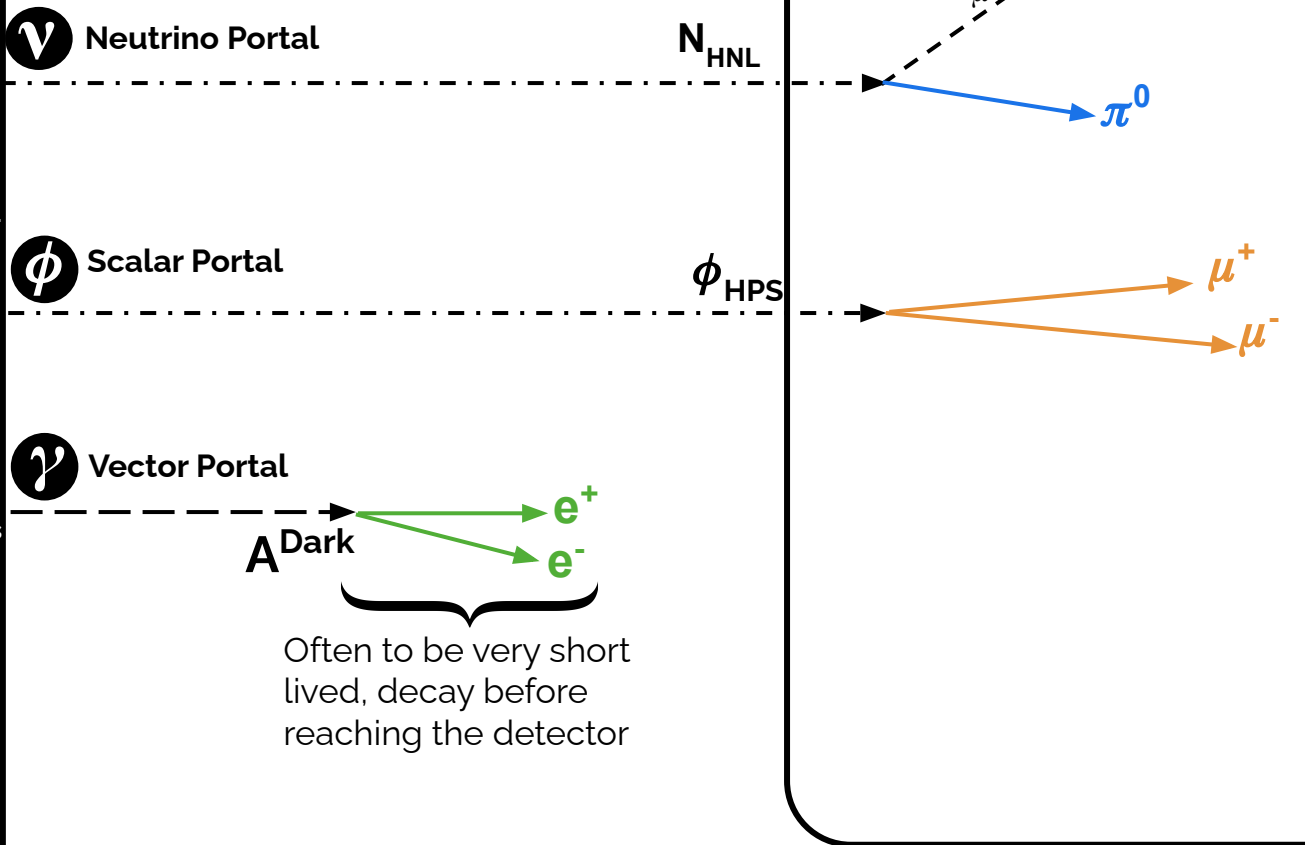
μ Cosmology

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ν_e Disappearance

ν_μ Cosmology

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Neutrino Portal

N_{HNL}

Neutrino Detector

ν_μ

π^0



Scalar Portal

ϕ_{HPS}

μ^+

μ^-



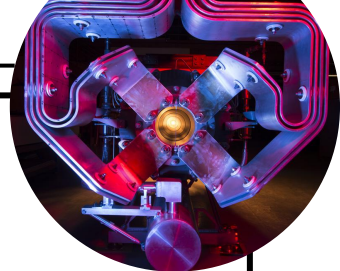
Vector Portal

A^{Dark}

χ

$\bar{\chi}$

If there is anything else in the dark sector, e.g **low-mass dark matter χ** , it could also be produced



Detection of Dark Sector Particles: Scattering

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Neutrino Portal

N_{HNL}

Neutrino Detector

ν_μ

π^0



Scalar Portal

ϕ_{HPS}

μ^+

μ^-



Vector Portal

A^{Dark}

$\bar{\chi}$

χ

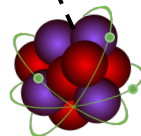
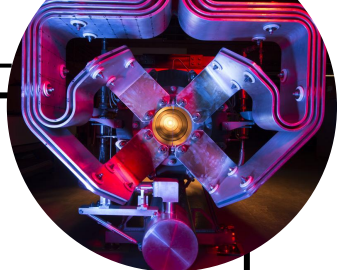
A^{Dark}

A^{Dark}

e^+

e^-

This dark matter candidate, χ , is stable but enters the detector and **scatters** off an atom, so-called trident e^+e^- production



Powerful Dark Sector Probes

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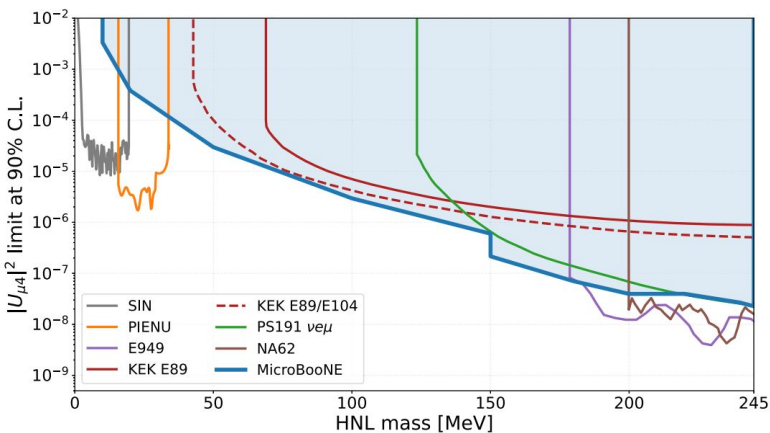
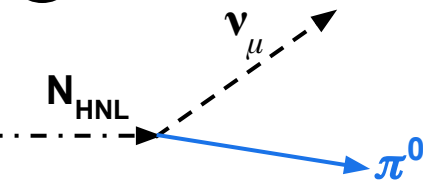
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Neutrino Portal

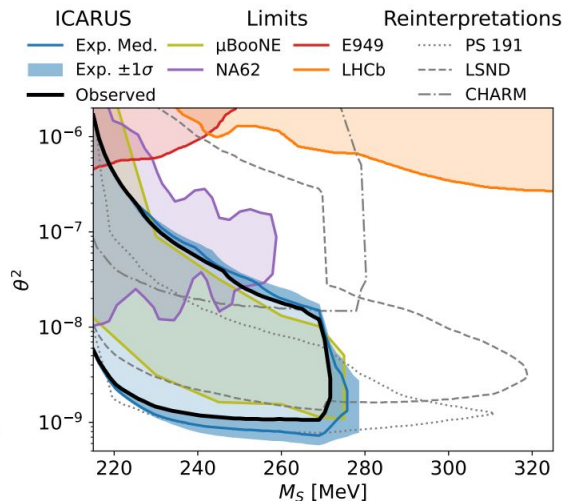
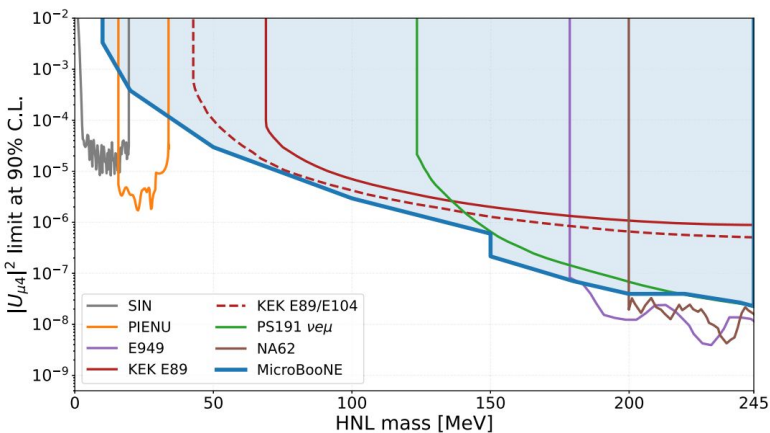
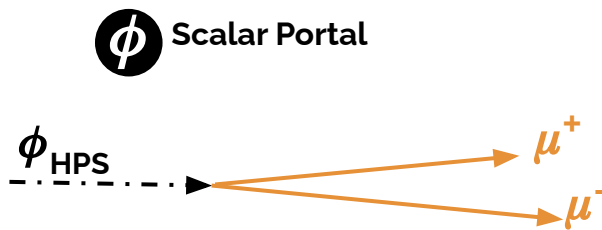
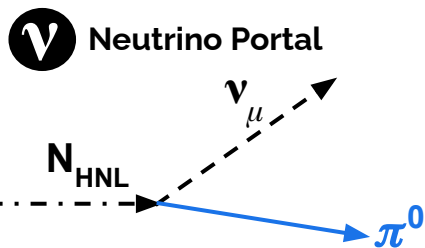


MicroBooNE collaboration

Phys. Rev. Lett. 132, 041801 2024

Powerful Dark Sector Probes: not just neutrino portals

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MicroBooNE collaboration

Phys. Rev. Lett. 132, 041801 2024

ICARUS collaboration

arXiv:2411.02727 [hep-ex] 2024

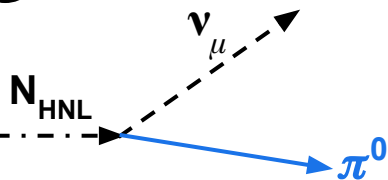
MicroBooNE Collaboration

arXiv:2501.08052 [hep-ex] 2025

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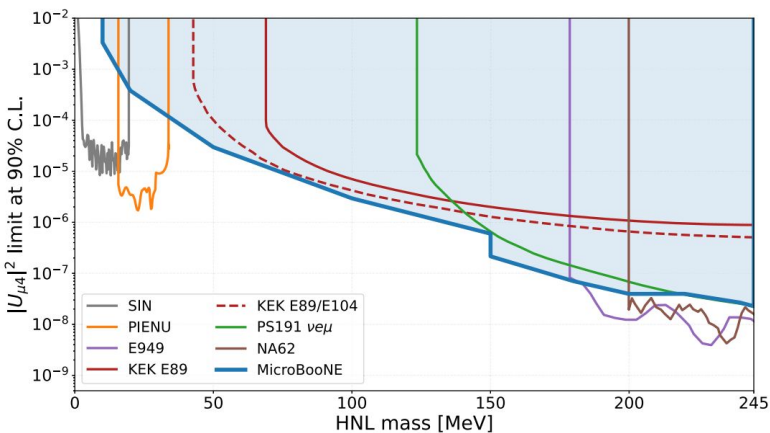
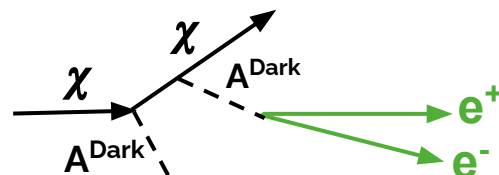
ν Neutrino Portal



ϕ Scalar Portal

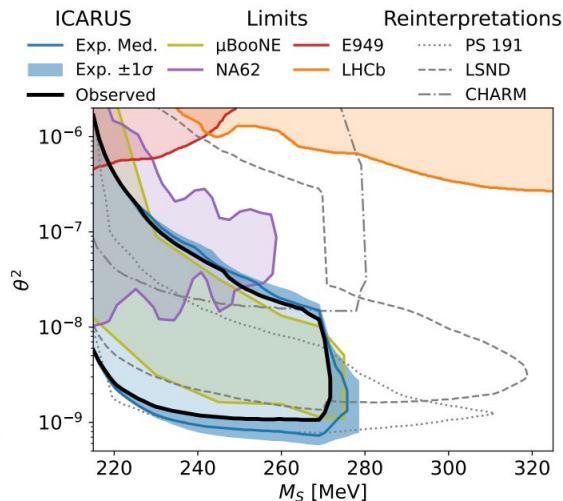


**γ Vector Portal
+ Scalar Dark Matter**



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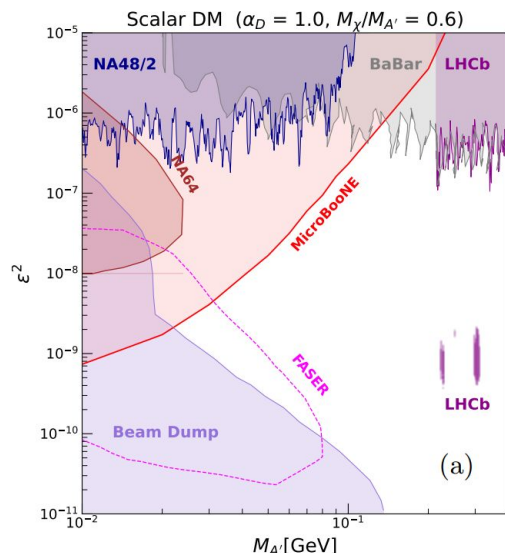


ICARUS collaboration

arXiv:2411.02727 [hep-ex] 2024

MicroBooNE Collaboration

arXiv:2501.08052 [hep-ex] 2025



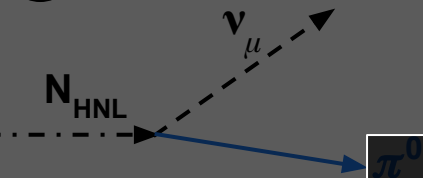
MicroBooNE Collaboration

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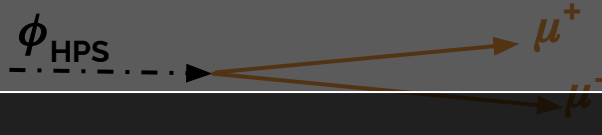
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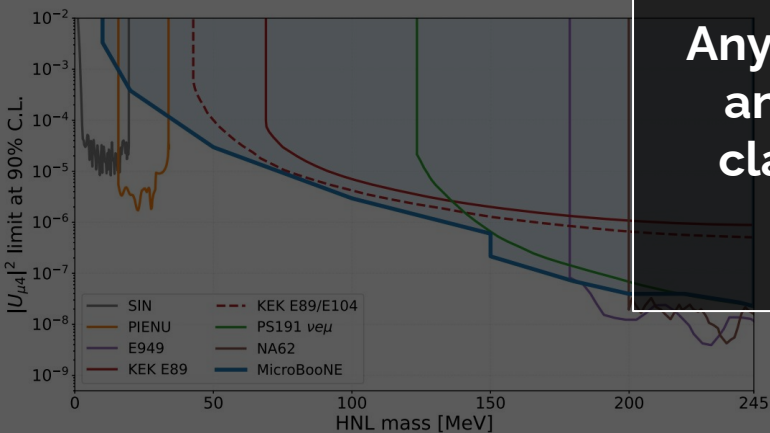
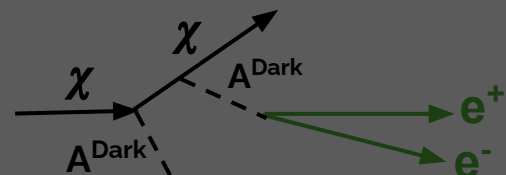
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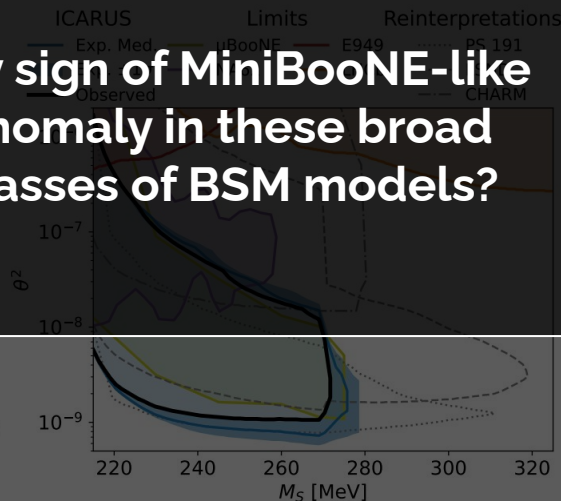
γ Vector Portal
+ Scalar Dark Matter



MicroBooNE collaboration

Phys. Rev. Lett. 132, 041801 2024

Any sign of MiniBooNE-like
anomaly in these broad
classes of BSM models?

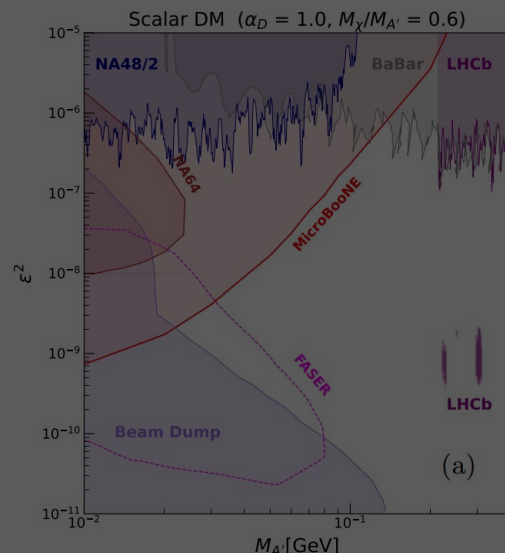


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MicroBooNE's extensive suite of searches: Summary

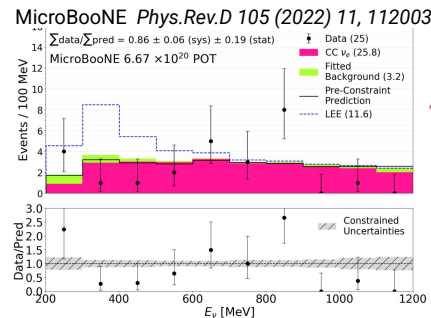
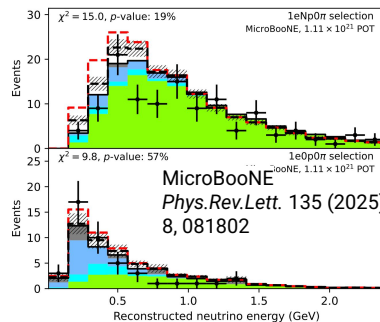
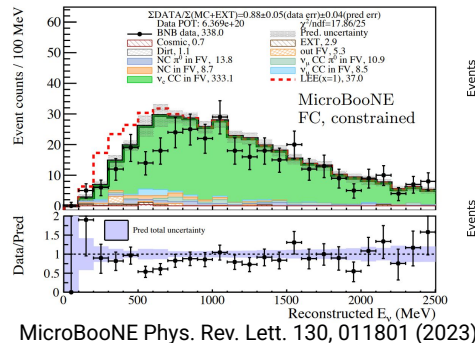
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No evidence
 for electron
 excess

MicroBooNE's extensive suite of searches: Summary

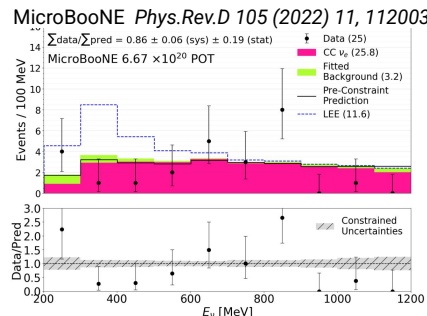
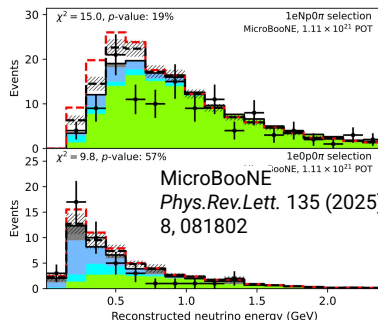
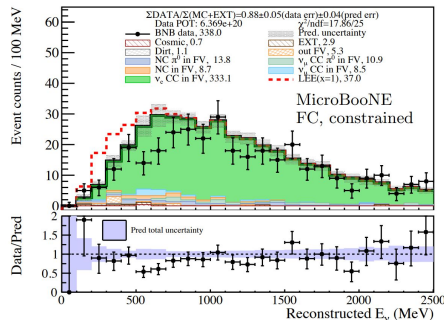
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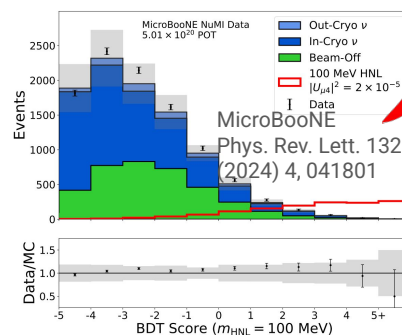
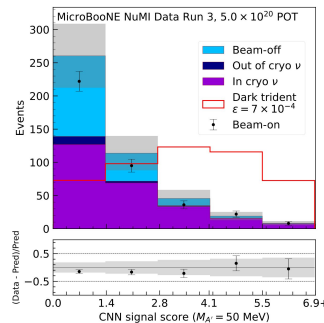
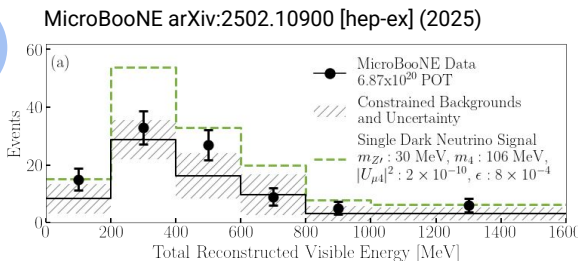
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No evidence for electron excess



No evidence for excess of e+e- pairs

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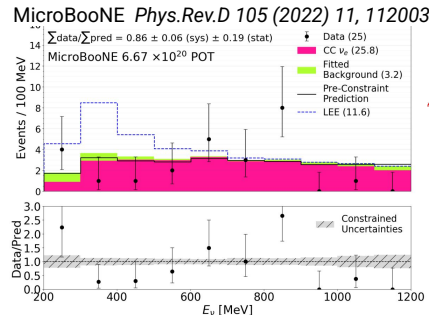
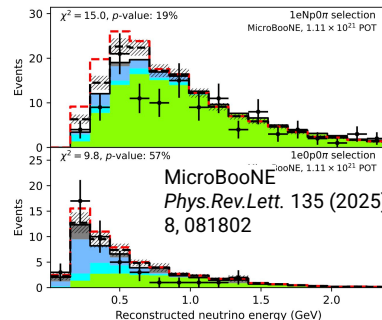
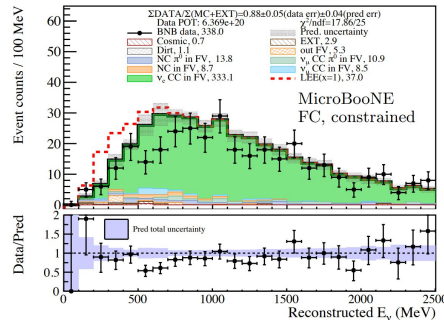
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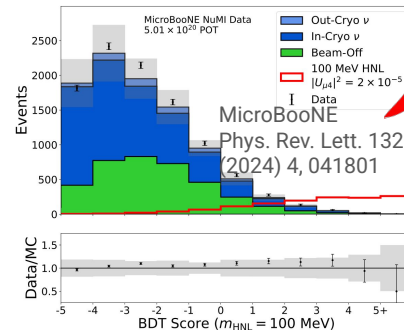
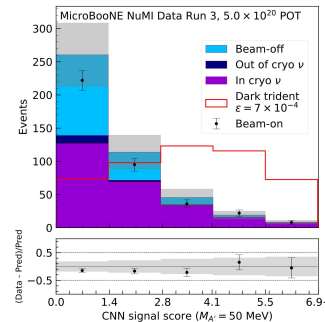
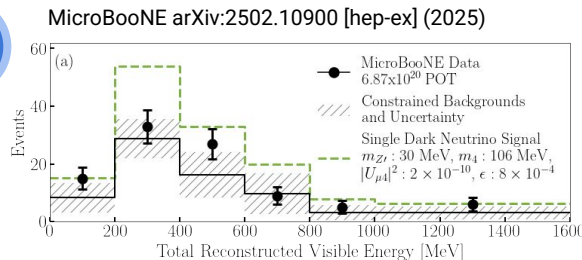
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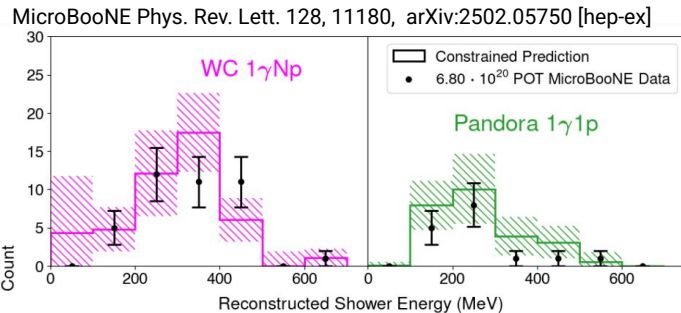
MicroBooNE



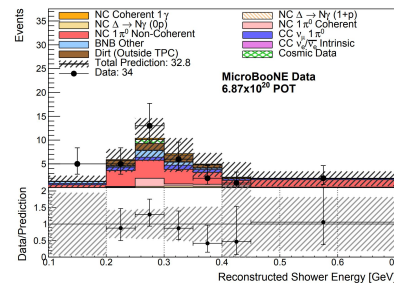
No evidence for electron excess



No evidence for excess of e+e- pairs



MicroBooNE arXiv:2502.06091 [hep-ex]



Little evidence for excess of photons

MicroBooNE's Inclusive Single-Photon Measurement

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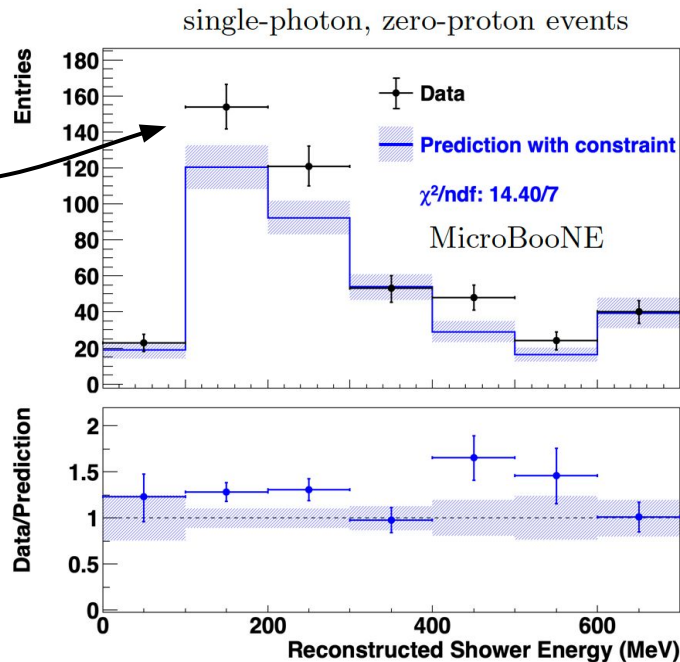
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MicroBooNE



A broad search **aiming to capture all possible single-photons**, of both SM and BSM origin

Mild, **2 σ excess** observed in single-photons with no associated protons



MicroBooNE [arXiv:2502.06064 \[hep-ex\] \(2025\)](#)

MicroBooNE's Inclusive Single-Photon Measurement

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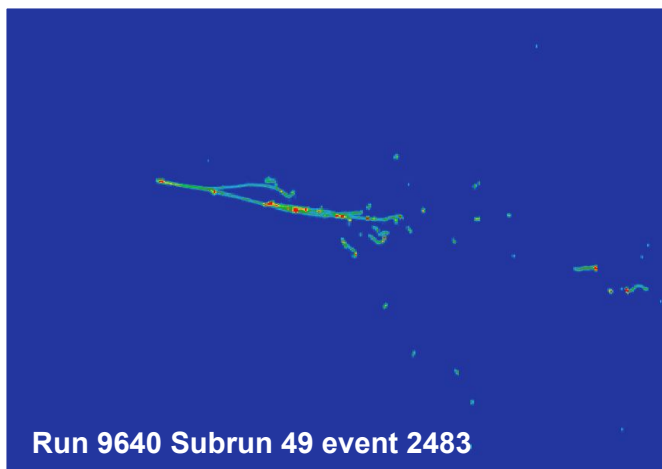
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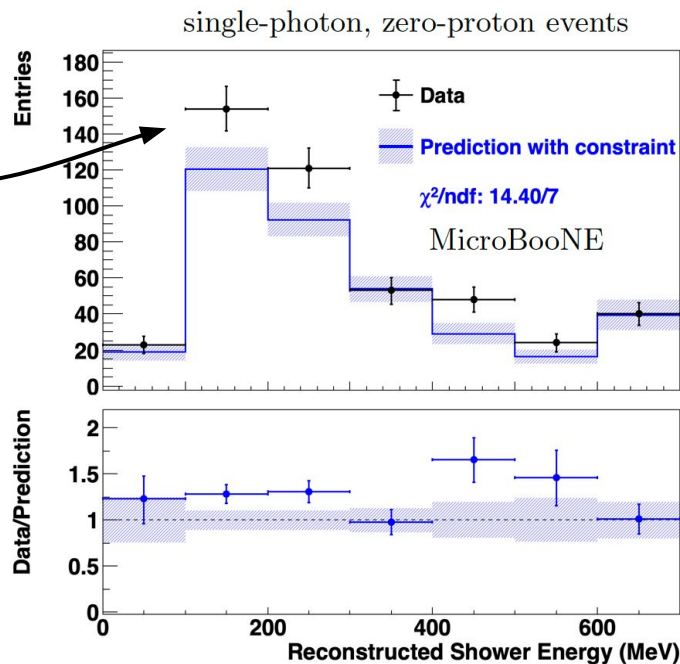


A broad search **aiming to capture all possible single-photons**, of both SM and BSM origin

Mild, **2σ excess** observed in single-photons with no associated protons

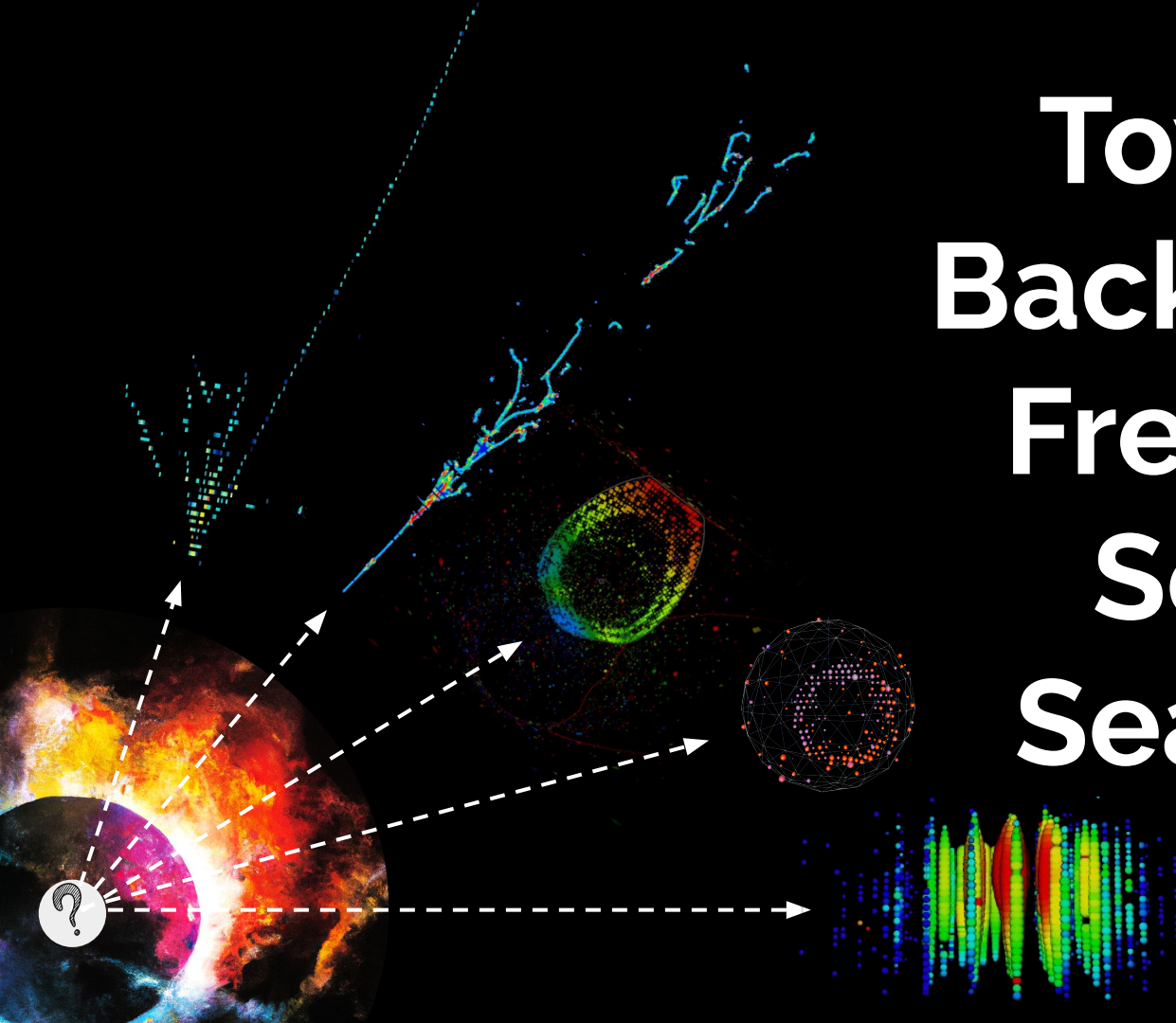


Extremely difficult channel, large backgrounds from NC π^0 !
Further investigations underway



MicroBooNE [arXiv:2502.06064 \[hep-ex\] \(2025\)](https://arxiv.org/abs/2502.06064)

Towards Background Free Dark Sector Searches



Powerful Dark Sector Probes: Only scratching the surface

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ν_e Disappearance

ν_μ Cosmology

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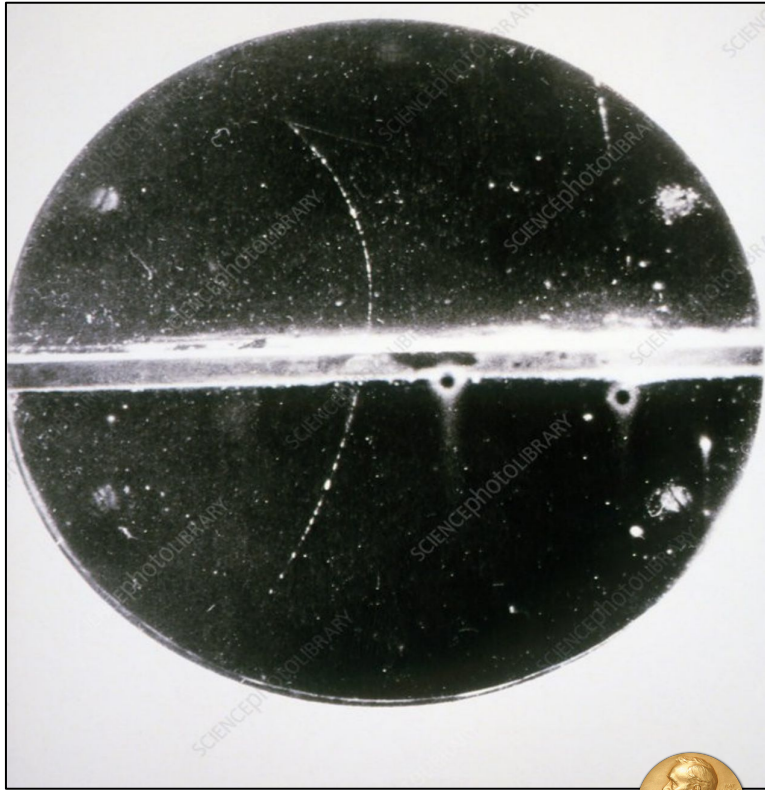
Minimal Portals

Accelerator Probes

MicroBooNE

5. Future

Towards Bkg Free



Discovery of the **Positron** by Carl
Anderson at Caltech , August 2nd, 1932

Powerful Dark Sector Probes: Only scratching the surface

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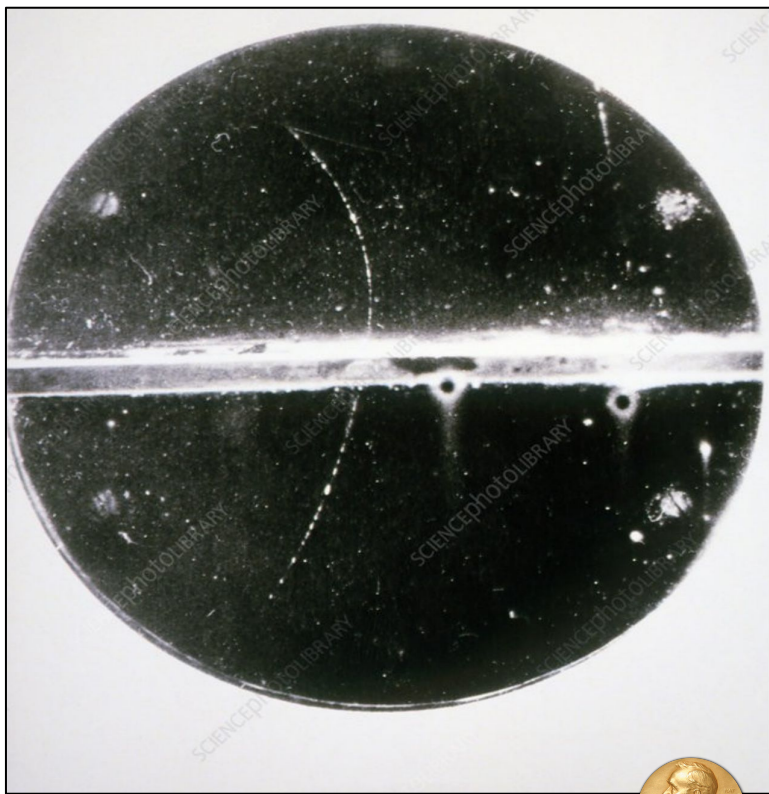
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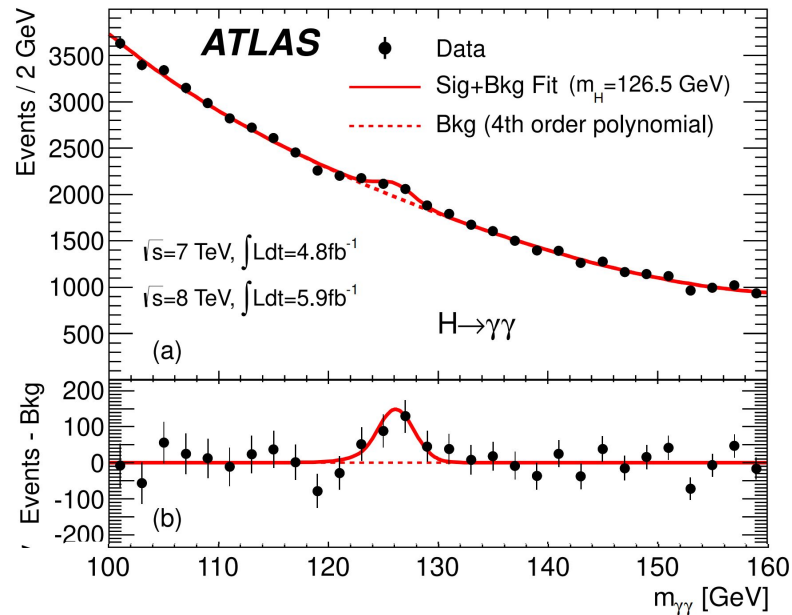
MicroBooNE

5. Future

Towards Bkg Free



Discovery of the **Positron** by Carl Anderson at Caltech, August 2nd, 1932



Discovery of the **Higgs** at CERN July 4th 2012

ATLAS Phys.Lett. B 716 (2012) 1-29

CMS Phys. Lett. B 716 (2012) 30

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Nano Second Timing

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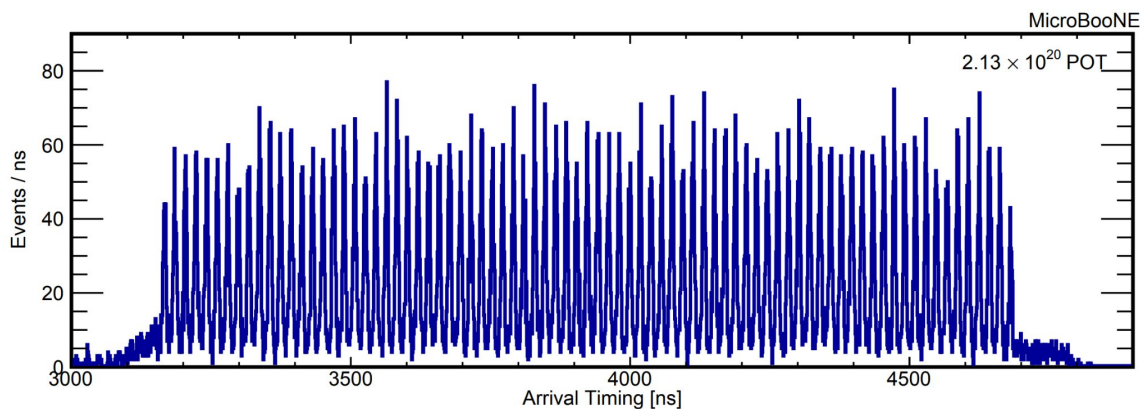
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Phys.Rev.D 108 (2023) 5, 05201

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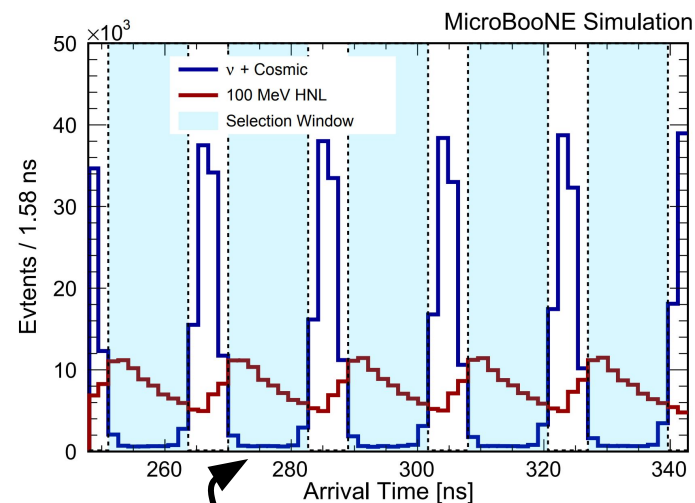
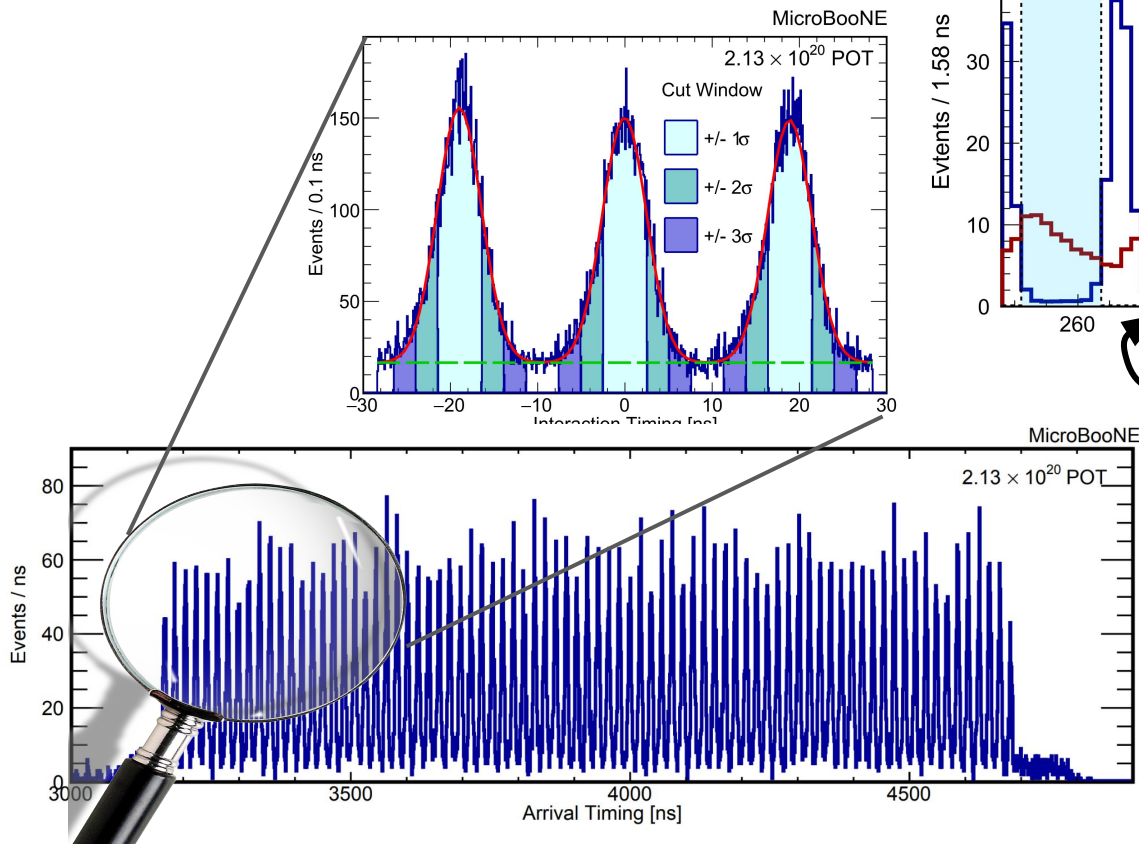
Accelerator Probes

MicroBooNE

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Nano Second Timing



Slow moving HNLs
arrive in between the
neutrino buckets

MicroBooNE
Phys.Rev.D 108 (2023) 5, 05201

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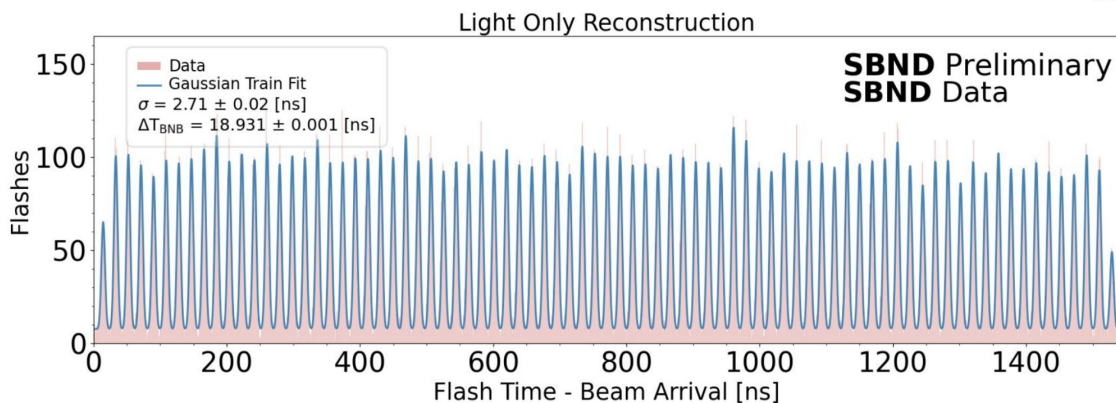
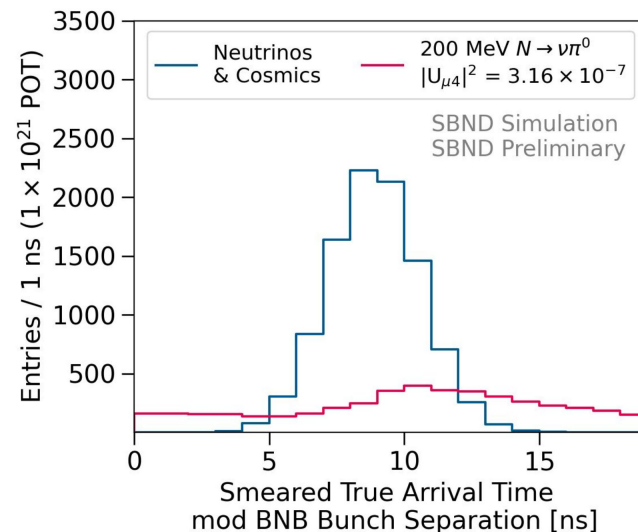
MicroBooNE

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See **Nguyen Vu Chi Lan's**
talk on Wednesday for
SBND's already impressive
performance [Talk](#)



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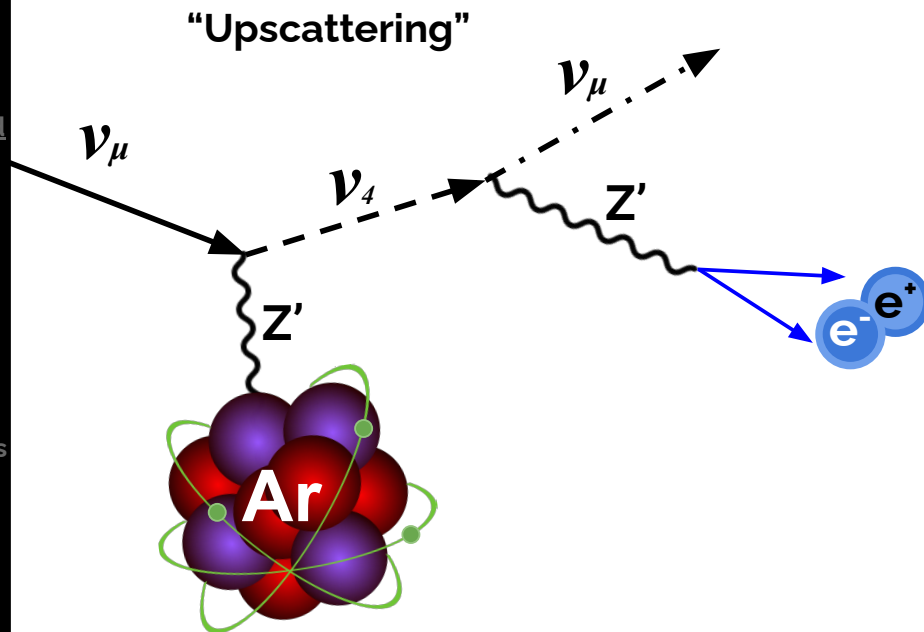
MicroBooNE

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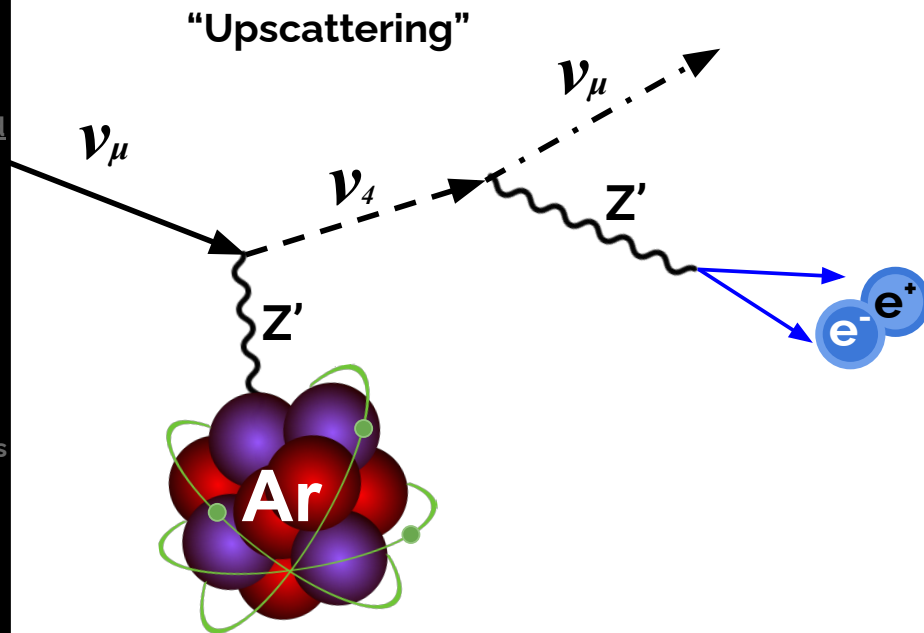
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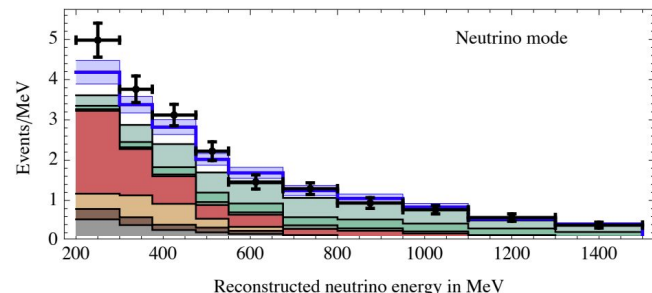


Phys. Rev. Lett. 121, 241801

FERMILAB-PUB-18-301
OSU-HEP-18-01

Dark Neutrino Portal to Explain MiniBooNE excess

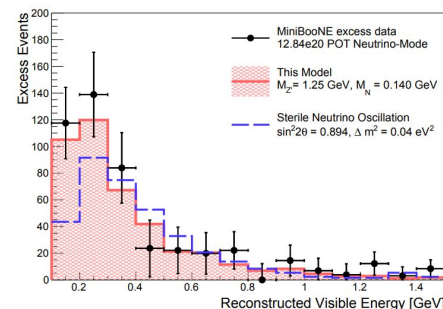
Enrico Bertuzzo,^{1,*} Sudip Jana,^{2,3,†} Pedro A. N. Machado,^{3,‡} and Renata Zukanovich Funchal^{1,§}



Phys. Rev. D 99, 071701

U(1)' mediated decays of heavy sterile neutrinos in MiniBooNE

Peter Ballett,^{1,*} Silvia Pascoli,^{1,†} and Mark Ross-Loneragan^{2,‡}



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Explosion of Dark Sector models!

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

Table from Snowmass [White Paper](#) on Light Sterile Neutrino
Searches and Related Phenomenology

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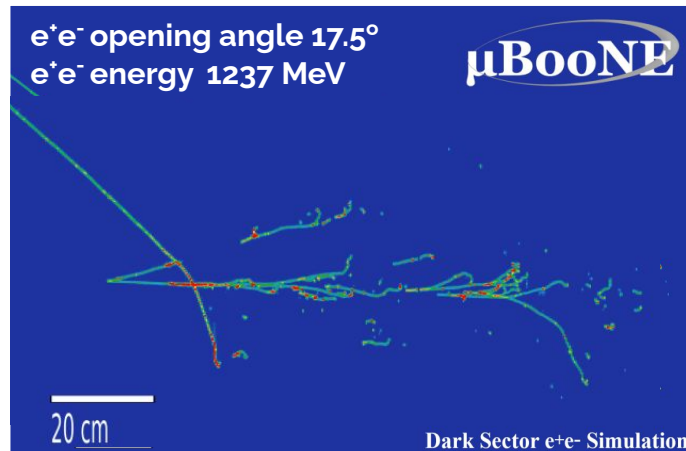
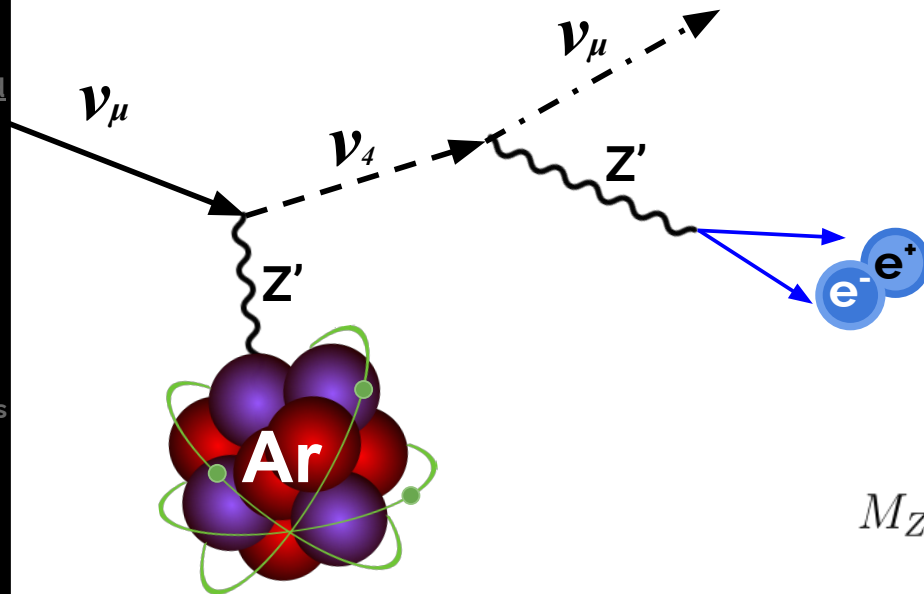
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5. Future
Towards Bkg Free

Nano Second
Timing

Angular
Resolution



For on-shell two-body Z' decays the **Invariant mass of the e^+e^- pair** proves a powerful tool

$$M_{Z'} = M_{e^+e^-} \approx \sqrt{2E_{e^+}E_{e^-}(1 - \cos \theta)}$$

Current reconstruction struggles on e^+e^- opening angles $< \sim 10^\circ$

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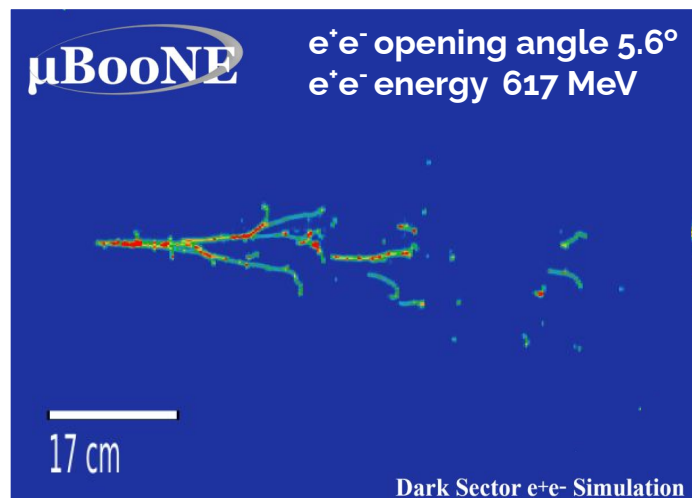
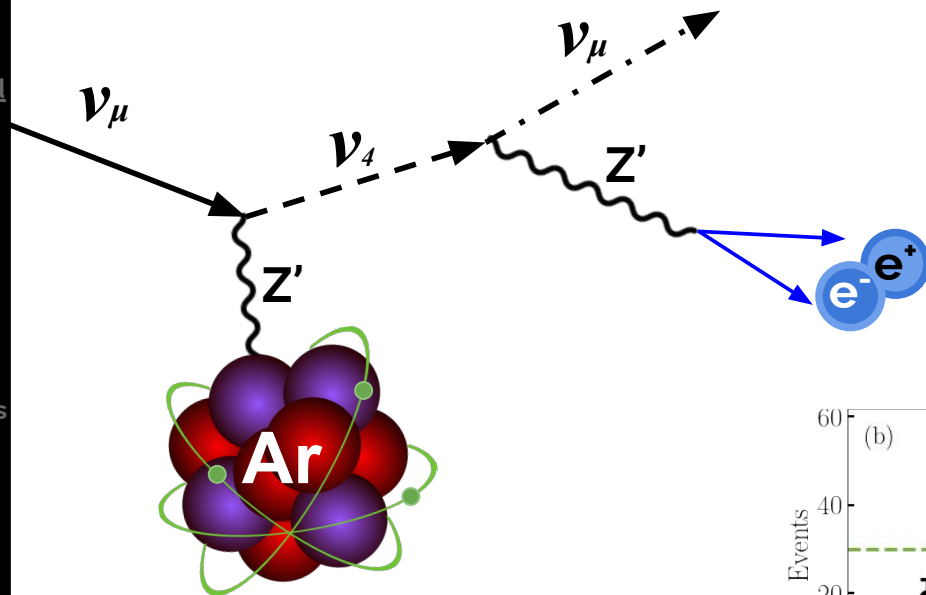
MicroBooNE

5. Future

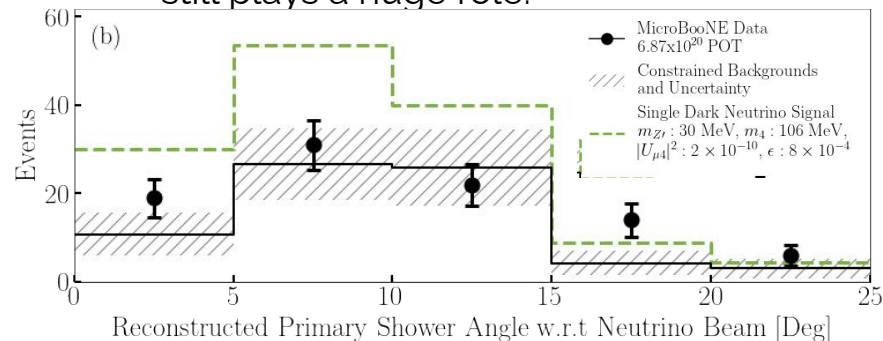
Towards Bkg Free

Nano Second
Timing

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For overlapping e^+e^- angular resolution still plays a huge role.



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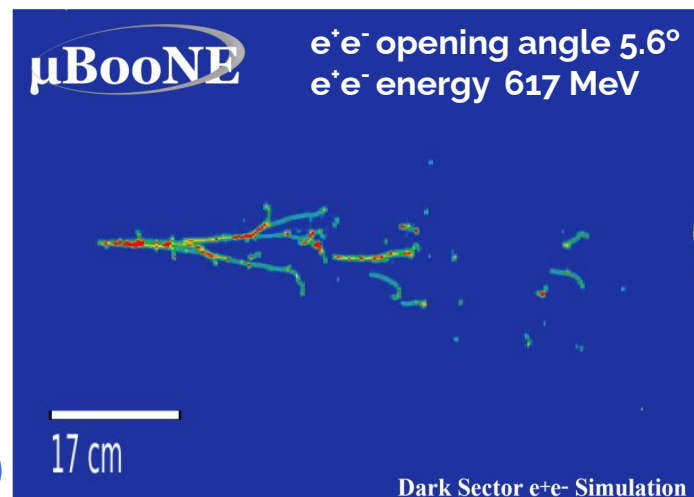
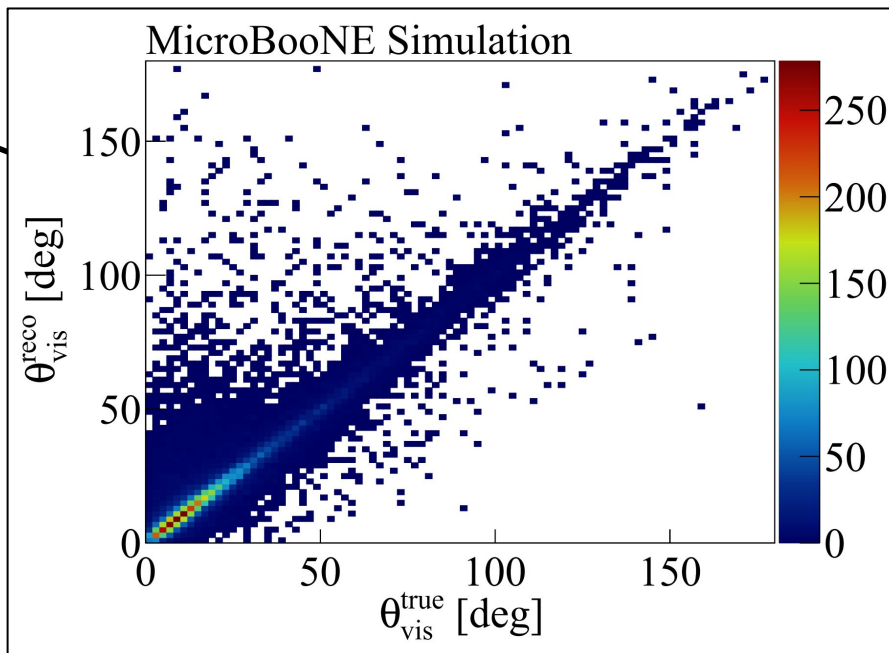
MicroBooNE

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For overlapping e^+e^- angular resolution still plays a huge role.

CC ν_μ MicroBooNE arXiv:2504.17758 [hep-ex]

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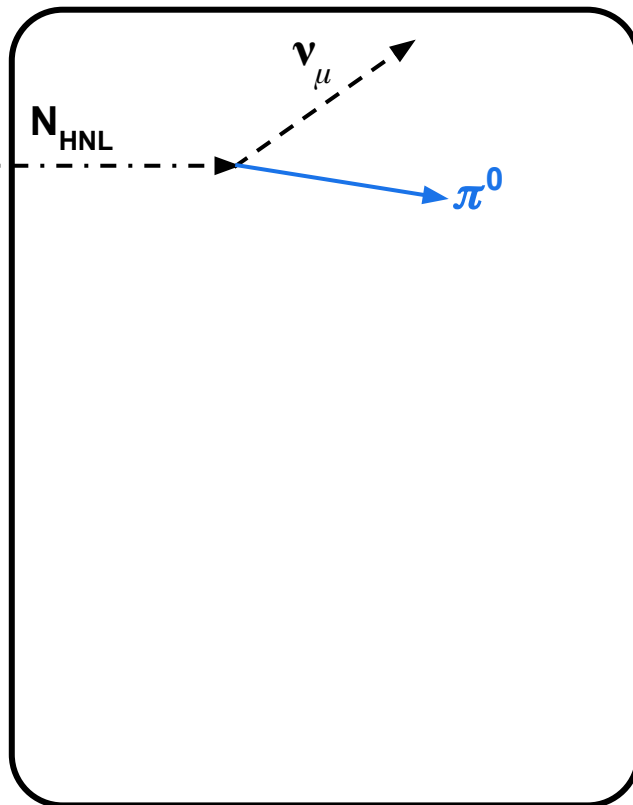
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Angular
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Vertex & MeV
Scale Activity



BSM
Decay
Process

Towards "Background Free" Dark Sector Searches

Nano Second
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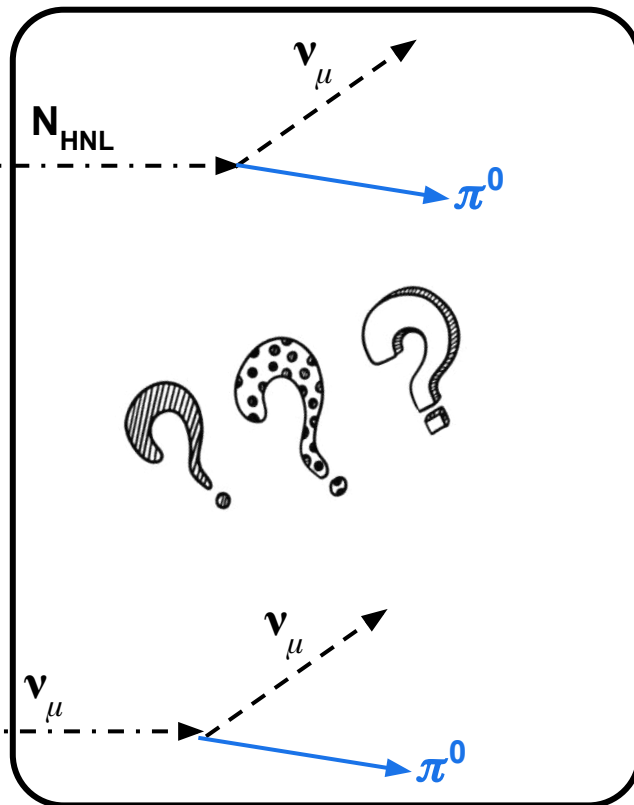
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Towards Bkg Free

M. Ross-Lonergan
Oct 24th 2025 138



BSM
Decay
Process

SM NC $1\pi^0$
scattering
background

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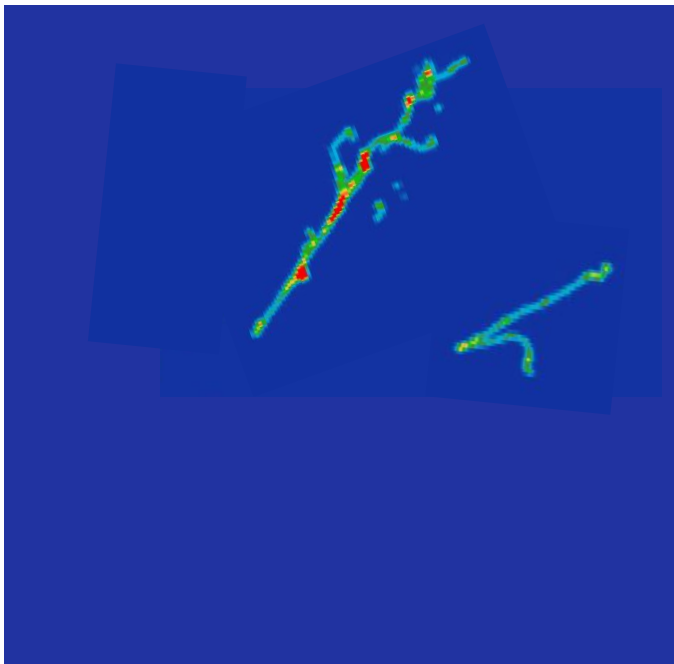
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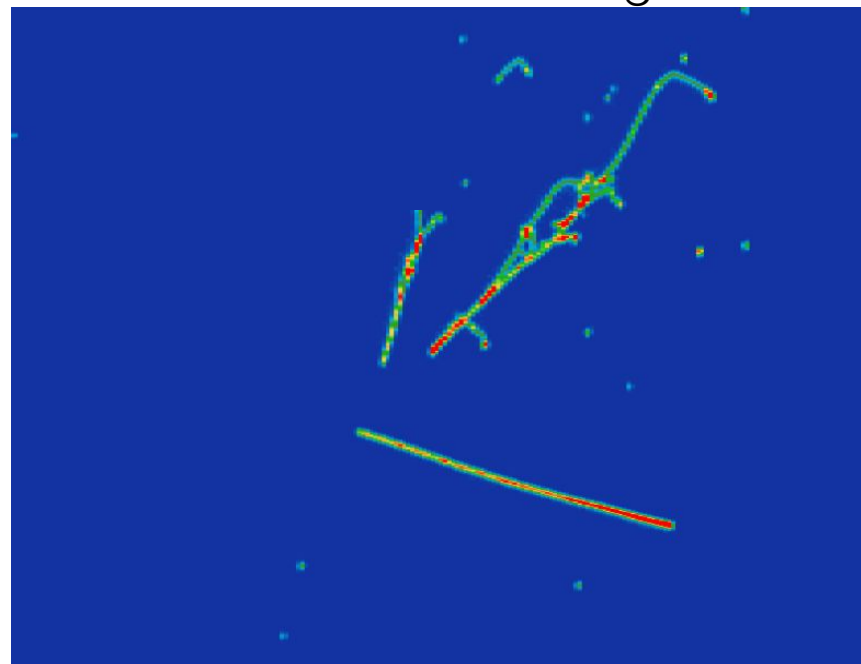
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Neutrino Scattering



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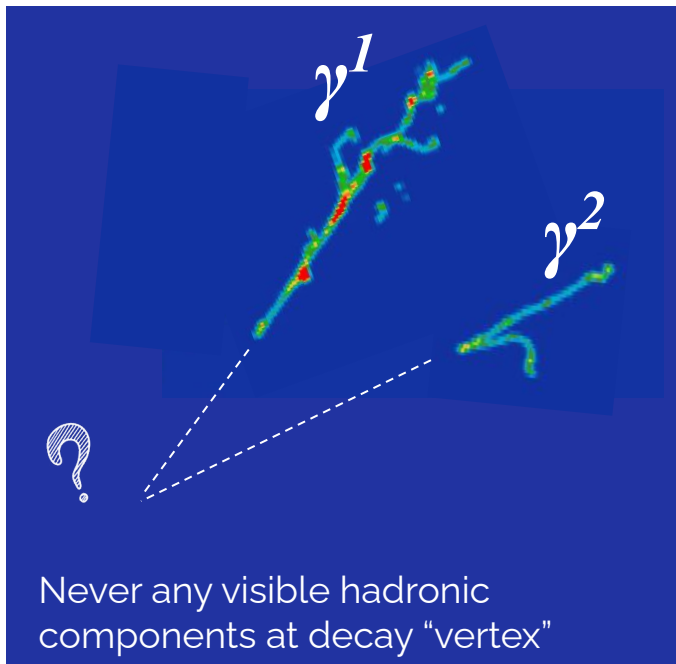
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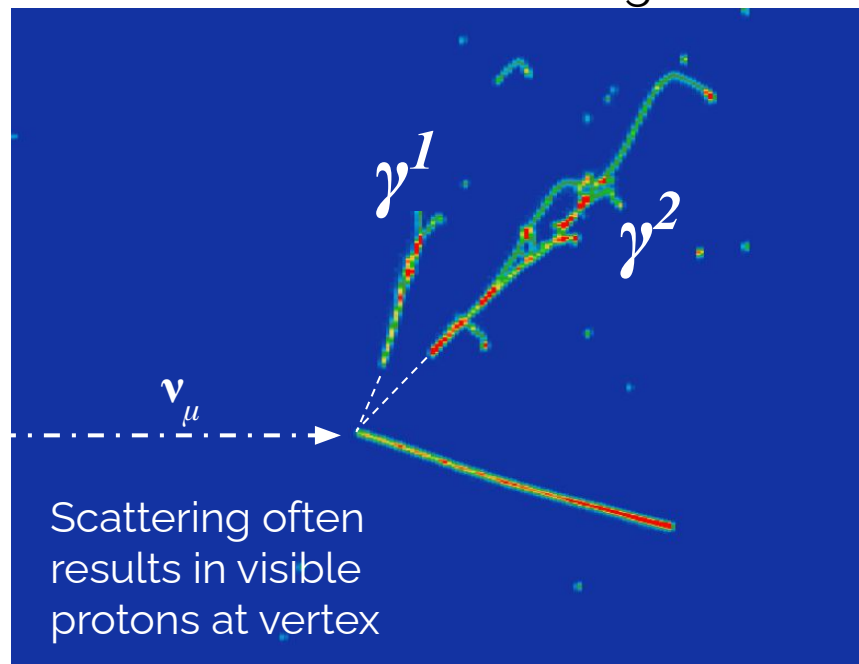
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Neutrino Scattering



Not just decays, any **coherent** scattering

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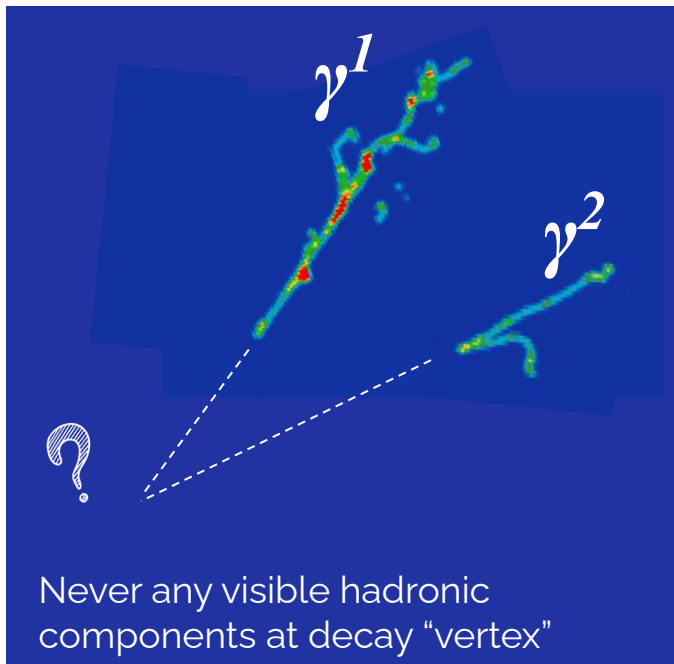
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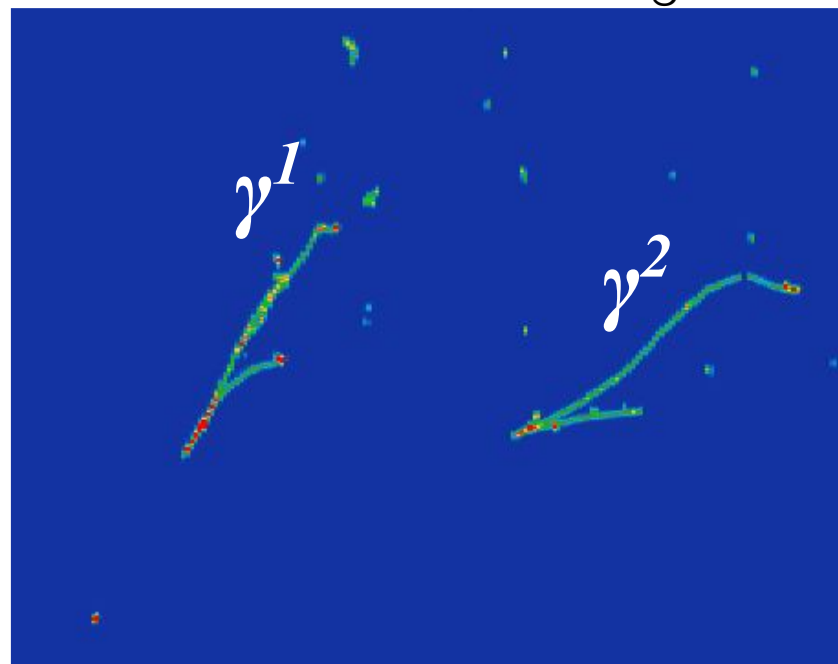
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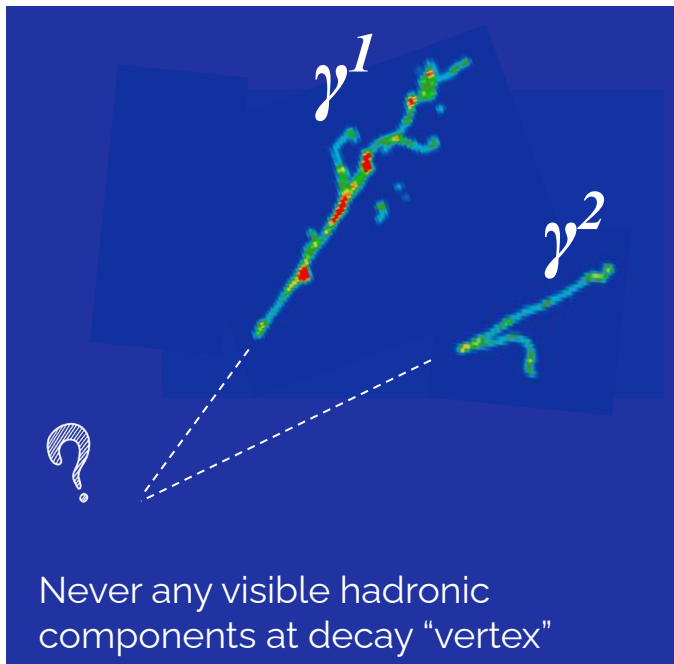
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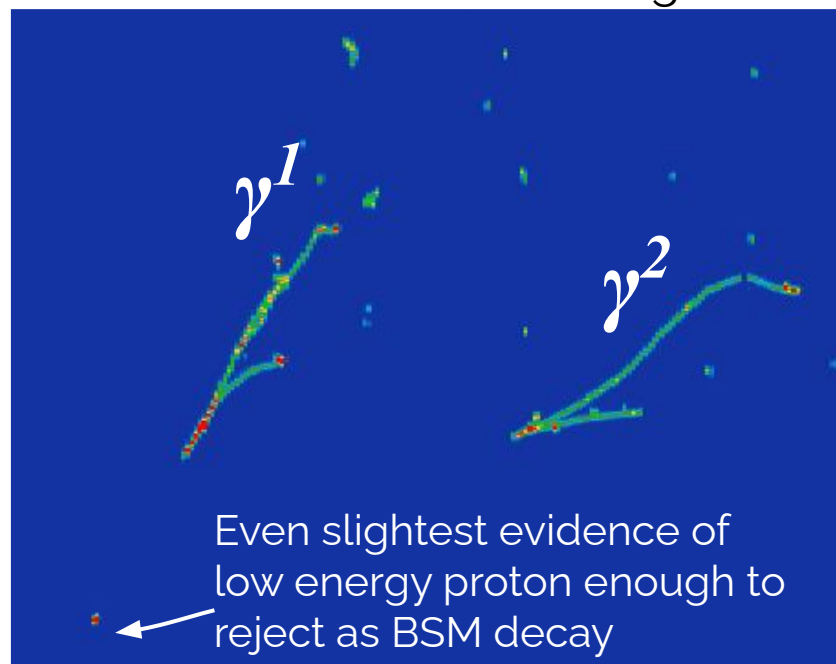
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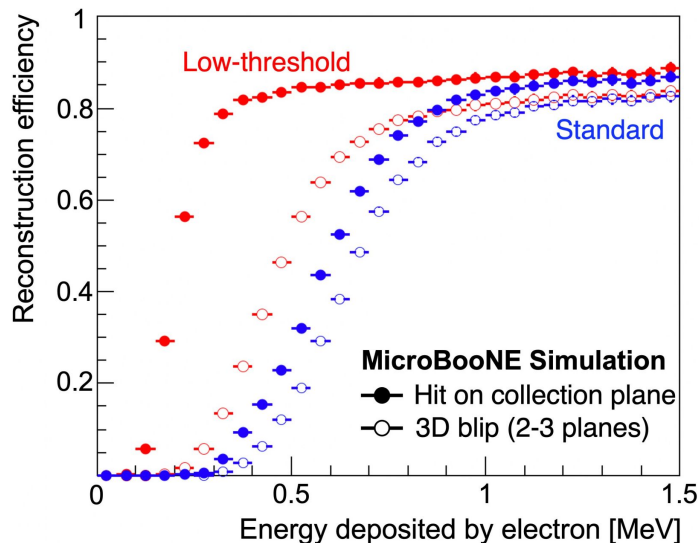
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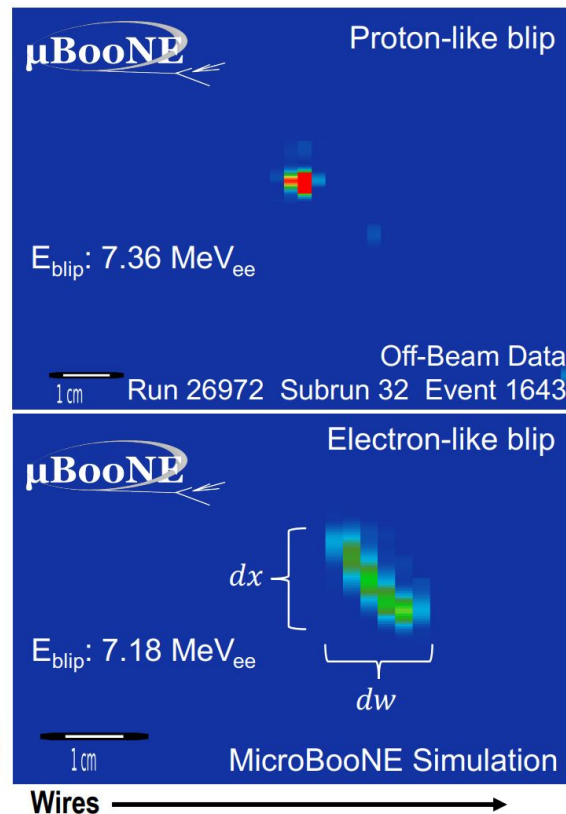
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"Demonstration of new MeV-scale capabilities in large neutrino LArTPCs using ambient radiogenic and cosmogenic activity in MicroBooNE"

Phys. Rev. D 111, 032005 (2025)

MicroBooNE Phys. Rev. D 109, 052007 (2024)



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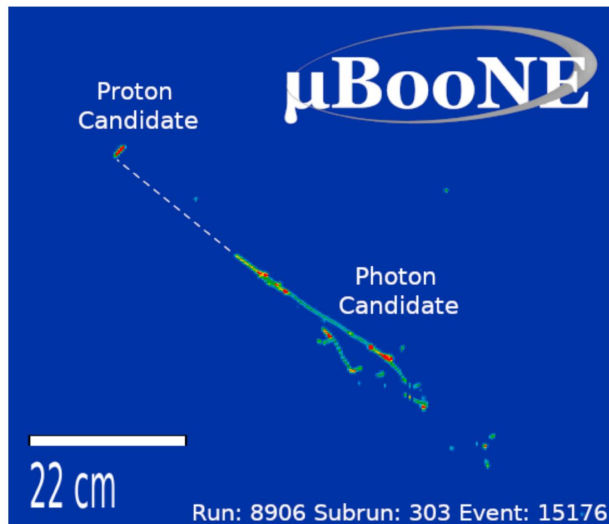
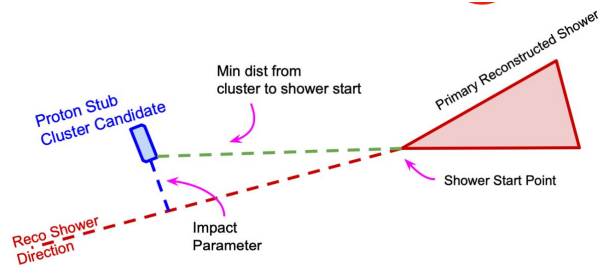
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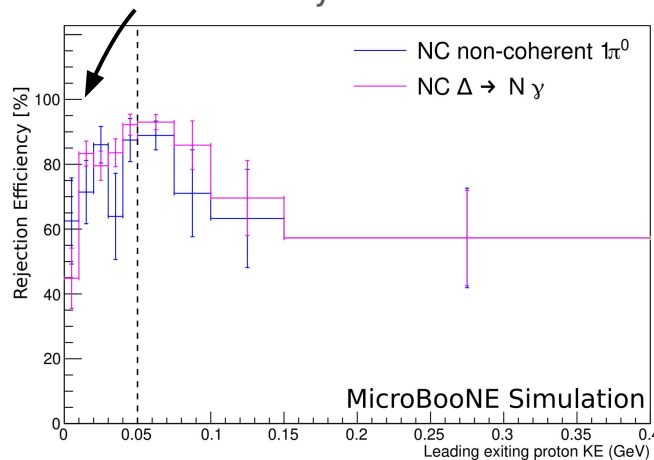
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Rejecting events with low energy proton "blips" below 20 MeV at ~60% efficiency



"First Search for Neutral Current Coherent Single-Photon Production in MicroBooNE"
MicroBooNE, arXiv:2502.06091 [hep-ex]

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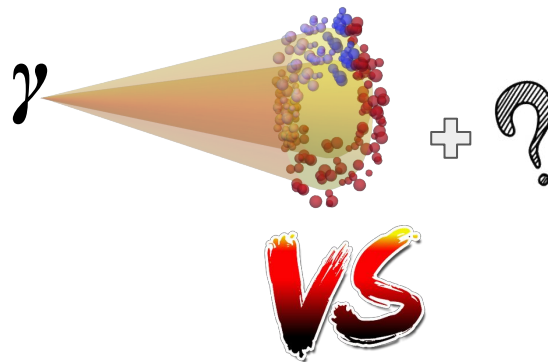
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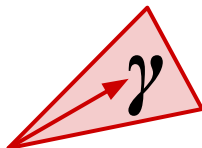
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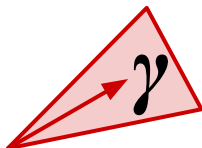
Vertex & MeV
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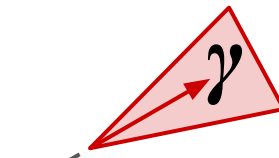
Isolated
Shower



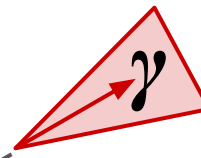
Shower +
proton
kinematics



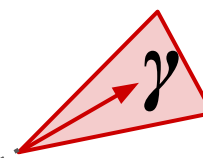
Shower + MeV
scale proton
"blip"



Shower +
neutron
evidence



Shower +
evidence of
BSM particle



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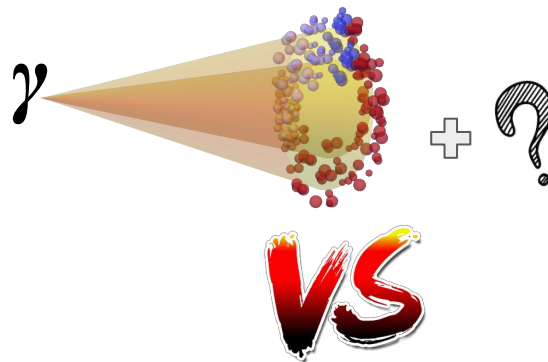
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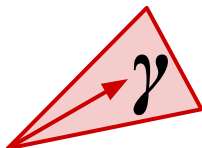


"Smoking Gun"

Isolated
Shower



Shower +
proton
kinematics



Shower + MeV
scale proton
"blip"



Shower +
neutron
evidence



Shower +
evidence of
BSM particle



Towards "Background Free" Dark Sector Searches

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Sterile Neutrinos

3. Where We Stand
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 ν_e Disappearance
 ν_μ Disappearance
 ν_μ Cosmology
New Ideas

4. The Dark Sector
Minimal Portals
Accelerator Probes
MicroBooNE

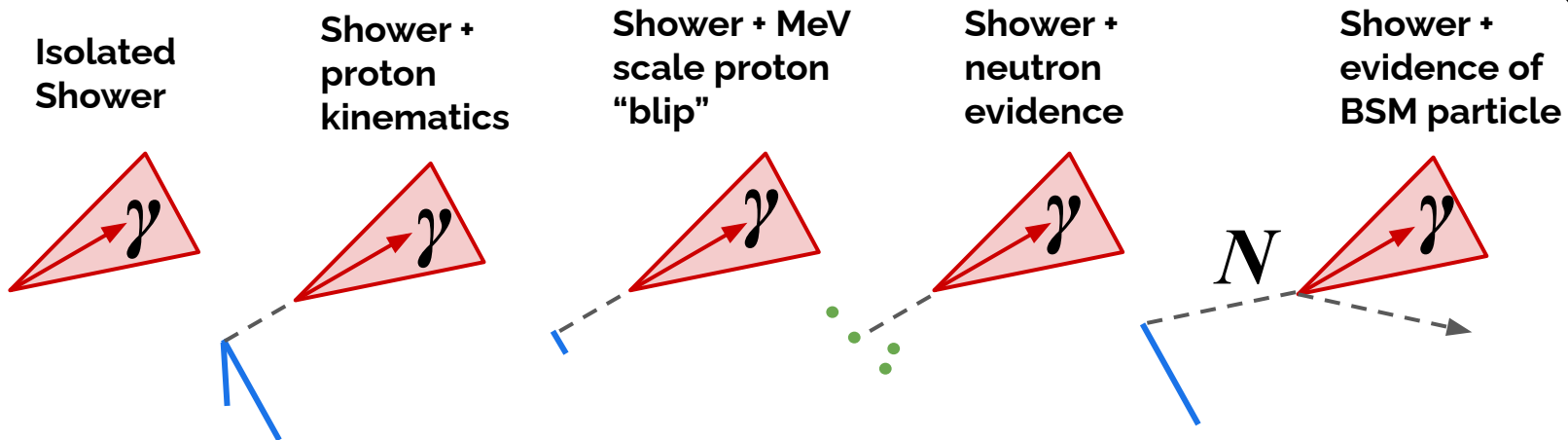
5. Future
Towards Bkg Free

Nano Second
Timing

Angular
Resolution

Vertex & MeV
Scale Activity

LArTPC capability to probe **detailed hadronic kinematics** and **MeV scale vertex activity** gives us a powerful handle to **distinguish between various SM and BSM signals**



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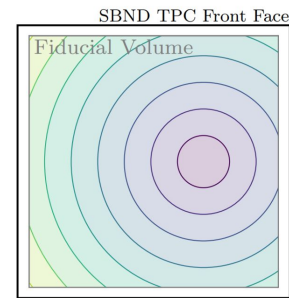
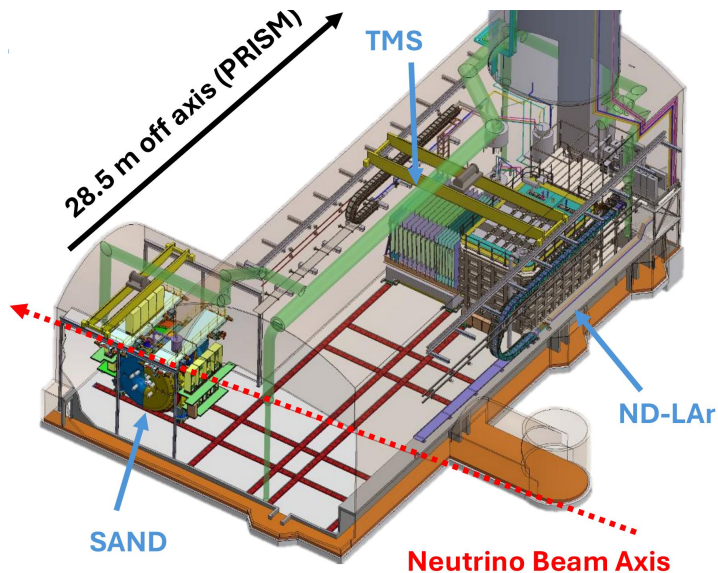
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Timing

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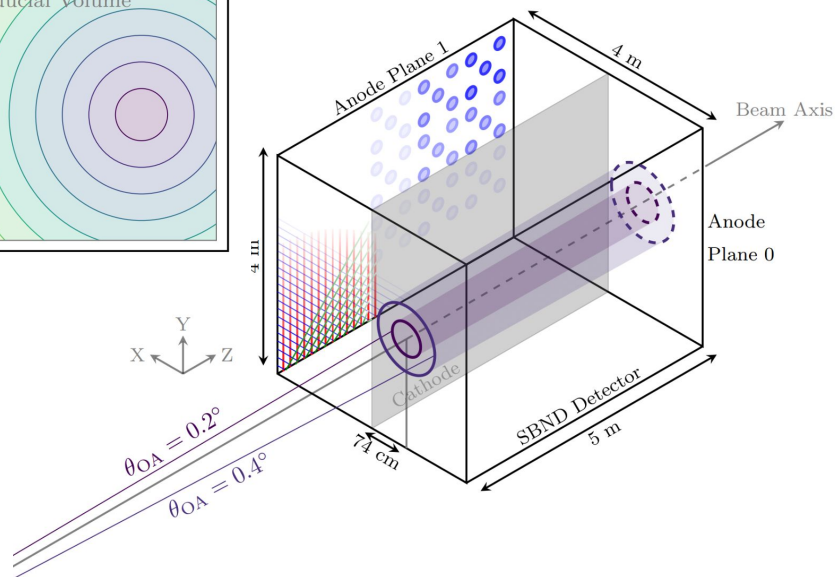
Vertex & MeV
Scale Activity

PRISM effect

DUNE-PRISM



SBND-PRISM



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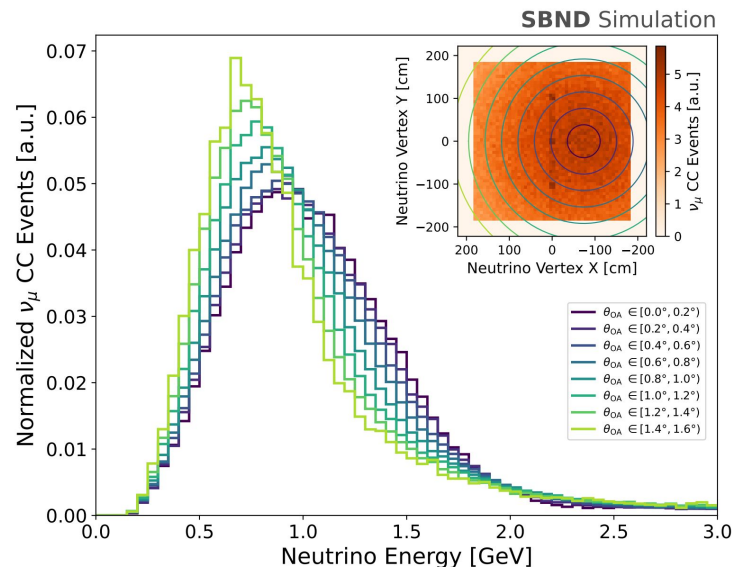
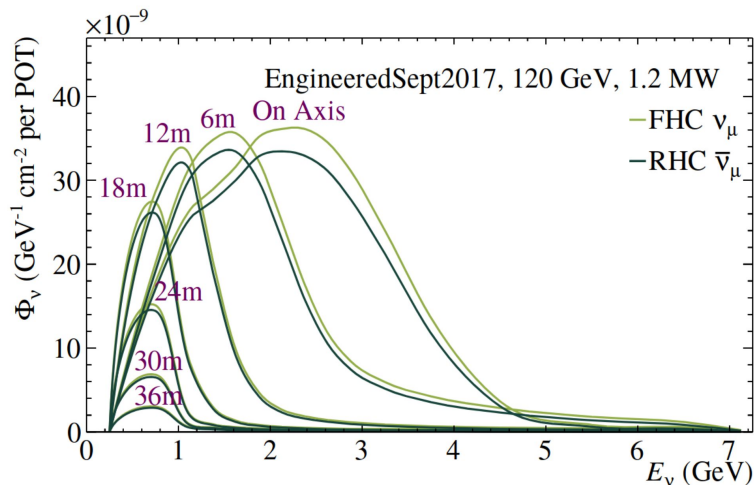
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Conceived as a way to greatly improve understanding of your flux and systematics

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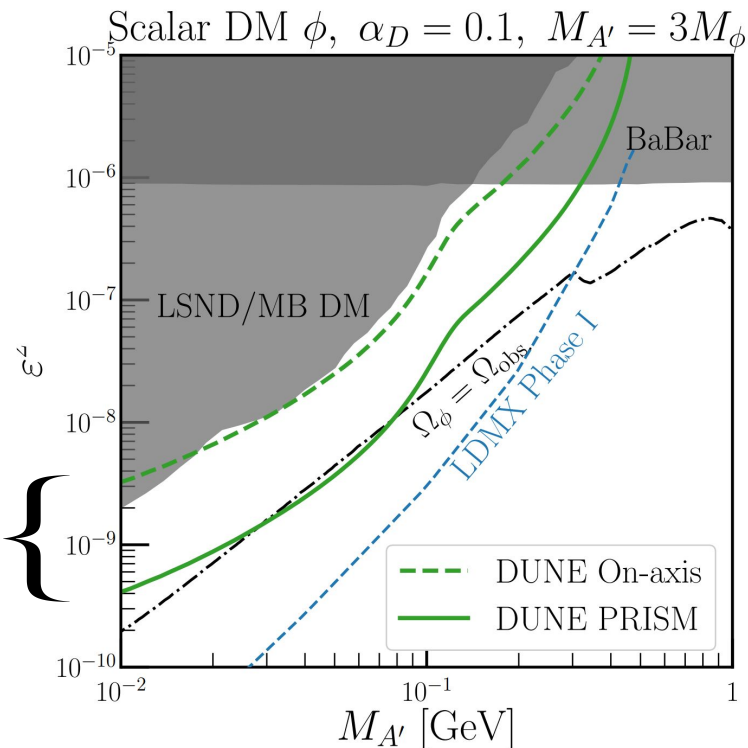
Angular
Resolution

Vertex & MeV
Scale Activity

PRISM effect

DUNE-PRISM

Almost an **order of magnitude**
increase in sensitivity using
PRISM for scalar light dark
matter models



V. De Romeri, K. Kelly, P.A.N. Machado Phys. Rev. D 100, 095010 (2019)

Towards "Background Free" Dark Sector Searches

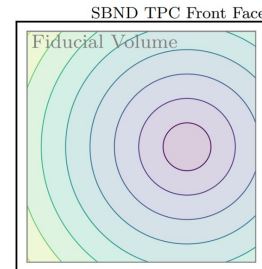
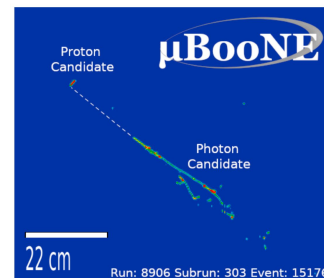
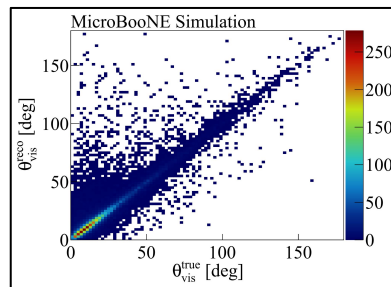
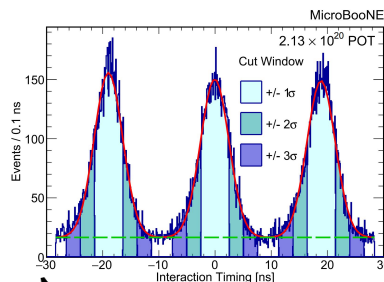
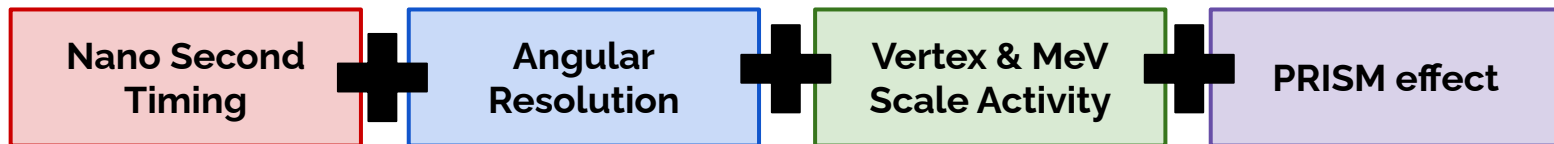
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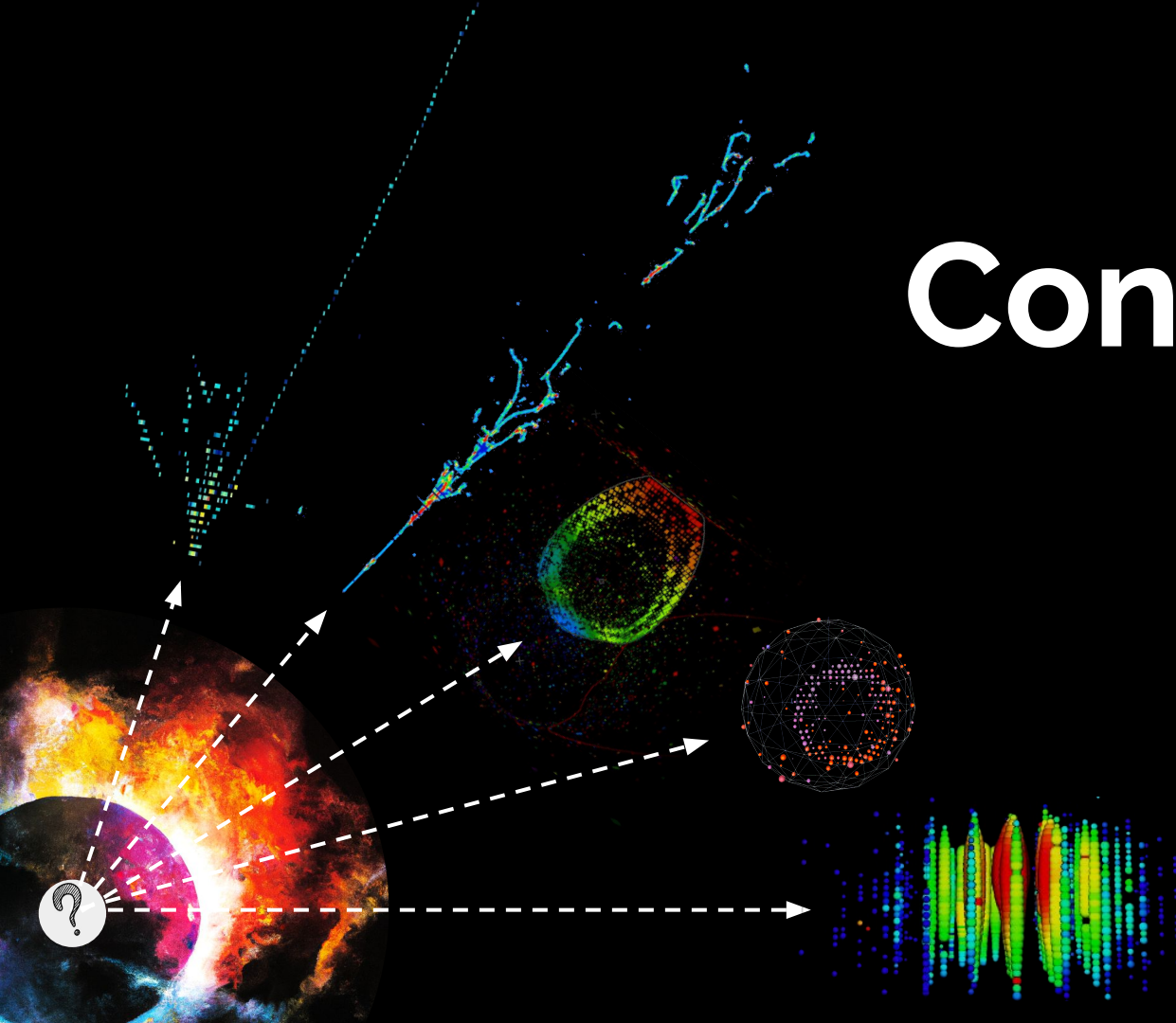
5. Future
Towards Bkg Free



Is this as clean as "single-event" positron discovery? Of course not!

But by **leveraging and combining multiple aspects of modern LArTPC** design short-baseline LArTPC's are an excellent probe of a wide array of dark sector and BSM searches

Conclusions



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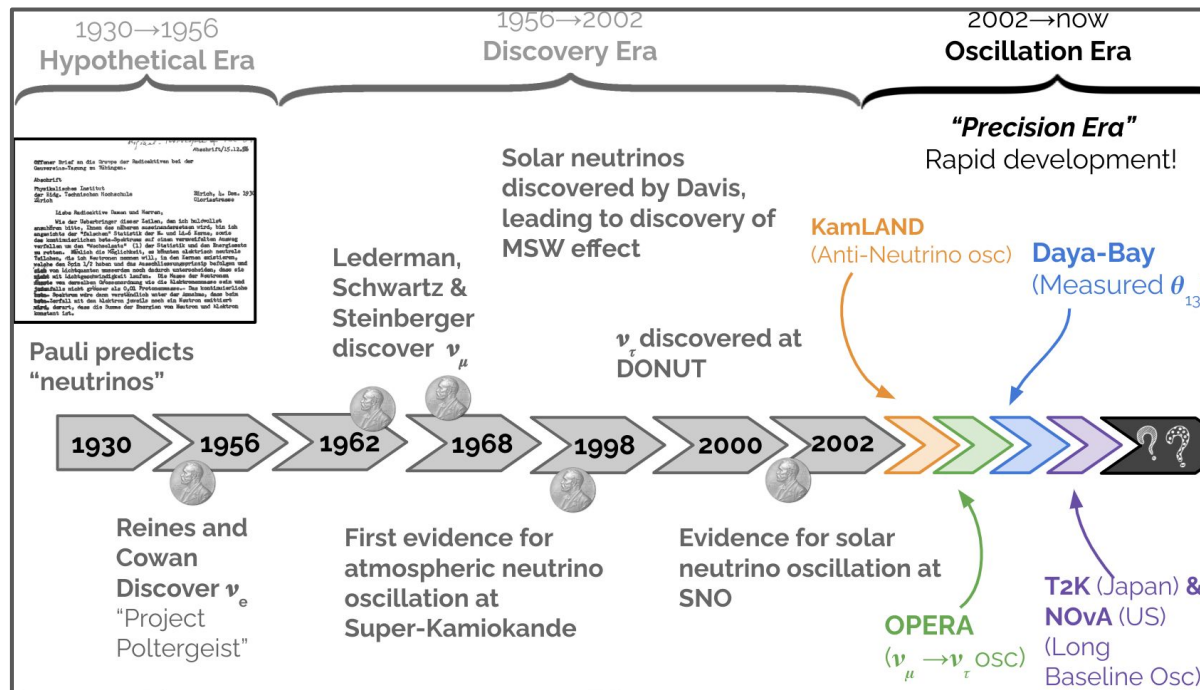
Towards Bkg Free

6. Conclusions

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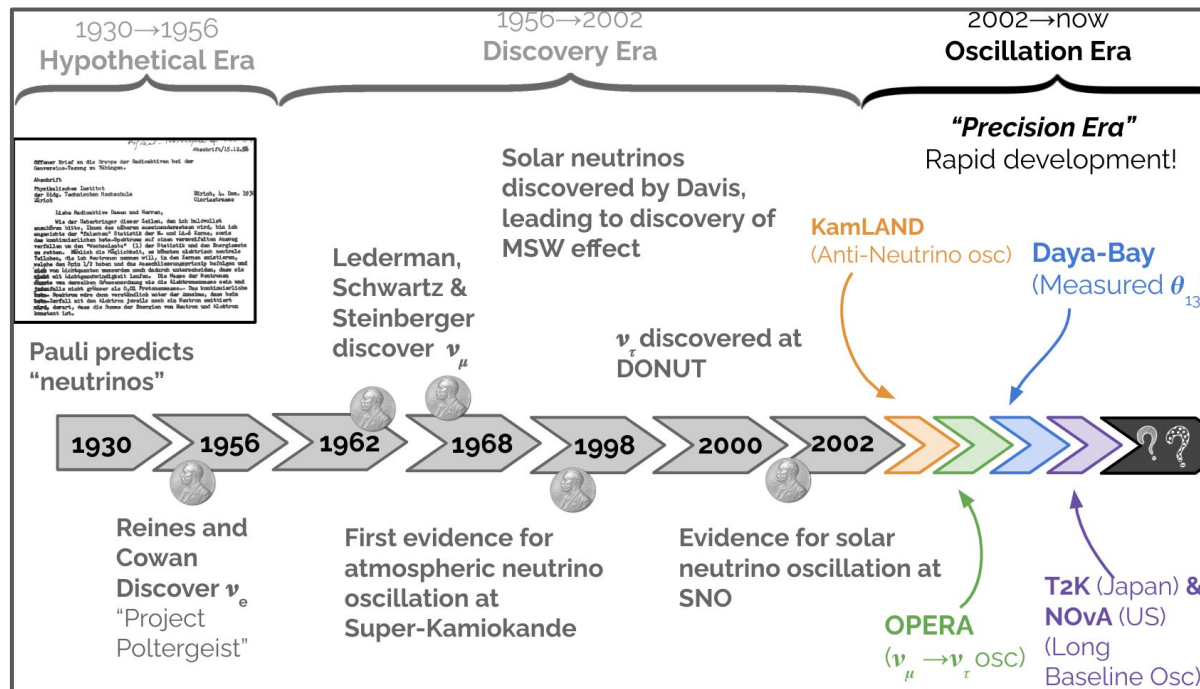
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Now→Future

+ "Portal Era"

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



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- 6. Conclusions

- As it stands, **three-neutrino paradigm** remains king. ν_e ν_μ ν_τ
 - The **light oscillating 3+1 sterile** neutrino interpretation of the anomalies **is very much in trouble** with global evidence against it extremely strong ν_4
 - Next generation MicroBooNE and SBN program will be capable of putting nail in the coffin



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 - Next generation MicroBooNE and SBN program will be capable of putting nail in the coffin
- Regardless of your belief in an eV scale sterile neutrino, **the Short-Baseline anomalies have so far survived scrutiny and remain unexplained!**
 - For MiniBooNE anomaly, **single-photon with zero-protons** remains one of the last plausible hiding places



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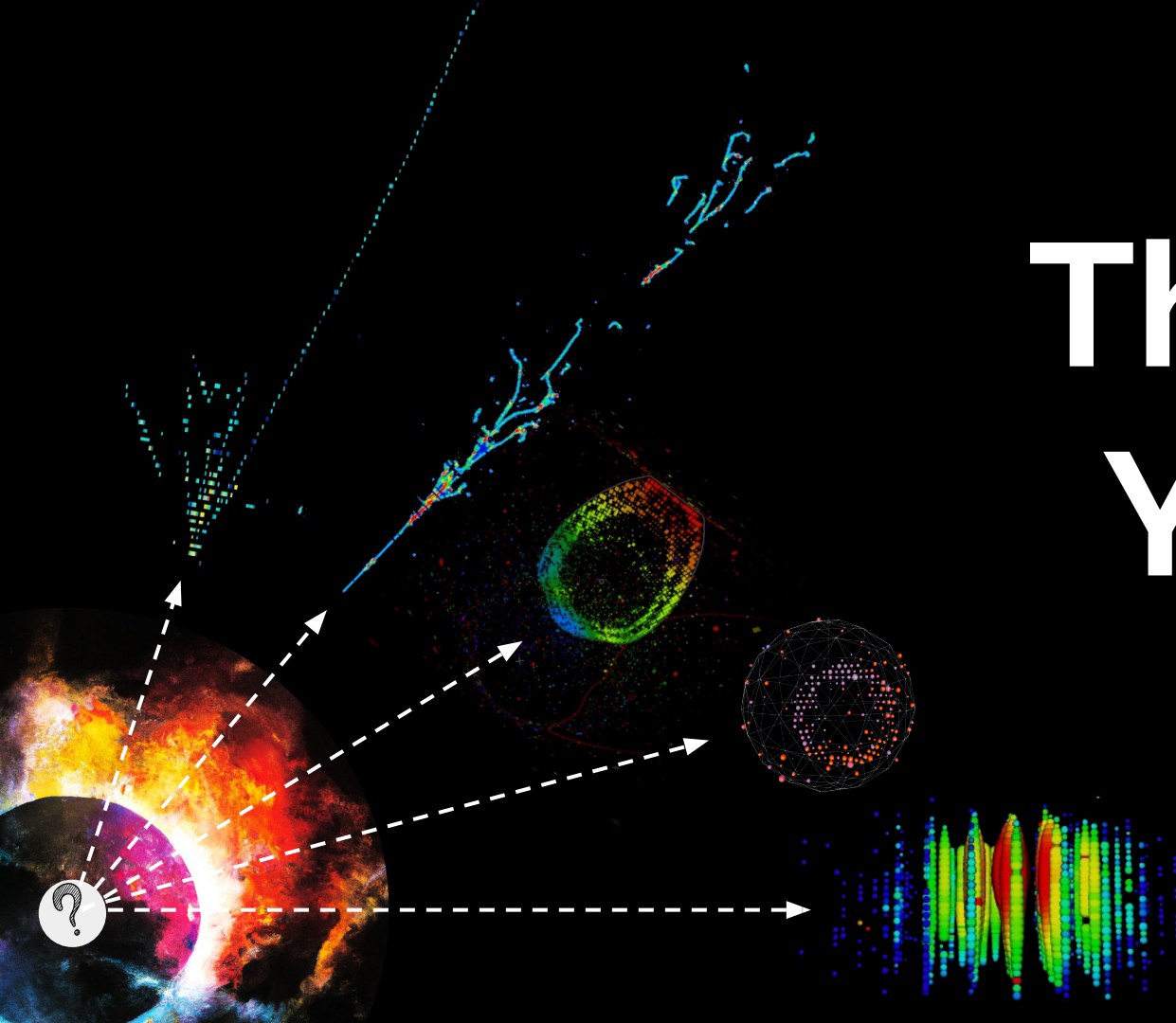
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6. Conclusions

- As it stands, **three-neutrino paradigm** remains king. ν_e ν_μ ν_τ
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 - Next generation MicroBooNE and SBN program will be capable of putting nail in the coffin
- Regardless of your belief in an eV scale sterile neutrino, **the Short-Baseline anomalies have so far survived scrutiny and remain unexplained!**
 - For MiniBooNE anomaly, **single-photon with zero-protons** remains one of the last plausible hiding places
- Recent results have highlighted the **capability and feasibility** of current and next generation neutrino experiments to **begin to probe into the dark sector**, an exciting and rapidly growing direction in neutrino physics



Thank You!

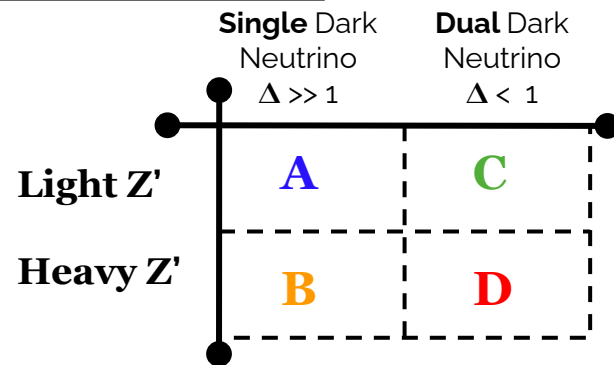


Features of the Dark Neutrino Signal

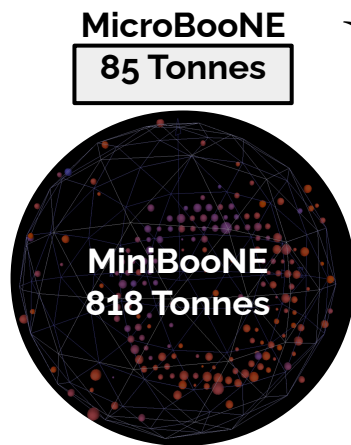
1. [Introduction](#)
MicroBooNE...
..and MiniBooNE
What we know

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Minimal Portals
Dark Neutrinos
Our e^+e^- Signal

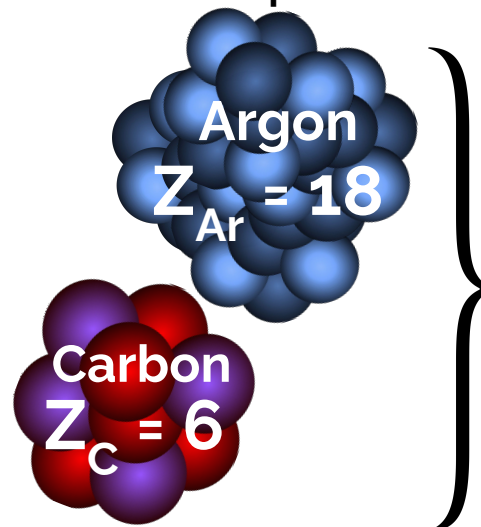
1. Wide distributions of e^+e^- opening angles
2. Events are very forward with respect to the neutrino beam
3. Total energy deposited can be quite varied
4. Both **coherent** and **incoherently** produced



This analysis focuses entirely on coherent (zero proton) scattering



~9.6 times less
active mass



Z' Coherent
scattering naively
scales as atomic
number squared:

$$\left(\frac{Z_{Ar}}{Z_C} \right)^2 = 9$$

The many ways to mimic a single-photon or e^+e^- pair

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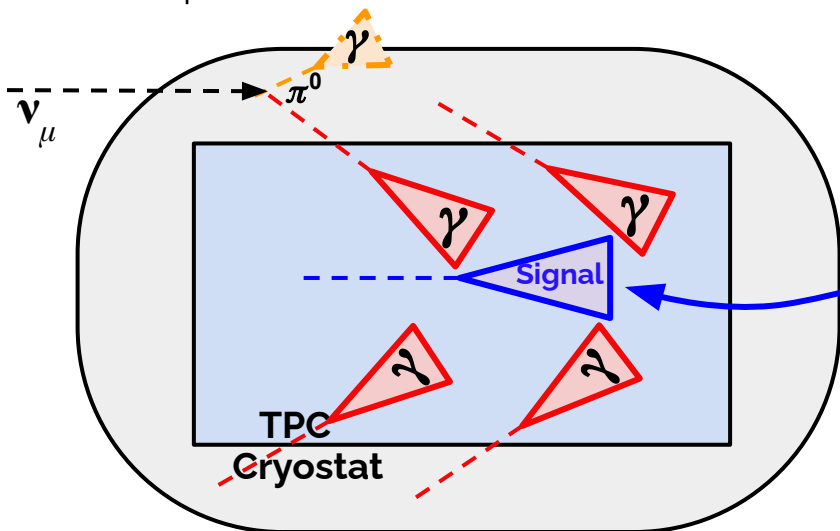
Our e^+e^- Signal

3. e^+e^- Selection

Reject Background

Background:

- (2) π^0 events from neutrino interactions **outside of the TPC** whose daughter photons scatter inside



How BDT Aims to Reject:

Due to the **long thin shape of MicroBooNE TPC** $2.56 \times 2.32 \times 10.36$ m

Most of this enters from the **long-edges**

Harder for this background to coincidentally look like **very forward going showers** (also the main phase space of our signal)

As such, the BDT preferentially select this **very forward events**

The many ways to mimic a single-photon or e^+e^- pair

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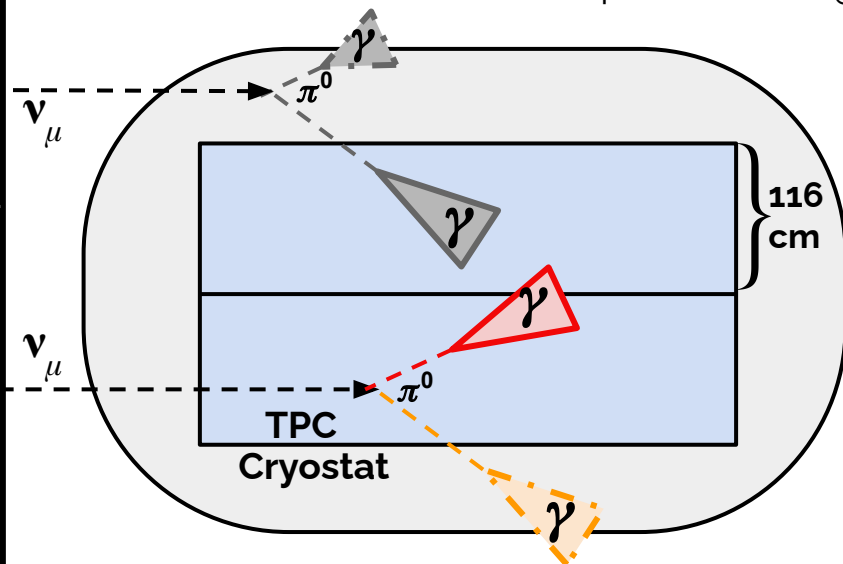
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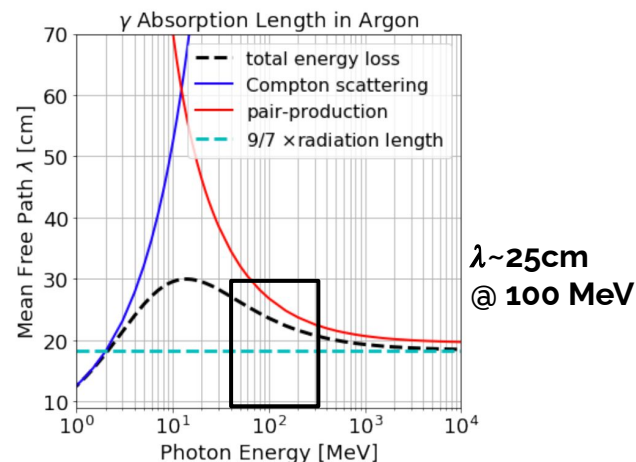
- (3) NC π^0 from neutrino interactions **inside of the TPC** where **one daughter photon leaves detector** before pair converting



How BDT Aims to Reject:

Both this and last similar.
Fiducialize?

Average distance to TPC boundary is **38 cm**



Average event is **less than 2 λ** from TPC boundary. **Very difficult**

MicroBooNE's Recent Dark Sector e^+e^- result

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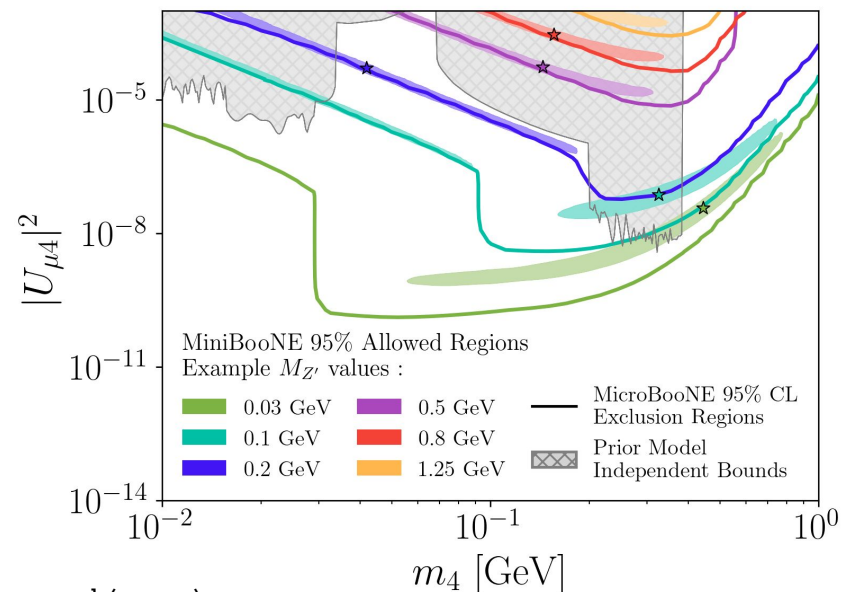
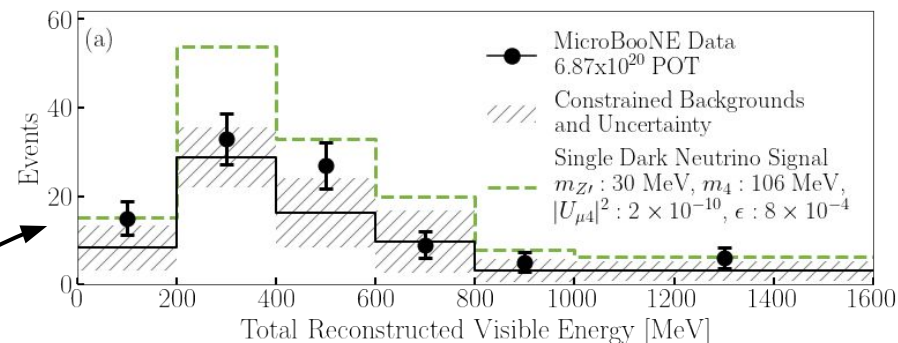
Bkg Prediction : 69.7 ± 17.3 events

Observed Data : 95 events

No evidence was observed for an e^+e^- signal consistent with MiniBooNE.

At 95% C.L. excluded the majority of the model phase space motivated by MB anomaly

Broad class of models tested, with varied dark gauge boson mass, as well as scenarios with both **single and dual dark neutrinos**



The Future of 3+1 Light Sterile Oscillation

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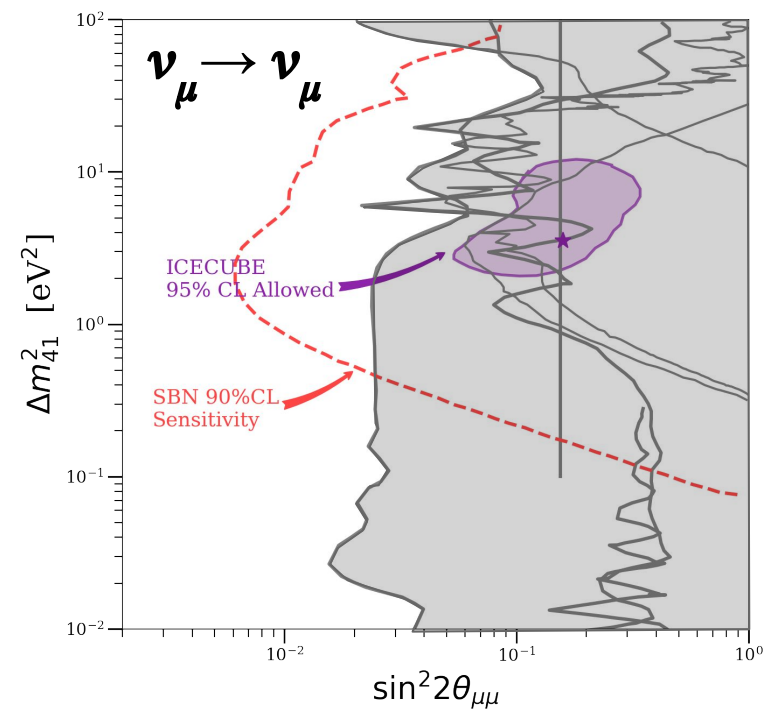
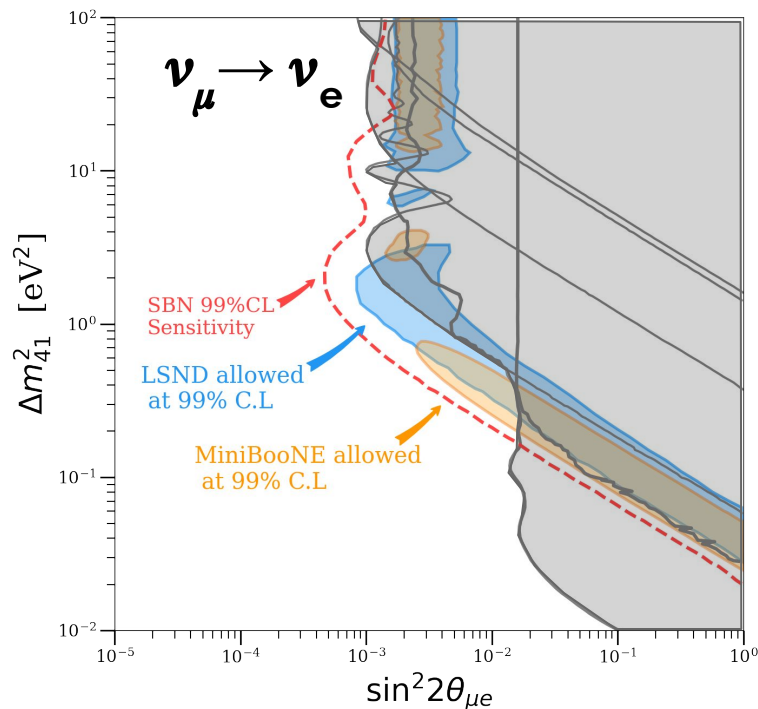
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5. The Future

For 3+1?



The **SBN program**, alongside experiments like **JSNS²-II**, will close the discussion on oscillating 3+1 sterile interpretation one way or another.

If a positive signal is indeed found, the difficulty is then **the extreme tension between global experiments**. Most likely require more new physics: 3+1+"something"

Δ Radiative γ

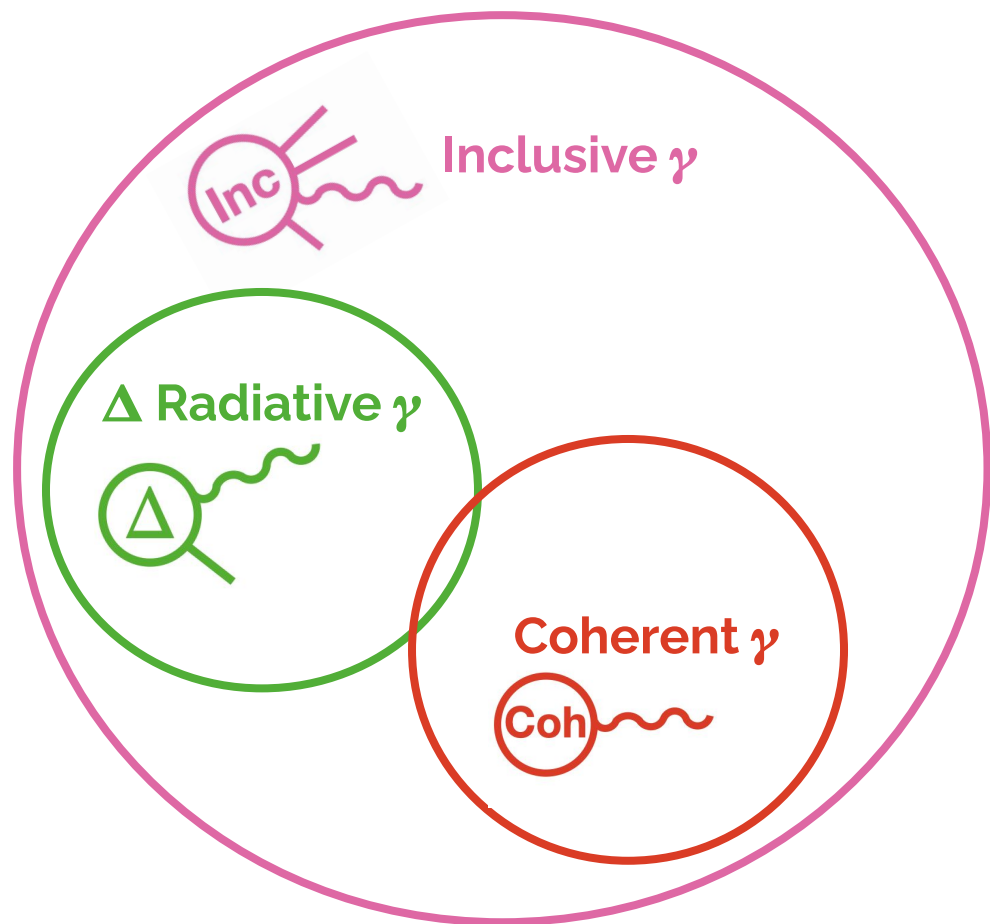
Improved search with ***almost double efficiency of first-gen analysis*** by combining reconstruction paradigms

Coherent γ

Search for ***coherent γ*** , an even rarer SM process than Δ Radiative.

Inclusive γ

A broad search ***aiming to capture all possible single-photons***, of both SM and BSM origin



Δ Radiative γ

Improved search with ***almost double efficiency of first-gen analysis*** by combining reconstruction paradigms

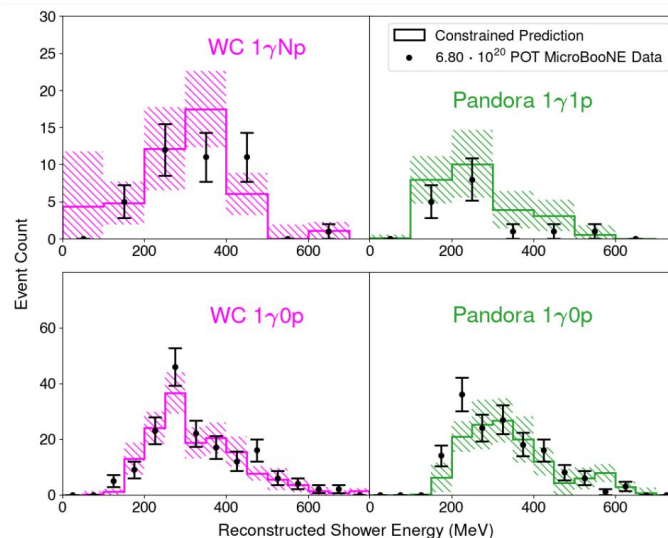
Coherent γ

Search for ***coherent γ*** , an even rarer SM process than Δ Radiative.

Inclusive γ

A broad search ***aiming to capture all possible single-photons***, of both SM and BSM origin

- Confirmed no anomalous NC Δ Radiative excess.
- Rejected hypothesis at 94.4% CL, consistent with 2021 analysis.
- Wire-Cell** and **Pandora** reconstruction show great agreement



[arXiv:2502.05750 \[hep-ex\] \(2025\)](https://arxiv.org/abs/2502.05750)

Δ Radiative γ

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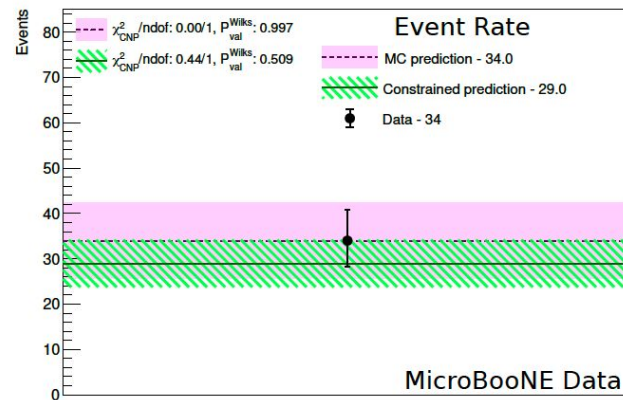
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Inclusive γ

A broad search ***aiming to capture all possible single-photons***, of both SM and BSM origin

- First ever search for this process. Developed tools to **veto protons** below 35 MeV Kinetic Energy
- **Observes no excess**
- Places an upper limit on the cross section of this process of $1.49 \times 10^{-41} \text{ cm}^2$ at 90% CL



Δ Radiative γ

Improved search with ***almost double efficiency of first-gen analysis*** by combining reconstruction paradigms

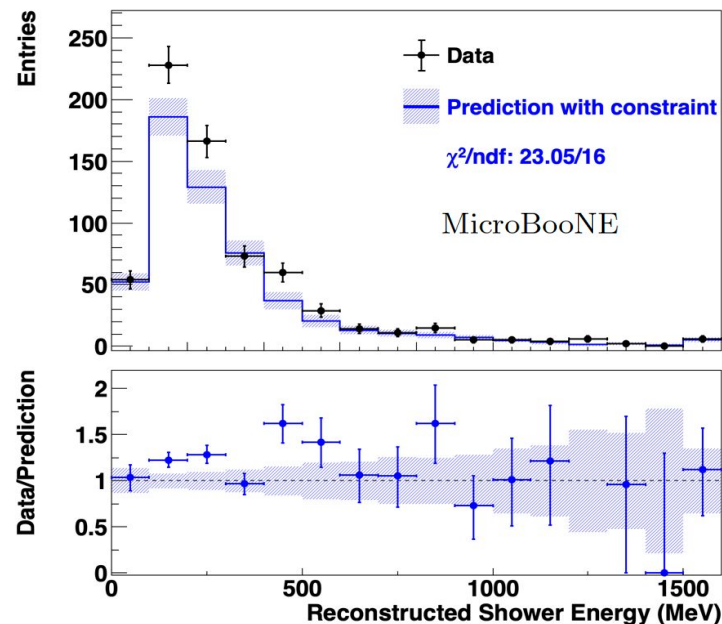
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A broad search ***aiming to capture all possible single-photons***, of both SM and BSM origin

- Total sample is consistent with background prediction to within **1.6σ**



[arXiv:2502.06064 \[hep-ex\] \(2025\)](https://arxiv.org/abs/2502.06064)

Δ Radiative γ

Improved search with ***almost double efficiency of first-gen analysis*** by combining reconstruction paradigms

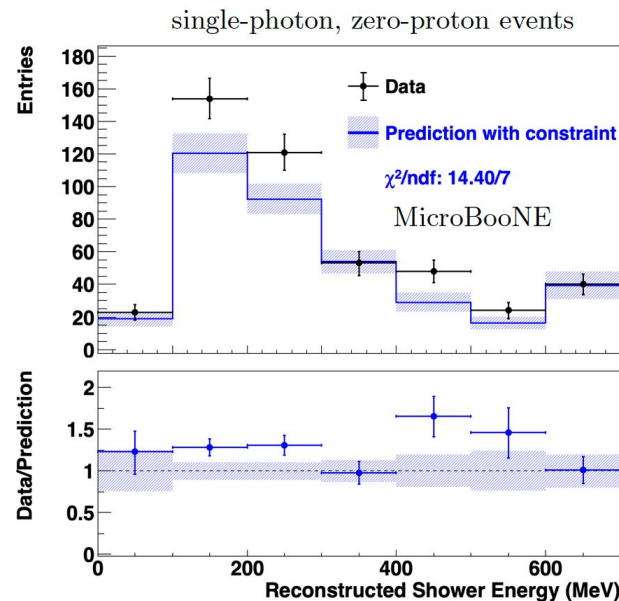
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Search for ***coherent γ*** , an even rarer SM process than Δ Radiative.

Inclusive γ

A broad search ***aiming to capture all possible single-photons***, of both SM and BSM origin

- Total sample is consistent with background prediction to within **1.6σ**
- In the **zero-proton sample** we observed a **2σ excess below 600 MeV** shower energies



[arXiv:2502.06064 \[hep-ex\] \(2025\)](https://arxiv.org/abs/2502.06064)

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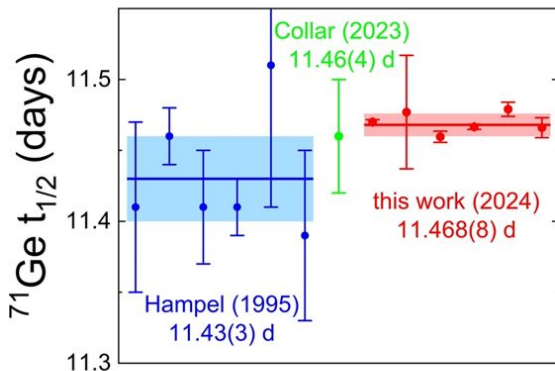
ν_μ Disappearance

ν_μ Cosmology

New Ideas

- BEST **was** the new testing ground for this decades old anomaly
- BEST result is **extremely compelling**, the **anomaly is confirmed** but sterile origin is NOT confirmed
-

Lots of scrutiny: E.g A larger value of the half-life of ^{71}Ge used to compute the neutrino cross sections on ^{71}Ga could explain the difference

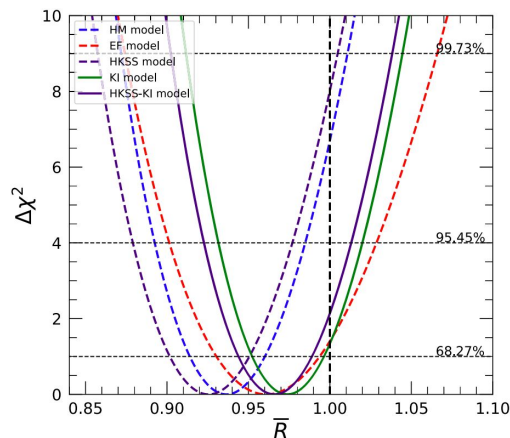


E.B Norman et al, [PhysRevC.109.055501 \(2024\)](https://arxiv.org/abs/2405.12345)

"With this experiment, the potential explanation of the Gallium Anomaly being due to an unexpectedly long ^{71}Ge half-life has been ruled out, leaving the anomaly's origin as an open question"

Reactor (RAA) Global Anomaly?

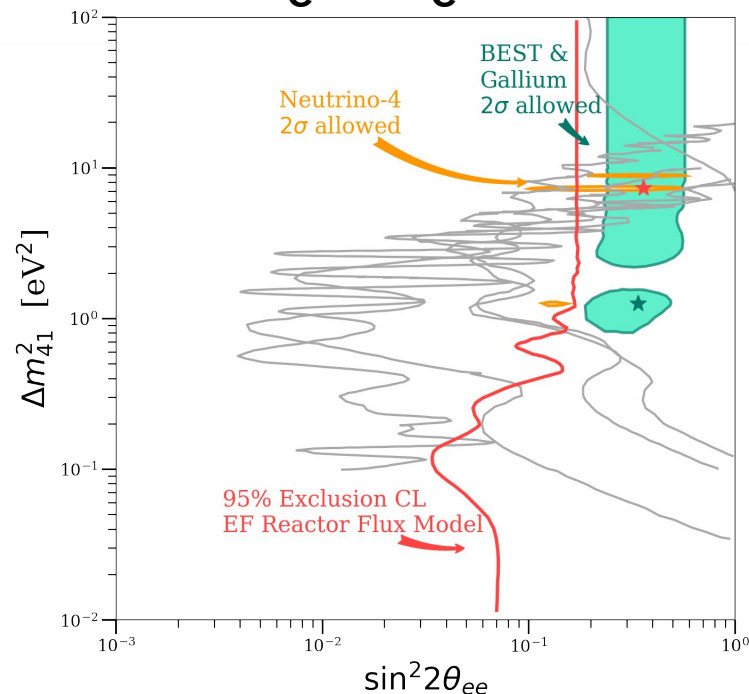
We have several valid models of reactor fluxes that **have no anomaly**.



C. Giunti et al Physics Letters B Volume 829, 10 June 2022, 137054

In fact, **global fits of reactors** essentially exclude the BEST and Neutrino-4 allowed regions. E.g the **Estienne-Fallot (EF) reactor flux** model

$$\nu_e \rightarrow \nu_e$$

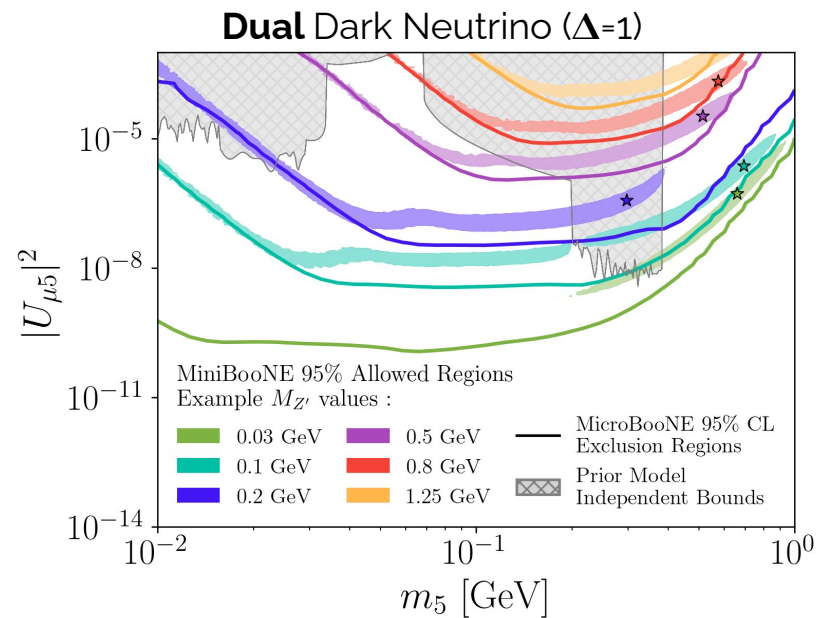
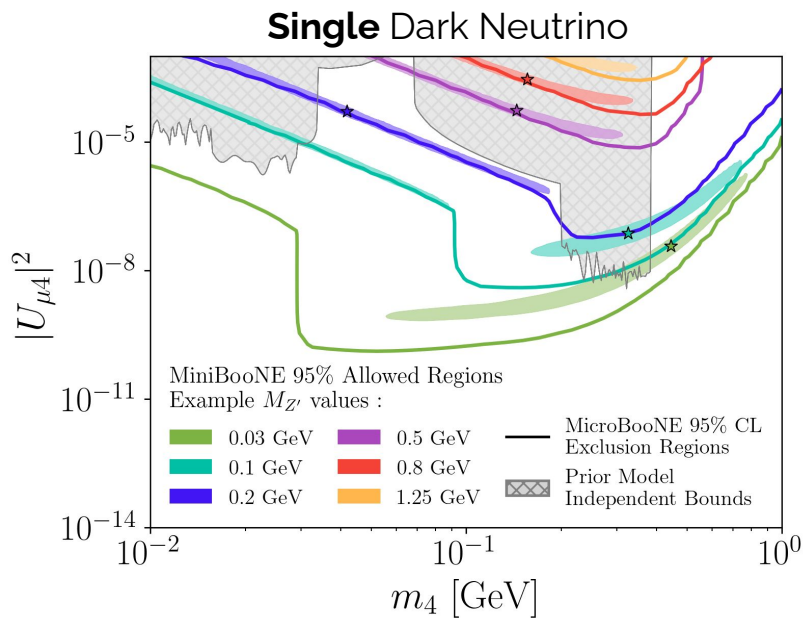


Positive Hints

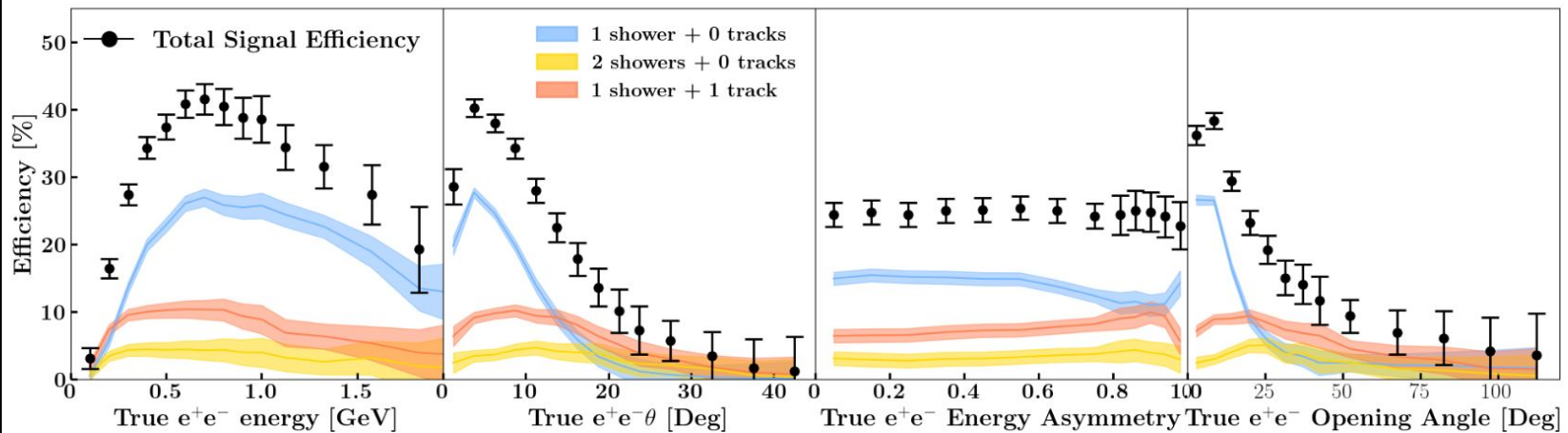
- Gallium
- Neutrino 4

Null Results

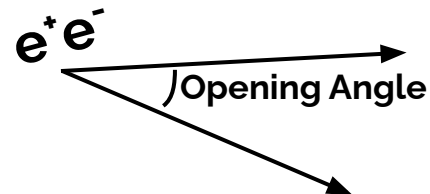
- DANSS
- NEOS+RENO
- STEREO
- PROSPECT-I
- KATRIN
- Global Reactors?



The world's first direct limits on these dark sector models and, at the 95% confidence level, **excludes the majority of the parameter space viable as a solution to the MiniBooNE anomaly** (especially for light Z' boson masses)



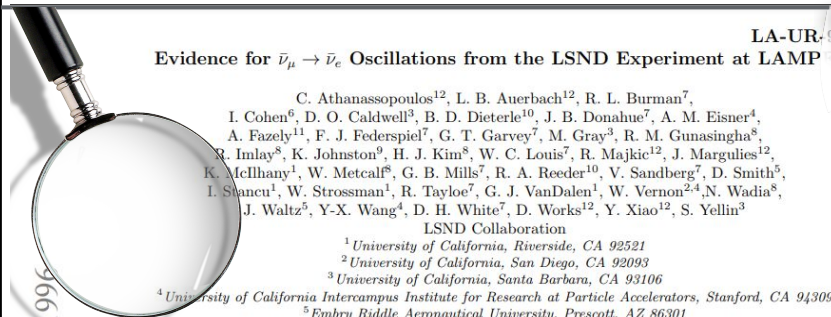
$$\frac{|E^{e^+} - E^{e^-}|}{E^{e^+} + E^{e^-}}$$



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arXiv:nuc1-ex/9605003v1 9 May 1996



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

C. Athanassopoulos¹², L. B. Auerbach¹², R. L. Burman⁷,
I. Cohen⁶, D. O. Caldwell³, B. D. Dieterle¹⁰, J. B. Donahue⁷, A. M. Eisner⁴,
A. Fazely¹¹, F. J. Federspiel⁷, G. T. Garvey⁷, M. Gray³, R. M. Gunasingha⁸,
R. Imay⁸, K. Johnston⁹, H. J. Kim⁸, W. C. Louis⁷, R. Majkic¹², J. Margulies¹²,
K. McIlhenny¹, W. Metcalfe⁶, G. B. Mills⁷, R. A. Reeder¹⁰, V. Sandberg⁷, D. Smith⁵,
I. Stancu¹, W. Strossman¹, R. Tayloe⁷, G. J. VanDalen¹, W. Vernon^{2,4}, N. Wadia⁸,
J. Waltz⁵, Y.-X. Wang⁴, D. H. White⁷, D. Works¹², Y. Xiao¹², S. Yellin³

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 Inter-campus 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

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(August 17, 2019)

A search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ 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 $\bar{\nu}_e p \rightarrow e^+ n$, correlated with a γ from $np \rightarrow d\gamma$ (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 $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations, this corresponds to an oscillation probability of $(0.31^{+0.11}_{-0.10} \pm 0.05)\%$.

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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 $\pi^+ \rightarrow \mu^+ \nu_\mu$, followed by $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$, 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 $7.6 \times 10^{-10} \bar{\nu}_\mu/\text{cm}^2/\text{proton}$.

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 3 ν paradigm was by **no means taken for granted** by entire HEP community

1. Introduction
3v Paradigm
How we got here

2. Short-Baselines
Anomalies
Sterile Neutrinos

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



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Phenomenology of Neutrino Oscillations

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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 been obtained in the atmospheric, solar and LSND experiments. We present the results of the analyses of the neutrino oscillation data in the framework of

*"..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**"*