Measuring the Sterile Wave:

a Short-Baseline ν_μ Disappearance Experiment using Neutrinos from Kaon Decay-at-rest

T. Wongjirad, S. Axani, G. Collin, J. Conrad, M. Shaevitz, J. Spitz

IPA 2015, Madison Wisconsin
May 5th, 2015

The Puzzle

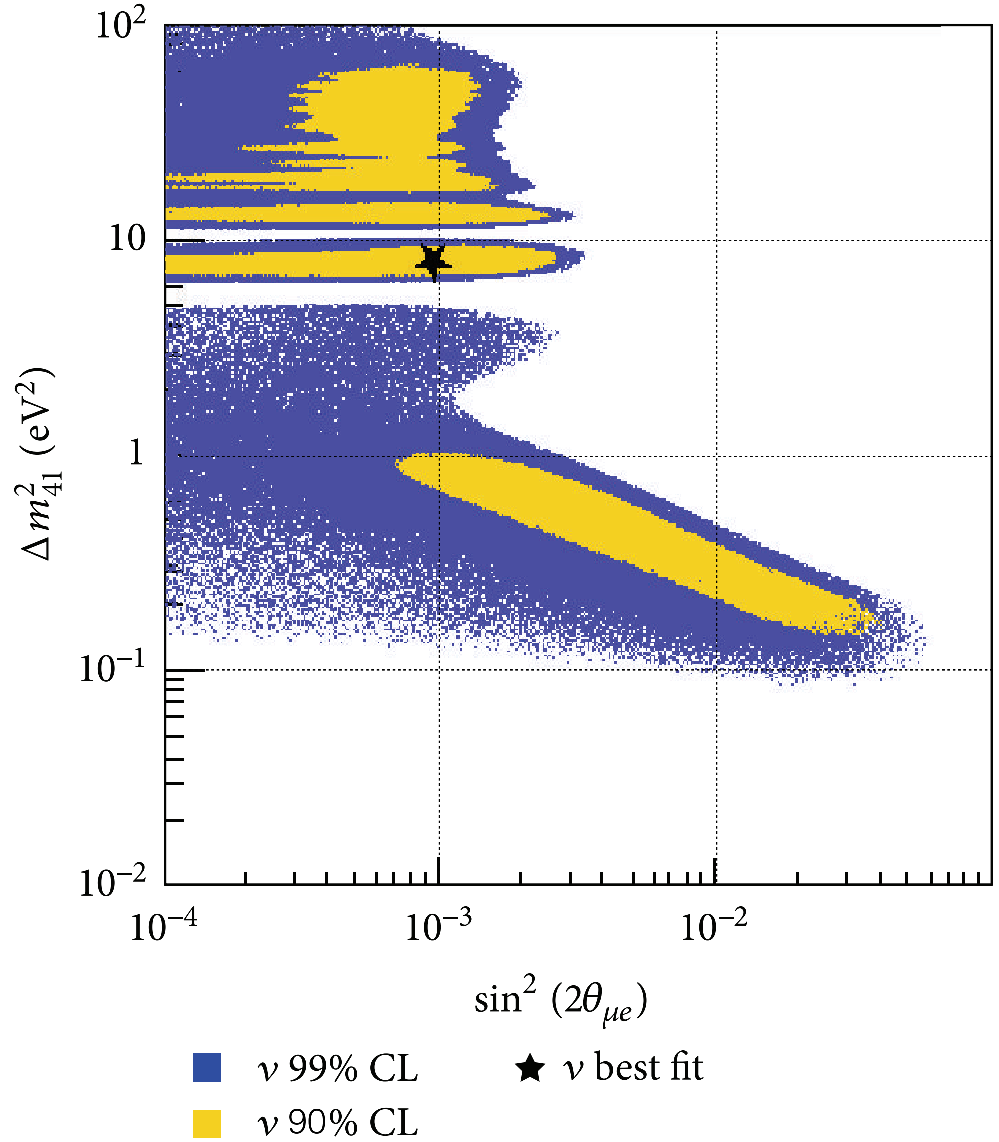
- A number of experiments see an unexpected deficit or excess of neutrino events
- Interpretable as coming from sterile neutrino oscillation with Δm^2 around 0.1-10 eV^2

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)	$1.4\text{-}3.0\sigma$ (varies)
GALLEX/SAGE	Source (electron capture)	electron disappearance (neutrino)	2.8σ

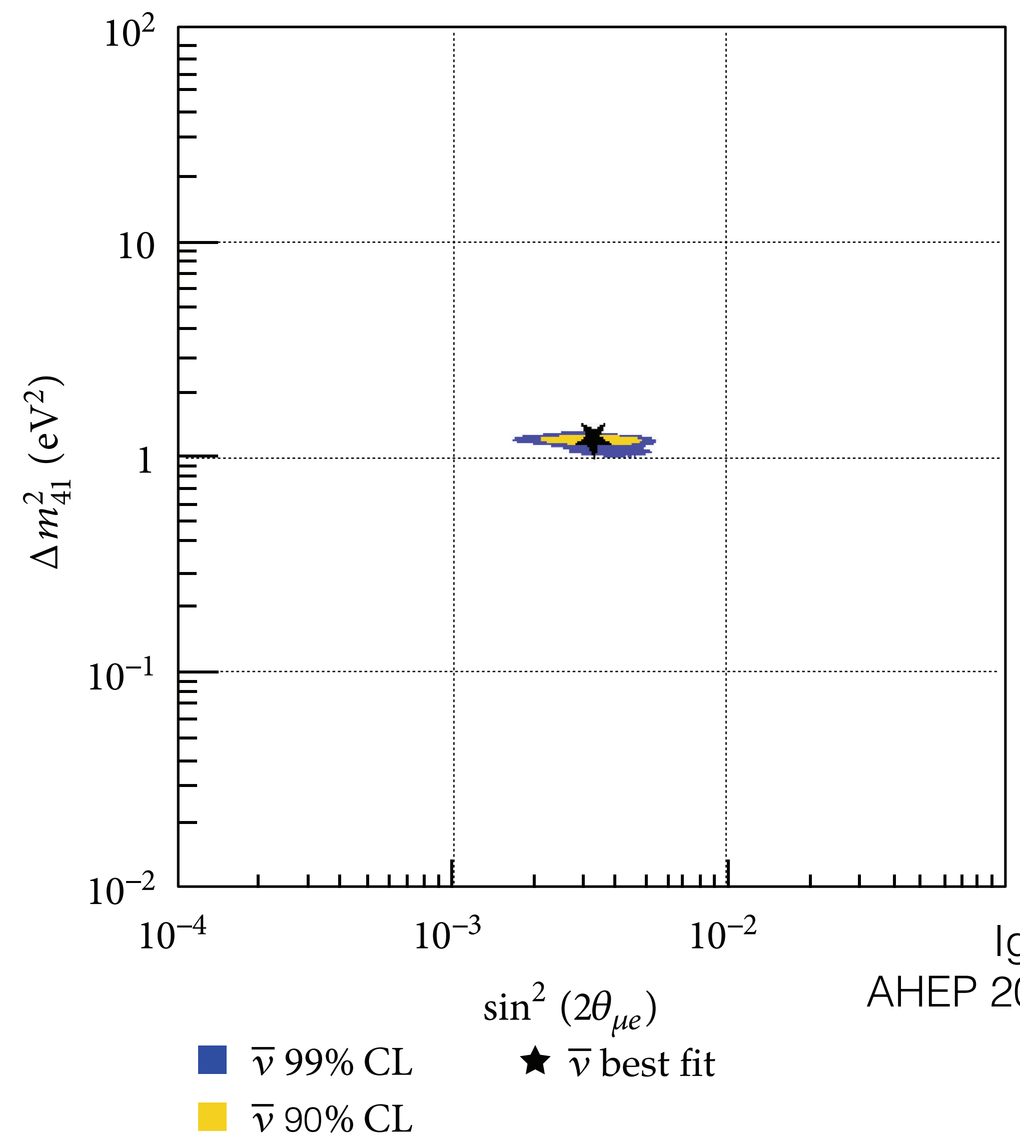
Sterile Neutrino

- Put all the data out there together and interpret with model with 1 additional sterile neutrino (3+1)

Global neutrino 3+1 allowed



Global antineutrino 3+1 allowed



Ignarra, *et al.*
AHEP 2013 163897 (2013)

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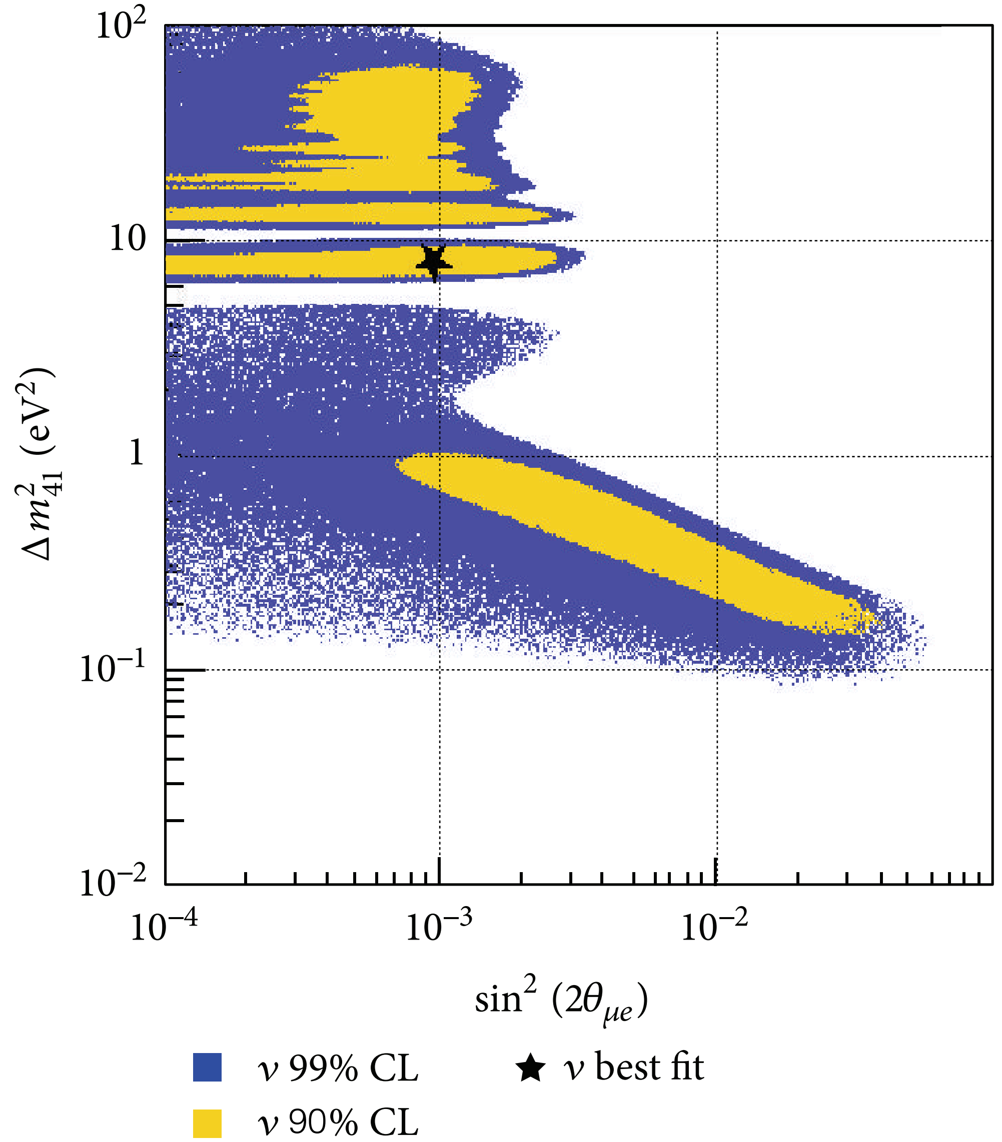

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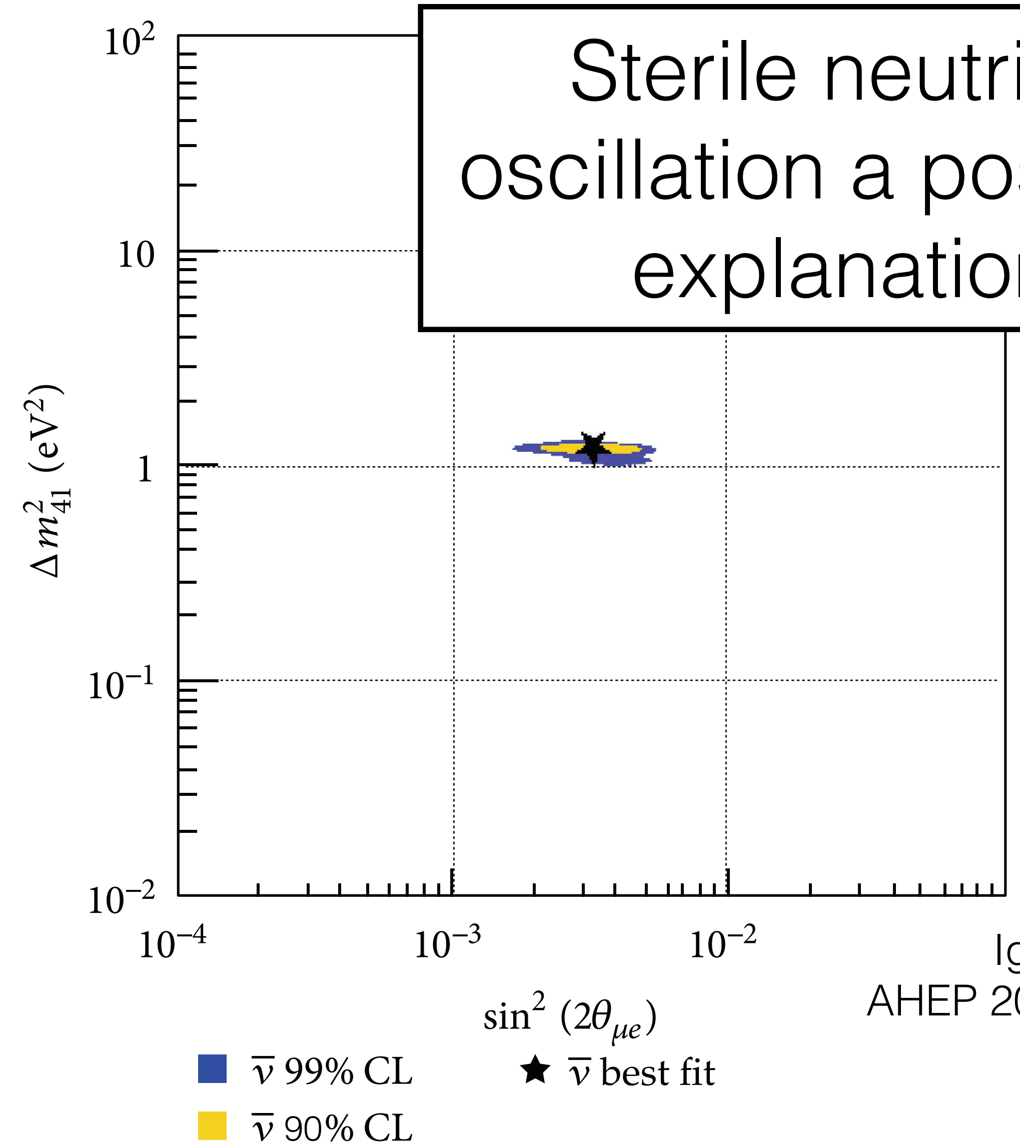

Sterile neutrino oscillation a possible explanation

Ignarra, *et al.*
AHEP 2013 163897 (2013)

Future Experiments

- Anomalies motivating experiments to verifying each type of anomaly directly

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High intensity ν sources, e.g. SOX, CeLAND, etc.		electron disappearance (neutrino)	2.8σ

Future Experiments

Joseph Zennamo, tomorrow 10:30
Liquid Argon

Anne Schukraft, tomorrow 11:00
MicroBooNE: a not-so-micro LArTPC

- Anomalies motivating experiments to verifying each type of anomaly directly

	Oscillation channel	Significance
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… ν sources, …LAND, etc.	electron disappearance (neutrino)	2.8σ

Karin Gilje, today 14:30
PROSPECT: a short-baseline reactor antineutrino measurement
(in non-accelerator parallel)

Future Experiments

- Experiments probing (anti-)ν_e oscillations
- Is there a complimentary approach?

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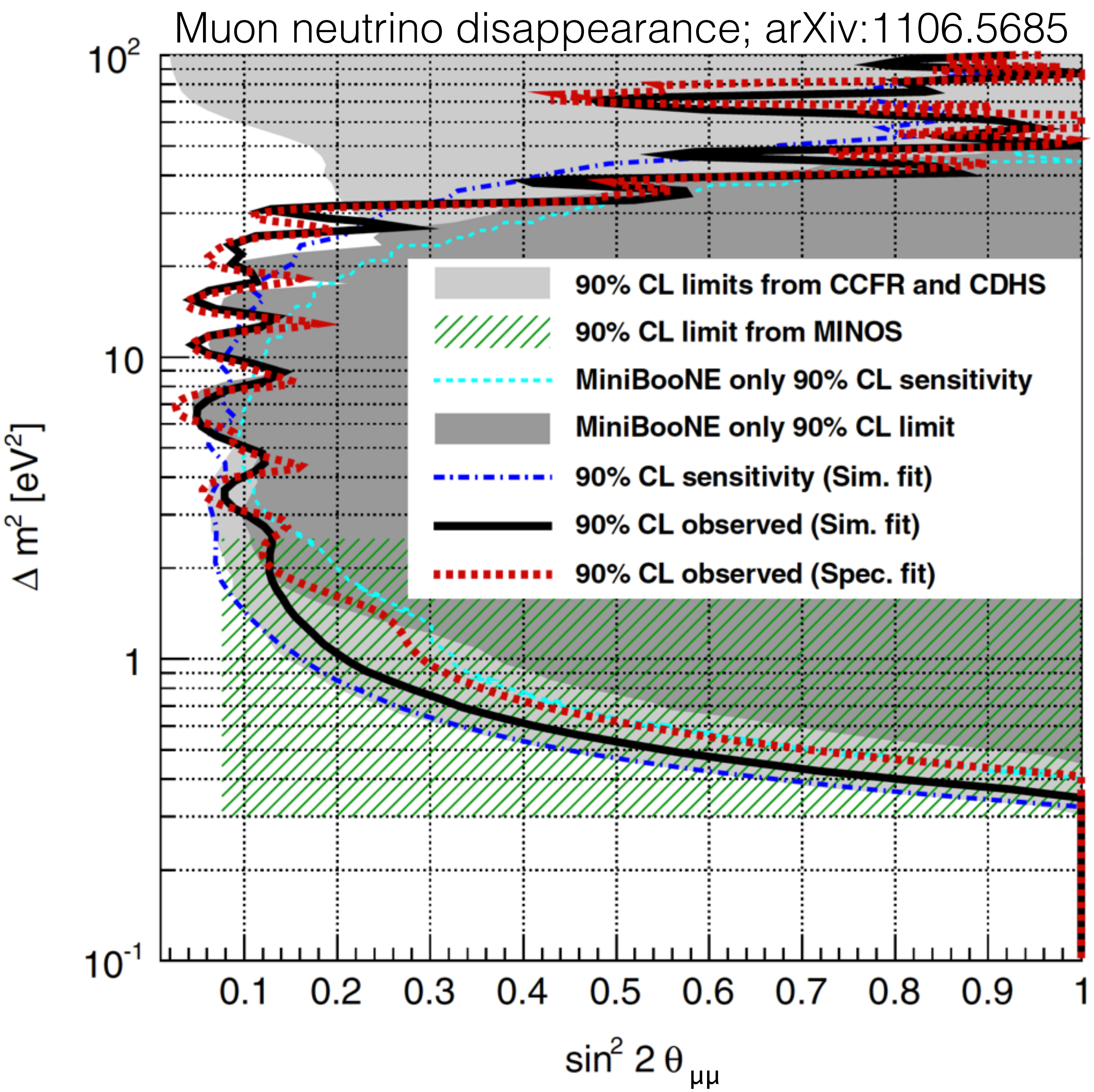
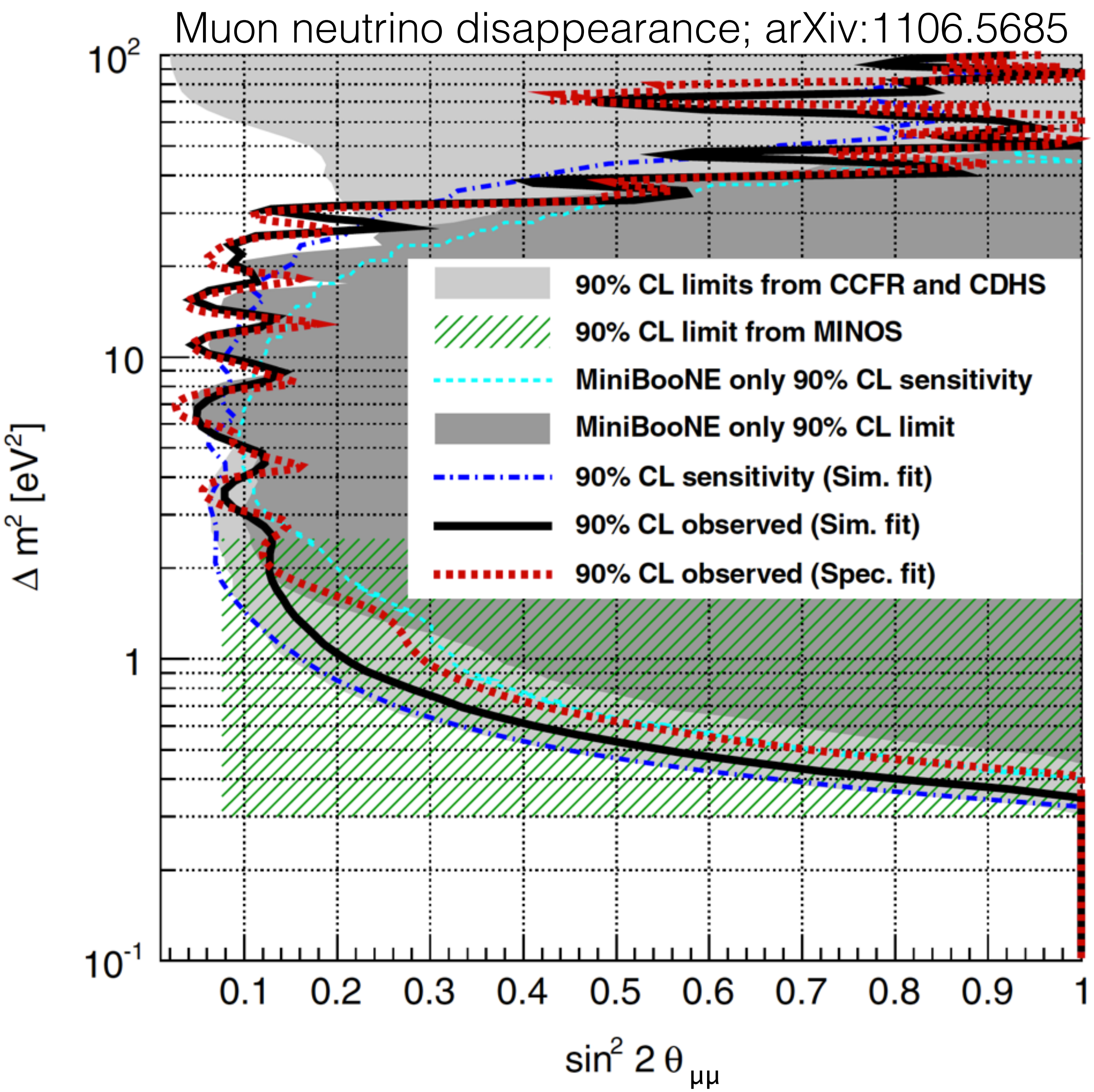
Muon Neutrino Disappearance



- Not all experiments see anomalies
- In fact, no experiment has seen muon neutrino disappearance
- An important constraint

Muon Neutrino Disappearance



- If sterile neutrinos exist, there must be some amount of muon neutrino disappearance!

A proposal, with constraints

- A call for proposals from the DOE at the WINP workshop (Feb 2015)
- Must satisfy the following:

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  - be a fraction of 10 million dollars

A proposal, with constraints

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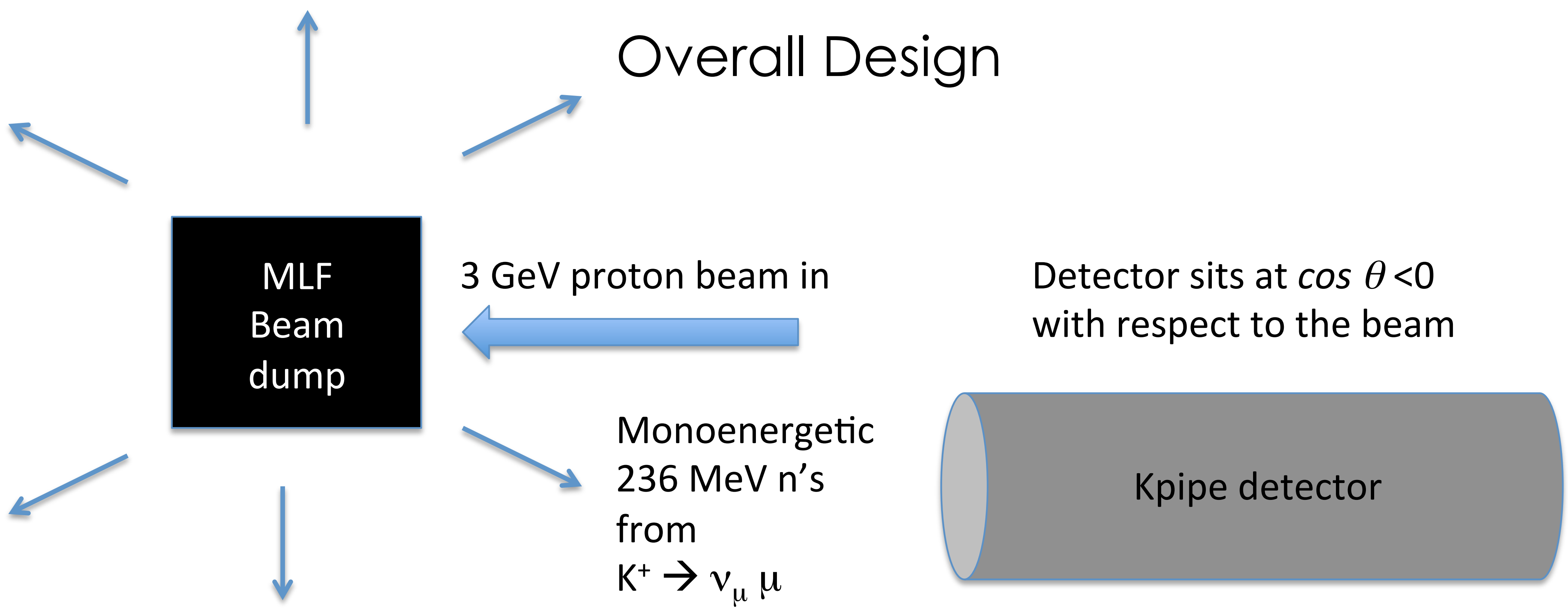
- Must satisfy the following:
  - Not associated with Fermilab program (e.g. SBN)
  - Decisive within 3 years of running
  - be a fraction of 10 million dollars
- Present such a proposal

KPipe

Overall Design



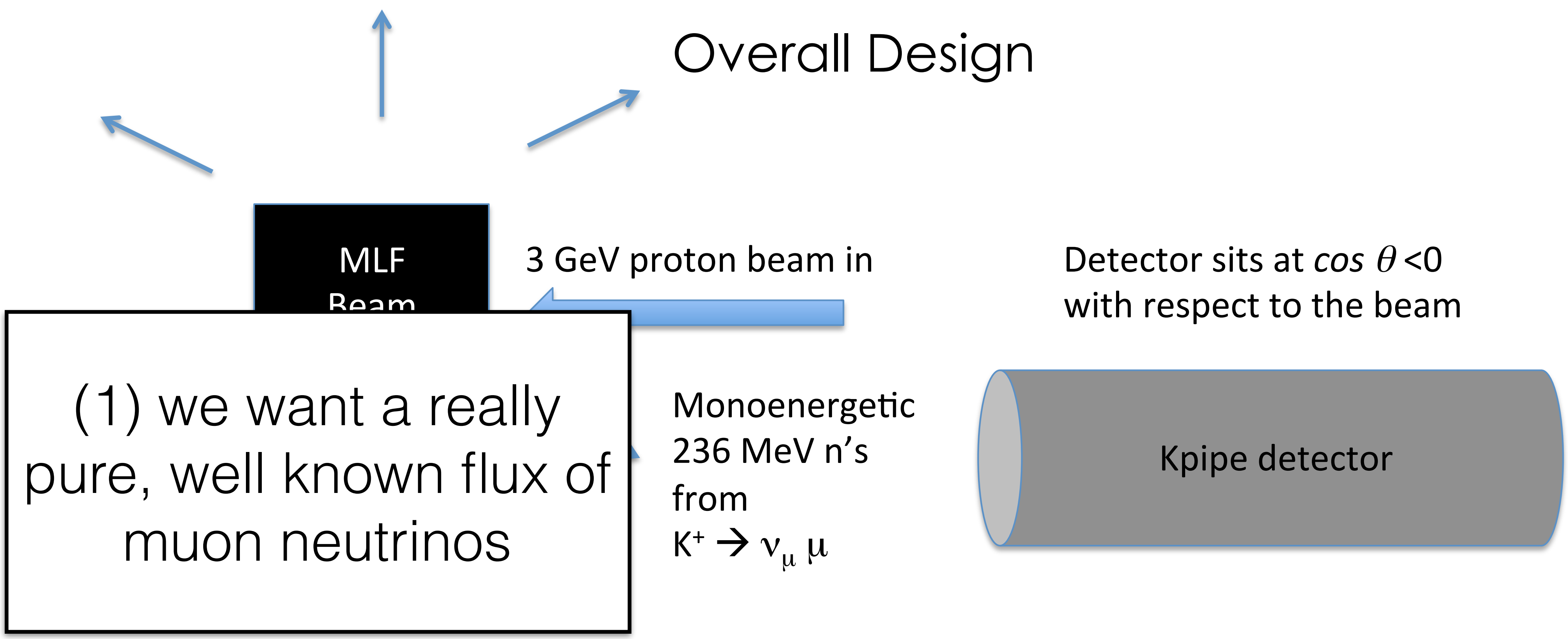
<u>BEAM</u>

- Neutrinos from a high-intensity beam of stopped kaons
- Muon neutrinos mono-energetic

<u>DETECTOR</u>

- A pipe, 3 m in diameter and 90 m in length, filled with liquid scintillator
- Measure oscillation wave

KPipe



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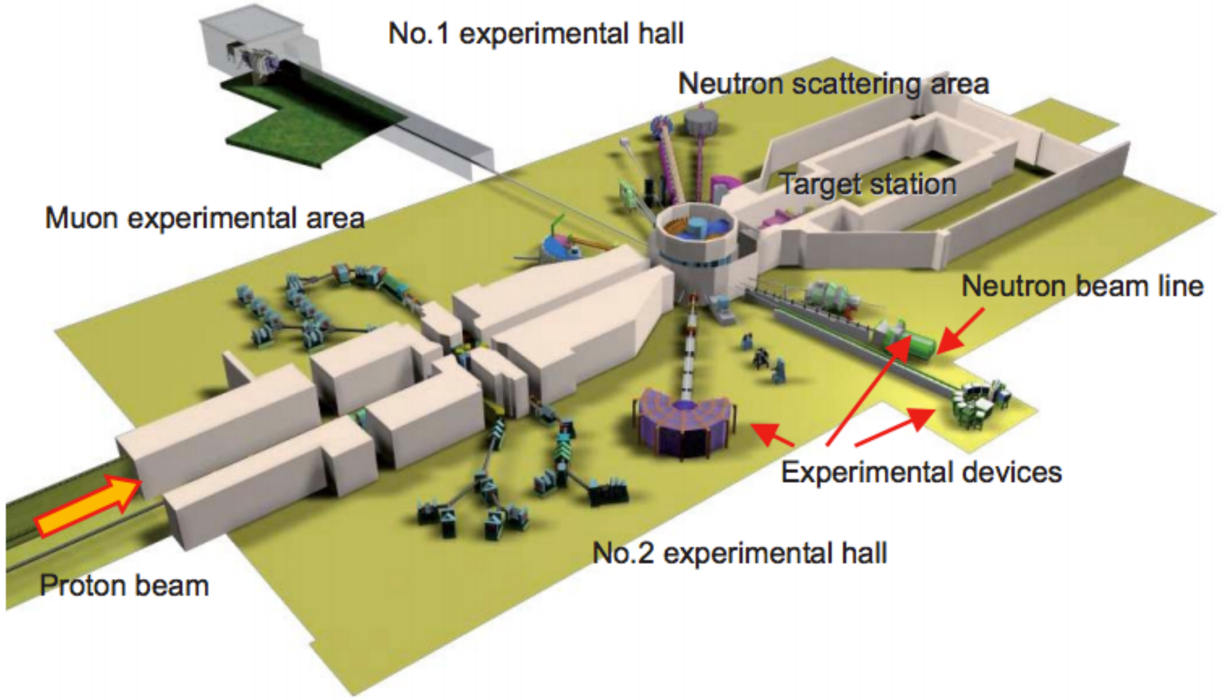
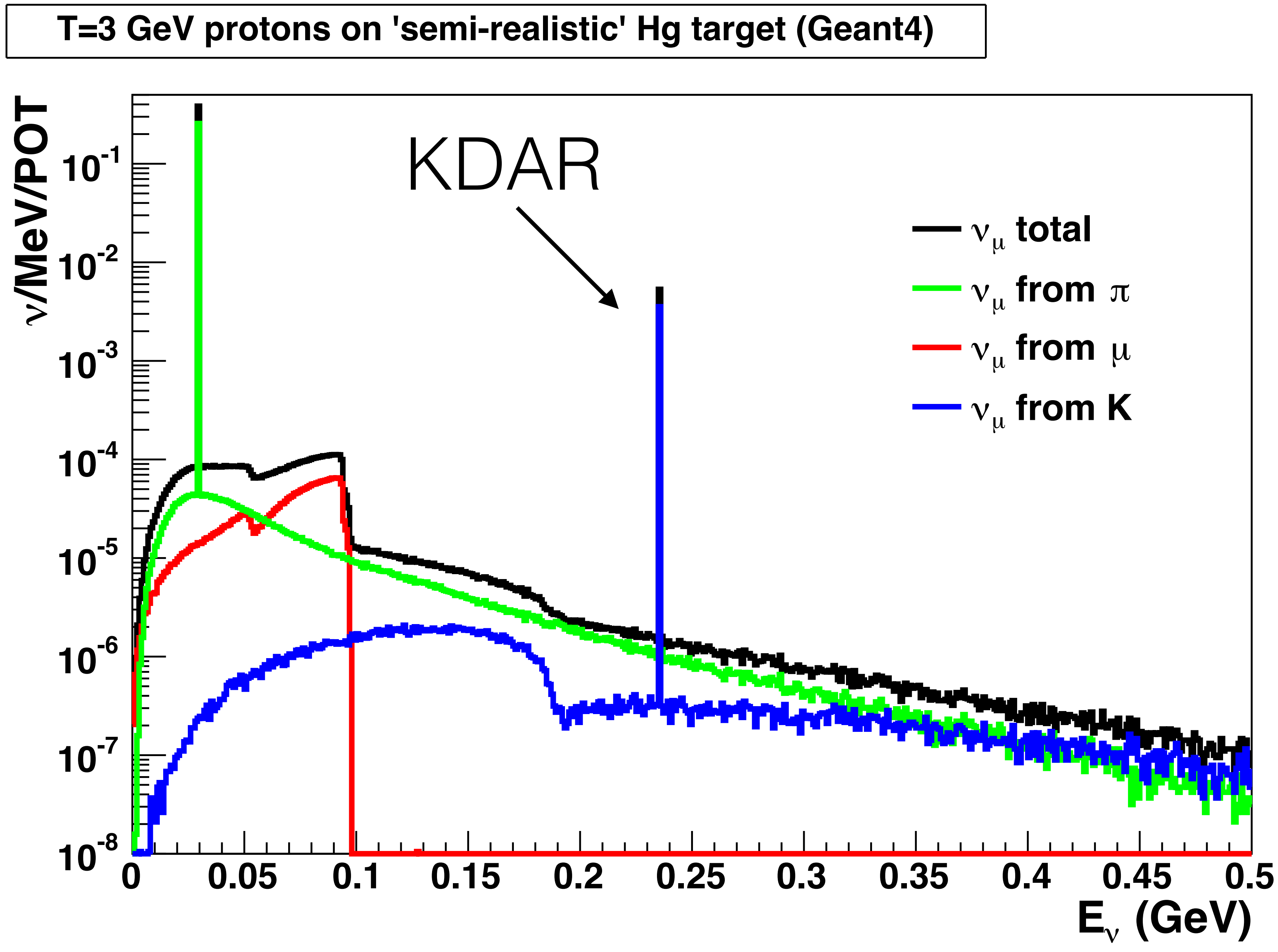
JPARC MLF



- Beam at Materials and Life Science Facility at JPARC
- 3 GeV protons on Hg
- target power: 1 MW
- pulsed with tight beam windows:
  2 pulses with 80 ns width, 540 ns apart at 25 Hz

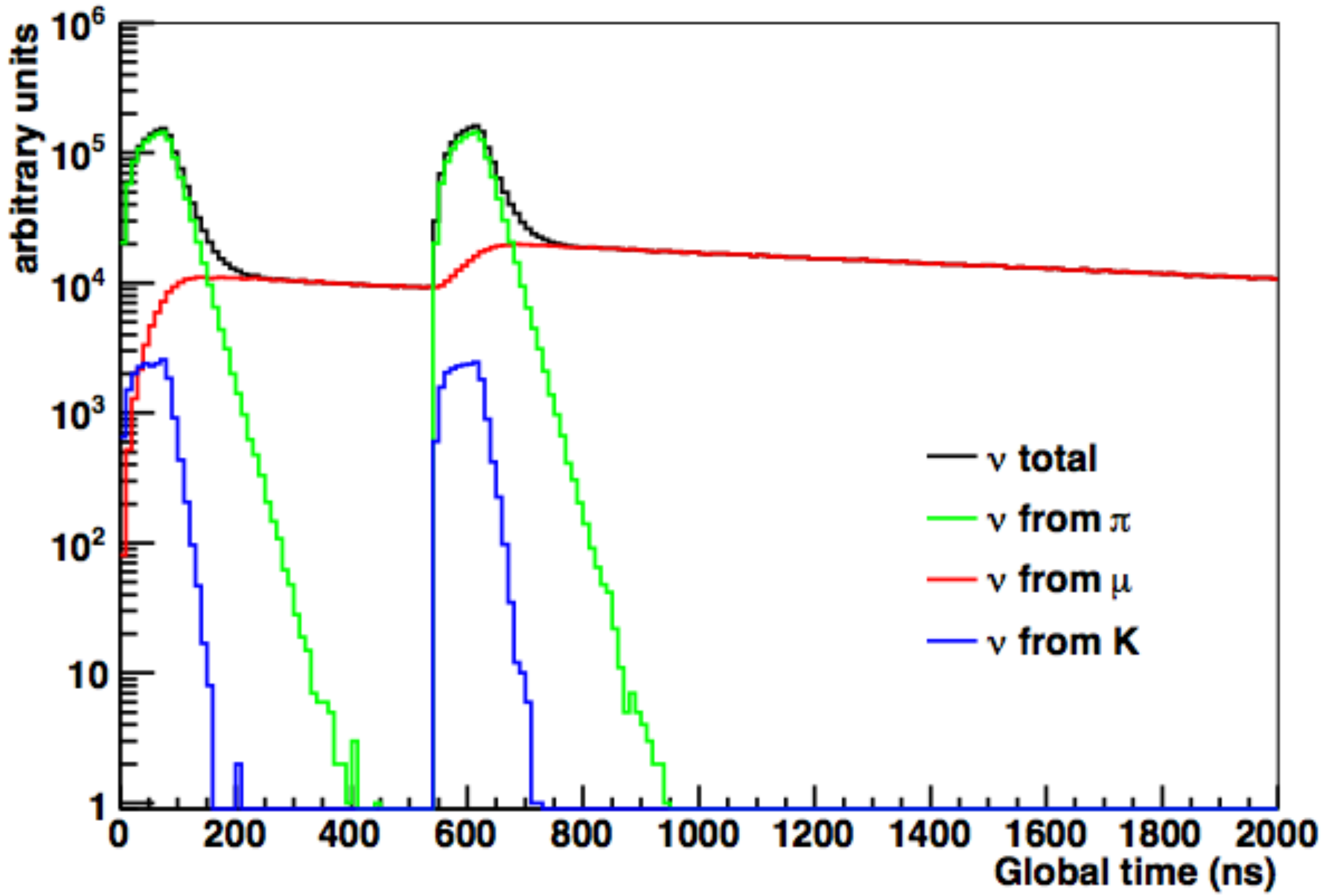
JPARC MLF

- Our flux simulation: 3 GeV hitting Hg target

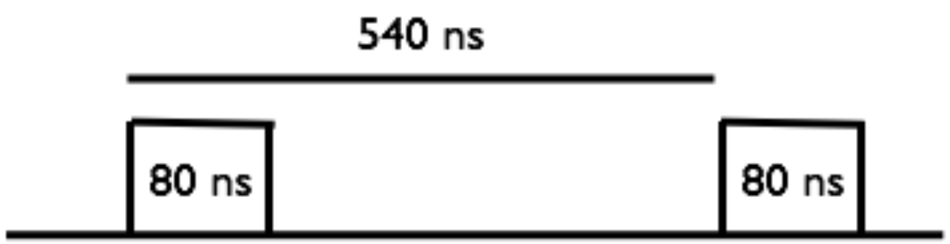


KDAR neutrinos: Energy known exactly

Beam Timing



- Timing of neutrinos should be well-known
- Look for interactions coming from neutrinos in the two windows

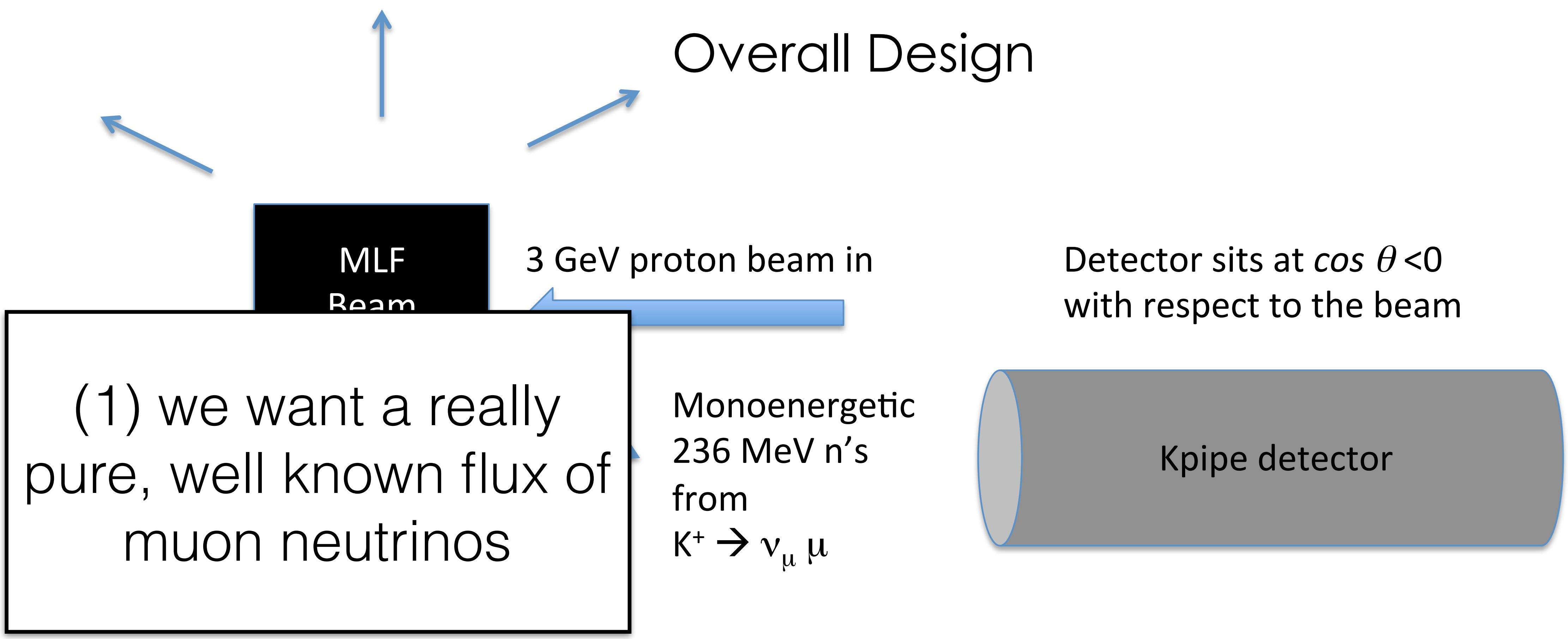


Beam structure

25 Hz

KPipe

Overall Design



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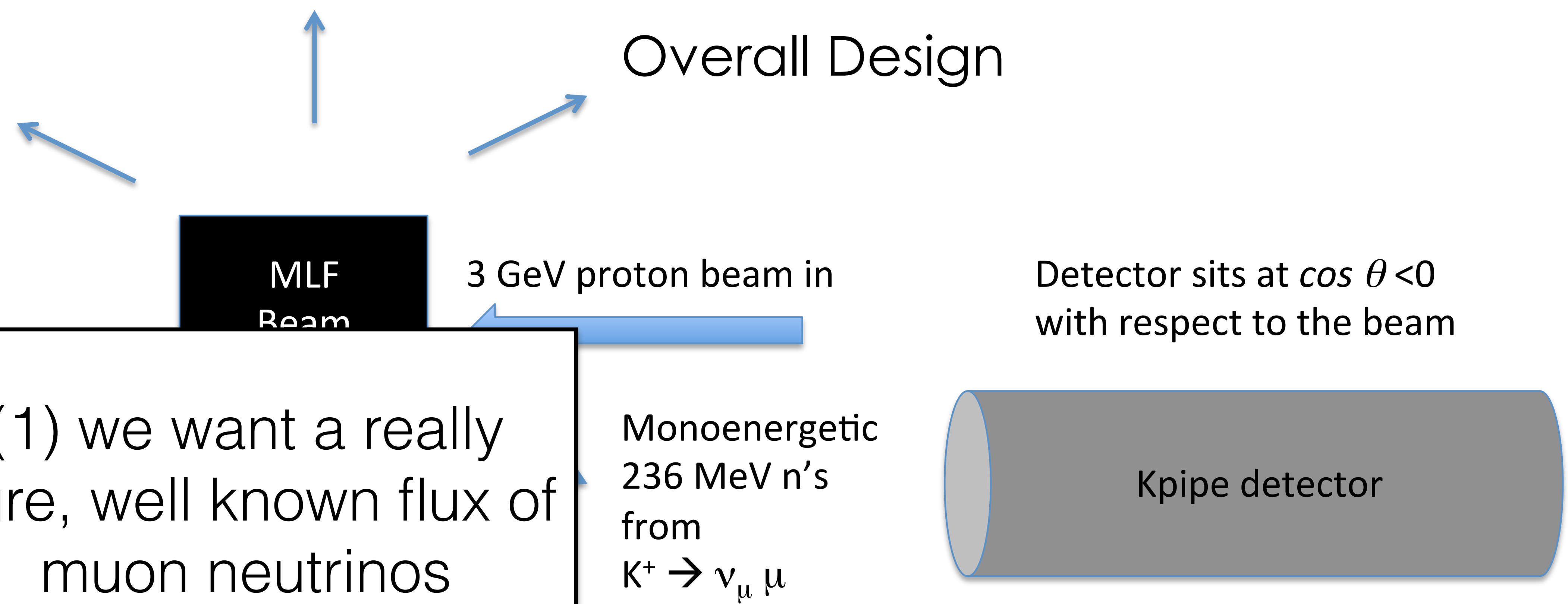


(1) we want a really pure, well known flux of muon neutrinos

BEAM

- Neutrinos from a high-intensity beam of stopped kaons
- Muon neutrinos mono-energetic

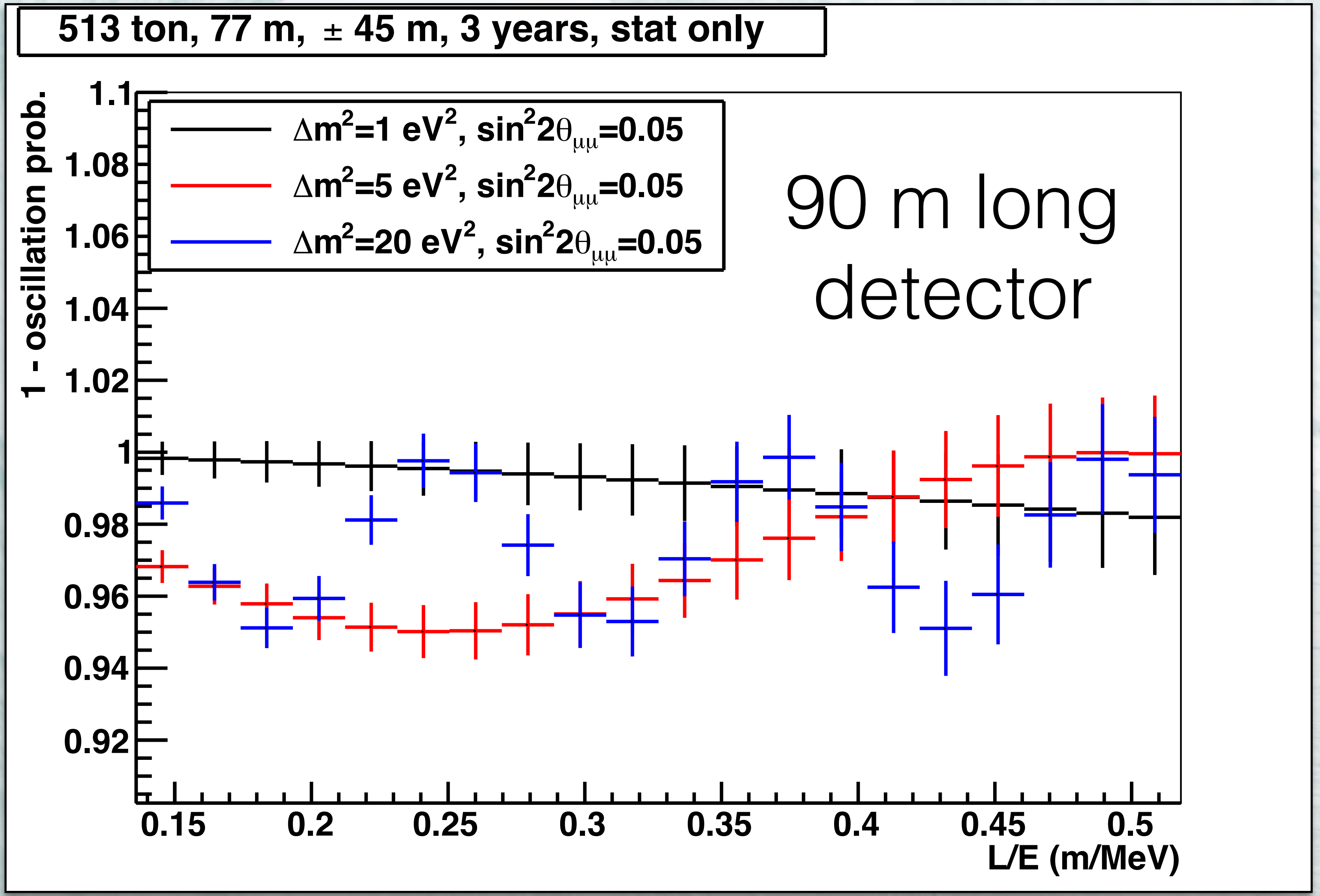
DETE

- A ... nd 90 ... lic

(2) long pipe to measure the oscillation wave

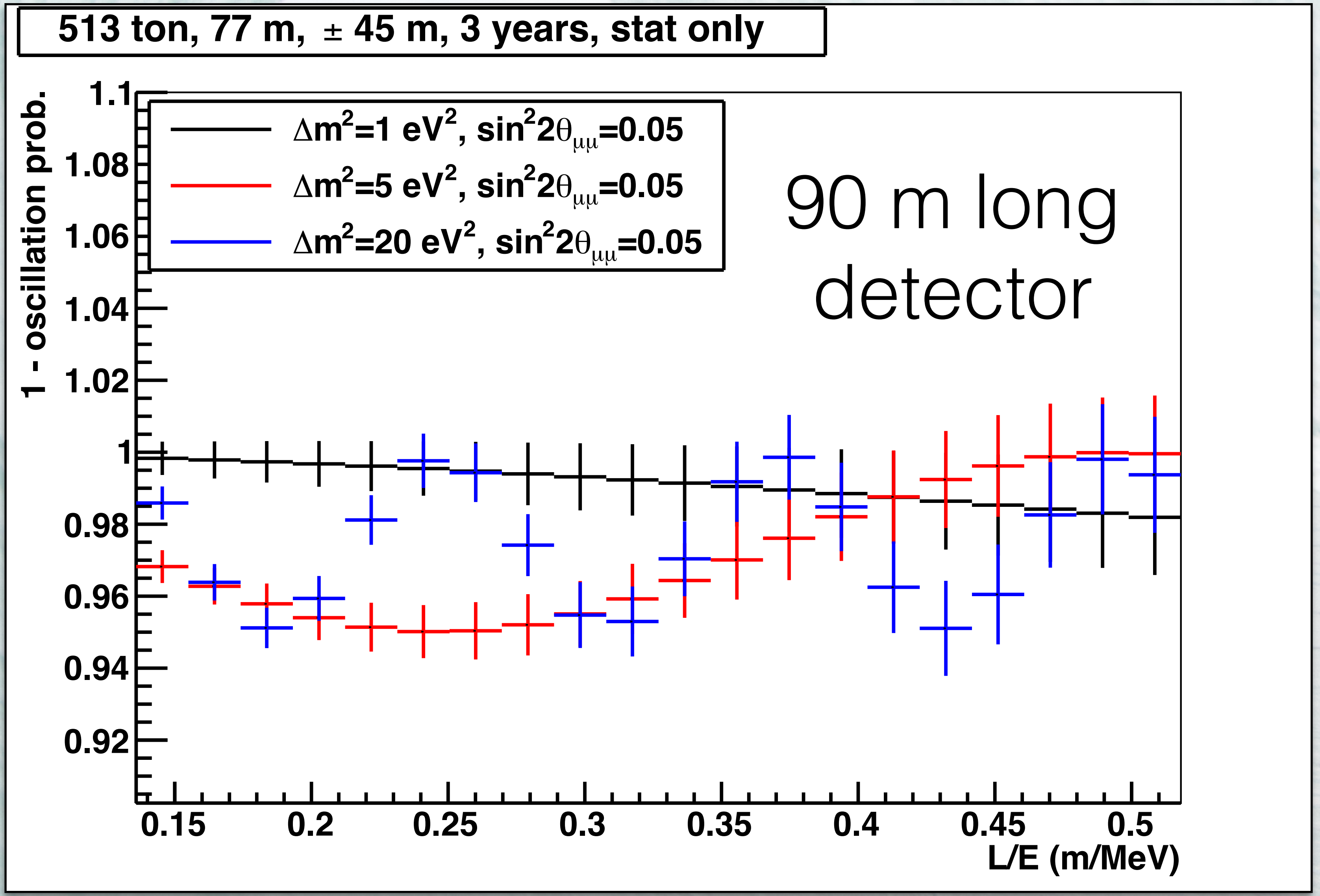
- Measure oscillation wave

What we want to measure



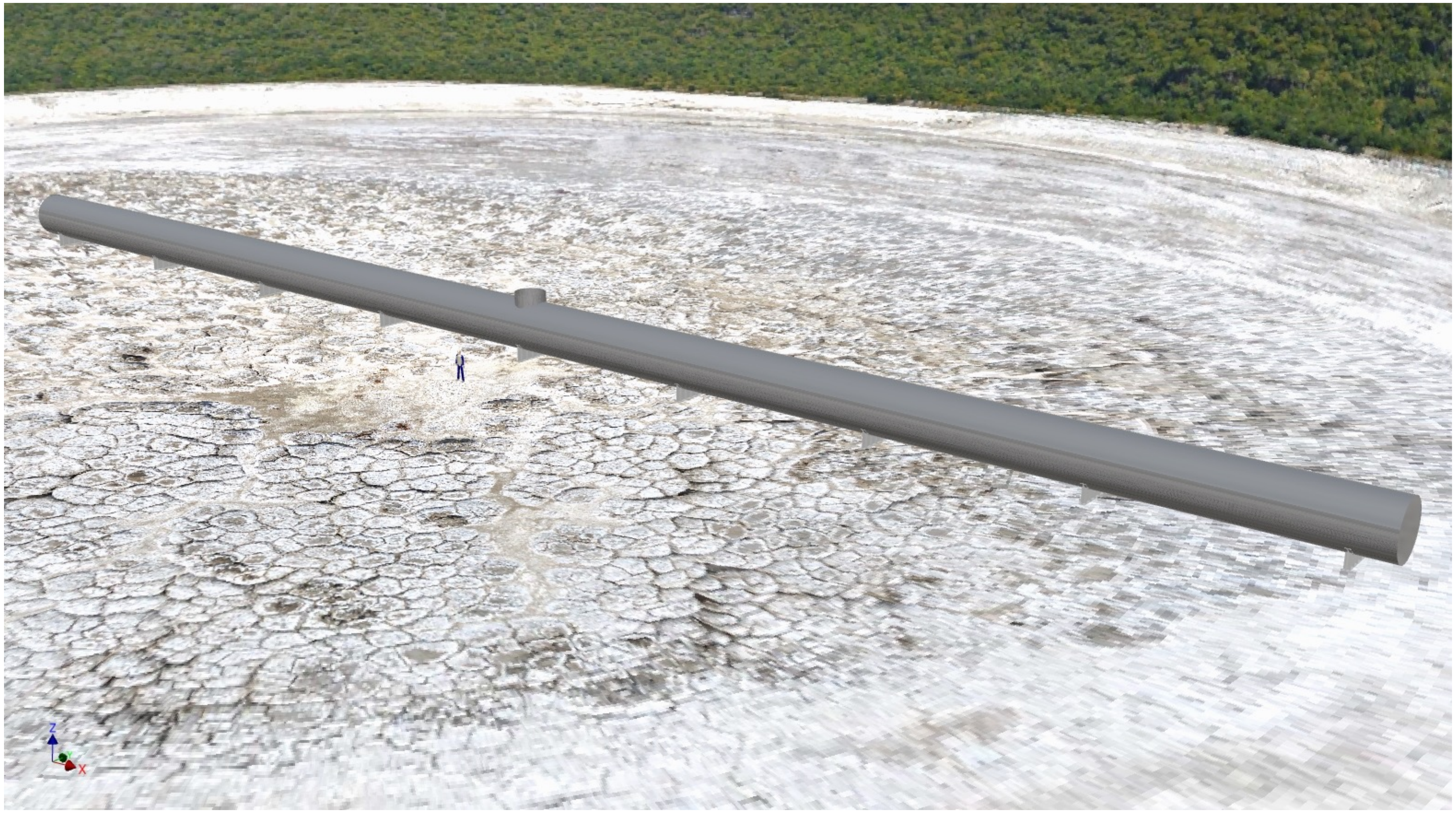
What we want to measure

Seeing the osc. wave would be definitive evidence for sterile ν's



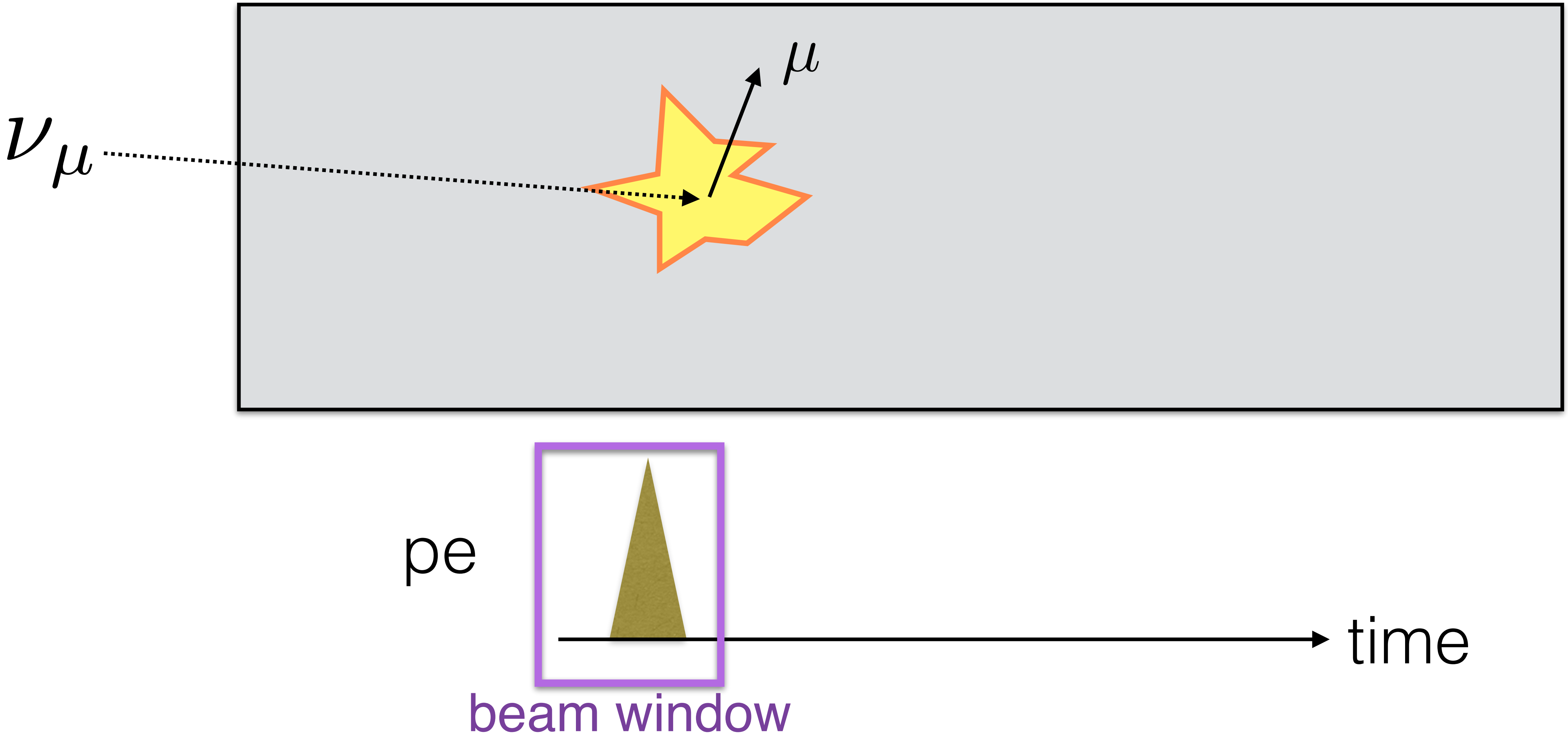
Detector

- A (BIG) pipe, 3 m diameter and 90 m long, filled with liquid scintillator



Detector Signal

- What we are after:



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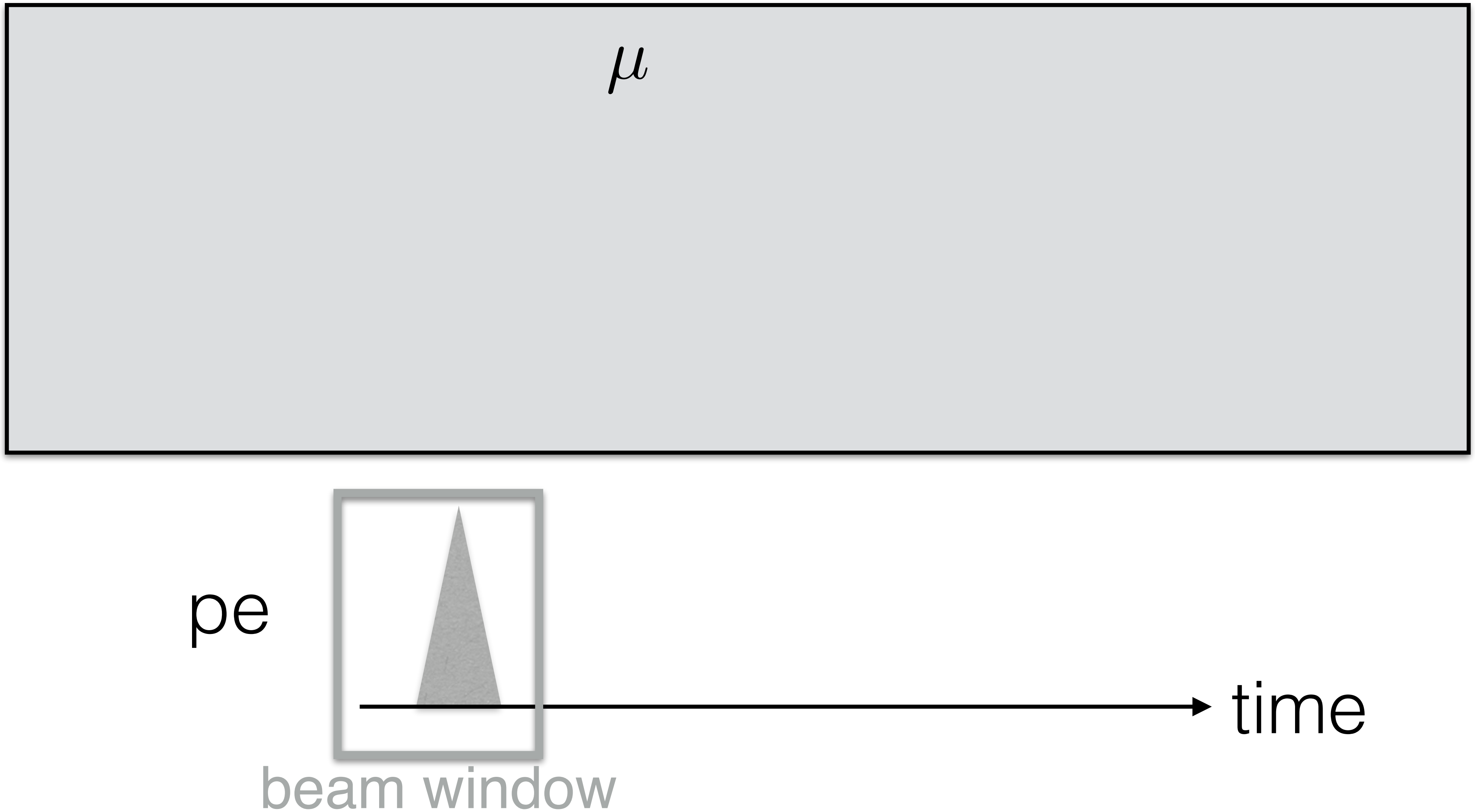

Detector Signal

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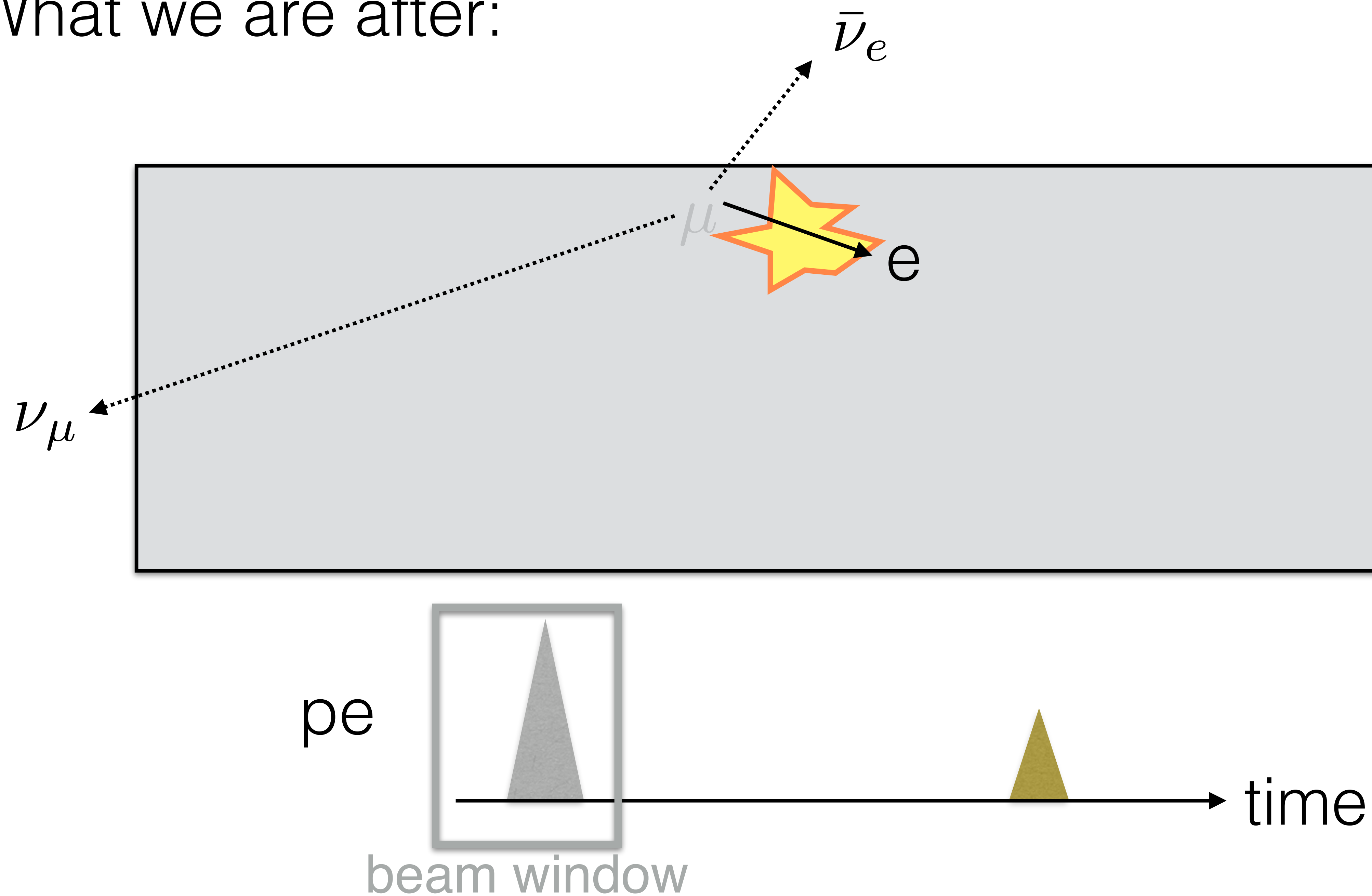
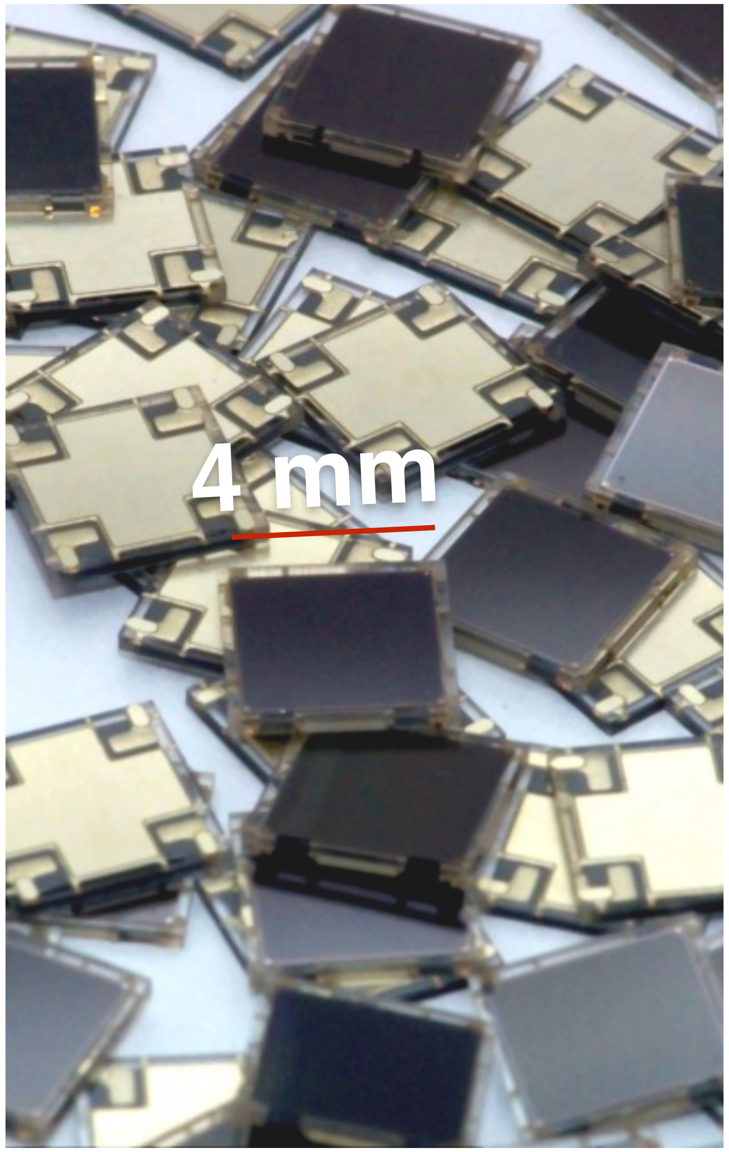


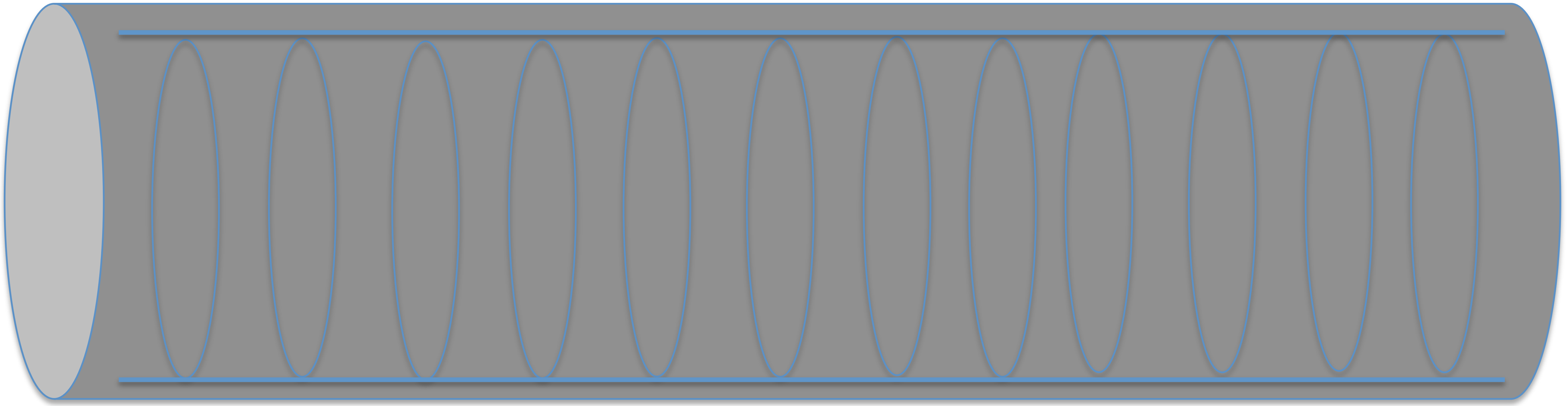
Photon Detector: SiPMs



- Silicon photomultipliers
  - compact
  - low voltage ~ 27 V bias needed
  - inexpensive: for very large bulk order, ~$20/SiPM

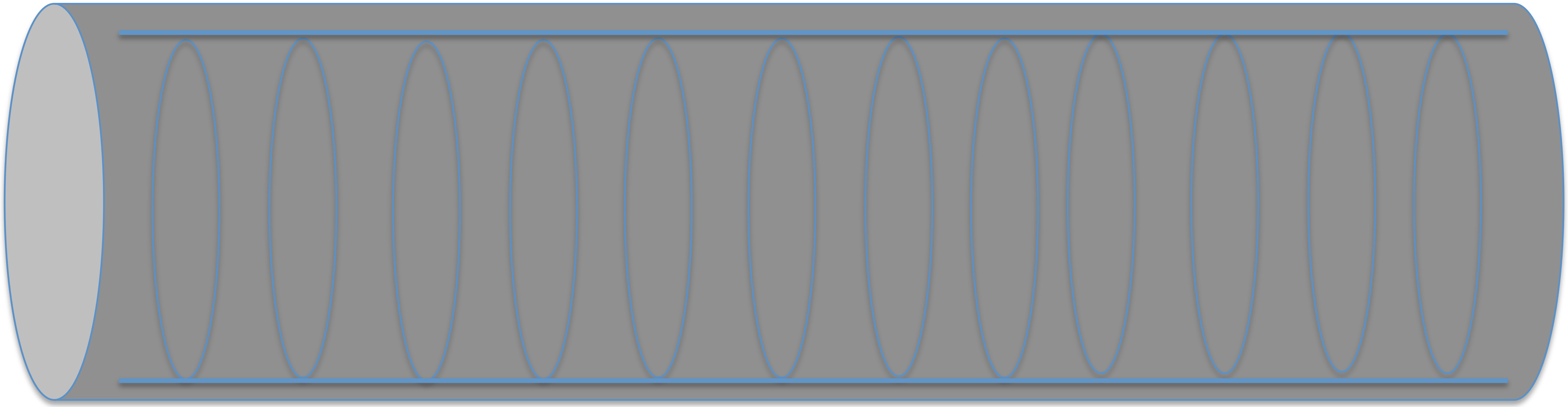
Instrumentation

Hoops of 100 SiPMs read out in quarters (25 SiPMs/quarter ganged together.
Quarter-hoops are mounted on panels that separate define inner target region
From veto region.
Veto region is read out as a block



Instrumentation

- Coverage only 0.4%
- Relying on high light yield of liquid scintillators to overcome sparse instrumentation
- How many SiPMs one of the key handles for lowering costs

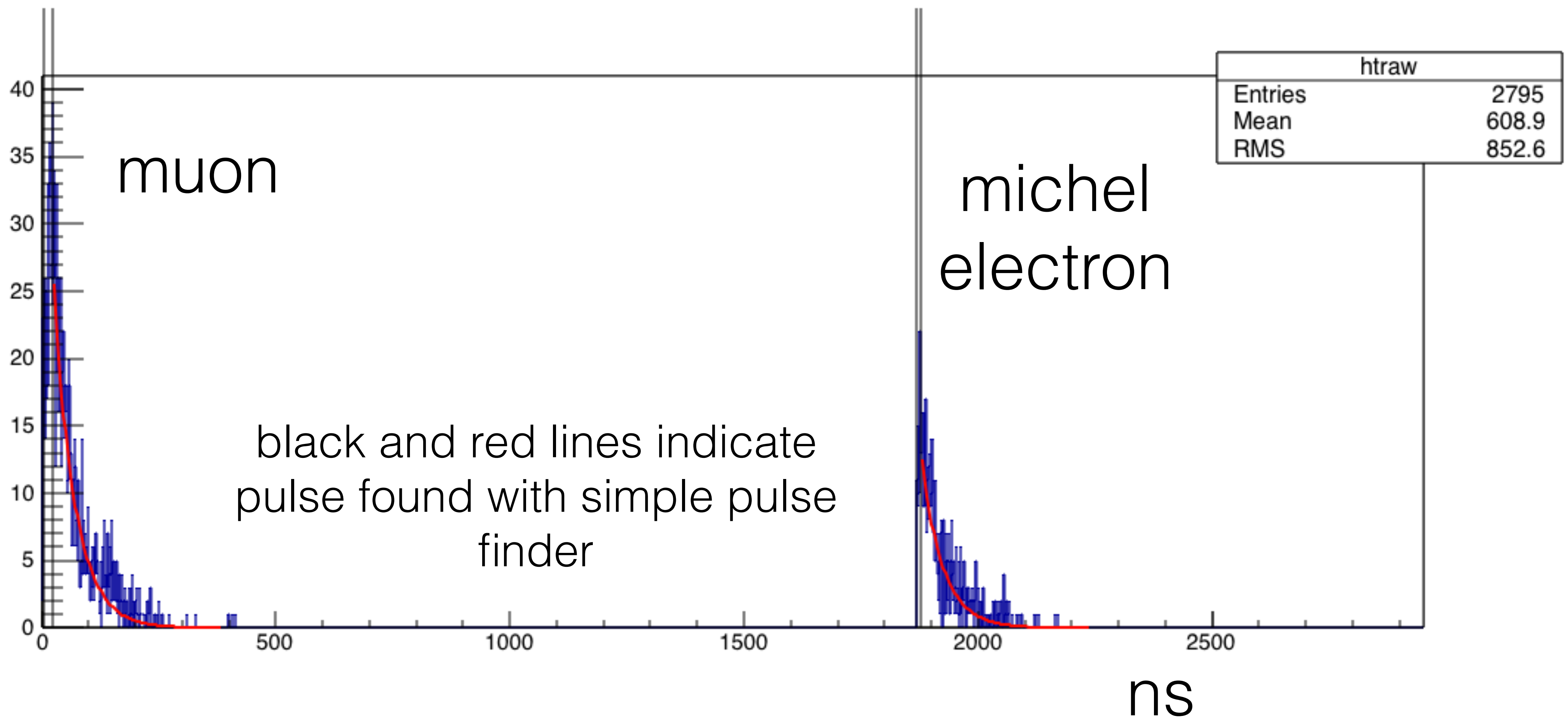


Signal Selection

- Signal events have neutrino-induced muon interactions. Remove backgrounds, which we expect will be mostly cosmic rays
  - 2 flashes: muon, then Michel electron
  - no veto hits
  - in time
  - 2 flashes close in Z
  - upper energy cut on both muon and Michel electron pulse, to remove high energy cosmic ray events
  - low energy threshold for noise
- Studied with detector MC

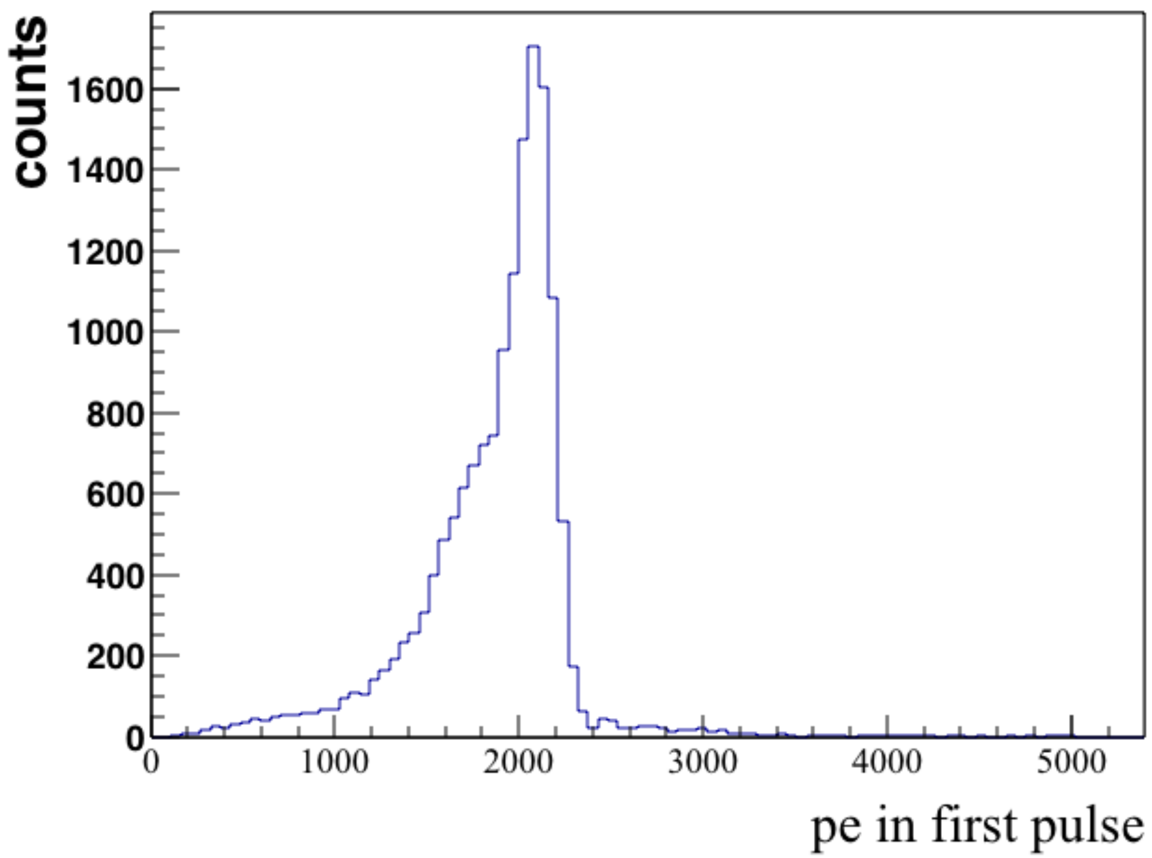
Signal Simulation

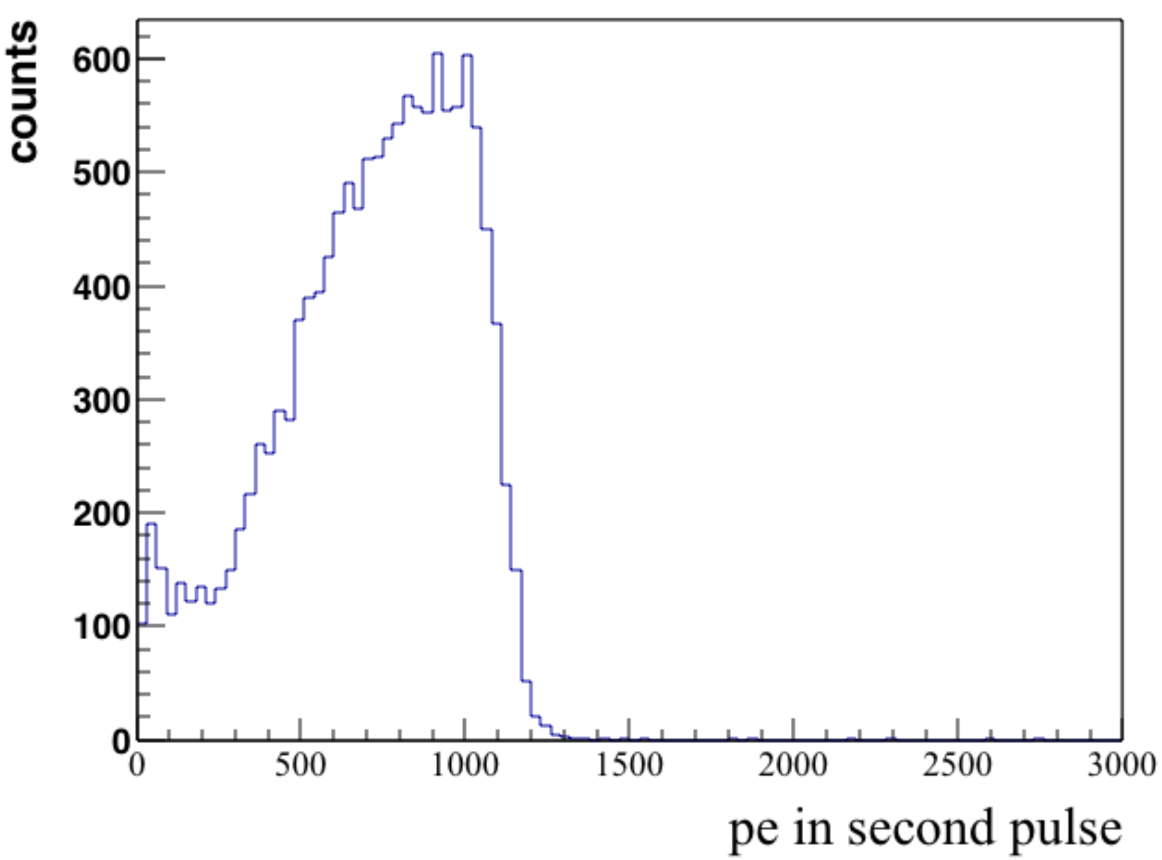
- simulated photon arrival time



Signal Simulation

- Estimated photons collected
- MC scintillator produces ~8000 photons/MeV
- With current coverage, seems to be enough light



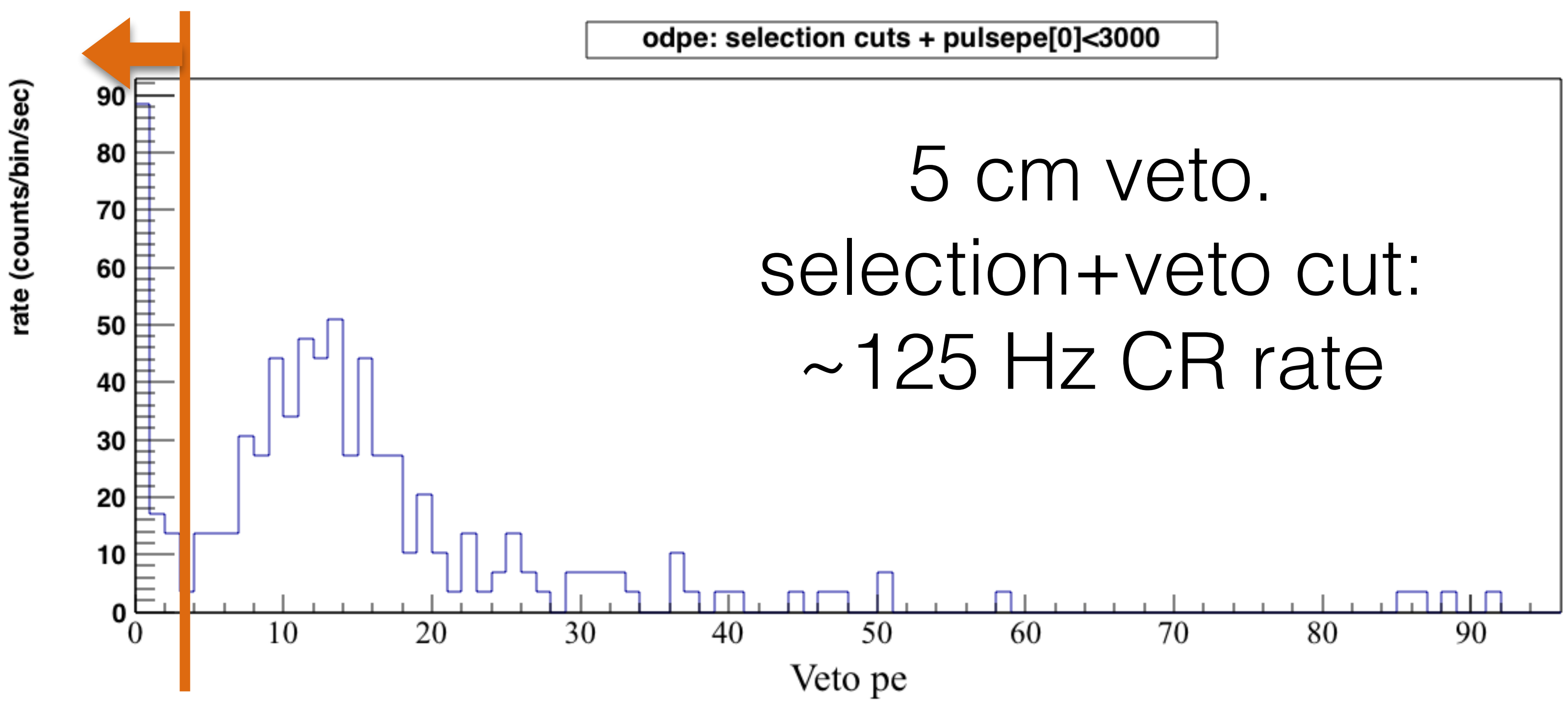


Backgrounds

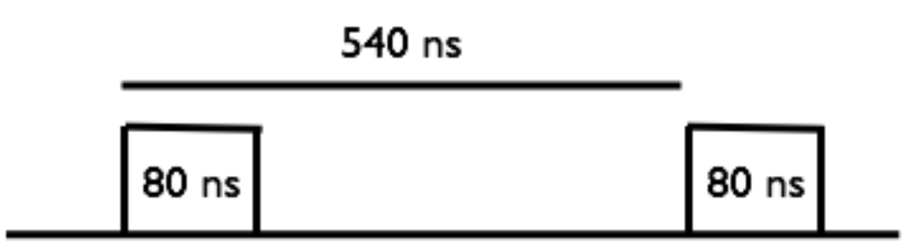
- Cosmic rays are main background
- Timing and selection will bring event background down
- Studied via simulation

Cosmic Ray Simulation

- Cosmic ray simulation is working
- preliminary: need to generate many more events
- so far, cosmic rate seems manageable with selection cuts
- ~1e-6 suppression factor when selecting events around beam time

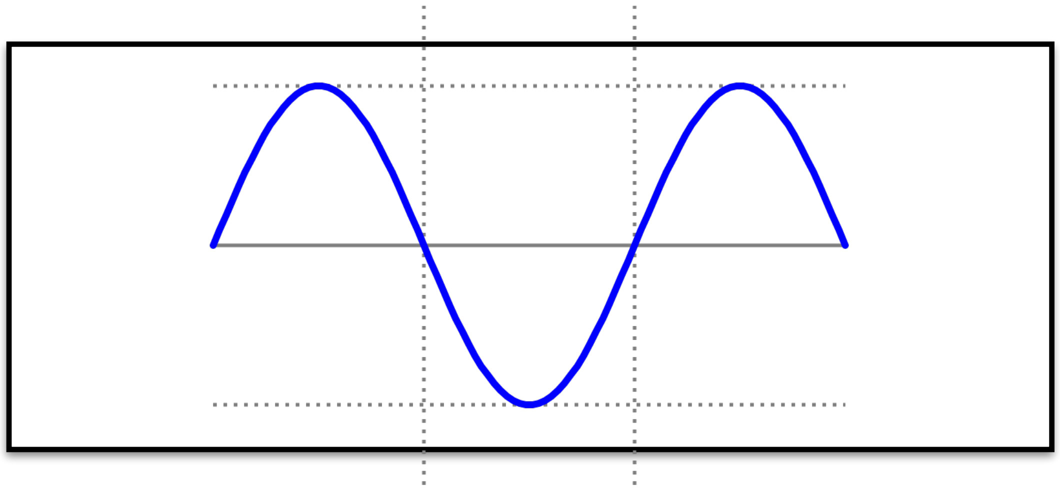


timing cut:
two ~250 ns windows
around proton pulses



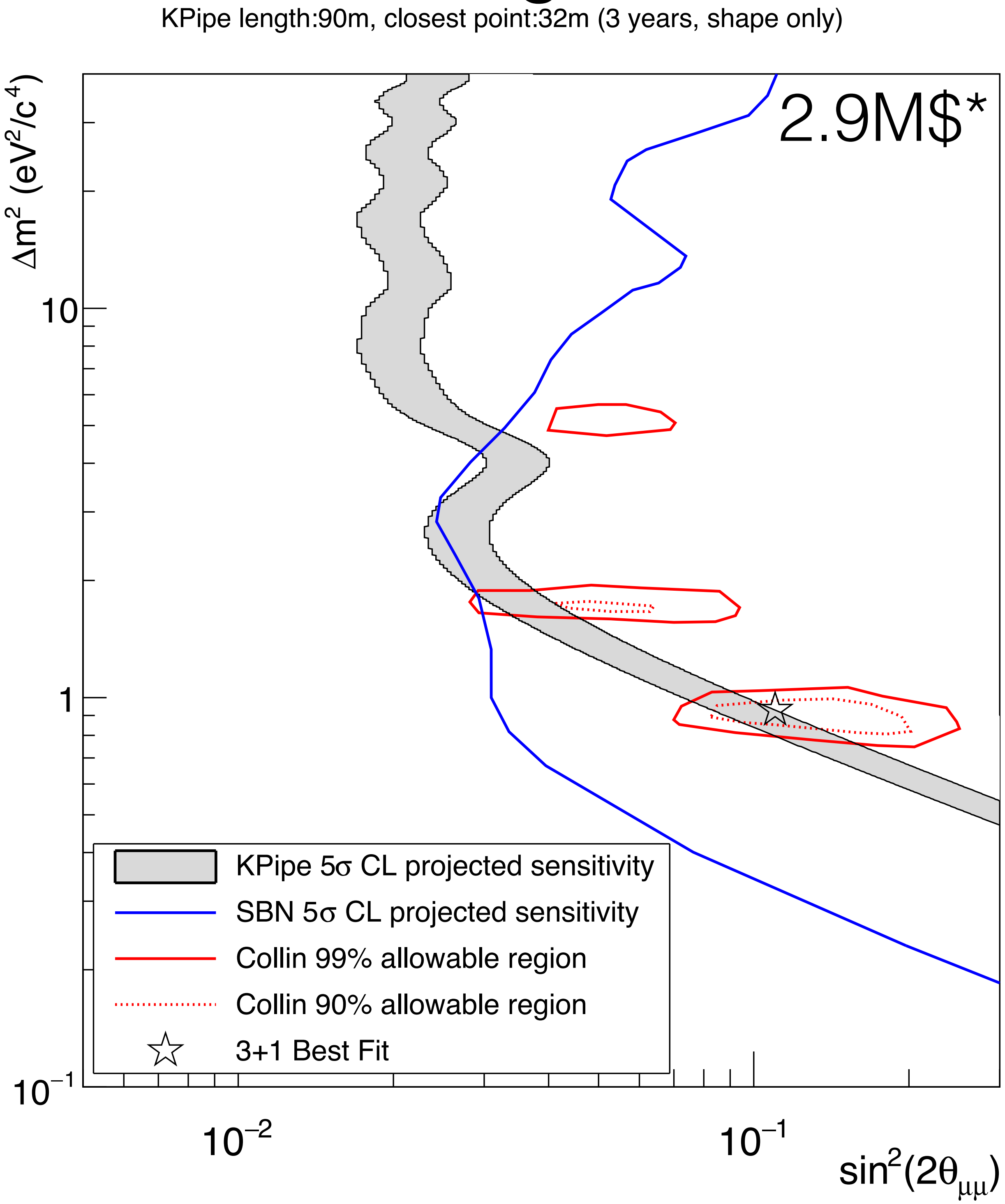
Sensitivity Study

- Inputs from kaon production and detector simulation
  - muon reconstruction uncertainty: 30 cm (gaussian)
  - kaon creation point uncertainty: 20 cm (uniform)
  - efficiency: 87%
- Shape only analysis
  - Fit only to frequency
  - ignore normalization of sin wave



Sensitivity Study

90 m long detector



- gray band shows uncertainty in sensitivity due to kaon production model.
- Have 2: Geant4 and MARS — 70% different

*costs do not include civil engineering

Sensitivity Study

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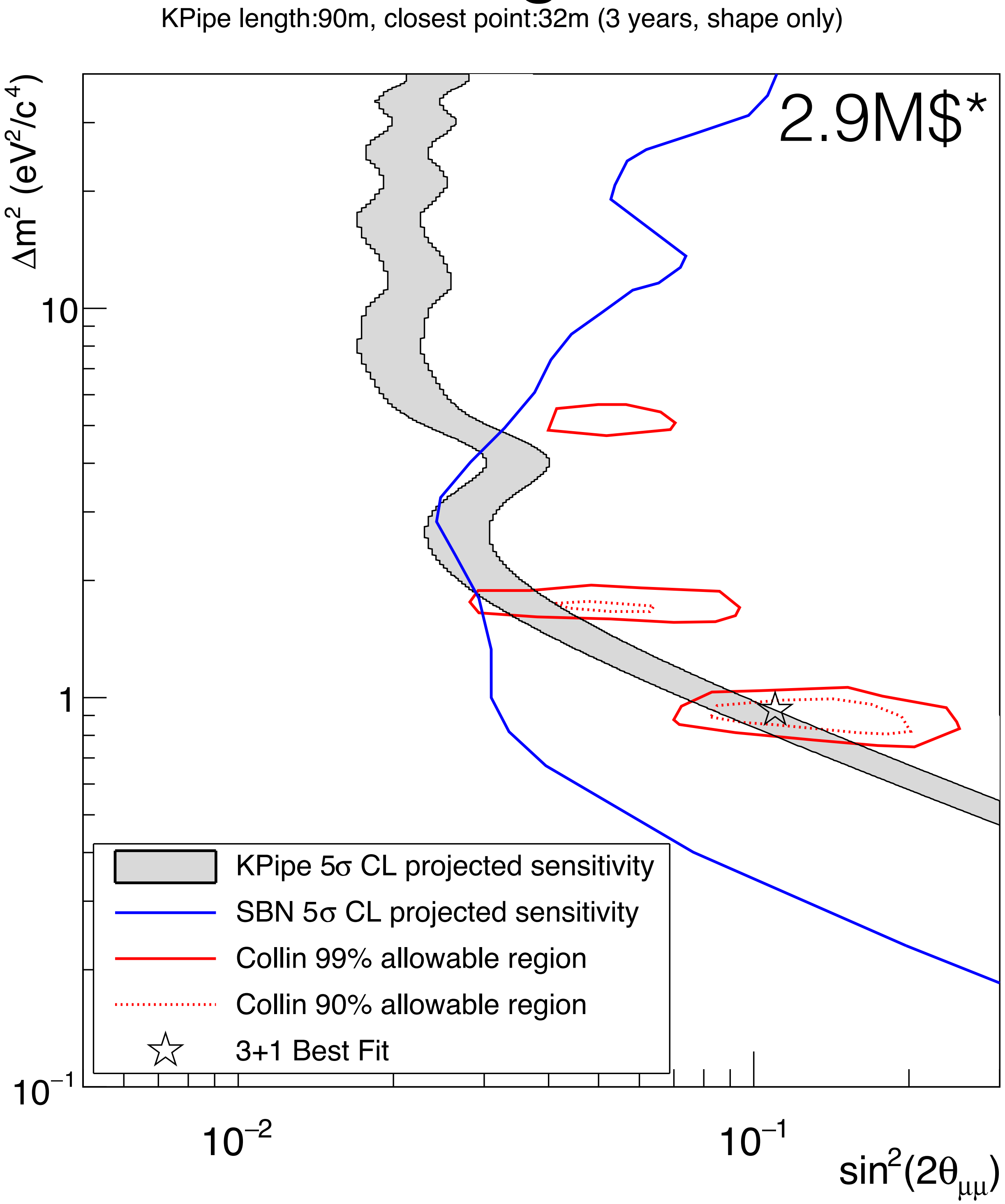


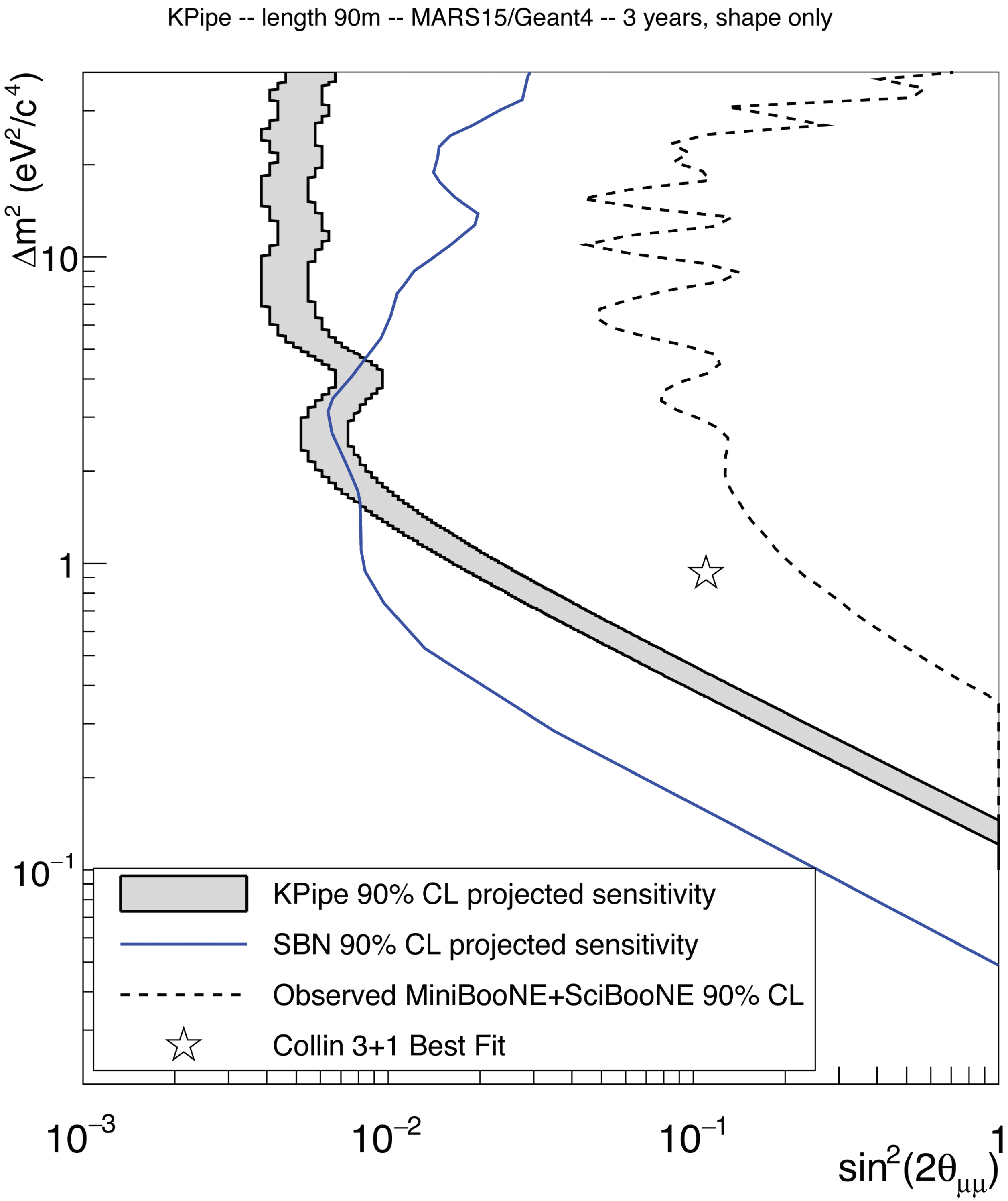
KPipe would exclude some of allowed 3+1 global fit parameter space at 5 sigma

complements other short-baseline experiment, SBN@Fermilab

*costs do not include civil engineering

Sensitivity Study

90 m long detector



- extend muon disappearance limit by an order of magnitude
- complimentary to SBN muon disappearance reach

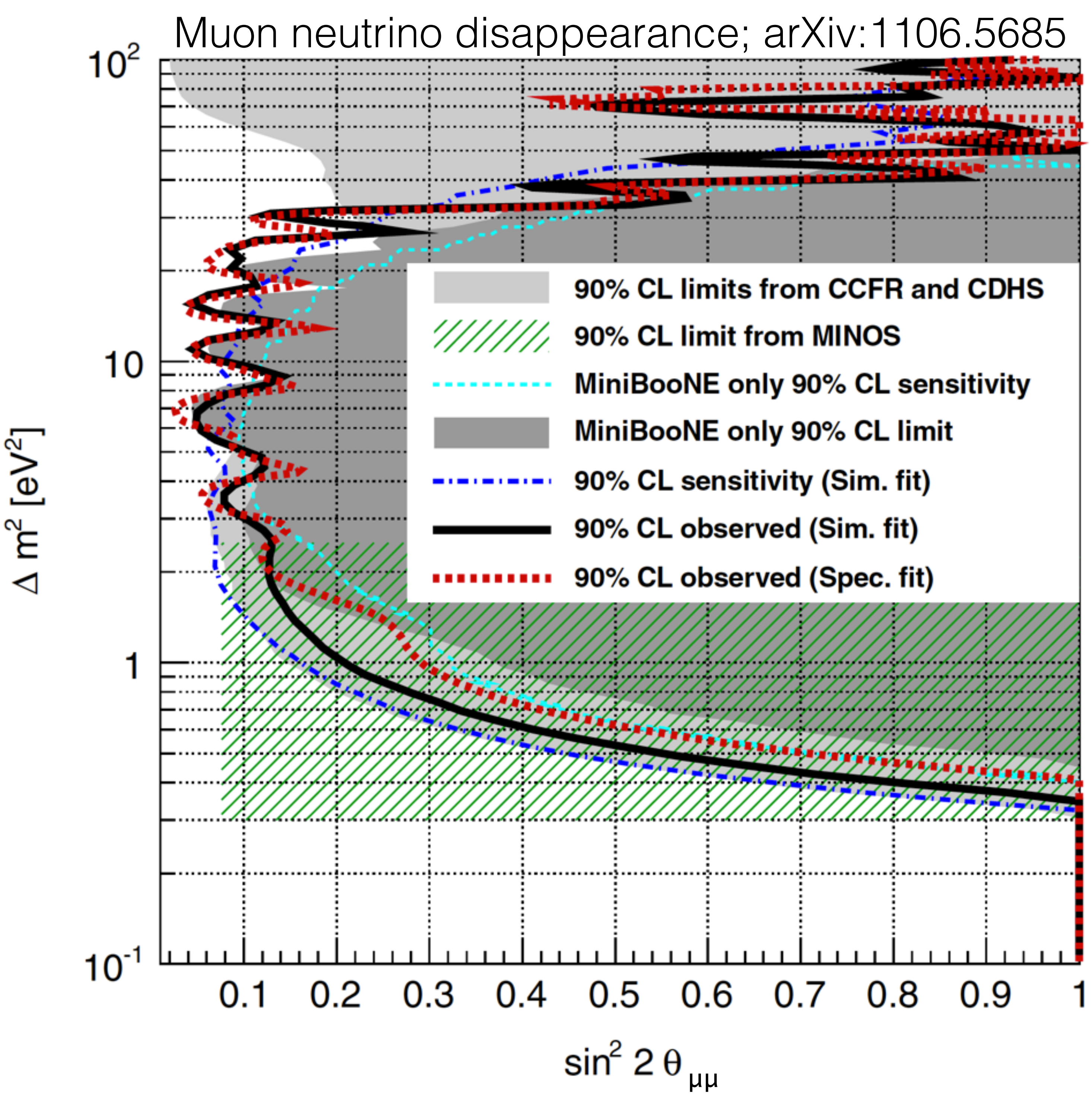
*costs do not include civil engineering

Summary

- Observation (or lack there of) of muon neutrino disappearance is important in understanding sterile anomaly
- KPipe is a proposal to look for muon neutrino disappearance at around 1-10 eV^2 given the WINP constraints
- Lots of power for less than 5 million dollars
- Preparing a paper with more details

Backup

Muon Neutrino Disappearance

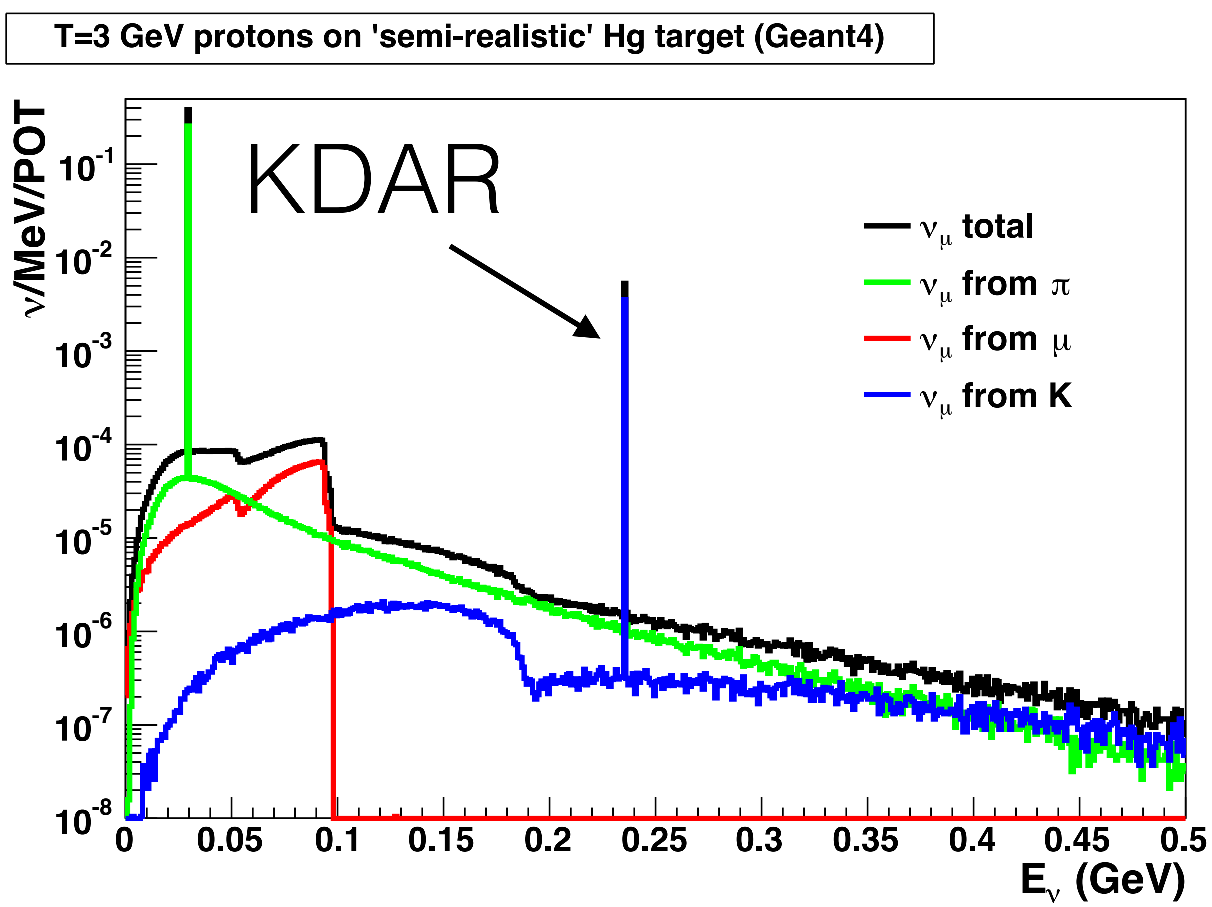


- overly optimistic case: sign of sterile neutrinos though muon disappearance just past limits
- more realistically, one or more data sets has a problem, so we need to check both appearance and disappearance

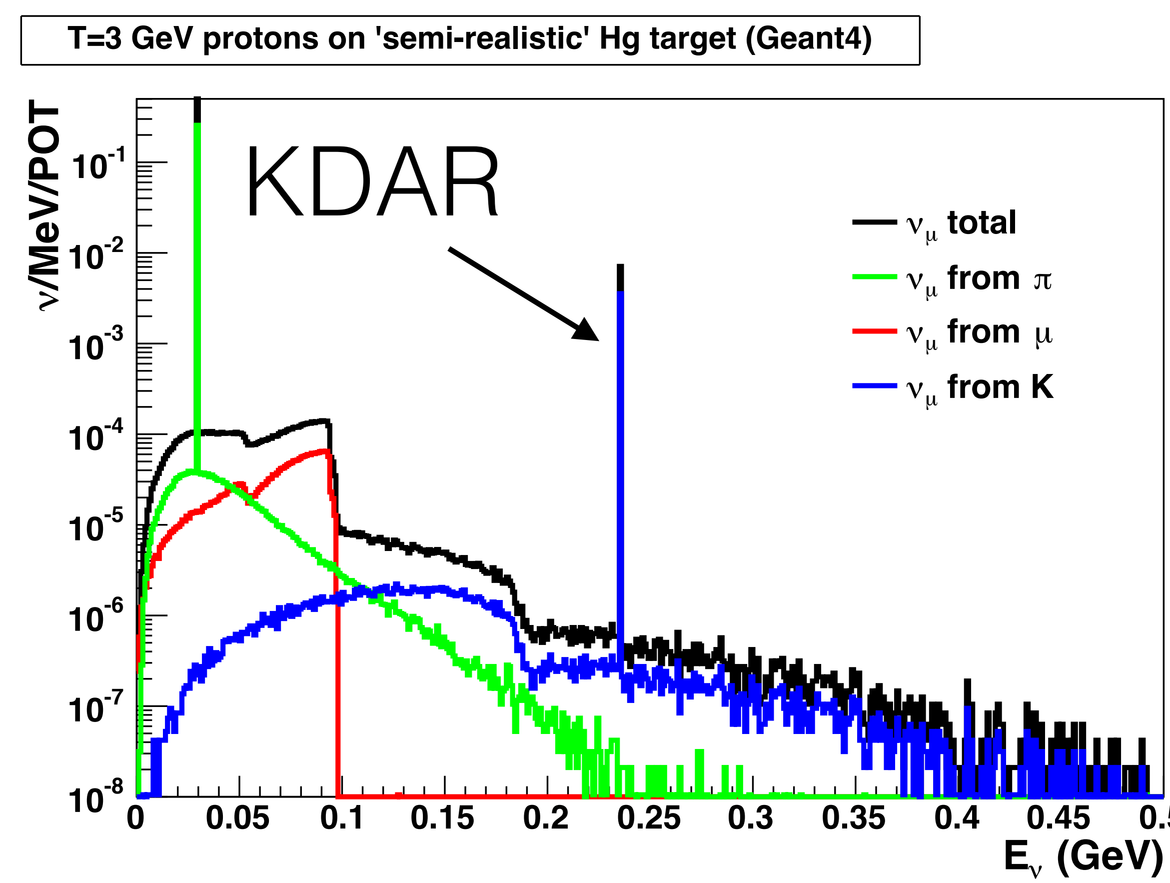
JPARC MLF

- Being on the upstream side of target reduces background from decay in flight neutrinos

all events



cos θ<0 (w.r.t proton direction)



n.b. scaled by 2 to allow comparison with left plot

Detector

- Such a big stainless pipe is likely very expensive
- Idea: use less expensive high density polyethylene vessel
- used for sanitation, irrigation, wastewater

DuroMaxx® – Steel Reinforced Polyethylene Technology

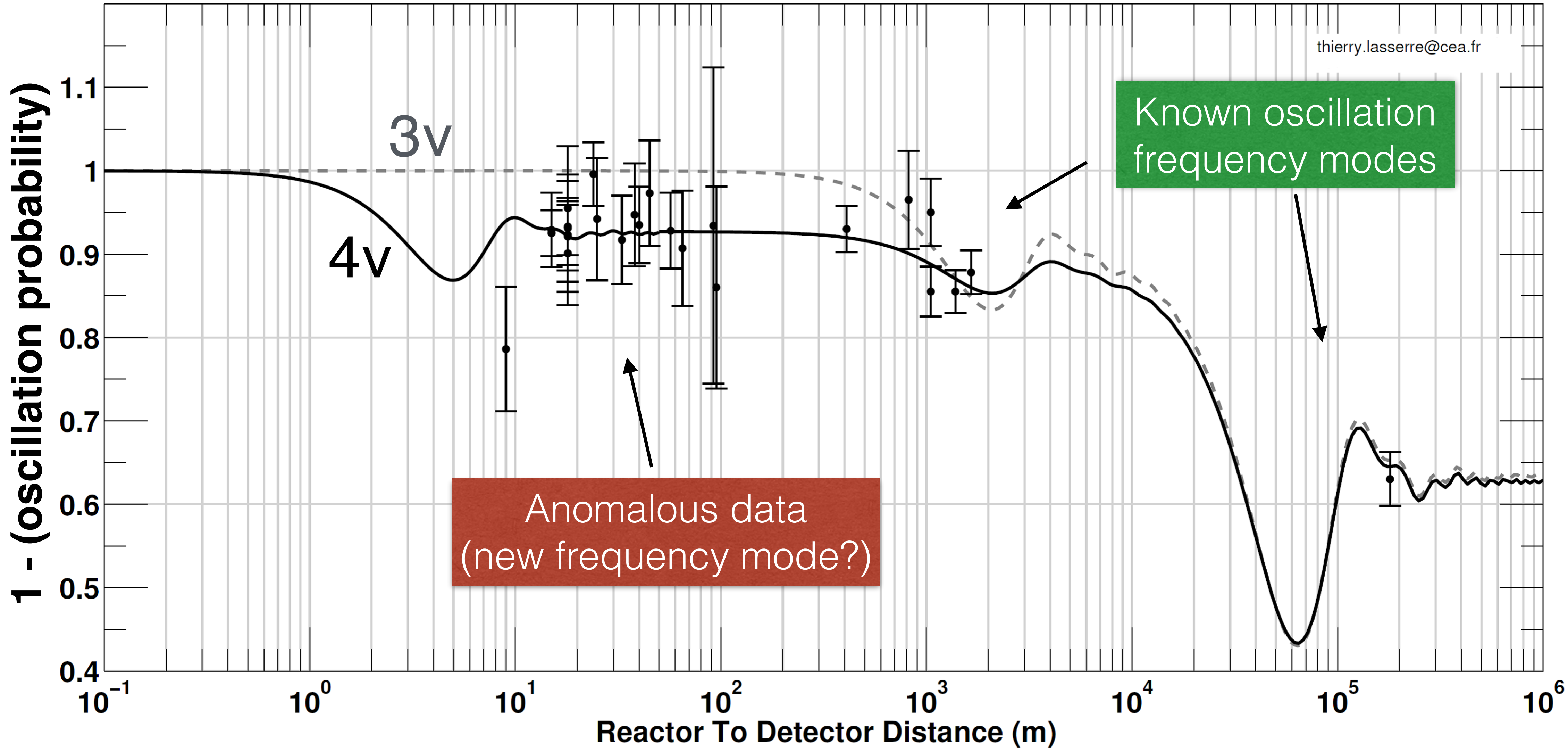
Detector Medium

- Fill vessel with liquid scintillator
- options:
  - Mineral oil + pseudocumeme
    - pros: used by another neutrino experiment, NOVA, supposedly inexpensive, about 4500 photons/MeV
    - cons: pseudocumeme can be aggressive solvent
  - LAB: linear alkyl benzene
    - pros: higher light yield ~10,000 photons/MeV, non-toxic
    - con: potentially more expensive

Reactor Anomaly

- World reactor neutrino data
- Interpret data with neutrino oscillations

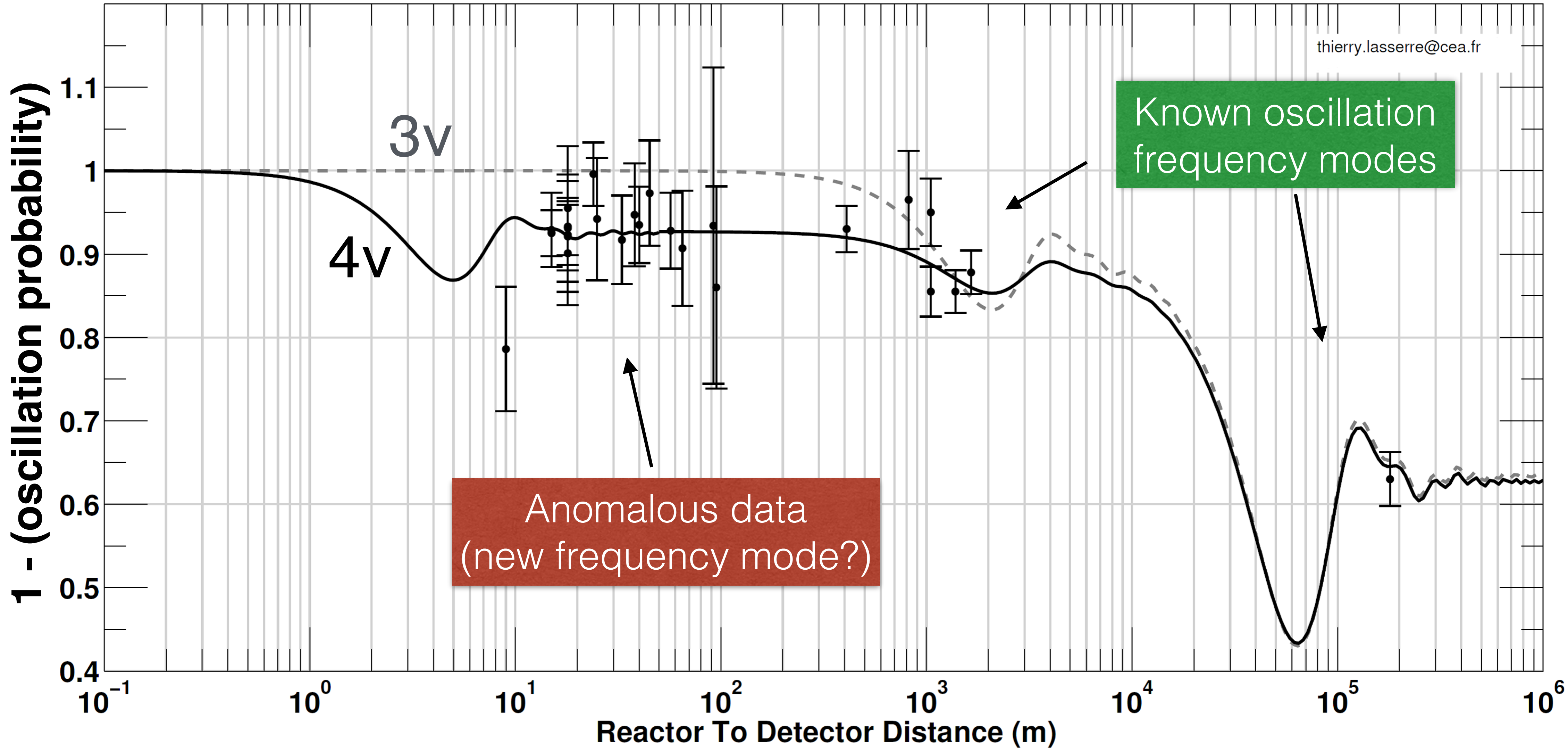
$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2(2\theta)\sin^2(\frac{\Delta m^2 L}{4E})$$



Reactor Anomaly

- Reanalysis of old reactor data sets show observed events is lower than expectation

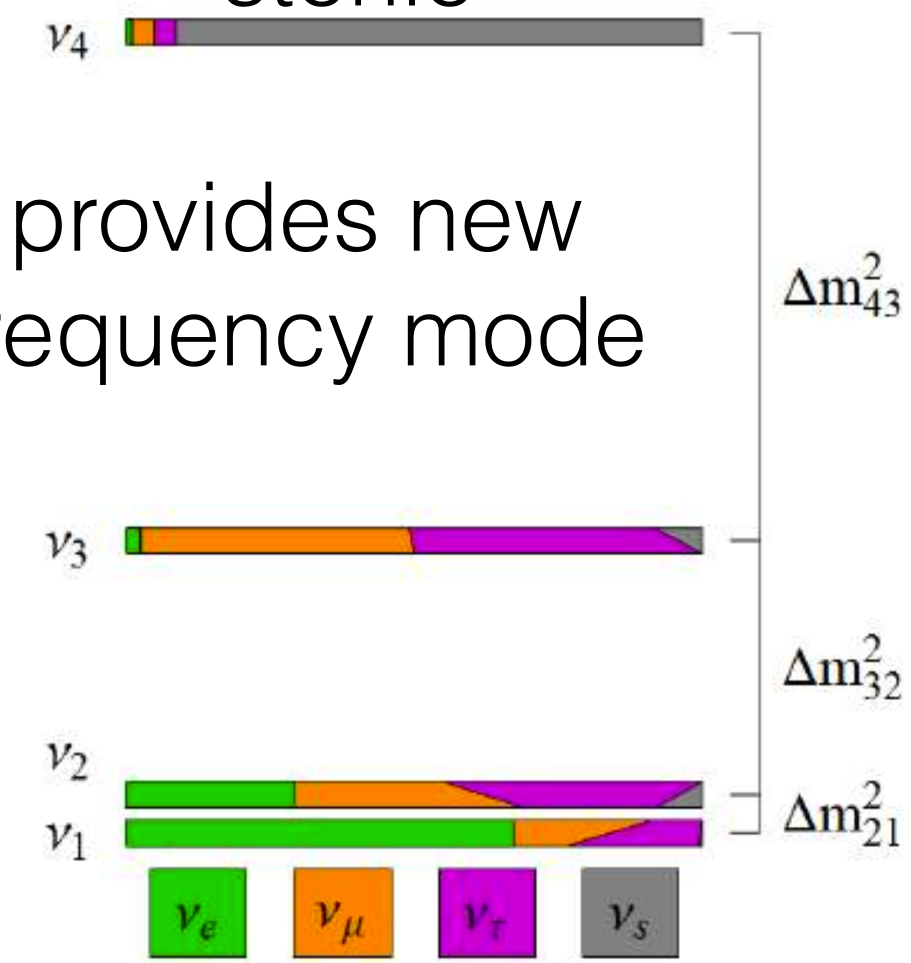
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$$



Sterile Neutrino

- How to interpret all of the anomalies?
- Could there be a new neutrino?
- New neutrino cannot interact via the weak force — width of the Z boson tells us only 3 couple weakly

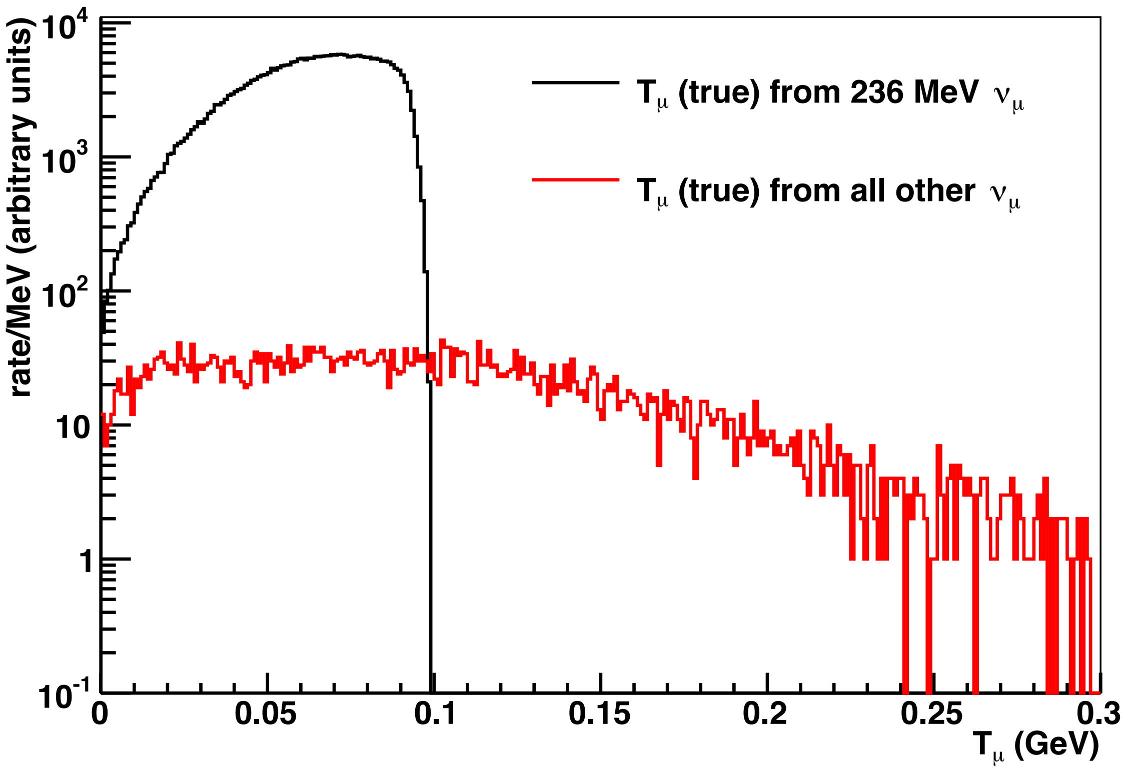
sterile



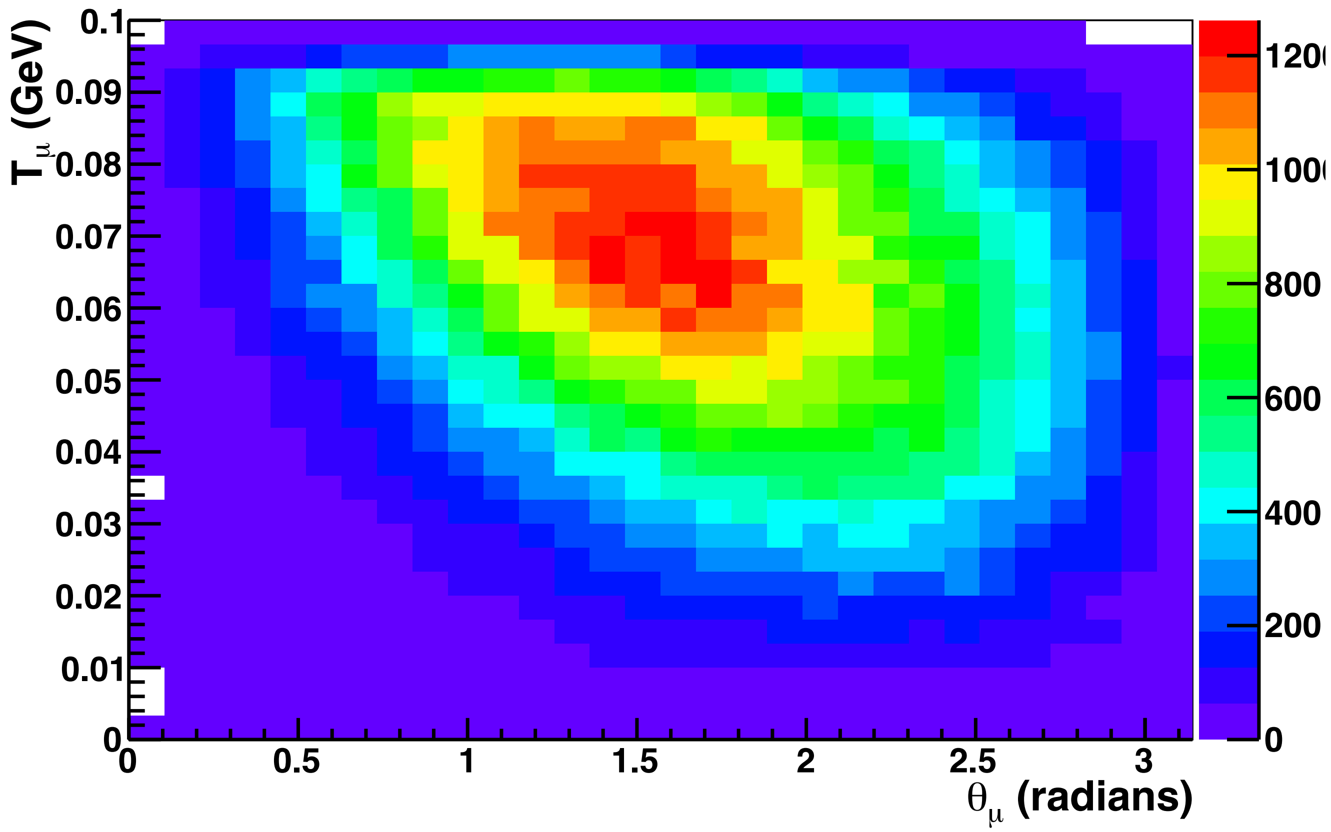
provides new frequency mode

Muon Kinematics

- In order to measure oscillation of muon neutrinos, measure interaction of neutrinos along pipe that make muons
- Signal from KDAR (black) >20 times larger than decay-in-flight background neutrinos



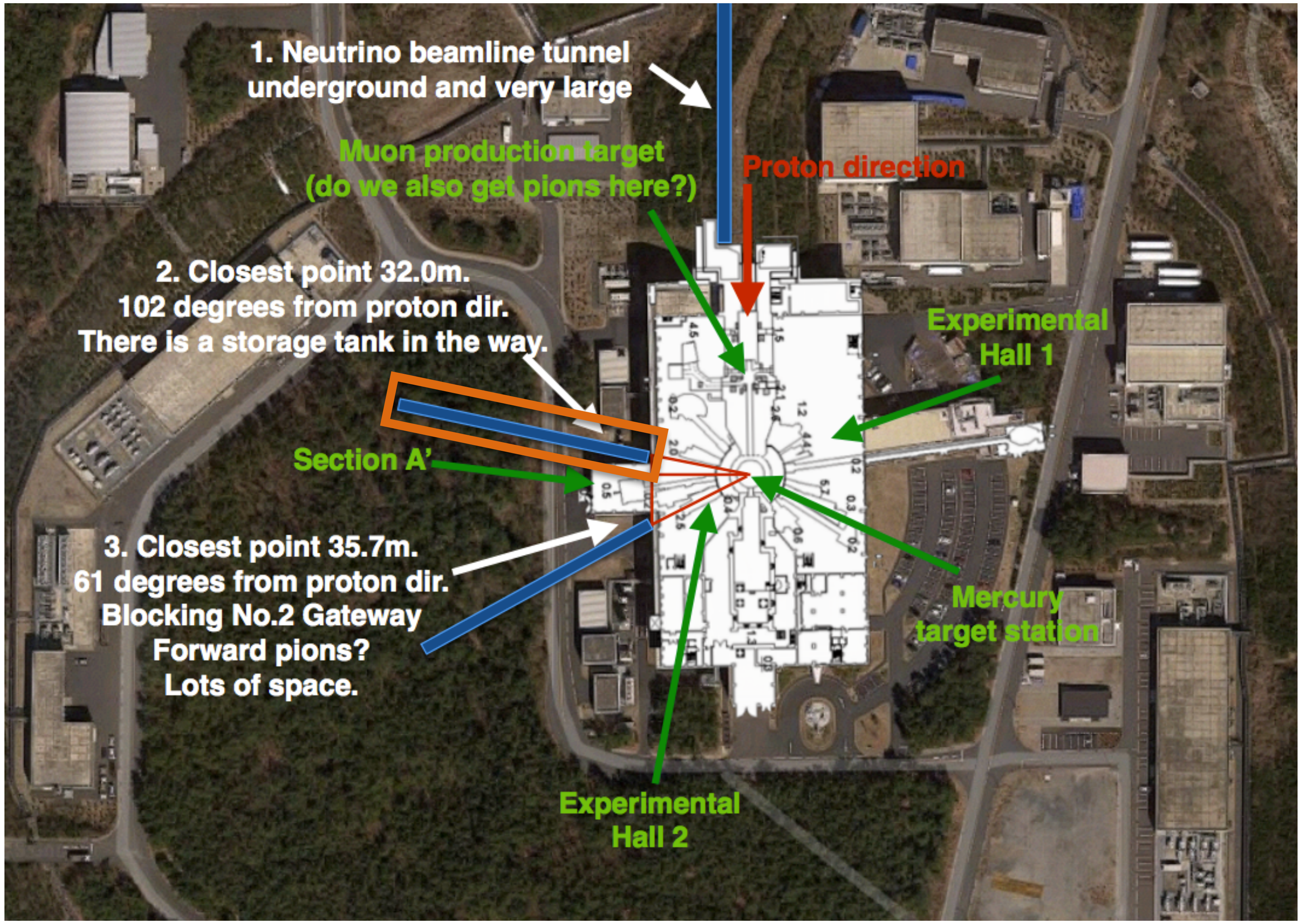
236 MeV muon neutrinos on C



Detector Location

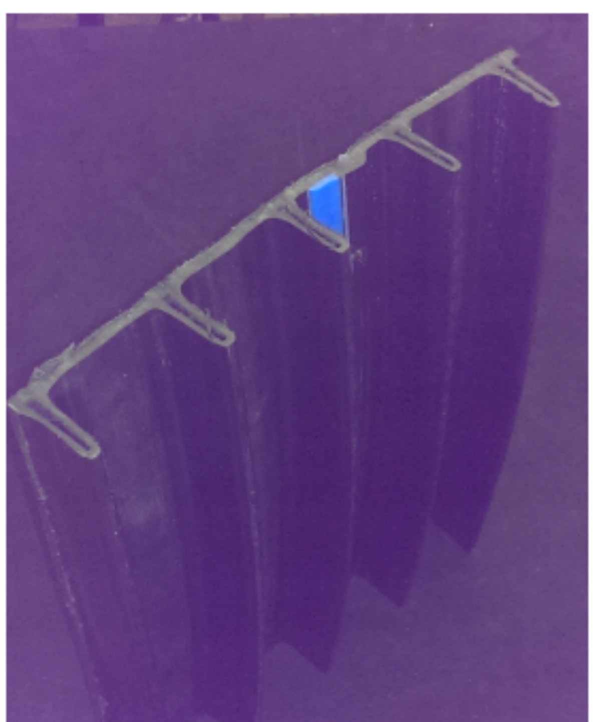
Studied possible locations of pipe around MLF building

Chose location (highlighted in orange) based on sensitivity



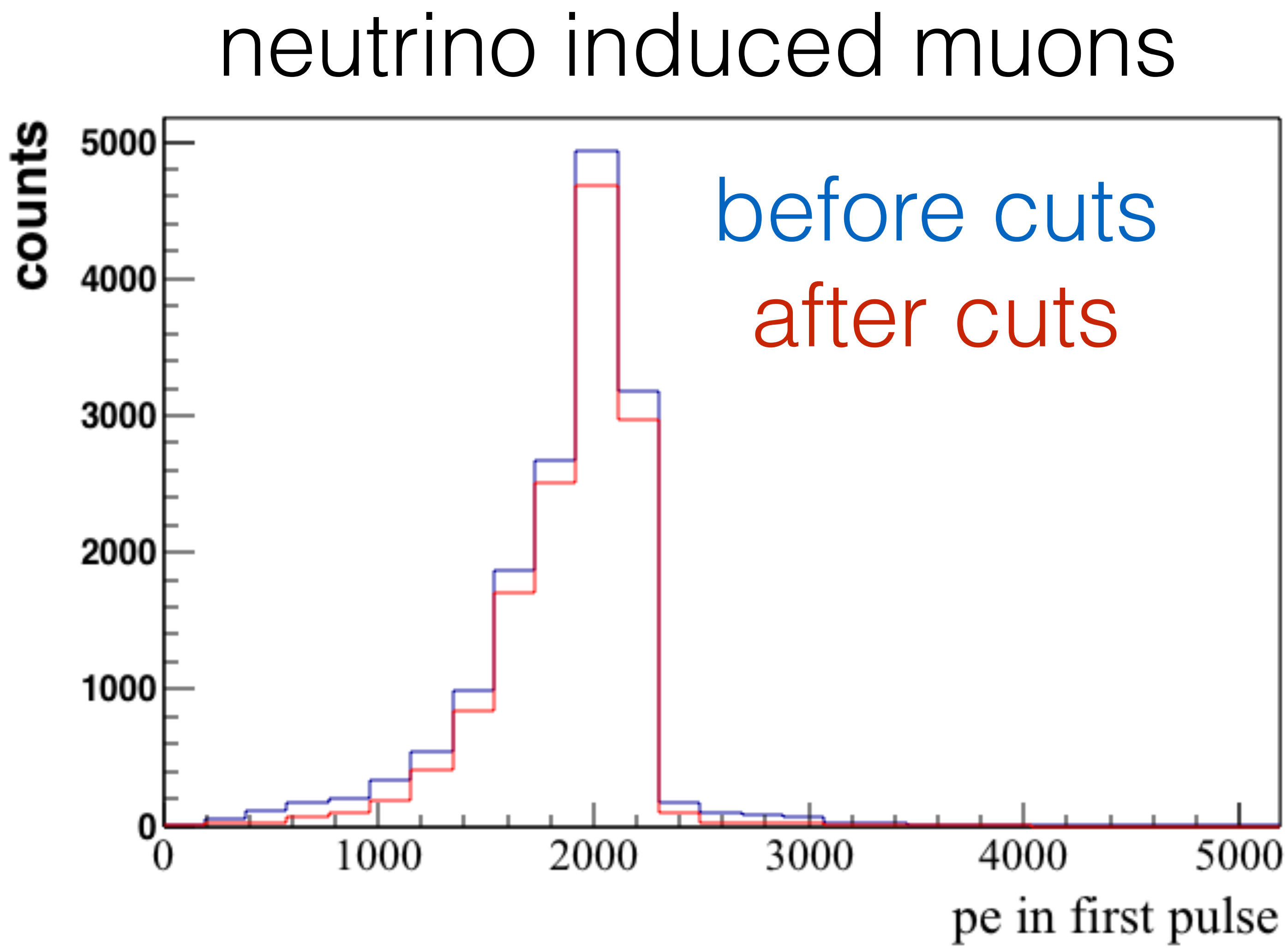
Detector Medium

- received test piece of HDPE
- testing to see if material withstands attack from pseudocumene
- in the process of trying to get some LAB



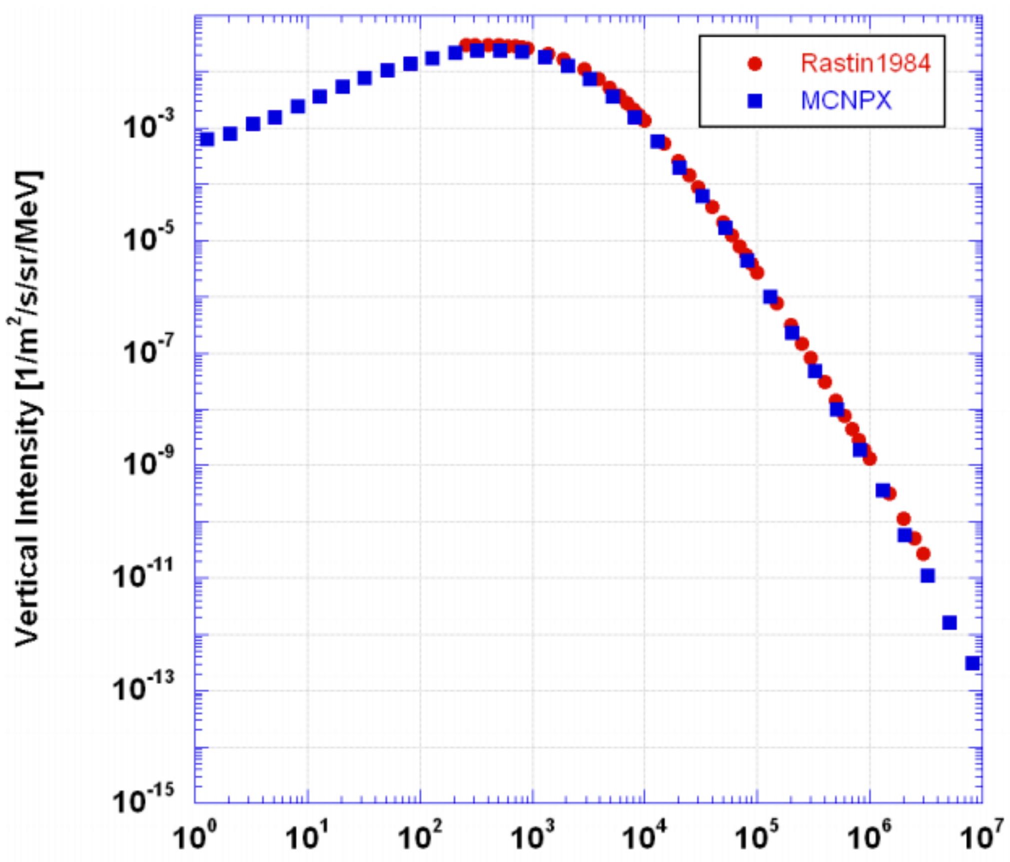
Efficiency

- According to simulation: ~87%
- matches analytic calculation using muon spectrum and expected range

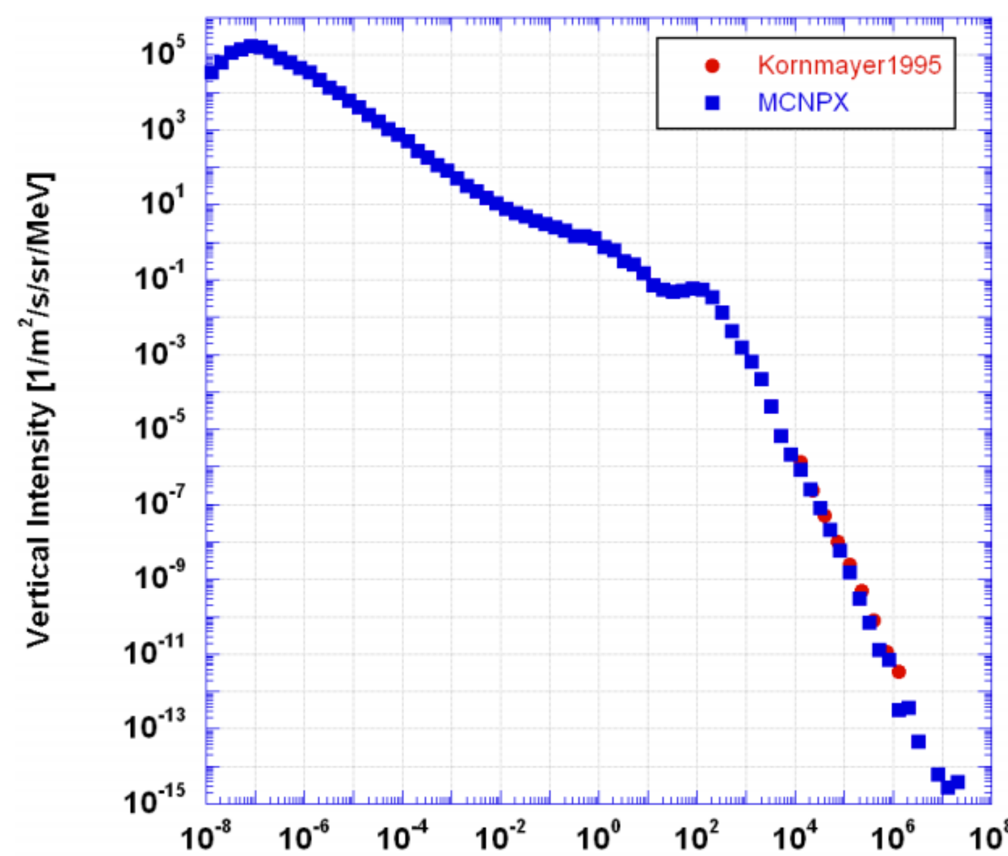


Cosmic Ray Simulation

- Cosmic ray simulation using package called CRY
- generates cosmic ray shower event at given latitude and altitude
- particles provided: muons, photons, pions, neutrons, protons

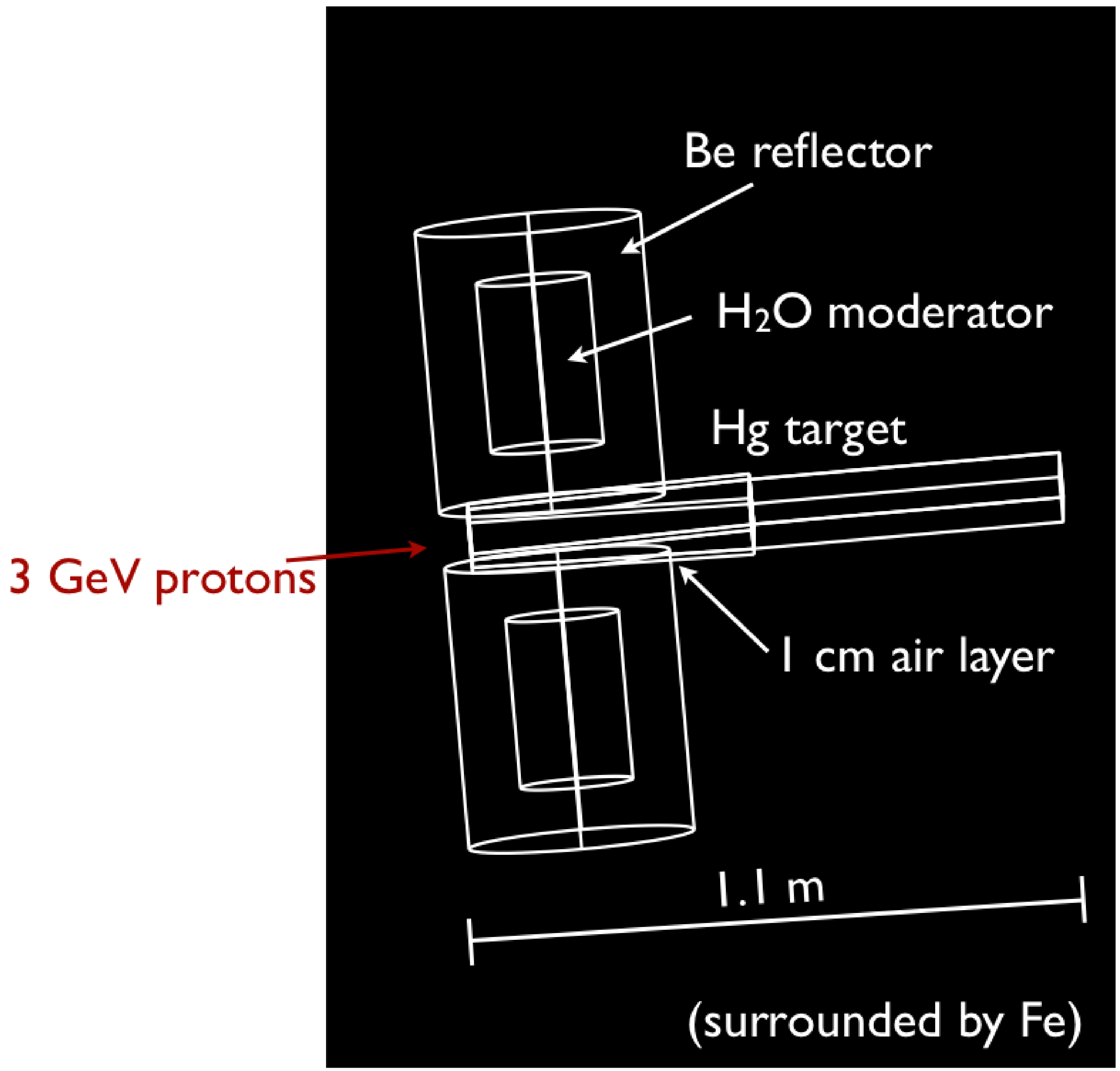


Muon energy [MeV]

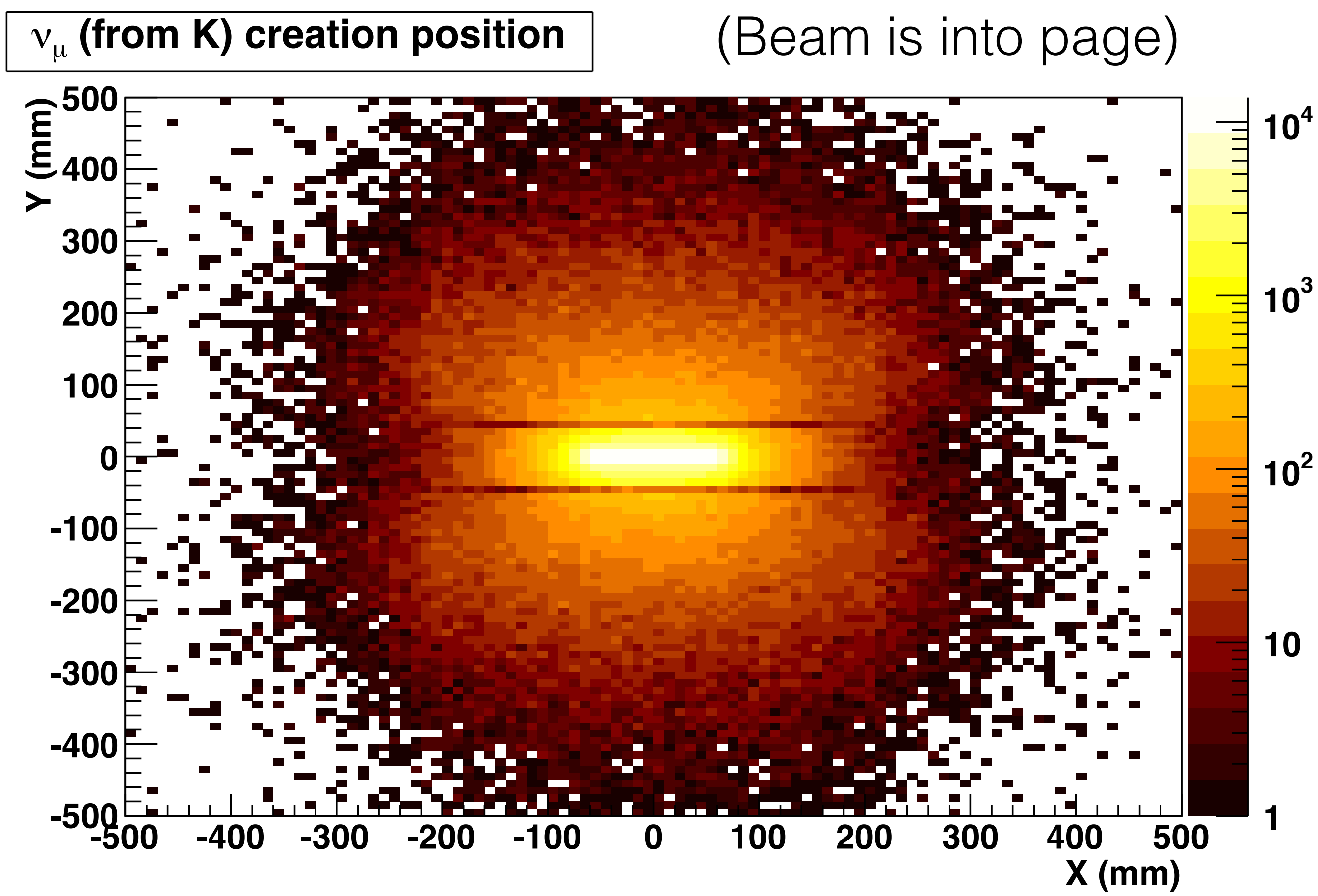


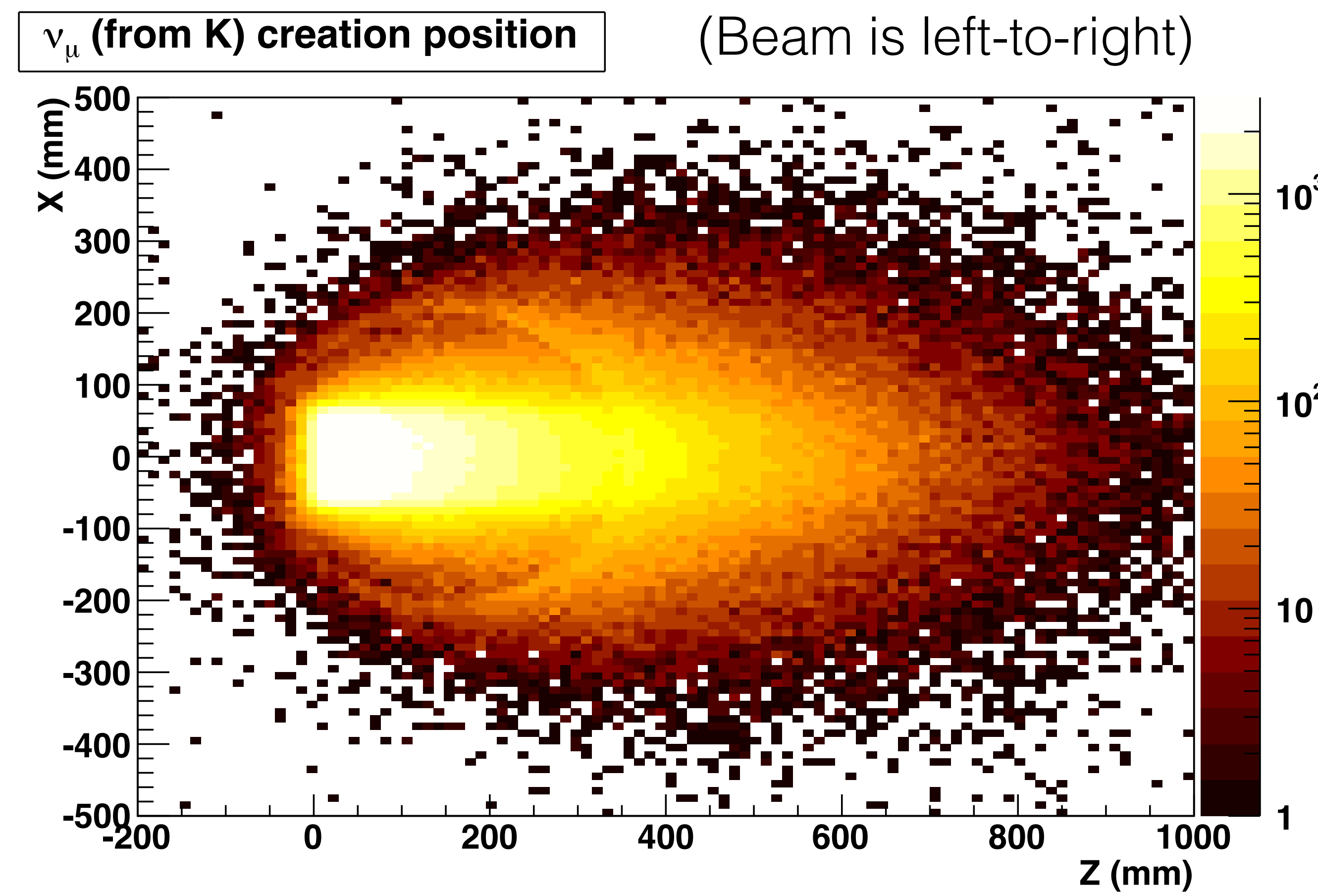
neutron energy [MeV]

Proton-on-target Geant4 sim (w/ simplified geometry)



KDAR neutrino creation position





Intrinsic baseline uncertainty is +/-25 cm or so.

Parent	Process	Cross section (cm^2)	events/ton/year
$K^+ \to \mu^+\nu_\mu$	$\nu_\mu C \to \mu^- N^*$	8.4×10^{-39}	757
$K^+ \to \mu^+\nu_\mu$	$\nu_\mu C \to \nu_\mu C^*$ (15.11)	4.2×10^{-41}	3.7
$K^+ \to \mu^+\nu_\mu$	0.26% $\nu_\mu \to \nu_e$, $\nu_e C \to e^- N^*$	1.4×10^{-38}	3.3
$\mu^+ \to e^+\overline{\nu}_\mu\nu_e$	0.26% $\overline{\nu}_\mu \to \overline{\nu}_e$, $\overline{\nu}_e p \to e^+ n$	9.5×10^{-41}	3.3
$\mu^+ \to e^+\overline{\nu}_\mu\nu_e$	$\nu_e C \to e^- N_{gs}$	8.9×10^{-42}	58.3
$\mu^+ \to e^+\overline{\nu}_\mu\nu_e$	$\nu_e C \to e^- N^*$	4.3×10^{-42}	28.1
$\mu^+ \to e^+\overline{\nu}_\mu\nu_e$	$\nu C \to \nu C^*$ (15.11)	10.5×10^{-42}	68.9
$\mu^+ \to e^+\overline{\nu}_\mu\nu_e$	$\nu_e e^- \to \nu_e e^-$	3.13×10^{-43}	8.2
$\pi^+ \to \mu^+\nu_\mu$	$\nu_\mu C \to \nu_\mu C^*$ (15.11)	2.8×10^{-42}	18.3

Assumptions that go into event rate (above):

Assumption	Value	Comment
Baseline	20 m	
Detection efficiency	100%	For simplicity
Detection target	CH_2	
π^+/p	0.256	Geant4 (semi-realistic geometry)
K^+/p	0.0035	Geant4 (semi-realistic geometry)
Protons on target	3E22 POT/year	Consistent with MLF plan

MARS predicts 75% more

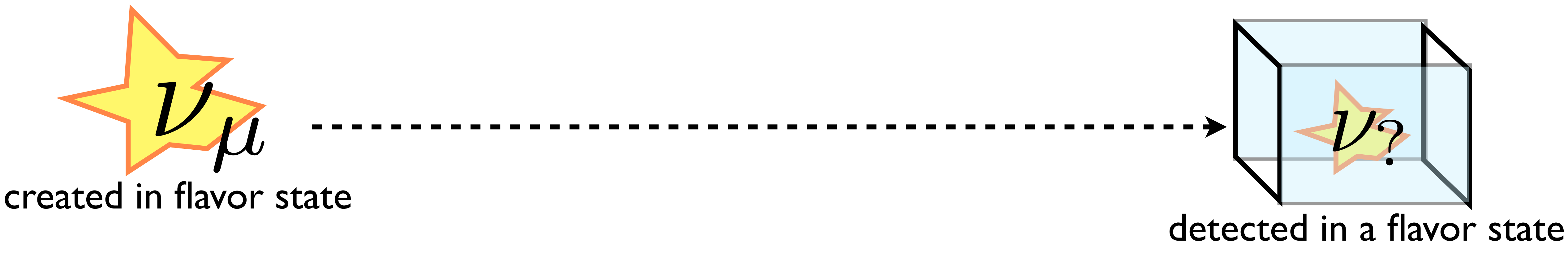
Neutrino

- One of the particles of the standard model
- There are three flavors: electron, muon, tau
- Interact through the weak force

from Particle Zoo

Neutrinos can change flavor

- Change flavor as they propagate
- Seen in many experiments over the past few decades



Neutrino Oscillation Model

- Requires that neutrinos have mass
- Mass and flavor eigenstates not the same: overlap parameterized by mixing matrix

$$|\nu_\alpha> = \sum_i U^*_{\alpha i} |\nu_i>$$

Neutrino Flavor Eigenstates	Unitary Mixing Matrix	Neutrino Mass Eigenstates

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

Oscillations

- Result: probability of detecting neutrinos with a certain flavor oscillates as a function of L/E

Flavor States | **Mixing Matrix** | Mass States

Example 2 ν model

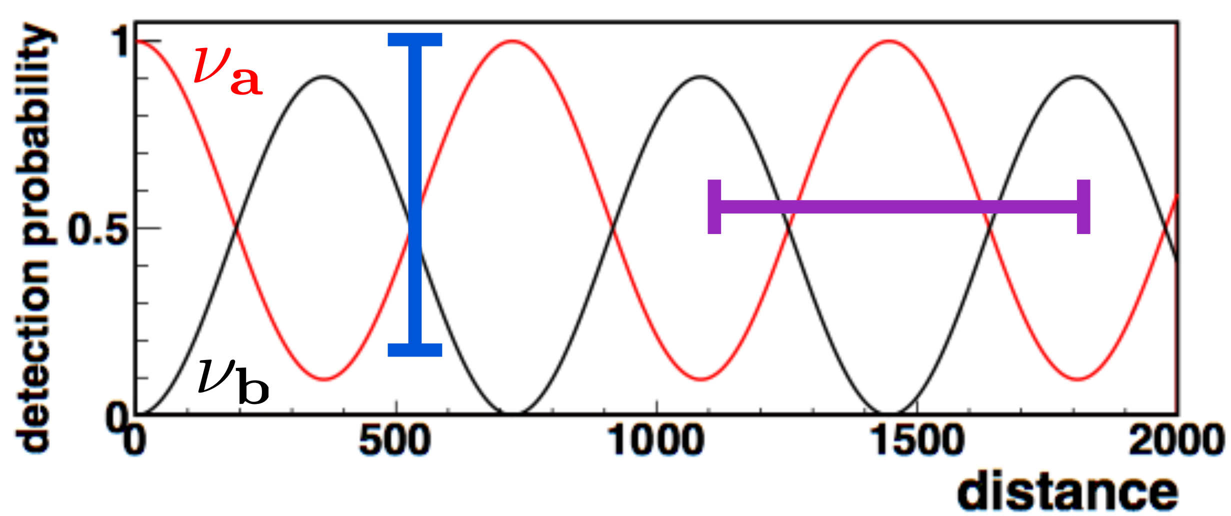
$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \quad \begin{matrix} \mathrm{w/mass}\ m_1 \\ \mathrm{w/mass}\ m_2 \end{matrix}$$

For a neutrino, ν_a, with energy, *E*, after a distance, *L*, in vacuum

$$P_{a\to b} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2}{4\hbar c}\frac{L}{E}\right)$$

where $\Delta m^2 = m^2_1 - m^2_2$

Result is sinusoidal probability, function of L/E



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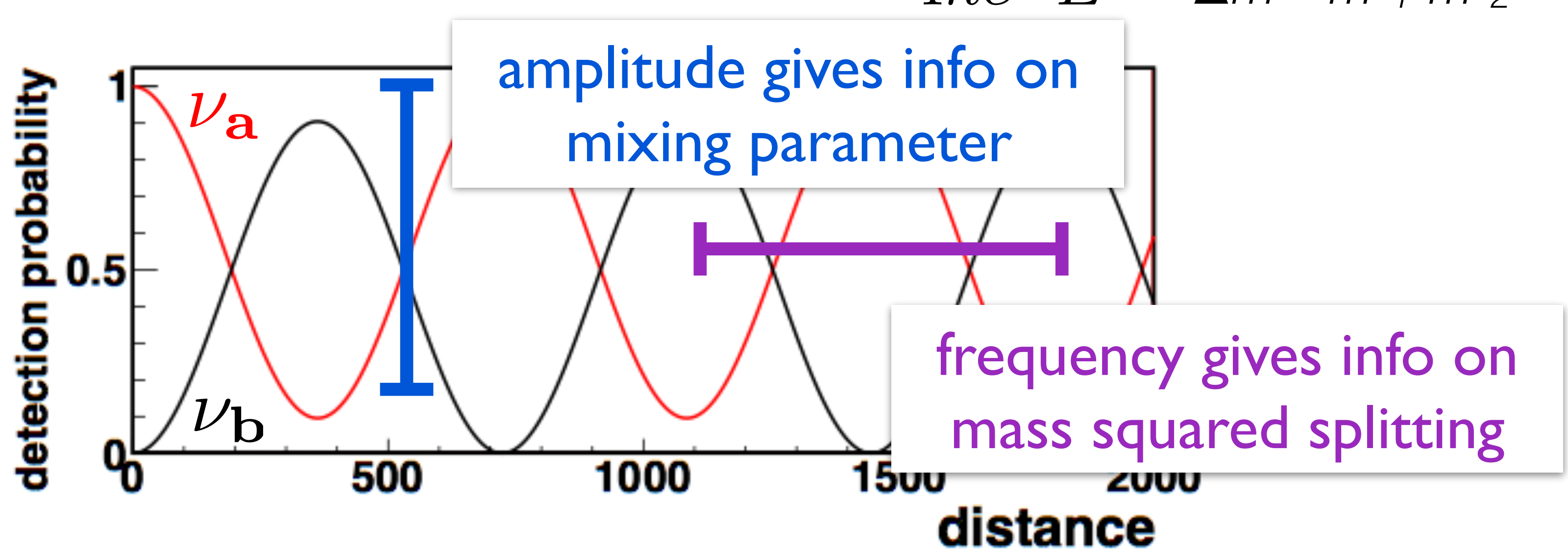
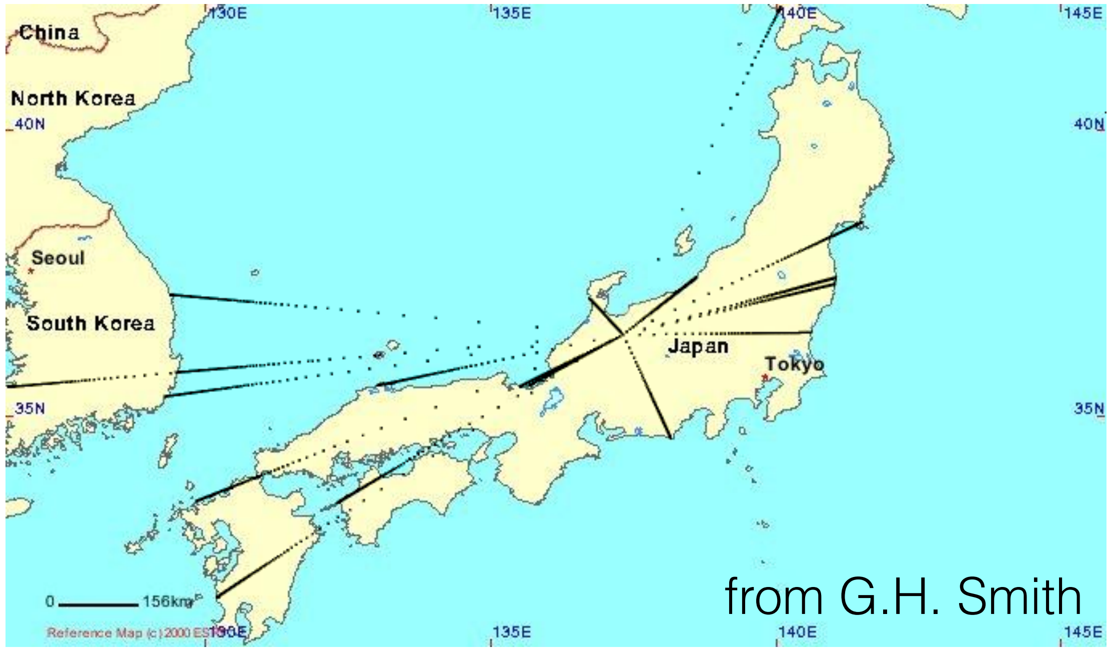


Oscillations

- Experimental Evidence

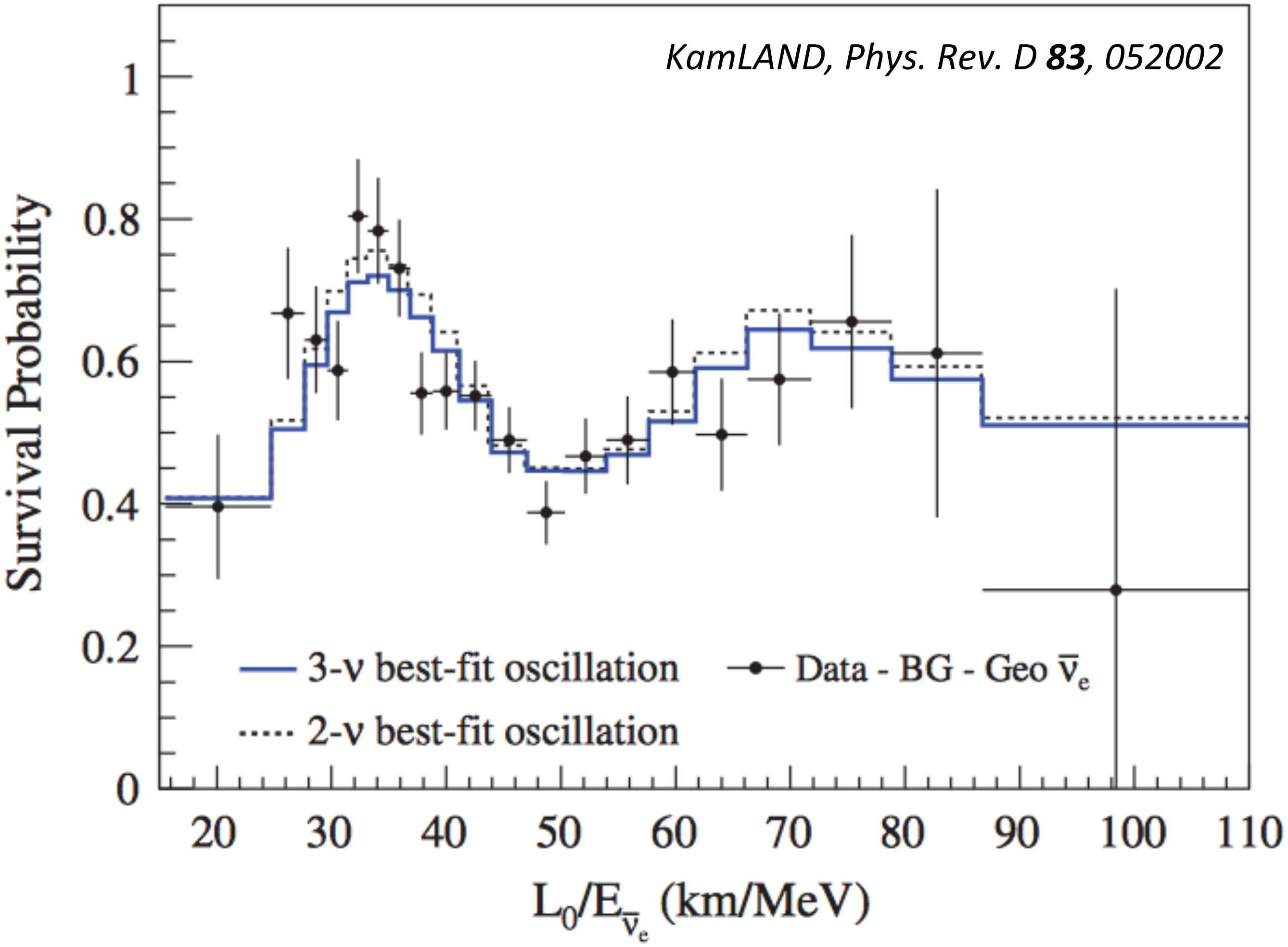
KamLAND experiment

experiment measuring neutrinos from several reactors around Japan and Korea



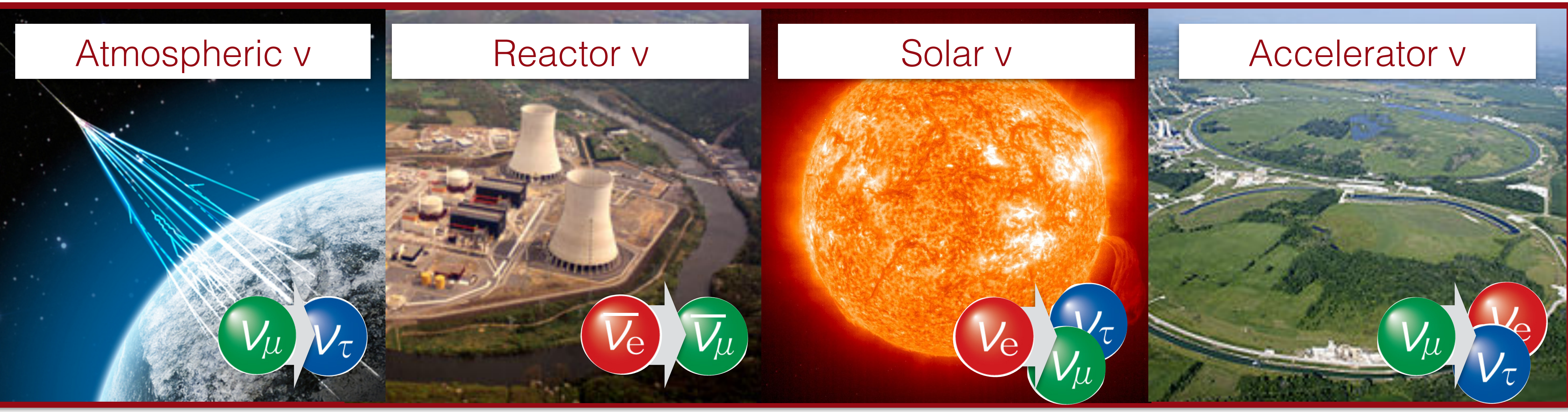
neutrinos at different L and E

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2(2\theta_{12}) \sin^2\left(\frac{1267\Delta m^2[\mathrm{eV}^2]L\ [\mathrm{km}]}{E_\nu\ [\mathrm{MeV}]}\right)$$



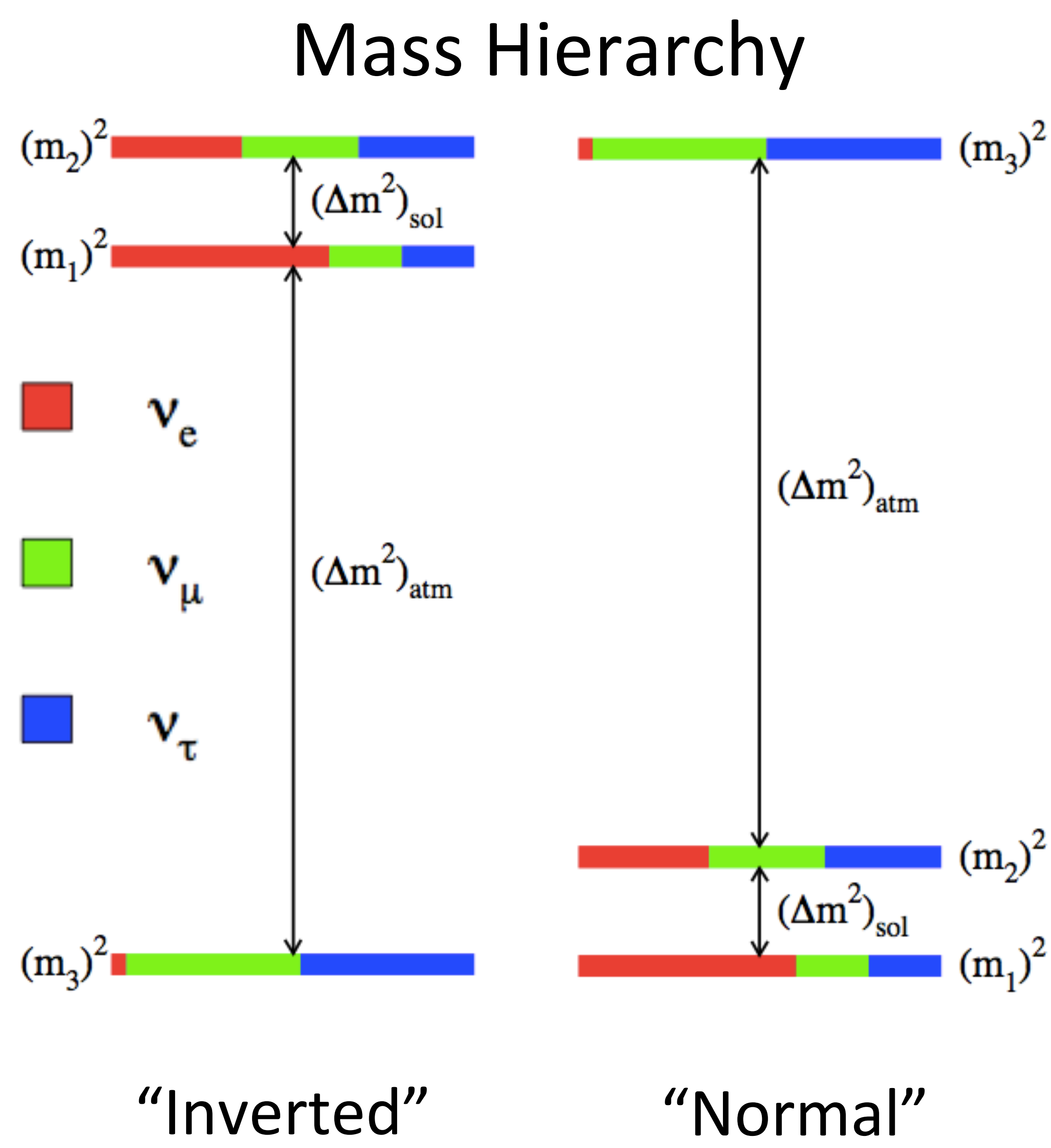
Oscillations

- Many measurements have been made using many different sources
- 3 neutrino model can explain almost all of the data



Oscillations

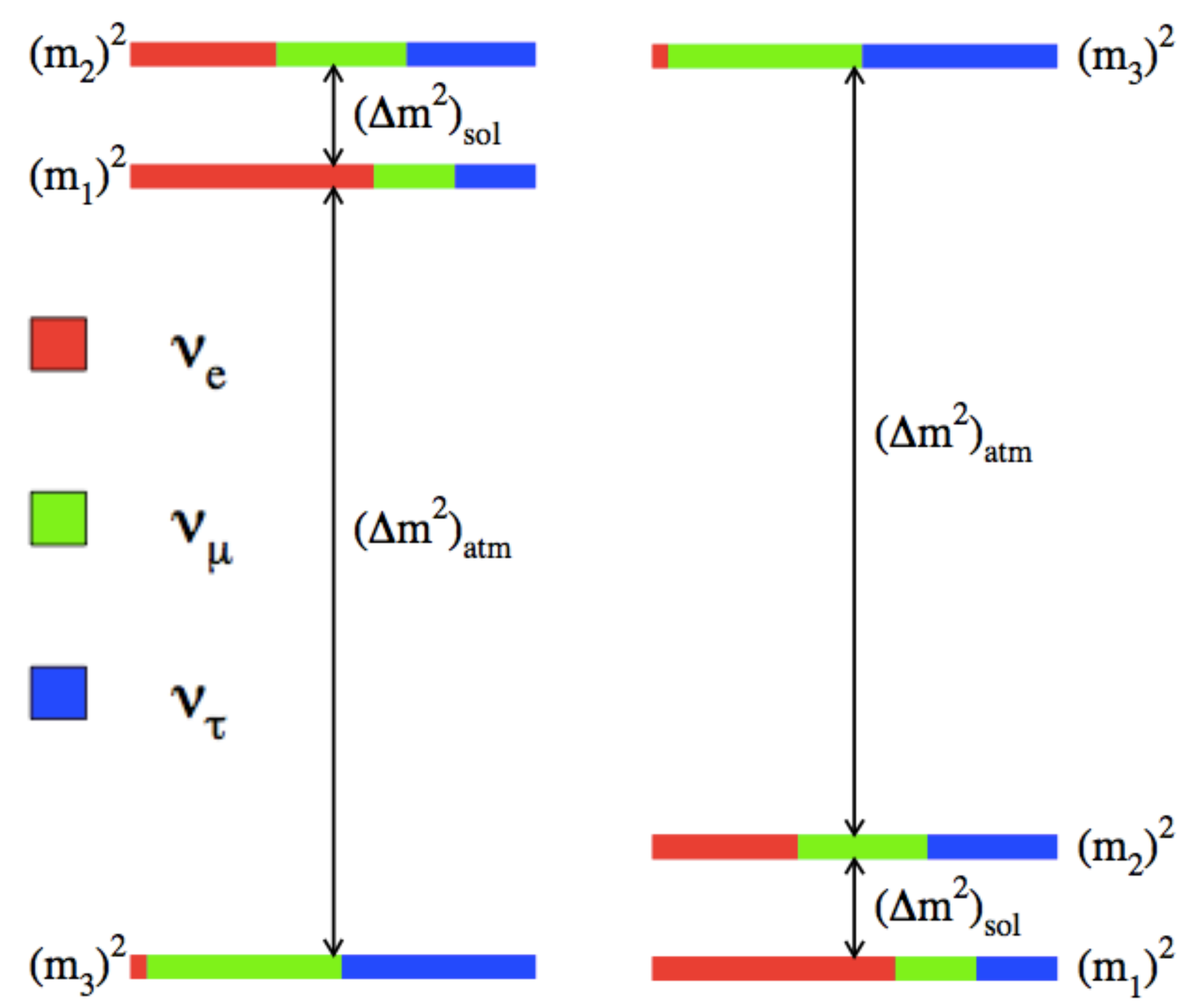
- Summary diagram:
  - bars depict mass states
  - colors show proportion of flavor mixture for each mass state
- Characterization of model incomplete
  - e.g. order of mass states unknown



Oscillations

- found two unique mass-squared values (though order of splittings unknown)
- one mass splitting much larger than other — reason why 2-flavor approximation is often good first order fit to data

Mass Hierarchy



"Inverted" "Normal"

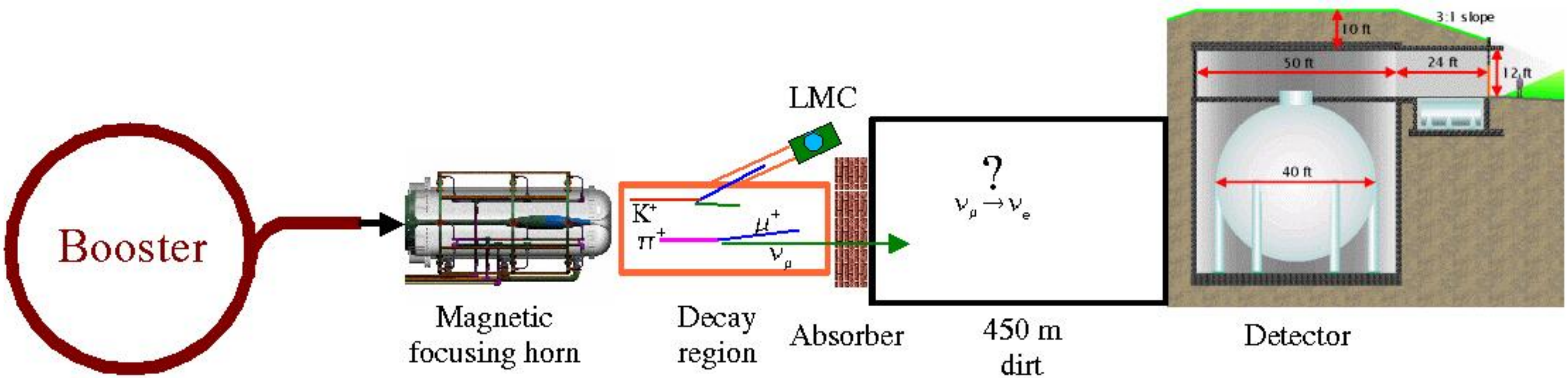
Anomalies

- But … not all neutrino data fits into 3 neutrino model

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

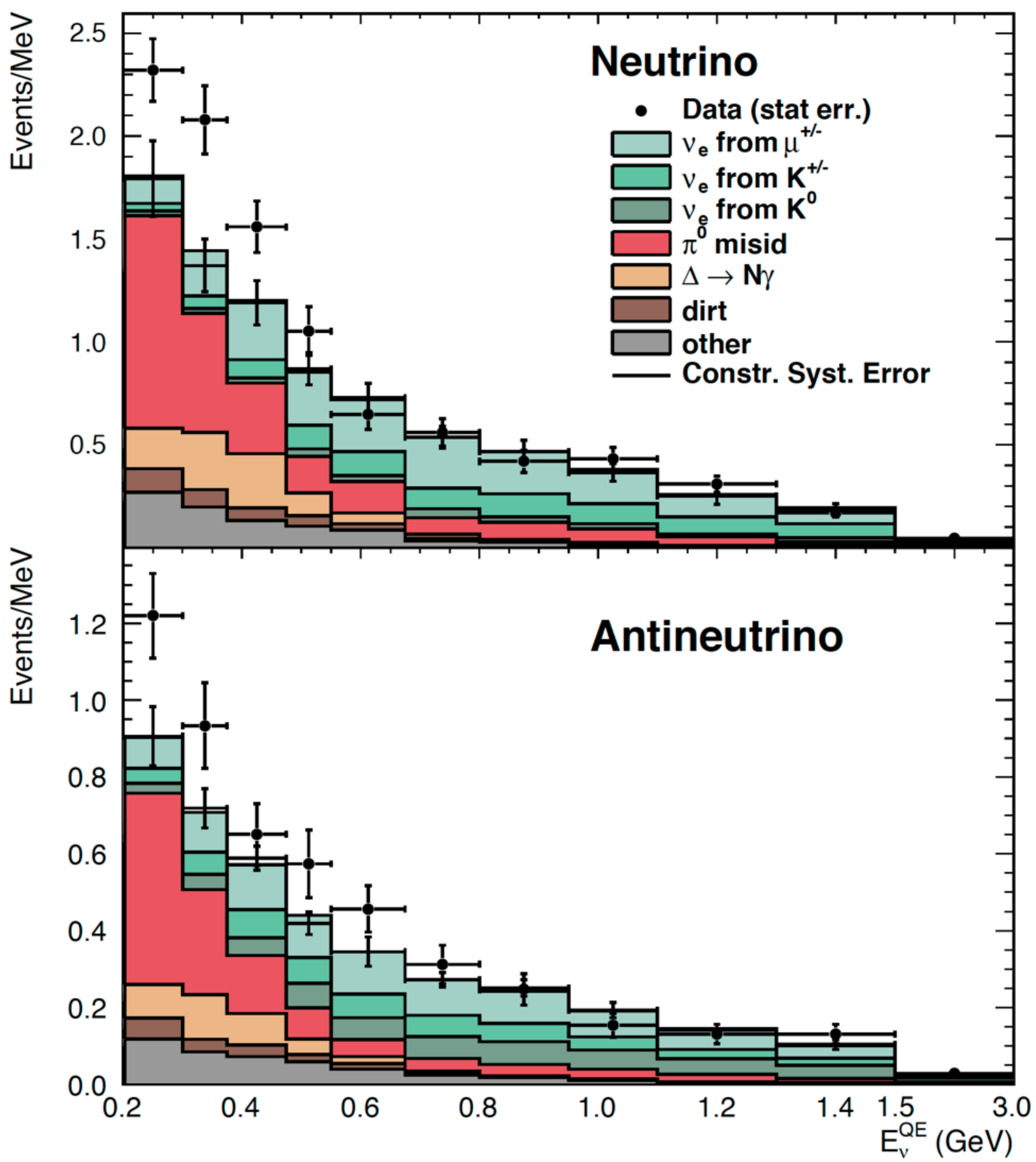
MiniBooNE

- MiniBooNE: (anti-)electron appearance experiment
  - accelerator neutrinos: mostly muon neutrinos
  - run in both neutrino and anti-neutrino mode
  - mineral oil detector



$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ or $P(\nu_\mu \rightarrow \nu_e)$

MiniBooNE



$\nu_\mu \to \nu_e$

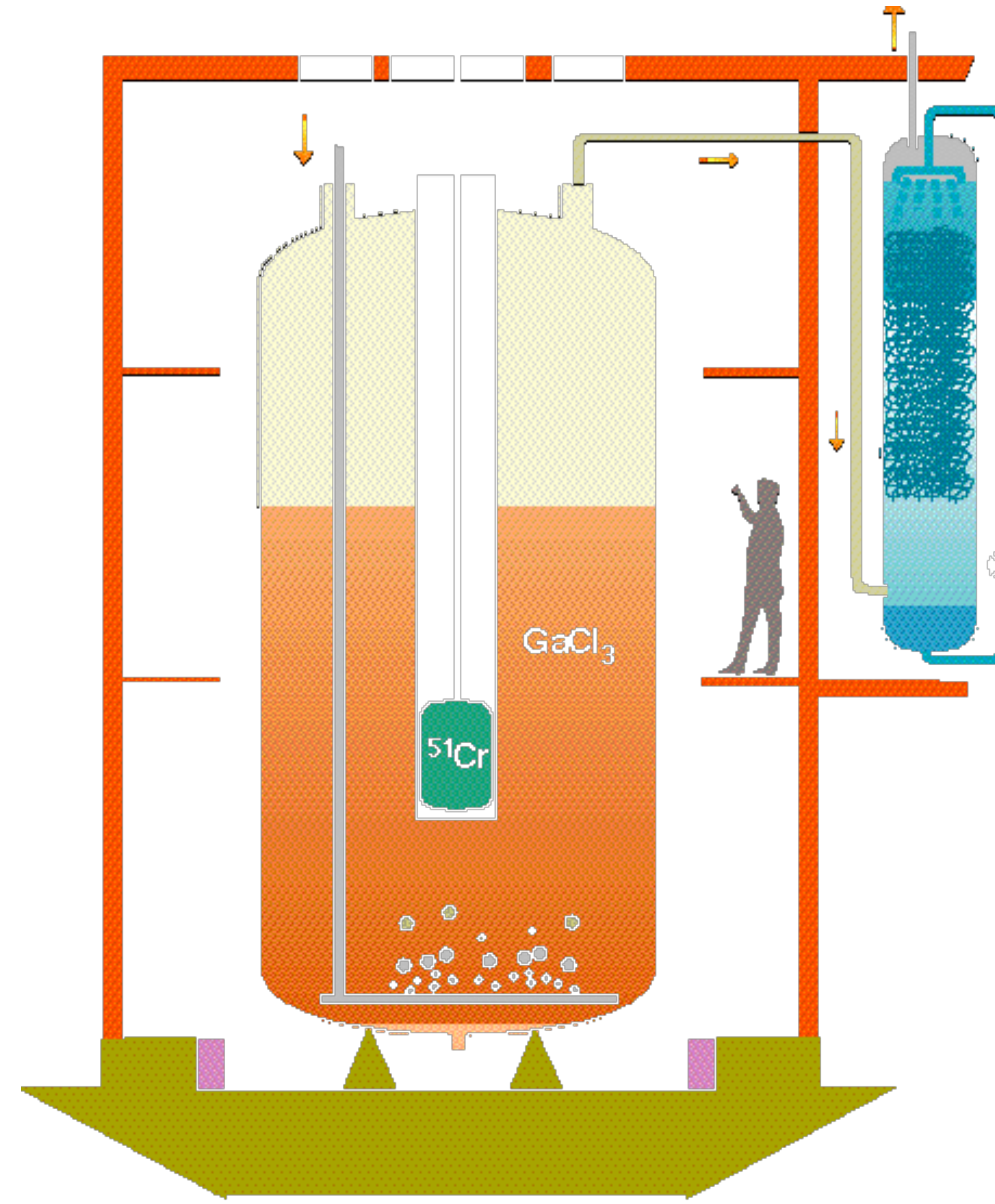
Neutrinos and antineutrinos from an accelerator seem to appear!

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

Radiochemical Anomalies

- SAGE and GALLEX experiments
  - detectors built for solar neutrino measurements
  - count neutrino interactions which convert Ga into ^{71}Ge

GALLEX



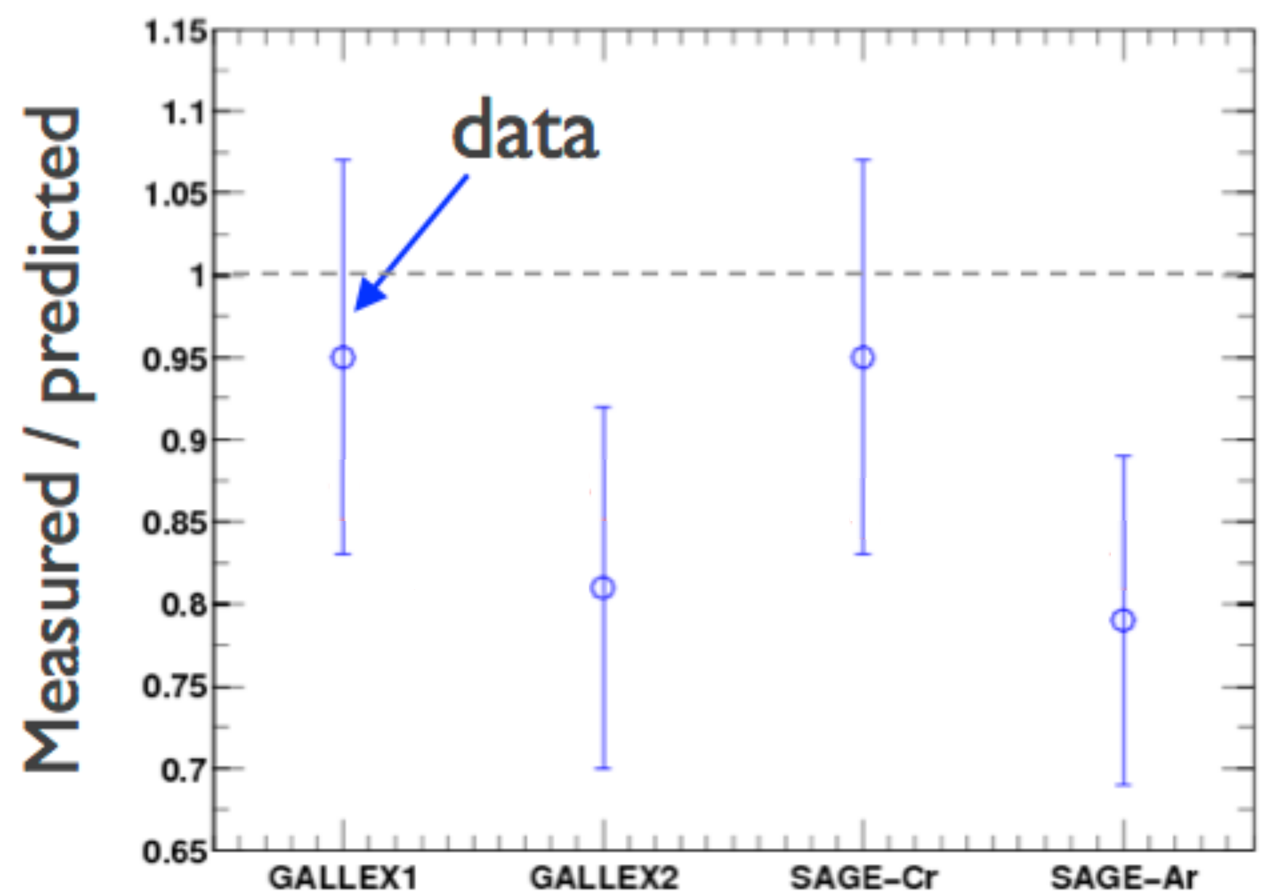
30.3 tons of Gallium
in an aqueous solution : $GaCl_3$ + HCl

Radioactive Anomalies

- high intensity electron neutrino source introduced to calibrate detectors
- number of neutrino events measured lower on average than expected
- can be interpreted as electron neutrino disappearance

$$P(\nu_e \rightarrow \nu_e)$$

electron neutrino disappearance



Summary of Anomalies

- Have several anomalies
- Alone might consider outliers, but together could they be a hint of something?

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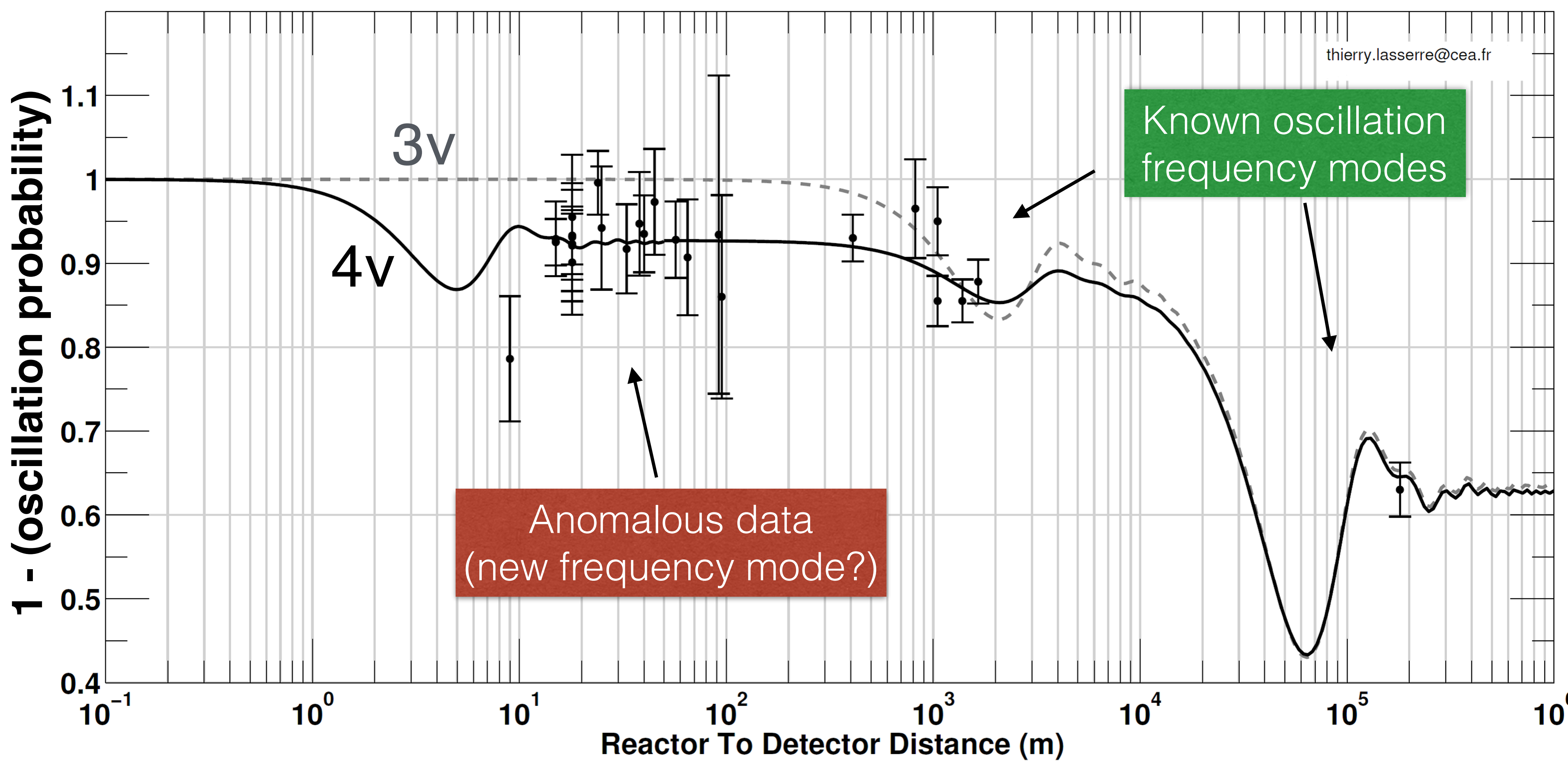
Reactors	Beta decay	electron disappearance (antineutrino)	1.4-3.0σ (varies)
GALLEX/SAGE	Source (electron capture)	electron disappearance (neutrino)	2.8σ

Reactor Anomaly

- Reanalysis of old reactor data sets show observed events is lower than expectation

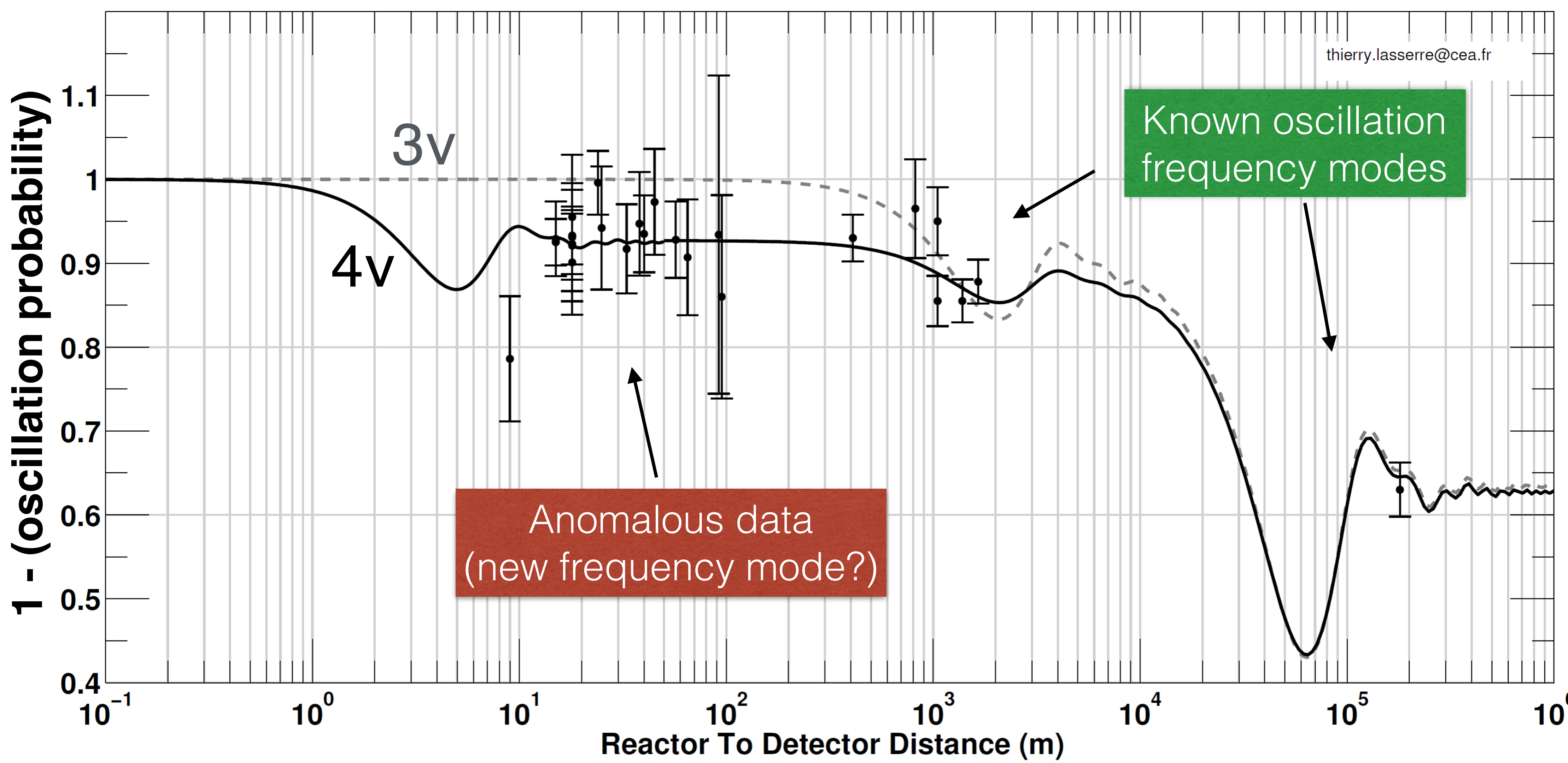
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$$



Reactor Anomaly

- If interpret as oscillations, at different frequency mode than other data

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$$

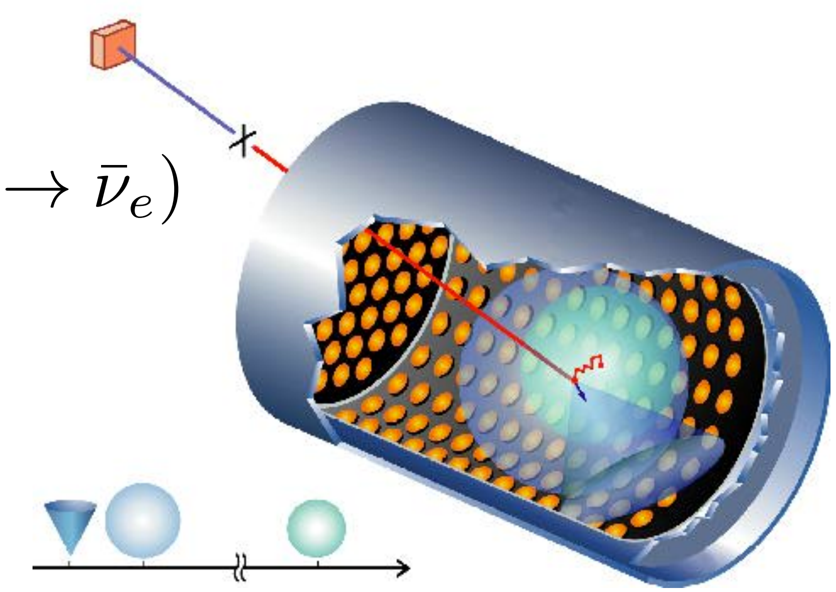


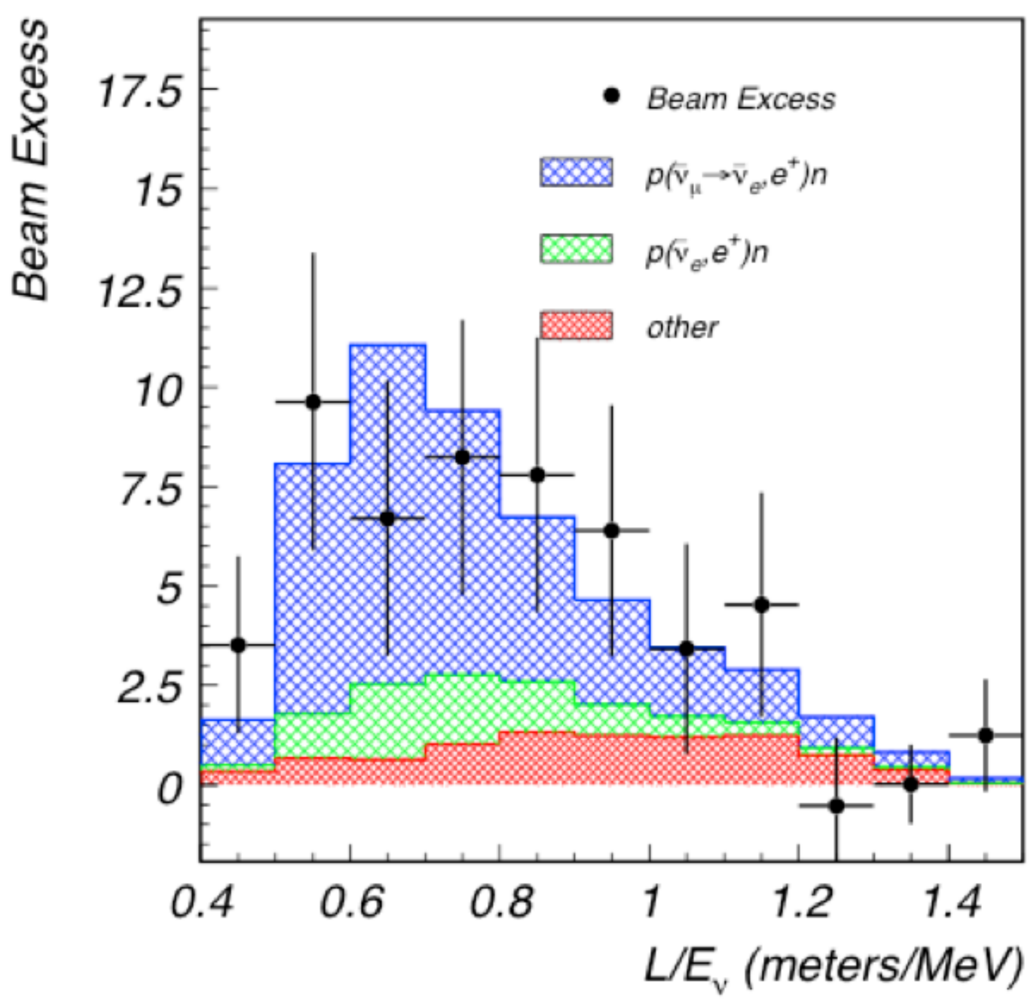
LSND

- LSND: anti-electron neutrino appearance
  - Pion decay at rest source: muon anti-neutrinos
  - Liquid scintillator detector

sees excess of anti-electron neutrino events

$P(\bar{\nu}_\mu \to \bar{\nu}_e)$

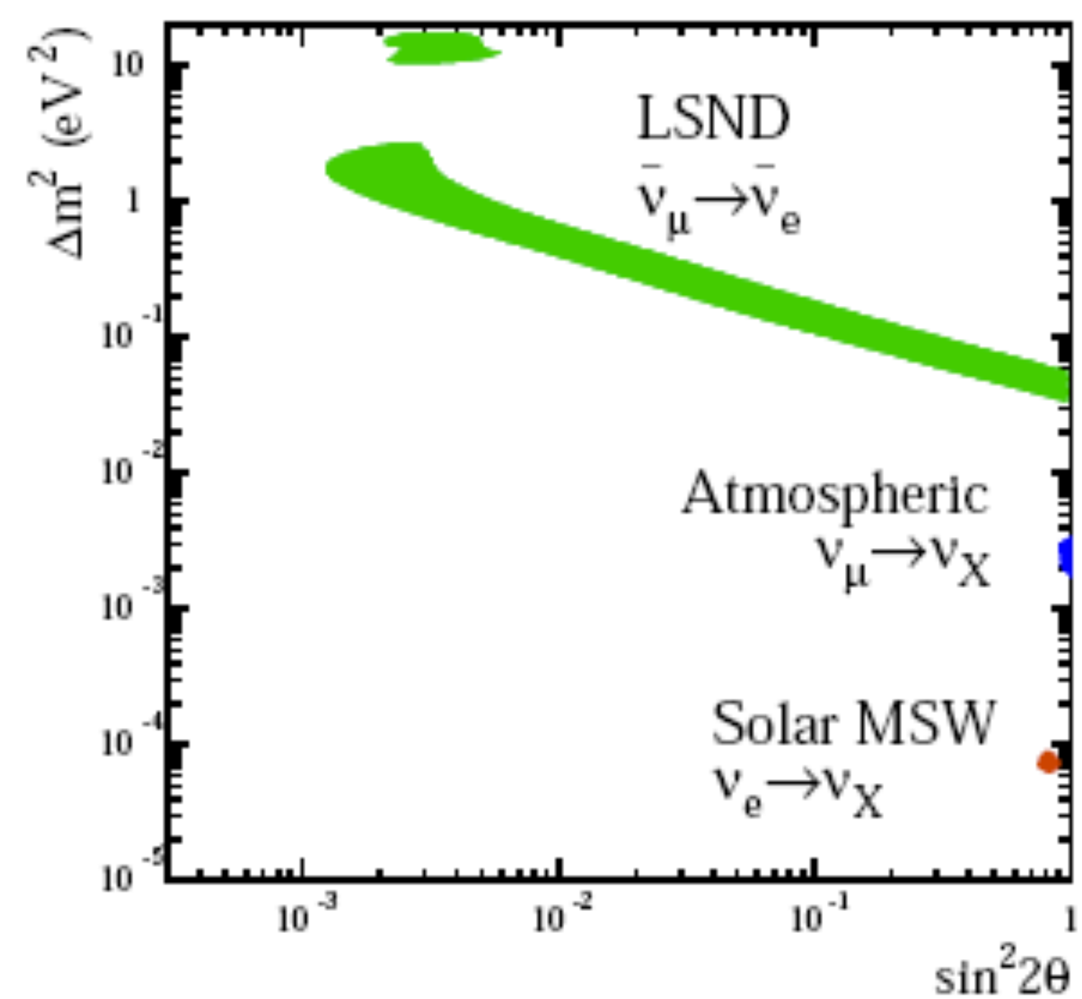




LSND

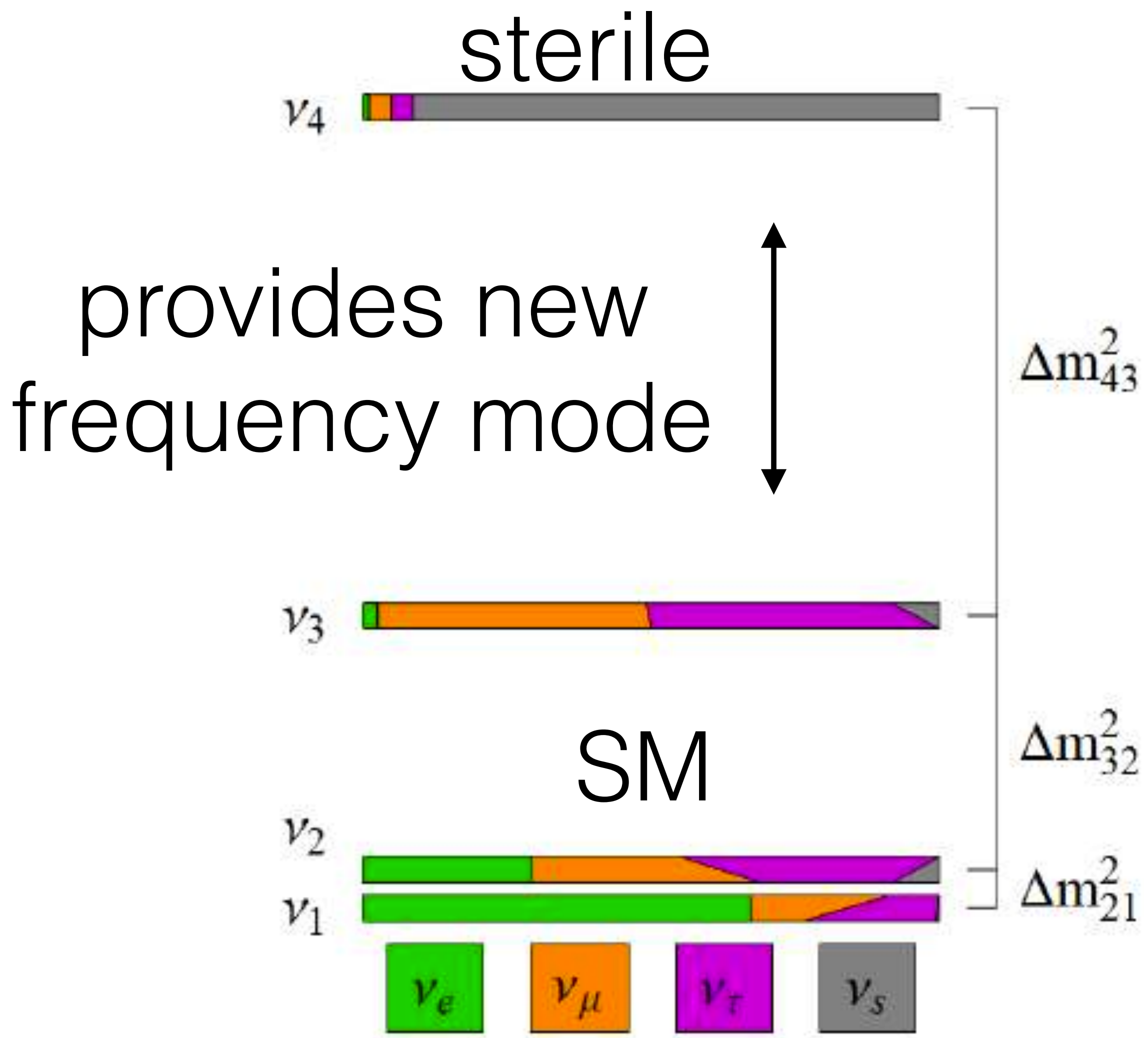
oscillation with Δm^2 ~ 1 eV^2

- Interpret LSND excess as oscillation signature
- oscillations with Δm^2 ~ 1 eV^2
- bigger than SM mass splittings — allows 2 neutrino approximation for fit



Sterile Neutrino

- How to interpret data?
- Could there be a new neutrino?
- New neutrino cannot interact via the weak force — width of the Z boson tells us only 3 couple weakly



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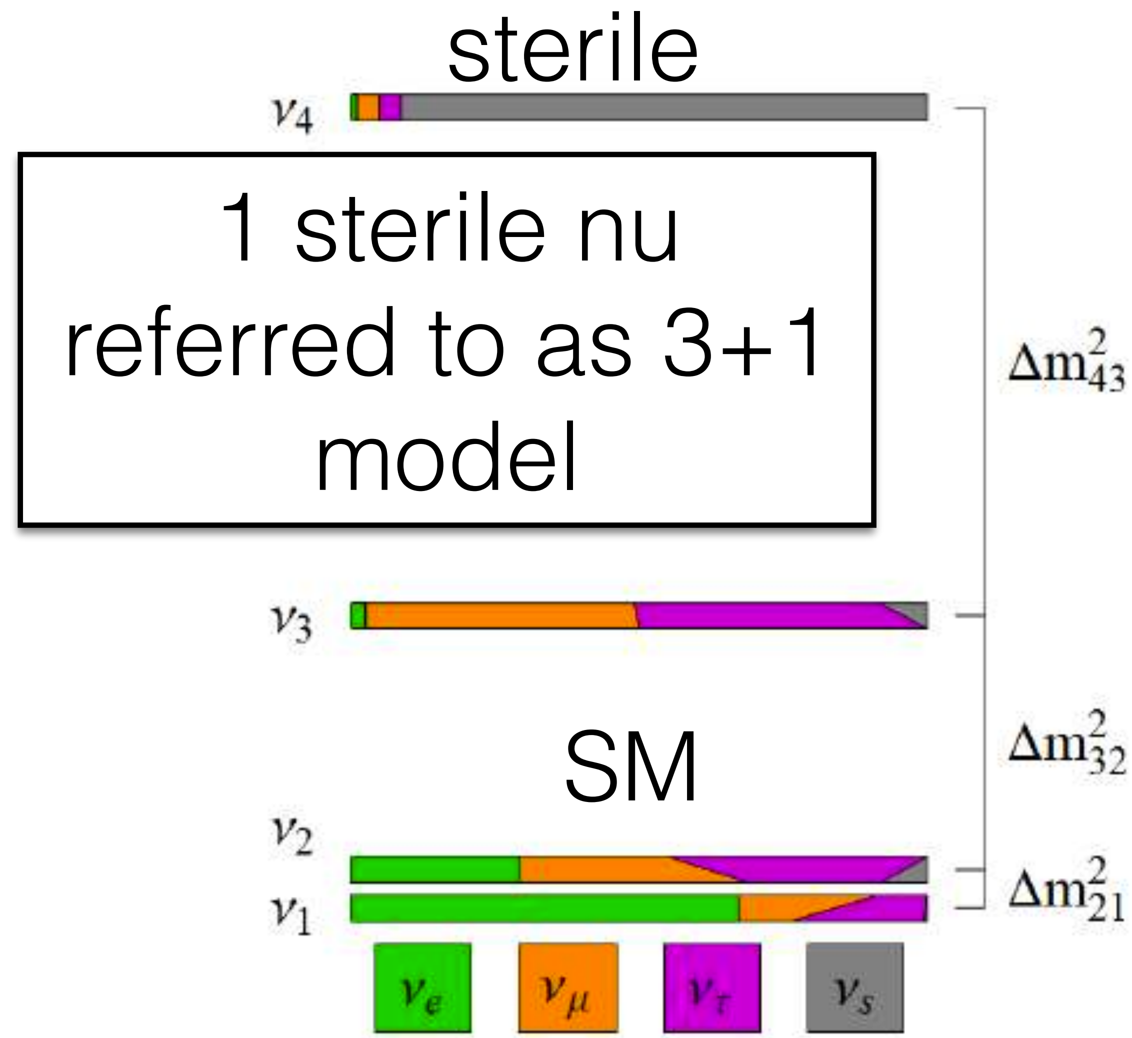

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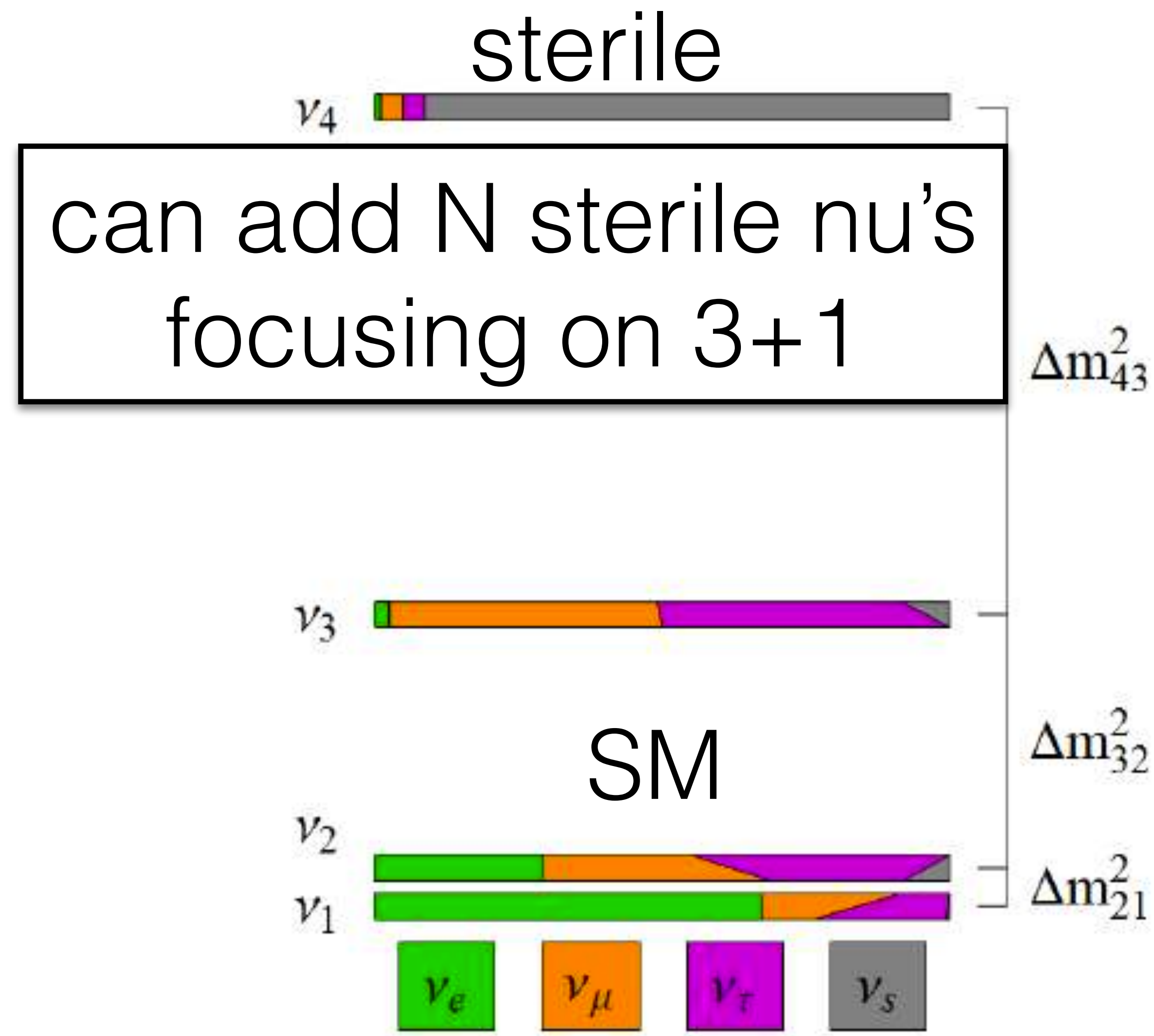
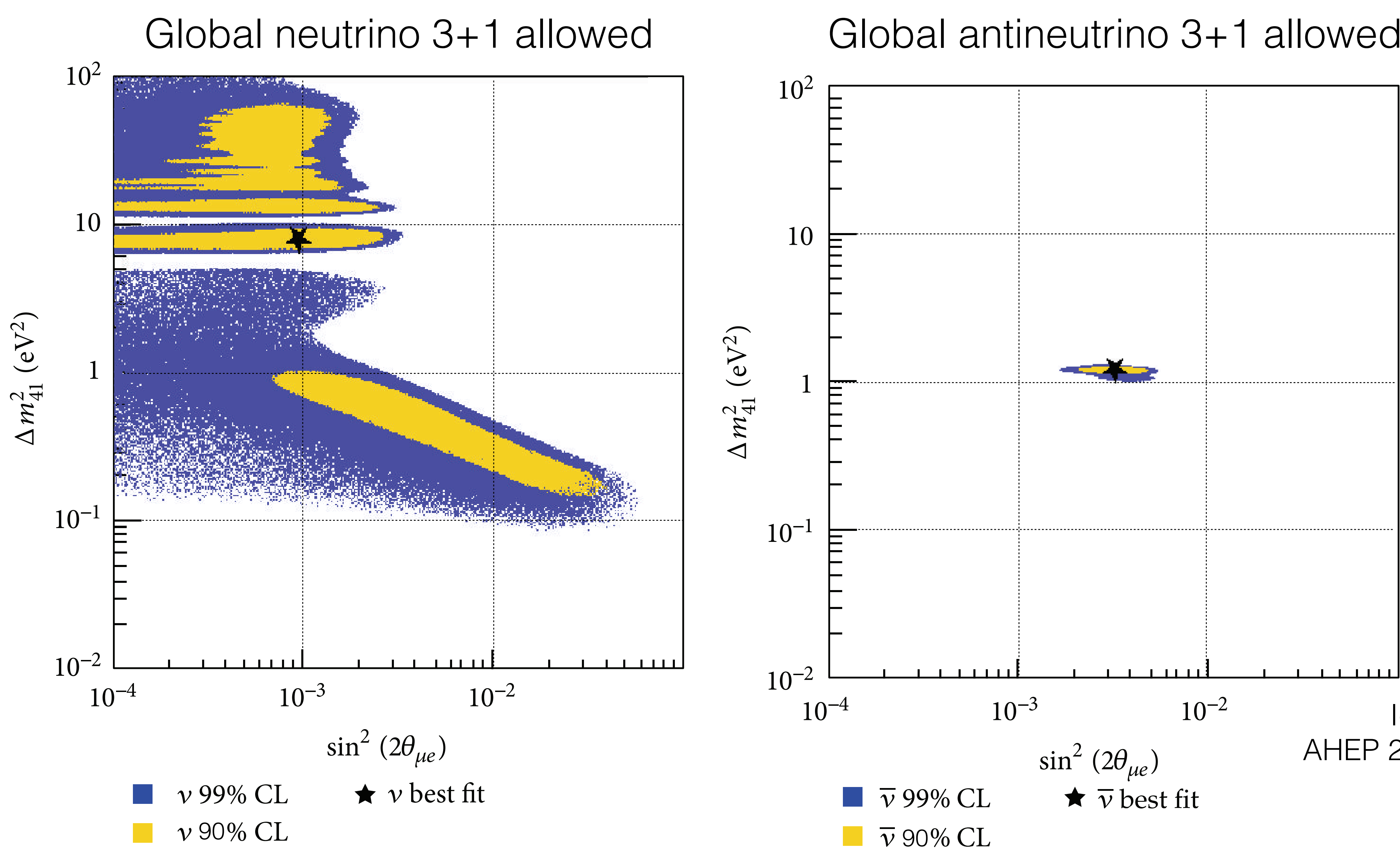


Global Fit

- Put all the data out there together and interpret with 3+1 sterile neutrino model

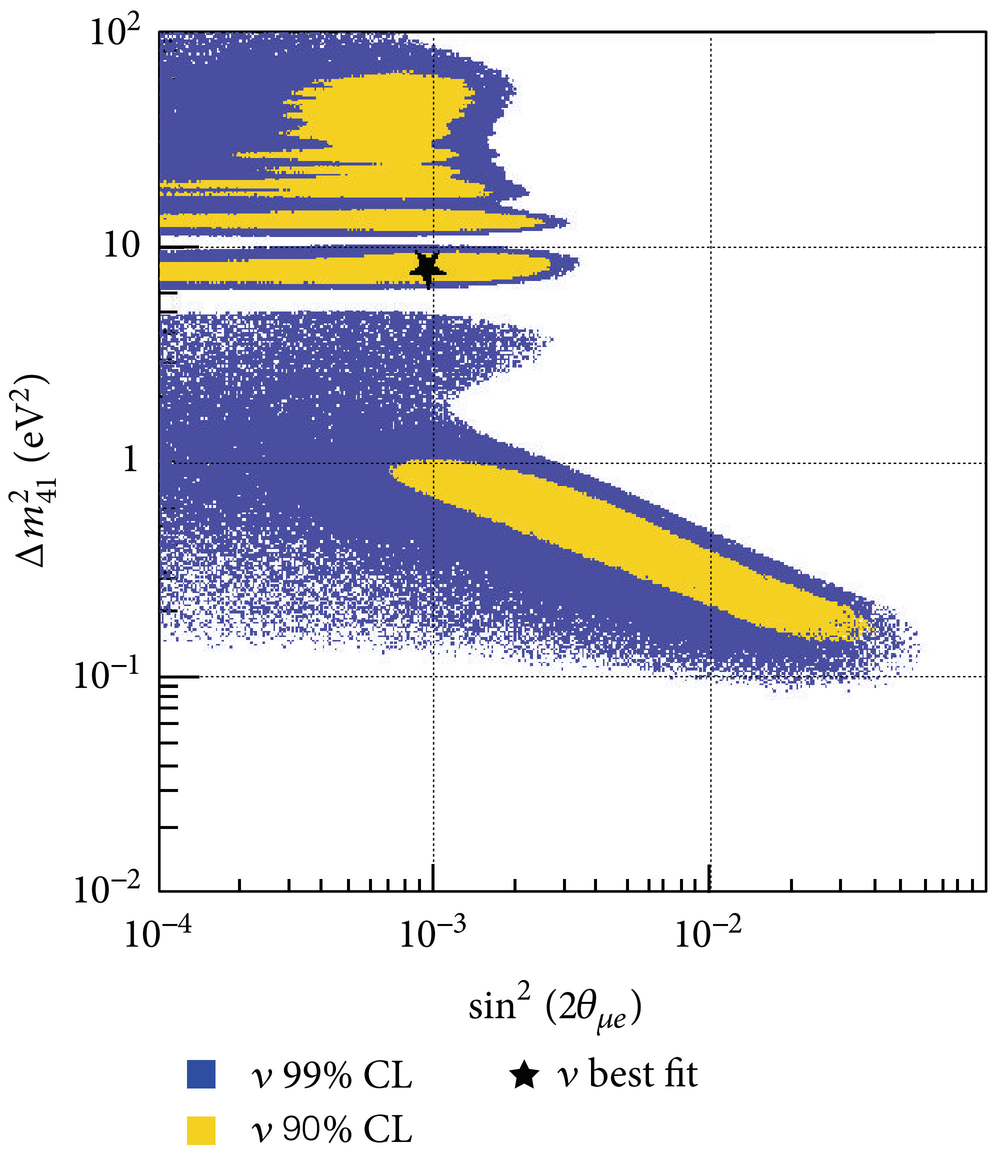


Ignarra, *et al.*
AHEP 2013 163897 (2013)

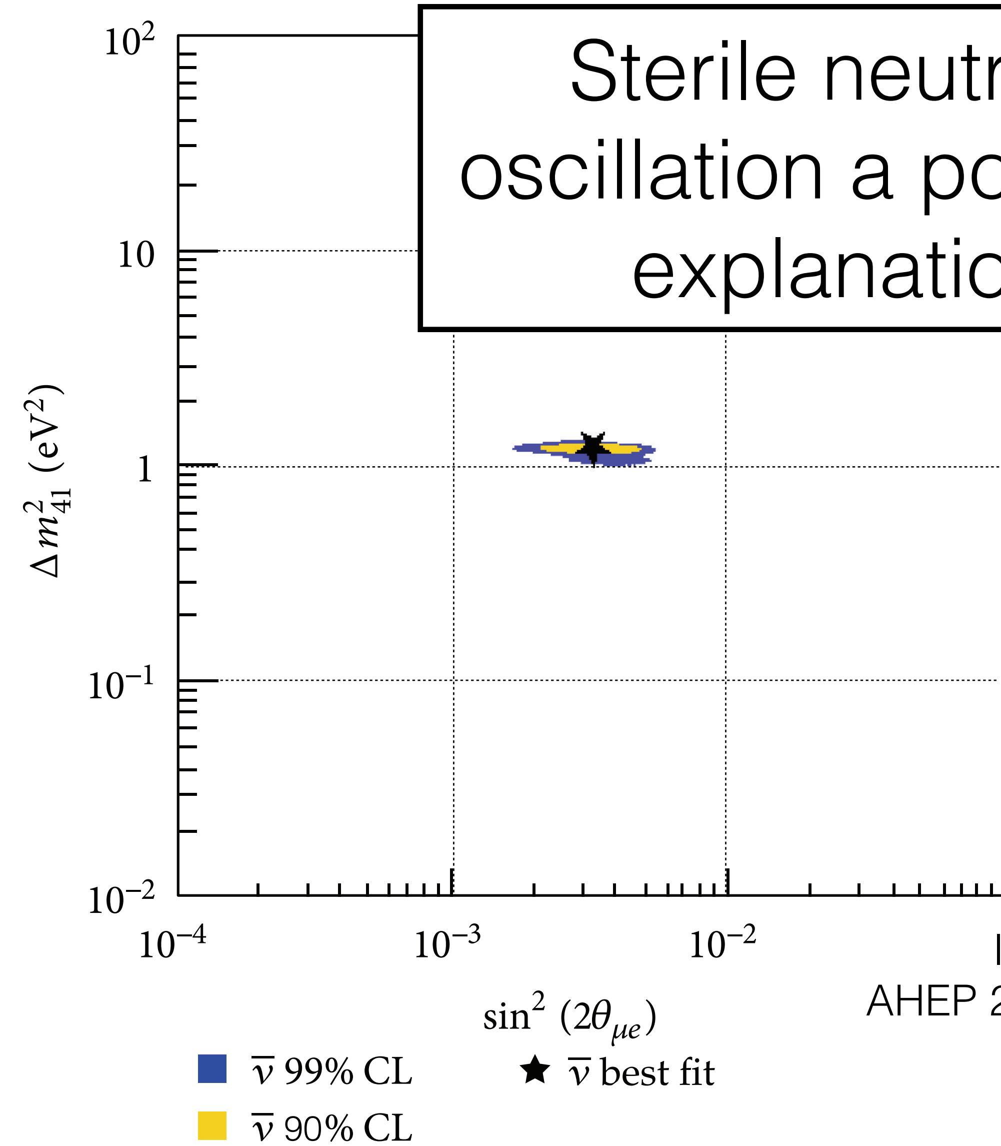
Global Fit

- Put all the data out there together and interpret with 3+1 sterile neutrino model

Global neutrino 3+1 allowed



Global antineutrino 3+1 allowed

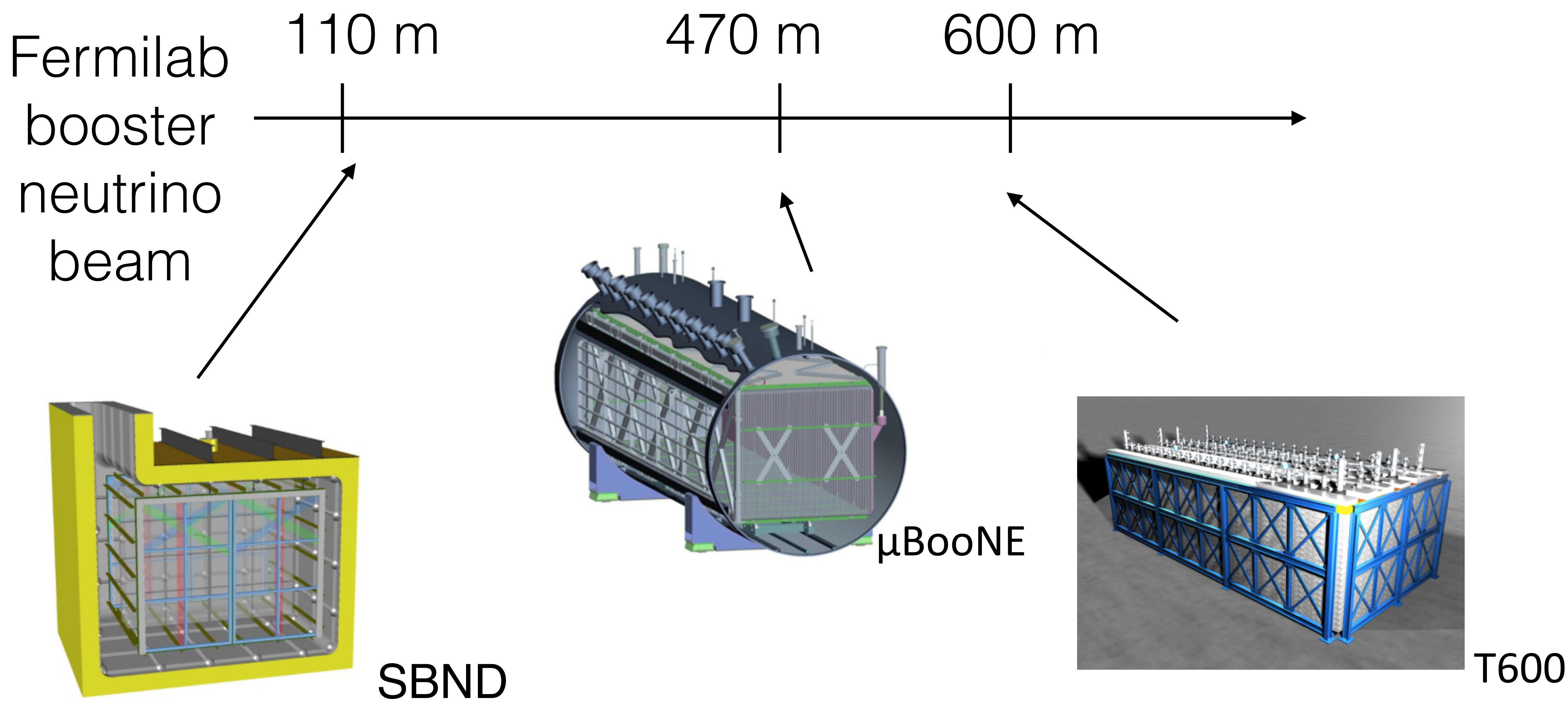


Sterile neutrino oscillation a possible explanation

Ignarra, *et al.*
AHEP 2013 163897 (2013)

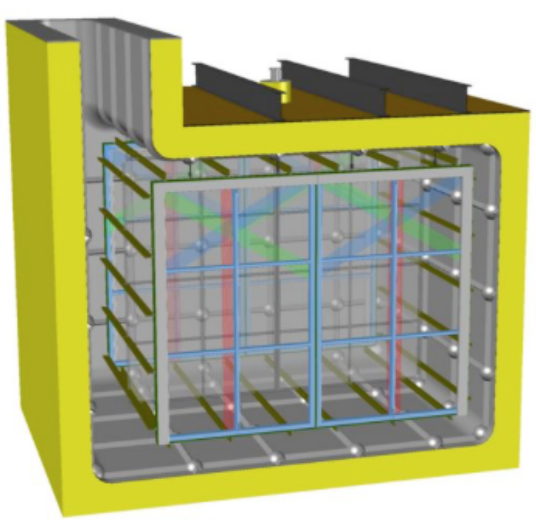
SBN at Fermilab

- Proposal for 3 liquid argon TPCs to look for short baseline oscillations

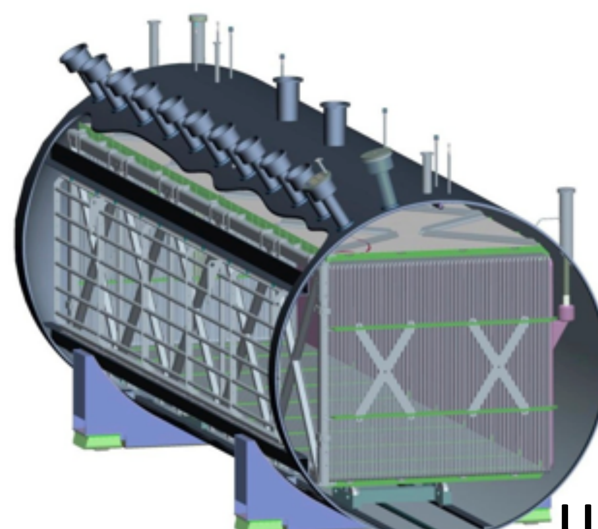


SBN at Fermilab

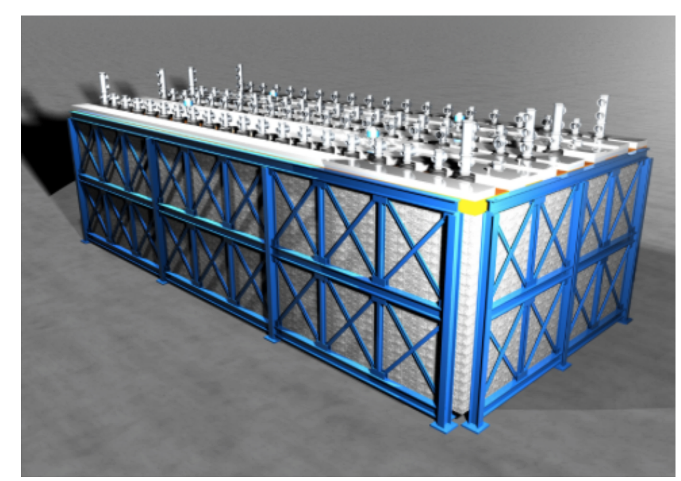
- Modeling flux and cross section to get correct predicted rate in detector is not easy
- Use ratio of events at different baselines removes some systematic uncertainties



SBND



μBooNE



T600

SBN at Fermilab

- Proposal for 3 liquid argon TPCs to look for short baseline oscillations

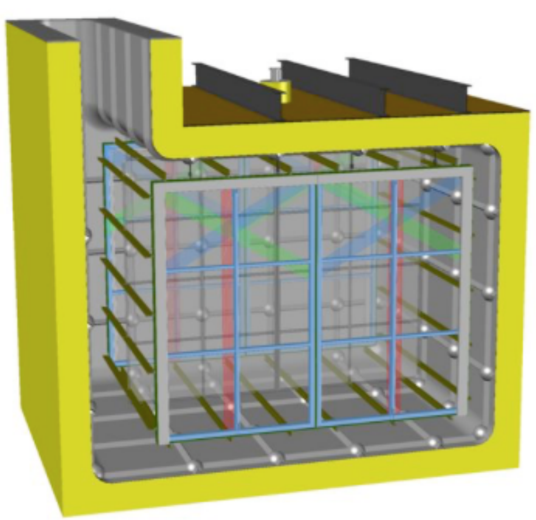
Fermilab booster neutrino beam

110 m

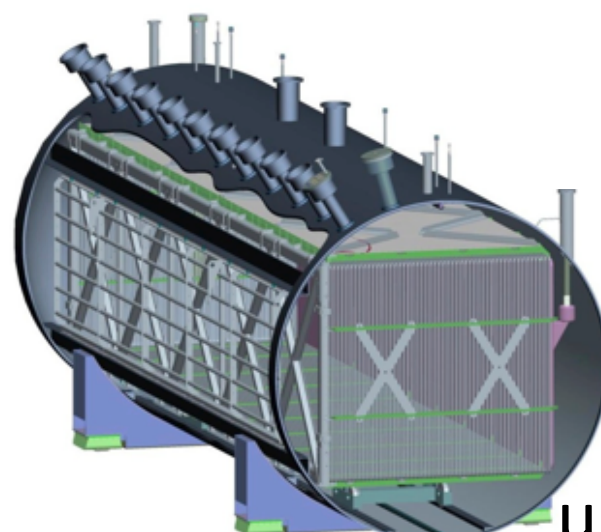
470 m

600 m

currently cooling down



SBND



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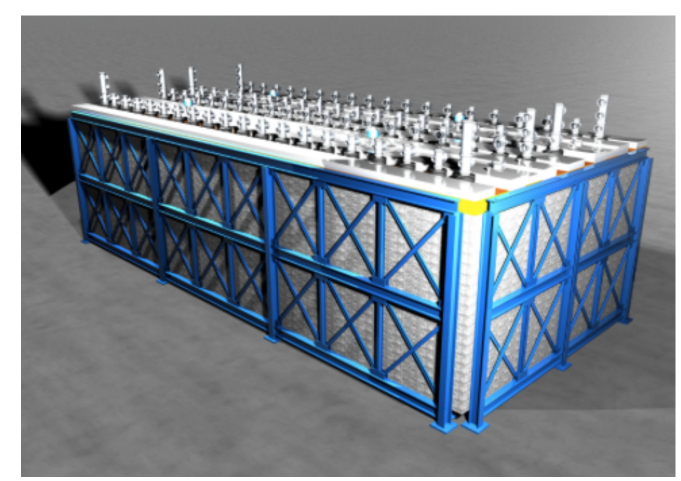

T600

SBN at Fermilab

- SBN detectors are liquid argon TPCs
- ability to produced detailed images of neutrino interactions
- aim is to use this information to reduce backgrounds