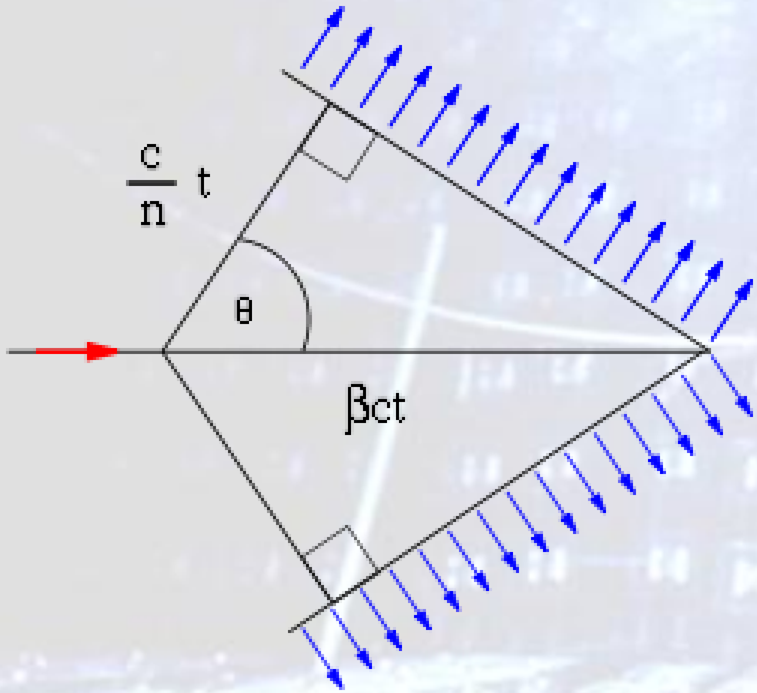
Water Cherenkov Detector Design Group

- Argonne NL
- Boston University*
- Brookhaven NL
- Caltech*
- Univ. of California, Davis*
- Univ. of California, Irvine*
- Drexel University*
- Duke University*
- Fermi NL
- Lawrence Livermore NL*
- Univ. of Maryland*
- Univ. of Minnesota
- Univ. of Pennsylvania*
- Rensselaer Poly. Inst.*
- Univ. of South Carolina*
- Univ. of Wisconsin*

* Funded through S4

What is a Water Cherenkov Detector?



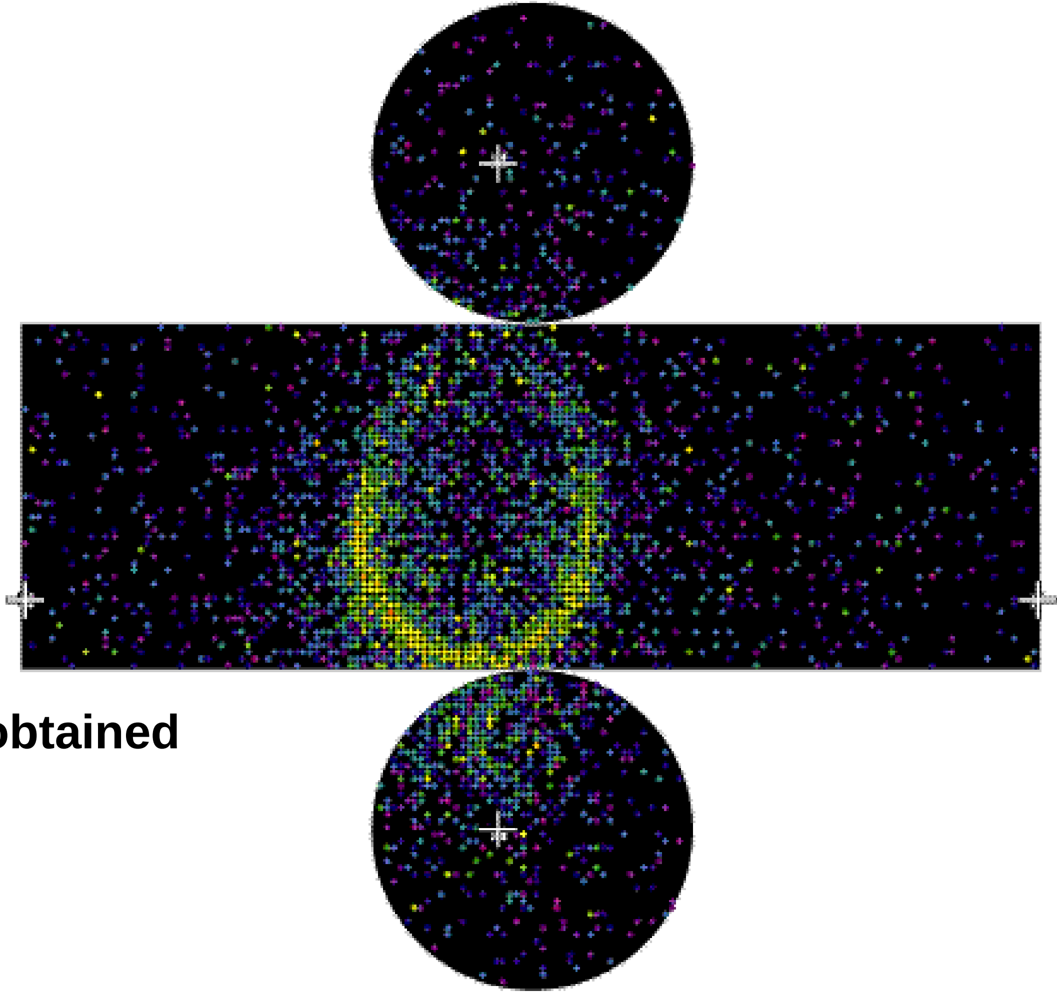
- Charged particles with velocity faster than c/n produce directional, polarized photons
- Light sensors such as photomultiplier tubes can be used to detect the light
- This provides particle tracking and identification

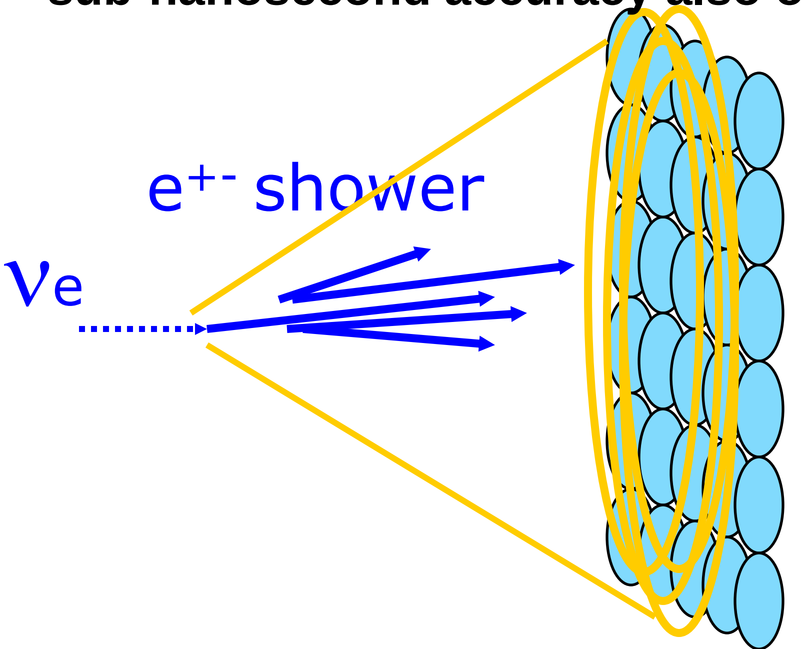
Example of an electron neutrino interaction

The detector is essentially a giant camera

color in this plot represents intensity of the light

Time-resolved images with sub-nanosecond accuracy also obtained

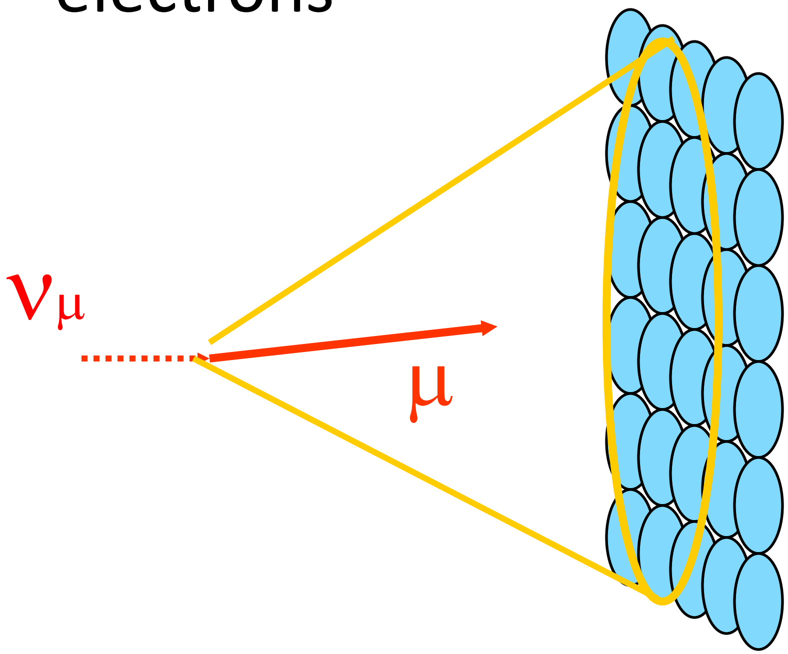


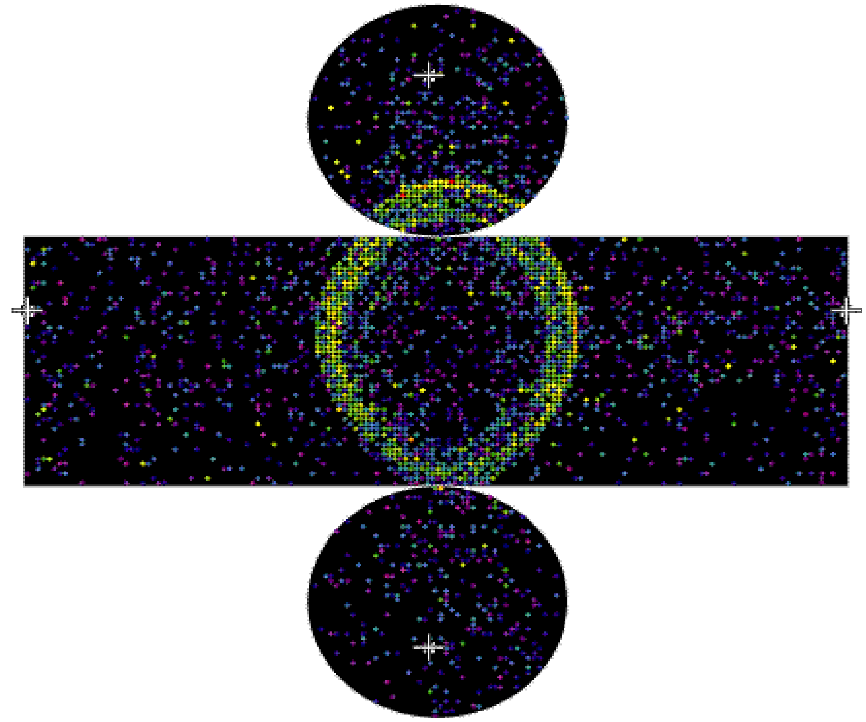


ν_μ C.C. interaction: particle ID

- Sharp Ring Edge
- Cherenkov Angle < 42^o

➔ Easy to identify from electrons

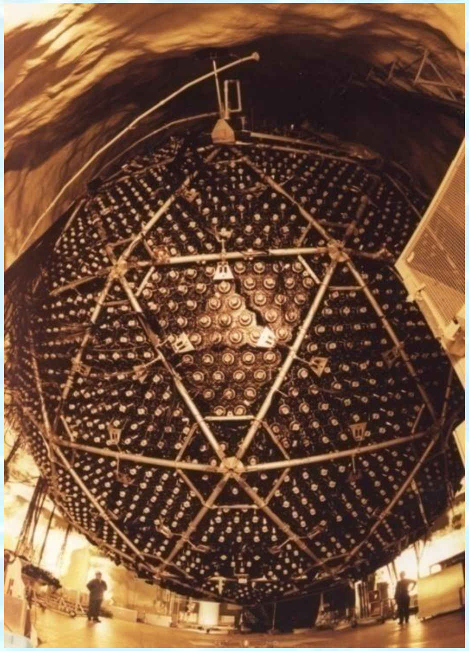




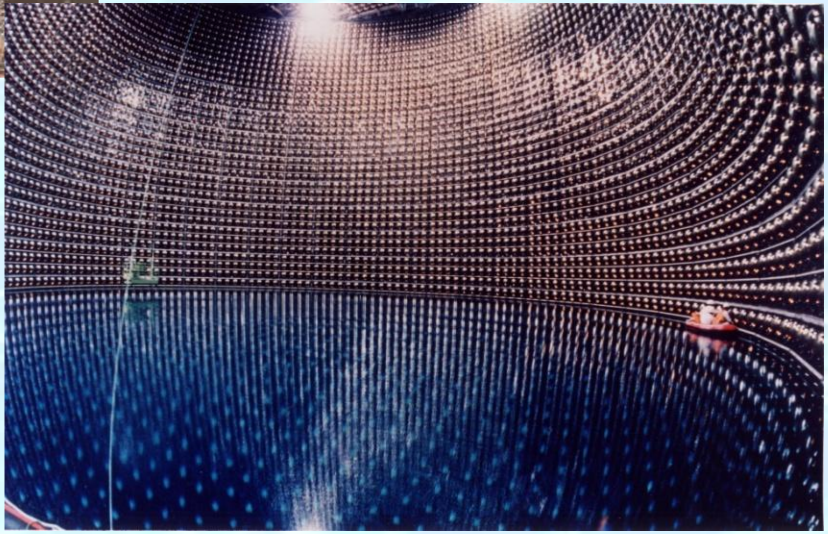
Water Cerenkov Detectors

IMB
3 ktons

Kamiokande
1 kton



SNO
1 kton



Super-Kamiokande
22 ktons

Detectors for DUSEL

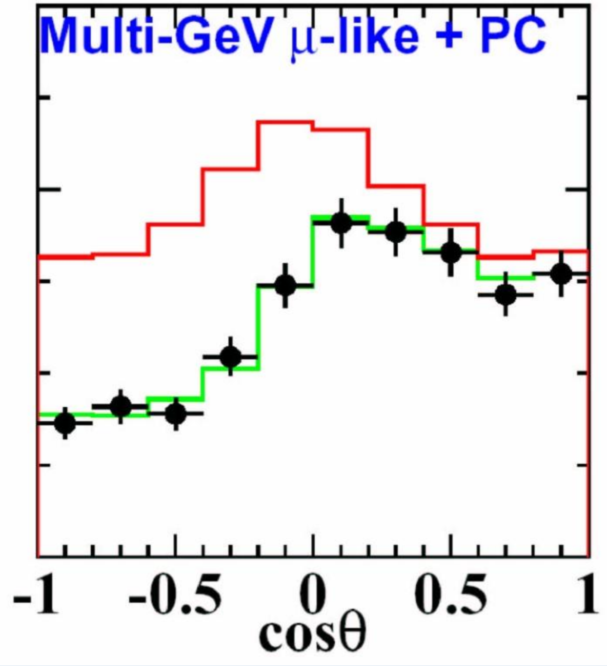
Note: the DUSEL detector will likely be realized in 2-3 modules

The muon rate in the DUSEL detector will be 1/30th that of Super-Kamiokande

IMB

Super-Kamiokande

DUSEL

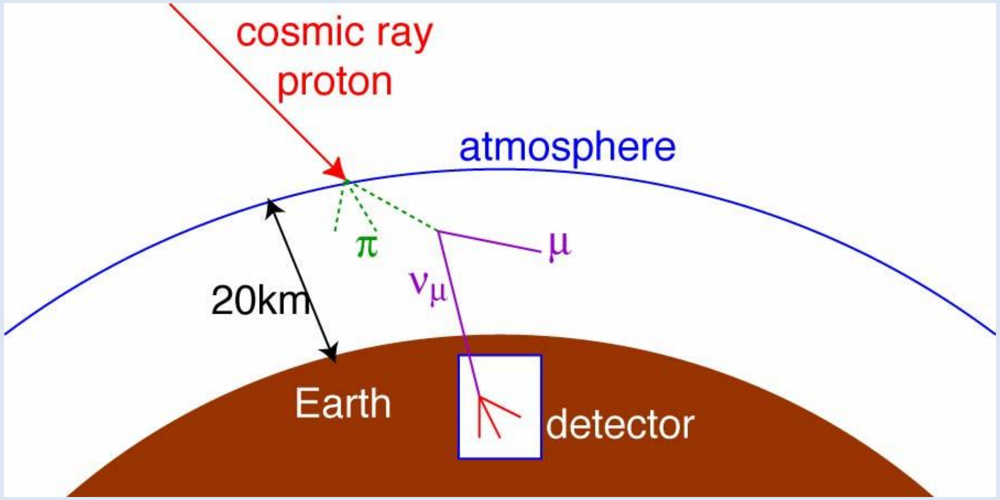


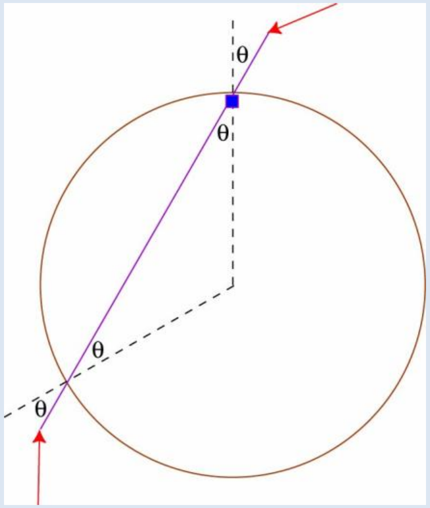
Cosmic ray induced neutrinos

Would pass Super-K in statistics after ~1.5 years.

Issues:

1. improved sensitivity to $\nu_\mu \rightarrow \nu_\tau$
2. oscillation mixing angle
3. “exotic” phenomenon



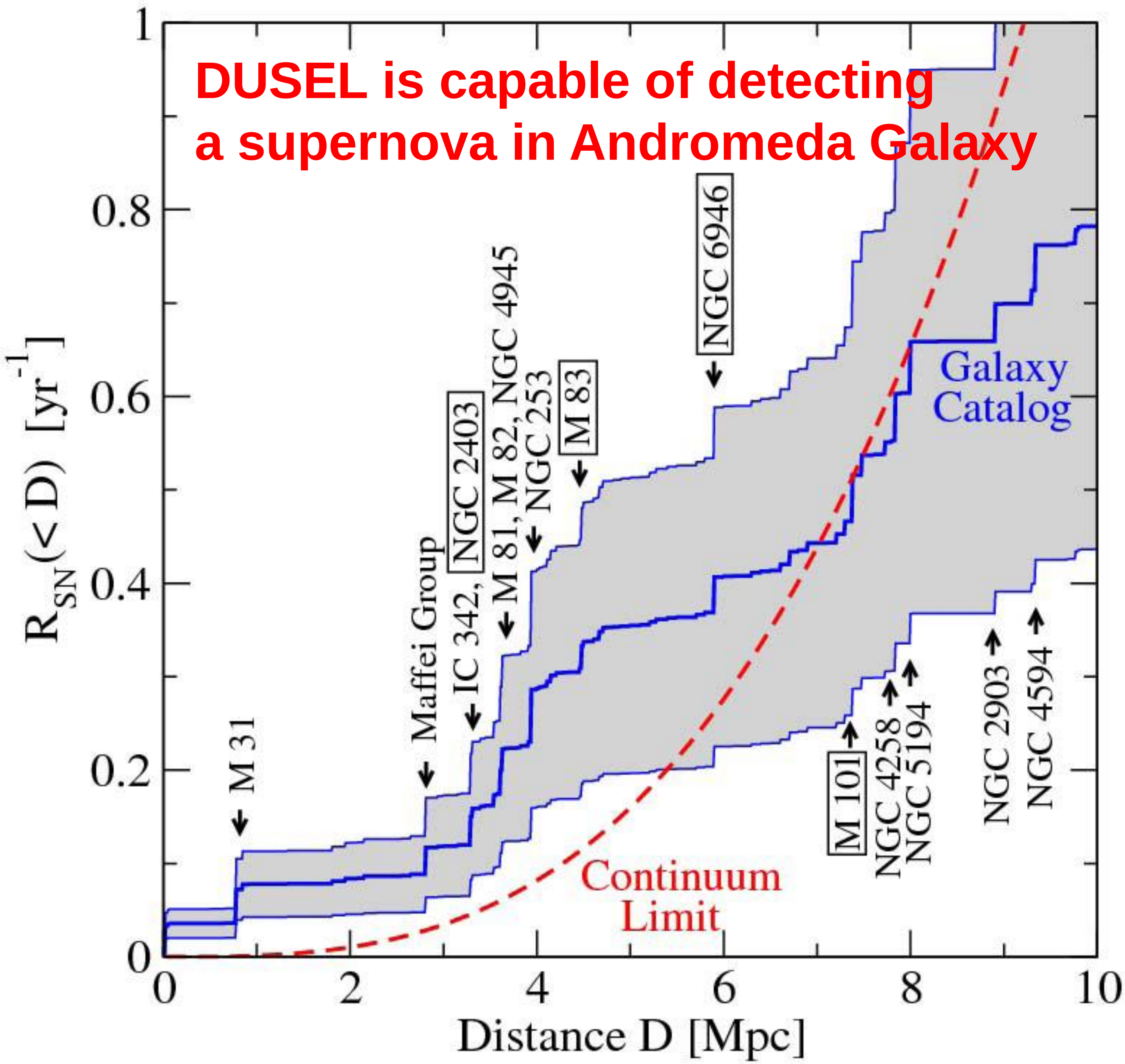


Supernova Burst

- Huge signal for a galactic supernova
- More importantly: very precise knowledge of the cross-section (~0.2%) for $\bar{\nu}_e + p \rightarrow e^+ + n$ makes the statistics meaningful!
- Double coincidence: zero background (need Gd)
- Positron spectrum mirrors neutrino spectrum

	10 kpc with 300 ktons
CC $\bar{\nu}_e$	70,000 events
NC ν_x	3,000 events
ES ν_e	3,000 events

S. Ando, J. F. Beacom and H.Yuksel, astro-ph/0503321



A SN in M31 would ~3-5 events/100 kton

It would be easily detectable in a large water detector of Size ~300 ktons

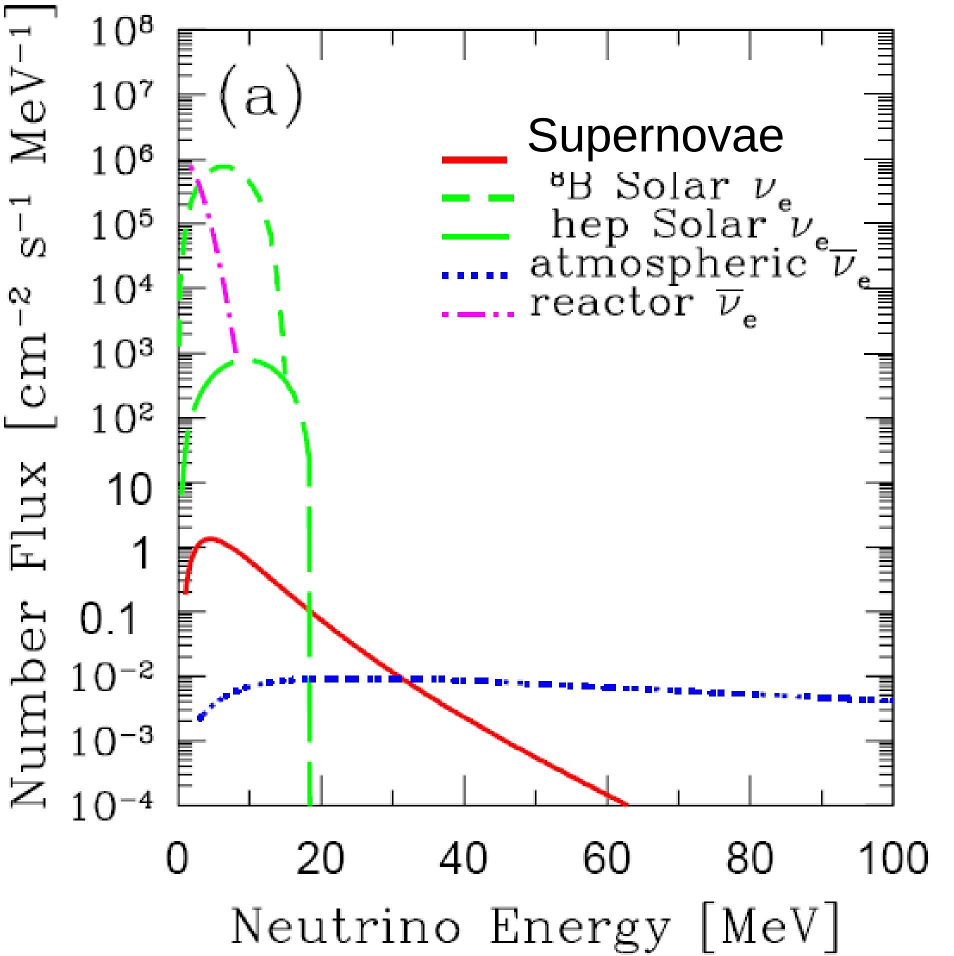
Background is large bursts of spallation products following a muon-induced shower

deeper is better

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.

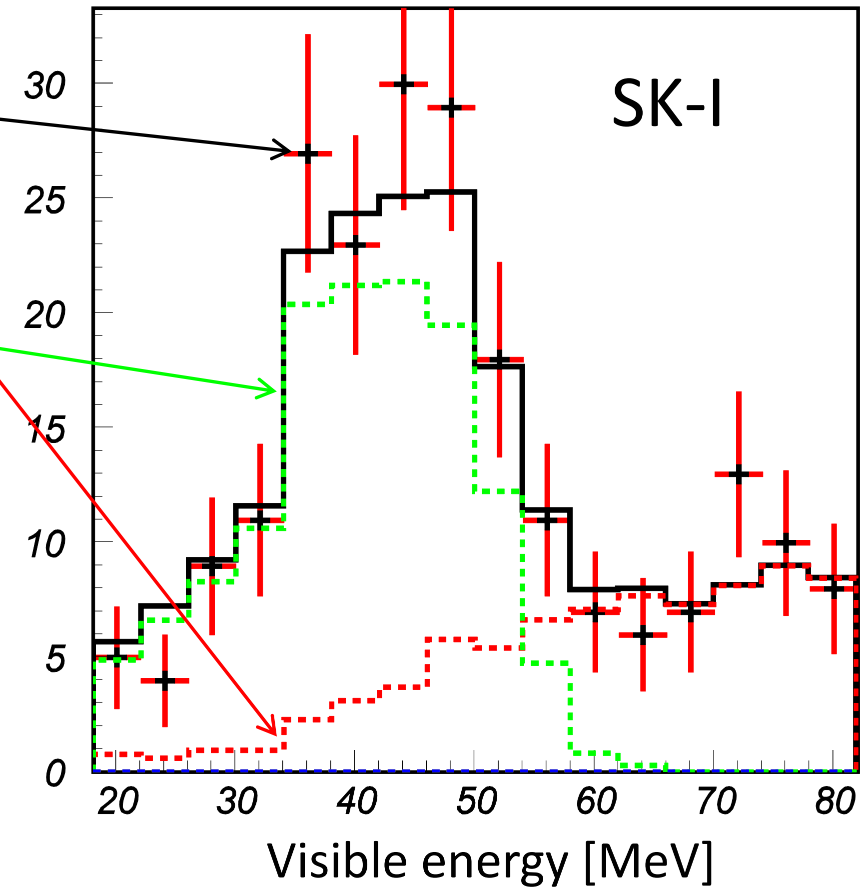
Spectrum fitting in SK-I

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

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

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

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



Courtesy Iida, ICRR

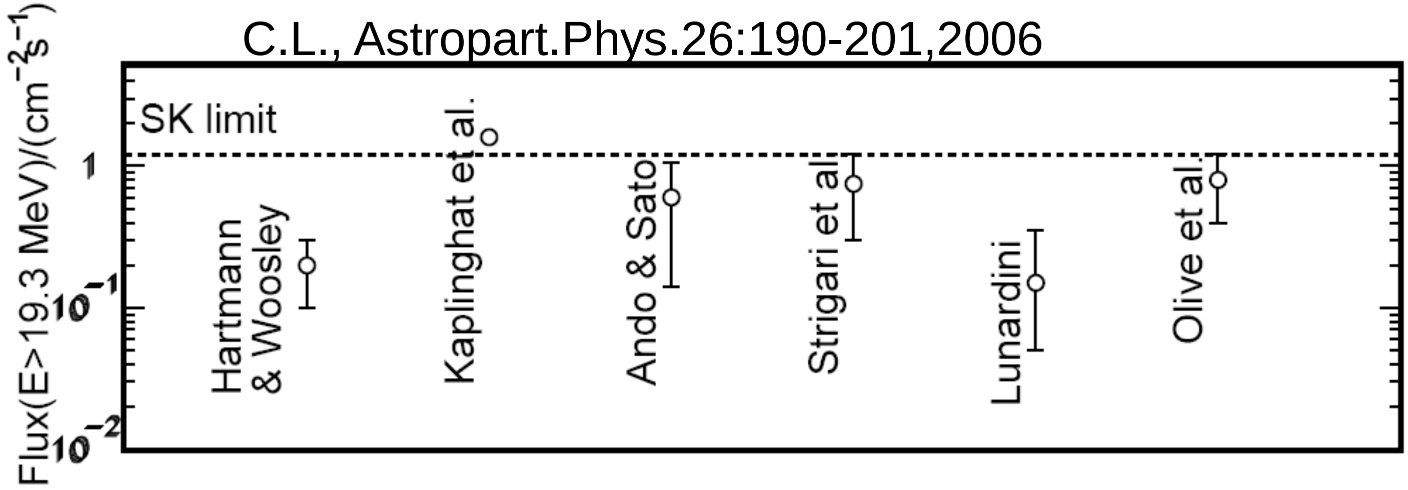
Gadolinium Doping

- Sensitivity to neutron capture via 8 MeV gamma cascade (e.g. M.Vagins, NNN08)
- Inexpensive, low risk. Could be implemented after construction completed, no schedule risk.
- Technical challenges:

  - material compatibility. Chose materials that do not contaminate the water.

  - water treatment . Remove impurities but leave gadolinium in solution.

Status of theory: anti-ν_e flux



- Differences due to different inputs/methods

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

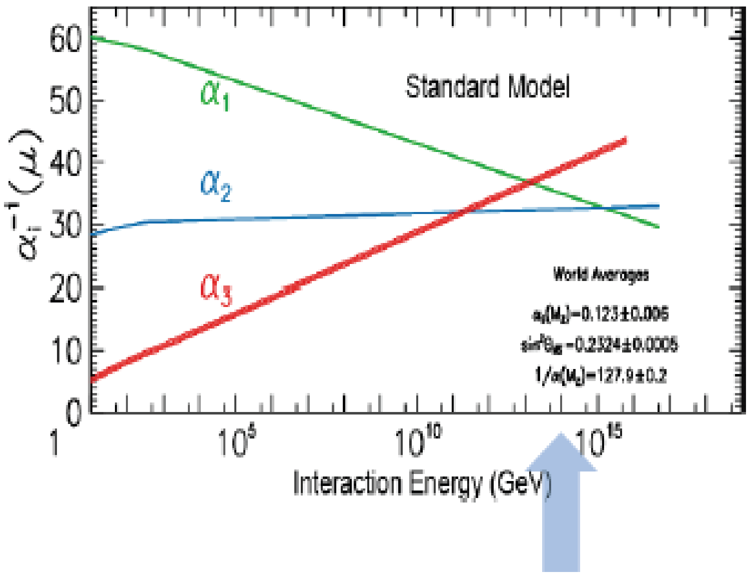
C.L., Astropart.Phys.26:190-201,2006, Fogli et al. JCAP 0504:002,2005, Volpe & Welzel, 2007, C.L. & O.L.G. Peres, to appear soon.

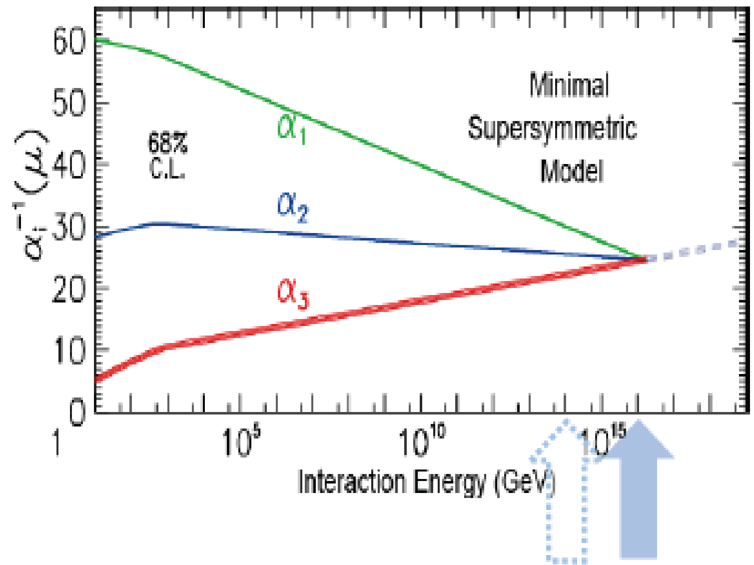
SK background of ~20/year significantly reduced by neutron tagging. (Beacom and Vagins)

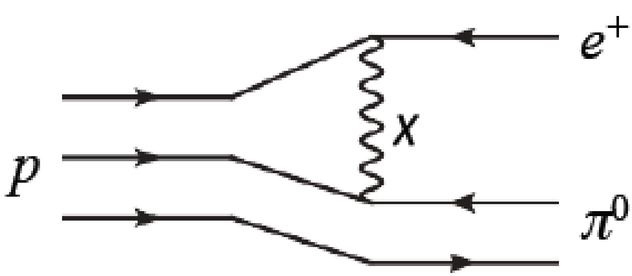
Nucleon Decay

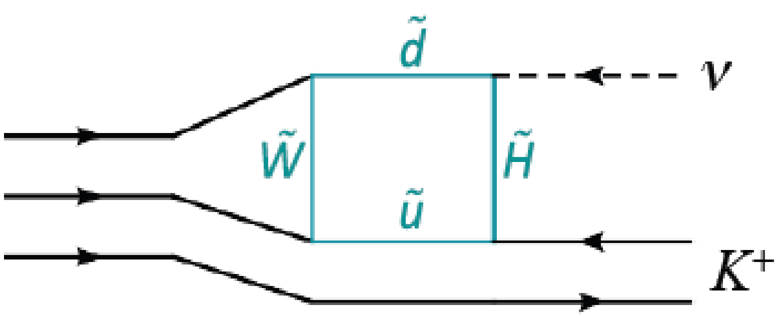
- Neutrinos, electrons, photons, and protons are the only known stable particles
- Stable over what time scale?
- Lifetime of universe 10^{10} years
- Many theories that try and unite the known forces of nature into a "Grand Unified Theory" (GUT) predict that free protons will decay with lifetimes of 10^{30} years or longer

Unification of Running Coupling Constants





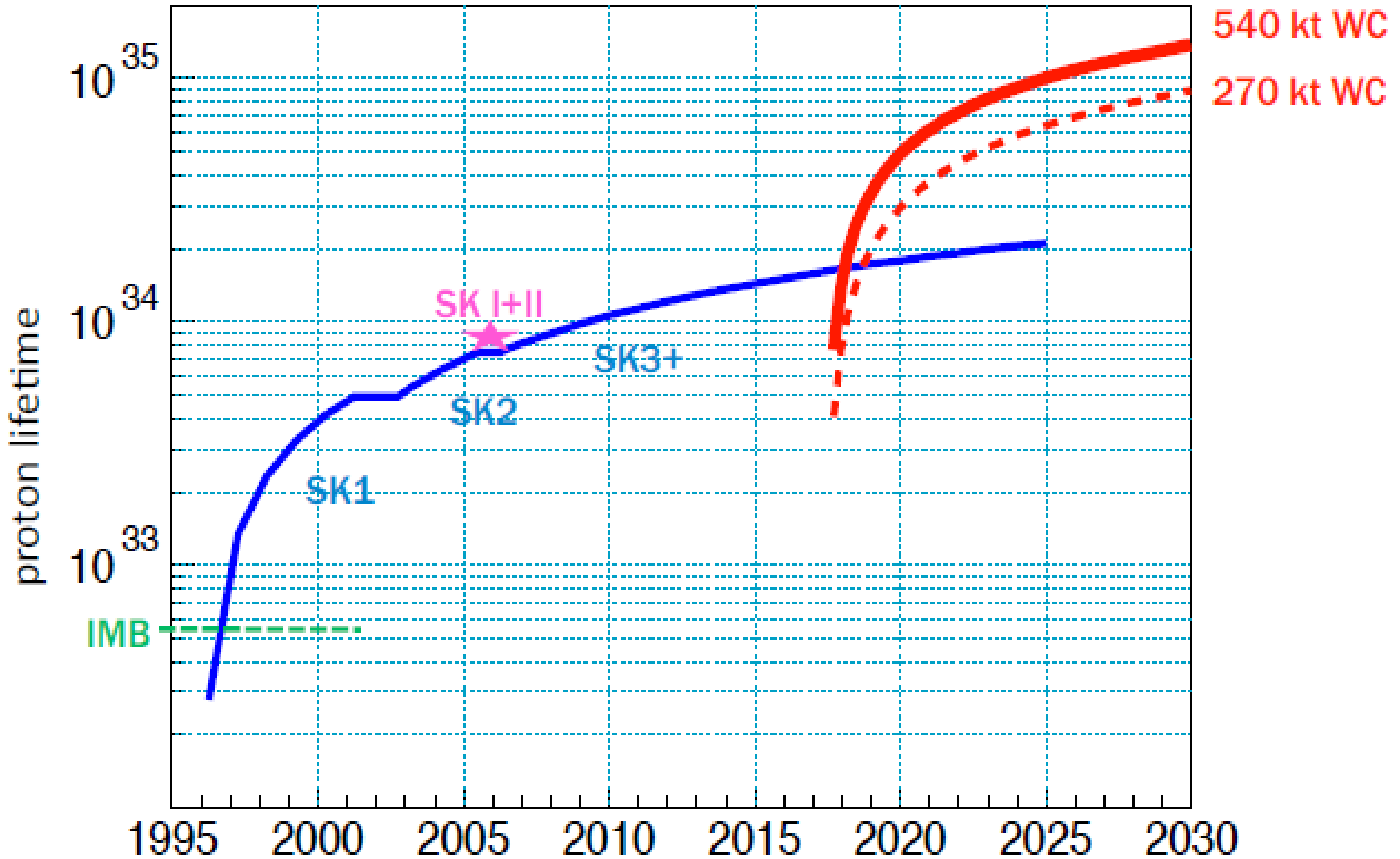




$\tau/B = 4.5 \times 10^{29\pm1.7}\text{years}\ \ \mathrm{SU(5)}$
$\tau/B > 8.4 \times 10^{33}\text{years}\ \ \mathrm{SK\ I+II}$

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

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



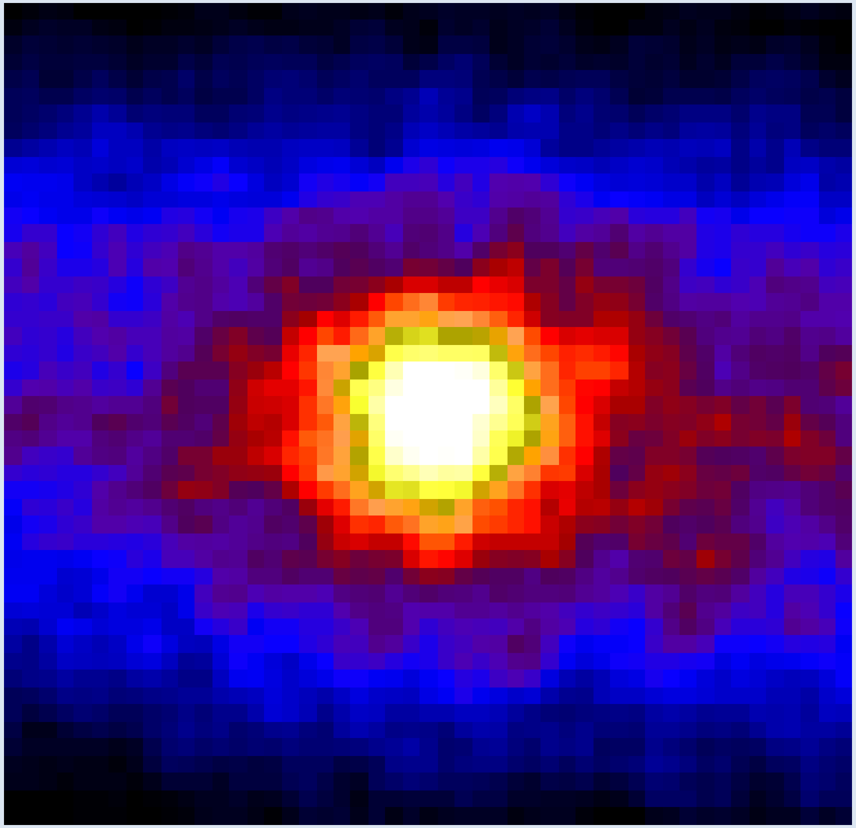
efficiency = 0.45

bg. rate = 0.2 evts/100 kty

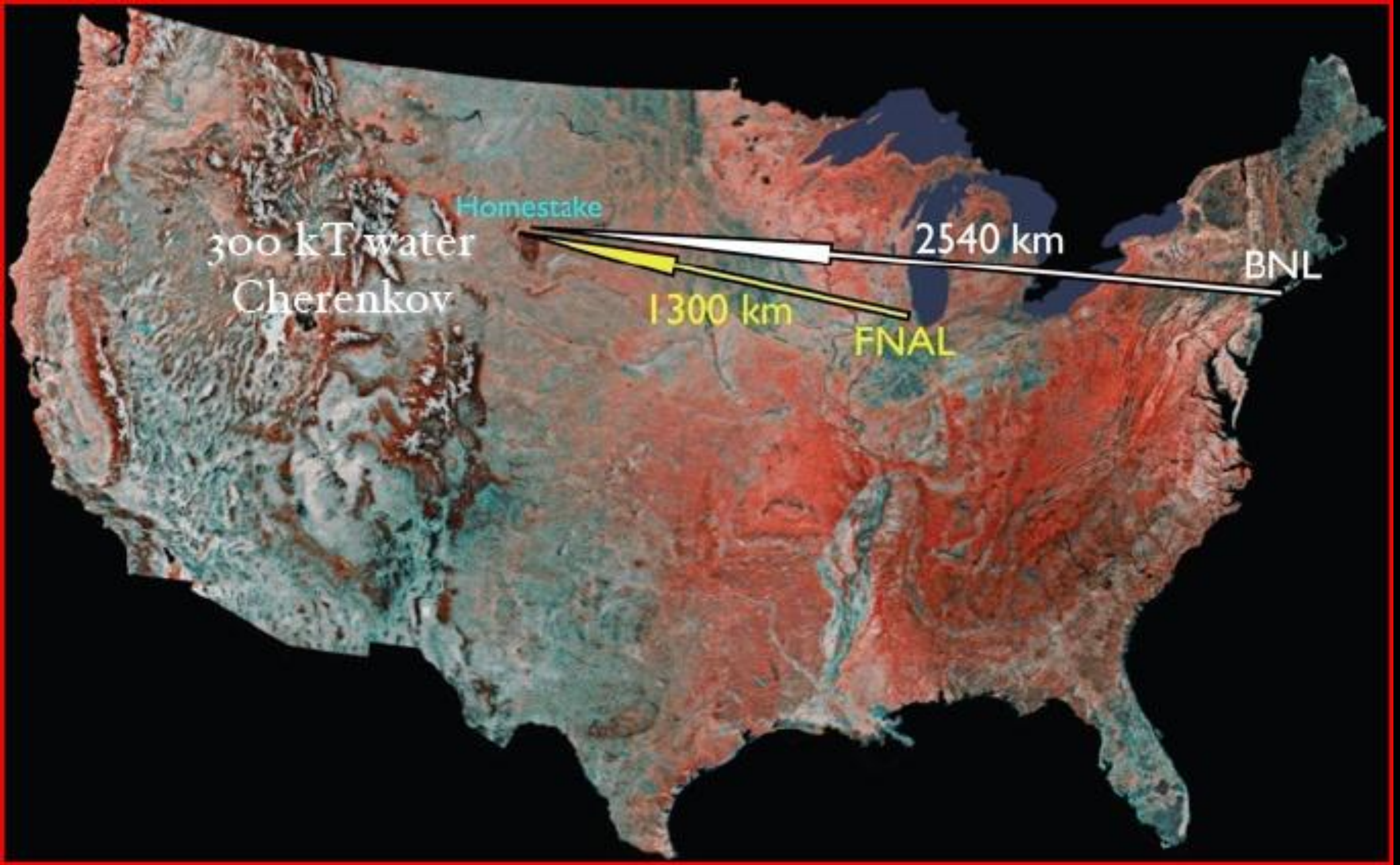
$N_{obs} = N_{bg}$

Solar Neutrinos: A well-understood beam of low-energy ν_e

- water Cherenkov technique allows for tracking
- neutrino-electron scattering preserves direction of parent neutrino
- recoil electron spectrum related to neutrino spectrum
- more than 200 per day!



DUSEL LONG BASELINE EXPERIMENT



Neutrino Mixing

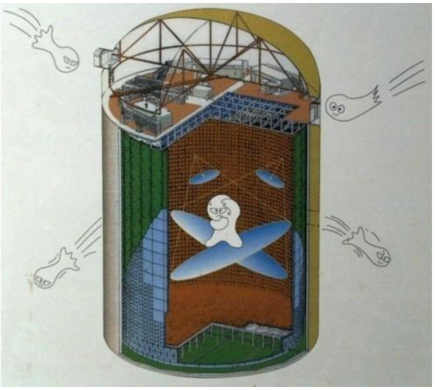
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

– U: 3 angles, 1 CP-phase + (2 Majorana phases)

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

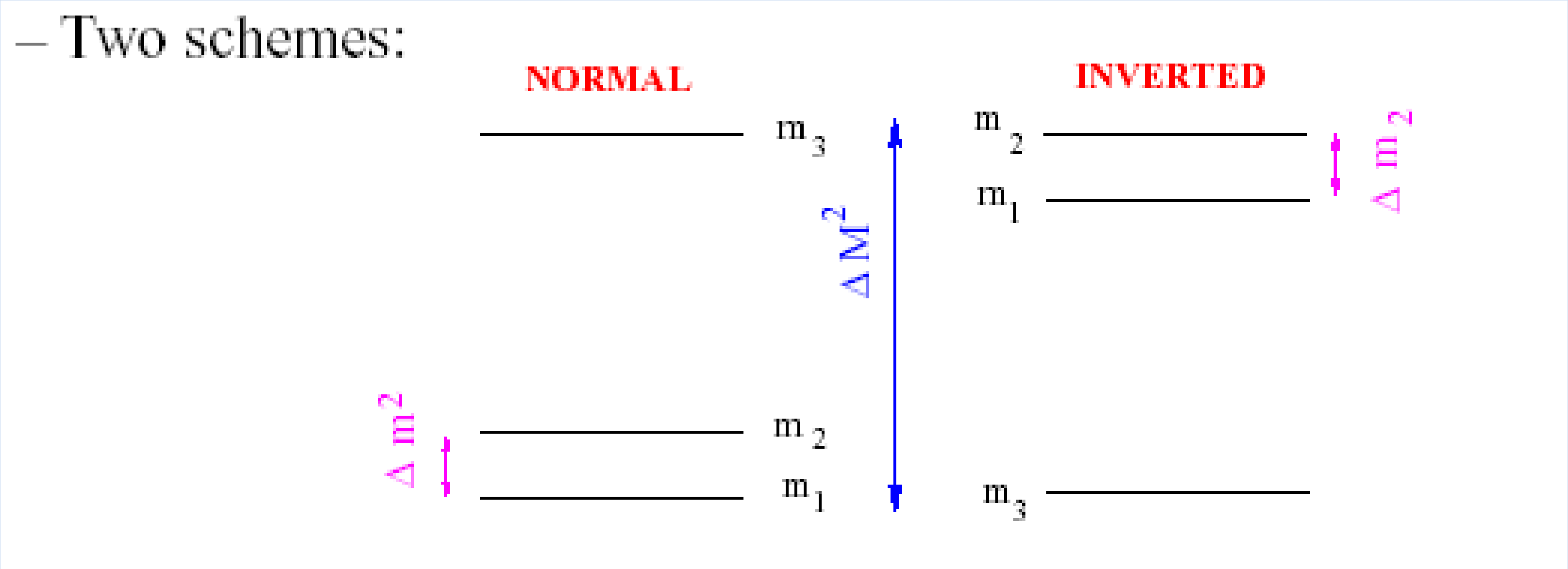
atmospheric

solar



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

but we don't know the **mass ordering** or **absolute mass scale**



Also –
Do ν's violate CP?

If θ_{13} is large enough Our DUSEL detector can answer the mass hierarchy and CP questions

ν_e appearance in a ν_μ beam

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

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

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

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

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

a = constant X $n_e E$

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

Experiments and Projects

An Experiment

A Project

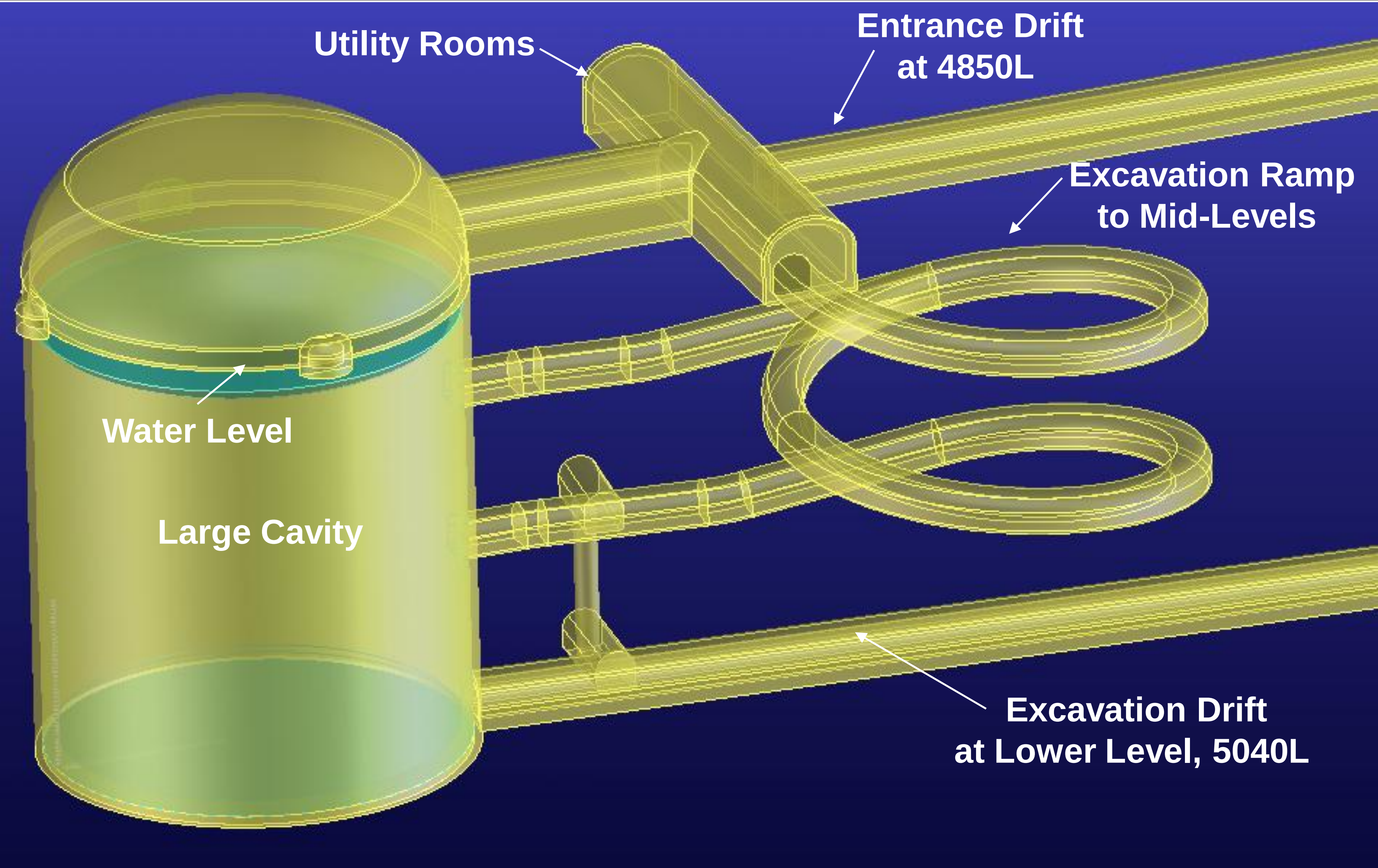
Major Project Components

- Neutrino Beam. Plan initially for 700 kw beam with potential for up to 3 MW later. Project Office at FNAL.
- Near Detector: for characterization of the beam. LANL proposed to have a major role.
- Far Detector. Project Office at BNL and S4 proposal from NSF for Water Cherenkov detector development. LAr detector development through FNAL (see Bonnie’s talk)

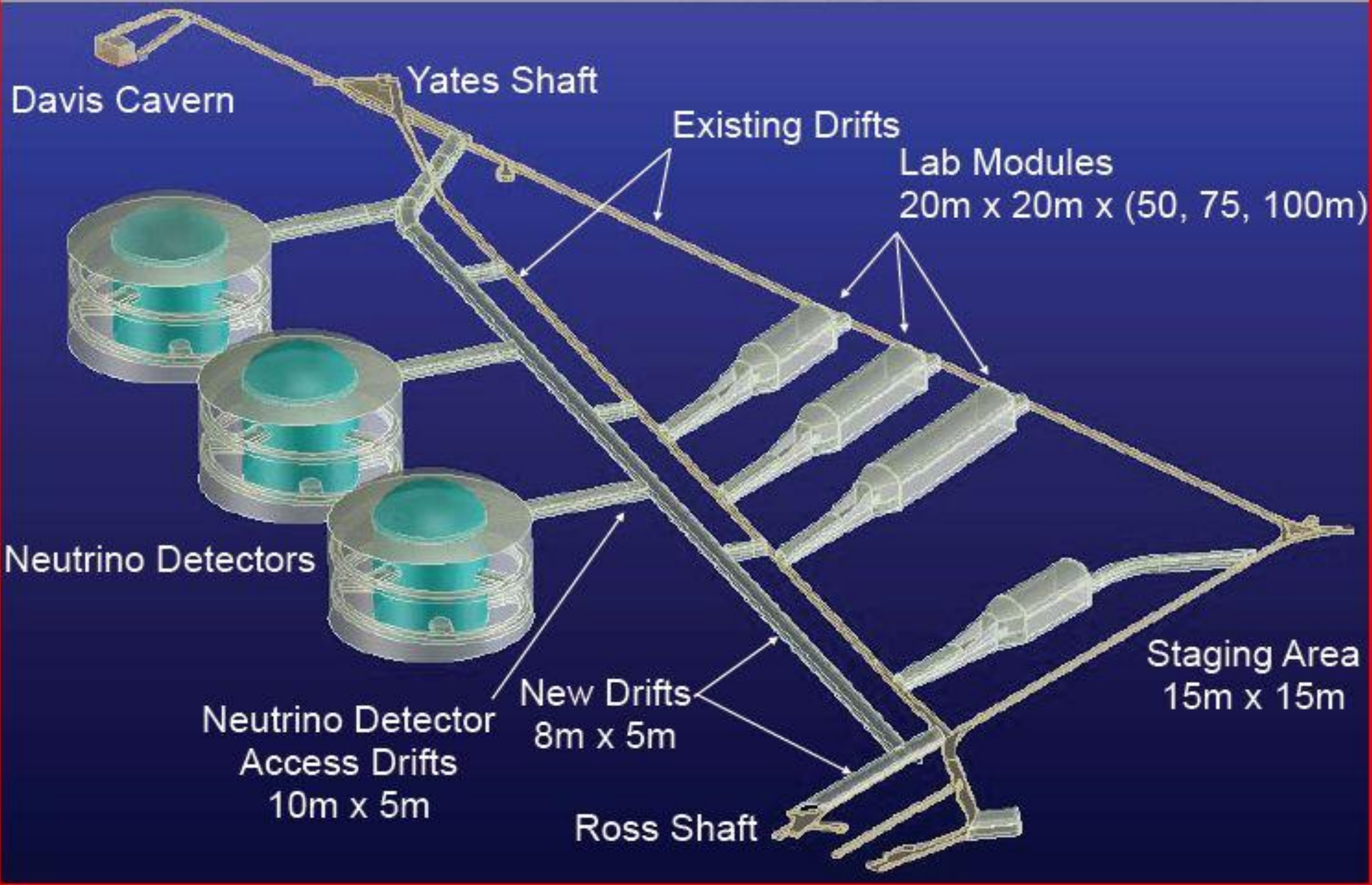
Large Cavity, Water Cerenkov Detector

Water: 53m Dia. x 54m vertical,

Fiducial Volume: 50m Dia. x 51m vertical



4850 Level Conceptual Layout



The Big Hole

- One large cavity is included in the scope of DUSEL
- Large Cavity Board report: a large 100 kton detector could be built safely and economically. 150 kton cavities may also be possible.
- RFP for cavity cost to be issued very soon
- DOE may also build one cavity

Water Containment

- Keep Rock out
- Keep water in
- Keep costs down

Possible Solutions

	Unit	Steel self supporting	Concrete blocks	Unitary post-stressed concrete vessel self supporting	Liner on shotcrete	Cast concrete against rock	Pressure balanced wall
Fiducail Radius	m	25	25	25	25	25	25
Gap between fiducial radius and PMT module	m	1	1	1	1	1	1
PMT module thickness	m	0.5	0.5	0.5	1	1	1
Gap between PMT module and tank wall	m	0	0	0	0.2	0	0.2
Sealing/coating layer thickness	m	0.005	0.005	0.005	0.005	0.005	0.01
Tank water radius	m	26.51	26.51	26.51	27.21	27.01	27.21
Tank wall thickness top	m	0.05	0.5	1	0.1	1	0.01
Tank wall thickness bottom	m	0.12	0.5	1.0	0.1	1	0.0
Tank wall thickness average	m	0.09	0.50	1.00	0.10	1.00	0.01
Tank outer radius	m	26.63	27.01	27.51	27.31	28.01	27.22
Access/drainage/balance gap	m	2	0.2	3	0	0	0.5
Rock wall raidus	m	28.63	27.21	30.51	27.31	28.01	27.72
Tank wall mass	tonne	5989	11453	23331	2316	23755	231
Fiducial volume	cu m	100000	100000	100000	100000	100000	100000
Fiducial height	m	51	51	51	51	51	51
Tank water height	m	54	54	54	54	54	54
Tank floor thickness	m	2	2	2	2	2	2
Excavation height	m	56	56	56	56	56	56
Excavation volume (without upper part)	cu m	144155	130207	163712	131166	137978	135184
Normalized		1.04	0.94	1.19	0.95	1.00	1.00

SK
miniBooNE

IMB, SNO
KamLAND

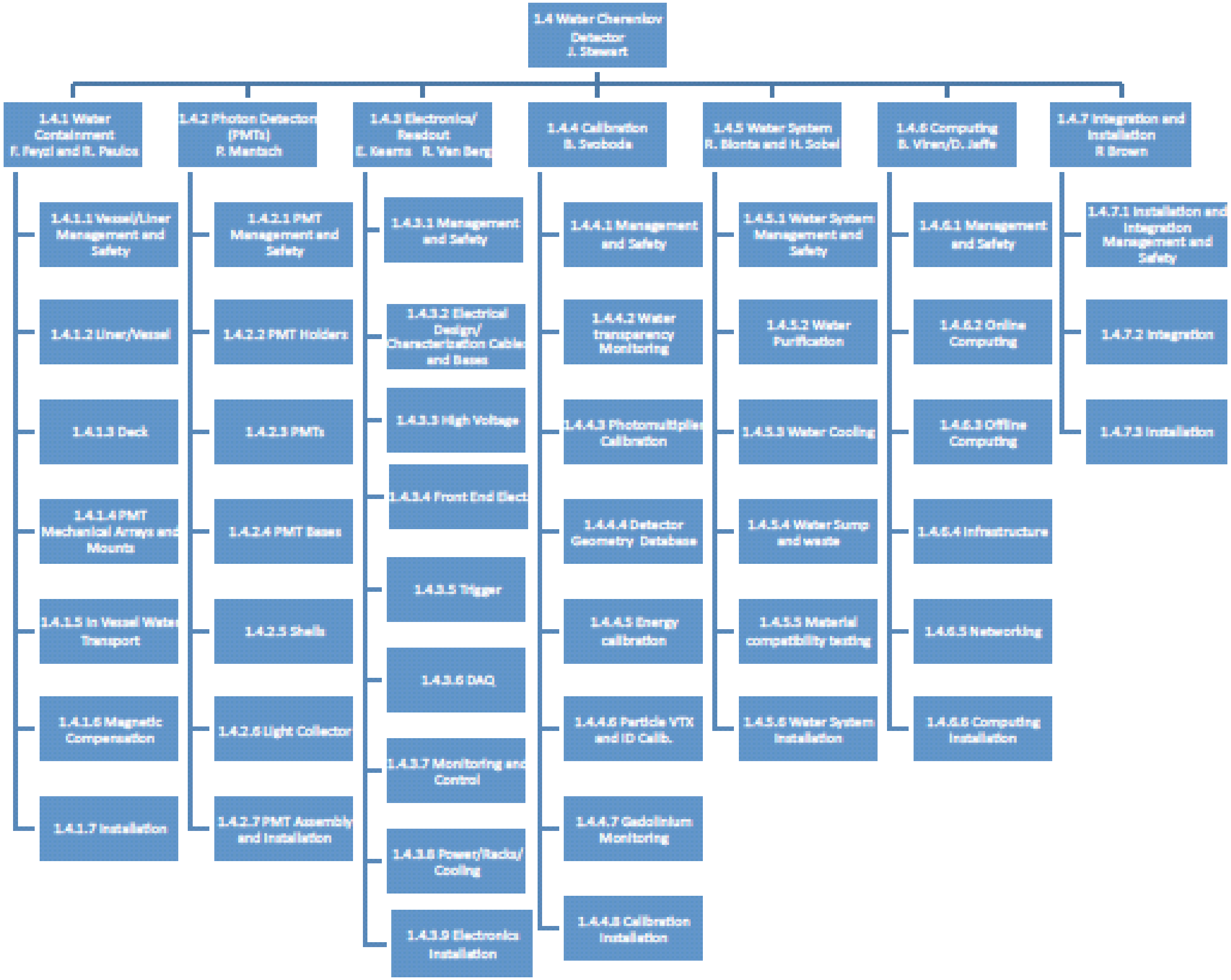
Photon Economics

- About 50% of the detector cost is expected to be in photosensors
- Even small improvements can make a big impact
- Development of light enhancement techniques underway
- New high QE PMTs are now available – will be tested in a statistically large sample this year
- Prevention of implosion chain reaction (BNL+U.S. Navy)
- Developments outside S4: waveshifting dyes, MCP development

Other Experiment Components

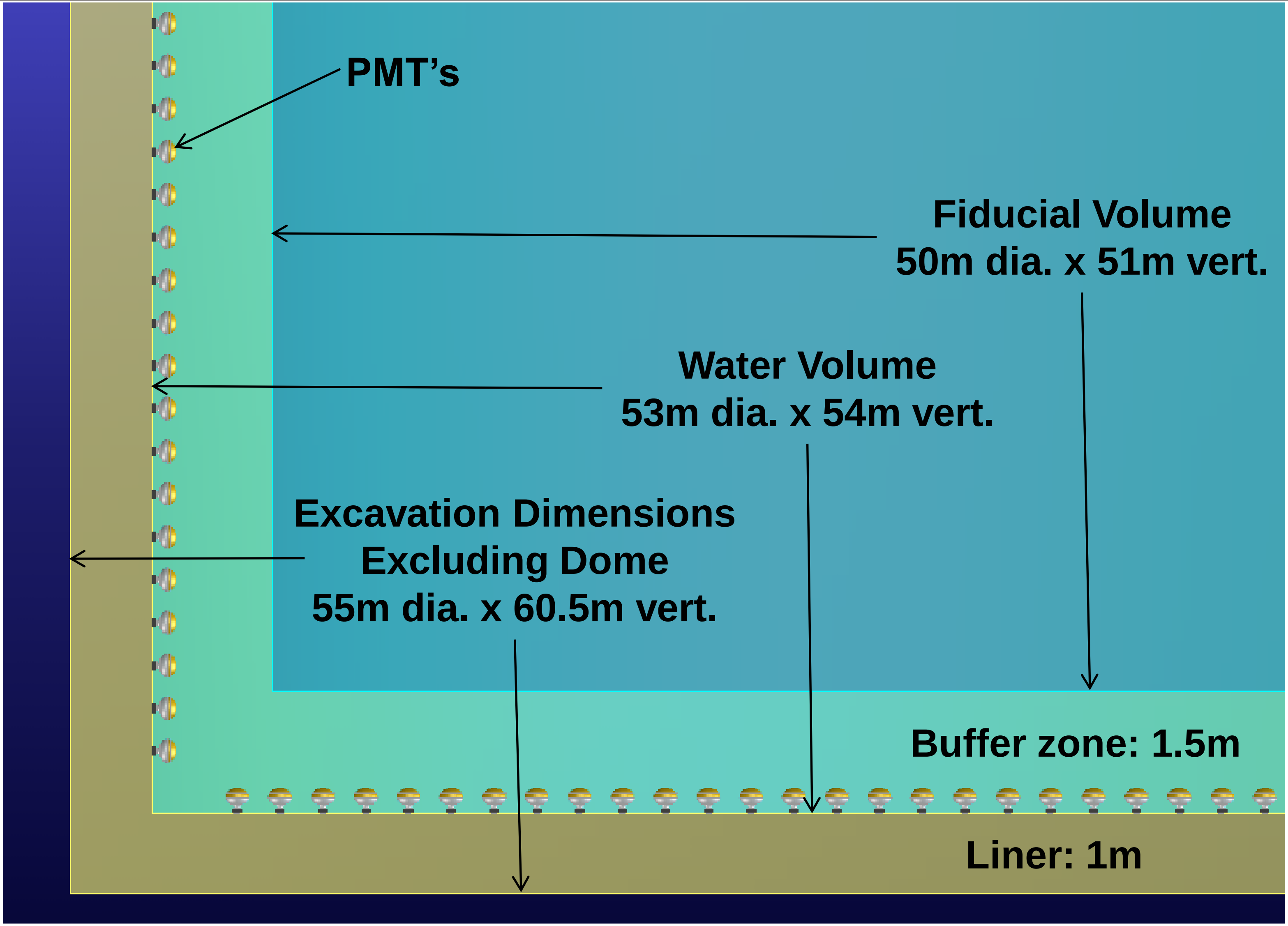
- Electronics
- Water transparency
- Gadolinium loading
- Calibrations
- Project Integration
- Safety
- Environmental Impact

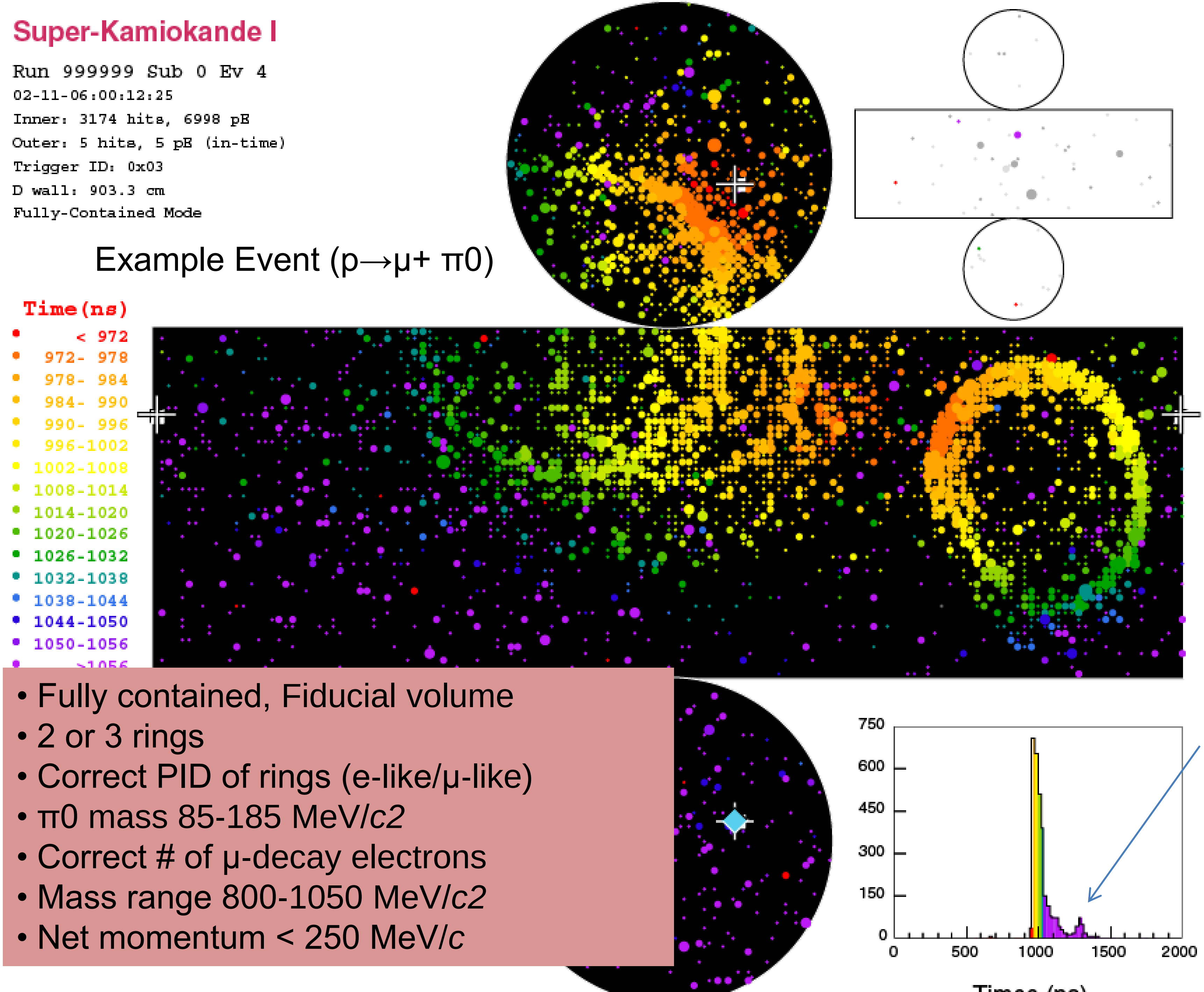
There is excellent cooperation between the DOE and NSF groups


1.4 Water Cherenkov Detector
J. Stewart
1.4.1 Water Containment
F. Feyzi and R. Paulos
1.4.2 Photon Detection (PMTs)
P. Mantsch
1.4.3 Electronics/ Readout
E. Kearns R. Van Berg
1.4.4 Calibration
B. Svoboda
1.4.5 Water System
R. Bionta and H. Sobel
1.4.6 Computing
B. Viren/D. Jaffe
1.4.7 Integration and Installation
R Brown
1.4.1.1 Vessel/Liner Management and Safety
1.4.1.2 Liner/Vessel
1.4.1.3 Deck
1.4.1.4 PMT Mechanical Arrays and Mounts
1.4.1.5 In Vessel Water Transport
1.4.1.6 Magnetic Compensation
1.4.1.7 Installation
1.4.2.1 PMT Management and Safety
1.4.2.2 PMT Holders
1.4.2.3 PMTs
1.4.2.4 PMT Bases
1.4.2.5 Shells
1.4.2.6 Light Collector
1.4.2.7 PMT Assembly and Installation
1.4.3.1 Management and Safety
1.4.3.2 Electrical Design/ Characterization Cables and Bases
1.4.3.3 High Voltage
1.4.3.4 Front End Elect
1.4.3.5 Trigger
1.4.3.6 DAQ
1.4.3.7 Monitoring and Control
1.4.3.8 Power/Racks/ Cooling
1.4.3.9 Electronics Installation
1.4.4.1 Management and Safety
1.4.4.2 Water transparency Monitoring
1.4.4.3 Photomultiplier Calibration
1.4.4.4 Detector Geometry Database
1.4.4.5 Energy calibration
1.4.4.6 Particle VTX and ID Calib.
1.4.4.7 Gadolinium Monitoring
1.4.4.8 Calibration Installation
1.4.5.1 Water System Management and Safety
1.4.5.2 Water Purification
1.4.5.3 Water Cooling
1.4.5.4 Water Sump and waste
1.4.5.5 Material compatibility testing
1.4.5.6 Water System Installation
1.4.6.1 Management and Safety
1.4.6.2 Online Computing
1.4.6.3 Offline Computing
1.4.6.4 Infrastructure
1.4.6.5 Networking
1.4.6.6 Computing Installation
1.4.7.1 Installation and Integration Management and Safety
1.4.7.2 Integration
1.4.7.3 Installation

The Goal

Large Cavity, Water Cerenkov Detector,
Cross Section at bottom



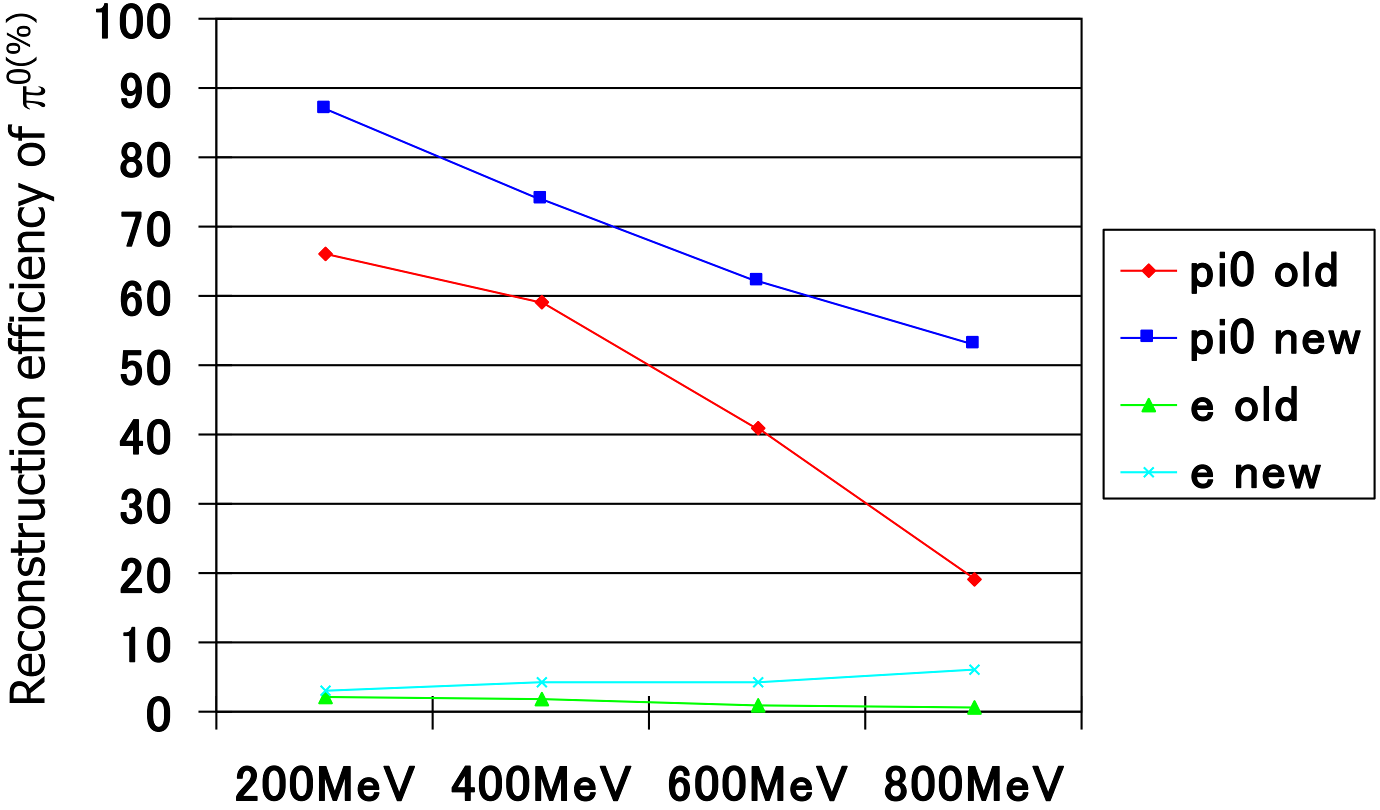


Example Event (p→μ+ π0)

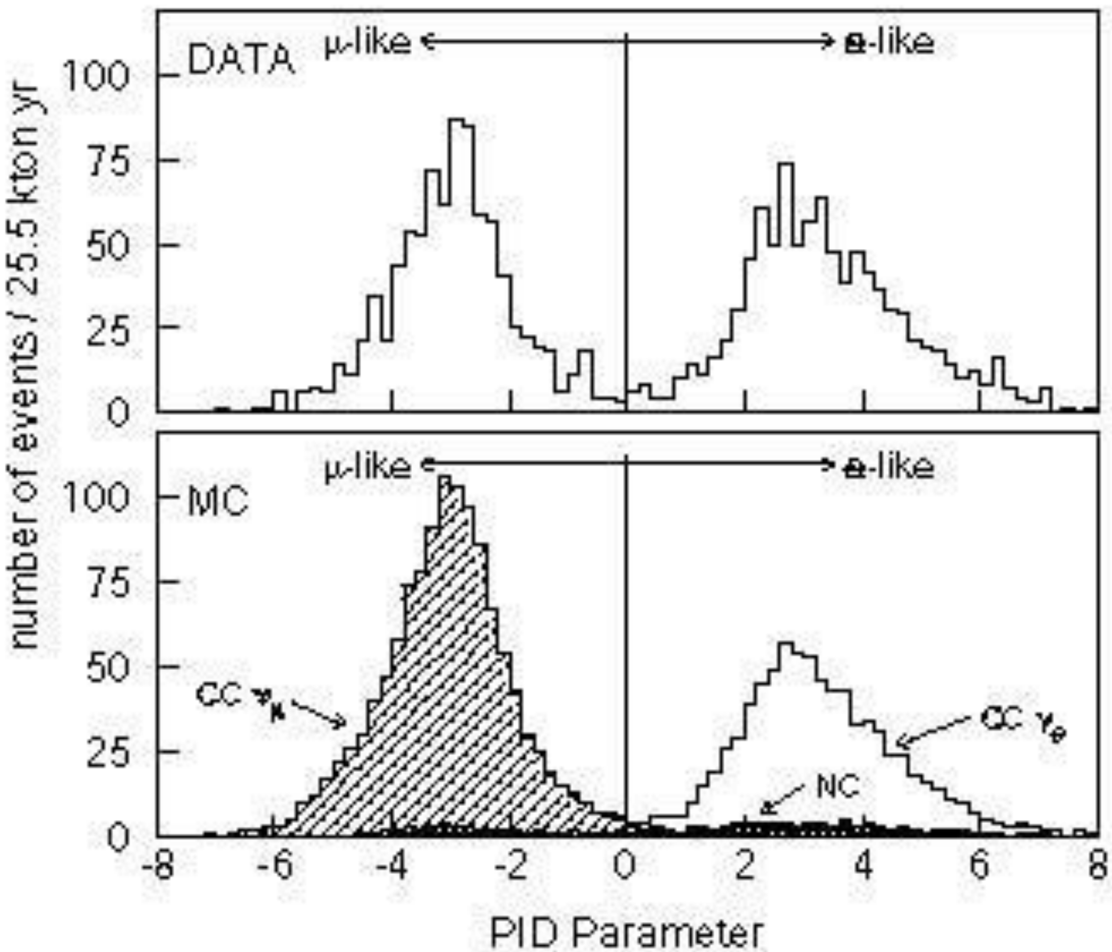
- Fully contained, Fiducial volume
- 2 or 3 rings
- Correct PID of rings (e-like/μ-like)
- π0 mass 85-185 MeV/*c2*
- Correct # of μ-decay electrons
- Mass range 800-1050 MeV/*c2*
- Net momentum < 250 MeV/*c*

Improved π^0/e separation

- 2-R e-like tag (old ring-finder)
- π^0 fitter (improved ring-finder)

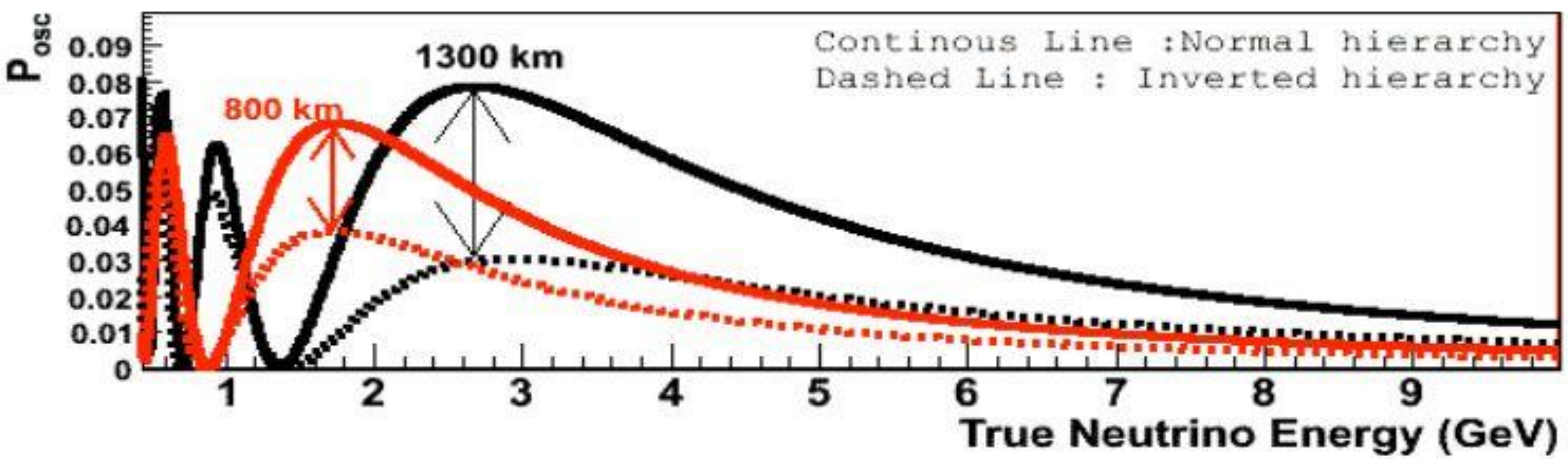


Excellent particle identification

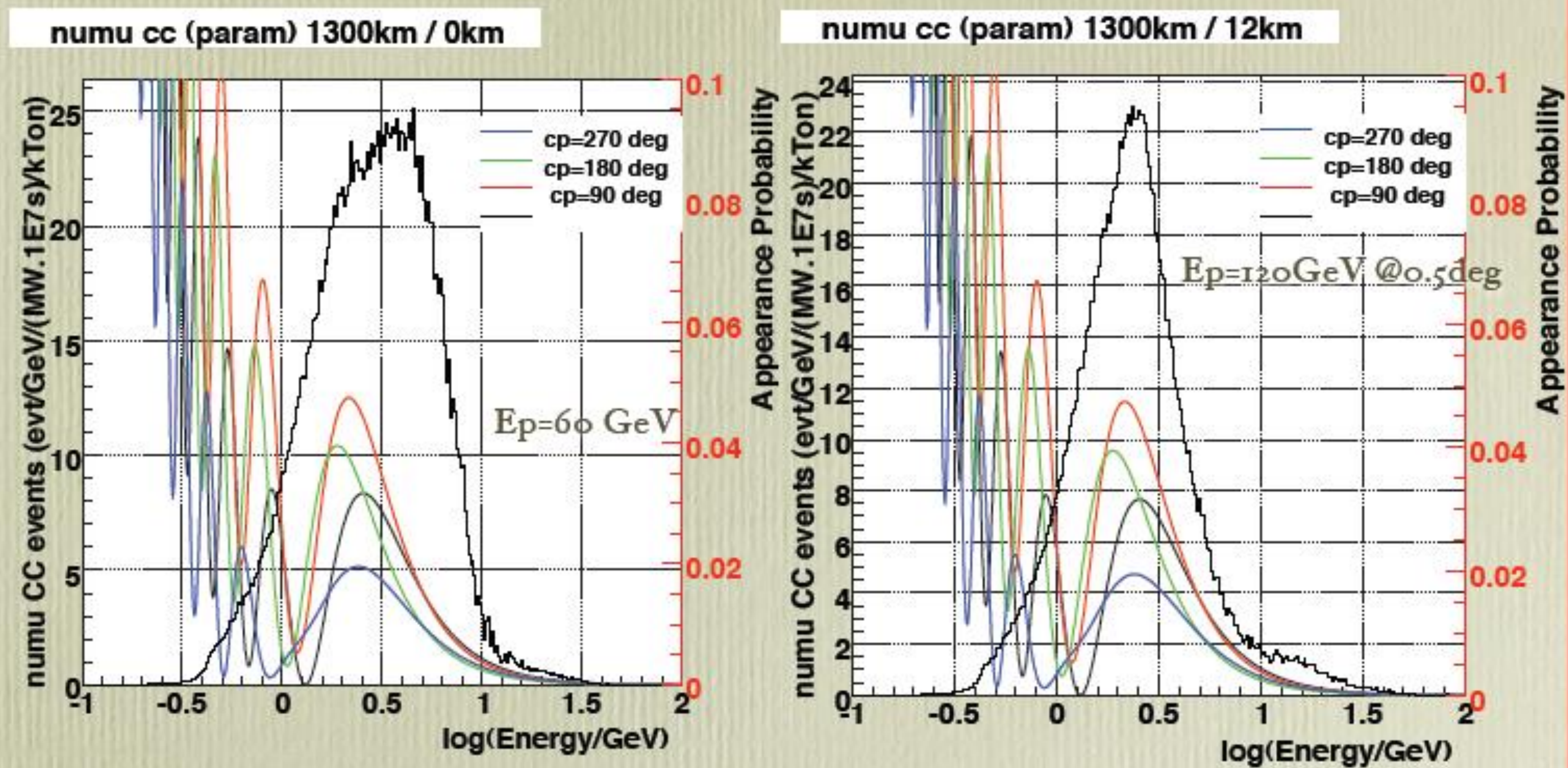


Why DUSEL?

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



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



- 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

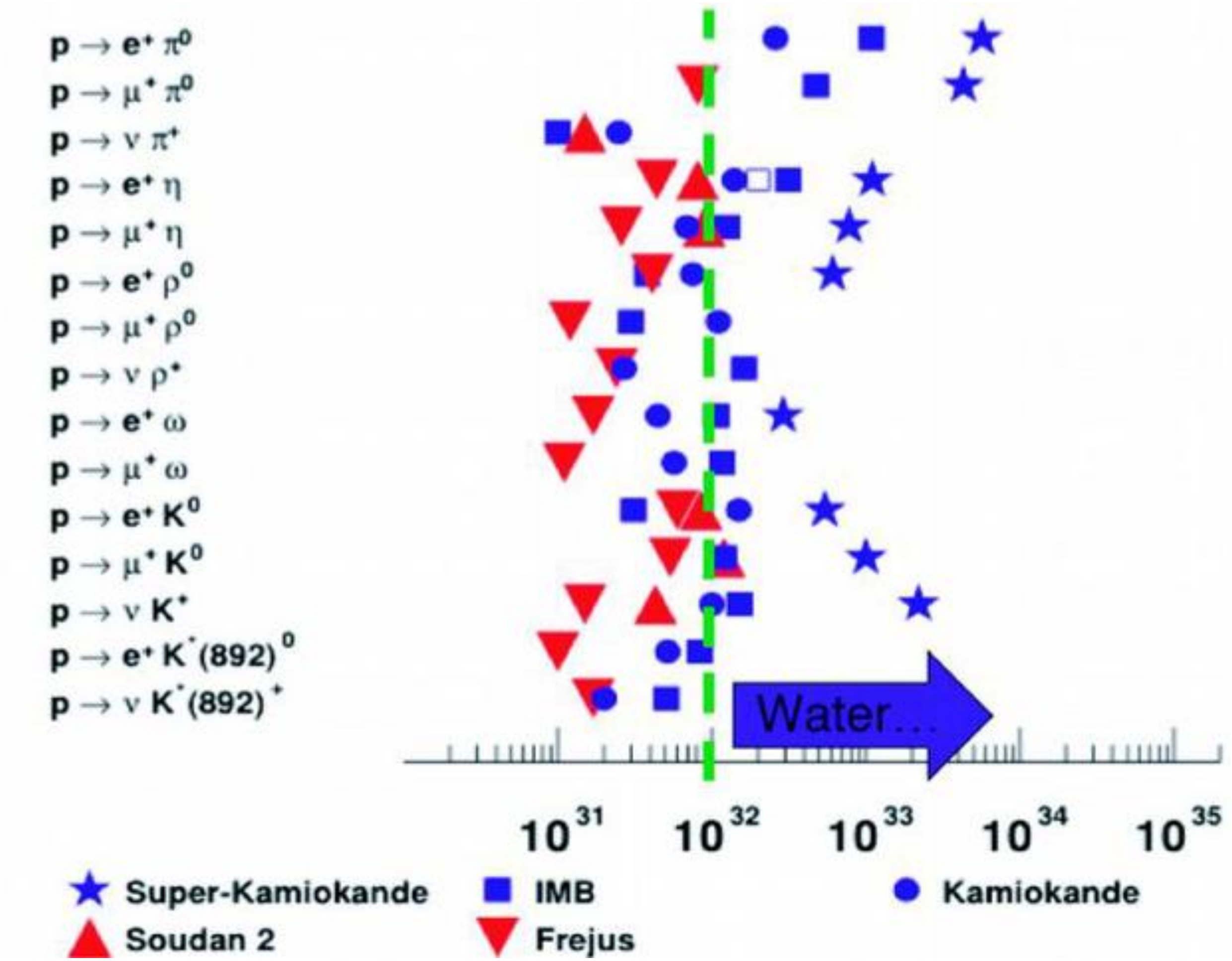
Office of Science U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY

PMT considerations

	10 inch R7081	20 inch R3600
Number (25% cov)	~50000	~14000
QE	25%	20%
CE	~80%	~70%
rise time	4 ns	10 ns
Tube length	30 cm	68 cm
Weight	1150 gm	8000 gm
Vol.	~5 lt	~50 lt
pressure rating	0.7Mpa	0.6Mpa
∢ coverage/pmt	0.6 deg	1.1 deg
∢ granularity	1.0 deg	2.1 deg

Proton Decay Limits



Data so far

PMT	size	Break Press
R7081/ng 1	10inch	148 psi
XP1807 1	12 inch	92 psi
xp18060 1	8 inch	35 psi
R7081 2	10 inch	cycled 132psi
R7081 3	10 inch	cycled 132 psi
R7081 4	10 inch	cycled 132 psi
R7081/lowr1	10 inch	205 psi
R7081/lowr 2	10 inch	218 psi
R7081	10 inch	292 psi
ETL 9350ka	8 inch	68 psi
R7081	10 inch	173 psi

Hamamatsu tested 3 R7081 upto ~10 atm.
One broke at 10 atm,
On each tube, there is data on glass thickness, pressure pulse duration, etc.
This it borosilicate glass with thickness ranging from 0.08 to 0.12 inch.

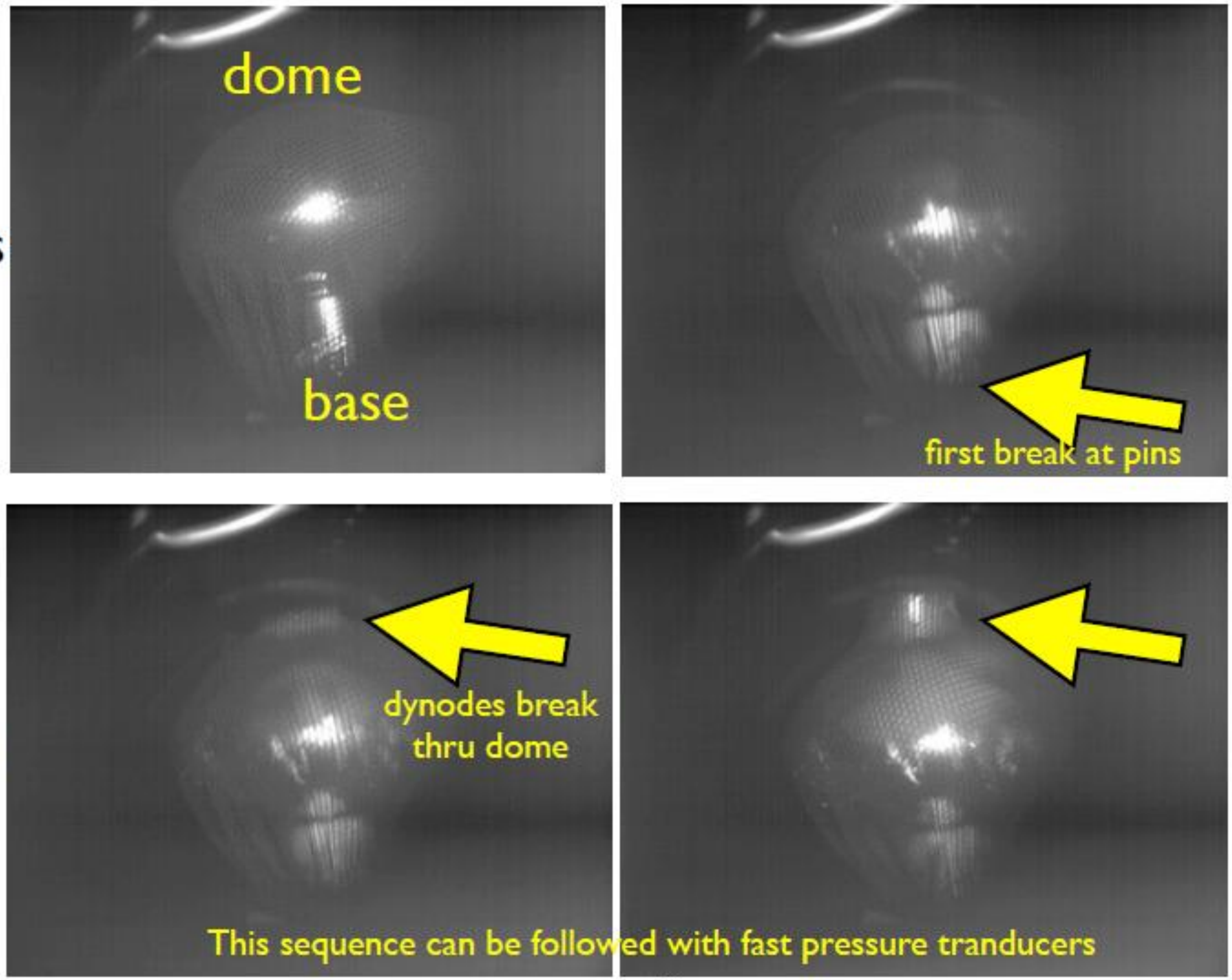
Typical R7081 failure
(TA3085 failed at 13.4 bar)

0 ms

2 ms

4 ms

6 ms



NAVSEA test stand

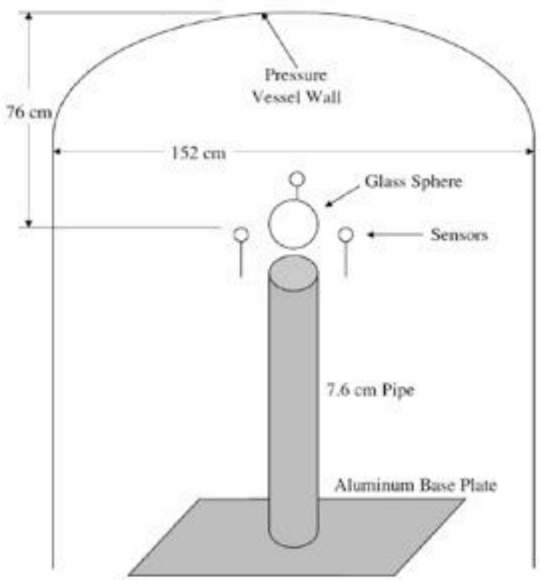
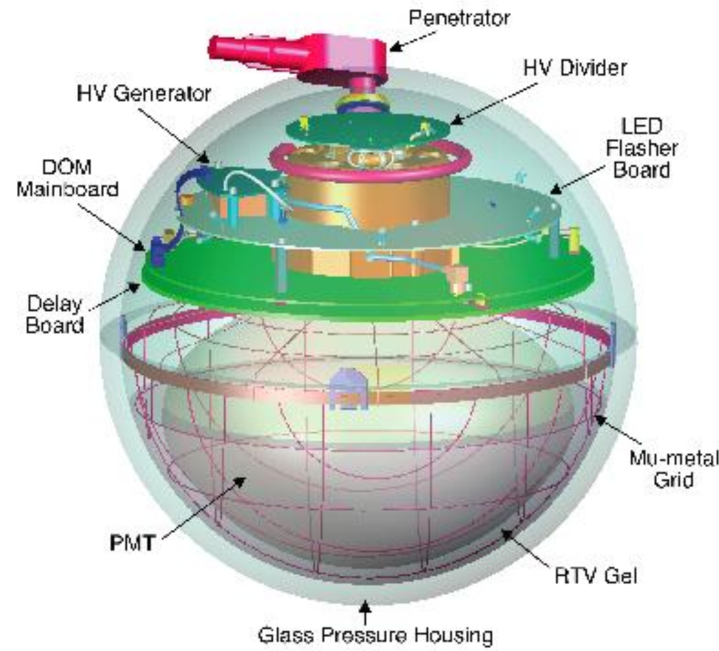


FIG. 2. Test stand schematic.

FIG. 1. Test stand with test sample and instrumentation installed.

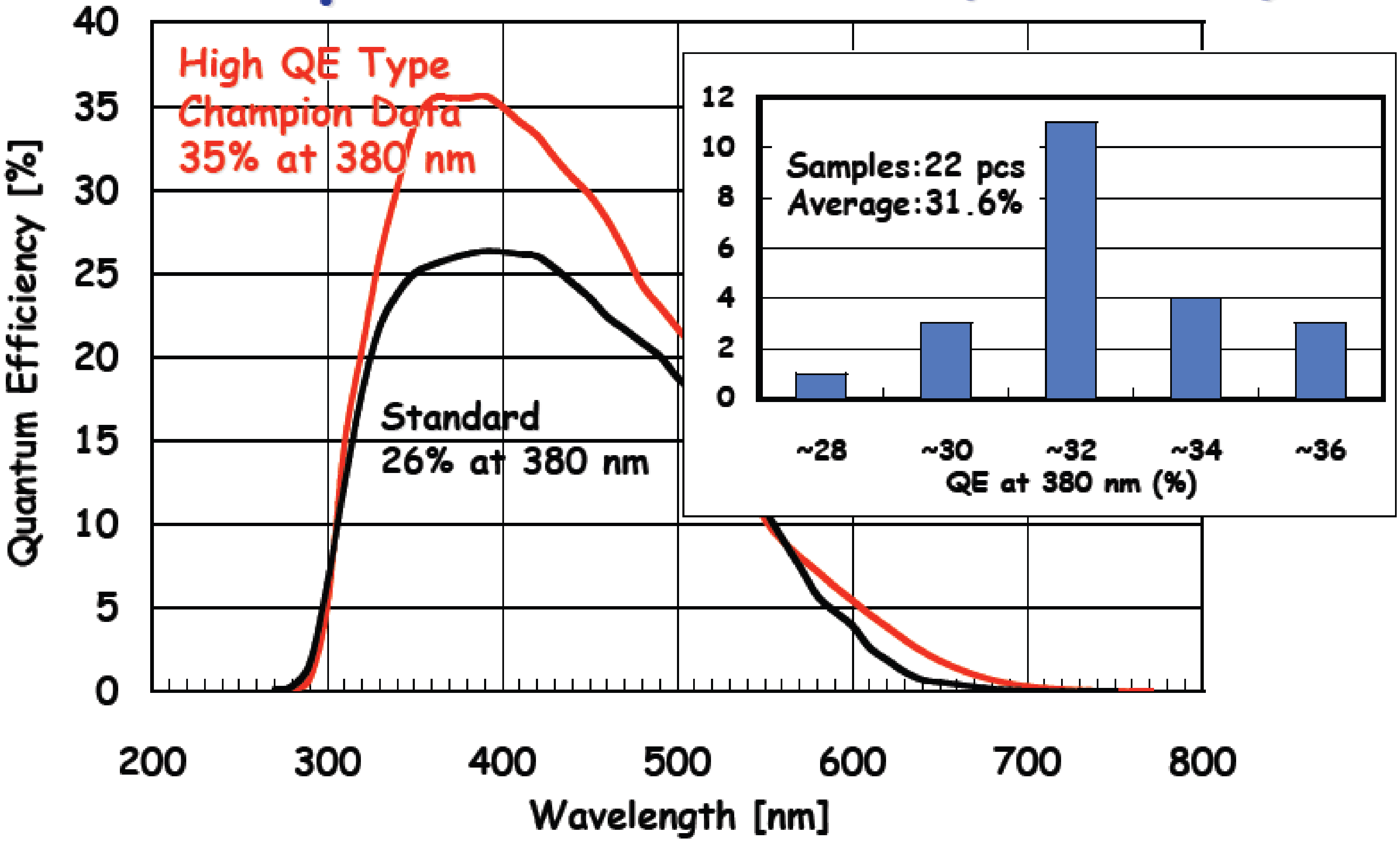
78 high quantum efficiency 10”PMT successfully tested for use in IceCube

- More than 4000 sensors with standard 10” PMT (R7081-02) integrated and tested in IceCube
- 78 high quantum efficiency PMT (10”) tested with IceCube standard production test program.
- Result:
  - Quantum efficiency ~38% higher (405 nm, -40C)
  - No problems found
  - Low temperature (-40C) noise behavior scales with quantum efficiency as expected.
- Plan to use high QE PMT on 6 Deep Core strings for enhanced sensitivity at low energies (<100GeV, dark matter)
- Sensors already at the South Pole



A. Karle, UW-Madison

Example data R7081 (10 inch)

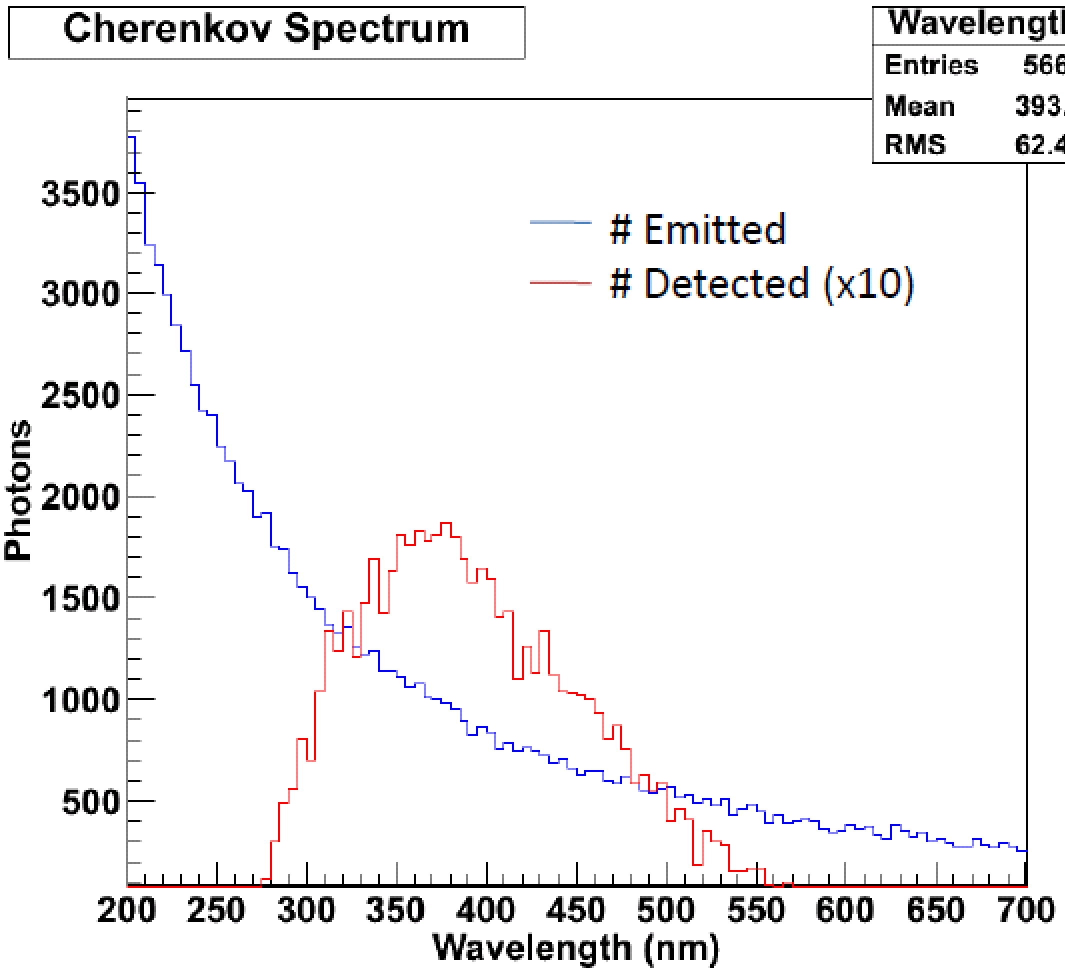


Goal of development is 43%

M.Diwan

Cherenkov Radiation:

$$\frac{d^2N}{dx\,d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$

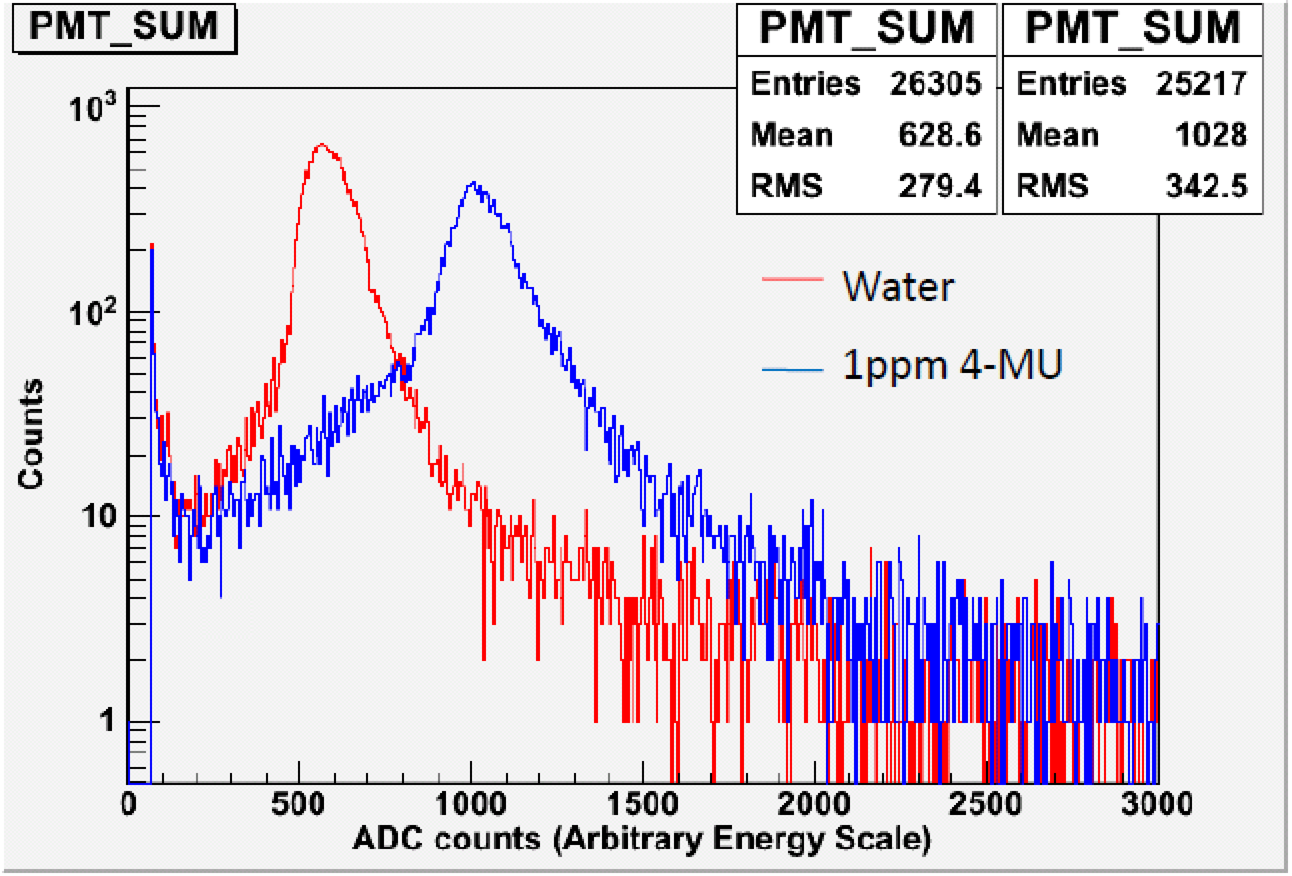


Cherenkov spectrum is dominated by UV photons. Typical PMT Quantum Efficiencies are poor in most of this range.

Idea: Absorb UV photons and re-emit them at longer wavelengths.

Preliminary Data (i.e. taken last week) :

Tagged muon spectrum:



Downward travelling muons are tagged in scintillator paddles.

UCDAVIS UNIVERSITY OF CALIFORNIA

Water Purification system:

Beakers are illuminated by a fluorescent UV light

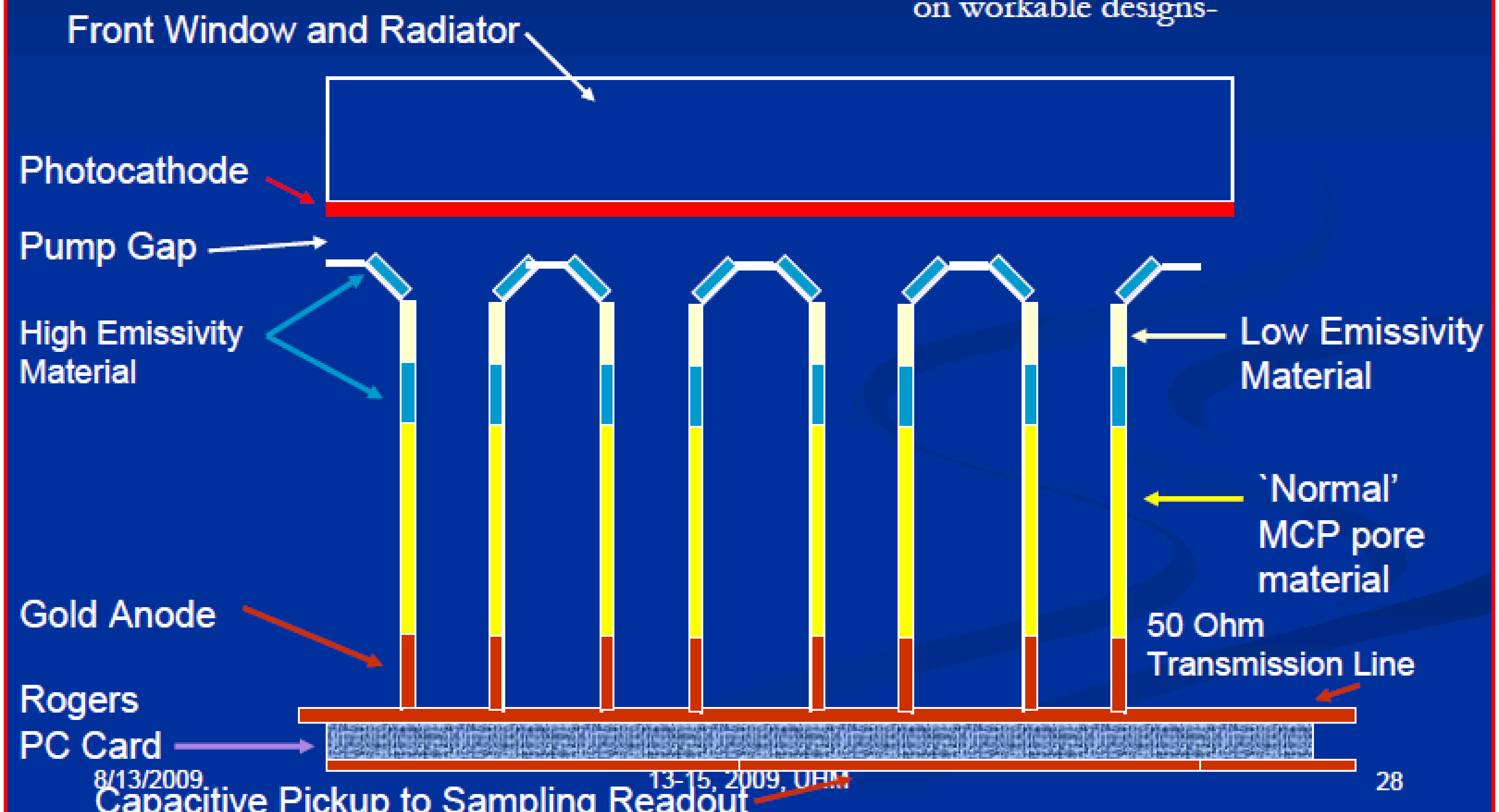
Tap Water 1ppm 4-MU

Tap Water 1ppm 4-MU after ~5min in DI system

UCDAVIS
UNIVERSITY OF CALIFORNIA

Large-area Micro-Channel Plate Panel "Cartoon"

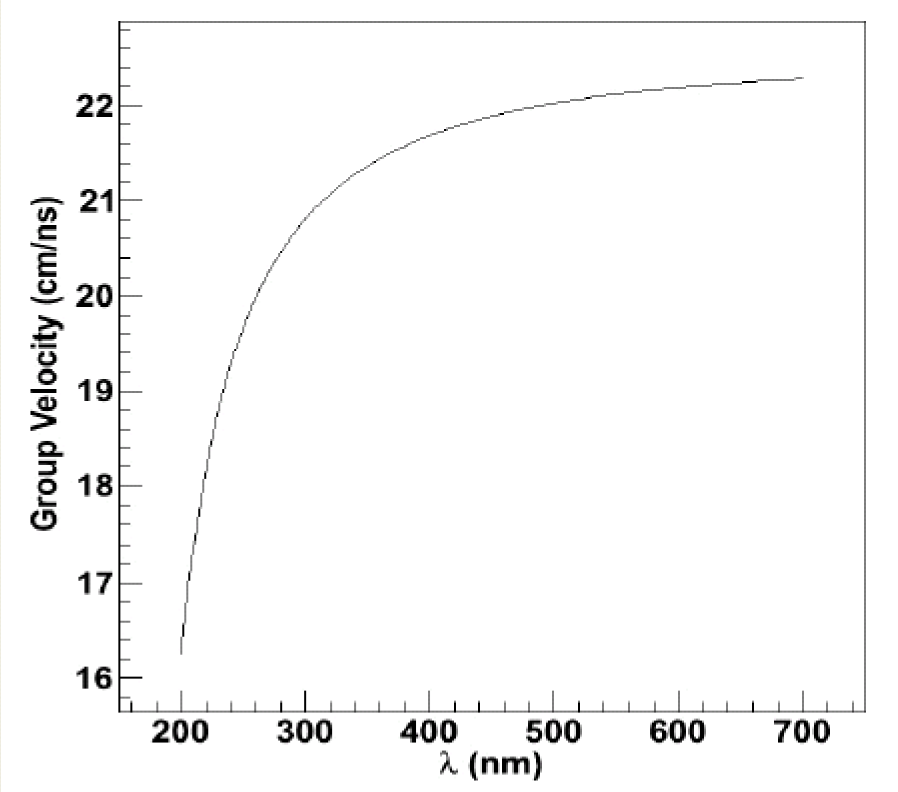
N.B.- this is a `cartoon'- working on workable designs-



Chromatic Dispersion in Water

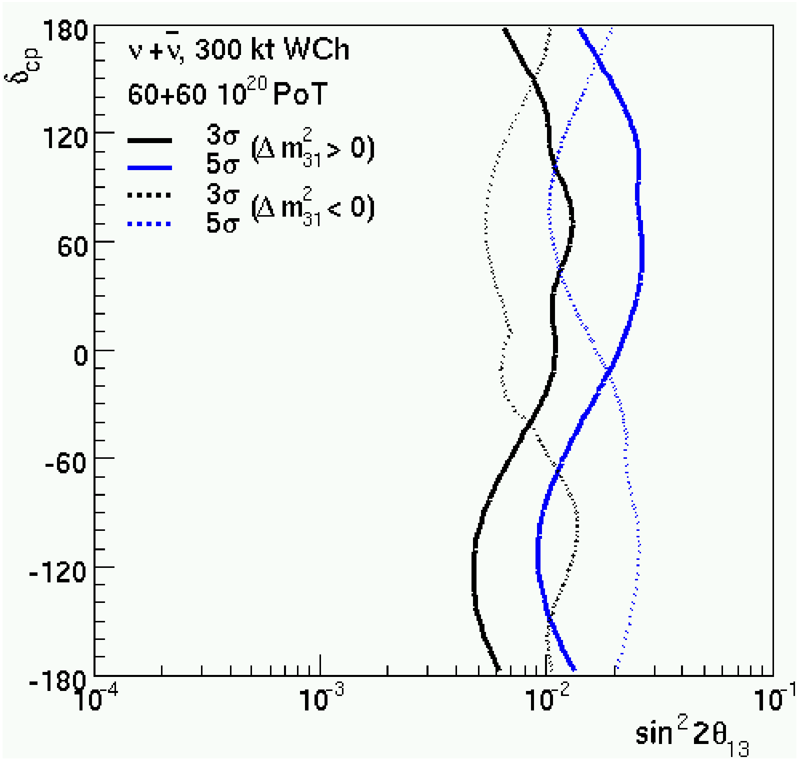
The Cherenkov photons will propagate at the group velocity given by:

$$v_g = \frac{d\omega}{dk} = c\left[\frac{1}{n(\lambda)} + \frac{\lambda}{n^2(\lambda)}\frac{dn}{d\lambda}\right]$$

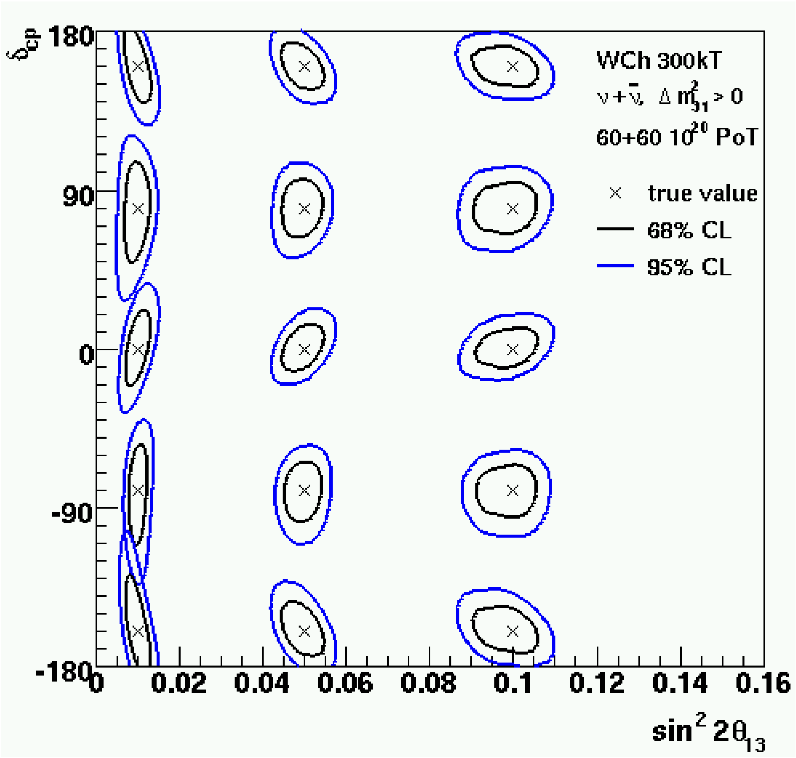


Higher energy photons will propagate slower. This becomes increasingly significant at sub 300nm wavelengths where detection sensitivities are already becoming very small.

300 kTon + 2.4 MW



Mass Hierarchy

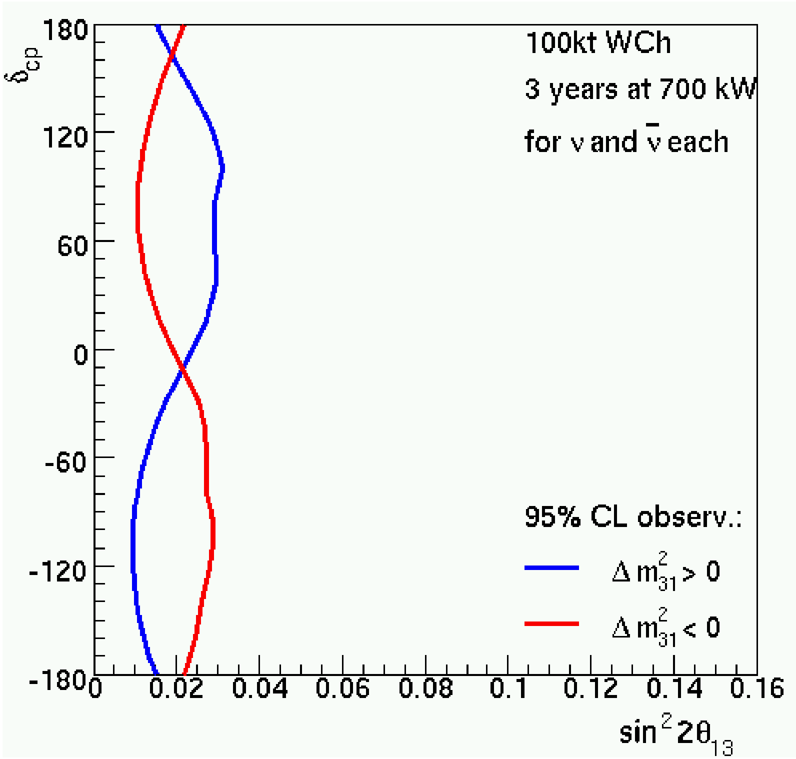


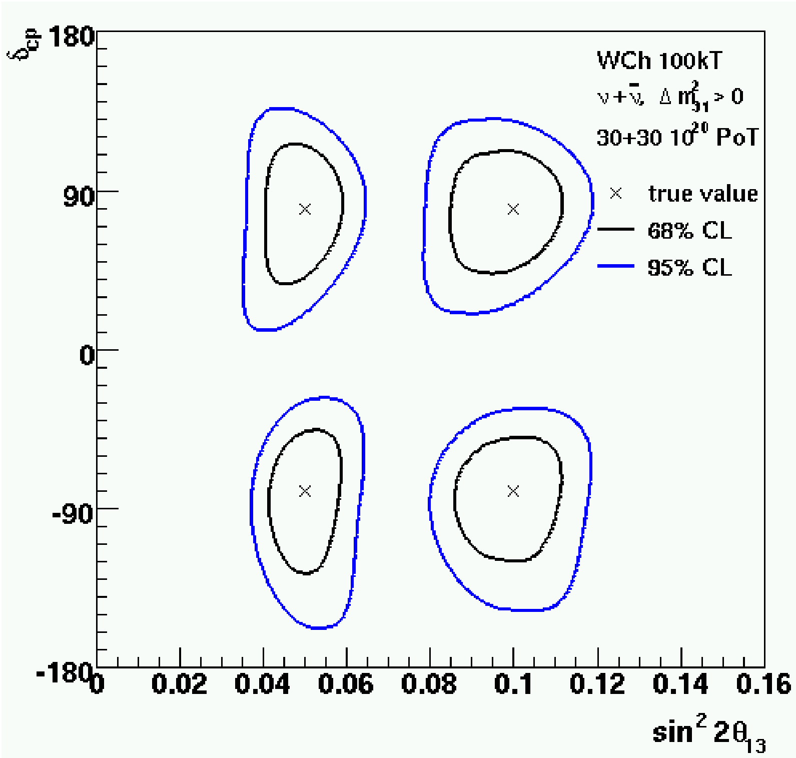
CP violation

M.Dierckxsens

5% background uncertainty
120 GeV 0.5 OA

100 kTon + 700 KW





Hierarchy

M.Dierckxsens

5% background uncertainty
120 GeV 0.5 OA