# Physics of a long and very long baseline neutrino program

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Office of Science
U.S. DEPARTMENT OF ENERGY

BROOKHAVEN
NATIONAL LABORATORY

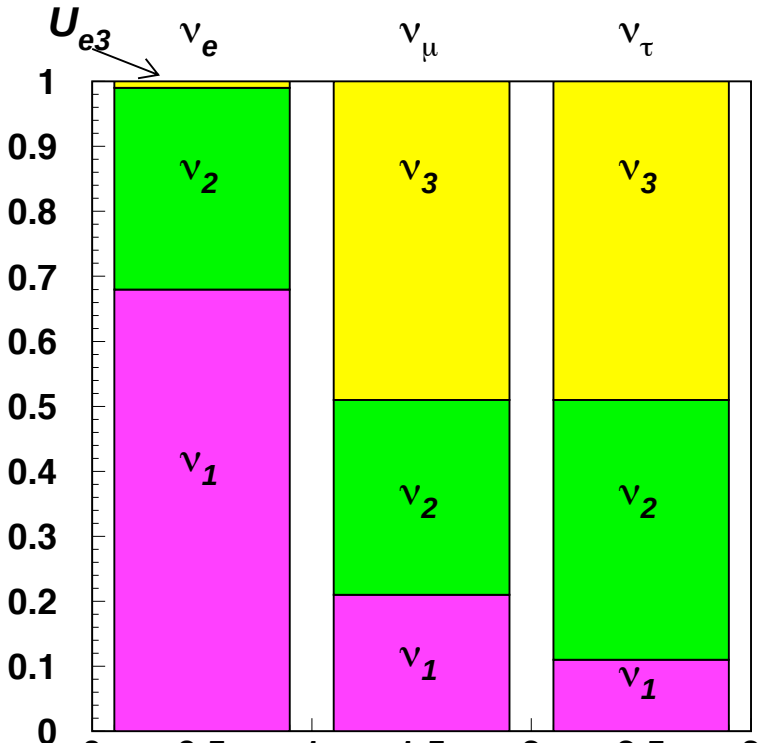
# Prologue

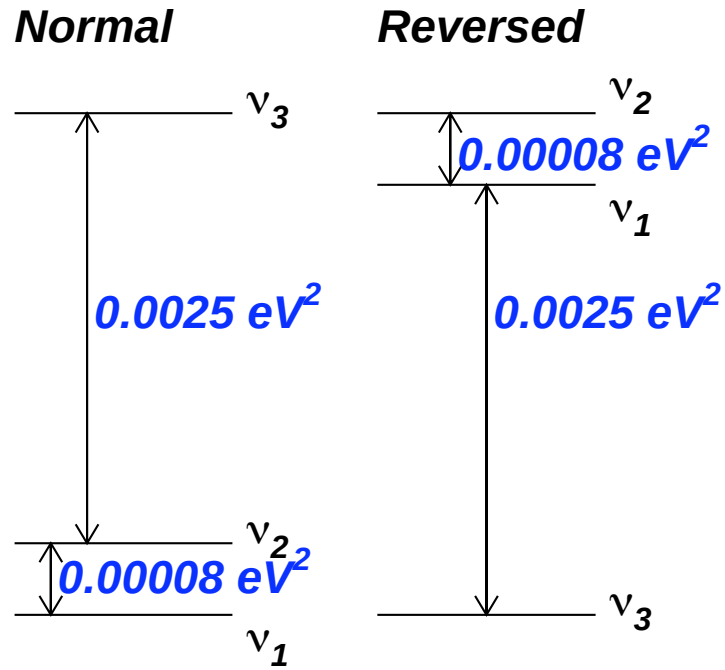
- Neutrino oscillations have emerged as a key topic that requires new intense high energy proton source.
- There is general agreement on the need for a source with Ep ~ 20-80 GeV.
- Power level is determined by the need for event rate. General agreement ~1-2 MW as first phase.
- In this I will focus on the physics case and two possible alternatives. I will also describe the FNAL/ BNL joint study to develop the next phase of this program. Please join this study.

# Apologies

- Japanese program will be covered in third talk.
- There is an international scoping study (ISS) in progress focussed on muon storage ring based ideas.
- My focus on conventional beams only.
- First part of talk should be general about the physics, but I will not talk about the LSND problem.

# 3 Generation oscillations




**Difference in mass squares: ($m_2^2$-$m_1^2$)**

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

3-nu:

$$P(\nu_a \to \nu_b) = \sum_i |U_{ai}|^2 |U_{bi}|^2 + 2Re(U_{a1}^* U_{b1} U_{a2} U_{b2}^* \times exp(-i\Delta m_{21}^2 L/2E)) + 2Re(U_{a1}^* U_{b1} U_{a3} U_{b3}^* \times exp(-i\Delta m_{31}^2 L/2E)) + 2Re(U_{a2}^* U_{b2} U_{a3} U_{b3}^* \times exp(-i\Delta m_{32}^2 L/2E))$$

CP phase

no matter effects

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

Solar : L~15000$km$

# Physics and Oscillation Nodes

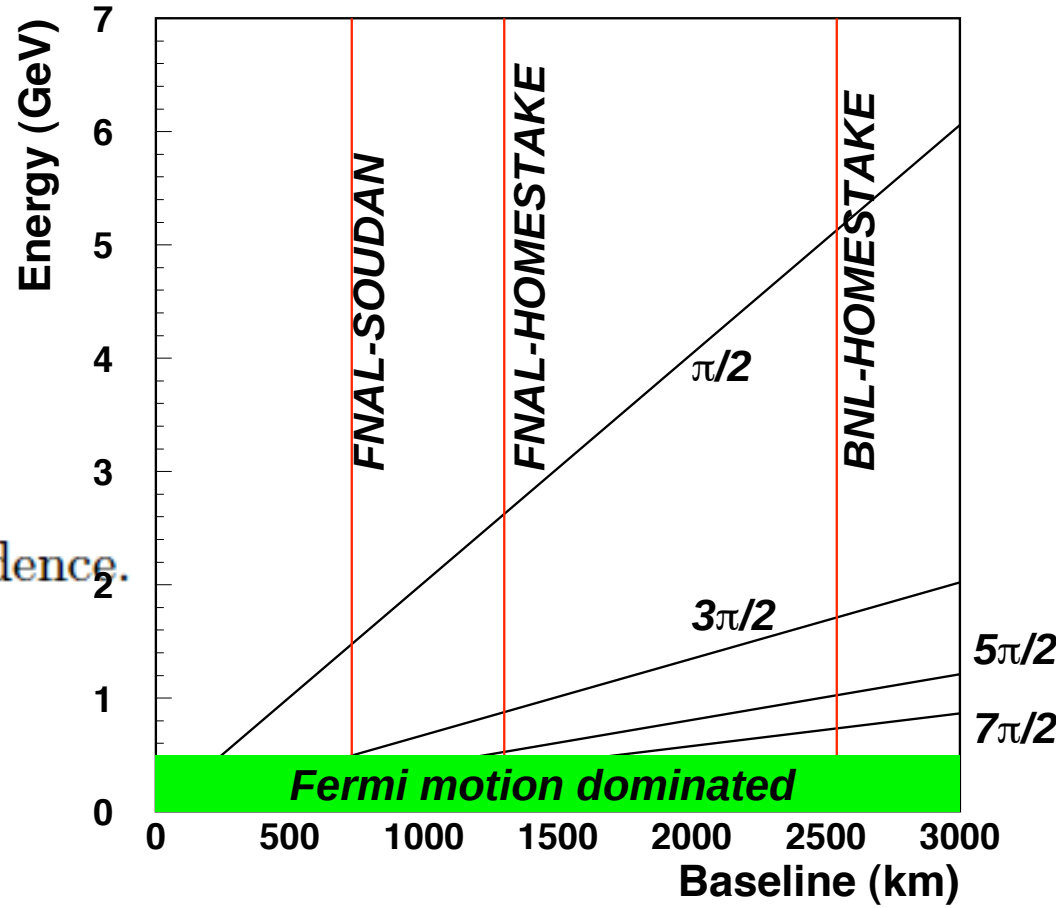
<u>First Generation</u>

- Focus on first node oscillations.
- Sensitivity for $\theta_{13}$.

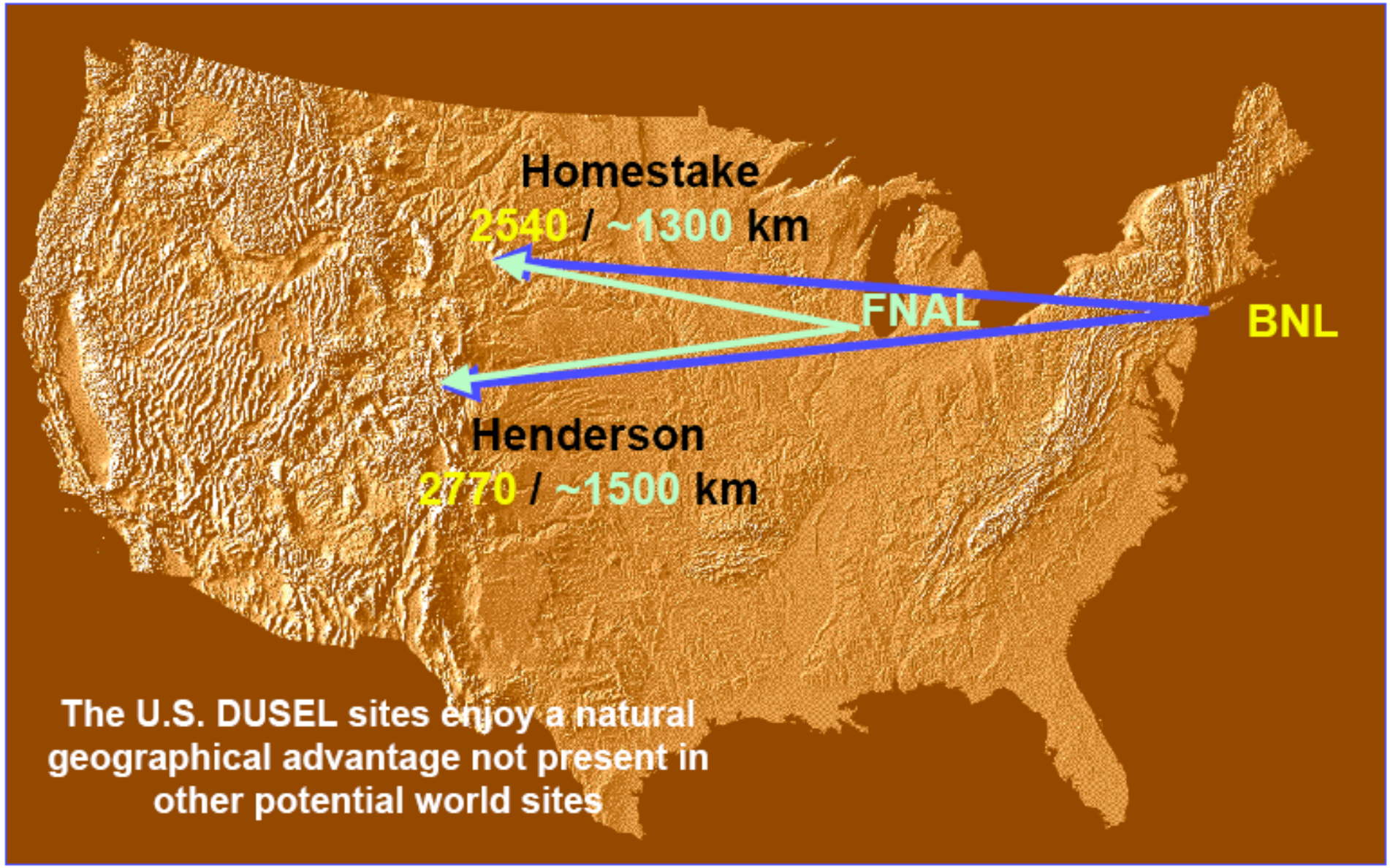
<u>Next Generation</u>

- Observe multiple nodes
  For precision and reduce flux dependence.
  Better sensitivity to $\theta_{13}$.
- Longer flight paths:
  Larger matter effects for hierarchy resolution and new physics.
- Better S/B for CP violation ($\delta_{CP}$) measurement.
  Flux $\sim L^{-2}$, but CP asymmetry $\sim L$; sensitivity to CPV independent of L. (Marciano hep-ph/0108181).

**Oscillation Nodes for $\Delta m^2 = 0.0025\ eV^2$**



# *Super Neutrino Beam* to DUSEL Candidate Sites



# $\nu_\mu \to \nu_e$ with matter effect

Approximate formula (M. Freund)

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

~7500 km no CPV. magic bln

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

CPV term approximate dependence ~L/E

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

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

solar term

linear dep.

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

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

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

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

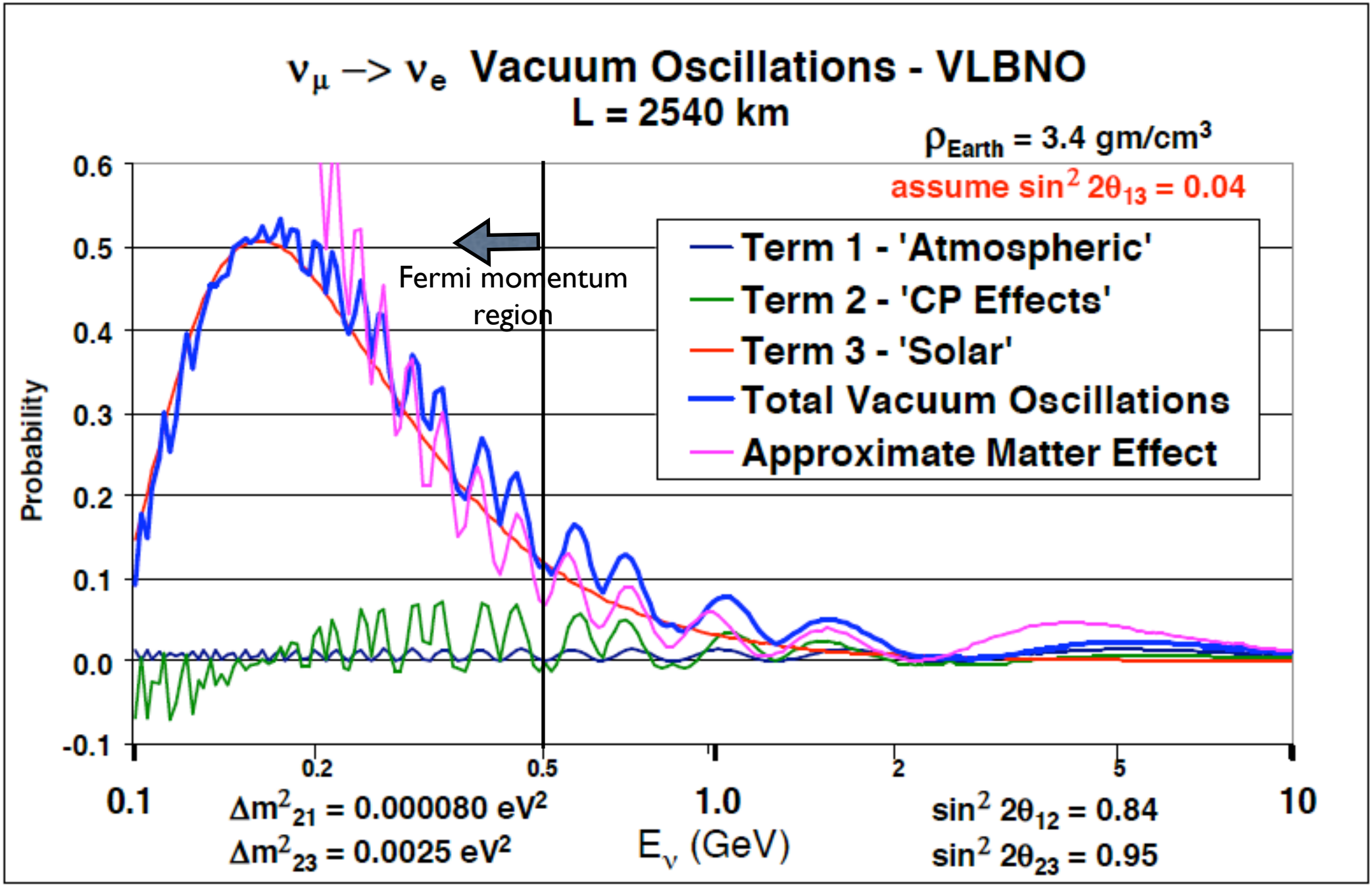
# Comments about matter effect

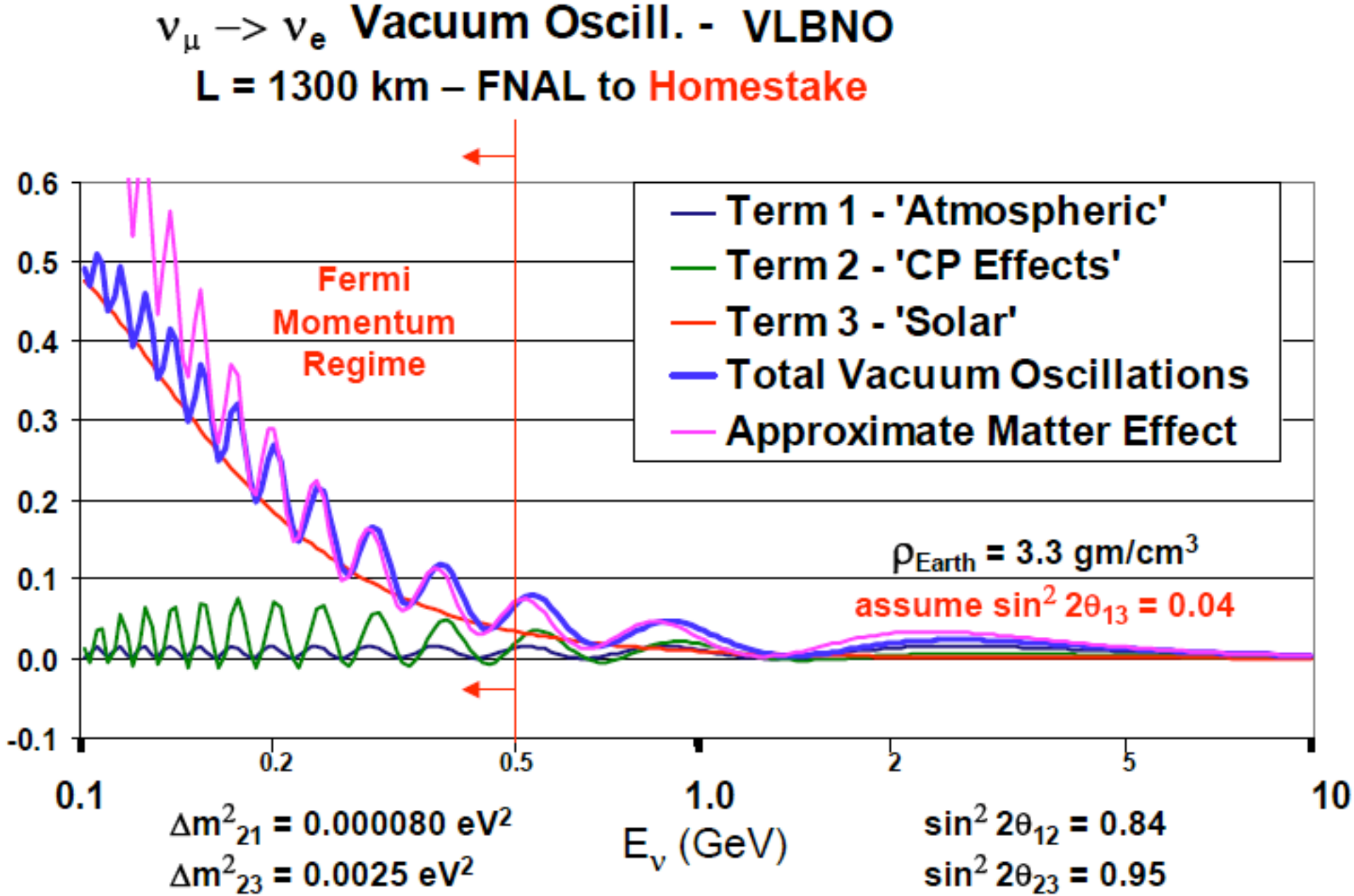
$V = \sqrt{2} G_F n_e$. $n_e$ is the density of electrons in the Earth.

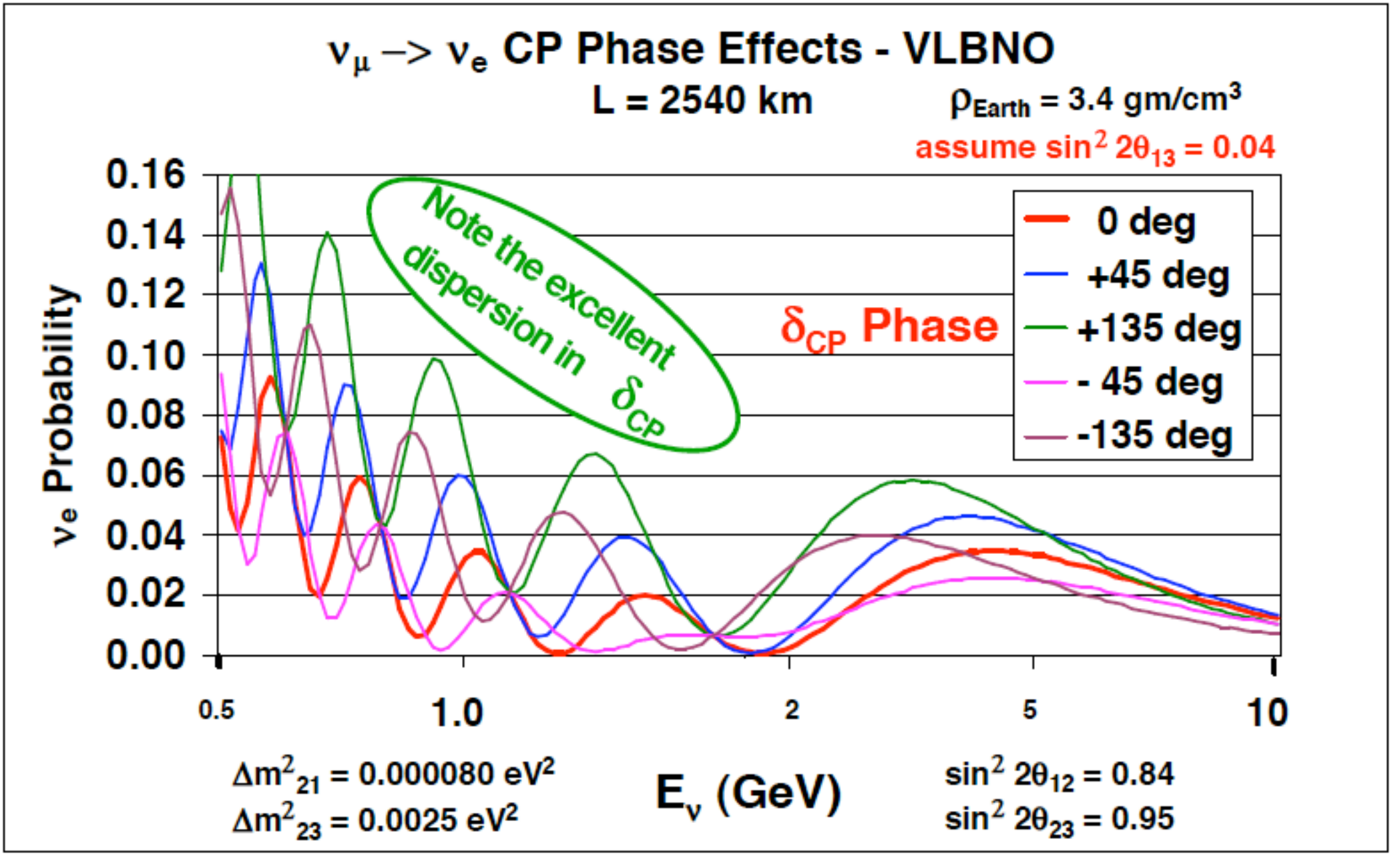
$\hat{A} = \approx 7.6 \times 10^{-5} \times (D/gm/cm^3) \times (E_\nu/GeV)/(\Delta m^2_{31}/eV^2)$,

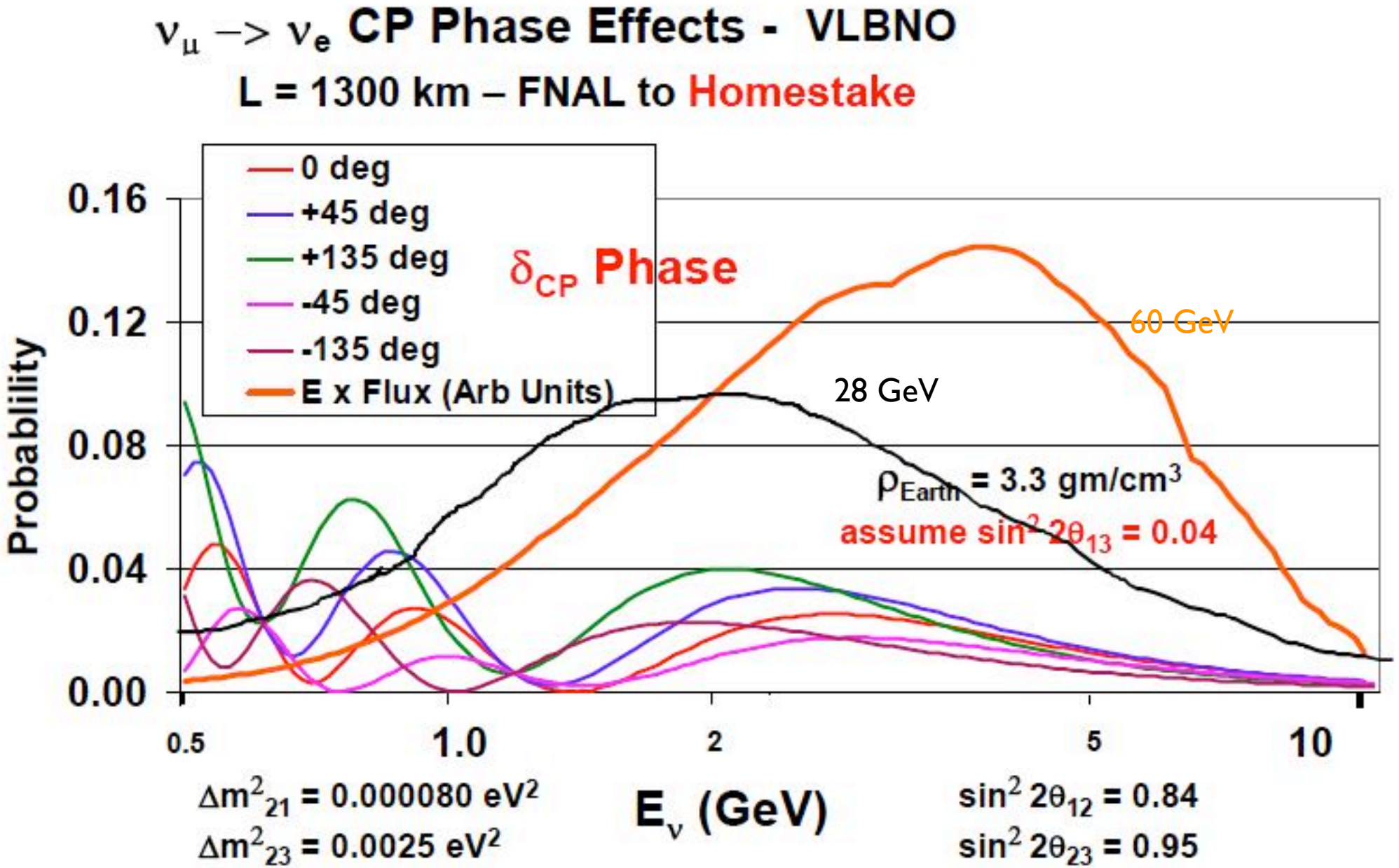
Also recall $\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$.

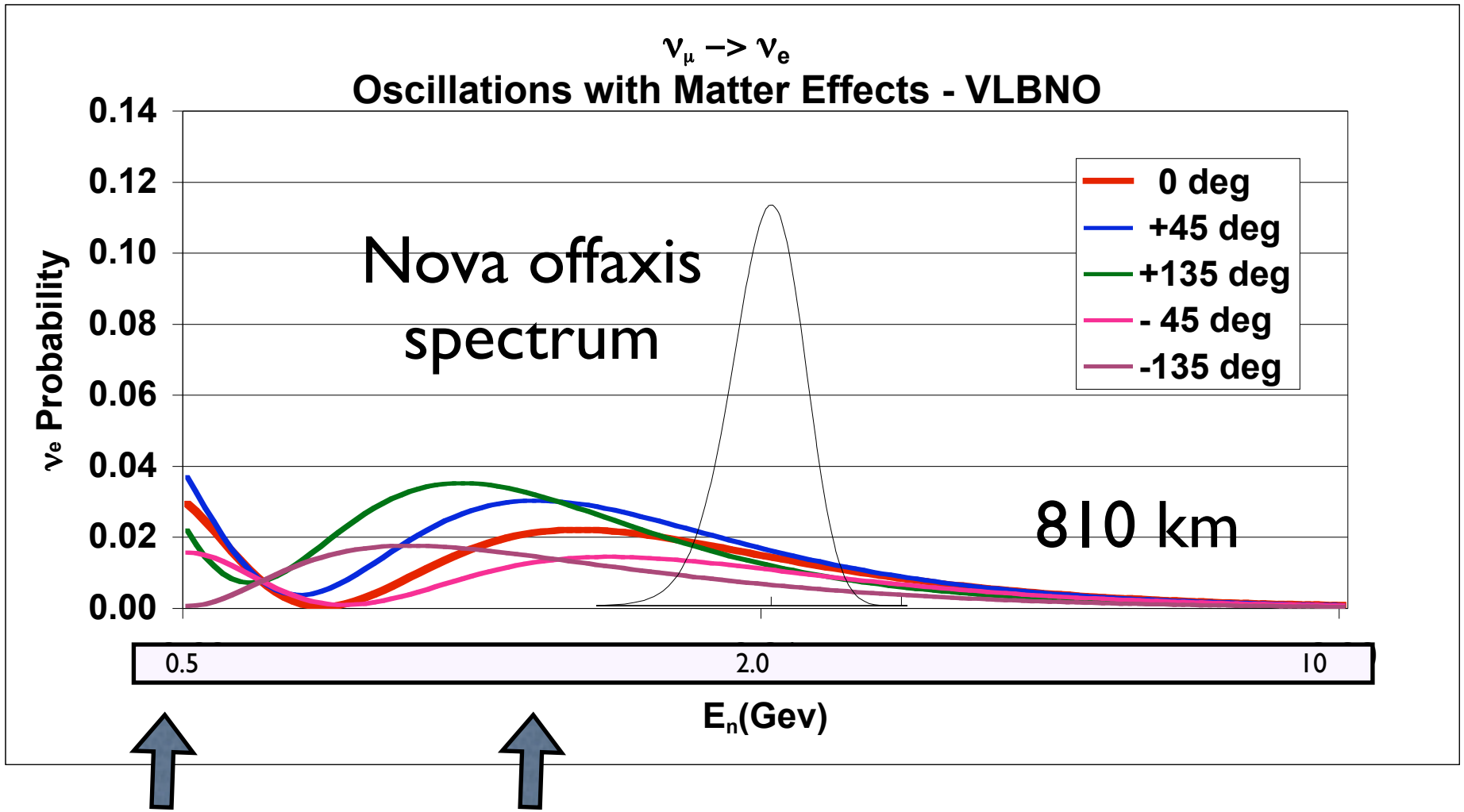
- This is a very approximate equation, not applicable below the first maximum.
- First term has the effect of $\sin^2 2\theta_{13}$ and matter.
- Second and third terms have effects of CP.
- Term with $J_{CP}$ changes sign for $(Anti - \nu_\mu) \rightarrow (Anti - \nu_e)$
- Last term is almost independent of $\Delta m^2_{31}$ and is purely dominated by the solar $\Delta m^2_{21}$


$\nu_\mu \rightarrow \nu_e$ Vacuum Oscillations - VLBNO
L = 2540 km
$\rho_{Earth}$ = 3.4 gm/cm$^3$
assume $\sin^2 2\theta_{13} = 0.04$
Fermi momentum region
Term 1 - 'Atmospheric'
Term 2 - 'CP Effects'
Term 3 - 'Solar'
Total Vacuum Oscillations
Approximate Matter Effect
Probability
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
0.1
0.2
0.5
1.0
2
5
10
$E_\nu$ (GeV)
$\Delta m^2_{21} = 0.000080$ eV$^2$
$\Delta m^2_{23} = 0.0025$ eV$^2$
$\sin^2 2\theta_{12} = 0.84$
$\sin^2 2\theta_{23} = 0.95$


$\nu_\mu \rightarrow \nu_e$ Vacuum Oscill. - VLBNO
L = 1300 km – FNAL to Homestake
Fermi Momentum Regime
Term 1 - 'Atmospheric'
Term 2 - 'CP Effects'
Term 3 - 'Solar'
Total Vacuum Oscillations
Approximate Matter Effect
$\rho_{Earth}$ = 3.3 gm/cm$^3$
assume $\sin^2 2\theta_{13} = 0.04$
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
0.1
0.2
0.5
1.0
2
5
10
$E_\nu$ (GeV)
$\Delta m^2_{21} = 0.000080$ eV$^2$
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$\sin^2 2\theta_{12} = 0.84$
$\sin^2 2\theta_{23} = 0.95$


$\nu_\mu \rightarrow \nu_e$ CP Phase Effects - VLBNO
L = 2540 km
$\rho_{Earth}$ = 3.4 gm/cm$^3$
assume $\sin^2 2\theta_{13} = 0.04$
Note the excellent dispersion in $\delta_{CP}$
$\delta_{CP}$ Phase
0 deg
+45 deg
+135 deg
- 45 deg
-135 deg
$\nu_e$ Probability
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.5
1.0
2
5
10
$\Delta m^2_{21} = 0.000080$ eV$^2$
$\Delta m^2_{23} = 0.0025$ eV$^2$
$E_\nu$ (GeV)
$\sin^2 2\theta_{12} = 0.84$
$\sin^2 2\theta_{23} = 0.95$


$\nu_\mu \rightarrow \nu_e$ CP Phase Effects - VLBNO
L = 1300 km – FNAL to Homestake
0 deg
+45 deg
+135 deg
-45 deg
-135 deg
E x Flux (Arb Units)
$\delta_{CP}$ Phase
60 GeV
28 GeV
$\rho_{Earth}$ = 3.3 gm/cm$^3$
assume $\sin^2 2\theta_{13}$ = 0.04
Probability
0.16
0.12
0.08
0.04
0.00
0.5
1.0
2
5
10
$E_\nu$ (GeV)
$\Delta m^2_{21}$ = 0.000080 eV$^2$
$\Delta m^2_{23}$ = 0.0025 eV$^2$
$\sin^2 2\theta_{12}$ = 0.84
$\sin^2 2\theta_{23}$ = 0.95




second max ~0.5GeV

first max ~1.5 GeV

Same parameters as before

# Observations

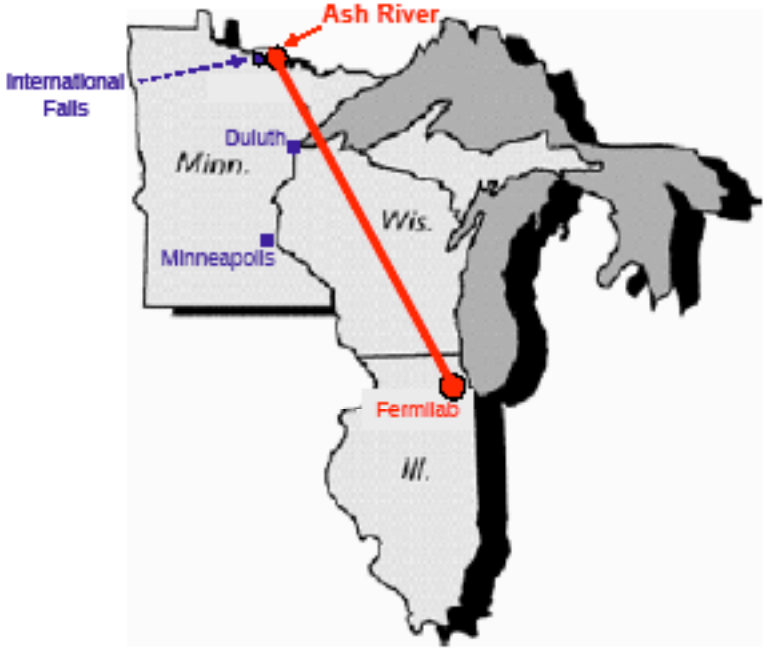
- Sensitivity to CP is independent of distance after ~1000km
- 1300 baseline = high statistics, small integrated effects.
  2540 baseline = bigger integrated effects, small statistics
- The size of detectors and beam power needed does not depend on theta_13 (as long as it is not very small, S. Parke)
- Two narrow band experiments could observe the signal with different strengths; need to examine ambiguities.
- The "solar" term could be observed with large L/E.
- For the future we need a low energy broad band beam.
  Must have ~4m wide tunnel. I have assumed 200 m length.
  Low energy horn also (with target deep inside)

# Two approaches

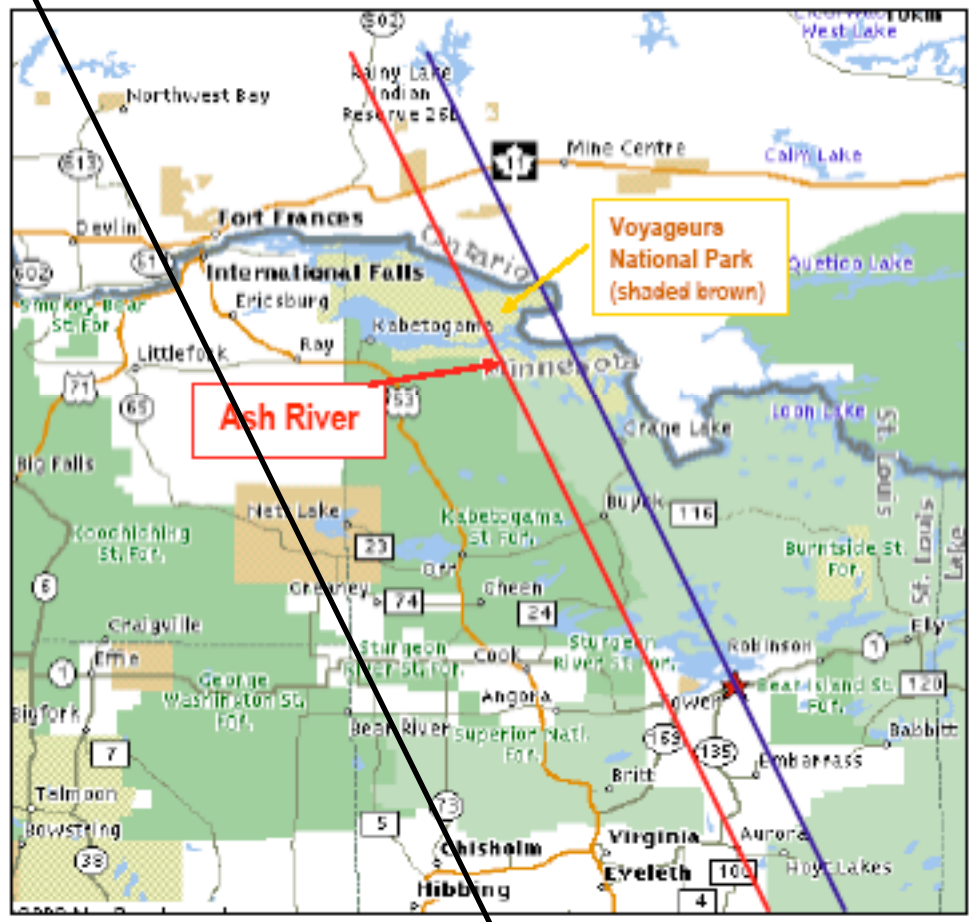
No new beam, but restricted physics because of surface det.

New beam, but detector capable of Nucleon Decay

- Off axis: Use existing NUMI beam. NOvA(25kT) will be built ~10mrad offaxis for the first maximum. NOvA2(50kT LAR) will be built at 40 mrad for second maximum. Both detectors will be on the surface. Combine the results to extract th13, mass hierarchy, and CPV.
- Low energy wide band: Couple the long baseline program to a new deep underground laboratory (DUSEL). Site a large detector (~200kT if water Cherenkov) at approximately 5000 mwe. Build a new wide beam with a spectrum shaped to be optimum (0.5-6 GeV). Use detector resolution to extract multiple nodes.
- Concerns: event rate, NC background, resolution, parameter sensitivity, total cost and timeliness.




**The Ash River site is the furthest available site from Fermilab along the NuMI beamline. This maximizes NOνA's sensitivity to the mass ordering.**



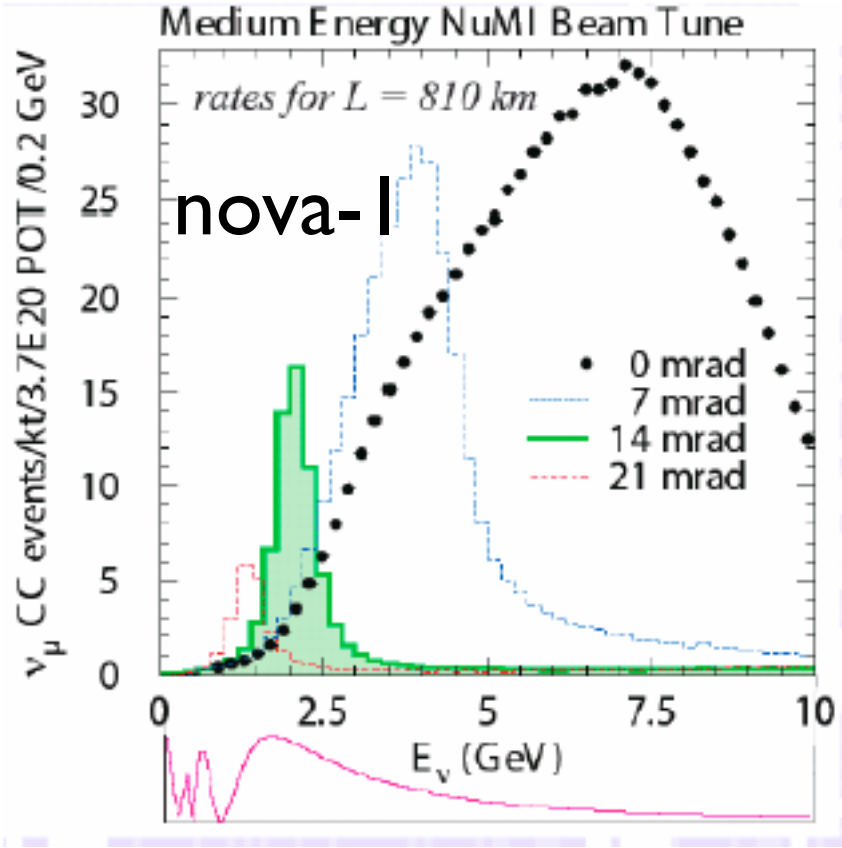

second max.

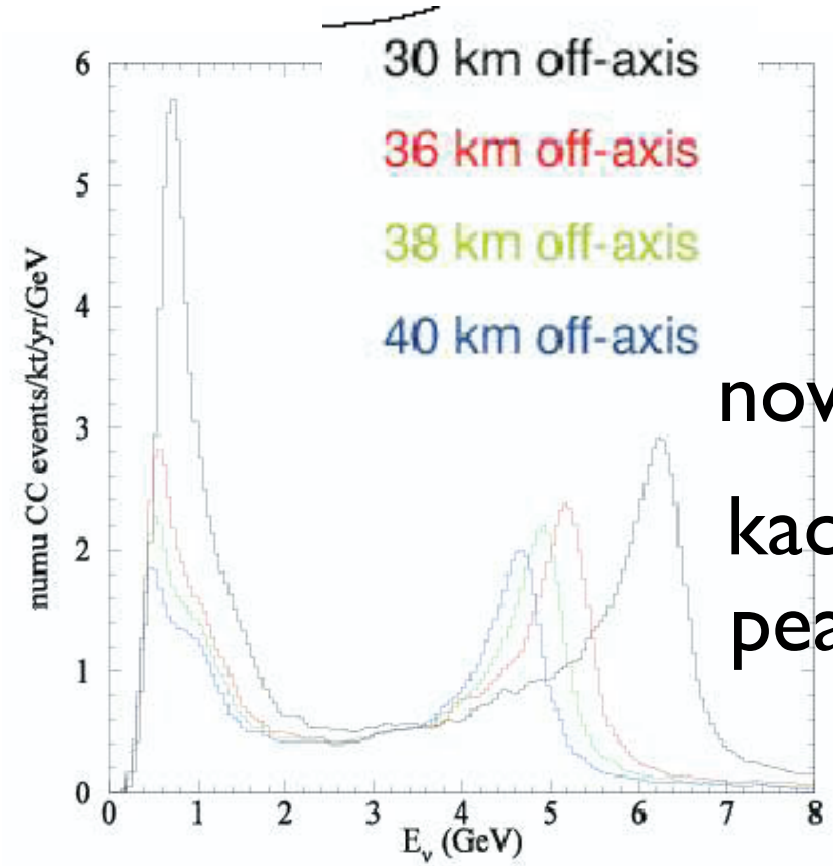
nova



# NOVA1 and NOVA2 locations

# off axis spectra



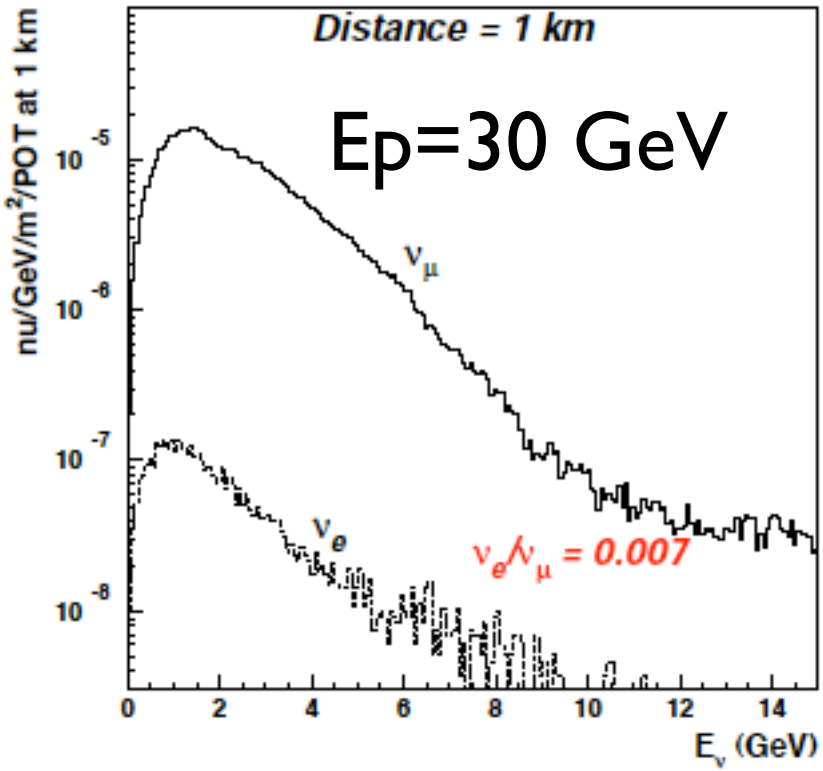



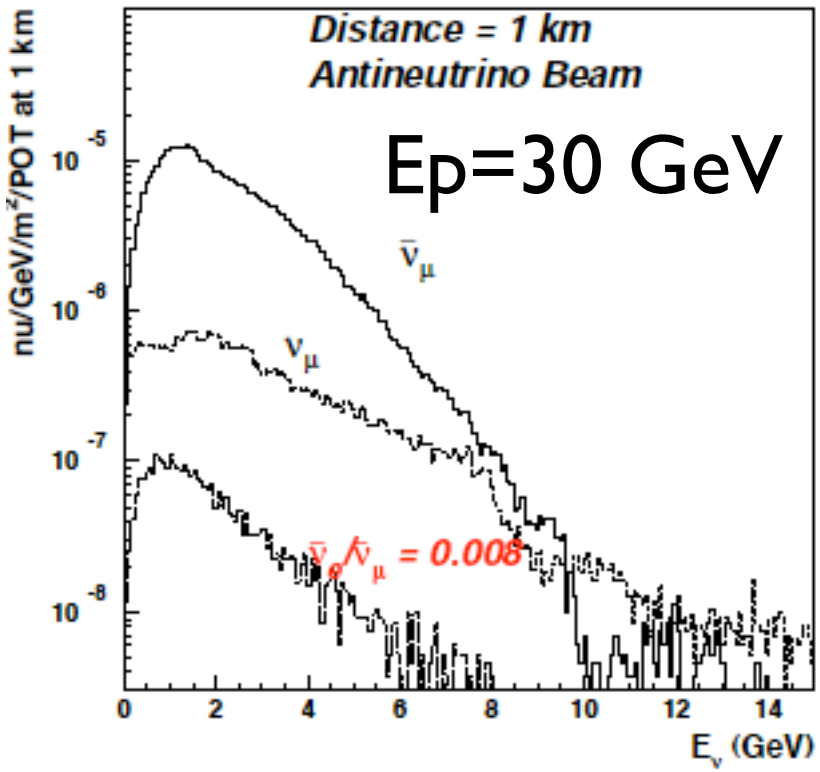

nova-2

kaon peak

- nova-I event CCrate: ~10000 (30kT*0.65MW*5e7sec)
- nova-II event CCrate: ~700 (50kT*0.65MW*5e7sec)

# wideband spectra




- Low energy wideband 0.5-6 GeV. 200 m decay tunnel.
- FNAL-HS (1300km) nu CC rate: 75000/200kT*1MW*5e7sec
- FNAL-HS (1300 km) anti-nu CC: 25000/200kT*1MW*5e7 sec

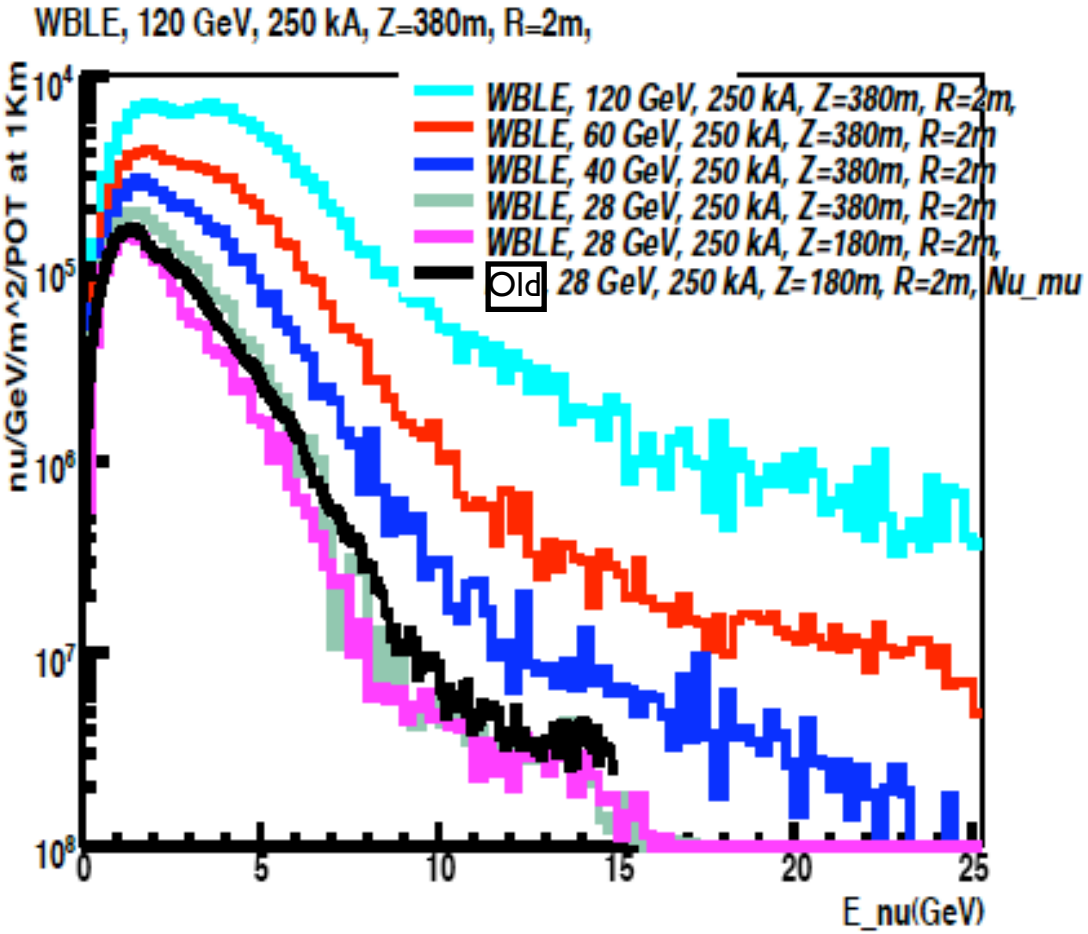
# US possibilities for new wideband beam

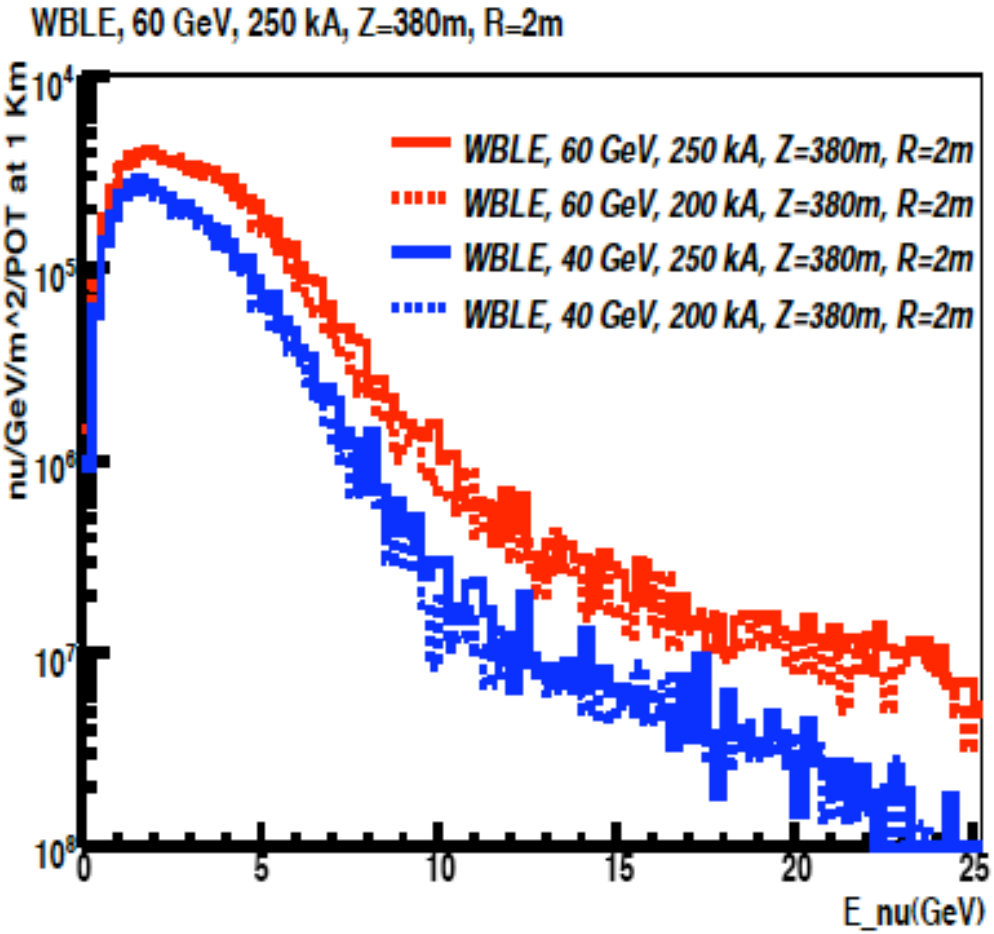
| Source | Proton beam energy | Proton beam power | |
|---|---|---|---|
| FNAL MI (upgrade using recycler) | Ep=8-120GeV | <1 MW X(Ep/ 120GeV) | A. Marchionni |
| FNAL MI (with 8GeV LINAC) | Ep=8-120 GeV | 2 MW @ any Ep | G. Apollinari |
| BNL-AGS (upgrade 2.5- 5 Hz) | Ep=28 GeV | 1-2 MW | BNL-73210 |

# WBLE Optimization - FLUKA05

## Decay pipe radius chosen to be 2m.

## Siting restrictions $\Rightarrow$ decay pipe is $\leq$ 400 m in length




new work From M. Bishai

# Event rates and optimization

For NuMI (735 km): 1st osc max is at 1.5 GeV, 2nd osc max is at 0.5 GeV

For FNAL-Homestake (1297 km): 1st osc max is at 2.6 GeV, 2nd osc max is at 0.8 GeV

| Beam scenario | Tunnel | numu CC /10^20 POT*kT | Total rate 5e7 sec | CC(nue/ numu) |
|---|---|---|---|---|
| WBLE 60GeV | R=2m L=380 | 13 (1300km) | 202800 (300kT*1MW) | 0.9% |
| WBLE 40GeV | R=2m L=380 | 6 (1300km) | 140400 (300kT*1MW) | 0.9% |
| WBLE 28GeV | R=2m L=380 | 3.4 (1300) | 114240 (300kT*1MW) | 0.8% |
| WBLE 28GeV | R=2m L=180 | 2.4 (1300) | 80640 (300kT*1MW) | 0.6% |
| NUMI-ME -120GeV 12km offaxs | R=1m L=677 | 20.3 (810km) | 15625 (30kT*1MW) | 2.2% (integrated) |
| NUMI-ME -120GeV 40 km offaxs | R=1m L=677 | 0.9 (810 km) | 1170 (50kT*1MW) | 5.5% (integrated) |

$$Total\ POT(10^{20}) = \frac{Beam\ power(kW)}{1.6E_p(GeV)} \times time(10^7 sec)$$

# Beam summary

- Higher confidence in event rates with new Monte Carlo.
- Have used WBLE (28 GeV) with old simulations for sensitivity calculations, but it is close to new simulations.
- Assume total exposure for WBLE to be 2500kT*MW*(10^7)sec for each polarity.
- 5 years of running at 1.7e7 sec/yr with 300kT for each polarity.
- At 60 GeV running 0.5 MW may be enough for total event rate (tails need examination).

# Total exposure

- Assume total exposure for wideband to be 2500kT*MW*(10^7)sec for each polarity.
- Off axis program exposure is more complex.
- nu: 30kT*2MW*6yr+ 80kT*2MW*3yr
- antinu:  same

# FNAL/BNL study

- Chairs: Hugh Montgomery, Sally Dawson
- First kick-off workshop was on March 6-7
- Very successful ! Very good work reported on physics sensitivity, backgrounds, possible beam from FNAL, etc.
- Study goals and initial work plan sent out.

***http://www.fnal.gov/directorate/DirReviews/Neutrino_Wrkshp.html***

FUTURE_LONG_BASELINE_LIST@fnal.gov

To get on the list send email to rameika@fnal.gov

**Timescale:**

The United States neutrino community is heavily engaged in operation and analysis of its existing program. On the other hand there are active discussions within advisory bodies and the agencies with a view to setting directions for future facilities inside the next year.

It would be desirable to see results of this **U.S. Long Baseline Neutrino Experiment Study** before October 2006, with a preliminary report by July 15, 2006.

# Goals of workshop and study

**U.S. Long Baseline Neutrino Experiment Study**

Compare the neutrino oscillation physics potential of:

1. A broad-band proposal using a either an upgraded beam of around 1 MW from the current Fermilab accelerator complex or a future Fermilab Proton Driver neutrino beam aimed at a DUSEL-based detector. Compare these results with those previously obtained for a high intensity beam from BNL to DUSEL.

2. Off-Axis next generation options using a 1-2 MW neutrino beam from Fermilab and a liquid argon detector at either DUSEL or as a second detector for the Nova experiment.

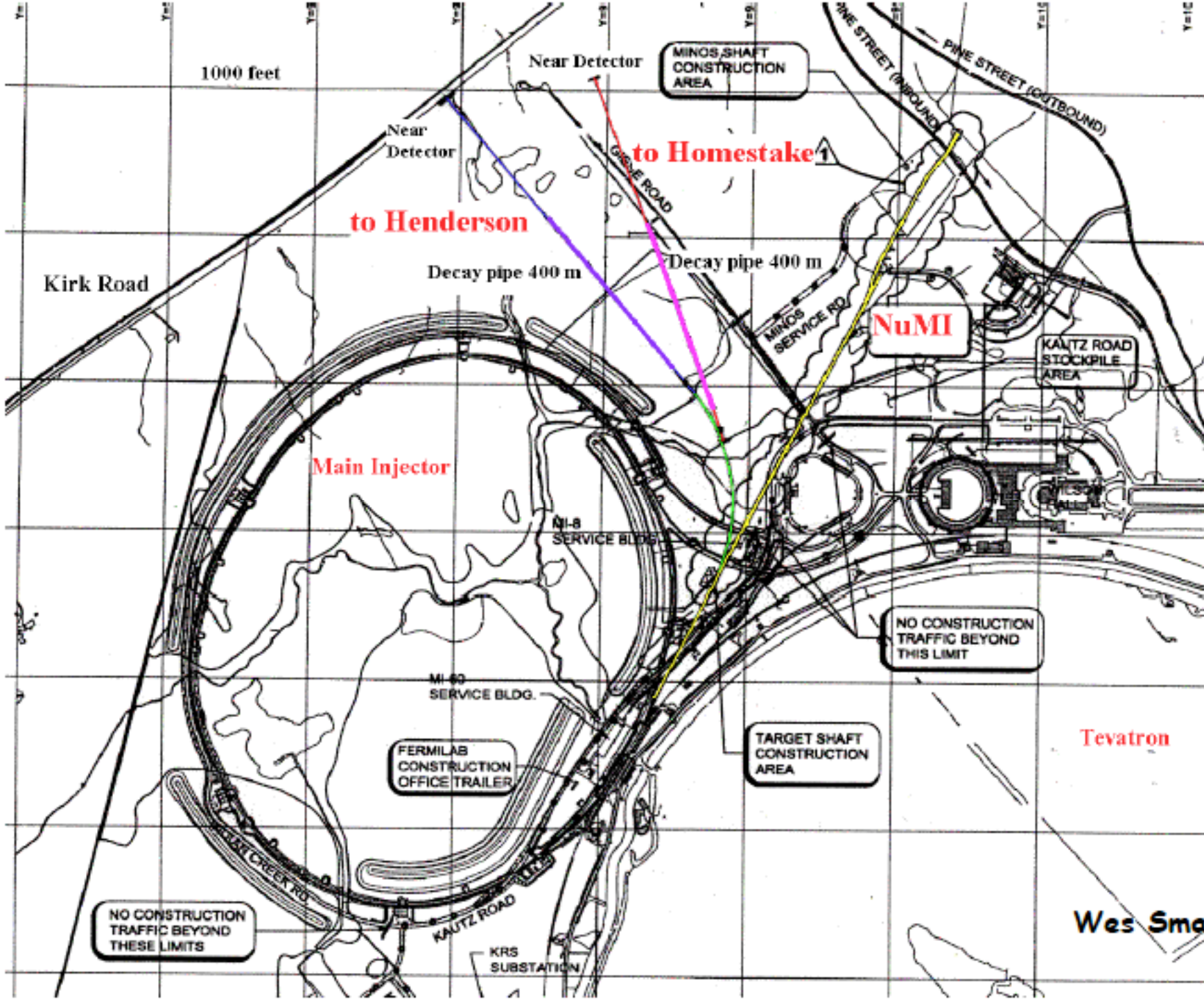
Considerations of each should include:

i) As a function of $\theta_{13}$, the ability to establish a finite $\theta_{13}$, determine the mass hierarchy, and search for CP violation and, for each measurement, the limiting systematic uncertainties.

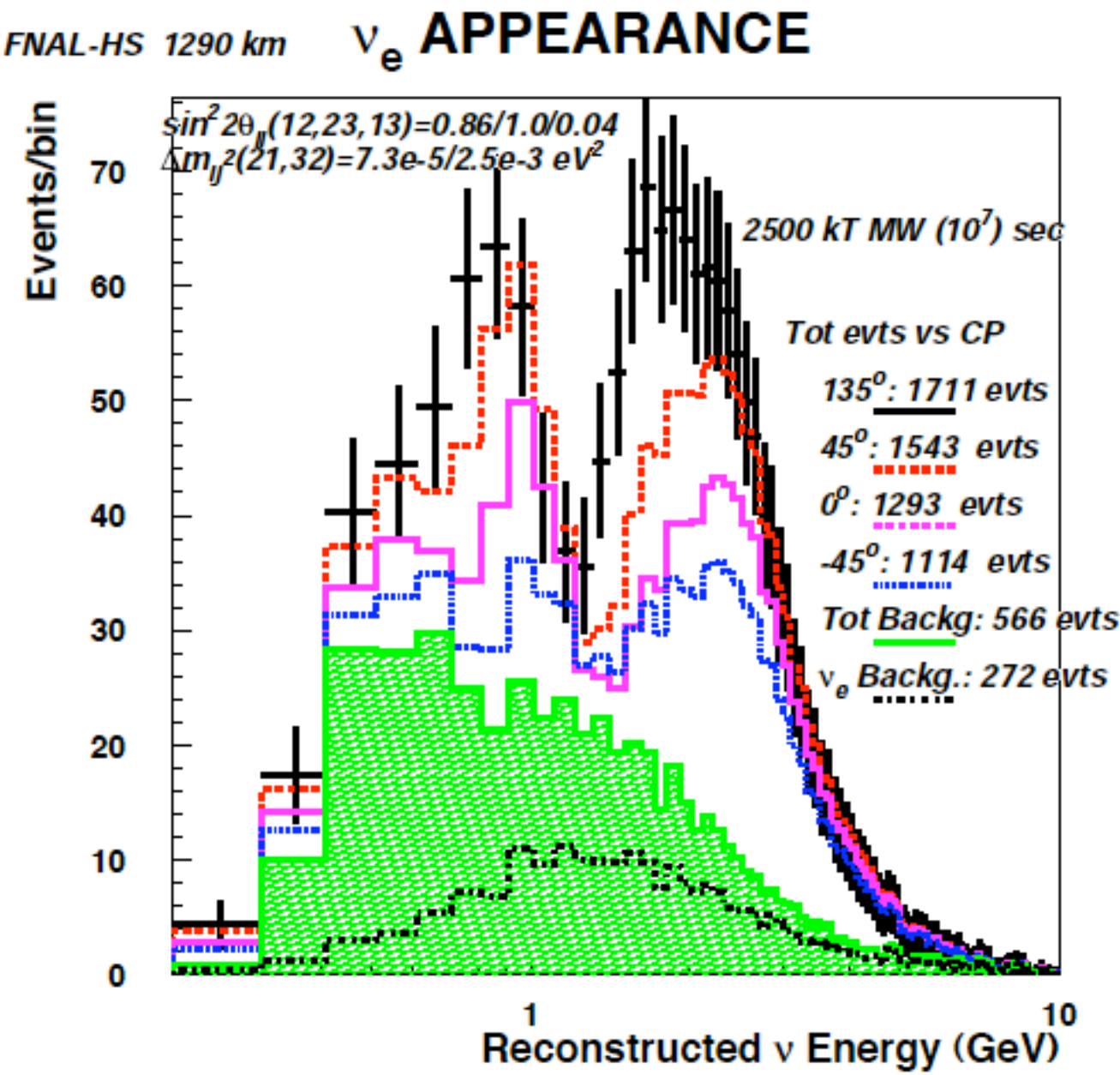
ii) The precision with which each of the oscillation parameters can be measured and the ability to therefore discriminate between neutrino mass models.

iii) Experiment Design Concepts including:

Optimum proton beam energy
Optimum geometries
Detector Technology
Cost Guesstimate


1000 feet
Near Detector
Near Detector
to Homestake
to Henderson
Decay pipe 400 m
Decay pipe 400 m
Kirk Road
Main Injector
NuMI
MINOS SHAFT CONSTRUCTION AREA
PINE STREET (INBOUND)
PINE STREET (OUTBOUND)
GROVE ROAD
MINOS SERVICE RD
KAUTZ ROAD STOCKPILE AREA
MI-8 SERVICE BLDG.
MI-60 SERVICE BLDG.
NO CONSTRUCTION TRAFFIC BEYOND THIS LIMIT
TARGET SHAFT CONSTRUCTION AREA
FERMILAB CONSTRUCTION OFFICE TRAILER
Tevatron
OAK CREEK RD.
KAUTZ ROAD
NO CONSTRUCTION TRAFFIC BEYOND THESE LIMITS
KRS SUBSTATION
Wes Smart

# $\nu_e$ Appearance




Backgrounds

- beam $\nu_e$
- Neutral current events

$\nu$ running

- measure $\sin^2 2\theta_{13}$ and $\delta_{CP}$.
- resolve mass hierarchy for $\sin^2 2\theta_{13} > 0.01$
- with $\bar{\nu}$ running $\sin^2 2\theta_{13} > 0.003$ at 90% C

If $\sin^2 2\theta_{13}$ too small $\delta_{CP}$ cannot be measured. (See Patrick's curves).

# $\nu_\mu$ Disappearance

Very easy to get this effect
Does not need extensive pattern recognition. Can enhance the second minimum by background subtraction.

Neutrino Running

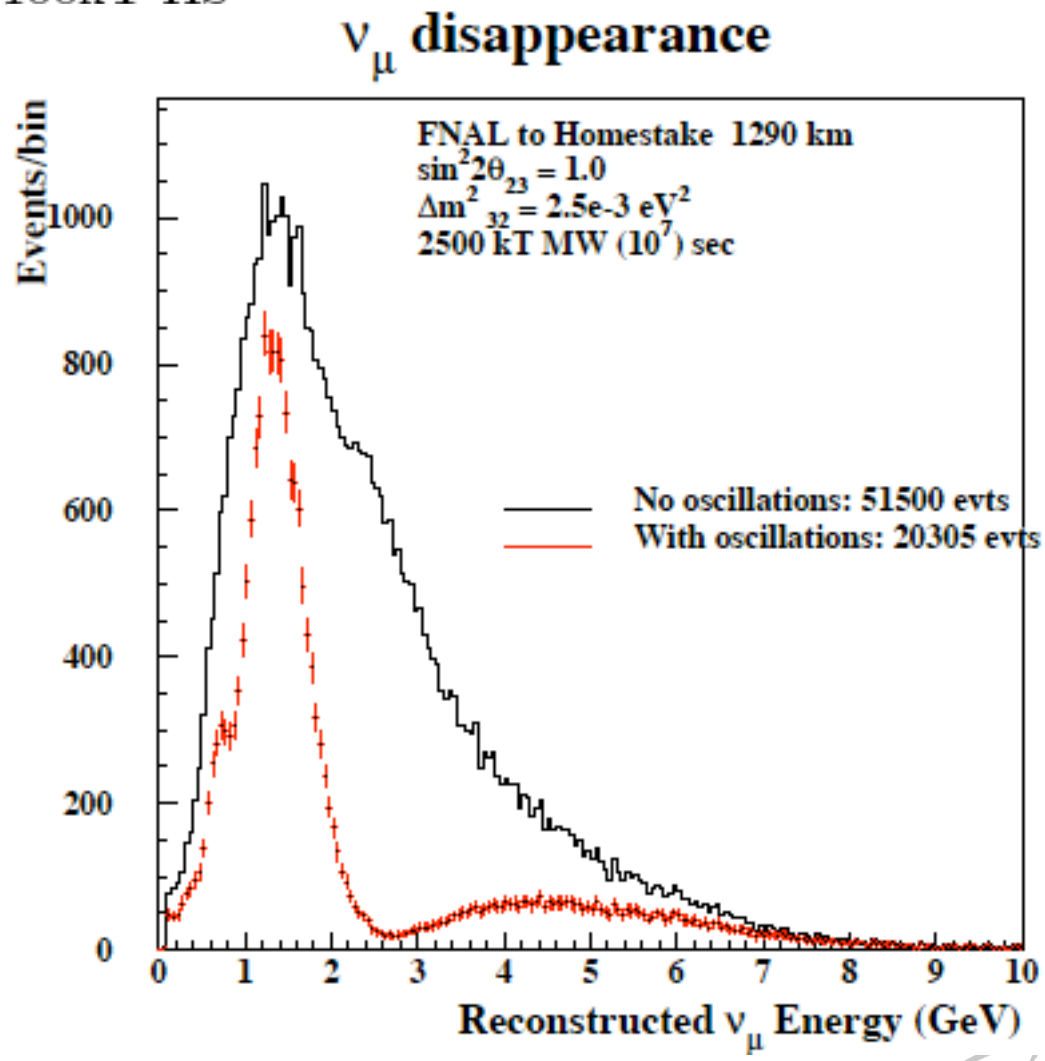
- Total exposure: 2500 kT.MW.$(10^7)$.sec
- 195000 CC evts/6yrs: 2MW-FNAL, 100kT-HS
- Use only clean single muon events.

Measurements

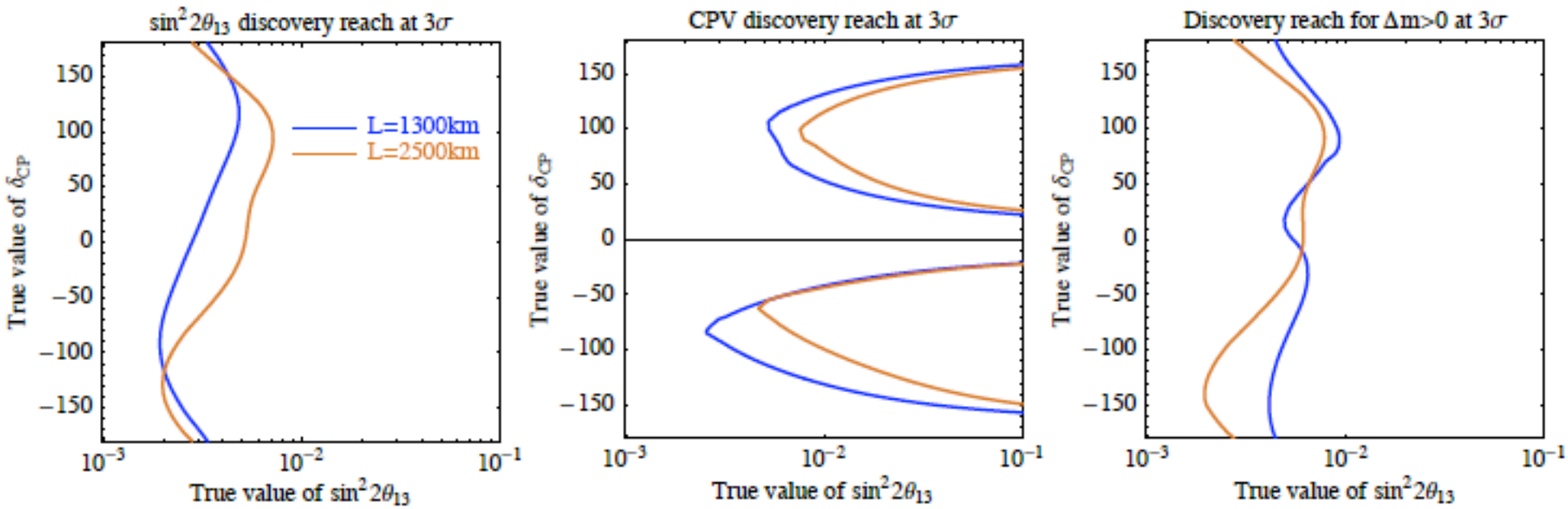
- 1% determination of $\Delta m^2_{32}$
- 1% determination of $\sin^2 2\theta_{23}$
- Most likely systematics limited.

$\bar{\nu}$ running

- Need twice the exposure for similar size data set.
- very precise CPT test possible.



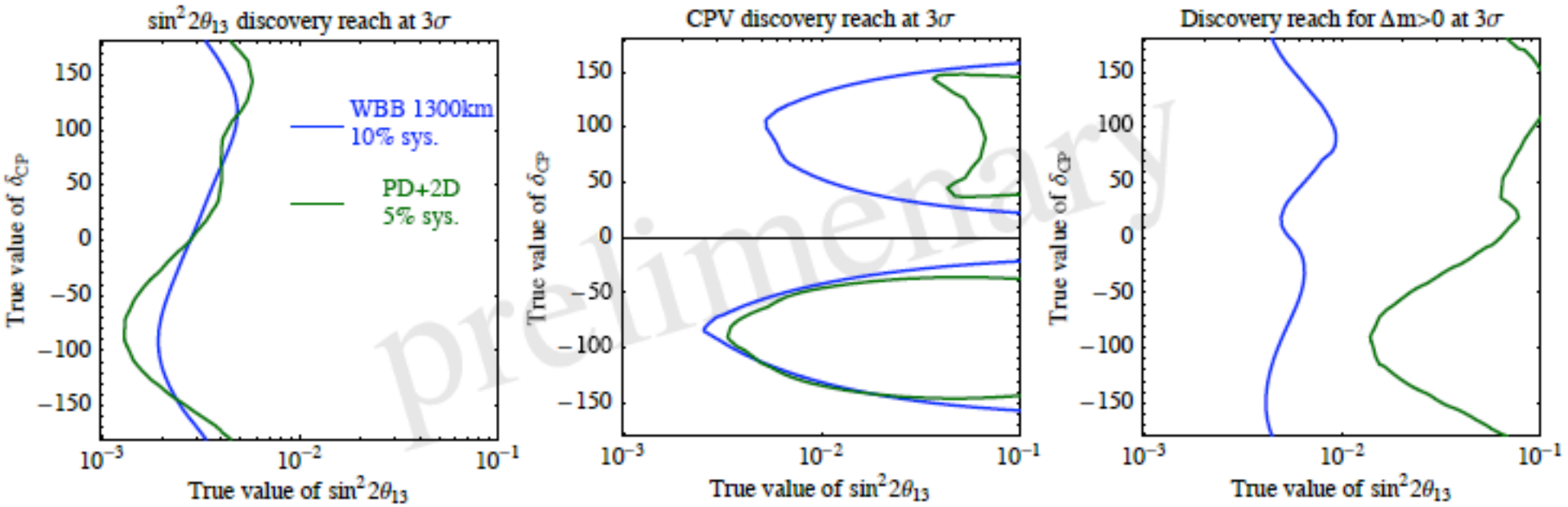
# Wide band beam




- very good resolution of the mass hierarchy
- no problems due to $\pi$-transit for $\sin\delta > 0$
- Baseline choice is not critical

includes anti running, but large fraction of the result is from nu running for normal hierarchy

# Summary

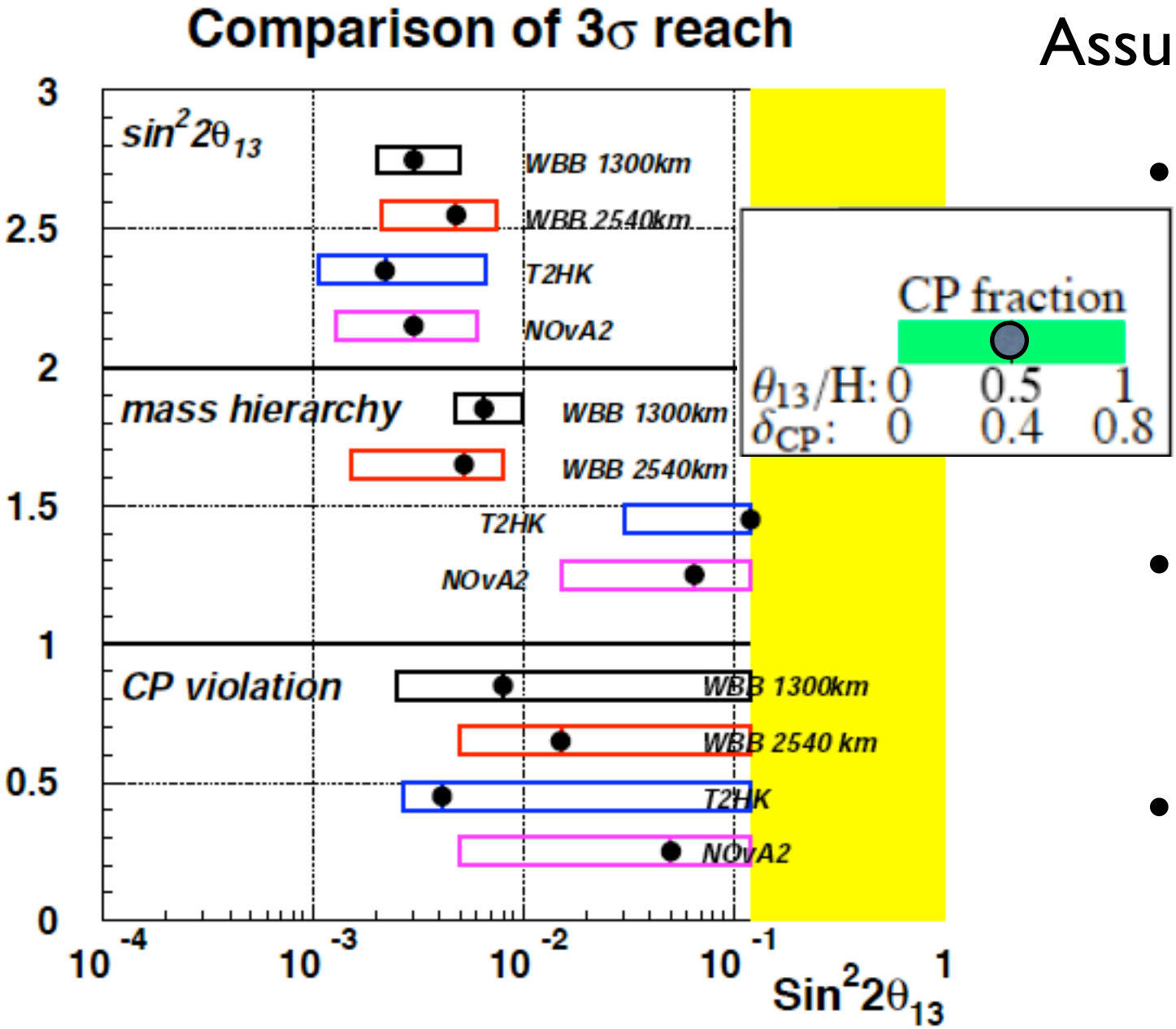



How would that picture look like with

- Liquid Argon
- 2nd peak in the OA spectrum

Preliminary comparison to off-axis program with a second detector

P. Huber – p.18/19




# Assumptions

- WBB:
  nu:300kT*1MW*5yr.
  antinu: 300kT*1MW*5yr
  syst: 10% on bck
  Antinu running is over-constraint for normal hierarchy.
- T2HK:
  nu: ~500kT*4MW*3yr
  antinu: ~500kT*4MW*3yr
  syst: 2% on bck+2% on eff
- NOVA2:
  nu:30kT*2MW*6yr+
  80kT*2MW*3yr
  antinu: same*6yr+3yr
  syst: 5% on bck

Preliminary result out of FNAL workshop

# Summary

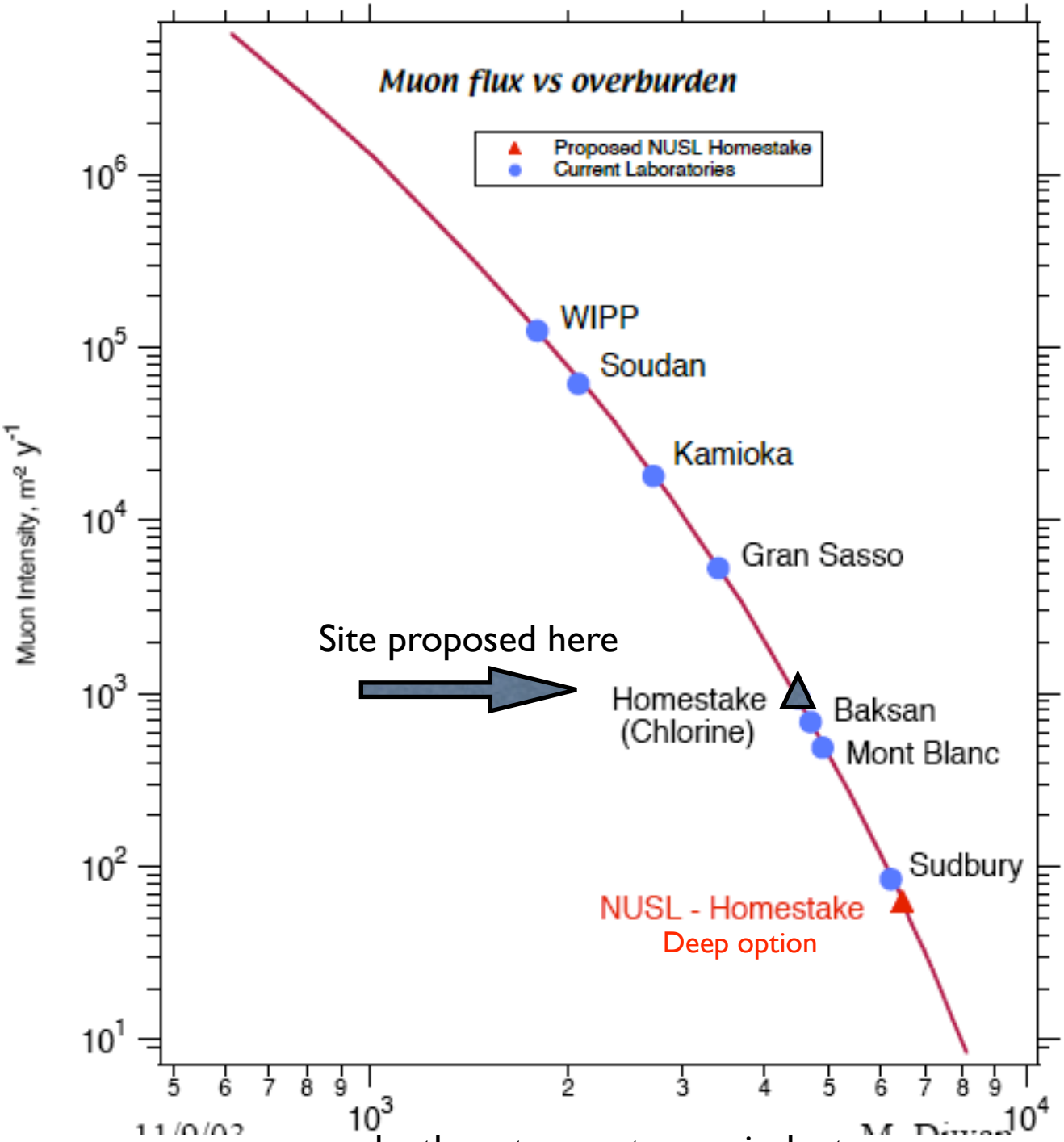
- I reviewed the physics considerations for a long baseline and very long baseline program.
- A new MW class proton machine in the US remains well-motivated.
- The two US possibilities are a two detector off axis program or a DUSEL based very long baseline program.
- A new joint laboratory (FNAL/BNL)study has been launched to evaluate these.
- The study will report to NUSAG this year.

# 4850ft: 100kT ~3M mu/yr

with rate of 1 mu/10 sec => may not need veto-counter

The Beam neutrinos will be obvious with a rate of 100-200/day in 10 mus spills.

No pattern recognition beyond time cut is needed.



# Exploring the possibility of neutrino beams towards a DUSEL site

W. Smart

| | Latitude | Longitude | Vertical angle from FNAL (deg) | Distance from FNAL (km) |
|---|---|---|---|---|
| **Homestake** | 44.35 | -103.77 | -5.84 | 1289 |
| **Henderson** | 39.76 | -105.84 | -6.66 | 1495 |

- Use of the present extraction out of the Main Injector into the NuMI line
- Construction of an additional tunnel, in the proximity of the Lower Hobbit door in the NuMI line, in order to transport the proton beam to the west direction
- Radius of curvature of this line same as the Main Injector, adequate for up to 120 GeV/c proton beam with conventional magnets
- Assumptions:
  - **a target hall length of ~45 m (same as NuMI for this first layout, probably shorter )**
  - **decay pipe of 400 m (adequate for a low energy beam), we would gain in neutrino flux by increasing the decay pipe radius (> 1 m)**
  - **distance of ~300 m from the end of the decay pipe to a Near Detector (same as NuMI).**

# Open issues on detector

- Depth and veto counter - has cost, schedule and physics implications. Perhaps only the first module is built without veto-counter for a fast start.
- Fiducial volume. If SK cut good enough => 75 kT.
- PMT coverage: 20 % adequate from SK experience. 40% if very low threshold is needed.
- PMT size: 13 inch versus 20 inch. Greater number of pixels will give better pattern recognition.
- Size of detector: very difficult to increase span. If made bigger has cost and schedule implications. 50 meter span seems adequate to contain beam events.

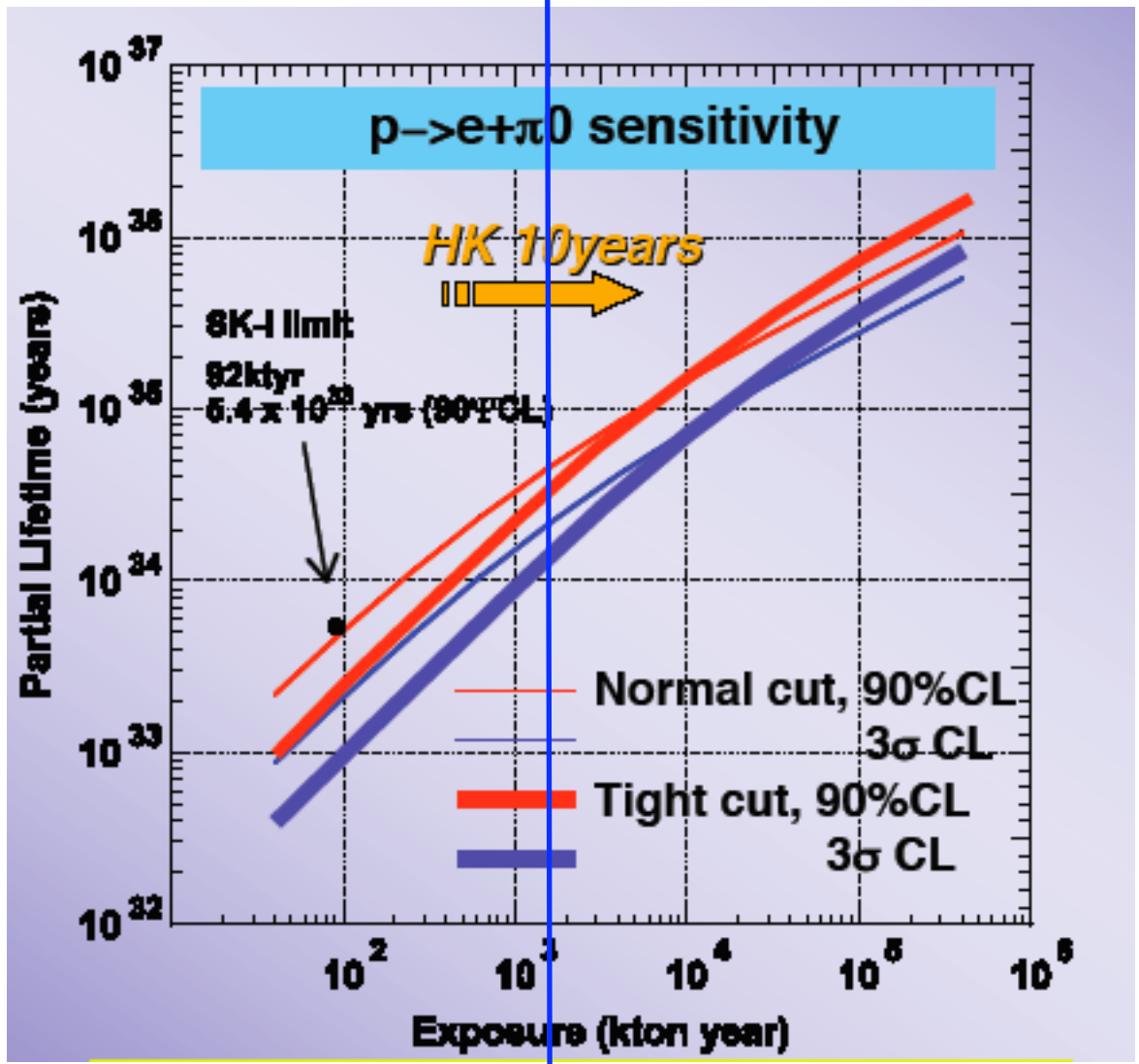
# Open issues on beam

- What is the correct proton energy and power level from FNAL
- What is the cost of a new beam
- To get intensity at low energies must have ~4 meters diameter tunnel. I have length of 200 meters to get the spectra in this talk.
- How should we tailor the spectrum for maximum signal/ noise ?
- If tunnel is wide WE CAN ALWAYS RUN OFFAXIS by moving and tilting the horn/target. (upto 1 deg.)
- What is the time sequence ? Proposal on next slide.

# Nucleon decay

- Large body of work by HyperK, and UNO.
- background levels for the positron+Pion mode
  - 3.6/MTon-yr (normal)
  - 0.15/MTon-yr (tight)

LMD-I and II (200kT) will hit backg. in ~1.5yrs. It could be important to perform this first step before building bigger. Sensitivity on K-nu mode is about ~8x10^33 yr



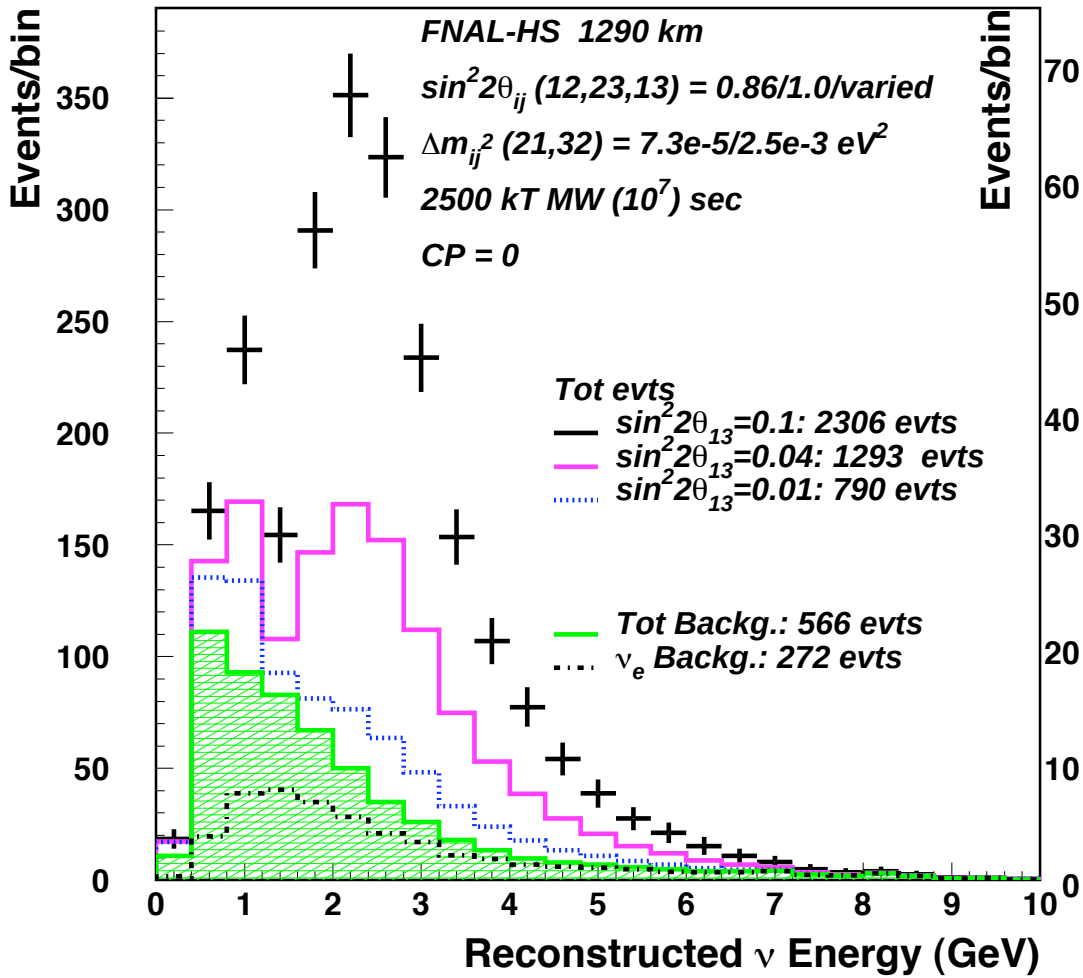

Ref: Shiozawa (NNN05) 150kTX10yrs 5X10^34 yrs

# Astrophysical Neutrinos
# Event rates. LMD-I&II(200kT), 5 yrs

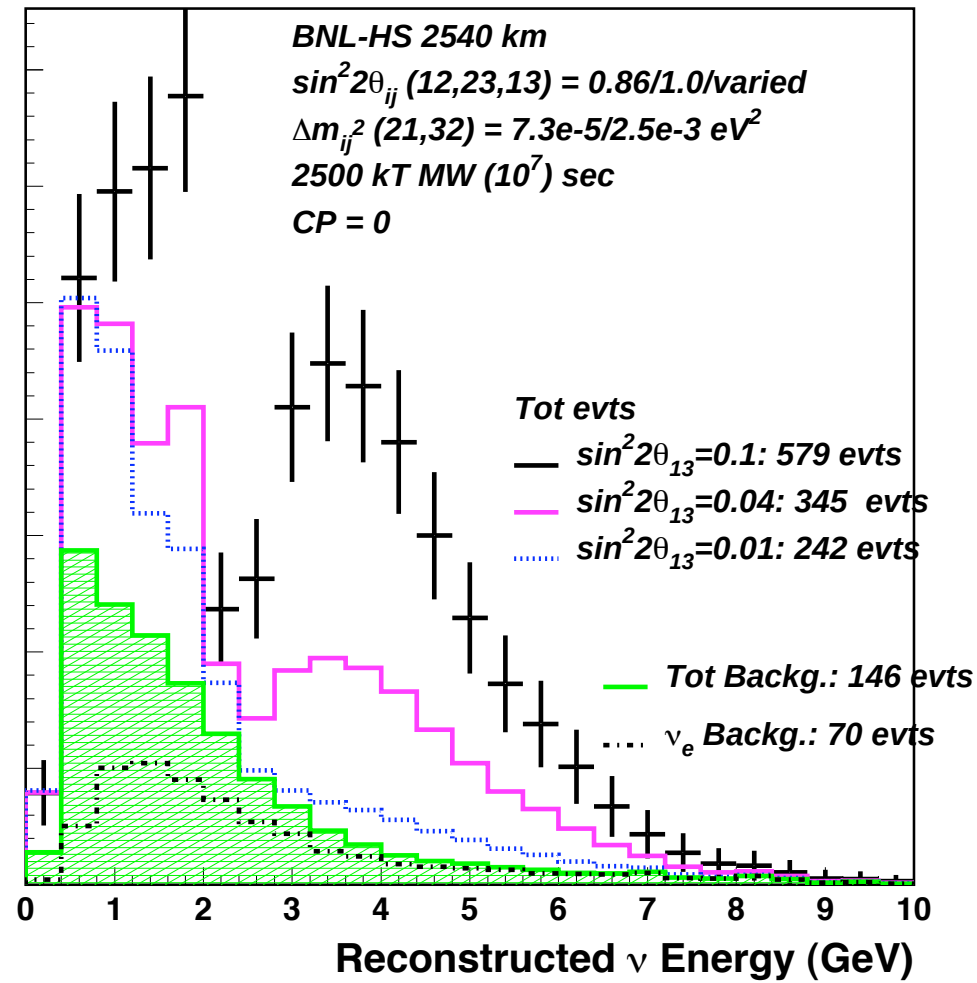
- Atmospheric Nus: ~20000 muon, ~10000 electrons. (Ref: Kajita nnn05)
- Solar Nus: >120000 elastic scattering E>5MeV (including Osc.) (Ref: uno)
- Galactic Supernova: ~60000/10 sec in all channels. (~2000 elastic events). (Ref: uno)
- Relic Supernova: (ref: Ando nnn05)
  - flux: ~5 (1.1) /cm2/sec Enu>10 (19) MeV
  - rate: 150 (70) events over backg ~200 !

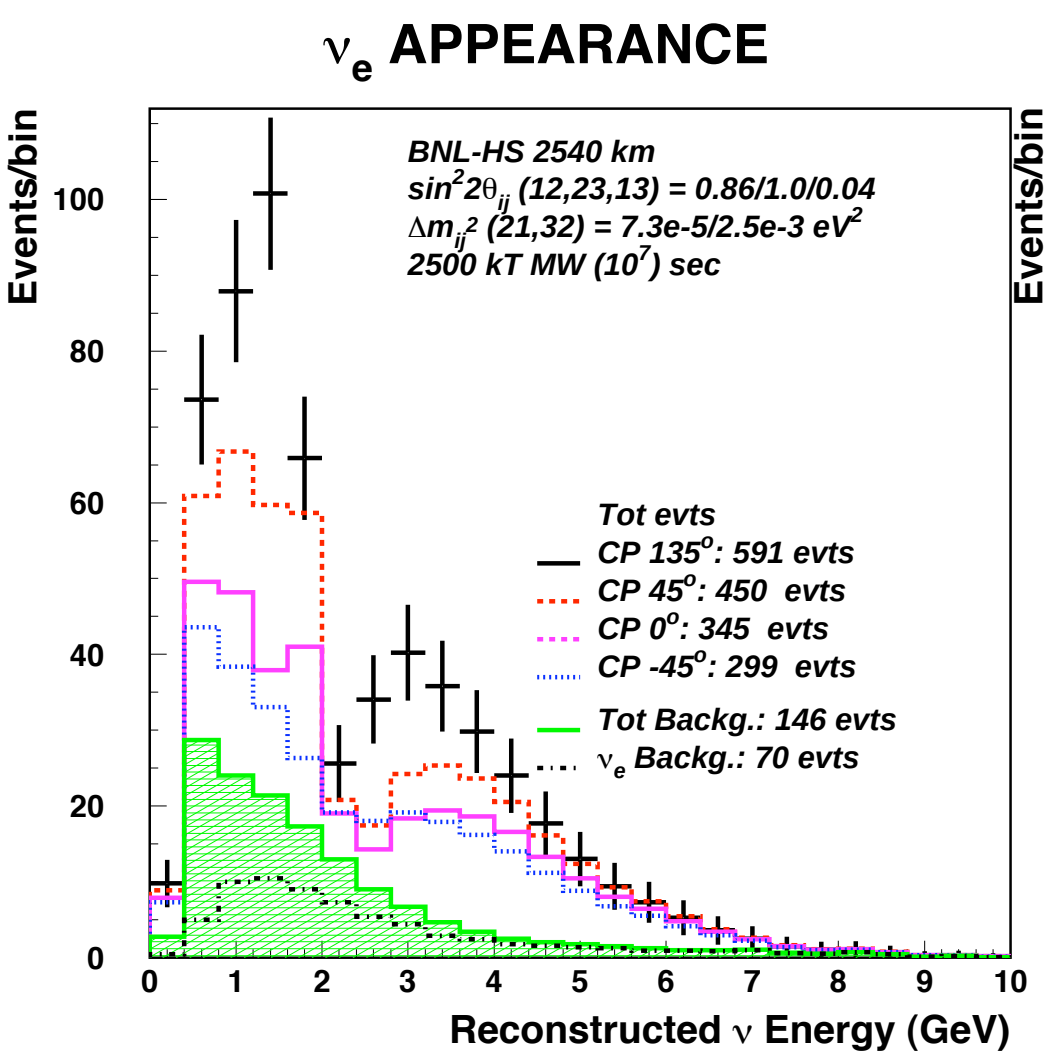
Need analysis with these numbers

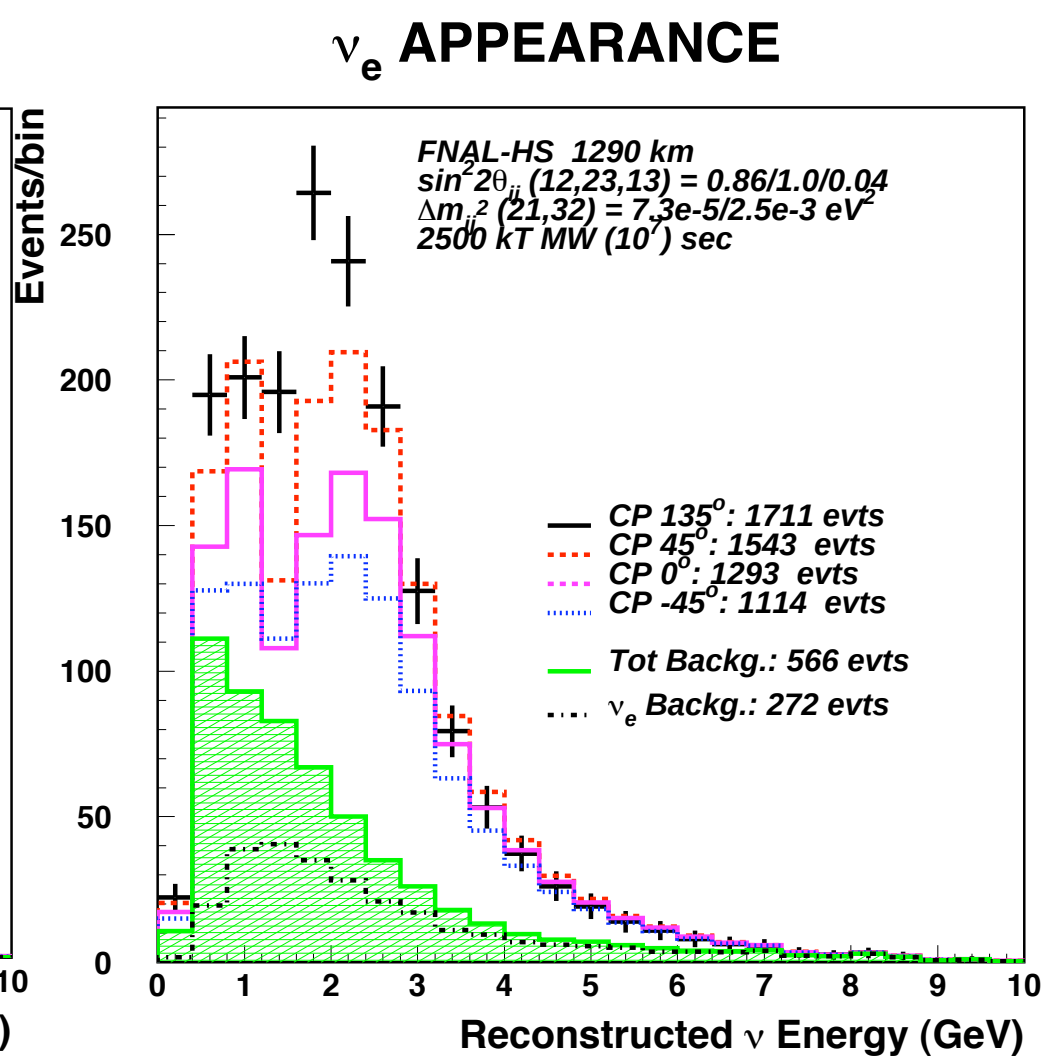
# $\nu_e$ APPEARANCE




# $\nu_e$ APPEARANCE






# Comparison to 1290 km to 2540 km