Hyper-Kamiokande: Detector Design and Physics Potential

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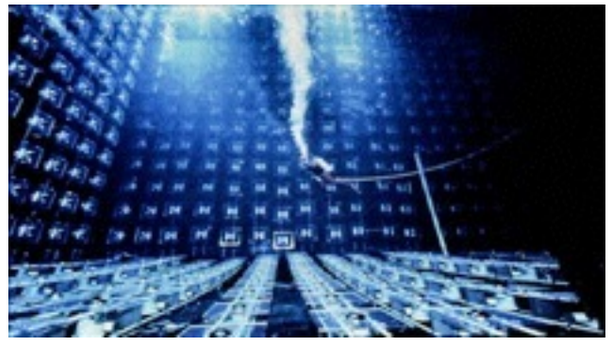
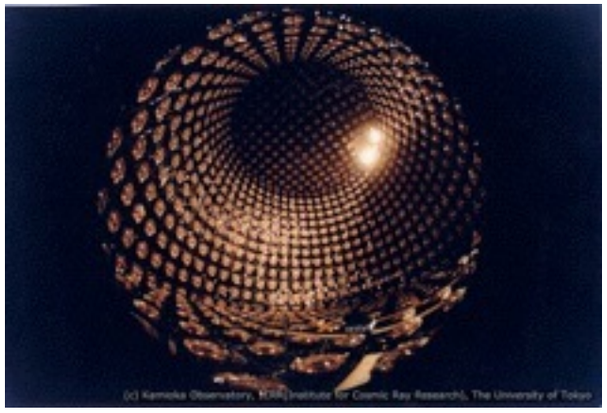
for Hyper-Kamiokande Working Group

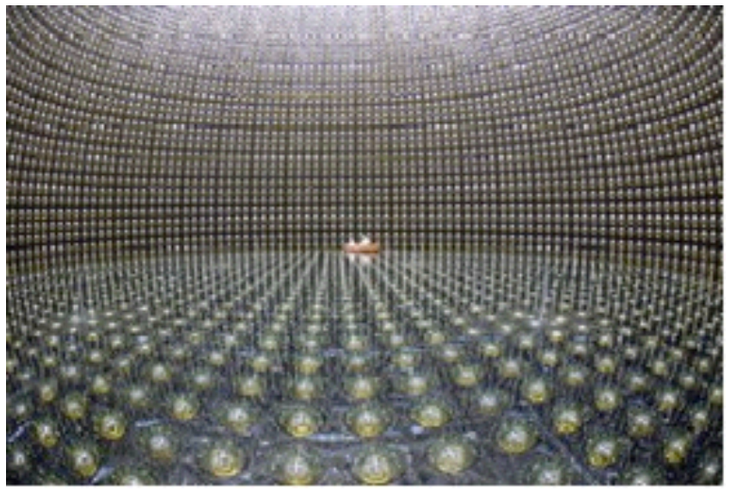
Multi-Messenger Astronomy Consortium bi-monthly meeting, Apr 15, 2014

Large Water Cherenkov Detectors



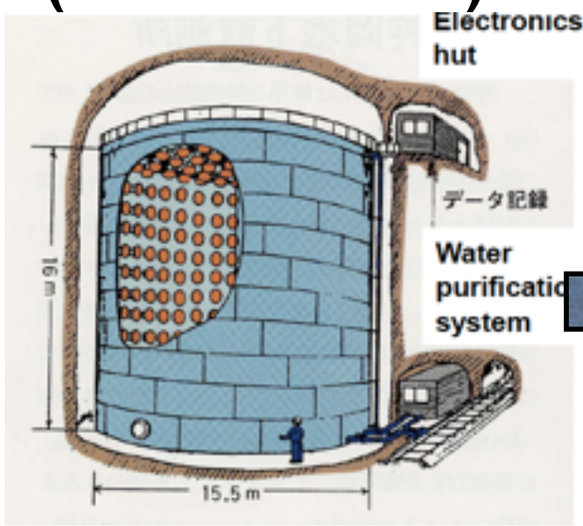


- Excellent performance
  - From ~MeV to ~TeV
- Scalability to ~Mton (and beyond)
- Established technology
  - 50 kton Super-K running for >15years
- Still evolving!!
  - Improved reconstruction algorithm (used for the latest T2K ν_e result)
  - Sensitivity improvement in $p \rightarrow \nu K$
  - Gd R&D in progress (as you heard)
  - ….

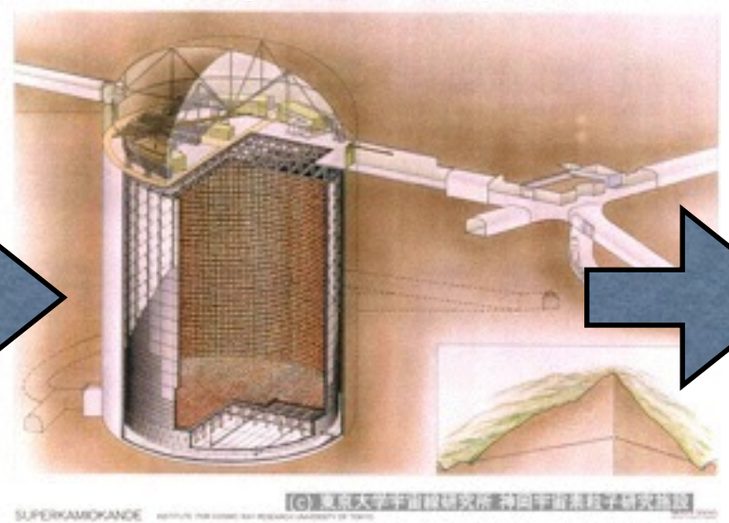


Three generations of Water Cherenkov Detectors at Kamioka

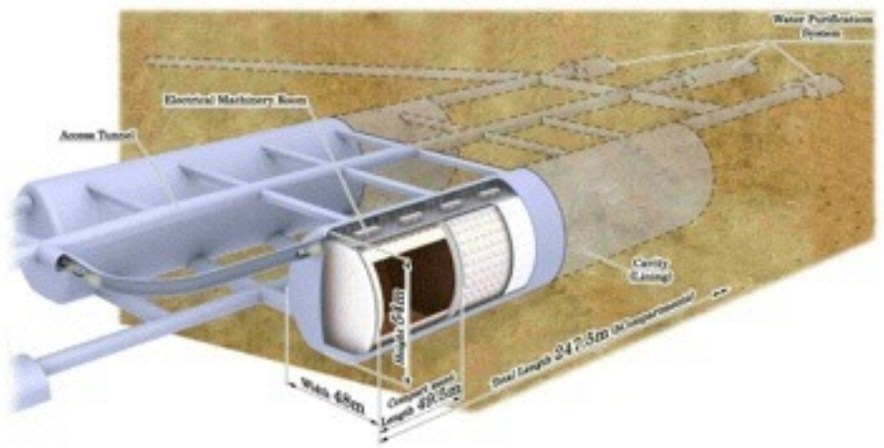
Kamiokande (1983-1996)



Super-Kamiokande (1996-)



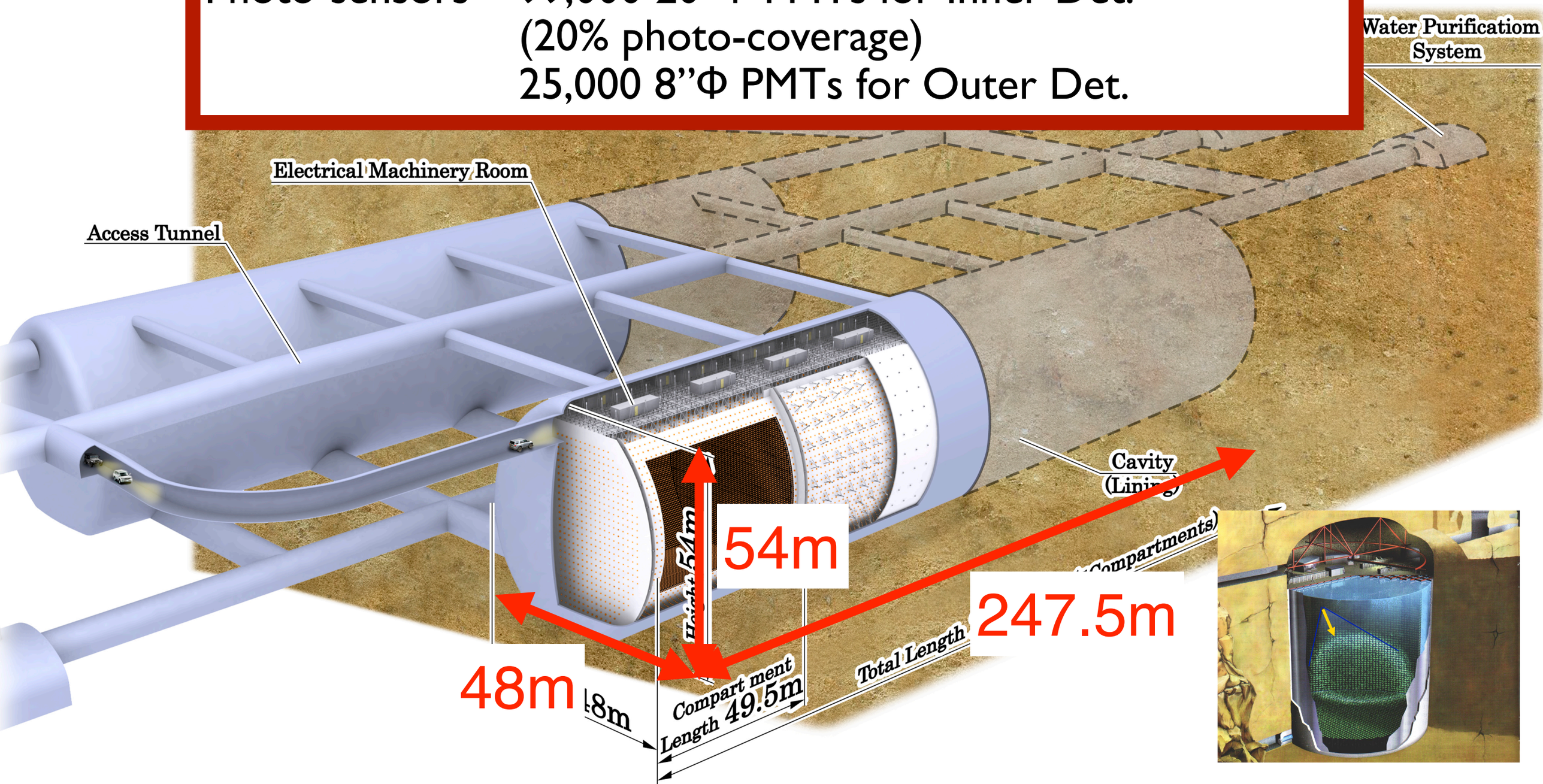
Hyper-Kamiokande (20??-)



3kton → (x17) → 50kton → (x20, x25 fiducial mass) → 1Mton=1000kton (560kton fiducial)

Hyper-Kamiokande

Total Volume	0.99 Megaton
Inner Volume	0.74 Mton
Fiducial Volume	0.56 Mton (0.056 Mton × 10 compartments)
Outer Volume	0.2 Megaton
Photo-sensors	99,000 20”Φ PMTs for Inner Det. (20% photo-coverage) 25,000 8”Φ PMTs for Outer Det.



Selected as one of 27 top projects in Japanese Master Plan for Large Scale Research Projects by Science Council of Japan (Feb. 2014)

提　言

第 22 期学術の大型研究計画に関する
マスタープラン
（マスタープラン 2014）

平成２６年（２０１４年）２月２８日
日　本　学　術　会　議
科学者委員会
学術の大型研究計画検討分科会

No.	Scien-tific Field No.	Project Name	Project Summary	Scientific Significance	Social Value	Project Duration	Financial Requirement (1billion yen)	Implementing Institution, or Affiliation of Proposer
85	23-2	Nucleon decay and neutrino oscillation experiment with an advanced large detector	The project aims to construct a one million ton-scale water Cherenkov detector, Hyper-Kamiokande, to succeed Super-Kamiokande and to perform world-leading neutrino and nucleon decay research in conjunction with the J-PARC accelerator facility.	The project will explore CP violation (matter-antimatter asymmetry) in neutrinos in order to help understand the evolution of the universe. Additionally, with the world's best nucleon decay searches it also aims to establish the unification of elementary particles and their forces.	Addressing profound questions concerning the elementary structure and evolution of the universe appeals directly to the inherent intellectual curiosity mankind harbors for comprehension of its origins and future. Additionally, dramatic advances in neutrino research with a world-leading project in Japan represent society's dreams for a rich program in basic science.	2015 to 2038	Total:1,880 Construction of Hyper-Kamiokande 800, Operating cost of Hyper-Kamiokande 450, Operating cost of J-PARC 600, Neutrino monitor 30	Lead by the Institute for Cosmic Ray Research, University of Tokyo and the High Energy Accelerator Research Organization. Participation from domestic and foreign universities and research institutions is anticipated.

A Long Baseline Neutrino Oscillation Experiment Using J-PARC Neutrino Beam and Hyper-Kamiokande

(Dated: April 14, 2014)

Abstract

Hyper-Kamiokande will be a next generation underground water Cherenkov detector with a total (fiducial) mass of 0.99 (0.56) million metric tons, approximately 20 (25) times larger than that of Super-Kamiokande.

A proposal to J-PARC Physics Advisory Committee just submitted *yesterday*!

anti-neutrino beams.

In this document, the physics potential of a long baseline neutrino experiment using the Hyper-Kamiokande detector and a neutrino beam from the J-PARC proton synchrotron is presented. The analysis has been updated from the previous Letter of Intent [K. Abe et al., arXiv:1109.3262 [hep-ex]], based on the experience gained from the ongoing T2K experiment. With a total exposure of 7.5 MW $\times$ 10^7 sec integrated proton beam power (corresponding to 1.56×10^{22} protons on target with a 30 GeV proton beam) to a 2.5-degree off-axis neutrino beam produced by the J-PARC proton synchrotron, it is expected that the

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York University (Canada): S. Bhadra

12 countries, 67 institutes, 240 persons

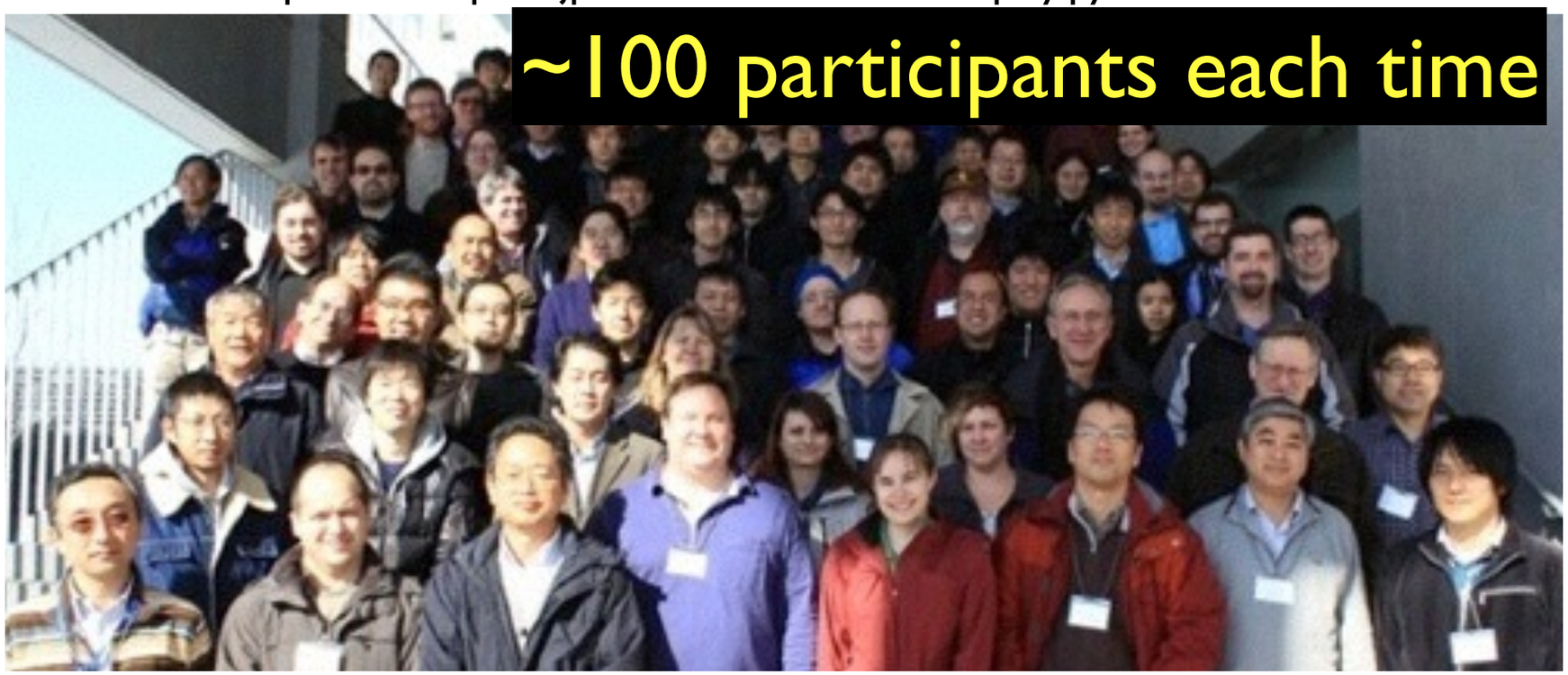
International open Hyper-K meetings

Hyper-K is completely open to the international community.

International WG was formed and actively working.

Four meetings (all held @ Kavli IPMU) so far.
Aug. 2012, Jan. 2013, Jun. 2013, Jan.2014

http://indico.ipmu.jp/indico/conferenceDisplay.py?&confId=23

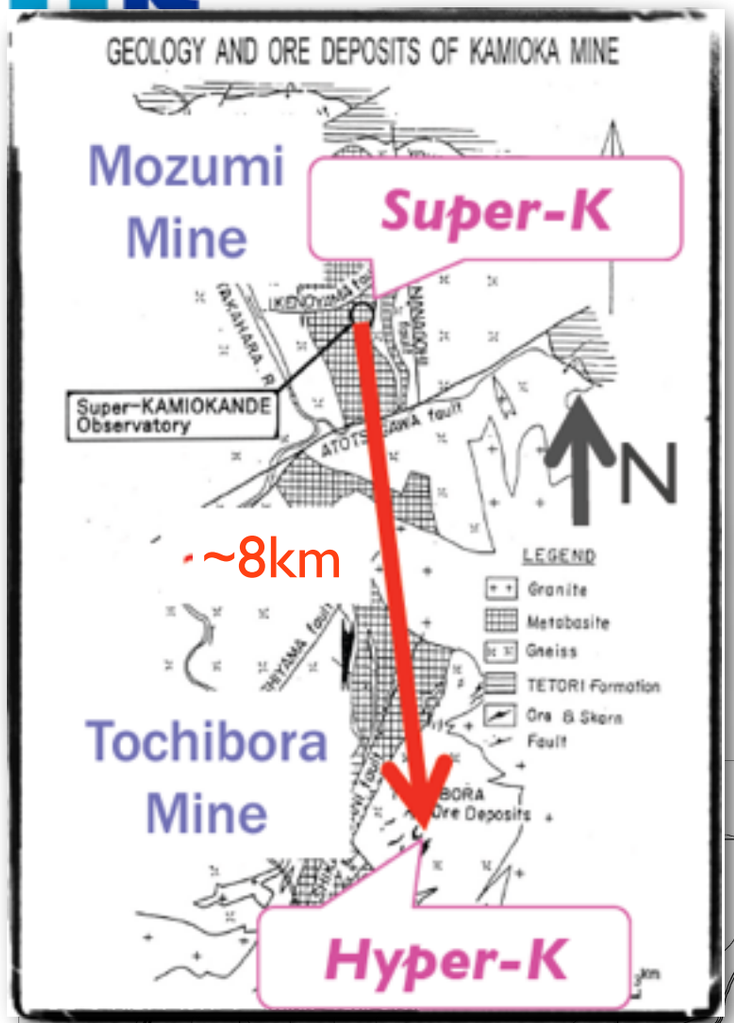


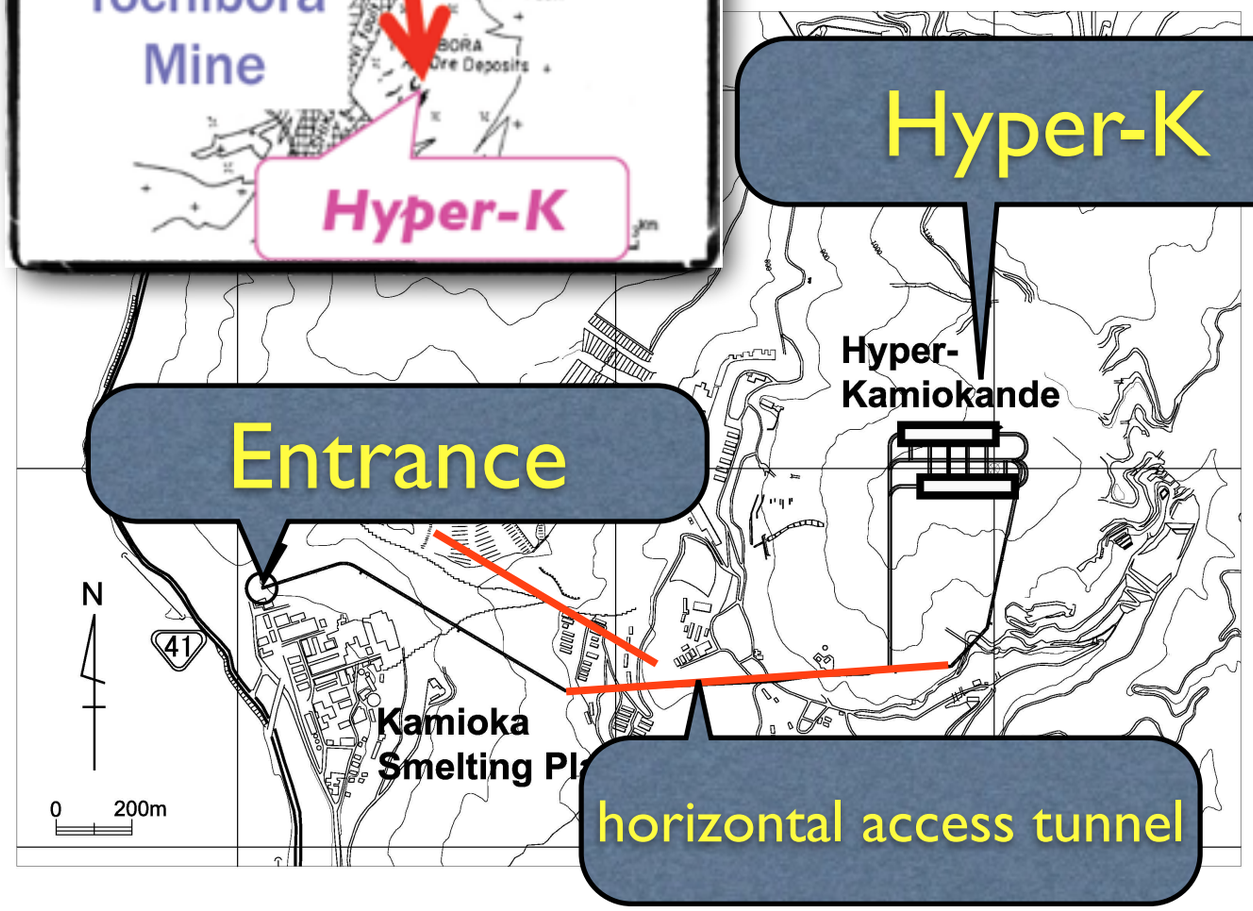
Next meeting: Jul. 19-21, 2014 @TRIUMF, Canada

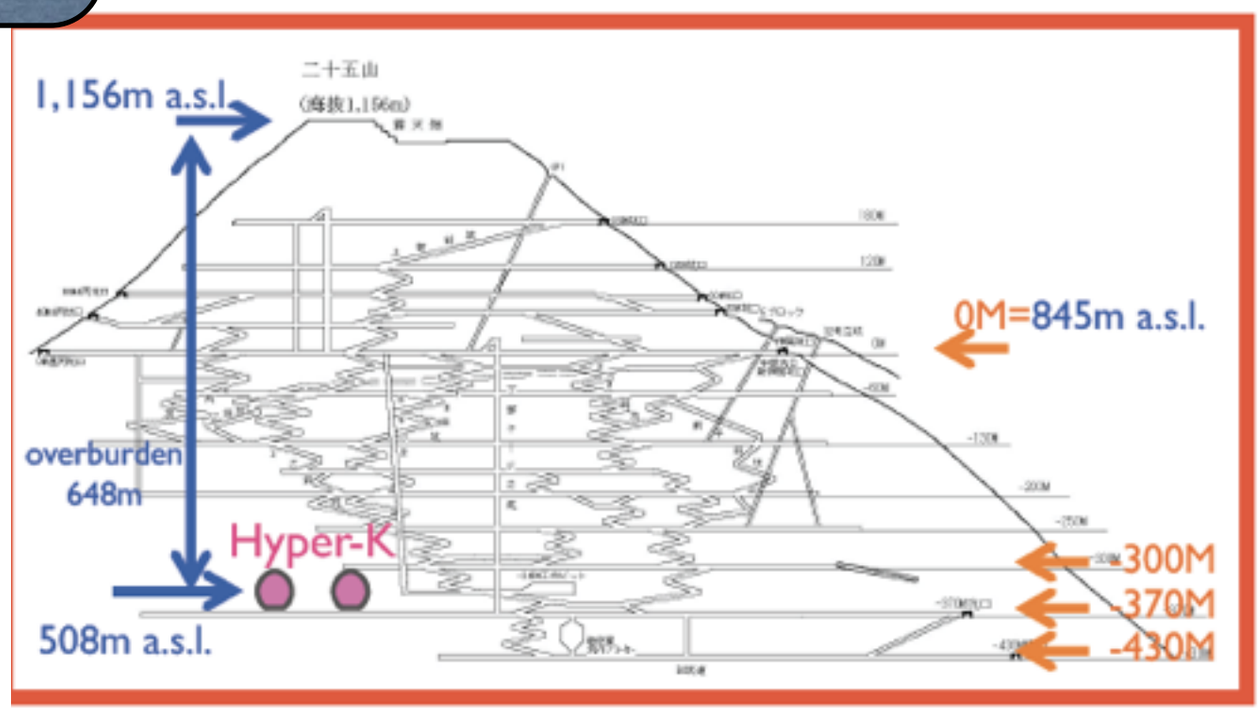
Open to anyone interested in HK!

Candidate site

- 8km south of Super-K
  - Same off-axis and baseline as T2K
- Horizontal drive from entrance
- 648m of rock (1750m.w.e.) overburden
- 13,000m^3/day natural water (1Mt/80days)

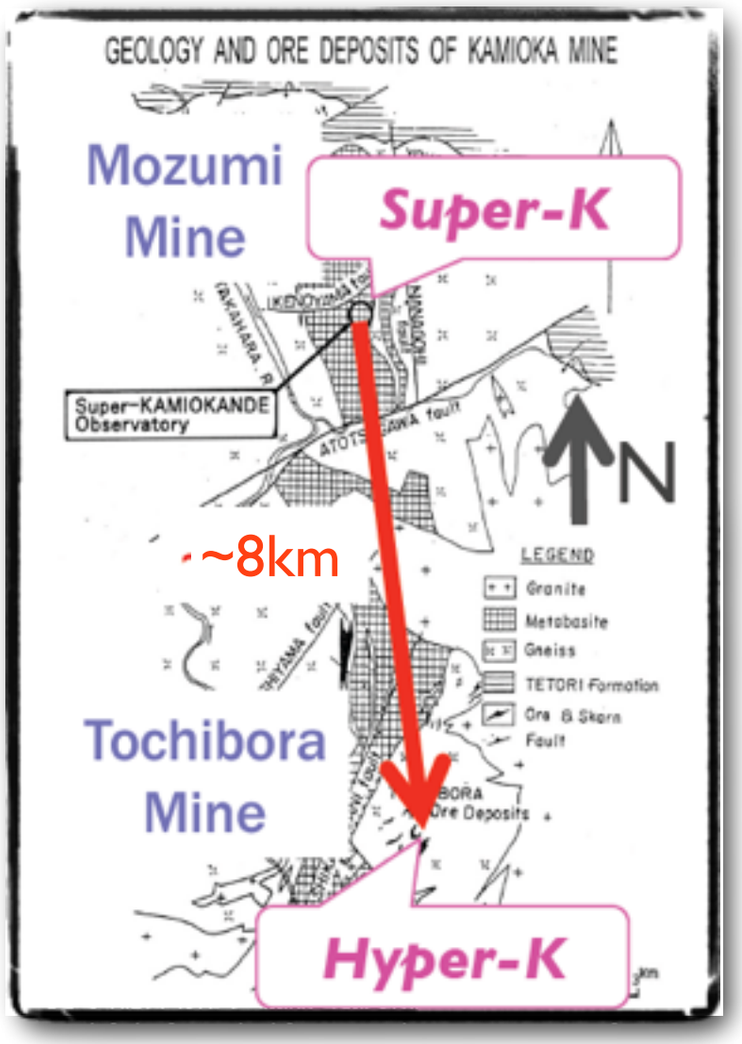




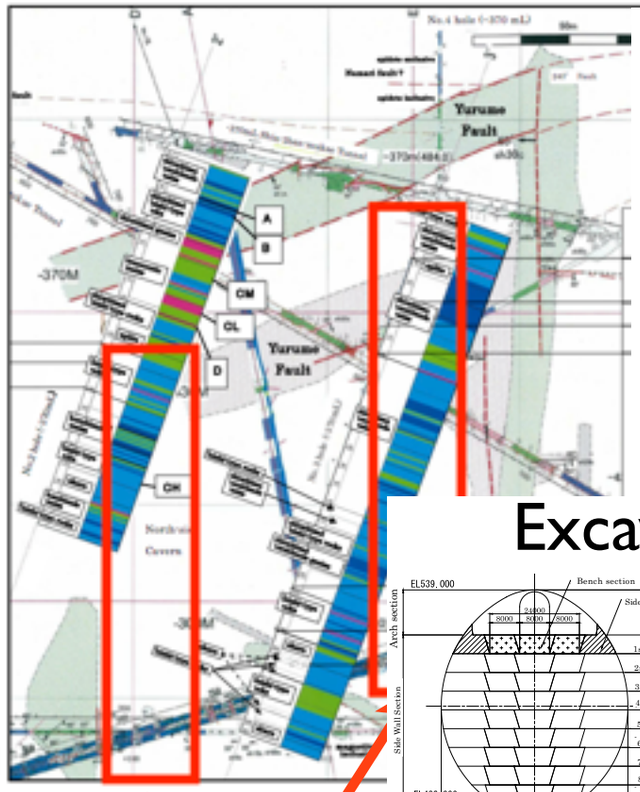


Site and Cavern

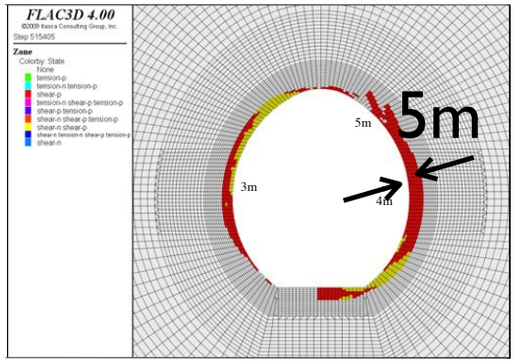
Candidate site: ~8km south of SK

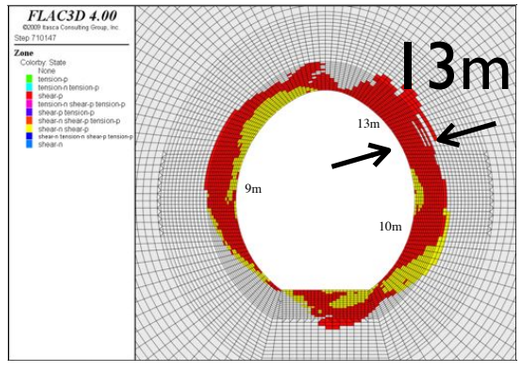


Rock mass characterization

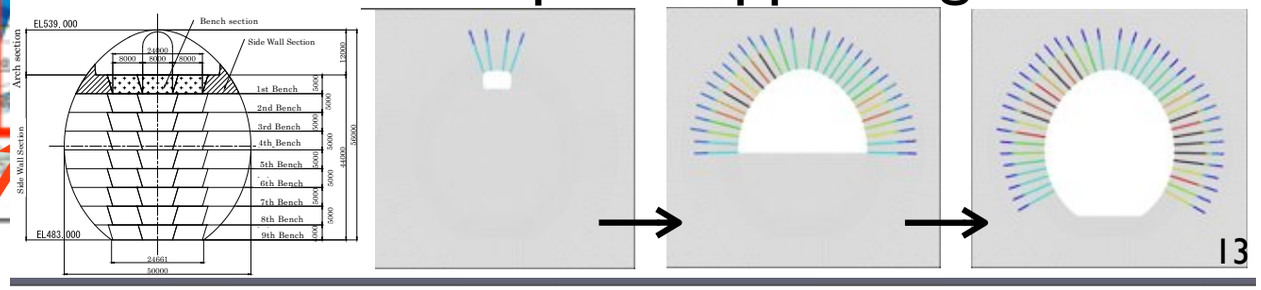


Cavern stability





Excavation steps & supporting method



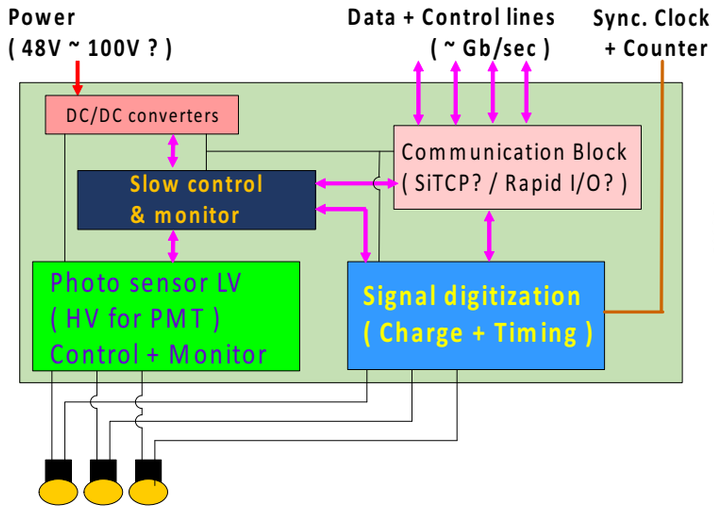
HK tank location

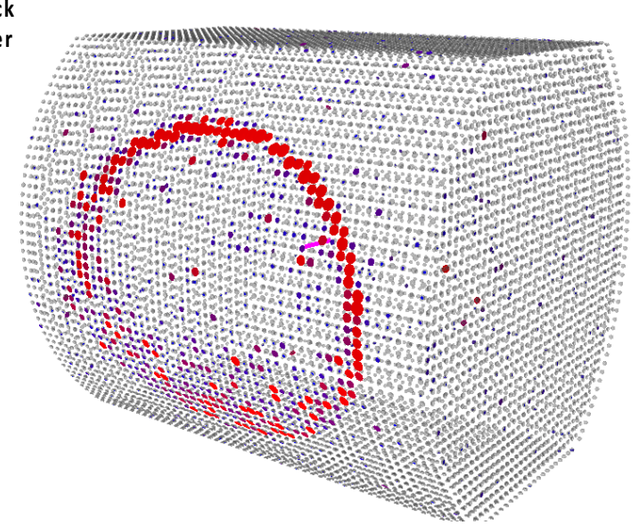
Cavity design studied based on the in-situ measurements of rock quality and stress

HK caverns can be constructed with existing technology.

Detailed detector design in progress

- R&D ongoing in many areas
  - Cavity and tank
  - Photosensor (→ previous talk)
  - Readout electronics
  - DAQ system
  - Software development
  - Calibration system
  - Water system

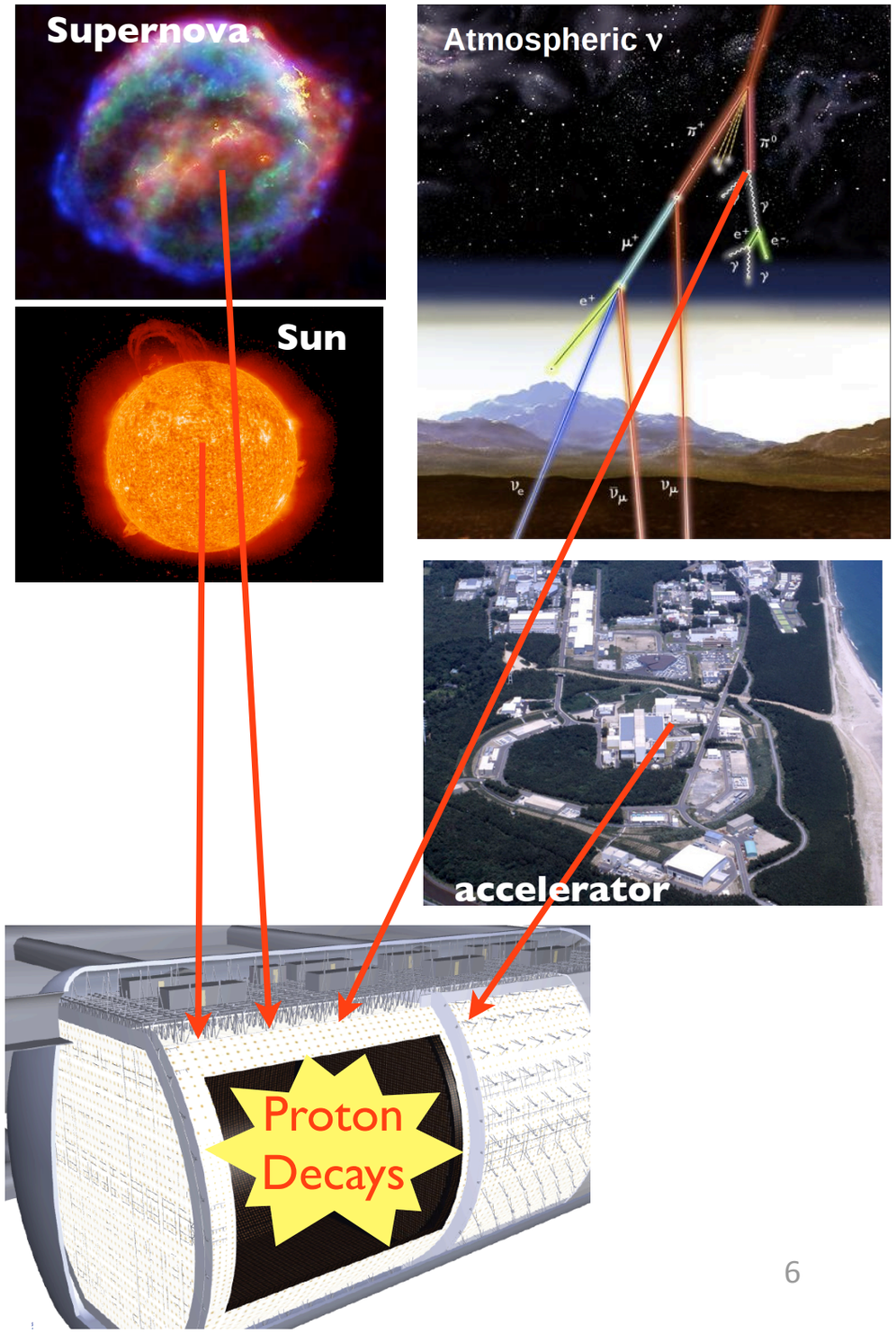




→ Verification with a prototype (~1kton) detector
(funded: JFY2013-2017)

Strong and broad science program

- ν oscillation
  - Accelerator ν beam
  - Atmospheric ν
  - Solar ν
- Nucleon decay
- Astrophysics
  - Supernova burst ν
  - SN relic ν
  - Monitoring of Sun
  - WIMP, GRB,
- Geophysics
- Maybe more (unexpected)



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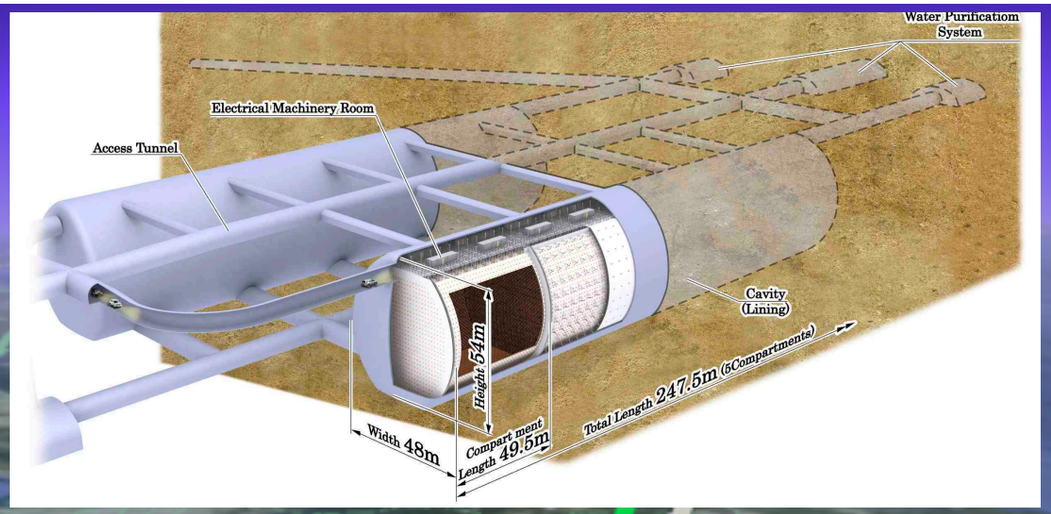
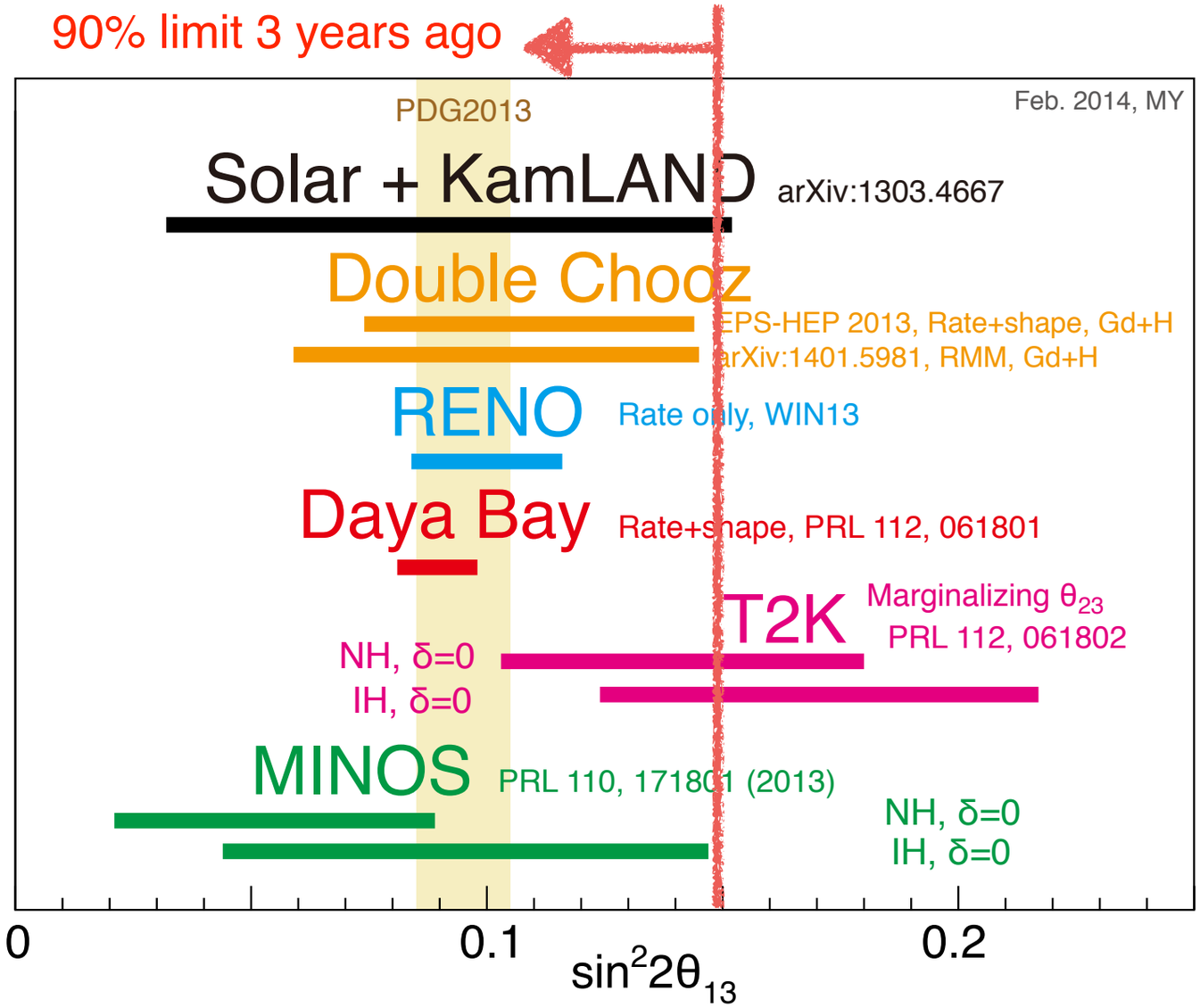
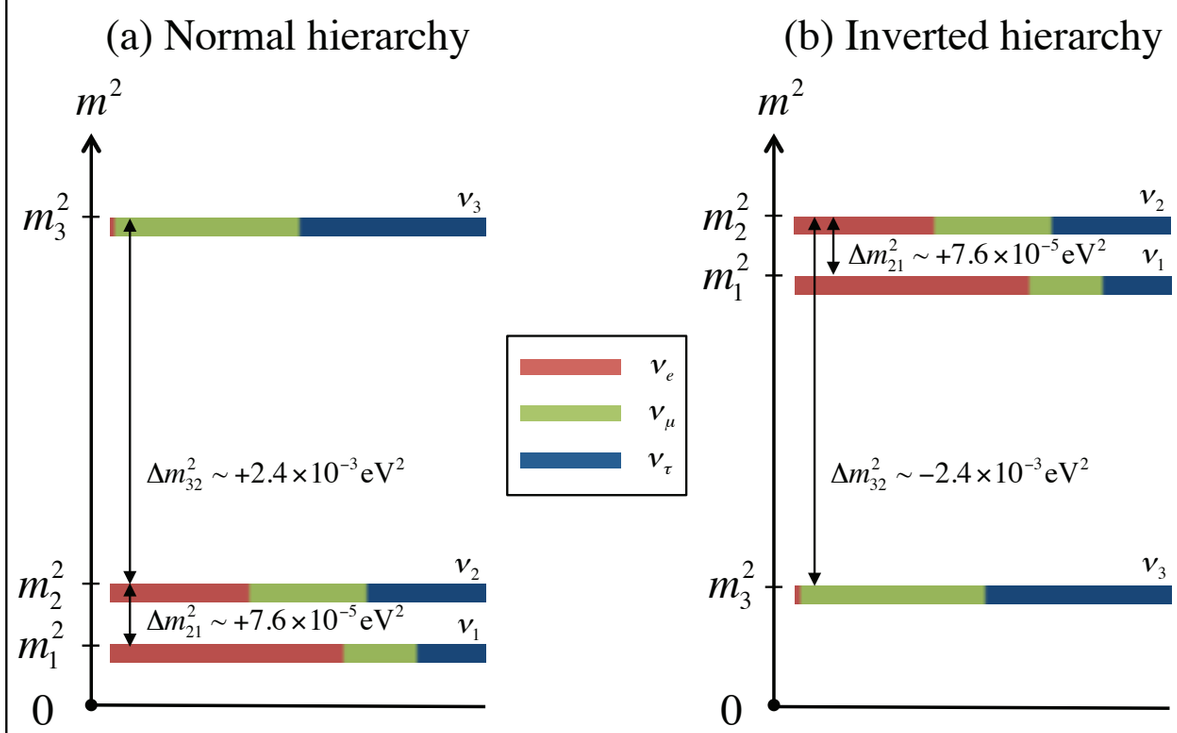
Accelerator neutrino beam



Recent rapid progress on θ_{13} opened a door to the next step!





All mixing angles measured to be non-zero

Remaining big unknowns (in ν mixing):

Mass hierarchy (sign of Δm^2_{32})

CP violation

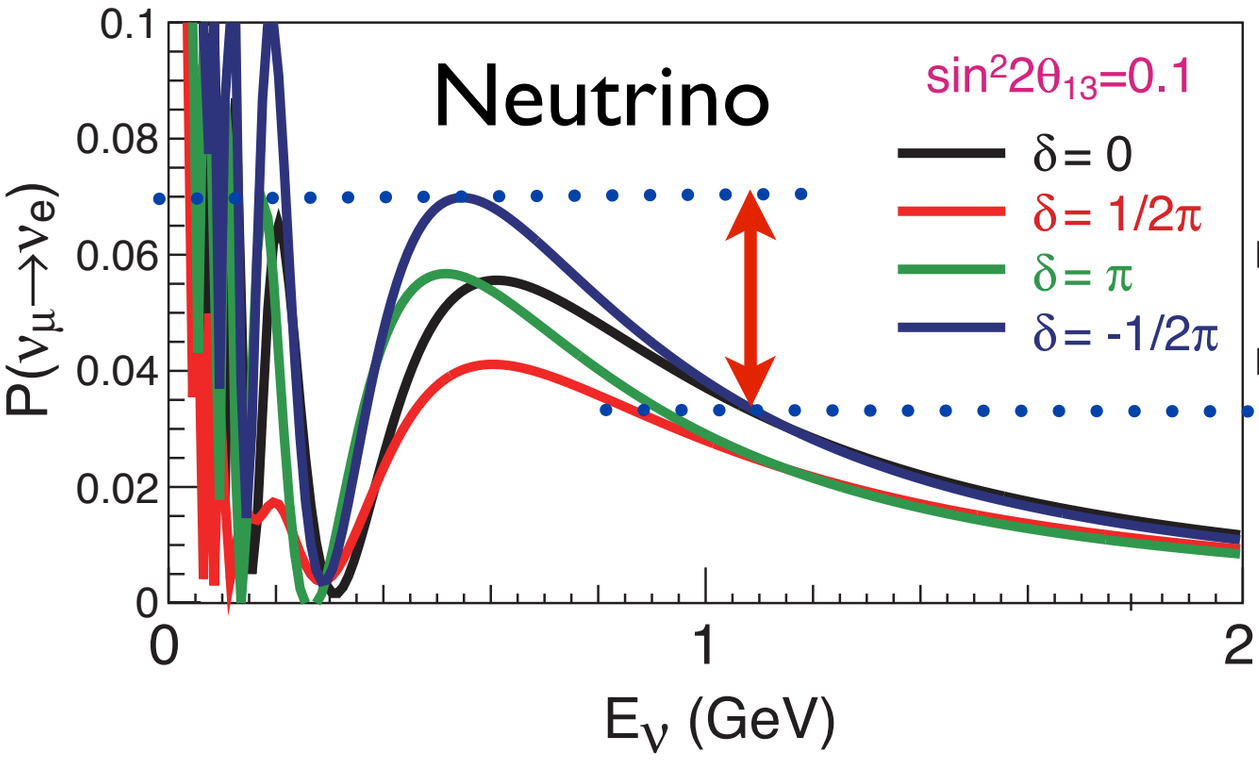
Long baseline experiment with J-PARC ν beam

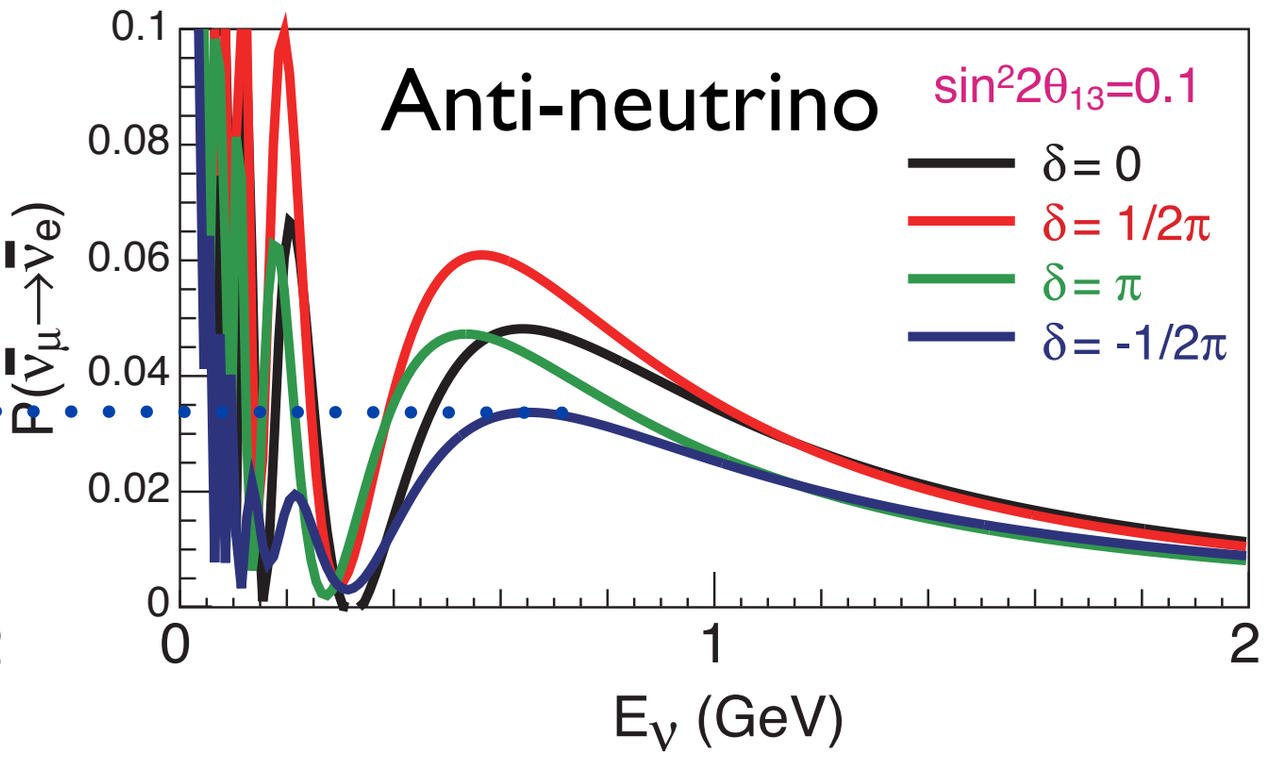
- Natural extension of technique being proved by T2K
  - Off-axis narrow band beam, E_ν~0.6GeV
  - HUGE water Cherenkov detector
  - 295km baseline (=less matter effect)
- Main focus on measurement of CP asymmetry
- Complementary to >1000km baseline experiments planned in other regions (LBNE in US, LBNO in EU)
  - Sensitivity (CP/MH), technology (WC/LAr)
- Also rich program with Near Detectors

Measurement of *CP* asymmetry

$P(\nu_\mu \rightarrow \nu_e)$: ν_e appearance probability (normal hierarchy)

for 295km baseline



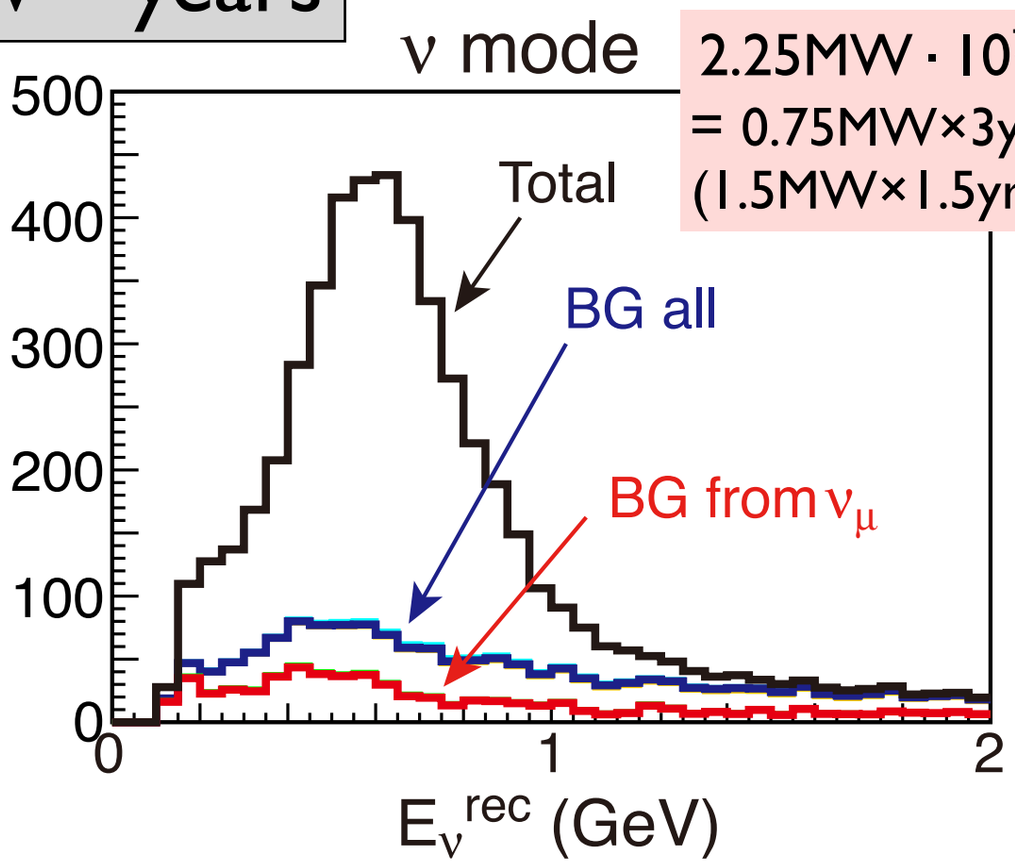


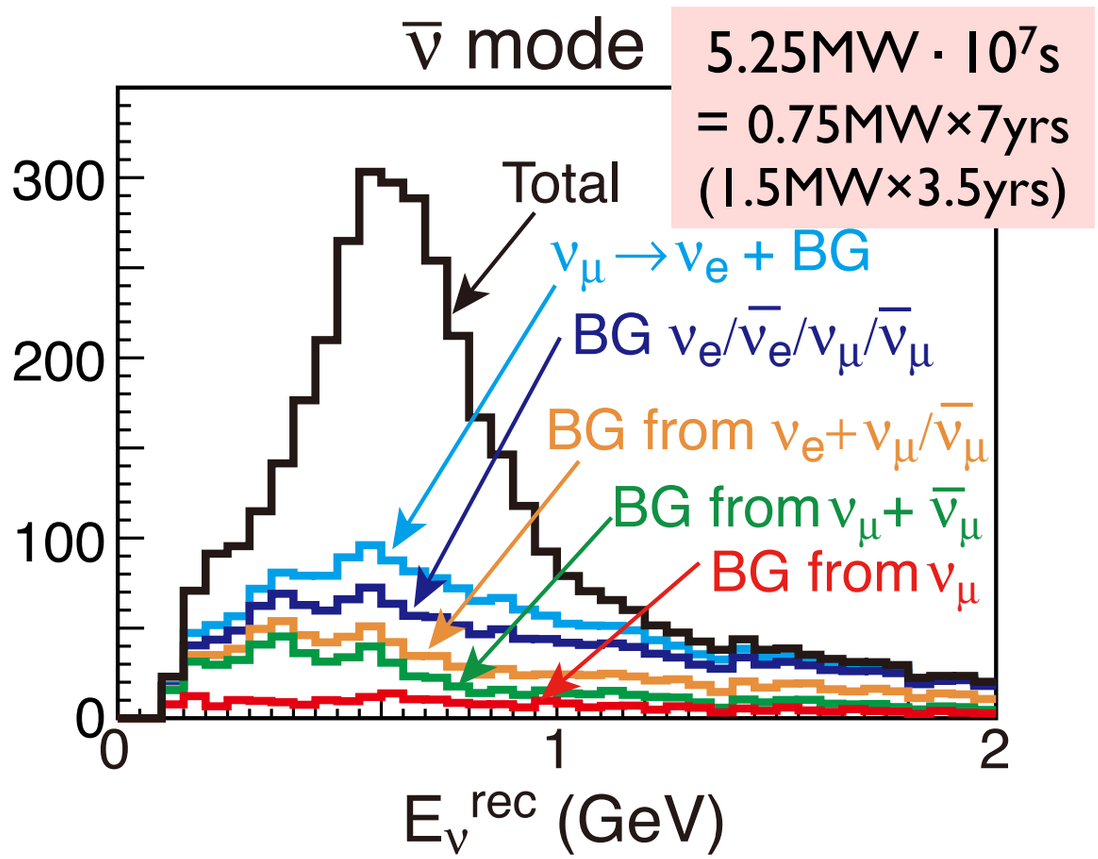
- Comparison of $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
  - Max. ~±25% change from δ=0 case
  - Sensitive to exotic (non-MNS) CPV source

ν_e candidate reconstructed energy distributions

7.5MW · years

$\sin^2 2\theta_{13}$=0.1,δ=0, normal MH





	Signal ($\nu_\mu \to \nu_e$ CC)	Wrong sign appearance	$\nu_\mu/\bar{\nu}_\mu$ CC	beam $\nu_e/\bar{\nu}_e$ contamination	NC
ν (2.25MW · 10^7s)	3,560	46	35	880	649
$\bar{\nu}$ (5.25MW · 10^7s)	1,959	380	23	878	678

※Further BG suppression expected with reconstruction improvement

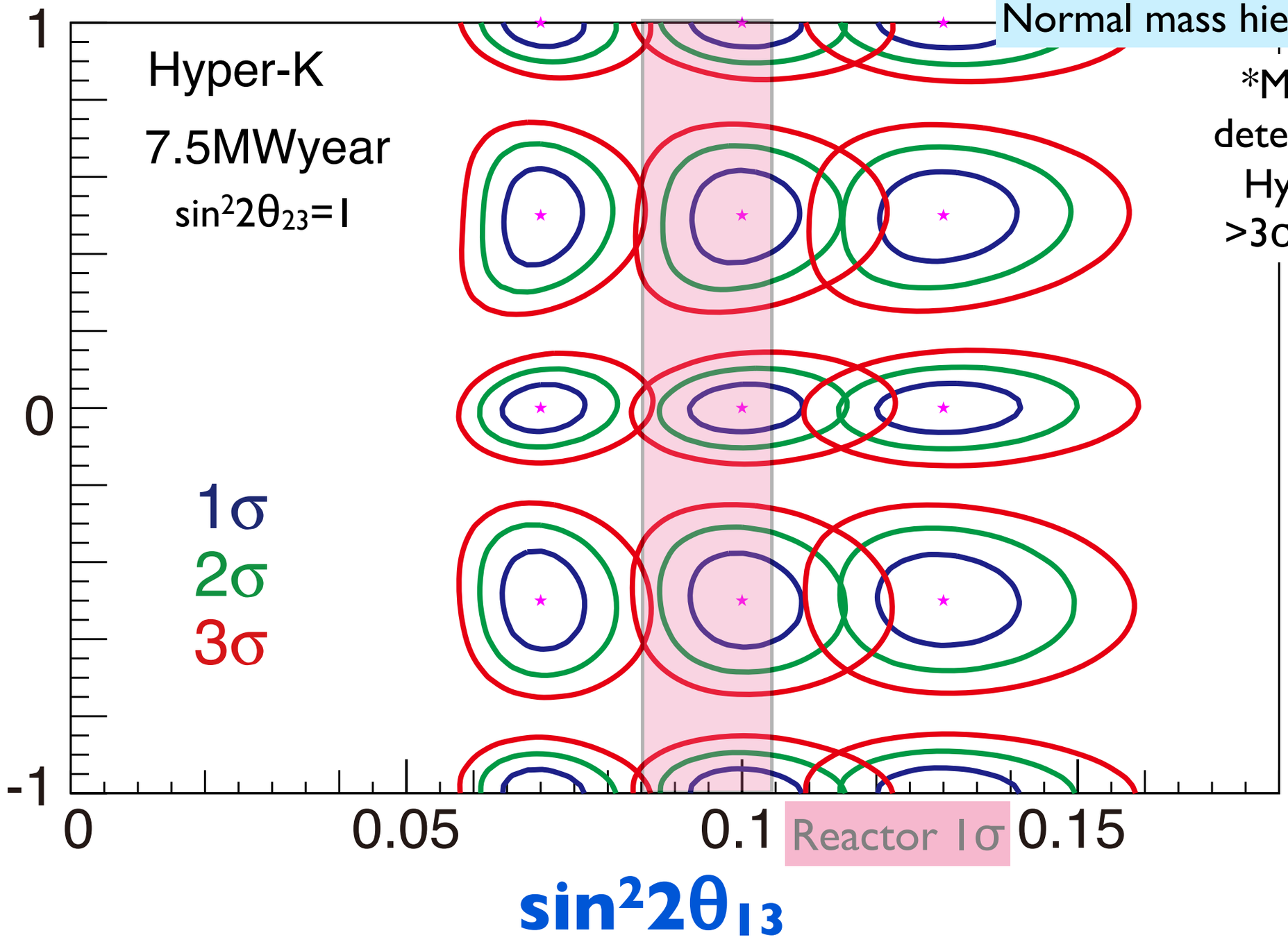
2000-4000 signal events for each of ν and $\bar{\nu}$

Expected sensitivity to CP asymmetry

7.5MW・years

5% systematics on signal, ν_μ BG, ν_e BG, $\nu/\overline{\nu}$

Normal mass hierarchy (known*)

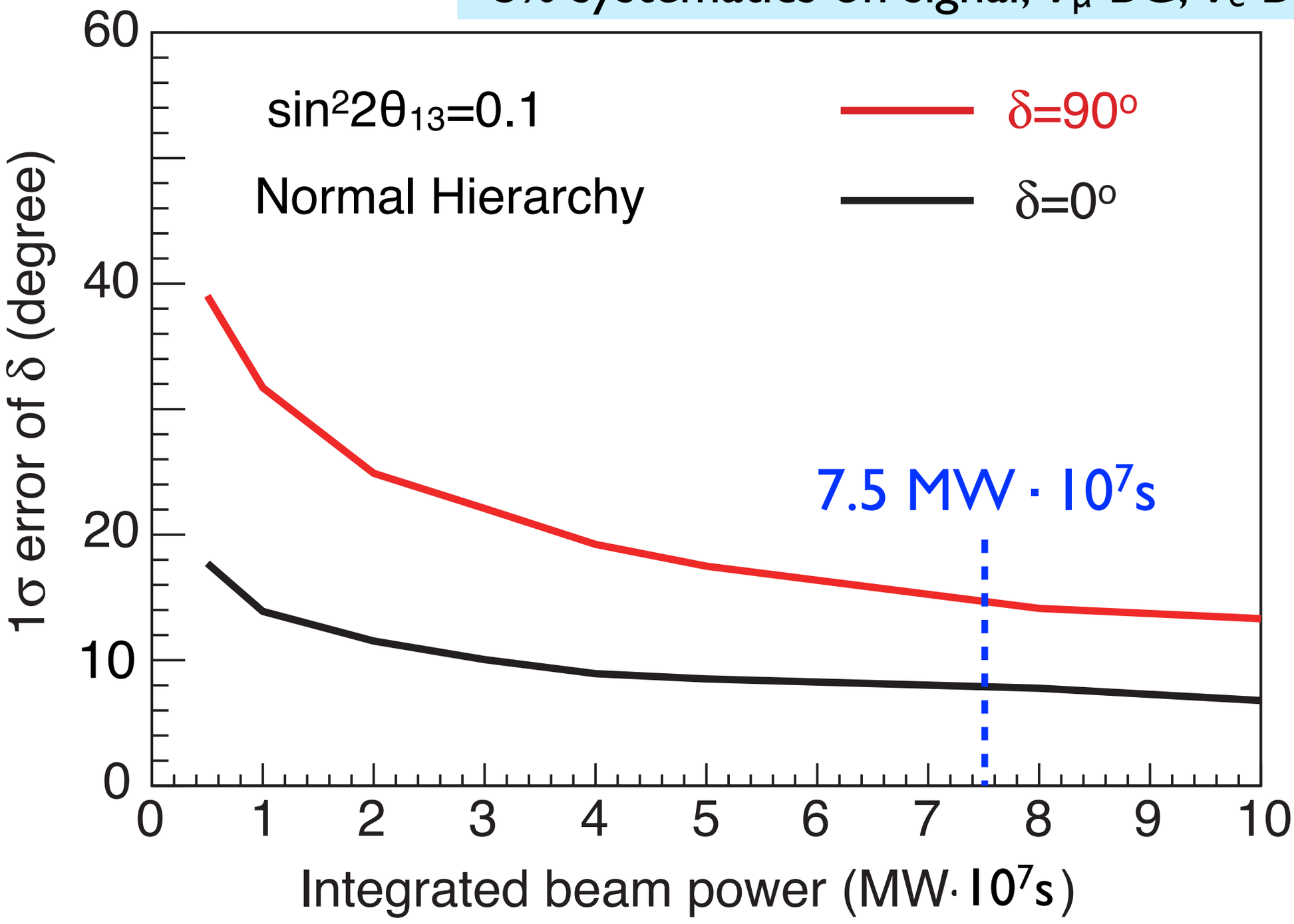


*Mass hierarchy determination with Hyper-K atm. ν: >3σ in 5-10 years

Good sensitivity for currently allowed values

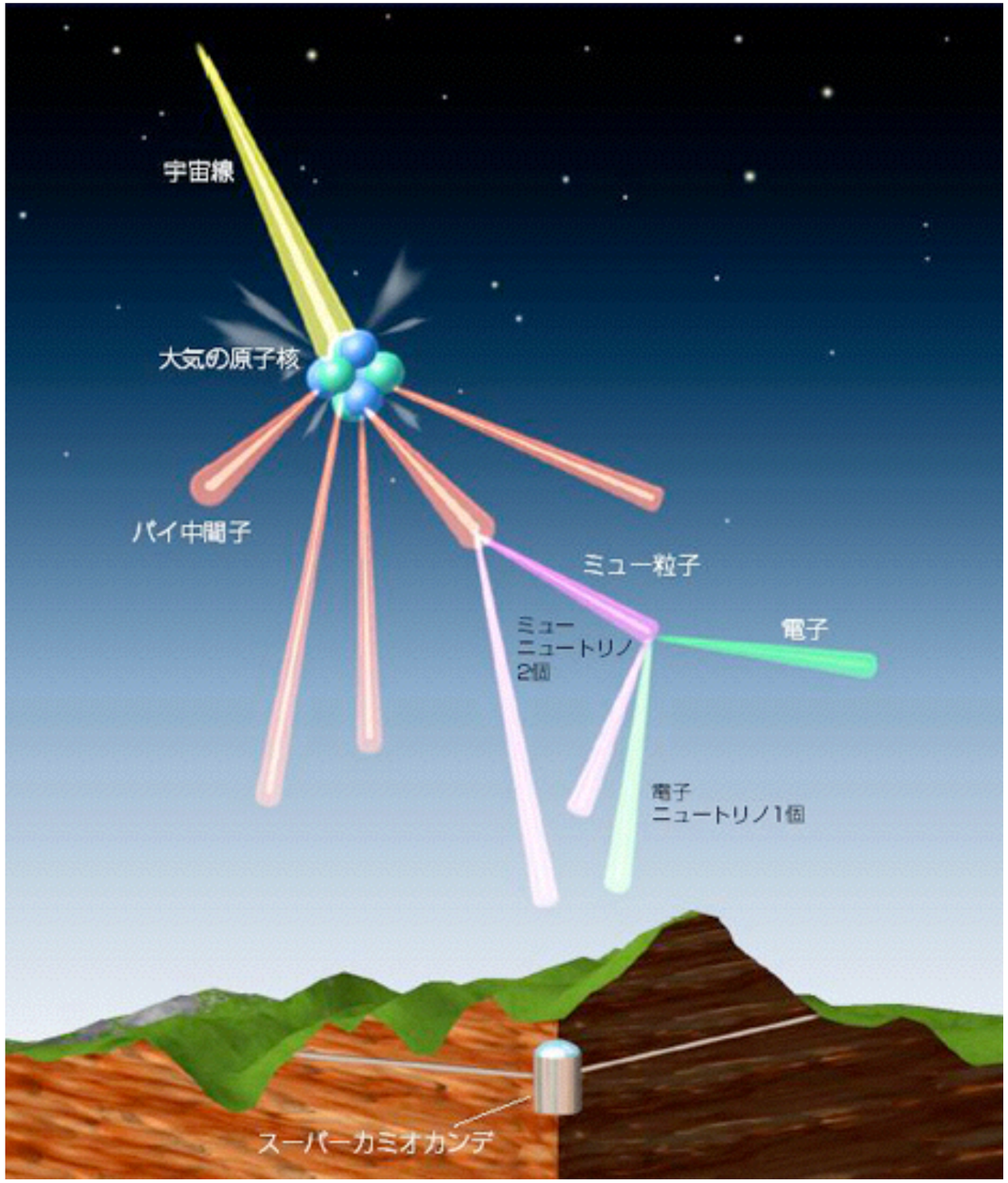
Expected uncertainty of δ (1σ)

5% systematics on signal, ν_μ BG, ν_e BG, $\nu/\overline{\nu}$



<20° (δ=90°), <10° (δ=0°)

Atmospheric neutrinos



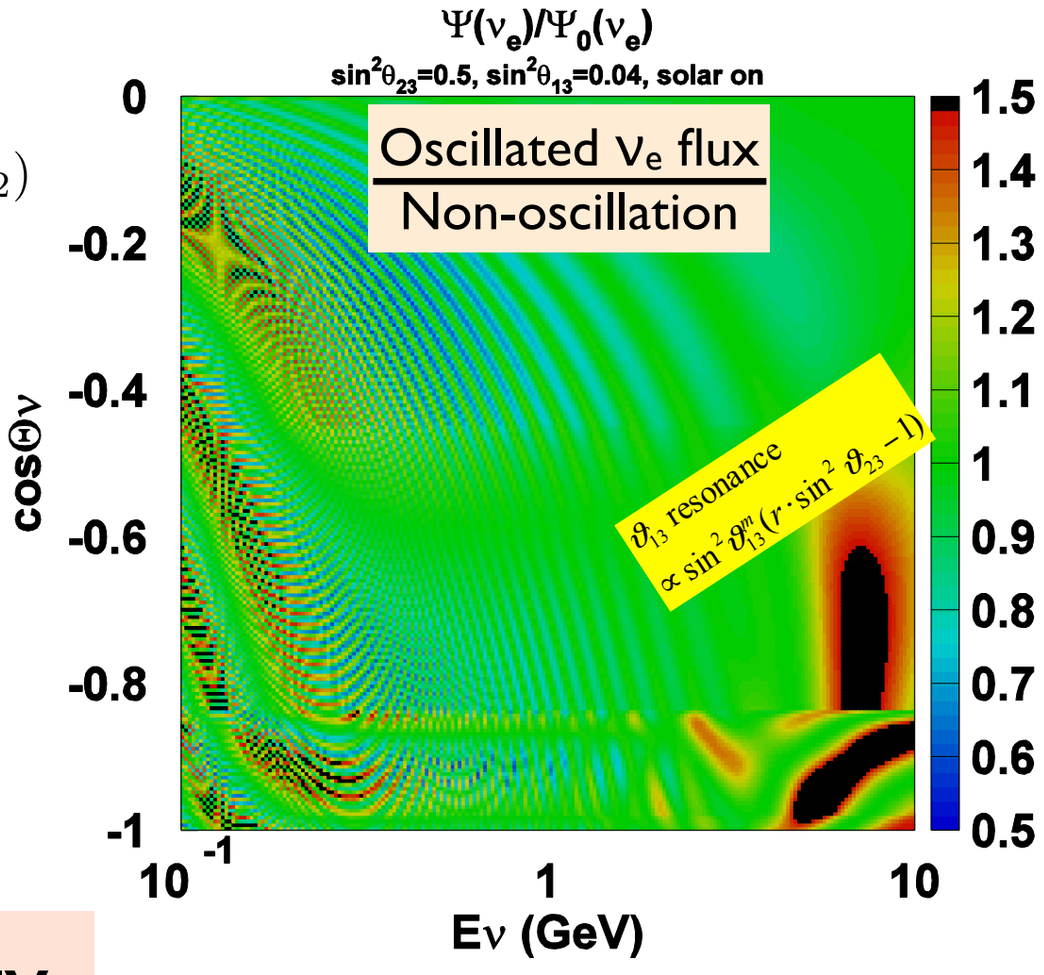
Wide range of E_ν, flavor, $\nu/\bar{\nu}$ available

Complementary to accelerator ν

Atmospheric neutrino

$\nu_\mu \rightarrow \nu_e$ appearance resonance in earth's core
either ν or $\bar{\nu}$ depending on mass hierarchy

$$\frac{\Phi(\nu_e)}{\Phi_0(\nu_e)} - 1 \approx P_2 \cdot (r \cdot \cos^2\theta_{23} - 1)$$
$$-r \cdot \sin\tilde{\theta}_{13} \cdot \cos^2\tilde{\theta}_{13} \cdot \sin 2\theta_{23} \cdot (\cos\delta \cdot R_2 - \sin\delta \cdot I_2)$$
$$+2\sin^2\tilde{\theta}_{13} \cdot (r \cdot \sin^2\theta_{23} - 1)$$

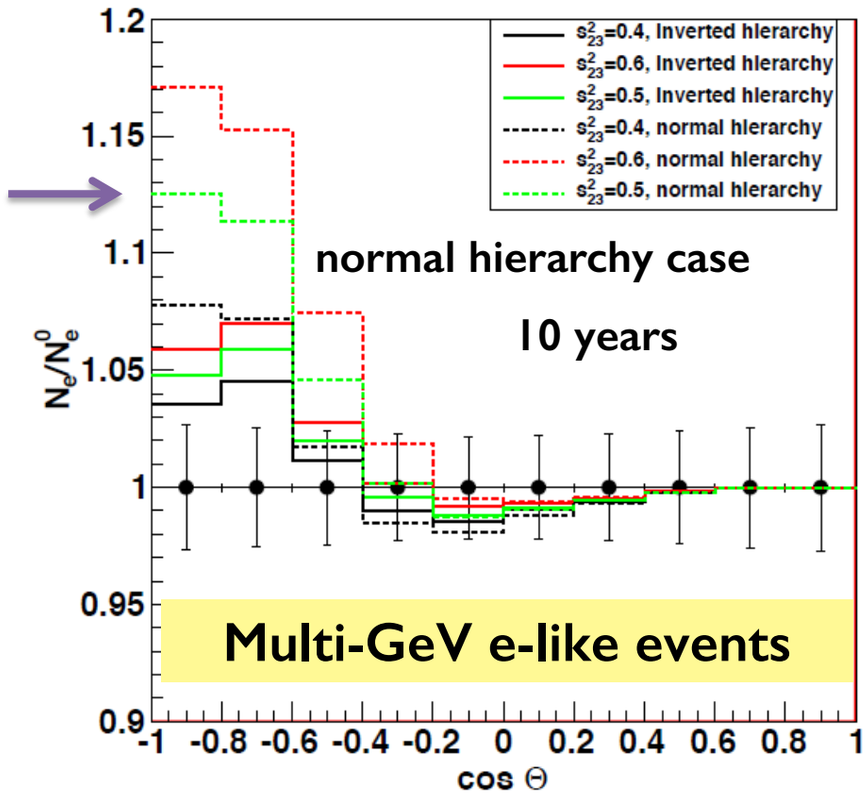


Sensitive to

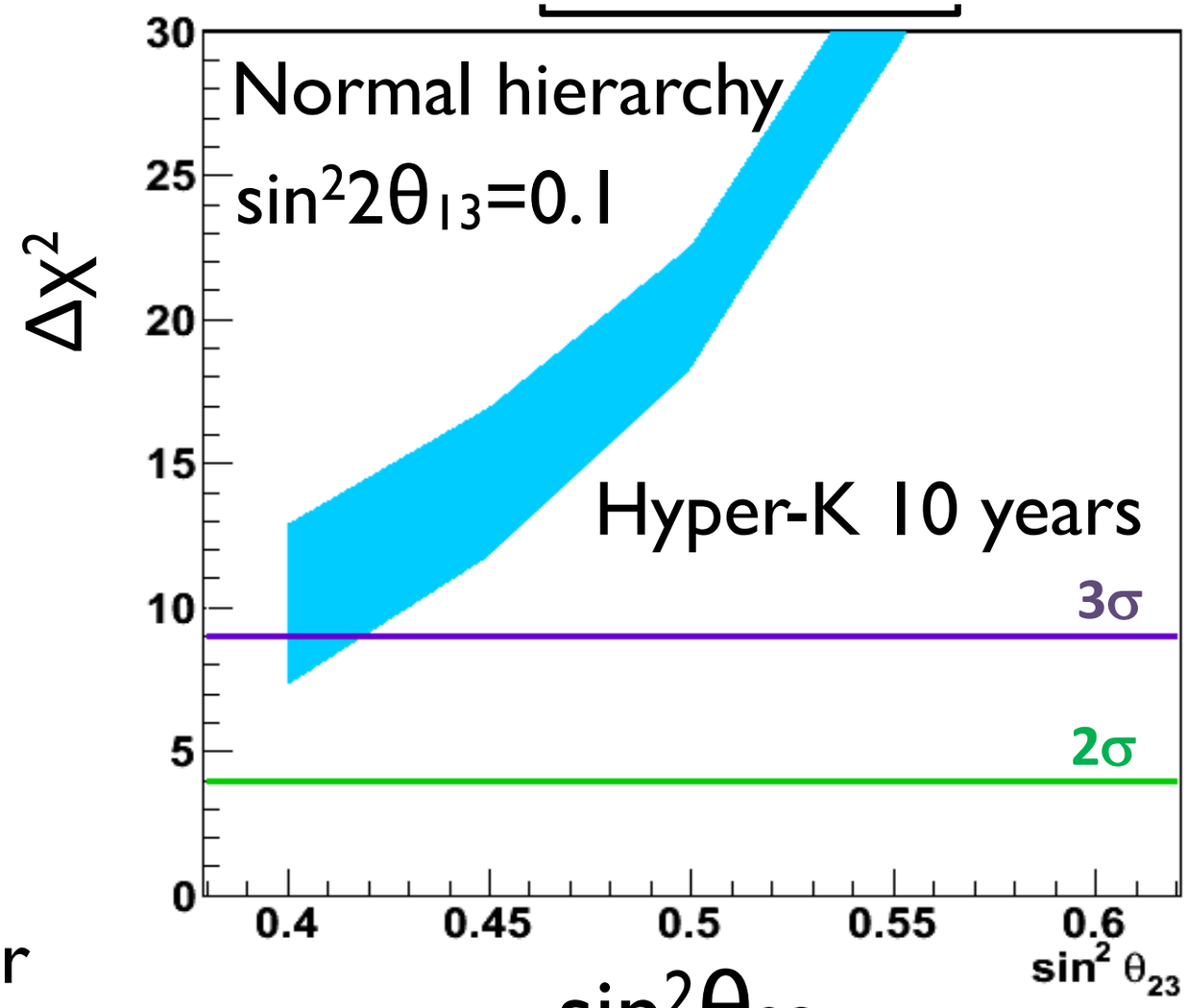
- Mass hierarchy
- θ_{23} octant
- CP asymmetry

larger θ_{13} gives better sensitivity

Mass hierarchy determination with atmospheric neutrinos



MSW effect in Earth's core
→ resonance effect on either
ν or anti-ν



$\sin^2\theta_{23}$

3σ determination with <10 year observation
(better sensitivity depending on the value of θ_{23})

atm ν: θ_{23} octant and CPV

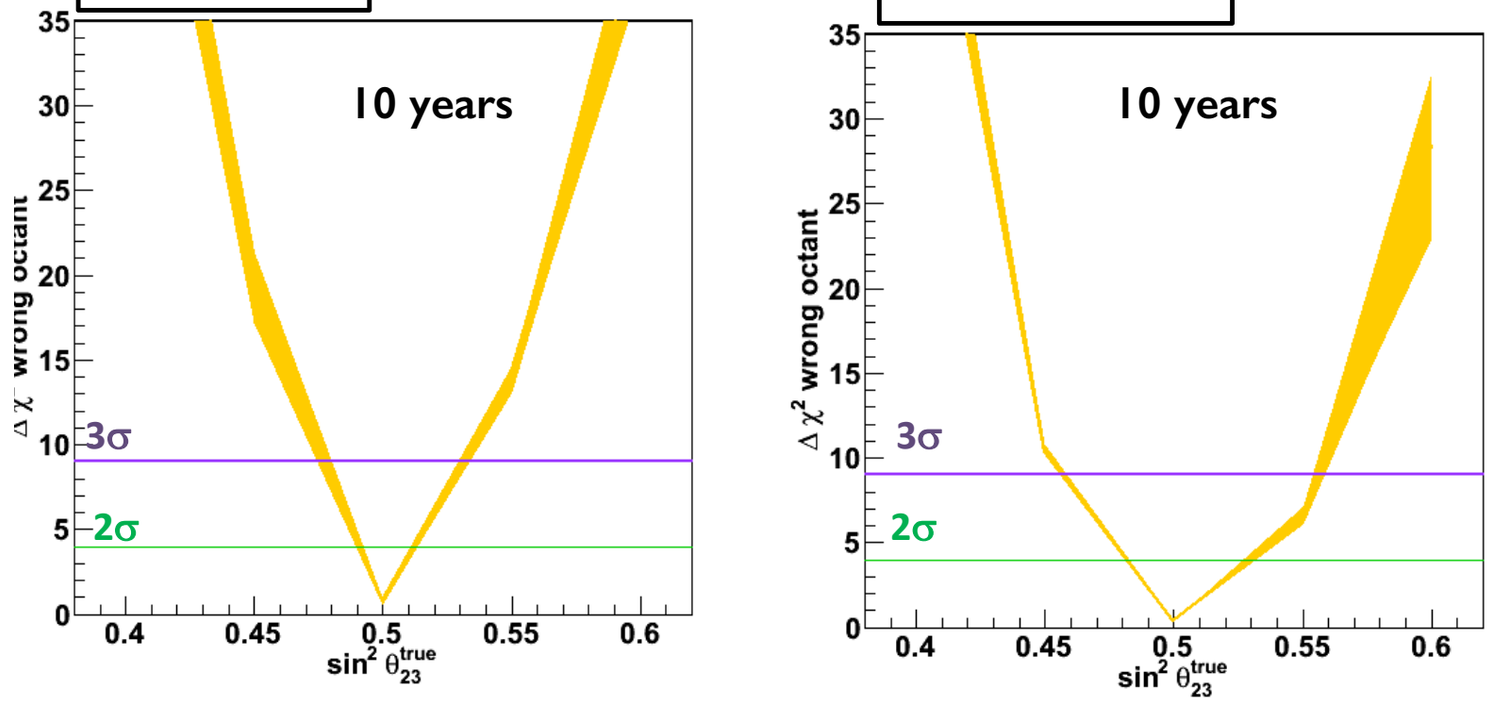
θ_{23} octant sensitivity

(band depends on δ)

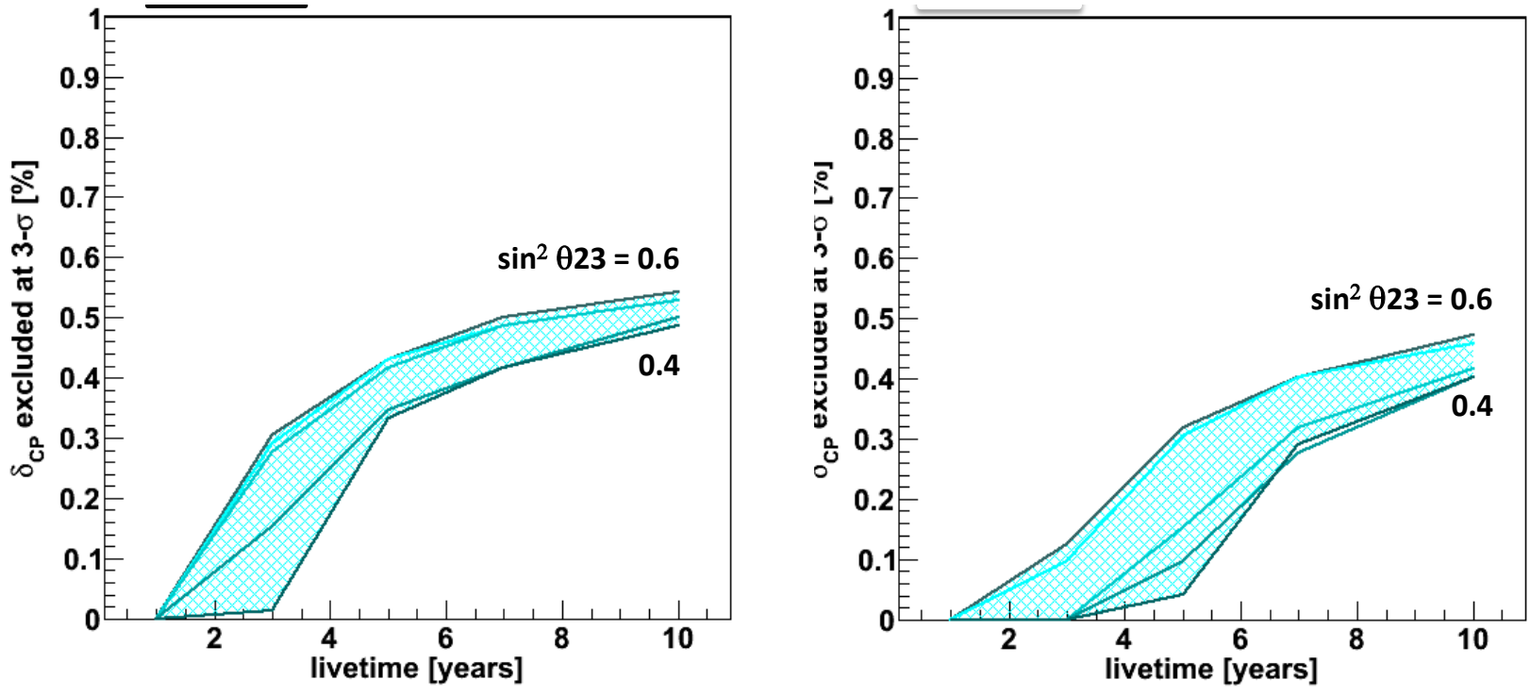
NH, unknown

θ_{13} is fixed : $\sin^2 2\theta_{13} = 0.10$

IH, Unknown

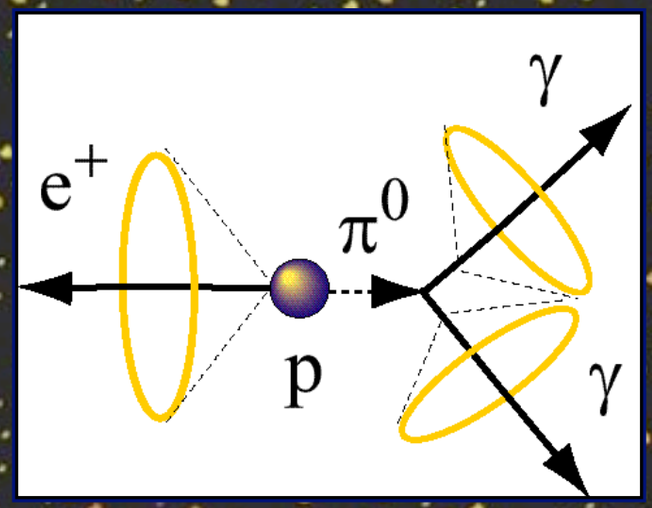


Fraction of δ_{CP} excluded (3 σ)

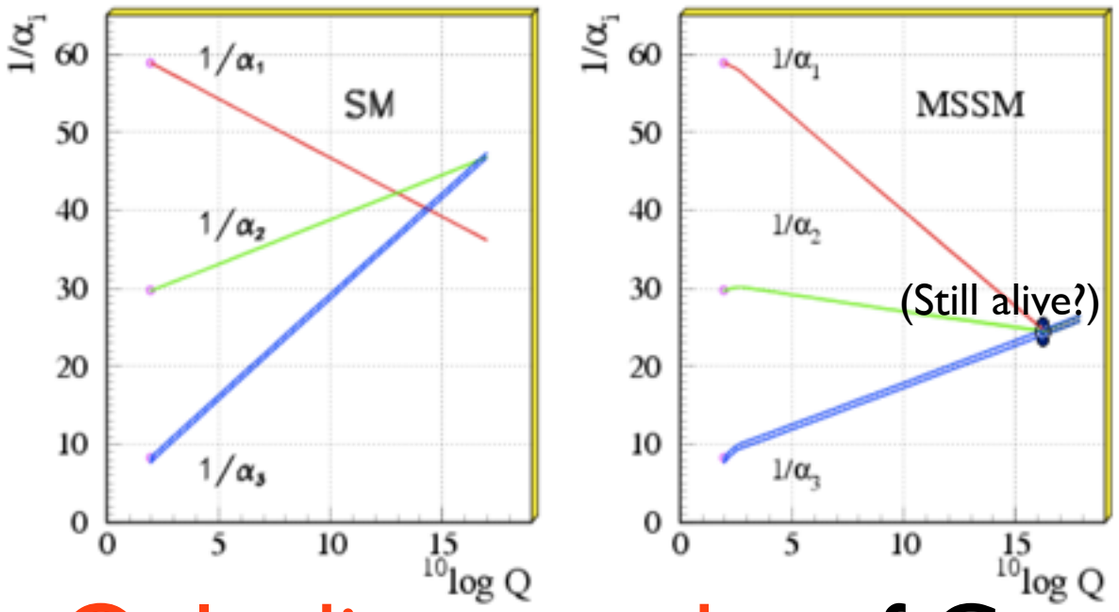


Complementary measurements to accelerator ν

Nucleon Decays



Nucleon decays

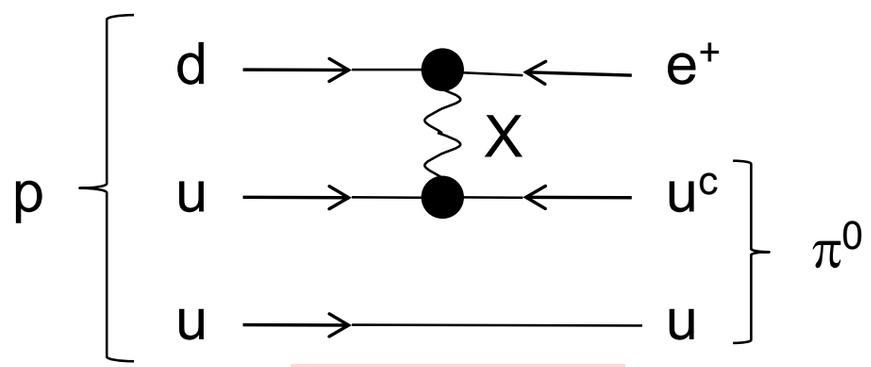


Many GUT models predict decays of protons and bound neutrons with $\tau = O(10^{34\text{-}35})$ years

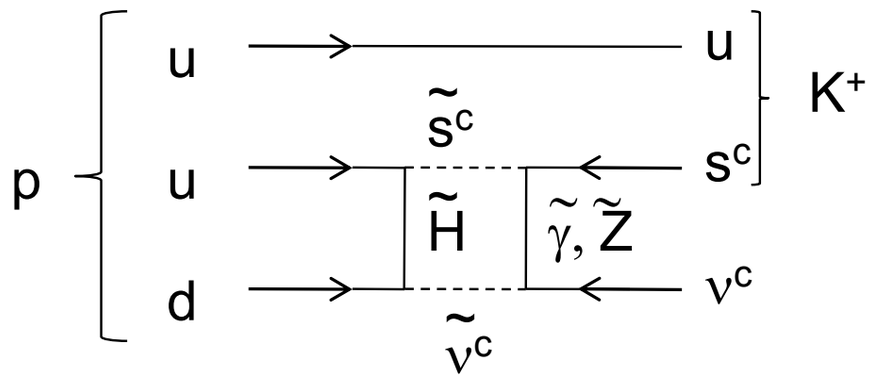
- Only direct probe of Grand Unified Theory

PDG2012

- Two famous modes:



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

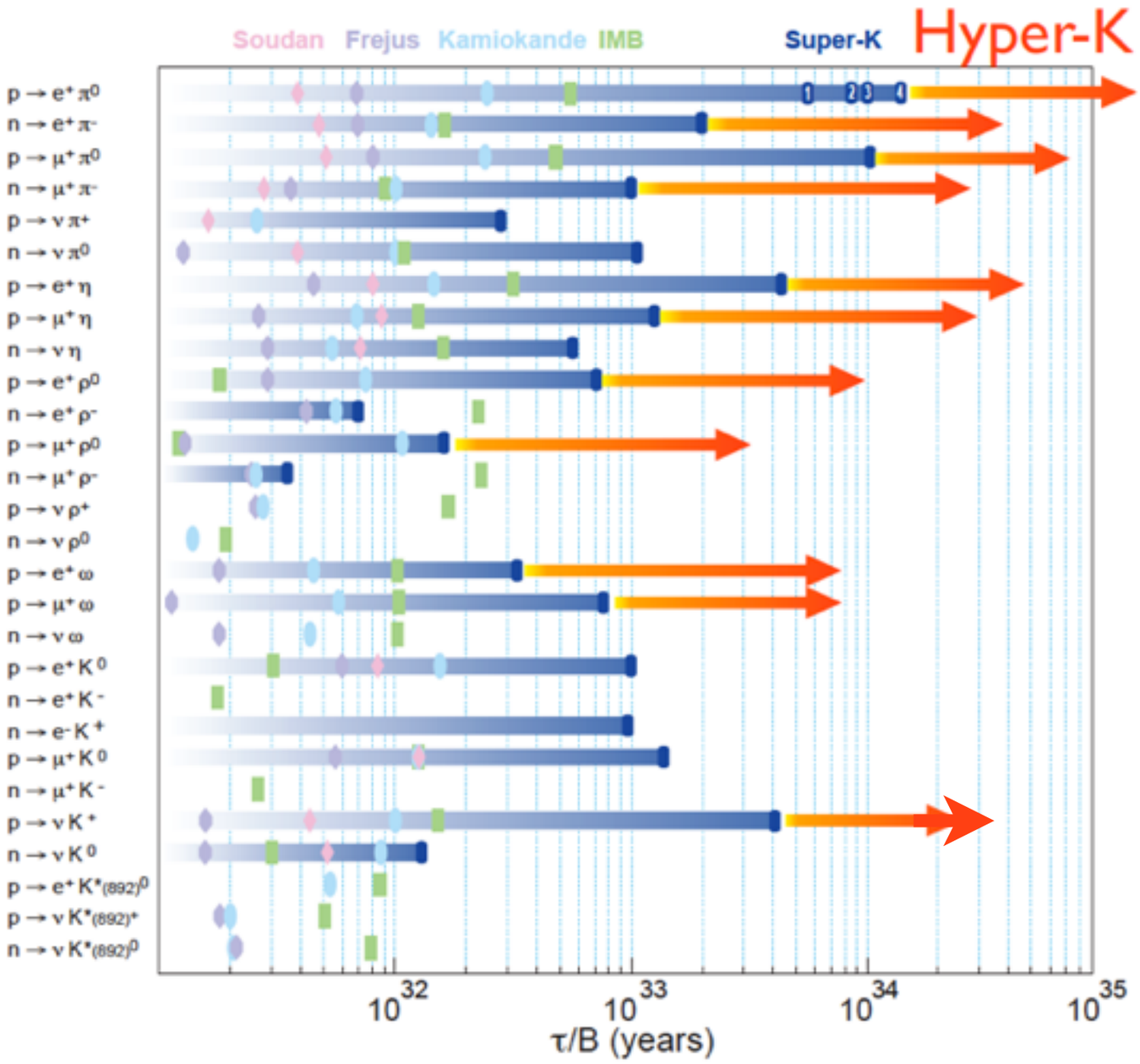


$p \rightarrow \bar{\nu} K^+$

Other modes are also important (we don't know correct model!)

Proton decay sensitivity

~10 times better sensitivity than current Super-K limits!

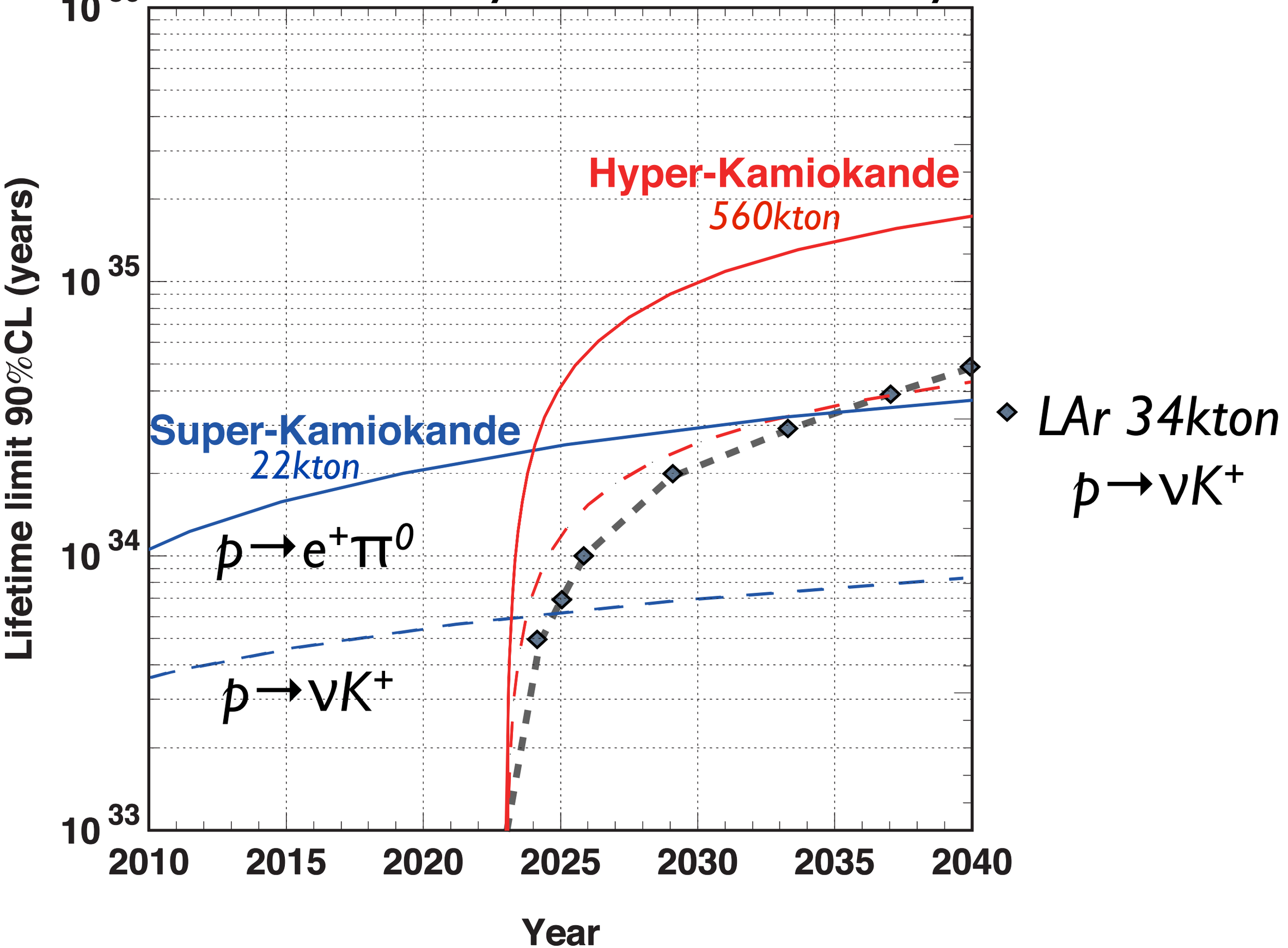


- $p \to e^+\pi^0$:
  - 1.3×10^{35}yrs (90%CL)
  - 5.7×10^{34}yrs (3σ)
- $p \to \bar{\nu}K^+$:
  - 3.2×10^{34}yrs (90%CL)
  - 1.2×10^{34}yrs (3σ)

>3σ possible for lifetime above current SK limits

- Superb sensitivity for $p \to e^+\pi^0$ due to huge mass
- Complementary to LAr in other modes, e.g. $p \to \bar{\nu}K$

Nucleon Decay 90% CL sensitivity

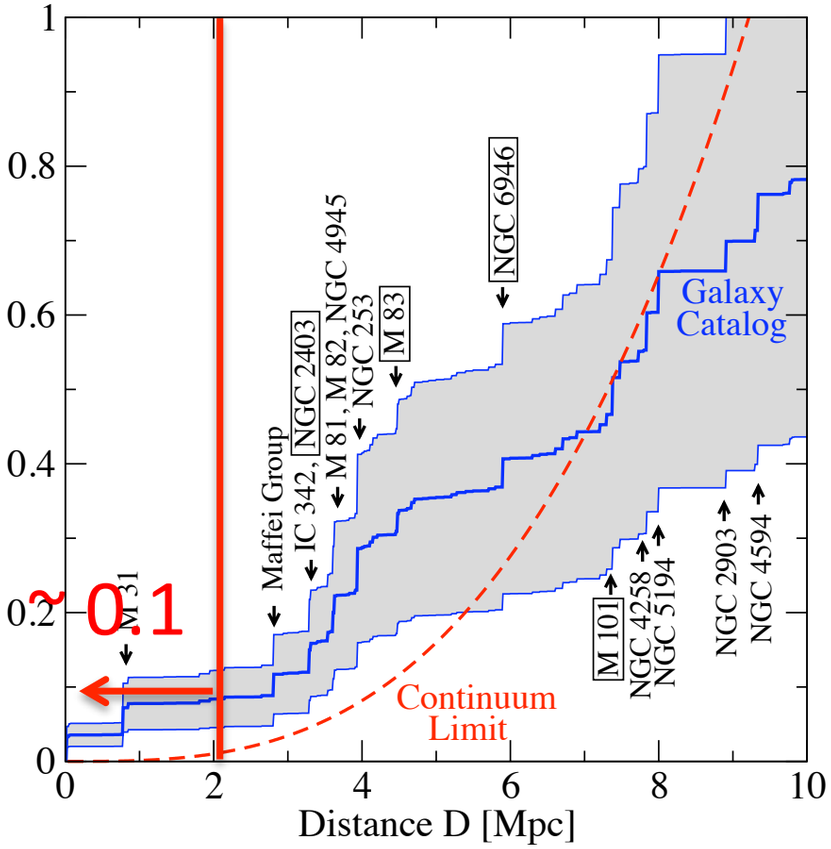


Neutrino astrophysics

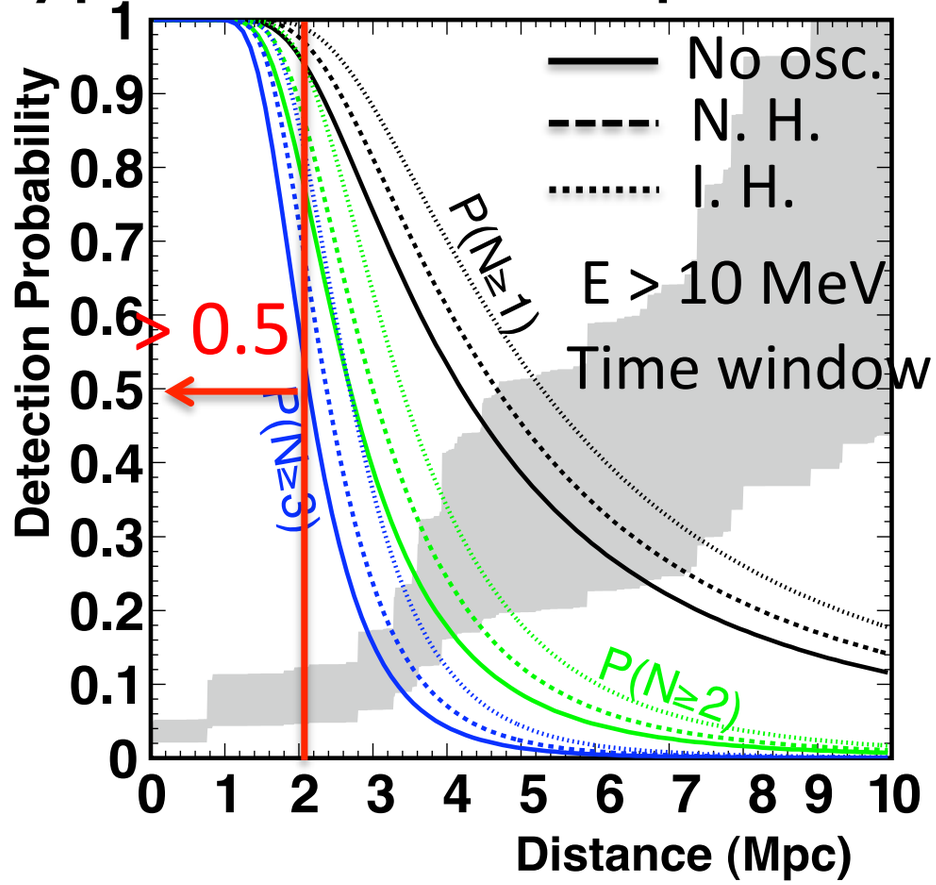
- **Supernova burst neutrino**
  - Huge statistics if SN in our Galaxy
    - ~200k events @ 10kpc
- **Supernova relic neutrino**
  - History of heavy element synthesis in the universe
- Precision measurements of solar neutrino
  - 200ν's / day
- Indirect WIMP Search
  - $\sigma_{SD} < 10^{39\text{-}40}$ cm^2
- Neutrino tomography inside the Earth

Supernova neutrinos

Cumulative supernova rate



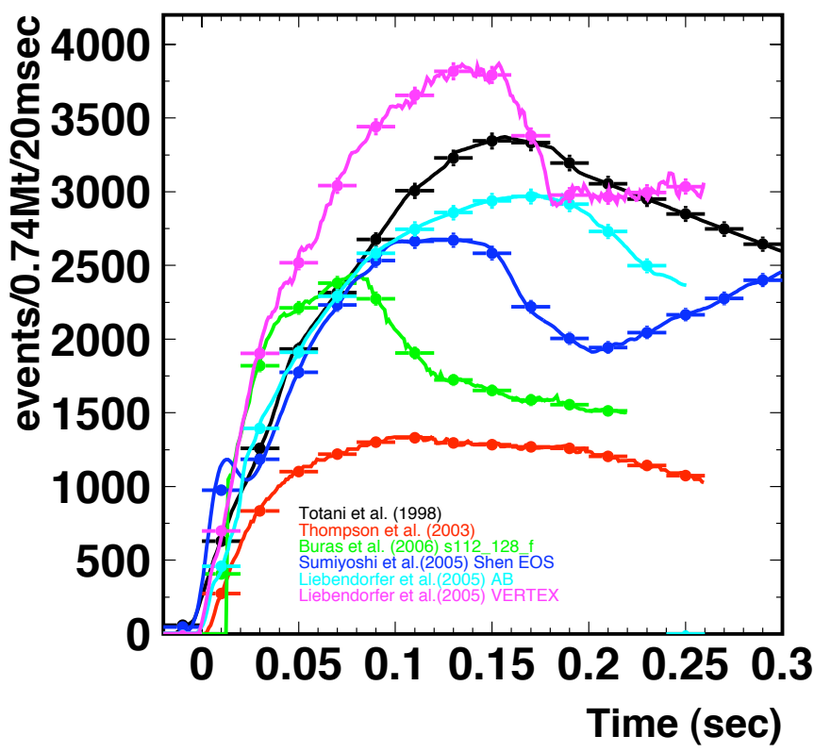
Hyper-K detection probability

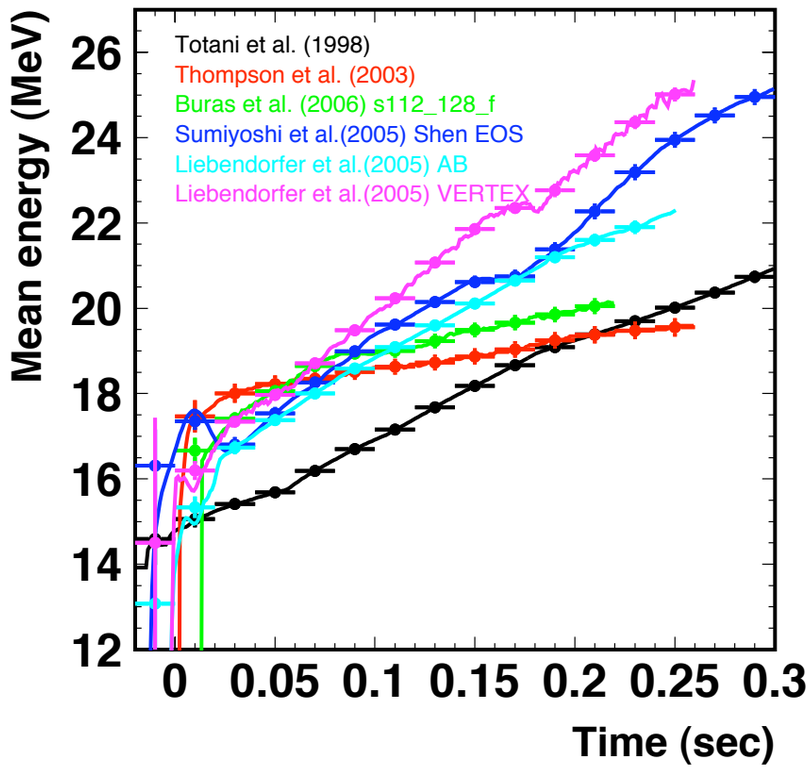


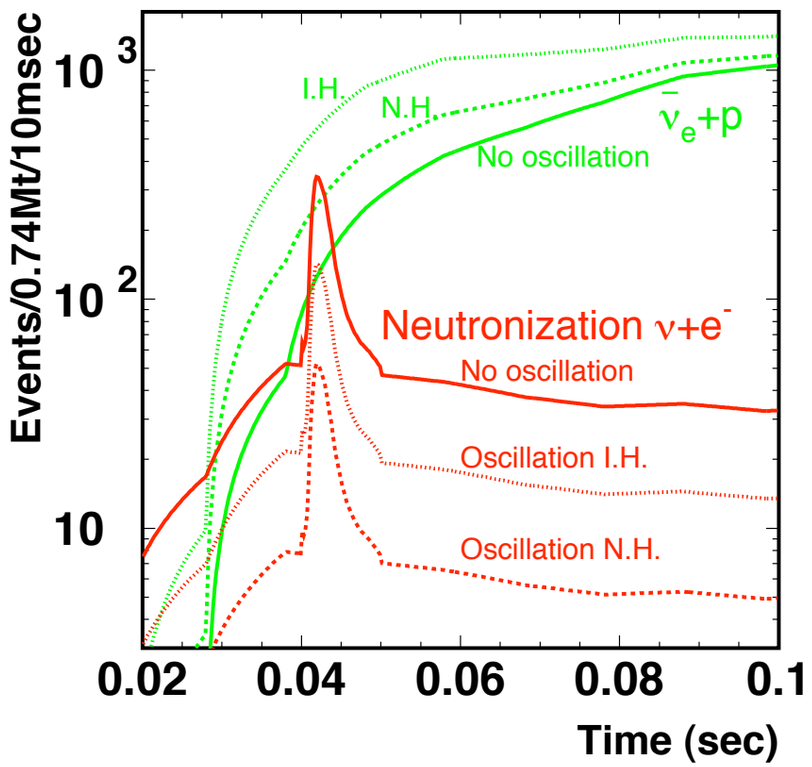
- 1SN about every 10 years is expected within 2 Mpc
- >50% efficiency is estimated for required signal multiplicity of 3 for SN at 2 Mpc distance.
- Further study will be performed on E threshold and expected BG.

SN ν burst @ 10kpc

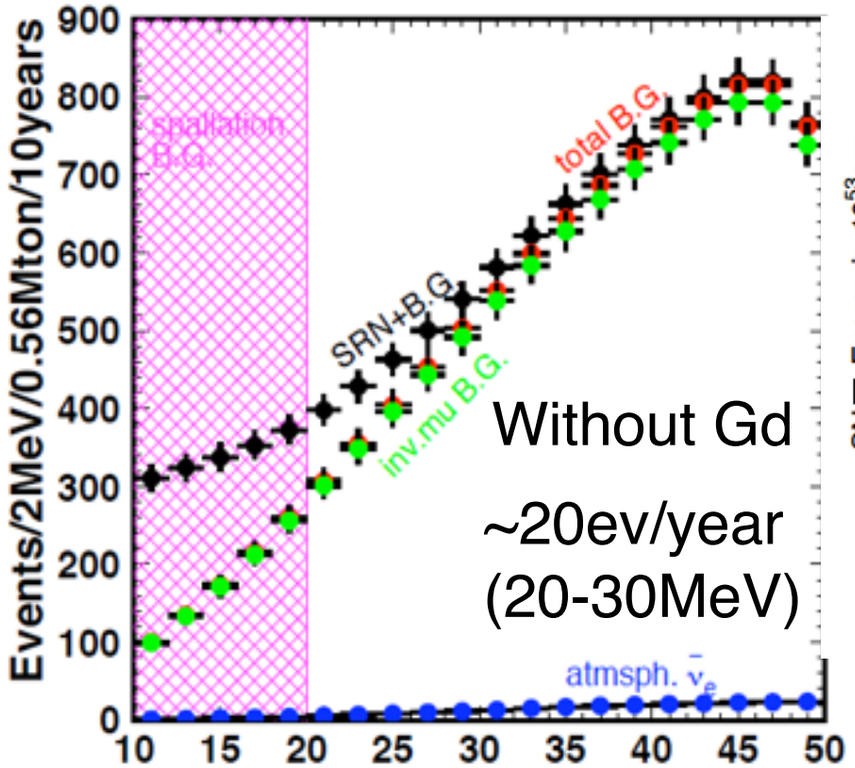
- ~200k ν events expected
  - Detailed measurement as a function of time possible
  - Exciting possibility of joint analysis with other methods (contribution to multi-messenger astronomy!)

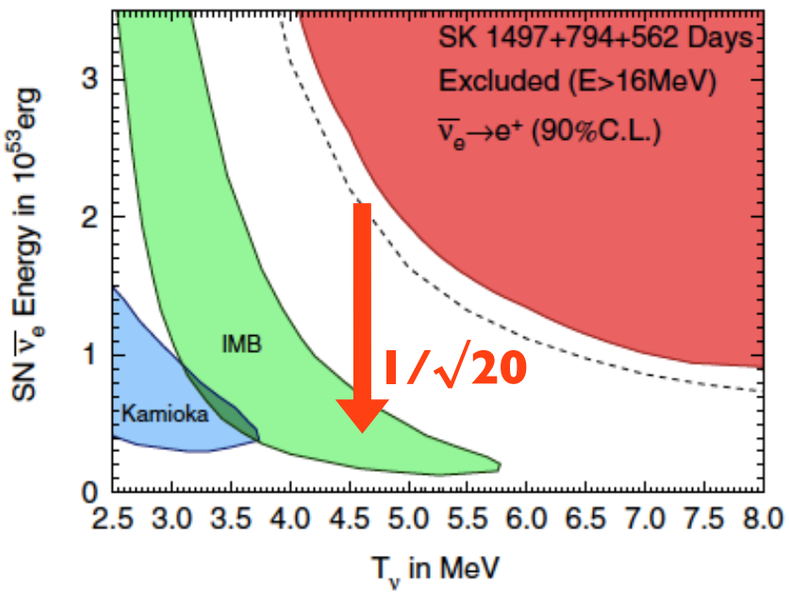


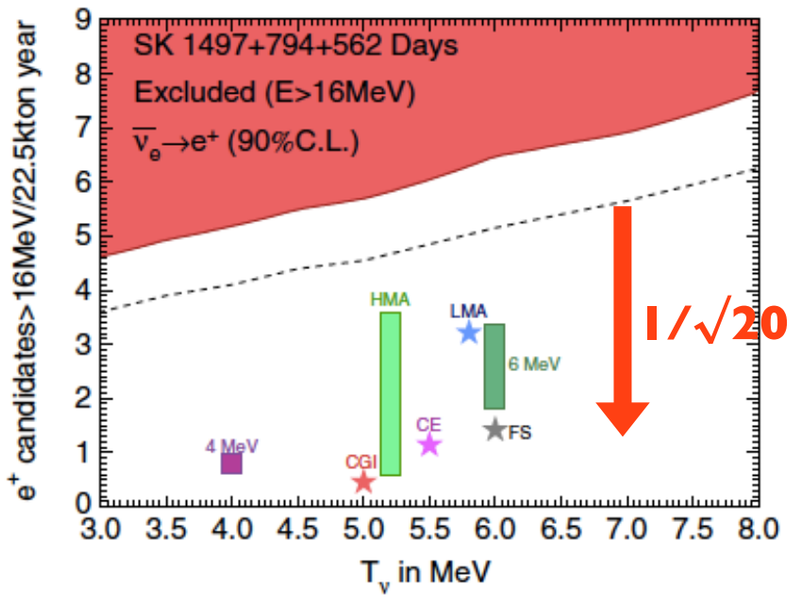


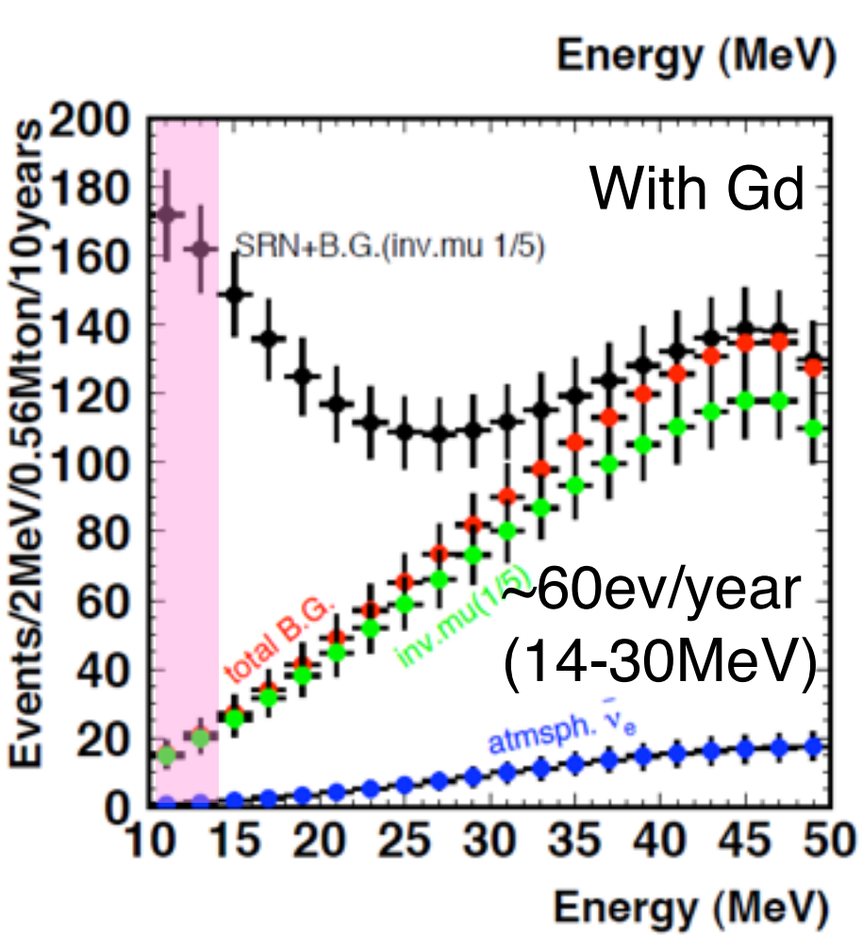


SN relic neutrino









- Significant events expected by much larger statistics than SK
- Gd will boost the sensitivity.

Summary

- Hyper-Kamiokande will provide excellent opportunity for wide range of physics topics
  - Neutrino mixing and CP violation
  - Nucleon decays
  - Neutrino astrophysics
- International working group is working towards its realization.
  - You are welcome to join!