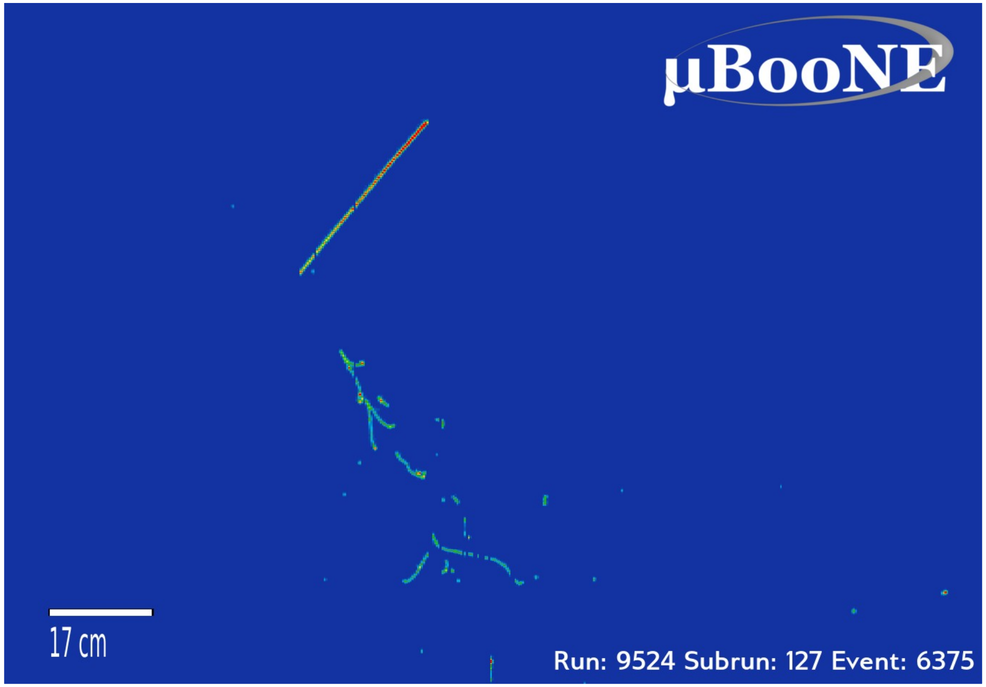
New Results from MicroBooNE



Steve Dennis

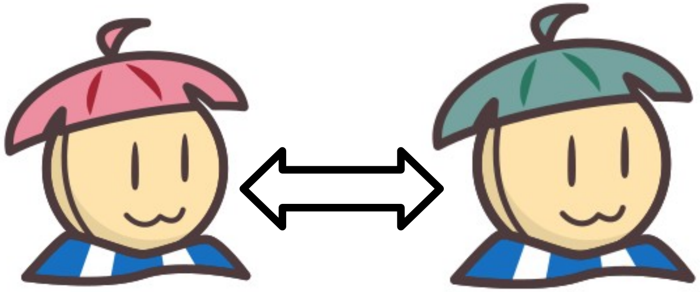
Les Rencontres de Physique de la Vallée d'Aoste

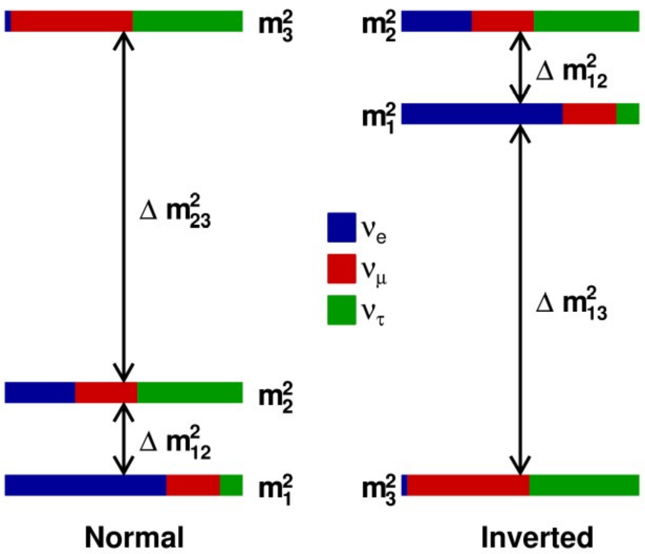
La Thuile

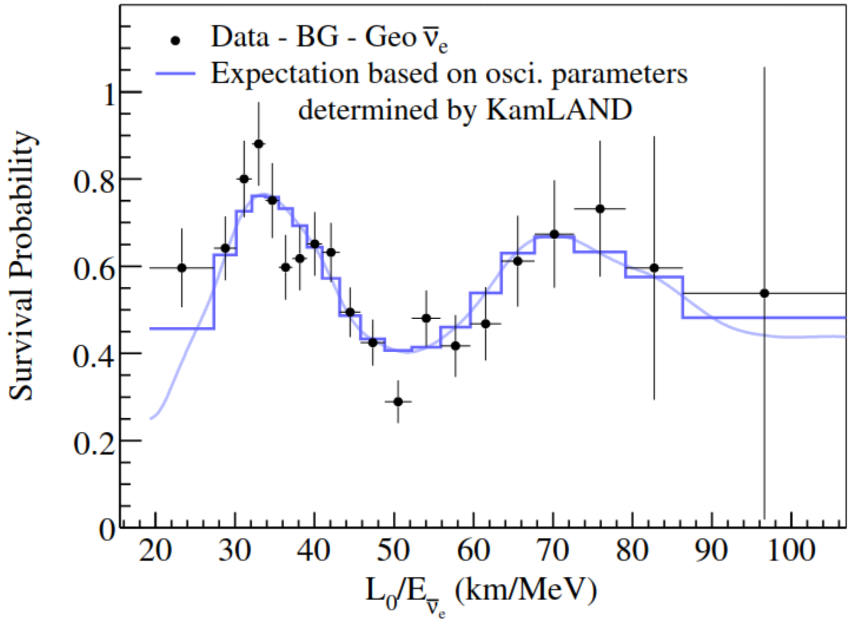
8th March 2022

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.







Two-flavour Oscillation

Just handles the units.

Controls the frequency

Controls the amplitude

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

Mass squared splitting.

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

Physics beyond the Standard Model!

Key Principle of 3F Oscillation Experiments

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

We directly measure this.

We want to know this.

So we control this.

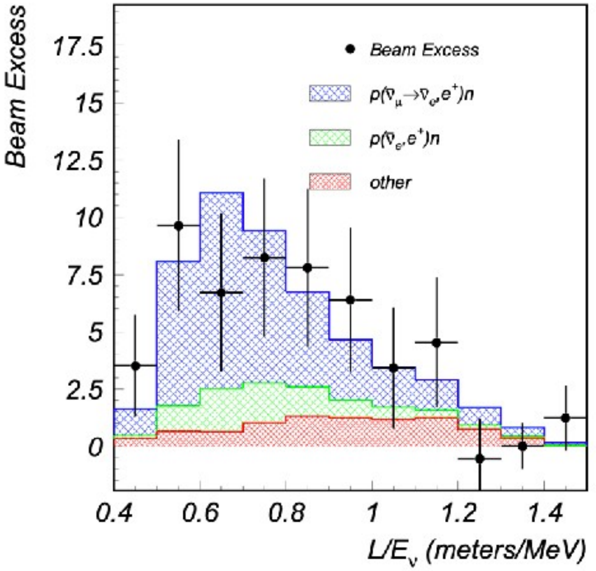
We control L by placing our detectors, and control E by tuning our sources (where possible)

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

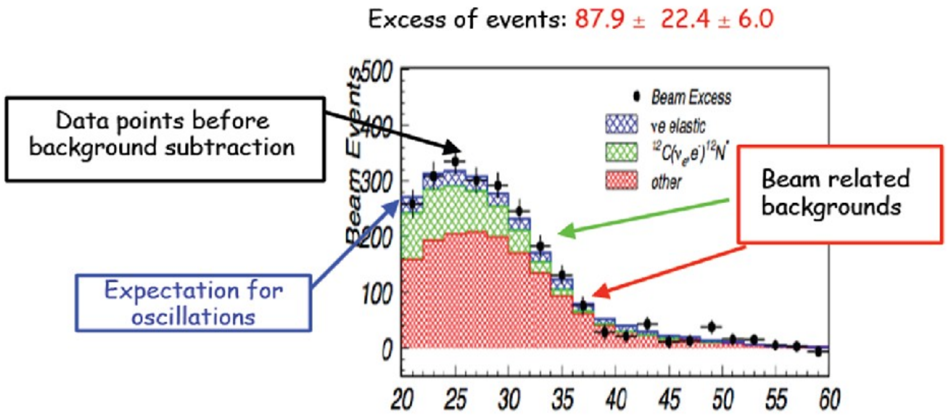
Mass splittings small!

The LSND and MiniBooNE Excess

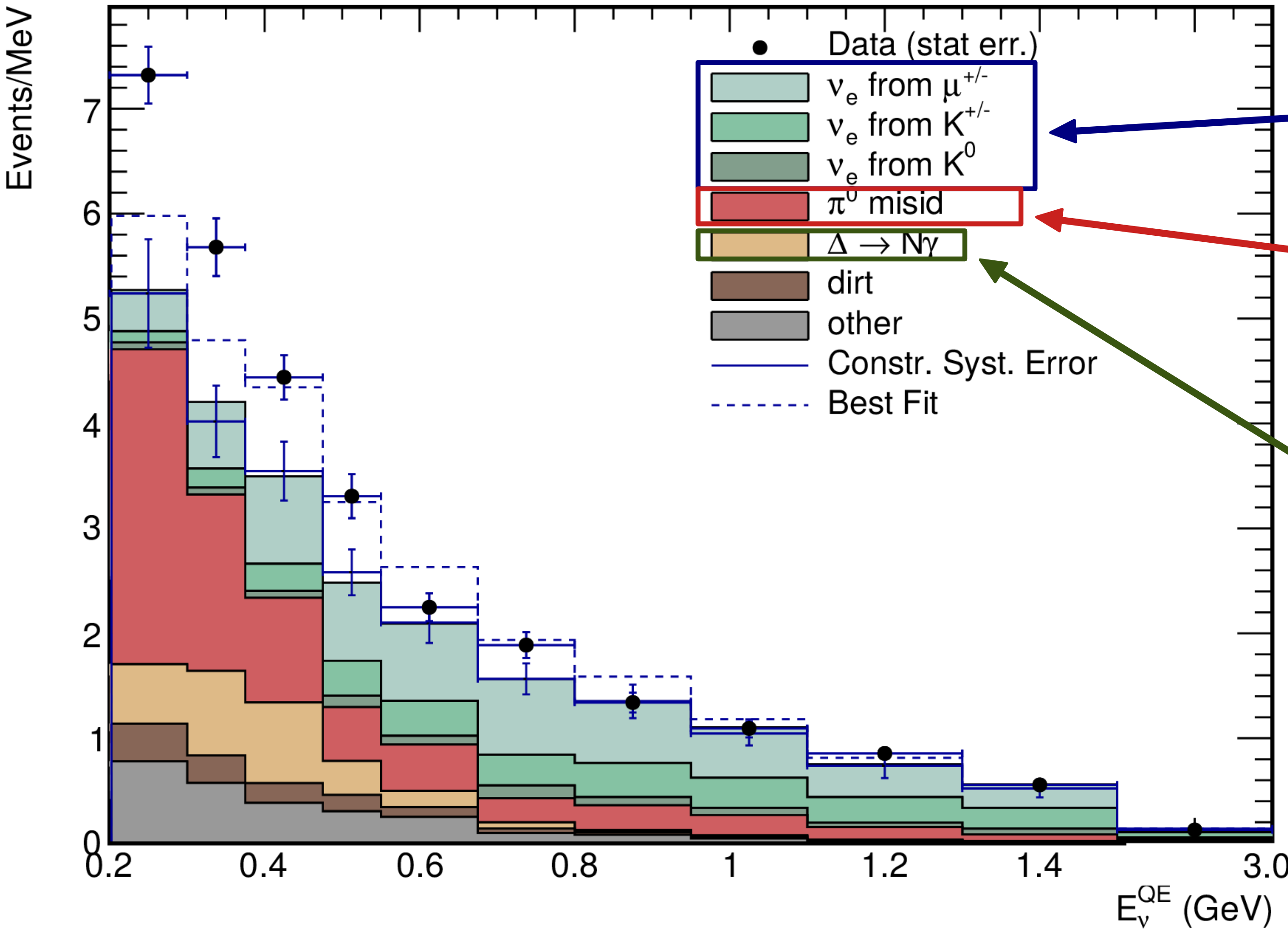
- 20 years ago, the Liquid Scintillator Neutrino Detector at LANL saw an unexpected excess. arXiv:nucl-ex/9605002
  - Excess of electron antineutrinos in a muon antineutrino beam at 3.8σ.
  - Could be interpreted as evidence for oscillation at mass 0.2-10eV²
    - Inconsistent with known neutrinos.



- Development of the MiniBooNE experiment to test this hypothesis.
  - Same L/E, different energy, different uncertainties.



MiniBooNE Electron-like Excess

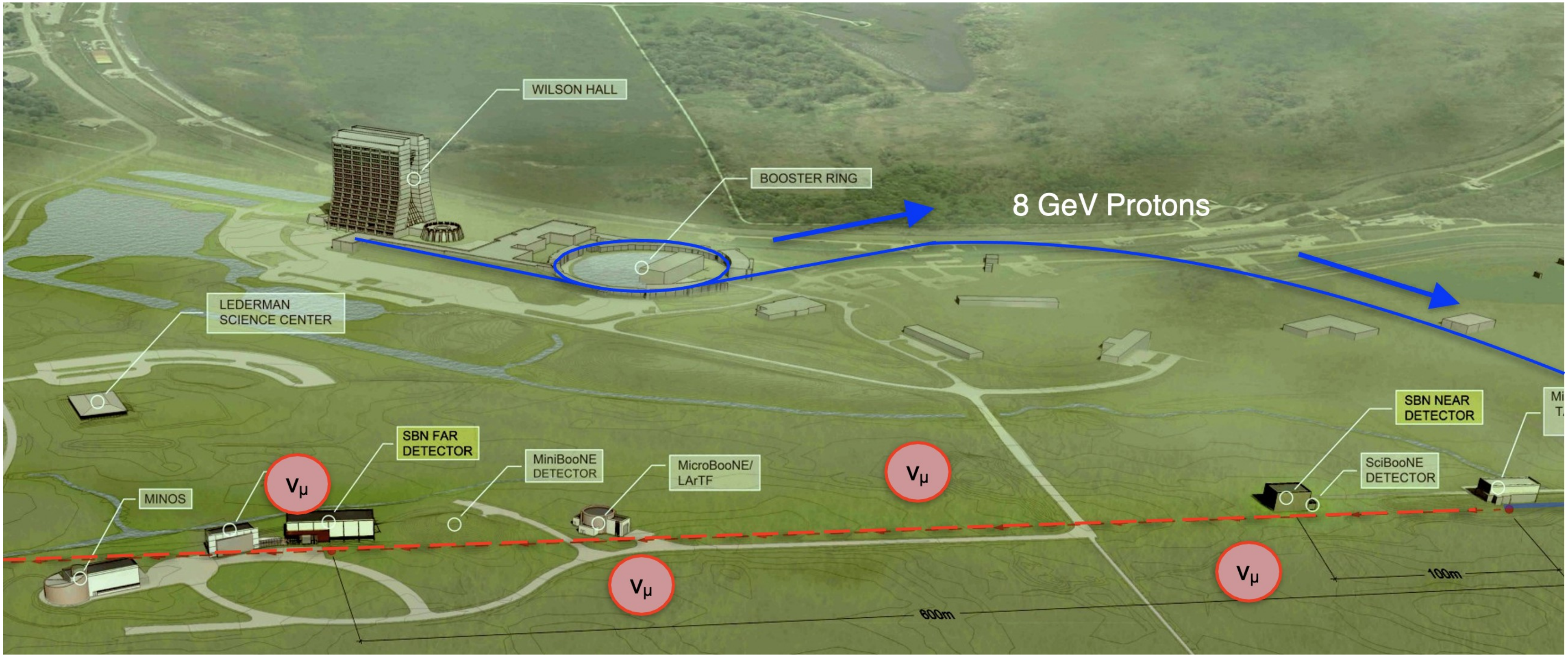


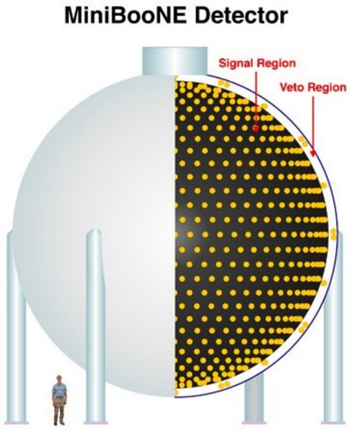
Or real electron neutrino appearance?

Electron-like selection has a lot of photon backgrounds.

- But sees 4.5σ excess in neutrino mode, 4.7σ in antineutrino.

MiniBooNE





MiniBooNE is a mineral oil Cerenkov detector.

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

Or something more exotic?

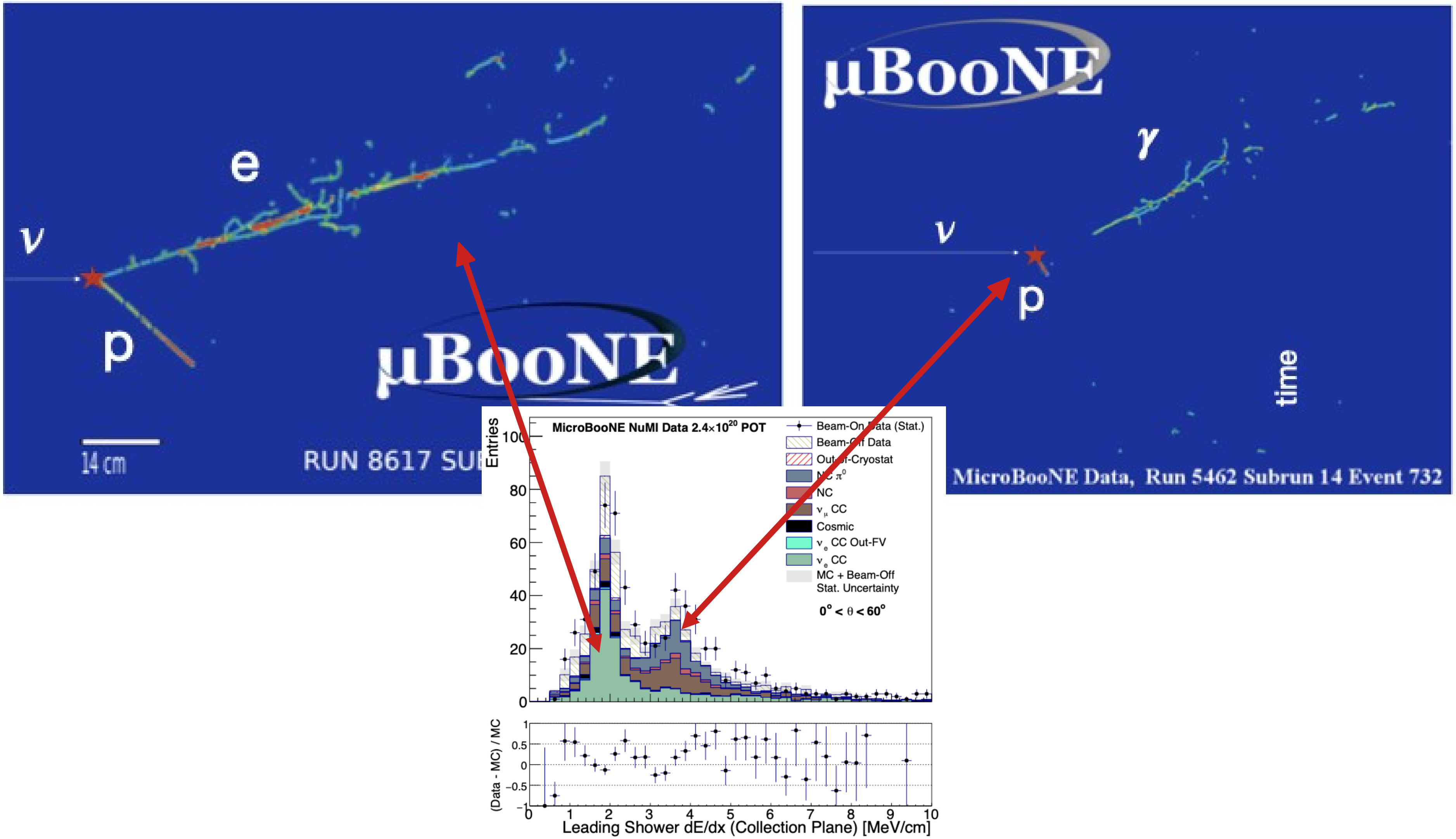
Enter MicroBooNE

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.

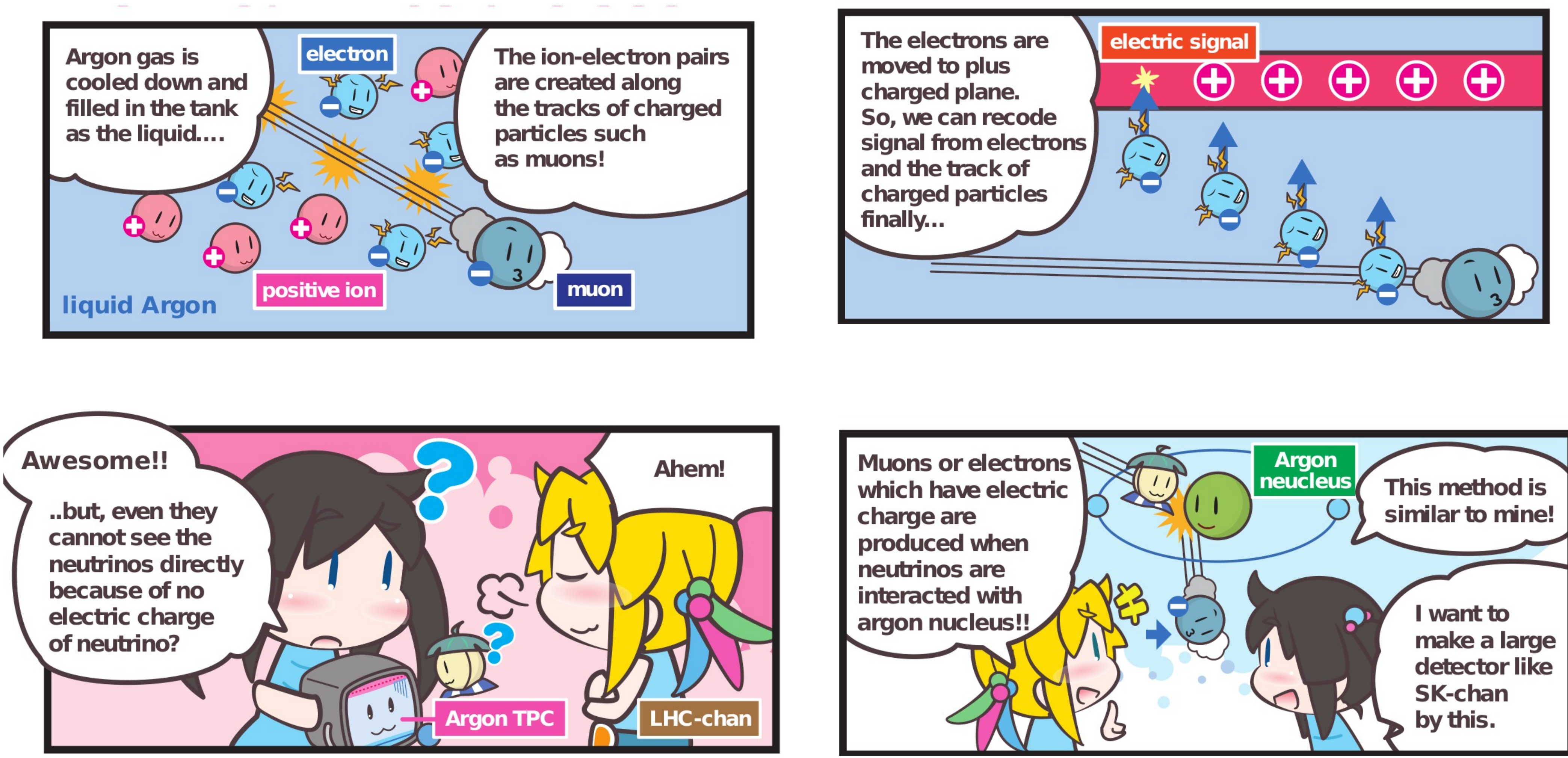
MicroBooNE Event Displays



Ability to see hadronic system allows vertexing.

Can determine shower distance from vertex:
→ Distinguish electrons and photons.

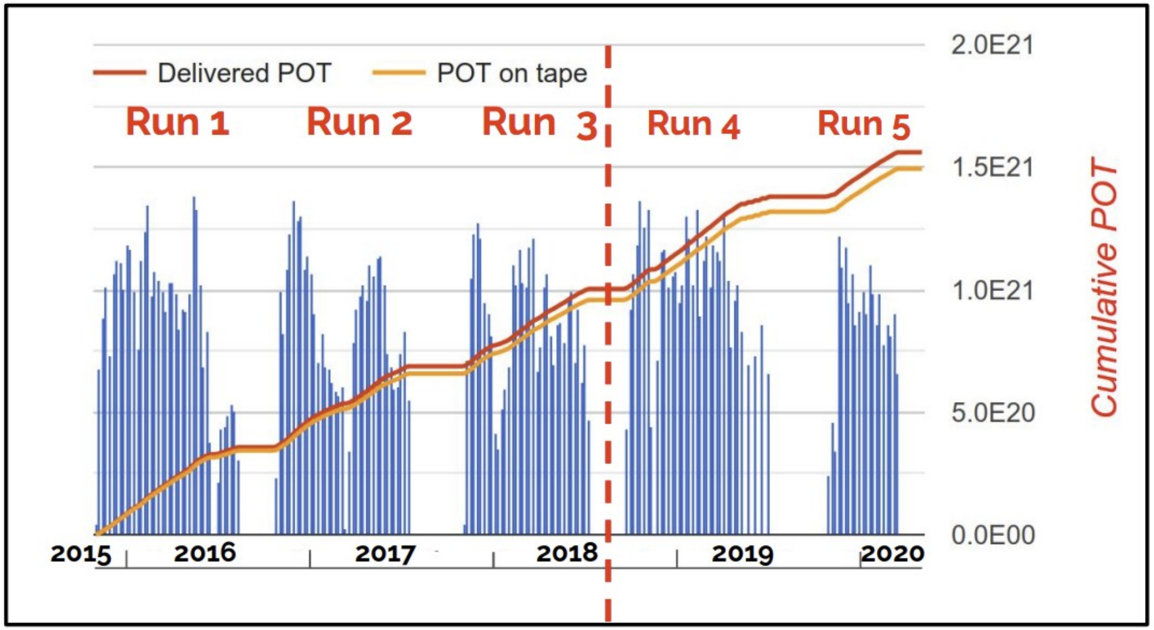
Liquid Argon TPC



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

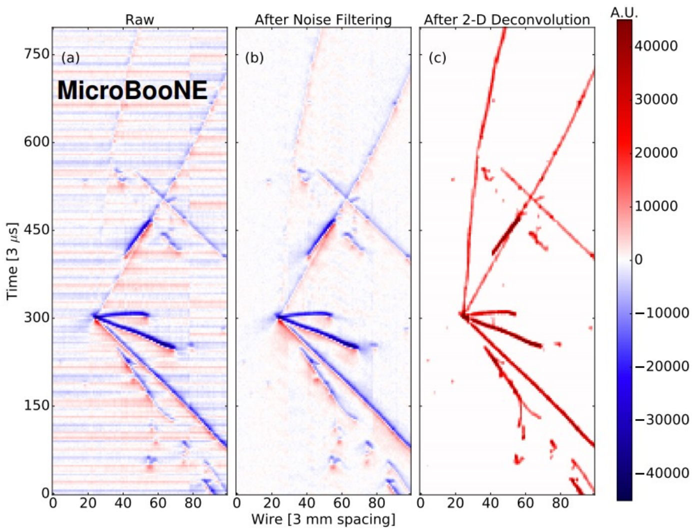
MicroBooNE Running

- 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.
- Longest continually running LArTPC to date.



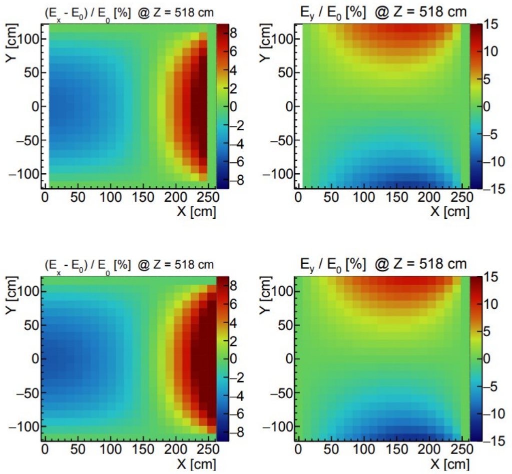
But before we start:

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



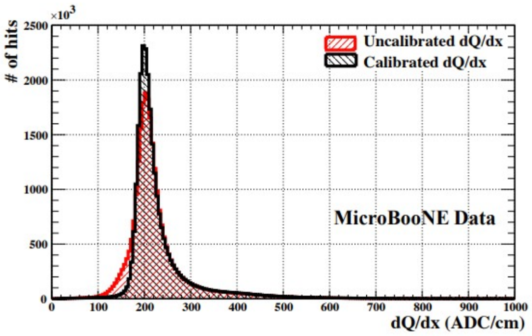
JINST 13, P07006 (2018) JINST 12 P08003 (2017)

Electric field calibration with lasers and cosmic muons



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

Calorimetry calibration with crossing muons and ^{0} samples



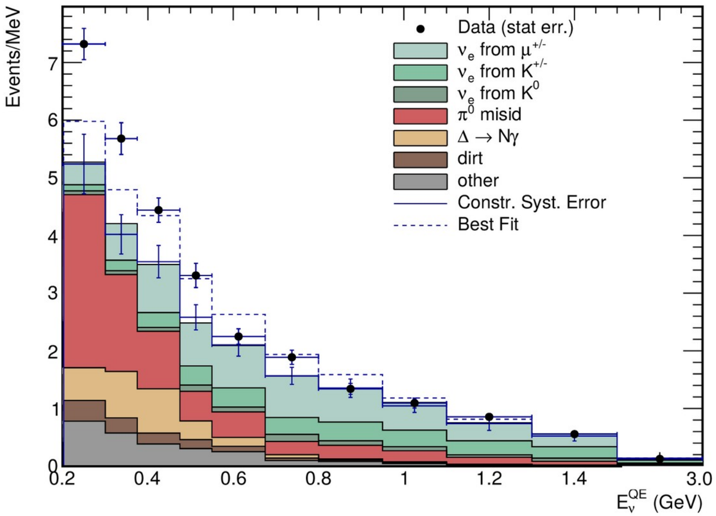
JINST 15 (2020) 03, P03022
JINST 15 (2020) 02, P02007

Adapted From J. Evans.

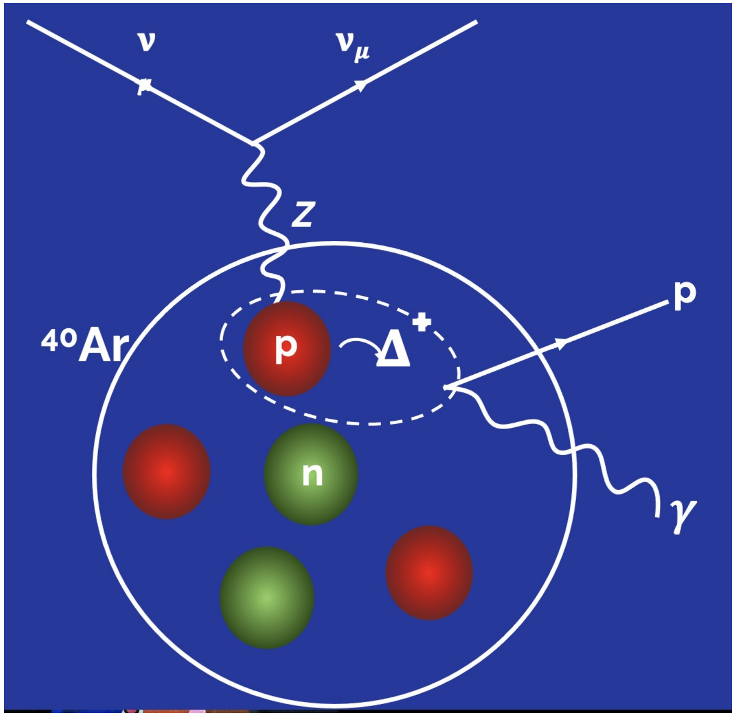
First complete analysis for LArTPC systematic uncertainties!

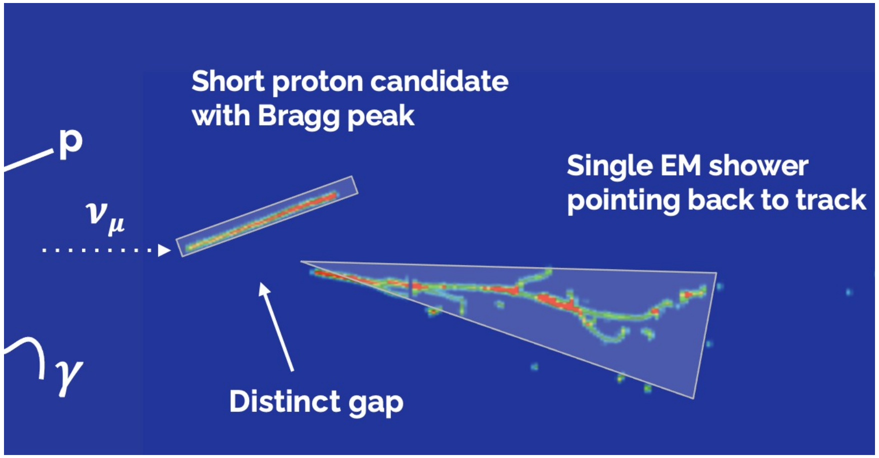
The MicroBooNE LEE Analyses

- 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 underlying 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 $\Delta \rightarrow N\gamma$ hypothesis
    - 1γ0p, 1γ1p



Photon-Like Analysis



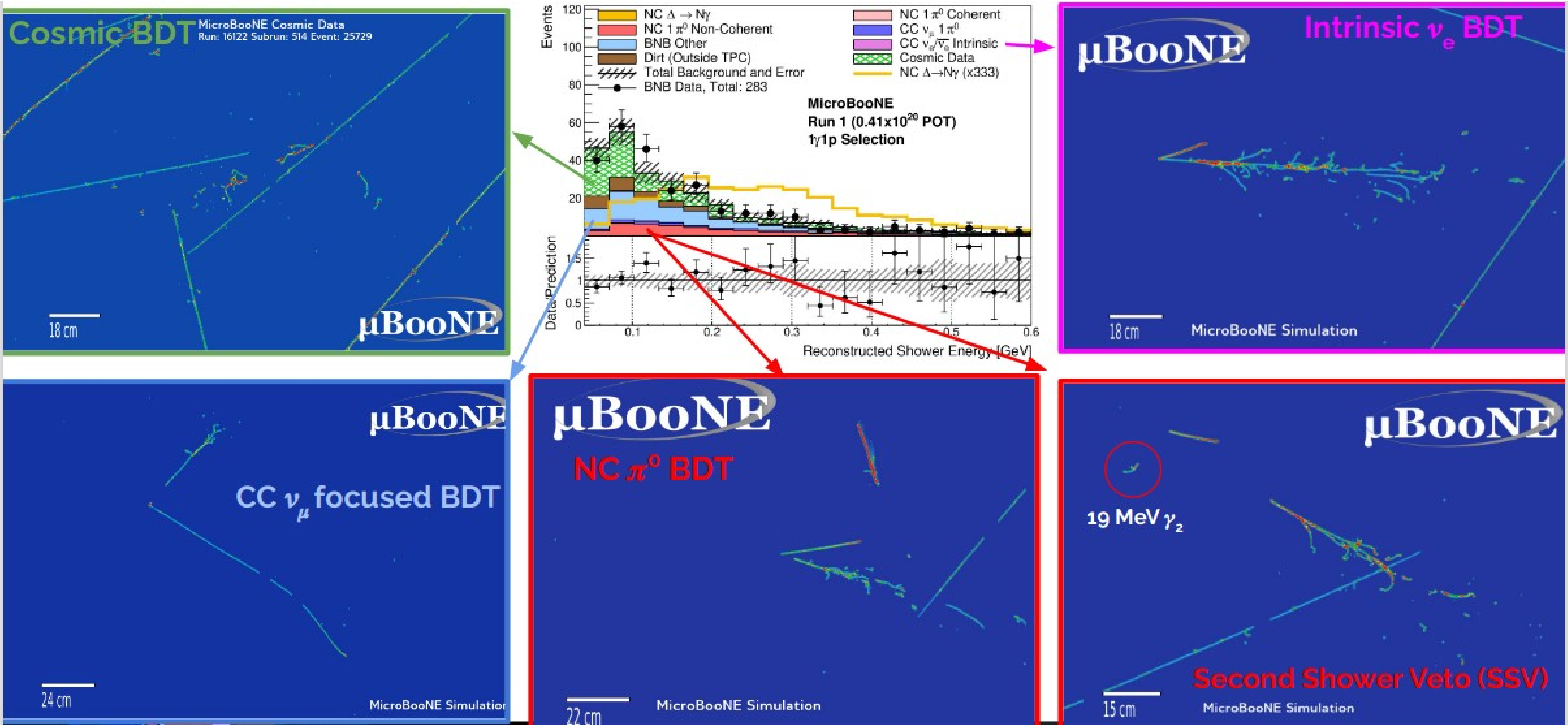


Uses two two-photon selections to constrain NCπ^0 background. Signal samples are single photon.

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

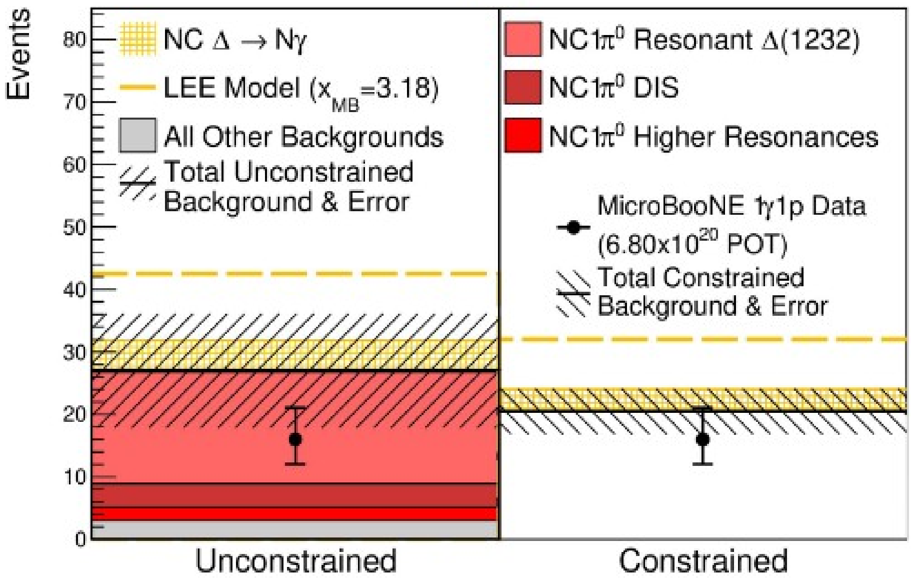
- To match MiniBooNE excess, requires 3.18x scaling of NC $\Delta \rightarrow N\gamma$ model.
- Rare process, never directly experimentally observed.

Photon selection BDTs

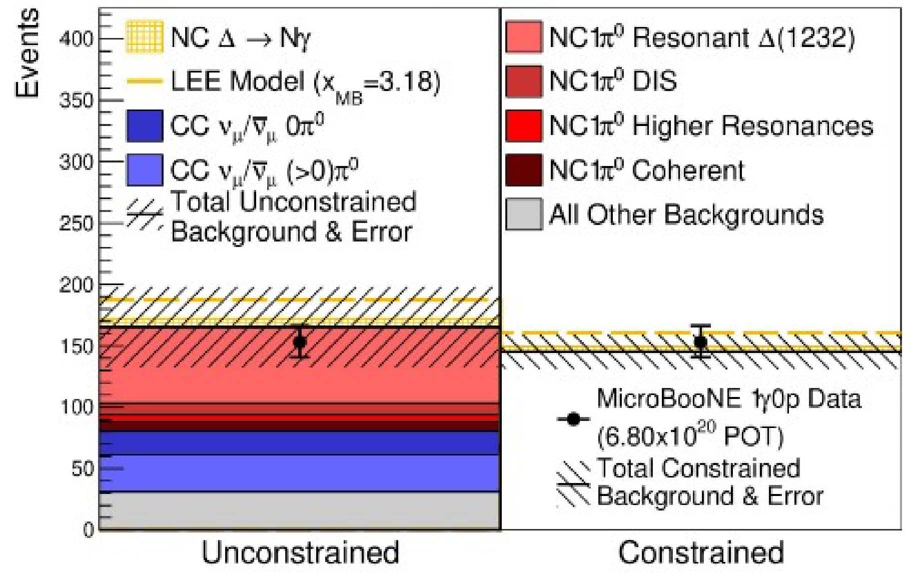


Photon-like data

$1\gamma 1p$



$1\gamma 0p$



$1\gamma 1p$

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

16
Data Events Observed

$1\gamma 0p$

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

153
Data Events Observed

Photon Results

Entirely consistent with nominal prediction at 1-sigma.

arXiv:2110.00409

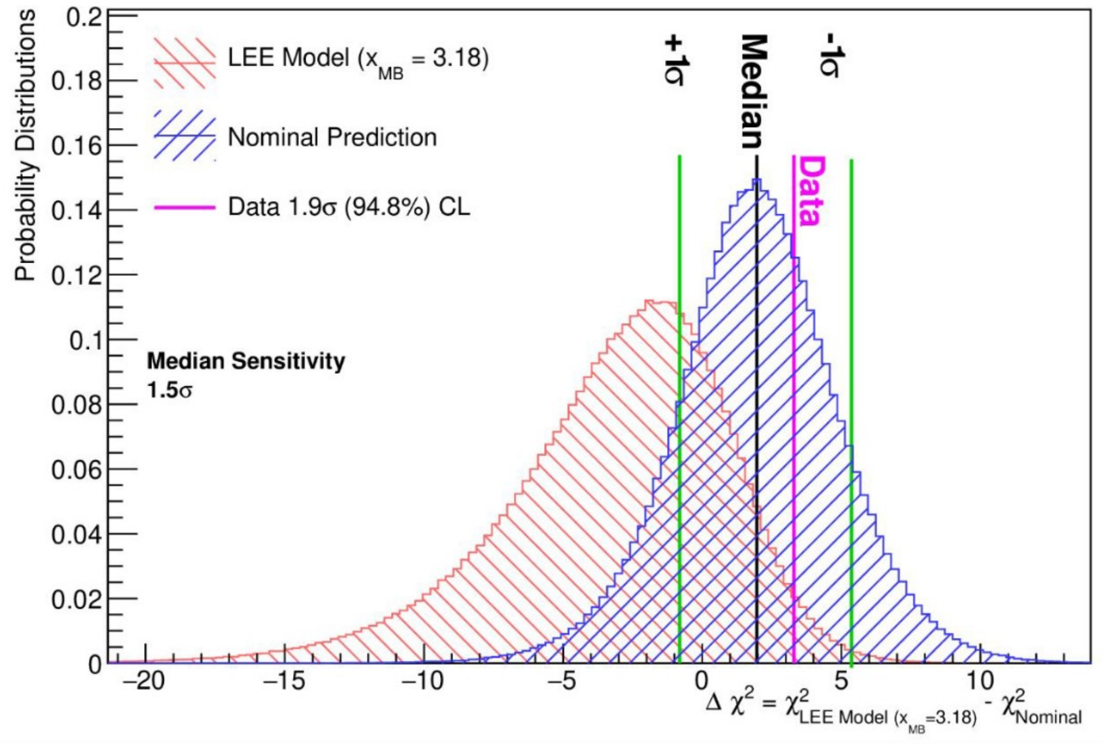
- **Rejects the NC Δ → Nγ LEE hypothesis at 94.8% CL.**

Interpreted as branching fraction:

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

90% CL

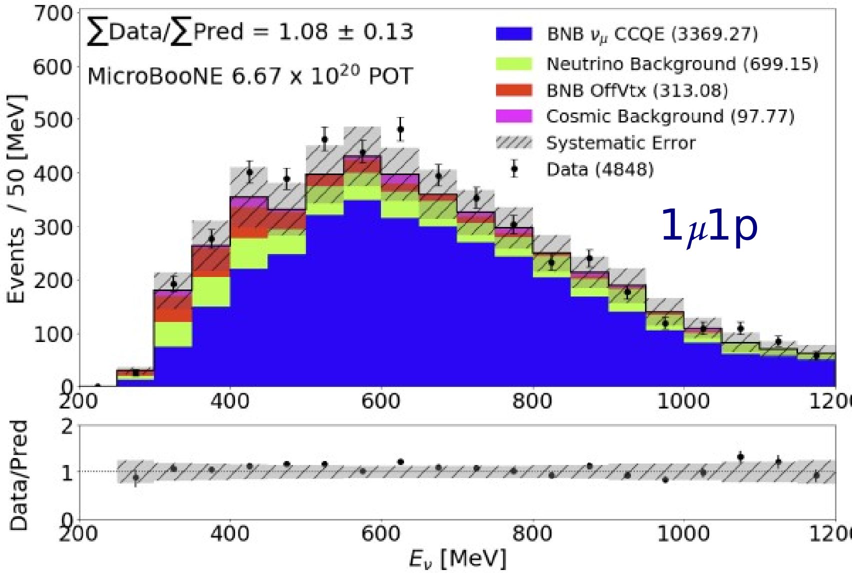
More than 50x better than world's previous limit!

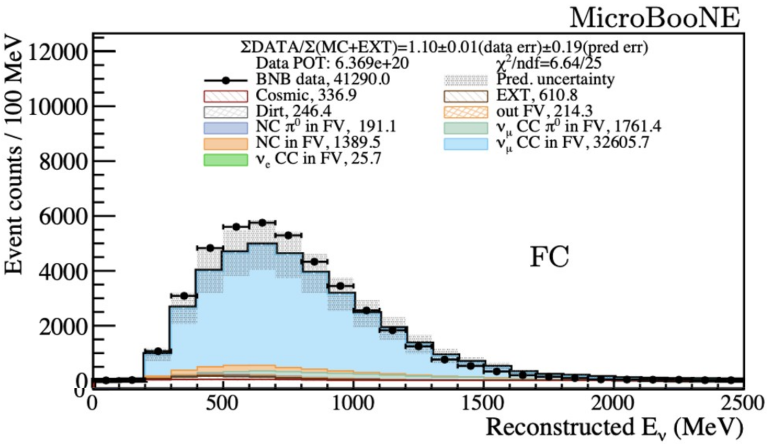


Electron-like Search.

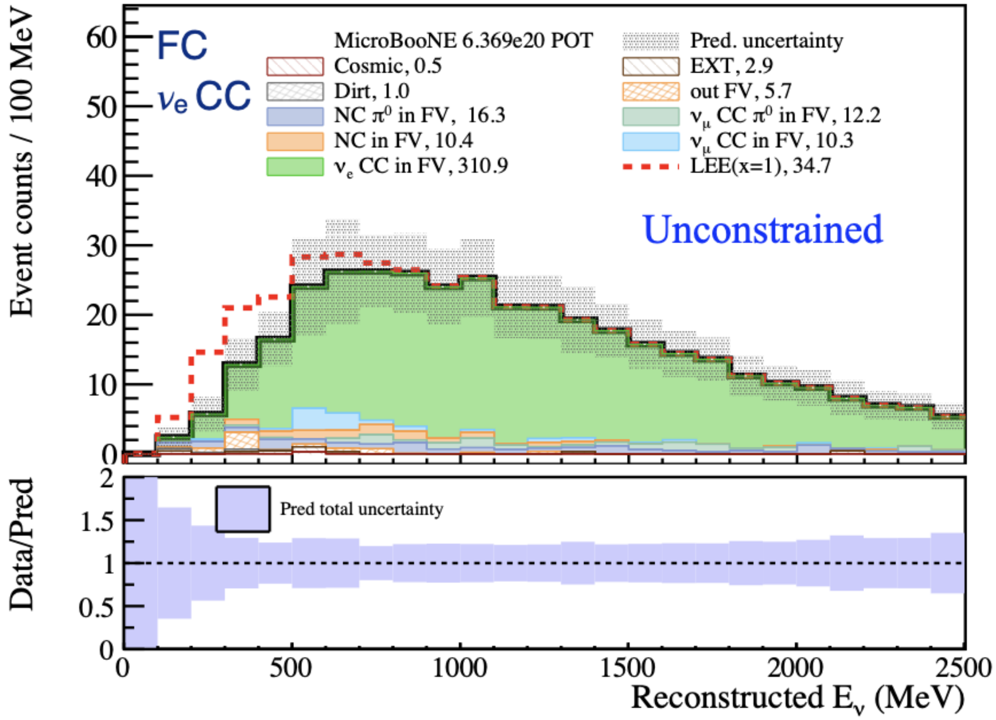
- Three independent analyses using different reconstruction.
  - Deep learning used for 1e1p.
  - Pandora used for 1eNp0pi/1e0p0pi.
  - Wire-Cell used for 1eX.
- Start with high-statistics muon-like samples.
  - Use to make data-driven electron-like prediction.
  - Heavily reduces uncertainties on electron-like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

  → Not a sterile model!

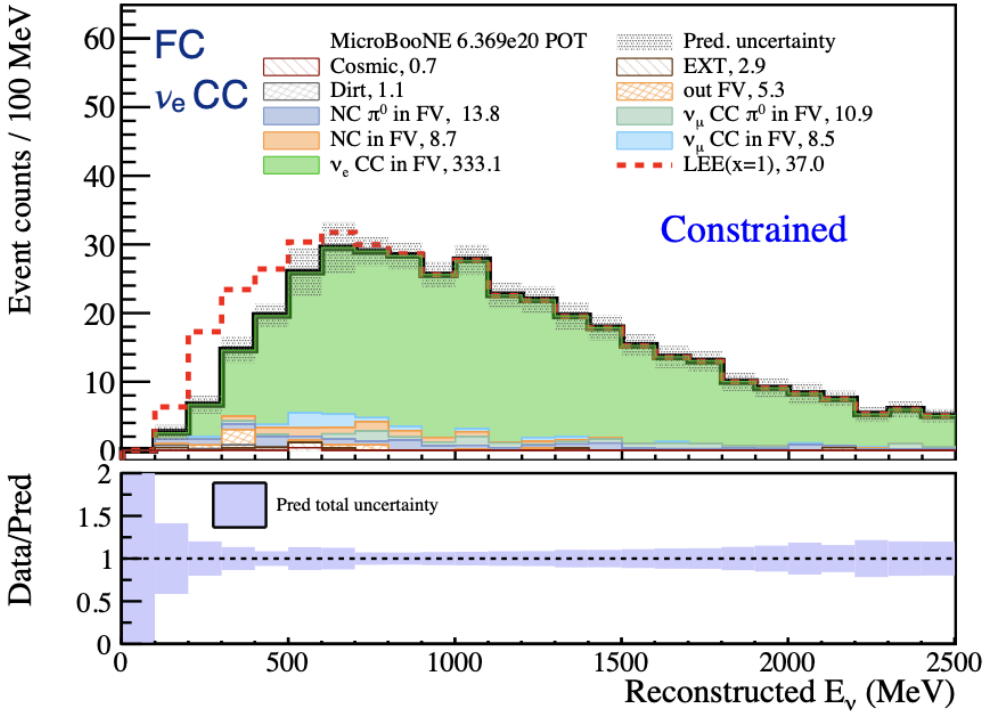




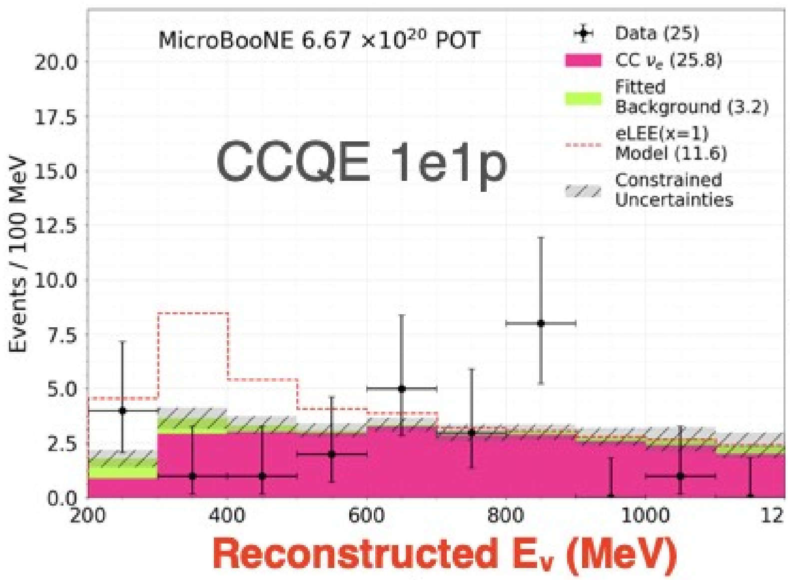
Constraints from muons

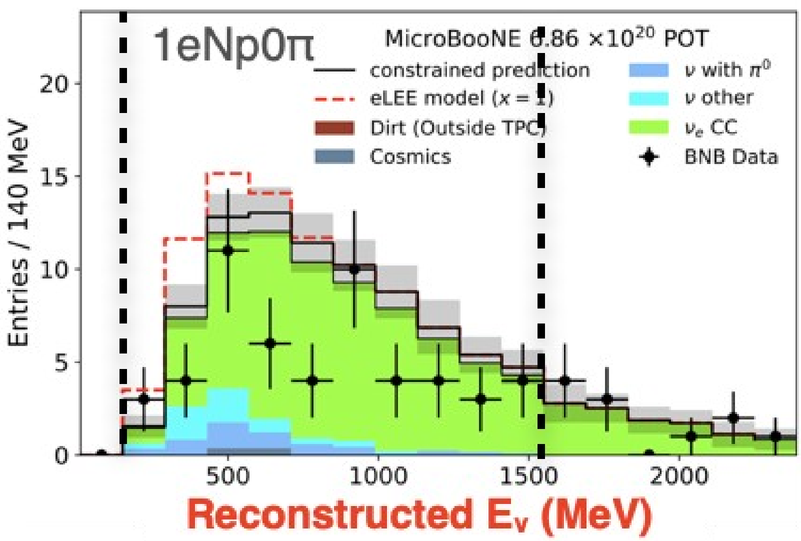


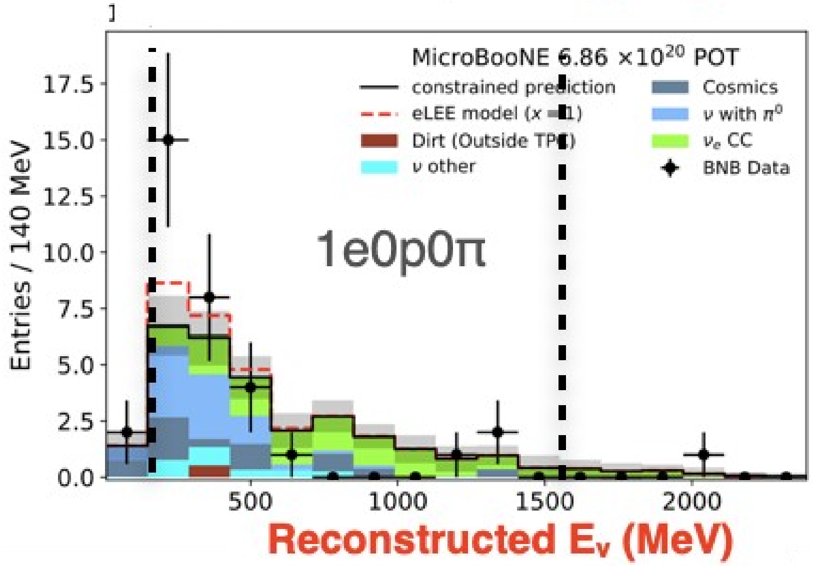
1eX

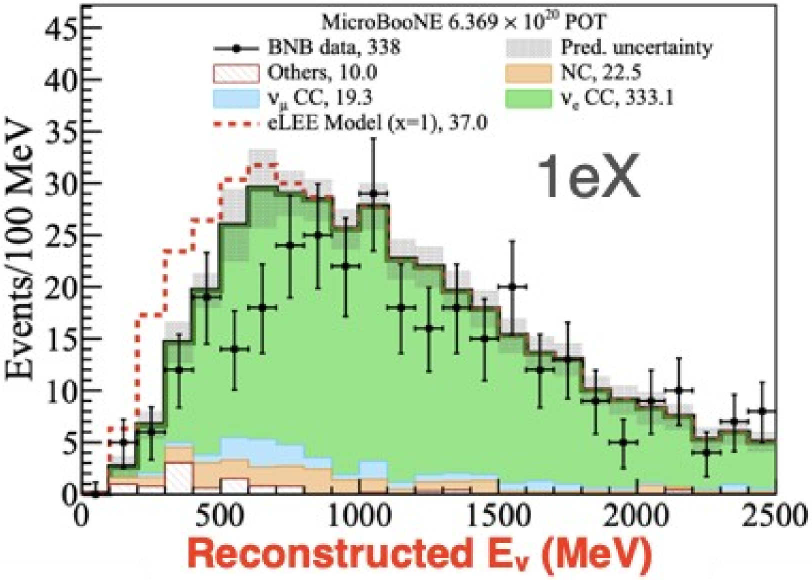


Electron-like Results - Neutrino Energy

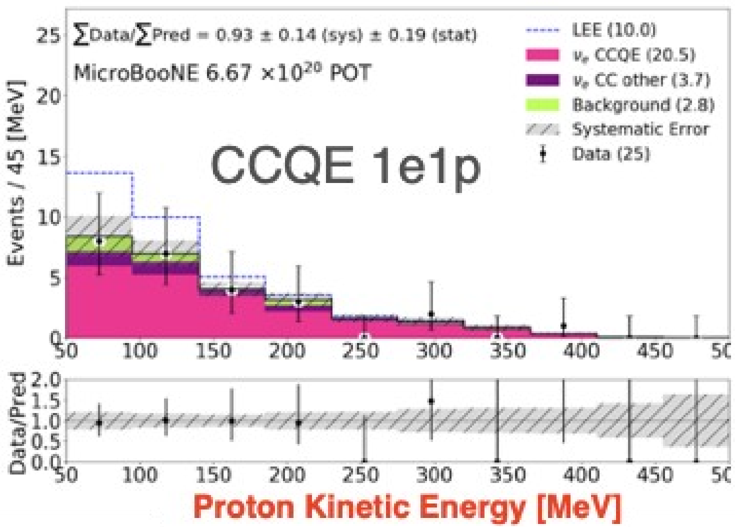


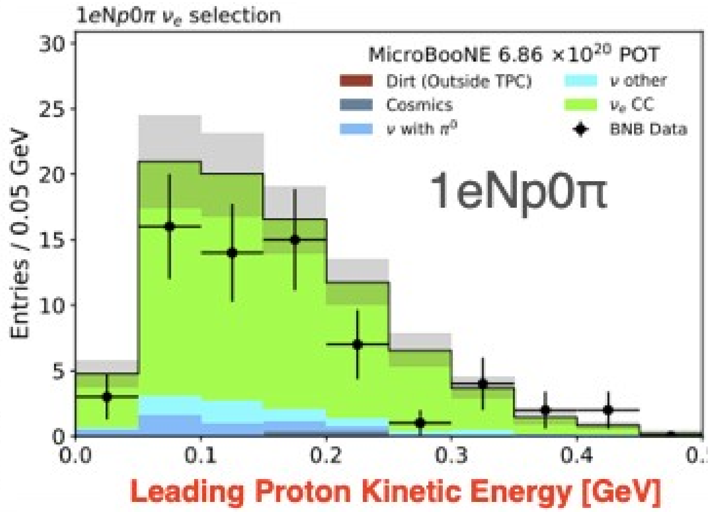


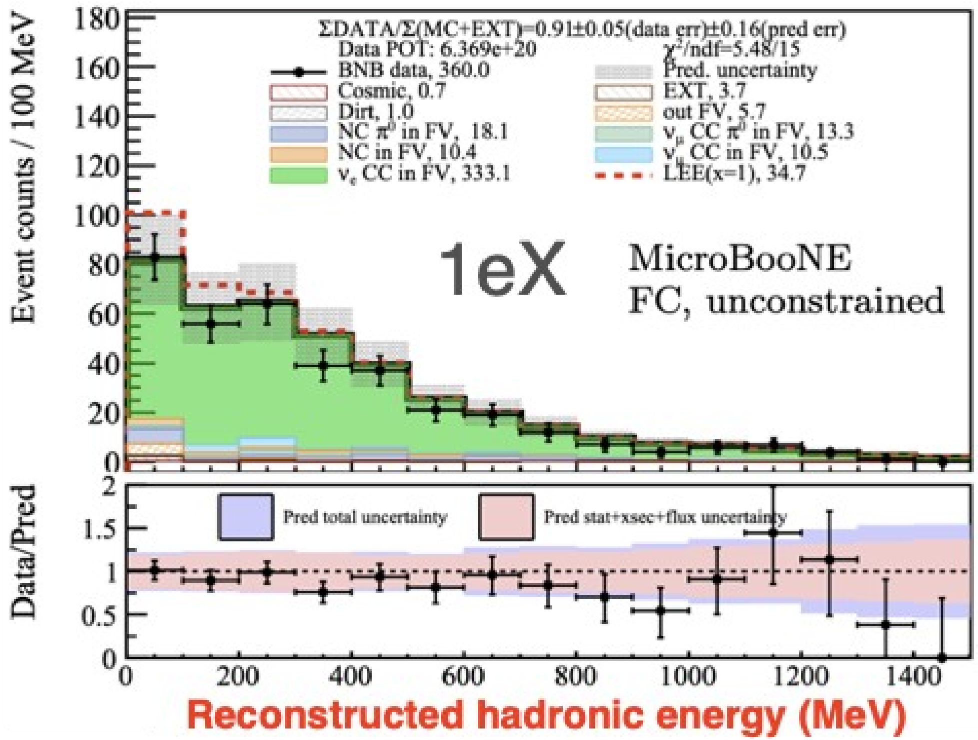




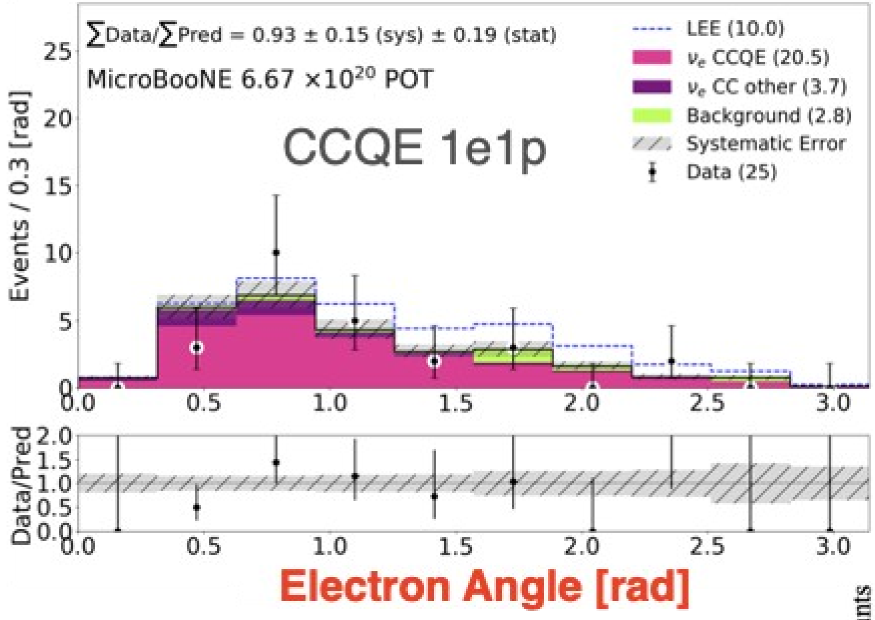
Electron-like Results – Hadronic Energy

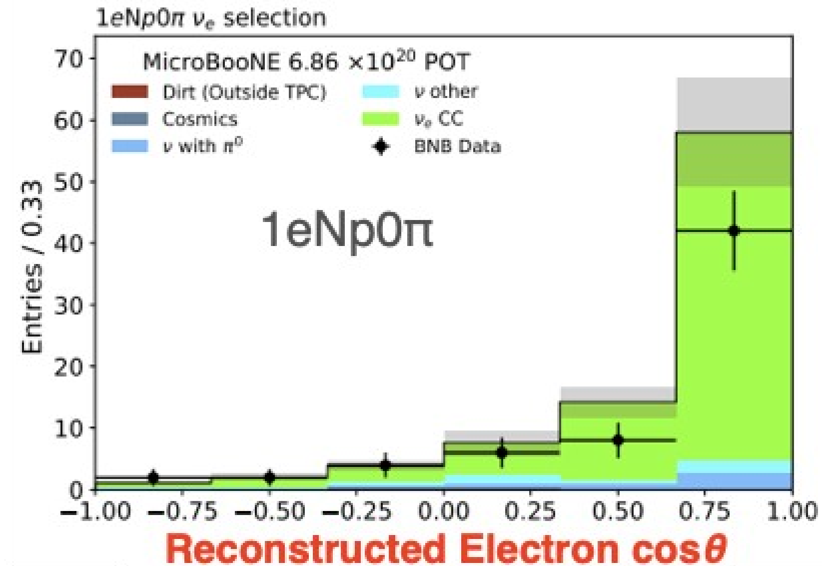


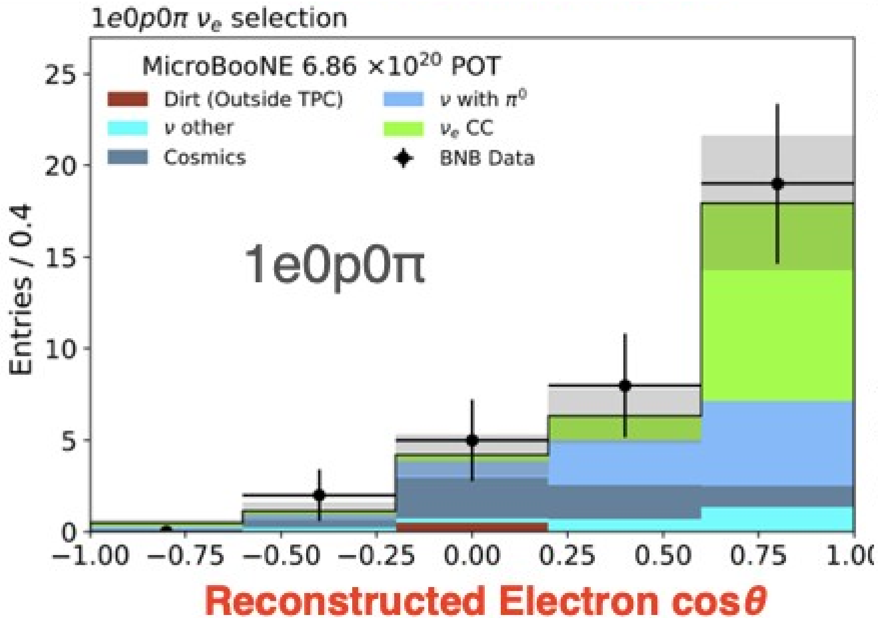


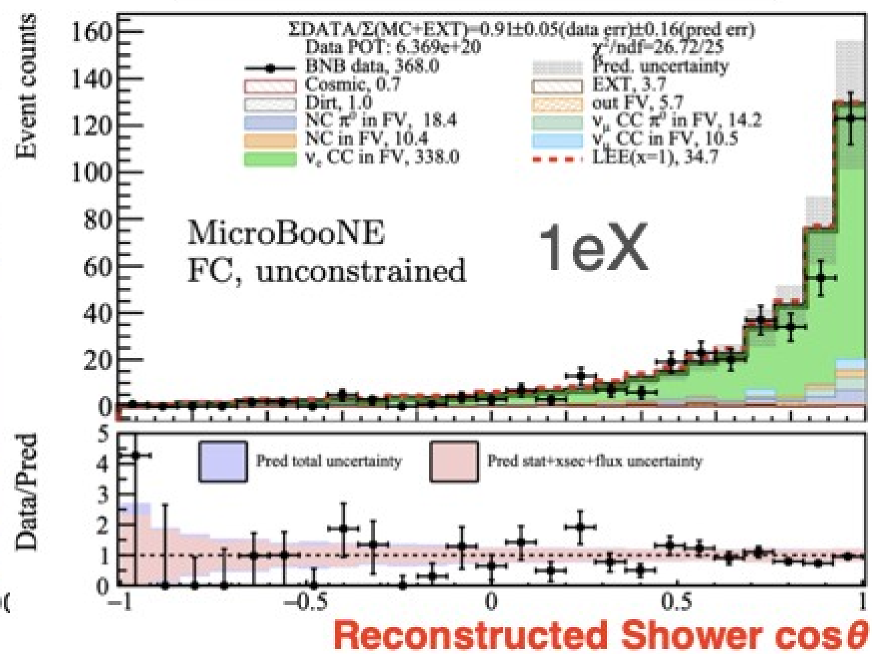


Electron-like Results – Lepton Angle

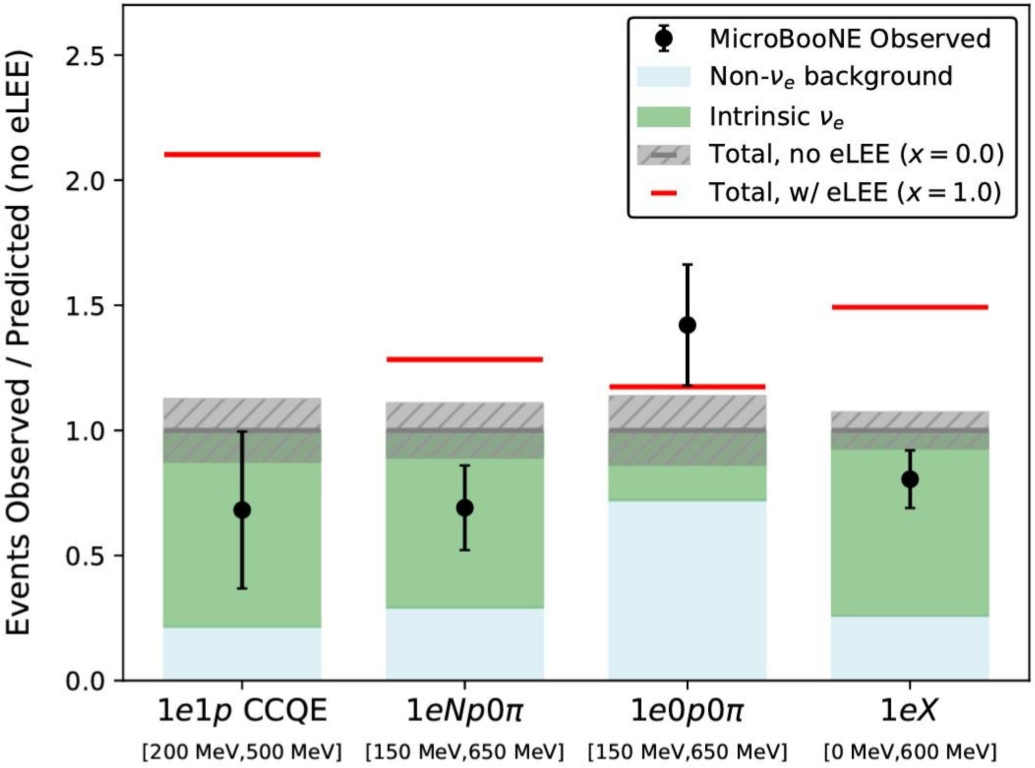








Electron-like Results



Observe electron neutrino candidates at or below predicted rates.

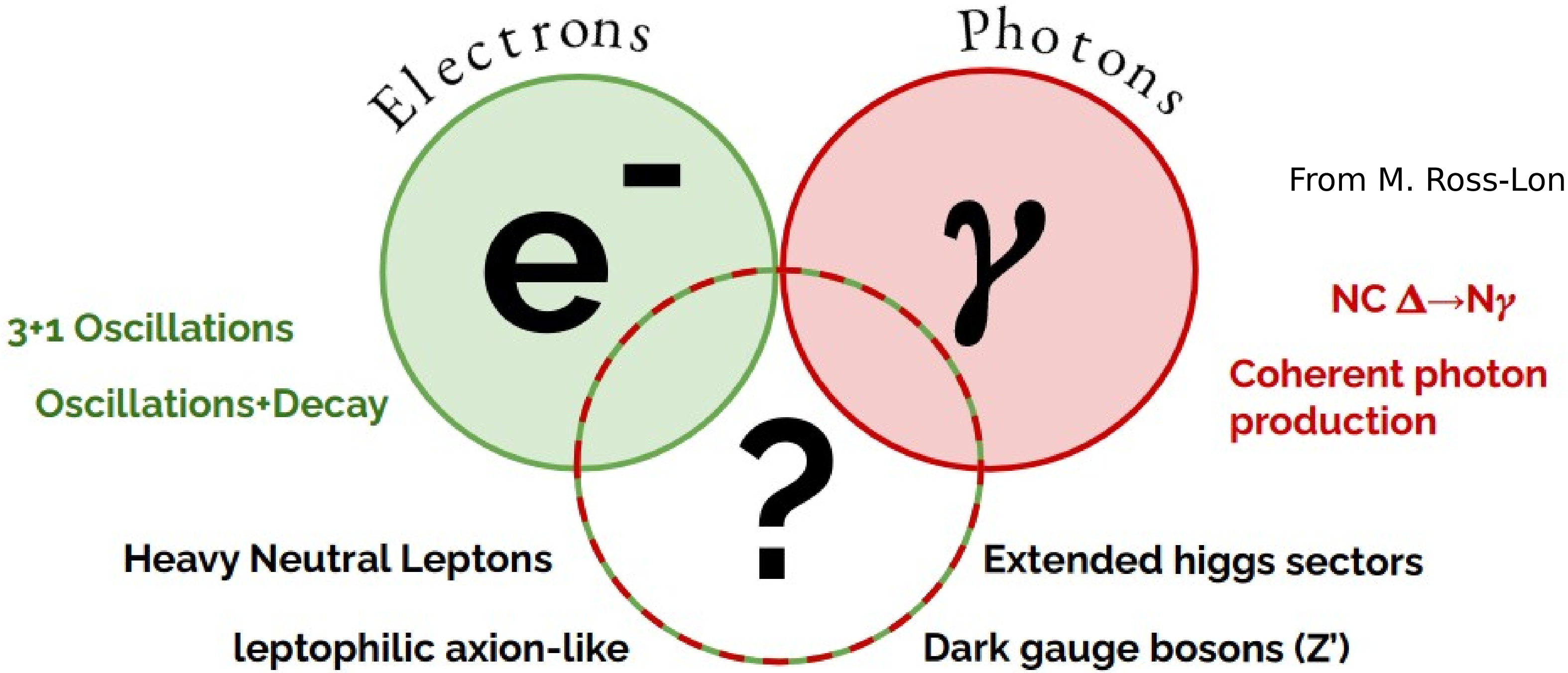
arXiv:2110.14054

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

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.

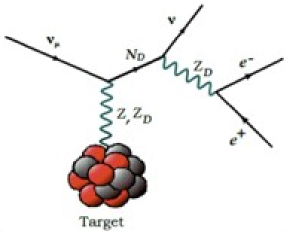
Or what else?

- 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.

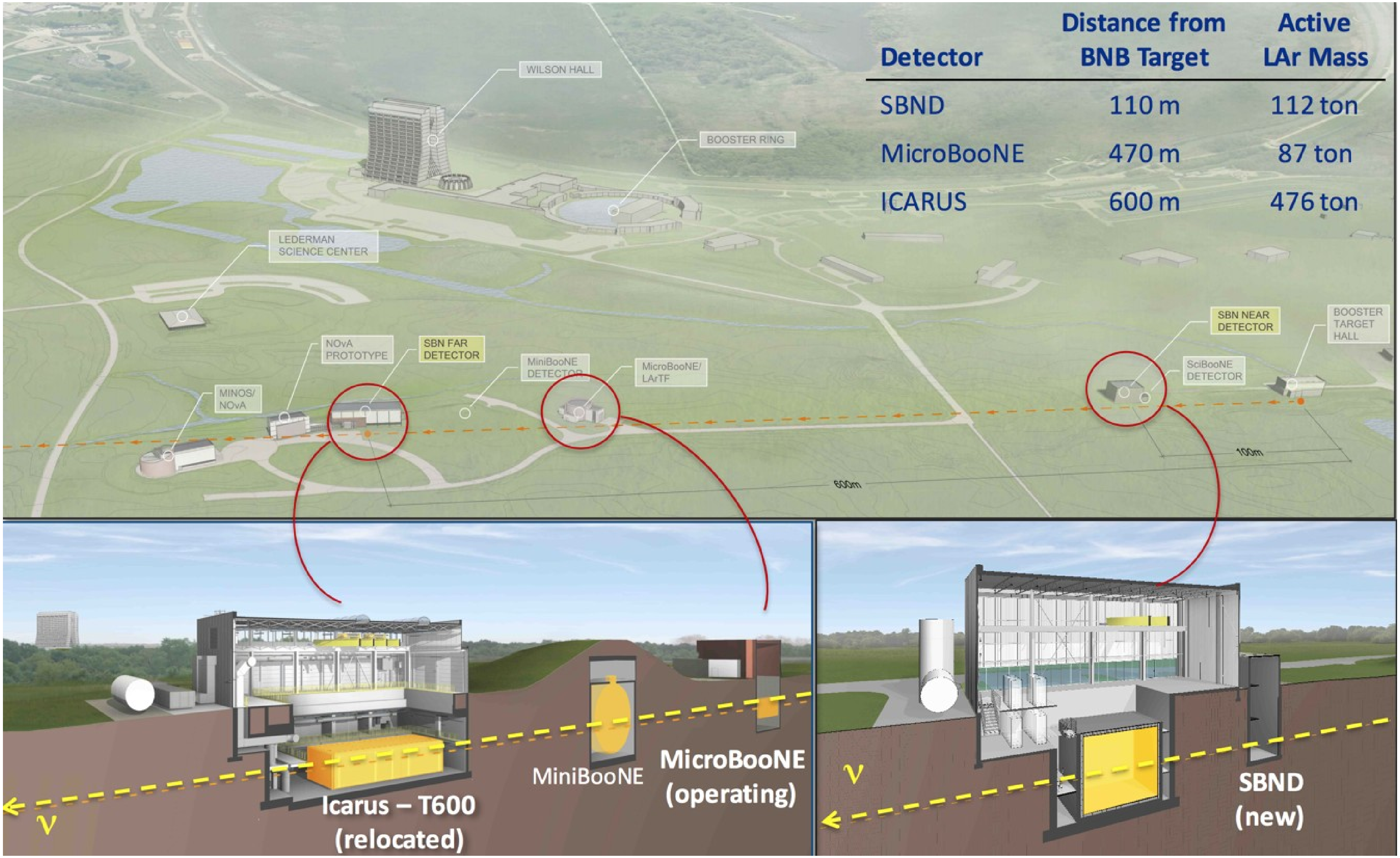
Already started probing with first LEE results

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

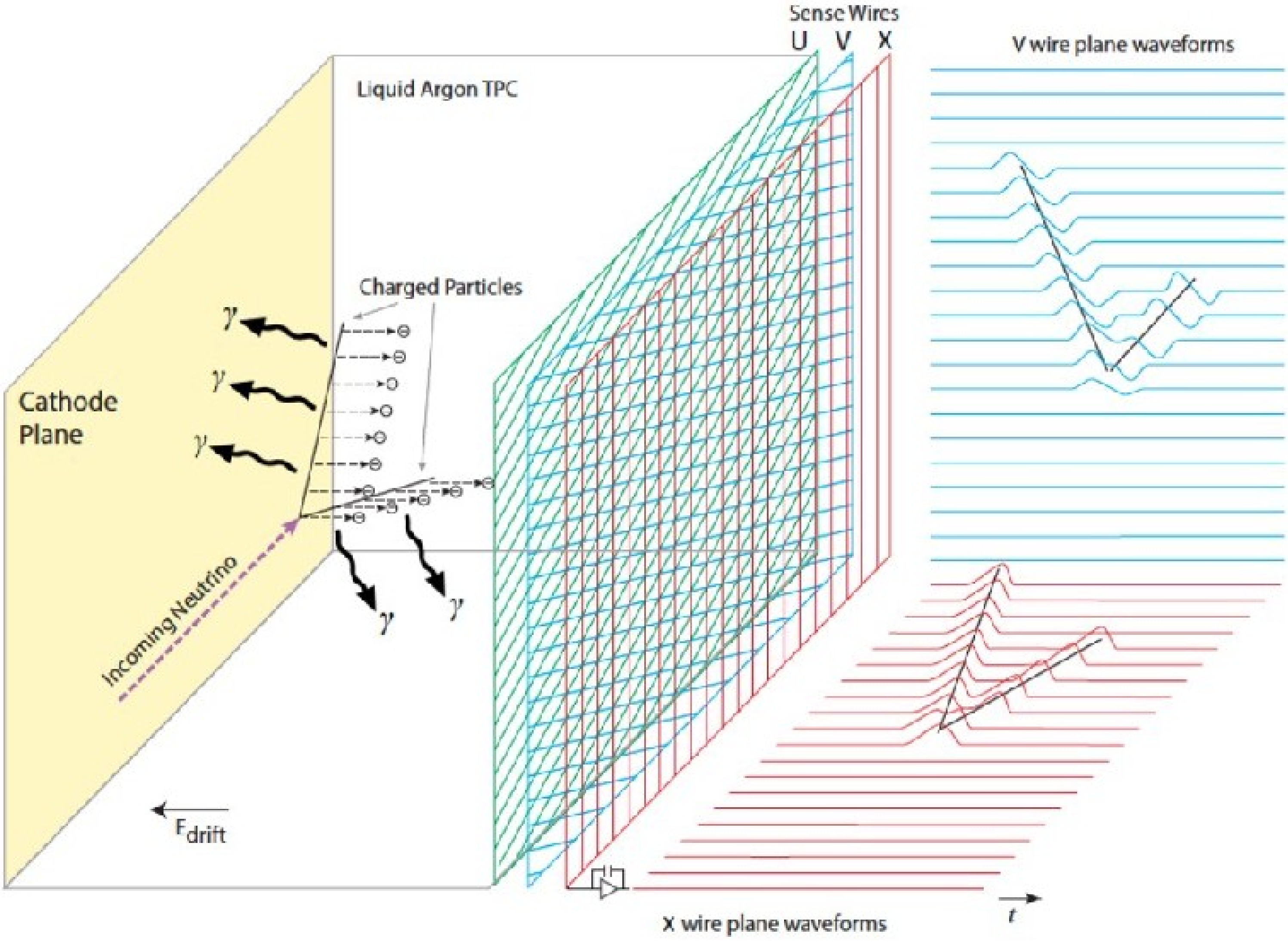
What next for MicroBooNE?

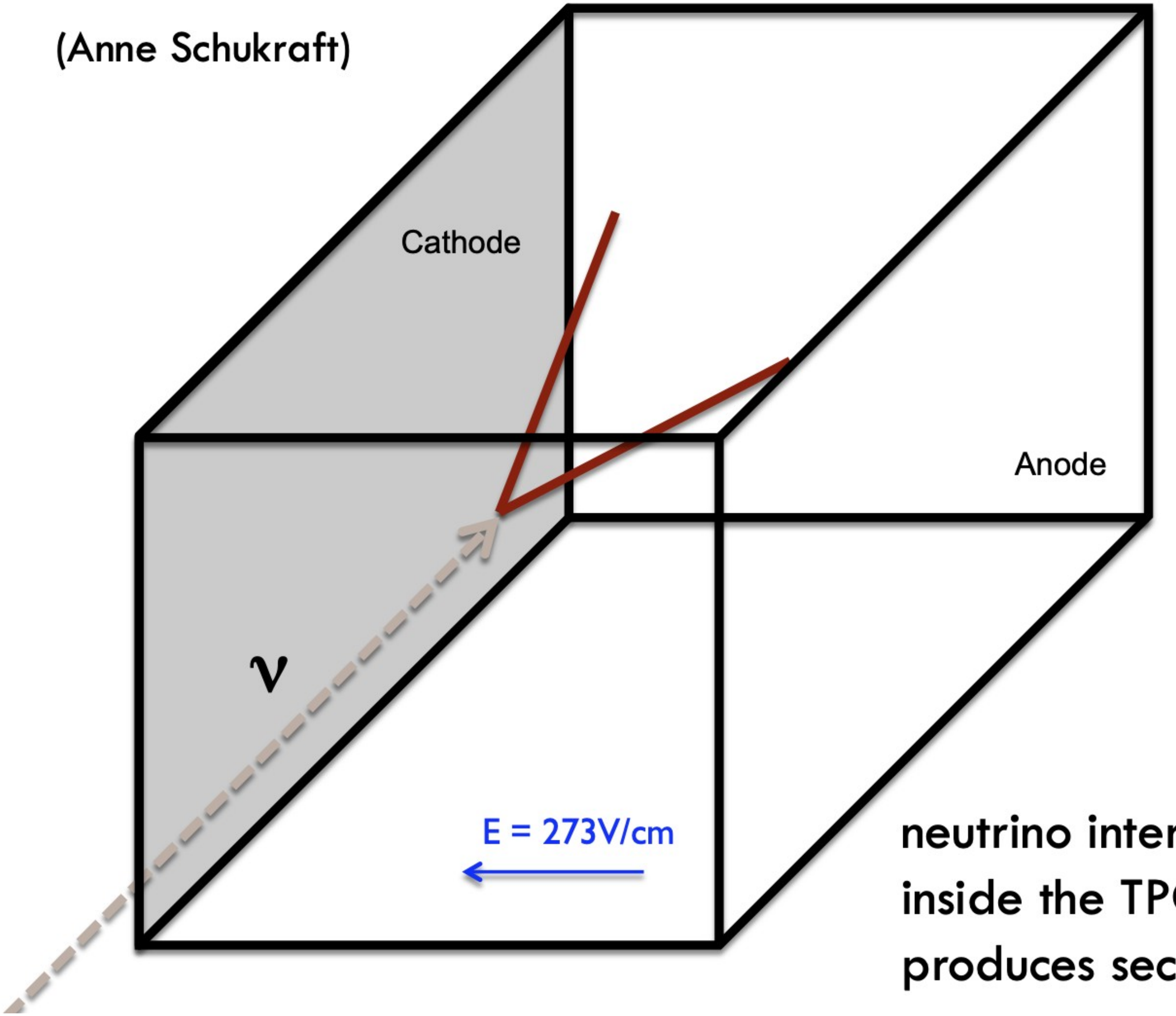
- Bright future!
  - Only analysed a fraction of the dataset, there will be updated LEE results.
    - More data.
    - More models.
    - Improved analyses.
  - Many neutrino cross-section results coming out.
  - Liquid Argon R&D to help future experiments.
- But also an upgraded short baseline program 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

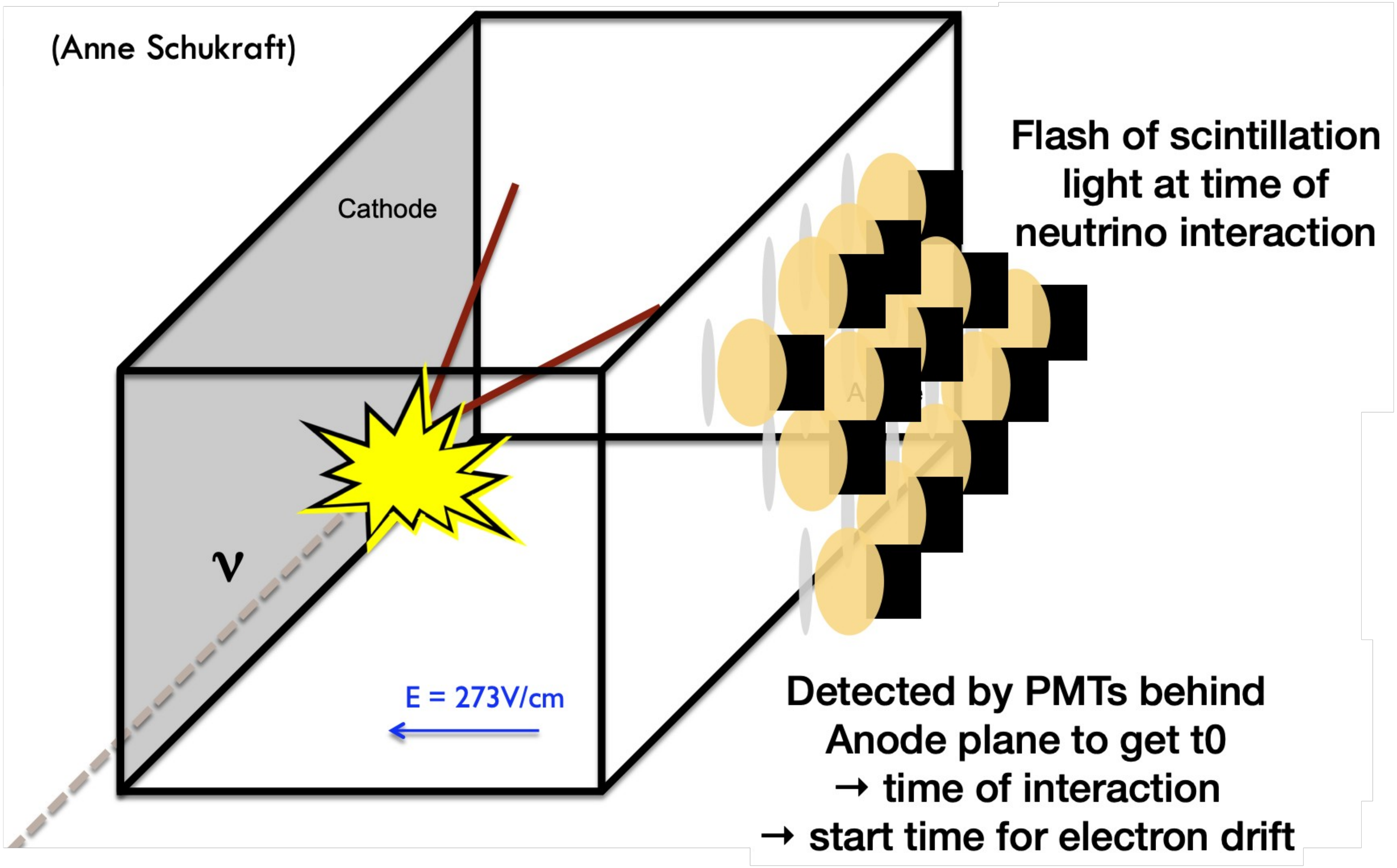
Liquid Argon TPCs

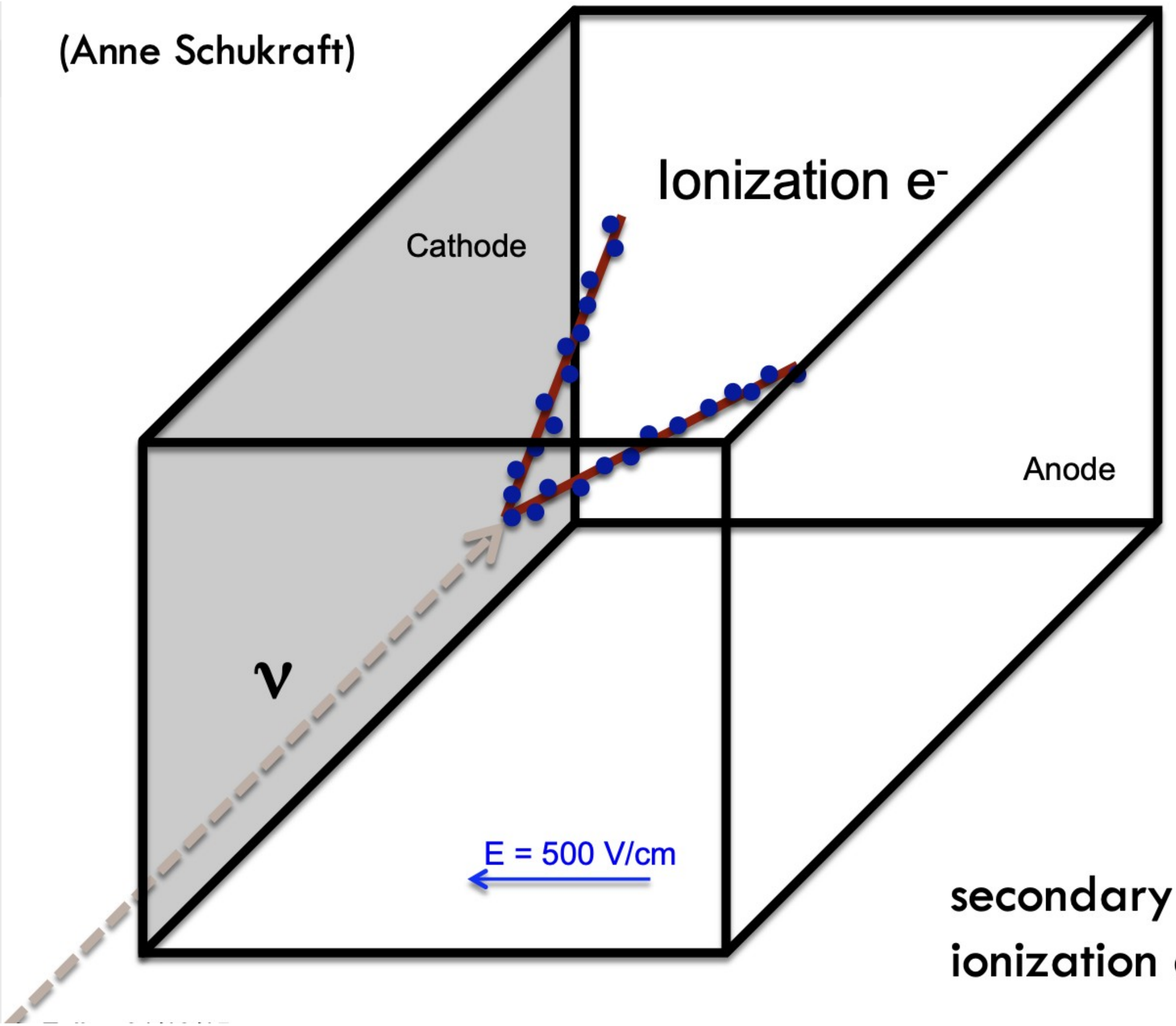




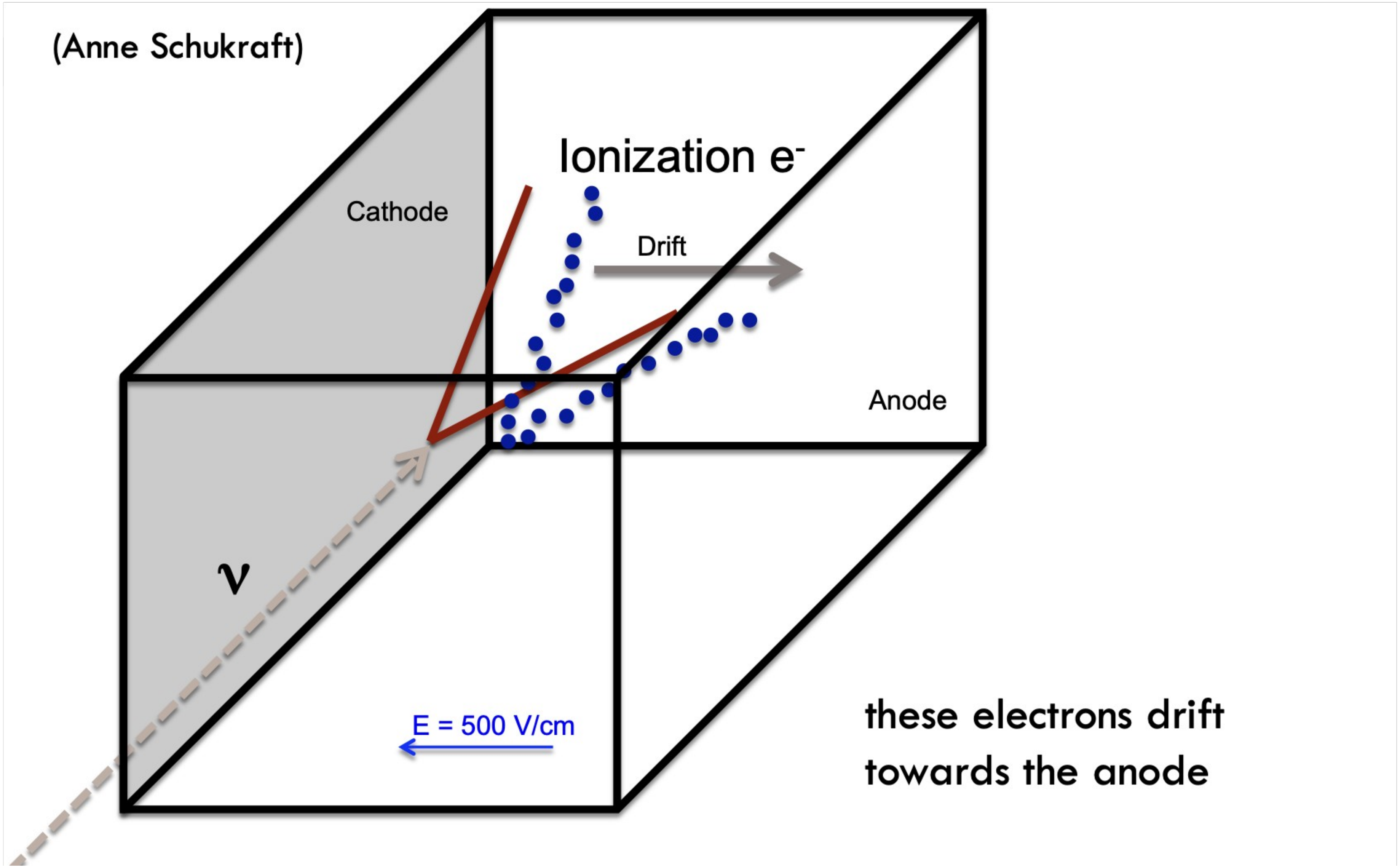
liquid argon detectors work differently than scintillator detectors so their “pictures” look different

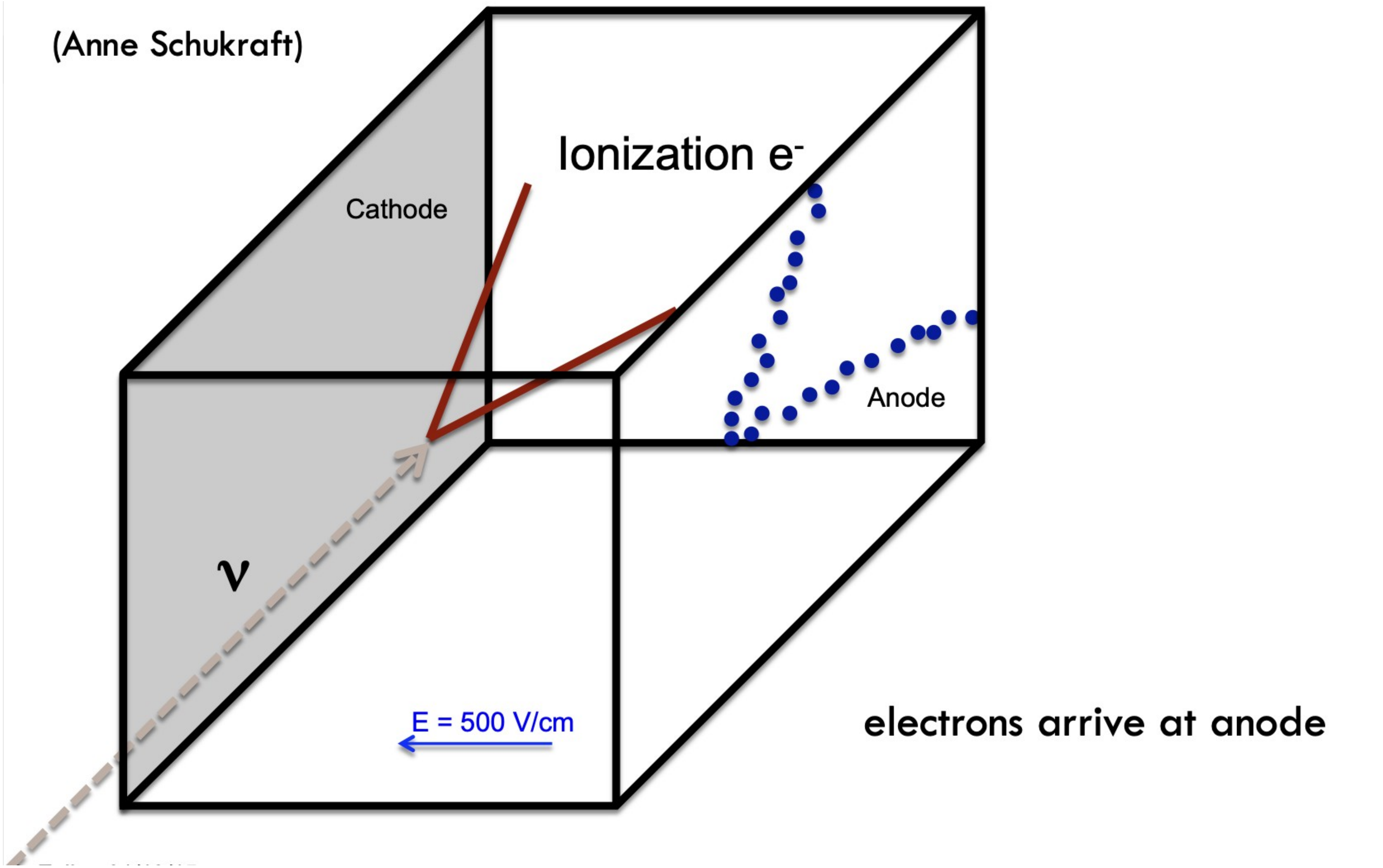
neutrino interacts with the argon inside the TPC volume and produces secondary particles

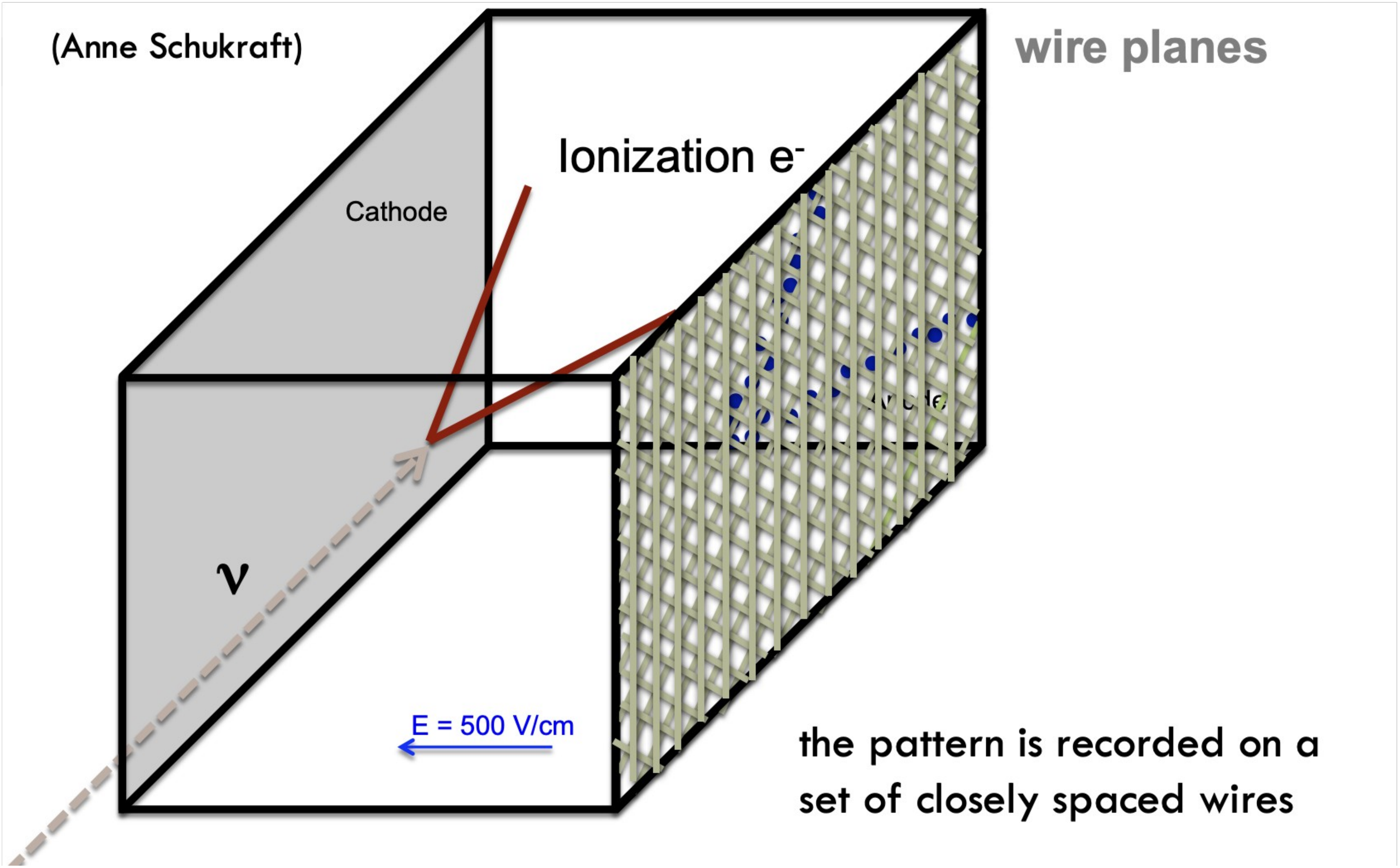

(Anne Schukraft)
Cathode
ν
E = 273V/cm
Flash of scintillation light at time of neutrino interaction
Detected by PMTs behind Anode plane to get t0
→ time of interaction
→ start time for electron drift

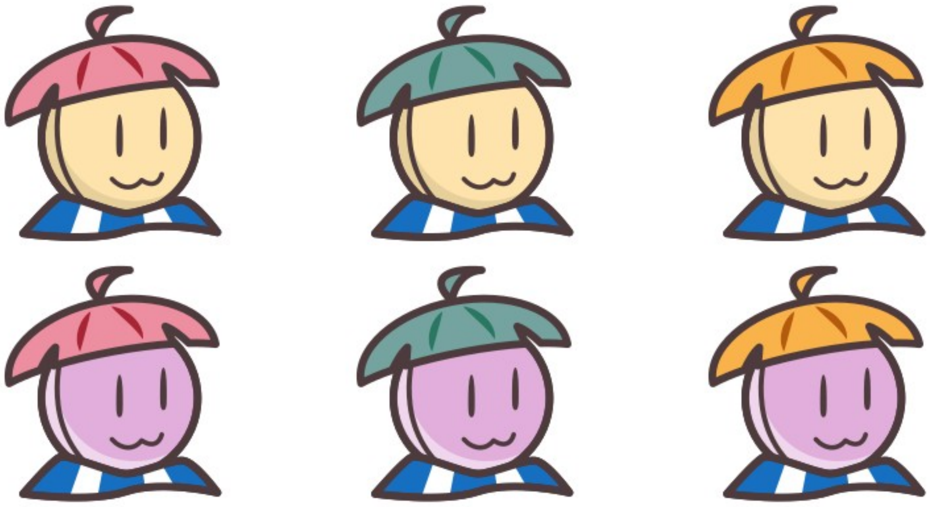


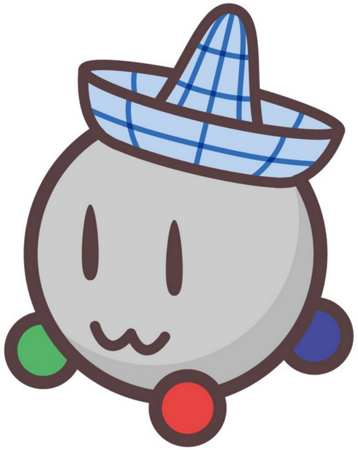
secondary particles produce ionization electrons


(Anne Schukraft)
Ionization e-
Cathode
Drift
Anode
ν
E = 500 V/cm
these electrons drift
towards the anode


(Anne Schukraft)
Cathode
Ionization e⁻
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





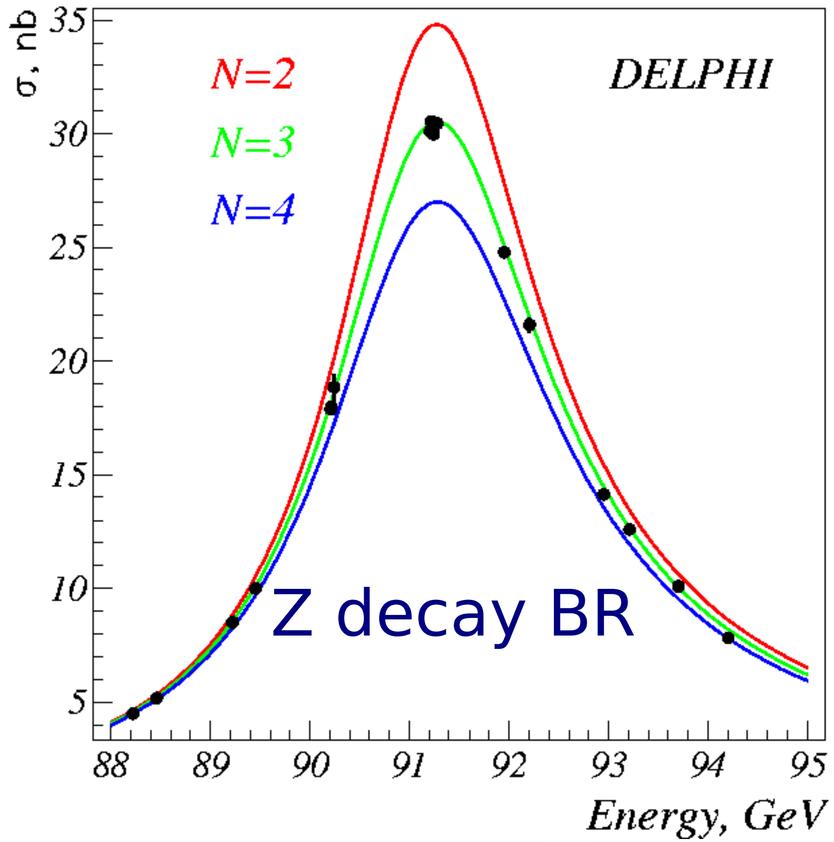
All cartoons by Yuki Akimoto - Higgstan
KEK Pamphlet

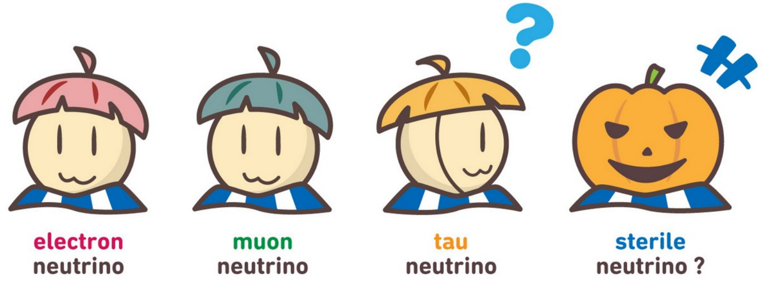
What’s a sterile neutrino?

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.

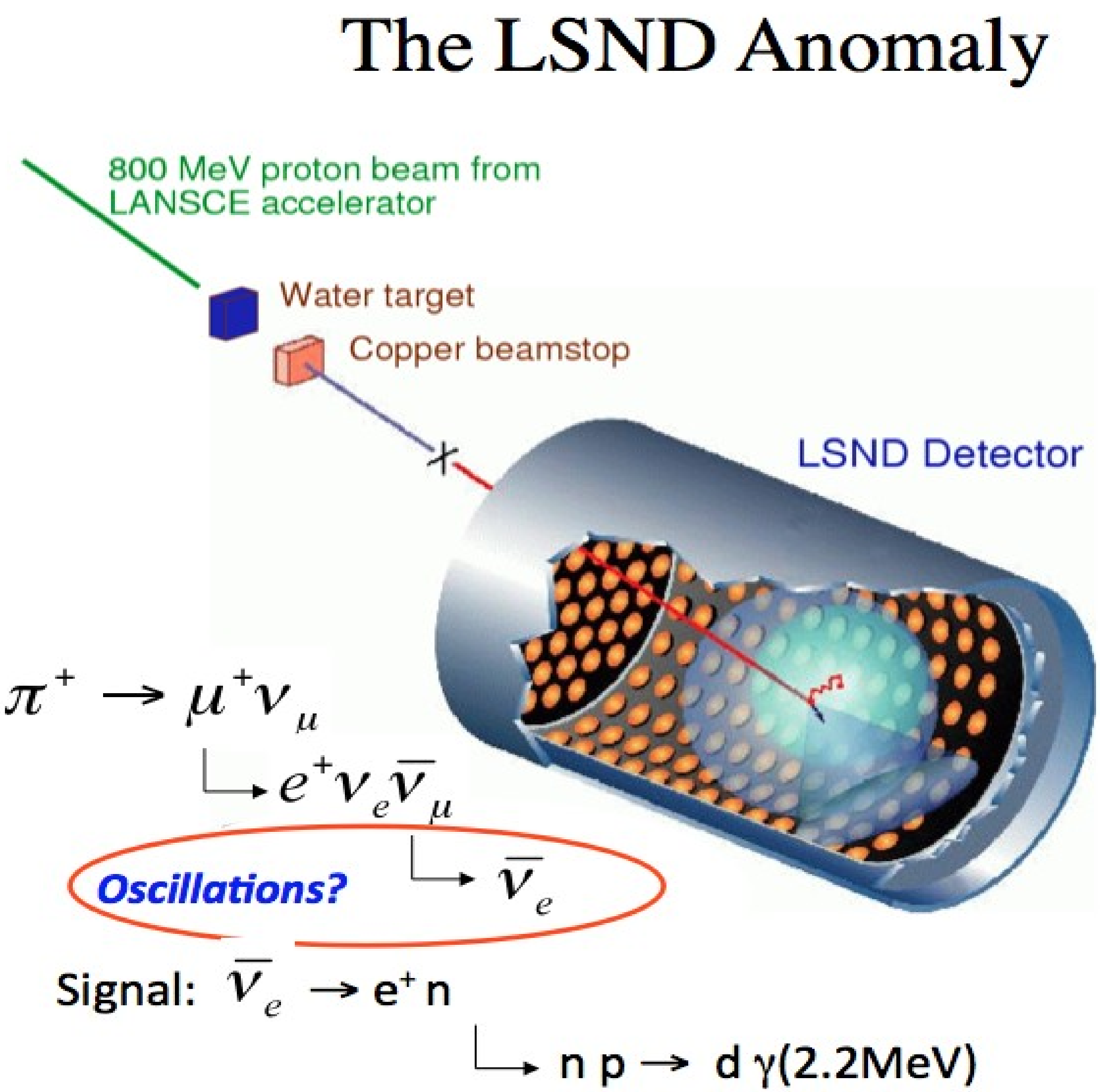
We know this neutrino doesn’t couple to the weak force, because it would affect the fraction of Z bosons that decay into neutrinos, unless it is extremely heavy (>40 GeV).

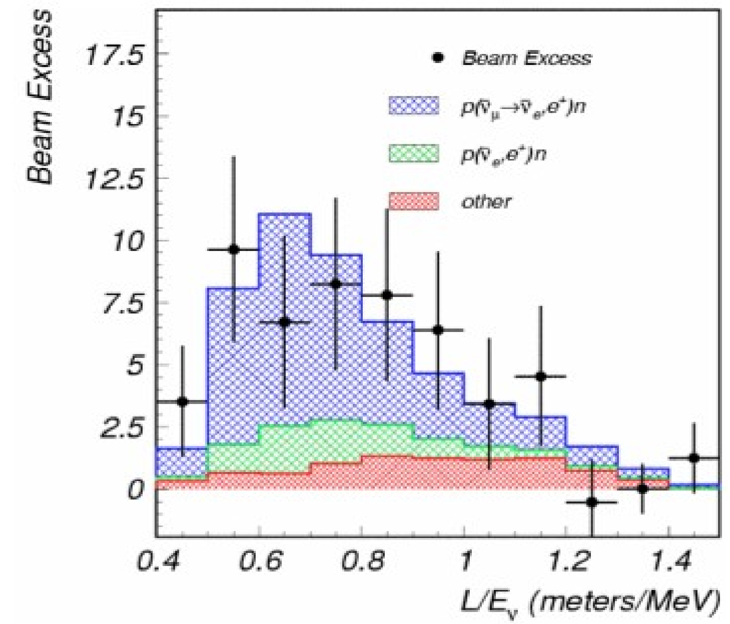




So this hypothesis is called sterile – it doesn’t interact directly, you only see it via effects like oscillation.

LSND Excess





3.8 sigma excess

arXiv:nucl-ex/9605002

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:

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