PROTON DECAY:

WHAT CAN WE LEARN FROM A NEW GENERATION OF BIG DETECTORS?

J. LEARNED AT 9TH νTEL WKSHP
VENICE, 7 MAR 2001

ν MASS & OSC ⟷ PDK
DEEPLY CONNECTED & EXPERIMENTALLY SIMILAR!

MOTIVATION
- PDK → $>10^{35}$ YRS, ESP K MODES (1MT = 6×10^{35} p)
  (NOW $< 10^{34}$ YRS)
  ⇒ ≳ 1MT MASS OR NEW TECH.

SYNERGY
- SUPERNOVAE OUT TO M31
- GRB DETECTION?
- MORE ATM ν'S
- FAR DETECTOR FOR LBL OR ν FACTORY (BUT MAGNETS)
- .... (×10 ⇒ NEW DISCOVERIES POSSIBLE)

IDEAS

(SK	50 KT)	
HYPER-KAM	1 MT	NAKAMURA
UNO	400 KT	JUNG
TITANIC	1 MT → 10 MT	SUZUKI
AQUA-RICH	1 MT	YPSILANTIS
LANNDD / SUPER ICARUS	80 KT	CLINE / RUBBIA
SCIPIO	80 KT	SVOBODA
OTHERS		

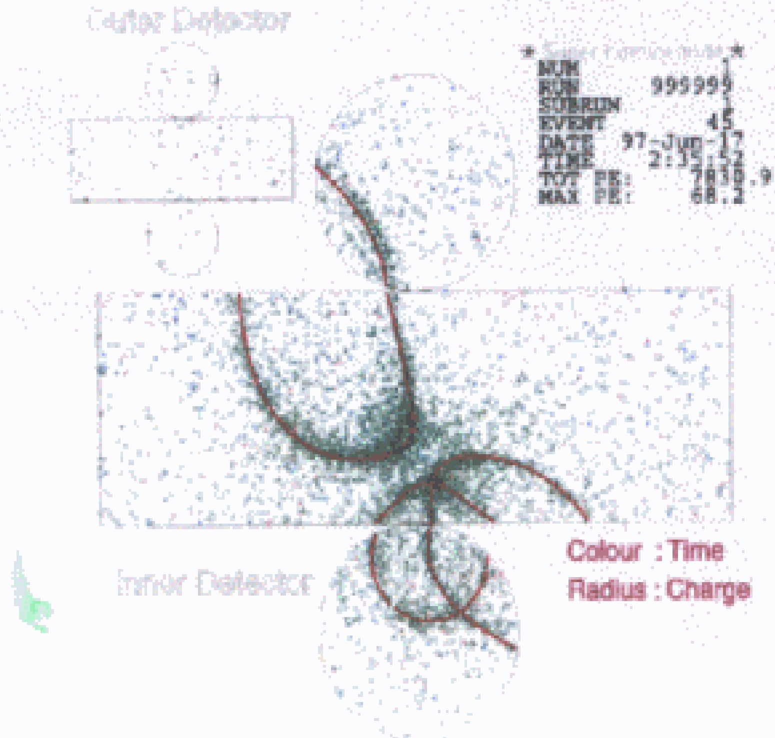
DEPTH & VENUE

COMPARE

CONCLUDE

$p \to e^+ \pi^0$ @Super-K

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



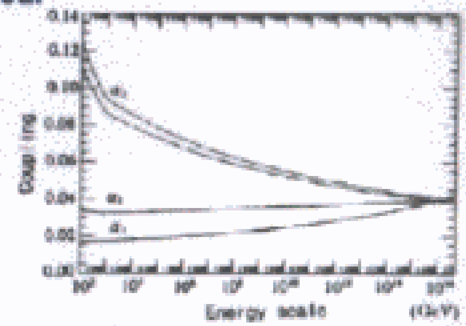
Criteria for $p \to e^+ \pi^0$

- 2 or 3 Cherenkov rings
- All rings are showering
- $85 < M_{\pi 0} < 185 MeV/c^2$ (3-ring)
- No decay electron
- $800 < M_p < 1050$ MeV/c^2
  $P_{tot} < 250$ MeV/c

NAKAMURA @ NOON 2000

SUSY-GUT Prediction for Proton Decay

- Higher unification scale: $M_X \sim 2\times10^{16}$ GeV
  - ⇒ Gauge-boson-mediated decay rate strongly suppressed.
  - $\tau/B(p \to e^+\pi^0) \sim 10^{36\pm1}$ yr



- However, SUSY-GUTs have dimension 5 operators mediated by the exchange of the color Higgs triplet, and proton decay is dominated by these operators.

- Dominant decay modes involve K mesons.
  - $\tau/B(p \to K^+\nu) \sim 10^{34}$ yr
- However, the predictions are strongly model-dependent.

Figure 1: Example of proton decay $p \to \bar{\nu}K^+$ via dimension five operators dressed by wino exchange in supergravity SU(5) theory.

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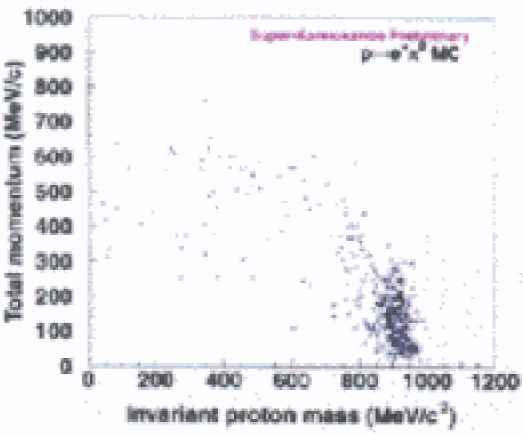
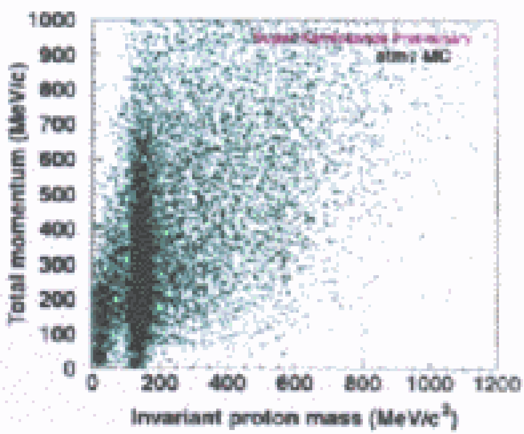
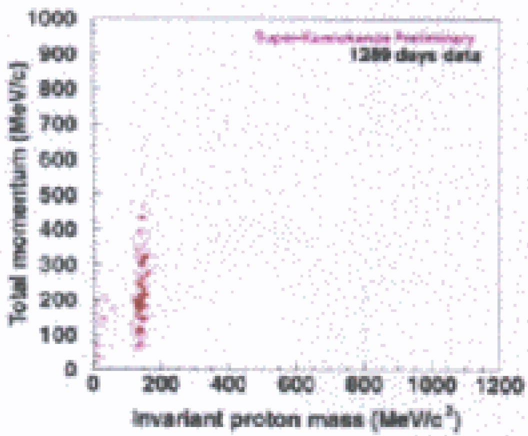
$p \rightarrow e^+ \pi^0$ (Super-Kamiokande)





ε = 43 %

0.2 exp'd BG

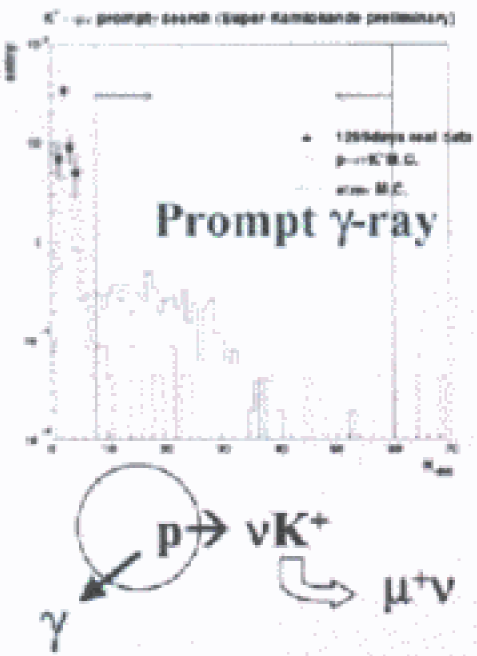


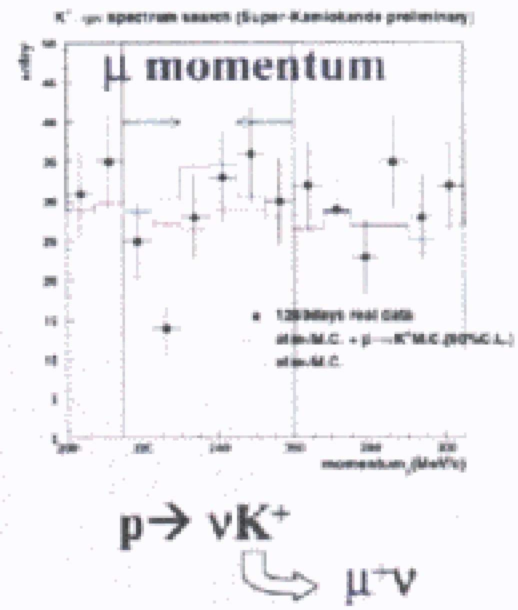
0 candidate

$\tau_p / B(p \rightarrow e^+ \pi^0)$

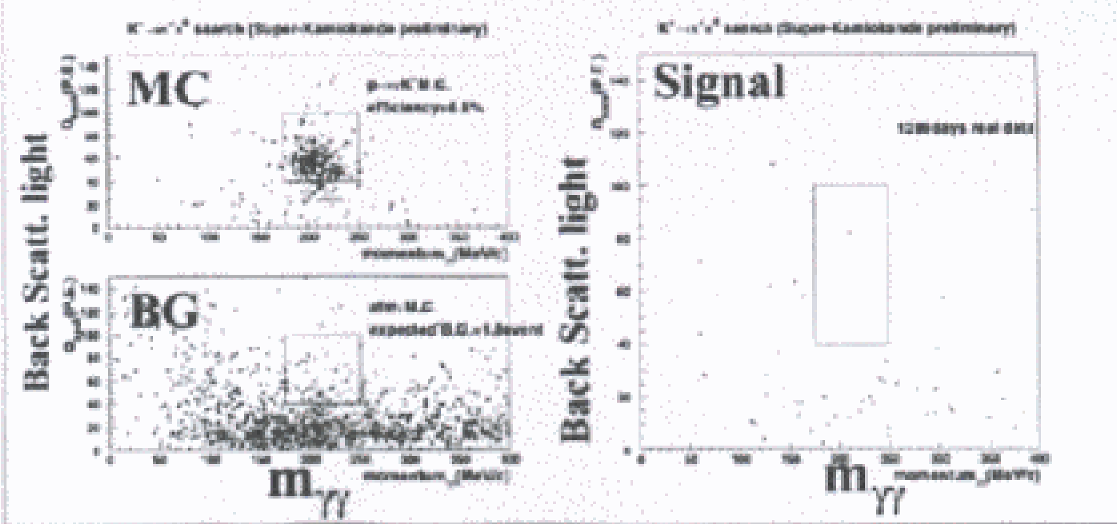
$> 5.0 \times 10^{33}$ years (90% CL)

νK^+ (Super-Kamiokande)





$K \rightarrow \pi^+\pi^0$



Combined: $\tau/B(p \rightarrow \nu K^+) > 1.6 \times 10^{33}$yr

$p \rightarrow \bar{\nu} K^+$ @SuperK Summary

1289 days (79.3 ktyr exposure)

	eff	B.G.	signal	limit($\times 10^{32}$yr)
prompty	8.8%	0.6	0	10
spec	33%	-----	-----	4.4
$K^+ \rightarrow \pi^+ \pi^0$	6.8%	1.8	1	5.9

3 mode combine

$\rightarrow \tau/B(p \rightarrow \nu K^+) > 1.6\times10^{33}$yr

NAKAMURA @ NOON 2000

Why multi-megaton?

Theorists's best bets :

$10^{35}\sim10^{36}$ yr for $e\pi^0$ ($10^{37}\sim10^{38}$: guaranteed??)

5×10^{34} yr for μK, νK (1×10^{36} : guaranteed??)

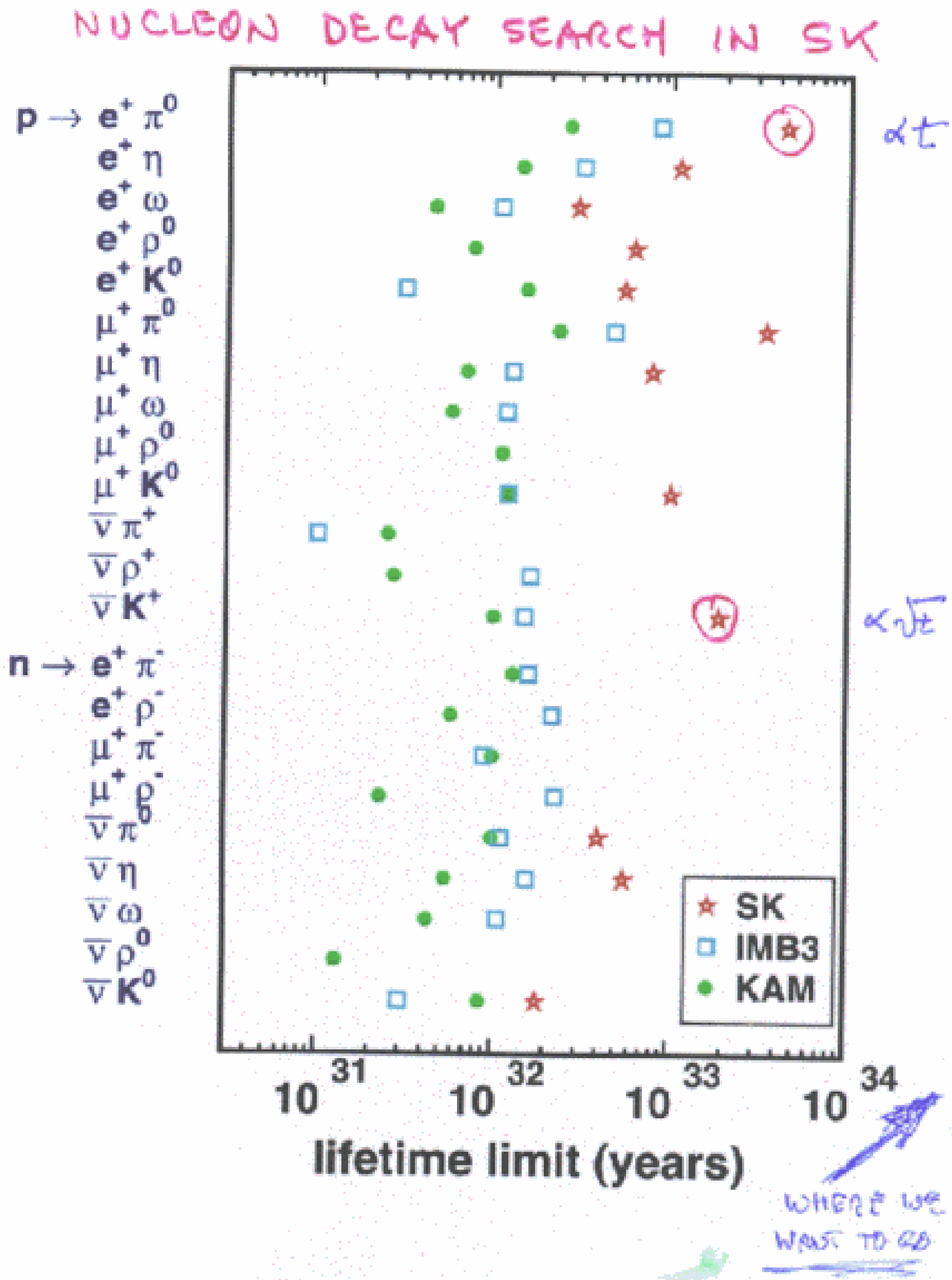
With 3σ (99.73%) discovery limit
- 1Mton $\times$ 10 years $\rightarrow$ $\sim7\times10^{34}$ years lifetime
- 10Mton $\times$ 10 years $\rightarrow$ $\sim4\times10^{35}$ years lifetime

YS: "**1Mt is not big enough!**"

(JGL:) THAT IS IF WE USE WATER CHERENKOV

Summary of Nucleon Decay Searches

mode	exposure (kt• yr)	εB_m (%)	observed event	B.G.	τ/B limit (10^{32} yrs)
$p \rightarrow e^+ + \pi^0$	70	43	0	0.1	44
$p \rightarrow \mu^+ + \pi^0$	70	32	0	0.4	34
$p \rightarrow e^+ + \eta$	45	17	0	0.3	11
$p \rightarrow \mu^+ + \eta$	45	12	0	0	7.8
$n \rightarrow \bar{\nu} + \eta$	45	21	5	9	5.6
$p \rightarrow e^+ + \rho$	61	6.8	0	0.6	6.1
$p \rightarrow e^+ + \omega$	61	3.3	0	0.3	2.9
$p \rightarrow e^+ + \gamma$	70	71	0	0.1	73
$p \rightarrow \mu^+ + \gamma$	70	60	0	0.2	61
$p \rightarrow \bar{\nu} + K^+$	70				19
$K^+ \rightarrow \nu\mu^+$ (spectrum)		34	--	--	4.3
prompt $\gamma + \mu^+$		9.3	0	1.1	9.5
$K^+ \rightarrow \pi^+\pi^0$		6.8	0	1.9	6.9
$n \rightarrow \bar{\nu} + K^0$	70				1.8
$K^0 \rightarrow \pi^0\pi^0$		9.6	27	30.5	2.2
$K^0 \rightarrow \pi^+\pi^-$		4.6	11	5.9	0.83
$p \rightarrow e^+ + K^0$	70				5.4
$K^0 \rightarrow \pi^0\pi^0$		11.8	1	1.4	8.8
$K^0 \rightarrow \pi^+\pi^-$					
2-ring		6.2	6	1.0	1.5
3-ring		1.4	0	0.2	1.4
$p \rightarrow \mu^+ + K^0$	70				10
$K^0 \rightarrow \pi^0\pi^0$		6.1	0	1.1	6.2
$K^0 \rightarrow \pi^+\pi^-$					
2-ring		5.3	0	1.5	5.4
3-ring		2.8	1	0.2	1.8



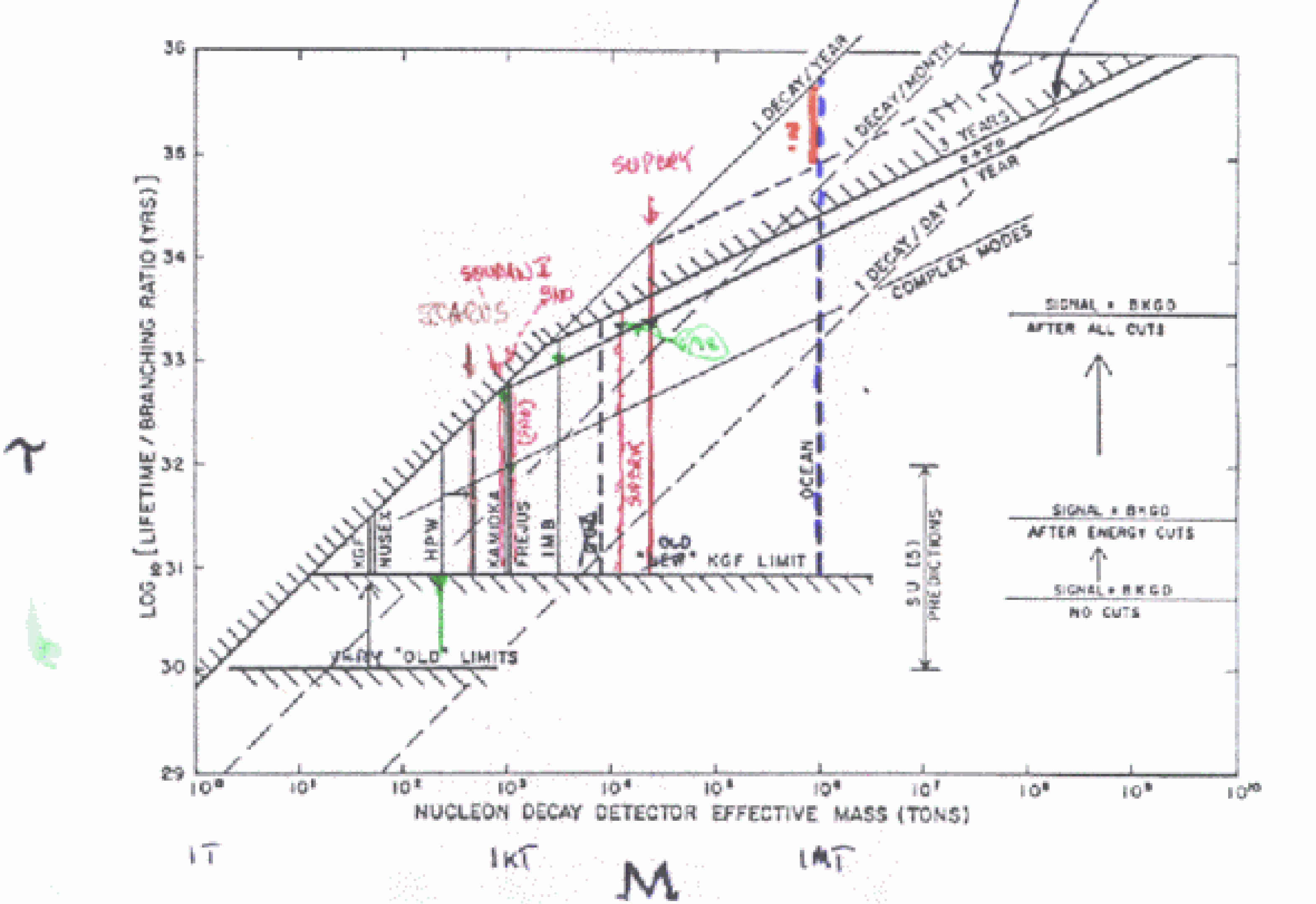
NUCLEON DECAY SEARCH IN SK
p → e+ π0
e+ η
e+ ω
e+ ρ0
e+ K0
μ+ π0
μ+ η
μ+ ω
μ+ ρ0
μ+ K0
ν̄ π+
ν̄ ρ+
ν̄ K+
n → e+ π-
e+ ρ-
μ+ π-
μ+ ρ-
ν̄ π0
ν̄ η
ν̄ ω
ν̄ ρ0
ν̄ K0
SK
IMB3
KAM
10^31
10^32
10^33
10^34
lifetime limit (years)
∝t
∝√t
WHERE WE WANT TO GO

PDK DETECTOR REACH VS MASS

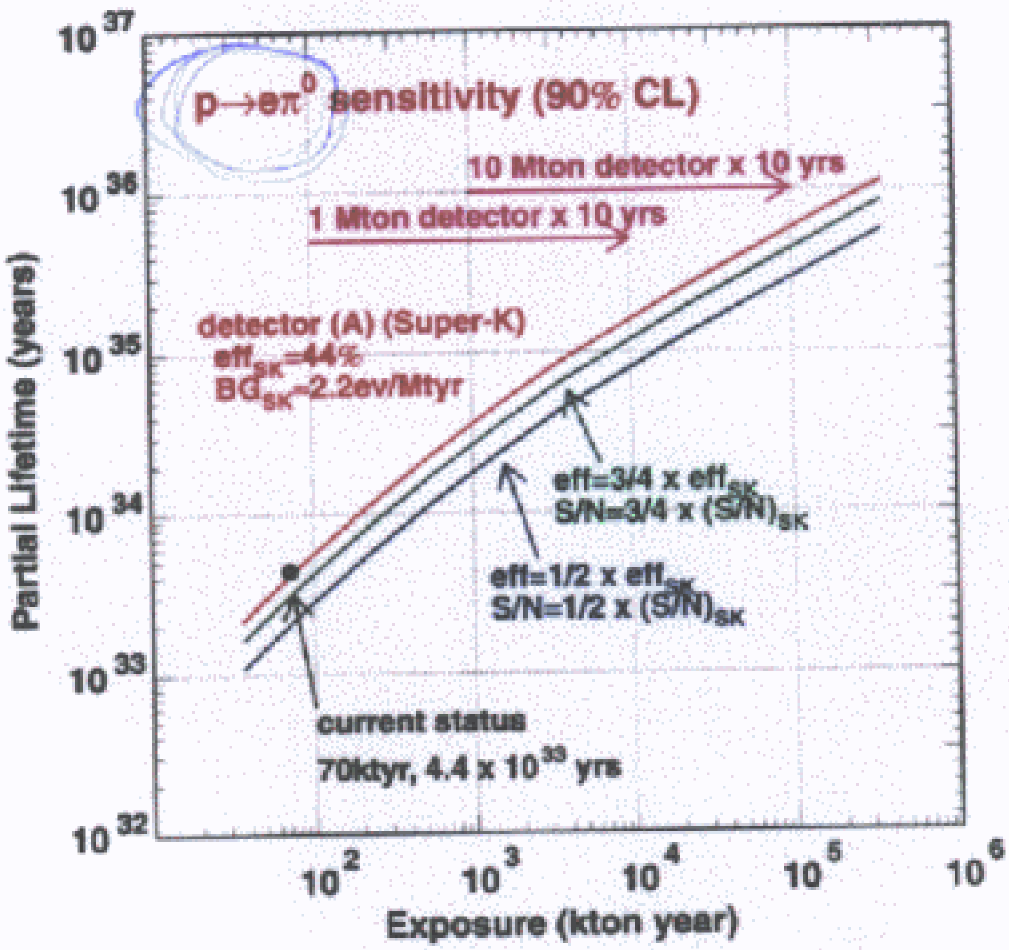
(DIRECT COUNTING)

THE TYRANNY OF LARGE NUMBERS

JGL 1983



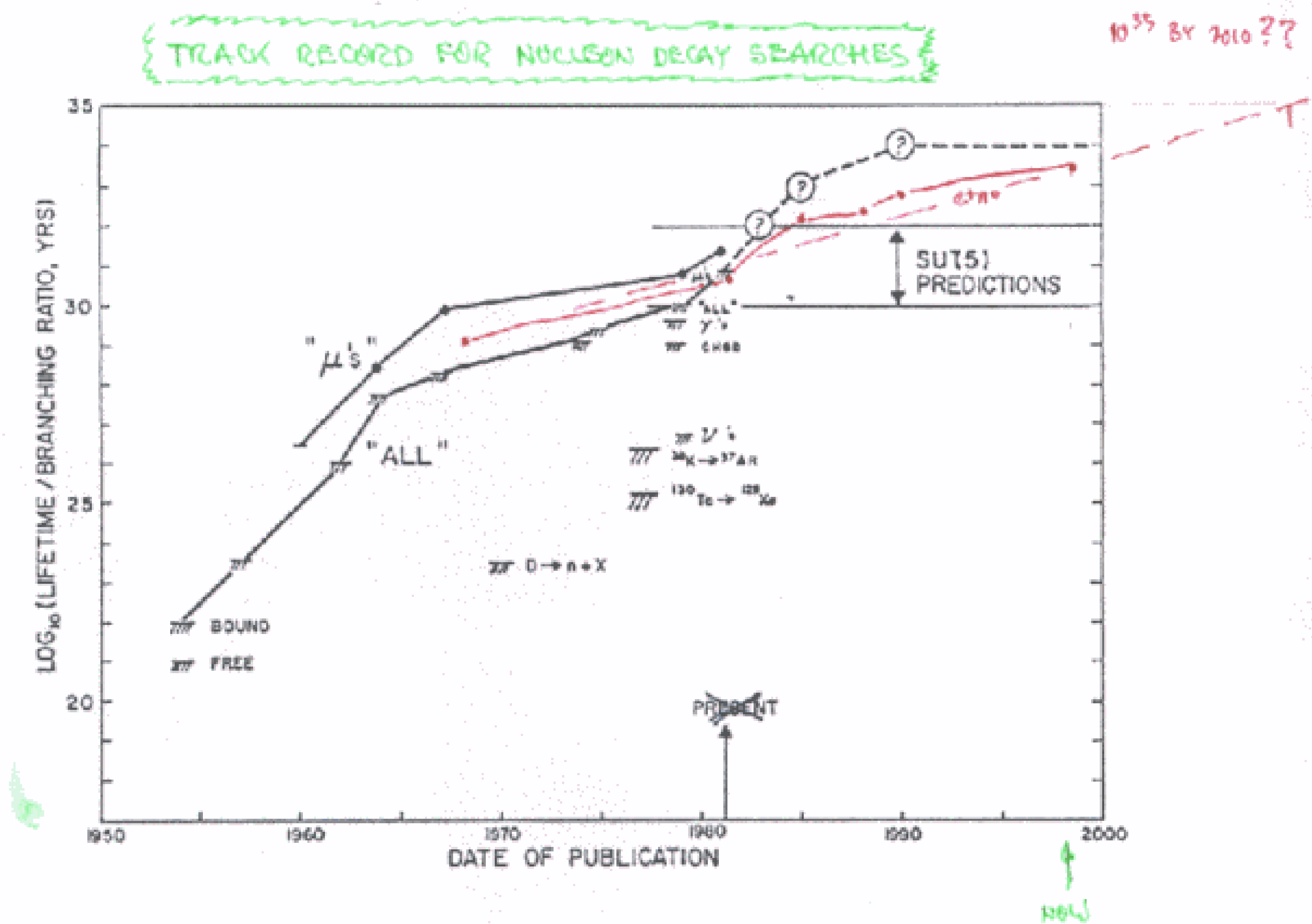
Lifetime sensitivity with usual cut



With 90% CL

- 1Mton × 10 years → ~1 × 10^{35} years lifetime
- 10Mton × 10 years → ~5 × 10^{35} years lifetime

SHIOZAWA / SUZUKI @ NOON2000


TRACK RECORD FOR NUCLEON DECAY SEARCHES
10^{35} BY 2010 ??
LOG10 (LIFETIME / BRANCHING RATIO, YRS)
35
30
25
20
1950
1960
1970
1980
1990
2000
DATE OF PUBLICATION
"μ's"
"ALL"
SU(5) PREDICTIONS
BOUND
FREE
D → n + X
ν's
γ's
PRESENT
NOW

HYPER-KAMIOKA

1 Mton Underground Detectors

Kenzo NAKAMURA
KEK
And
Masato Shiozawa
ICRR

NOON2000 (2nd Workshop on Neutrino Oscillations and Their Origin)
December 8, 2000
Sanjo-Hall, the University of Tokyo

Hyper-Kamiokande — next generation water Cherenkov detector at Kamioka

- Assume the reach of the next generation nucleon decay experiment as

$e^+\pi^0$	$\sim 10^{35}$ yr
$K^+\nu$	$\sim 10^{34}$ yr

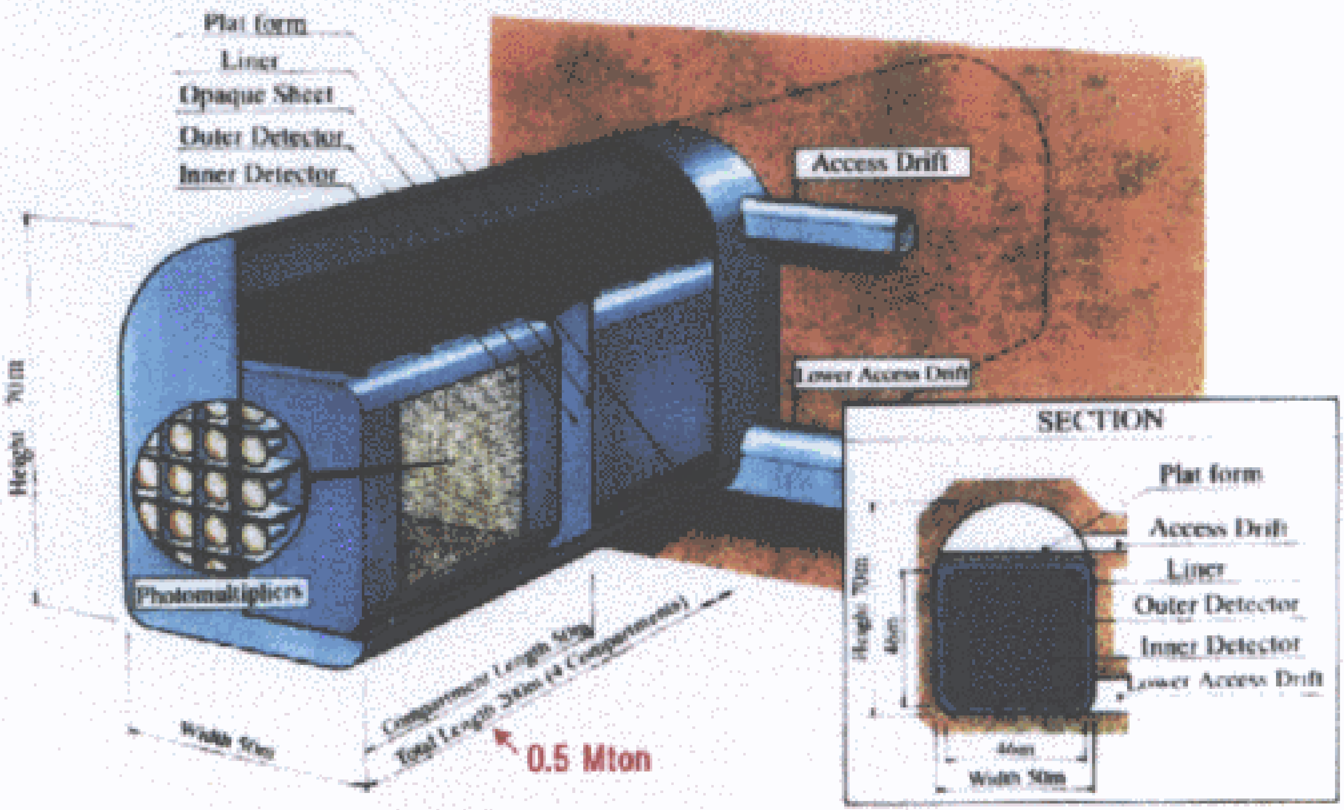
- Required mass:

  ~ 20 × SK
  Total: ~ 1 Megaton
  Fiducial: ≥ 0.6 Megaton

- Physical constraints:
  - Overburden as deep as ~1000 m
  - Light attenuation in water (72 m @ 400 nm)
  - Water pressure ≤ ~ 5 atm
  - Sensitivity to 6 MeV gamma
- To construct such a big underground detector in Japan, Kamioka is the only practical site.

NAKAMURA @ NOON2001

Linear Hyper-Kamiokande



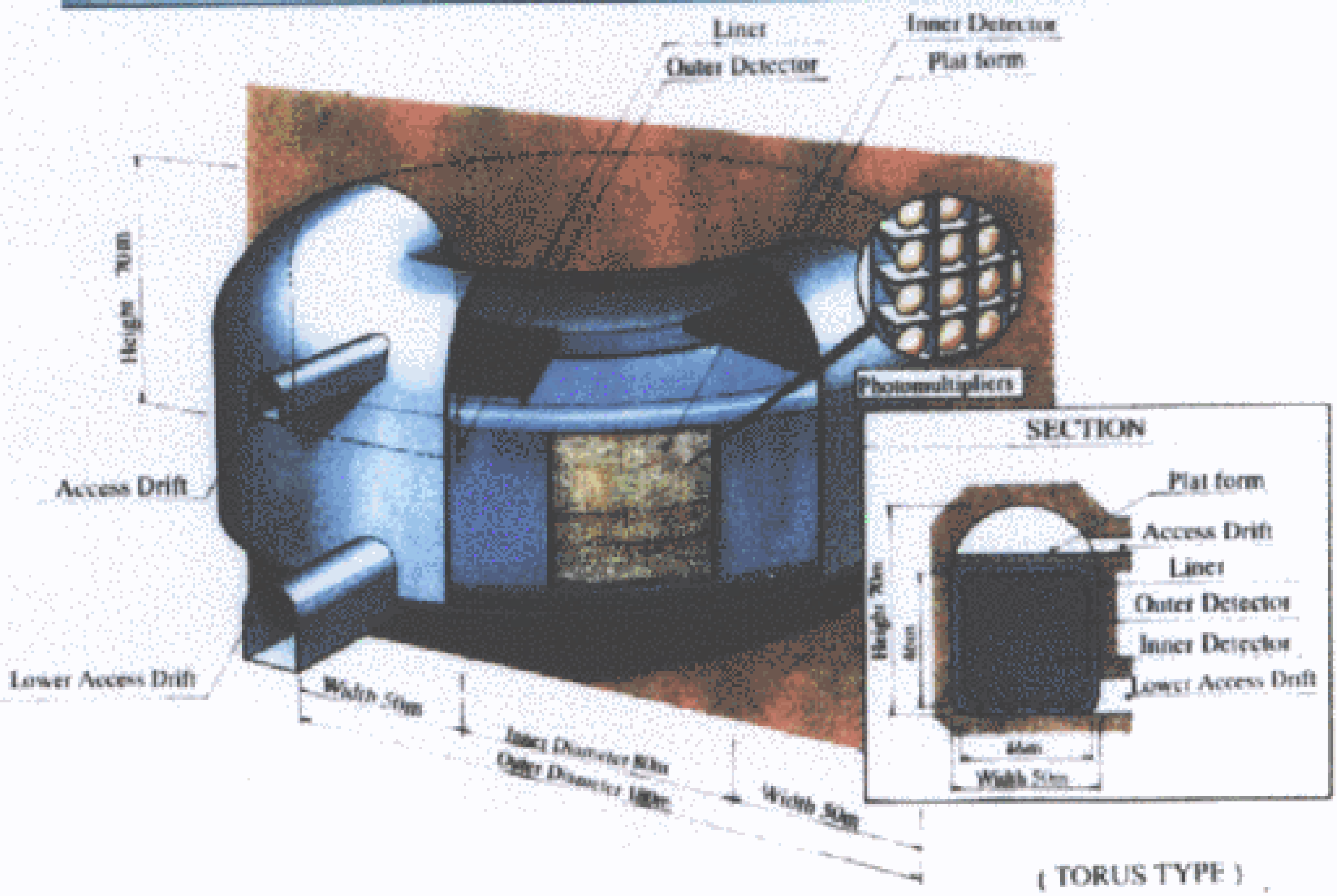
1 Mton: Total Length 400m (8 Compartments)

(STRAIGHT TYPE)

NAKAMURA @ NOON 2000

OLD "DONUT" IDEA OF KOSHIBA

Circular Hyper-Kamiokande



(TORUS TYPE)

NAKAMURA@ KOONKOU

Long Baseline Neutrino Oscillation Experiments at JHF

Purpose

Precise measurement of oscillation parameters Δm^2_{23}, θ_{23}, θ_{13}

ν_μ disapearance, ν_e appearance with low energy (~GeV) ν_μ beam

Basic Strategy

1. First 1year, Wide band beam,
   → pin-point Δm^2_{23} ($\pm 2\times10^{-4}eV^2$)
2. Narrow band beam ~5years
   → θ_{23}, θ_{13} w/ less systematics

NAKAMURA @ NOON 2000

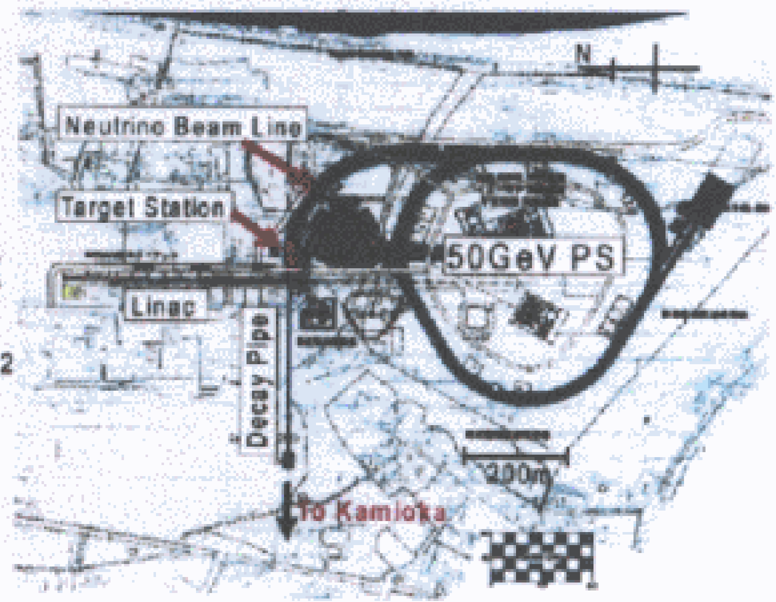
Japan Hadron Facility (JHF) Project

Genken @ Tokai-mura, Ibaraki-ken
Construction ~ 2006

Proton synchrotron

	JHF	KEK
Energy	: 50 GeV	13
Intensity	: 3.2×10^{14} ppp	6×10^{12}
Cycle	: 0.3 Hz	0.45

"1year" ≡ 10^{21} POT

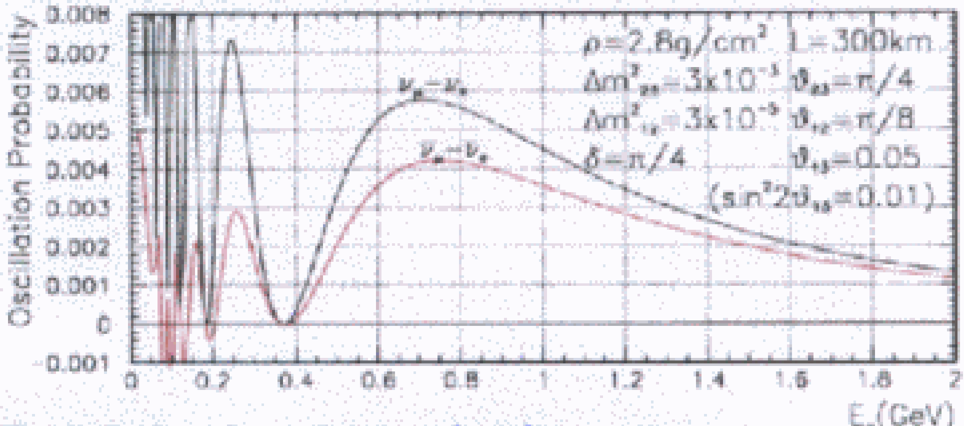


[JGL: LATER MAY EVOLVE TO ν FACTORY]

NAKAMURA @ NOON 2000

ν CP Violation with low-energy neutrino beam

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \propto \sin\delta_{CP} \cdot \frac{L}{E}$$



A. Konaka
TRIUMF

CP violation is enhanced at low energy

+ 1 Mton water Cherenkov (good at low E)

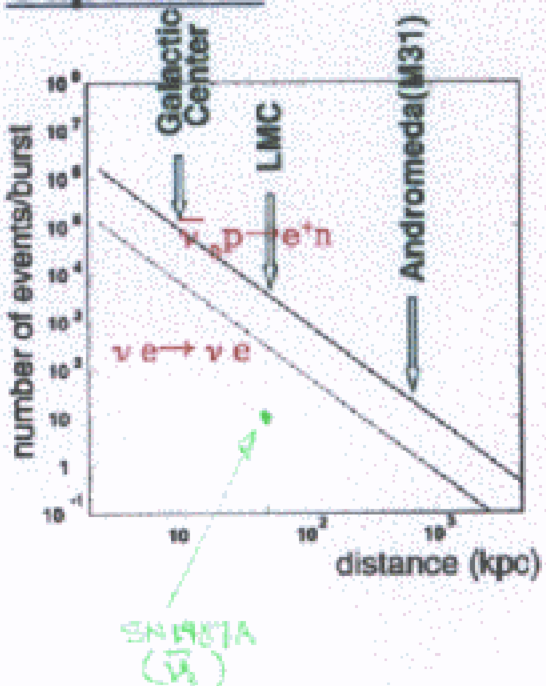
+ Narrow band $\nu_\mu/\bar{\nu}_\mu$ beam (JHF: 4MW, 4yrs)

$\sin^2 2\theta_{13}$	$A_{CP}(\delta_{CP}=45°)$	$n_{\nu\mu}+n_{\overline{\nu\mu}}$	$n_{\nu\mu}-n_{\overline{\nu\mu}}(\delta_{CP}=45°)$
0.01	15 %	1000 ev.	150±30 ev.

NAKAMURA@NNN2000

Supernova neutrino observation with a 1 Mton (fiducial volume) water Cherenkov

Supernova



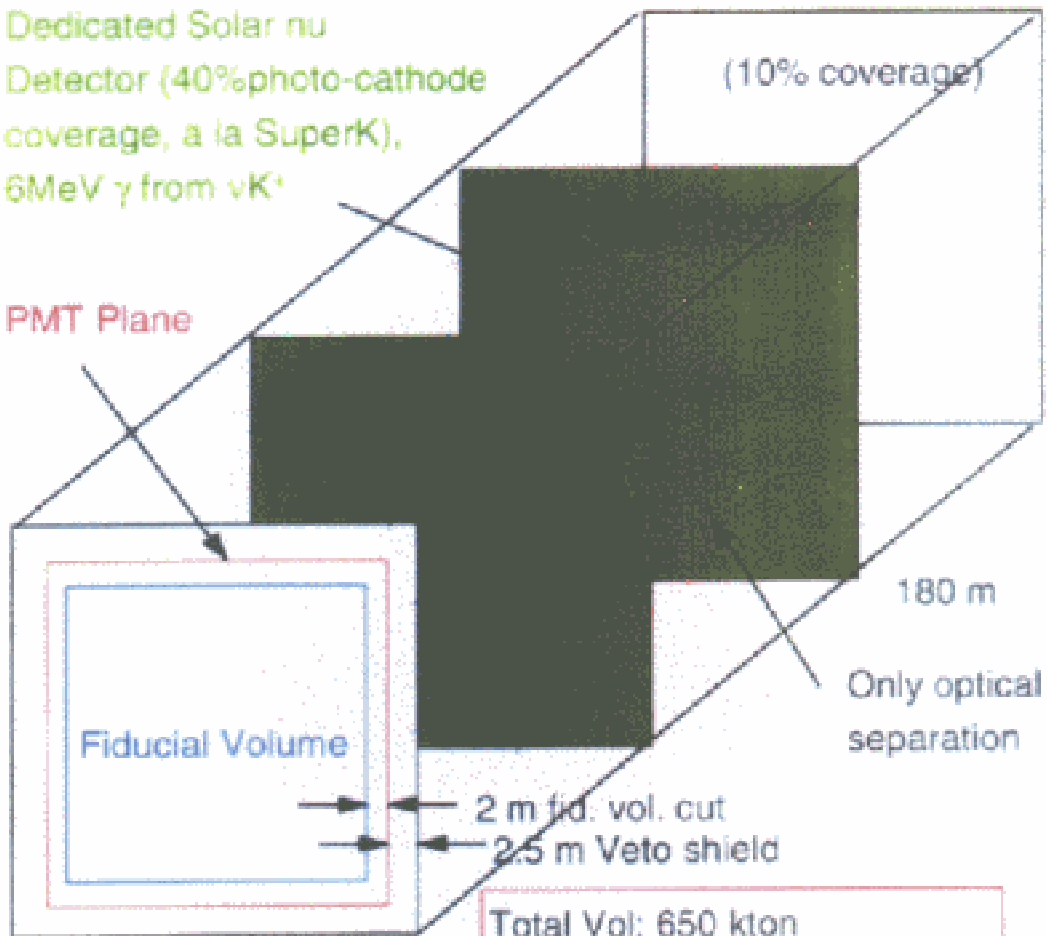
~100,000 $\bar{\nu}_e p \rightarrow e^+ n$ events
~8,000 $\nu e \rightarrow \nu e$ events
(for Galactic Center SN)

~20 events at Andromeda

Precise observation of explosion process and neutrino mass test <~1eV

NAKAMURA @ NOON 2000

UnNnO Baseline Configuration

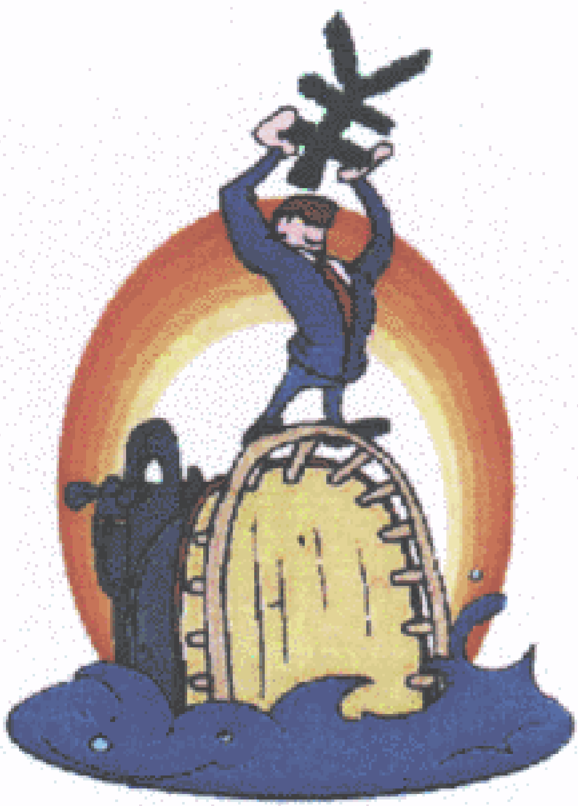


Total Vol: 650 kton
Fid. Vol: 445 kton (20xSuperK)
r_v = 0.69
# of 20" PMTs: 56,000
(1/2 of all 40% coverage case)
# of 8" PMTs: 14,900

Titanic

TITANIC

Totally Immersible Tank Assaying Nucleon Immortality Cost-effectively



Multi-Megaton Water Cherenkov Detector

2000.12.08
@NOON2000

Y. Suzuki, Kamioka Observatory
ICRR, Univ. of Tokyo

MC Calculation
by
M. Shiozawa (Kamioka Obs.,ICRR)

μ-rate
By
A.Okada
Neutrino Center
ICRR

1st Multi-Megaton
DONUT
By M.Koshiba
(before SuperK)

What kind of detector

Requirements for the detector

1) Expandability: May start with 1 Mton,
   but can be expandable.
2) Low cost
3) Short construction time

↓

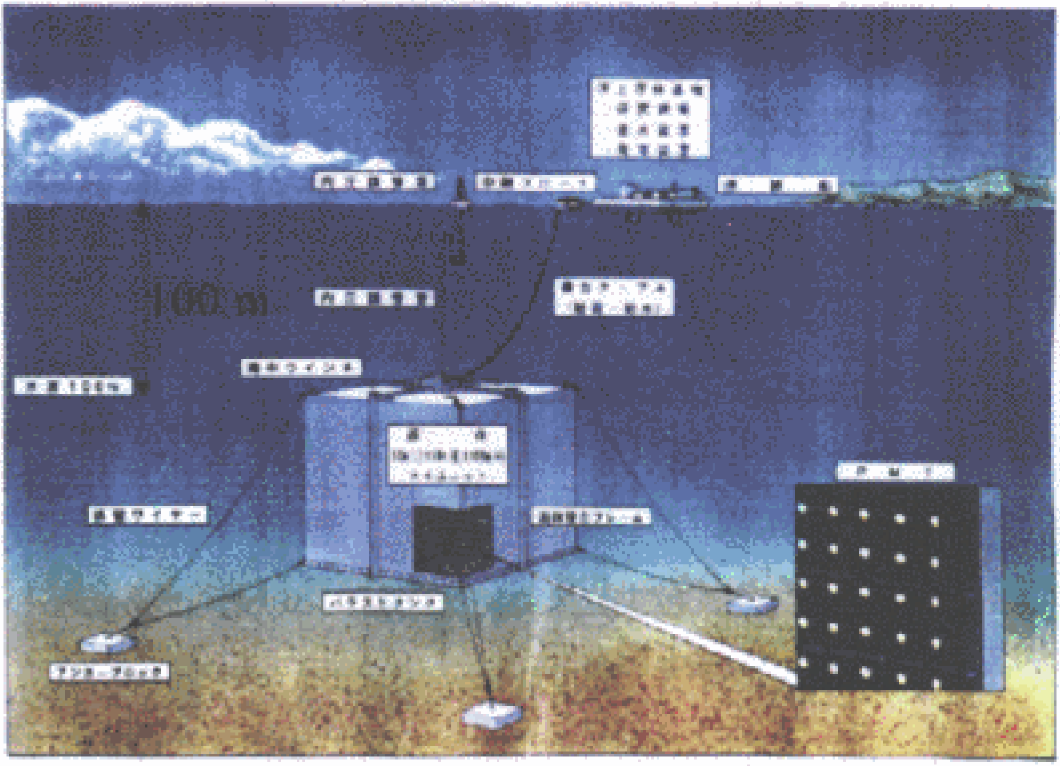
shallow under-water detector

Disadvantage

1) No solar neutrino measurements
2) May not have high sensitivity to νK mode
   → under study
3) Cosmic Ray backgrounds
   → create dead time

Detector

1) 50m x 50m x 100m x 4 units = 1.0 Mton
   (0.813 Mton fiducial : SK x 36)
2) 70m x 70m x 100m x 4 units = 1.96 Mton
   (1.673 Mton fiducial : SK x 74)
   → close to the maximum size
   → add one more module → ~ 4Mton



浮沈式陽子崩壊実験装置イメージ図

For 1 Mton module
Steel + epoxy lining
29,000 tons
4 units

→ **Balance to the buoyancy force**

AQUA-RICH
TOM YPSILANTIS

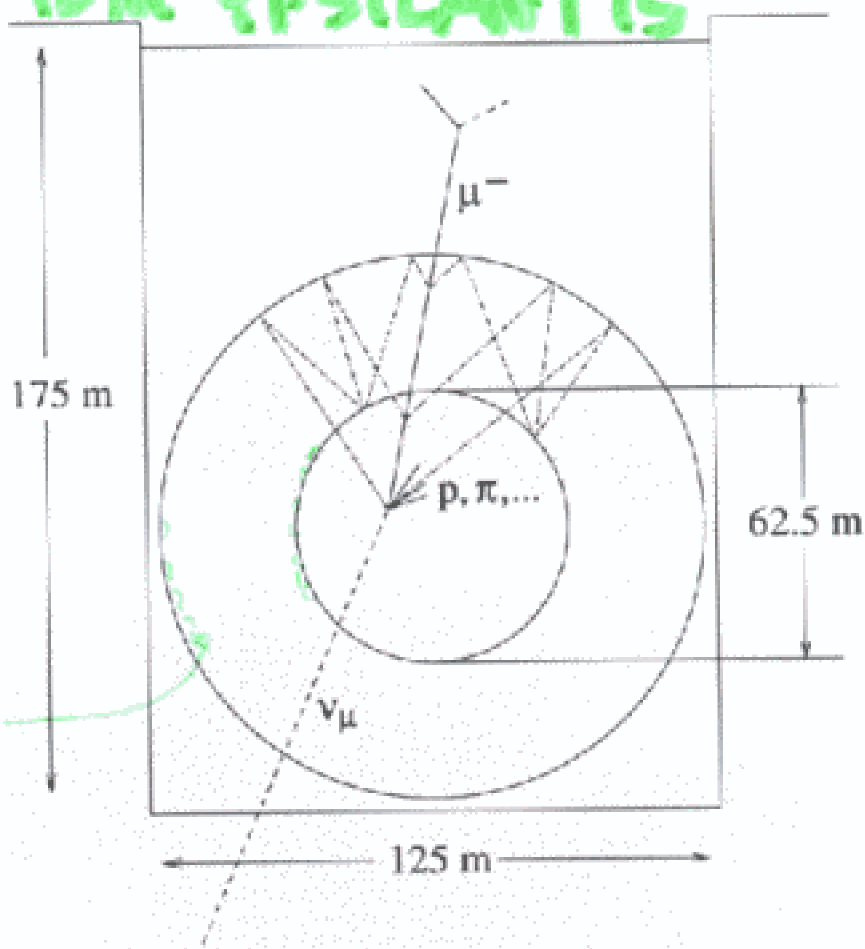


Figure 1: A schematic view of the 1Mt AQUA-RICH detector and an upward going ν_μ charged current interaction. The inner dome (62.5 m diameter) supports 3125 outward looking dHPDs (20% coverage). The outer 125 m diameter sphere is reflective and supports 2185 mHPDs (3.5% coverage). From the top of the mirror sphere to the water level there are 50 m water to stop dowaward going muons with momenta below 10 GeV/c.

(NEUTRINO-EYE)

KAI ZUBER

Particle Identification

GREAT IMPROVEMENT OVER SUPERK

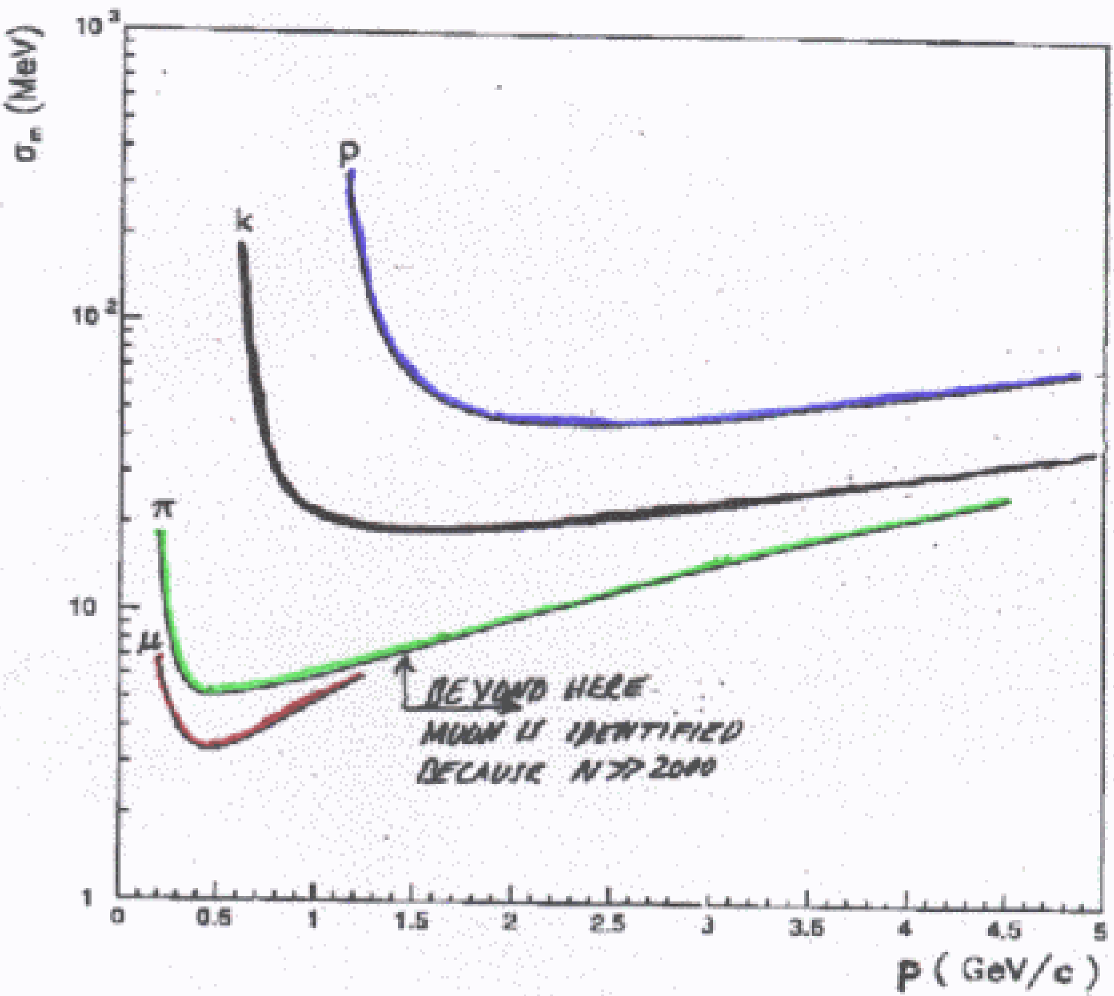


Fig. 8. The mass resolution σ_m vs p for (μ, π, K, P) in water with geometry of Fig. 1. The solid curves (Eq. 19) are from combined measurements of multiple scattering and β.

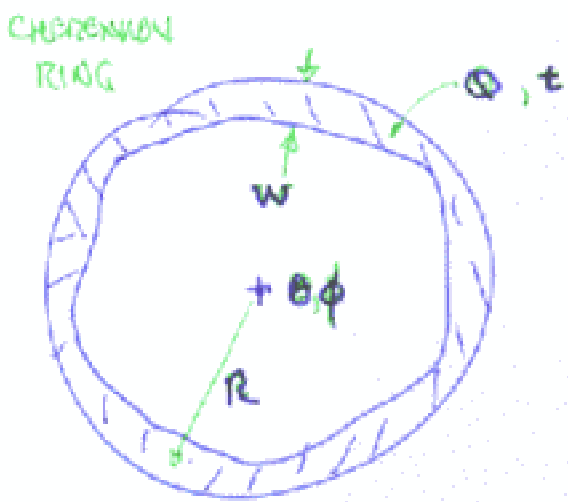
AQUA-RICH

TY

NEUTRINO EYE CONCEPT

IDEA BORROWED & EXTENDED

AQUA-RICH	TOM YPSILANTIS & COLLEAGUES
RICH	ART ROBERTS
LONG AGO	DICK DAVISSON



- t — TRAJECTORY
- θ, φ — DIRECTION
- Q — ENERGY
- R — β
- W — $\vec{p}$ (VIA MULTIPLE SCATTERING, IF DOMINANT ABERRATIONS)

COMBINED INFORMATION LEADS TO

- RESOLUTION OF MULTIPLE TRACKS
- PARTICLE IDENTIFICATION

⇨ ORDER OF MAGNITUDE IMPROVEMENT OVER PREVIOUS WATER CHERENK DETS (eg. SUPERK)

EVENTS GENERATED RANDOMLY IN A $(30m)^3$ WATER VOLUME $\nu_\mu + N \rightarrow \mu^- + p^+$

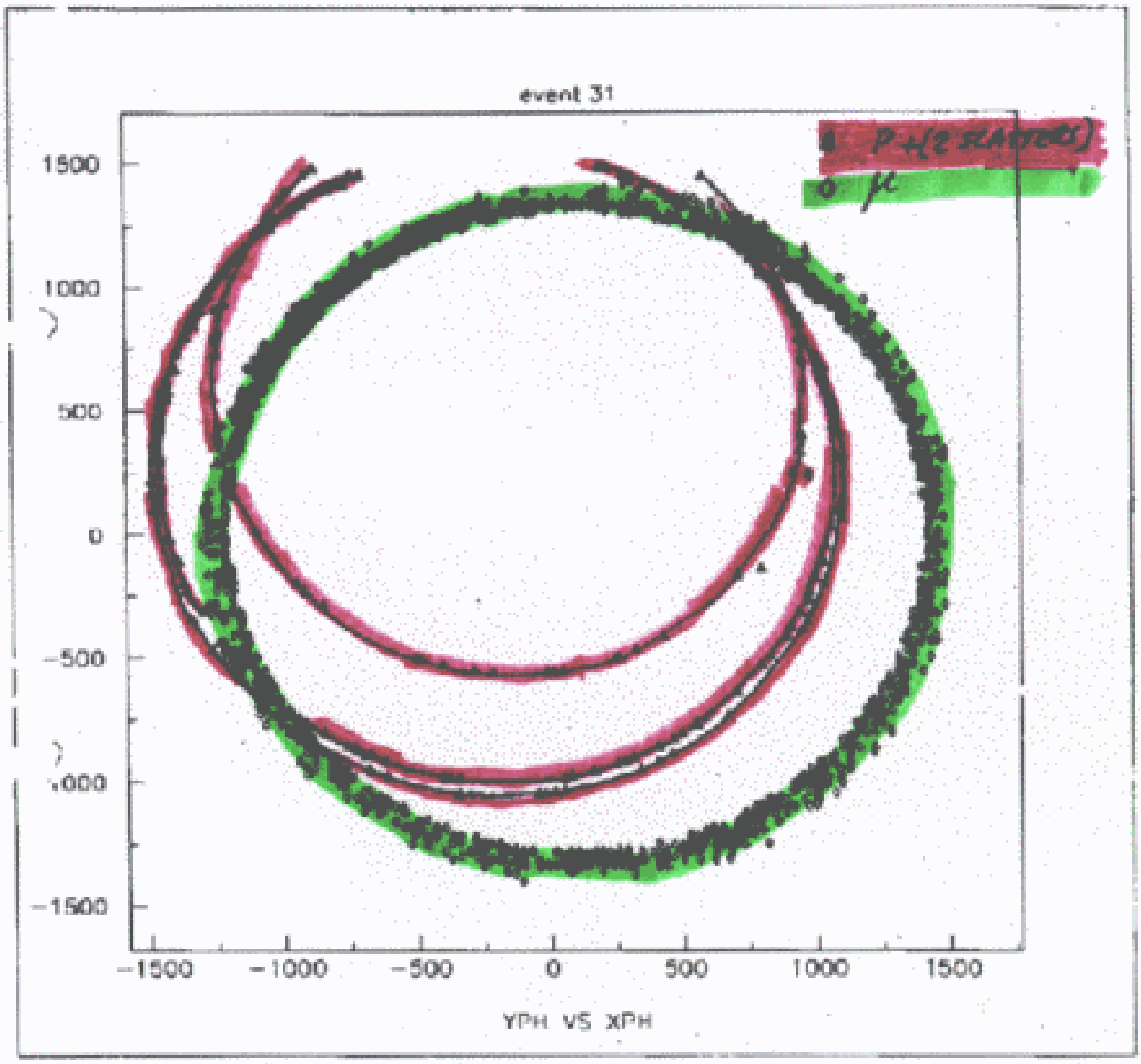


Fig. 5. A Monte Carlo simulation of a quasi-elastic event (#31) $\nu_\mu + N \rightarrow \mu^- + P$ for $E_\nu = 12$ GeV. It has [redacted] proton rings (black triangles) (the smaller one is due to a scatter) and one very dense muon ring (open diamonds). Muon identification here is obvious. The diffuseness of the image is due to the long muon pathlength thus emission point errors dominate. This effect can be removed by time slicing the image (thus breaking the track up into a series of shorter segments) and reconstructing each segment.

$\nu_e + N \rightarrow e^- + P^+$

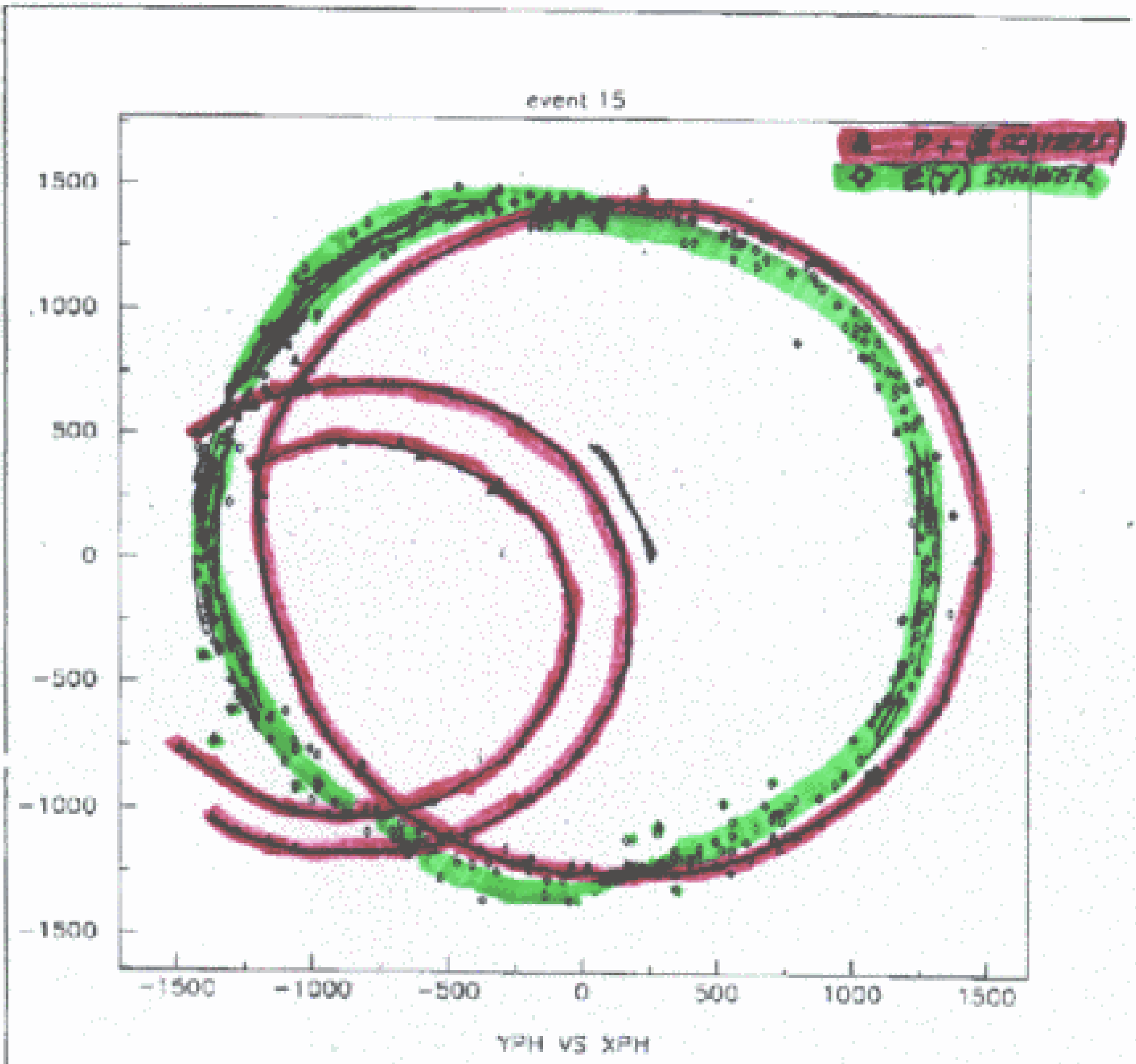


Fig. 10. A Monte Carlo simulation of a quasi-elastic event (#15) $\nu_e + N \rightarrow e^- + P$ for $E_{\nu e} = 12$ GeV. It has three proton rings (black triangles) (the smaller ones are due to a scatterings) and one electron ring (open diamonds).

HPD

BEING BUILT NOW 10" VERSION
CERN TESTS

HPD PHOTODETECTOR

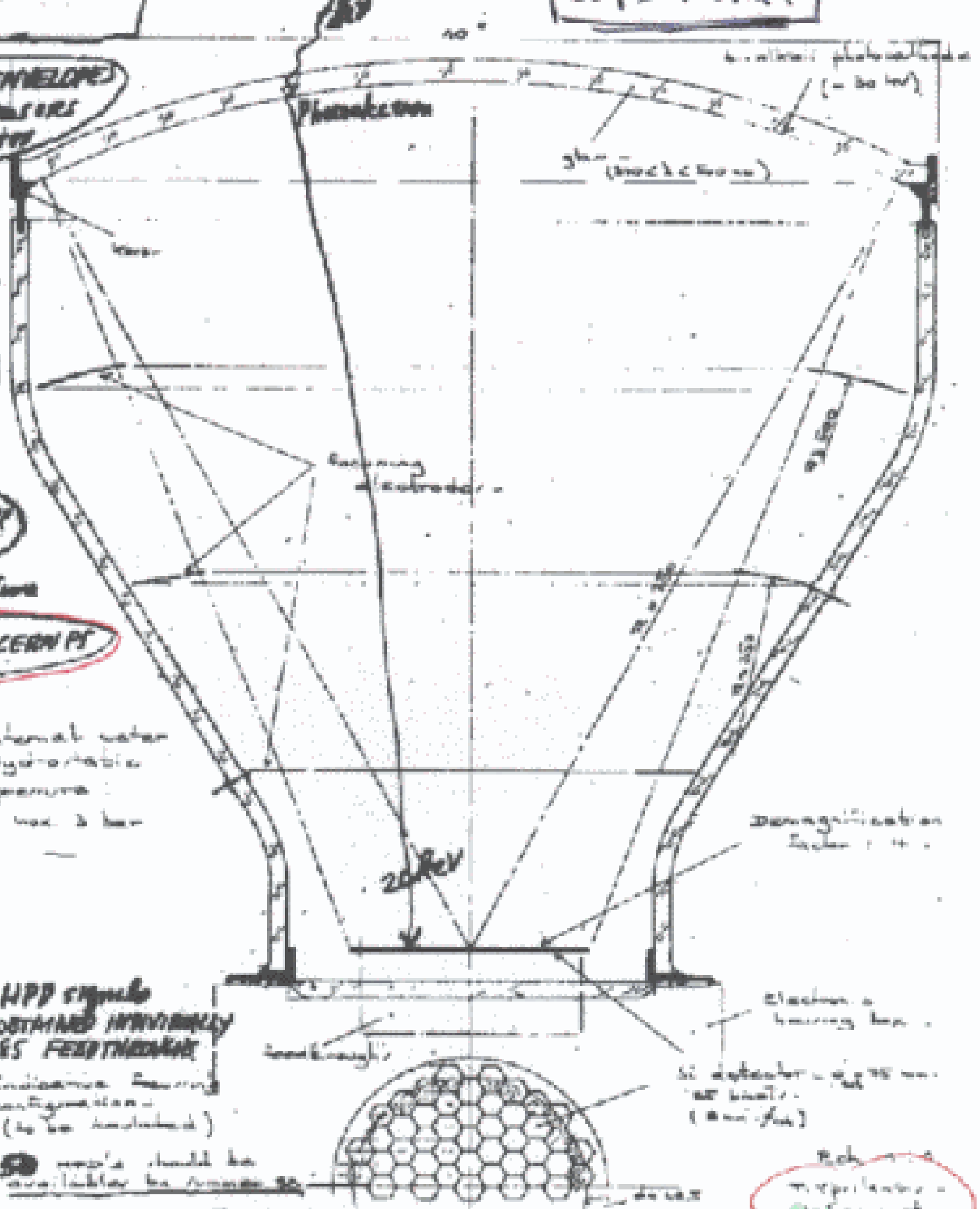
NOW (FOR MINI-RICH TEST) BUILDING 10" HPD, 25 PADS

FUTURE (FOR MINI-RICH) 20" HPD, 85 PADS

20" Ø DEMAGNIFICATION BY FACTOR 4 (500→125 mm)
85 PADS, DIRECT OUTPUT FOR FAST TIMING

100 PS TIMING!

25 GLASS ENVELOPES
25 Silicon Sensors
25 Base Plates
↓
CERN April 98
↓ Cannot
Send to Matsusada, Novosibirsk, DEP
↓
Return Summer–Fall 98
↓ Beam Time
Nov. 98 Beam T11, CERN PS

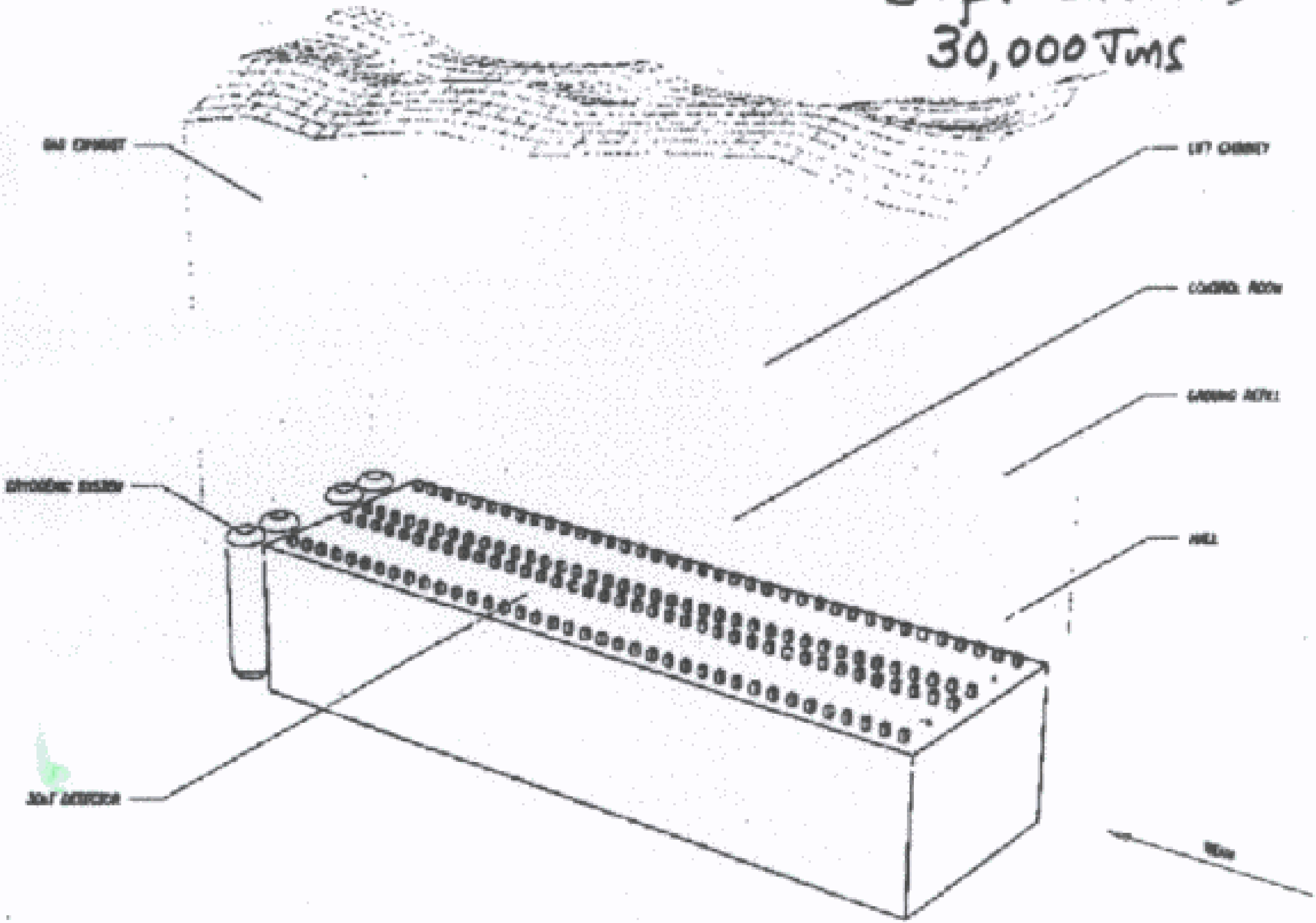


85 HPD signals are obtained individually via 85 feedthroughs
↙
FAST AMPL. 2GHz FADC (WAVE FORM SAMPLING)

10" HPD FOR LBL RICH

- MATSUSADA, DEP + NOVOSIBIRSK WILL MAKE PHOTOCATHODES, VACUUM + SEAL
- WE BUY THE AMPULES, SILICON + BASE PLATE (TO BETTER CONTROL THE PRICE

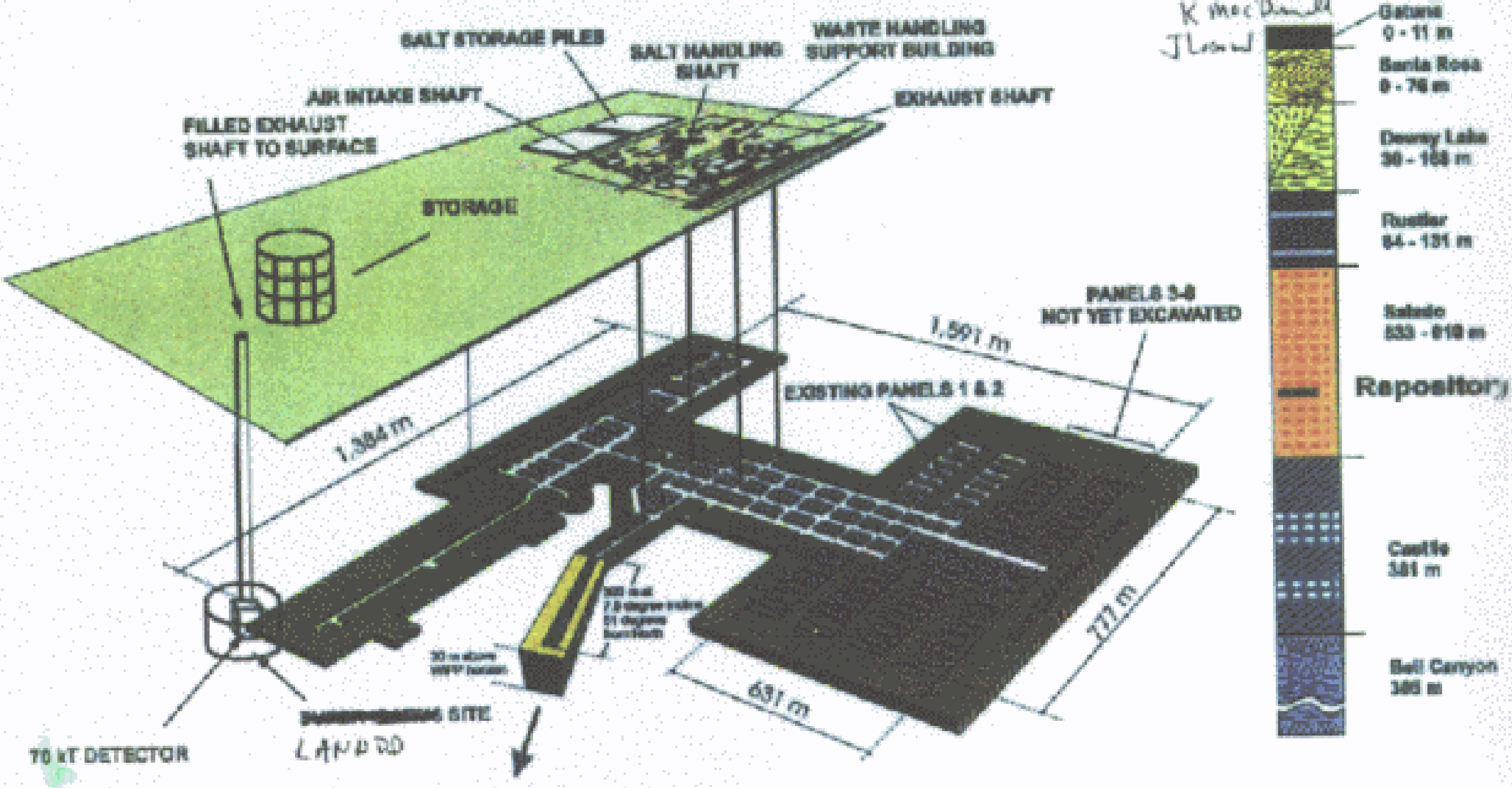
Supr ICARUS
30,000 Tons

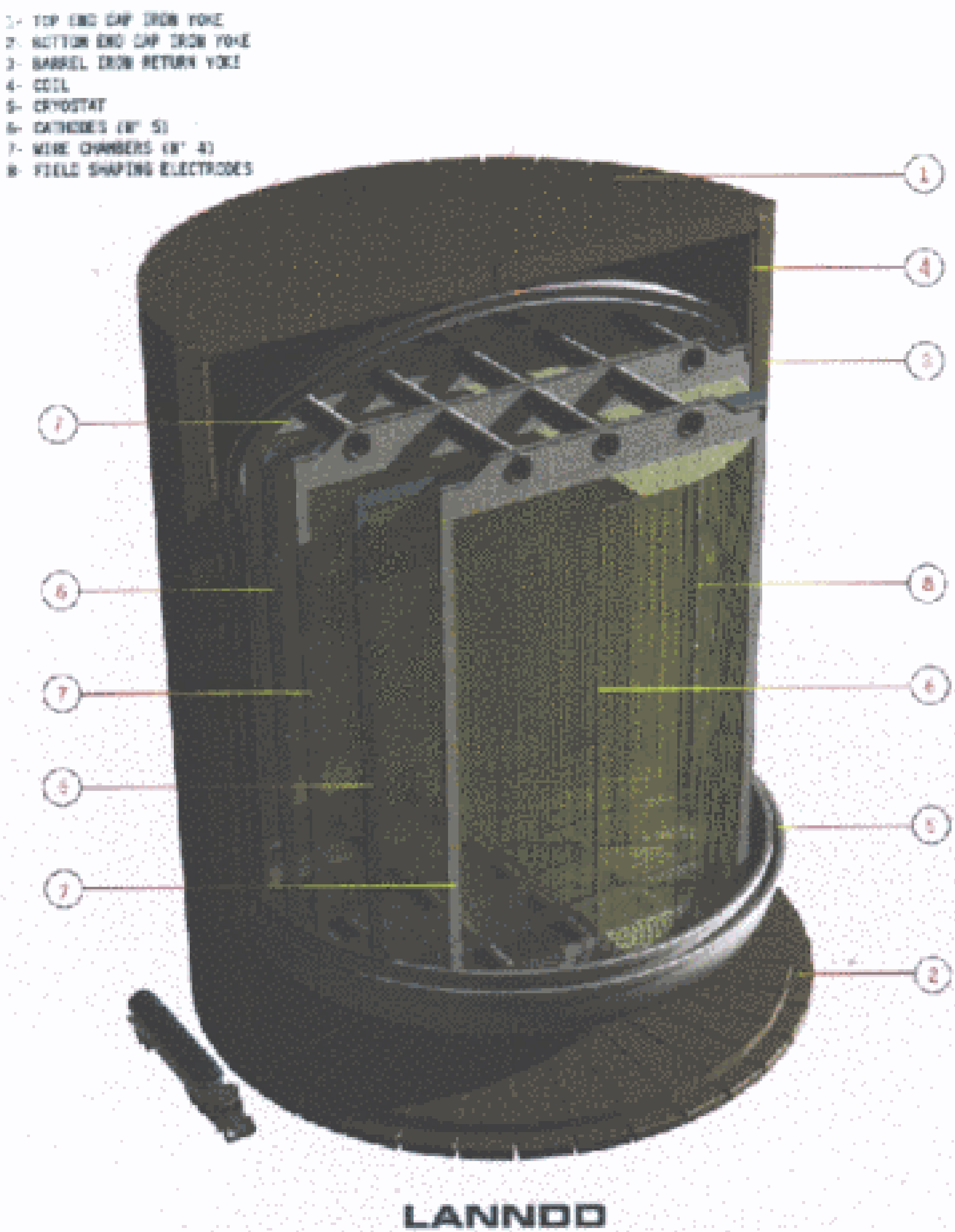


A. RUBBIA, et al

Liquid Argon Neutrino and Nucleon Decay Detector

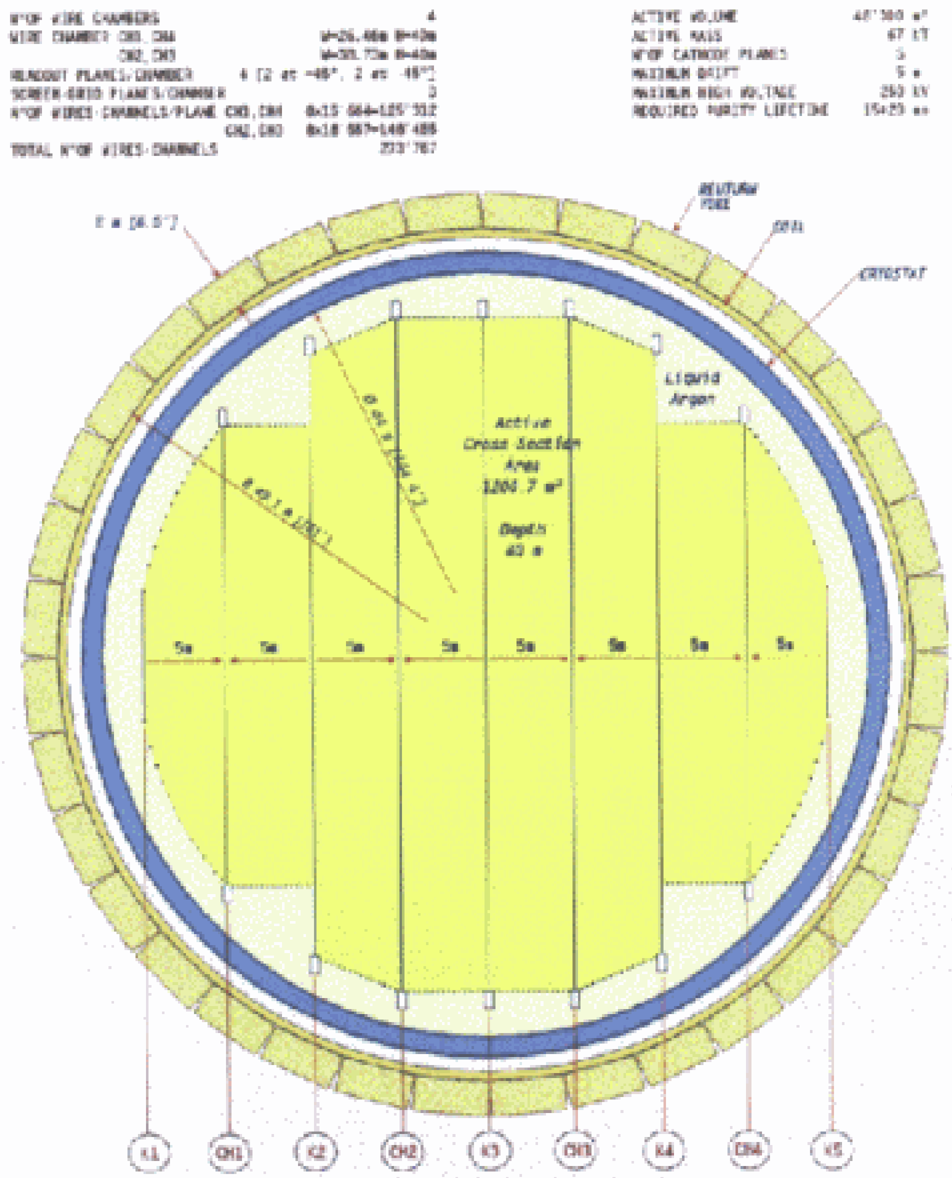
D Cline
F Sergiampietri
K McDonald
J Lozano





LANNDD

Liquid Argon Neutrino and Nucleon Decay Detector



LANNDD

Liquid Argon Neutrino and Nucleon Decay Detector
Horizontal Cross-Section

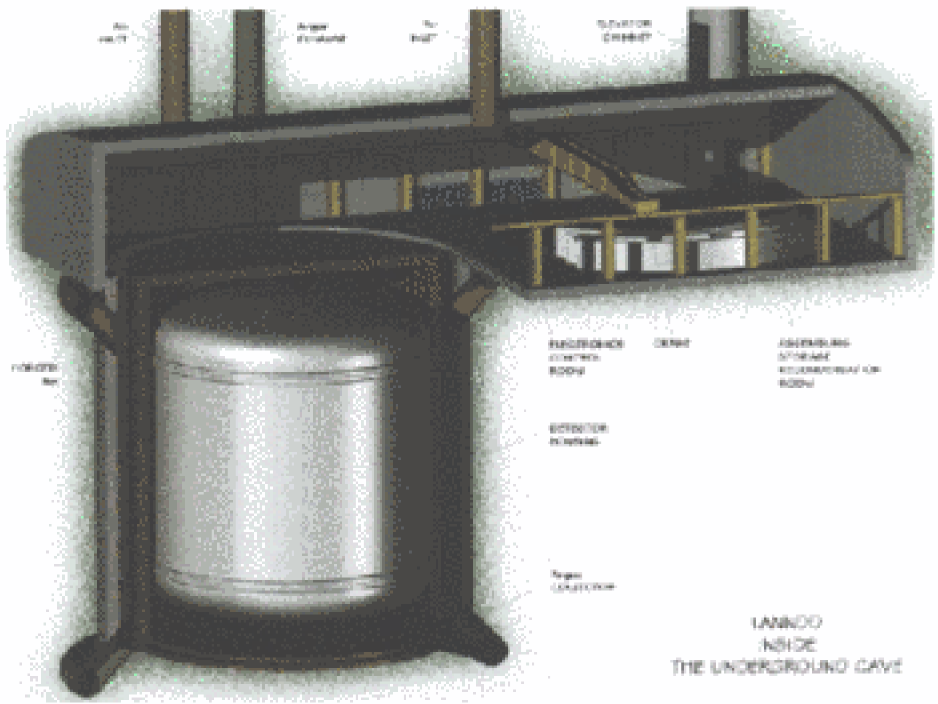


Figure 3. The LANNDD inside the underground cave

ScIPIO

Scintillating Proton
Instability Observatory

Charged kaons easily visible

Excellent energy resolution
typically 5–6 times better
than water cherenkov

R. SVOBODA

to get factor of 40 better than SuperK need about 80 kton

20 x 20 x 200 meters

what would events look like?

$K^+ \longrightarrow \nu \mu^+$

$\beta = 0.91$

not much above Cherenkov threshold

$K \longrightarrow 2\pi$

$\beta = 0.83$ same here

$K \longrightarrow 3\pi$

$\beta = 0.67$ invisible

R. SVOBODA

Similar problems for K^o

$K_L \longrightarrow 3\pi$ interacts before decay

$\tau = 52$ ns d = 30–40 cm

$K_S \longrightarrow 2\pi$

$\tau = 0.09$ ns

Is there a detector that can detect low energy charged K's and maybe neutral K's?

R. SVOBODA

Super–K Results

$p \rightarrow \bar{\nu}\ K^{+}$

$K^{+} \rightarrow \pi^{+}\ \pi^{o}$

6.9×10^{32} years

obs: 0 exp: 1.9

$\varepsilon B = 6.8\%$

$K^{+} \rightarrow \mu^{+} \nu$ + prompt γ

9.5×10^{32} years

$\varepsilon B = 9.3\%$ (model dependent)

$p \rightarrow e^+ \pi^o$

44×10^{32} years

Why so much worse?

$p \rightarrow \nu K$

$\beta = 0.57$

below Cherenkov threshold

$p \rightarrow e^+ + K^o$

$K^o \rightarrow \pi^+ \pi^-$

obs: 6 exp: 1.2

$K^o \rightarrow \pi^o \pi^o$

obs: 1 exp: 1.4

5.4×10^{32} years $\varepsilon B = 19.4\%$

Supernovae

In additional to the usual inverse beta decay, KamLAND can also see neutral current excitation of carbon

$$\nu + {}^{12}C \quad \cdot \quad {}^{12}C^{*}(15.11\ \mathrm{MeV})$$

at 10 kpc SciPIO would see about 4000 of these.

KamLAND expects about
50 events/year < 2 Mev from
U/Th decays in the Earth

SciPIO would get about
4000 events/year

... + U/Th activity in
nuclear waste. (<1 /yr)

Cost

KL scintillator 1M$/kton

may not need such high light production (KL is about 25–30 times SuperK)

dilute scintillator about 80M$

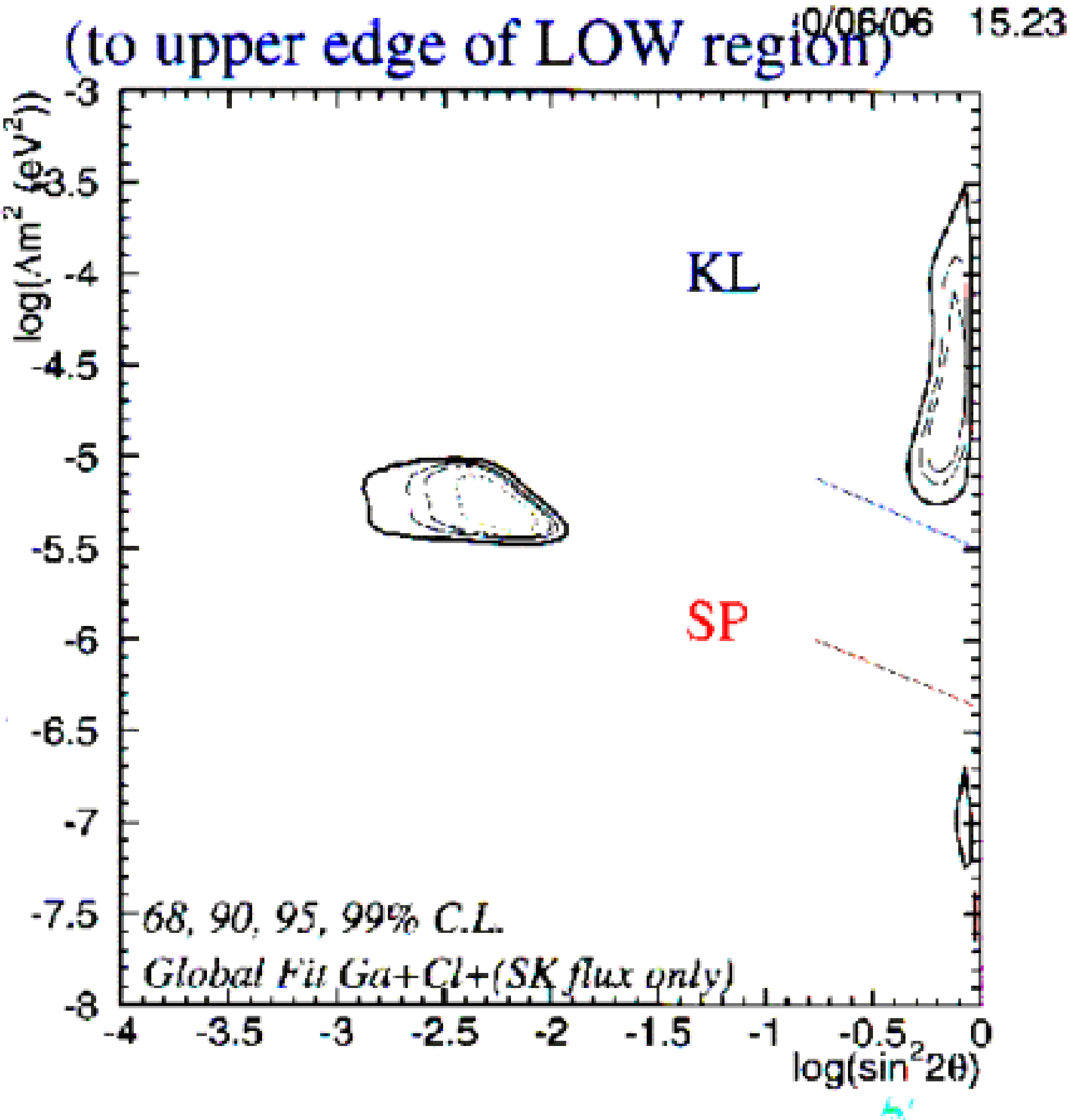
KamLAND–level PMT coverage would require 40,000 PMTs

reactor	pwr(GW)	L	evt/kt/yr
Palo Verde	11.4 GW	813 km	6.3
Commanche Peak	6.8 GW	606 km	6.7
S.Texas Project	7.4 GW	808 km	4.1
San Onofre	6.7 GW	1274 km	1.5
Wolf Creek	3.4 GW	1010 km	1.2
Diablo Canyon	6.8 GW	1563 km	1.0
other			1.0
TOTAL	22 EVENTS/KT/YR		

1760 events/year

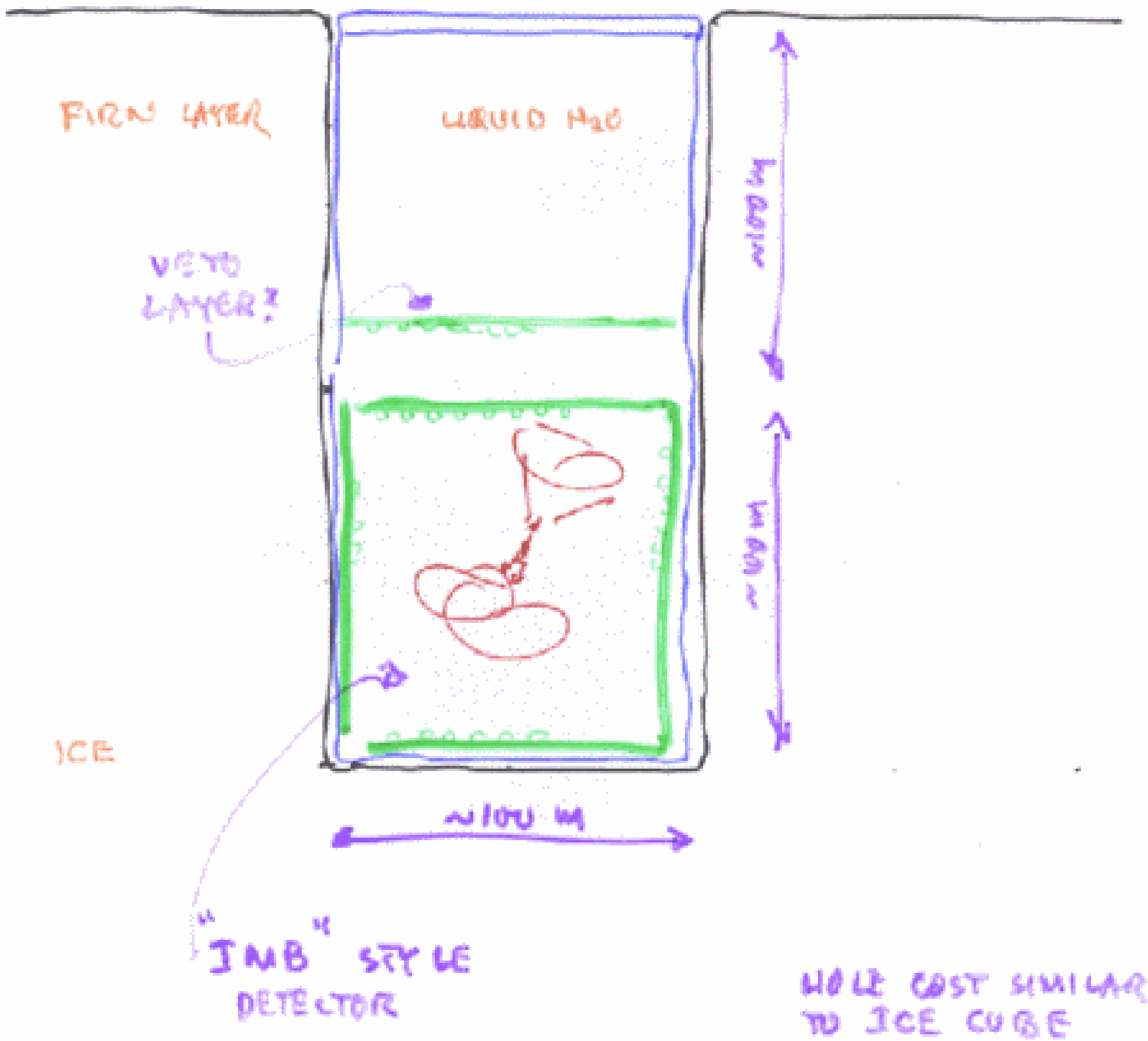
with 5x distance and 2xstatistics we can do roughly 6 times better than KamLAND in δm^2

(to upper edge of LOW region)



A SHALLOW NNN AT SOUTH POLE ?

1 MT 100 m DEPTH



OTHER VENUES ?

COLOCATE ? WITH ANTARES, BAIKAL, NESTOR OR ICE CUBE ?

ADVANTAGES:
- INFRASTRUCTURE
- VETO "FREE" (EAS, ↓μ's ...)
- CATCH EXITING EVENTS
- SN TRIG → KM^3 (TIME PROFILE)

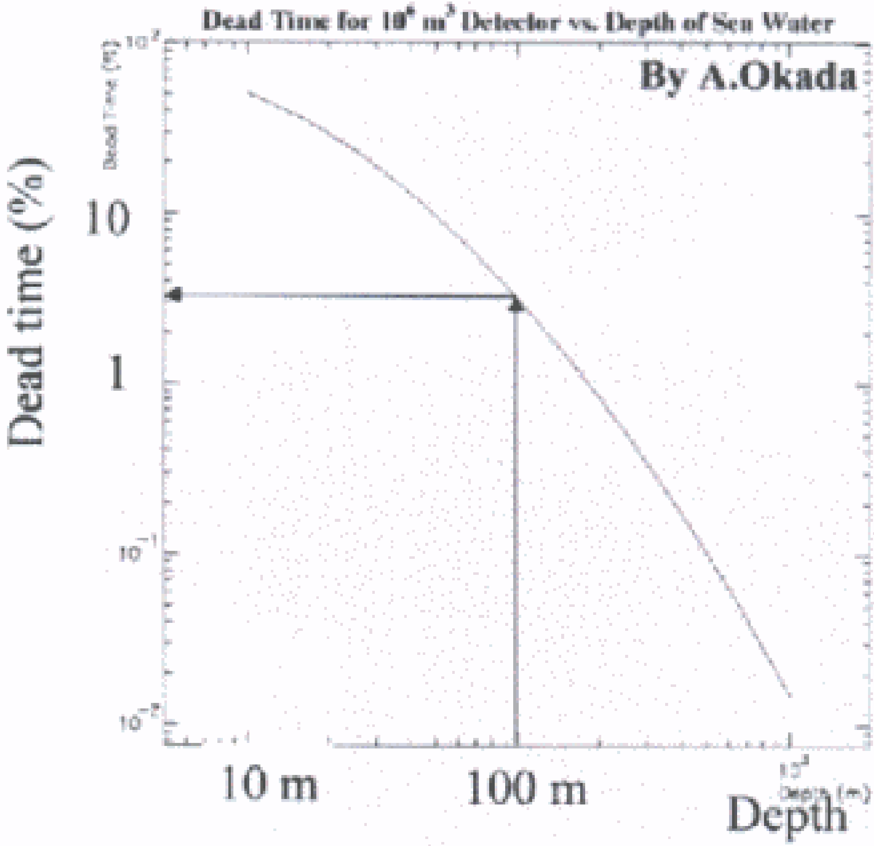
⋮

LOCATION OPTIONS

	SHALLOW (~100 m)	DEEP (~2 km)
MINE:	~ GRANITE PIT / QUARRY ?	KAM., G.S., WIPP, ...
LAKE:	LAKE SUPERIOR ? JAPAN IN-SHORE,	1 km BAIKAL
ICE:	SOUTH POLE	w/ ICE CUBE
OCEAN:	NEAR JAPAN	NESTOR, ANTARES
	↑ BKGDS ? LIMIT PHYSICS @ LE	↑ COST OF DEEP DEPLOY

Cosmic Ray background and dead time

Assumption: 1μsec dead time for CR events



Dead time < a few %

→ go deeper than 100m w.e.

(Depend on the segmentation)

SUMMARY

- EXISTS STRONG MOTIVATION TO FIND PDK
  BUT MUST → $\tau/B \gtrsim 10^{35}$ YR

  ⇒ MT DETECTORS IF WATER
  OR
  ~100 KT IF "FANCIER" TECHNIQUE

- A HUGE PDK INSTRUMENT IS USEFUL FOR
  MANY INVESTIGATIONS! ν OSC, ASTRO ν's, ...

- CAN WE COUPLE SUCH AN INSTRUMENT WITH
  A NEUTRINO FACTORY ?

  → MAY BE, BUT NEED $\mu^{\pm}$ ≢ $e^{\pm}$
  ↑
  VERY TOUGH
  (L Ar ?)

- WE (THE COMMUNITY) HAVE TIME:

  → INVESTIGATE
  - SK × YR (HYPERK, TITANIC, UNO, ...)
  - AQUA-RICH
  - LIQ. AR (LANNDD, SUPER-ICARUS)
  - SCINT. ... (SCIPIO)
  - VARIOUS LOCATIONS (OCEAN? SP?)

3 NNN MTGS IN US 8/99, 1/00, 7/00
NEXT @ LSD

- NEED, PROBABLY, SOME NEW TECHNOLOGY (PMTS)
  TO KEEP COSTS ≲ $1 B

- A PROMISING FUTURE