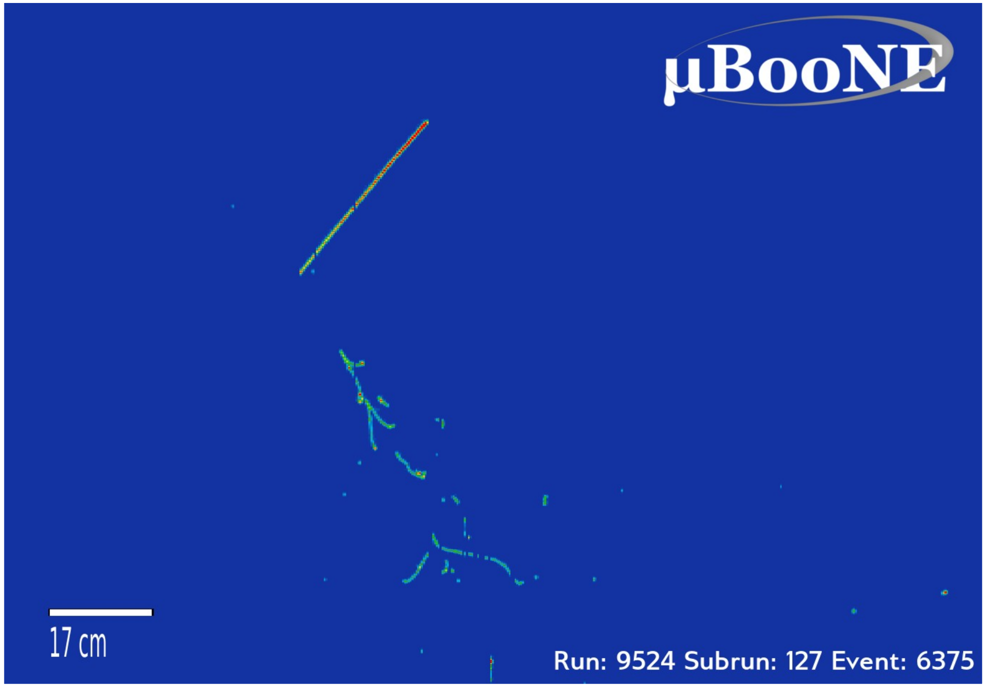
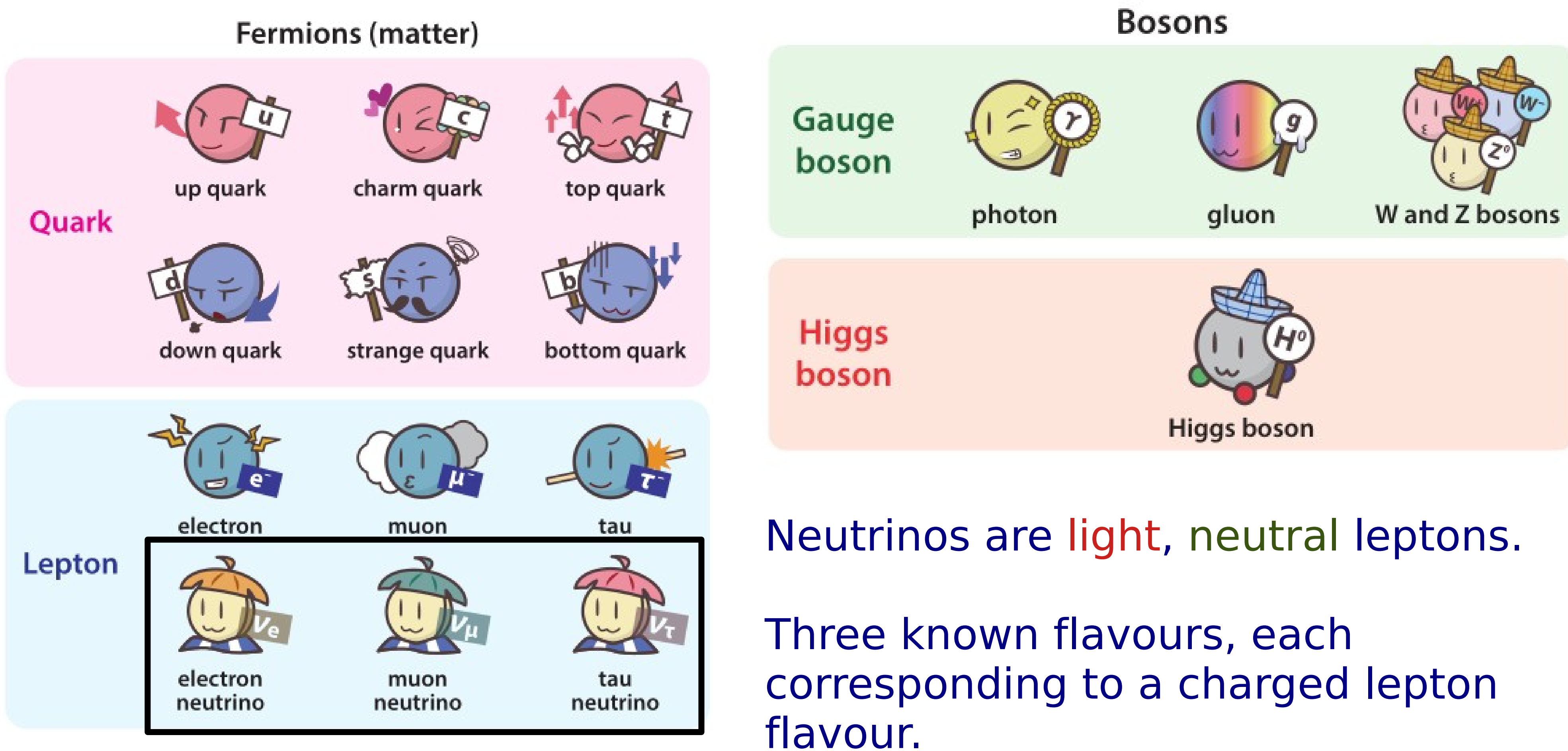
New Low-Energy Excess Results from MicroBooNE



Steve Dennis
University of Warwick Seminar
17th February 2022

Neutrinos in the Standard Model



Neutrinos are light, neutral leptons.

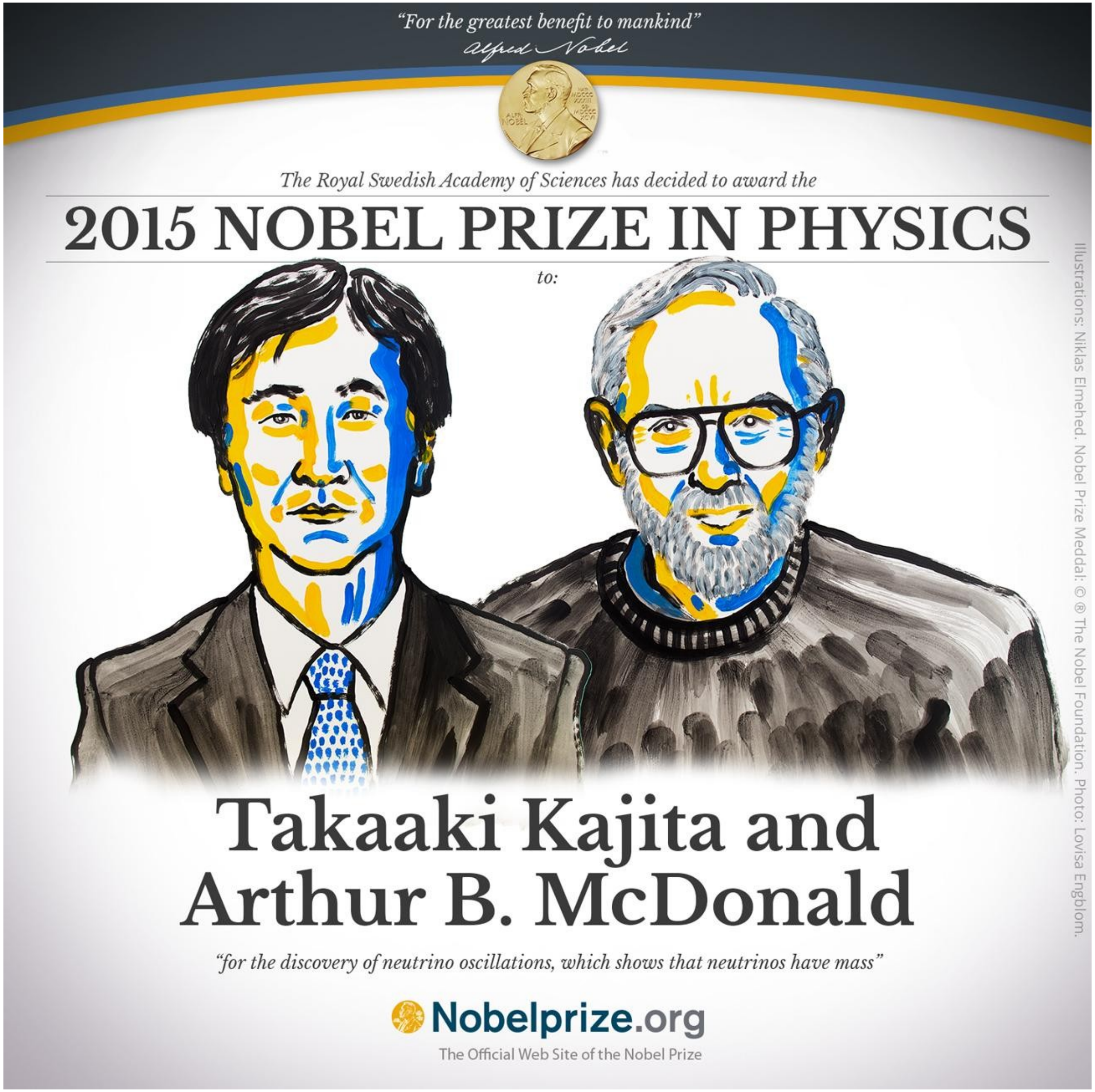
Three known flavours, each corresponding to a charged lepton flavour.

Interact only via the weak force: low cross-sections.

- Charged current respects charged neutrino flavour.
- Neutral current does not.

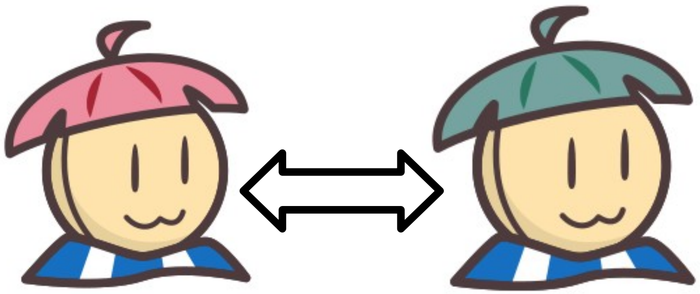
But we can go beyond the Standard Model?

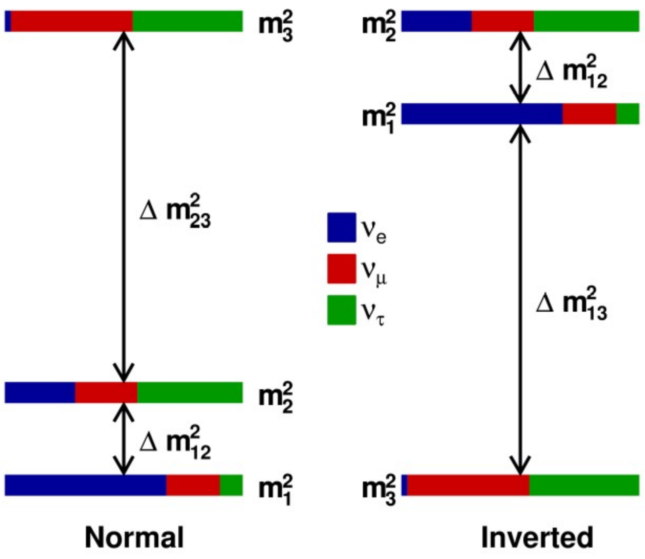
Of course we can.

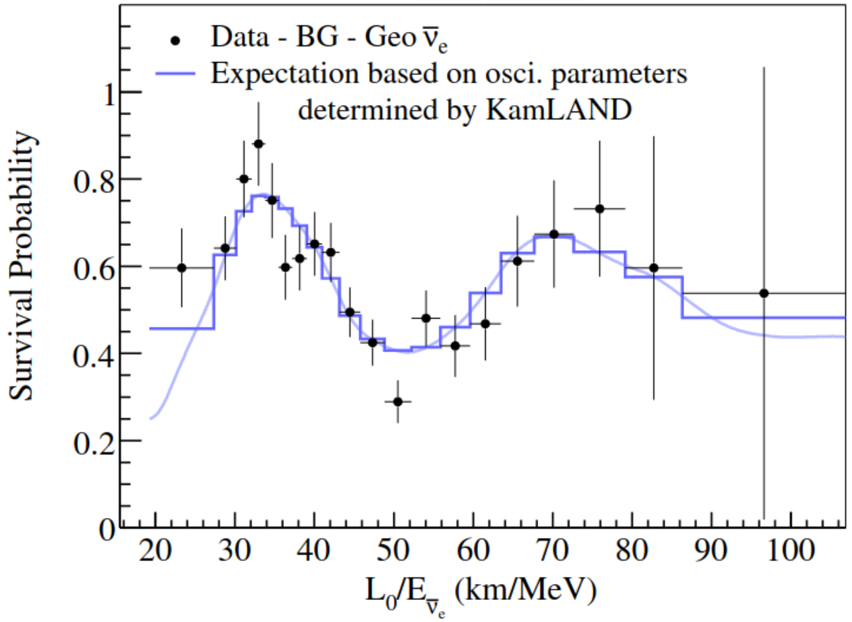


Neutrino Oscillation

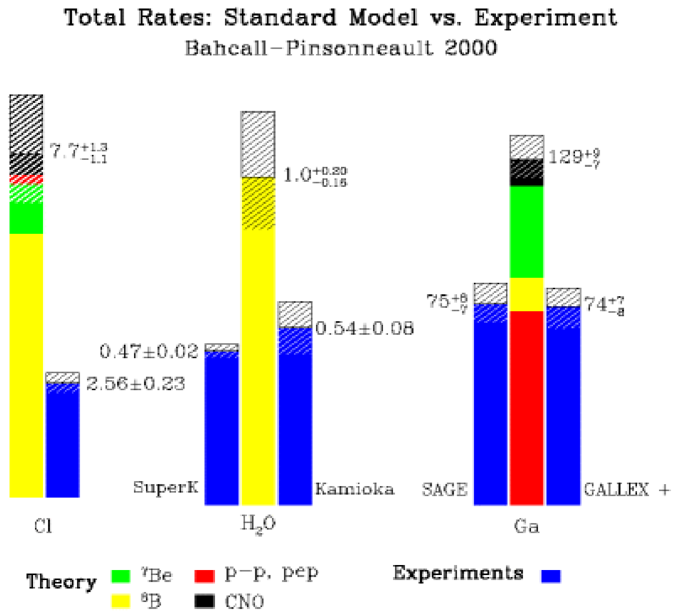
- Neutrinos change flavour as they propagate.
  - Dependent on **L/E** and neutrino mass.
- Know of three active flavours, each corresponding to a charged lepton flavour.
- Two known mass splittings.

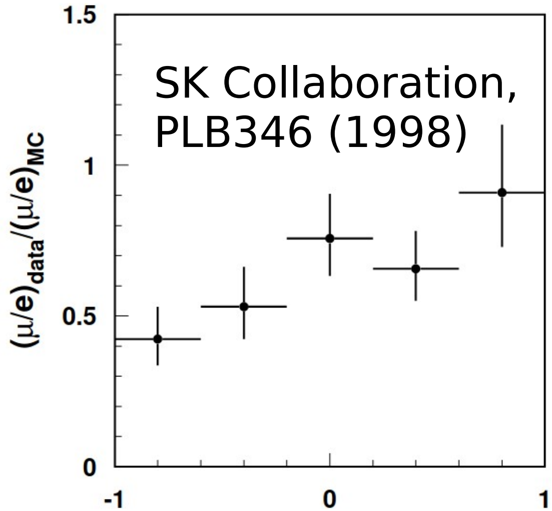




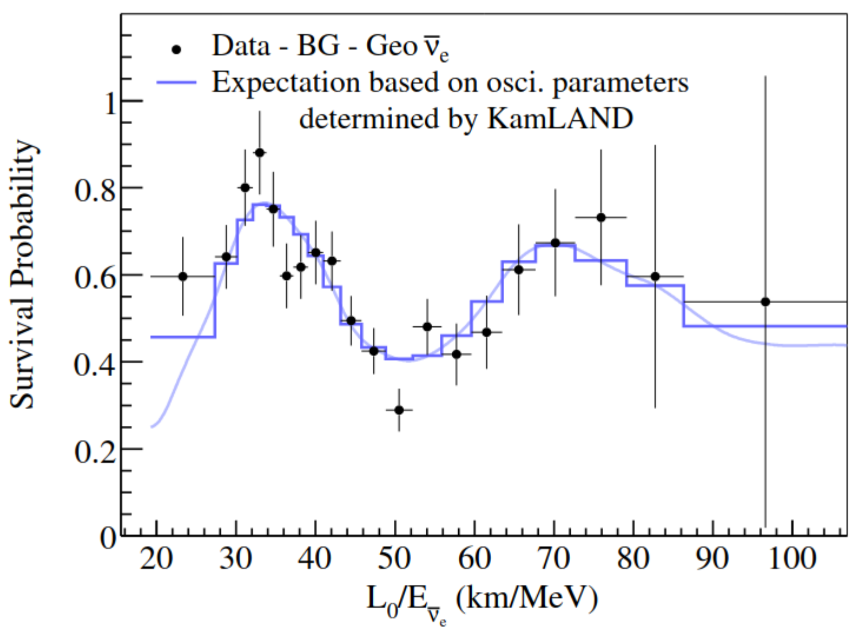


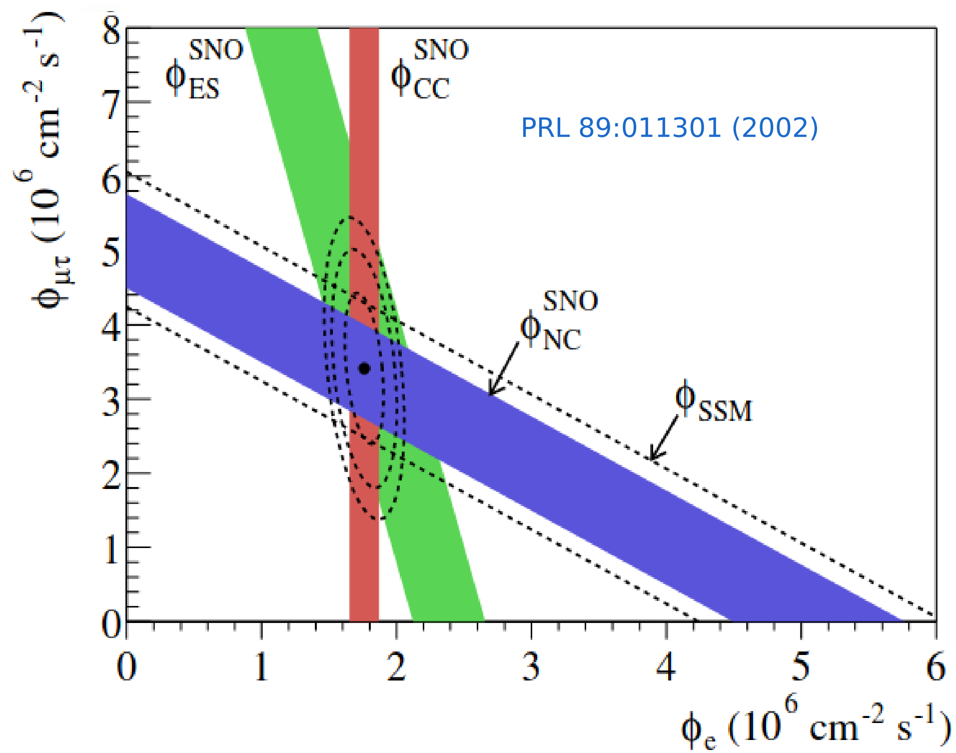
Neutrino Oscillation - Discovery





Lots of experimental evidence for 3F oscillation.





Neutrino Oscillation

Neutrino oscillation is a quantum mechanical phenomenon in which a neutrino created with a specific lepton family number ("lepton flavor": electron, muon, or tau) can later be measured to have a different lepton family number. The probability of measuring a particular flavor for a neutrino varies between three known states, as it propagates through space

(from Wikipedia, forgive me)

Neutrinos have different mass states and flavour states: they propagate as mass states but interact as flavour states. The mixing is controlled by the PMNS matrix U:

$$|\nu_\alpha\rangle = \sum_k U_{\alpha k} |\nu_k\rangle \qquad |\nu_k\rangle = \sum_\alpha U^*_{\alpha k} |\nu_\alpha\rangle$$

With only two flavours, the oscillation probabilities take the form:

$$P(\nu_x \rightarrow \nu_y) = \sin^2(2\theta)\sin^2(1.27\Delta m^2(\mathrm{eV}^2)\frac{L(\mathrm{km})}{E(\mathrm{GeV})})$$

Three-flavour Neutrino Oscillation

Parameterise with the PMNS Matrix.

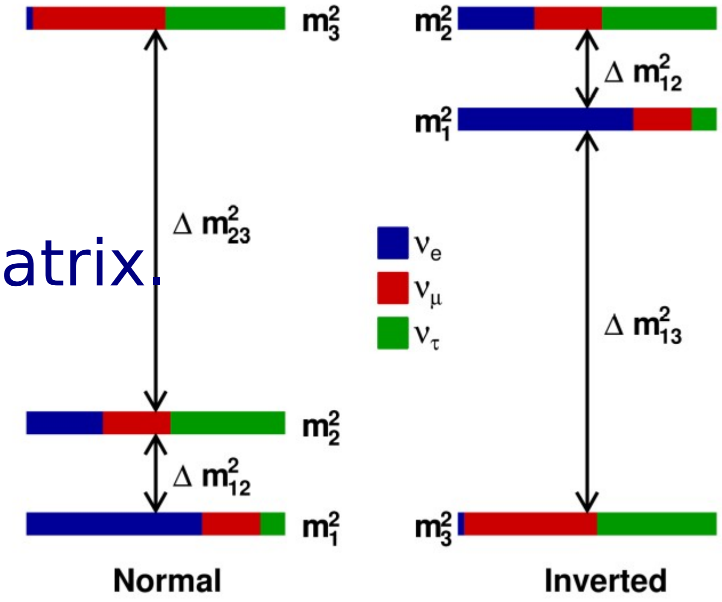
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{cp}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{cp}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric & LBL disappearance

Reactor & LBL appearance

Solar & Reactor

6 parameters: three mixing angles, two mass-squared splittings and a CP-violating phase form the PMNS matrix.

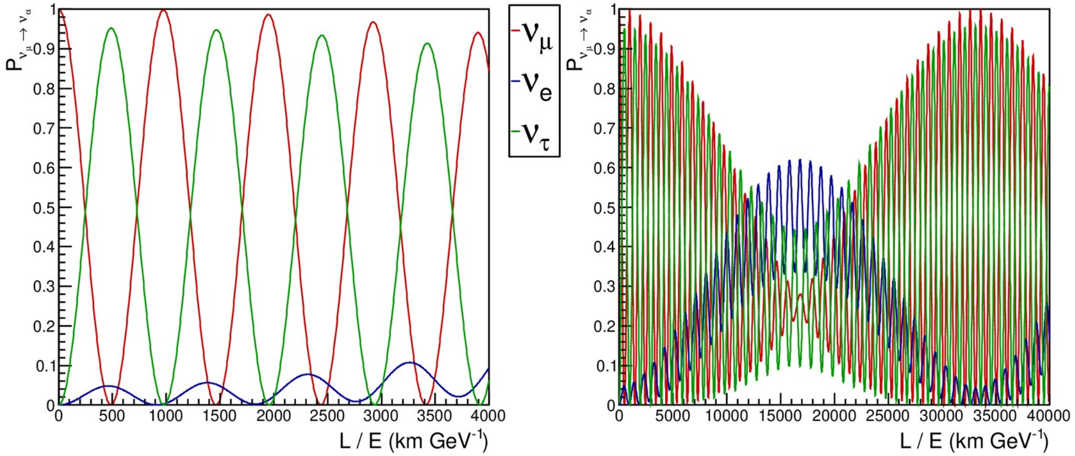


The PMNS Matrix.

- There are three active neutrinos, and it has been shown they all mix, that opens up the possibility for the mixing matrix to be complex.

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{cp}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{cp}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

This complex phase causes neutrinos and antineutrinos to behave differently. If $\sin(\delta_{cp})!=0$, we have a source of CP violation. But only in appearance: disappearance has T-symmetry, so CP-violation would also be CPT-violation.



Global Fits to PMNS Parameters

- The global status here I am using is NuFit 5.1.
  - Very much up-to-date (October 2021).

$\sin^2(\theta_{12})$ has 1-sigma uncertainty of ~5%, driven by solar/reactor experiments.

$\sin^2(2\theta_{23})$ is ~2%, but octant degeneracy smears our $\sin^2(\theta_{23})$ to have 3-sigma uncertainty of ~20%, driven by LBL/atmospheric experiments.

$\sin^2(\theta_{13})$ uncertainty is ~3%, driven by reactor experiments, aided by LBL experiments.

Δm^2_{solar} uncertainty is about 3%, driven by solar/reactor experiments.

Δm^2_{atm} uncertainty is about 1%, driven by LBL experiments, aided by reactors.

Not much known about CPV violation.

NuFIT 5.1 (2021)

without SK atmospheric data		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.6$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
	$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.77}_{-0.74}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.573^{+0.018}_{-0.023}$	$0.405 \to 0.620$	$0.578^{+0.017}_{-0.021}$	$0.410 \to 0.623$
	$\theta_{23}/^\circ$	$49.2^{+1.0}_{-1.3}$	$39.5 \to 52.0$	$49.5^{+1.0}_{-1.2}$	$39.8 \to 52.1$
	$\sin^2\theta_{13}$	$0.02220^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02238^{+0.00064}_{-0.00062}$	$0.02053 \to 0.02434$
	$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.98$
	$\delta_{CP}/^\circ$	194^{+52}_{-25}	$105 \to 405$	287^{+27}_{-32}	$192 \to 361$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.515^{+0.028}_{-0.028}$	$+2.431 \to +2.599$	$-2.498^{+0.028}_{-0.029}$	$-2.584 \to -2.413$

with SK atmospheric data		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$	$31.27 \to 35.87$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.570^{+0.016}_{-0.022}$	$0.410 \to 0.613$
	$\theta_{23}/^\circ$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$49.0^{+0.9}_{-1.3}$	$39.8 \to 51.6$
	$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$	$0.02060 \to 0.02435$	$0.02241^{+0.00074}_{-0.00062}$	$0.02055 \to 0.02457$
	$\theta_{13}/^\circ$	$8.62^{+0.12}_{-0.12}$	$8.25 \to 8.98$	$8.61^{+0.14}_{-0.12}$	$8.24 \to 9.02$
	$\delta_{CP}/^\circ$	230^{+36}_{-25}	$144 \to 350$	278^{+22}_{-30}	$194 \to 345$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$

Two-flavour Oscillation

Controls the amplitude

Just handles the units.

Controls the frequency

$$P(\nu_x \rightarrow \nu_y) = \sin^2(2\theta)\sin^2(1.27\Delta m^2(\mathrm{eV}^2)\frac{L(\mathrm{km})}{E(\mathrm{GeV})})$$

Mass squared splitting.

Can be same flavour (disappearance),
or different (appearance)

Physics beyond the Standard Model!

Key Principle of 3F Oscillation Experiments

$$P(\nu_x \to \nu_y) = \sin^2(2\theta)\sin^2\left(1.27\Delta m^2(\mathrm{eV}^2)\frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

We directly measure this.

We want to know this.

So we control this.

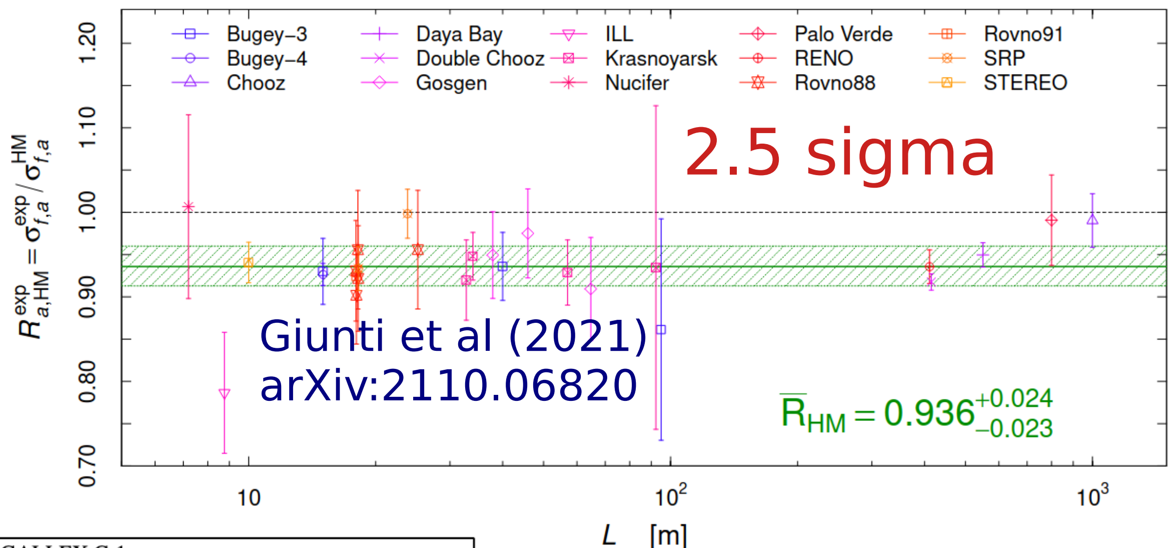
We control L by placing our detectors, and control E by tuning our sources (where possible)

Solar $\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	⟷	3 MeV reactor neutrino first maximum at 100km
Atm $\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.515^{+0.028}_{-0.028}$	⟷	1 GeV beam neutrino first maximum is at 500km
		⟷	3 MeV reactor neutrino first maximum at 1km

Reactor and Gallium Anomalies

Many reactor experiments see deficit of electron antineutrinos.

Far too many interesting things with reactors to talk about here!

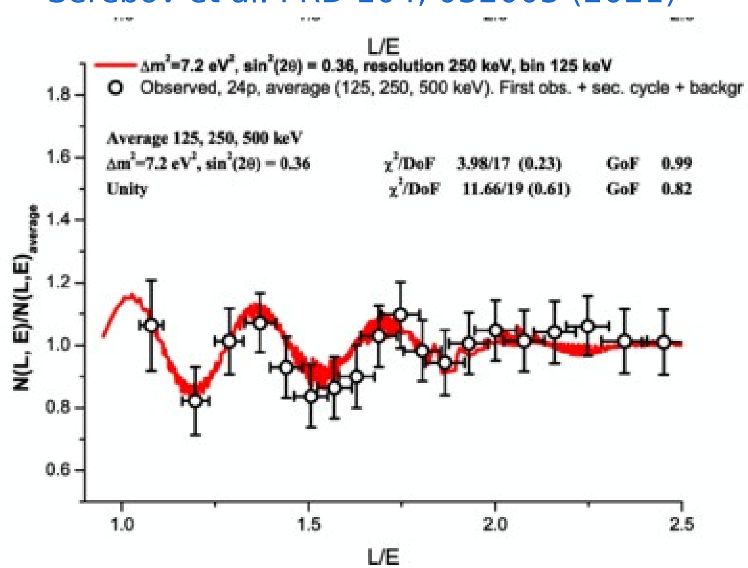


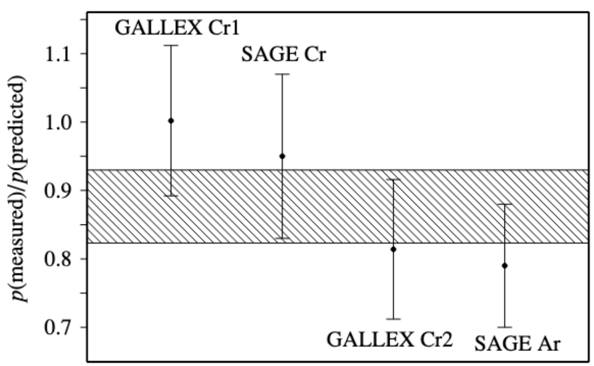
2.5 sigma

Giunti et al (2021) arXiv:2110.06820

Neutrino-4 may have oscillatory pattern?

Serebov et al. PRD 104, 032003 (2021)





Sage/GALLEX use electron capture radioactive sources, see deficit of electron neutrinos.

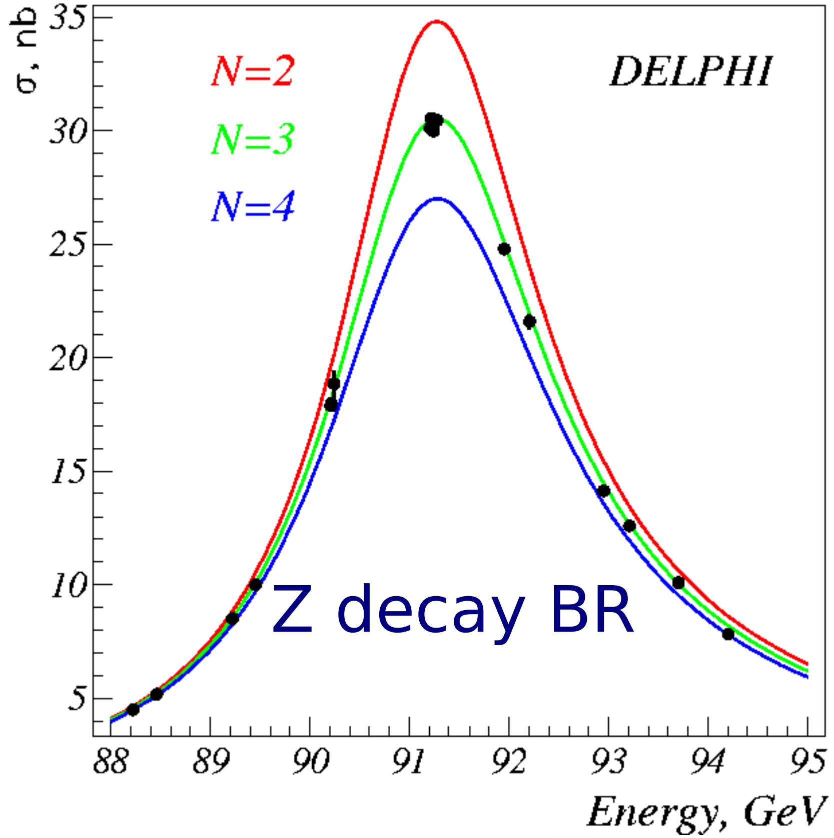
Could indicate additional neutrinos?

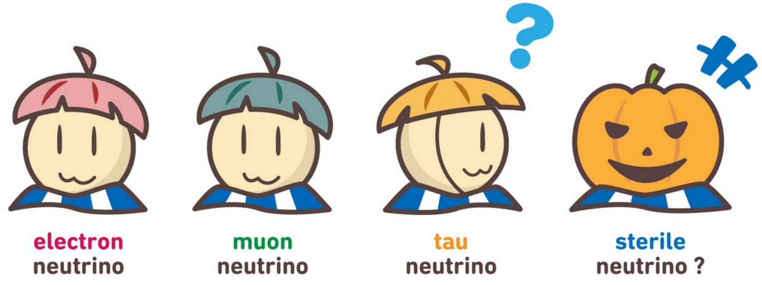
What's a sterile neutrino?

We know there are three active neutrinos (that couple to the weak force) thanks to colliders.

But if there's another mass splitting, there has to be a fourth neutrino.

We know this neutrino doesn't couple to the weak force, because it would affect the fraction of Z bosons that decay into neutrinos, unless it is extremely heavy (>40 GeV).



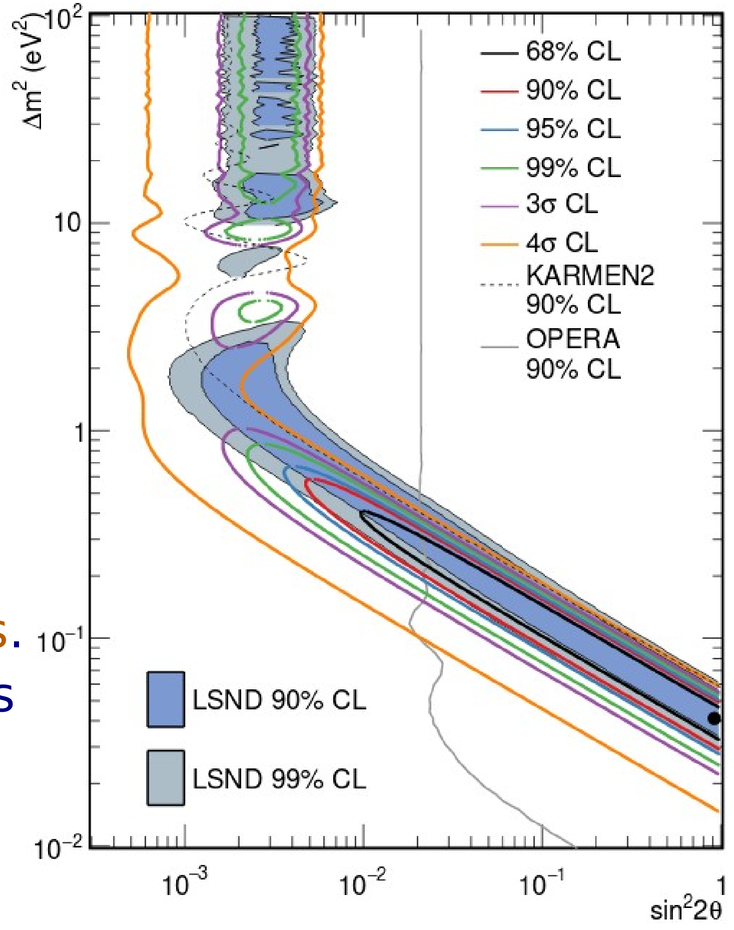


So this hypothesis is called sterile – it doesn't interact directly, you only see it via effects like oscillation.

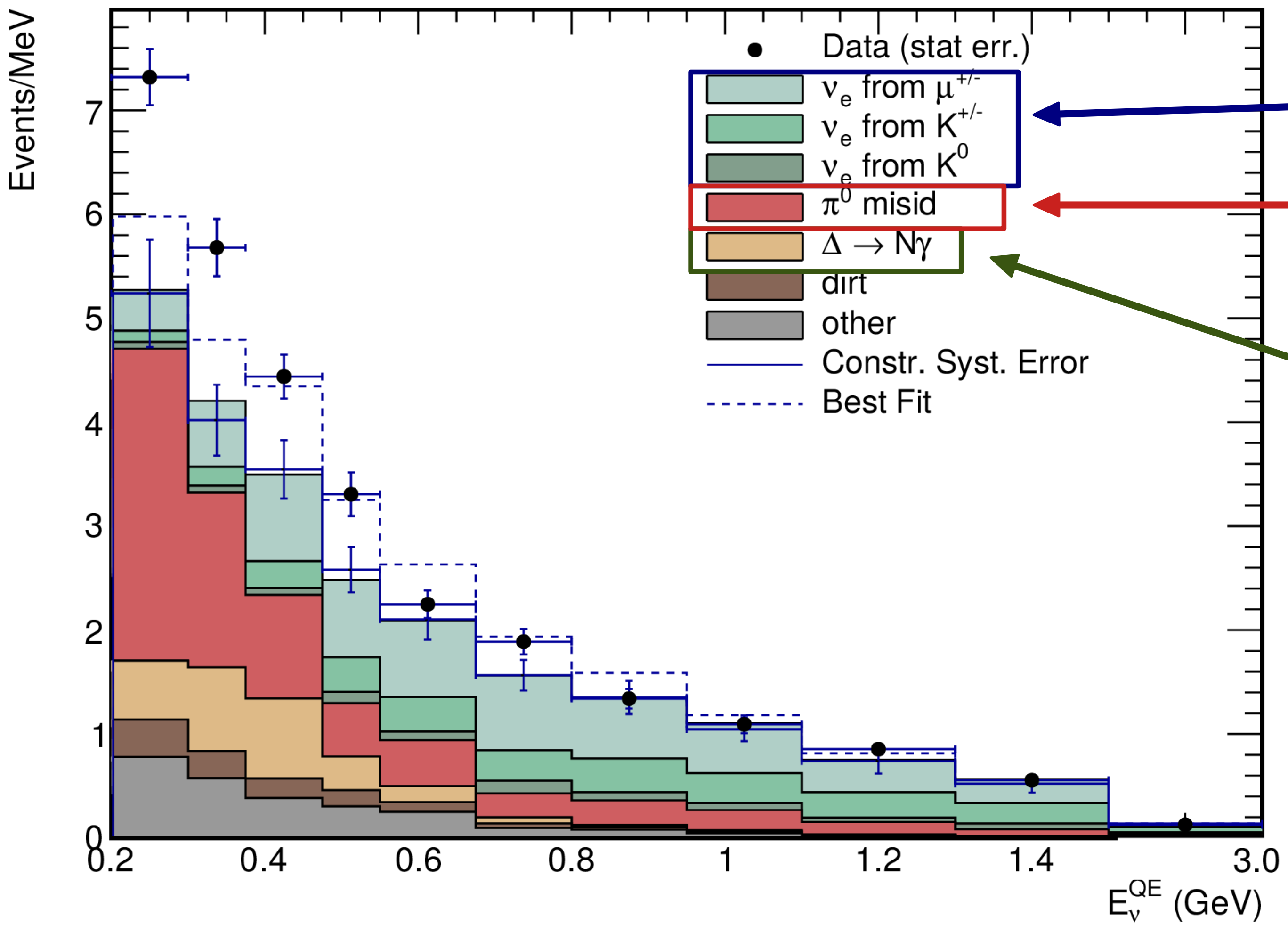
The LSND and MiniBooNE Excess

- 20 years ago, the Liquid Scintillator Neutrino Detector at LANL saw an unexpected signal. arXiv:nucl-ex/9605002
  - Excess of electron antineutrinos in a muon antineutrino beam, 3.8σ.
  - Note that this an excess rather than a deficit.
  - Evidence for a 1eV sterile neutrino?

- Development of the MiniBooNE experiment to test this hypothesis.
  - MiniBooNE collected 12.84E20 POT in neutrino and 11.27E20 POT in antineutrino mode between 2002 and 2017.
  - Same L/E, different energy, different uncertainties.
  - Also observed excess of electron-like CCQE events
    - 4.5σ excess in neutrino mode.
    - 4.7σ excess in antineutrino mode.
    - 6.0σ when combined with LSND.



MiniBooNE Electron-like Excess



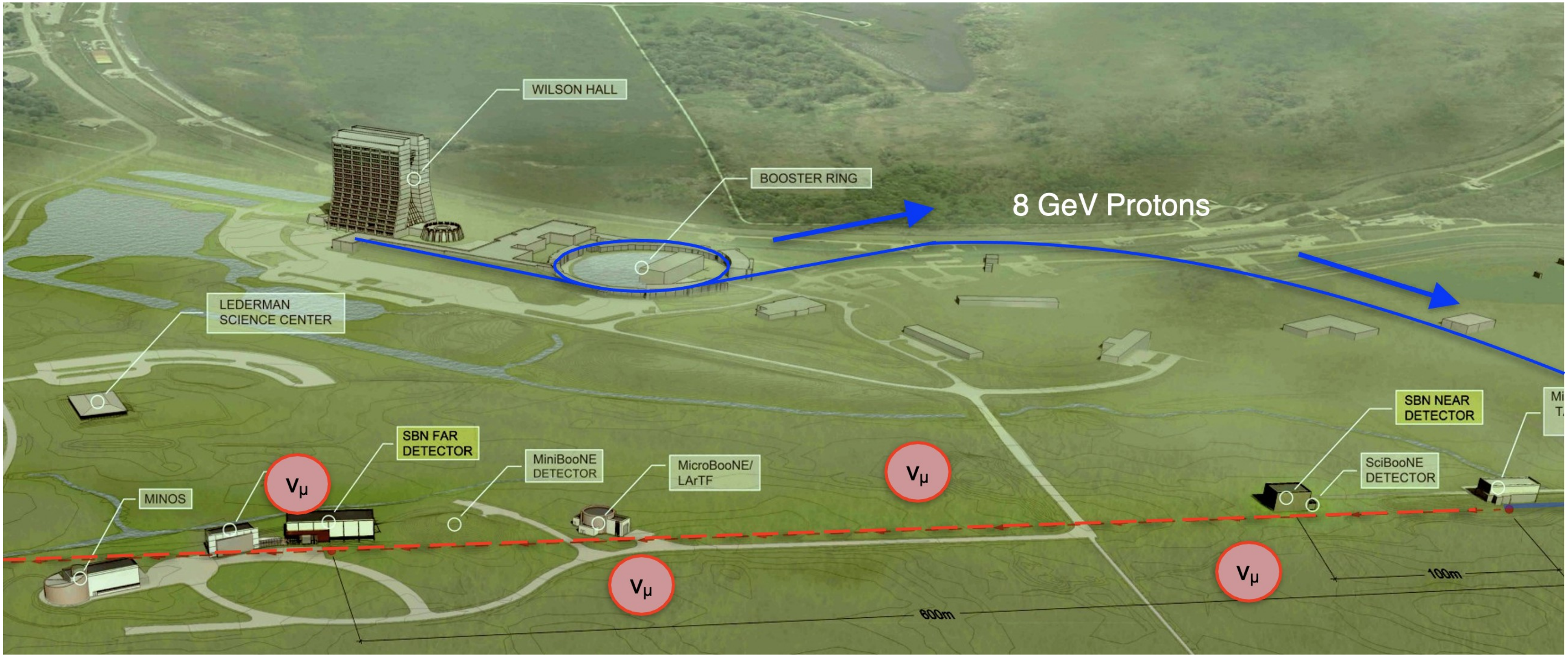
Flux?

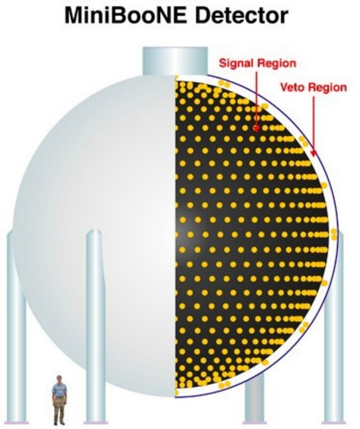
Mis-ID'd pi-zero background (measured in-situ)

Mis-ID'd photon background?

Or real electron neutrino appearance?

MiniBooNE





MiniBooNE is a mineral oil Cerenkov detector.
→ Poor electron-photon separation.

Excess could be photon-like (mismodeled backgrounds) or electron-like (sterile neutrino?)

Or something more exotic?

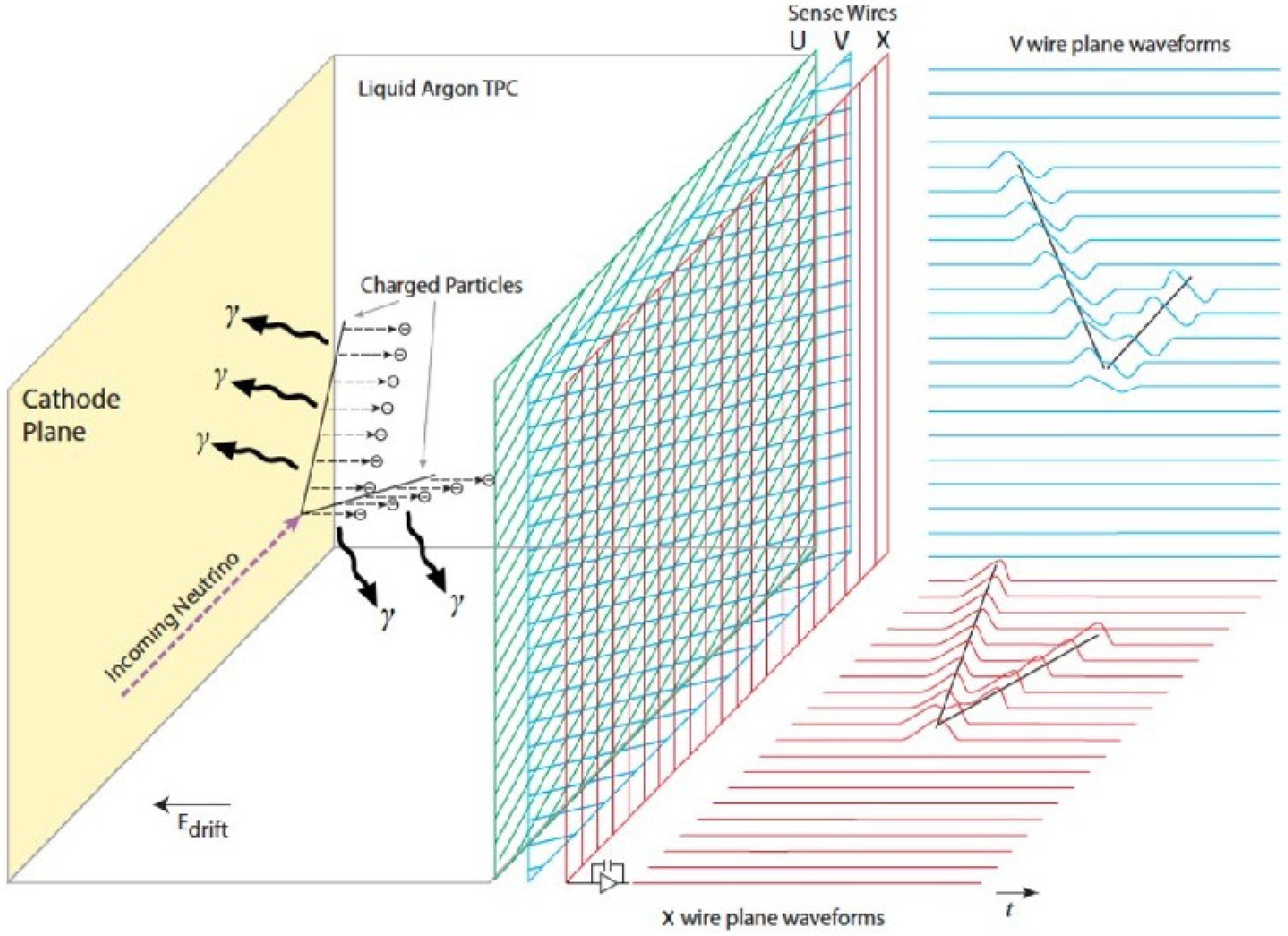
Enter MicroBooNE

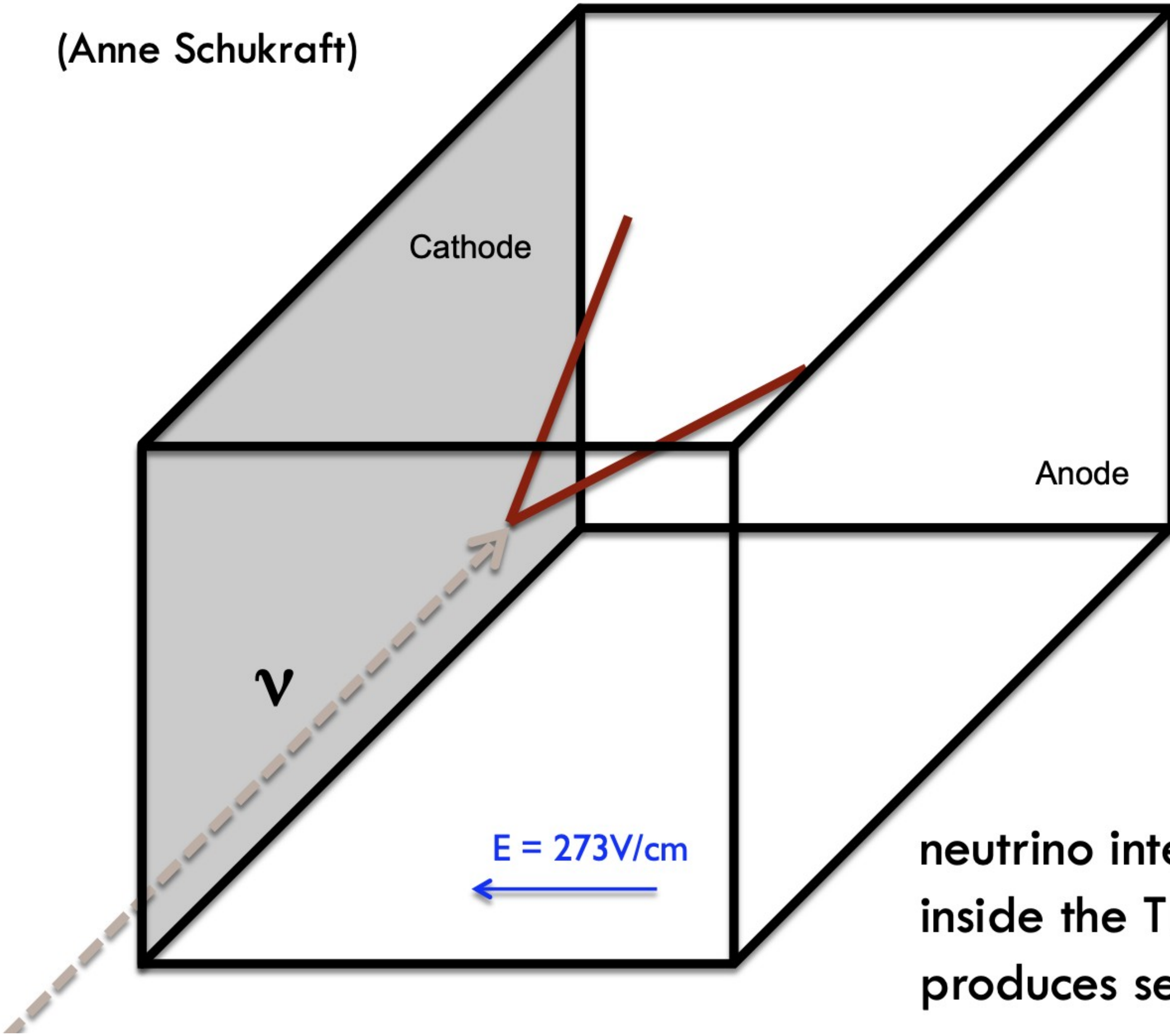
MicroBooNE?

- Designed to probe the LSND-MiniBooNE anomaly.
  - Same beam, baseline, L/E as MiniBooNE.
  - But a vastly improved detector technology – the LArTPC.
- Liquid Argon TPCs have excellent ability to distinguish between electrons and photons.
  - Which lets us understand if the MiniBooNE excess was really caused by electron neutrinos, or some kind of photon background induced by the remaining muon neutrinos in the beam.

85 t fiducial LArTPC
Exposed in the same beam as MiniBooNE.

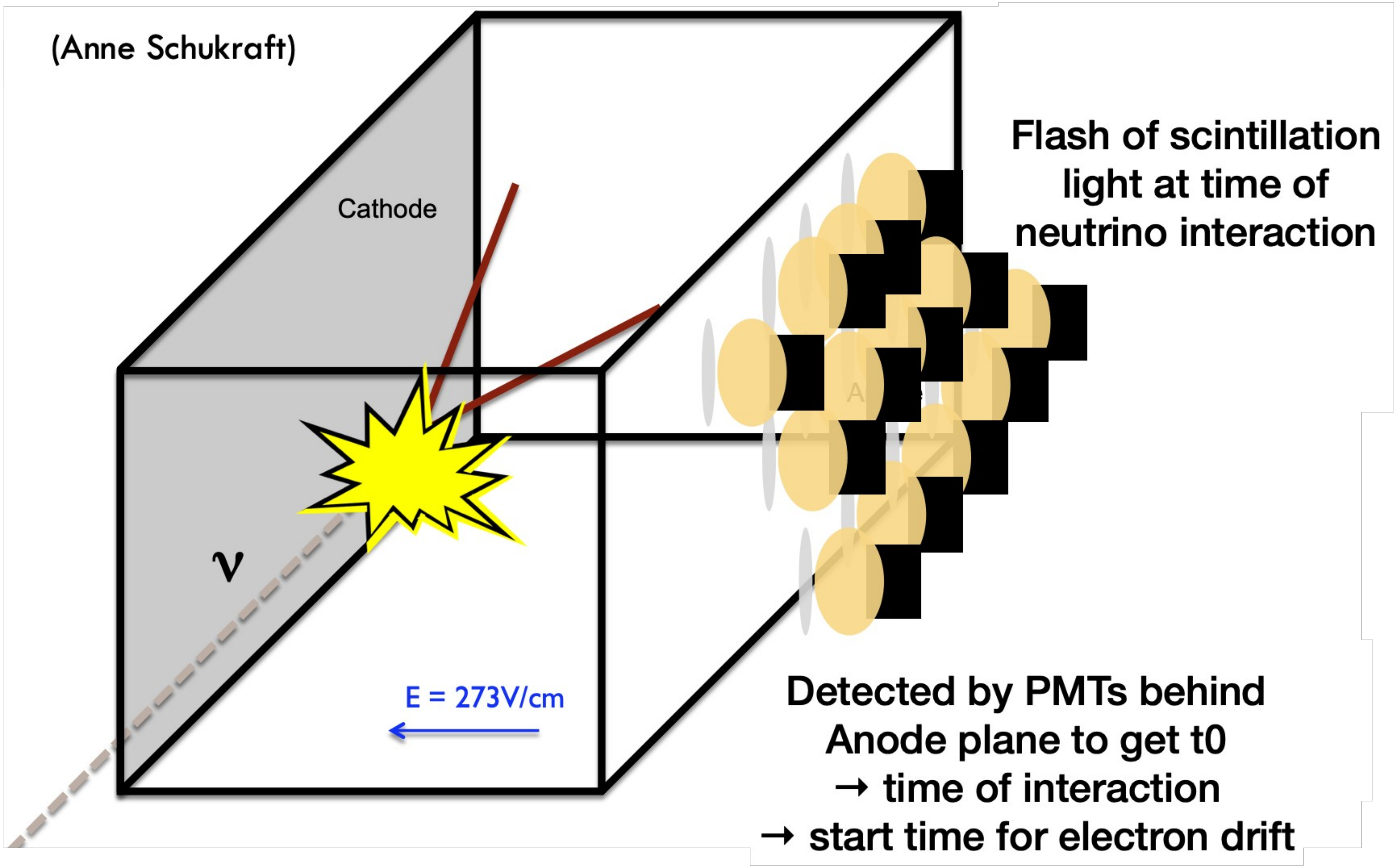
Liquid Argon TPCs

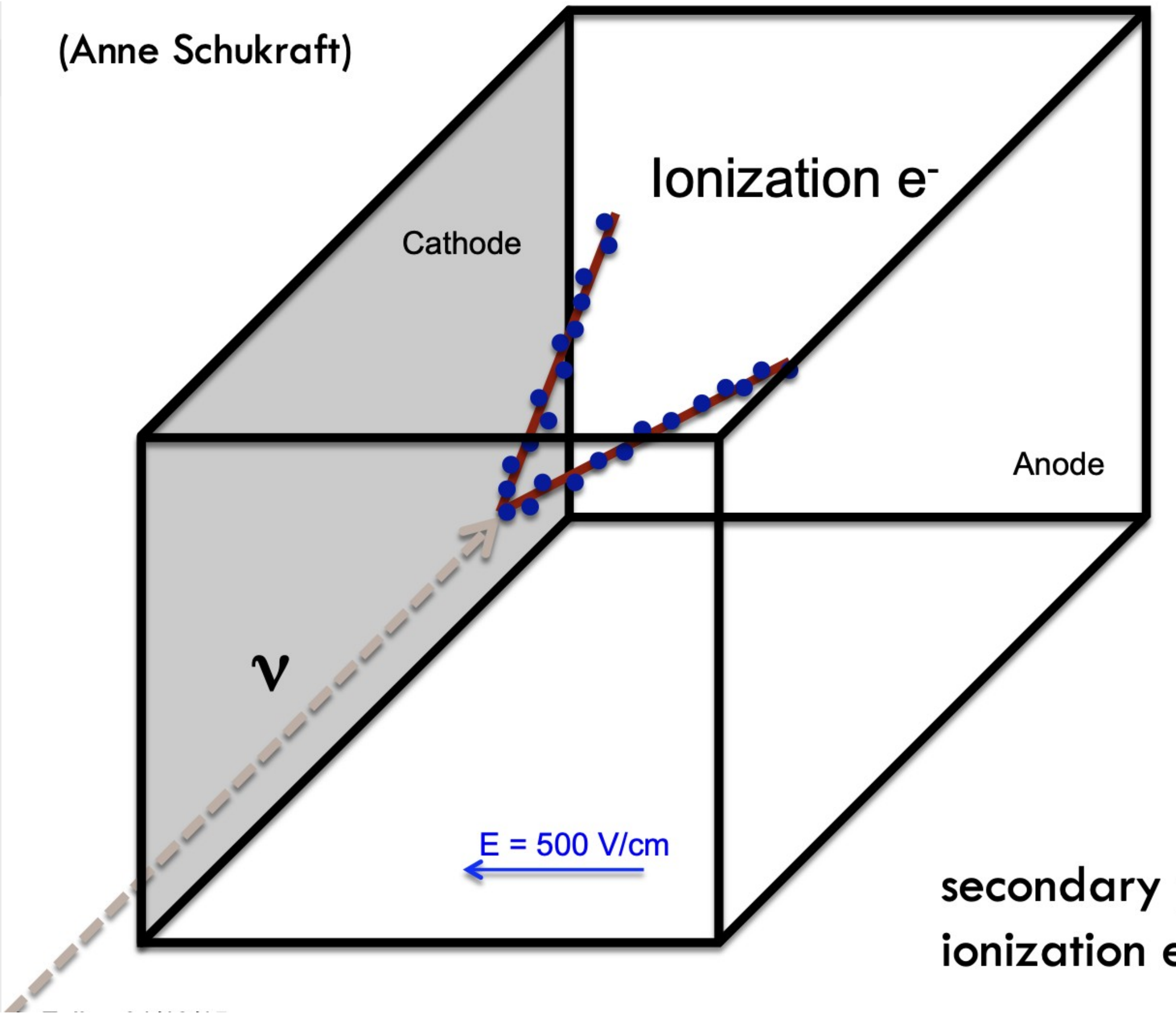




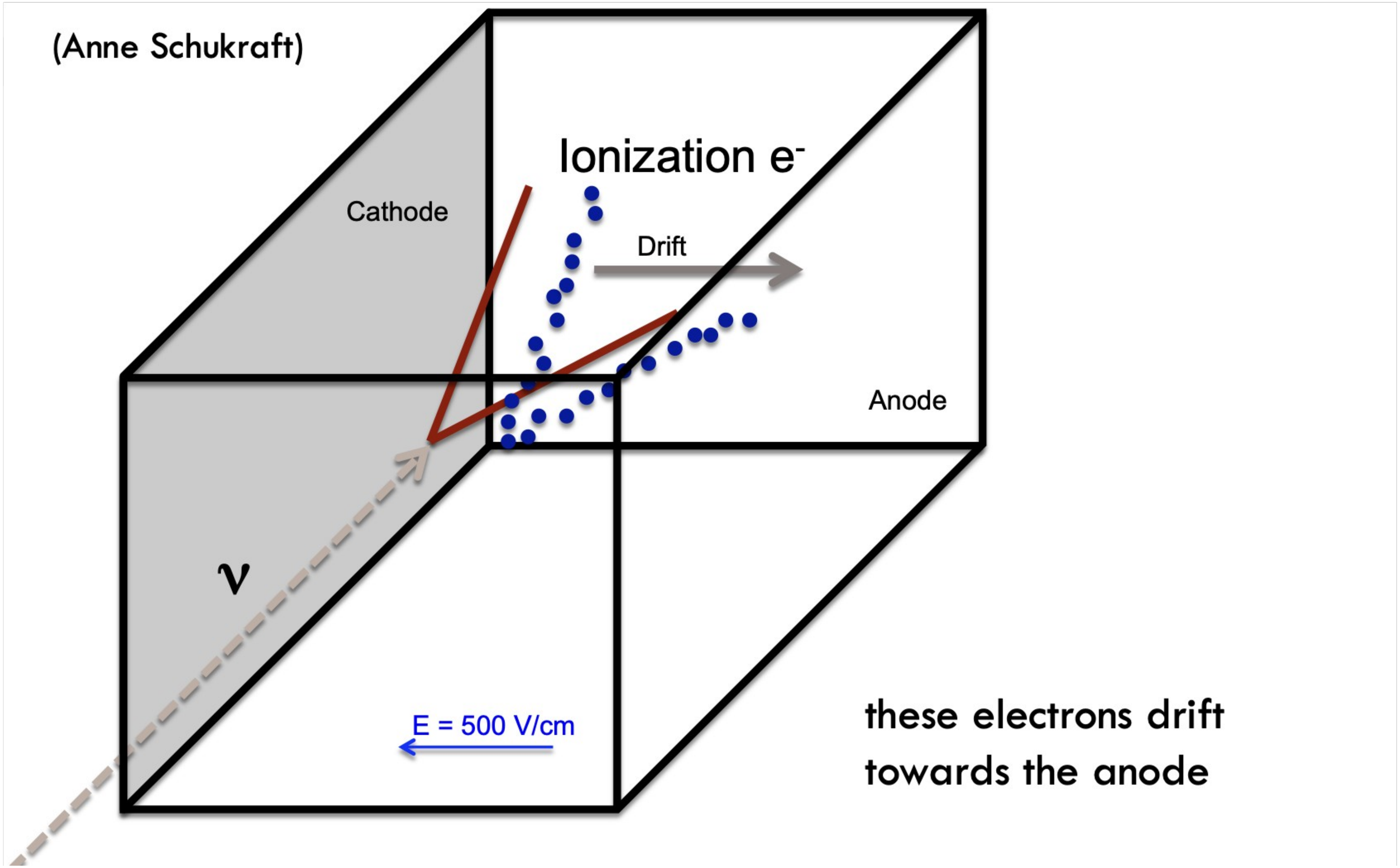
liquid argon detectors work differently than scintillator detectors so their “pictures” look different

neutrino interacts with the argon inside the TPC volume and produces secondary particles

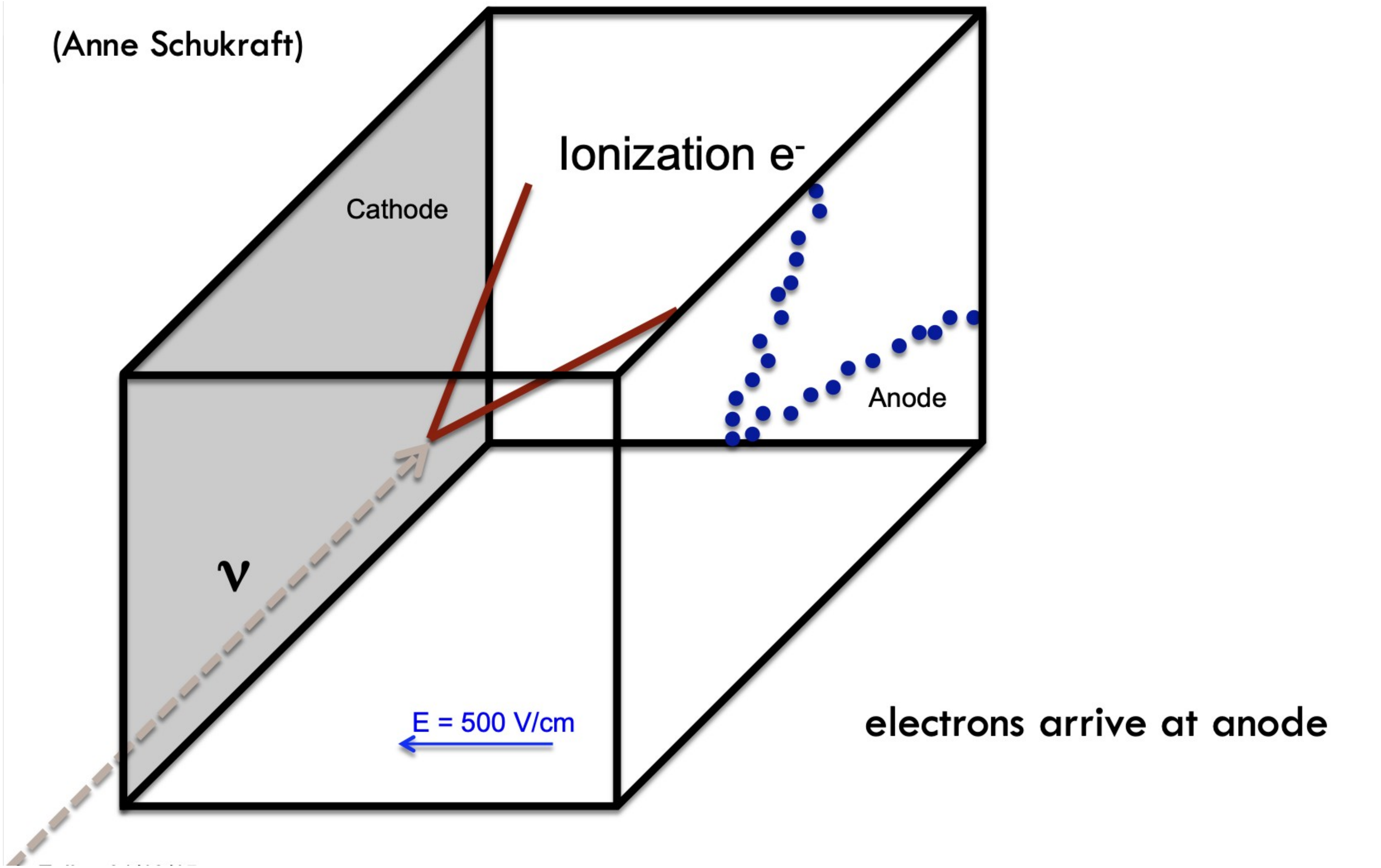

(Anne Schukraft)
Cathode
ν
E = 273V/cm
Flash of scintillation light at time of neutrino interaction
Detected by PMTs behind Anode plane to get t0
→ time of interaction
→ start time for electron drift

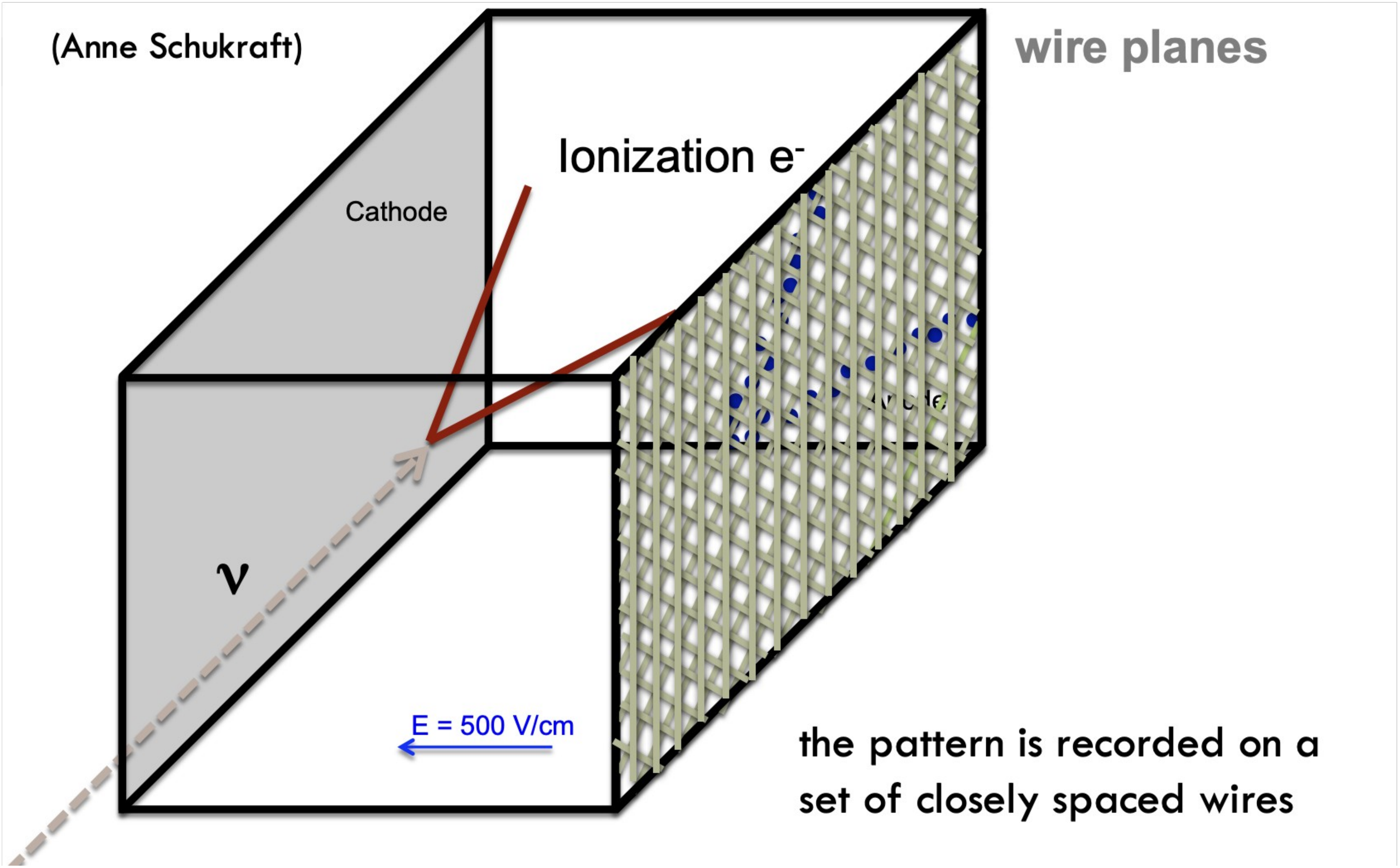


secondary particles produce ionization electrons

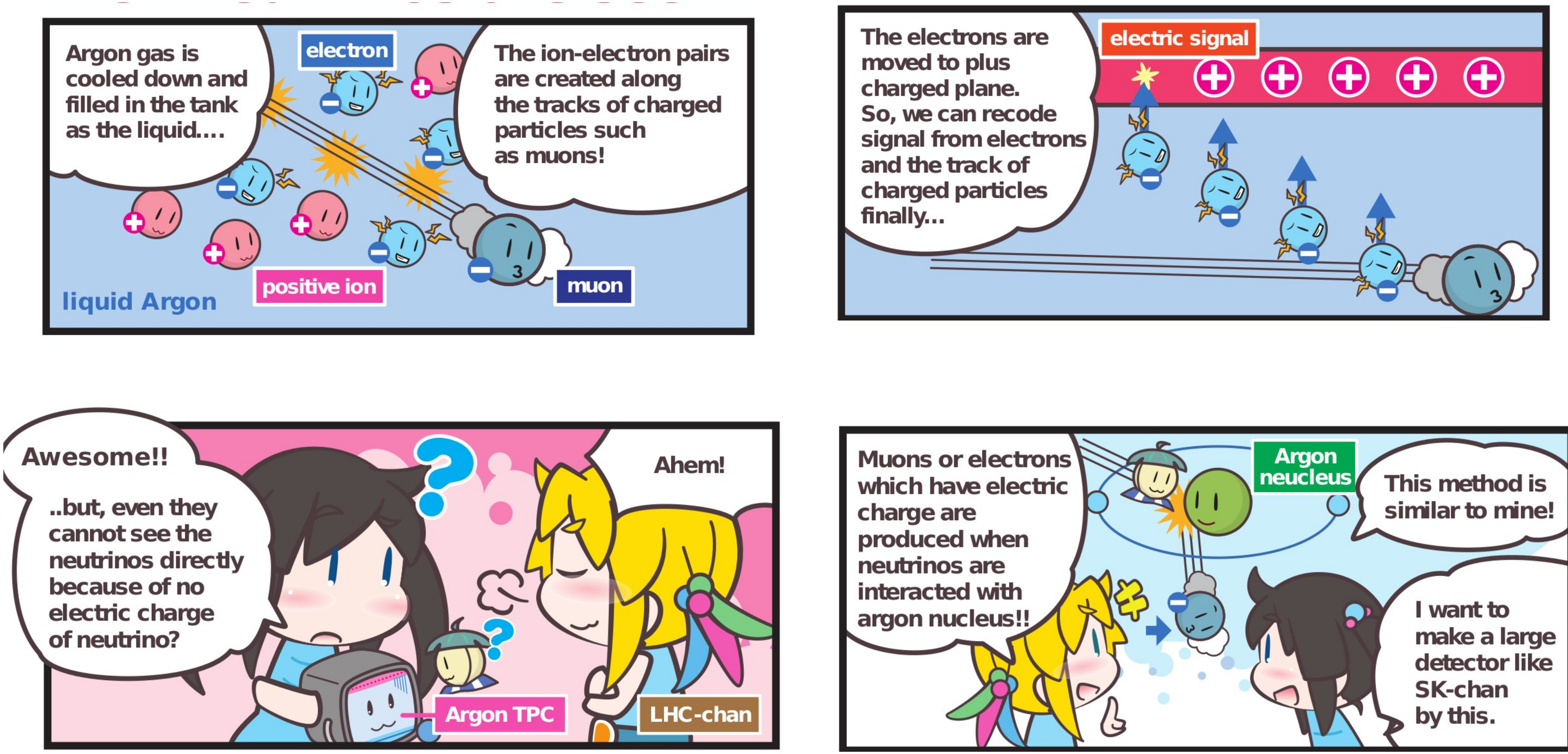


these electrons drift towards the anode


(Anne Schukraft)
Ionization e-
Cathode
Anode
ν
E = 500 V/cm
electrons arrive at anode

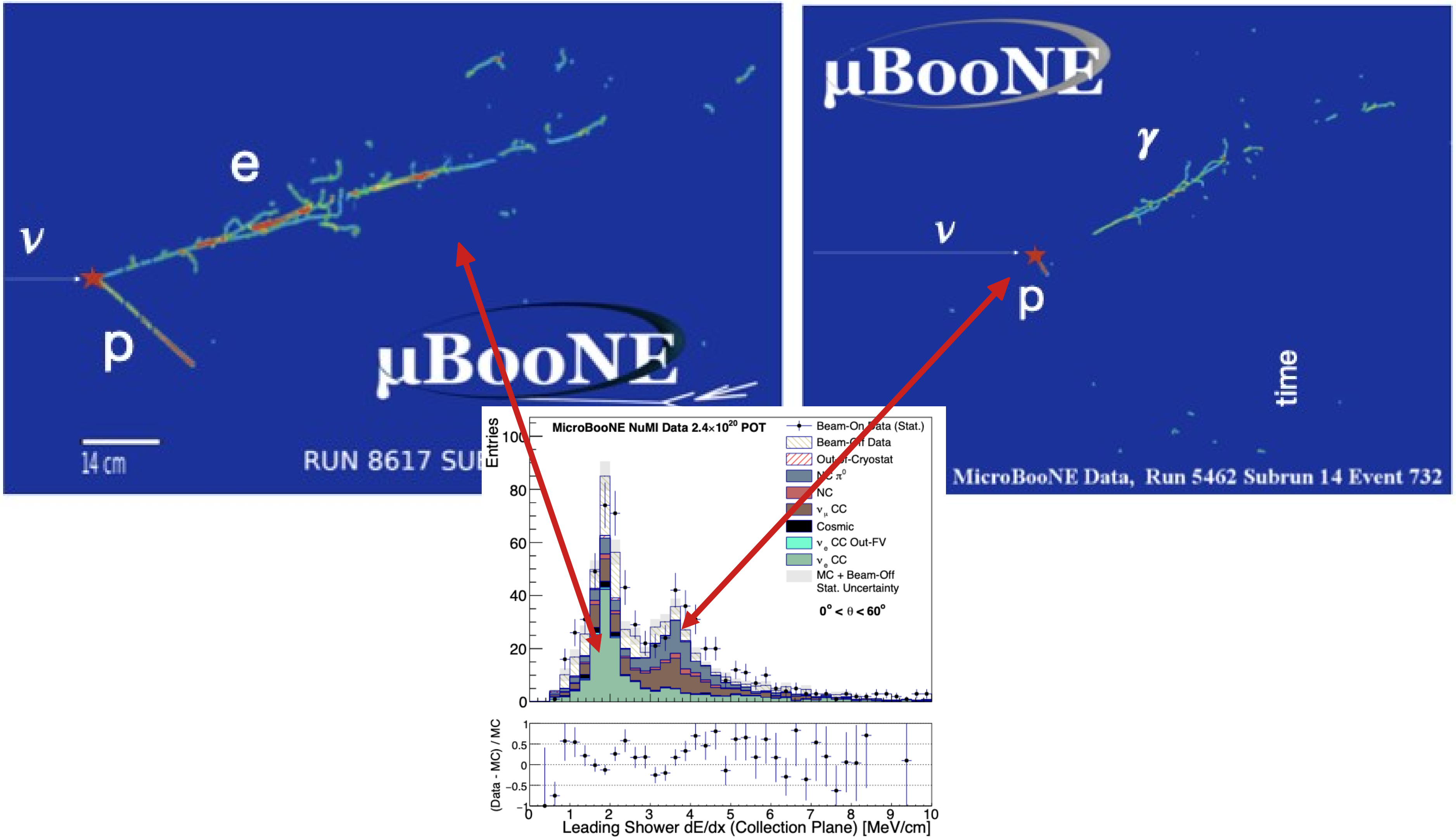

(Anne Schukraft)
wire planes
Ionization e⁻
Cathode
ν
E = 500 V/cm
the pattern is recorded on a set of closely spaced wires

Liquid Argon TPC



A fully active tracking calorimeter: excellent resolution, and target-as-tracker is great for neutrinos which need high density.

MicroBooNE Event Displays



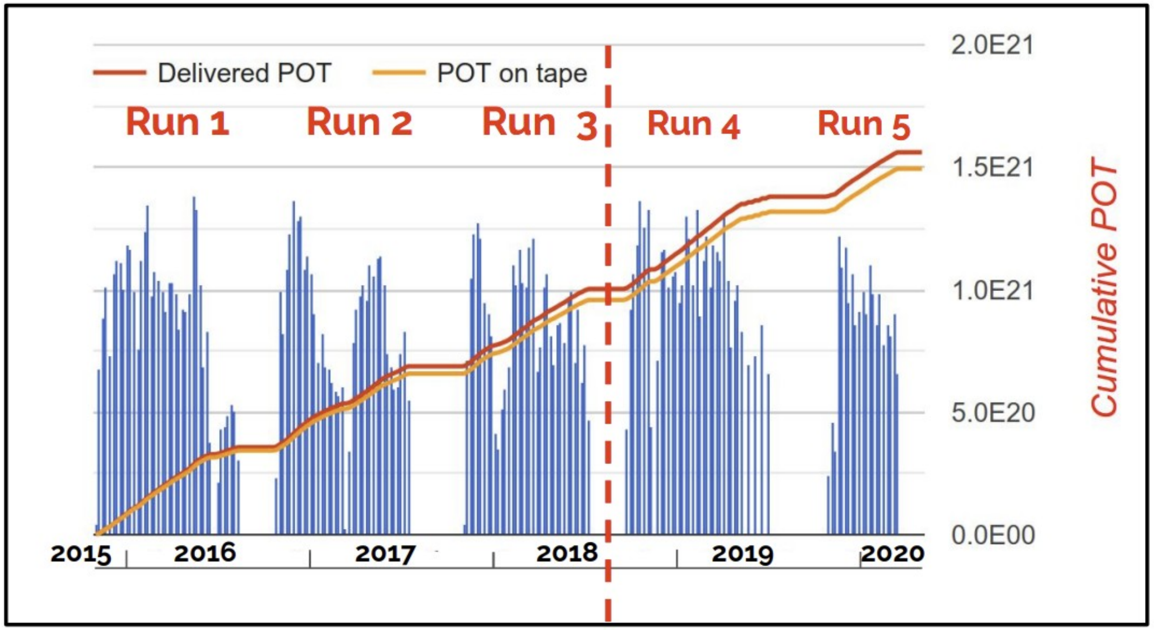
Ability to see hadronic system allows vertexing.

Can determine shower distance from vertex:

→ Distinguish electrons and photons.

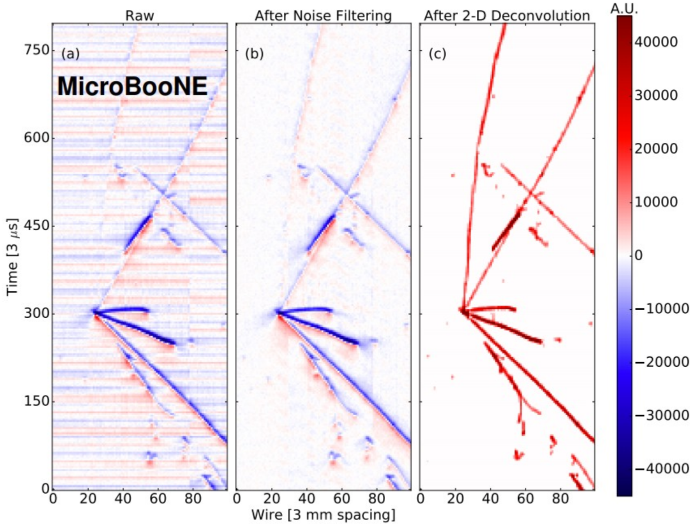
MicroBooNE Running

- Collected data since 2015.
  - Currently analysing half of the collected POT (6.8×10^{20} POT)
- Successfully operating LArTPC.
  - Important for future experiments! (eg DUNE)
- Neutrino interaction measurements.
- BSM physics searches.



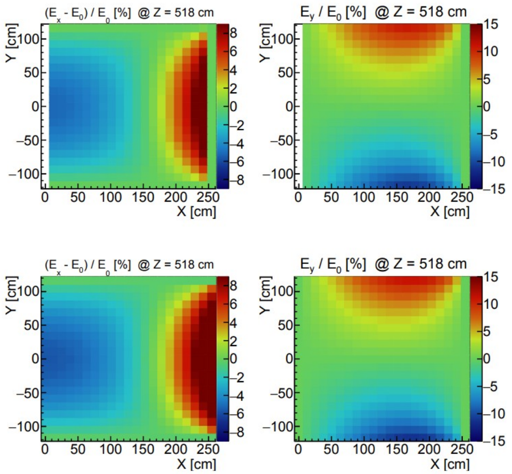
But before we start:

Signal Processing:
From raw signals on wires to
2D reconstructed "hits"



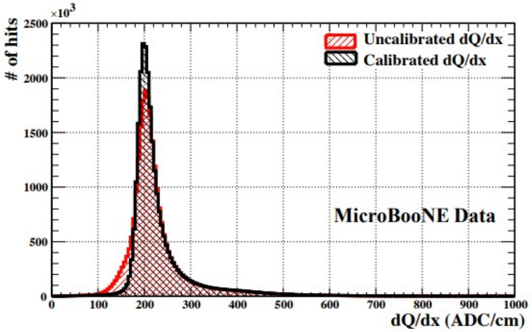
JINST 13, P07006 (2018) JINST 12 P08003 (2017)

Electric field calibration with lasers and cosmic muons



JINST 15 (2020) 07, P07010
JINST 15 (2020) P12037

Calorimetry calibration with crossing muons and π^0 samples

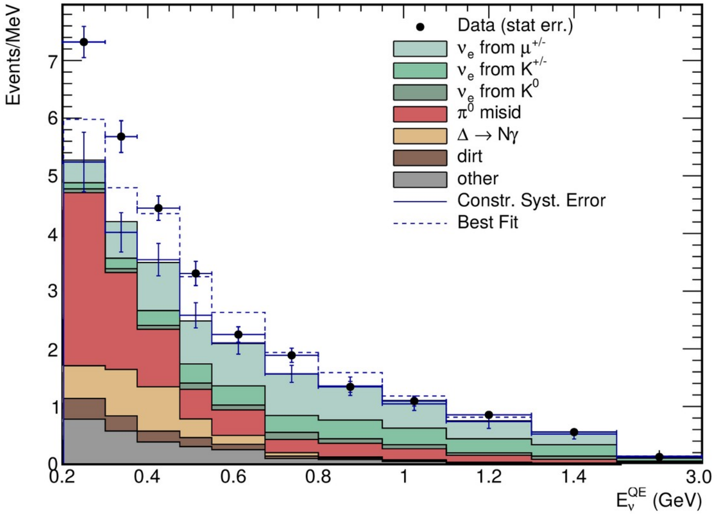


JINST 15 (2020) 03, P03022
JINST 15 (2020) 02, P02007

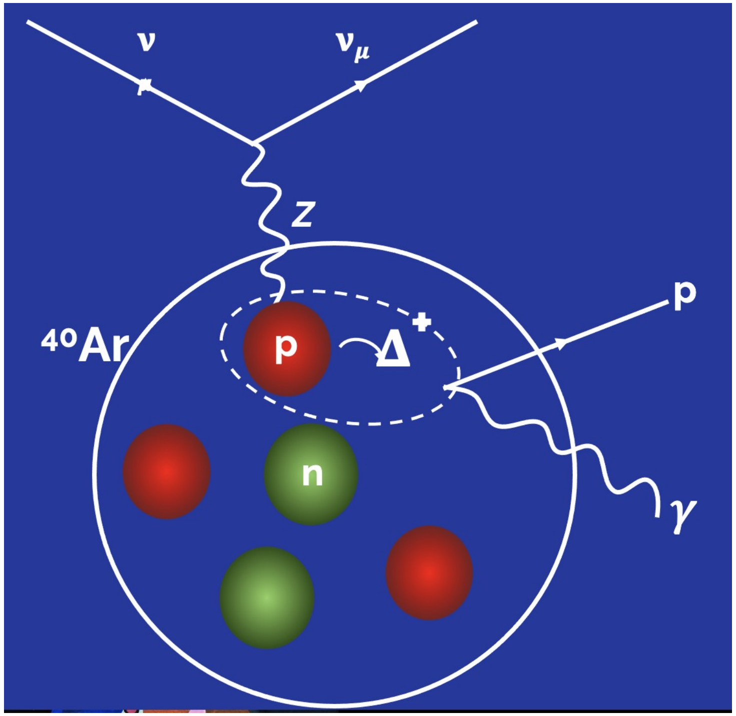
Adapted From J. Evans.

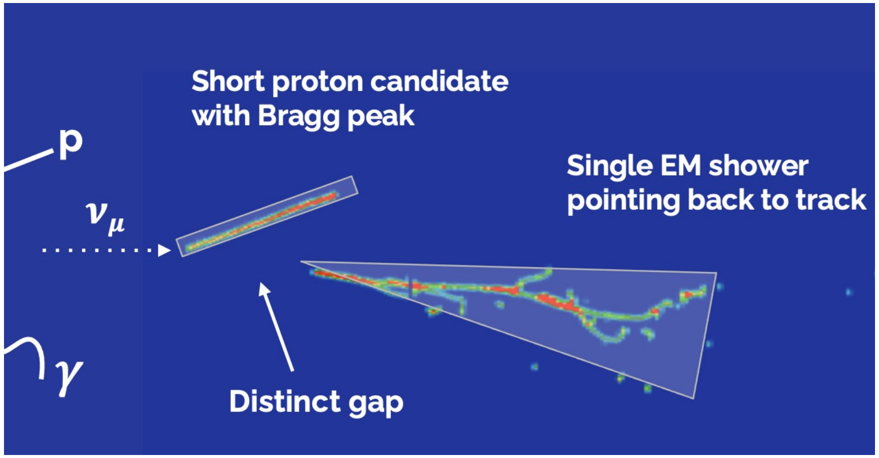
The MicroBooNE LEE Analyses

- Released four independent Low Energy Excess analyses.
  - Carefully validated before unblinding.
  - Search for a MiniBooNE-like excess in our data – which we can do without assuming a specific new-physics hypothesis.
- Three search for an electron-neutrino induced MiniBooNE-like excess.
  - Exclusive two-body charged current quasi-elastic nuE scattering (1e1p).
  - Semi-inclusive charged current nuE scattering without final state pions (1eNp0pi and 1e0p0pi)
  - Inclusive nuE scattering (1eX).
- One searches for a photonic MiniBooNE-like excess.
  - Using NC Δ → Nγ hypothesis
    - 1γ0p, 1γ1p



Photon-Like Analysis





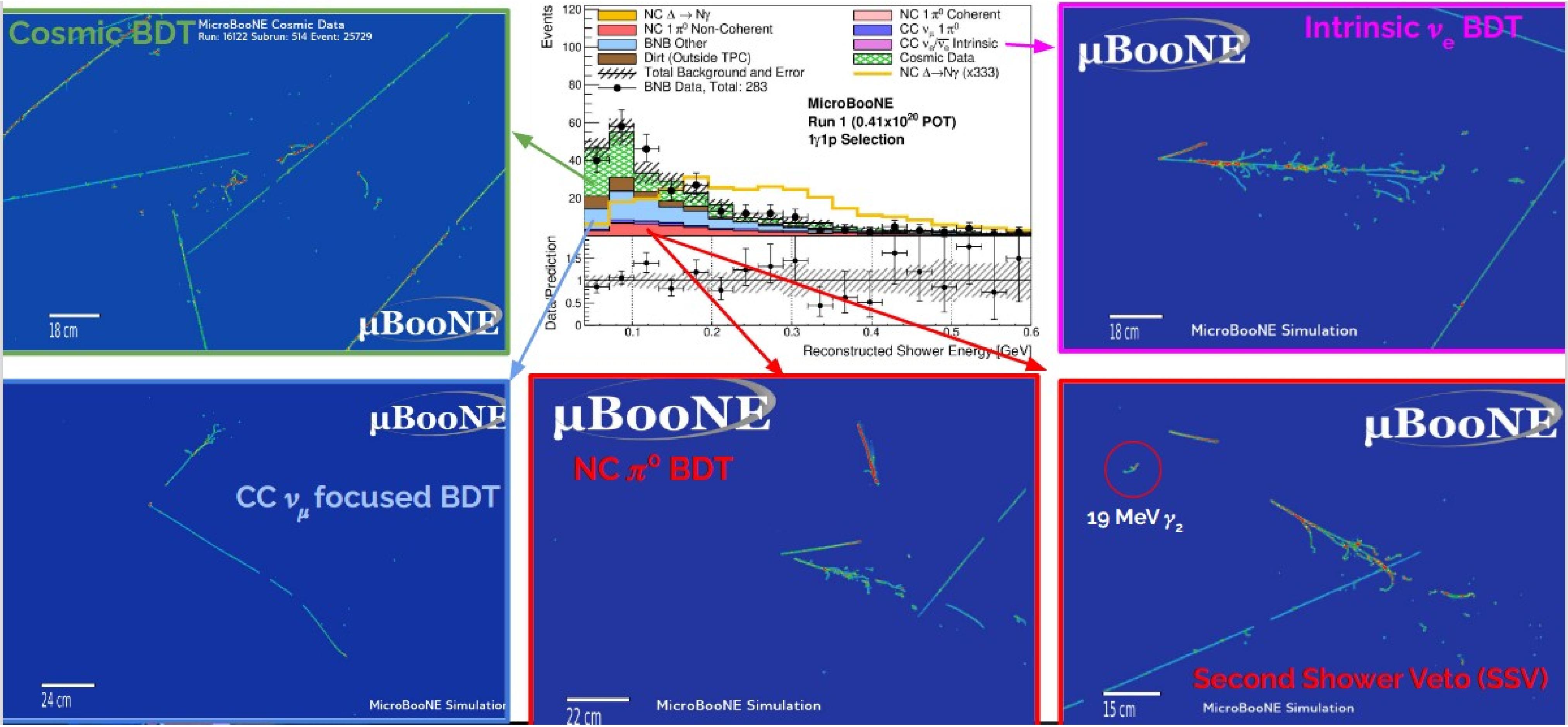
Uses two two-photon selections to constrain NCπ^0 background.

Physics modeled with GENIE v3.0.6
→ Berger-Sehgal resonance model.

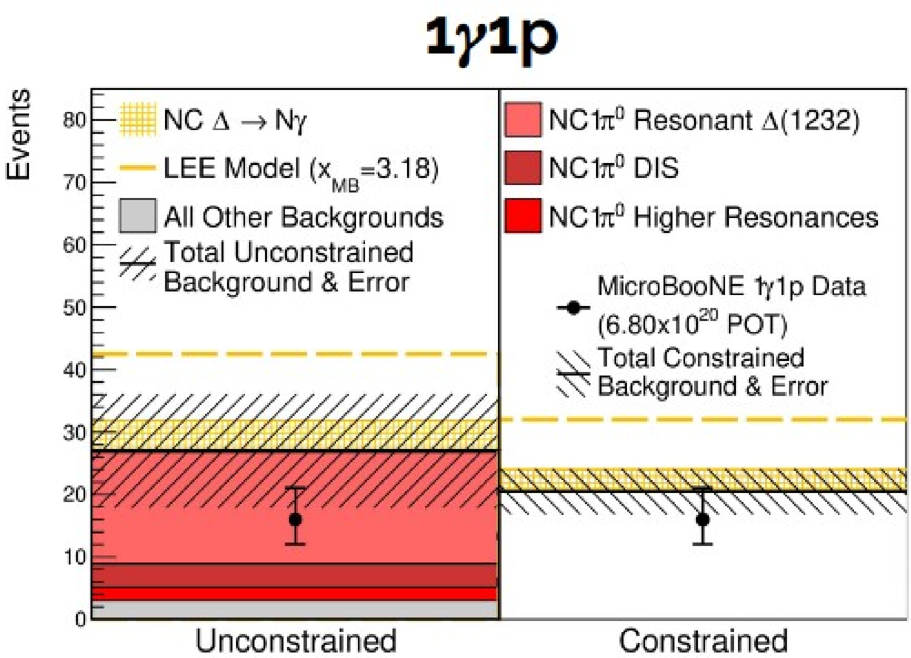
- To match MiniBooNE excess, requires 3.18x scaling of NC Δ → Nγ model.

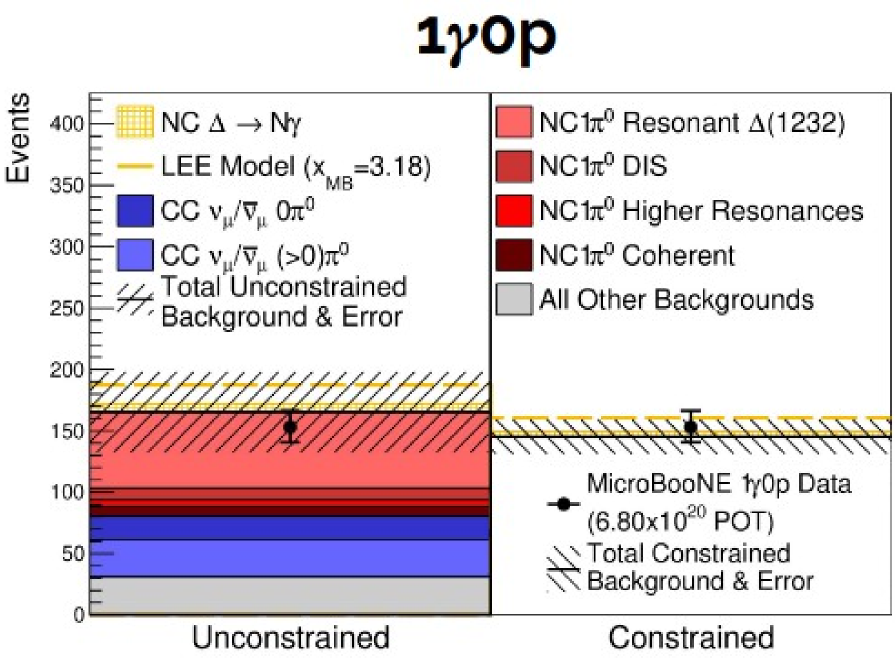
- Rare process, never directly observed, GENIE predicts 121.4 events for our $6.8\text{x}10^{20}$ POT dataset (pre-scaling).

Photon selection BDTs



Photon-like data





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

16
Data Events Observed

1γ0p	
Unconstr. bkgd.	165.4 ± 31.7
Constr. bkgd.	145.1 ± 13.8
NC $\Delta \to N\gamma$	+ 6.55
LEE ($x_{\text{MB}} = 3.18$)	+ 20.1

153
Data Events Observed

Photon Results

Entirely consistent with nominal prediction at 1-sigma.

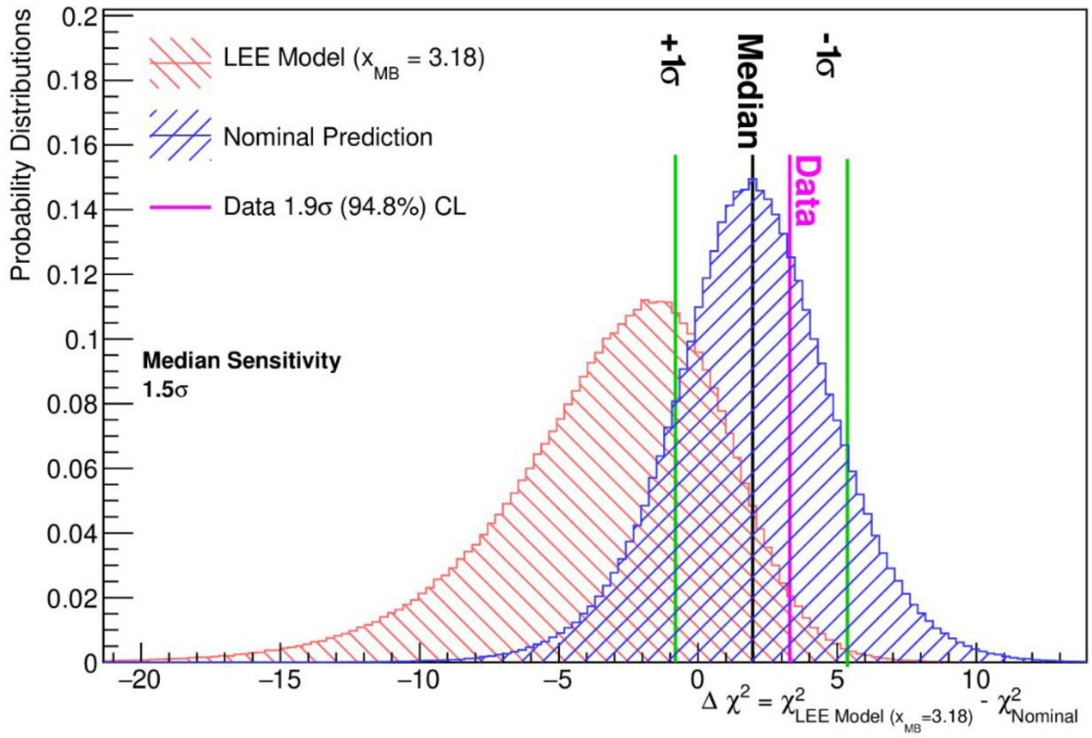
arXiv:2110.00409

- **Rejects the NC Δ → Nγ LEE hypothesis at 94.8% CL.**

Interpreted as branching fraction:

$$\mathcal{B}_{\text{eff}}(\Delta \to N\gamma) < 1.38\%$$

90% CL

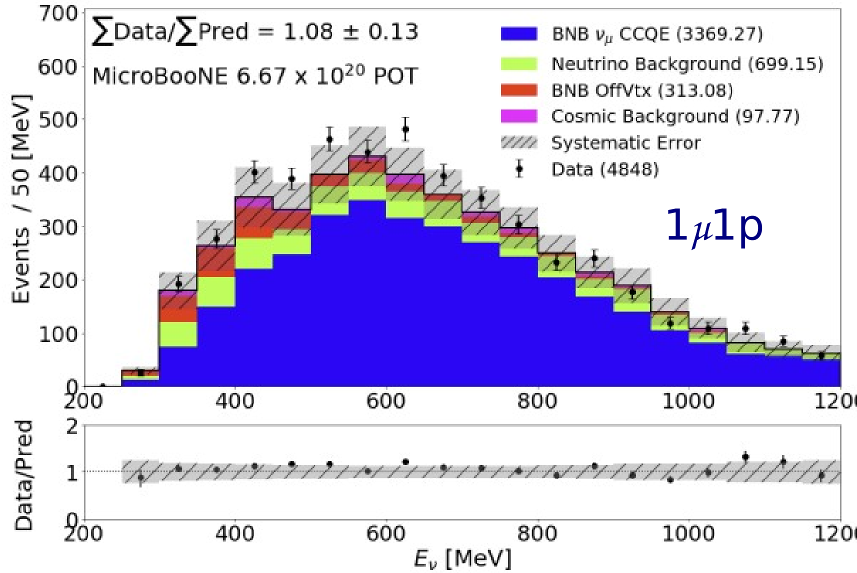


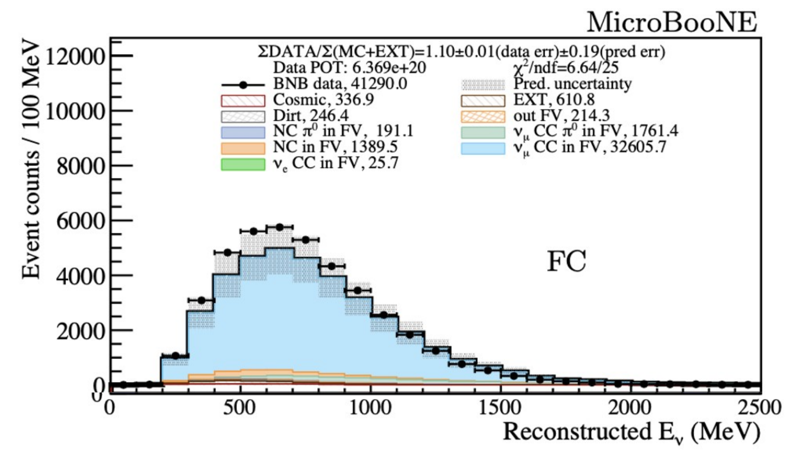
More than 50x better than world's previous limit!

Electron-like Search.

- Three independent analyses using different reconstruction.
  - Deep learning used for 1e1p.
  - Pandora used for 1eNp0pi/1e0p0pi.
  - Wire-Cell used for 1eX.
- Start with high-statistics muon-like samples.
  - Use to make data-driven electron-like prediction.
  - Heavily reduces uncertainties on electron-like spectrum.
- Use unfolded MiniBooNE-like excess to test hypothesis.

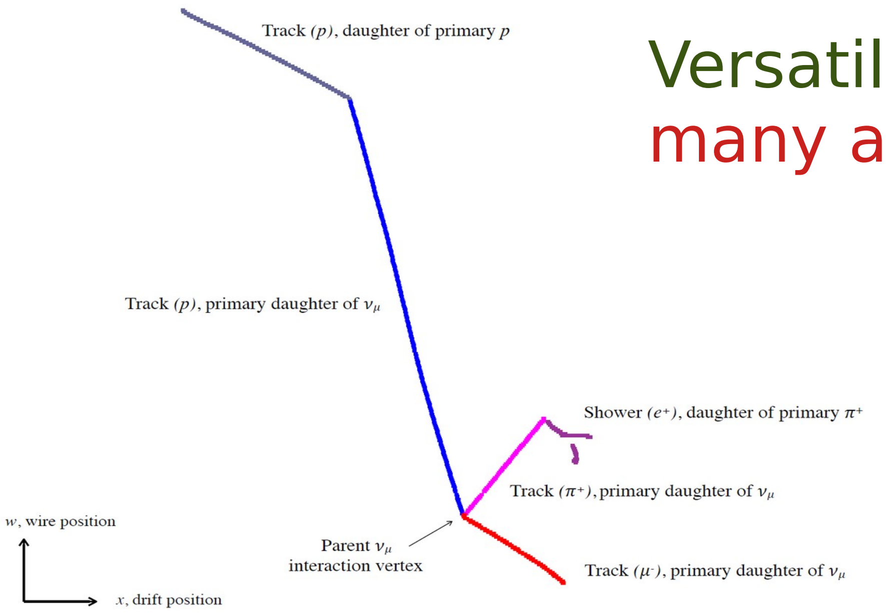
  → Not a sterile model!

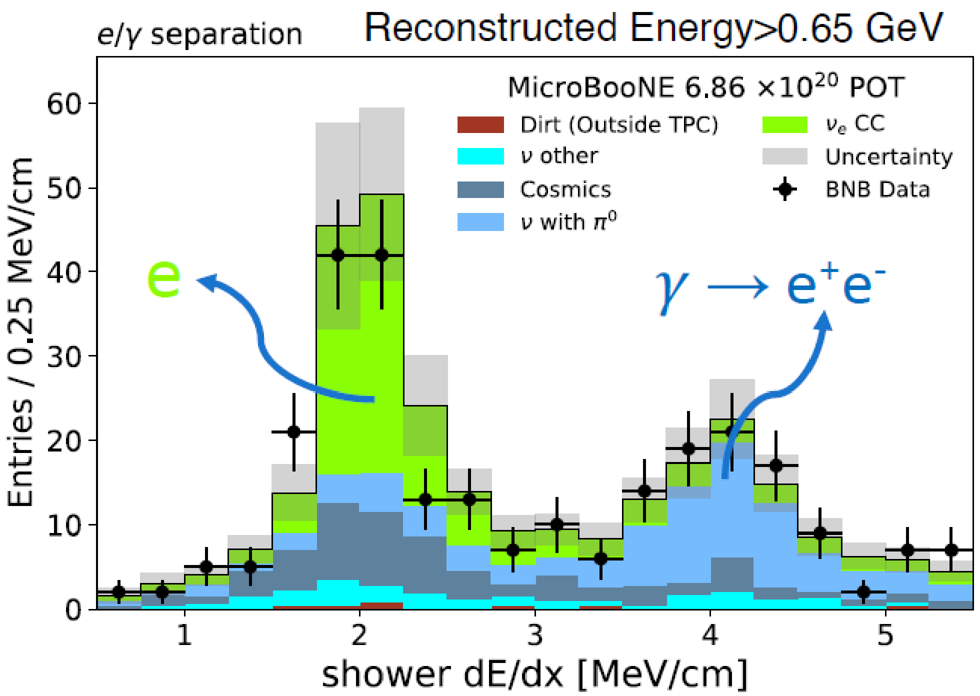


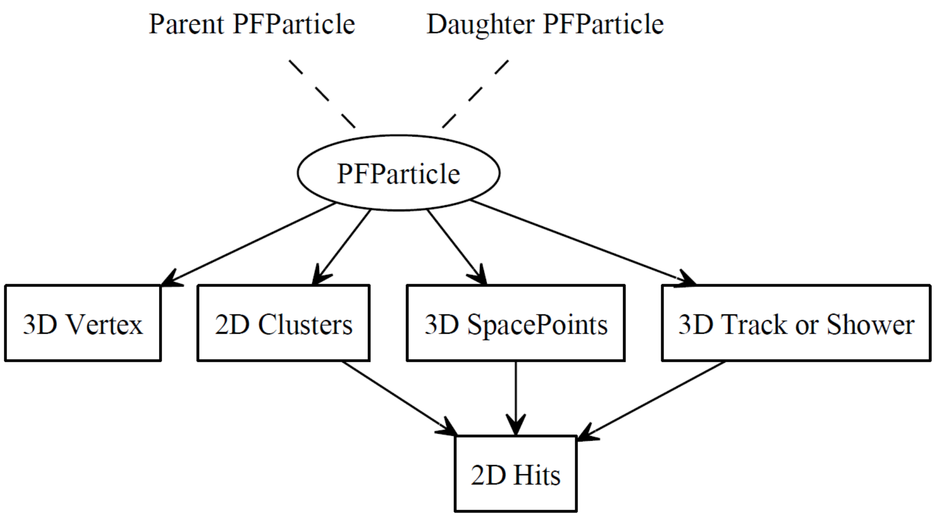


Pandora Reconstruction

Versatile pattern recognition used across many analyses and experiments.

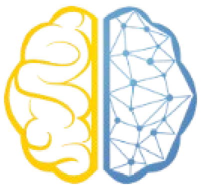


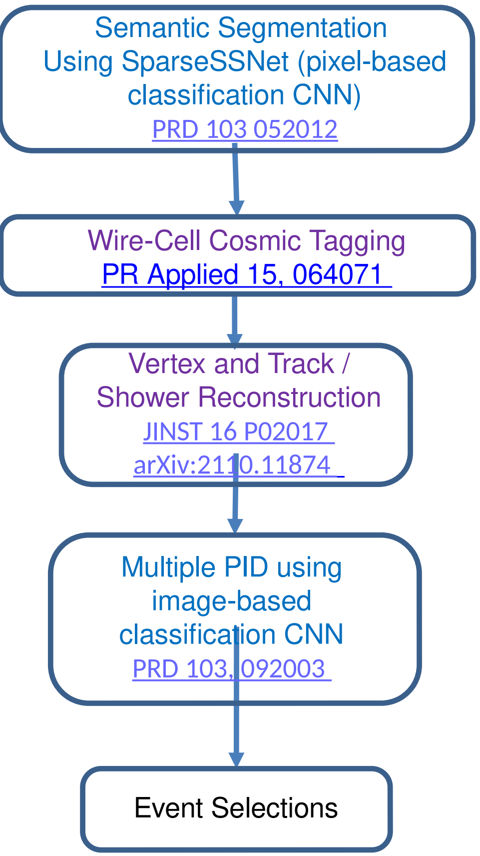


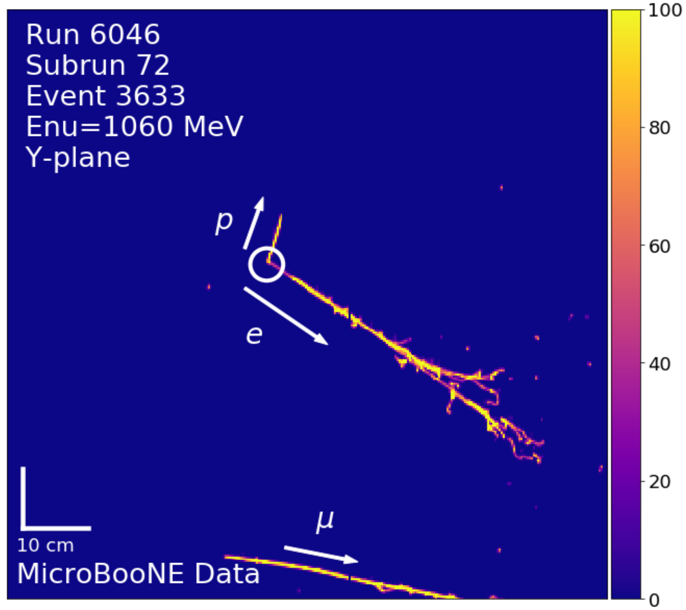


Eur. Phys. J. C78, 82 (2018)

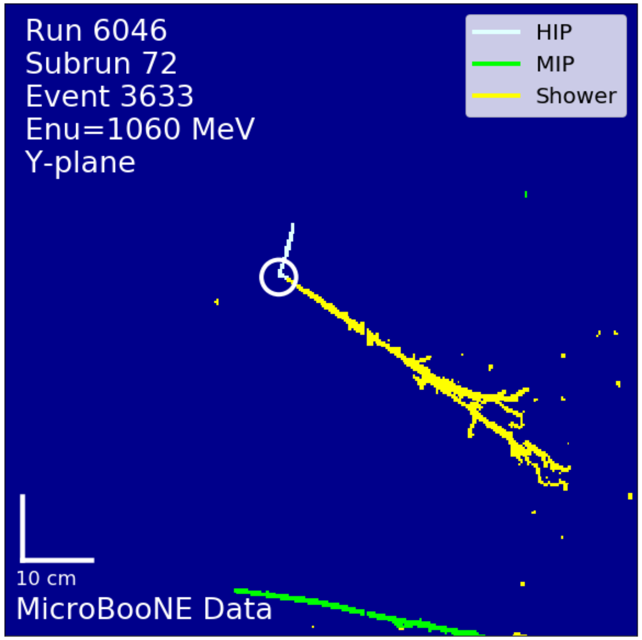
Deep Learning Reconstruction

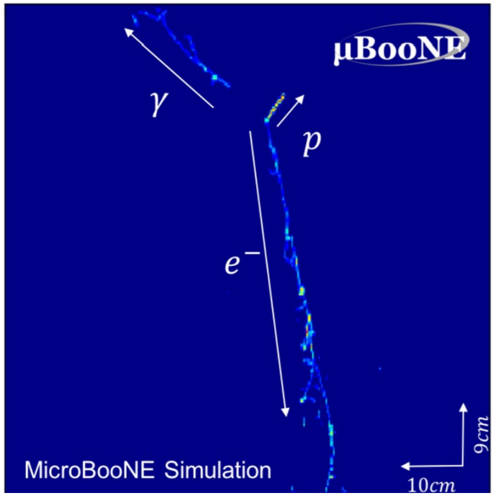






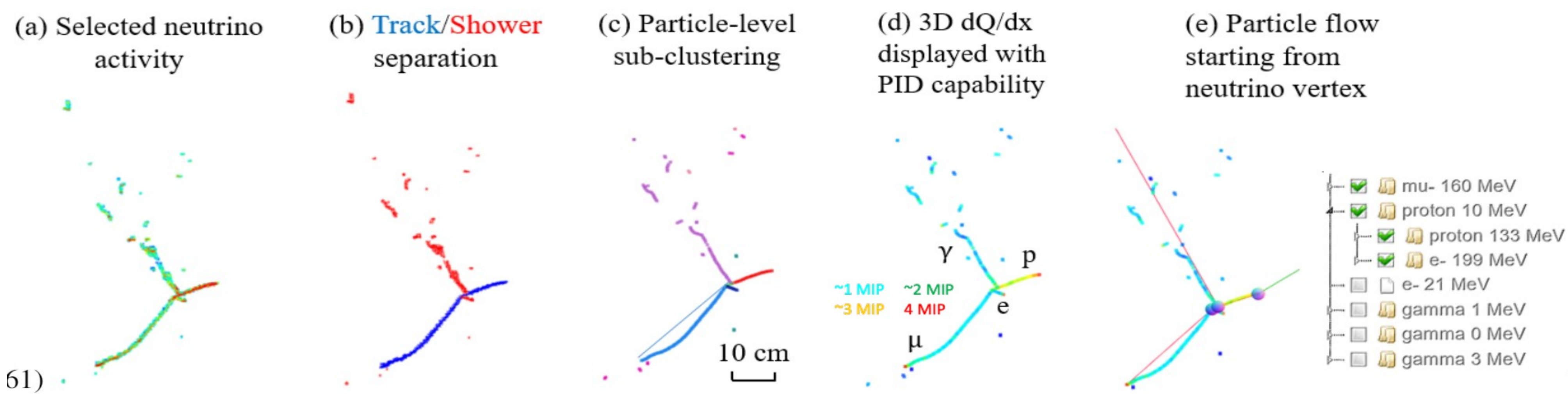
Uses computer vision methods for event classification.

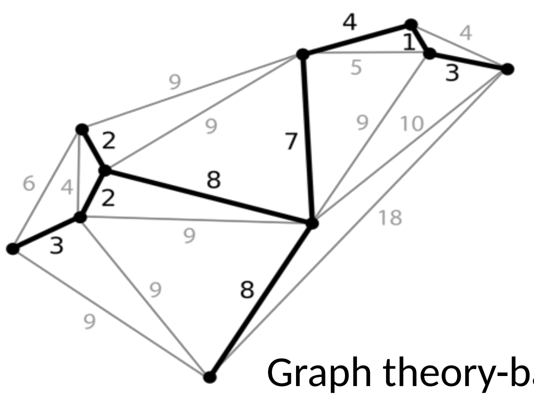




	p	e^-	γ	μ^-	$\pi^\pm$
MPID Score	0.89	0.95	0.85	0.06	0.17

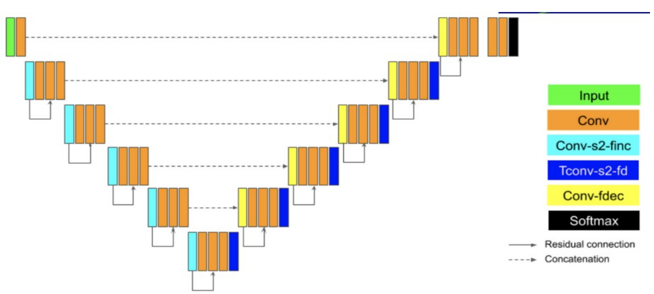
Wire-Cell Reconstruction





Graph theory-based multi-track fitting (e.g. Steiner tree)

Hybrid of Traditional and Deep-Learning based approaches

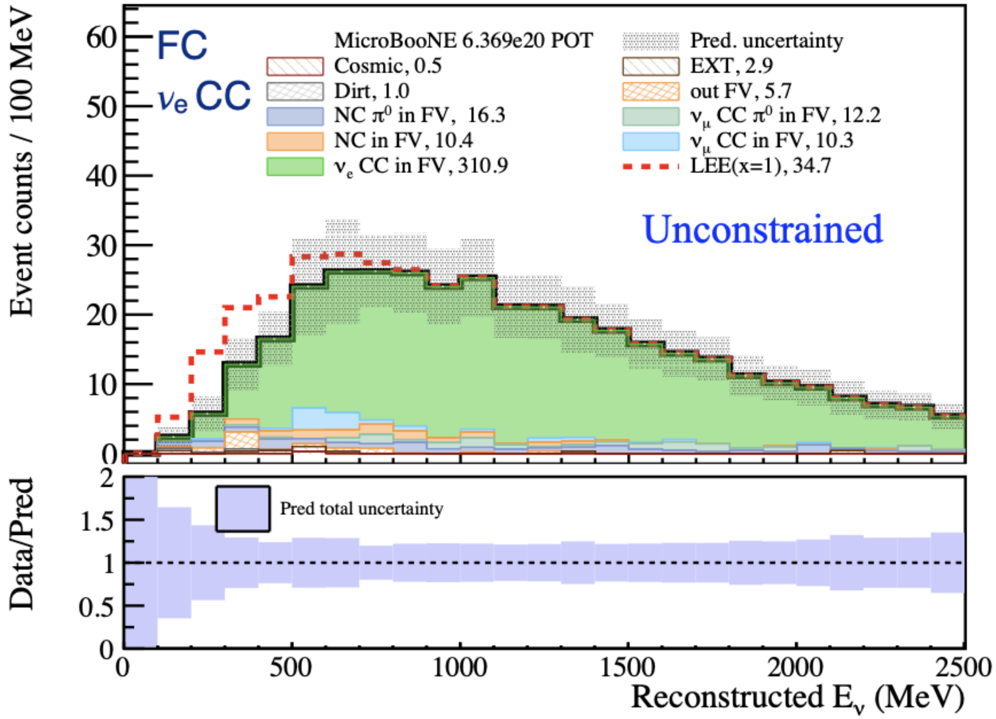


Deep-learning neural network for neutrino vertex identification

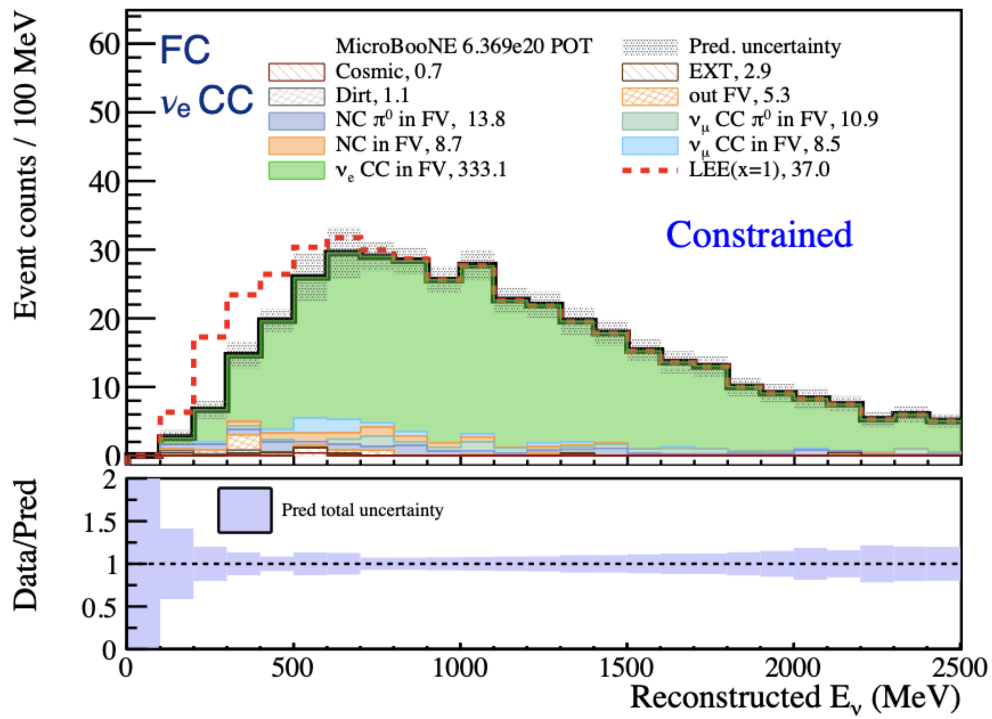
38

From X. Qian.

Constraints from muons



1eX (Wire-Cell)

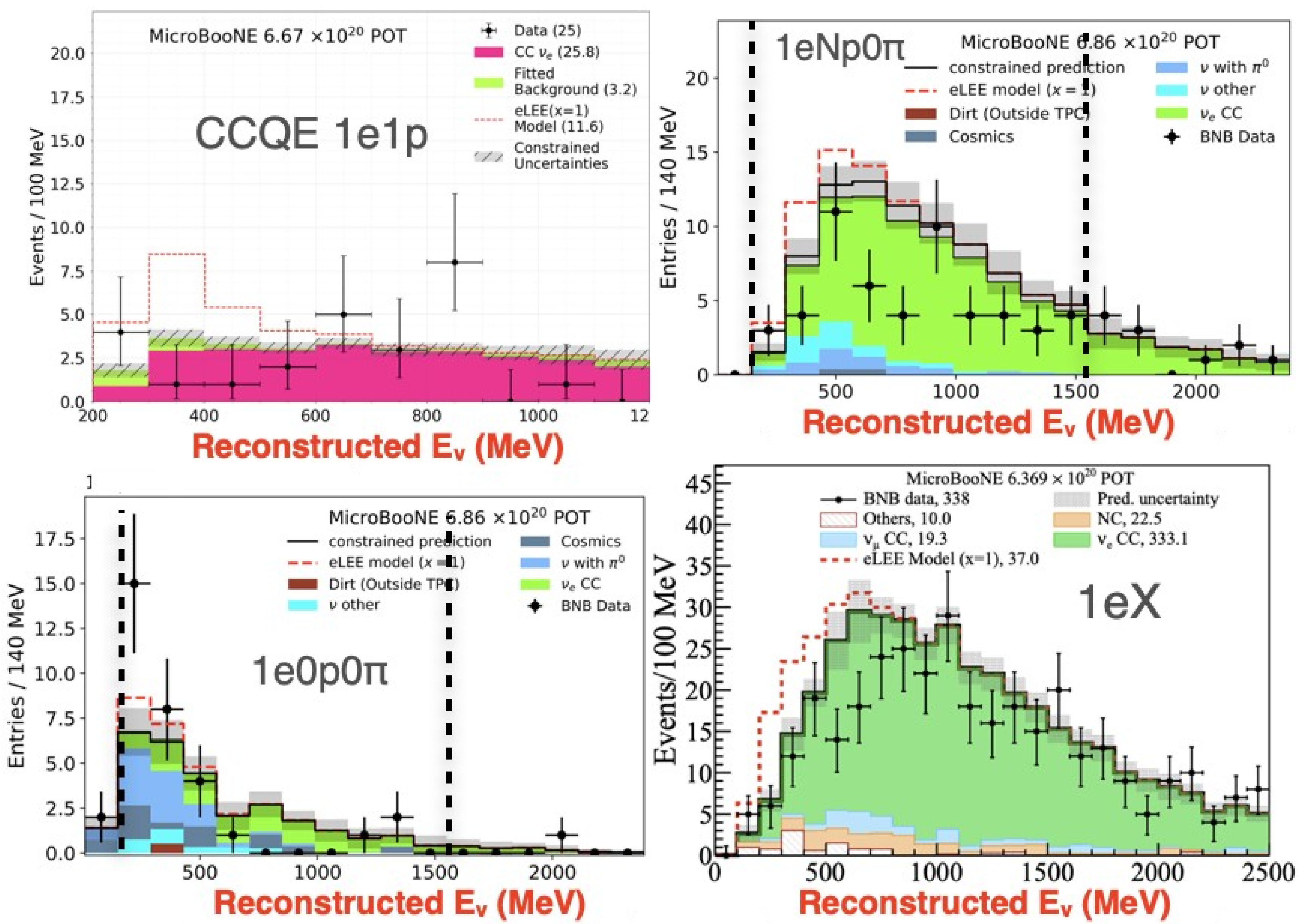


First complete analysis for LArTPC systematic uncertainties!

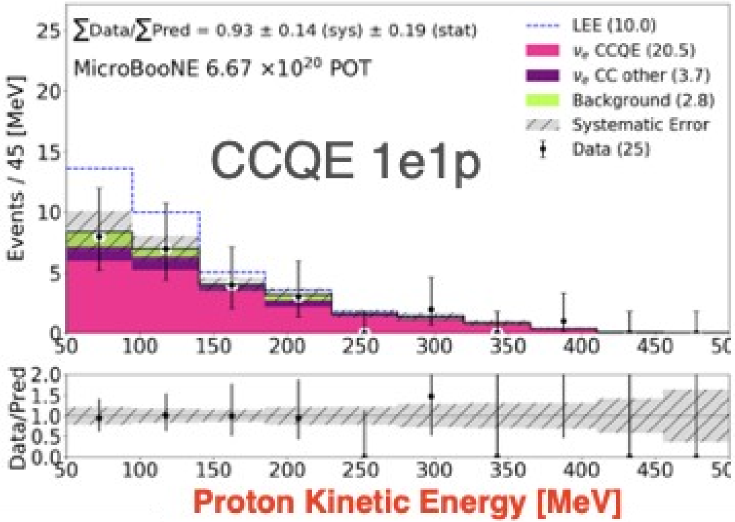
arXiv:2111.03556

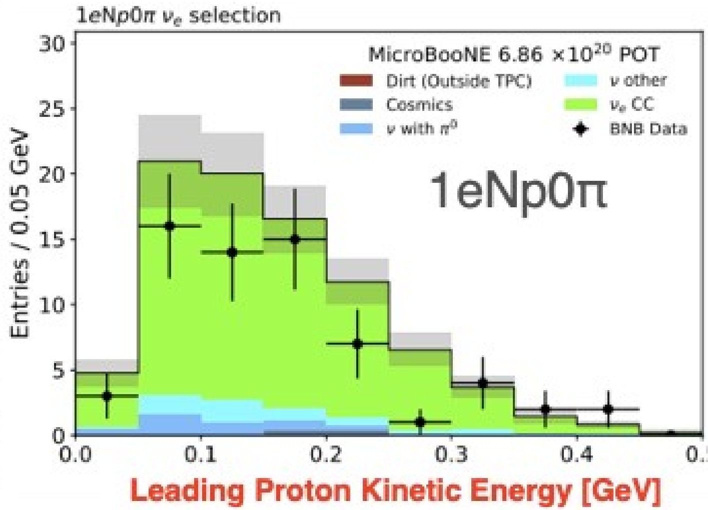
Uses novel data-driven technique.

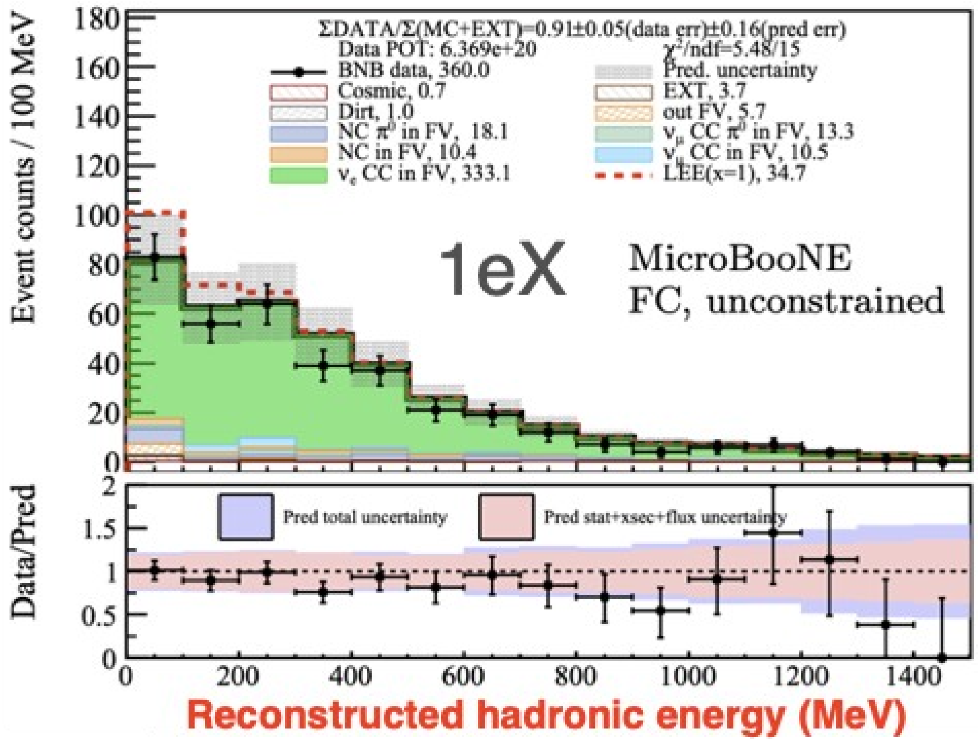
Electron-like Results - Neutrino Energy



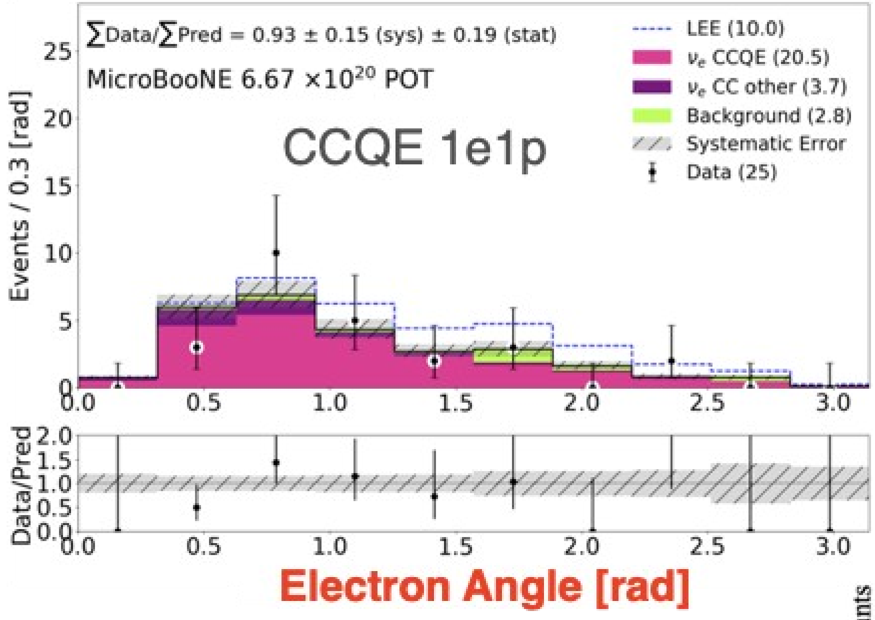
Electron-like Results – Hadronic Energy

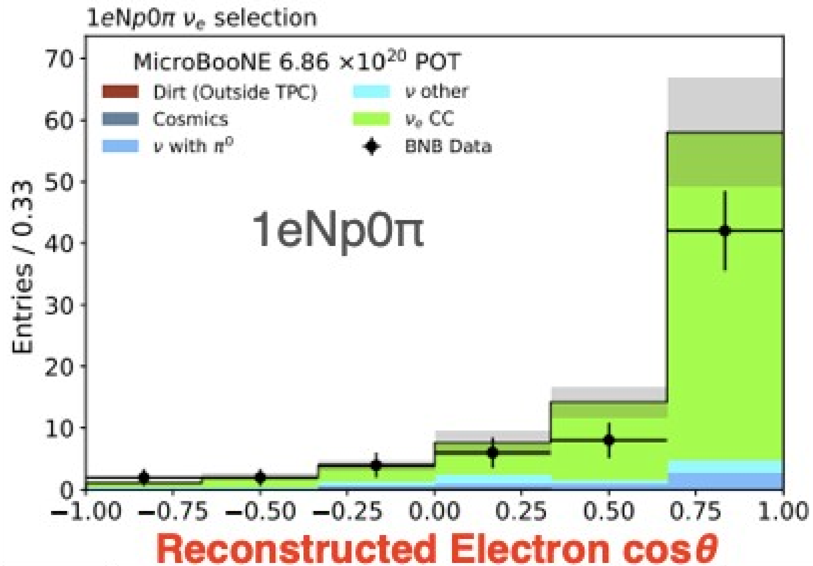


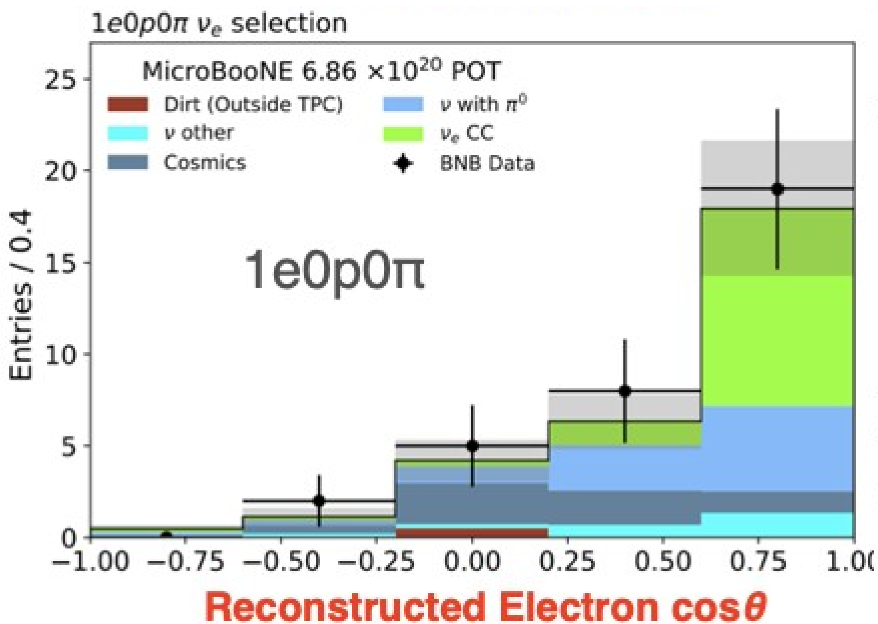


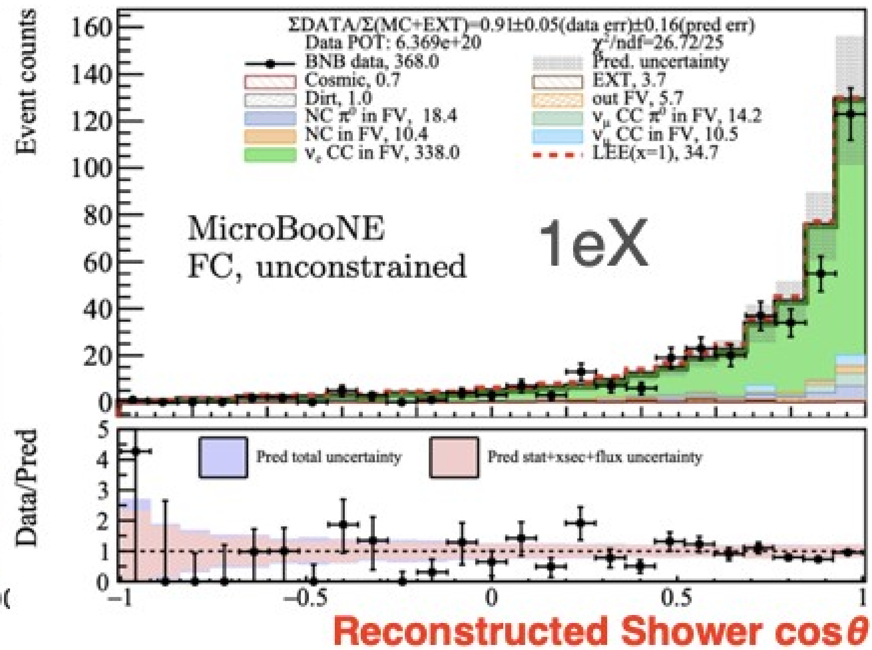


Electron-like Results – Lepton Angle

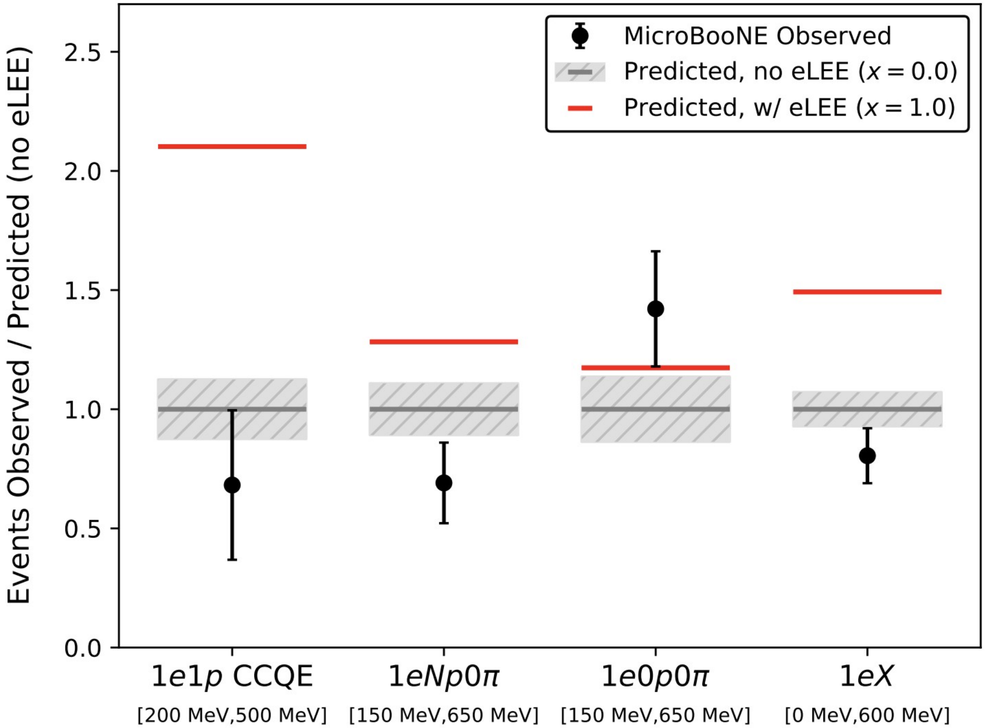








Electron-like Results



Observe electron neutrino candidates at or below predicted rates.

arXiv:2110.14054

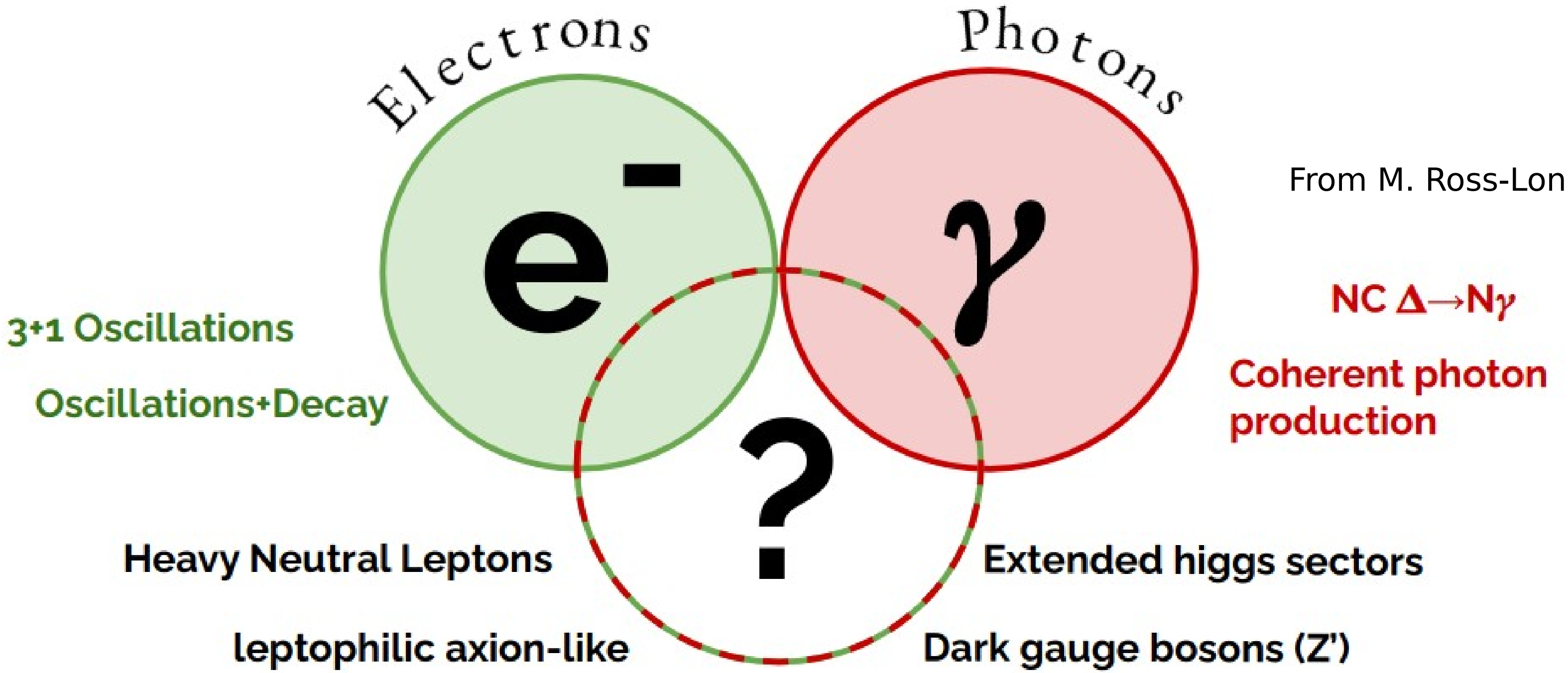
Reject the hypothesis that simple electron neutrino charged current explains fully the MiniBoonE results at >97% CL in all analyses.

1eX analysis rejected median MiniBooNE electron-like model at 3.75σ

UNIVERSITY OF CAMBRIDGE

So, what's happening?

- I don't know.
  - But it's going to be interesting to find out.



From M. Ross-Lonergan

But the LSND-MiniBooNE data exists. It doesn't go away just because another experiment didn't see it. It still needs to be explained.

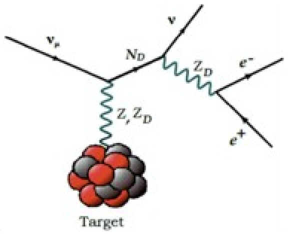
Or what else?

- Decay of O(keV) Sterile Neutrinos to active neutrinos
  - *[13] Dentler, Esteban, Kopp, Machado Phys. Rev. D 101, 115013 (2020)*
  - *[14] de Gouvêa, Peres, Prakash, Stenico JHEP 07 (2020) 141*
- New resonance matter effects
  - *[5] Asaadi, Church, Guenette, Jones, Szelc, PRD 97, 075021 (2018)*
- Mixed O(1eV) sterile oscillations and O(100 MeV) sterile decay
  - *[7] Vergani, Kamp, Diaz, Arguelles, Conrad, Shaevitz, Uchida, arXiv:2105.06470*
- Decay of heavy sterile neutrinos produced in beam
  - *[4] Gninenko, Phys.Rev.D83:015015,2011*
  - *[12] Alvarez-Ruso, Saul-Sala, Phys. Rev. D 101, 075045 (2020)*
  - *[15] Magill, Plestid, Pospelov, Tsai Phys. Rev. D 98, 115015 (2018)*
  - *[11] Fischer, Hernandez-Cabezudo, Schwetz, PRD 101, 075045 (2020)*
- Decay of upscattered heavy sterile neutrinos or new scalars mediated by Z' or more complex higgs sectors
  - *[1] Bertuzzo, Jana, Machado, Zukanovich Funchal, PRL 121, 241801 (2018)*
  - *[2] Abdullahi, Hostert, Pascoli, Phys.Lett.B 820 (2021) 136531*
  - *[3] Ballett, Pascoli, Ross-Lonergan, PRD 99, 071701 (2019)*
  - *[10] Dutta, Ghosh, Li, PRD 102, 055017 (2020)*
  - *[6] Abdallah, Gandhi, Roy, Phys. Rev. D 104, 055028 (2021)*
- Decay of axion-like particles
  - *[8] Chang, Chen, Ho, Tseng, Phys. Rev. D 104, 015030 (2021)*
- A model-independent approach to any new particle
  - *[9] Brdar, Fischer, Smirnov, PRD 103, 075008 (2021)*

Produces true electrons

Produces true photons

Produces e^+e^- pairs



PRL 121, 241801 (2018)

- Many of these models predict more complex final states (e^+e^-) and/or differing levels of hadronic activity

→ *The hadronic state is becoming increasingly more important as a model discriminator*

- We are fortunate that LArTPCs are sensitive to these possibilities

From J. Evans.

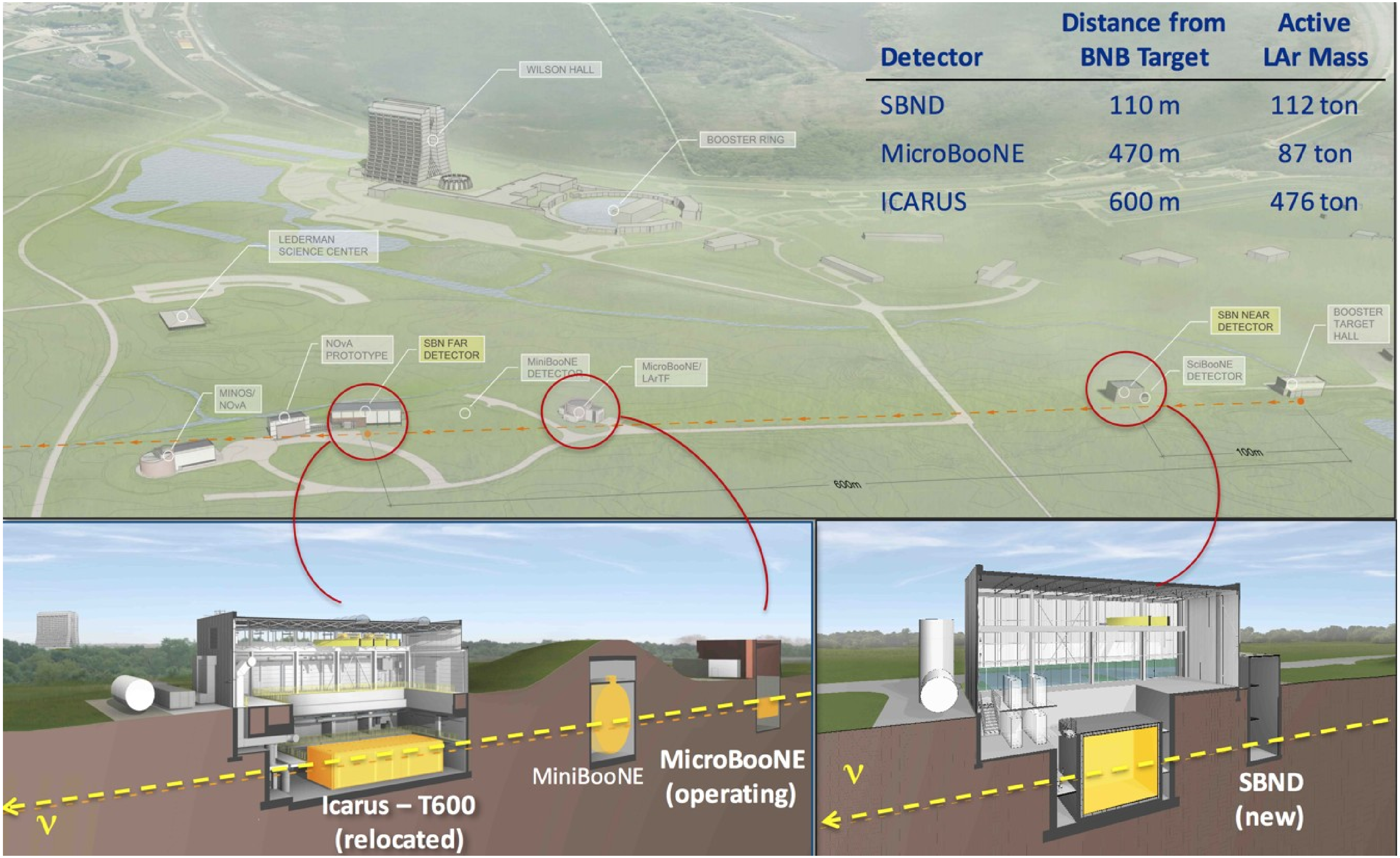
Already started probing with first LEE results

Models \ Reco topology	1e0p	1e1p	1eNp	1eX	e^+e^- + nothing	e^+e^-X	$1\gamma 0p$	$1\gamma 1p$	$1\gamma X$
eV Sterile ν Osc	✔	✔	✔	✔					
Mixed Osc + Sterile ν	✔ [7]	✔ [7]	✔ [7]	✔ [7]			✔ [7]		
Sterile ν Decay	✔ [13,14]	✔ [13,14]	✔ [13.14]	✔ [13,14]			✔ [4,11,12,15]	✔ [4]	✔ [4]
Dark Sector & Z' *	✔ [2,3]				✔ [2,3]	✔ [2,3]	✔ [1,2,3]	✔ [1,2,3]	✔ [1,2,3]
More complex higgs *					✔ [10]	✔ [10]	✔ [6,10]	✔ [6,10]	✔ [6,10]
Axion-like particle *					✔ [8]		✔ [8]		
Res matter effects	✔ [5]	✔ [5]	✔ [5]	✔ [5]					
SM γ production							✔	✔	✔

*Requires heavy sterile/other new particles also

From J. Evans.

Short Baseline Neutrino Program



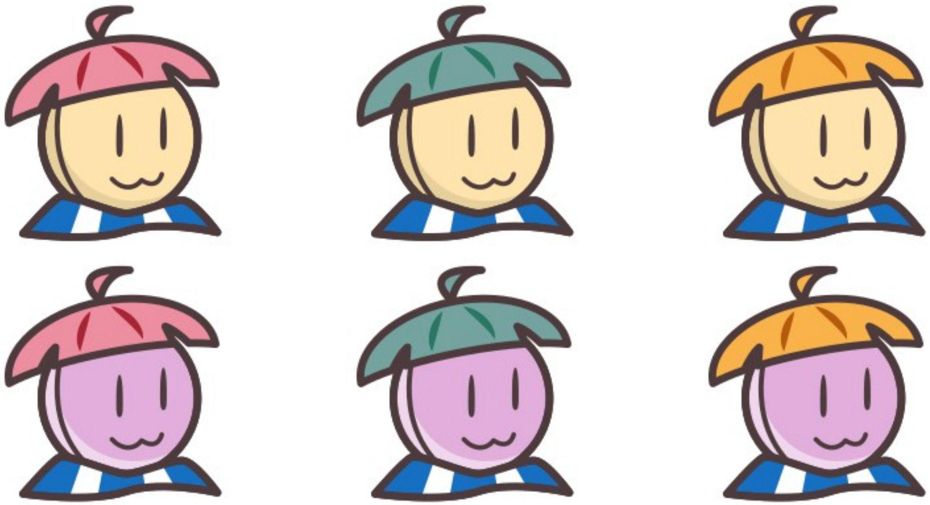
Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton

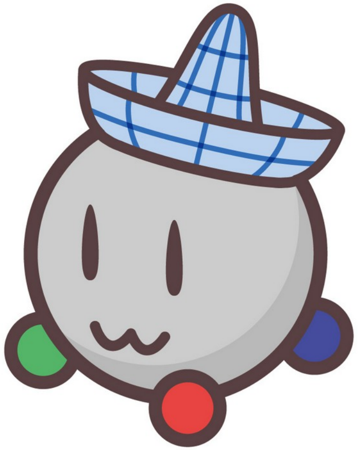
What next for MicroBooNE?

- Bright future!
  - Only analysed a fraction of the dataset, there will be updated LEE results, with higher sensitivity.
  - Many neutrino cross-section results coming out.
  - Liquid Argon R&D to help future experiments.
- But also an upgraded short baseline program at FNAL.
  - Two new detectors:
    - One upstream of MicroBooNE (SBND)
    - One downstream (ICARUS)
  - Can use the powerful near-detector method to drastically reduce systematic uncertainties on baseline-dependent physics.
    - All LArTPCs, so additional interaction and detector uncertainties can be cancelled.

Thanks for listening

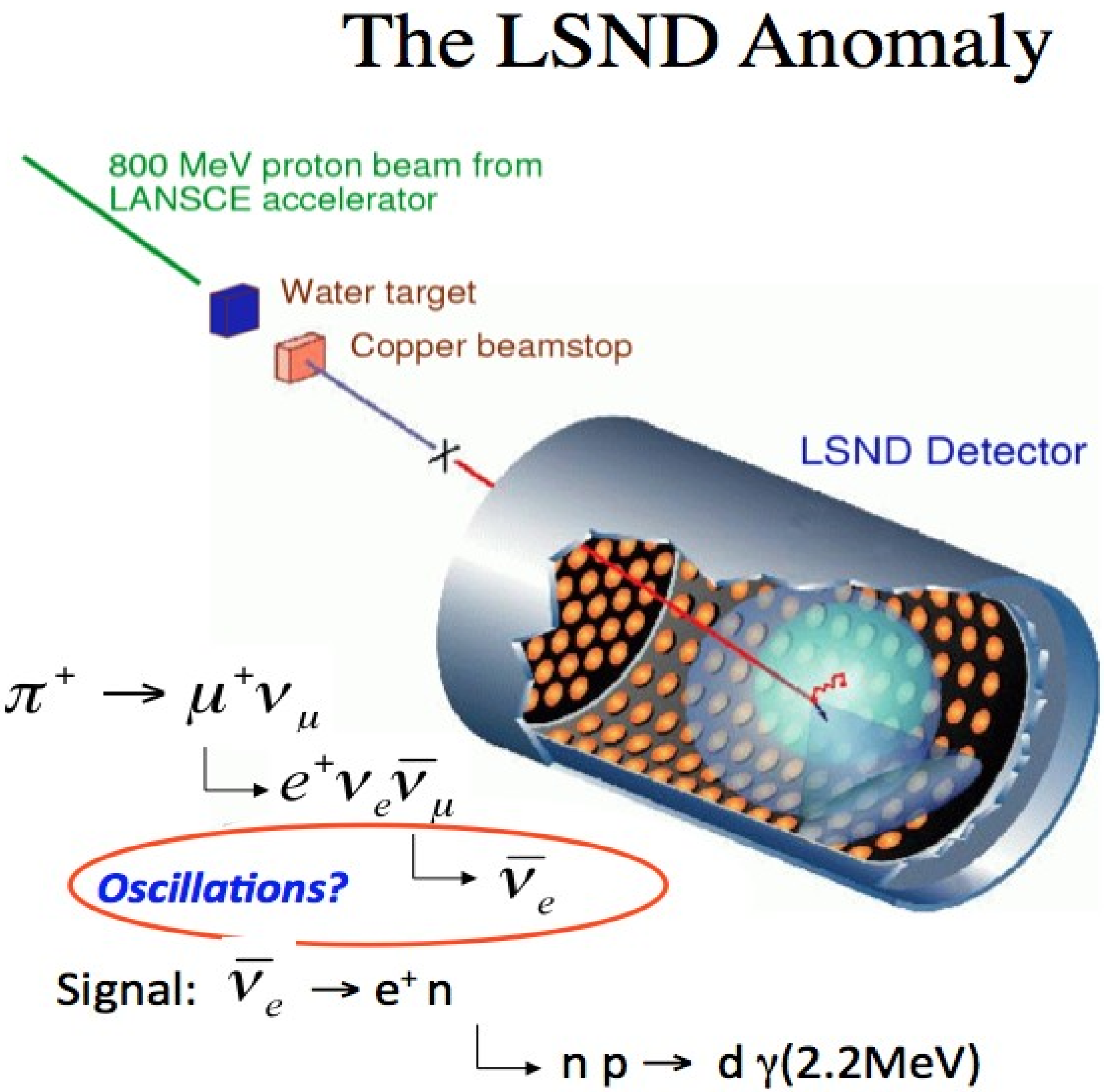
Backup Slides

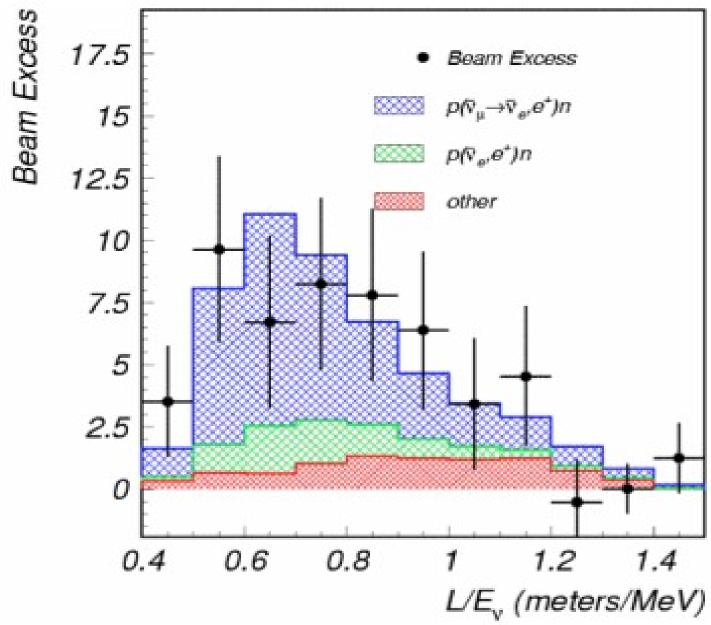




All cartoons by Yuki Akimoto - Higgstan KEK Pamphlet

LSND Excess





3.8 sigma excess

arXiv:nucl-ex/9605002

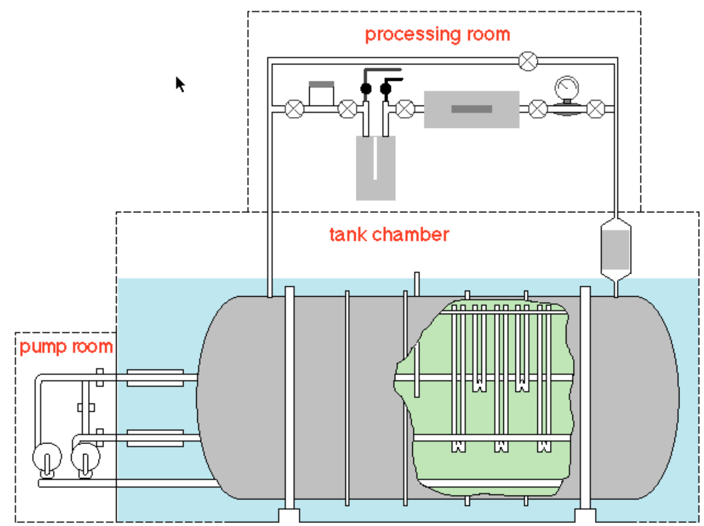
Solar Neutrinos

- Nuclear processes in the Sun produce a lot of neutrinos.
  - Solar neutrino flux accurately predicted by
    J. Bahcall (PRL 12,300 1964)
  - Measured by the Homestake Experiment by
    R. Davis et al(PRL 20,1205 1968)
  - Homestake was 380m^3 of dry-cleaning fluid, rich in Chlorine.
  - Captured electron neutrinos via inverse beta decay.

$$^{37}\mathrm{Cl} + \nu_e \rightarrow {}^{37}\mathrm{Ar} + e^-$$

Only saw a third of the predicted rate!

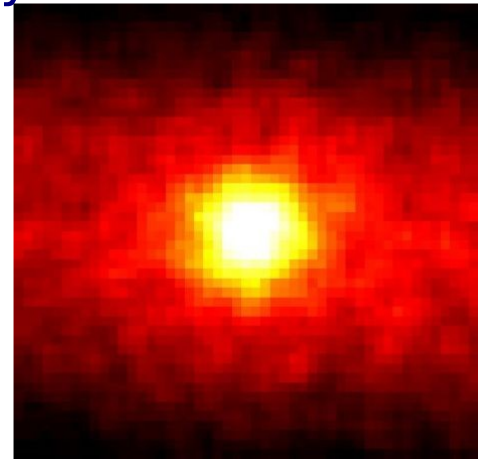
- We have a problem.



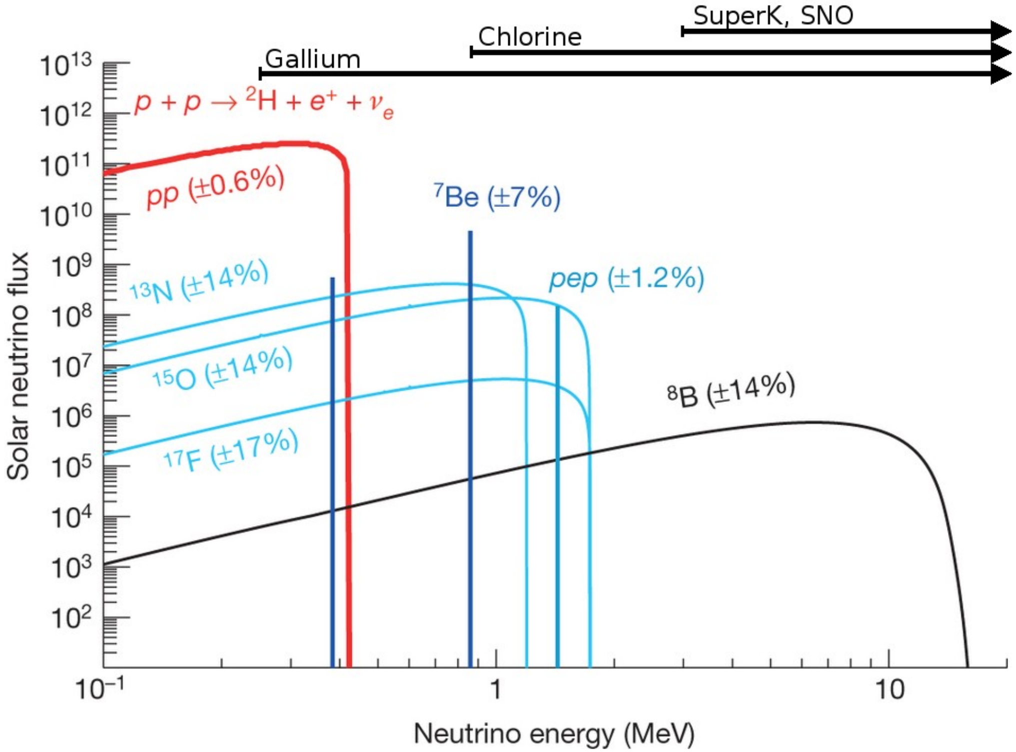
Is there a problem?

- Initially, many people believed the Homestake experimental result was wrong.
  - It's counting single digit numbers of argon atoms on a monthly basis, who even knows if they're from solar neutrinos?
- But other solar neutrino experiments were conducted, and the experimental deficit became fully accepted.

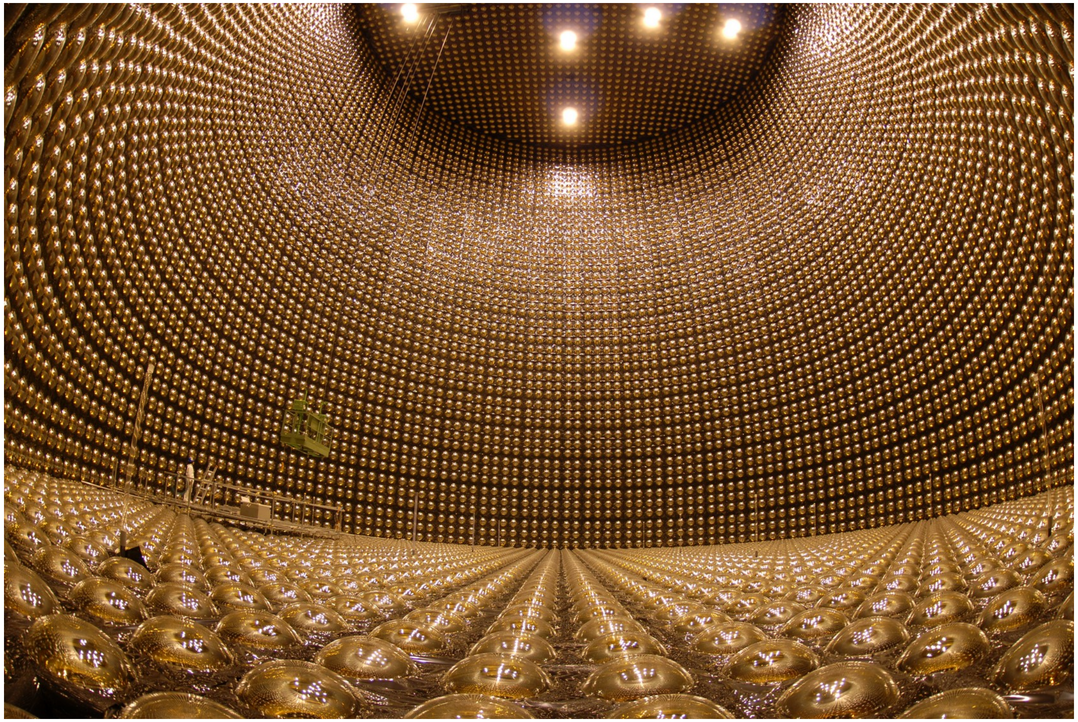
- For example, Super-Kamiokande detected using elastic scattering, at a much higher threshold.
  - Can reconstruct direction, actually see they're from the sun.

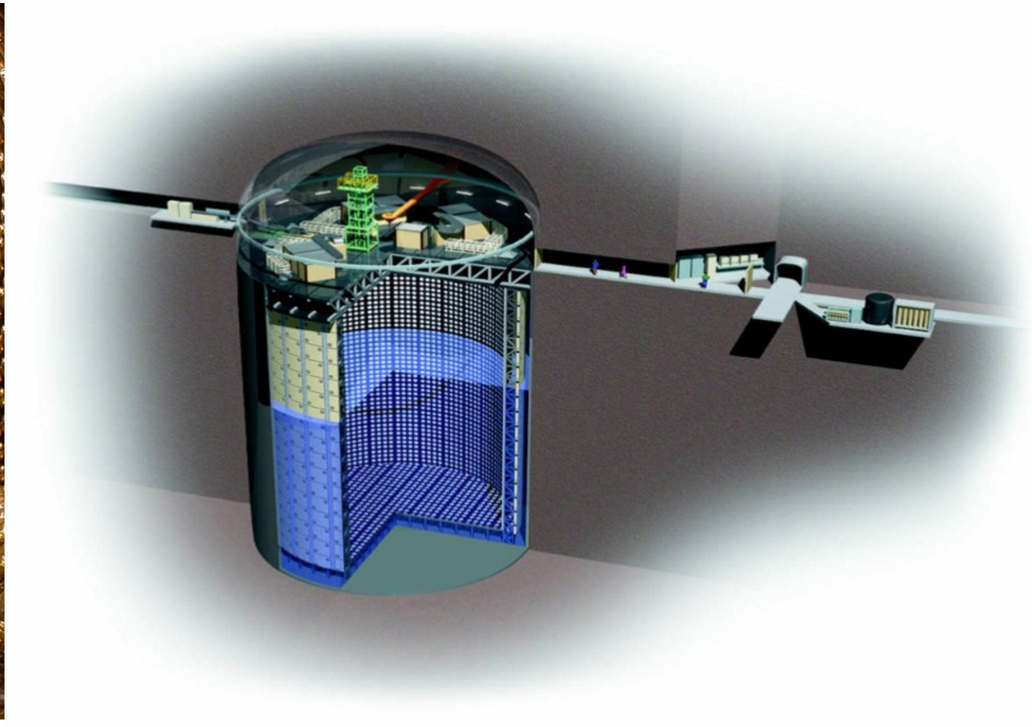


R. Svoboda and K. Gordan, LSU



Super-Kamiokande



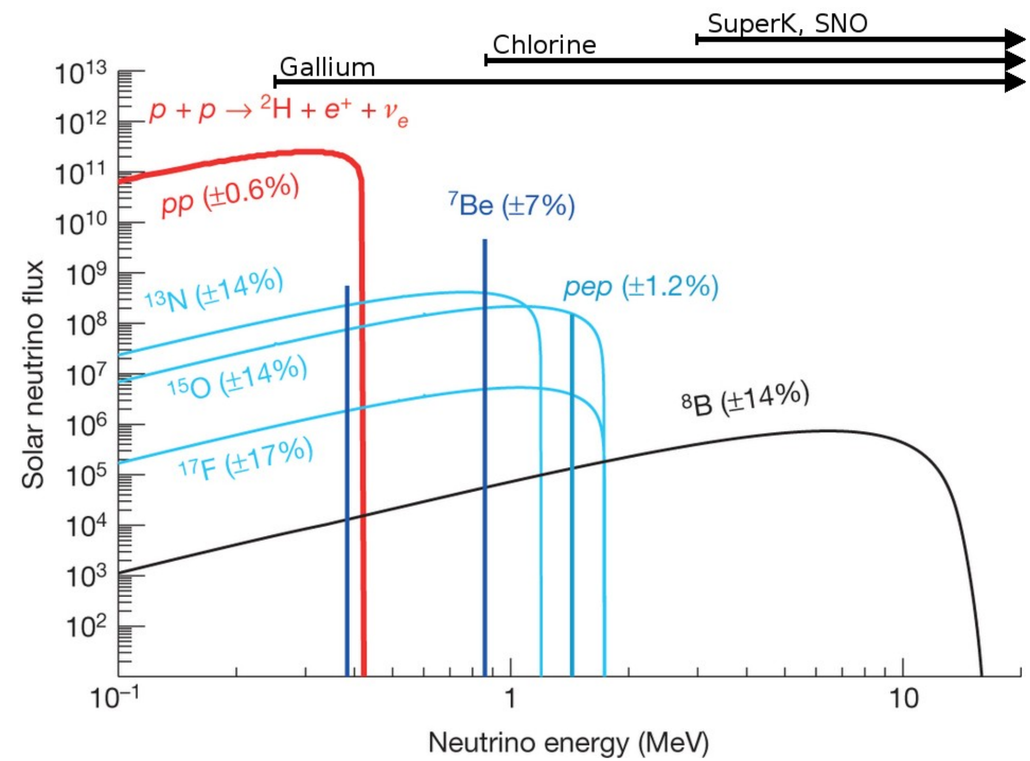


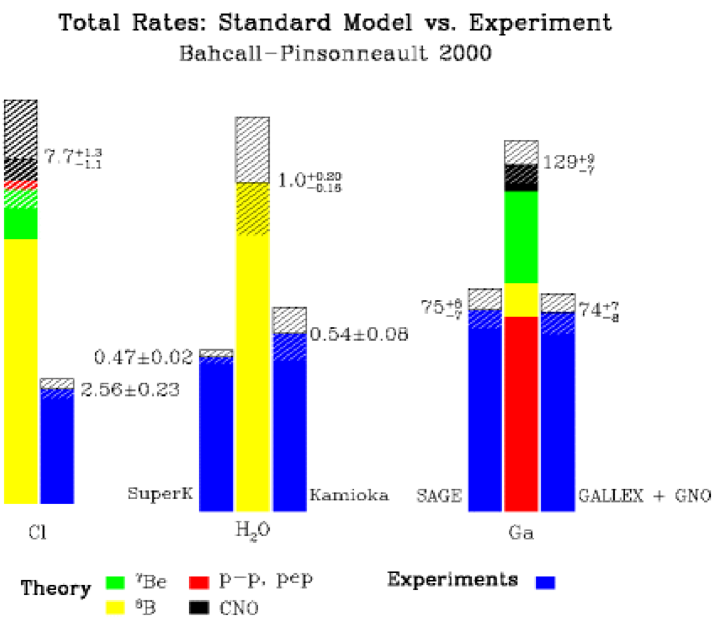
50 kt ultrapure water Cherenkov detector instrumented with 11,000 PMTS in the inner detector for 40% photo-coverage.
1 km underground to reduce background.

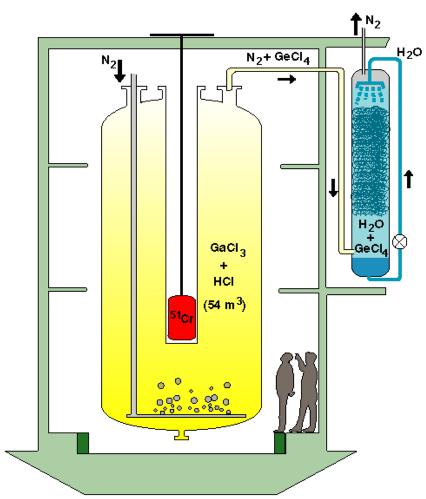
Excellent muon-electron separation
You’ll be seeing this again later...

Other solar experiments

- Also, important to mention the Gallium experiments, SAGE and GALLEX.
  - Observed much lower energy neutrinos.
  - Saw a smaller deficit.
  - The deficit is energy dependent?







Solar Neutrino Problem

- So, the deficit is real.
  - Is the solar model wrong?
  - Bahcall's Standard Solar Model works very well for everything except neutrinos.
  - Eg helioseismology.
- No way to change the solar model to reduce the neutrino flux enough without breaking it in other ways.
  - Something "wrong" with the neutrinos!

Great, another anomaly.

- But Super-K wasn't just looking at solar neutrinos.
- They could study atmospheric neutrinos.
  - Produced in the upper atmosphere, by high energy cosmic rays.
  - As they're not attenuated by the Earth, flux should be isotropic.
  - Not only did they see a reduced rate of muon-like neutrinos compared to electron-like, but with a dependence on zenith angle – effectively how far the neutrino had travelled since being created in the upper atmosphere.