Short-baseline neutrino experiments and phenomenology

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COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

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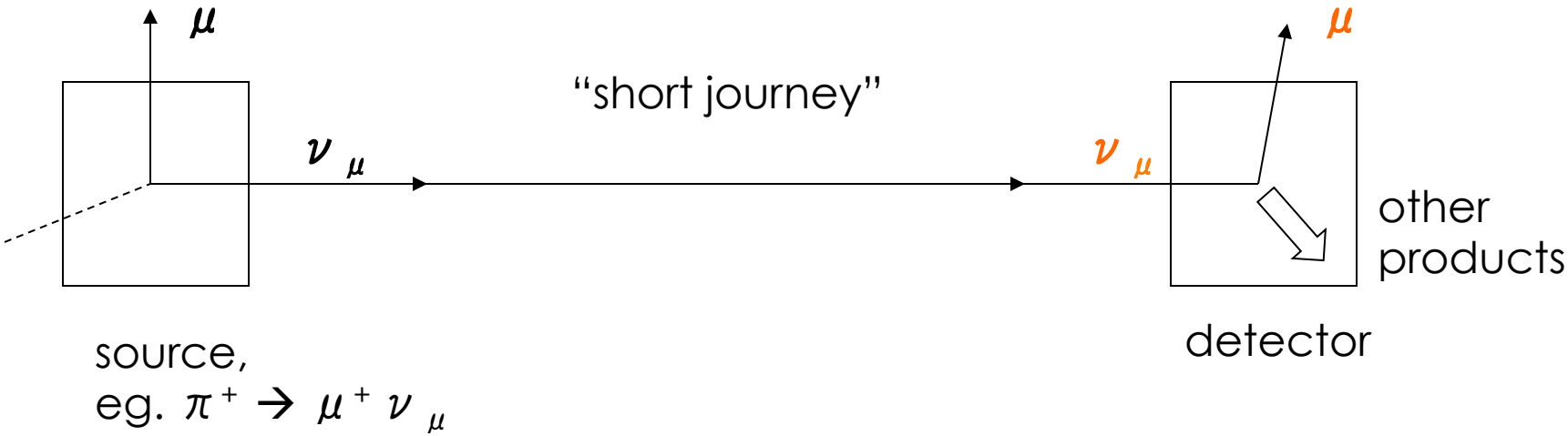
12th International Neutrino Summer School
Fermilab

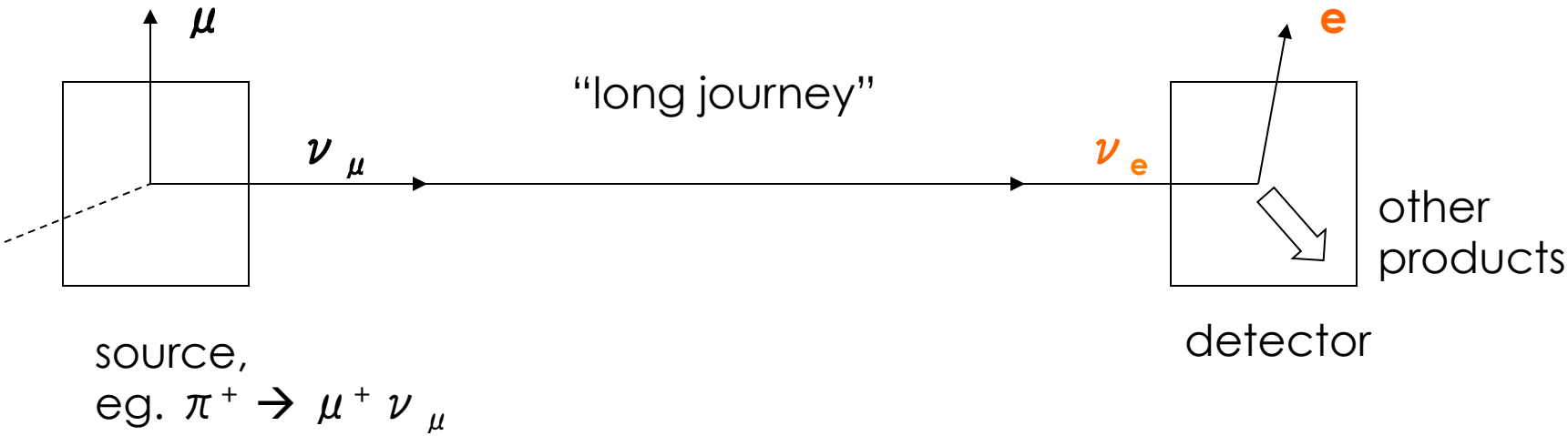
Neutrino Oscillation: Refresh

How do we detect neutrinos experimentally?



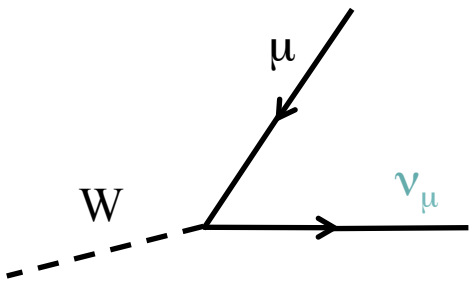
Neutrino Oscillation: Refresh

Experimental effect of neutrino oscillation:

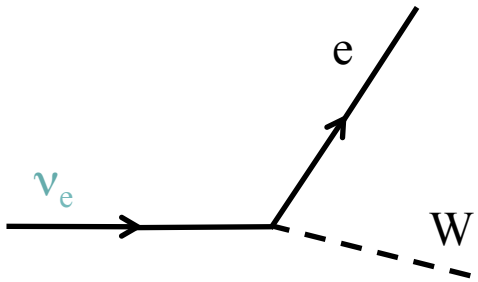


This change from one state to another is what we call ***oscillation.***

Neutrino Oscillation: Refresh



neutrino production



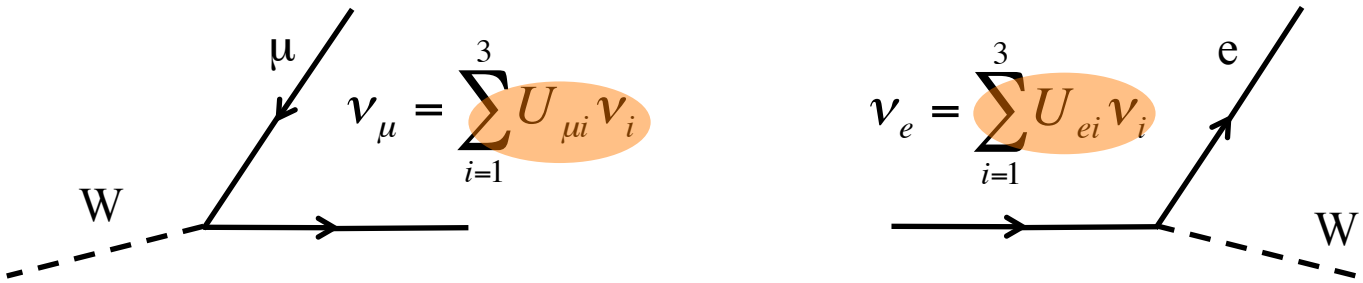
neutrino detection

Neutrinos are produced and detected as one of three definite weak eigenstates: ν_e, ν_μ, ν_τ

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3}e^{i\delta} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

weak eigenstates — 3×3 unitary mixing matrix *U* — mass eigenstates

Neutrino Oscillation: Refresh



neutrino production

neutrino detection

Neutrinos are produced and detected as one of three definite ~~weak eigenstates: ν_e, ν_μ, ν_τ~~

sums over three mass eigenstates: ν_1, ν_2, ν_3

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weak eigenstates

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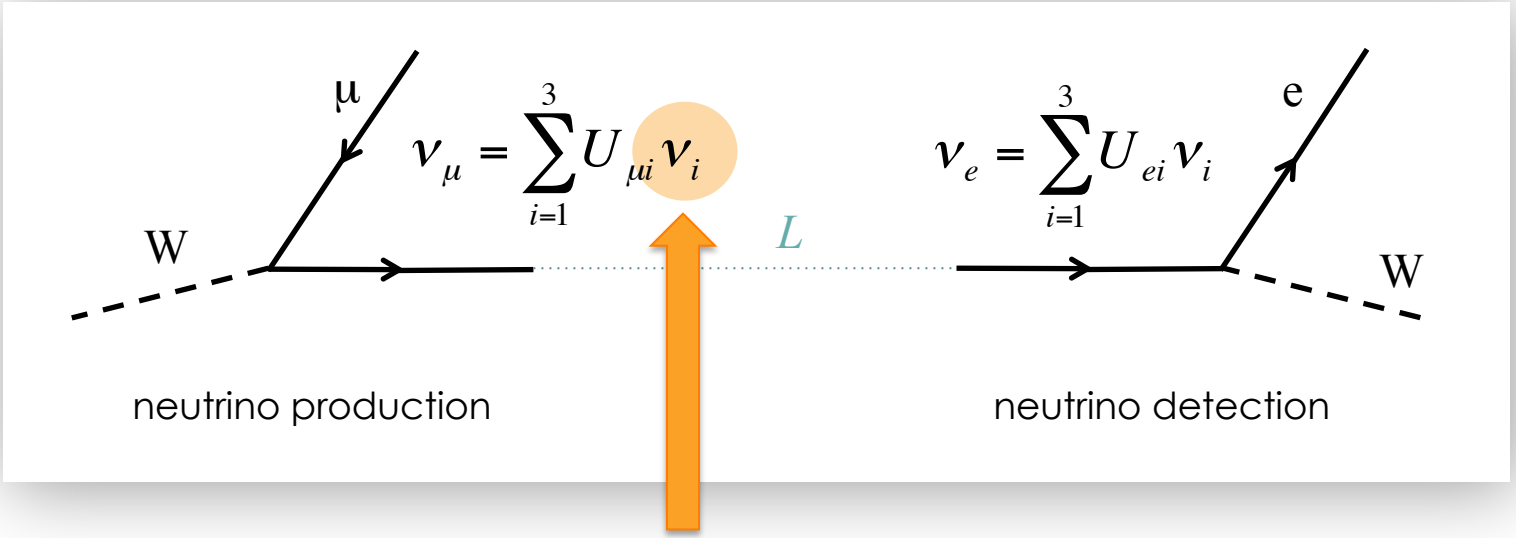
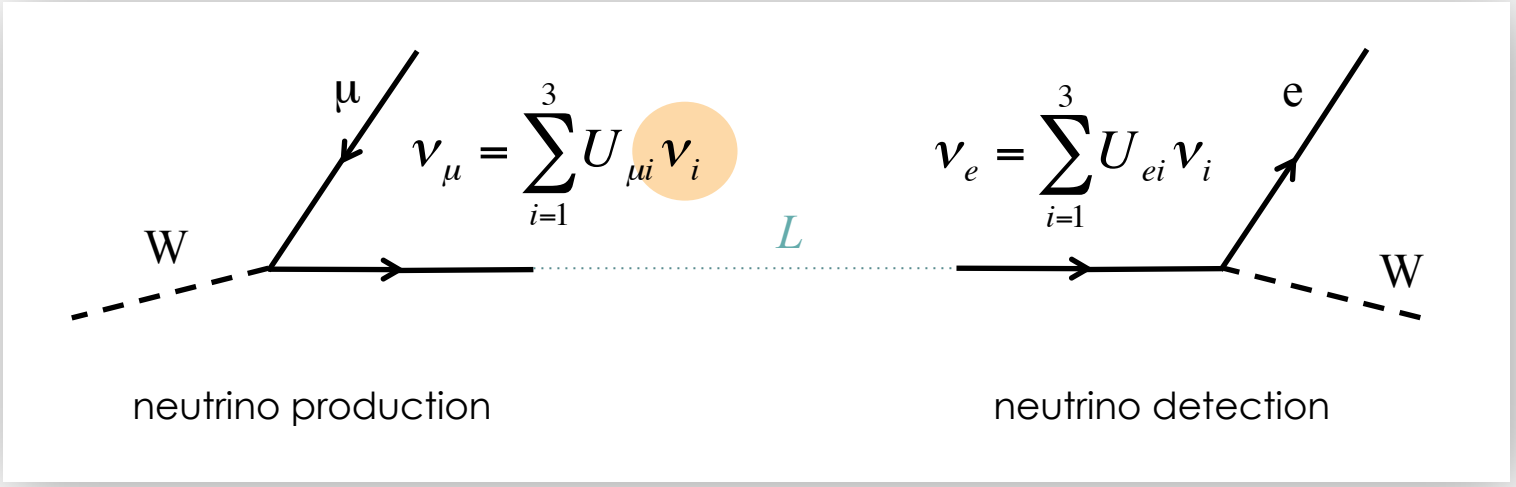
mass eigenstates

Neutrino Oscillation: Refresh



If m_i are distinct, after traveling some distance L, the ν_i get out of phase with each other. Their sum no longer corresponds to a ν_μ!

Neutrino Oscillation: Refresh



Probability of ν_α production followed by ν_β detection after some distance L:

$$P(\nu_\alpha \to \nu_\beta) = \left|\langle \nu_\beta | \nu_\alpha(t) \rangle\right|^2 = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left\{U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right\} \sin^2\left[1.27\Delta m^2_{ij} L/E\right]$$

$$P\left(\nu_\alpha \xrightarrow{\alpha\neq\beta} \nu_\beta\right) = \sin^2 2\theta_{\alpha\beta} \sin^2\left(1.27\Delta m^2_{\beta i} L/E\right)$$

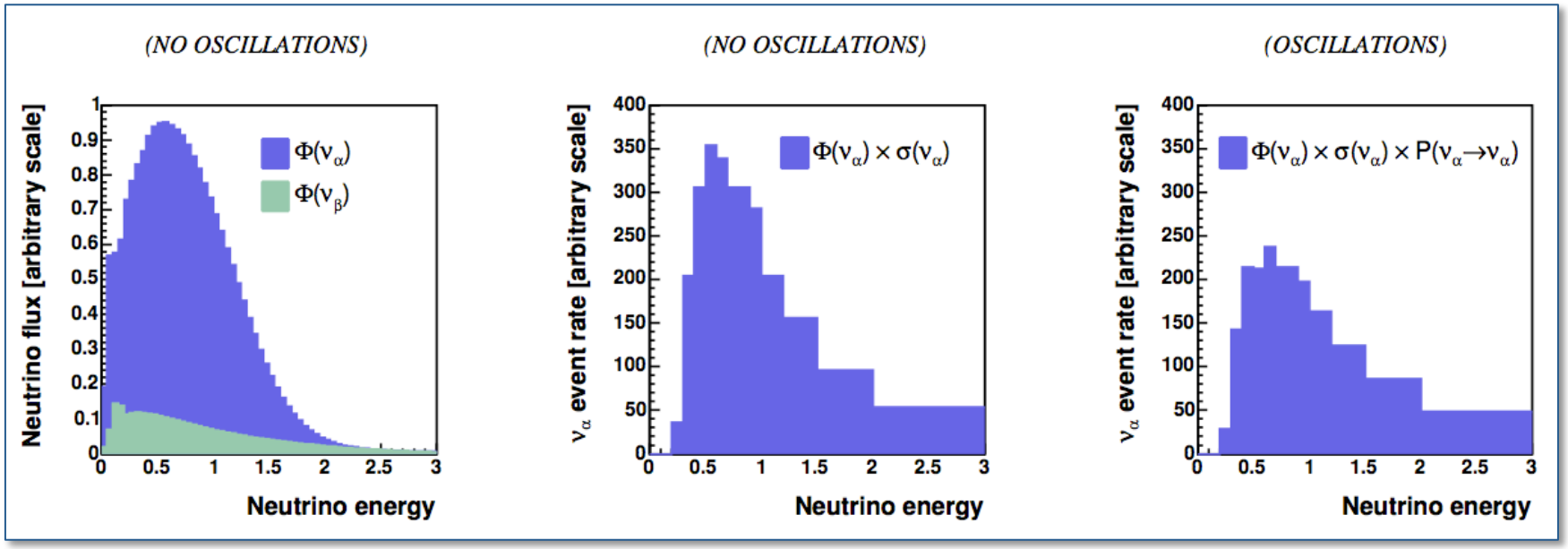
$$P\left(\nu_\alpha \to \nu_\alpha\right) = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2\left(1.27\Delta m^2_{\alpha i} L/E\right) + 2\sum_{i>j} \mathrm{Im}\left\{U^*_{\alpha i} U_{\alpha i} U^*_{\alpha j} U_{\alpha j}\right\} \sin\left[2.54\Delta m^2_{ij} L/E\right],$$

"two-neutrino approximation"

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

Neutrino Oscillation: Signatures

Neutrino disappearance signature: $\nu_\alpha \rightarrow \nu_\alpha$



$$P\left(\nu_\alpha \rightarrow \nu_\alpha\right) = 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(1.27\Delta m^2 L / E\right)$$

- Neutrino flux is primarily ν_α, with very small ν_β contamination.
- **Look for deficit of ν_α events with the "right" energy dependence.**

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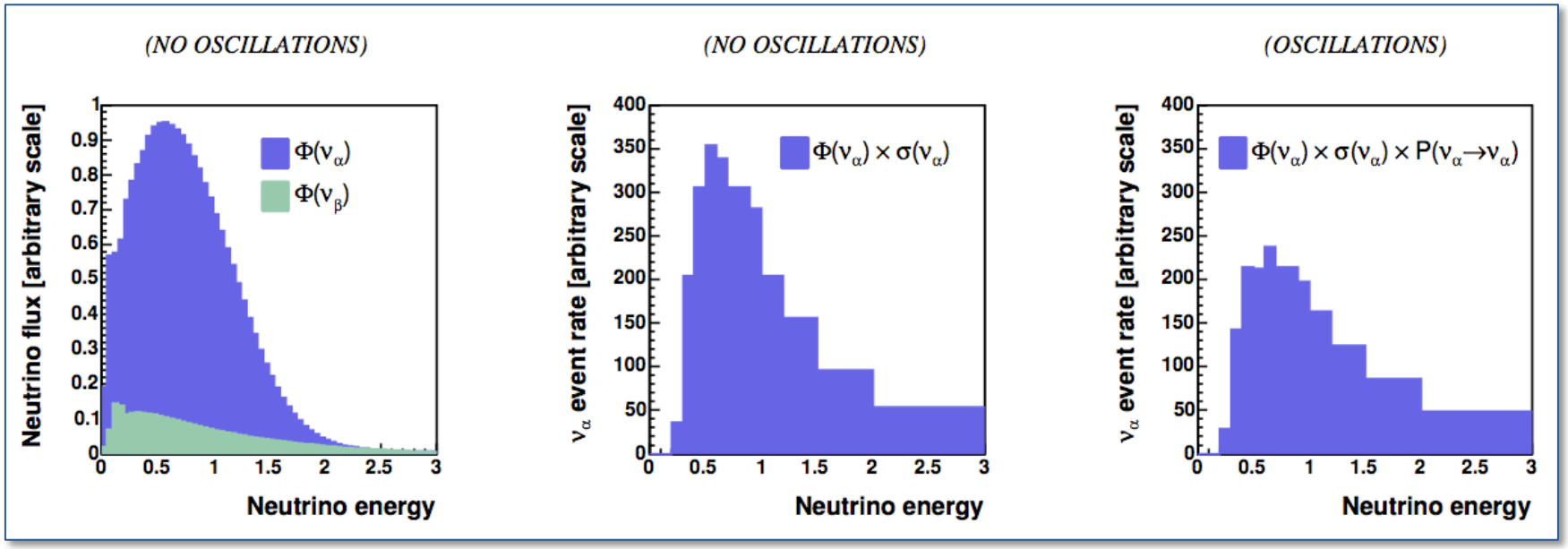

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number of signal events (E) =

ν_α flux (E) x oscillation probability (E) x ν_α cross section (E) x detector efficiency (E)

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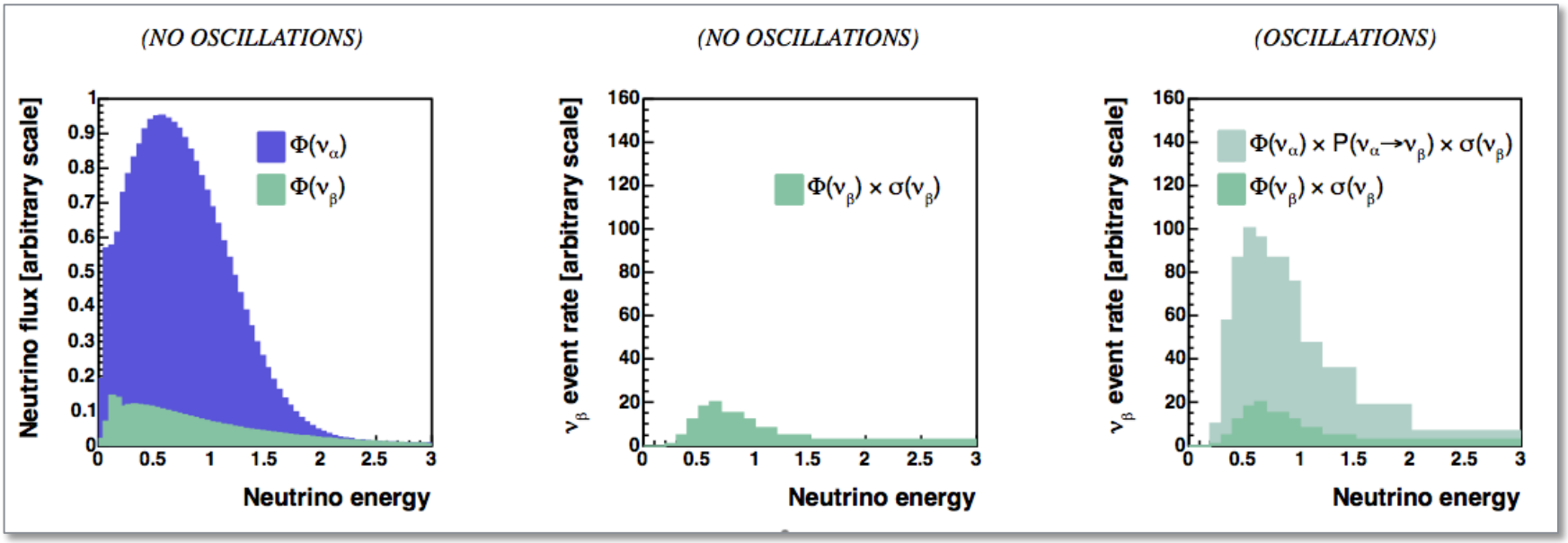
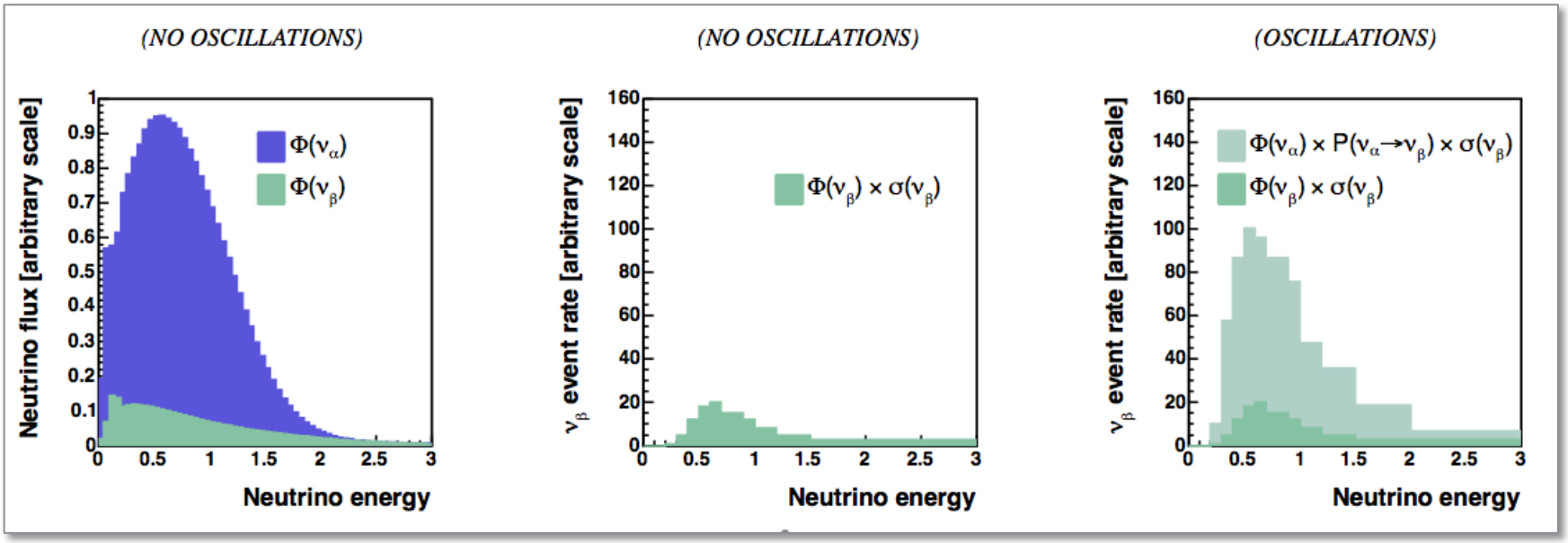


$$P\left(\nu_\alpha \rightarrow \nu_{\beta\neq\alpha}\right) = \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(1.27\Delta m^2 L / E\right)$$

- Neutrino flux is primarily ν_α, with very small ν_β contamination.
- **Look for excess ν_β events with the "right" energy dependence.**

Neutrino Oscillation: Signatures

Neutrino appearance signature: $\nu_\alpha \rightarrow \nu_{\beta \neq \alpha}$



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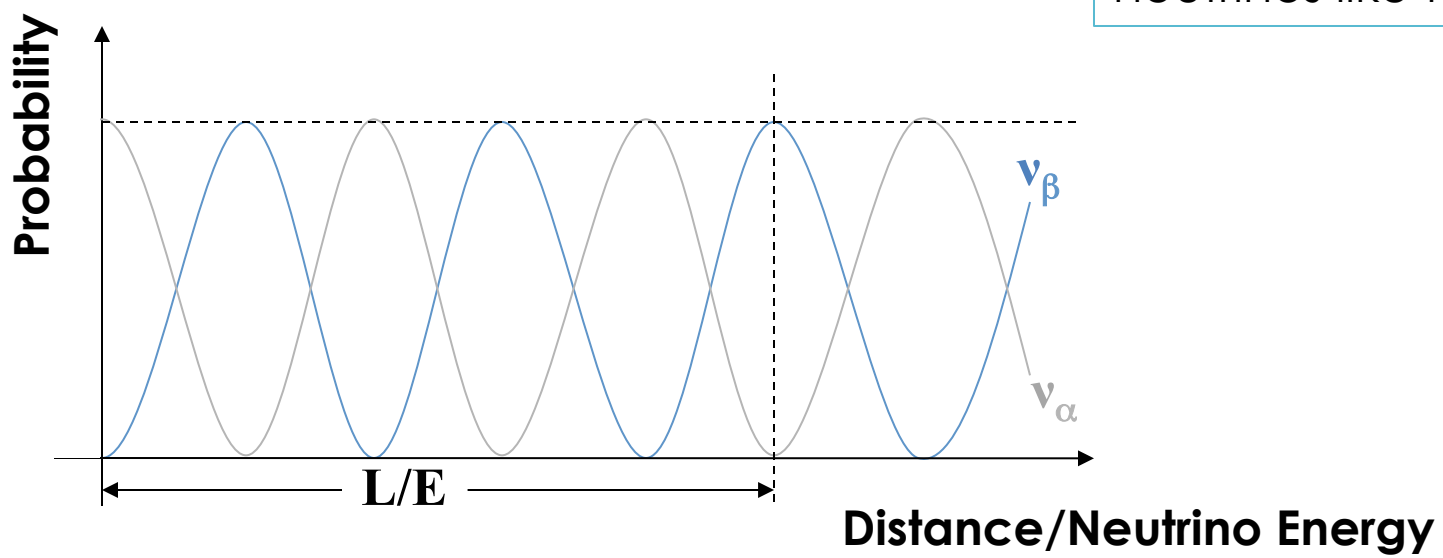
$$P\left(\nu_\alpha \to \nu_{\beta\neq\alpha}\right) = \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(1.27\Delta m^2 L/E\right)$$

$$P\left(\nu_\alpha \to \nu_\alpha\right) = 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(1.27\Delta m^2 L/E\right)$$

oscillation amplitude; "how much" neutrinos like to oscillate

oscillation frequency; "how quickly," as a function of L/E, neutrinos like to oscillate



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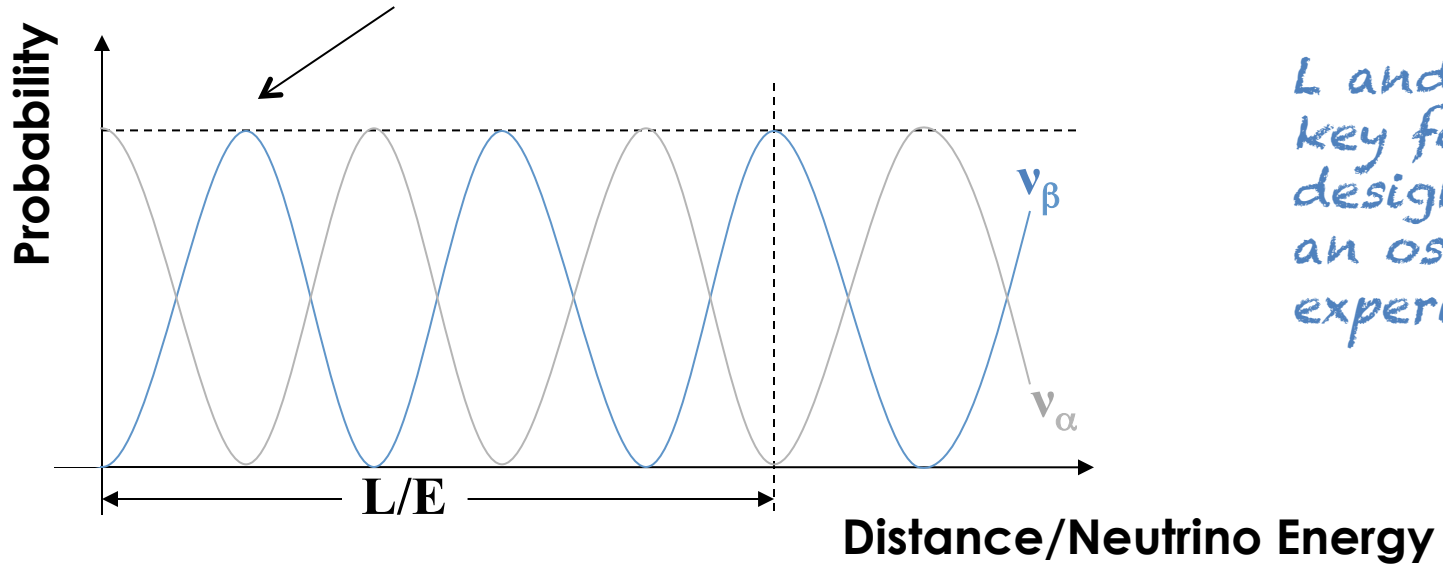
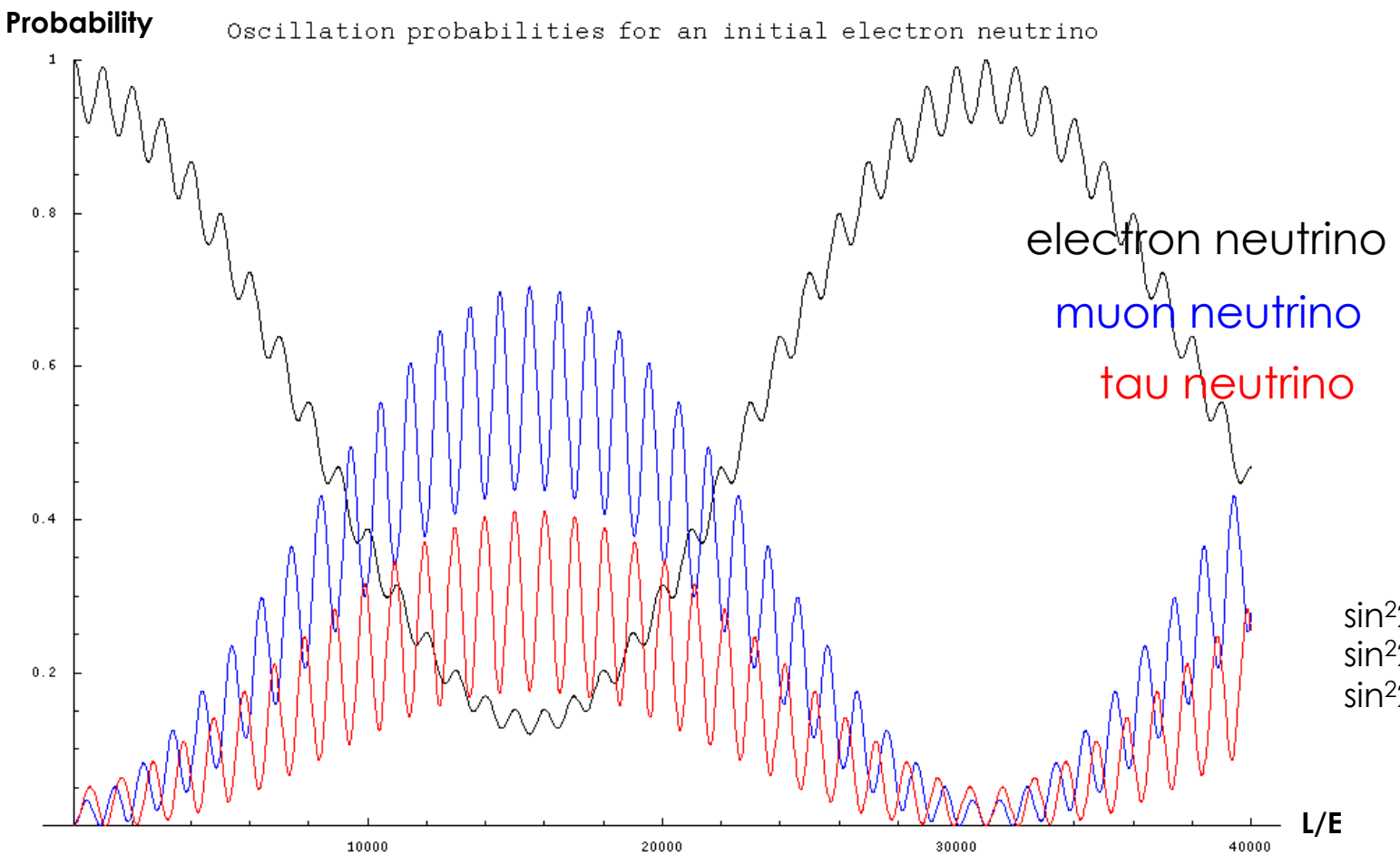
"First oscillation maximum": $(1.27\ \Delta m^2\ L/E) = \pi/2$



L and E are key for designing an oscillation experiment!

Neutrino Oscillation: Refresh

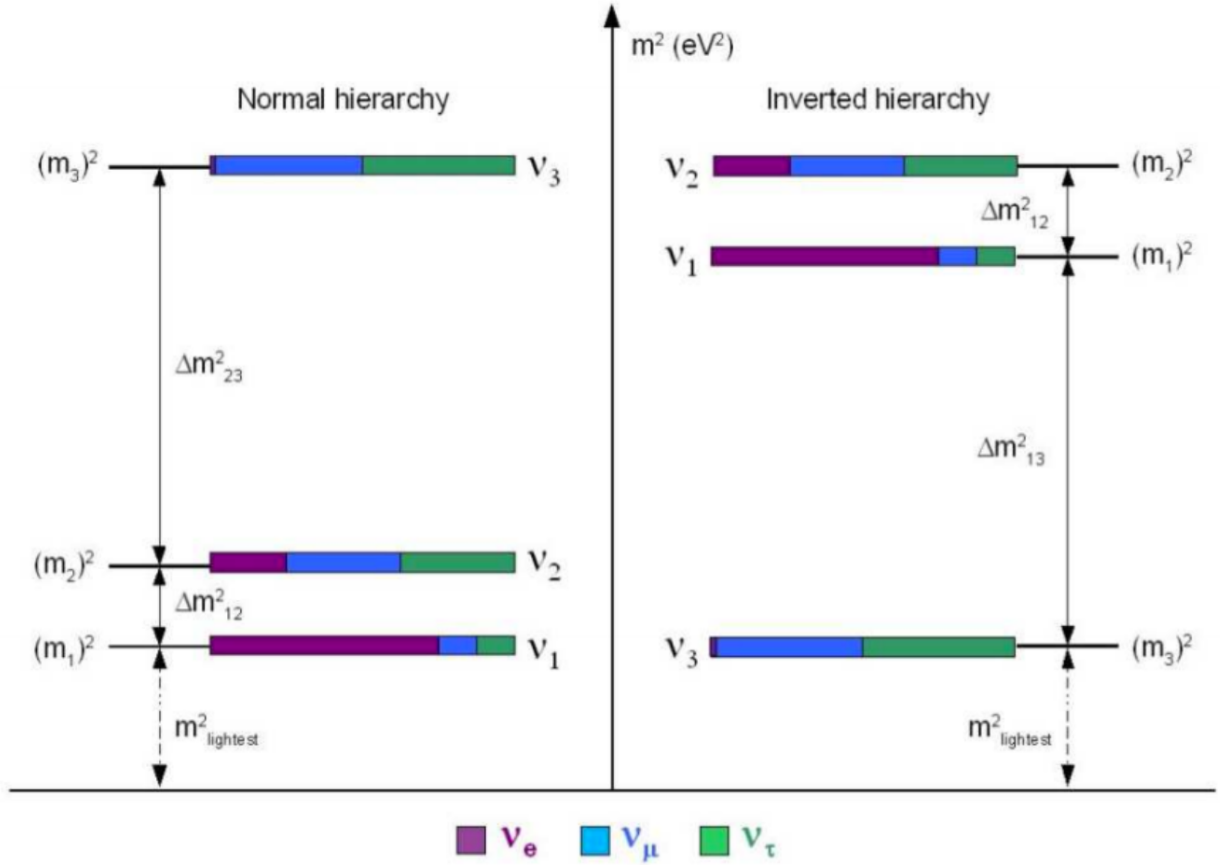
Of course, there are **three neutrinos, and two oscillation frequencies**...



$\sin^2 2\theta_{12} \sim 0.86$
$\sin^2 2\theta_{13} \sim 0.08$
$\sin^2 2\theta_{23} \sim 0.97$

Neutrino Oscillation: Refresh

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3}e^{i\delta} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



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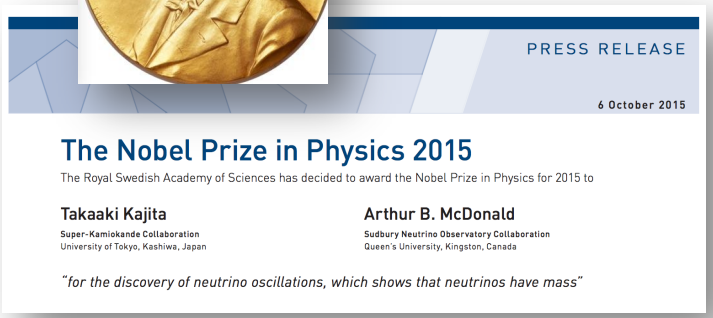


PRESS RELEASE

6 October 2015

The Nobel Prize in Physics 2015

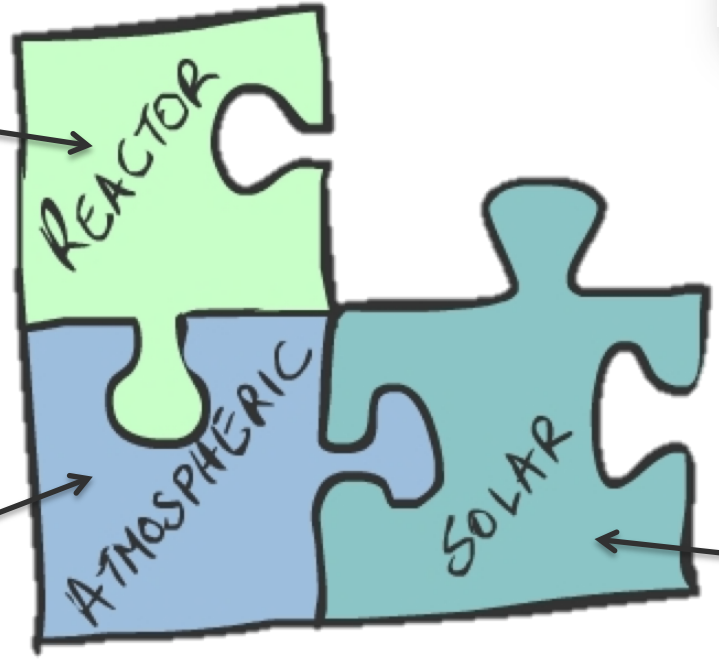
The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2015 to

Takaaki Kajita
Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan

Arthur B. McDonald
Sudbury Neutrino Observatory Collaboration
Queen's University, Kingston, Canada

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

also accelerator long-baseline



also accelerator long-baseline

also reactor long-baseline

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[PDG 2018]

Parameter	best-fit	3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	7.37	$6.93 - 7.96$
$\Delta m^2_{31(23)}$ $[10^{-3}$ eV $^2]$	2.56 (2.54)	$2.45 - 2.69$ $(2.42 - 2.66)$
$\sin^2\theta_{12}$	0.297	$0.250 - 0.354$
$\sin^2\theta_{23}$, $\Delta m^2_{31(32)} > 0$	0.425	$0.381 - 0.615$
$\sin^2\theta_{23}$, $\Delta m^2_{32(31)} < 0$	0.589	$0.384 - 0.636$
$\sin^2\theta_{13}$, $\Delta m^2_{31(32)} > 0$	0.0215	$0.0190 - 0.0240$
$\sin^2\theta_{13}$, $\Delta m^2_{32(31)} < 0$	0.0216	$0.0190 - 0.0242$
δ/π	1.38 (1.31)	2σ: (1.0 - 1.9) (2σ: (0.92-1.88))

Neutrino Oscillation: Refresh

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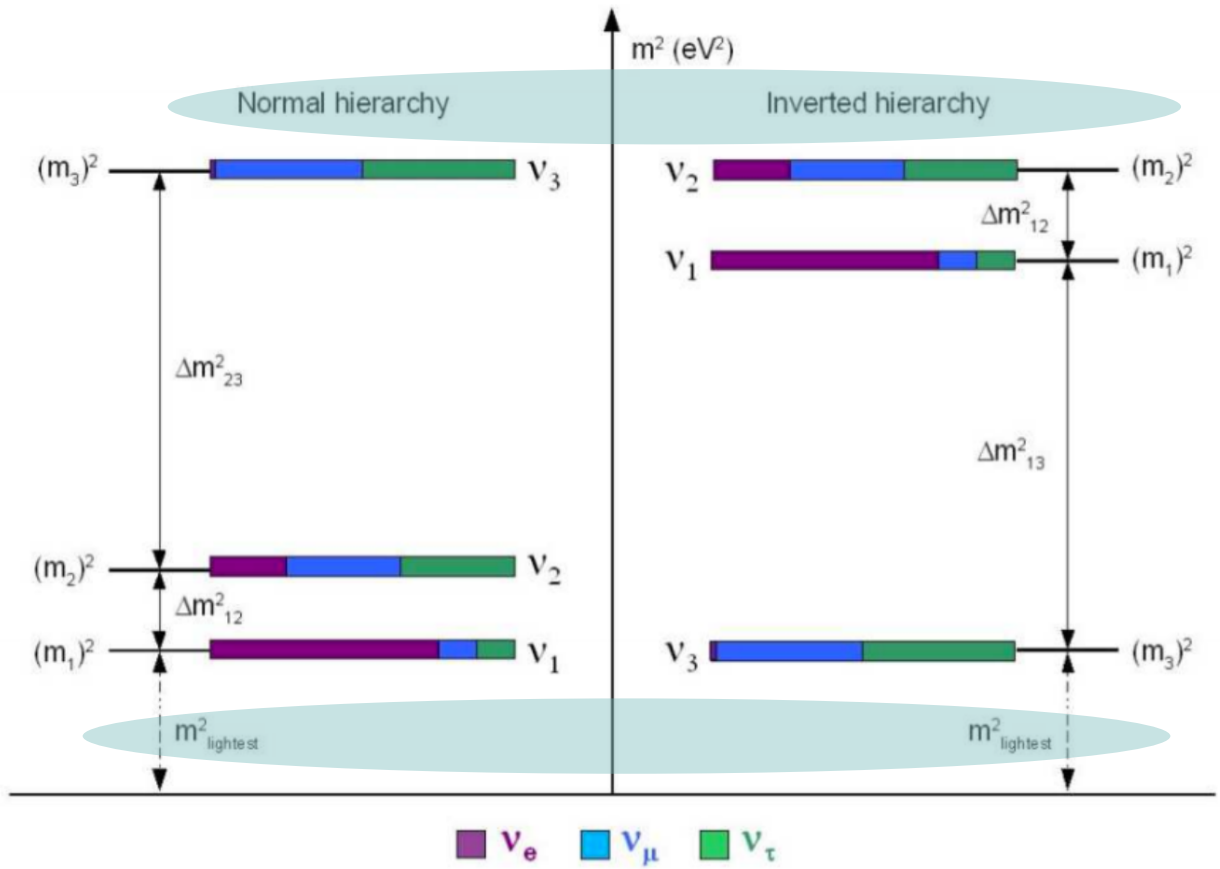
Parameters which are yet to be determined.

CP violation phase

If non-zero, could provide clues about matter-antimatter asymmetry in our universe.

Accessible through accelerator-neutrino oscillation measurements at long baselines.



Long-baseline vs. short-baseline ???

It's all relative (to energy)!

Most terrestrial neutrino sources produce neutrinos of energy:

~1 MeV (reactors) … ~10 GeV (accelerator beams)

For $\Delta m^2 \sim 2.5\text{x}10^{-3}$ eV^2 and $\Delta m^2 \sim 7.4\text{x}10^{-5}$ eV^2

the two-neutrino **oscillation probability is maximized** when

L ~ 500m (1 MeV) and ~200 km (10 GeV)

specifically, when $(1.27\ \Delta m^2\ [\text{eV}^2]\ L[\text{m}] / E\ [\text{MeV}]) \sim \pi/2$,

or when $L[\text{m}] / E\ [\text{MeV}] \sim 1/\Delta m^2\ [\text{eV}^2]$

"Short-baseline" means: $L/E \ll 1/\Delta m^2\ [\text{eV}^2]$

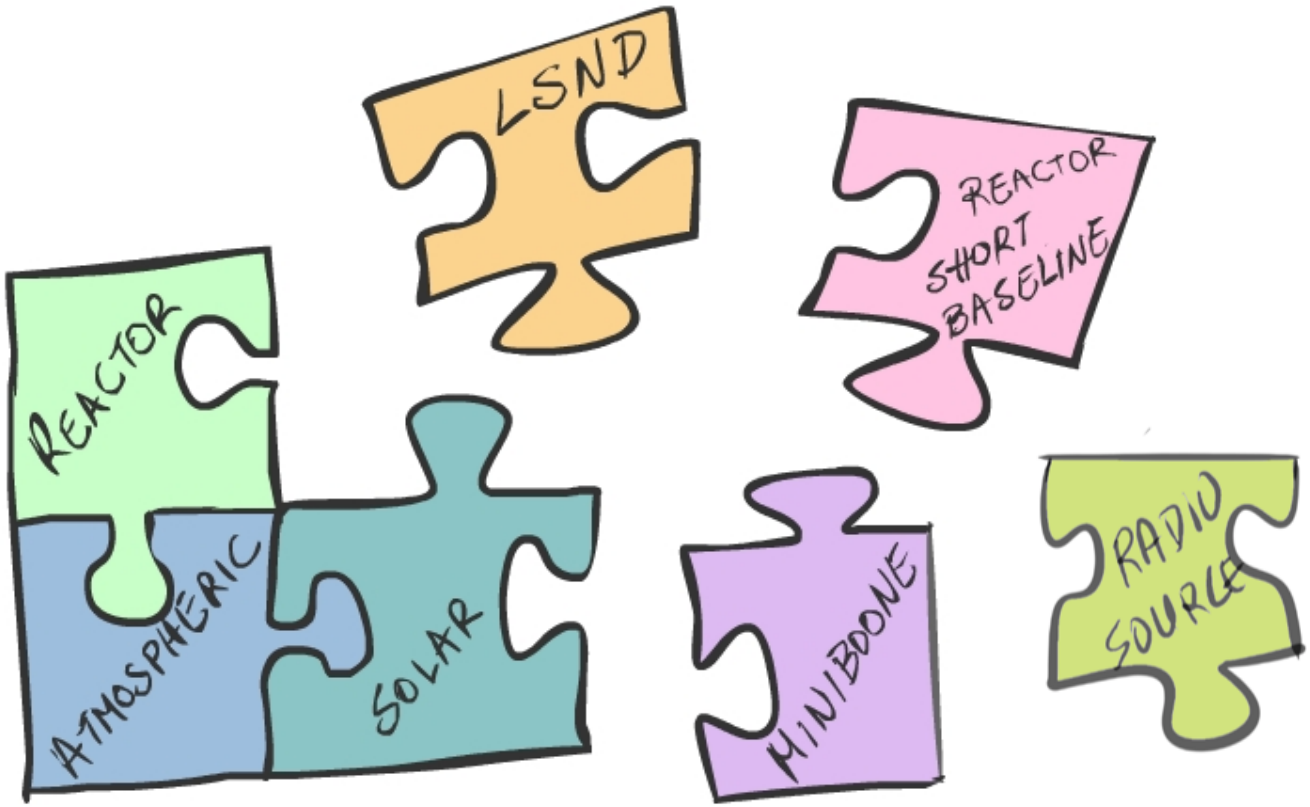
Long-baseline vs. short-baseline ???

At short baselines (L~0), the probability should be 0…

Why short-baseline experiments?

1. Understand neutrinos and their interactions in absence of oscillations!
   – Do we understand their production/flux, interaction/cross-section?
2. Look for deviations which might suggest new physics!
   – High-frequency oscillations (additional neutrino species)?
   – Zero appearance/disappearance probability assumes unitarity of the neutrino mixing matrix
3. Follow-up on anomalous signatures!

Anomalous hints: Is our three-neutrino picture incomplete?



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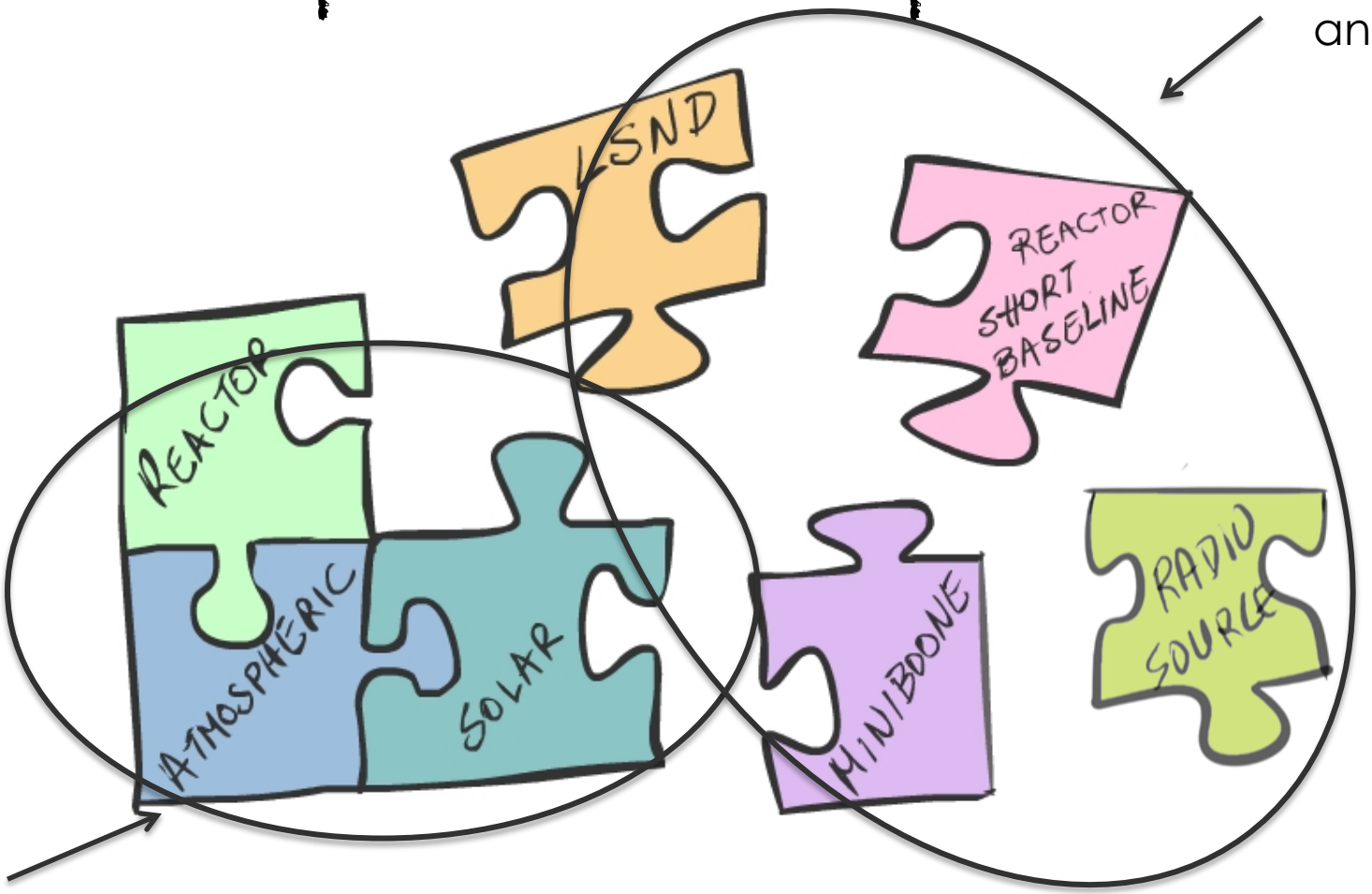
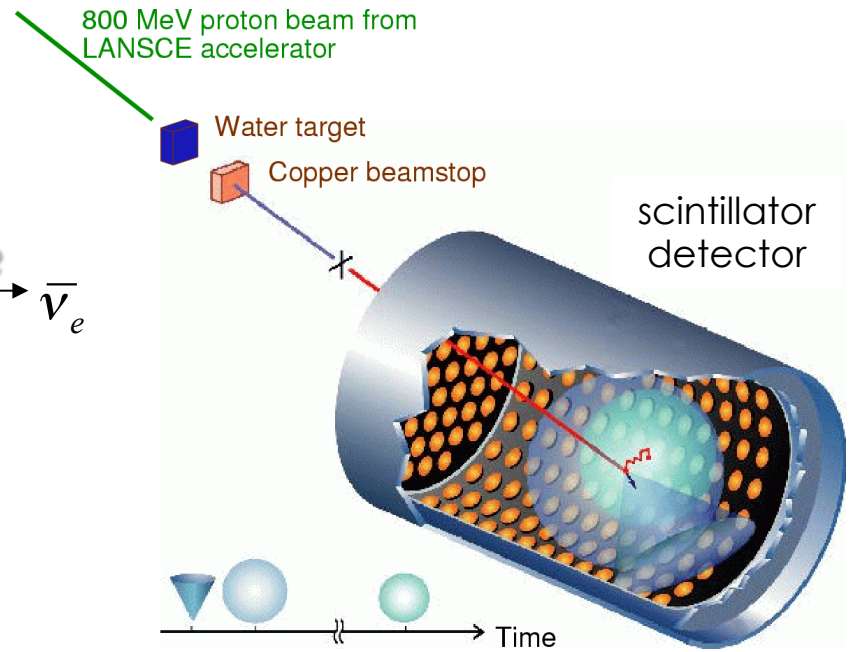


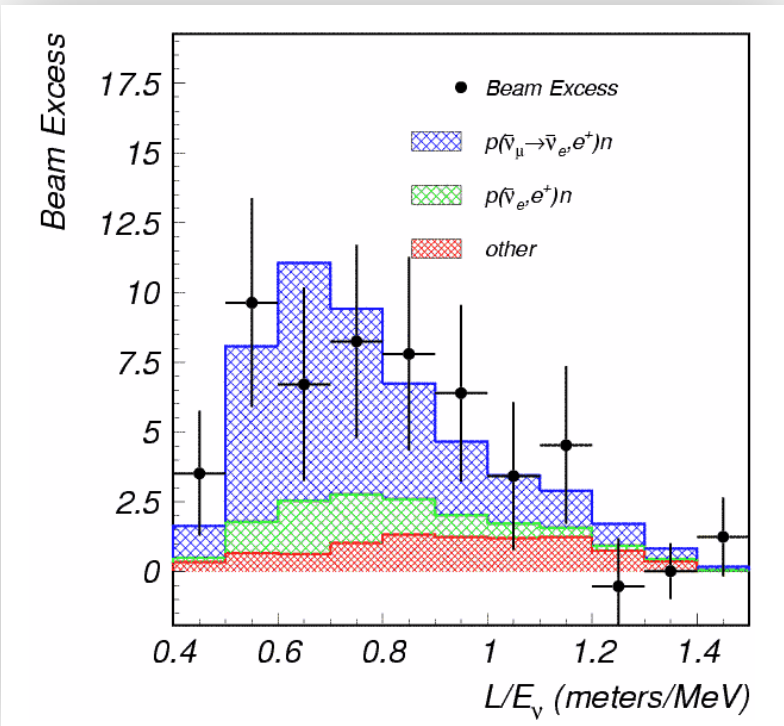
1. Short-baseline anomalies

Liquid Scintillator Neutrino Detector

μ^+ decay-at-rest experiment:

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$
$$\overset{?}{\hookrightarrow} \bar{\nu}_e$$





Observed excess of $\bar{\nu}_e$
described by oscillation probability:
$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = (0.264 \pm 0.067 \pm 0.045)\ \%$

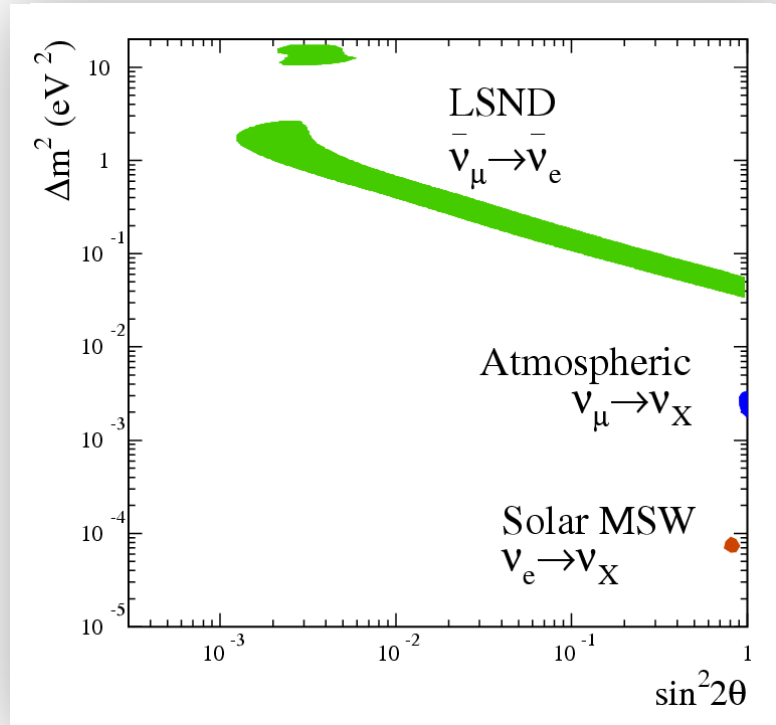
(3.8σ evidence)

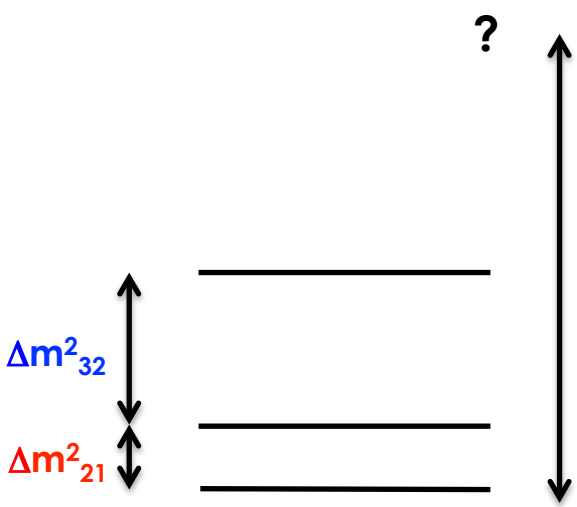
[C. Athanassopoulos et al., Phys. Rev. Lett. 75, 2650 (1995); 81,1774(1998); A.Aguilar et al., Phys. Rev. D64, 112007(2001)]

Liquid Scintillator Neutrino Detector

Points to large Δm^2 if interpreted as two-neutrino oscillations:

$$P(\nu_\mu \to \nu_e) = \sin^2 2\vartheta_{\mu e} \sin^2(1.27\Delta m^2 L/E)$$

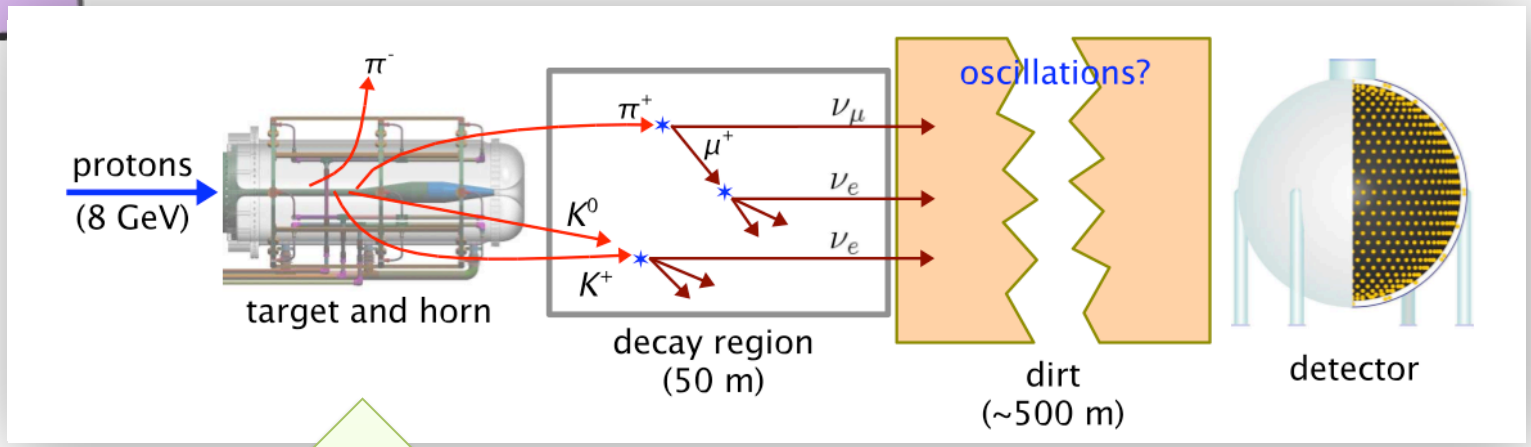




$\Delta m^2_{LSND} >> \Delta m^2_{21} + \Delta m^2_{32}$

Anomalous signature: requires at least four neutrinos to accommodate a **third, independent Δm^2** !

Follow-up to LSND: MiniBooNE



magnetic field polarity selects ν or $\bar{\nu}$

$\pi^+ \rightarrow \mu^+ \nu_\mu$

$\mu^+ \rightarrow \nu_e$?

$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$

$\mu^- \rightarrow \bar{\nu}_e$?

Similar L/E as LSND

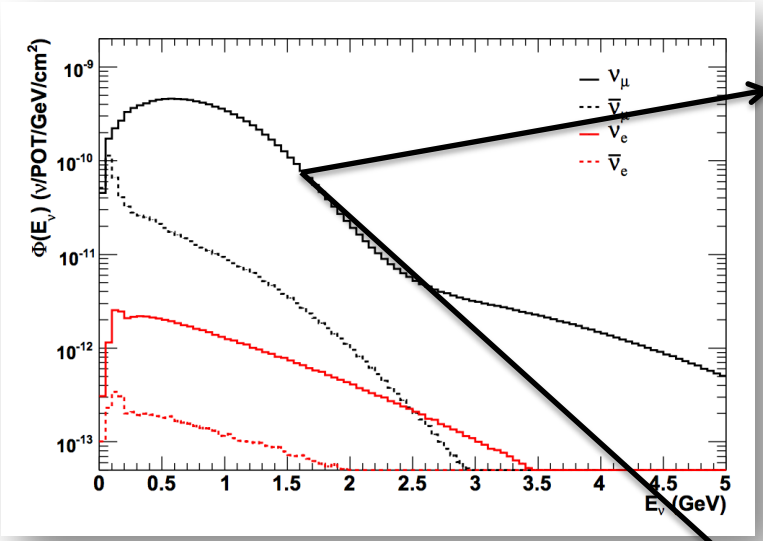
but

Different energy, beam and detector systematics

Different event signatures and backgrounds (Cherenkov detector)

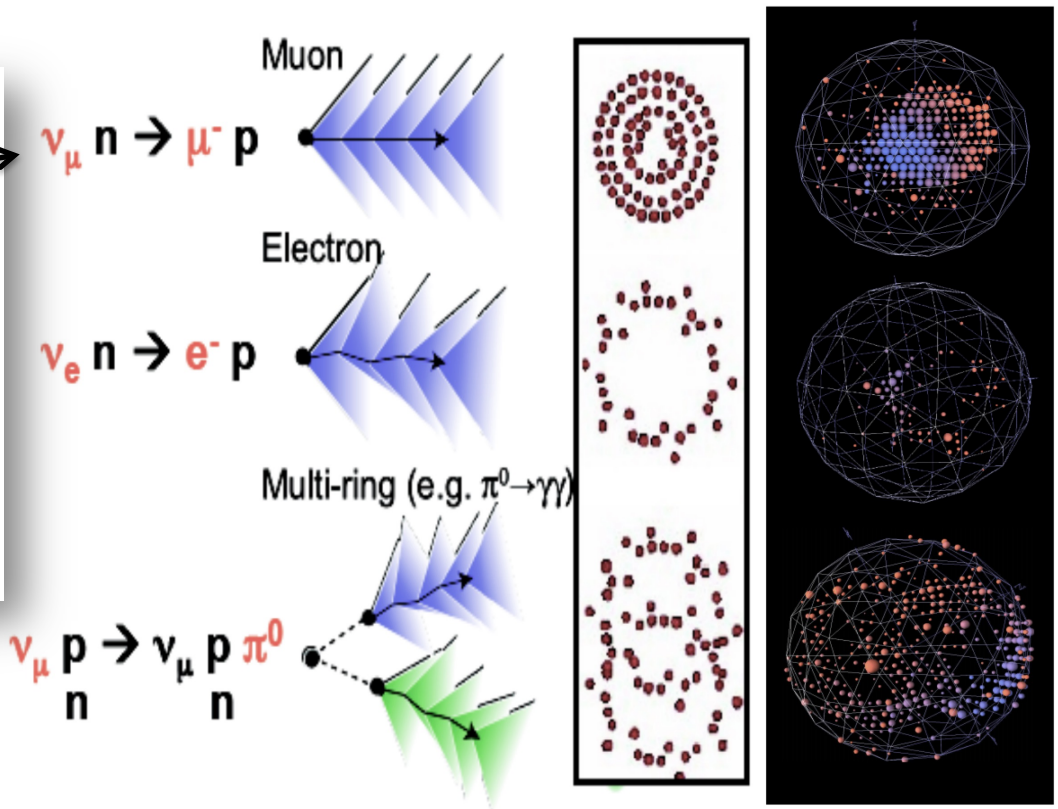
Follow-up to LSND: MiniBooNE

MiniBooNE flux (neutrino mode):



[Phys. Rev. D79 (2009) 072002]

Three main event signatures:



Cherenkov ring topology provides PID

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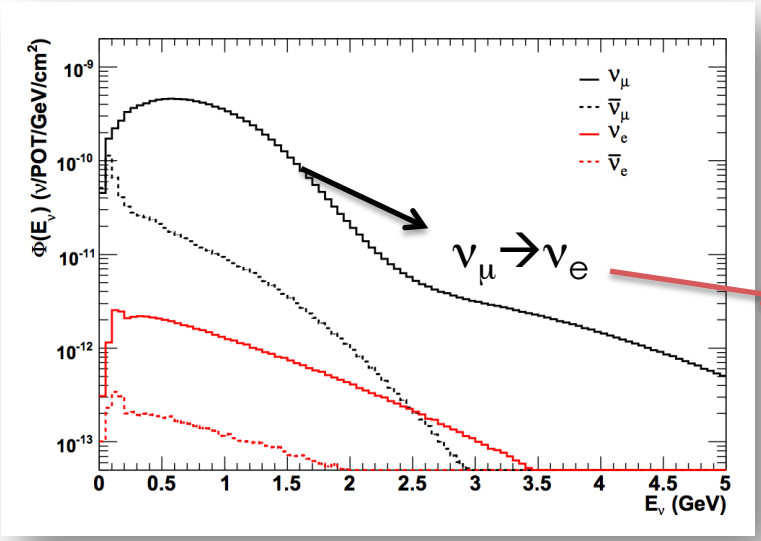

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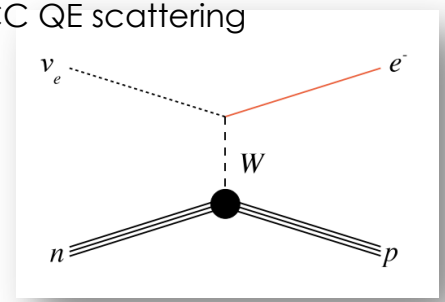
ν_e CC QE scattering



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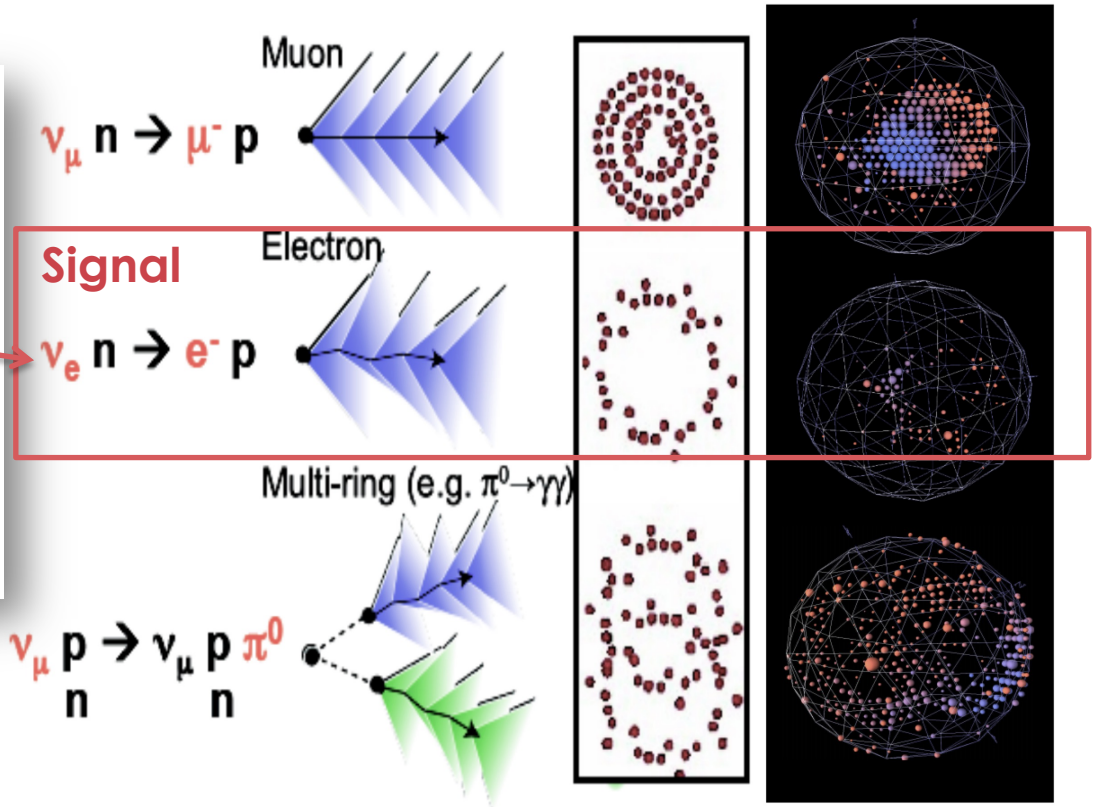

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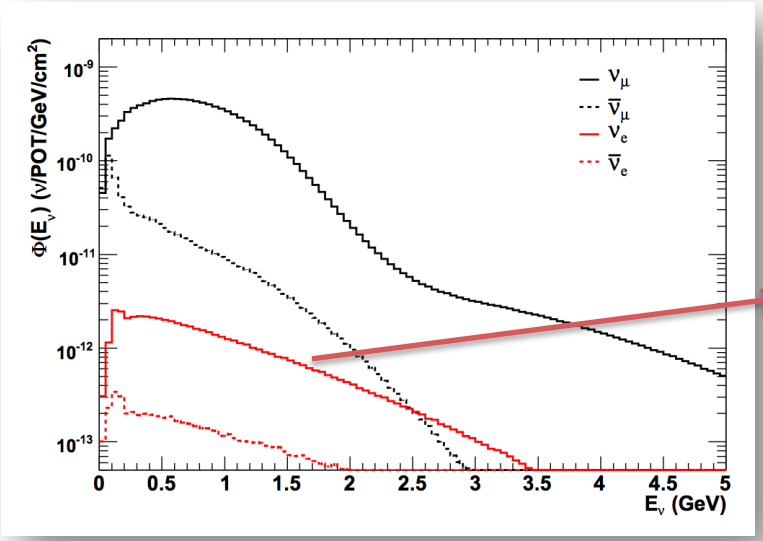
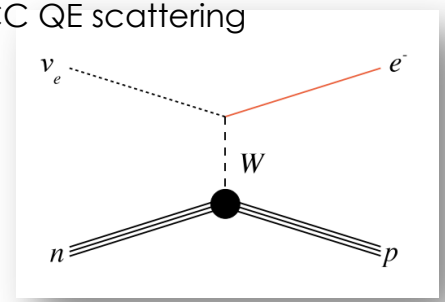
Follow-up to LSND: MiniBooNE

MiniBooNE flux (neutrino mode):

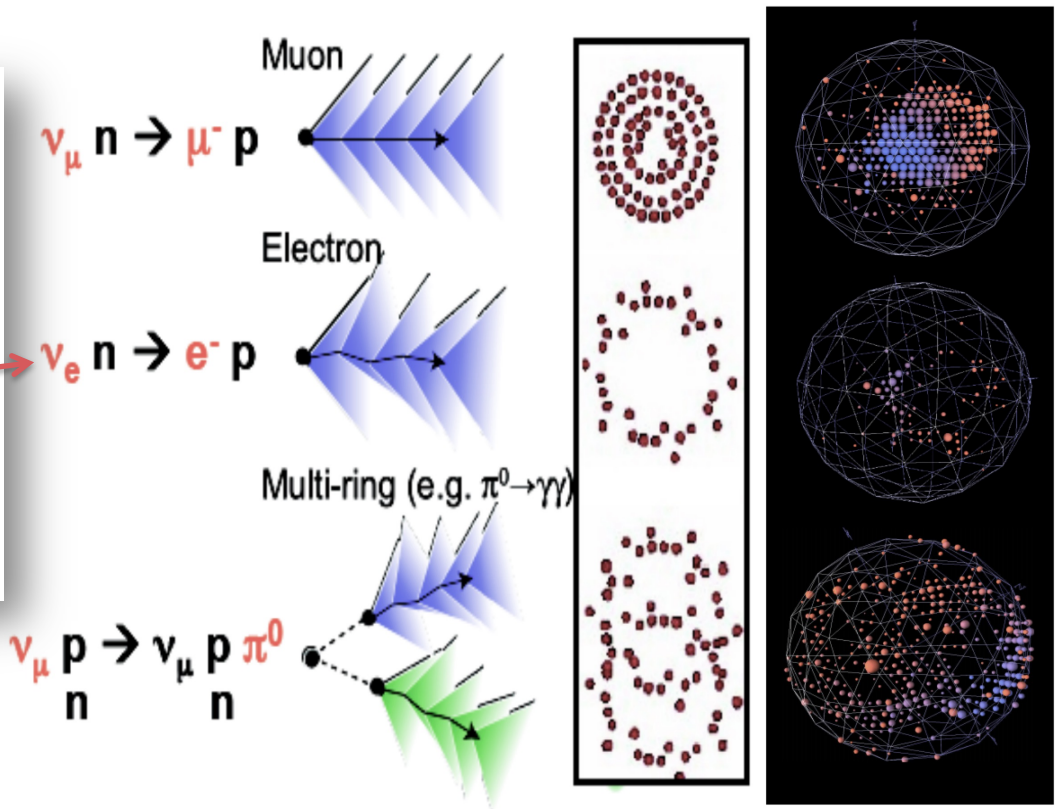


[Phys. Rev. D79 (2009) 072002]

ν_e CC QE scattering



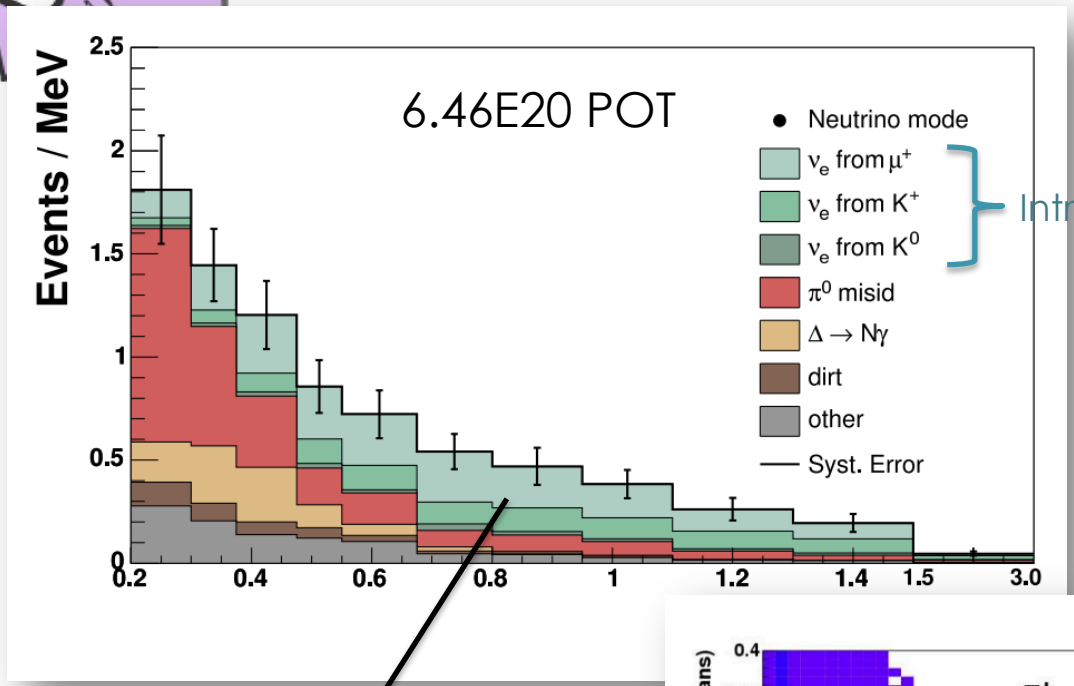
Three main event signatures:



Cherenkov ring topology provides PID

Follow-up to LSND: MiniBooNE

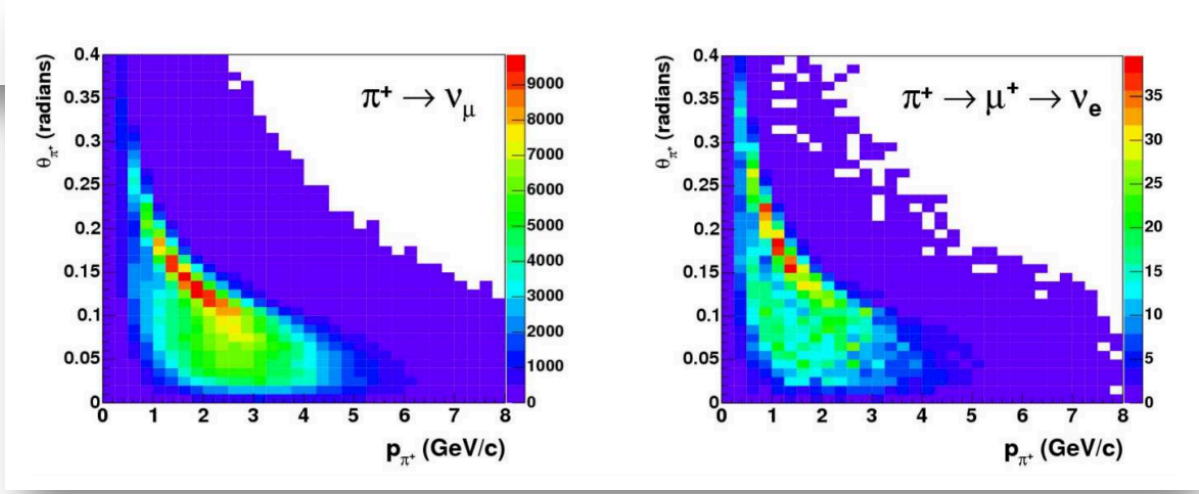
MiniBooNE background (no oscillations) prediction:



Intrinsic beam ν_e backgrounds

Event rate (flux x cross-section) constrained through a **high-statistics measurement of ν_μ CCQE** spectrum in MiniBooNE.

For the most part, **ν_e from $\pi \rightarrow \mu$ decay** (sharing the same ancestors as the high-statistics ν_μ sample)



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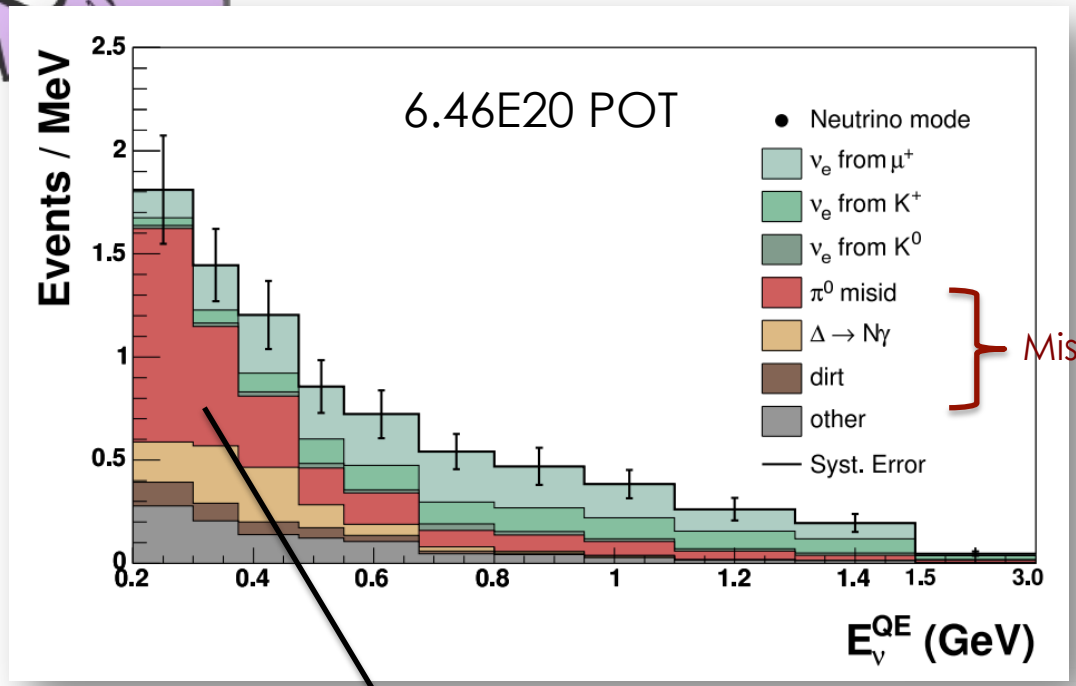
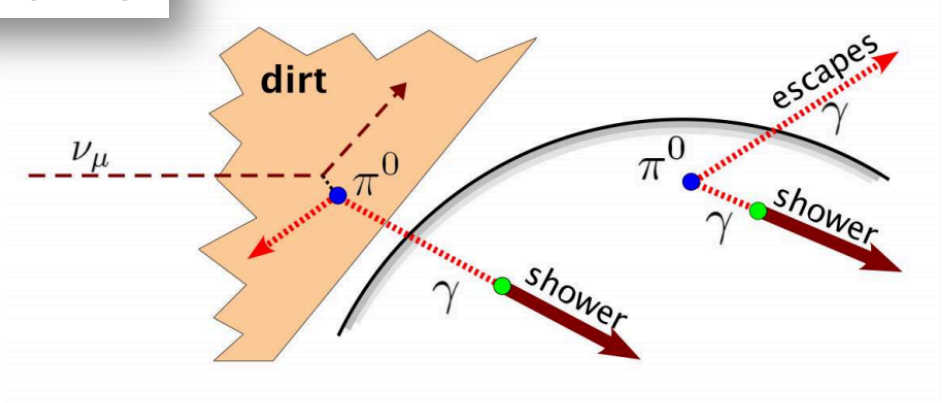
MiniBooNE background (no oscillations) prediction:



Mis-identified γ backgrounds

Majority is contributed from **NC π^0 decays** with mis-reconstructed or escaping γ.



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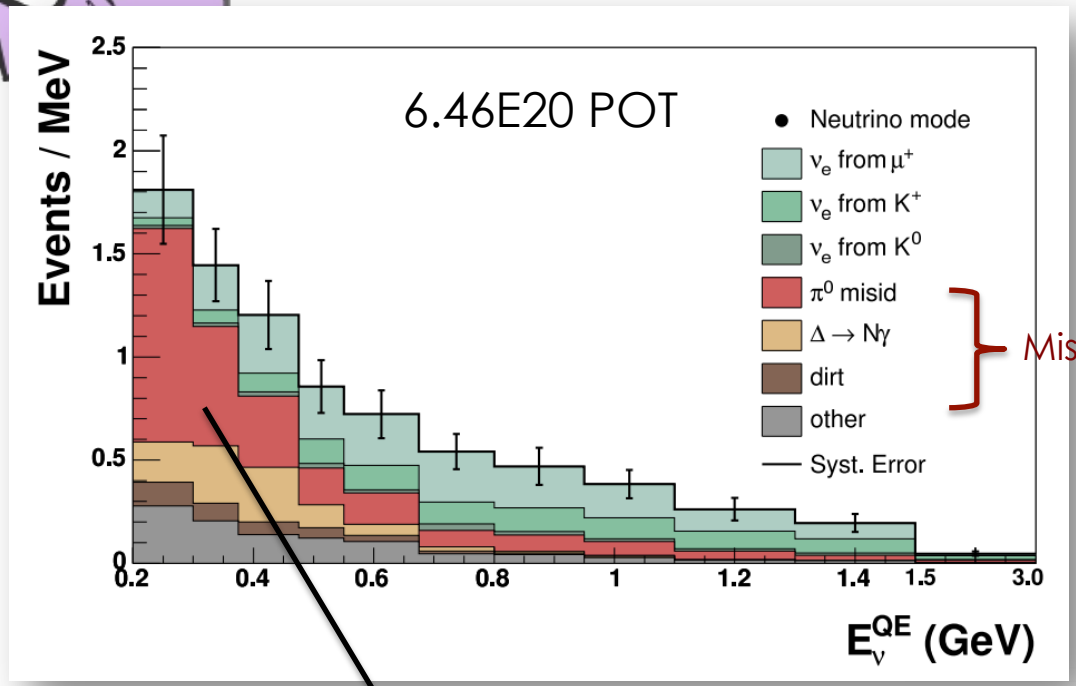
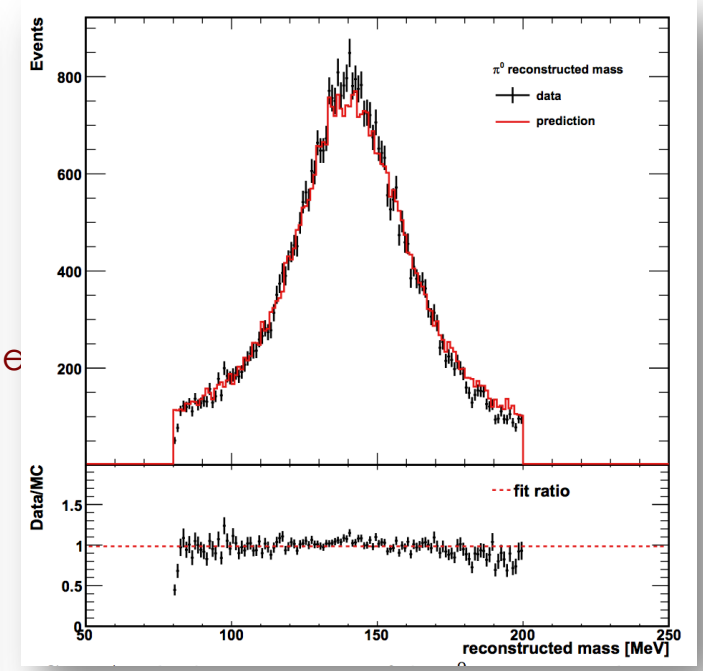
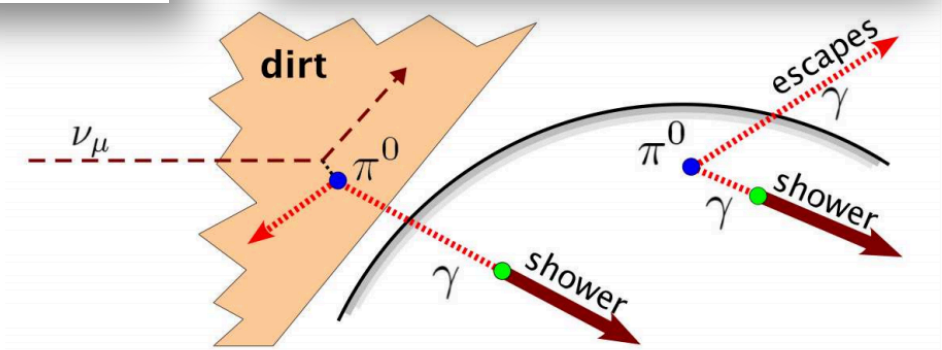


Mis-ide



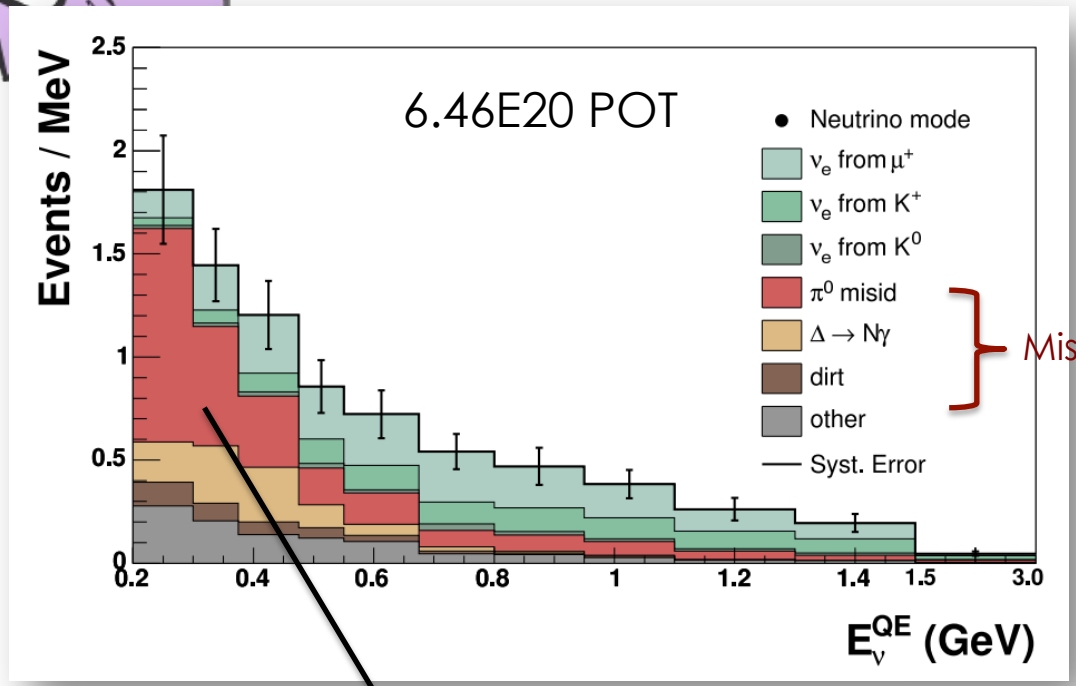
Majority is contributed from **NC π^0 decays** with mis-reconstructed or escaping γ.

$\pi^0 \rightarrow \gamma\gamma$ rate measured in situ and used to constrain overall π^0 mis-ID rate (to ~7%).



Follow-up to LSND: MiniBooNE

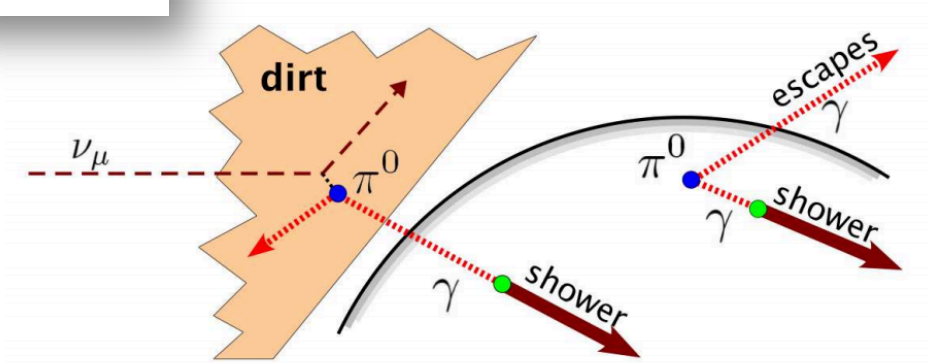
MiniBooNE background (no oscillations) prediction:



Mis-identified γ backgrounds

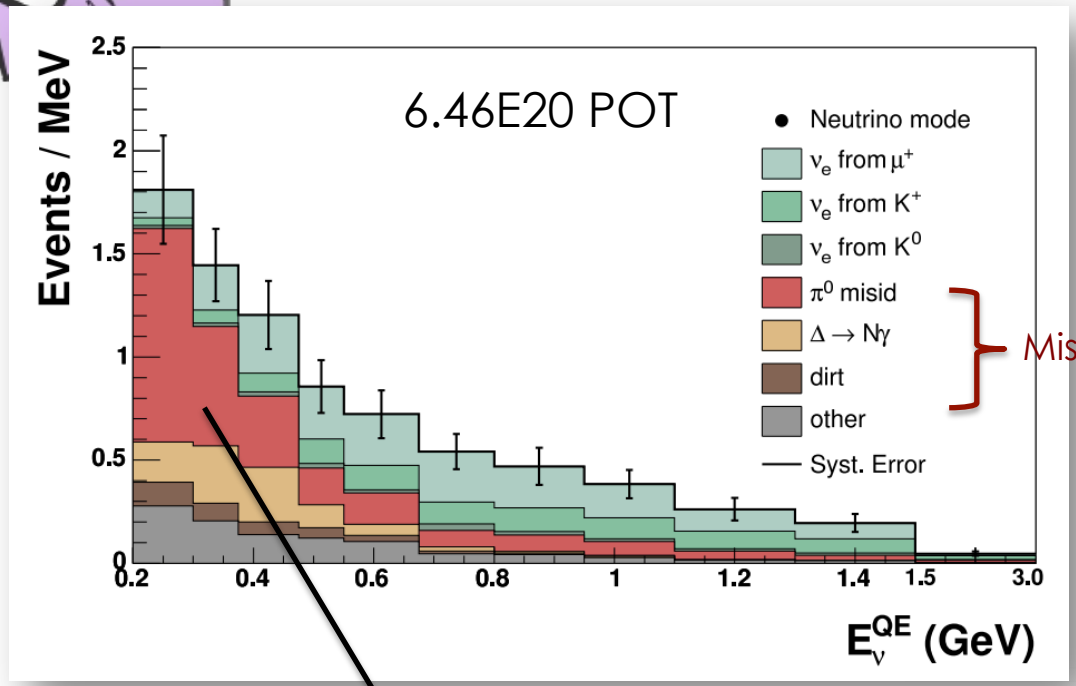
NC resonant production of **Δ followed by radiative decay** is an irreducible background

$\Delta \rightarrow N\gamma$ rate is tied to the NC π^0 rate measured in situ (BR~0.5%), and constrained to ~12%.



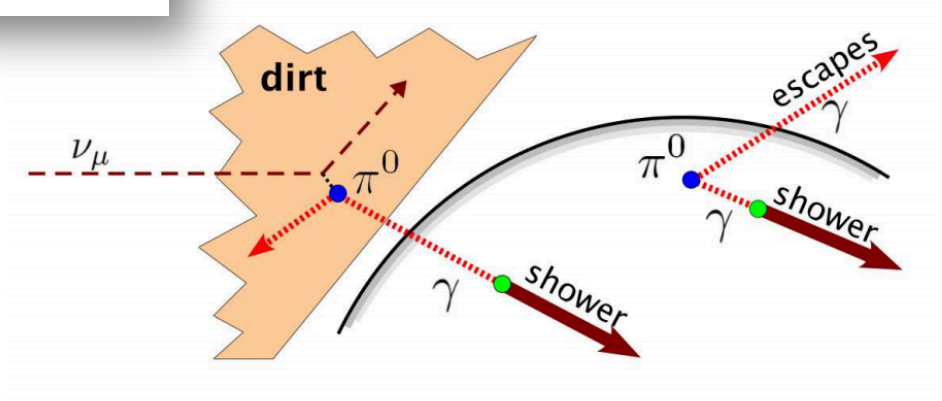
Follow-up to LSND: MiniBooNE

MiniBooNE background (no oscillations) prediction:

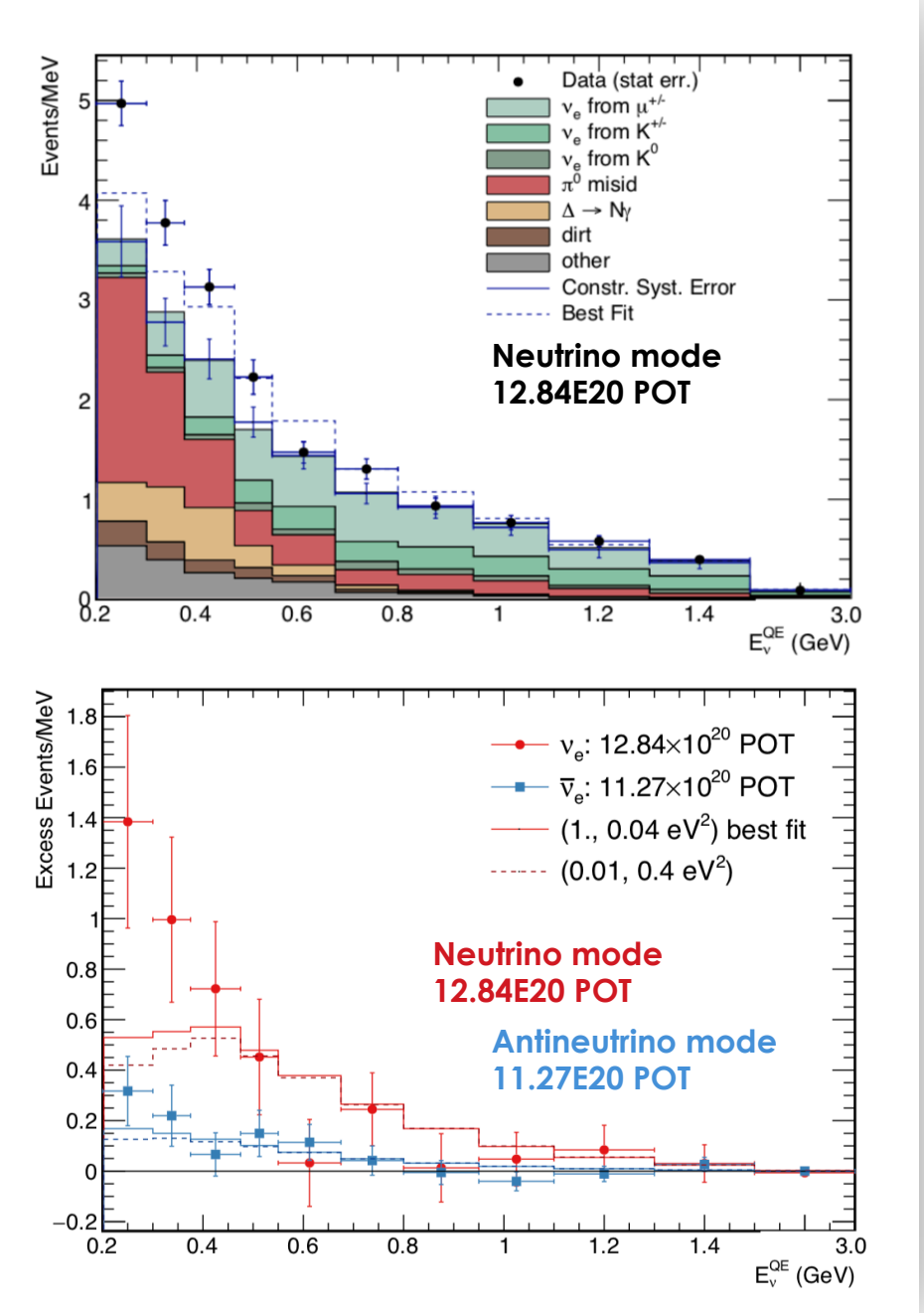


Mis-identified γ backgrounds

"Dirt" events are constrained in situ by isolating a high-radius, low visible energy, inward pointing shower ("dirt-enhanced") sample of events (to ~15%).



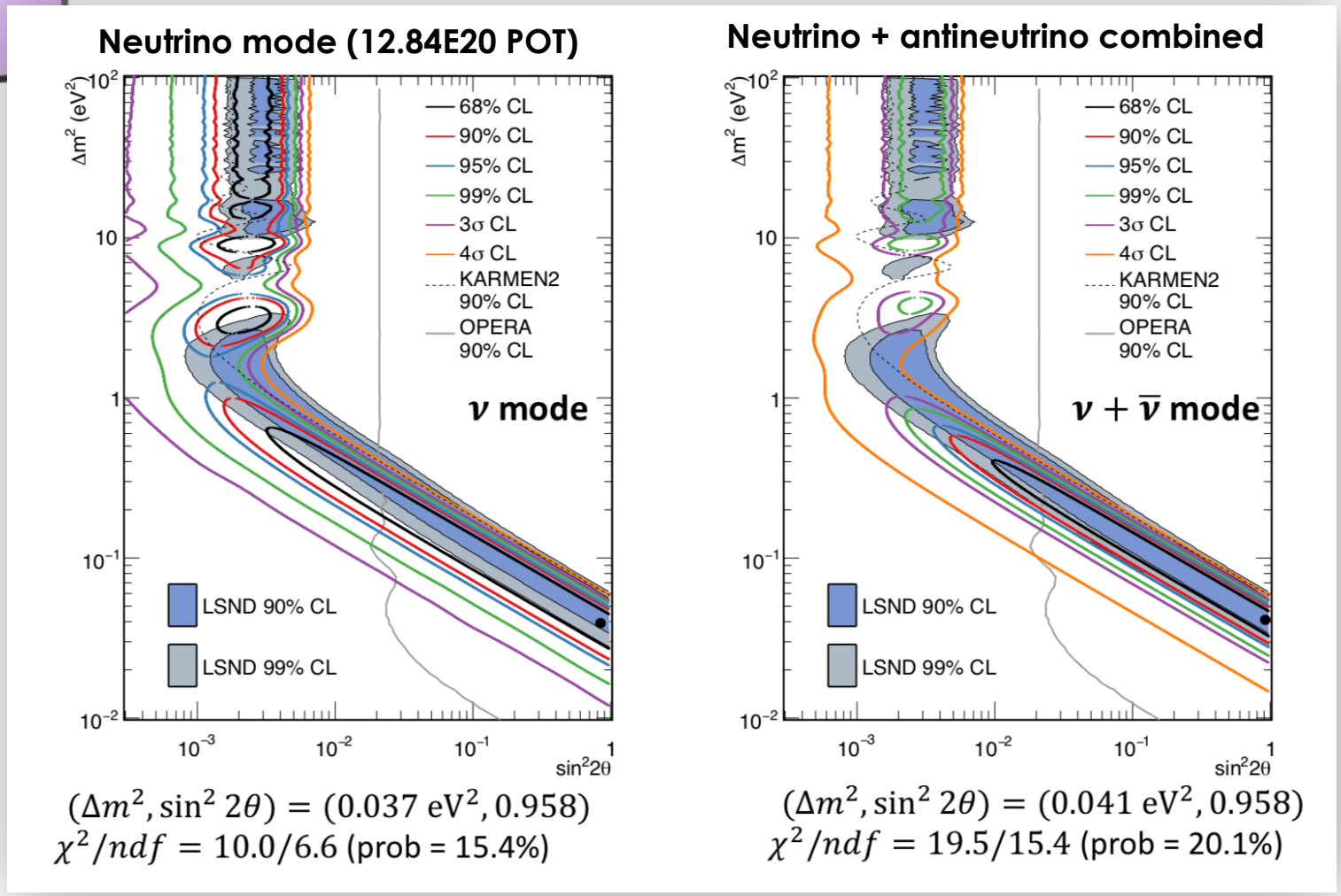
MiniBooNE
2018 ν_e appearance results:



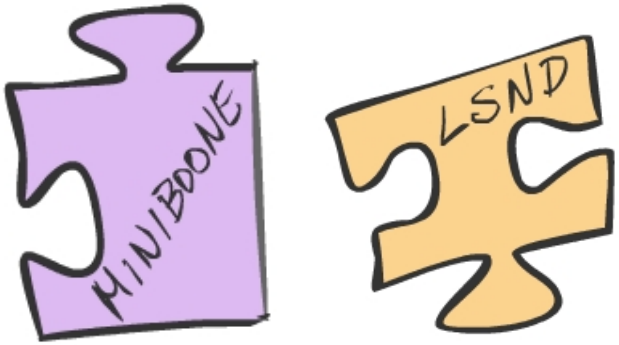
Total neutrino mode excess (12.84E20 POT):
381.2 +/- 85.2 excess events (**4.5σ**)
Best-fit χ^2-prob = 15%

Combined with antineutrino mode:
460.5 +/- 95.8 excess events (**4.8σ**)
Best-fit χ^2-prob = 20%

Follow-up to LSND: MiniBooNE



Neutrino and antineutrino fits are consistent with LSND allowed regions and high-Δm^2 oscillation interpretation



LSND vs. MiniBooNE

- Muon (anti)neutrino beam
- Low intrinsic electron (anti)neutrino background
- Excess of electron (anti)neutrino at L/E of ~ 1 m/MeV

→ Both consistent with two-neutrino oscillation with $\Delta m^2 \sim 1$ eV2 and sub-% oscillation amplitude.

→ **How do we reconcile this signature with long/medium-baseline oscillations?**

2. Interpretations

Neutrino physics: The bigger picture?

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \vdots \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3}e^{i\delta} & \dots & U_{en} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \dots & U_{\mu n} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \dots & U_{\tau n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ U_{s1} & U_{s2} & U_{s3} & \dots & U_{sn} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \vdots \\ \nu_n \end{pmatrix}$$

(and more CP-violating phases…)

Q: Why only 3x3 ?

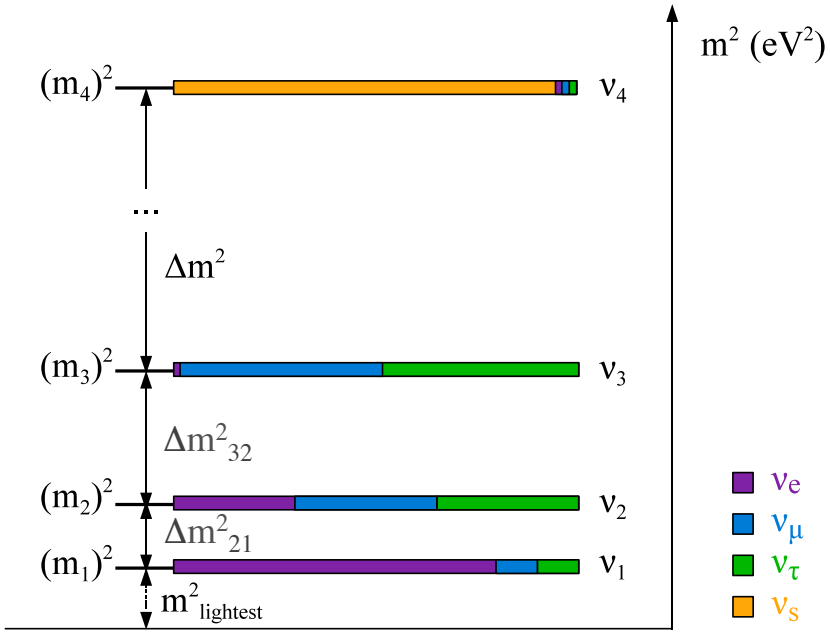
Additional, (mostly) sterile neutrinos

sterile neutrino
/ˈstɛrʌɪl/ /nju:ˈtri:nəʊ/

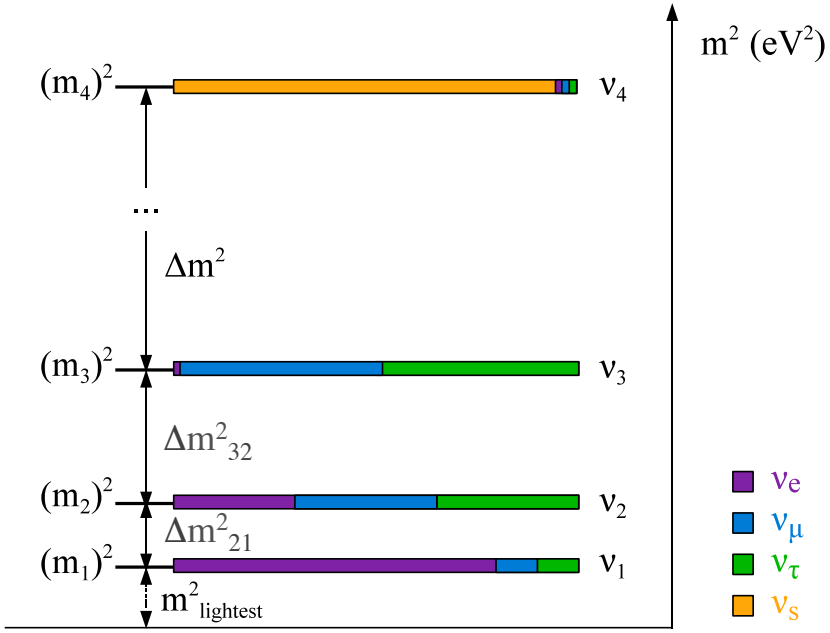
Additional neutrino "flavor" states which **do not experience weak interactions** (through the standard model W/Z bosons)

The additional mass states associated with them are assumed to be produced through mixing with the standard model neutrinos

→ Can affect neutrino oscillations through mixing



Simplest (3+1) sterile neutrino model



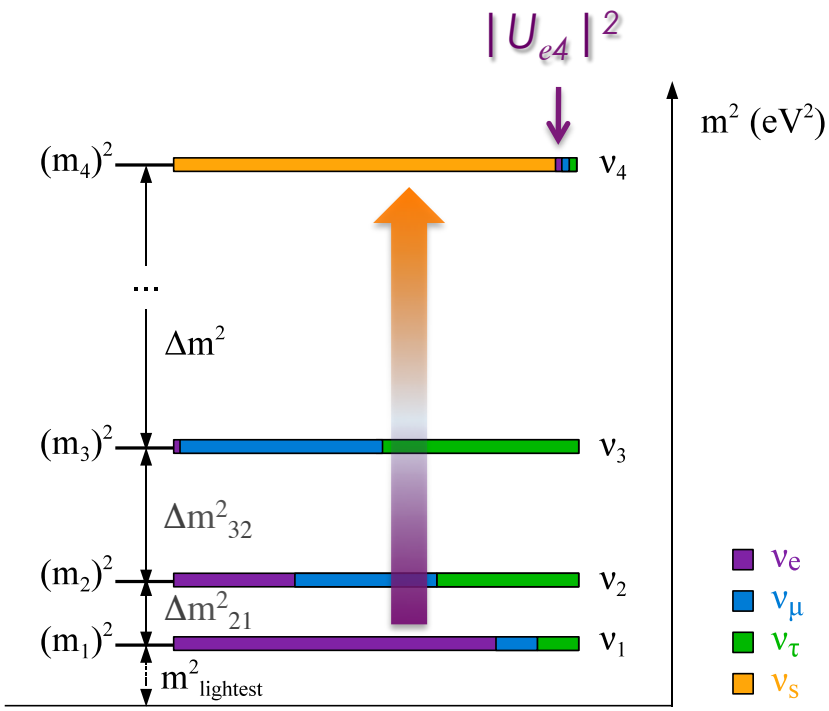
Simplest (3+1) sterile neutrino model

Large Δm^2 implies oscillations manifest at baselines much shorter than those between three known neutrinos. Can approximate $m_1 \sim m_2 \sim m_3 \sim 0$.

ν_e disappearance:

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\vartheta_{ee} \sin^2(1.27\Delta m^2 L/E)$$

$$\hookrightarrow \; 4|U_{e4}|^2\left(1 - |U_{e4}|^2\right)$$



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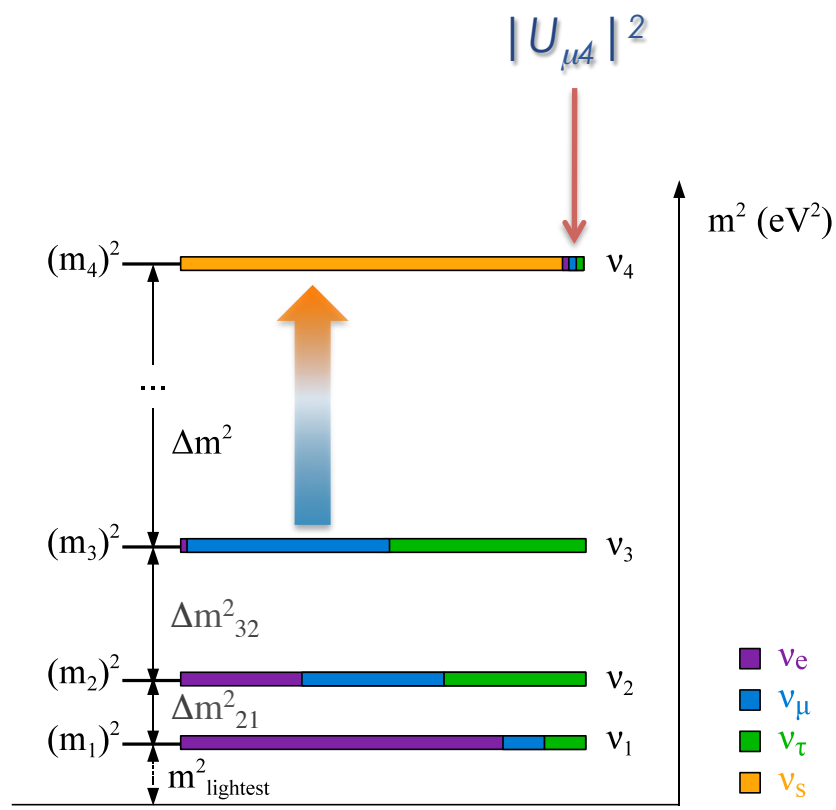

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ν_μ disappearance:

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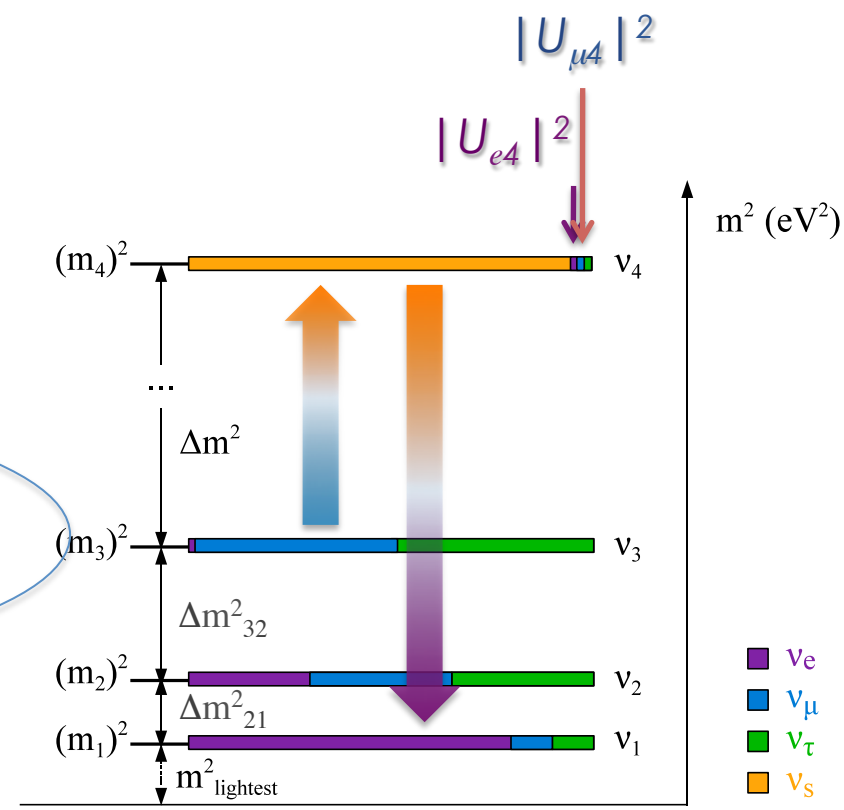
$\nu_\mu \rightarrow \nu_e$ appearance:

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\vartheta_{\mu e} \sin^2(1.27\Delta m^2 L/E)$$

$$\hookrightarrow 4|U_{e4}|^2|U_{\mu 4}|^2$$

Can describe LSND and MiniBooNE observations



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ν_μ disappearance:

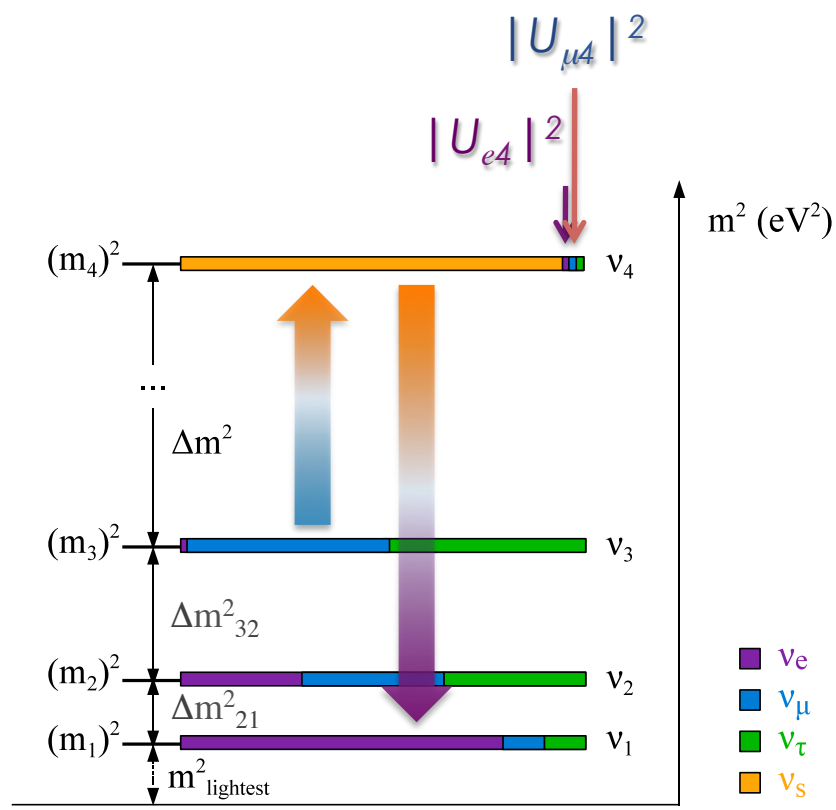
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\vartheta_{\mu\mu} \sin^2(1.27\Delta m^2 L/E)$$

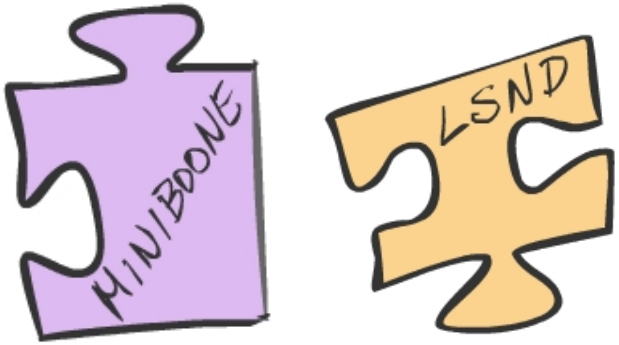
$\nu_\mu \rightarrow \nu_e$ appearance:

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\vartheta_{\mu e} \sin^2(1.27\Delta m^2 L/E)$$

$$\hookrightarrow 4|U_{e4}|^2|U_{\mu 4}|^2$$

<u>Note</u>: $\sin^2 2\theta_{\mu e} \approx \frac{1}{4}\sin^2 2\theta_{\mu\mu} \sin^2 2\theta_{ee}$

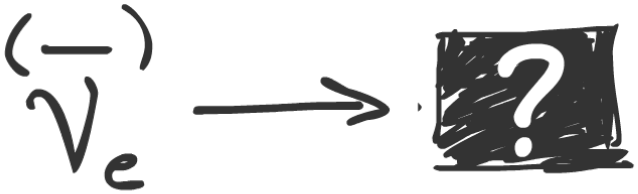




LSND vs. MiniBooNE

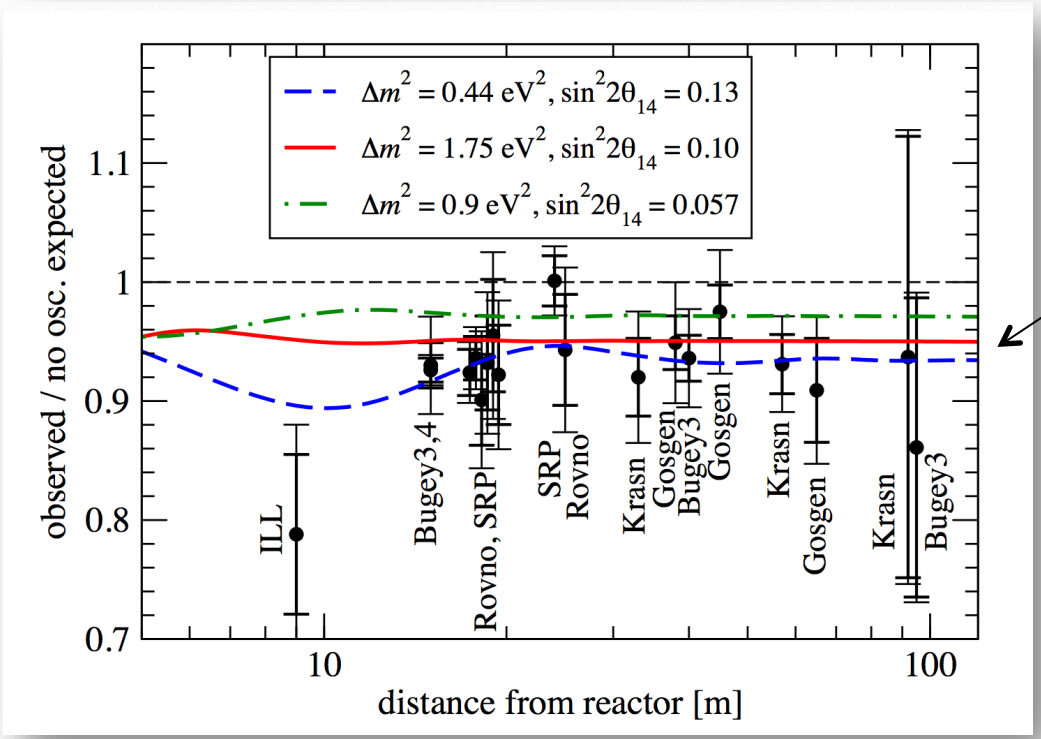
→ Both consistent with two-neutrino oscillation with $\Delta m^2 \sim 1$ eV2 and sub-% oscillation amplitude.

→ **Do we see any other corresponding flavor transitions with other experiments?**



"Reactor Anomaly"

Measured $\bar{\nu}_e$ flux from reactors is 3.5% (~3σ) lower than expected from predictions → oscillation of $\bar{\nu}_e$ into $\bar{\nu}_s$?



Anomalous deficit can be interpreted as ν_e disappearance at high-Δm^2

The effect came about after re-analyses of detailed physics involved in nuclear beta-decay of fission fragments in reactors.

[Mueller et al. 1101.2663, Huber 1106.0687]

"Reactor Anomaly"

Predicting reactor $\bar{\nu}_e$ fluxes:

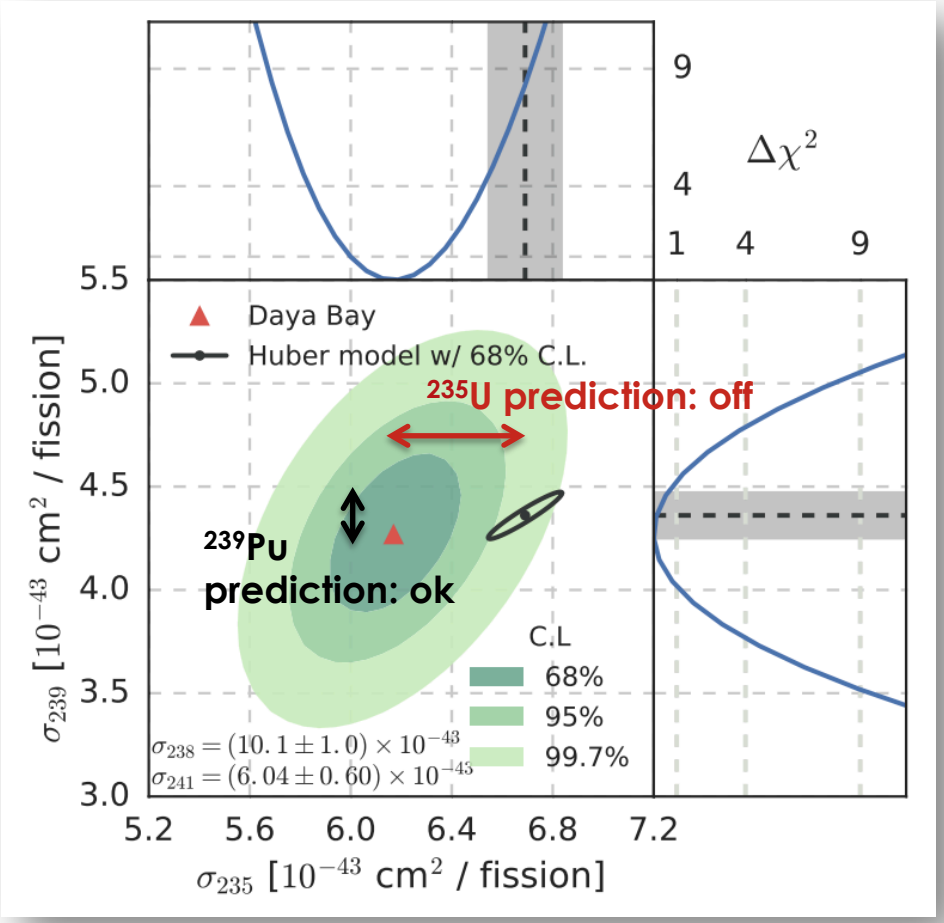
- Use measured β spectra from ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu fission
- Convert to $\bar{\nu}_e$ spectrum
- For single β decay, $E_\nu = Q - E_e$
- Thousands of decay branches, many not precisely known
- Use (incomplete) information from nuclear data tables...
- ... complemented by a fit to effective decay branches

Anomaly has been investigated as a **flux misinterpretation**:
e.g. Do we see an isotope-dependent deficit? (Sterile neutrinos would lead to isotope-independent deficit.)

[e.g., Daya Bay PRL 118, 251801 (2017)]

"Reactor Anomaly"

Daya Bay isotopic evolution measurements: Necessity for further flux corrections.



But, **no clear data preference** for "fit to free fluxes" over "fixed fluxes with oscillations"

[Hernandez et al., arXiv:1709.04294]

[e.g., Daya Bay PRL 118, 251801 (2017)]

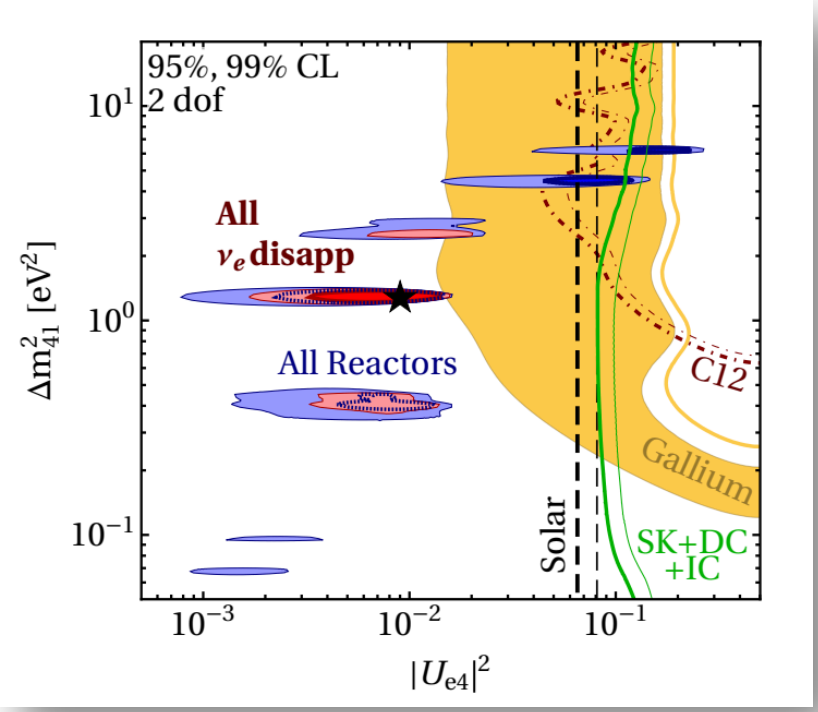
"Reactor Anomaly"

Multiple new results from SBL reactor experiments have been pouring in over the last few years...

but still **not a clear picture** of $\overline{\nu}_e$ disappearance

"Radioactive Source Anomalies"

[M. Dentler, et al., JHEP 1808 (2018) 010]

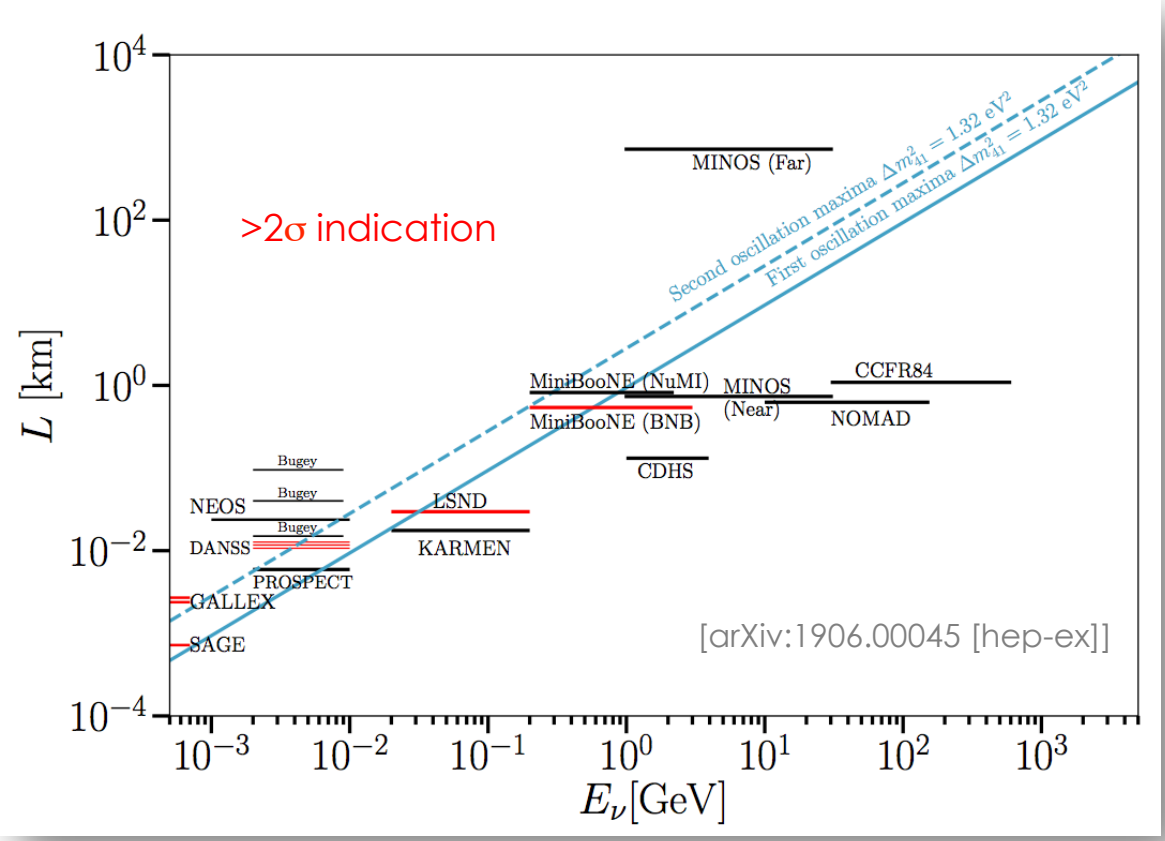


GALLEX and **SAGE**:
Solar neutrino experiments which used radioactive ν_e sources (Cr-51 and Ar-37) for calibration

Observed large (~20%) ν_e disappearance

Summary: Is our three-neutrino picture incomplete?

- Anomalous signals observed at "short baselines": L/E ~ 1 m/MeV
- Cannot be reconciled with Δm^2 oscillations driving atmospheric, solar, reactor long-baseline (L/E >>1) oscillations
- Possible solution: existence of light sterile neutrino(s) driving oscillations at $\Delta m^2 \sim 1\ eV^2$



General constraints to 3+N

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \vdots \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \dots & U_{en} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \dots & U_{\mu n} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \dots & U_{\tau n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ U_{s1} & U_{s2} & U_{s3} & \dots & U_{sn} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \vdots \\ \nu_n \end{pmatrix}$$

Perfectly allowed, as long as:

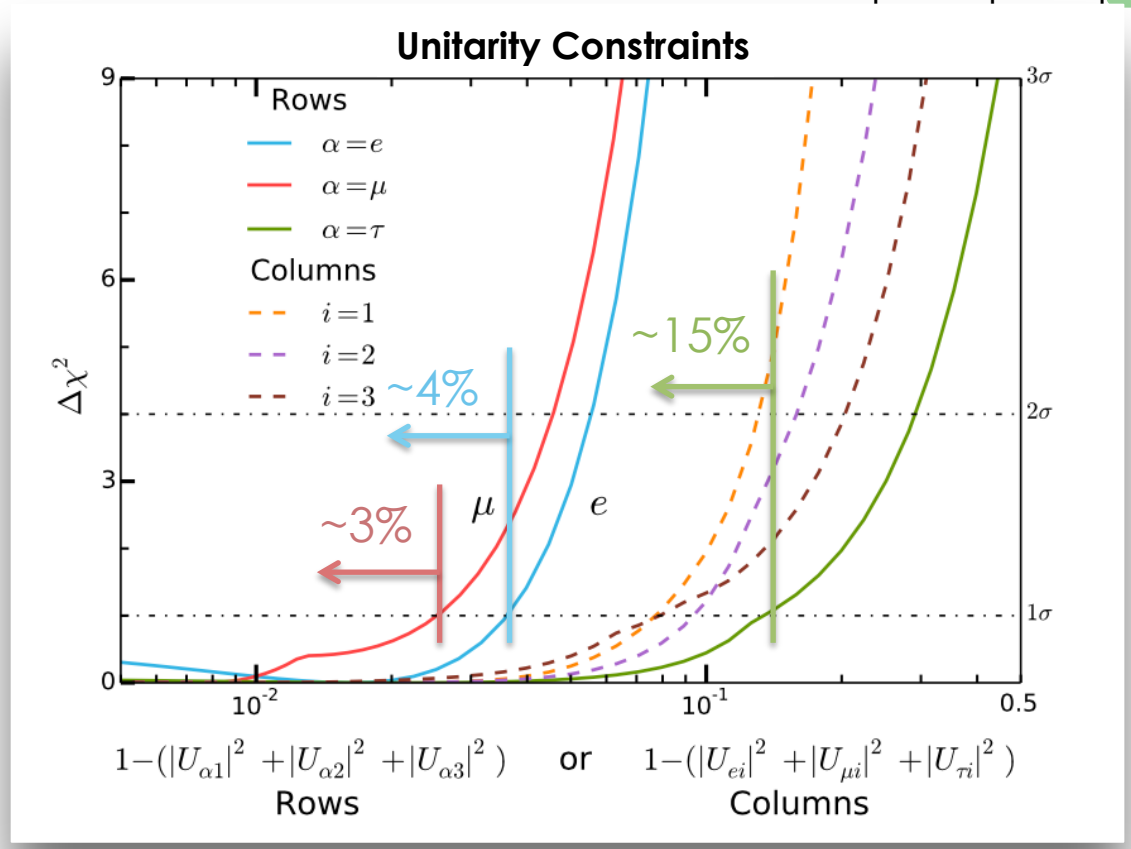
(1) only 3 weakly interacting neutrinos that are light ($m_i < m_Z/2$).

(2) the sum over all neutrino masses does not become significantly larger than ~1 eV.

(3) the overall (3+N)x(3+N) mixing matrix is unitary.

General constraints to 3+N

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \cdots & U_{en} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \cdots & U_{\mu n} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \cdots & U_{\tau n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ U_{s1} & U_{s2} & U_{s3} & \cdots & U_{sn} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \vdots \\ \nu_n \end{pmatrix}$$



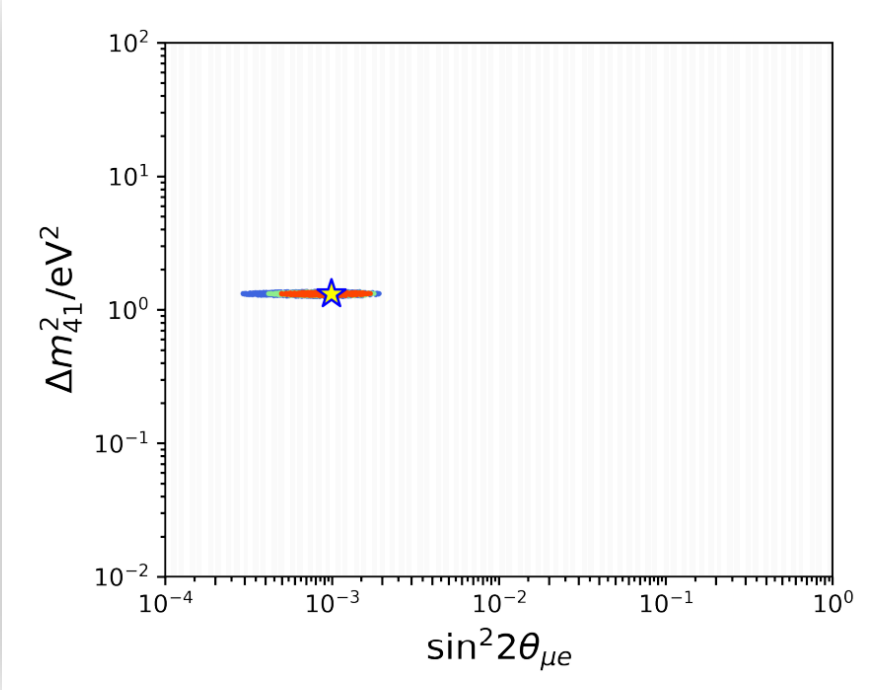
[S. Parke, M. Ross-Lonergan, hep-ph/1508.05095]

Combined with unitarity constraints on the 3x3 sub-block, this requires that any additional neutrinos are mostly "sterile", and that they mix very little with active neutrinos.

Putting it all together

[Diaz et al., arXiv:1906.00045 [hep-ex]]

When combined with all other available experimental constraints, MiniBooNE, LSND, Reactor SBL and radioactive source experiments **seem to indicate a strong preference for a (3+1) signal**



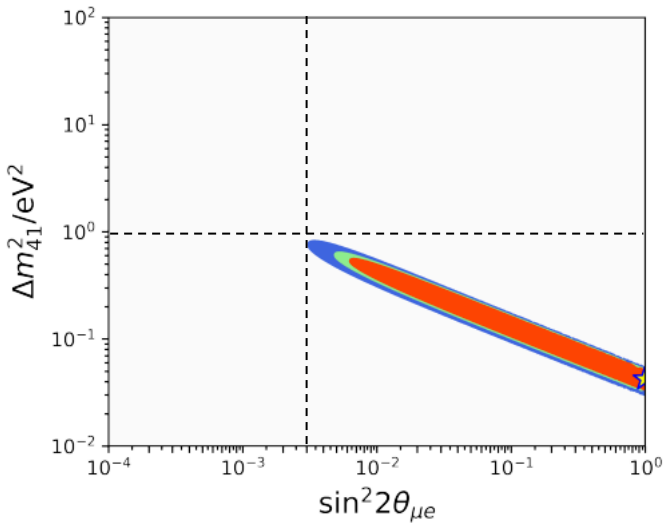
Data sets include:

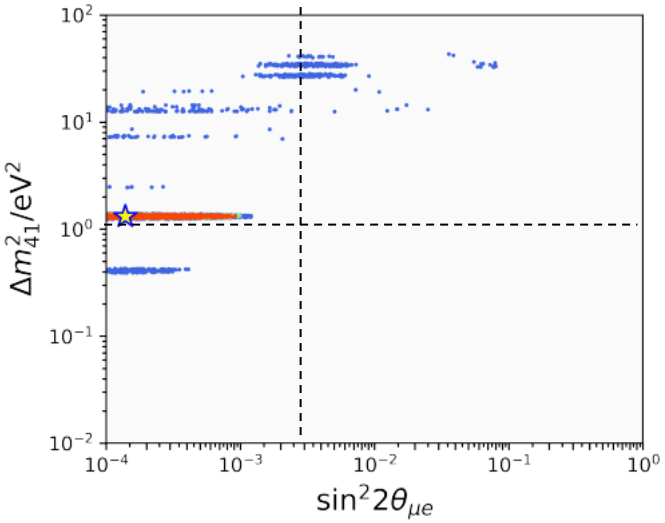
	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\mu$	$\nu_e \to \nu_e$
Neutrino	MiniBooNE (BNB) $*$ MiniBooNE(NuMI) NOMAD	SciBooNE/MiniBooNE CCFR CDHS MINOS	KARMEN/LSND Cross Section Gallium $*$
Antineutrino	LSND $*$ KARMEN MiniBooNE (BNB) $*$	SciBooNE/MiniBooNE CCFR MINOS	Bugey NEOS DANSS $*$ PROSPECT

Not so fast!

Goodness-of-fit of global (3+1) fits can be deceptive...
A closer examination reveals **tension between datasets**:

Appearance **vs.** **Disappearance**



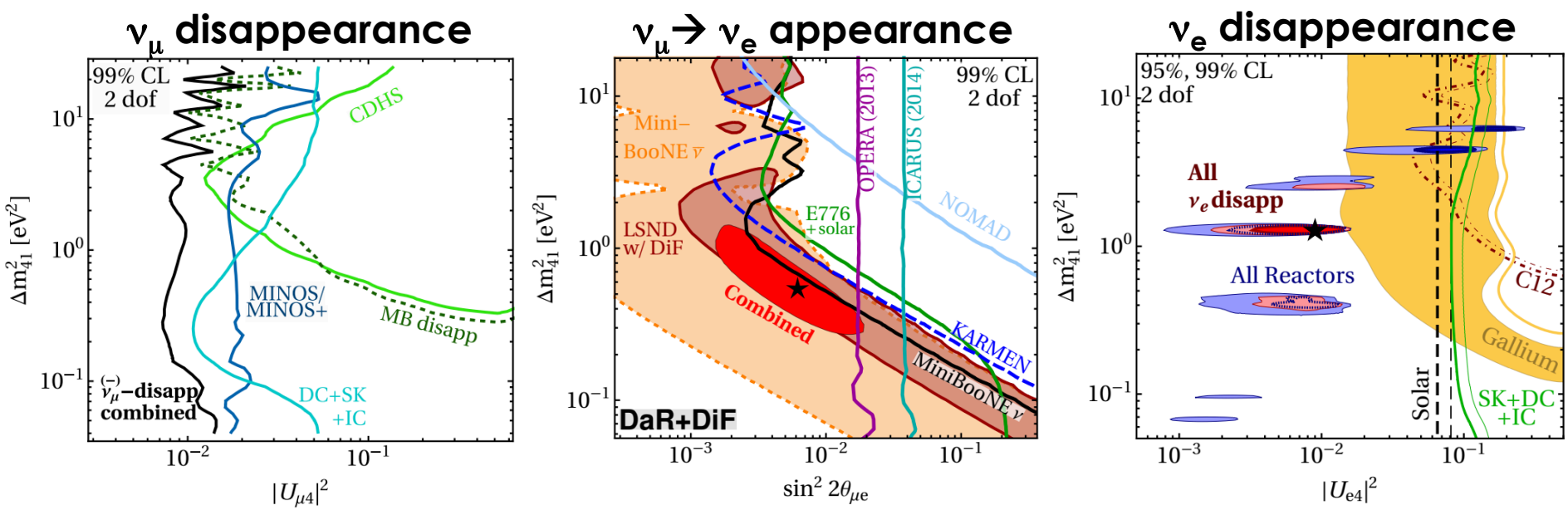


[Diaz et al., arXiv:1906.00045 [hep-ex]]

Tension also exists among neutrino and antineutrino datasets.

Short-baseline pieces don't quite fit together!

[M. Dentler, et al., JHEP 1808 (2018) 010]



If one accepts (ν_e appearance and ν_e disappearance) signals as real, **source of tension is ν_μ disappearance searches**:

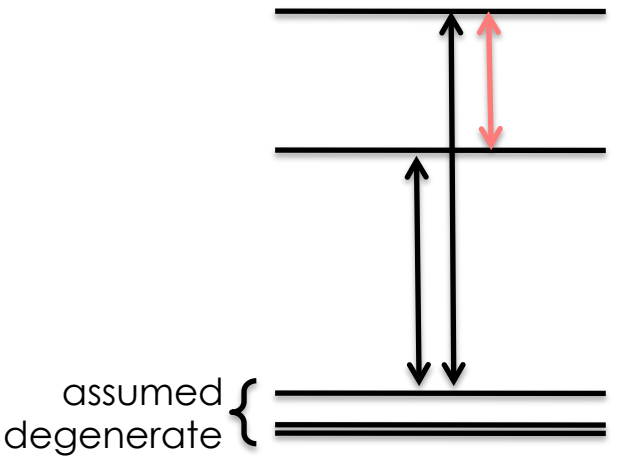
$\sin^2 2\theta_{\mu e} \sim \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$ → Implies non-zero ν_μ disappearance.

But no ν_μ disappearance has been observed!

Is there any wiggle room?

More neutrinos?!

(Extra degrees of freedom, interference terms,
CP violating terms in oscillation probabilities...)



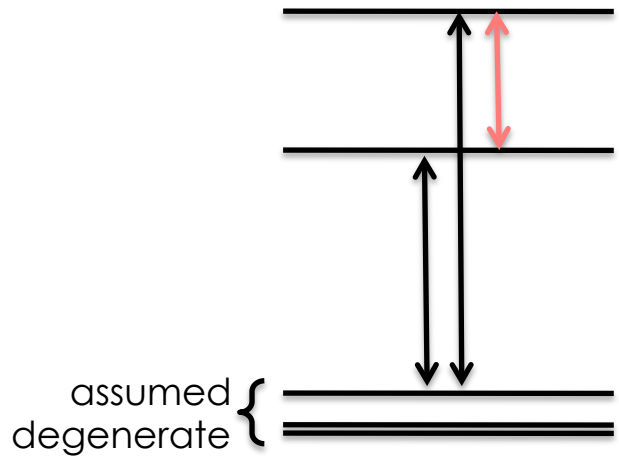
→ two effective Δm^2

Is there any wiggle room?

- Can CP violation allowed within 3+2 help?

$$P(\nu_\alpha \to \nu_{\beta\neq\alpha}) = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2 \sin^2 x_{41} + 4|U_{\alpha 5}|^2|U_{\beta 5}|^2 \sin^2 x_{51} + 8|U_{\alpha 5}||U_{\beta 5}||U_{\alpha 4}||U_{\beta 4}| \sin x_{41} \sin x_{51} \cos(x_{54} - \phi_{45})$$

$$x_{ji} \equiv 1.27\Delta m^2_{ji} L/E$$



→ two effective Δm^2

- What about more fit parameters, CP phases, in 3+3?

3+2, 3+3 global fits

[D. Cianci, et al., in preparation]

3+2

m_4	$\lvert U_{e4} \rvert$	$\lvert U_{\mu 4} \rvert$	m_5	$\lvert U_{e5} \rvert$	$\lvert U_{\mu 5} \rvert$	ϕ_{45}
0.68 eV	0.116	0.187	0.95 eV	0.159	0.103	5.71 rad

χ^2 bf (dof) = 244.8 (236)
χ^2 probability = 33%

(Compare, previously, χ^2 (dof) = 238.2 (236))

PRELIMINARY

3+3

m_4	$\lvert U_{e4} \rvert$	$\lvert U_{\mu 4} \rvert$	m_5	$\lvert U_{e5} \rvert$	$\lvert U_{\mu 5} \rvert$	m_6	$\lvert U_{e6} \rvert$	$\lvert U_{\mu 6} \rvert$
0.68 eV	0.119	0.080	0.88 eV	0.139	0.086	0.97 eV	0.105	0.106

ϕ_{45}	ϕ_{46}	ϕ_{56}
5.26 rad	5.75 rad	6.03 rad

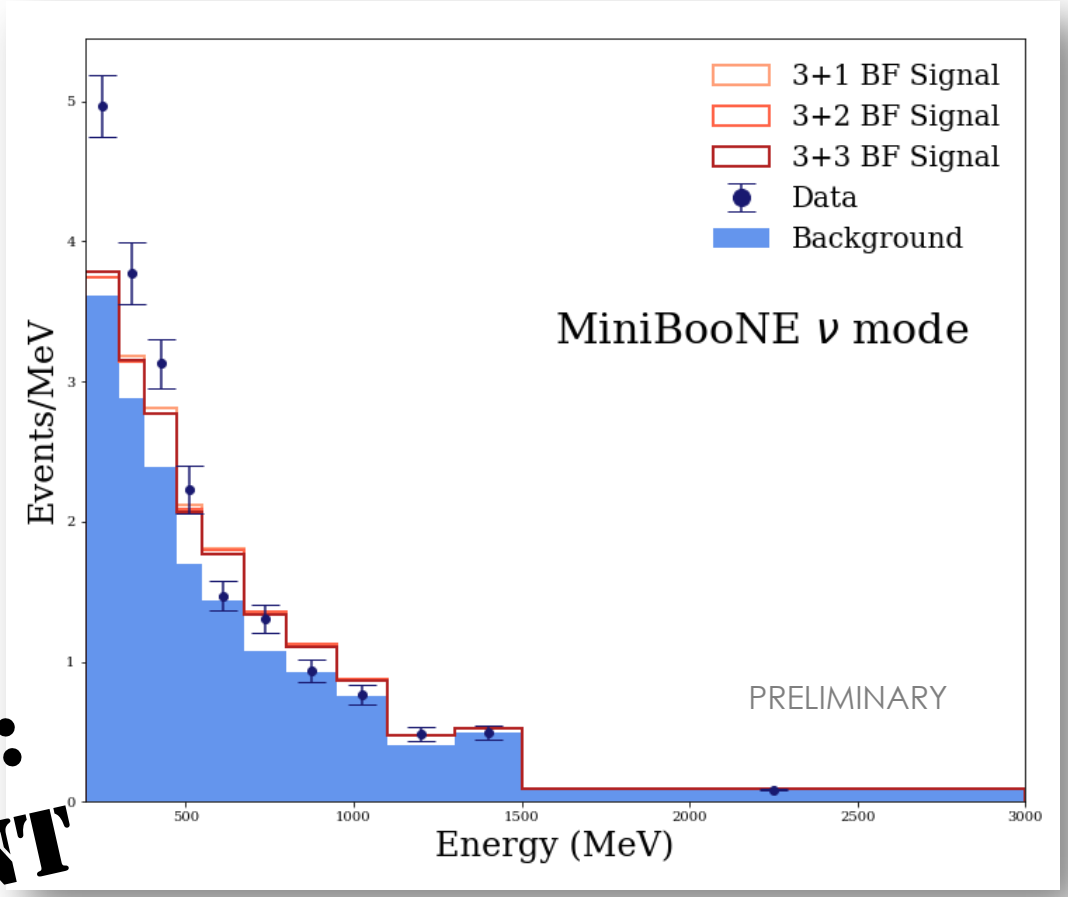
χ^2 bf (dof) = 240.5 (231)
χ^2 probability = 32%

(Compare, previously, χ^2 (dof) = 232.5 (231))

PRELIMINARY

3+2, 3+3 global fits

Yet another shortcoming:
Failure to accommodate MiniBooNE low-energy excess



"3+N STERILE NEUTRINOS": INSUFFICIENT

[D. Cianci, et al., in preparation]

3+N: Summary

1. Global fits to 3+1 reveal **incompatibilities** among appearance and disappearance signals

   Caveat: "Parameter Goodness of Fit": Is this a reasonable metric?

2. Incompatibility has motivated further consideration of 3+2, 3+3, and more **extended** sterile neutrino frameworks;
   still, **not clear that this issue can be evaded**

What's next?

- Better **statistical treatment** of data in global fits

- **Follow-up high-sensitivity, direct experimental tests** (ongoing, planned and proposed sterile neutrino oscillation searches):

  – Accelerator-based: **SBN**, **IsoDAR**
  – Reactor-based: **SoLiD, Neutrino-4, DANSS, NEOS, STEREO, PROSPECT, CHANDLER, …**
  – Radioactive source: **BEST**

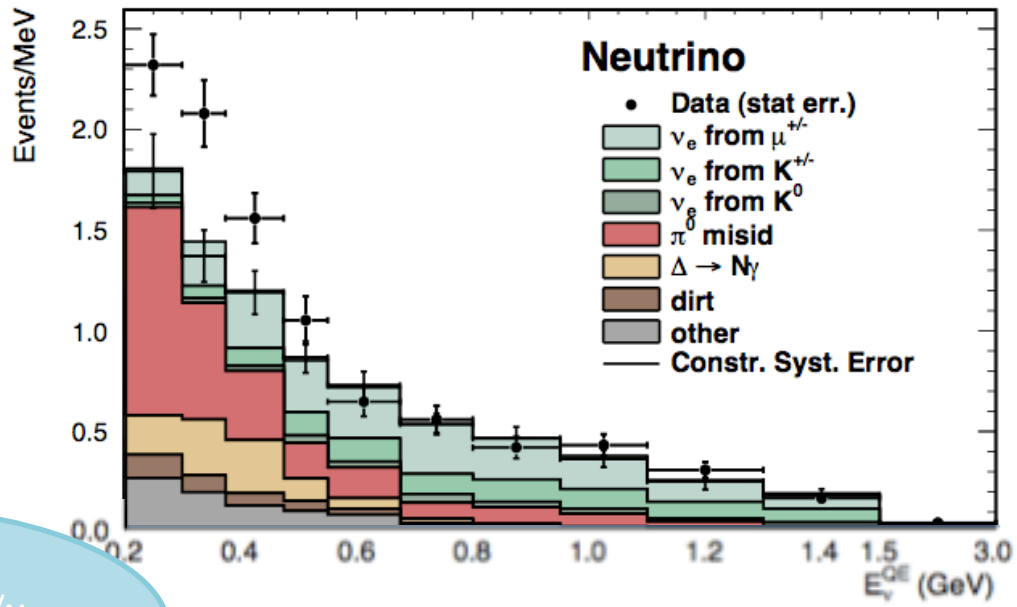
  – Also searches at long-baseline experiment near detectors and (high-energy) atmospheric neutrino experiments (**MINOS/MINOS+, NOvA**, **T2K, IceCube/DeepCore, Super-K**, …)

  – And neutral-current based searches with coherent scattering (e.g. **COHERENT, CEvNS**)

- **Alternate models**: non-standard interactions, sterile neutrino decay, …

What else?

A closer look into the MiniBooNE low-energy excess…



Unaccounted ν_e/ν_μ disappearance?

Energy reconstruction? Cross-section/nuclear effects?

Electron-like misestimated or new background?

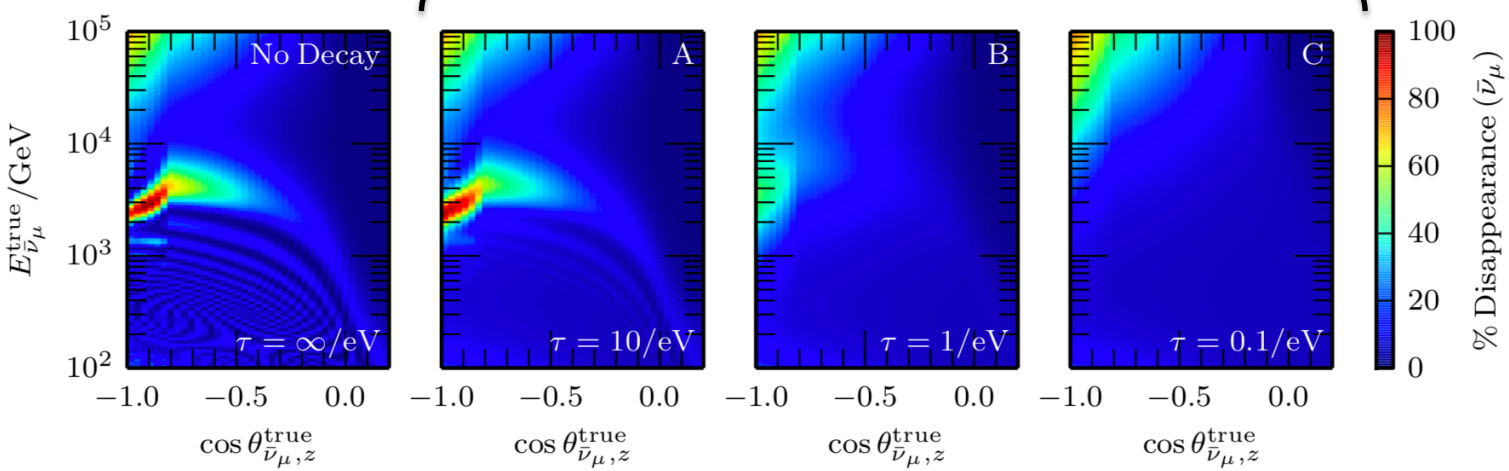
Single-photon mis-estimated or new background?

A shift in focus

The inability of 3+N global fits to provide a satisfactory, coherent explanation to all SBL anomalies has prompted the **exploration of new (physics) ideas**:

1. **Sterile neutrino + decay** [A. Diaz et al., ICHEP 2018]

4th (mostly sterile) neutrino mass eigenstate
has finite lifetime, resulting in decoherence in
neutrino propagation and no resonant matter effects
→ Evades IceCube limits from ν_μ disappearance



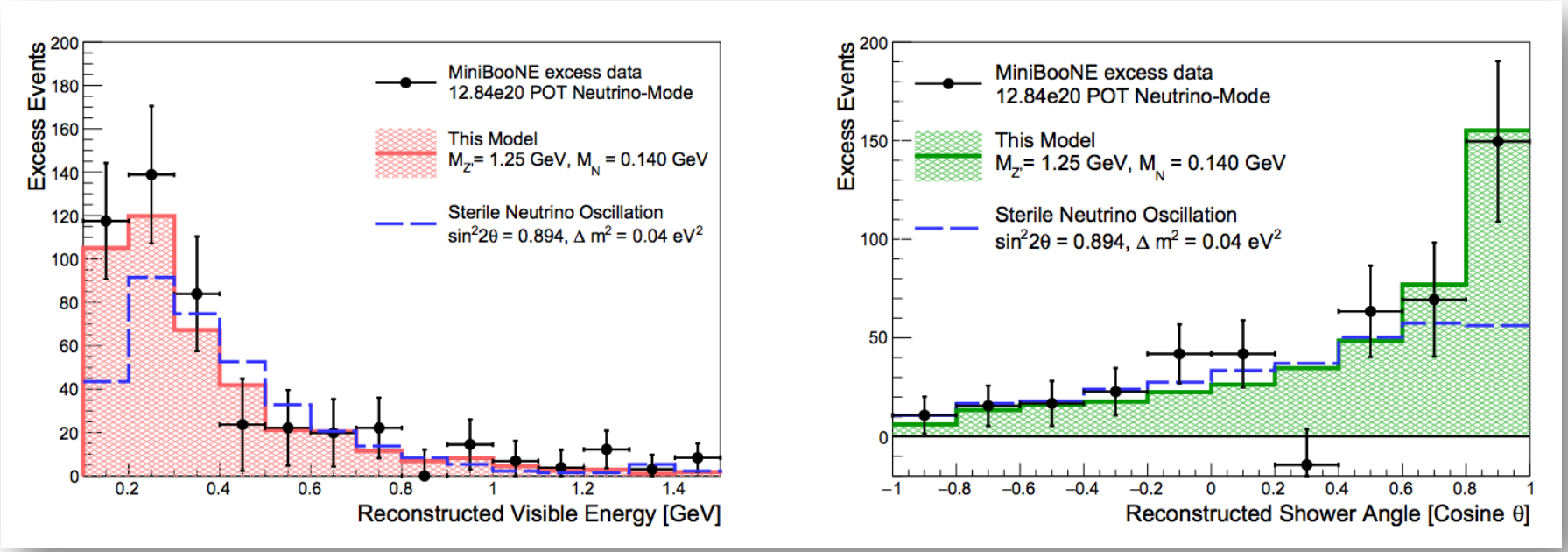
This model modestly relieves tension.

A shift in focus

The inability of 3+N global fits to provide a satisfactory, coherent explanation to all SBL anomalies has prompted the **exploration of new (physics) ideas**:

2. Sterile neutrino + decay through Z' [P. Ballet, et al., arXiv:1808.02915]

$$\nu_\mu + \mathcal{N} \to \nu_4 + \mathcal{N} \qquad \nu_4 \to \nu_\alpha \; e^+ \; e^-$$



Best fit: m_4 = 0.14 GeV, $m_{Z'}$ = 1.25 GeV, χ^2 = 5E-6
$|U_{\mu 4}|$ = 1.5E-6, $|U_{\tau 4}|$ = 7.8E-4

3. Up and coming SBL experiments

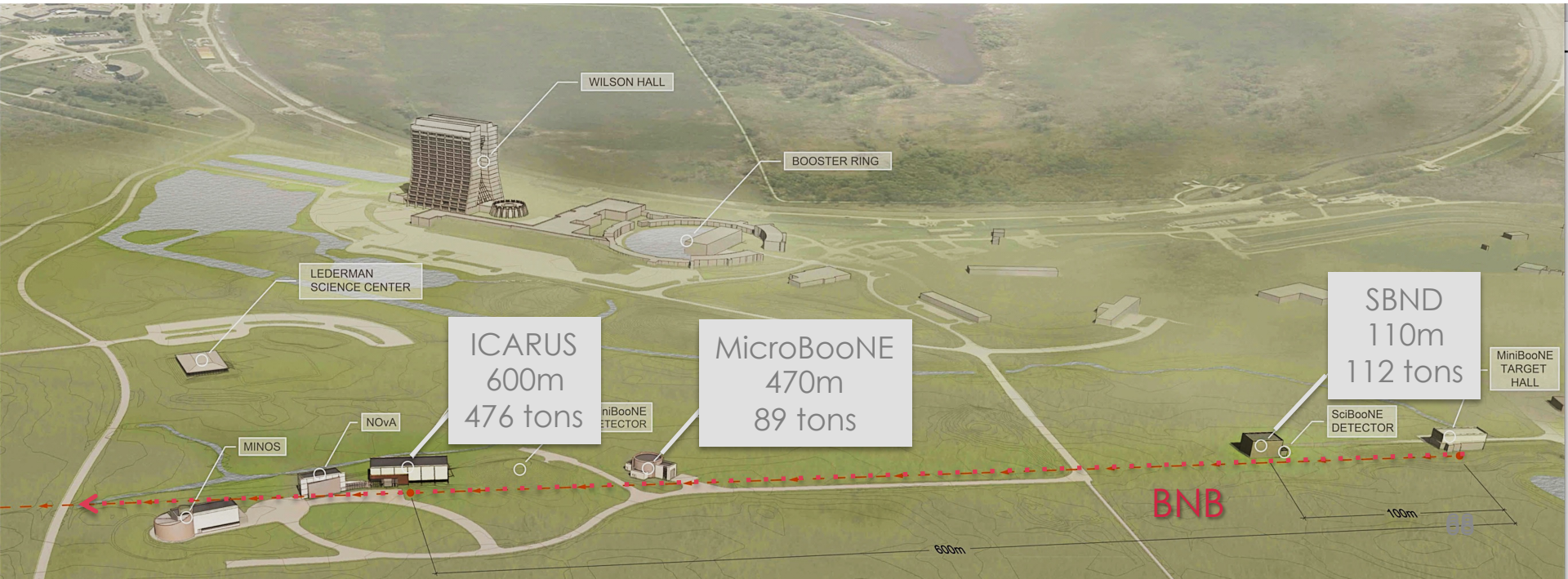
(*focus on SBN at Fermilab)

What's next: Short Baseline Neutrino (SBN) Program at Fermilab

Aim: Search for short-baseline neutrino oscillations (sterile neutrinos) and perform a definitive test of light sterile neutrino oscillation interpretation.

Status:

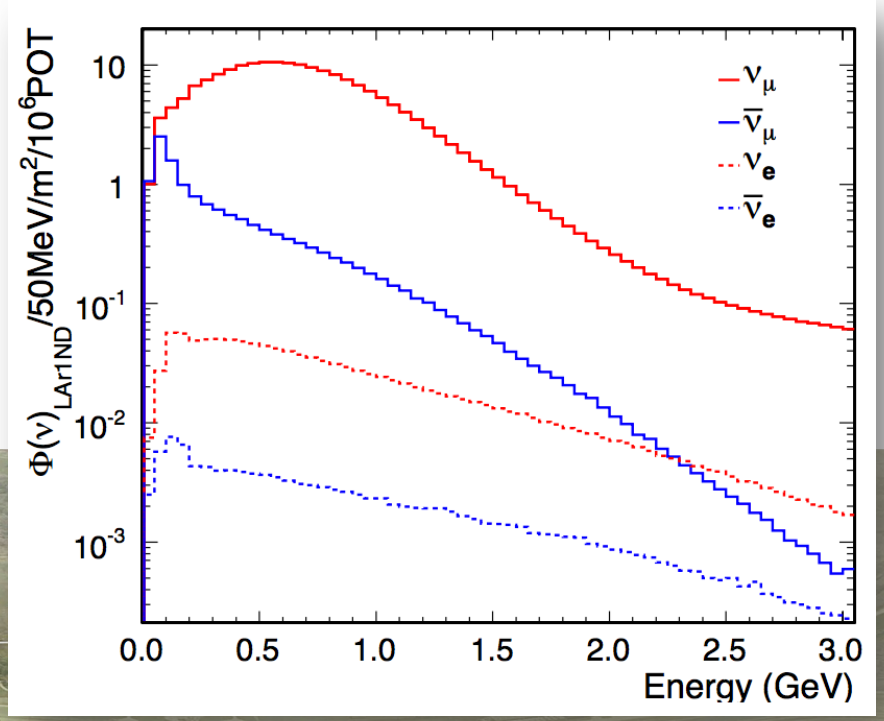
SBND: Under construction; expected to begin operations in 2021
MicroBooNE: Operating detector, taking data since Oct. 2015
ICARUS: Under installation; expected to begin operations by 2020

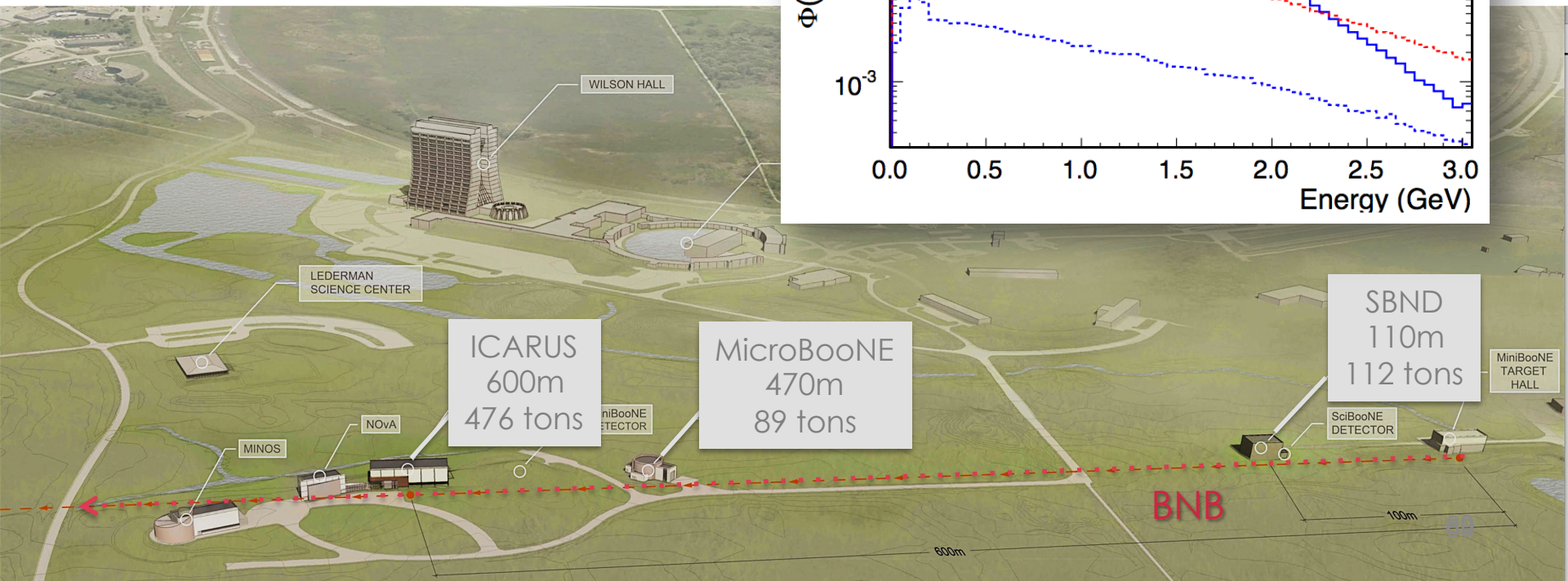


What's next: Short Baseline Neutrino (SBN) Program at Fermilab

Flux at SBND:
>99% ν_μ

Similar flux profiles at MicroBooNE and ICARUS

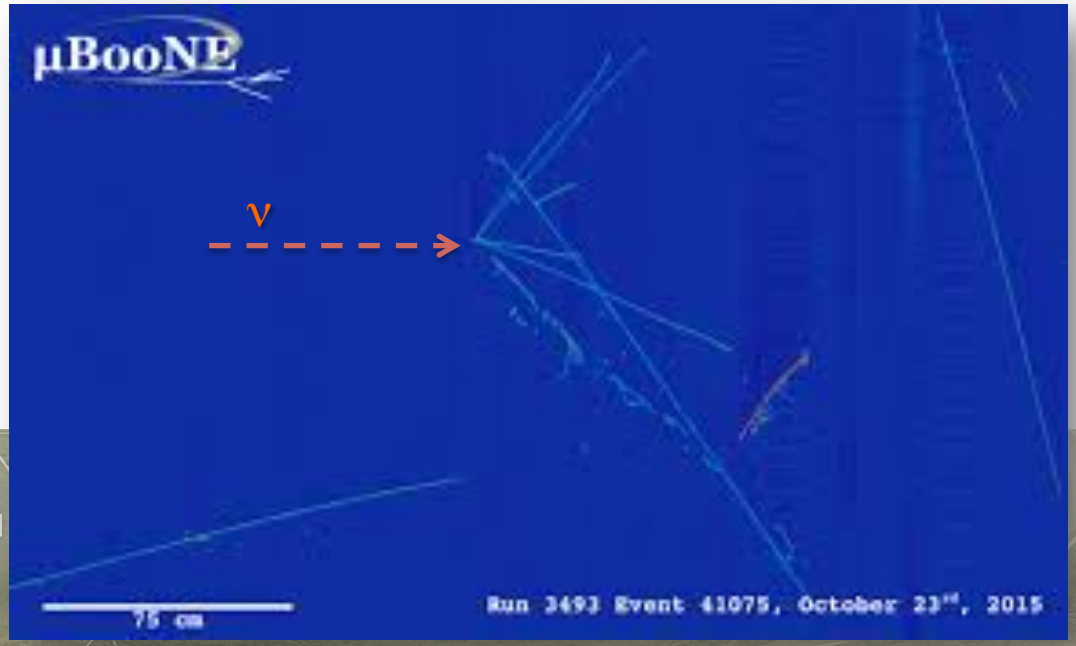


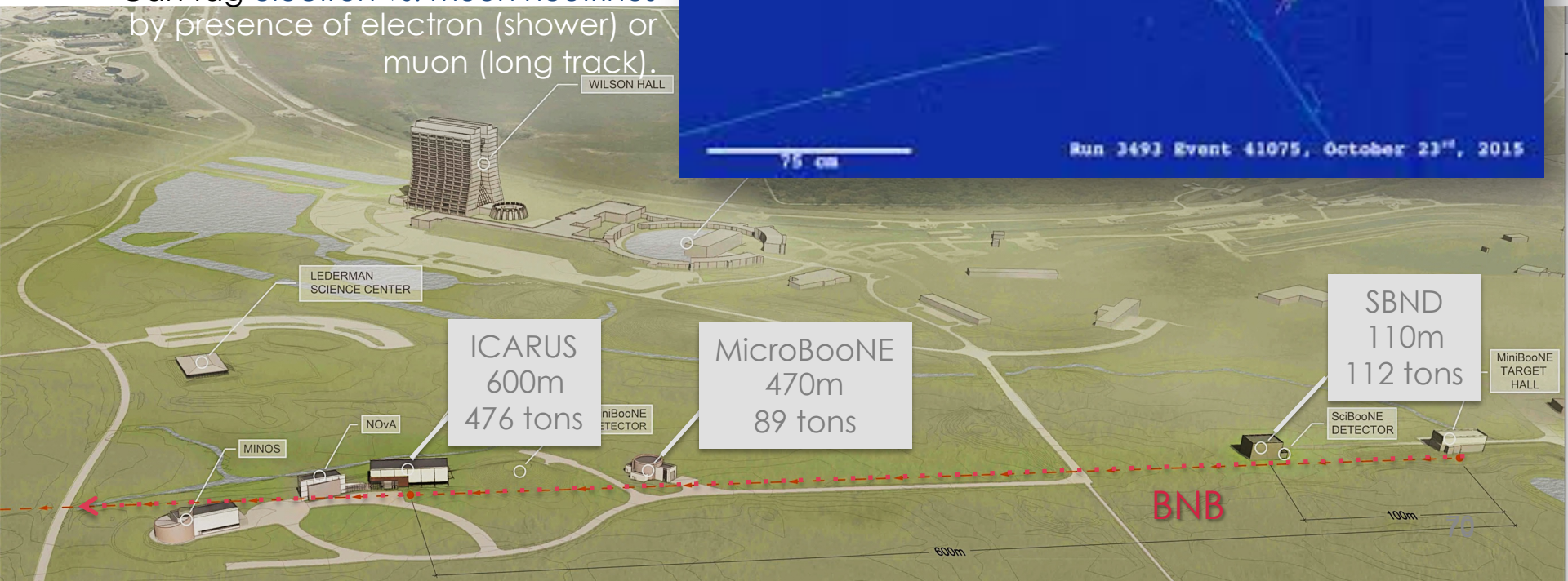


What's next: Short Baseline Neutrino (SBN) Program at Fermilab

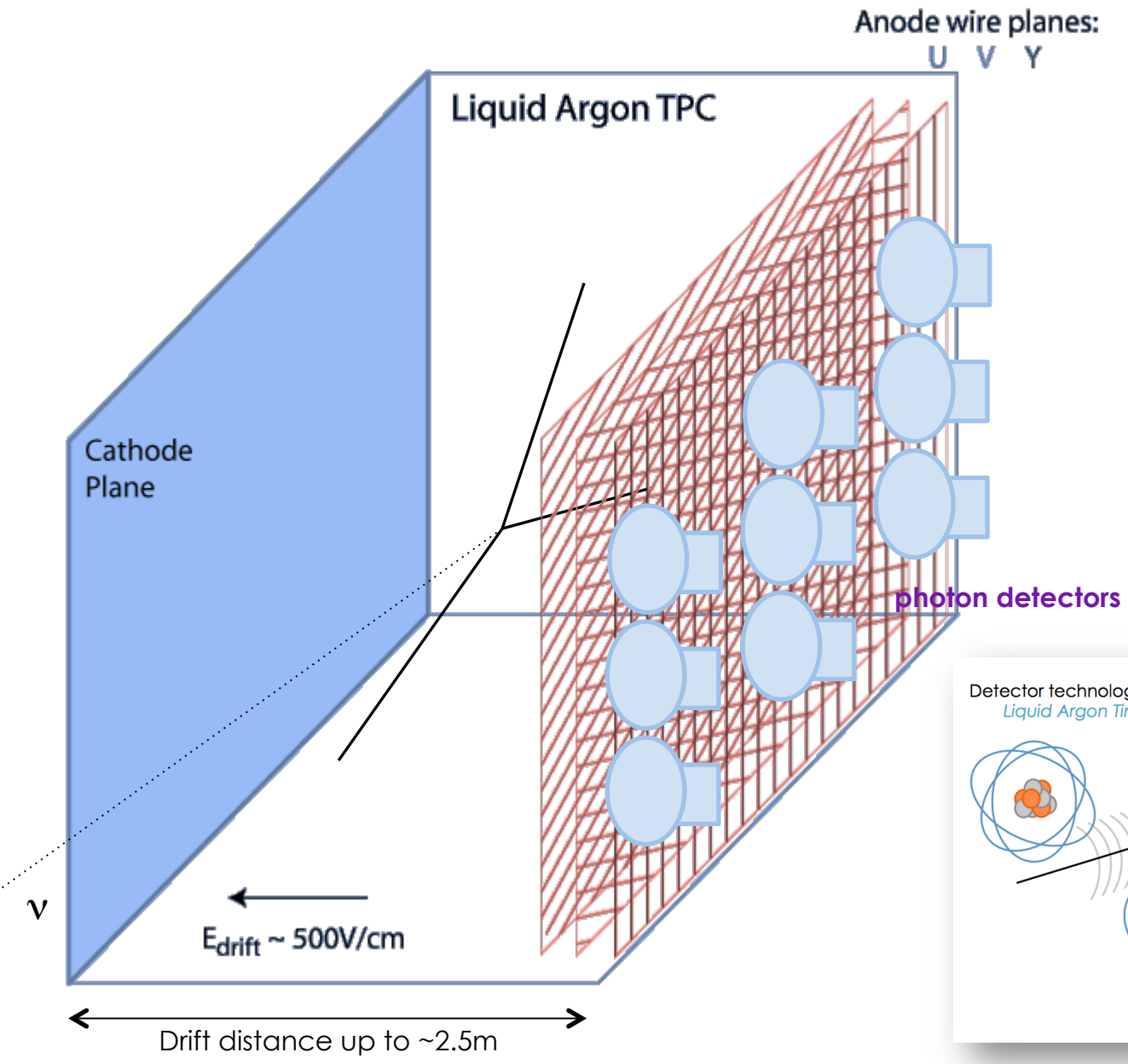
LArTPC detectors:
high-resolution 2D→3D imaging
of charged particles produced in neutrino interactions in liquid argon.

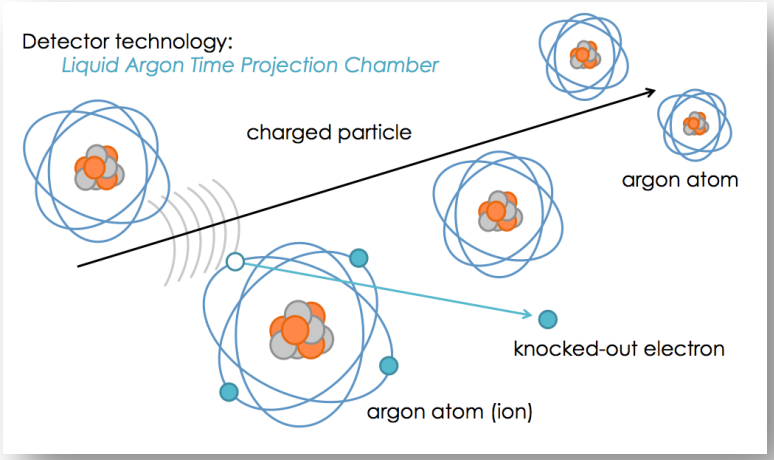
Can tag electron vs. muon neutrinos by presence of electron (shower) or muon (long track).





How a LArTPC works:





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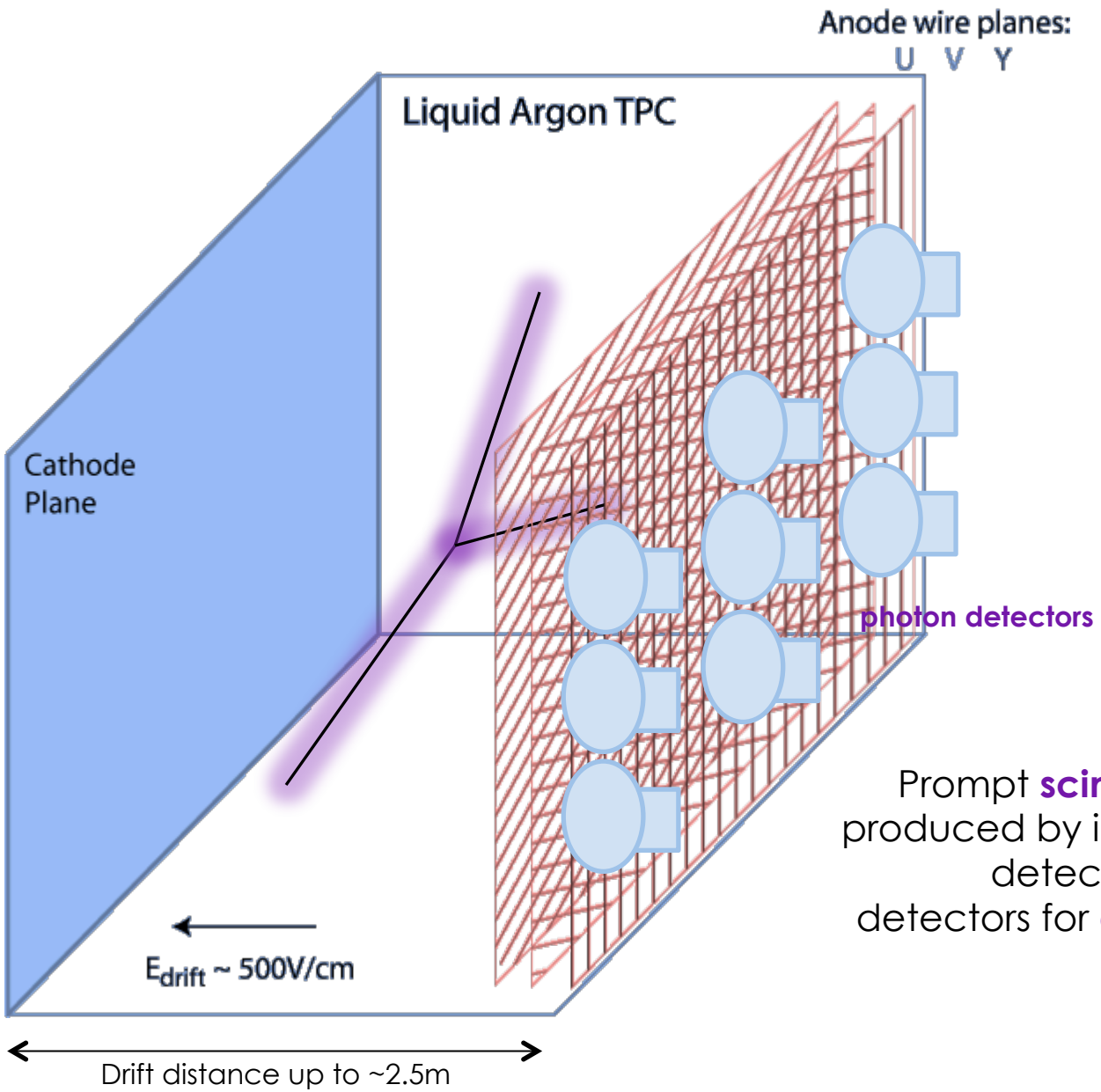
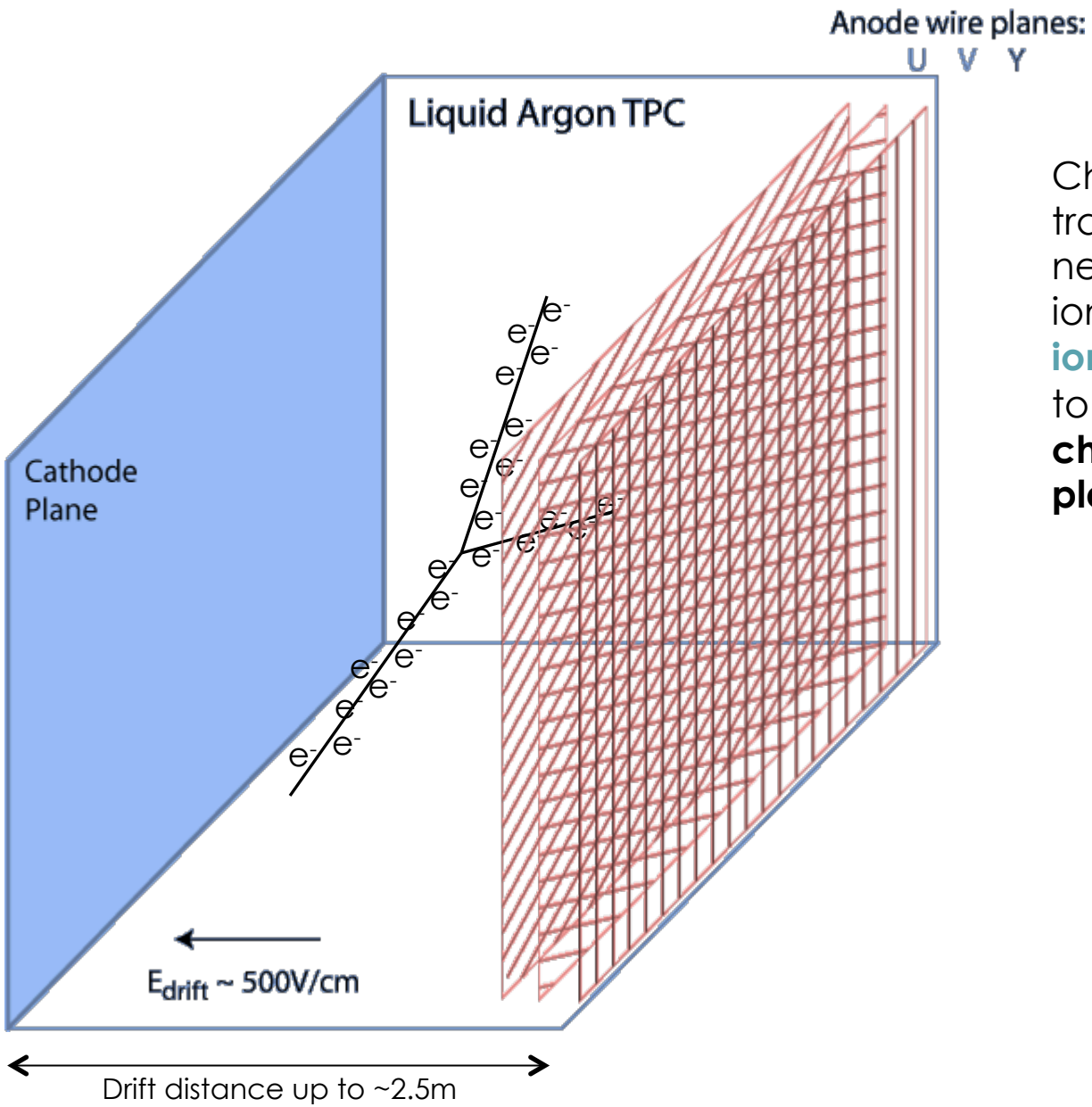


Prompt **scintillation light** (**~few ns**) produced by interaction products is detected by photo-sensitive detectors for **event t_0** determination (allows for triggering)

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.

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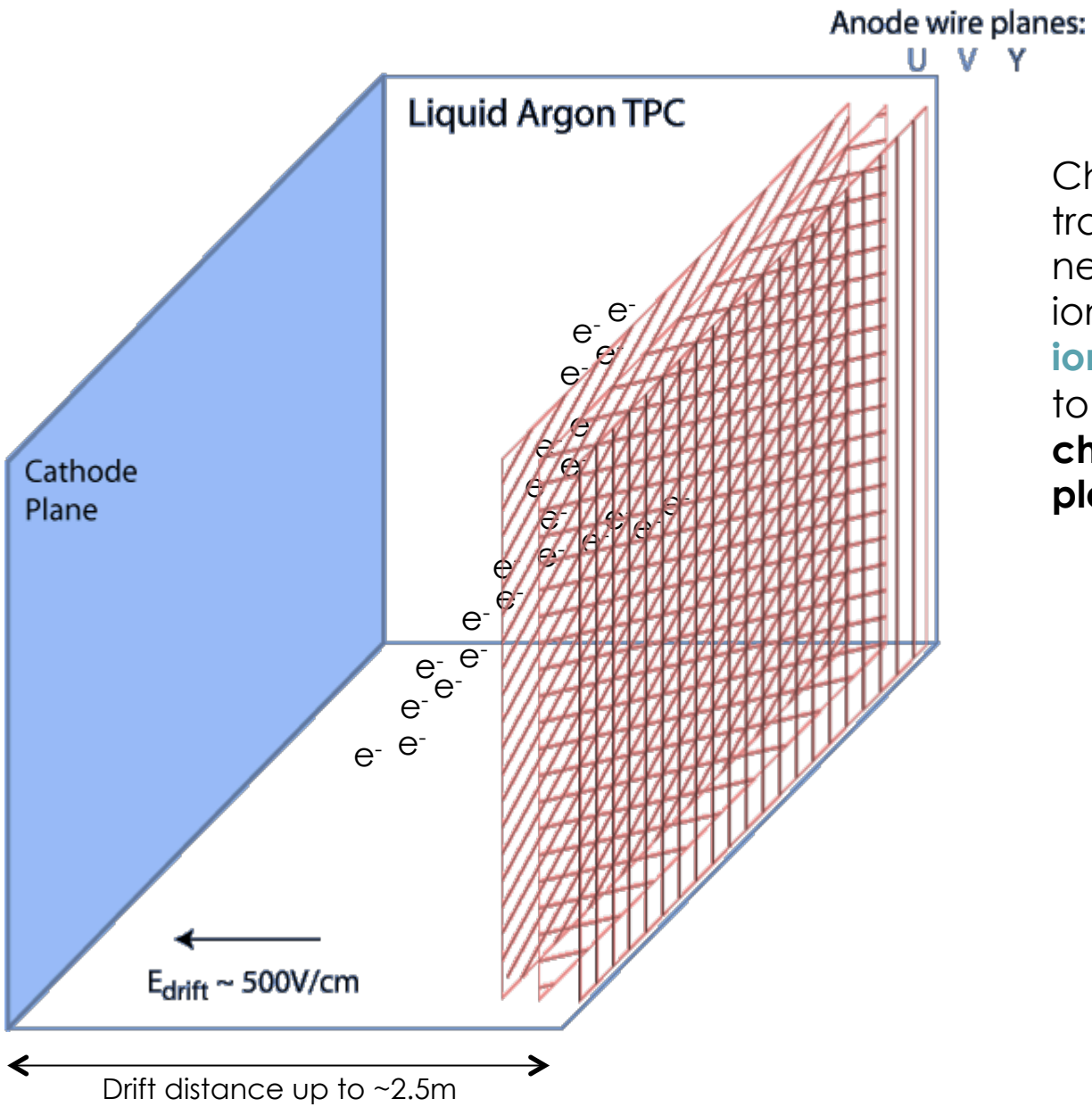

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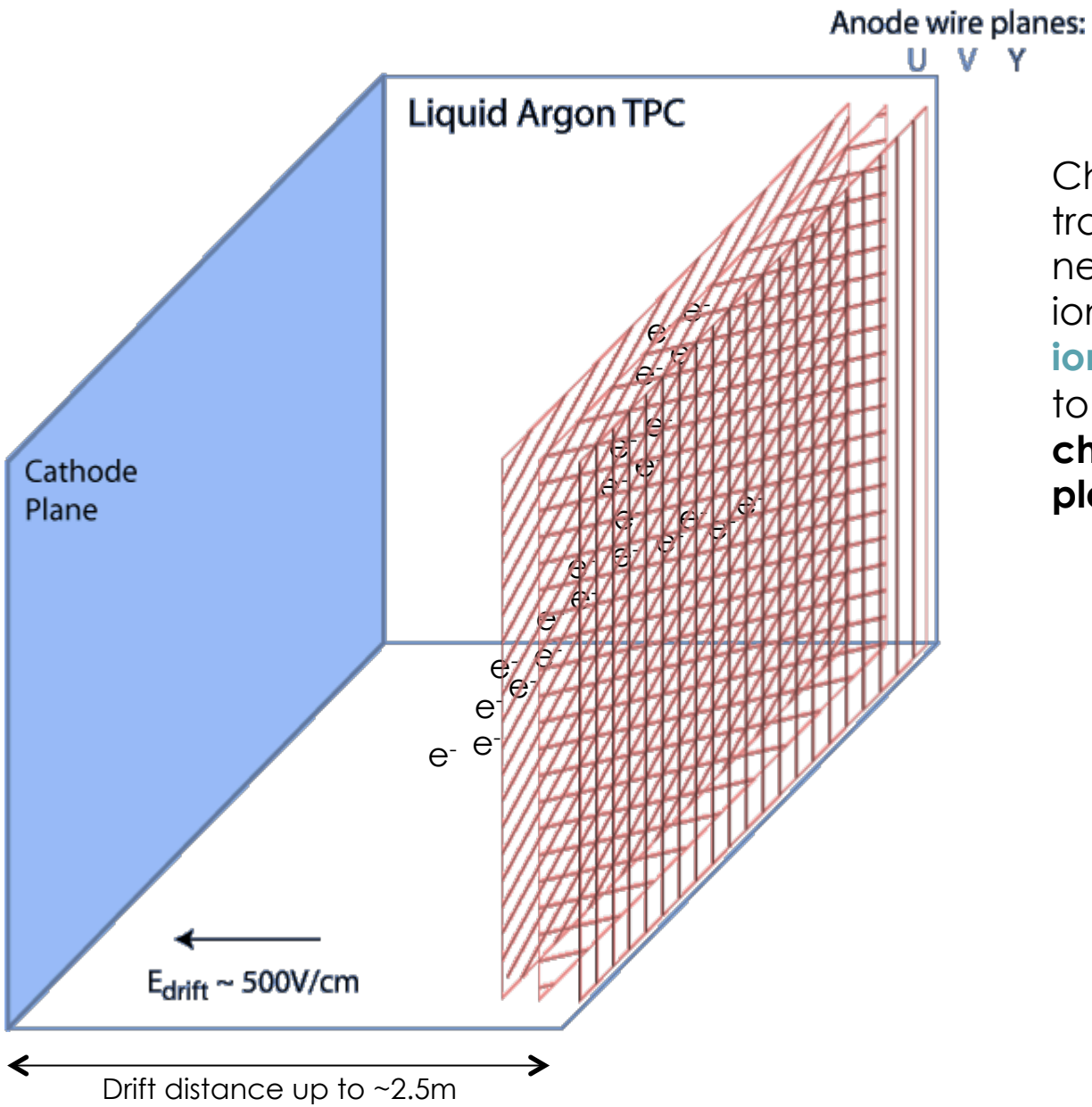

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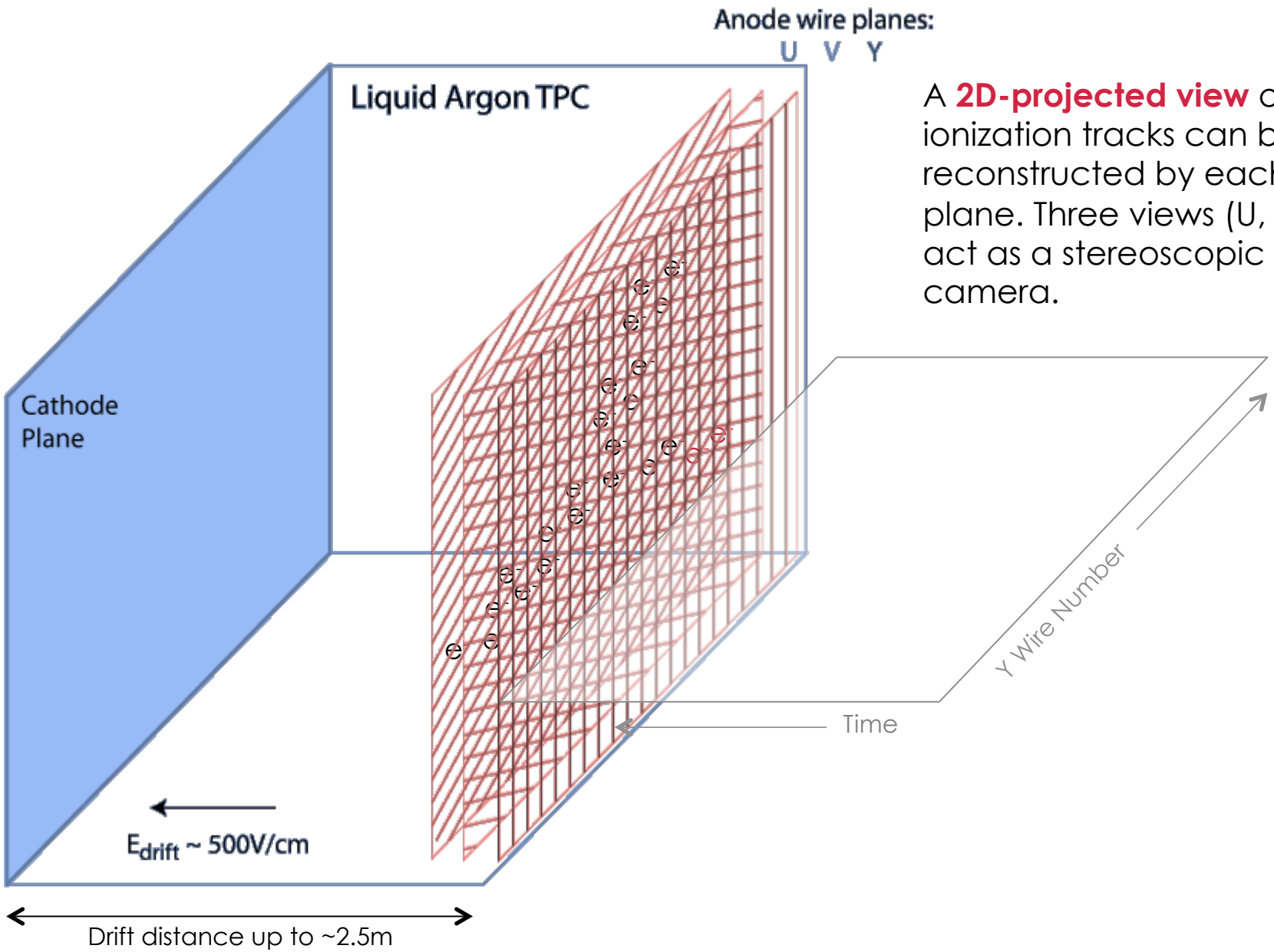

A **2D-projected view** of the ionization tracks can be reconstructed by each wire plane. Three views (U, V, Y) act as a stereoscopic camera.

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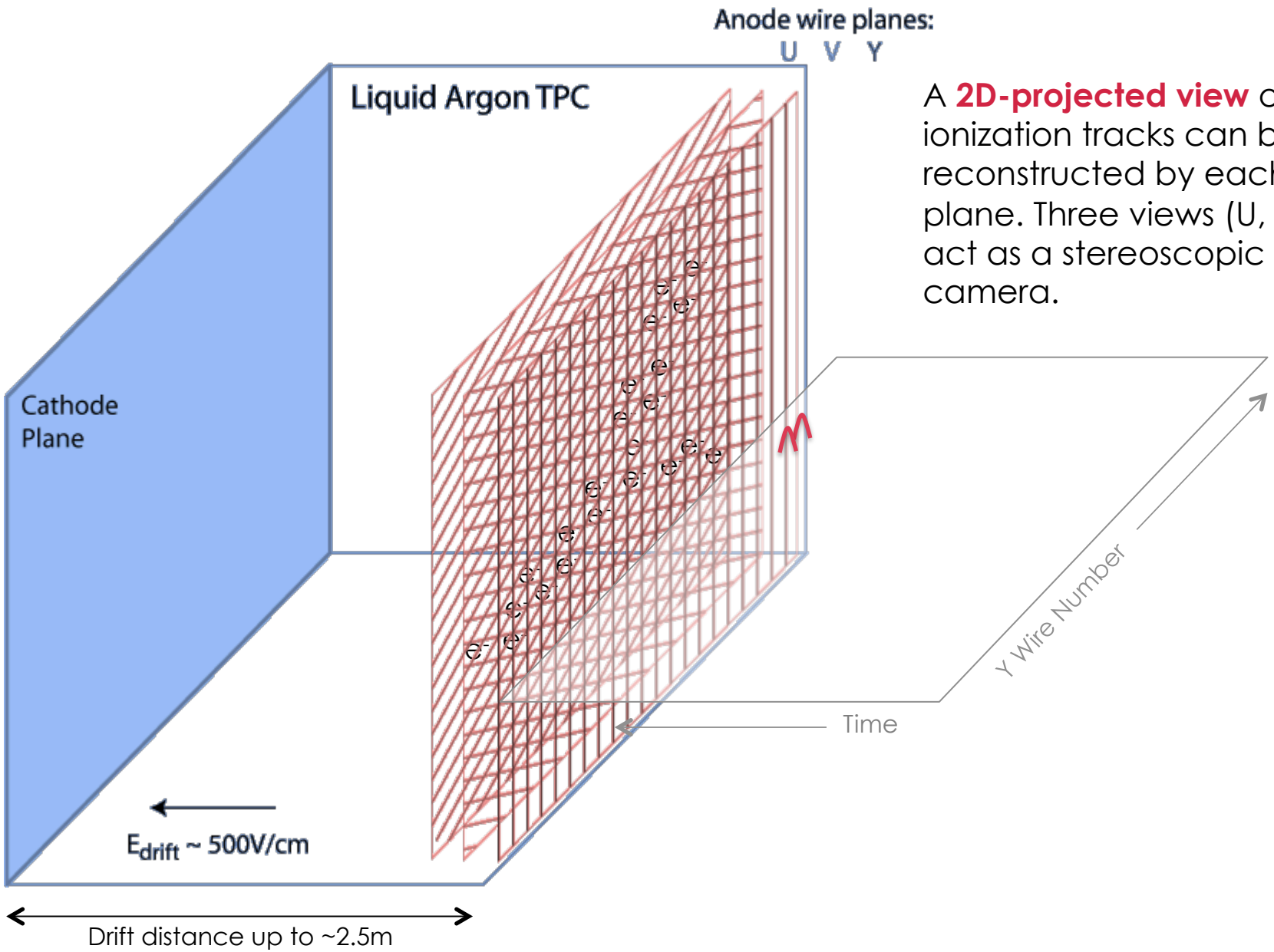

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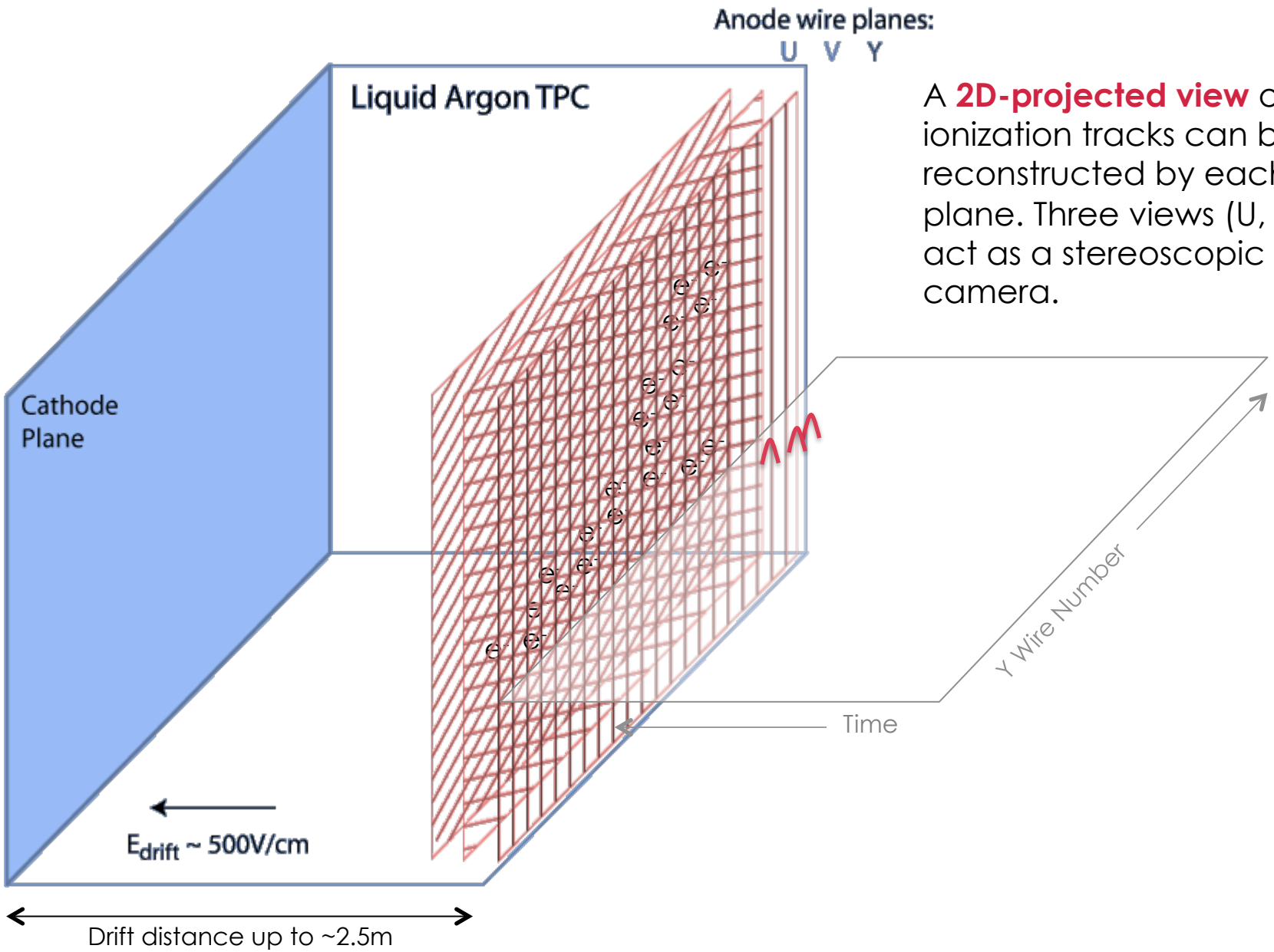

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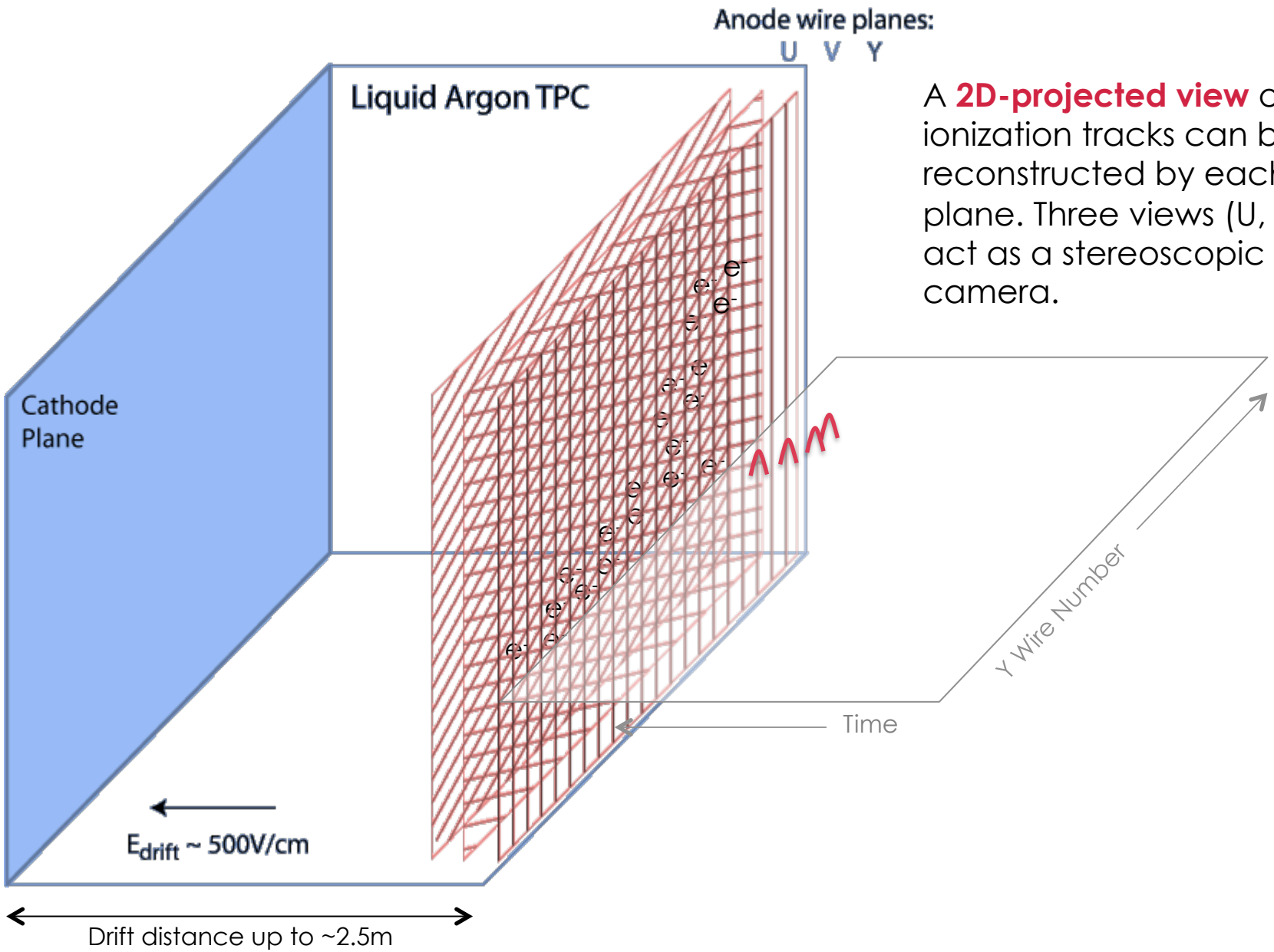

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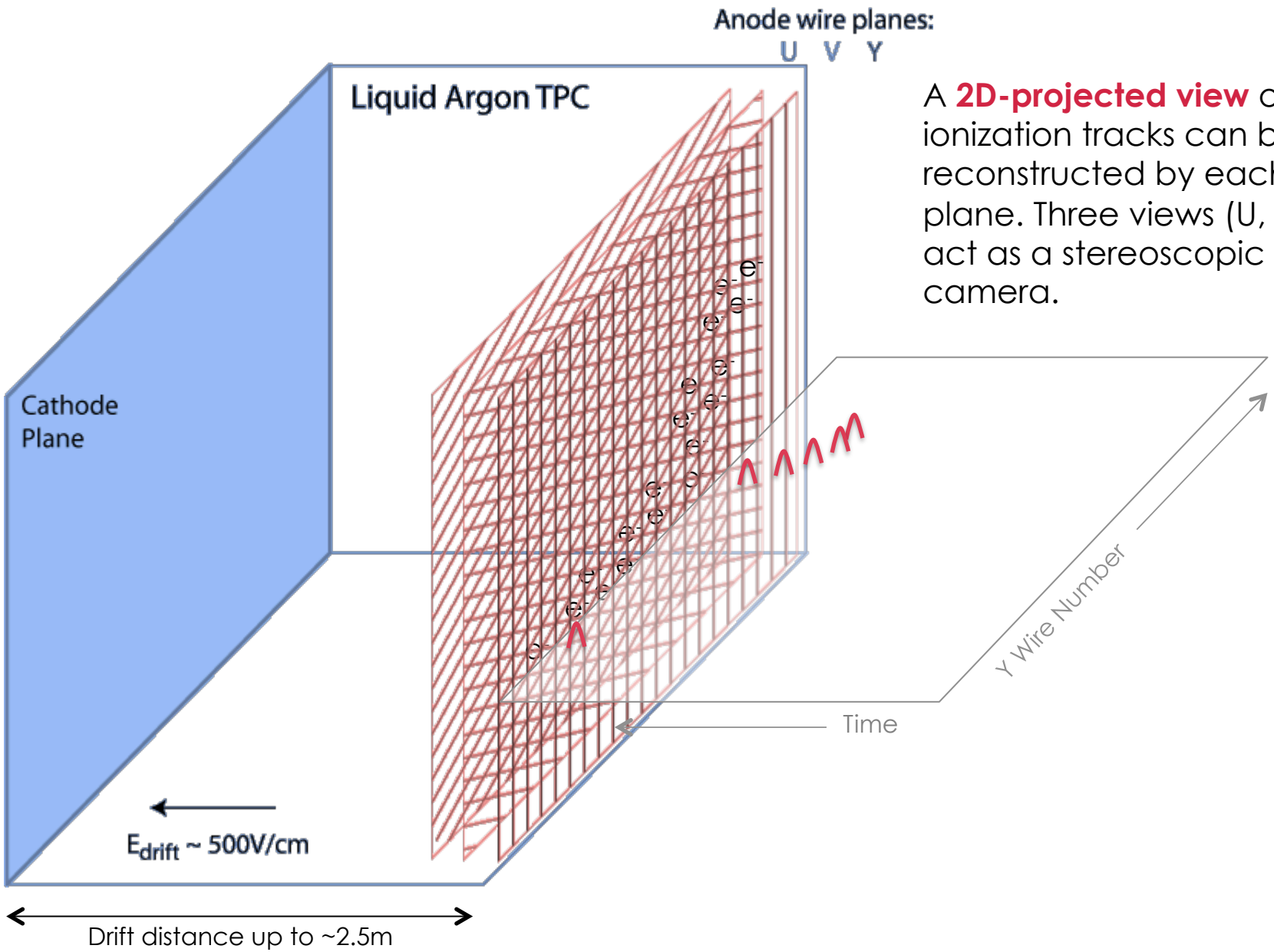

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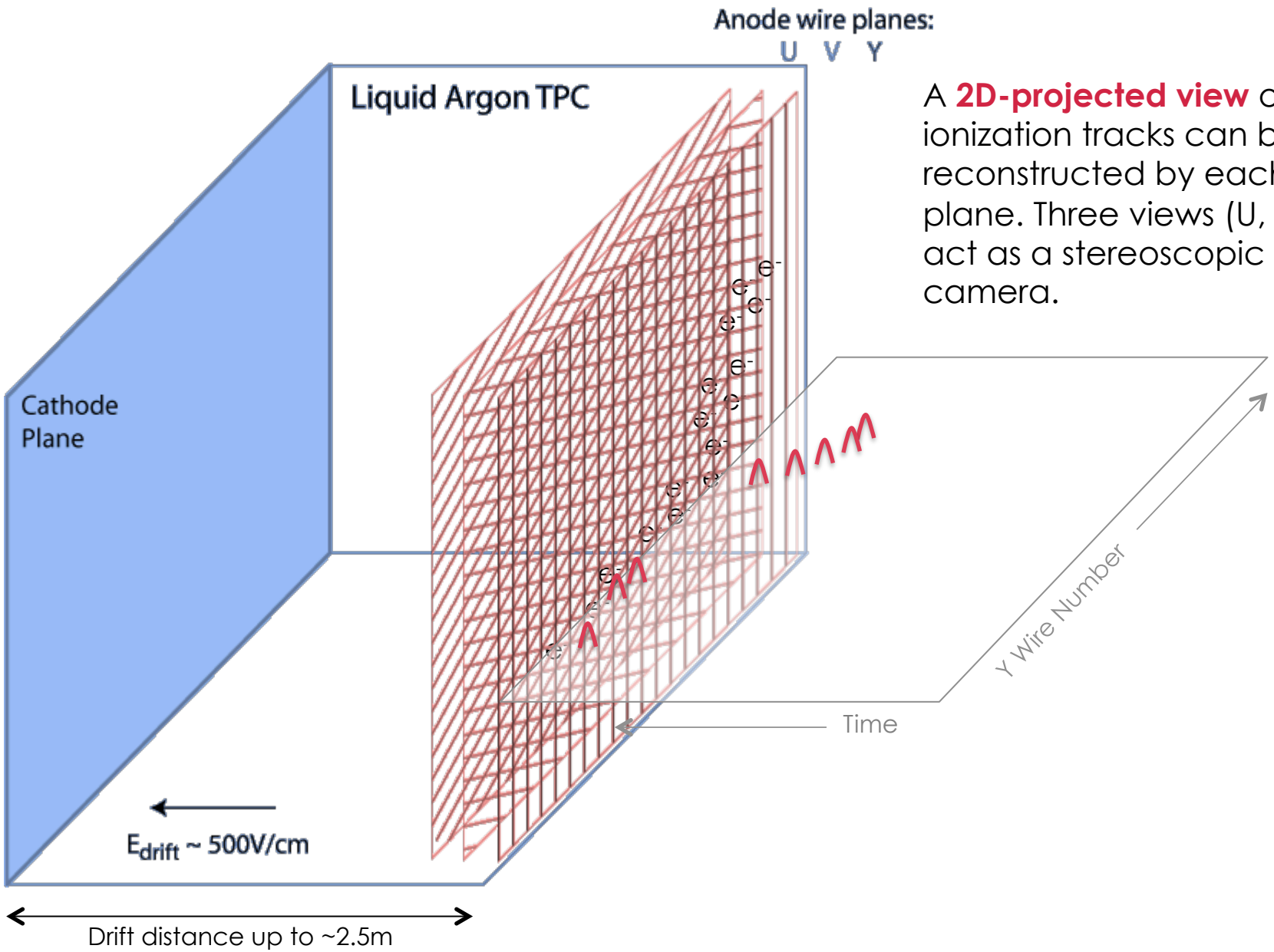

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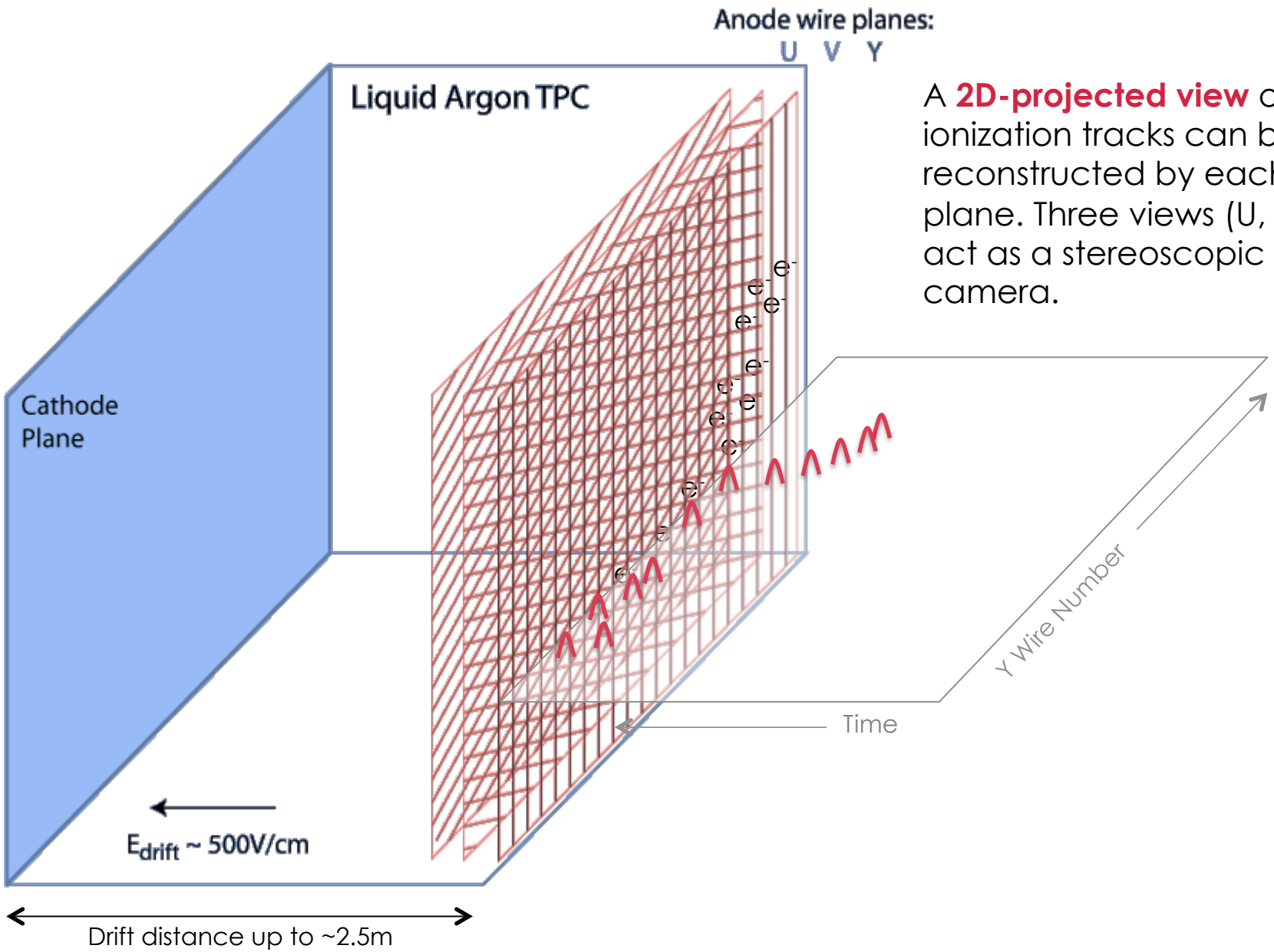

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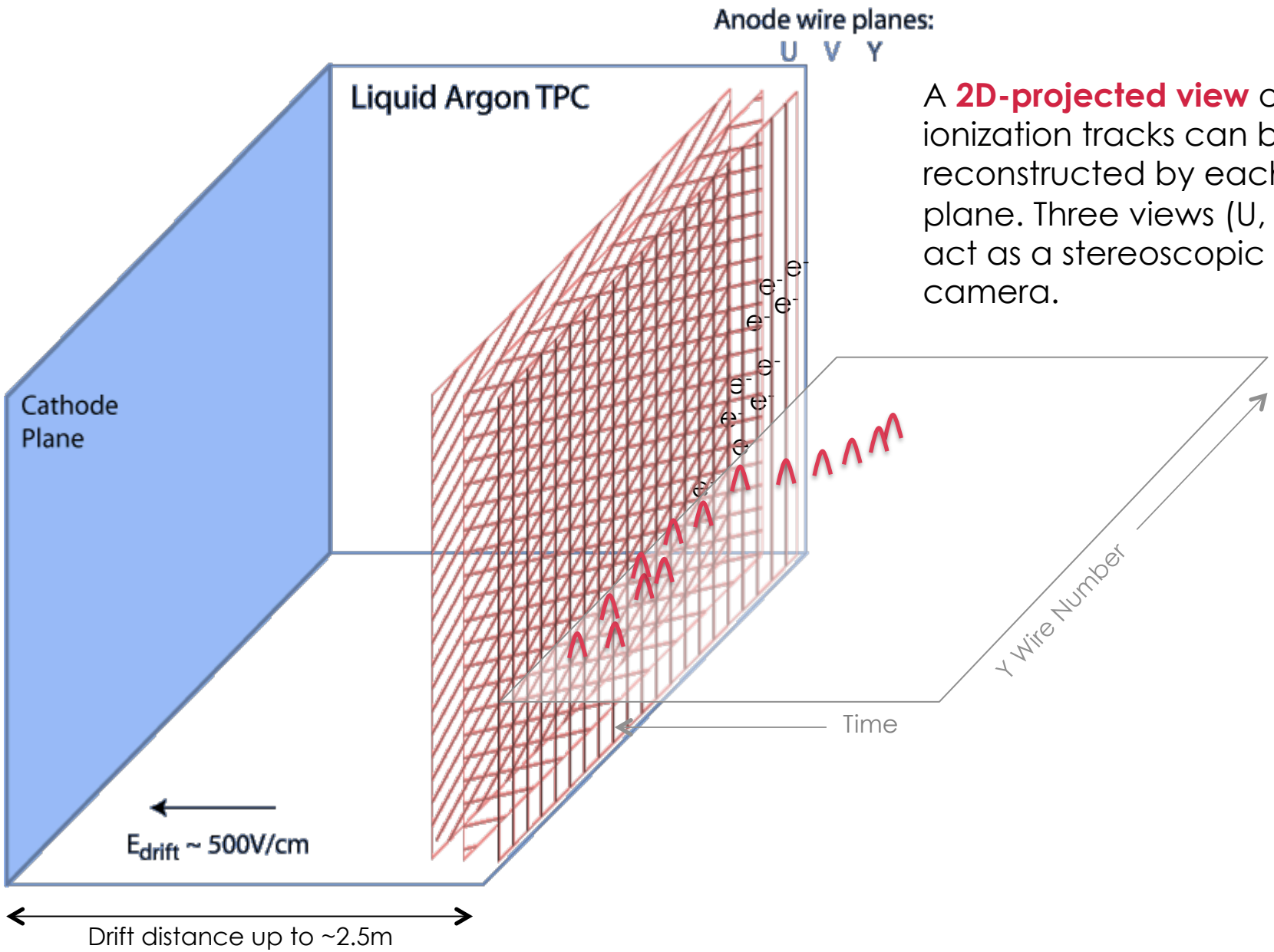

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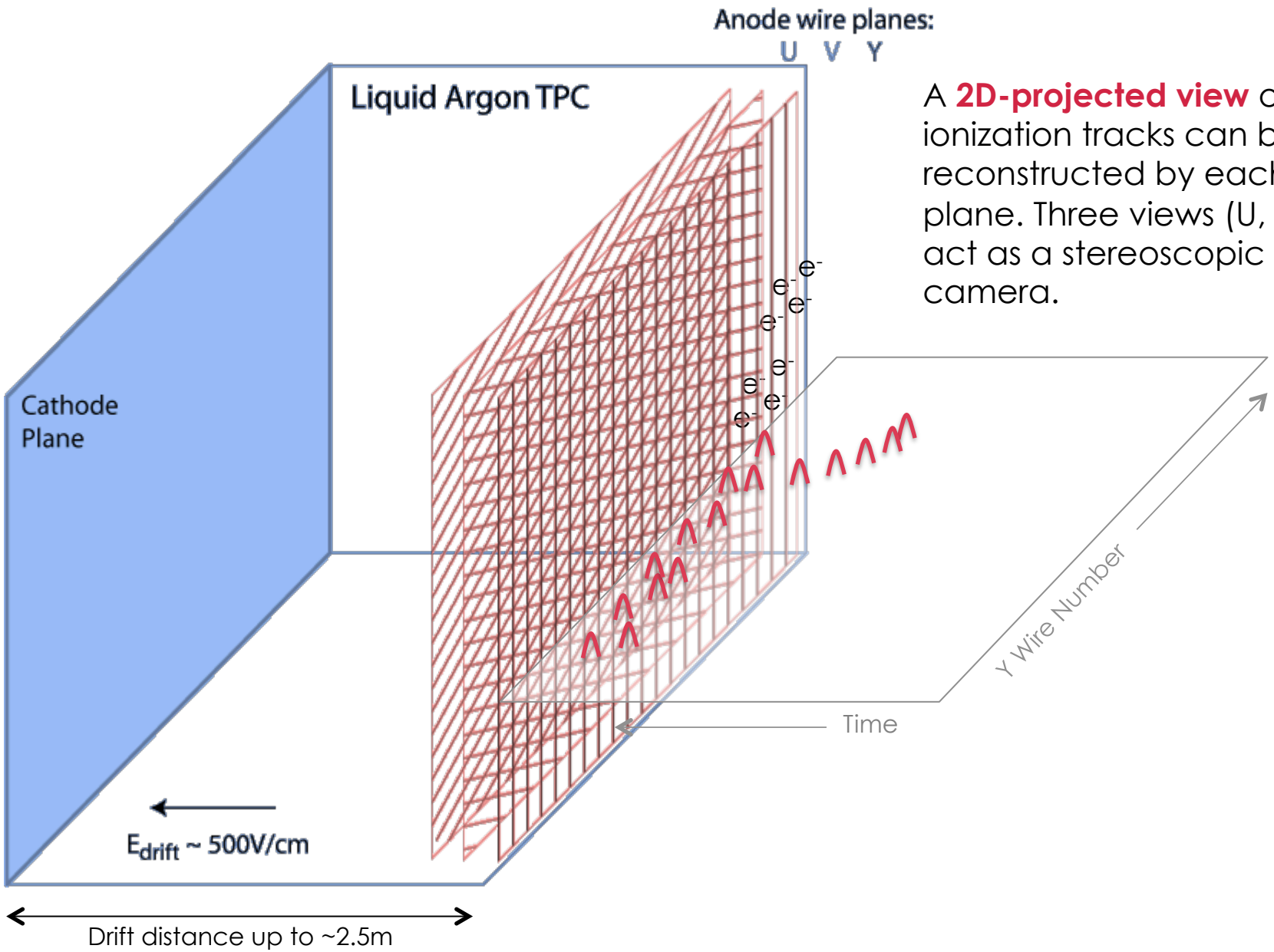

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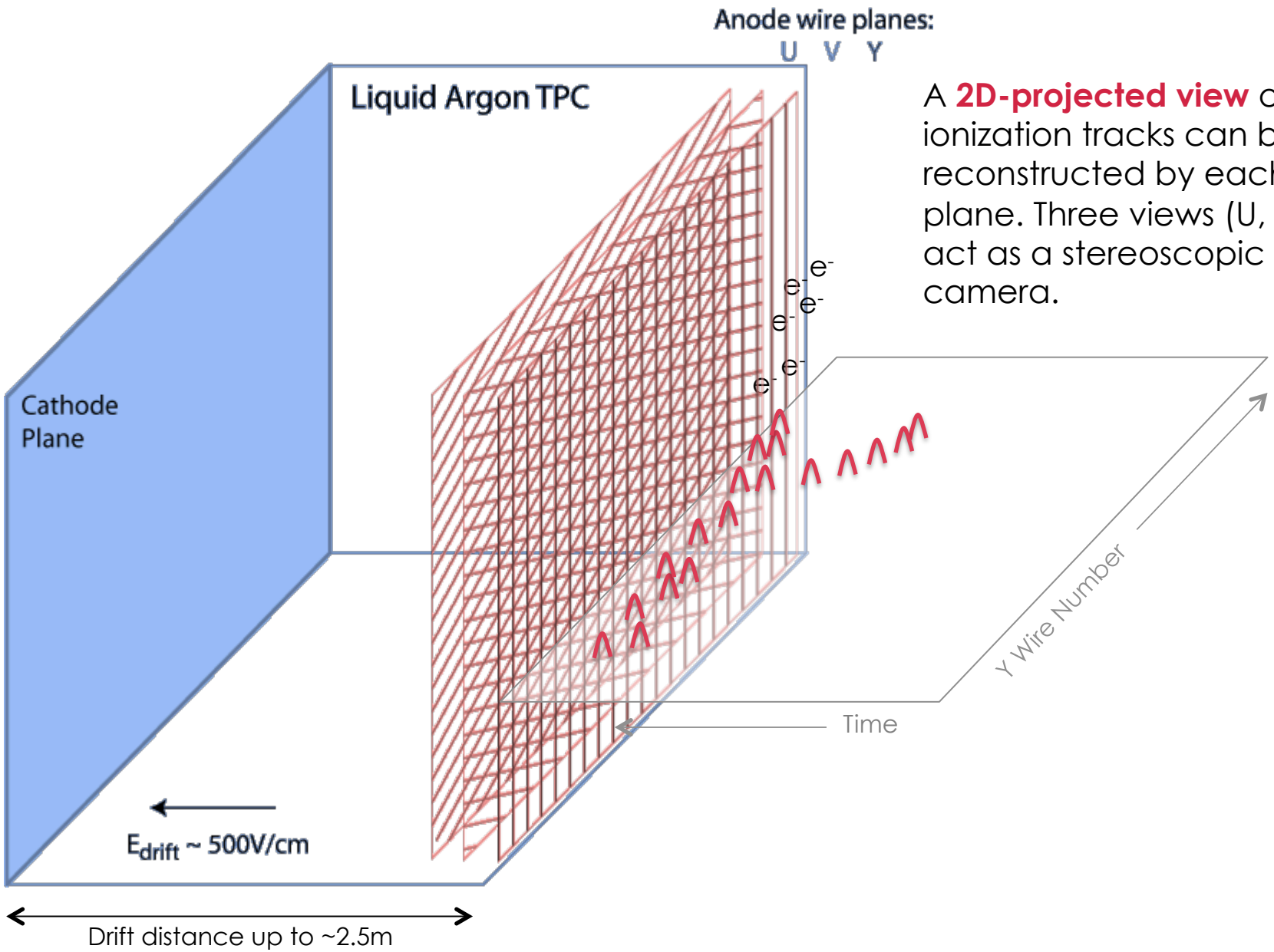

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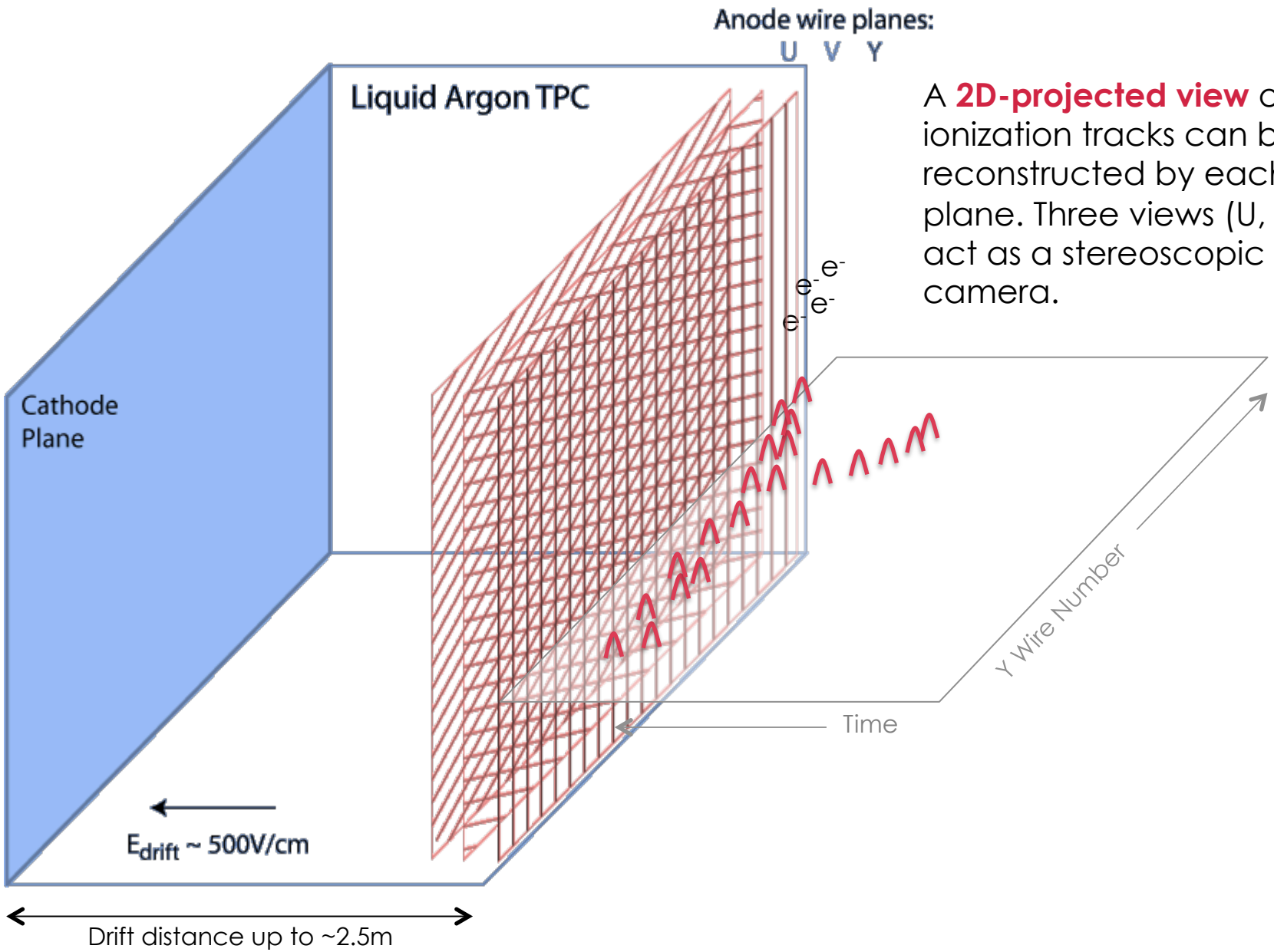

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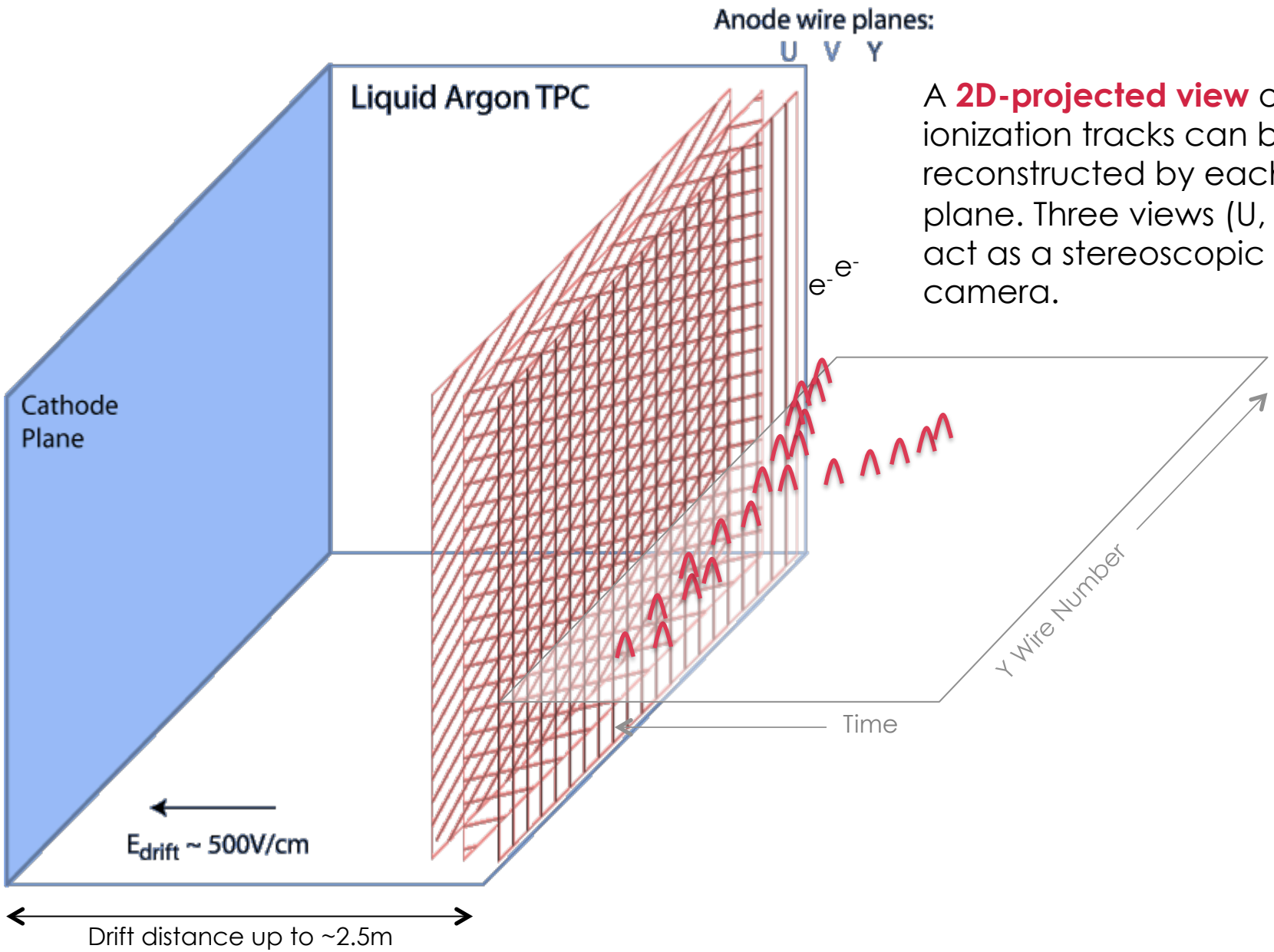

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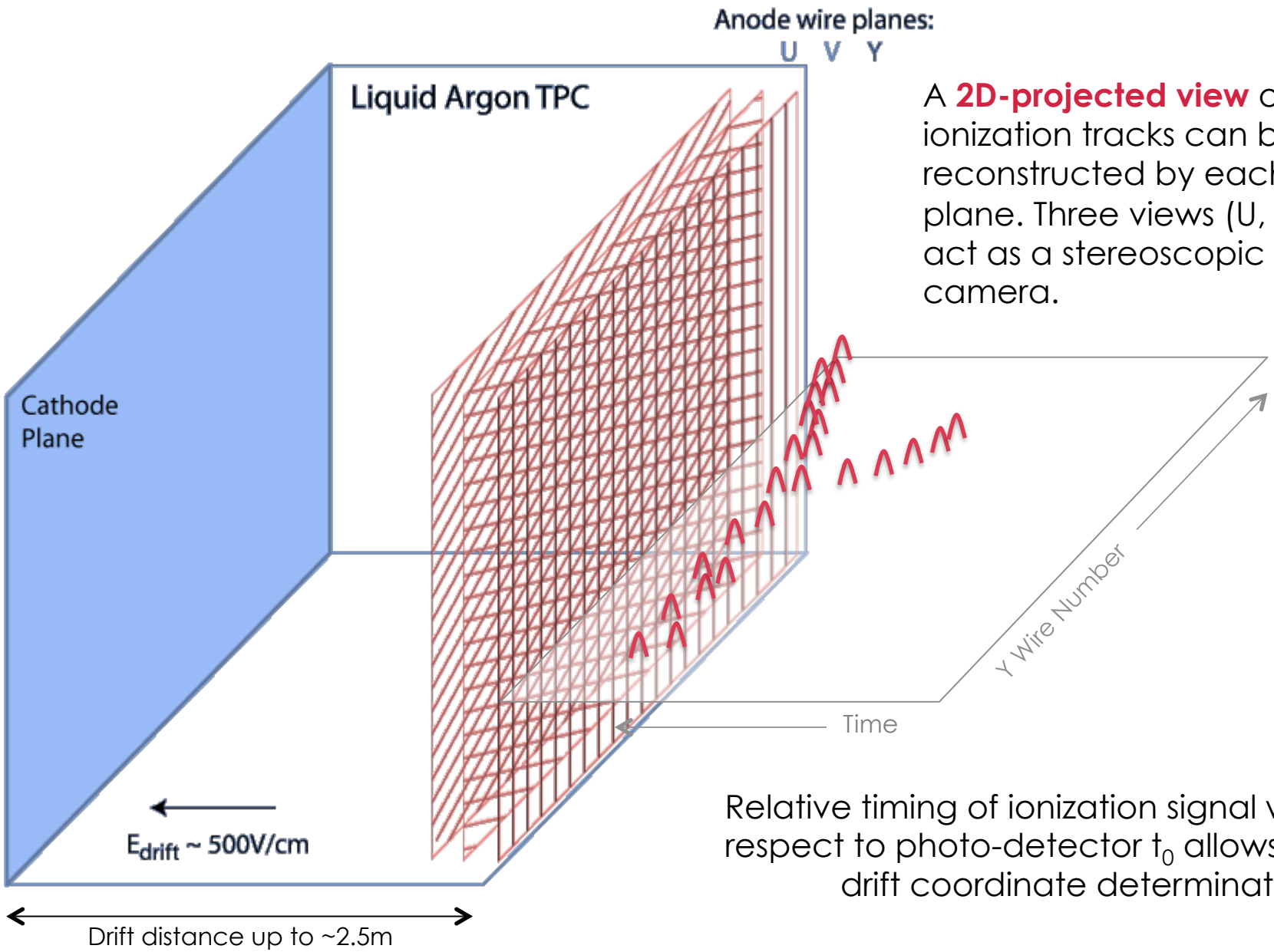
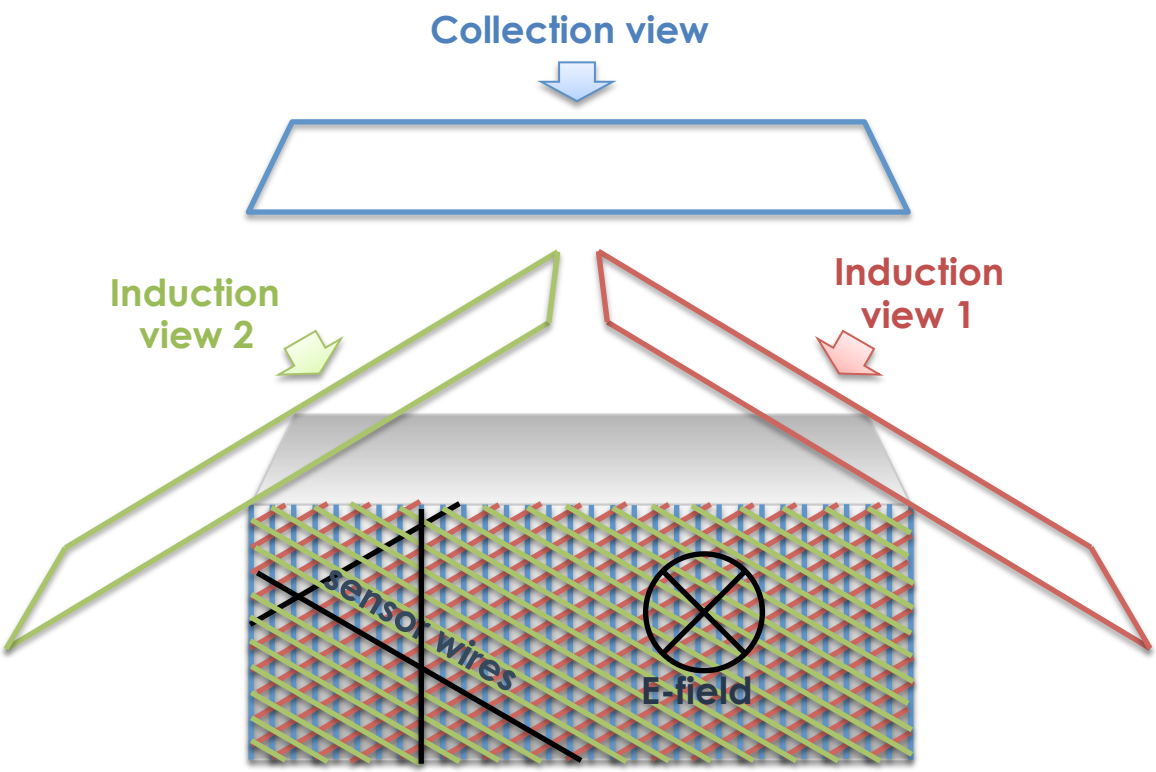


A **2D-projected view** of the ionization tracks can be reconstructed by each wire plane. Three views (U, V, Y) act as a stereoscopic camera.

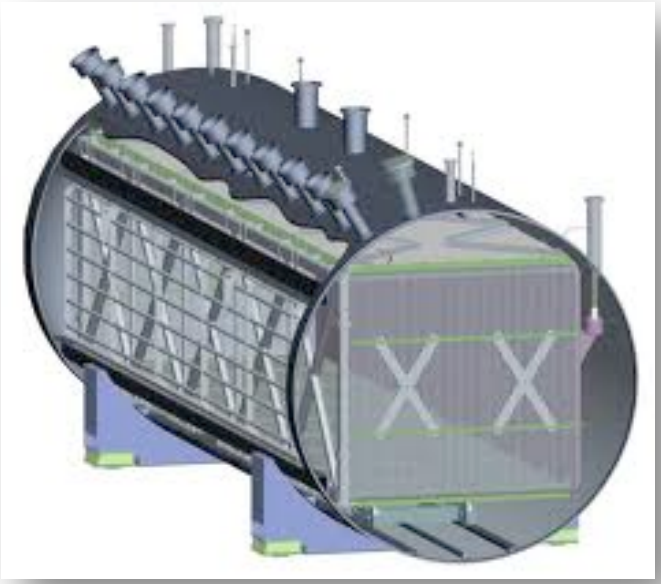
Relative timing of ionization signal with respect to photo-detector t_0 allows for drift coordinate determination.

How a LArTPC works:

Three wire orientations → three 2D projection views

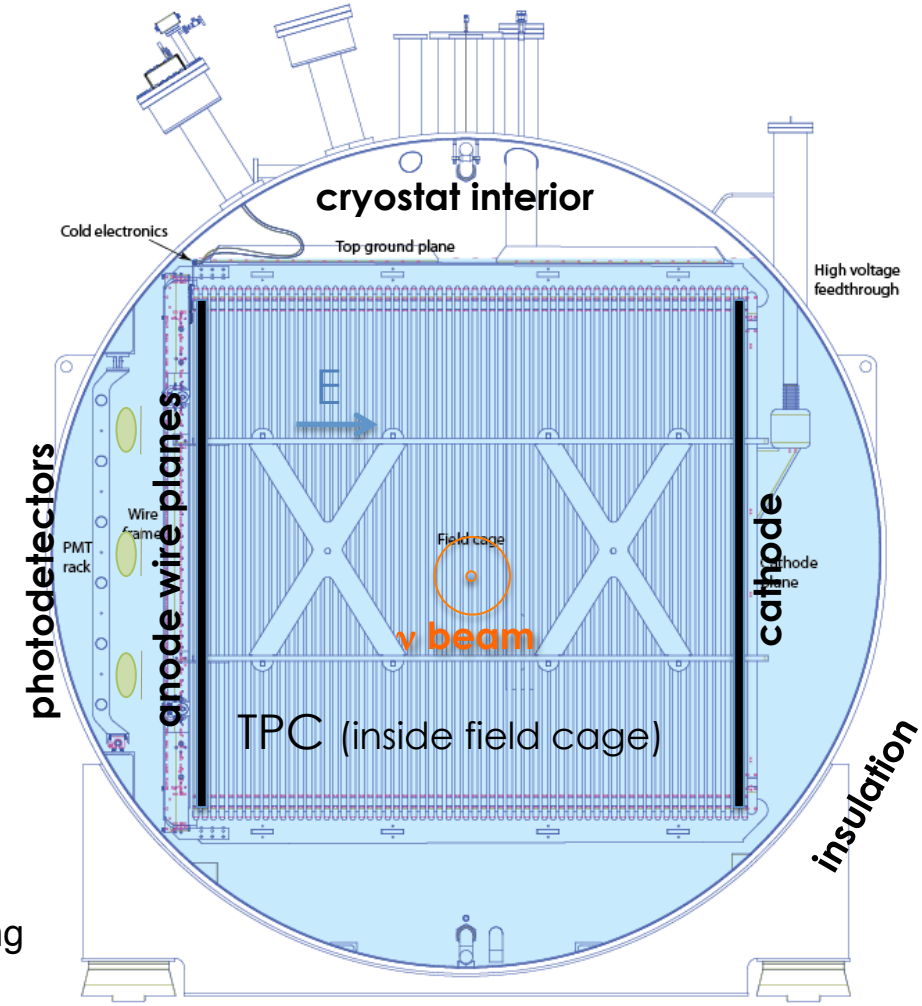


MicroBooNE Detector Parameters

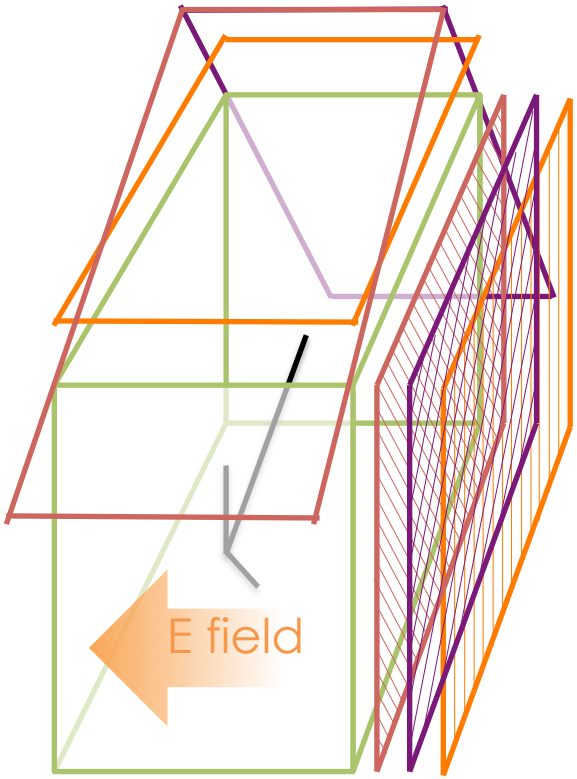


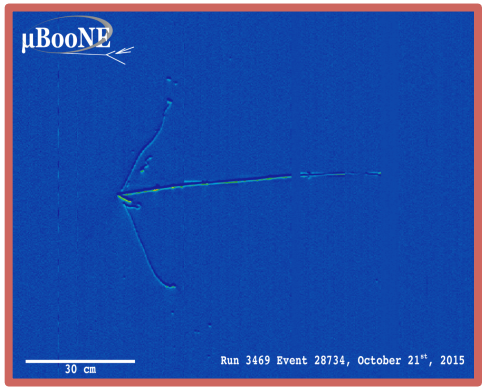
- 2.5 m x 2.3 m x 10.2 m TPC
- **170 (89) tons total (active) LAr mass**
- 2.5 m drift length
  -128kV on cathode (design)
- 3 wire planes: 0, ±60° from vertical,
  3 mm wire separation
- 8256 wires, digitized at 2MHz
- 32 PMT's digitized at 64MHz
  for t_0, drift coordinate determination, and triggering
  for empty beam spill rejection

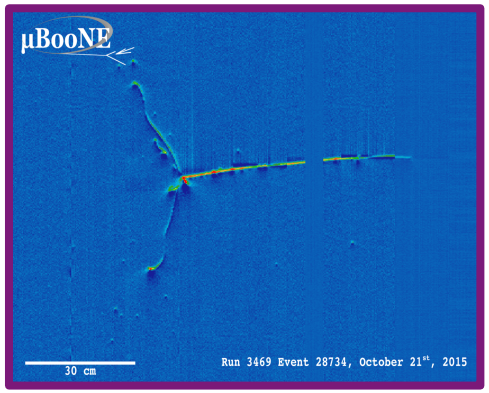
Cross section of detector:

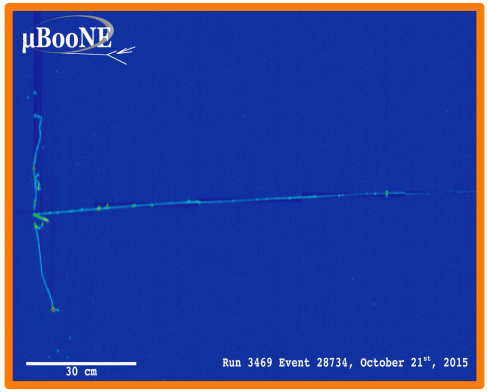


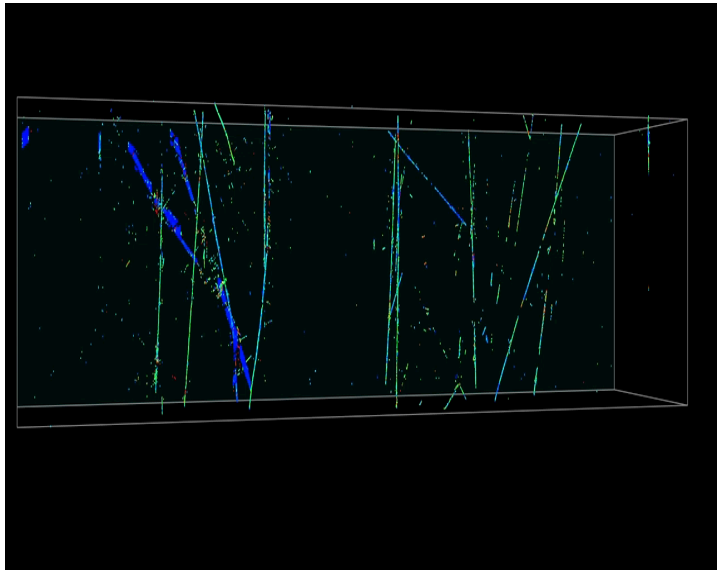
MicroBooNE: A high-resolution 3D camera for charged particles





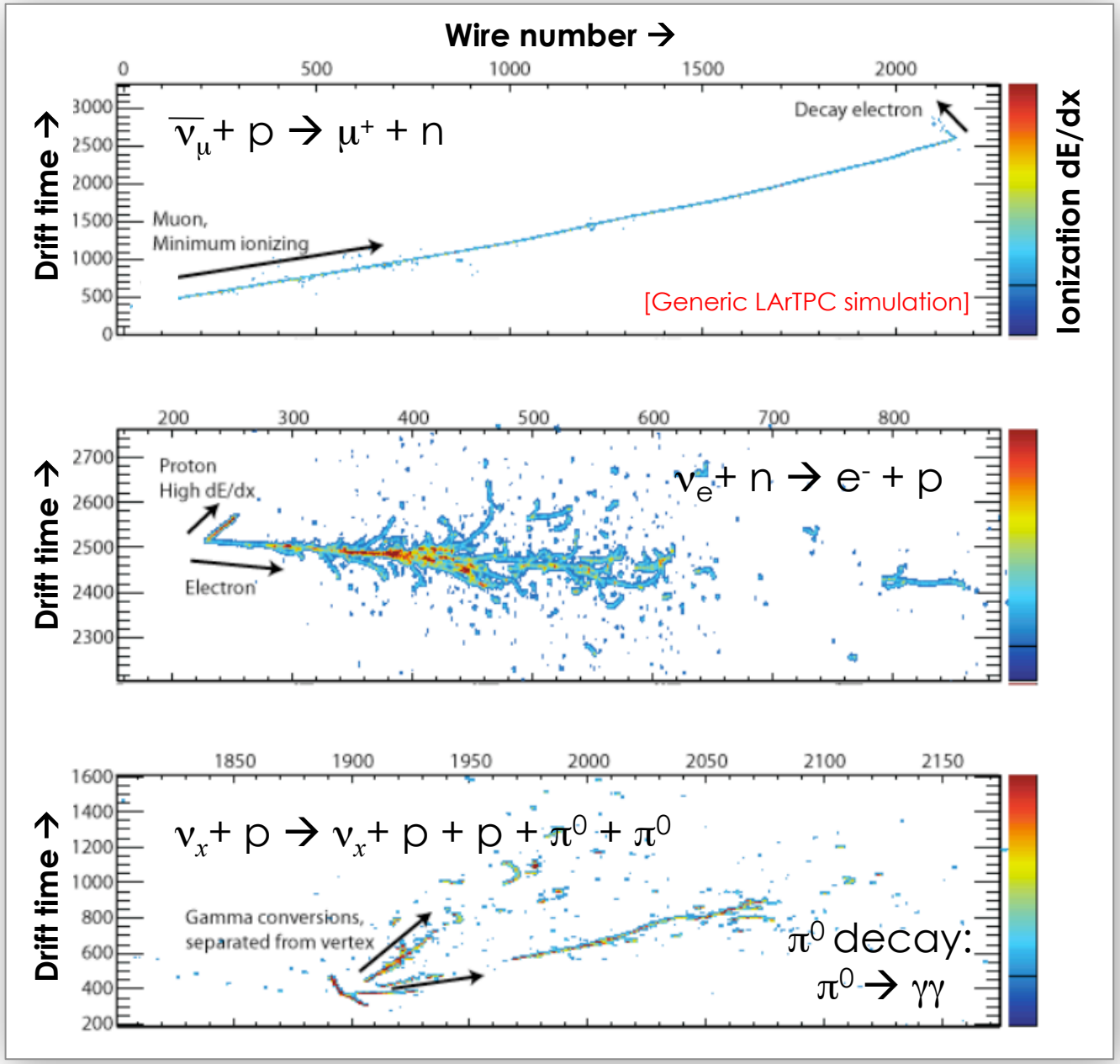






What does a neutrino look like in a LArTPC?

Well-contained collection of charged particle tracks (products of a neutrino interacting on argon)



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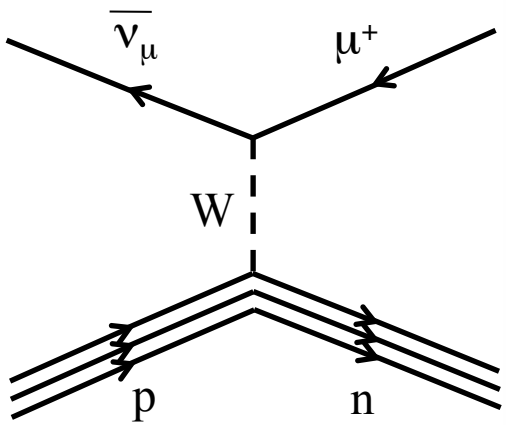
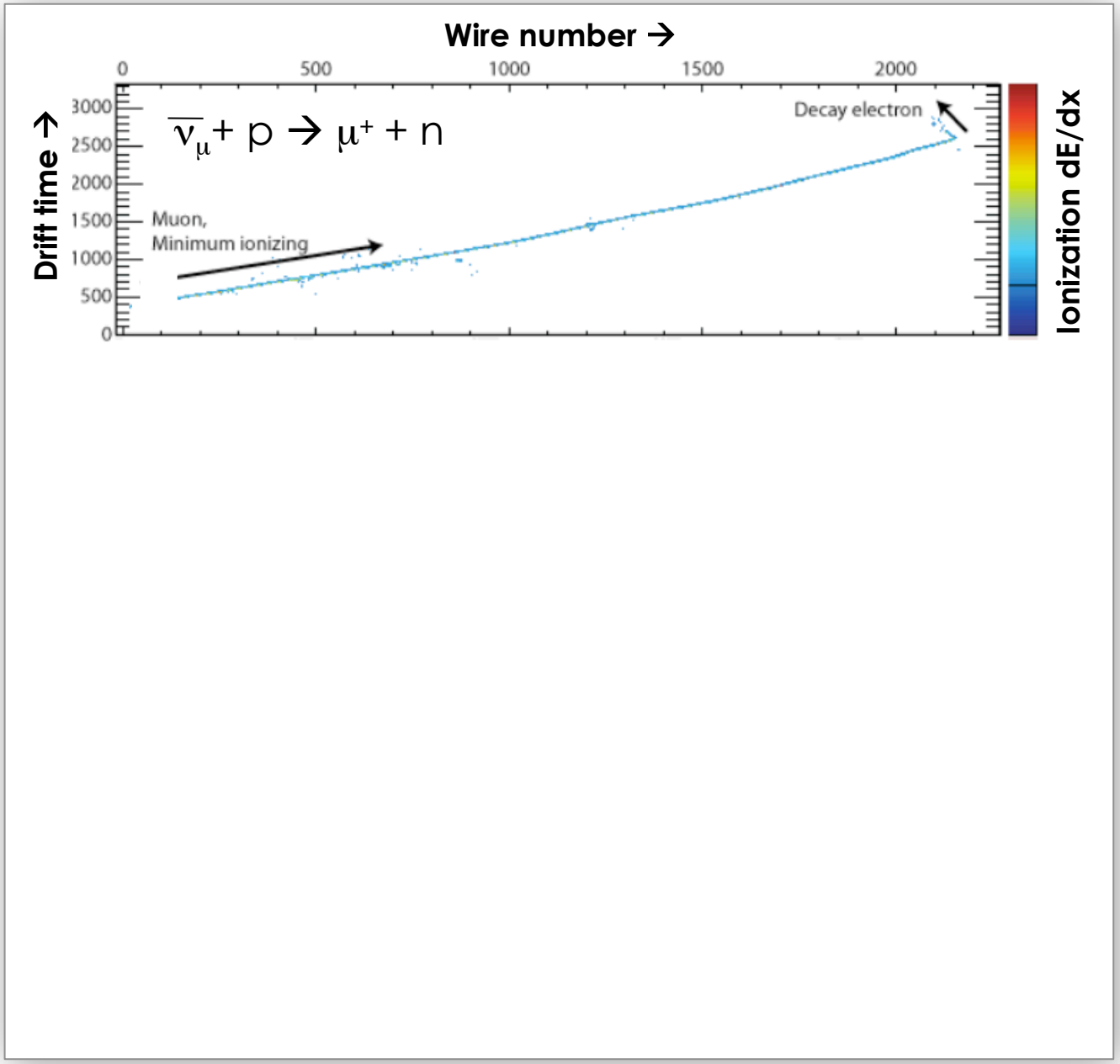
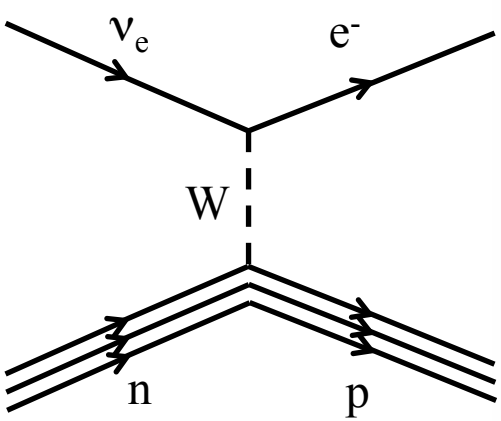
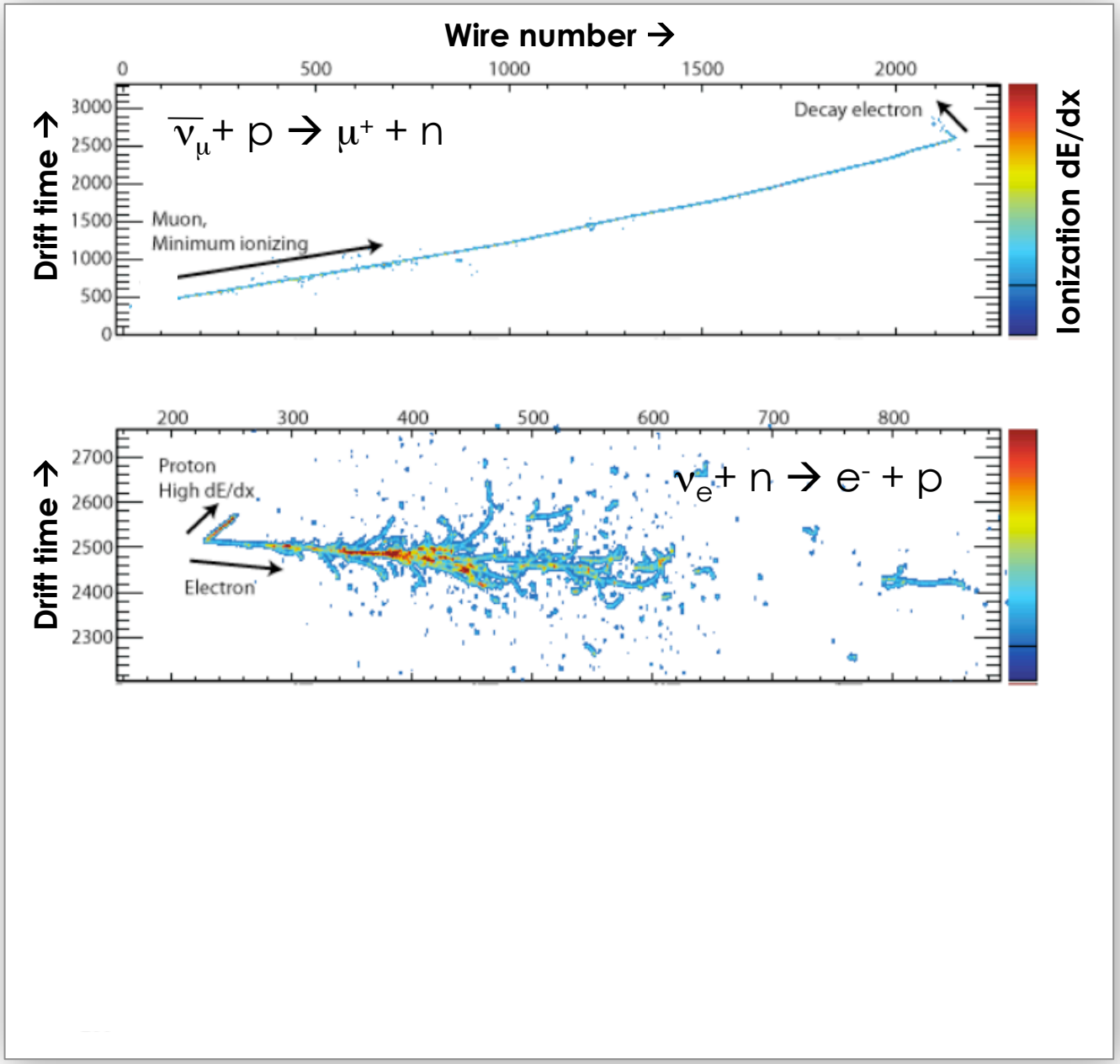




Example simulated neutrino events (E_ν ~ 0.5-1 GeV)

What does a neutrino look like in a LArTPC?





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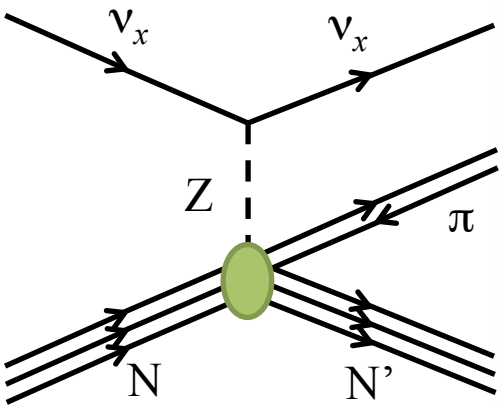

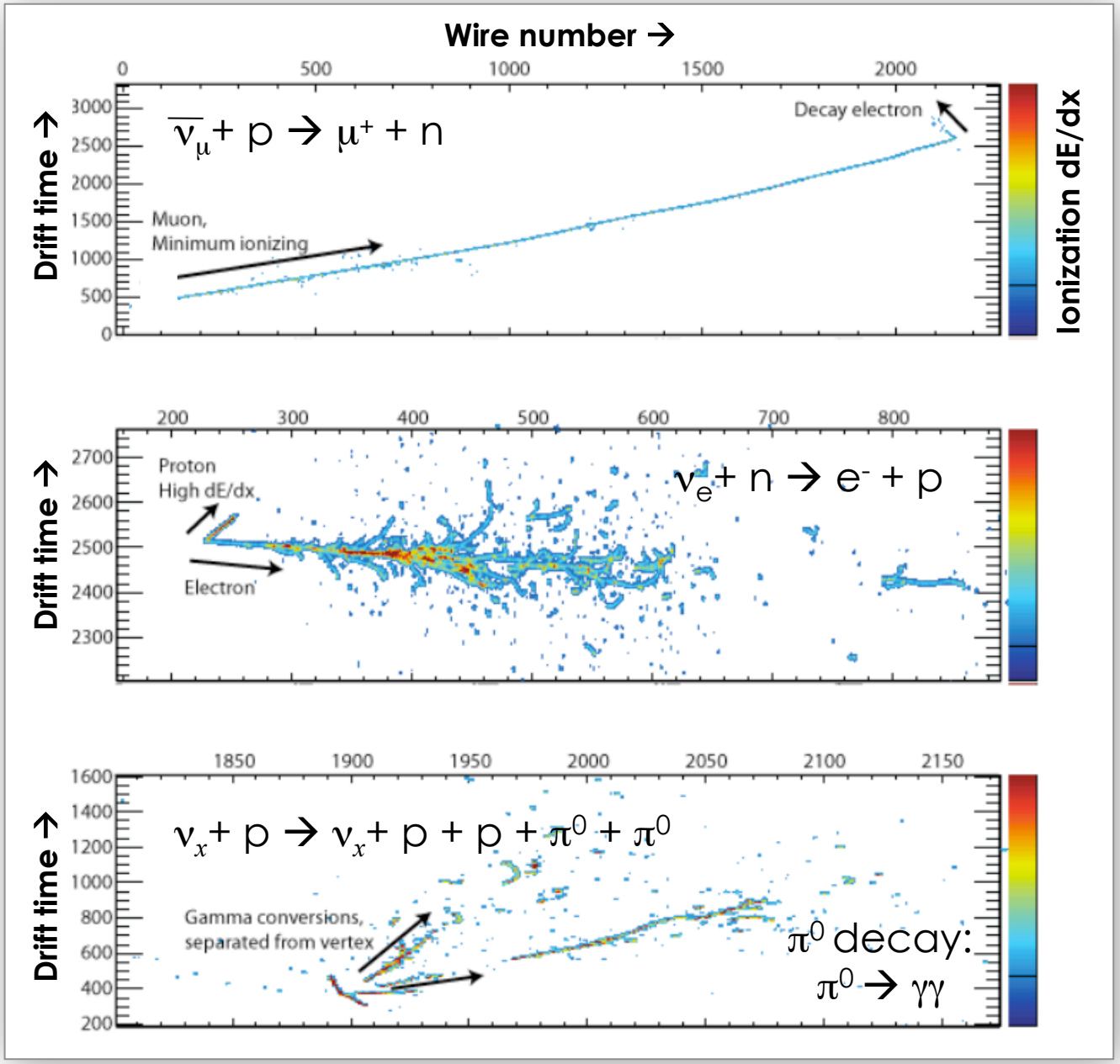

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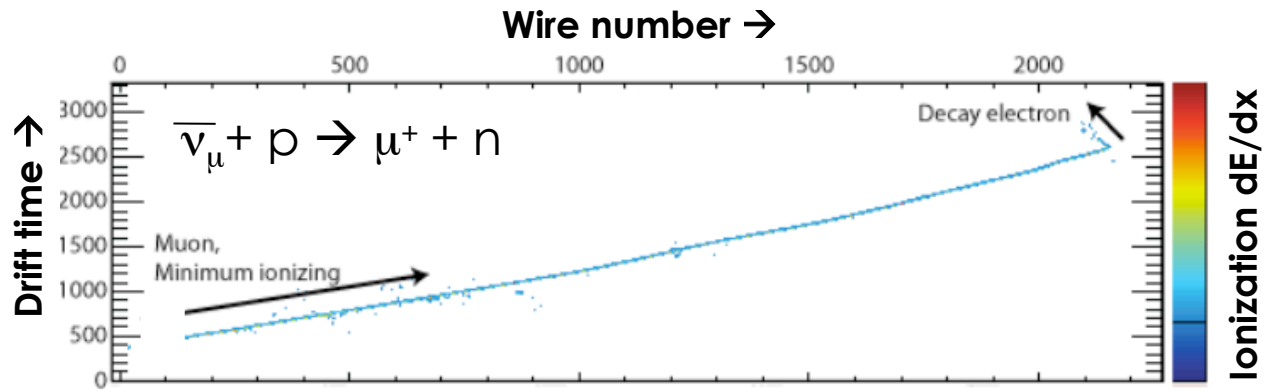
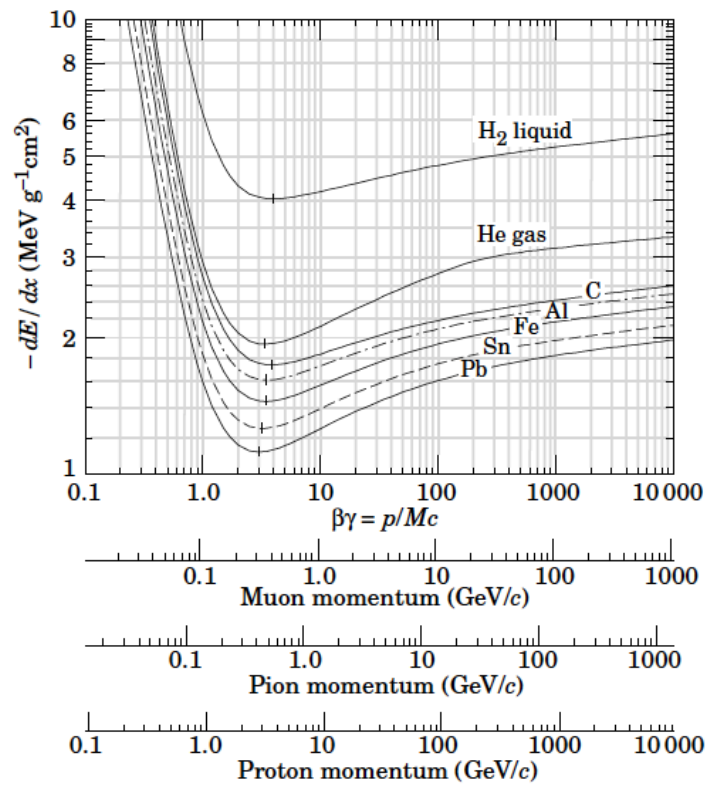


- Particle energy loss to ionization (dE/dx) is a well understood process. We can identify each particle type by its dE/dx vs. x, and furthermore determine its momentum.

- **Neutrino flavor identification** is possible by event topology (shower vs. long track) and further particle identification, and final state kinematics considerations.
- **Neutrino energy reconstruction** is possible once the energy and momentum of (charged) interaction final states is determined.



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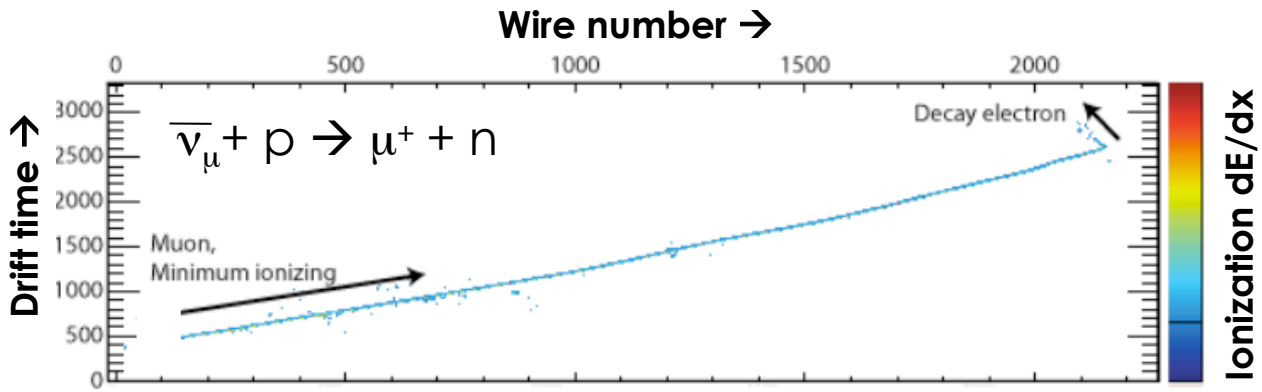


Challenges: subsequent effects affect/distort collected ionization charge:

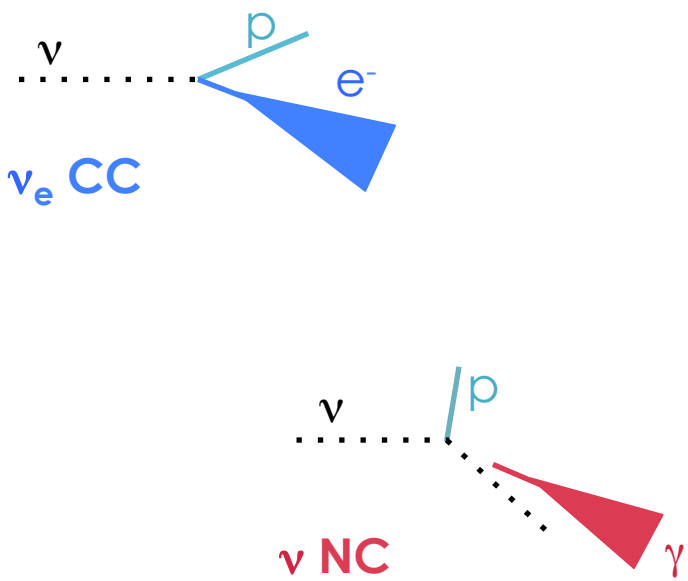
- ion recombination
- electron capture by impurities
- field non-uniformity
- electronics response and gain

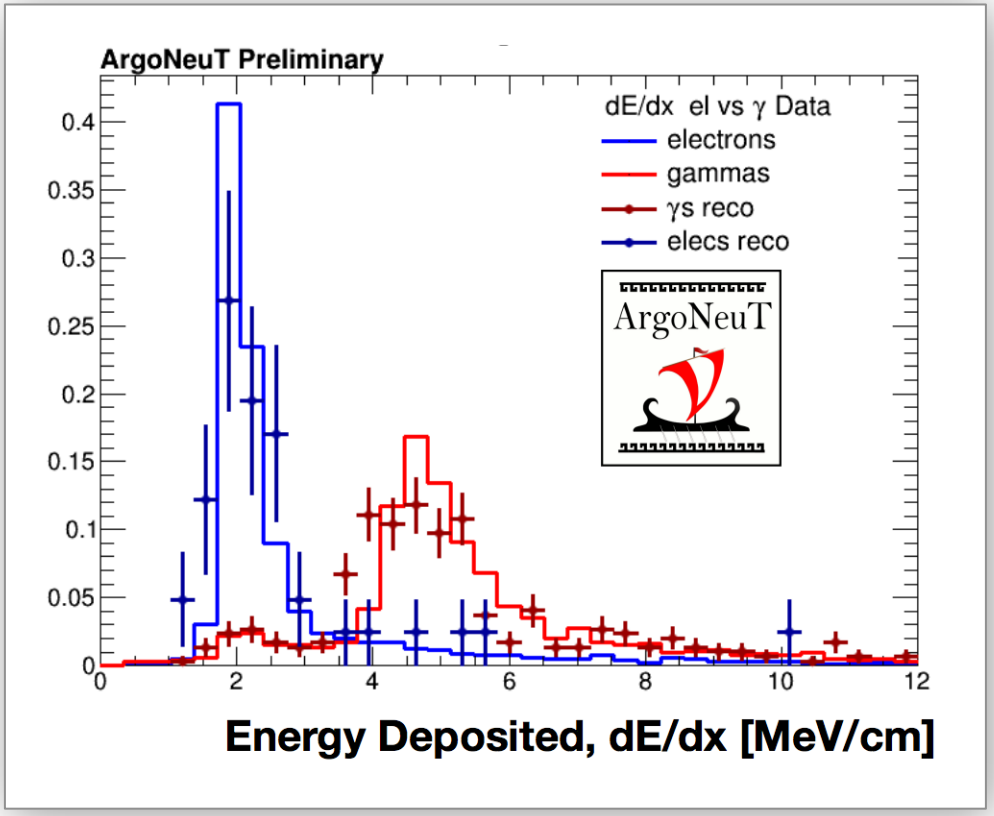
Need proper detector effects **modeling**, and detector **calibration.**

Electron/Photon Separation

Neutrino events with γ are differentiated on the basis of:

1. Detached shower vertex from neutrino interaction vertex
2. Larger dE/dx deposited at the beginning of the shower (2 MIP vs 1 MIP)



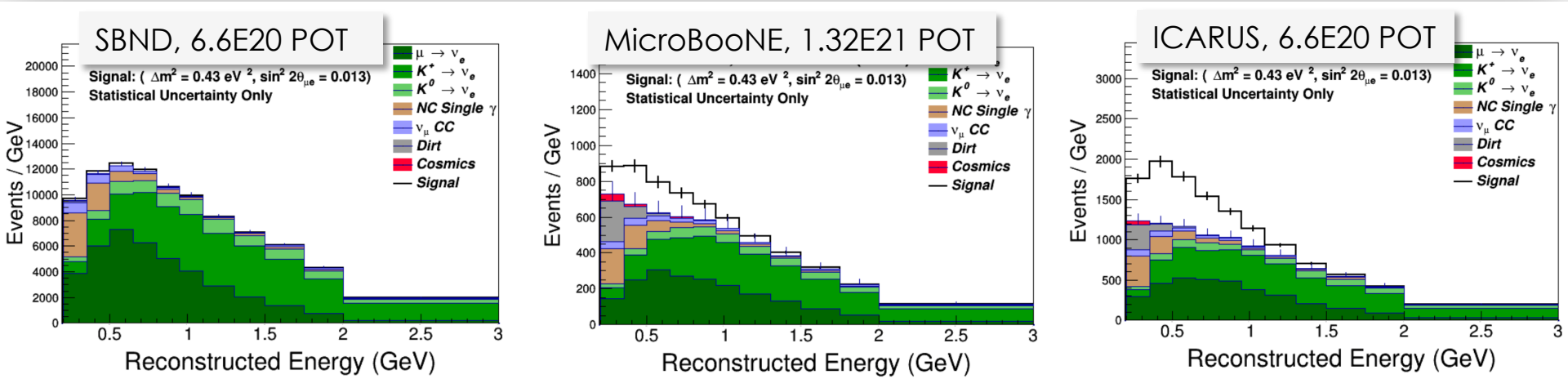


Typical e/γ separation: ~90% → Ideal technology for ν_e measurements

SBN at Fermilab

Same beam, neutrino target, detector technology
→ flux and cross-section are highly correlated, expected to mostly cancel out in comparing event rate measurements at each detector location
→ allows for precise L-dependent event rate (oscillation probability) measurement

Assuming 3+1 oscillations, predicted ν_e spectra at each detector location:



[SBN Proposal 2015]

SBN at Fermilab

Search strategy: Look for excess events above ν_e background prediction and fit assuming ν_μ in the beam oscillate into ν_e given some (Δm^2, $\sin^2 2\theta$).

$$\chi^2(\Delta m^2_{41}, \sin^2 2\theta) = \sum_{i,j} \left[N_i^{null} - N_i^{osc}(\Delta m^2_{41}, \sin^2 2\theta)\right] (E_{ij})^{-1} \left[N_j^{null} - N_j^{osc}(\Delta m^2_{41}, \sin^2 2\theta)\right]$$

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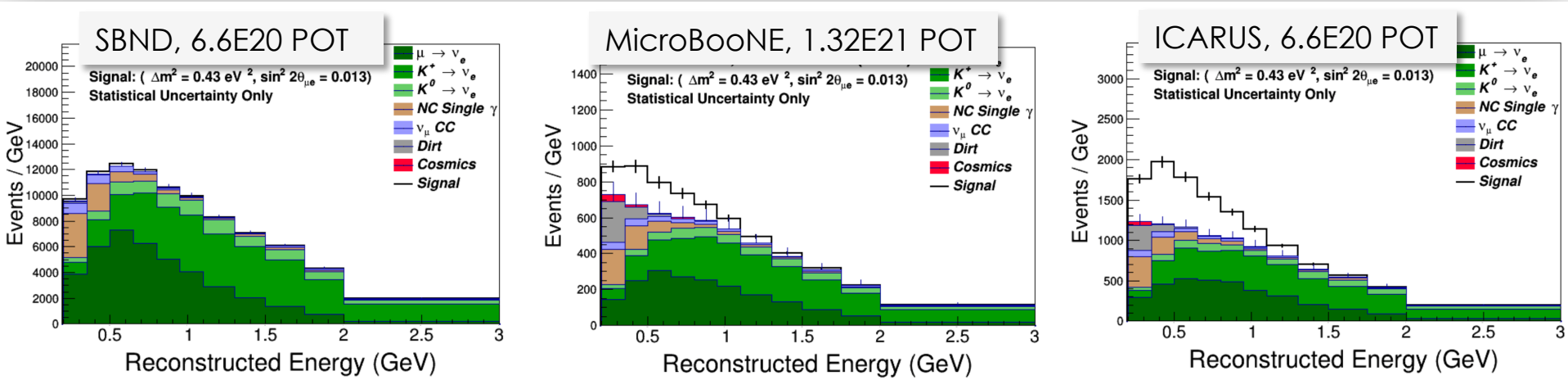

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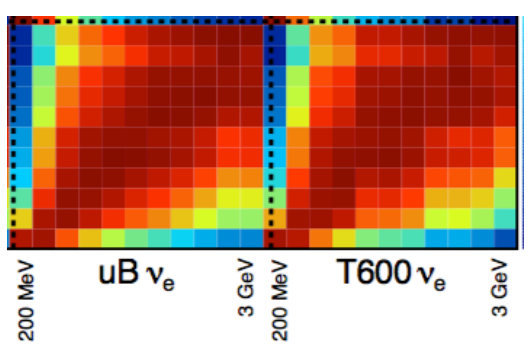
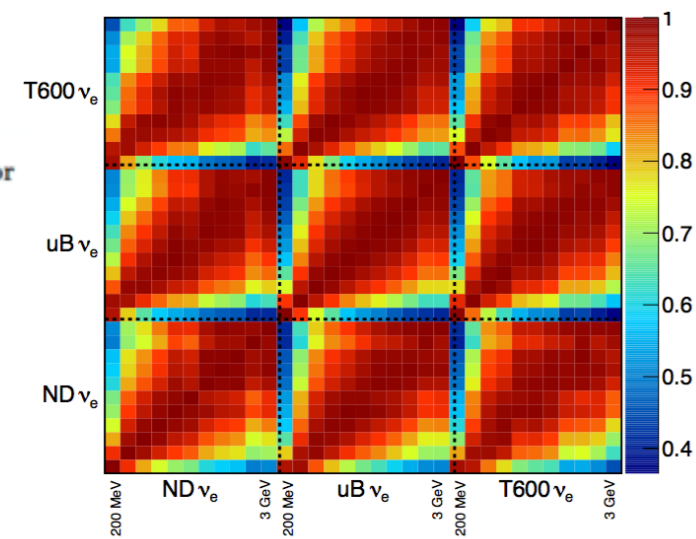
Fit to three detector ν_e distributions side by side, using a covariance matrix encompassing all systematic uncertainties and bin-to-bin correlations (within a single detector distribution, and across multiple detectors):

$$E^{\text{syst}} = E^{\text{flux}} + E^{\text{cross section}} + E^{\text{cosmic bkgd}} + E^{\text{dirt bkgd}} + E^{\text{detector}}$$



3 Detector ν_e Background Systematics Correlation Matrix
(flux and cross section systematics)



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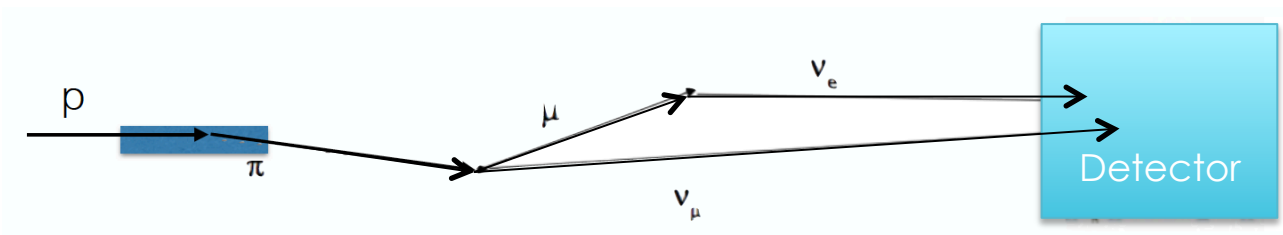


Example:
Flux correlation

$$E^{syst} = E^{flux} + E^{cross\ section} + E^{cosmic\ bkgd} + E^{dirt\ bkgd} + E^{detector}$$

Every component constructed as sum of:

$$\mathcal{M}^\sigma_{ij} = \frac{1}{\mathcal{N}} \sum_{n=1}^{\mathcal{N}} \left(P_i - V^\sigma_{i,n}\right) \times \left(P_j - V^\sigma_{j,n}\right)$$

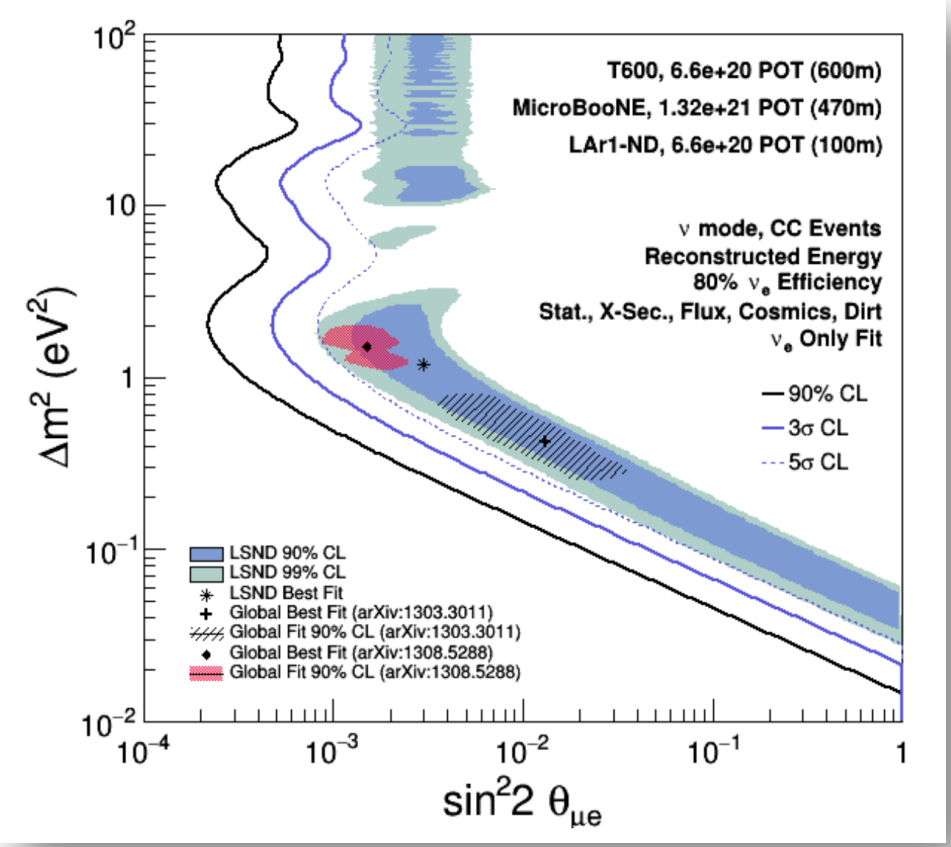
P_i is central value of Monte Carlo prediction for bin i; V_i^σ is one of many (N) variations (throws) for a given systematic uncertainty σ.

SBN at Fermilab

SBN ν_e appearance sensitivity:

SBN projects being able to test existing indications for ν_e appearance at 5σ level.

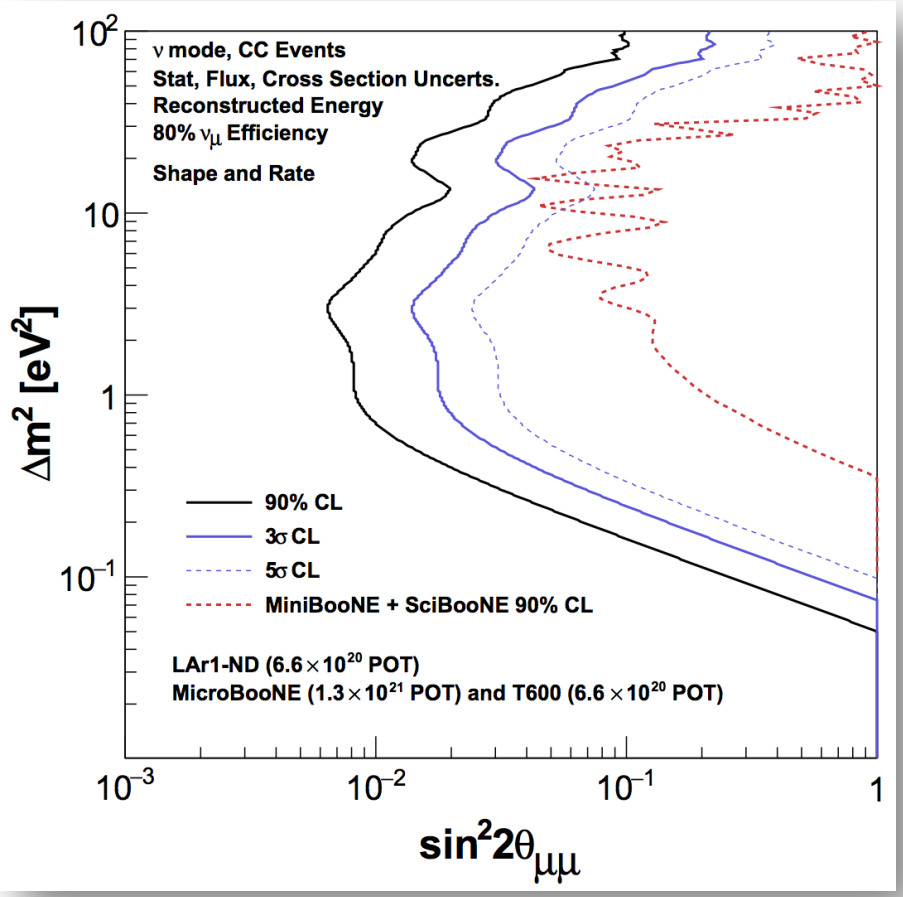
Assumption: no significant ν_e background disappearance.



[SBN Proposal 2015]

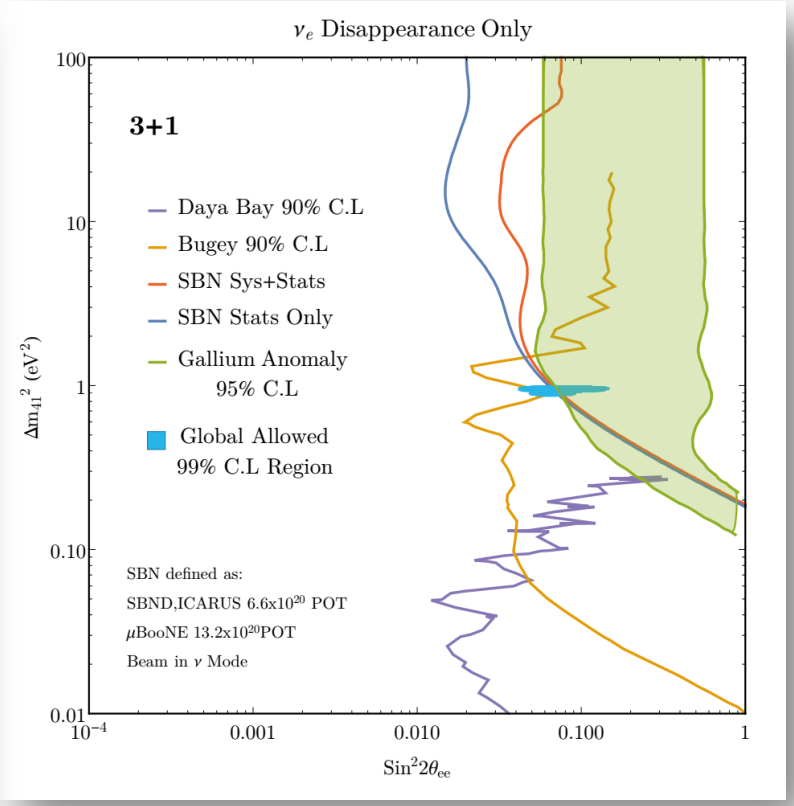
SBN at Fermilab

Following similar approach:



[SBN Proposal 2015]

ν_μ disappearance



[Cianci, Furmanski, GK, Ross-Lonergan, arXiv:1702.01758]

ν_e disappearance
(assuming no ν_e appearance)

Going beyond exclusive oscillation searches

In theory, a ν_e appearance search ($\sin^2 2\theta_{\mu e}$!= 0) with assumption of no ν_e or ν_μ disappearance ($\sin^2 2\theta_{\mu\mu} = \sin^2 2\theta_{ee} = 0$) is non-physical:

$$\sin^2 2\theta_{\mu e} = \tfrac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$$

In past experiments, this assumption *has* been (questioned, but) found to be a reasonable approximation. In SBN, this approximation is no longer valid…!

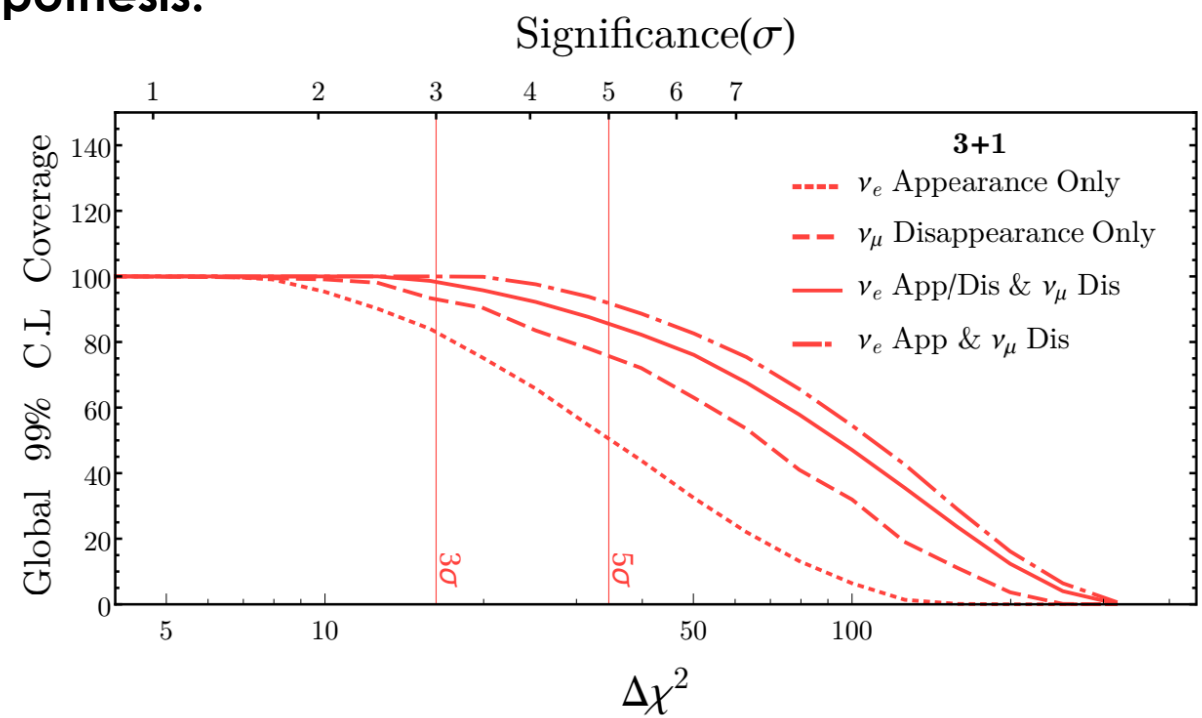
One should **consider all oscillation effects simultaneously**, and in doing so one may benefit from looking (fitting) across multiple samples (ν_e, ν_μ, possibly also neutral current):

More powerful constraints, more quantitatively robust!

Inclusive 3+1 oscillation search

3+1 hypothesis:

[Phys. Rev. D 96, 055001 (2017)]



- ν_e app/dis and ν_μ disap search: 85% coverage of 99%CL allowed phase-space at 5σ
- Overall sensitivity to 3+1 is **enhanced** when combining multiple oscillation channels in the fit
- Simultaneous search for ν_e and ν_μ disappearance without consideration of ν_e disappearance **overestimates** sensitivity

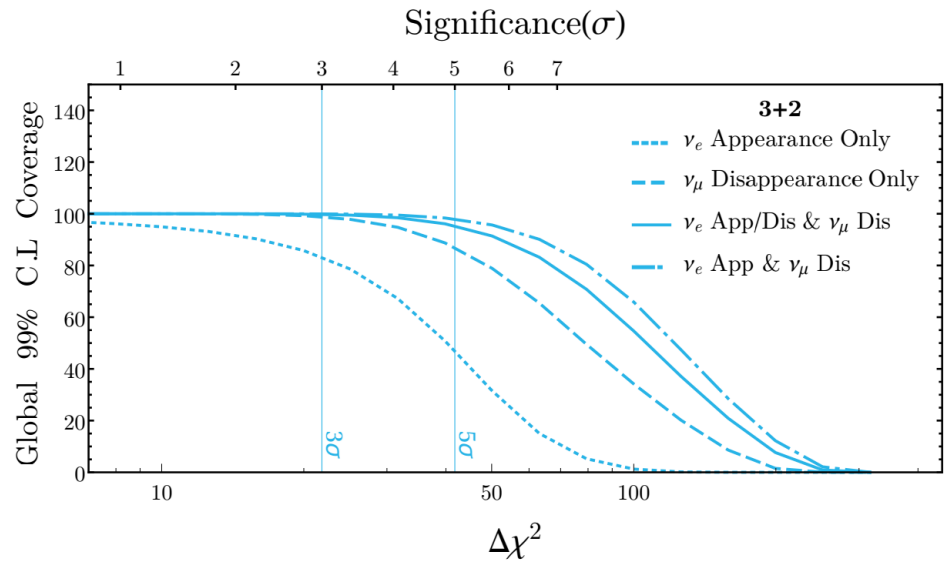
Going beyond 3+1:

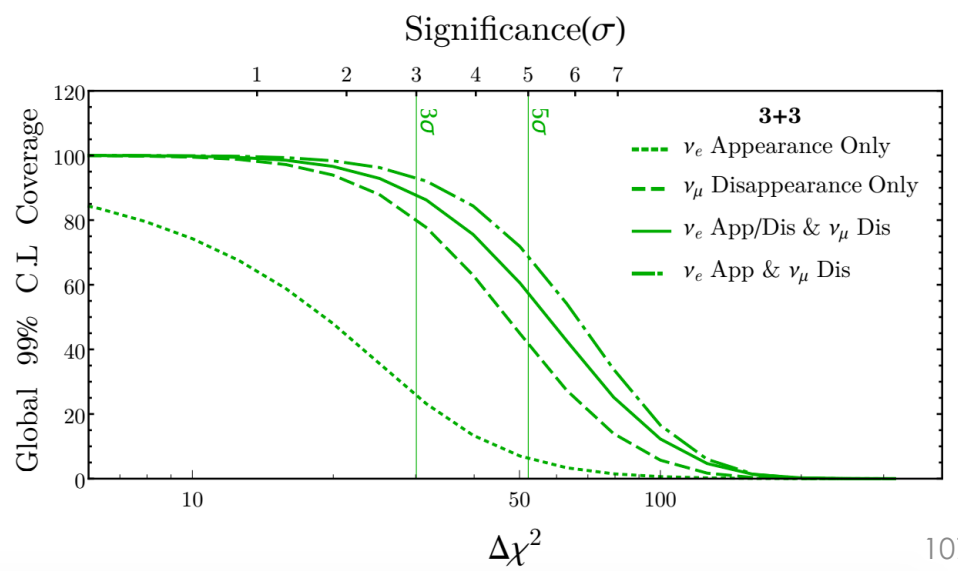
3+2 and 3+3 multi-channel SBN sensitivities:

- Improvement in sensitivity is significant even in extended scenarios with multiple sterile neutrinos!
- ν_e app/dis and ν_μ dis search:

95% coverage of 99%CL allowed phase-space at 5σ

55% coverage of 99%CL allowed phase-space at 5σ





[Phys. Rev. D 96, 055001 (2017)]

Short Baseline Experiments: Summary

- Short-baseline (L/E~1 m/MeV) experiments probe unique physics associated with neutrinos, beyond the three-neutrino paradigm.

- Current and near-future experiments include reactor-based very-short-baseline experiments, radioactive source (in/near-detector deployment) experiments, and accelerator-based short-baseline experiments

- At Fermilab, the SBN program will be "online" in the next 2 years, to test several "anomalies" which have been accumulating over the past 2-3 decades, indicative of new neutrino species/new physics associated with the neutrino sector

  – A wonderful "playground" to look for new physics in the neutrino sector!