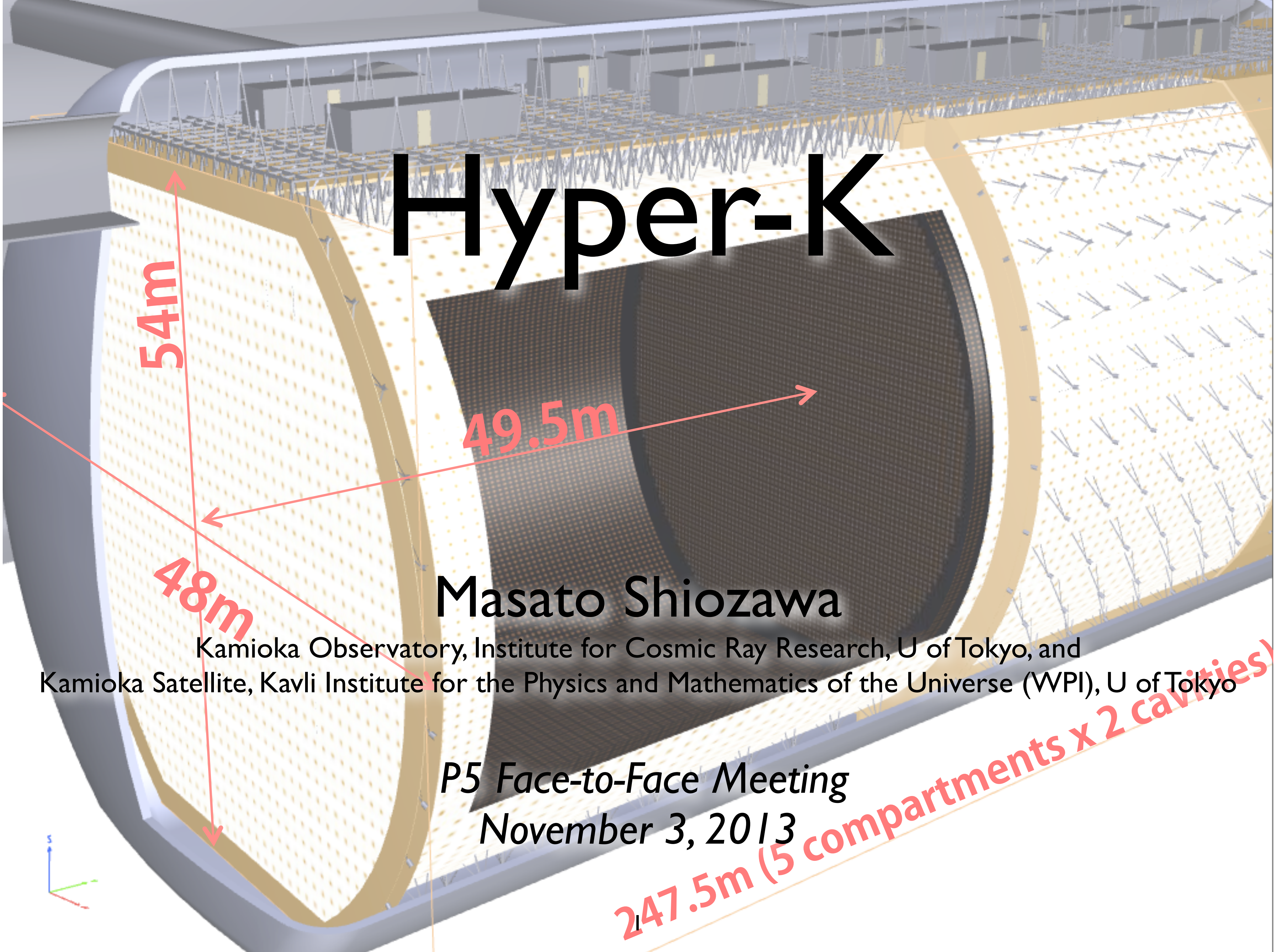
Hyper-K



Masato Shiozawa

Kamioka Observatory, Institute for Cosmic Ray Research, U of Tokyo, and
Kamioka Satellite, Kavli Institute for the Physics and Mathematics of the Universe (WPI), U of Tokyo

P5 Face-to-Face Meeting
November 3, 2013

Specific questions from P5

1) a brief summary of the physics case coupled with the explicit scope of the experiment, and a notional timeline for construction start, data taking, and specific anticipated results. What makes this experiment unique, and how does fit in the overall picture of this area, particularly with respect to LBNE?

2) what scope of international participation is required, and what is the status of these arrangements? How do you anticipate this will develop over time? What, specifically, would you be looking for from the U.S.?

3) anything you wish to reinforce from, or add to, Snowmass findings about this project, and anything else you would like to communicate to P5.

“BIG” questions in Snowmass

http://www.symmetrymagazine.org/article/october-2013/the-big-questions

- **The Higgs particle is unlike any other particle we have ever encountered. Why is it different? Are there more?**

ν oscillation, supernova ✓
- **Neutrinos are very light, elusive particles that change their identity as they travel. How do they fit into our understanding of nature?**

indirect DM search ✓
- **The known particles constitute one-sixth of all the matter in the universe. The rest we call dark matter. But what is it? Can we detect these particles in our labs? Are there other undiscovered particles in nature?**

proton decays, ν's mass & mixing ✓
- **There are four known forces in nature. Are these manifestations of a single unified force? Are there unexpected new forces?**

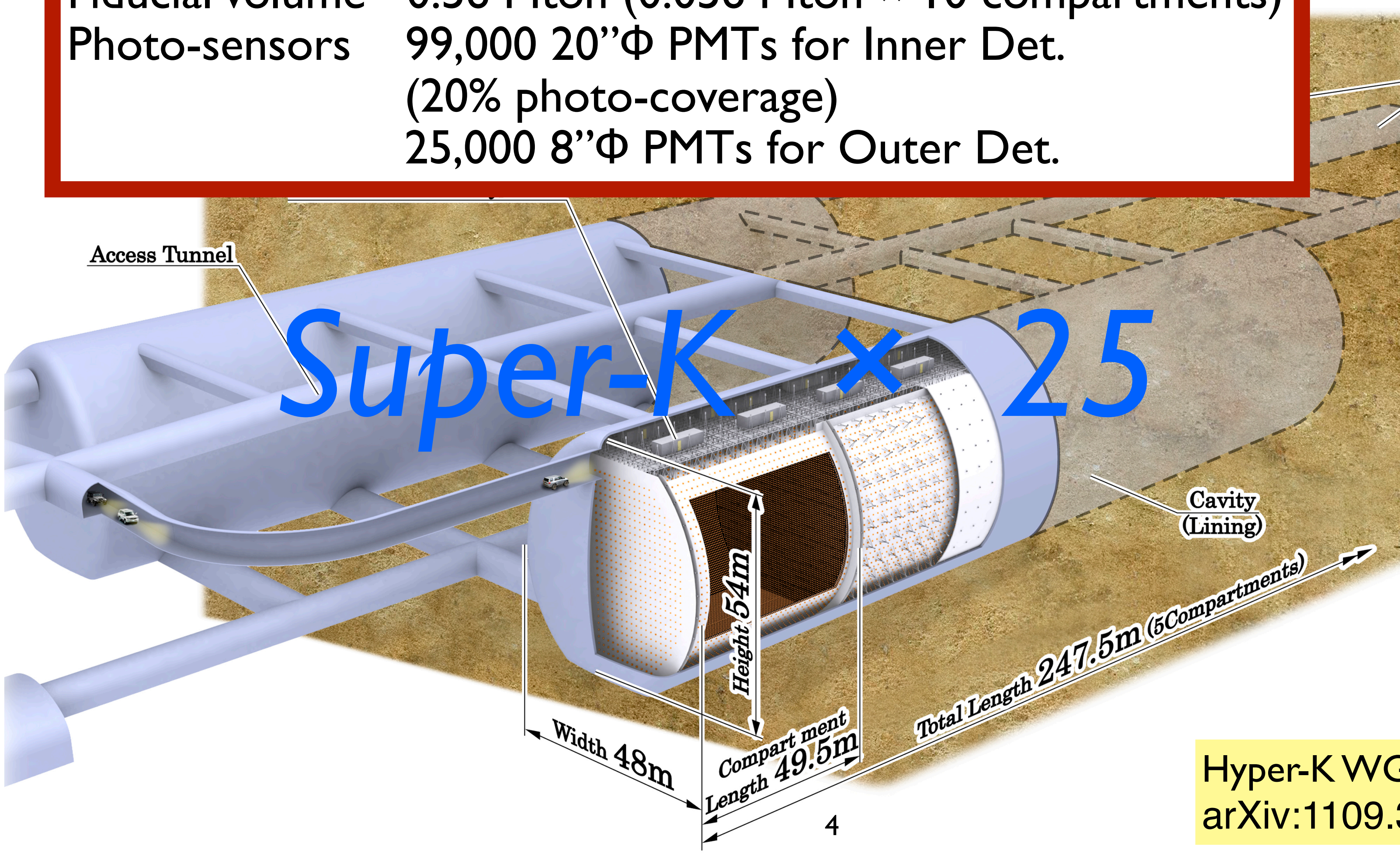
✓
- **Are there new hidden dimensions of space and time?**

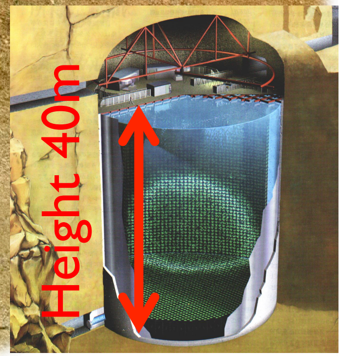
ν's CPV, proton decays ✓
- **Both matter and antimatter were produced in the big bang, but today our world is composed only of matter. Why?**
- **Why is the expansion of the universe accelerating?**

Neutrino & nucleon decay experiments address many “BIG” questions.

Gigantic Water Cherenkov Detector: Hyper-Kamiokande

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





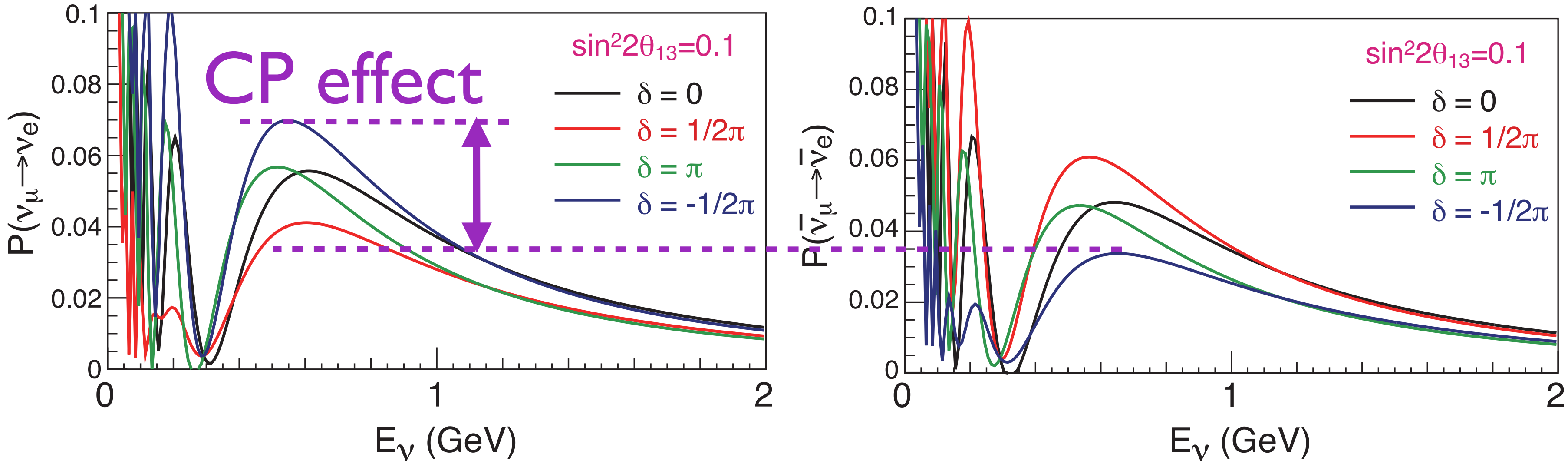
Hyper-K WG, arXiv:1109.3262 [hep-ex]

CP measurement w/ Hyper-K/J-PARCν

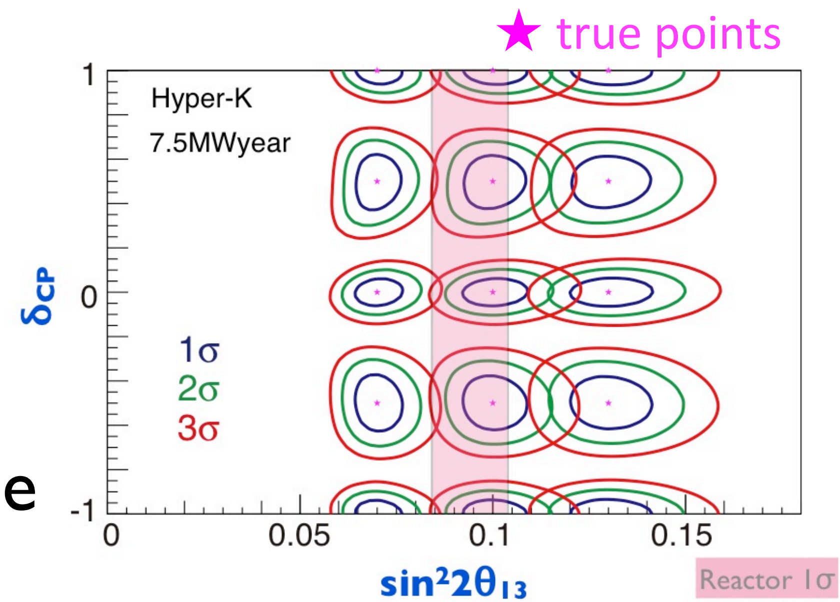
Appearance probability at Hyper-K (baseline=295km)

Normal hierarchy

Neutrino | Anti-Neutrino

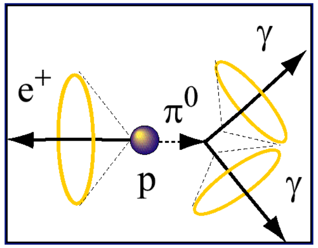


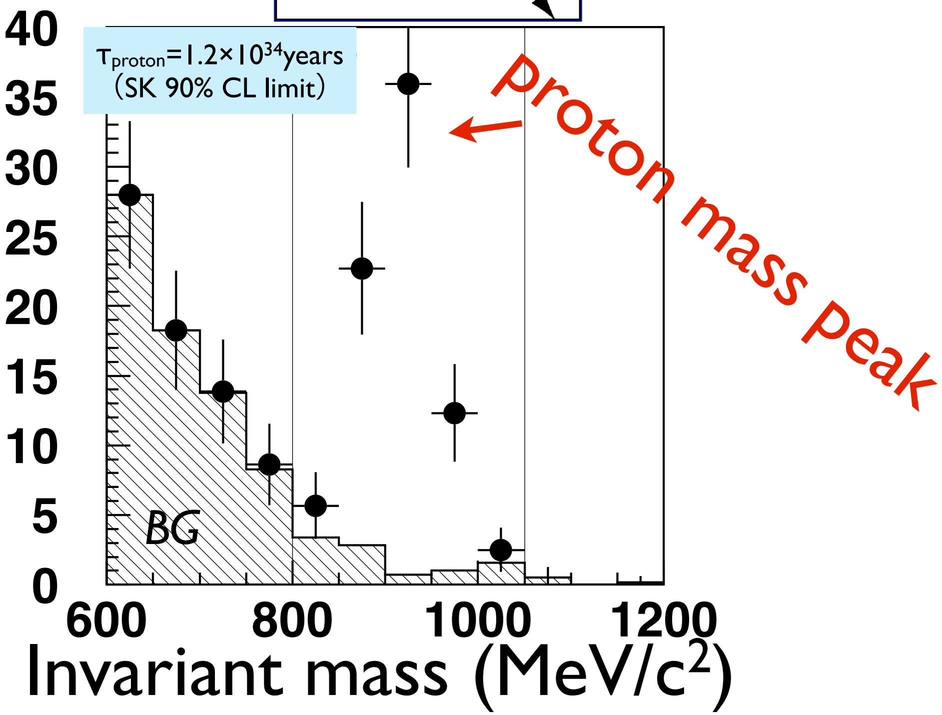
- Direct CPV test by comparing $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$. >3σ for 70% of δ space.
- δ measurement (w/ precision of 10°~20°), Test of (exotic) CPV origin
- Good chance to determine MH by J-PARC ν alone (50% of δ space).
- High statistic atmospheric ν data will be enable to determine MH.



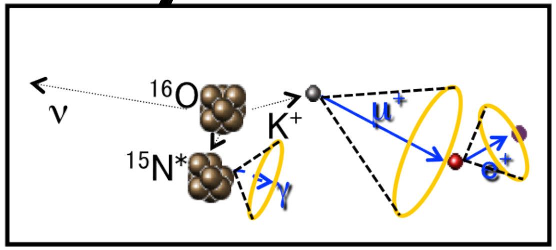
GUT tests by Nucleon Decay Searches

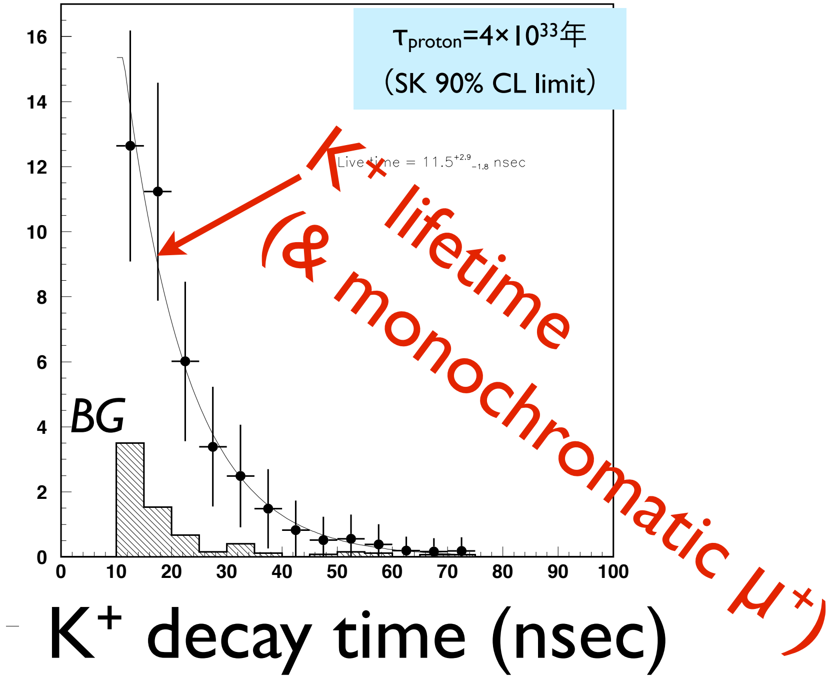
$p \rightarrow e^+\pi^0$





$p \rightarrow \nu K^+$





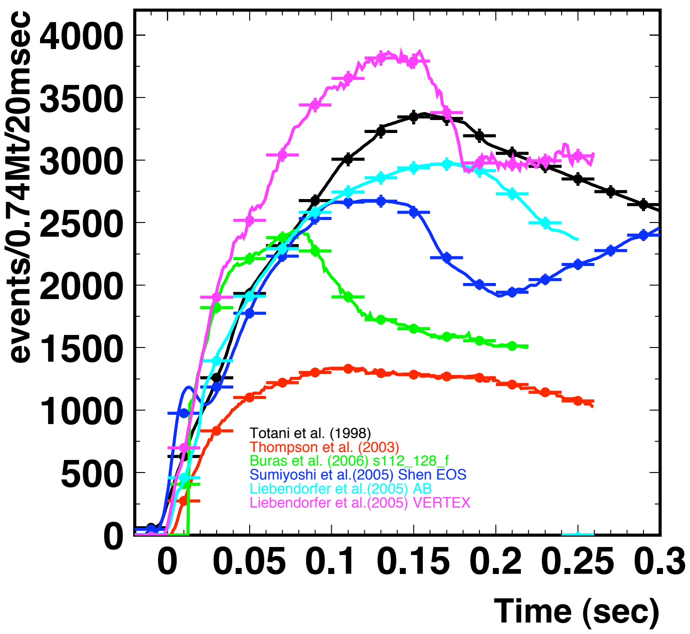
- Discovery reach (3σ)
  - $\tau(p \rightarrow e^+\pi^0) \sim 5.4\times10^{34}$years (HK 10yrs)
- Limit (90%CL)
  - $\tau(p \rightarrow e^+\pi^0) > 1.3\times10^{35}$years (HK 10yrs)

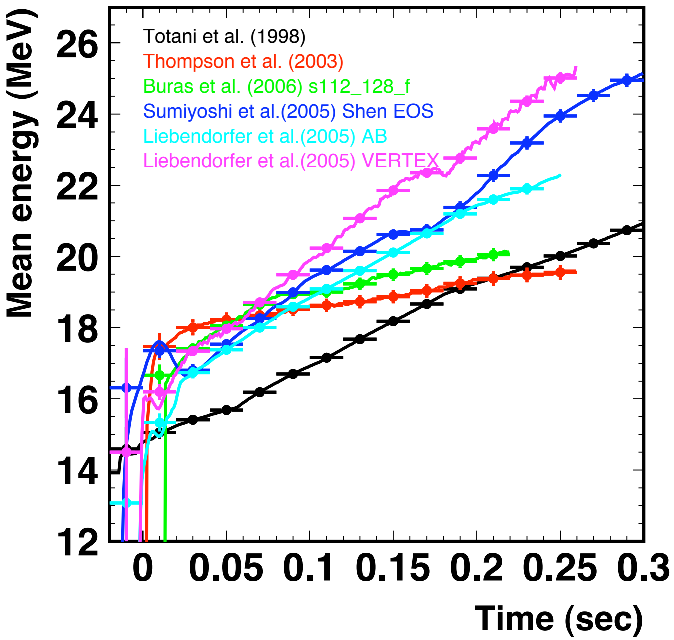
- Discovery reach (3σ)
  - $\tau(p \rightarrow \nu K^+) \sim 1.2\times10^{34}$years (HK 10yrs)
- Limit (90%CL)
  - $\tau(p \rightarrow \nu K^+) > 3.2\times10^{34}$years (HK 10yrs)

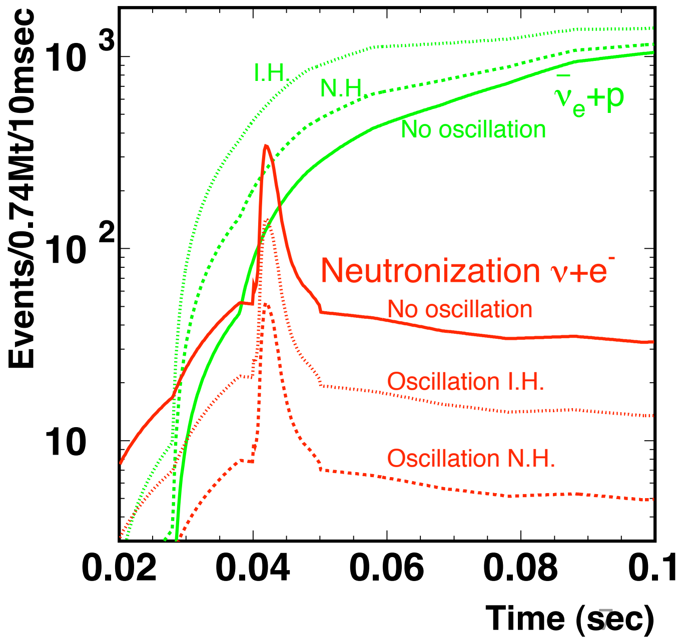
Good discovery potential, 90% CL sensitivity of $10^{34} \sim 10^{35}$ yrs

ν burst @ Milky way (10kpc)

- High statistical observation by 200,000 ν events
  - Time variation of (ν luminosity, temperature, flavor)
  - Explore core collapse and cooling mechanism (model)
    - exp'd νe from neutronization is 20(NH) or 56(IH) in 10msec duration→precise moment when a neutron start is born.
    - Precise time determination~1ms→combined study w/ optical and gravitational wave observation
  - Absolute ν mass (ν's TOF)→0.3~1.3eV/c^2
  - Energy spectrum transition by ν mass hierarchy



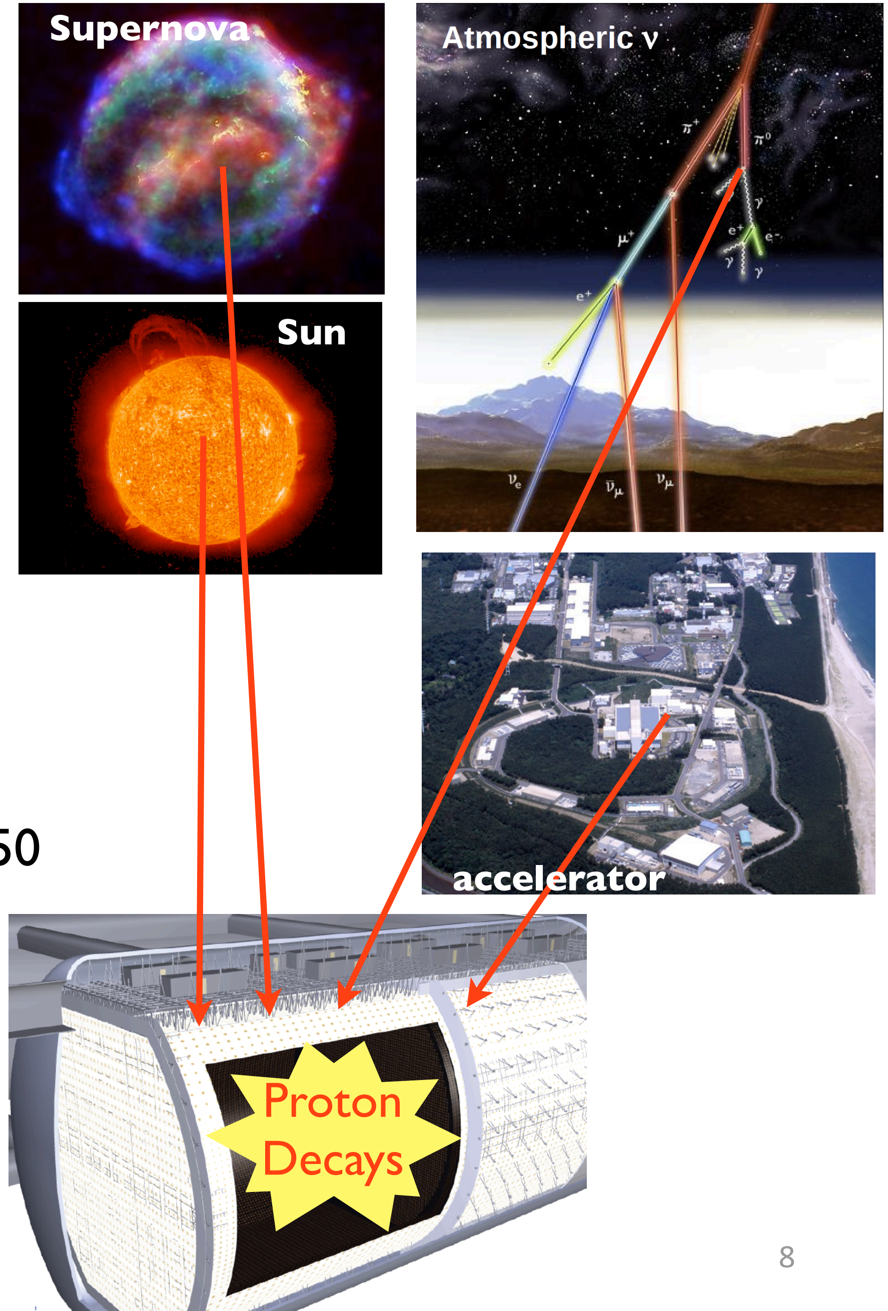




Letter of Intent, Hyper-K WG, arXiv:1109.3262 [hep-ex]

Multi-purpose detector, Hyper-K

- Total (fiducial) volume is 1 (0.56) million ton
  - 25 × Super-K
- Explore full picture of neutrino oscillation parameters.
  - Discovery of leptonic CP violation (Dirac δ)
  - ν mass hierarchy determination(Δm^2_{32}>0 or <0)
  - θ_{23} octant determination ($\theta_{23}<\pi/4$ or $>\pi/4$)
- Extend nucleon decay search sensitivity
  - $\tau_{proton}=10^{34}\sim10^{35}$ years (~10×Super-K)
- Neutrinos from astrophysical objects
  - 250,000 ν's from Supernova @Galactic-center (50 from Andromeda)
  - ~300 ν's / 10 years (>20MeV) SN relic ν
  - 200 ν's / day from Sun
    - possible time variation, ~3σ day/night asym.
  - Indirect Dark Matter Detection, etc



Uniqueness & Complementarity

Hyper-K	LBNE
H_2O 1 Mton	LAr 34 kton
300km, 0.6 GeV off-axis (narrow band) Good in CP asymmetry	1,300km, a few GeV on-axis (wide band) Good discri. power of MH
proton decays w/ high mass w/ free protons 10^{35} yrs for gauge mediated $p \rightarrow e^+\pi^0$ 10^{34} yrs for SUSY $p \rightarrow \nu K^+$	proton decays w/ high resolution low BG in SUSY $p \rightarrow \nu K^+$
supernova w/ high mass anti-nue	supernova nue
high statistics solar ν	solar?

Uniqueness of Hyper-K

- Well-proven & high performance detector technique w/ the successful experiences in Super-K

- Established sensitivities in accelerator/natural neutrino studies, proton decay searches

- Scalable to 1 million ton ← Super-K 50kton
  - High statistics measurement of ν_e appearance
  - Only realistic proposal to reach proton lifetime of 10^{35} years
  - High statistics observation of SNν → determination of onset time of Supernova ($\Delta t \sim 1$msec) and precise moment when a new neutron star or black hole is born

- J-PARC is expected to be upgraded to ~700kW by 2019 and beyond

- Rich physics topics, many discovery potentials

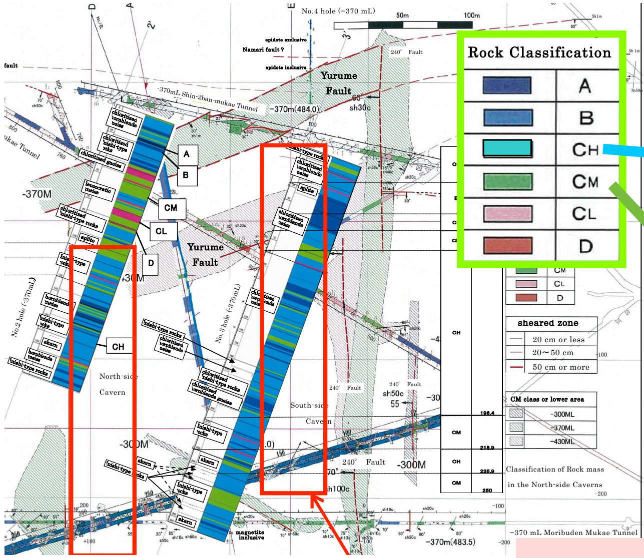
Complementarity with LBNE

- Accelerator based ν oscillation studies
  - Test of (non-)standard scenario in wide energy range and different baseline and technology (systematics)
  - HK: High statistics measurement of 1st oscillation maximum → good CP asymmetry measurement
  - LBNE: very long baseline → good discri. power of MH
  - Degeneracy of CPδ and MH in Hyper-K might be solved by LBNE if MH hasn't been determined

- Proton Decays
  - LBNE 34kt will detect K^+ in SUSY favored $p \to \nu K^+$ mode w/ less backgrounds→Comparable sensitivity in HK w/ more BG
  - HK has order of magnitude better sensitivity for $p \to e^+ \pi^0$ which many GUT models predict to occur
  - Independent confirmation of proton decays would be necessary to establish proton decays.

- Supernova ν
  - LBNE is sensitive to νe while HK is sensitive to anti-νe
  - HK will detect huge (~200,000) ν's at Galactic center
    - detailed information of explosion mechanism

Geological survey



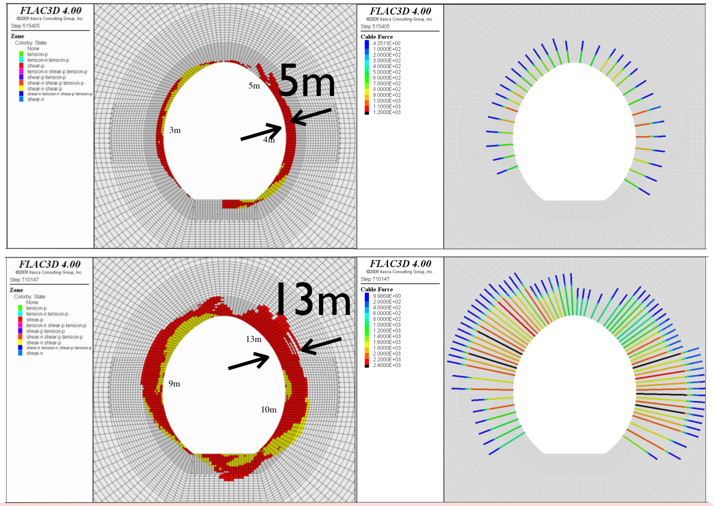
Cavern Design and Analysis

Plasticity region depth

PS-anchor tension

CH class

CM class

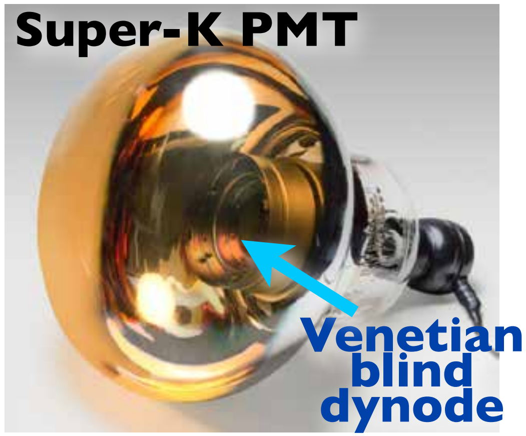


For dominant rock classes (B,CH,CM), the cavern construction is feasible, made design of supports.

Photo-detectors

R&D going on to get better performance and lower cost.

established

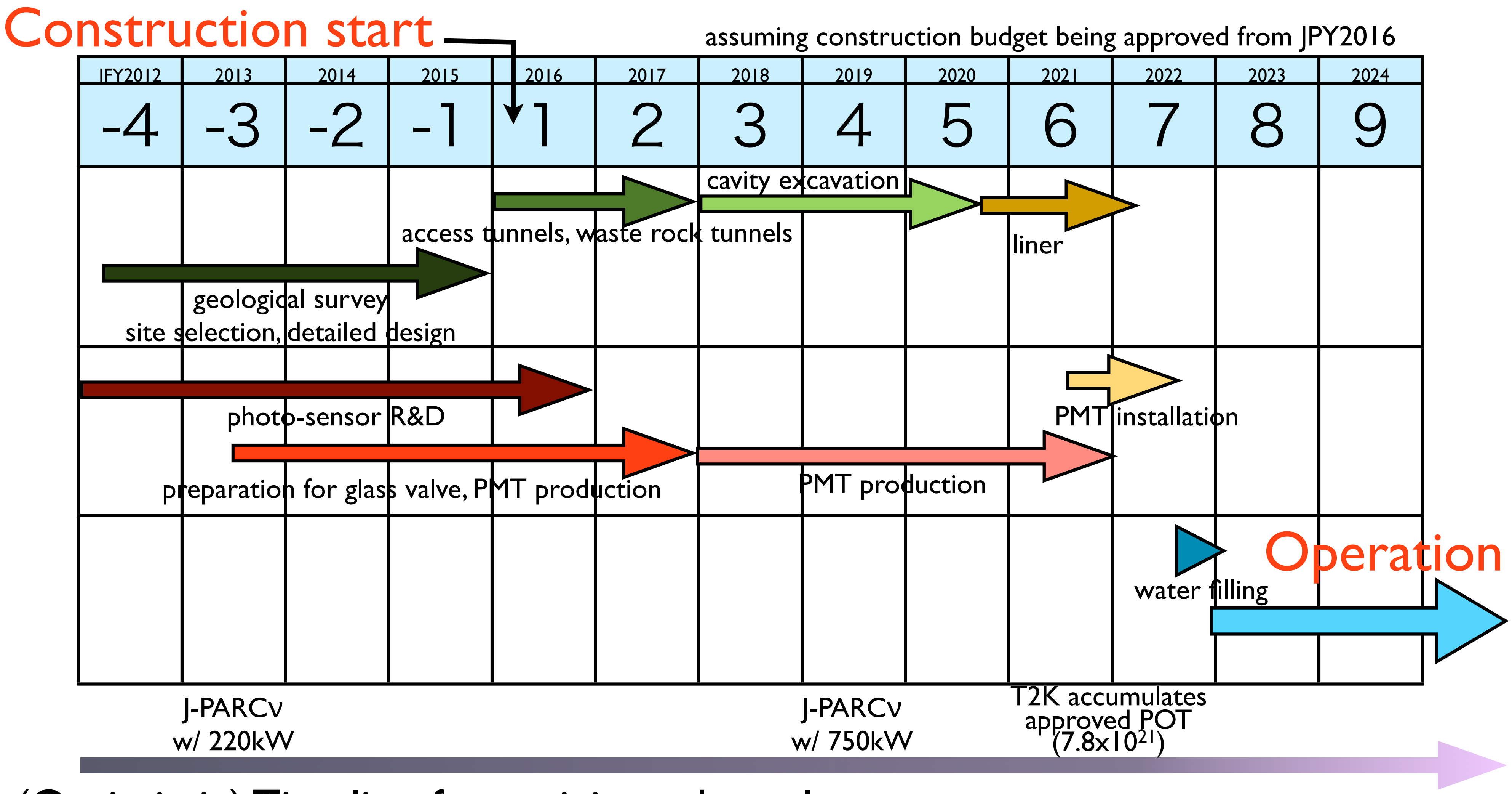


R&D

R&D

quantum eff. (QE)	22%	30%	30%
collection eff. (CE)	80%	93%	95%
timing resolution (FWHM)	5.5 nsec	2.7 nsec	1 nsec

Notional Timeline



<u>(Optimistic) Timeline for anticipated results</u>

-2022 ~2σ CPV indication (sinδ=1) by T2K+reactors (also in Nova)

-2023 *Start Hyper-K data taking*

-2026 Discovery of leptonic CPV w/ >5σ (MH at the same time or earlier)

-2028 Discovery of proton decays

-20XX Always ready for Supernova neutrino burst

International Hyper-K Working Group

- International open Hyper-K meetings: Aug. 2012, Jan. 2013, Jun. 2013. Next meeting is January 27-28, 2014.
- ~100 participants from Canada, Japan, Korea, Russia, Spain, Switzerland, UK, US, and so on. ~Half from outside of Japan.
- International Hyper-K working group has been formed.
  - We are still open to communities in the world
  - Organization is being improved for international

US participation history

- There is long and successful US-Japan partnership
  - Merged IMB and Kamiokande forces on Super-K and we also collaborated on K2K and T2K
  - US contributions to SK, K2K and T2K:
    - outer detector
    - calibration
    - electronics
    - low energy trigger system
    - radon free air system
    - T2K near detector and horns
    - K2K near detectors and water system
  - successful collaboration in KamLAND
- Major US participation and leadership in the Hyper-K are welcome and indispensable

Snowmass whitepaper "Hyper-Kamiokande Physics Opportunities" (arXiv:1309.0184)

- 167 authors from 49 institutes, 9 countries
- 59 authors from 14 institutes in Japan
- 43 authors from 13 institutes in US

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Chonnam National University (Korea): K.K. Joo

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* **University of California, Irvine (USA):** G. Carminati, S. Horiuchi, W.R. Kropp, S. Mine, M.B. Smy, H.W. Sobel

University of Liverpool (UK): N. McCauley, C. Touramanis

University of Oxford (UK): G. Barr, D. Wark, A. Weber

* **University of Pittsburgh (USA):** V. Paolone

University of Sheffield (UK): J.D. Perkin, L.F. Thompson

* **University of Washington (USA):** J. Detwiler, N. Tolich, R. J. Wilkes

University of Warwick (UK): G.J. Barker, S. Boyd, D.R. Hadley, M.D. Haigh

University of Winnipeg (Canada): B. Jamieson

* **Virginia Tech (USA):** S. M. Manecki, C. Mariani, S. D. Rountree, R. B. Vogelaar

York University (Canada): S. Bhadra

* interests from US

Toward budget request in Japan

- Grant-in-Aid ($2.3M/5year) R&D money for 5 years from 2013.

- We submitted the proposal to the Science Council of Japan in March 2013.
    - Hyper-K (far detector) construction and operation cost.
    - J-PARC operation w/ ~1MW and a near detector construction in the same package.

- **”SCJ Master plan of large scale research projects” is expected in March 2014**

- **“Roadmap of large scale research projects” to be released by MEXT in 2015.**

Europe

- Hyper-K opportunity submitted to European strategy process (Krakow meeting)

- First "Hyper-Kamiokande EU Open Meeting" will be held on December 18, 2013

- Statement-of-Interest (SoI) to STFC for HK has been approved. Full proposal to be submitted in 2014.

Canada

- Proposal to Canadian Foundation for Innovation under preparation

- Green light from TRIUMF to proceed

- Final proposal some time in June 2014

Cost Estimate

Total	800M USD*	
Cavern	300M USD	
Tank & structure	200M USD	
Photo-sensors	200M USD	High QE HPD
Near Detector	30M USD	@Tokai

*The cost of rock disposal and water purification system to be added in the future

- Contribution from each country is under discussion in the Hyper-K WG
- Proportional sharing in an international project is ideal.

- The target for international contribution is 30% to 50% of the cost.

Possible foreign contributions

A conceptual design exists.
We are open to ideas toward a full design.

- Cavity and structure (500M USD)
  - contribution of innovative design and materials welcome e.g. LBNE WC liner & PMT mounting
- Photosensors (200M USD)
  - open to manufacturers other than Hamamatsu. Competition helps reduce cost.
  - Innovative ideas like MPC PMT welcome.
- Electronics, Calibration
  - This is an area where foreign contributions are expected.
- Other systems of modest scope
  - outer detector
  - water system
  - near detector
- Accelerator (J-PARC) and beamline intensity upgrade.
  - history of accelerator lab collaboration.

Summary

- The Hyper-K project has strong physics cases, promising sensitivities and discovery potentials.
  - aiming to establish unification of forces
  - understand ν's mass, mixing, and CPδ
  - inputs to understand the history of universe

- Major US participation and leadership in the project are welcome and indispensable.

- Need strong support by P5.

Supplements

Hyper-K Working Group Organization

- oversee the HK group
- channel for contacting to the group
- involve non-Japanese in future

Steering Committee
Nakaya (chair)
Aihara, Nakahata,
Shiozawa, Yokoyama
+ a few more

- PL oversees the sub-WGs
- WG conveners may be composed of one Japanese plus some non-Japanese.

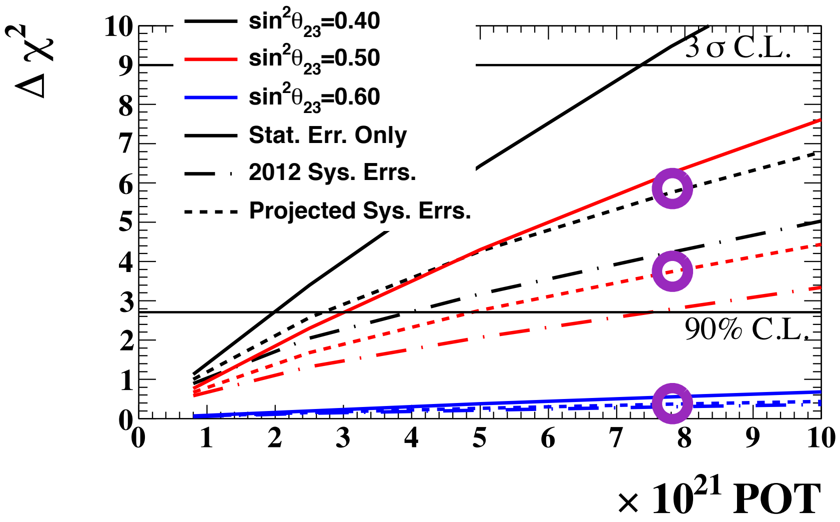
Project Leader
Shiozawa

- WG1: Shiozawa
- WG2: Sekiya, Vagins
- WG3: Nakayama, Nishimura
- WG4: Hayato
- WG5: Miura, Walter, F.D.Lodovico
- WG6: Hide Tanaka, Hiro Tanaka, Koshio, Mine, Mccauley
- WG7: Hartz
- Physics WG conveners: Yokoyama
  - Phys-WG1: Yokoyama
  - Phys-WG2: Wendell
  - Phys-WG3: Takeuchi

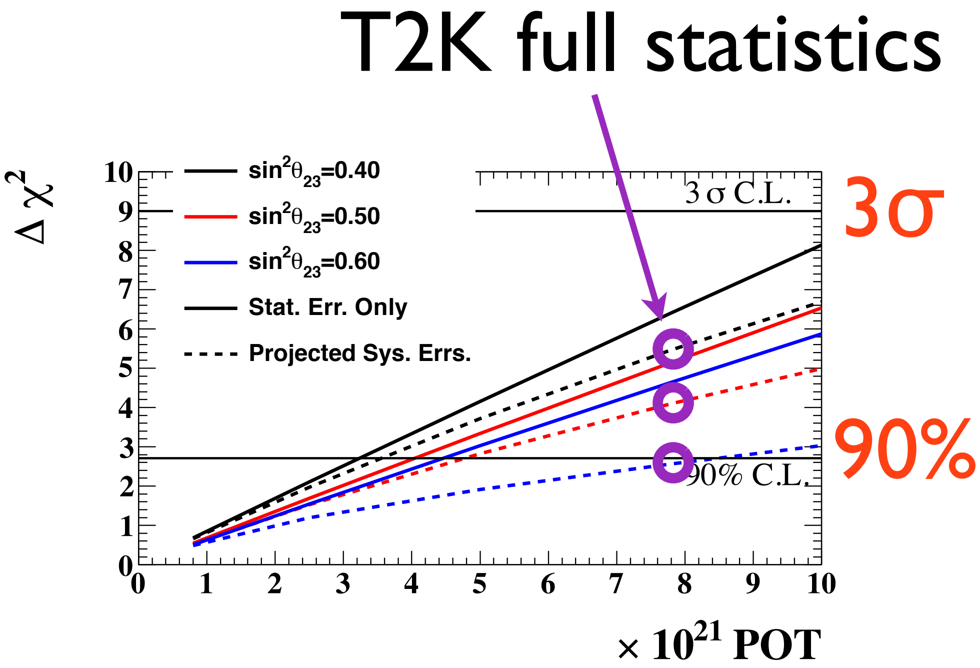
WG1: Cavity and Tank
WG2: Water
WG3: Photo-sensor
WG4: DAQ
WG5: Software
WG6: Calibration
WG7: Accelerator&Near Detectors

Phys-WG1: Accelerator
Phys-WG2: Atmν+Nucleon decays
Phys-WG3: Astroparticle Physics (SN, solarν, etc)

CPV w/ T2K



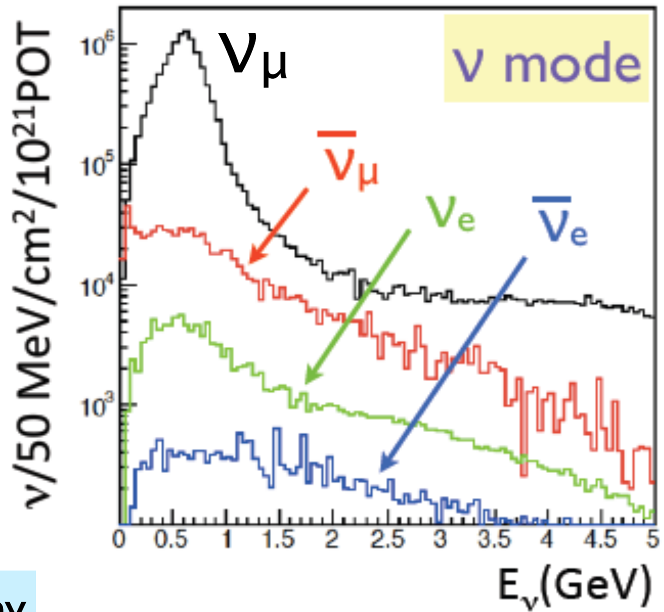
(a) 100% ν-running.

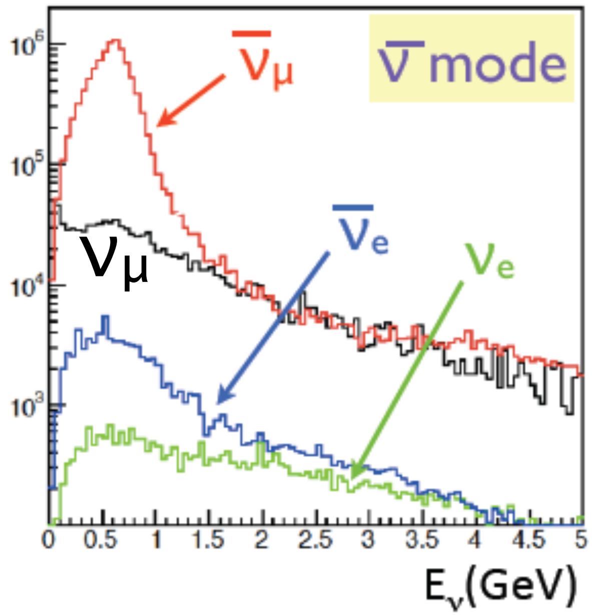


(b) 50% ν-, 50% $\bar{\nu}$ running.

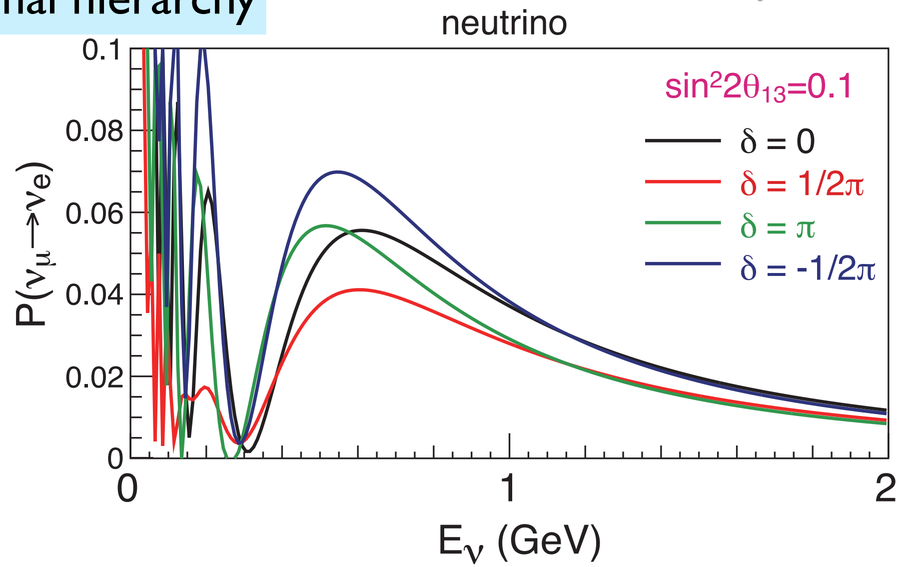
Figure 26: The expected $\Delta\chi^2$ for $\sin\delta_{CP} = 0$ plotted as a function of POT. Plots assume true $\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = +90°$, inverted MH, and various true values of $\sin^2\theta_{23}$ (as given in the plot legends). The solid curves include statistical errors only, while the dash-dotted (dashed) curves assume the 2012 systematic errors (the projected systematic errors). Note that the sensitivity heavily depends on the assumed conditions, and that the conditions applied for these figures ($\delta_{CP} = +90°$, inverted MH) correspond to the case where the sensitivity for $\sin\delta_{CP} \neq 0$ is maximal.

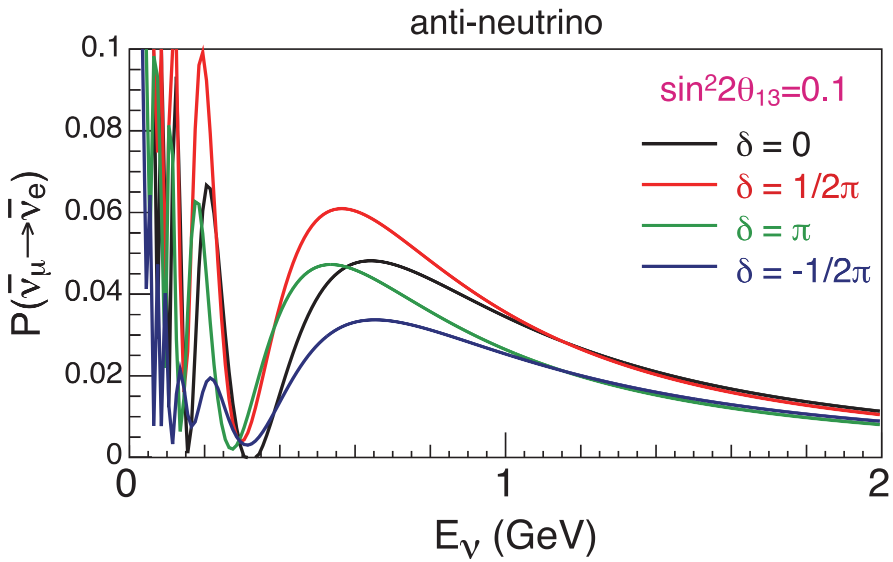
$\nu_\mu \rightarrow \nu_e$ vs $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$





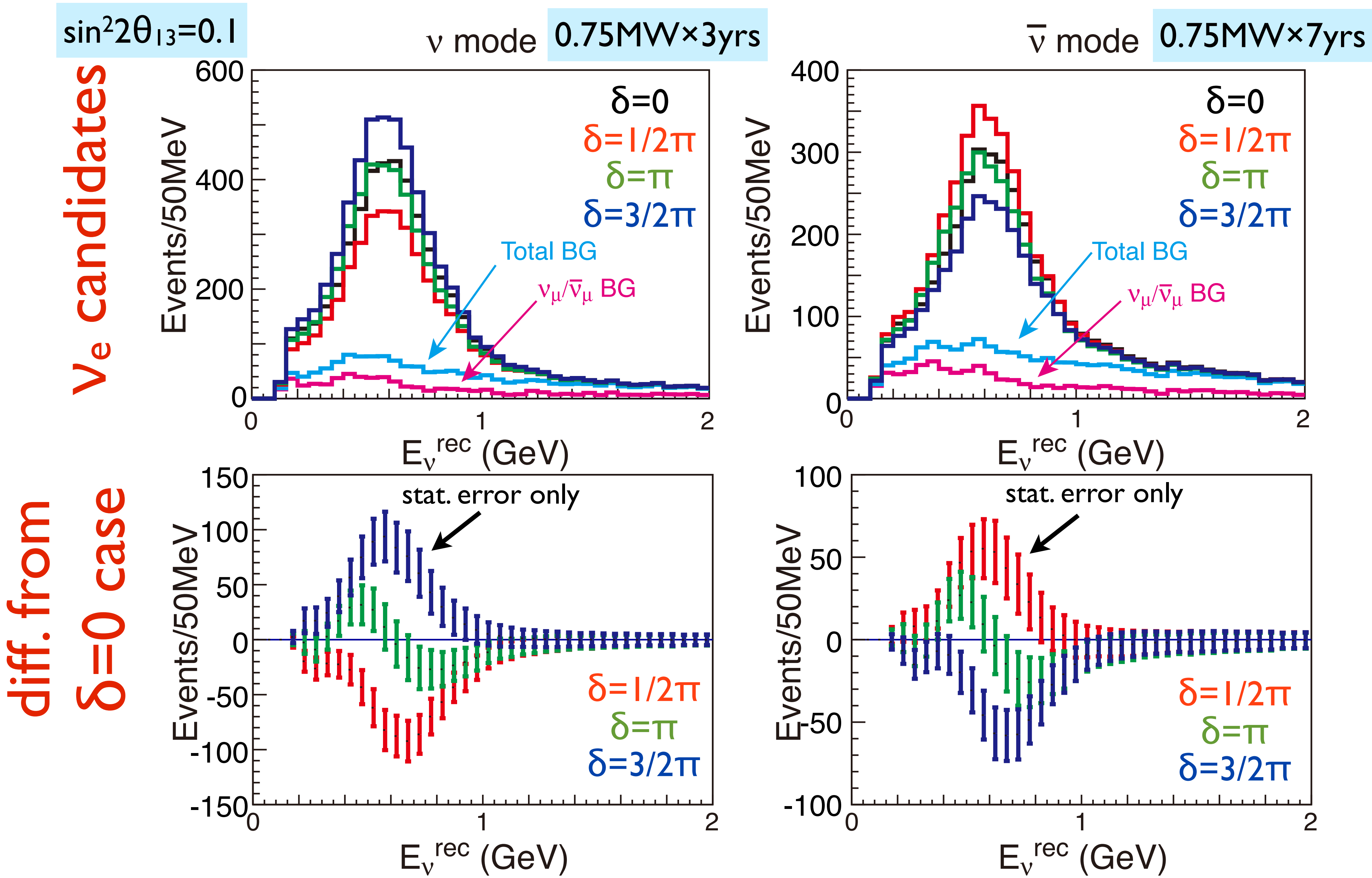
Normal hierarchy





- CPV test by comparing $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- sensitive to exotic CPV (non MNS matrix origin)

Expected ν_e CC candidates



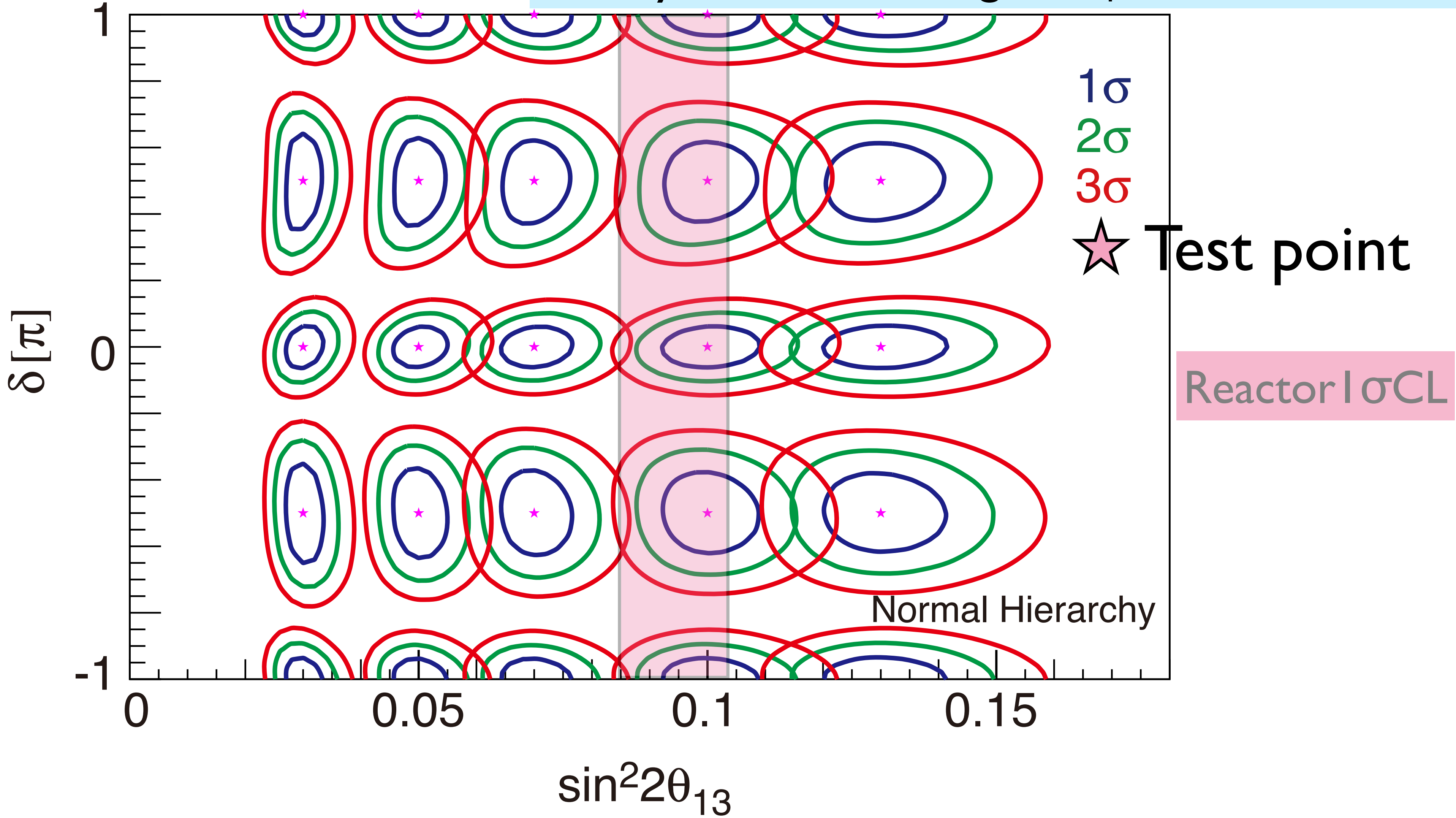
- νe: ~3500 events, $\bar{\nu}$e: ~2000 events
- ±25% variation due to CP δ

Contours

7.5MW・years

Normal mass hierarchy (known)

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

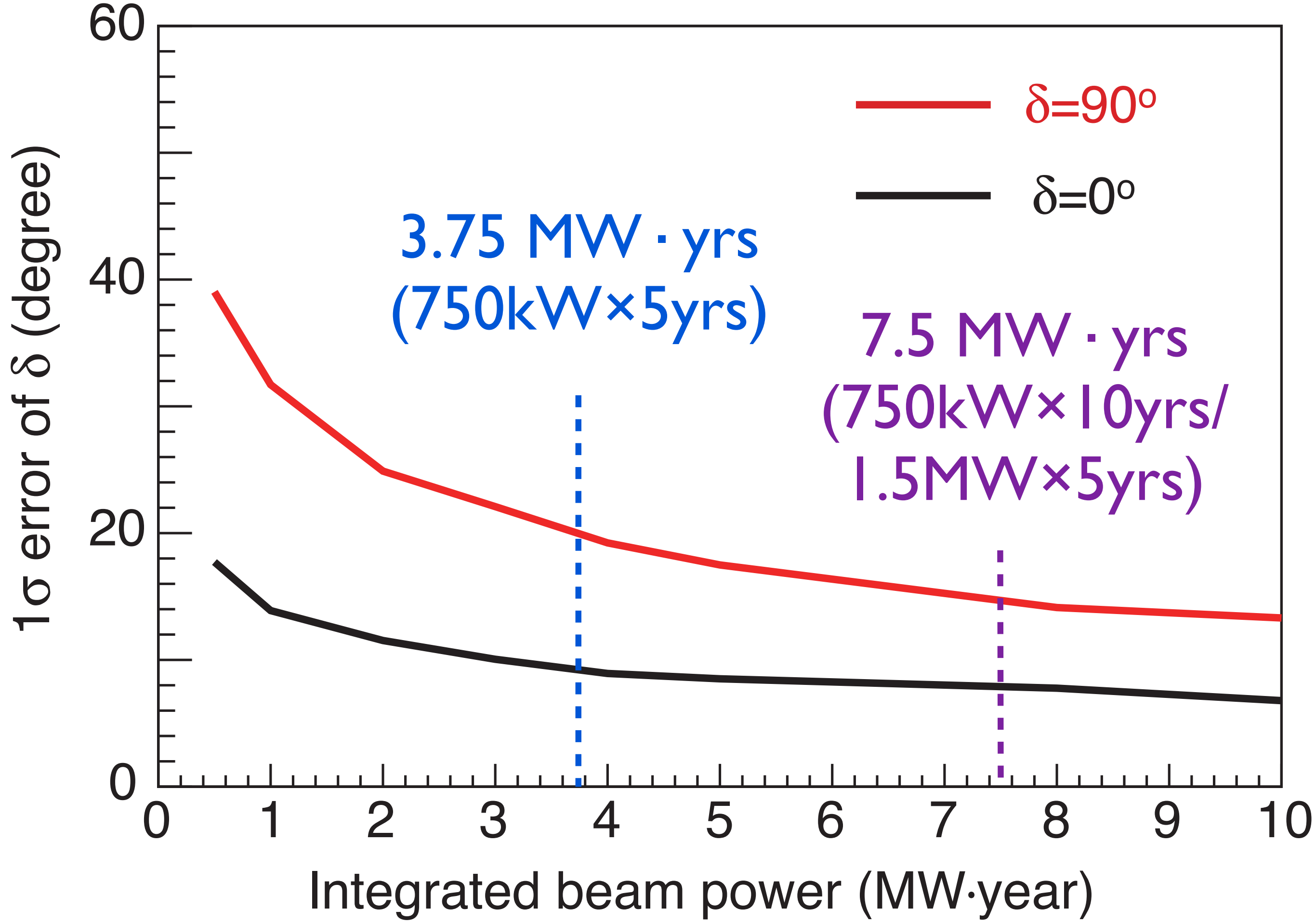


- Good sensitivity for CPV

δ resolution (1σ)

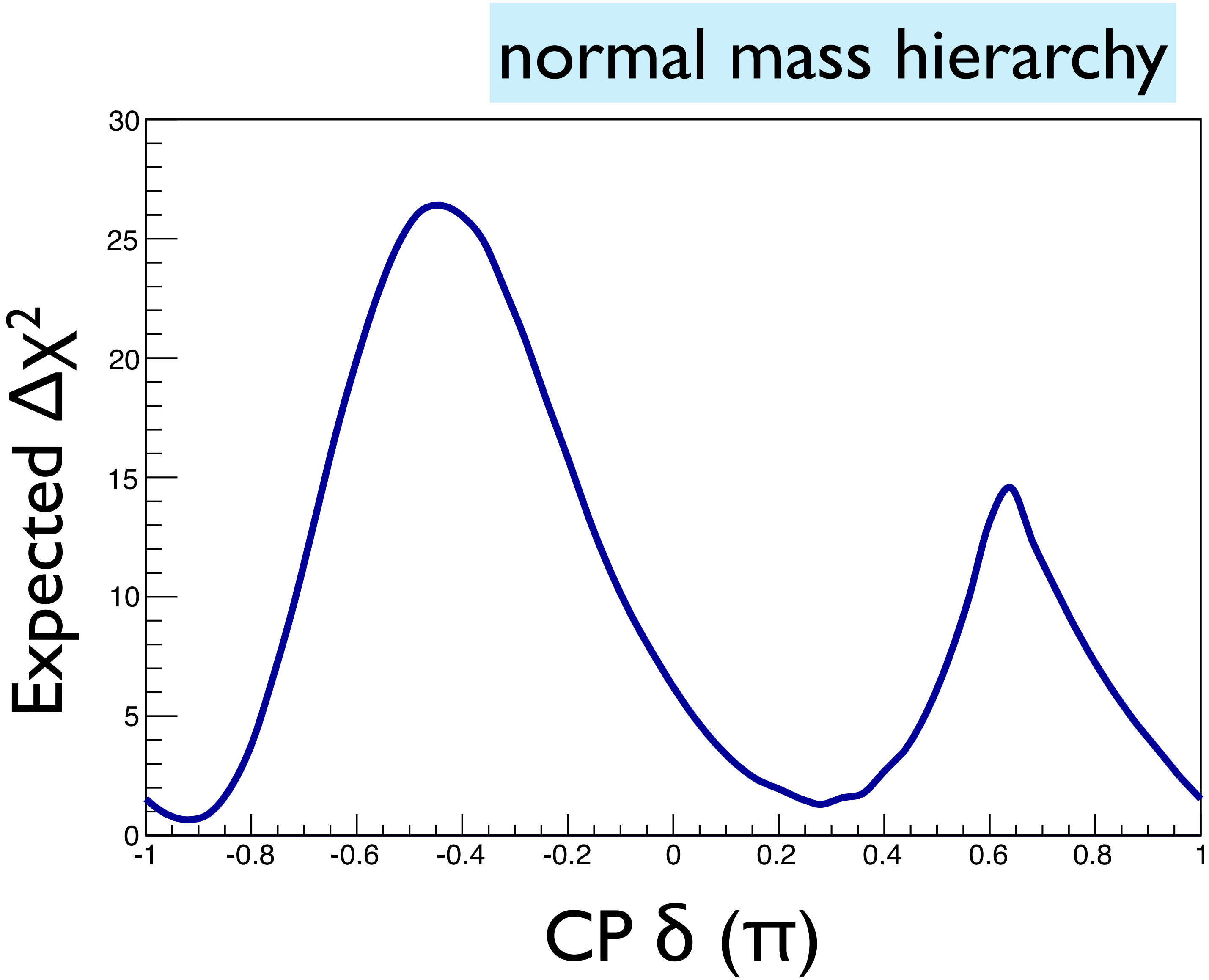
Normal mass hierarchy (known)

$\sin^2 2\theta_{13}=0.1$



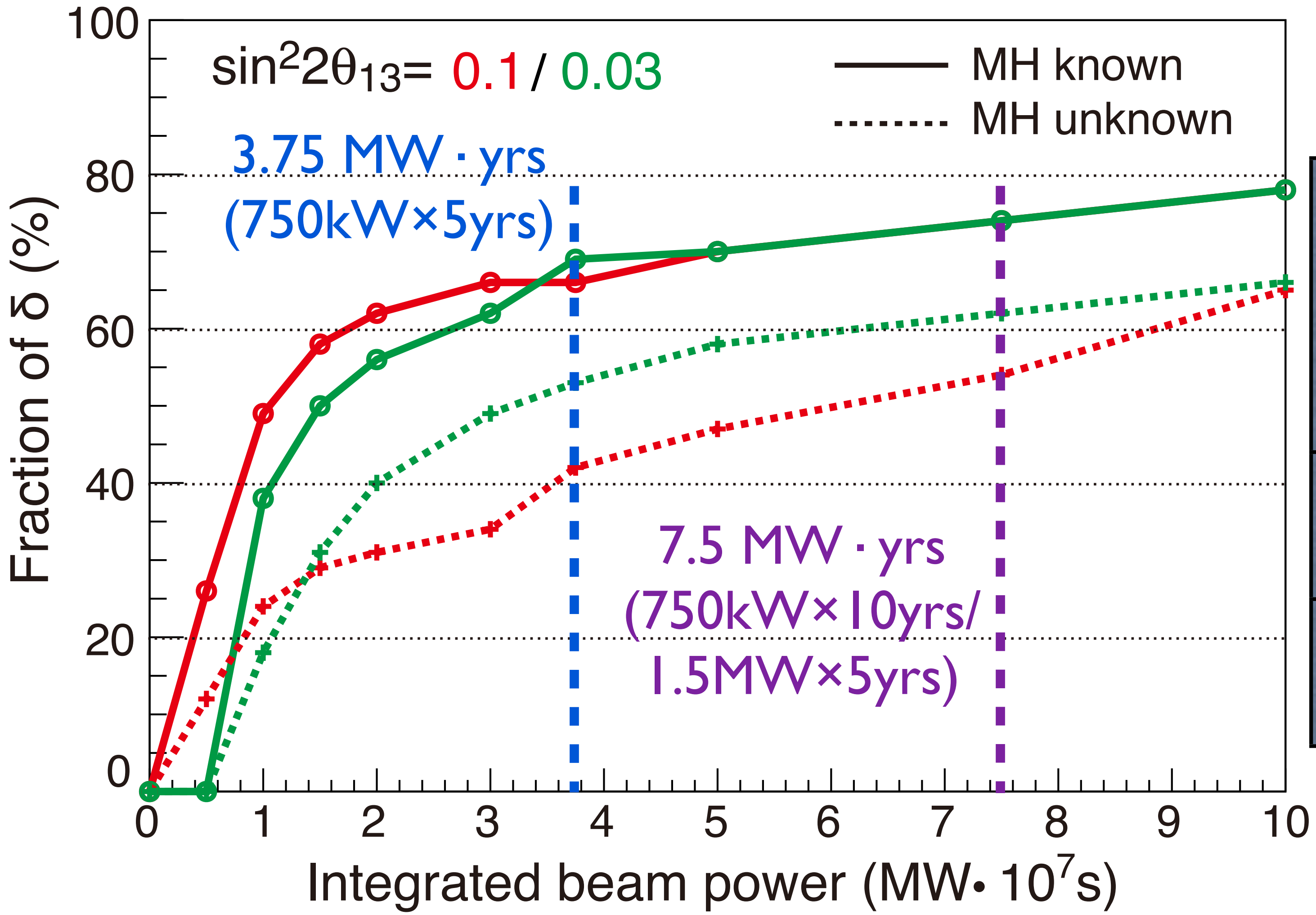
- δ precision < 20° (δ=90°)
  < 10° (δ= 0°)

MH determination w/ Hyper-K/J-PARC



Fraction of δ (%) for CPV discovery

Fraction of δ in % for which expected CPV ($\sin\delta \neq 0$) significance is $>3\sigma$



$\sin^2 2\theta_{13}=0.1$

(MW× yrs)	Mass hierarchy	
	known	unknown
3.75	69%	42%
7.5	74%	54%

- Effect of unknown mass hierarchy is limited
  - Input from atm ν and other experiments also expected for MH

Atmospheric ν_e oscillation

NuclPhysB669,255(2003)

NuclPhysB680,479(2004)

$$\frac{\Phi(\nu_e)}{\Phi_0(\nu_e)} - 1 \approx P_2(r \cdot \cos^2\theta_{23} - 1) \quad \text{Solar term}$$
$$- r \cdot \sin\tilde{\theta}_{13} \cdot \cos^2\tilde{\theta}_{13} \cdot \sin 2\theta_{23}(\cos\delta \cdot R_2 - \sin\delta \cdot I_2) \quad \text{Interference term } (\delta CP)$$
$$\boxed{+2\sin^2\tilde{\theta}_{13}(r \cdot \sin^2\theta_{23} - 1)} \quad \theta_{13} \text{ resonance term} \qquad (3)$$

r : μ/e flux ratio (~2 at low energy)

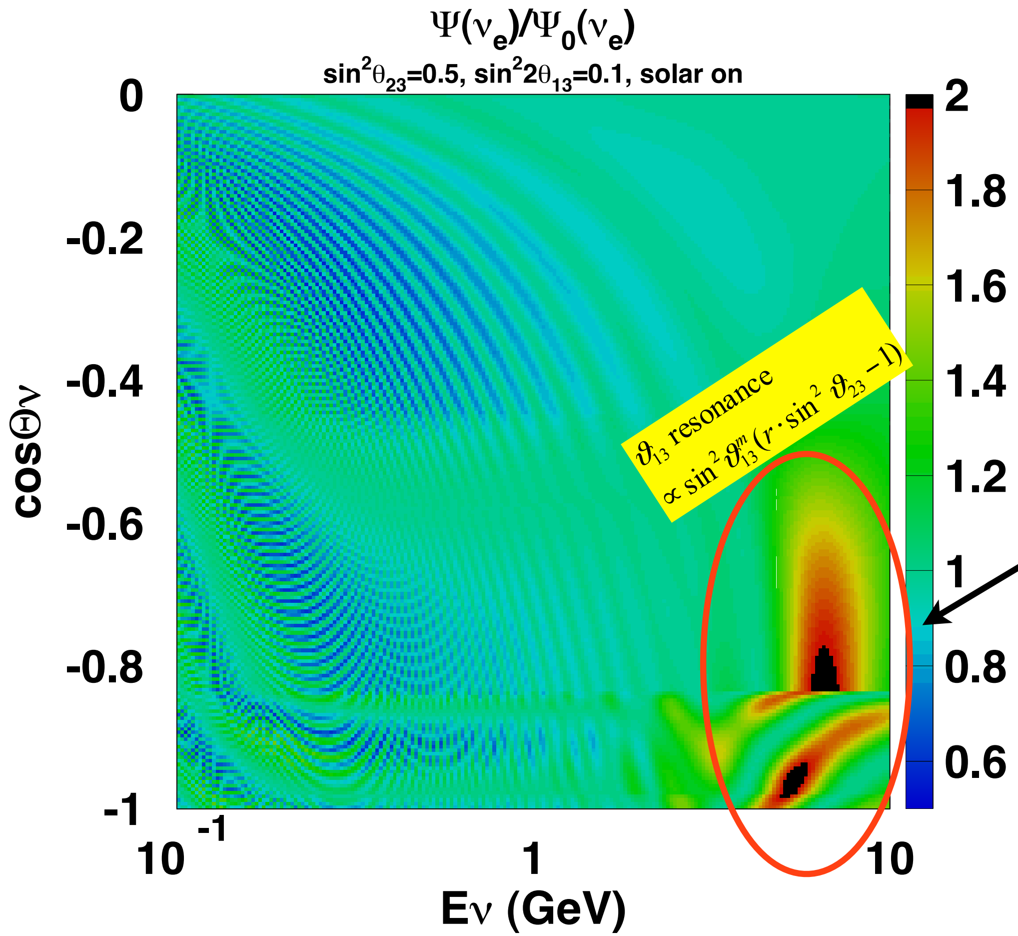
$P_2 = |A_{e\mu}|^2$: 2ν transition probability $\nu_e \rightarrow \nu_{\mu\tau}$ in matter

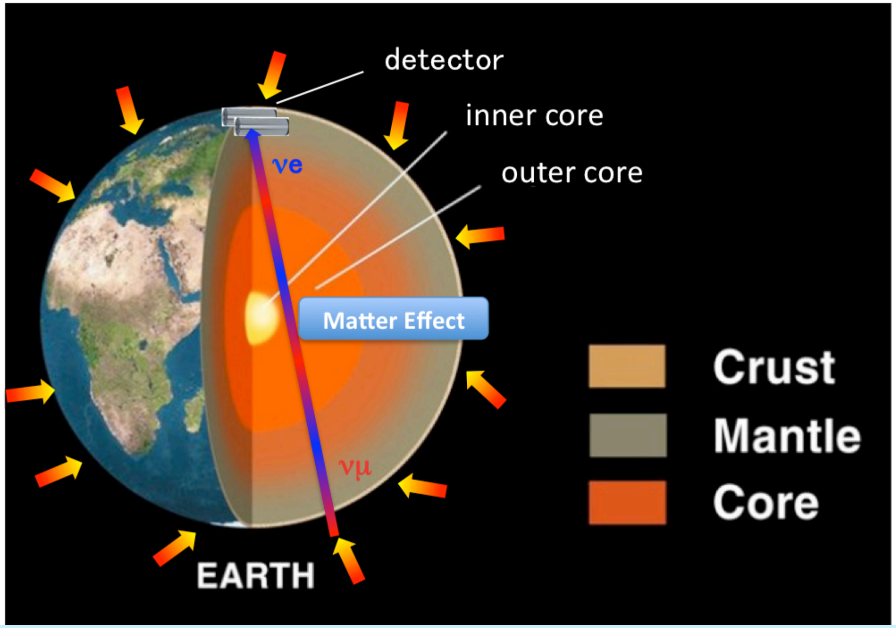
$R_2 = \mathrm{Re}(A^*_{ee}A_{e\mu})$

$I_2 = \mathrm{Im}(A^*_{ee}A_{e\mu})$

A_{ee} : survival amplitude of the 2ν system

$A_{e\mu}$: transition amplitude of the 2ν system





ν_e appearance (and ν_μ distortion) is expected due to MSW effect in the Earth's matter

- happens in ν in the case of normal mass hierarchy
- in anti-ν in inverted mass hierarchy

Large θ_{13} value gives us a good chance to discriminate mass hierarchy.

ν_e-like and anti-ν_e-like sample

$$\nu_e + N \rightarrow e^- + X$$
$$\bar{\nu}_e + N \rightarrow e^+ + X$$

- ν_e CC produce more π^+
  - more muon decays
- More energy transfer to hadronic system
  - lower charged lepton energy
  - more pions (muon decays)

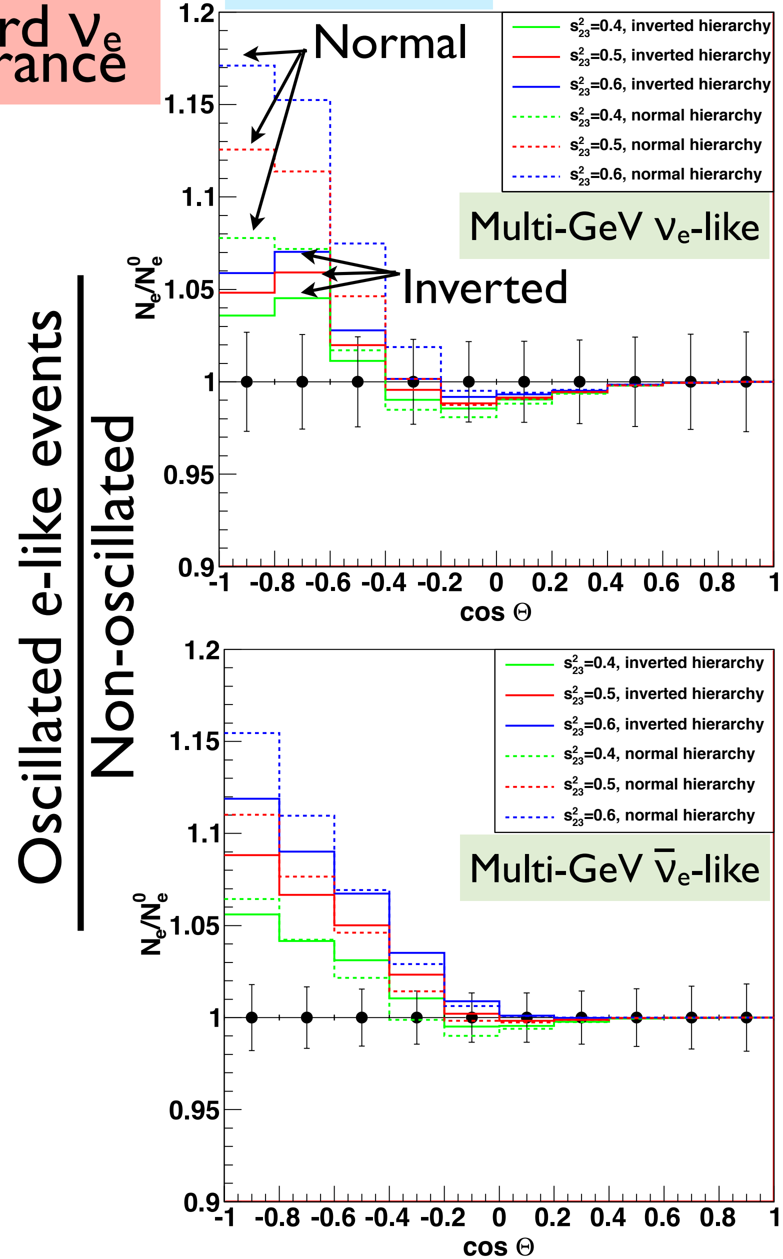
enrichment by variables

- # of rings
- # of muon decay electrons
- Lepton energy fraction
- transverse momentum

	νe CC	anti-νe CC	others	Total
νe-like	57%	11%	32.0%	100%
anti-νe-like	55%	34%	11%	100%

Upward ν_e appearance

$\sin^2 2\theta_{13}$=0.1

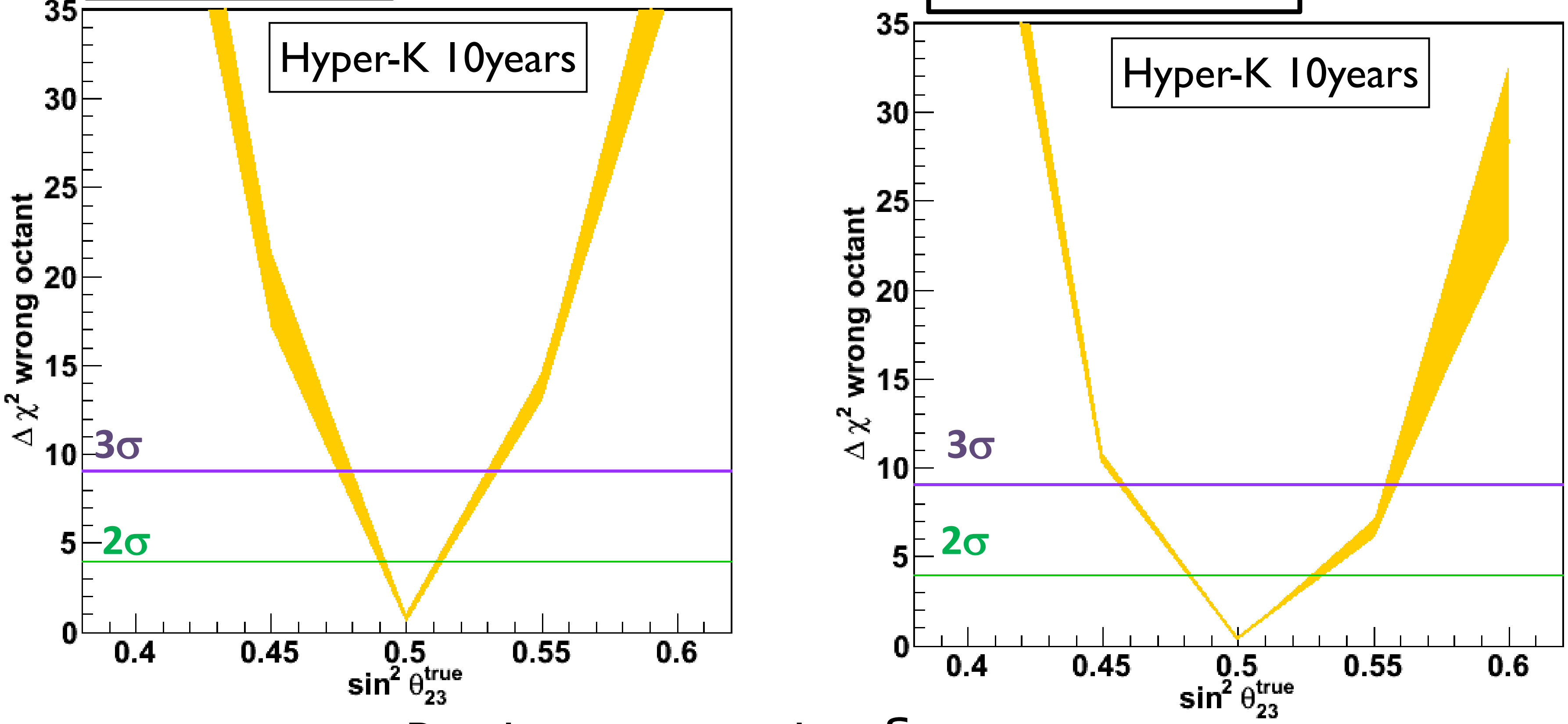


θ_{23} octant

NH, unknown

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

IH, Unknown



Bands correspond to δ_{CP} uncertainty

If $\sin^2 2\theta_{23}<0.99$ ($\sin^2\theta_{23}<0.45$ or $\sin^2\theta_{23}>0.55$), θ_{23} octant can be determined at $>3\sigma$.

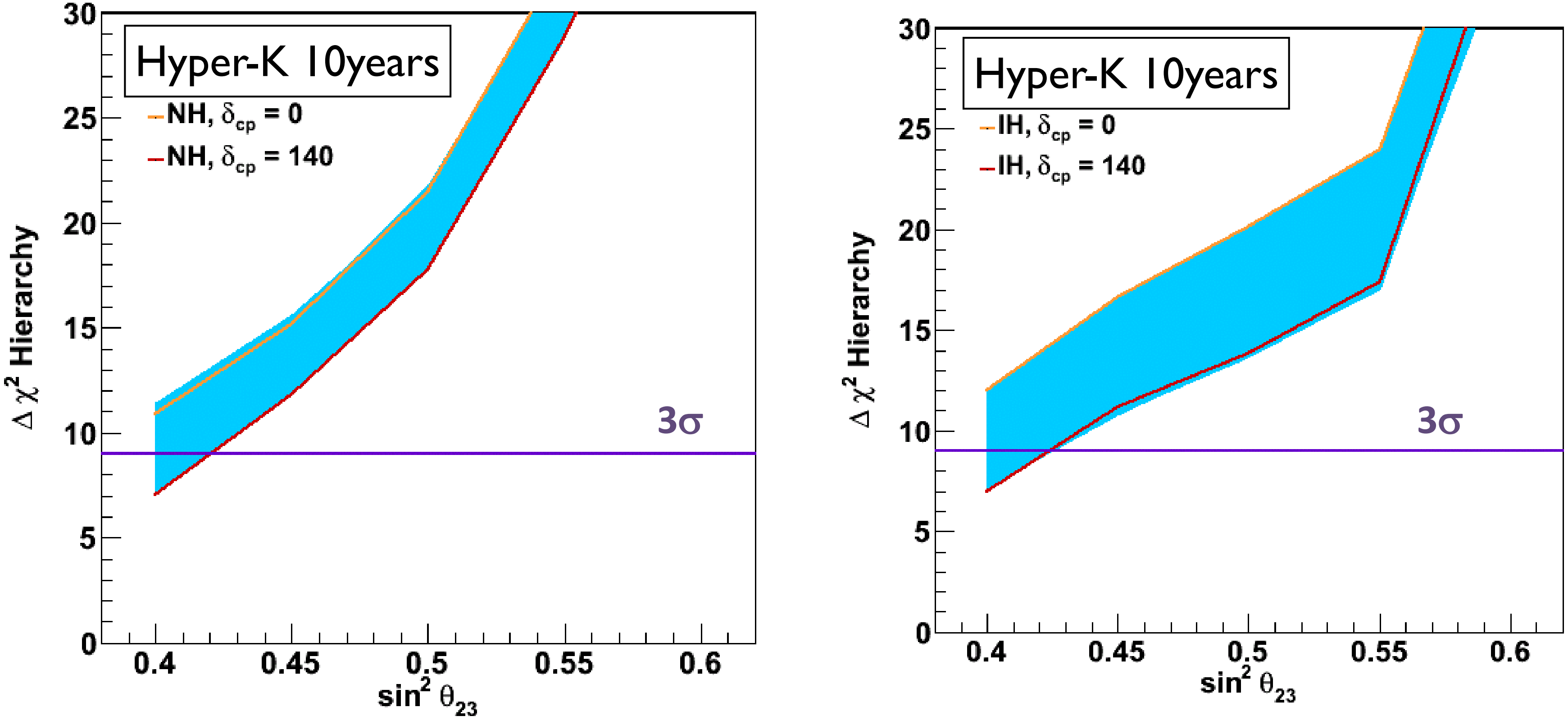
Expect constraints on δ_{CP} as complement to the accelerator ν studies.

Mass hierarchy discrimination power

NH, unknown

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

IH, Unknown

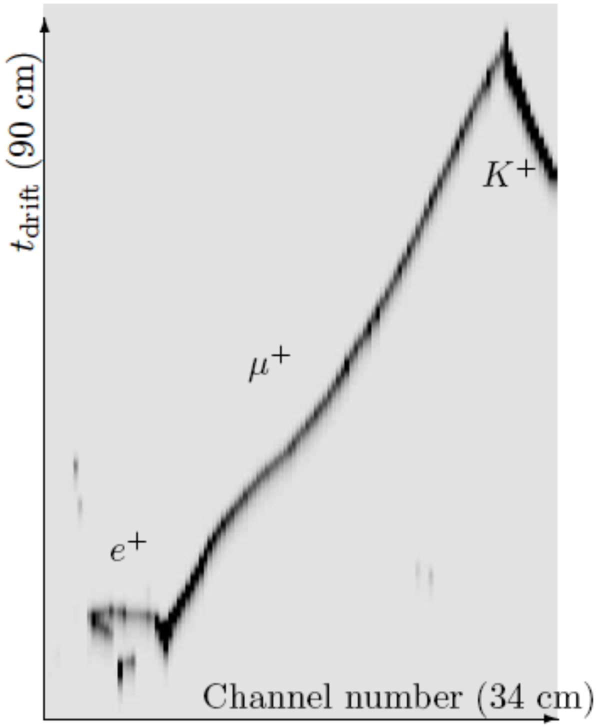


Bands correspond to δ_{CP} variation

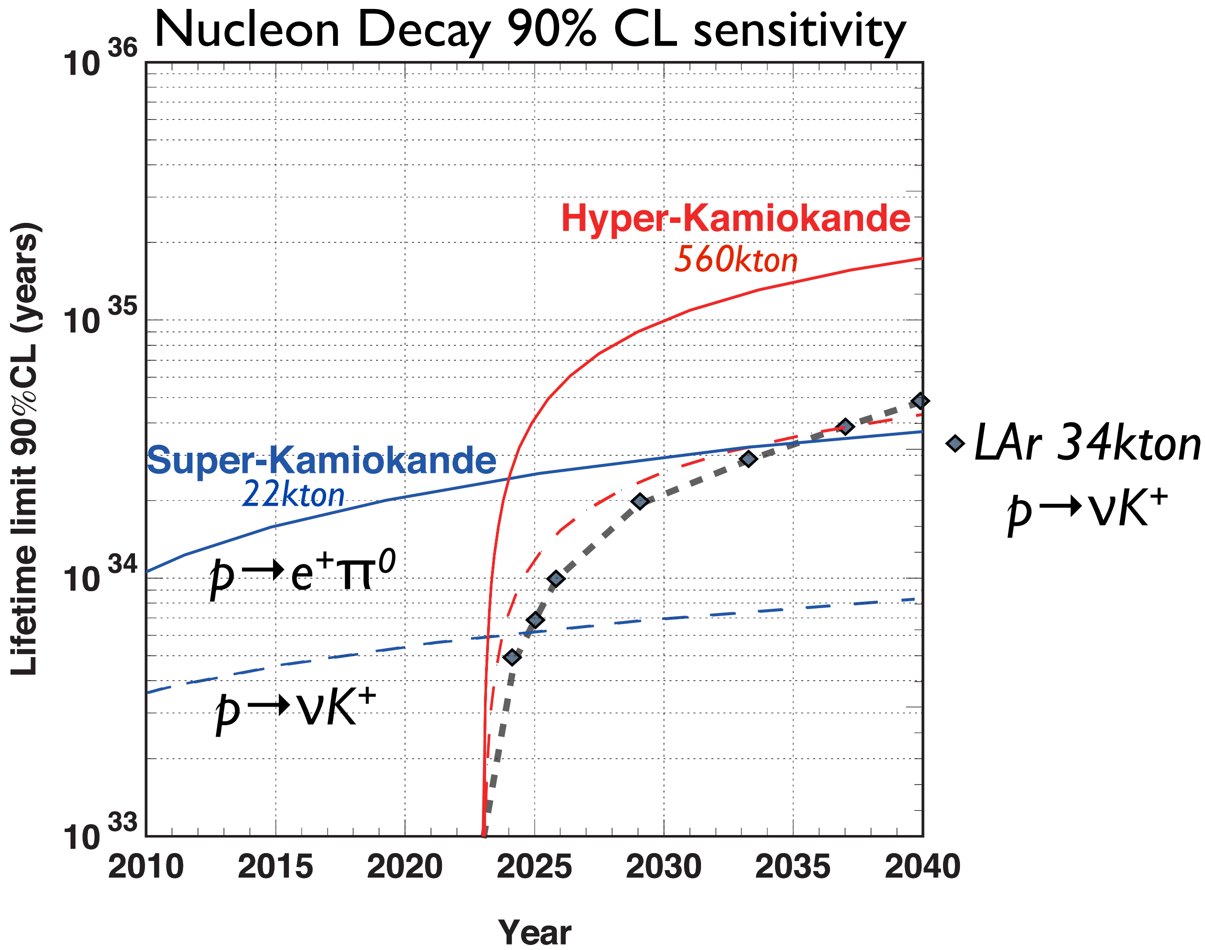
- expect to discriminate normal from inverted hierarchy w/ 3σ significance by <~10years data.
- Higher significance and shorter time for larger θ_{23}

Proton Decays in HK & LBNE

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



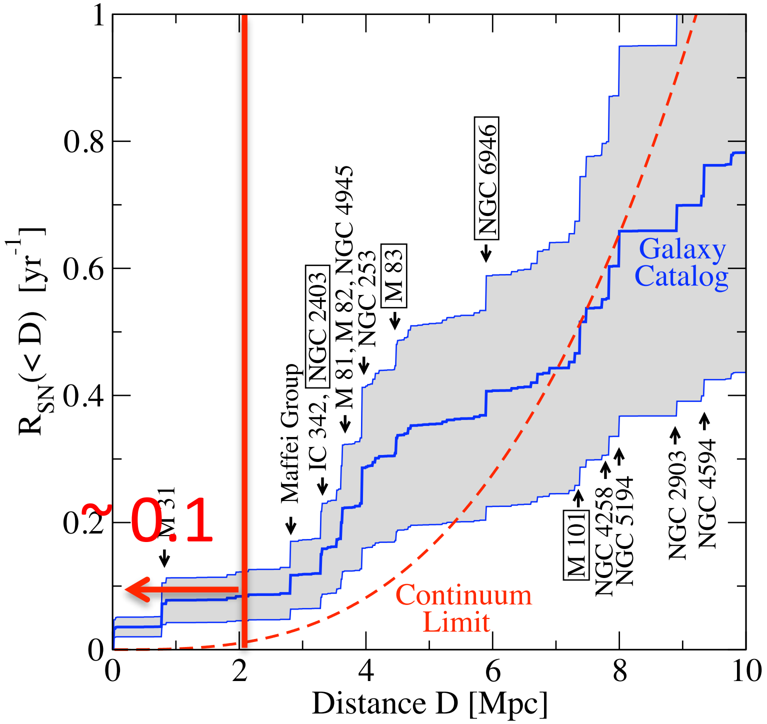
Excellent particle tracking capability, high momentum resolution
→efficiency=98%!
BG=0.3ev/10years



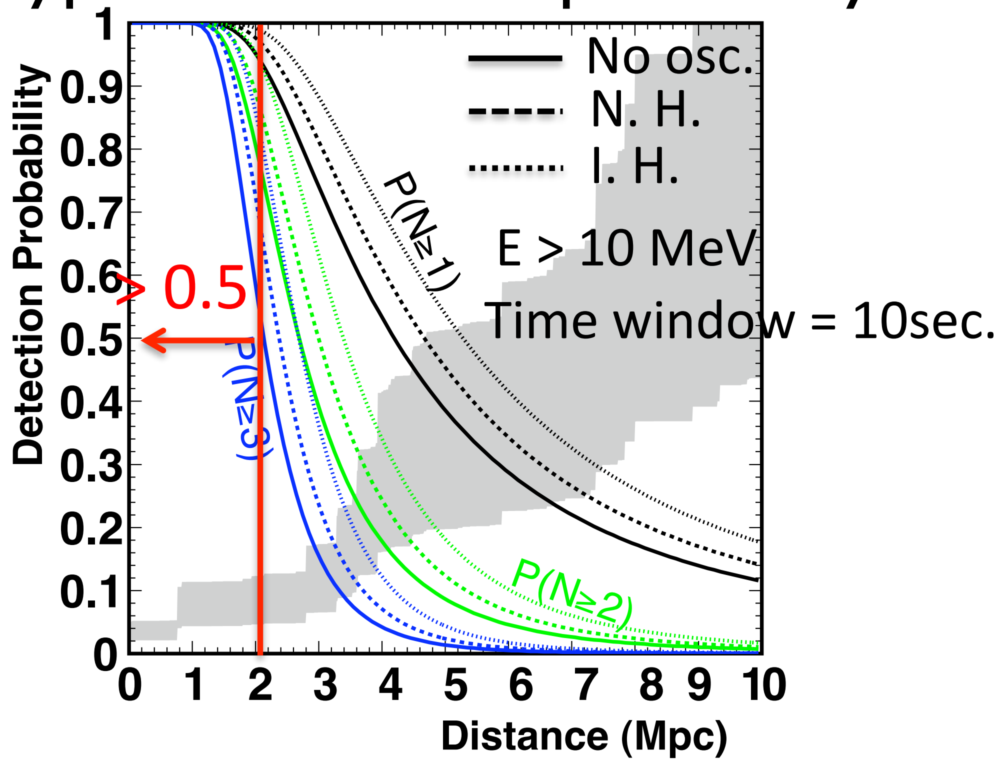
• competitive and complementary with water detector
• would become more important in the era of precise measurements of proton decay branches.

Supernova neutrinos

Cumulative supernova rate



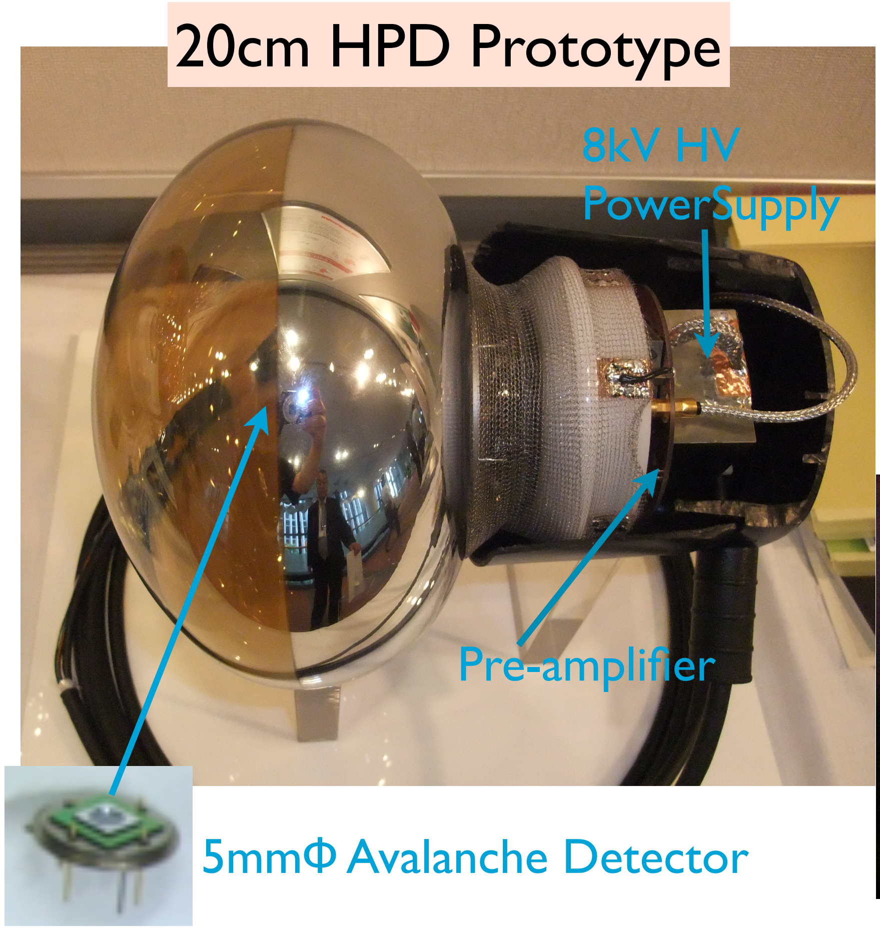
Hyper-K detection probability

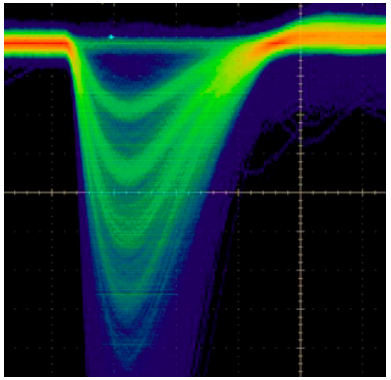


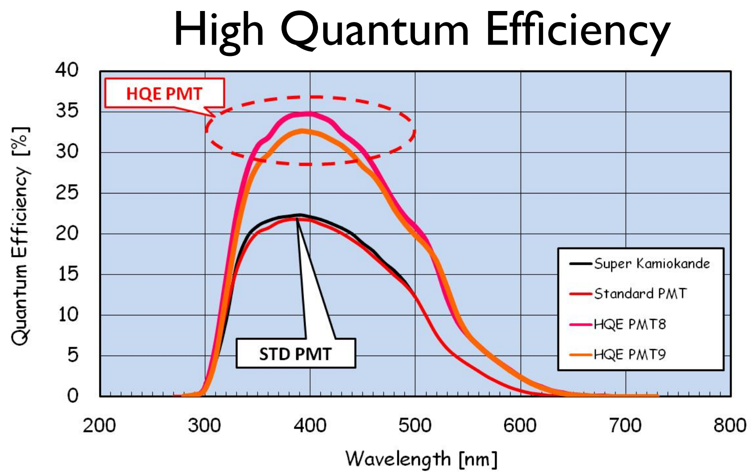
- 1SN about every 10 years is expected within 2 Mpc
- >50% efficiency is estimated for required signal multiplicity of 3 for SN at 2 Mpc distance.
- Further study will be performed on E threshold and expected BG.

Photo-detector R&D

- Candidates
  - 50cm Super-K PMT
  - [NEW] High QE 50cmΦ Hybrid Photo Detector (HPD)
  - [NEW] High QE re-designed 50cm PMT
- Test of 20cm HPD and 50cm HQE PMT in water tank from August 2013
- 50cm HPD prototype expected in August 2013







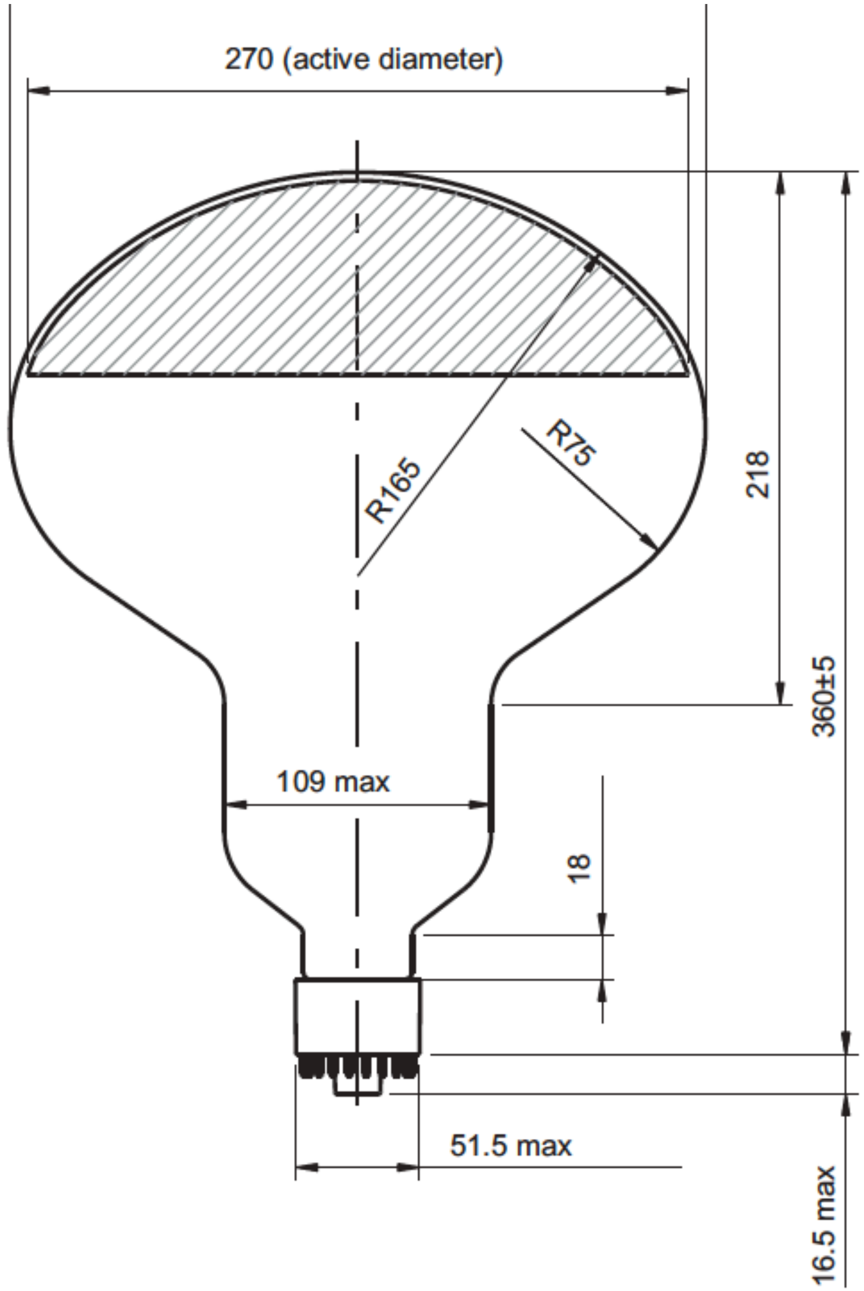
"Texas" PMT's

- ✓ Currently, only Hamamatsu produces large (>8") PMT's for use in physics experiments. Lack of competition for a device used in many physics experiments is not healthy.
- ✓ US NSF S4 program includes development of alternative domestic supplier of PMTs. This program will end next year after delivery and testing of ~20 11" prototype PMT's from ADIT/ETL, in Sweetwater Texas. This same company owns Ludlum Instruments and Eljen and has purchased Electron Tubes, Limited.
- ✓ The 11" PMT could be a suitable candidate for the Hyper-Kamiokande Outer Detector, and some U.S. folks are pursuing this possibility.

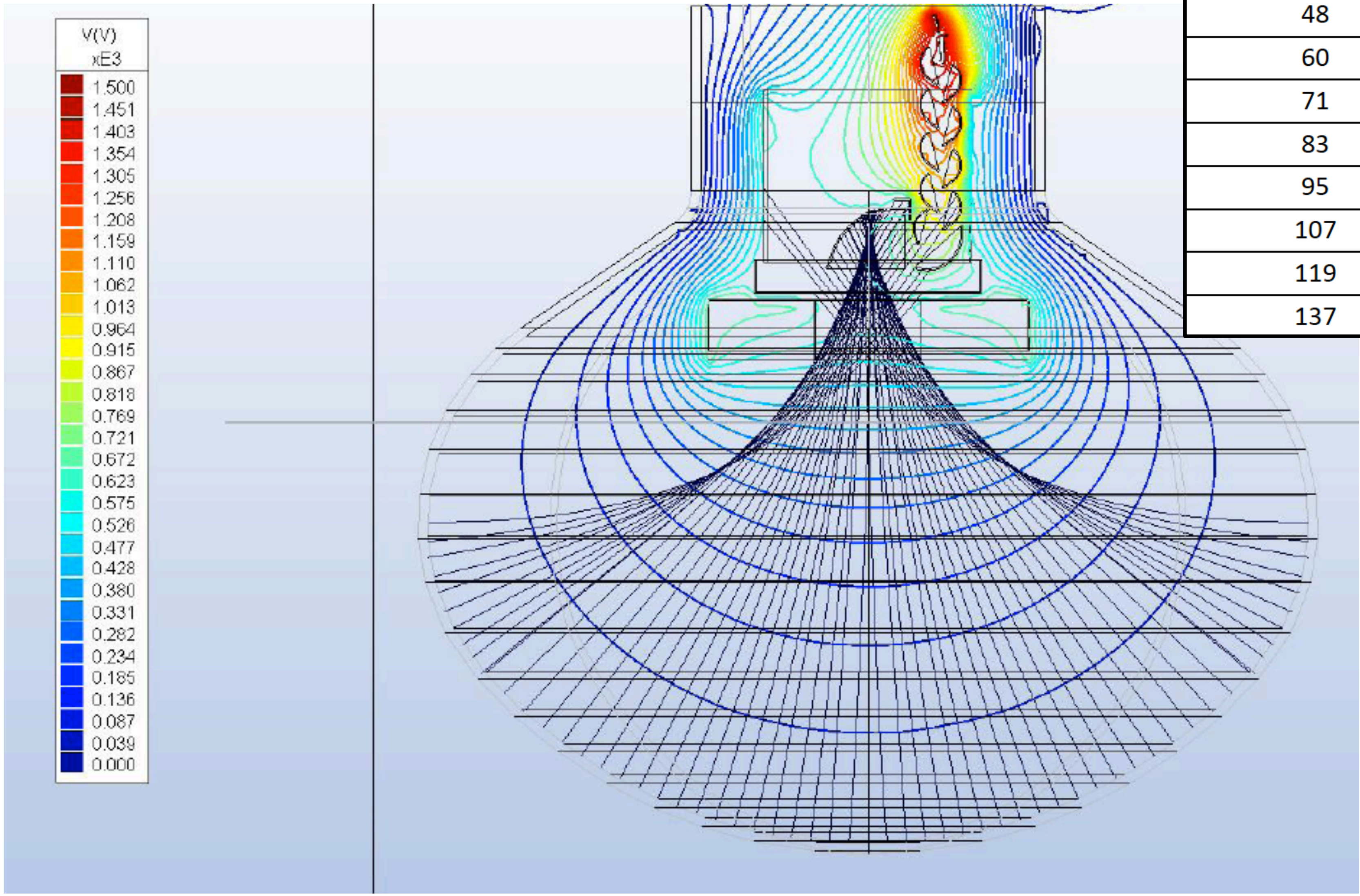
280 mm (11″) photomultiplier
D784KFLB provisional data sheet

ET Enterprises electron tubes

	unit	min	typ	max
photocathode: bialkali				
active diameter	mm		270	
active surface area	cm^2		800	
quantum efficiency at peak	%		30	
luminous sensitivity	µA/lm		70	
with CB filter		8	12	
with CR filter			1	
dynodes: 12LFSbCs				
anode sensitivity in divider A:				
nominal anode sensitivity	A/lm		500	
max. rated anode sensitivity	A/lm		2000	
overall V for nominal A/lm	V		1400	1800
overall V for max. rated A/lm	V		1550	
gain at nominal A/lm	$\times 10^6$		7	
dark current at 20 °C:				
dc at nominal A/lm	nA		20	200
dc at max. rated A/lm	nA		80	
dark count rate	s^{-1}		20000	
pulsed linearity (-5% deviation):				
divider A	mA		30	
divider B	mA		100	
pulse height resolution:				
single electron peak to valley	ratio		2	
rate effect (I_a for $\Delta g/g$=1%):	µA		20	
temperature coefficient:	% $°C^{-1}$		± 0.5	
timing:				
single electron rise time	ns		5	
single electron fwhm	ns		6	
single electron jitter (fwhm)	ns		3	
transit time	ns		62	
weight:	g		2600	
maximum ratings:				
anode current	µA			100
cathode current	nA			2000
gain	$\times 10^6$			30
sensitivity	A/lm			2000
temperature	°C	-30		60
V (k-a)[(1)]	V			2350
V (k-d1)	V			750
V (d-d)[(2)]	V			300
ambient pressure (absolute)	kPa			808



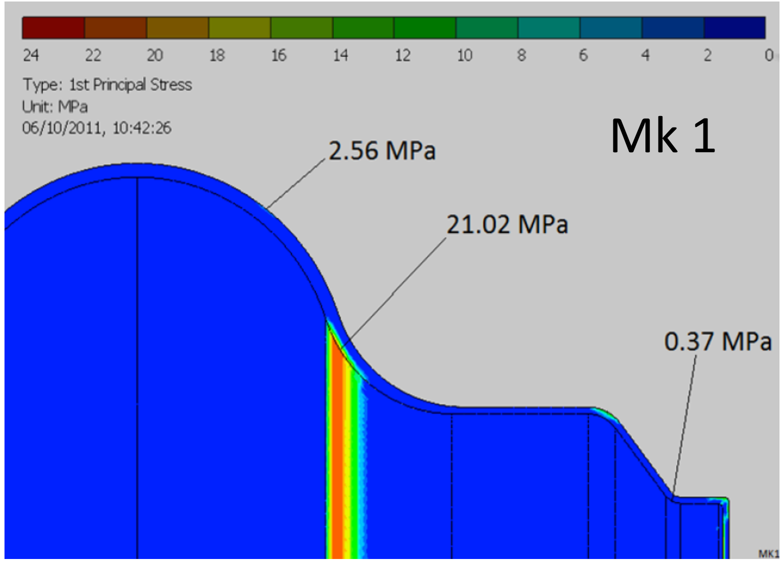
Electron Optical design is complete.

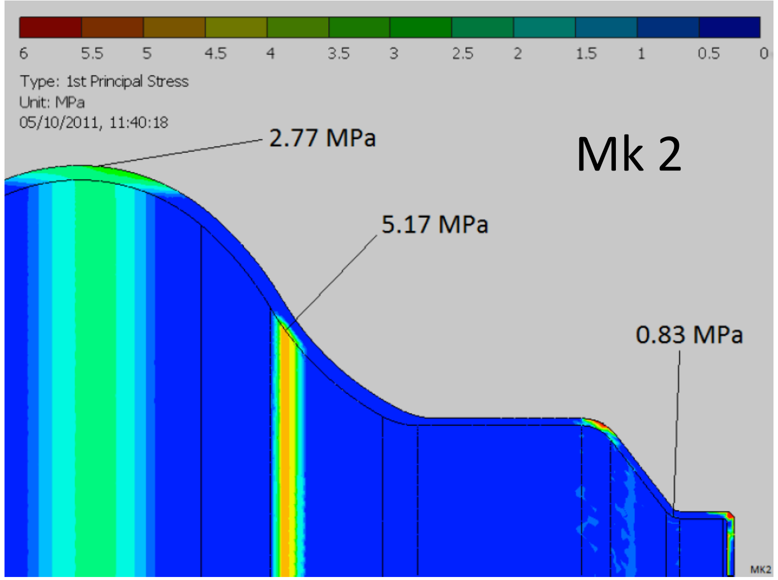


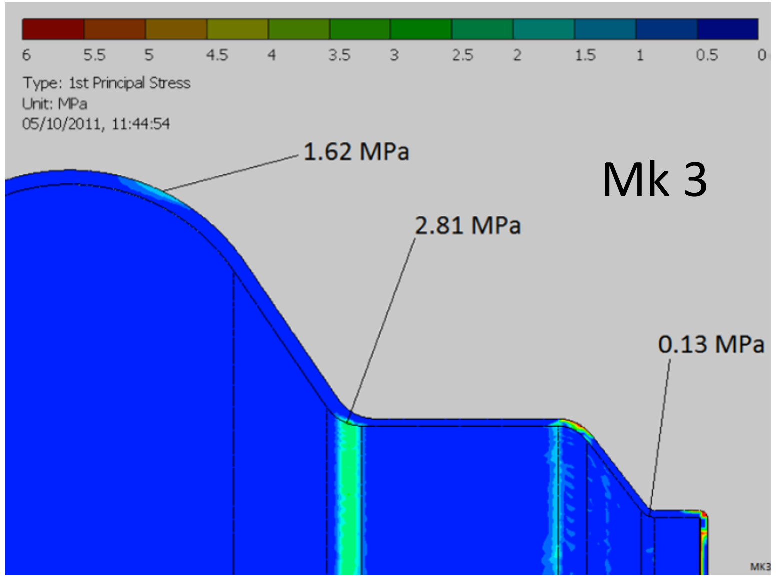
Launch distance ⊥ to tube axis (mm)	k-d1 transit time (ns)
0	36.1
12	36.1
24	36.0
36	36.0
48	35.9
60	35.7
71	35.7
83	35.4
95	35.2
107	35.2
119	35.6
137	34.9

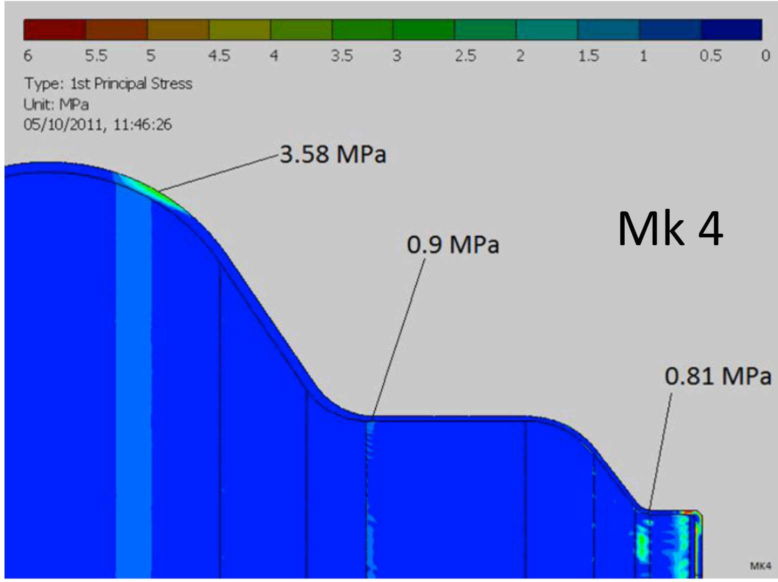
note 1.2 ns expected transit time spread

Envelope design will be suitable for HK









Texas PMT Schedule


- Expected first prototypes by summer 2014. These will be made in the U.K.
- First prototypes will not have full submergence envelopes – they will be designed for testing electro-optical performance
- Testing facilities at UC Davis, Penn, Drexel (same ones used for evaluation of Hamamatsu 10" and 12" HQE PMT's for LBNE)
- Completion of testing by end of FY14
- WATCHMAN may request a follow-on order of ~200 PMT's in FY14 for delivery in FY15. These would be built in Texas and have full submergence capability. Cost of initial 200 would be high, but could be shared between different US agencies.
- A suitable number of 12" PMTs would also be ordered from Hamamatsu for comparison.

4. Summary

- J-PARC MR/neutrino exp. facility realized 220kW operation
  - 30GeV, 2.5s cycle, $1.2\text{x}10^{14}$ppp: world record of extracted *ppp* for synchrotron.
  - The first set of 3 horns/target has been used w/o serious troubles for all periods.
- Upgrade plan of J-PARC accelerators towards rated 750kW oper.
  - Increase #p/bunch : $1.2\ \text{x}10^{14} \rightarrow 2.0\text{x}10^{14}$ *ppp*
    - MR collimator capability: 450W → 2KW → 3.5kW
    - LINAC energy upgrade : 181MeV → 400MeV
    - LINAC frontend (IS/RFQ) upgrade: 30mA → 50mA
  - Double MR rep-rate: 2.5s → 1.3s cycle
    - Replace all magnet power supplies / higher gradient RF core etc.
  - 5yr plan for MR upgrade to realize 750kW beam (*before hadron hall accident*)
    - We are making the best efforts to investigate the cause / prevention of recurrence.
    - Schedule of beam restart / LINAC upgrade are both not yet determined.
- Upgrade of neutrino beam-line to accept 750kW beam
  - Doubled rep.rate is plausible to reduce thermal shock on target
  - Individual 3 power supply for each horn make 320kA-1Hz oper. possible.
  - Current all 3 horns (target) to be replaced to ones with upgrades
    - Hydrogen-oxygen recombination in coolant water / efficient strip line cooling