Particle Physics: Neutrinos – part II

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Columbia University Science Honors Program

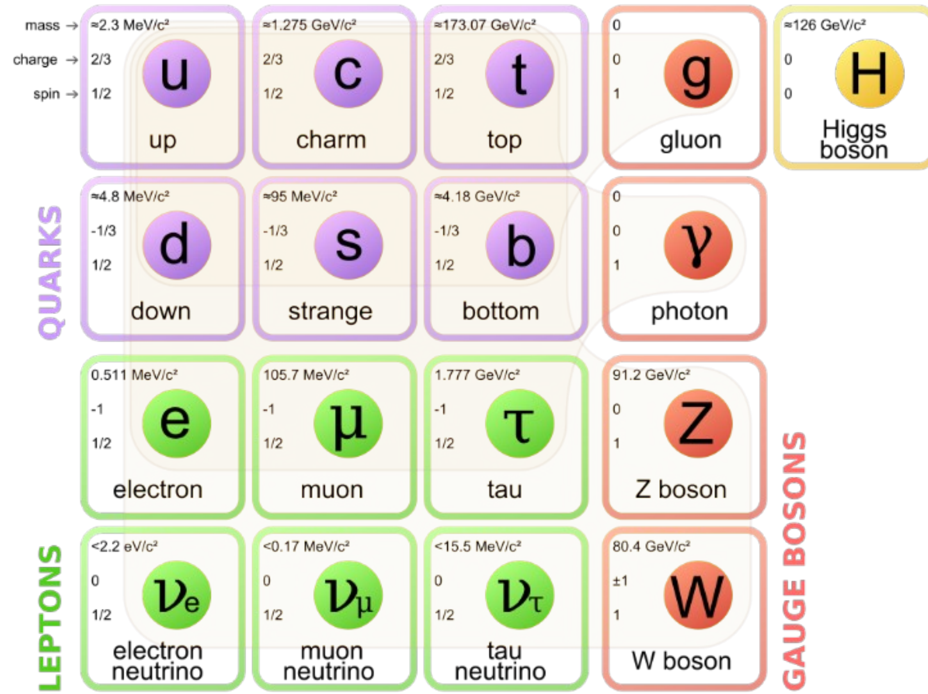
COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

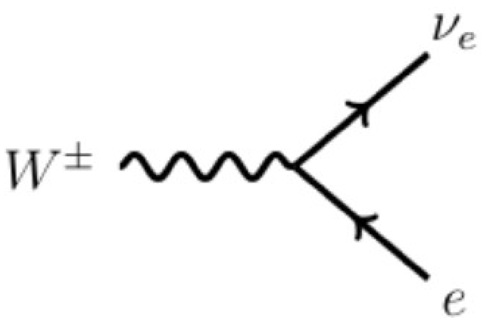
NEVIS LABORATORIES

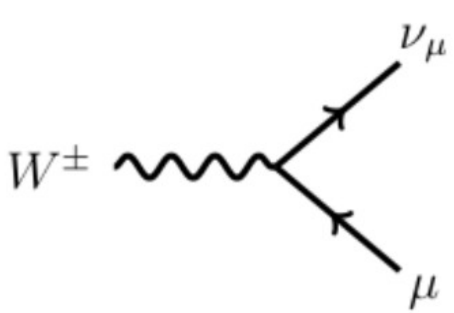
3 evidences for 3 neutrinos

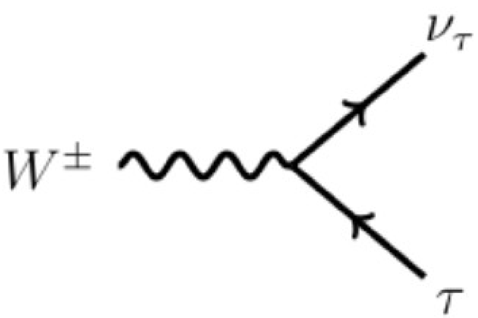
3 neutrinos: 3 charged leptons

- 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.**

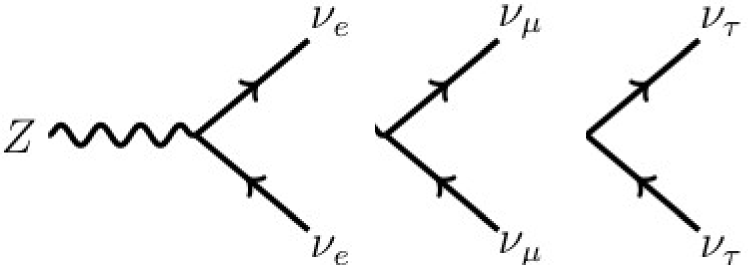








3 neutrinos: the Z boson width



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

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

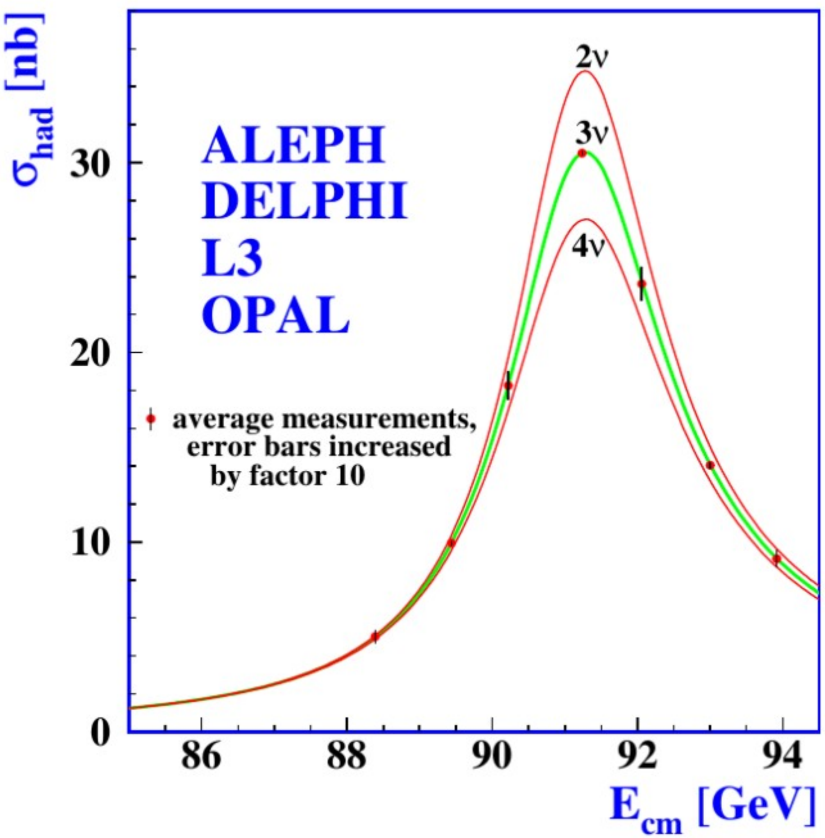
- This width is proportional to the number of disintegration modes and their frequency.
- The width of the Z boson is ~ 2.5 GeV and ~ 20% of the times the Z decays into neutrinos (invisible width).
- The 4 detectors of LEP (predecessor of the LHC at CERN) measured this width, which is related to the number of neutrinos*.

N_ν = 2.9840 ± 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

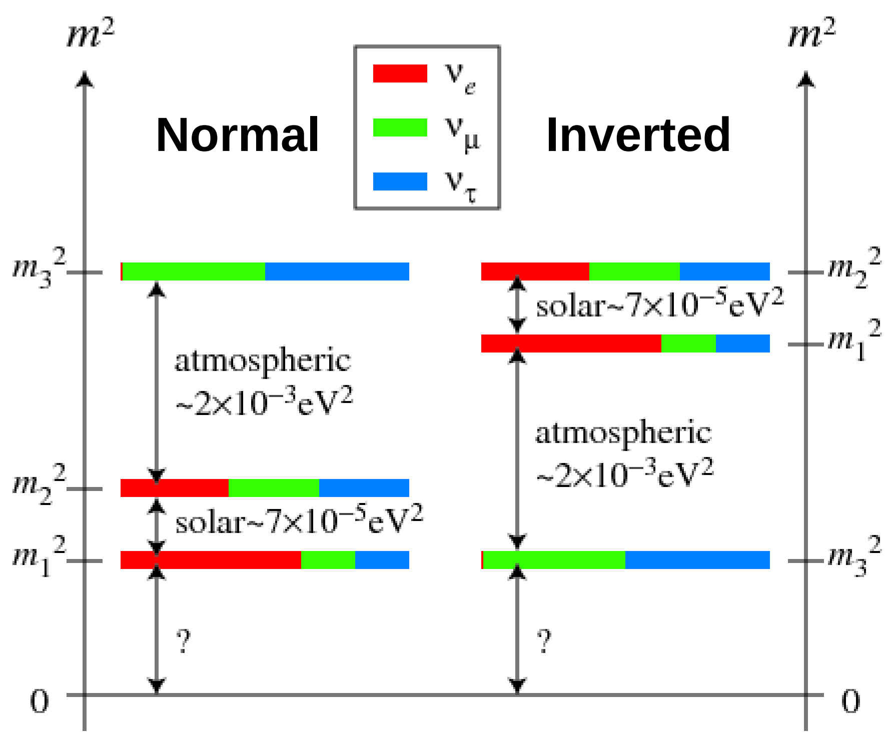
3 neutrinos: mass hierarchy

- 2 squared-mass differences → **3 neutrinos.**

PMNS matrix: U

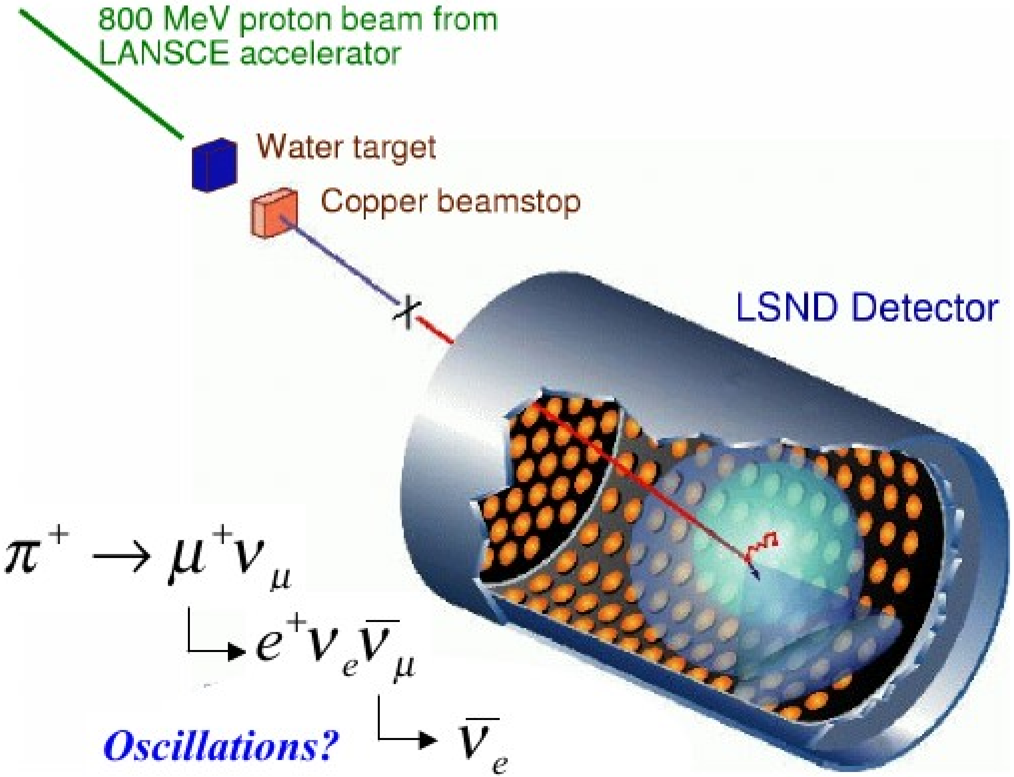
$$c_{ij} = \cos\theta_{ij},\ s_{ij} = \sin\theta_{ij}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13} e^{-i\delta} \\ & 1 & \\ -s_{13} e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \begin{matrix} \to m_1 \\ \to m_2 \\ \to m_3 \end{matrix}$$

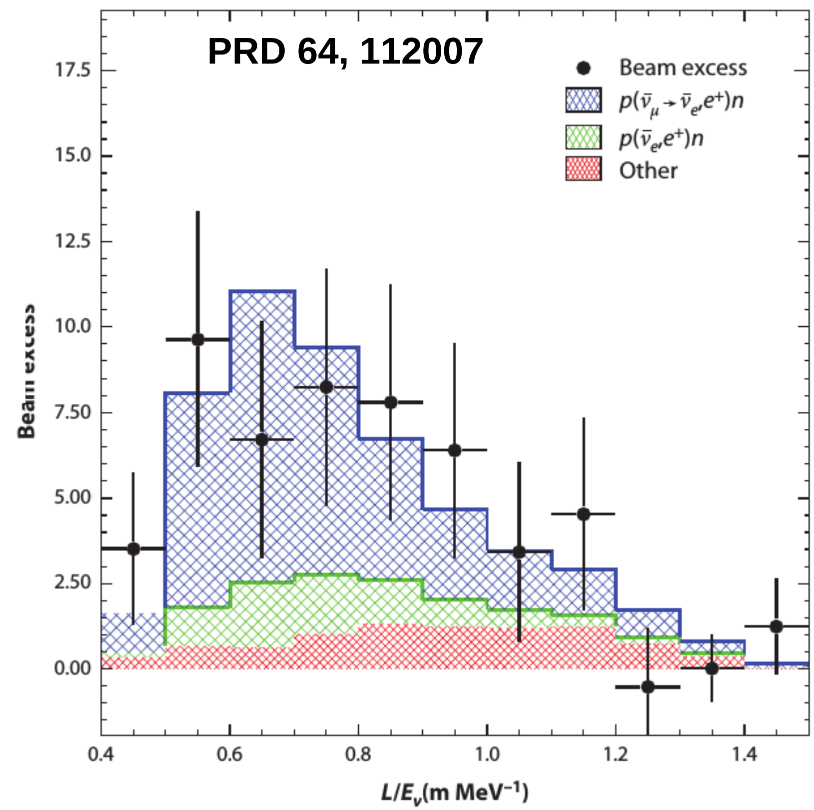


End of story?

LSND anomaly



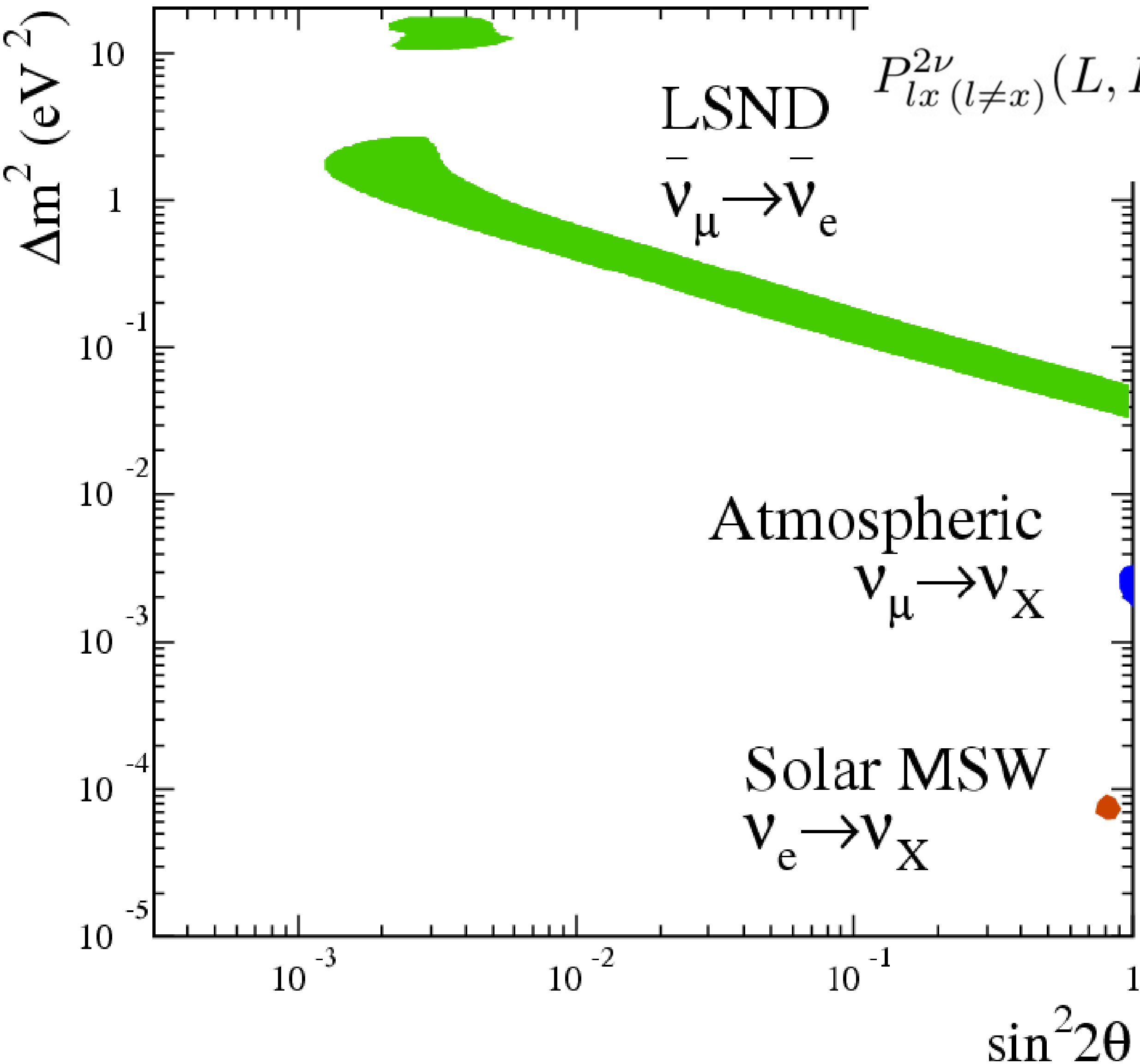
Excess of 87.9 ± 22.4 ± 6.0 events.



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

LSND anomaly

Oscillation probability: (0.264 ± 0.067 ± 0.045)%



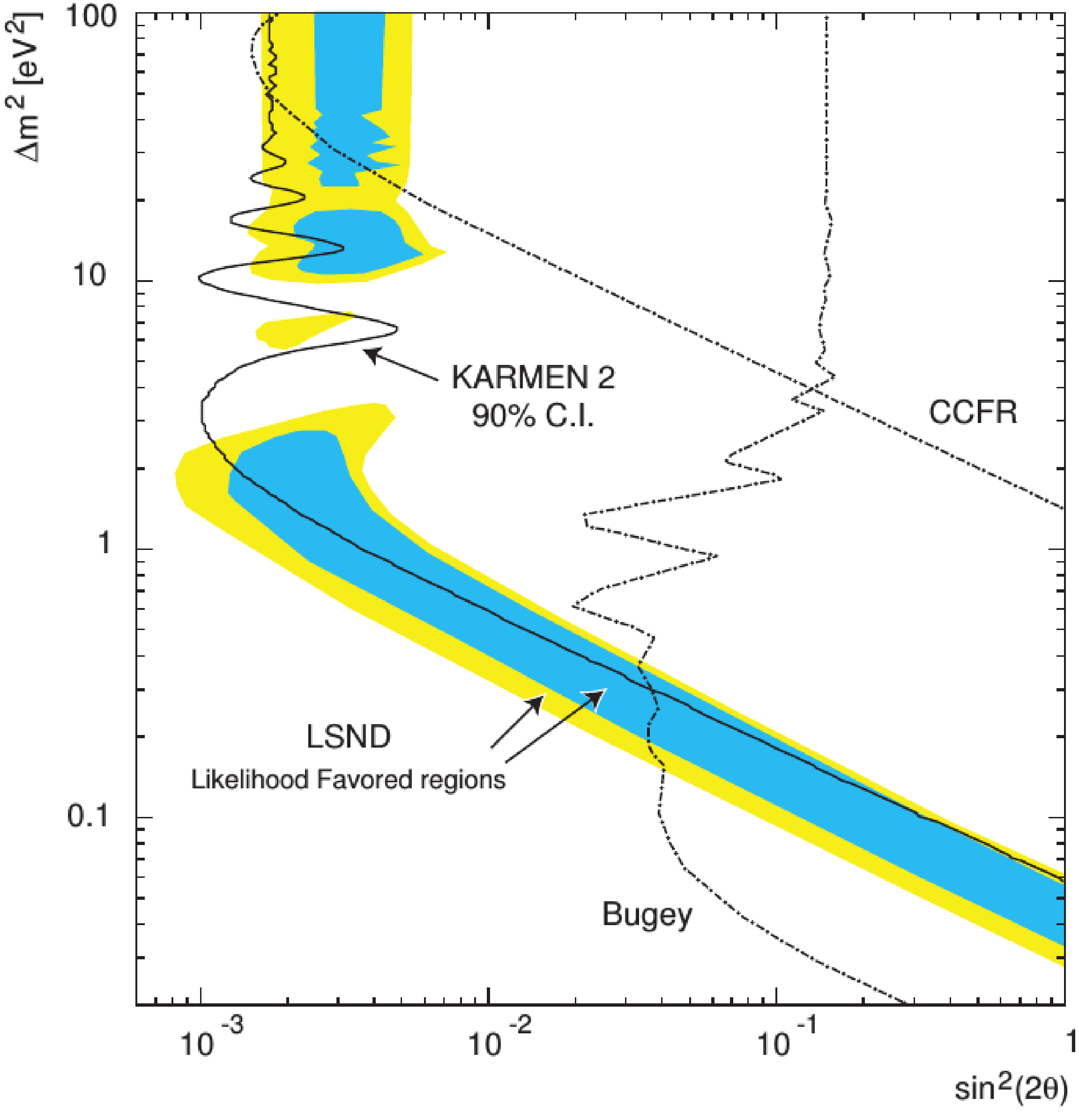
$$P^{2\nu}_{lx\,(l\neq x)}(L,E) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Cannot be explained with just 3 neutrinos!

Difference between squared masses 3 and 2, 1

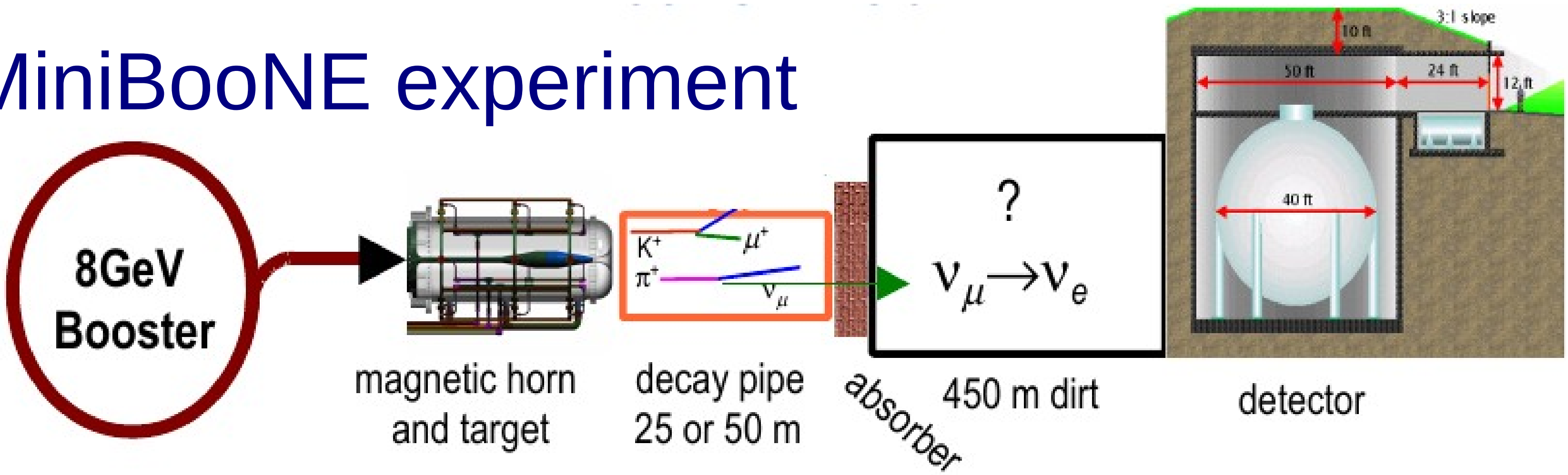
Difference between squared masses 2 and 1

LSND anomaly

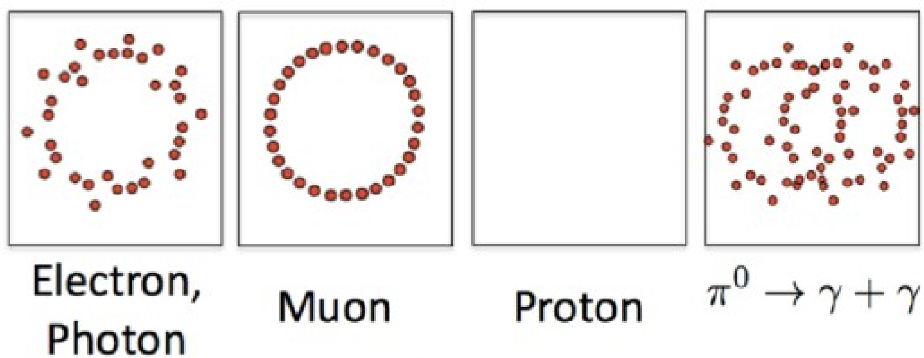


A big portion of the allowed region is excluded by the lack of oscillation signal in other experiments, but it cannot be ruled out completely

MiniBooNE experiment



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



- Different ene me oscillation region.

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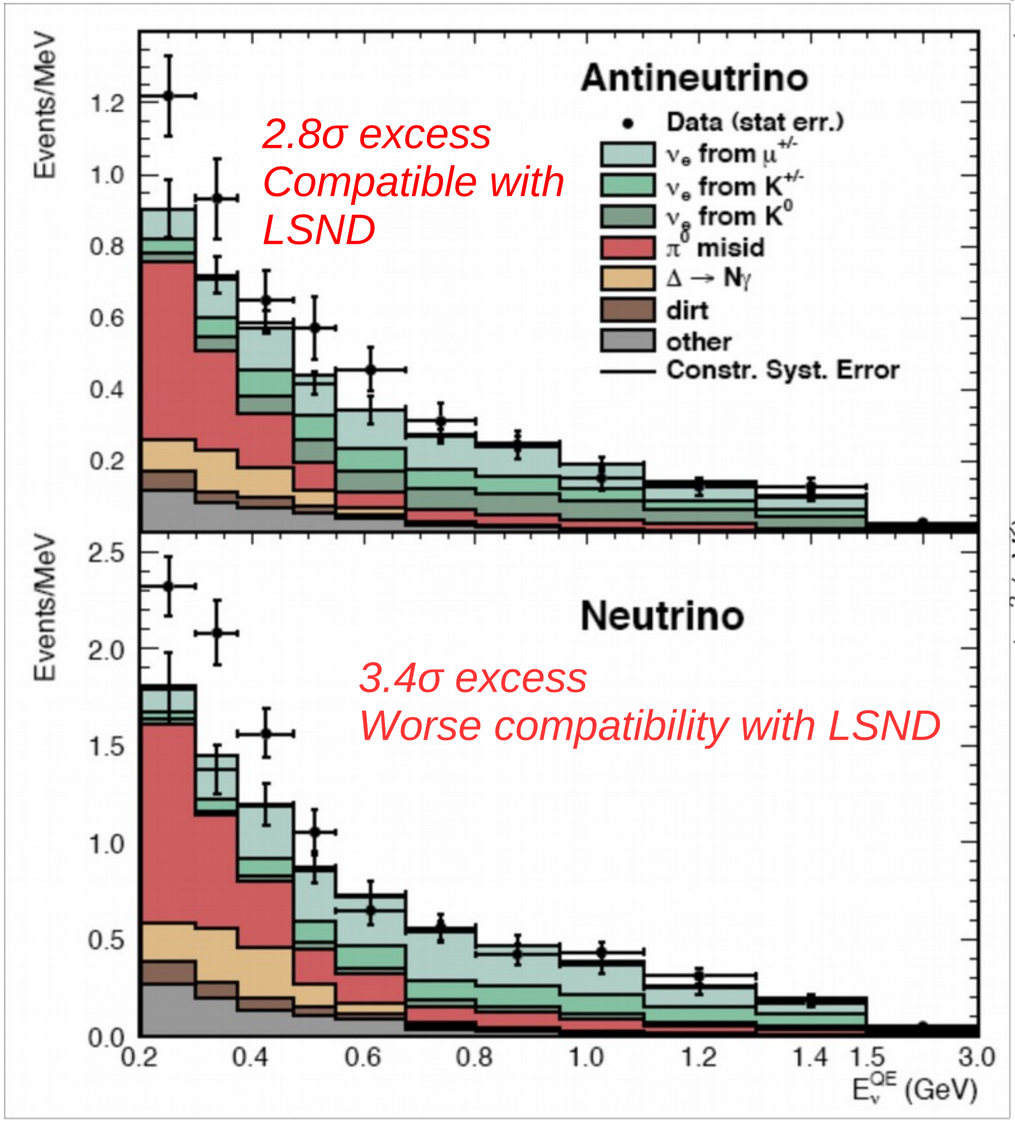
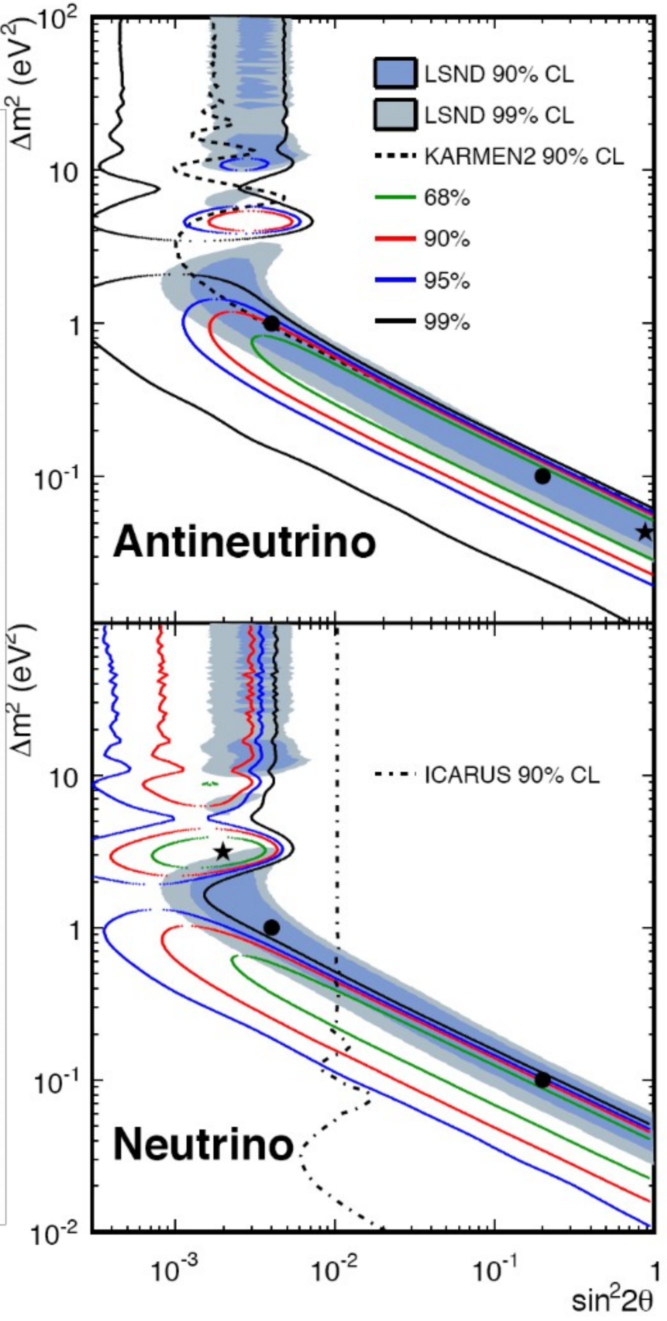
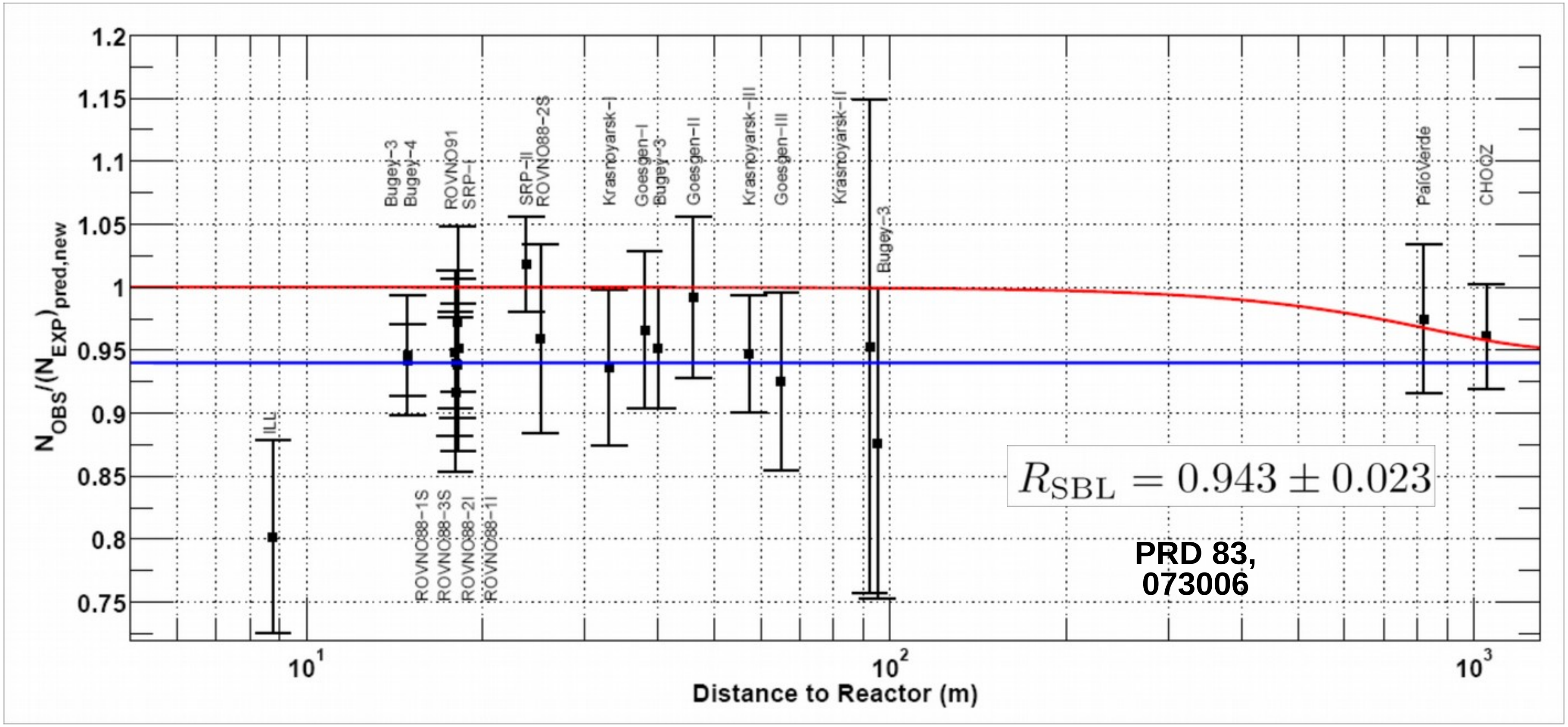
MiniBooNE anomaly





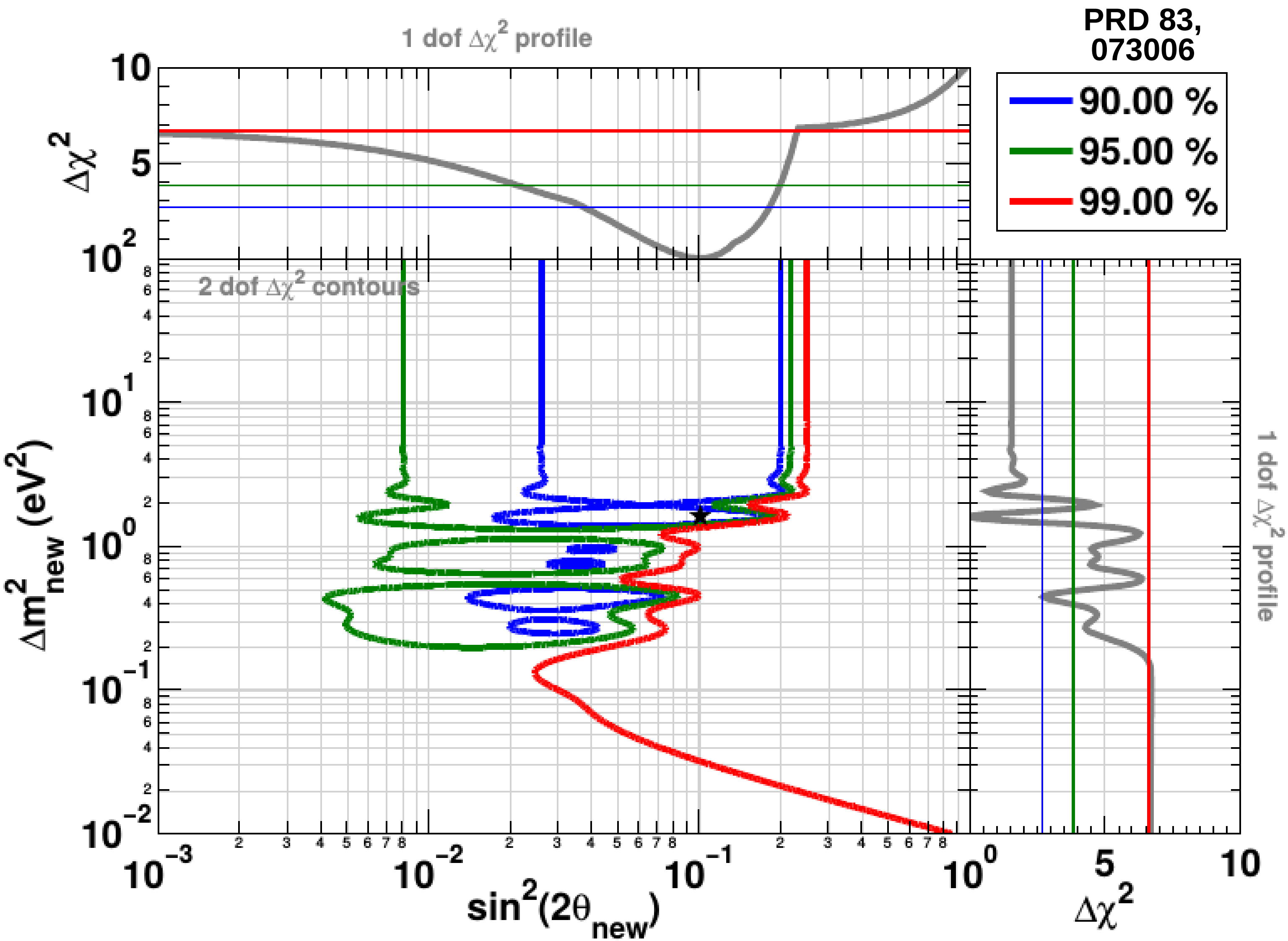
Reactor anomaly



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

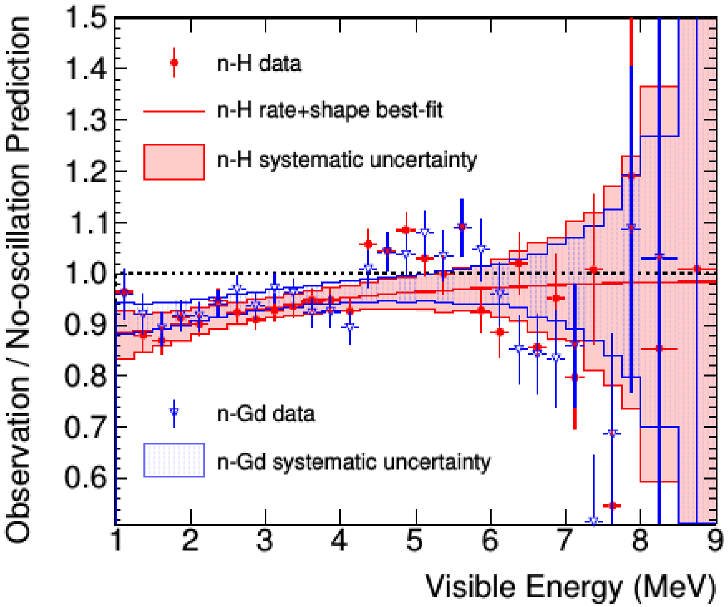
- Can be interpreted as the result of neutrino oscillation driven by a $\Delta m^2 \gtrsim 1\ eV^2$

Reactor anomaly



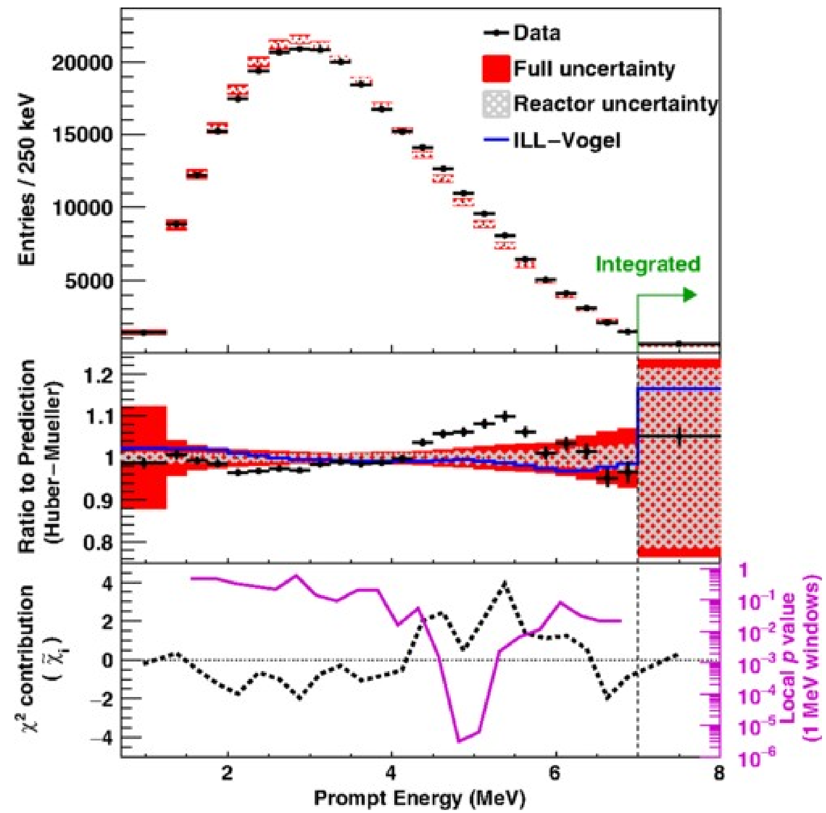
Reactor anomaly: spectrum distortion in 3 experiments

Double Chooz (JHEP01 (2016) 163)

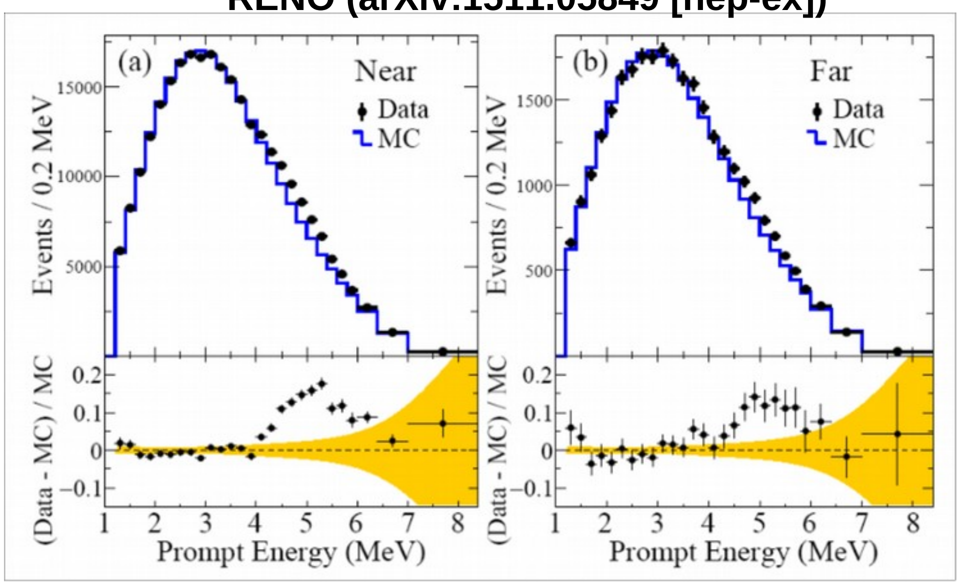


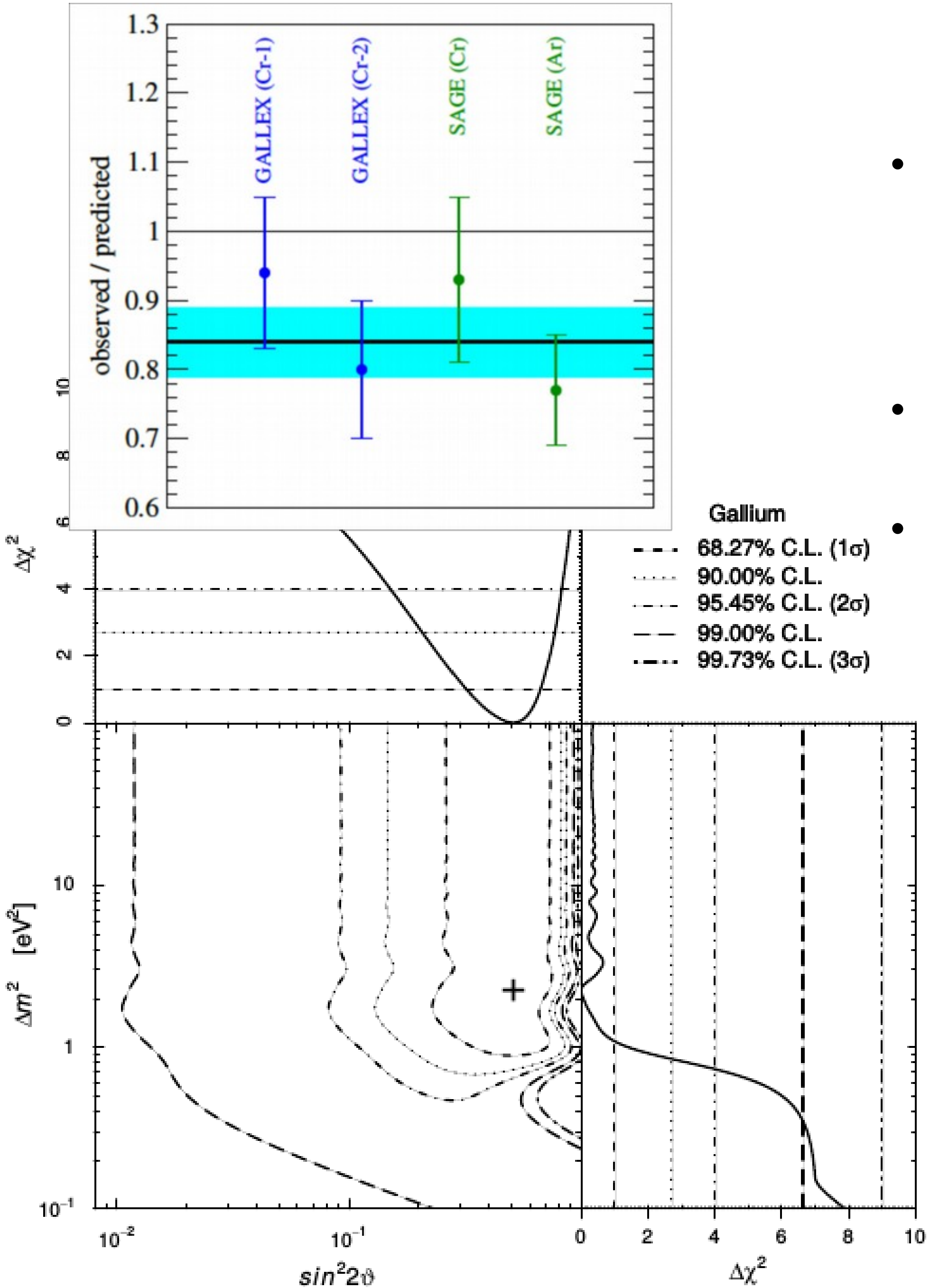
Alternative: predicted reactor flux is wrong.

Daya Bay (PRL 116, 061801)



RENO (arXiv:1511.05849 [hep-ex])





Gallium anomaly

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

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

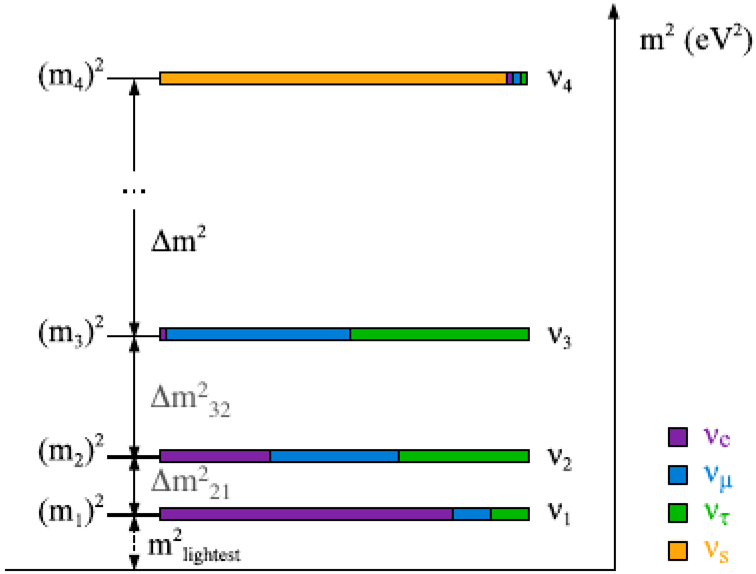
- $R_{Ga} = 0.86 \pm 0.05$

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

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

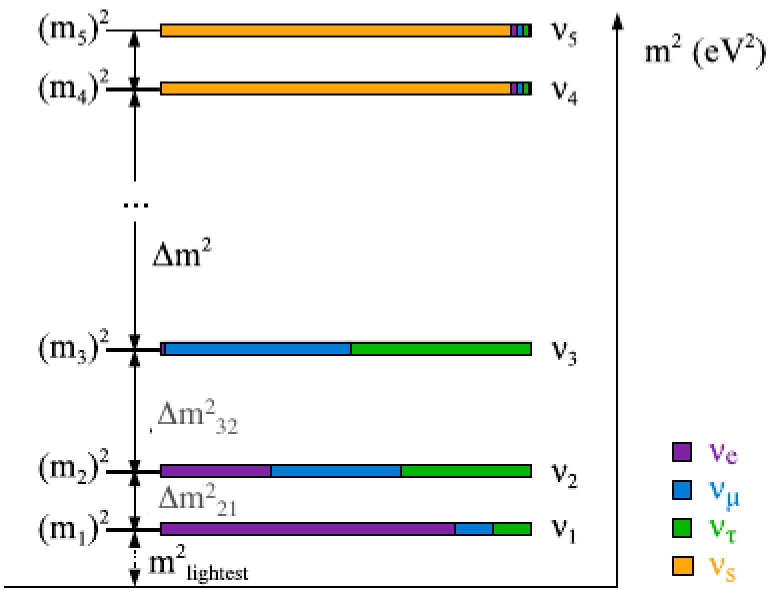
- Can be interpreted as the result of neutrino oscillation driven by a $\Delta m^2 \gtrsim 1$ eV^2

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



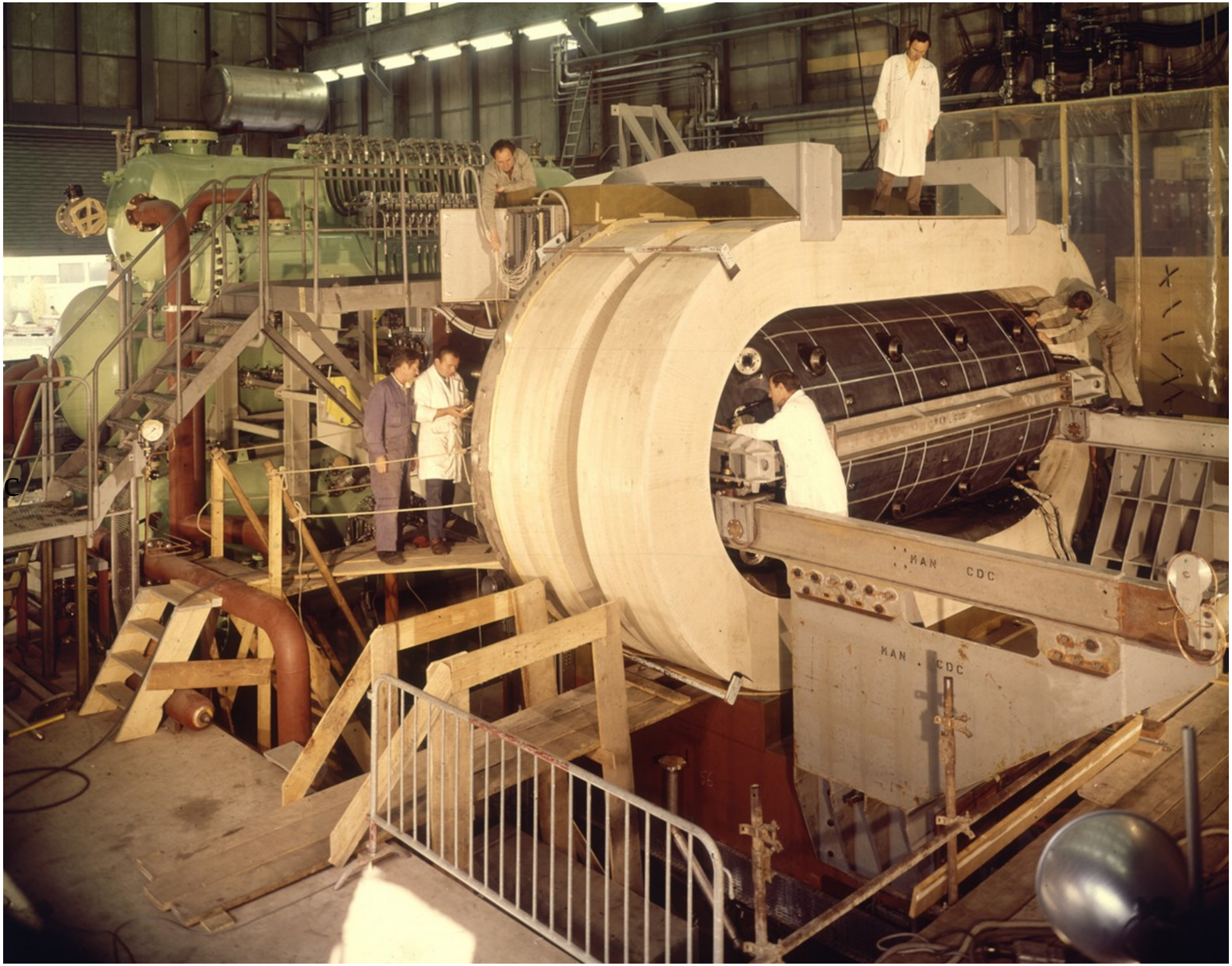
3 + 2

- 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.

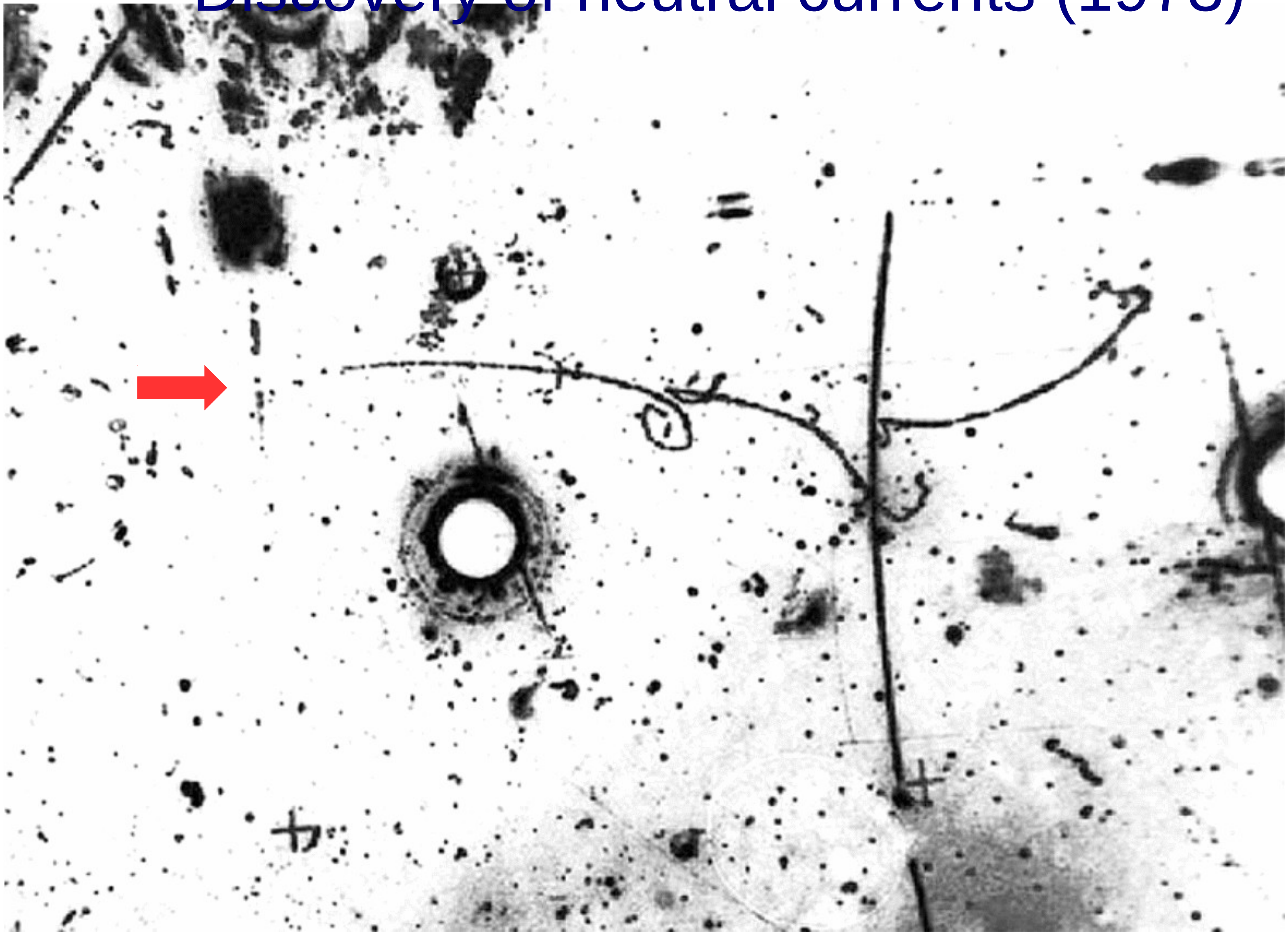
3 + 3 does not improve the situation.

The Short Baseline Neutrino Program at Fermilab

Bubble chamber: Gargamelle (1970 - 1979)

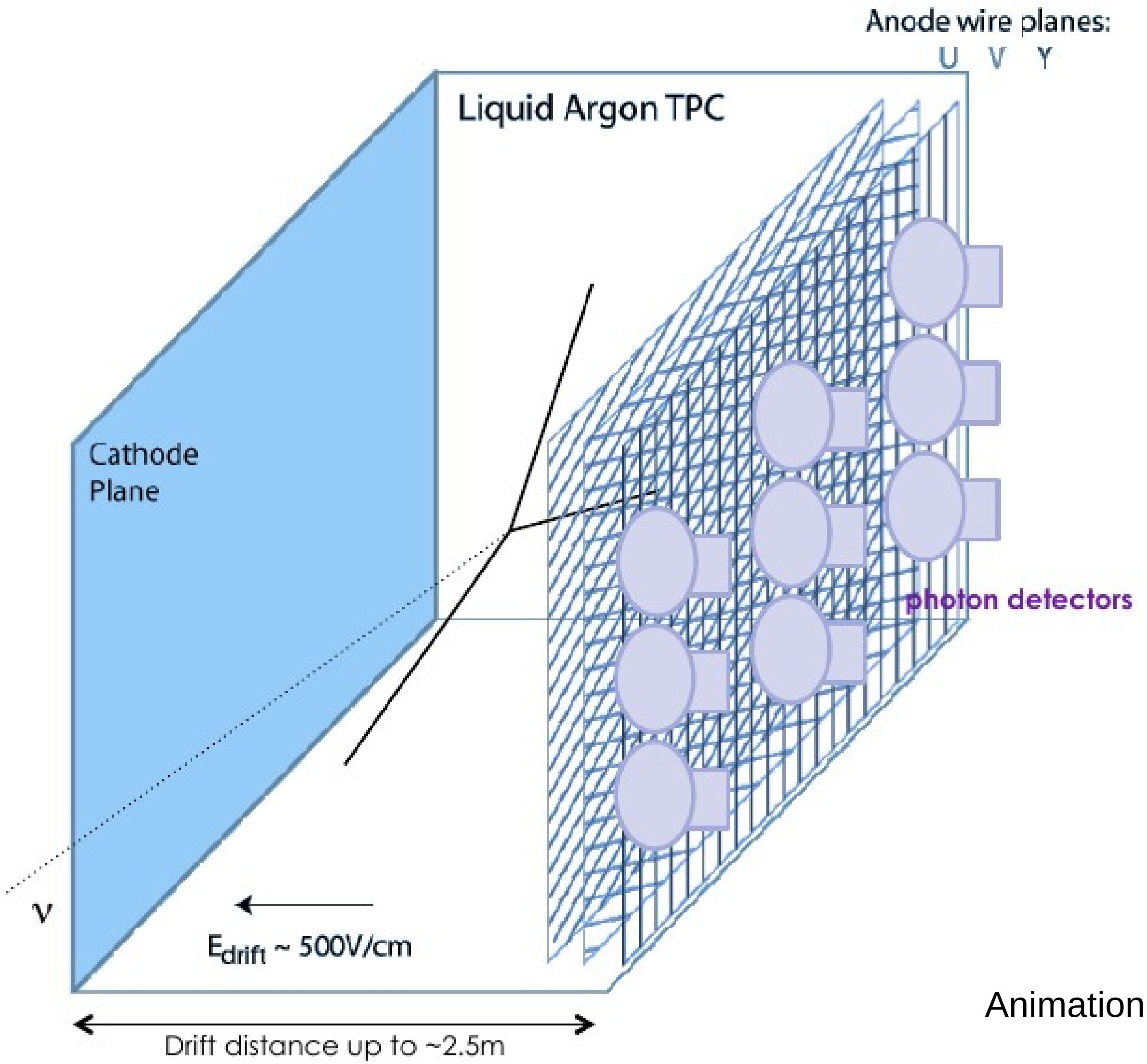


Discovery of neutral currents (1973)



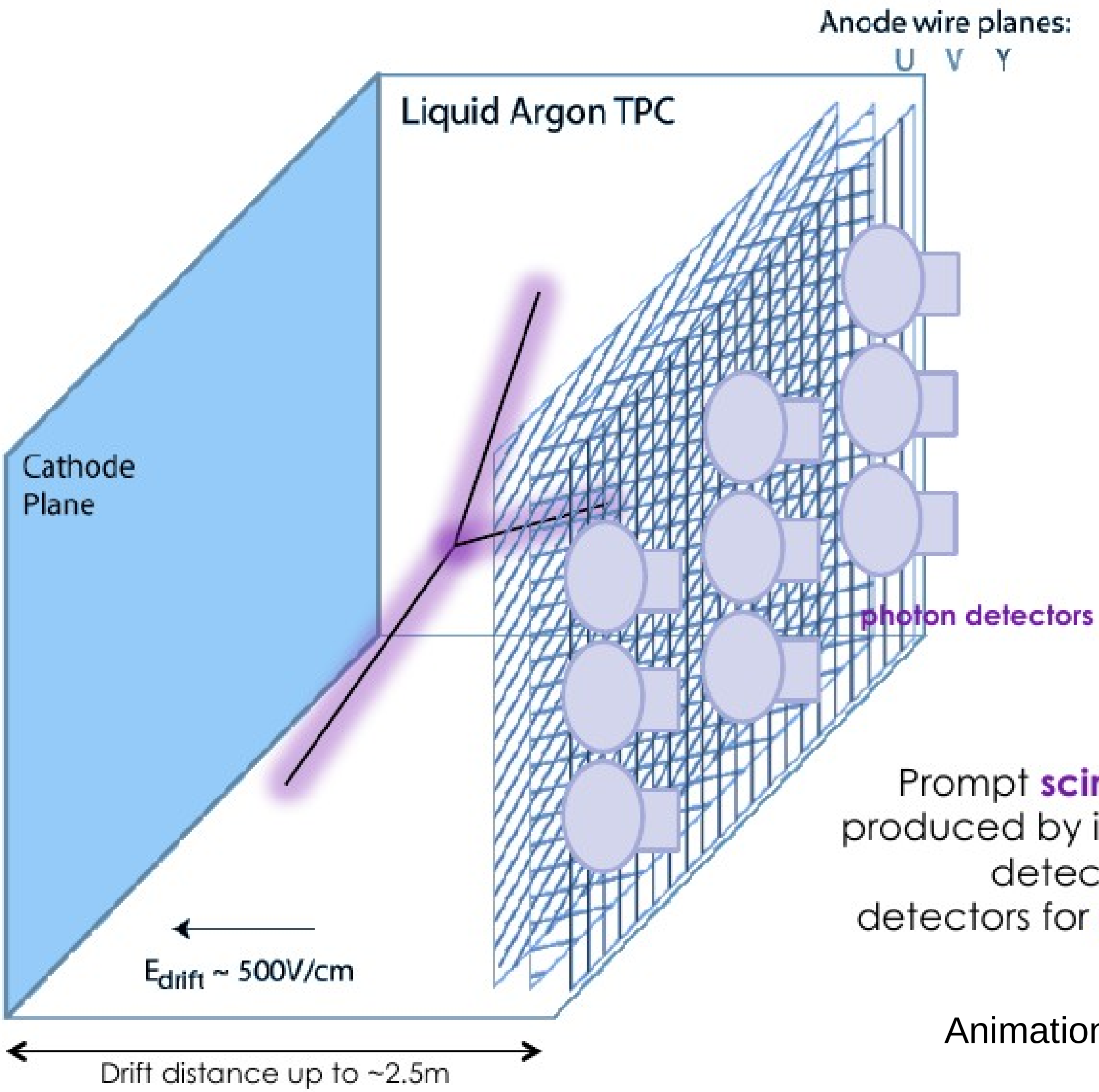
Liquid argon time projection chamber

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

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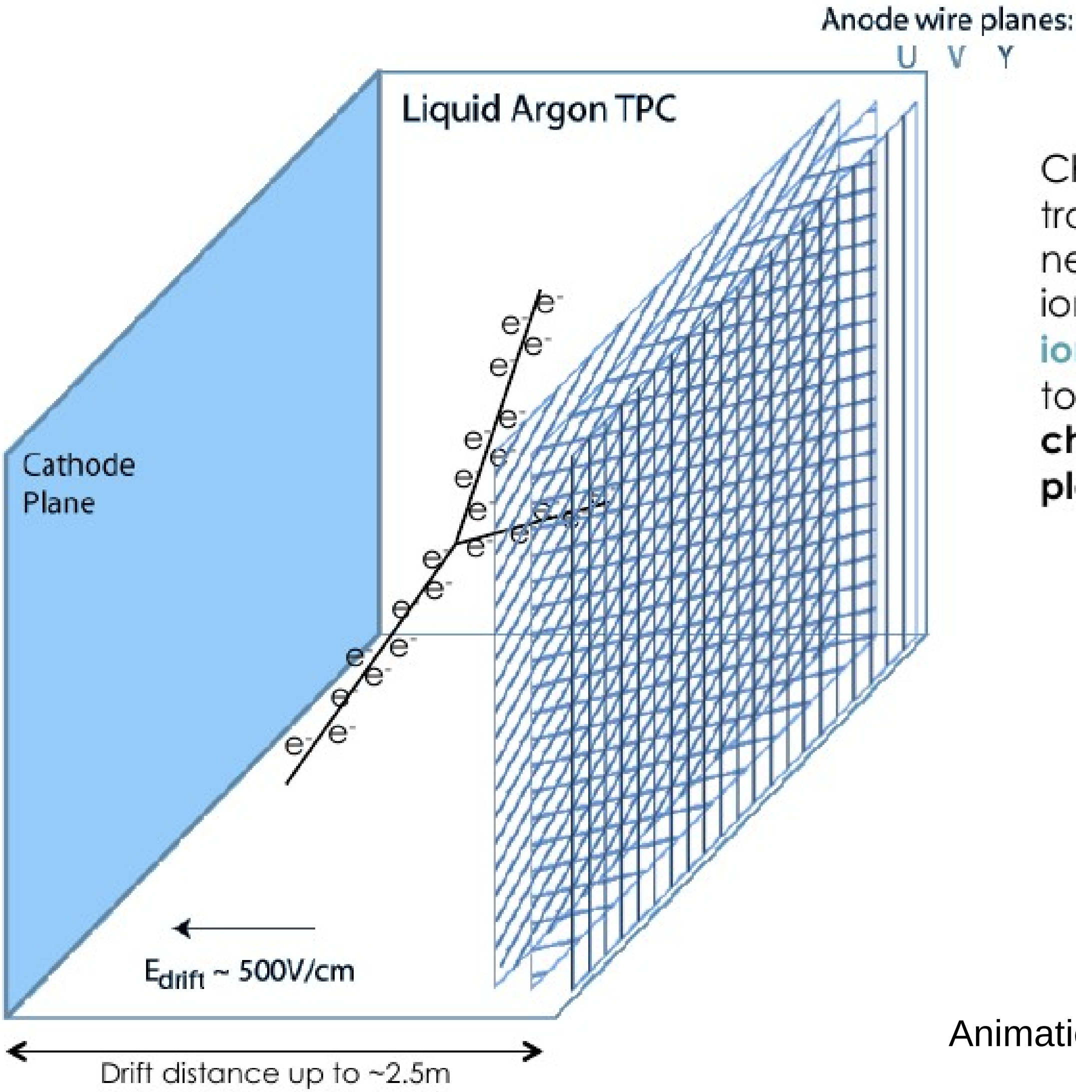
How a LArTPC works:



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

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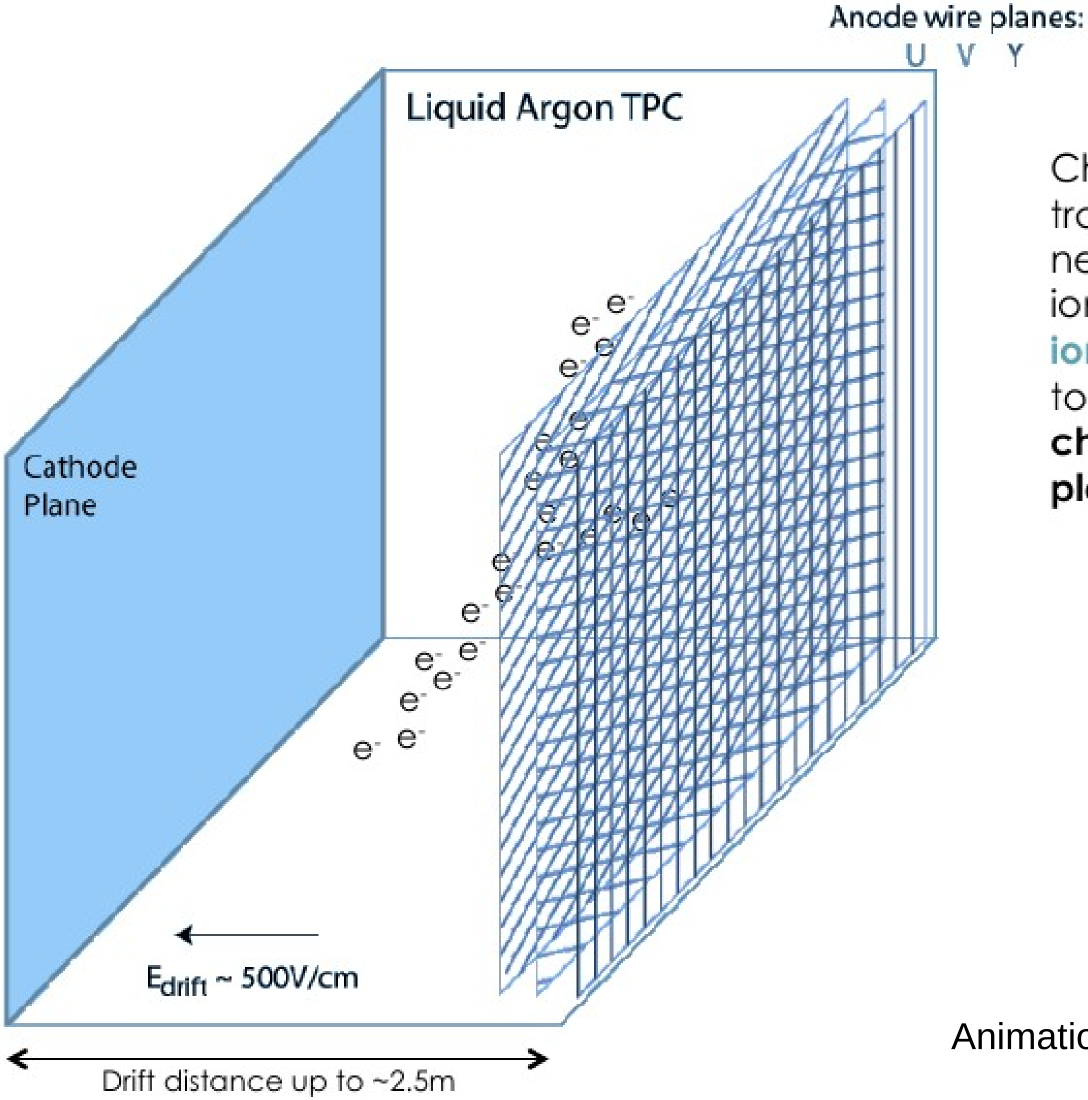

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Animation by Georgia Karagiorgi

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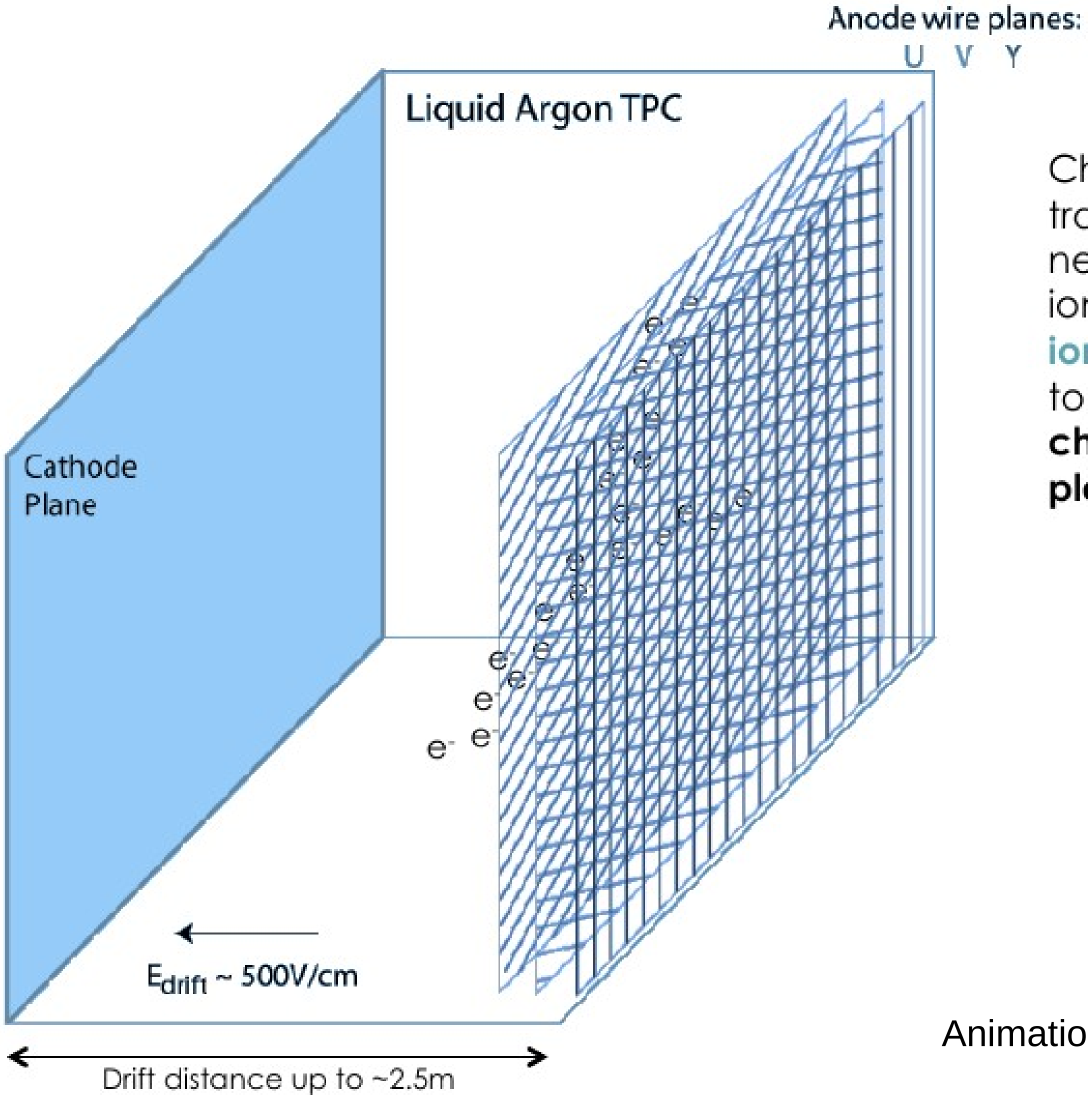

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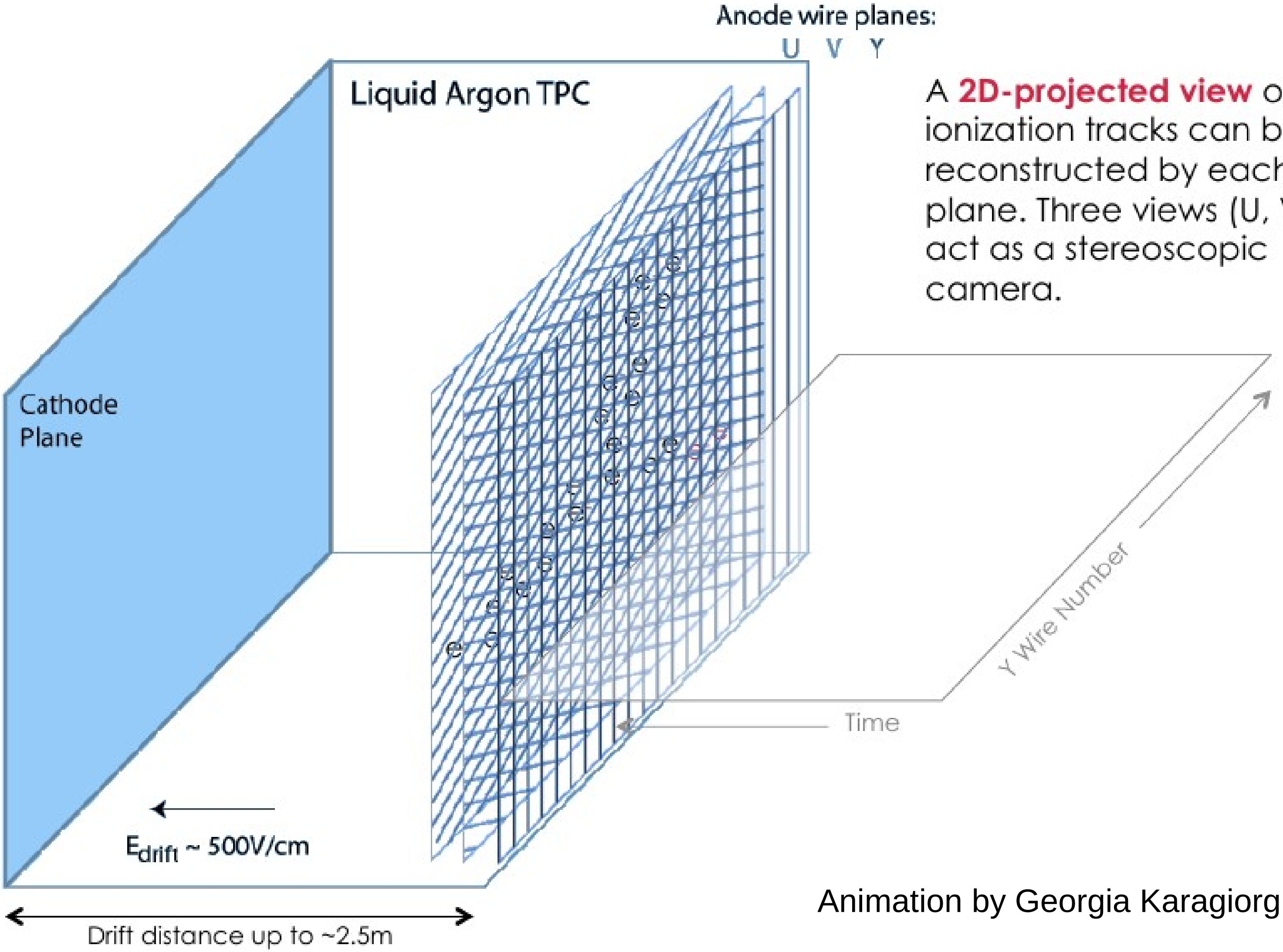

A **2D-projected view** of the ionization tracks can be reconstructed by each wire plane. Three views (U, V, Y) act as a stereoscopic camera.

Animation by Georgia Karagiorgi

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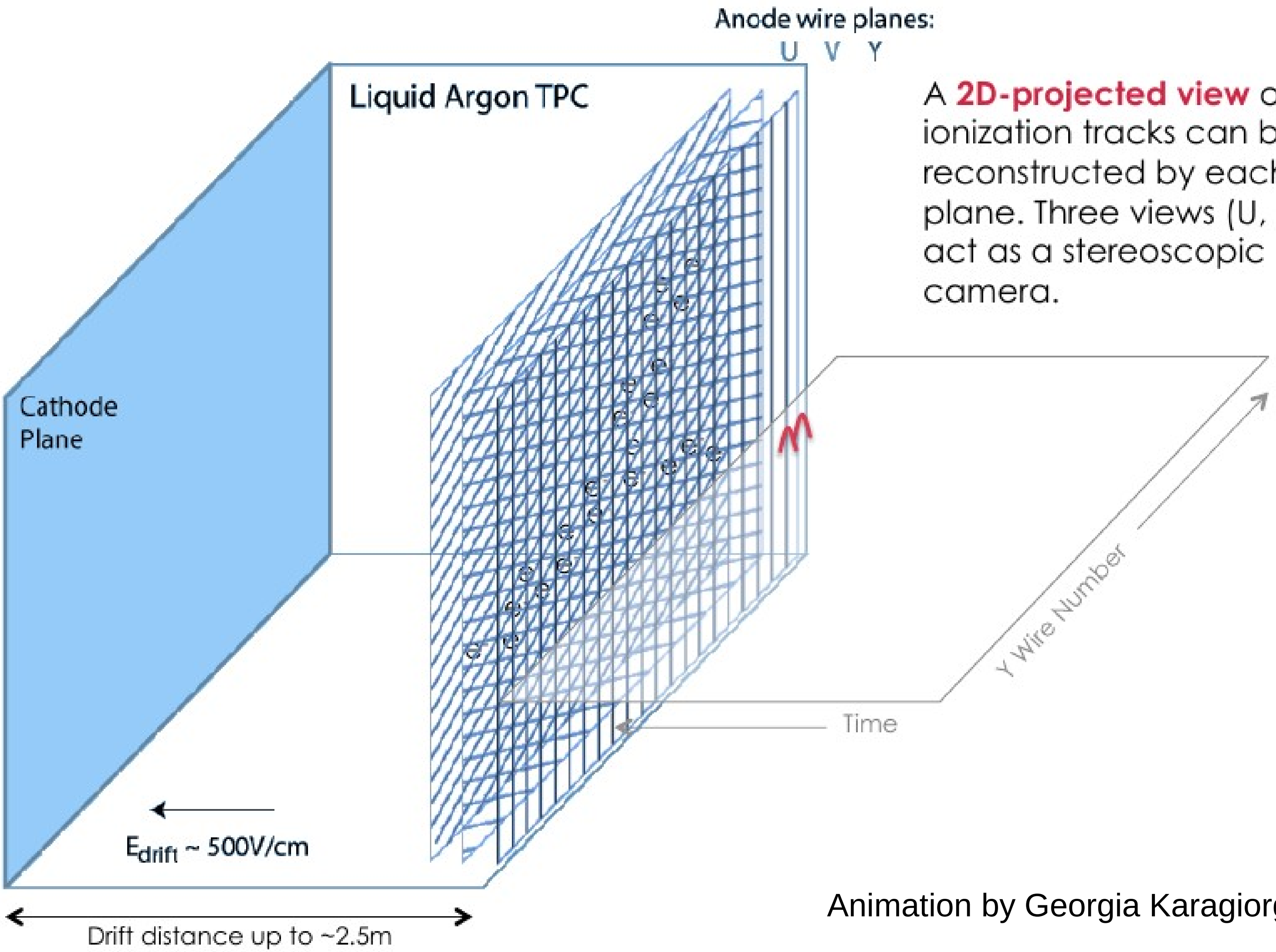

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Animation by Georgia Karagiorgi

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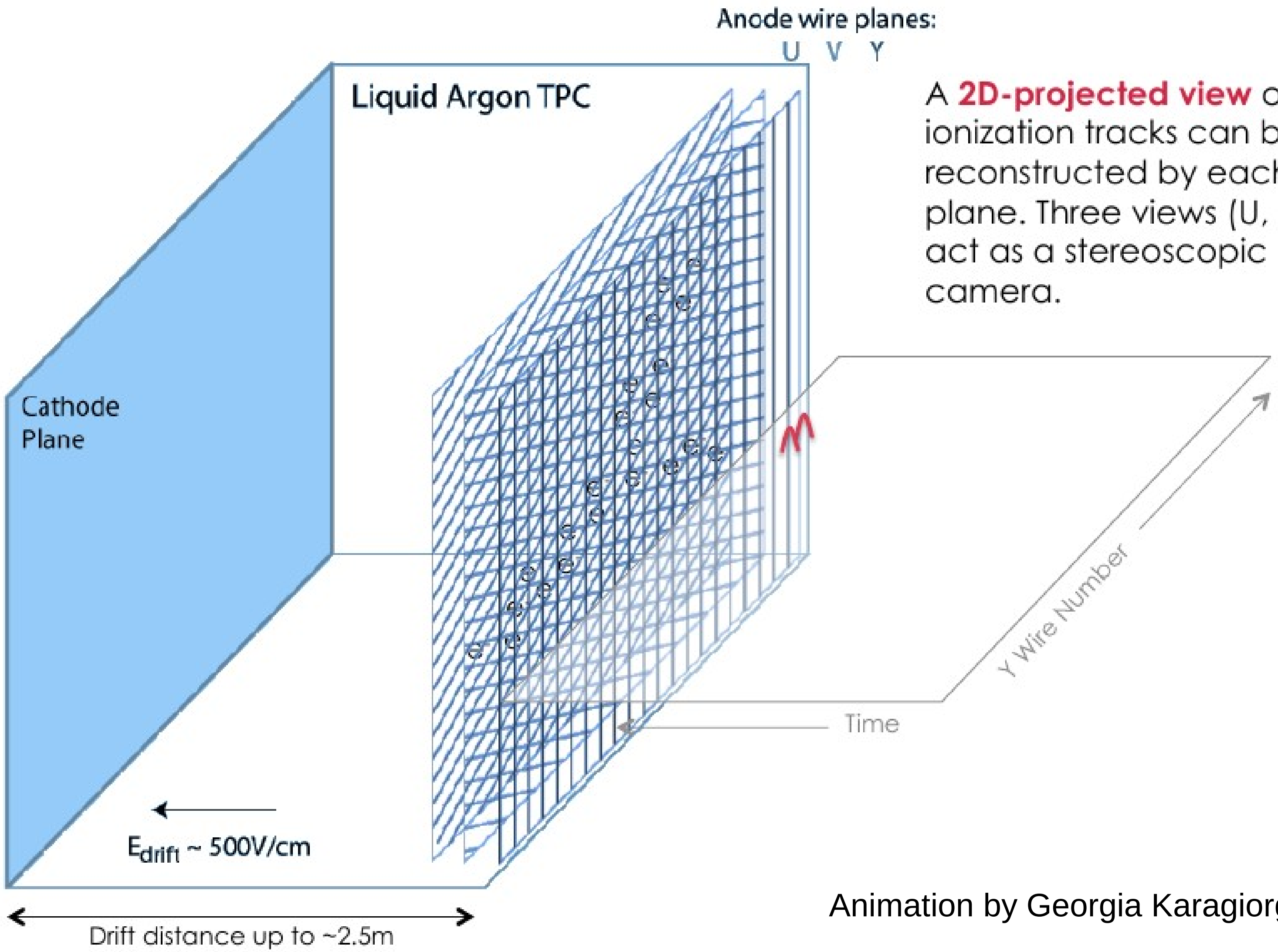

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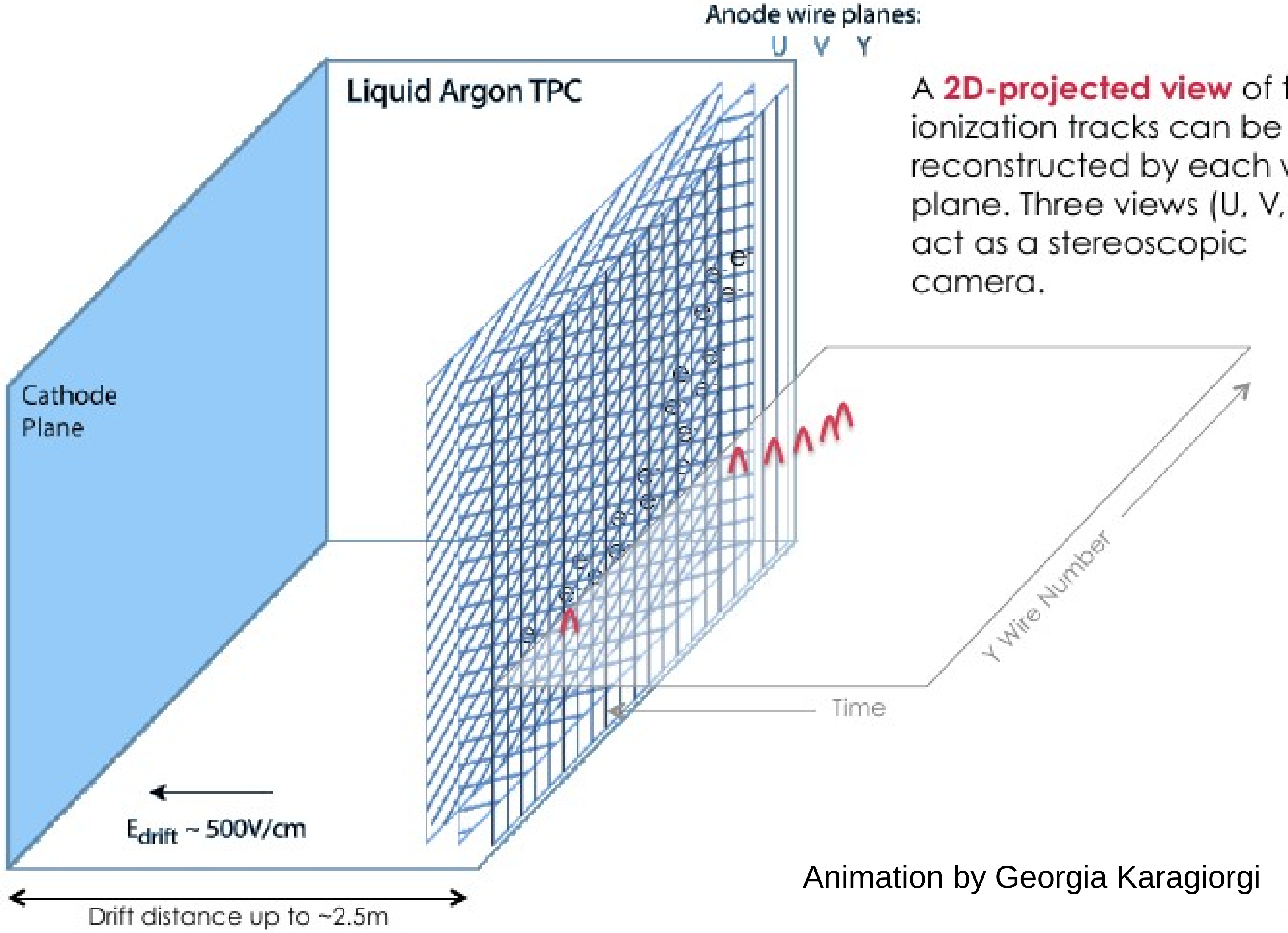

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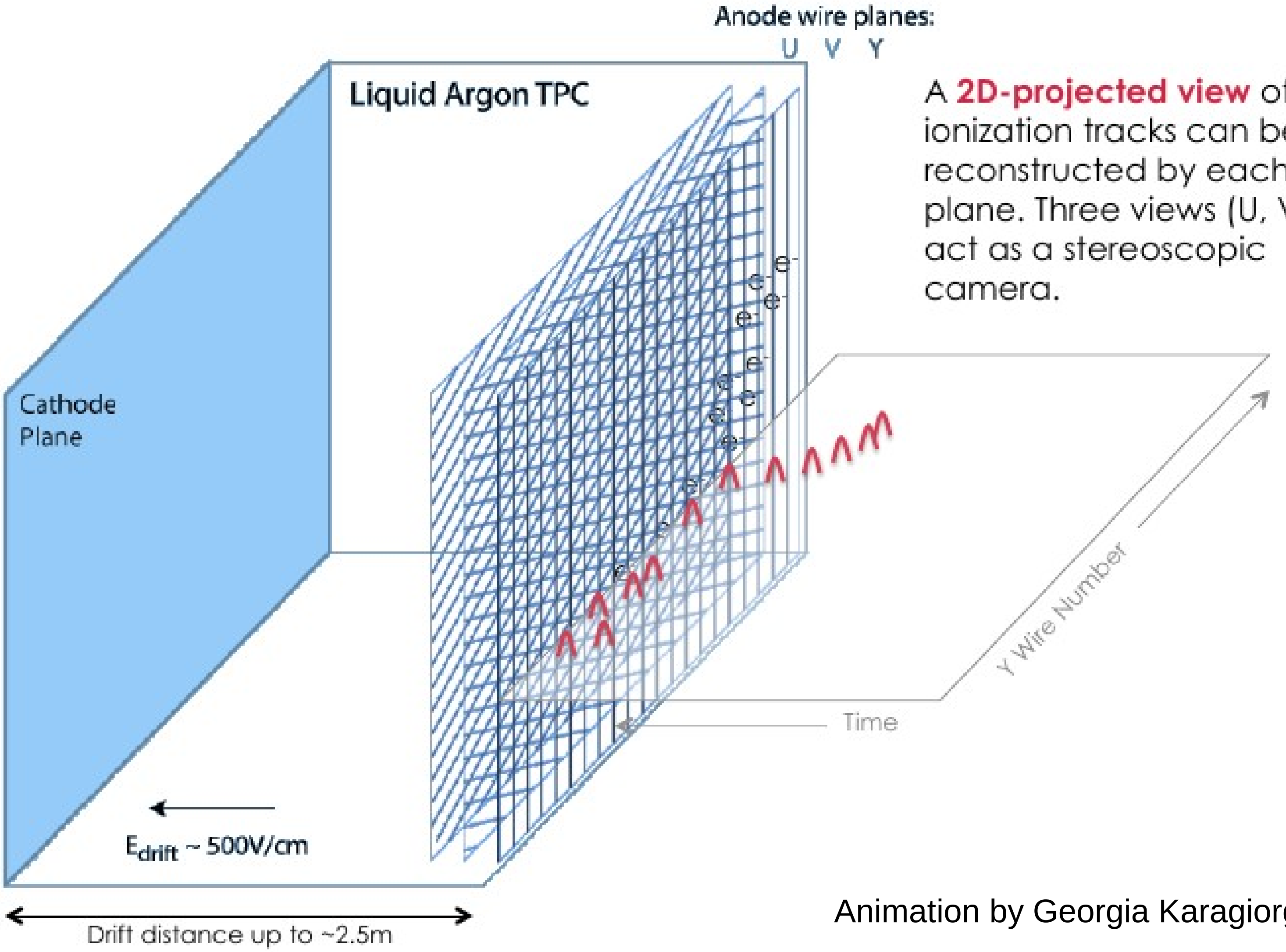

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Animation by Georgia Karagiorgi

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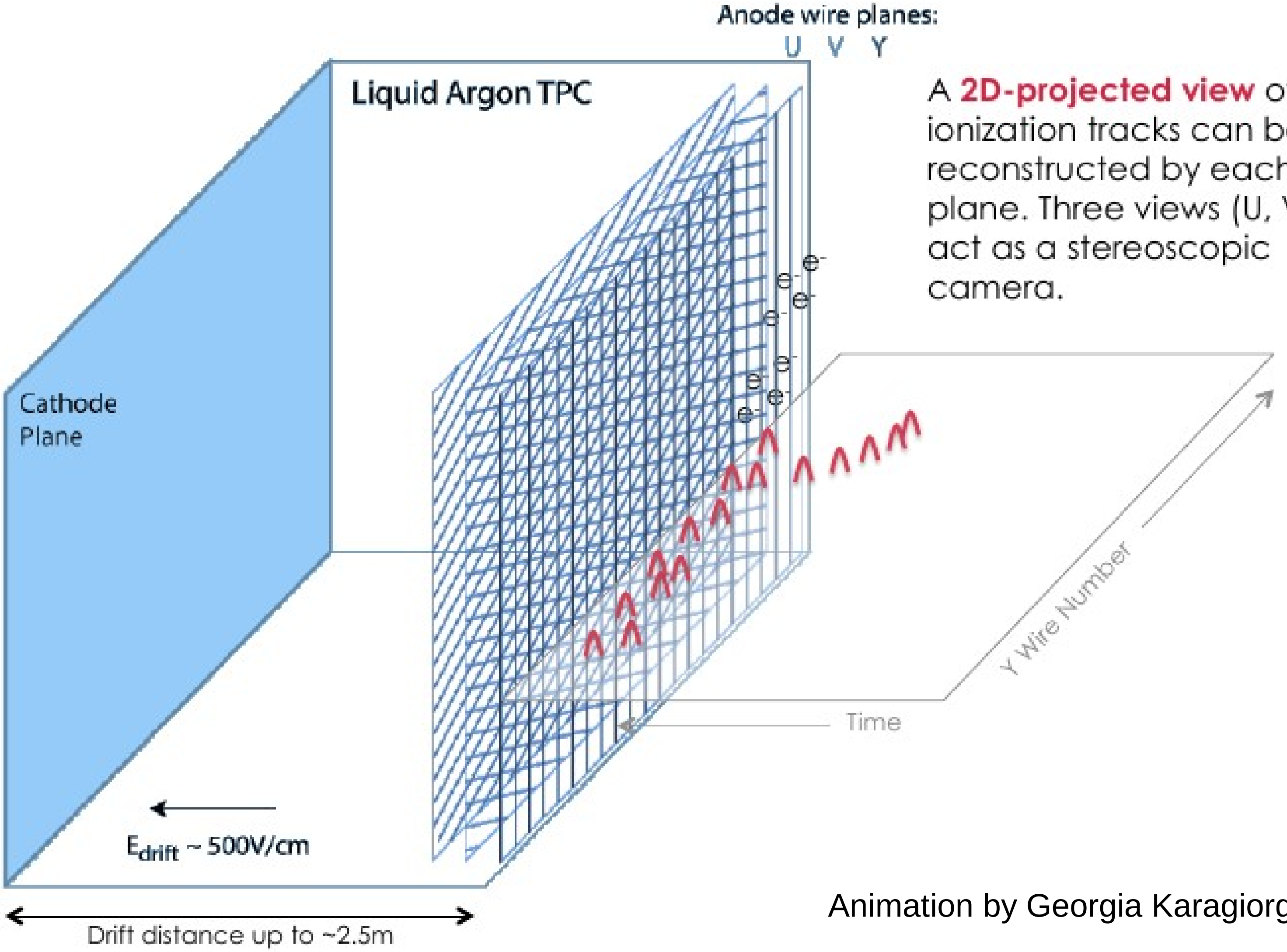

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Animation by Georgia Karagiorgi

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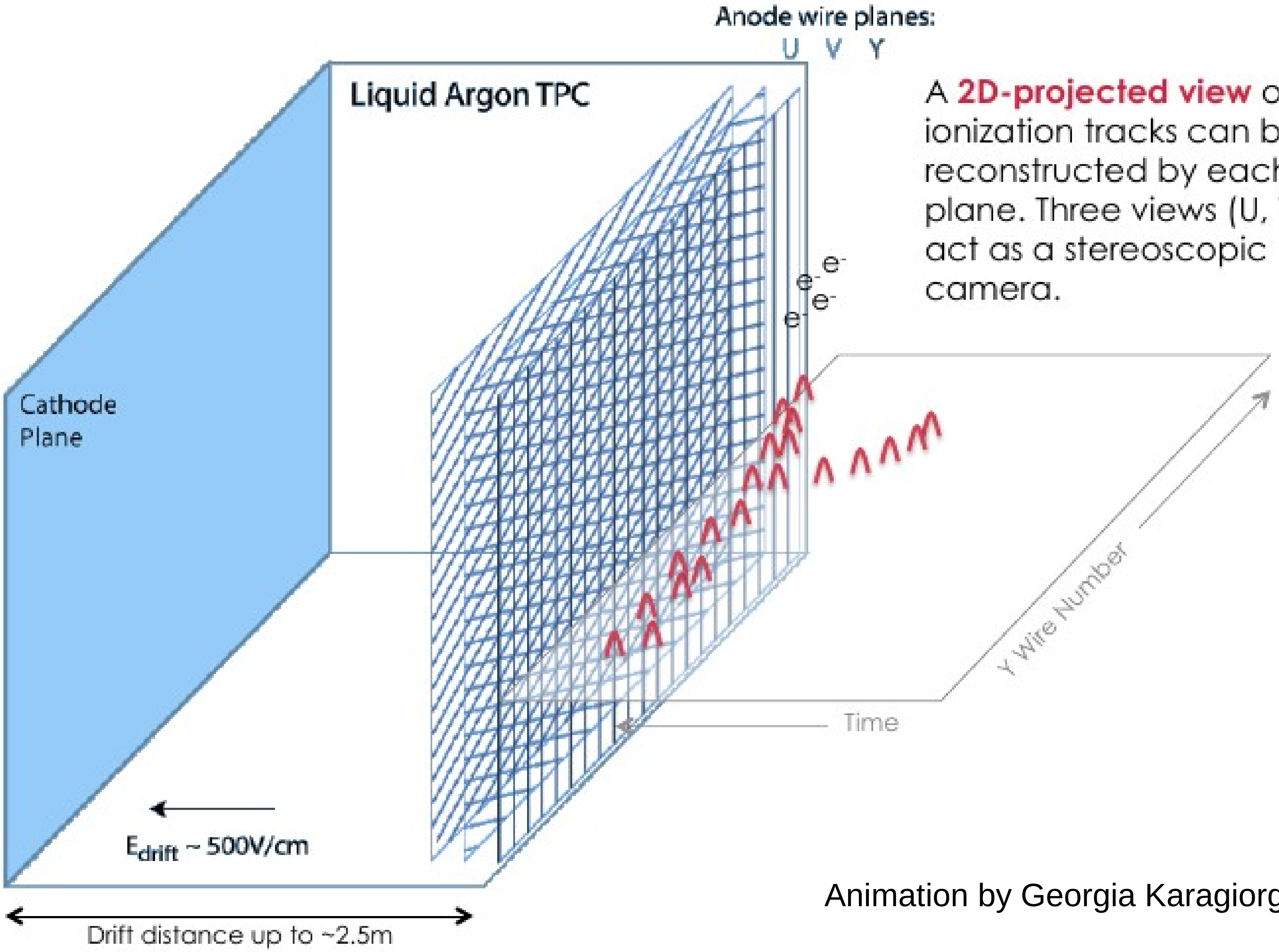

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Animation by Georgia Karagiorgi

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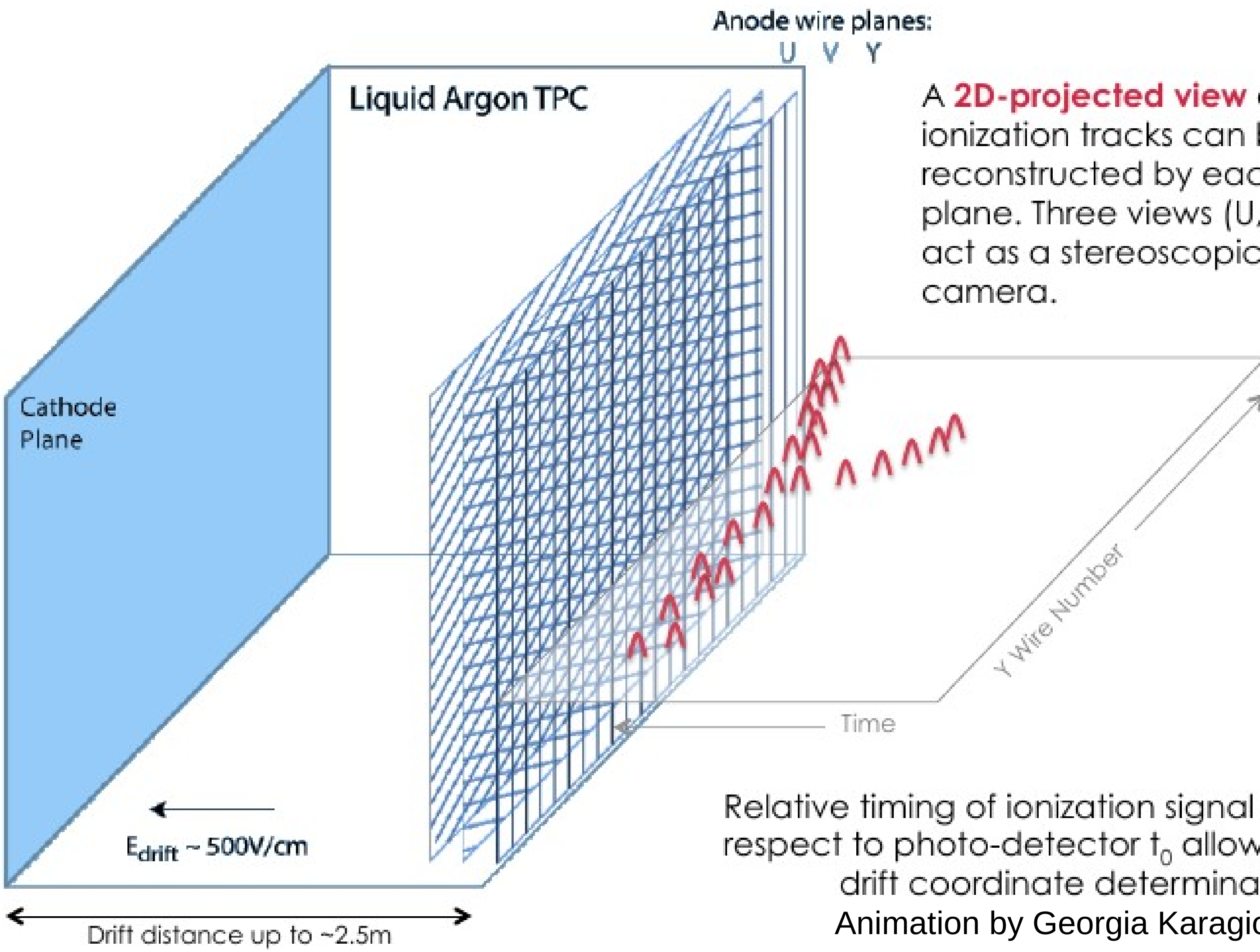
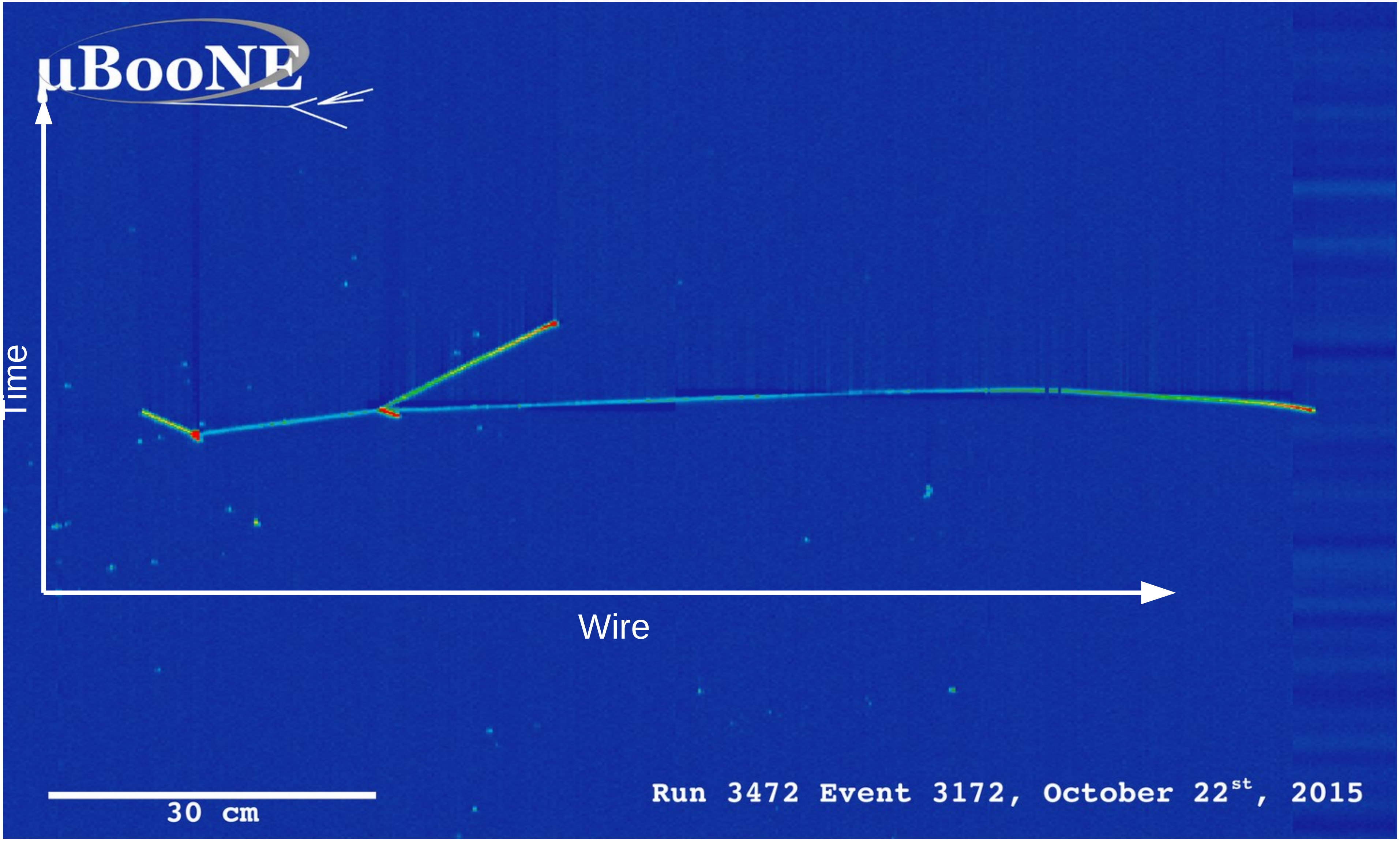


A **2D-projected view** of the ionization tracks can be reconstructed by each wire plane. Three views (U, V, Y) act as a stereoscopic camera.

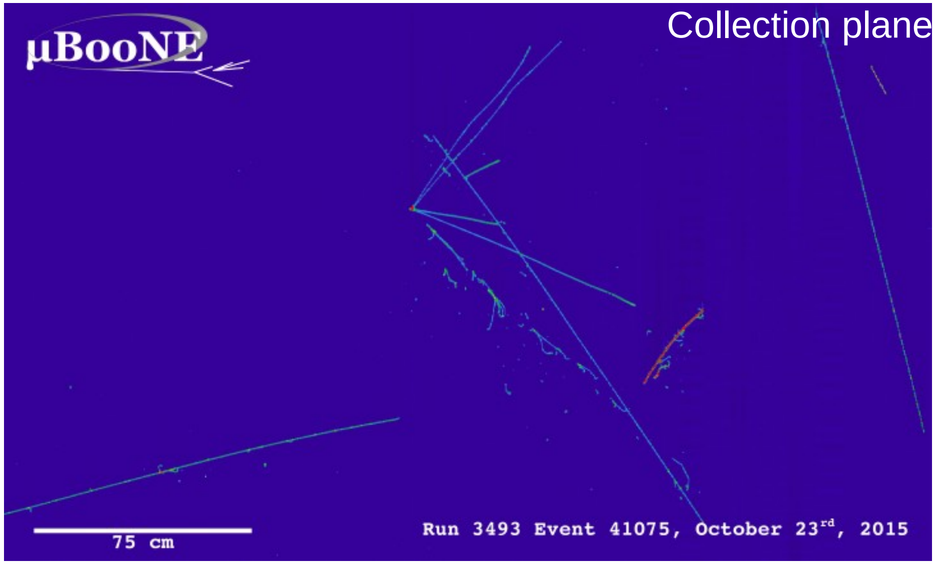
Relative timing of ionization signal with respect to photo-detector t_0 allows for drift coordinate determination.

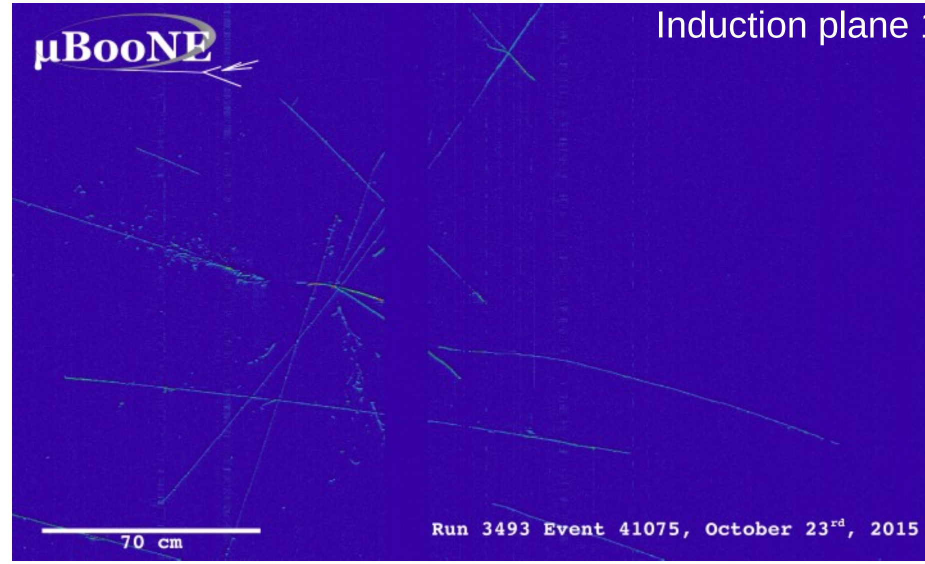
Animation by Georgia Karagiorgi

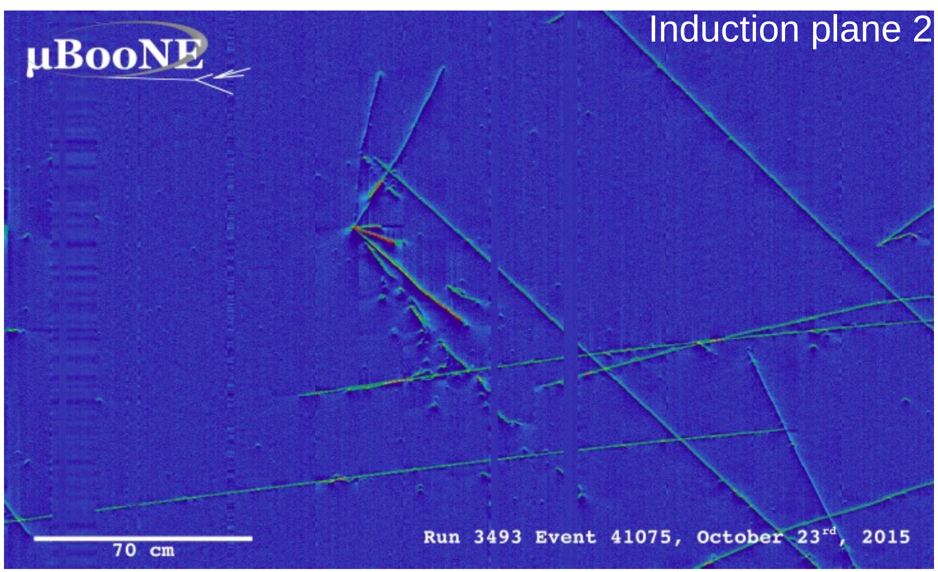
A real neutrino candidate in a LArTPC



Neutrino candidate in LArTPC







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

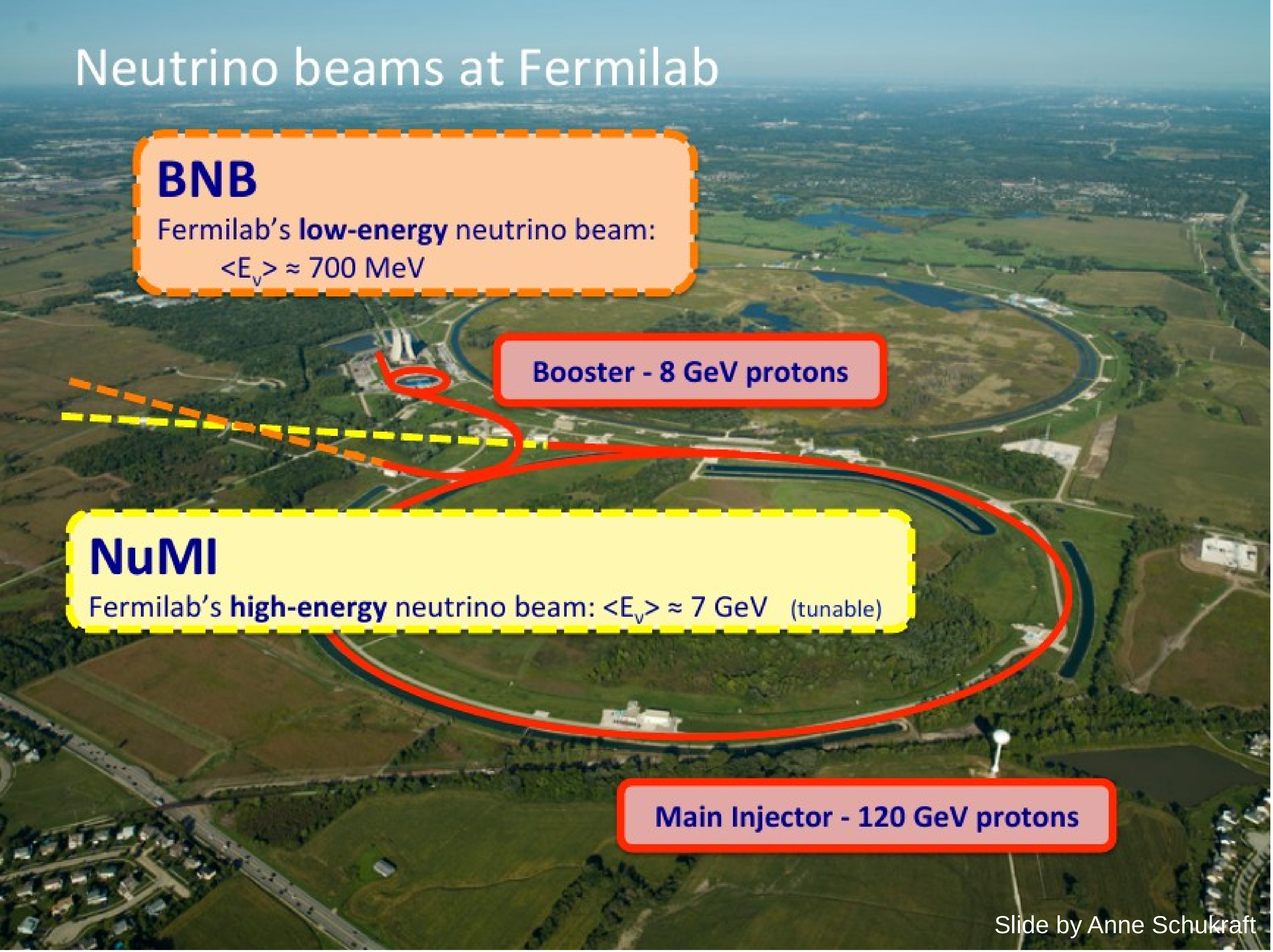
LArTPC

Why **liquid argon**?

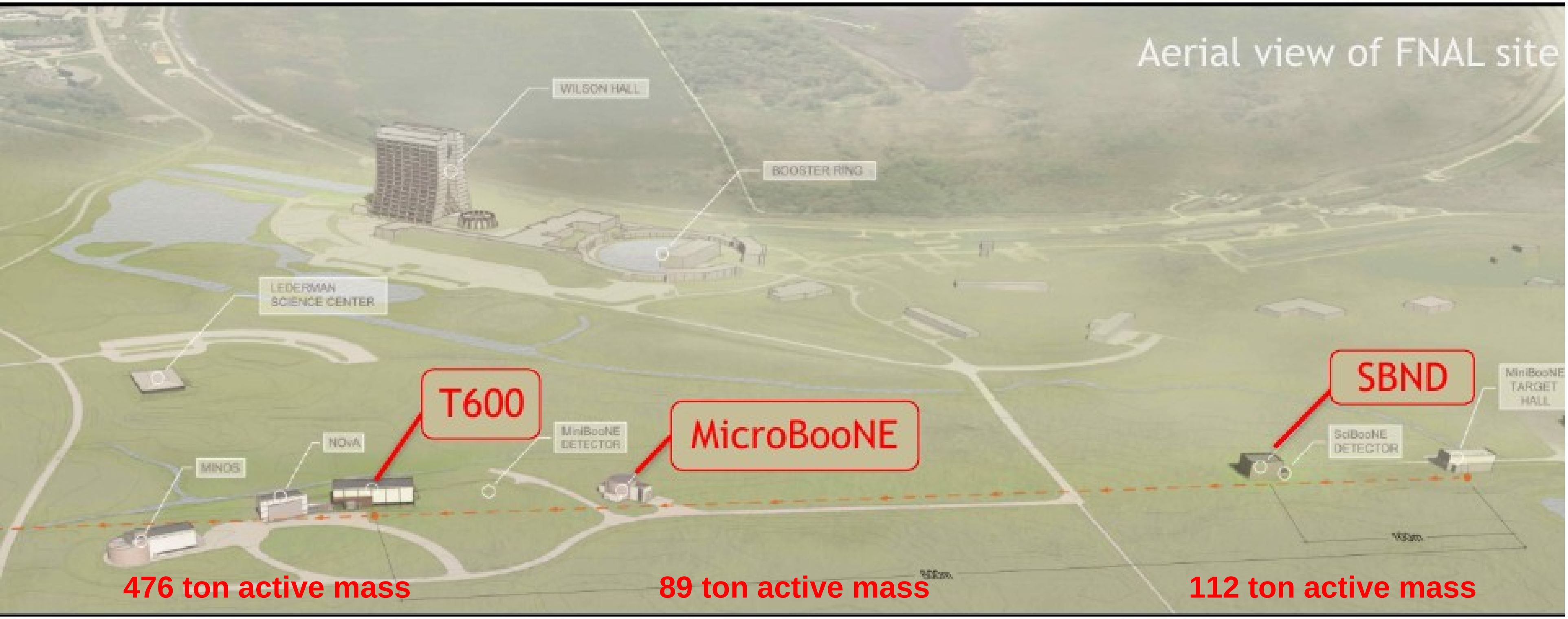
- It is dense (1.4 g/cm^3): more targets for neutrinos per volume.
- It is relatively cheap.
- It can be purified (electronegative elements -oxygen- capture electrons, nitrogen quenches scintillation light): detectors can be bigger.
- Bright scintillator (40000 photons/MeV). Transparent to its own light.

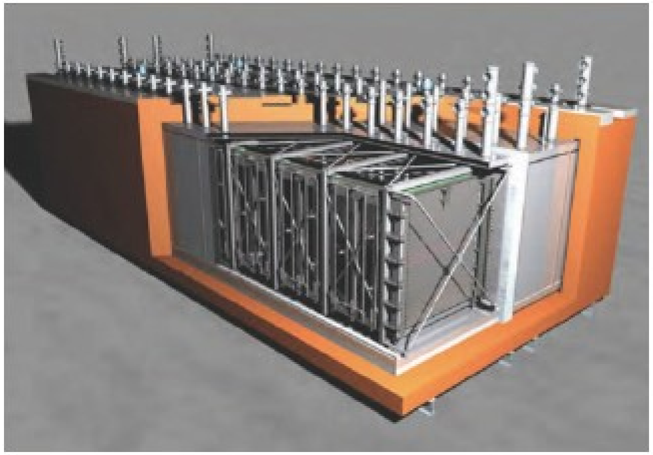
Why **time projection chamber**?

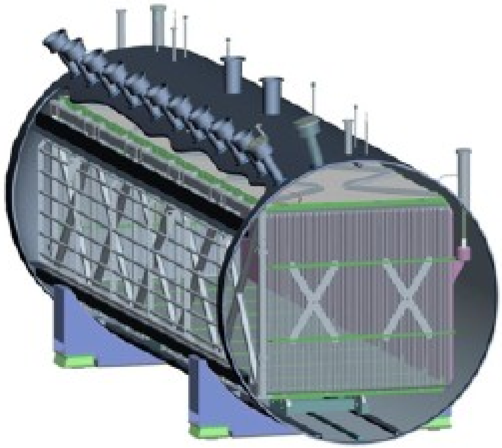
- Modern bubble chamber: very good granularity thanks to a small wire pitch but with automated readout and 3D reconstruction.
- Number of readout channels scales with detector length: less electronics needed.
- Several ways to estimate particle energy: ionization, range... They can be used to identify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

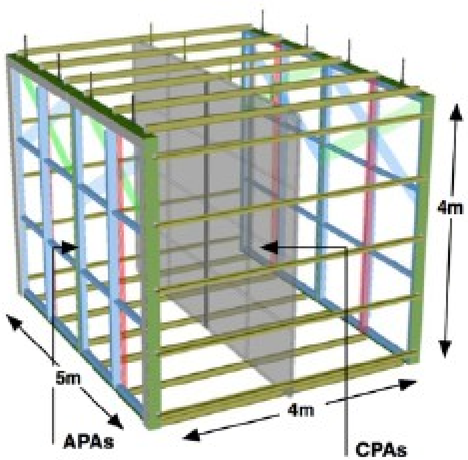

Neutrino beams at Fermilab
BNB
Fermilab's **low-energy** neutrino beam:
<E$_\nu$> ≈ 700 MeV
Booster - 8 GeV protons
NuMI
Fermilab's **high-energy** neutrino beam: <E$_\nu$> ≈ 7 GeV (tunable)
Main Injector - 120 GeV protons
Slide by Anne Schukraft

The short-baseline program at Fermilab

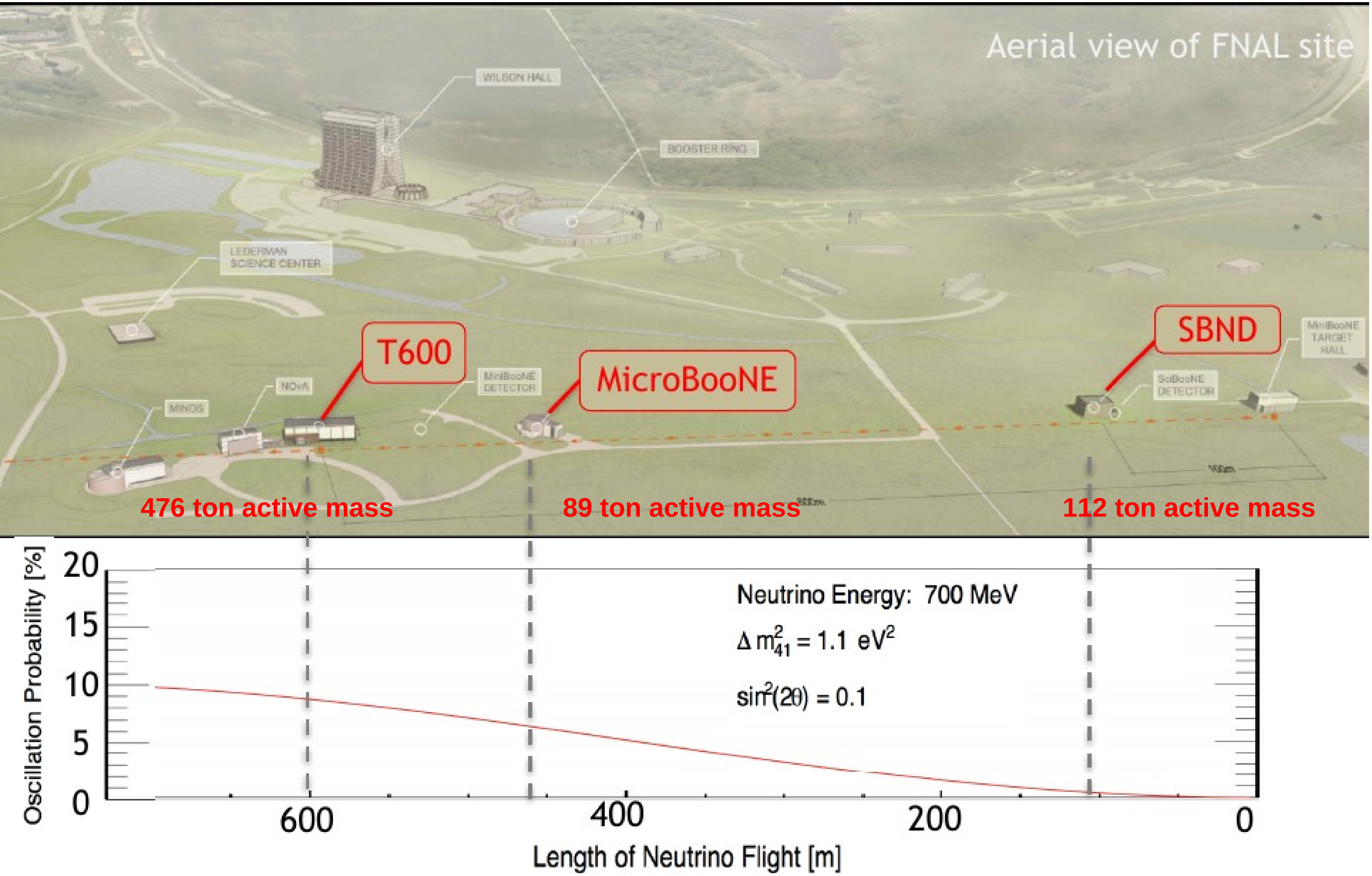






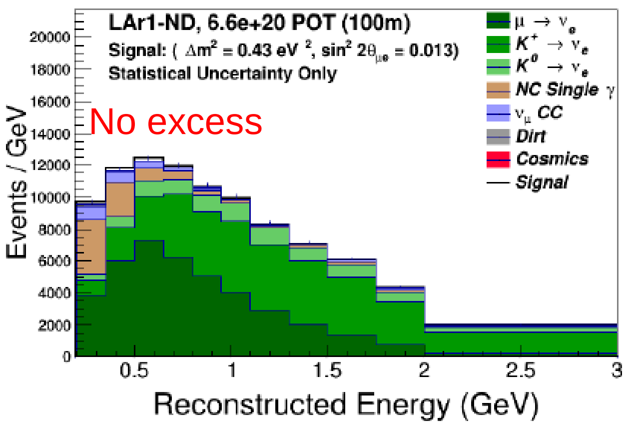


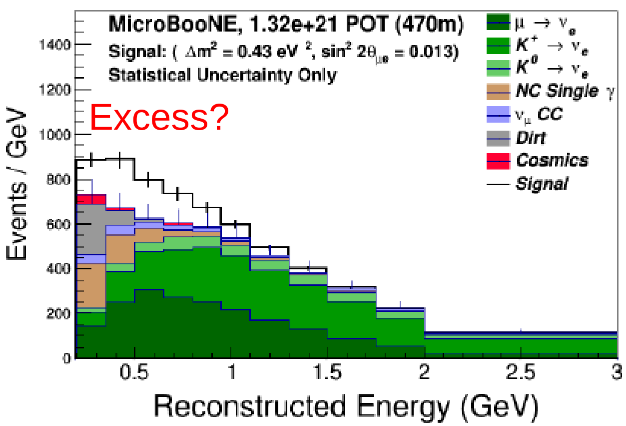
The short-baseline program at Fermilab

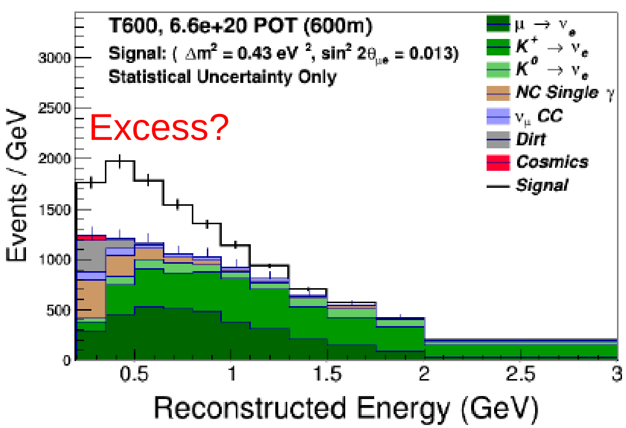


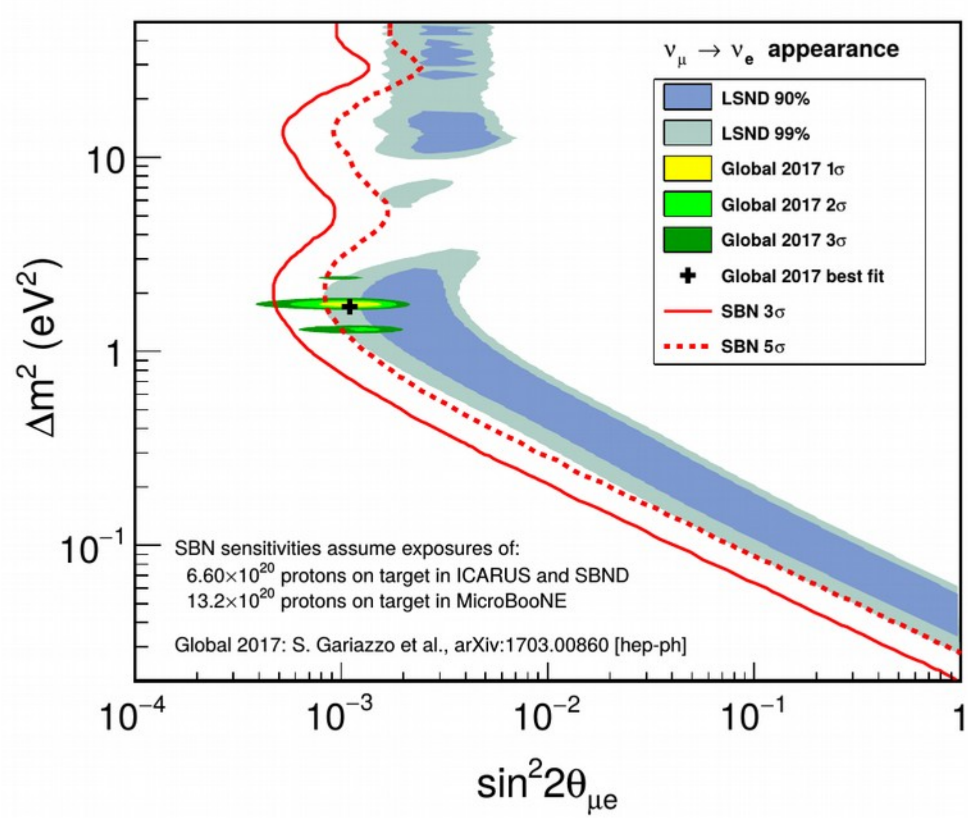
SBND Physics: ν_e appearance

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.

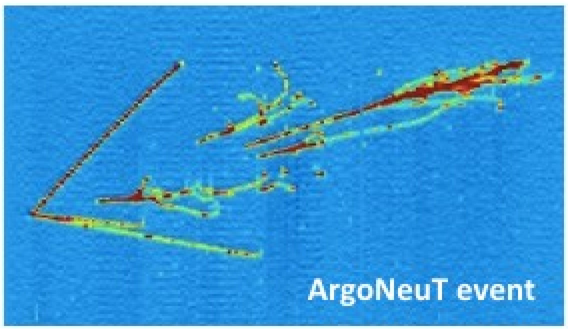
$$P^{3+1}_{\nu_\mu \to \nu_e} = \sin^2 2\theta_{\mu e} \sin^2 \left(\frac{\Delta m^2 L}{4E_\nu} \right) \qquad \sin^2 2\theta_{\mu e} \equiv 4|U_{\mu 4} U_{e4}|^2$$

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

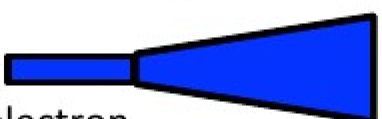
Electron vs. gamma discrimination

Proof of principle with ArgoNeuT data!

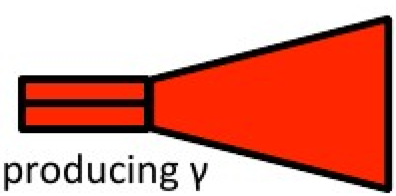
Case 1: The neutral γ (π^0) is observed as gap between vertex and EM shower:



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



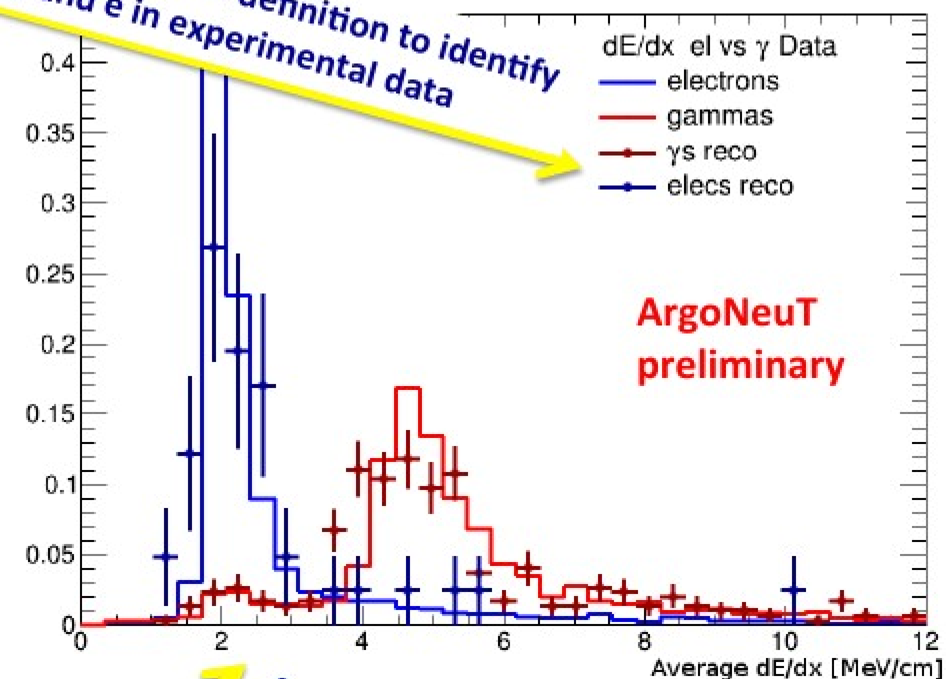
Single electron



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



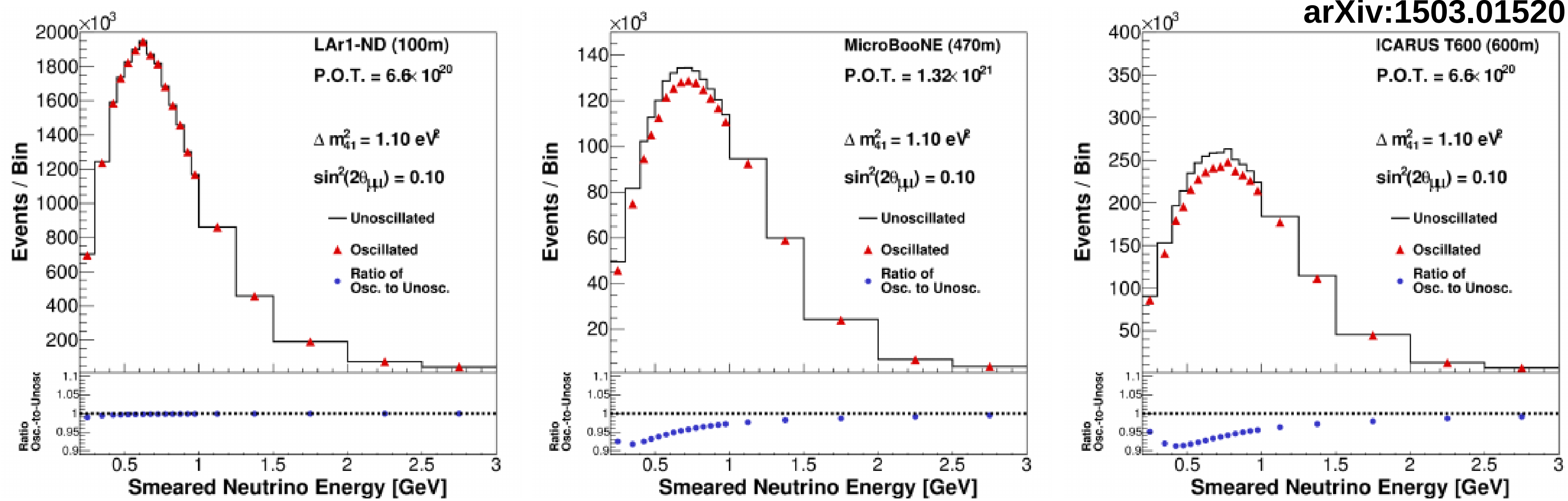
Plot the dE/dx distribution for these events

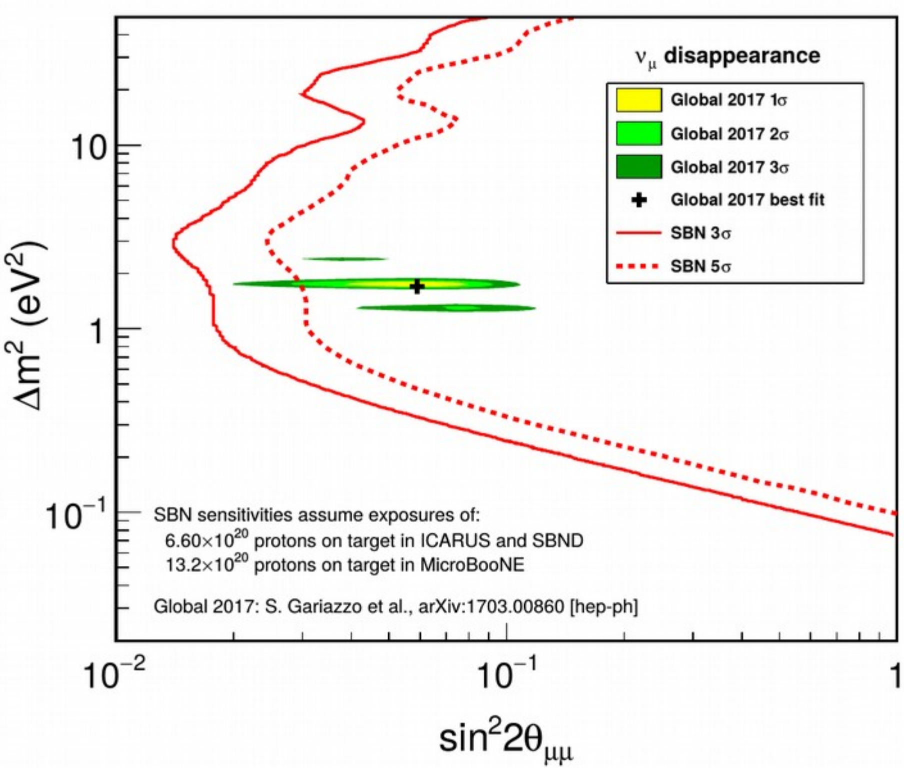
MicroBooNE will be able to resolve the nature of the MiniBooNE low-energy excess!

Slide by Anne Schukraft

SBND Physics: ν_μ disappearance

arXiv:1503.01520





- ν_e appearance must be accompanied by ν_μ disappearance.

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

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

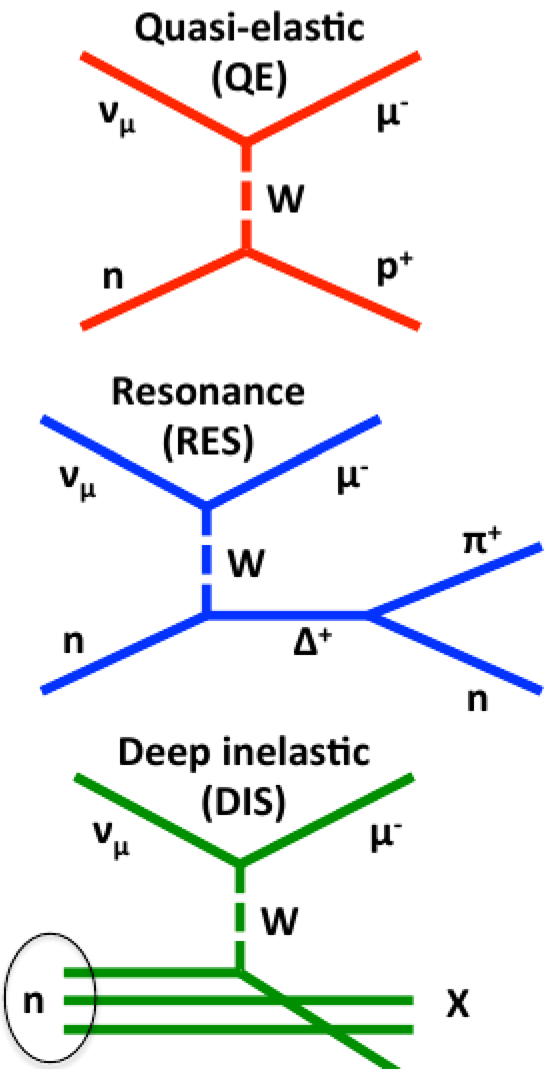
$$P^{3+1}_{\nu_\mu\to\nu_\mu} = 1 - \sin^2 2\theta_{\mu\mu}\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

- SBND will measure the unoscillated ν_μ flux.
- MicroBooNE & ICARUS will search for a deficit of ν_μ.

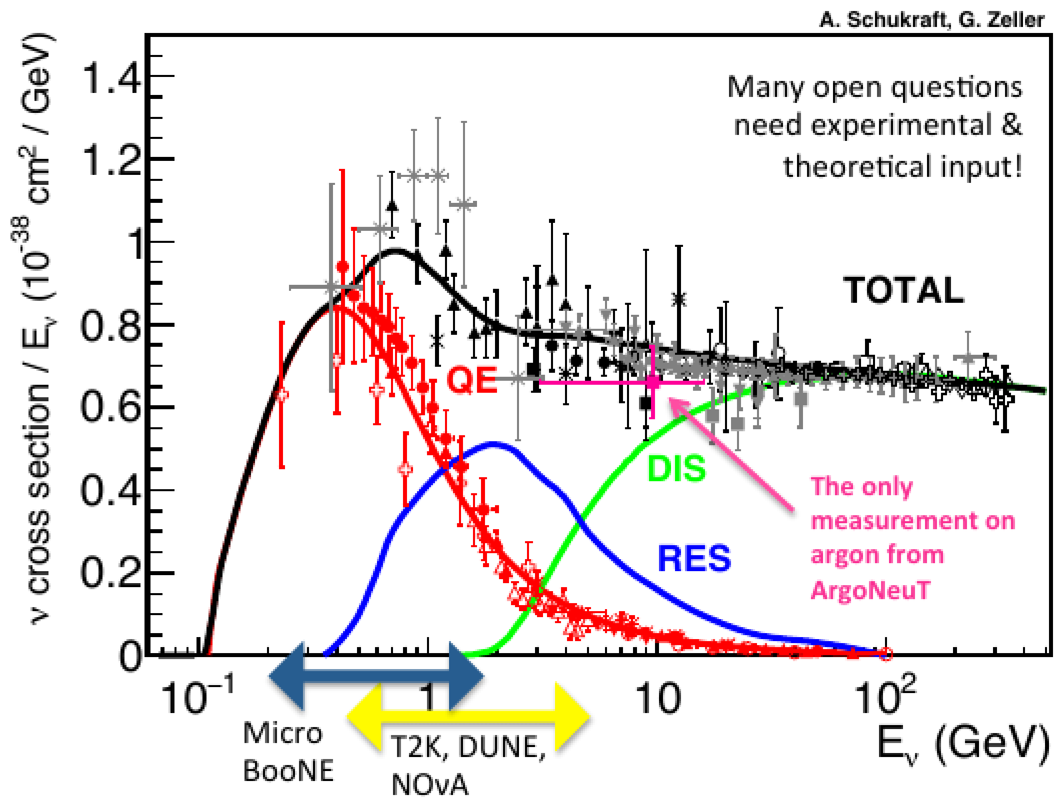
  Only possible thanks to the reduction on the flux normalization systematic uncertainty brought by SBND.
- SBN covers almost the full allowed region region with 5σ.

Cross-section program

Neutrinos interacting with nucleons

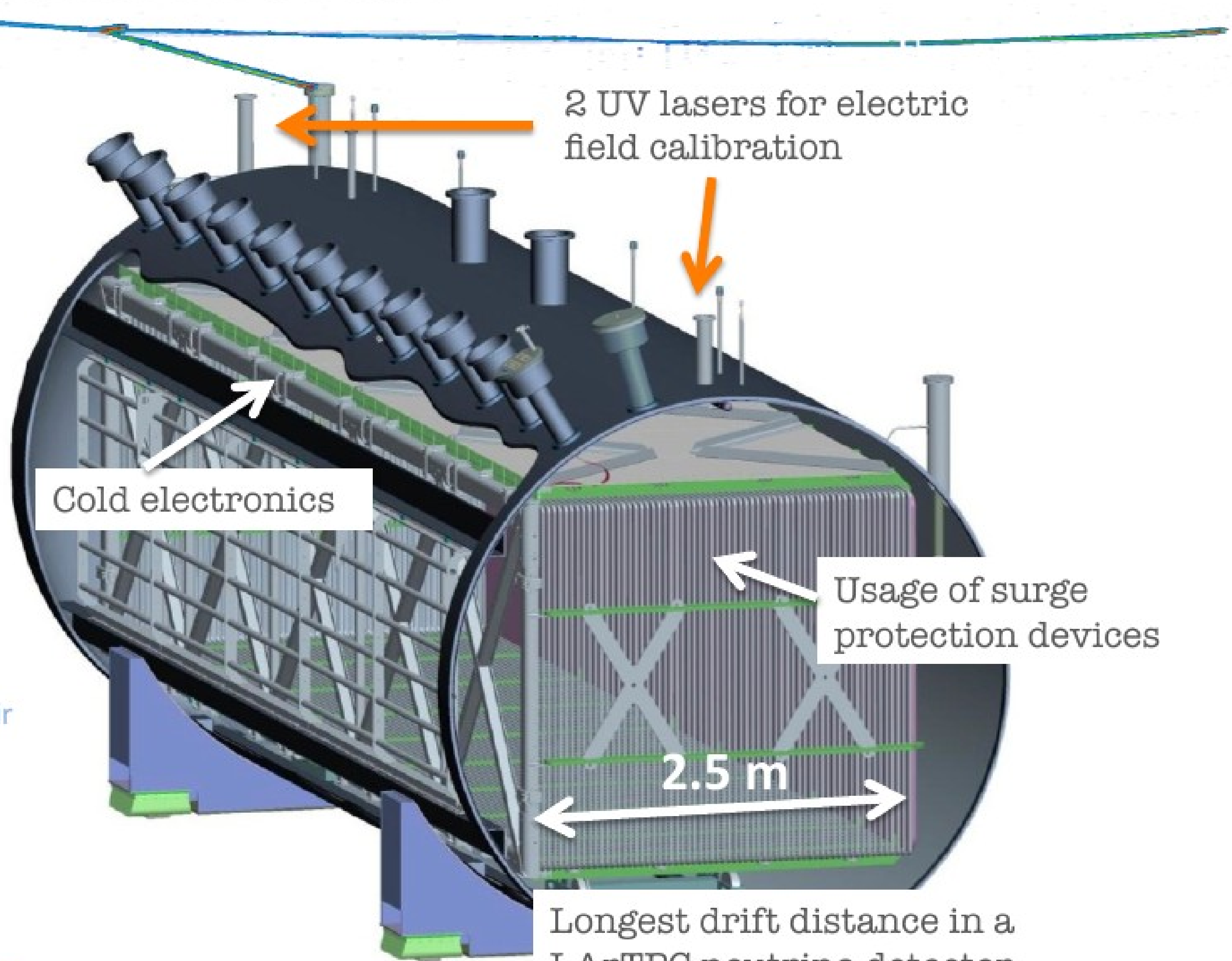


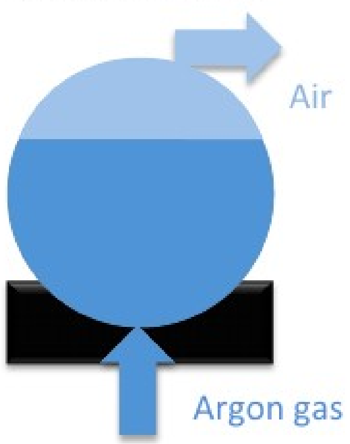
Lots of interesting (nuclear) physics over all energy ranges.



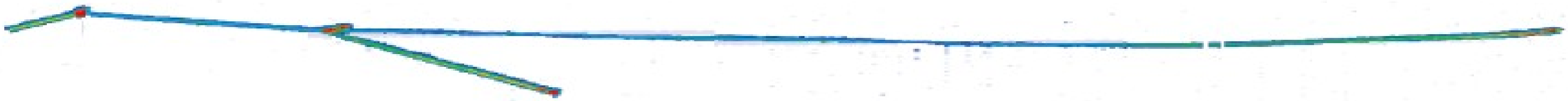
We need to understand neutrino-nucleon scattering to understand event rates, final states and neutrino energy estimation in oscillation experiments

R&D in MicroBooNE

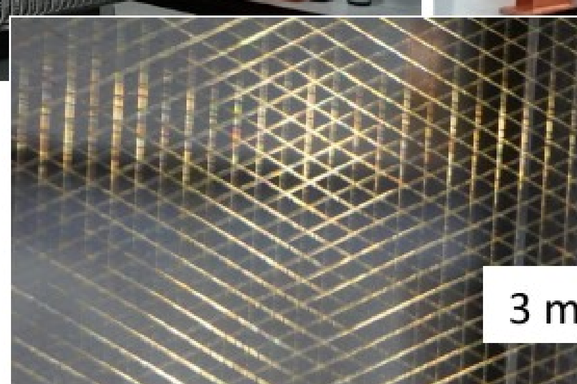




MicroBooNE construction



TPC construction: 2013



3 mm wire spacing

Slide by Anne Schukraft

Installation – a picture series

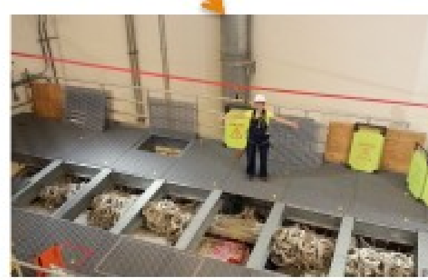
PMT system installation: Dec 2013

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

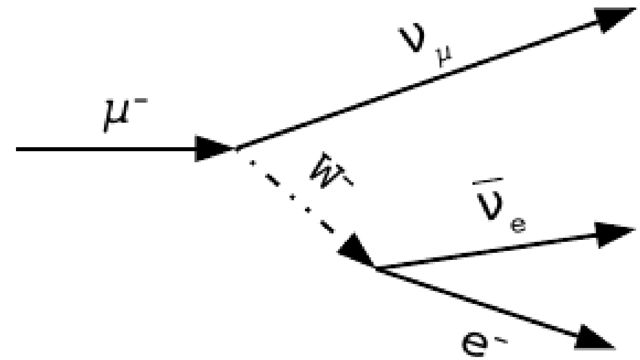


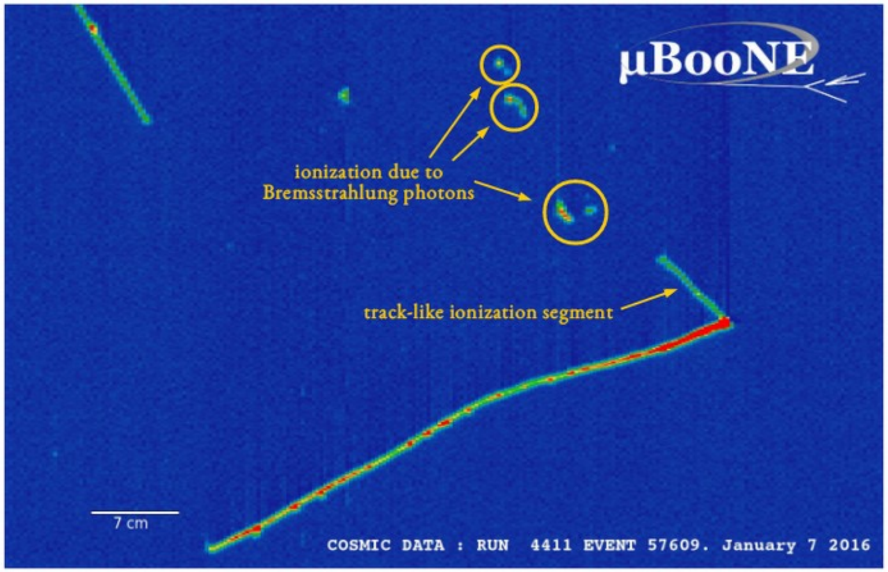
Cabled up! Sept. 2014

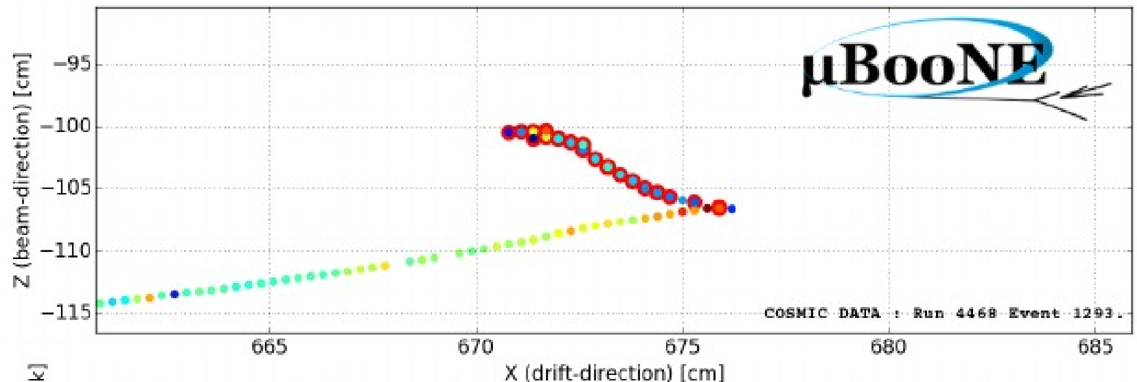
All electronics in! Dec. 10, 2014

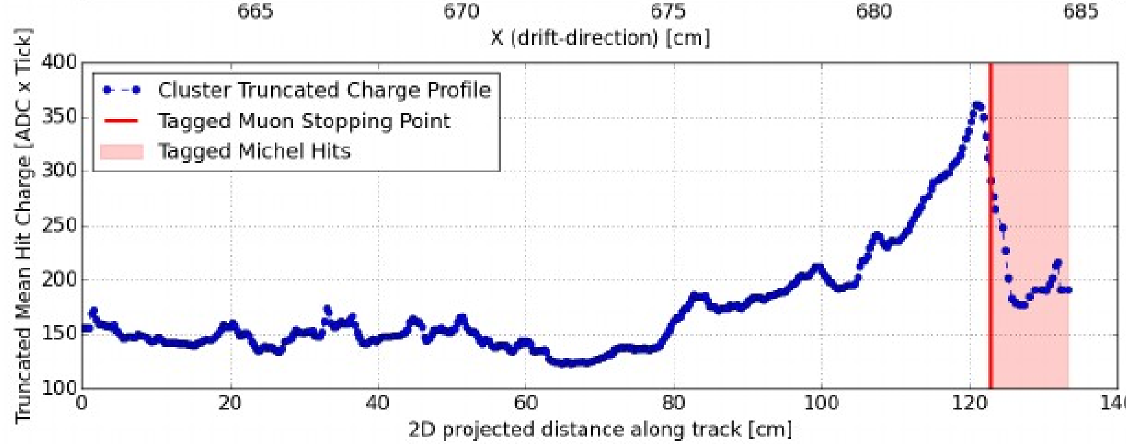
Slide by Anne Schukraft

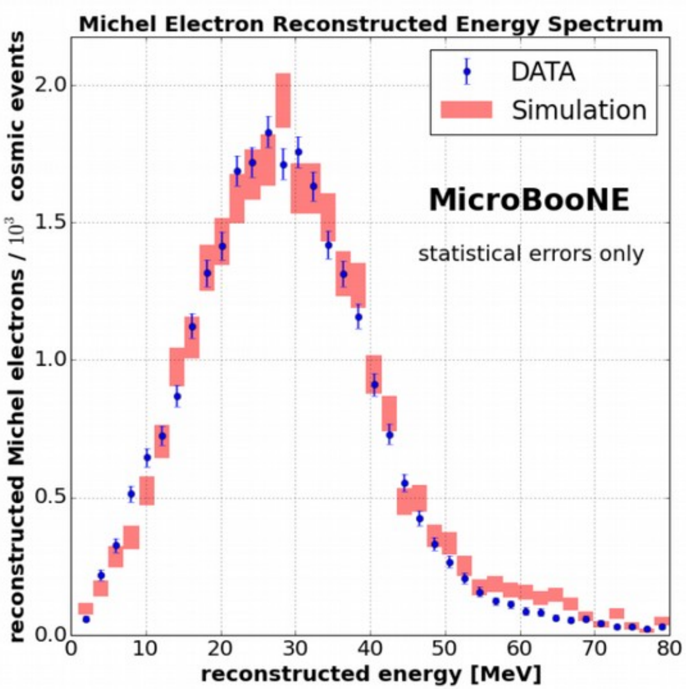
Michel electrons in MicroBooNE









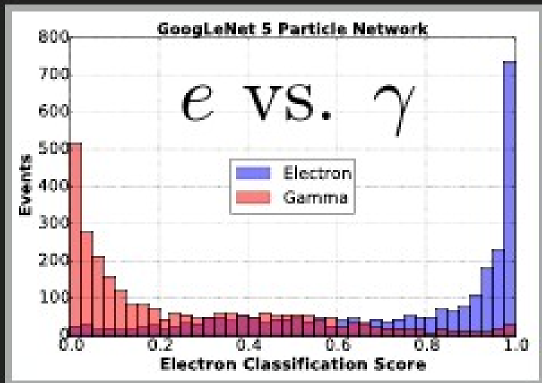


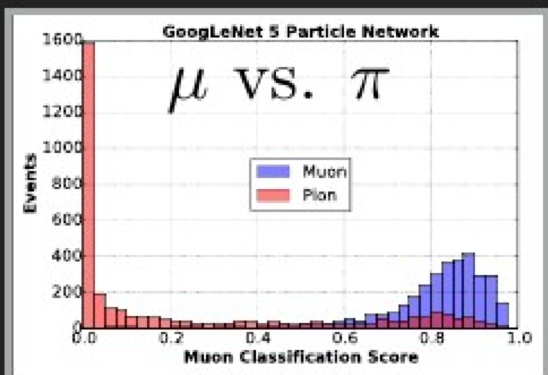
Use calorimetry to identify Bragg peak of stopping muon.

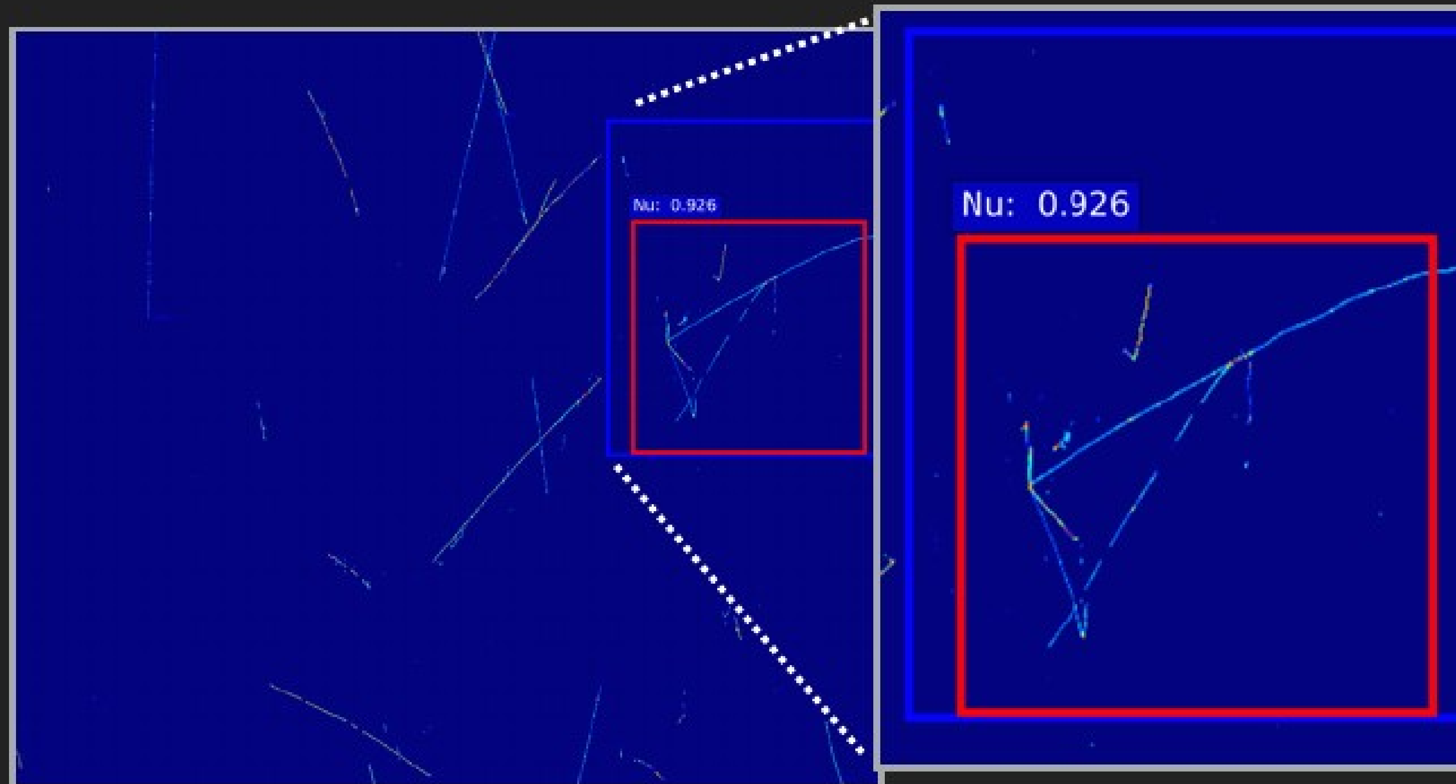
Similarly look for spatial kink.

Analysis by David Caratelli, Nevis PhD student

Particle classification using Deep Learning



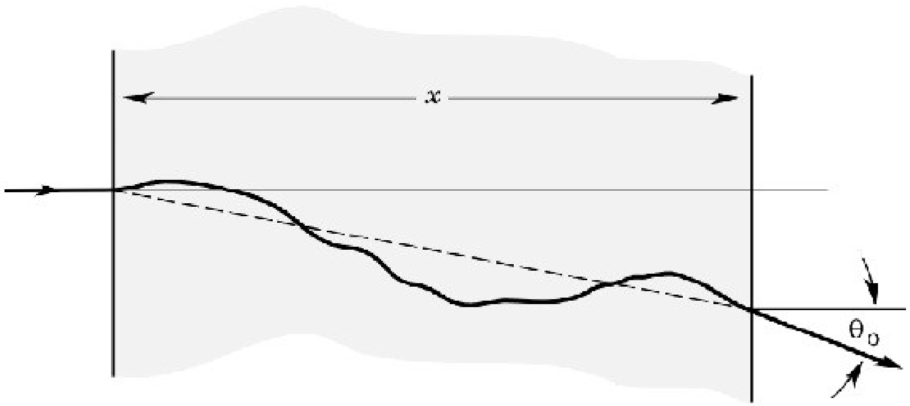


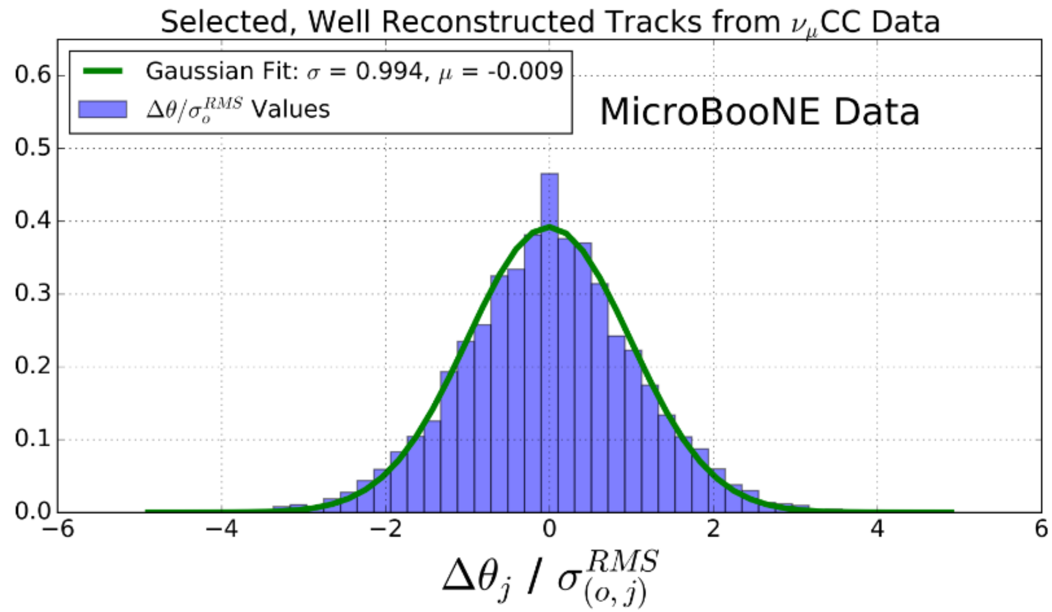


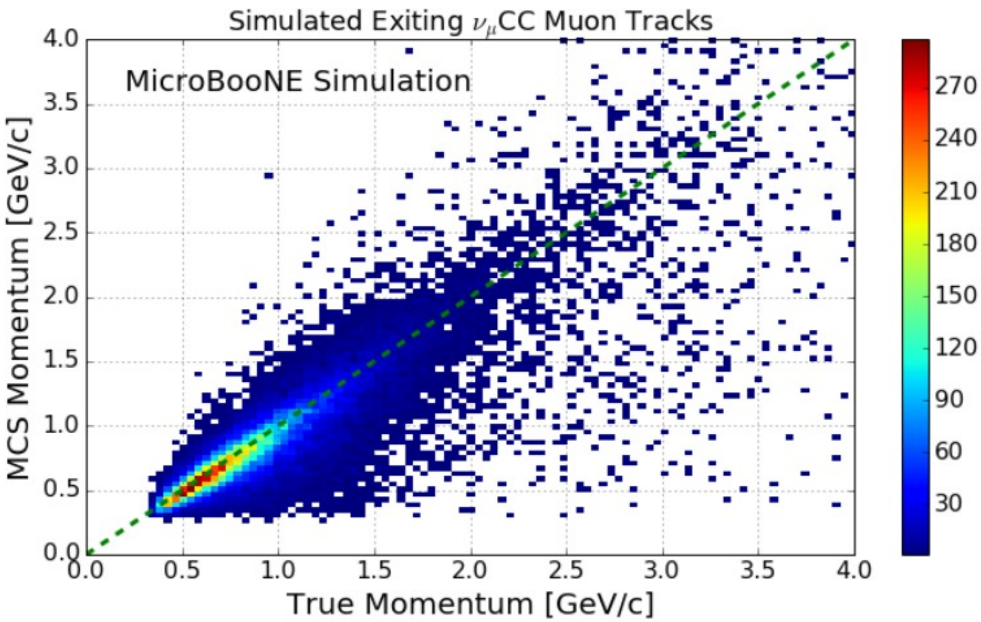
- Feed the LArTPC data to a computer as an image.
- Apply computer-vision techniques (convolutional neural networks) to the classification of particles or for localizing neutrino interactions.
- Application of GPUs to scientific research.

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

Multiple Coulomb Scattering



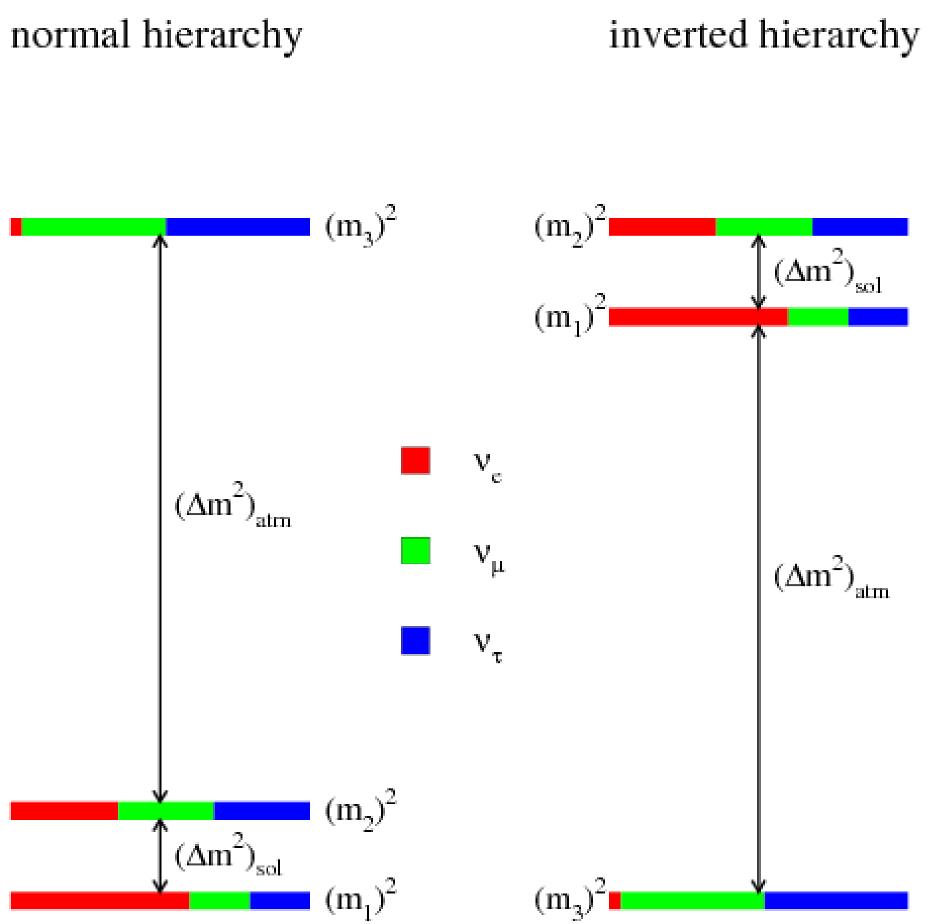




- The width of the distribution of scattering angles is proportional to the momentum of the particle traversing the medium.
- Measure the momentum of particles (e.g. muons) leaving the detector.
- Last year REU project, now a paper submitted for publication!

Measurement of neutrino mass

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:

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

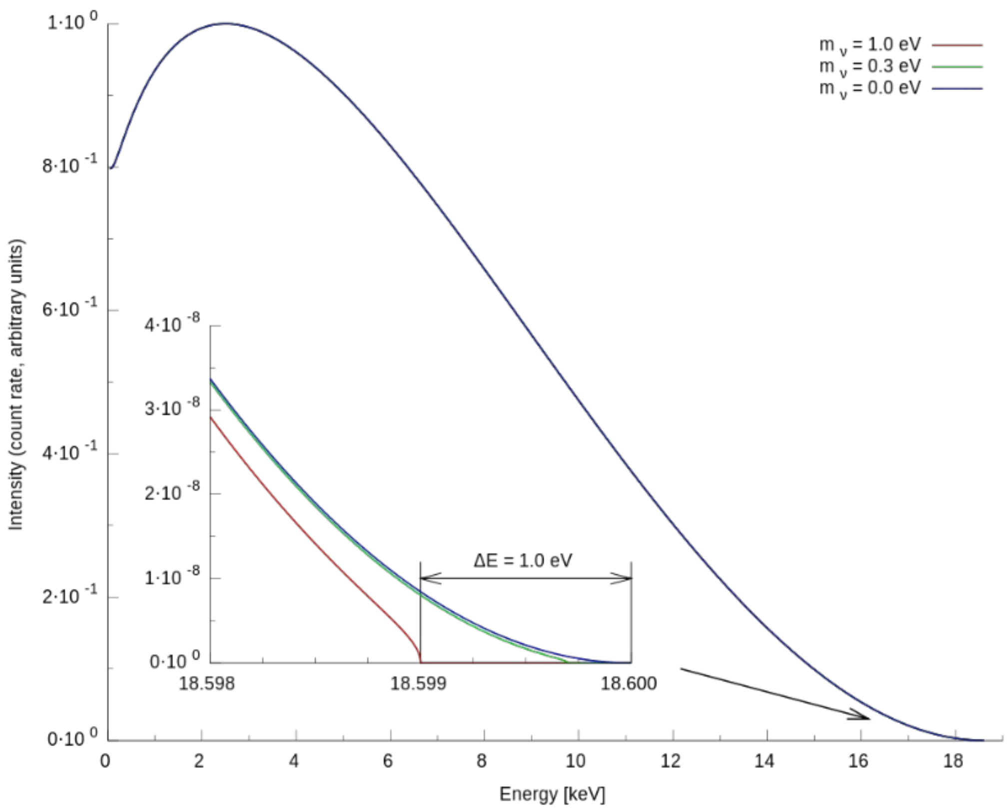
$$m_3 \geq \sqrt{\Delta m^2_{32} + \Delta m^2_{21}} = 0.0502 \pm 0.0006\,\mathrm{eV}$$

- For inverted hierarchy:

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

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

Kinematic limits



- Example: tritium decay

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

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:

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

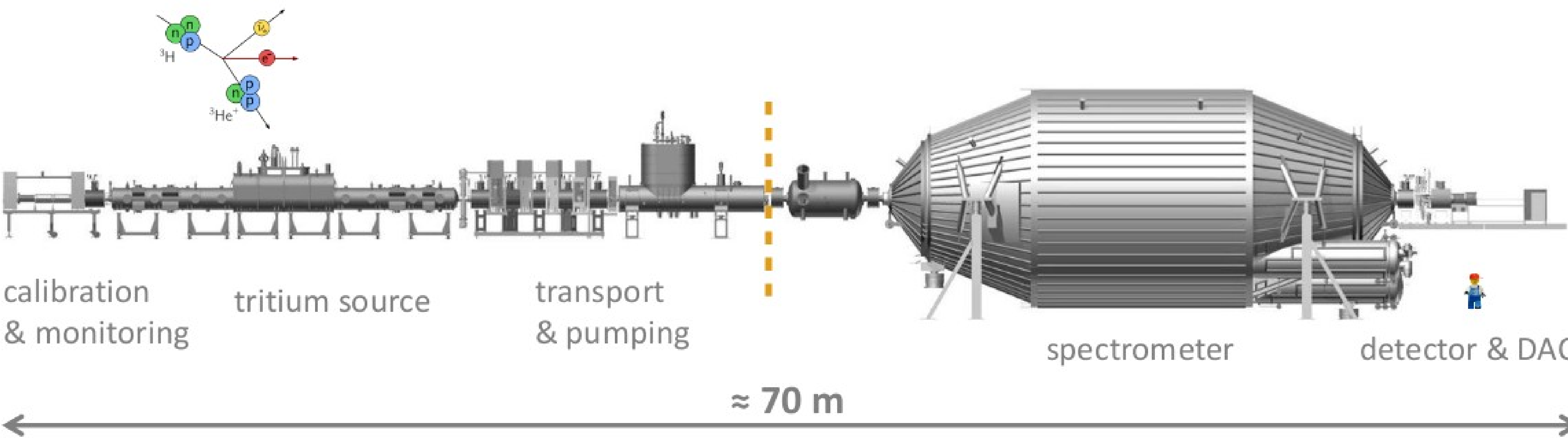
$$m_\beta = \left[\sum_{j=1}^{3} |U_{ej}|^2 m_j^2\right]^{\frac{1}{2}}$$

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

$$m_\beta < 2.05\,\mathrm{eV} \quad \text{(Troitsk)}$$
$$m_\beta < 2.3\,\mathrm{eV} \quad \text{(Mainz)}$$

KATRIN experiment

Sensitivity of 0.2 eV (90% C.L.)

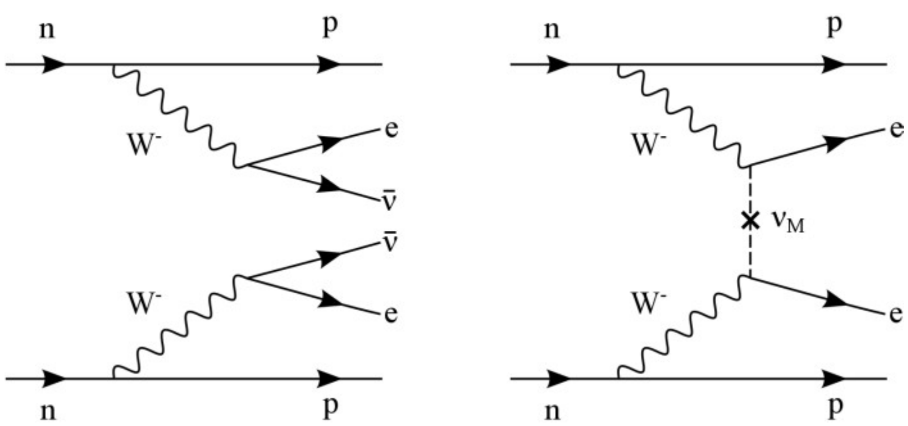


Other kinematic limits

$\pi^+ \rightarrow \mu^+ + \nu_\mu$ $\quad (m_{\nu_\mu}^{\text{eff}})^2 = \sum_{j=1}^{3} |U_{\mu j}|^2 m_j^2 \quad m_{\nu_\mu}^{\text{eff}} < 0.17\,\text{MeV}$ (90% C.L.)

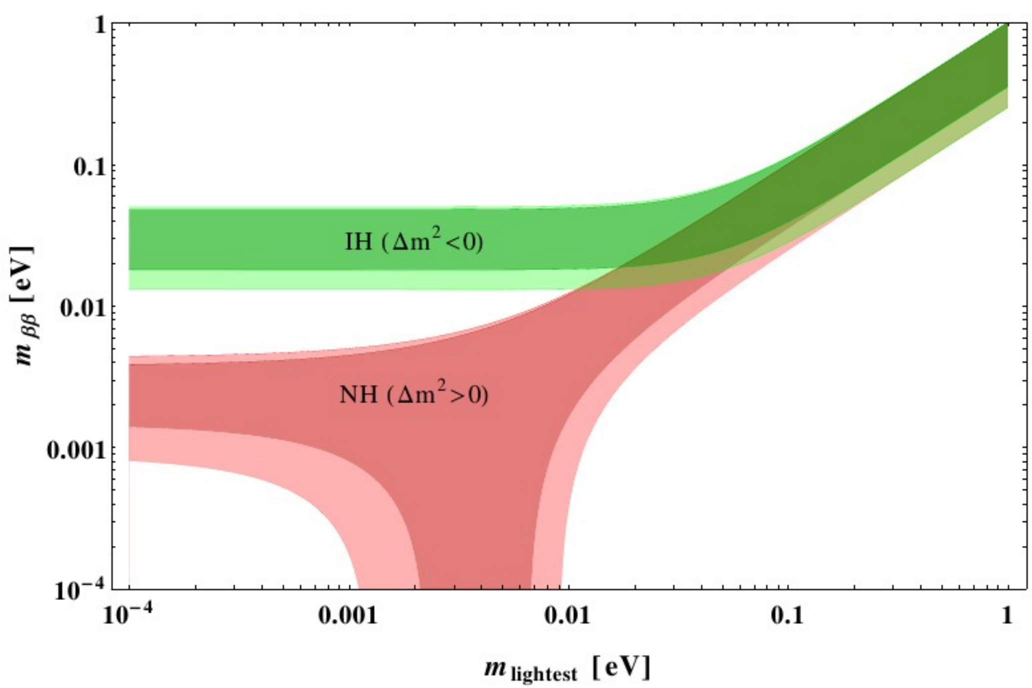
$\tau^- \rightarrow 2\pi^-\pi^+\nu_\tau$
$\quad\quad 3\pi^- 2\pi^+(\pi^0)\nu_\tau$ $\quad (m_{\nu_\tau}^{\text{eff}})^2 = \sum_{j=1}^{3} |U_{\tau j}|^2 m_j^2 \quad m_{\nu_\tau}^{\text{eff}} < 18.2\,\text{MeV}$ (95% C.L.).

Neutrinoless double beta-decay



Allowed by Standard Model

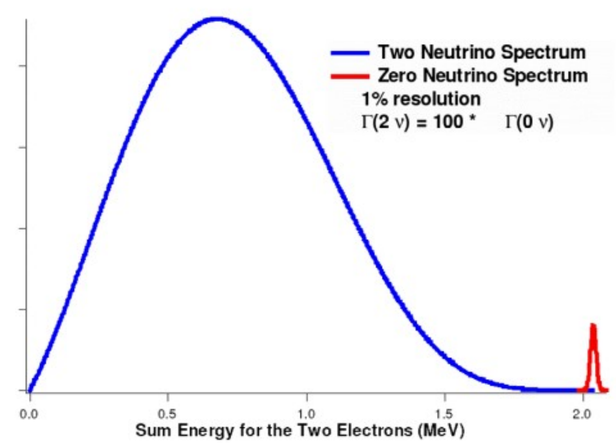
Physics beyond Standard Model



- Neutrinos might be Majorana fermions. "They are their own antiparticle".
- Majorana mass does not require left and right-handed states (as the Higgs-based one does, a.k.a. as Dirac mass).
- The Majorana nature of neutrinos can be tested by looking for neutrinoless double beta-decay.

$$T^{0\nu}_{1/2}(X) = \left[G^{0\nu}_X \left|\mathcal{M}^{0\nu}_X\right|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2 \right]^{-1}$$

$$m_{\beta\beta} = \left| \sum_{j=1}^{3} U^2_{ej} m_j \right|$$
$$= \left| c^2_{12} c^2_{13} m_1 + \mathrm{e}^{2\mathrm{i}\alpha_1} s^2_{12} c^2_{13} m_2 + \mathrm{e}^{2\mathrm{i}(\alpha_2-\delta)} s^2_{13} m_3 \right|$$



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.

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

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

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”.
  - $N_{eff} = 3.046$