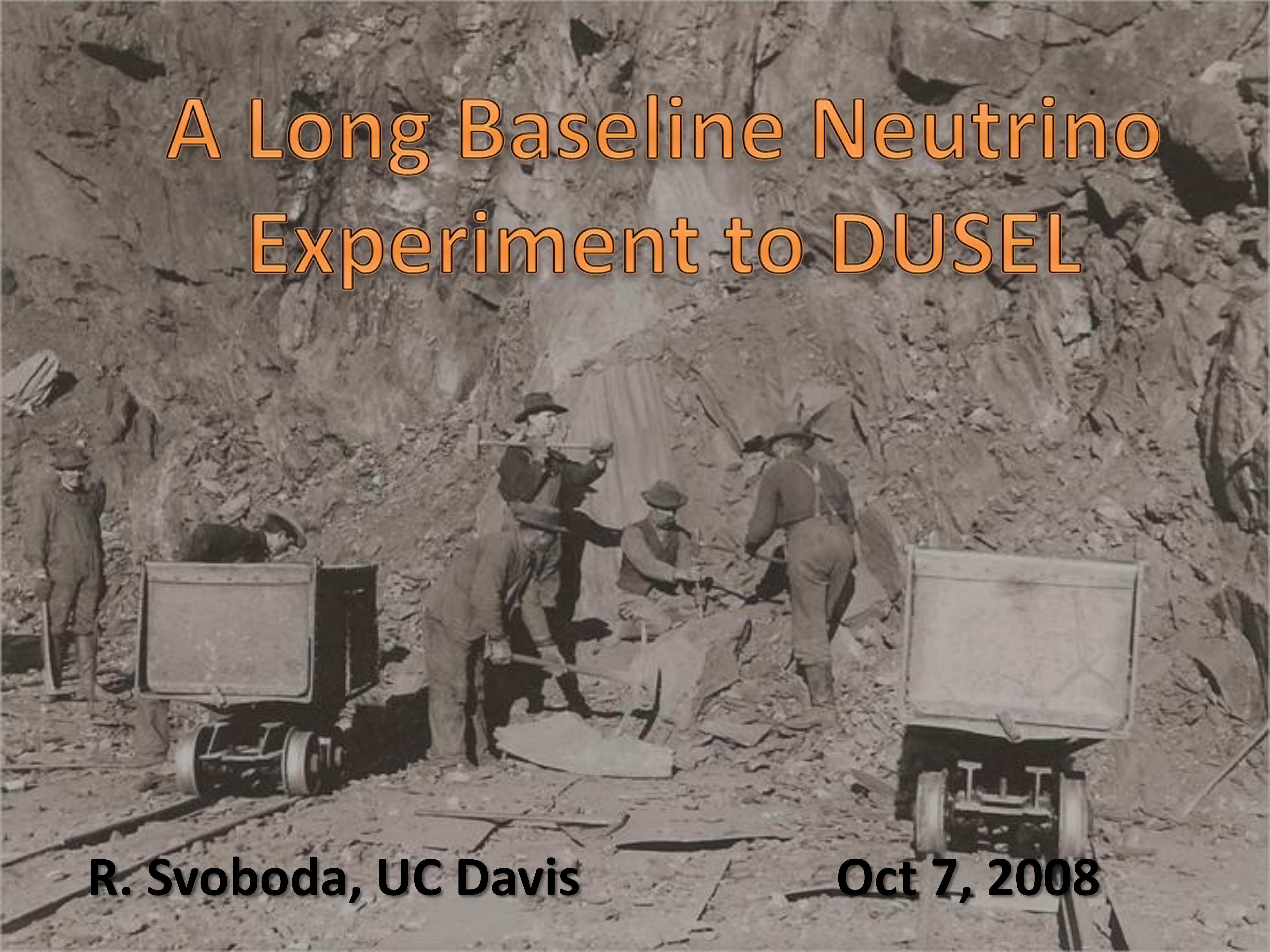
A Long Baseline Neutrino Experiment to DUSEL



R. Svoboda, UC Davis

Oct 7, 2008

Neutrino Mixing

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

– U: 3 angles, $\boxed{\text{1 CP-phase}}$ + (2 Majorana phases)

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric solar

$s_{ij} = \sin\theta_{ij} \quad c_{ij} = \cos\theta_{ij}$

We now have numbers to put in!

$\theta_{12} = 30^o$

$\theta_{23} = 45^o$

$$\Rightarrow \begin{pmatrix} 0.9 & 0.5 & s_{13}e^{i\delta} \\ -0.35-0.6s_{13}e^{i\delta} & 0.6-0.35s_{13}e^{i\delta} & 0.7 \\ 0.35-0.6s_{13}e^{i\delta} & -0.6-0.35s_{13}e^{i\delta} & 0.7 \end{pmatrix}$$

…but δ unknown

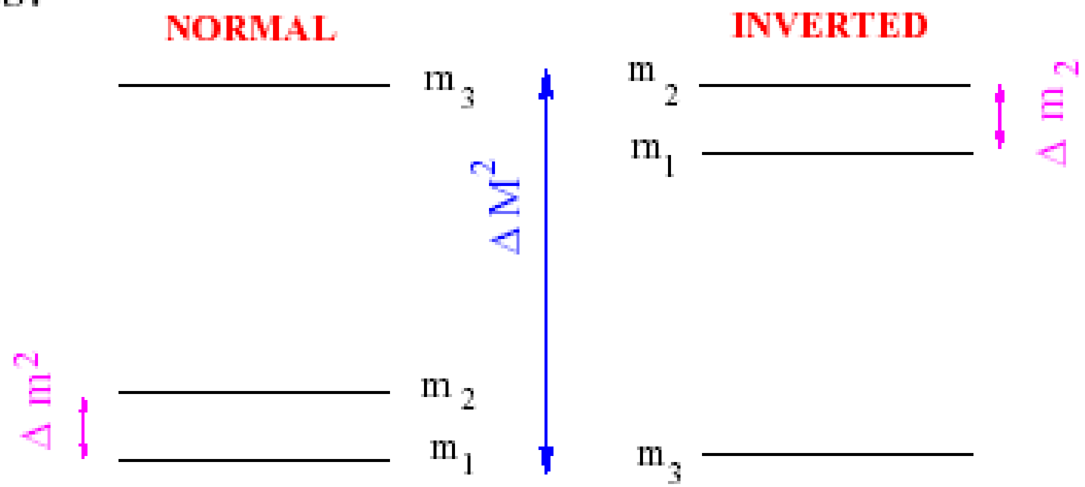
$\theta_{13} < 13^o$

$$\Rightarrow \begin{pmatrix} 0.9 & 0.5 & s_{13}e^{i\delta} \\ -0.35 & 0.6 & 0.7 \\ 0.35 & -0.6 & 0.7 \end{pmatrix}$$

U_{e3} is 100% sensitive to the mixing angle θ_{13} ⇦

but we don’t know the mass ordering

- Two schemes:



Do ν’s violate CP? Is θ_{13} non-zero?

Can use an accelerator ν_μ beam,
But there are complications…

ν_e appearance in a ν_μ beam

$P(\nu_\mu \rightarrow \nu_e) = (2c_{13}s_{13}s_{23})^2 \sin^2\Phi_{31}$

$+8c_{13}^2s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$

↙ CP violating

$-8c_{13}^2c_{12}^2c_{23}s_{12}s_{13}s_{23}\sin\delta\,\sin\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$

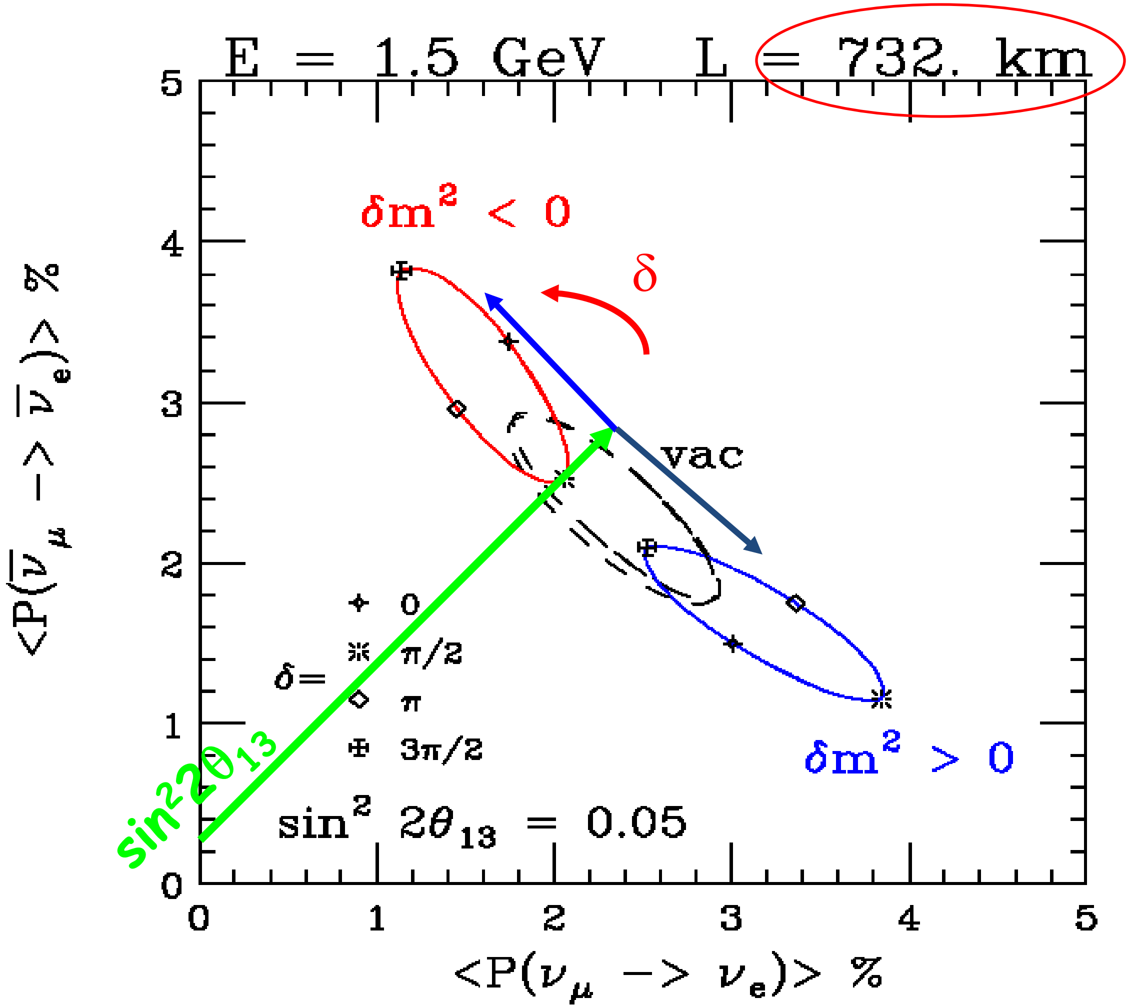
$+4s_{12}^2c_{13}(c_{12}^2c_{23}^2+s_{12}^2s_{23}^2s_{13}^2-2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta)\sin^2\Phi_{21}$

$-8c_{13}^2s_{13}^2s_{23}^2(1-2s_{13}^2)(aL/4E)\cos\Phi_{32}\sin\Phi_{31}$

a = constant X n_eE

CP: $a \rightarrow -a$, $\delta \rightarrow -\delta$

There are *Degeneracy Issues*



Minakata and Nunokawa, hep-ph/0108085

2 Observables:

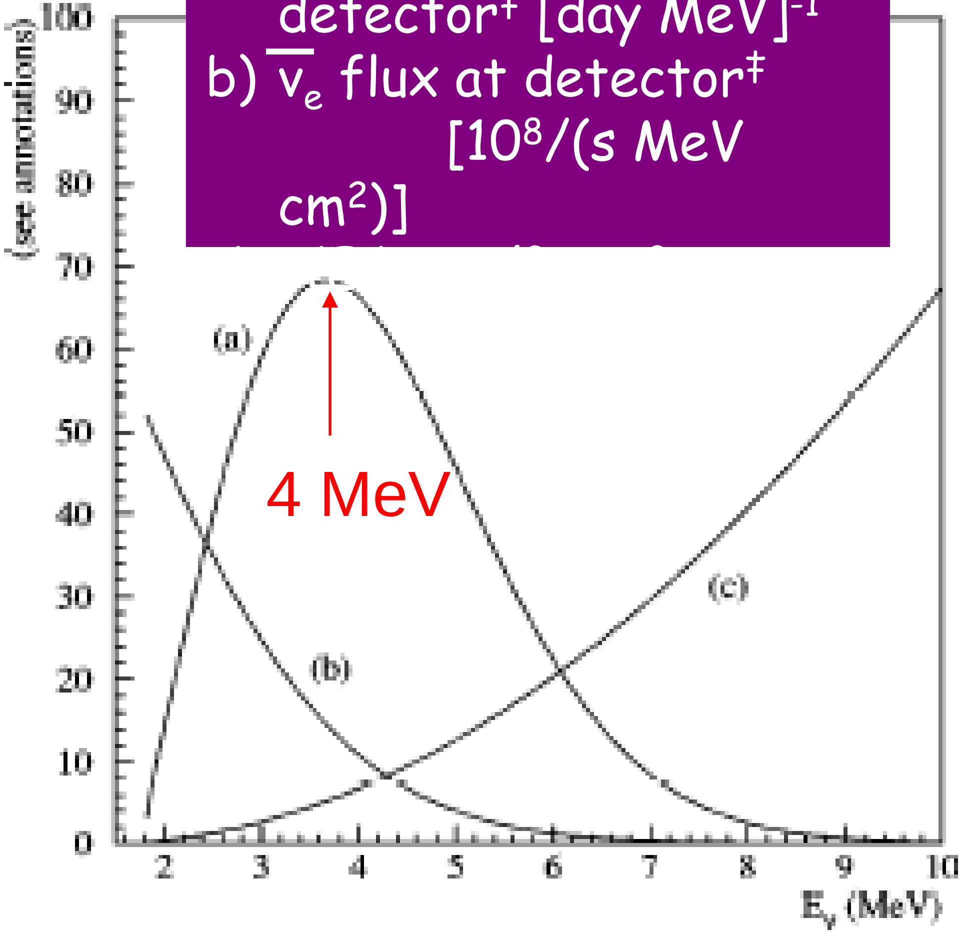
- $P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$
- $P(\nu_\mu \rightarrow \nu_e)$

Reactor Experiments

- reactors are an intense "free" source of ν_e
- low energy means distance need only be one or two km
- free of CP and matter effect uncertainties

a) $\overline{\nu}_e$ interactions in detector‡ [day MeV]$^{-1}$

b) $\overline{\nu}_e$ flux at detector‡ [10^8/(s MeV cm^2)]



‡ from Palo Verde

Oscillation Probability (with both Δm^2)

$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1$

$- \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2(\Delta m^2_{12} L/4E)$

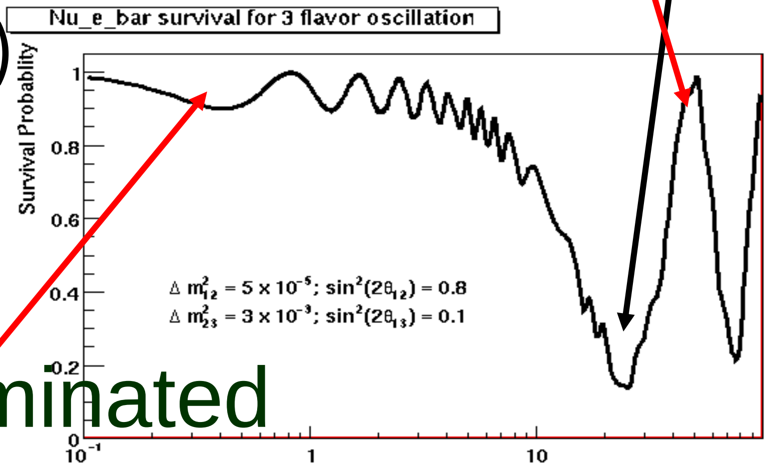
$- \sin^2 2\theta_{13} \sin^2(\Delta m^2_{atm} L/4E)$

(Ignores tiny matter effect)

$L = pE/(2.54\ \Delta m^2)$

~ 1-2 km

Δm^2_{12} dominated



P

Δm^2_{23} dominated

L/E(km/MeV)

The Double Chooz Experiment

Univ. of Alabama, ANL,
Univ. of Chicago, Columbia,
U.C. Davis, Drexel Univ.,
Kansas State, Illinois Inst. Tech.,
LLNL, Notre Dame, SNL,
Univ. of Tennessee

CBPF, UNICAMP

Hiroshima Inst. Tech.,
Kobe Univ., Miyagi Univ.,
Niigata Univ., Tohoku Univ.,
Tohoku Gakuin Univ.,
Tokyo Metro. Univ.,
Tokyo Inst. Tech.

APC Univ. of Paris,
SUBATECH (Nantes)
DAPNIA CEA/Saclay

Aachen Univ., Hamburg Univ.,
MPIK Heidelberg, T.U. Munchen,
E.K. Univ. Tubingen,

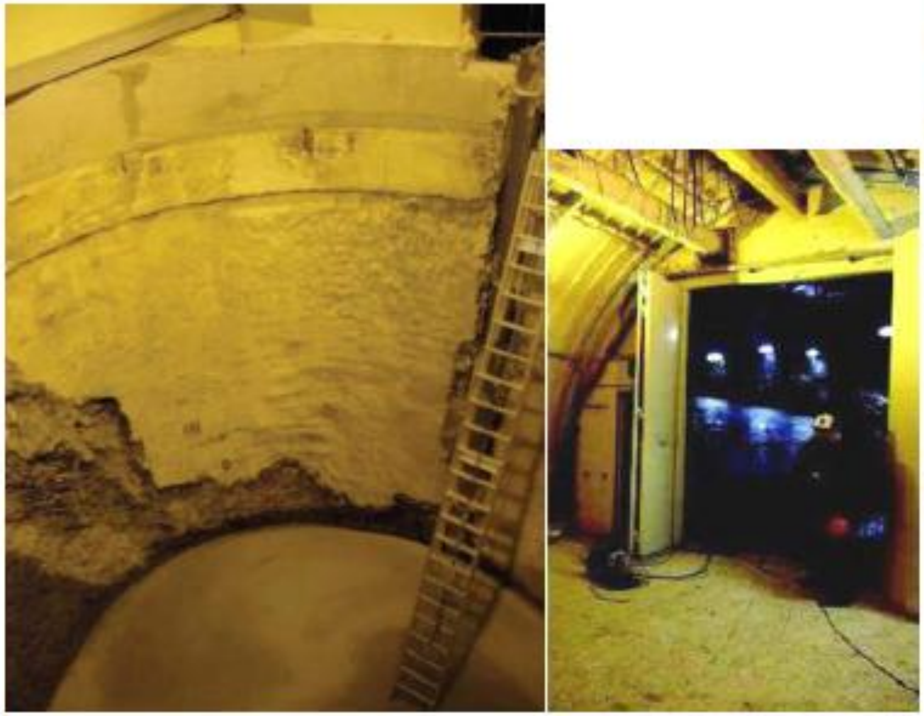
INR-RAS, IPC-RAS,
RRC Kurchatov

CIEMAT Madrid

Univ of Sussex

The experimental site

Far detector site status



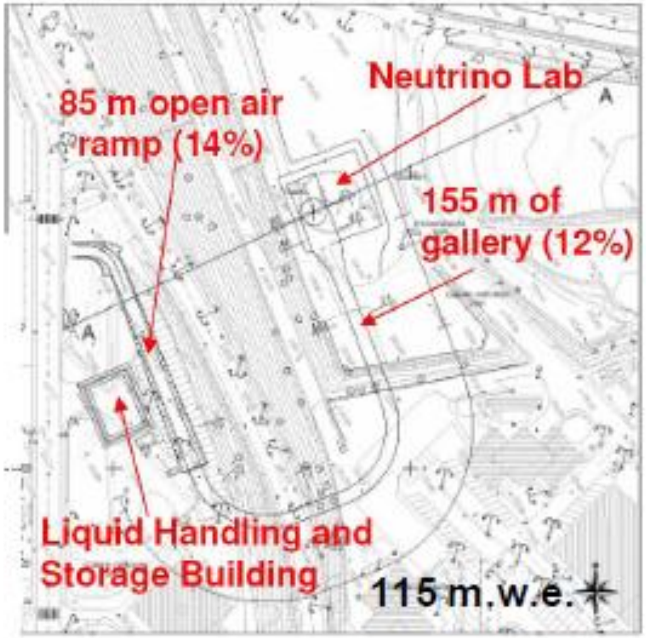
Civil engineering work has been finished (detector pit refurbished, doors enlarged, new ventilation system, safety system).

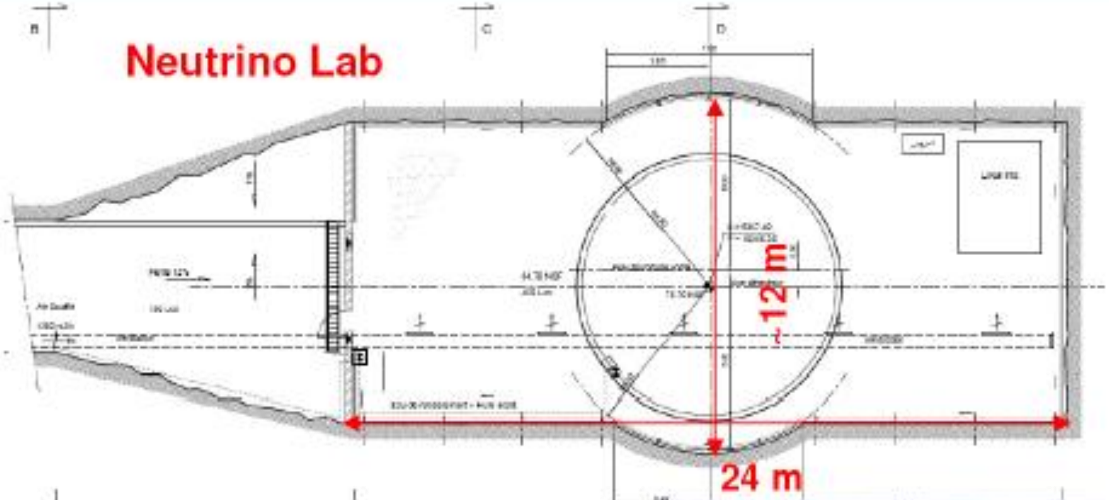
Installation in the Liquid Handling Building has started (6 large storage tanks from TUM)

09092008

Shielding steel bars have been mounted in the pit.

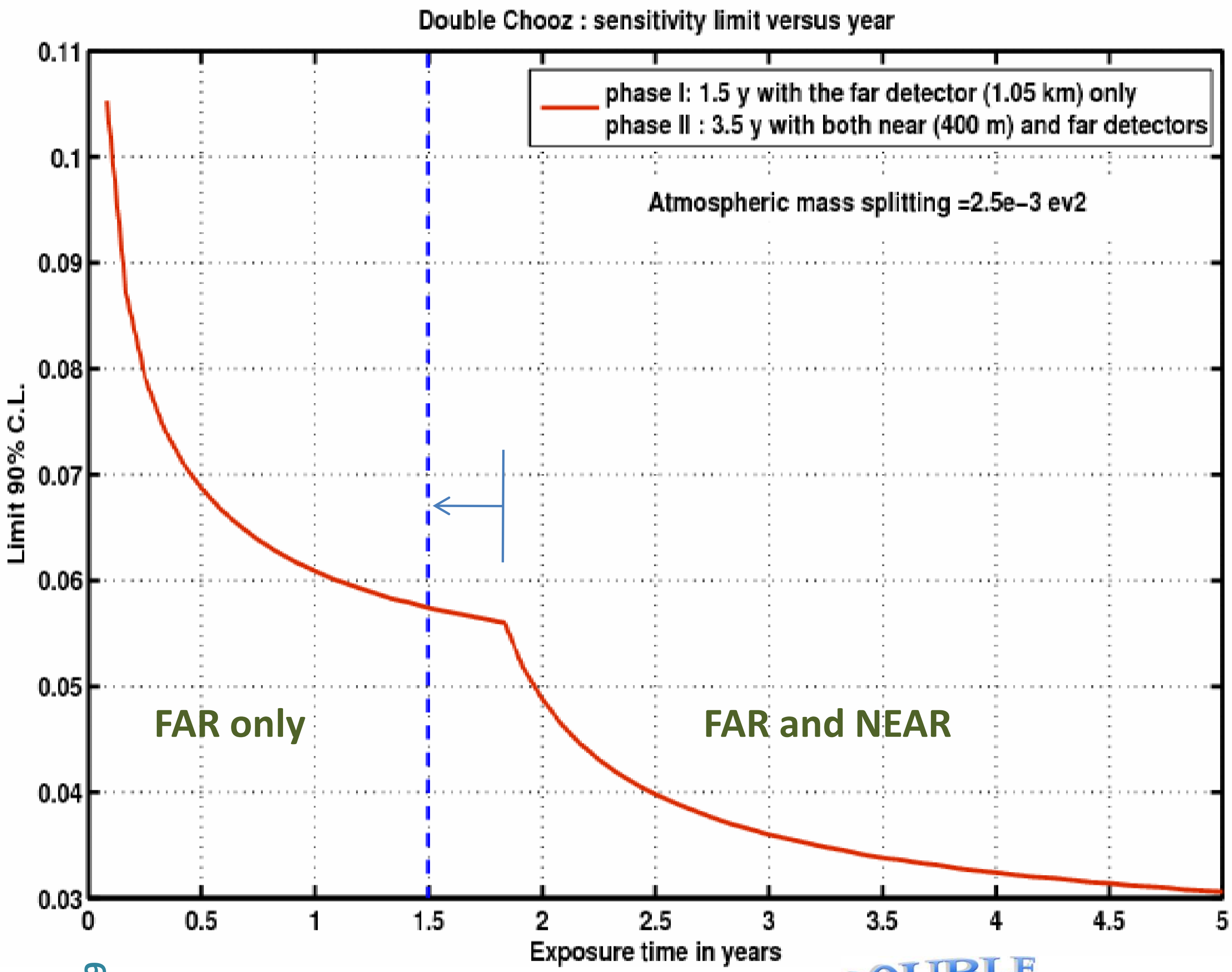
Near detector lab





Site has been chosen with >45m overburden, almost flat topology.

Geological site study completed.
Tender process for construction.
Schedule: lab available end of 2009.



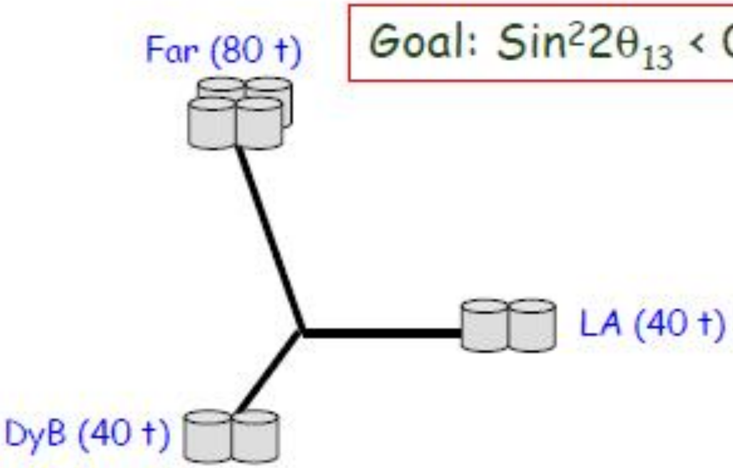
June, 2009

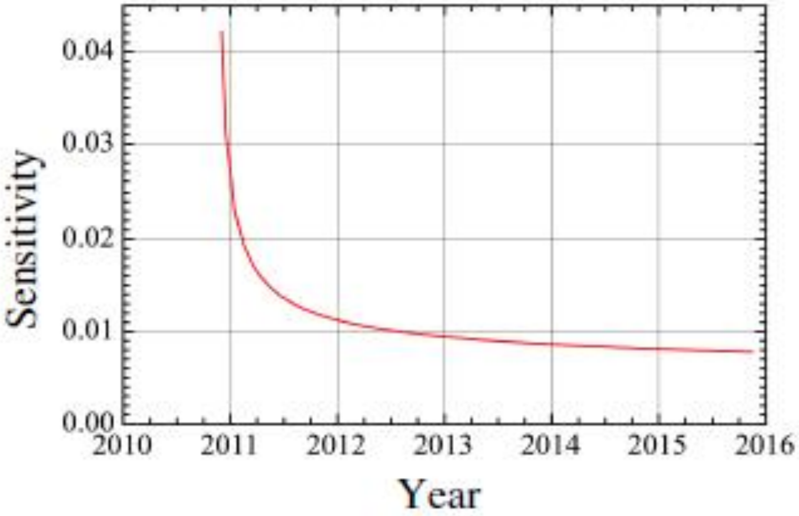
Dec, 2010

Sensitivity of Daya Bay

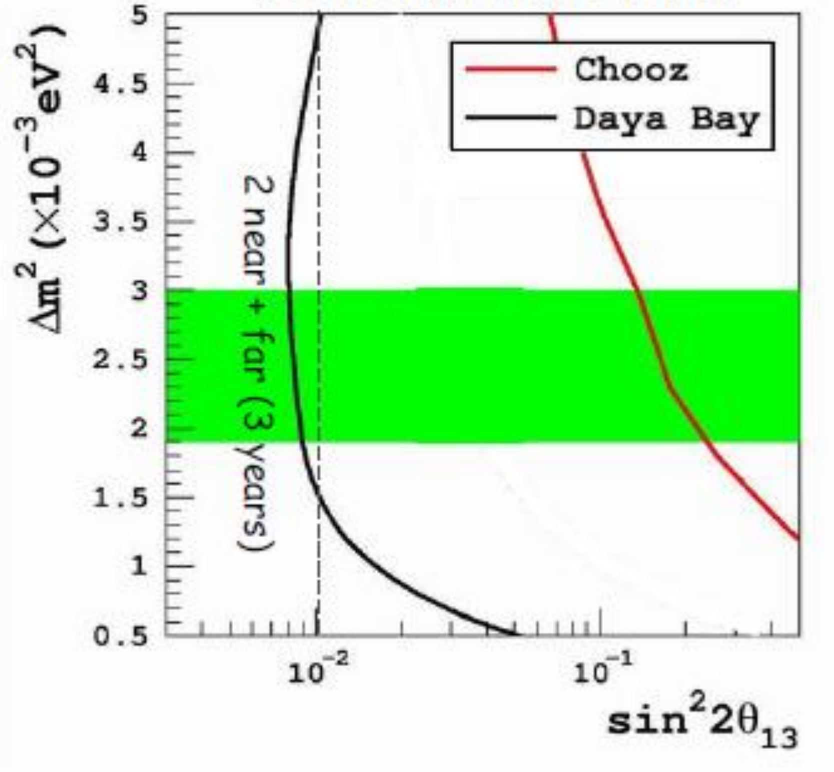
Goal: $\sin^2 2\theta_{13} < 0.01$

- Use rate and spectral shape
- input relative detector syst. error of 0.38%/detector

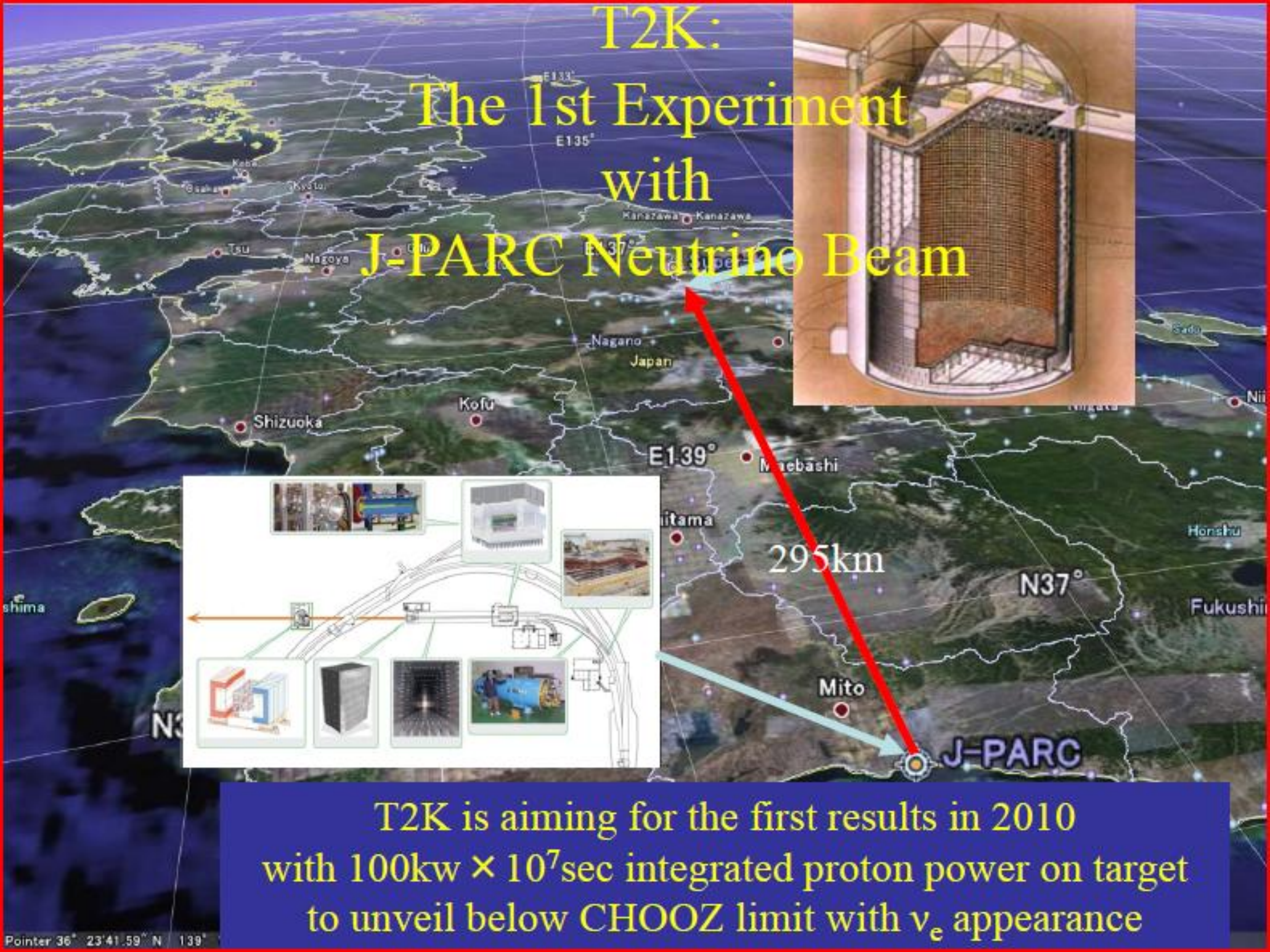




90% confidence level

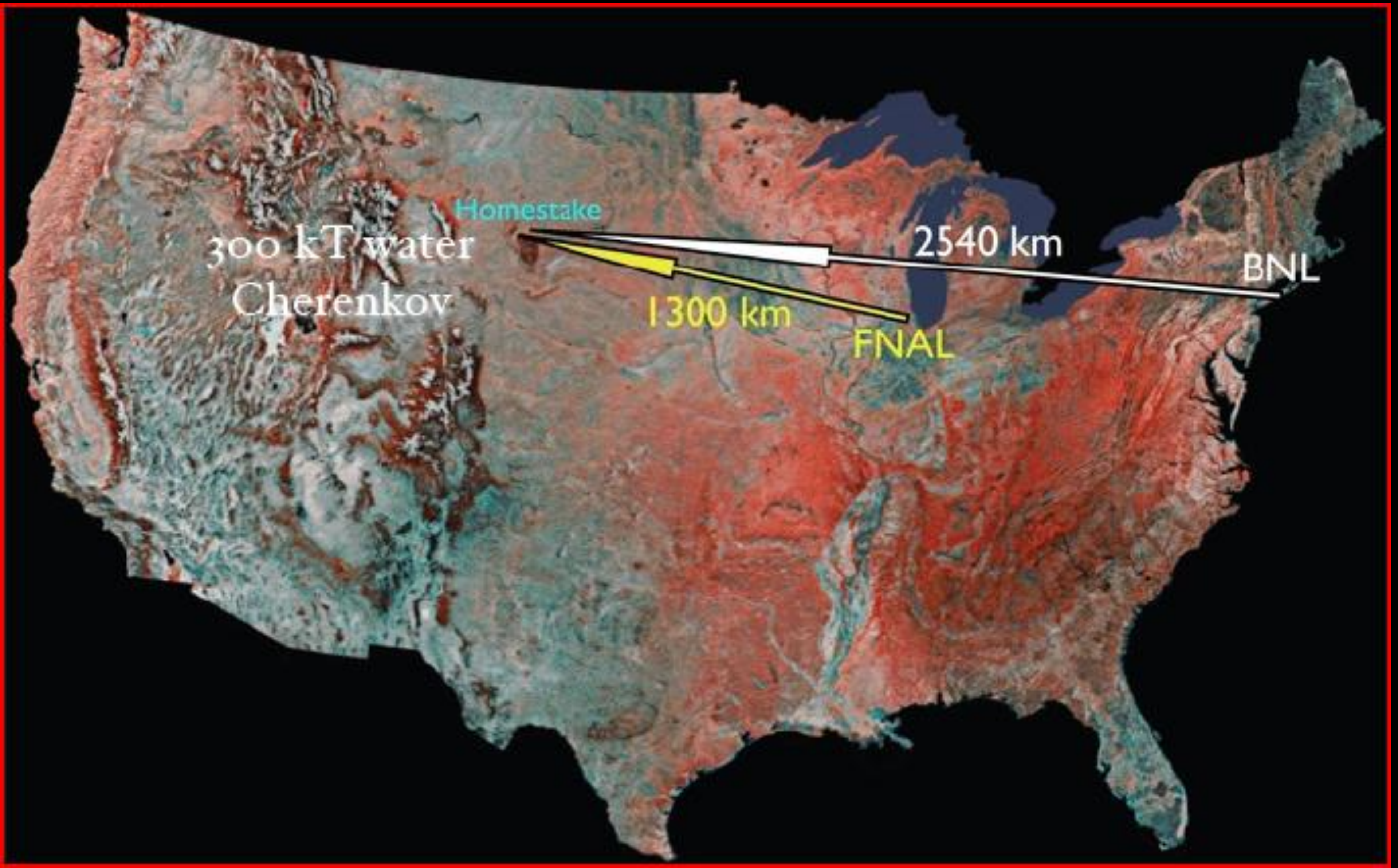


T2K:
The 1st Experiment with J-PARC Neutrino Beam



T2K is aiming for the first results in 2010
with 100kw × 10^7sec integrated proton power on target
to unveil below CHOOZ limit with ν_e appearance

DUSEL LONG BASELINE EXPERIMENT

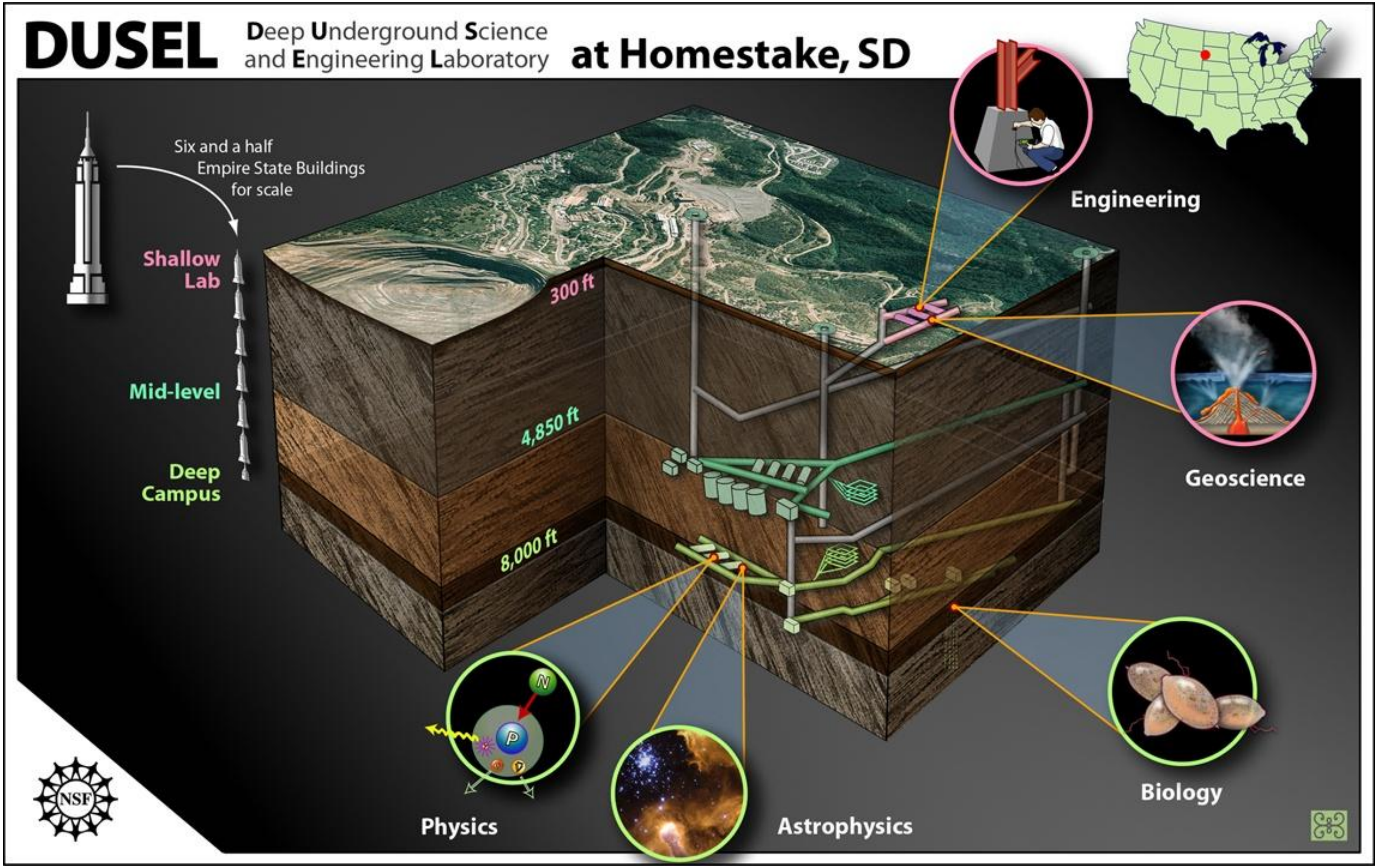


DUSEL Experiment Development and Coordination (DEDC)

Internal Design Review

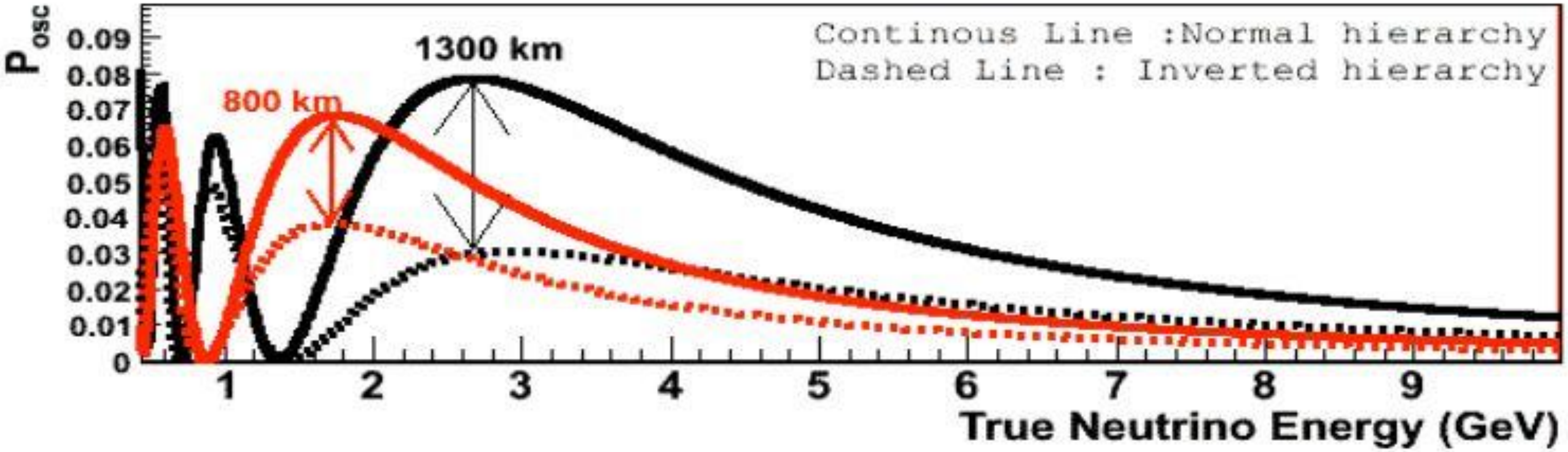
July 16-18, 2008

Steve Elliott, Derek Elsworth, Daniela Leitner, Larry Murdoch, Tullis C. Onstott and Hank Sobel

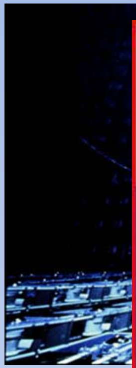


Why DUSEL?

- 1300 km distance is significant for determination of neutrino mass hierarchy
- Deep underground site allows rich physics program in addition to LB neutrinos



Water Cerenkov



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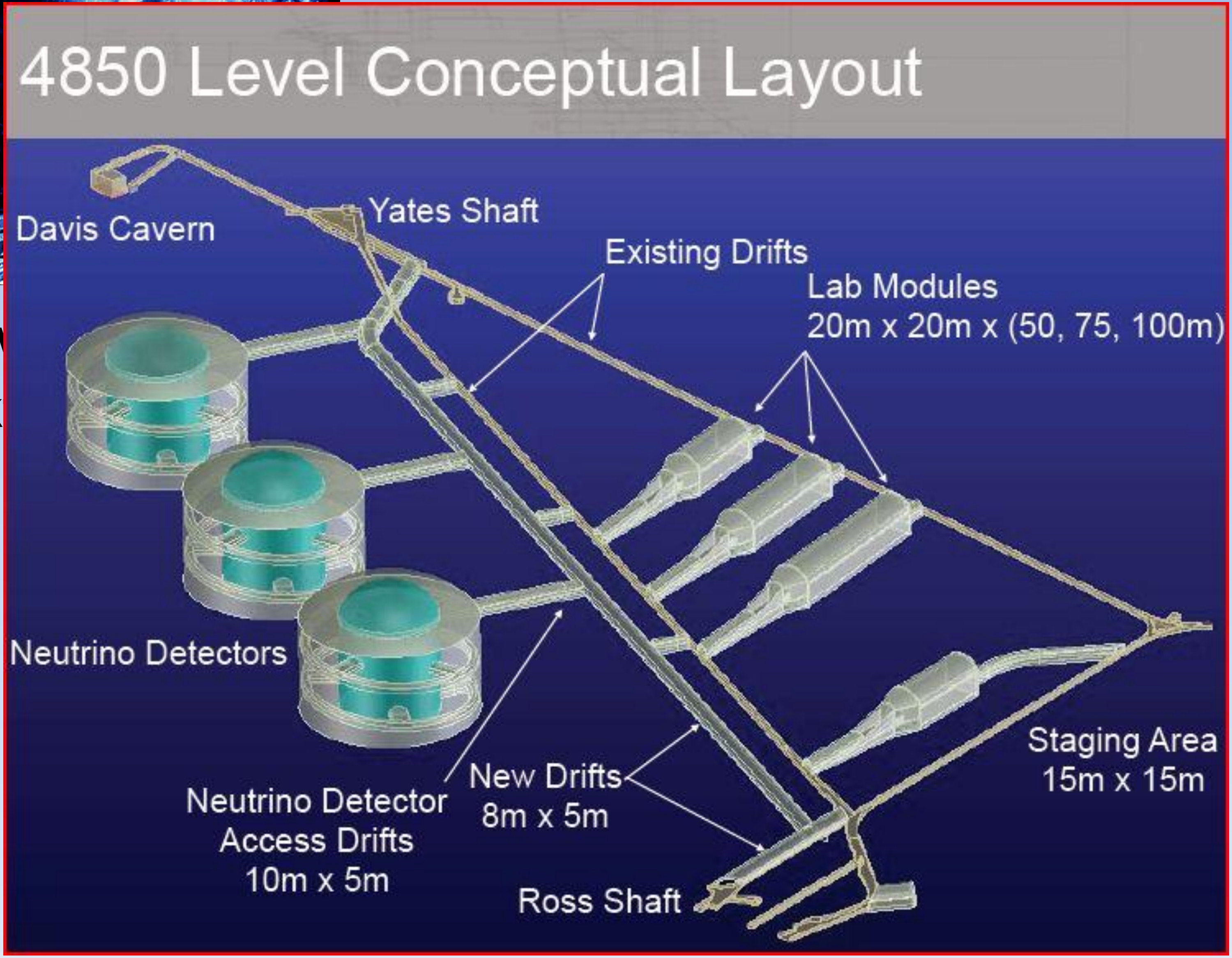
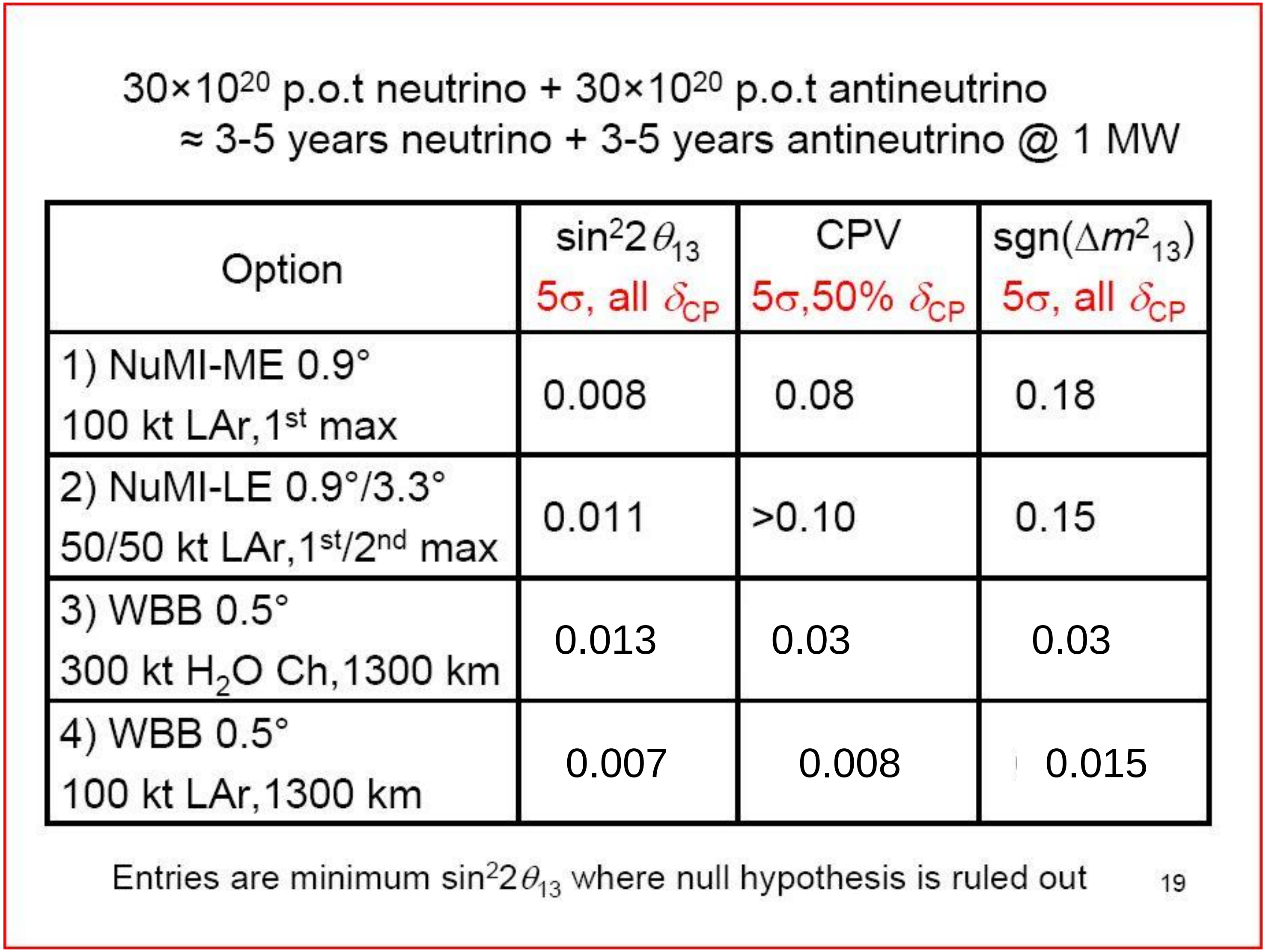


NuSAG Report



30×10^{20} p.o.t neutrino + 30×10^{20} p.o.t antineutrino
≈ 3-5 years neutrino + 3-5 years antineutrino @ 1 MW

Option	$\sin^2 2\theta_{13}$ 5σ, all δ_{CP}	CPV 5σ,50% δ_{CP}	$\mathrm{sgn}(\Delta m^2_{13})$ 5σ, all δ_{CP}
1) NuMI-ME 0.9° 100 kt LAr, 1st max	0.008	0.08	0.18
2) NuMI-LE 0.9°/3.3° 50/50 kt LAr, 1st/2nd max	0.011	>0.10	0.15
3) WBB 0.5° 300 kt H_2O Ch, 1300 km	0.013	0.03	0.03
4) WBB 0.5° 100 kt LAr, 1300 km	0.007	0.008	0.015

Entries are minimum $\sin^2 2\theta_{13}$ where null hypothesis is ruled out

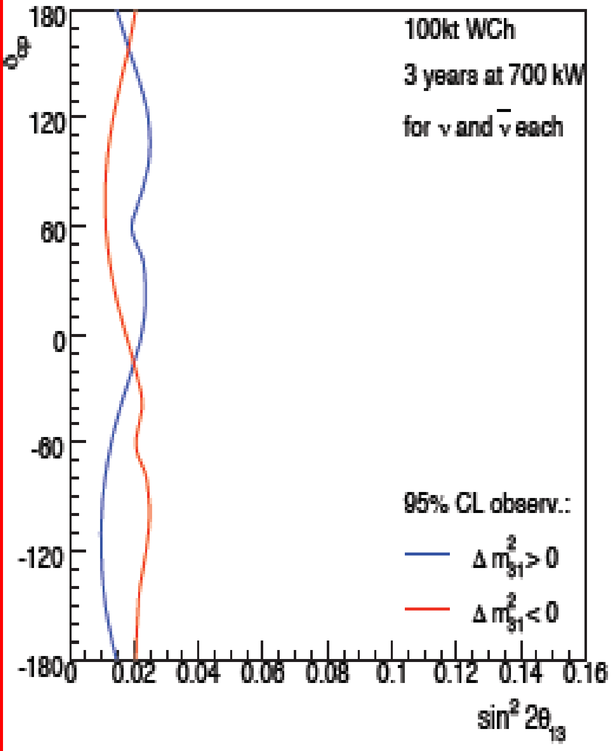
1kt LAr ≈ 3kt H_2O

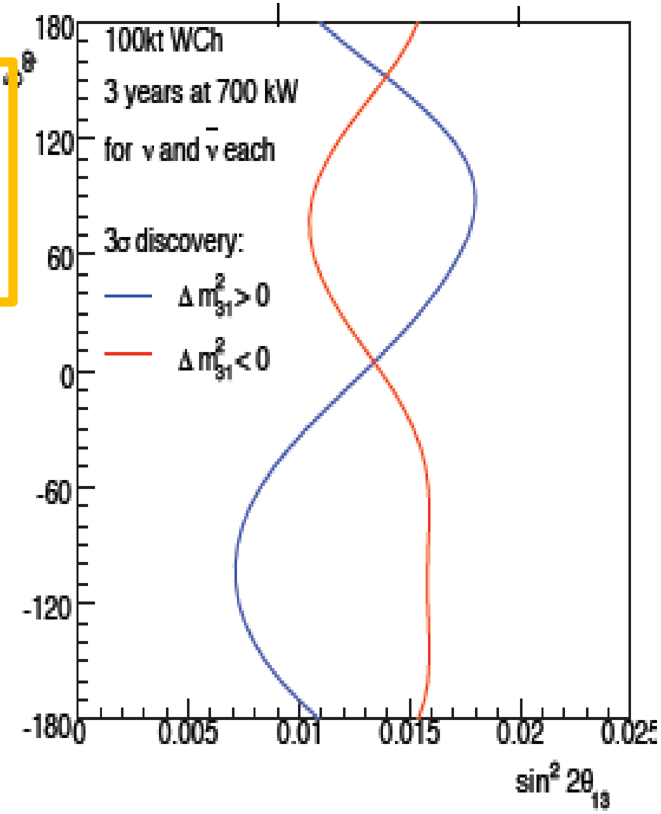
Θ_{13}

$18\text{x}10^{20}$ POT each

A 100 kton Water Detector

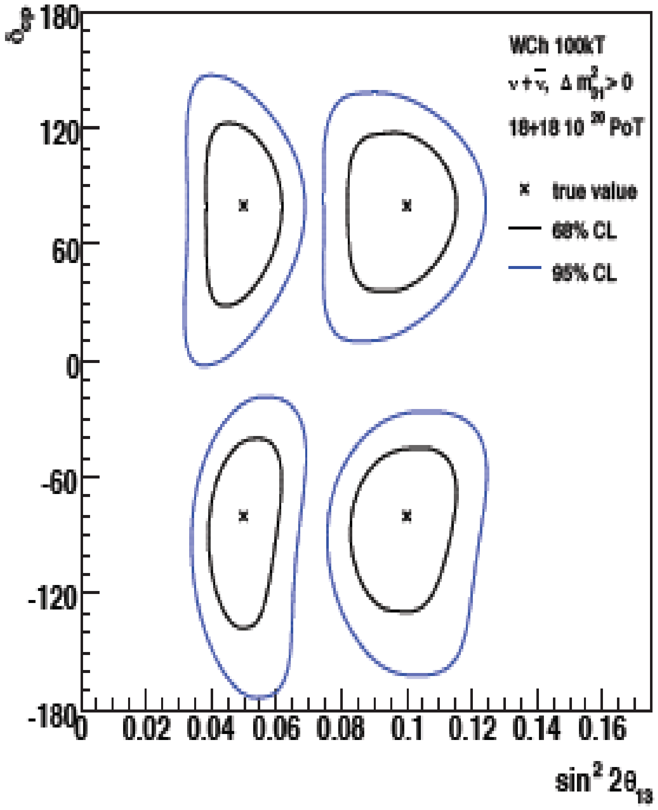
Mass Hierarchy



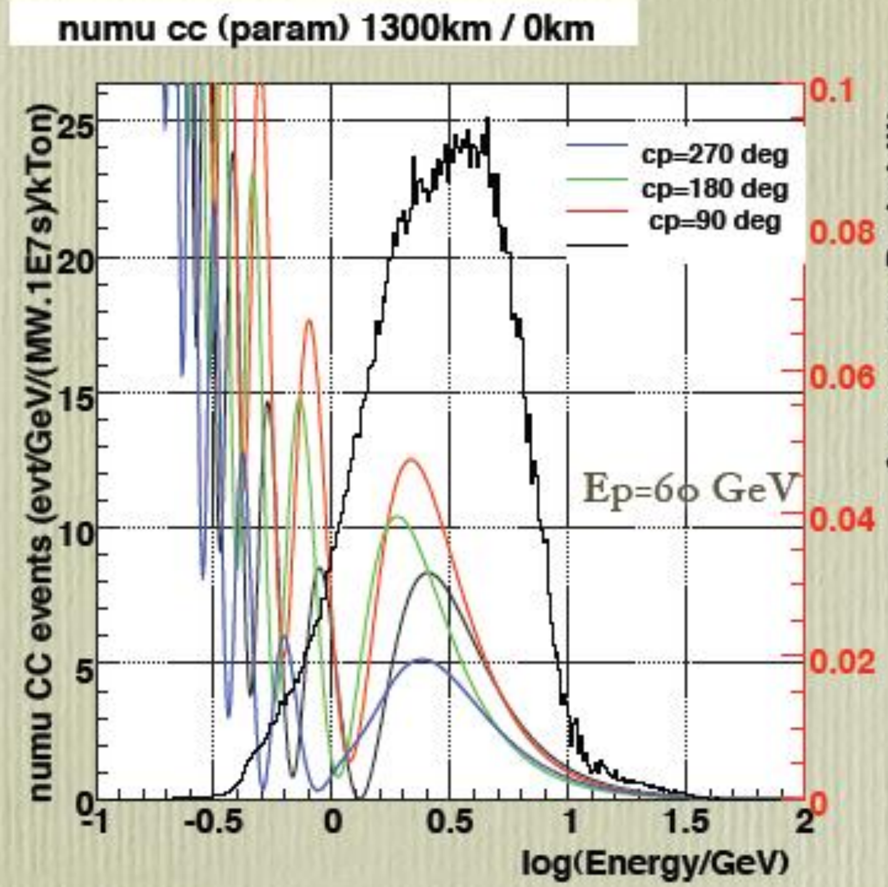


from Mark Dierckxsens
Milind Diwan
Mary Bishal

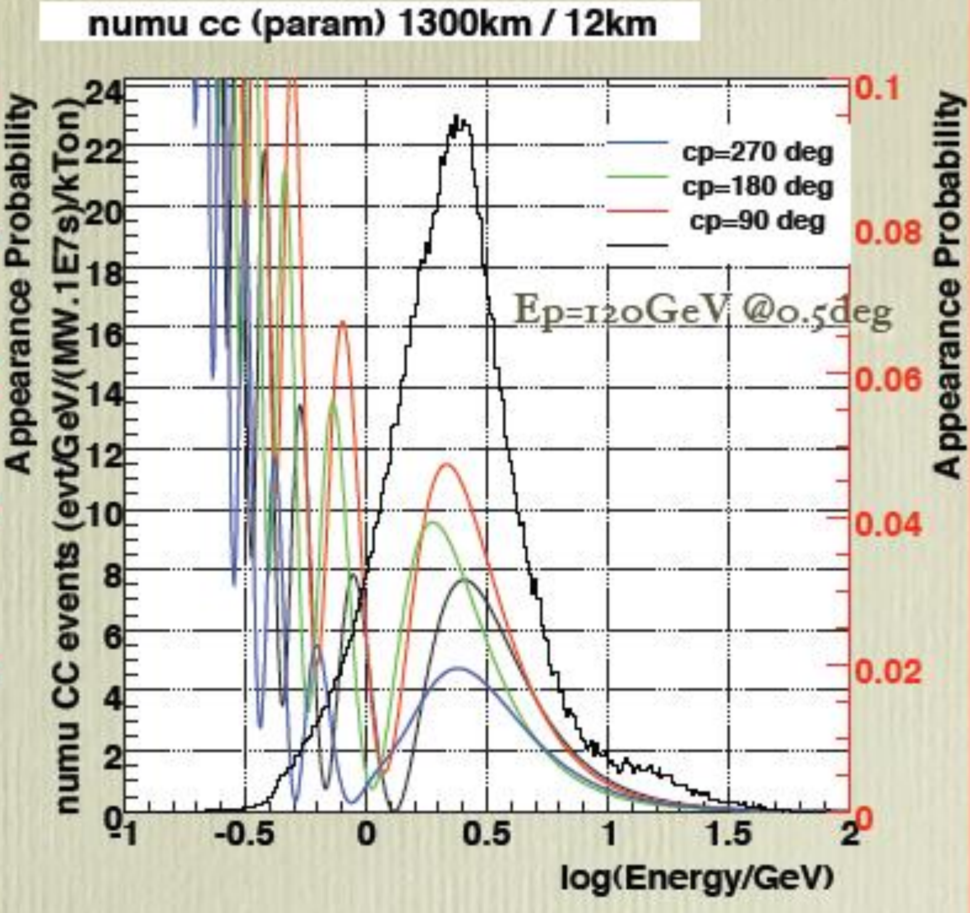
Determination of CP Phase



Spectra FNAL to DUSEL (WBLE:wide band low energy)


numu cc (param) 1300km / 0km

Ep=60 GeV


numu cc (param) 1300km / 12km

Ep=120GeV @0.5deg

- 60 GeV at 0deg: CCrate: 14 per (kT*10^20 POT)
- 120 GeV at 0.5deg:CCrate: 17 per(kT*10^20POT)

Work of M. Bishai and B. Viren using NuMI simulation tools

Office of Science
U.S. DEPARTMENT OF ENERGY

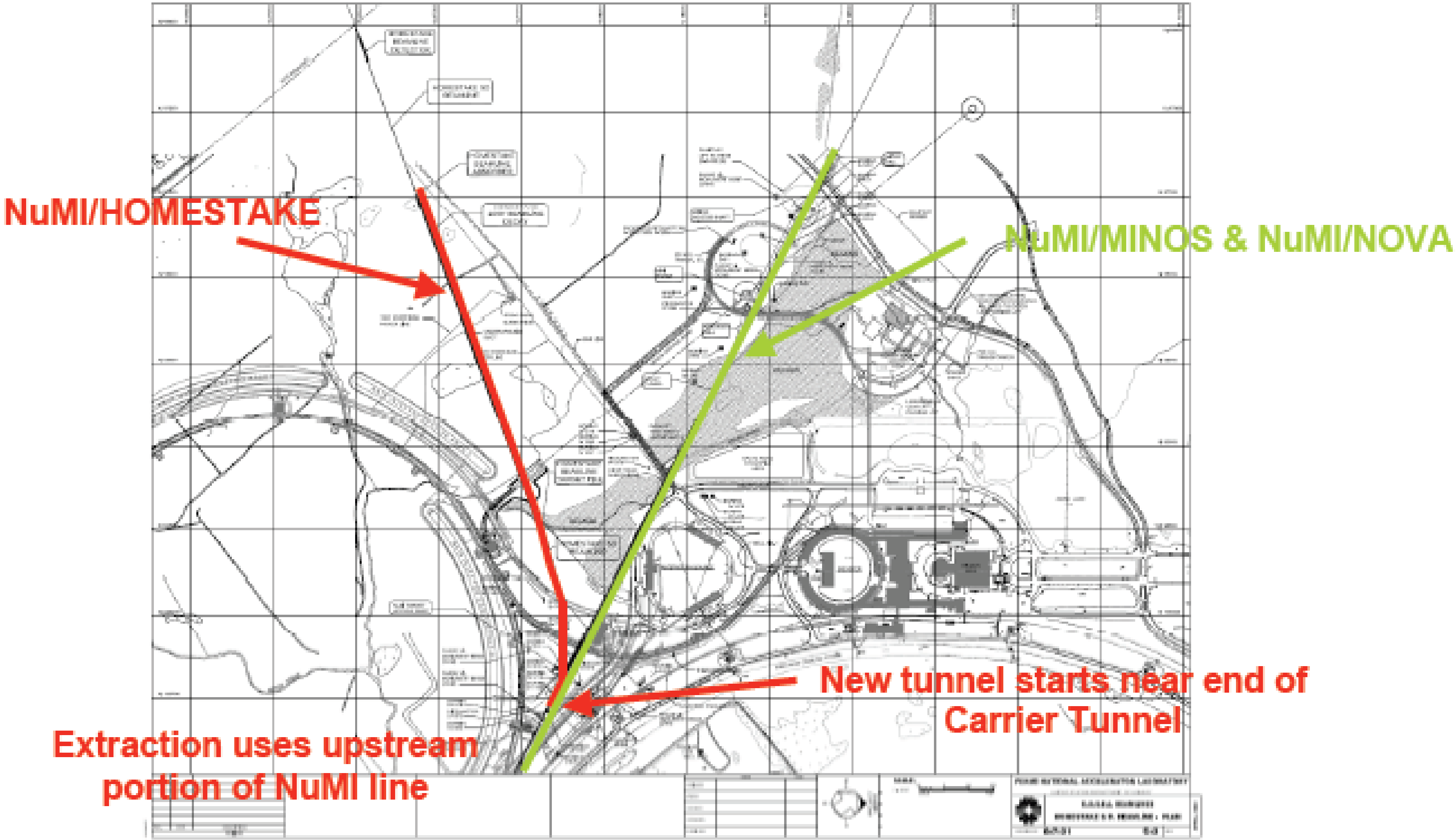
BROOKHAVEN
NATIONAL LABORATORY

Neutrino Beam Requirements*

- The maximal possible neutrino fluxes to encompass at least the 1st and 2nd oscillation nodes, which occur at 2.4 and 0.8 GeV respectively
- Since neutrino cross-sections scale with energy, larger fluxes at lower energies are desirable to achieve the physics sensitivities using effects at the 2nd oscillation node
- To detect $\nu_\mu \rightarrow \nu_e$ at the far detector, it is critical to minimize the neutral-current contamination at lower energy, therefore minimizing the flux of neutrinos with energies greater than 5 GeV where there is little sensitivity to the oscillation parameters is highly desirable
- The irreducible background to $\nu_\mu \rightarrow \nu_e$ appearance signal comes from beam generated ν_e events, therefore, a high purity ν_μ beam with as low as possible ν_e contamination is required

**From "Simulation of a Wide-Band Low-Energy Neutrino Beam for Very Long Baseline Neutrino Oscillation Experiments", Bishai, Heim, Lewis, Marino, Viren, Yumiceva*

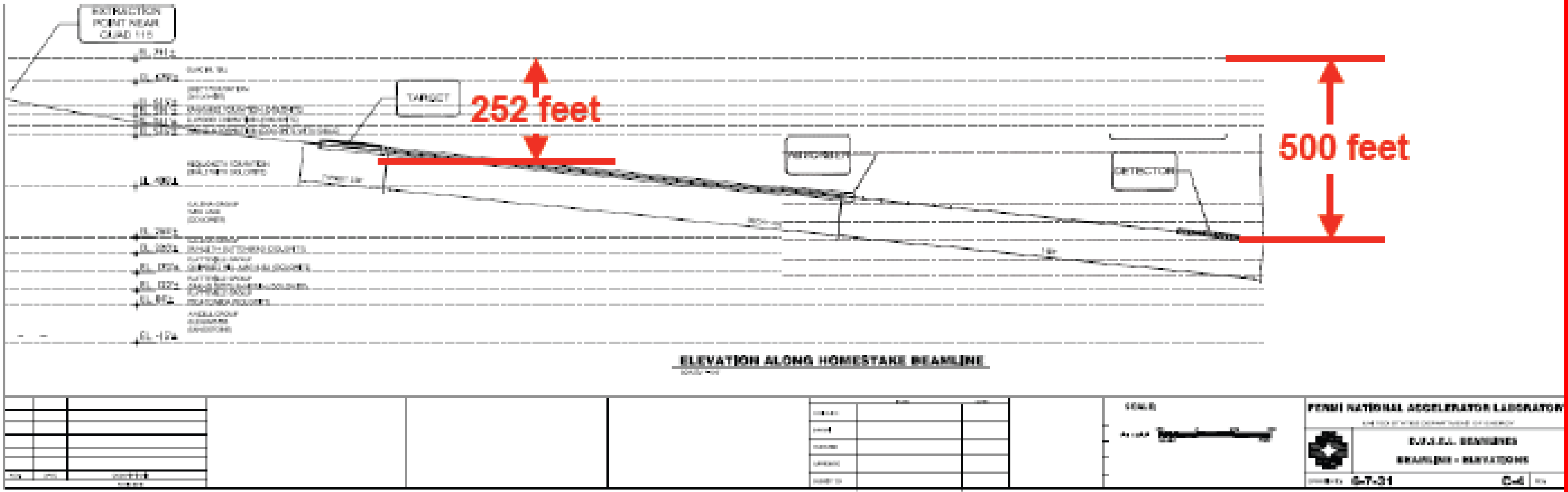
Location of the Homestake Beamline



Homestake/DUSEL Neutrino Beam

Second Elevation View of the Homestake Beamline

Project X Workshop
Neutrinos
17 November 2007
Dixon Bogert



This elevation view of the Homestake Beamline (-5.84°) is drawn with the decay pipe limited to 400m. This shortens the beamline by 741 feet, and lifts The detector hall (and shaft) by about 75 feet (500 feet deep). Overall, this configuration will be cheaper to build and is probably adequate.

NuMI-Homestake Event Rates

$\Delta m^2_{21,31} = 8.6 \times 10^{-5}, 2.5 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{12,23} = 0.86, 1.0$

Unoscillated ν_μ rates at 1300km:

120 GeV on-axis: 20,000 CC/MW.100kT.10^7, 9mrad off-axis: 9,000 CC/MW.100 kT.10^7s

60 GeV on-axis: 15,000 CC/MW.100kT.10^7s

Oscillated rates at 1300km:

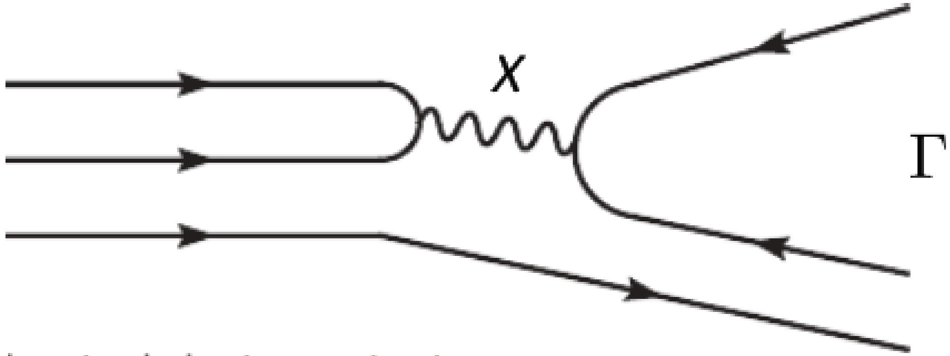
		$\nu_\mu \rightarrow \nu_e$ rate				$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ rates			
(sign of Δm^2_{31})	$\sin^2 2\theta_{13}$	δ_{CP} deg.							
		0°	-90°	180°	+90°	0°	-90°	180°	+90°
WBLE beams at 1300km, per 100kT. MW. 10^7s									
120 GeV, 9 mRad off-axis		Beam ν_e = 47**				Beam $\bar{\nu}_e$ = 17**			
(+/-)	0.0	14	N/A	N/A	N/A	5.0	N/A	N/A	N/A
(+)	0.02	87	134	95	48	20	7.2	15	27
(-)	0.02	39	72	51	19	38	19	33	52
60 GeV, on-axis		Beam ν_e = 61**				Beam $\bar{\nu}_e$ = 22**			
(+)	0.02	138	189	125	74	30	12	19	37
(-)	0.02	57	108	86	34	46	27	48	67

* = 0-3 GeV ** = 0-5 GeV, 1 MW. 10^7s = 5.2×10^{20} POT at 120 GeV, 1yr $= 2 \times 10^7 s$

Rich Physics Program

- **Nucleon Decay:** 300 ktons = 13 x Super-K
- **Galactic Supernova:** @ 10 kpc 25,000 $\bar{\nu}_e$, 1,000 forward scatter events, 2,500 NC+CC nuclear excitation events in WC
- **Relic Supernovae:** 100 kton WC detector doped with Gd *should see* these. ~40% of these should come from SN with z>0.5.
- **HEP Solar Neutrinos:** 18 MeV endpoint neutrinos from H-e-p reactions. Predicted but never seen. Super-K just on the edge.

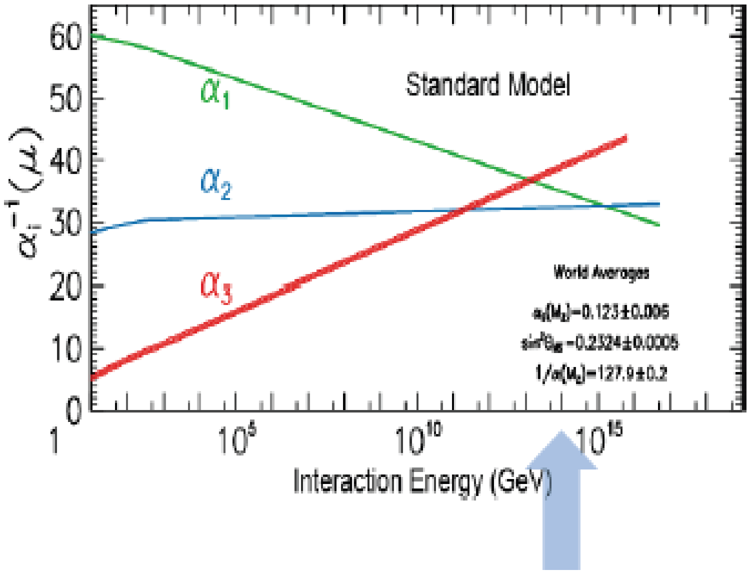
Nucleon Decay

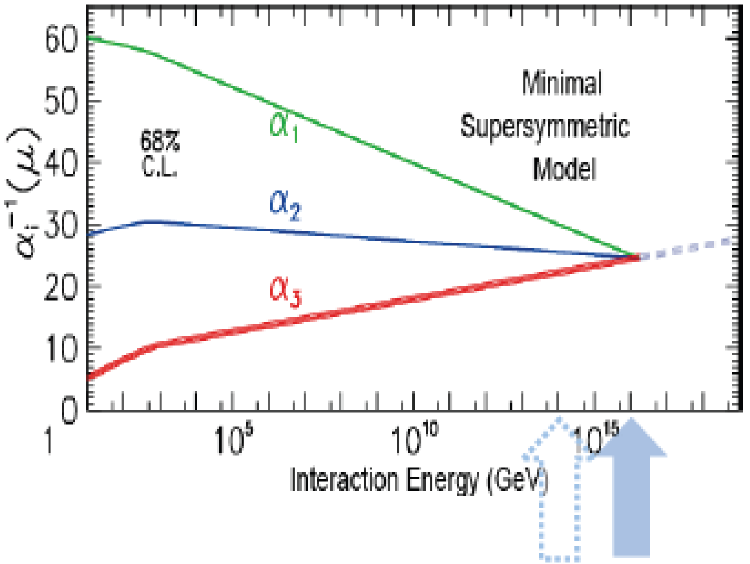


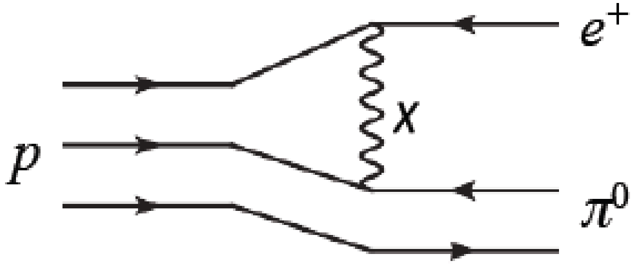
$$\Gamma \sim \frac{\alpha M_X^4}{m_p^5}$$

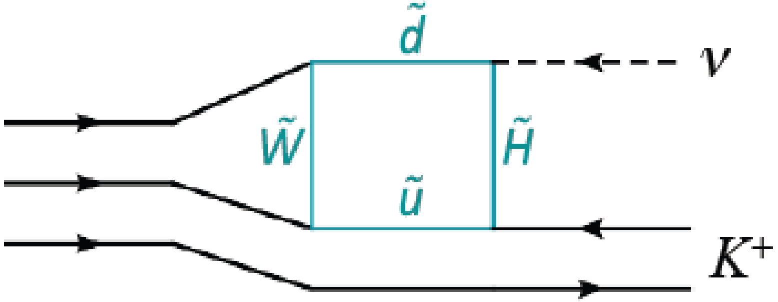
- ★ Highly prized physics motivation:
  Grand Unification of strong, weak, and electromagnetic forces!
  New force carrying particle!
- ★ Connections to neutrino mass, inflation, BAU ...
- ★ Test of basic symmetries: baryon number and lepton number.
- ★ Supersymmetric versions of GUTs are of great interest and value.
- ★ ~10^{15} GeV energy scale – inaccessible to accelerators.
- ★ Long lifetime (from SK) is already a difficult constraint
  which new models must work hard to evade.

Unification of Running Coupling Constants









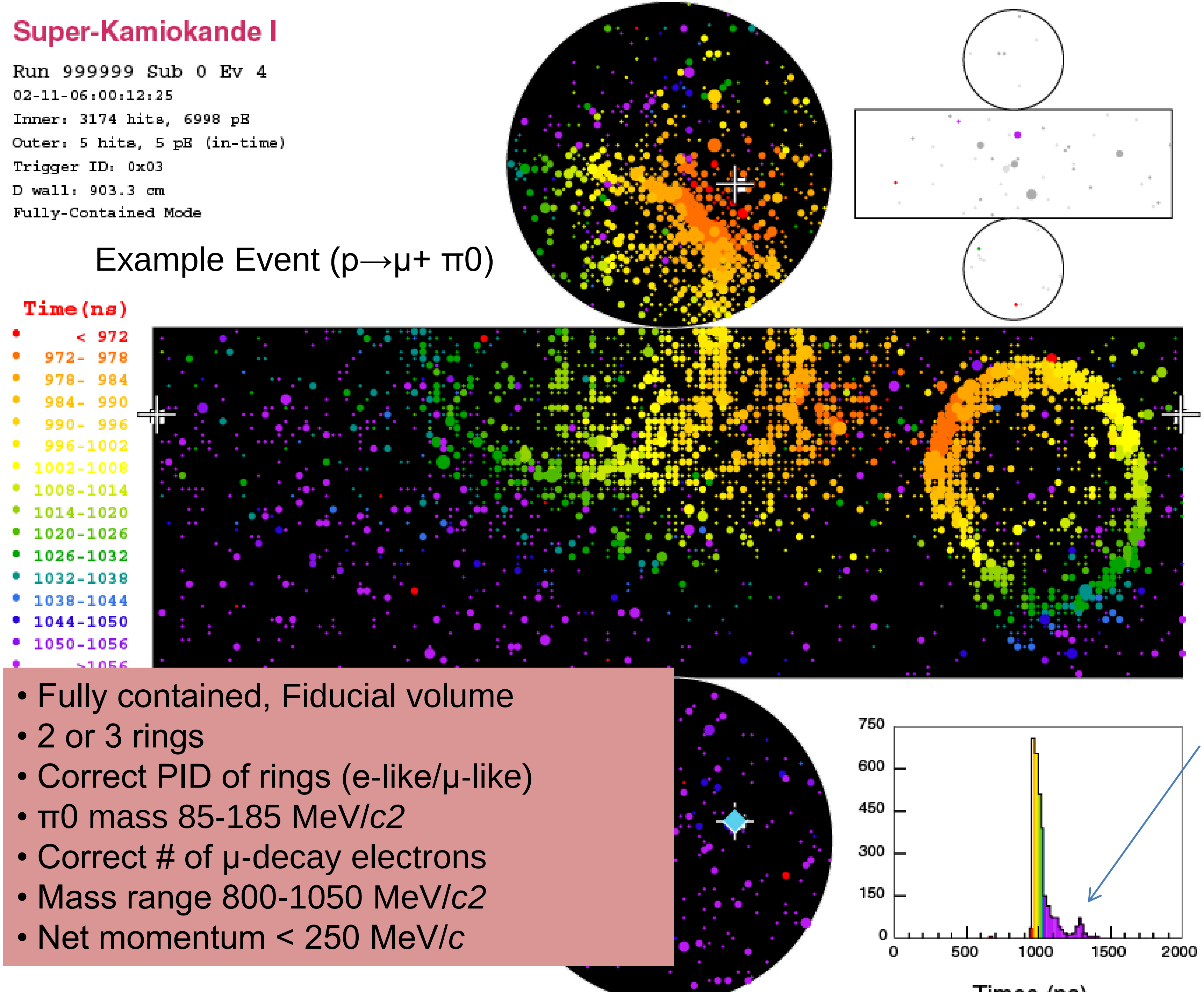
$\tau/B = 4.5\times 10^{29\pm1.7}\text{years}\quad \mathrm{SU}(5)$
$\tau/B > 8.4\times 10^{33}\text{years}\quad \mathrm{SK\ I+II}$

$\tau/B = 10^{29-35}\text{years}\quad \mathrm{SUSY}$
$\tau/B > 2.3\times 10^{32}\text{years}\quad \mathrm{SK\ I}$

Model	Ref.	Modes	τ_N (years)
Minimal $SU(5)$	Georgi, Glashow [2]	$p \to e^+\pi^0$	$10^{30} - 10^{31}$
Minimal SUSY $SU(5)$	Dimopoulos, Georgi [11], Sakai [12] Lifetime Calculations: Hisano, Murayama, Yanagida [13]	$p \to \bar{\nu}K^+$ $n \to \bar{\nu}K^0$	$10^{28} - 10^{32}$
SUGRA $SU(5)$	Nath, Arnowitt [14, 15]	$p \to \bar{\nu}K^+$	$10^{32} - 10^{34}$
SUSY $SO(10)$ with anomalous flavor $U(1)$	Shafi, Tavartkiladze [16]	$p \to \bar{\nu}K^+$ $n \to \bar{\nu}K^0$ $p \to \mu^+K^0$	$10^{32} - 10^{35}$
SUSY $SO(10)$ MSSM (std. $d=5$)	Lucas, Raby [17], Pati [18]	$p \to \bar{\nu}K^+$	$10^{33} - 10^{34}$
		$n \to \bar{\nu}K^0$	$10^{32} - 10^{33}$
SUSY $SO(10)$ ESSM (std. $d=5$)	Pati [18]	$p \to \bar{\nu}K^+$	$10^{33} - 10^{34}$ $\lesssim 10^{35}$
SUSY $SO(10)/G(224)$ MSSM or ESSM (new $d=5$)	Babu, Pati, Wilczek [19, 20, 21], Pati [18]	$p \to \bar{\nu}K^+$	$\lesssim 2 \cdot 10^{34}$
		$p \to \mu^+K^0$	$B \sim (1-50)\%$
SUSY $SU(5)$ or $SO(10)$ MSSM ($d=6$)	Pati [18]	$p \to e^+\pi^0$	$\sim 10^{34.9\pm1}$
Flipped $SU(5)$ in CMSSM	Ellis, Nanopoulos and Wlaker[22]	$p \to e/\mu^+\pi^0$	$10^{35} - 10^{36}$
Split $SU(5)$ SUSY	Arkani-Hamed, *et. al.* [23]	$p \to e^+\pi^0$	$10^{35} - 10^{37}$
$SU(5)$ in 5 dimensions	Hebecker, March-Russell[24]	$p \to \mu^+K^0$ $p \to e^+\pi^0$	$10^{34} - 10^{35}$
$SU(5)$ in 5 dimensions option II	Alciati *et.al.*[25]	$p \to \bar{\nu}K^+$	$10^{36} - 10^{39}$
GUT-like models from Type IIA string with D6-branes	Klebanov, Witten[26]	$p \to e^+\pi^0$	$\sim 10^{36}$

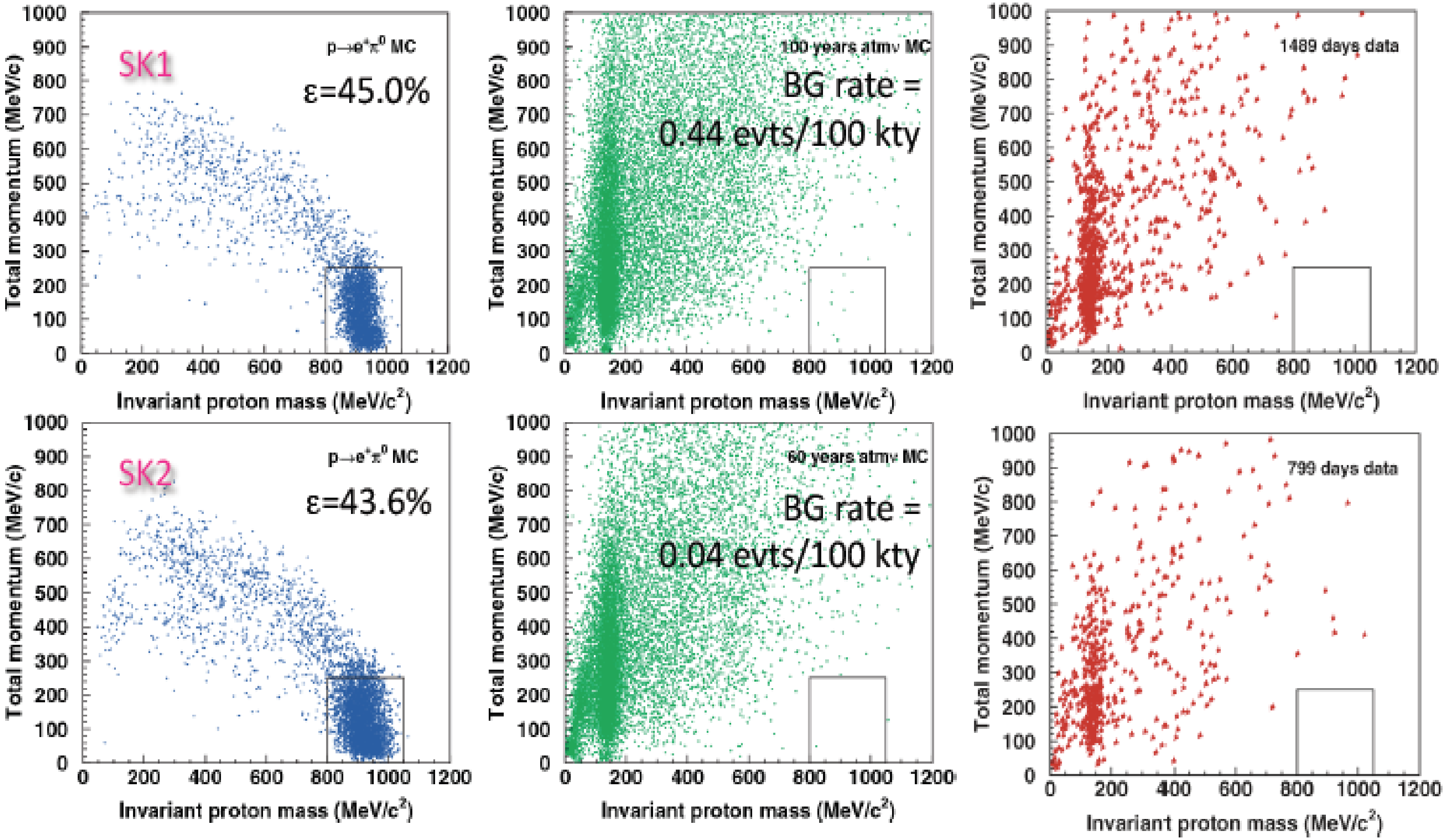
TABLE I: Summary of the expected nucleon lifetime in different theoretical models.

Example Event (p→μ+ π0)



- Fully contained, Fiducial volume
- 2 or 3 rings
- Correct PID of rings (e-like/μ-like)
- π0 mass 85-185 MeV/*c2*
- Correct # of μ-decay electrons
- Mass range 800-1050 MeV/*c2*
- Net momentum < 250 MeV/*c*

Super-Kamiokande Results ($p \rightarrow e^+ \pi^0$)



SK1

ε=45.0%

BG rate = 0.44 evts/100 kty

SK2

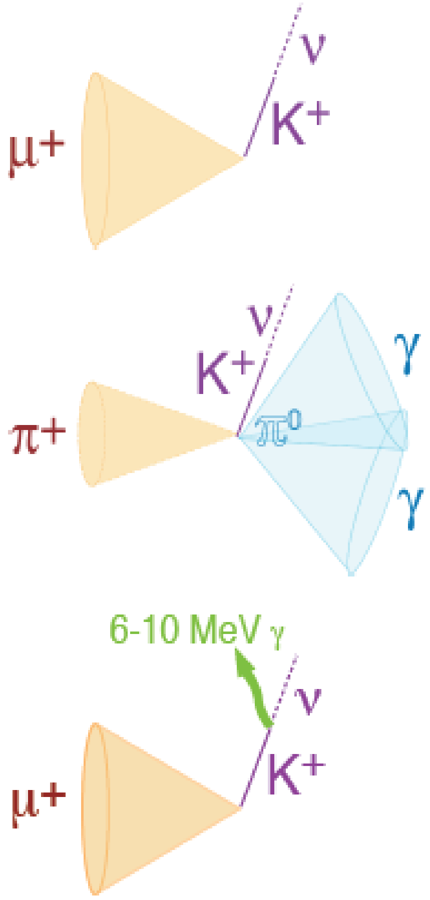
ε=43.6%

BG rate = 0.04 evts/100 kty

Indep. (Nuance MC) BG est. for SK1:
BG rate = 0.21 evts/100 kty

BG est. based on K2K 1KT:
BG rate = 0.16±0.07 evts/100 kty

Super-Kamiokande Search for ($p \to K^+ \nu$)

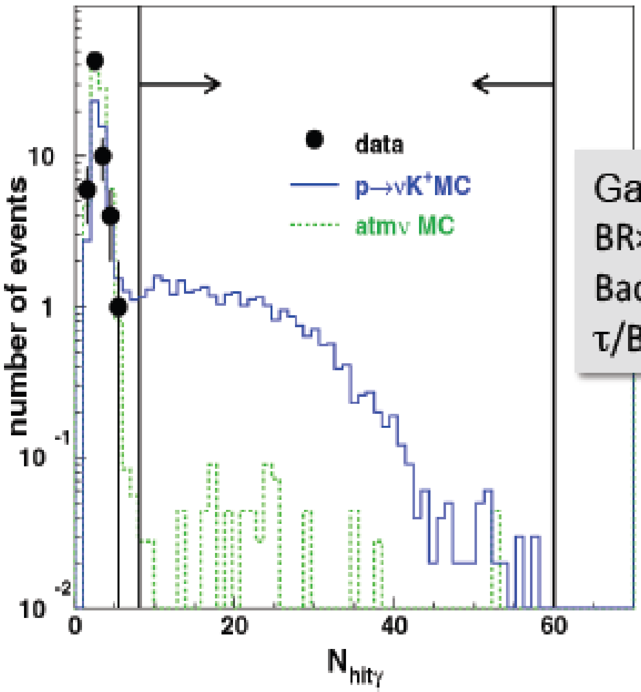


★ K^+ below Cherenkov threshold

★ Essentially a search for K^+ decay at rest

★ Three searches (eventually combined)

- Monochromatic muon (65% BR, large background)
- $K^+ \to \pi^+\pi^0$ (21% BR)
- $K^+ \to \mu^+ \nu$ with early gamma tag from $^{16}O^*$



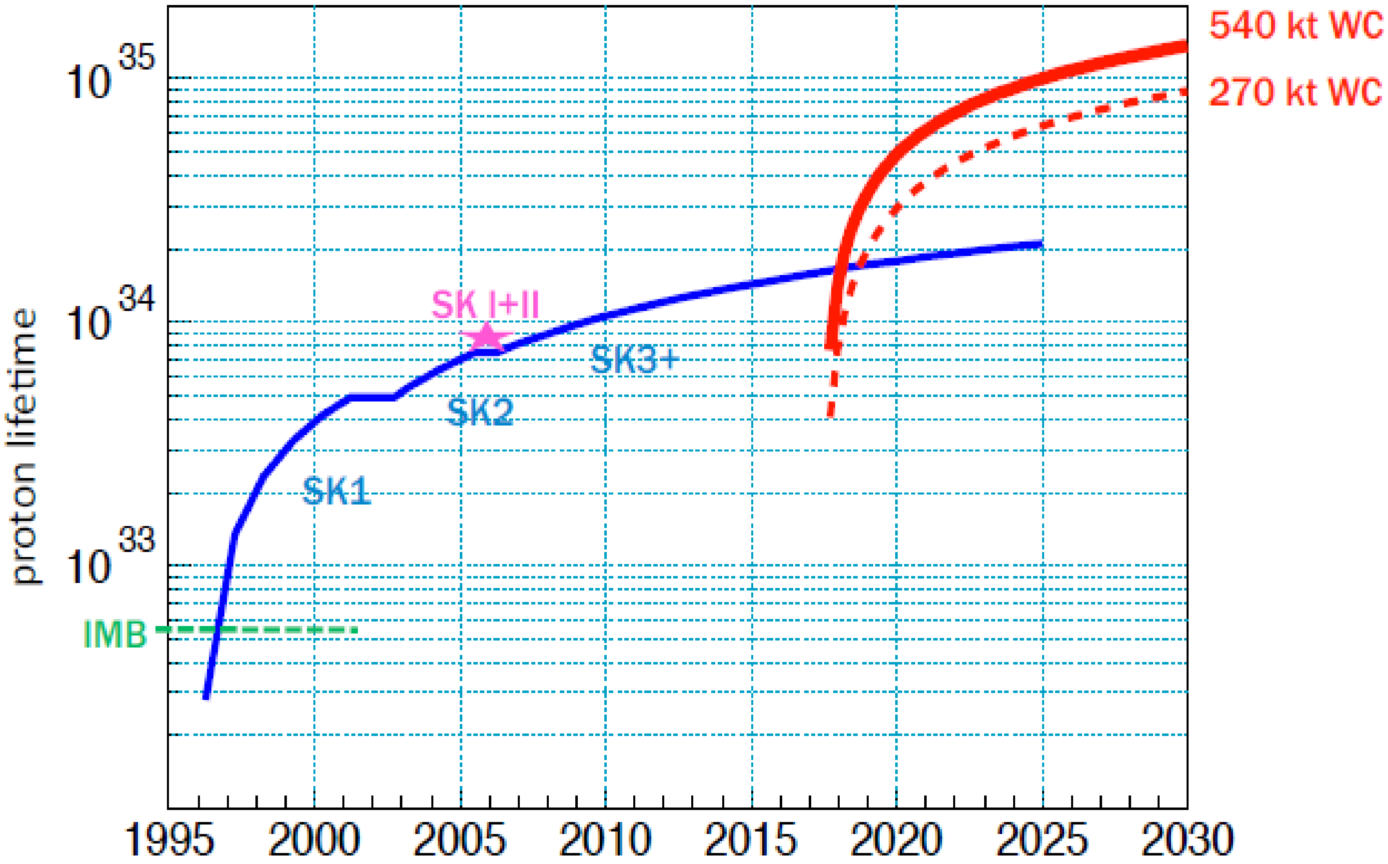
Gamma Tag Search:

$BR\times\varepsilon = 8.6\pm20_{sys}\%$

Background = 0.7 events (±59%)

$\tau/B < 10\times10^{32}$ years

$p \to e^+\pi^0$

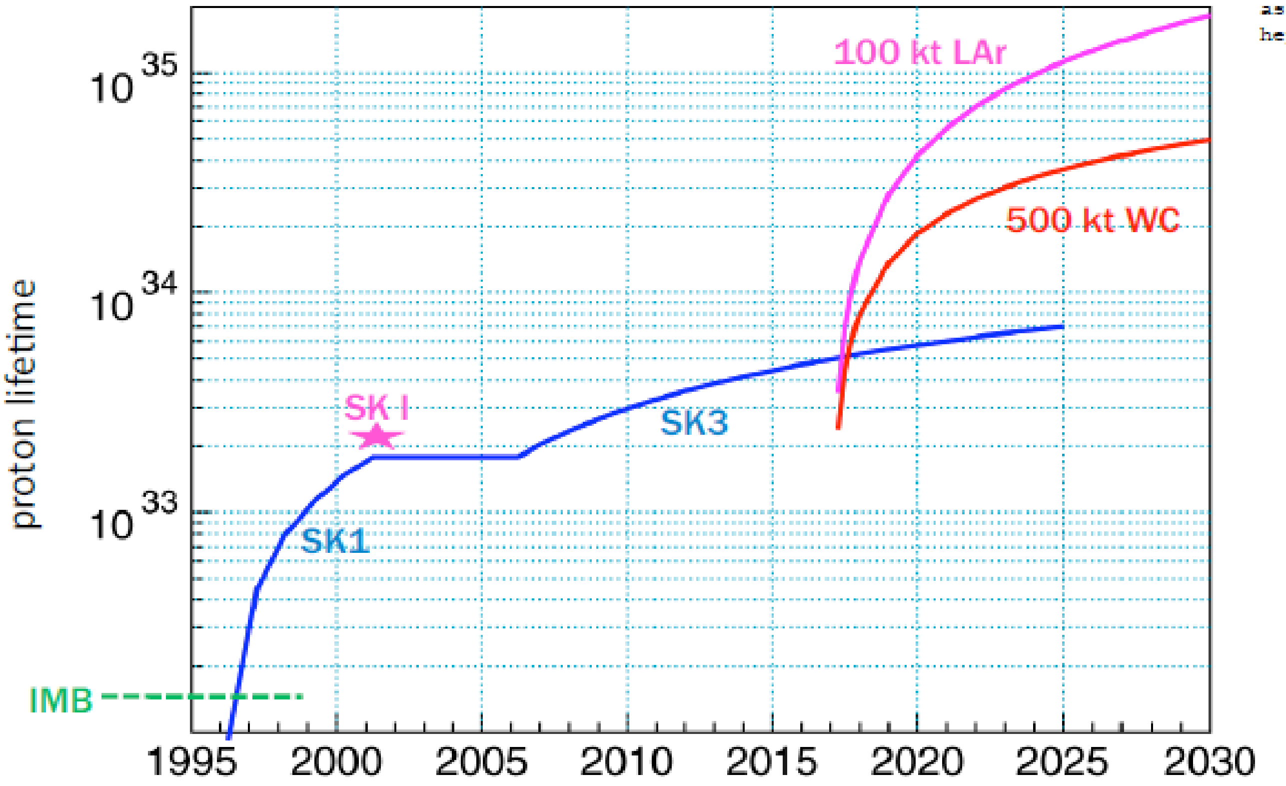


efficiency = 0.45

bg. rate = 0.2 evts/100 kty

$N_{obs} = N_{bg}$

$$p \rightarrow K^+ \nu$$

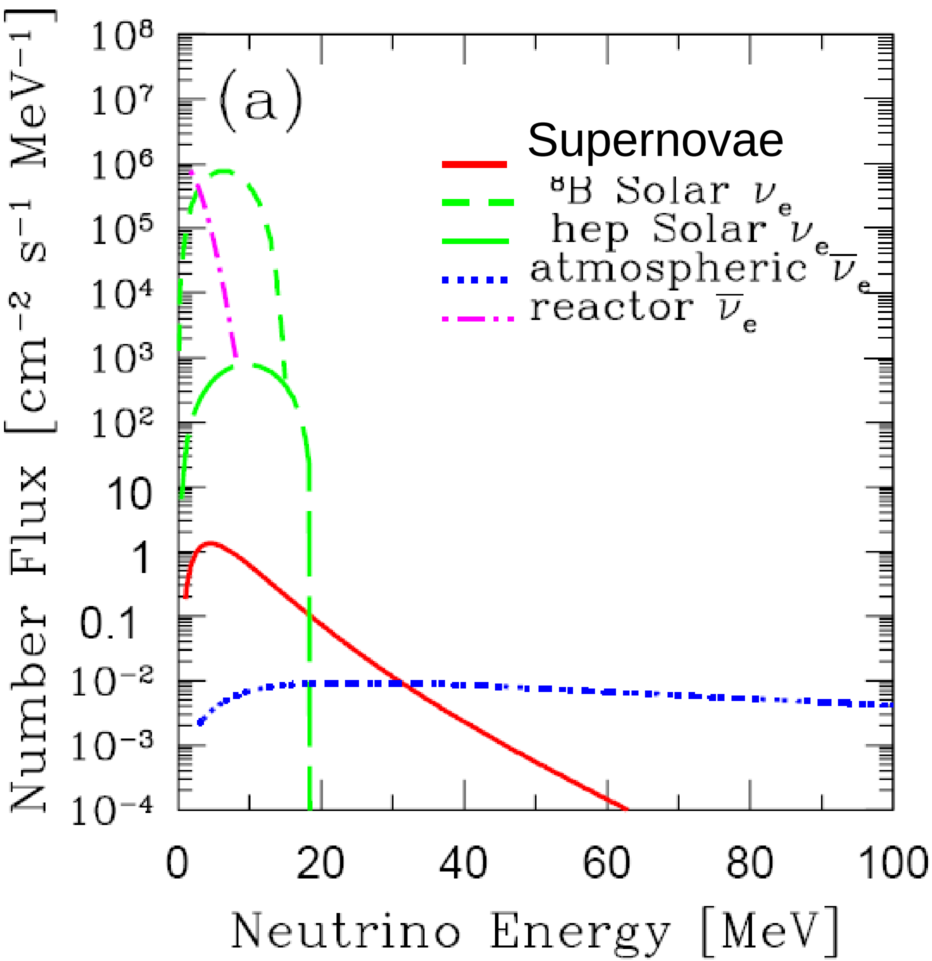


assumptions of hep-ph/0701101

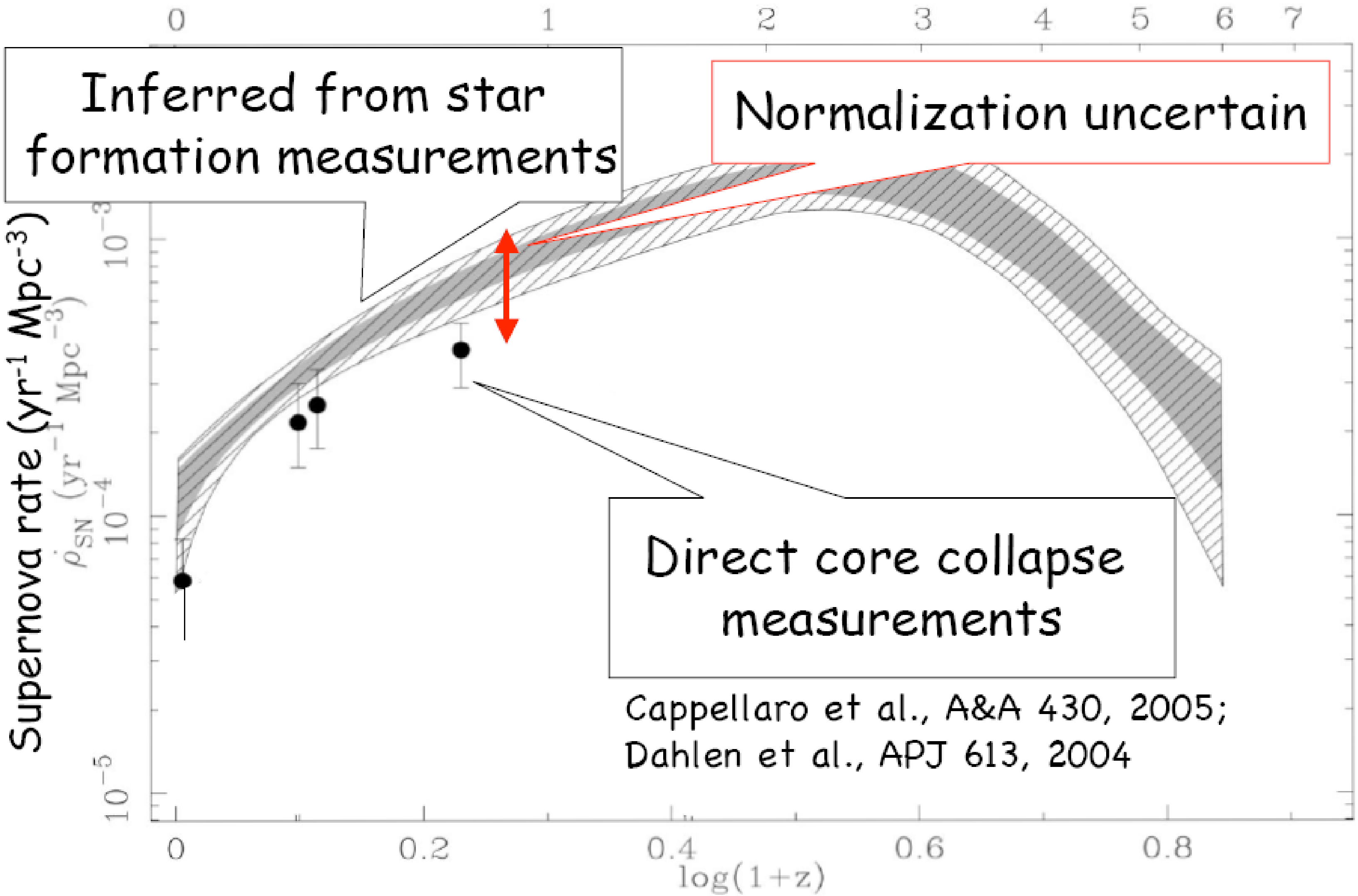
The feeble signal of all SNe

- Sum over the whole universe:

$$\sum_{\star} \Phi_{\nu}^{\star}$$



S. Ando and K. Sato, New J.Phys.6:170,2004.



Inferred from star formation measurements

Normalization uncertain

Direct core collapse measurements

Cappellaro et al., A&A 430, 2005;
Dahlen et al., APJ 613, 2004

Adapted from Beacom & Hopkins, astro-ph/0601463

Spectrum fitting in SK-I

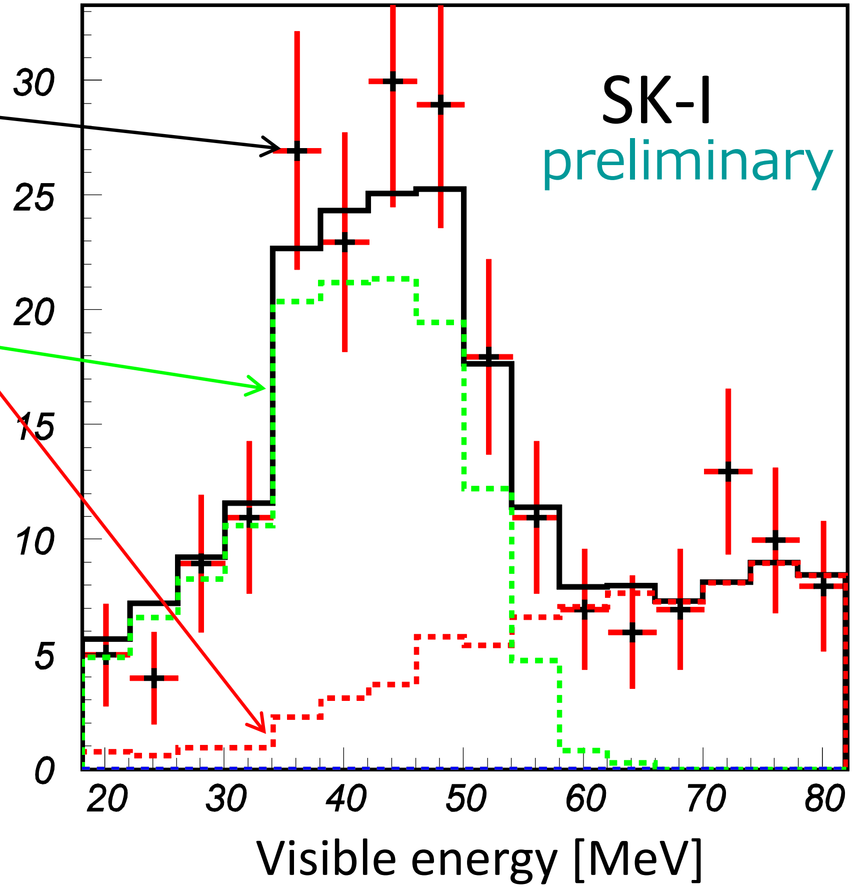
$$\chi^2 = \sum_i \frac{\left[N_{data}(i) - (\alpha \times N_{relic}(i) + \beta \times N_{\nu_e}(i) + \gamma \times N_{\nu_\mu}(i)\right]^2}{\sigma^2_{data} + \sigma^2_{MC} + \sigma^2_{systematic}}$$

$N_{data}(i) : real\ Data\ spectrum$

$N_{relic}(i) : SRN\ \ MC\ spectrum$

$N_{\nu_e}(i)\ \ : atmospheric\ \nu_e\ \ spectrum$

$N_{\nu_\mu}(i)\ \ : atmospheric\ \nu_\mu\ \ spectrum$



free parameter

$\alpha = 0.0$: factor of SRN

$\beta = 1.30 \pm 0.2$: factor of ν_e

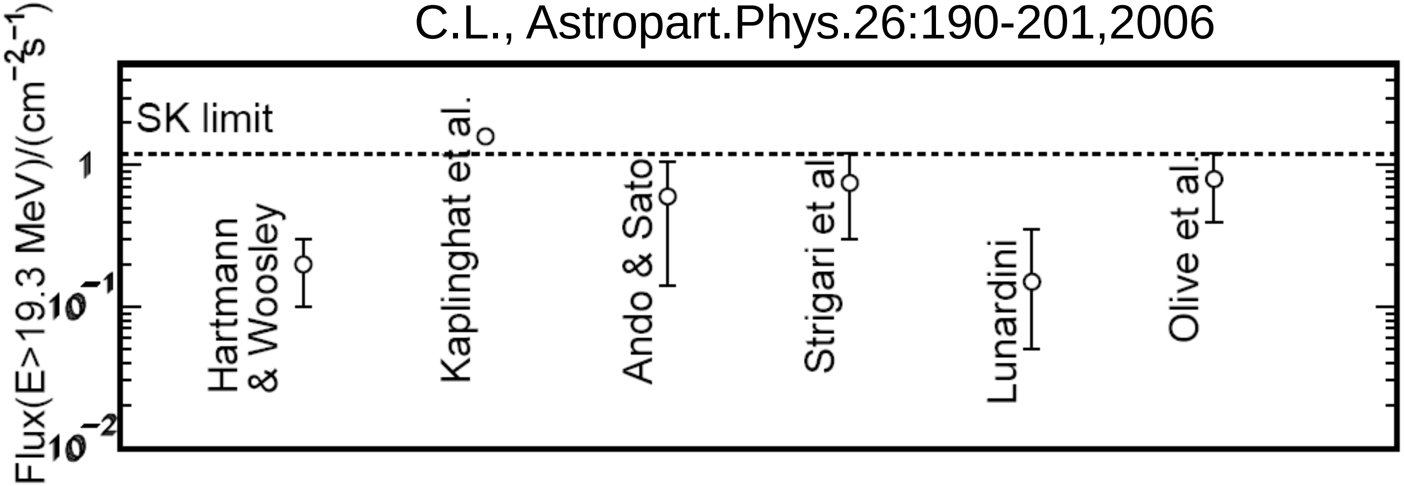
$\gamma = 0.45 \pm 0.1$: factor of ν_μ

$\chi^2 =$ 7.2 / 13 d.o.f

Courtesy Iida, ICRR

Status of theory: anti-ν_e flux

C.L., Astropart.Phys.26:190-201,2006



- Differences due to different inputs/methods

For a Gd-loaded 100 kton WC detector, estimates range from 2-20 events/year.

C.L., Astropart.Phys.26:190-201,2006, Fogli et al. JCAP 0504:002,2005, Volpe & Welzel, 2007, C.L. & O.L.G. Peres, to appear soon.

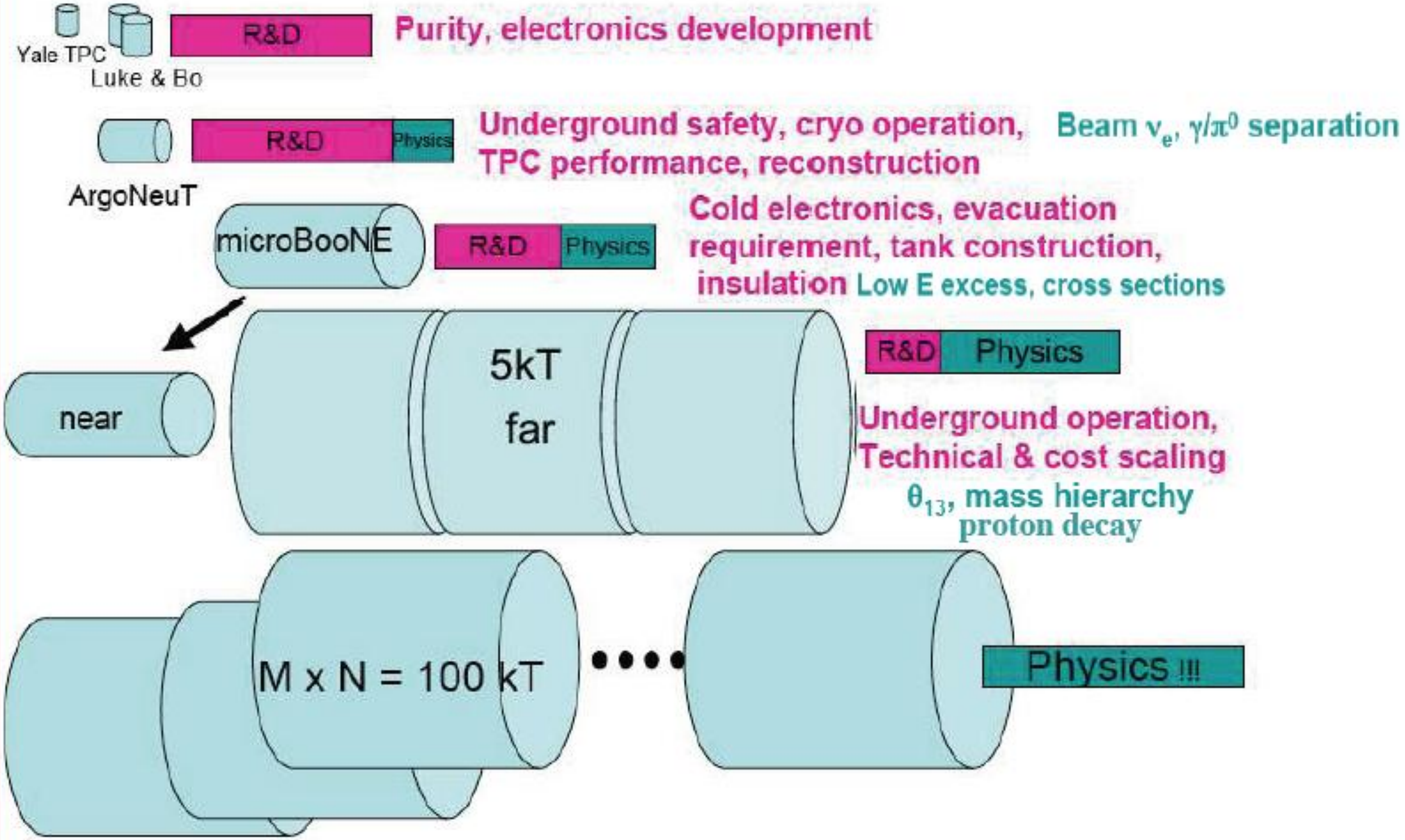
SK background of ~20/year significantly reduced by neutron tagging. (Beacom and Vagins)

Water Cerenkov R&D Issues

- What is the PMT coverage required for efficiency neutron capture detection?
- What is the PMT coverage required for detection of precursor gamma ray from $p \rightarrow \nu K$? (Note: 20% coverage in SK-II was too little).
- Can PMT’s be installed without SK style “mufflers”? BNL is working on PMT implosion testing.

- How can Gd-loaded water be cleaned without removing the Gd? Is removal of Fe ions only enough– or do we have to worry about other things also?
- Can the walls of a large cavern be coated directly? Do we need to have concrete and/or a liner? How to mount PMTs cheaply?
- Do we need a veto region? SK had one, but DUSEL 4850 is much deeper. Note: IMB operated successfully without a veto region.
- Can efficiency for e/π^0 be improved?

Evolution of the Liquid Argon Physics Program in the US



Purity, electronics development

Underground safety, cryo operation, TPC performance, reconstruction

Beam ν_e, γ/π^0 separation

Cold electronics, evacuation requirement, tank construction, insulation

Low E excess, cross sections

Underground operation, Technical & cost scaling

θ_{13}, mass hierarchy
proton decay

Liquid Argon R&D Issues

- Feasibility: insulation, purity, cold electronics, necessity for evacuation of vessel
- Underground safety – this is a major concern
- What is the cost?
- Also predictability of costs and minimization of risk

LB DUSEL Interest Group

- **ANL:** M.Goodman, M.Sanchez
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- **Univ. of California, Irvine:** W.R.Kropp, M.Smy, H.Sobel, M.Vagins
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- **Colorado State Univ:** N.Buchanan
- **Columbia University:** Z.Djurcic, M.Shaevitz
- **Drexel Univ.:** C.Lane, J.Maricic
- **Duke Univ.:** K.Scholberg, C.Walter
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- **Indiana Univ.:** C.Bower, M.D.Messier, S.Mufson, J.Musser, J.Paley, J.Urheim
- **INFN:** R.Potenza, V.Bellini
- **Kansas State Univ.:** G.Horton-Smith
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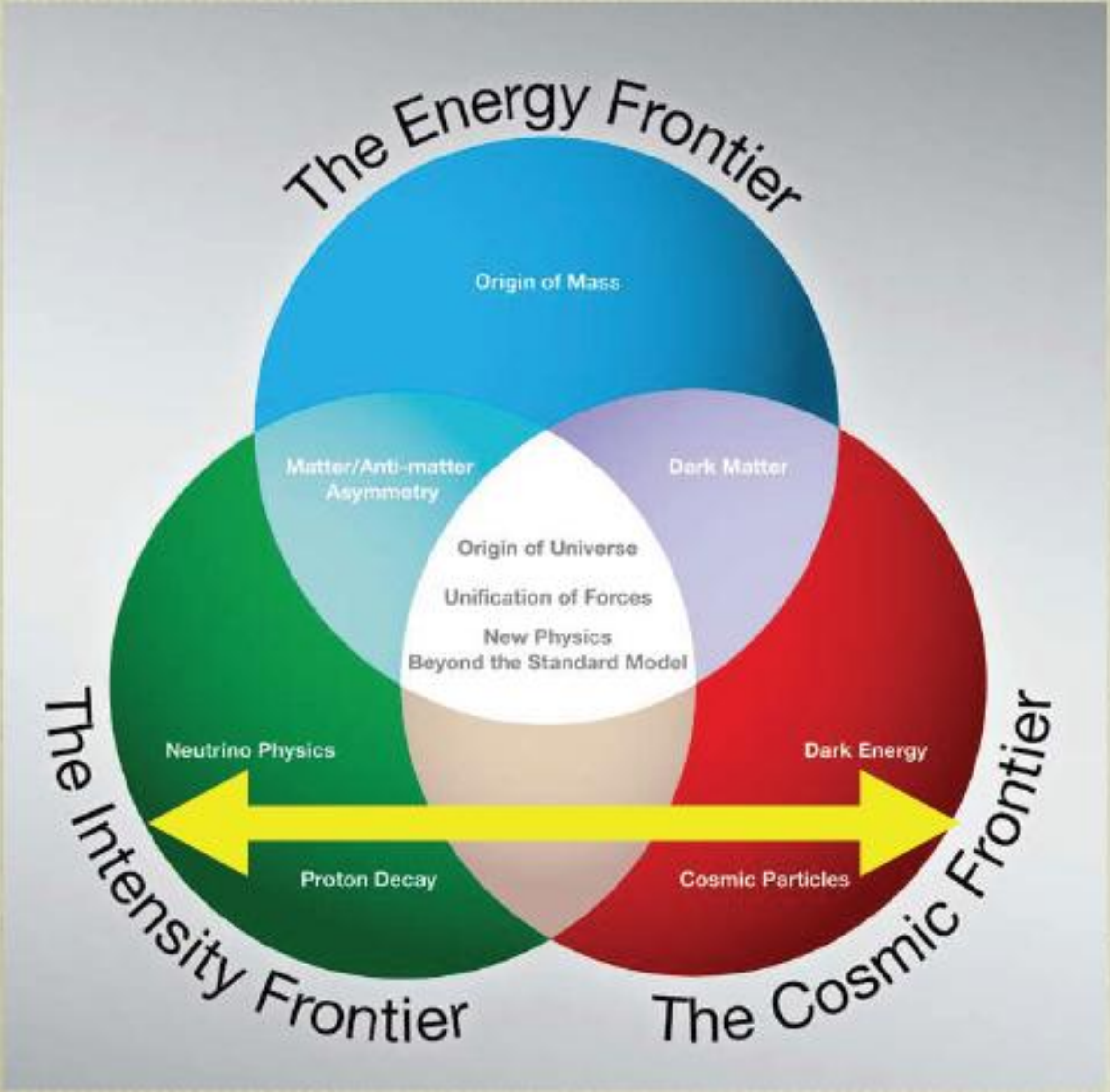
- **LLNL:** A.Bernstein, S.Dazeley
- **LNGS:** M.Antonello**,** O.Palamara
- **Louisiana State University:** T.Kutter
- **Univ. of Maryland:** G.Sullivan
- **Massachusetts Institute of Technology:** W.A.Barletta, J.Conrad, P.Fisher, G.Sciolla, D.Yamamoto
- **Michigan State Univ.:** C.Bromberg, D.Edmunds
- **Univ. of Minnesota, Duluth:** A.Habig
- **Univ. of Minnesota:** M.Marshak, W.Miller
- **Univ. of Pennsylvania:** W.Frati, J.Klein, K.Lande, A.K.Mann, R. van Berg
- **Penn. State. Univ:** D.Elsworth
- **Princeton Univ.:** K.McDonald
- **Rensselaer Polytechnic Institute:** J.Napolitano
- **Univ. of Sussex:** E.Falk, J.Hartnell, S.Peeters
- **Univ. of Texas, Austin:** K.Lang, S.Kopp
- **Tufts Univ.:** T.Mann, J.Schneps, W.Oliver, T.Kafka.
- **William and Mary:** M.Kordosky, J.Nelson, P.Vahle
- **Univ. of Wisconsin**: B.Balantekin, H.Band, F.Feyzi, K.Heeger, W.Wang
- **Yale:** B.Fleming, M.Soderberg

Science



From 2008 P5 report

Complementary to the physics of the energy frontier

Size, neutrino beam intensity, distance: the next step in neutrino physics.

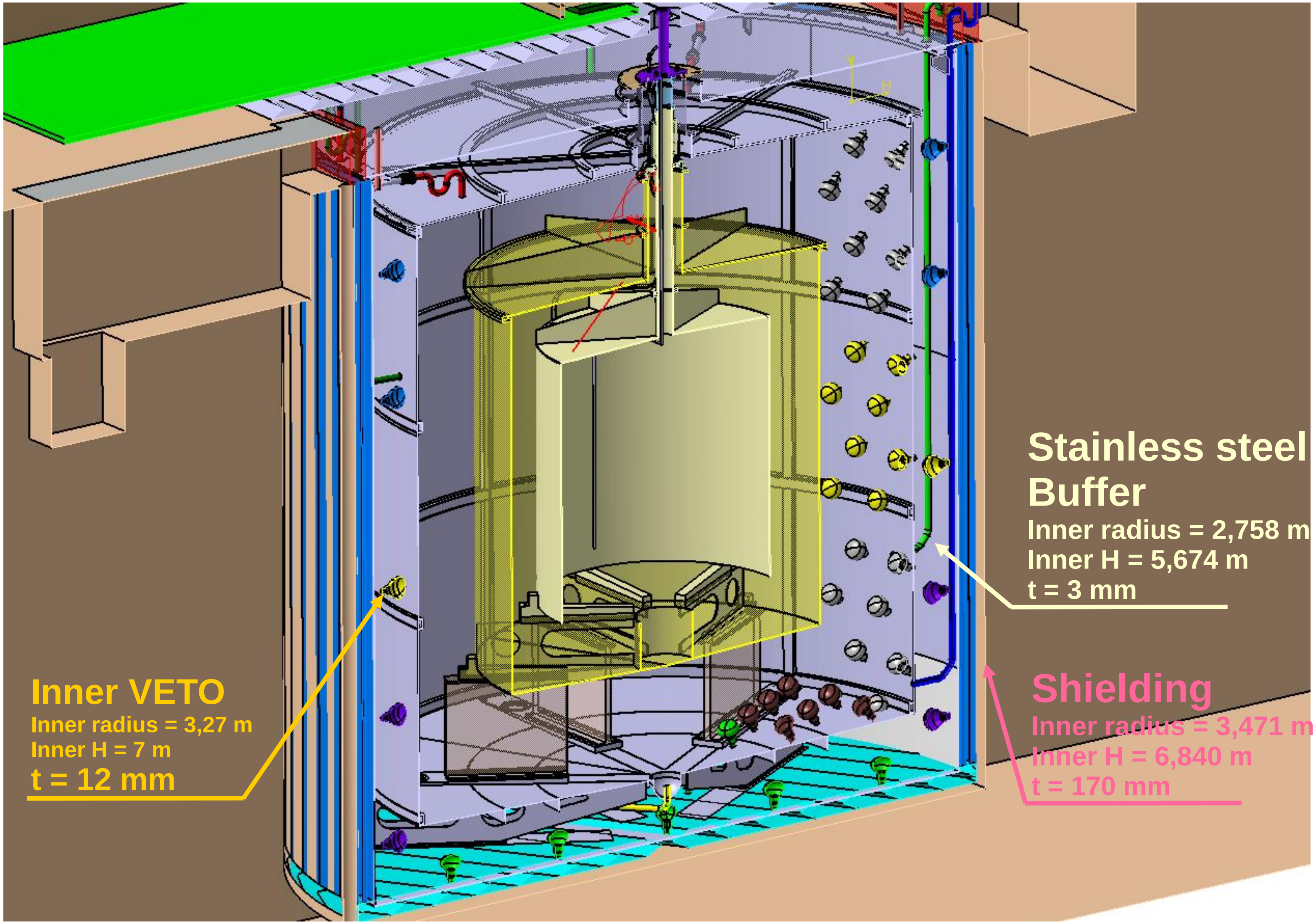
Size gives improved sensitivity to proton decay, our window to the unification of forces.

Depth and low background allows detection of neutrinos from present and past supernova at cosmological distances.

Very large increases to data from known natural neutrino sources: the Sun, and the atmosphere.

backup

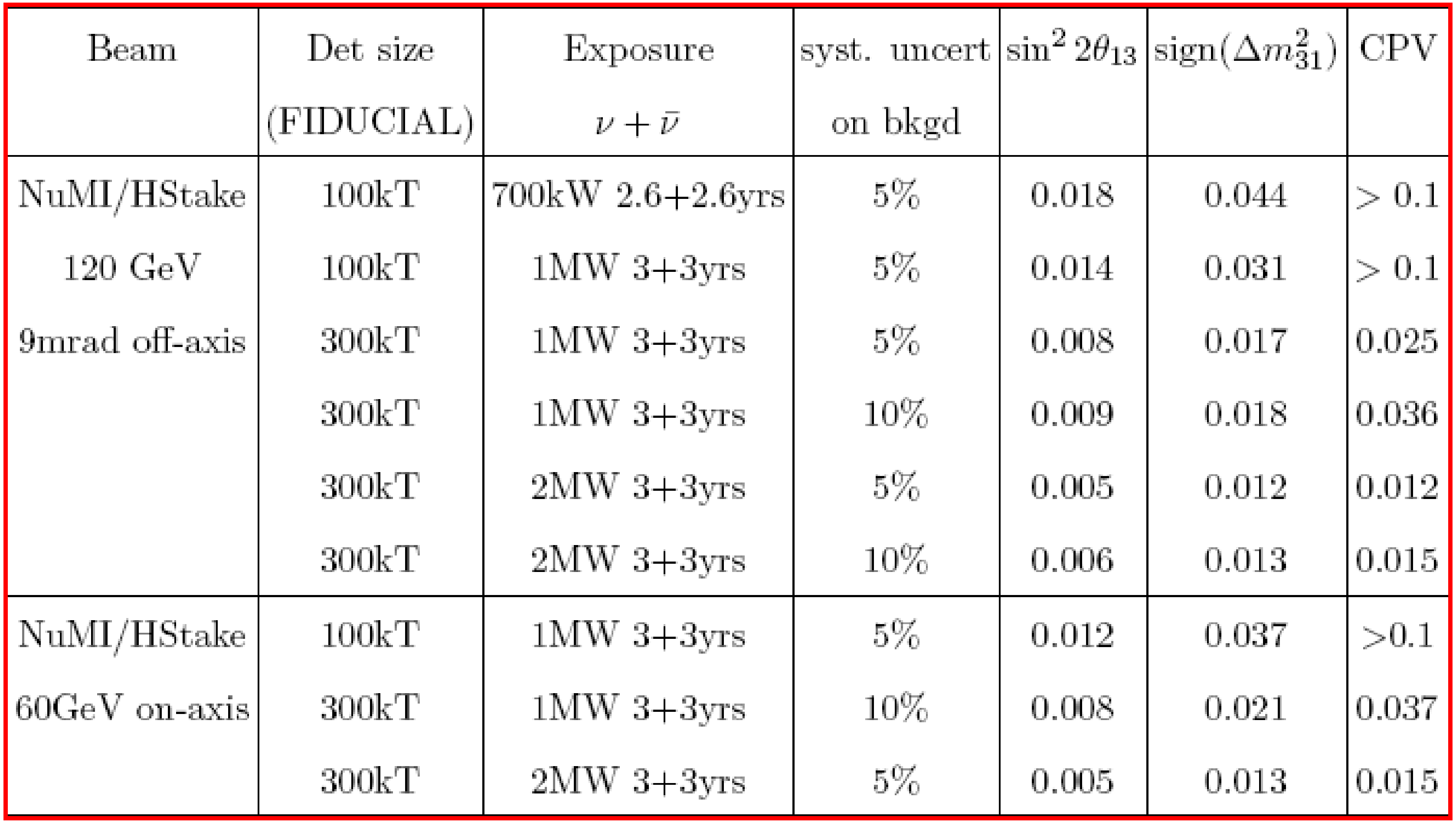
Detector Layout



Stainless steel Buffer
Inner radius = 2,758 m
Inner H = 5,674 m
t = 3 mm

Inner VETO
Inner radius = 3,27 m
Inner H = 7 m
t = 12 mm

Shielding
Inner radius = 3,471 m
Inner H = 6,840 m
t = 170 mm



Beam	Det size (FIDUCIAL)	Exposure $\nu + \bar{\nu}$	syst. uncert on bkgd	$\sin^2 2\theta_{13}$	$\mathrm{sign}(\Delta m^2_{31})$	CPV
NuMI/HStake	100kT	700kW 2.6+2.6yrs	5%	0.018	0.044	> 0.1
120 GeV	100kT	1MW 3+3yrs	5%	0.014	0.031	> 0.1
9mrad off-axis	300kT	1MW 3+3yrs	5%	0.008	0.017	0.025
	300kT	1MW 3+3yrs	10%	0.009	0.018	0.036
	300kT	2MW 3+3yrs	5%	0.005	0.012	0.012
	300kT	2MW 3+3yrs	10%	0.006	0.013	0.015
NuMI/HStake	100kT	1MW 3+3yrs	5%	0.012	0.037	>0.1
60GeV on-axis	300kT	1MW 3+3yrs	10%	0.008	0.021	0.037
	300kT	2MW 3+3yrs	5%	0.005	0.013	0.015

M.Bishai, ANL, P5 presentation