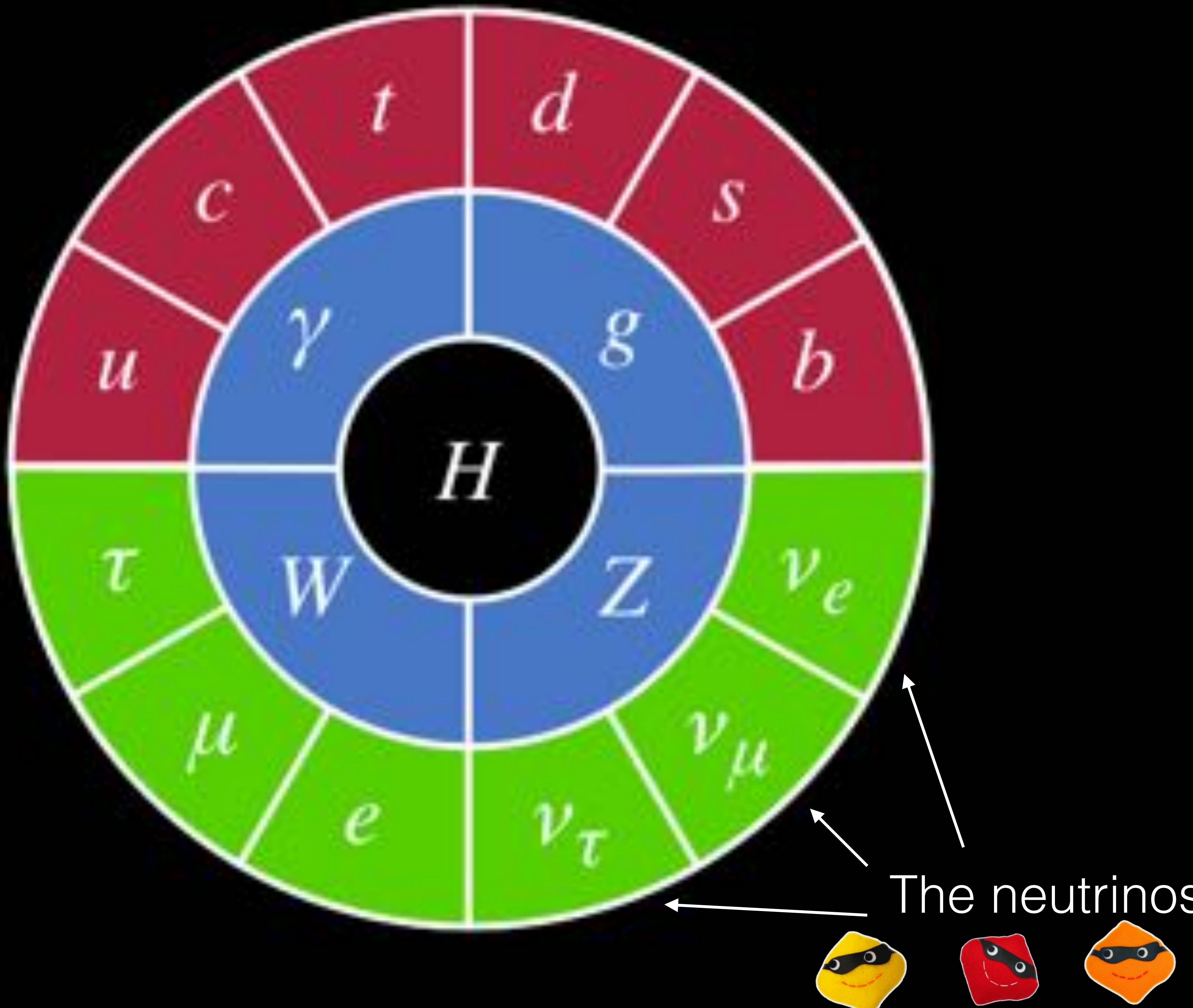
Using kaons to unlock the secrets of the neutrino

Joshua Spitz, MIT
UC Irvine Seminar, 2/20/2015

Outline

- The big picture in neutrino oscillation physics today
- The holy grail: measuring a difference between neutrinos and antineutrinos called “CP violation”.
- Problem 1: The sterile neutrino
    - Solutions (w/ kaons)
- Problem 2: Neutrino cross sections
    - Solutions (w/ kaons)



Credit: Particle Fever

Neutrinos come in three flavors

electron tau muon

When an X is produced an X neutrino comes with it:

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

When an X neutrino interacts it produces an X:

$$\nu_e + n \longrightarrow p + e^-$$

Neutrino oscillation

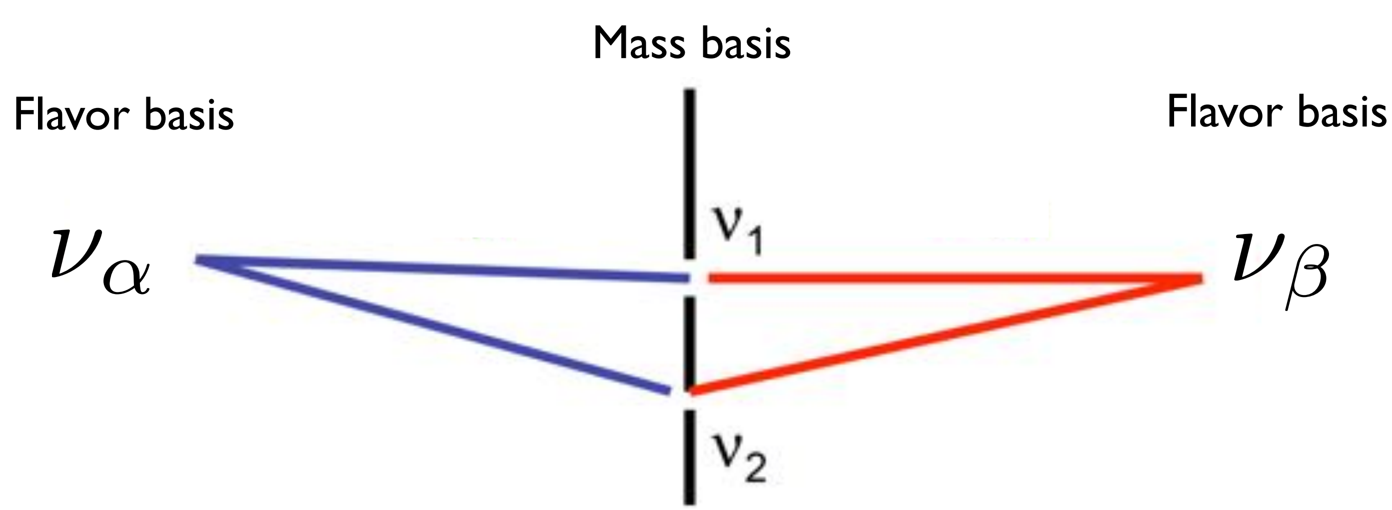
- We know that neutrinos oscillate.
  - A neutrino created as one flavor can change into another flavor.

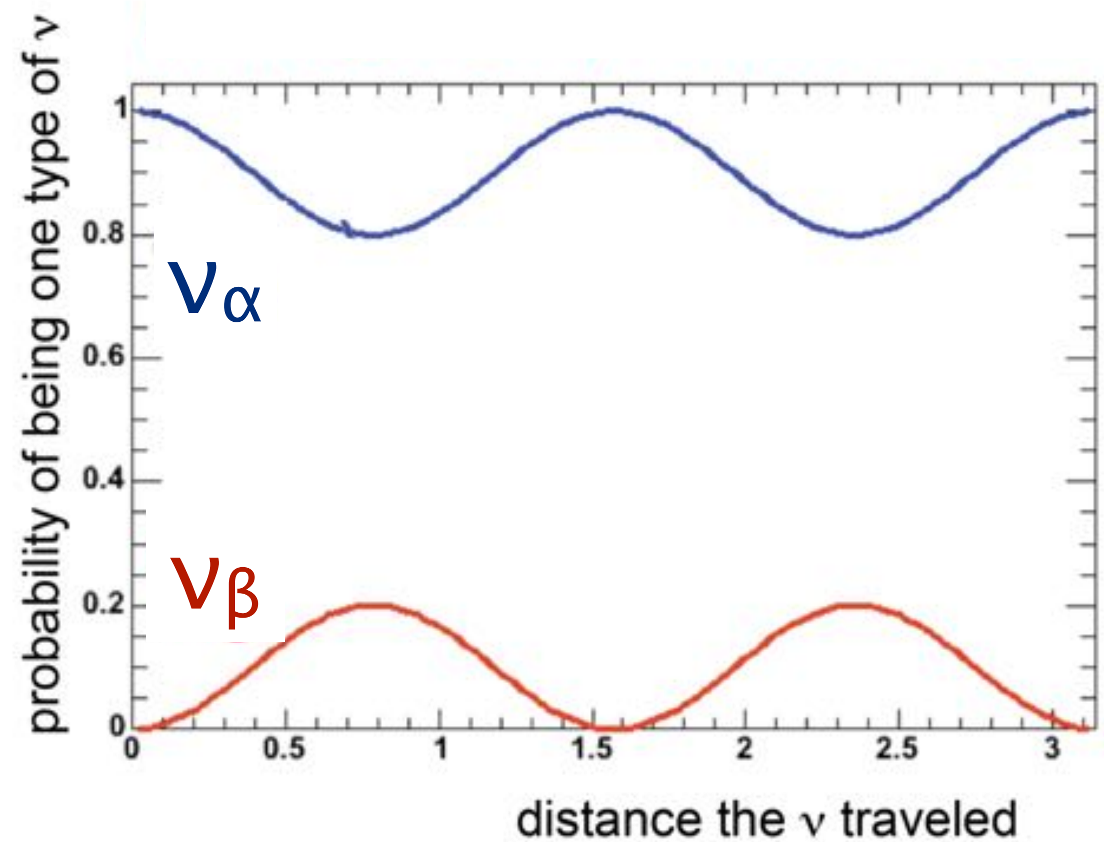
Born as a muon neutrino!

Can be detected as an electron neutrino.

Two neutrino oscillation

Neutrino oscillations are due to a mismatch between the neutrino's mass eigenstate and flavor eigenstate.





distance traveled

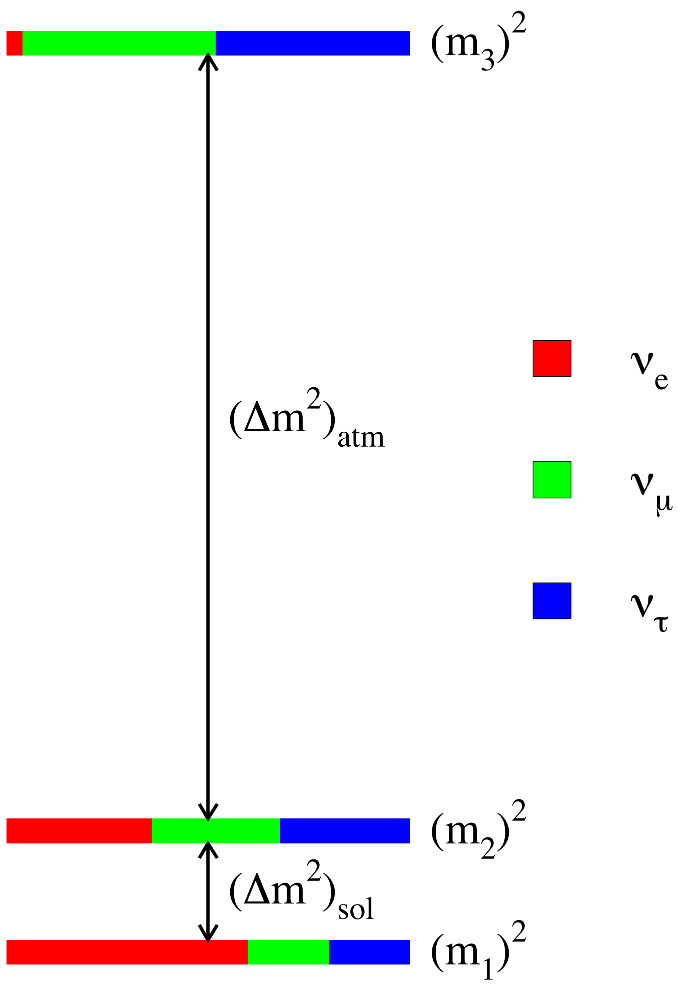
$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(1.267\frac{\Delta m^2 L}{E}\frac{\mathrm{GeV}}{\mathrm{eV}^2\,\mathrm{km}}\right)$$

energy

The 3 neutrino oscillation picture

Atmospheric neutrinos
Solar neutrinos
Accelerator neutrinos
Reactor neutrinos

} Well established oscillations



- Almost all of our observed oscillation results fit nicely within the three neutrino picture (two mass splittings and three mixing angles).
- Neutrinos from different sources are oscillating according to the same rulebook!

Neutrino oscillation is a big deal

The time evolution of the neutrino state implies that is has mass!

Big Bang cosmology

Why is the universe made of matter?

Dark matter?

Supernova evolution

How do reactors burn fuel?

How does the sun shine?

How are the neutrino masses ordered?

3, 4, 5, 6 neutrinos?

A hidden sector?

neutrino=antineutrino?

Do neutrinos obey fundamental symmetries?

Heavy element formation

How does the neutrino get its mass?

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How to probe neutrino oscillations?

e.g. for measuring neutrino CP violation

1. Make a lot of neutrinos.
2. Count them.
3. Compare to how many you expected.

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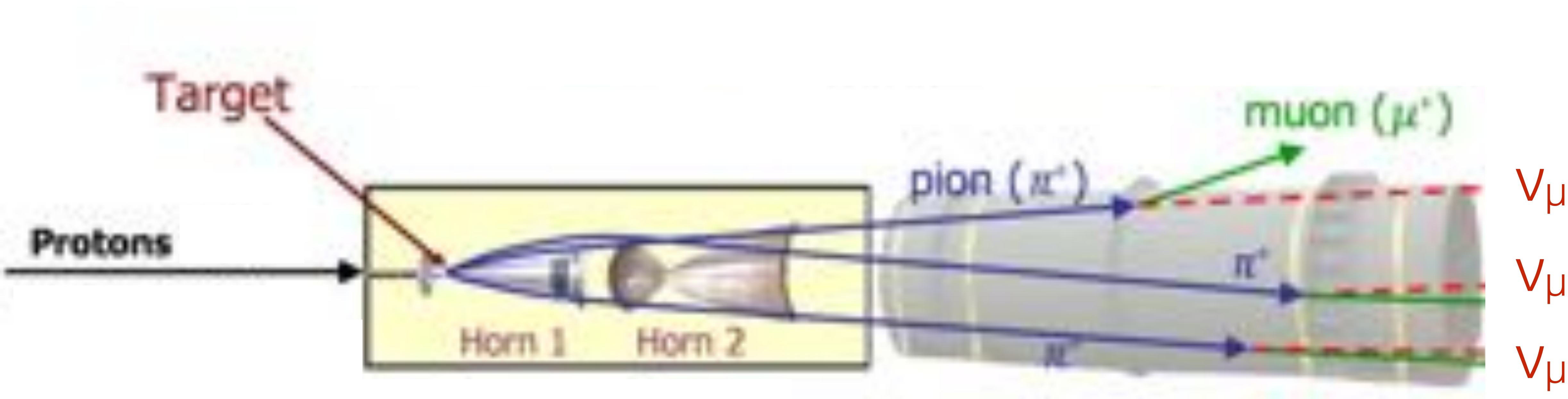
Accelerators (e.g. Fermilab)

Creating a neutrino beam

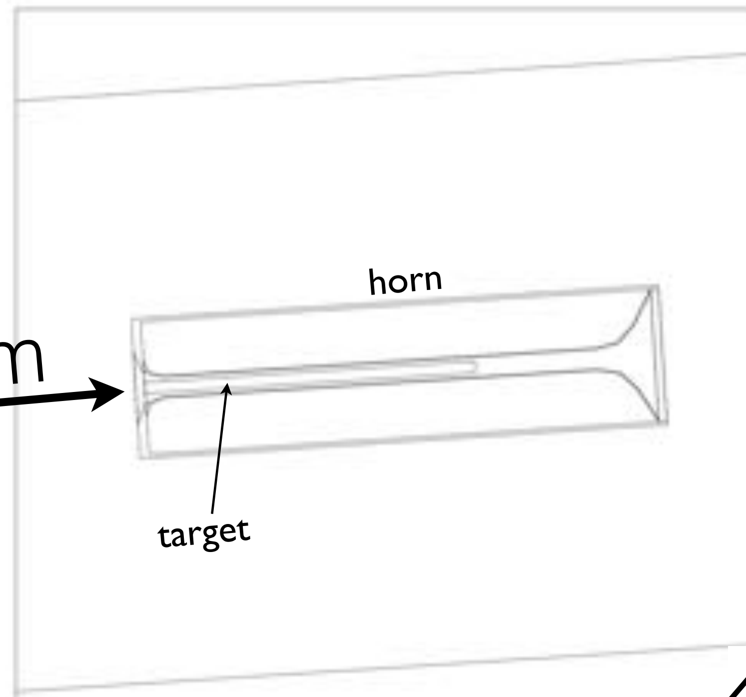


Neutrino beam $\pi^+ \rightarrow \mu^+ \nu_\mu$

Antineutrino beam $\pi^- \rightarrow \mu^- \overline{\nu}_\mu$

Creating a neutrino beam

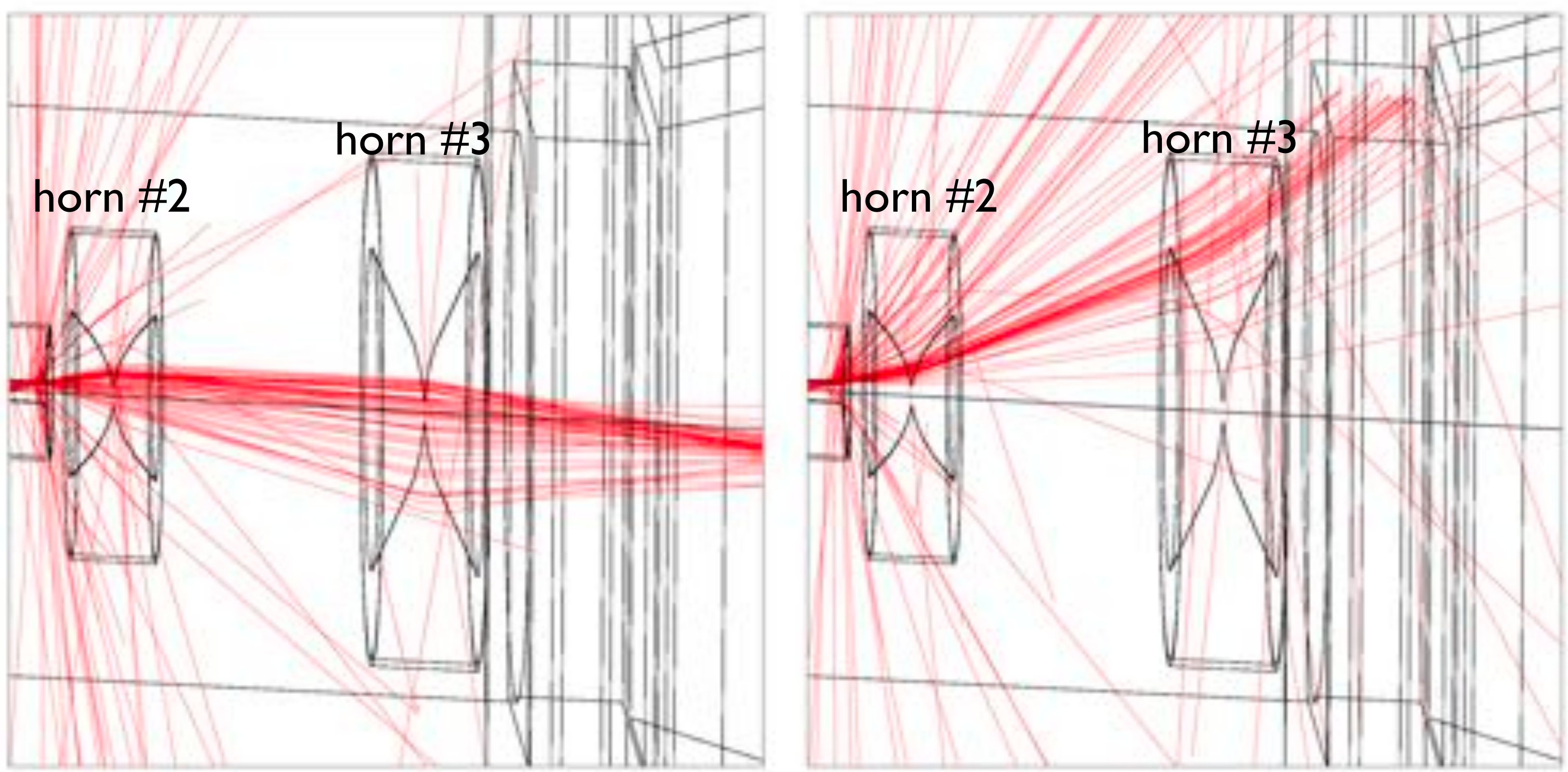
proton beam



pion

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

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



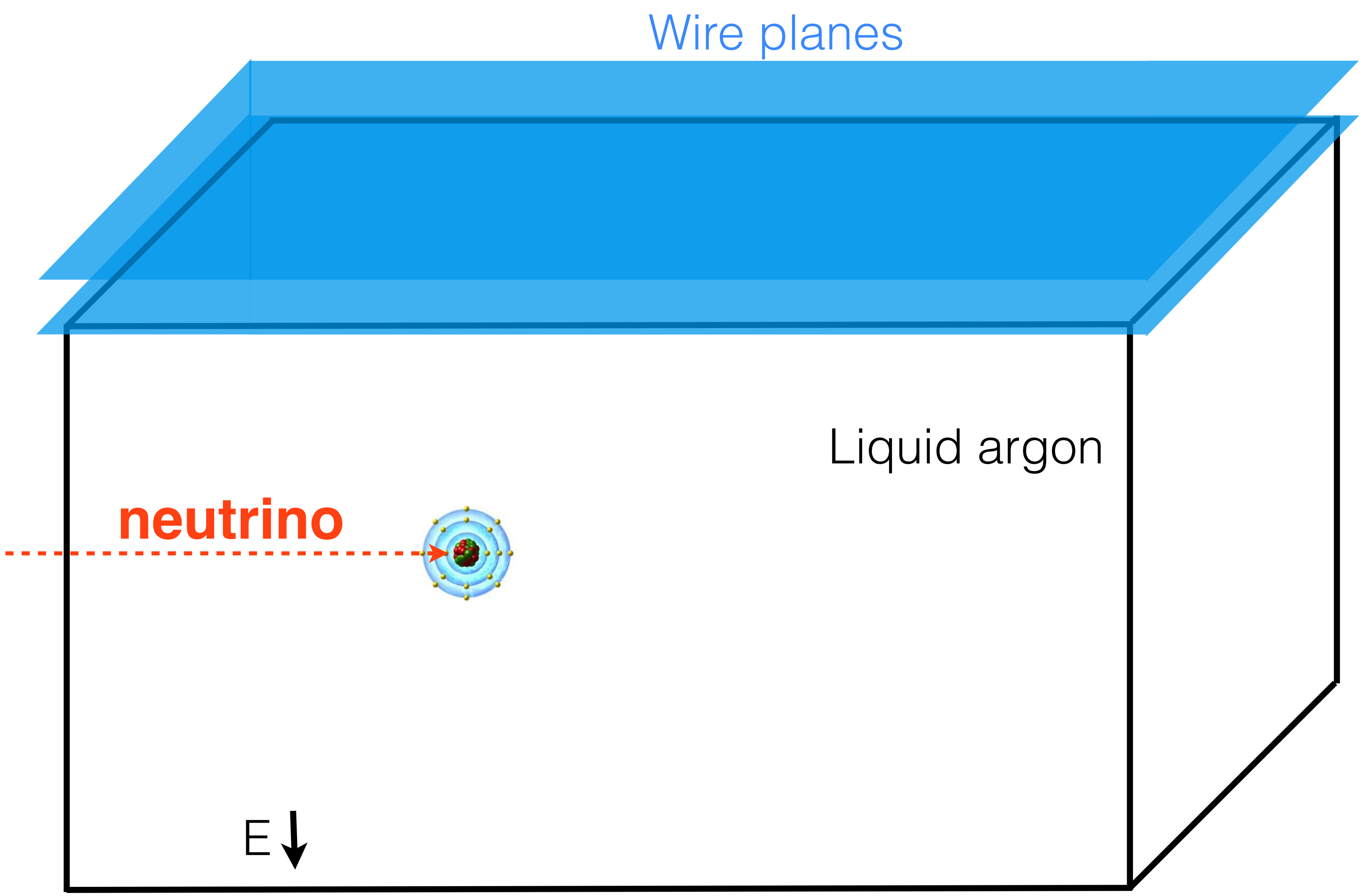
Warning: aspect ratio has been distorted

How to probe neutrino oscillations?

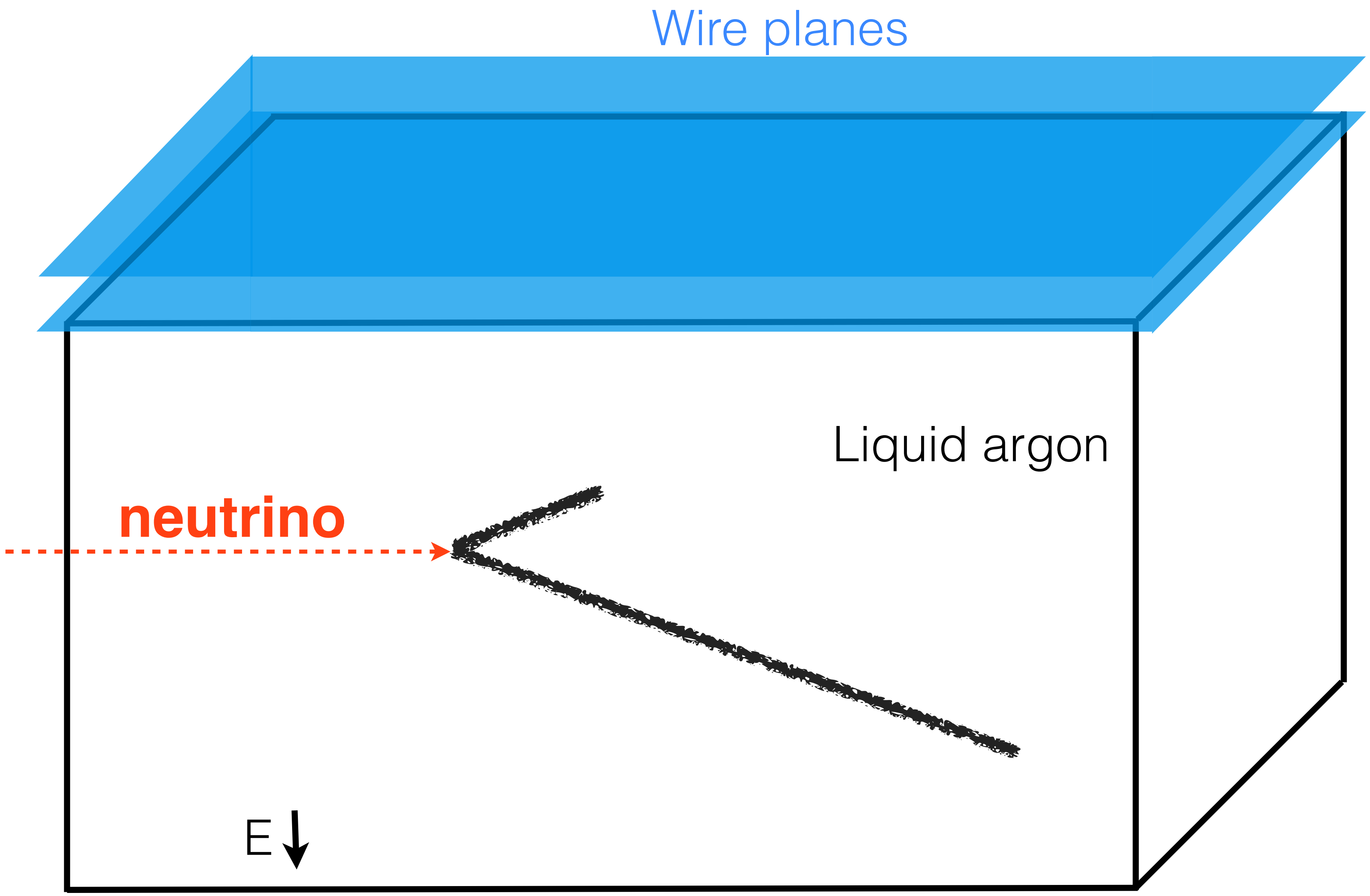
1. Make a lot of neutrinos.
2. Count them.
3. Compare to how many you expected.

Studying neutrinos requires a **big** detector that is **capable** of measuring the flavor and energy of neutrinos.

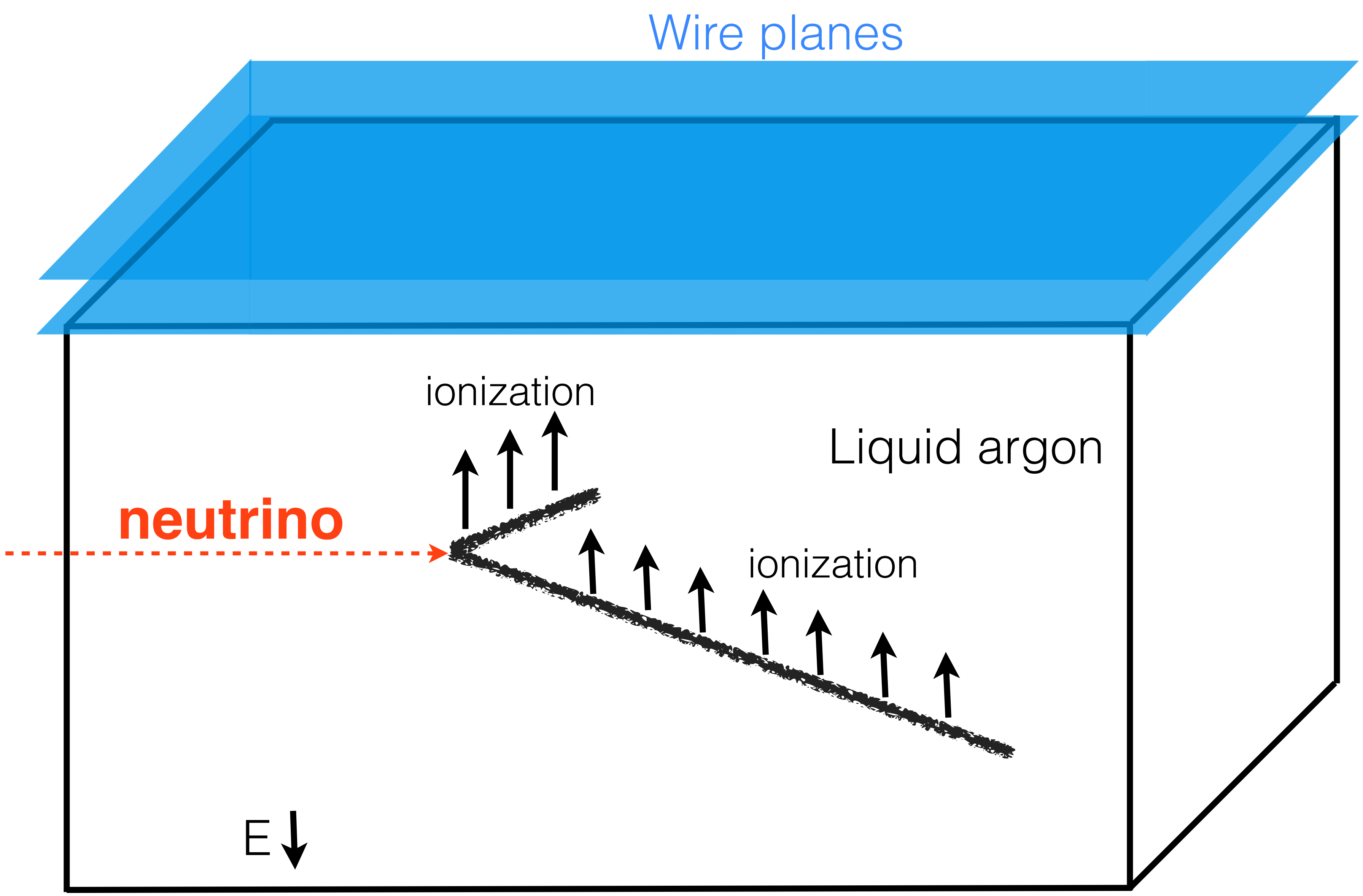
Liquid Argon Time Projection Chamber



Liquid Argon Time Projection Chamber



Liquid Argon Time Projection Chamber



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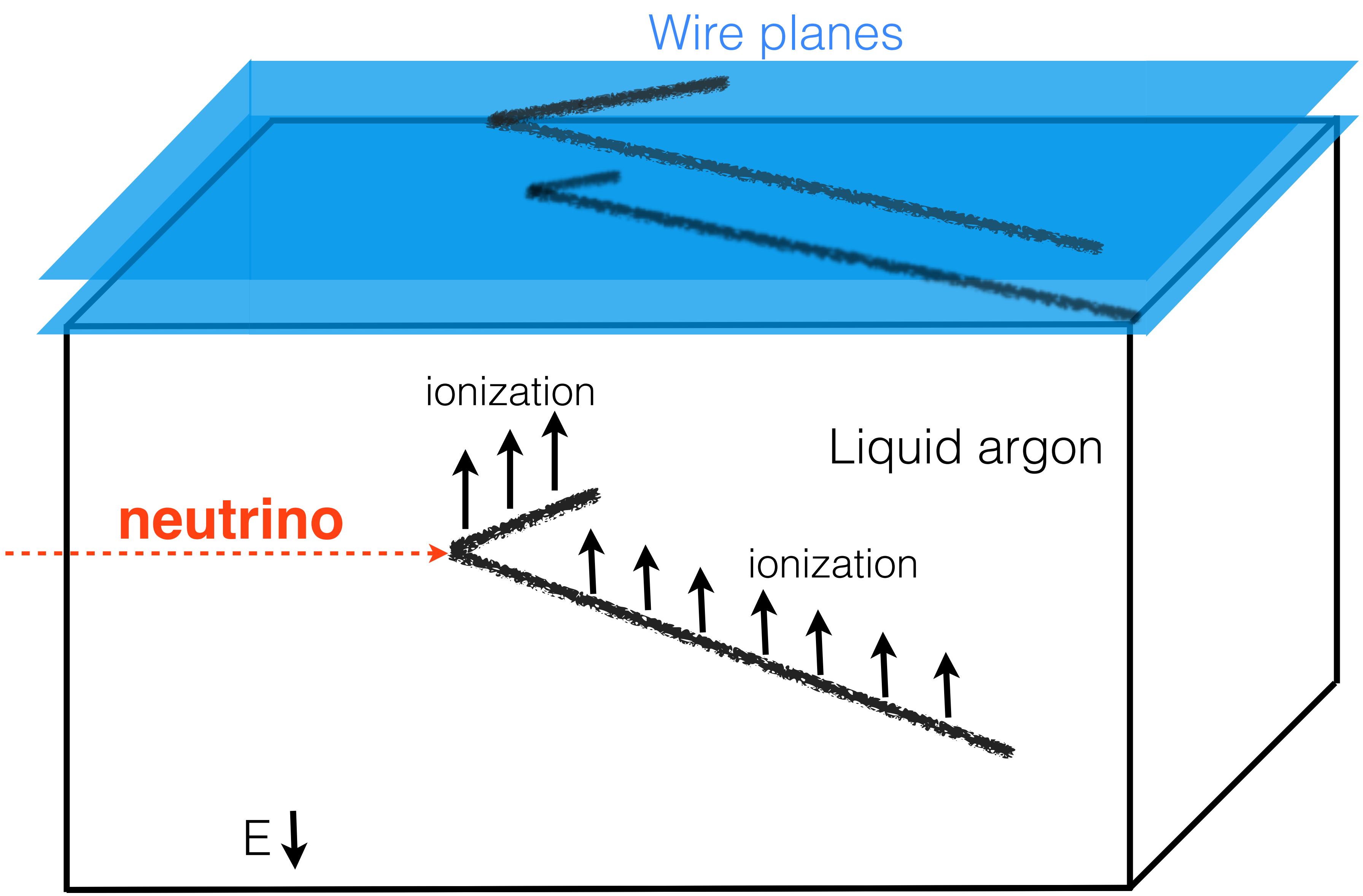
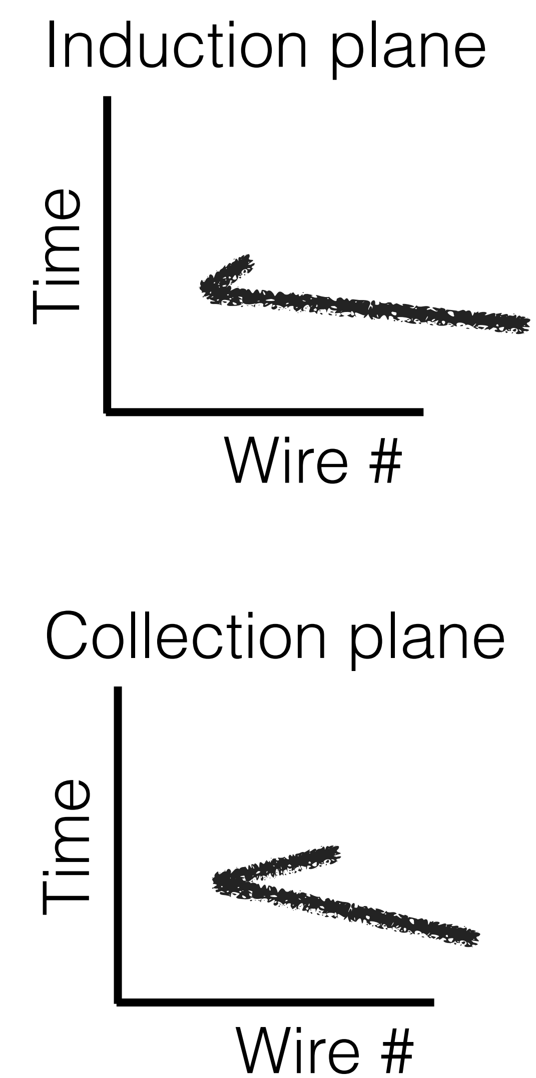
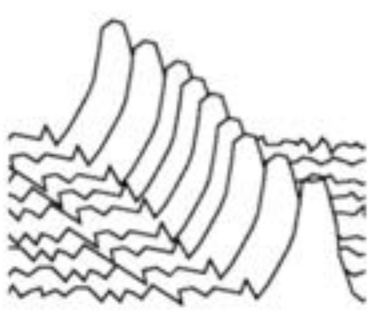


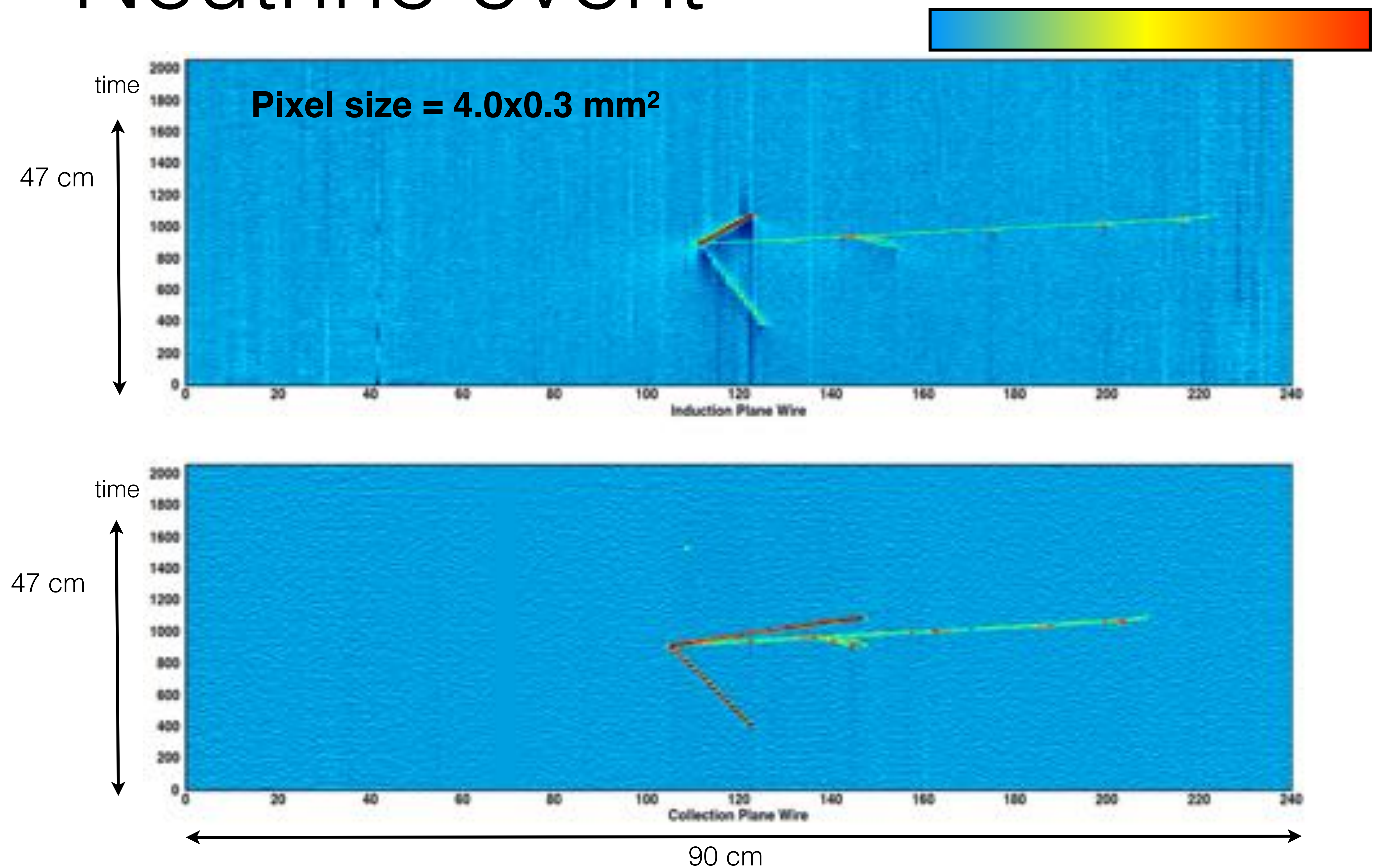




Wire pulses in time give the drift coordinate of the track

induction plane + collection plane + time = 3D image of event

Neutrino event

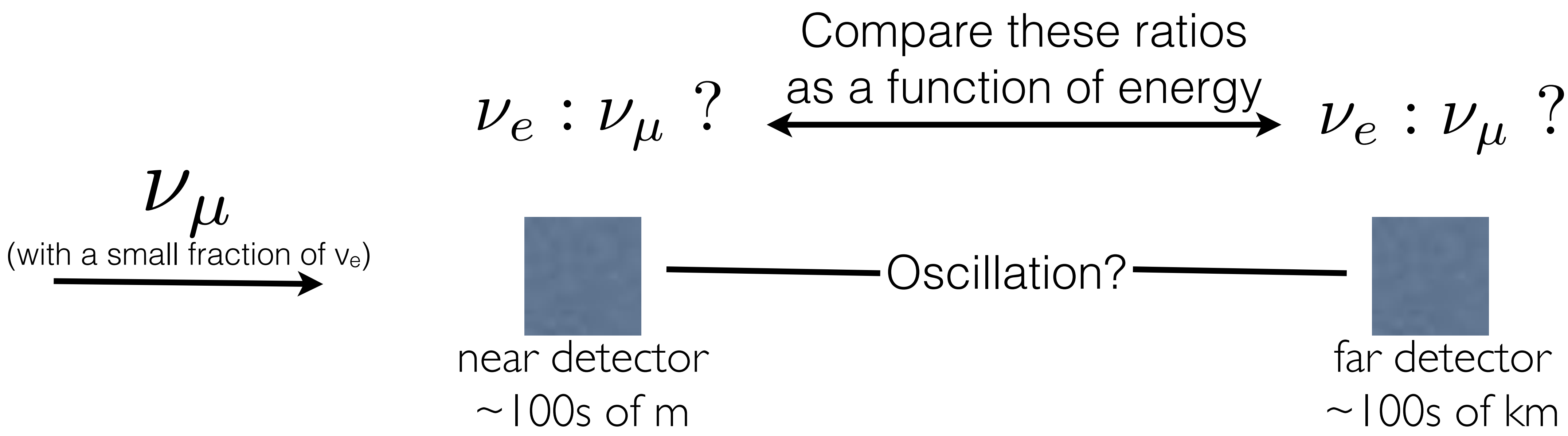


This picture is from my graduate thesis, with the “ArgoNeuT” experiment

How to probe neutrino oscillations?

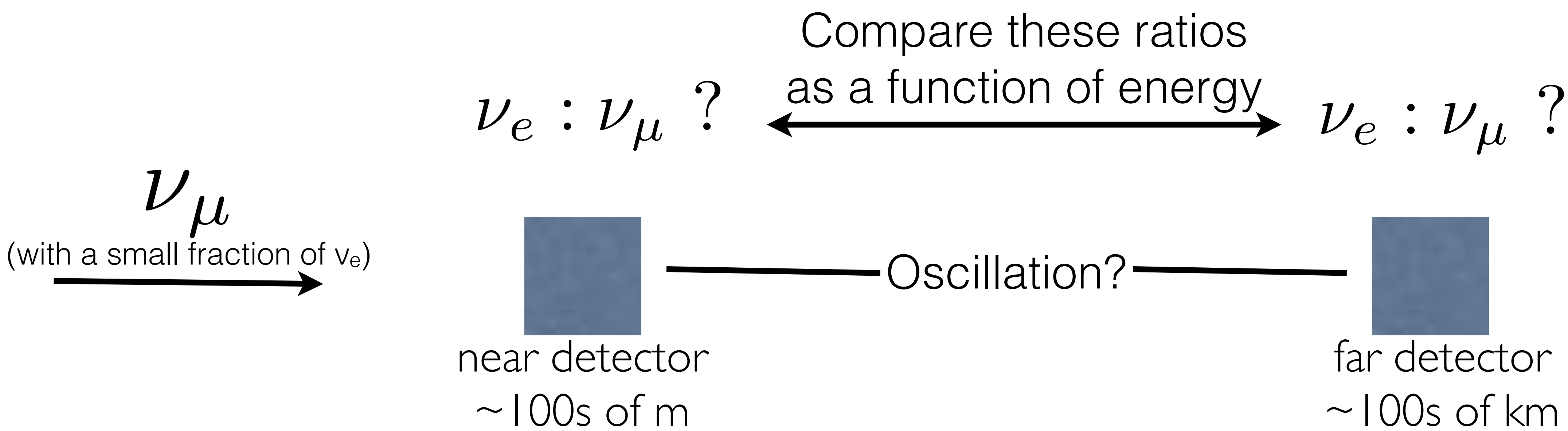
1. Make a lot of neutrinos.
2. Count them.
3. Compare to how many you expected.

A conventional long baseline oscillation experiment



What is $P[\nu_\mu \rightarrow \nu_e]$ **?**

A conventional long baseline oscillation experiment



CP violation in neutrinos? $P[\nu_\mu \rightarrow \nu_e] \neq P[\overline{\nu}_\mu \rightarrow \overline{\nu}_e]$?

The path to neutrino CP violation

- The US is pursuing a long baseline neutrino experiment (ELBNF), featuring an envisioned 40 kiloton Liquid Argon Time Projection Chamber (LArTPC) far detector in an accelerator-based neutrino beam.
- Going from 0.3 tons to 40 kilotons is pretty hard…and it will take >10 years.
- There are a lot of challenges along the way.
- There is also a lot of physics along the way too!!


Oscillation Land
δ_{CP}
$\theta_{13}, \theta_{23}, \theta_{12}$
Mass hierarchy
ν_τ
MSW
Sterile ν
Lorentz violation
Δm^2's
Non-standard ν interactions
ν cross sections
ν as a probe of the nucleus
Detector R&D

Sterile ν

***Proposal for an Electron Antineutrino Disappearance Search Using High-Rate ^{8}Li Production and Decay**
A. Bungau *et al.*, Physical Review Letters **109** 141802 (2012).

***Measuring Active-to-Sterile Neutrino Oscillations with Neutral Current Coherent Neutrino-Nucleus Scattering**
A.J. Anderson, J.M. Conrad, E. Figueroa-Feliciano, C. Ignarra, G. Karagiorgi, K. Scholberg, M.H. Shaevitz, and J. Spitz, Physical Review D **86** 013004 (2012).

***Sterile Neutrino Search with Kaon Decay at Rest**
J. Spitz, Physical Review D **85** 093020 (2012).

ν_τ

***Atmospheric Tau Neutrinos in a Multi-kiloton Liquid Argon Detector**
J. Conrad, A. de Gouvêa, S. Shalgar, and J. Spitz, Physical Review D **82** 093012 (2010).

***Renaissance of the ∼1-TeV Fixed-Target Program**
T. Adams *et al.*, International Journal of Modern Physics A **25** 777 (2010).

Lorentz violation

***Search for Neutrino-Antineutrino Oscillations with a Reactor Experiment**
J.S. Díaz, T. Katori, J. Spitz, and J.M. Conrad, Physics Letters B **727** 412 (2013).

***First Test of Lorentz Violation with a Reactor-based Antineutrino Experiment**
Y. Abe *et al.* [Double Chooz Collaboration], Physical Review D **86** 112009 (2012).

Non-standard ν interactions

***Coherent Neutrino Scattering in Dark Matter Detectors**
A.J. Anderson, J.M. Conrad, E. Figueroa-Feliciano, K. Scholberg, and J. Spitz, Physical Review D **84** 013008 (2011).

Detector R&D

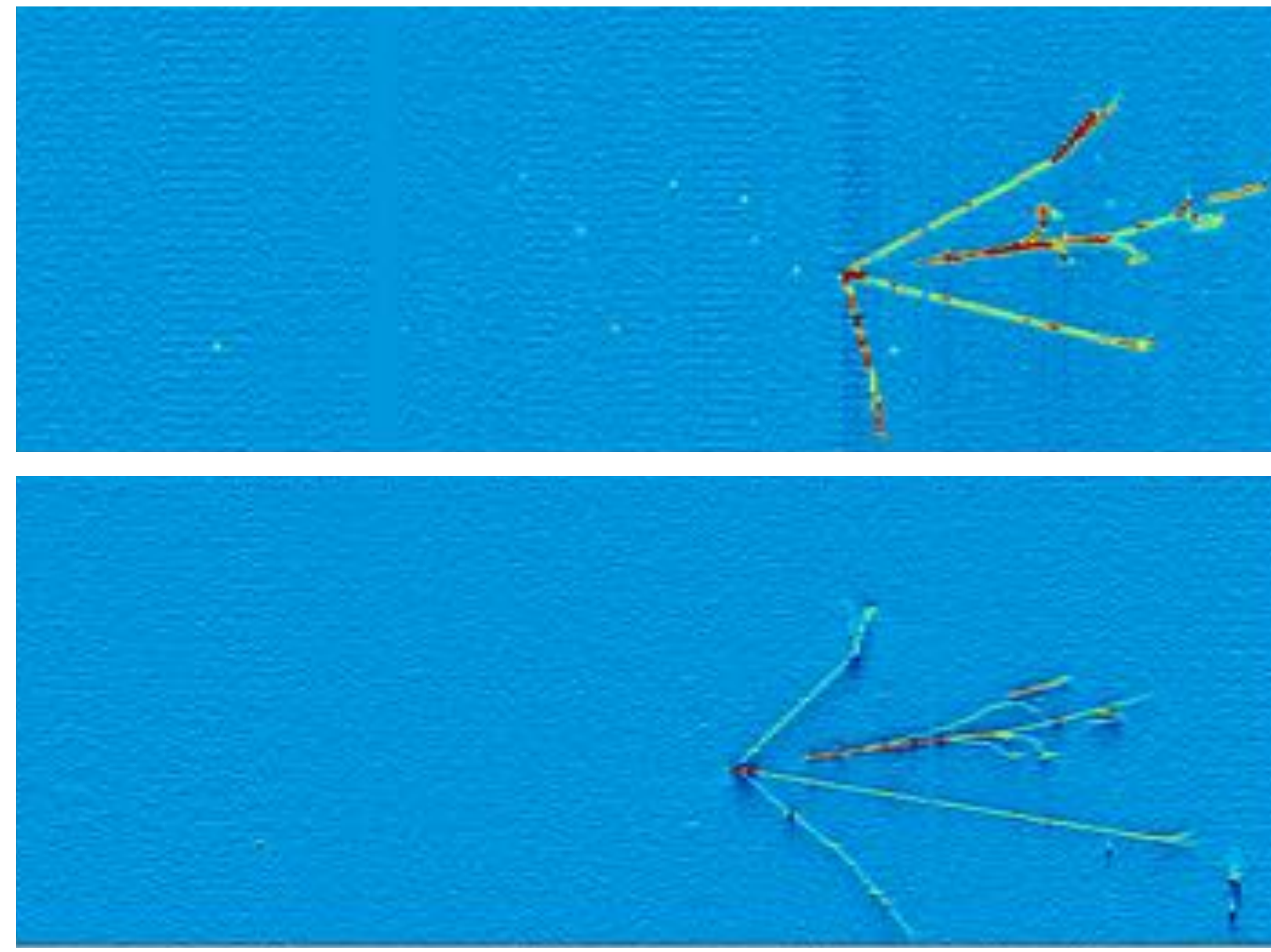
***A Regenerable Filter for Liquid Argon Purification**
A. Curioni *et al.*, Nuclear Instruments and Methods in Physics Research A **605** 306 (2009).

ν cross sections

***Cross Section Measurements with Monoenergetic Muon Neutrinos**
J. Spitz, Physical Review D **89** 073007 (2014).

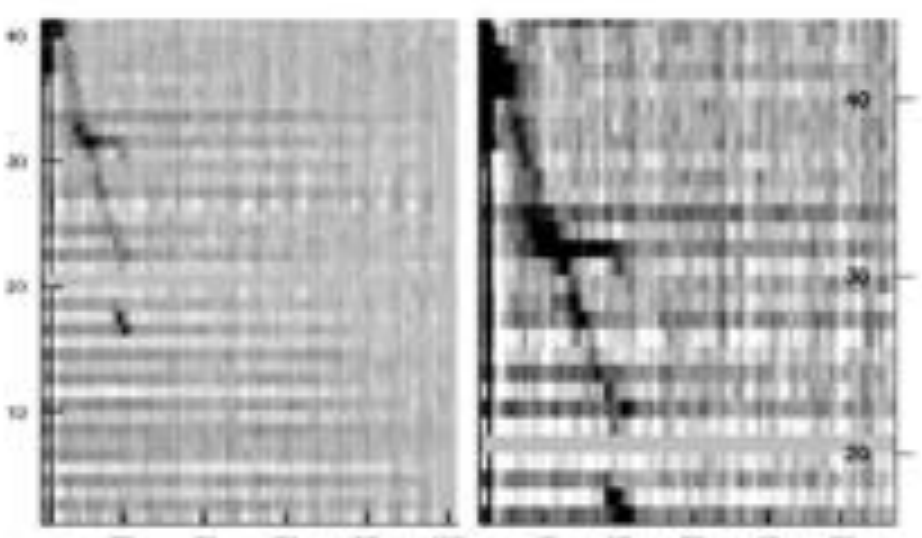
***First Measurements of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon**
C. Anderson *et al.* [ArgoNeuT Collaboration], Physical Review Letters **108** 161802 (2012).

Addressing LAr challenges (moving towards the kiloton-scale)

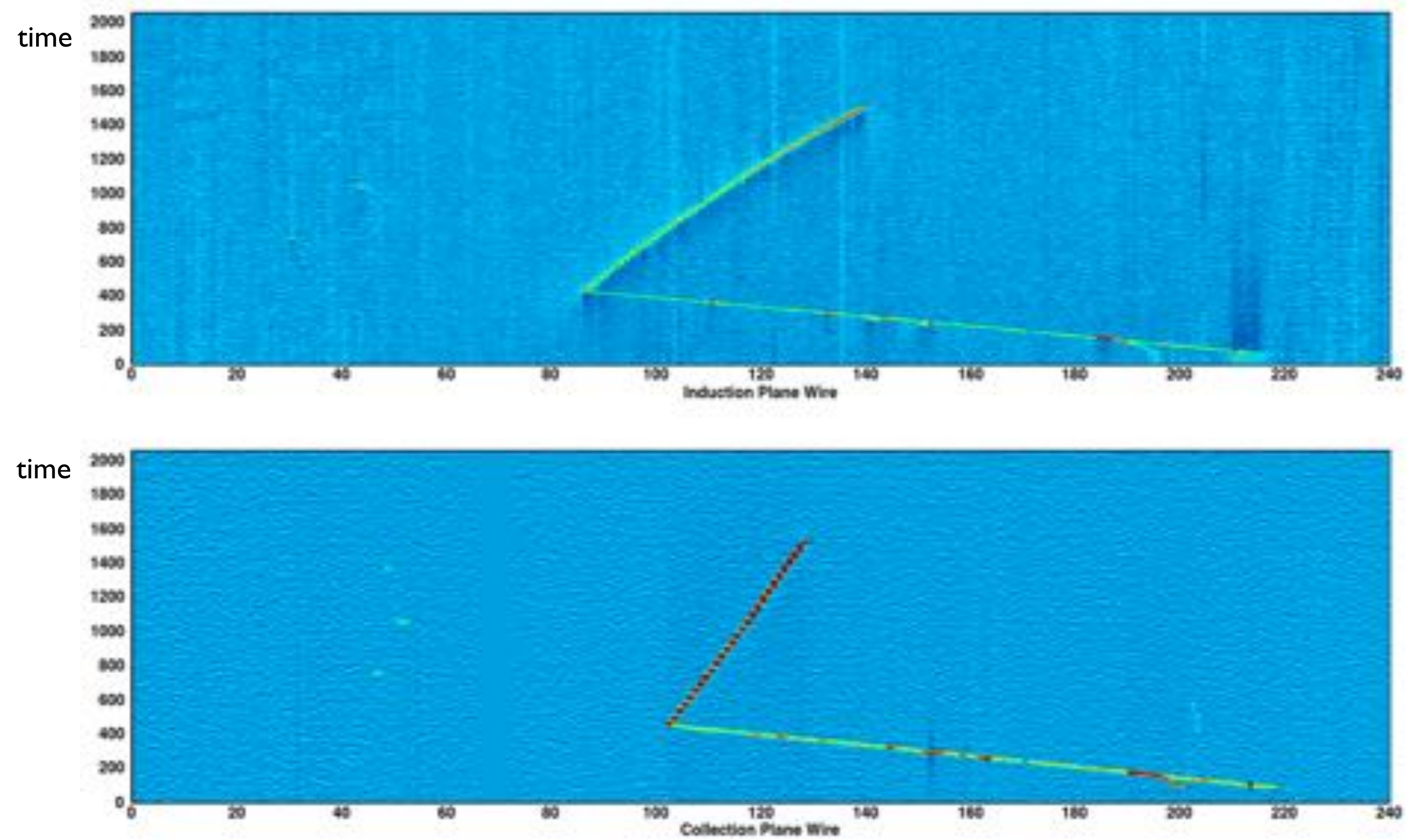


- Cryogenics and Purity
  - Insulation and cooling.
  - Achieving and maintaining purity.
  - How do detector materials affect purity?
- Electronics
  - Signal/noise.
- Detector components
  - Cryostat, field cage, high voltage, wires,…
- Making the detector smarter
  - Light collection, doping for better calorimetry, etc.
- Software
  - Simulated event generation, propagation through nucleus and LAr, and (automated) reconstruction.

Look how far we've come!



LArTPC tracks,
Yale (2007)



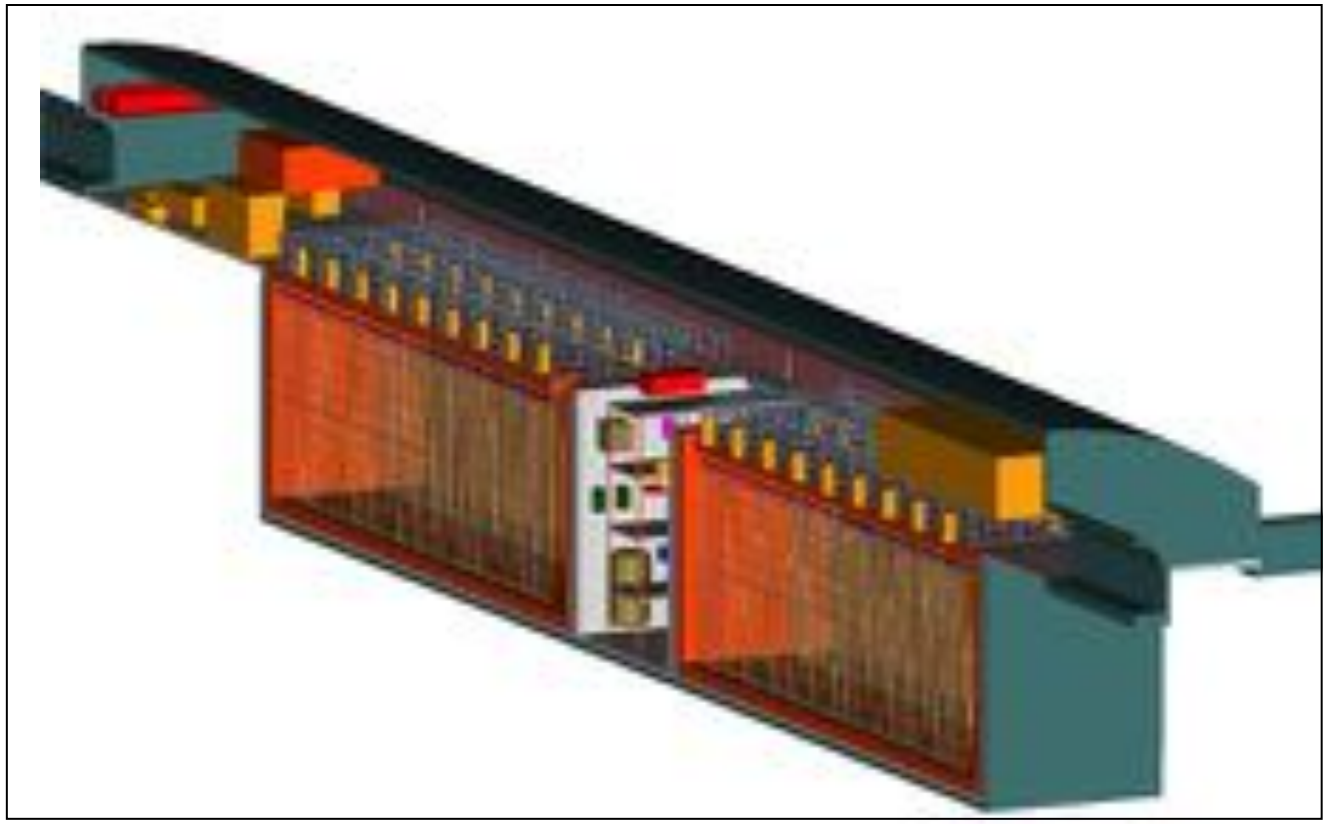
Physics w/ ArgoNeuT (2012)

PRL **108,** 161802 (2012) PHYSICAL REVIEW LETTERS week ending 20 APRIL 2012

First Measurements of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon

Look where we're going

MicroBooNE, starting at Fermilab in 2015
(TPC is 2.6x2.3x10.4 m)



Kiloton-scale LArTPC

Aside from technical challenges associated with building an enormous liquid argon detector, there are a number of “problems” associated with the measurement itself.

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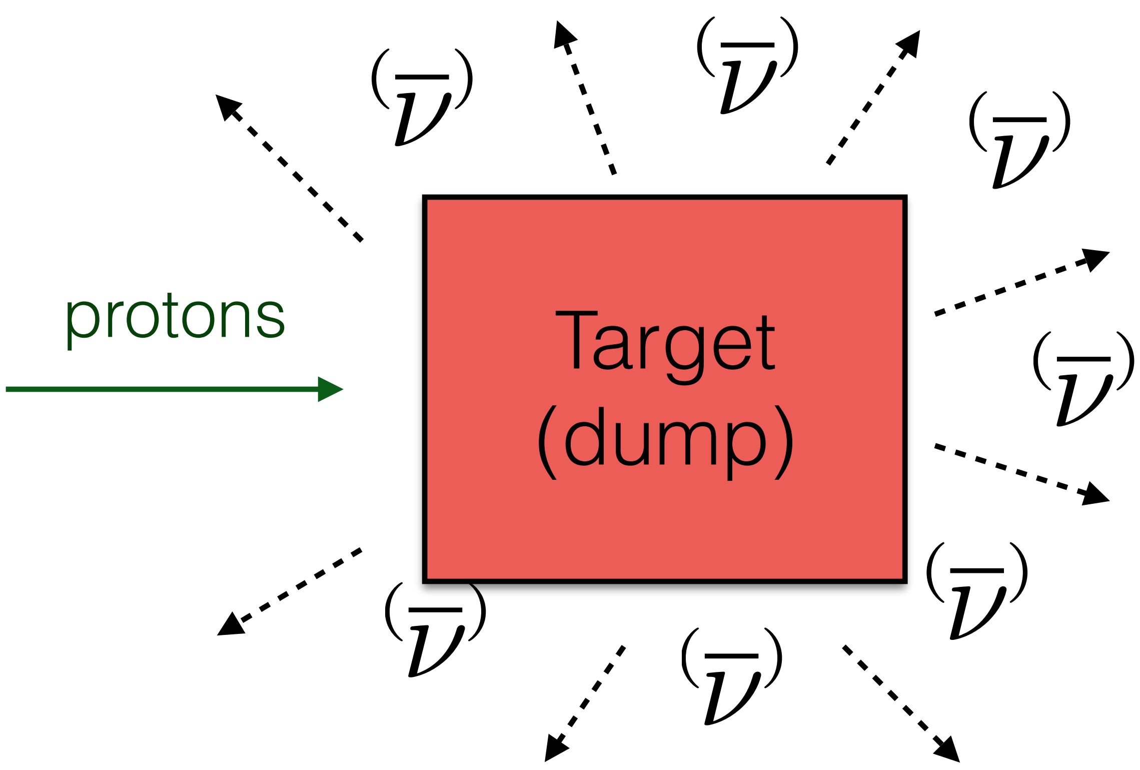
A new neutrino?

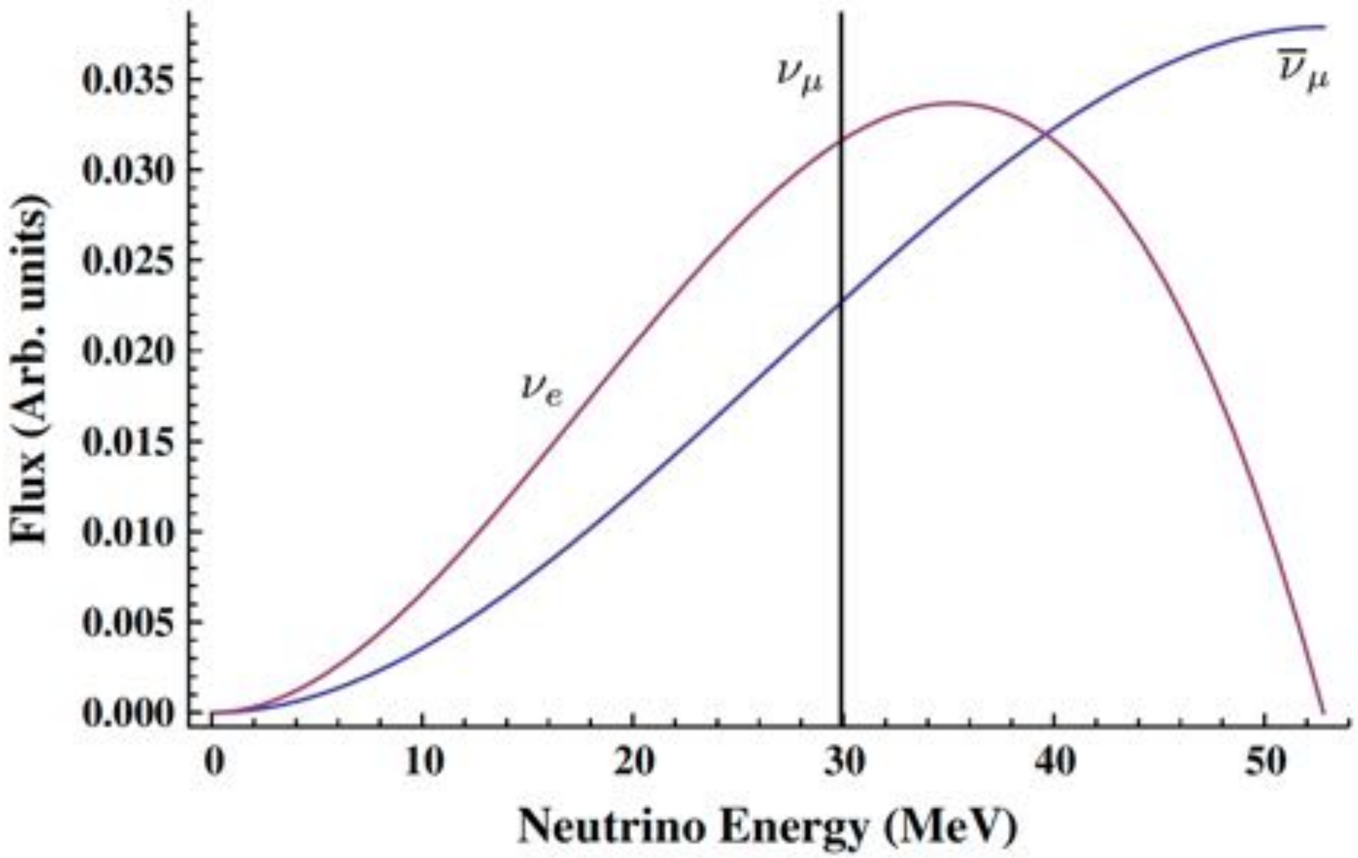
The three neutrino oscillation picture works extraordinarily well.

But, there are some anomalies that don't fit.

The Liquid Scintillator Neutrino Detector anomaly

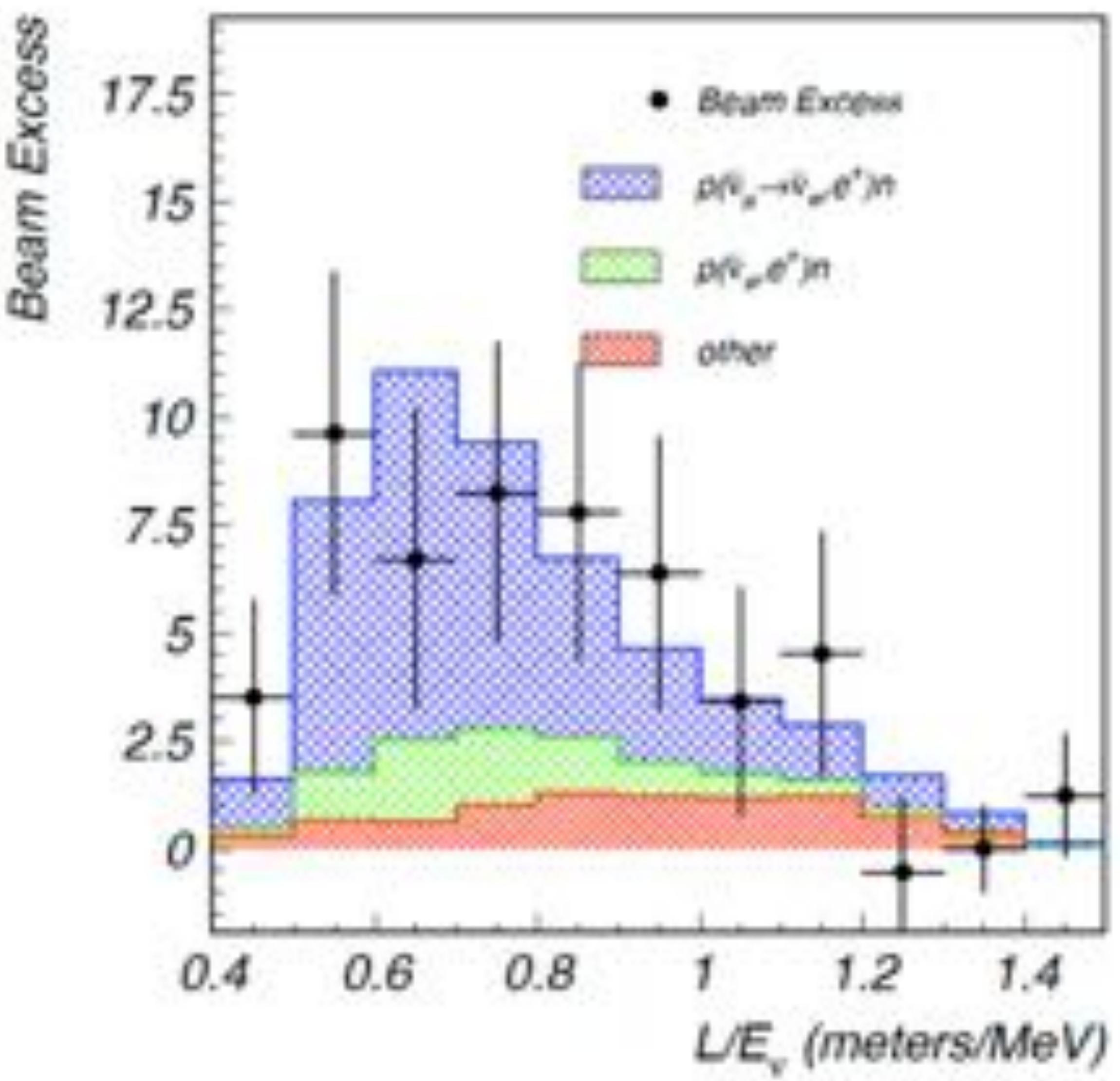
$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$?





The Liquid Scintillator Neutrino Detector anomaly

Antineutrinos from an accelerator seem to appear!



- LSND observed $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ at 3.8σ significance with a characteristic oscillation frequency of $\Delta m^2 \sim 1$ eV^2.

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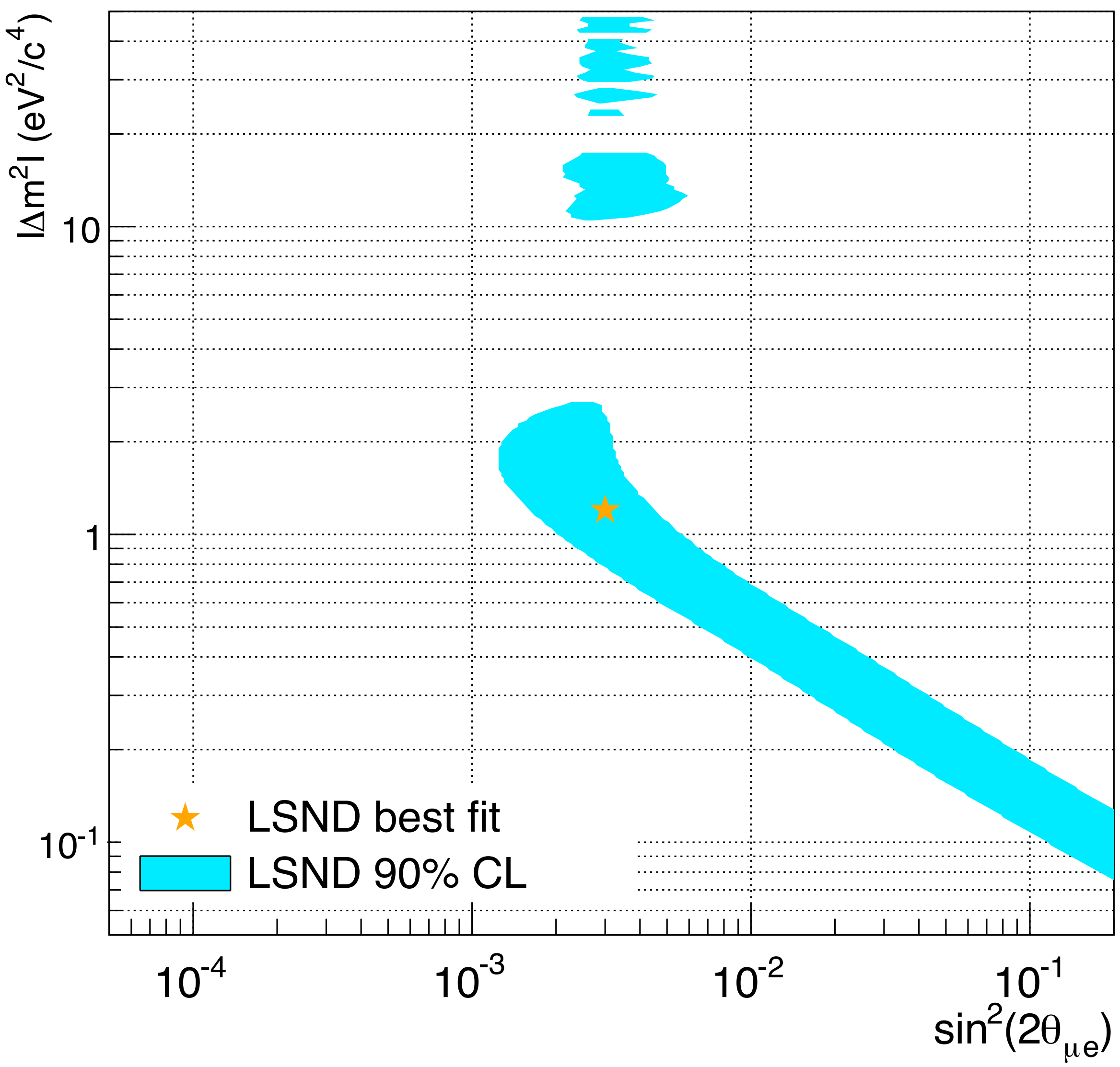
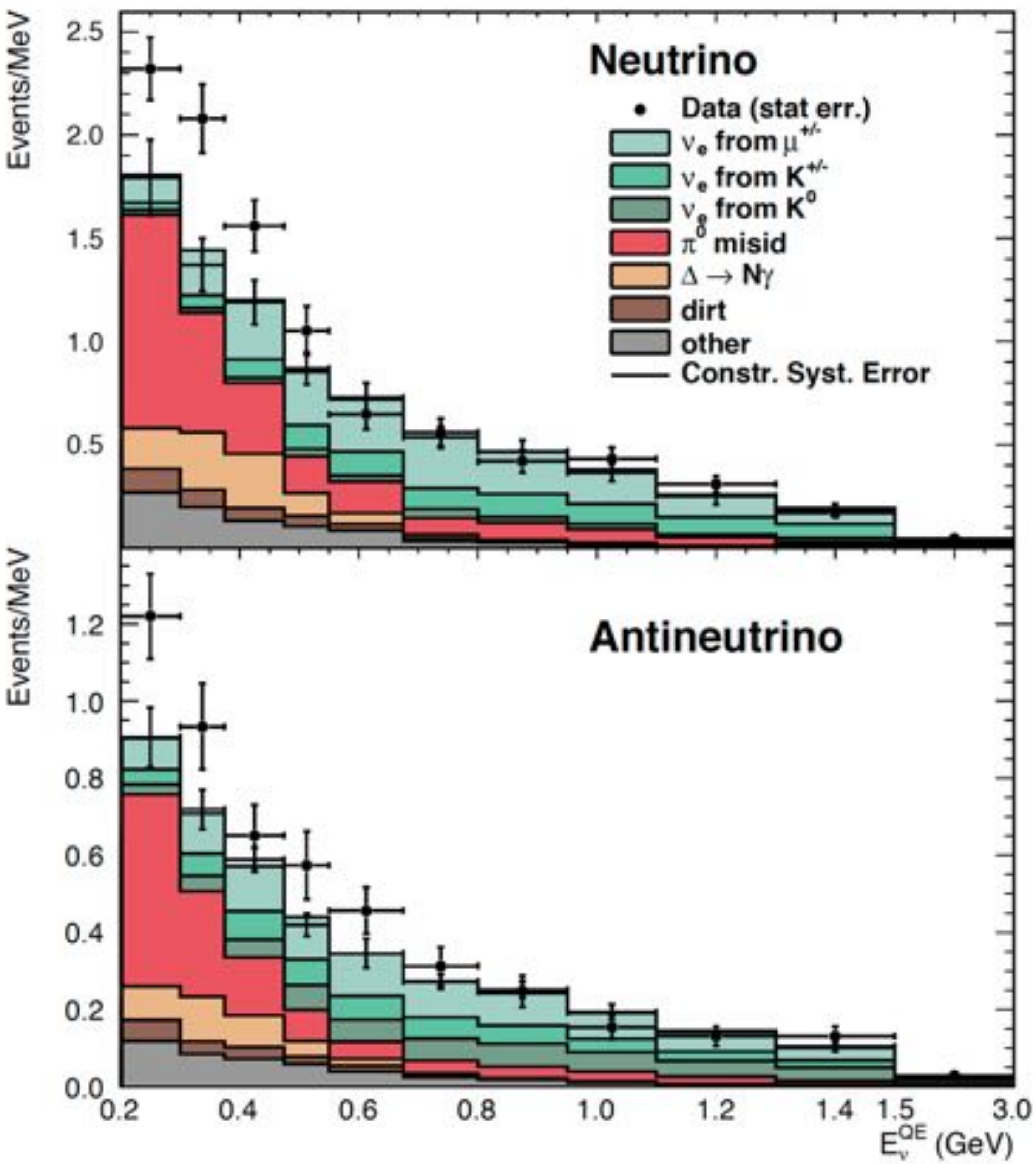


- LSND observed $\overline{\nu}_\mu \to \overline{\nu}_e$ at 3.8σ significance with a characteristic oscillation frequency of $\Delta m^2 \sim 1\ eV^2$.
- That's odd. There are two characteristic oscillation frequencies in the three neutrino picture and they are precisely measured.

$$\Delta m^2_{LSND} \gtrsim 0.2\,eV^2 \quad (\gg \Delta m^2_{ATM} \gg \Delta m^2_{SOL})$$

The MiniBooNE anomalies

The MiniBooNE anomalies



$\nu_\mu \rightarrow \nu_e$

Neutrinos and antineutrinos from an accelerator seem to appear!

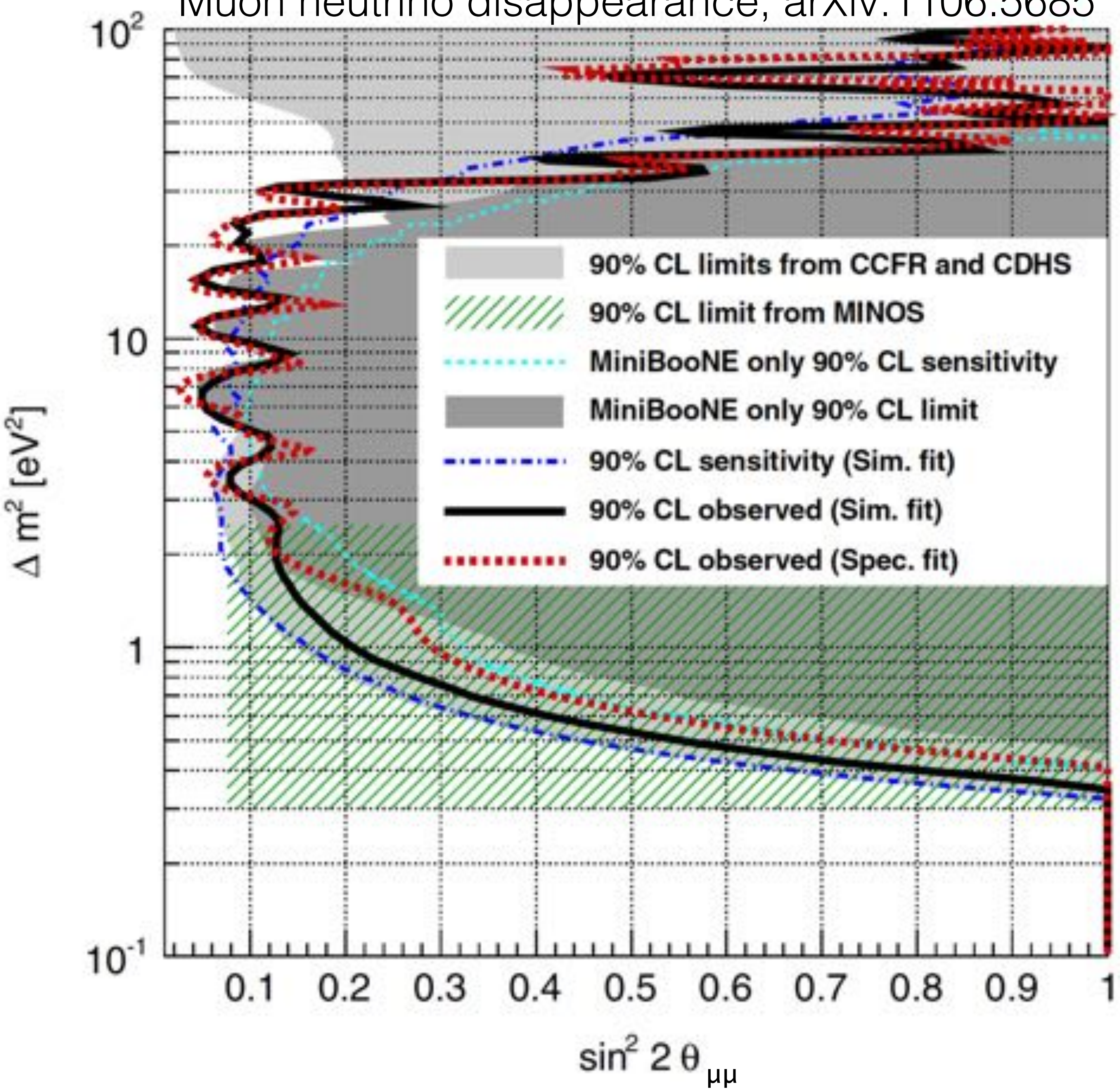
$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$

Basically, the anomalies seem to indicate that there may be a new characteristic oscillation frequency mode (indicative of a new neutrino state).

Experiment name	**Type**	**Oscillation channel**	**Significance**
LSND	Low energy accelerator	muon to electron (antineutrino)	3.8σ
MiniBooNE	High(er) energy accelerator	muon to electron (antineutrino)	2.8σ
MiniBooNE	High(er) energy accelerator	muon to electron (neutrino)	3.4σ
Reactors	Beta decay	electron disappearance (antineutrino)	1.4-3.0σ (varies)
GALLEX/SAGE	Source (electron capture)	electron disappearance (neutrino)	2.8σ

Sterile neutrino limits

Muon neutrino disappearance; arXiv:1106.5685



- There do exist a number of strict limits on ν_μ/ν_e disappearance and ν_e appearance.
- In particular, the lack of observed muon neutrino/antineutrino disappearance causes issues when trying to form a coherent picture of an extra neutrino mass eigenstate.

$$P(\nu_e \rightarrow \nu_s) \cdot P(\nu_\mu \rightarrow \nu_s) \geq P(\nu_\mu \rightarrow \nu_e)$$

Present status

A number of experiments hint at a new neutrino mass state.

A number of other experiments don't seem to see anything.

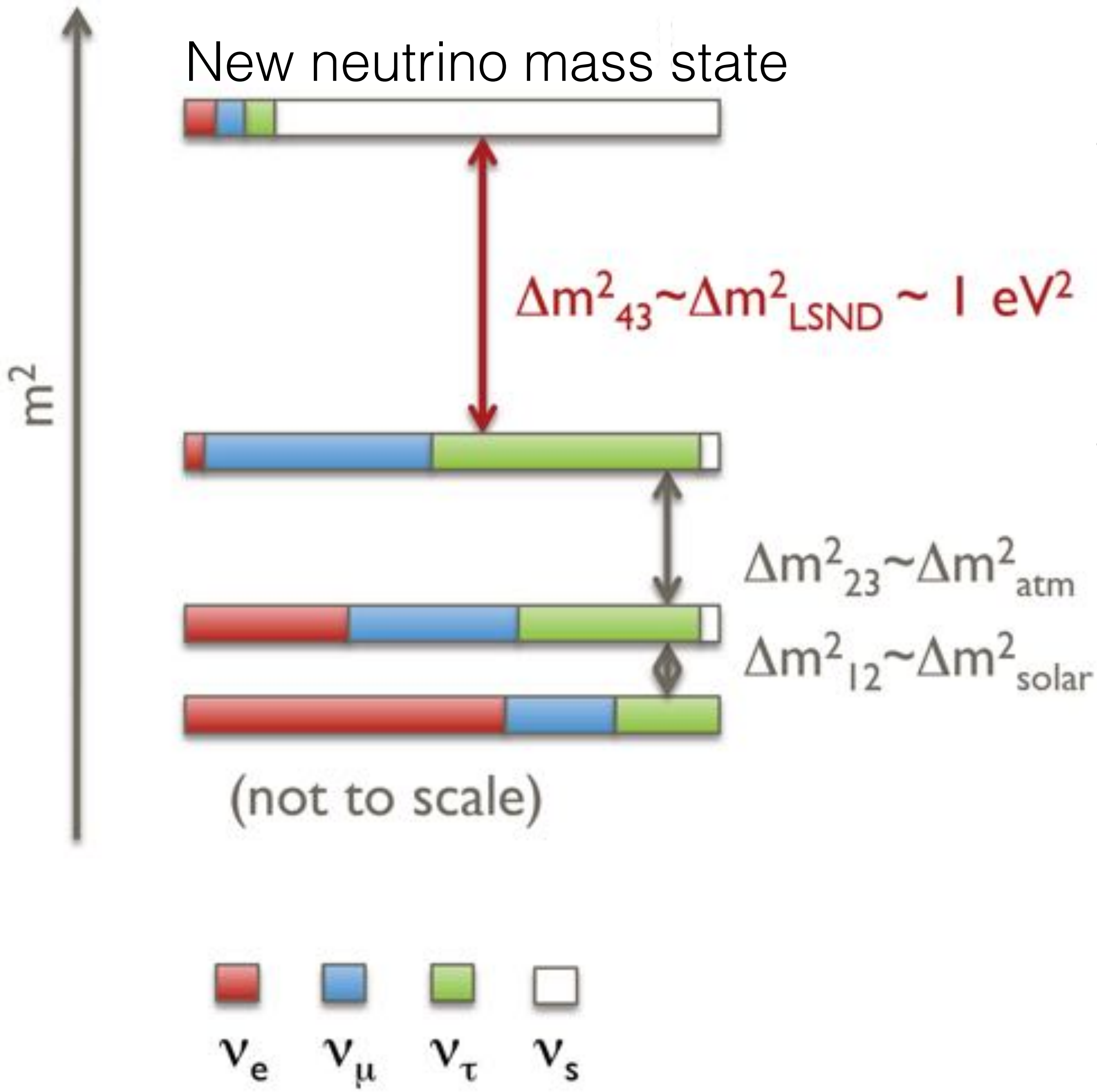
A definitive probe of this new neutrino is necessary.

If it exists, what is this new neutrino?

We know the Z boson decays into three neutrinos.

A new, fourth neutrino would therefore have to be “sterile”.
That is, it doesn’t feel Standard Model interactions.

Where does it fit?



- The observation of neutrino mass implies that there can be sterile, right-handed neutrinos. So, this is not completely unexpected.
- A light sterile neutrino would have profound effects on:
  - Radiation density in the early universe.
  - Supernova evolution.
  - Possible warm dark matter candidate?
  - Active neutrino oscillations and particle physics in general.

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Opportunity 1

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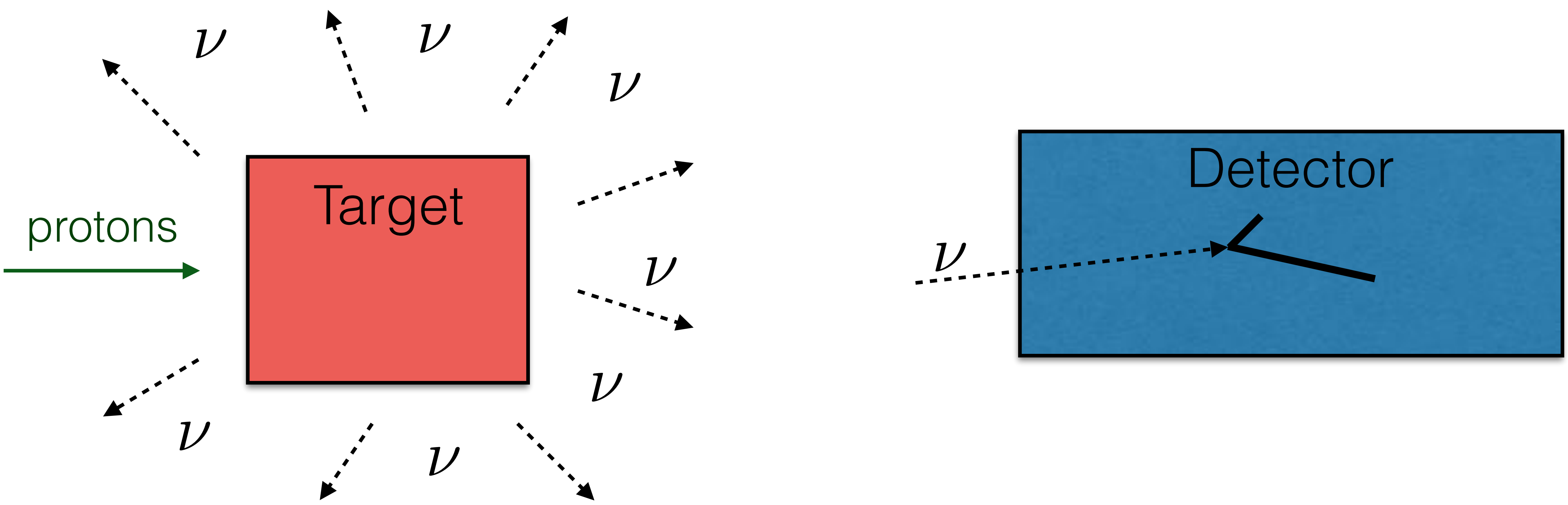
strange
quark


muon-
neutrino

A sterile neutrino search w/ kaon decay at rest

J. Spitz, Phys. Rev. D 85 093020 (2012)

$\nu_\mu \to \nu_e$?

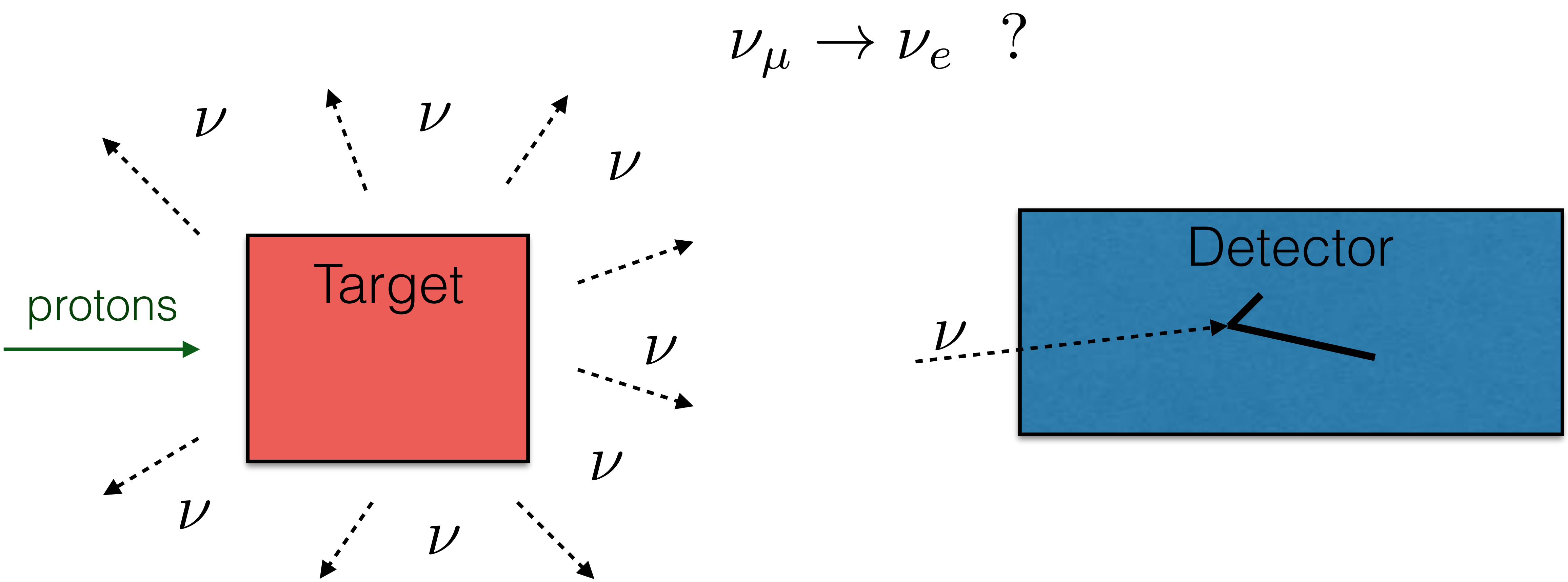


Monoenergetic (236 MeV) neutrino!

$K^+ \to \mu^+ \nu_\mu$

A sterile neutrino search w/ kaon decay at rest

J. Spitz, Phys. Rev. D 85 093020 (2012)



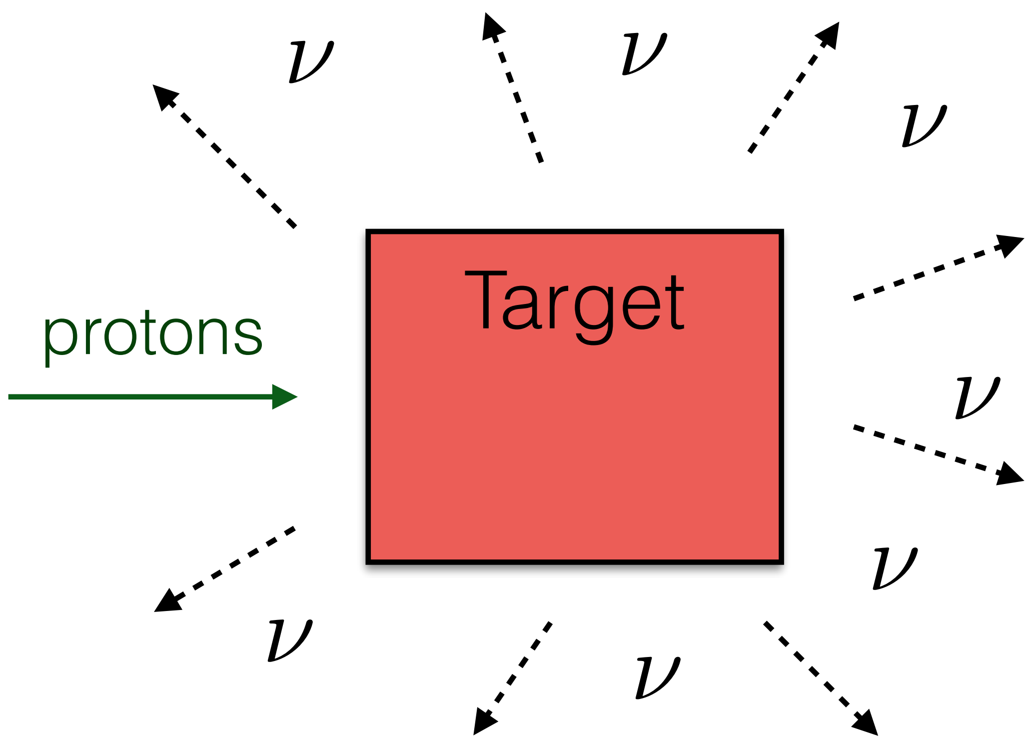
Monoenergetic (236 MeV) neutrino!

$$K^+ \rightarrow \mu^+ \nu_\mu$$

Backgrounds $\left\{ \begin{array}{l} K^+ \rightarrow \pi^0 e^+ \nu_e \\ K^0_L \rightarrow \pi^- e^+ \nu_e \end{array} \right.$

A sterile neutrino search w/ kaon decay at rest

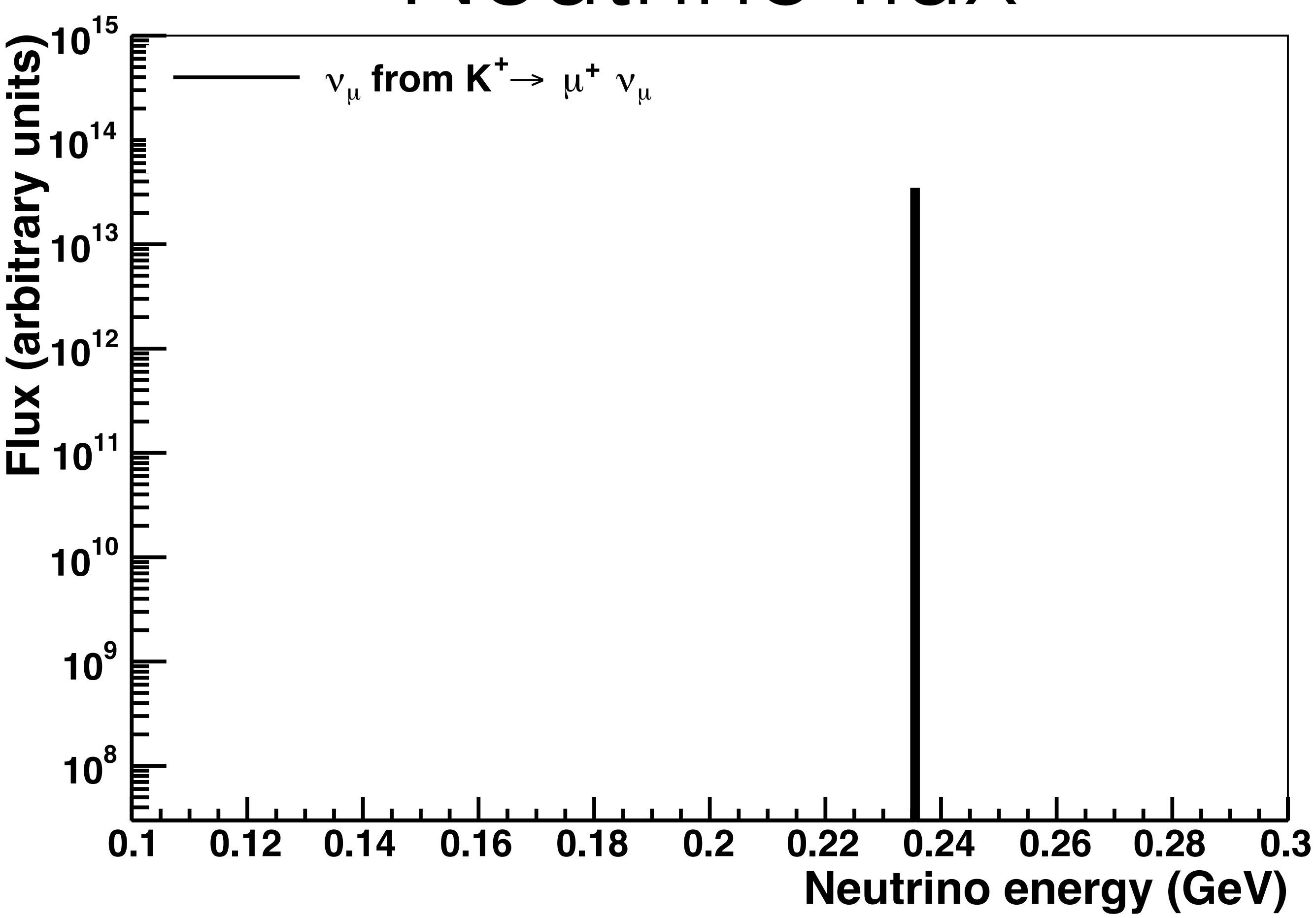
J. Spitz, Phys. Rev. D 85 093020 (2012)



$$K^+ \to \mu^+ \nu_\mu$$

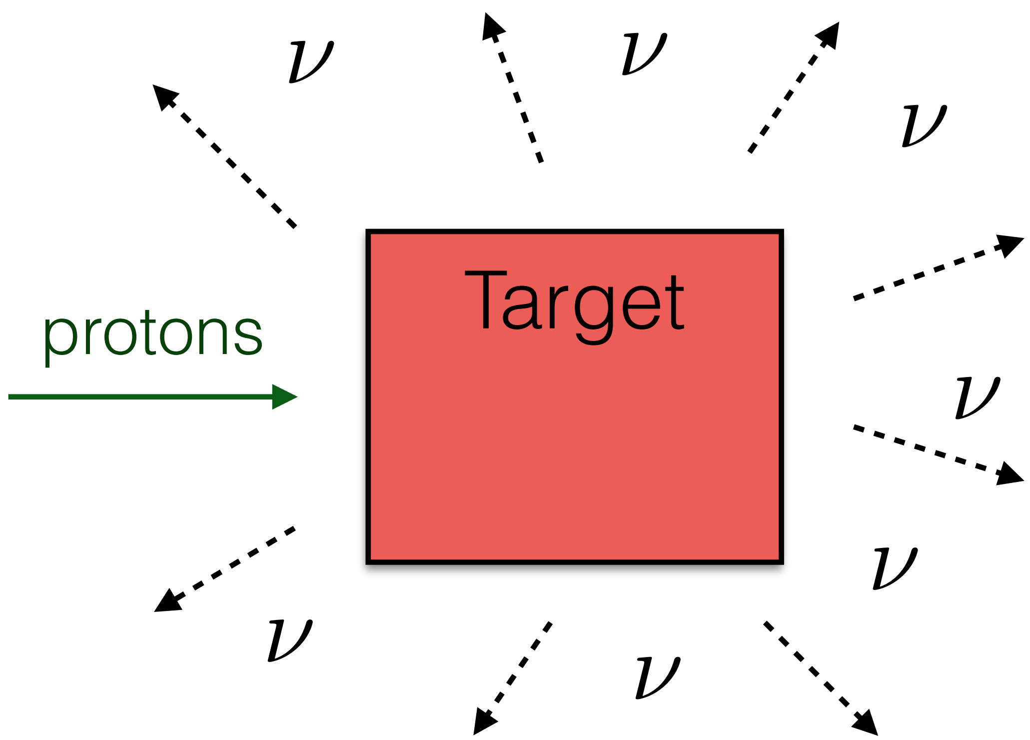
$$\nu_\mu \to \nu_e \quad ?$$

Neutrino flux



A sterile neutrino search w/ kaon decay at rest

J. Spitz, Phys. Rev. D 85 093020 (2012)



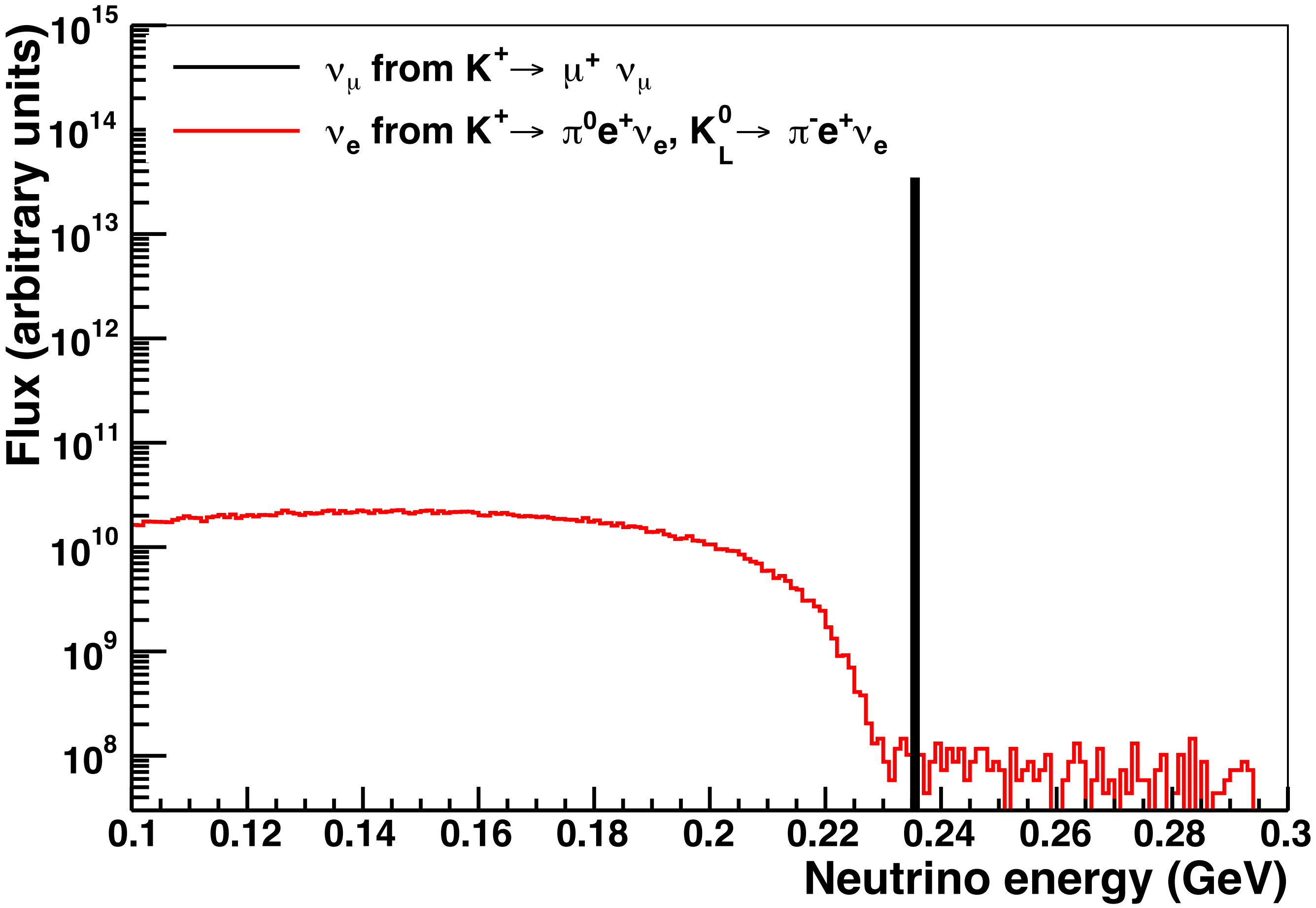
$$K^+ \rightarrow \mu^+ \nu_\mu$$

$$K^+ \rightarrow \pi^0 e^+ \nu_e$$

$$K^0_L \rightarrow \pi^- e^+ \nu_e$$

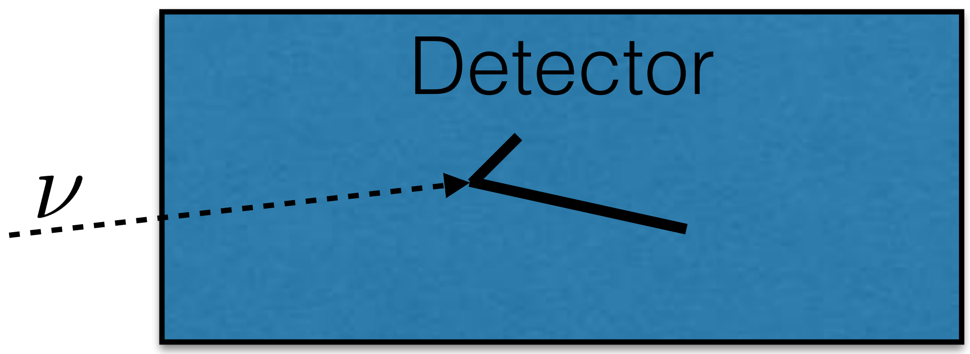
$$\nu_\mu \rightarrow \nu_e \quad ?$$

Neutrino flux



A sterile neutrino search w/ kaon decay at rest

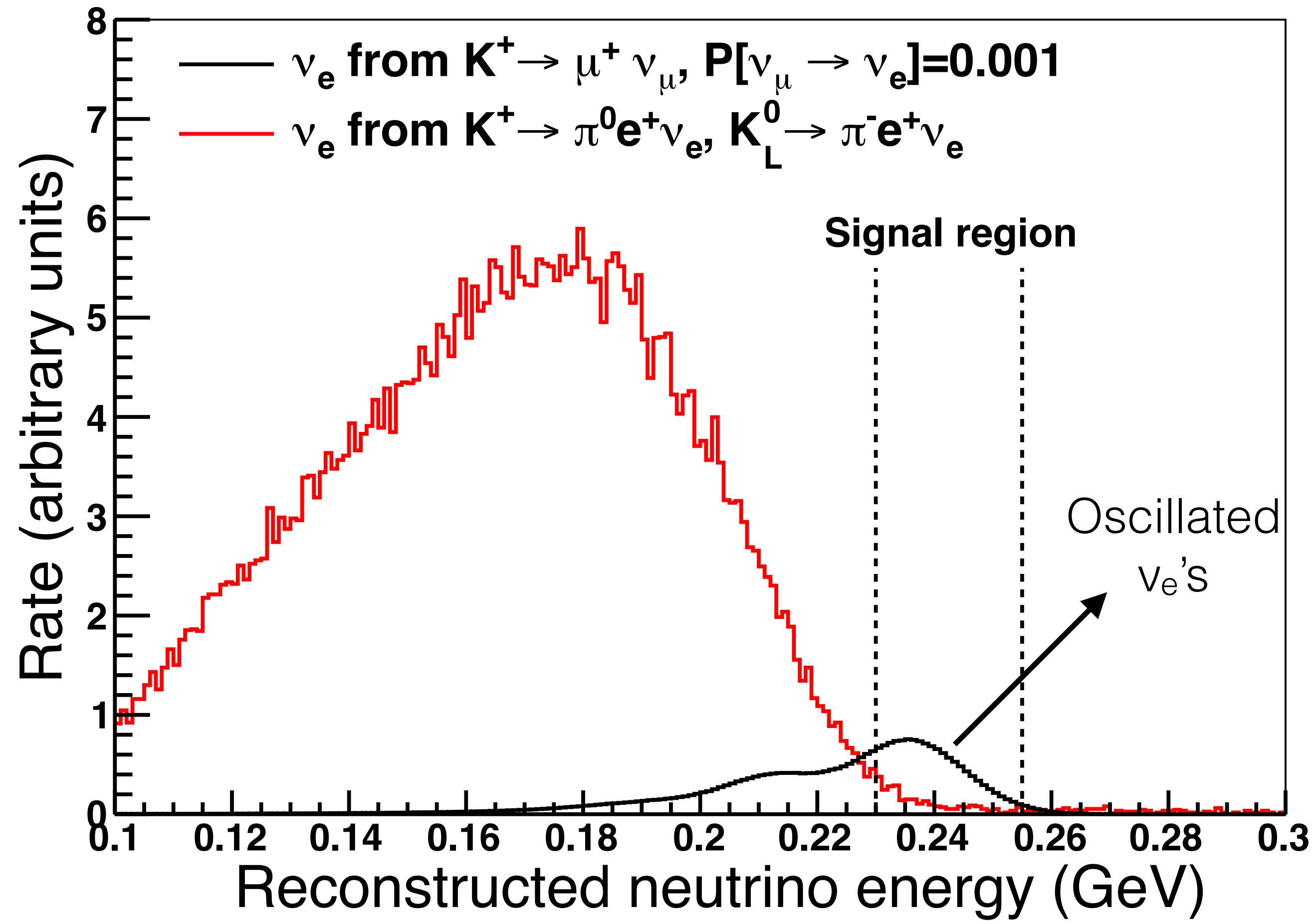
J. Spitz, Phys. Rev. D 85 093020 (2012)



$$\nu_\mu \rightarrow \nu_e \quad ?$$

$$\nu_e n \rightarrow e^- p$$

Neutrino rate



- Look for an excess near the endpoint of a well understood and measured background distribution.

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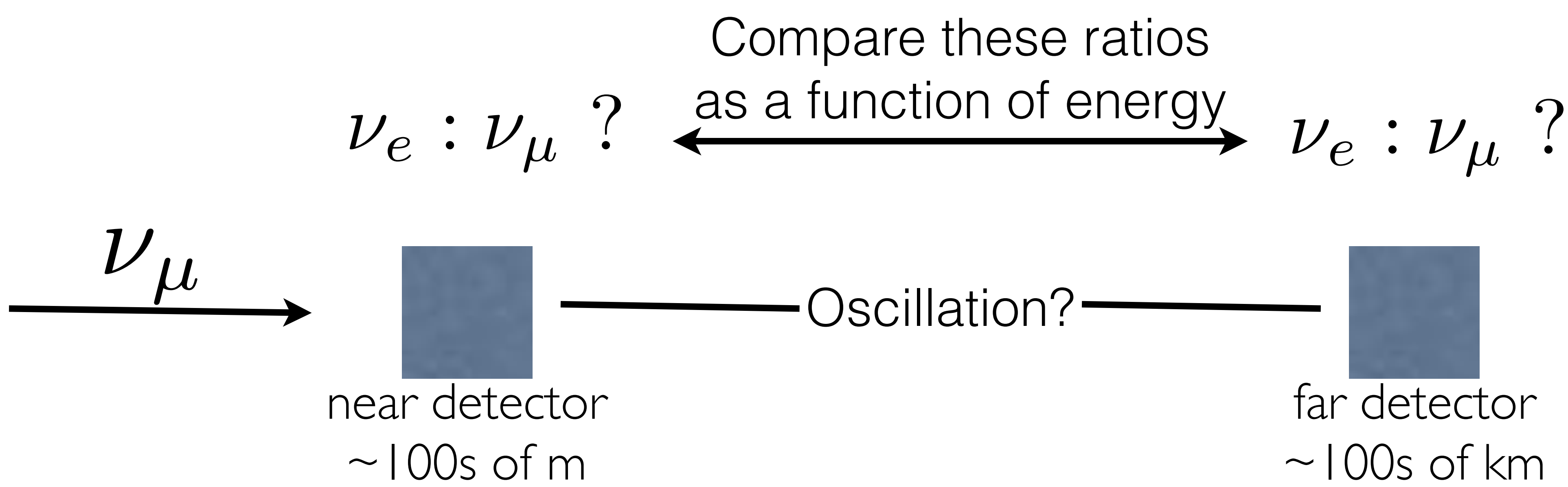
Opportunity 2

- Solutions (w/ kaons)

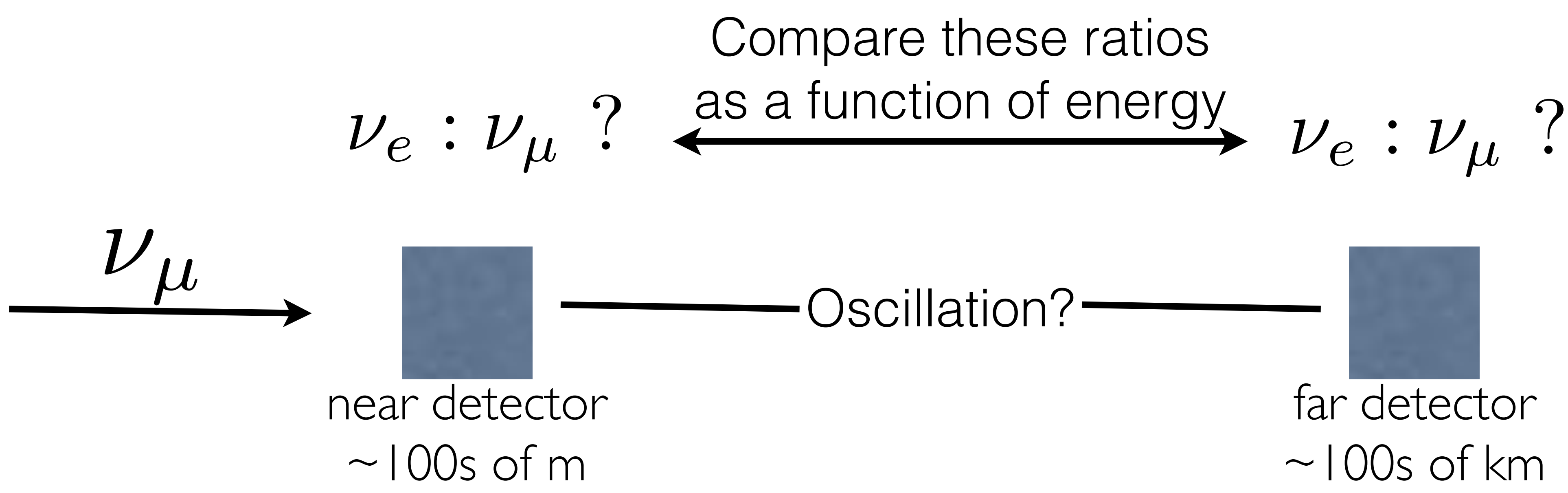
Reminder



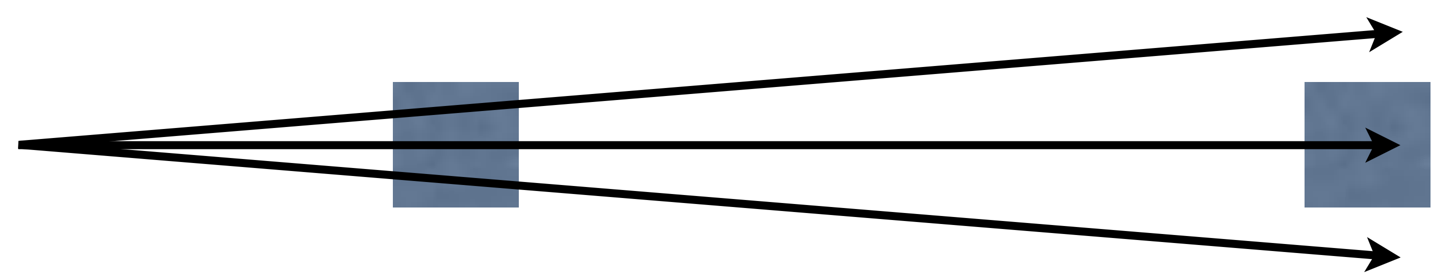
CP violation in the lepton sector?

$$P[\nu_\mu \rightarrow \nu_e] \neq P[\overline{\nu}_\mu \rightarrow \overline{\nu}_e] \ ?$$

The problem



The near and far fluxes are inherently different! So, we need to rely on cross section knowledge for a proper comparison.



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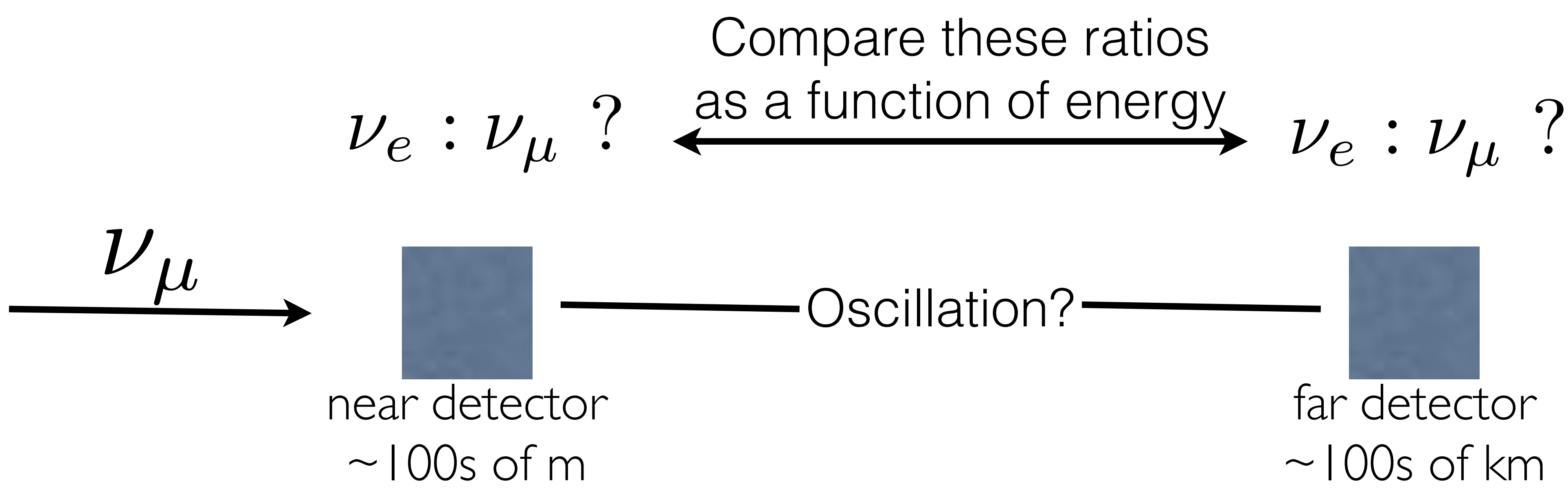
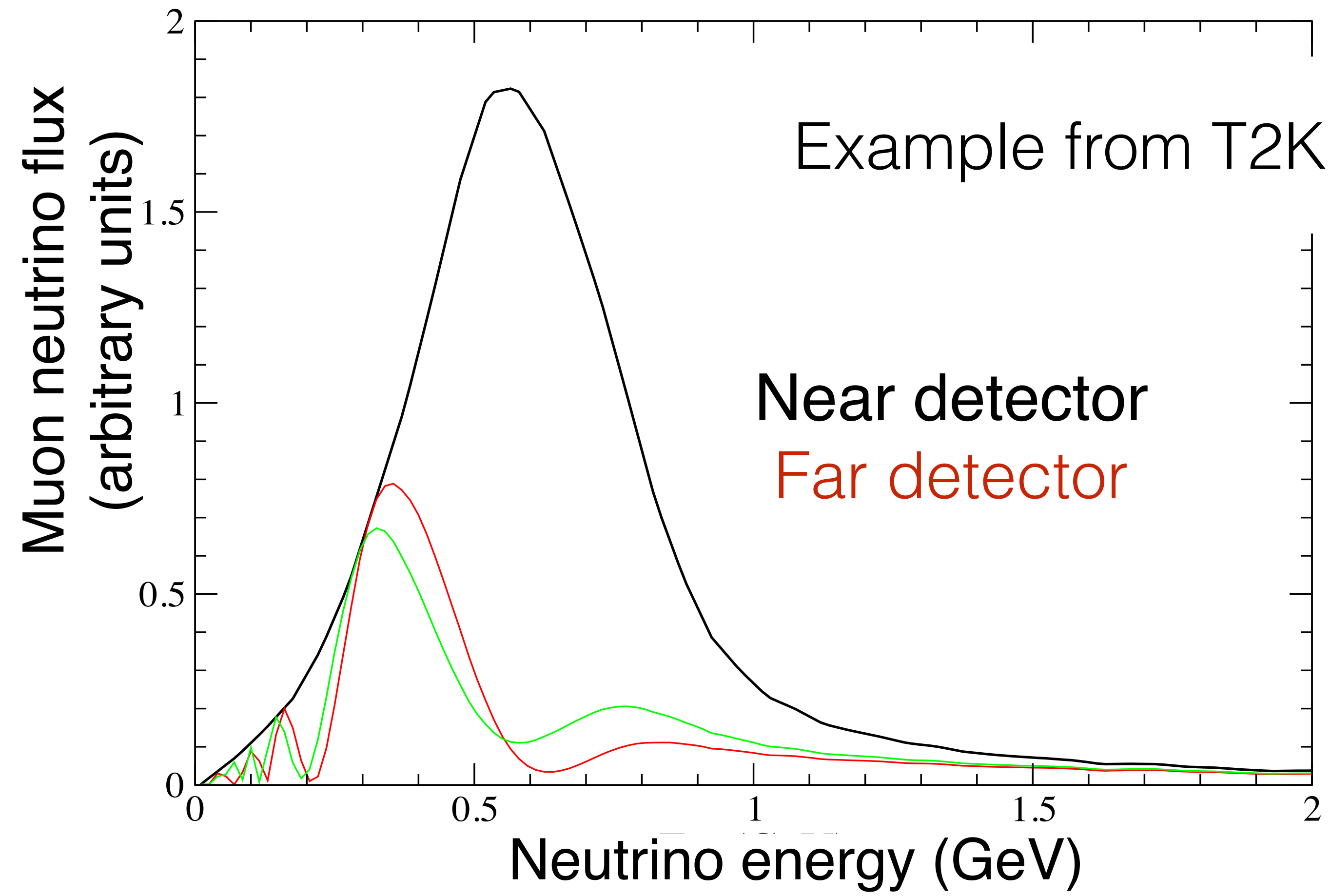


The near and far fluxes are inherently different! So, we need to rely on cross section knowledge for a proper comparison.



The problem

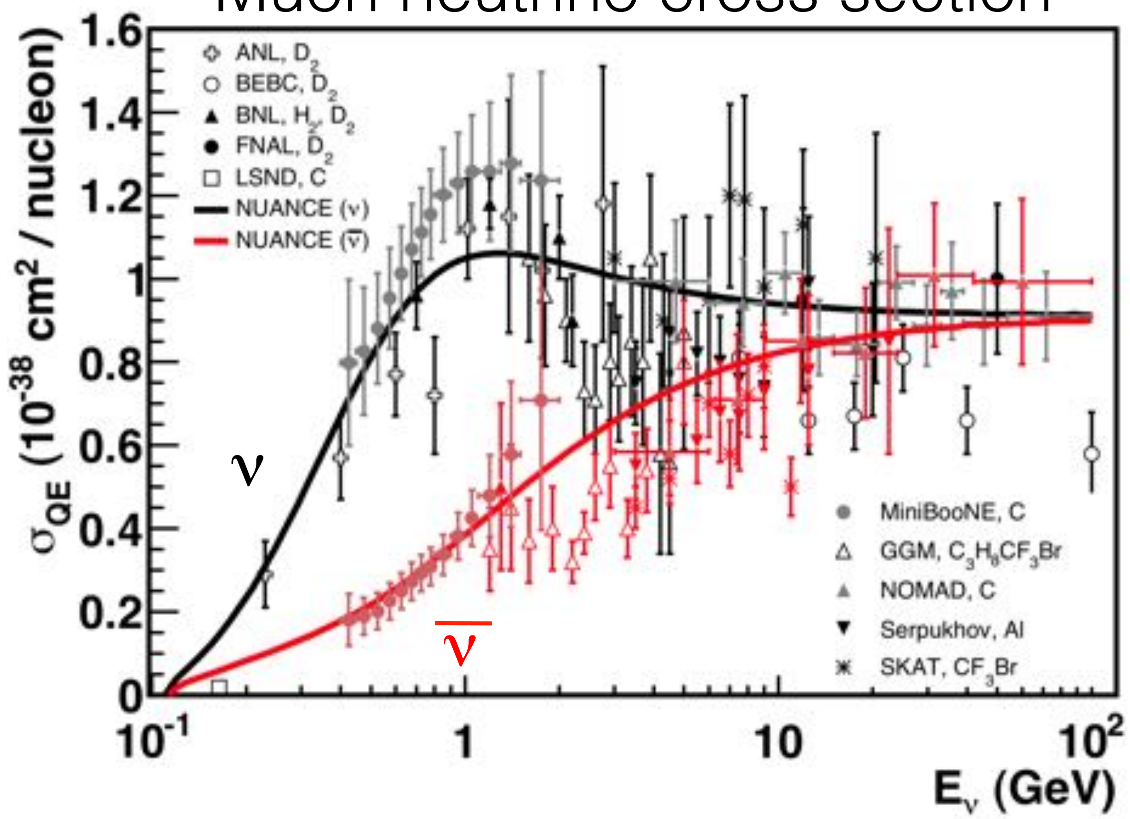
$\nu_e : \nu_\mu$?　　Compare these ratios as a function of energy　　$\nu_e : \nu_\mu$?

ν_μ → near detector ——— Oscillation? ——— far detector

near detector
~100s of m

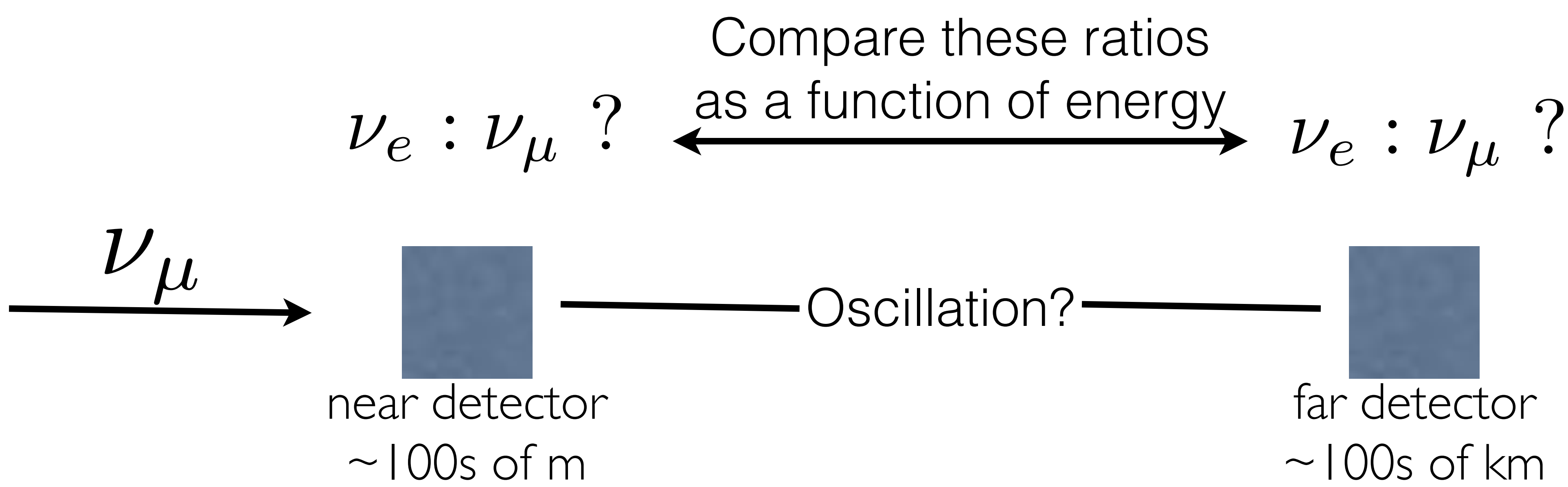
far detector
~100s of km

Muon neutrino cross section



Our cross section knowledge is quite weak!

The other problem



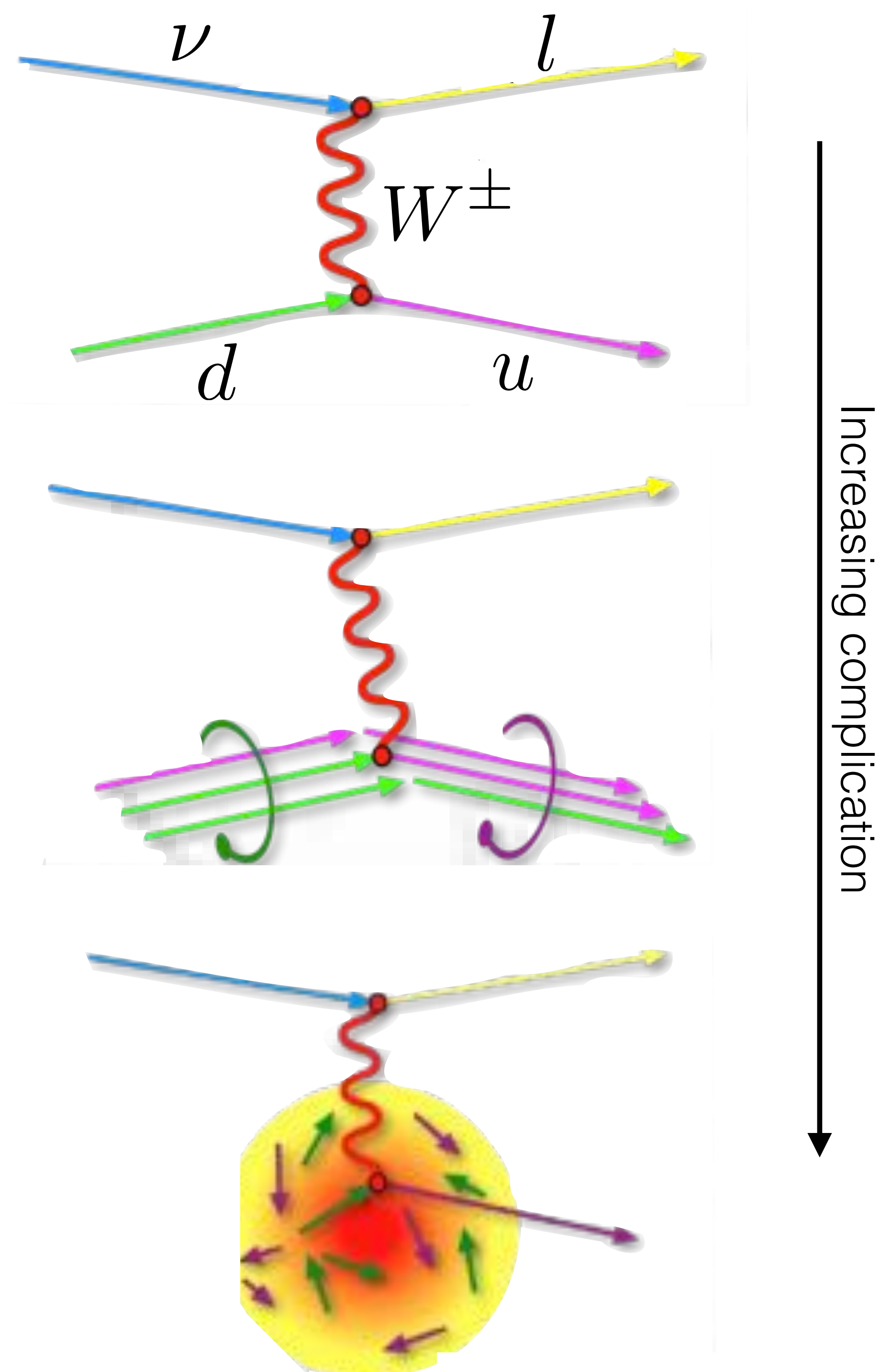
The oscillation probability is a function of neutrino energy….
but it's hard to reconstruct the energy of the neutrino!

$$P_{\alpha\rightarrow\beta,\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(1.267\frac{\Delta m^2 L}{E}\frac{\mathrm{GeV}}{\mathrm{eV}^2\,\mathrm{km}}\right)$$

$$\frac{\Delta E}{E} > 20\% \text{ is typical}$$

Calculation and reconstruction issues

- Neutrino interactions with nuclei are complicated!
    - Fermi motion.
    - Pauli blocking.
    - Correlations between nucleons.
    - Final state interactions.
- Detector limitations
    - Energy resolution.
    - Event classification issues.
    - Cerenkov threshold.



Problem summary

- The systematics associated with the interaction currently lead the uncertainties on the predicted number of electron neutrino appearance candidates in our long baseline experiments.

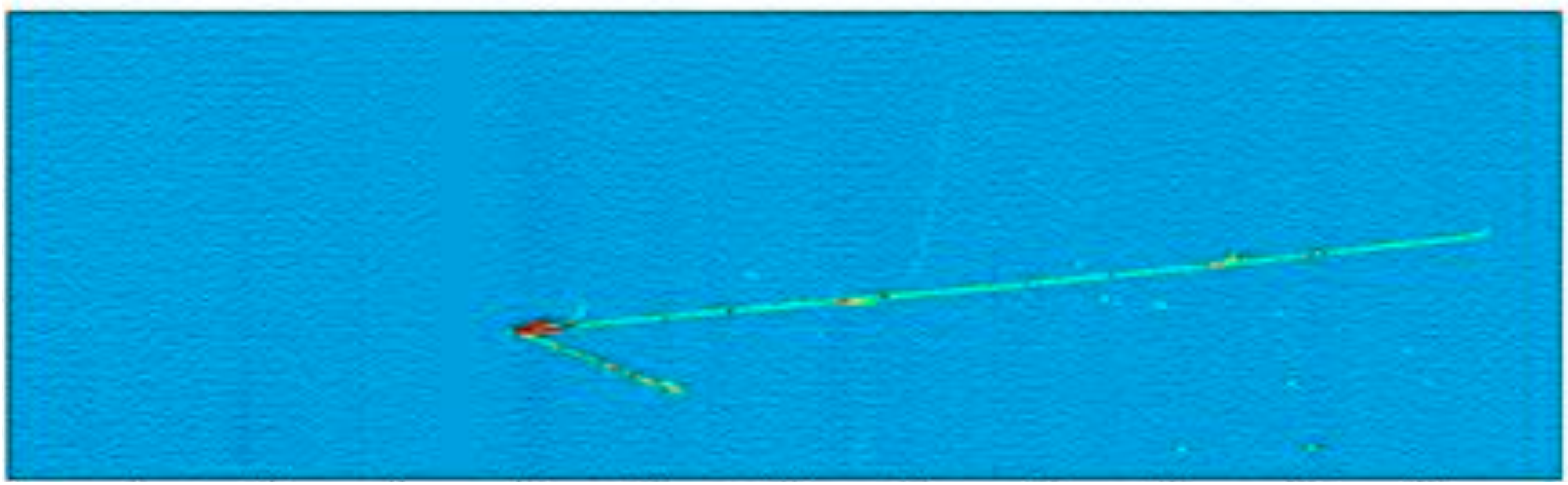
Error source [%]	$\sin^2 2\theta_{13} = 0.1$
Beam flux and near detector	2.9
(without ND280 constraint)	(25.9)
Uncorrelated ν interaction	7.5
Far detector and FSI + SI + PN	3.5
Total	8.8

T2K Collaboration, PRL 112, 061802 (2014)

- These systematics are expected to continue to dominate in future neutrino CP-violation measurements.

Solutions to our problems

- Detector technology
  - Being able to see the low energy part of the interaction.
  - Energy resolution.



- Differential and total cross section measurements across all relevant nuclear targets and neutrino energies.
  - From-kaon neutrinos can be used as part of this program.

Outline

- The big picture in neutrino oscillation physics today
- The holy grail: measuring a difference between neutrinos and antineutrinos called “CP violation”.
- Opportunity 1: The sterile neutrino
  - Solutions (w/ kaons)
- ~~Problem 2:~~ Neutrino cross sections

Opportunity 2

  - Solutions (w/ kaons)

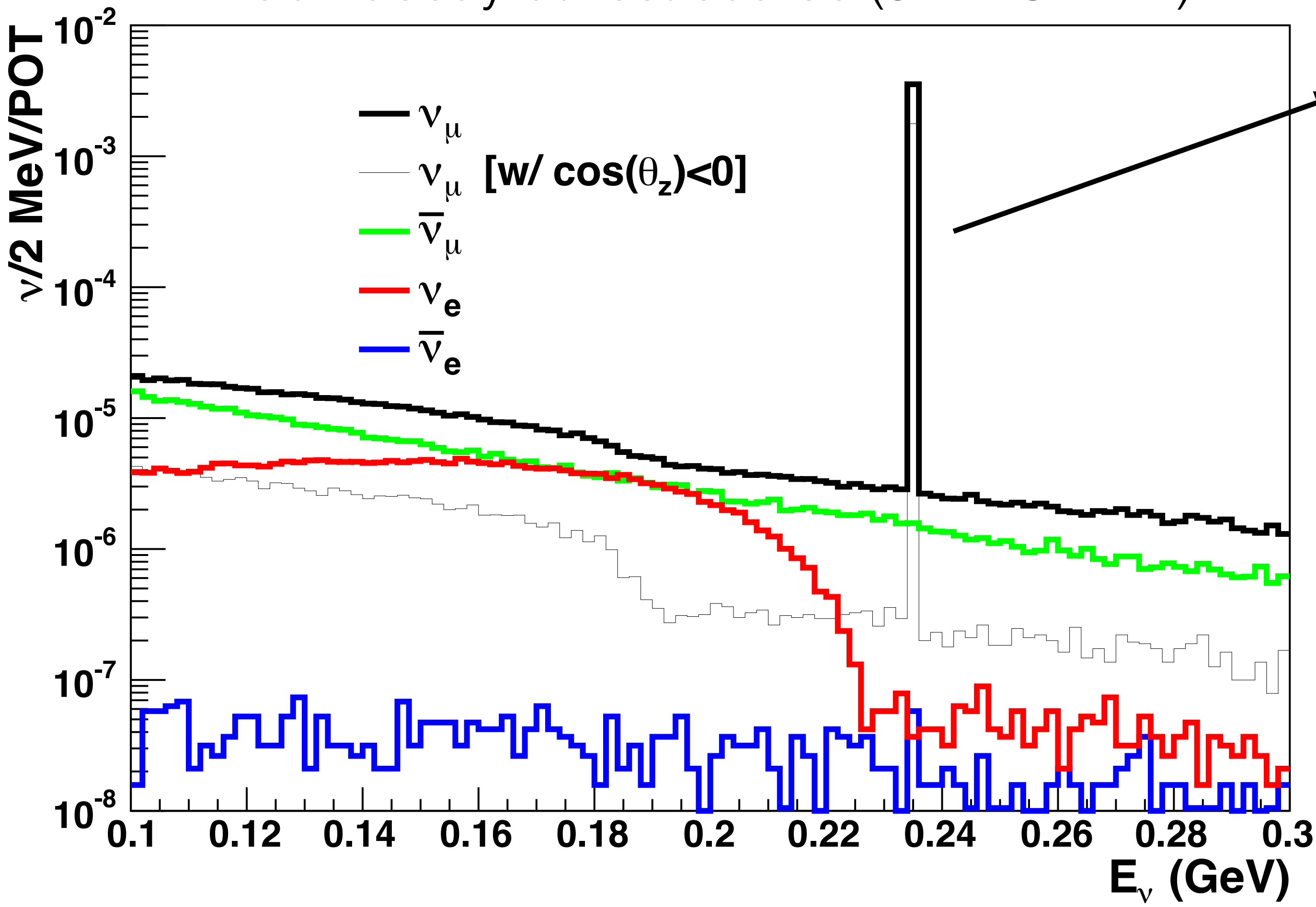

strange
quark


muon-
neutrino

Cross section measurements with monoenergetic muon neutrinos

J. Spitz, Phys. Rev. D 89 073007 (2014)

Neutrino flux from typical kaon decay-at-rest source (JPARC-MLF)



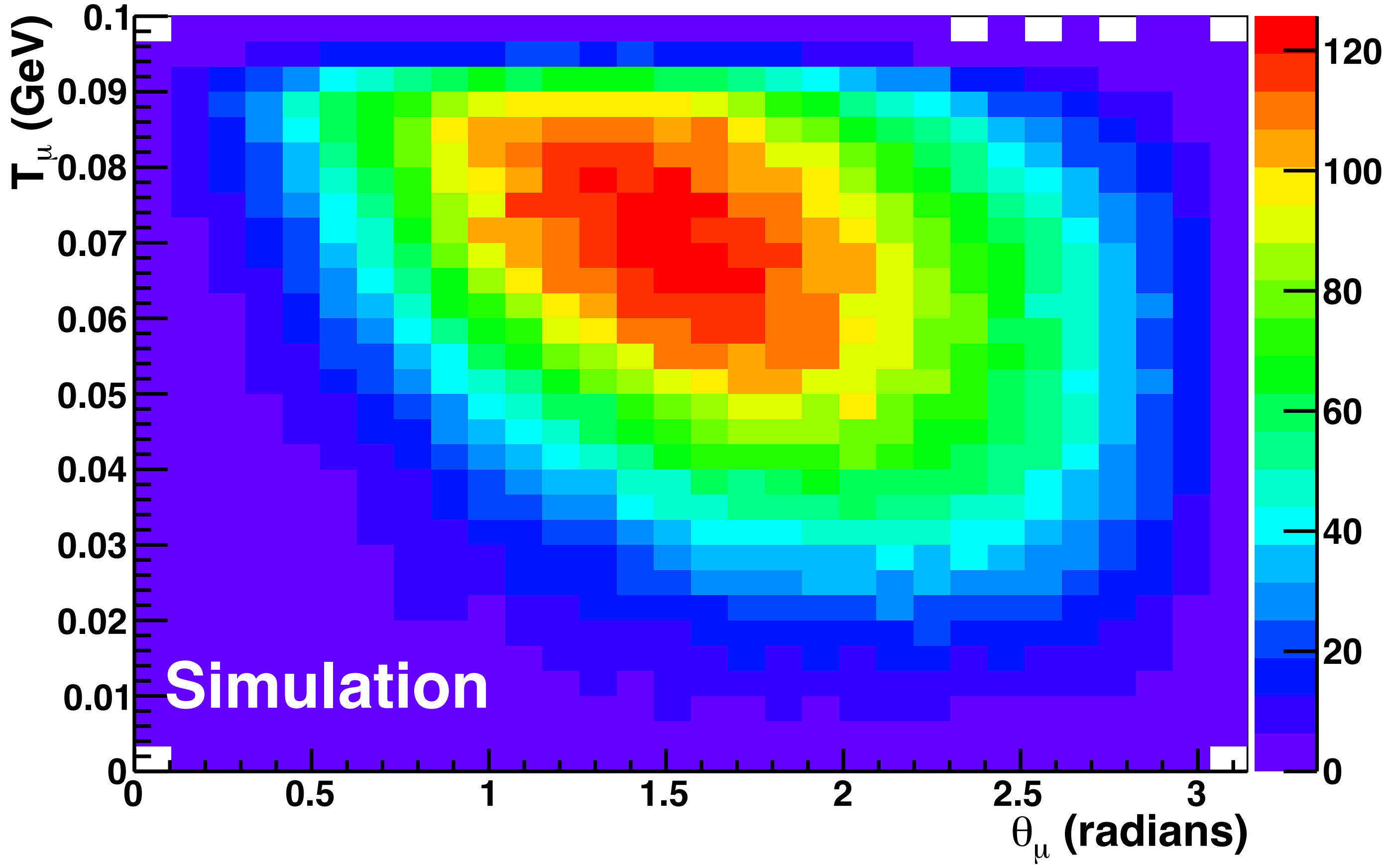
This unique neutrino can be used to provide a set of cross section measurements at a known-energy.

- Reducing systematics associated with near/far comparison.
- Neutrino as a probe of the nucleus.
  - For the first time ever, we can probe the nucleus with a known-energy (muon) neutrino.

Cross section measurements

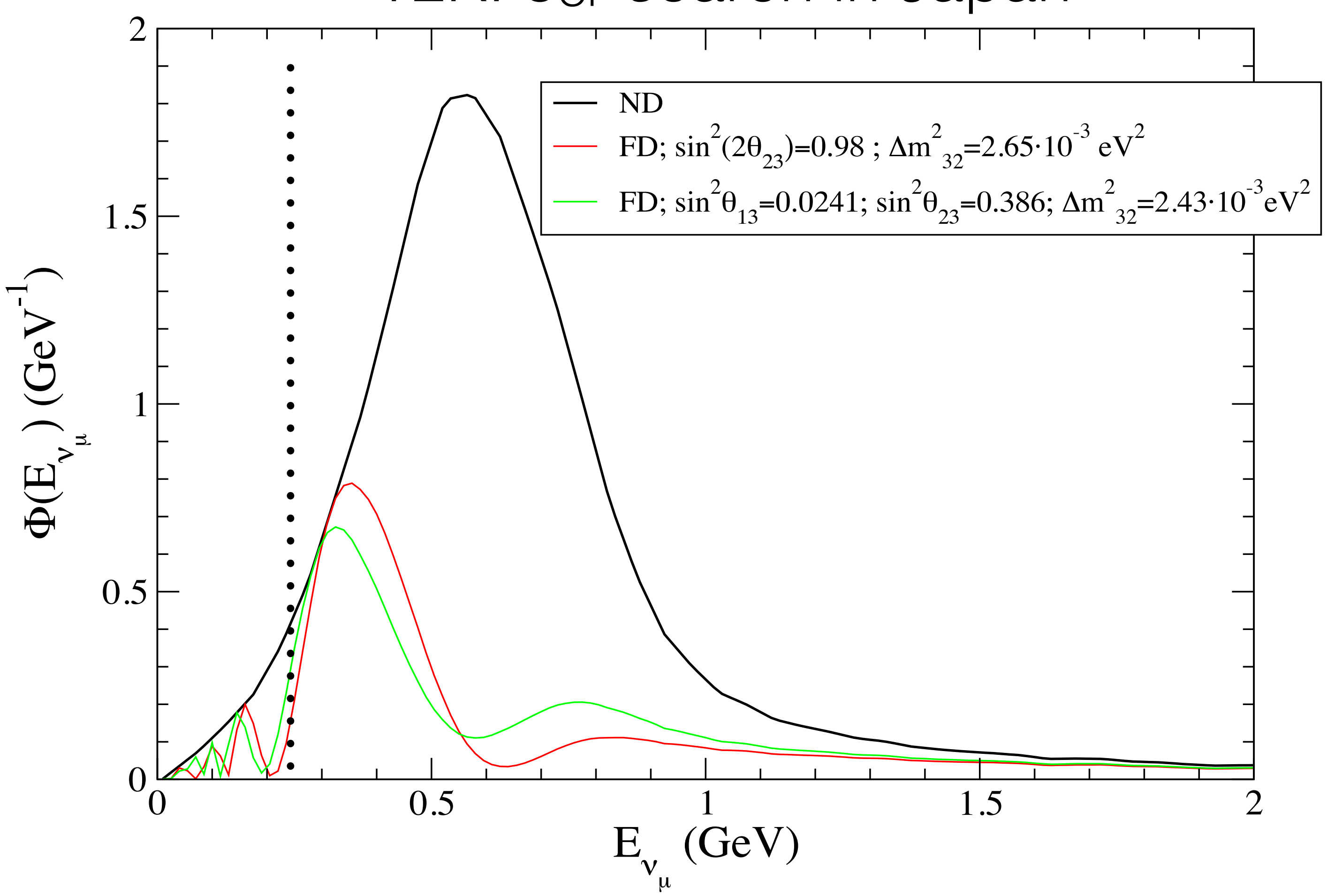
- The 236 MeV muon neutrino can provide a map of muon angle and kinetic energy for a known neutrino energy. This "standard candle" would be unprecedented.
- This is especially relevant for those experiments which solely rely on muon kinematics for reconstructing the neutrino energy.

J. Spitz, Phys. Rev. D 89 073007 (2014)

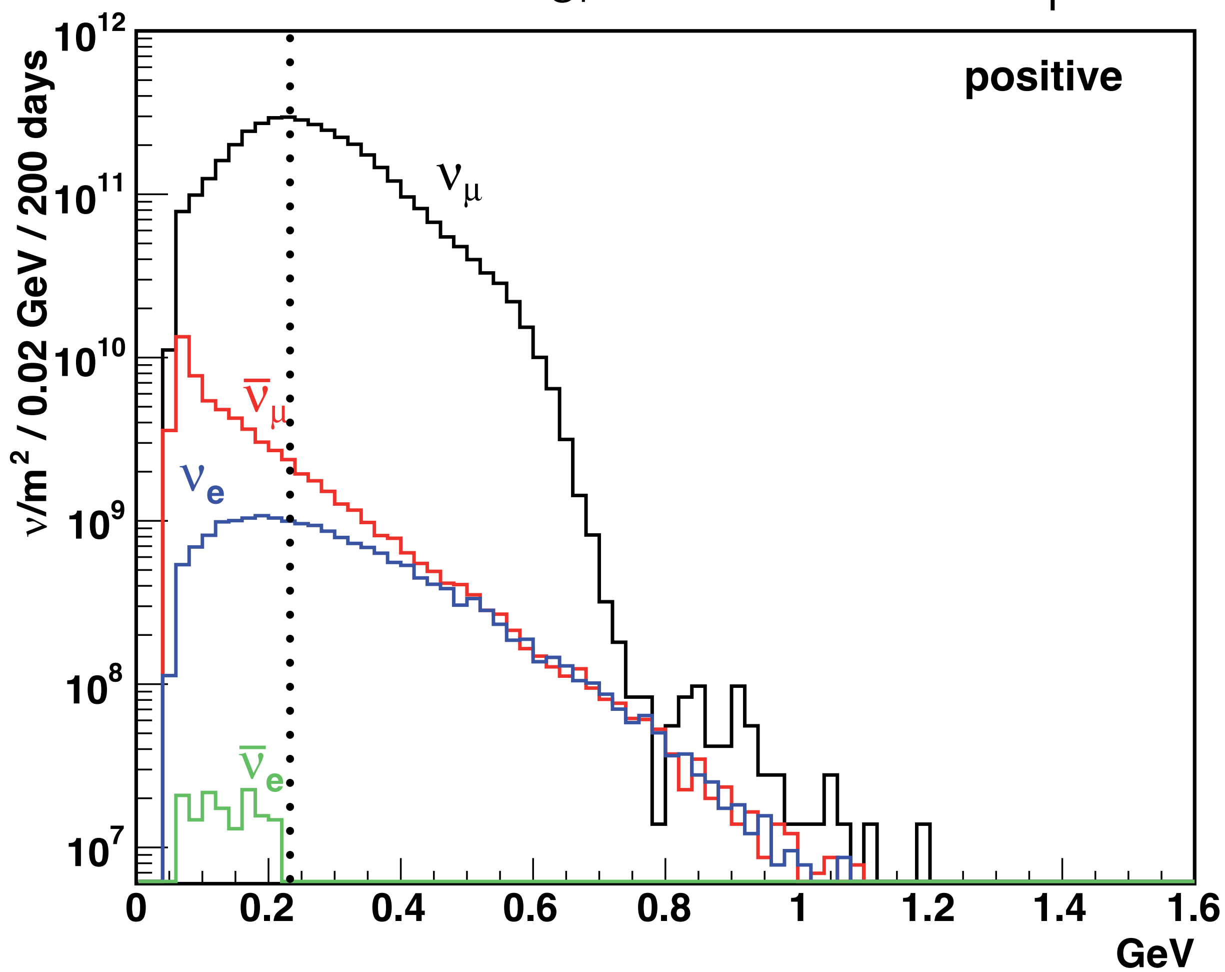


Direct relevance to future CP violation searches

T2K: δ_{CP} search in Japan

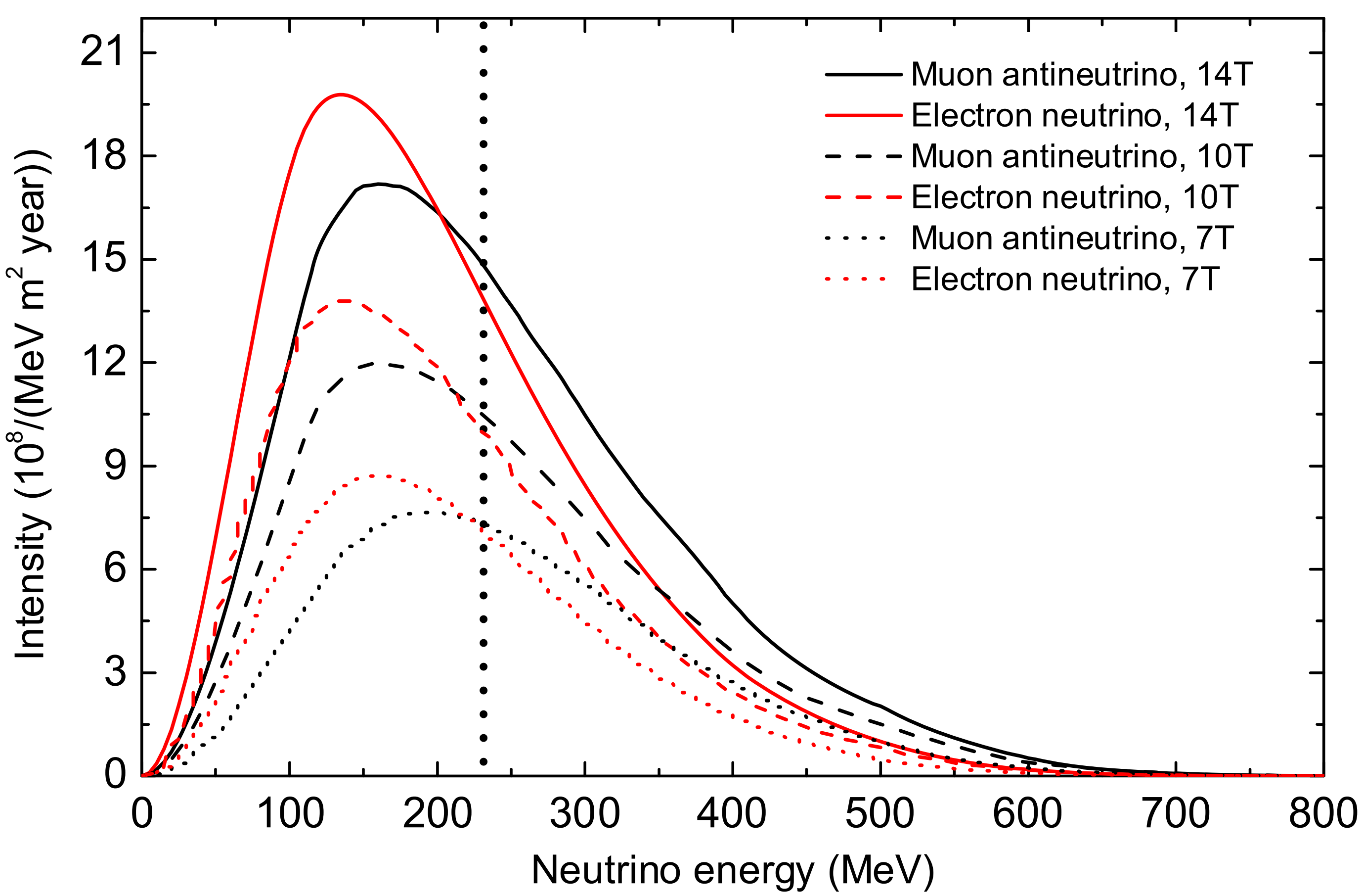


ESSνSB: δ_{CP} search in Europe

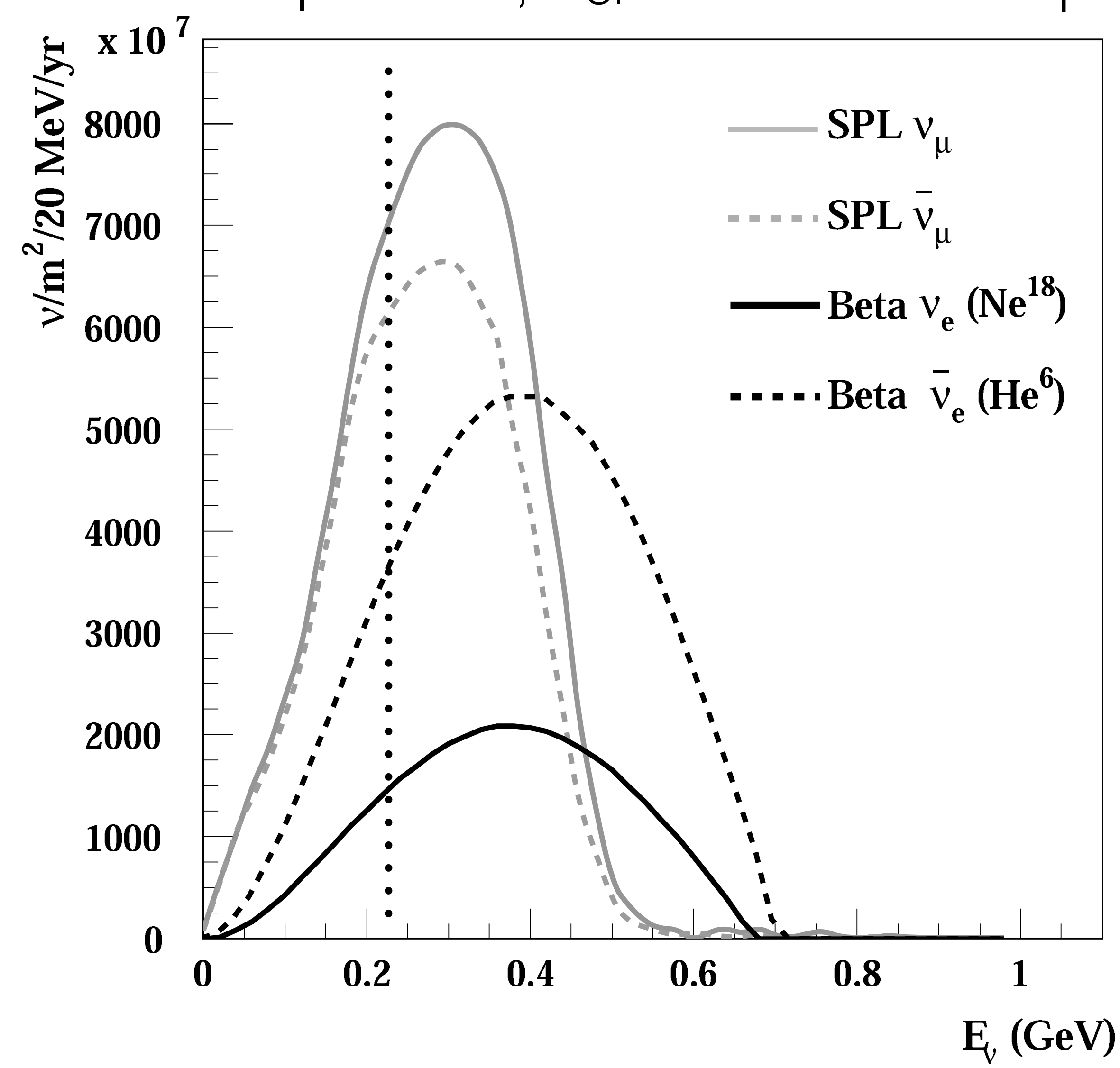


Direct relevance to future CP violation searches

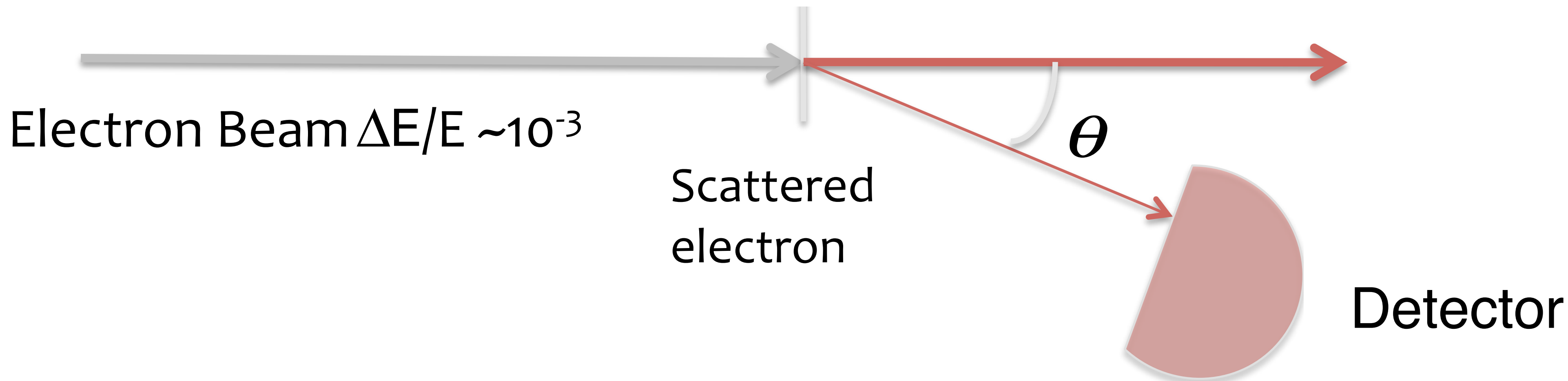
MOMENT; δ_{CP} search in China

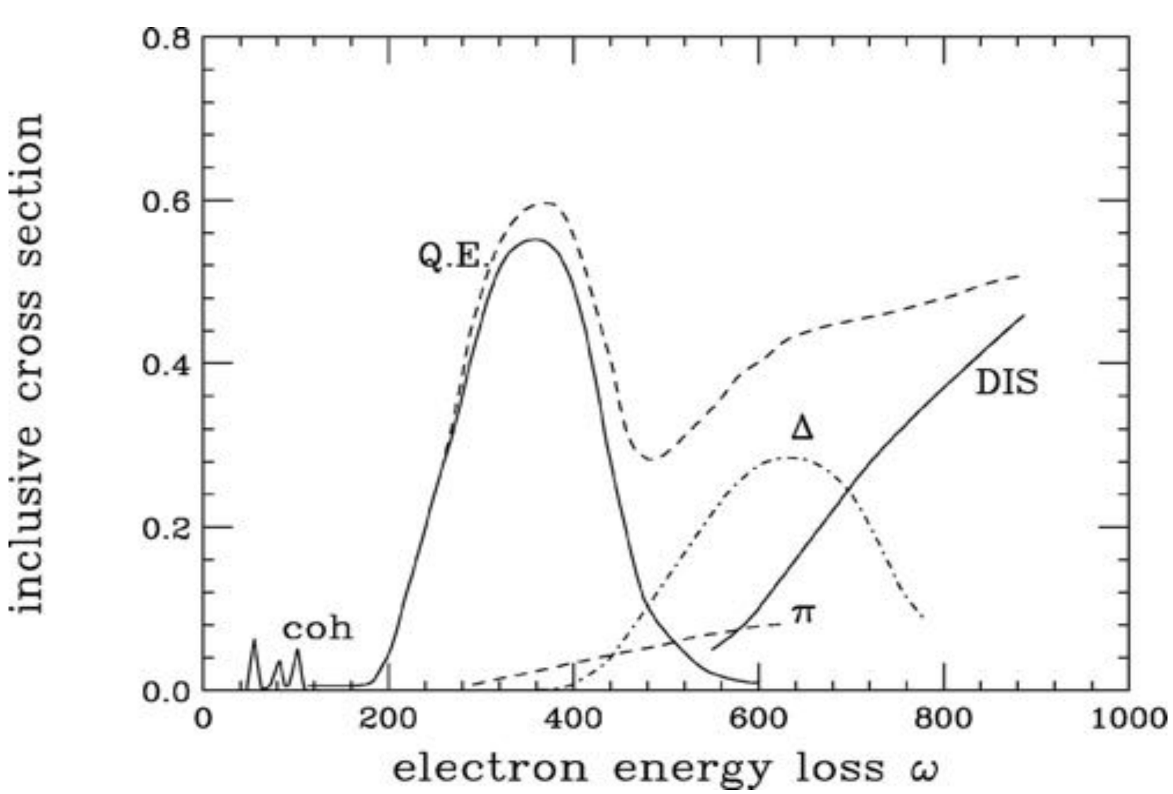


CERN Super Proton Linac and β-beam; δ_{CP} search in Europe



Probing the nucleus





$$(E,0,0,p),\ \ (E',p'\sin\theta,0,p'\cos\theta)$$

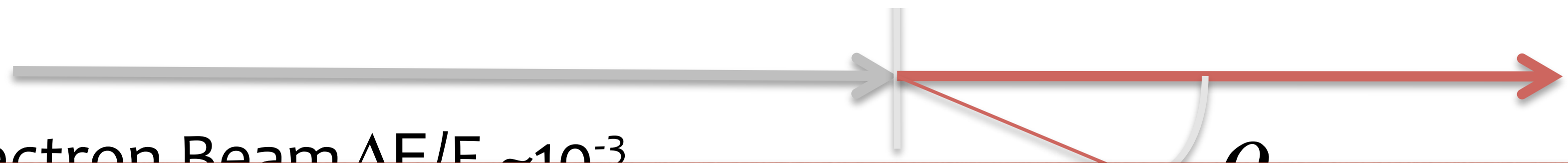
$$\omega \equiv E - E'$$

$$\vec{q} = \vec{p} - \vec{p}\,'$$

Thus q and ω are precisely known <u>without any reference to the nuclear final state</u>

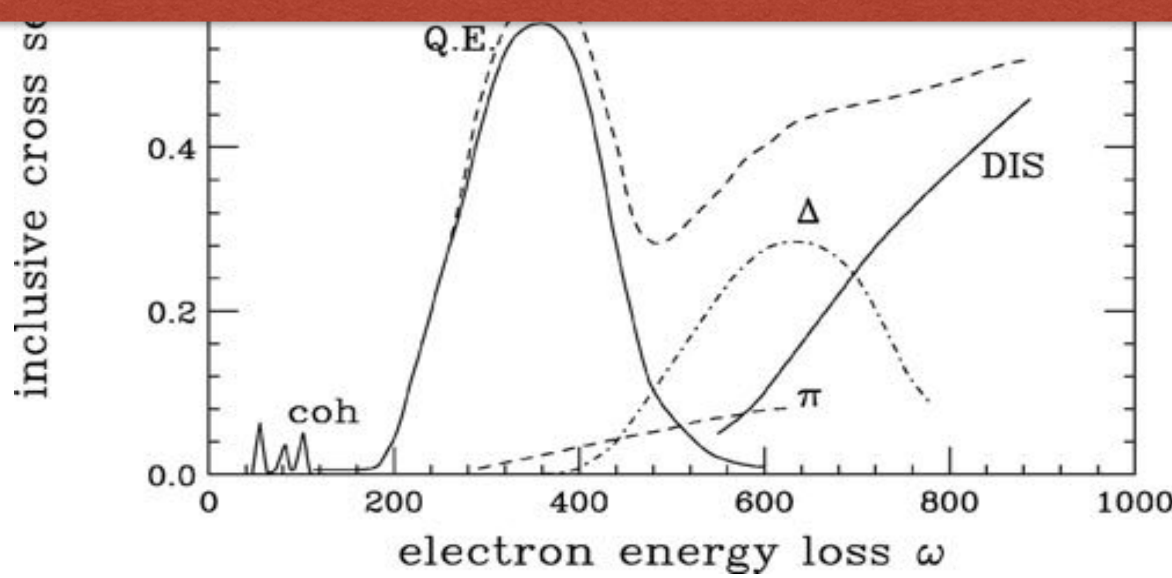
Slide adapted from G. Garvey

Probing the nucleus



Electron Beam ΔE/E ~10^{-3}

Not possible with neutrinos…until now!



$(E,0,0,p),\ \ (E',p'\sin\theta,0,p'\cos\theta)$

$$\omega \equiv E - E'$$

$$\vec{q} = \vec{p} - \vec{p}\,'$$

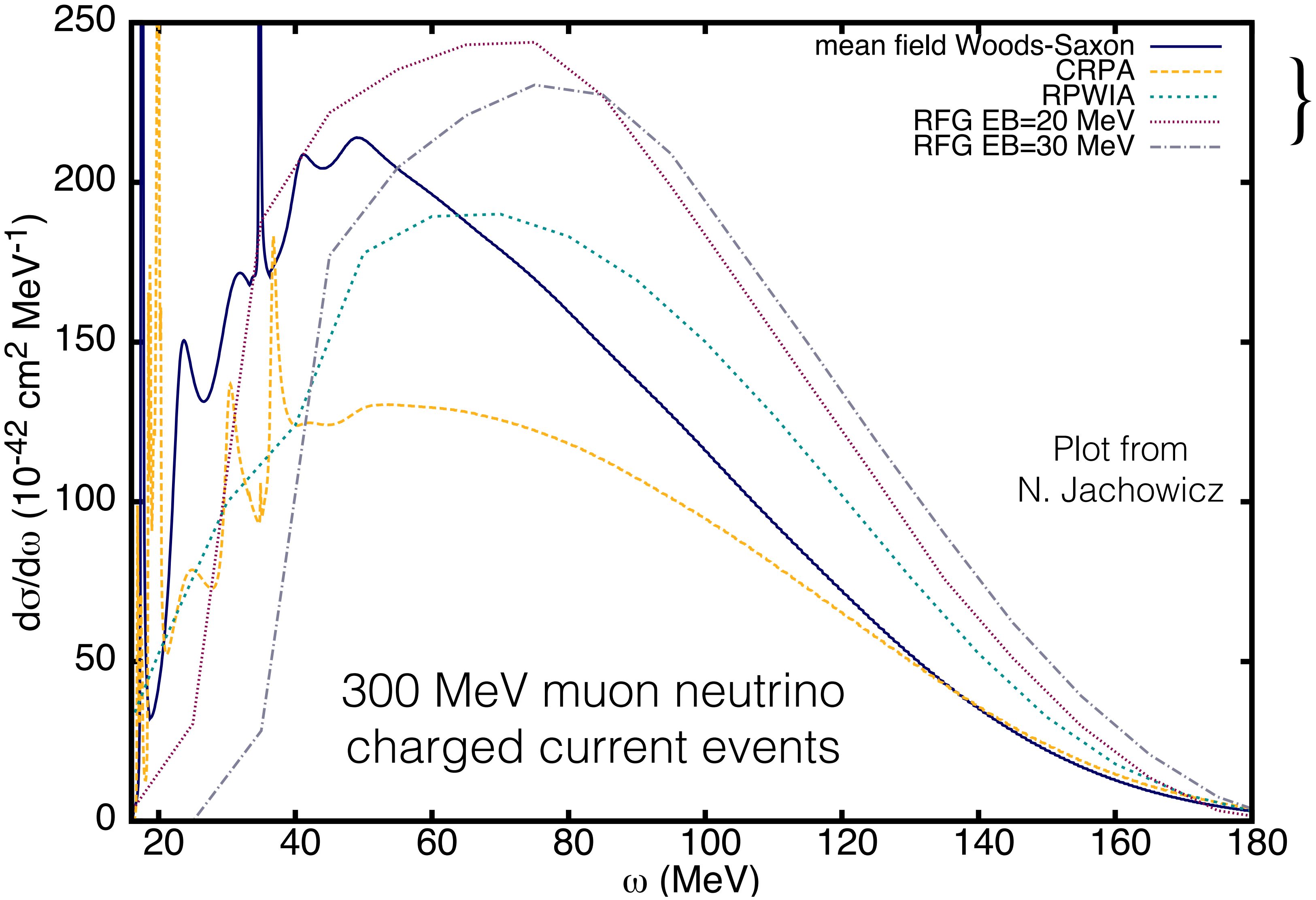
Thus q and ω are precisely known <u>without any reference to the nuclear final state</u>

Slide adapted from G. Garvey

Neutrinos as a nuclear probe

J. Spitz, Phys. Rev. D 89 073007 (2014)

- For the first time, we can make these measurements with neutrinos!
- A known-energy, purely weak interacting probe of the nucleus.



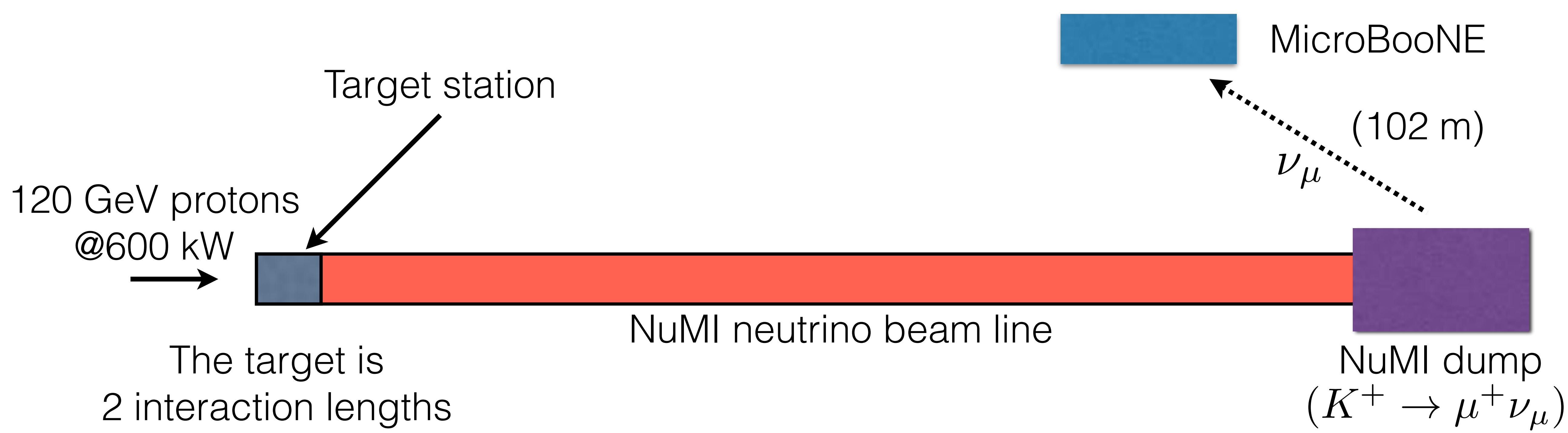
} Various ways to treat the nucleus

Which model of the nucleus, relevant for neutrinos, is correct?

Where to?

- There are basically two places in the world where one can currently do neutrino physics with kaon decay-at-rest.

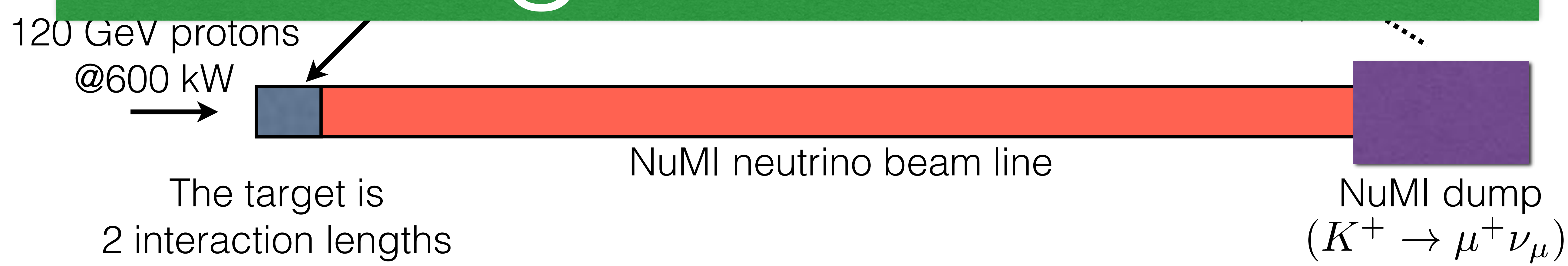
  - NuMI beam dump at Fermilab



Where to?

- There are basically two places in the world where one can currently do neutrino physics with kaon decay-at-rest.

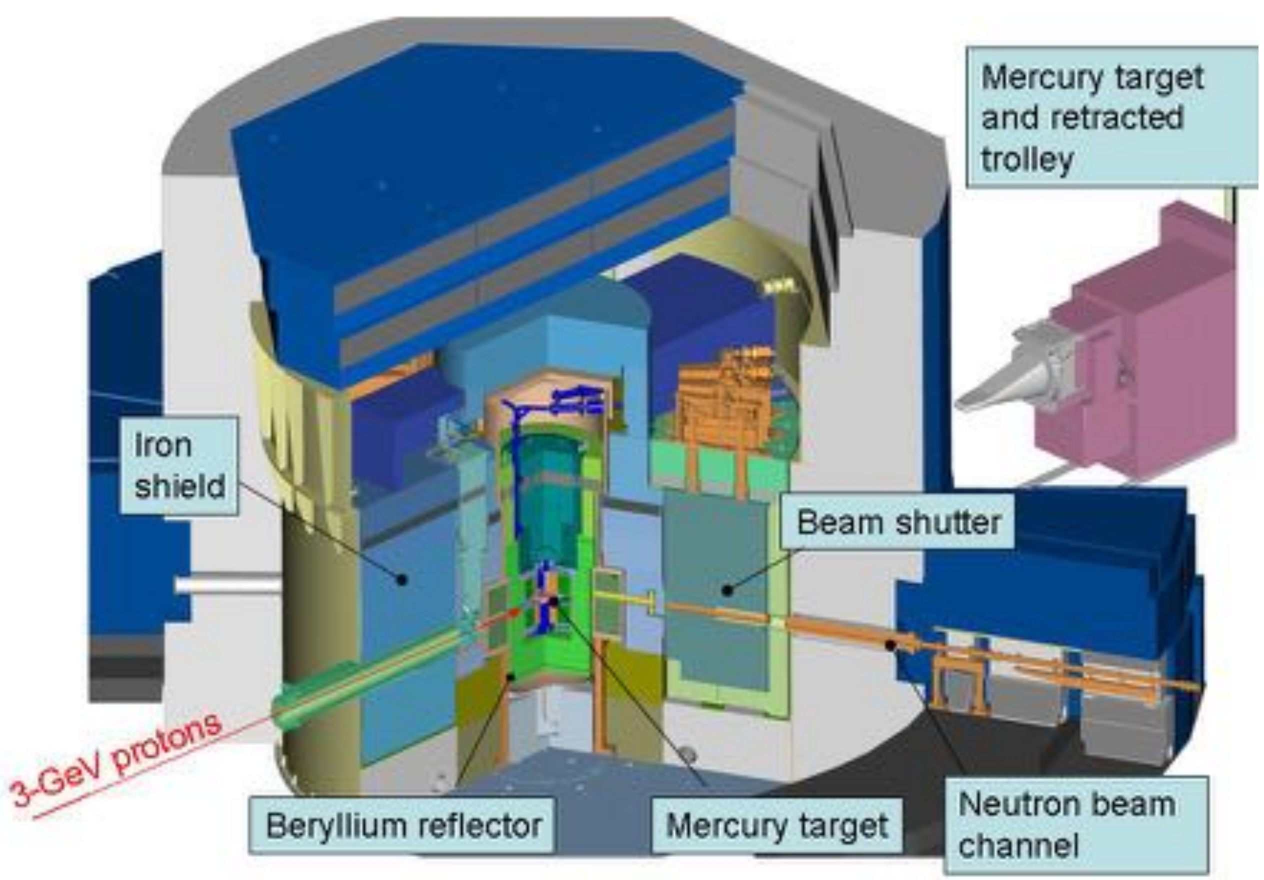
MicroBooNE:
Coming online in 2015



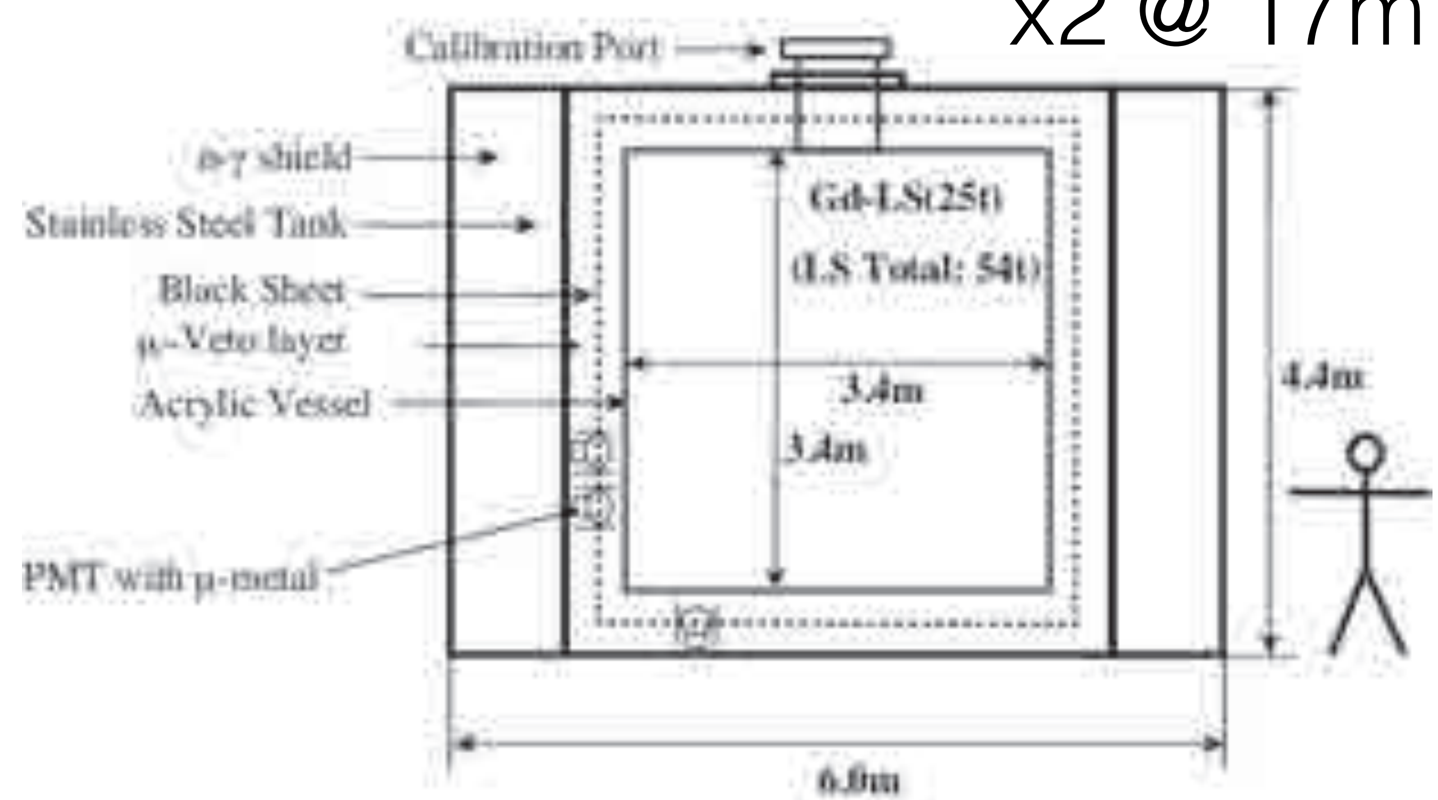
Where to?

- There are basically two places in the world where one can currently do neutrino physics with kaon decay-at-rest.

  - JPARC 3 GeV spallation neutron source



x2 @ 17m



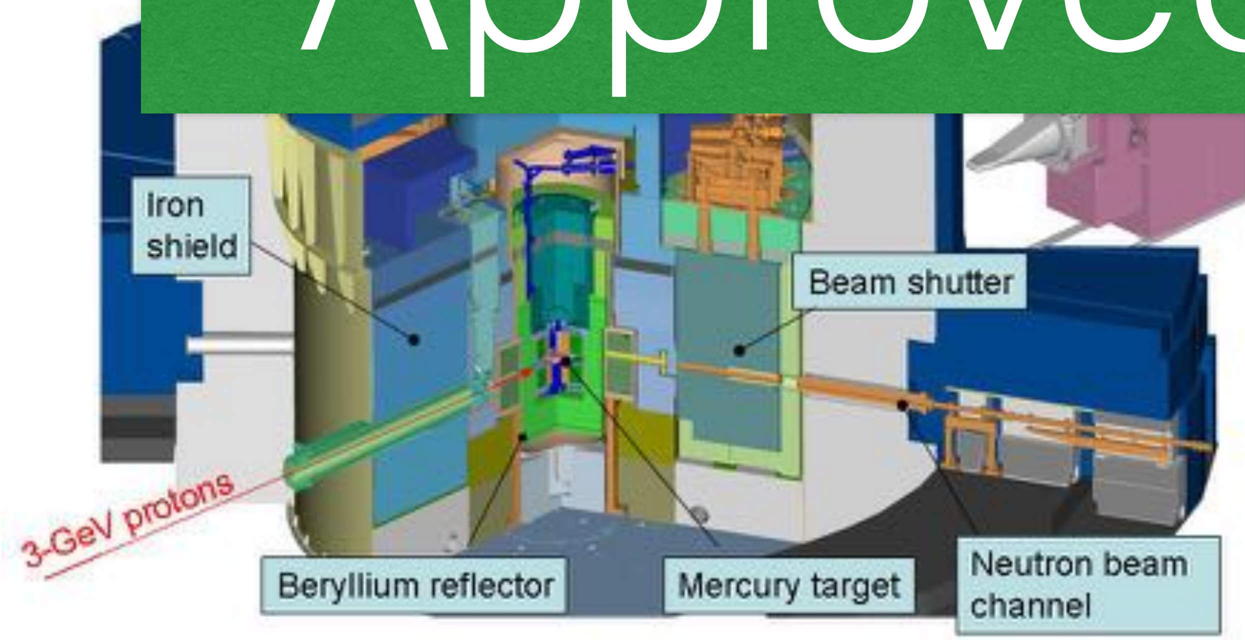
arXiv:1310.1437 [hep-ex]
(nominally an LSND-like experiment)

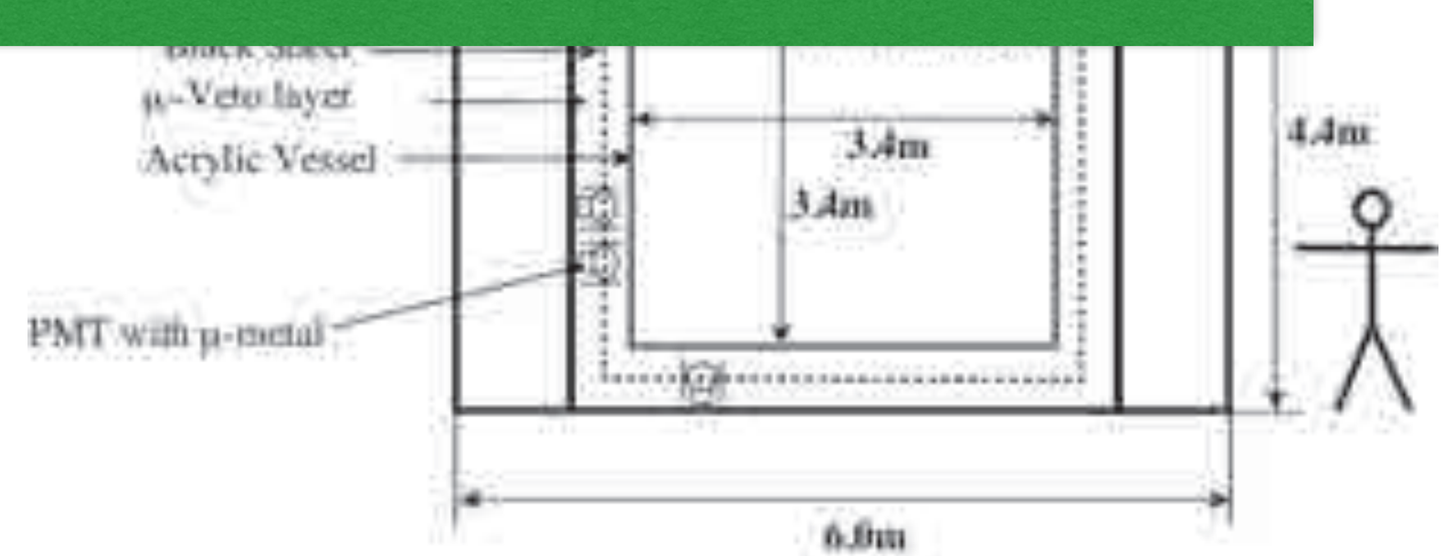
Where to?

- There are basically two places in the world where one can currently do neutrino physics with kaon decay-at-rest.

JPARC E56:
Approved Feb. 2015

7m



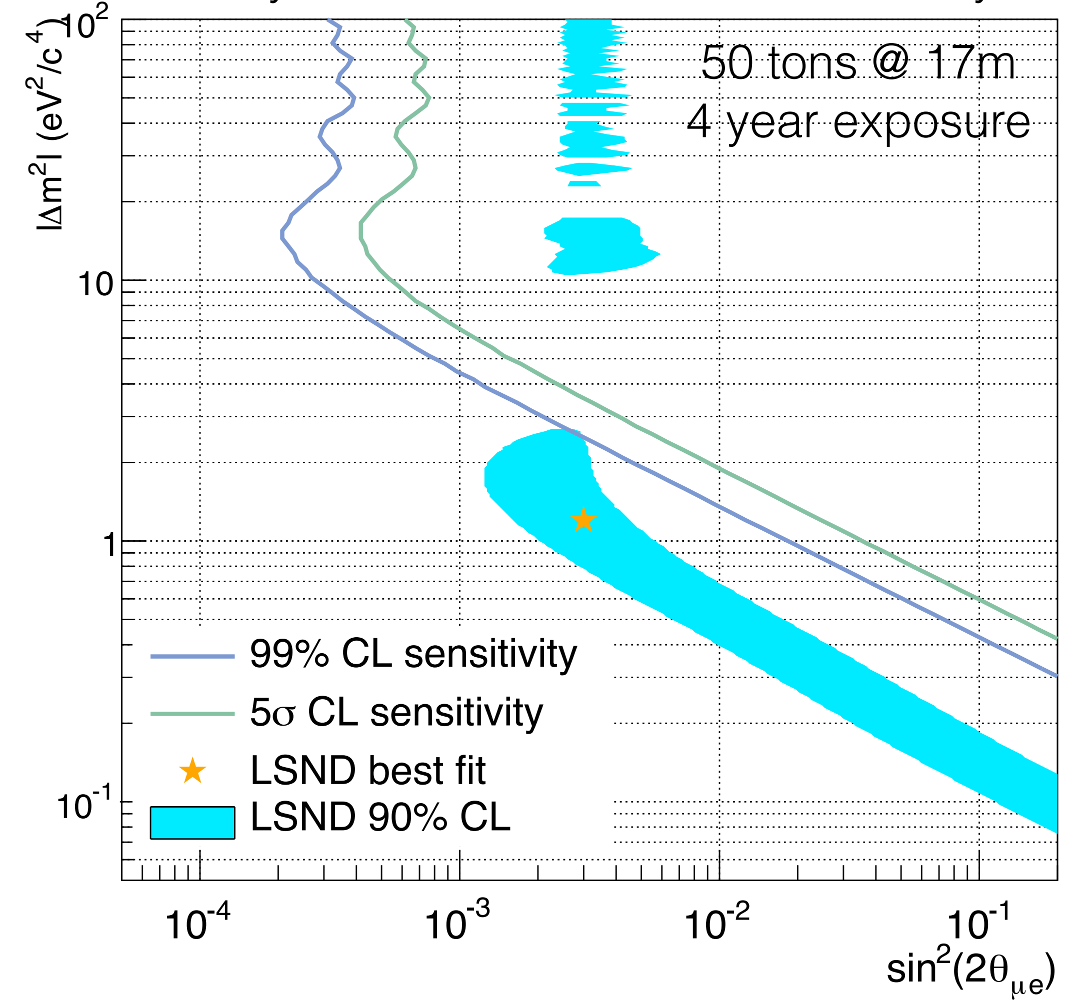


arXiv:1310.1437 [hep-ex]
(nominally an LSND-like experiment)

Prospects

- The JPARC-E56 experiment will detect nearly 200,000 monoenergetic muon neutrino charged current events in 4 years.
    - **Sterile neutrino discovery-level sensitivity above ~4 eV^2.**
    - **xsec measurements and nuclear probe.**
    - **6,000 electron neutrino events (100-225 MeV) coming from a well known flux shape.**
- MicroBooNE will collect a much more modest sample but detect enough events to provide an important input for understanding the MiniBooNE low energy excess.

Sterile neutrino sensitivity with kaon decay-at-rest at the JPARC-MLF facility



Detector (source)	Target (mass)	Exposure	Distance from source	236 MeV ν_μ events
MicroBooNE (NuMI dump)	LAr (90 ton)	1.2×10^{21} POT (2 years)	102 m	2300
Liq. scint. (JPARC-MLF)	Gd-LS (50 ton)	1.2×10^{23} POT (4 years)	17 m	194000

MicroBooNE: Coming online in 2015

Sterile ν

Detector R&D

ν cross sections

ν as a probe of the nucleus

Kaon decay-at-rest measurements within 2 years

JPARC E56: Approved Feb. 2015

Sterile ν

ν cross sections

ν as a probe of the nucleus

Kaon decay-at-rest measurements within 3-4 years

From Snowmass 2013 Executive Summary on Neutrinos arXiv:1310.4340 [hep-ex]

While these large, ambitious projects are vigorously developed, the following medium and small-scale neutrino activities need to be pursued.

- *Precision measurements and theories of neutrino cross sections and a detailed understanding of the neutrino flux from pion-decay-in-flight neutrino beams.* These activities can be pursued in the near- detectors associated with the large long-baseline projects or alongside R&D projects related to next-next generation neutrino beams, as well as by small-scale dedicated experiments. A well-considered program of precision scattering experiments in both low- and high-energy regimes, combined with a renewed dedicated theoretical effort to develop a reliable, nuclear-physics-based description of neutrino interactions in nuclei is mandatory. Scattering measurements may also be of intrinsic interest.
- *Definite resolution of the current short-baseline anomalies.* These will (probably) require neutrino sources other than pion-decay-in-flight and the pursuit of different flavor-changing channels, including $\nu_{e,\mu}$ disappearance and $\nu_\mu \to \nu_e$ appearance, using a combination of reactor, radioactive source and accelerator experiments. In addition to small-scale dedicated experiments, such experiments can be carried out as part of R&D projects related to next-next generation neutrino beams (e.g., nuSTORM, IsoDAR).
- *Vigorous pursuit of R&D projects related to the development of next-next generation neutrino experiments.* As discussed above, these medium and small experiments will also address several key issues in neutrino physics.

ν as a probe of the nucleus

ν cross sections

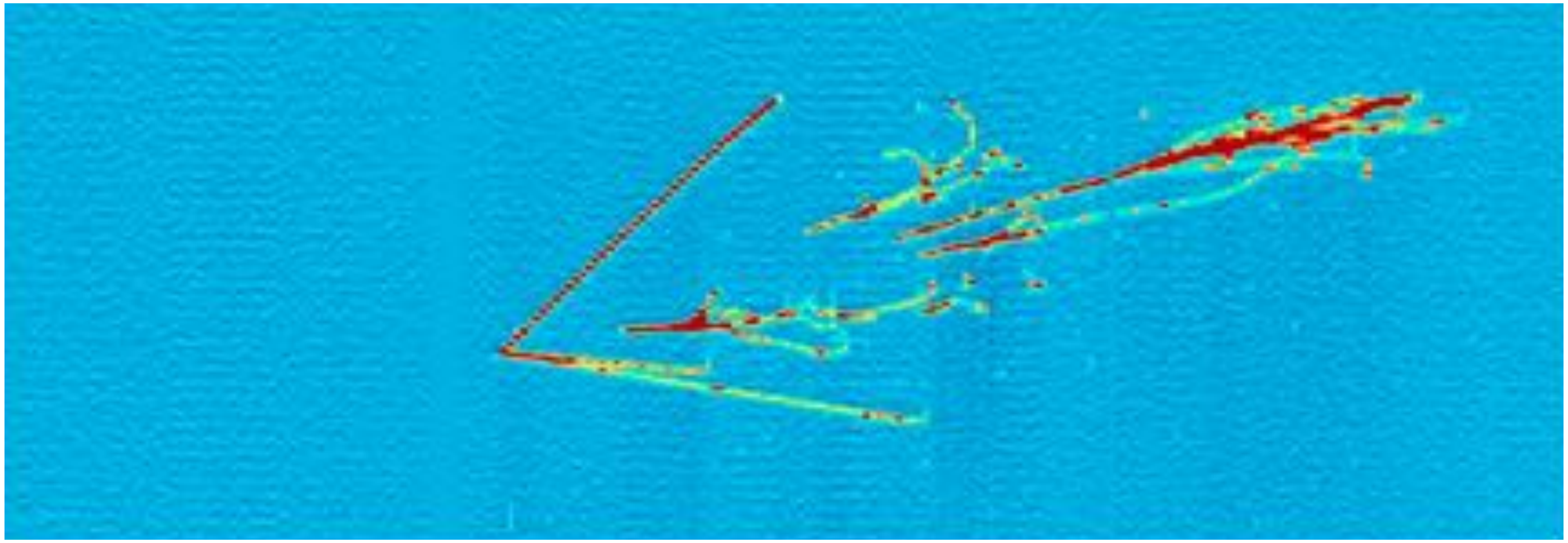
Sterile ν

Detector R&D

- I hope I have convinced you that kaon decay-at-rest is an amazing and completely unique source of neutrinos that has been completely neglected until now.
- With our new state-of-the-art detectors and intense sources, we are now able to take advantage of kaon-induced neutrinos for performing a number of crucial measurements.

The journey and the destination

- We are well on our way toward a measurement of CP violation in neutrinos. This measurement may help us understand why the Universe is made out of matter.
- There is a lot of physics on this path.




Oscillation Land
δ_{CP}
$\theta_{13}, \theta_{23}, \theta_{12}$
Mass hierarchy
ν_τ
MSW
Sterile ν
Lorentz violation
Δm^2's
Non-standard ν interactions
ν cross sections
ν as a probe of the nucleus
Detector R&D