# The Hyper - Kamiokande Project

Hyper-Kamiokande

Super-Kamiokande

Kamiokande


Laboratoire LEPRINCE-RINGUET
École polytechnique - IN2P3/CNRS

ÉCOLE POLYTECHNIQUE
UNIVERSITÉ PARIS-SACLAY

LLR École polytechnique
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GDR – LPNHE Novembre 2017


Michel Gonin

# OUTLINE

- Introduction
- HK detector: design and R&D
- JPARC and Near Detectors for T2HK
- Oscillations physics
- Proton decays
- Neutrino Astronomy
- Schedule and conclusion

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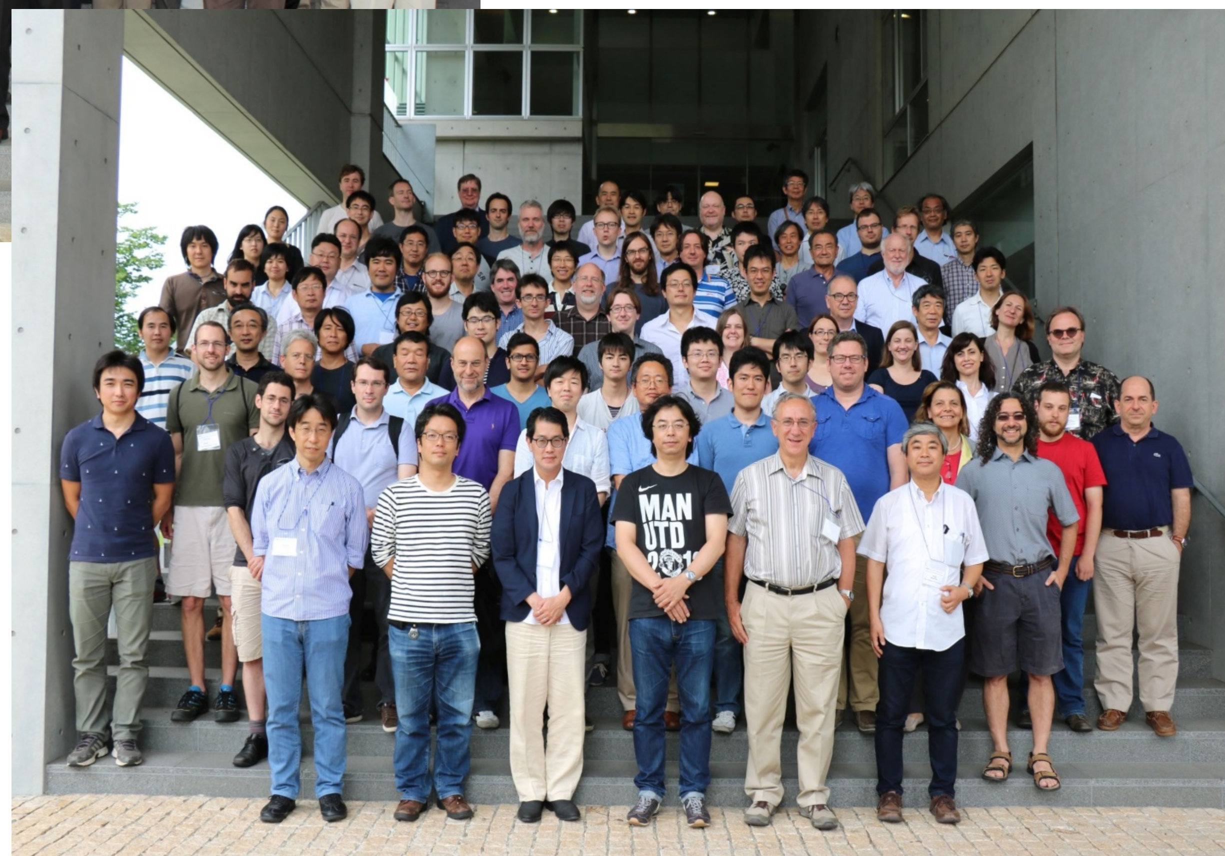
# HK Proto Collaboration was formed on January 2015

Symposium at Kashiwanoha


- MOU between Tokyo Univ – ICRR and KEK – IPNS
- Reviews by an International HK Advisory Committee
- International groups formed and developing
- New proposal submitted in March 2017 to the Science Council of Japan
- Reviewed by the KEK-PIP committee – top priority

First HK meeting
Kashiwa
June 2013



First Proto Collaboration meeting HK
Kashiwa
June 2015

- July 2017 ： Hyper-K got listed in the MEXT-Roadmap
- Hyper-K got highest evaluation results. Necessary for funding request

Hyper-K Meeting , Kashiwa September 2017

August 2017. University of Tokyo (+KEK+IPMU+ICRR) launched NNSO
New organisation for the Hyper-Kamiokande project
Director T. Kajita, http://nnso.jp


Inauguration “Next-generation Neutrino Science Organization”
Mozumi, November 2017

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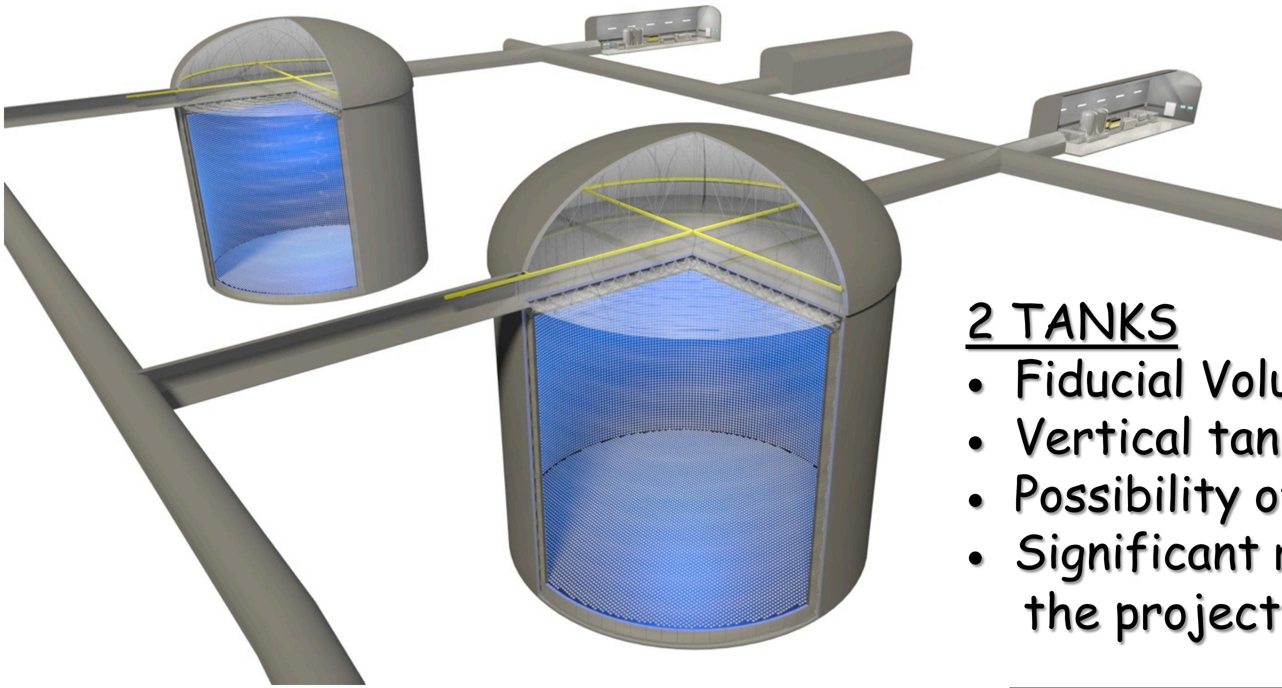
# A new design for HK submitted in February 2016

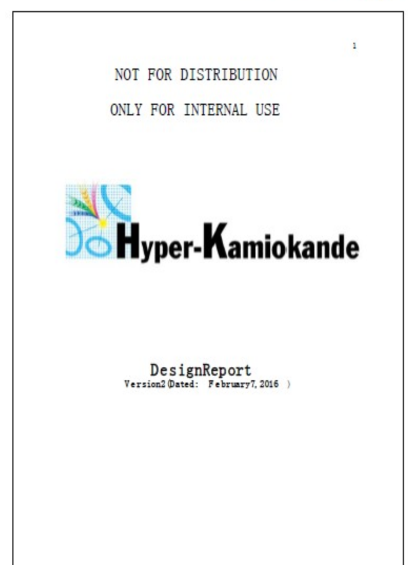


## 2 TANKS

- Fiducial Volume : 2/3 of original design
- Vertical tanks
- Possibility of staging
- Significant reduction for the cost of the project

## EACH TANK

- 260 Kton total
- 10 x SK fiducial volume
- Very good PMT coverage (40%)
- 60 m height x 74 m diameter



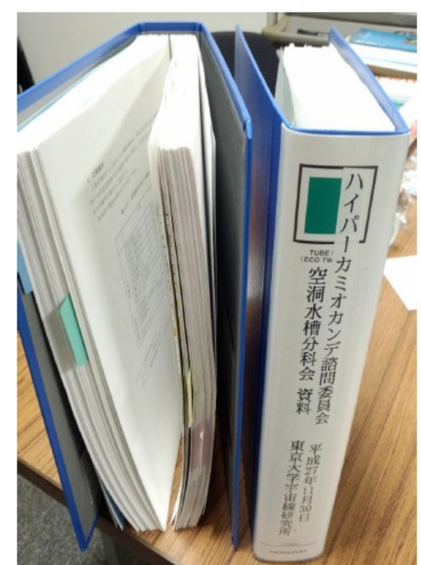
NOT FOR DISTRIBUTION

ONLY FOR INTERNAL USE

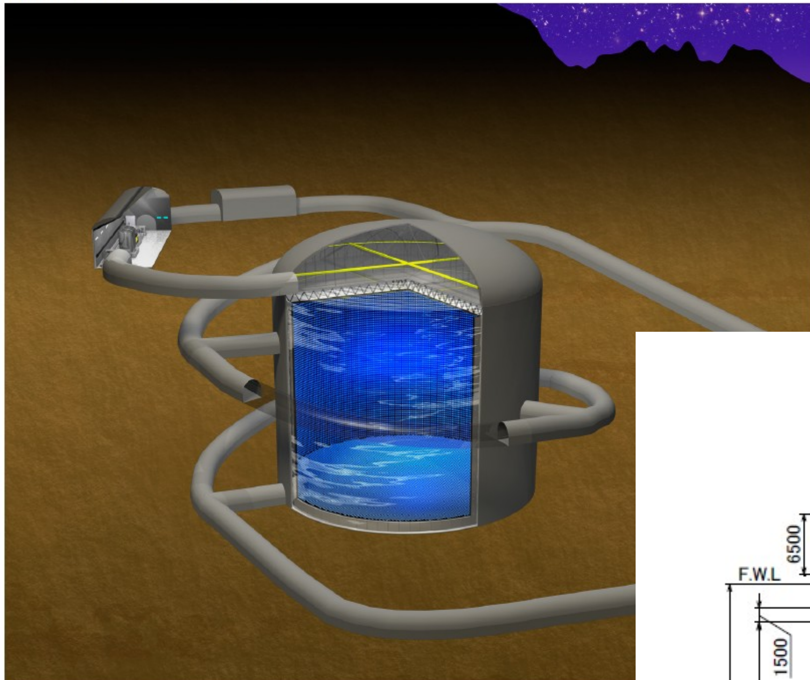
Hyper-Kamiokande

DesignReport

Version2 (Dated: February7, 2016 )



Hyper-Kamiokande project



# Hyper-K Detector

| | Super-K | Hyper-K (1st tank) |
|---|---|---|
| **Site** | Mozumi | Tochibora |
| **Number of ID PMTs** | **11,129** | **40,000** |
| **Photo-coverage** | 40% | 40% (**×2 sensitivity**) |
| **Mass / Fiducial Mass** | 50 kton / **22.5 kton** | 260 kton / **187 kton** |

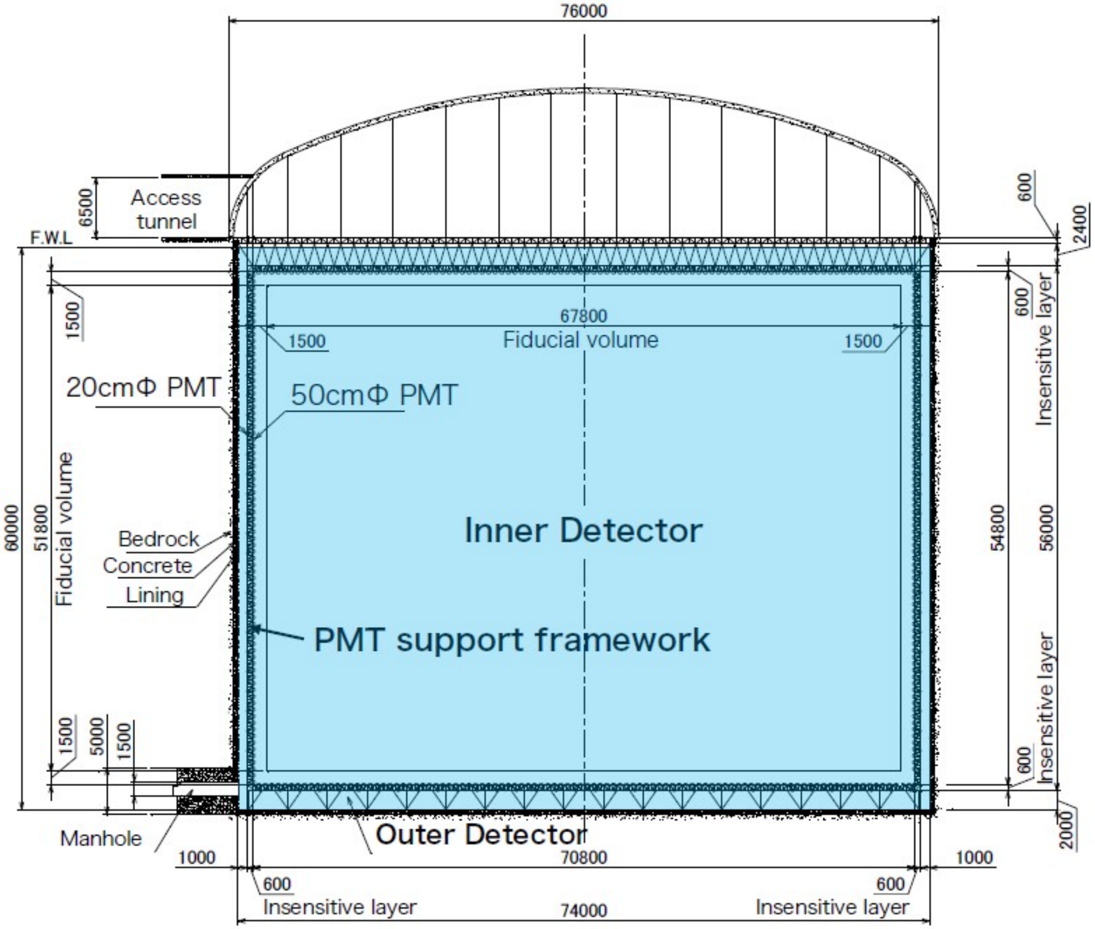
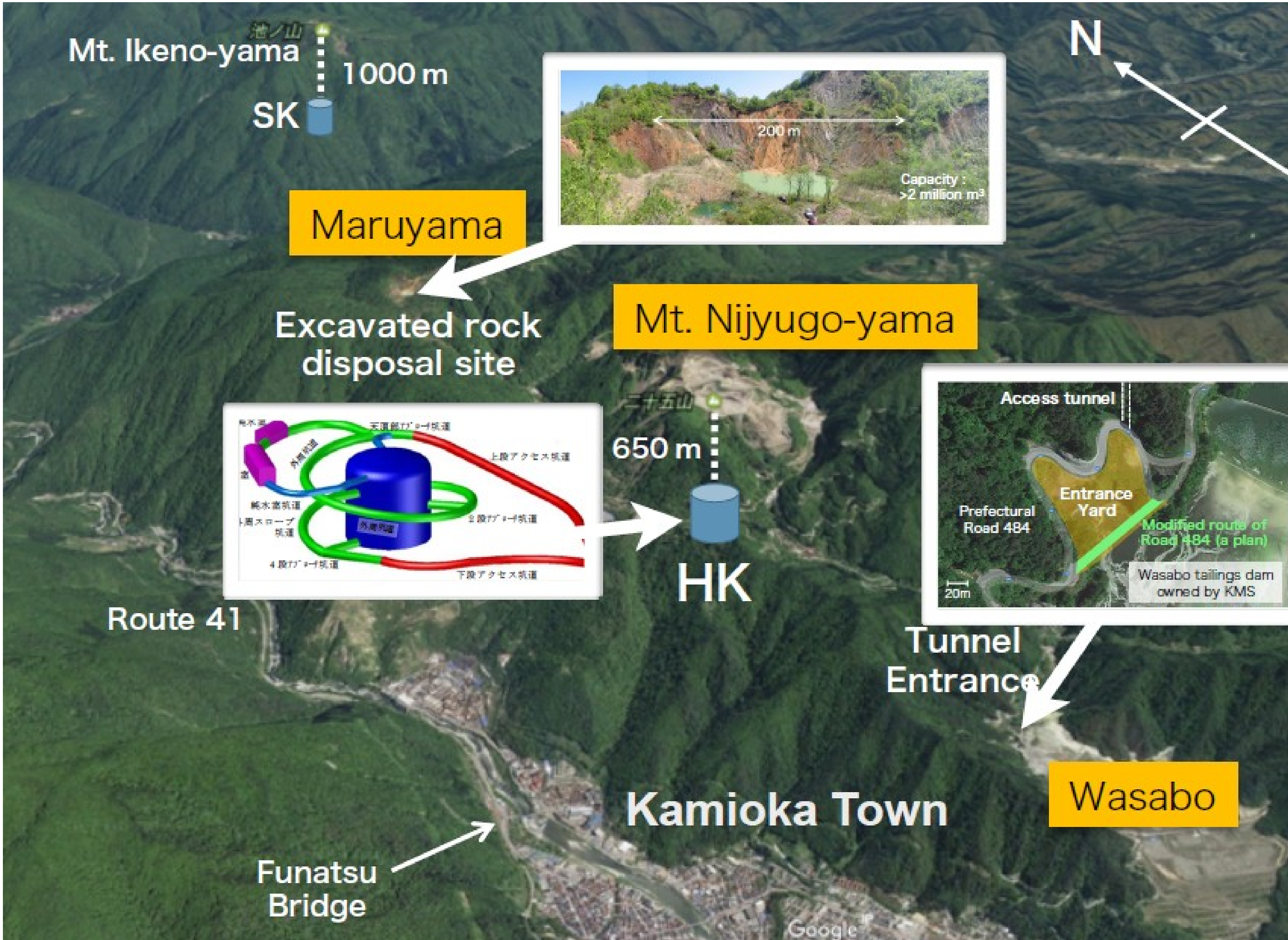
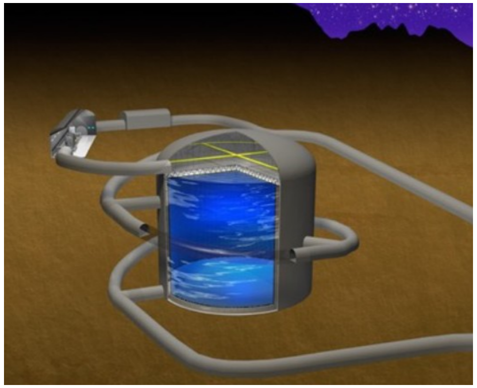



Figure 1: Schematic view of the Hyper-Kamiokande detector

**Sensitivity goals were maintained for HK oscillations physics**



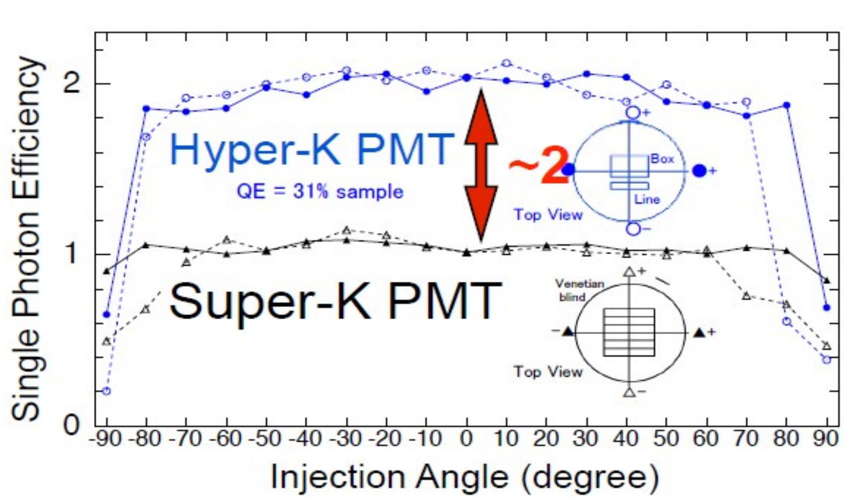
Mt. Ikeno-yama
1000 m
SK
200 m
Capacity :
>2 million m³
N
Maruyama
Excavated rock
disposal site
Mt. Nijyugo-yama
650 m
HK
Access tunnel
Entrance
Yard
Prefectural
Road 484
Modified route of
Road 484 (a plan)
Wasabo tailings dam
owned by KMS
20m
Route 41
Tunnel
Entrance
Wasabo
Kamioka Town
Funatsu
Bridge

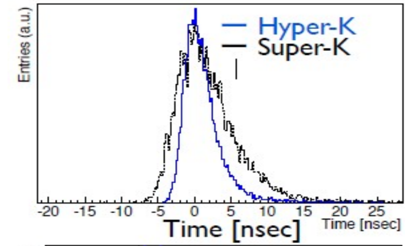


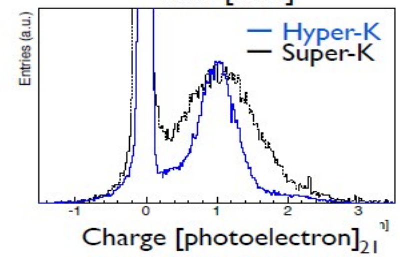
# HK photosensors

New technologies and on going studies for PMT

50cm Ø PMT



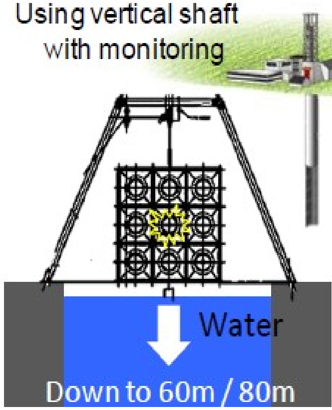

- Significant improvement of single photon efficiency
- Better time and charge resolution (x 2 wrt SK)

## Still possible mixed technologies in HK for PMT

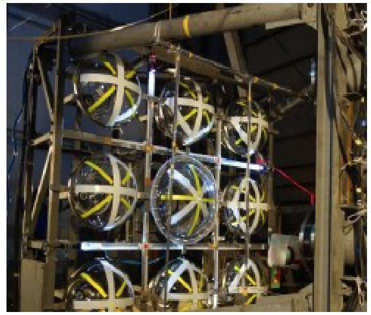
- Worldwide studies for new photo sensors detectors (JUNO, IceCube, KM3NET, …)
- Foreseen collaborative efforts of HK with other experiments

## Validation test of cover at Kamisunagawa in 60 m / 80 m water

Using vertical shaft with monitoring




Confirmed with artificial implosion at central PMT



Prototype of cover to stop chain implosion

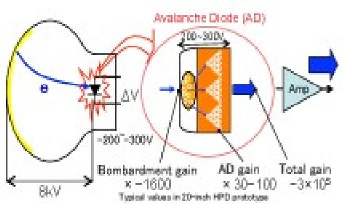
15 mm acrylic

Stainless steel (3 mm)

- No damage for all tests
  - 3 times w/cover (2 with surrounding PMTs)
  - OK for 60 m (HK), and for 80 m also

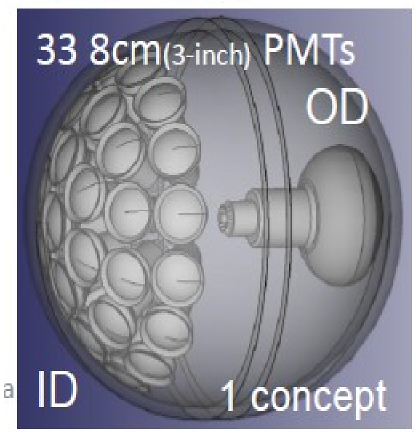
### Hybrid Photo Detectors (HPDs)

50cm HQE HPD w/ 20mm ϕ AD




Under viability study

### Multi-PMTs




Working concept from KM3NeT but:
- peripheral ID/OD
- lower pressure tolerance required.
- ultrapure water.

International contribut.

- Worldwide studies for new photo sensors detectors (JUNO, IceCube, KM3NET, …)
- Foreseen collaborative efforts of HK with other experiments

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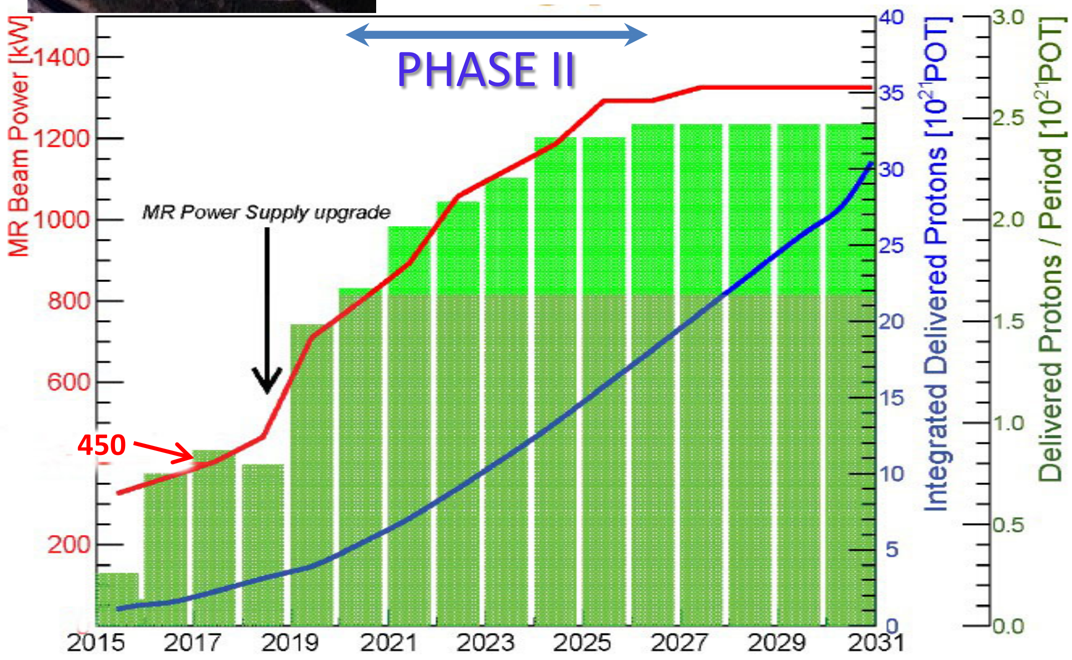
# JPARC and Near Detectors for T2HK


Beam Upgrades (MR power supply, upgrade MR RF, …)



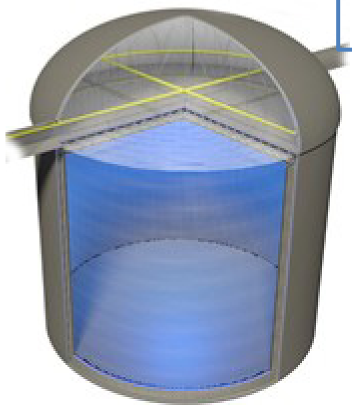

Step by step

- Decrease bunch intervals from 2.48 sec to 1.3 sec, then 1.16 sec
- Increase protons/bunch from 2.7 $10^{14}$ to 3.2 $10^{14}$
- Increase horn current form 250 kA to 320 kA

Proposal for T2K phase II @ 1.3 MW (funded)

Increase total delivered protons from 7.8 x $10^{21}$ to 20.0 x $10^{21}$

# T2HK systematic errors for oscillation analysis



Estimations and simulations will be based on *T2K and SK studies with real data*

$\nu$-mode $\nu_e$ candidates

| Source of uncertainty | $\delta N_{SK}/N_{SK}$ |
|---|---|
| SKDet+FSI+SI | 3.48% |
| SKDet only | 2.28% |
| FSI+SI only | 2.63% |
| Flux | 3.67% |
| 2p-2h (corr) | 3.90% |
| 2p-2h bar (corr) | 0.05% |
| NC other (uncorr) | 0.15% |
| NC 1gamma (uncorr) | 1.47% |
| XSec nue/numu (uncorr) | 2.61% |
| XSec Tot (corr) | 4.26% |
| XSec Tot | 5.21% |
| Flux+XSec (ND280 constrained) | 2.90% |
| Flux+XSec (All) | 4.17% |
| Flux+XSec+SKDet+FSI+SI | 5.45% |
| Flux+XSec+SKDet+FSI+SI (pre-fit) | 12.1% |
| Oscillations | 4.20% |
| All | 6.91% |
| All (pre-fit) | 12.6% |

$\overline{\nu}$-mode $\overline{\nu}_e$ candidates

| Source of uncertainty | $\delta N_{SK}/N_{SK}$ |
|---|---|
| SKDet+FSI+SI | 3.95% |
| SKDet only | 3.11% |
| FSI+SI only | 2.43% |
| Flux | 3.84% |
| 2p-2h (corr) | 3.04% |
| 2p-2h bar (corr) | 2.36% |
| NC other (uncorr) | 0.33% |
| NC 1gamma (uncorr) | 2.95% |
| XSec nue/numu (uncorr) | 1.46% |
| XSec Tot (corr) | 4.46% |
| XSec Tot | 5.55% |
| Flux+XSec (ND280 constrained) | 3.20% |
| Flux+XSec | 4.60% |
| Flux+XSec+SKDet+FSI+SI | 6.28% |
| Flux+XSec+SKDet+FSI+SI (pre-fit) | 13.5% |
| Oscillations | 4.00% |
| All | 7.38% |
| All (pre-fit) | 14.1% |

## Goal

Reduction from ~ 6-7% in T2K

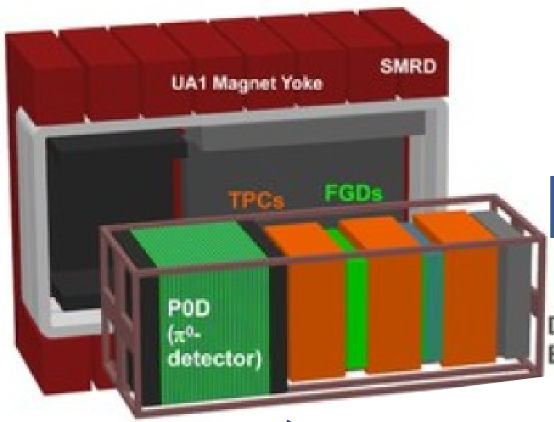
to ~ 3-4% in T2HK for the expected number of events.

Beam flux, XSections, HK Detector, New Near Detectors.

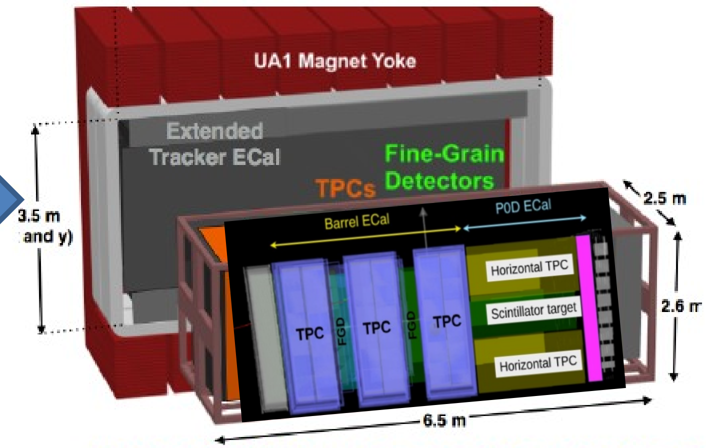
# Beam flux and Xsections

## The Near Detector ND280 upgrades for T2K-II

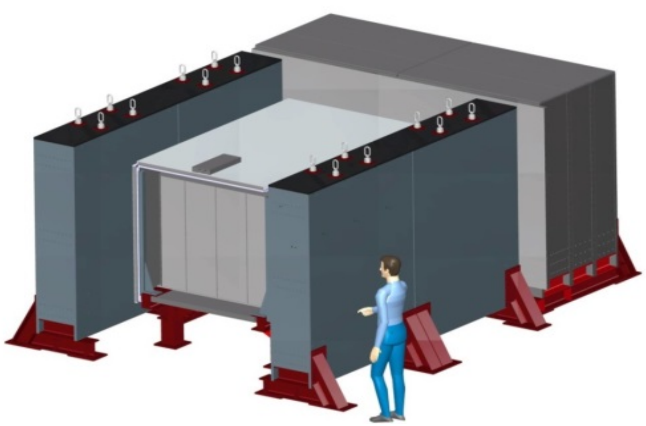
ND280 (NOW)




ND280 (Upgrade)




WAGASCI



- ND280 should continue to perform for T2HK
- Same narrow band beam centered at 600 MeV

<-- Cross section measurements in WATER

- Investigation of the nuclear effects (FSI,....)

# Beam flux and Xsections

## Proposals for New Intermediate Water Cherenkov detectors at **1.2 Km** for T2HK

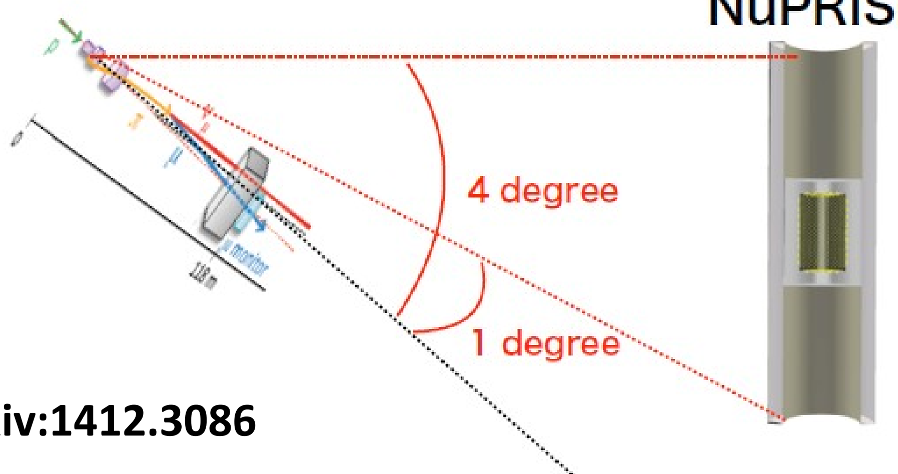

NUPRISM

Off-axis angle spanning orientation. Some new and original approach to extrapolate neutrino events in HK.

- TITUS

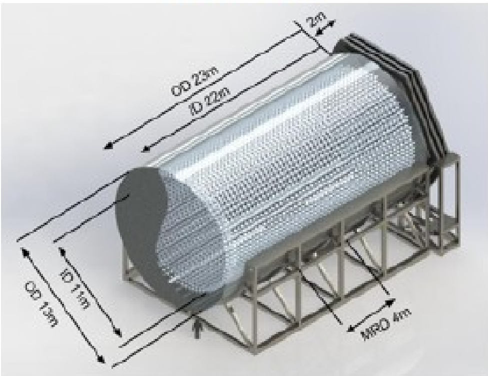
Gd loading, magnetized muon range detector. Good Near/Far flux ratios for prediction in HK

NuPRISM




**arXiv:1412.3086**

TITUS




**arXiv:1606.08114**

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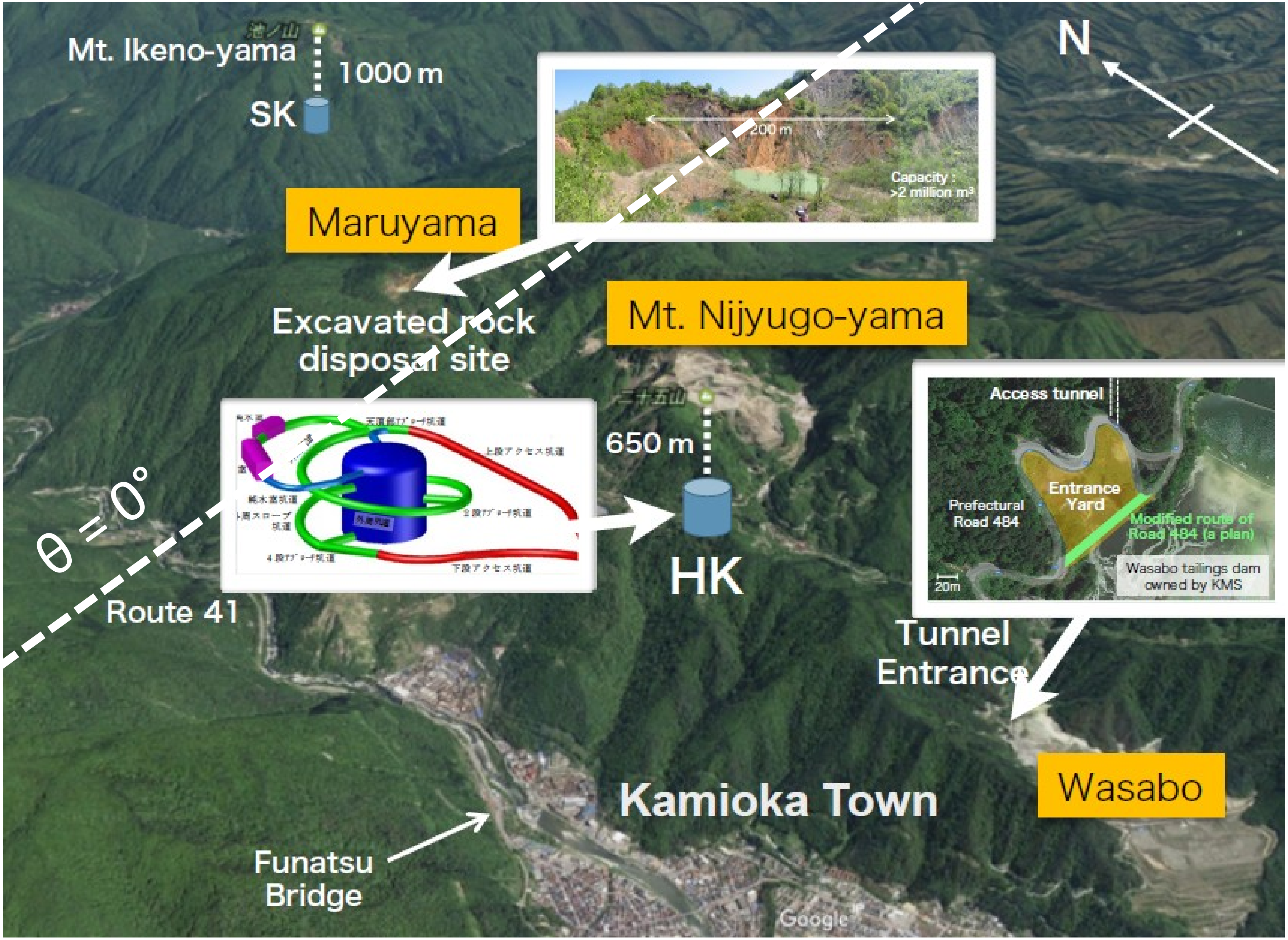
Very large physics program CPV, precision measurement for mixing parameters and mass hierarchy, in addition to proton decay (world leading researches) and astrophysics-cosmic neutrinos

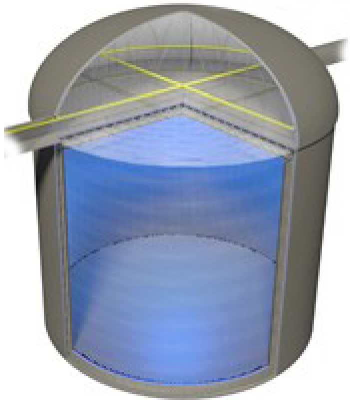
**The experiment "T2HK" will be an off-axis long baseline experiment L = 295 km @ 2.5 degrees (similar to T2K)**

- Well known state-of-the-art water Cherenkov technique
- Reasonable and predictable total cost
- Reasonable timescale for construction and commissioning
- Will greatly benefit from SK and T2K expertise and momenta
- Approved and foreseen upgrades of the JPARC muon-neutrino beam



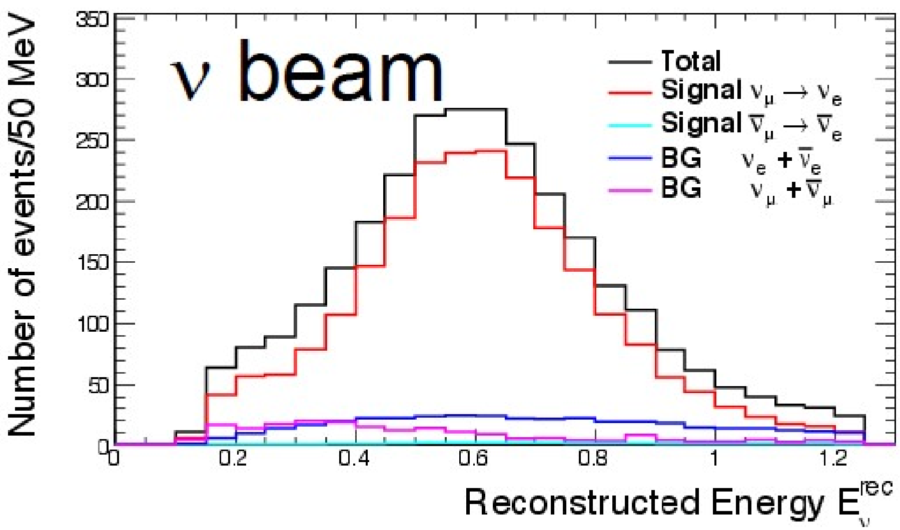
Mt. Ikeno-yama
1000 m
SK
200 m
Capacity :
>2 million m³
N
Maruyama
Excavated rock
disposal site
Mt. Nijyugo-yama
650 m
HK
θ = 0°
Route 41
Access tunnel
Entrance
Yard
Prefectural
Road 484
Modified route of
Road 484 (a plan)
Wasabo tailings dam
owned by KMS
20m
Tunnel
Entrance
Wasabo
Kamioka Town
Funatsu
Bridge
Google

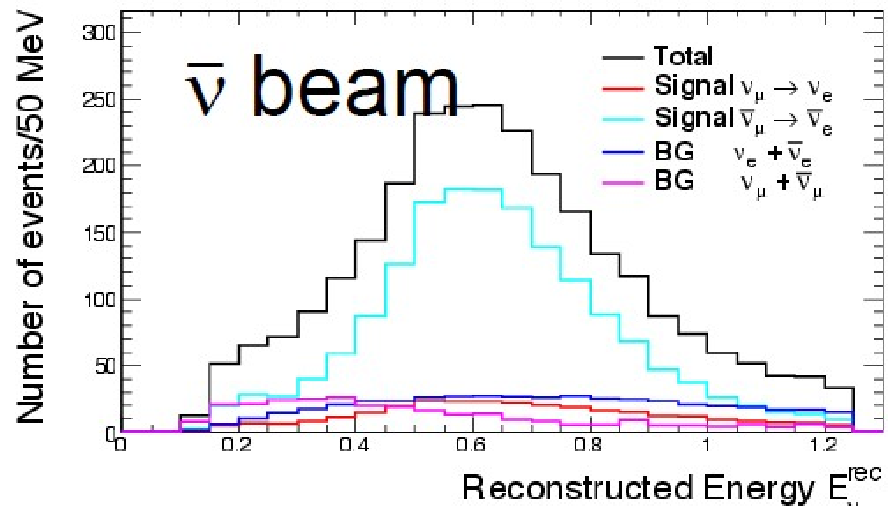
# Physics performance for oscillation studies



Assuming
- 10 years of running
- 1.3 MW for JPARC proton beam
- 1 tank
- ~ 40% PMT coverage in HK
- 3-4% systematic uncertainties

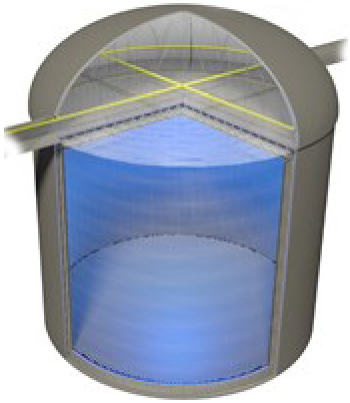
## Electron-neutrino appearance



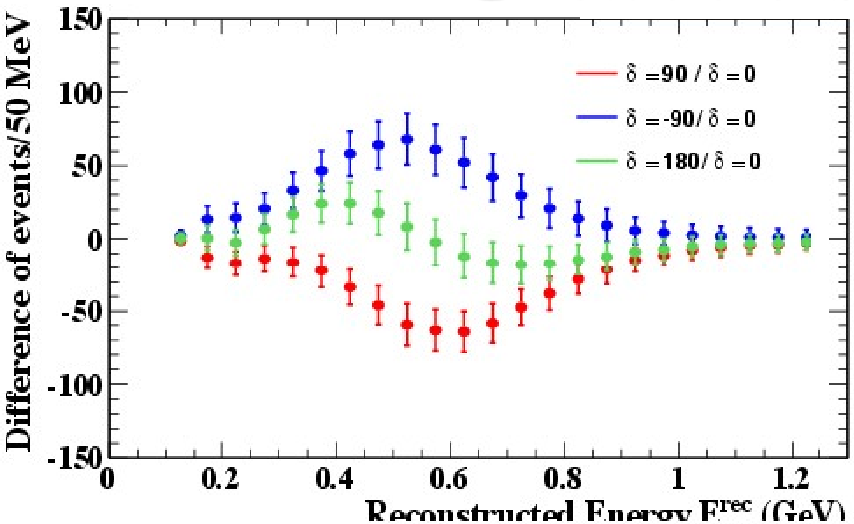

| $\delta$=0 | Signal ($\nu_\mu \to \nu_e$ CC) | Wrong sign appearance | $\nu_\mu, \bar{\nu}_\mu$ CC | Beam $\nu_e, \bar{\nu}_e$ contamination | NC |
|---|---|---|---|---|---|
| $\nu$ beam | 2300 | 21 | 10 | 362 | 188 |
| $\bar{\nu}$ beam | 1656 | 289 | 6 | 444 | 274 |

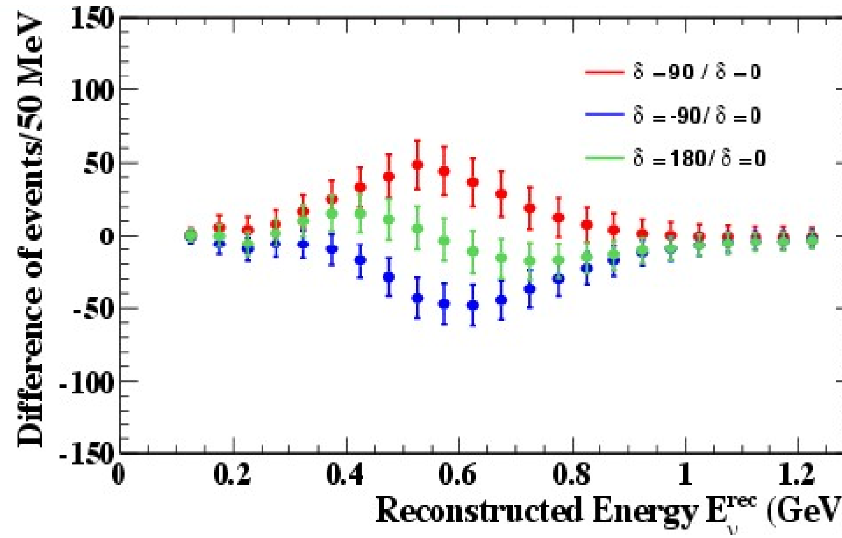
# Physics performance for oscillation studies



Assuming
- 10 years of running
- 1.3 MW for JPARC proton beam
- 1 tank then 2 tanks
- ~ 40% PMT coverage in HK
- 3-4% systematic uncertainties

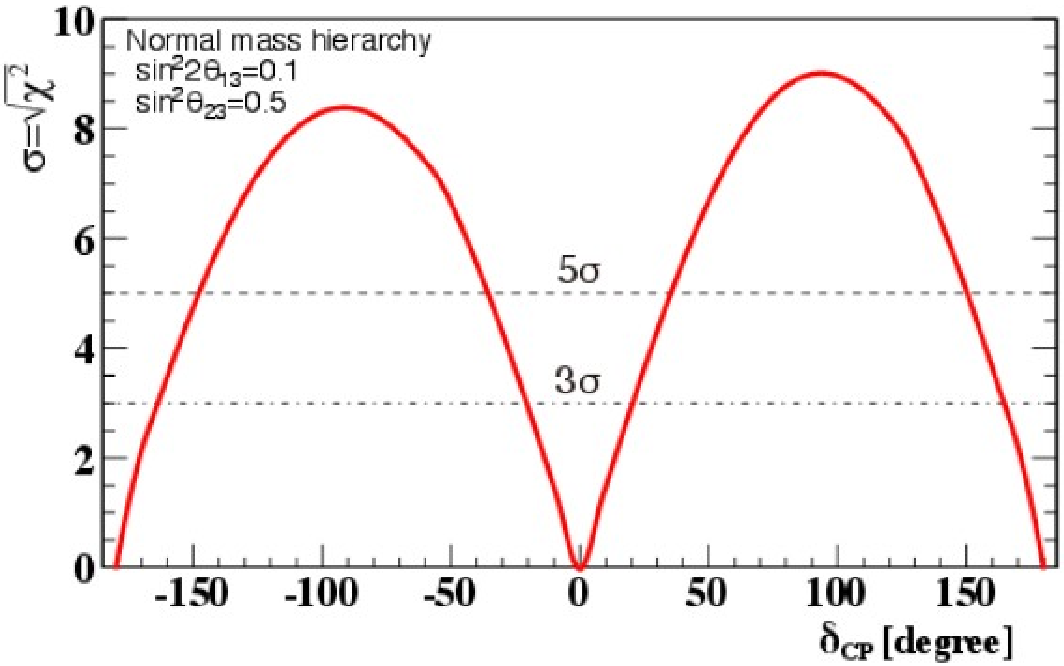
## Electron-neutrino appearance



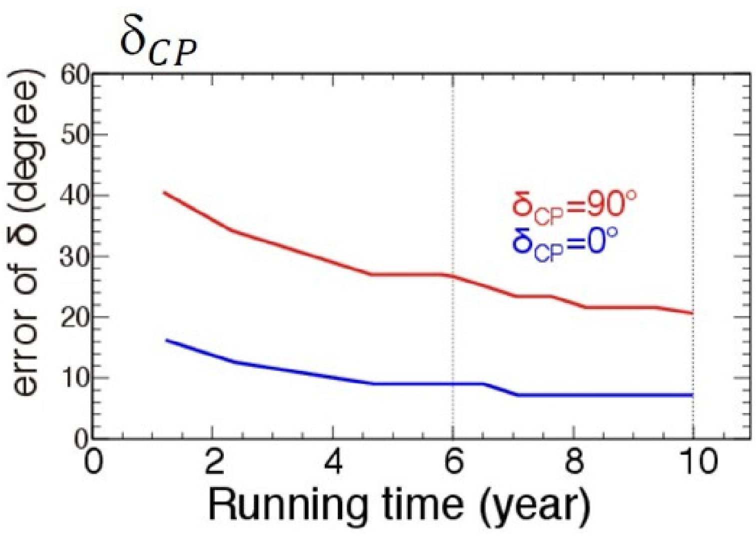




Possibility of using shape information in energy to distinguish different values for δ (CP)

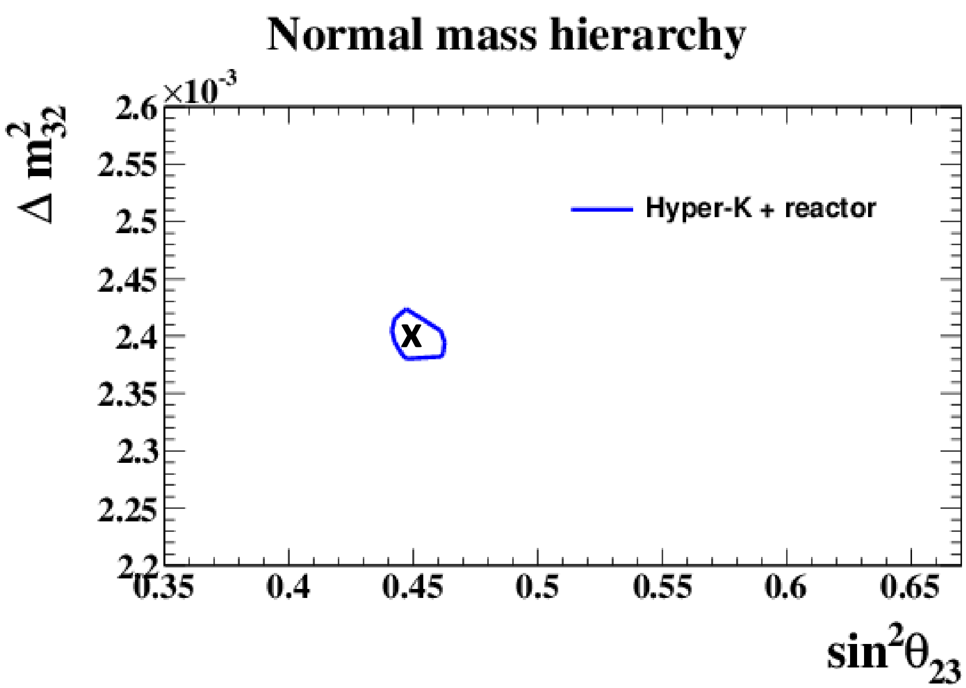
# Physics performance for CPV studies

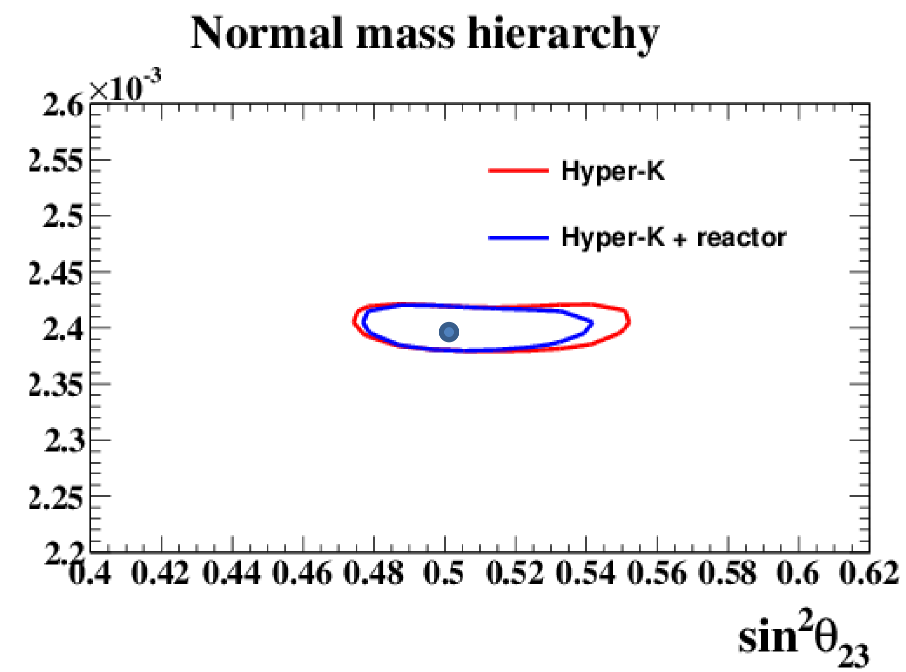



- Exclusion of sin$\delta_{CP}$=0
  - 8σ for δ=-90°
  - 80% coverage of δ parameter space for CPV discovery w/ >3σ
- $\delta_{CP}$ precision measurement
  - 20° for δ=-90°
  - 7° for δ=0°



# Physics performance for oscillation parameter measurements



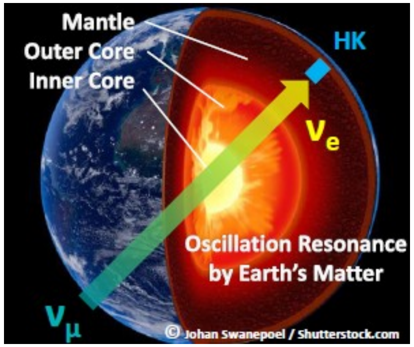




$\sin^2\theta_{23} = 0.50$ ,  $\Delta(\sin^2\theta_{23}) \sim 0.015$ ●

$\sin^2\theta_{23} = 0.45$ ,  $\Delta(\sin^2\theta_{23}) \sim 0.006$ x

T2K

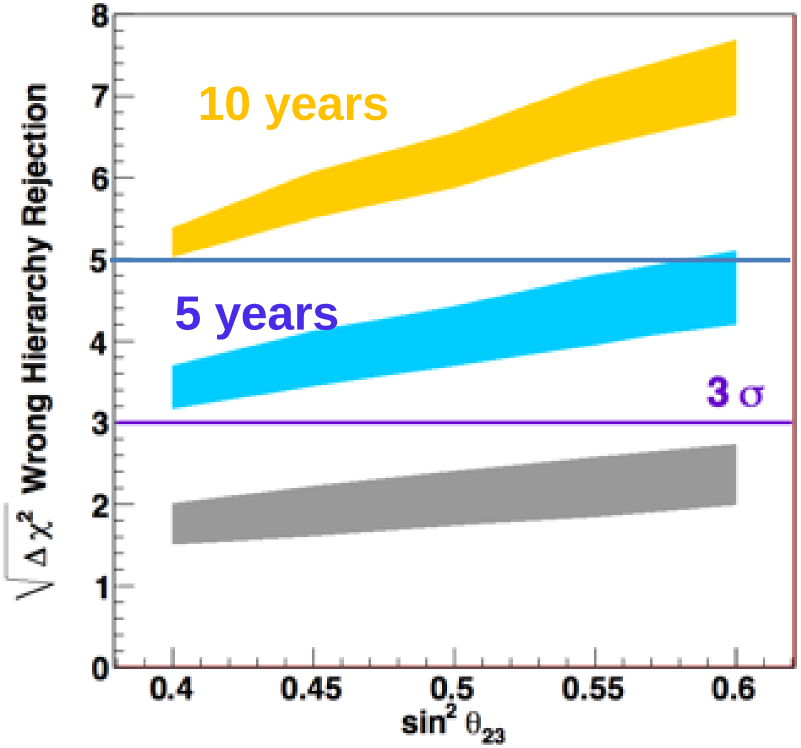
| | |
|---|---|
| $\sin^2\theta_{23}$ | $0.532^{+0.044}_{-0.060}$ |

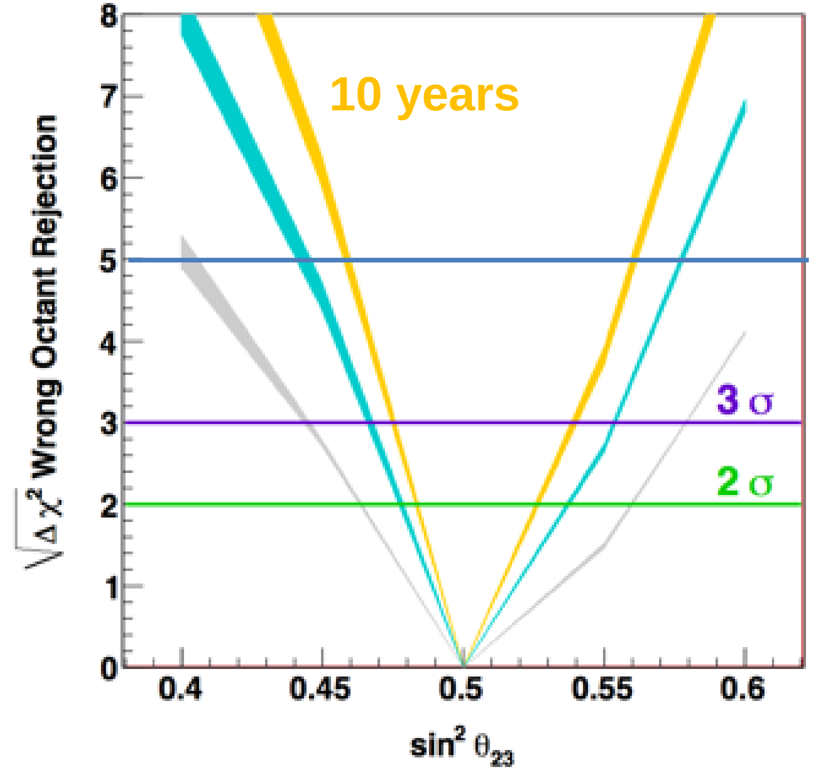



# Physics performance for oscillation parameter measurements

JPARC Beam + Atmospheric neutrinos

*Normal Hierarchy*




M.H. determination ~ 5σ.

Good performance for octant determination

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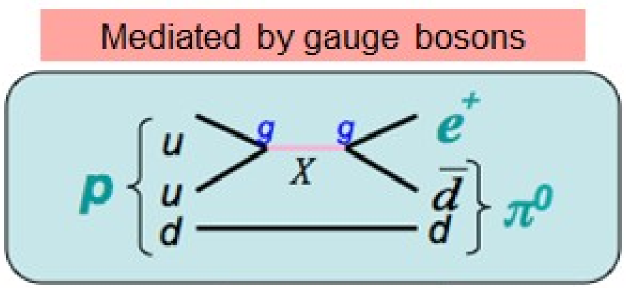
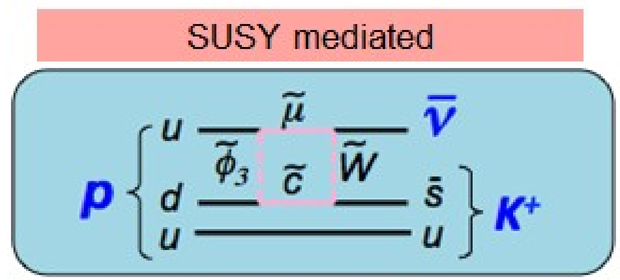
# Proton Decay Sensitivity

- One of the few predictions of the various Grand Unification (SUSY) Theories
- In general, similar analysis as in SK but with neutron tagging for background reduction
- An order of magnitude better sensitivity than SK due to a larger volume and lower background
- We need to pursue both decay modes for discovery, given the variety of predictions




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

$$\Gamma(p \to e^+\pi^0) \sim \frac{g^4 m_p^5}{M_X^4}$$

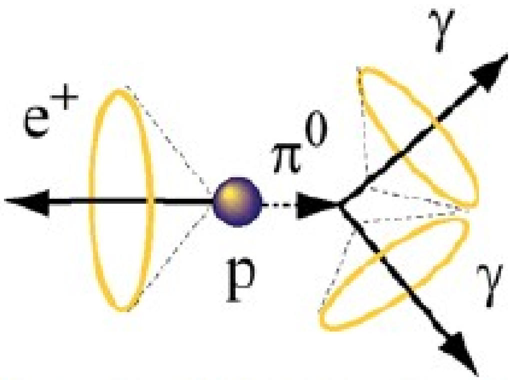



$p \to \nu K^+$

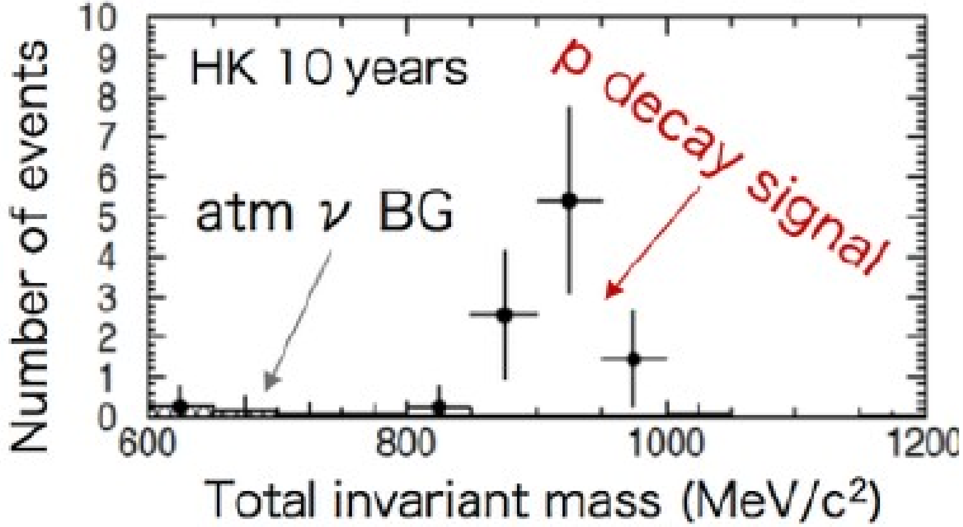
$$\Gamma(p \to \bar{\nu} K^+) \sim \frac{\tan^2 \beta \times m_p^5}{M_{\tilde{q}}^2 \times M_3^2}$$

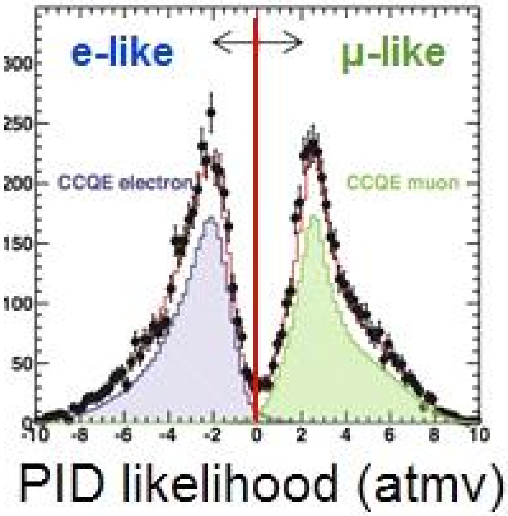
- Searches for other modes are also important

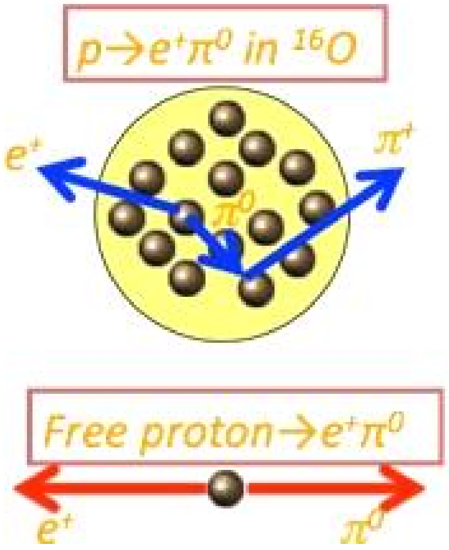
# Proton Decay Sensitivity




Invariant mass assuming τ/Br = 1.7 × $10^{34}$ years (SK 90% C.L. limit)

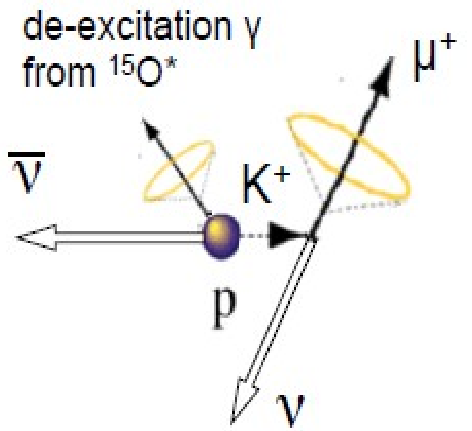



- Great potential for discovery

# Proton Decay Sensitivity

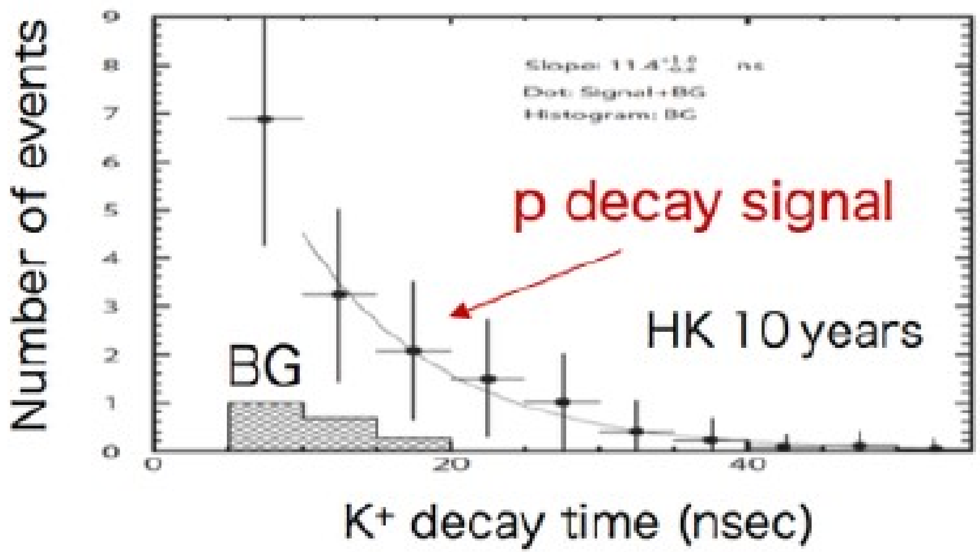



**$K^+$ identification by decay products**

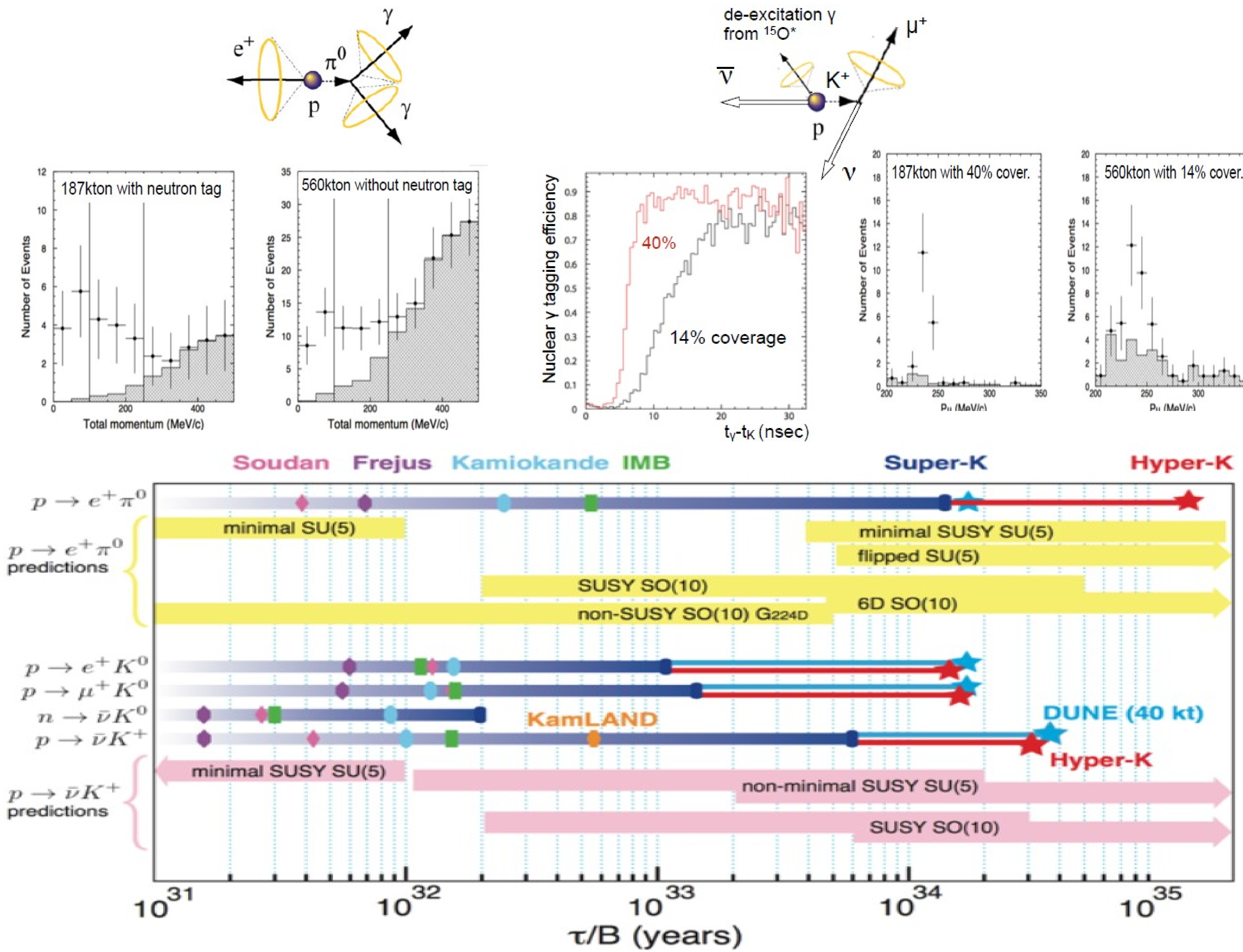
$K^+ \rightarrow \mu^+ \nu$ (64%) 236 MeV/c $\mu^+$ + decay $e^+$
de-excitation $\gamma$ from $^{16}O^*$ (6 MeV)

$K^+ \rightarrow \pi^+ \pi^0$ (21%) 205 MeV/c $\pi^+$ + $\pi^0$ back-to-back

$K^+$ decay time assuming $\tau/Br$ = $6.6 \times 10^{33}$ years (SK 90% C.L. limit)




- Great potential for discovery



e+
π0
γ
γ
p
de-excitation γ from 15O*
μ+
ν̄
K+
p
ν
187kton with neutron tag
560kton without neutron tag
Number of Events
Total momentum (MeV/c)
Nuclear γ tagging efficiency
40%
14% coverage
tγ-tK (nsec)
187kton with 40% cover.
560kton with 14% cover.
Soudan
Frejus
Kamiokande
IMB
Super-K
Hyper-K
p → e+π0
minimal SU(5)
minimal SUSY SU(5)
flipped SU(5)
SUSY SO(10)
6D SO(10)
non-SUSY SO(10) G224D
p → e+π0 predictions
p → e+K0
p → μ+K0
n → ν̄K0
p → ν̄K+
KamLAND
DUNE (40 kt)
Hyper-K
minimal SUSY SU(5)
non-minimal SUSY SU(5)
SUSY SO(10)
p → ν̄K+ predictions
τ/B (years)

# OUTLINE

- Introduction
- HK detector: design and R&D
- JPARC and Near Detectors for T2HK
- Oscillations physics
- Proton decays
- **Neutrino Astronomy**
- Schedule and conclusion

Hyper Kamiokande
@HyperKamiokande

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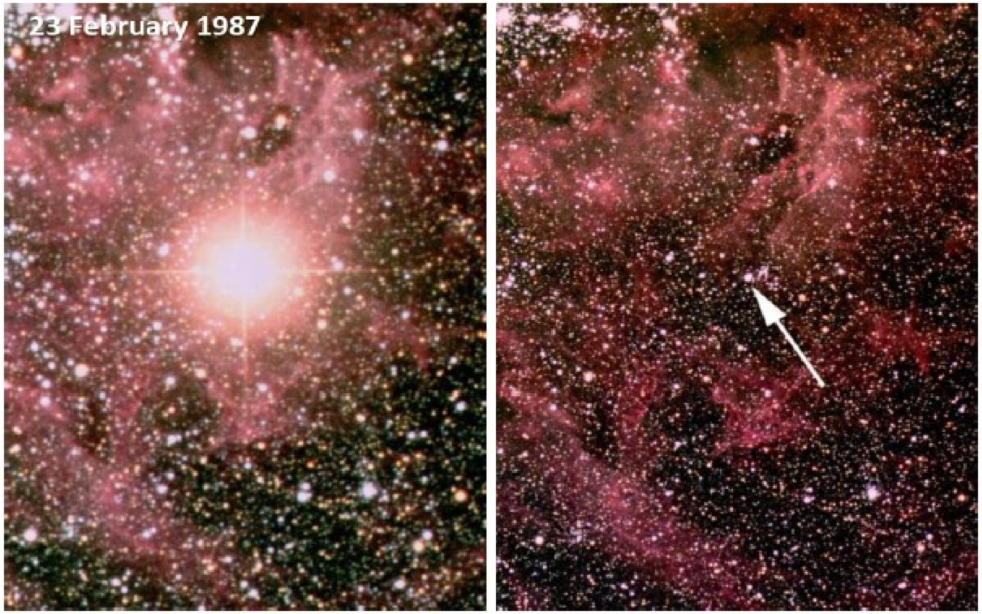
École polytechnique - IN2P3/CNRS

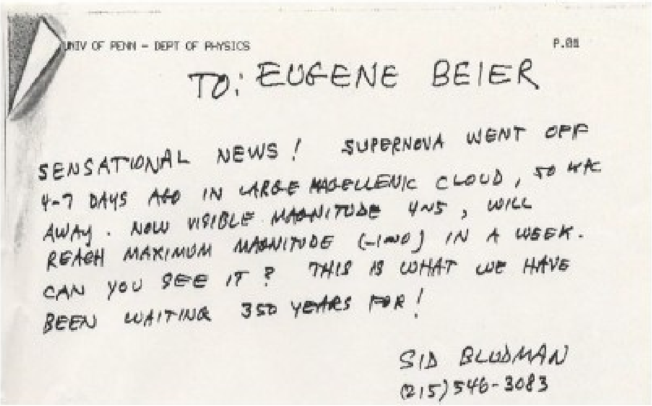
# Neutrino Astronomy

## Supernova burst neutrinos





*Feb. 25th, 1987: A fax was sent to Univ. of Tokyo*



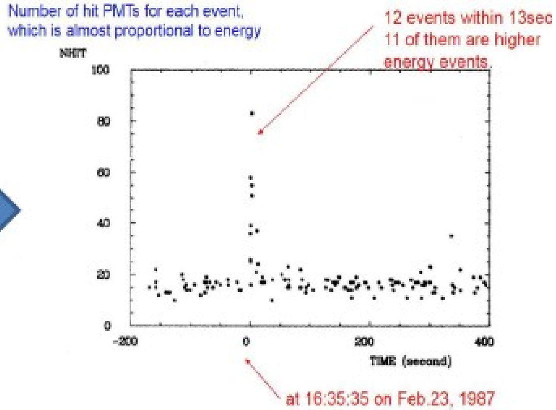
UNIV OF PENN – DEPT OF PHYSICS P.01

TO: EUGENE BEIER

SENSATIONAL NEWS! SUPERNOVA WENT OFF 4-7 DAYS AGO IN LARGE MAGELLENIC CLOUD, 50 KPC AWAY. NOW VISIBLE MAGNITUDE 4.5, WILL REACH MAXIMUM MAGNITUDE (~1 MO) IN A WEEK. CAN YOU SEE IT? THIS IS WHAT WE HAVE BEEN WAITING 350 YEARS FOR!

SID BLUDMAN
(215) 546-3083

**NEUTRINO SIGNALS !**



# Neutrino Astronomy

## Supernova burst neutrinos

Hyper-Kamiokande

Super-Kamiokande

Kamiokande

11 observed events

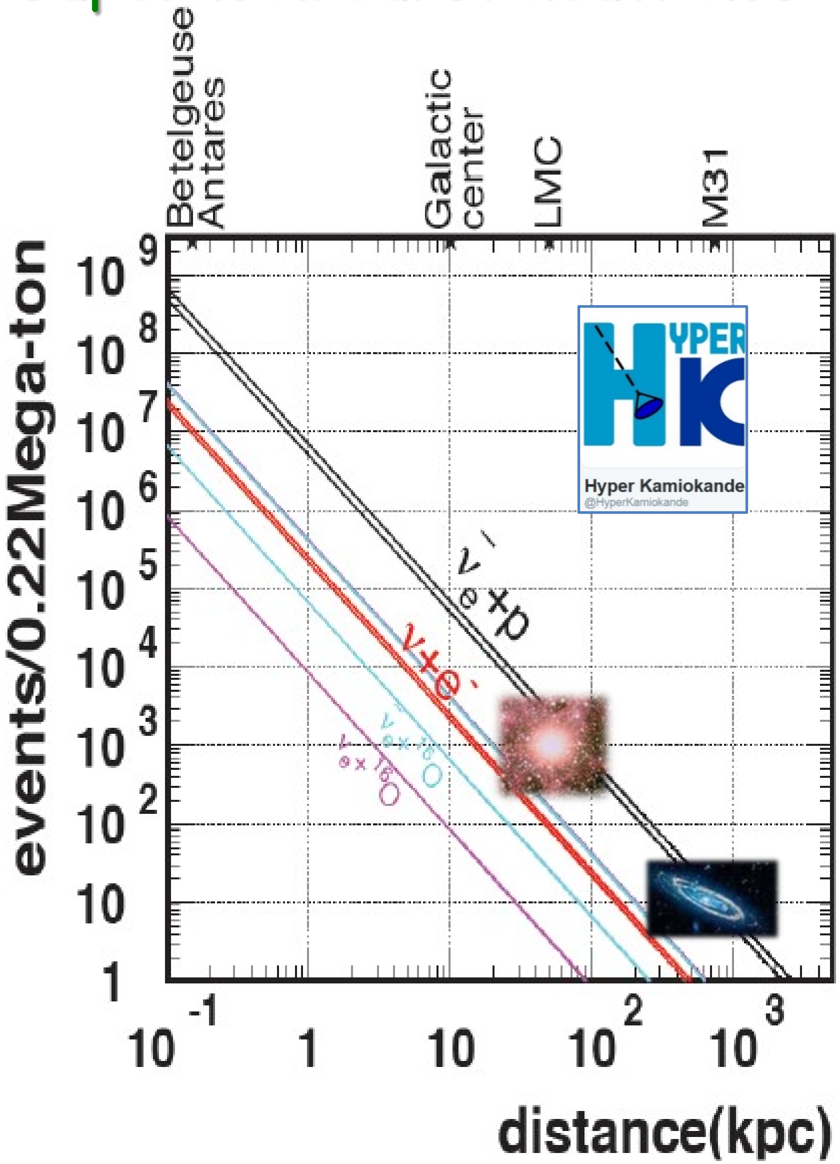
~ 250 events

~ 3000 events

Much more events … in addition to reduced background

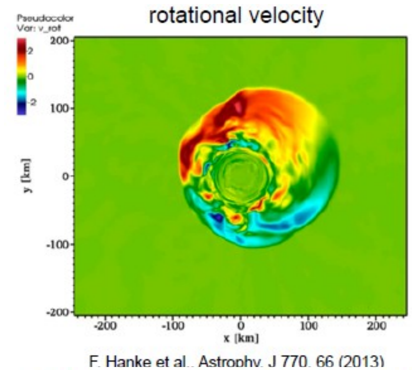
# Neutrino Astronomy

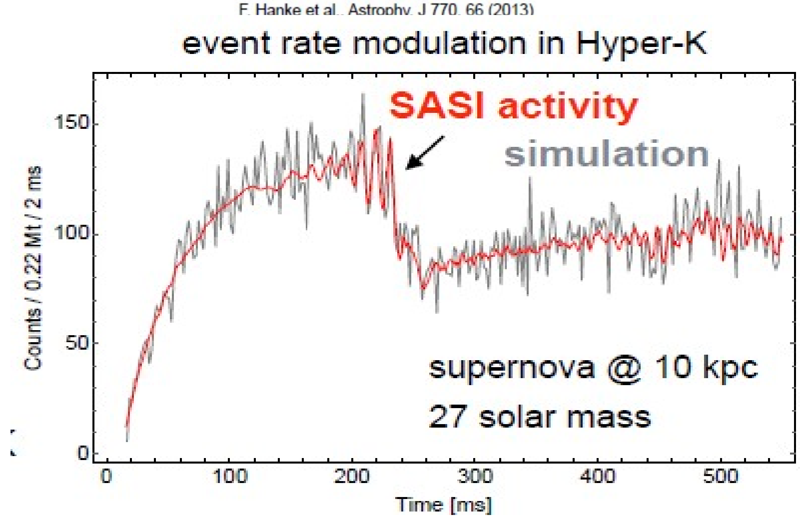
## Supernova burst neutrinos




- HK can extend the supernova search distance to extra-galaxy such as Andromeda

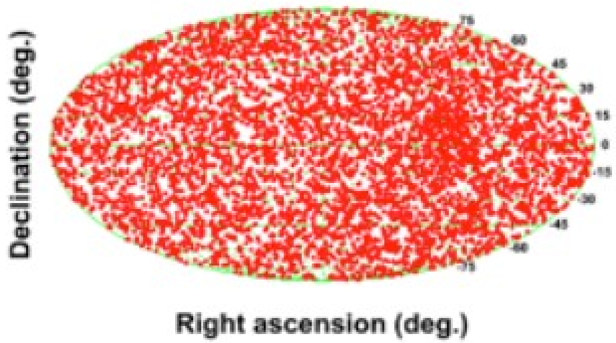
- HK will test the supernova neutrino flux modulation

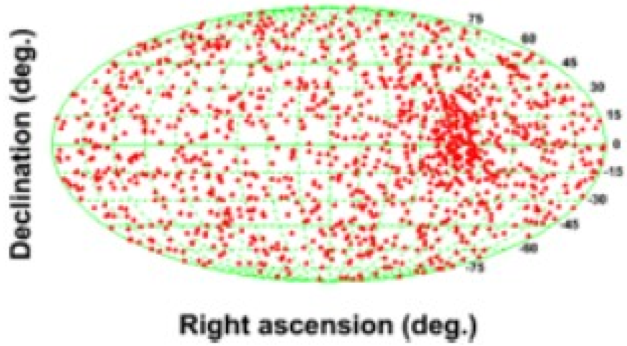


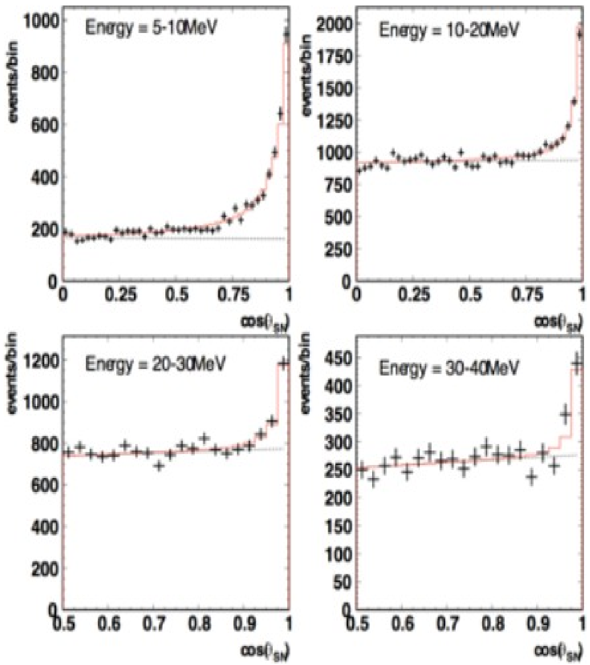



# Neutrino Astronomy

## Supernova burst neutrinos

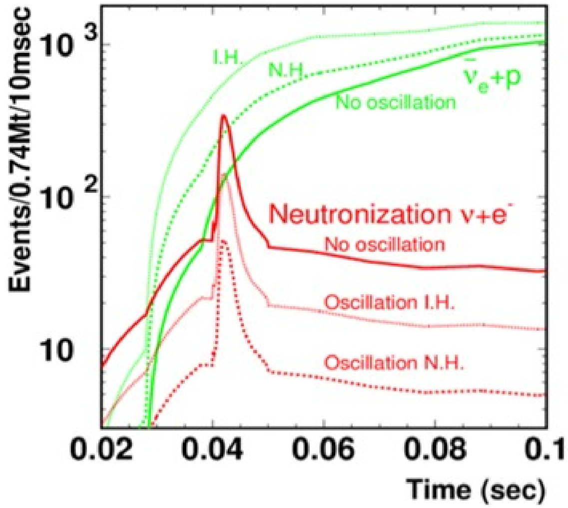



Low energy threshold and good neutron tagging allow :

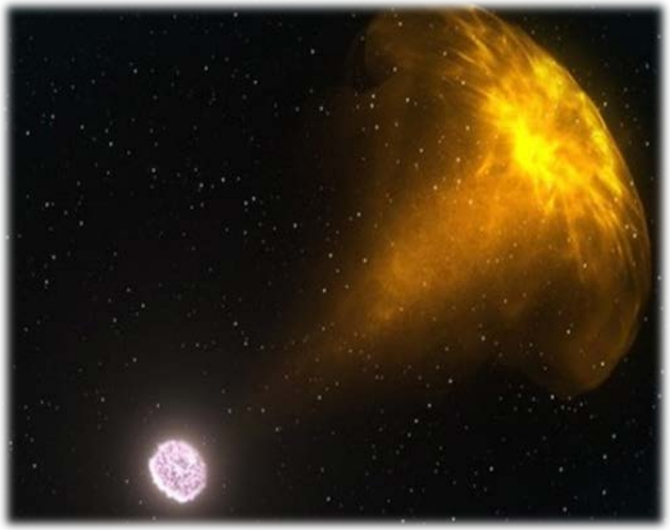
- Good precision for the SN direction (elastic)
- Detect neutrinos from SN "neutronization"



# Neutrino Astronomy

## Gravitational waves neutrinos (neutron stars, black holes)

**The revolutionary era of multi-messenger astronomy has officially begun (actually not …) including soon or later detection of low energy neutrinos**



The merging of 2 neutrons stars GW170817

- GW neutrinos will provide detailed information on the mechanism after the merging

- The timing between the GW, light and neutrinos emissions could lead to the first measurement of the absolute masses of the neutrinos

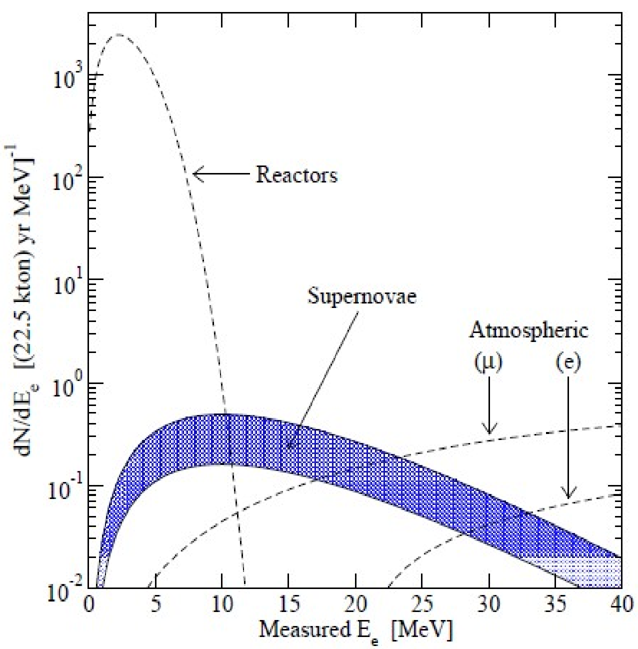
In the near future, experiment Super-Kamiokande will increase its sensitivity for GW neutrinos detection. Significant potential for big discovery !

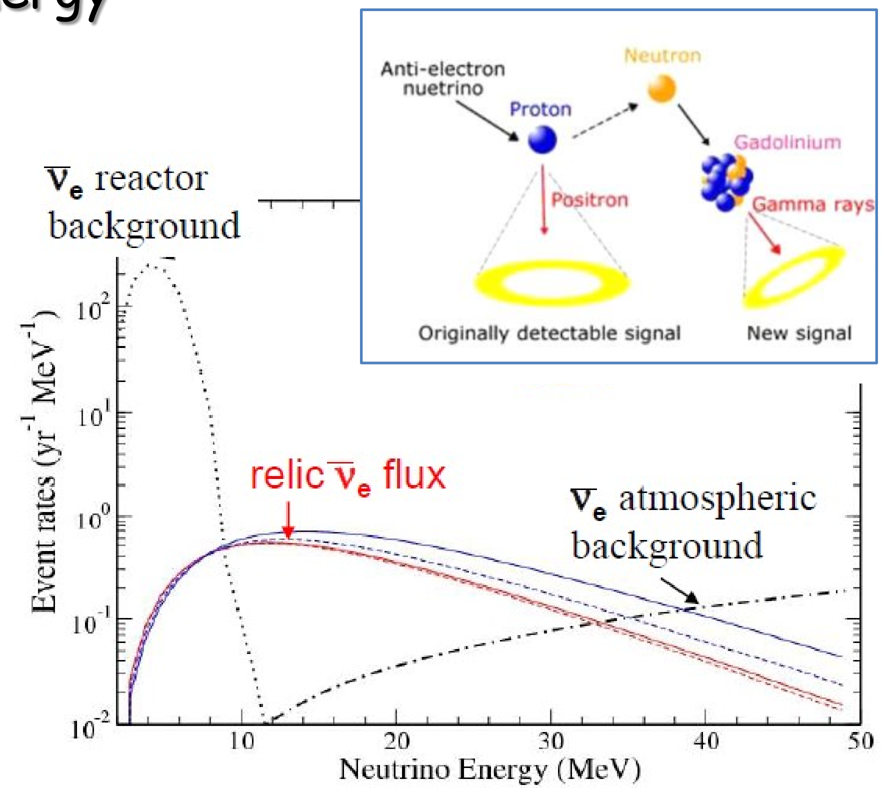
# Upgrade for the Super-Kamiokande experiment

*LLR group is the only French group in SK (since November 2016)*

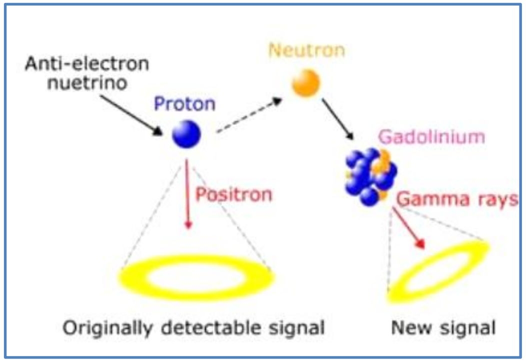
The goal of the upcoming upgrade is to improve neutron tagging for :

- anti electron-neutrino high efficiency detection
- background reduction at low energy



# Upgrade for the Super-Kamiokande experiment



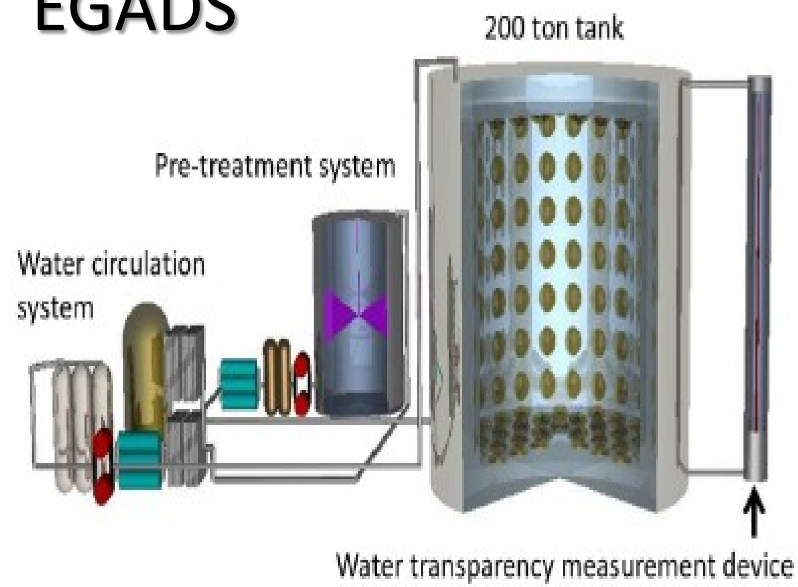

## SK-Gd Overview

- Add 100 tons 0.2% $Gd_2(SO_4)_3$ to SK
  - Use neutrons to tag $\bar{\nu}$
  - > 90% of neutrons capture on Gd
- First proposed by Beacom and Vagins
  - PRL93,171101 (2004)
- New tech for new physics
  - Diffuse supernova background
  - Also improve existing signals

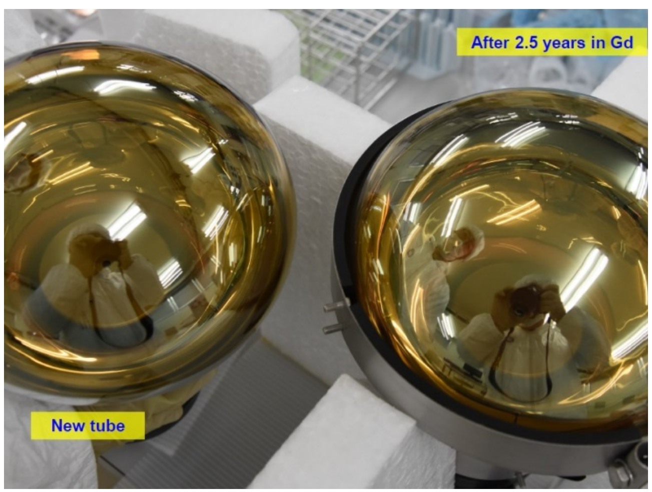
## Challenges of Gd

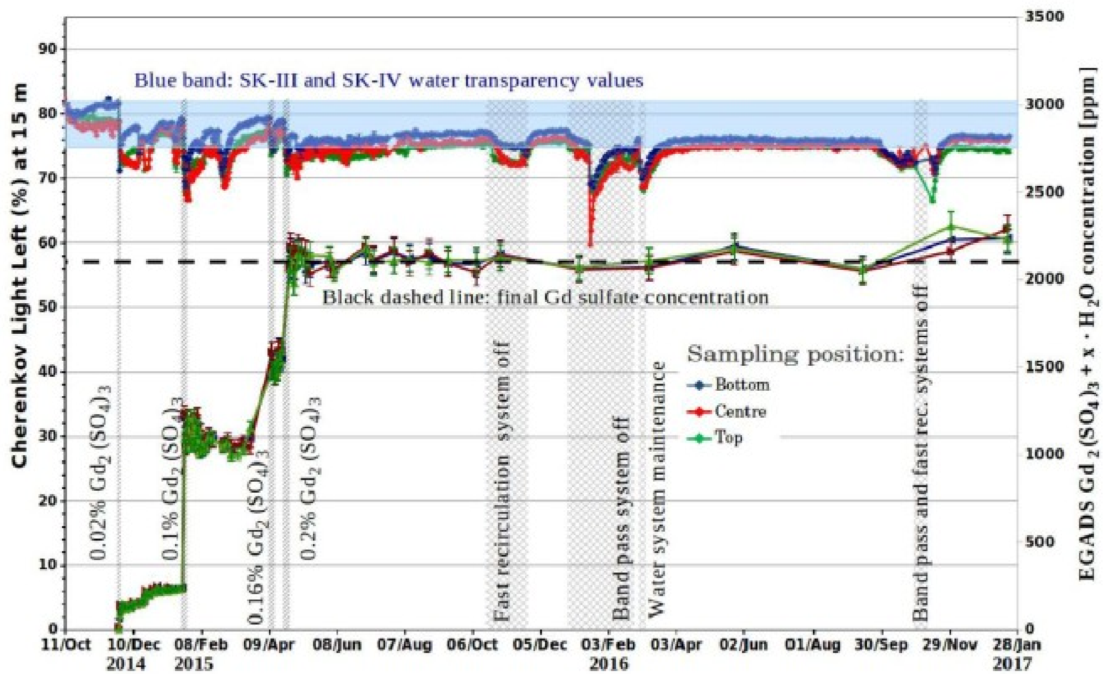
- Add Gd while maintaining water transparency
  - New water circulation system
- Avoid erosion of detector components
  - Use only resistant materials
- Remove Gd when necessary
  - Resin based Gd capture
- High radiopurity – low contamination
  - Backgrounds for lowe analysis

## EGADS



# Upgrade for the Super-Kamiokande experiment

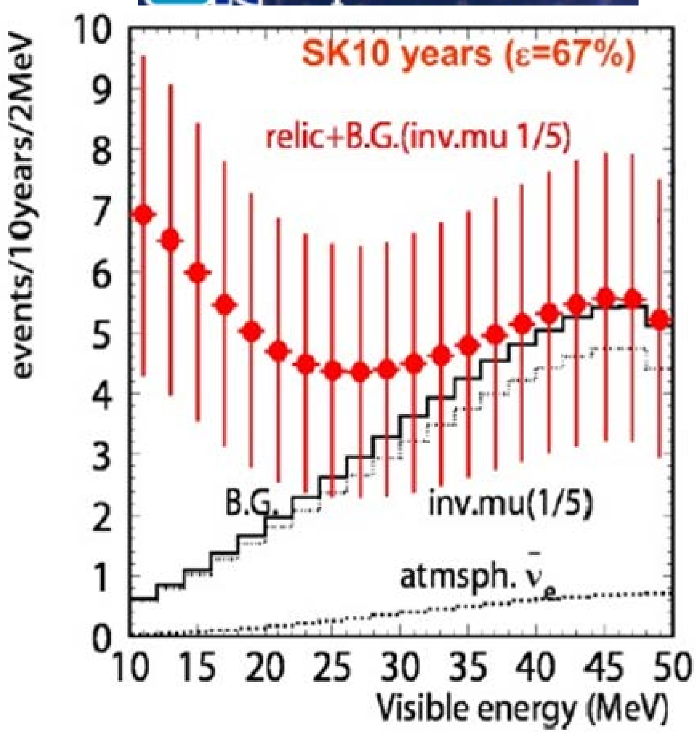
# Neutrino Astronomy

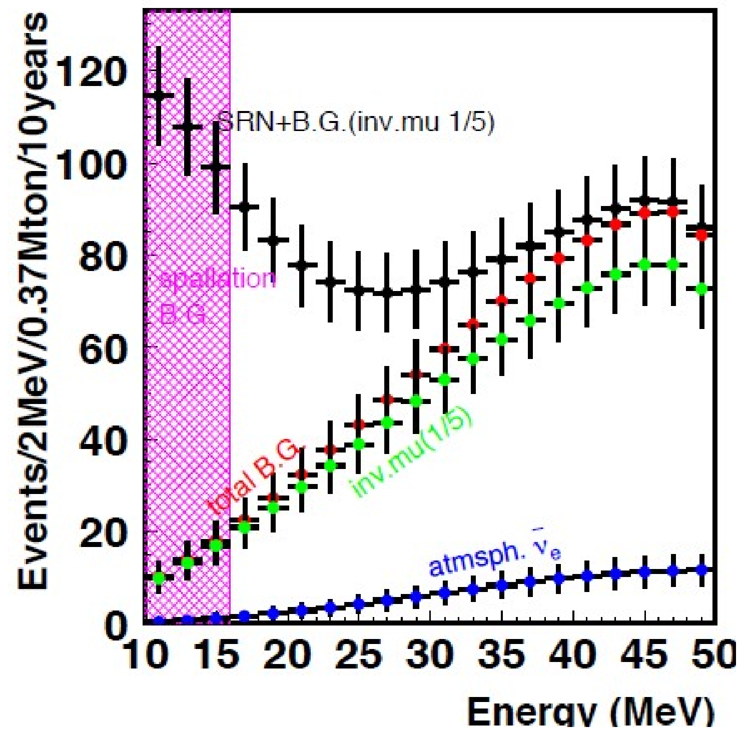
## Supernova relic neutrinos

Diffuse Supernova Neutrino Background (DSNB)

Accumulation since the beginning of the Universe of past Supernova burst

**Super-Kamiokande is expected to discover DSNB**

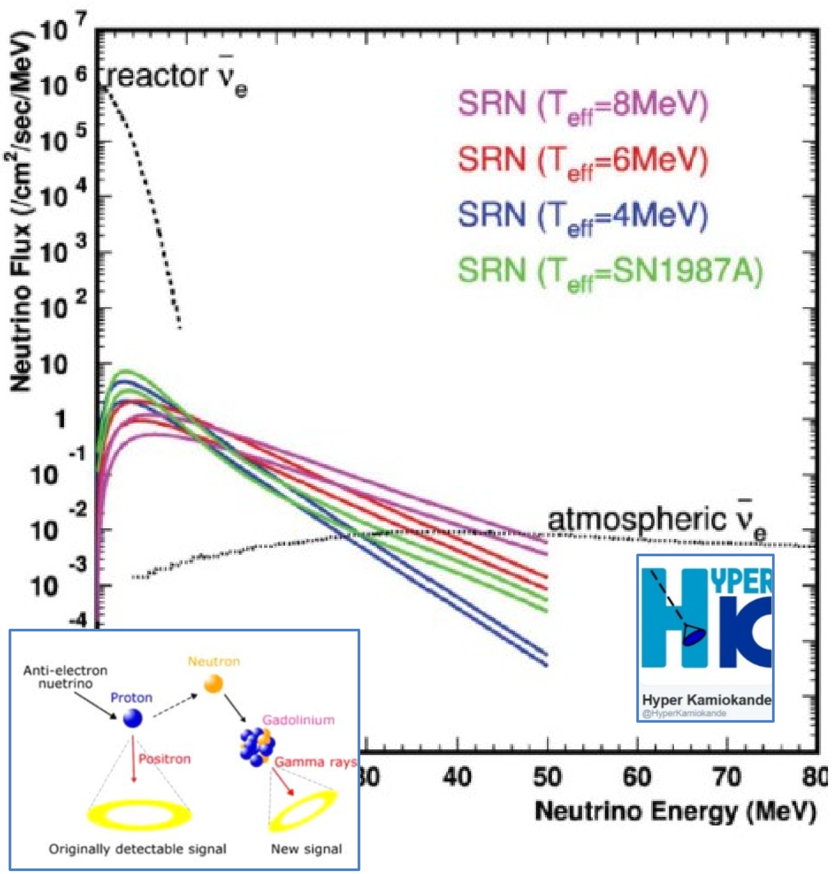


# Neutrino Astronomy

Diffuse Supernova Neutrino Background (DSNB)
Accumulation since the beginning of the Universe of past Supernova burst

Goal of HK : measurement of DSNB energy spectrum

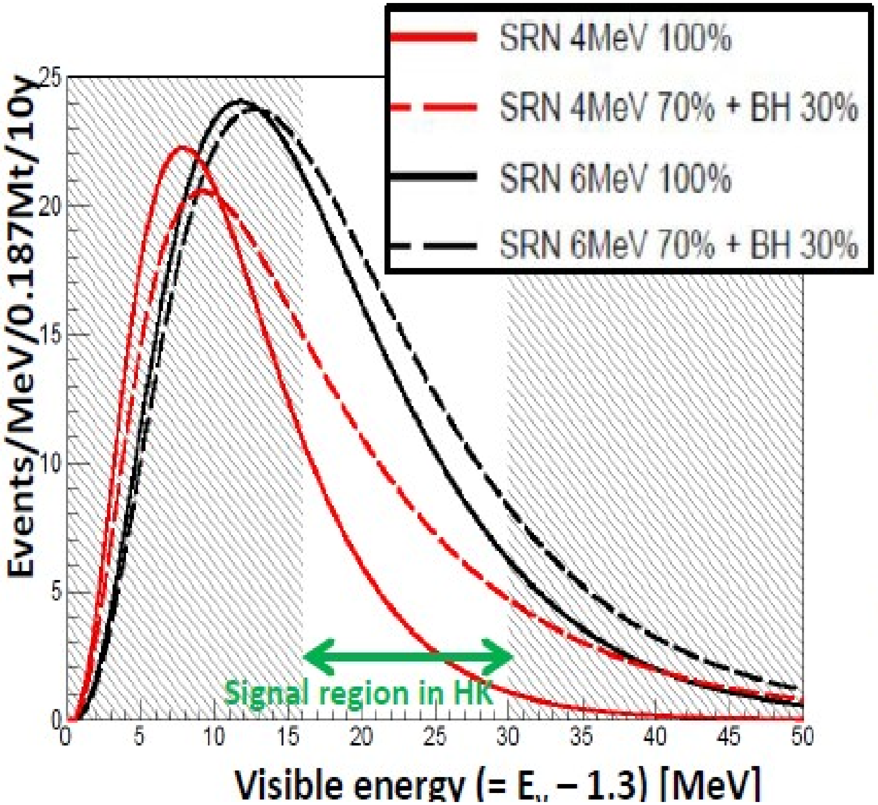


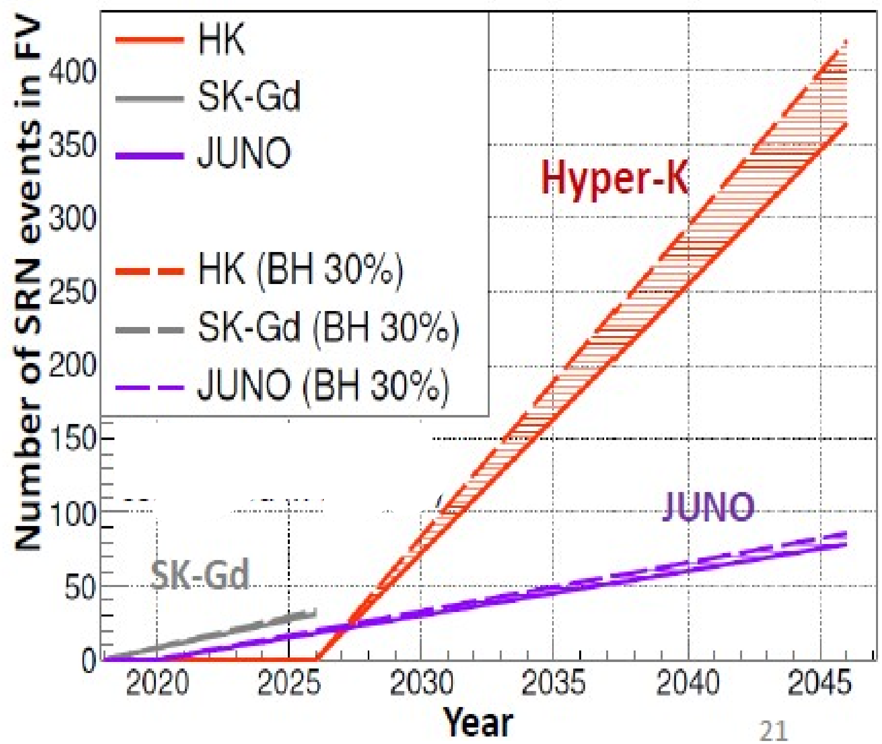

- Spectrum depends on the time when SN burst
- Early time → larger red shift → lower temperature
- Study of stars, black hole, neutron merging history

# Neutrino Astronomy

Diffuse Supernova Neutrino Background (DSNB)
Accumulation since the beginning of the Universe of past Supernova burst

Goal of HK : measurement of DSNB energy spectrum




- Use Gd doped in water to detect neutrons
- Expected events in SN in 10y ~ 150

# OUTLINE

- Introduction
- HK detector: design and R&D
- JPARC and Near Detectors for T2HK
- Oscillations physics
- Proton decays
- Neutrino Astronomy
- **Schedule and conclusion**

Hyper Kamiokande
@HyperKamiokande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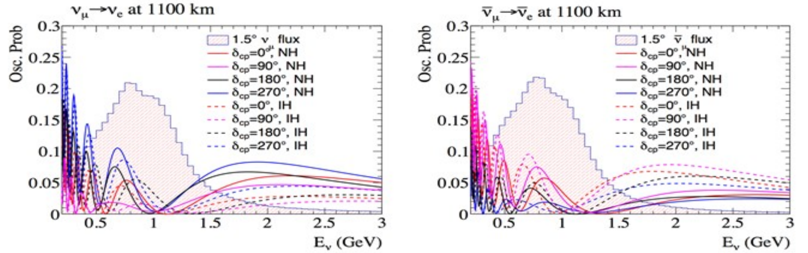
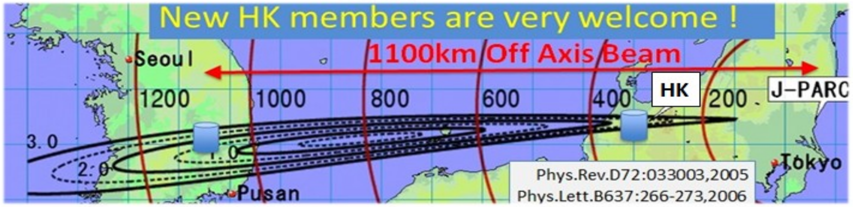
Laboratoire LEPRINCE-RINGUET
École polytechnique - IN2P3/CNRS

| | | HK (1 tank) |
|---|---|---|
| LBL (1.3MW×10years) | δ precision | 7°-23° |
| | CPV coverage (3/5σ) | 76%/57% |
| | $\sin^2\theta_{23}$ error (for 0.5) | ±0.017 |
| ATM+LBL (10 years) | MH determination | 3-7σ |
| | Octant determination (3σ) | $\lvert\theta_{23}-45°\rvert>2°$ |
| Proton Decay (20 years) | $e^+\pi^0$ (3σ) | $1\times10^{35}$ |
| | $\bar{\nu}K$ (3σ) | $3\times10^{34}$ |
| Solar (10 years) | Day/Night (from 0/from KL) | 8σ/4σ |
| | Upturn | >3σ |
| Supernova | Burst (10kpc) | 52k-79k |
| | Relic | 3σ(5σ) in 5(15) years |

Korean option for the second tank ?

Just started to study sensitivity and the physics case




- Great potential for large CP violation discovery in the lepton sector
- Great potential for proton decays
- Great potentials for discovery of DSNB and GW neutrinos
- Final optimized tank design. Staging approach.
- HK is based on existing technologies for neutrino detection but with the use of new generation of photo sensors
- Upgrades of the ND280 detectors for T2K-II.
- HK Proposal for new Intermediate Detector (NUPRISM)


- Formed in January 2015
- ~300 members, 75 institutions, from 15 countries (as of April 2017)
- ~70% from oversea countries

International collaborations.
Possibility for wide variety contributions.

- Tokyo Institute of Technology (Japan)
- Boston University (USA)
- Chonnam National University (Korea)
- Dongshin University (Korea)
- Gwangju Institute of Science and Technology (Korea)
- Duke University (USA)
- ETH Zurich (Switzerland)
- Imperial College London (UK)
- Institute for Particle Physics Phenomenology, Durham University (UK)
- INFN and Dipartimento Interateneo di Fisica di Bari (Italy)
- INFN-LNF (Italy)
- INFN and Università di Napoli (Italy)
- INFN and Università di Padova (Italy)
- INFN Roma (Italy)
- Institute for Nuclear Research (Russia)
- Iowa State University (USA)
- IRFU, CEA Saclay (France)
- Laboratoire Leprince-Ringuet, Ecole Polytechnique (France)
- Lancaster University (UK)
- Los Alamos National Laboratory (USA)
- Louisiana State University (USA)
- National Centre for Nuclear Research (Poland)

## Kamioka

- PMTs
- DAQ, Electronics
- Calibration

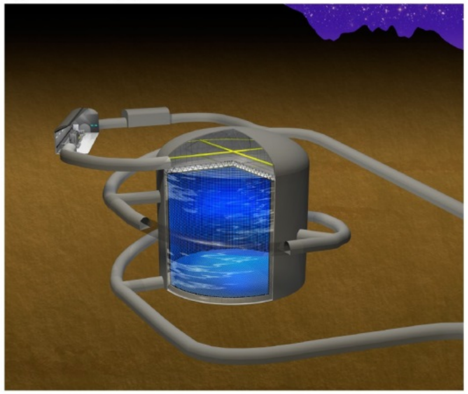
## Tokai

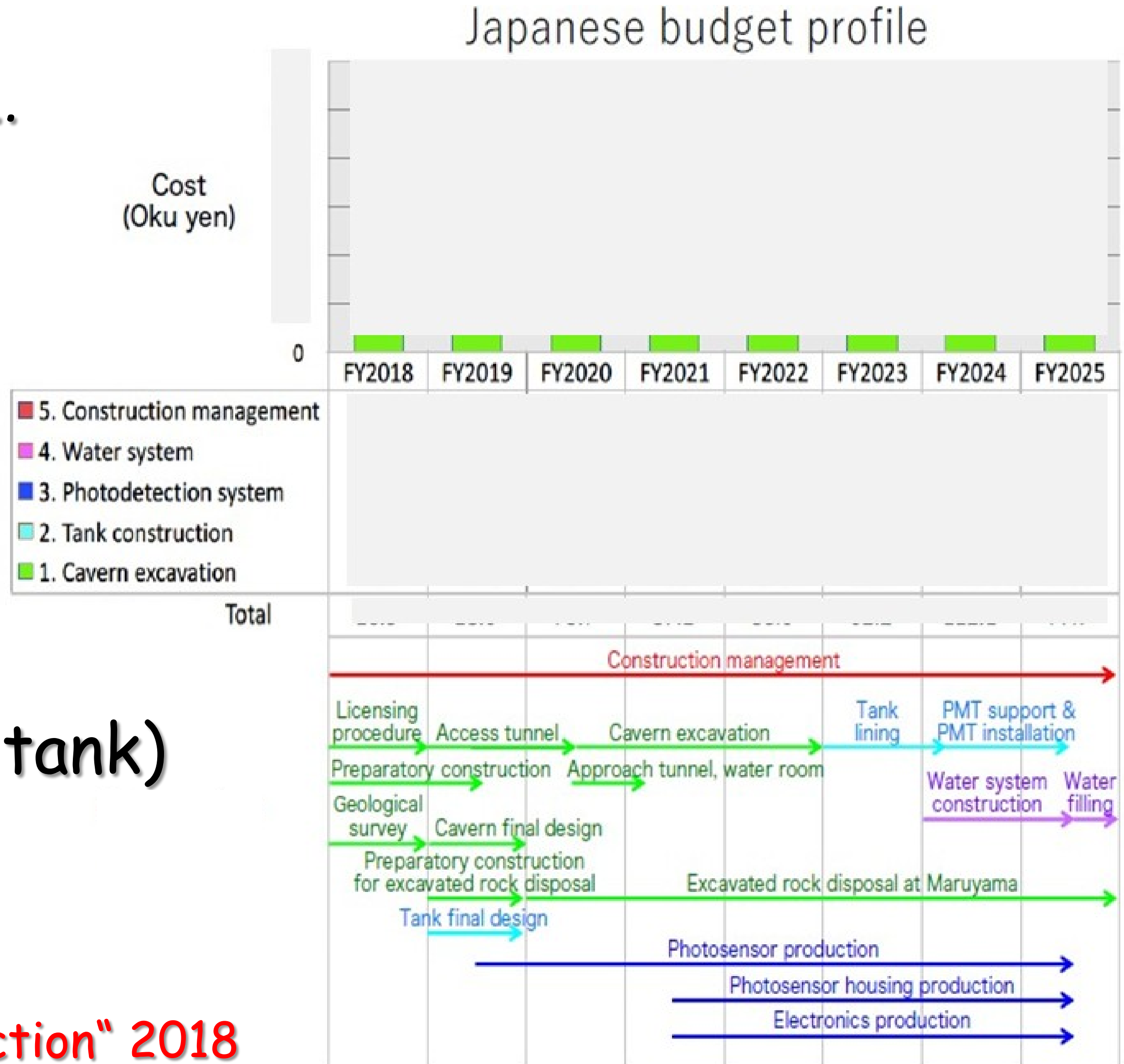
- Near and intermediate detectors
- Beam upgrades

- Software, computing, analysis

# Budget Profile …

Hyper-Kamiokande project






# Schedule (first tank)

Beginning of "construction" 2018
for the HK detector

Laboratoire LEPRINCE-RINGUET
École polytechnique - IN2P3/CNRS

LLR École polytechnique
F - 91128 PALAISEAU cedex

5 physicists
1 postdoc
2 PhD students

Present → 2026-

Super-K, 22kton Fid. mass → Super-K Gadolinium 2019 - → Hyper-Kamiokande

T2K J-PARC 470 KW beam → T2K–II J-PARC > 750 KW beam → Hyper-Kamiokande

**Hyper-Kamiokande**
2026~, 190kton mass, >1.3MW beam

**BIG chance for BIG discovery !**

| Year | DUNE | Hyper-Kamiokande |
| --- | --- | --- |
| 2017 | Far detector cavern excavation | |
| 2018 | Prototype detector test @CERN | Geological survey, Obtaining permits, Preparatory construction |
| 2019 | | Access tunnel construction & Detector cavern excavation |
| 2020 | | |
| 2021 | Start 1st detector (10kt) construction | |
| 2022 | | |
| 2023 | Start 2nd detector (10kt) construction | Tank liner construction, Photo-sensor installation |
| 2024 | Commissioning of two detectors (3rd and 4th detectors in stage) | |
| 2025 | | Water filling |
| 2026 | **Start neutrino beam delivery (1.2MW)** | **Start detector operation & neutrino beam (1.3MW)** |

| Year | DUNE | Hyper-Kamiokande |
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