Hyper-Kamiokande

--- Concept and R&D ---

Kenzo NAKAMURA
KEK

August 1-2, 2005
Neutrino Meeting
IIT-Bombay, Mumbai, India

Science with large underground detectors

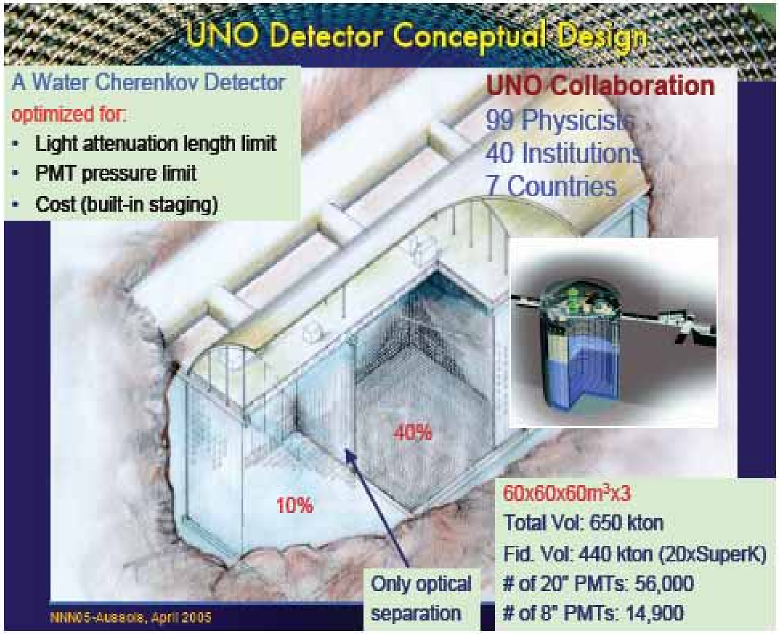
- Neutrino physics
  - w/ accelerator-produced beam
    - LBNO, VLBNO
    - θ_{13}, sign(Δm_{23}^2), δ_{CP}, precision measurement of (θ_{23}, Δm_{23}^2)
  - wo/ accelerator-produced beam
    - solar ν, atm ν, ν burst from SN, relic SN ν
- Nucleon decay
  - $p \rightarrow e^+\pi^0$, νK^+, other decay modes
- Most of large detectors are multi-purpose
  - Water Cherenkov (~Mton)
  - Liq. Ar (~100 kton)
  - Liq. Scintillator (~50 kton)

Next-generation water Cherenkov detectors

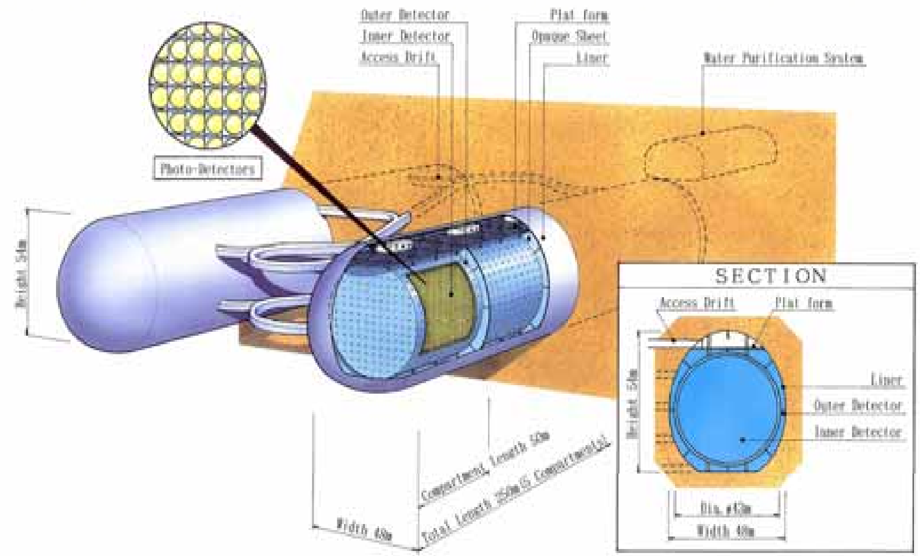
- Concept of a Mton water Cherenkov detector dates back to 1992
  - M. Koshiba: "DOUGHNUTS"   Phys. Rep. 220 (1992) 229
- Conceptual idea of next-generation water Cherenkov detectors
  - 1999: UNO & Hyper-K
  - 2002: MEMPHYS
- Time line of each detector (from talks @ NNN05)
  - UNO @ Henderson Mine
    - DUSEL proposal: 2005
    - Construction: 10 years, wish to start as soon as possible
  - Hyper-K @ Tochibora Mine (Kamioka)
    - Some years after start-up of T2K-1
    - Construction: 10 years, hopefully 2013 – 2022
  - MEMPHYS @ Frejus Tunnel
    - CERN-based Super and beta beams hopefully ready before 2020
    - Construction: hopefully 2010 – 2019 (first module 2017)

Recently, NSF selected Henderson Mine and Homestake Mine as candidates for DUSEL

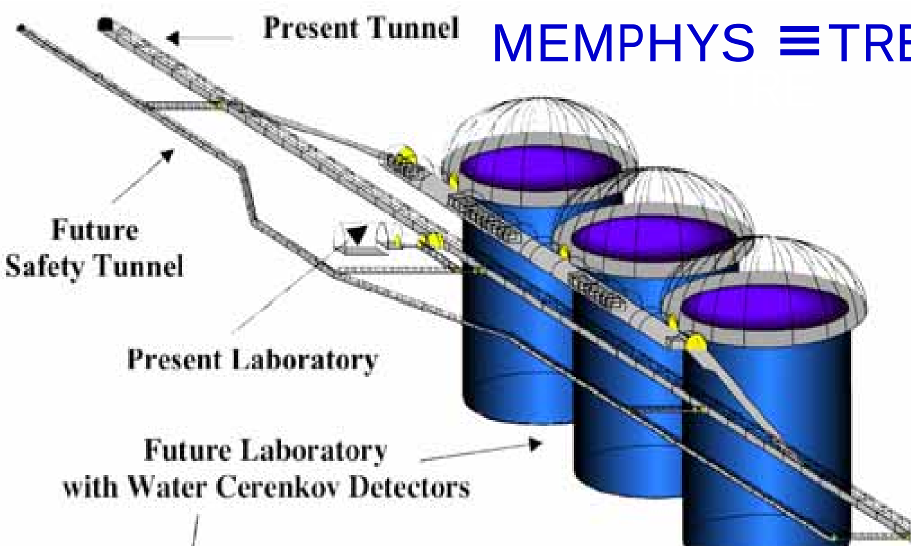
Study of the possibility to construct in 7 years started



Hyper-Kamiokande ≡DUE

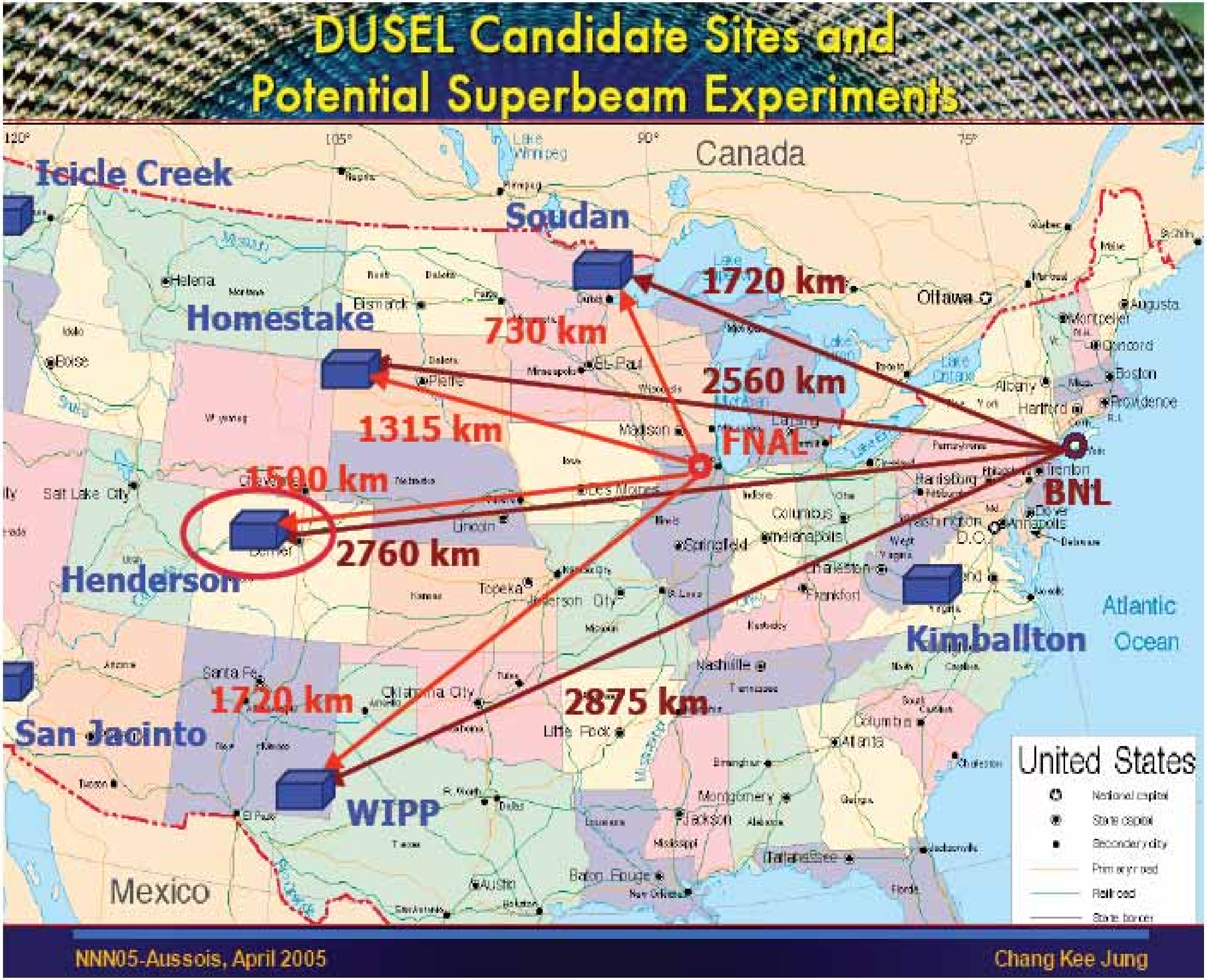


MEMPHYS ≡TRE



- DUE and TRE have a choice to put Gd in one module in order to enhance the sensitivity to low-energy antineutrino detection.
  → Relic SN detection
- See, an interesting paper [PRL 93 (2004) 171101] by Beacom and Vagins on GADZOOKS (Gadolinium Antineutrino Detector Zealously Outperforming Old Kamiokande, Super!)

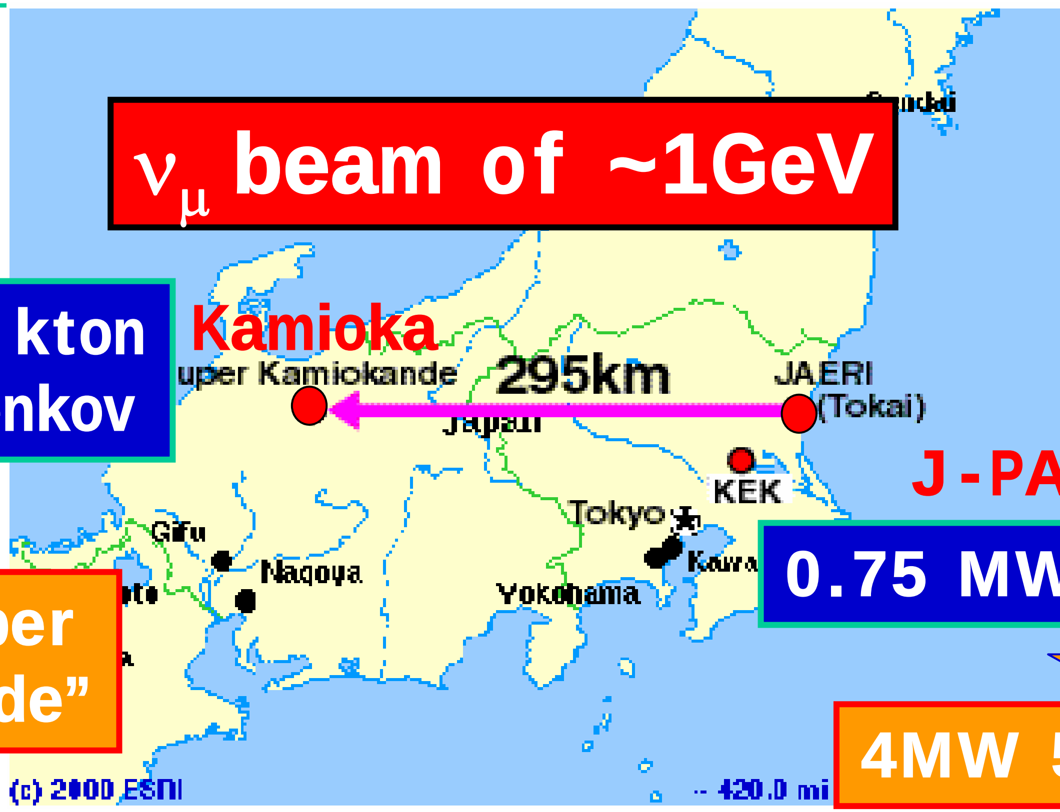
- LBNO: each detector has its own project
  - UNO-BNL or UNO-Fermilab: 1500 – 2800km
  - HyperK-J-PARC: 295 km
  - European detector-CERN super and beta beams: 130 km



DUSEL Candidate Sites and
Potential Superbeam Experiments
Canada
Icicle Creek
Soudan
Homestake
Henderson
San Jacinto
WIPP
Kimballton
FNAL
BNL
1720 km
730 km
2560 km
1315 km
1500 km
2760 km
1720 km
2875 km
Atlantic
Ocean
Mexico
United States
National capital
State capital
Secondary city
Primary road
Railroad
State border
NNN05-Aussois, April 2005
Chang Kee Jung

Overview of the T2K Experiment

A word of warning: T2K-II ≠ J-PARC Phase II, rather beyond J-PARC Phase II



ν_μ beam of ~1GeV

Super-K: 50 kton Water Cherenkov

~Mt "Hyper Kamiokande"

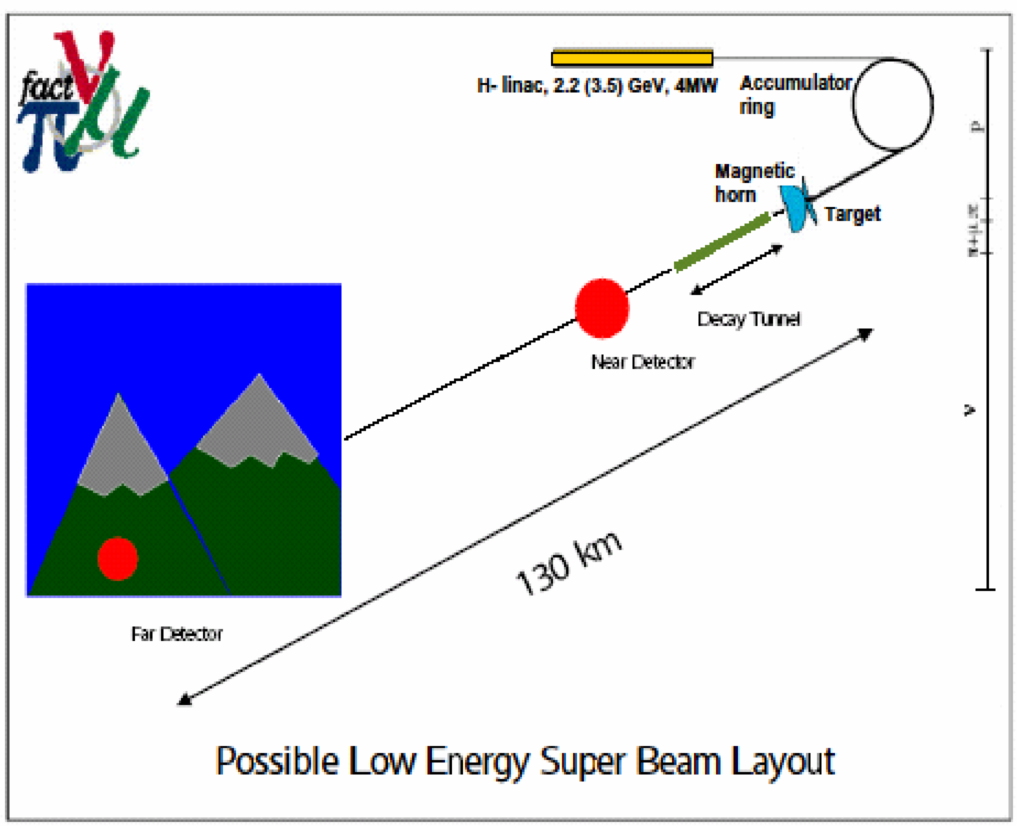
0.75 MW 50 GeV PS

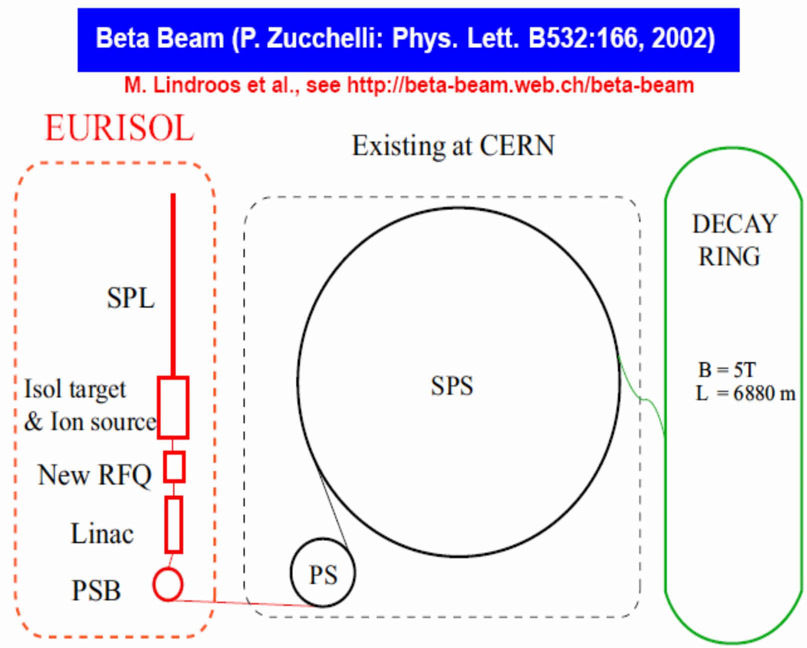
4MW 50 GeV PS

1st Phase
- $\nu_\mu \rightarrow \nu_x$ disappearance
- $\nu_\mu \rightarrow \nu_e$ **appearance**
- NC measurement

Future
- **CPV**
- **proton decay**

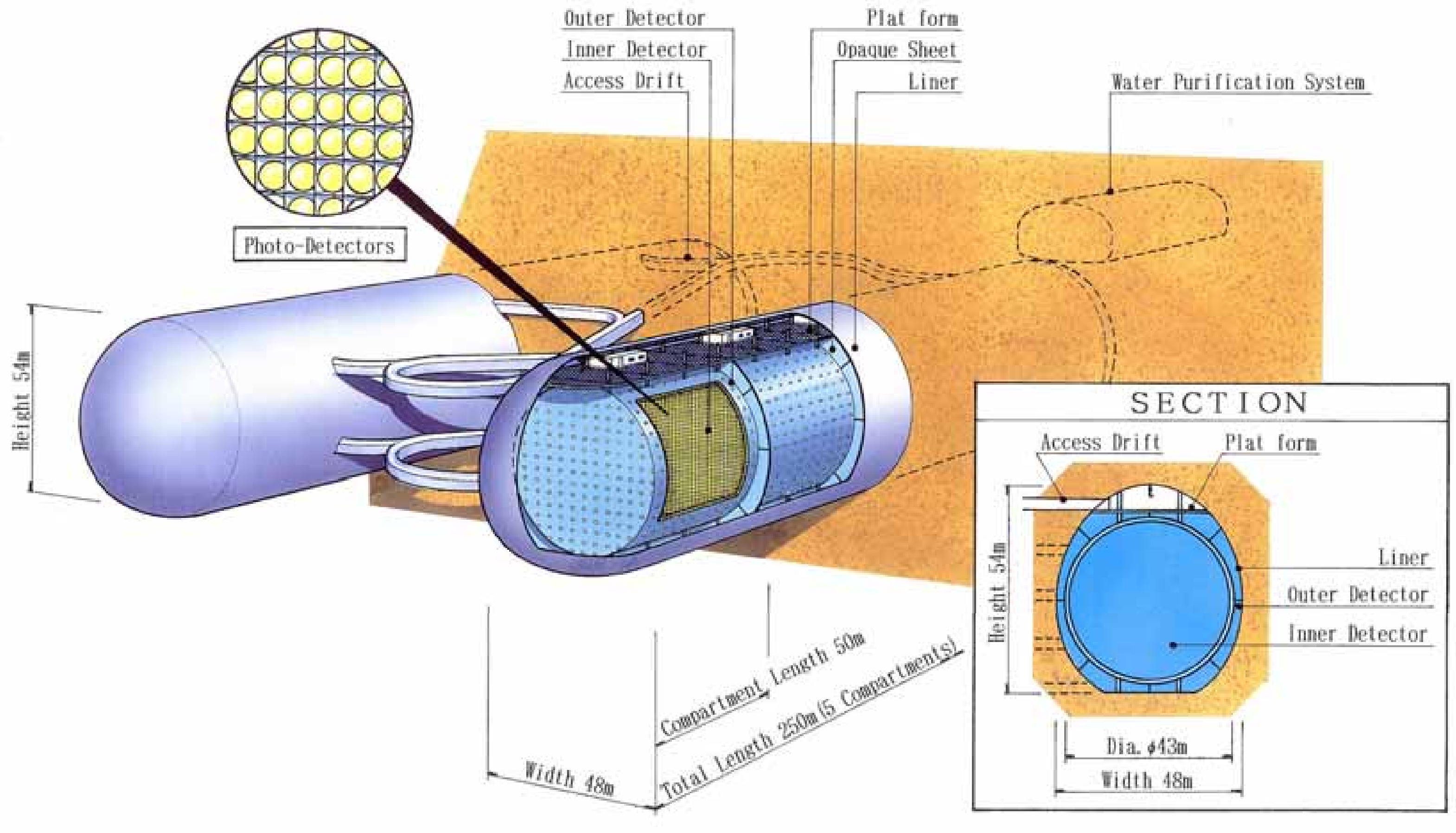
CERN to Frejus: Super and Beta Beams





Conceptual Design of Hyper-Kamiokande

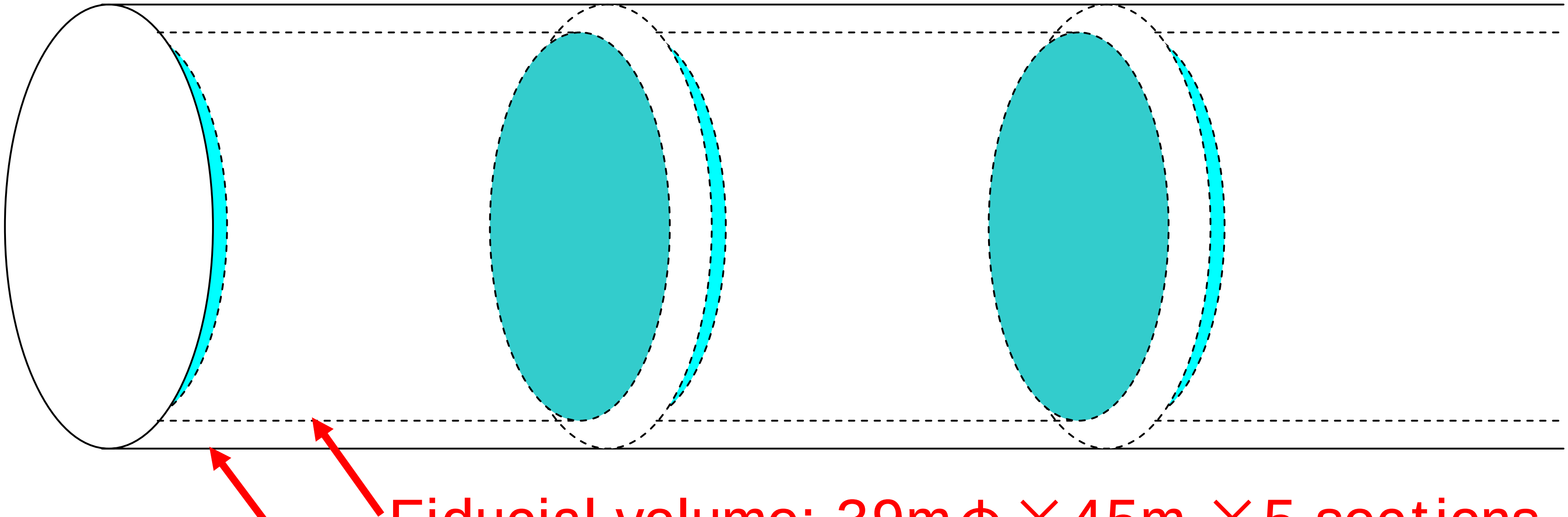
~1 Mton water Cherenkov detector at Kamioka



Why this design has been chosen ?

- Water depth < 50 m
  (If the present 20-inch PMT or similar one will be used.)
- Linear dimensions for light path < 100 m
- Optimization of M_{FID}/M_{TOTAL}
- Rock stability
  - Avoid sharp edges. Spherical shape is the best.
- Our solution: Tunnel-shaped cavity
- Single Cavity or Twin Cavities?
  - Single Cavity
    - M_{FID}/M_{TOTAL} is better
    - Cost is lower
    - Larger area of stable rock mass needed.
  - Twin Cavities
    - Two detectors are independent. One detector is alive when the other is calibrated or maintained.
    - Both cavities should be excavated at the same time. But staging scenario is possible for the later phase of the detector construction.
- Our solution: Twin cavities

Fiducial / Total



Fiducial volume: 39mφ×45m ×5 sections ×2 = 0.54 Mton

Total Inner detector volume: 43mφ×49m ×5 sections ×2 = 0.72 Mton

Total detector volume: 1 Mton

Total number of PMTs: 200,000 (if 2/m^2)

Comparison of 3 Generations of Kamioka Nucleon Decay Experiments

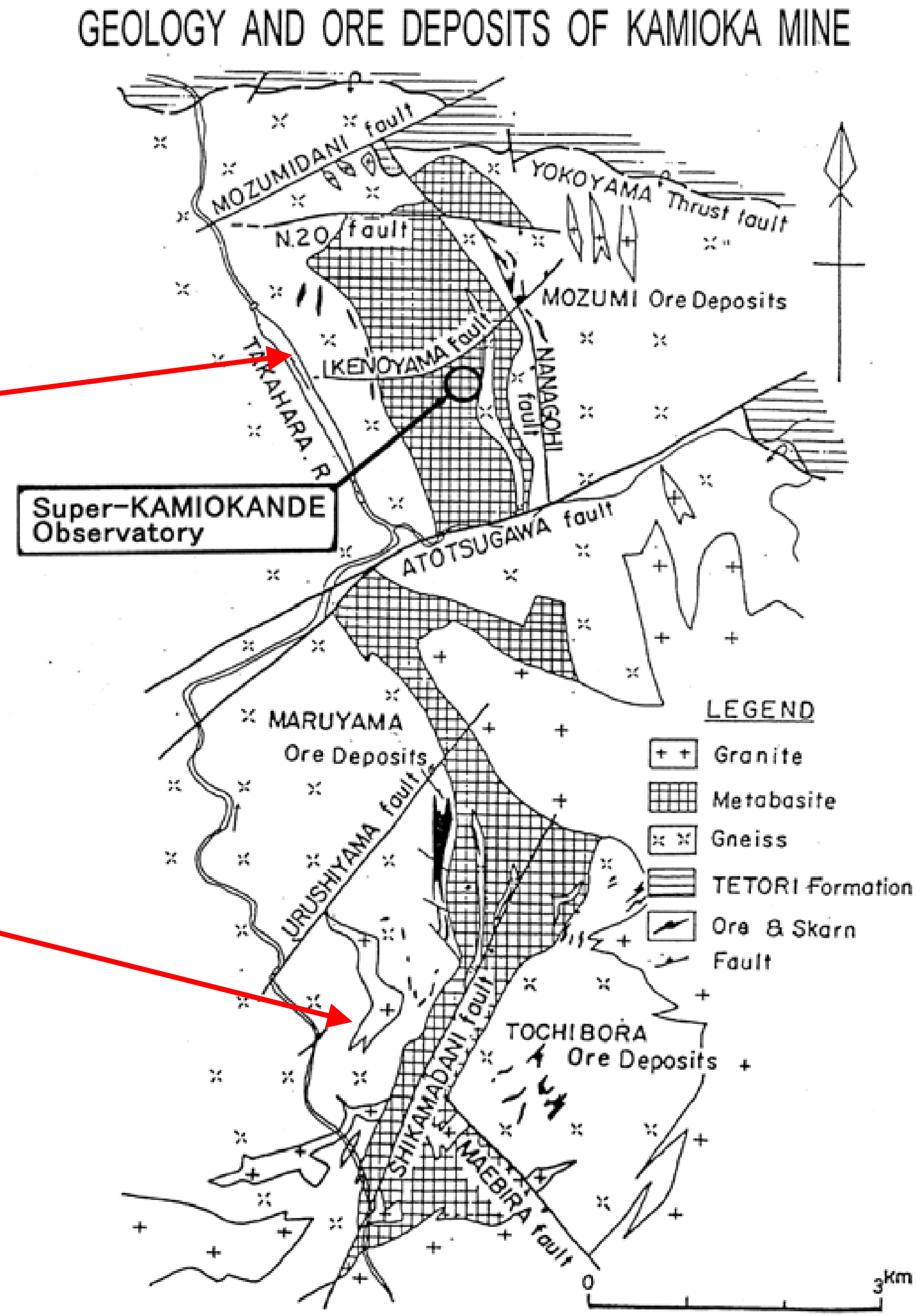
	Kamiokande	Super-Kamiokande	Hyper-Kamiokande
Mass	3,000 t (+1,500 t)	50,000 t	1,000,000 t
Photosensitive Coverage	20 %	40 % (SK-I and -III) 20 % (SK-II)	?
Observation Started	1983	1996	?
Cost (Oku-Yen)*	5	100	500?**

* 1 Oku-Yen ≈ 1M$
** Target cost; No realistic estimate yet

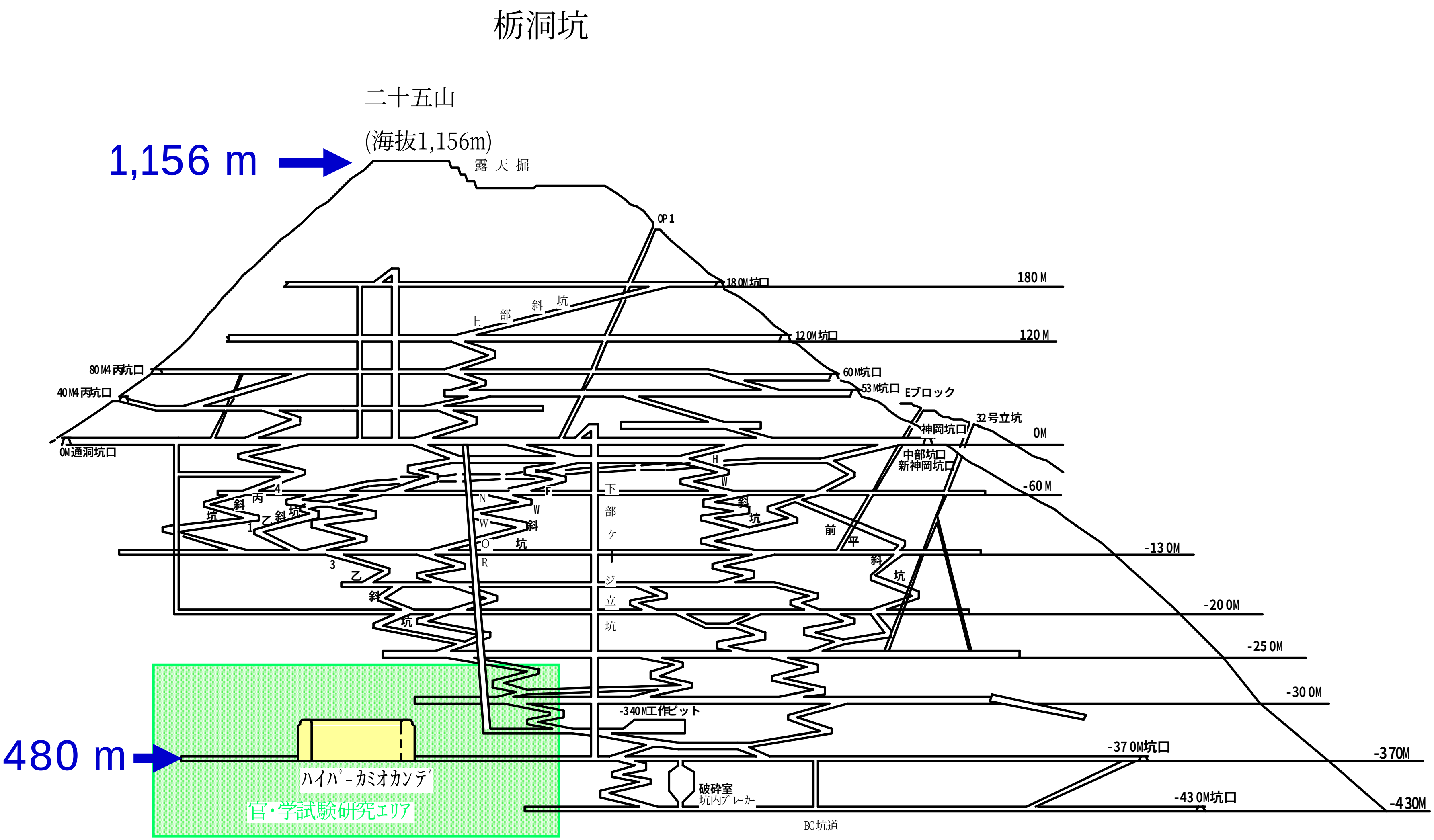
Kamioka Mine Geological Map

MOZUMI Mine

TOCHIBORA Mine



Hyper-Kamiokande in Tochibora Mine

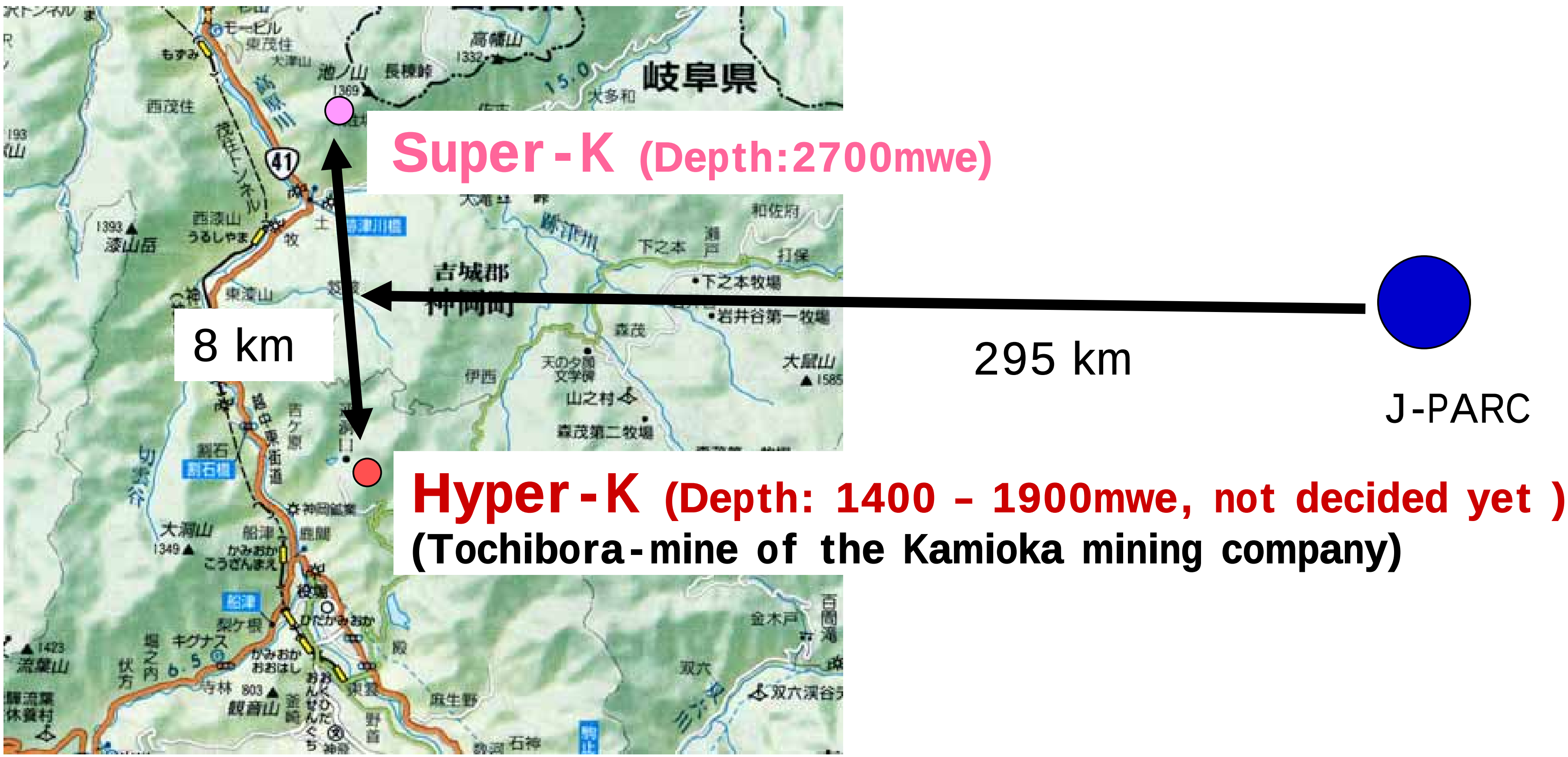


Hyper-Kamiokande

Why Tochibora Mine?

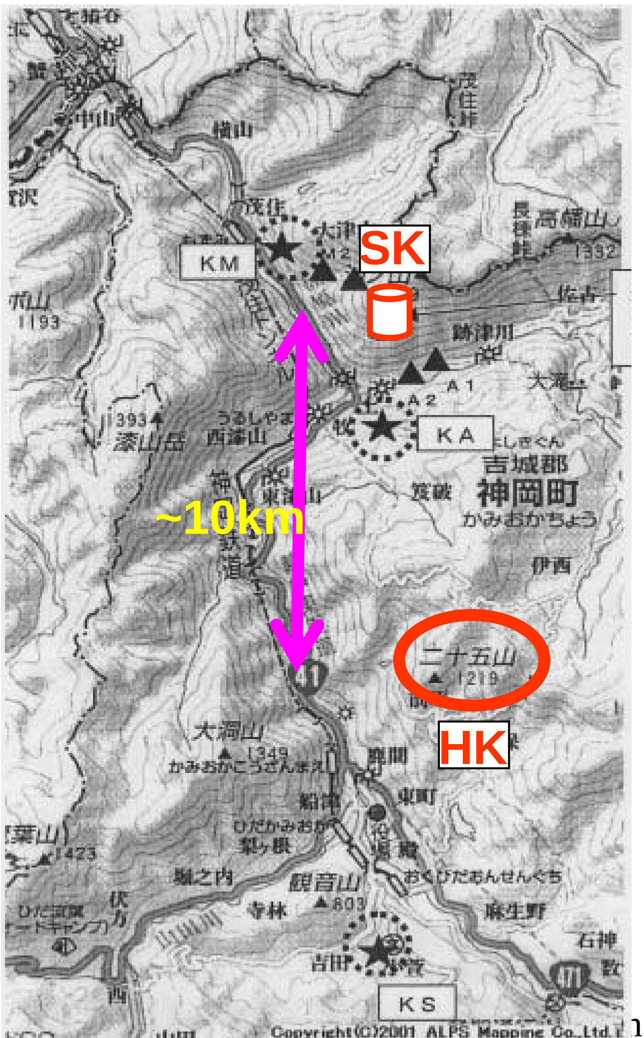
- Rock mass quality is better at Tochibora site. That at Mozumi site is not preferable for excavation of a very large cavity.
- Large-scale blasting should be avoided near the Super-K and KamLAND detectors.
- Tochibora site is shallower than Mozumi site, but OK for events with > 100 MeV deposited energy or with good timing definition.
- We consider the Tochibora site as the primary candidate for Hyper-Kamiokande.

Candidate Site: Relation with T2K

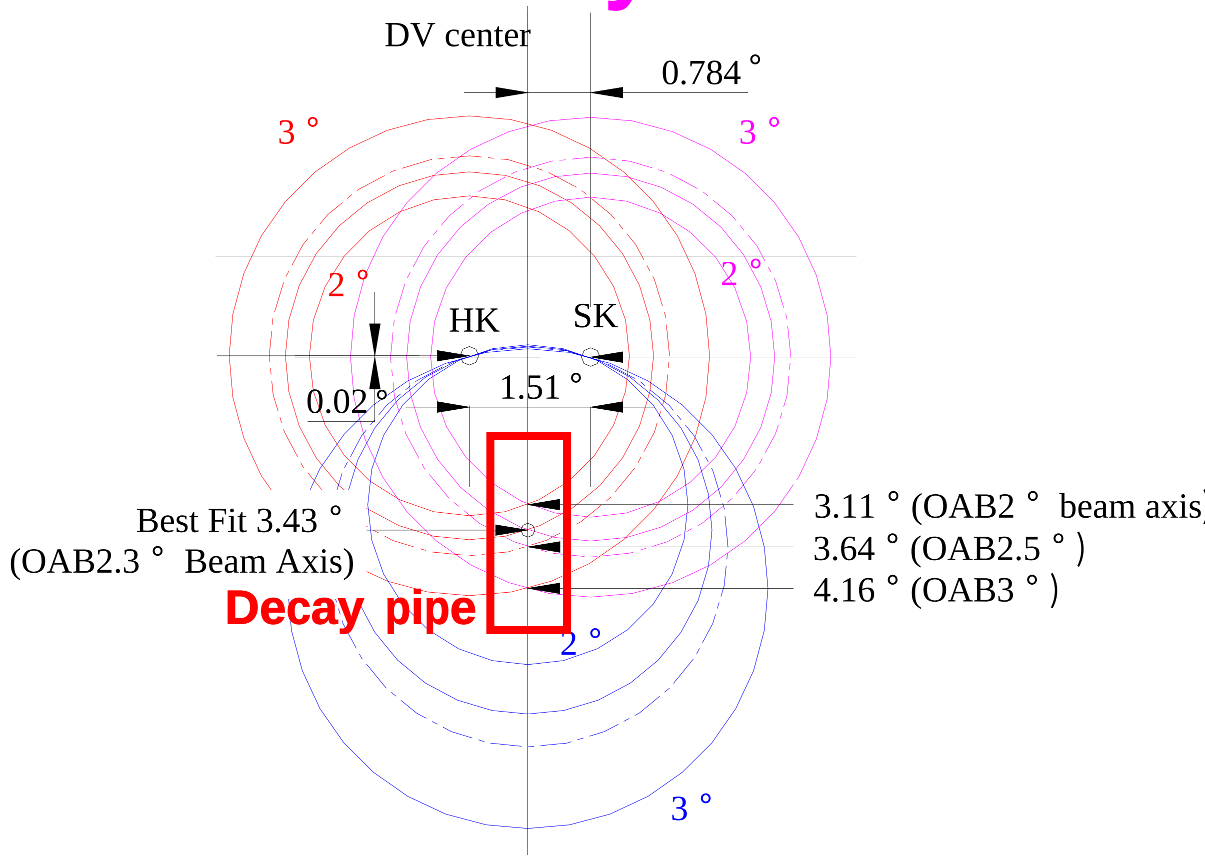


Decay Pipe Common for SK/HK

Possible site for Hyper-K



Beam eye



must cover p/π beam axis -(3〜4) deg

corresponding to $\Delta m^2 = (2.2\sim3.2)\times10^{-3}\ \mathrm{eV}^2$

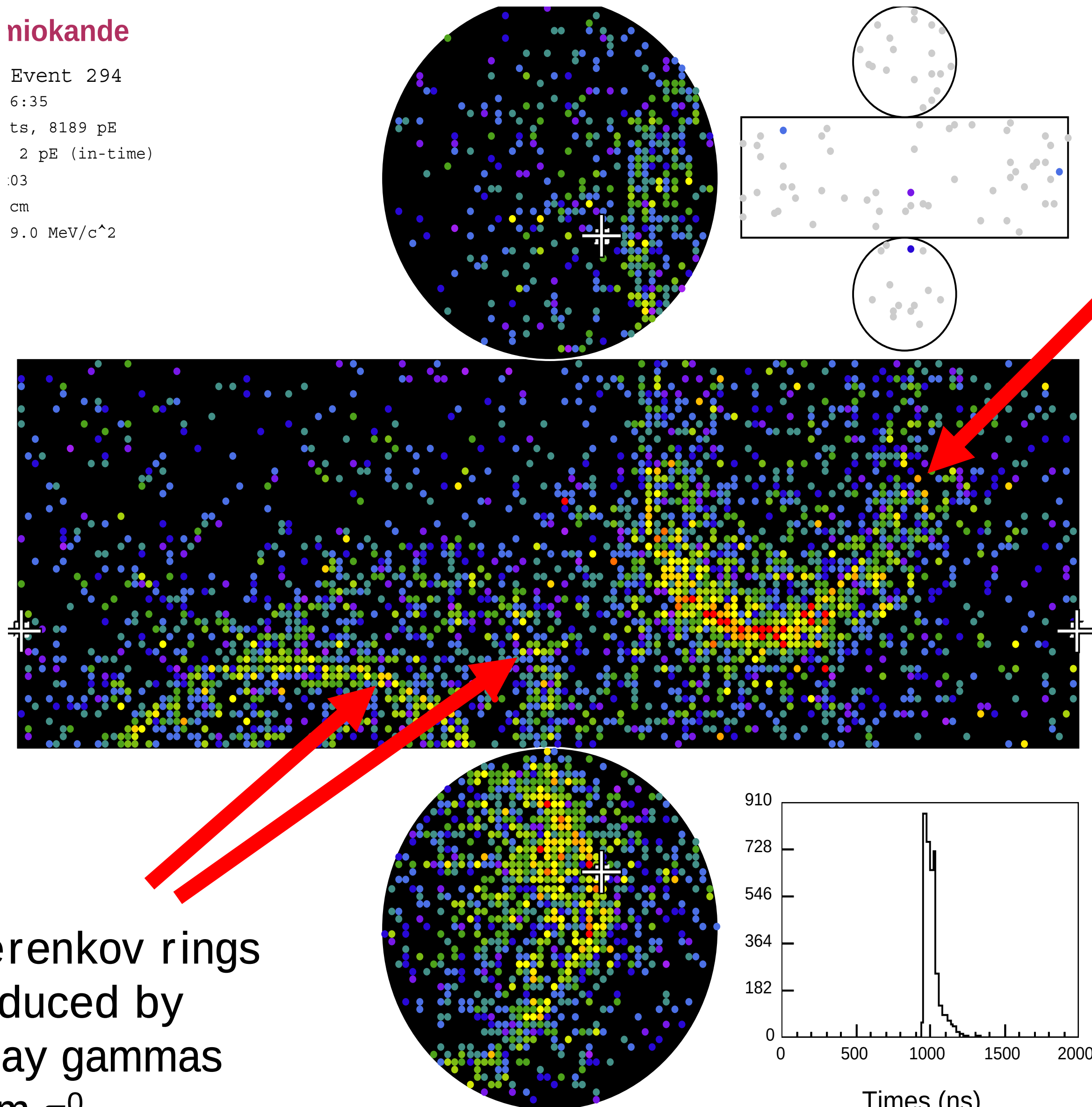
What can be done with Hyper-K ?

- T2K long baseline neutrino oscillation experiment:
  - 2nd phase, CP violation
  - If the θ_{13} measurement in the 1st phase gives only an upper limit, the 2nd phase will enhance the reach
- Proton decay
  - $e^+\pi^0$ Reach: $\tau_p(e^+\pi^0)/B \sim 10^{35}$ yr
  - νK^+ $\tau_p(\nu K^+)/B \sim 10^{34}$ yr
  - and other modes
- Neutrino oscillation measurements with atmospheric neutrinos: θ_{13}, sgn(Δm^2), sub-dominant osc., CP phase
- Measurements of low-energy neutrinos
  - Supernova neutrino ($\sim$x10^5 neutrinos for a SN at the center of the galaxy)
  - Relic supernova neutrinos
  - Solar neutrino measurements
    - Possible at the Hyper-K site (600-700 m overburden) ? Under study.

Physics Objectives

Other than Long Baseline Neutrino Oscillations (see the other my talk), Atmospheric Neutrino Observations (see Nakayama's talk), and Solar Neutrino Observations (HK site is shallow)

Search for proton decays

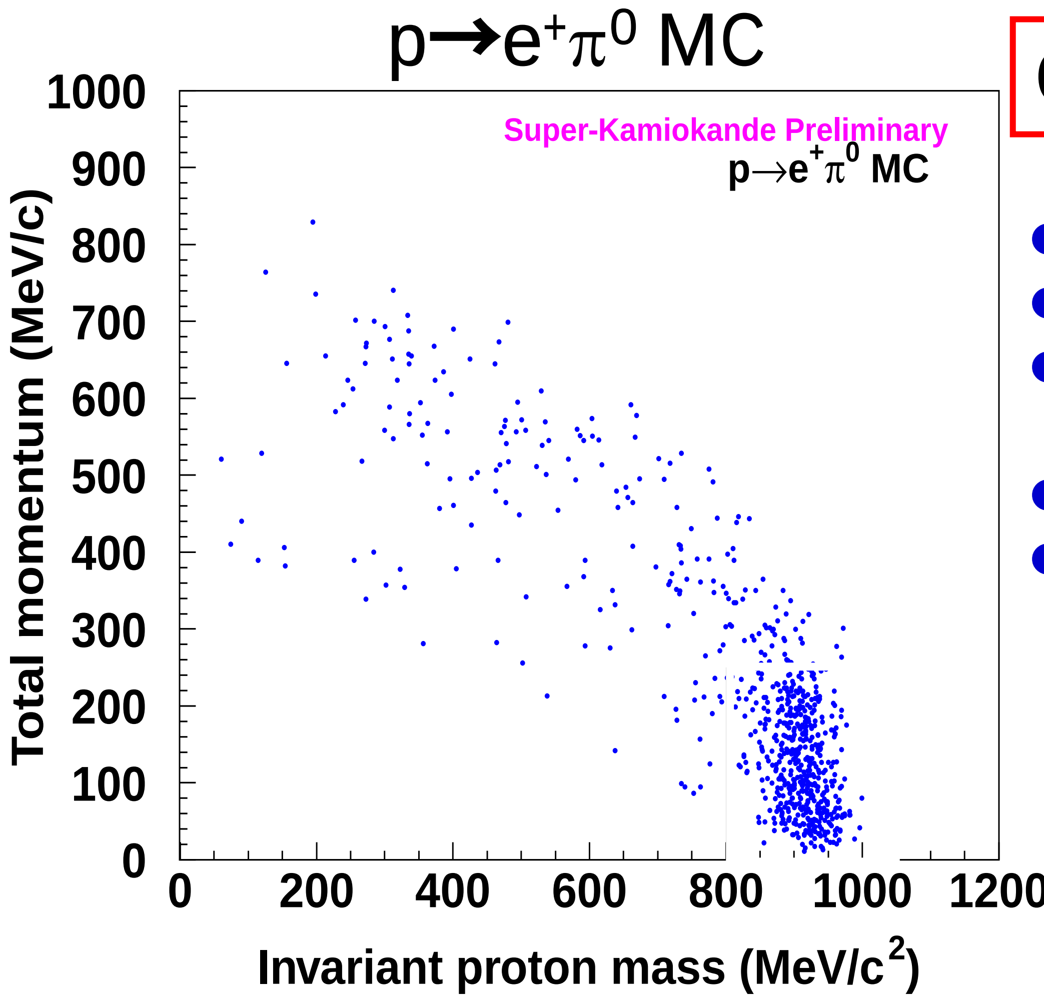


Cherenkov ring produced by a positron

Cherenkov rings produced by decay gammas from π^0

- The following discussion assumes the same photo-sensitive coverage as SK-I (40%).
- The sensitivity to proton decay with reduced photo-sensitive coverage should be studied.

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



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

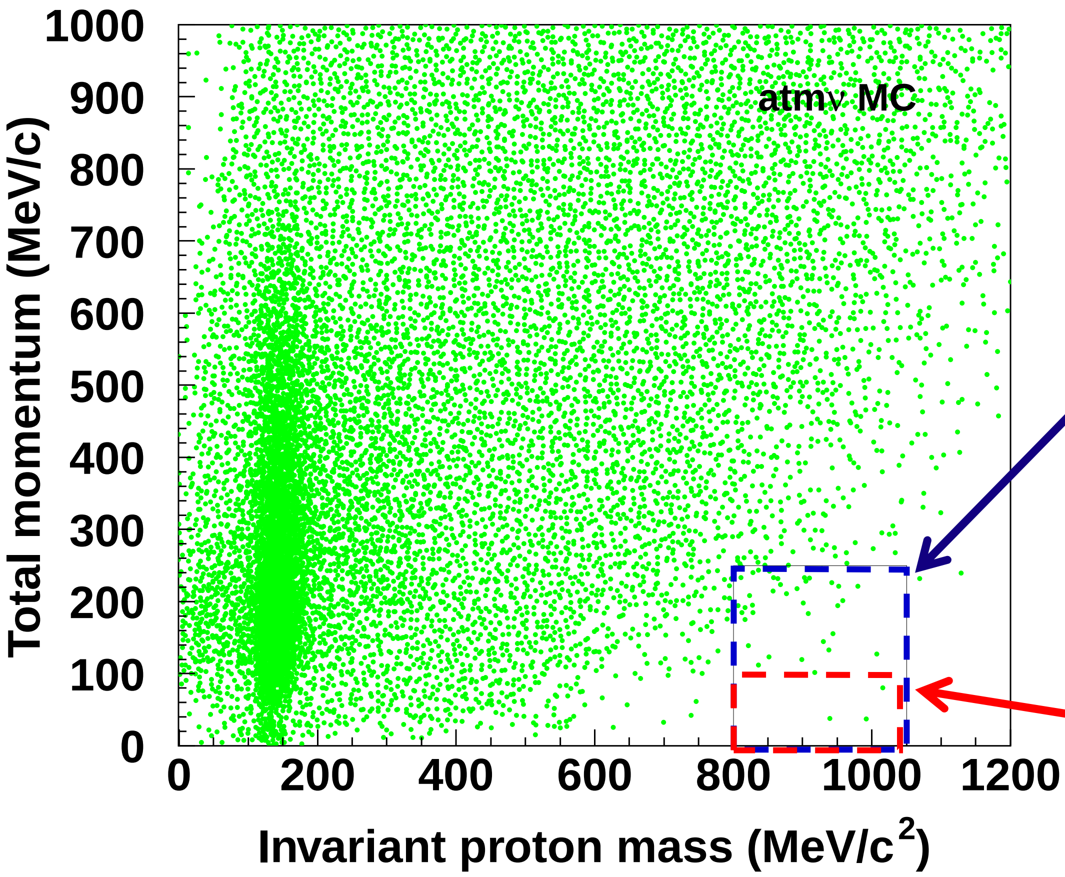
- 2 or 3 Cherenkov rings
- All rings are showering
- $85 < M_{\pi^0} < 185 MeV/c^2$ (3-ring)
- No decay electron
- $800 < M_{proton} < 1050 MeV/c^2$
  $P_{total} < 250 MeV/c$

⇩

ε = 40 % in SK-I

$p \rightarrow e^+\pi^0$ in Hyper-K

20 Mton·yr atm ν BG MC



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

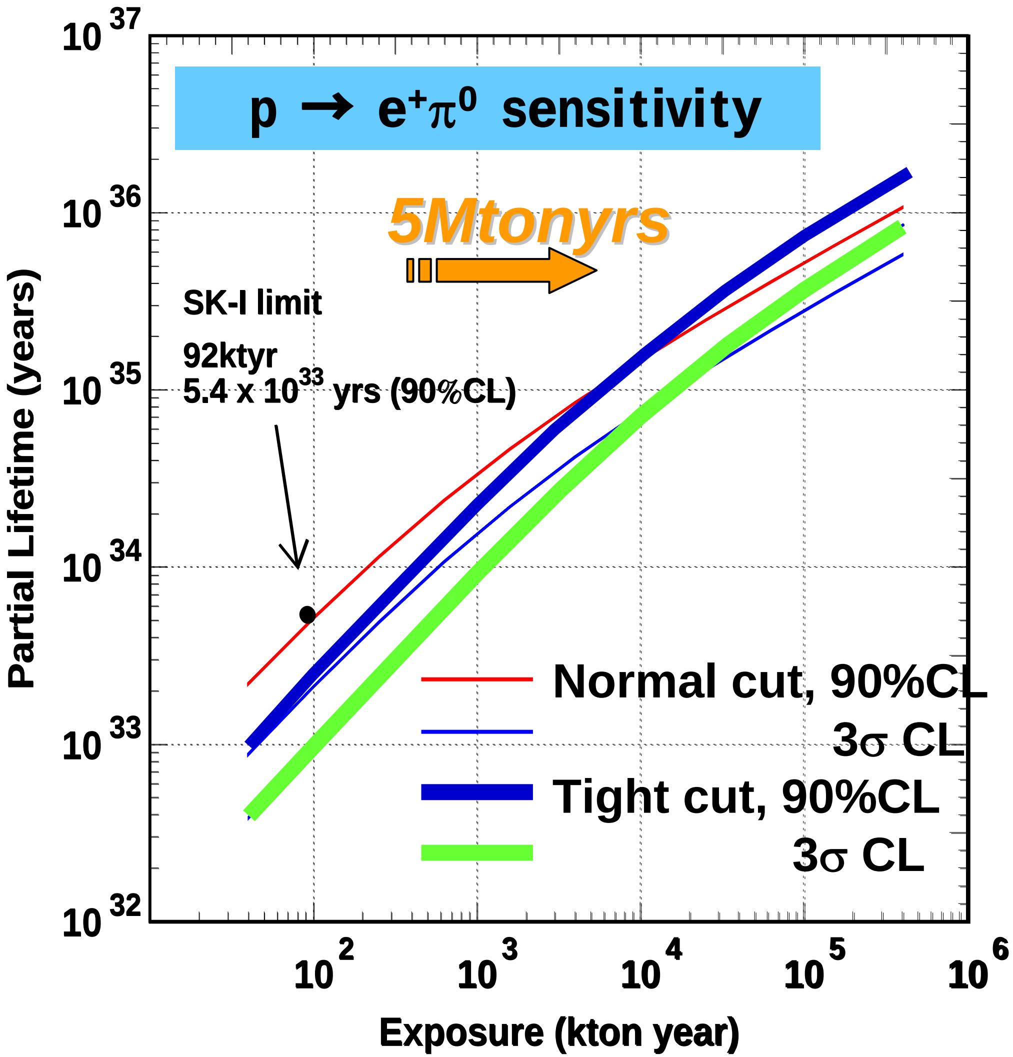
"SK cut"

~2.3 events/Mton·yr
ε = 43 %

"tight cut"

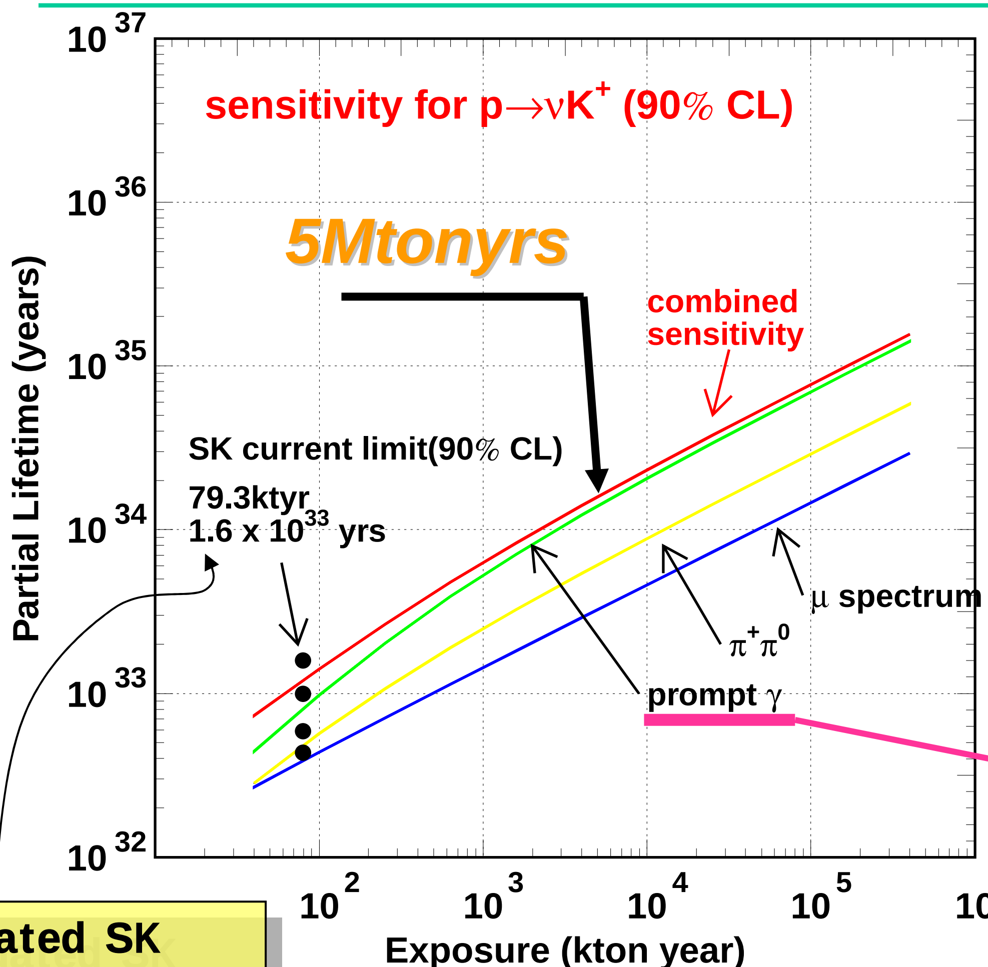
~0.15 events/Mton·yr
ε = 17 %

Lifetime sensitivity for $p \rightarrow e^+\pi^0$

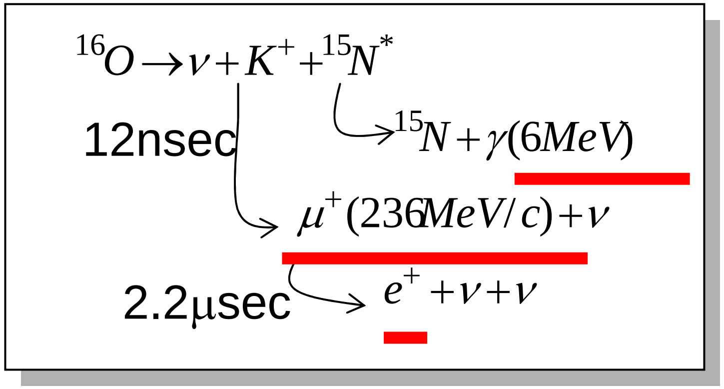


5 Mton·yr ➔
~10^{35} yr @90% CL
~4×10^{34} yr @3σ

Lifetime sensitivity for νK^+ (based on SK criteria)



$\tau/B > 2 \times 10^{34}$ yr
(5Mton·yr, 90% CL)

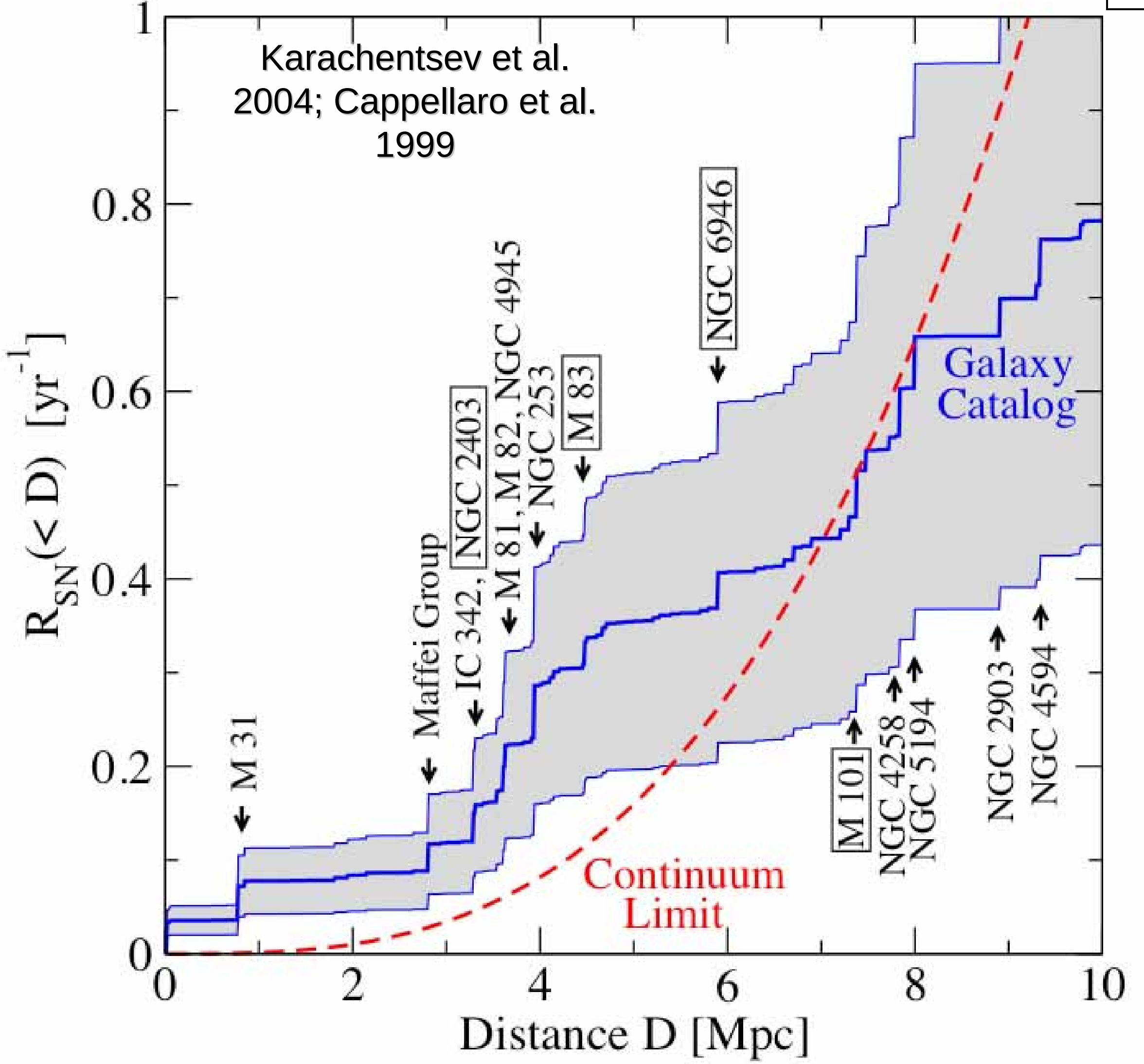


updated SK result = $2,3\times10^{33}$ yrs

Question: How much photo cathode coverage is necessary?

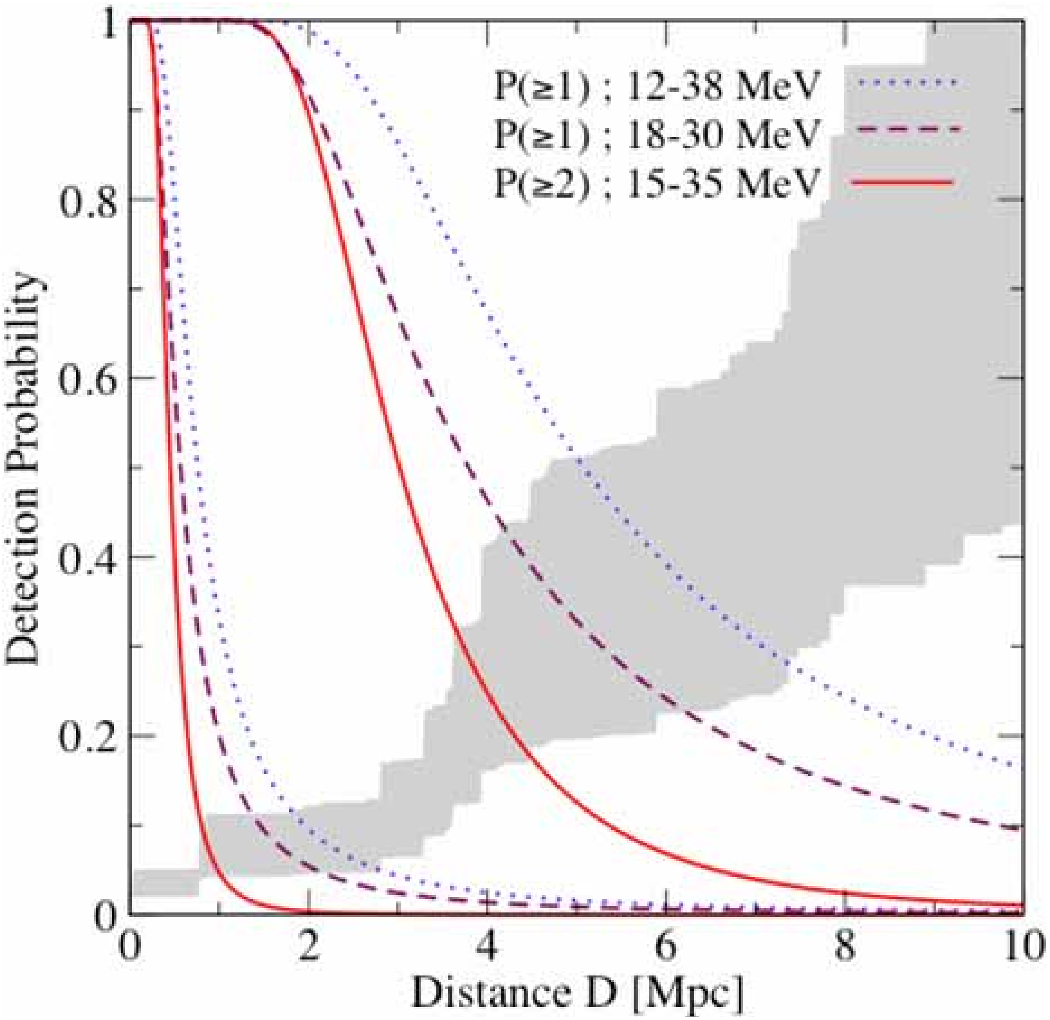
Supernova Rate in Nearby Galaxies

S. Ando, NNN05



Detection Probabilities

S. Ando, NNN05



1 Mton fiducial mass assumed

- Real chance to detect more than 1 or 2 events
- More than 2-event detection
  - Essentially background-free
  - Accidental coincidence rate: ~ 0.1 /yr
- 1-event detection
  - Need astronomers' help to restrict time-bin.

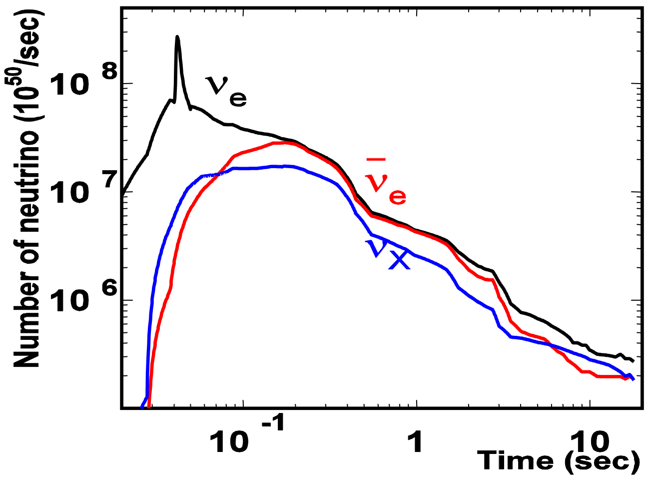
Supernova event rate in Mega-ton detector

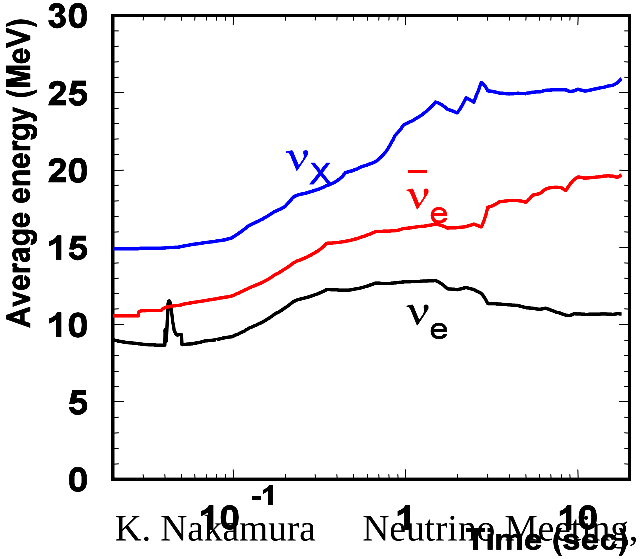
Livermore simulation

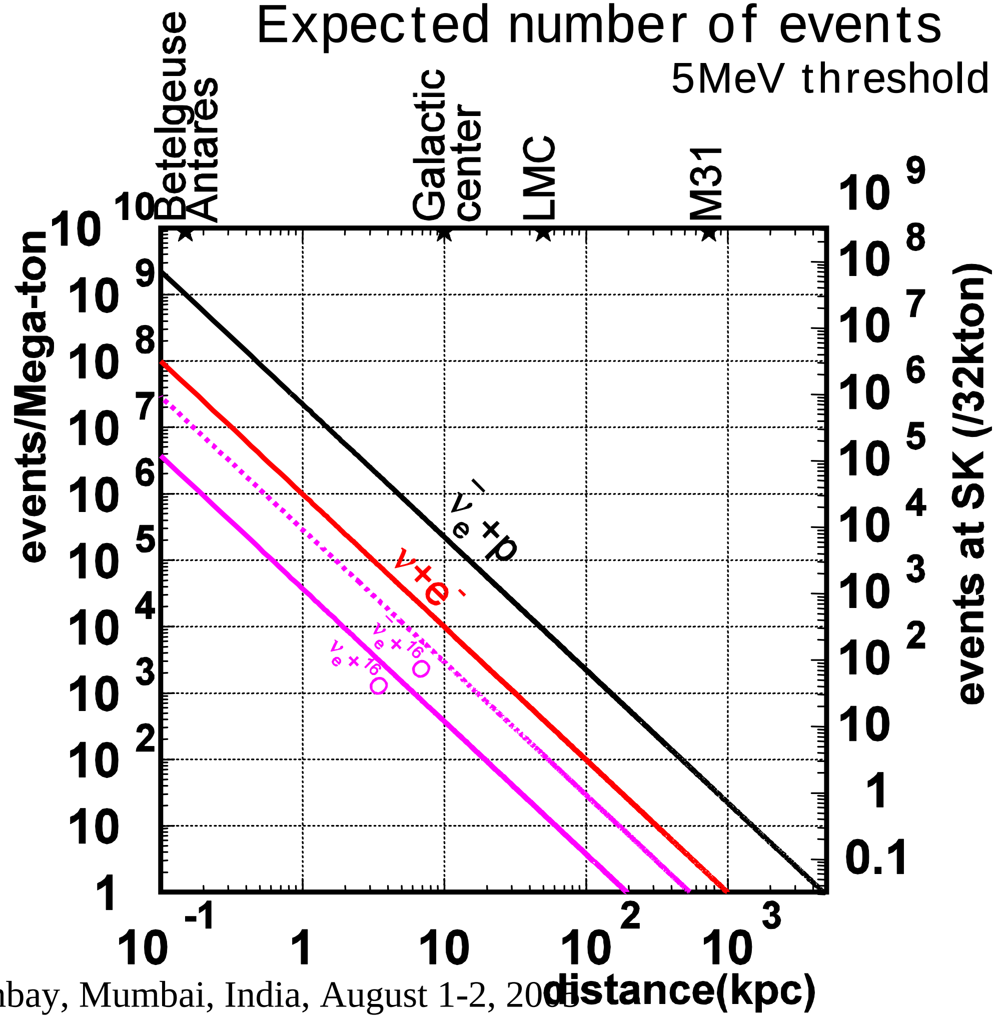
(T.Totani et al., ApJ.496,216(1998))

M. Nakahata, NNN05

1 Mton fiducial mass assumed



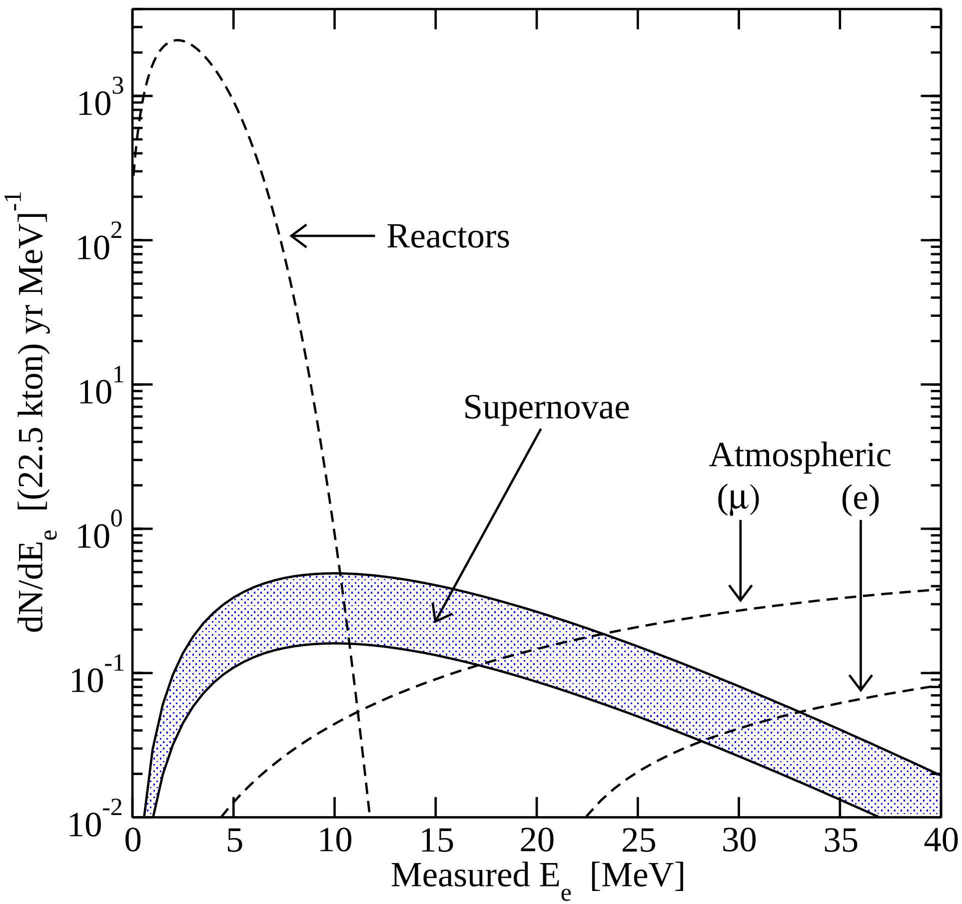




Relic Supernova Neutrinos

From our GADZOOKS! paper, here's what the coincident signals in SK or HK):

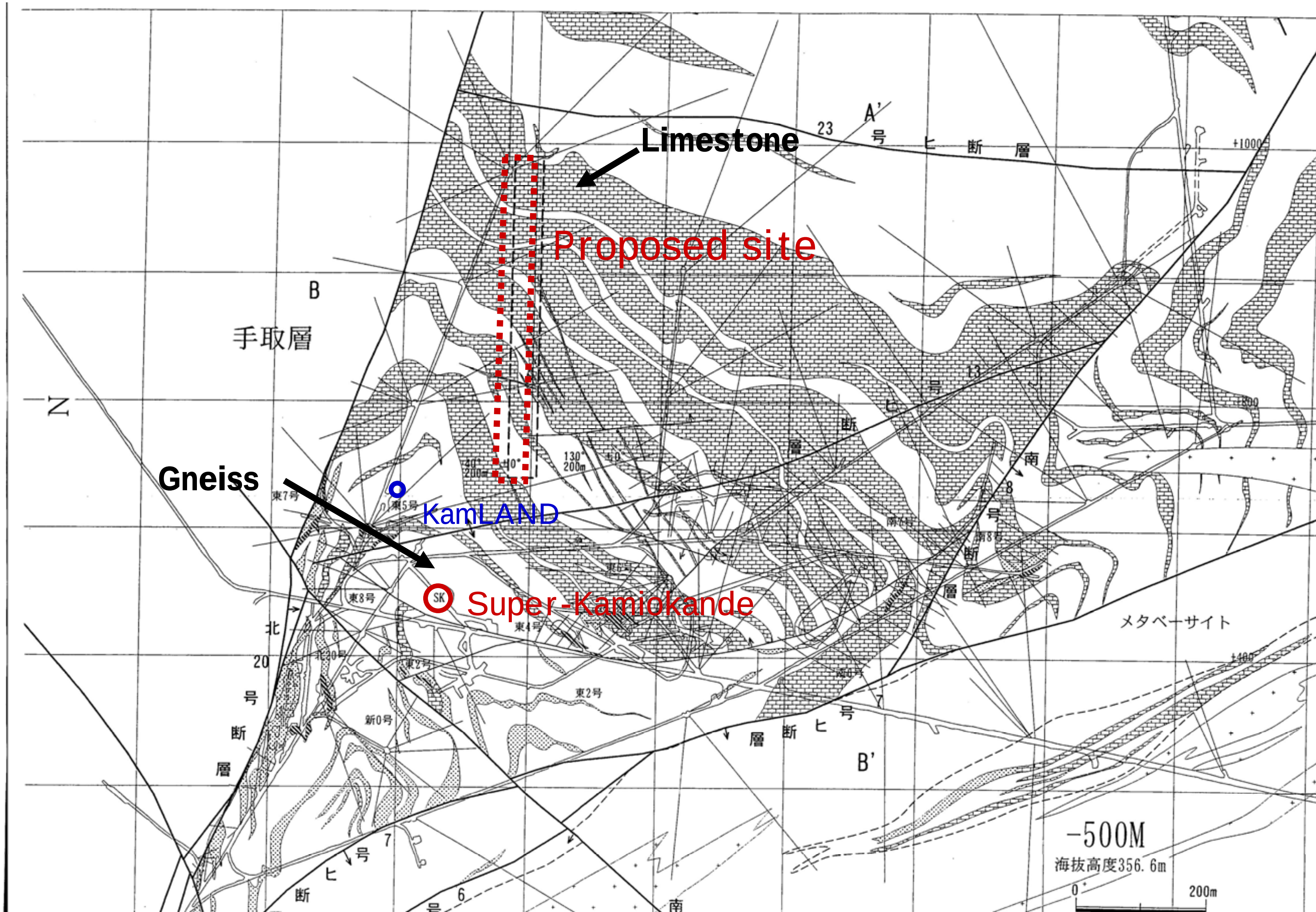
M. Vagins, NNN05



HK will collect >100 clean Diffuse SN Background (relic) events per year!

Site Studies

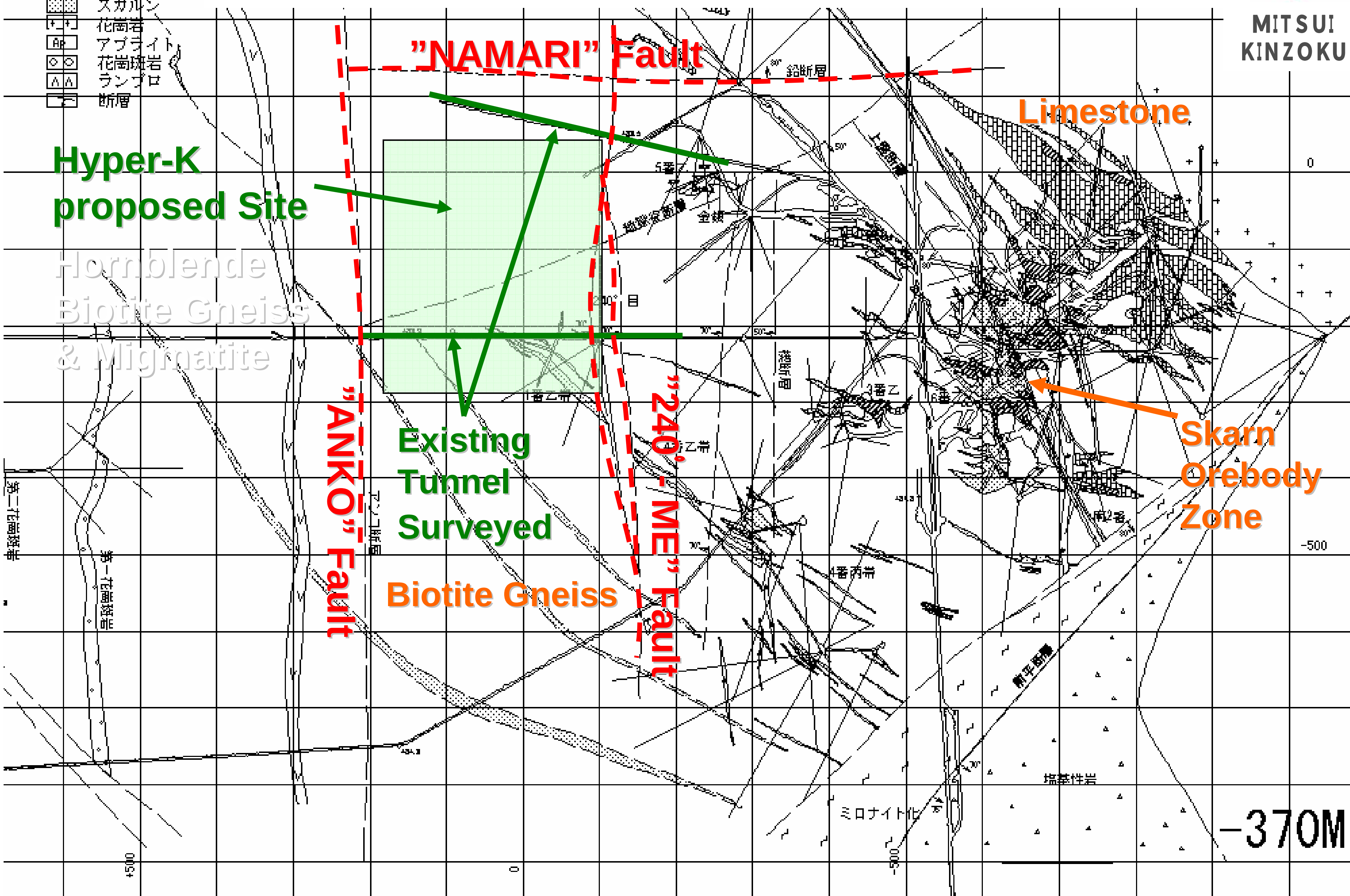
Mozumi Mine



Limestone
Proposed site
Gneiss
KamLAND
Super-Kamiokande
手取層
B
A'
B'
メタベーサイト
-500M
海抜高度356.6m
200m

Geological Map of Proposed Site at TOCHIBORA mine

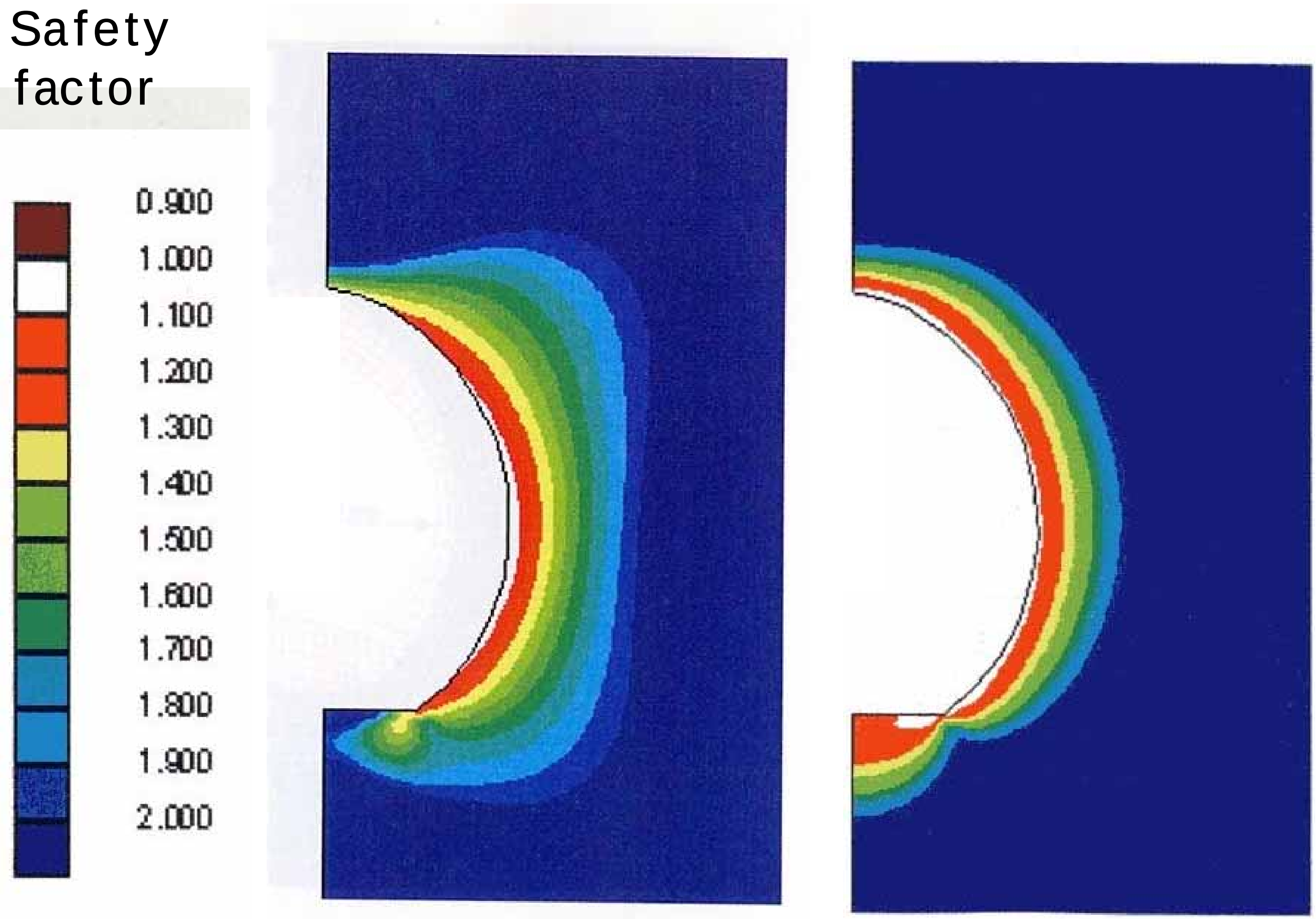
Plan View of + 480mEL



Rock Properties at Proposed Sites for Hyper-KAMIOKANDE Cavern

Items		Location: MOZUMI Mine	Location: TOCHIBORA MINE
Overburden (Subsurface Depth)		870 m	600-700 m
Rock Types		Hornblende Gneiss, Migmatite, partly with Limestone	Hornblende Biotite Gneiss, and Migmatite
Density		0.026 MN/m3	0.026 MN/m3
Compressive Strength		105 MPa - 120 MPa	150 MPa - 250 MPa
Tensile Strength		9 MPa	8 - 10 MPa
Young's Modulus		48 GPa	45 - 55 GPa
Poisson's Ratio		0.26	0.25
Discontinuities	Spacing	0.2 - 0.6 m	0.6 - 2 m
	Condition	Slightly Rough	Very Rough
	Orientation	Favorable	Very Favorable
Ground Water		None	None
Rock Quality Designation (RQD)		78 %	85 %
Rock Mass Ratings (RMR)		79	89
Rock Mass Classification		II	I
		Good Rock Mass	Very Good Rock Mass
Rock Class (Japanese)		B - C$_H$	A - B

Finite Element Analysis of the Hyper-K Cavity Using the Rock Condition at the Tochibora Site



$$\frac{presure\,(horizontal)}{pressure\,(vertical)} = 0.45 \qquad = 1.0$$

Experts say:

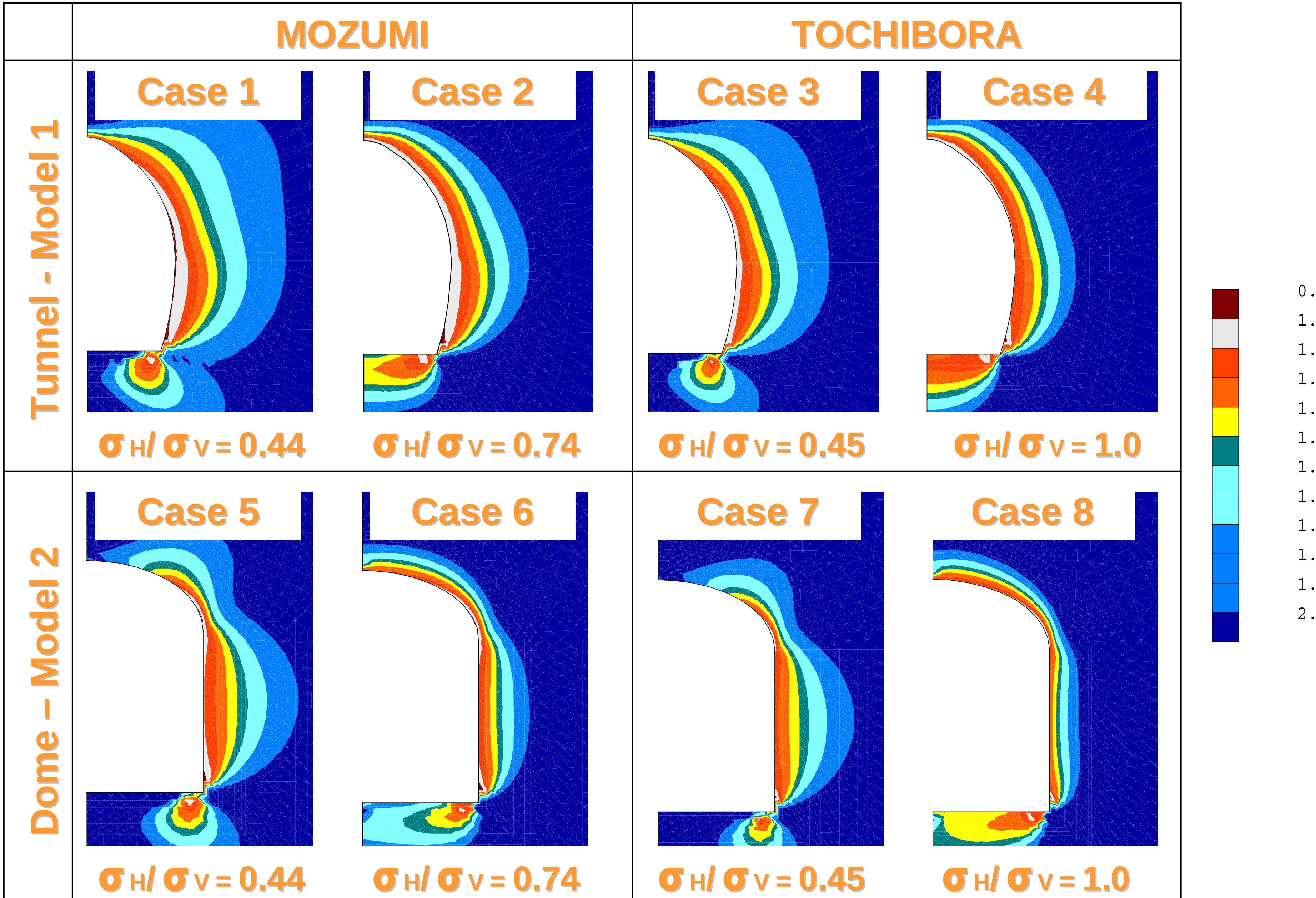
Regions with the safety factor < 1.3 need supports (rock bolt or wire)

The depth of the region with safety factor < 1.3 is similar to that in Super-K.

⇩

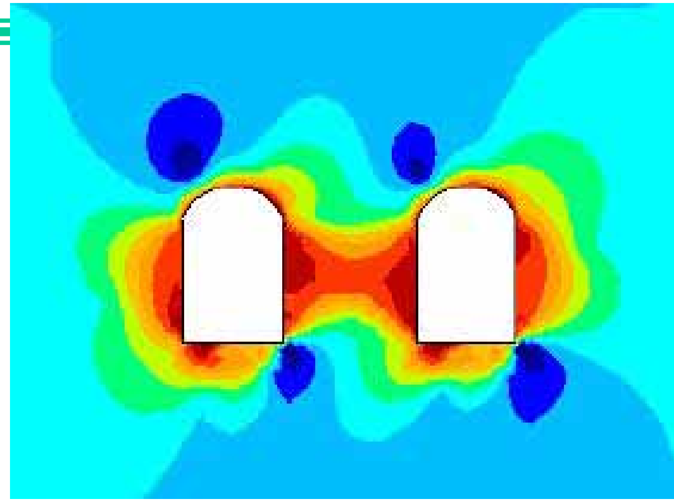
It seems possible to excavate the Hyper-K cavity.

Safety Factor Diagram around the Proposed Hyper-K Cavern

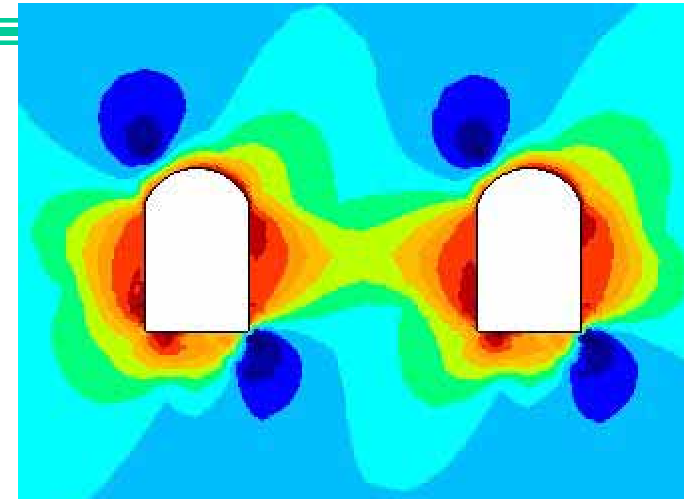


Safety Factor Diagram around Hyper-K Two Parallel Cavern Model for Spacing Optimization Analysis at TOCHIBORA Mine

Vertical Cross Section in the Middle



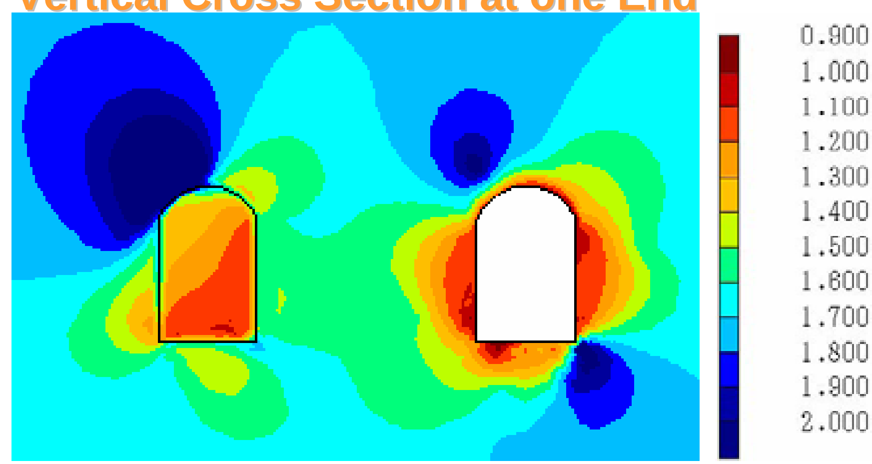
Spacing = 60 m



Spacing = 100 m

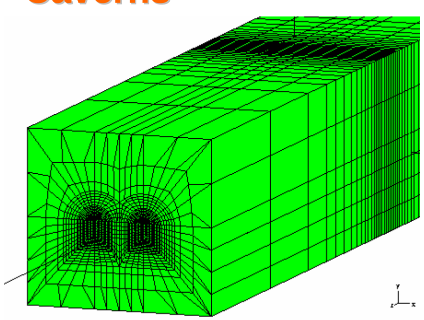
Spacing of 100 m is preferable.

Vertical Cross Section at one End



Spacing = 100 m

Mesh Model of Two Caverns



In any case, the Shape of Cavern-Ends should be considered and modified to relieve Stress Concentrations.

MITSUI KINZOKU

R&D of Large HPDs

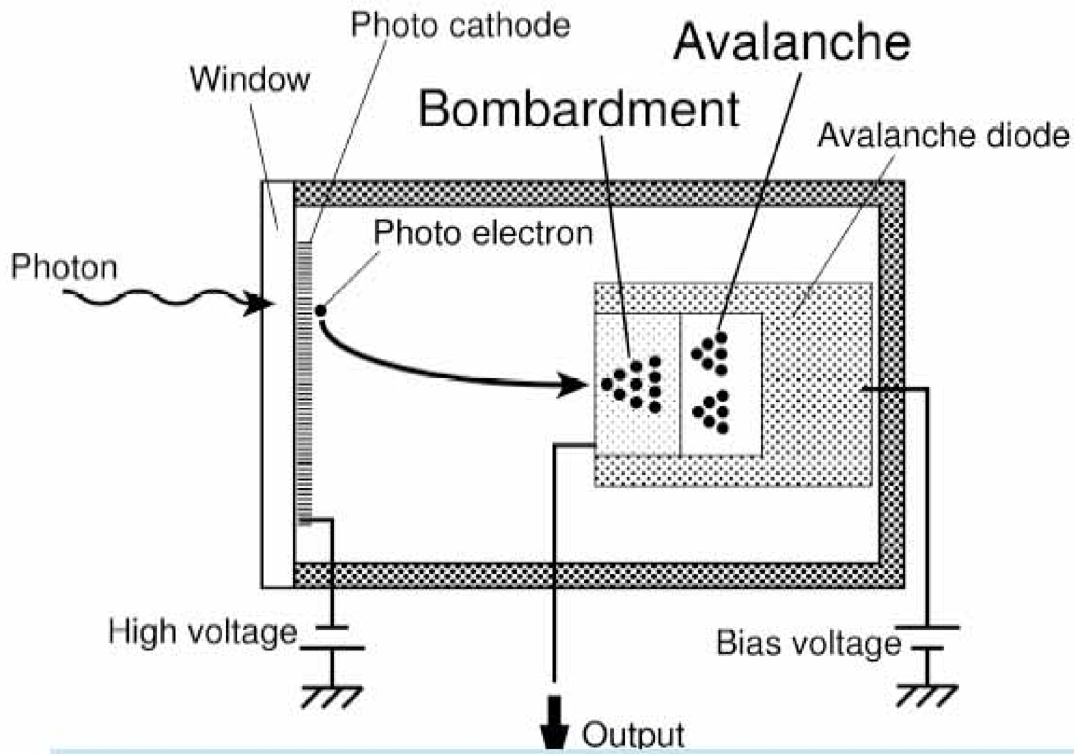
A.Kusaka and H.Aihara (Univ. of Tokyo),
M.Shiozawa (ICRR,Univ. of Tokyo),
M.Tanaka (KEK), and
HPK Electron Tube Center

Based on the talk by H. Aihara, NNN05

Why Large HPDs?

- We want to have high-sensitivity, but low-cost optical device.
- Cost per unit photosensitive area of the optical device and associated electronics would be saved if the size of the unit device can be increased.
- However, we have to take the lesson of the Super-Kamiokande accident seriously.
- Cost would be lower for optical device with simpler structure.
- These considerations made us focus on R&D of large-area HPDs in collaboration with Hamamatsu.

Principle of HPD



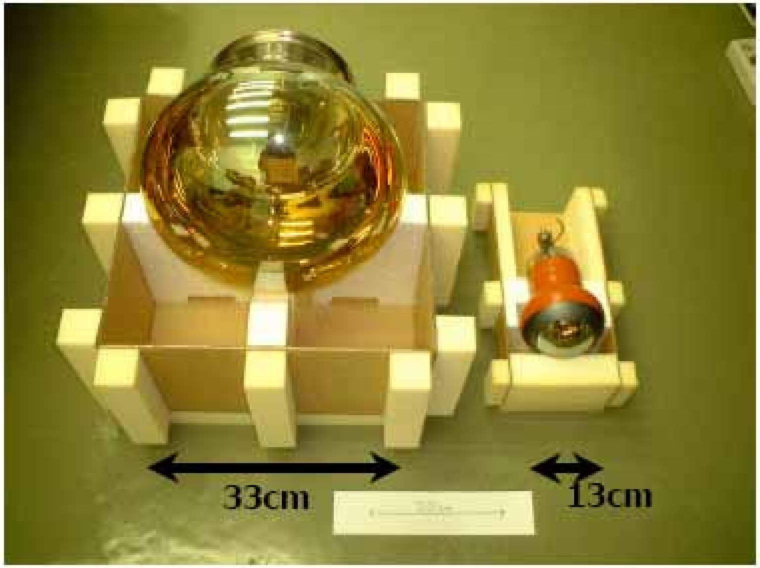
Bonbardmend Gain (dE/dX in Si / 3.6 eV) ~4,500@20kV

× Avalanche Gain (~30-50)

Total Gain ~ $10^5 < 10^7$ of SK-PMT

13-inch HPD

13inch HPD

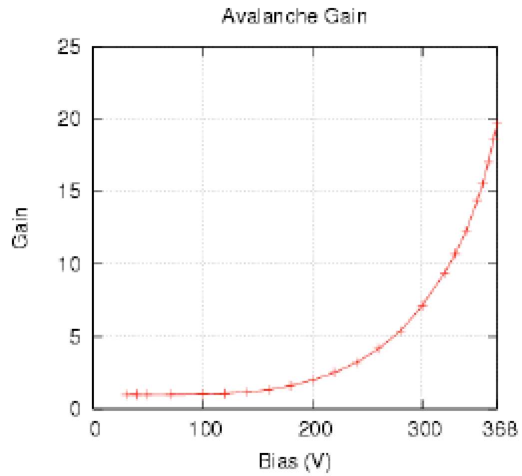


13inch 5inch

Avalanche/Bombardment Gain

- Avalanche Gain

HV=12kV(fixed), Bias=sweep



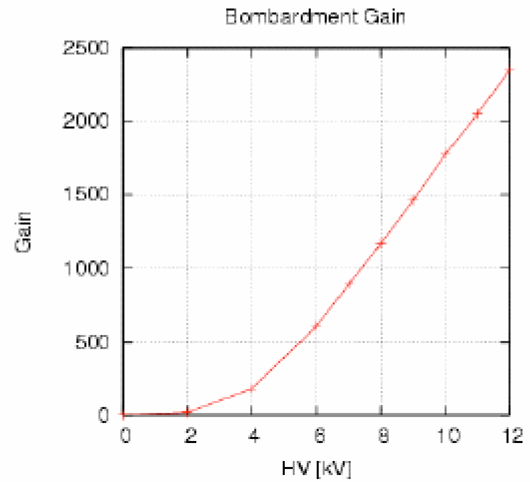
Gain≡1@Bias=40V

(no avalanche effect ≲40V)

Gain ~20 @368V

- Bombardment Gain

Bias=50V(fixed), HV=sweep

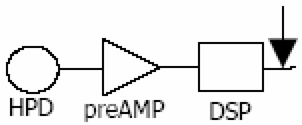


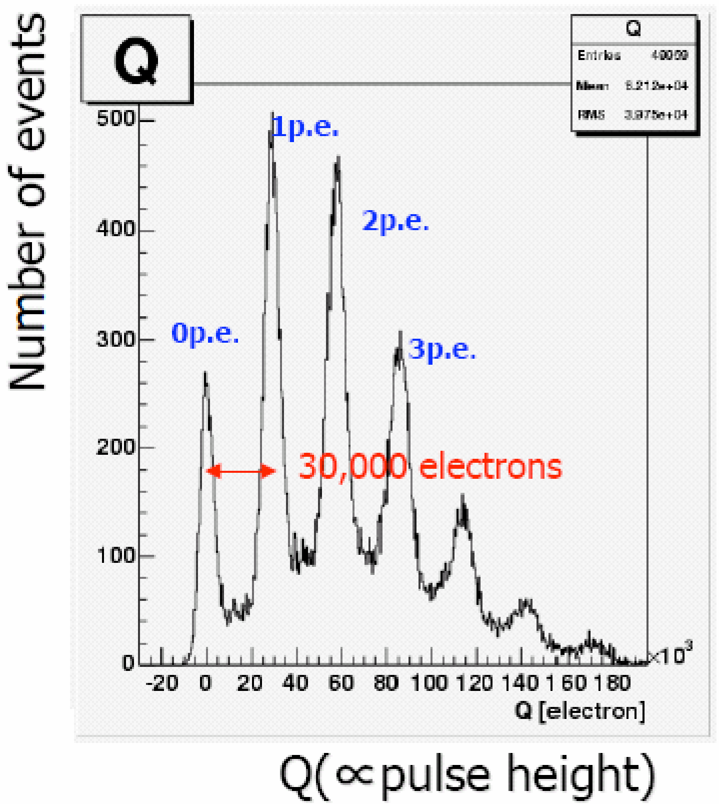
Gain ~2400 @12kV

Gain rises >3kV (energy loss in an insensitive layer on AD)

→ <u>Total gain ~50,000</u>

Single Photon Sensitivity





Pulse height distribution after DSP

→ very clear 1, 2, .. p.e. peaks

Gain ~30,000

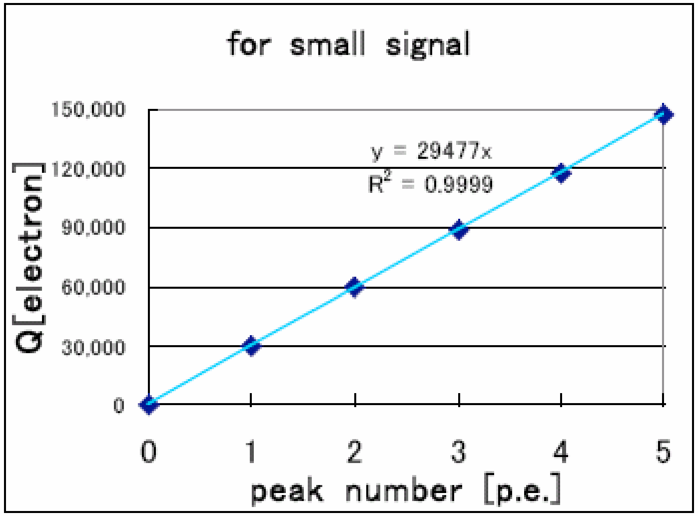
ENC~3,000

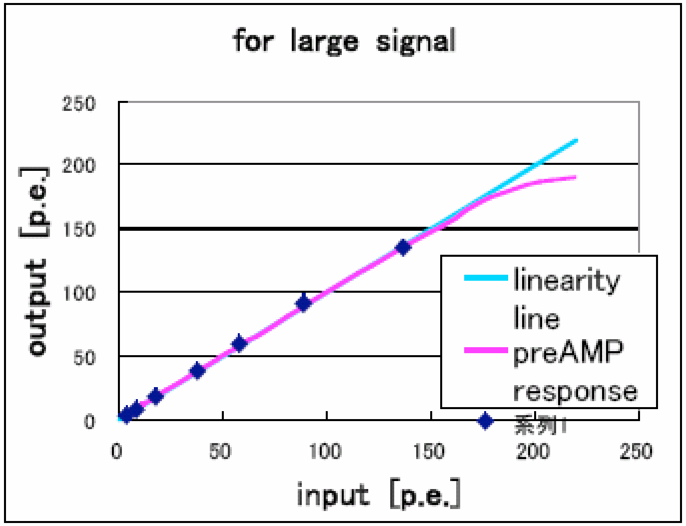
→ S/N = <u>10</u> @1p.e.

Single Photon Sensitivity!

Gain Linearity

Peak positions in the Q-histogram





Linearity is quite good

~5p.e.

Good linearity up to

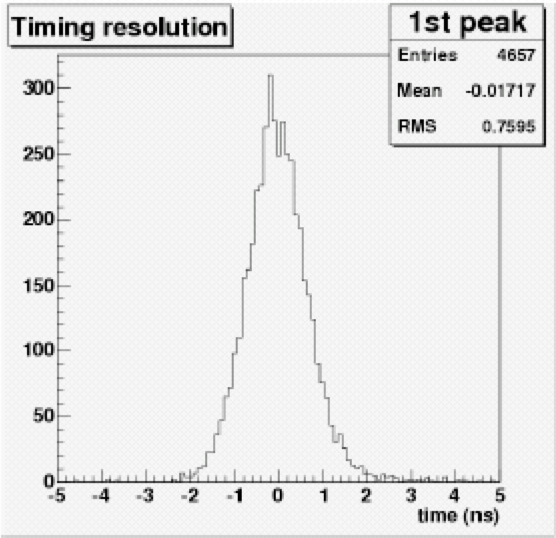
~150p.e.(preAMP limit)

Timing Resolution (1)

Timing Resolution for 1p.e.

Timing resolution directly affects to

the neutrino vertex reconstruction performance. ($\Delta x \sim c\Delta t$)



timing (ns)

Timing resolution

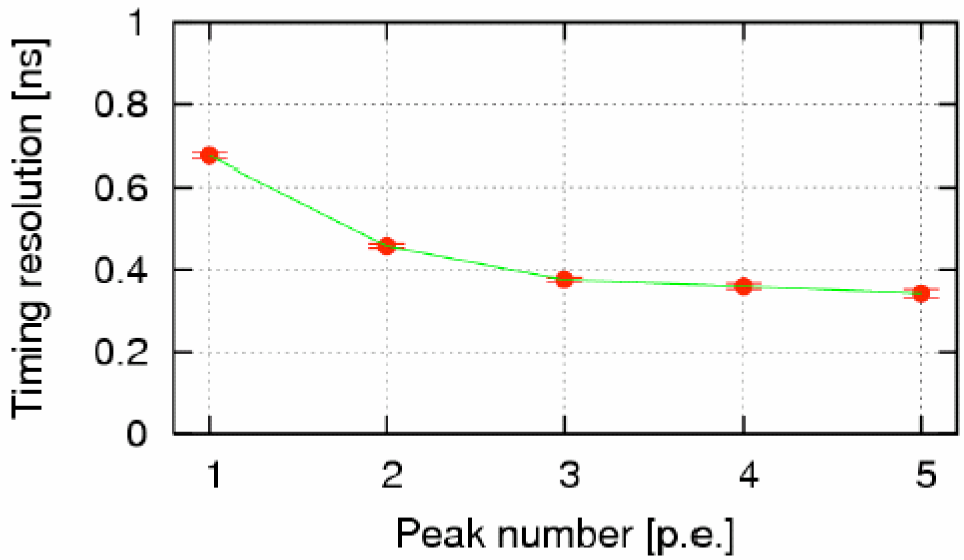
~0.7ns@1p.e.

cf. PMT-SK

~2.3ns@1.p.e.

Timing Resolution (2)

Timing Resolution for multi photoelectrons

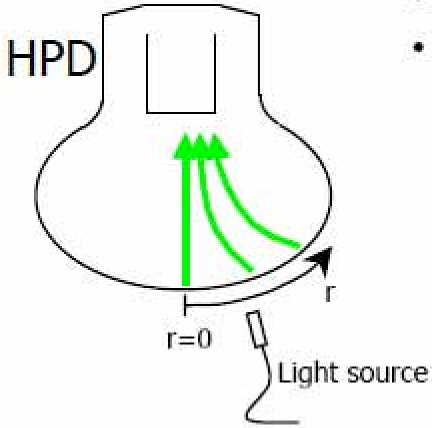


Timing resolution $\lesssim$0.5ns

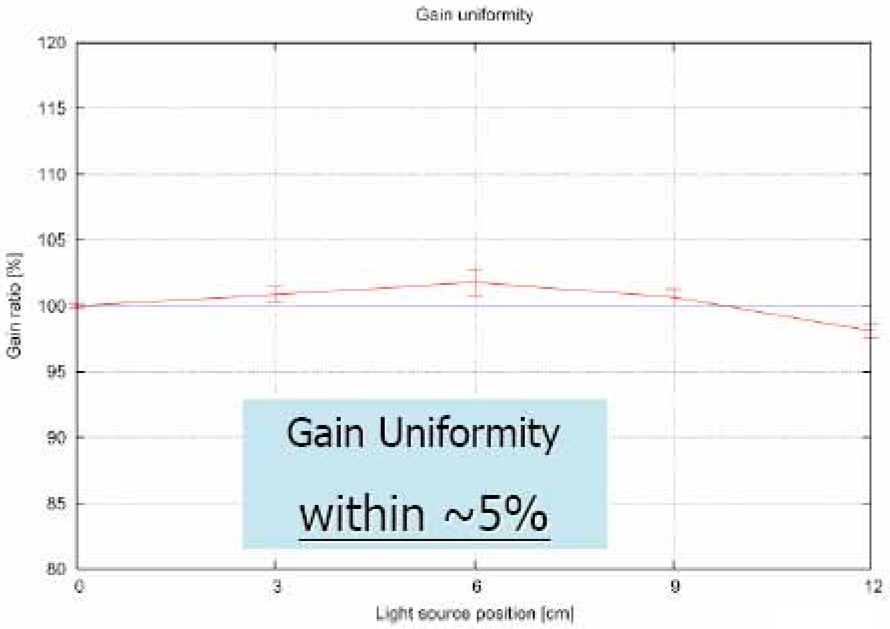
for $\geq$2p.e.

Meet the requirement (~1ns)

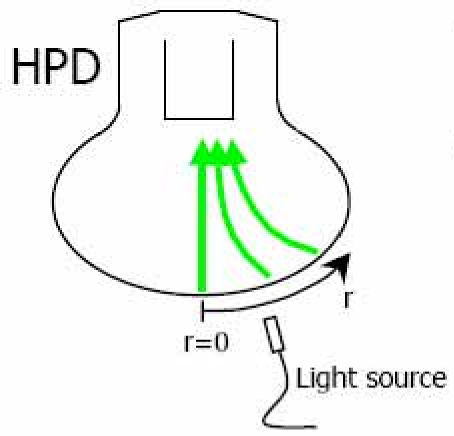
Gain Uniformity



- Gain vs. position on the photocathode
- Light input: 1p.e.

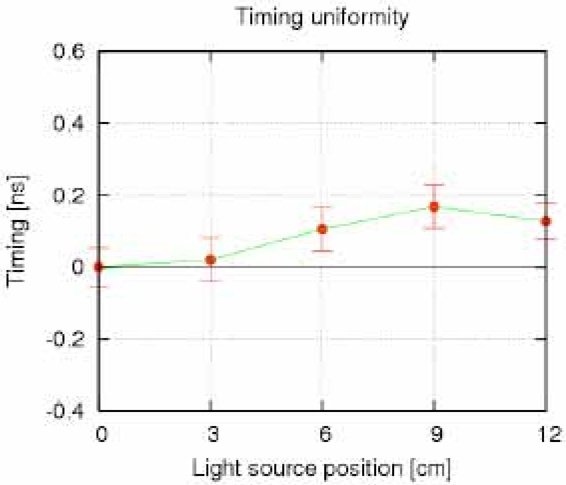


Timing Uniformity



- T.O.F (photocathode~AD) vs. position on the photocathode
- light input: ~30p.e.

  (timing resolution: 0.06ns@30p.e.)



Timing uniformity

~0.1ns

Quick Summary of HPD R&D

- Proof of principle
  - 5-inch done
  - 13-inch well advanced
- Initial study shows excellent performance
  - Single photon sensitivity
  - Wide dynamic range (up to the readout limit)
  - Good timing resolution (better than 1 ns)
  - Good uniformity (over a large photocathode)
- Promising

Schedule, Cost, etc.

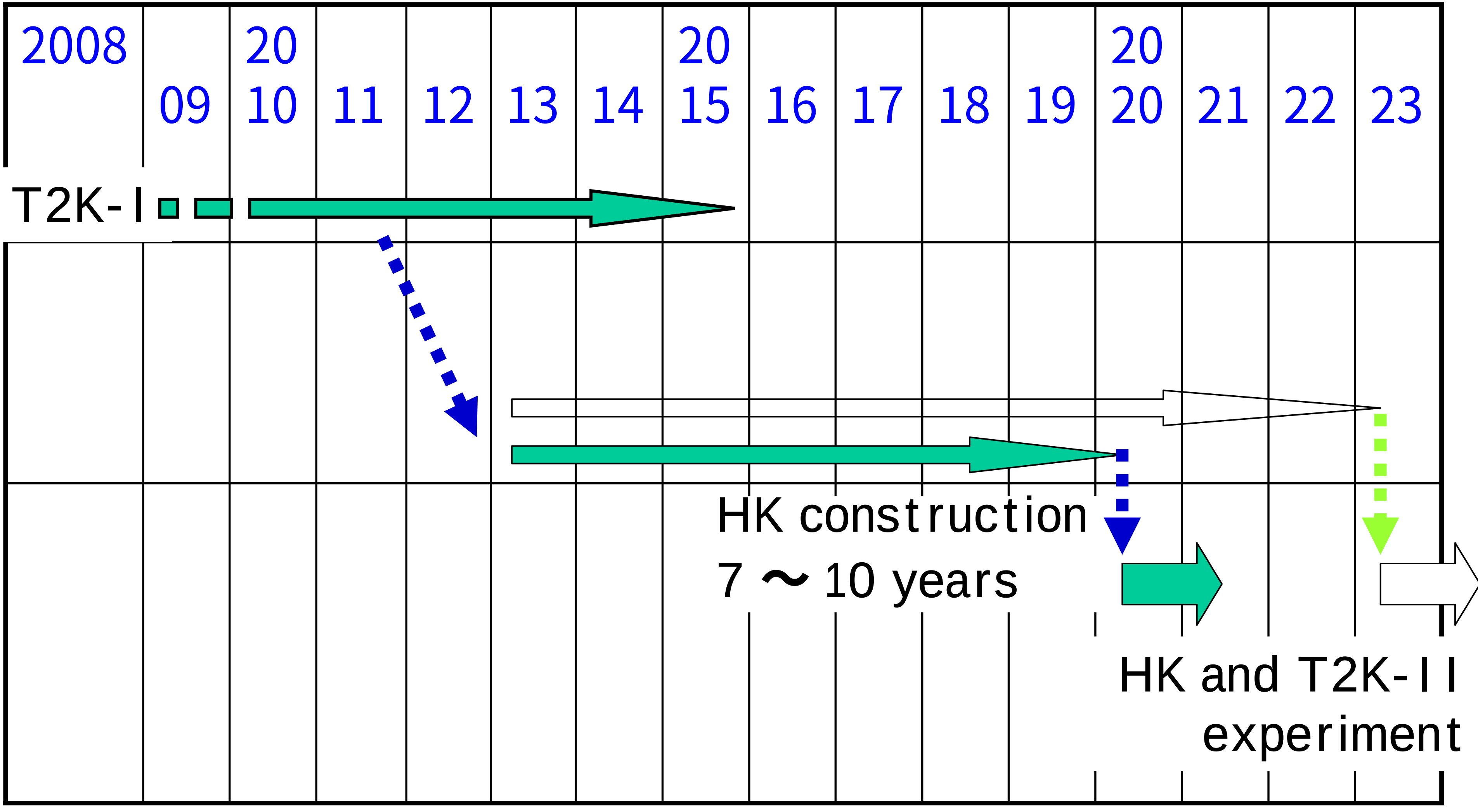
HK Excavation Schedule

Year	1st	2nd	3rd	4th	5th	6th -
Access tunnel						
Other tunnel						
Detector cavities						
Water-plant cavity						
Equipments						

Problem in the Optical Device Production

- 100,000 – 200,000 20-inch PMTs or HPDs
- In principle, Toyota's "Kanban" process of production, or "just-in-time" production, would be ideal.
- But, a huge investment for the factory and equipment construction would be needed.
- Conventional Hamamatsu production schedule would be ∼8 years or more.
- Storage space will be a big problem.

T2K Phase Ⅰ → ⅠⅠ Time Line



Cost ?

- Need realistic design study and optimization
- Very rough estimation (or target)

Excavation	1.3 Mm^3	@ 20,000 Yen	260 Oku-Yen
Plastic coating	40,000 m^2	@ 40,000 Yen	16
PMT Support + Top Structure		SK $\times$ 10	40
PMT + Cable	100,000	@ 200,000 Yen	200
Electronics	100,000	@ 10,000 Yen	10
Outer Detector			10
Other Items			20
Total			556

(should be reduced to < 500)

Hyper-K Planning and R&D: Summary

- Design: Twin cavities
- Site: Tochibora mine is considered as a candidate site.
- Cavity excavation: FEA in progress; Geological survey and boring done; *in situ* measurement of initial stress yet to be done, rock sample should be taken from the candidate site for mechanical tests, etc.
- Spherical HPD: 13-inch prototype test in progress.
- Realistic cost estimation: Yet to be done.
- Physics simulation with reduced photo-sensitive coverage: Yet to be done.