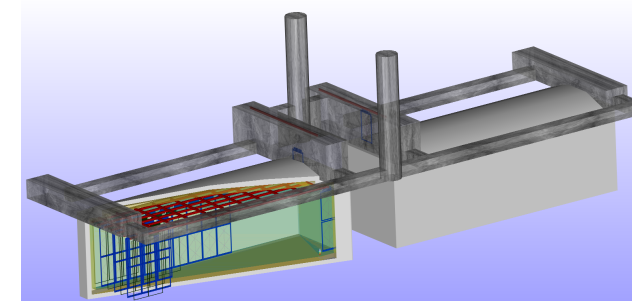
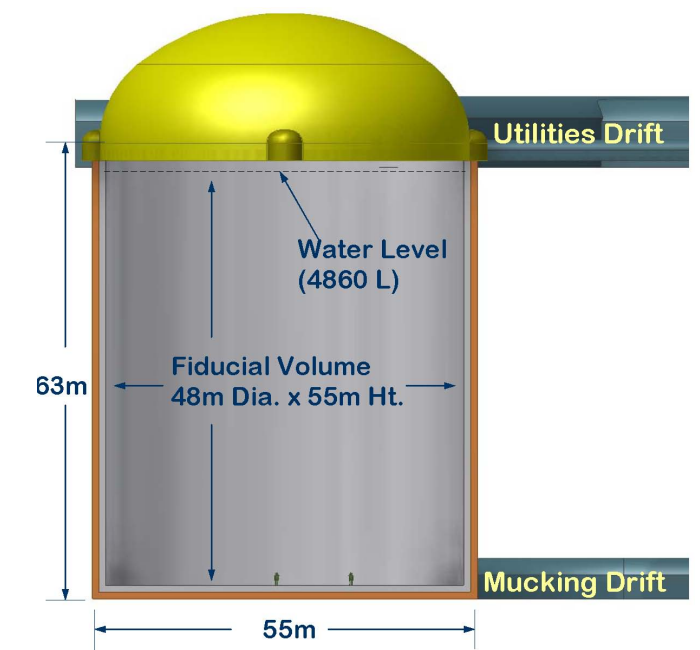
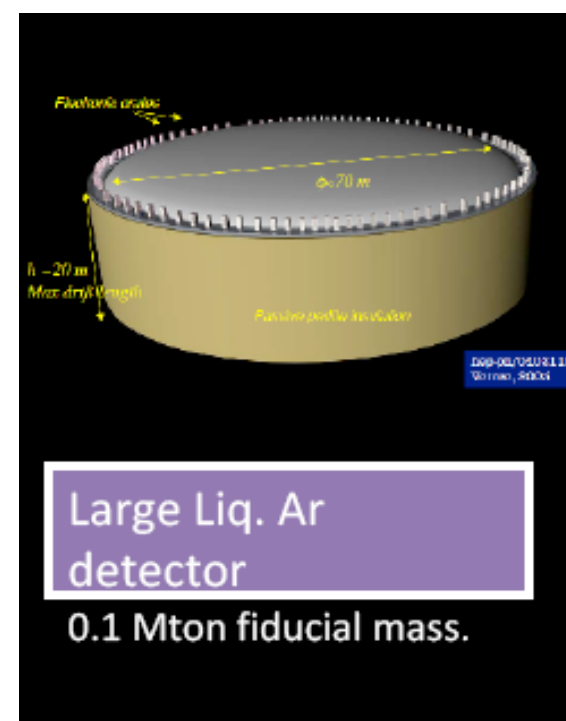
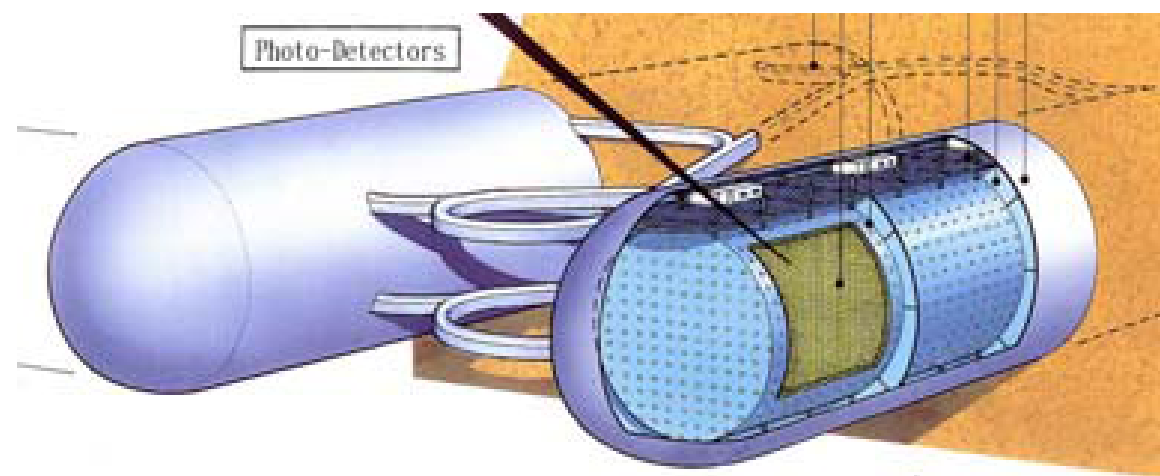
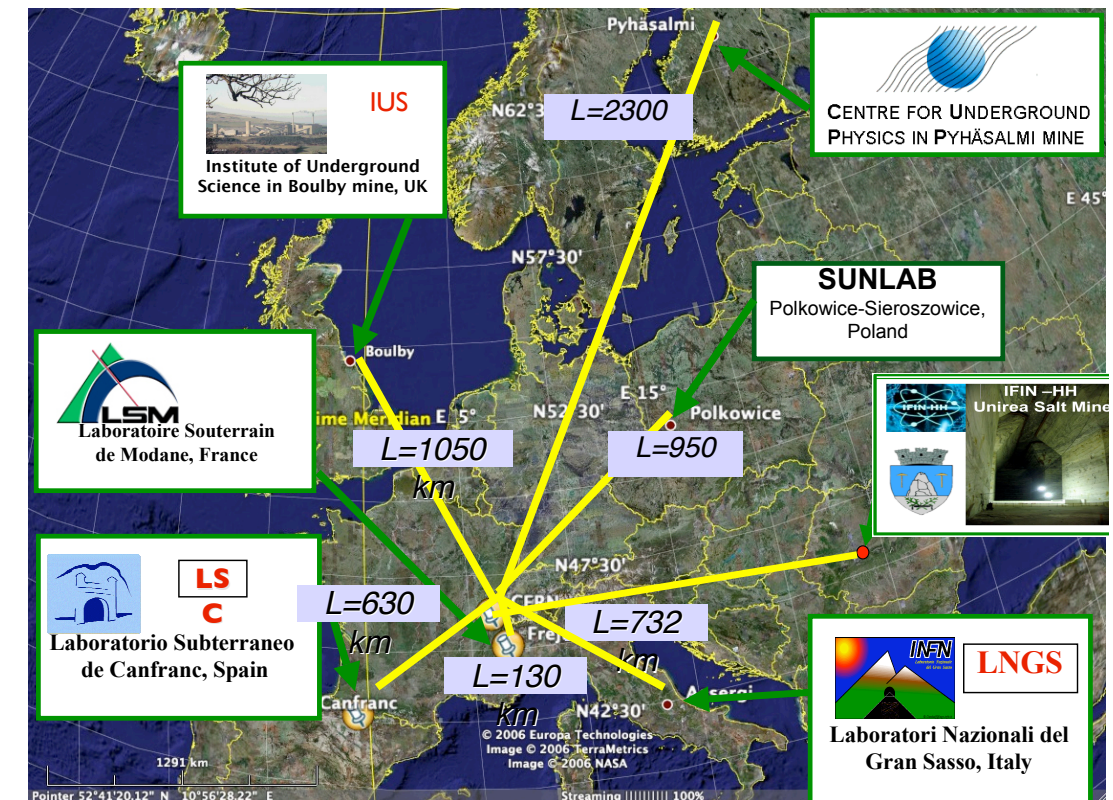
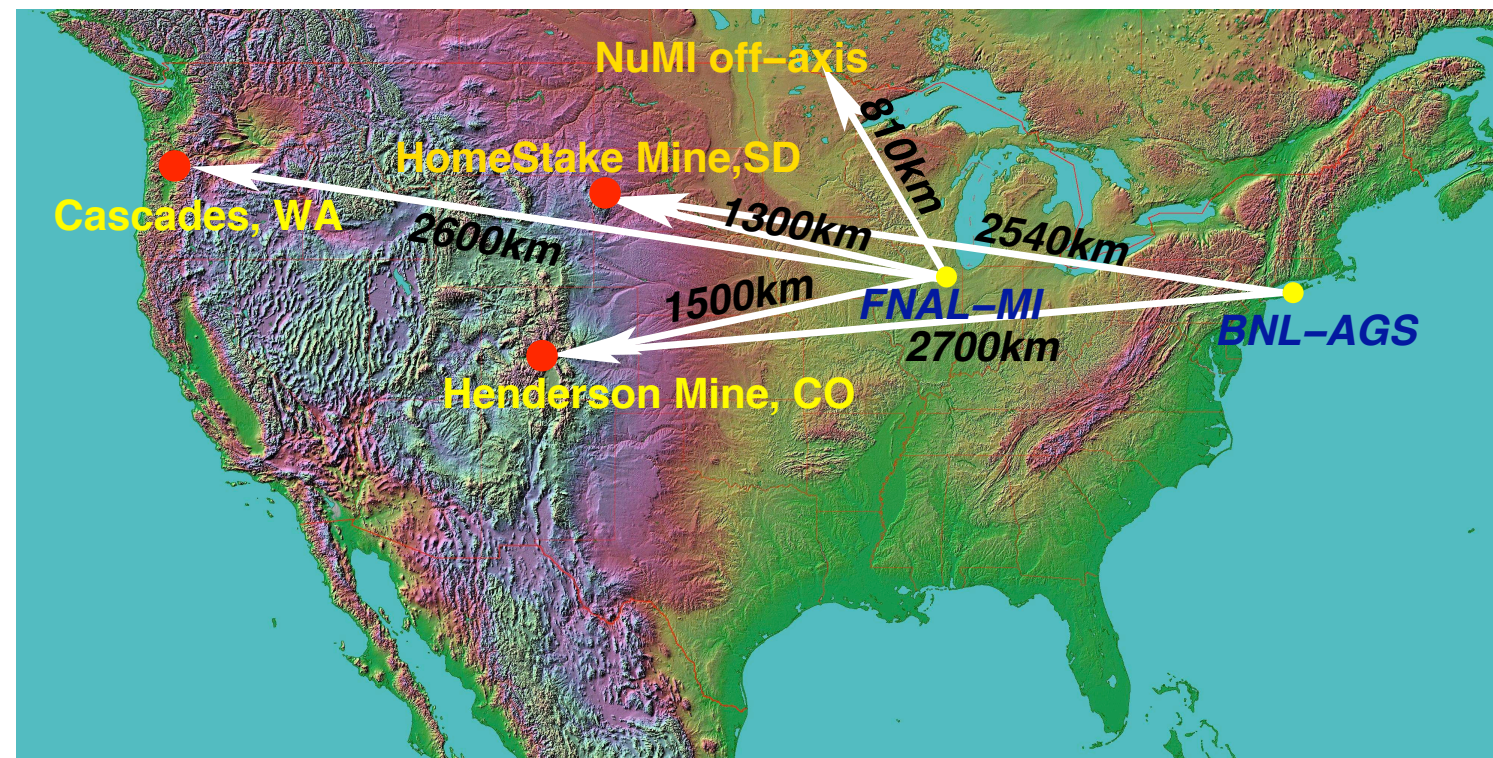
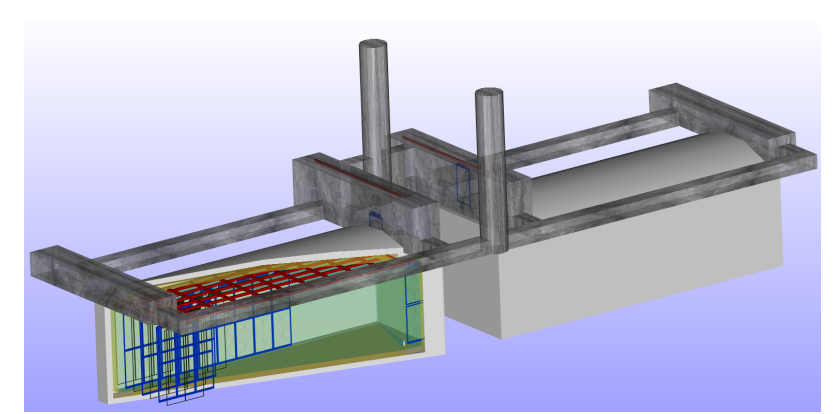
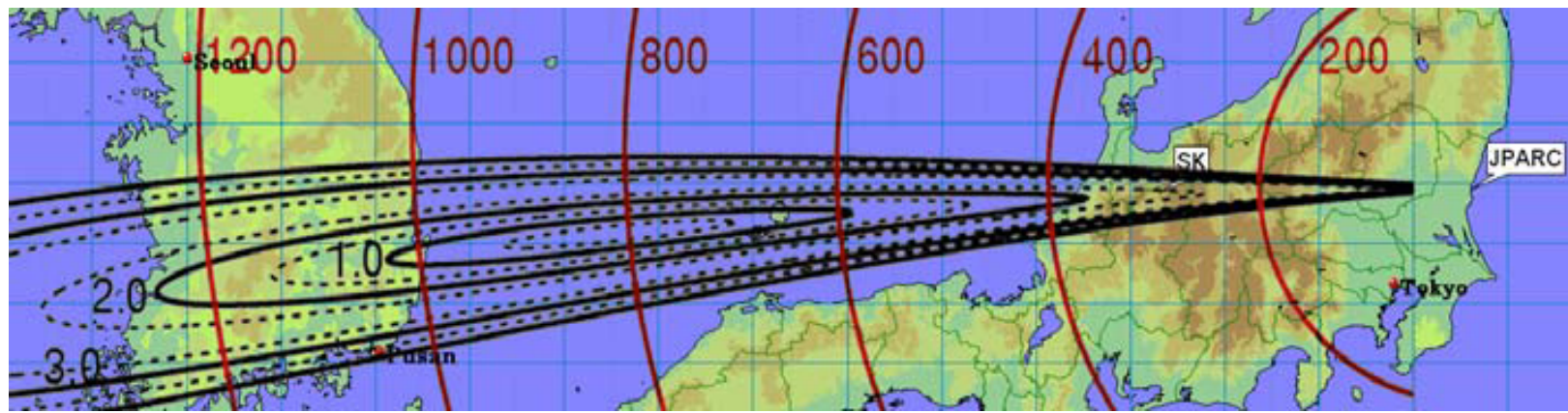


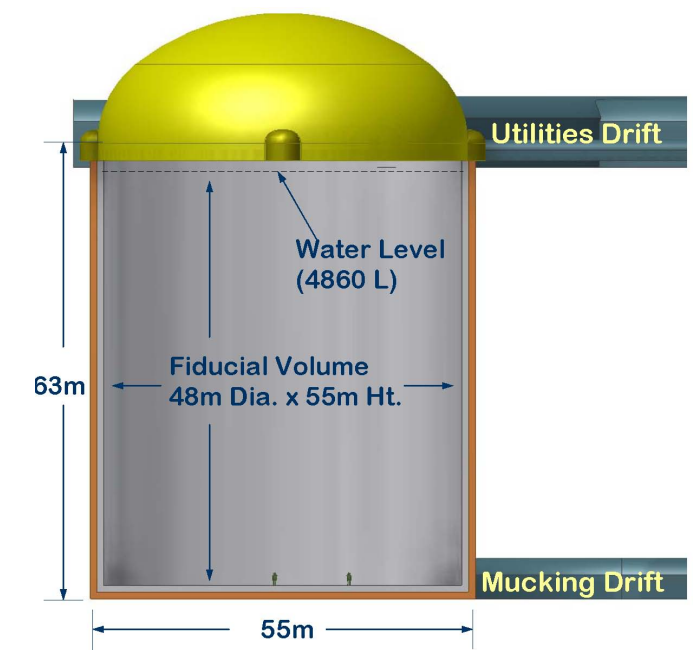
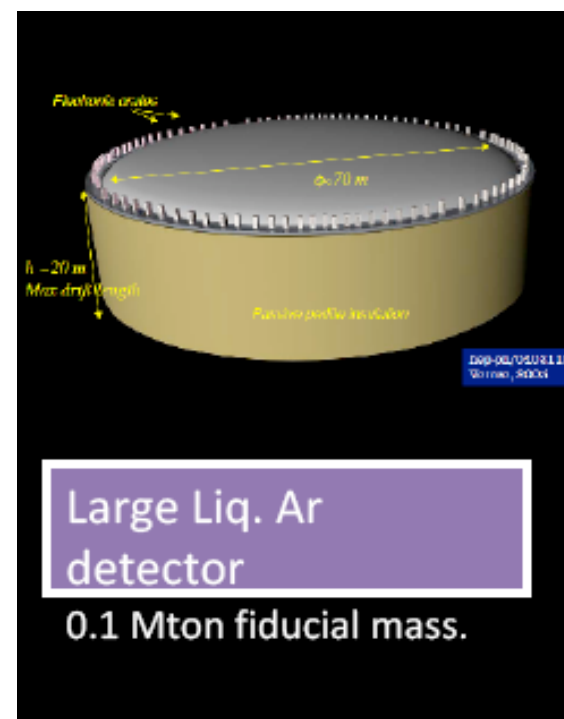
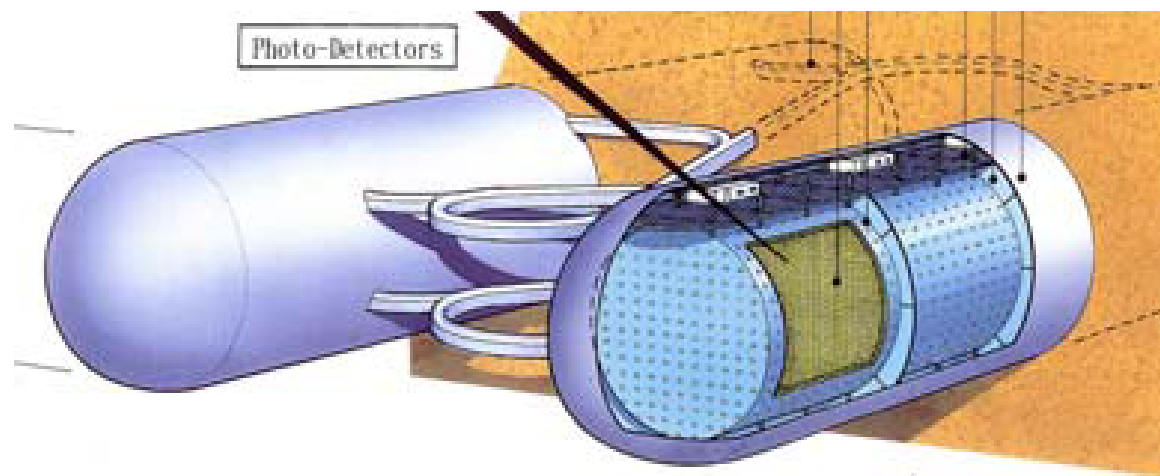
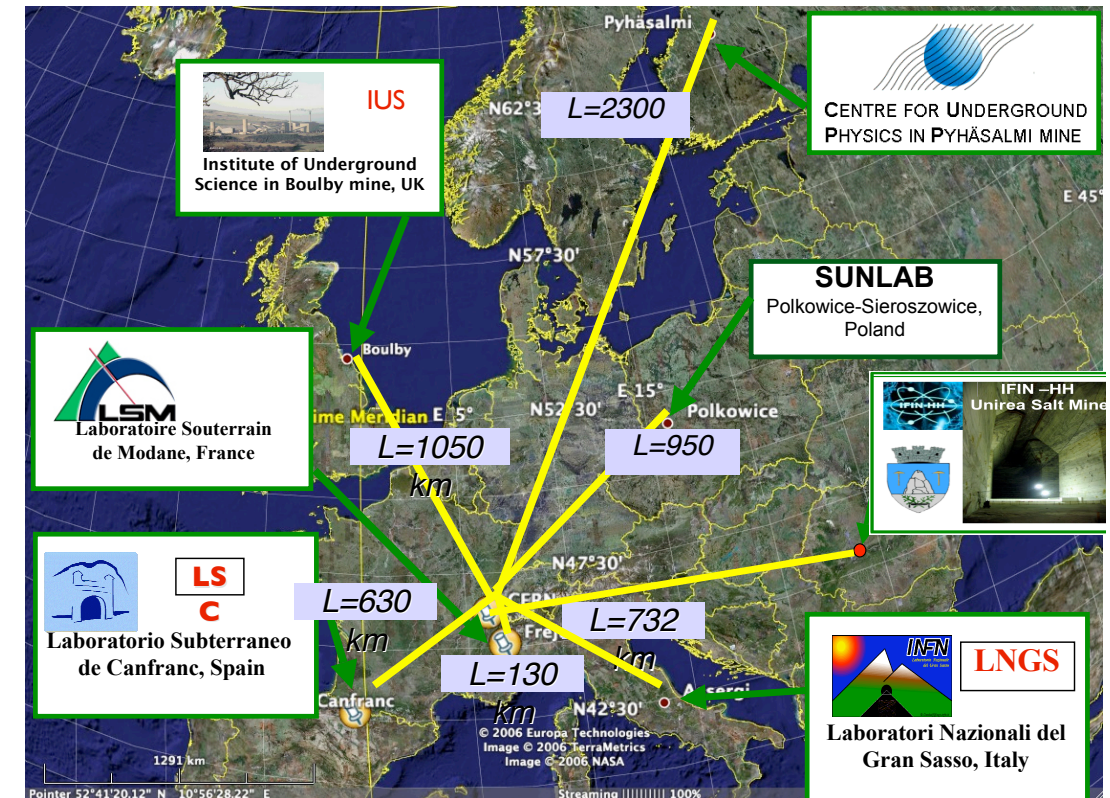
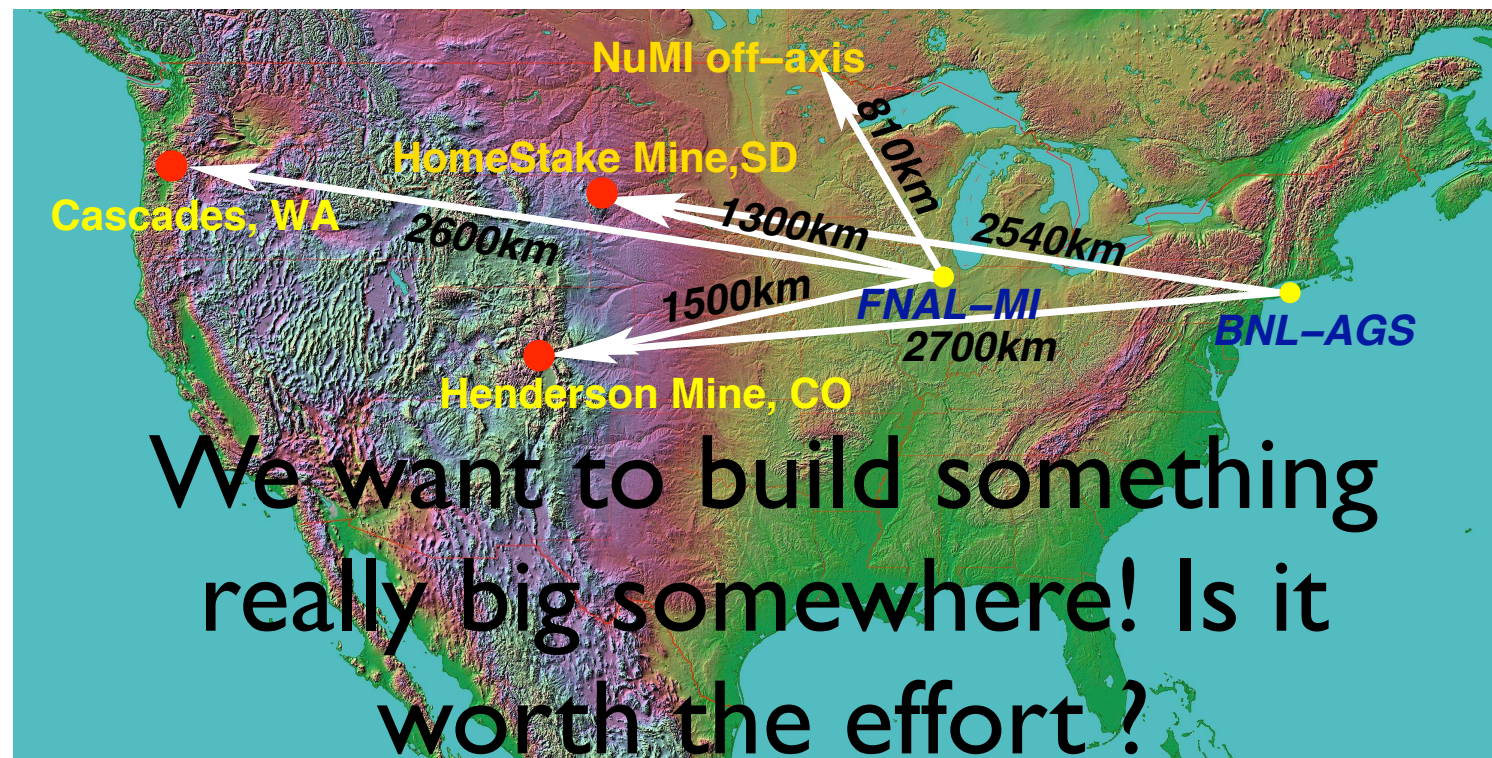
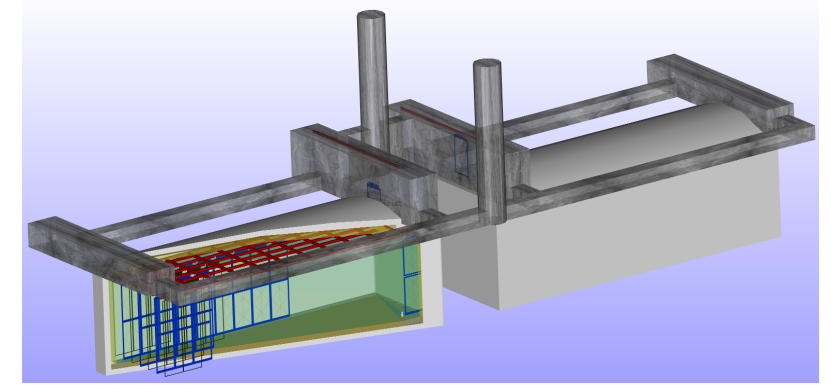
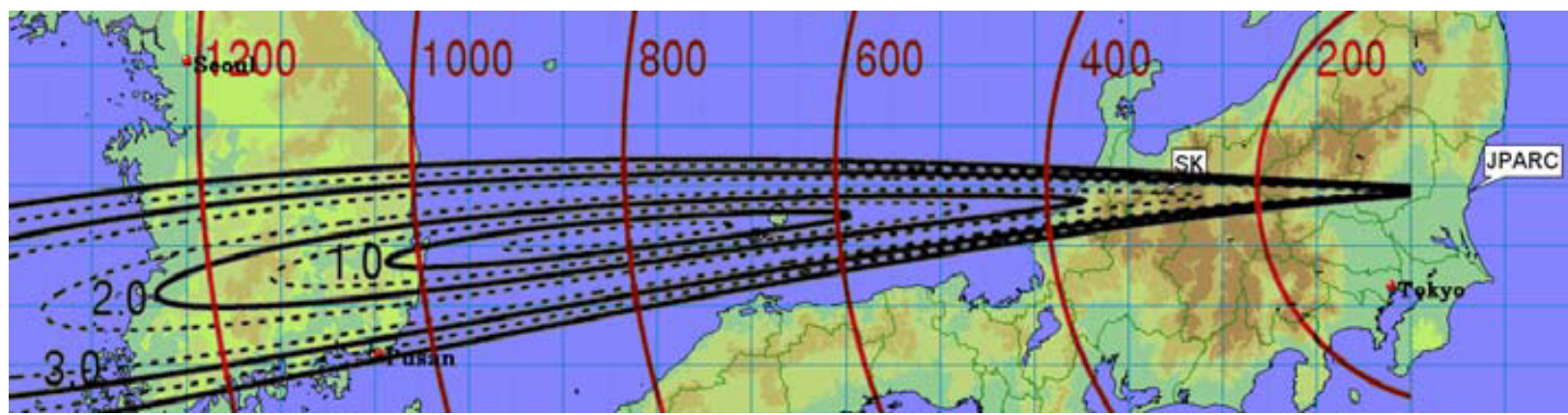
Overview of Long Baseline Neutrino Physics Experiments

Milind Diwan

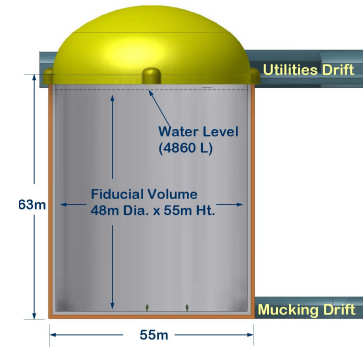
Workshop for Giant Liquid Argon Counter
Jyvaskyla, Finland, 6/7/2011



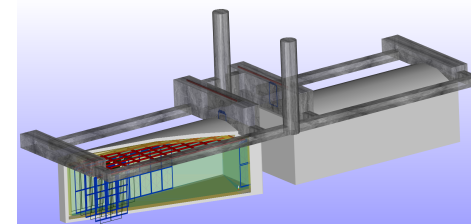




Outline



- The reason for a new large accelerator neutrino experiment.
- Neutrino properties summary
- Lessons from some previous experiments (not comprehensive)
- Description of possible accelerator beams
- Possible strategies for the detector
- Final observations and requirements that must be fulfilled.



The real reason



- By taking our sense of sight far beyond the realm of our forebears' imagination, these wonderful instruments, the telescopes, open the way to a deeper and more perfect understanding of nature.
—René Descartes, 1637

4) In weak processes neither parity P nor charge conjugation C are conserved although the laws of nature are (almost) invariant with respect to the combined inversion PC , which changes simultaneously the signs of coordinates and charges. Non conservation of parity implies longitudinal polarization of particles and thus there arose the theory of two component neutrino of Landau, Lee and Yang, Salam and Sakurai, which is an old theory of Weil, made plausible by parity non-conservation. A good model of the neutrino according to this theory is a screw. Actually it was shown experimentally by Goldhaber that neutrinos are left-handed. Anti-neutrinos are right-handed. Thus we have two states only and not four, as for an actual screw: screw left-handed, screw right-handed, antiscrew left-handed, antiscrew right-handed. Now the importance of the longitudinal neutrino is that such neutrino gives us the prototype of the behaviour of all other (not massless) fermions, under weak interaction. A simple mnemonic rule is that, under weak interaction, all fermions are left-handed, all anti-fermions are right-handed. This has been incorporated in the famous universal weak interaction $V-A$ theory

Pontecorvo 1981

What is the scientific interest in neutrinos ?

FERMIONS			matter constituents		
			spin = 1/2, 3/2, 5/2, ...		
Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c ²	Electric charge	Flavor	Approx. Mass GeV/c ²	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times 10^{-9}$	0	u up	0.002	2/3
e electron	0.000511	-1	d down	0.005	-1/3
ν_M middle neutrino*	$(0.009-0.13)\times 10^{-9}$	0	c charm	1.3	2/3
μ muon	0.106	-1	s strange	0.1	-1/3
ν_H heaviest neutrino*	$(0.04-0.14)\times 10^{-9}$	0	t top	173	2/3
τ tau	1.777	-1	b bottom	4.2	-1/3

- ~15 yrs ago all neutrino masses were thought to be 0 and all neutrino flavors distinct.

- With new discoveries a distinct, unexpected pattern has emerged.

- We do not understand this pattern and have no clue of relationship between leptons and quarks.

- Science of neutrinos is has deep connections to understanding of matter, cosmology, and astrophysics.

- Existence of neutrino mass itself is physics beyond the standard model because of the left/right properties of the neutrino as well as the smallness of the mass. It implies a new mechanism for mass generation in which neutrinos are their own anti-particles.

Basic Interactions of neutrinos

All the particles of a given kind are identical.
All **electrons** are absolutely identical.
Electrons do not have birthmarks.
But there are 3 kinds, or flavors, of electron-like particles:

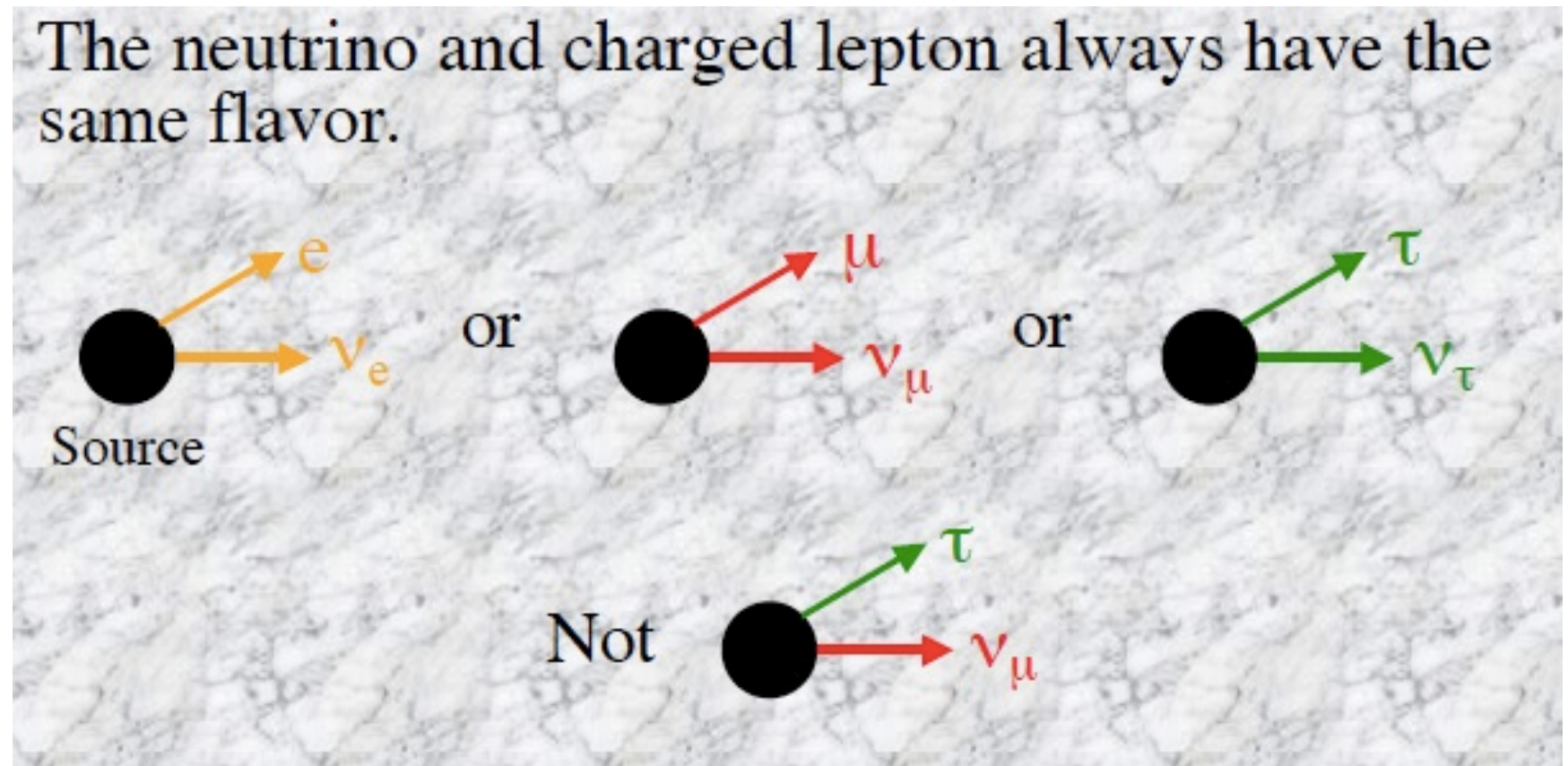
<u>Particle</u>	<u>Symbol</u>	<u>Mass</u>	<u>Associated Neutrino</u>
Electron	e	1	ν_e
Muon	μ	200	ν_μ
Tau	τ	3500	ν_τ

Charged
leptons

Neutrinos or
neutral leptons

Neutrinos are always produced or destroyed in association with their charged partner with the Weak interaction. (or with their anti-particle partners).

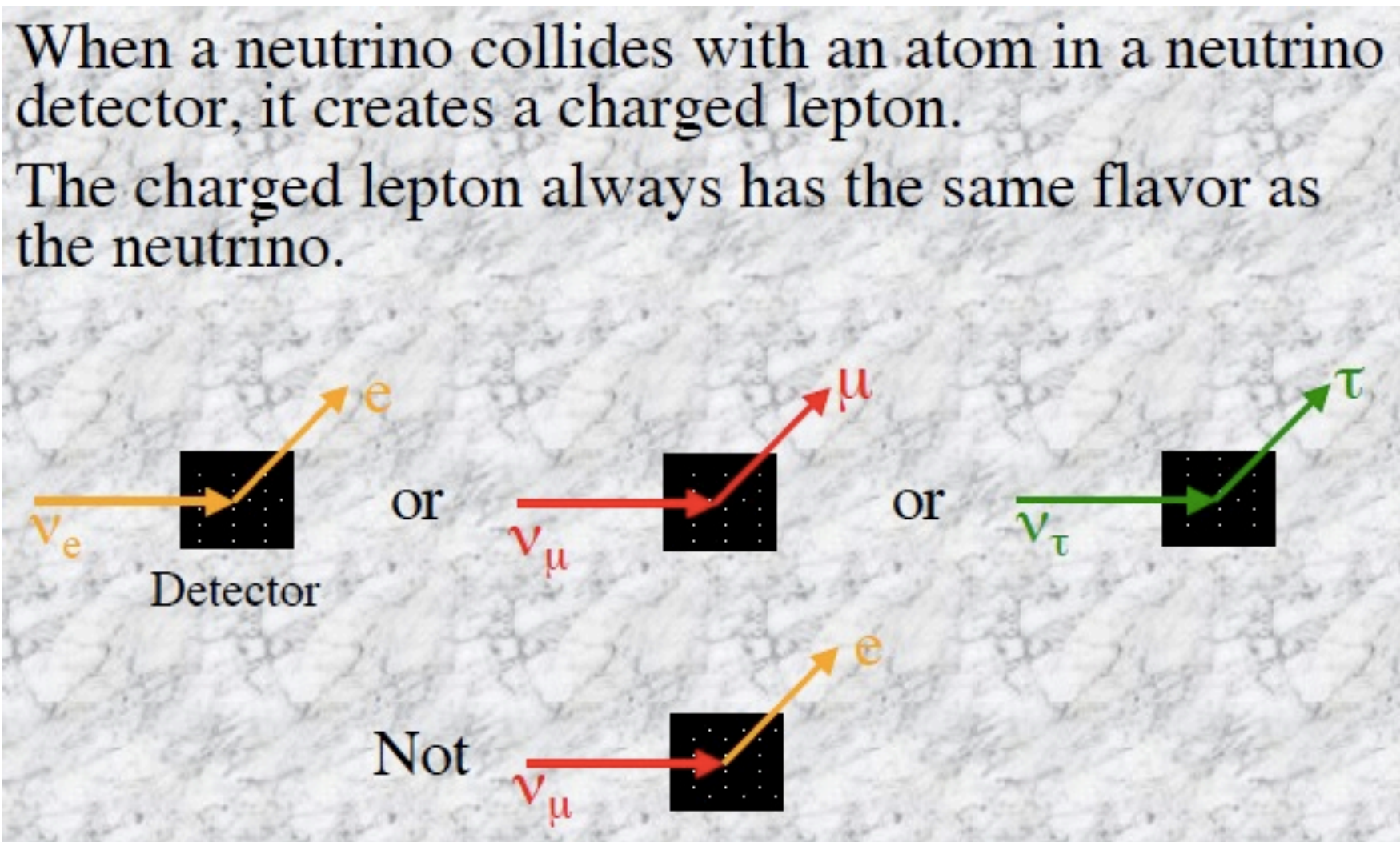
Creation



Detection

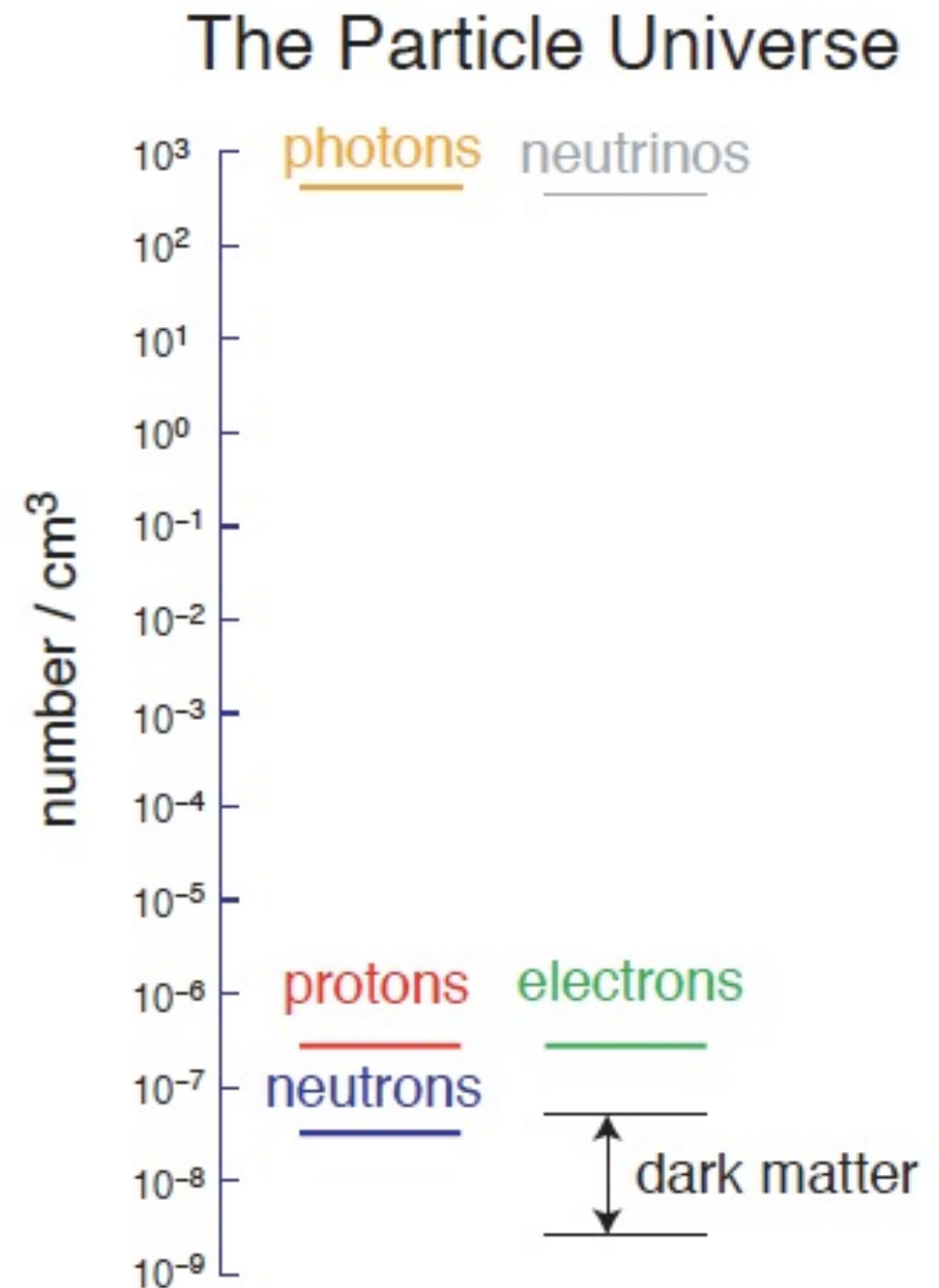
These are called “Charged current” interactions in which neutrino changes electrical charge.

There are also “neutral current” interactions in which a neutrino has an elastic interaction that leaves observable energy in detector.

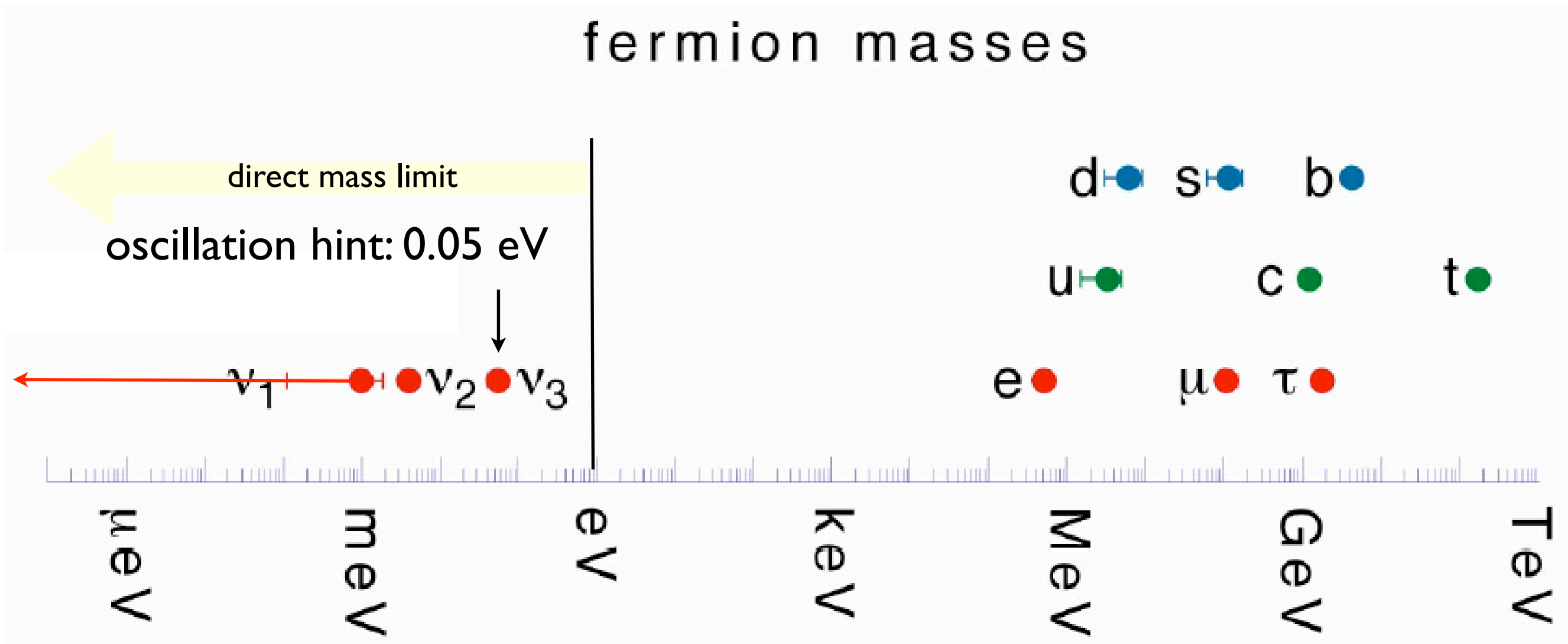


Neutrinos in Cosmology

- The most abundant particle is the photon: $\sim 400/\text{cc}$
- The most abundant matter particle is the neutrino at 56/cc of each type.
- CNB (1.95K) is a relic of the big bang similar to the CMB (2.725K). Neutrinos decoupled at 2 sec while photons decoupled at $\sim 400,000$ yrs.



Current picture of neutrino masses points to another mass generation mechanism.



Mass is a coupling of the left and right components of the Fermion field, unless it is a neutral fermion in which case mass can couple fields of same handedness.

If neutrinos have mass; the massive states need not be the same as the Weak interaction states.

This will lead to interference effects

$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \rightarrow \nu_b) &= |\langle \nu_b | \nu_a(t) \rangle|^2 \\ &= \sin^2(\theta) \cos^2(\theta) |e^{-iE_2 t} - e^{-iE_1 t}|^2 \end{aligned}$$

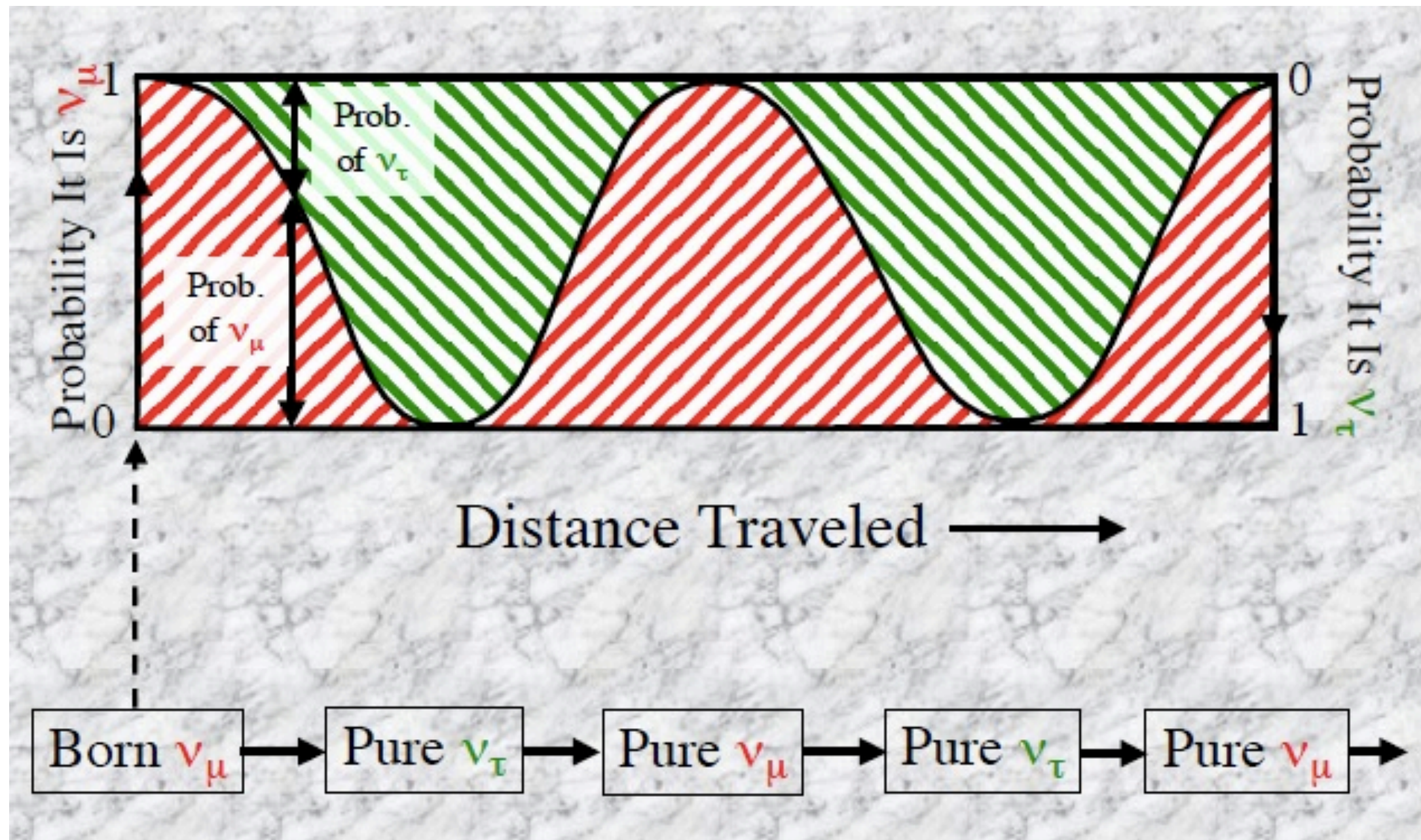
Sufficient to understand most of the physics:

$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27((m_2^2 - m_1^2)/eV^2)(L/km)}{(E/GeV)}$$

$$P(\nu_a \rightarrow \nu_a) = 1 - \sin^2 2\theta \sin^2 \frac{1.27(\Delta m^2/eV^2)(L/km)}{(E/GeV)}$$

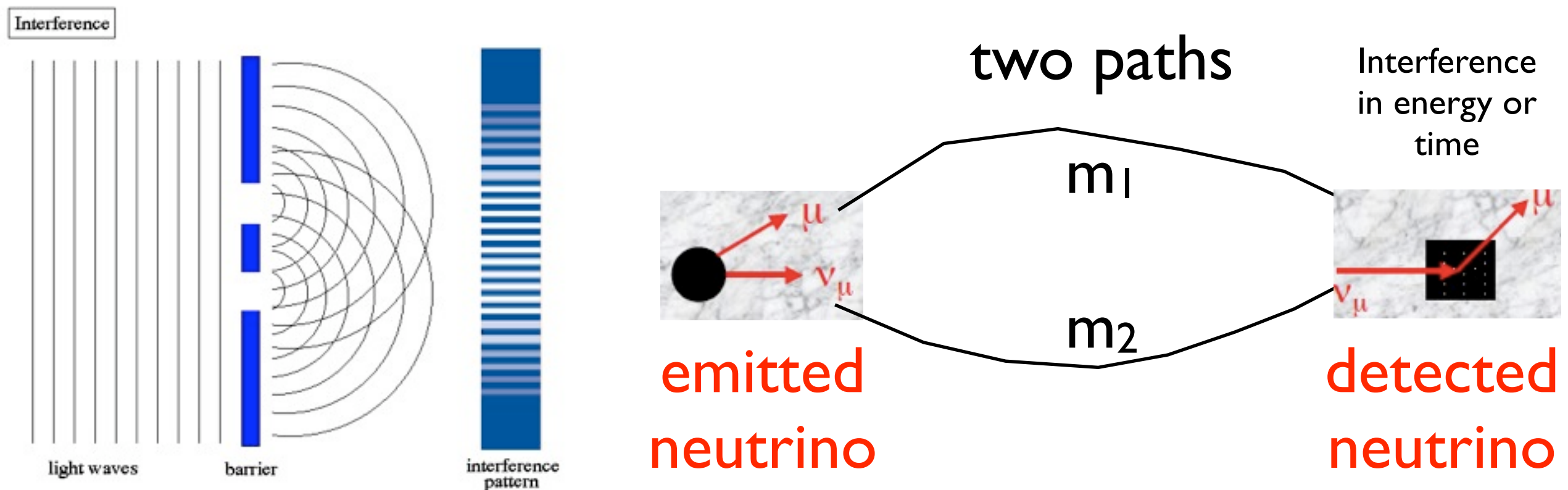
Oscillation nodes at $\pi/2, 3\pi/2, 5\pi/2, \dots$ ($\pi/2$): $\Delta m^2 = 0.0025 eV^2$,
 $E = 1 GeV$, $L = 494 km$.

Picture with $\theta = 45$ deg



Astonishingly this is reality

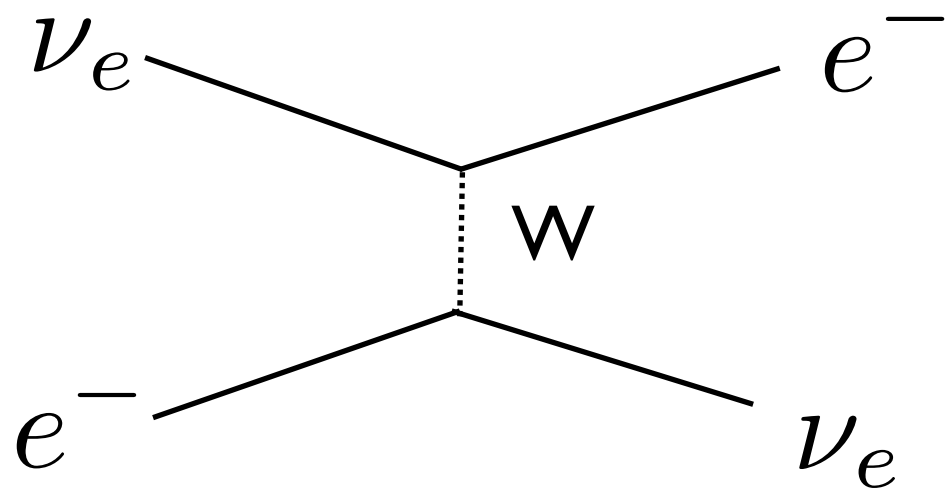
Oscillations is a new interferometry.



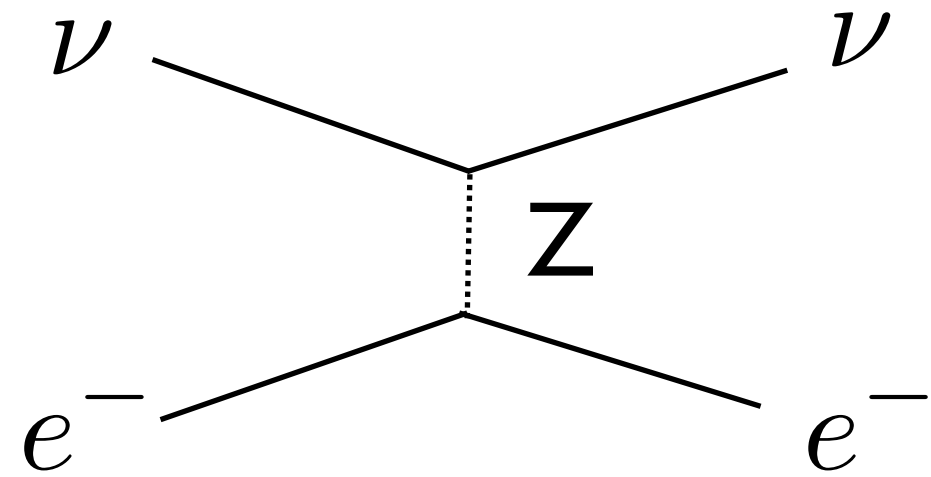
- Just as classic optical interferometry has led to new precision, neutrino interferometry has potential to be sensitive to new scales.
- e.g. Measure extremely small masses or interactions.

$$i \frac{d}{dx} \nu_f = H R_\theta \nu_m$$

L. Wolfenstein: Oscillations need to be modified in presence of matter.



Charged Current
for electron type only



Neutral Current
for all neutrino types

Additional potential for ν_e ($\bar{\nu}_e$): $\pm \sqrt{2} G_F N_e$

N_e is electron number density.

An example of how additional phases come into the interferometry.

Oscillations in presence of matter

$$i \frac{d}{dx} \nu_f = R_\theta H(\nu_m) + H_{mat}(\nu_f)$$

$$i \frac{d}{dx} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \frac{1}{4E} \left(R_\theta \begin{pmatrix} m_2^2 - m_1^2 & 0 \\ 0 & m_1^2 - m_2^2 \end{pmatrix} R_\theta^T + 2E \begin{pmatrix} \sqrt{2} G_F N_e & 0 \\ 0 & -\sqrt{2} G_F N_e \end{pmatrix} \right) \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} \quad (3)$$

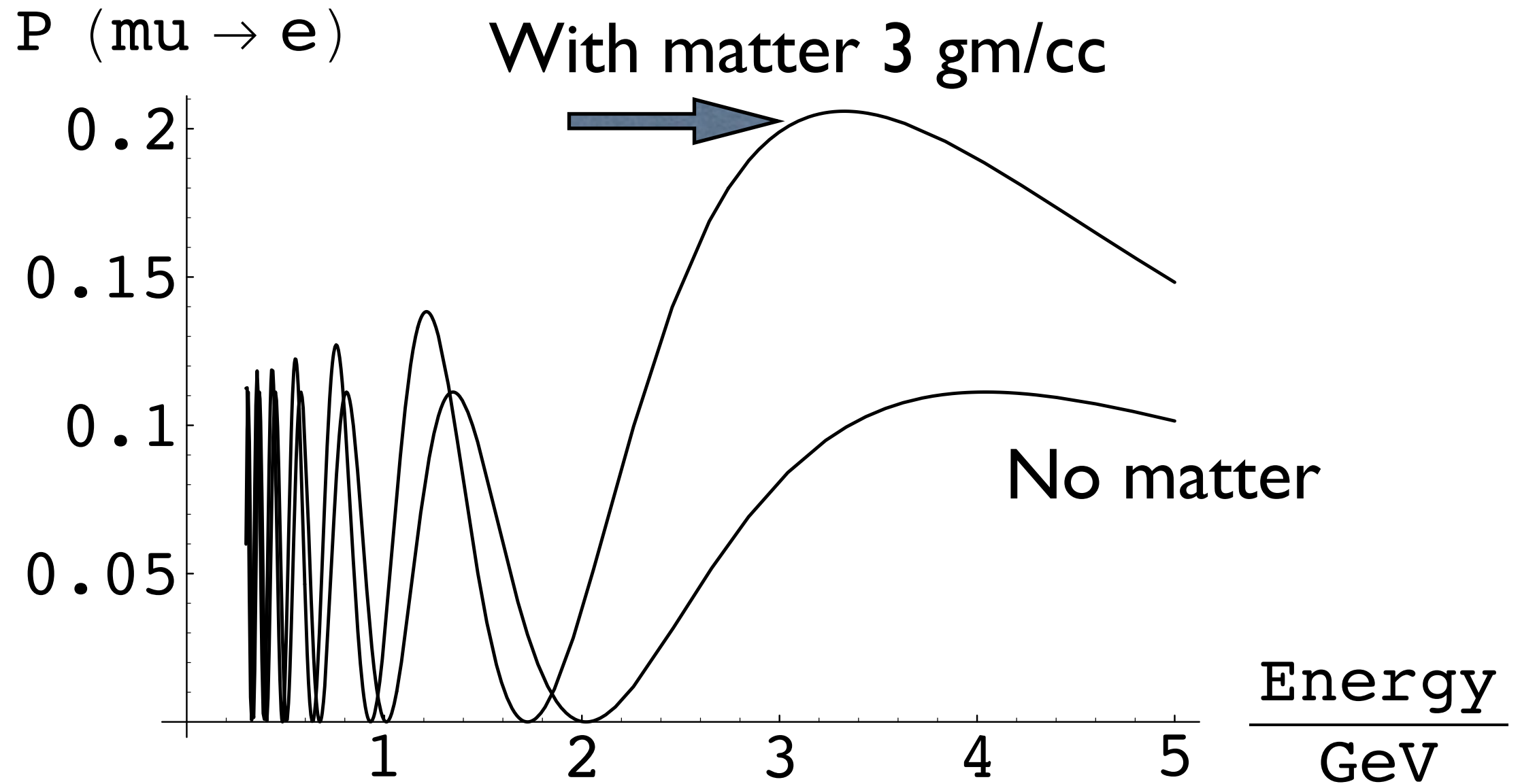
Looking at conversions of muon to electron neutrinos.

$$P_{\mu \rightarrow e} = \frac{\sin^2 2\theta}{(\cos 2\theta - a)^2 + \sin^2 2\theta} \times \sin^2 \frac{L \Delta m^2}{4E} \sqrt{(a - \cos 2\theta)^2 + \sin^2 2\theta}$$

$$\begin{aligned} a &= \frac{2\sqrt{2} E G_F N_e}{\Delta m^2} \\ &\approx 7.6 \times 10^{-5} \times D / (gm/cc) \times E_\nu / GeV / (\Delta m^2 / eV^2) \end{aligned} \quad (4)$$

This effect present if electron neutrinos in the mix

2-neutrino picture



Osc. probability: 0.0025 eV^2 , $L = 2000 \text{ km}$, $\Theta = 10^\circ$

So far.

- 3 types of neutrinos
- Still many unknowns about these particles, but they play an important role in the early universe as well as current astrophysical processes.
- They have mass with fundamental consequences.
- In next slides I will review the complete picture of the 3 neutrinos: masses and mixing.

Mixing Matrix:

$$|\nu_e, \nu_\mu, \nu_\tau\rangle_{flavor}^T = U_{\alpha i} |\nu_1, \nu_2, \nu_3\rangle_{mass}^T$$

$$U_{\alpha i} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}$$

Atmos. L/E $\mu \rightarrow \tau$ Atmos. L/E $\mu \leftrightarrow e$ Solar L/E $e \rightarrow \mu, \tau$ $0\nu\beta\beta$ decay

500km/GeV

15km/MeV

$$c_{ij} \equiv \cos \theta_{ij}$$

$$s_{ij} \equiv \sin \theta_{ij}$$

$$\theta_{12} \approx \theta_{sol} \approx 34^\circ, \theta_{23} \approx \theta_{atm} \approx 37-53^\circ, \theta_{13} \lesssim 10^\circ$$

δ would lead to $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$. \cancel{CP}

Since there are 3 neutrinos, there must be a 3X3 matrix with 3 angles and 1 phase (observable) and 2 Δm^2

What about θ_{13} and δ ?

One Global Fit:

Dominated by

parameter	best fit	2σ	3σ
Δm_{21}^2 [10^{-5}eV^2]	$7.65^{+0.23}_{-0.20}$	7.25–8.11	7.05–8.34
$ \Delta m_{31}^2 $ [10^{-3}eV^2]	$2.40^{+0.12}_{-0.11}$	2.18–2.64	2.07–2.75
$\sin^2 \theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.27–0.35	0.25–0.37
$\sin^2 \theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39–0.63	0.36–0.67
$\sin^2 \theta_{13}$	$0.01^{+0.016}_{-0.011}$	≤ 0.040	≤ 0.056

KamLAND

MINOS

SNO

SuperK

Chooz

arXiv:0808.2016

Schwetz, Tortola, Valle

Not yet updated for newest results.

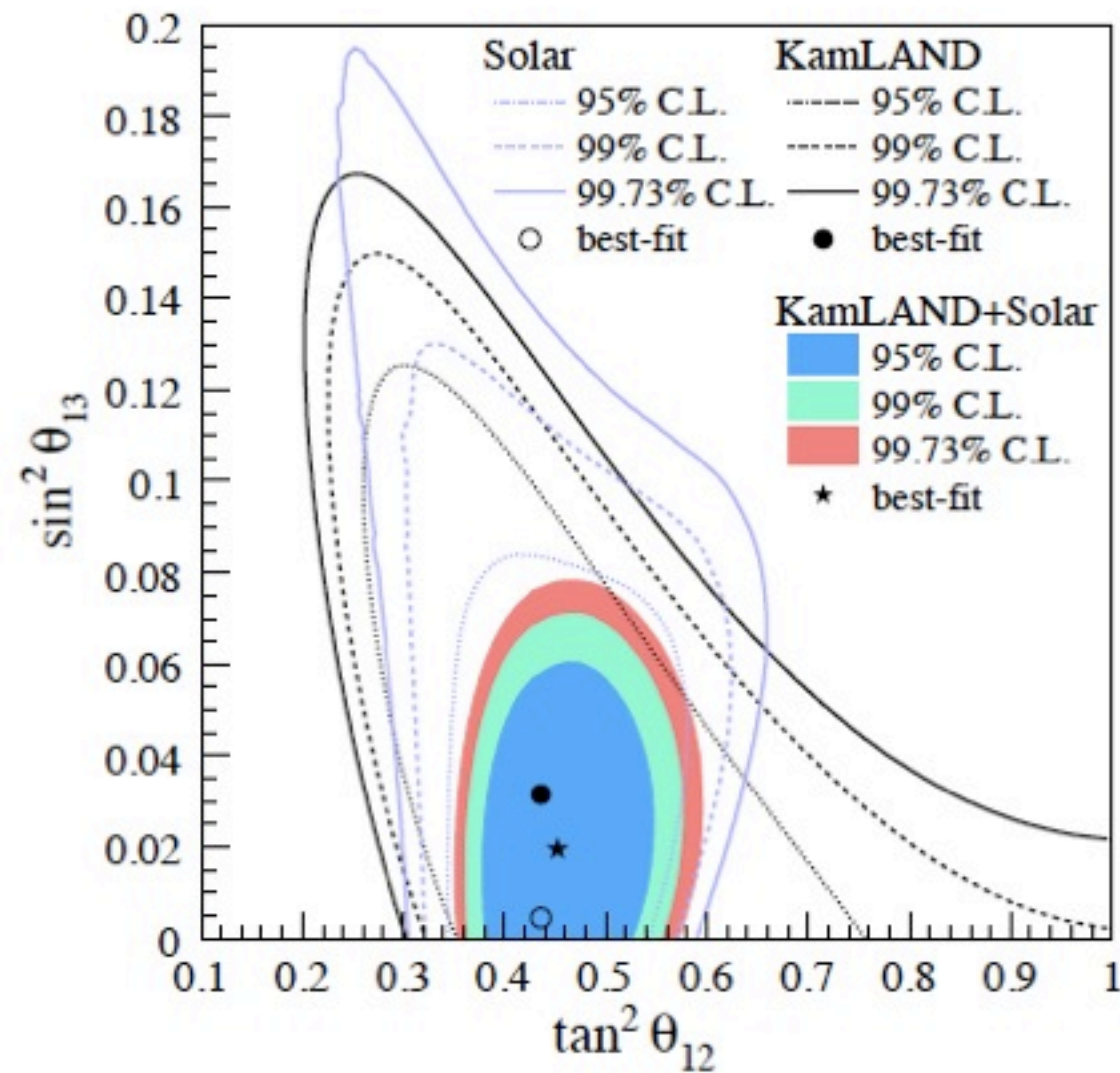


FIG. 3: Allowed regions from the solar and KamLAND data projected in the $(\tan^2 \theta_{12}, \sin^2 \theta_{13})$ plane for the three-flavor analysis.

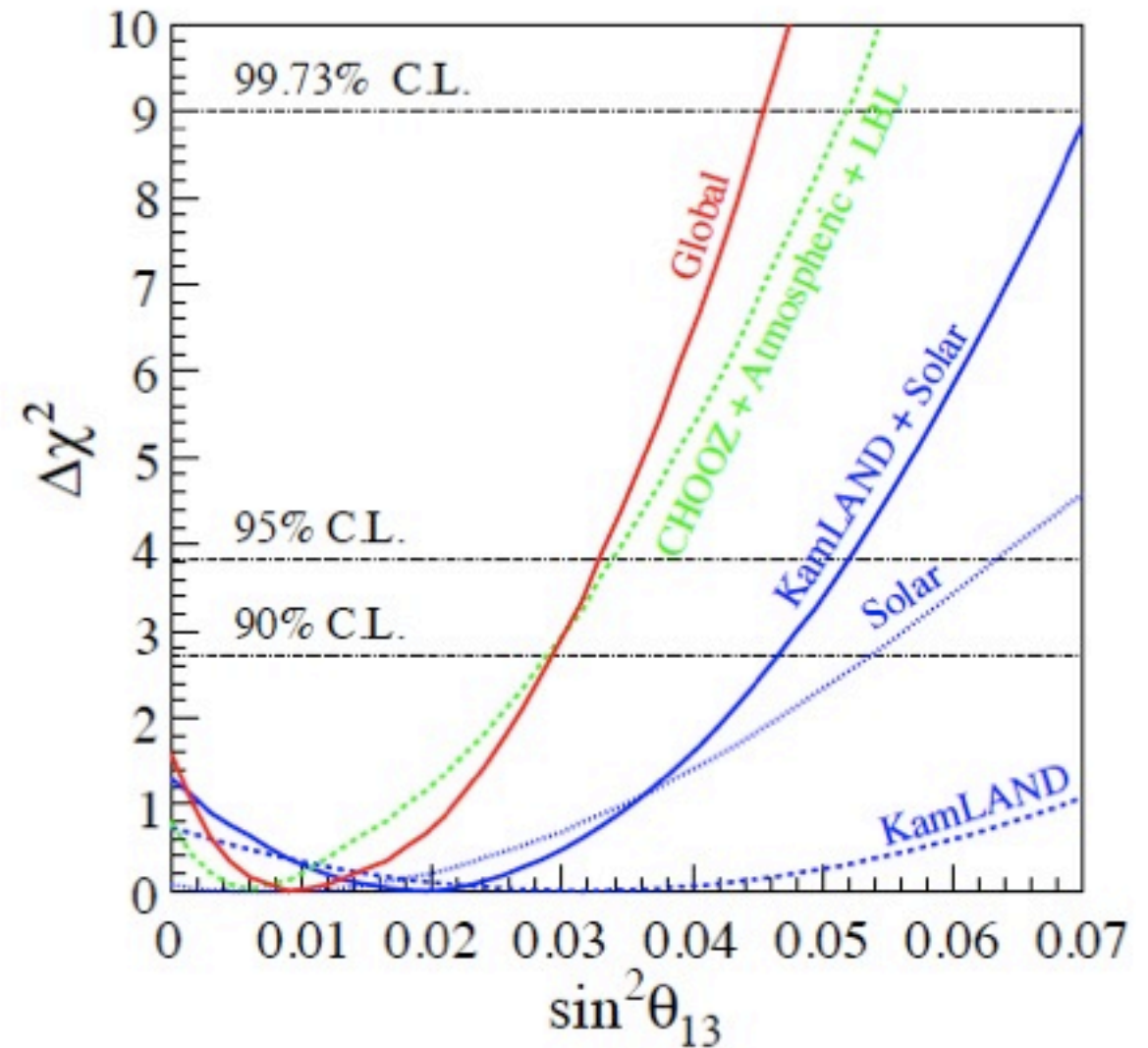
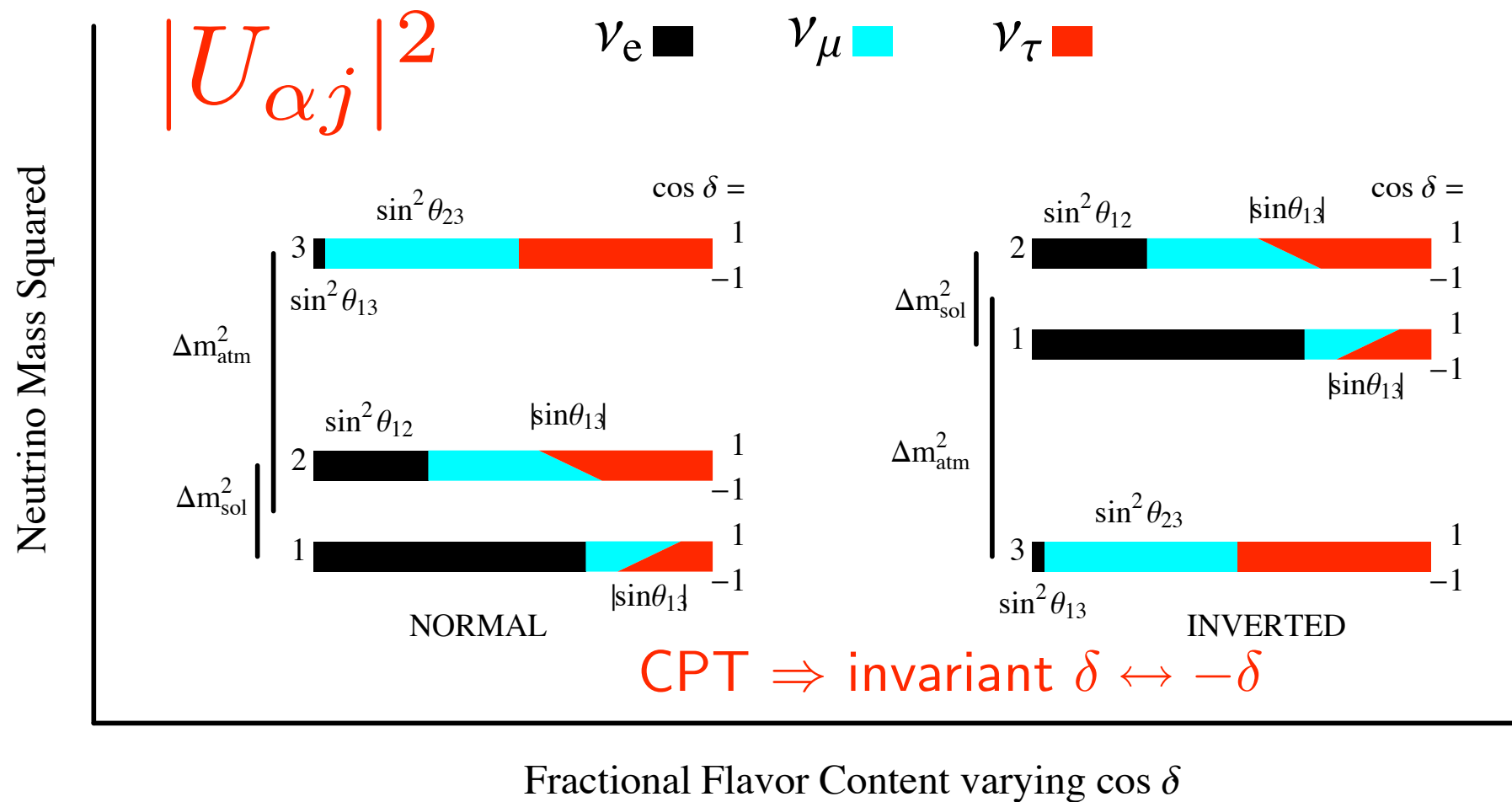


FIG. 4: $\Delta\chi^2$ -profiles projected onto the $\sin^2 \theta_{13}$ axis for different combinations of the oscillation data floating the undisplayed parameters $(\tan^2 \theta_{12}, \Delta m_{21}^2)$.

- Solar and Reactor data has weak evidence for the last mixing angle: θ_{13}
- The new calculation of reactor neutrinos affects this if we use the new calculated spectra. We need to stay tuned.



$$\delta m_{sol}^2 = +7.6 \times 10^{-5} \text{ eV}^2$$

$$|\delta m_{atm}^2| = 2.4 \times 10^{-3} \text{ eV}^2$$

$$|\delta m_{sol}^2| / |\delta m_{atm}^2| \approx 0.03$$

$$\sqrt{\delta m_{atm}^2} = 0.05 \text{ eV} < \sum m_{\nu_i} < 0.5 \text{ eV} = 10^{-6} * m_e$$

$$\sin^2 \theta_{12} \sim 1/3$$

$$\sin^2 \theta_{23} \sim 1/2$$

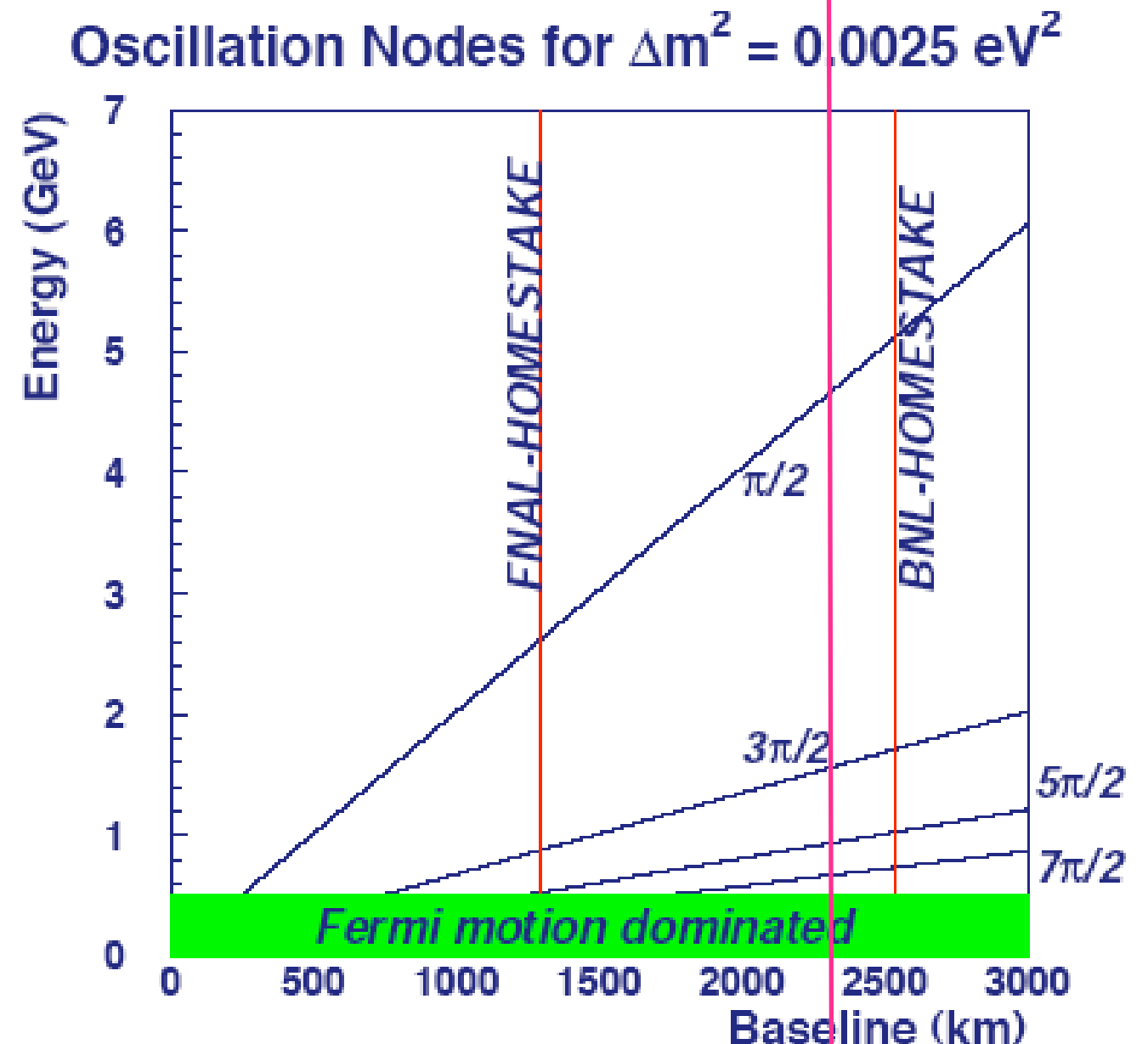
$$\sin^2 \theta_{13} < 3\%$$

$$0 \leq \delta < 2\pi$$

parke

Interest at this meeting: Must see full consequences of oscillations

- Must see multiple nodes in a spectrum for precise measurements
- Need E: 1-6 GeV
- Need ~ 2000 km
- Need intense beam.
- Need very large (200kTon WCD detector to get enough events.
- Need good electron PID.
- Must place detector underground (beam time is not enough)



(M. Diwan, hep-ex/0407047)

CERN-Pyhasalmi

$\nu_\mu \rightarrow \nu_e$ with matter effect

Approximate formula (M. Freund)

matter effect $\sim E$

~ 7500 km
no CPV.
magic bln

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \frac{\sin^2 2\theta_{13}}{(\hat{A} - 1)^2} \sin^2((\hat{A} - 1)\Delta)$$

CPV term
approximate
dependence
 $\sim L/E$

$$+ \alpha \frac{8J_{CP}}{\hat{A}(1 - \hat{A})} \sin(\Delta) \sin(\hat{A}\Delta) \sin((1 - \hat{A})\Delta)$$

$$+ \alpha \frac{8I_{CP}}{\hat{A}(1 - \hat{A})} \cos(\Delta) \sin(\hat{A}\Delta) \sin((1 - \hat{A})\Delta)$$

$$+ \alpha^2 \frac{\cos^2 \theta_{23} \sin^2 2\theta_{12}}{\hat{A}^2} \sin^2(\hat{A}\Delta)$$

solar term

linear dep.

$$J_{CP} = 1/8 \sin \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$

$$I_{CP} = 1/8 \cos \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$

$$\alpha = \Delta m_{21}^2 / \Delta m_{31}^2, \quad \Delta = \Delta m_{31}^2 L / 4E$$

$$\hat{A} = 2VE / \Delta m_{31}^2 \approx (E_\nu / \text{GeV}) / 11 \text{ For Earth's crust.}$$

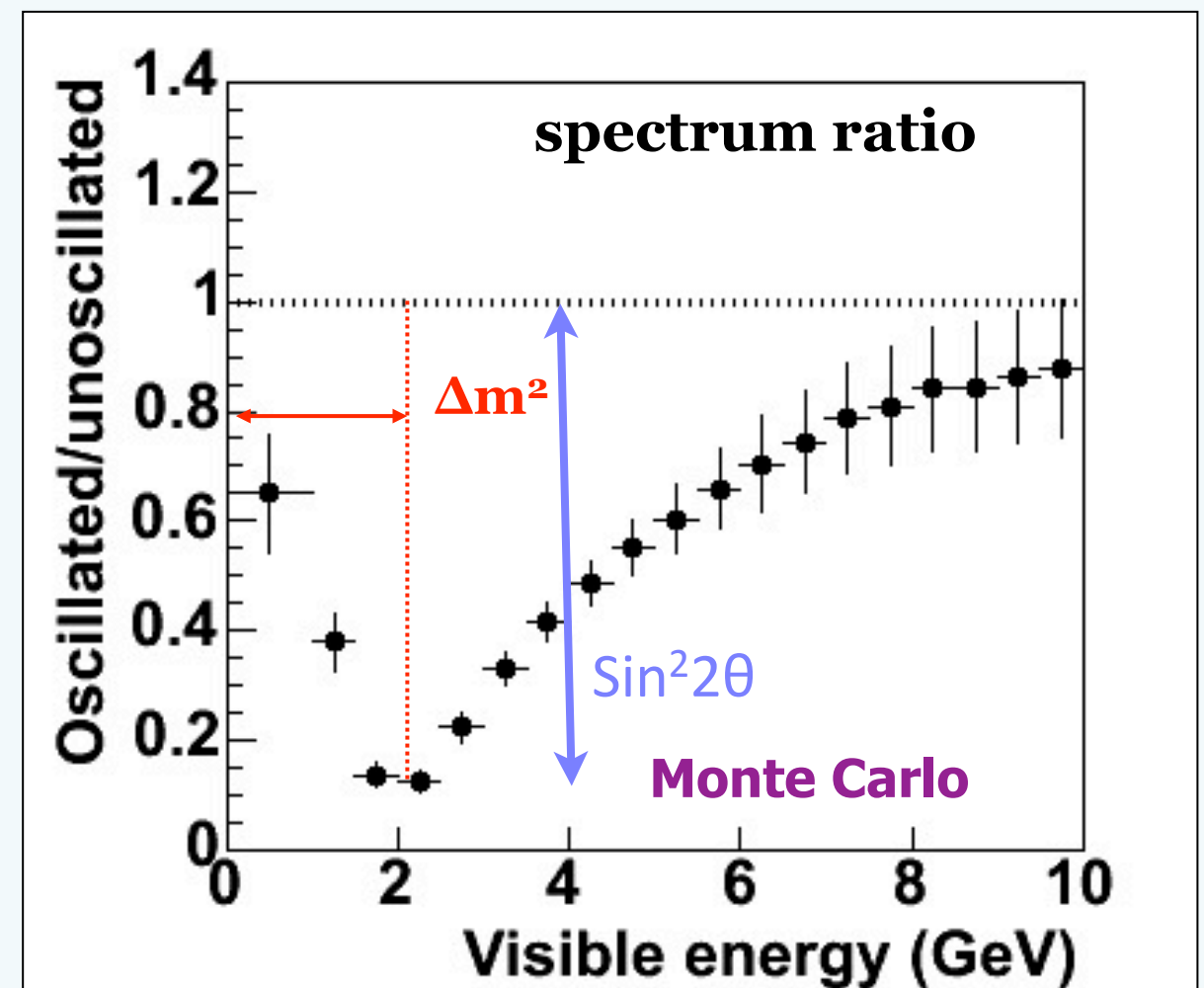
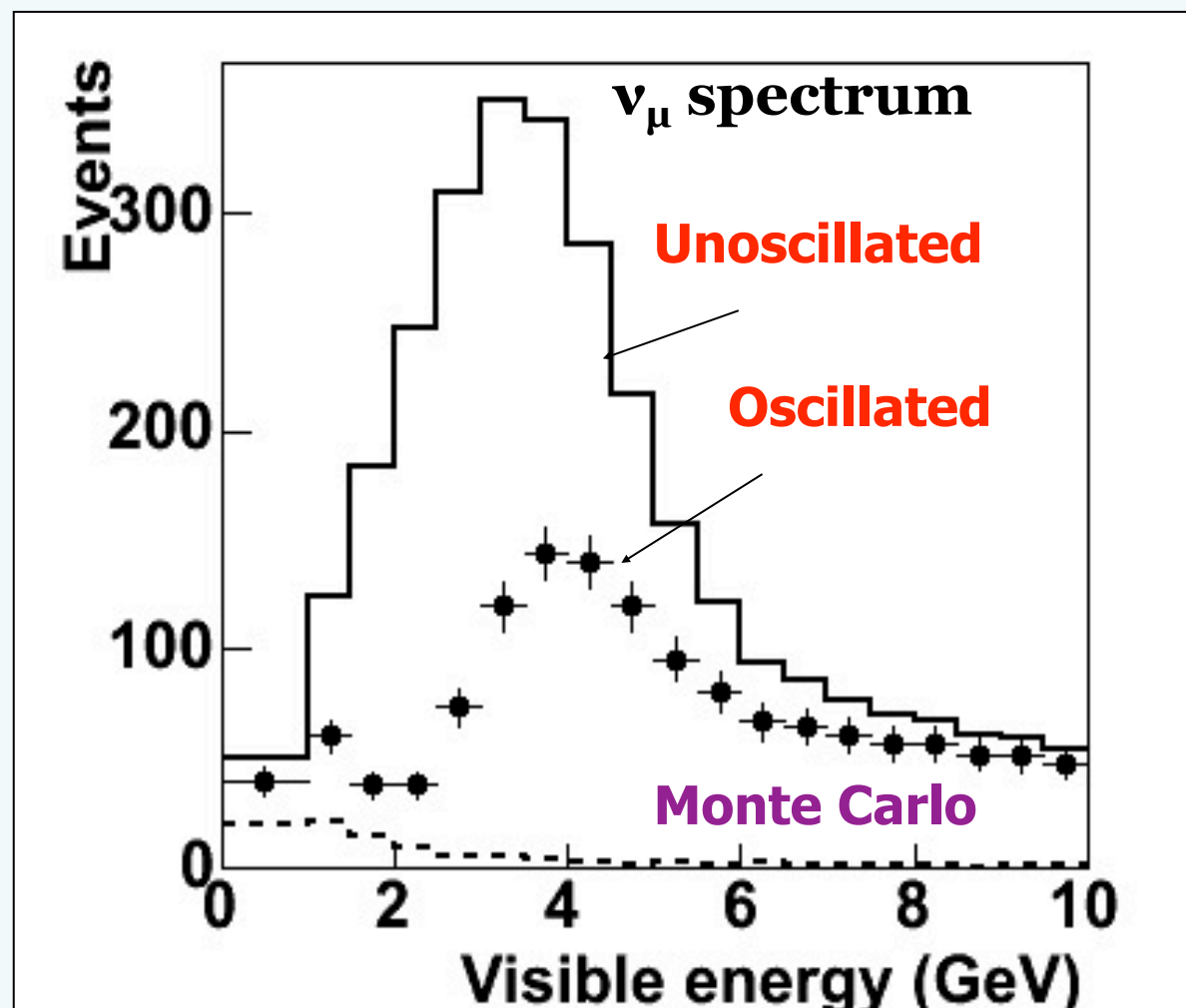
CP asymmetry grows as
th13 becomes smaller

- **Show animation.**

ν_μ Disappearance

- How is a Long baseline ν_μ disappearance experiment done ?
- Predict unoscillated CC spectrum at Far Detector using near data and $\sim 1/r^2$ extrapolation
- Compare with measured spectrum to extract oscillation parameters. Plot is made for these two parameters.

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.267 \Delta m^2 L / E)$$

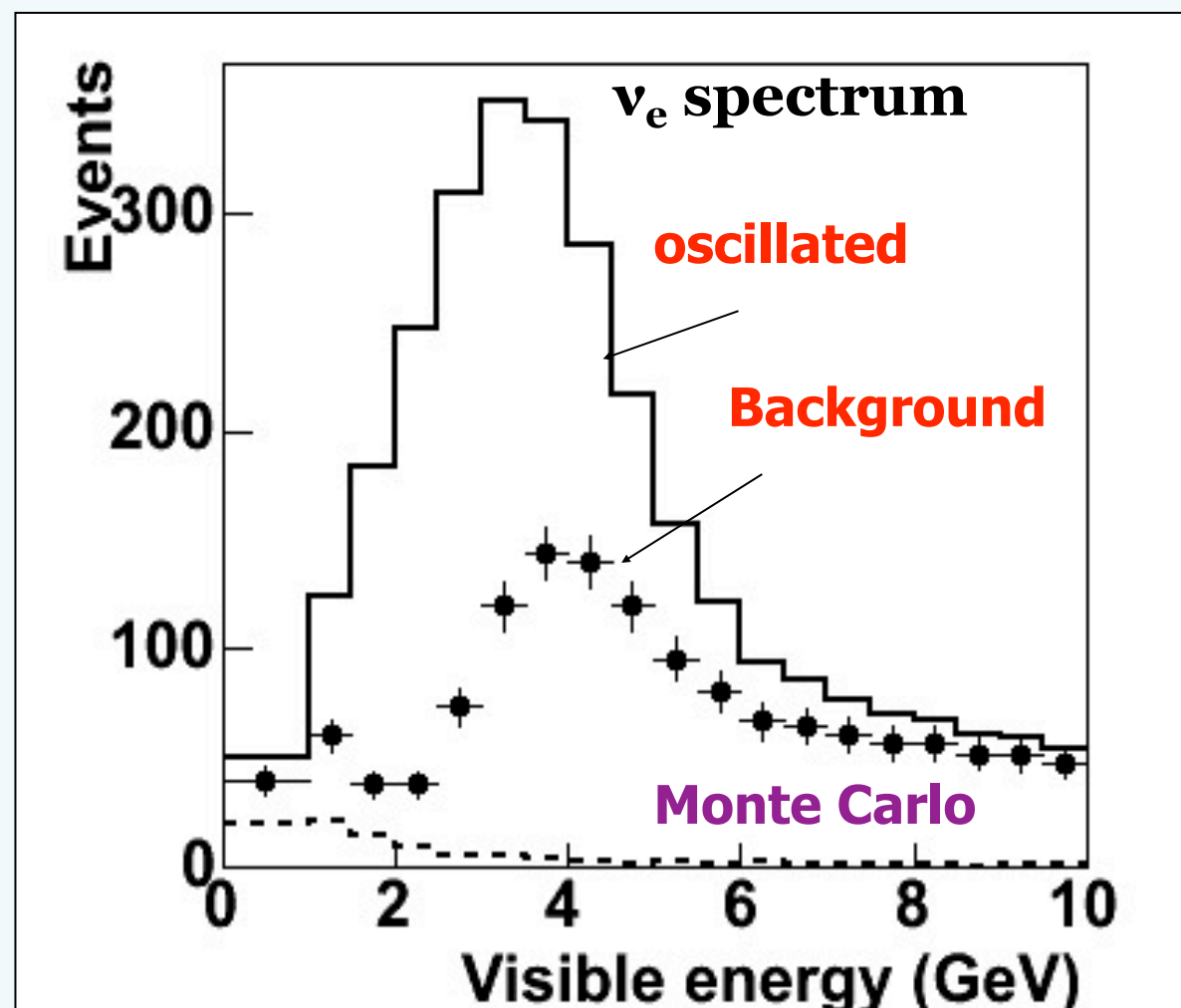


ν_e appearance

Look for electron neutrino events in the far detector.

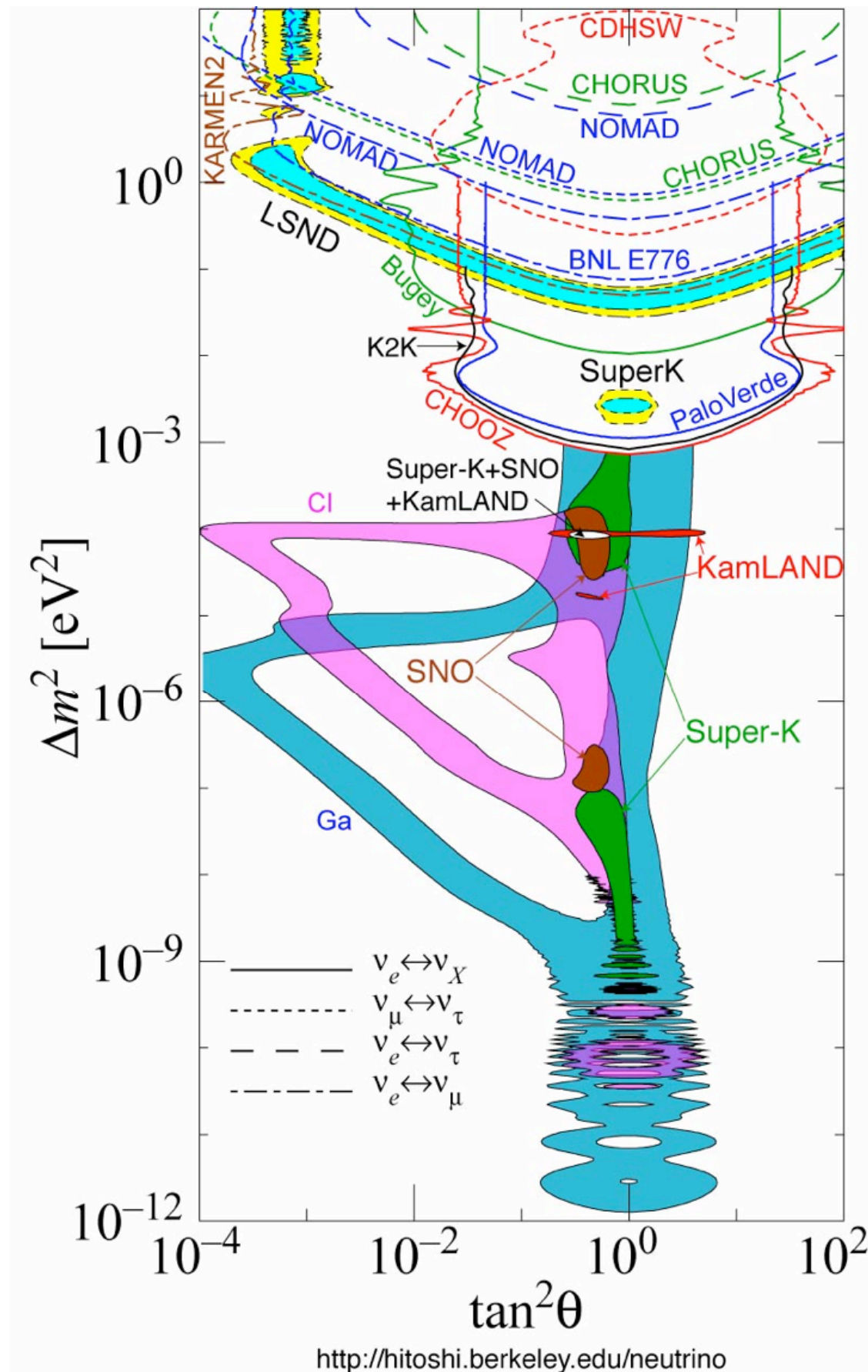
- Predict the background at Far Detector using near data and $\sim 1/r^2$ extrapolation.
- Compare with measured spectrum to extract oscillation parameters. Plot is made for these two parameters.

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2(1.267 \Delta m^2 L / E)$$



A cartoon
example using
same curves

Summary of experiments

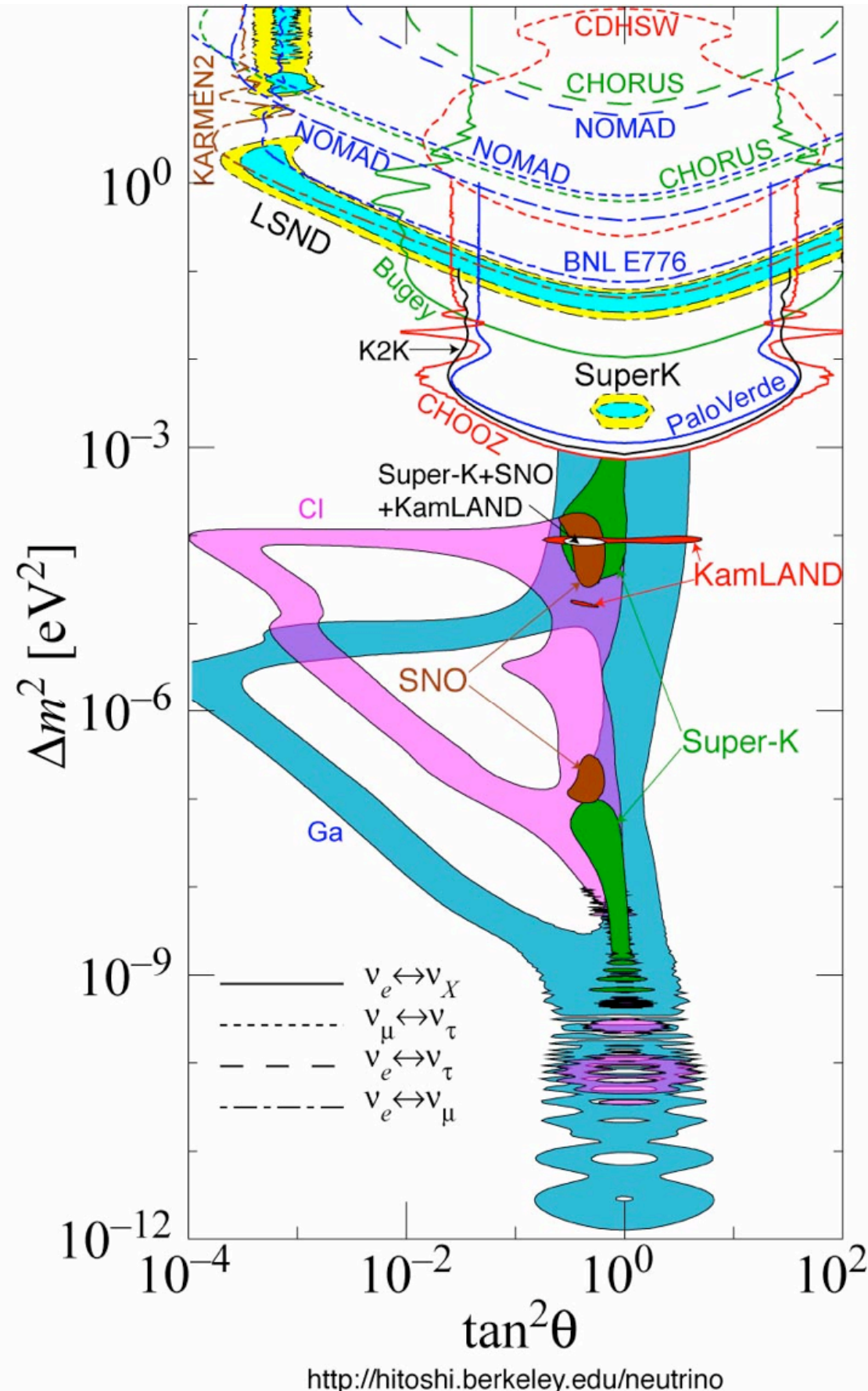


$\theta_{\text{atmospheric}}$ (primarily θ_{23})

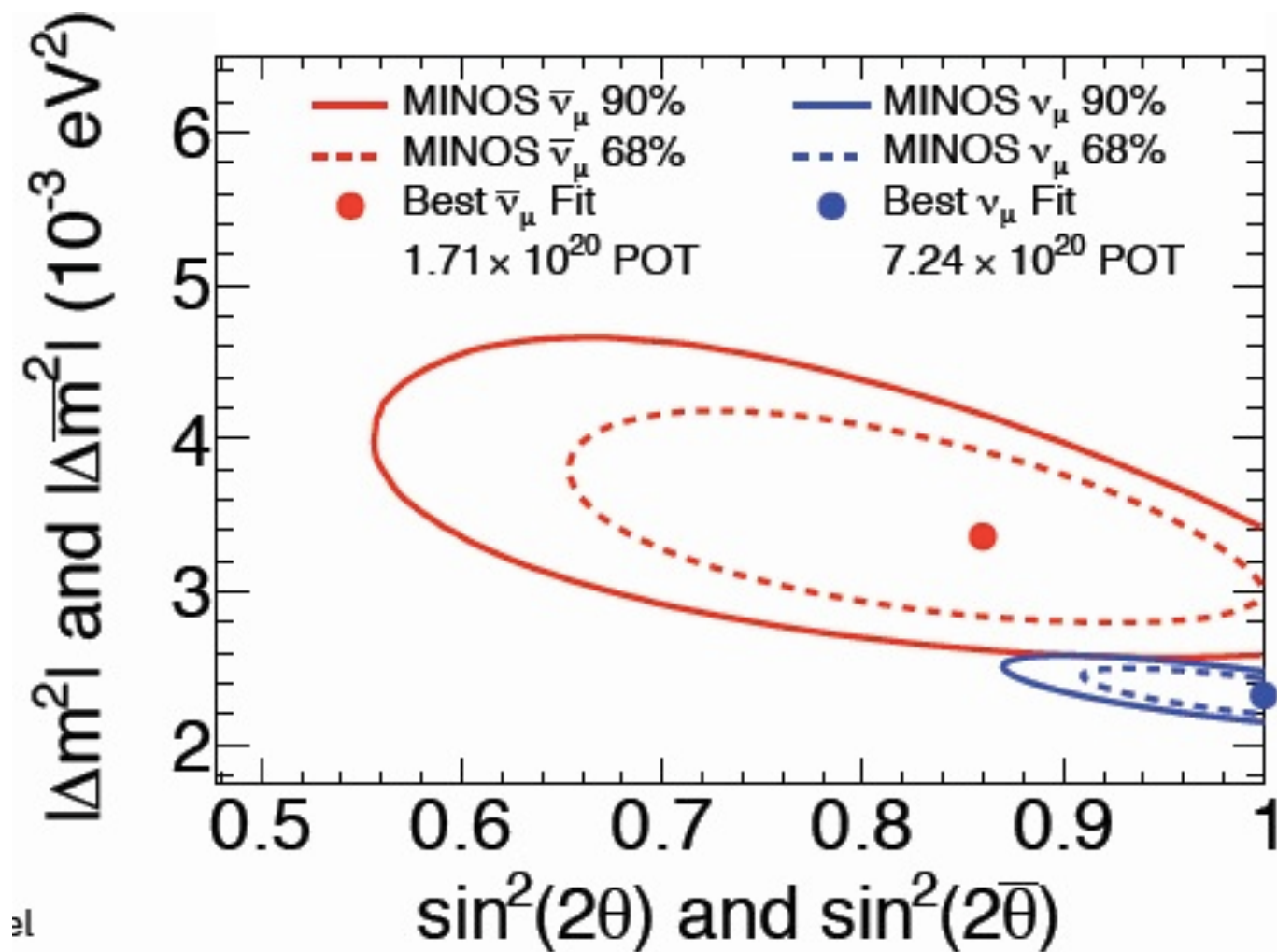
θ_{solar} (primarily θ_{12})

Why did it take this long to find the big effects ?

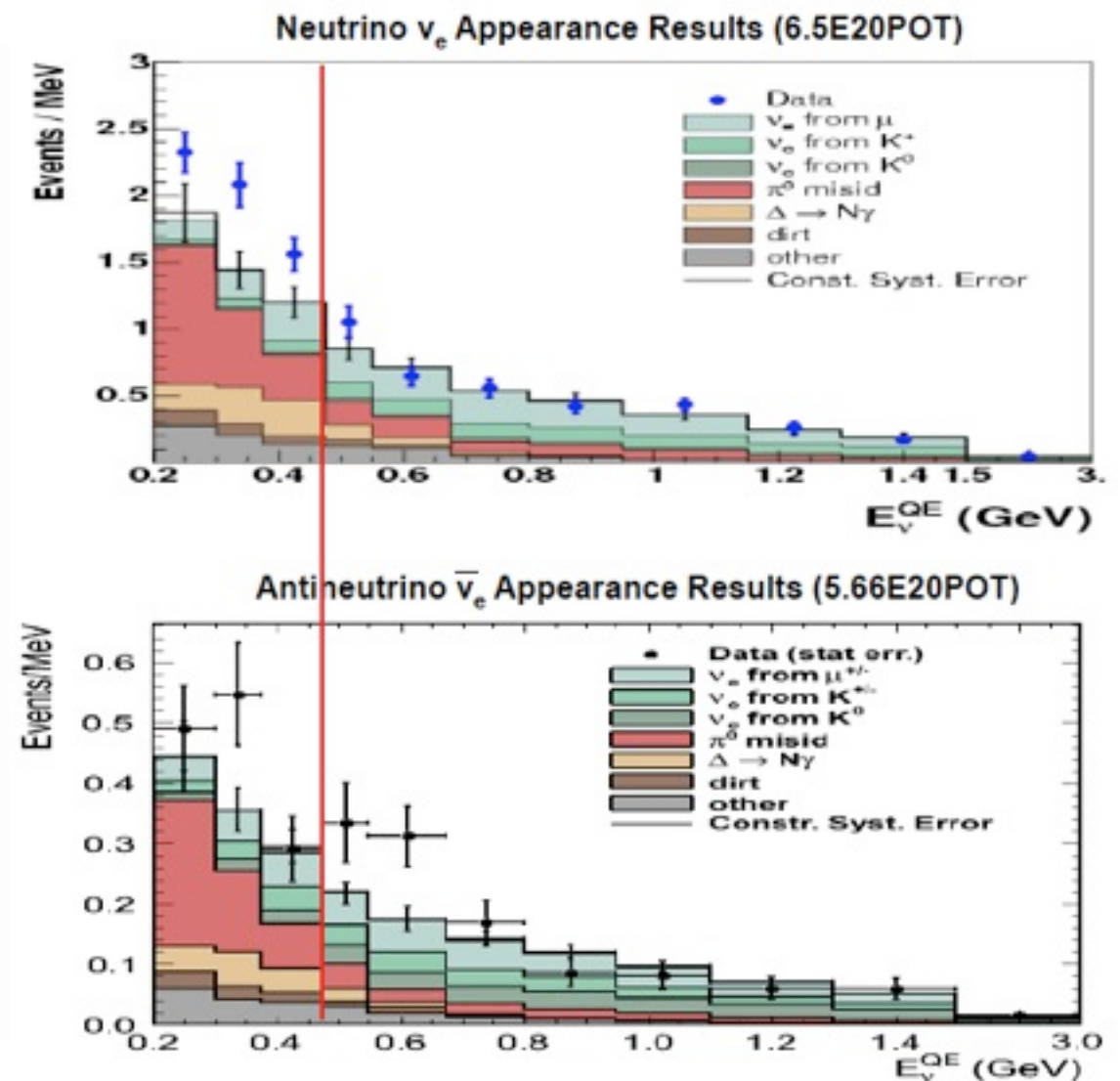
- Initial hints in Cl experiments set the scale, but knowledge of the source was suspect.
- Intolerance of large mixing !
- Hints from early atmospheric oscillations were considered artifacts because the effect was too large.
- Cosmological arguments for larger masses.
- Failure to grasp the scale of the detector needed for the job.



New Recent Results/not yet fully digested



MINOS may have observed a small difference between neutrino and antineutrino parameters



Miniboone appears to have some excess nue events in both polarities, but at different L/E

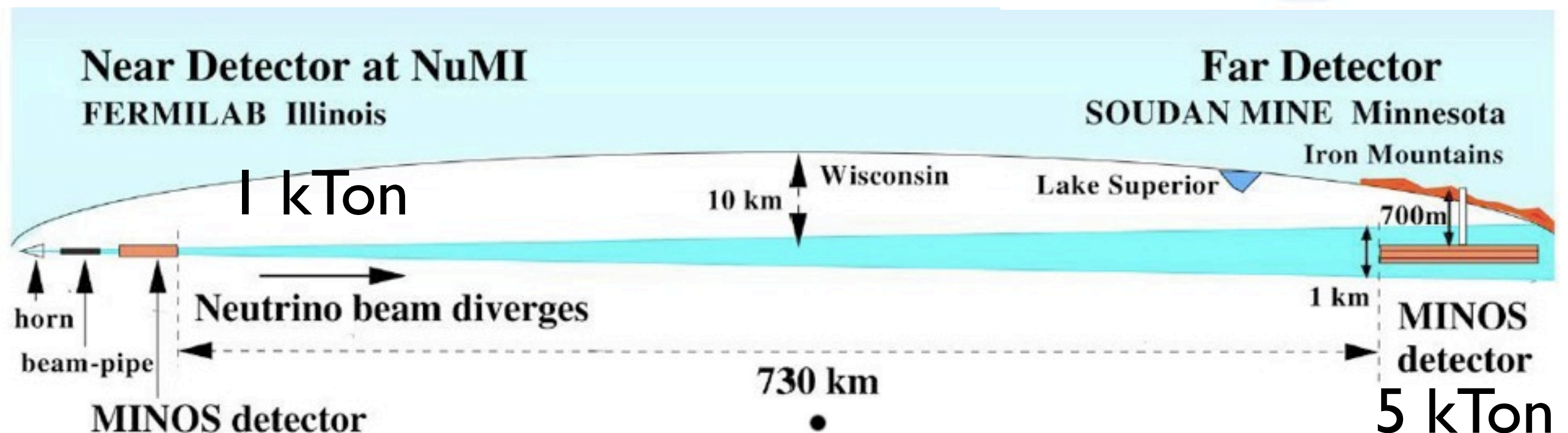
Some previous experiments (only to understand performance. This is not a physics analysis)

Exp	year	L(km)/E (GeV)	backg	$\text{Sin}^2 2\theta$ sens for (dis)appearance	Comment
CERN/ Steinberger	1983	0.8/1.0	3300(mu)/ {290cosr}	0.053	2 detectors/ disappearance
BNL-E734	1984	0.1/1.0	{418e,235nc}	$3.4 \cdot 10^{-3}$	Backg using tagged events
BNL-E776/ WBB	1992	1.0/1.0	{37e,94nc}	$3 \cdot 10^{-3}$	Backg estimate uses data input
Mini-Boone	2008	0.4/0.7	{249e,137nc}	$\sim 3 \cdot 10^{-3}$	Excess <475 MeV
NOMAD	2003	0.25/24	{5584e,0nc}	$1.3 \cdot 10^{-3}$	Very fine grained detect
CNGS (tau app)	2011	730/20	1 event seen	--	low stat for electrons
K2K	2006	250/1.3	{0.4e,1.3nc}	~ 0.2	Low statistics
MINOS/nue	2010	735/3	{5e,44nc}	~ 0.1	2 detectors

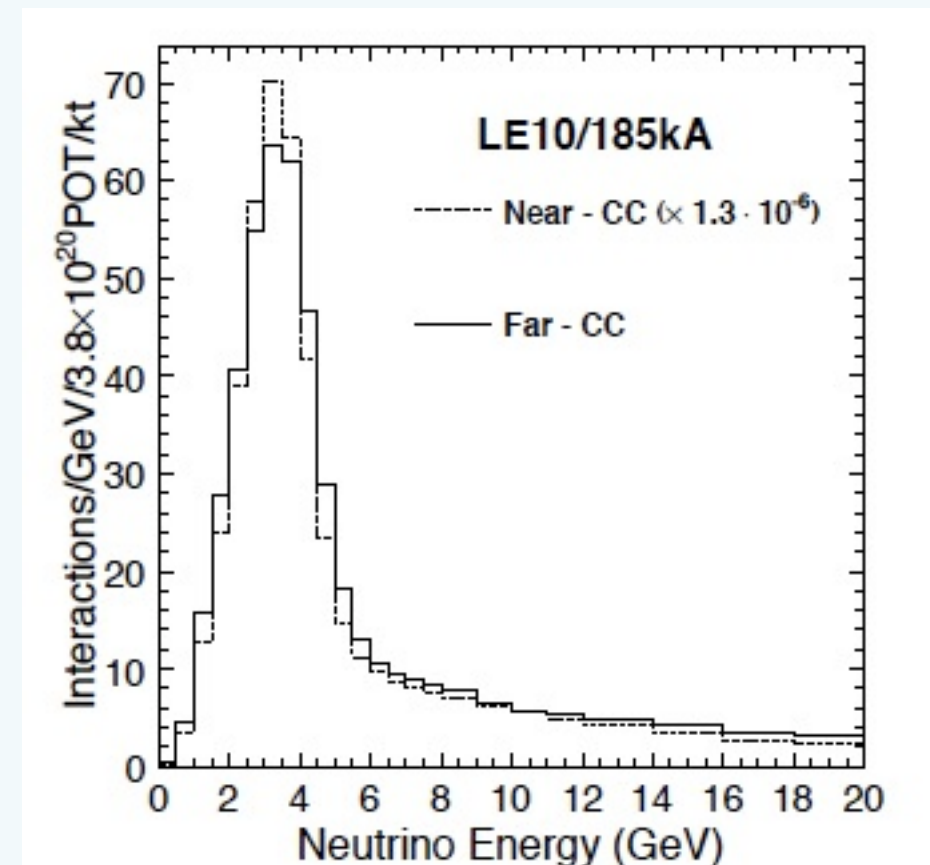
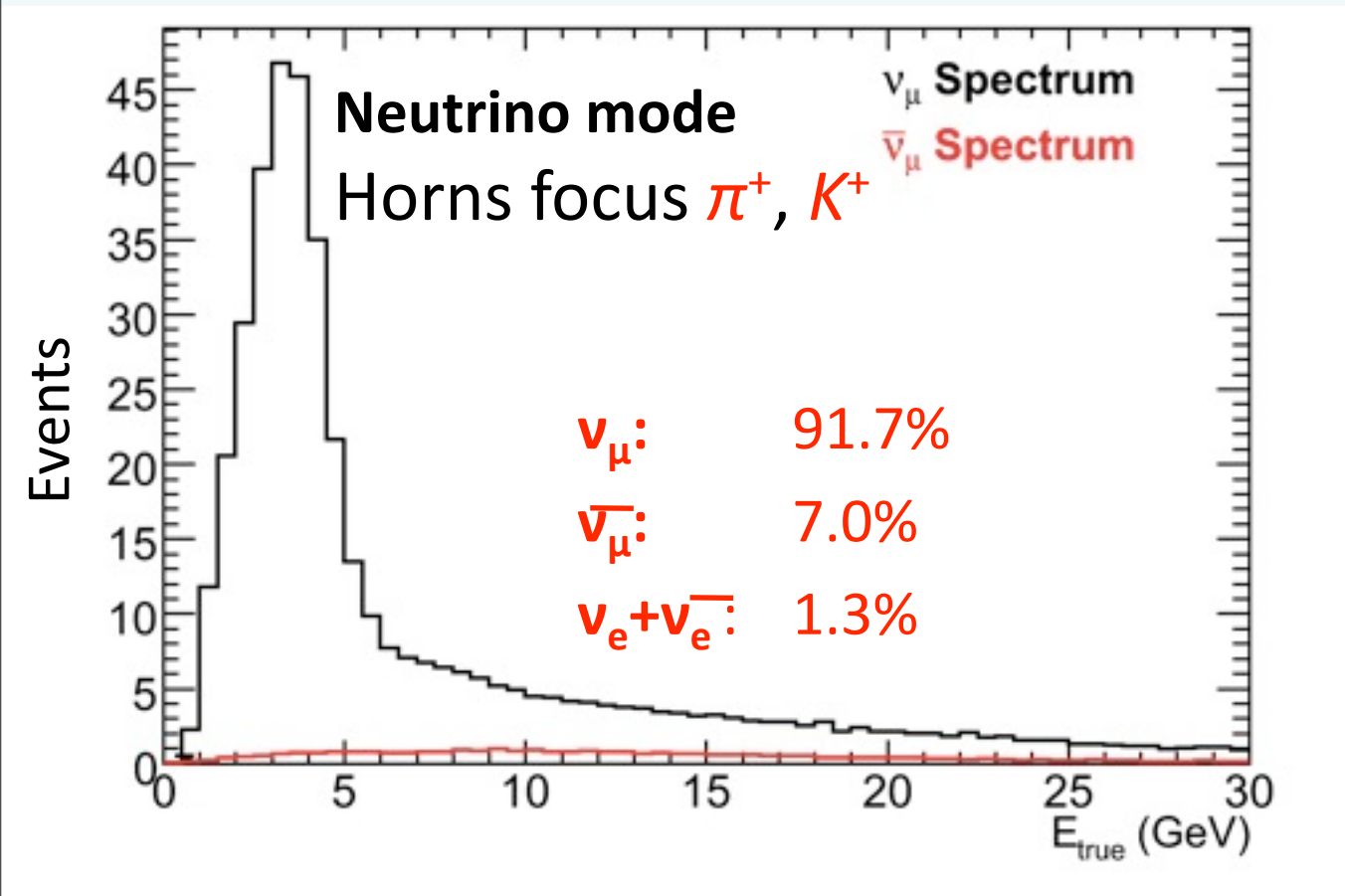
Background types: Cosmic, NC, electron neutrino contamination

MINOS experimental design

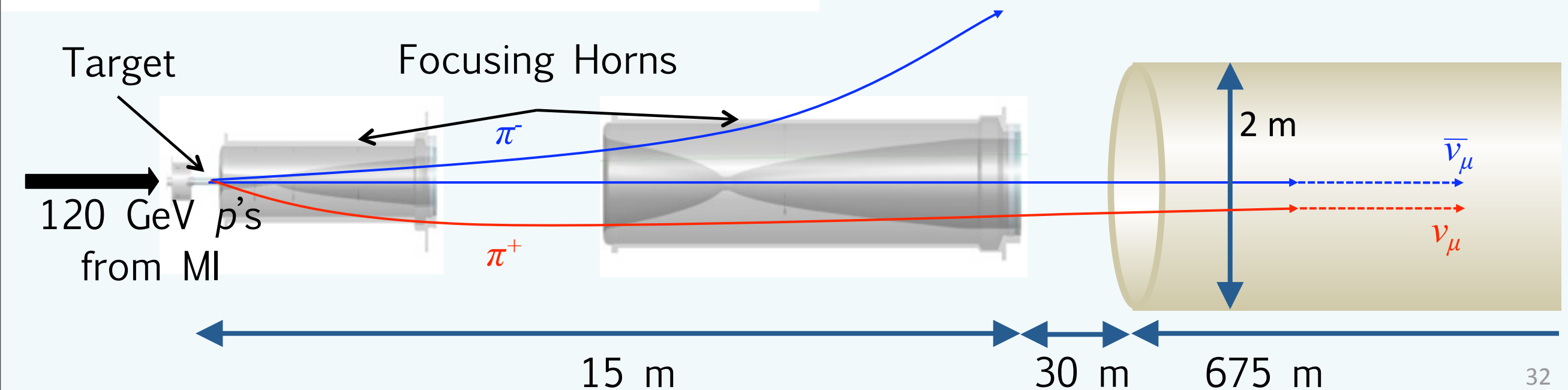
- Prepare a pure beam of muon neutrino beam.
- Aim it towards a large muon detector.
- Observe spectrum of muon neutrinos to see oscillations in energy.
- Magnetic field to measure charge.
- Two detectors mitigate uncertainties
 - beam flux
 - Cross section



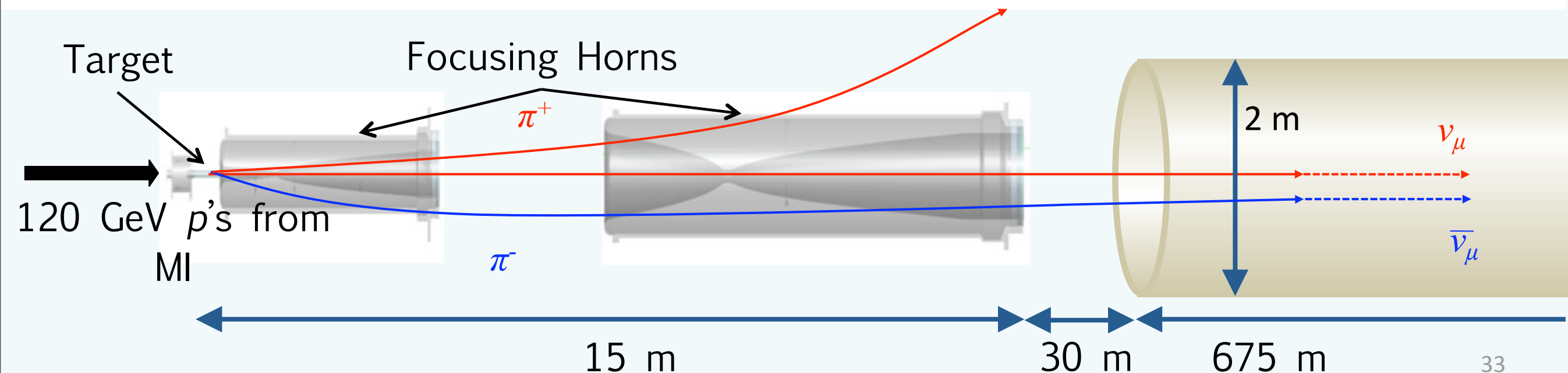
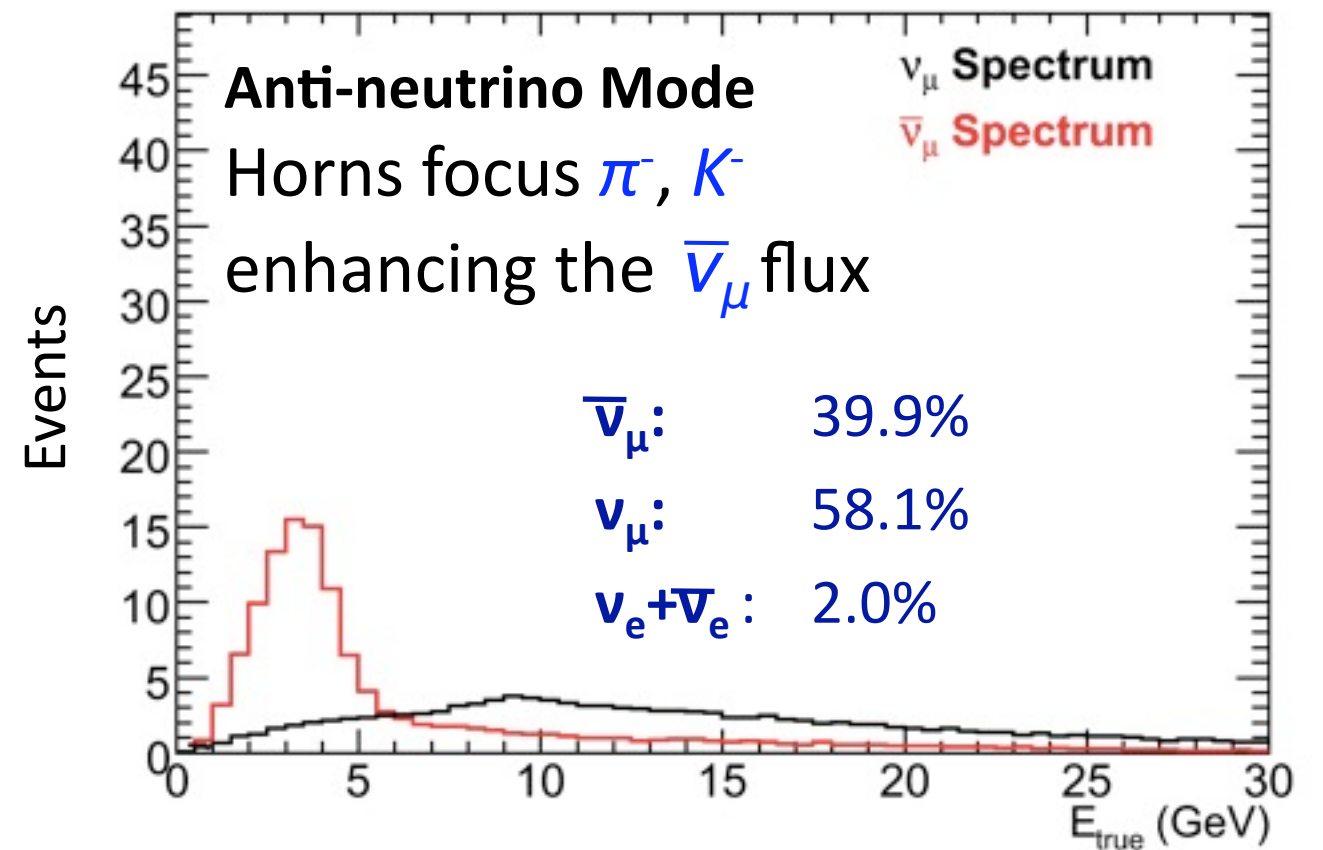
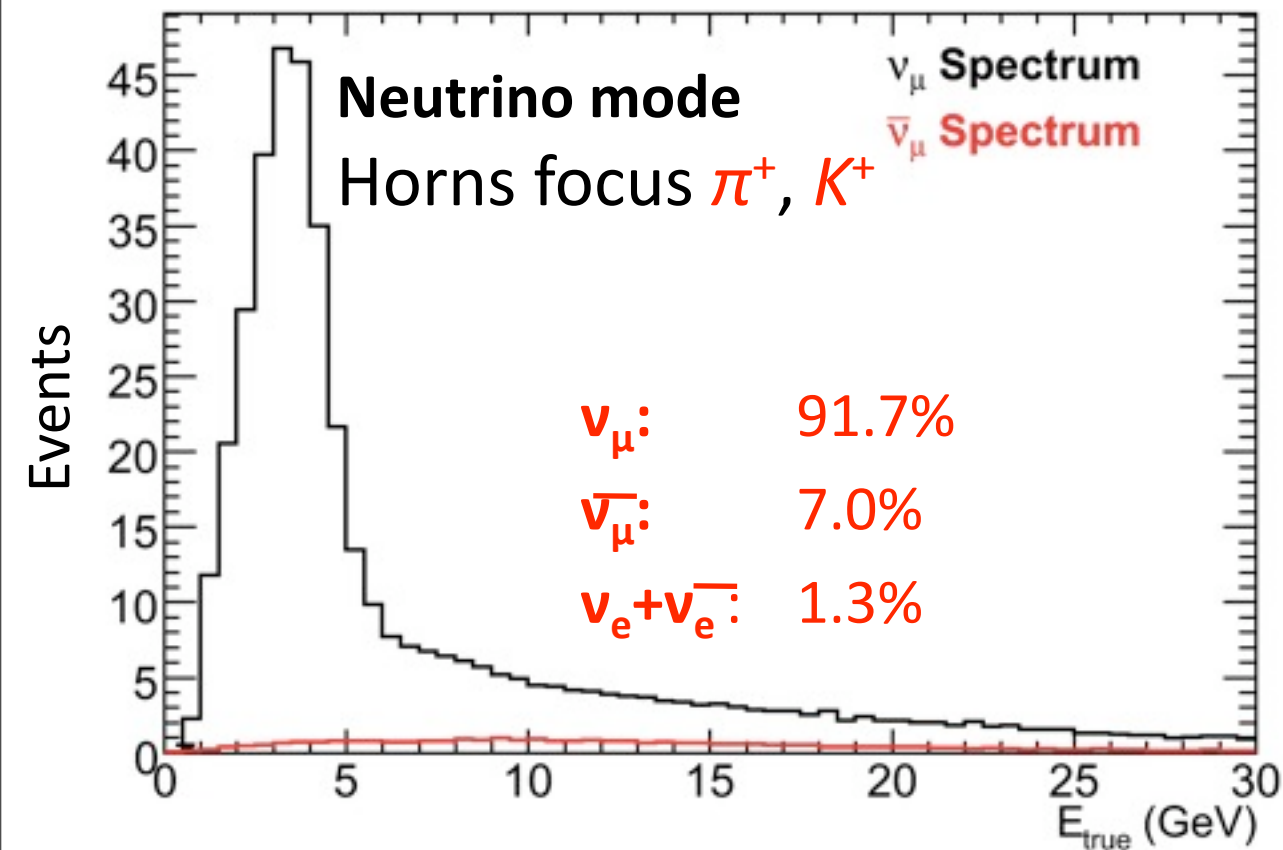
Making a neutrino beam



Source size makes near and far different

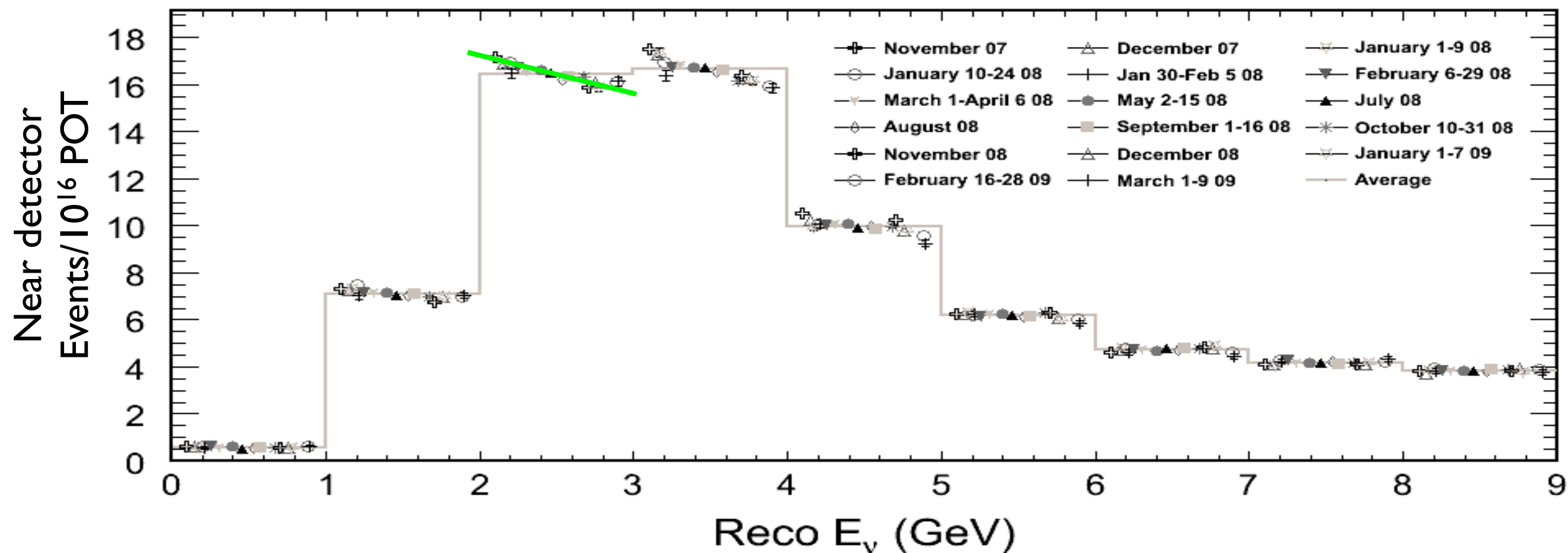


Making an anti-neutrino beam

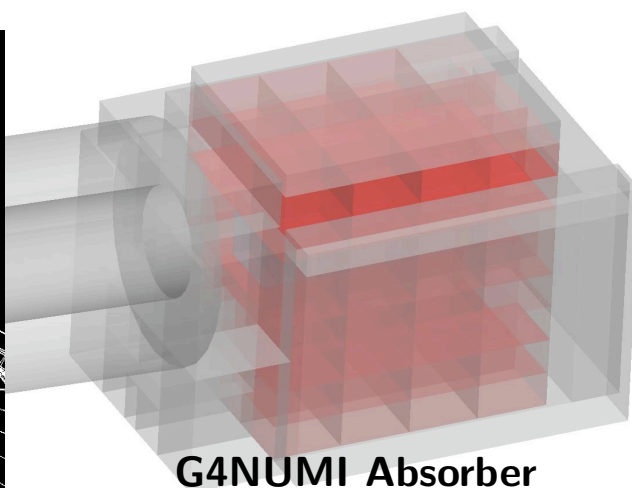
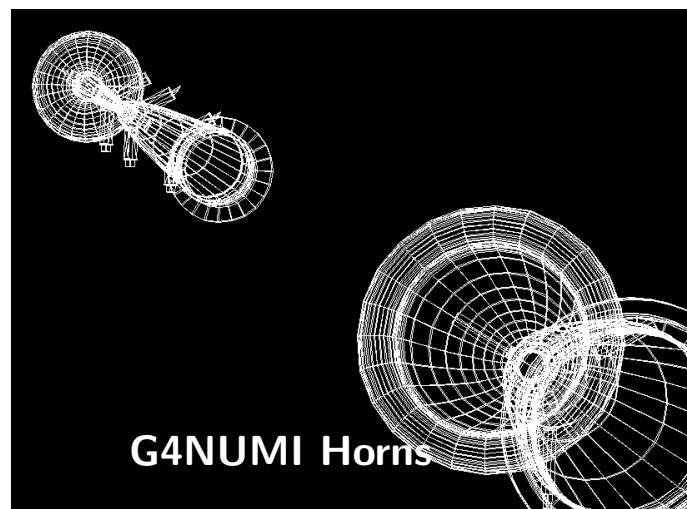


MINOS Beam Performance

Neutrino Energy Spectrum Stability

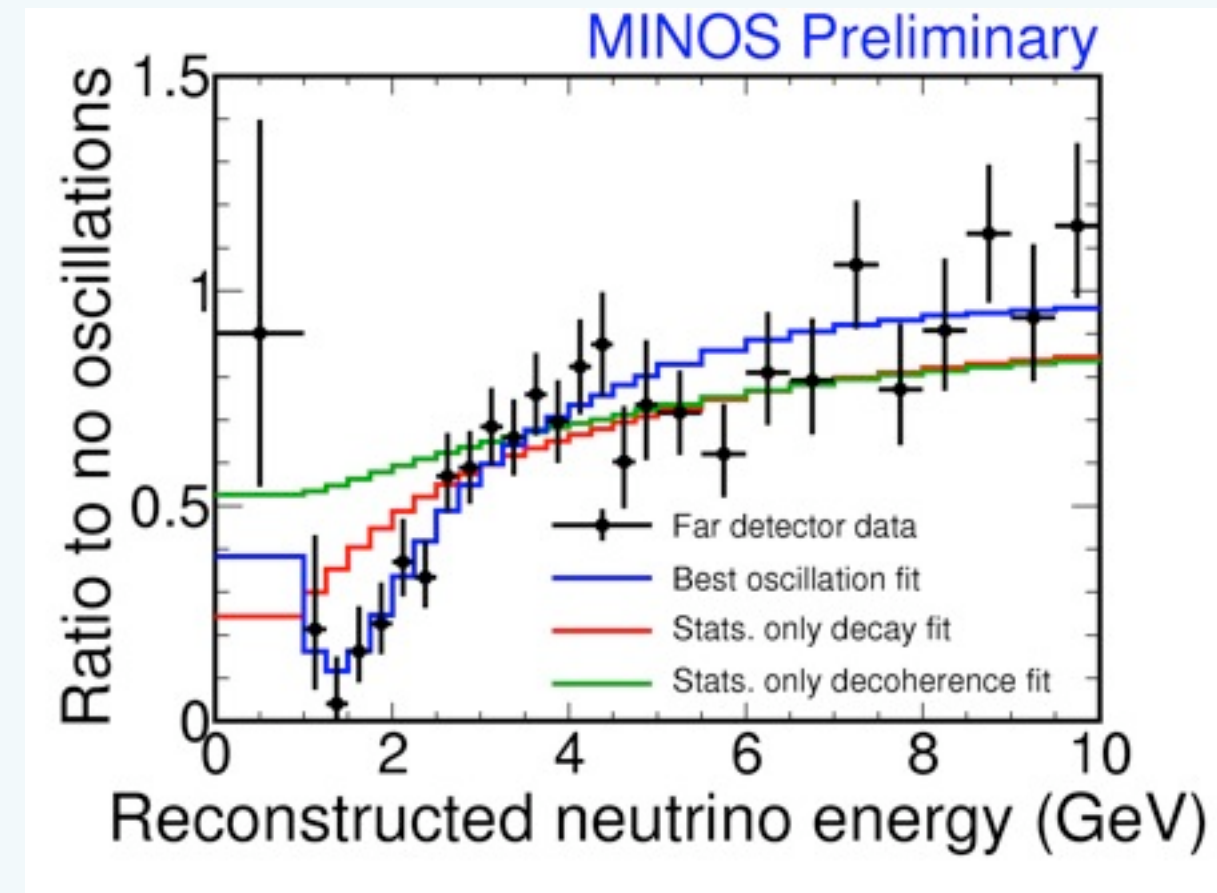
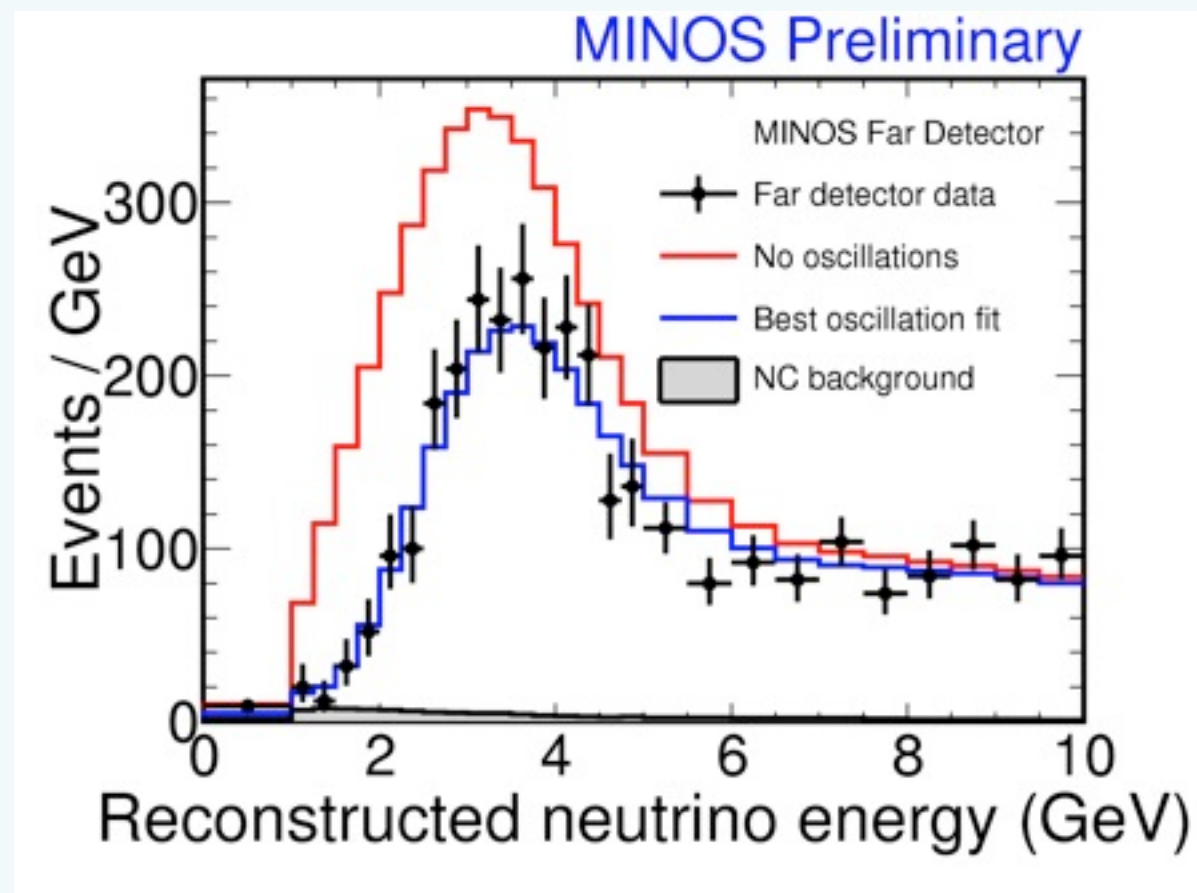


FLUGG = G4NuMI geometry + FLUKA08 unified interaction/focusing simulation



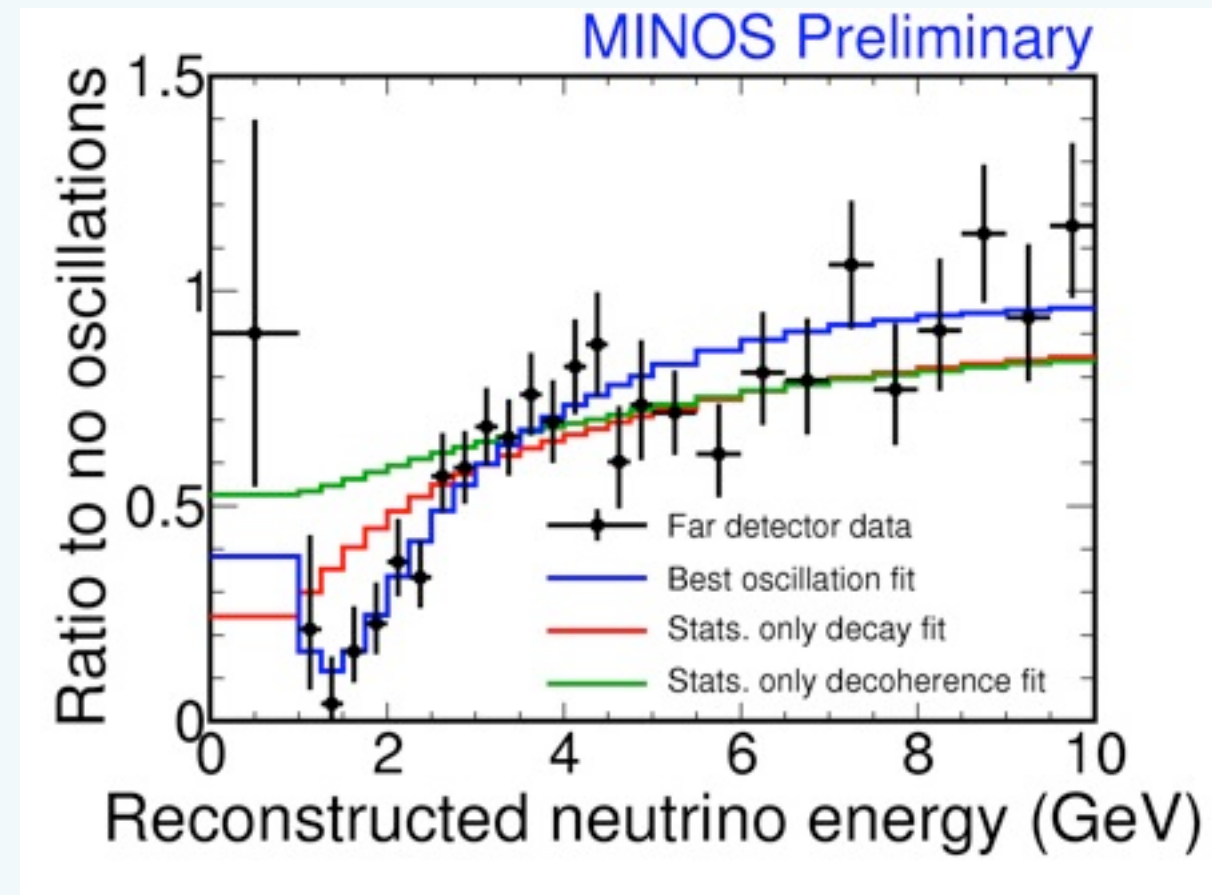
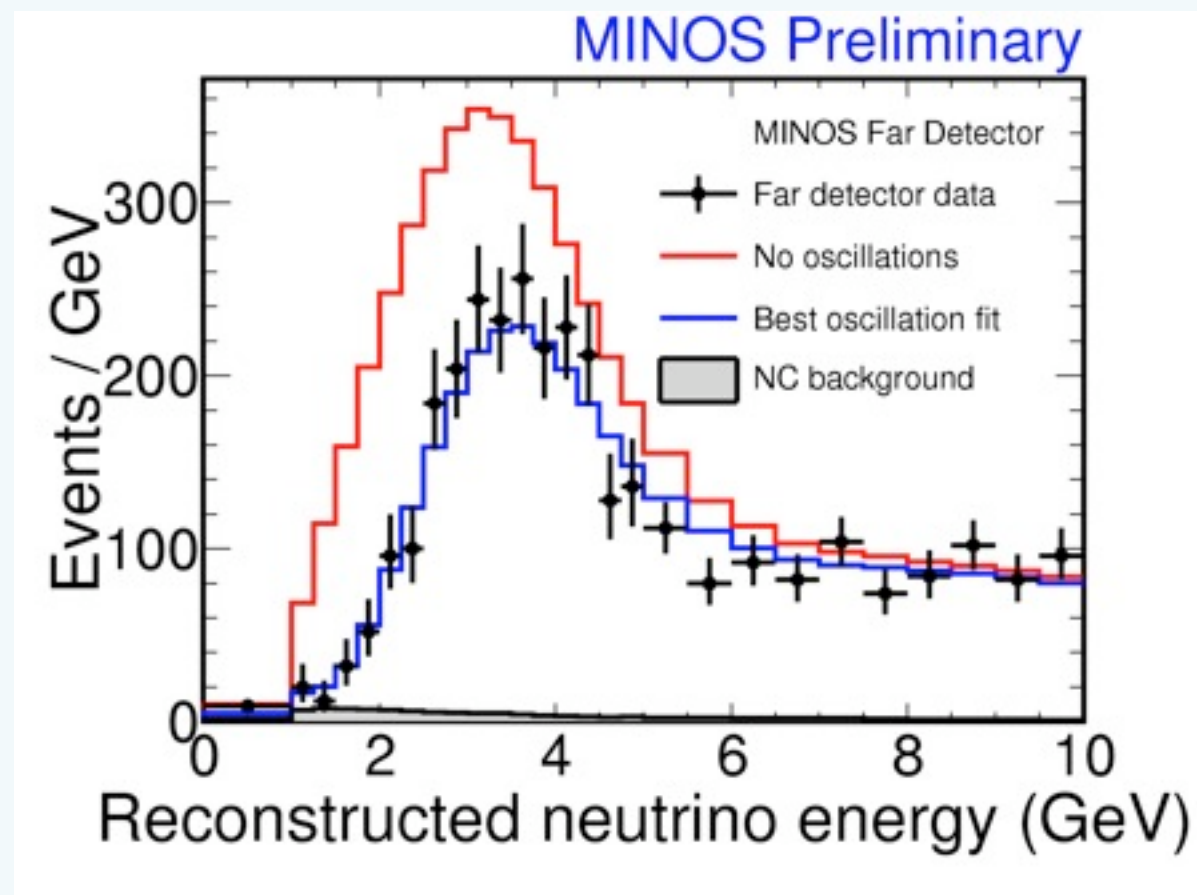
- Slow decrease in event rate seen at the peak, due to target degradation.
- Extremely precise simulation work in progress.
- Simulation based on data with broad applicability.

ν_μ Disappearance Result



No Oscillations:	2451
Observation:	1986

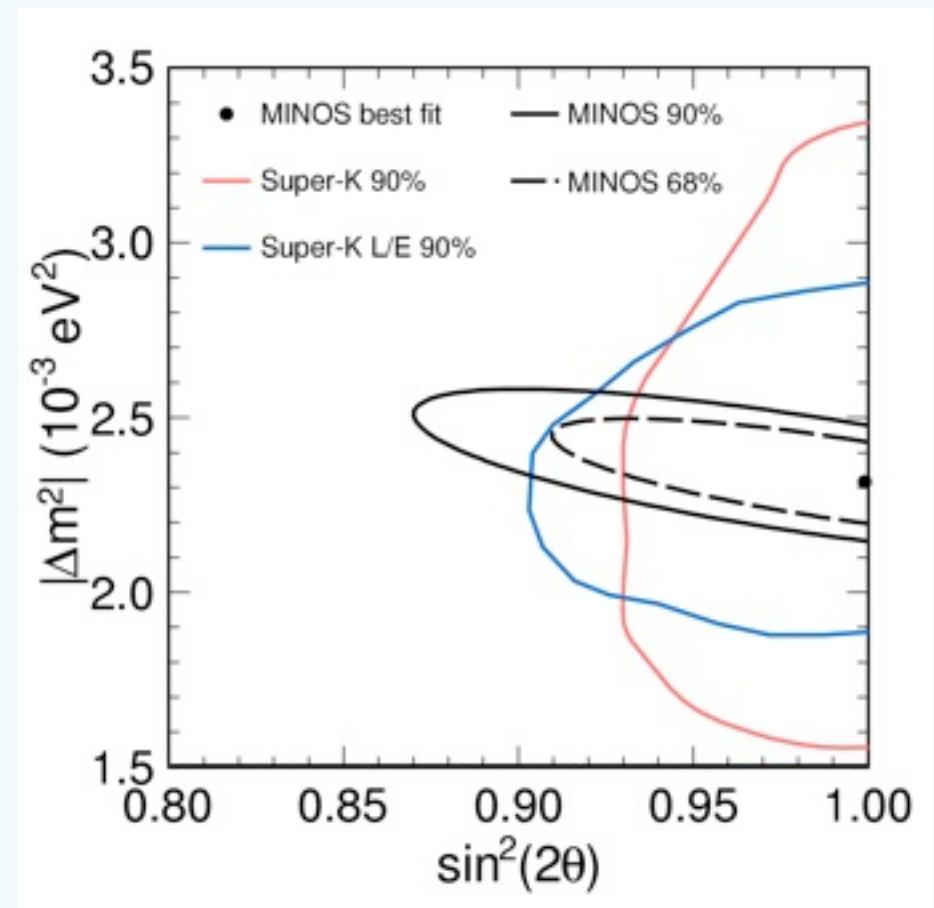
ν_μ Disappearance Result



$$|\Delta m^2| = 2.32^{+0.12}_{-0.08} \times 10^{-3} \text{ eV}^2$$

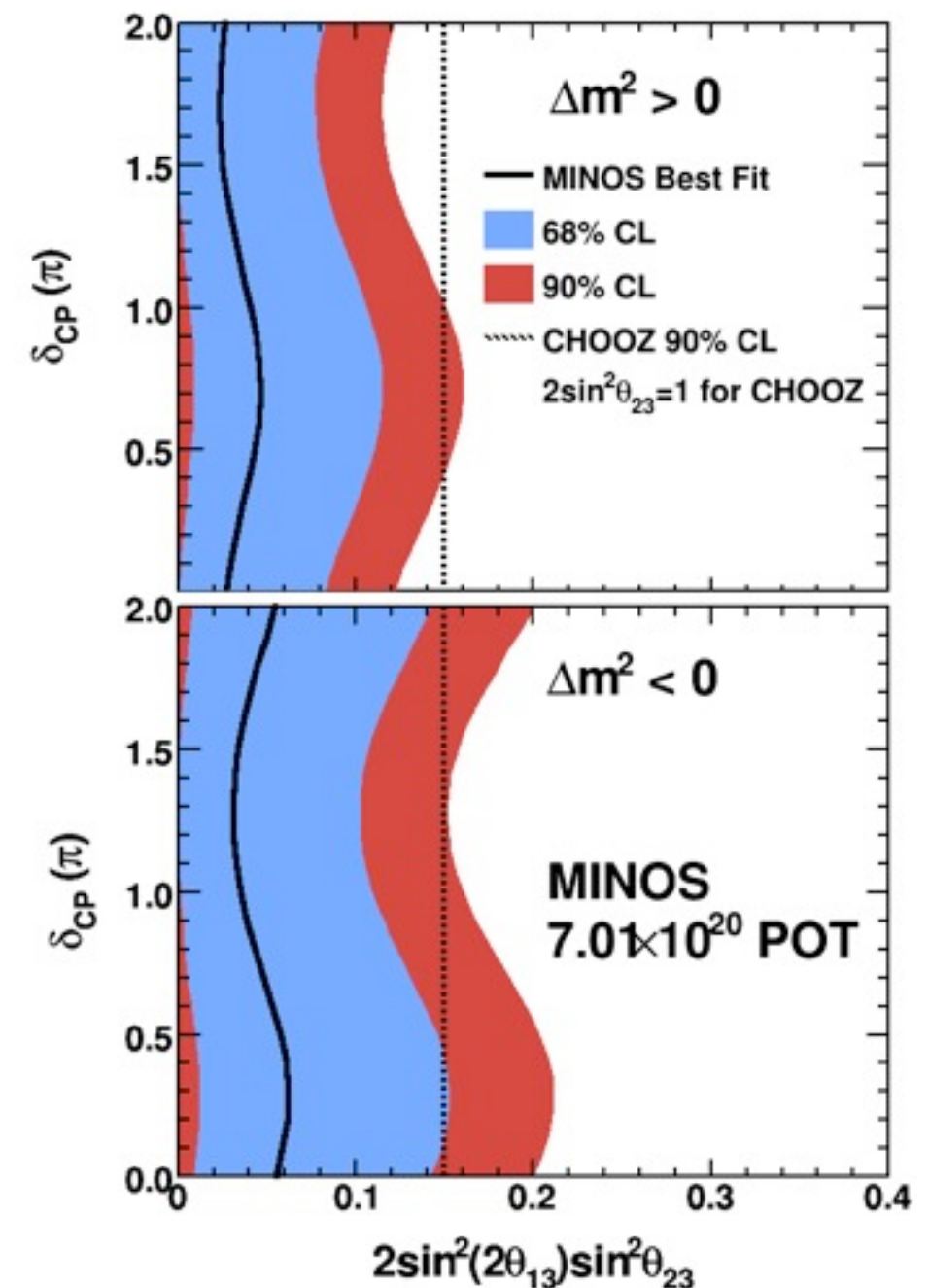
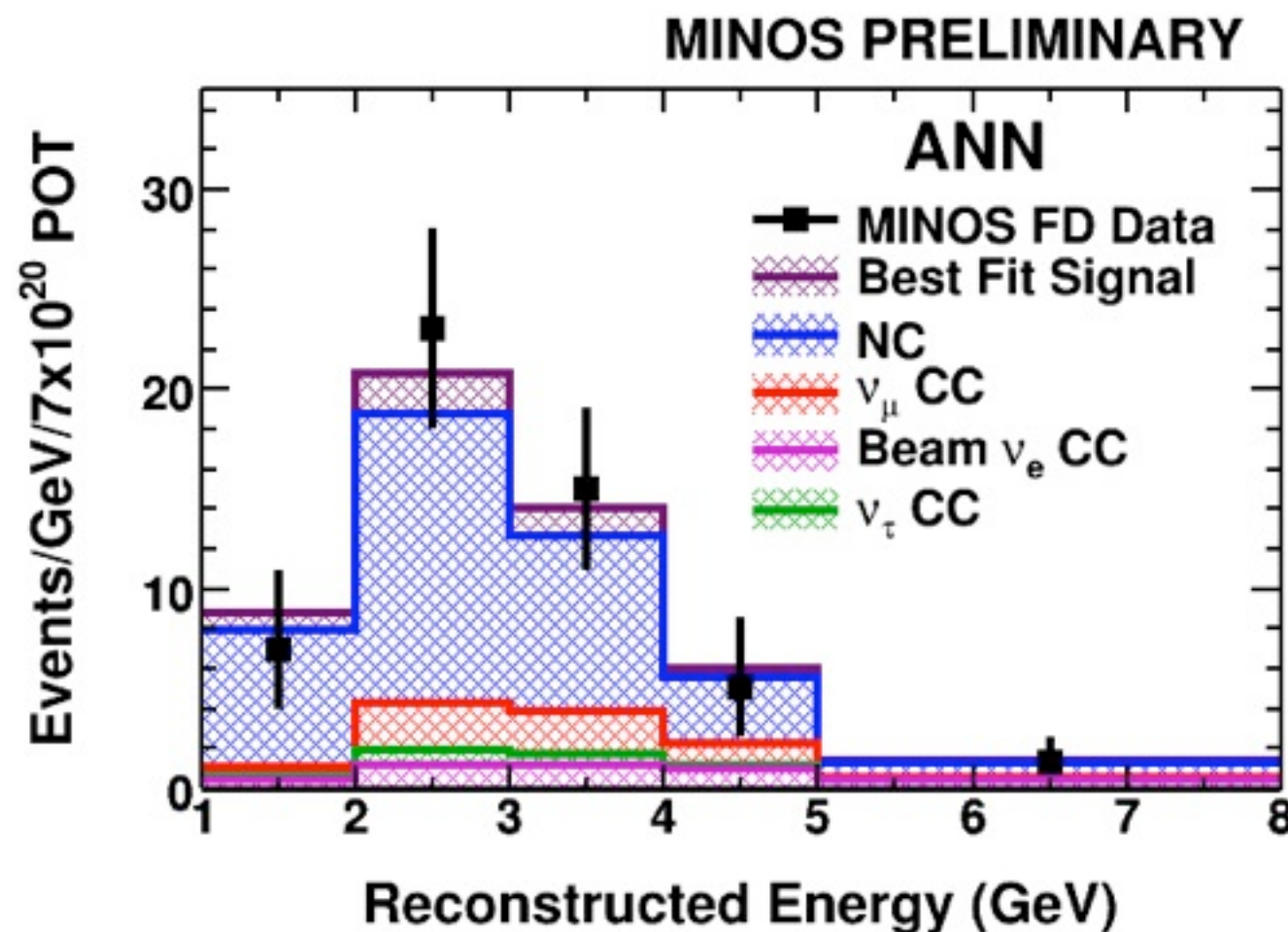
$$\sin^2(2\theta) > 0.90 \text{ (90\% C.L.)}$$

Super-K latest published contour, uses full 3 flavour mixing



ν_e Appearance Results

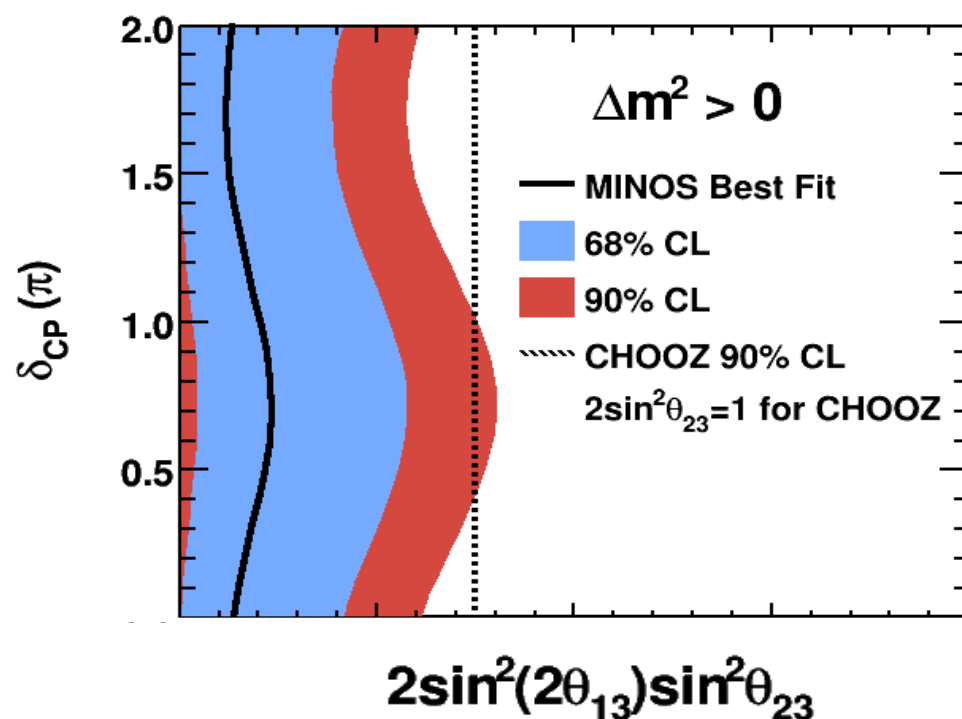
- Based on ND data, expect: $49.1 \pm 7.0(\text{stat.}) \pm 2.7(\text{syst.})$
- Observe: **54** events in the FD, a 0.7σ excess



θ_{13} Updates



3.23×10^{19} POT
 1 ν_e observed
 8 ν_μ observed
 have 4x data
 Earthquake!
 Restart in ~ 1 yr.

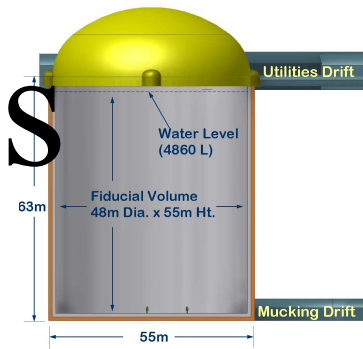


MINOS
 New analysis
 is on way

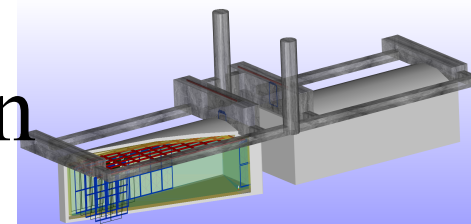
for $\delta_{CP} = 0$, $\sin^2(2\theta_{23}) = 1$,
 $|\Delta m_{32}^2| = 2.43 \times 10^{-3} \text{ eV}^2$

$\sin^2(2\theta_{13}) < 0.12$ normal hierarchy
 $\sin^2(2\theta_{13}) < 0.20$ inverted hierarchy
 at 90% C.L.

Future Experimental strategies

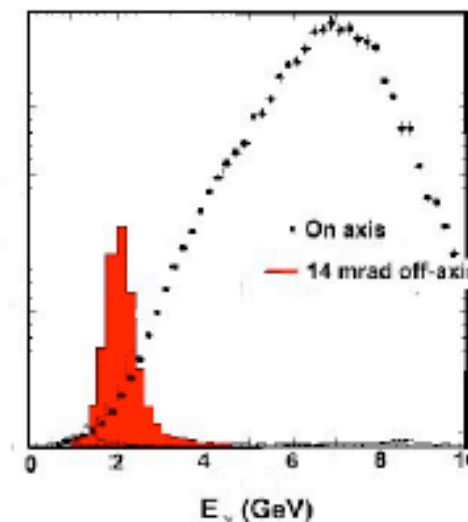


- Use a horn produced high energy beam (off versus on-axis debate). Horn produced beam will provide high intensity and flexibility in spectrum and energy. Much experience since 1963 (Van Der Meer). But has a small contamination wrong flavor neutrinos.
- Try to produce a very pure beam
 - Make beam from decays of muons (muon storage ring neutrino factory)
 - Or make beam from decays of nuclei that have been accelerated (betabeam)
 - These technologies are in infancy and need muon detectors. For nufact it must be magnetized.



Off-Axis Beams

BNL 1994

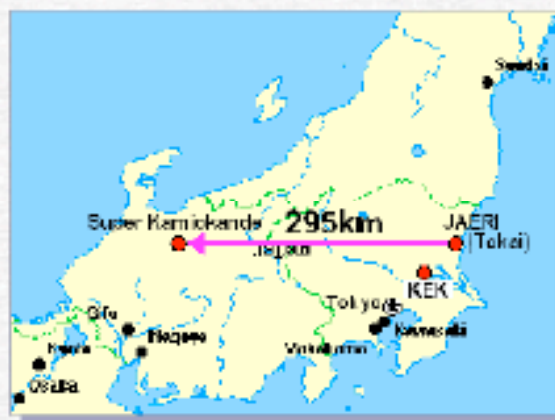


π^0 suppression

T2K

JHF \rightarrow Super-Kamiokande

- 295 km baseline
- Super-Kamiokande:
 - 22.5 kton fiducial
 - Excellent e/μ ID
 - Additional π^0/e ID
- Hyper-Kamiokande
 - 20 \times fiducial mass of SuperK
- Matter effects small
- Study using fully simulated and reconstructed data

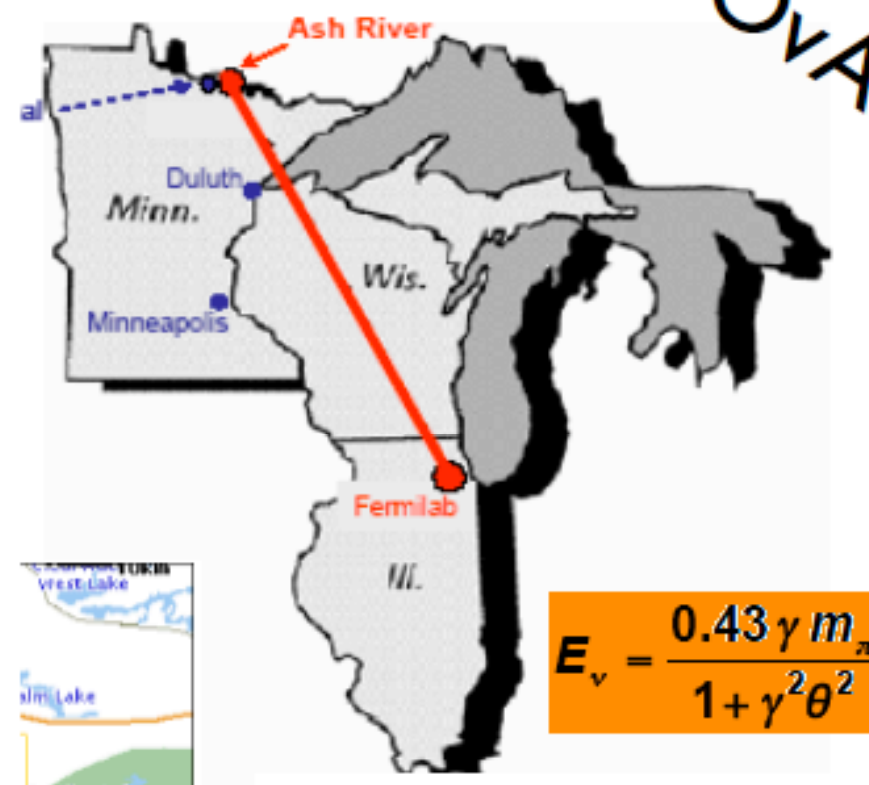


$L=295$ km and
Energy at Vac. Osc. Max. (vom)

$$E_{vom} = 0.6 \text{ GeV} \left\{ \frac{\delta m_{32}^2}{2.5 \times 10^{-3} \text{ eV}^2} \right\}$$

0.75 upgrade to 4 MW

NOVA



$$E_\nu = \frac{0.43 \gamma m_\pi}{1 + \gamma^2 \theta^2}$$

$L=700 - 1000$ km and
Energy near 2 GeV

$$E_{vom} = 1.8 \text{ GeV} \left\{ \frac{\delta m_{32}^2}{2.5 \times 10^{-3} \text{ eV}^2} \right\} \times \left\{ \frac{L}{820 \text{ km}} \right\}$$

0.4 upgrade to 2 MW

Detector Strategies

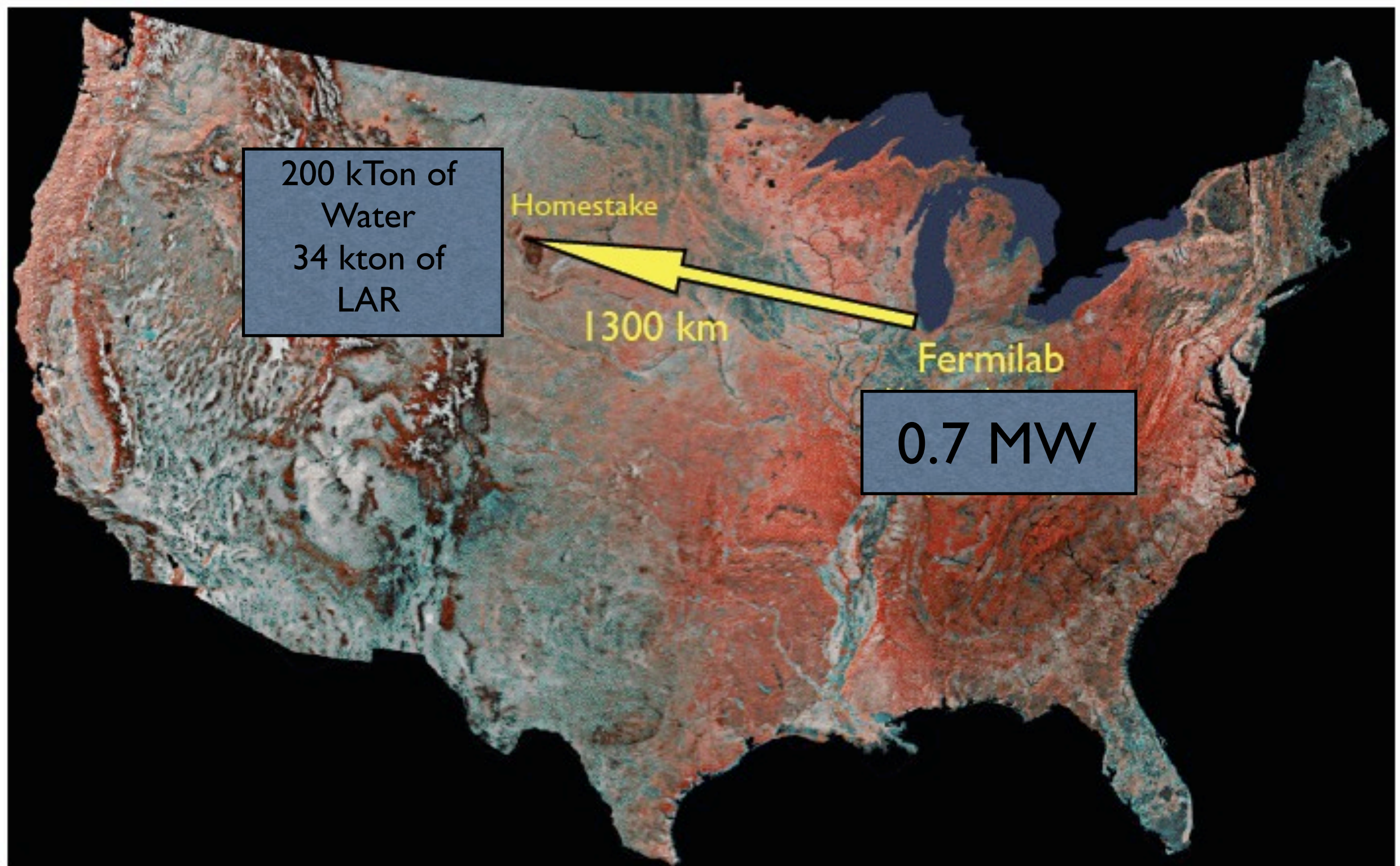
Water Cherenkov

- Use a crude detector, but only select well identified single electron events(QE) to keep background low and energy resolution high.
- Known, successful technology with wide dynamic range (5 MeV-50GeV).
- Can perform both p-decay, astrophysical sources,
- Can be deployed deep scaled up: 50kT to fewX100kTon.
- Will have low efficiency and need very large mass.

Liquid argon

- Very high resolution detector should allow use of much higher fraction of cross section including multi-track events.
- Energy resolution might need attention if using all cross section.
- Could use the fine resolution and below Cher threshold for background tagging.
- Could do the specialized proton decay searches very well.
- Dynamic range for physics is less well-known.
- Scale up factor needs to be substantial ~ 100 .

Long-Baseline Neutrino Experiment in US

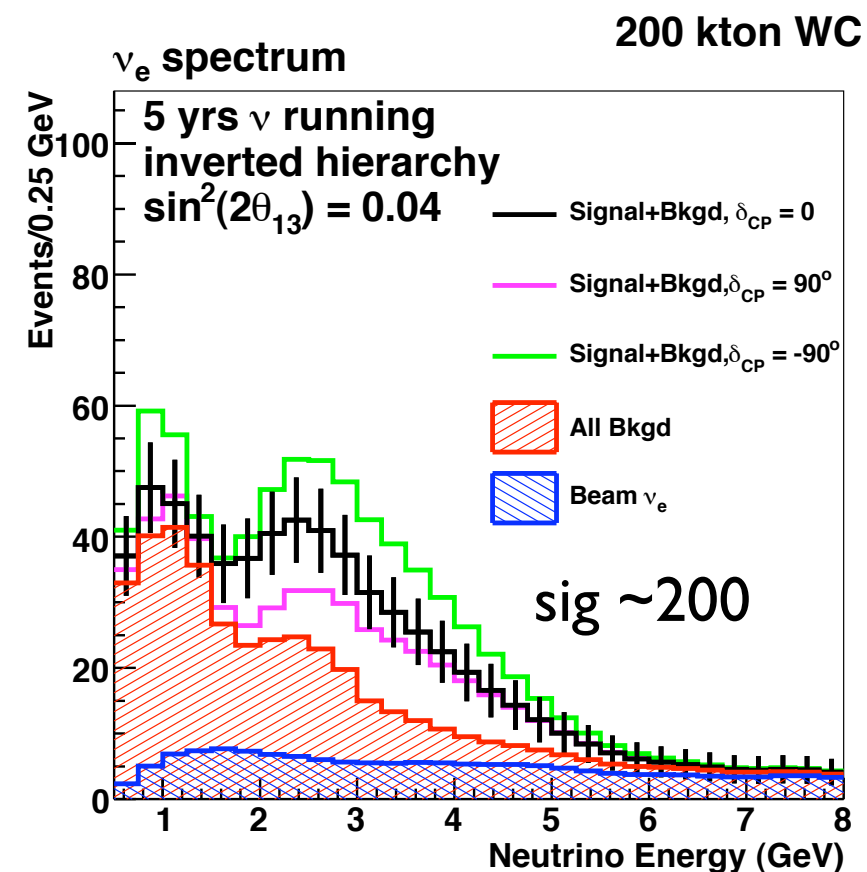
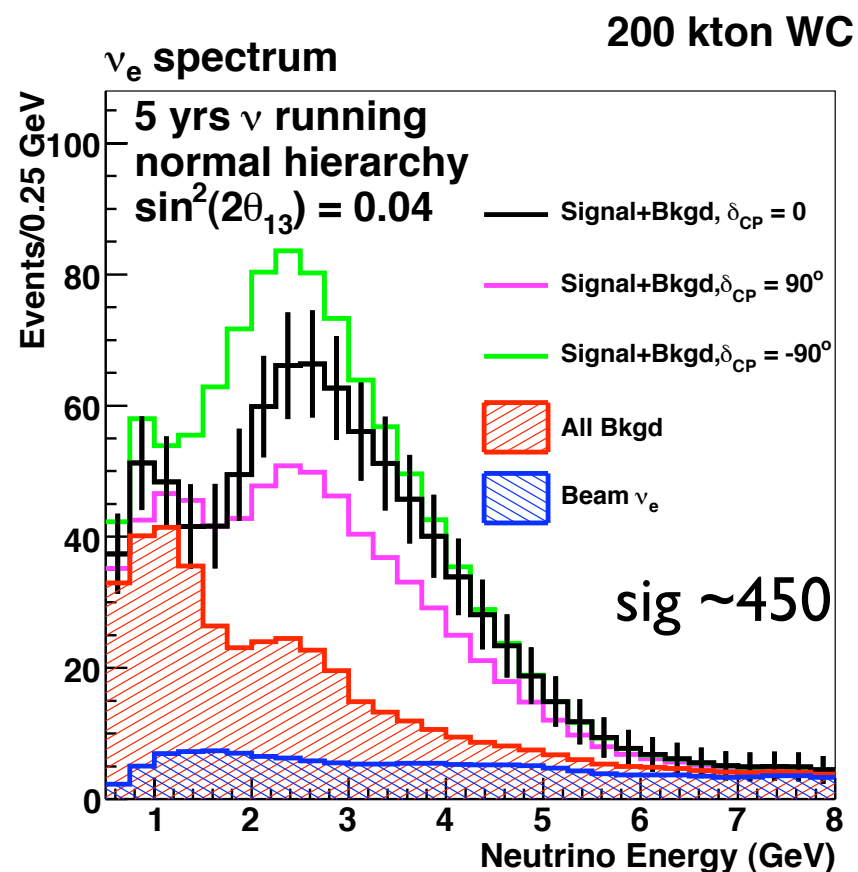


Use this as example to illustrate event rates and sensitivity.

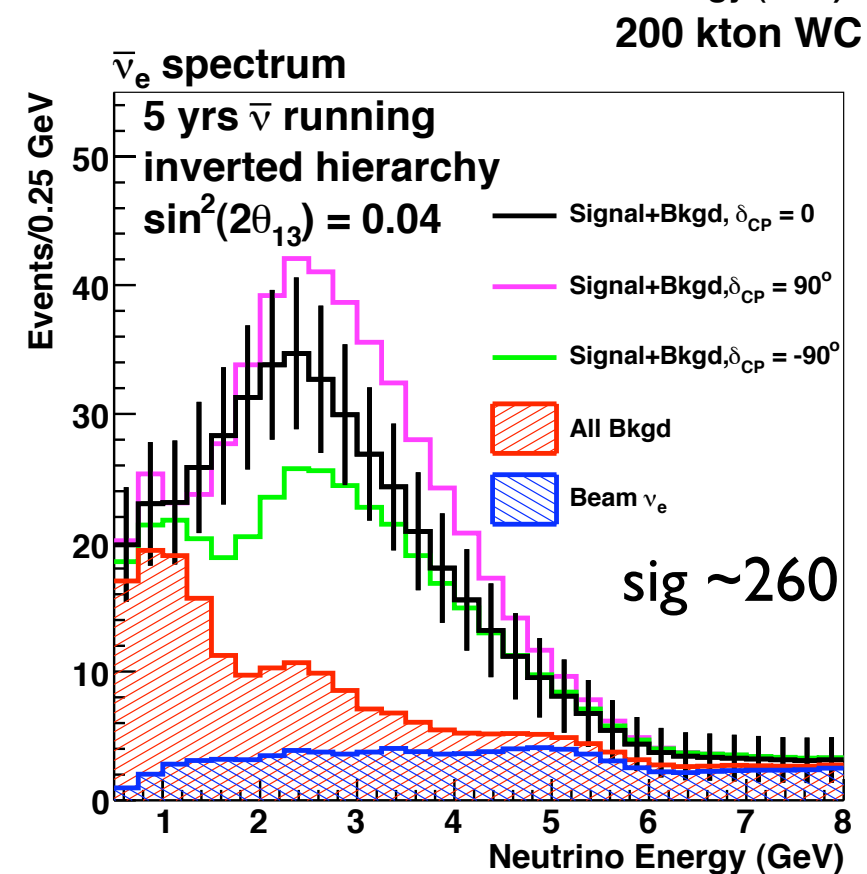
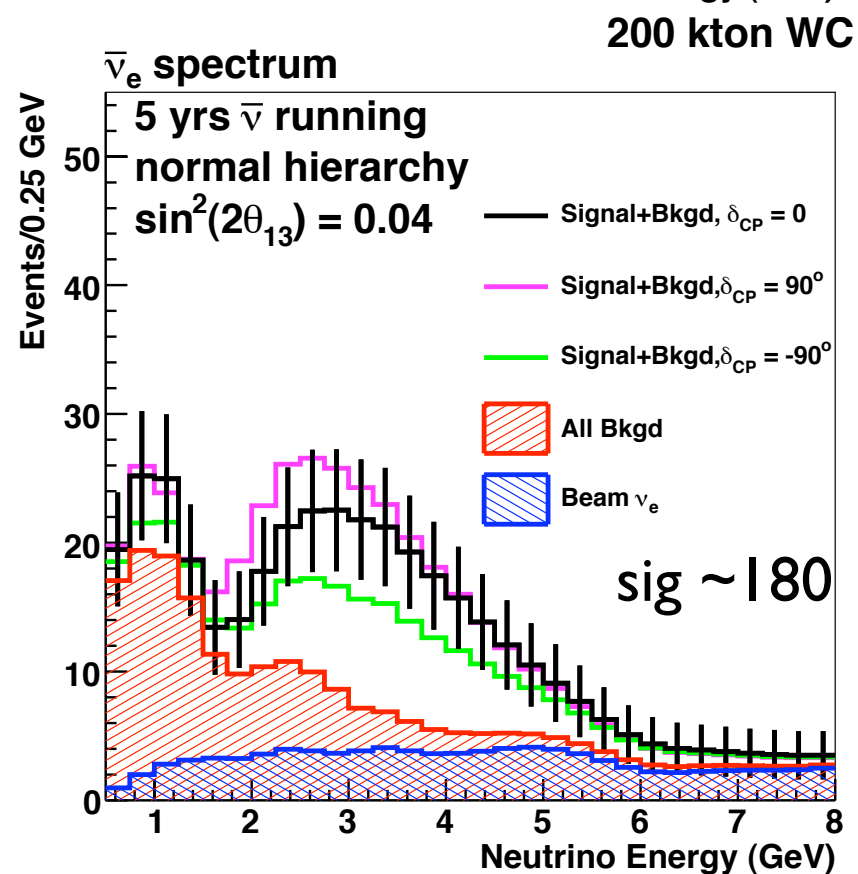
normal

inverted

nu



anti-nu

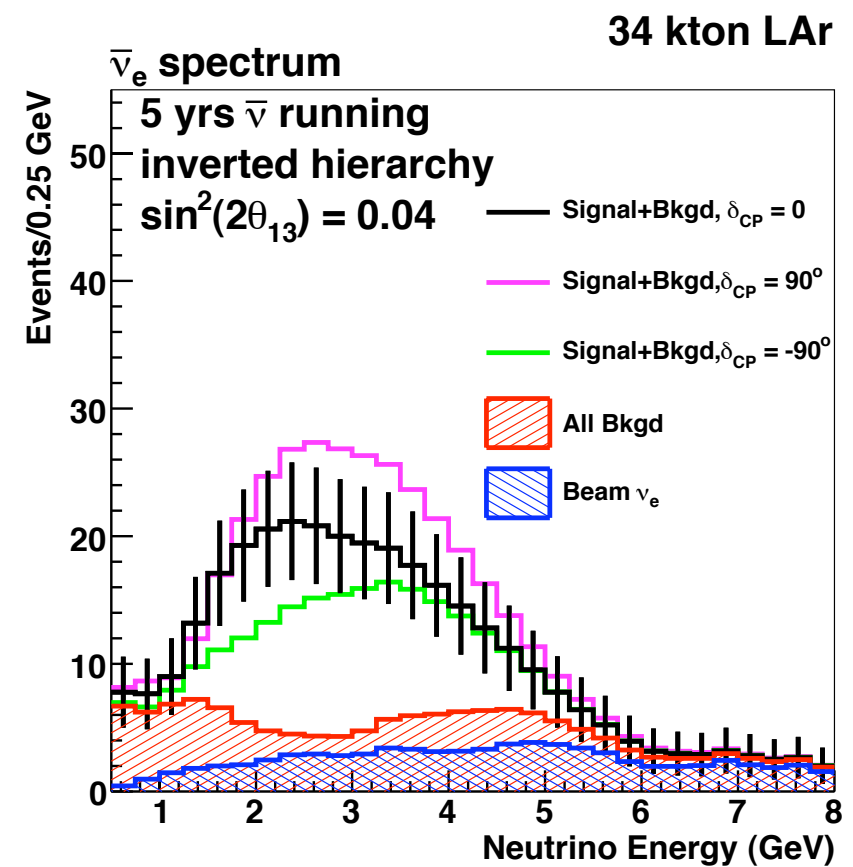
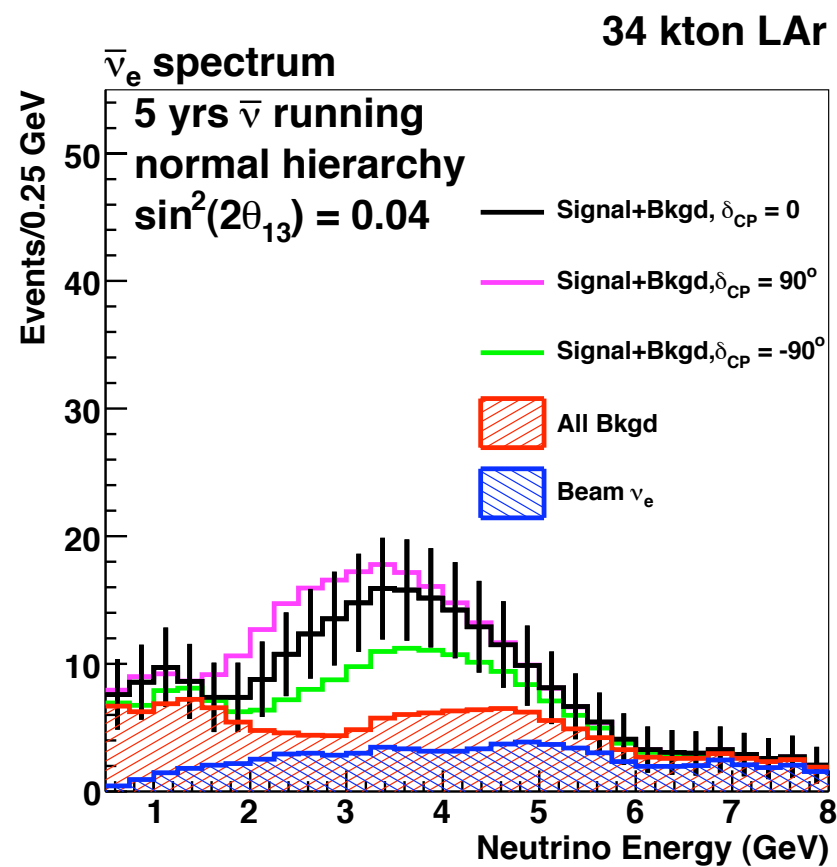
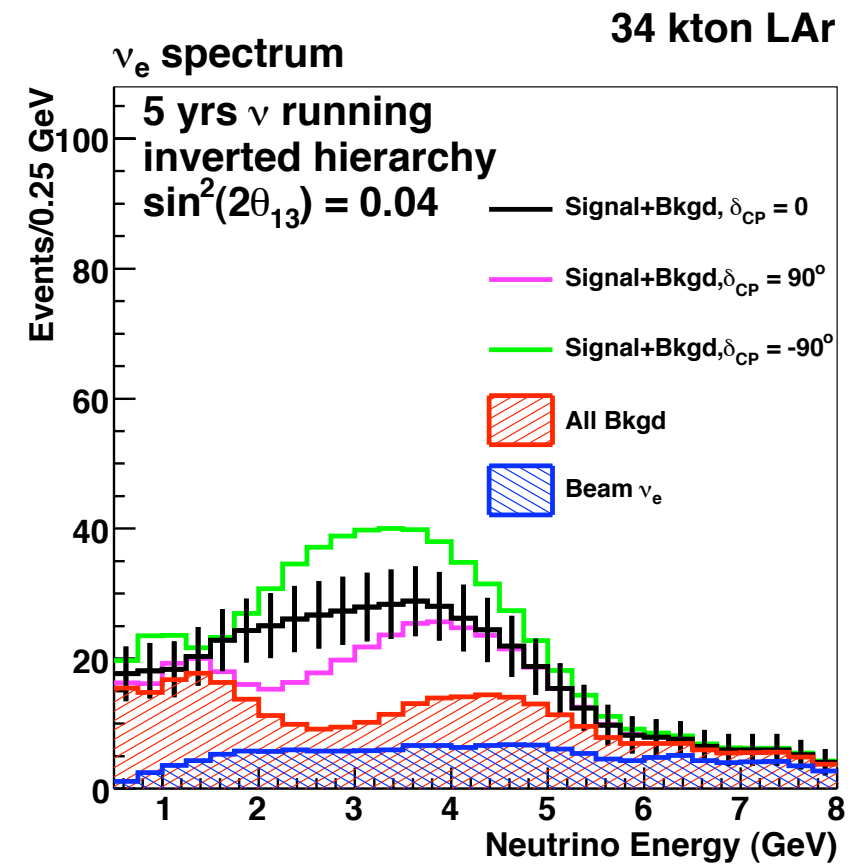
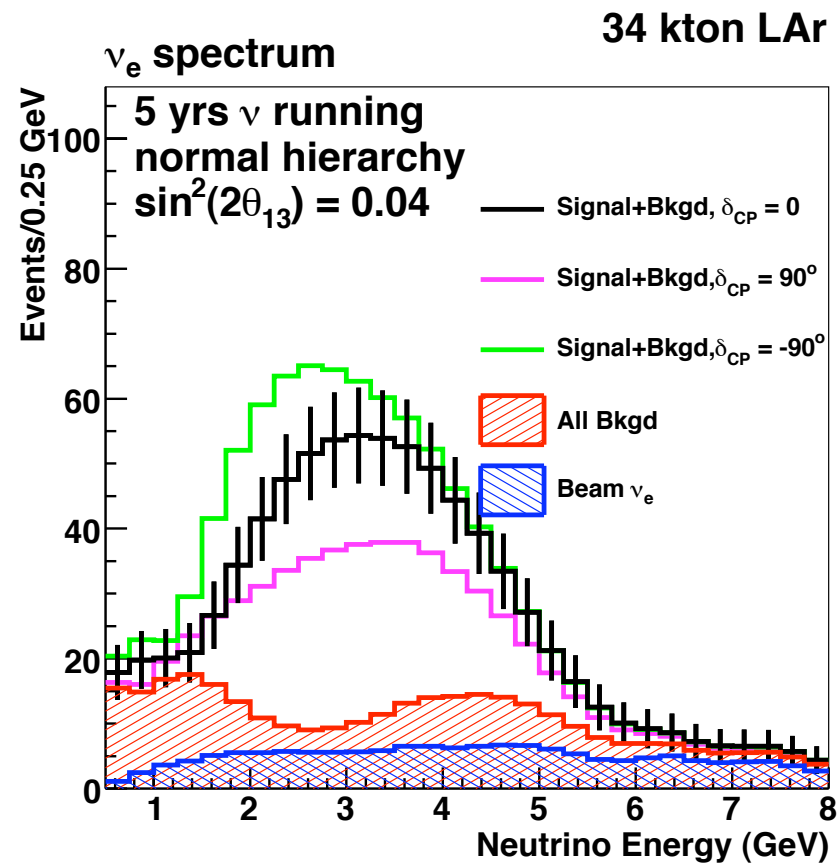


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normal

inverted

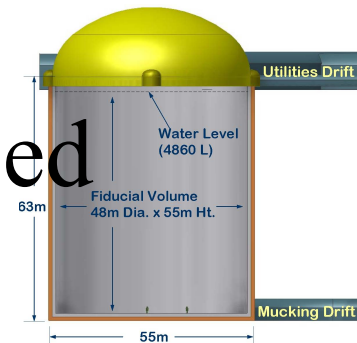
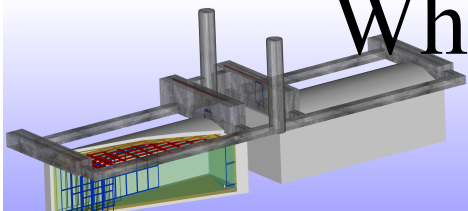
nu



anti-nu

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What is a reasonable systematic error to assume based on experience?



	WC (ν mode)	WC ($\bar{\nu}$ mode)
Normal mass hierarchy:		
Oscillated $\nu_e + \bar{\nu}_e$	484	180
Beam $\nu_e + \bar{\nu}_e$	218	115
NC Bkd	276	118
Mis-identified ν_μ CC	15	7
Inverted mass hierarchy:		
Oscillated $\nu_e + \bar{\nu}_e$	212	261
Beam $\nu_e + \bar{\nu}_e$	221	114
NC Bkd	276	118
Mis-identified ν_μ CC	15	7

Table 6-1: Number of ν_e and $\bar{\nu}_e$ events expected in a 200 kton WC detector in 5 years each of neutrino and antineutrino running in a 700 kW beam. Rates have been integrated over the region from 0.5 – 12 GeV. In correspondence with Figure 6-1, this assumes $\sin^2 2\theta_{13} = 0.04$ and $\delta_{CP} = 0$. 'NC' refers to backgrounds from neutral current events looking like ν_e events.

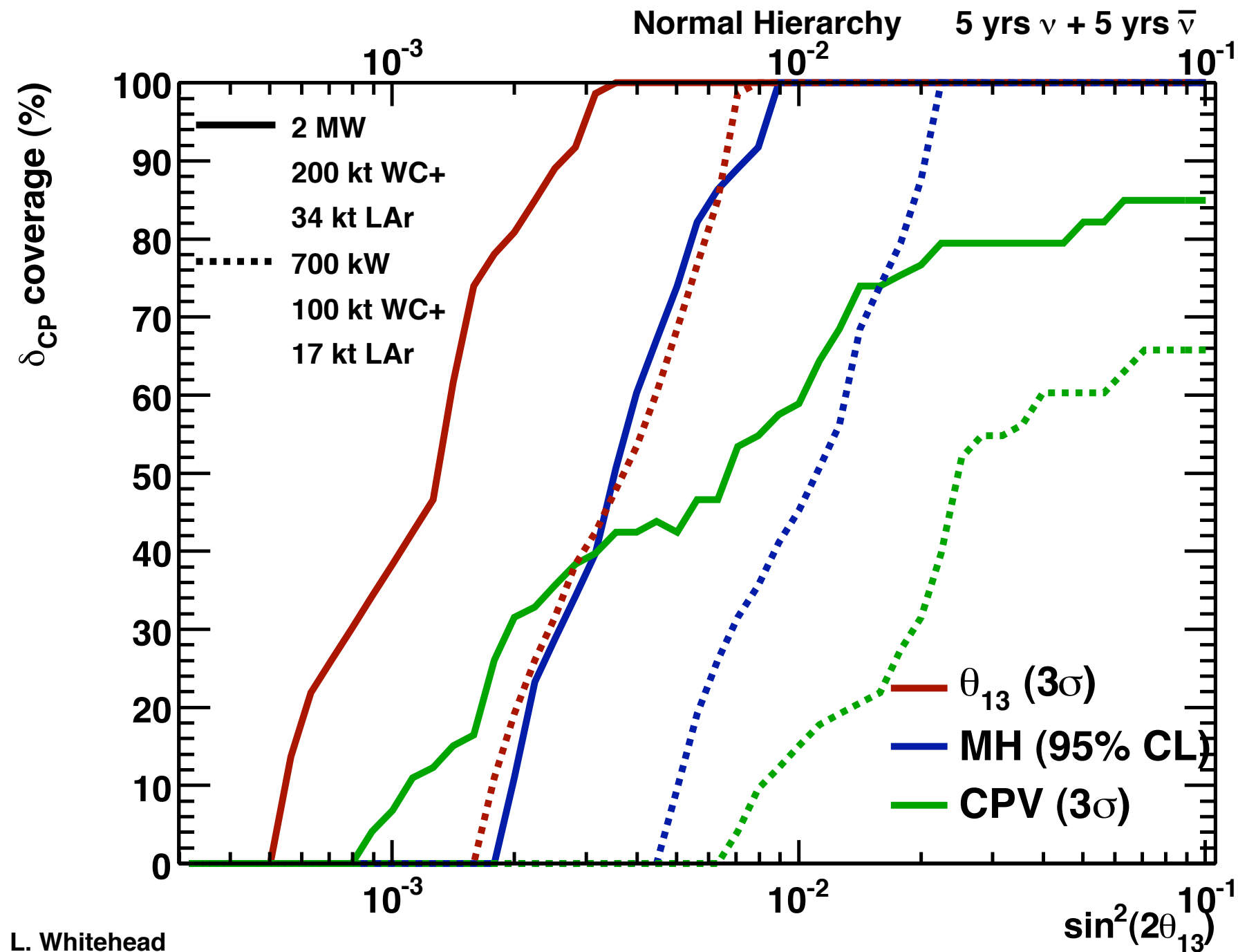
	LAr (ν mode)	LAr ($\bar{\nu}$ mode)
Normal mass hierarchy:		
oscillated $\nu_e + \bar{\nu}_e$	497	112
beam $\nu_e + \bar{\nu}_e$	326	168
NC	81	34
mis-identified CC	162	52
Inverted mass hierarchy:		
oscillated $\nu_e + \bar{\nu}_e$	212	261
beam $\nu_e + \bar{\nu}_e$	329	167
NC	81	34
mis-identified CC	162	52

Table 5-1: Number of ν_e and $\bar{\nu}_e$ events expected in a 34-kt LAr detector at 1300 km in 5 years each of neutrino and antineutrino running in a 700 kW beam [3]. Rates have been integrated over the region from 0.5 – 60 GeV. Like Figure 5-4, this assumes $\sin^2 2\theta_{13} = 0.04$ and $\delta_{CP} = 0$.

Bckg ~500 evts. Total Bckg systematics should be maintained at or below the statistical errors. Currently assume no e-dependence.

- Survey of past experiments show that systematic errors on the background can be decreased by improved analysis.
- MINOS near detector reduced Monte Carlo dependence. Background estimate is data-based and largest systematic is due to near-far extrapolation and energy scale.
- 5% is the goal for future. This will need a capable near detector.

Sensitivity summary



L. Whitehead

Summary

- Discovery of oscillations and neutrino mass has opened a new field for measurement.
- The current focus is on full understanding of the quantum mechanical mixing phenomena which takes place on a very large scale and huge dynamic ranges.
- A new program of experiments is in discussion and design. It requires detectors that are order of magnitude bigger and beam intensities that are much higher.
- The current technology can be pushed to achieve desirable sensitivities.

Performance features desired for the new long baseline program

- An intense (>1 MW) broad band (0-5 GeV) beam with some tunability. Spectrum should be weighted towards lower energies.
- Baseline of 1000 to 2000 km to have large matter effects. (any new physics is expected to be related to matter-like effects).
- A underground detector(~ 100 kTon of efficient mass) capable of clean identification of electron neutrino events in 1 GeV range.
- Statistical and systematic power to get to $\text{Sin}^2 2\theta_{13} \sim 0.001$ is possible with current technology. Perhaps with upgrades to beam power.

Conclusions

CONCLUSIONS

What happened in neutrino physics the last years is a miracle. Everything, that is the Glashow-Salam-Weinberg theory of electro-weak interactions, looks perfectly O.K. It is too good. The appetite comes while eating and this means Grand Unification. But I do not believe that elementary particle physics will soon die of abundance of understanding and or lack of problems to be solved. Let us not discuss now about unexpected things, since anyway about such things one does not talk seriously in a lecture entitled "Fifty Years of Neutrino Physics". But there are already more or less important things. One of them, finite neutrino masses (together with the instability of the proton) is in the head and in the mouth of everybody. Its implications - neutrino oscillations - are extremely informative (masses of neutrinos, number of them, and mixing angles), if something can be done, as it seems, in controllable experiments of various types (reactor, accelerator, cosmic, solar). It is not excluded* that the ν_e mass may be measured directly from the ^3H beta spectrum, although I am not sure that this can be done, just because of the fantastic, I would say acrobatic, difficulty of the experiment, which incidentally, is a relatively cheap one⁵.

Be as it may, finite neutrino masses not only would confirm modern theoretical thinking and give us very necessary parameters but would originate a revolution in cosmology, astrophysics and neutrino astronomy.