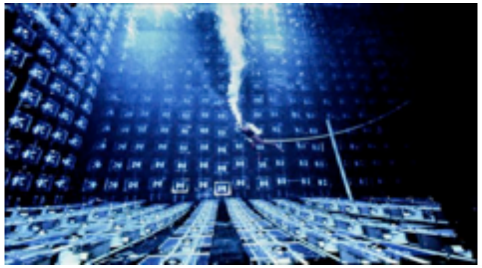
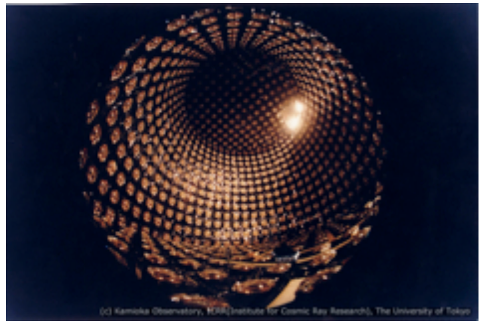
Hyper-Kamiokande: Detector Design and Physics Potential

Masashi Yokoyama
(Department of Physics, Univ. of Tokyo)
for Hyper-Kamiokande Working Group

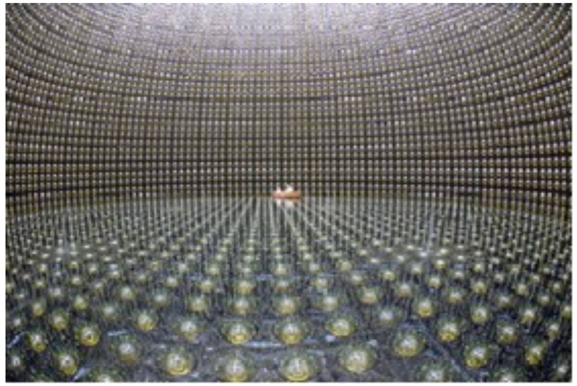
At "Snowmass on the Mississippi," Aug 1, 2013

Large Water Cherenkov Detectors





- Excellent performance
  - From ~MeV to ~TeV
- Scalability to ~Mton (and beyond)



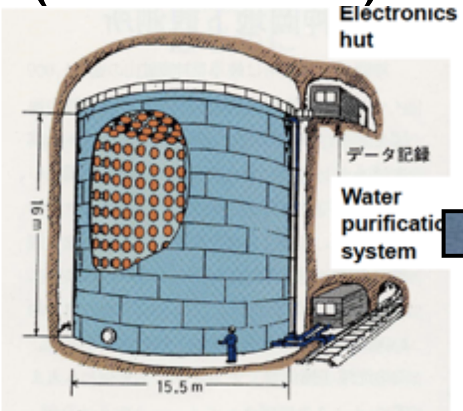
- Established technology
  - 50 kton Super-K running for >15years
- Still evolving!!
  - Improved reconstruction (used for latest T2K νe result)
  - Sensitivity improvement in $p \rightarrow \nu K$
  - Gd R&D in progress

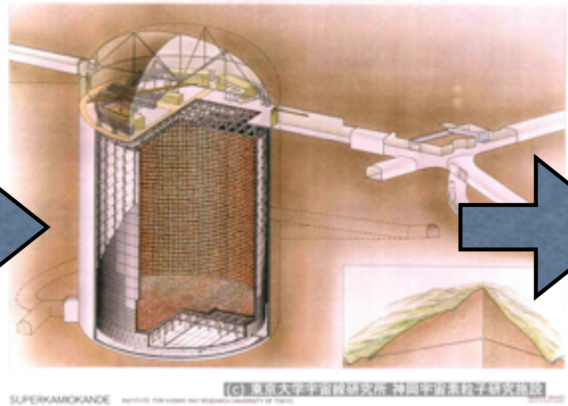
Three generations of Water Cherenkov Detectors at Kamioka

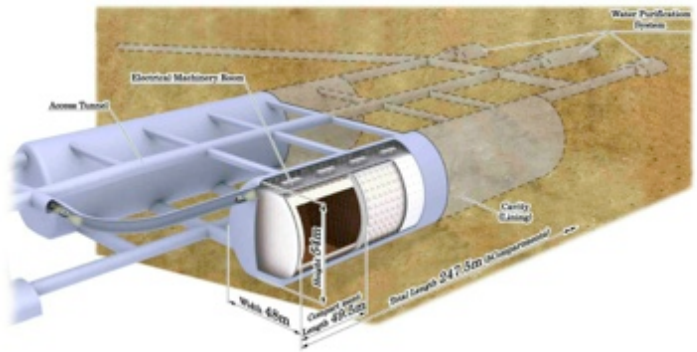
Kamiokande
(1983-1996)

Super-Kamiokande
(1996-)

Hyper-Kamiokande
(20??-)







3kton

50kton

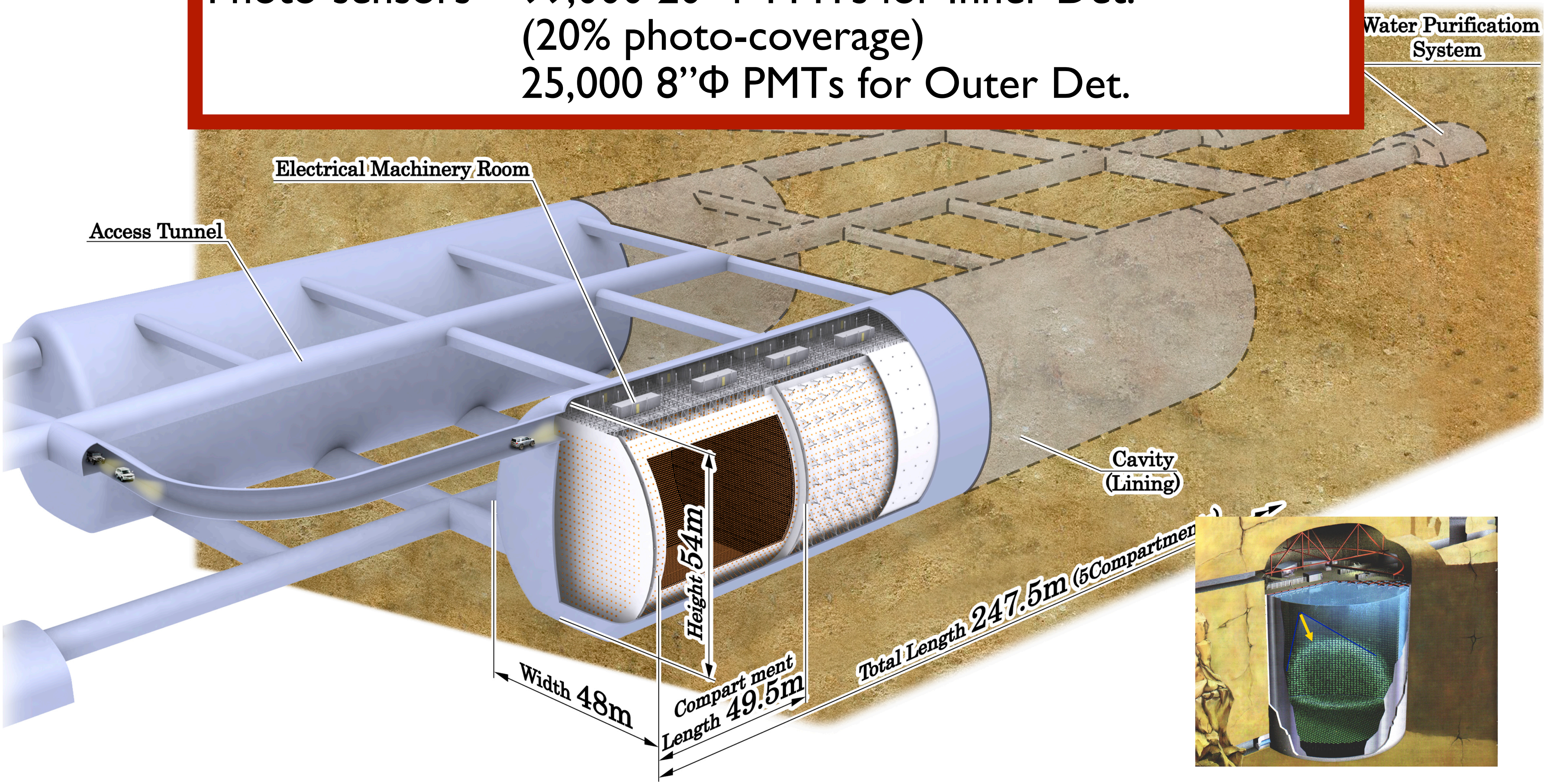
1Mton=1000kton
(560kton fiducial)

x17

x20
(x25 fiducial mass)

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.



Hyper-K WG,
arXiv:1109.3262 [hep-ex]

Sep. 2011

Letter of Intent:

The Hyper-Kamiokande Experiment

— Detector Design and Physics Potential —

K. Abe,[12,14] T. Abe,[10] H. Aihara,[10,14] Y. Fukuda,[5] Y. Hayato,[12,14] K. Huang,[4] A. K. Ichikawa,[4] M. Ikeda,[4] K. Inoue,[8,14] H. Ishino,[7] Y. Itow,[6] T. Kajita,[13,14] J. Kameda,[12,14] Y. Kishimoto,[12,14] M. Koga,[8,14] Y. Koshio,[12,14] K. P. Lee,[13] A. Minamino,[4] M. Miura,[12,14] S. Moriyama,[12,14] M. Nakahata,[12,14] K. Nakamura,[2,14] T. Nakaya,[4,14] S. Nakayama,[12,14] K. Nishijima,[9] Y. Nishimura,[12] Y. Obayashi,[12,14] K. Okumura,[13] M. Sakuda,[7] H. Sekiya,[12,14] M. Shiozawa,[12,14,*] A. T. Suzuki,[3] Y. Suzuki,[12,14] A. Takeda,[12,14] Y. Takeuchi,[3,14] H. K. M. Tanaka,[11] S. Tasaka,[1] T. Tomura,[12] M. R. Vagins,[14] J. Wang,[10] and M. Yokoyama[10,14]

(Hyper-Kamiokande working group)

[1]*Gifu University, Dep*

[2]*High Energy Accelerator R*

[3]*Kobe University, Dep*

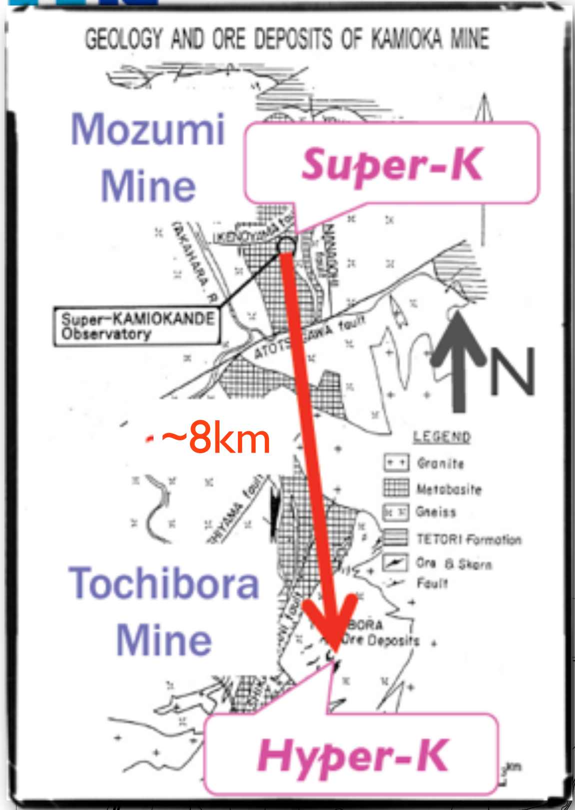
[4]*Kyoto University, Dep*

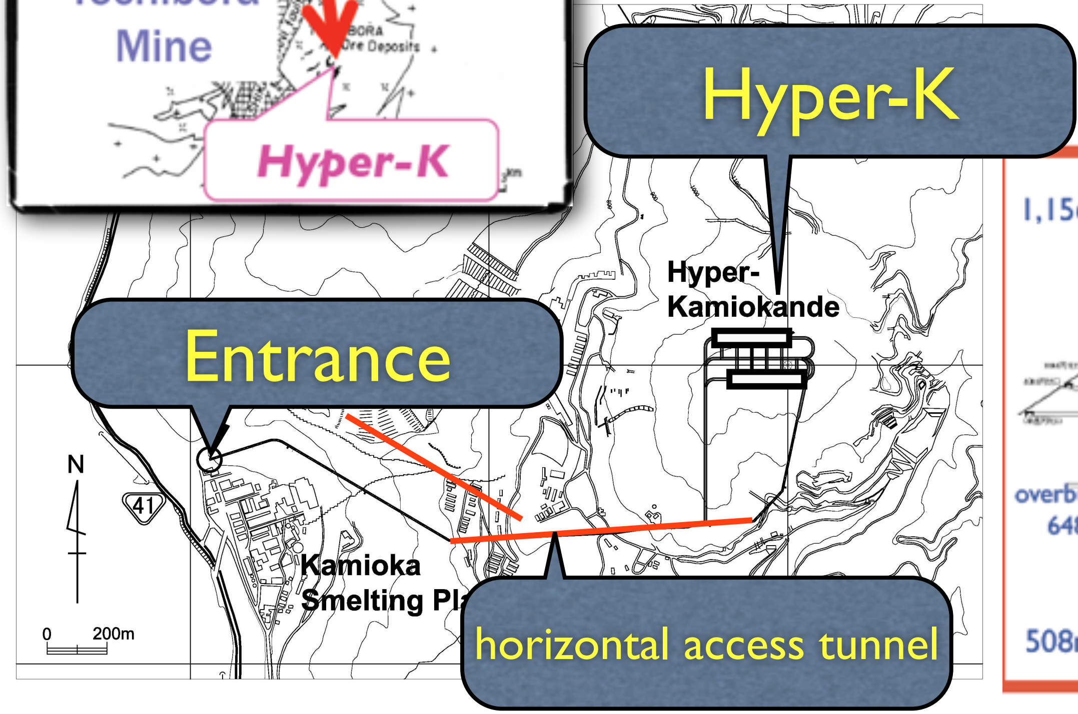
[5]*Miyagi University of Education, Department of Physics, Sendai, Miyagi 980-0845, Japan*

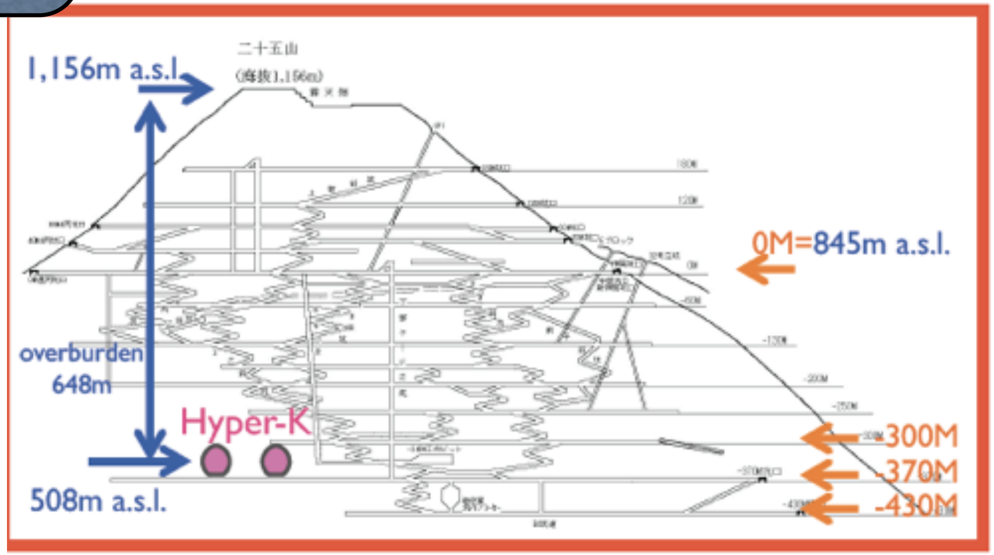
International WG was formed in 2012.
Current members are from
Japan, Canada, Korea, Spain,
Switzerland, Russia, UK, and US.

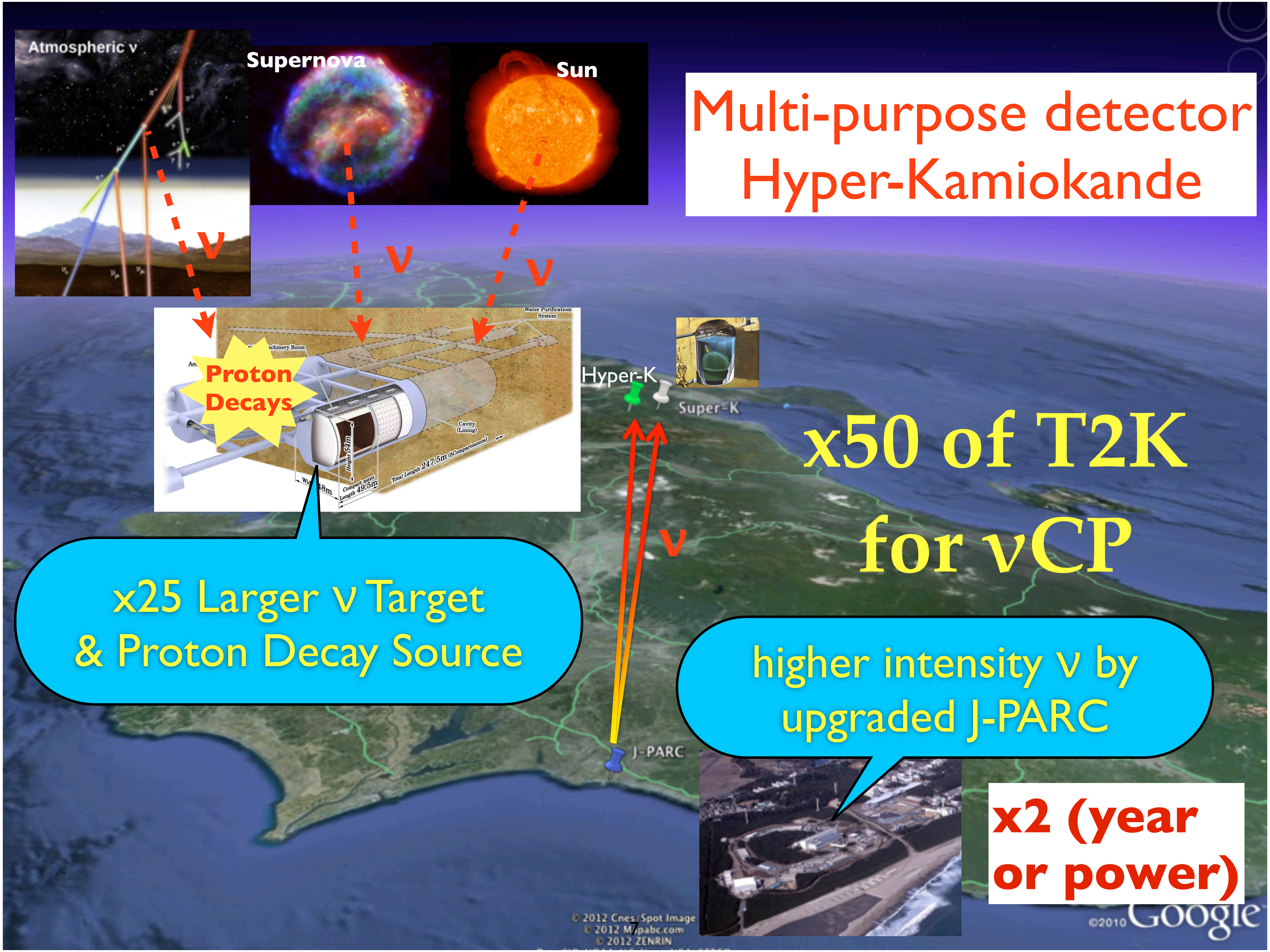
Candidate site

- 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)








Atmospheric ν
Supernova
Sun
Multi-purpose detector
Hyper-Kamiokande
ν
ν
ν
Water Purification System
Proton
Decays
Cavity (Lining)
Height 54m
Compartment Length 49.5m
Total Length 247.5m (5Compartments)
Hyper-K
Super-K
x50 of T2K
for νCP
ν
x25 Larger ν Target
& Proton Decay Source
higher intensity ν by
upgraded J-PARC
J-PARC
x2 (year
or power)
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Physics topics

- Neutrino beam from J-PARC
  (≥1MW expected)

Neutrino mixing, CPV

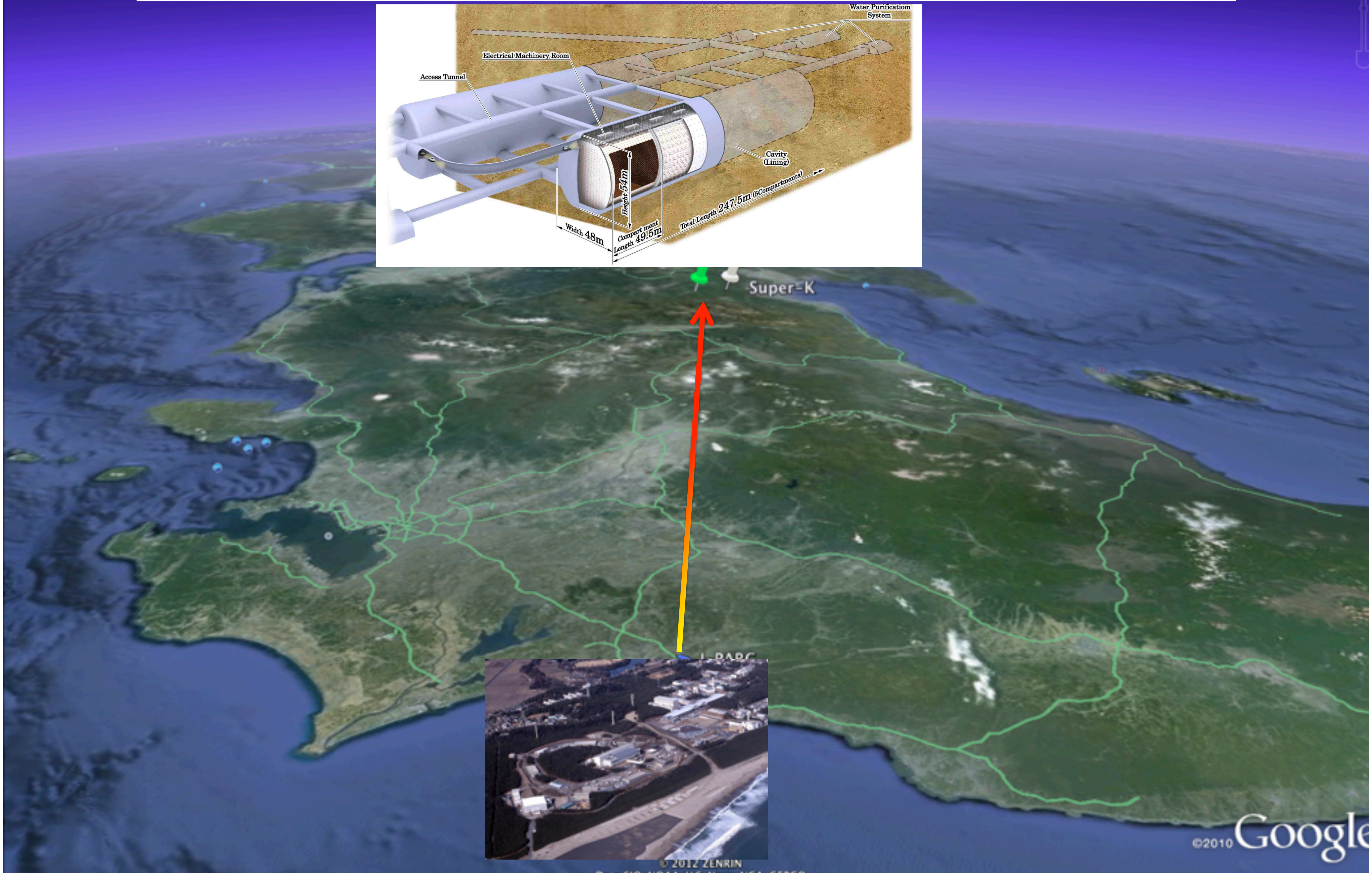
- Atmospheric neutrinos
- Search for proton decay

GUT

- Solar neutrinos
- Astrophysical neutrinos (supernova, dark matter, ...)
- Neutrino geophysics
- More idea?

Breadth of physics by a large underground detector

Accelerator neutrino beam



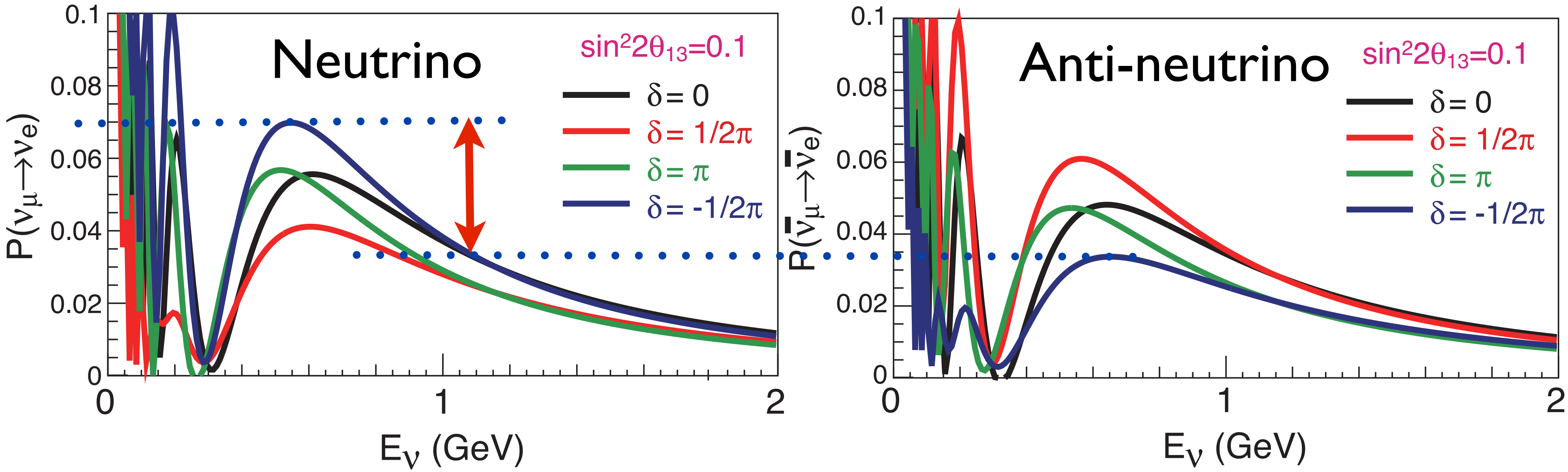
Long baseline experiment with J-PARC ν beam

- 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 (e.g. LBNE)
  - 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

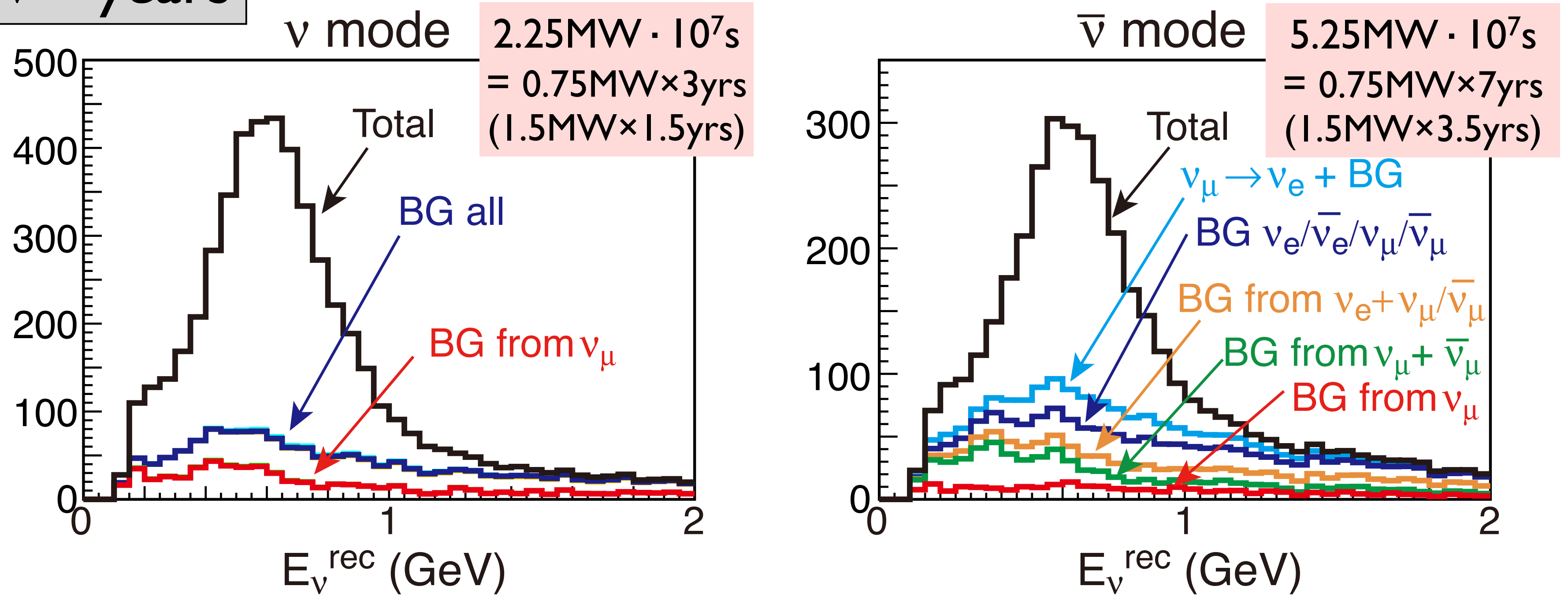


- Comparison of $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
  - Max. ~±25% change from δ=0 case
  - Sensitive to exotic (non-MNS) CPV source

ν_e candidate reconstructed energy distributions

7.5MW・years

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



	Signal ($\nu_\mu \rightarrow \nu_e$ 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

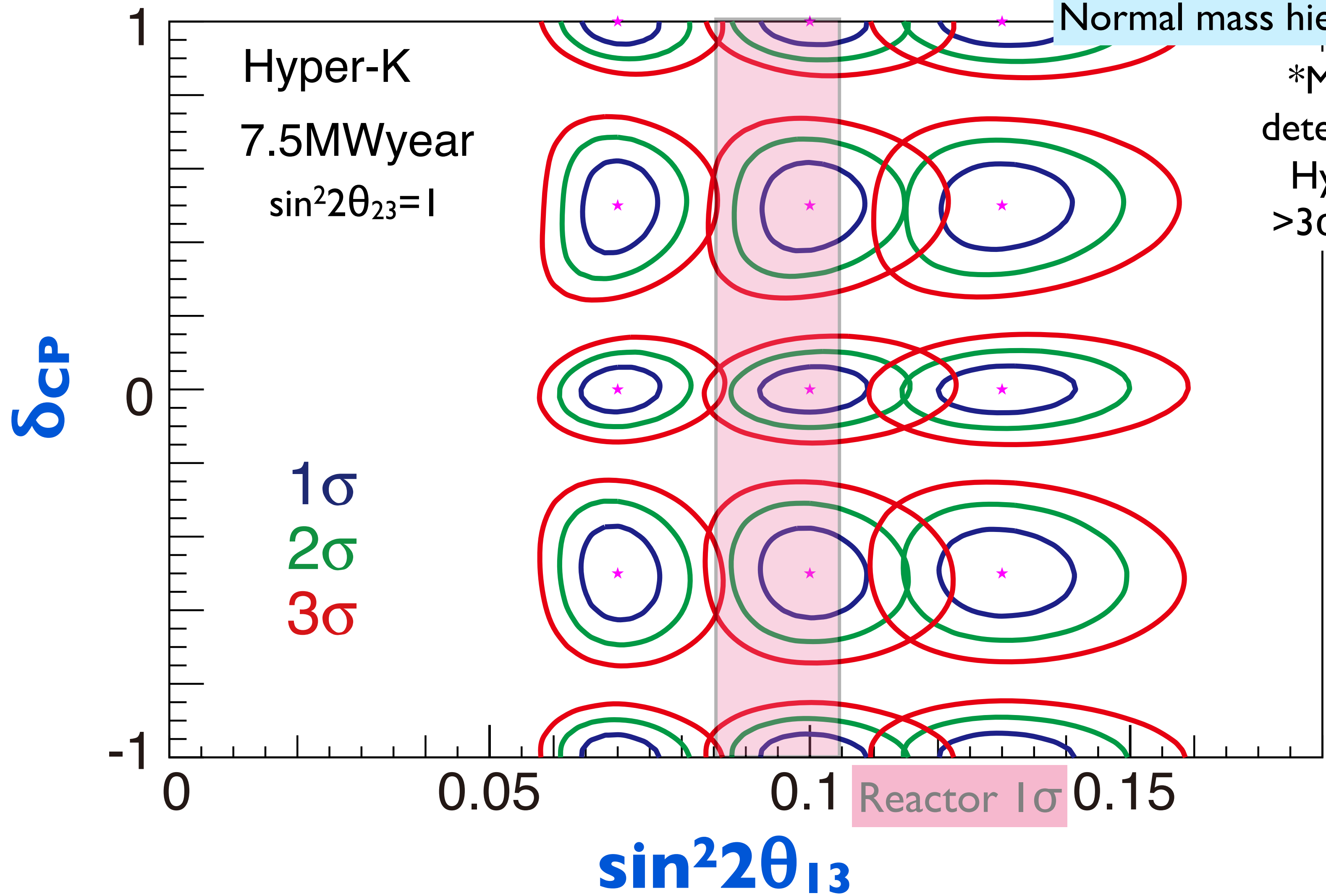
2000-4000 signal events for each of ν and $\bar{\nu}$

Expected sensitivity to CP asymmetry

7.5MW・years

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

Normal mass hierarchy (known*)

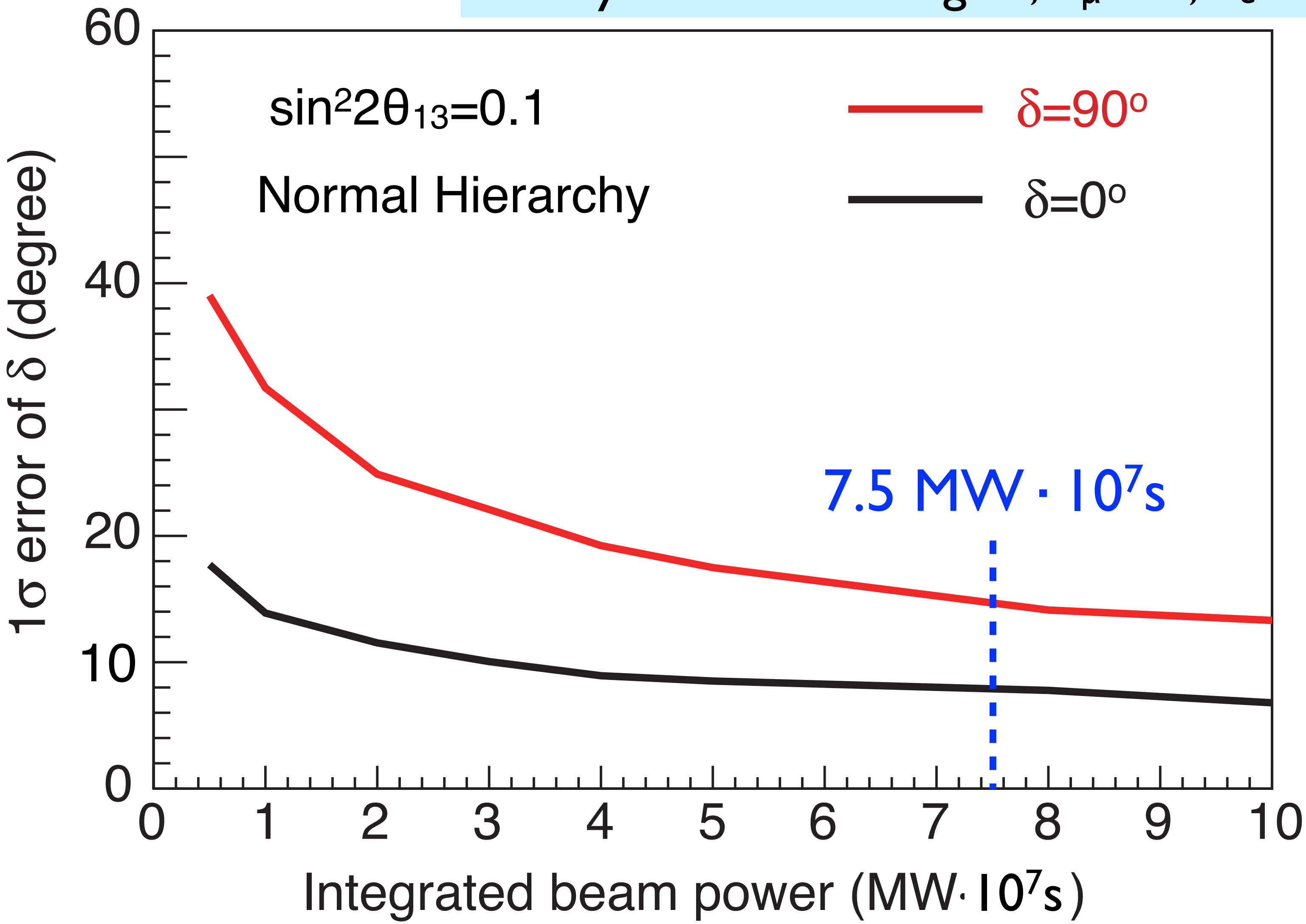


*Mass hierarchy determination with Hyper-K atm. ν: >3σ in 5-10 years

Good sensitivity for currently allowed values

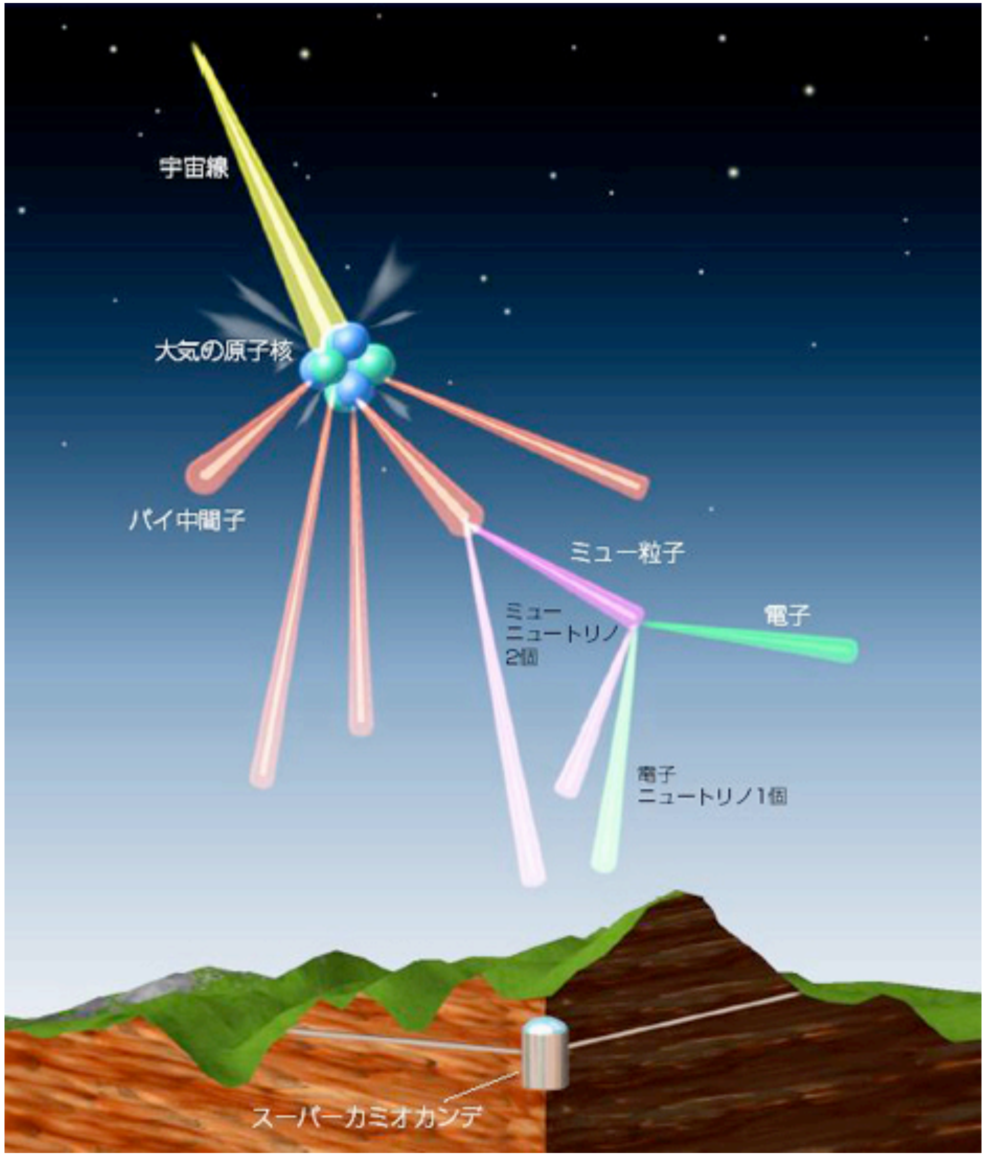
Expected uncertainty of δ (1σ)

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



<20° (δ=90°), <10° (δ=0°)

Atmospheric neutrinos



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

Complementary to accelerator ν

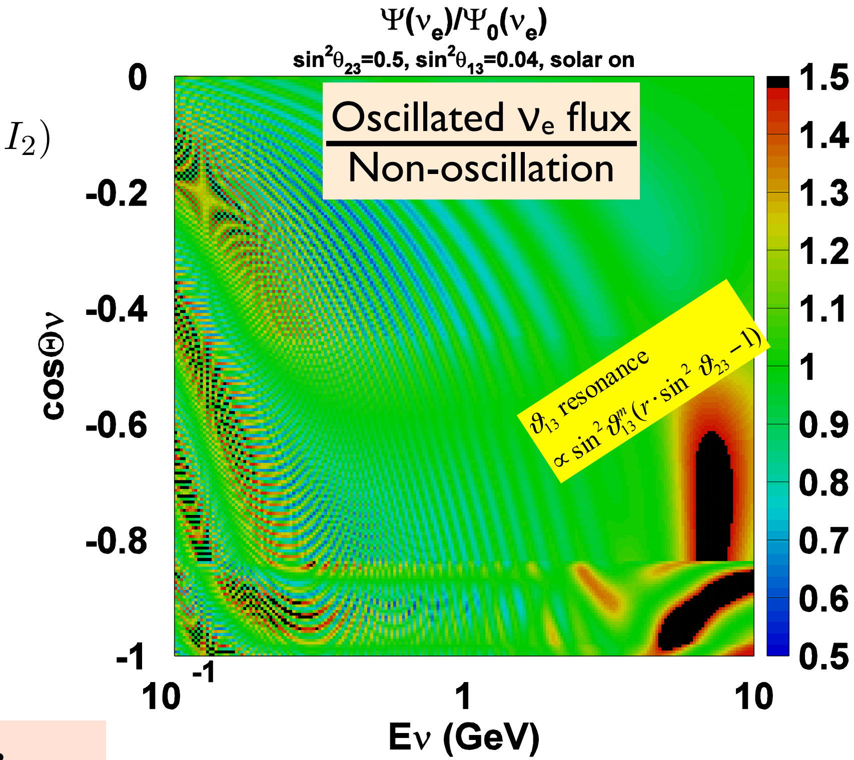
Atmospheric neutrino

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

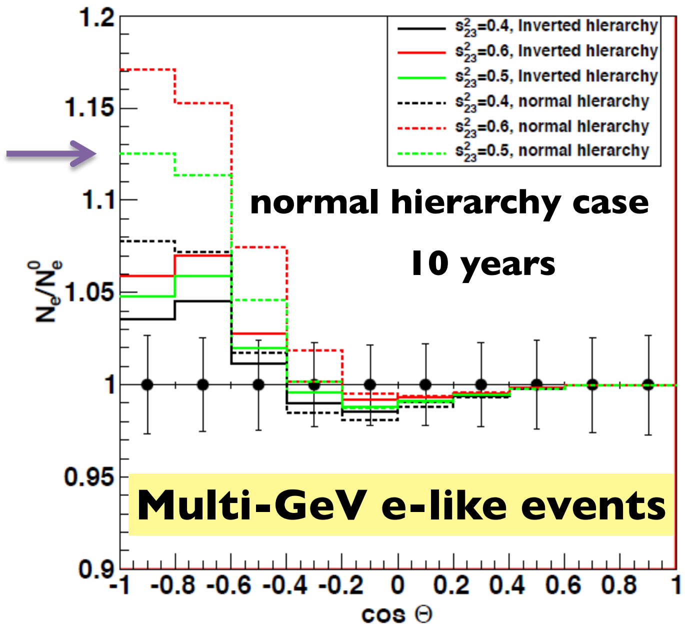
$$\frac{\Phi(\nu_e)}{\Phi_0(\nu_e)} - 1 \approx P_2 \cdot (r \cdot \cos^2\theta_{23} - 1)$$
$$- r \cdot \sin\tilde{\theta}_{13} \cdot \cos^2\tilde{\theta}_{13} \cdot \sin 2\theta_{23} \cdot (\cos\delta \cdot R_2 - \sin\delta \cdot I_2)$$
$$\underline{+2\sin^2\tilde{\theta}_{13} \cdot (r \cdot \sin^2\theta_{23}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

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

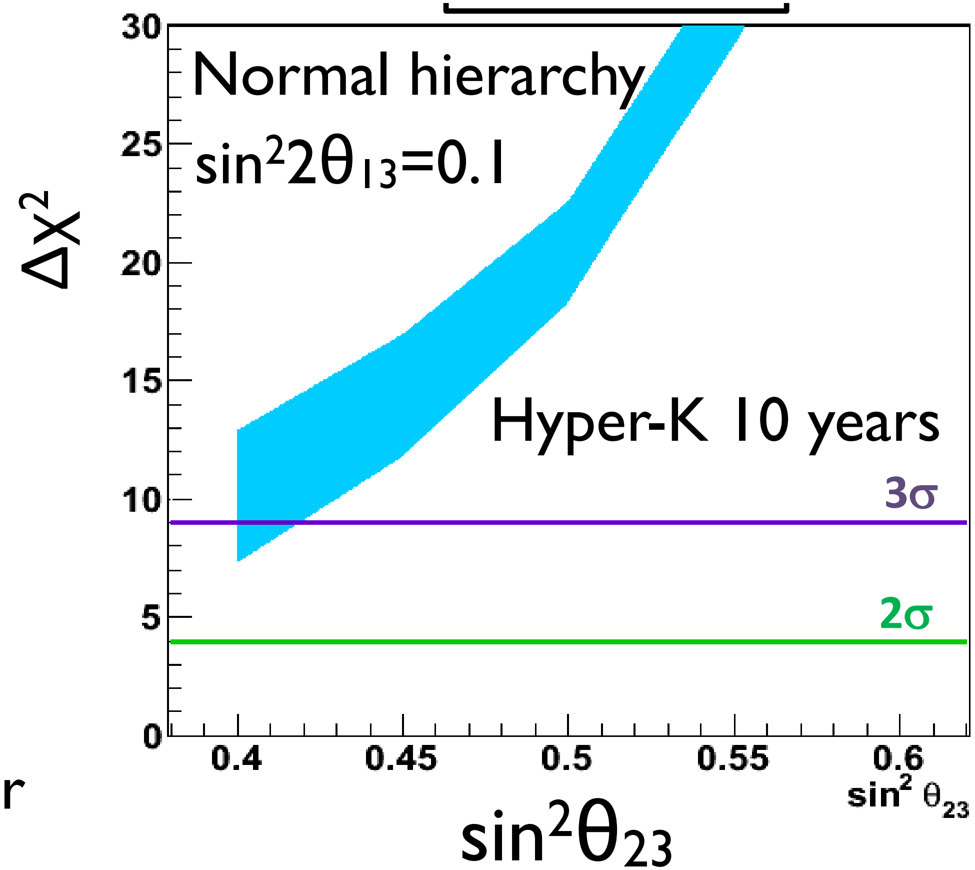
larger θ_{13} gives better sensitivity



Mass hierarchy determination with atmospheric neutrinos



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



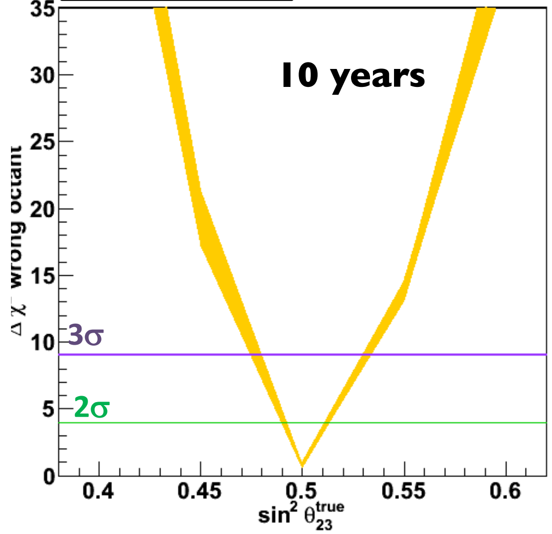
3σ determination with <10 year observation
(better sensitivity depending on the value of θ_{23})

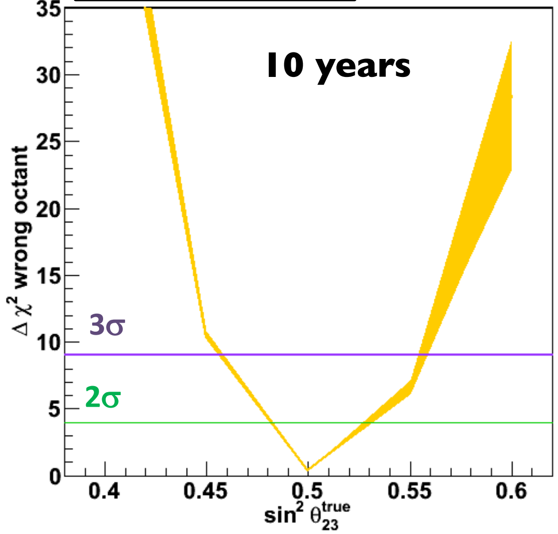
atm ν: θ_{23} octant and CPV

NH, unknown | θ_{13} is fixed : $\sin^2 2\theta_{13} = 0.10$ | IH, Unknown

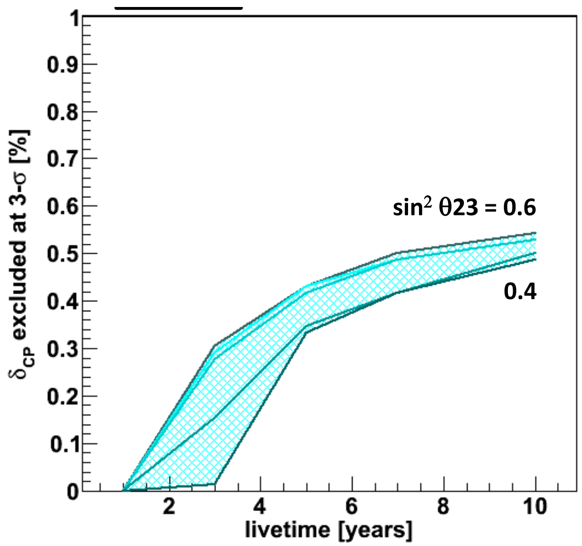
θ_{23} octant sensitivity

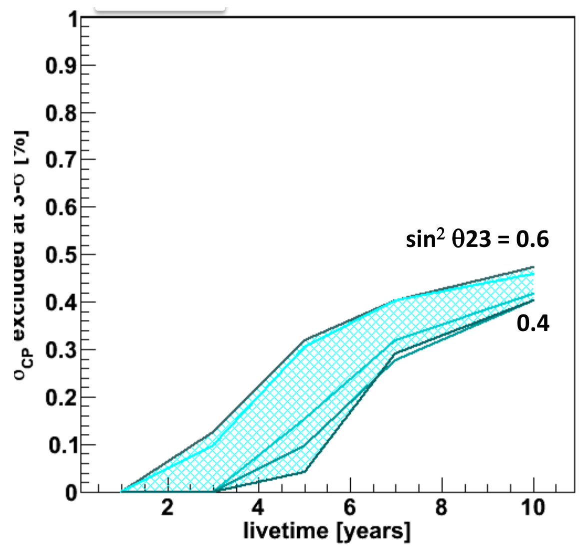
(band depends on δ)





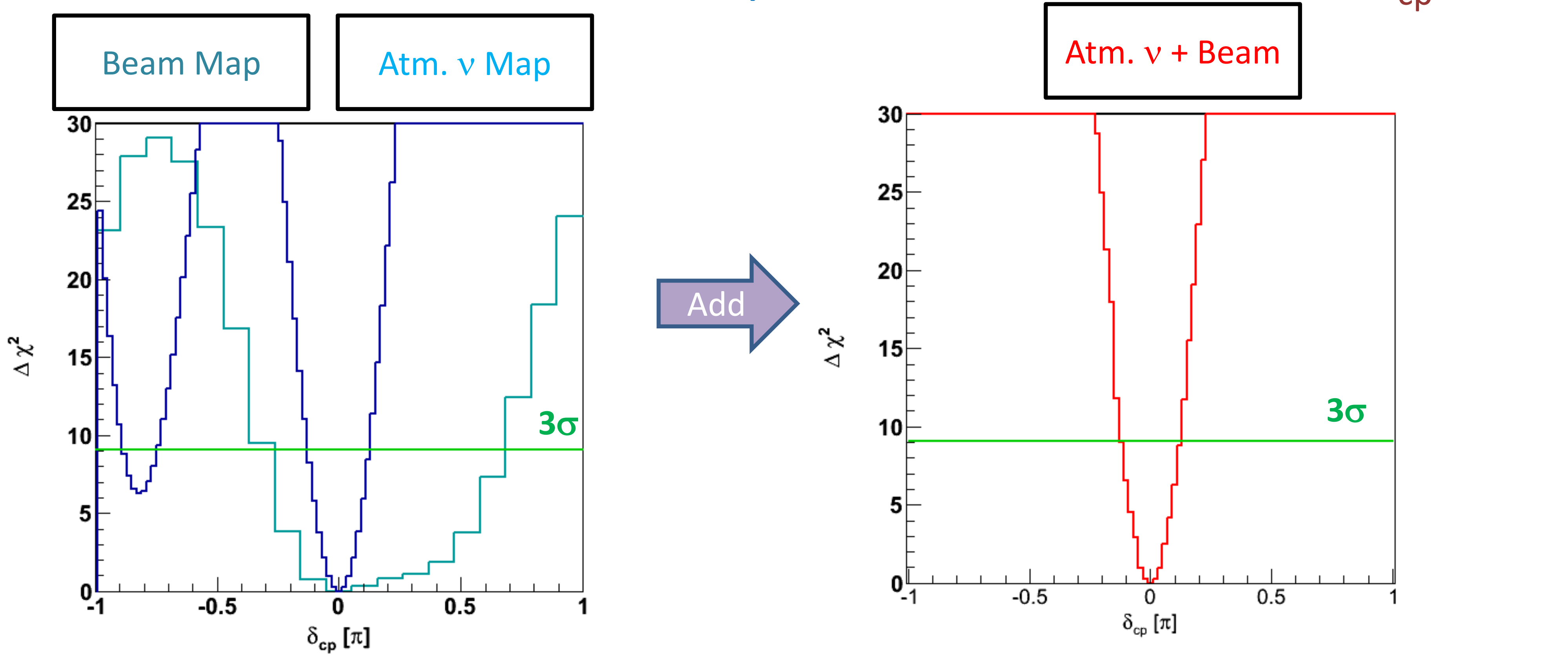
Fraction of δ_{CP} excluded (3 σ)





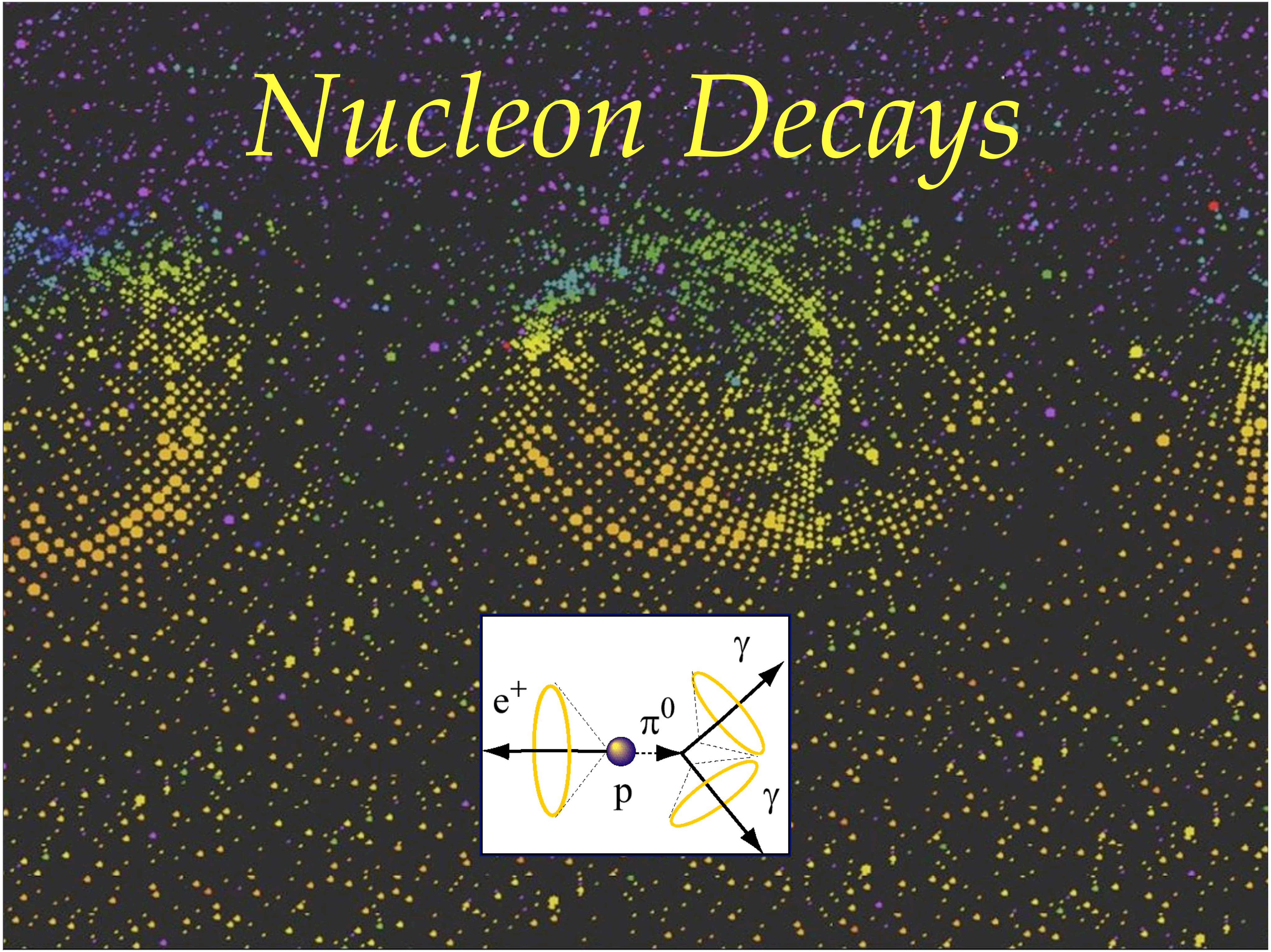
Complementary measurements to accelerator ν

Combination of Beam and Atmospheric Neutrinos : Allowed δ_{cp}

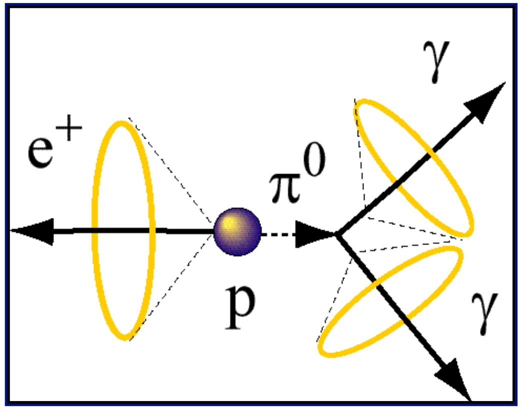


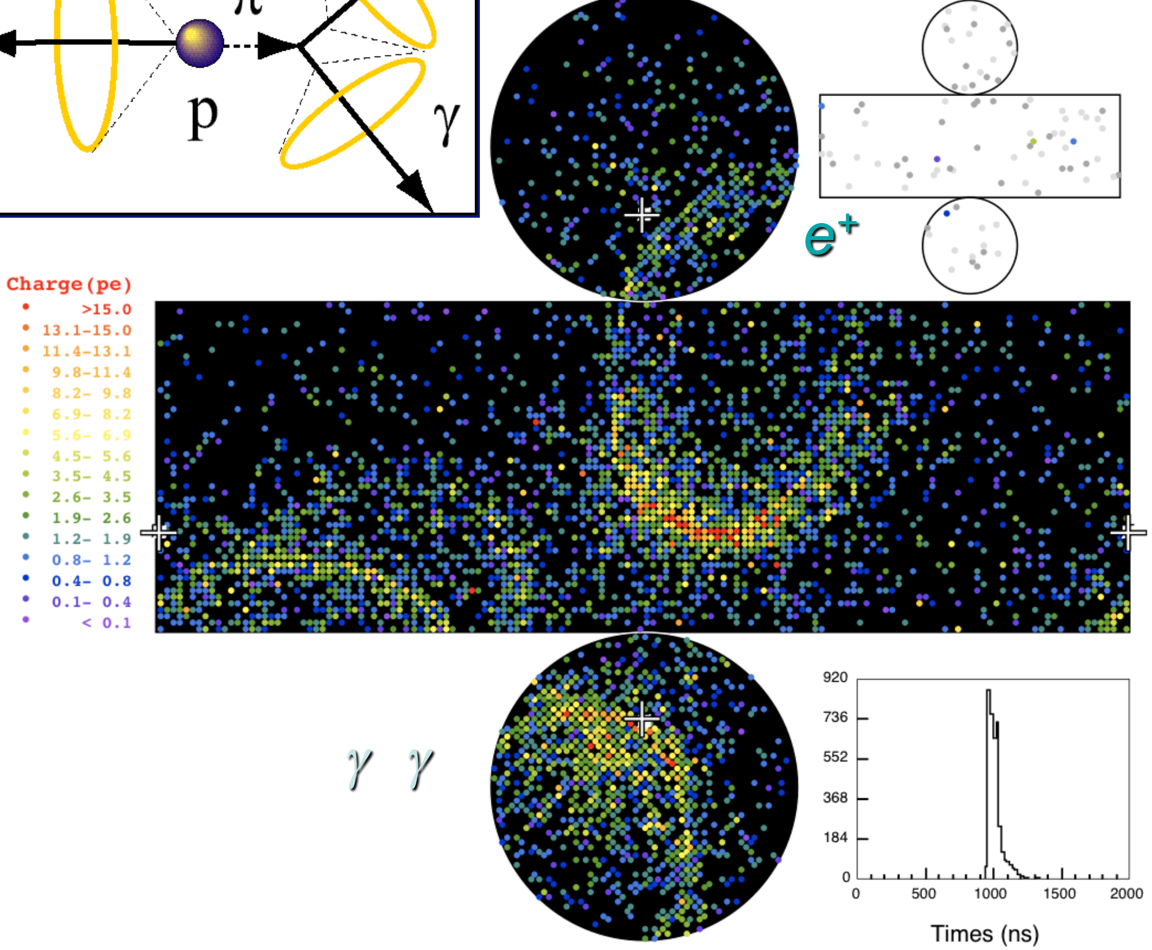
- Hierarchy is unknown, but NH is true
- True δ_{cp} = 0.0
- True $\sin^2 2\theta_{13}$ = 0.10
- Maximal mixing , $\sin^2 2\theta_{23}$ = 1.0
- Degenerate solution exists at 3σ in the beam only case - just add the χ^2 maps
- In the real world, something more sophisticated is in order

Nucleon Decays



$p \rightarrow e^{+}\pi^{0}$ search





$e^{+}\pi^{0}$ selection

Invariant mass of p
Momentum balance

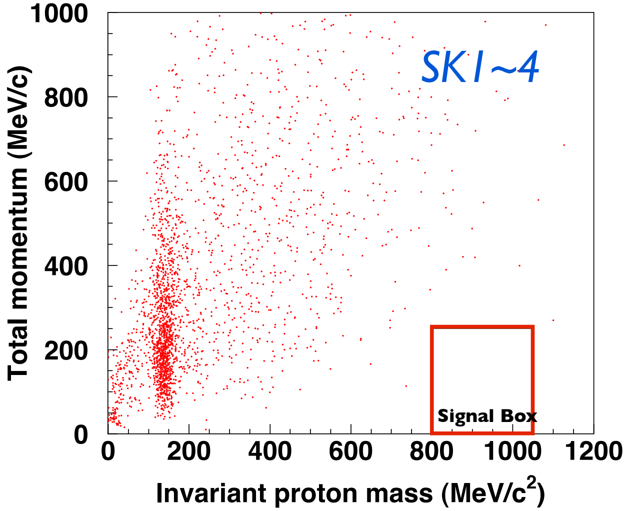
- 2 or 3 e-like rings
- No decay-e
- $85 < M_{\pi^0} < 185$ MeV/c^2 (3ring)
- $800 < M_p < 1050$ MeV/c^2
- $p_{tot} < 250$MeV/c

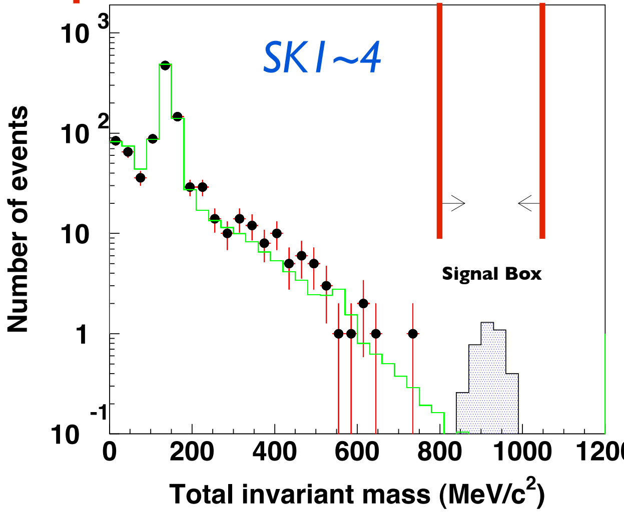
Efficiency ~40%
(87% for free proton)

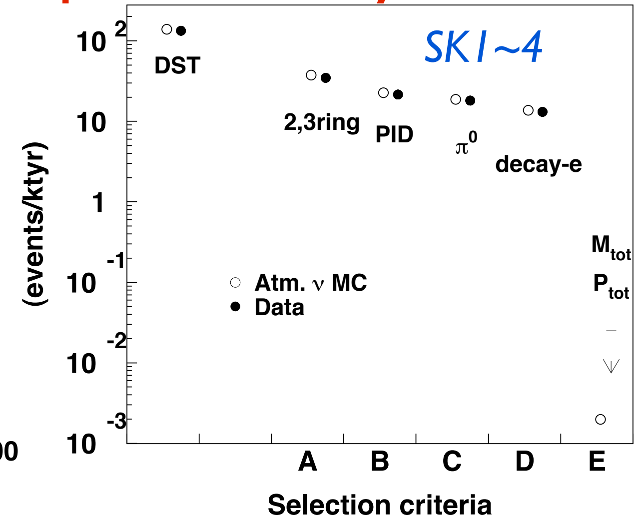
2/10 free protons in H_2O

$p \rightarrow e^{+}\pi^{0}$ search: BG estimate

Super-K data are well reproduced by BG MC.

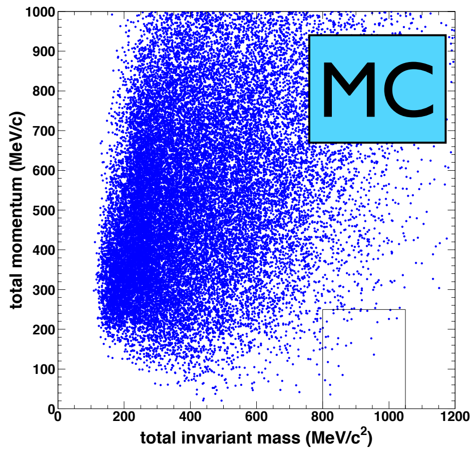


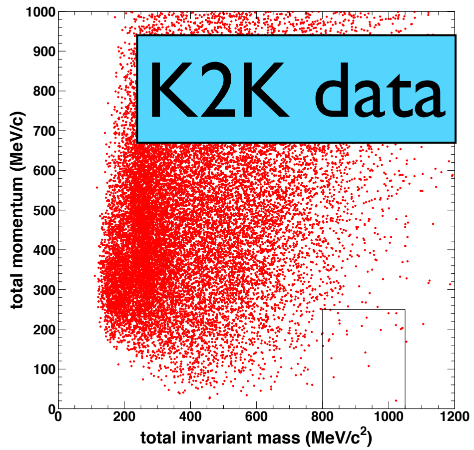




BG prediction confirmed with high statistics K2K 1kton near detector measurement

PRD 77, 032003(2008)





$$1.63^{+0.42}_{-0.33}(stat.)^{+0.45}_{-0.51}(syst.)[\mathrm{Mt} \times \mathrm{years}]^{-1}(E_{\nu} < 3GeV)$$

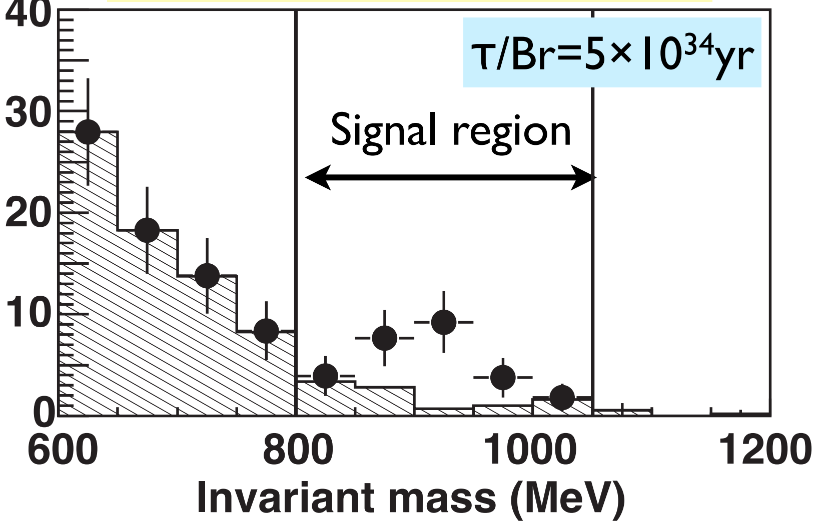
Consistent w/ simulation 1.8±0.3(stat.)

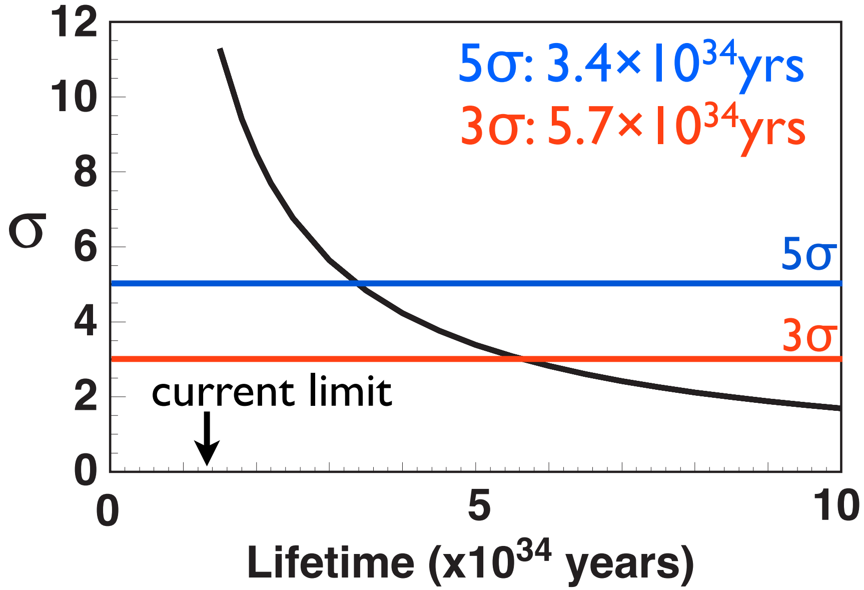
Reliable prediction of next generation experiment

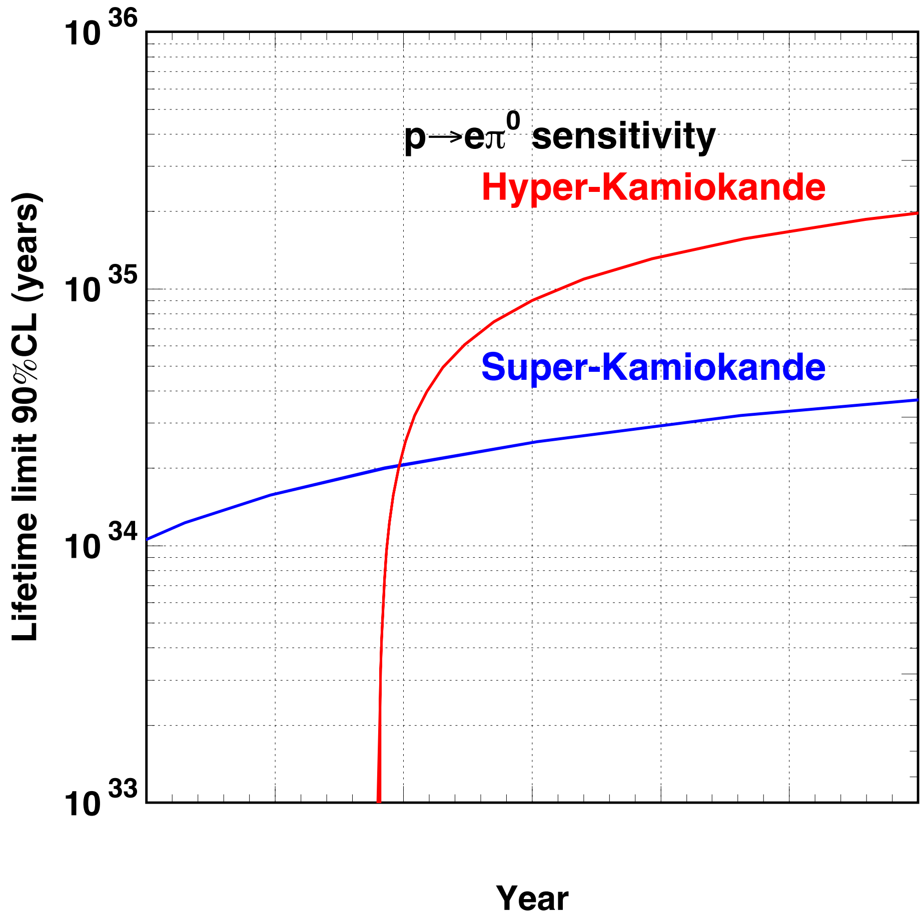
Hyper-K $p \rightarrow e^{+}\pi^{0}$ sensitivity

(Using only number of events)

10 years exposure





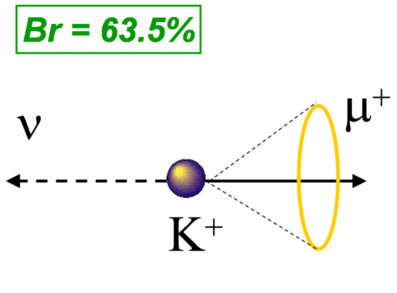


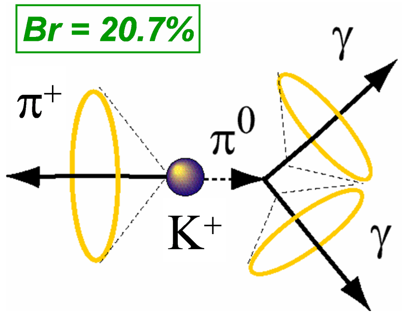
Will surpass SK limit in ~1 year.

90% limit with 10 years: 1.3×10^{35}yrs

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

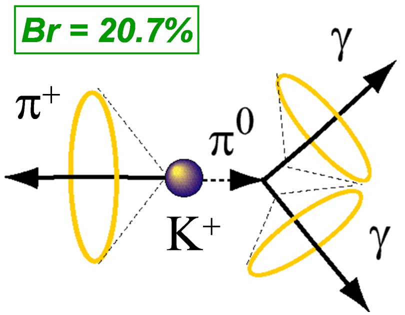
- K^+ invisible (below Cherenkov threshold)
- $K^+ \rightarrow \mu\nu$ (Br: 63.5%)
    - Method 1: Tag with nuclear de-excitation γ
        - Measurement of de-excitation γ: nucl-ex/0604006
    - Method 2: Search excess in P_μ distribution
- $K^+ \rightarrow \pi^+\pi^0$ (Br: 20.7%)
    - 205 MeV/c π^0 + activity in opposite direction (π^+ just above threshold)





Recent improvement in analysis

$K^+ \to \pi^+\pi^0$ improvement



π^+ just above threshold
→ search for light opposite to π^0 direction

Selection in LoI

- Two e-like rings with decay-e
- $85<M\pi^0<185$ MeV/c^2
- $175<P\pi^0<250$ MeV/c
- Sum of visible energy in 140°–180° from π^0 direction: 7-17MeV
- Sum of visible energy in 90°–140° from π^0 direction: <12MeV

Improvements

- Add 1 ring e-like event with π^0 fitter used for T2K BG rejection

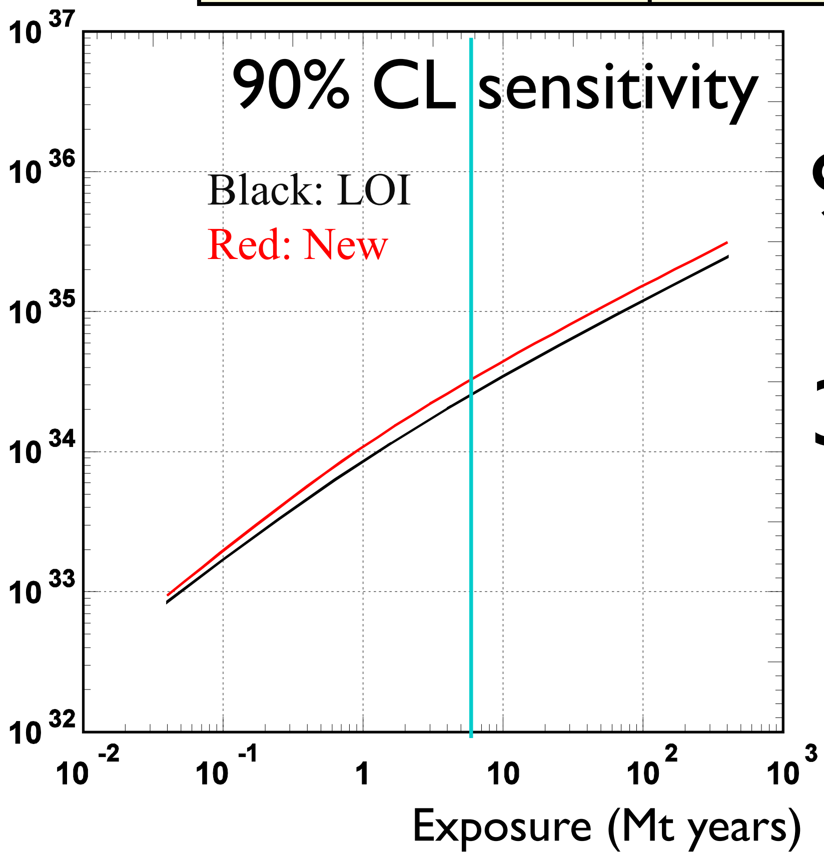
→ Increase efficiency

- Optimize range to 145°-180°
- Use shape information

→ Reduce background

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

	Efficiency (%)	BG (/Mtyr)
$K \rightarrow \mu\nu$+nucl. γ	7.1	1.6
$K \rightarrow \mu\nu$, P_μ	43	1940
$K \rightarrow \pi\pi$	~~6.7~~ 7.6	~~6.7~~ 1.8

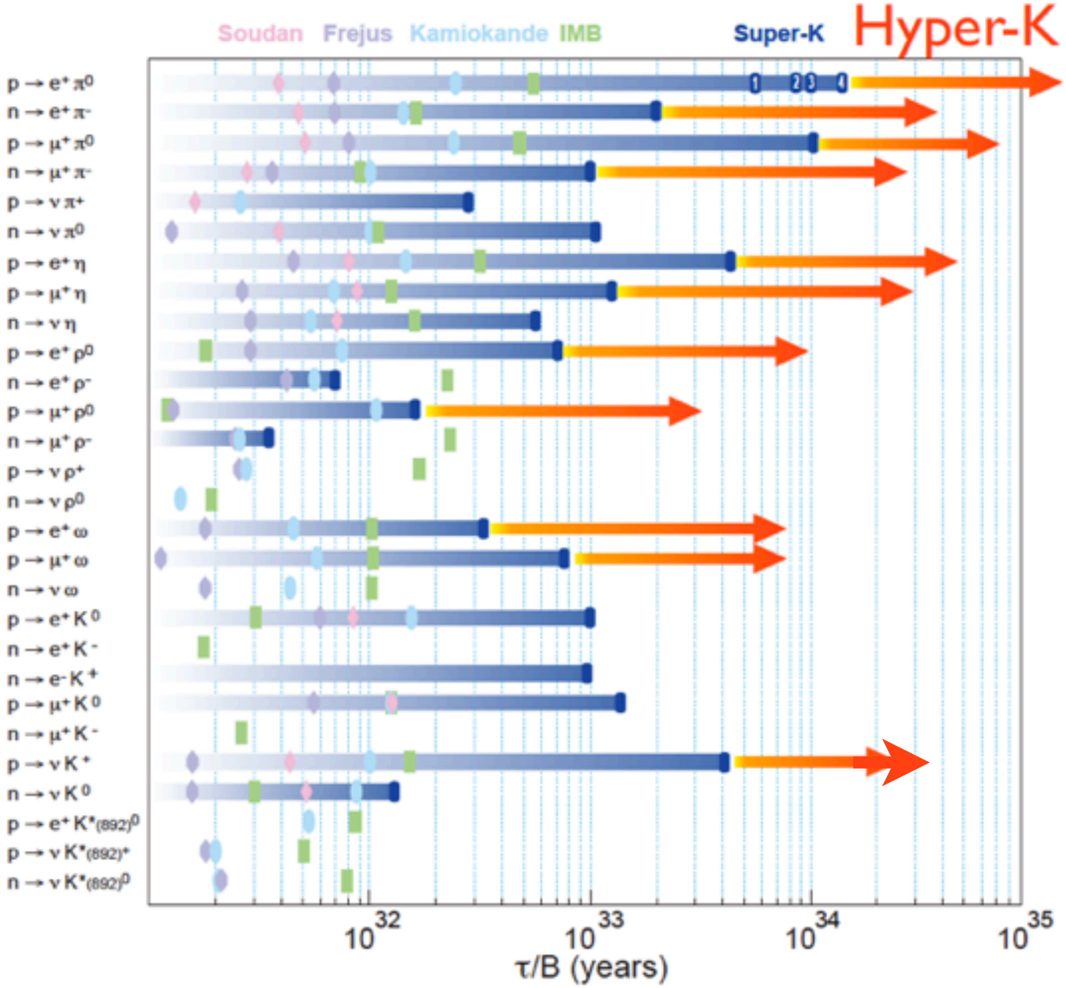


90% CL sensitivity:
$2.5\times10^{34} \rightarrow 3.2\times10^{34}$ yrs

3σ observation potential:
$0.95\times10^{34} \rightarrow 1.2\times10^{34}$ yrs

Proton decay sensitivity

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

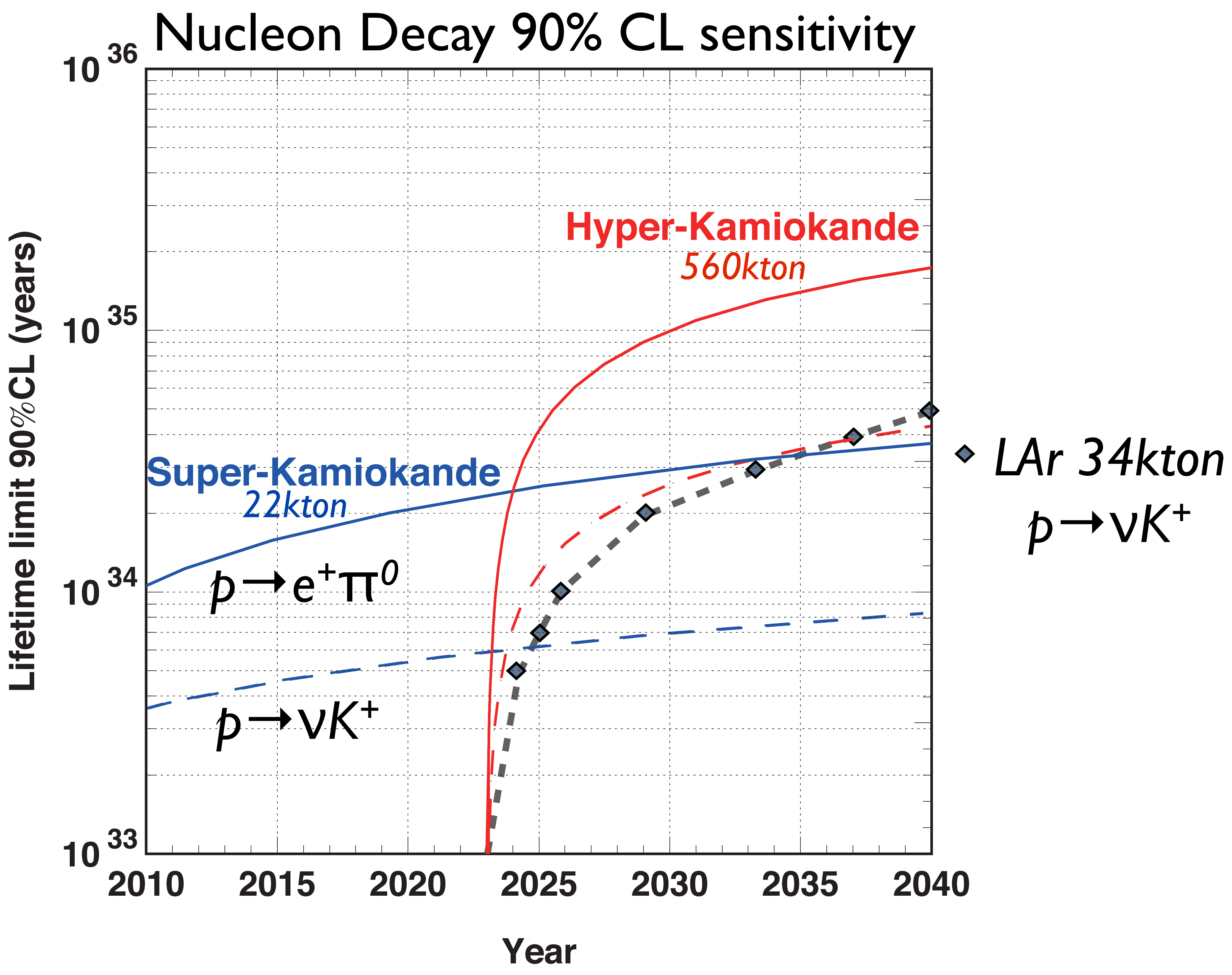


- $p \to e^+\pi^0$:
  - 1.3×10^{35}yrs (90%CL)
  - 5.7×10^{34}yrs (3σ)

$p \to \bar{\nu}K^+$:
  - 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
Lifetime limit 90%CL (years)
10^36
10^35
10^34
10^33
2010
2015
2020
2025
2030
2035
2040
Year
Hyper-Kamiokande
560kton
Super-Kamiokande
22kton
p→e+π0
p→νK+
LAr 34kton
p→νK+

Neutrino astrophysics

- **Supernova burst neutrino**
  - ~250k events (Garactic center) /
    ~25 events (Andromeda)
  - Reveal the detailed mechanism of supernova explosions with very large statistics sample
- **Supernova relic neutrino**
  - Study the history of heavy element synthesis in the universe
- Precision measurements of solar neutrino
- Indirect WIMP Search

Summary

- Hyper-Kamiokande will provide excellent opportunity for wide range of physics topics
  - Neutrino mixing and CP violation
  - Nucleon decays
- Capability complementary to large LAr detectors such as LBNE in many ways
  - It will be important to realize both to fully exploit the opportunities in front of us.

Status of R&D and project → next talk