Very Long Baseline Neutrino Physics

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Brookhaven National Laboratory

3/23/2006

first phase detector:
~200kT water Cherenkov, Total Fiducial: 150kT

Participants

- A LOI to Homestake was made by D. Cline, M. Diwan, K. Lande, R. Lanou, A. K. Mann, W. Marciano
- Close cooperation with Henderson/UNO and Chang Kee Jung's SBU group on the science.
- We advocate building one or two 100 kT cavities as soon as possible.
- We need support for participation in the DUSEL TDR, and detector design.

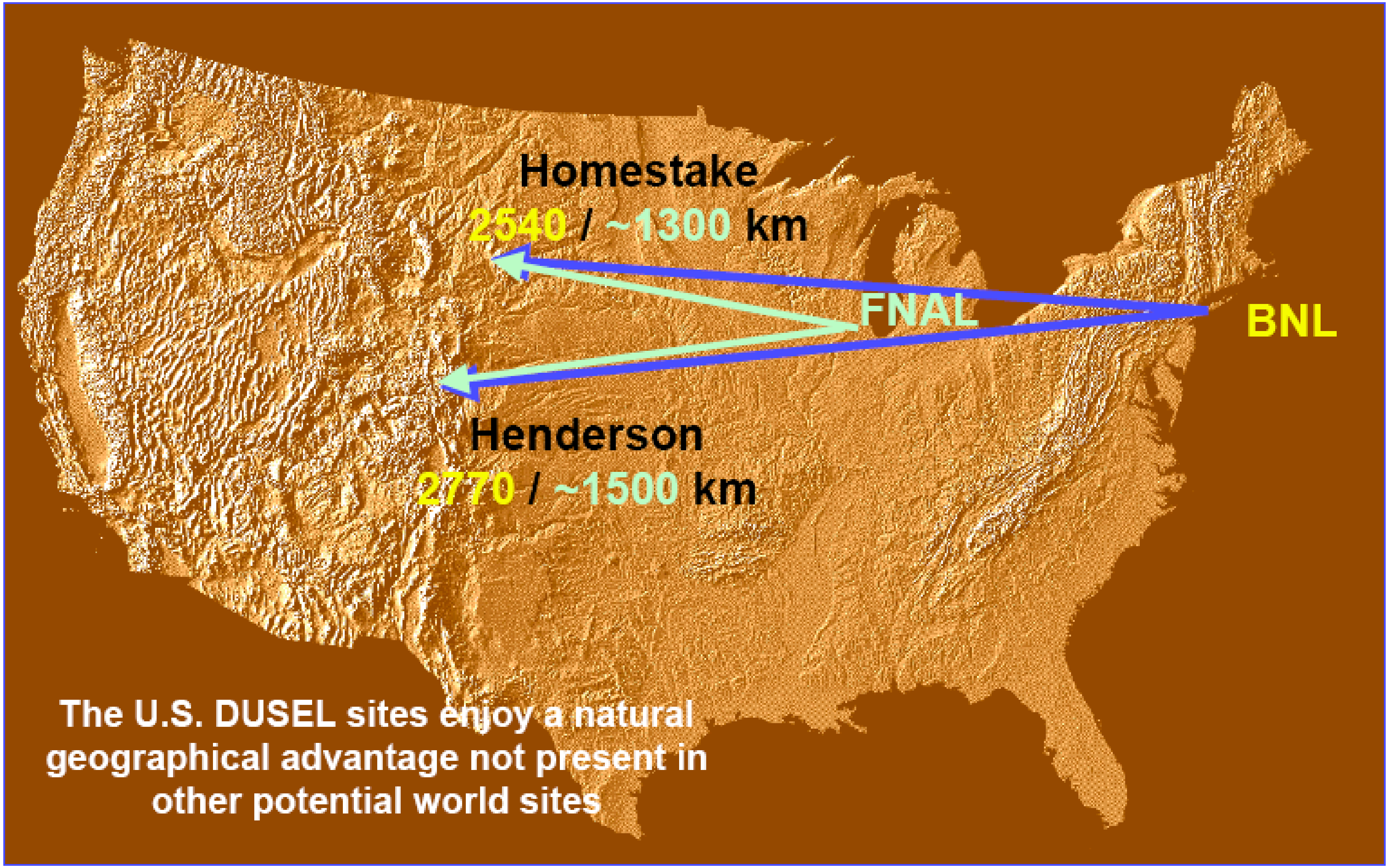
Outline of this talk

- Physics topics:
  - Very Long Baseline Neutrino Oscillation
  - two ~100 kT water Cherenkov detectors
  - Nucleon decay
  - Astrophysical neutrinos

(In the extra slides at the end)

- The NSF DUSEL process
- Brief of study from the FNAL (Mar 6-7) workshop.

Super Neutrino Beam to DUSEL Candidate Sites



Why Very Long Baseline?

observe multiple nodes in oscillation pattern

☞ less dependent on flux normalization

neutrino travels larger distance through earth

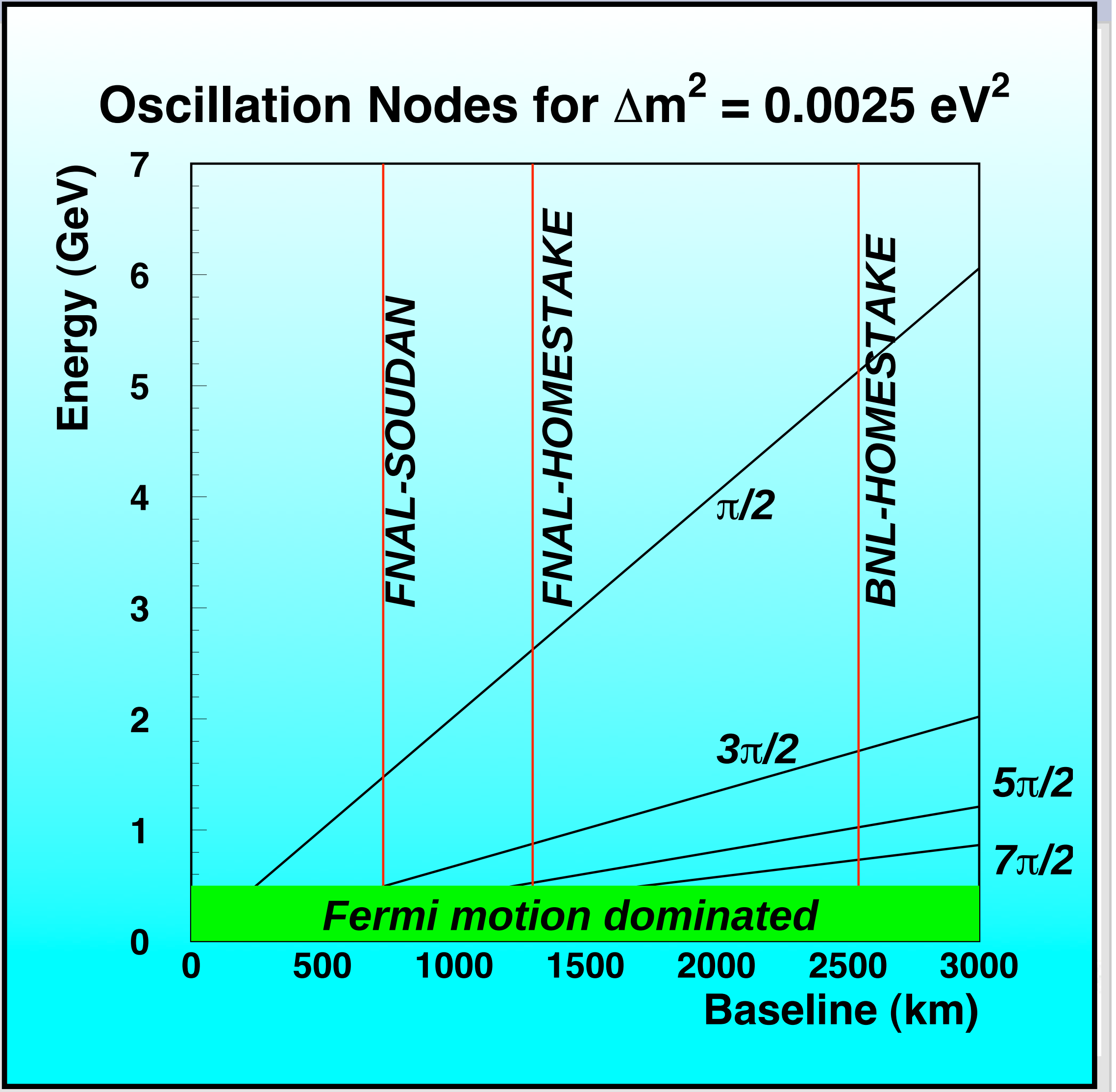
larger matter effects

flux ~ L^{-2}: lower statistics

but: CP asymmetry ~ L

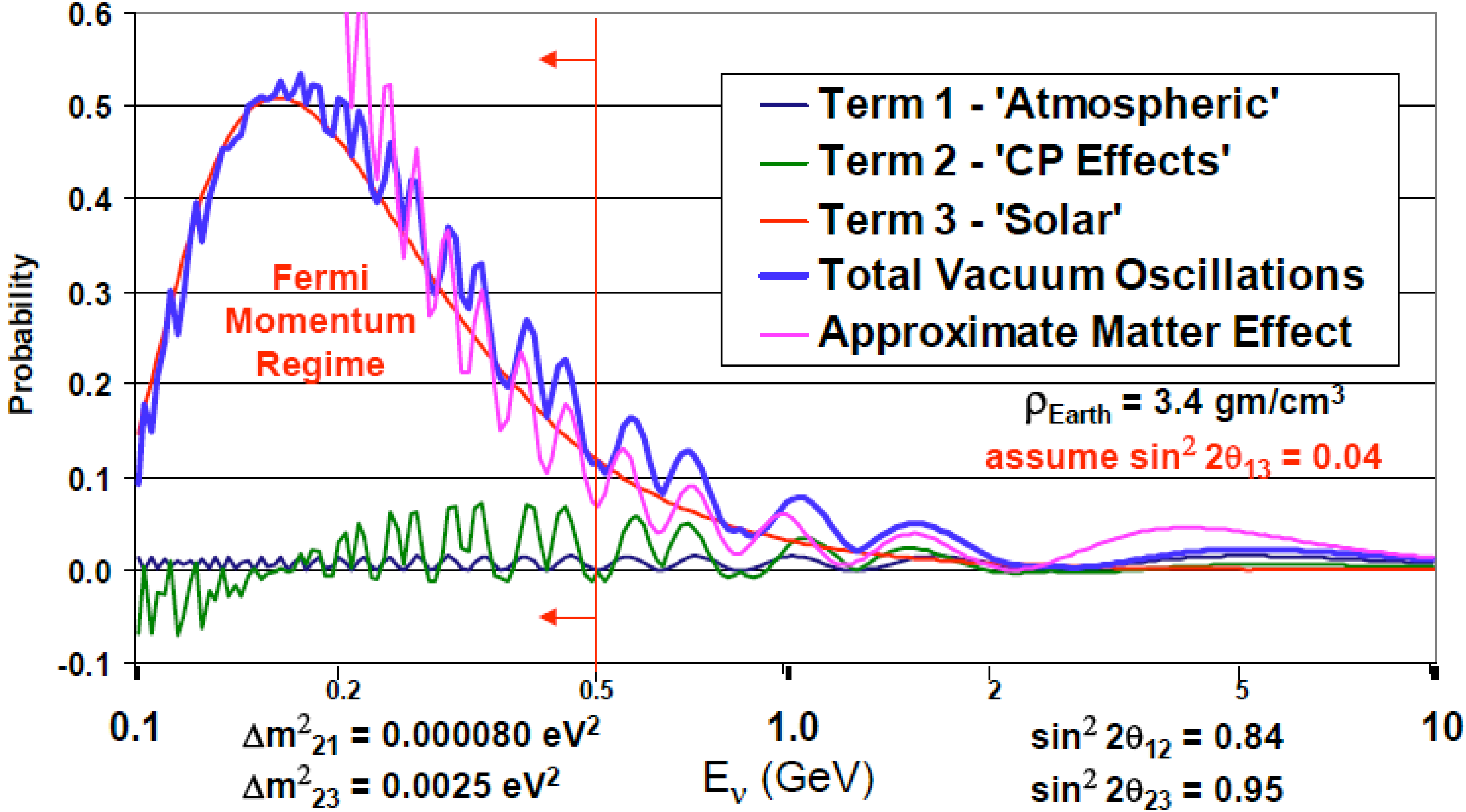
sensitivity to δ_{CP} independent of distance!

better S:B



(Marciano hep-ph/0108181)

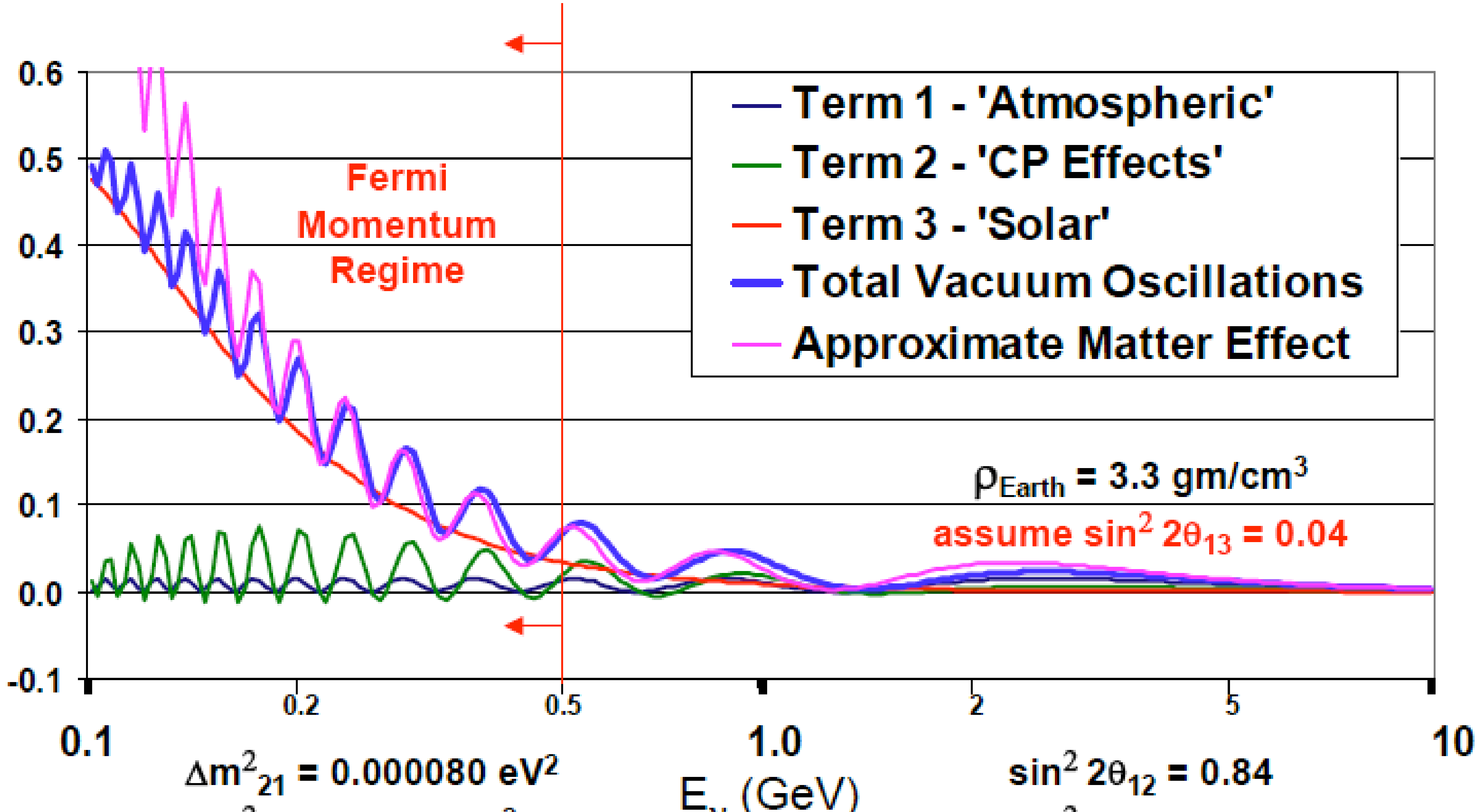
$\nu_\mu \rightarrow \nu_e$ Vacuum Oscillations - VLBNO
L = 2540 km – BNL to Homestake



From T. Kirk

$\nu_\mu \rightarrow \nu_e$ Vacuum Oscill. - VLBNO

L = 1300 km – FNAL to Homestake



$\Delta m^2_{21} = 0.000080\ eV^2$

$\Delta m^2_{23} = 0.0025\ eV^2$

$\sin^2 2\theta_{12} = 0.84$

$\sin^2 2\theta_{23} = 0.95$

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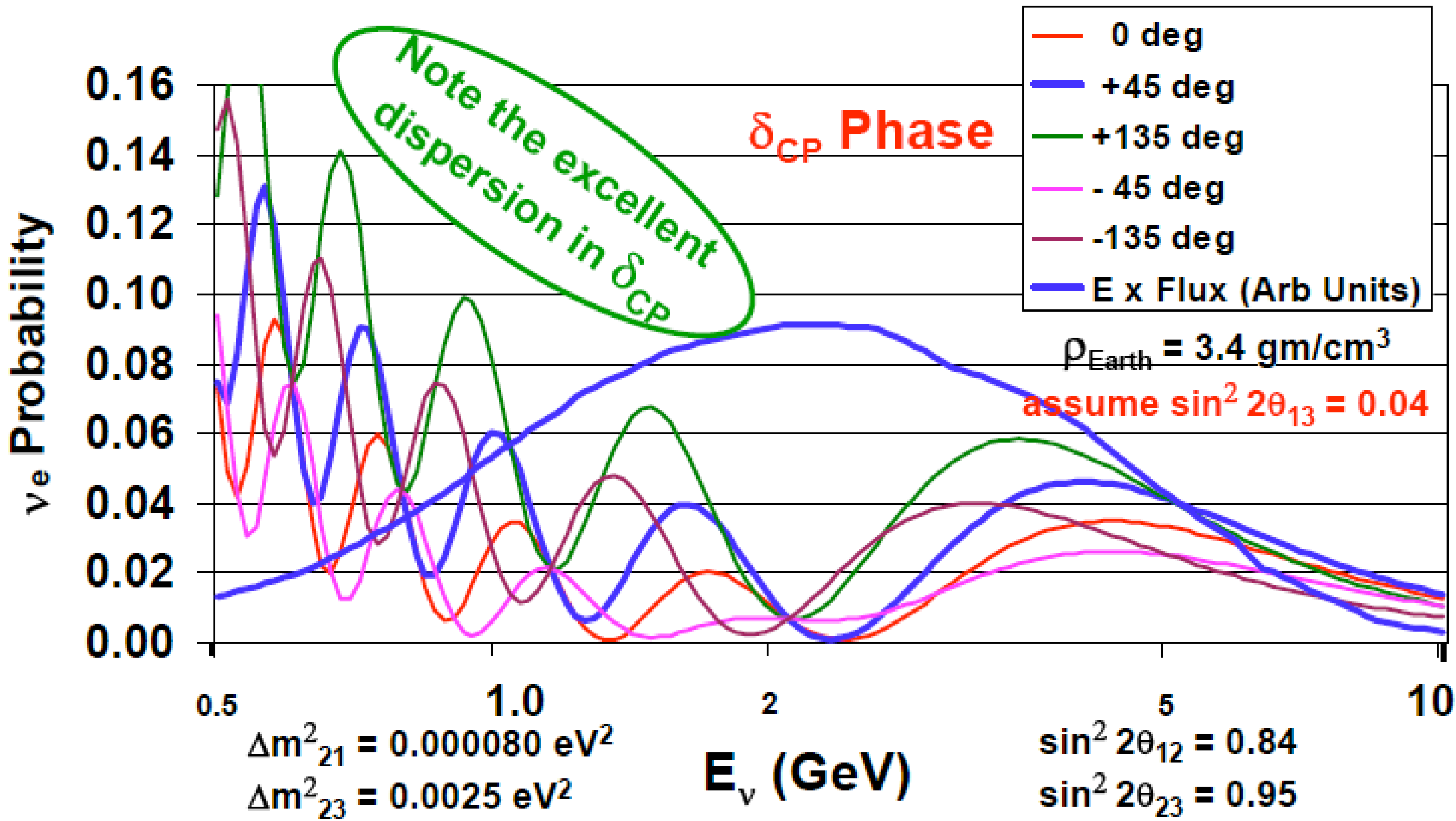
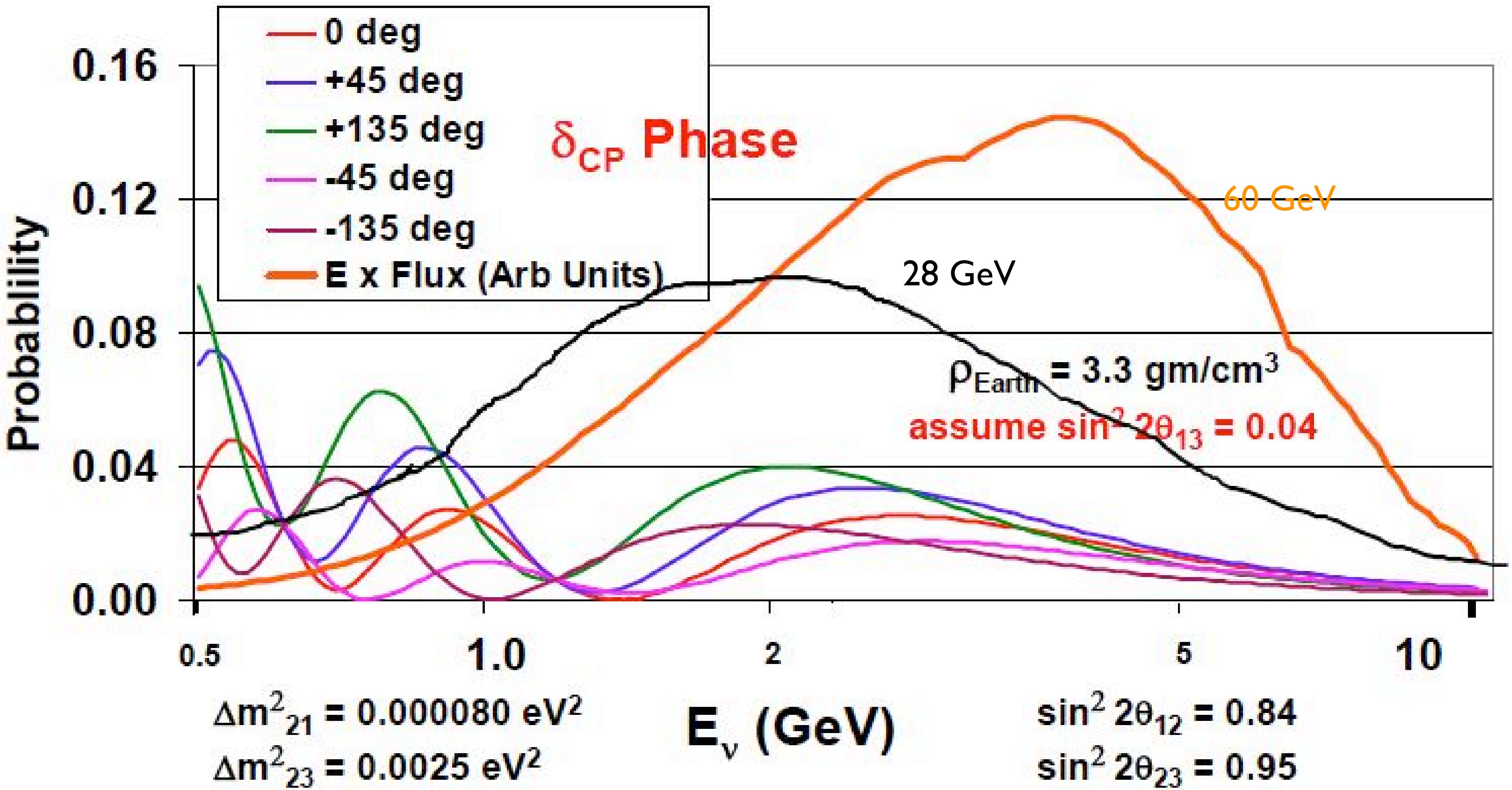
$\nu_\mu \rightarrow \nu_e$ CP Phase Effects - VLBNO
L = 2540 km – BNL to Homestake



$\nu_\mu \rightarrow \nu_e$ CP Phase Effects - VLBNO

L = 1300 km – FNAL to Homestake



Important points

- Sensitivity to CP is independent of distance after 1000km! (see P. Huber's calculation)
- The size of detectors and beam power needed does not depend on theta_13 (as long as it is not very small, S. Parke)
- We need low energy broad band beam. Must have ~4m wide tunnel. I have assumed 200 m length. Low energy horn also(with target deep inside)

FNAL/BNL study launched

- Chairs: Hugh Montgomery, Sally Dawson
- Study is yet to get a charge.
- First kick-off workshop was on March 6-7
- Very successful ! Very good work reported on physics sensitivity, backgrounds, possible beam from FNAL, etc.

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

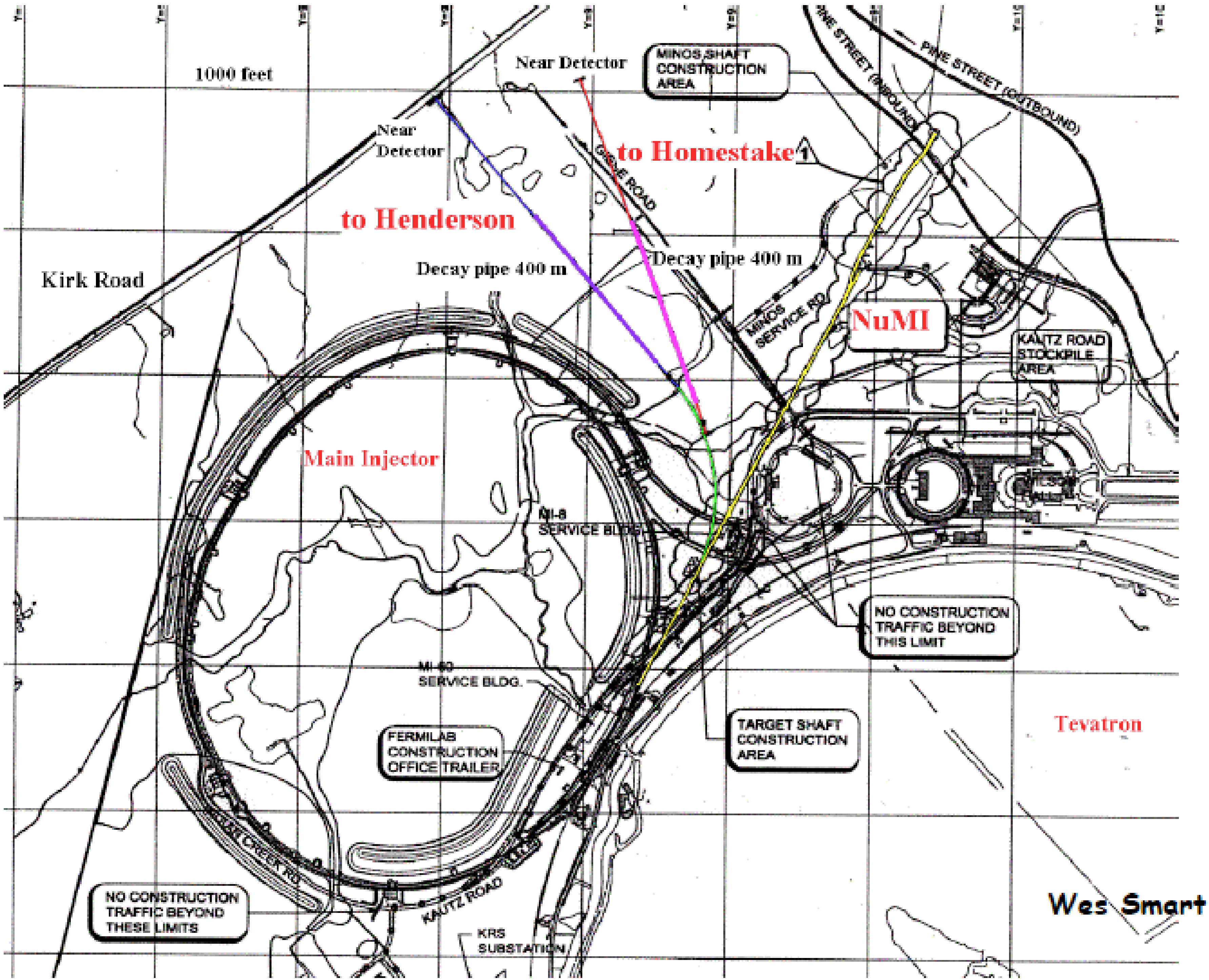
US possibilities for beam

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	

US possible baselines

Source	Detector	Distance	Depth	Comment
FNAL	Homestake	1290 km	4850/ 7700ft	no beam, DUSEL site, capable of large exca.
FNAL	Henderson	1500km	~4000 ft	no beam, DUSEL site, capable of large exca.
BNL	Homestake	2540km	4850/ 7700 ft	study of beam and physics exists and documented
BNL	Hendersn	2767km	~4000 ft	--

shorter baseline means more events.
longer baseline means bigger effects.



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

Neutrino Event rates

Source-det	Detector size	beam E and power	Event rate for neutrino running
FNAL-HS(1290)	200kT	0.5MW@60GeV	~60,000CC ~20,000NC
FNAL-Hend(1500)	200kT	0.5MW@60GeV	~44,000 ~15000
FNAL-HS(1290)	200kT	1MW@28GeV	78,000CC 27,000NC
BNL-HS(2540)	500kT	1MW@28GeV	50000 CC 17000 NC
NOVA(810)*	30kT	0.65MW@120	~10000 CC ~3000 NC

5 X 10^7 sec of running assumed

*rescaled: NOvA assumes 2e7sec * 5 yrs of running in their proposal

How to achieve the total exposure

- For CP violation we need (indep. of baseline or size of theta_13) (Marciano)
  - 2500 kT*MW*(10^7) sec for neutrinos

1 yr ~ 1e7 sec

500kT
1 MW
5 yrs

Past approach

1 yr ~ 2 10^7 sec

100kT
2 MW
6.25yrs

We could go to 200 kT if only 1 MW

Possible at FNAL with new Proton driver

Detector parameters

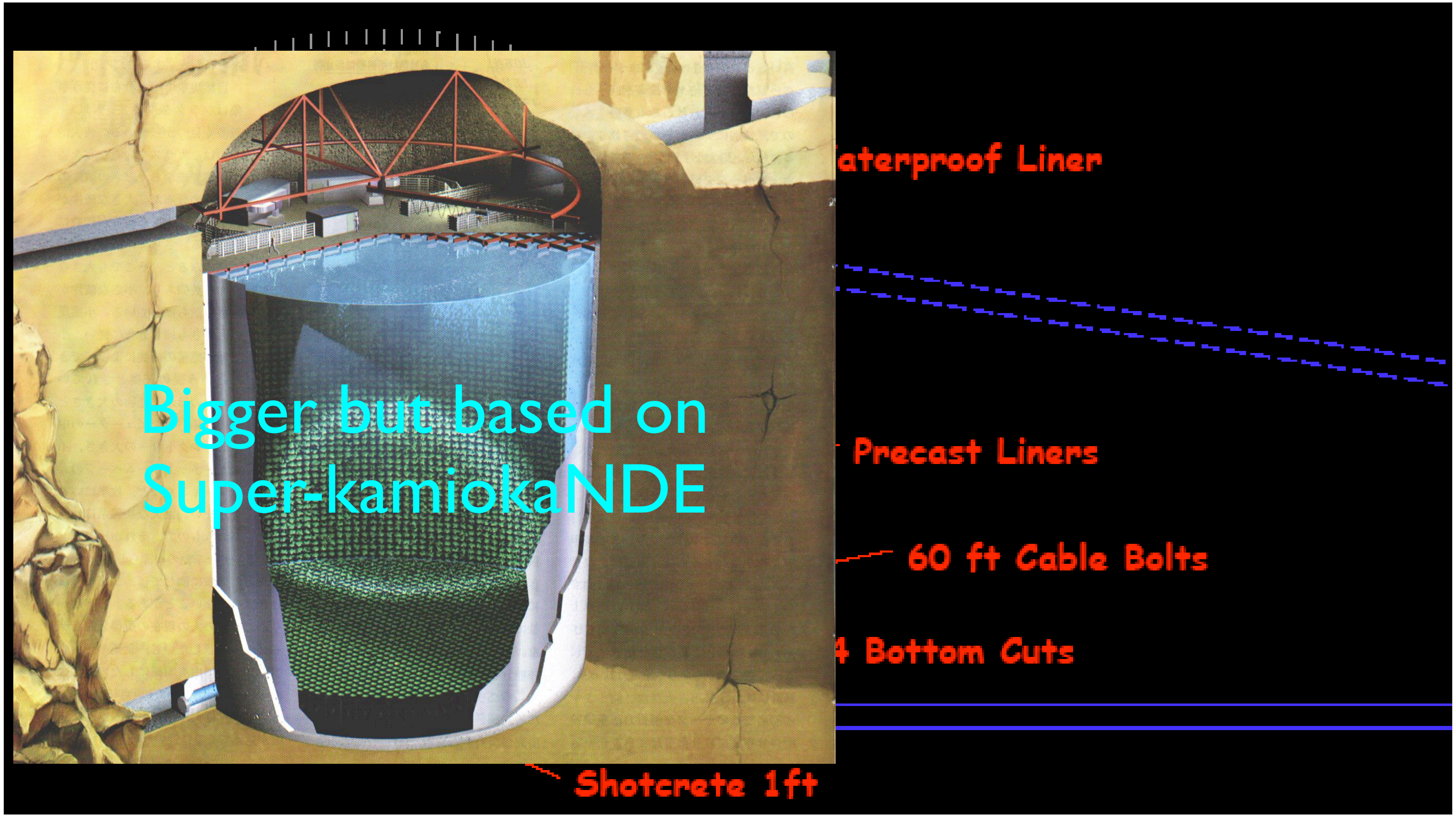
- Need 500 kT fiducial mass for proton decay, neutrino astrophysics.
- 200 kT is initial step => 2 cavities of approximately 50 m dia X 50 m size. (LMD-I and LMD-II)
- depth ? May not need anti-counter if deep enough.
- ~10% energy resolution on quasilelastics.
- Threshold of 5 MeV for solar and supernova
- Time res. ~few ns for pattern recognication.
- Good mu/e separation. <1%.
    - 1,2,3 track separation, NC rejection ~X20.

This level of performance can be obtained with water Cherenkov detector with 20-40% PMT coverage.

=> 11000 to 22000 20inch PMTs for 100kT.

What does it look like

50 m diameter and 50 m tall



SuperKamiokaNDE: 22.5-50kT LMD-1: ~75-100kT

Cavity cost

✓ Estimated Costs For 1 Chamber ($MM)

⇨ Labor & Benefits			$ 5.51
⇨ Mining & Construction			
	★ Equipment Operation	$ 1.30	
	★ Supplies	$ 4.51	
	★ Precast Concrete Liner	$ 3.25	
		Subtotal	$ 9.06
⇨ Other (Outside Contractor)			$ 0.12
⇨ 15% Contingency			$ 2.20
		TOTAL	$ 16.89

From
K. Lande
and
M. Laurenti

208 weeks
could be accelerated

4 cavities for $44 M

Mark A. Laurenti

March 2002

Detector cost

Exca … llion

Phot …

and … lion

Wat … lion

Misc … lion

Cont … lion

TOT … llion

Point of this is that it is NOT $0.5 billion.

But of course, this is what we need to work on now !

… d

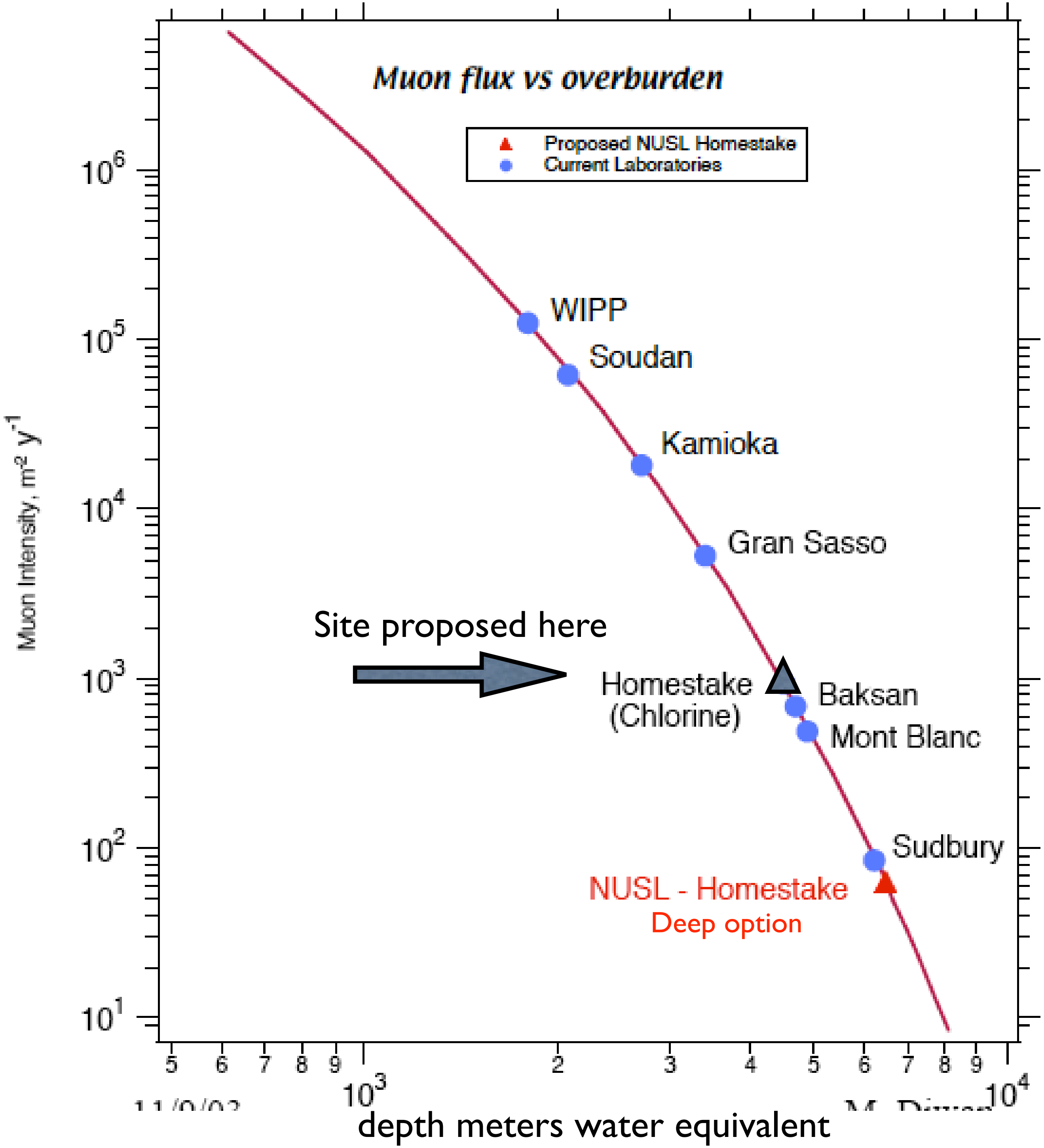
escalated. PMT coverage must be settled, etc.

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.



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- How is analysis done ?
  - Use of SK atmospheric neutrino MC
    - Standard SK analysis package + special π^0 finder
    - Flatten SK atm. ν spectra and reweight with BNL beam spectra
    - Normalize with QE events: 12,000 events for ν_μ , 84 events for beam ν_e for 0.5 Mt F.V. with 5 years of running, 2,540 (1,480) km baseline

2500 kt• MW•10^7 sec
BNL 30 GeV AGS

distance from BNL to Homestake
(distance from Fermilab to Henderson)

    - Reweight with oscillation probabilities for ν_μ and for ν_e
  - Oscillation parameters used:
    - **Δm^2_{21} =7.3 x 10^{-5} eV^2, Δm^2_{31}=2.5 x 10^{-3}eV^2**
    - **$\sin^2 2\theta_{ij}$(12,23,13)=0.86/1.0/0.04, δ_{CP}=0,+45,+135,-45,-135^o**

Probability tables from Brett Viren of BNL

Yanagisawa

Selection criteria used to improve

- Initial cuts: Traditional SK cuts only
  - One and only one electron-like ring with energy and reconstructed neutrino energy more than 100 MeV without any decay electron

$$E_\nu^{rec} = \frac{m_N E_e}{m_N - (1 - \cos\theta_e) E_e}$$

To reduce events with invisible charged pions

- Likelihood analysis using the following 9 variables: With π^0 finder
  - π^0 mass (pi0mass)
  - energy fraction (efrac)
  - costh
  - π^0-likelihood (pi0-like)
  - e-likelihood (e-like)
  - Δ log π^0-likelihood (Δlog pi0like)
  - single ring-ness (dlfct)
  - total charge/electron energy (poa)
  - Cherenkov angle (ange)

Yanagisawa

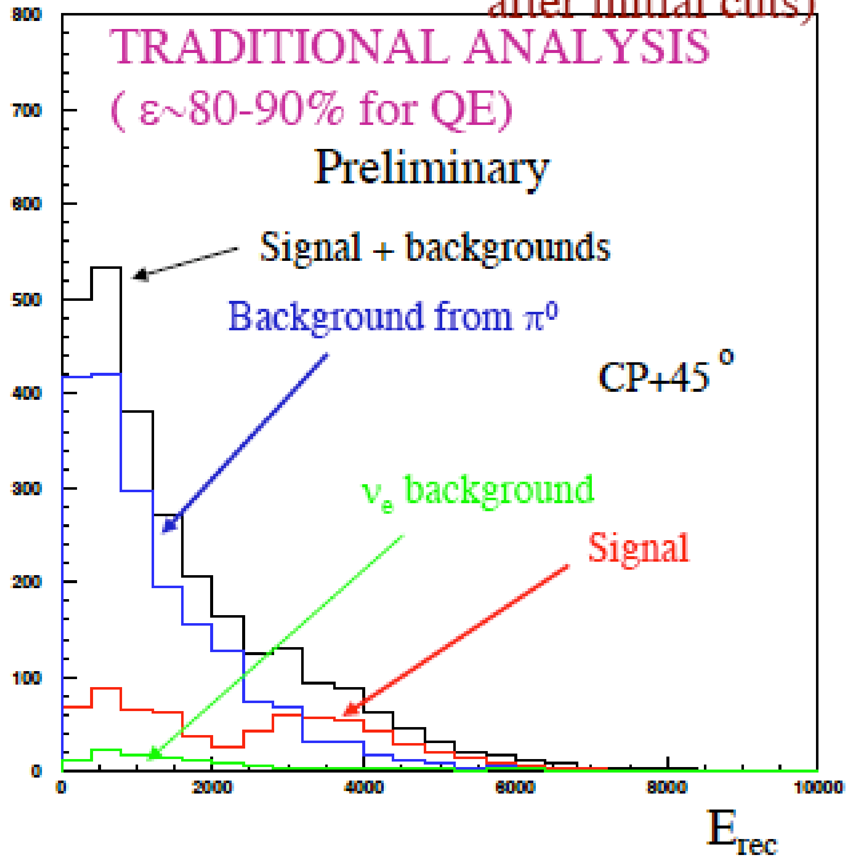
BNL-Homestake (2540 km)

- Effect of cut on Δ log likelihood

ν_e CC for signal ; all $\nu_{\mu,\tau,e}$ NC , ν_e beam for background

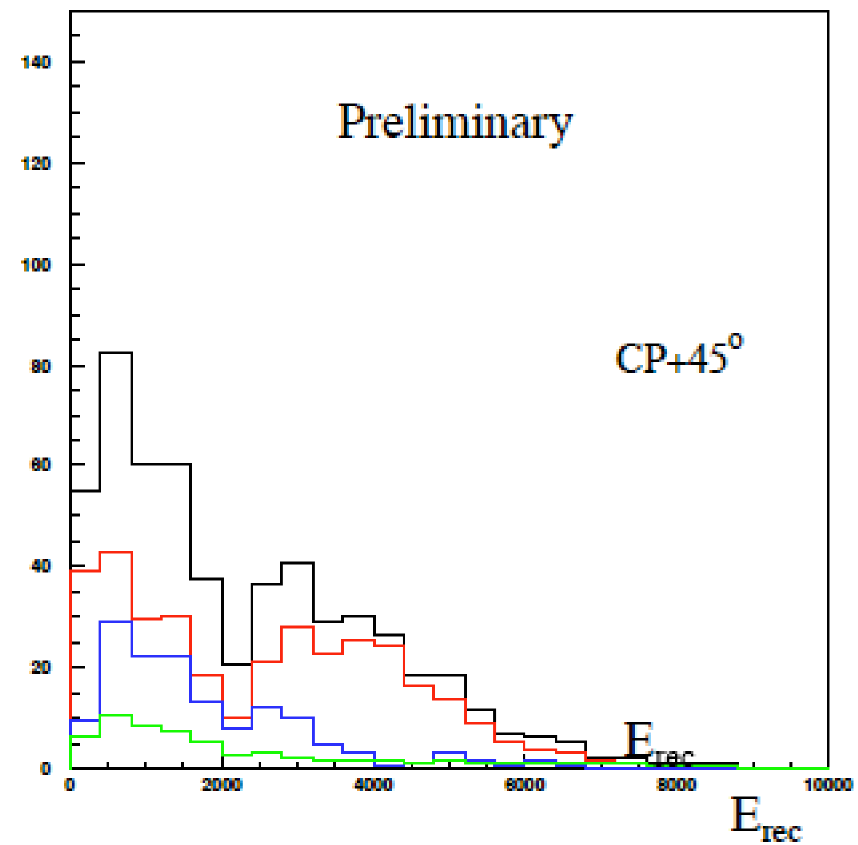
After initial cuts

No Δ log likelihood cut (100% signal retained after initial cuts)



Signal 700 ev Bkgs 2004
(1877 from π^0+others)
(127 from ν_e)

Δ log likelihood cut (~50% signal retained)



Signal 350 ev Bkgs 169
(147 from π^0+others)
(61 from ν_e)

Yanagisawa

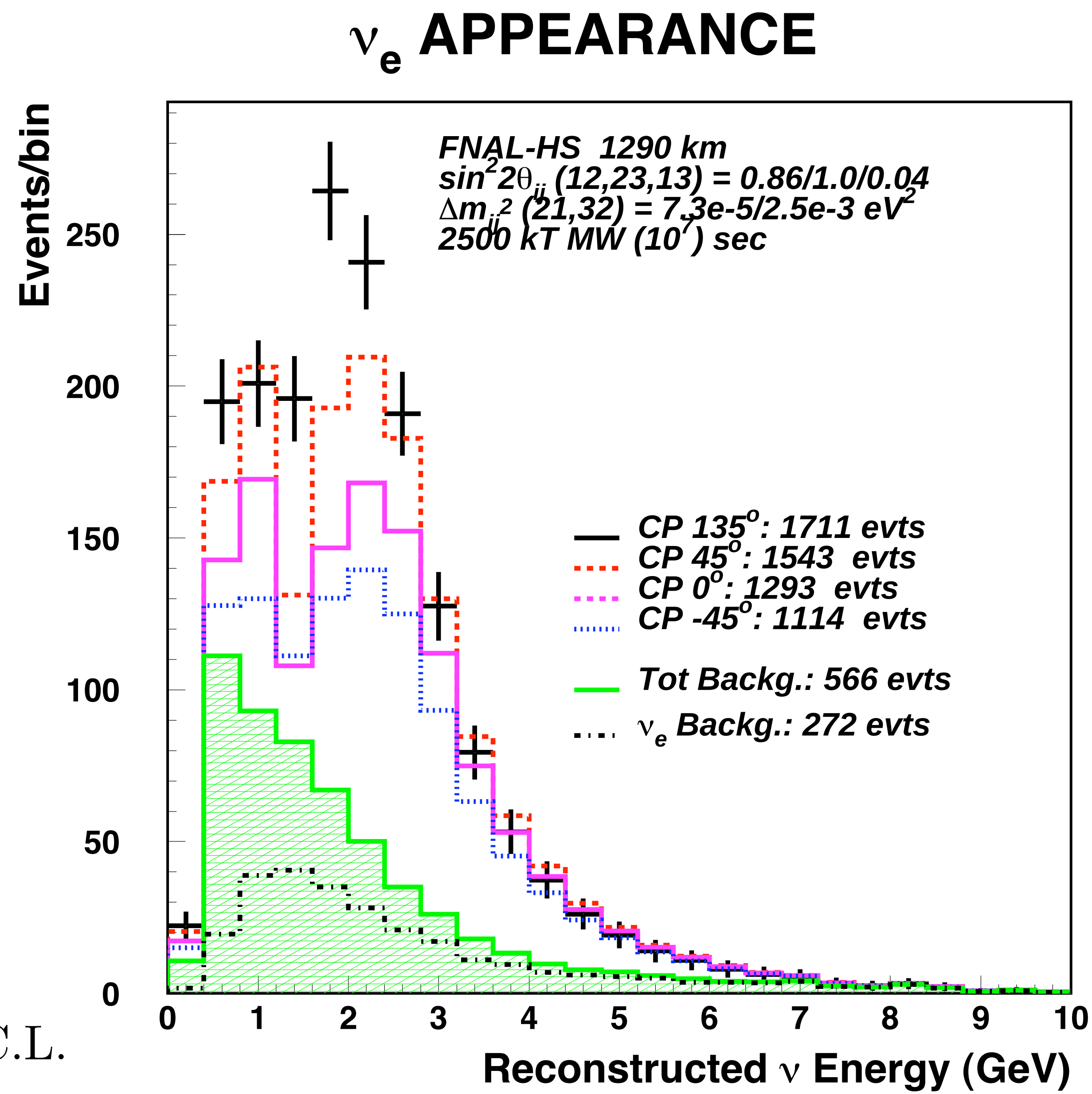
ν_e Appearance

<u>Backgrounds</u>

- beam ν_e
- Neutral current events

<u>ν running</u>

- measure $\sin^2 2\theta_{13}$ and δ_{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.L.



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

ν_μ Disappearance

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

Neutrino Running

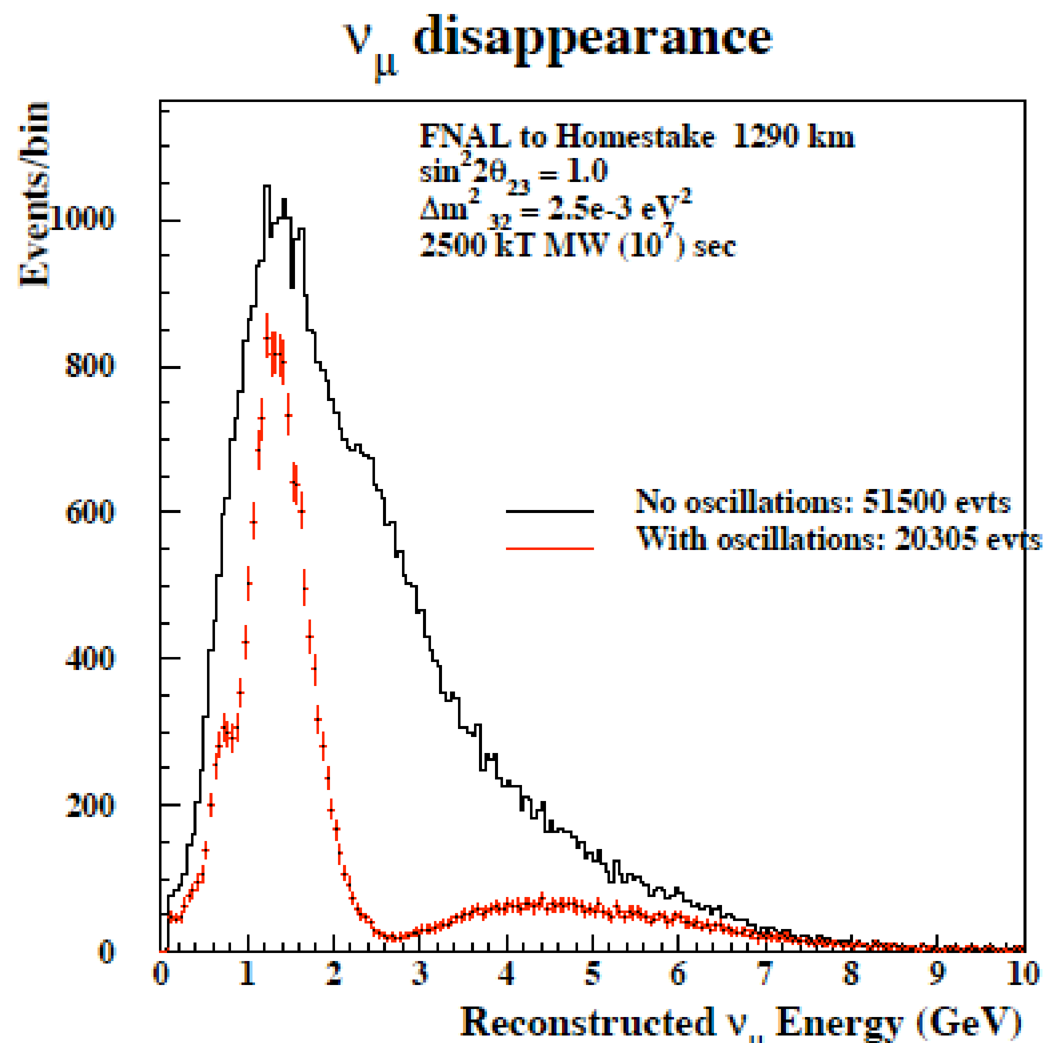
- Total exposure: 2500 kT.MW.(10^7).sec
- 195000 CC evts/6yrs: 2MW-FNAL, 100kT-HS
- Use only clean single muon events.

Measurements

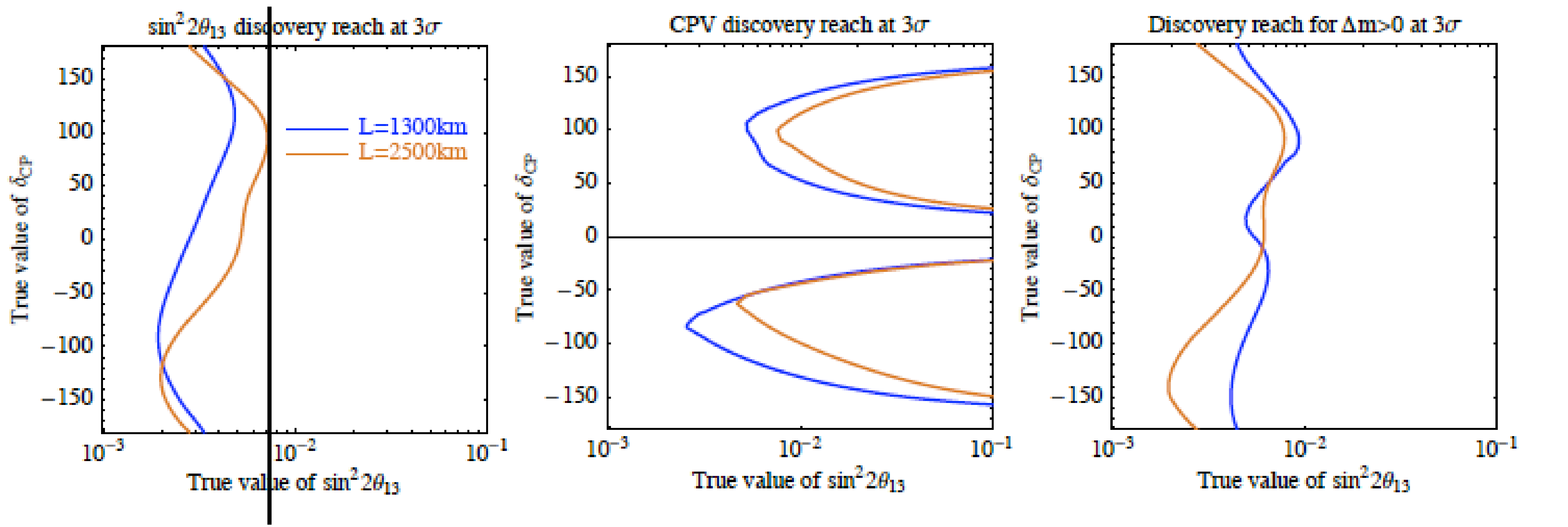
- 1% determination of Δm^2_{32}
- 1% determination of $\sin^2 2\theta_{23}$
- Most likely systematics limited.

$\bar{\nu}$ running

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



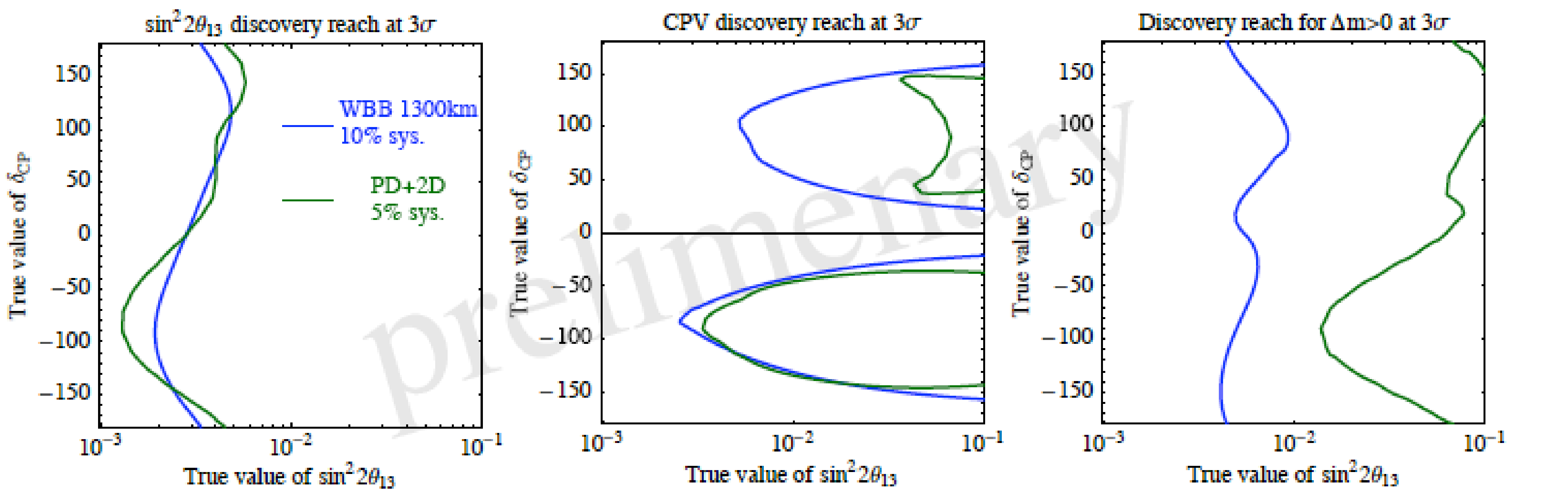
Wide band beam



- very good resolution of the mass hierarchy
- no problems due to π-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

2nd Maximum experiment

Mark has produced beam spectra that peak near the second maximum (525 MeV at 810 km)

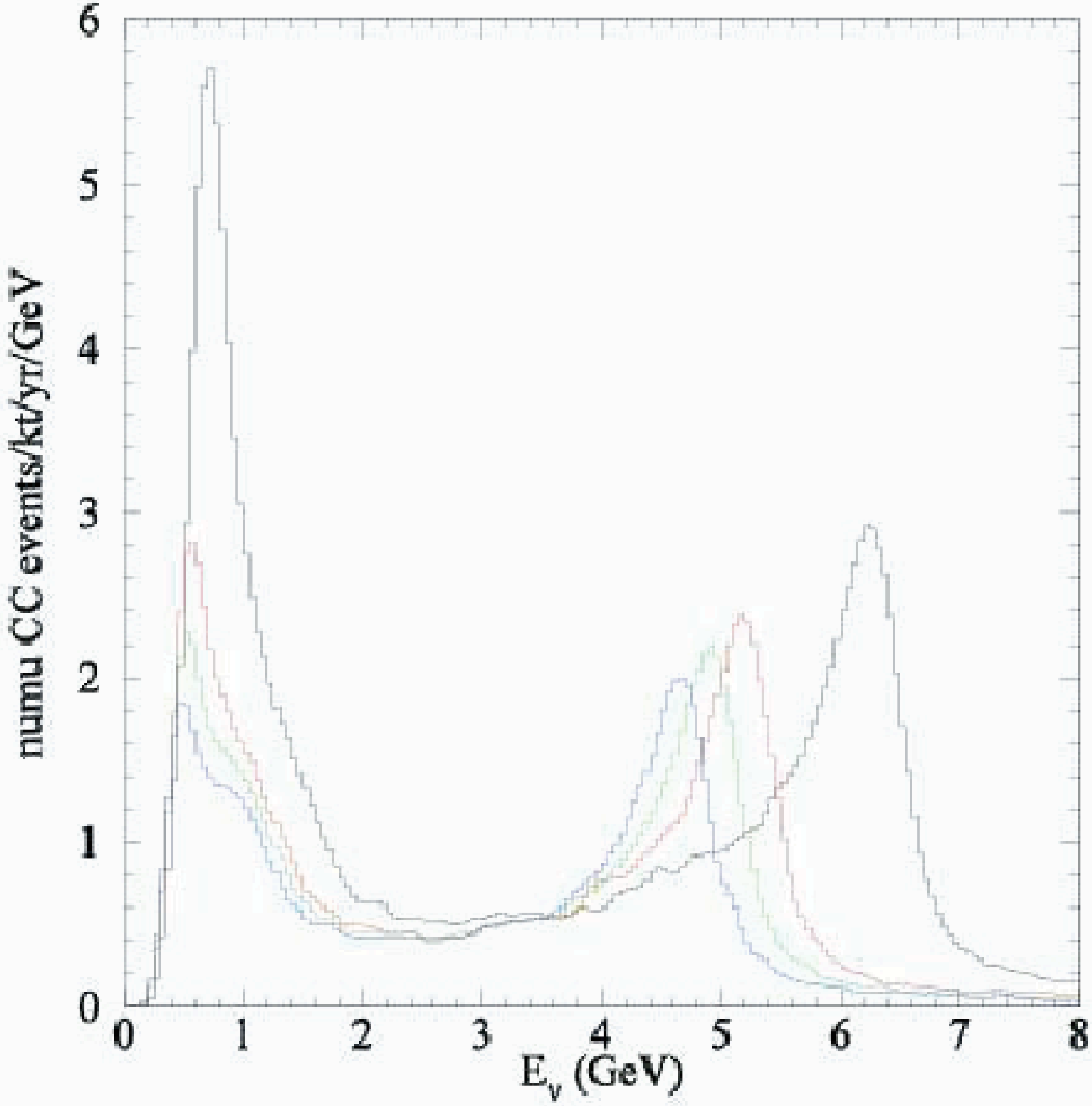
30 km off-axis

36 km off-axis

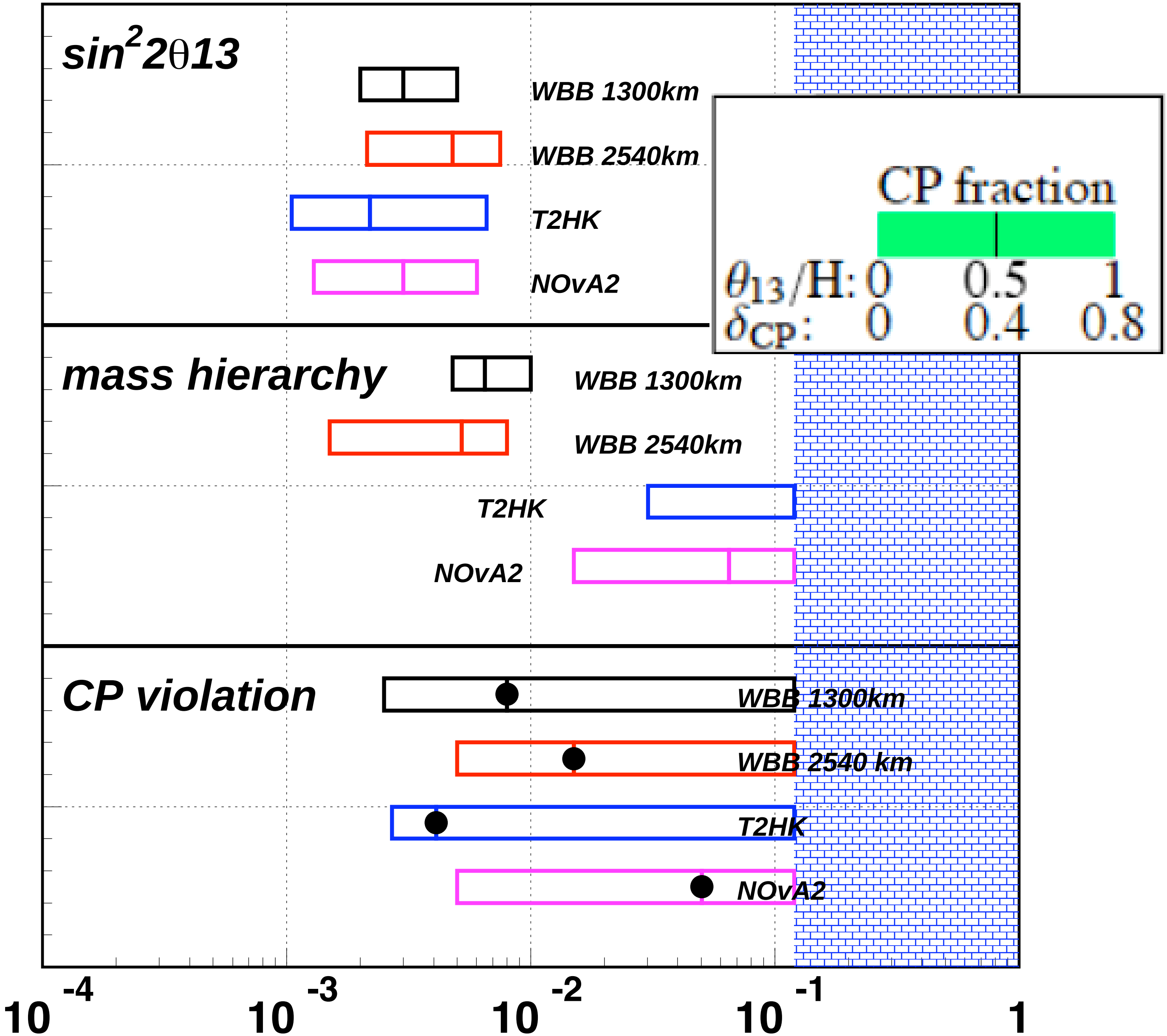
38 km off-axis

40 km off-axis

B. Fleming



Comparison of 3σ reach



Assumptions

- WBB:
  nu:200kT*1MW*6yr.
  antinu: 200kT*1MW*6yr
  syst: 10% on bck
  Antinu running is over-constraint for normal hierarchy.
- T2HK:
  nu: 1000kT*4MW*3yr
  antinu: 1000kT*4MW*3yr
  syst: 2% on bck
- NOVA2:
  nu:30kT*2MW*6yr+ 80kT*2MW*3yr
  antinu: same*6yr+3yr
  syst: 5% on bck

Preliminary result out of FNAL workshop

DOE/NSF DUSEL Working Group

- Division/Office representatives:
  - R. Boyd, NSF, Division of Physics (Nuclear Astrophysics)
  - R. Fragaszy, NSF, Division of Civil & Mechanical Systems (Engineering)
  - G. Henry, DOE, Office of Nuclear Physics (Nuclear Physics)
  - J. Kotcher, NSF, Division of Physics (Experimental Particle Physics)
  - D. Lambert, NSF, Division of Earth Sciences (Geosciences)
  - P.K. Williams, DOE, Office of High Energy Physics (High Energy Physics)
  - N. Woodward, DOE, Office of Basic Energy Sciences (Geosciences)
- First discussion at DOE Germantown, 15 February 2006
- MoU being drafted that outlines initial agreement to participate in early DUSEL planning & process and interagency discussions
  - Goal is to ensure compatibility with planning needs of each of the agencies
  - Will grow in complexity as project, experimental plans mature
- Laboratory infrastructure responsibility of NSF, experiments will be joint DOE/NSF (+ foreign) initiatives.

source: Jon Kotcher

DUSEL Process

- Three-tier process, announced to community March 2004:
- Solicitation 1:
  - January 2005, $400k award, Chair: B. Sadoulet
  - Site-independent science and engineering cases evaluated and endorsed
- Solicitation 2:
  - 15 September 2005: $500k awards to PIs for Henderson (CO - Jung) and Homestake (SD - Lesko)
  - Proponents developing site-specific conceptual designs. Will detail:
    - How the site will accommodate the science and engineering objectives;
    - Management and organizational plan for construction and operations;
    - Geologic, environmental, permitting and safety issues;
    - Risk analysis and mitigation;
    - Initial scientific program and timeline;
    - Engineering needs for accommodation of longer-term scientific program.
  - Submission of CDRs due to NSF June 23, 2006
  - Target: down-select in summer/fall 2006.

Kotcher

DUSEL Process

- Solicitation 3:
  - Develop site-specific technical design, cost, schedule for construction of DUSEL infrastructure, and initial suite of experiments
  - Evaluate proposal(s) ~ fall 2006
  - Award amount(s) under discussion – at least few $M, Fall 2006
- Process could result in construction start in FY09

Kotcher

We at BNL want to participate in this science regardless of the location. We are working with both DUSEL sites in different capacities.

Some Important Attributes of a DUSEL

- Depth
  - Dark matter, double-beta, solar, mega-detector all suggest min ~ 4500 mwe
  - More depth as experimental sensitivity increases
- Detector Halls
  - Capability to customize underground space, experimental areas
- The capacity to accommodate a mega-detector at appropriate depth
  - Excavation, integrity of rock, etc.
- Cleanliness
  - Natural underground radiation backgrounds, clean facilities, etc.
- Importance of round-the-clock access
- Safety, special materials, and materials handling
- Environmental assessments, considerations
- Access for large and heavy equipment
- Quietness and stability: electrical, mechanical, seismic
- Adequate support facilities and strong scientific environment
- Baseline for high intensity neutrino beam, CP violation
  - 1000 – 3000 km
- Education and outreach

Kotcher

Homestake Progress

- 2004, SDSTA formed, agreement in principle with Barrick, and conversion plan created which creates DUSEL in two stages: 4850 stage and deep stage.
- 2005, several workshops, selection as one of the finalists, calls for Letters of Intent.
- The LOIs have ben examined by a PAC.
  Physics chair: Frank Sciulli.
- Total of $45M now available from state.
- Authority has $100M bonding ability.
- Indemnity, immunity statues, and water permits in place.
- The water accumulation issue has been demonstrated to be not important as long as we do not delay too much.

Summary

- Physics case for a 200 kT detector at Homestake.
- nucleon decay, astrophysical neutrinos, long baseline.

Many open issues on detector

- Lowest risk most cost effective option for a long baseline second generation experiment.

Many open issues on beam

- Possible time sequence:
  - 100 kT + 0.5 MW (60GeV)=> 68 evts/day
  - 200 kT + 1 MW (30GeV) => 180 evts/day
  - 200 kT + 2 MW (30 GeV)=> 360 evts/day

Request

- Full support for this program from this PAC
- Need much increased manpower to resolve the open issues.
- Need close cooperation with FNAL for the beam design and physics strategy.
- Suggestion: BNL take large role on the detector design at DUSEL (either site).

EXTRAS

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.

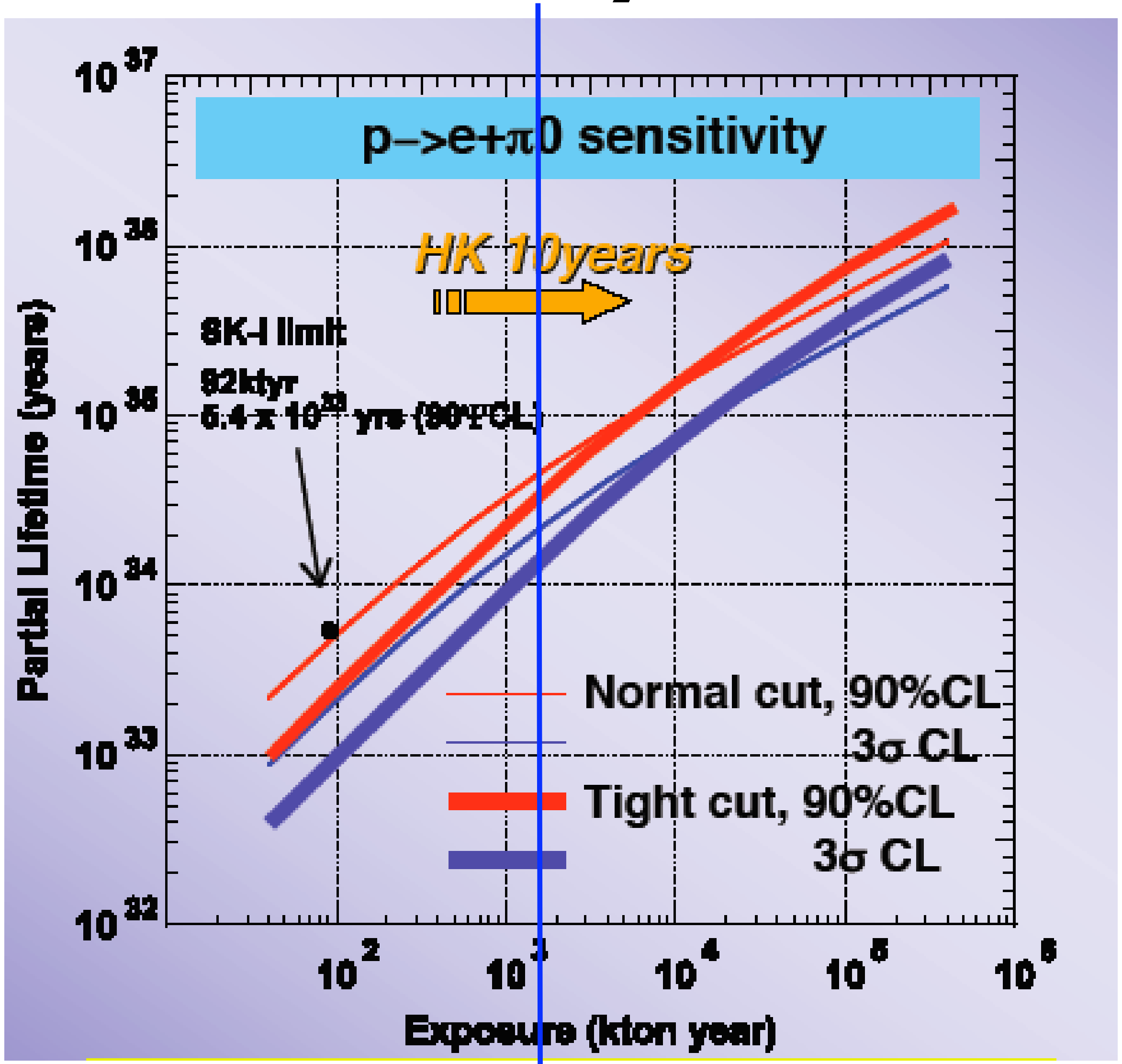
Open issues on beam

- 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

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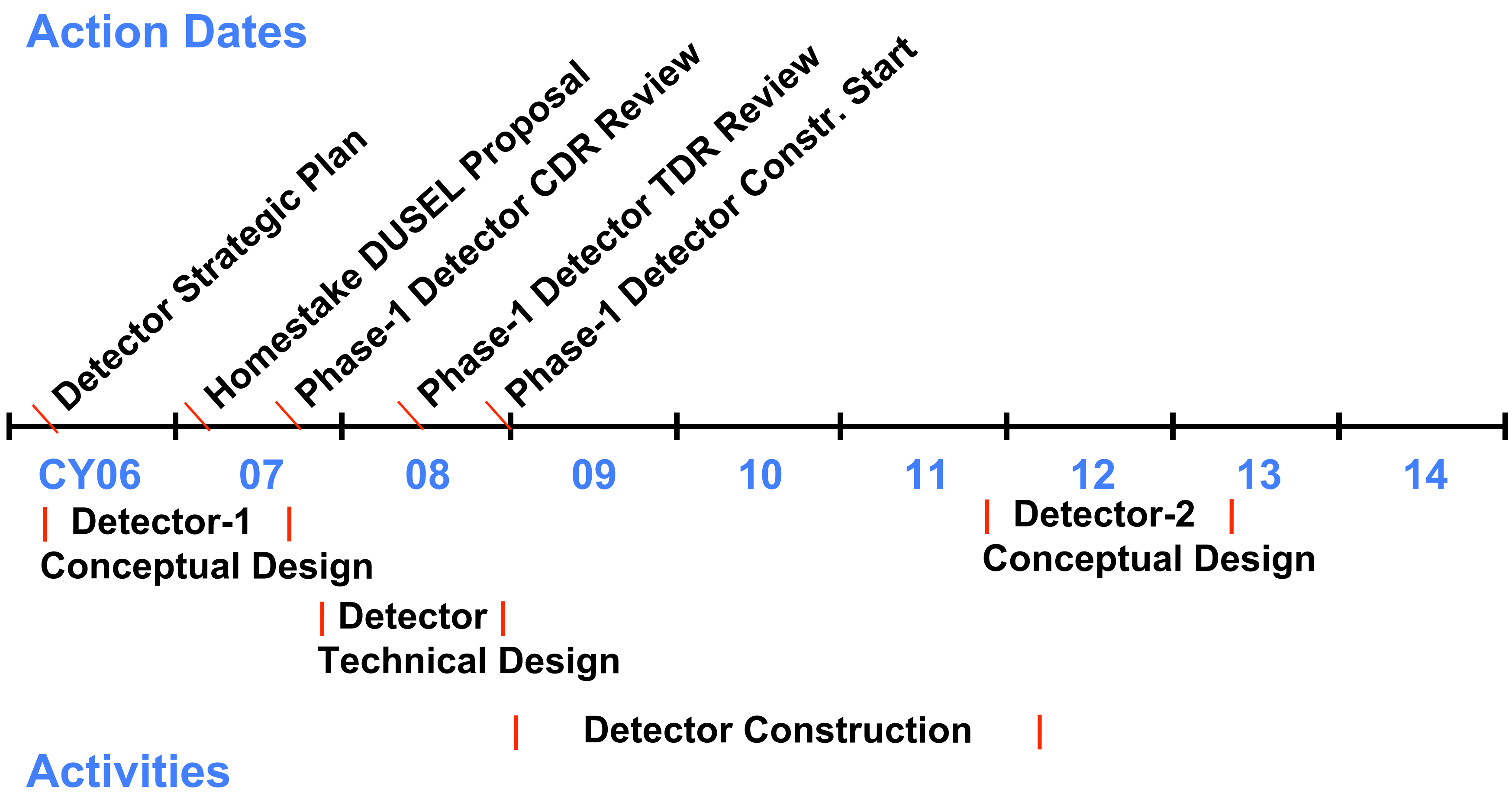
Astrophysical Neutrinos
Event rates. LMD-I&II(200kT), 5 yrs

- 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

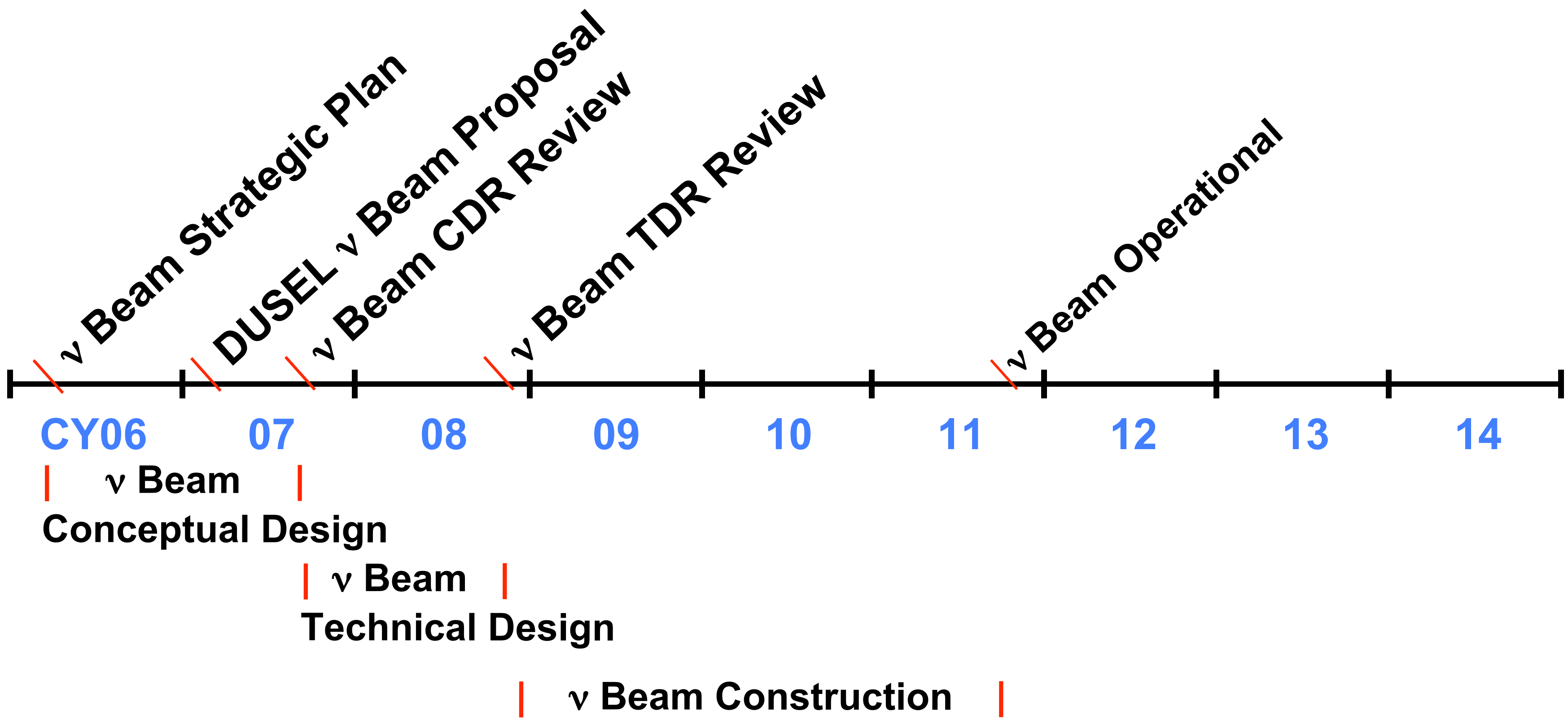
Homestake VLBNO Program Timeline



from T. Kirk

ν Beam Accelerator Program Timeline

Action Dates



Activities

from T. Kirk

Electron neutrino appearance physics parameter extraction

For 1000 - 2000 km baseline
effects across energy band.

	$E_\nu < 1$ GeV	$1 < E_\nu 2 <$GeV	$E_\nu > 2$ GeV
$\sin^2 2\theta_{13}$	$\surd$	$\surd$	$\surd$
$sign(\Delta m^2_{32})$	-	-	$\surd\surd\surd$
δ_{CP}	$\surd$	$\surd\surd$	$\surd$
solar	$\surd\surd\surd$	$\surd$	-

- It's a complex picture with many effects!
- But, effects have different strength at different energies.
- Measuring across the wide energy band makes it possible to sort them out.

What about anti-nu running

- Depends on mass hierarchy.
- To be completely risk-free need
  - 5000 kT*MW*(10^7) sec

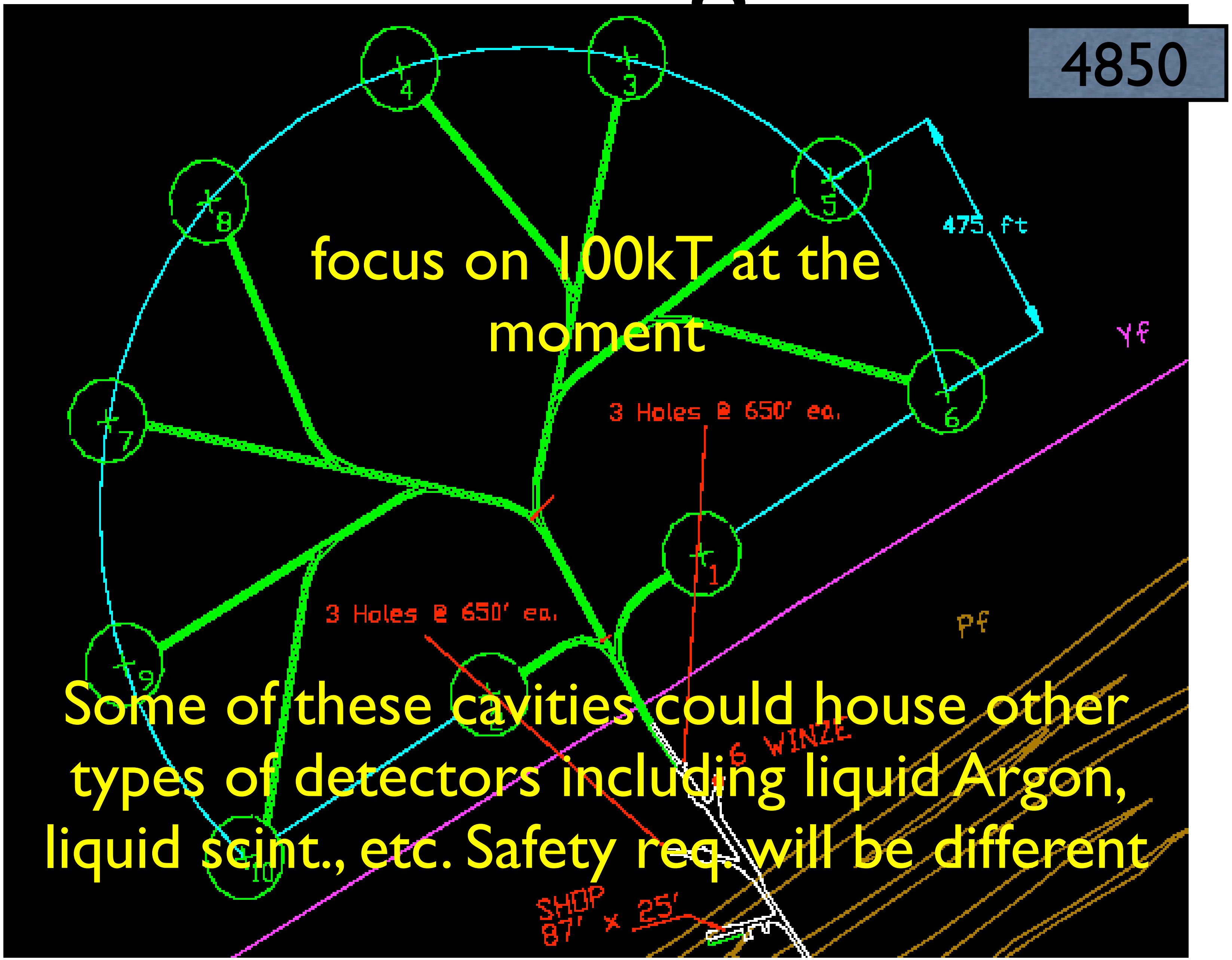
1 yr ~ 1e7 sec

500kT
2 MW
5 yrs
Past approach

1 yr ~ 2e7 sec

200kT
2 MW
6.25yrs
Possible at FNAL with new Proton Driver

We want to grow to..

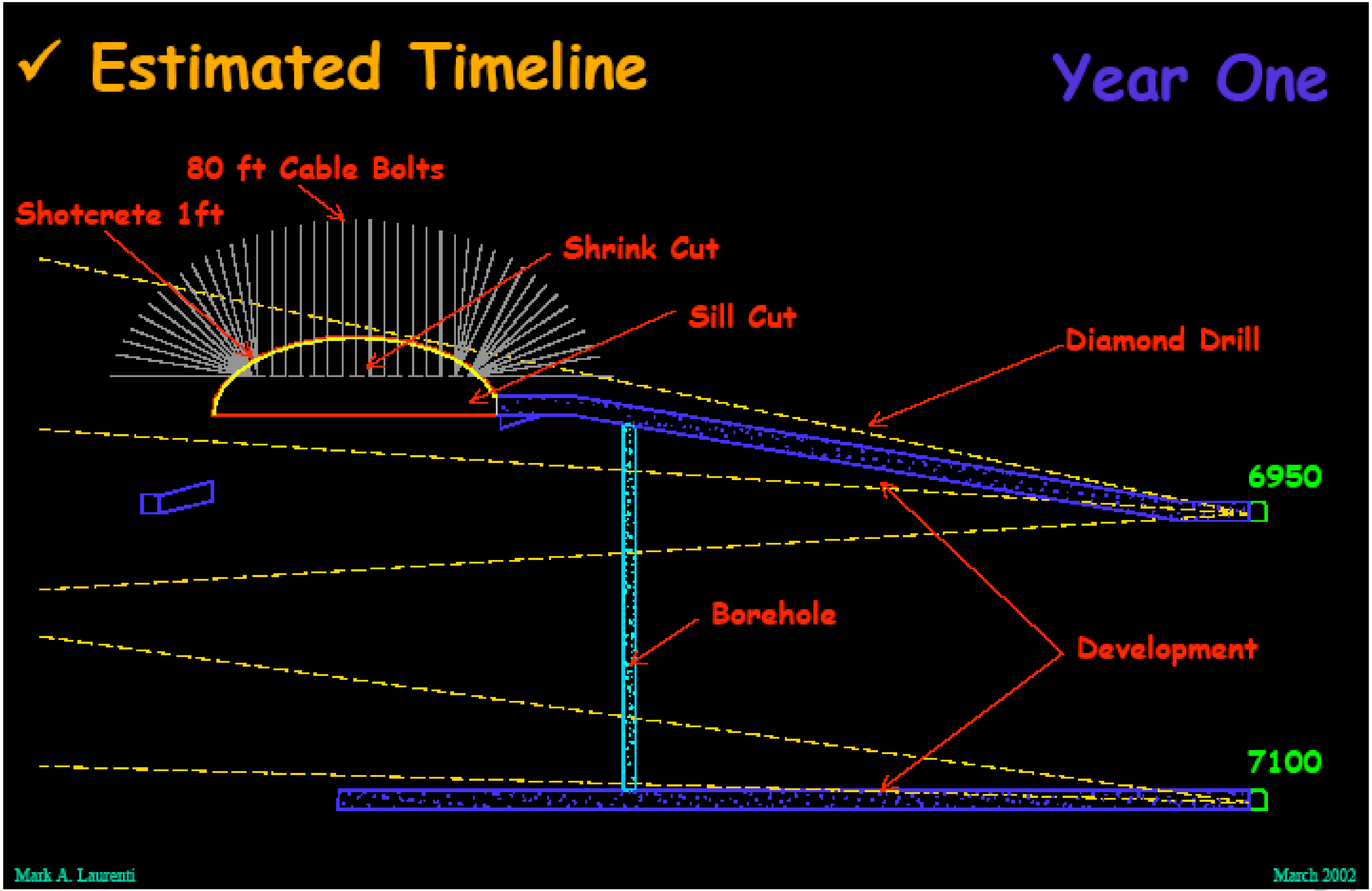


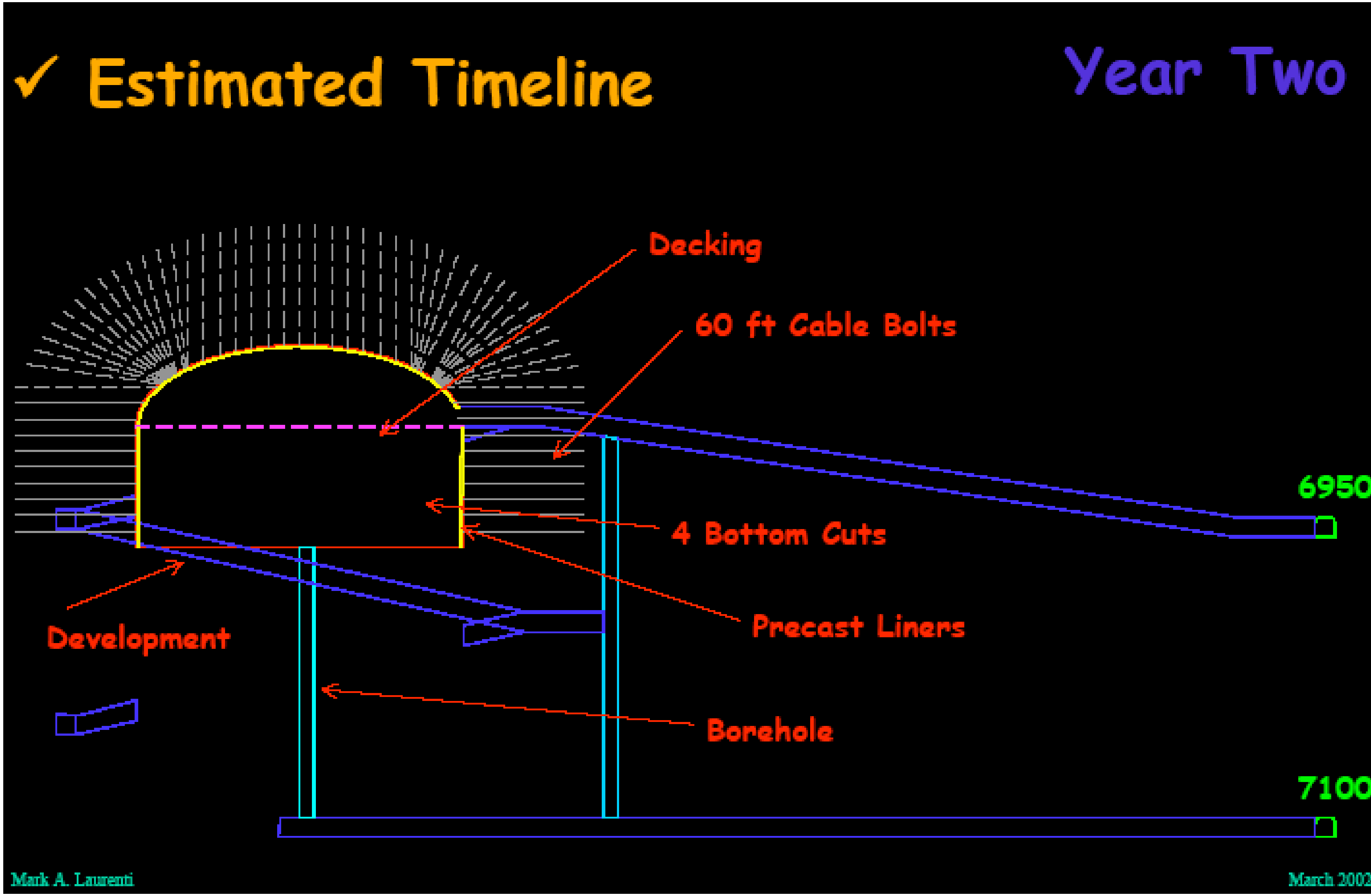
Office of Science
U.S. DEPARTMENT OF ENERGY

M.Diwan

BROOKHAVEN NATIONAL LABORATORY

How to build it..

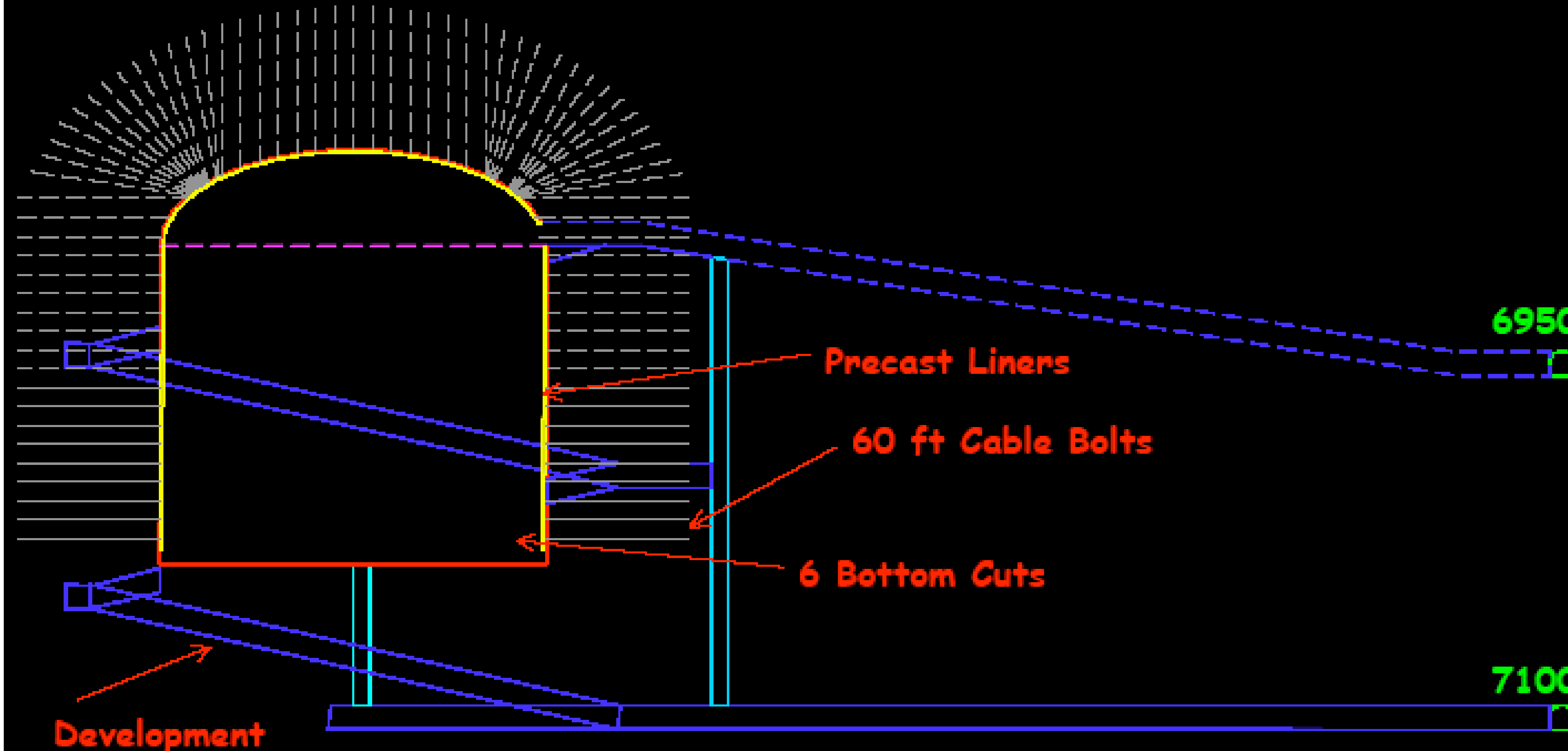




✓ Estimated Timeline
Year Two
Decking
60 ft Cable Bolts
6950
4 Bottom Cuts
Precast Liners
Development
Borehole
7100
Mark A. Laurenti
March 2002

✓ Estimated Timeline

Year Three

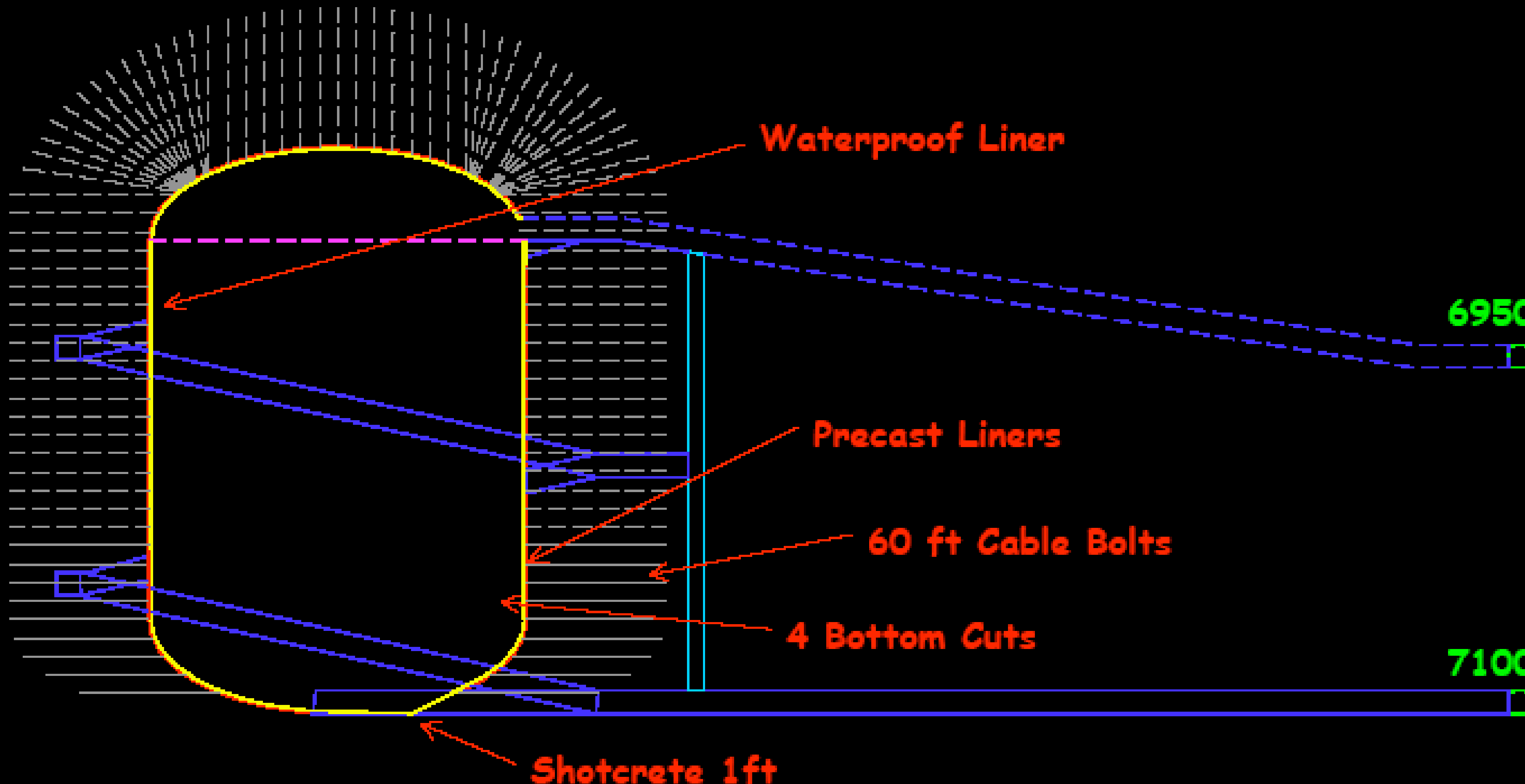


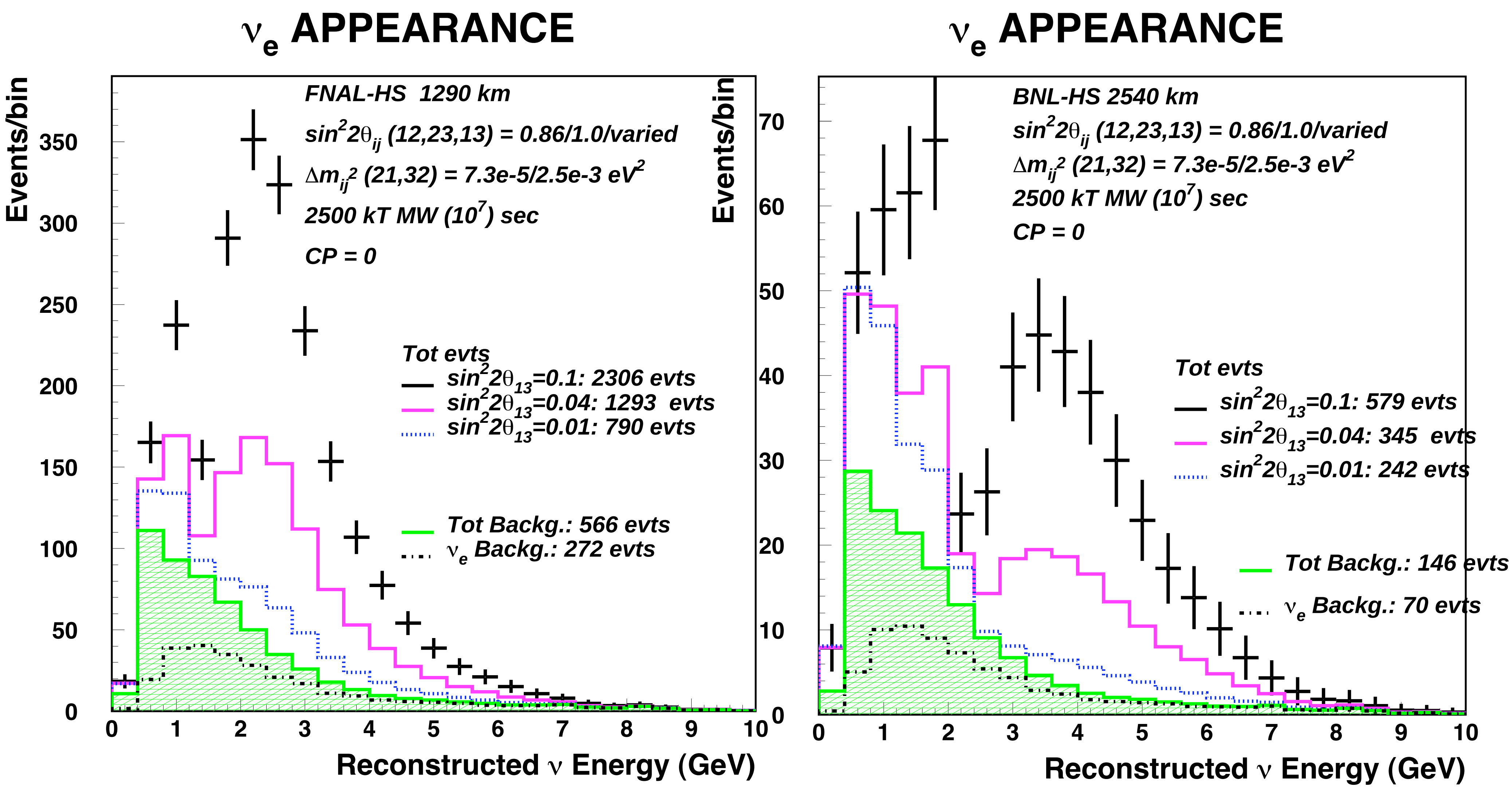
Mark A. Laurenti

March 2002

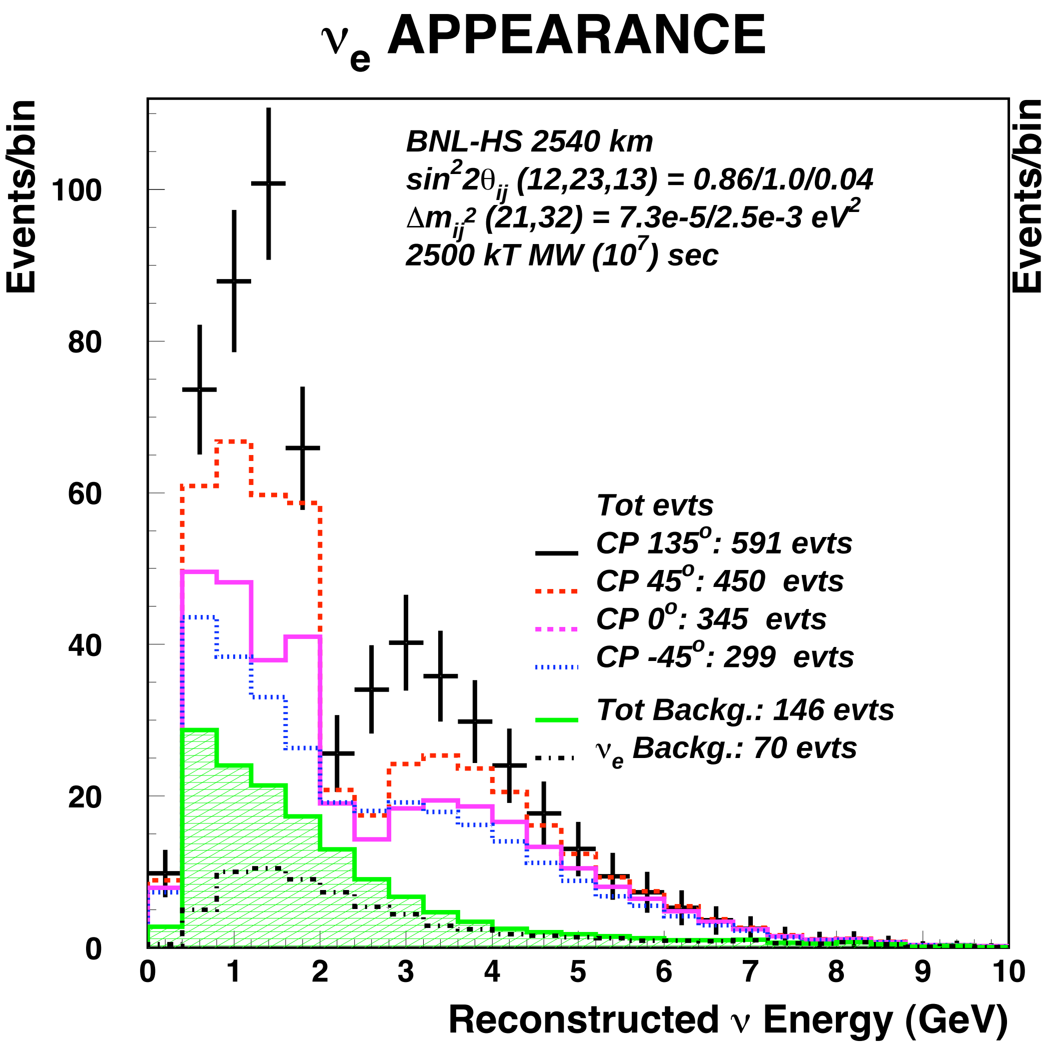
✓ Estimated Timeline

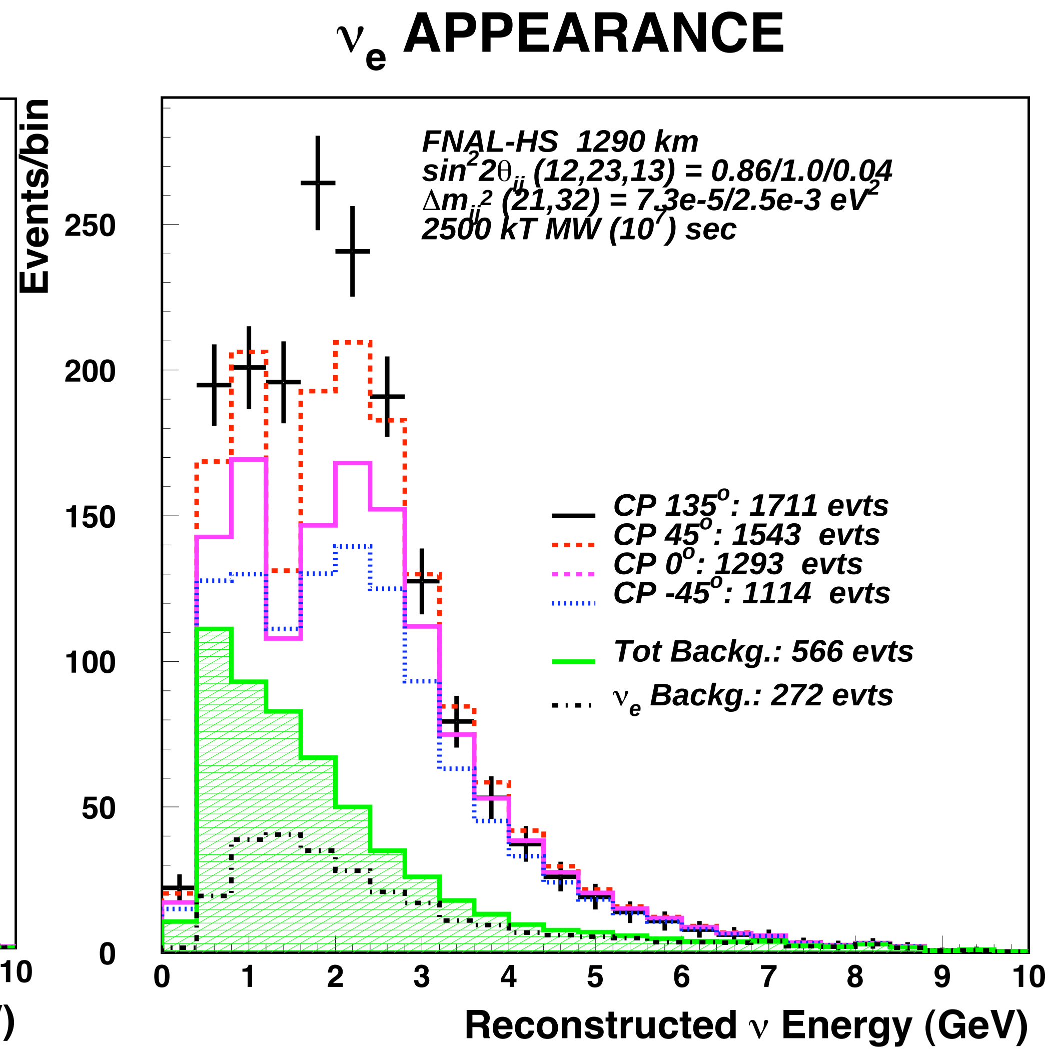
Year Four





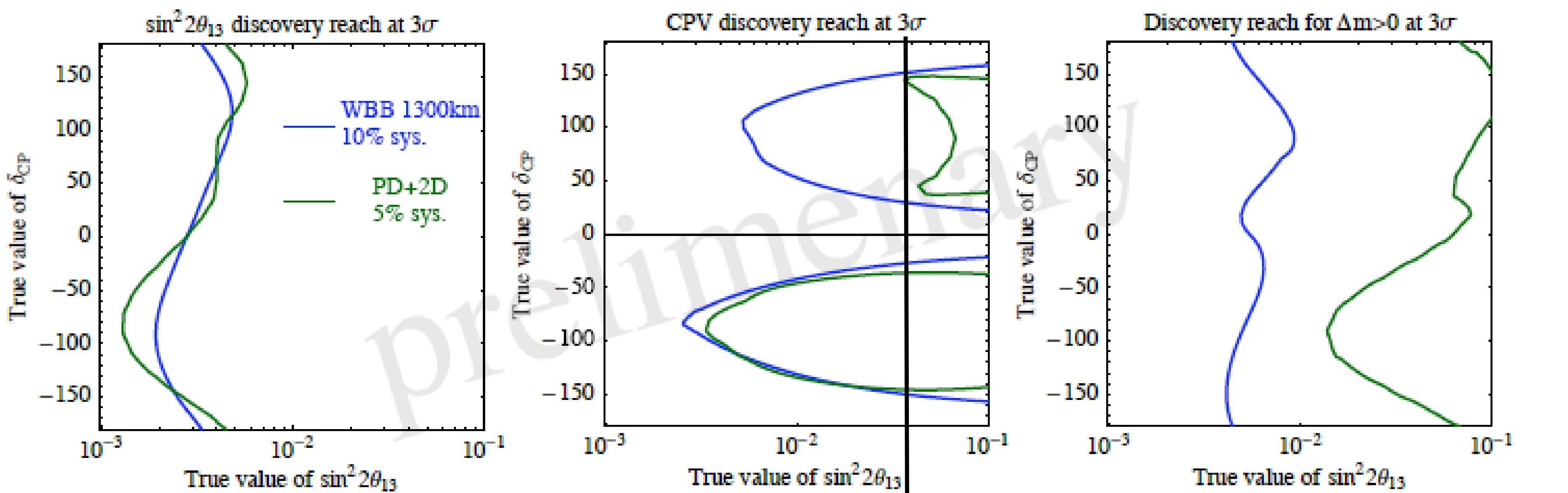
νe APPEARANCE
FNAL-HS 1290 km
sin²2θij (12,23,13) = 0.86/1.0/varied
Δmij² (21,32) = 7.3e-5/2.5e-3 eV²
2500 kT MW (10⁷) sec
CP = 0
Tot evts
sin²2θ13=0.1: 2306 evts
sin²2θ13=0.04: 1293 evts
sin²2θ13=0.01: 790 evts
Tot Backg.: 566 evts
νe Backg.: 272 evts
Events/bin
Reconstructed ν Energy (GeV)
νe APPEARANCE
BNL-HS 2540 km
sin²2θij (12,23,13) = 0.86/1.0/varied
Δmij² (21,32) = 7.3e-5/2.5e-3 eV²
2500 kT MW (10⁷) sec
CP = 0
Tot evts
sin²2θ13=0.1: 579 evts
sin²2θ13=0.04: 345 evts
sin²2θ13=0.01: 242 evts
Tot Backg.: 146 evts
νe Backg.: 70 evts
Events/bin
Reconstructed ν Energy (GeV)





Comparison to 1290 km to 2540 km

Summary



How would that picture look like with

- Liquid Argon
- 2nd peak in the OA spectrum

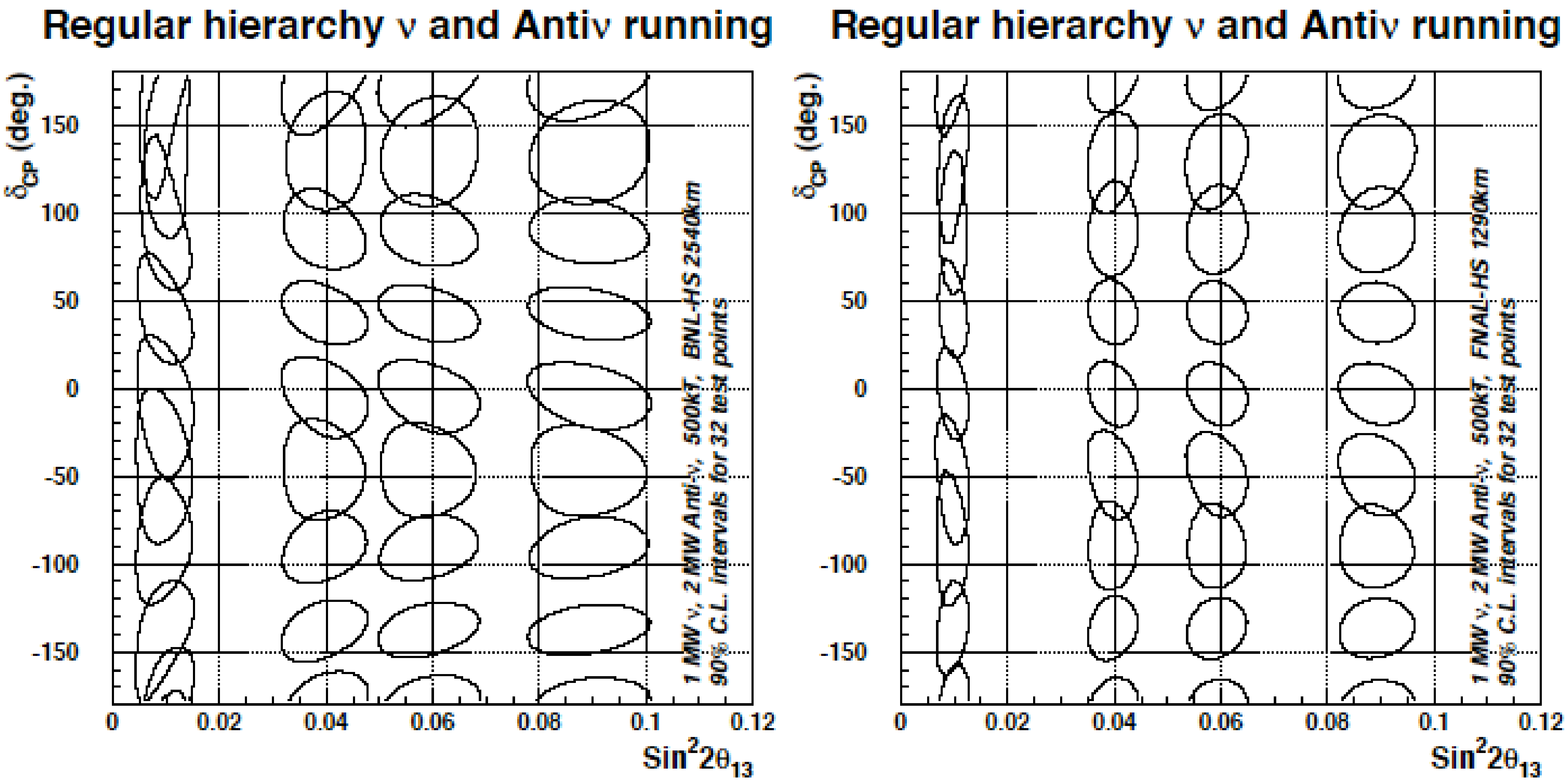


Figure 7: *90% confidence level error contours in* $\sin^2 2\theta_{13}$ *versus* δ_{CP} *for statistical and systematic errors for 32 test points. This simulation is for combining both neutrino and anti-neutrino data. Left is for BNL-HS and right is for FNAL-HS. We assume 10% systematic errors for this plot.*

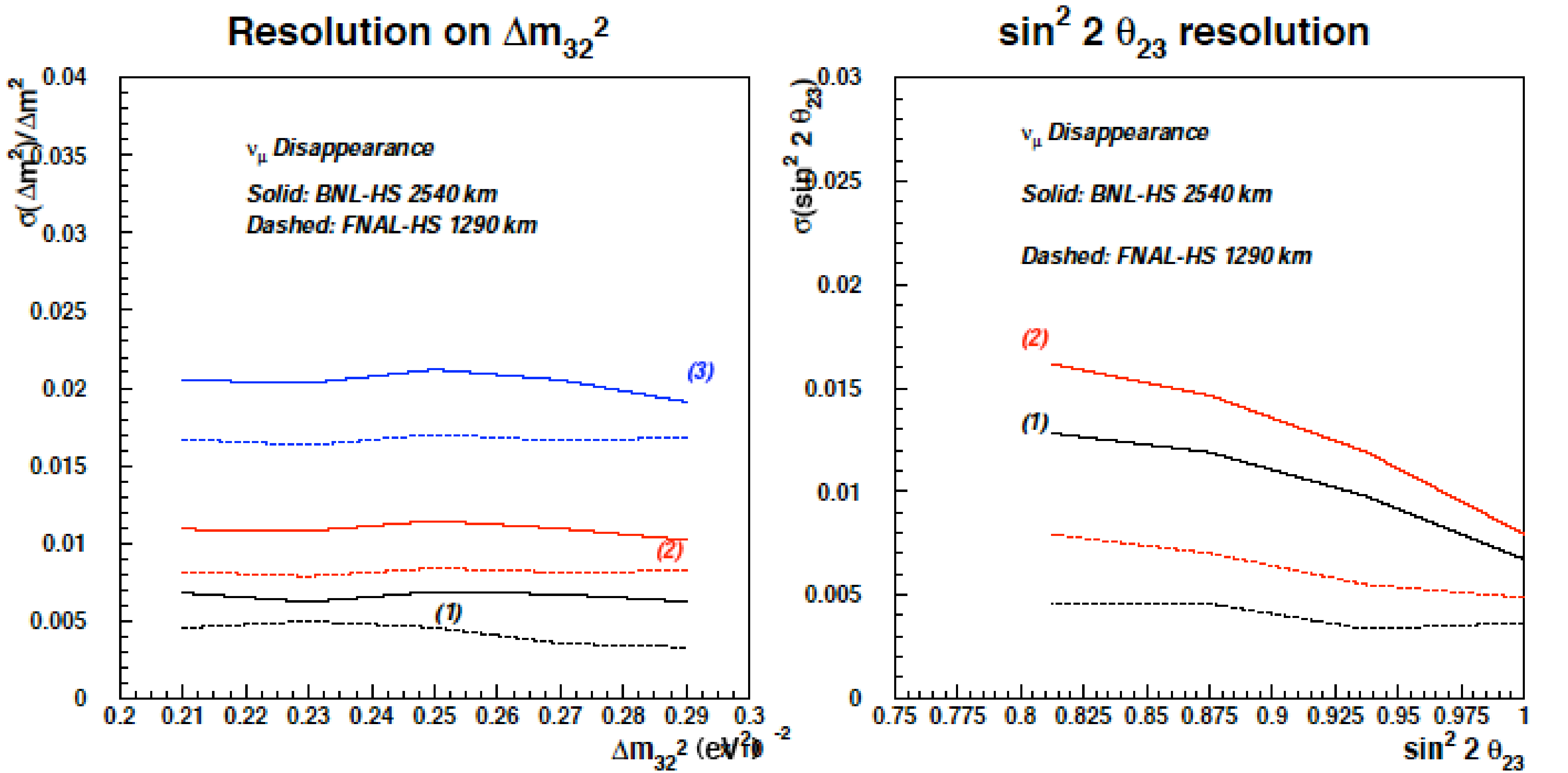


Figure 3: *1 sigma resolutions on* Δm^2_{32} *(left) and* $\sin^2 2\theta_{23}$ *(right) expected after analysis of the oscillation spectra from Figure 2. The solid curves are for BNL-HS 2540 km baseline, and the dashed are for FNAL-HS 1290 km baseline. The curves labeled 1 and 2 correspond to statistics only and statistics and systematics, respectively (similarly for dashed curves of the same color). The curve labeled (3) on the left has an additional contribution of* 1% *systematic error on the global energy scale.*