Particle Physics: Neutrinos – part II

Edward Dunton

Week 9: November 17, 2018
Columbia University Science Honors Program

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

NEVIS LABORATORIES

Course policies

- Classes from 10:00 AM to 12:30 PM (10 min break at ~ 11:10 AM).
- **Attendance record counts.**
  - Up to four absences
  - Lateness or leaving early counts as half-absence
    - Send email notifications of all absences to shpattendance@columbia.edu

- Please, no cell phones during class

- **Please, ask questions!**

- Lecture materials + Research Opportunities + Resources to become a particle physicist

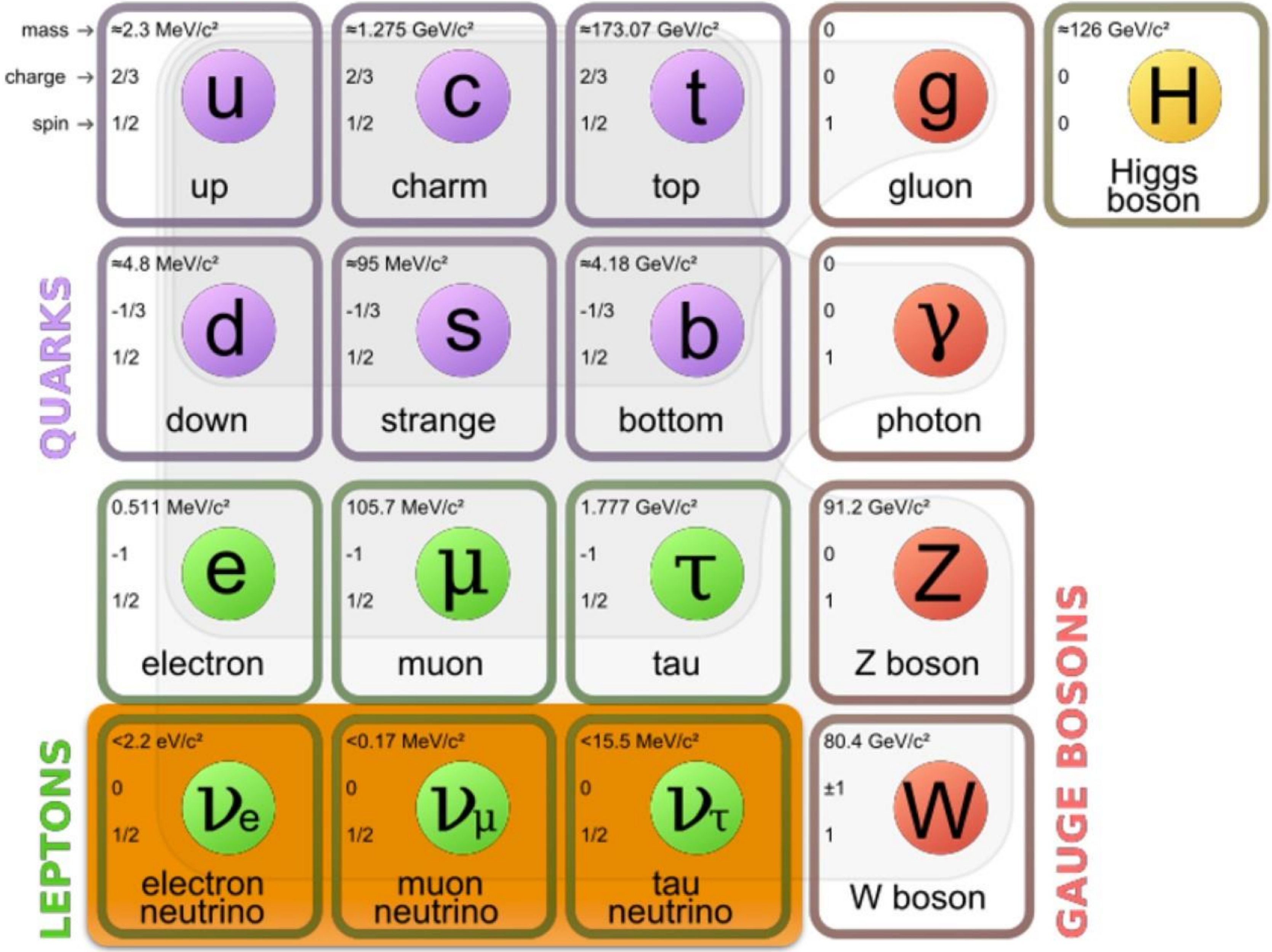
https://twiki.nevis.columbia.edu/twiki/bin/view/Main/ScienceHonorsProgram

Schedule

Month	Day	Lecture	Teacher
~~September~~	~~22~~	~~Introduction~~	~~Yeon-jae~~
	~~29~~	~~History of Particle Physics~~	~~Yeon-jae~~
~~October~~	~~6~~	~~Special Relativity~~	~~Edward~~
	~~13~~	~~Quantum Mechanics~~	~~Edward~~
	~~20~~	~~Experimental Methods~~	~~Edward~~
	~~27~~	~~The Standard Model - Overview~~	~~Yeon-jae~~
~~November~~	~~3~~	~~The Standard Model - Limitations~~	~~Yeon-jae~~
	~~10~~	~~Neutrino Theory~~	~~Edward~~
	17	Neutrino Experiment	Edward
	24	No classes, SHP break	
December	1	LHC and Experiments	Yeon-jae
	8	The Higgs Boson and Beyond	Yeon-jae
	15	Particle Cosmology	Edward

Review

THE WORLD, ACCORDING TO A PARTICLE PHYSICIST



≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c^2 0 0 H Higgs boson
≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	
0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z Z boson	
<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson	

NEUTRINO MIXING FORMALISM

- Write the most general matrix that conserves number of particles.
  - Like rotations in three dimensions, but with complex numbers…

Weak / Flavor states

"Atmospheric" parameters

- The Pontecorvo-Maki-Nakagawa-Sakata (**PMNS**) matrix.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

$$\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{+i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

"Reactor" parameters

CP violating phase

"Solar" parameters

Mass states

- We wouldn't be in this mess if neutrinos were **massless**!!

- So how do we know they're **not**?

NEUTRINO OSCILLATIONS

- Assume, for simplicity only two neutrinos.
  - Two weak states that mix with two mass states.

- Wave functions "evolve" with time by rotating in the complex plane:

$$\begin{aligned}
\begin{pmatrix} |\nu_1(x,t)> \\ |\nu_2(x,t)> \end{pmatrix} &= \begin{pmatrix} e^{-i\phi_1} & 0 \\ 0 & e^{-i\phi_2} \end{pmatrix} \begin{pmatrix} |\nu_1(0,0)> \\ |\nu_2(0,0)> \end{pmatrix} \\
&= \begin{pmatrix} e^{-i\phi_1} & 0 \\ 0 & e^{-i\phi_2} \end{pmatrix} \begin{pmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{pmatrix} \begin{pmatrix} |\nu_\alpha(0,0)> \\ |\nu_\beta(0,0)> \end{pmatrix}
\end{aligned}$$

- With a few lines of trigonometry:

$$P(\nu_\alpha \rightarrow \nu_\beta) = sin^2(2\theta) sin^2(\frac{\phi_2 - \phi_1}{2})$$

NEUTRINO OSCILLATIONS

$$P(\nu_\alpha \rightarrow \nu_\beta) = sin^2(2\theta) sin^2(\frac{\phi_2 - \phi_1}{2})$$

- Time evolution determined by energy of the state. If we assume* the two superimposed mass states are produced with the same energy, we get:

$$\phi_2 - \phi_1 = (\frac{m_1^2}{2E_1} - \frac{m_2^2}{2E_2})L = \frac{\Delta m^2 L}{2E}$$

- Substituting in oscillation probability expression gives:

$$P(\nu_e \rightarrow \nu_\mu) = \underbrace{sin^2(2\theta)}_{\text{Oscillation amplitude}} sin^2(\underbrace{1.27\Delta m^2 \frac{L}{E_\nu}}_{\text{Oscillation frequency}})$$

* Assumption not necessary if more detailed wavepacket formulation is used.

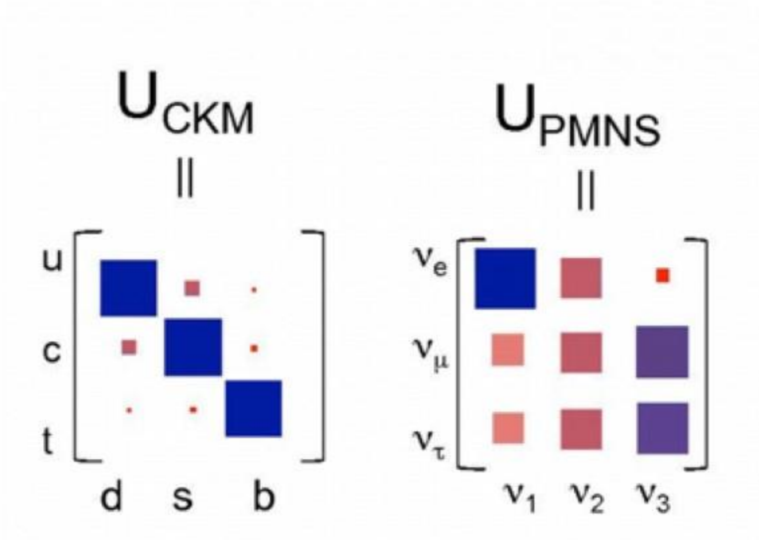
3 neutrinos: mixing matrix

$c_{ij}=\cos\theta_{ij},\ s_{ij}=\sin\theta_{ij}$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \overbrace{\underbrace{\begin{pmatrix}1 & & \\ & c_{23} & s_{23}\\ & -s_{23} & c_{23}\end{pmatrix}}_{\text{Atmospheric \& Long-baseline accelerator experiments}} \underbrace{\begin{pmatrix}c_{13} & & s_{13}e^{-i\delta}\\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13}\end{pmatrix}}_{\text{Reactor \& Long-baseline accelerator experiments}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1\end{pmatrix}}_{\text{Solar \& KamLAND experiments}}}^{\text{PMNS matrix: U}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} \begin{matrix}\to m_1\\ \to m_2\\ \to m_3\end{matrix}$$

$$\Delta m^2_{jk} \equiv m_j^2 - m_k^2$$

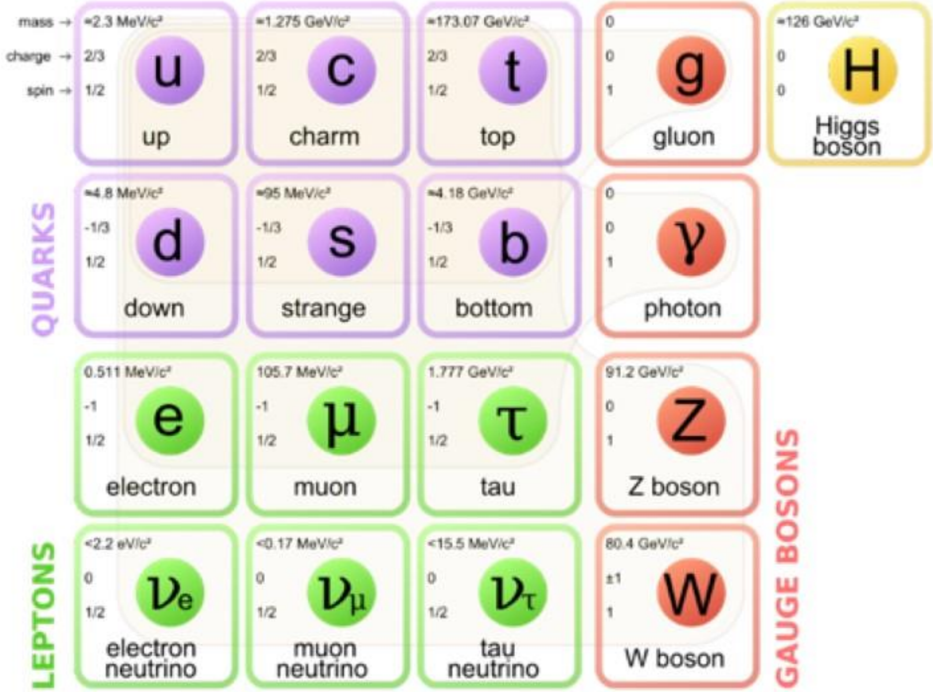
- **3 angles measured (mnemonic approximation):**
  - $\theta_{12} \approx 34°$
  - $\theta_{23} \approx 45°$ (symmetry?)
  - $\theta_{13} \approx 9°$
- CP-violating phase δ?
- Why so different from quark mixing?

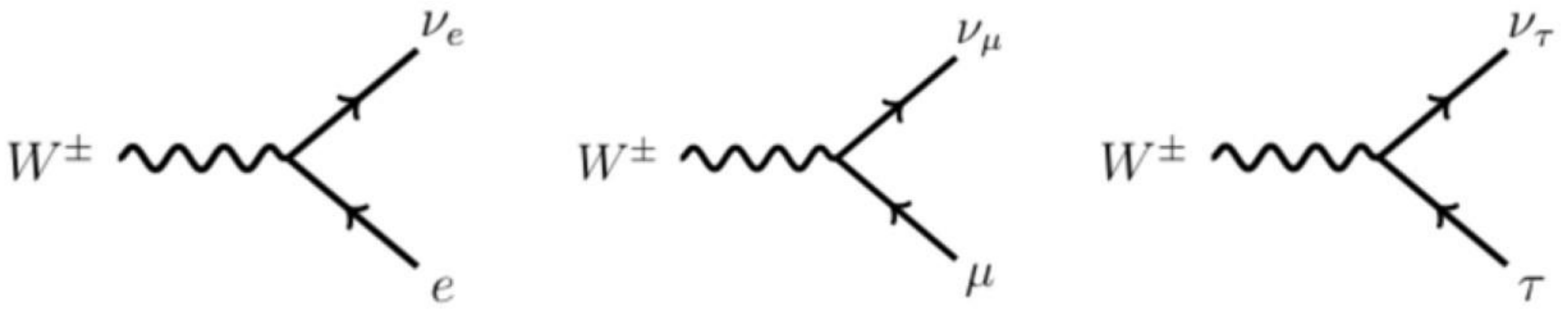


3 evidences for 3 neutrinos

3 neutrinos: 3 charged leptons

- Neutrinos are the only neutral elementary fermions → **only weak interaction.**
- Weak interaction only couples to **left-handed neutrinos or right-handed antineutrinos.**
- The **neutrino flavor** is assigned according to the charged lepton they accompany in the charged-current weak interaction (mediated by the W bosons).
- **3 charged leptons → 3 neutrinos.**

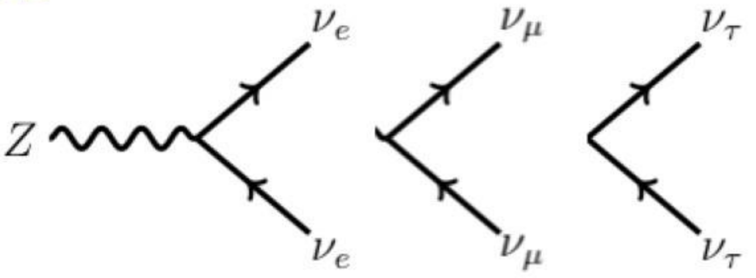




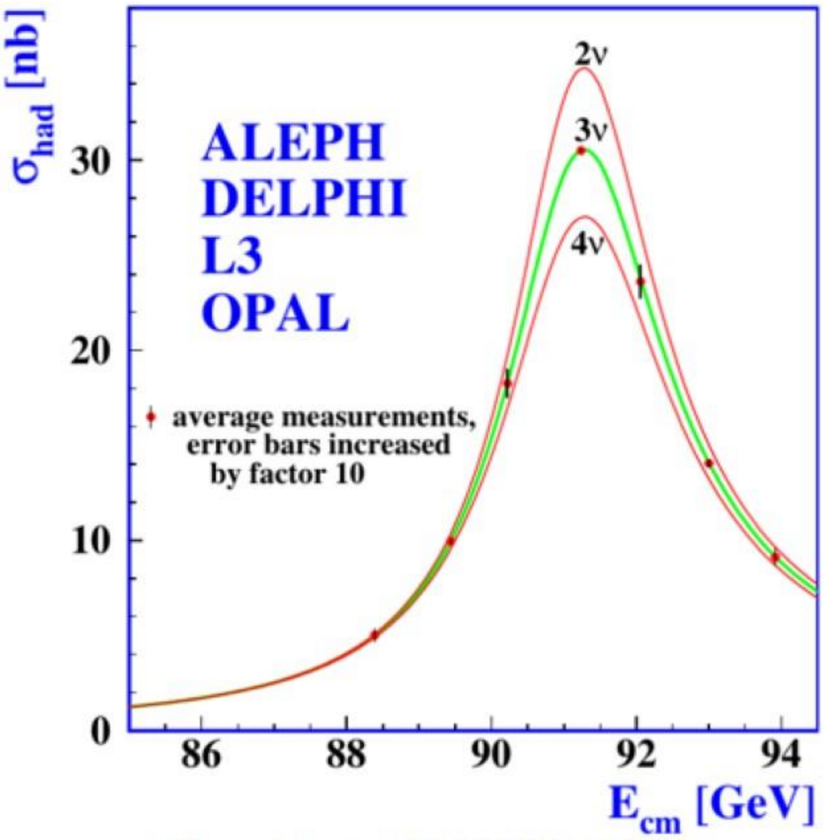
3 neutrinos: the Z boson width

- Unstable particles have an intrinsic uncertainty (width) on their mass (*Heisenberg uncertainty principle*):

$$\Delta E \cdot \Delta t \geq \frac{\hbar}{2}$$



- This width is proportional to the number of disintegration modes and their frequency.
- The width of the Z boson is ~ 2.5 GeV and ~ 20% of the times the Z decays into neutrinos (invisible width).
- The 4 detectors of LEP (predecessor of the LHC at CERN) measured this width, which is related to the number of neutrinos*.
- **$N_\nu = 2.9840 \pm 0.0082$.**
- (*) Only possibilities left:
- Very heavy neutrinos ($> m_Z/2 \approx 45$ GeV).
- Neutrinos which do not couple to the Z boson: **sterile neutrinos...**



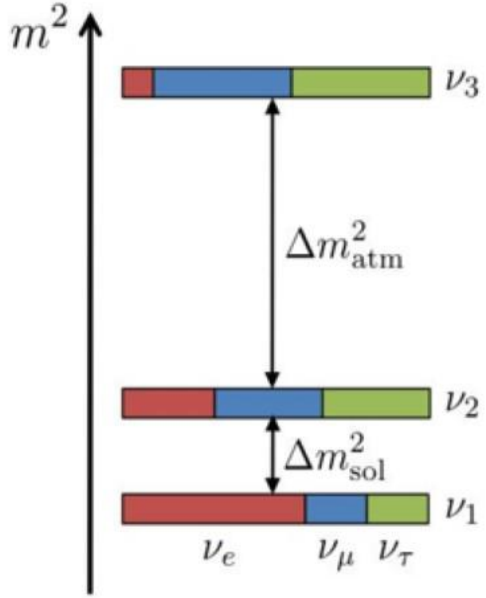
Phys. Rept. 427 (2006) 257-454

3 neutrinos: mixing matrix

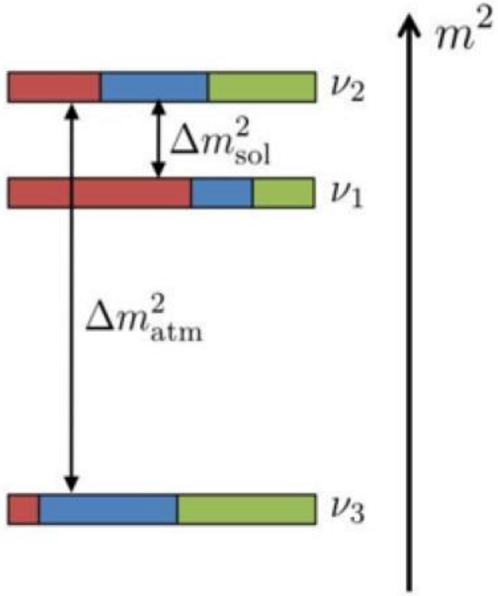
$c_{ij}=\cos\theta_{ij},\ s_{ij}=\sin\theta_{ij}$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \overbrace{\begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}}^{\text{PMNS matrix: U}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \begin{matrix} \rightarrow \mathrm{m}_1 \\ \rightarrow \mathrm{m}_2 \\ \rightarrow \mathrm{m}_3 \end{matrix}$$

normal hierarchy (NH)



inverted hierarchy (IH)

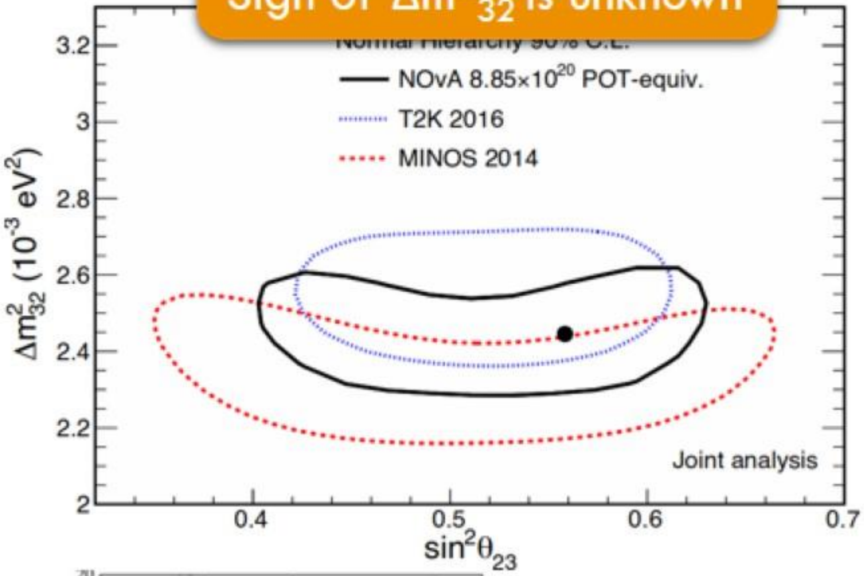


FROM NEUTRINO OSCILLATIONS

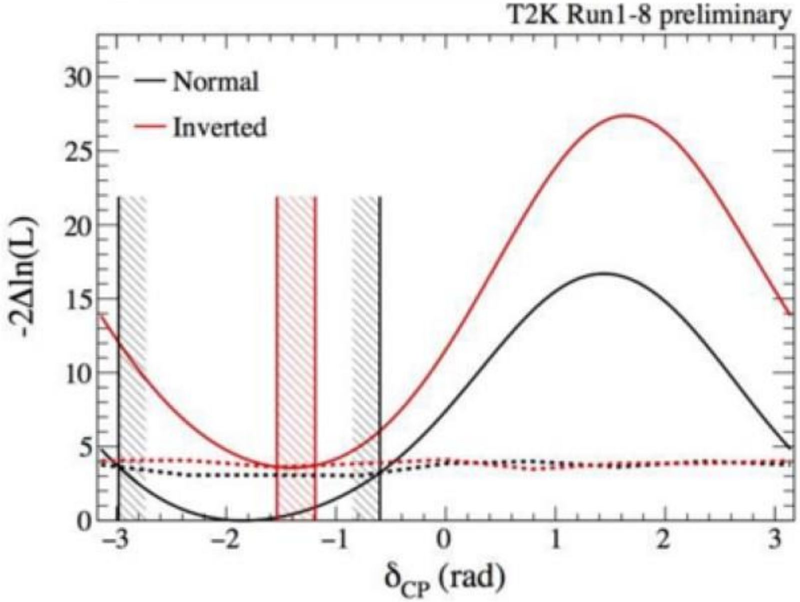
- There are at least two (very) different neutrino mass splittings:
  - At least **3** neutrino mass states, but one of them might be zero.
  - But don't know which of the mass states is the lightest.
- The three mixing angles are non-zero and large.
  - Unlike in the quark sector, where they are small.
  - This makes it possible to measure the **CP violating** phase in the PMNS matrix.
    - Wouldn't be possible if any of the angles was zero, and it would be very difficult if any of the angles was very small.

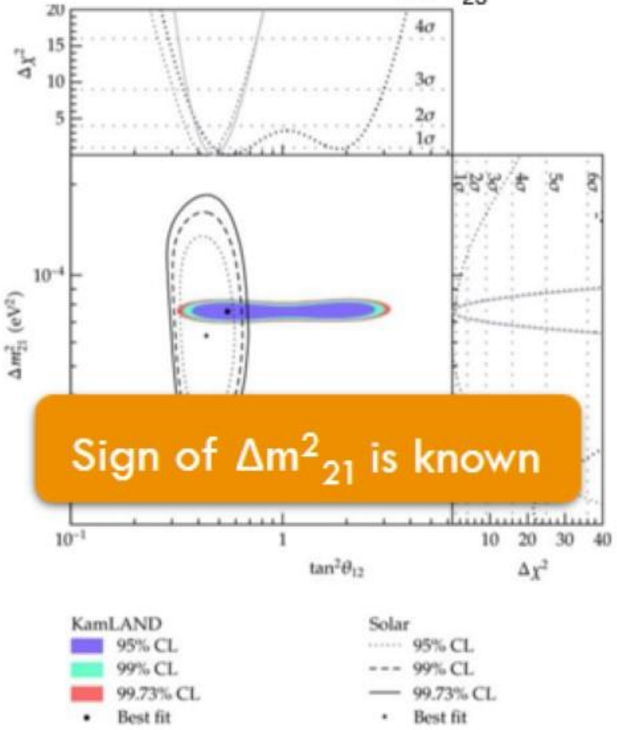
CURRENT STATUS OF THE PMNS MODEL

Θ_{23} might be maximal
Sign of Δm^2_{32} is unknown

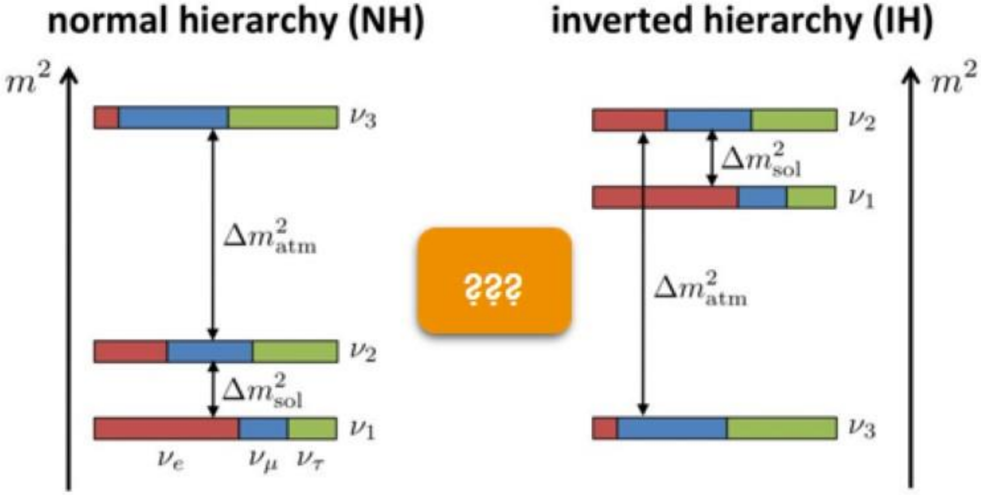


CP might not be conserved





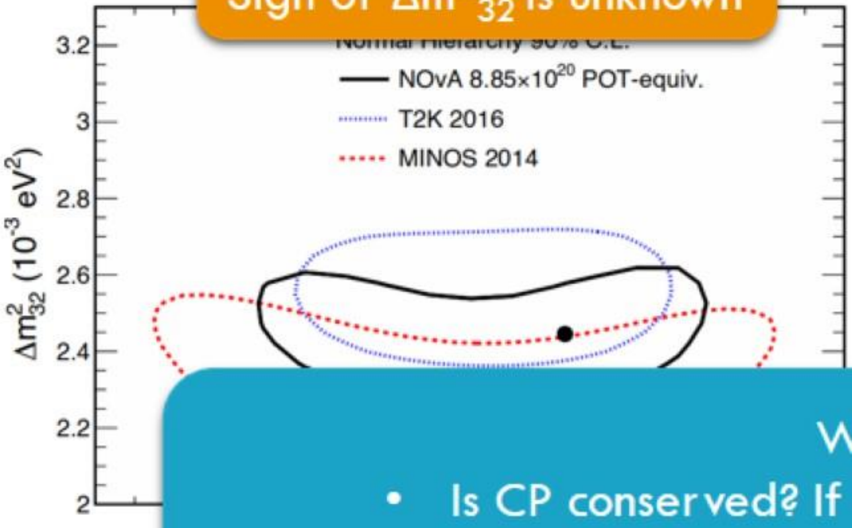
Sign of Δm^2_{21} is known



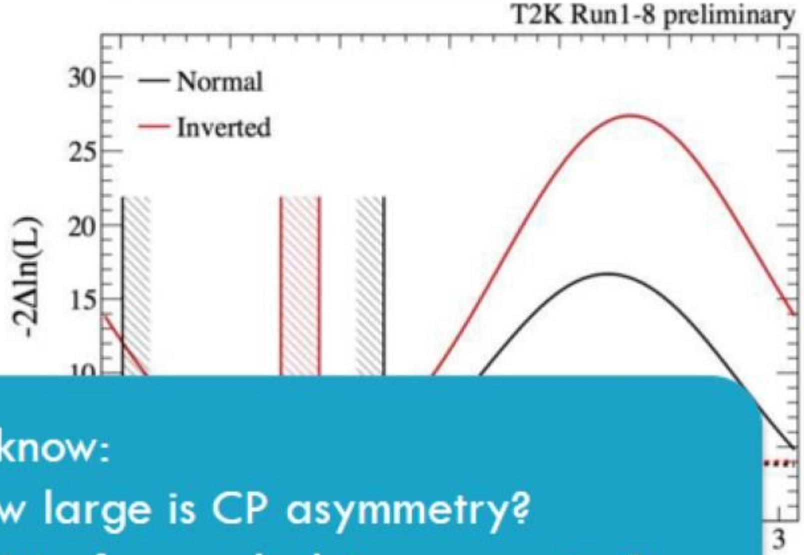
???

CURRENT STATUS OF THE PMNS MODEL

Θ_{23} might be maximal
Sign of Δm^2_{32} is unknown

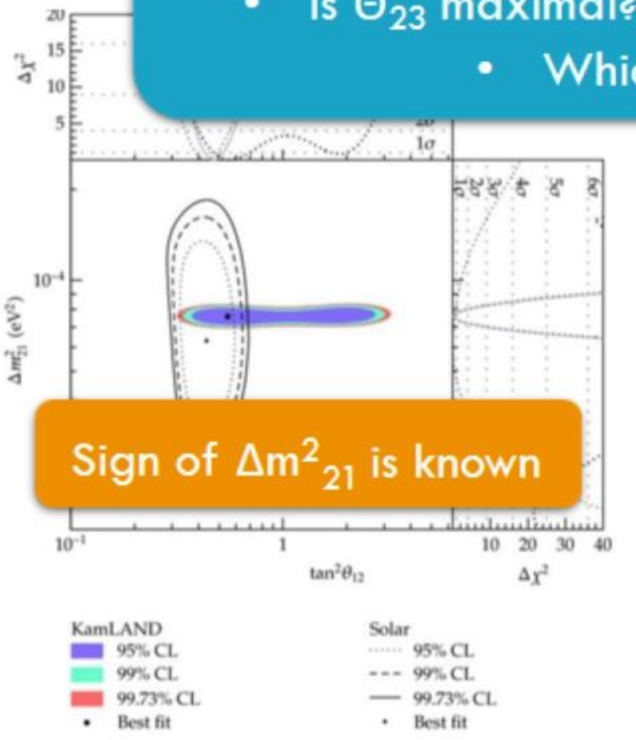


CP might not be conserved

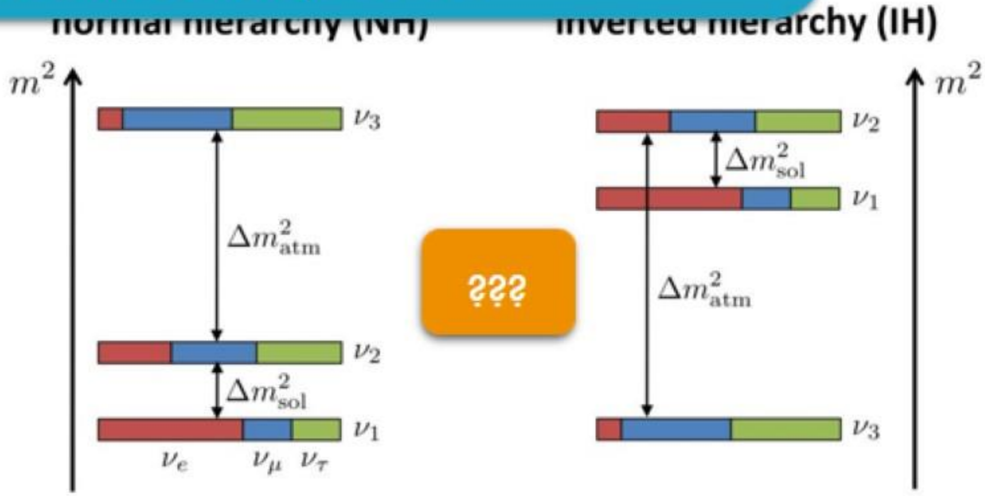


Want to know:

- Is CP conserved? If not, how large is CP asymmetry?
- Is Θ_{23} maximal? If so, is that a hint of an underlying symmetry?
- Which is the heaviest mass state, 3 or 2?



Sign of Δm^2_{21} is known



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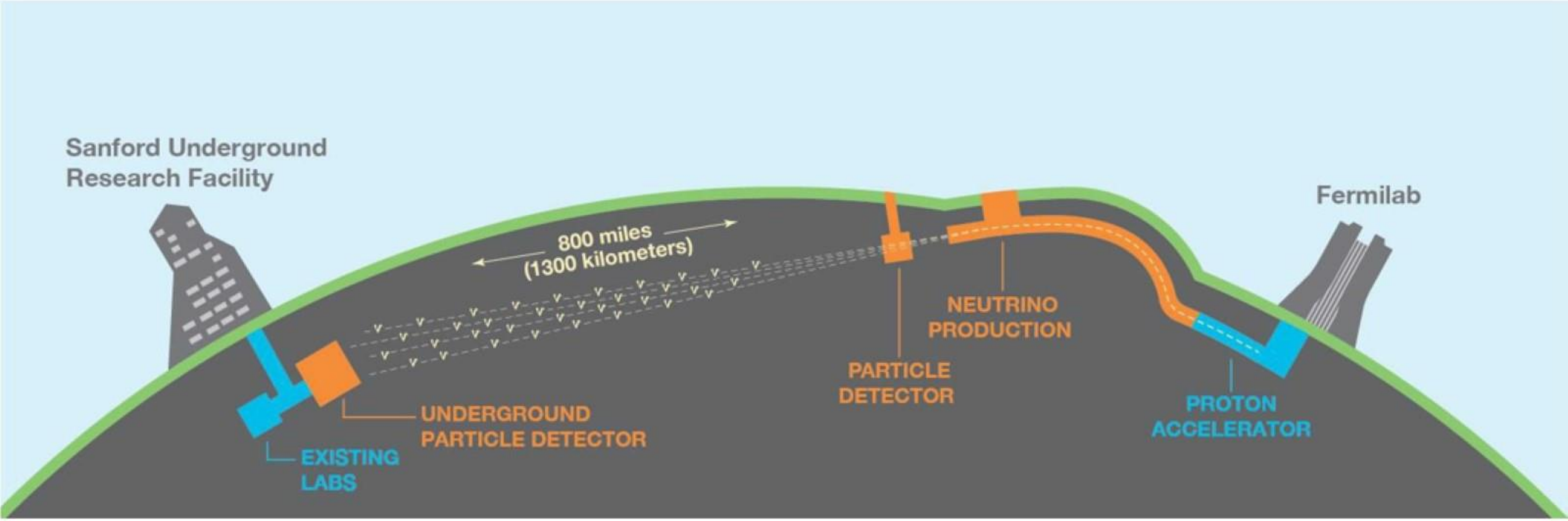
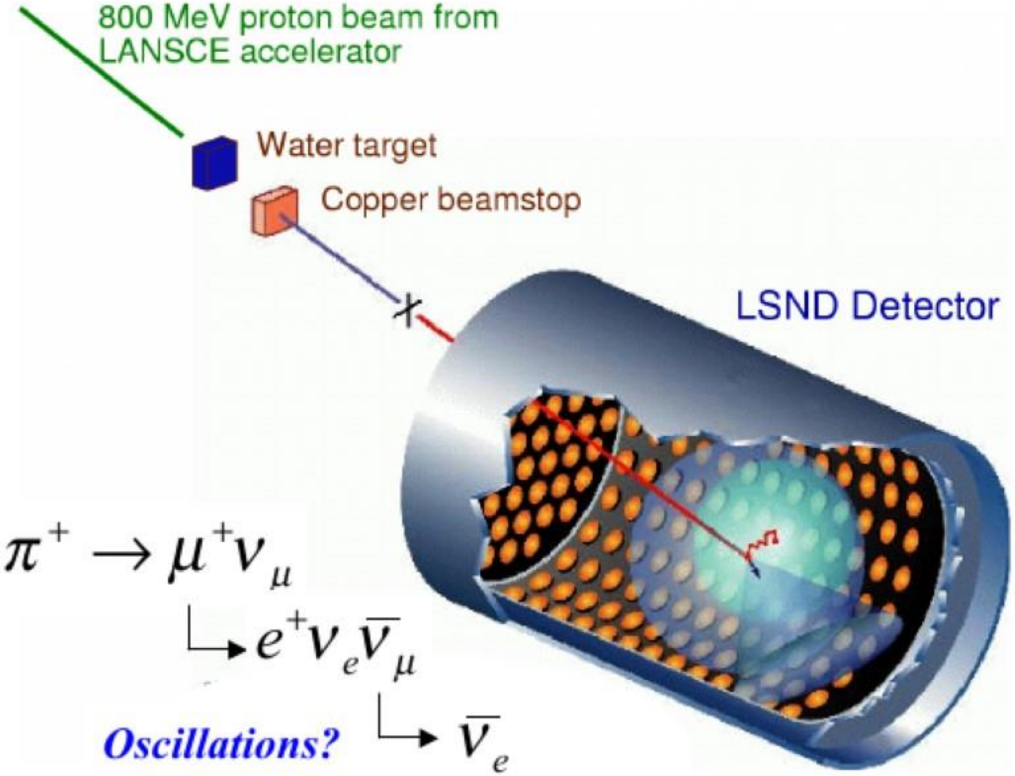
DEEP UNDERGROUND NEUTRINO EXPERIMENT

- https://www.youtube.com/watch?v=nv13DswIKr8



End of story?

LSND anomaly



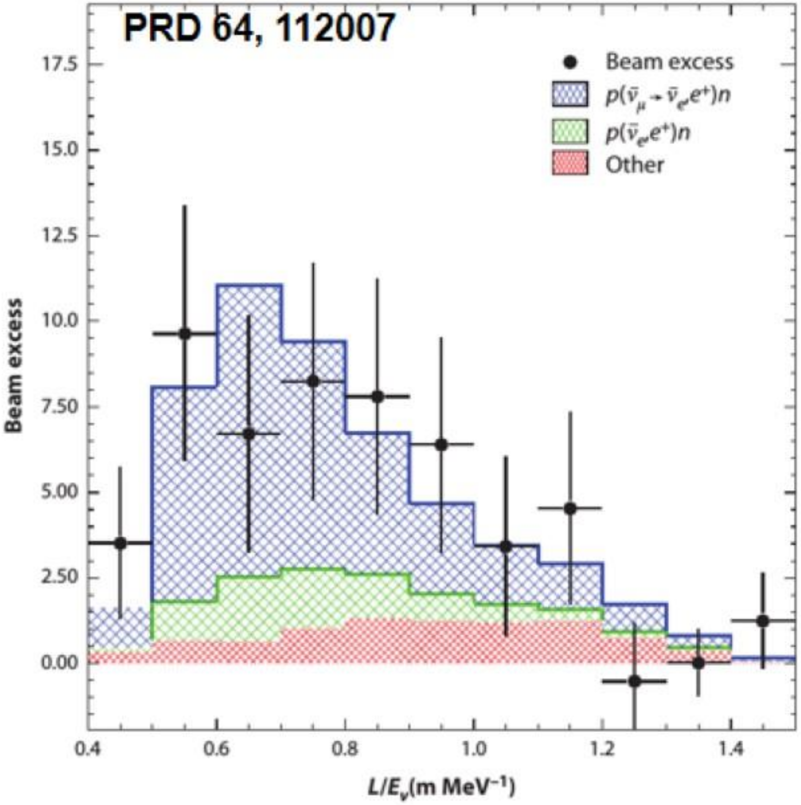
$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\hookrightarrow e^+ \nu_e \overline{\nu}_\mu$$

Oscillations? $\hookrightarrow \overline{\nu}_e$

μ⁺ decay-at-rest experiment.
Very low $\overline{\nu}_e$ contamination.
Liquid scintillator detector.
Low background: inverse β-decay detection:

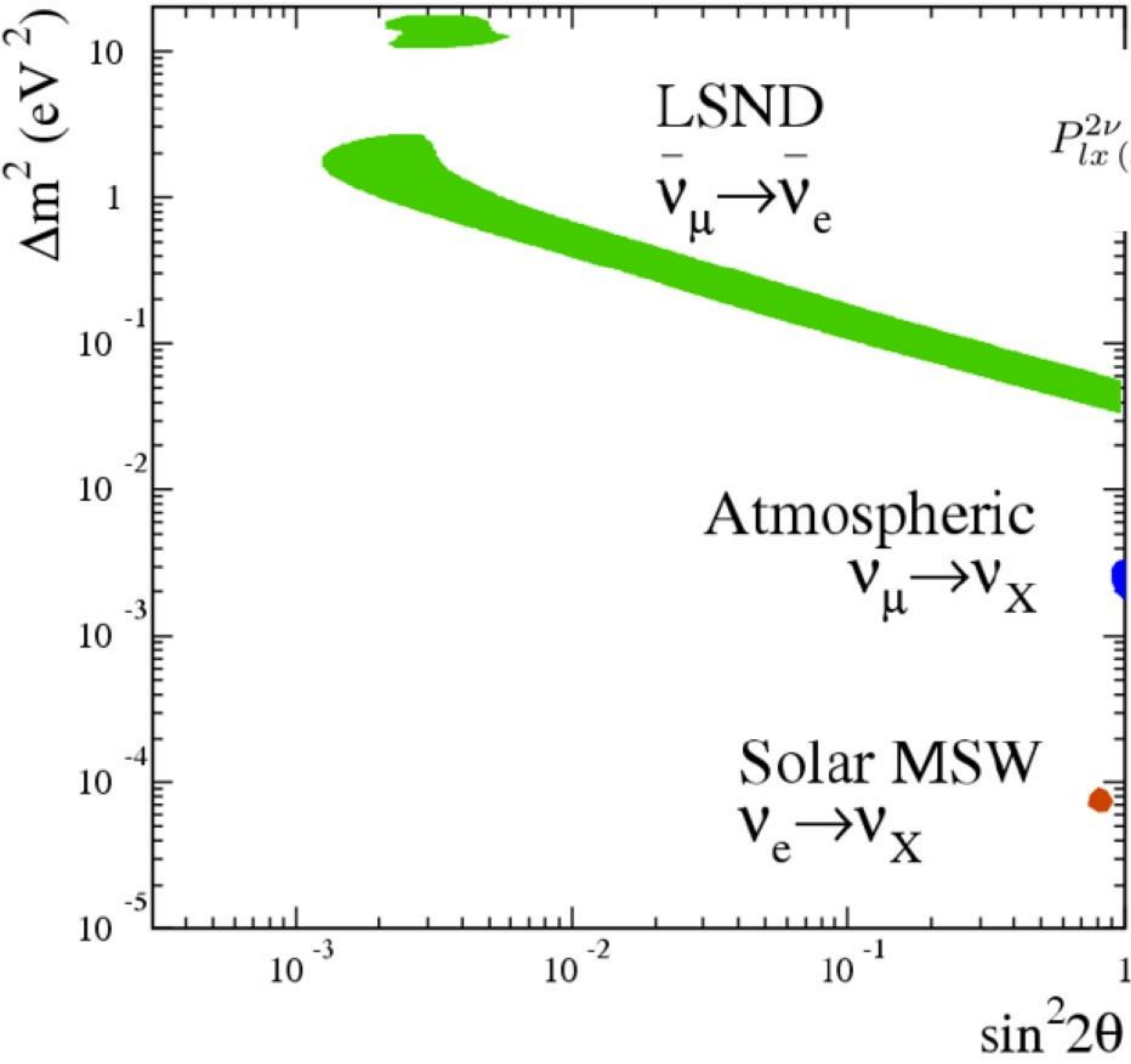
$$\overline{\nu}_e + p \rightarrow e^+ + n$$

Excess of 87.9 ± 22.4 ± 6.0 events.


PRD 64, 112007

LSND anomaly

Oscillation probability: (0.264 ± 0.067 ± 0.045)%



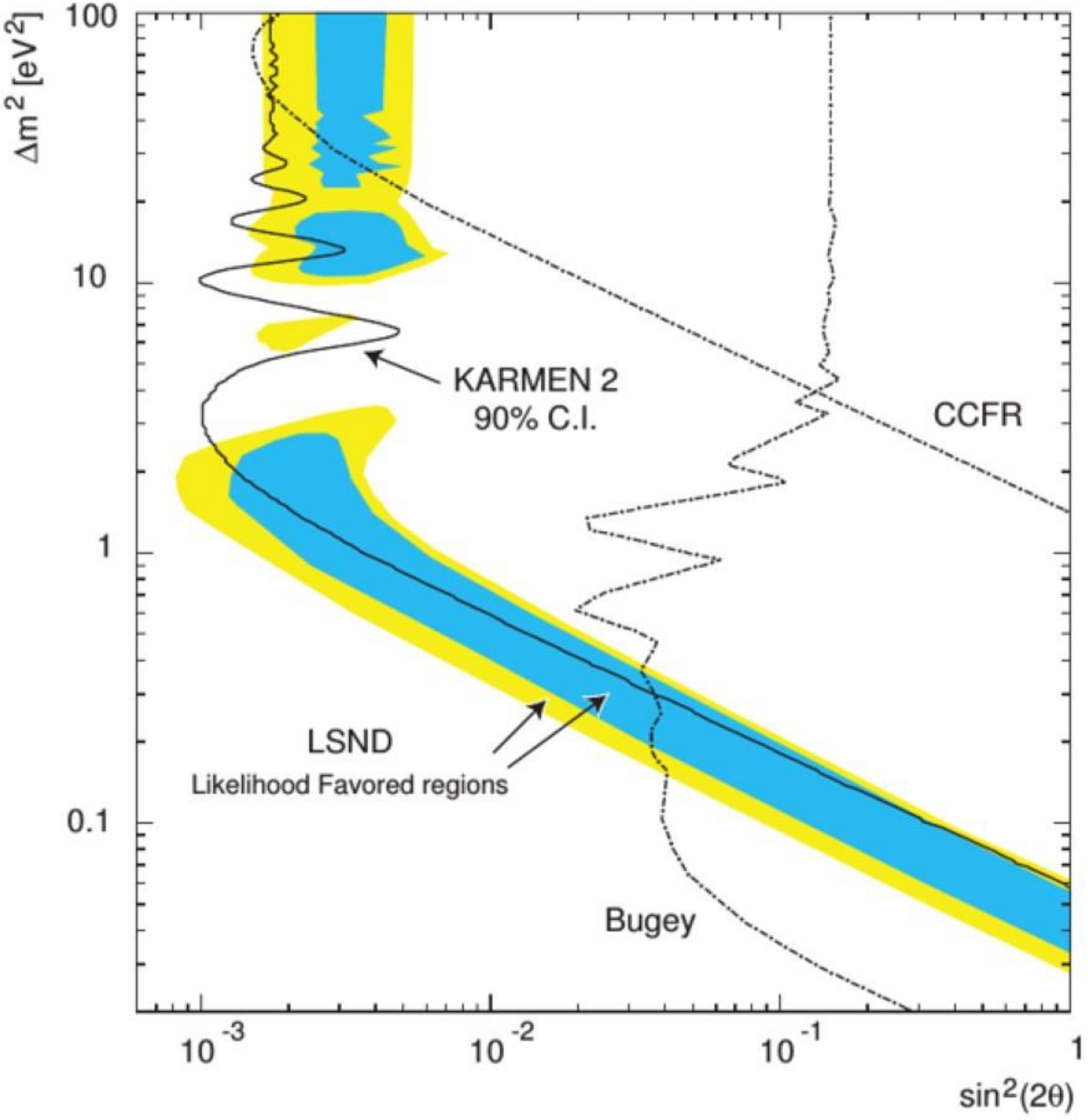
$$P^{2\nu}_{lx\,(l\neq x)}(L,E) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Cannot be explained with just 3 neutrinos!

Difference between squared masses 3 and 2, 1

Difference between squared masses 2 and 1

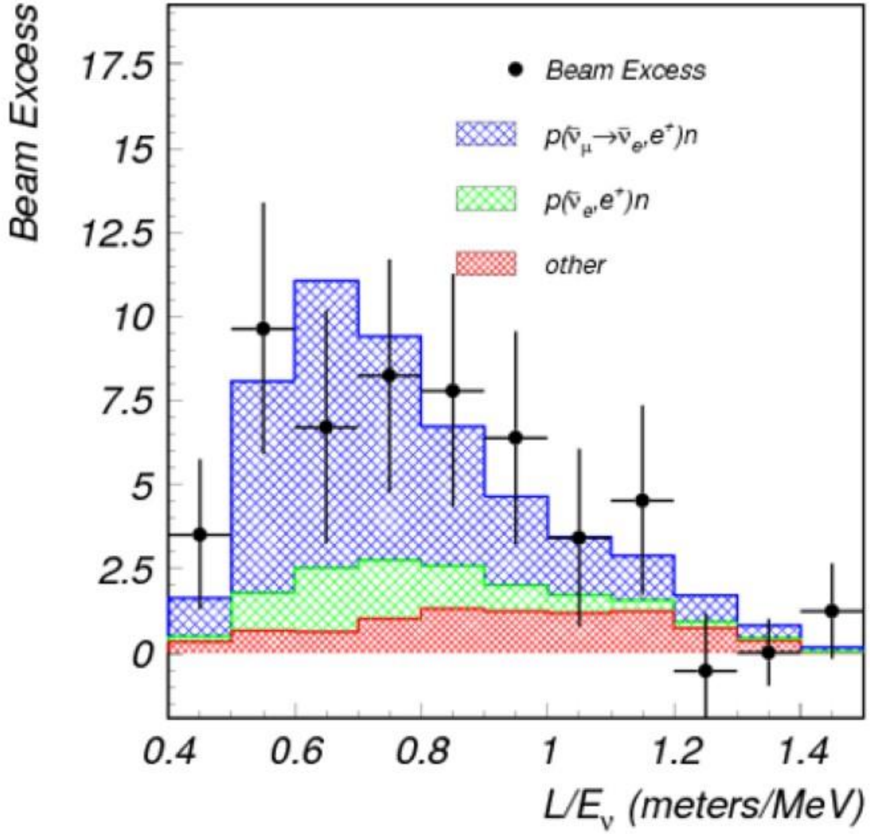
LSND anomaly

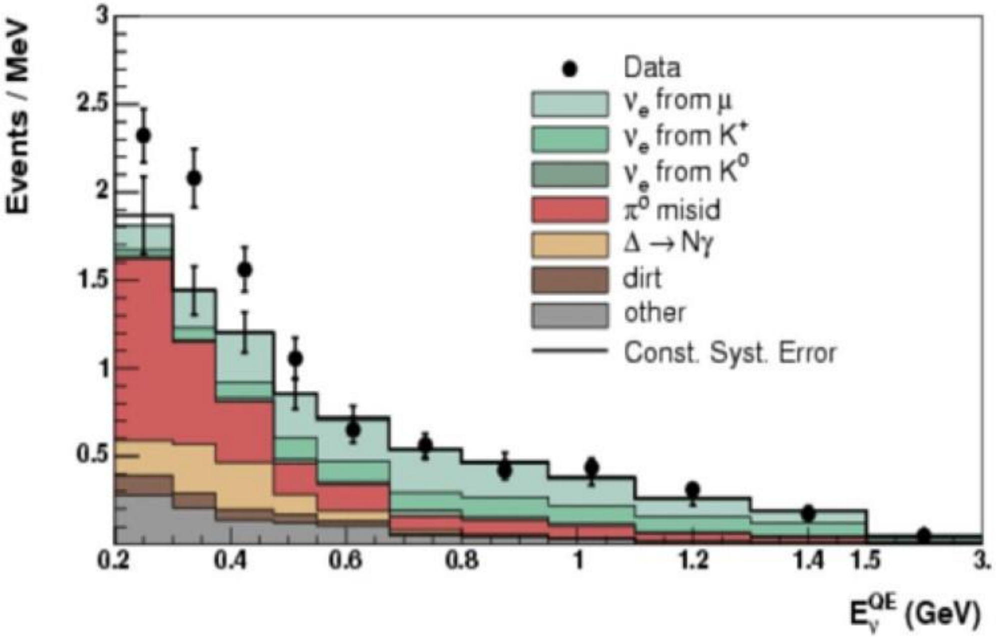


A big portion of the allowed region is excluded by the lack of oscillation signal in other experiments, but it cannot be ruled out completely

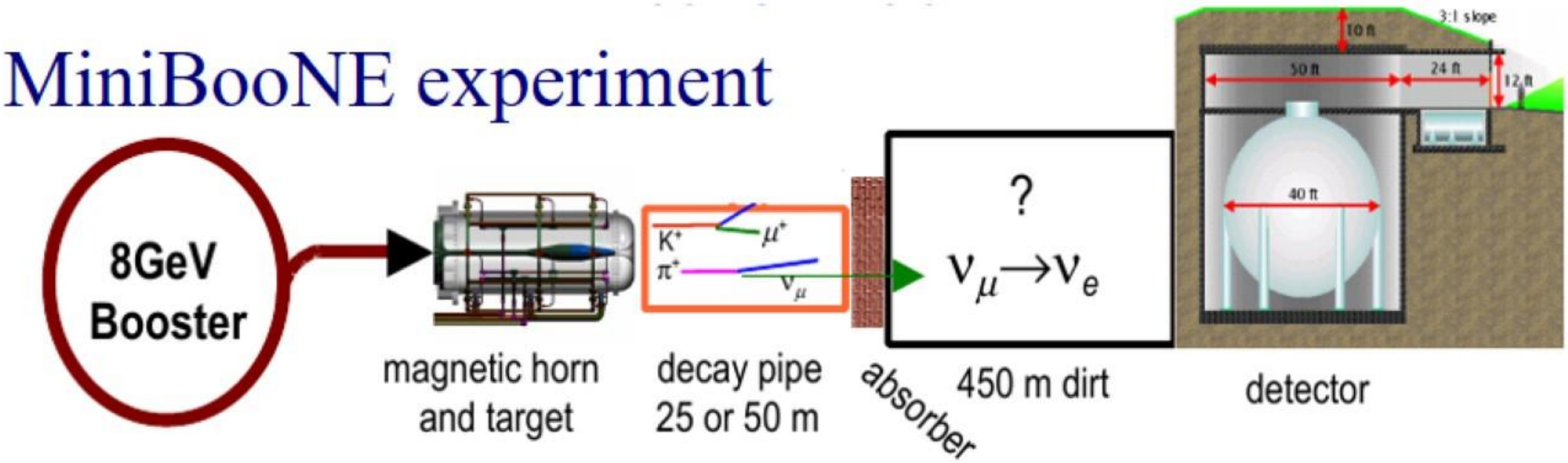
BEYOND THE PMNS FRAMEWORK

- Is the PMNS framework the full story?
- In the late 90s, the Liquid Scintillator Neutrino Detector (LSND) claimed observation of electron neutrino appearance from a muon neutrino beam with a very short baseline.
  - Implication: there is a very large squared-mass splitting, around 1 eV^2, so there must be a 4th (heavier) neutrino mass state!
- MiniBooNE experiment built to confirm or disprove LSND result.
  - Also found excess of electron neutrinos, but **not** compatible with LSND…

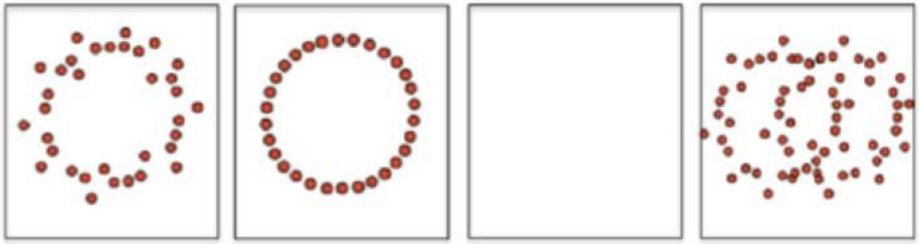




MiniBooNE experiment



- Different beam: mostly pion decay-in-flight experiment.
- Different detector: Cherenkov detector.



Electron, Photon

Muon

Proton

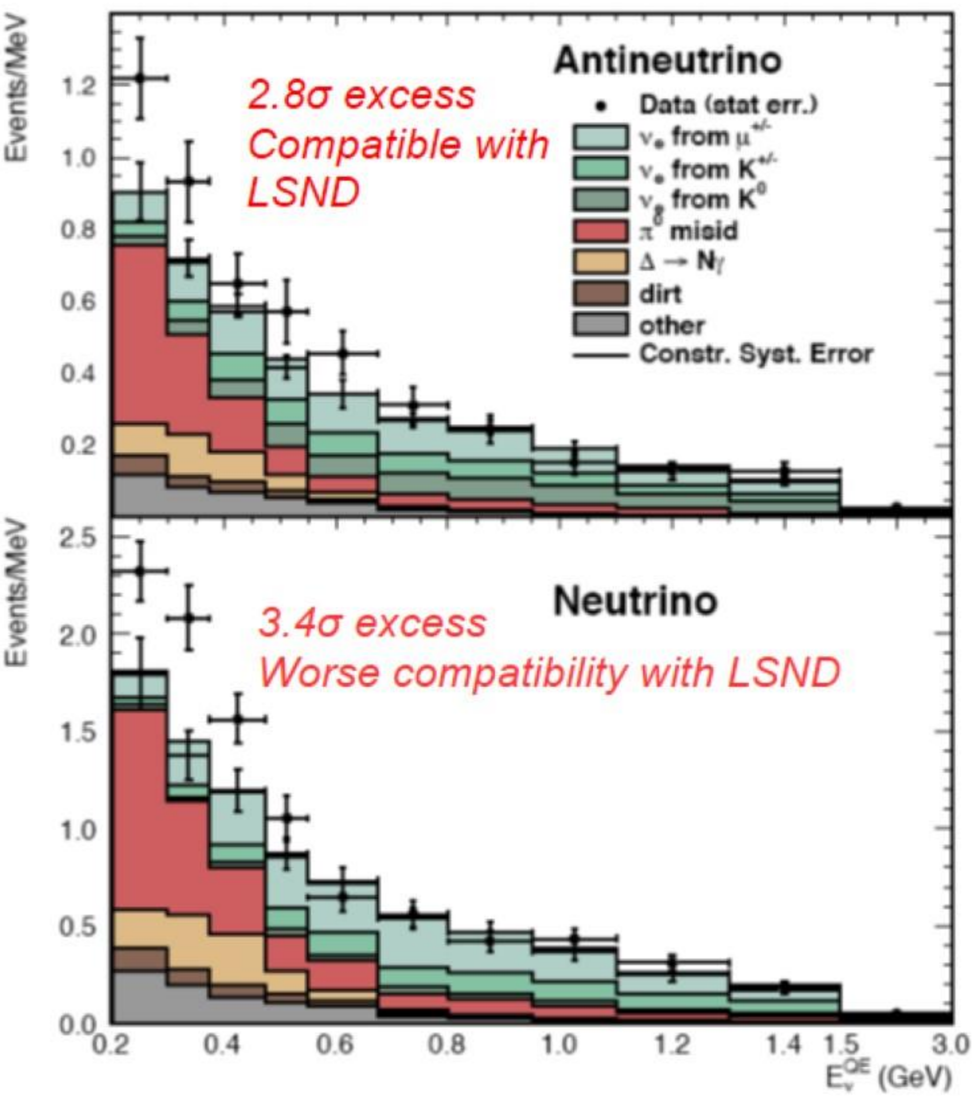
$\pi^0 \to \gamma + \gamma$

- Different energy and baseline, but same L/E: explore the same oscillation region.

$$P^{2\nu}_{lx\,(l\neq x)}(L,E) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

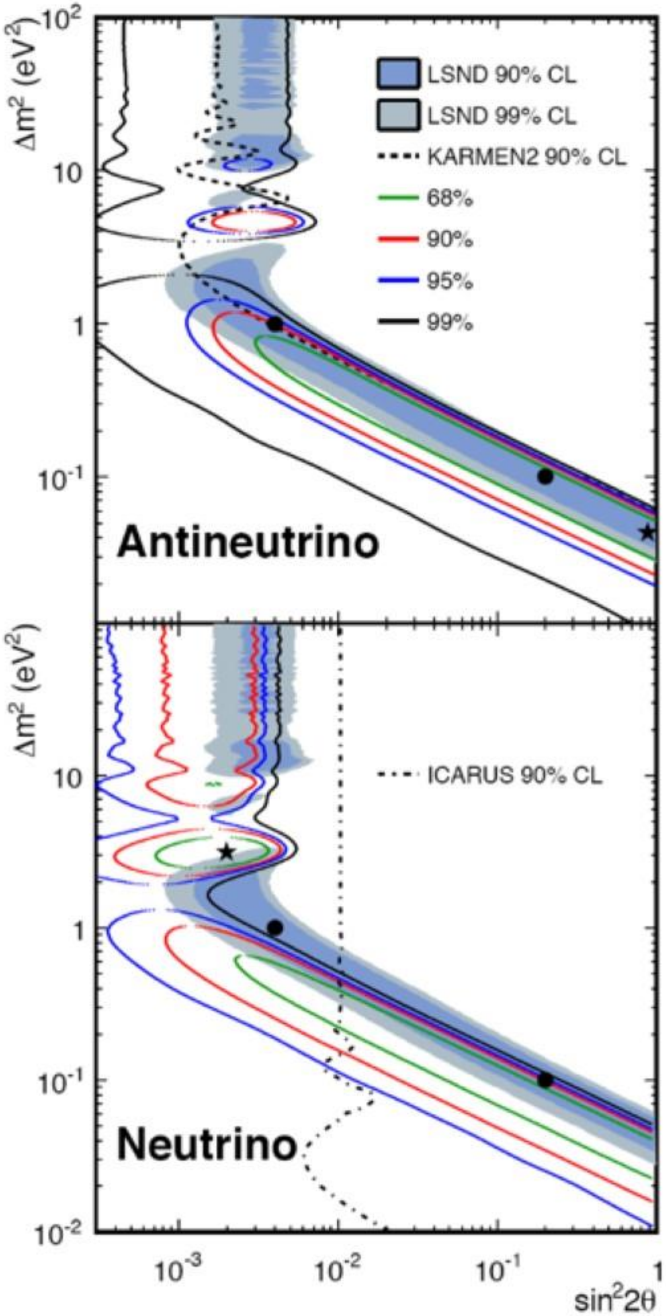
MiniBooNE anomaly

PRL 110, 161801

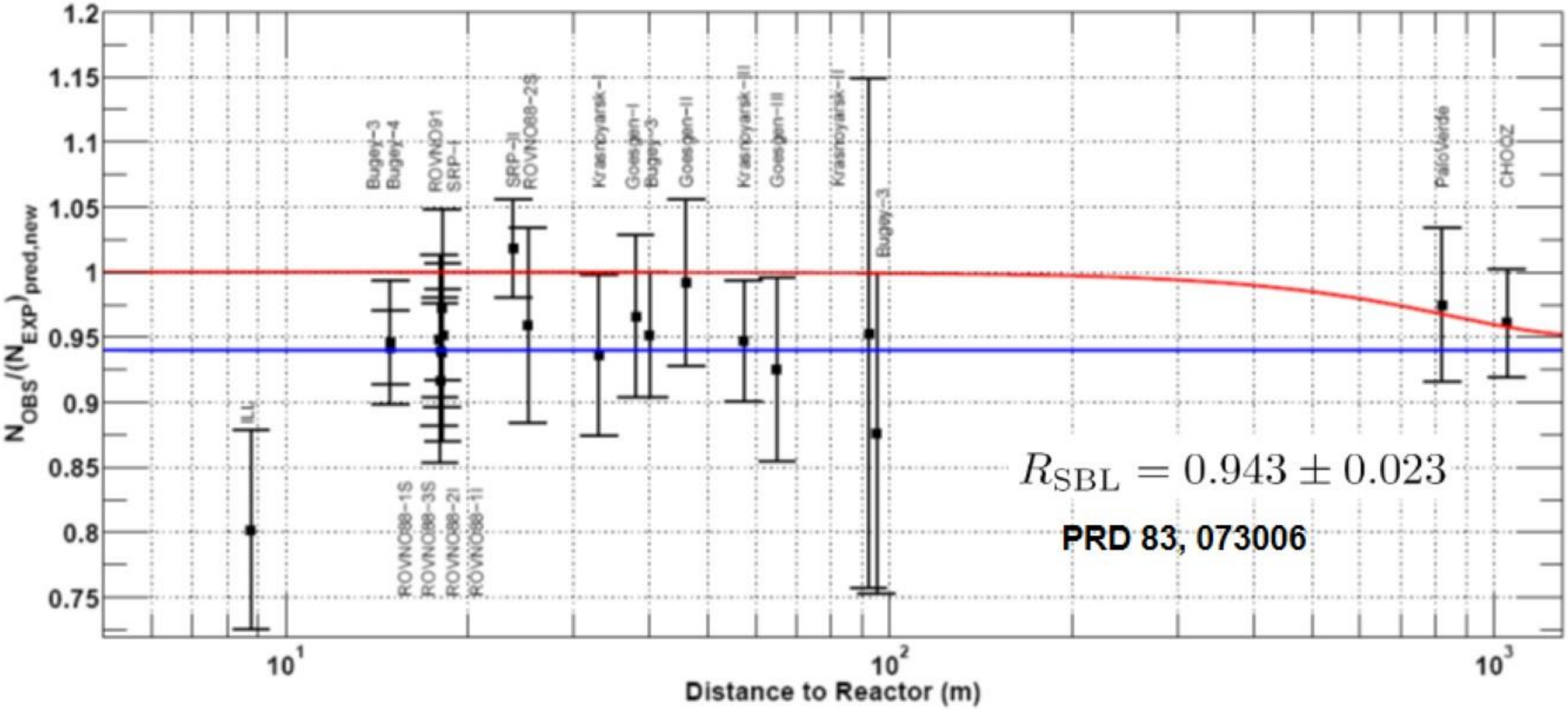


2.8σ excess
Compatible with LSND

3.4σ excess
Worse compatibility with LSND



Reactor anomaly



$R_{\mathrm{SBL}} = 0.943 \pm 0.023$

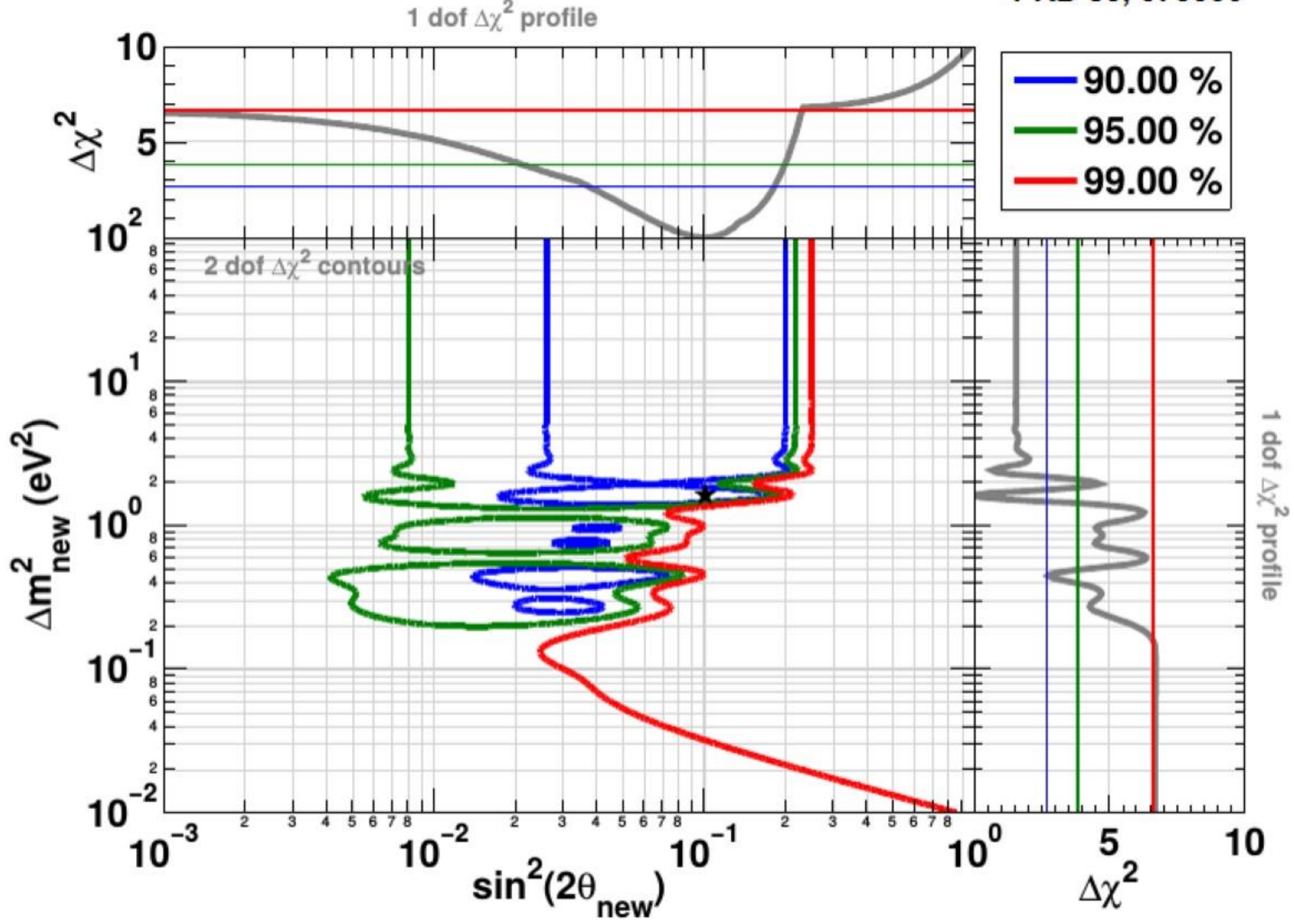
PRD 83, 073006

- After re-calculation of the predicted reactor flux, all past short-baseline reactor experiments observe a deficit of electron antineutrinos.

- Can be interpreted as the result of neutrino oscillation driven by a $\Delta m^2 \gtrsim 1$ eV^2

Reactor anomaly

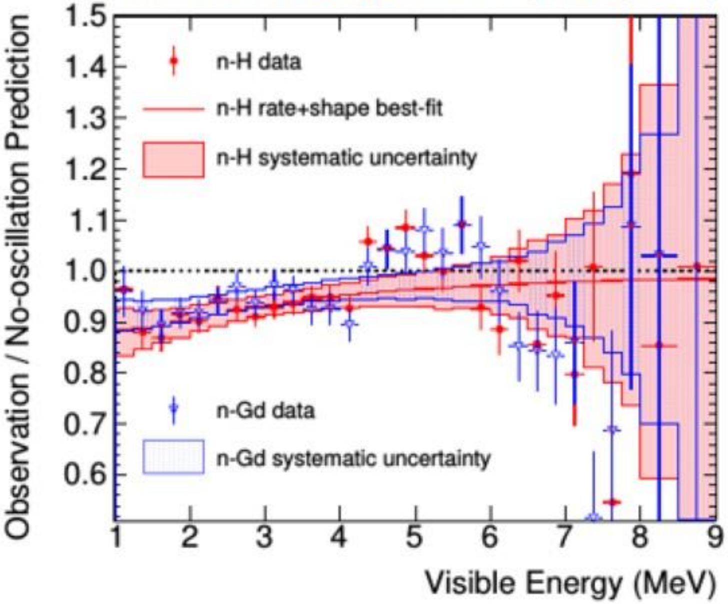
PRD 83, 073006



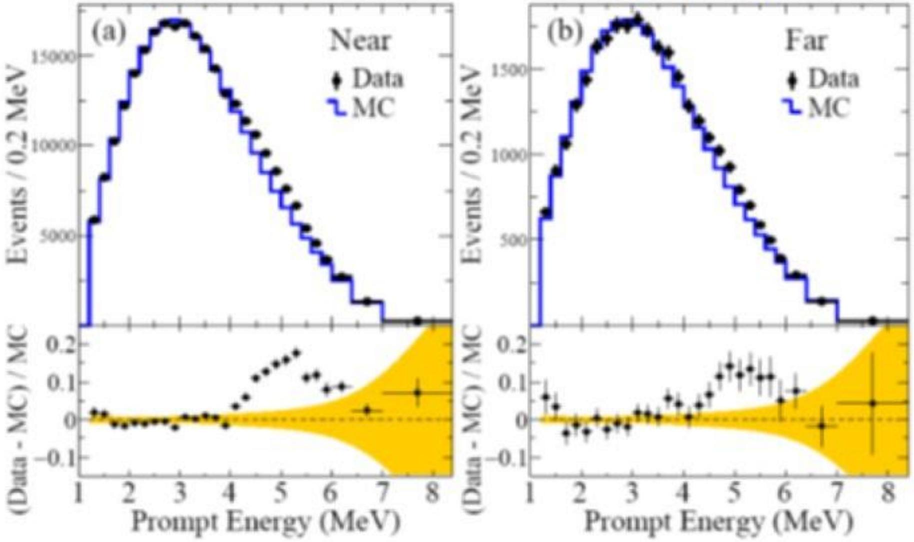
Reactor anomaly: spectrum distortion in 3 experiments

Alternative: predicted reactor flux is wrong.

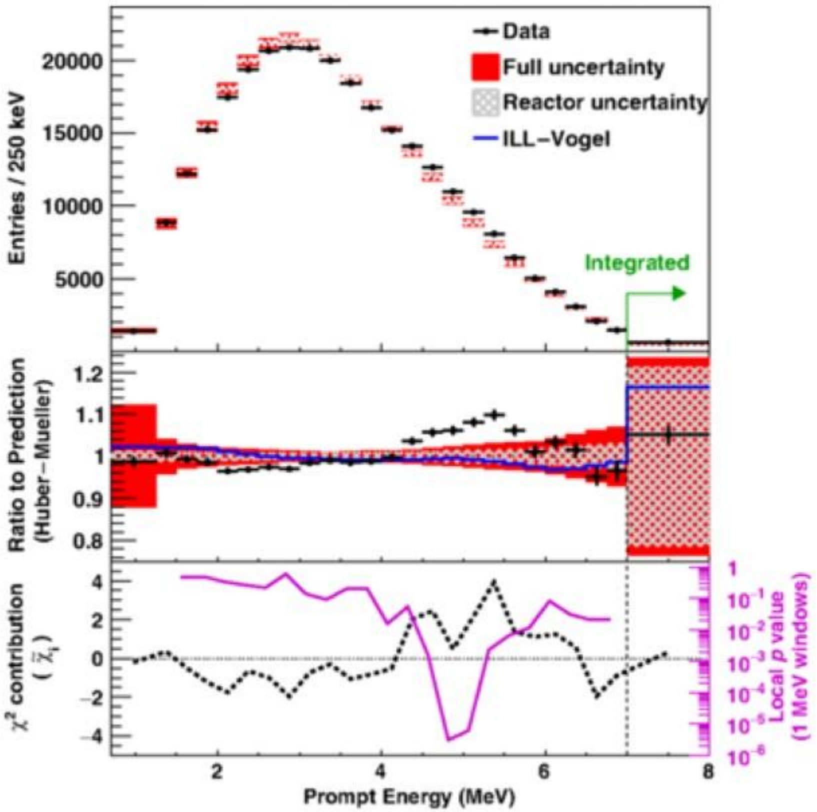
Double Chooz (JHEP01 (2016) 163)



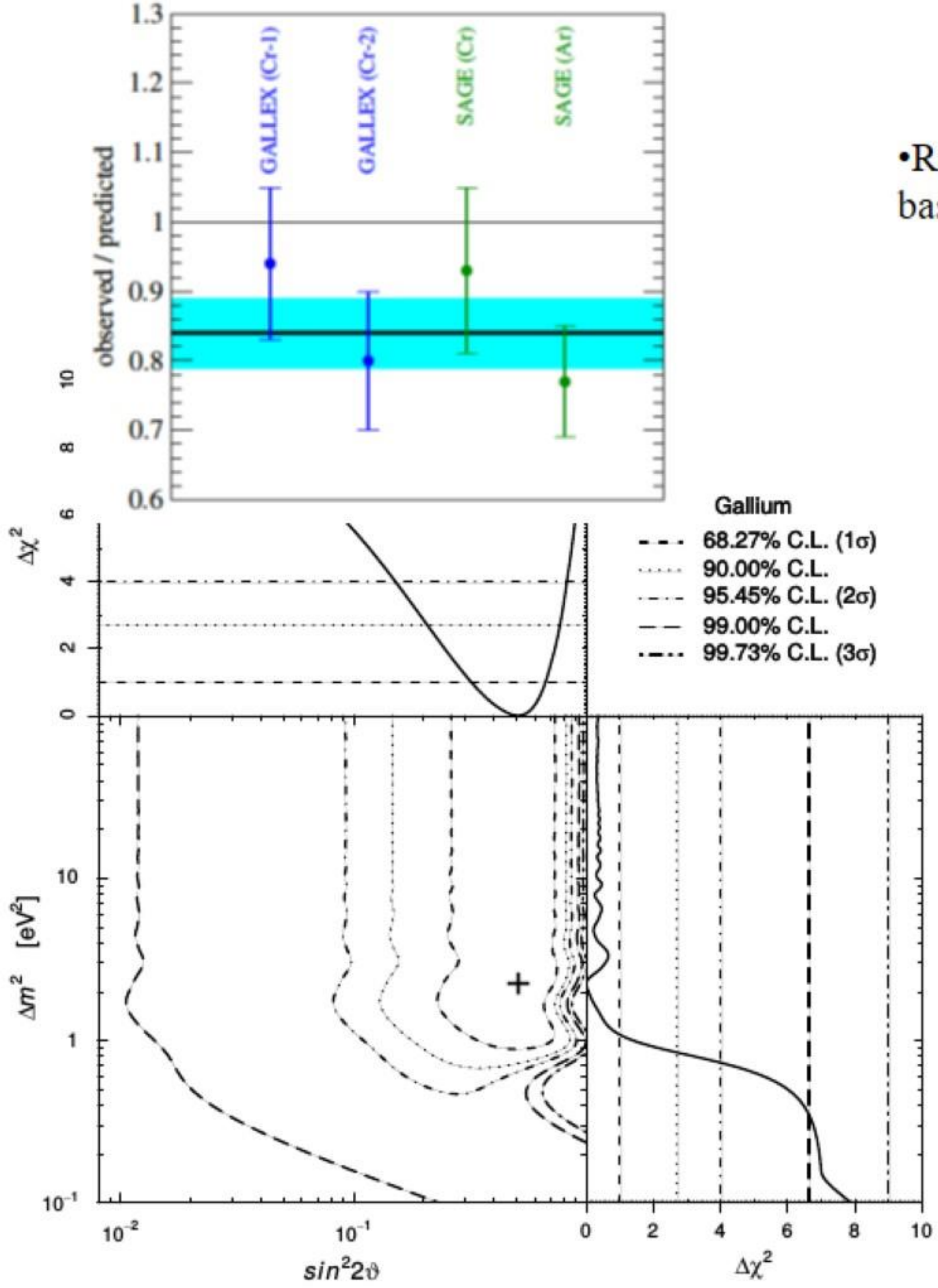
RENO (arXiv:1511.05849 [hep-ex])



Daya Bay (PRL 116, 061801)



Gallium anomaly



- Radioactive sources used to calibrate gallium-based solar experiments:

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

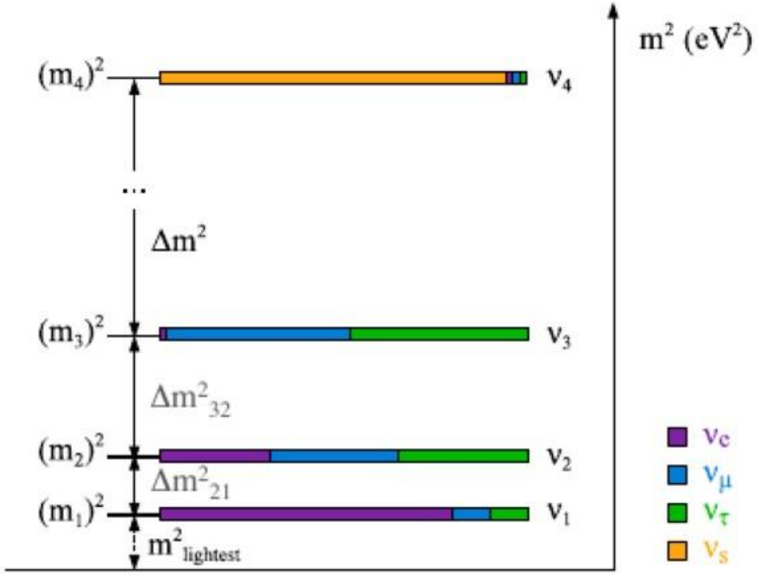
- $R_{Ga} = 0.86 \pm 0.05$

- Taking into account the uncertainty in the cross-section and the transition to the two excited states of ^{71}Ge (**PRC (2011) 065504**):

$$R_{Ga} = 0.76^{+0.09}_{-0.08}$$

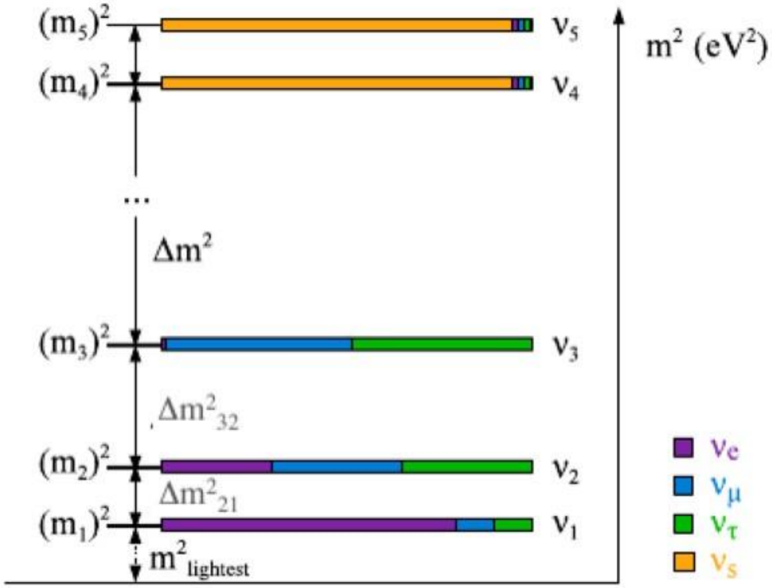
- Can be interpreted as the result of neutrino oscillation driven by a $\Delta m^2 \gtrsim 1$ eV^2

Sterile neutrino models



3 +1

- The sterile neutrino gives the high Δm^2
- Cannot explain differences between neutrinos/antineutrinos in MiniBooNE.
- Cannot explain the non-disappearance of the muon flavor

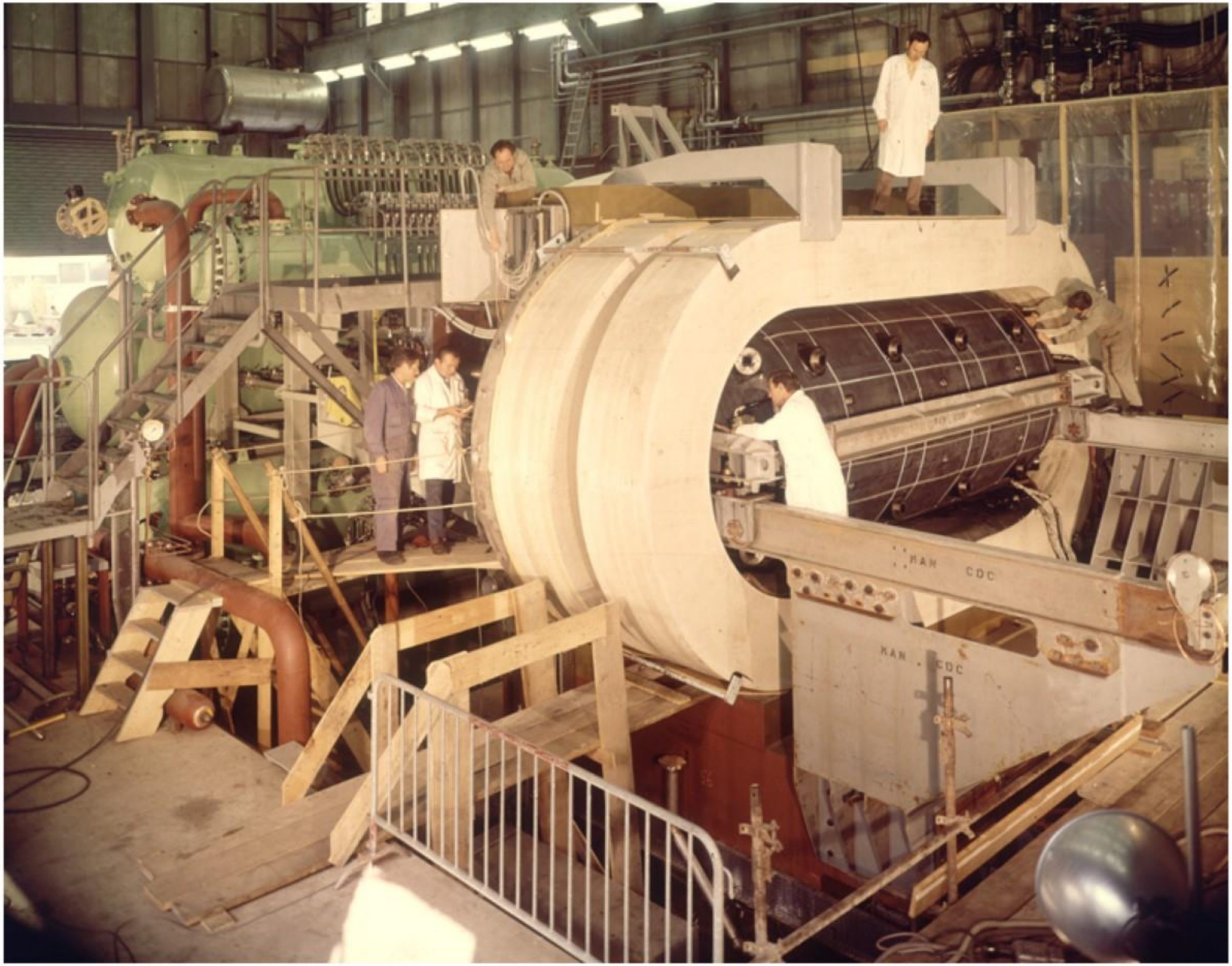


- **3 + 2**
- The two sterile neutrinos give the high Δm^2
- Incorporates CP violation: neutrinos and antineutrinos oscillate differently.
- The non-disappearance of the muon flavor still unexplained.

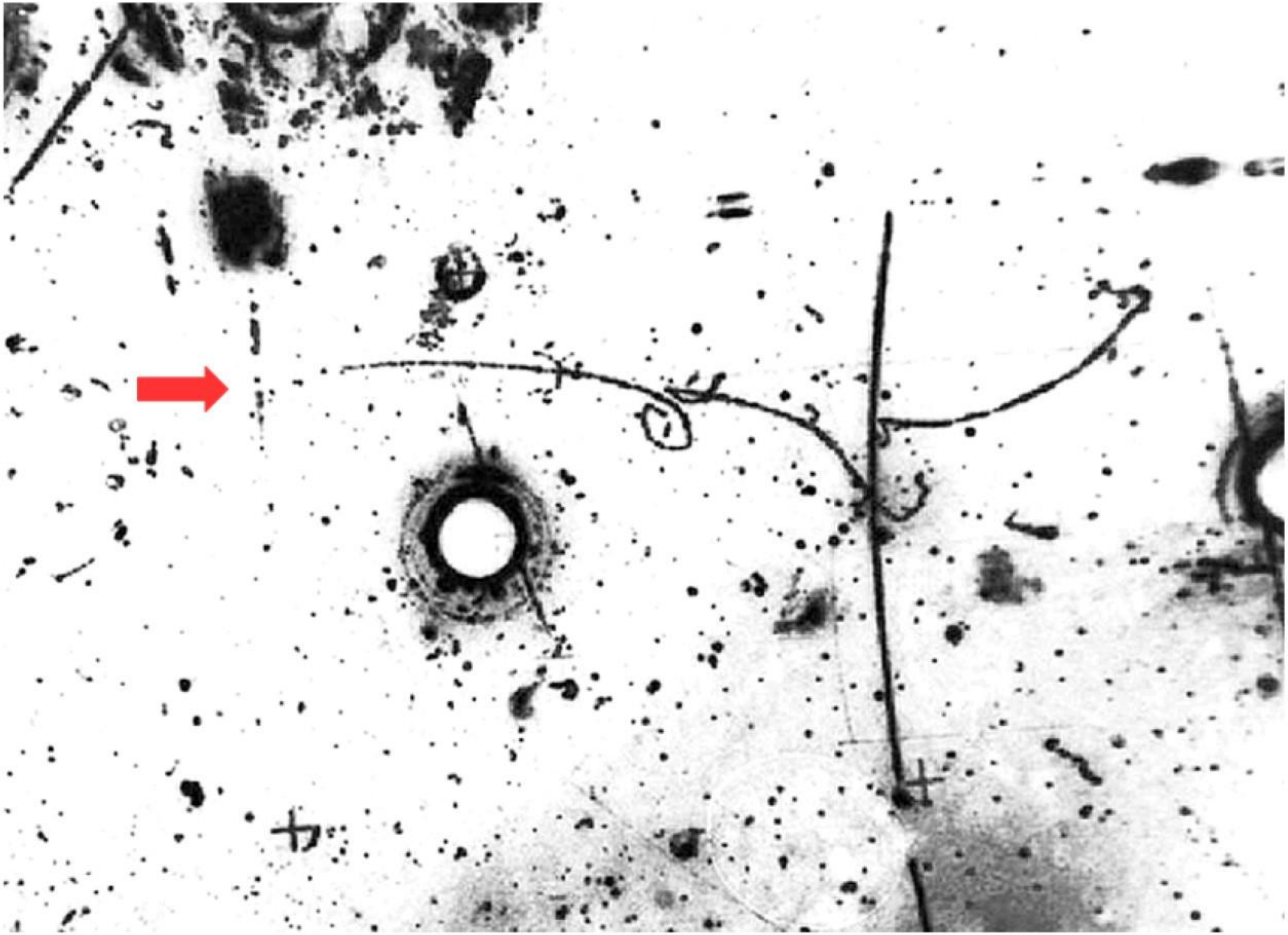
- 3 + 3 does not improve the situation.

The Short Baseline Neutrino Program at Fermilab

Bubble chamber: Gargamelle (1970 - 1979)

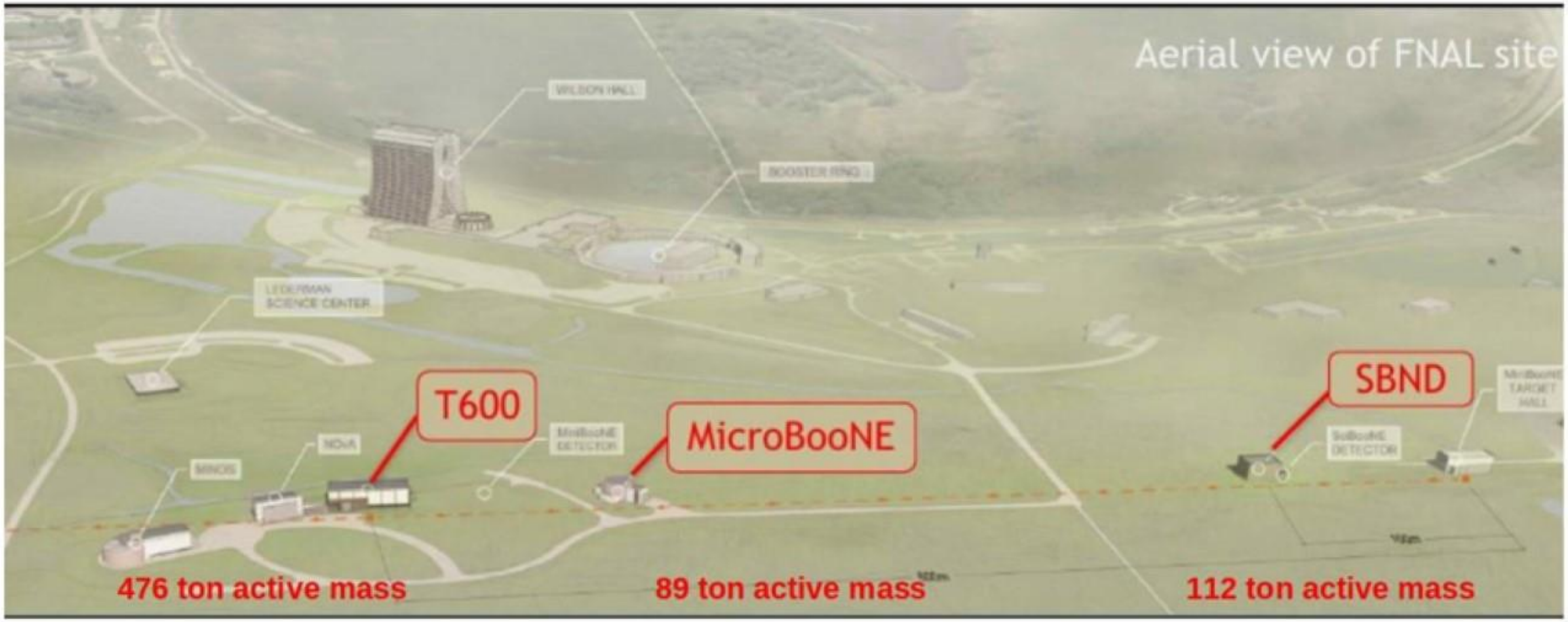


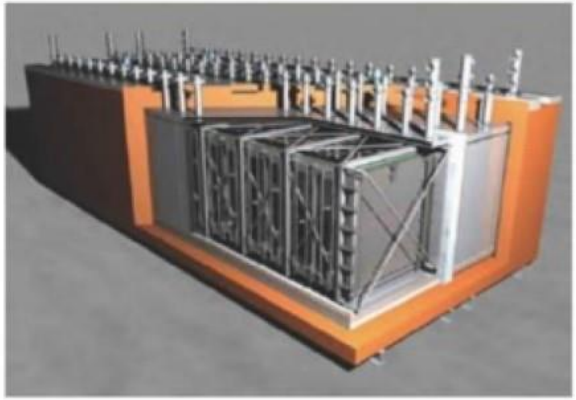
Discovery of neutral currents (1973)

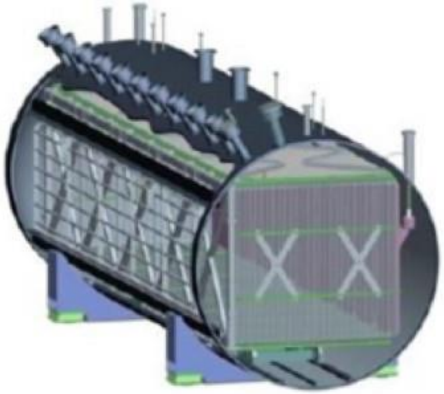


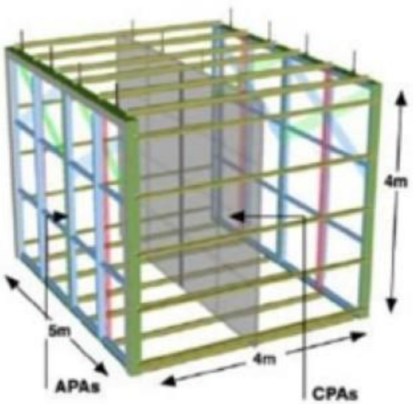
SHORT BASELINE PROGRAM AT FERMILAB

- Use liquid argon TPC technology to try to settle the matter!



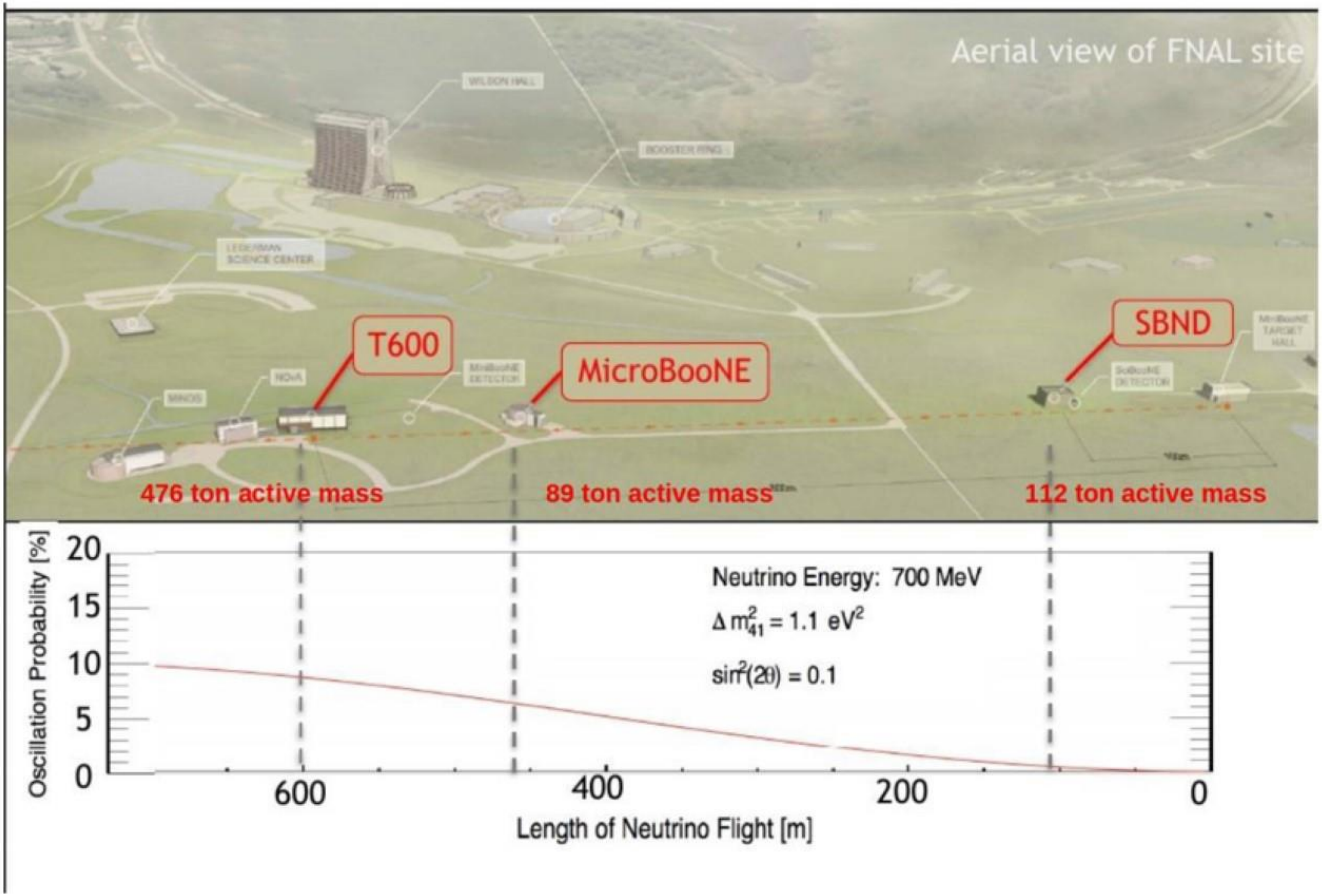






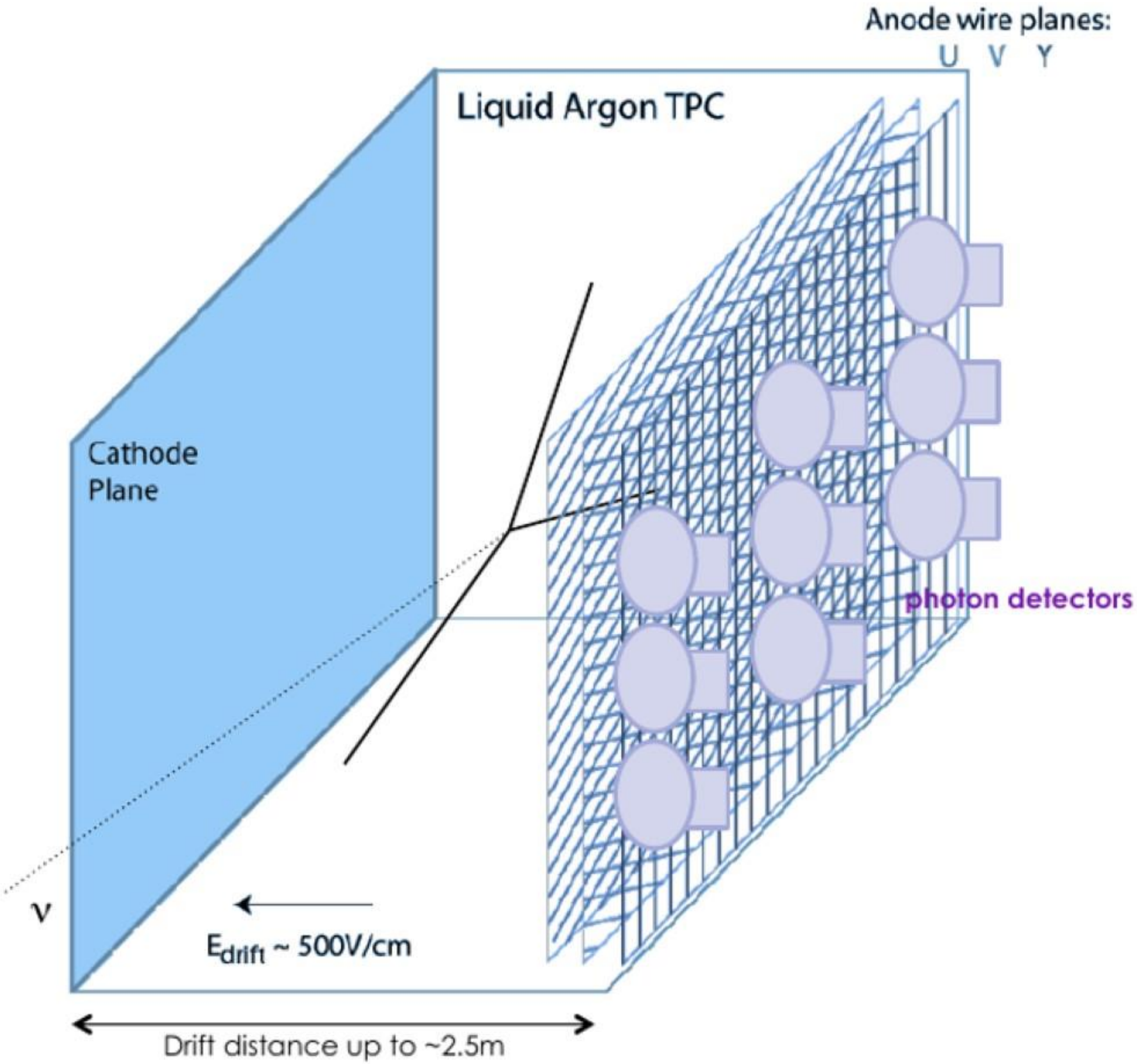
SHORT BASELINE PROGRAM AT FERMILAB

- Use liquid argon TPC technology to try to settle the matter!



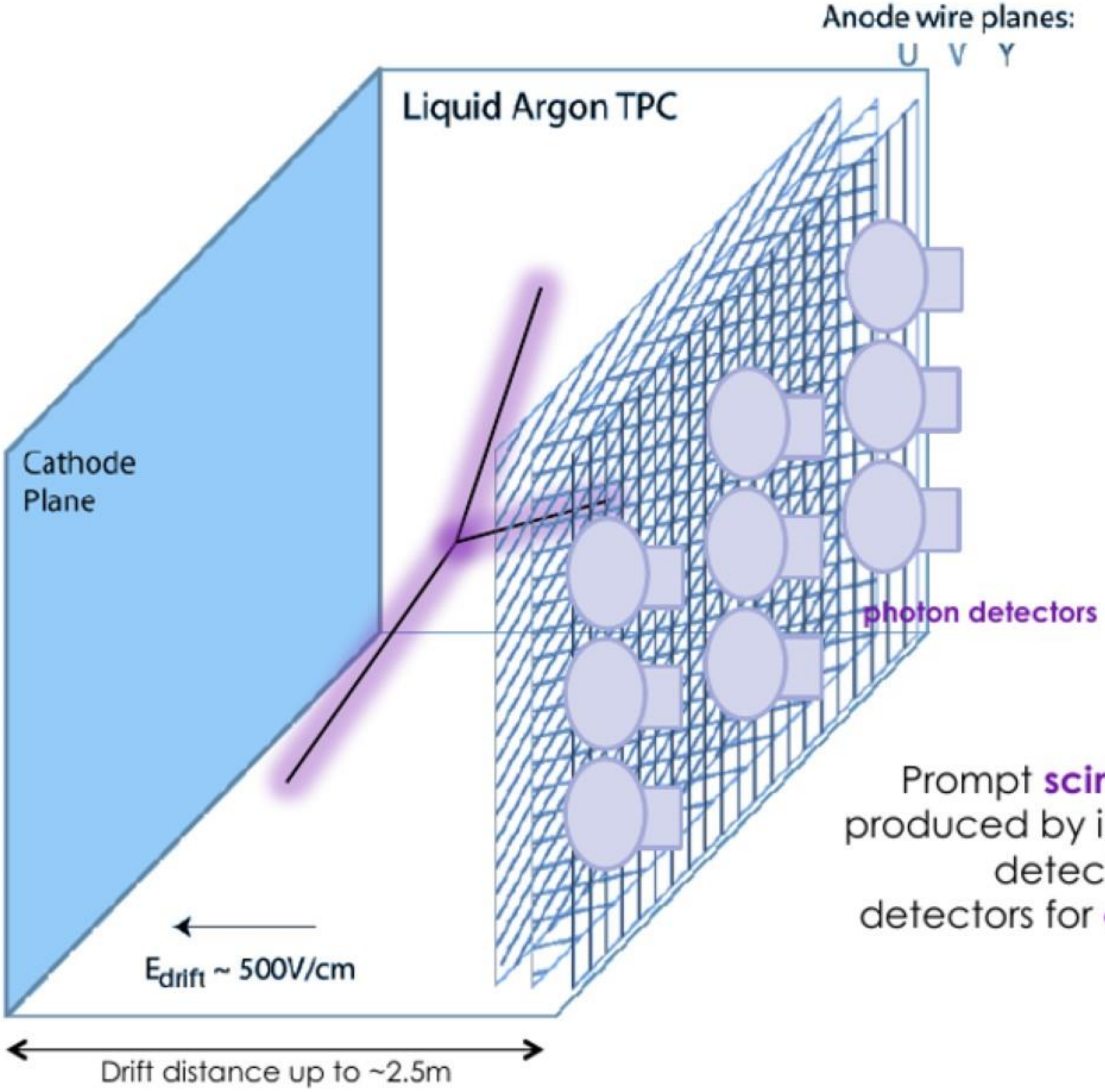
Liquid argon time projection chamber

How a LArTPC works:



Animation by Georgia Karagiorgi

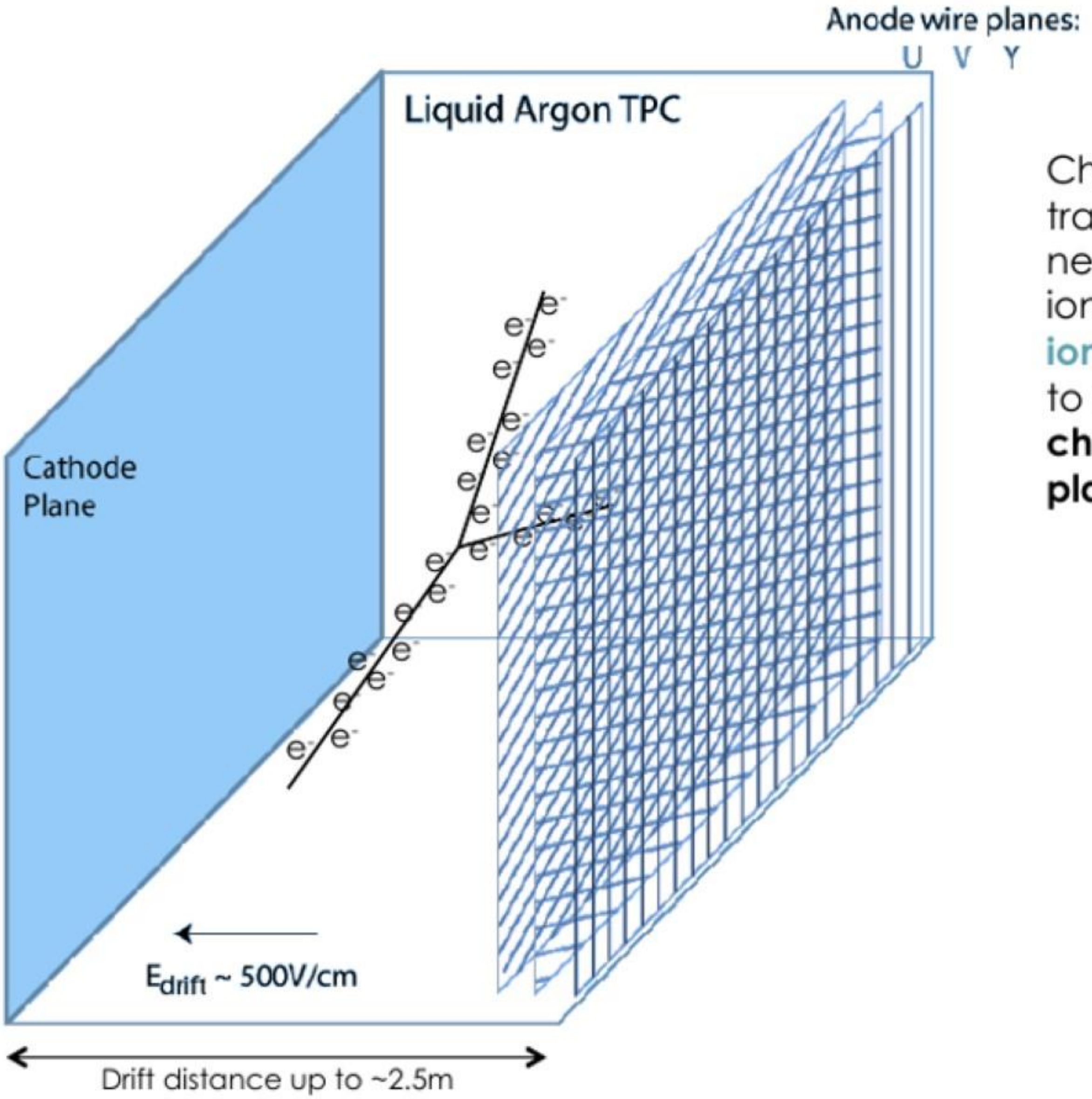
How a LArTPC works:



Prompt **scintillation light** (**~few ns**) produced by interaction products is detected by photo-sensitive detectors for **event t_0** determination (allows for triggering)

Animation by Georgia Karagiorgi

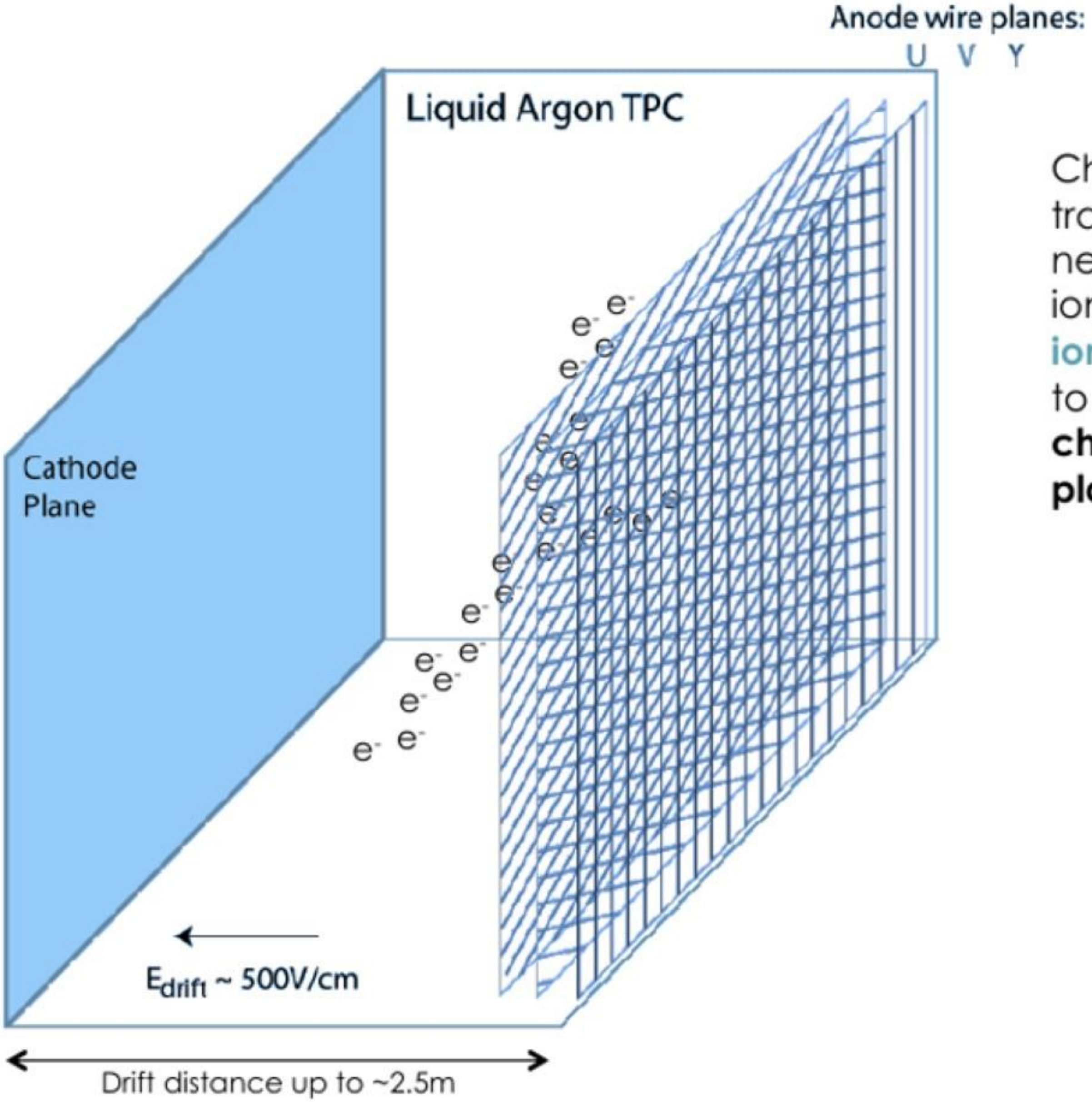
How a LArTPC works:



Charged particle tracks produced in neutrino interaction ionize argon atoms; ionization charge drifts to **finely segmented charge collection planes** over ~1-few ms.

Animation by Georgia Karagiorgi

How a LArTPC works:



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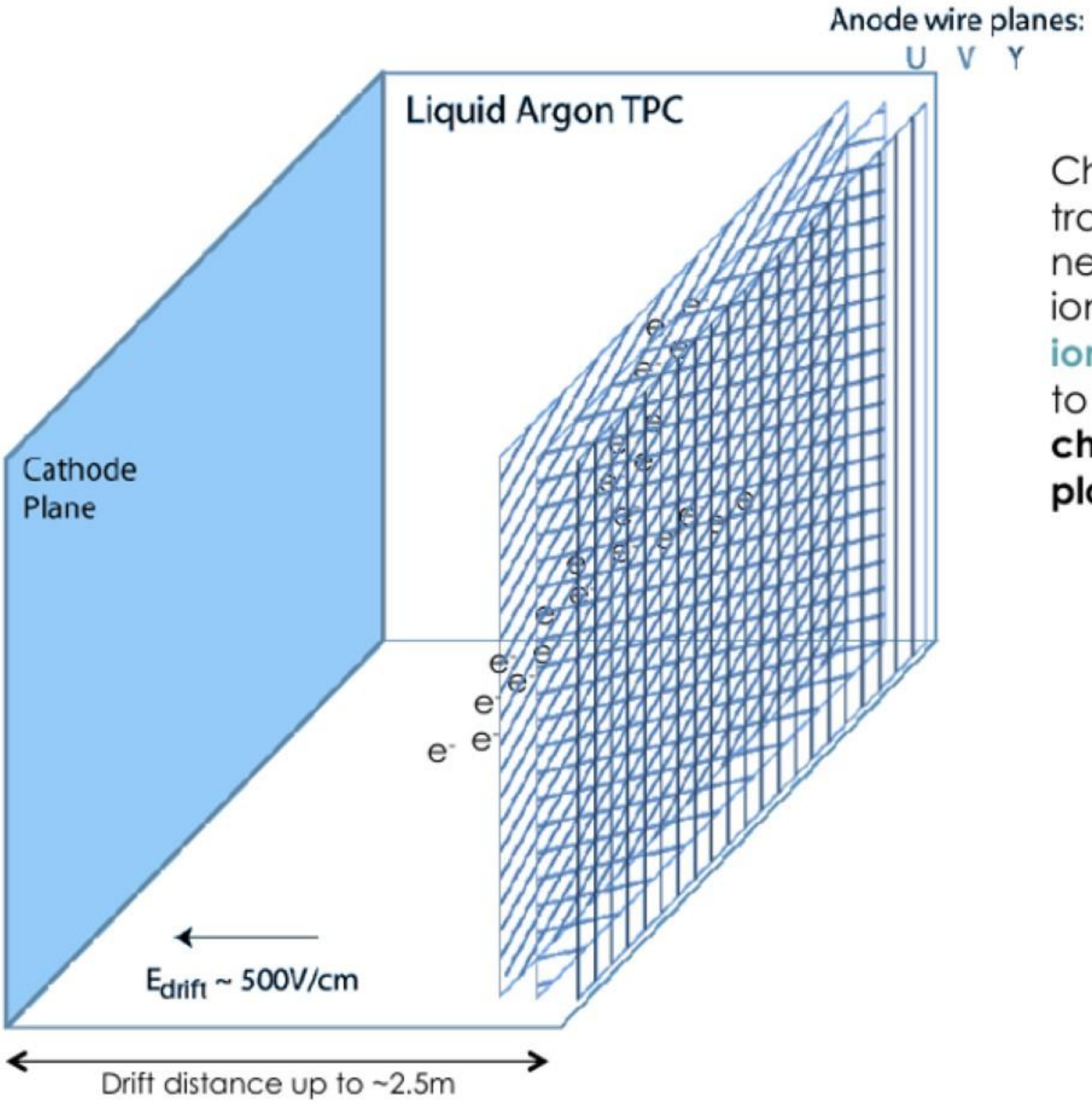

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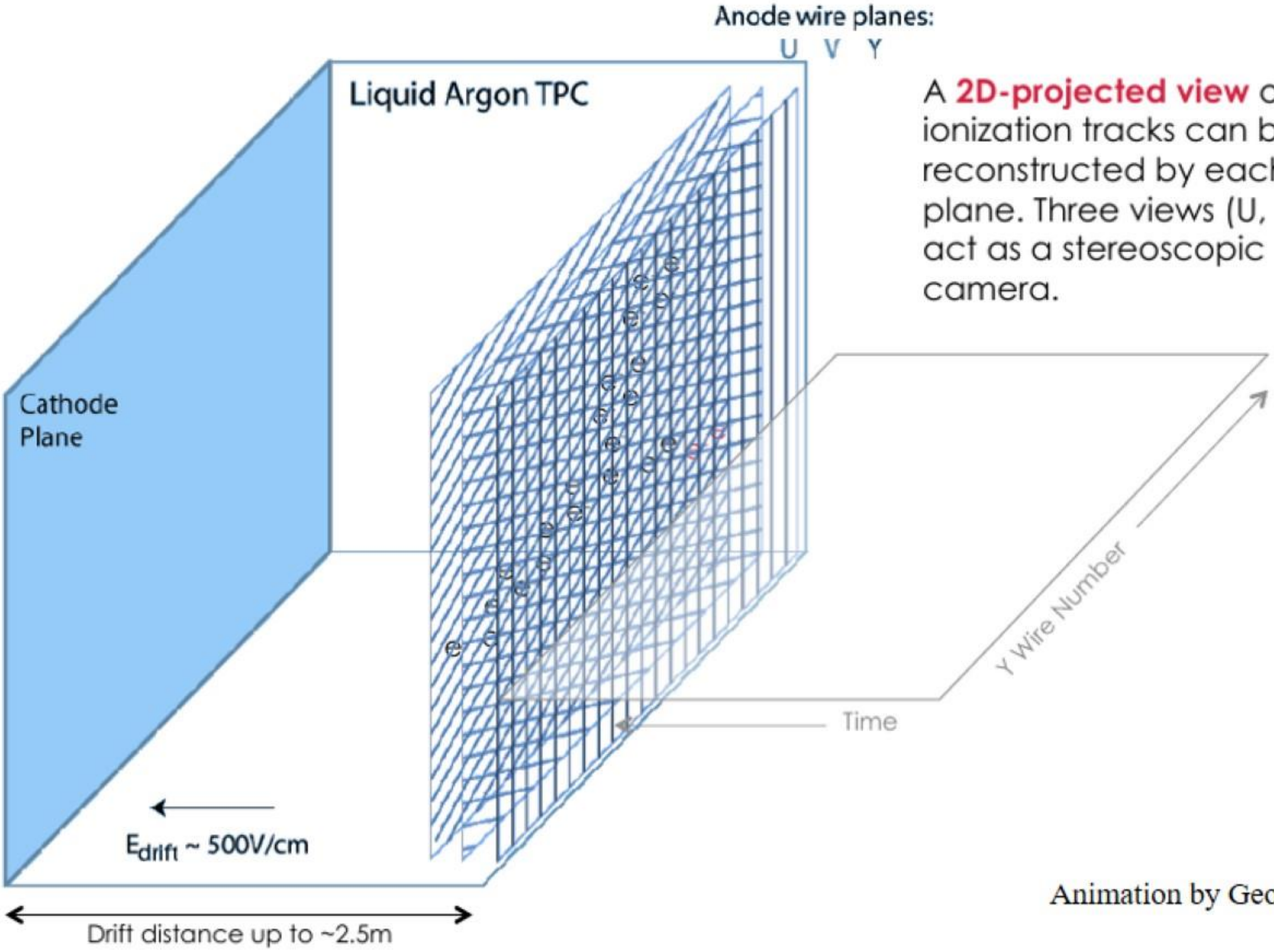
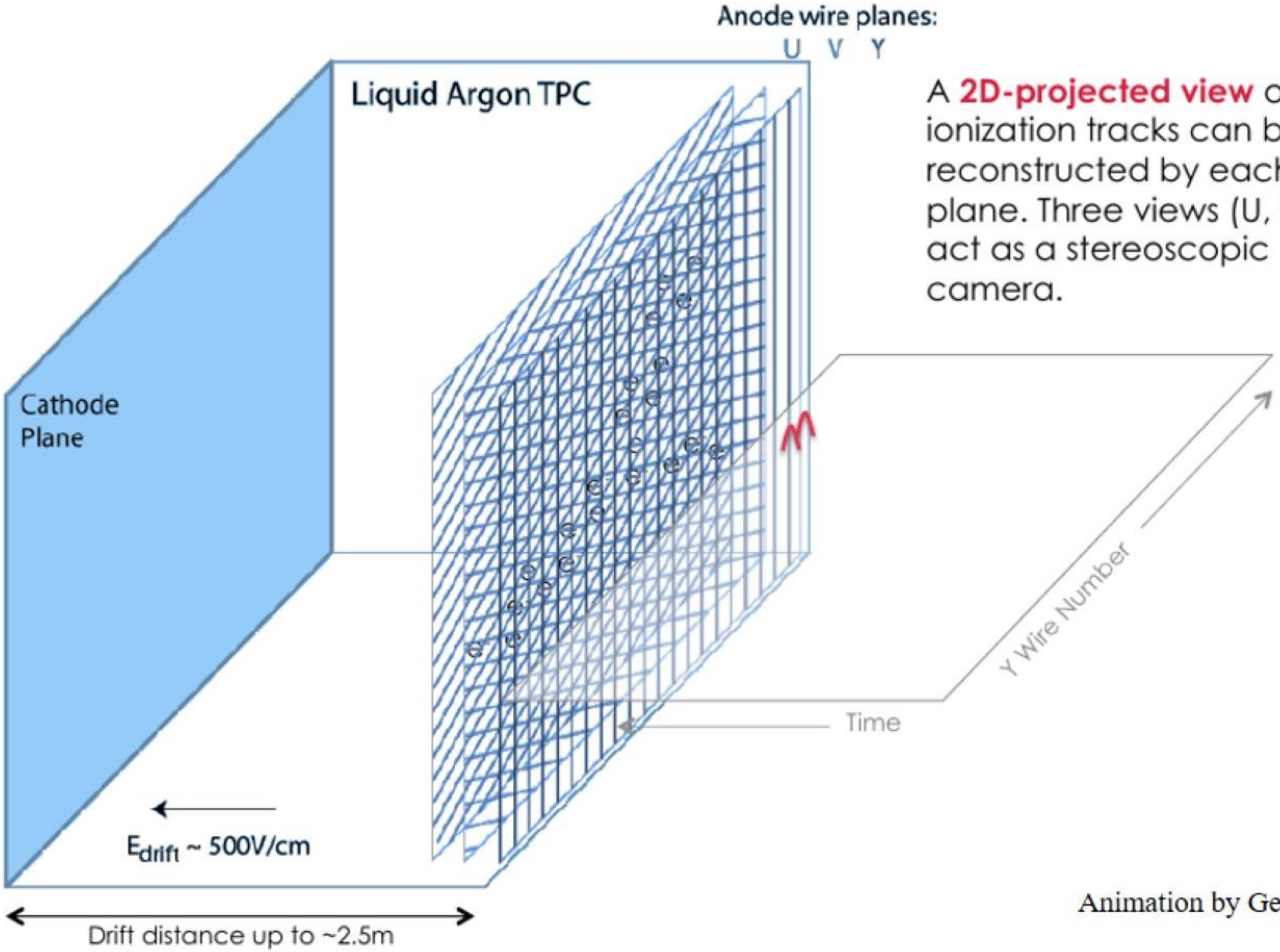


A **2D-projected view** of the ionization tracks can be reconstructed by each wire plane. Three views (U, V, Y) act as a stereoscopic camera.

Animation by Georgia Karagiorgi

How a LArTPC works:



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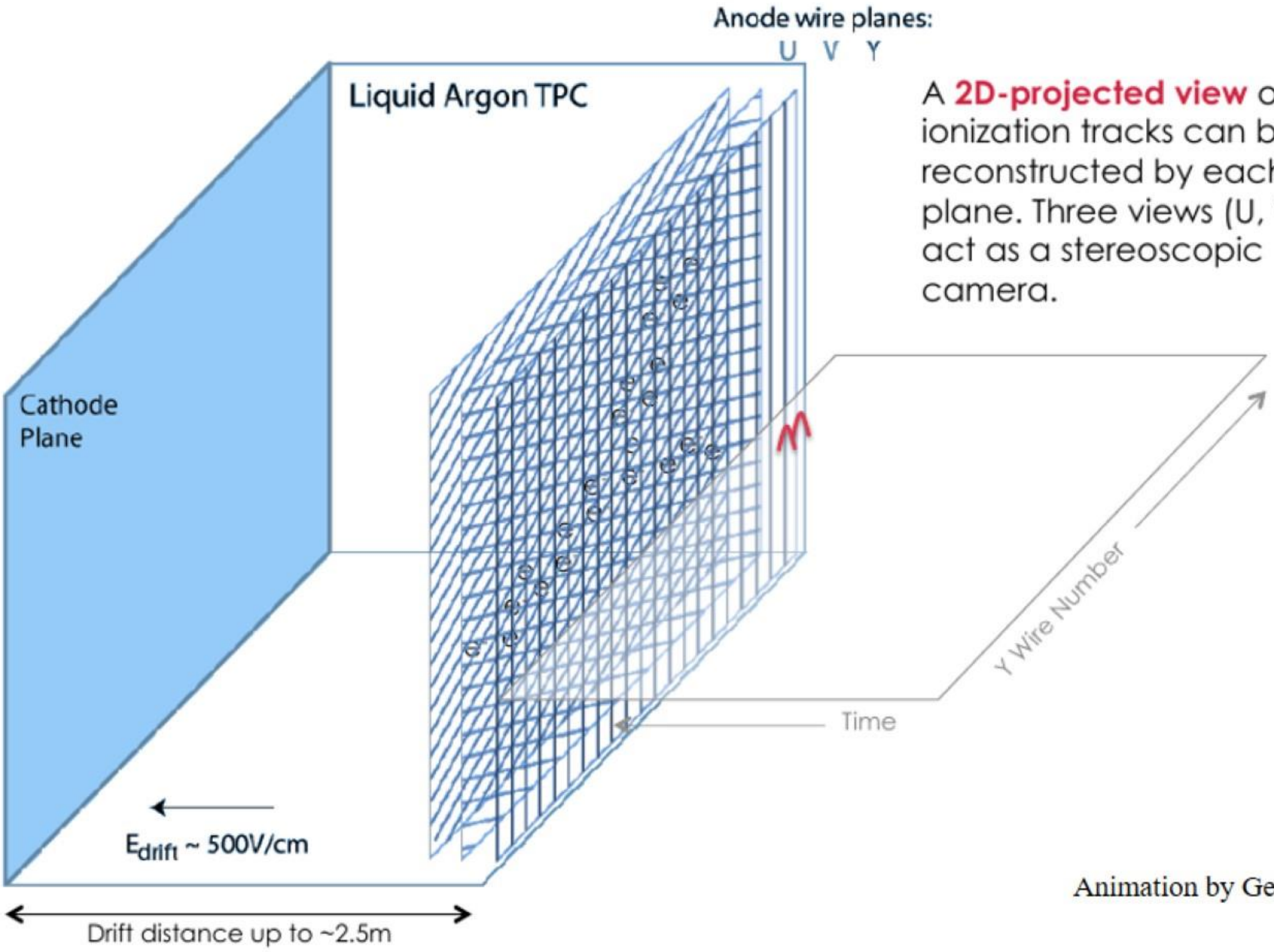

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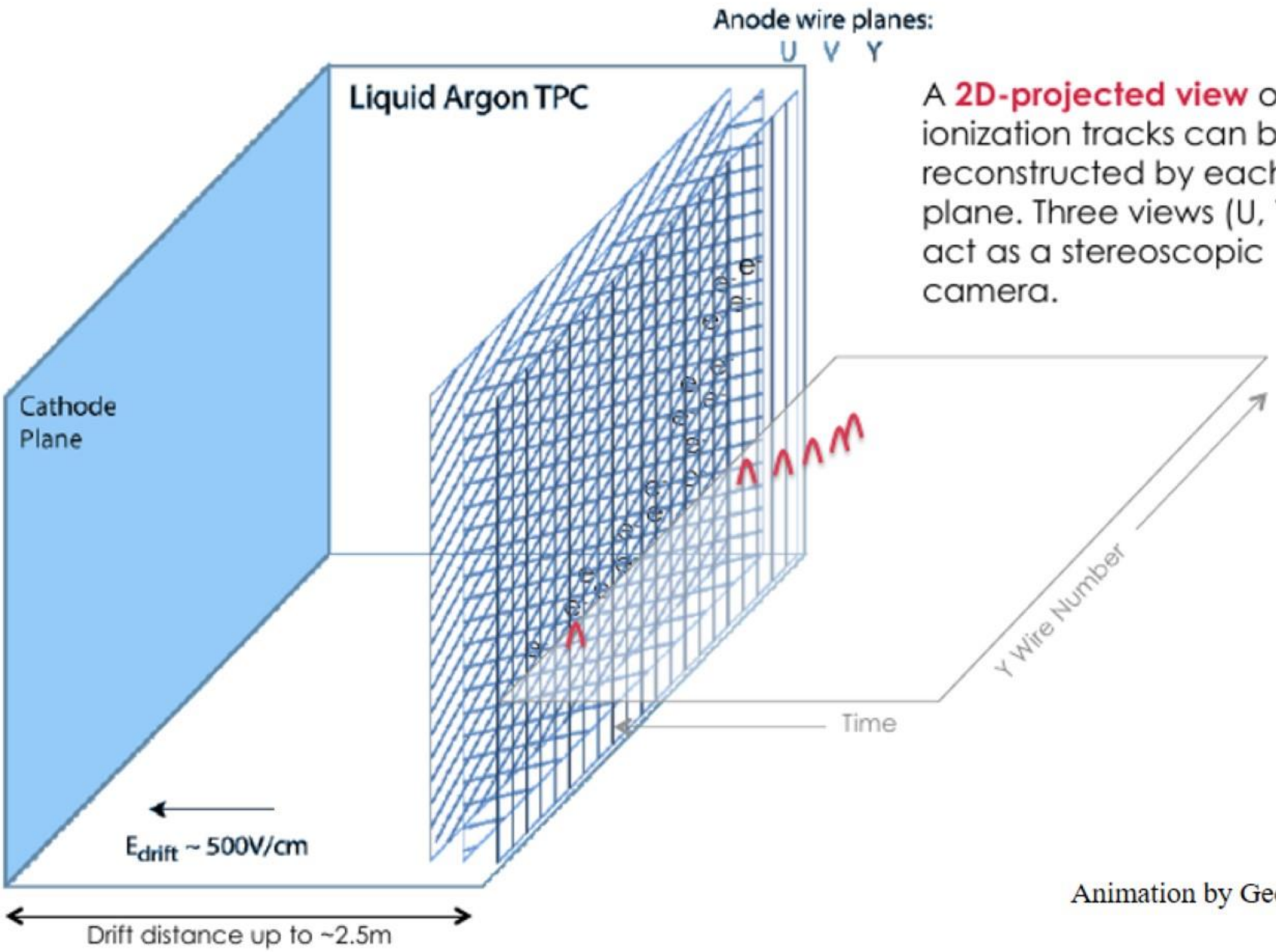

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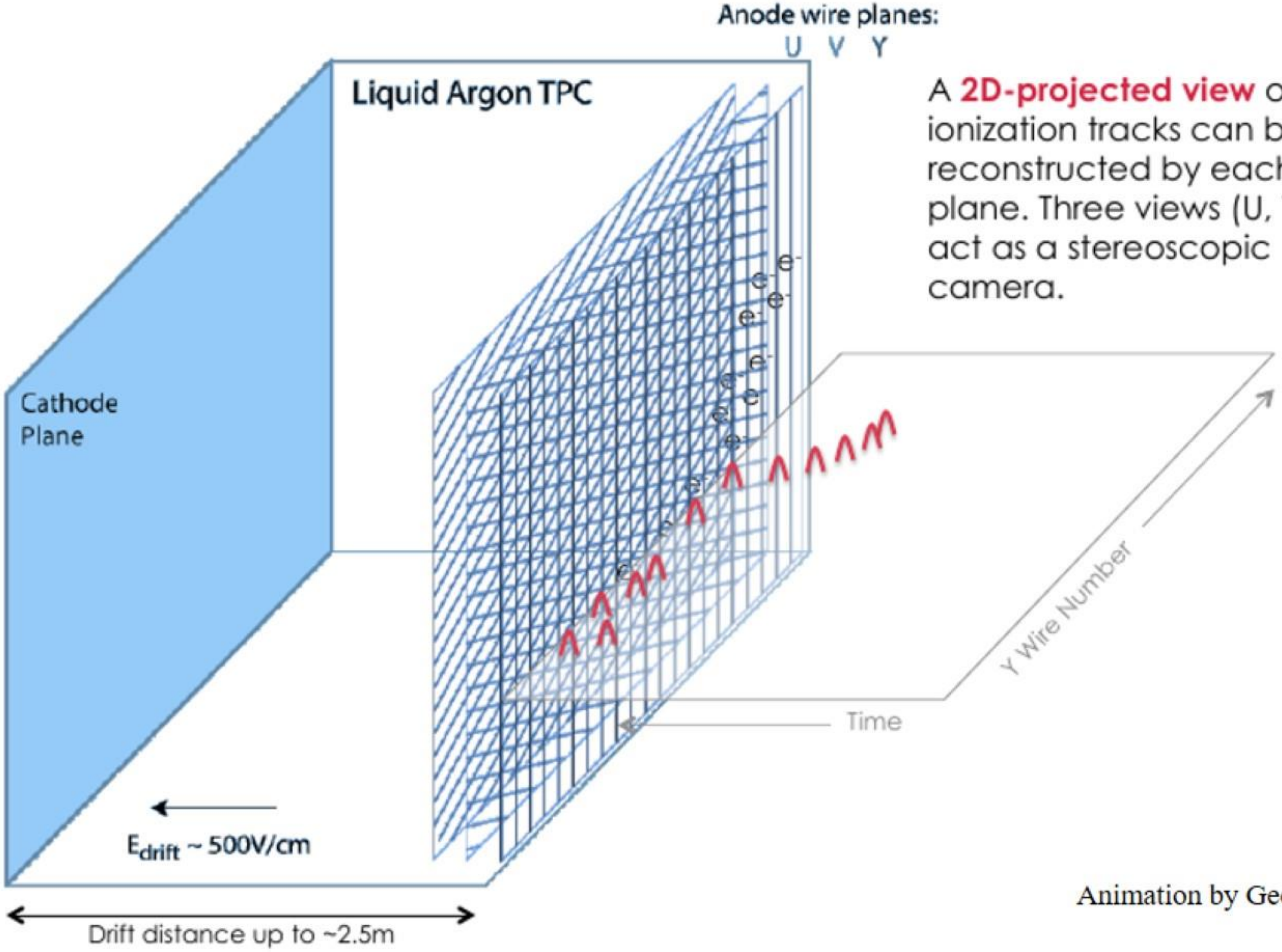

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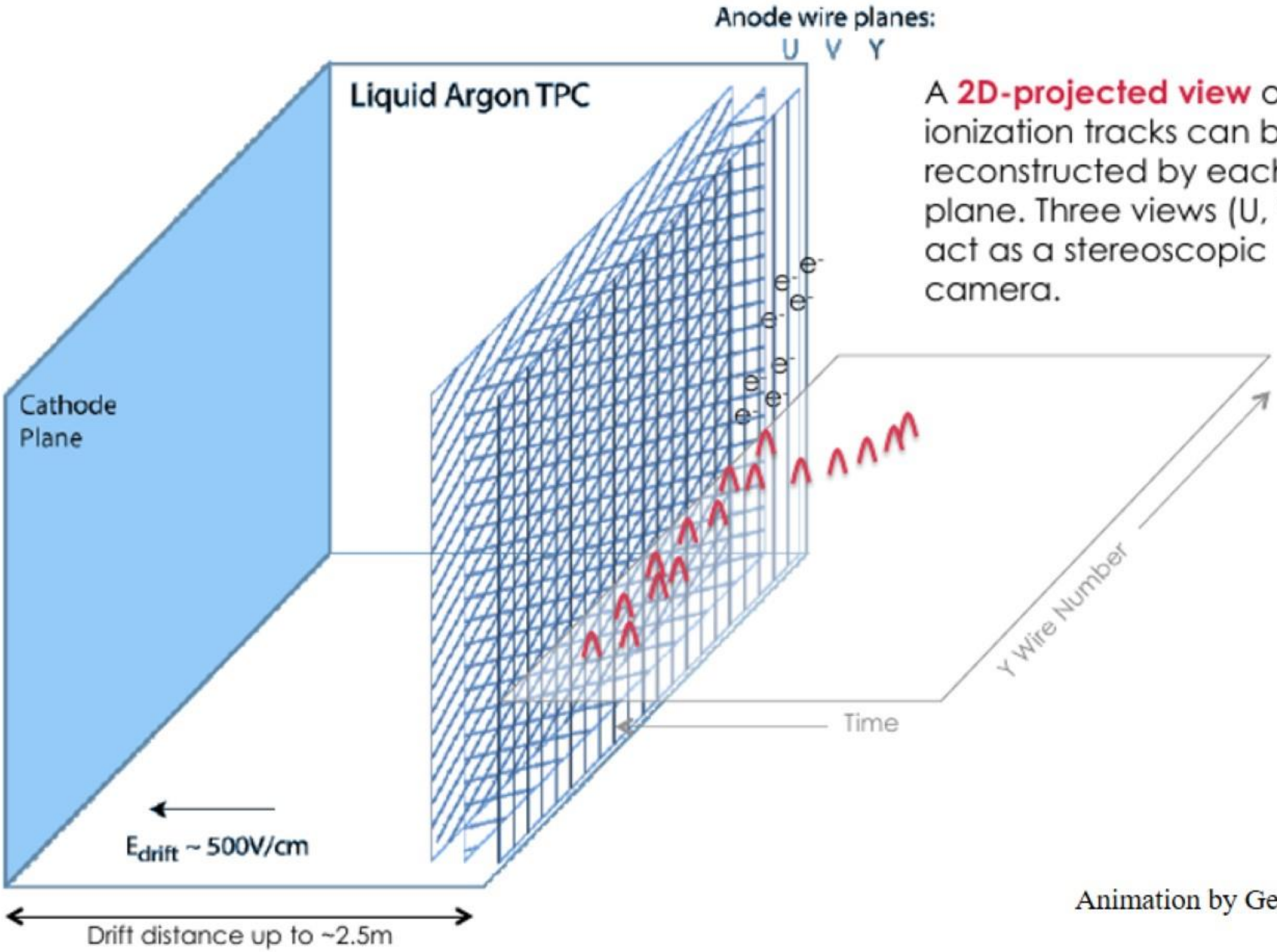

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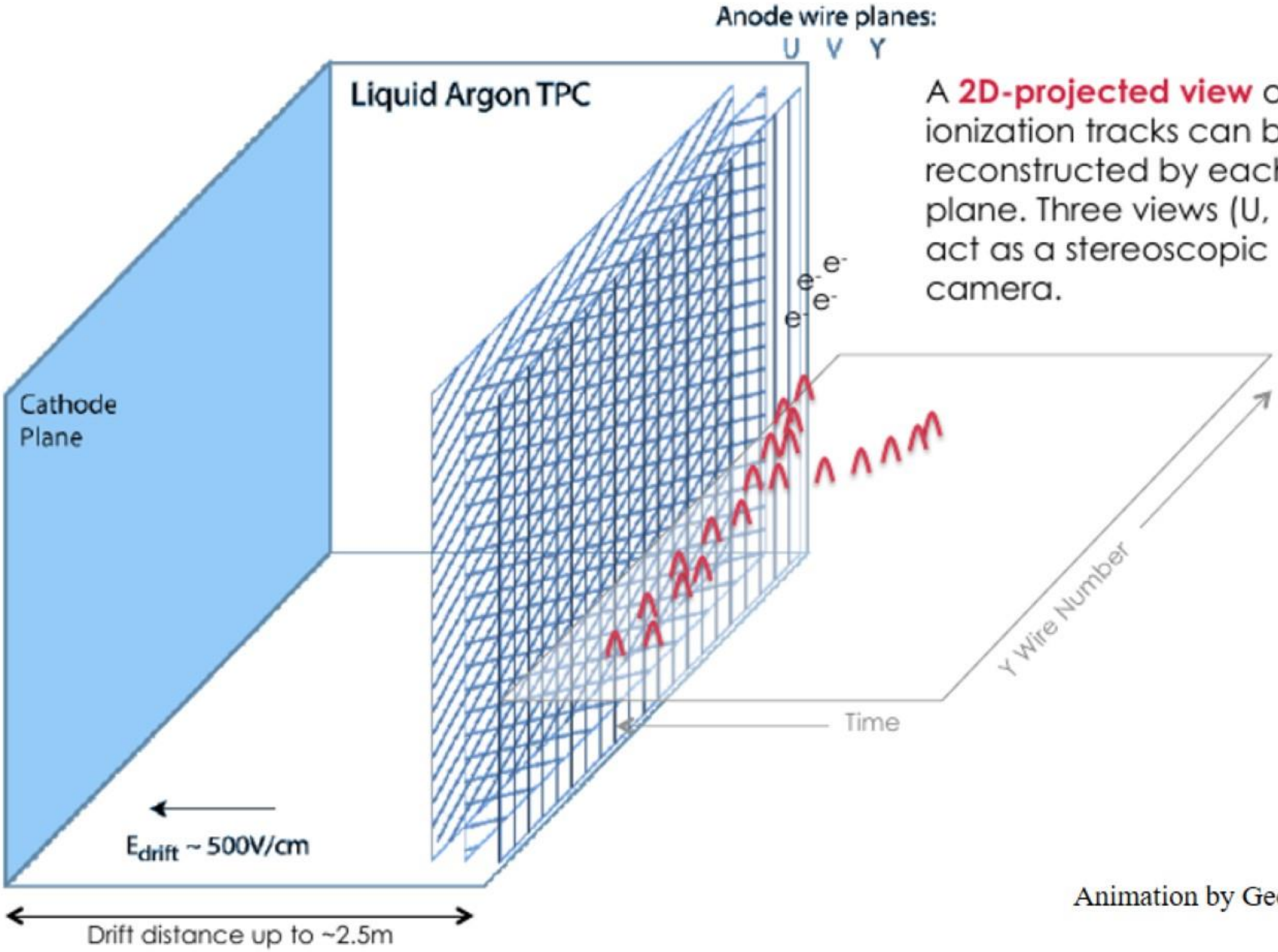

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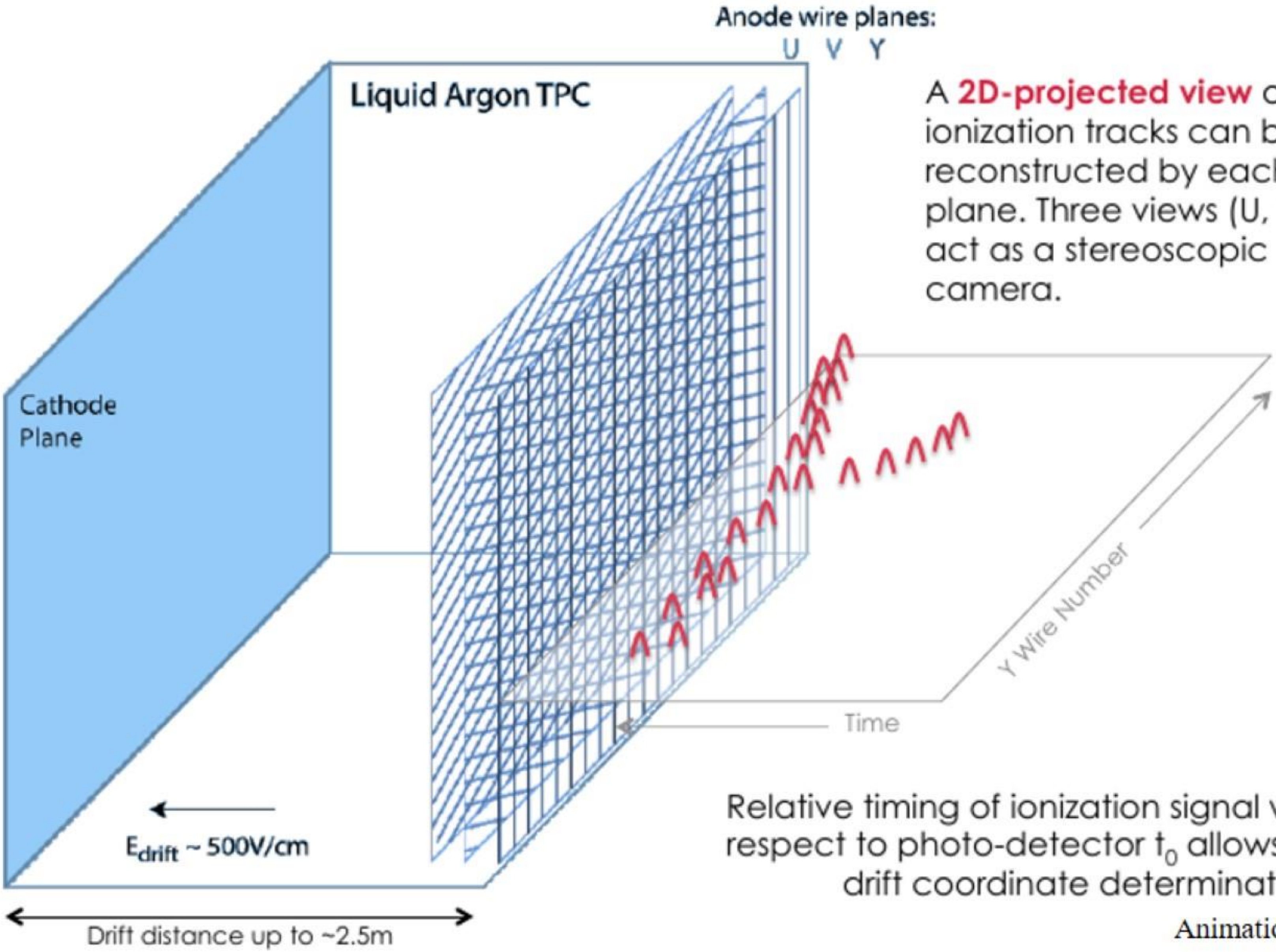
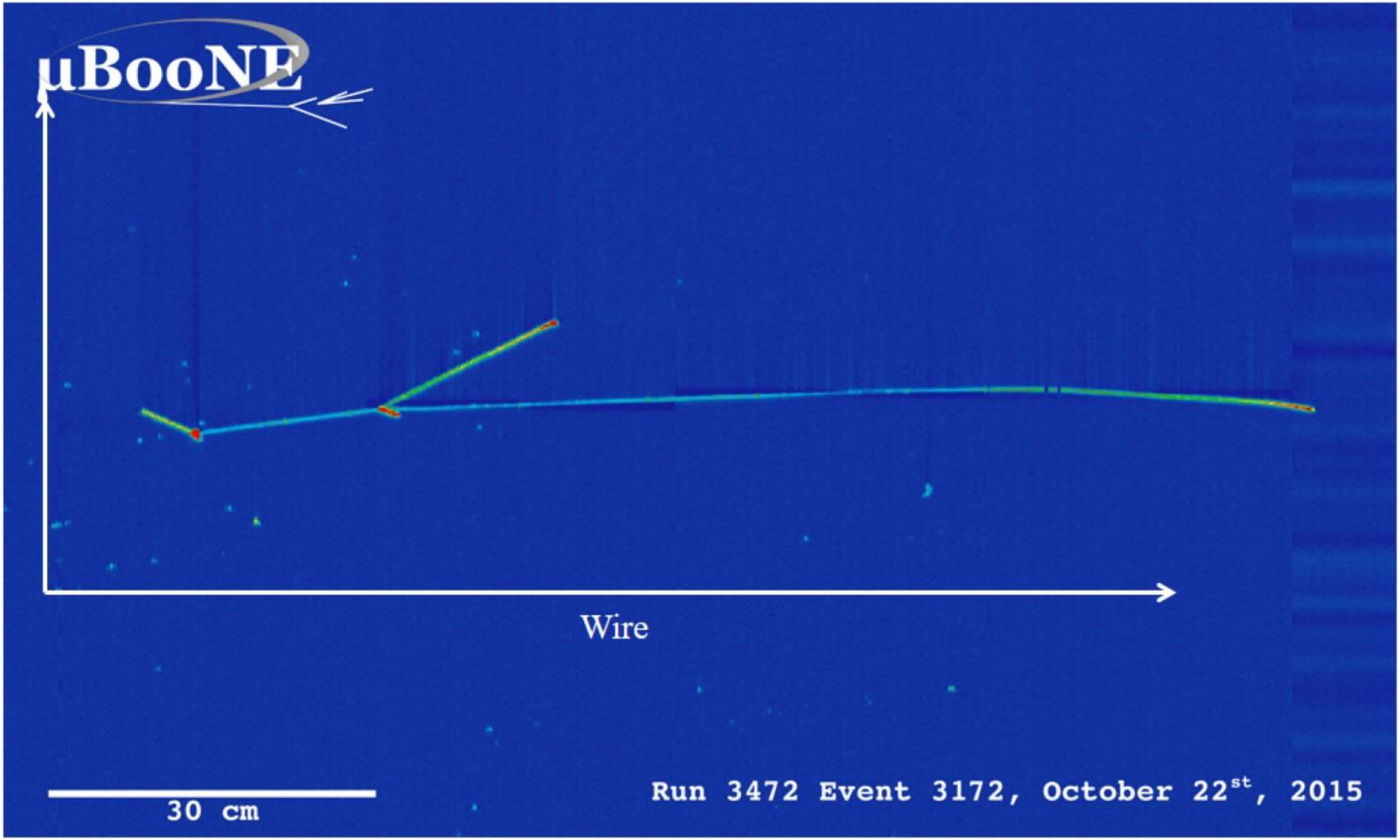


A **2D-projected view** of the ionization tracks can be reconstructed by each wire plane. Three views (U, V, Y) act as a stereoscopic camera.

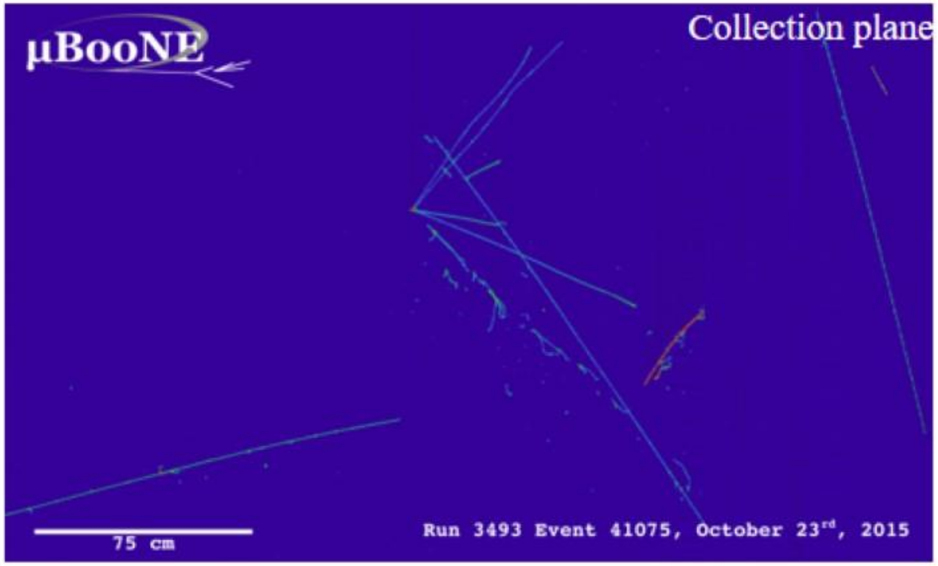
Relative timing of ionization signal with respect to photo-detector t_0 allows for drift coordinate determination.

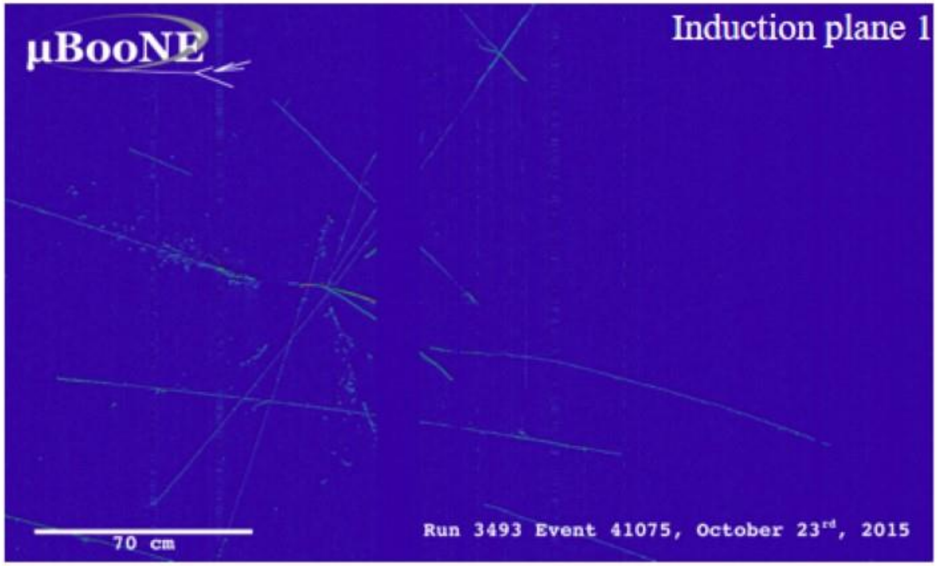
Animation by Georgia Karagior

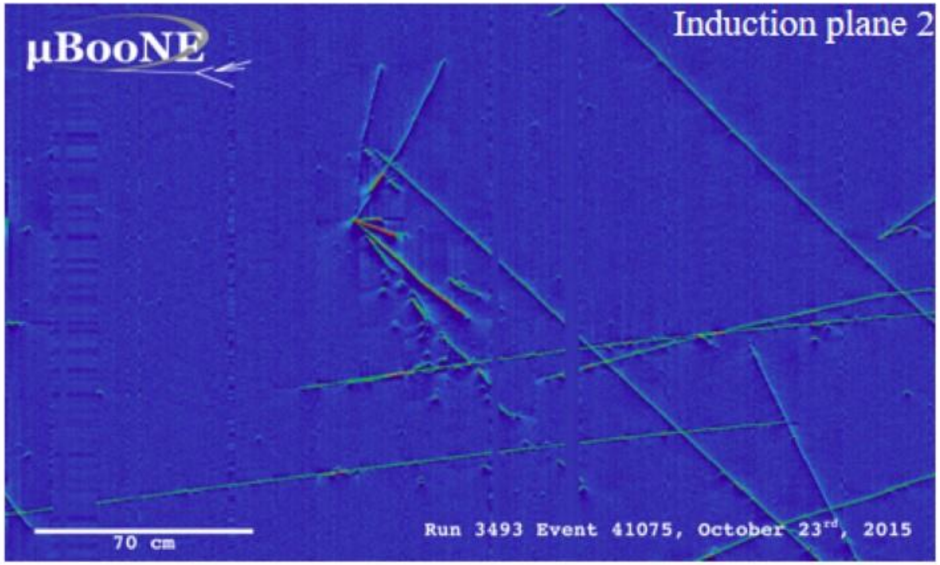
A real neutrino candidate in a LArTPC



Neutrino candidate in LArTPC







- The 3D view of the event is projected onto three planes.

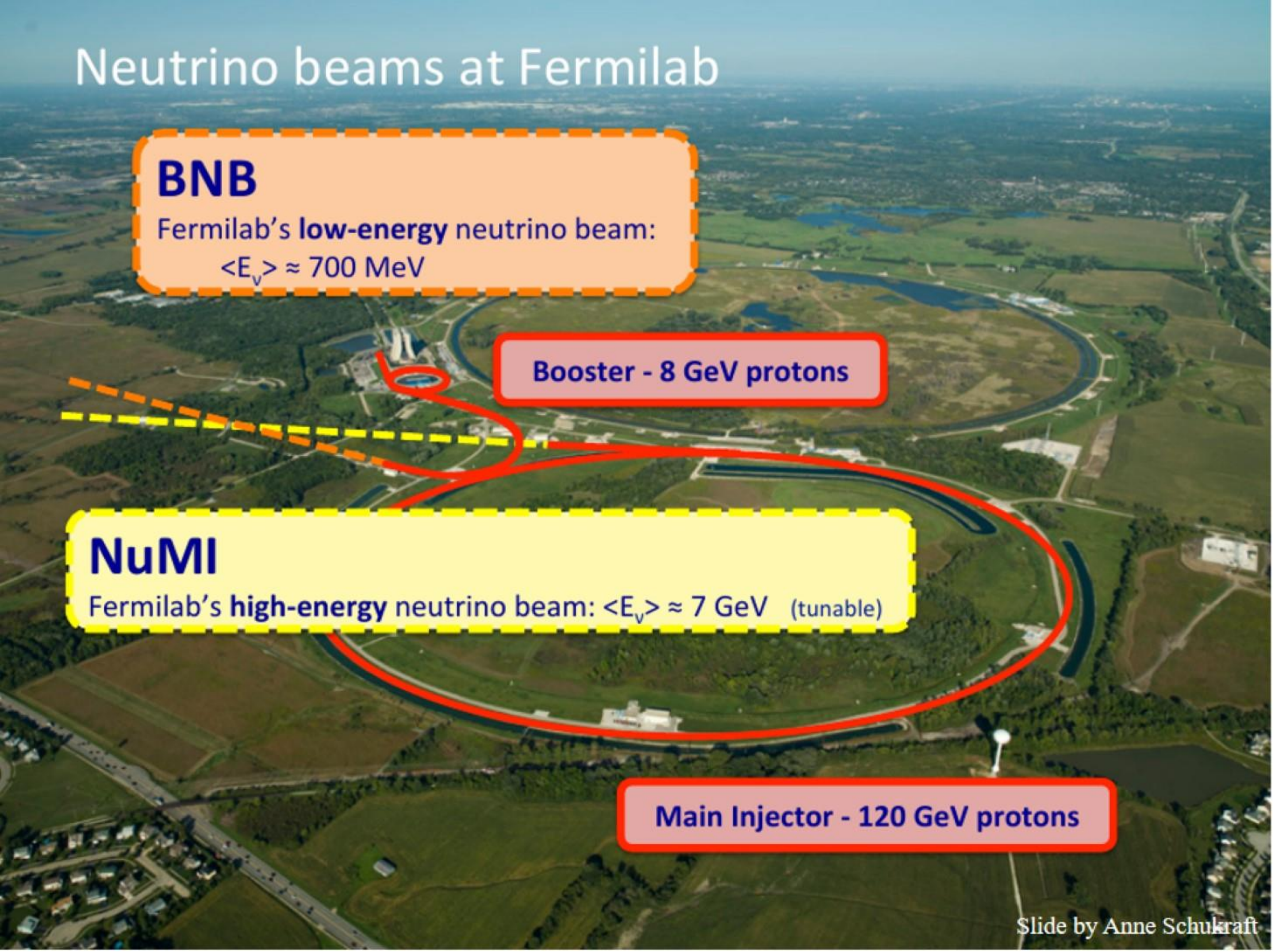
LArTPC

Why **liquid argon**?

- It is dense (1.4 g/cm^3): more targets for neutrinos per volume.
- It is relatively cheap.
- It can be purified (electronegative elements -oxygen- capture electrons, nitrogen quenches scintillation light): detectors can be bigger.
- Bright scintillator (40000 photons/MeV). Transparent to its own light.

- Why **time projection chamber**?
- Modern bubble chamber: very good granularity thanks to a small wire pitch but with automated readout and 3D reconstruction.
- Number of readout channels scales with detector length: less electronics needed.
- Several ways to estimate particle energy: ionization, range... They can be used to identify the particle.

Neutrino beams at Fermilab



BNB

Fermilab's **low-energy** neutrino beam:
$\langle E_\nu \rangle \approx 700$ MeV

Booster - 8 GeV protons

NuMI

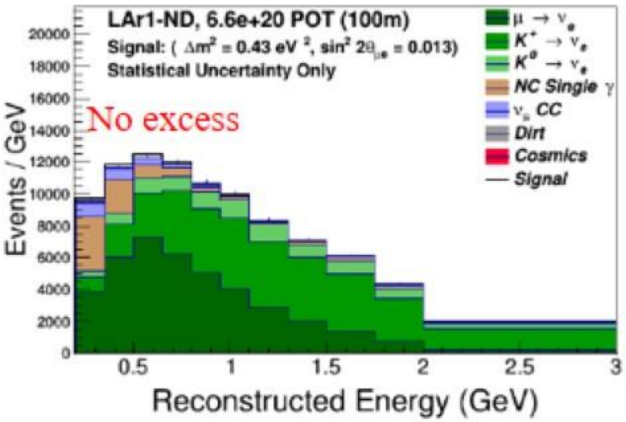
Fermilab's **high-energy** neutrino beam: $\langle E_\nu \rangle \approx 7$ GeV (tunable)

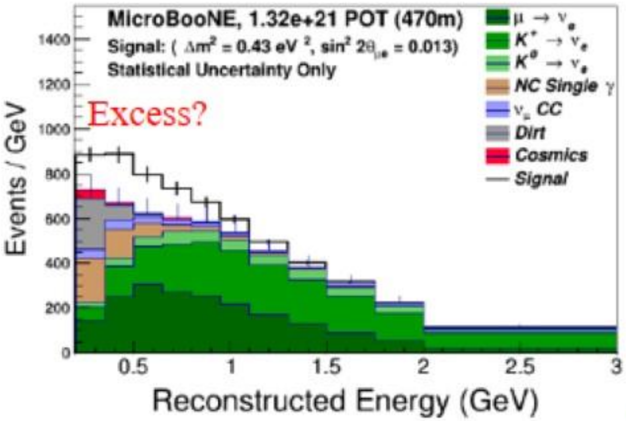
Main Injector - 120 GeV protons

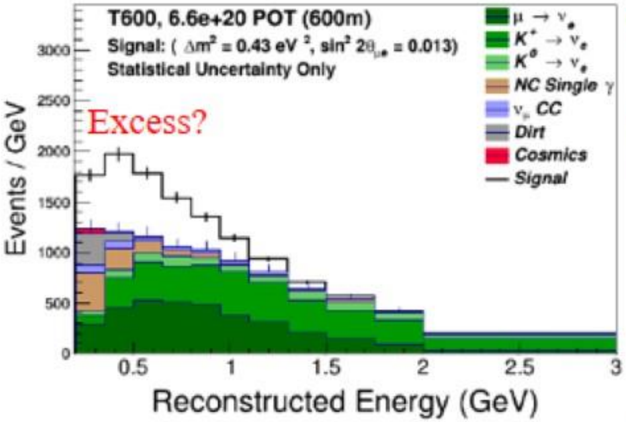
Slide by Anne Schukraft

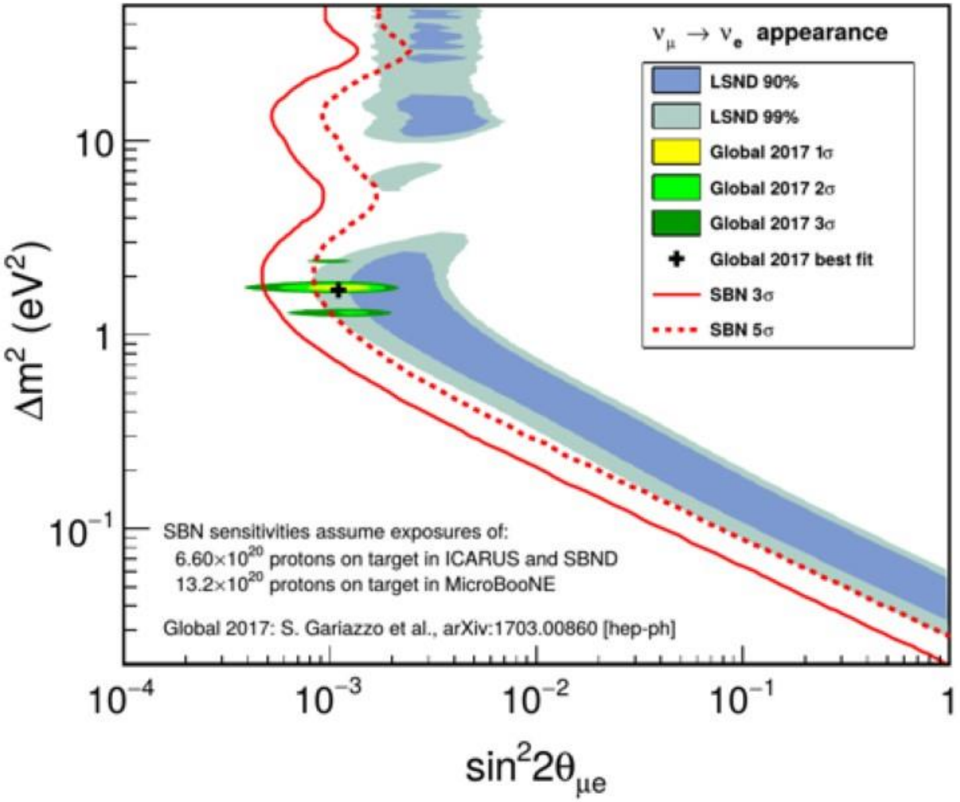
SBND Physics: ν_e appearance

arXiv:1503.01520









- **SBND will measure the intrinsic ν_e component of the BNB flux with large statistics before any oscillation affects it.**
- MicroBooNE & ICARUS will search for an excess of ν_e using SBND measurement as reference.

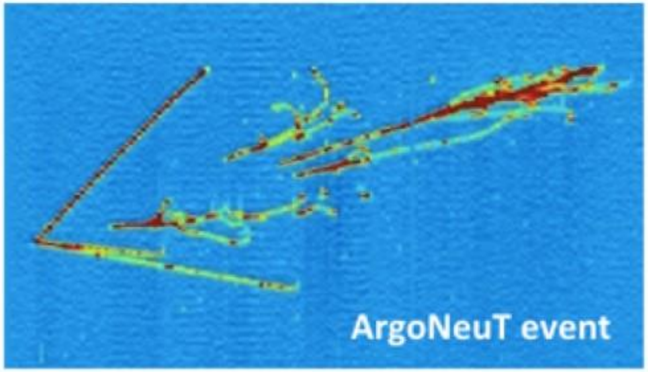
$$P^{3+1}_{\nu_\mu \to \nu_e} = \sin^2 2\theta_{\mu e} \sin^2 \left(\frac{\Delta m^2 L}{4E_\nu} \right) \qquad \sin^2 2\theta_{\mu e} \equiv 4|U_{\mu 4}U_{e4}|^2$$

- SBN will be able to explore the LSND-favored region with 5σ.

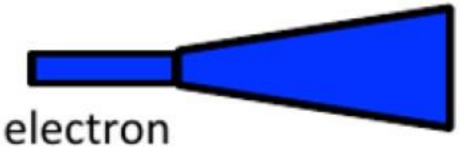
Electron vs. gamma discrimination

Proof of principle with ArgoNeuT data!

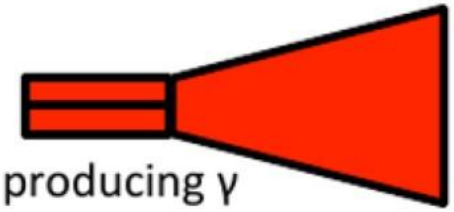
Case 1: The neutral γ (π^0) is observed as gap between vertex and EM shower:



Case 2: If the gap is too small to be observed, the charge at the start of the shower can be reconstructed through a measurement of dE/dx



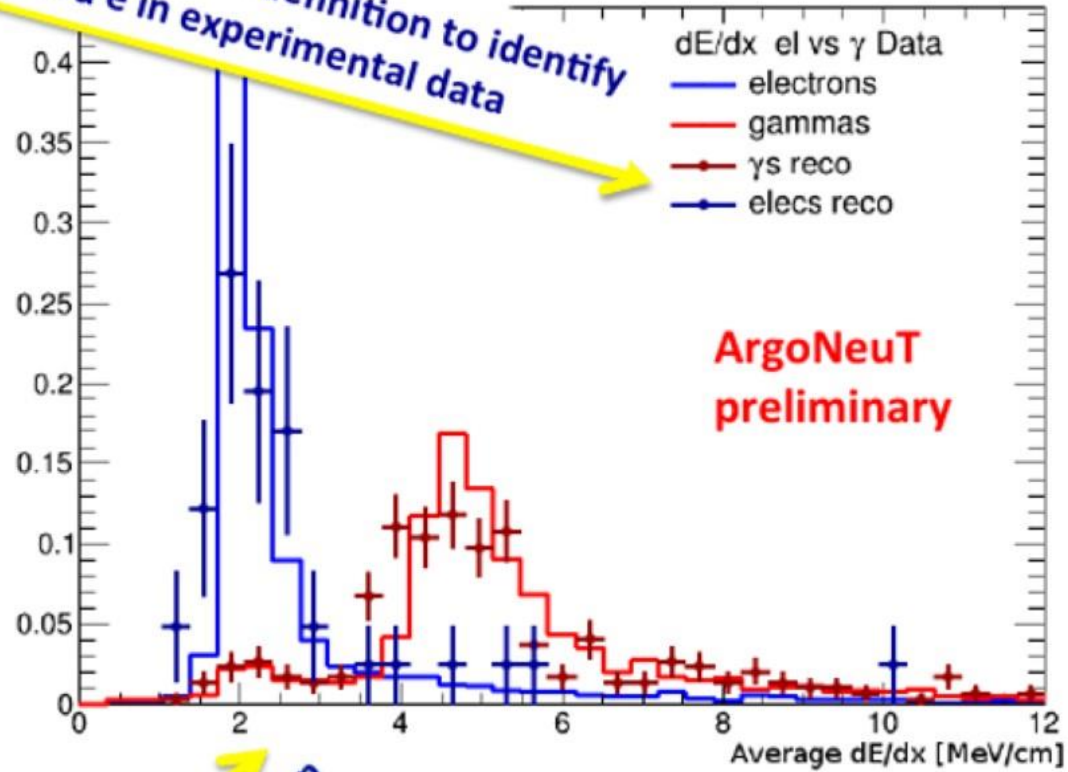
Single electron



e^+/e^- pair producing γ

Use the topological definition to identify γ and e in experimental data

First presented @ NEUTRINO2014
by A. Szelc for ArgoNeuT

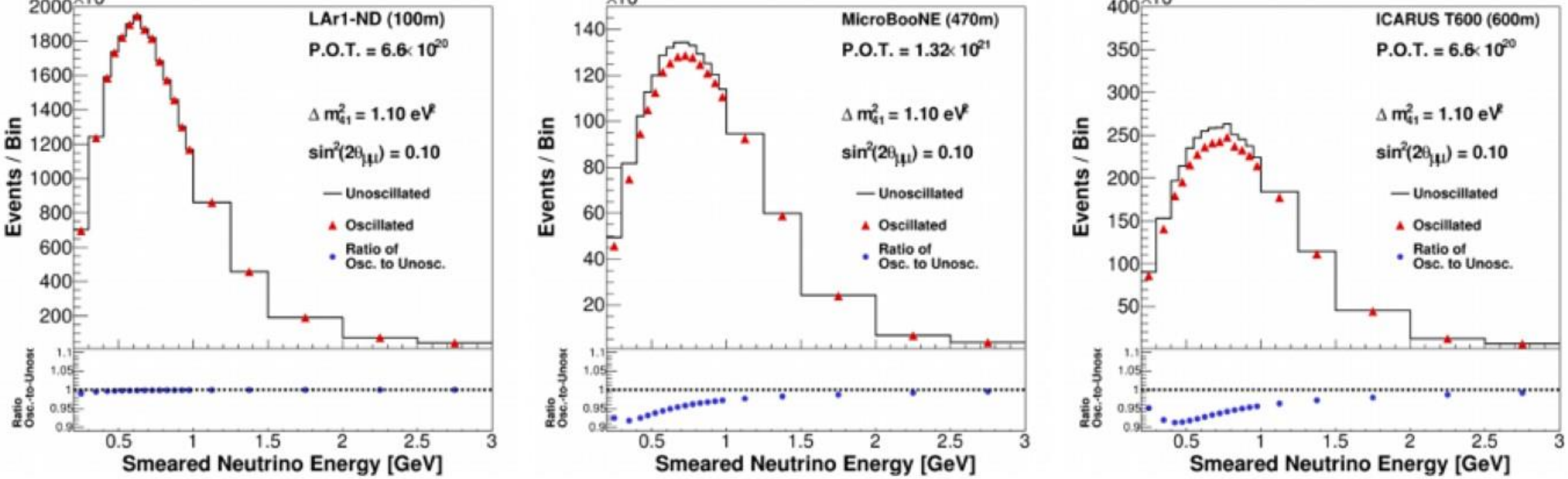


Plot the dE/dx distribution for these events

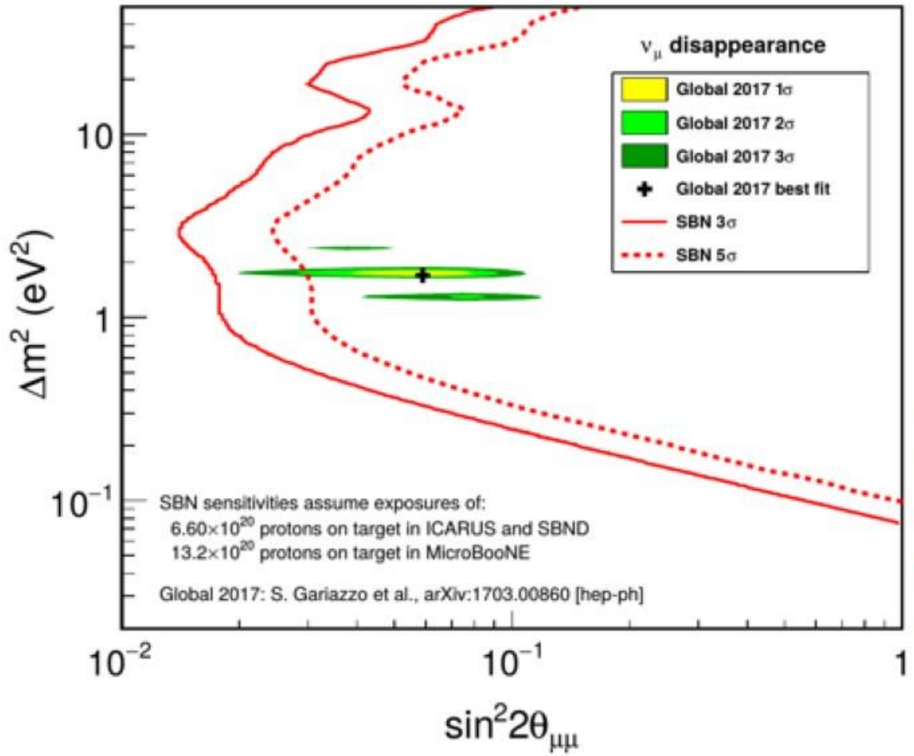
MicroBooNE will be able to resolve the nature of the MiniBooNE low-energy excess!

Slide by Anne Schukraft

SBND Physics: ν_μ disappearance



arXiv:1503.01520



- ν_e appearance must be accompanied by ν_μ disappearance.

$$\sin^2 2\theta_{\mu e} \equiv 4|\boxed{U_{\mu 4}}U_{e4}|^2$$

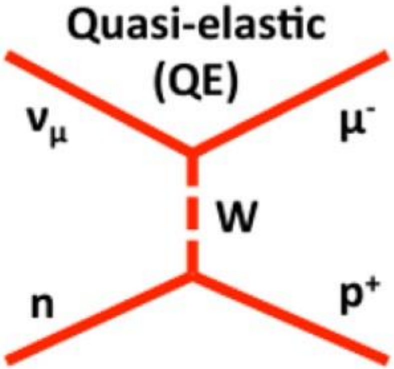
$$\sin^2 2\theta_{\mu\mu} \equiv 4|\boxed{U_{\mu 4}}|^2(1-|\boxed{U_{\mu 4}}|^2)$$

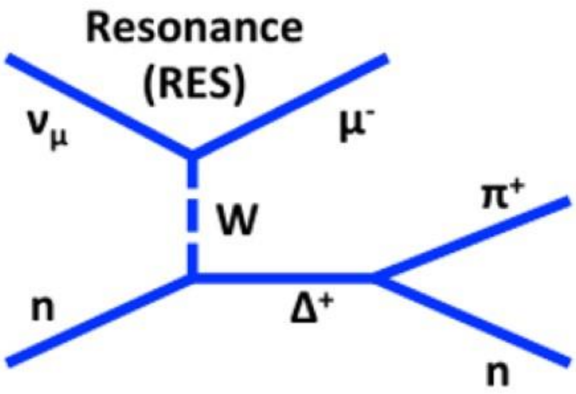
$$P^{3+1}_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 2\theta_{\mu\mu} \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

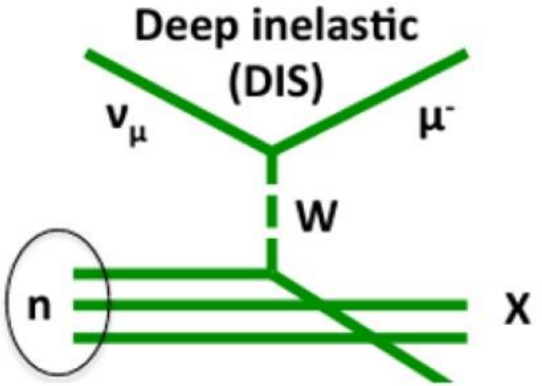
- SBND will measure the unoscillated ν_μ flux.
- MicroBooNE & ICARUS will search for a deficit of ν_μ.
- **Only possible thanks to the reduction on the flux normalization systematic uncertainty brought by SBND.**
- SBN covers almost the full allowed region region with 5σ.

Cross-section program

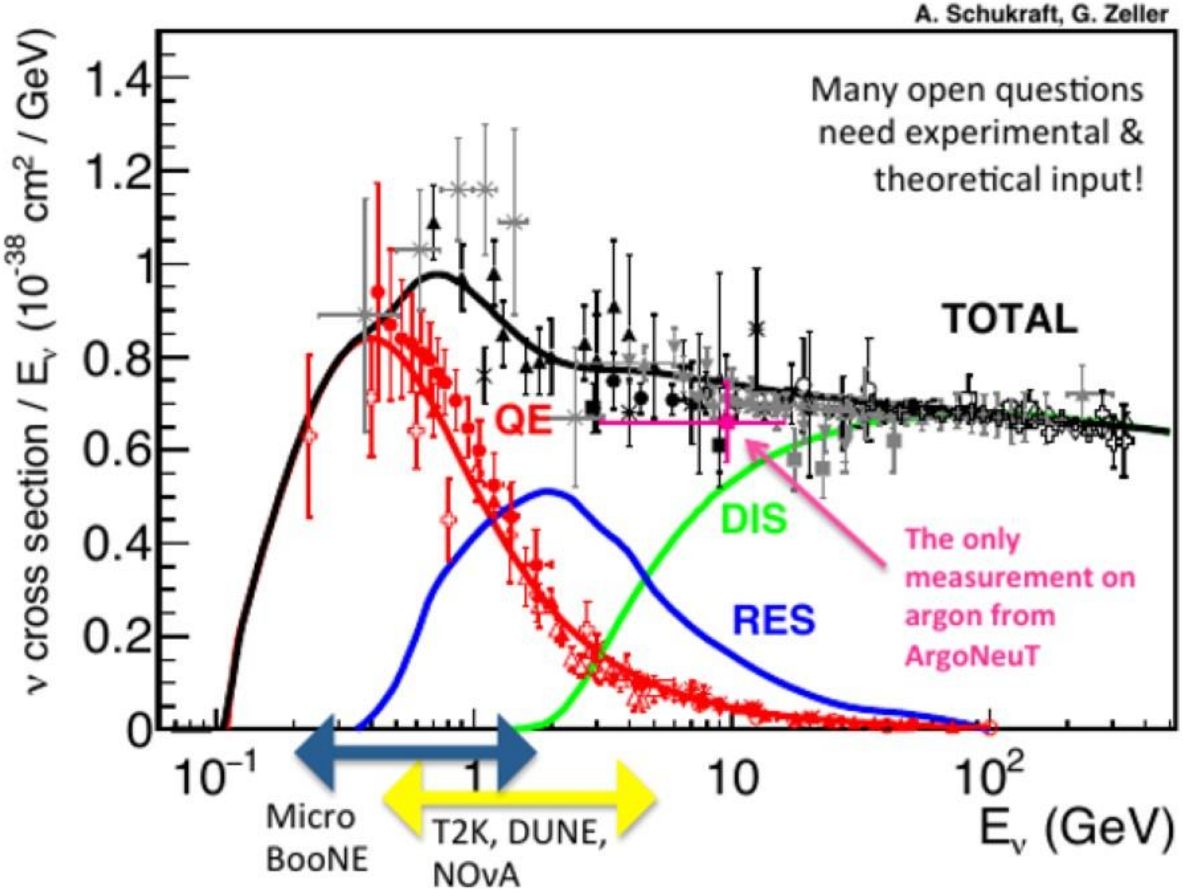
Neutrinos interacting with nucleons







Lots of interesting (nuclear) physics over all energy ranges.



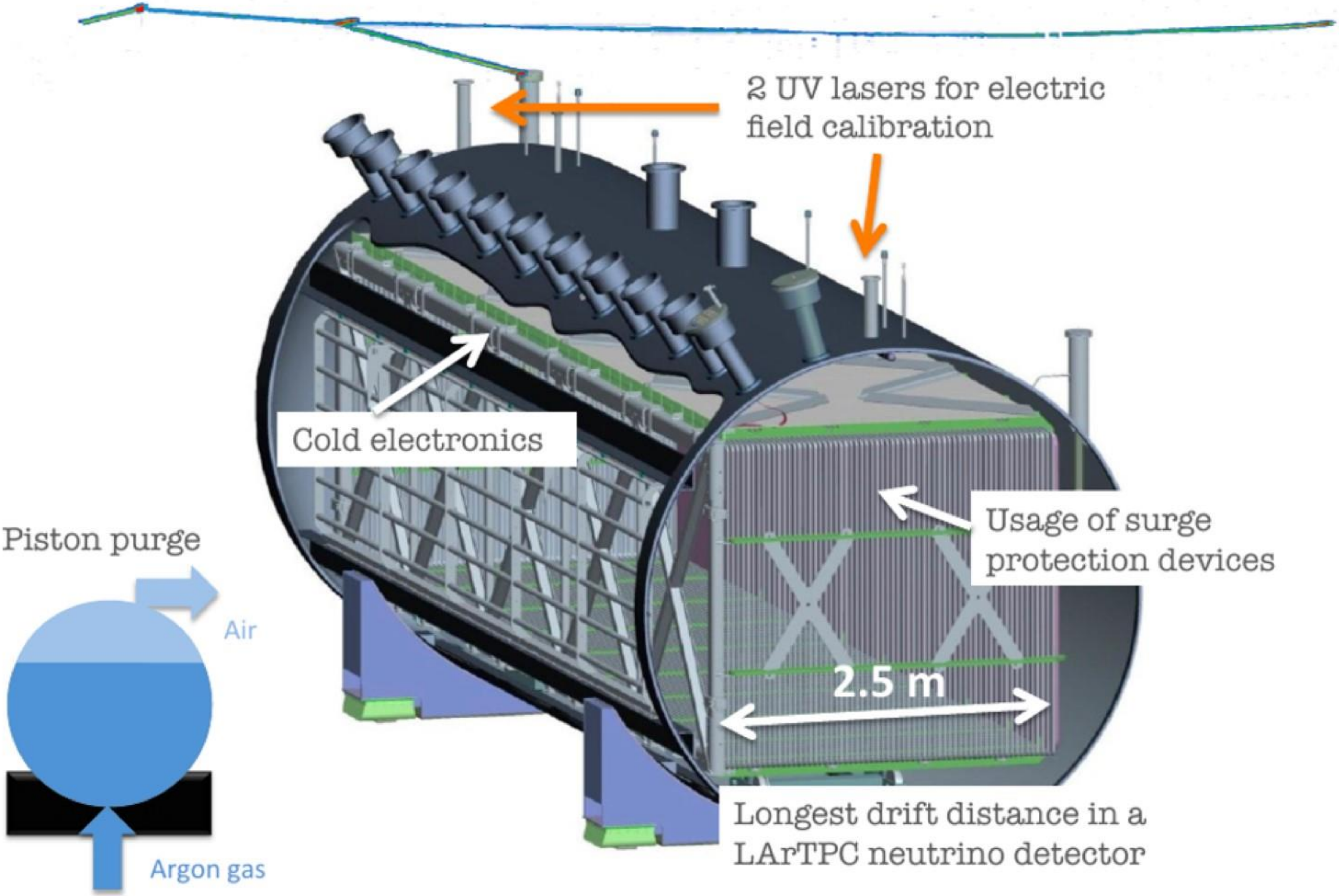
A. Schukraft, G. Zeller

Many open questions need experimental & theoretical input!

The only measurement on argon from ArgoNeuT

We need to understand neutrino-nucleon scattering to understand event rates, final states and neutrino energy estimation in oscillation experiments

R&D in MicroBooNE



2 UV lasers for electric field calibration

Cold electronics

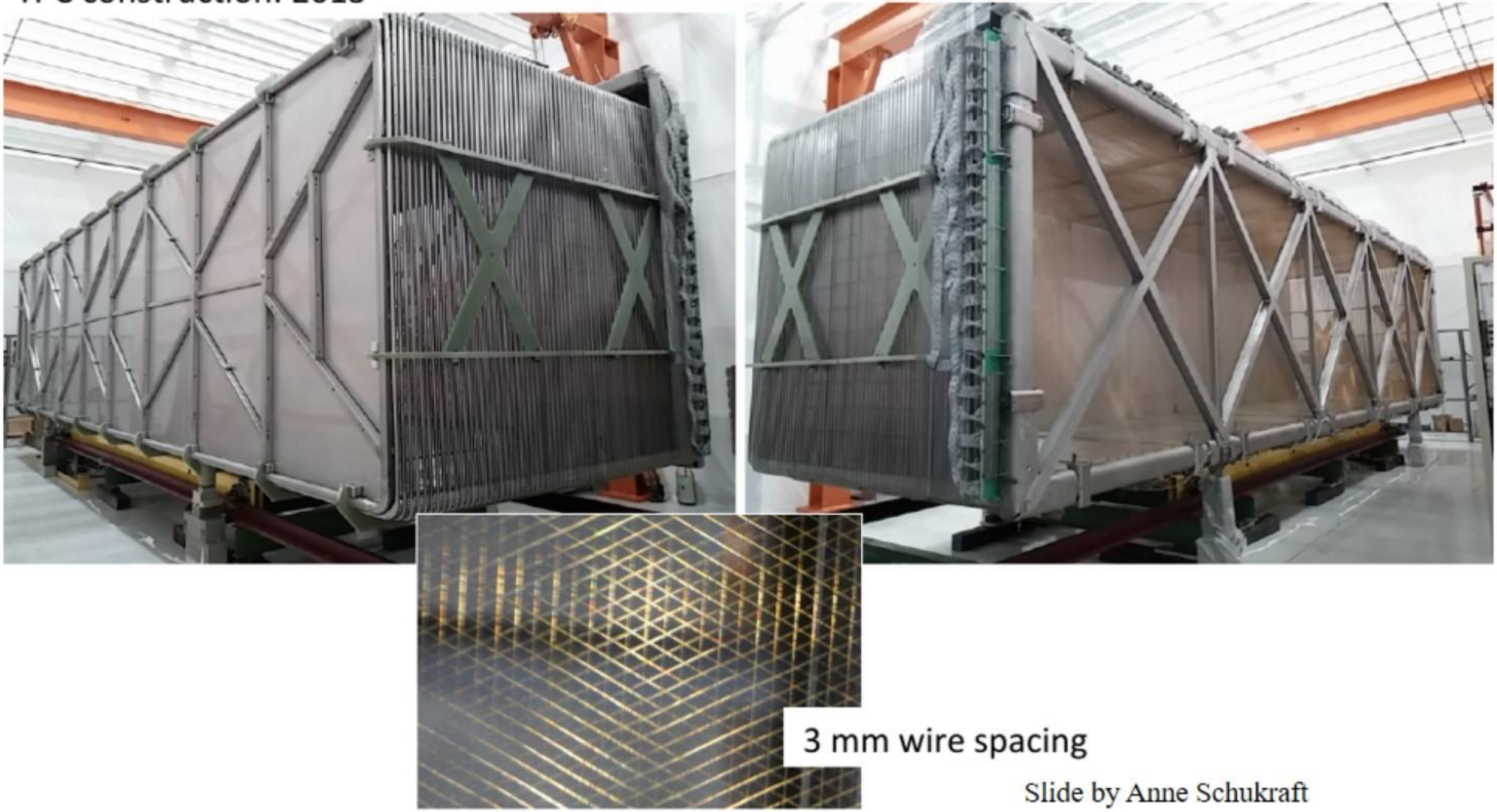
Usage of surge protection devices

Longest drift distance in a LArTPC neutrino detector

Piston purge

MicroBooNE construction

TPC construction: 2013

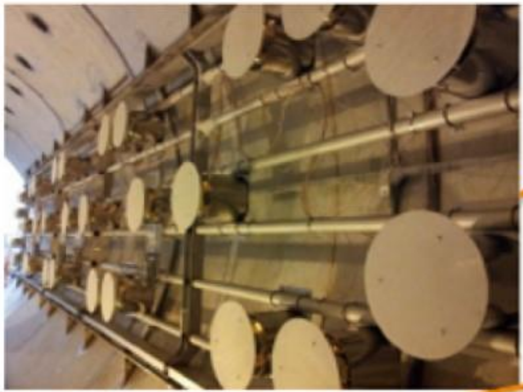


3 mm wire spacing

Slide by Anne Schukraft

Installation – a picture series

PMT system installation: Dec 2013



TPC insertion: Dec 23rd, 2013

Moving day! June 23rd, 2014

MicroBooNE's home in the beam line: The LAr Test Facility

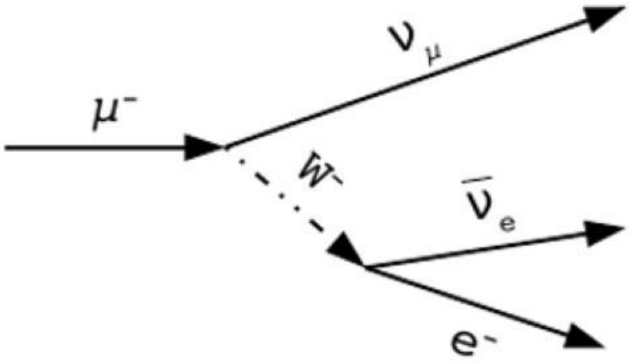
Foamed in! July 2014

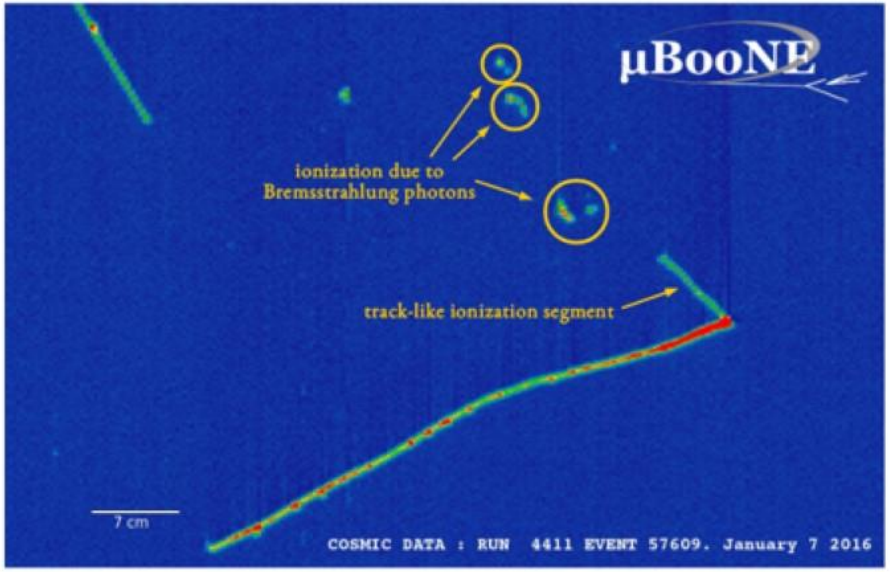
Cabled up! Sept. 2014

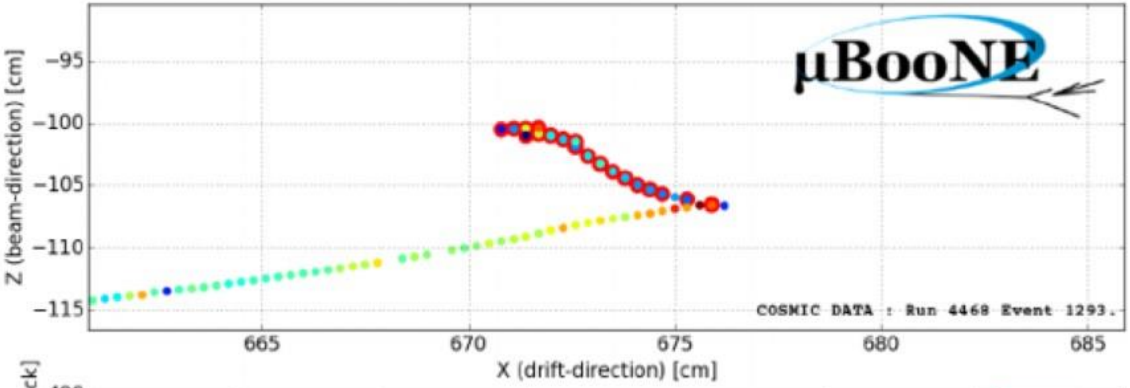
All electronics in! Dec. 10, 2014

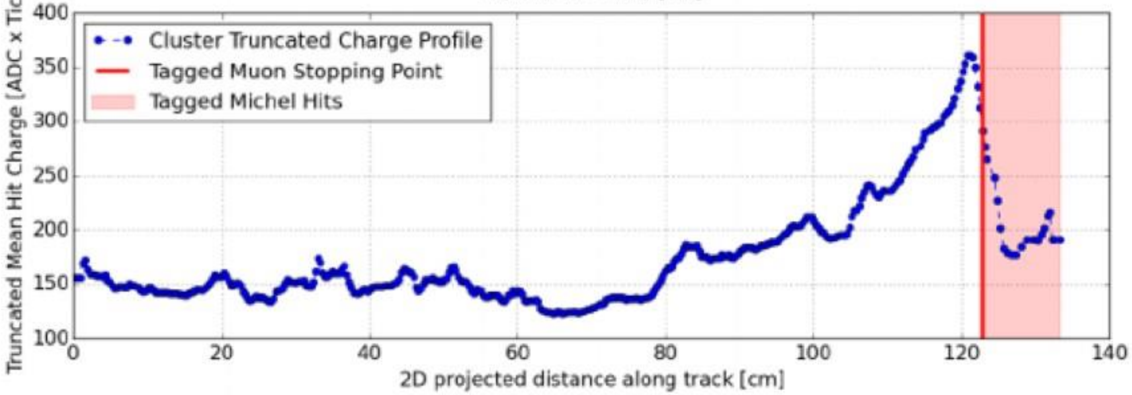
Slide by Anne Schukraft

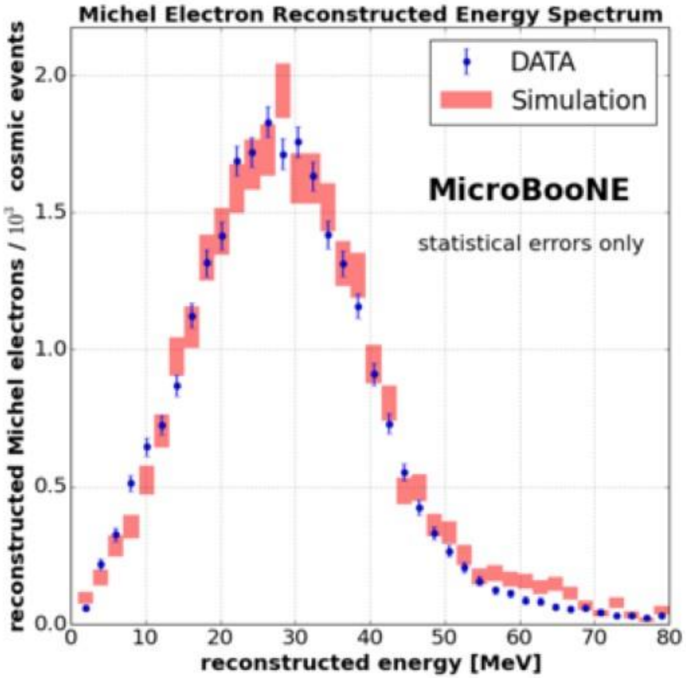
Michel electrons in MicroBooNE









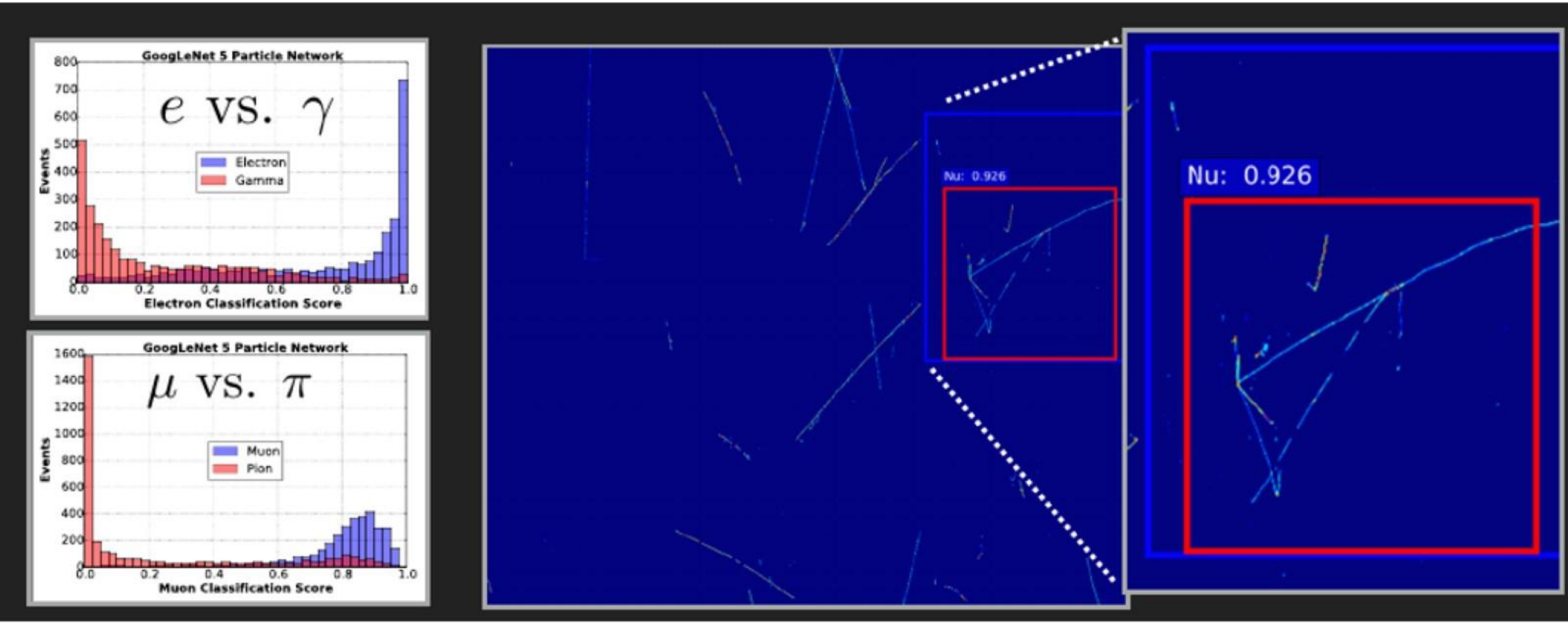


Use calorimetry to identify Bragg peak of stopping muon.

Similarly look for spatial kink.

Analysis by David Caratelli, Nevis PhD student

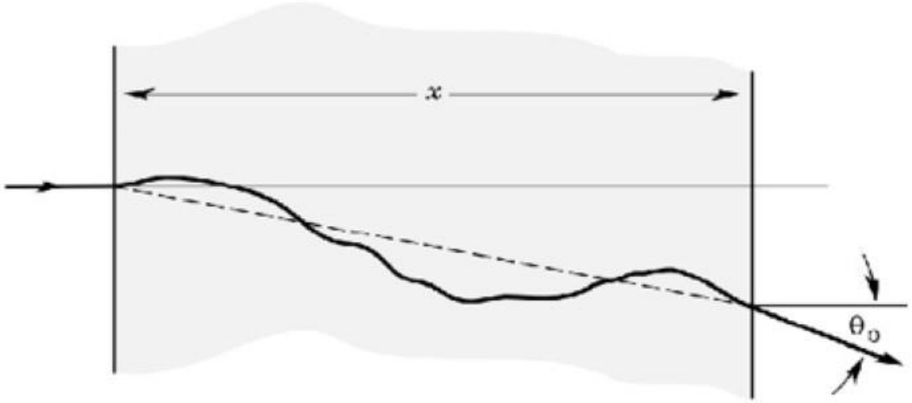
Particle classification using Deep Learning

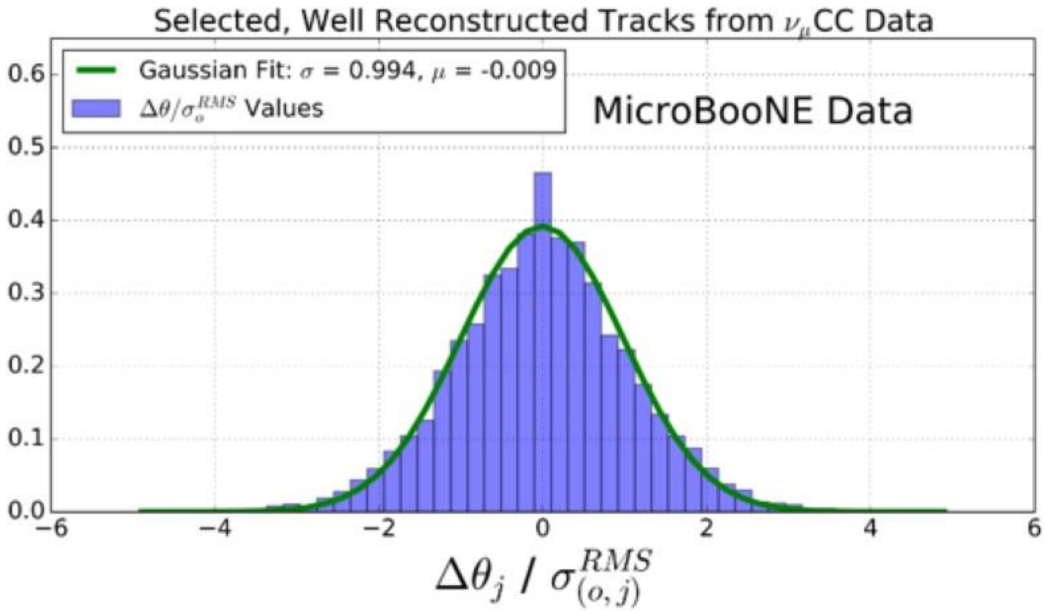


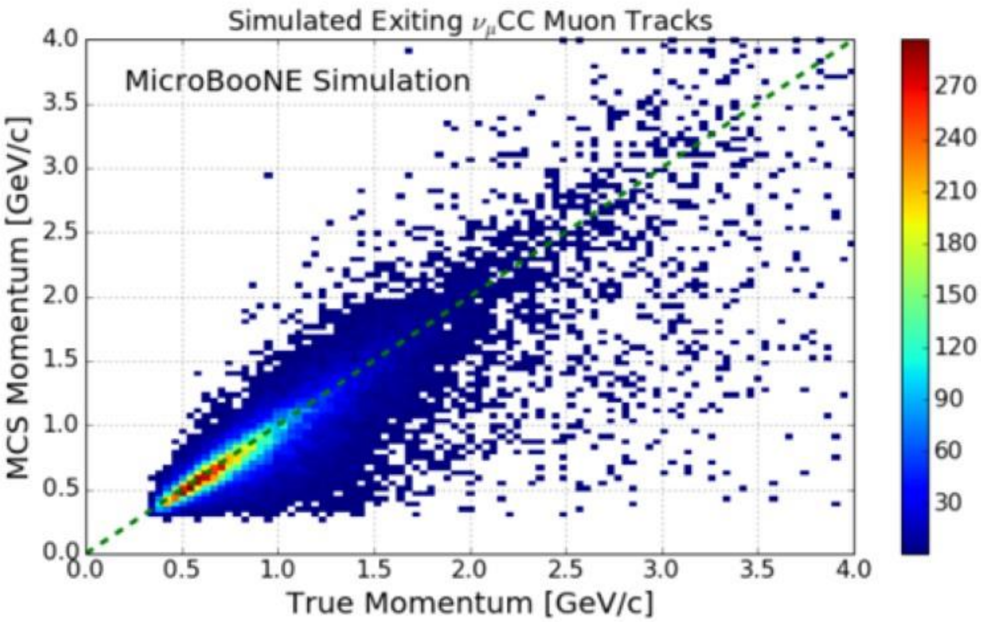
- Feed the LArTPC data to a computer as an image.
- Apply computer-vision techniques (convolutional neural networks) to the classification of particles or for localizing neutrino interactions.
- Application of GPUs to scientific research.

Analysis by Kazuhiro Terao (Fermilab postdoc), and Victor Genty (Nevis PhD student) et al.

Multiple Coulomb Scattering





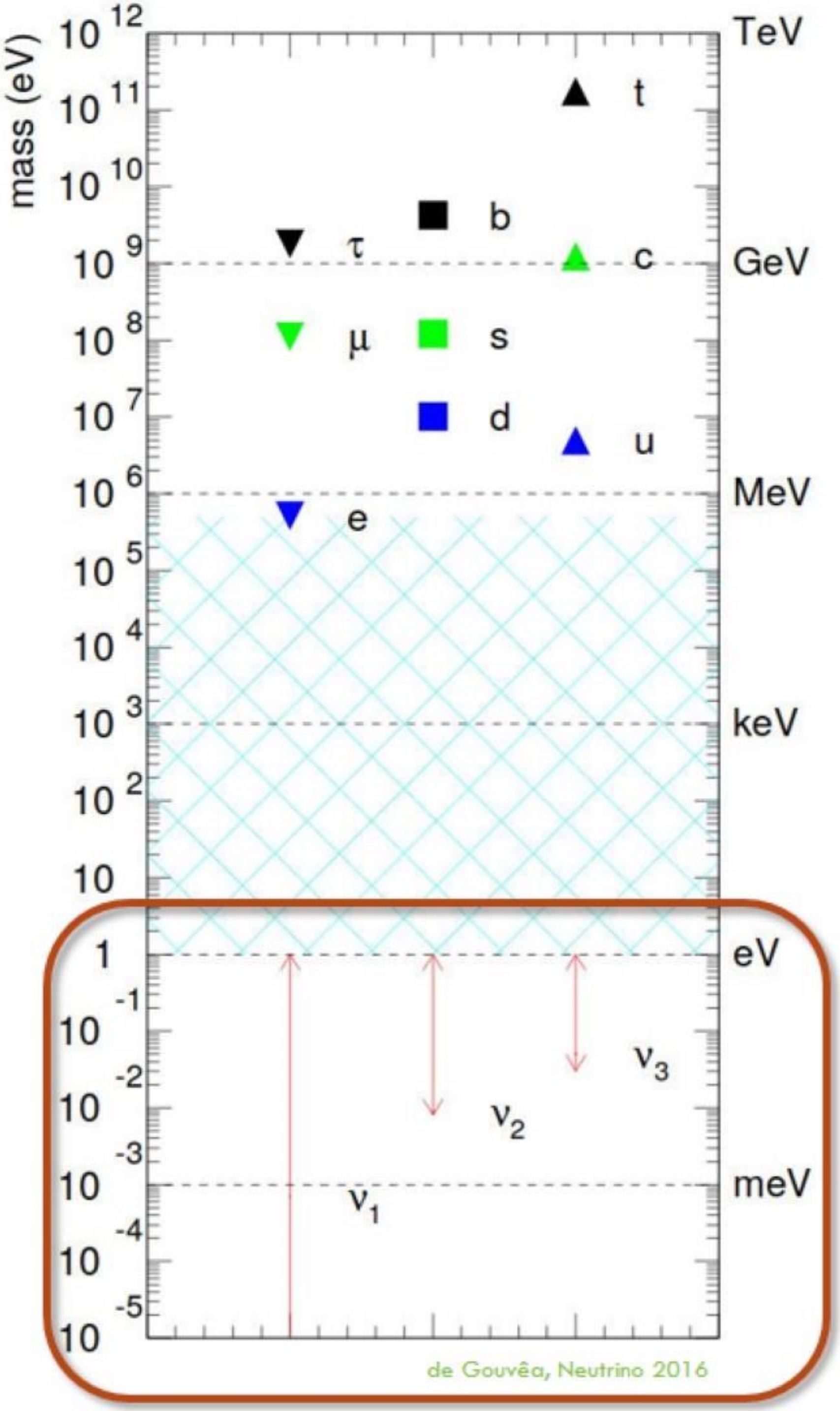


- The width of the distribution of scattering angles is proportional to the momentum of the particle traversing the medium.
- Measure the momentum of particles (e.g. muons) leaving the detector.

Measurement of neutrino mass

PARTICLE MASSES

- "There remains one especially unsatisfactory feature [of the Standard Model of particle physics]: the observed masses of the particles, m. There is no theory that adequately explains these numbers. We use the numbers in all our theories, but we do not understand them – what they are, or where they come from. I believe that from a fundamental point of view, this is a very interesting and serious problem."
  - R. P. Feynman

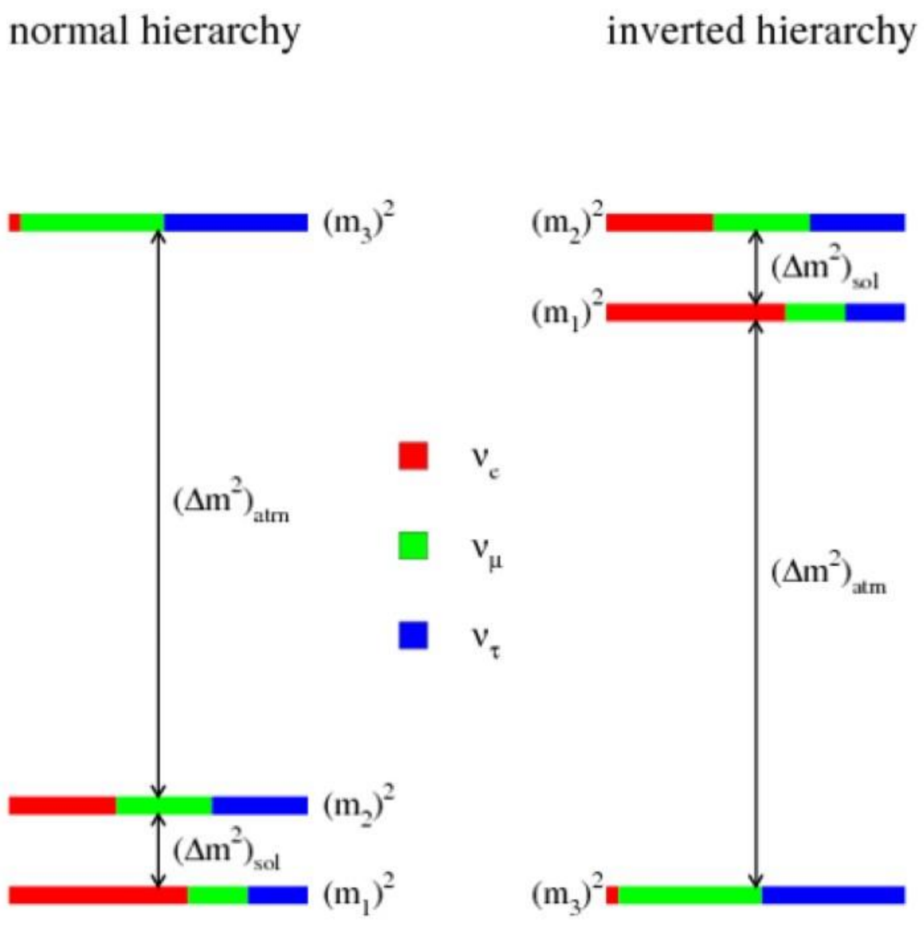


de Gouvêa, Neutrino 2016

WHAT'S SPECIAL ABOUT NEUTRINO MASS?

- It seems to be ridiculously small, compared to the rest of the mass spectrum…
  - We would like to imagine that particle masses are generated through some dynamic mechanism, and we wouldn't like to have to fine-tune it.
- Neutrinos are the only fundamental neutral fermions we know.
  - This means they could be their own anti-particle.
  - In a nutshell: if we want neutrino masses to be just like the other fermions (Yukawa couplings arising from coupling to Higgs field) then we need to postulate **right-handed** neutrino fields (**and left-handed** anti-neutrino fields) that **do not interact.**
  - It might be that there these fields do not exist and that the only difference between what we call a neutrino and what we call an anti-neutrino is its helicity.
    - These are called Majorana neutrinos, and lead to non-conservation of lepton number.
    - Also might help explain the smallness of neutrino masses, through see-saw mechanisms.

Lower limits



- If we take the lightest neutrino mass to be 0, we can derive lower limits for the other mass eigenstates.
- For normal hierarchy:

$$m_2 \geq \sqrt{\Delta m^2_{21}} = 0.0087 \pm 0.0001\,\mathrm{eV}$$

$$m_3 \geq \sqrt{\Delta m^2_{32} + \Delta m^2_{21}} = 0.0502 \pm 0.0006\,\mathrm{eV}$$

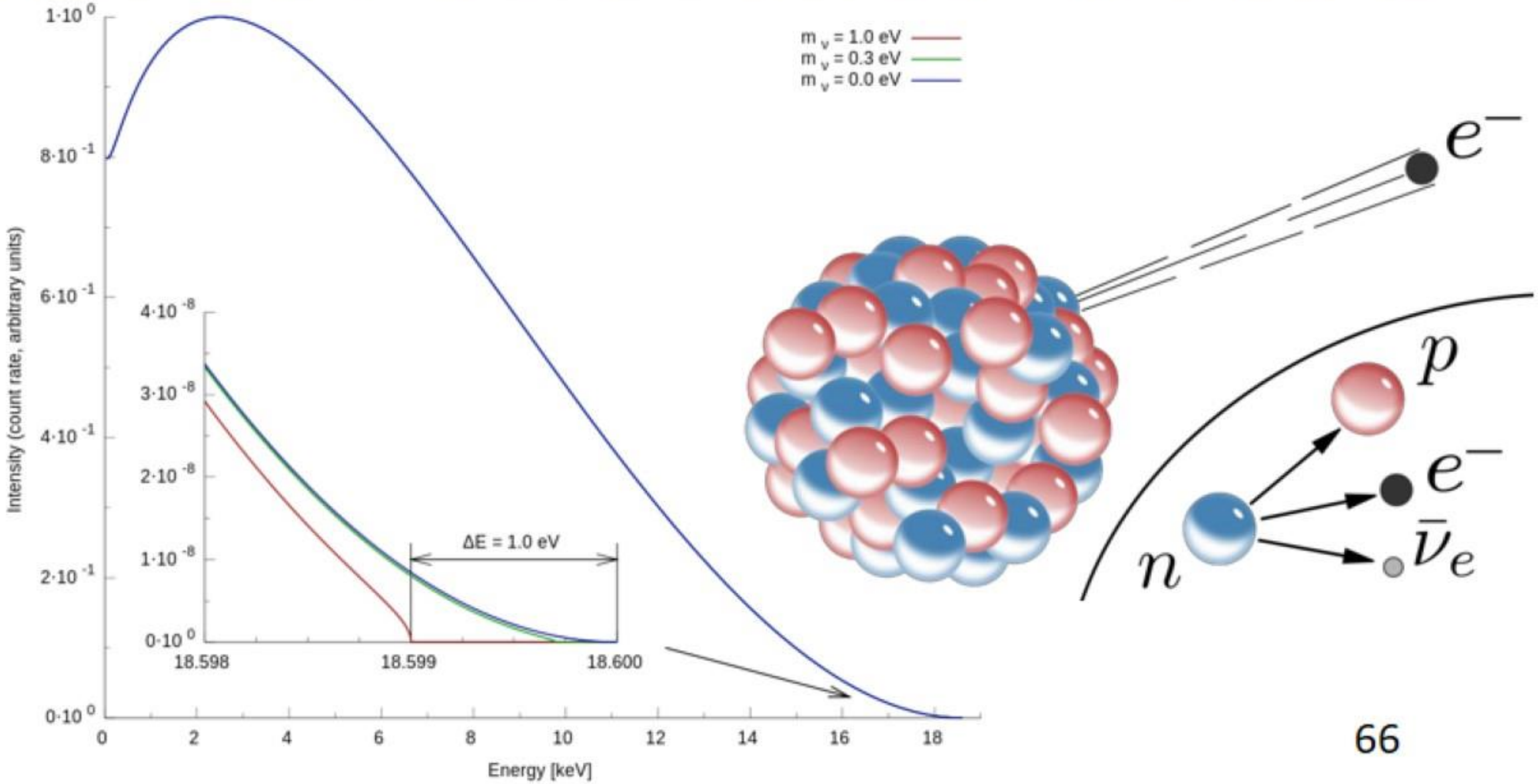
- For inverted hierarchy:

$$m_1 \geq \sqrt{|\Delta m^2_{32}| - \Delta m^2_{21}} = 0.0494 \pm 0.0007\,\mathrm{eV}$$

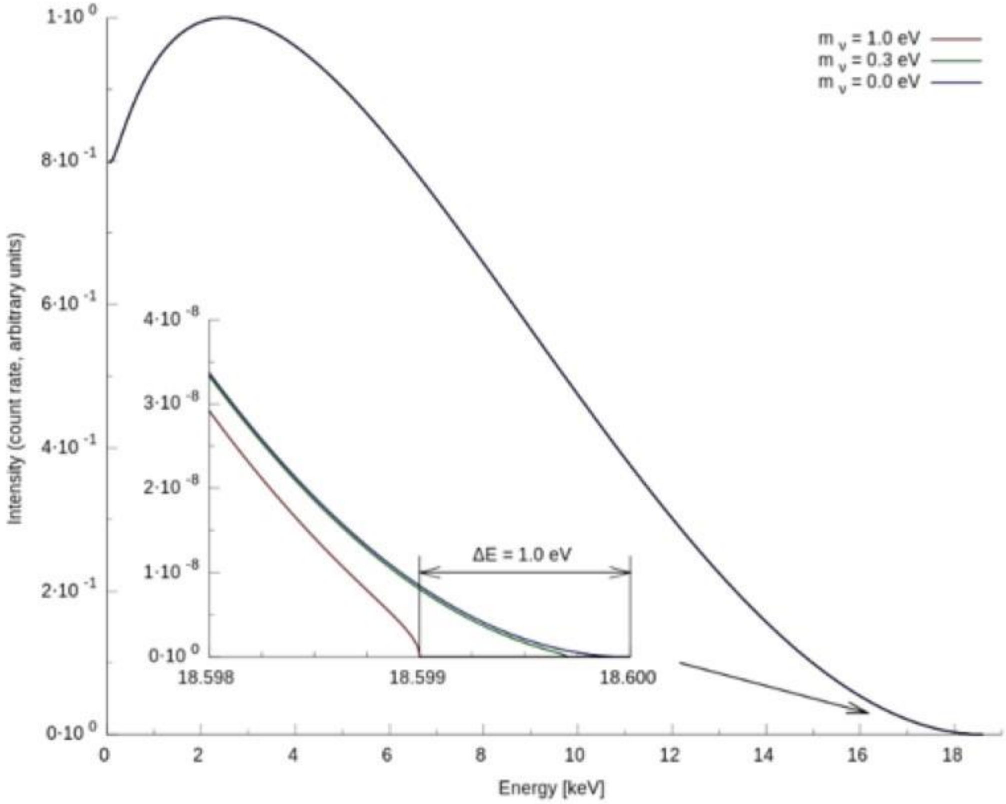
$$m_2 \geq \sqrt{|\Delta m^2_{32}|} = 0.0502 \pm 0.0007\,\mathrm{eV}$$

DIRECT MASS MEASUREMENTS

- Neutrino oscillations give us only mass differences.
- If we are to understand the puzzle of neutrino mass, we need to measure the absolute mass scale of neutrinos.
- The most promising way to do this is to precisely measure the end-point of the beta-decay spectrum.
  - Conservation of energy requires that the maximum energy the electron can carry is the difference in mass between the initial and final state nucleus **minus** the neutrino mass.



DIRECT MASS MEASUREMENTS



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- Example: tritium decay

$$^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^- + \overline{\nu}_j$$

- Q value: 18.6 keV; half-life: 12.3 y
- The masses of ^{3}H, ^{3}He and the electron are known precisely. Using conservation of energy and momentum, the mass of the antineutrino can be inferred.
- Kurie function:

$$K(T) \simeq \left[(Q_\beta - T)\sqrt{(Q_\beta - T)^2 - m_\beta^2}\right]^{\frac{1}{2}}$$

$$m_\beta = \left[\sum_{j=1}^{3} |U_{ej}|^2 m_j^2\right]^{\frac{1}{2}}$$

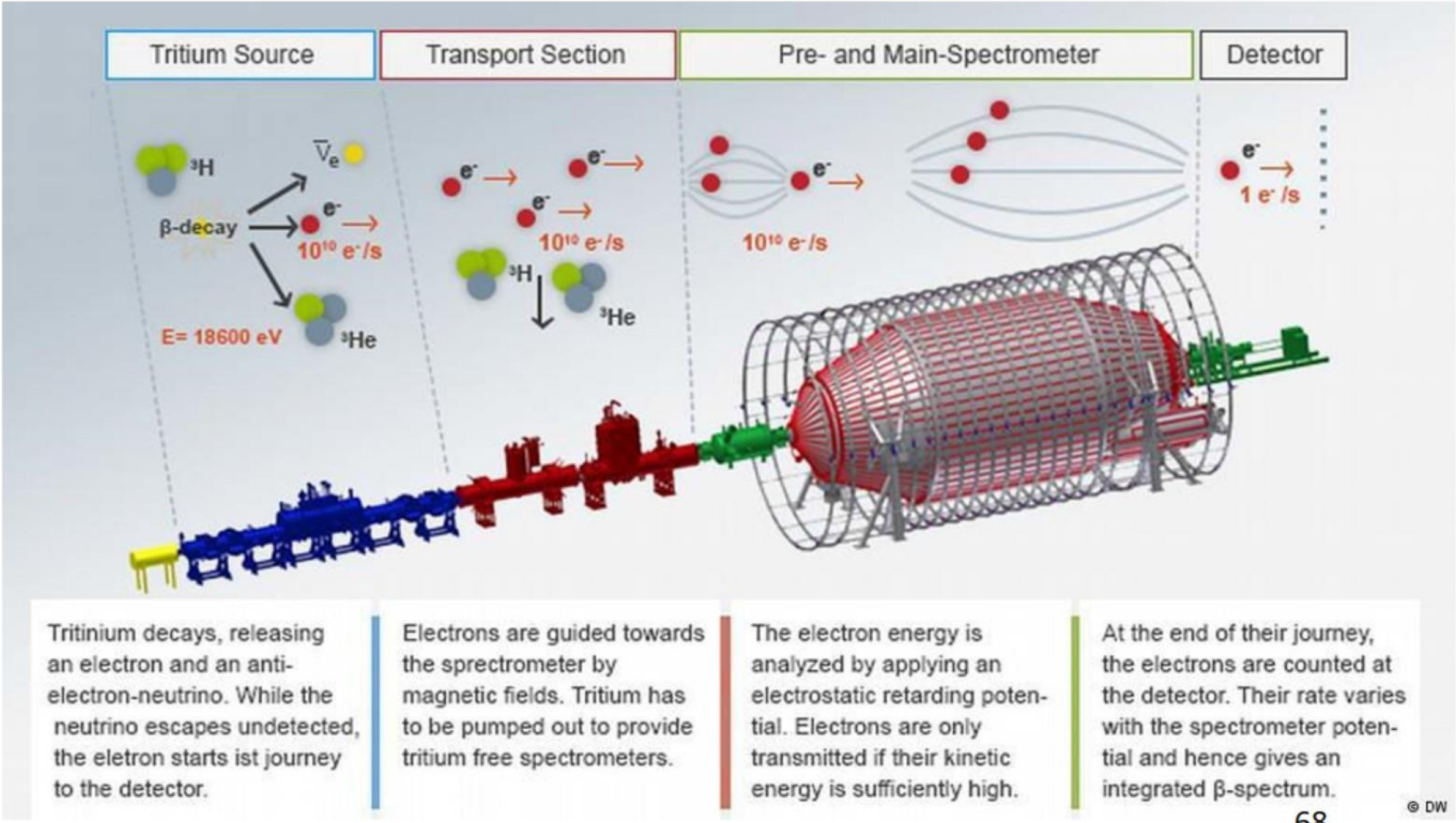
$$= \left[c_{12}^2 c_{13}^2 m_1^2 + s_{12}^2 c_{13}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$

$$m_\beta < 2.05\,\mathrm{eV} \quad (\mathrm{Troitsk})$$

$$m_\beta < 2.3\,\mathrm{eV} \quad (\mathrm{Mainz})$$

THE KATRIN EXPERIMENT

- An enormous spectrometer to look at the end point of the beta-decay of tritium.



Tritinium decays, releasing an electron and an anti-electron-neutrino. While the neutrino escapes undetected, the eletron starts ist journey to the detector.

Electrons are guided towards the sprectrometer by magnetic fields. Tritium has to be pumped out to provide tritium free spectrometers.

The electron energy is analyzed by applying an electrostatic retarding potential. Electrons are only transmitted if their kinetic energy is sufficiently high.

At the end of their journey, the electrons are counted at the detector. Their rate varies with the spectrometer potential and hence gives an integrated β-spectrum.

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© DW

Current upper bound: 2.2 eV
Katrin sensitivity: 0.2 eV
Cosmology bound: ~0.3 eV

Other kinematic limits

$$\pi^+ \to \mu^+ + \nu_\mu \qquad (m_{\nu_\mu}^{\rm eff})^2 = \textstyle\sum_{j=1}^{3} |U_{\mu j}|^2 m_j^2$$

$$\Rightarrow \quad m_{\nu_\mu}^{\rm eff} < 0.17\,\mathrm{MeV}\ (90\%\ \mathrm{C.L.})$$

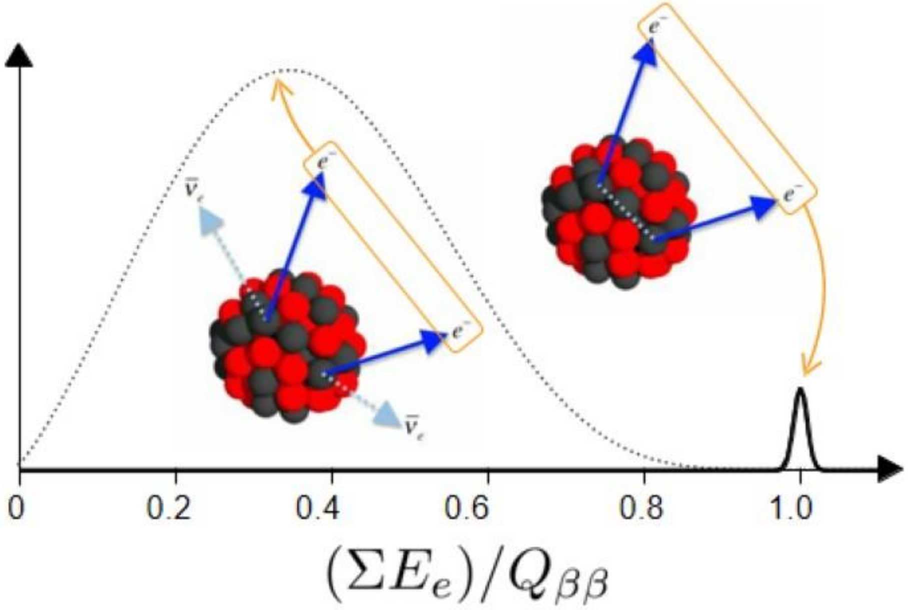
$$\tau^- \to 2\pi^-\pi^+\nu_\tau \qquad (m_{\nu_\tau}^{\rm eff})^2 = \textstyle\sum_{j=1}^{3} |U_{\tau j}|^2 m_j^2$$

$$3\pi^-2\pi^+(\pi^0)\nu_\tau$$

$$\Rightarrow \quad m_{\nu_\tau}^{\rm eff} < 18.2\,\mathrm{MeV}\ (95\%\ \mathrm{C.L.}).$$

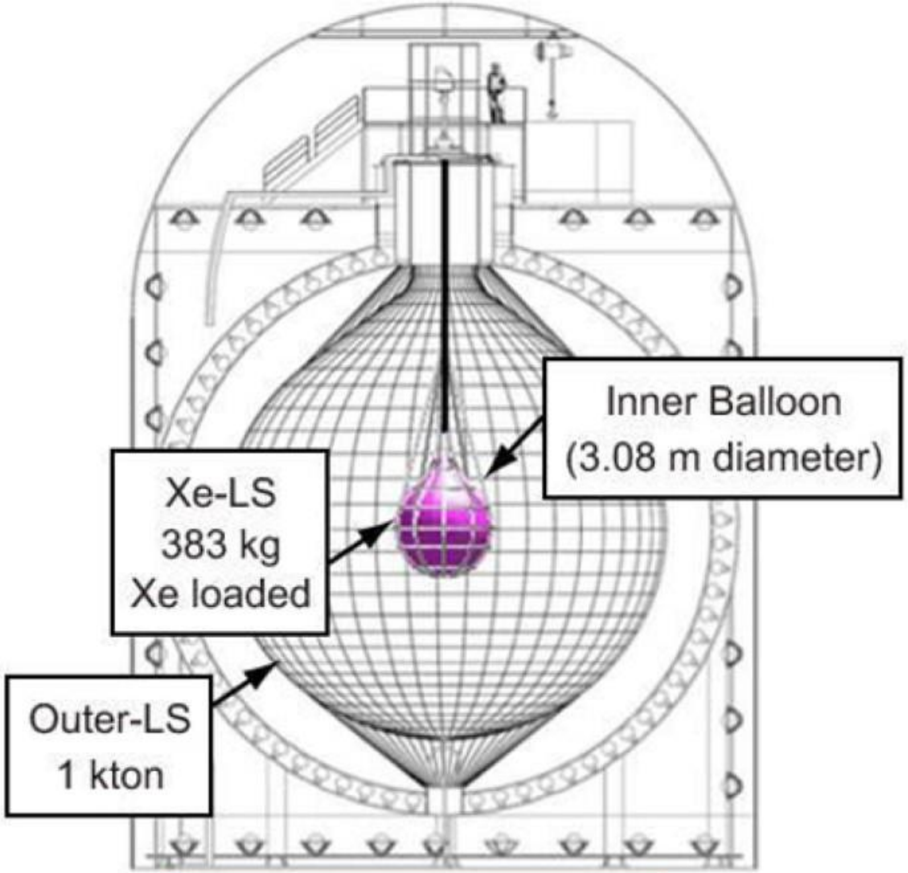
NEUTRINOLESS DOUBLE-BETA DECAY

- Double-beta decay is a rare process where two beta decays occur simultaneously in a nucleus where a single beta decay is energetically forbidden.
  - Typicall half-lives are on the order of 10^{20} years!
- If neutrinos are Majorana particles (and hence their own antiparticles) the two neutrinos usually emitted in such a process might annihilate each other: neutrinoless double-beta decay!
- Observing such a process would imply that neutrinos are Majorana particles, and it would also give the absolute mass scale of neutrinos, as the rate for the process depends on it.

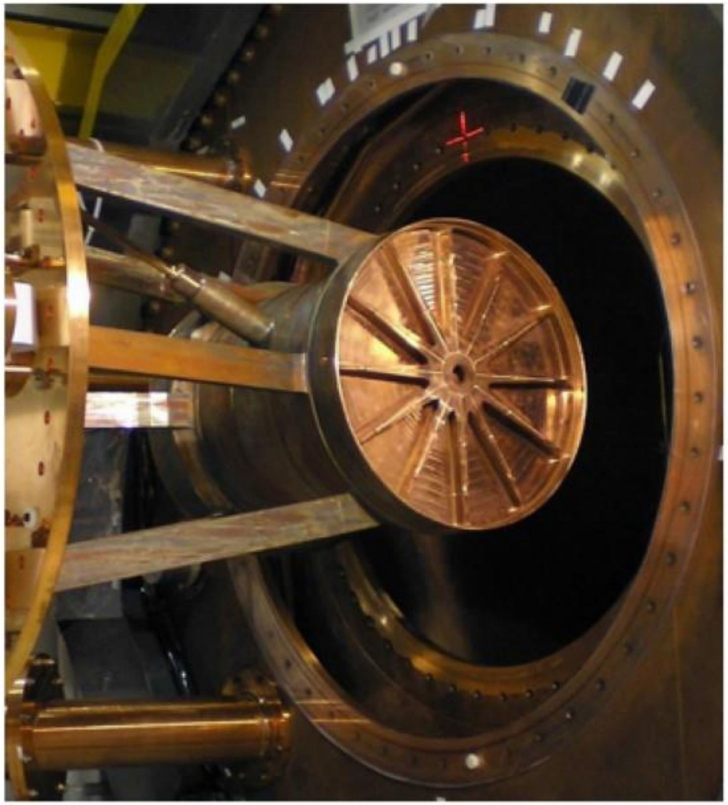


NEUTRINOLESS DOUBLE-BETA DECAY

- Current best limits on the existence of this process come from two experiments that use xenon-136 as their source.



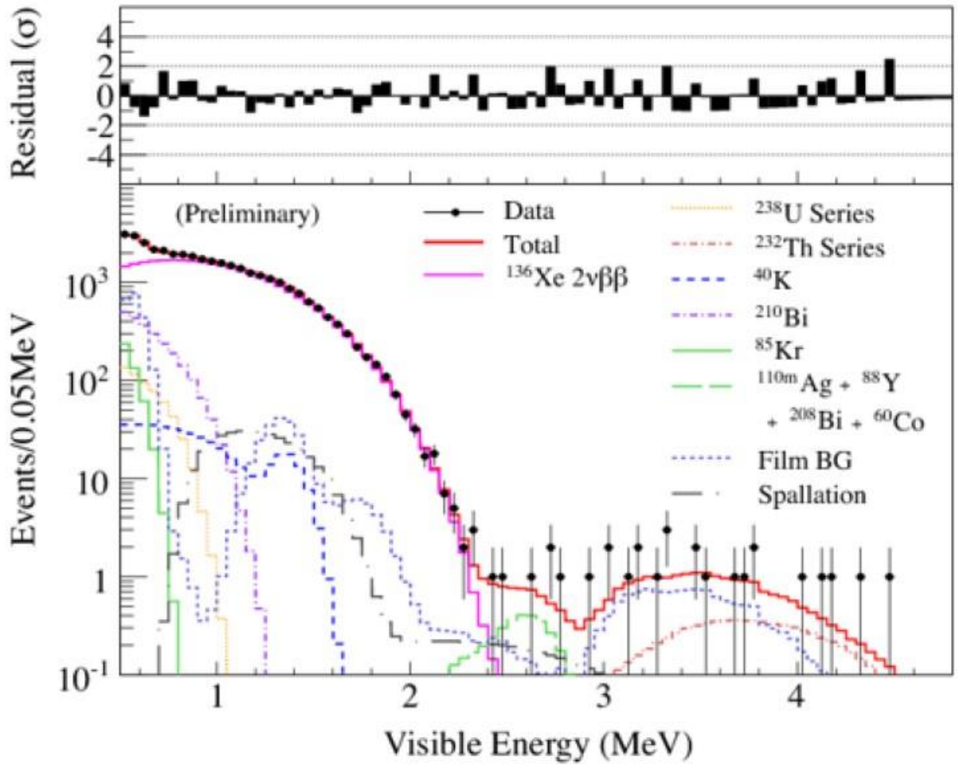
KamLAND Zen

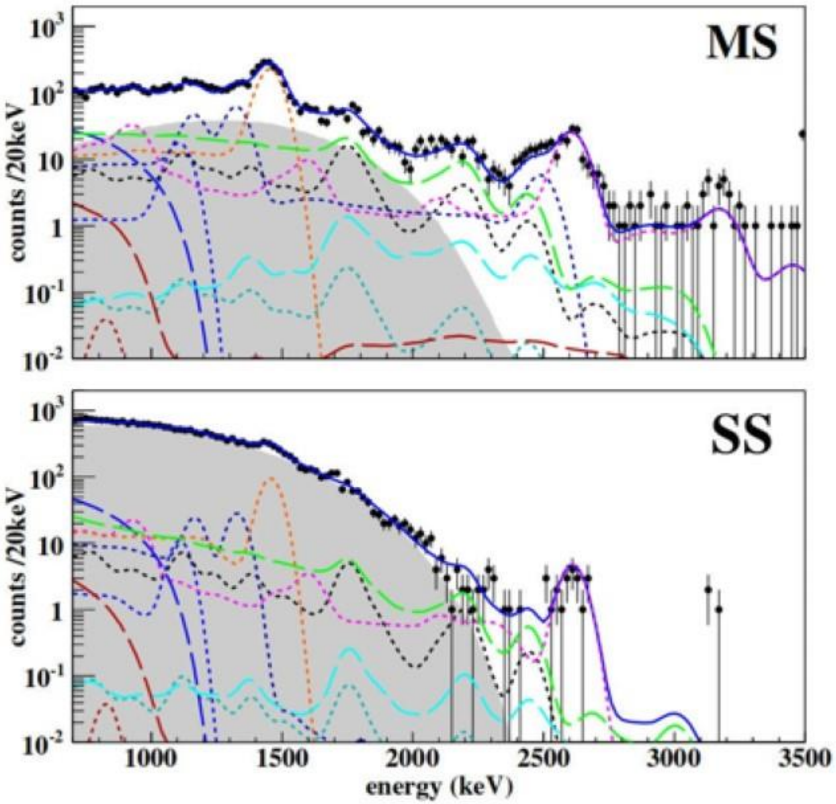


EXO

NEUTRINOLESS DOUBLE-BETA DECAY

- Current best limits on the existence of this process come from two experiments that use xenon-136 as their source.

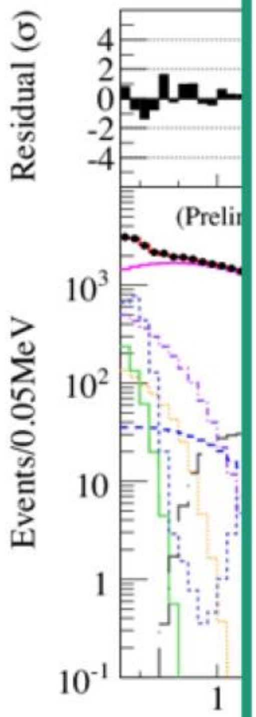




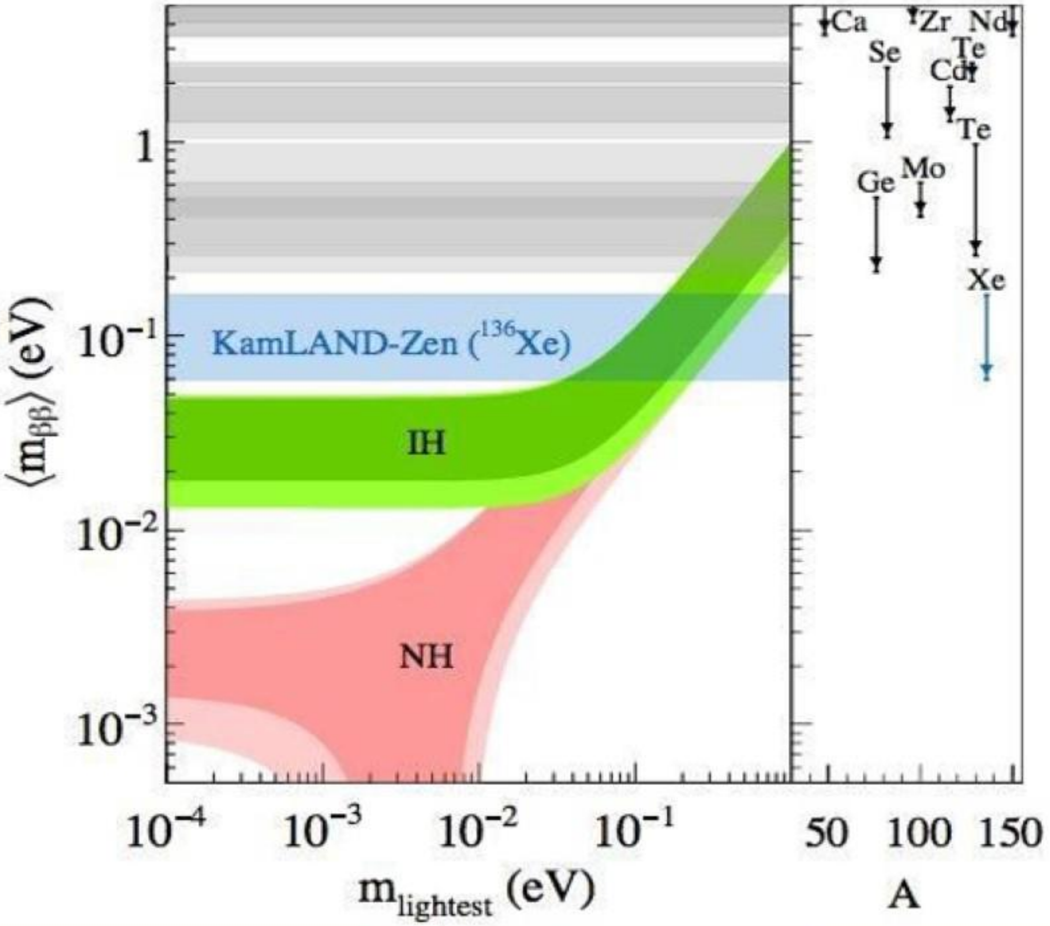
KamLAND Zen

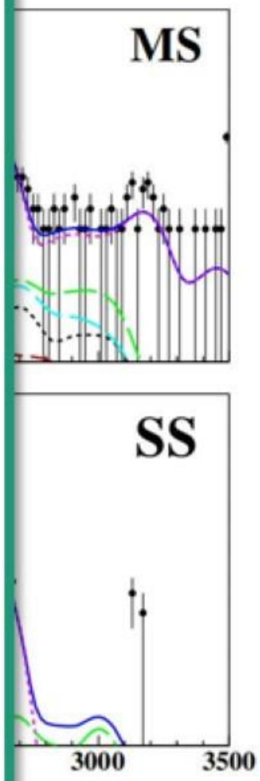
EXO

NEUTRINOLESS DOUBLE-BETA DECAY



How does it fit in?





KamLAND Zen

EXO

Many experiments...

… with different isotopes.

- GERDA, MAJORANA: germanium solid-state detectors enriched with ^{76}Ge.
- CUORE: bolometer with ^{130}Te crystals.
- SNO+: ^{130}Te dissolved in liquid scintillator in the SNO detector.
- EXO: TPC with liquid ^{136}Xe.
- NEXT: TPC with high-pressure gaseous ^{136}Xe.
- KamLAND-Zen: a balloon filled with liquid scintillator doped with ^{136}Xe in the KamLAND detector.
- SuperNEMO: multiple isotopes in a calo-tracker detector.

- NO SIGNAL* YET

Seesaw mechanism

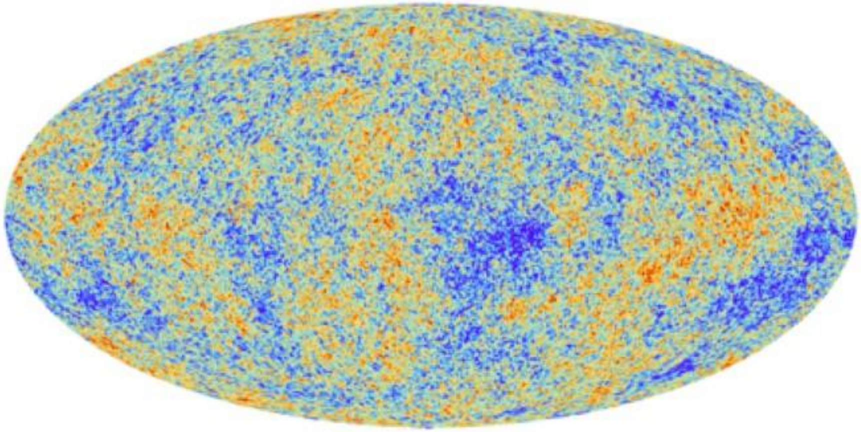
- Neutrinos can have both Dirac and Majorana masses.
- The active neutrinos we know seem to be so light because they would be being “lifted up” by heavy sterile neutrinos.
  - The light neutrinos would be mostly left-handed.
  - The heavy neutrinos would be mostly right handed, so their interactions are suppressed.

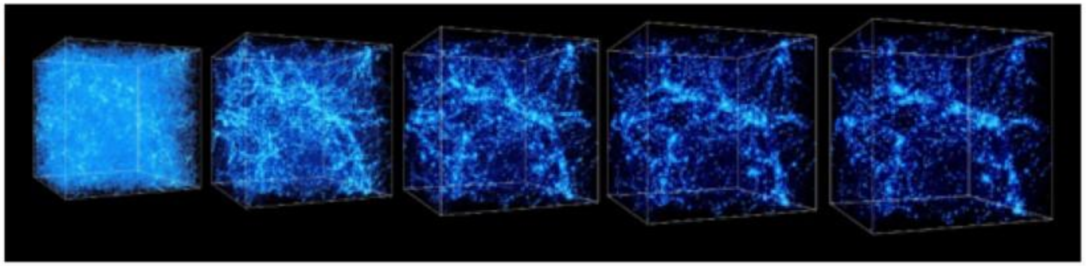
$$m_{\text{light}} \simeq \frac{(M_{\mathrm{D}}^{\nu})^2}{M_{\mathrm{M}}^{\nu}}$$

$$m_{\text{heavy}} \simeq M_{\mathrm{M}}^{\nu}$$

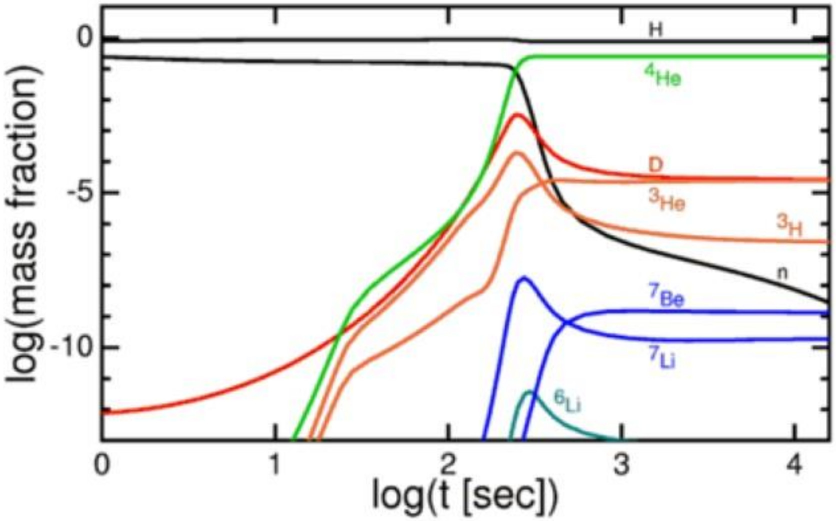
Cosmology bound

- The masses of the neutrinos have an effect on cosmology observables:
  - Cosmic microwave background.
  - Large-scale structure of the Universe.
  - Element abundances from Big Bang Nucleosynthesis.





- From Cosmology, the sum of the masses of the neutrinos is < 0.2 eV.
  - Model dependent fit.
  - Depends on datasets used.



- Cosmological data is also sensitive to the number of "neutrinos".
  - $N_{eff} = 3.046$