Results and Perspectives from Short Baseline Neutrino Experiments

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*21st Conference on **Flavor Physics and CP Violation***
Institute of Physics of the 2 Infinities
Lyon University

Los Alamos
NATIONAL LABORATORY

Why *Short* Baselines?

We study short baselines because something **very strange is happening at short baselines.**

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Introduction

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There are **several anomalous results** that hint towards new physics in experiments at **baselines** and **energies** where we would **not** expect to see any measurable neutrino oscillation effect if there was only 3 neutrinos.

$$\mathcal{P}_{\alpha\rightarrow\beta} = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

Neutrino Energies E_ν
O(100) keV → O(1) GeV

Baselines
< O(100) m

$$\boxed{\Delta m^2 \sim 0.1\ \text{eV}^2 \rightarrow 100\ \text{eV}^2}$$

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ν_4

Need a 4th "sterile" neutrino
"SM Singlet Fermion"

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

ν_3

ν_2

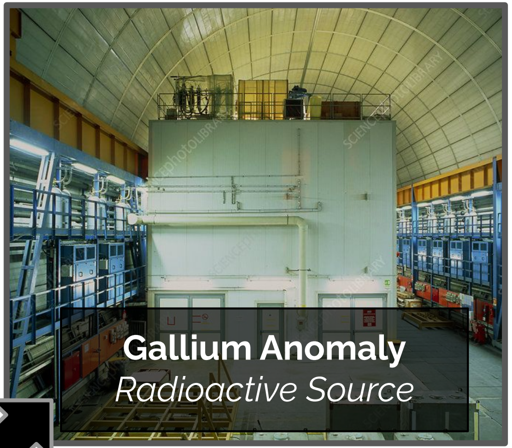
ν_1

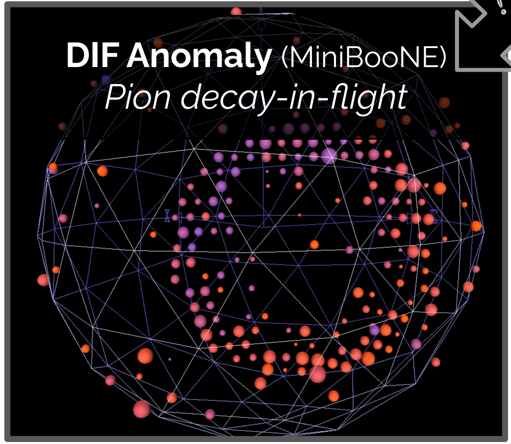
3 Neutrino Paradigm

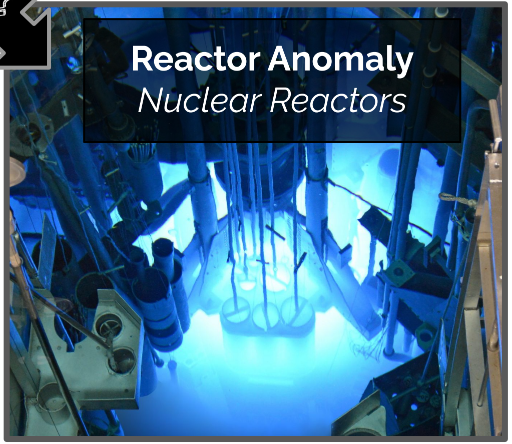
$\Delta m^2_{31} = 2.5 \times 10^{-3}\mathrm{eV}^2$

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

The Short-Baseline *Anomalies*

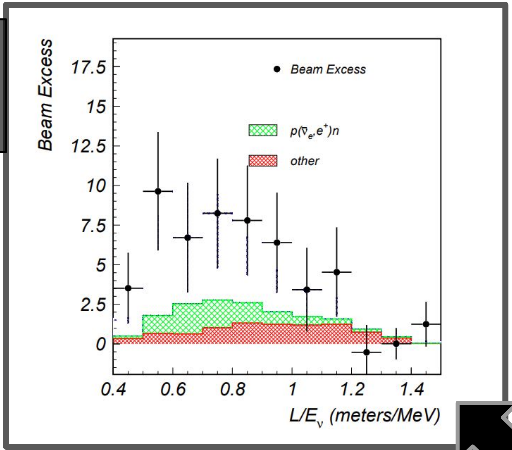






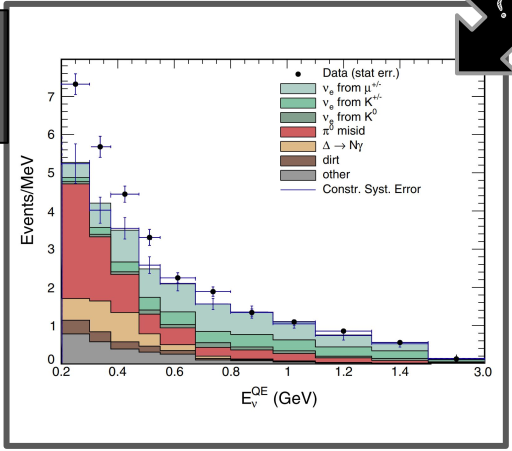
The Short-Baseline *Anomalies*

DAR Anomaly (LSND)
Pion decay-at-rest



Anomalous **excess** of $\bar{\nu}_e$ like events

DIF Anomaly
(MiniBooNE)
Pion decay-in-flight



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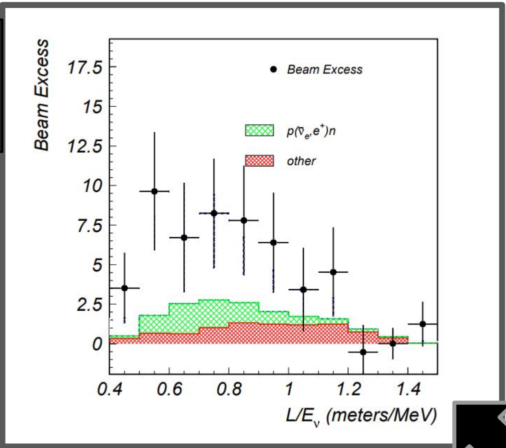
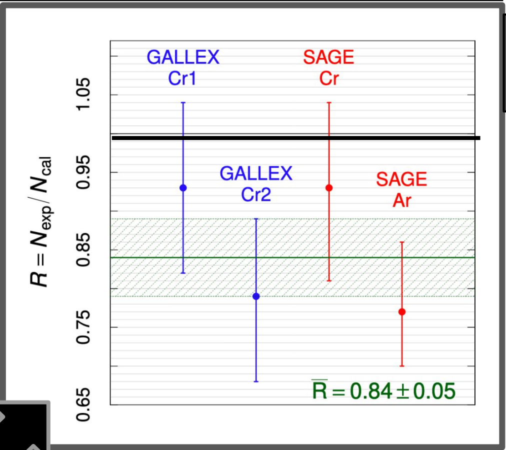
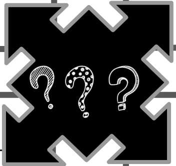




Gallium Anomaly
Radioactive Source

Anomalous **deficit** of ν_e from radioactive sources



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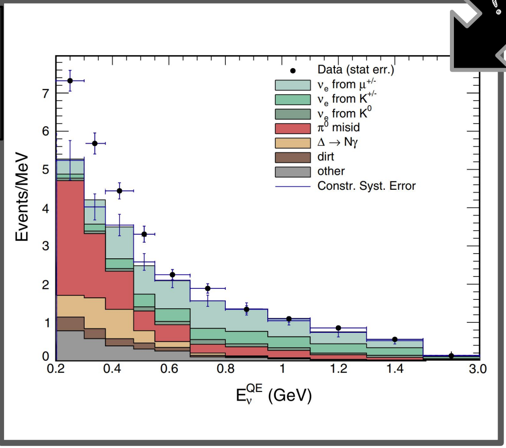

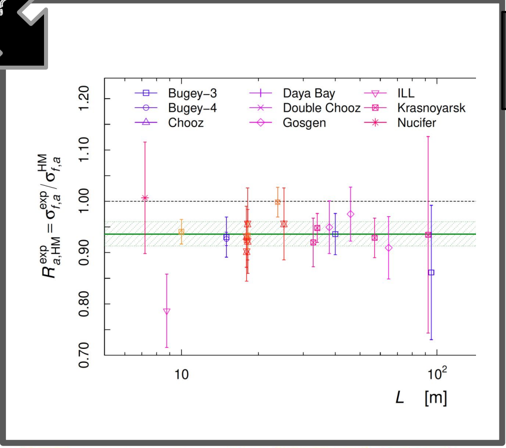

Reactor Anomaly
Nuclear Reactors

Anomalous **deficit** of $\overline{\nu}_e$ from nuclear reactors sources

The Short-Baseline *Anomalies:* Evidence for sterile neutrinos?

DAR Anomaly (LSND)
Pion decay-at-rest

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

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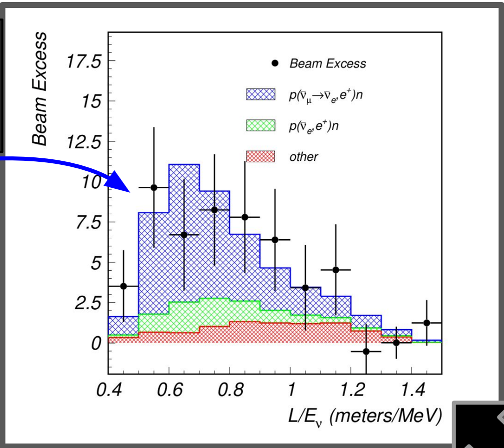

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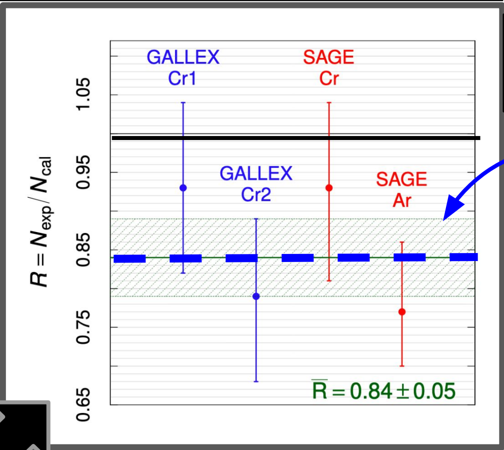

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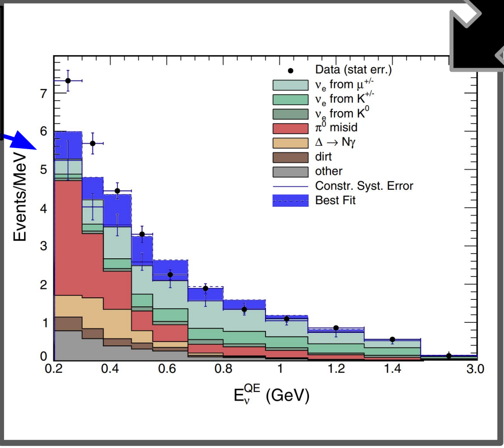

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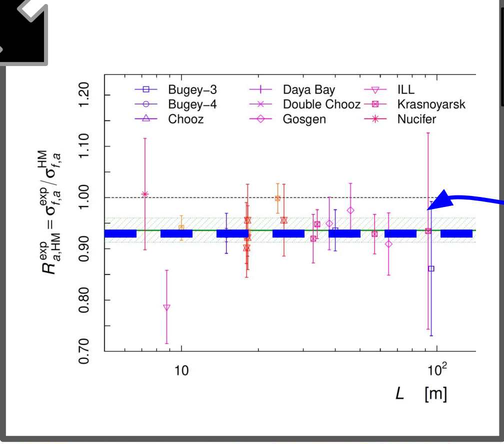
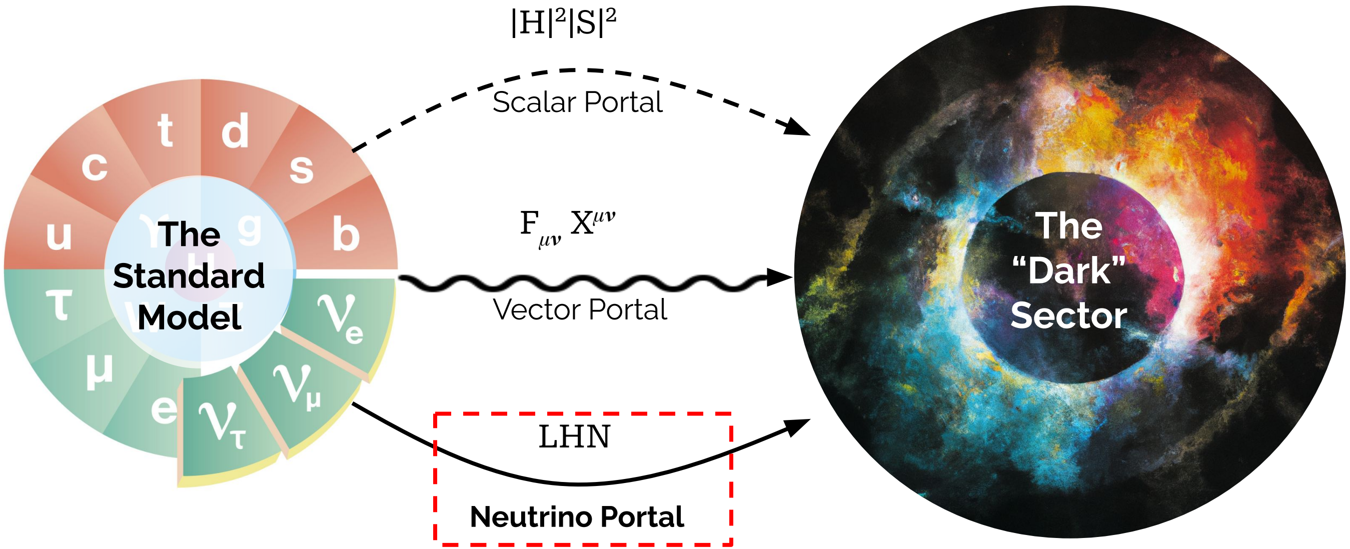


A Caveat/ Warning

- The **historical context** for all these anomalies is the **"3+1 sterile neutrino"** model
- This simple extension is somewhat **out of fashion** due to tension in global data, and neutrino community is now focusing on more complex models in which neutrinos act as a portal to a phenomenologically complex **"dark sector"**
- Nonetheless, the 3+1 sterile neutrino picture is a **powerful tool** and allows a **common comparison between experiments**



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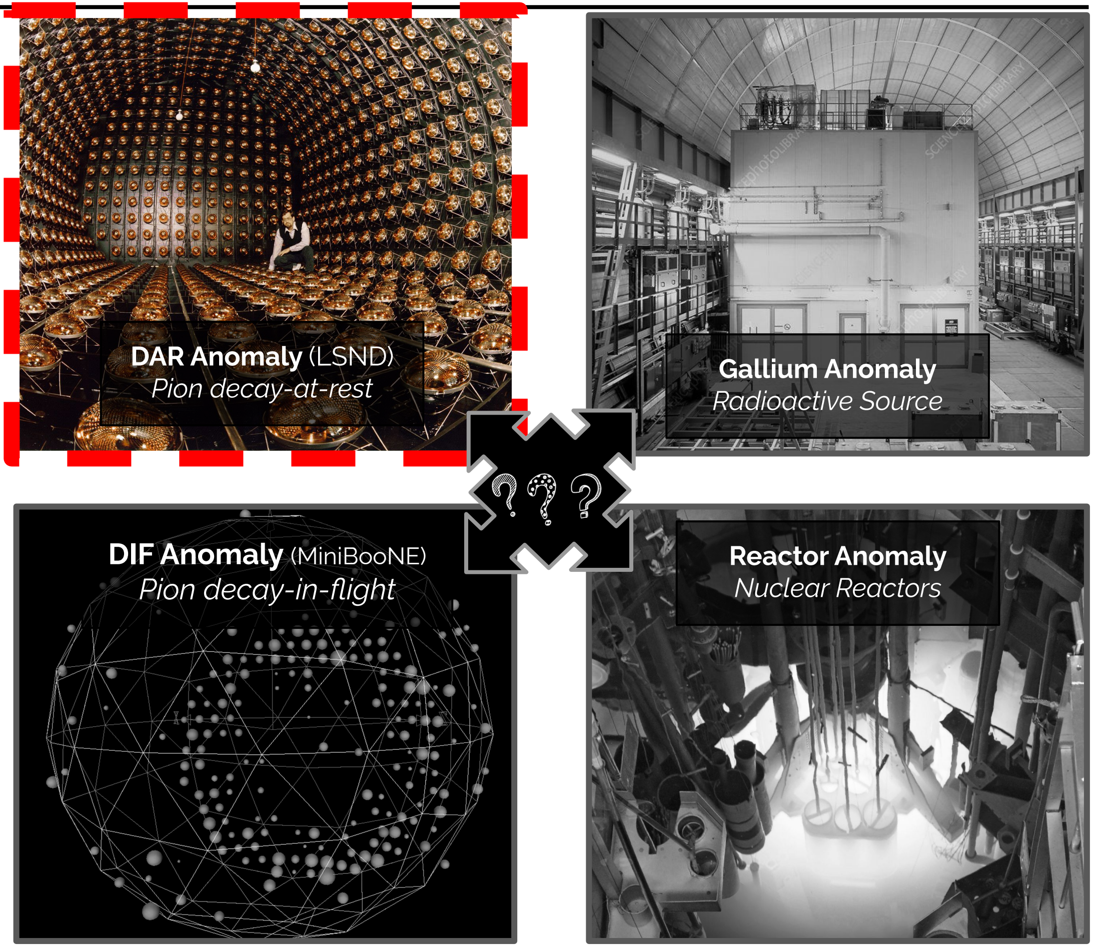


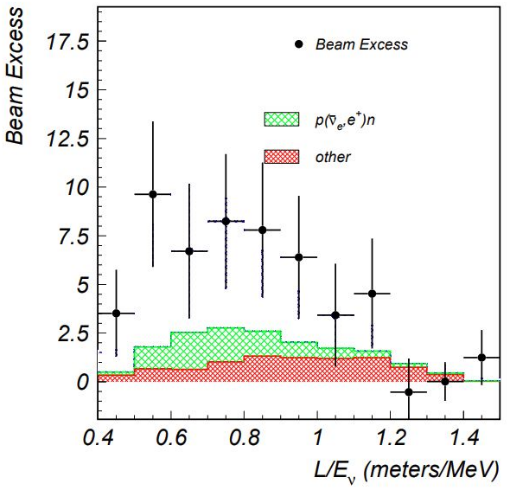
The LSND decay-at-rest Anomaly

LSND at Los Alamos National Lab was searching for **$\bar{\nu}_e$ appearance in a extremely pure $\bar{\nu}_\mu$ beam.**

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

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

$\bar{\nu}_e$ contamination was at the level of **0.078%**



3.8σ Significance

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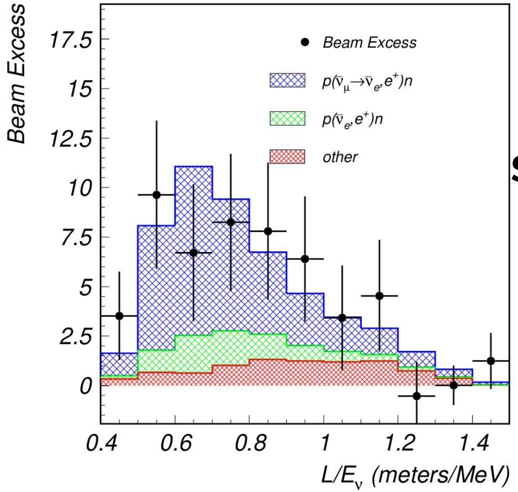

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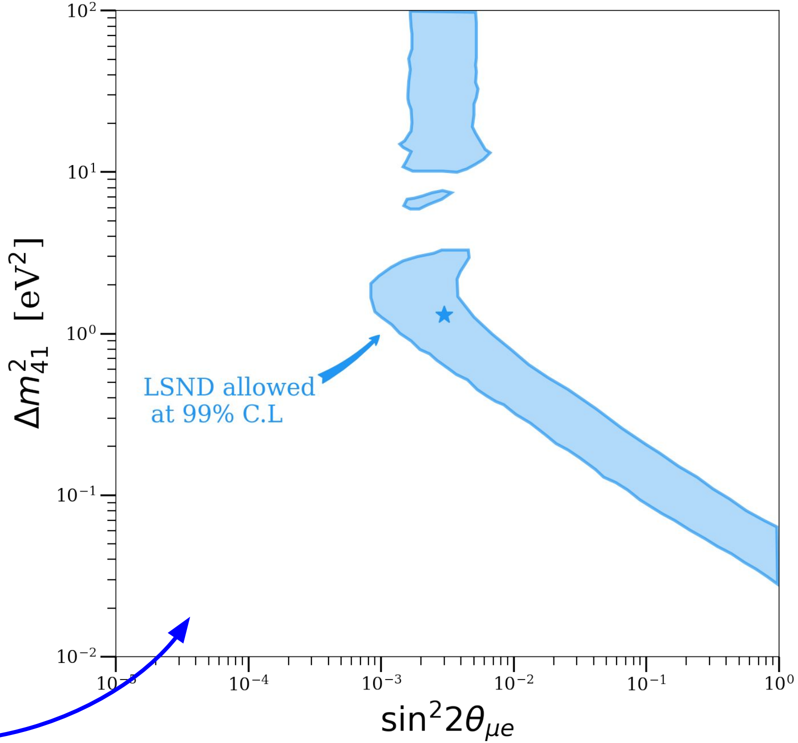
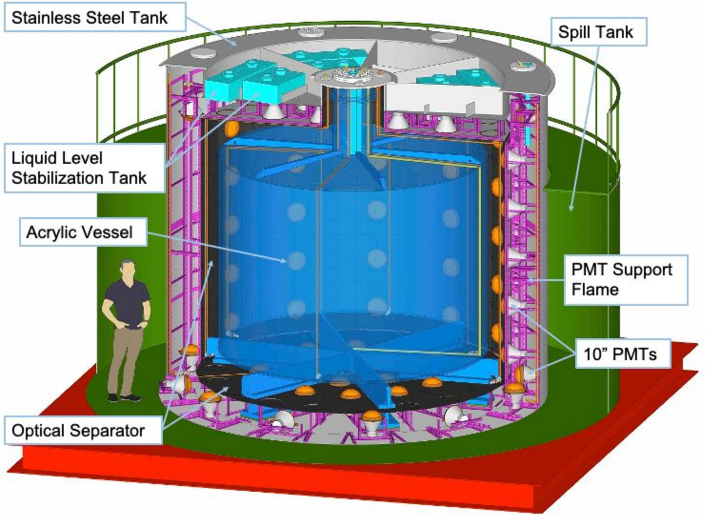


If interpreted as a sterile neutrino, **best fit Δm^2 ~ 1eV^2**

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

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



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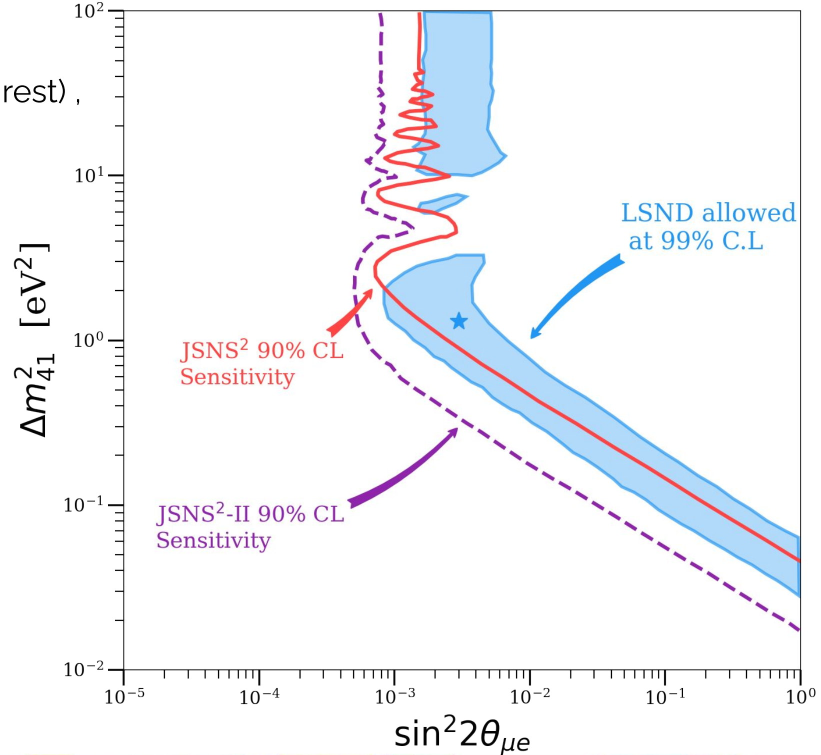
1st Phase: JSNS² [1310.1347]

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

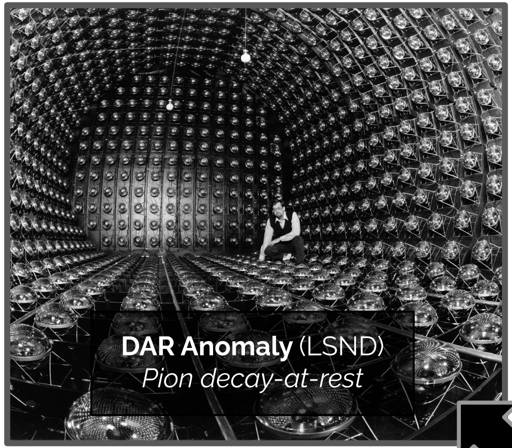
2nd Phase: JSNS²-II [2012.10807[

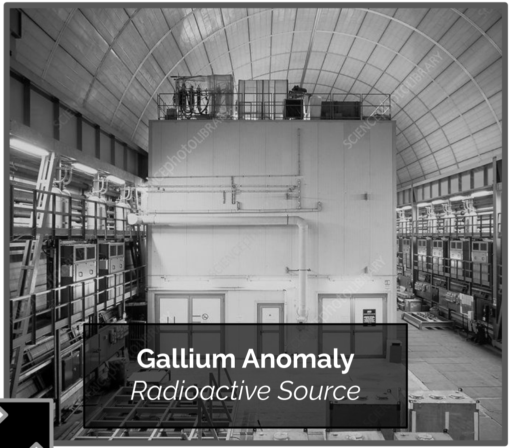
Upgrade to **two detectors**, Has been granted stage-2 approval
- Near@24m (17 tons, 120 10'' PMTs
- Far @ 28m (32 tons, 220 10'' PMTs)

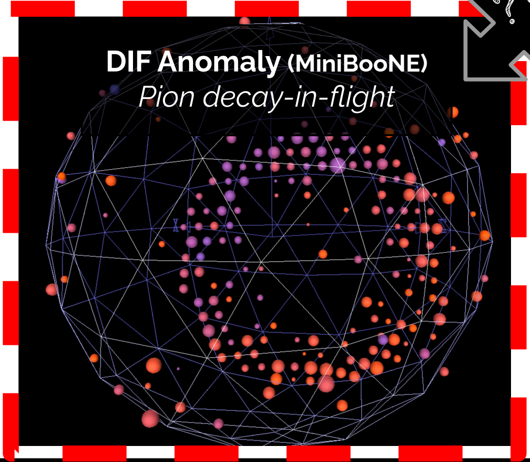
Expected data taking in late 2023.

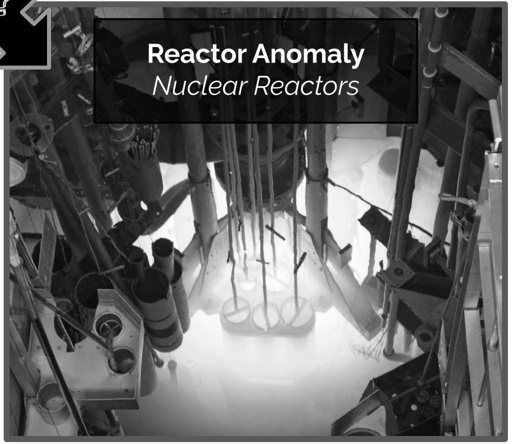


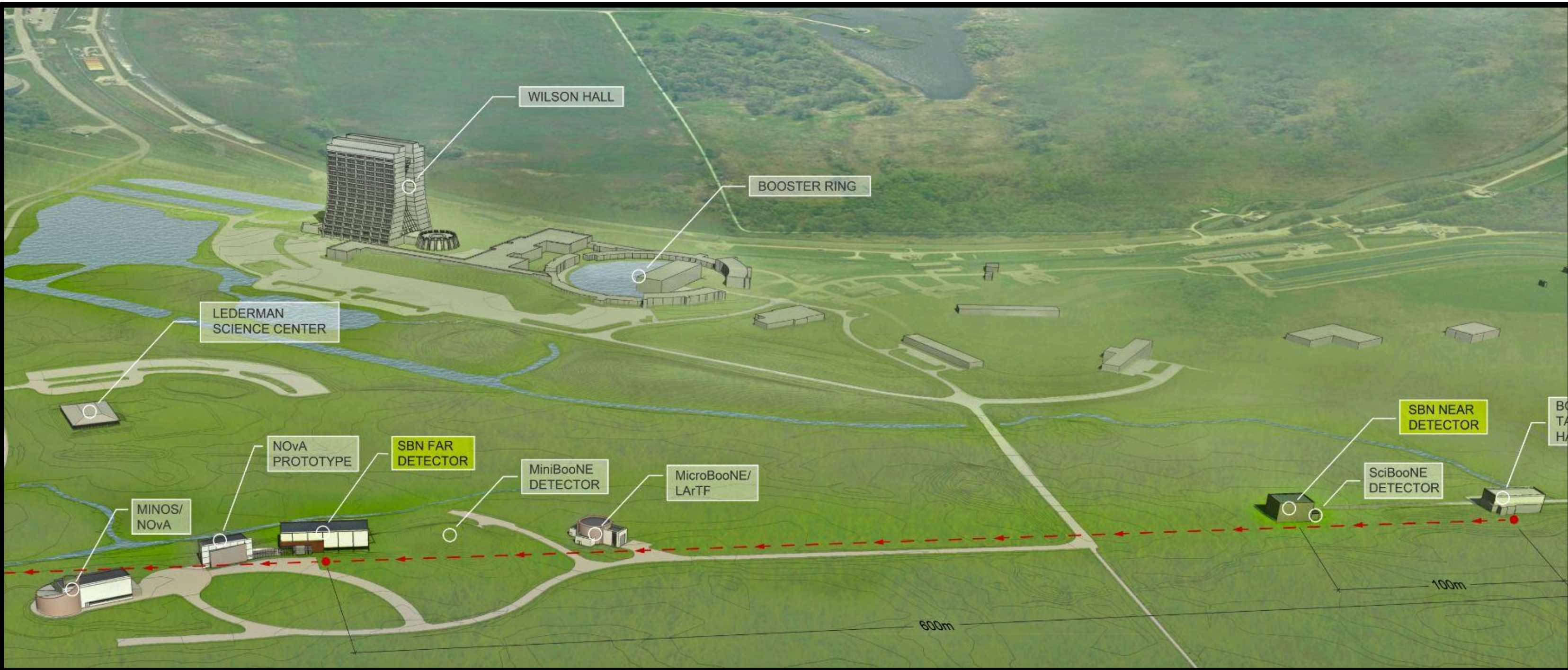
The Decay-in-Flight Anomaly (MiniBooNE)



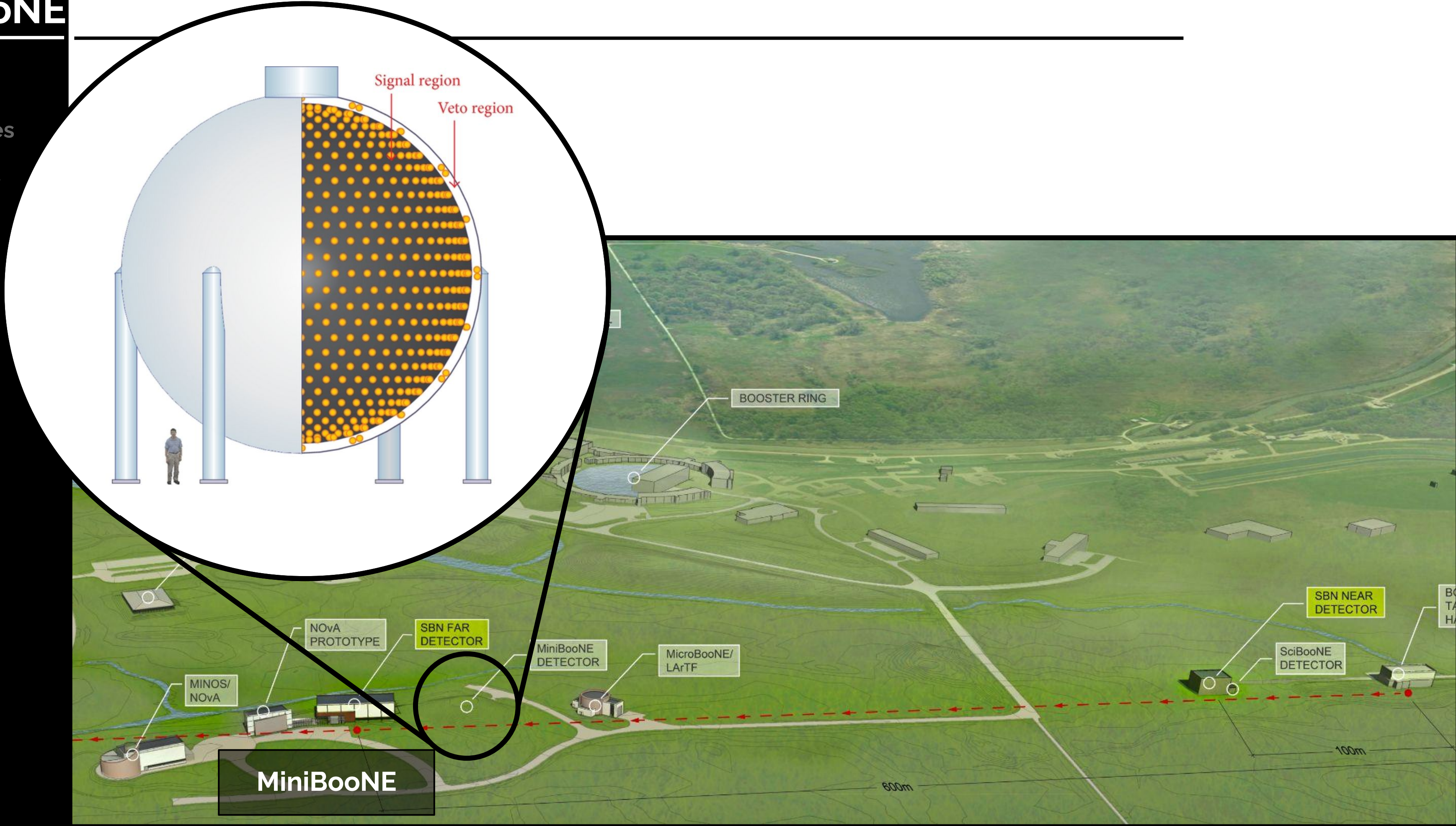







WILSON HALL
BOOSTER RING
LEDERMAN SCIENCE CENTER
NOvA PROTOTYPE
SBN FAR DETECTOR
MiniBooNE DETECTOR
MicroBooNE/ LArTF
MINOS/ NOvA
SBN NEAR DETECTOR
SciBooNE DETECTOR
100m
600m

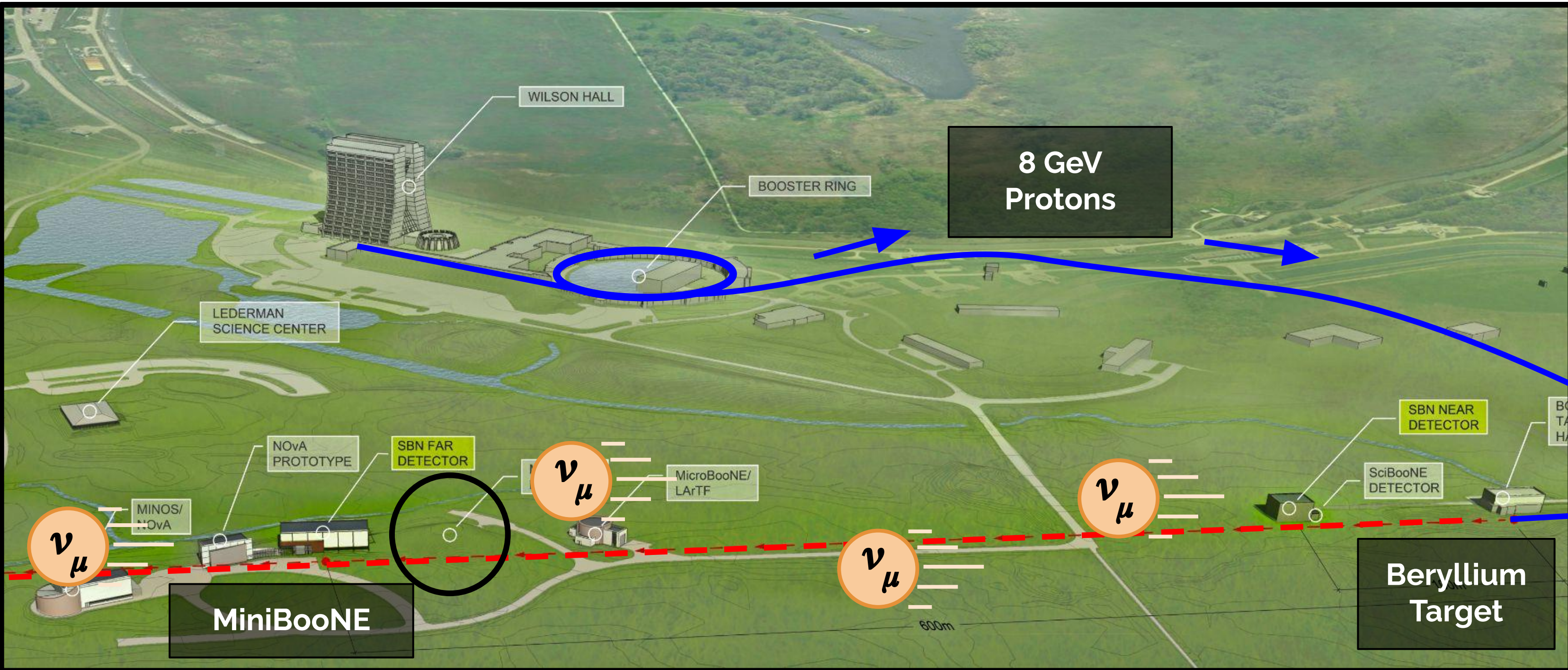
MiniBooNE



Signal region
Veto region
BOOSTER RING
SBN NEAR DETECTOR
SciBooNE DETECTOR
MicroBooNE/ LArTF
MiniBooNE DETECTOR
SBN FAR DETECTOR
NOvA PROTOTYPE
MINOS/ NOvA
100m
600m
MiniBooNE

Fermilab's Booster Neutrino Beam (BNB)

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



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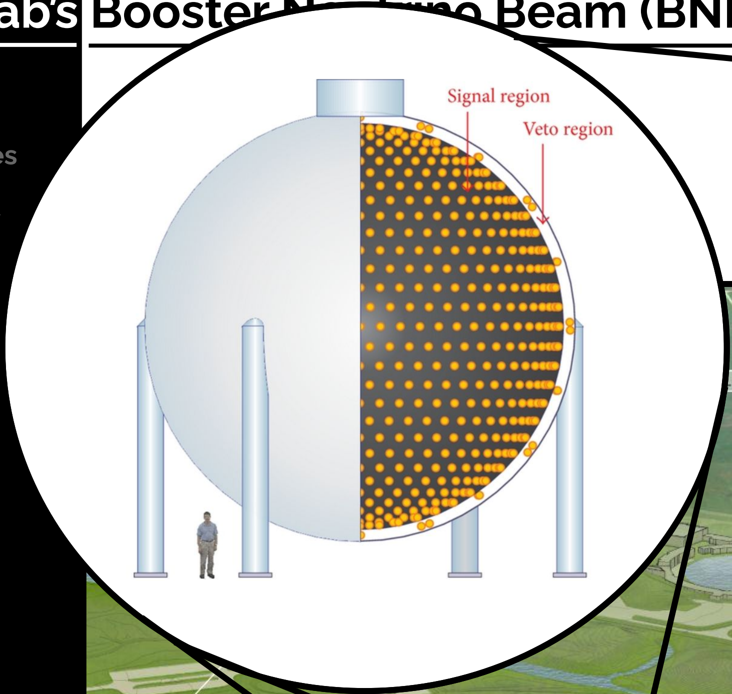

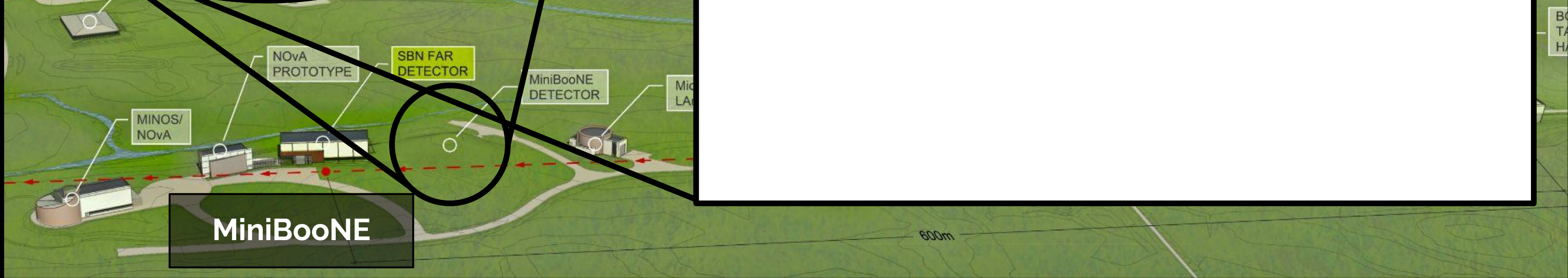

Idea: Search for $\nu_\mu \rightarrow \nu_e$ **appearance** at different E and L, but similar L/E

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

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

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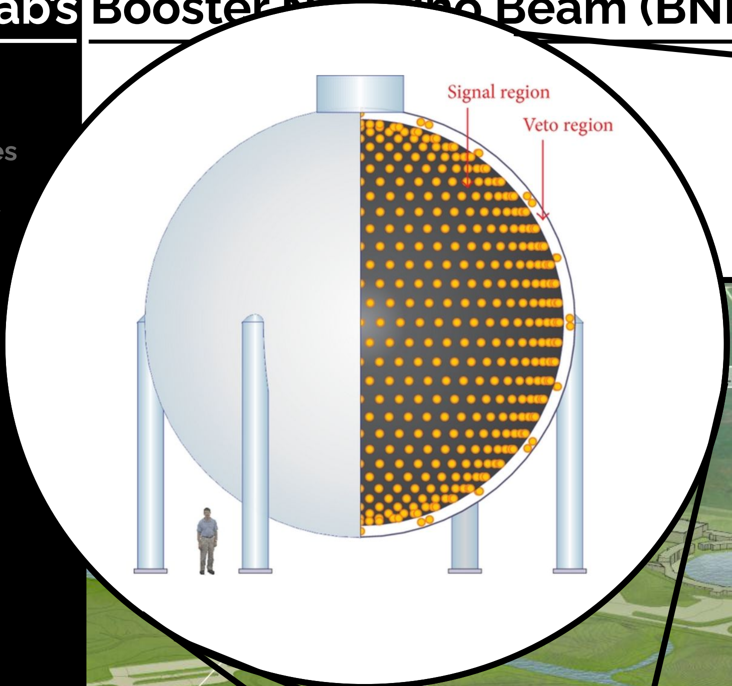

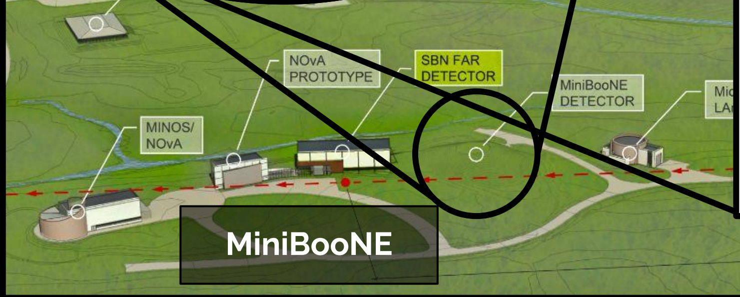

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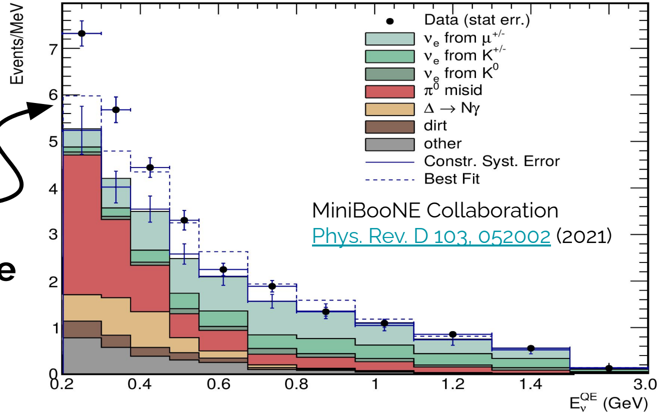
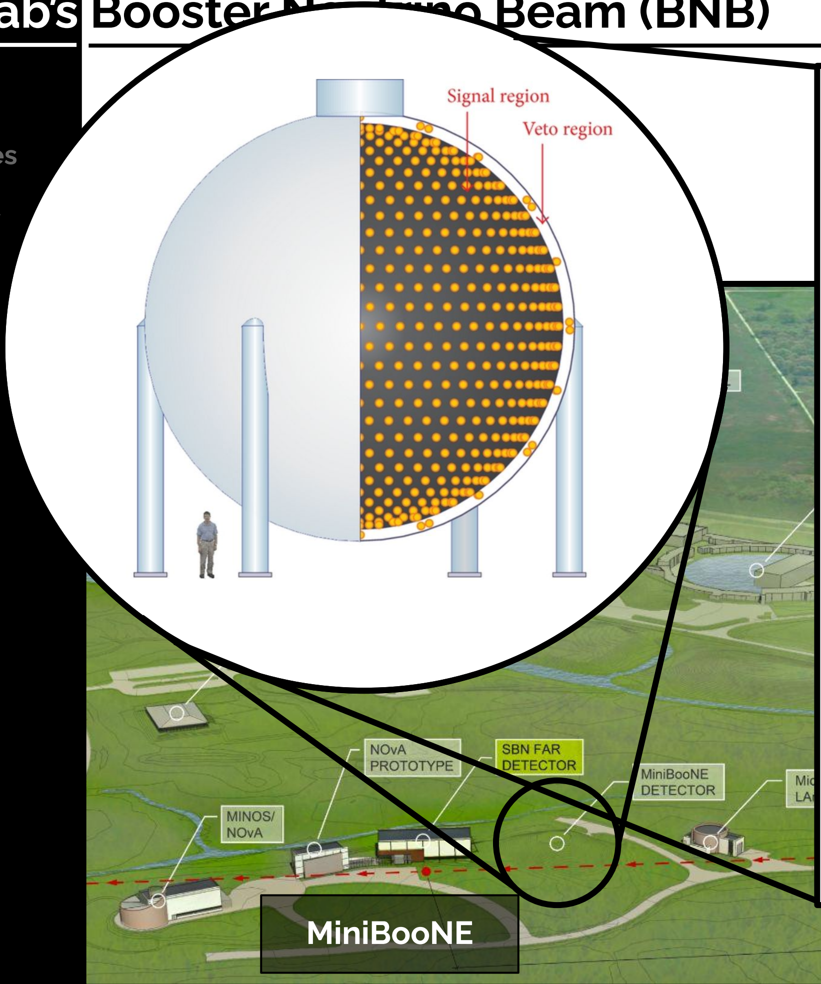
An excess of electron-like events!

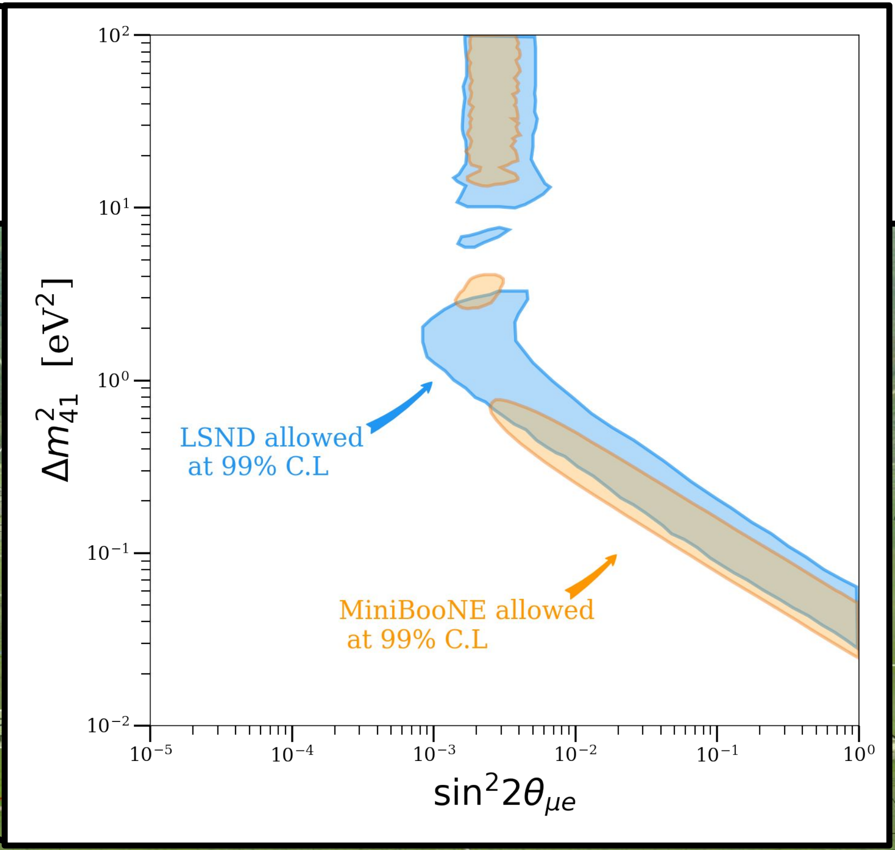
Significance ~4.8σ



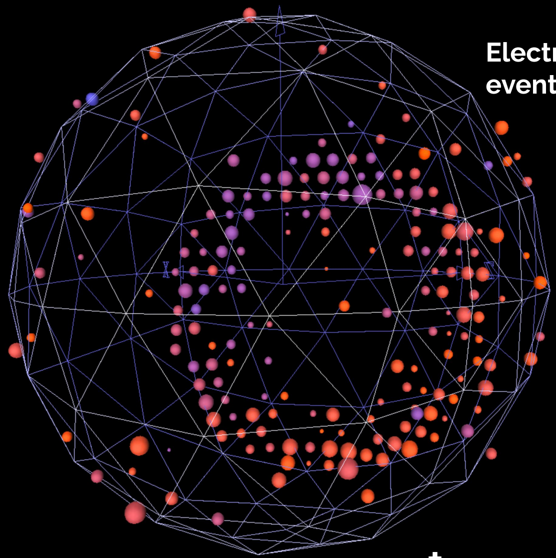
MiniBooNE Collaboration
Phys. Rev. D 103, 052002 (2021)

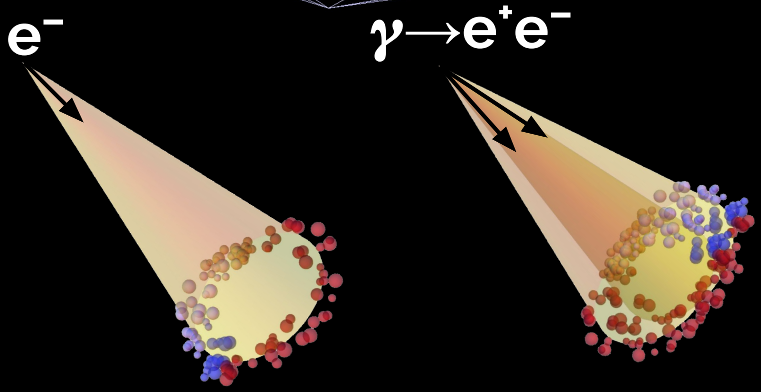
Fermilab's Booster Neutrino Beam (BNB)





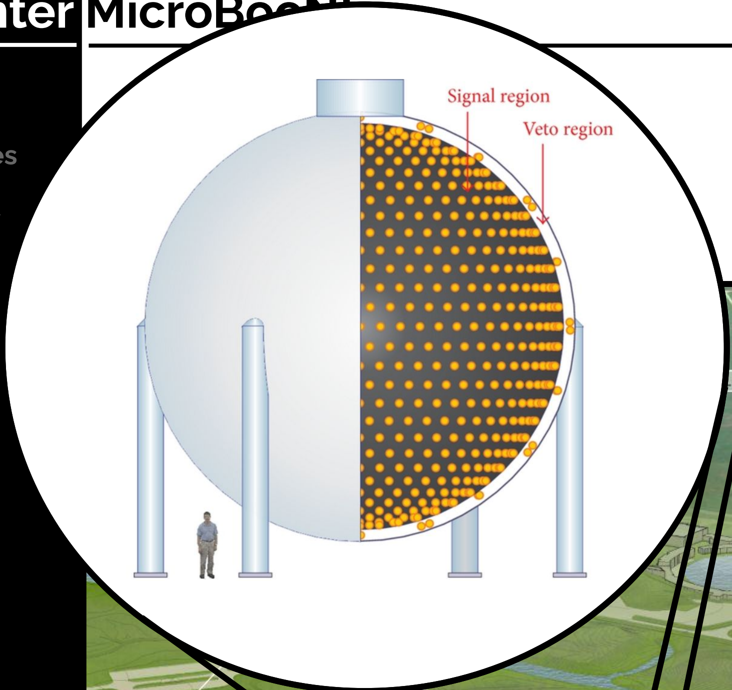
Electrons or Photons?



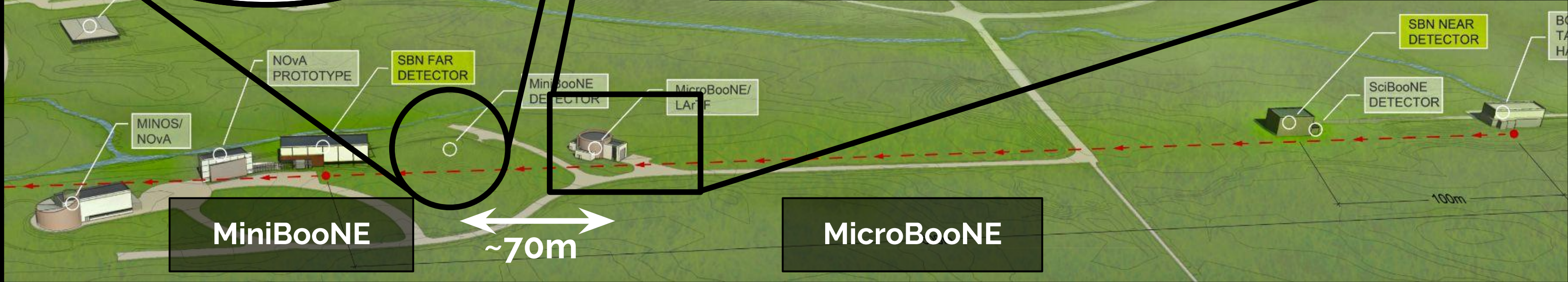


Before claiming discovery of sterile neutrinos, need to ensure the excess is truly electron in nature!

Enter MicroBo



A **L**iquid **A**rgon **T**ime **P**rojection **C**hamber **(LArTPC)**



Electrons or Photons?

Introduction

The Anomalies

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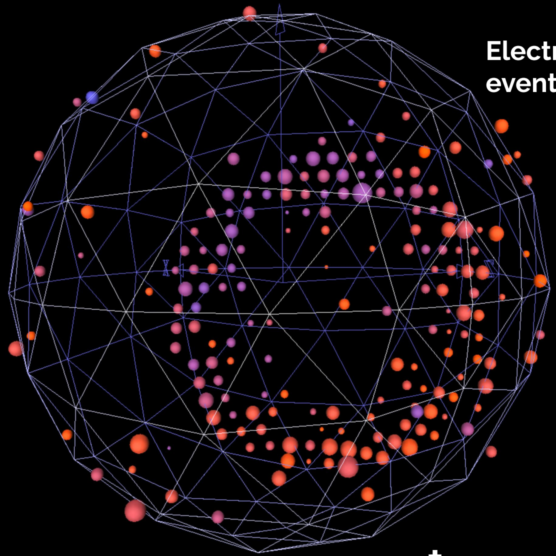
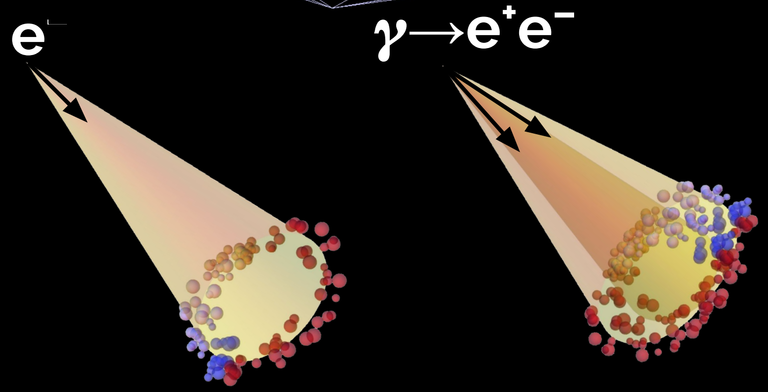
JSNS²

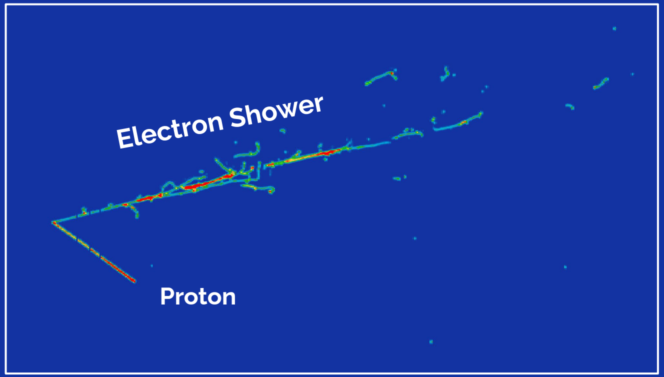
DIF Anomaly
MicroBooNE

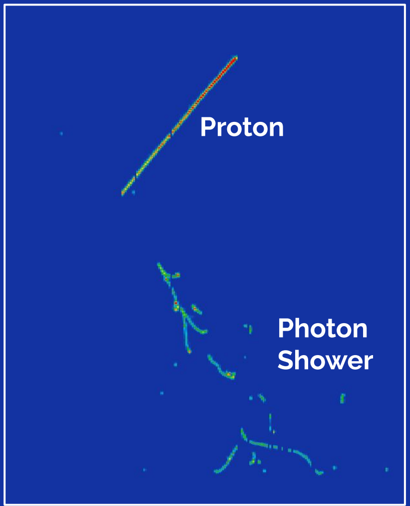


Electron Cherenkov ring event in MiniBooNE



CC ν_e + 1 proton event



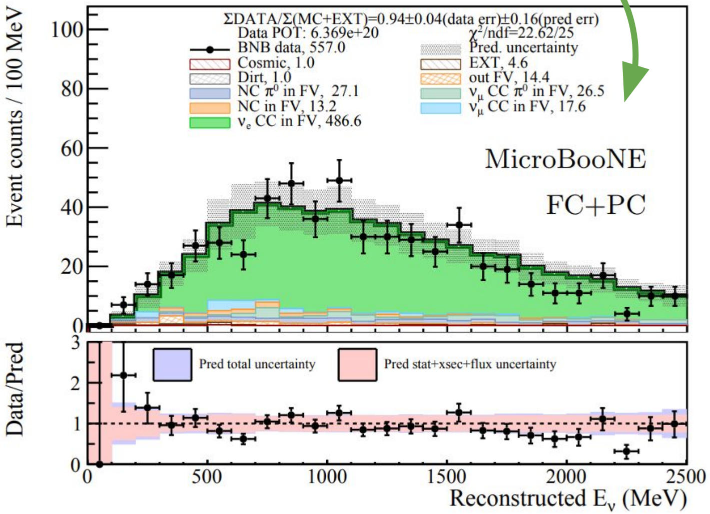


NC single-photon + 1 proton event

LArTPC's give us **fully active calorimeter** alongside **high-resolution tracking**

Allows for strong **photon ↔ electron separation**

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



No evidence of an excess of ν_e above expected intrinsic ν_e in the beam

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

MicroBooNE: PhysRevLett.128.241801

MicroBooNE : A direct test of the MiniBooNE anomaly

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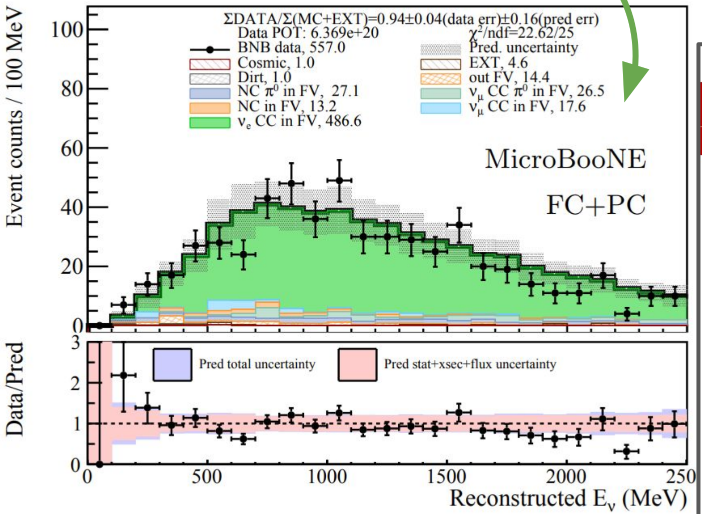

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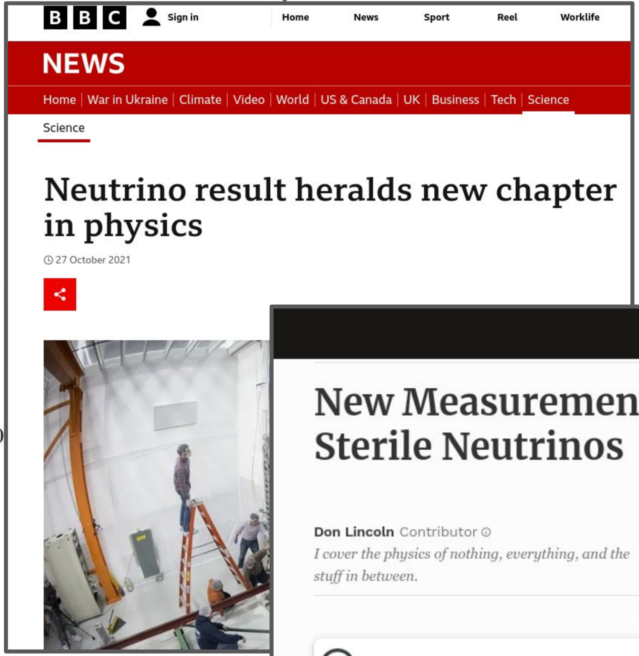
"The search failed to find the particle, known as the sterile neutrino."



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Science

Neutrino result heralds new chapter in physics

27 October 2021

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

Forbes

New Measurement Rules Out Sterile Neutrinos

Don Lincoln Contributor

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

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MicroBooNE: A direct test of the MiniBooNE anomaly

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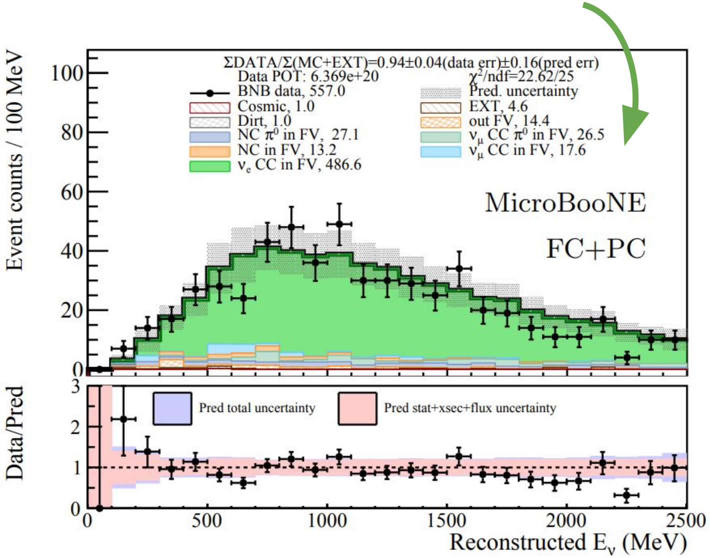

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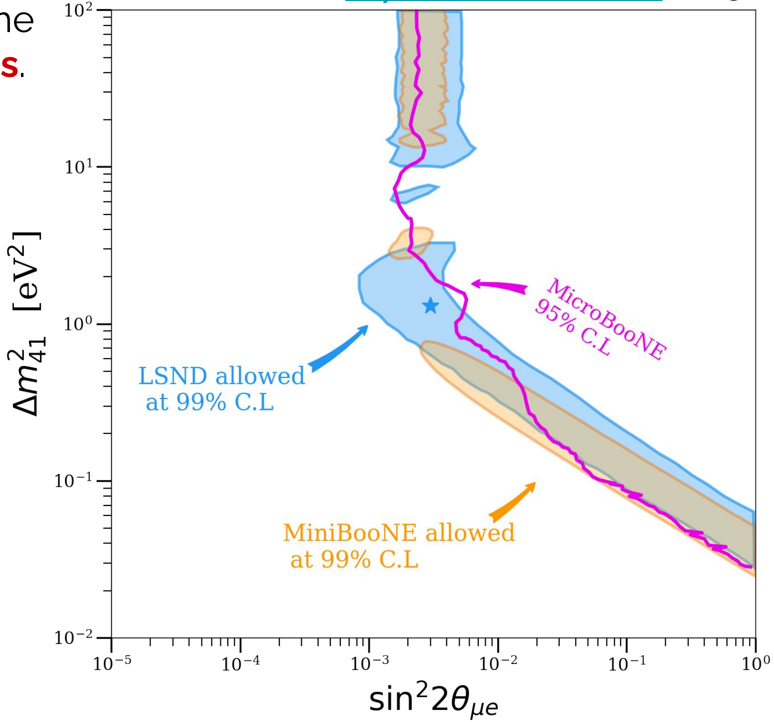
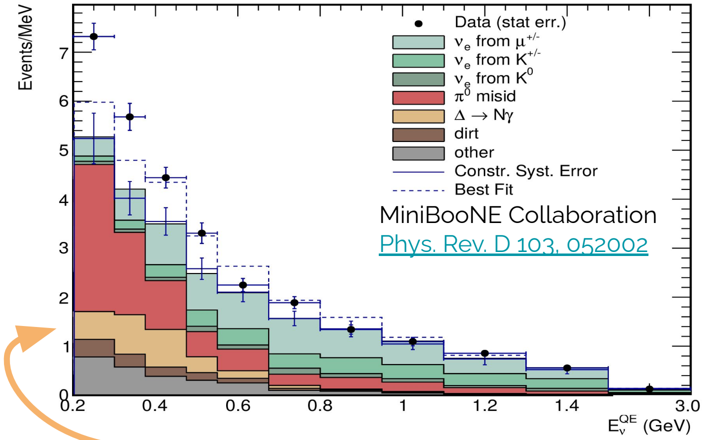
MicroBooNE PhysRevLett.130.011801 (2023)



Reinterpreted as a bound on 3+1 sterile neutrinos, **not yet sufficient to fully rule out MiniBooNE or LSND.** This is due to a degeneracy between $\boldsymbol{\nu}_e$ appearance and $\boldsymbol{\nu}_e$ disappearance

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

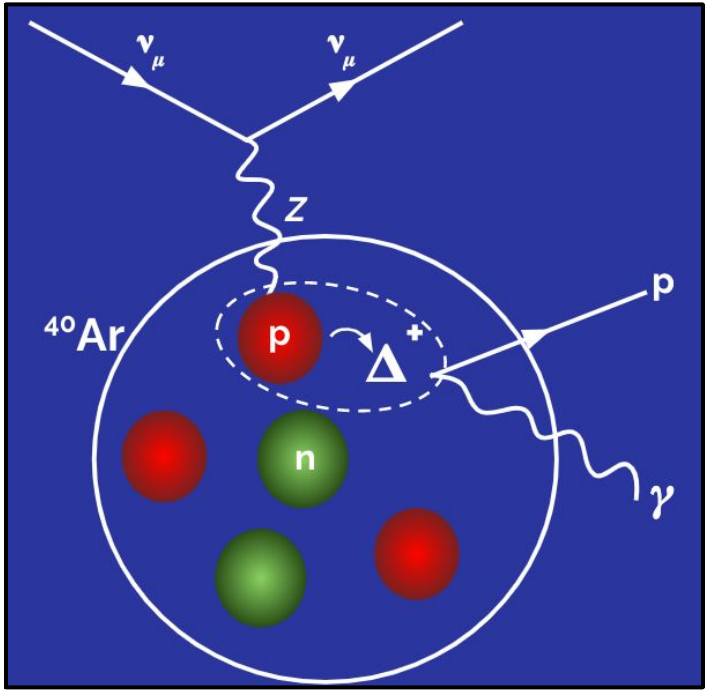
First results focused on the extremely rare and unmeasured standard model process, **neutrino induced neutral current Δ radiative decay (NC $\Delta \to N\gamma$)**



MiniBooNE Collaboration
Phys. Rev. D 103, 052002

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

NC $\Delta \to N\gamma$



MicroBooNE: PhysRevLett.128.111801

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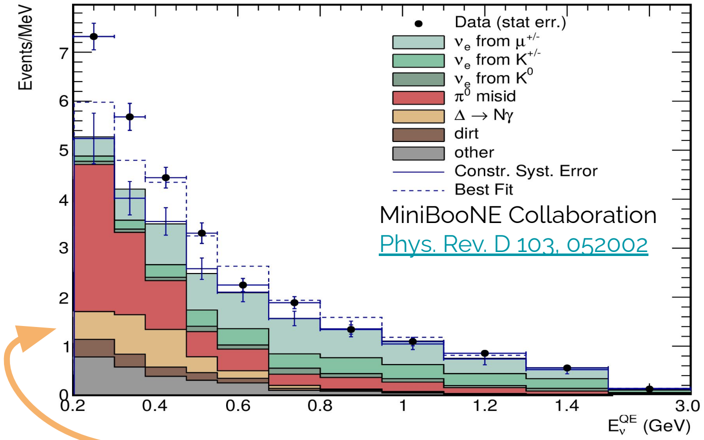
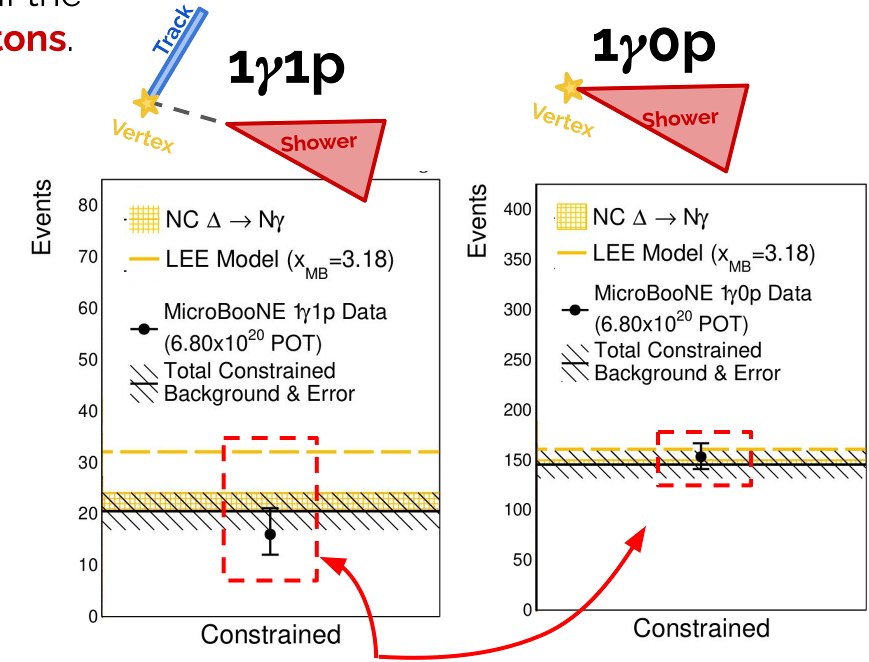
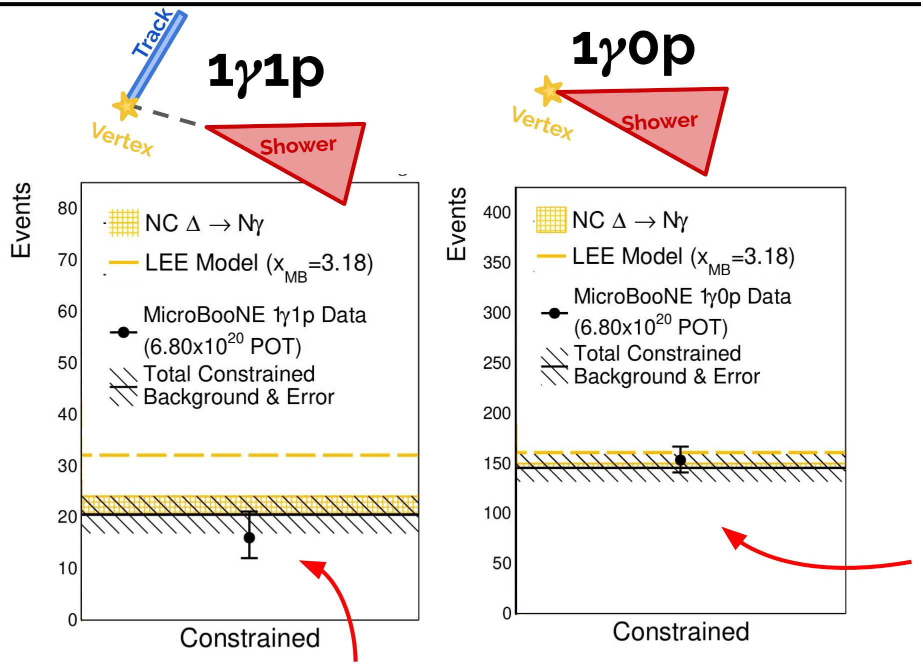


Only needs to be **~3.18 times higher than predicted** in order to **explain the MiniBooNE anomaly**



No excess of photons was observed

Disfavors NC Δ→Nγ backgrounds as a sole source of the MiniBooNE excess at **94.8% C.L**



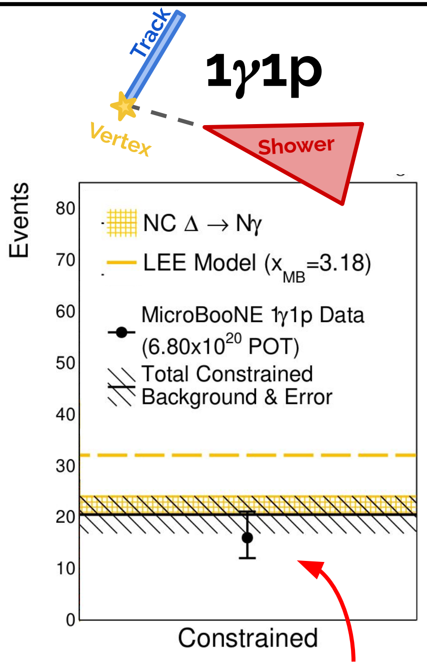
MicroBooNE's search was a **model specific NC Δ→Nγ search**

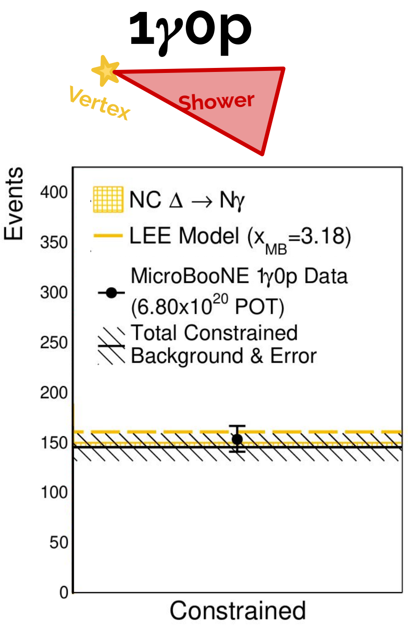
Vast majority of rejection power comes from **1γ1p** sample

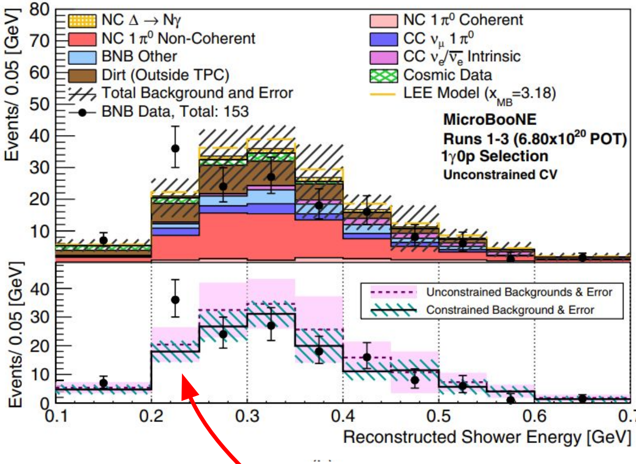
If the excess is photons from another source, with **no associated protons** (coherently produced) then **MicroBooNE's bounds are significantly weaker**

MicroBooNE: PhysRevLett.128.111801

MicroBooNE: Photon Caveats







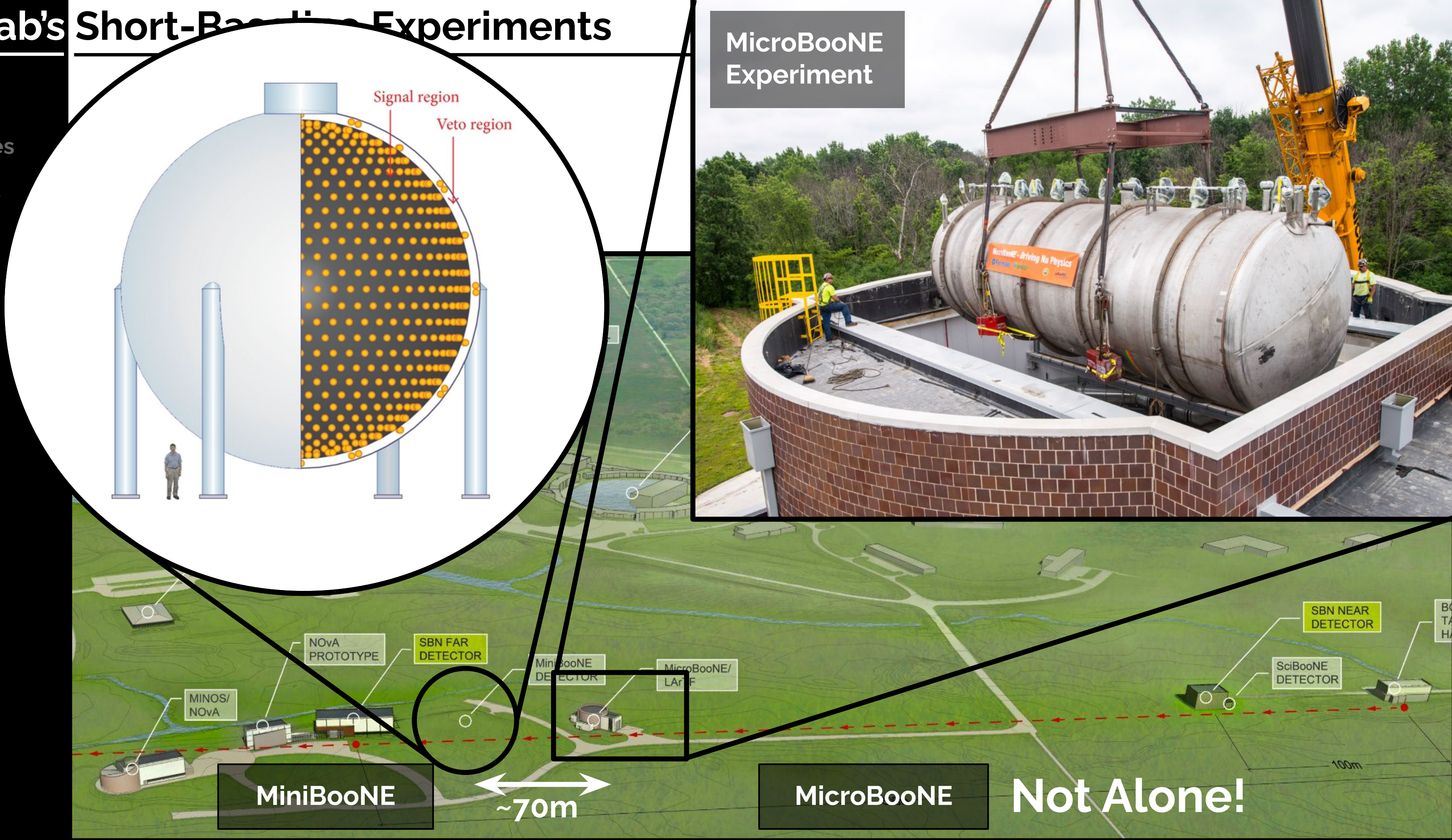
In fact **mild (local 2.7σ) excess** at lower energy in the **1γ0p** selection

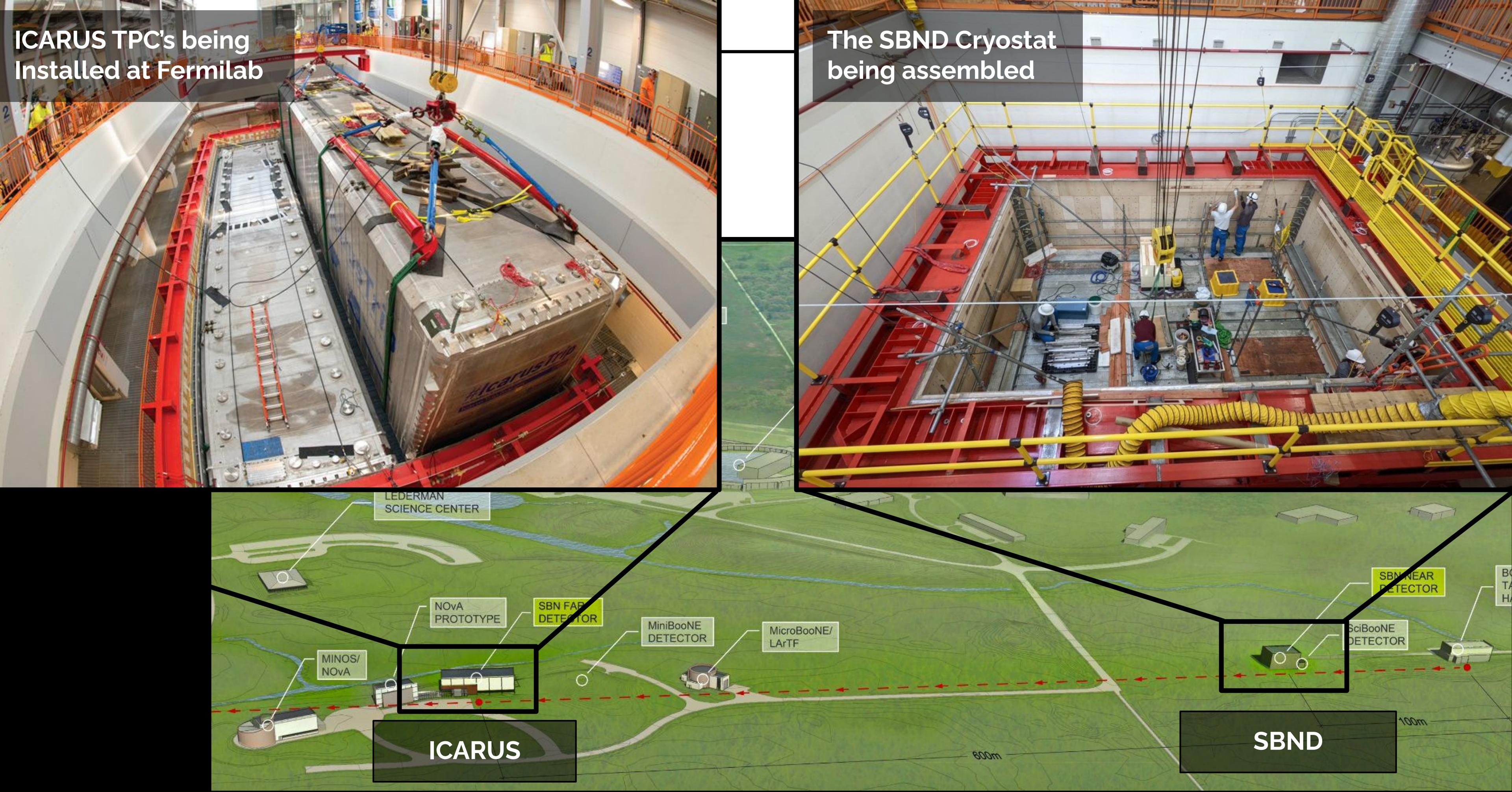
MicroBooNE's search was a **model specific NC Δ→Nγ search**

Vast majority of rejection power comes from **1γ1p** sample

MicroBooNE: PhysRevLett.128.111801

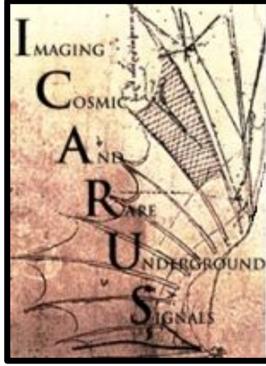
Fermilab's Short-Baseline Experiments

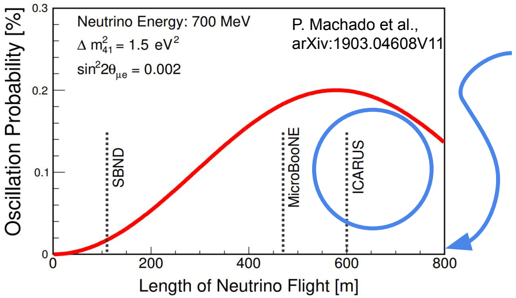



ICARUS TPC's being Installed at Fermilab
The SBND Cryostat being assembled
LEDERMAN SCIENCE CENTER
NOvA PROTOTYPE
MINOS/ NOvA
MiniBooNE DETECTOR
MicroBooNE/ LArTF
SciBooNE DETECTOR
ICARUS
SBND
600m
100m

ICARUS : The SBN programs far-detector

ICARUS was the first large scale demonstration of LArTPC technology for neutrino physics, when it ran for 3 years (2010-2013) at Gran Sasso in Italy, using the CERN Neutrino to Gran Sasso (CNGS) beam.

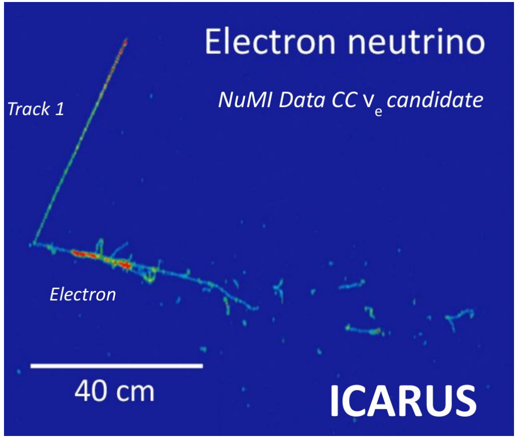




ICARUS sits at **600m** from the BNB target, as the **far-detector of the SBN program**, close to the oscillation maximum for O(1 eV²) sterile neutrinos.

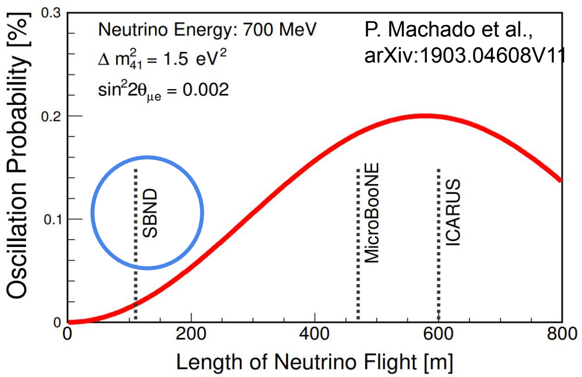
Has an **active volume over five times that of MicroBooNE.** ~Significantly increased exposure!

Full physics data began 9th June 2022!



SBND is a **brand new LArTPC** being constructed at Fermilab.

Located only **110m** from the BNB target, one of the main goals of SBND is to **constrain the un-oscillated flux** for sterile neutrino searches



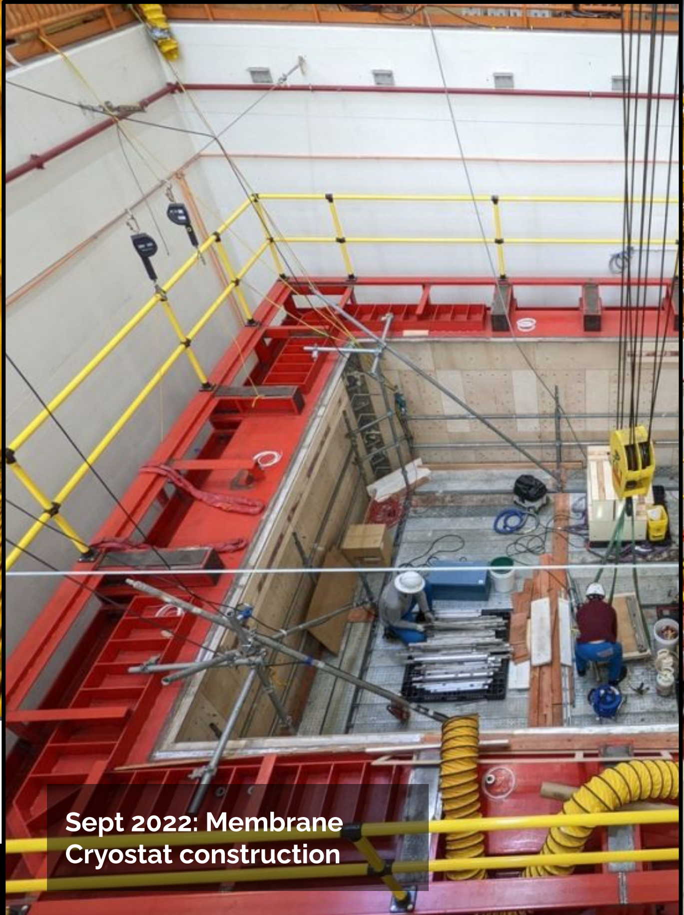
- More than **2 million neutrino interactions** will be collected per year
  - Of which **12,000 intrinsic ν_e interactions** will be recorded
- SBND will collects **more data in 1 month, than MicroBooNE did in 2 years**

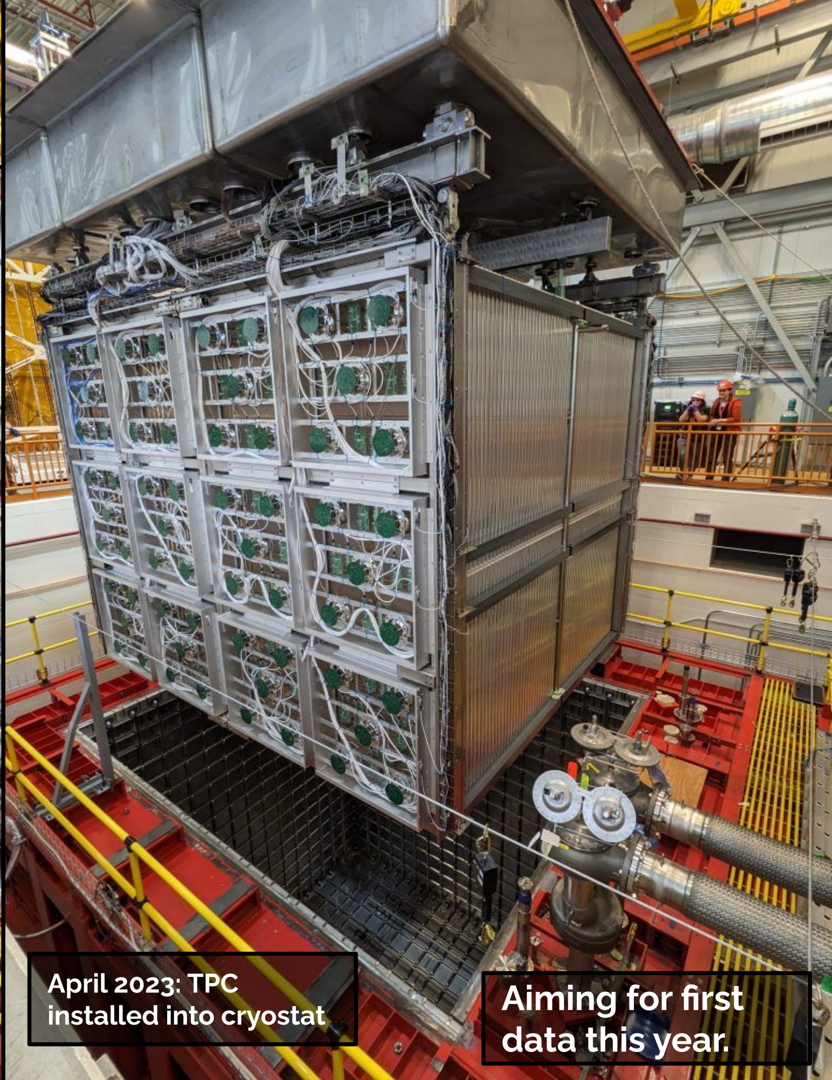
July 2022: TPC
Assembly completed

July 2022: TPC Assembly completed

Sept 2022: Membrane Cryostat construction


July 2022: TPC Assembly completed


Sept 2022: Membrane Cryostat construction


April 2023: TPC installed into cryostat

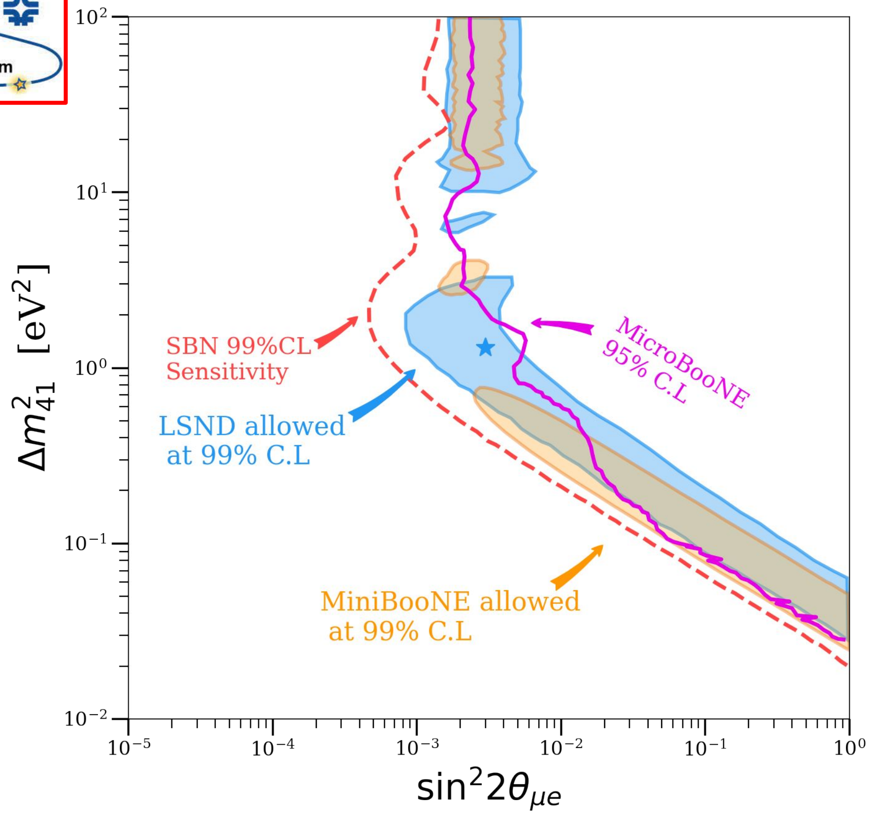
Aiming for first data this year.

Full SBN program performance

μBooNE

SBN Program

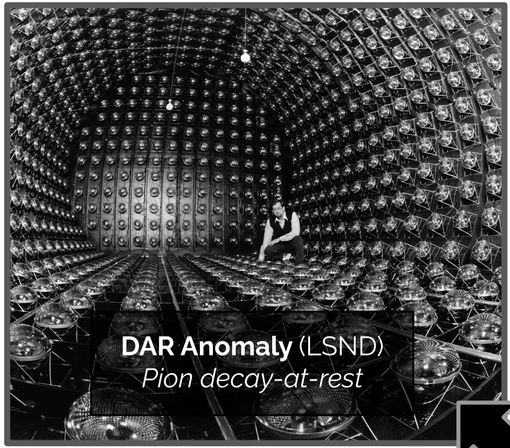
The **full SBN program** will cover the LSND and MiniBooNE allowed regions at **> 3σ**, and the BF points at **> 5σ**

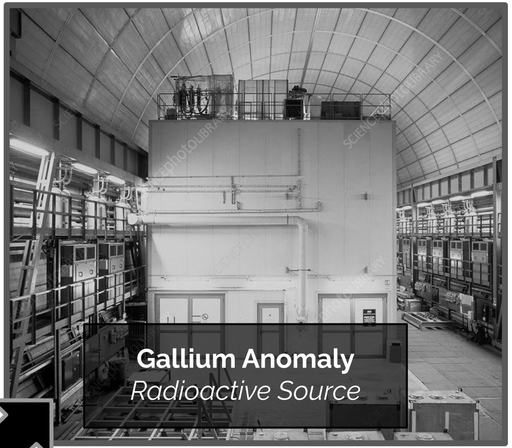


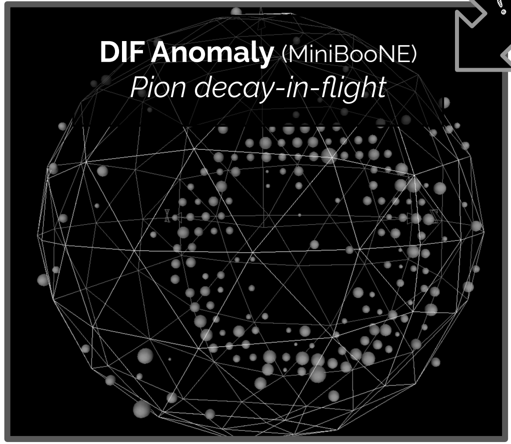
Not just limited to $\nu_\mu \to \nu_e$ appearance searches:

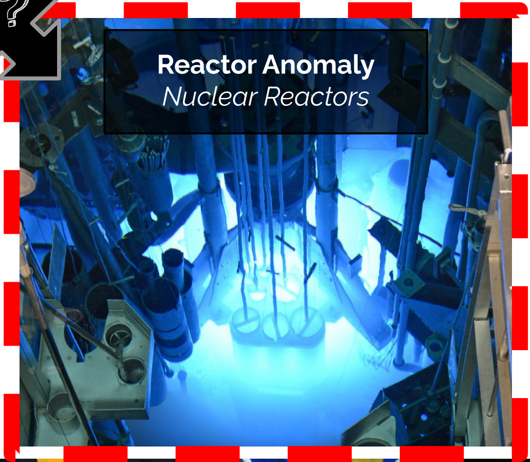
- $\nu_\mu \to \nu_\mu$ disappearance
- $\nu_e \to \nu_e$ disappearance
- Wide range of other dark sector and BSM searches

The Reactor Antineutrino Anomaly (RAA)



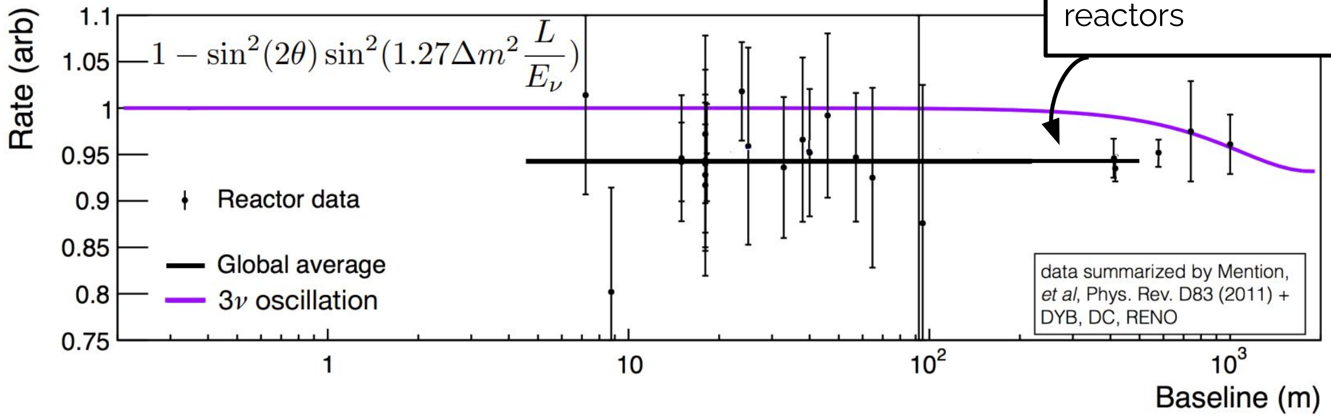






The Reactor Antineutrino Anomaly (RAA)

Apparent **~6% deficit** in neutrinos from all nuclear reactors



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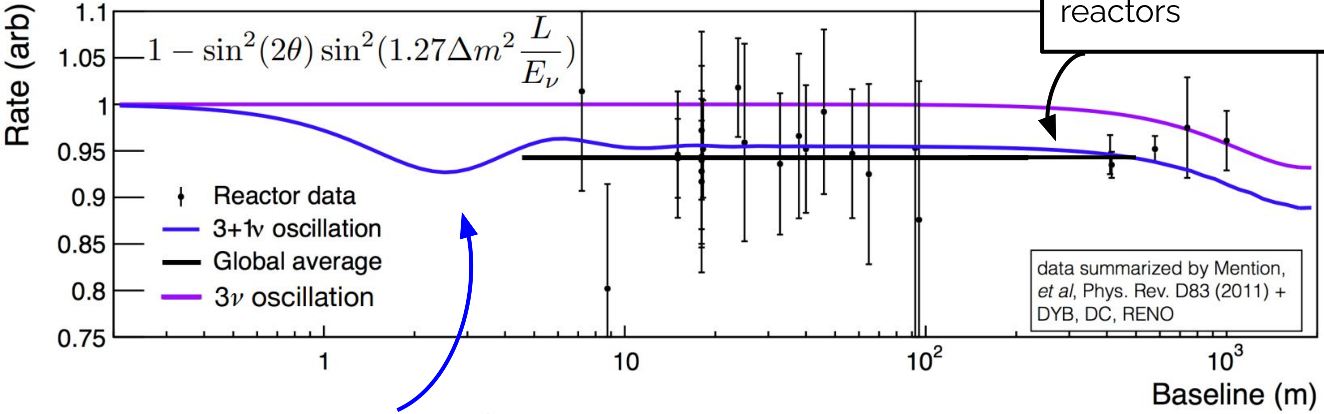

Need to **observe oscillation frequencies directly at baselines < 10m** to definitively test eV-scale sterile neutrinos hypothesis

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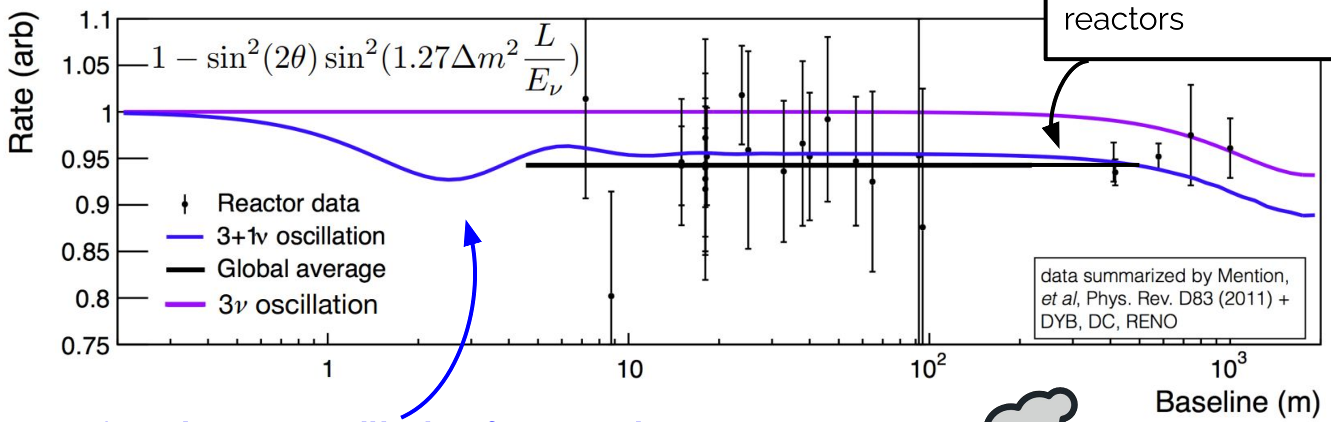
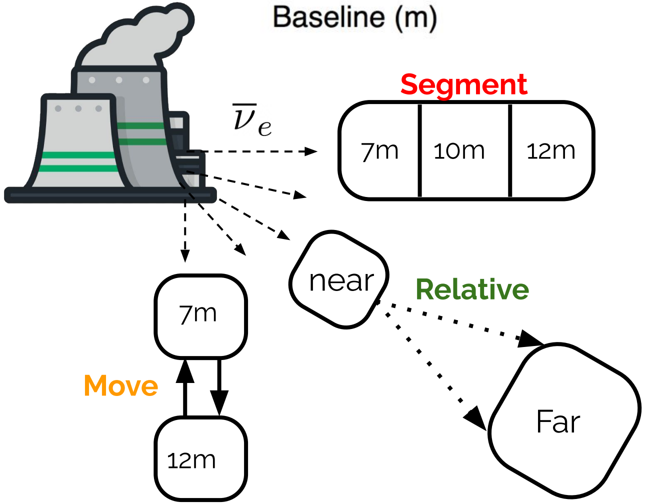


Need to **observe oscillation frequencies directly at baselines < 10m** to definitively test eV-scale sterile neutrinos hypothesis

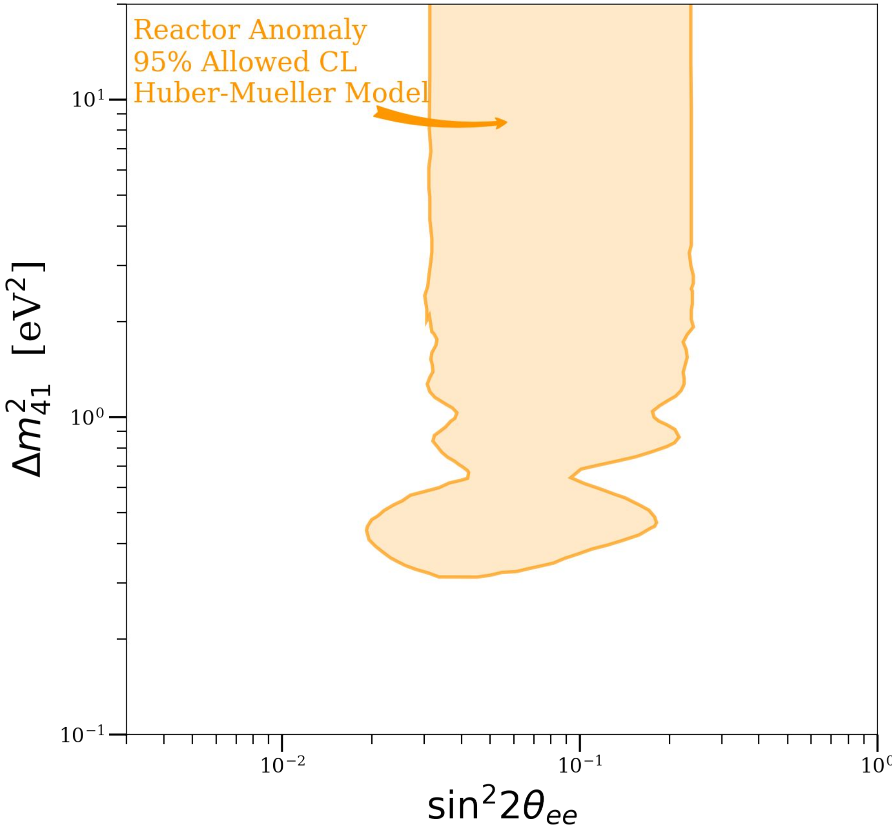
Three strategies in recent years

- **Segment** a single detector to measure $\overline{\nu}_e$ rate at different average baselines
- **Move** the whole detector to various average baselines
- Calculate **relative** to large far detector so absolue flux and reactor modelling isn't important

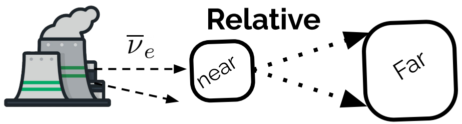


The Reactor Antineutrino Anomaly (RAA)

C.Guinti et al. J.physletb.2022.137054

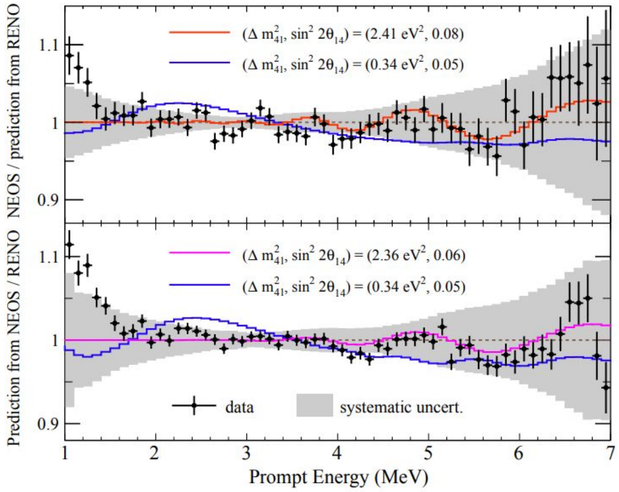


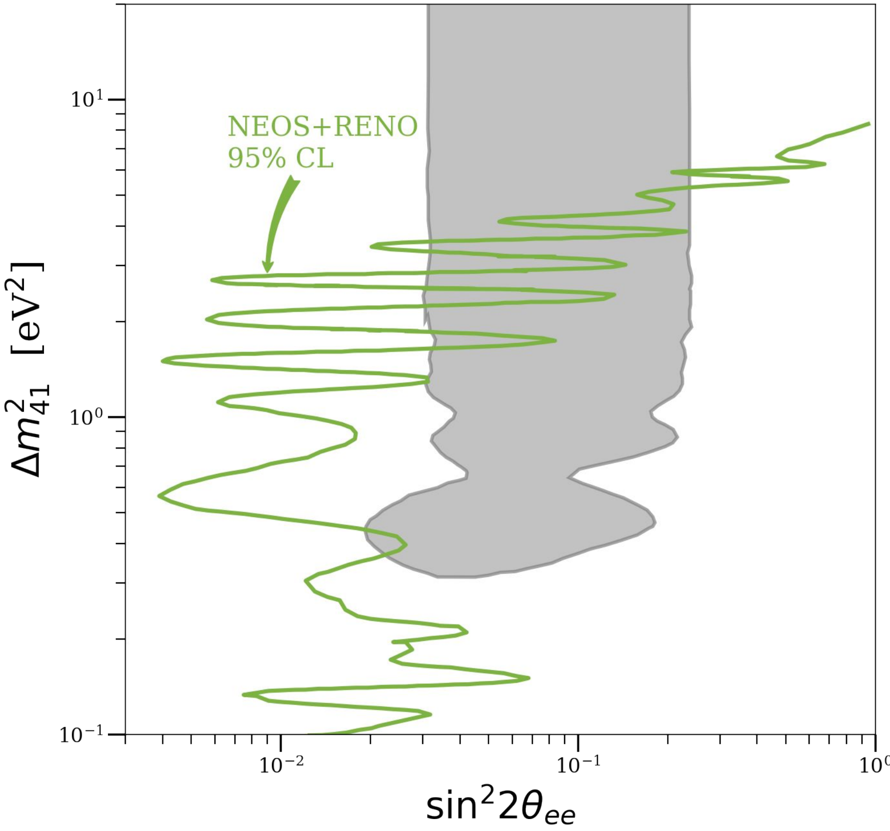
NEOS + RENO Joint Result



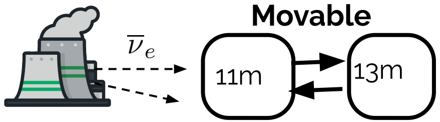
- Commercial reactor, 2800 GW_{th} in South Korea
- Low-Enriched Uranium (LEU)
- ~24m baseline

Uses **relative spectral** fit with far detector RENO to perform reactor model independent sterile neutrino search



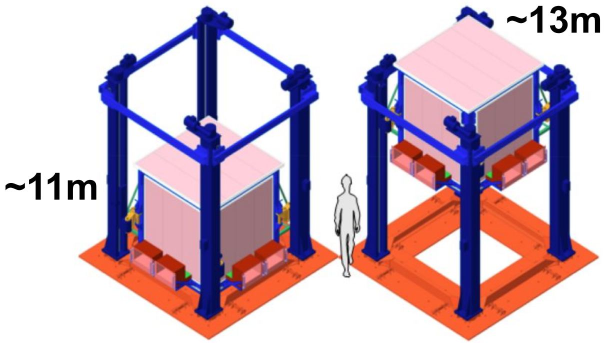


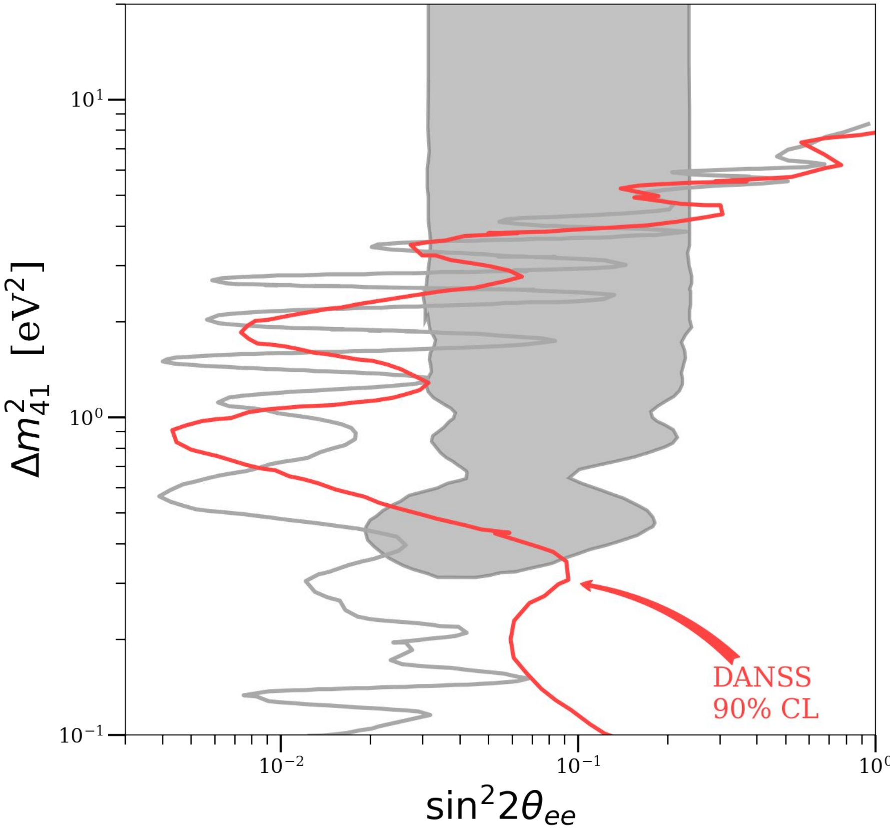
NEOS/RENO: https://doi.org/10.1103/PhysRevD.105.L111101



- Commercial reactor, 3100 GW_{th} in Russia
- Low-Enriched Uranium (LEU)
- **Movable**: 11-13m baseline

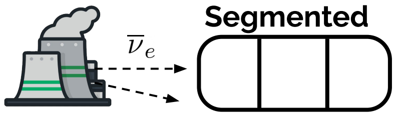
Sits below reactor. Detector position changed frequently, **2-3 times a week**, in order to reduce systematic effects.





DANSS (Preliminary) https://doi.org/10.48550/arXiv.2211.01208

Segmented Detectors: STEREO and PROSPECT



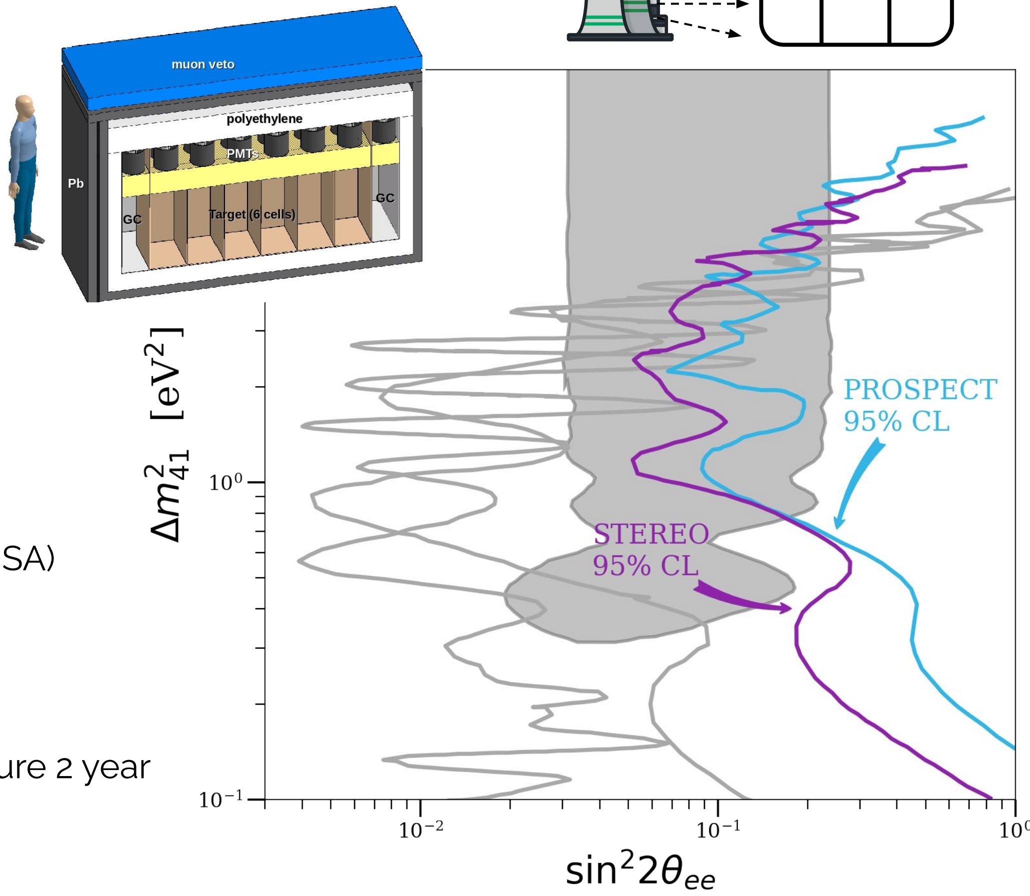
STEREO (ILL, Grenoble, France)

- Research reactor, 58.3 MW_{th}
- Highly-Enriched Uranium (HEU)
- 334 days reactor on data
- **9.4 to 11.1 m Baselines**

STEREO rejects Reactor Anomaly best fit at **> 4σ significance**

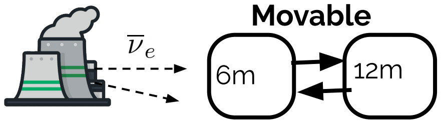
PROSPECT (Oak Ridge National Lab, USA)

- Research reactor, 85 MW_{th}
- Highly-Enriched Uranium (HEU)
- 96 days reactor on data
- **7-9 m Baselines**
  - Planned upgrades and future 2 year run



STEREO *J. Phys.: Conf. Ser.* 2156 012156, PROSPECT https://doi.org/10.1103/PhysRevD.103.032001

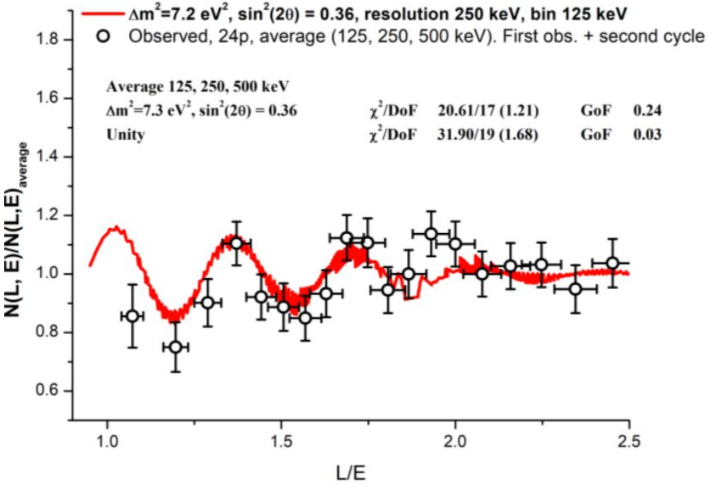
Neutrino-4 : A positive signal?

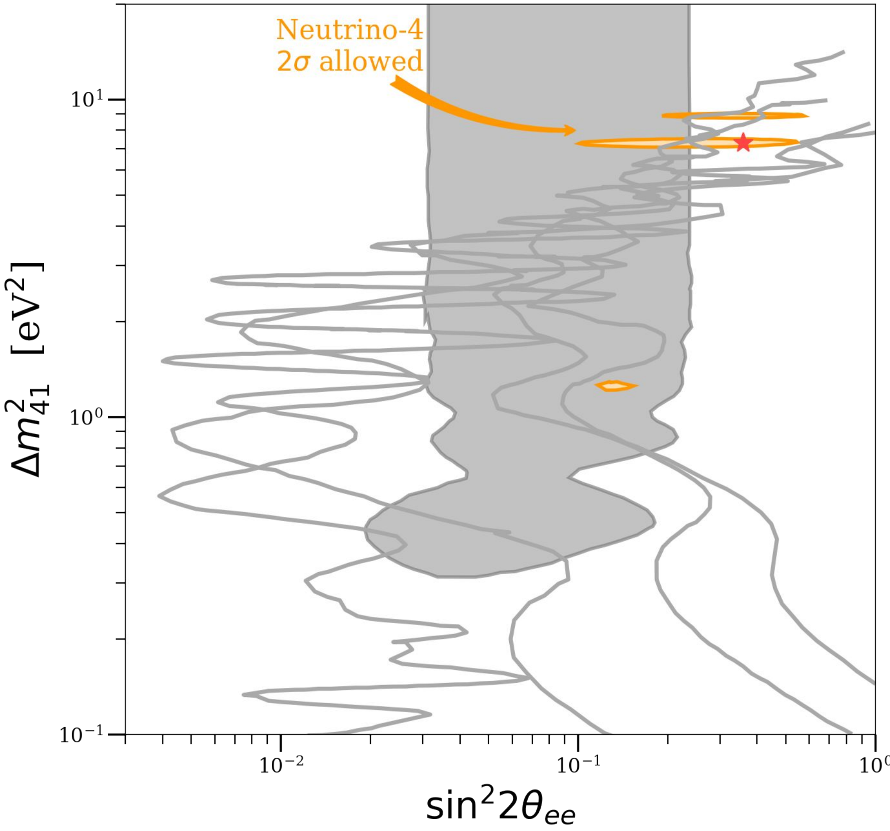


- Commercial reactor, 100 MW_{th} in Russia
- 334 days reactor on data
- 6-12 m Baselines

Slides forward and back relative to reactor

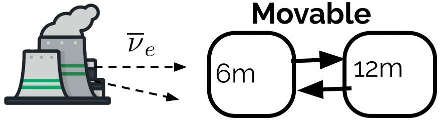
Best-Fit oscillation Δm^2 = 7.3 eV^2, $\sin^2 2\theta$ = 0.36 @ **2.9σ significance**





Neutrino4: PhysRevD.104.032003

: A positive signal?



- Commercial reactor, 100 MW_{th} in Russia
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- 6-12 m Baselines

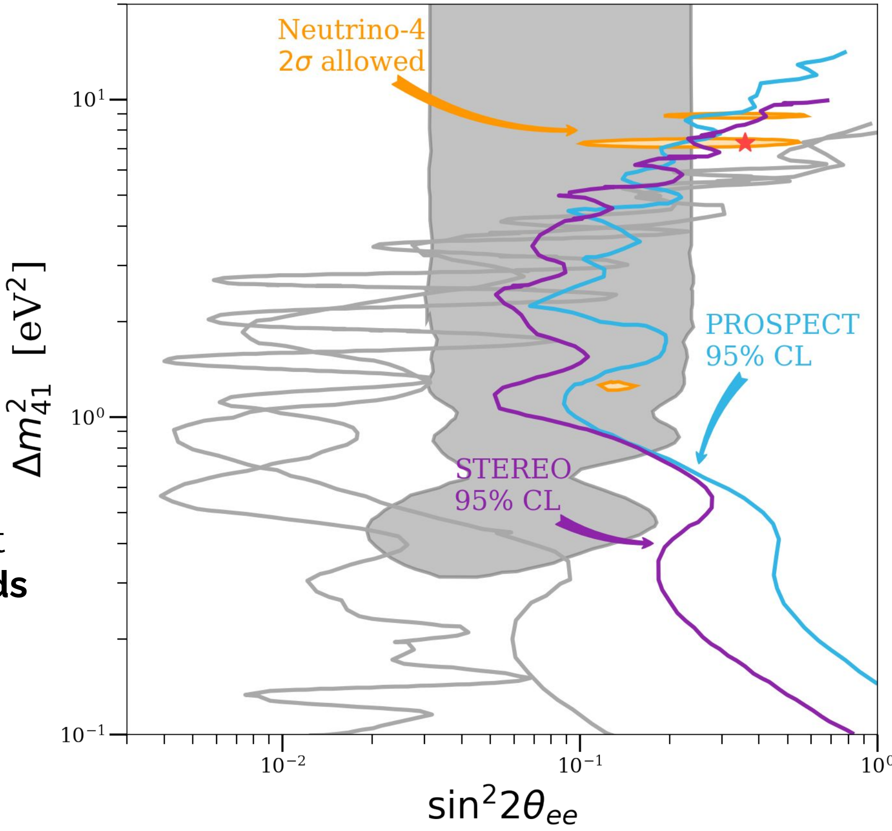
Slides forward and back relative to reactor

Best-Fit oscillation Δm^2 = 7.3 eV², $\sin^2 2\theta$ = 0.36 @ **2.9σ significance**

Note: **STEREO** and **PROSPECT** already both disfavour this best fit point at > 95% CL

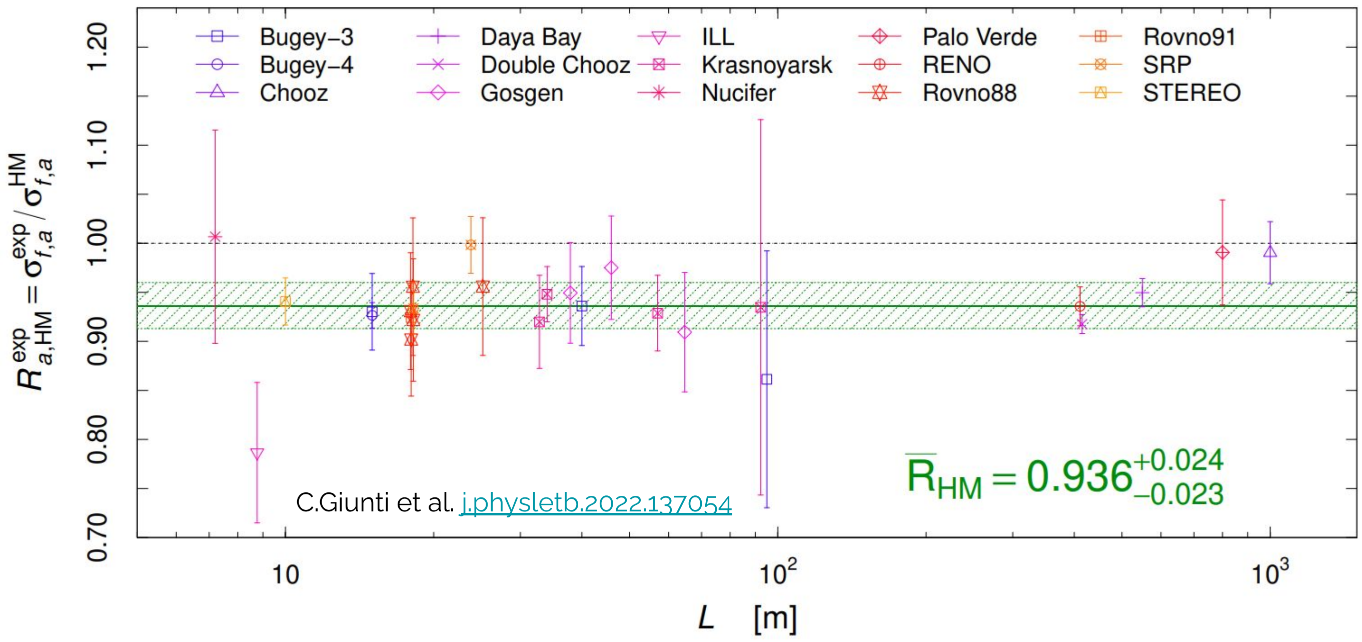
Several questions have been raised by community so far, including the **effects of the statistical approach used,** and impact of **systematics** and **expected backgrounds**

- arXiv:2006.13147
- j.physletb.2021.136214
- JETP Lett 112, 452–454



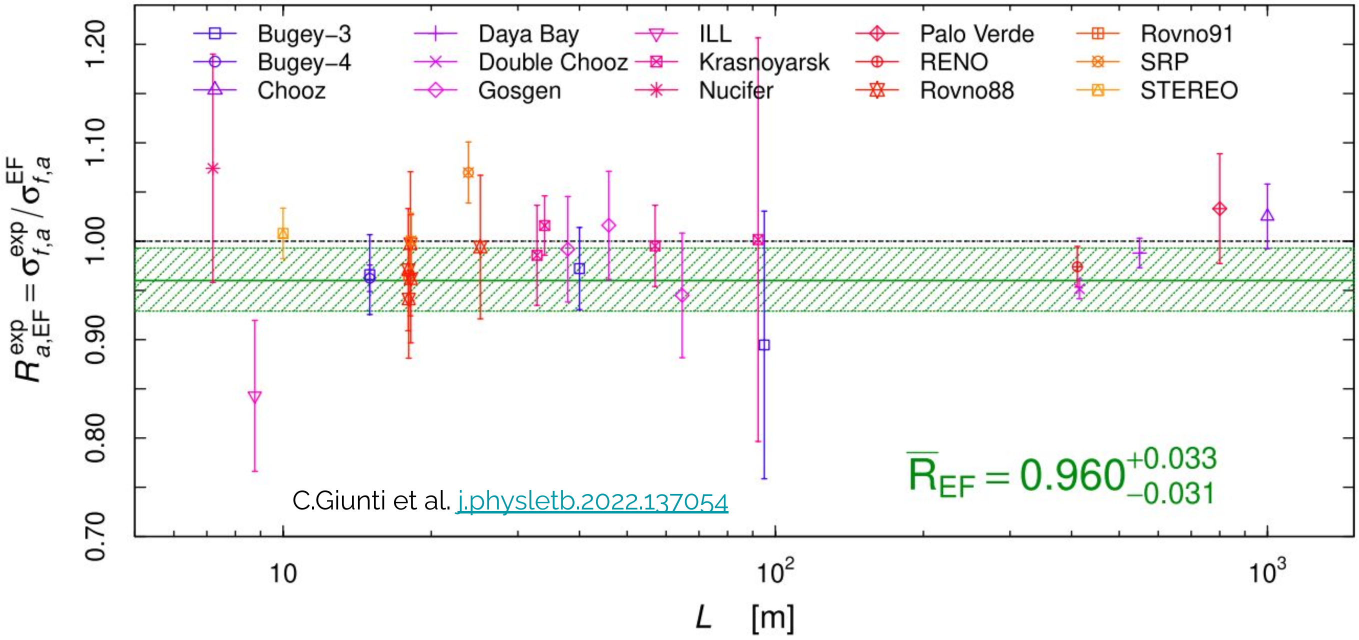
Neutrino4: PhysRevD.104.032003

Another spanner in the works?



Reactor anomaly came to light in 2011 with new reactor flux calculations, Huber-Mueller (HM) Model.

Another spanner in the works?



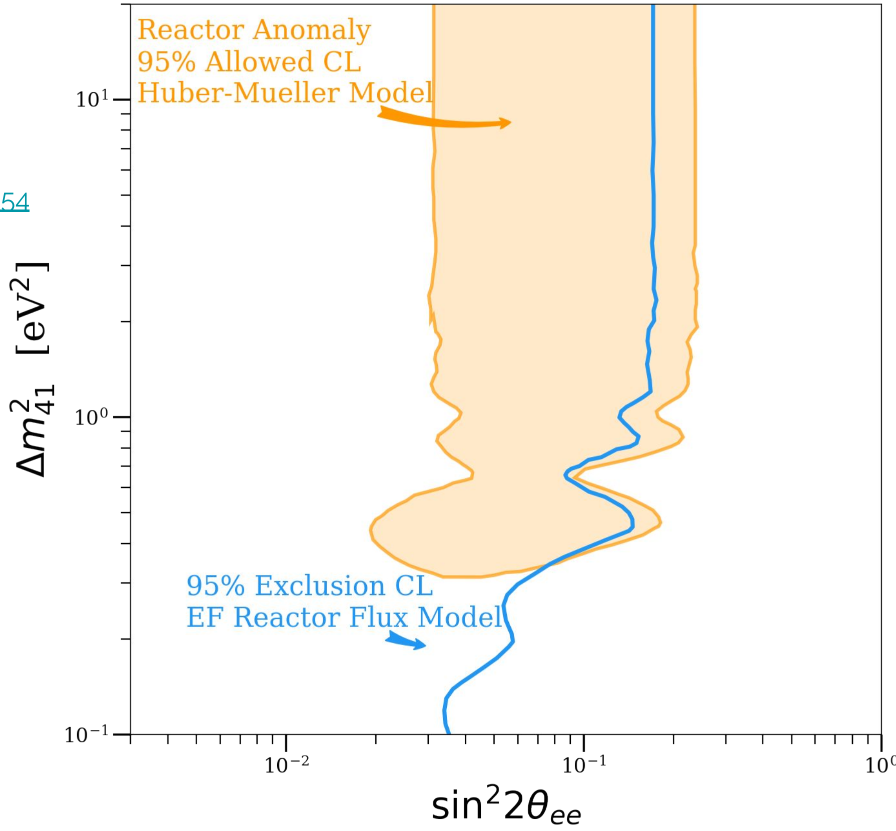
Reactor anomaly came to light in 2011 with new reactor flux calculations, Huber-Mueller (HM) Model.

But last year, several **new reactor flux calculations** (**EF model** 1904.09358) were analyzed reducing the "reactor anomaly" deficit to ~1σ level

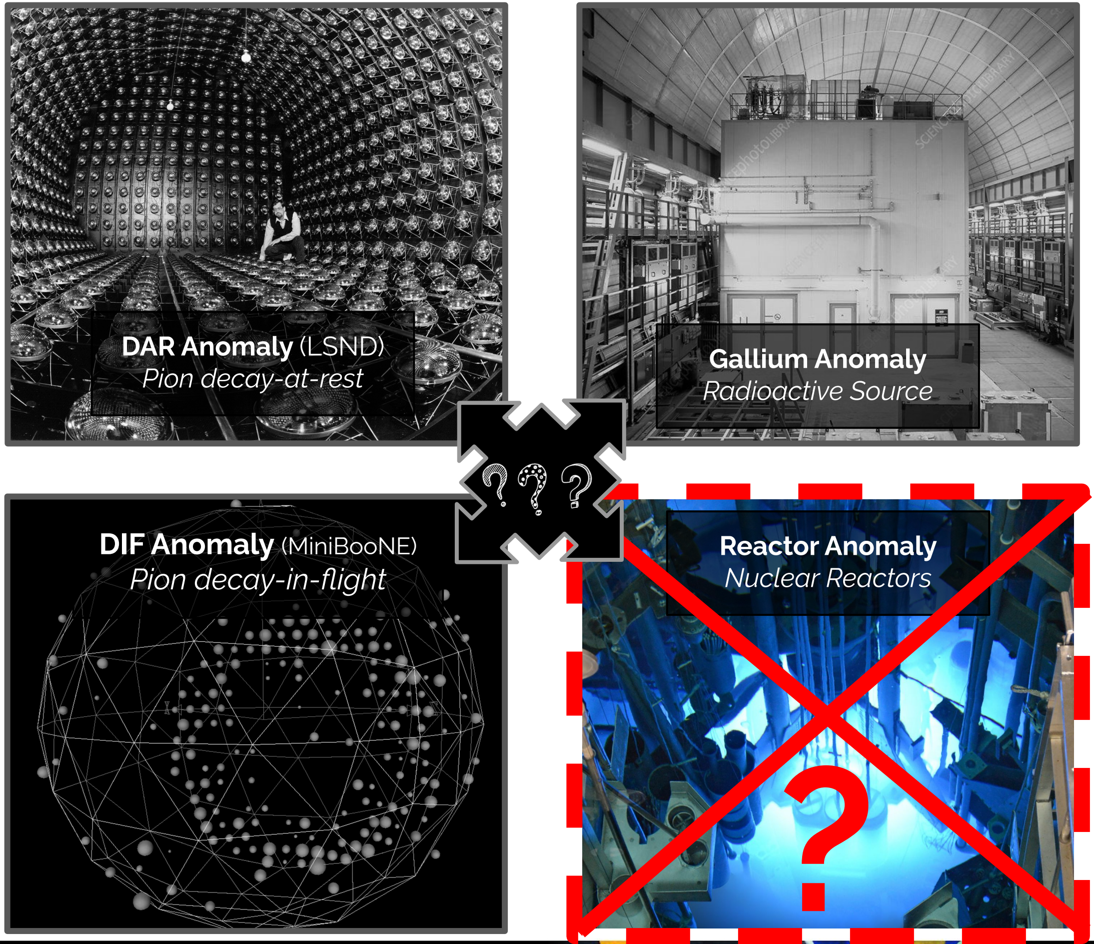
These new reactor fluxes offer

*"a plausible robust **demise of the reactor antineutrino anomaly**"*

C.Giunti et al. j.physletb.2022.137054



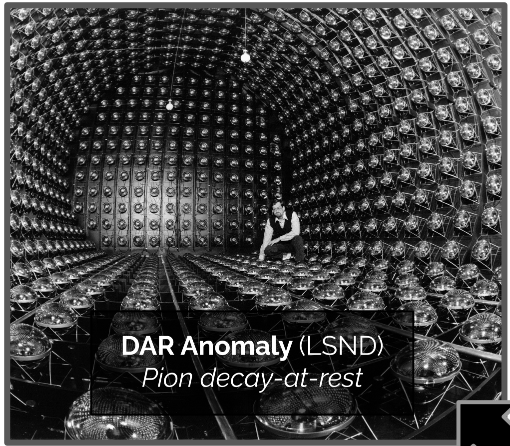
The Reactor Anomaly

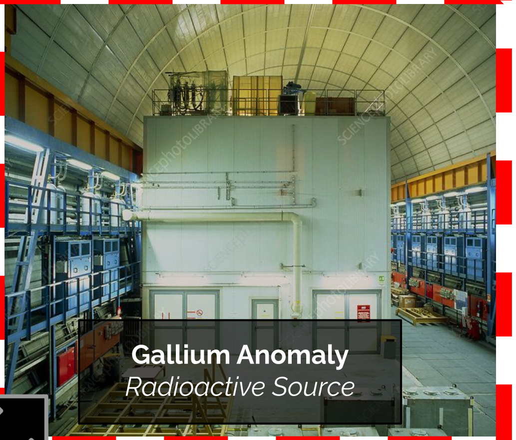


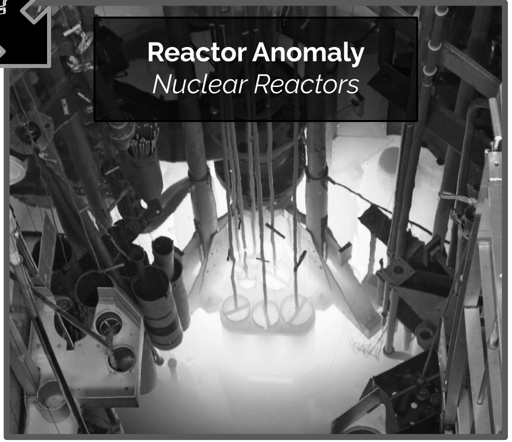
$$\nu_e \to \nu_e$$

$$\overline{\nu}_e \to \overline{\nu}_e$$

The Gallium Radioactive Source Anomaly

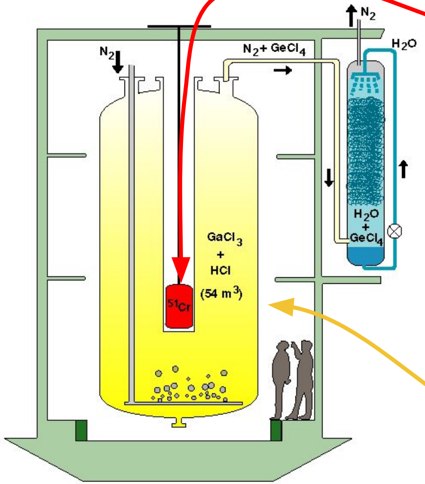






The Gallium Radioactive Source Anomaly

Radioactive ^{51}Cr and ^{37}Ar sources in two experiments SAGE and GALLEX.



GALLEX experiment.

$$e^- + {}^{51}\mathrm{Cr} \to {}^{51}\mathrm{V} + \nu_e$$

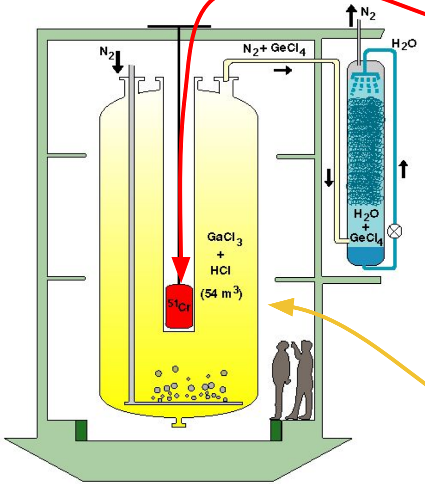
$\boldsymbol{\nu_e}$

$$\nu_e + {}^{71}\mathrm{Ga} \to \boxed{{}^{71}\mathrm{Ge}} + \mathrm{e}^-$$

Extracted and counted

The Gallium Radioactive Source Anomaly

Radioactive ^{51}Cr and ^{37}Ar sources in two experiments SAGE and GALLEX. Observed a **2.6σ deficit of ν_e**



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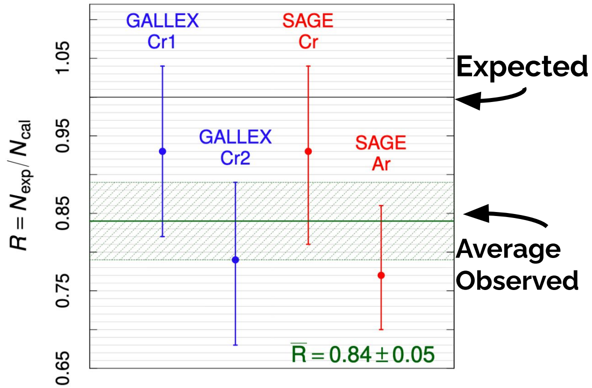
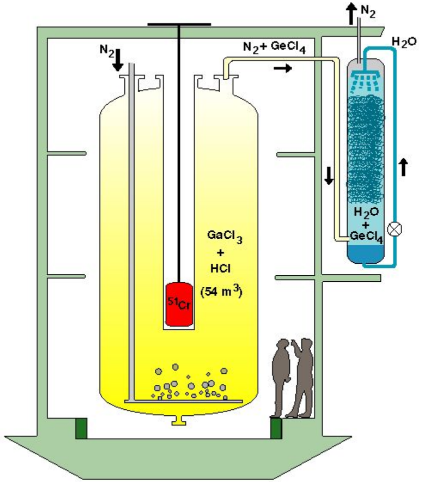


BEST : Baksan Experiment on Sterile Transitions

BEST experiment designed to confirm or disprove the Gallium anomaly PhysRevLett.128.232501 (2022)



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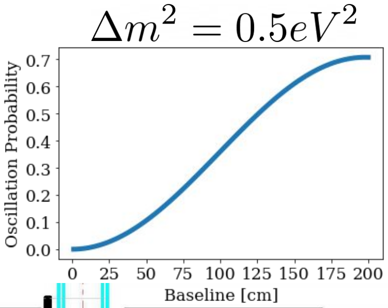
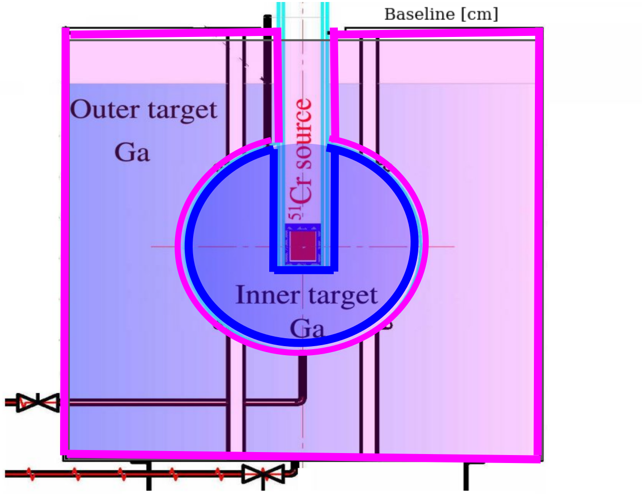
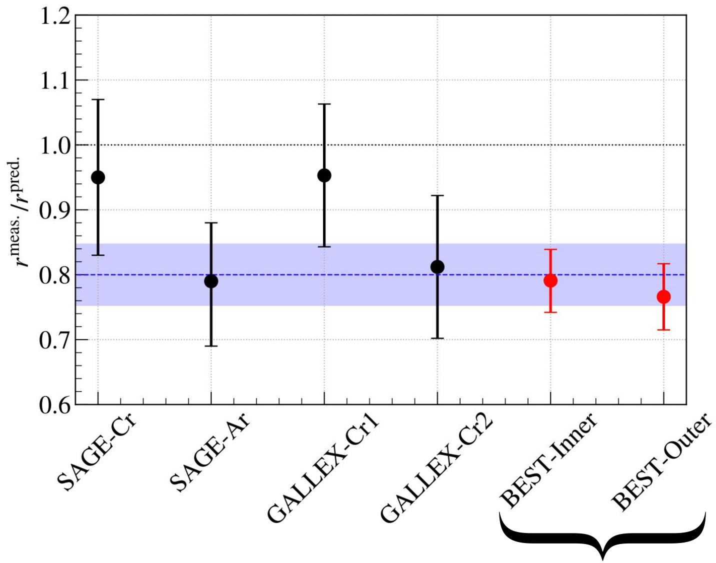


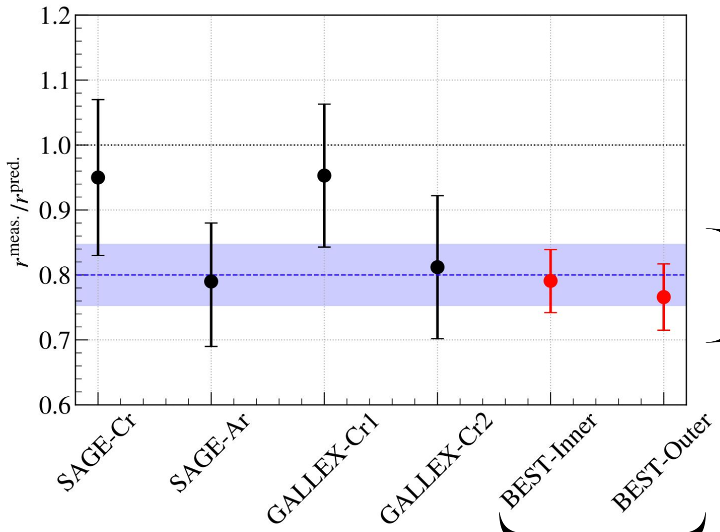


BEST designed as a two-distance oscillation experiment from the start **Inner** and **Outer** volumes



In 2022 BEST confirmed gallium anomaly with significantly lower uncertainty @ **4σ significance**

BEST https://doi.org/10.1103/PhysRevLett.128.232501



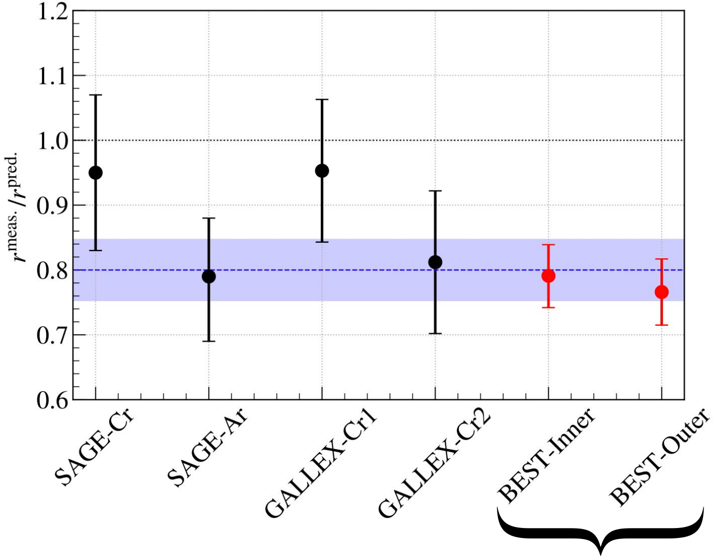
In 2022 BEST confirmed gallium anomaly with significantly lower uncertainty @ **4σ significance**

However, while the anomaly has been confirmed, the same deficit was seen in both inner and outer volume

BEST-Inner	0.791 ± 0.05
BEST-Outer	0.766 ± 0.05

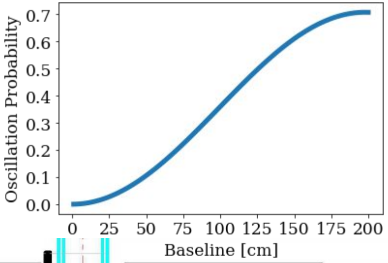
So while it **confirms the anomaly**, it does **not confirm sterile neutrino explanation,** they are merely consistent with BEST results.

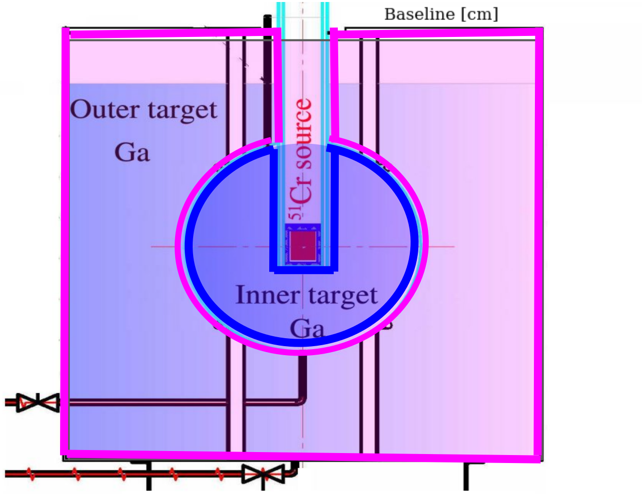
BEST https://doi.org/10.1103/PhysRevLett.128.232501



In 2022 BEST confirmed gallium anomaly with significantly lower uncertainty @ **4σ significance**

$$\Delta m^2 = 0.5 eV^2$$

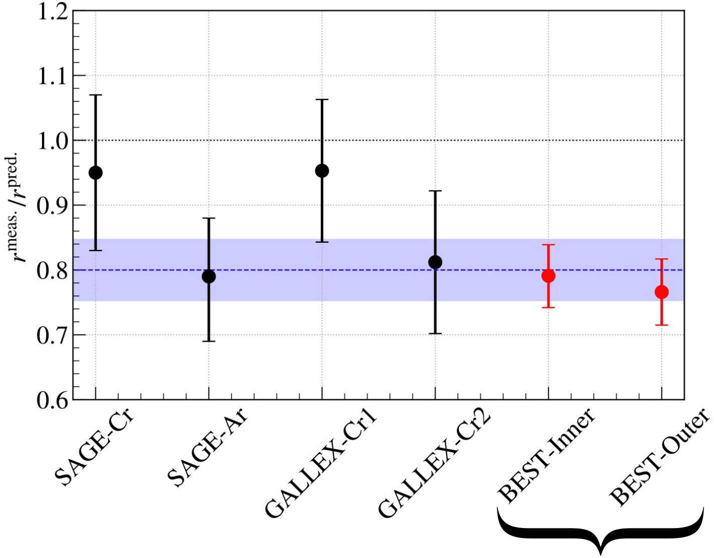




BEST-Inner	0.791 ± 0.05
BEST-Outer	0.766 ± 0.05

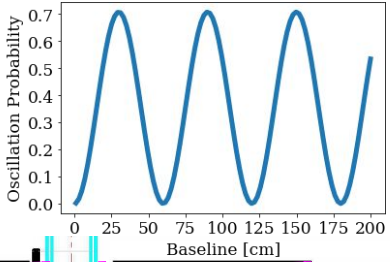
BEST https://doi.org/10.1103/PhysRevLett.128.232501

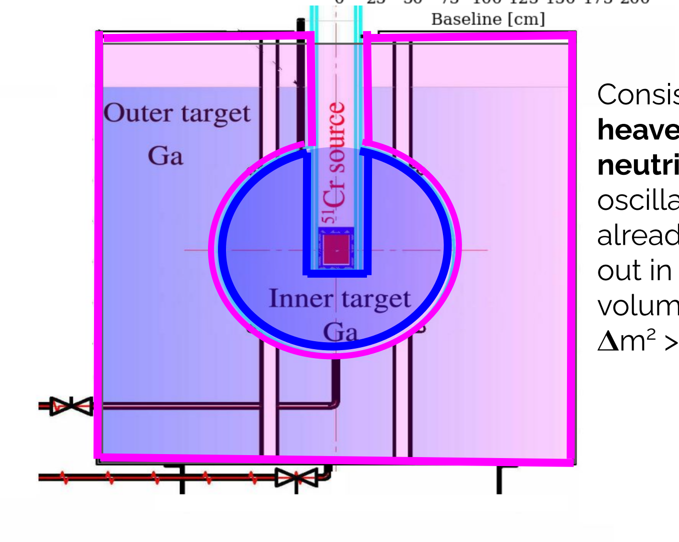
BEST : Results



In 2022 BEST confirmed gallium anomaly with significantly lower uncertainty @ **4σ significance**

$$\Delta m^2 = 3.3eV^2$$





Consistent with **heaver sterile neutrinos** whose oscillations have already averaged out in the inner volume:
$\Delta m^2 > 1$ eV²

BEST-Inner	0.791 ± 0.05
BEST-Outer	0.766 ± 0.05

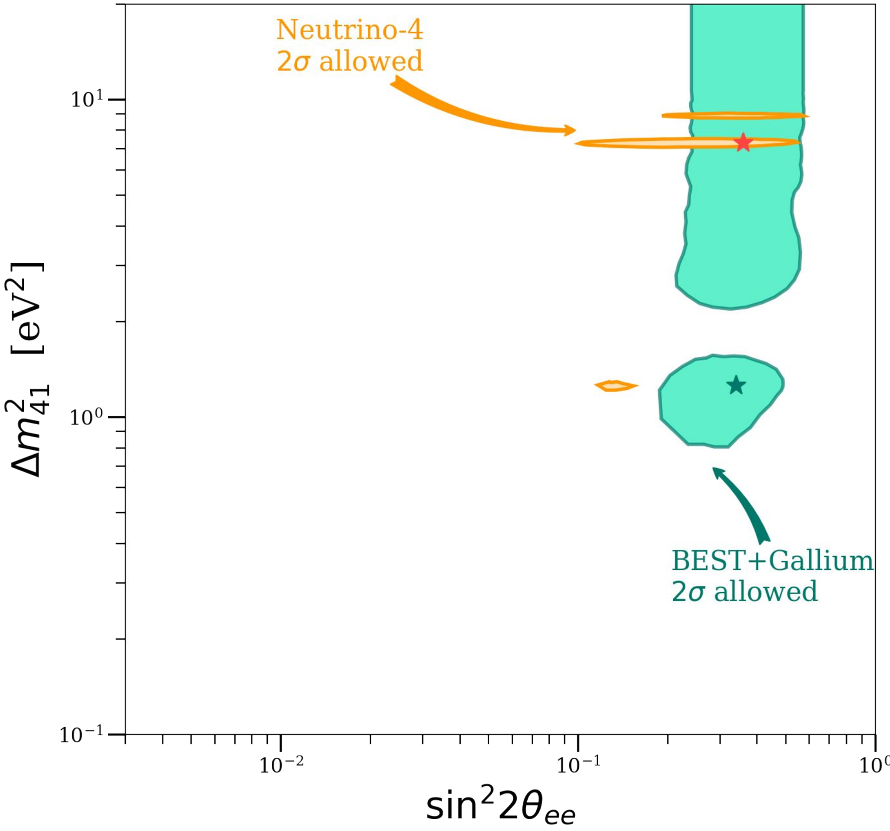
BEST https://doi.org/10.1103/PhysRevLett.128.232501

BEST results in global context

~20% disappearance probability is a **very large** effect.

Needs **very large mixing**, BF of all Gallium experiments;

$$\sin^2 2\theta = 0.34, \qquad \Delta m^2 = 1.25 eV^2$$



BEST results in global context

Introduction

The Anomalies

DAR Anomaly
JSNS²

DIF Anomaly
MicroBooNE
ICARUS
SBND

Reactor Anomaly
NEOS
DANSS
STEREO
PROSPECT
Neutrino4

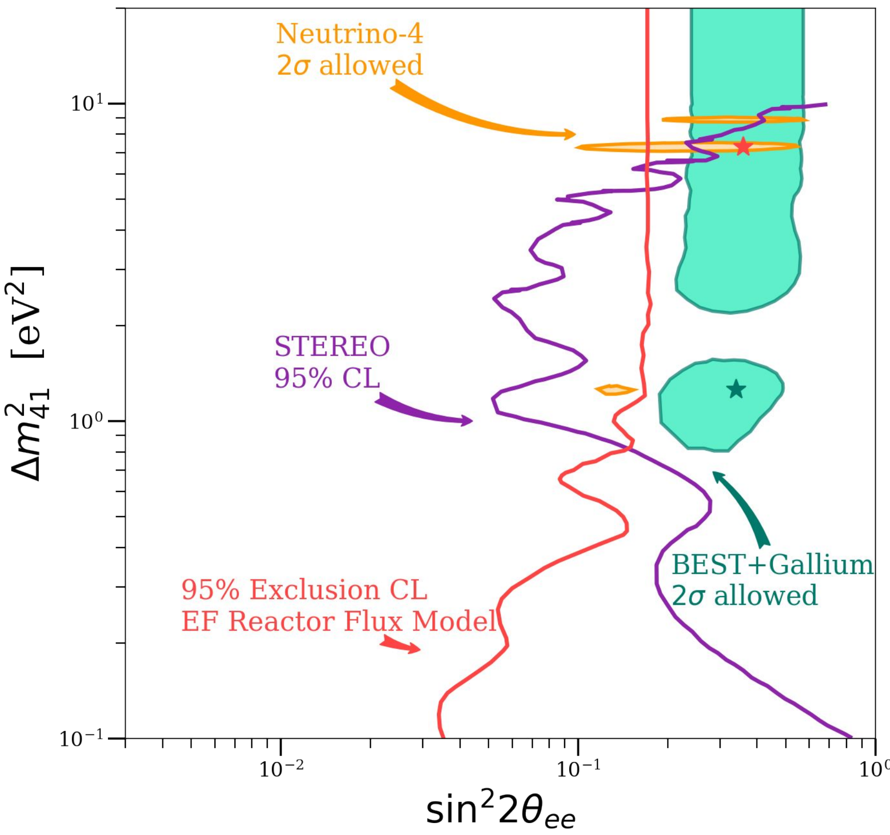
Gallium Anomaly
BEST

~20% disappearance probability is a **very large** effect.

Needs **very large mixing**, BF of all Gallium experiments;

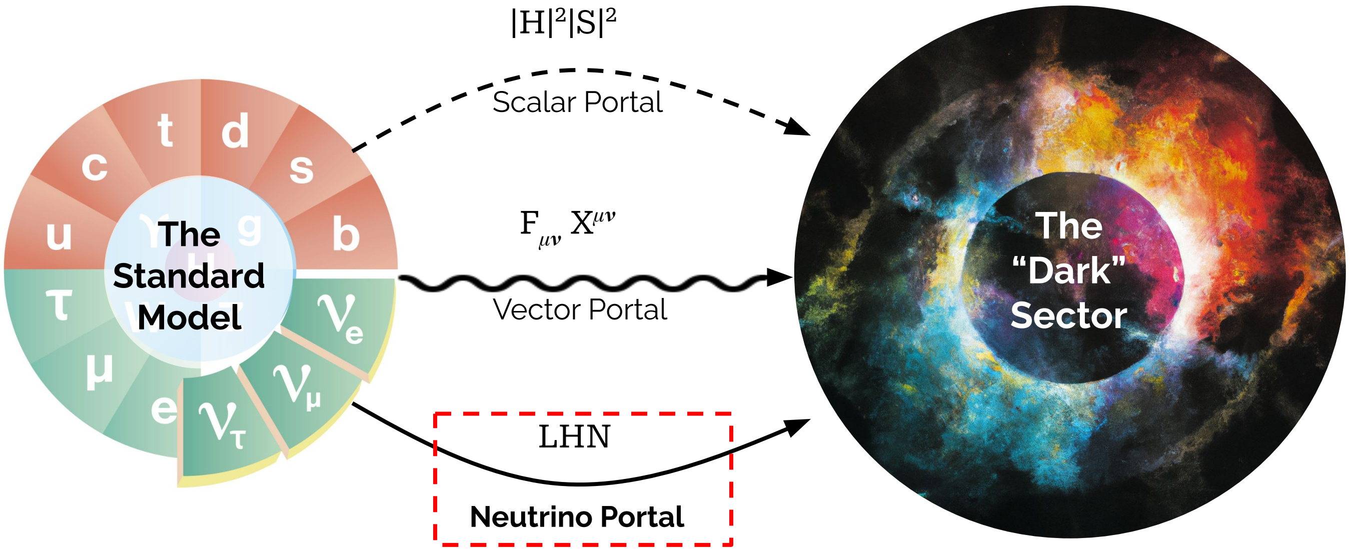
$$\sin^2 2\theta = 0.34, \qquad \Delta m^2 = 1.25eV^2$$

Already **huge tension** exists between BEST and **new reactor flux calculations** and most SBL reactors such as **STEREO**



A Caveat/ Warning "Reminder"

- The **historical context** for all these anomalies is the **"3+1 sterile neutrino"** model
- This simple extension is somewhat **out of fashion** due to tension in global data, and neutrino community is now focusing on more complex models in which neutrinos act as a portal to a phenomenologically complex **"dark sector"**
- Nonetheless, the 3+1 sterile neutrino picture is a powerful tool and allows a **common comparison between experiments**



A world of exciting models: White paper on Sterile Phenomonology arXiv.2203.07323

- Introduction
- The Anomalies
- DAR Anomaly
  - JSNS²
- DIF Anomaly
  - MicroBooNE
  - ICARUS
  - SBND
- Reactor Anomaly
  - NEOS
  - DANSS
  - STEREO
  - PROSPECT
  - Neutrino4
- Gallium Anomaly
  - BEST
- **Conclusions**

Category	Model	Signature	Anomalies: LSND	MiniBooNE	Reactors	Sources	References
Flavor transitions Secs. 3.1.1-3.1.3, 3.1.5	(3+1) oscillations	oscillations	✓	✓	✓	✓	Reviews and global fits [95, 105, 107, 108]
	(3+1) w/ invisible sterile decay	oscillations w/ ν_4 invisible decay	✓	✓	✓	✓	[153, 157]
	(3+1) w/ sterile decay	$\nu_4 \to \phi \nu_e$	✓	✓	✓	✓	[161–164, 272]
Matter effects Secs. 3.1.4, 3.1.7	(3+1) w/ anomalous matter effects	$\nu_\mu \to \nu_e$ via matter effects	✓	✓	✗	✗	[145, 149, 273–275]
	(3+1) w/ quasi-sterile neutrinos	$\nu_\mu \to \nu_e$ w/ resonant ν_s matter effects	✓	✓	✓	✓	[150]
Flavor violation Sec. 3.1.6	Lepton-flavor-violating μ decays	$\mu^+ \to e^+ \nu_\alpha \overline{\nu_e}$	✓	✗	✗	✗	[176, 177, 276]
	neutrino-flavor-changing bremsstrahlung	$\nu_\mu A \to e \phi A$	✓	✓	✗	✗	[277]
Decays in flight Sec. 3.2.3	Transition magnetic mom., heavy ν decay	$N \to \nu\gamma$	✗	✓	✗	✗	[208]
	Dark sector heavy neutrino decay	$N \to \nu(X \to e^+e^-)$ or $N \to \nu(X \to \gamma\gamma)$	✗	✓	✗	✗	[209]
Neutrino Scattering Secs. 3.2.1, 3.2.2	neutrino-induced upscattering	$\nu A \to NA$, $N \to \nu e^+ e^-$ or $N \to \nu\gamma\gamma$	✓	✓	✗	✗	[206, 207, 210–217]
	Transition magnetic mom. or polarizability photons	$\nu A \to NA$, $N \to \nu\gamma$ or $\nu A \to \nu\gamma A$	✓	✓	✗	✗	[40, 187, 189, 190, 192, 194, 221, 235, 278]
Dark Matter Scattering Sec. 3.2.4	dark particle-induced upscattering	γ or e^+e^-	✗	✓	✗	✗	[218]
	dark particle-induced inverse Primakoff	γ	✓	✓	✗	✗	[218]

3+1 oscillations is one of the only models that can explain ALL 4 anomalies

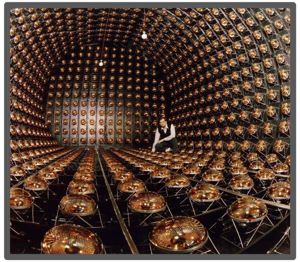
But HUGE tension exists to do so simultaneously

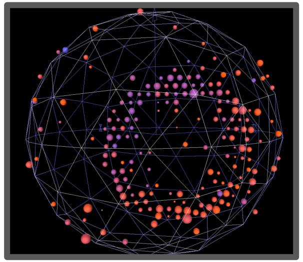
But we **don't need to address simultaneously**, of course can be widely different physics at play.

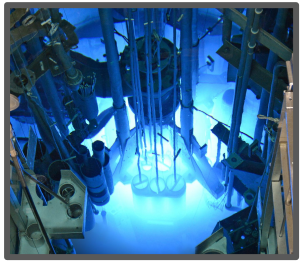
Wide range of new BSM models to potentially solve the anomalies

Status and Prospects

- **DAR Anomaly** (LSND)
  - Large global tension under simple 3+1 hypothesis.
  - JSNS² should begin to weigh in this year (2023)
- **DIF Anomaly** (MiniBooNE)
  - MicroBooNE **disfavours electron** and **1γ1p hypothesis**
  - **1γ0p excess remains one of the last allowed explanations** consistent with both MiniBooNE and MicroBooNE
  - Full SBN due to come online this year and definitively answer (2023 first data)
- ~~**Reactor Anomaly**~~
  - Modern flux calculations can reduce significance to little or nothing.
    - No longer an anomaly?
  - Replace with **"Neutrino-4 Anomaly" ?** Not quite yet!
- **Gallium Anomaly**
  - **Confirmed by BEST**
  - Greater than **5σ combined** with SAGE and GALLEX
  - **Large tension** between BEST and global reactors
    - Very difficult to explain in parallel with LSND/MiniBooNE also

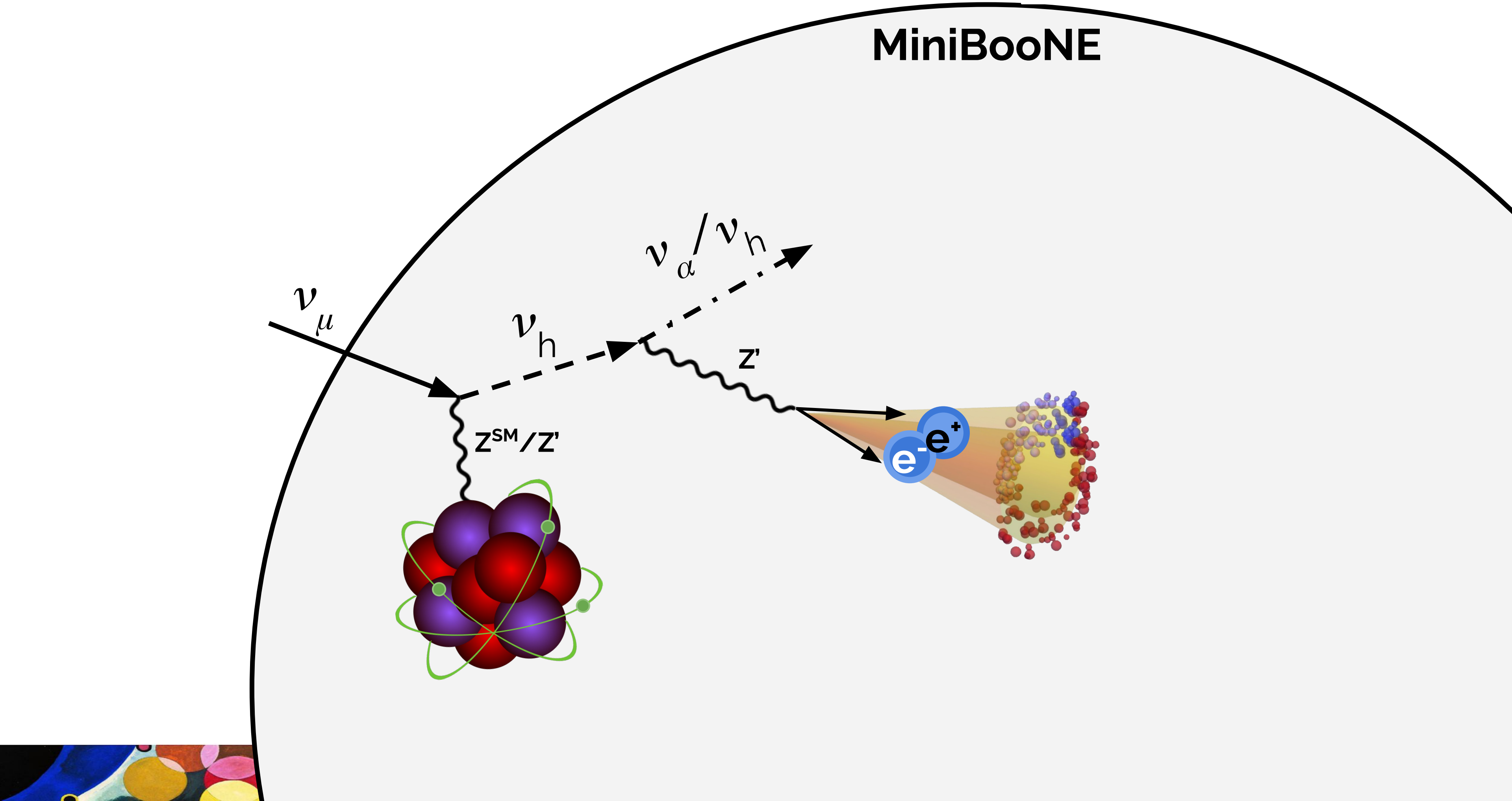


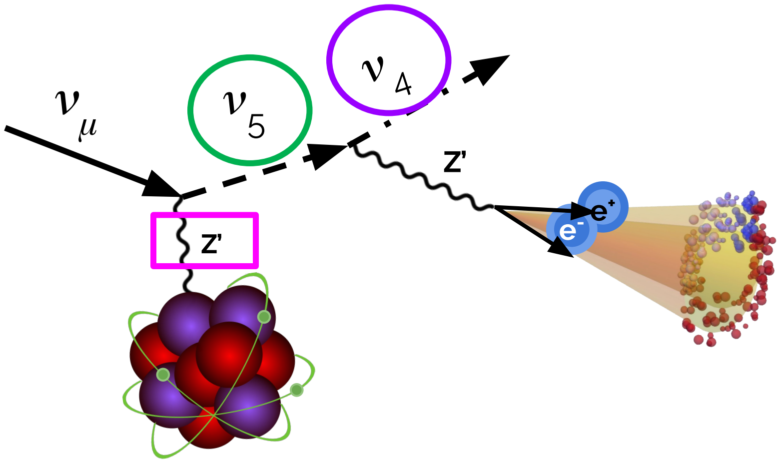




Backup Slides




MiniBooNE
ν_μ
ν_h
ν_α / ν_h
Z'
Z^{SM}/Z'
e^-
e^+



Larger more generic models have arisen which contain at least **2 sterile neutrinos,** allowing for a cascading decay that can achieve larger decay rates while **avoiding issues with larger Uτ4 mixing**

(P. Ballett, M. Hostert, S. Pascoli https://doi.org/10.1103/PhysRevD.101.115025)

Analogous benchmark to "Heavy regime" as mentioned before

$$m_4 = 80\ \text{MeV},\ m_5 = 140\ \text{MeV},$$
$$|U_{\mu 5}|^2 = 4/7 \times |U_{\mu 4}|^2 = 1.5 \times 10^{-6},$$
$$|U_{D4}|^2 = 7/4 \times |U_{D5}|^2 = 7/11,$$
$$g' = 2,\ \chi^2 = 1 \times 10^{-5},\ \text{and}\ \boxed{m_{Z'} = 1.25\ \text{GeV}.}$$

M_4 : Long decay length O(30km) ~stable

M_5 : Prompt decay < 1m. Produce MiniBooNE signal

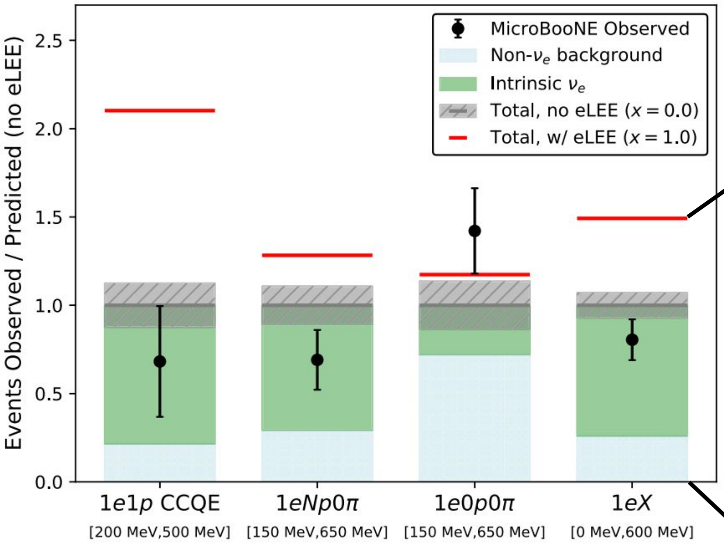
JSNS^2 vs. LSND

Slides from JungsicPark

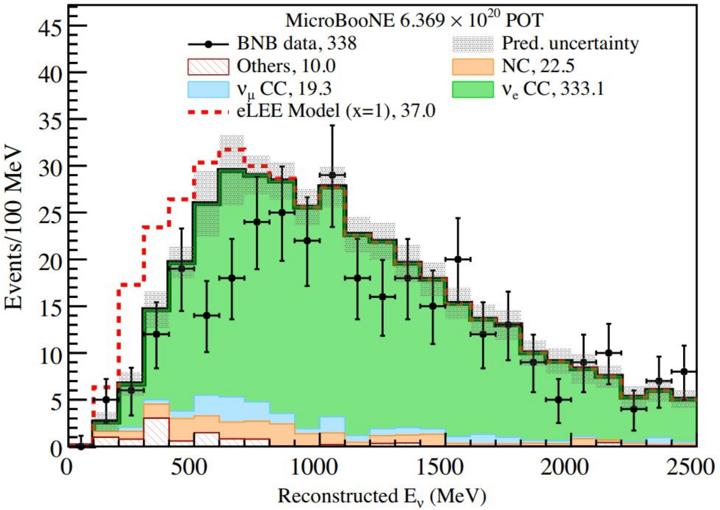
	LSND	JSNS^2	Advantage of JSNS^2
Detector Mass	167 Tons	17 Tons	
Baseline	30 m	24 m	
Beam Kinetic Energy	0.8 GeV	3.0 GeV	**Allows for KDAR measurement / 10 times higher pion production**
Beam Power	0.8 MW	1.0 MW (designed)	**More intense beam**
Beam Pulse	600 us, 120 Hz	100 ns (x2), 25 Hz	**300 times less steady-state background for BID**
Capture Nucleus	H (2.2 MeV)	Gd (~8 MeV)	**Shorter capture time, higher signal to ratio**

MicroBooNE's First Low-Energy Excess (Electron) Results

https://doi.org/10.1103/PhysRevLett.128.241801



Inclusive CC ν_e results (1eX)

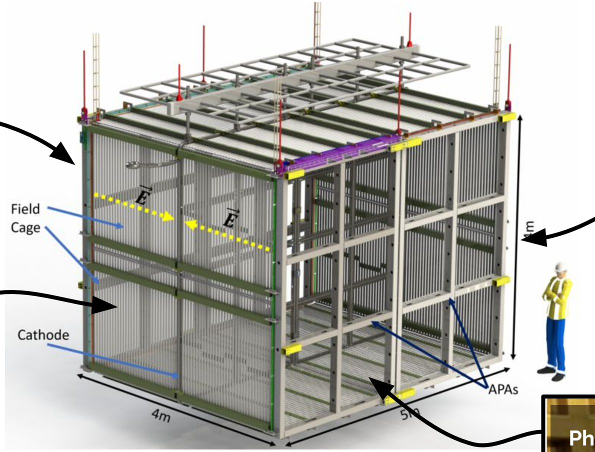


The hypothesis that ν_e events are fully responsible for the median MiniBooNE LEE is **rejected at >3σ** in the **inclusive channel.**

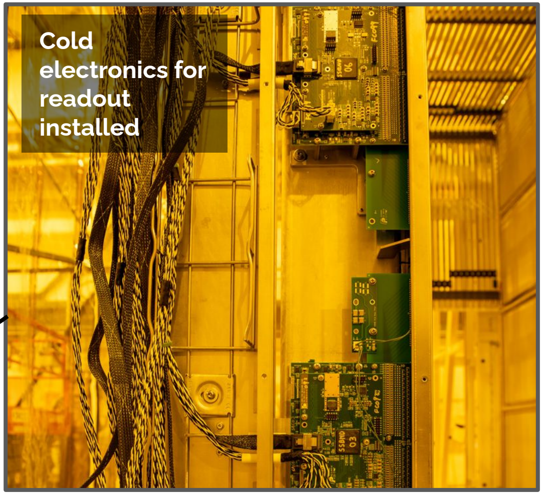
- Observed ν_e rates are statistically consistent with the predicted background rates
- With exception of the low- ν_e-purity (1e0p0π) channel, a mild deficit of intrinsic ν_e is actually observed

TPC Construction

Field cage

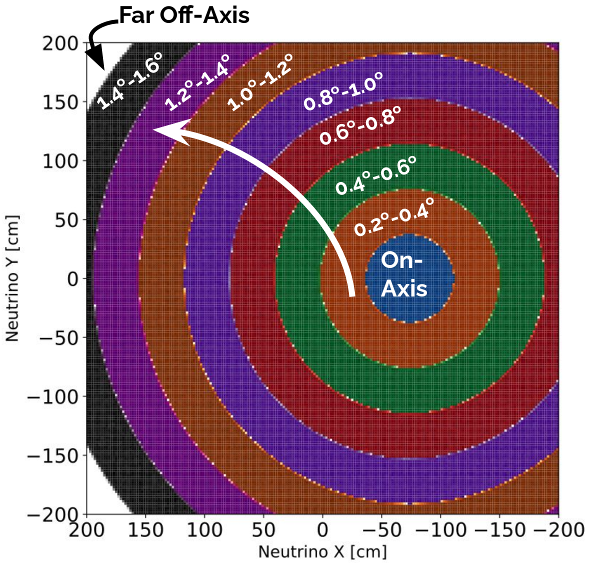


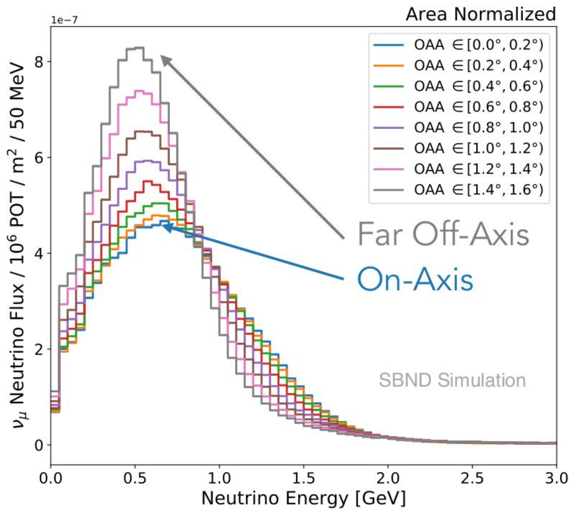
Cathode



SBND-PRISM: Sampling Multiple Off-Axis Fluxes with the Same Detector

As SBND is so close (~110m) to the intense BNB beam, different sections of the detector see different fluxes based on their effective off-axis angle.





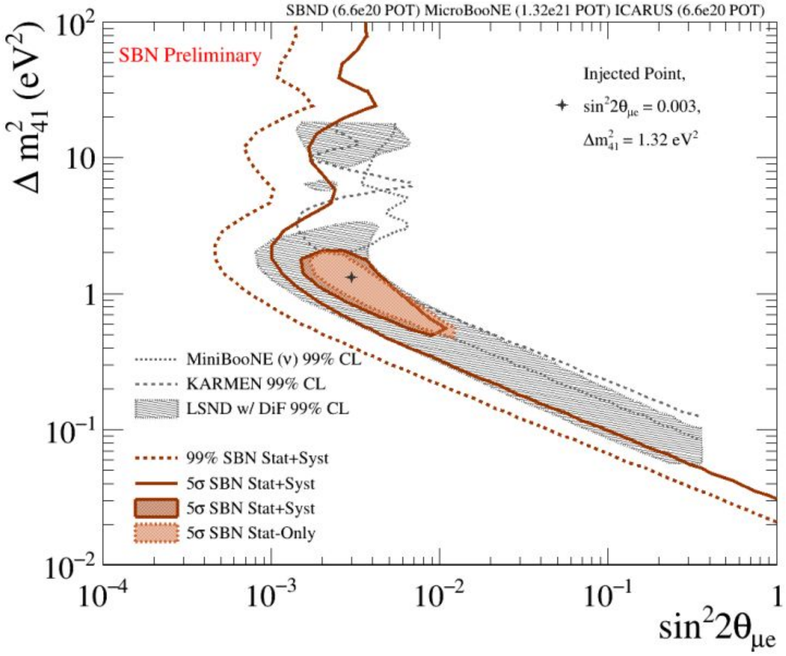
Ongoing studies exploring the physics potential of SBND-PRISM:

- Improve flux & cross-section constraints
- Study Energy Dependance of Cross Section
- Reduced backgrounds for increasing off-axis in BSM searches
- . . . and more!

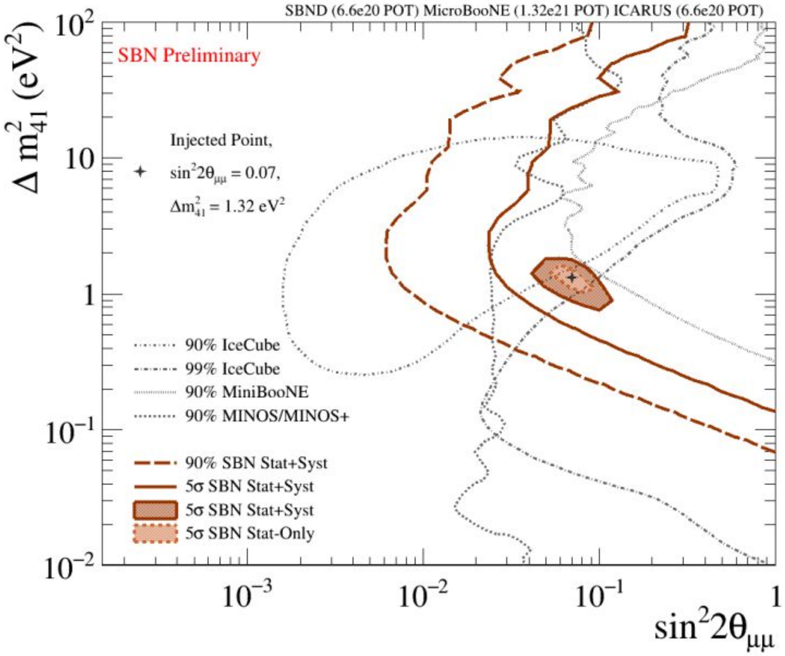
Can select **lower energy**, more **mono-chromatic** beams by **going more off axis**.

Sterile Neutrino Sensitivities

SBN ν_e **appearance only**

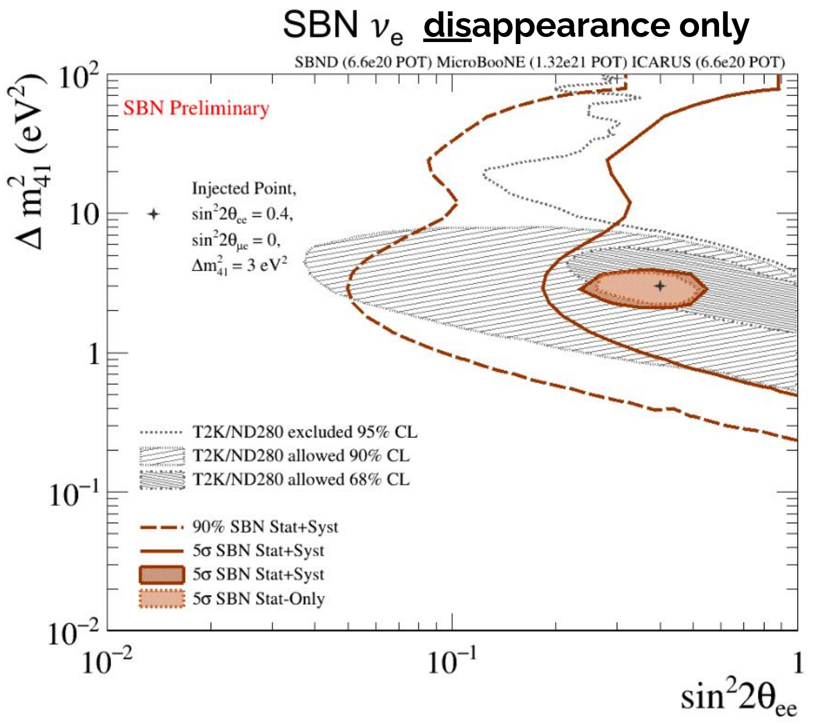


SBN ν_μ **disappearance only**



- SBN sensitivities for 6.6 x 10^{20} protons on the BNB target (MicroBooNE at 13.2e20) as per SBN proposal
- Updated from proposal sensitivities to reflect as-built detector size/position, more realistic systematics, etc..

Sterile Neutrino Sensitivities



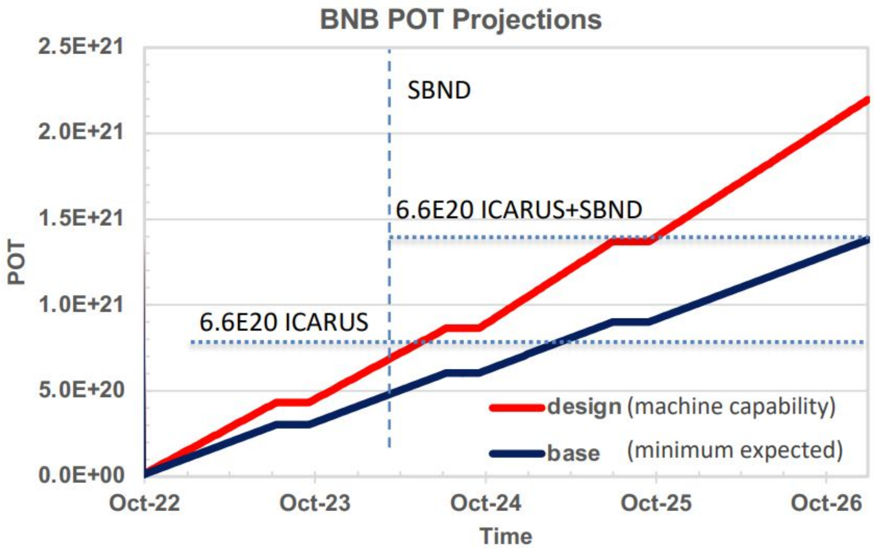
- As mentioned SBND will see over **35,000 intrinsic ν_e** in 6.6e20 POT.
- Allows for a direct accelerator based ν_e disappearance search, **complementary to both reactor and radioactive source ν_e disappearance experiments**
- In addition **ICARUS** will leverage its position ~5.7^o off axis in the **NuMI beam** to **perform a ν_e disappearance** search as part of **Neutrino-4 signal investigation**

Protons-on-target (POT) exposure

The BNB has delivered high quality beam for almost two decades, regularly achieving "design" capability

The original SBN proposal was for **6.6e20** POT

However, current plans are for BNB to continue to operate at design until the LBNF long-shutdown ~Jan. 2027.



As such by 2027

- **ICARUS** will have obtained over **x3 the proposal POT**
- **SBND+ICARUS** will have obtained over **x2 the proposal POT**
    - Stay tuned for updated sensitivities including larger dataset soon!

Evolving Theory Landscape, not just a simple sterile ν anymore!

- **Decay of O(keV) Sterile Neutrinos** to active neutrinos
  - *Dentler, Esteban, Kopp, Machado Phys. Rev. D 101, 115013 (2020)*
  - *de Gouvêa, Peres, Prakash, Stenico JHEP 07 (2020) 141*
- New **resonance matter** effects
  - *Asaadi, Church, Guenette, Jones, Szelc, PRD 97, 075021 (2018)*
  - *Alves, Louis, deNiverville, [hep-ph]2201.00876 (2022)*
- **Mixed** O(1eV) sterile **oscillations and** O(100 MeV) **sterile decay**
  - *Vergani, Kamp, Diaz, Arguelles, Conrad, Shaevitz, Uchida, arXiv:2105.06470*
- Decay of **heavy sterile neutrinos produced in beam**
  - *Gninenko, Phys.Rev.D83:015015,2011*
  - *Alvarez-Ruso, Saul-Sala, Phys. Rev. D 101, 075045 (2020)*
  - *Magill, Plestid, Pospelov, Tsai Phys. Rev. D 98, 115015 (2018)*
  - *Fischer, Hernandez-Cabezudo, Schwetz, PRD 101, 075045 (2020)*
  - *Dutta, Kim, Thompson, Thornton, Van de Water [hep-ph]2110.11944*
- Decay of **upscattered heavy sterile neutrinos** or new scalars mediated by **Z'** or more **complex higgs sectors**
  - *Bertuzzo, Jana, Machado, Zukanovich Funchal, PRL 121, 241801 (2018)*
  - *Abdullahi, Hostert, Pascoli, Phys.Lett.B 820 (2021) 136531*
  - *Ballett, Pascoli, Ross-Lonergan, PRD 99, 071701 (2019)*
  - *Dutta, Ghosh, Li, PRD 102, 055017 (2020)*
  - *Abdallah, Gandhi, Roy,Phys. Rev. D 104, 055028 (2021)*
- Decay of **axion-like particles**
  - *Chang, Chen, Ho, Tseng, Phys. Rev. D 104, 015030 (2021)*

Produces True Electrons

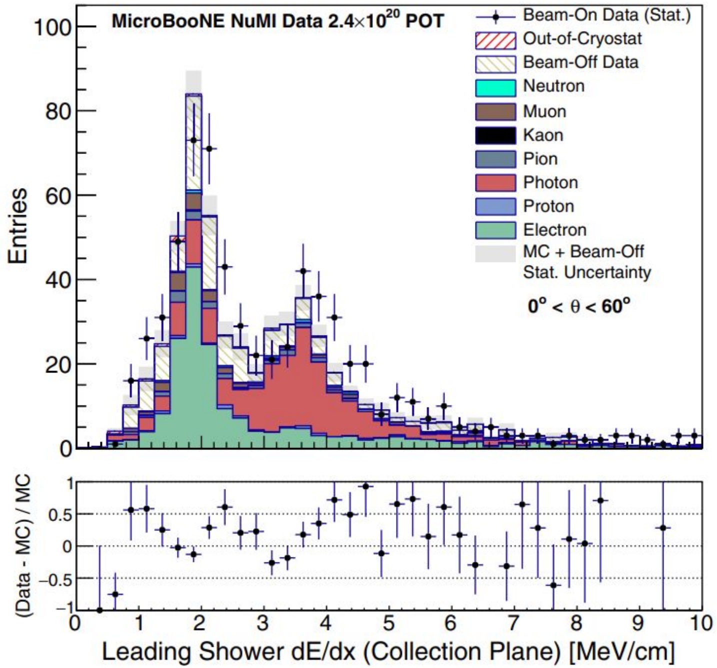
Produces True Photons

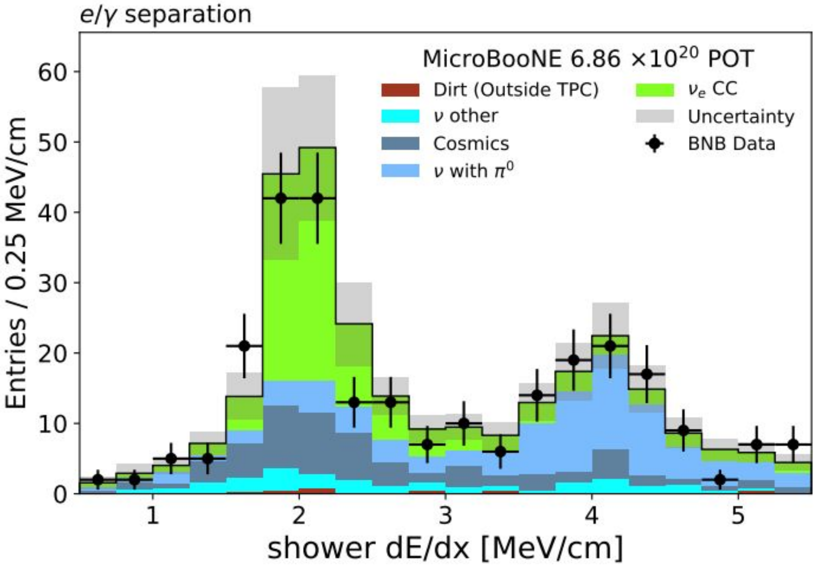
Produces e^+e^- pairs

The SBN program is the perfect platform to explore to this *rapidly growing field*! Majority of these in last couple years!

(Caution: not an exhaustive list!)

LArTPC electron-photon separation

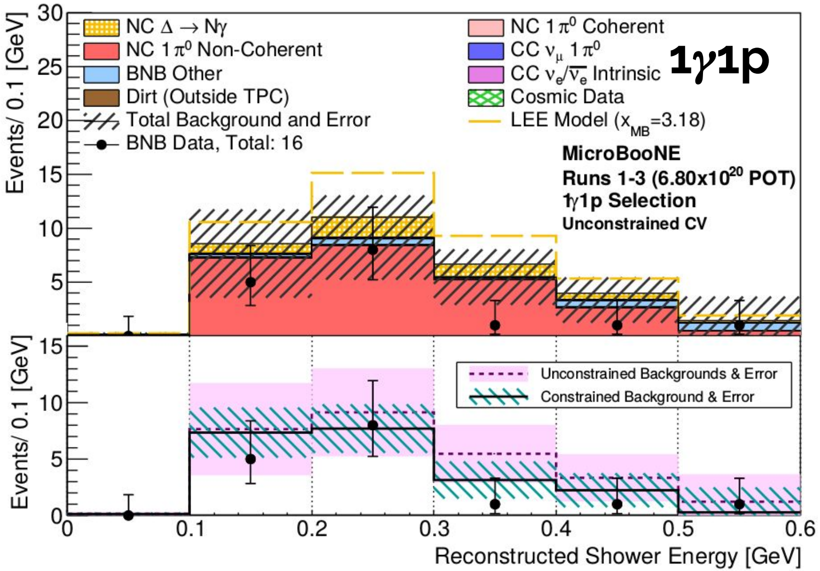


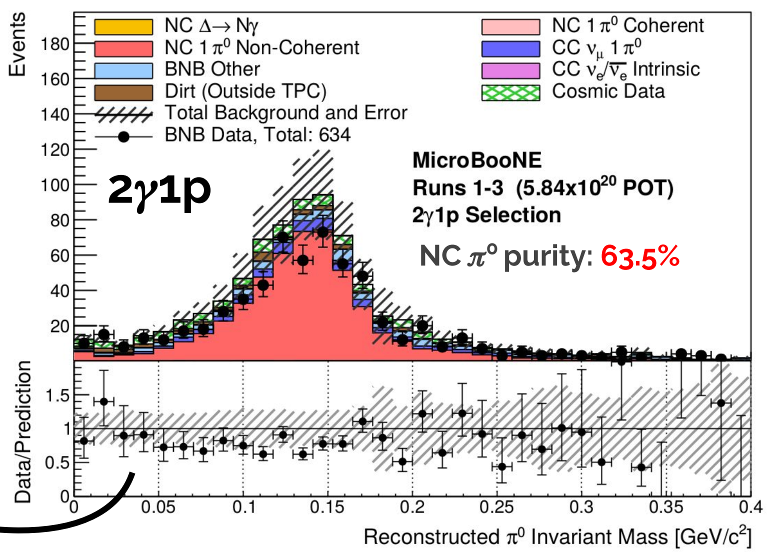


https://journals.aps.org/prd/pdf/10.1103/PhysRevD.104.052002

https://doi.org/10.1103/PhysRevD.105.112004

Effect of 2γ1p constraint



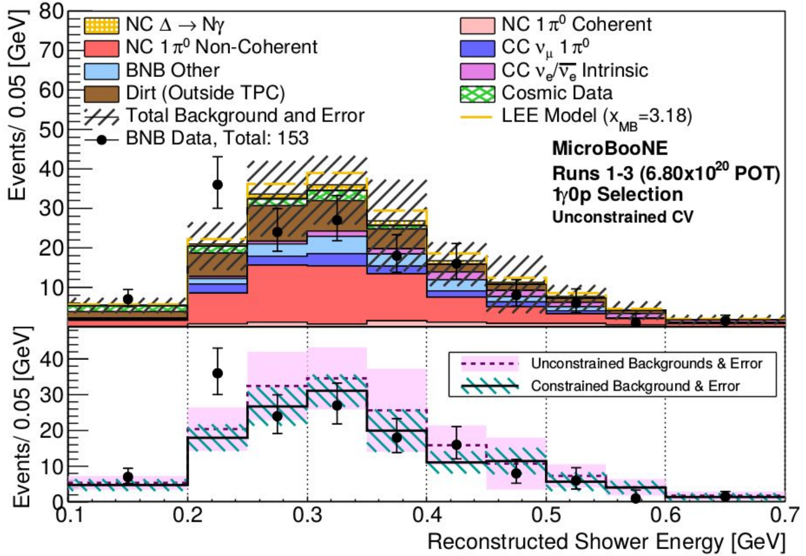


Constraint has two effects:

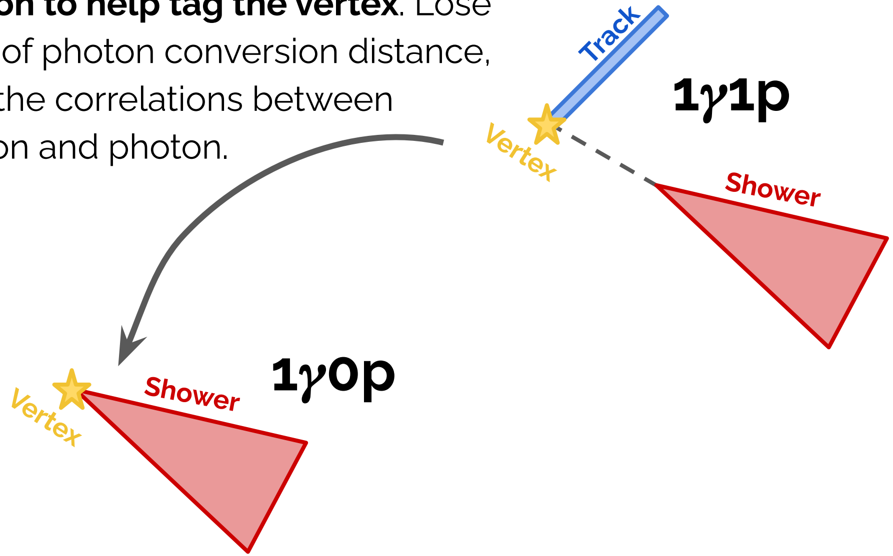
- Overall **drop in expected backgrounds** by **24.1%**
- **Reduction in systematic uncertainty (29.8% →17.8%)**

Use high statistics NC π^0 2γ1p sample to **constrain** the NC π^0 backgrounds in signal rich 1γ1p sample

What about 1γ0p ? (no proton sample)



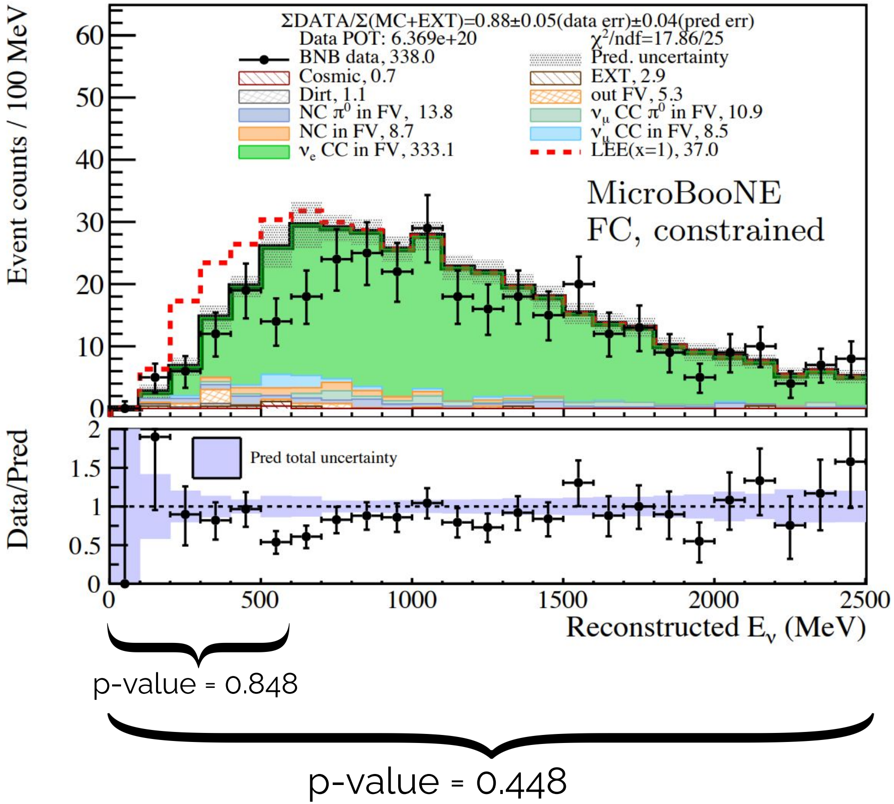
Going from 1γ1p to 1γ0p we lose the **proton to help tag the vertex**. Lose idea of photon conversion distance, and the correlations between proton and photon.



Overall, this results in a lower NC $\Delta \rightarrow N\gamma$ purity and a more **diverse category of backgrounds** (still NCπ^0 dominant).

Less sensitive to enhanced NC $\Delta \rightarrow N\gamma$ rates.

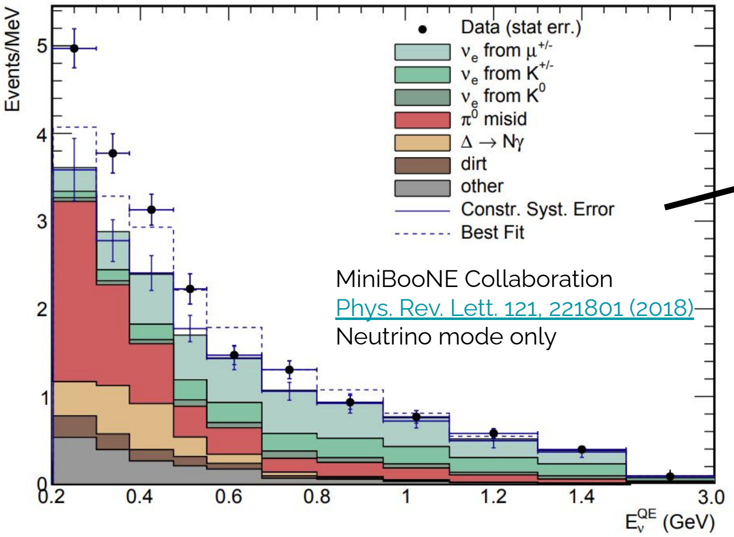
Quantify: How well does data agree with our constrained prediction?



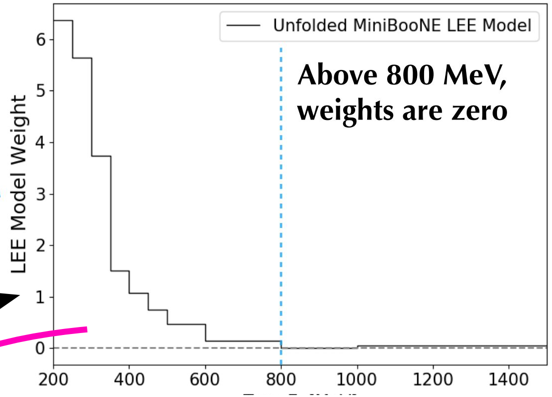
From this we can conclude that the **observed data is in good agreement with our predicted ν_e**

Unlike **NC $\Delta \rightarrow N\gamma$** can't just use a flat scaling here as the **shape of intrinsic ν_e is completely different!**

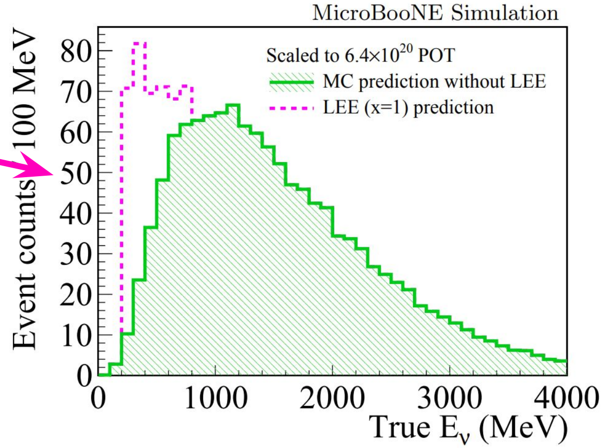
Need an **energy dependent scaling**



Unfold the MiniBooNE data under the hypothesis the excess is solely due to intrinsic ν_e



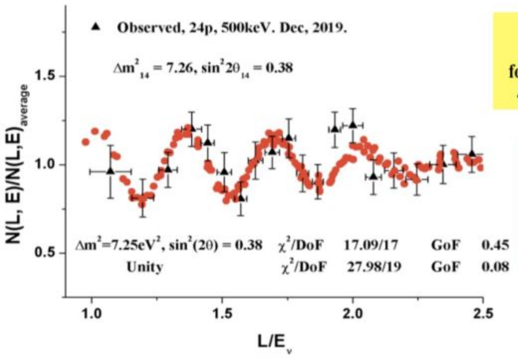
Map this to MicroBooNE by scaling our prediction of the ν_e spectrum!



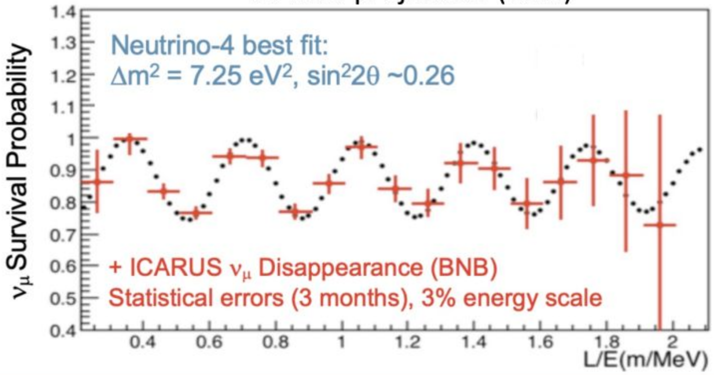
Search for Neutrino-4 Oscillation signal with ICARUS

- The Neutrino-4 collaboration claim a reactor neutrino disappearance signal with a clear modulation with L/E ~1-3 m/MeV
- ICARUS has sensitivity to this parameter space as a single-detector and is planning an oscillation analysis investigating the Neutrino-4 signal using data taken in the coming year (prior SBND operations)
- ICARUS will do analyses in two independent channels using different neutrino beams
  - ν_μ disappearance using the BNB
  - ν_e disappearance using NuMI

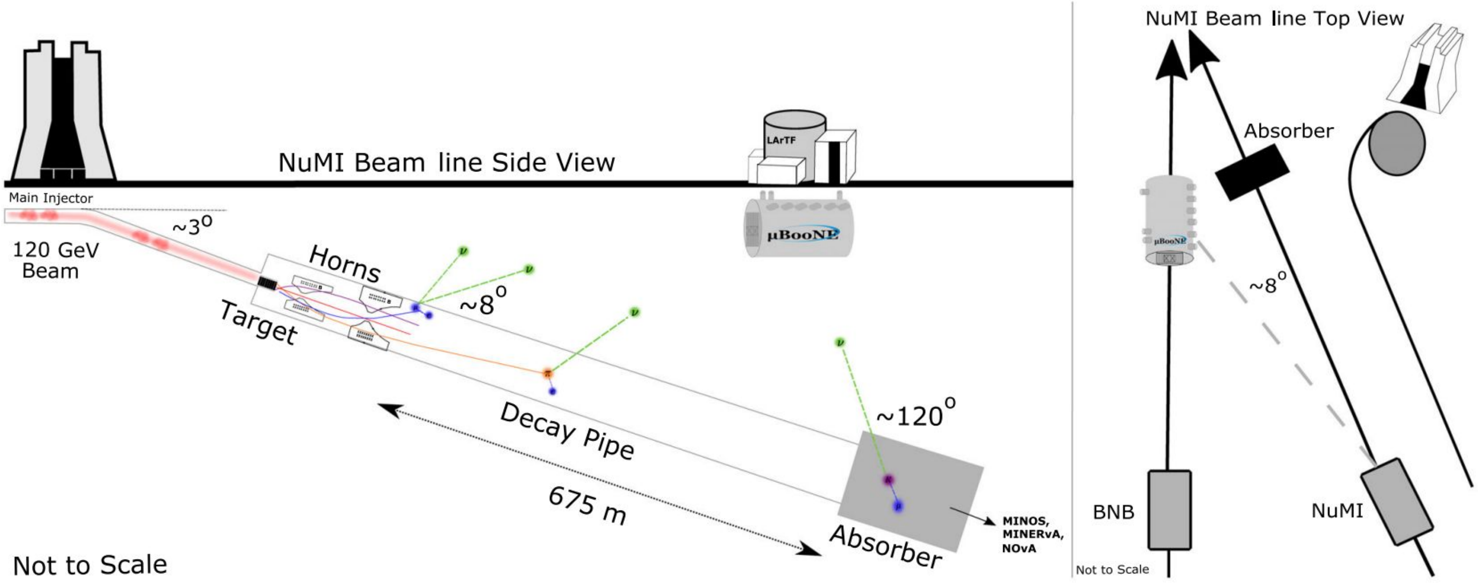
NEUTRINO-4 reactor signals



ICARUS projection (BNB)



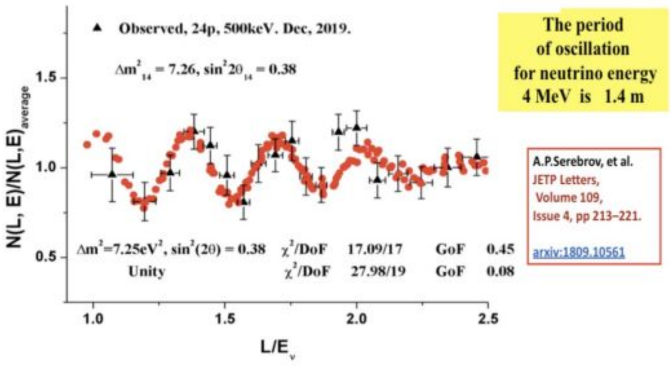
NuMi @ MicroBooNE



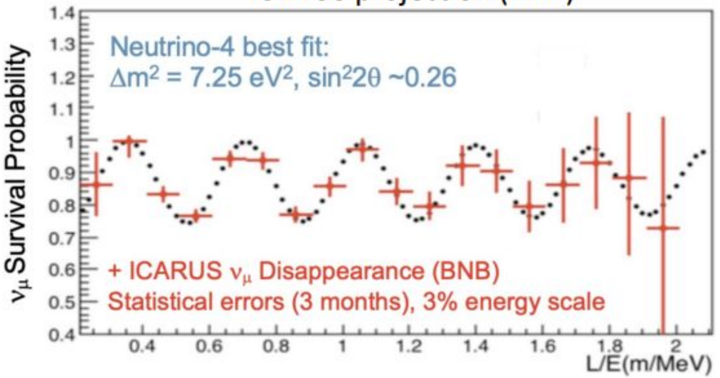
Search for Neutrino-4 Oscillation signal with ICARUS

- The Neutrino-4 collaboration claim a reactor neutrino disappearance signal with a clear modulation with L/E ~1-3 m/MeV
- ICARUS has sensitivity to this parameter space as a single-detector and is planning an oscillation analysis investigating the Neutrino-4 signal using data taken in the coming year (prior SBND operations)
- ICARUS will do analyses in two independent channels using different neutrino beams
  - ν_μ disappearance using the BNB
  - ν_e disappearance using NuMI

NEUTRINO-4 reactor signals



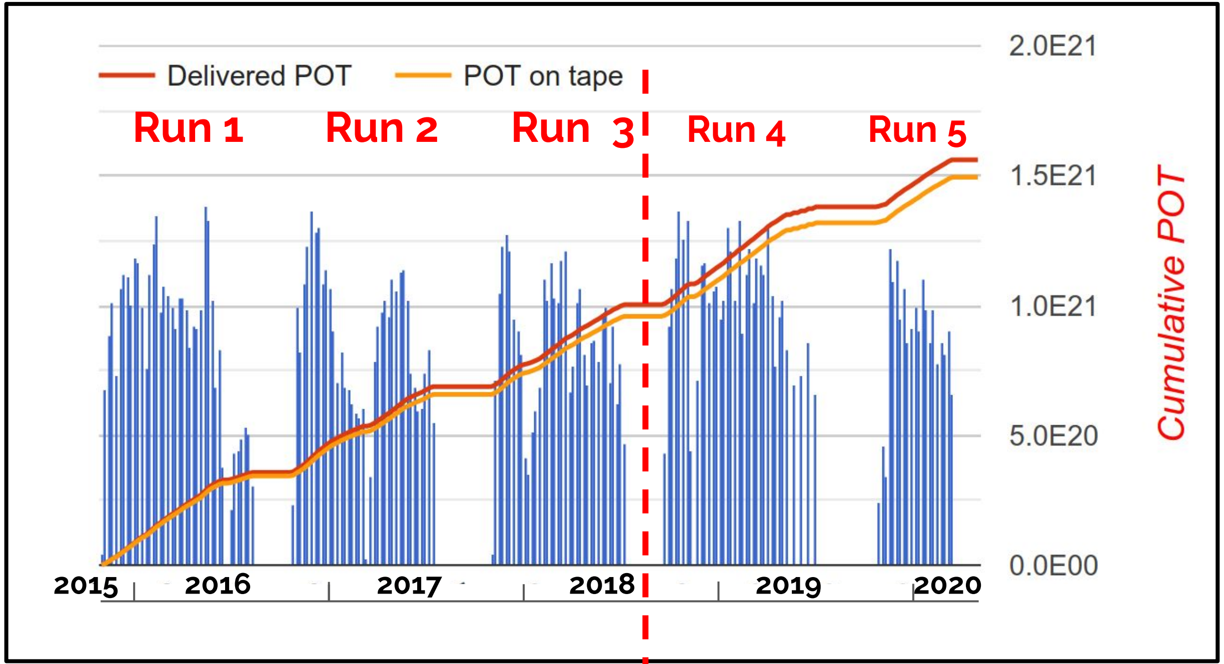
ICARUS projection (BNB)



Slide From Bob Wilsons Snomass talk LINK

Successful running for over 5 years

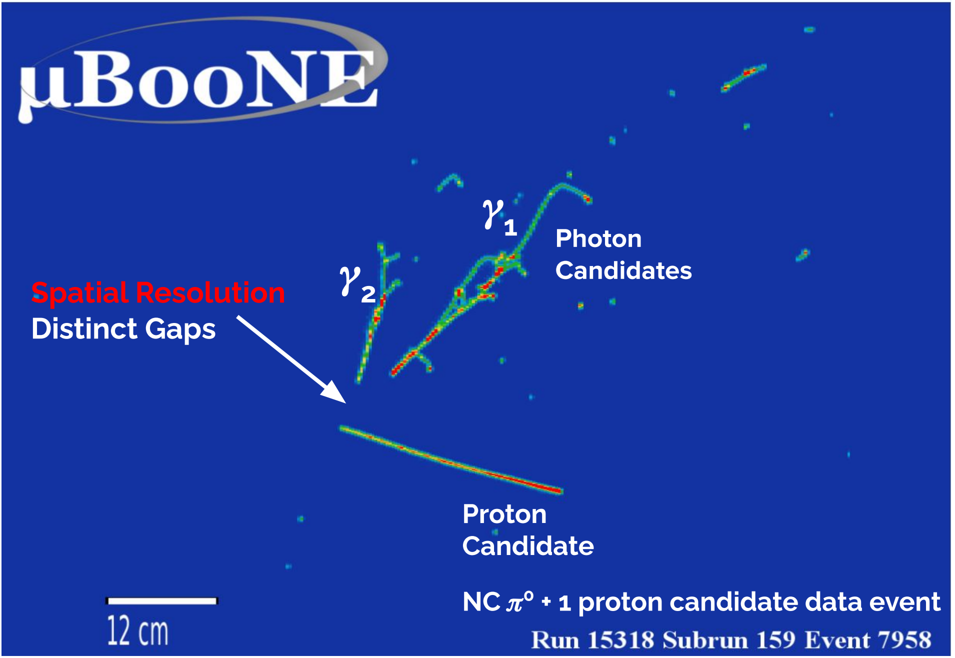
Since turning on in 2015, MicroBooNE has amassed the **largest sample of neutrino interactions on argon in the world**

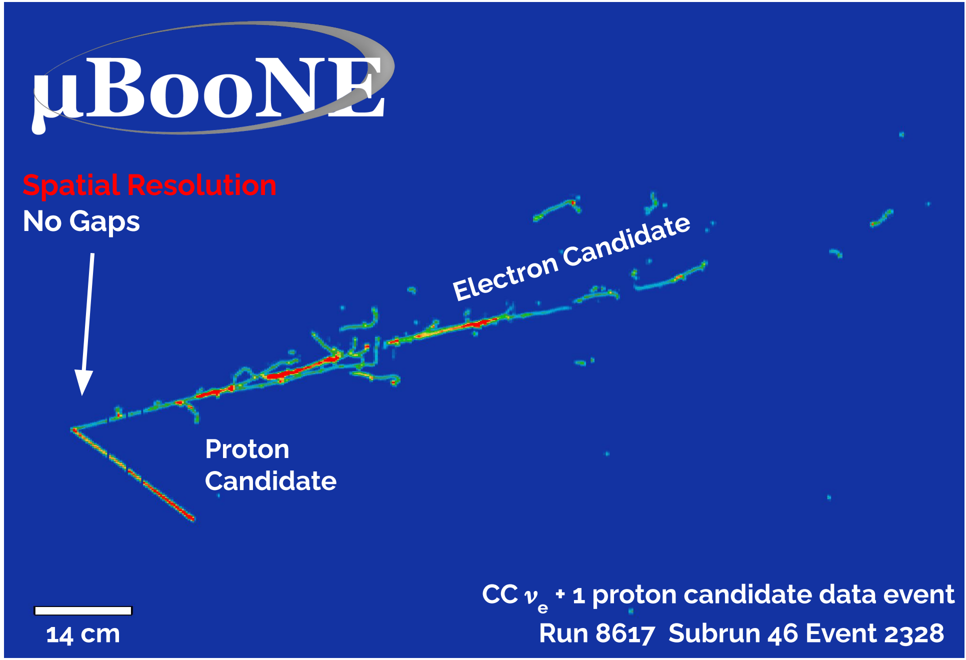


In today's talk I will be presenting results based on **6.80×10^{20} protons-on-target (POT)** from **Runs 1-3**

Analyzing remaining ½ of our data from Runs 4-5 is well underway!

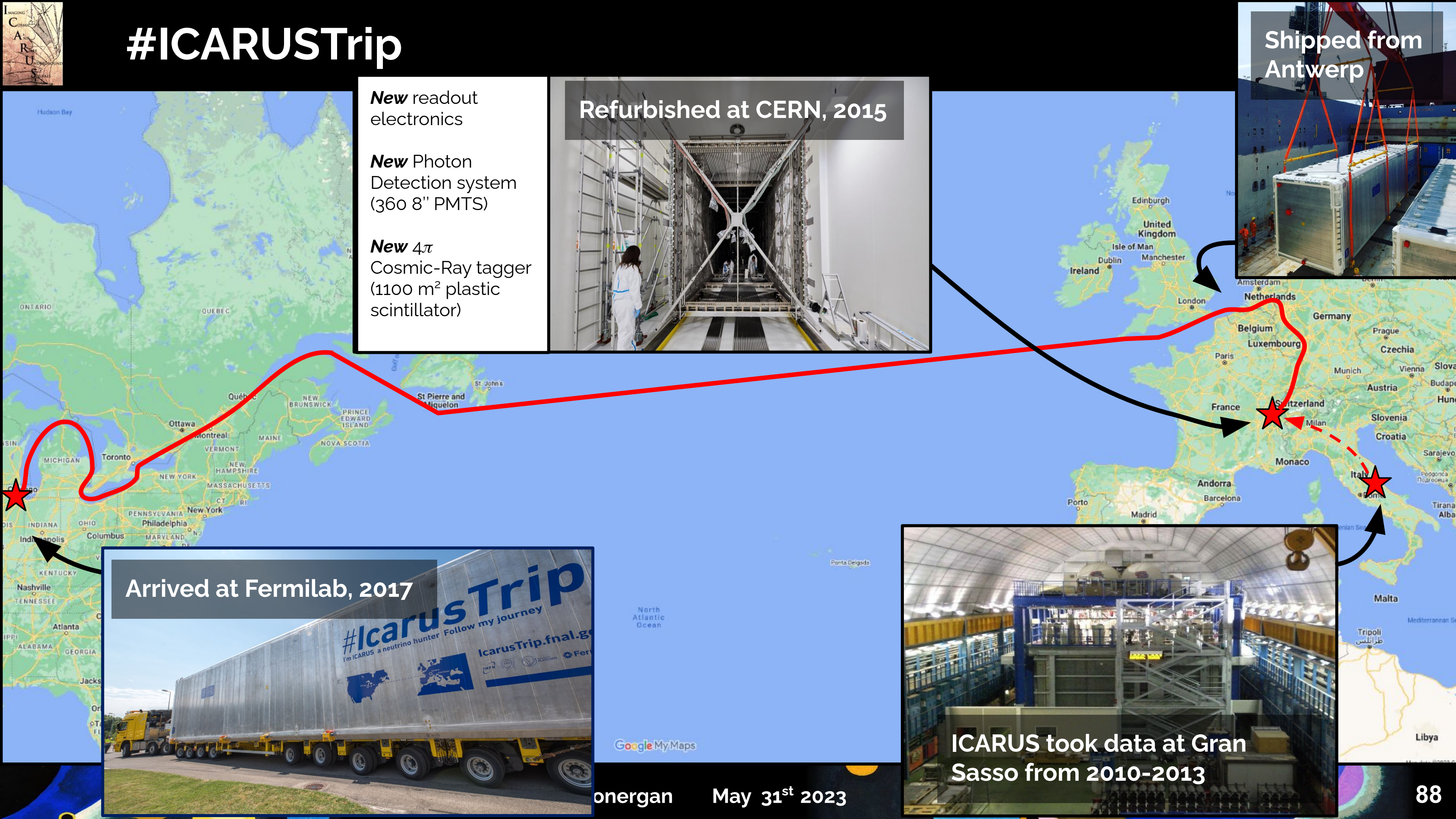
LArTPC's give us **fully active calorimeter** alongside **high-resolution tracking**





Allows for strong **photon** ↔ **electron separation**

#ICARUSTrip



New readout electronics

New Photon Detection system (360 8'' PMTS)

New 4π Cosmic-Ray tagger (1100 m² plastic scintillator)

Refurbished at CERN, 2015

Shipped from Antwerp

Arrived at Fermilab, 2017

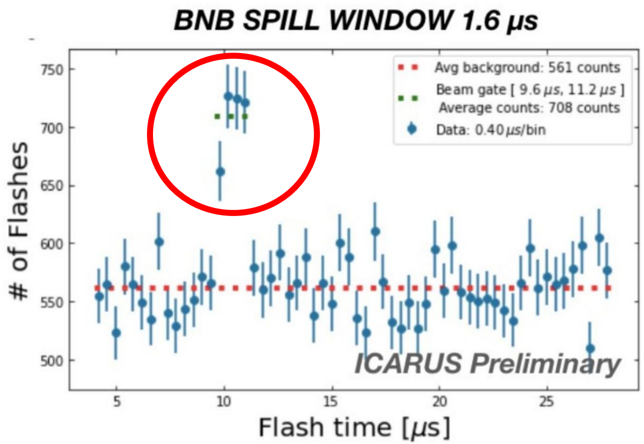
ICARUS took data at Gran Sasso from 2010-2013

Commissioning the ICARUS detector at Fermilab

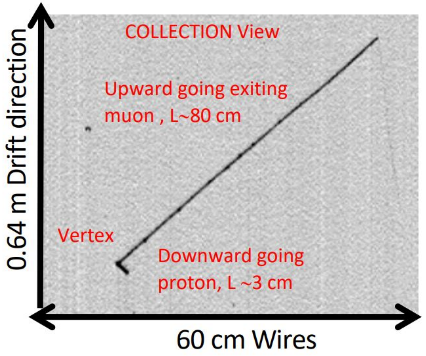
While physics data with full CRT and overburden began June 2022, **ICARUS was taking data with both BNB & NuMI beams since March 2021**, in parallel with commissioning activities.

This data that has been collected is being used for **trigger**, **calibration** and **reconstruction studies** that are in progress

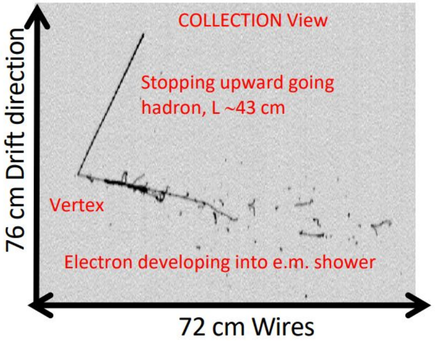
Excellent performance so far, the detector shows stable noise level with **electron lifetime > 3ms**



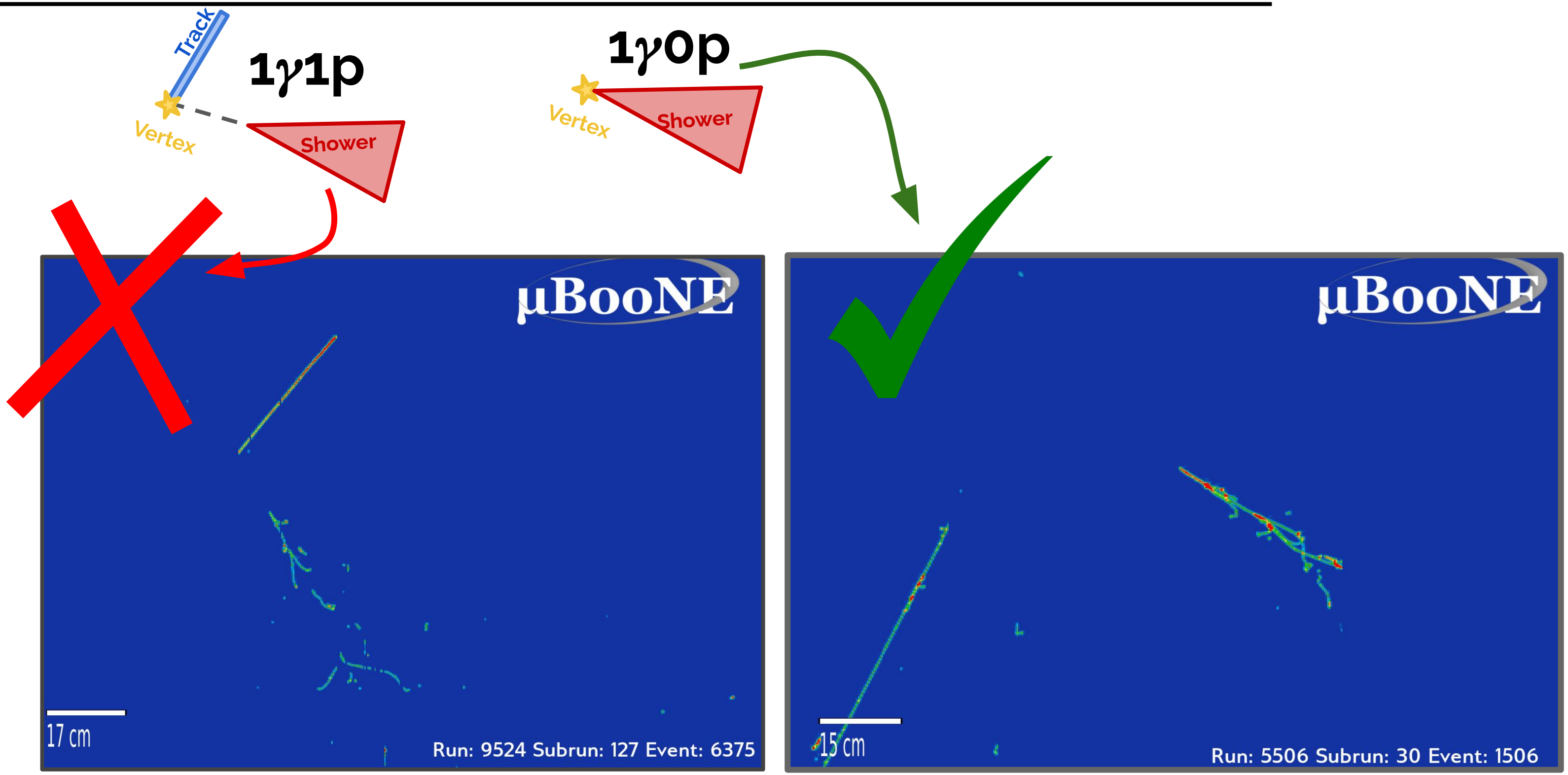
BNB CC QE muon neutrino candidate, E_{DEP} ~ 200 MeV



Contained NuMI CC QE electron neutrino candidate, E_{DEP} ~ 800 MeV



For more info on calibrations see **Gray Putnam's** talk [Aug 5th, 3:32pm in WG6]



MicroBooNE: PhysRevLett.128.111801

Fermilab's Short-Baseline Experiments

Same Neutrino Beam, **Same** Liquid Argon Time Projection Chamber (**LArTPC**) detector technology.

ICARUS-T600 Factsheet

BNB Baseline: **600m**
Dimensions: 2x (19.6 x 3.6 x 3.9 m^3)
Total LAr mass 760 ton
Active LAr mass 476 ton
-75 kV high voltage
1.5 m drift distance
53,248 Wires in TPC
360 8" PMTs

MicroBooNE Factsheet

BNB **Baseline: 470m**
Dimensions: (2.33 x 2.56 x 10.37 m^3)
Total LAr mass 170 ton
Active LAr mass 90 ton
-70kV high voltage
2.5 m drift distance
8,256 Wires in TPC
32 8" PMTs

SBND Factsheet

BNB Baseline: **110m**
Dimensions: (4 x 4 x 5 m^3)
Total LAr mass 270 ton
Active LAr mass 112 ton
-100 kV high voltage
2m drift distance
11,263 Wires in TPC
120 8" PMTs & 192 X-ARAPUCAs