Hyper-Kamiokande

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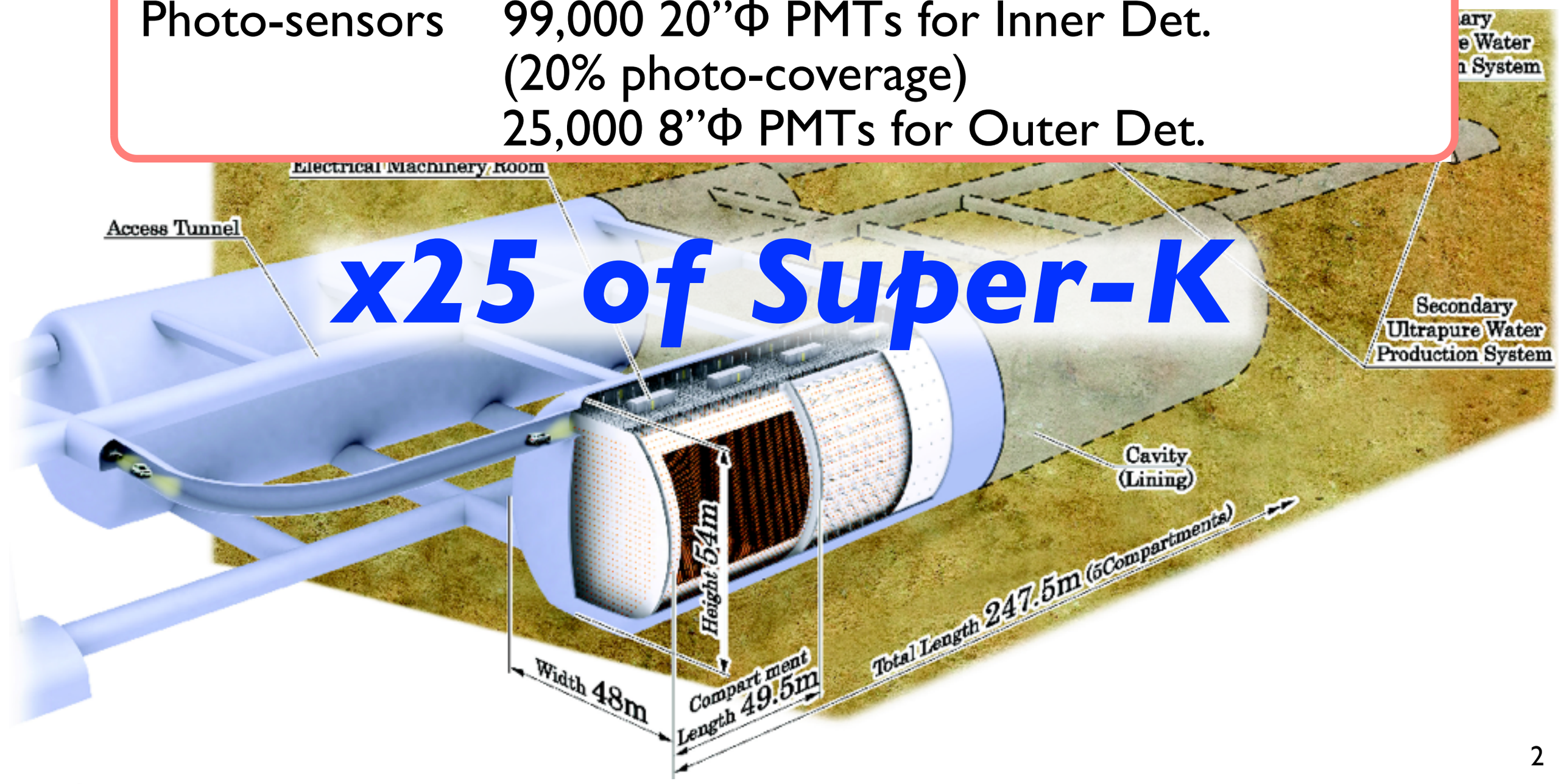
(ICRR, U. Tokyo)

for Hyper-K Working Proto-collaboration

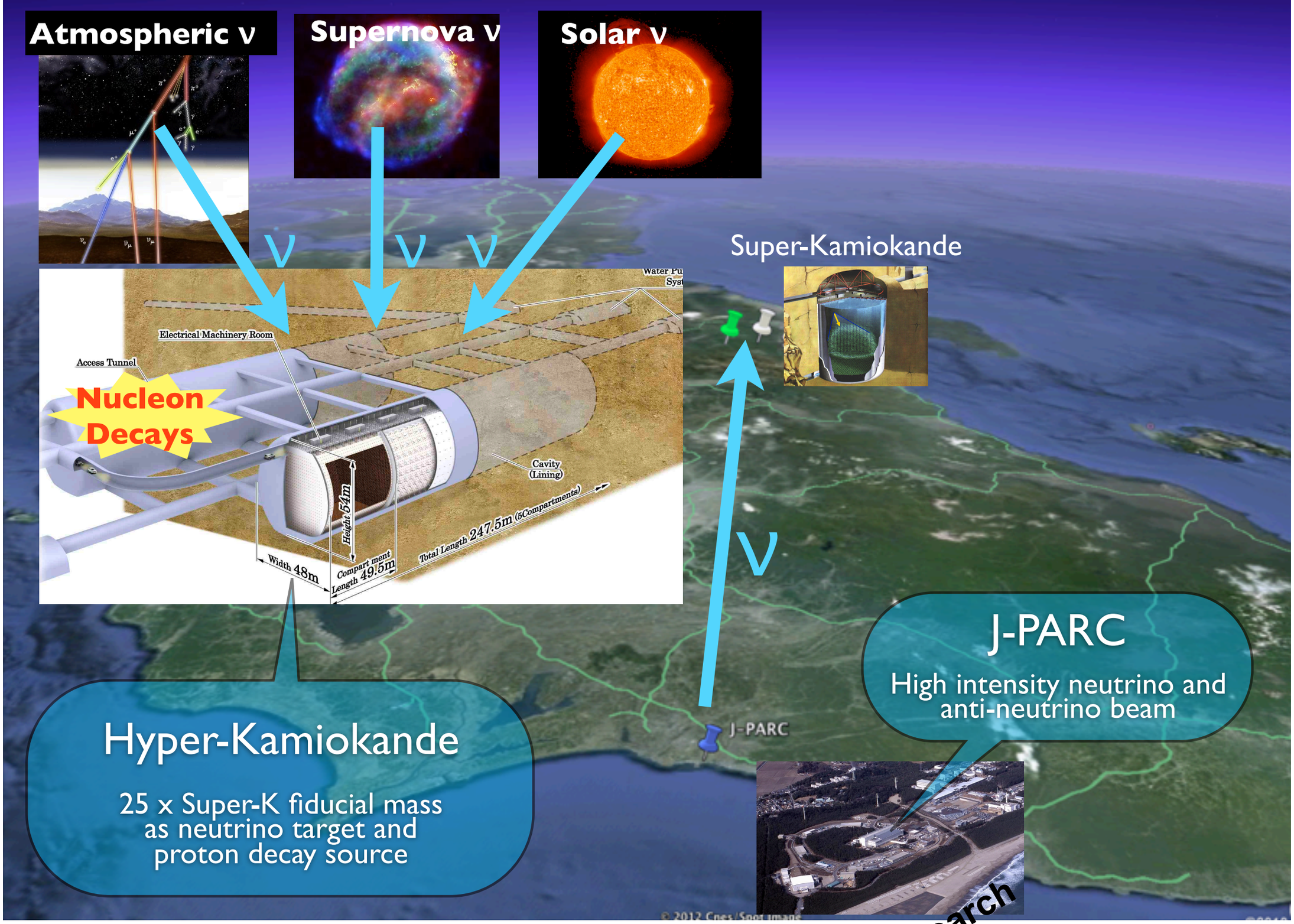
NNN15, Oct. 30, 2015

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.



x25 of Super-K



Solar ν

Supernova ν

J-PARC ν

Proton decay

Dark matter search

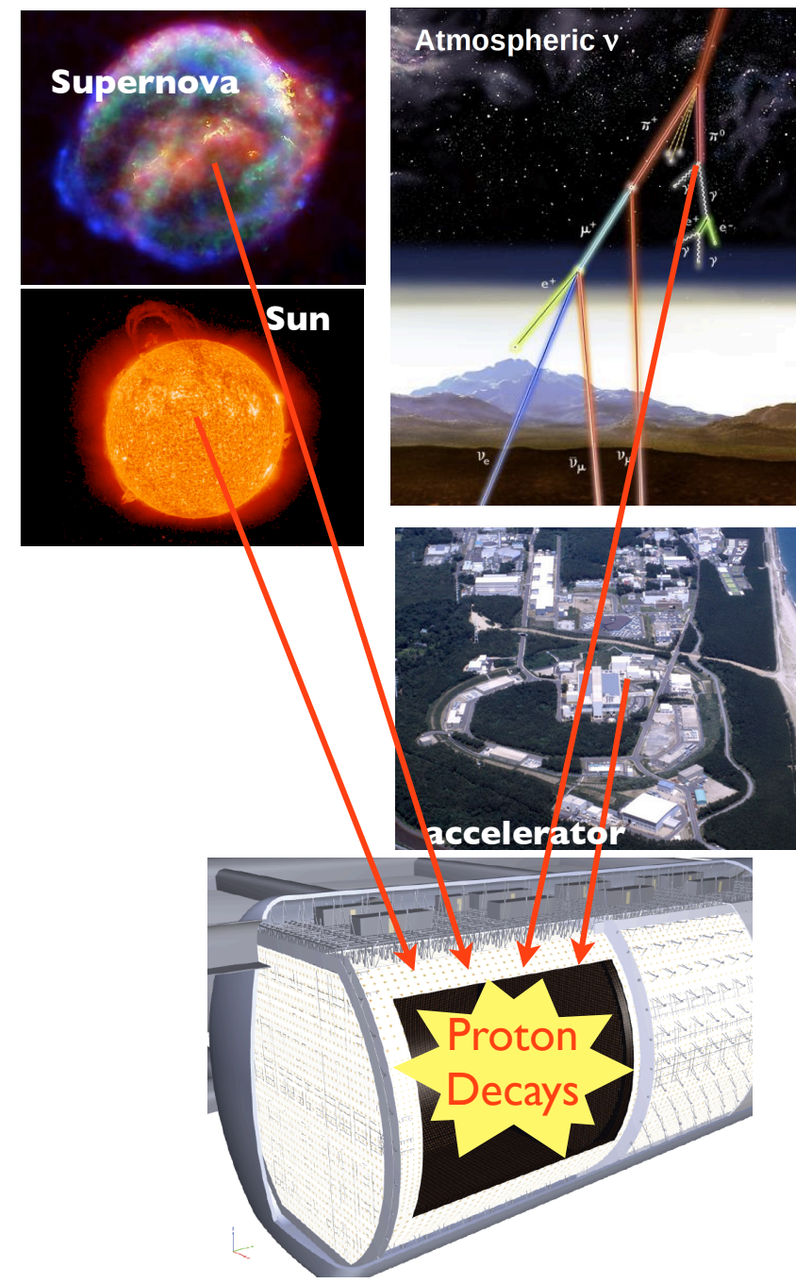
Atmospheric ν

a few MeV ~20 ~100 ~1 GeV TeV

Hyper-K: multi-purpose detector

* Letter of Intent: arXiv:1109.3262
* LBL studies: PTEP 2015, 053C02 (arXiv:1502.05199)

- **Proton decay 3σ discovery potential**
  - 5×10^{34} years for $p\rightarrow e^+\pi^0$
  - 1×10^{34} years for $p\rightarrow \nu K^+$
- **Comprehensive study of ν oscillation**
  - CPV: 76% of δ space w/ 3σ, <20° precision
  - MH determination for all δ with J-PARC/Atm ν
  - θ_{23} octant: $\sin^2\theta_{23}<0.47$ or $\sin^2\theta_{23}>0.53$
  - <1% presicion of Δm^2_{32}
  - Test standard ν oscillation scenario w/ acc/atm ν
- **Astrophysical neutrino**
  - Supernova up to 2Mpc distance, 1SN/10 years
  - Supernova relic ν signal (~200ν's/10 years)
  - Dark matter neutrinos from Sun, Galaxy, Earth
  - Solar neutrino ~200ν's/day



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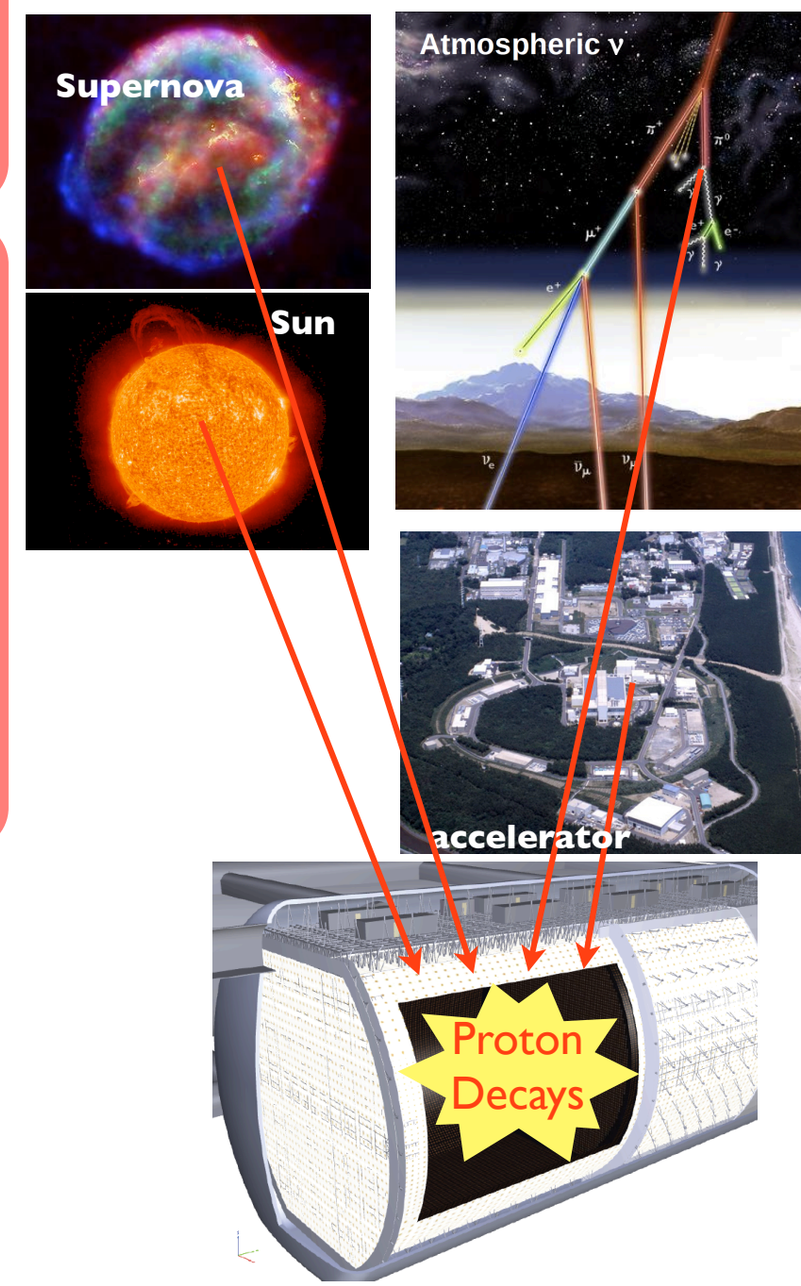


Hyper-K proto-collaboration w/ cooperation of KEK-IPNS and U.Tokyo-ICRR

Hyper-K Proto-Collaboraiton formed

- **KEK-IPNS** and **U.Tokyo-ICRR** signed **MOU** to cooperate in promoting the Hyper-Kamiokande

The Nobel Prize in Physics 2015

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

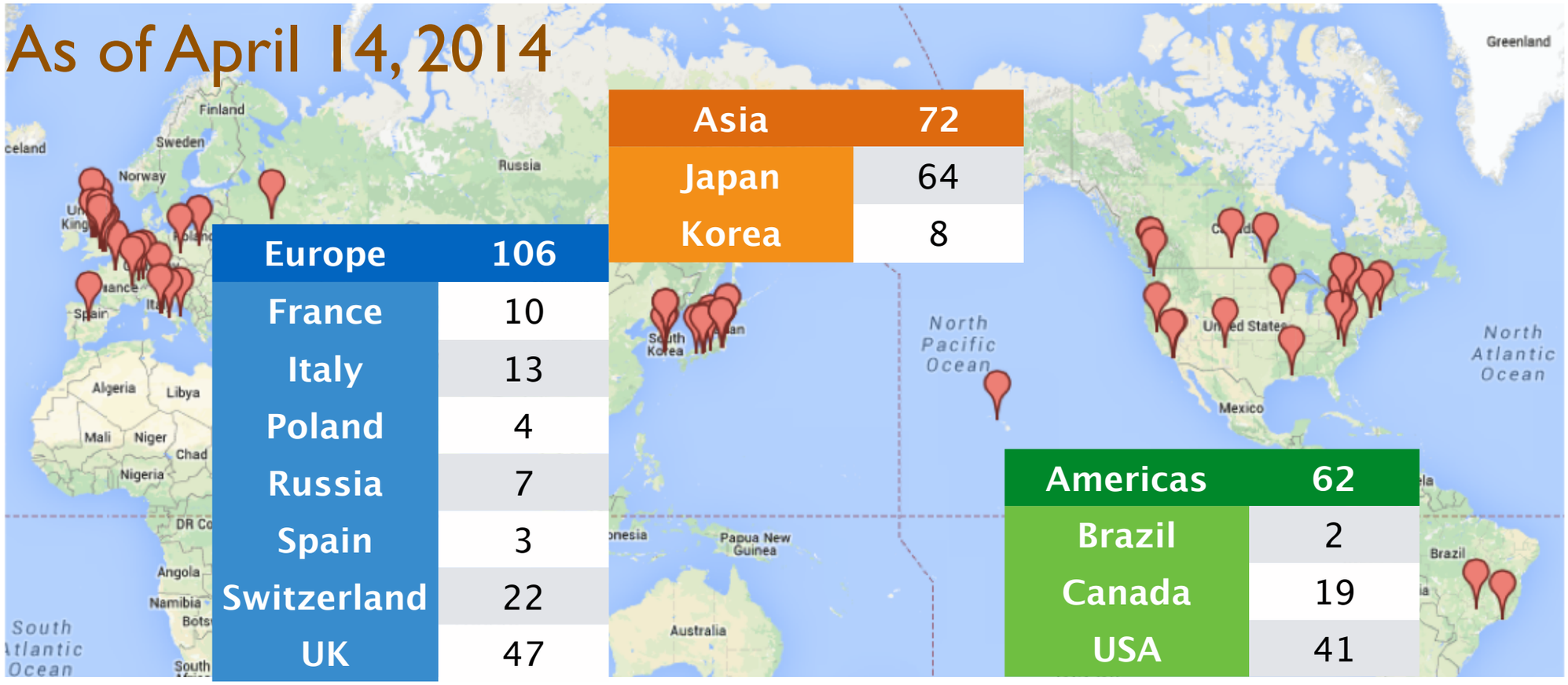
Takaaki Kajita

(Super-Kamiokande)

Arthur B. McDonald

(SNO)

Hyper-K Collaboration



Europe	106
France	10
Italy	13
Poland	4
Russia	7
Spain	3
Switzerland	22
UK	47

Asia	72
Japan	64
Korea	8

Americas	62
Brazil	2
Canada	19
USA	41

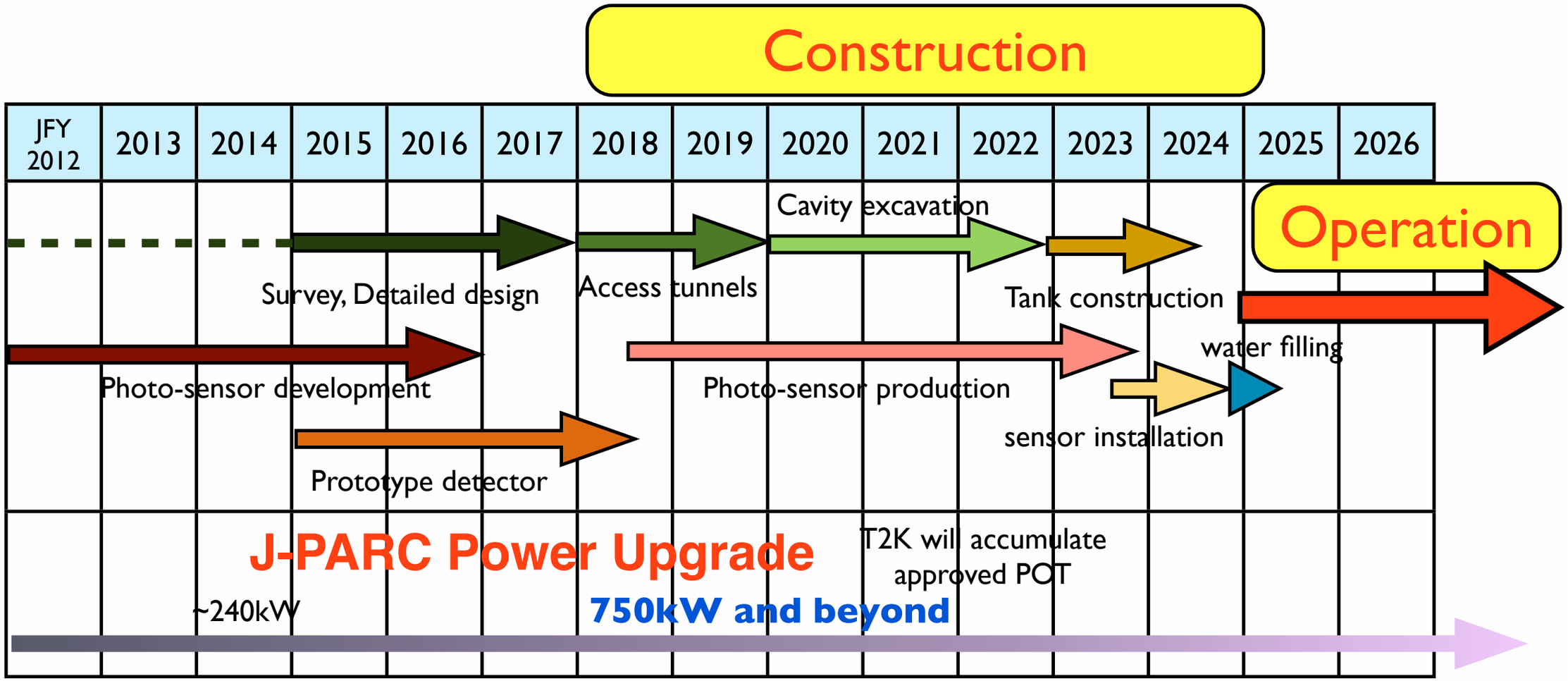
- 240 members from 13 countries (and growing)
- Hyper-K Governance Structure has been defined
  - Steering Committee, International Board Representatives, Working Groups Conveners Board

Project status

- Design Report is requested by KEK/ICRR
  - To be prepared in 2015 toward the budget request
    - cf. the next round of the SCJ master-plan and MEXT roadmap will be in 2016-2017
    - Optimum design, construction cost and period, J-PARC ν-beam, near detector, international responsibilities
  - International review will proceed under KEK/ICRR to promote the project
- Once the budget is approved, the construction can start 2018 and the operation will begin in 2025

It is a critical time to promote the project
Open for new collaborators ;)

Hyper-K target timeline



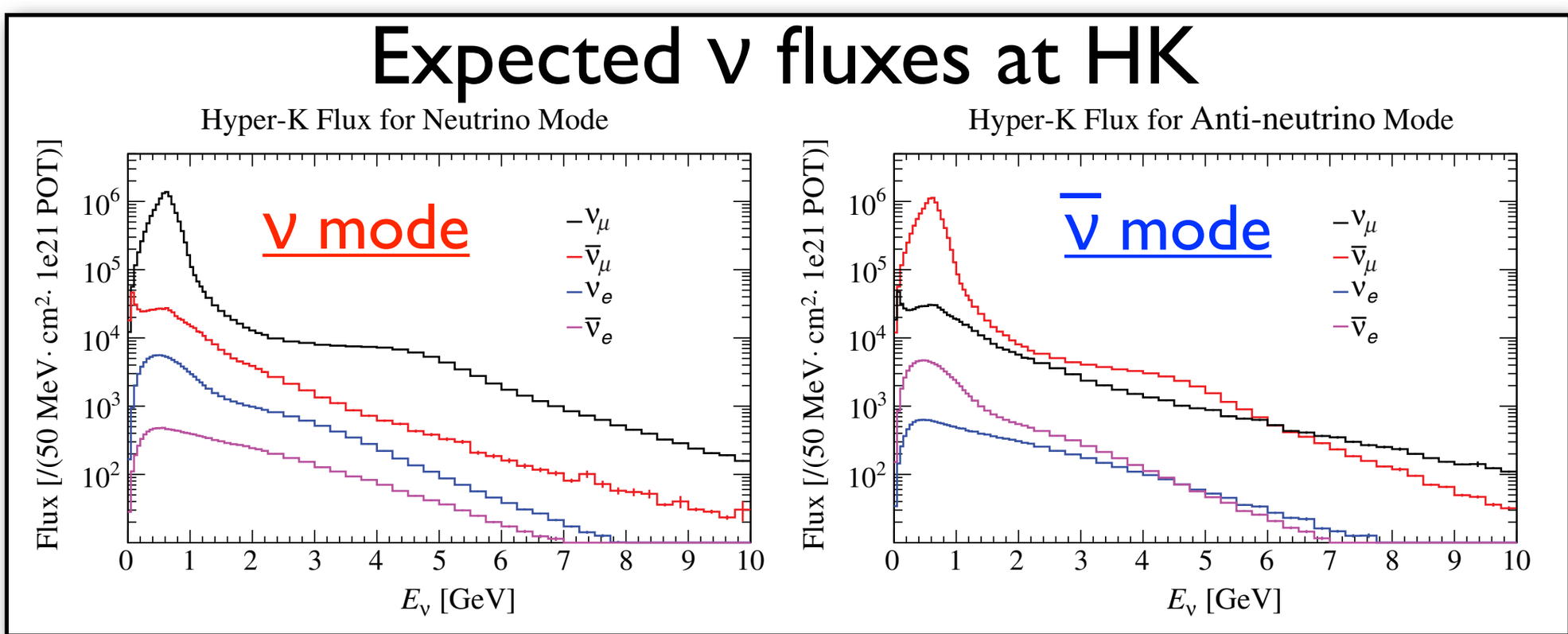
- 2018 Construction start
- 2025 Data taking start
- J-PARC beam power upgrade
  - ≥360kW achieved in 2015 for T2K
  - Design power 750kW in 2018-2019
  - ≥1MW in 2020-2025

From Koseki-san's slides @HINT2015 workshop

Physics with Hyper-K

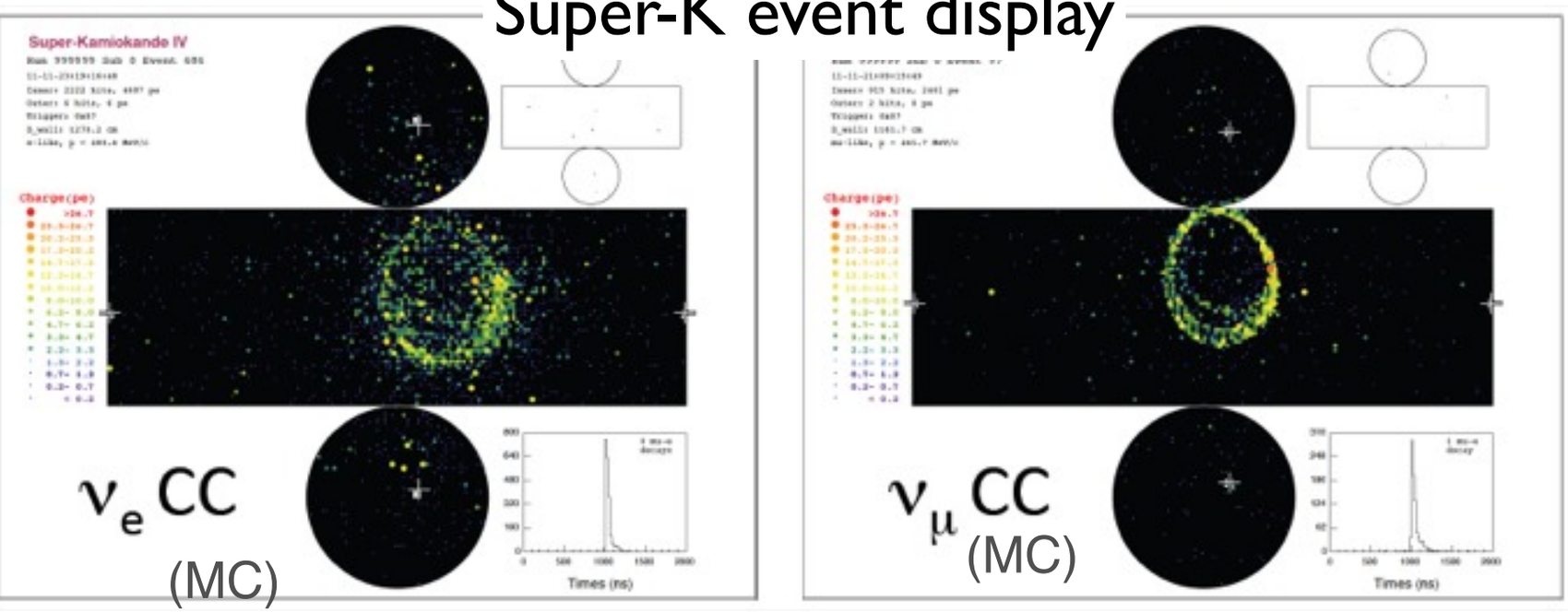
J-PARC to Hyper-K

- Relatively short baseline (295km, same as T2K)
  - Less matter effect: good for CP measurement
  - Complementary to other experiments with longer baseline (>1000km)
- 2.5 deg. Off-Axis beam (same as T2K)
- Low energy (~0.6GeV) and narrow band beam
  - Peak around oscillation maximum
  - Good match for Water Cherenkov detector

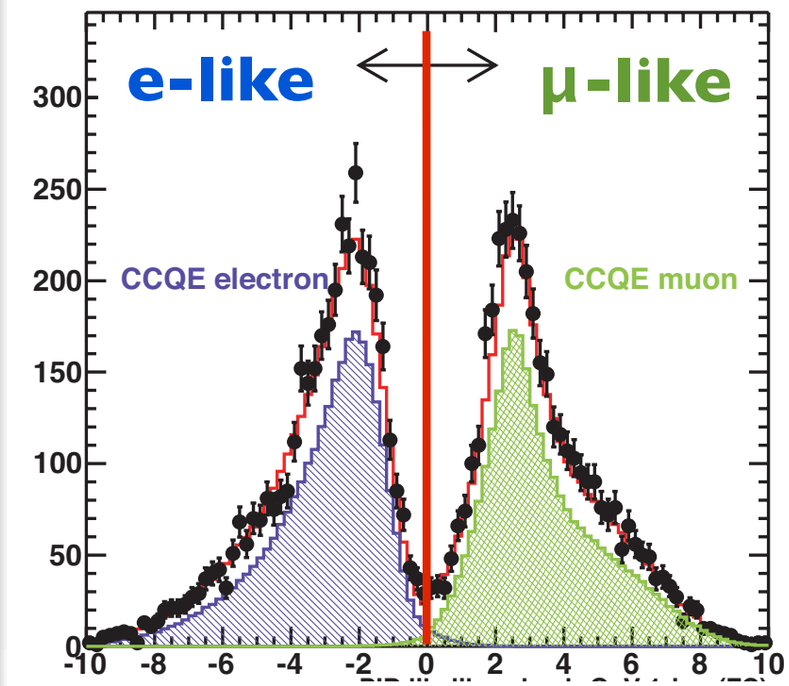


Detector performance

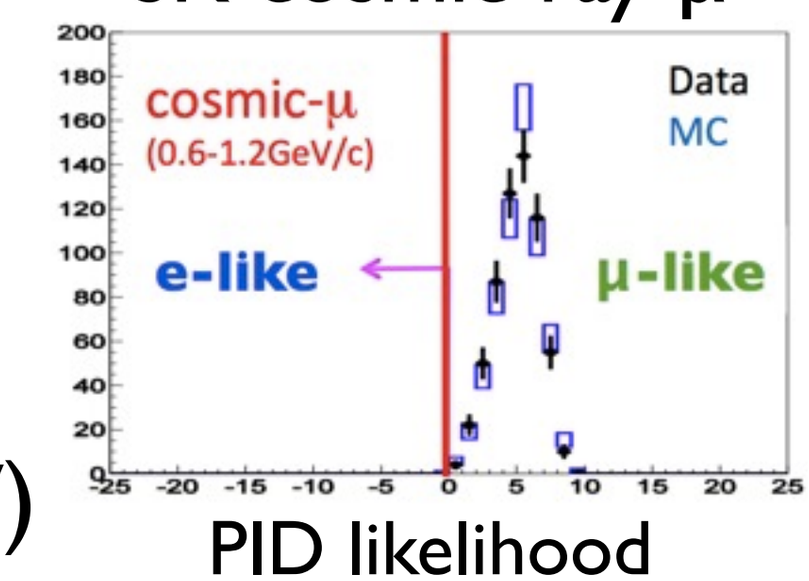
Super-K event display



SK atmospheric ν



SK cosmic-ray μ



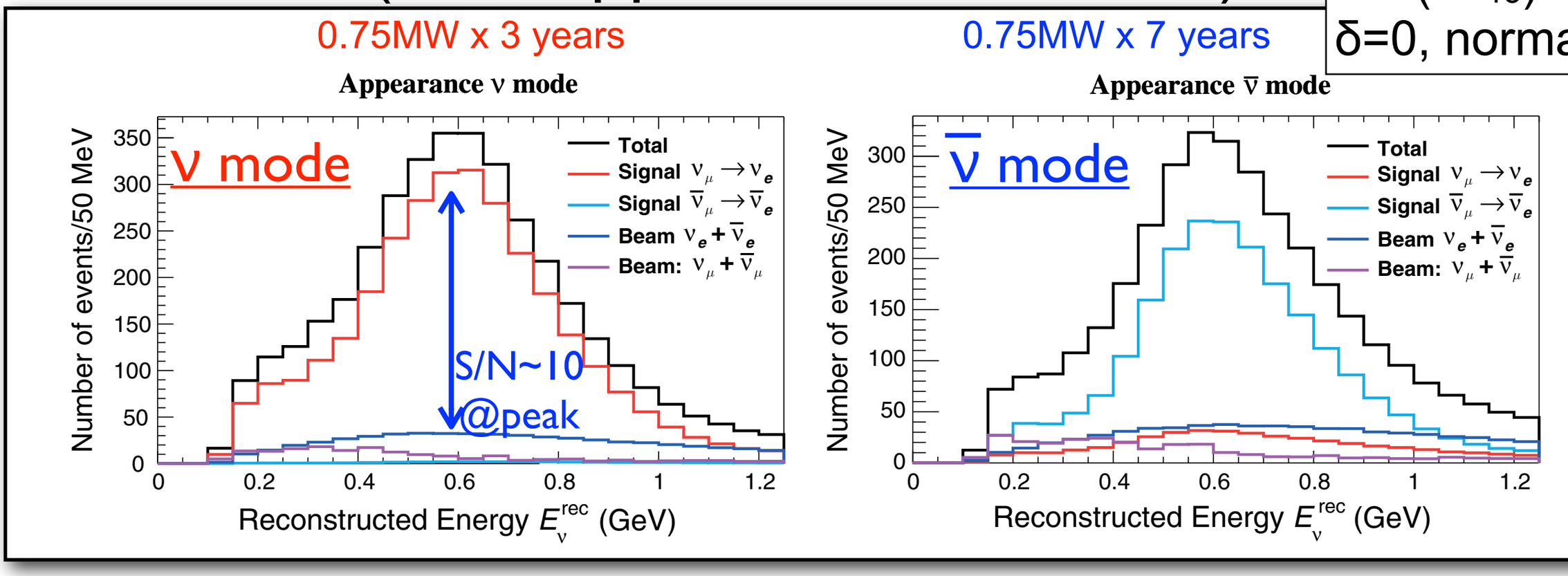
mis-PID:
Data: 0.00±0.16(stat.)%
MC : 0.10±0.10(stat.)%

- Large mass (25 x Super-K FV)
  - Statistics is always critical
- Excellent particle ID (e/μ)
  - Mis-identification <1%
- Energy resolution e/μ ~3%
- Quasi-elastic is dominant (sub-GeV)
  → Clean one-ring event

ν_e CC candidates

Reconstructed ν energy distributions (after applied selection cuts)

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

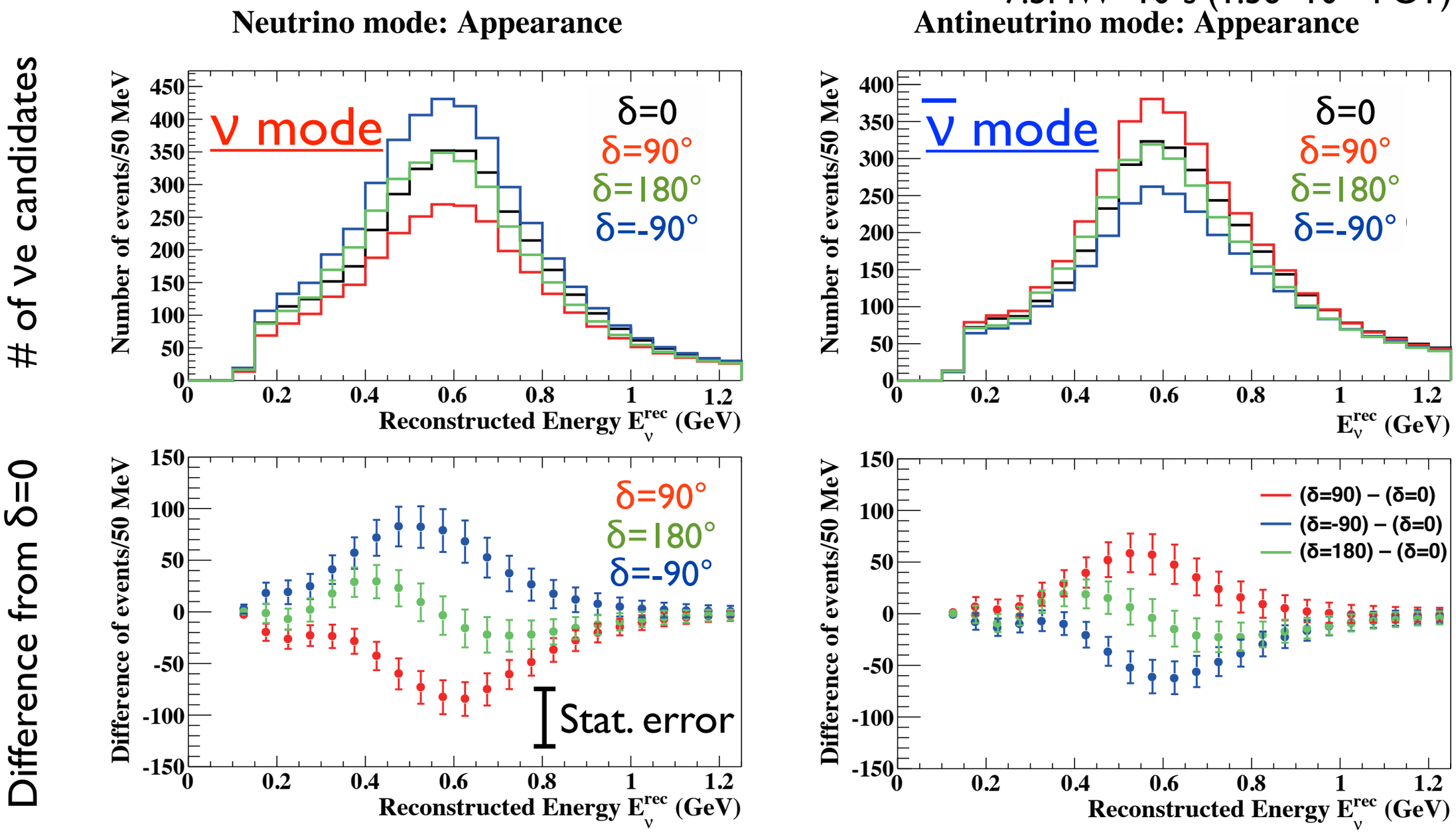


	Signal ($\nu\mu \to \nu e$ CC)	Wrong-sign appearance	Beam $\nu\mu/\bar{\nu}\mu$ CC	Beam $\nu e/\bar{\nu} e$ CC	NC
ν-mode (0.75kW x 3yrs)	3,016	28	11	523	172
ν̄-mode (0.75kW x 7yrs)	2,110	396	9	618	265

- S/N~10 at peak (>99% ν_μCC/NC bkg rejection)
- High ν_e-signal selection efficiency: ≥60%

Effect of $\delta_{CP} \neq 0$

7.5MW×10^7s (1.56×10^{22} POT)



- Sensitive to all δ values
- also sensitive to any non-standard CPV, if any

Systematic uncertainties

Realistic estimation based on SK/T2K

- Syst. errors based on SK/T2K experience and prospect
  - Error matrices of T2K adopted in HK sensitivity
  - Near detector: constrain cross section error w/ water target
  - Far detector: systematic error reduced by large stat. atm-ν

Uncertainty on the expected number of events at Hyper-K (%)

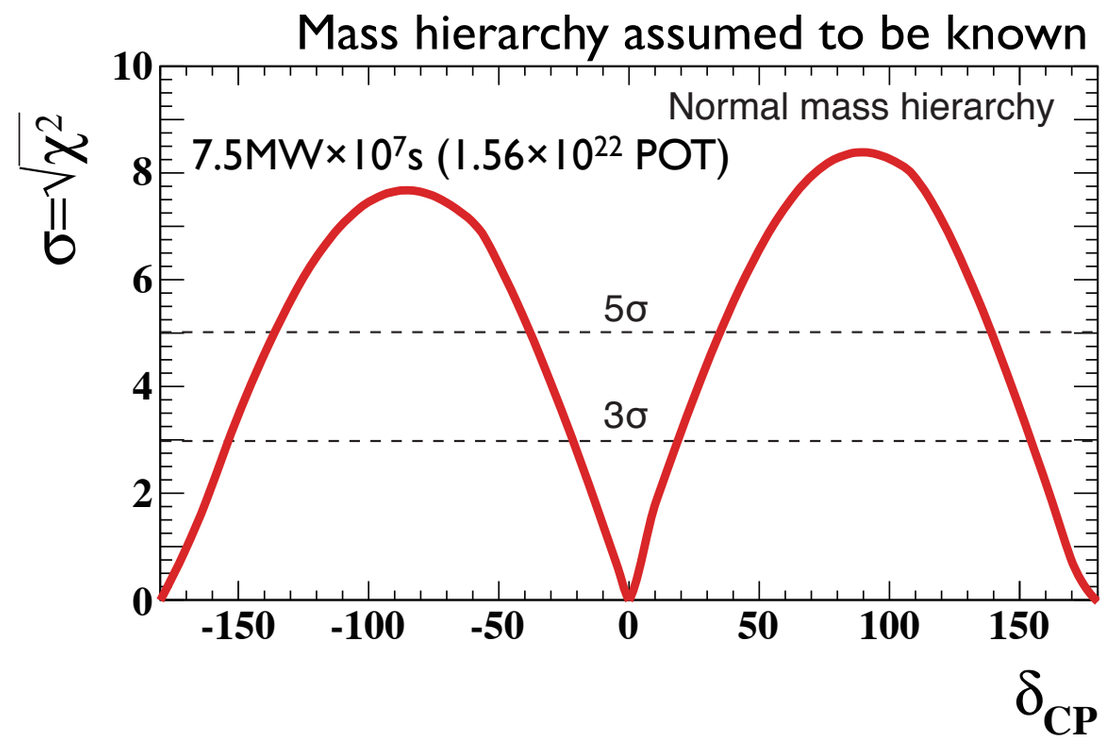
	ν mode		anti-ν mode		(T2K 2014)	
	νe	νμ	$\bar{\nu}$e	$\bar{\nu}$μ	νe	νμ
Flux&ND	3.0	2.8	5.6	4.2	3.1	2.7
XSEC model	1.2	1.5	2.0	1.4	4.7	5.0
Far Det. +FSI	0.7	1.0	1.7	1.1	3.7	5.0
Total	3.3	3.3	6.2	4.5	6.8	7.6

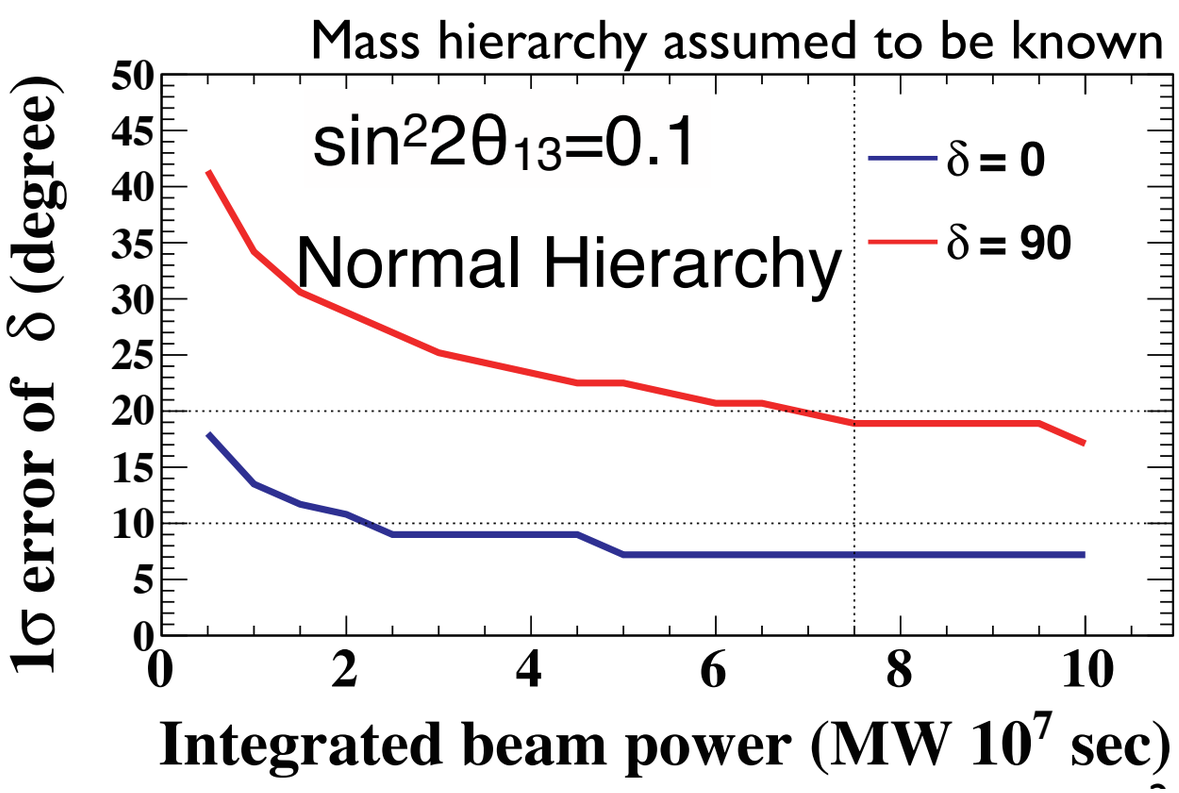
Expect further improvements with SK/T2K experience

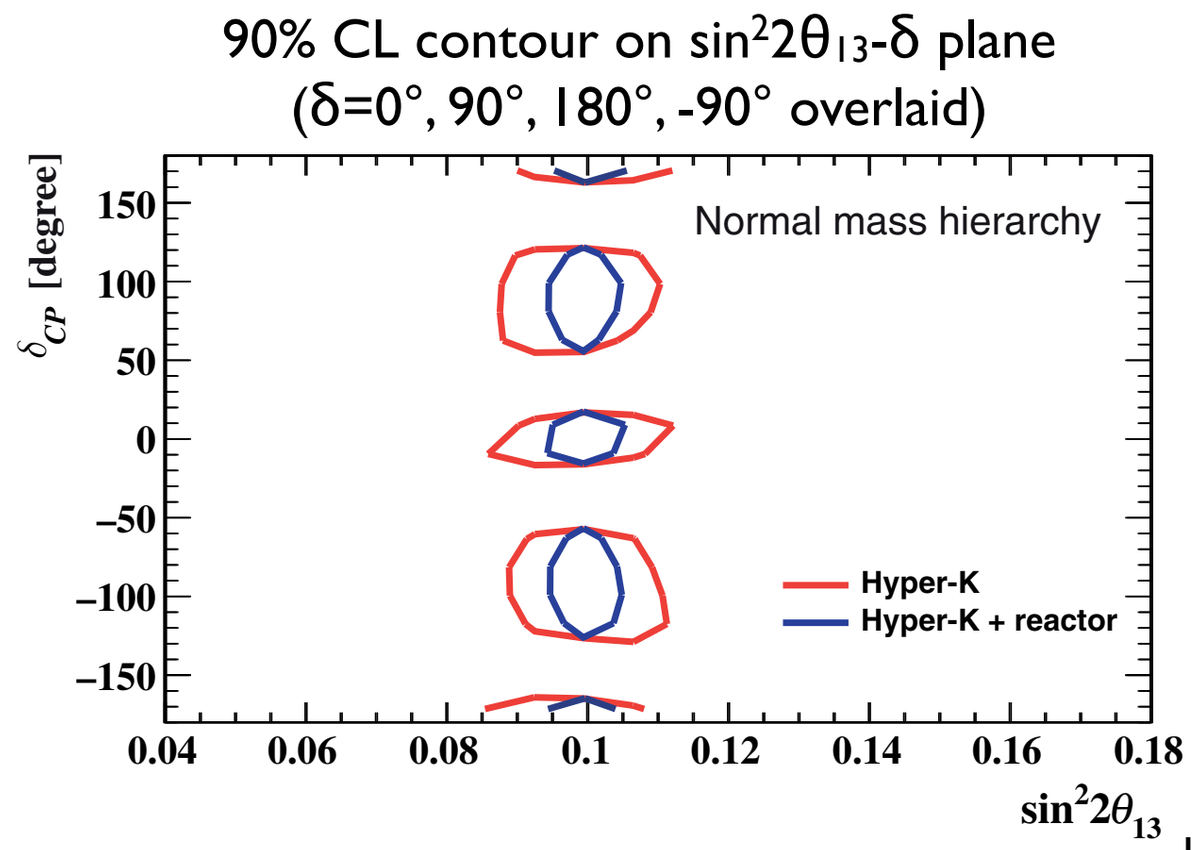
→ *See Sam Short's talk for further details*

Sensitivity to CP violation

- Exclusion of sinδ=0
  - >3σ for 76% of δ space
  - >5σ for 58% of δ space
- δ resolution 8°~19° depending on the true δ value







Mass hierarchy determination with atmospheric ν

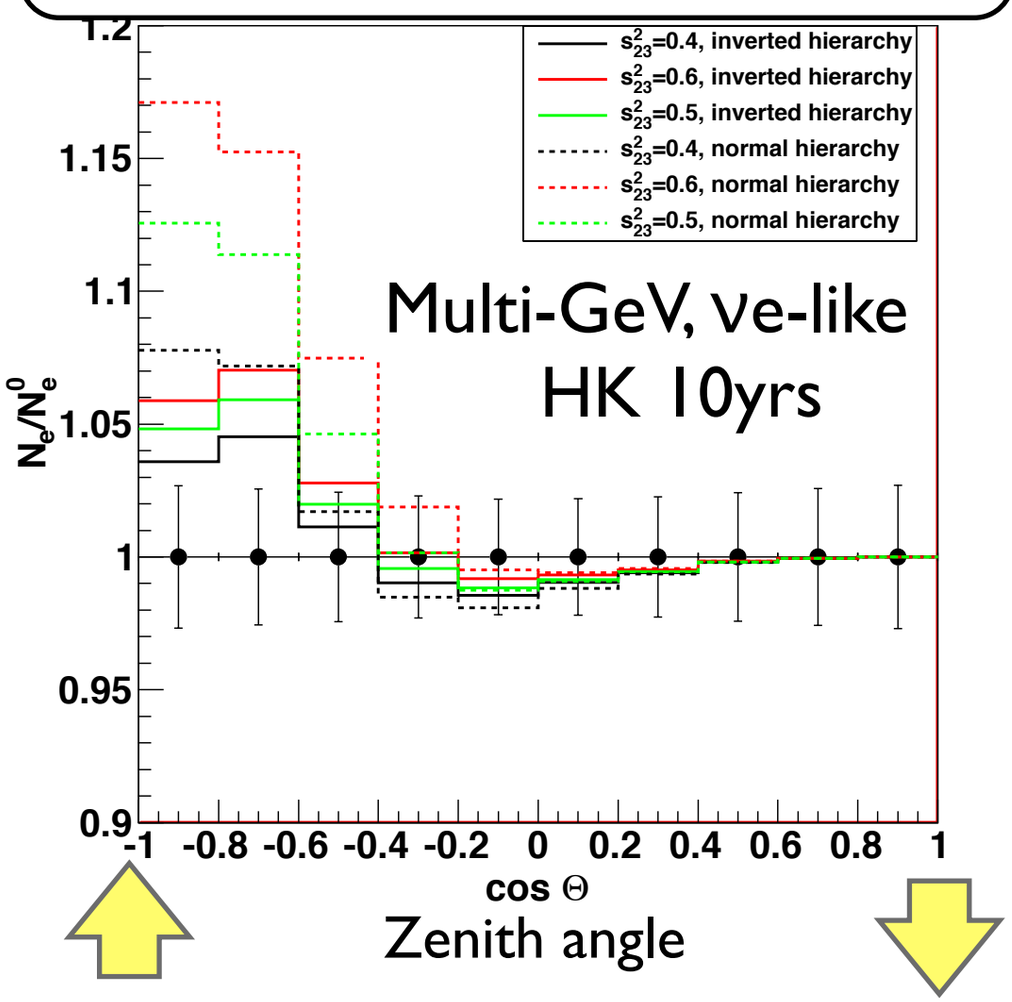
e-like event rate (in zenith angle)

ratio to no-oscillation

$\sin^2\theta_{23}=0.4$ —— inverted hierarchy

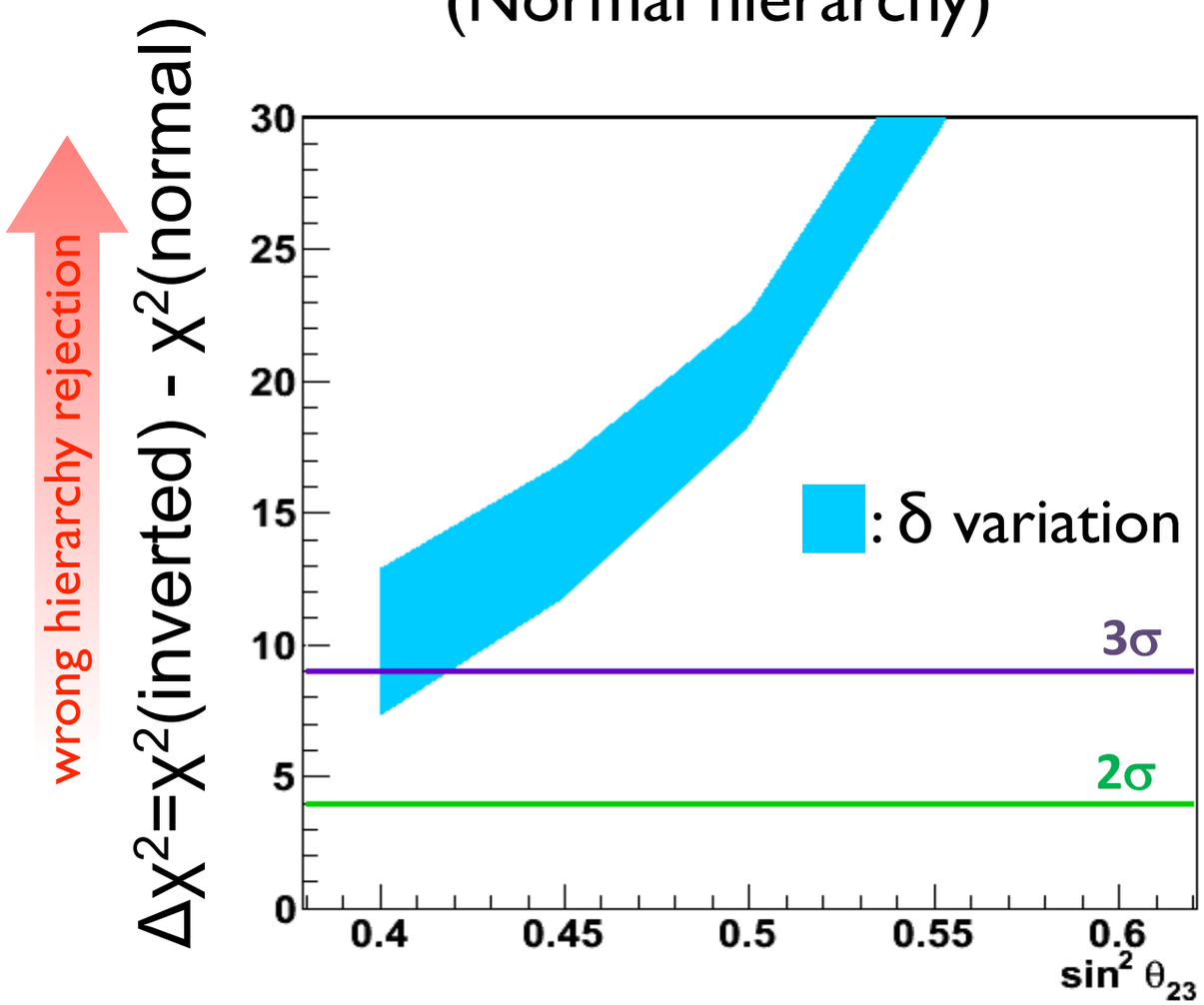
$\sin^2\theta_{23}=0.5$

$\sin^2\theta_{23}=0.6$ - - - - - normal hierarchy



Expected significance MH

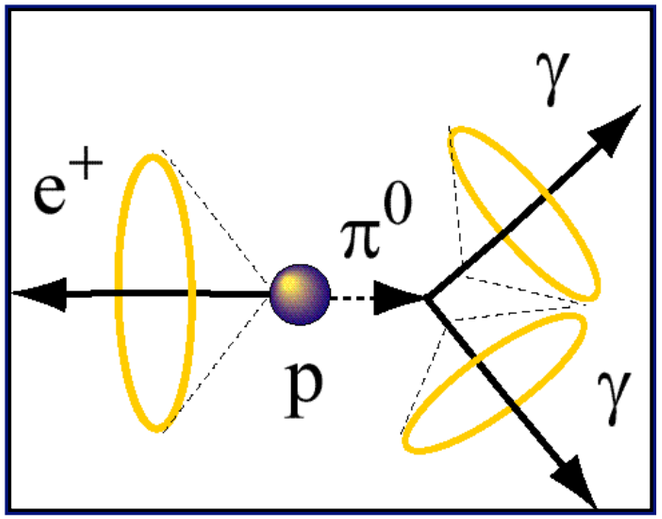
(Normal hierarchy)



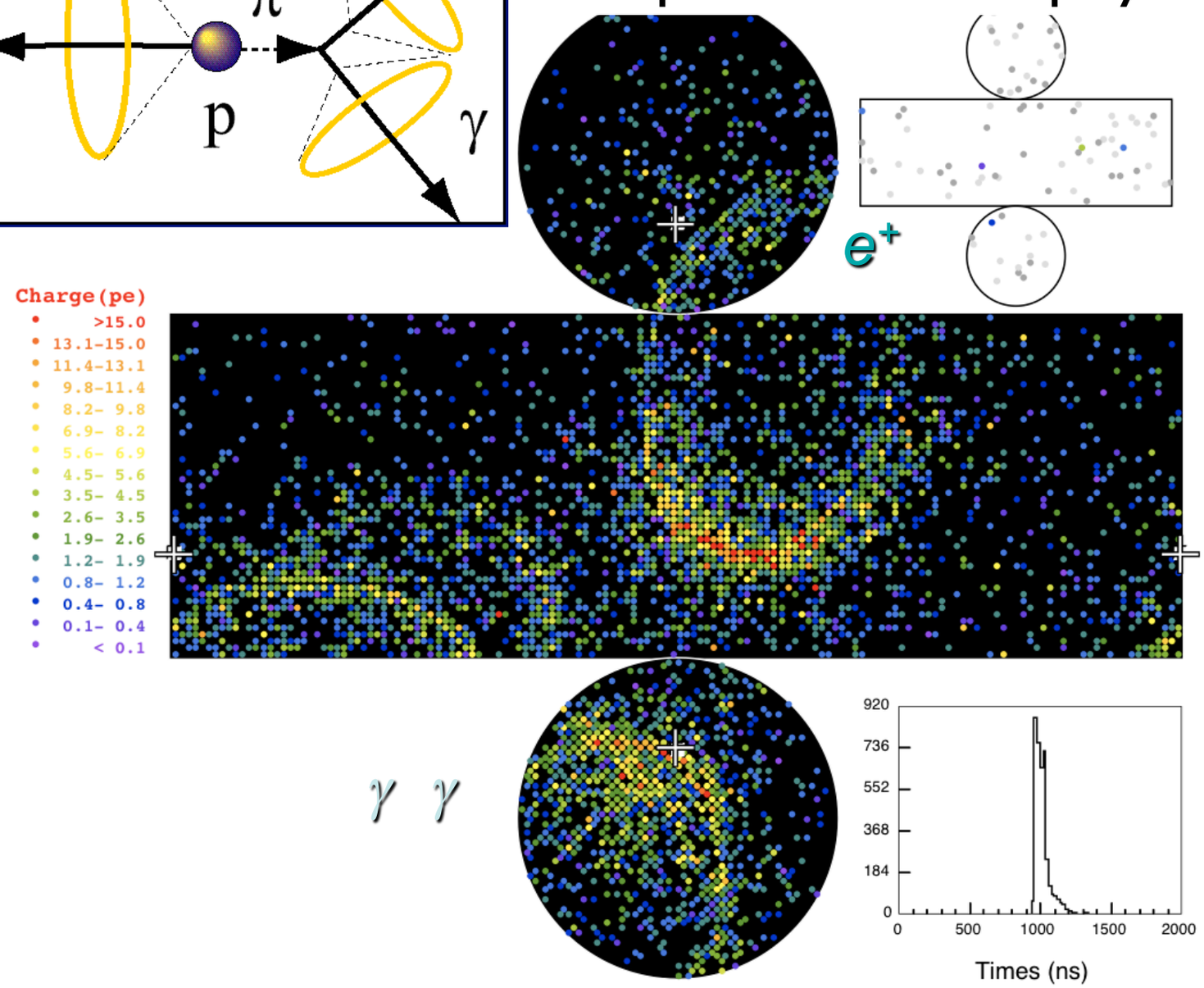
3σ determination with <10 years exposure

Nucleon decay search

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



Super-K event display



Golden channel in Č detector

$e^+\pi^0$ 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

Signal efficiency 40%

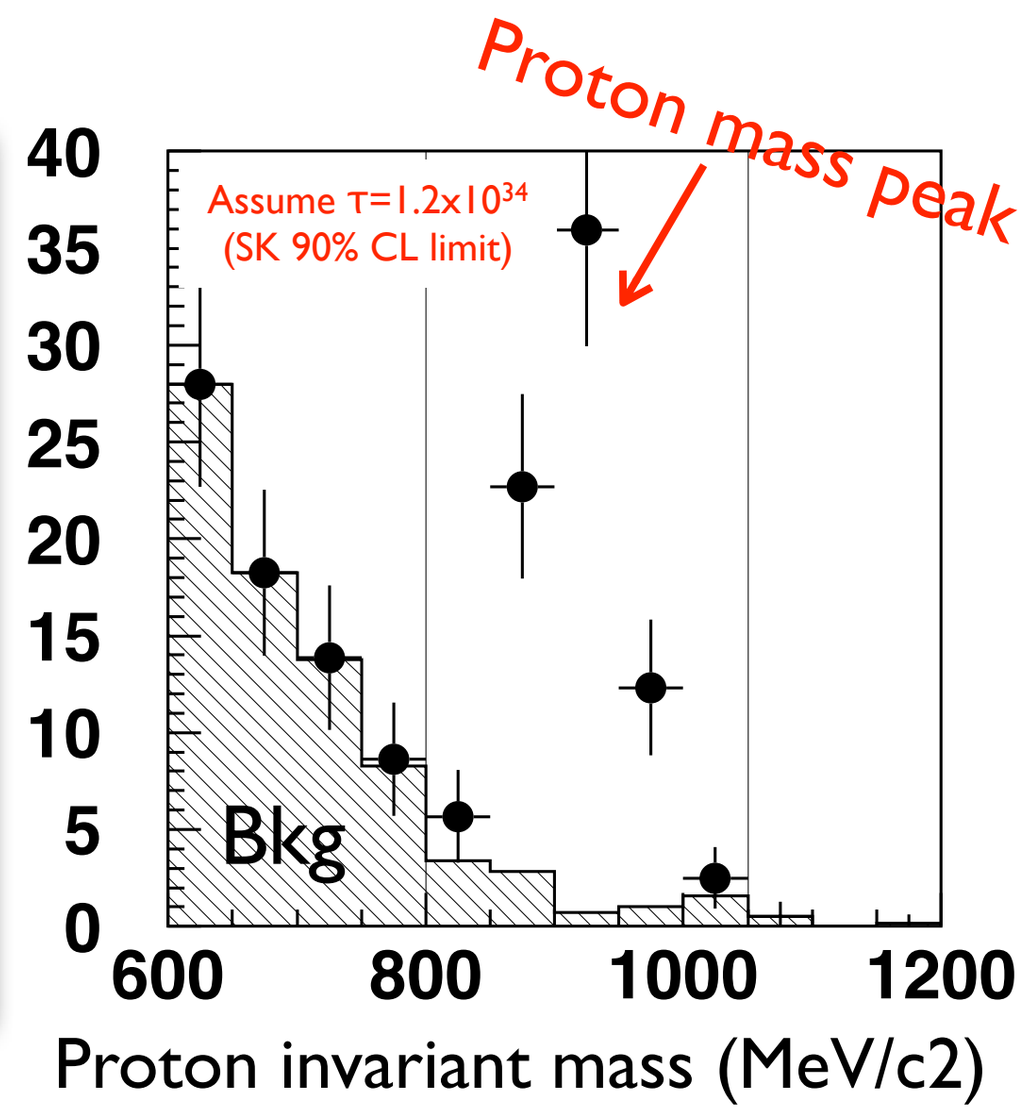
(Inefficiency due to π^0 interaction in nucleus)

99.998% atmospheric ν background rejection

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

- Discovery potential with 3σ
  - $\tau(p \rightarrow e^+\pi^0)$ ~5×10^{34} yrs (HK 10ys)
- Sensitivity (90% CL limit)
  - $\tau(p \rightarrow e^+\pi^0)$ >1×10^{35} yrs (HK 10ys)

(Sensitivity study uses Super-K analysis method)

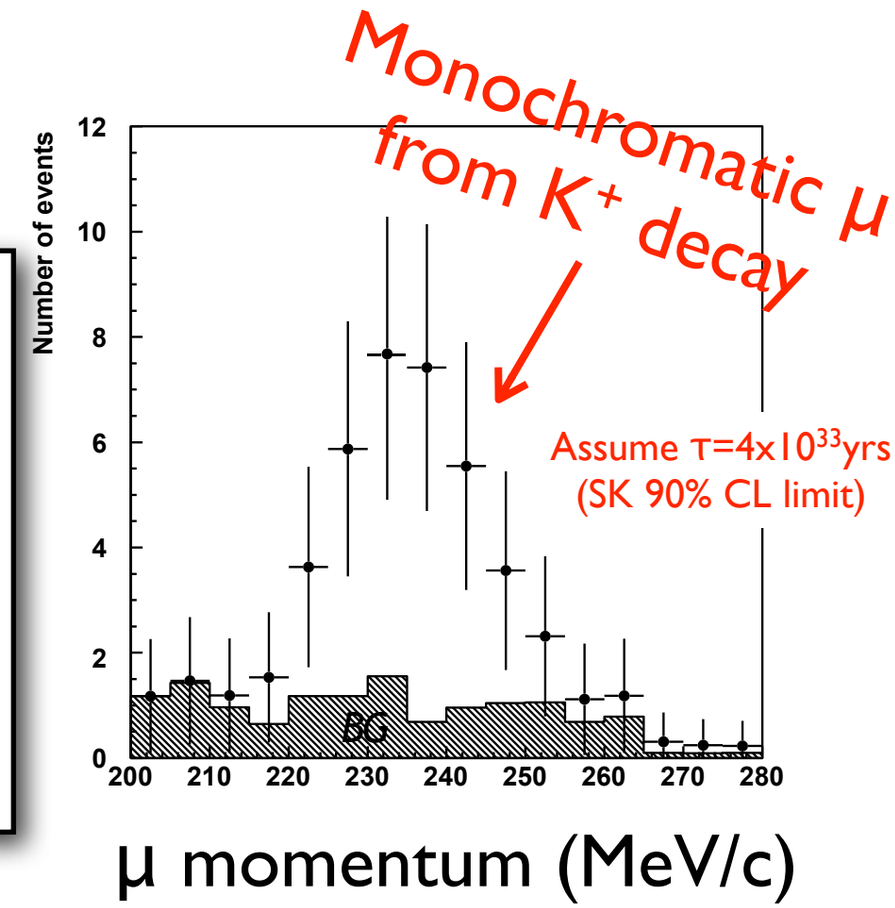


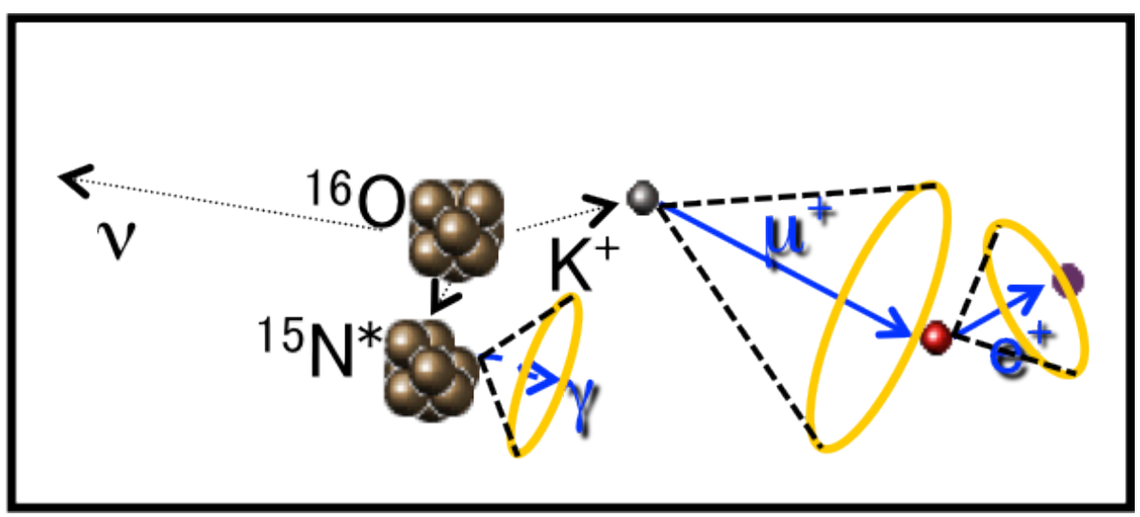
Expect further improvement in analysis method, and photo-sensor performance (see latter slides)

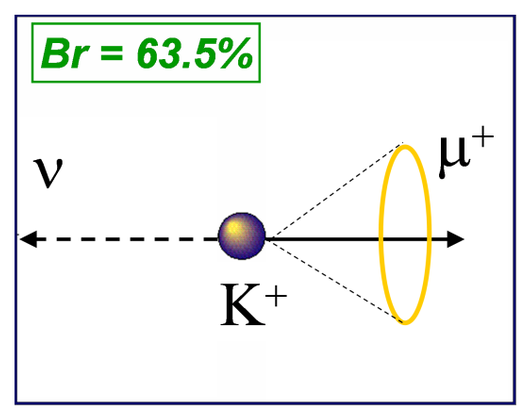
Discovery potential

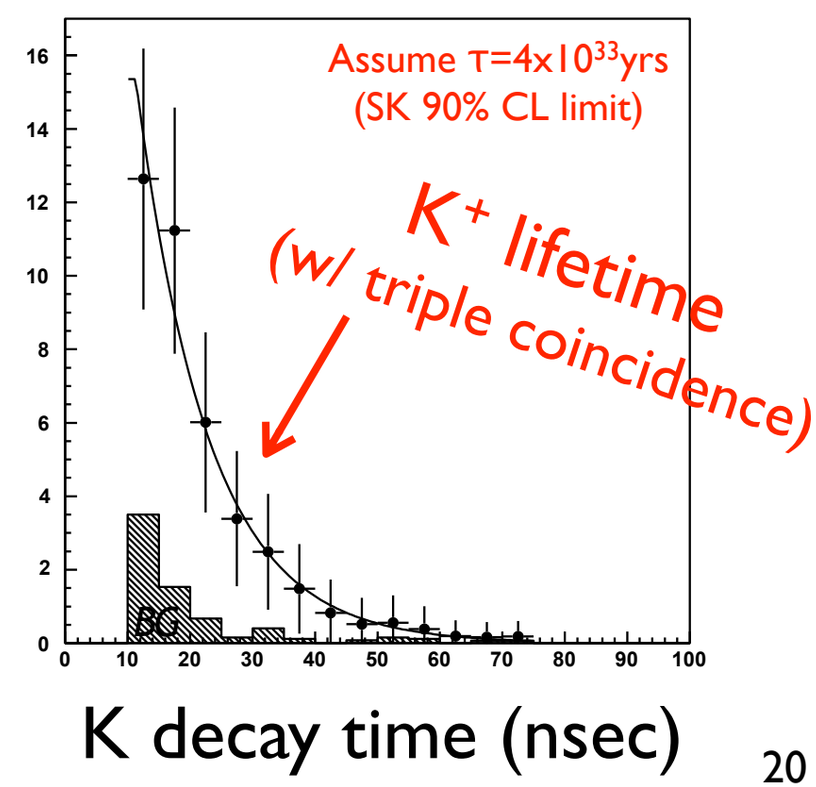
$p \rightarrow \nu K^+$

- Discovery potential with 3σ
  - $\tau(p \rightarrow \nu K^+)$ ~1×10^{34} yrs (HK 10ys)
- Sensitivity (90% CL limit)
  - $\tau(p \rightarrow \nu K^+)$ >3×10^{34} yrs (HK 10ys)



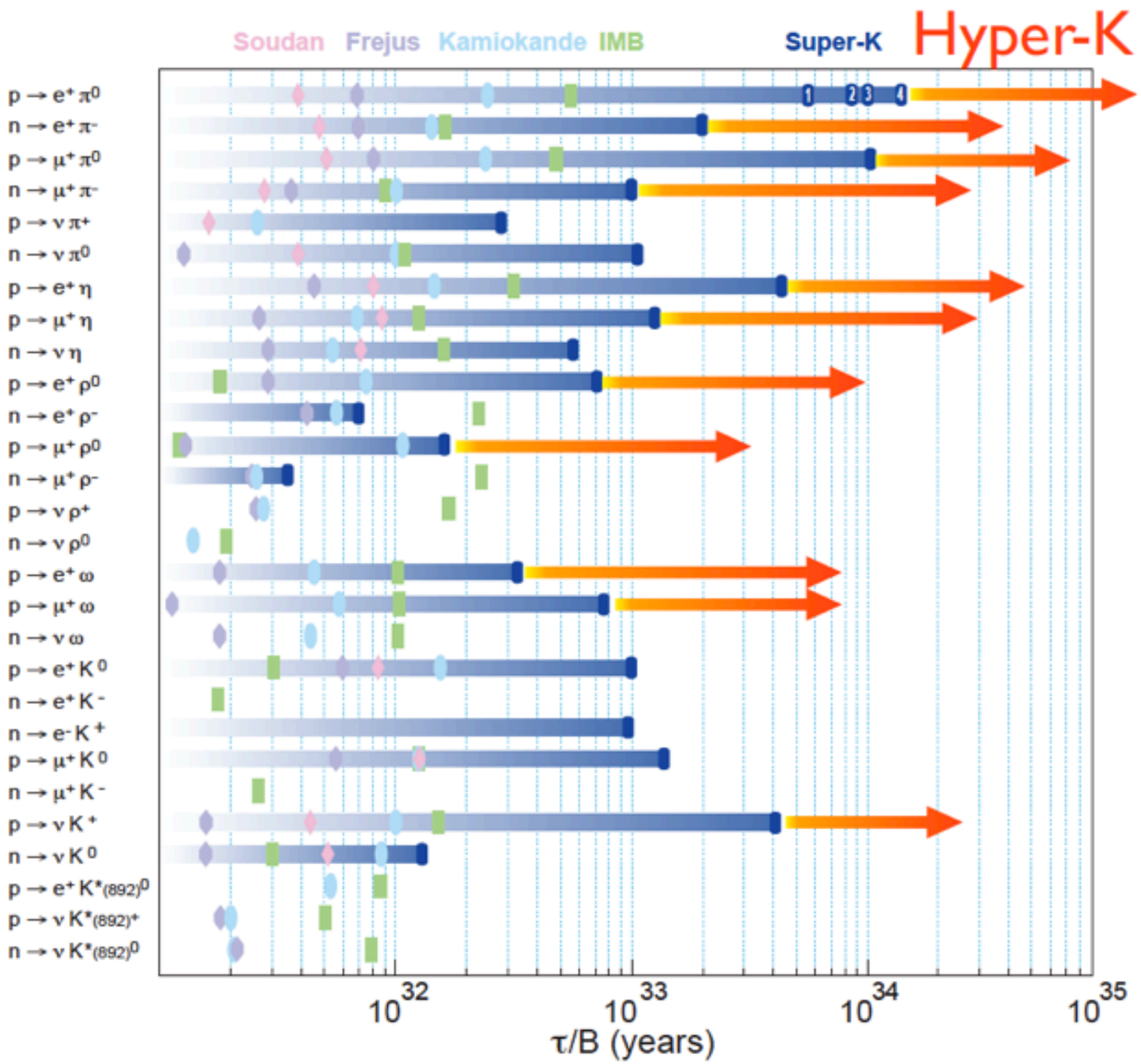






Triple coincidence: $^{16}O \rightarrow {}^{15}N^*$ de-excitation γ (6.3MeV), $K \rightarrow \mu\nu$, and Michel-e

Search for nucleon decays

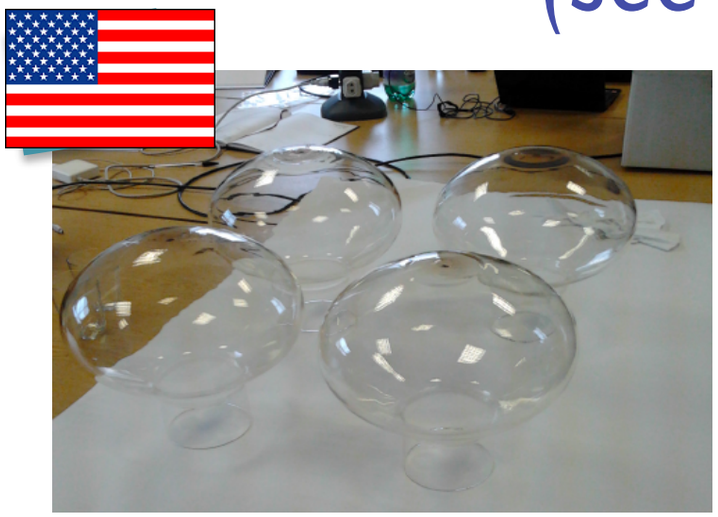


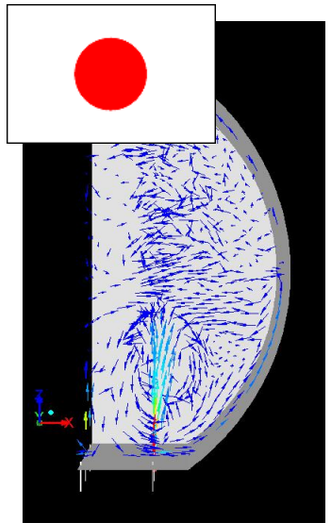
For all decay modes ≥10 times higher sensitivity than current SK limits w/ HK 10 yrs operation

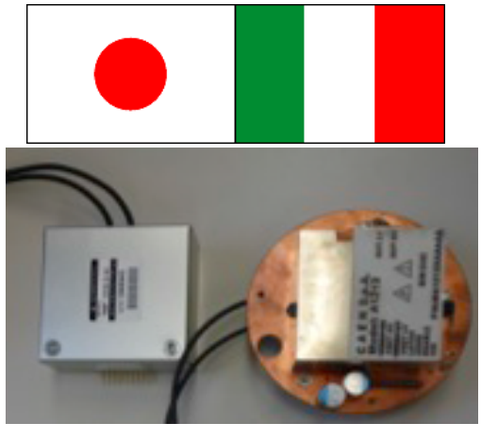
Status of R&D

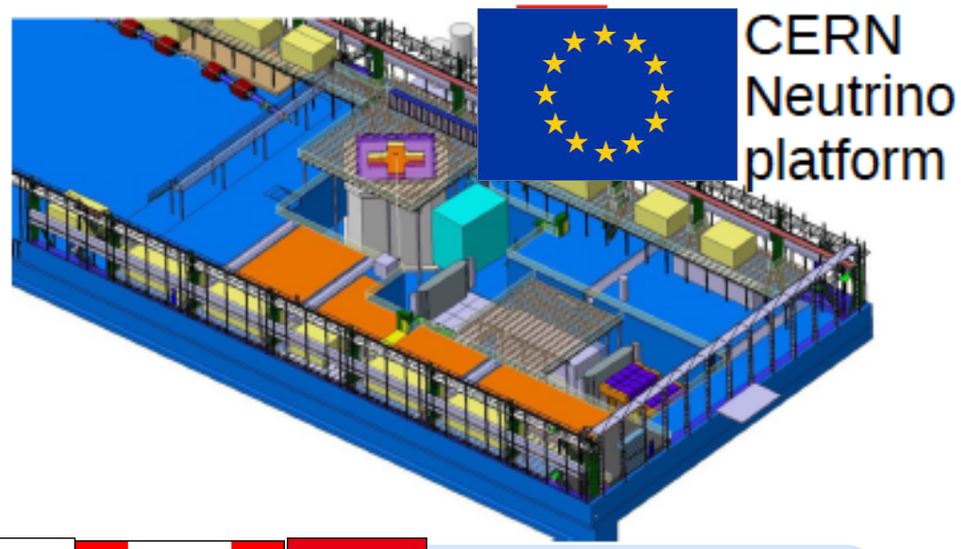
R&D progress in worldwide

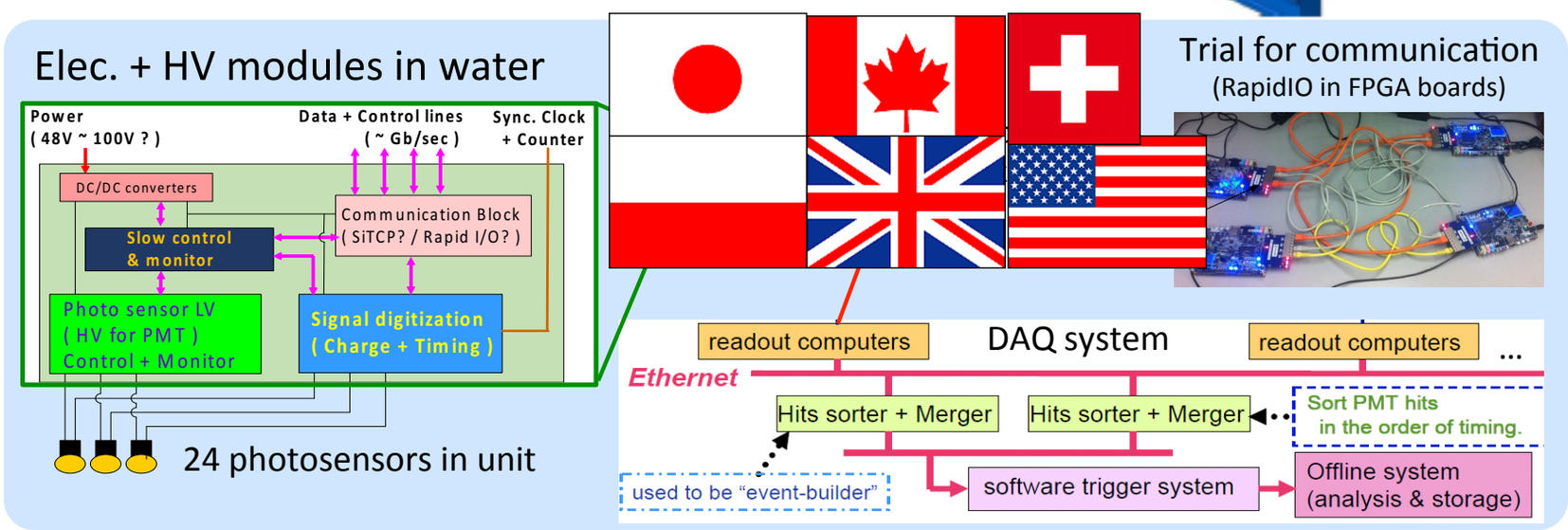
(see Nishimura-san's talk for details)

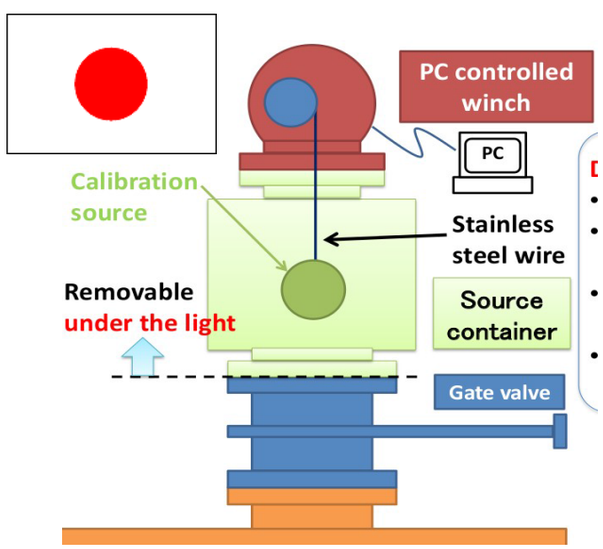




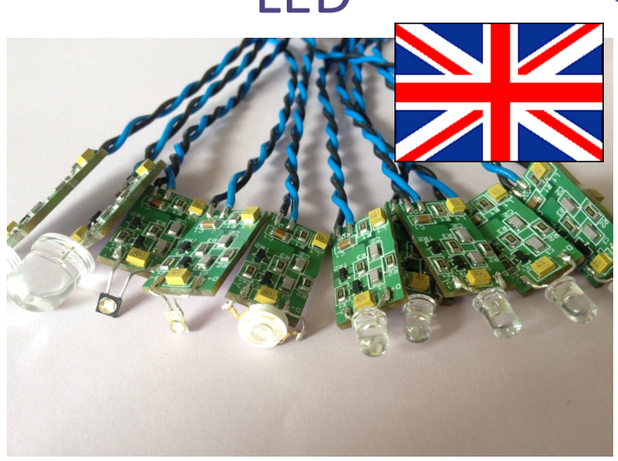




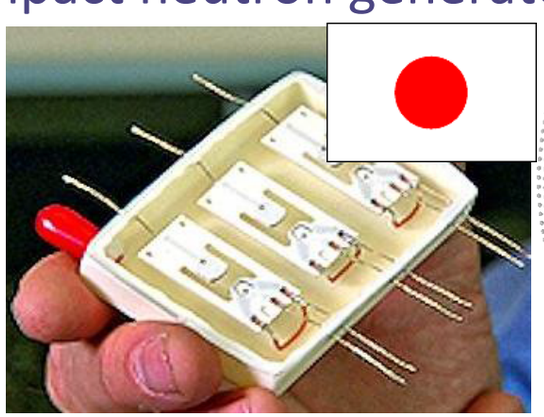


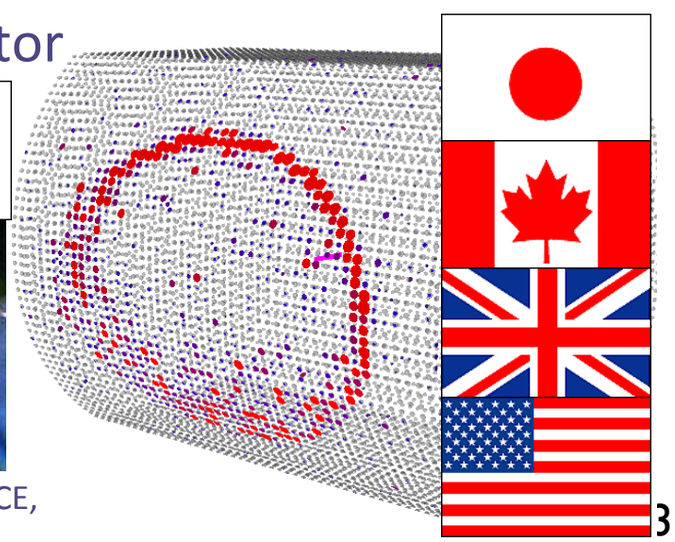


LED



Compact neutron generator

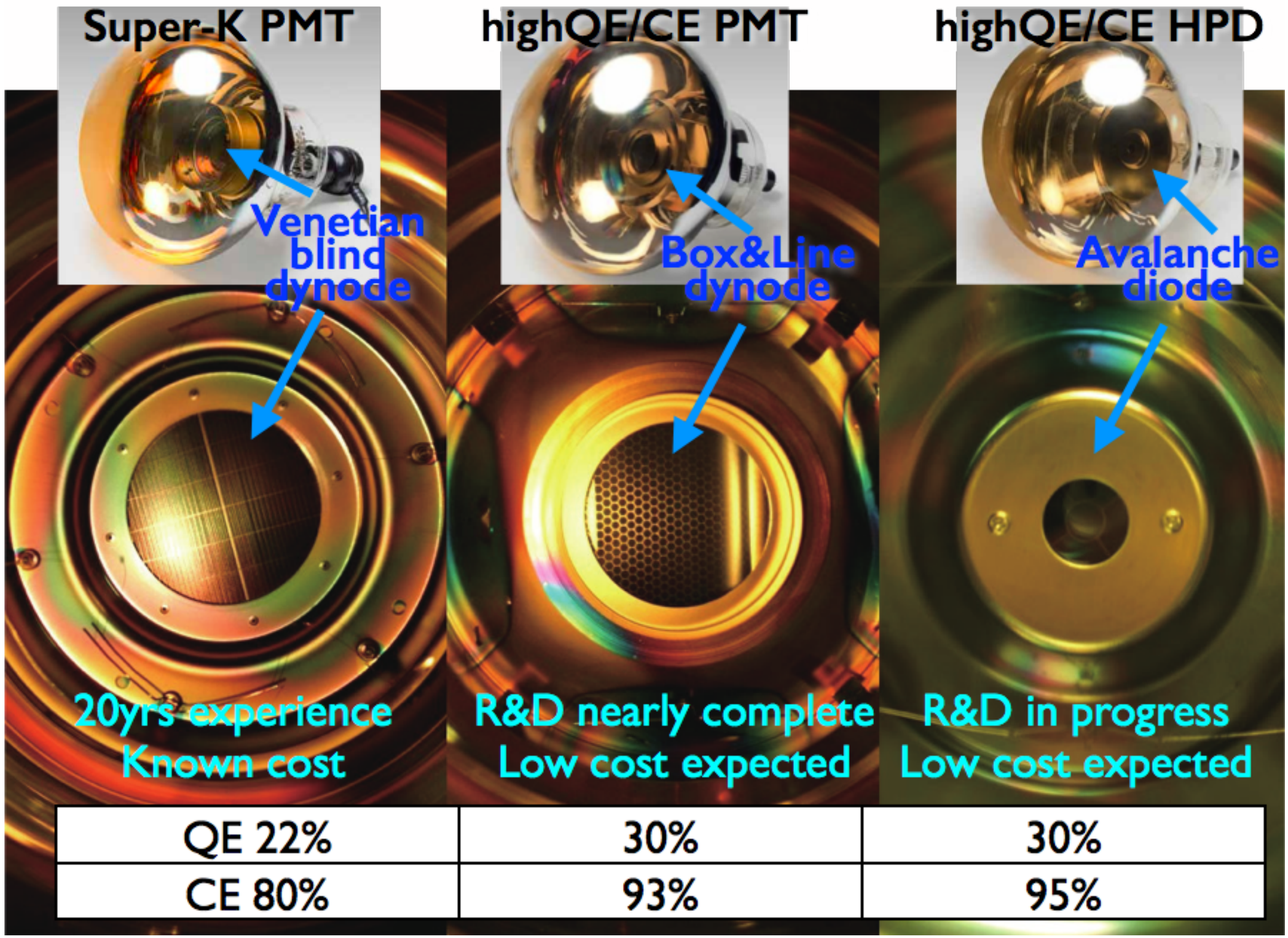




IEEE TRANSACTIONS ON PLASMA SCIENCE,
VOL. 40, NO. 9, SEPTEMBER 2012

New 20” photo-sensors

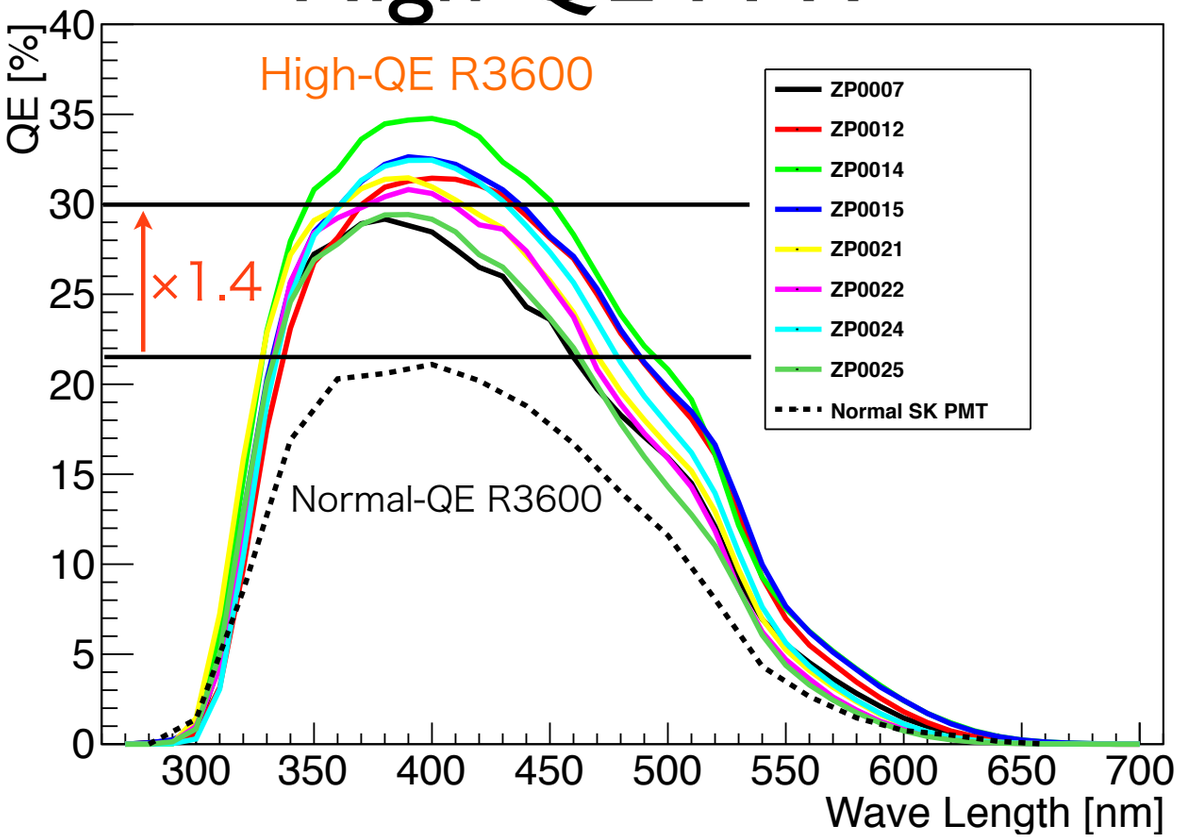
Super-K PMT | Box&Line dynode PMT | Hybrid photo-detector (HPD)



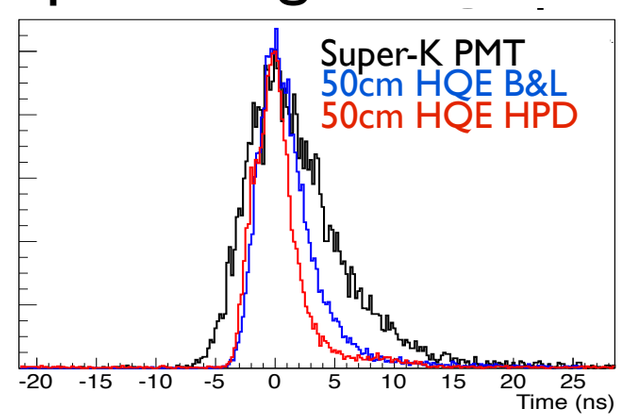
QE 22%	30%	30%
CE 80%	93%	95%

Performance of new photosensors

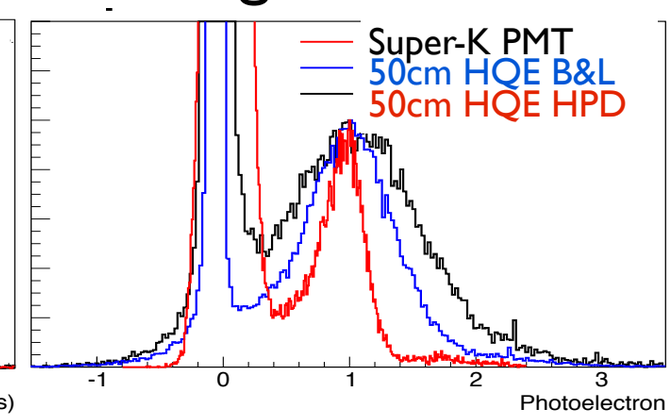
High QE PMT



1pe timing resolution



charge resolution



	SK PMT	B&L PMT	HPD
1p.e. Δt (ns)	2.1	1.1	1.4
1p.e. ΔQ/Q (%)	53	35	16
Peak/Valley ratio	2.2	4.3	3.9

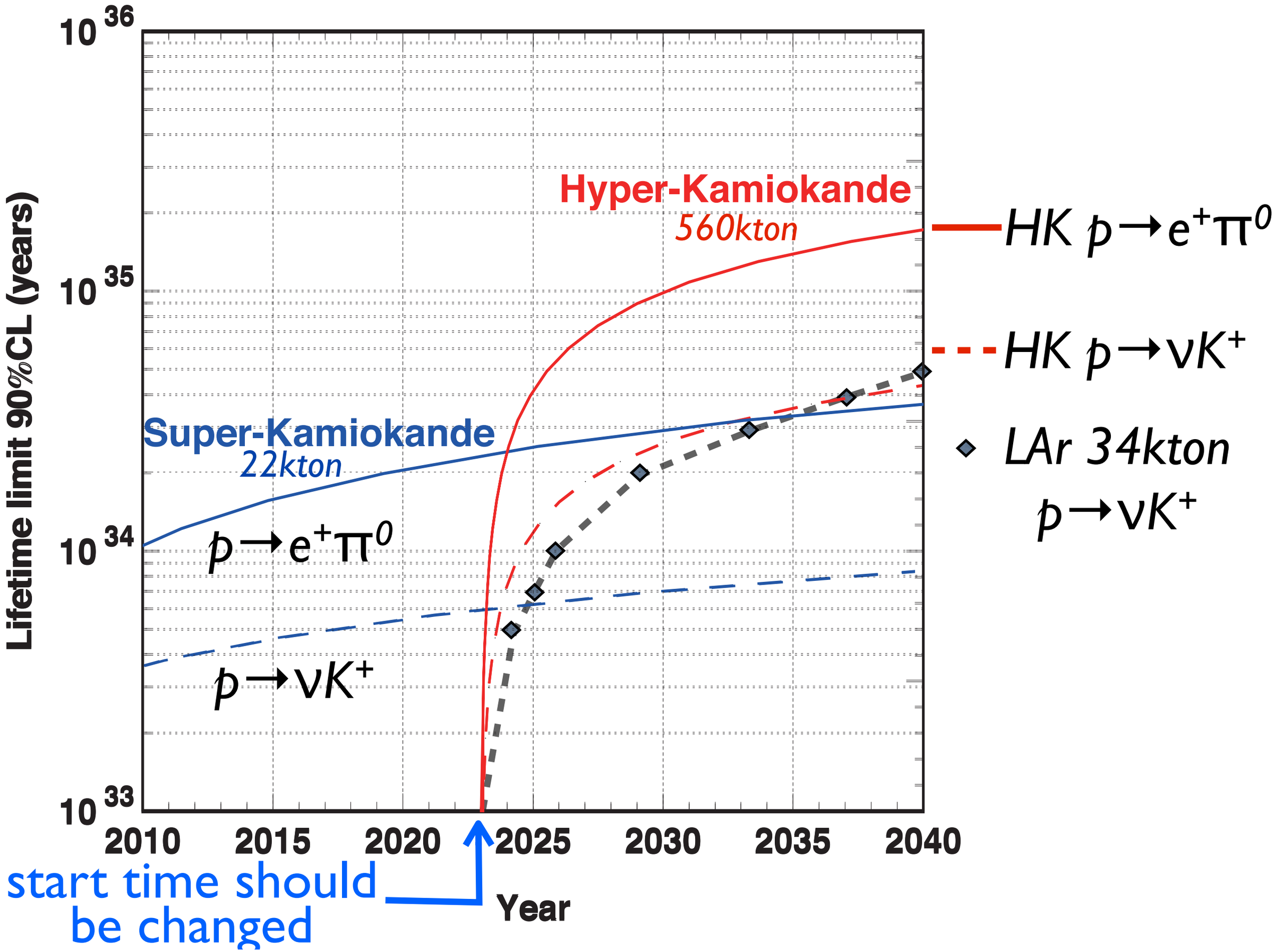
- New photo-sensors:
  - High QE ~30% (cf. SK PMT ~20%)
  - High CE ≥93% (cf. SK PMT ~80%)

  } ≥1.7 times better efficiency than SK PMT
  - Better resolution of timing and charge
  - Proof-test is in progress in Č detector (EGADS detector)
  - R&D will be completed in 2016 to select one technology

Summary

- **Wide Physics topics, many discovery potentials**
  - ν CPV: 76% of δ space w/ 3σ, δ resolution <20°
  - Proton decay discovery
  - SN burst, SN relic ν, indirect WIMP search, etc
- **Many good results in R&D**
  - Large cavity excavation and its support
  - Water containment system, e.g. HPDE liner
  - 50cm high-performance photosensors, etc
- **Boost promoting the project**
  - International proto-collaboration formed
  - Design Report written up shortly
  - Cooperation with KEK/ICRR to develop the project
  - Open for new collaborators

Supplements


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
$p \to e^+\pi^0$
$p \to \nu K^+$
HK $p \to e^+\pi^0$
HK $p \to \nu K^+$
LAr 34kton
$p \to \nu K^+$
start time should be changed

J-PARC MR for neutrinos

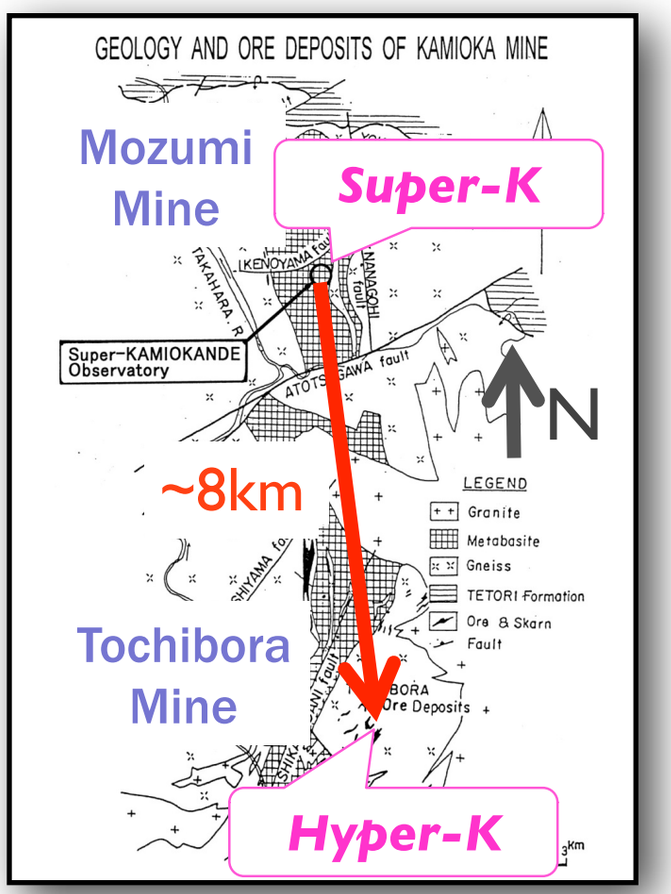
Koseki-san's slide @HINT2015 workshop

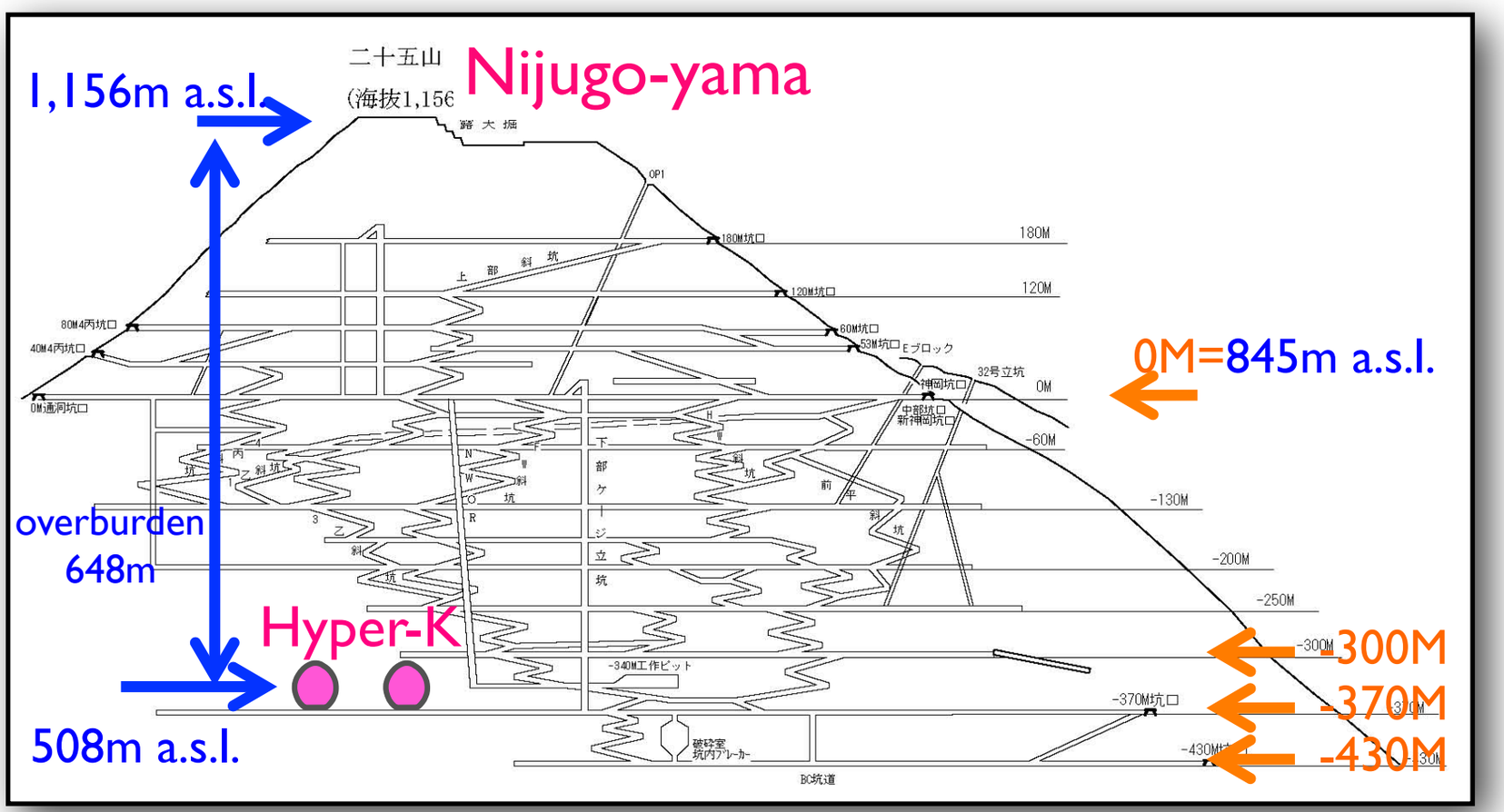
FX: The high repetition rate scheme is adopted to achieve the design beam intensity, 750 kW. Rep. rate will be increased from ~ 0.4 Hz to ~1 Hz by replacing magnet PS's, RF cavities and some injection and extraction devices.
SX: Parts of stainless steel ducts are replaced with titanium ducts to reduce residual radiation dose. The beam power will be gradually increased toward 100 kW watching the residual activity.

JFY	2014	2015	2016	2017	2018	2019	2020
	Li. current upgrade		New PS buildings				
FX power [kW] (study/trial)	320	> 360	400	450	700	800	900
SX power [kW] (study/trial)	-	33 - 40	50	50-70	50-70	~100	~100
Cycle time of main magnet PS New magnet PS	2.48 s R&D	Large scale 1st PS	Mass production installation/test		1.3 s	1.3 s	1.2 s
High gradient rf system 2nd harmonic rf system VHF cavity	Manufacture, installation/test R&D, manufacture, installation/test R&D						
Ring collimators		Add.collimators (2 kW)	Add.collimators (3.5kW)				
Injection system FX system	Kicker PS improvement, Septa manufacture /test Kicker PS improvement, LF septum, HF septa manufacture /test						
SX collimator / Local shields		Local shields					
Ti ducts and SX devices with Ti chamber	Beam ducts	ESS					

Candidate Site

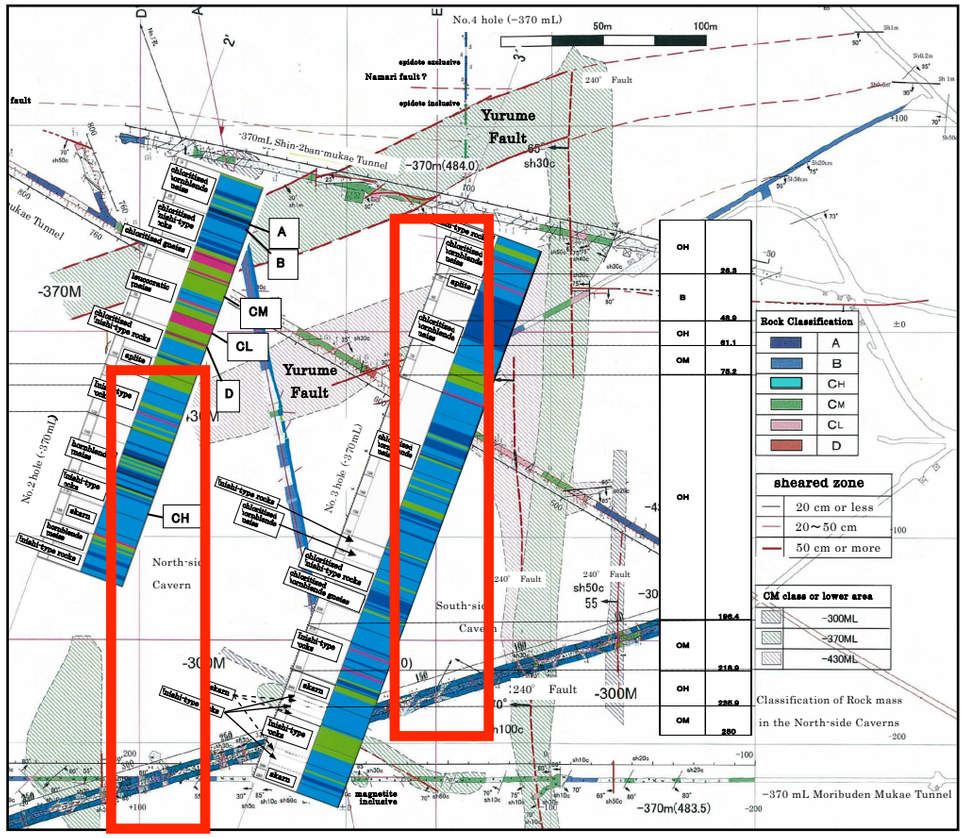
- The candidate site locates under “Nijugo-yama” (Mt. 25)
  - ~8km south from Super-K
  - Identical baseline and off-axis angle to T2K (295km, 2.5 deg)
- Overburden ~650m (~1755 m.w.e.)



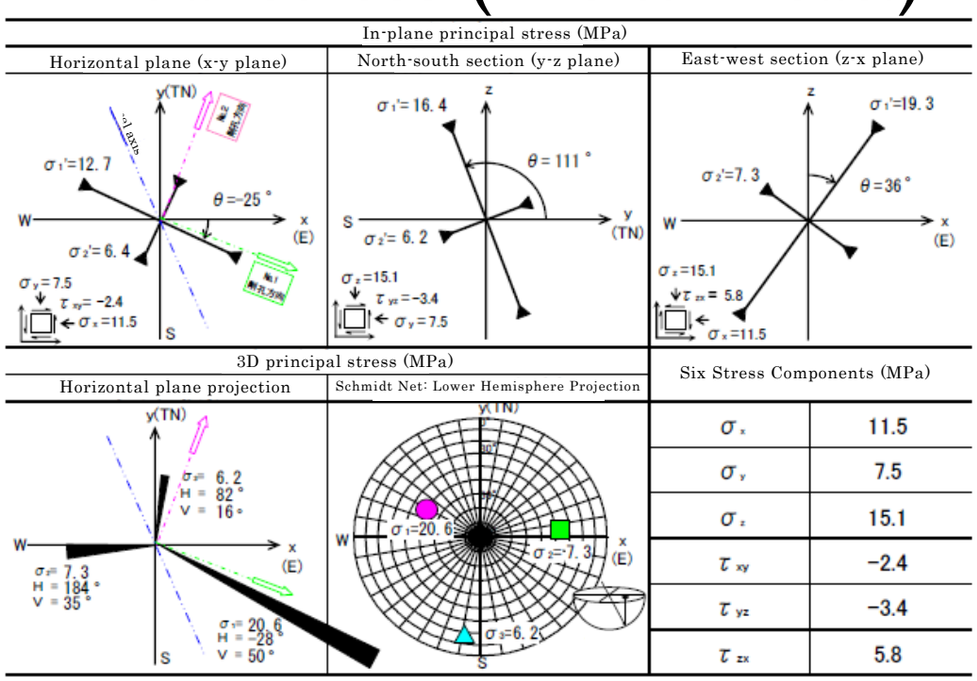


Geological survey & Cavern stability

Rock mass characterization

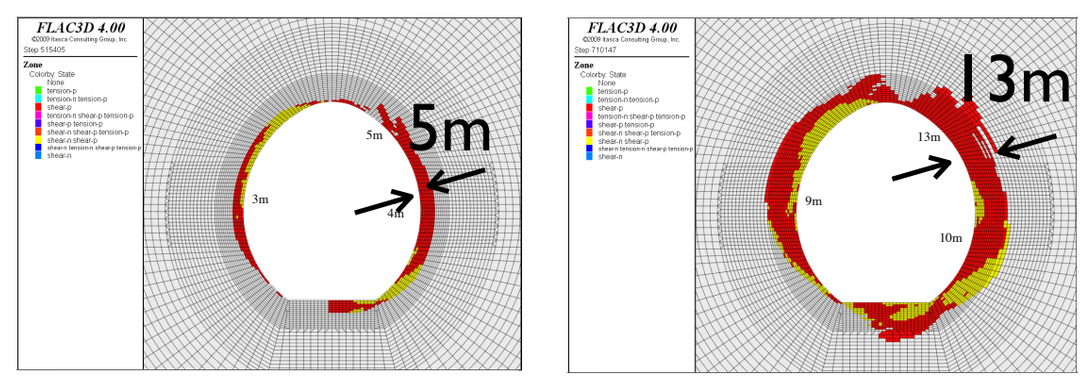


Initial stress (in-situ meas.)

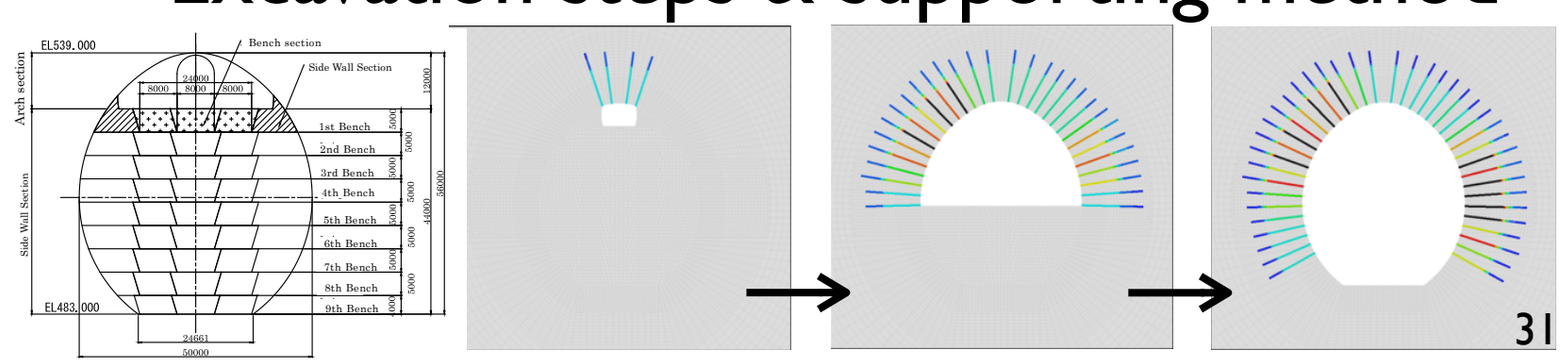


- Detailed geological surveys at the candidates site vicinity
- Cavern stability and its supporting method has been studied
- Confirmed that the HK cavern can be constructed with the existing techniques

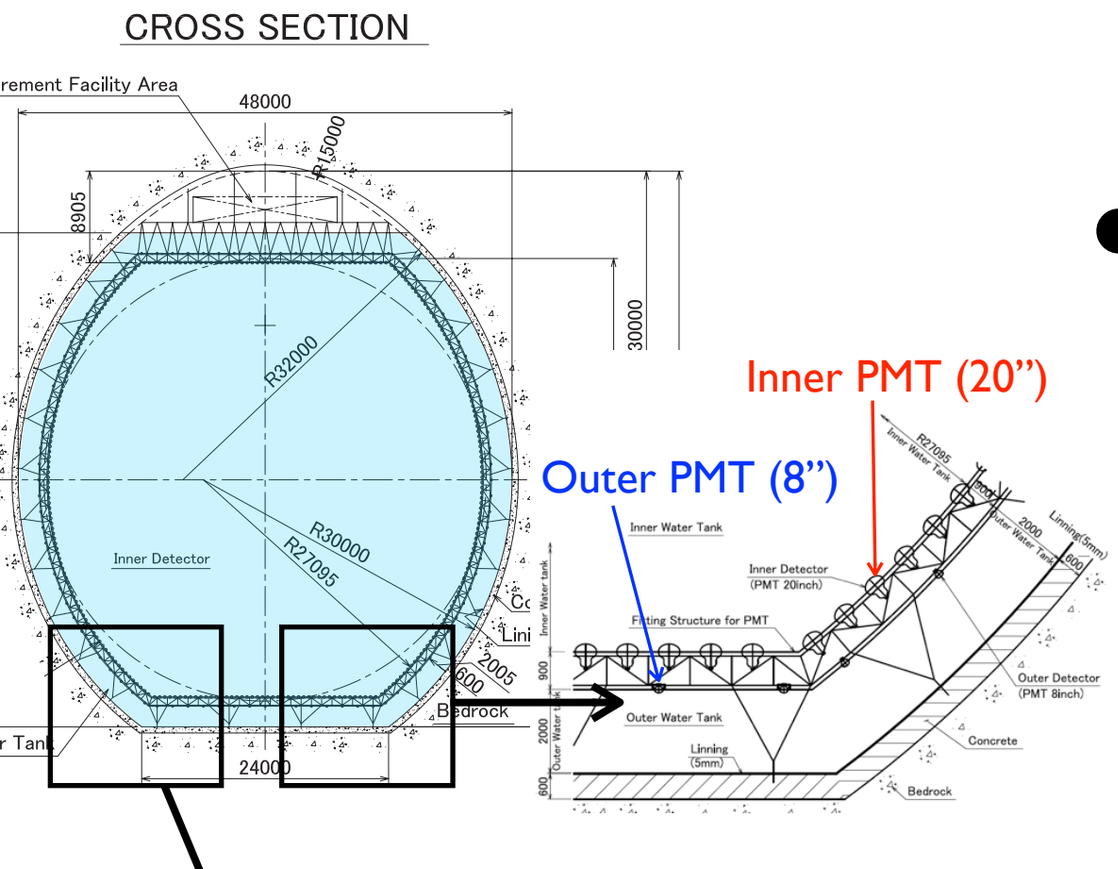
Cavern stability



Excavation steps & supporting method

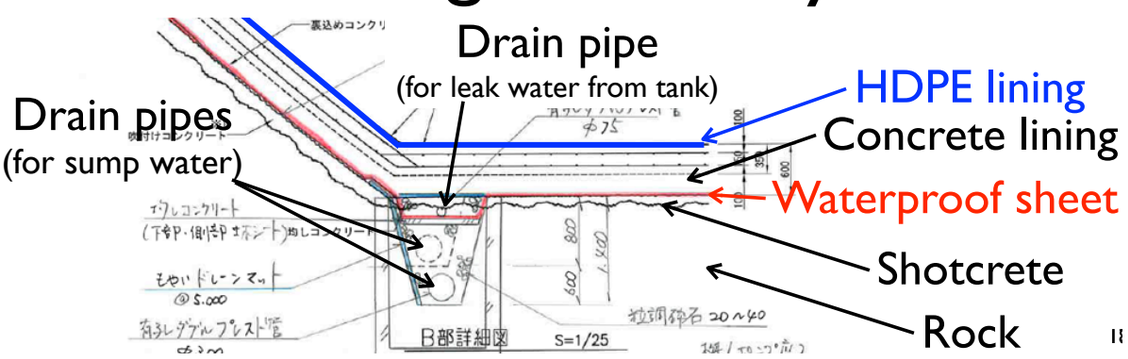


Tank and photo-sensor support



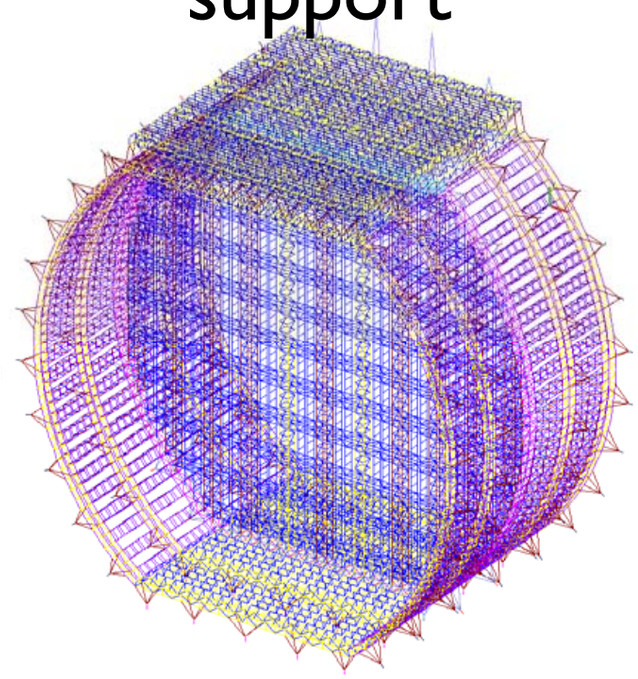
- Baseline designs of the water containment system and photo-sensor support are ready

Lining & drain system

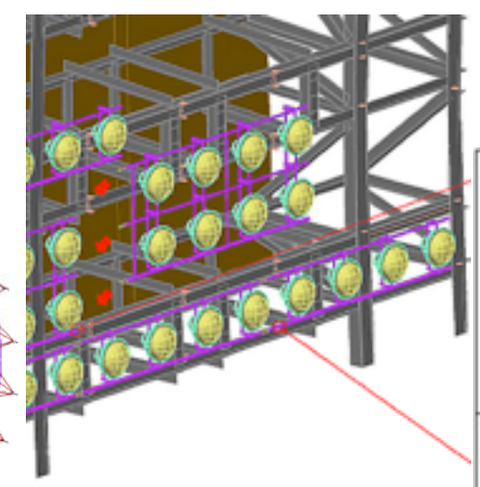


Polyethylene sheet

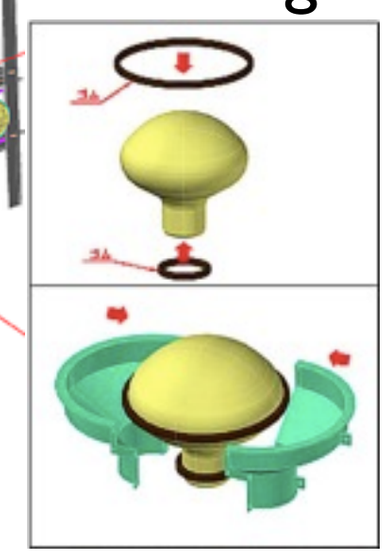
Photo-sensor support



Mounting Photo-sensor



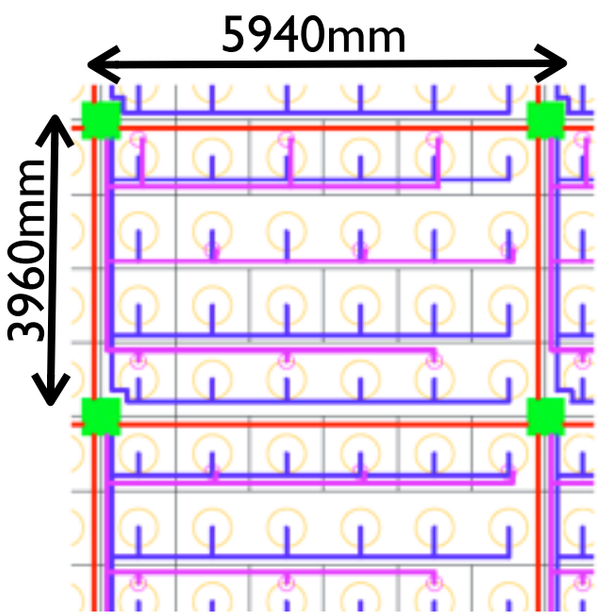
Housing



Designing work...

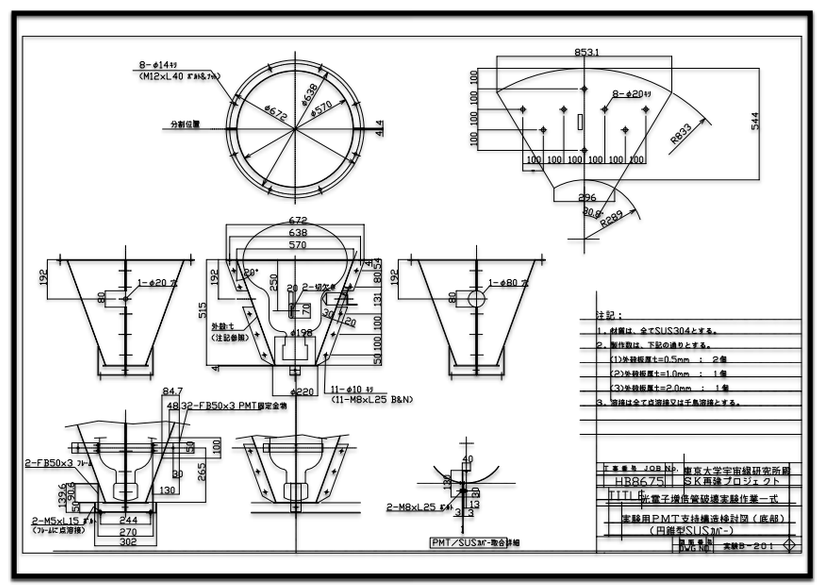
- All major part of HK tank has been designed.
  - Include layout of water pipes, front-end electronics, cables, calibration holes, plug manholes, ... etc.

Electronics & cable layout

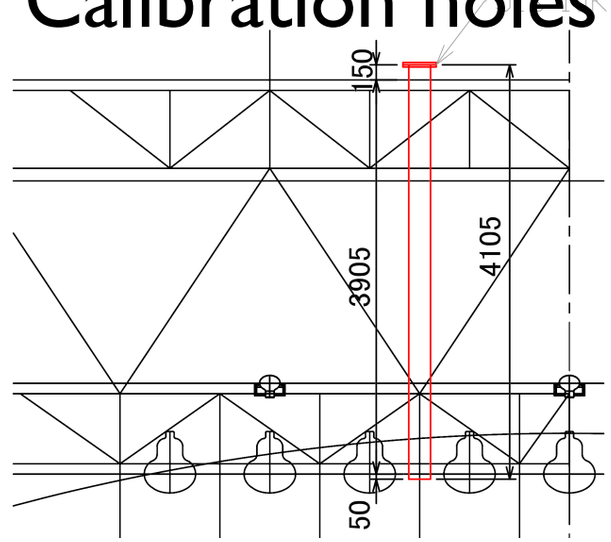


: Support structure
: Cable for inner PMT
: Cable for outer PMT
: Network/Power cable
: Hub / Front End Electronics
: Inner photo-sensor (20")
: Outer photo-sensor (8")

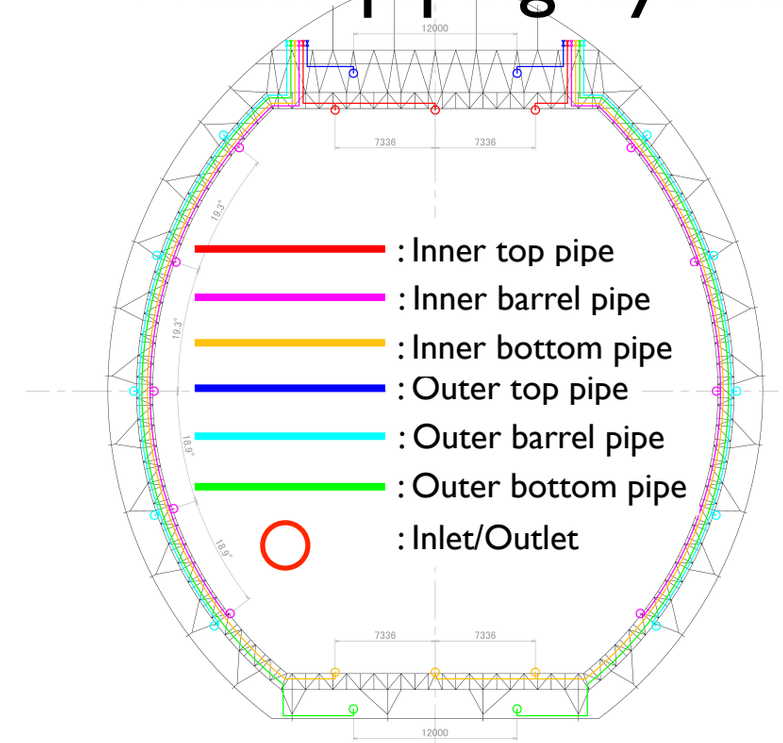
Photo-sensor housing



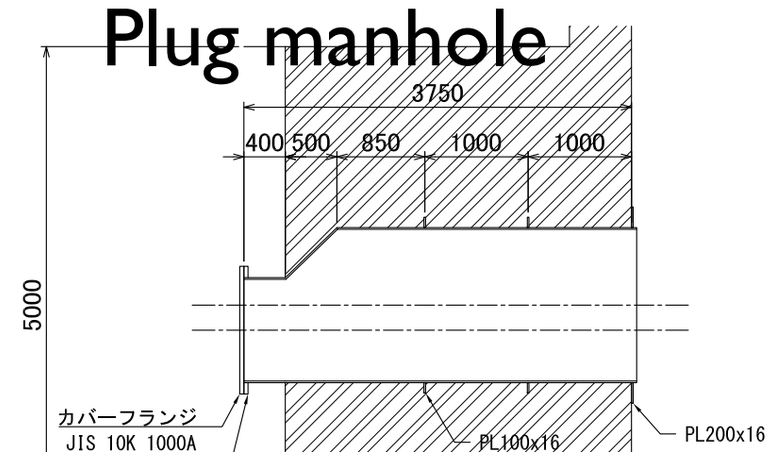
Calibration holes



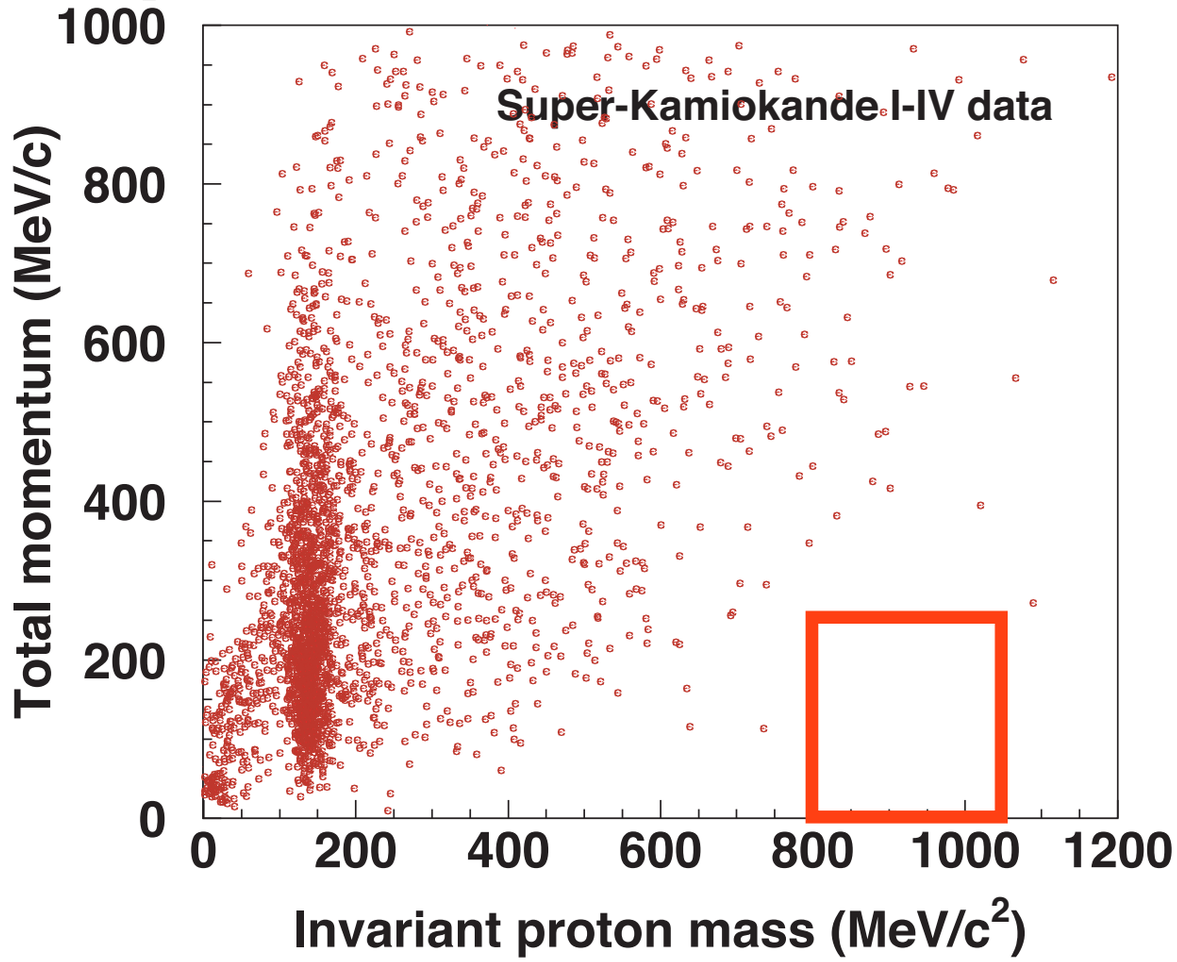
Water piping layout

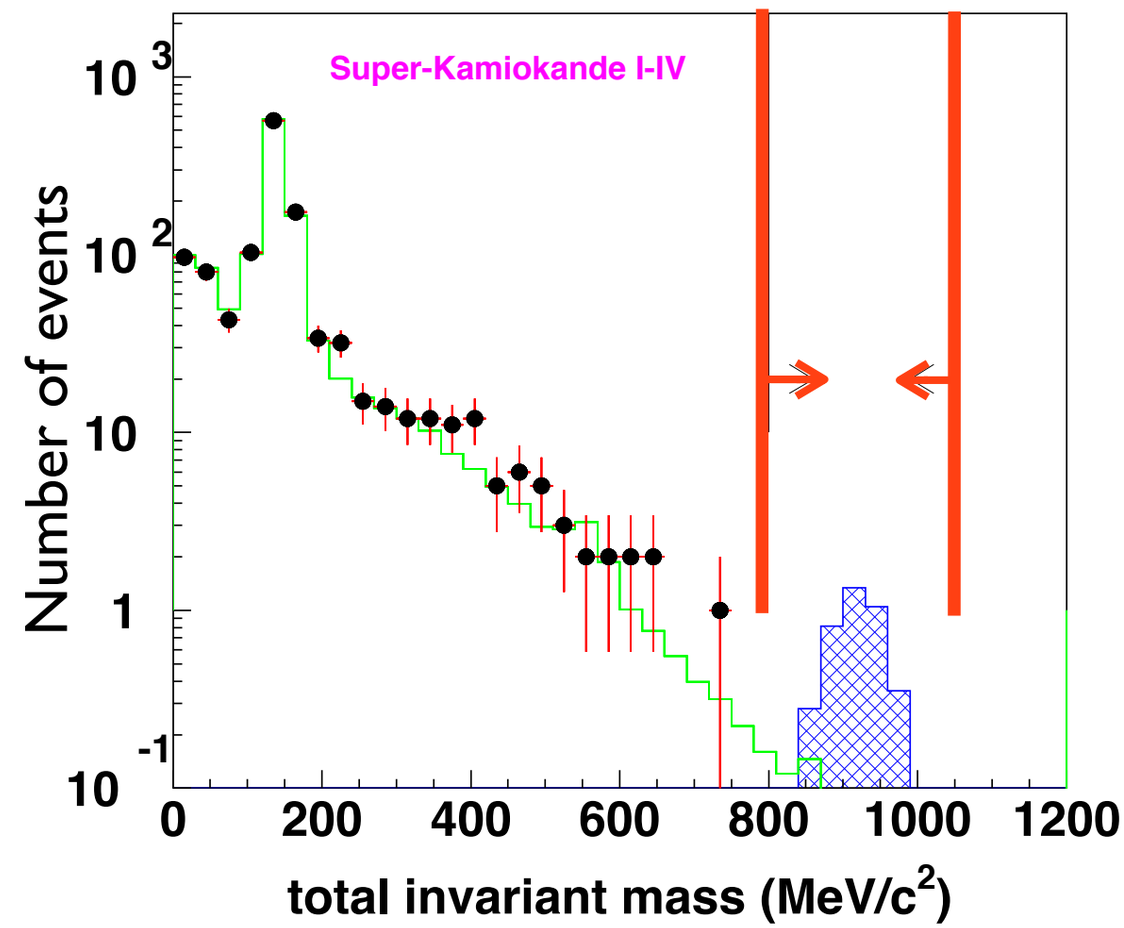


Plug manhole



$p \rightarrow e^+ + \pi^0$ in SK I-IV (260kt×yrs)





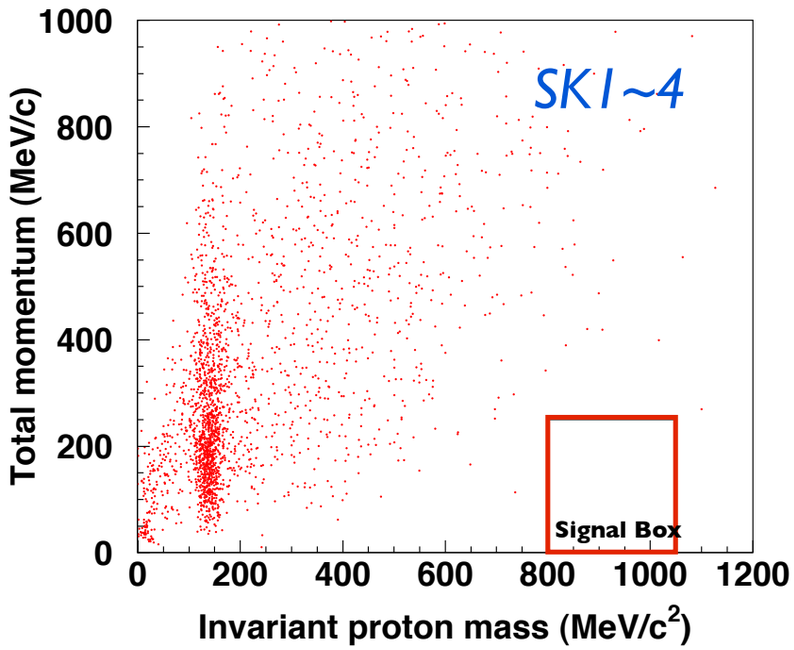
$p \rightarrow e^+ + \pi^0$

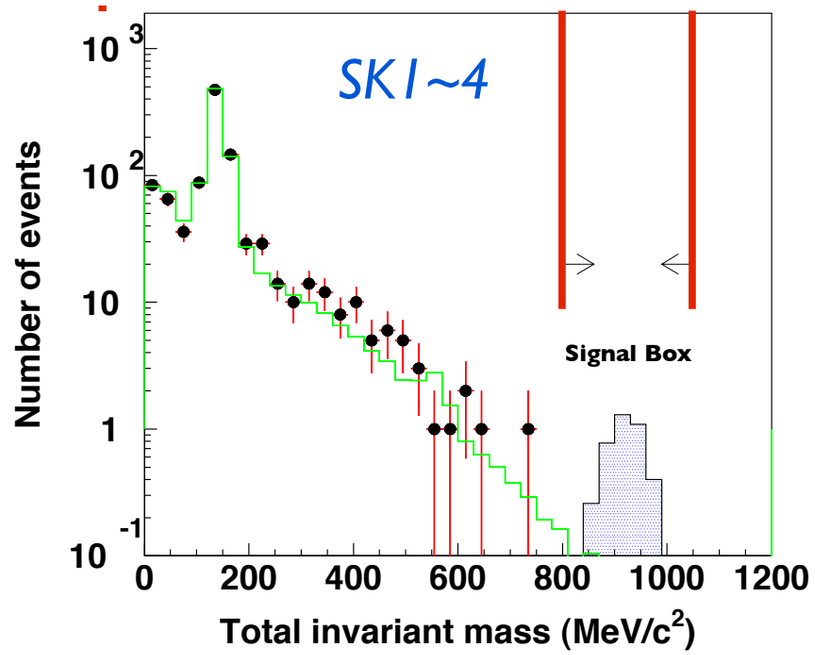
- detection efficiency = 40%
- atmospheric ν BG = 0.7 events in 260kton×years
  2.7±0.3(stat.)±1.2(syst.) $(\text{Mton}\times\text{years})^{-1}$
- $\tau_{proton}/Br > 1.4 \times 10^{34}$ years @ 90%C.L.

- Succeed to keep the background low. More reduction is under study.
- BG rate was confirmed by K2K accelerator ν beam

PRD77:032003,2008

$p \rightarrow e^+\pi^0$ search: BG (atm ν)



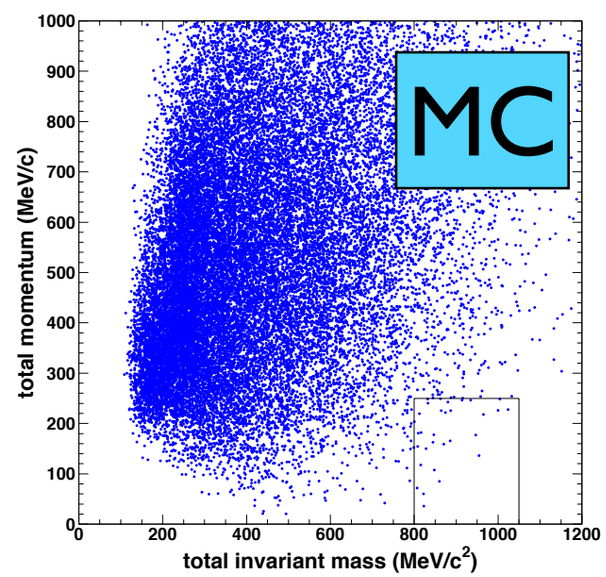


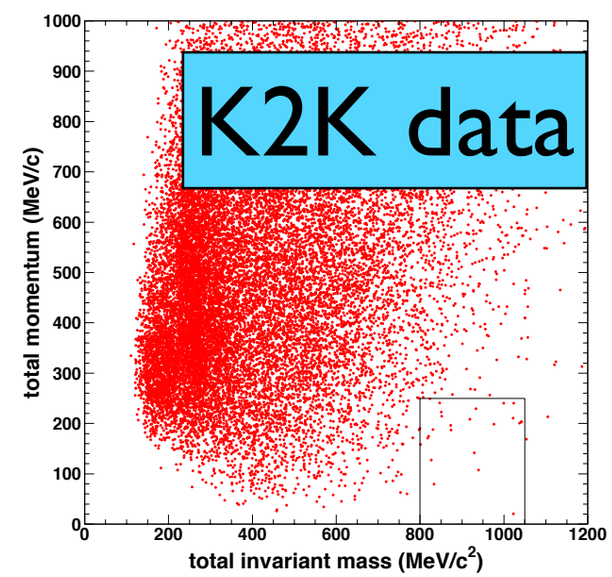
SK data well reproduced with Bkg MC.

Major Bkg: atmospheric ν CC evts (ex. $\bar{\nu}_e p \rightarrow e^+ n \pi^0$, $\nu_e n \rightarrow e^- n \pi^+$ w/ charge exchange)

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

PRD 77, 032003(2008)





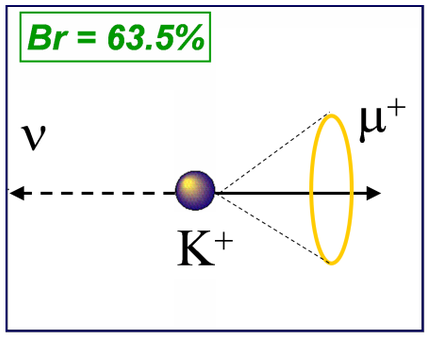
$1.63^{+0.42}_{-0.33}(stat.)^{+0.45}_{-0.51}(syst.)[\mathrm{Mt} \times \mathrm{years}]^{-1}(E_\nu < 3GeV)$

Consistent w/ simulation 1.8±0.3(stat.)

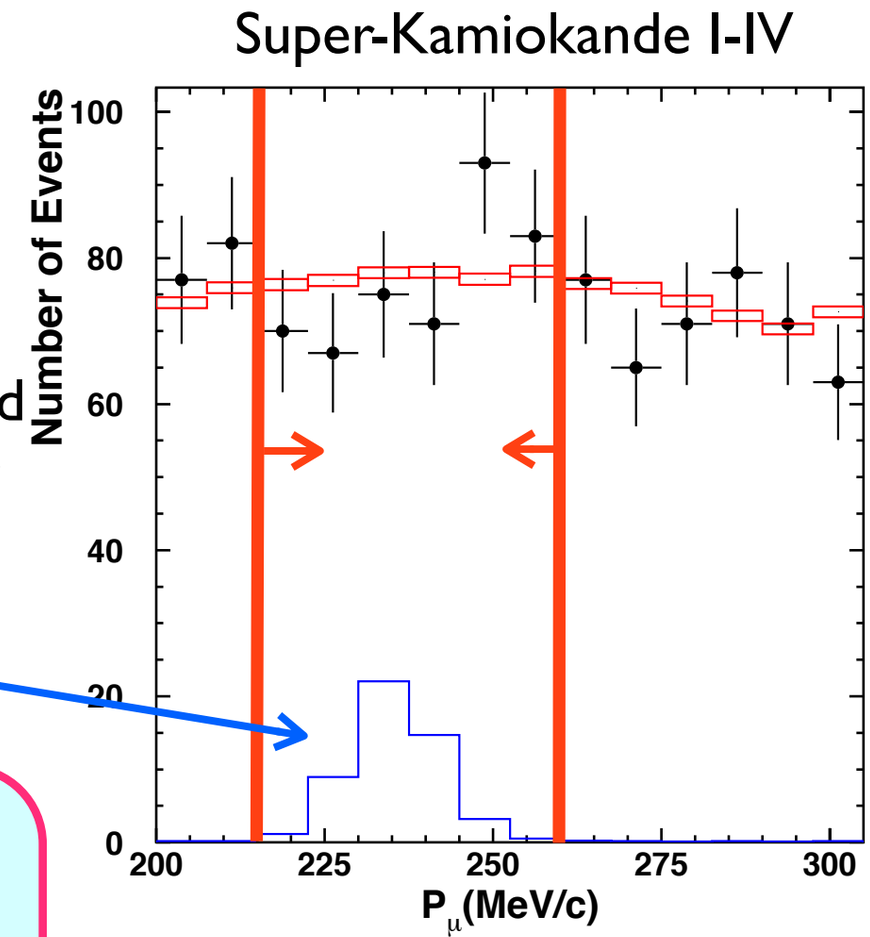
Reliable prediction of next generation experiment

$p \to \nu + K^+$ searches in SK

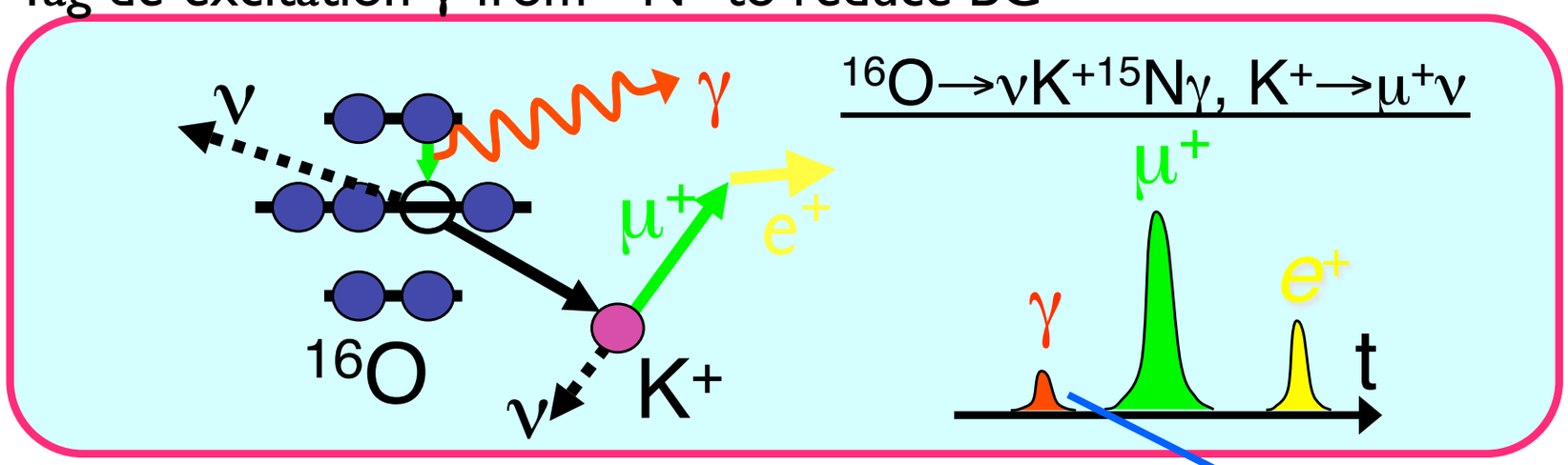
(I) $K^+ \to \mu^+\nu$, $\mu^+ \to e^+\nu\nu$

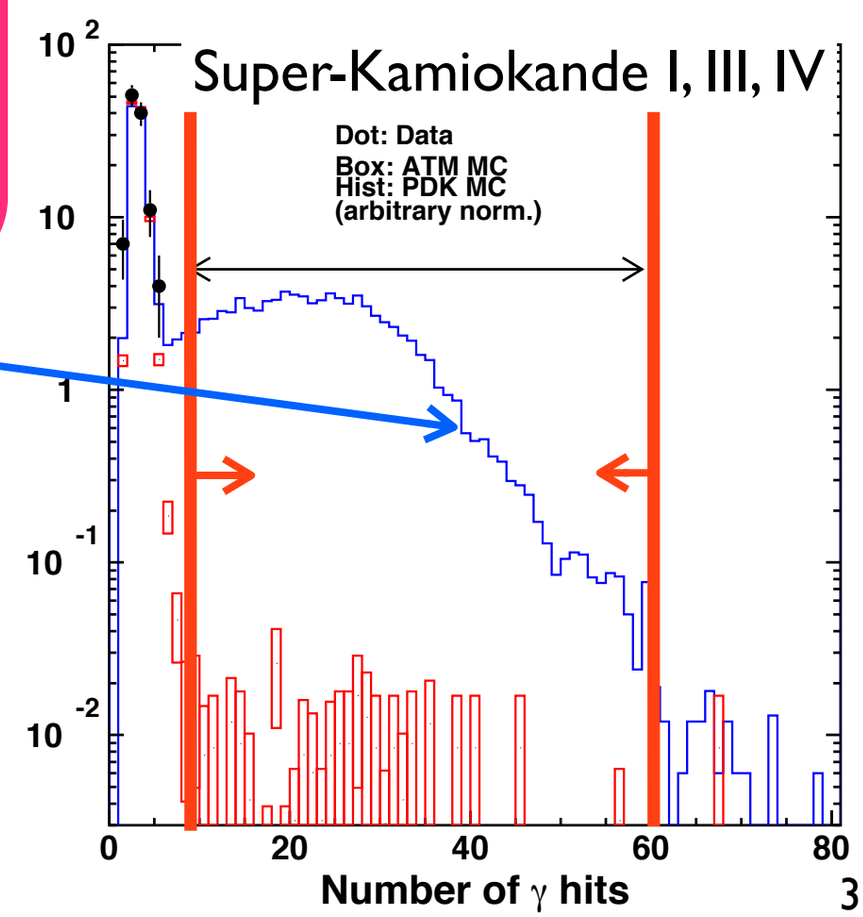


K^+ is below Cherenkov threshold
→ 236MeV/c μ and muon decay electrons



Tag de-excitation γ from $^{15}N^*$ to reduce BG





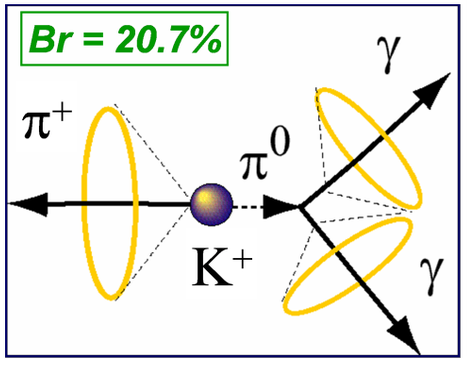
Many efforts to improve analyses

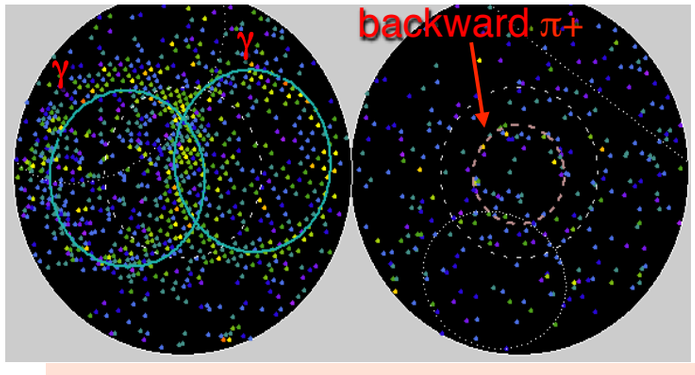
PRD90, 072005 (2014)

1. γ tagging efficiency has been improved.
2. high muon decay electrons efficiency in SK-IV.
3. better momentum reconstruction is employed.

$p \to \nu + K^+$ searches

(II) $K^+ \to \pi^+ \pi^0$





PRD90, 072005 (2014)

- π^0 efficiency was improved by dedicated π^0 finding algorithm
- Shape information of π^+ hits for BG reduction

$p \to \nu + K^+$

- 260 kton×years exposure (SK-I+II+III+IV)
- $\tau_{proton}/Br > 5.9 \times 10^{33}$ years @ 90%CL

Summary of prompt γ and ππ searches

PRD72,052007

SK-I paper in 2005 91.7 kt y 14.6% 1.3 evts.

PRD90, 072005 (2014)

	data livetime	$p \to \nu K^+$ signal efficiency	atmos. ν estimated bkg.	atmos. ν bkg. rate (evts/Mt/y)
SK-I	91.7 kt y	$15.7 \pm 0.2\%$	0.3 evts.	2.8 ± 0.4
SK-II	49.2 kt y	$13.0 \pm 0.2\%$	0.3 evts.	6.2 ± 0.8
SK-III	31.9 kt y	$15.6 \pm 0.2\%$	0.1 evts.	3.1 ± 0.5
SK-IV	87.3 kt y	$19.1 \pm 0.2\%$	0.3 evts.	3.5 ± 0.4

Atmospheric ν oscillation

NPB 689 (2004) 479

r: νμ/νe flux ratio (~2 at low energy)

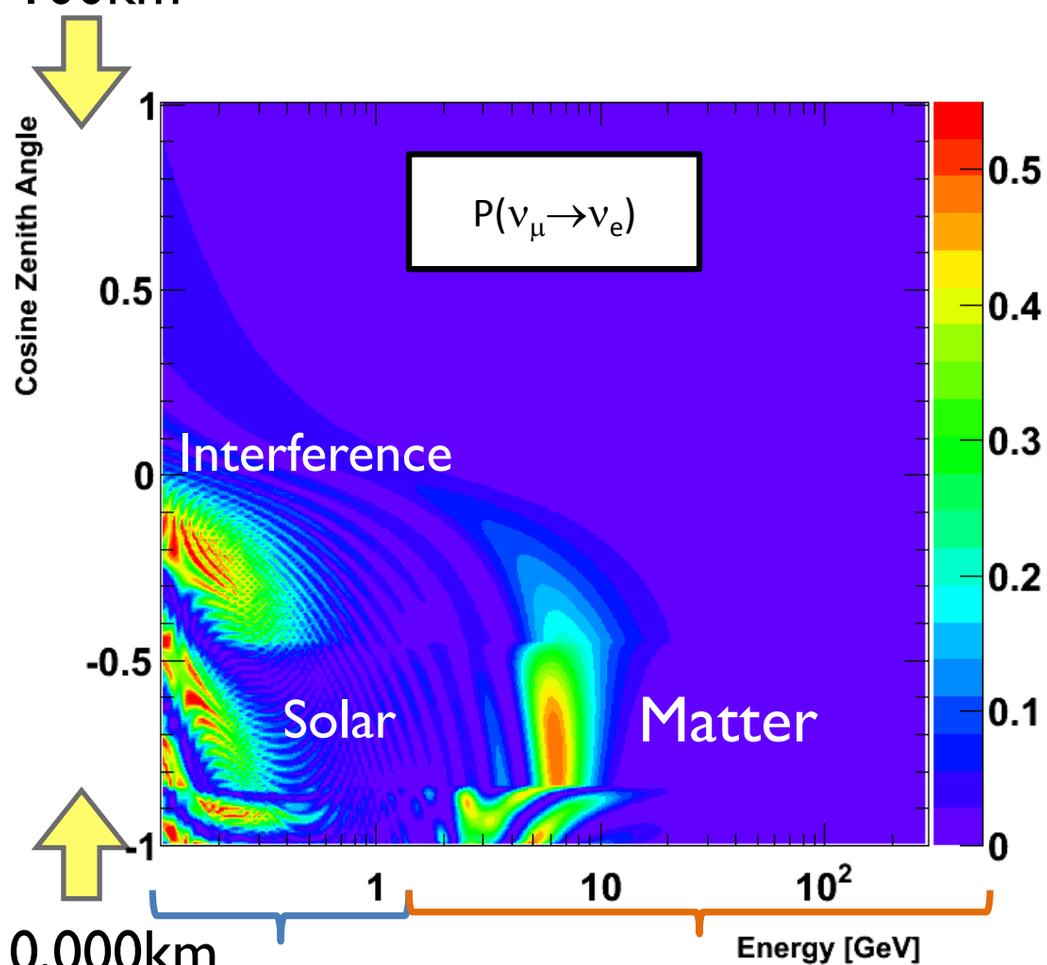
P_2: νe→νx transition prob. in matter

$$\frac{\Phi(\nu_e)}{\Phi_0(\nu_e)} - 1 \approx P_2 \cdot (r \cdot \cos^2\theta_{23} - 1)$$ solar term

$$-r \cdot \sin\tilde{\theta}_{13} \cdot \cos^2\tilde{\theta}_{13} \cdot \sin 2\theta_{23} \cdot (\cos\delta \cdot R_2 - \sin\delta \cdot I_2)$$ interference term

$$+2\sin^2\tilde{\theta}_{13} \cdot (r \cdot \sin^2\theta_{23} - 1)$$ θ_{13} resonance term (matter effect)

baseline: ~100km



~10,000km

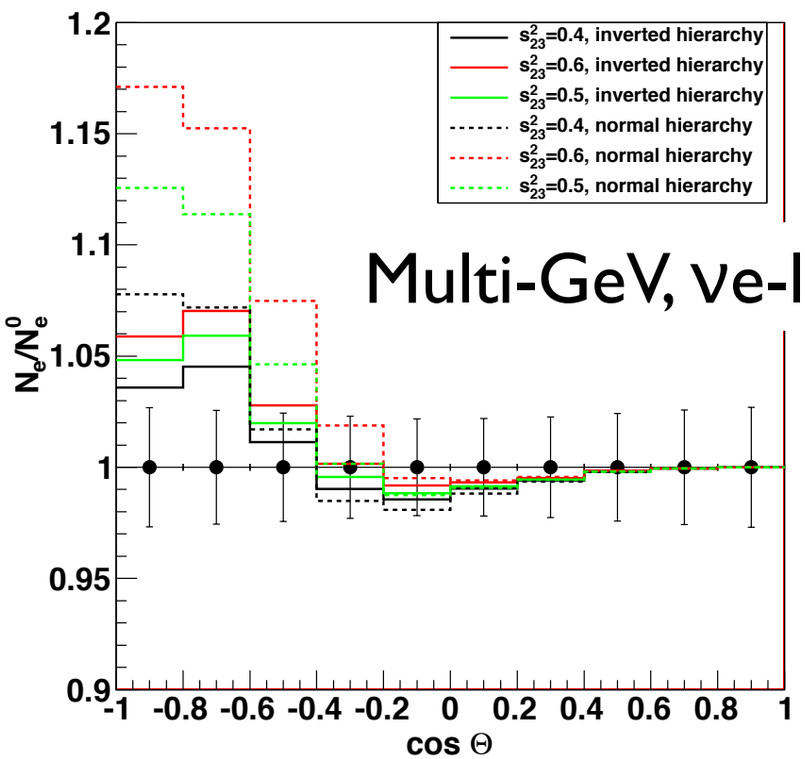
"Sub-GeV" "Multi-GeV"

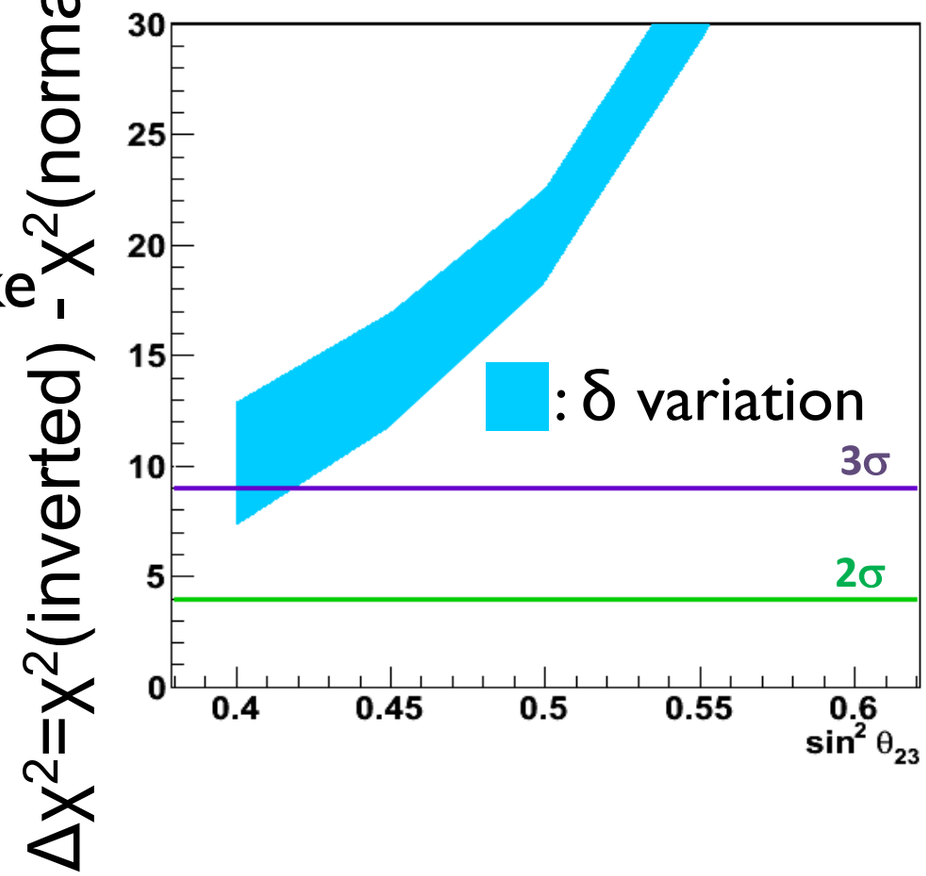
- Resonance enhancement of νe appearance (νμ distortion) via Earth's matter effect
  - Only ν if normal hierarchy, only $\bar{\nu}$ if inverted hierarchy
- Large θ_{13} helps for MH determination

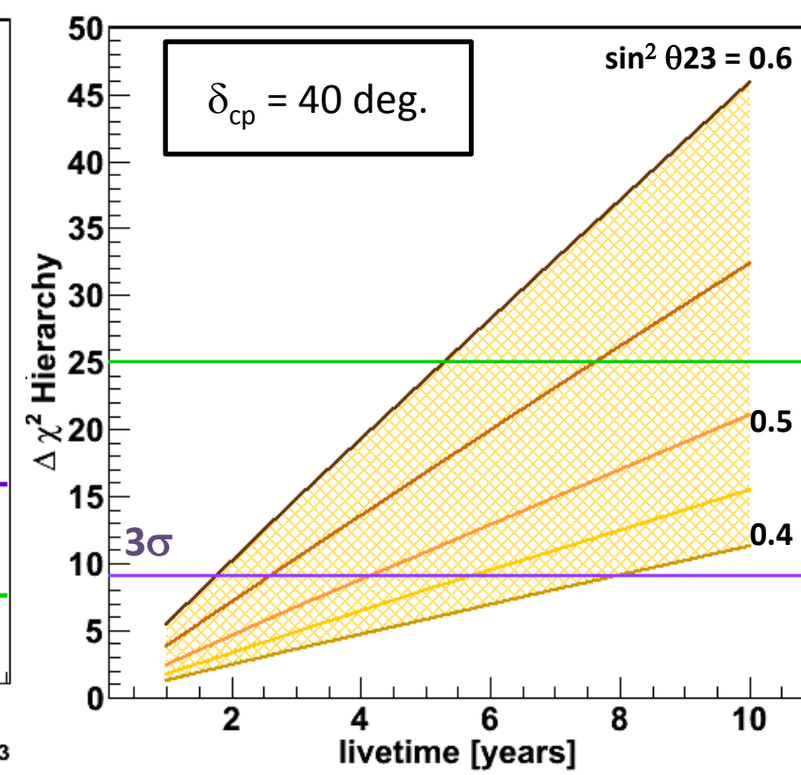
Mass hierarchy determination with atmospheric ν

$\sin^2\theta_{23}=0.4$ —— inverted hierarchy
$\sin^2\theta_{23}=0.5$
$\sin^2\theta_{23}=0.6$ - - - - - normal hierarchy

Normal hierarchy



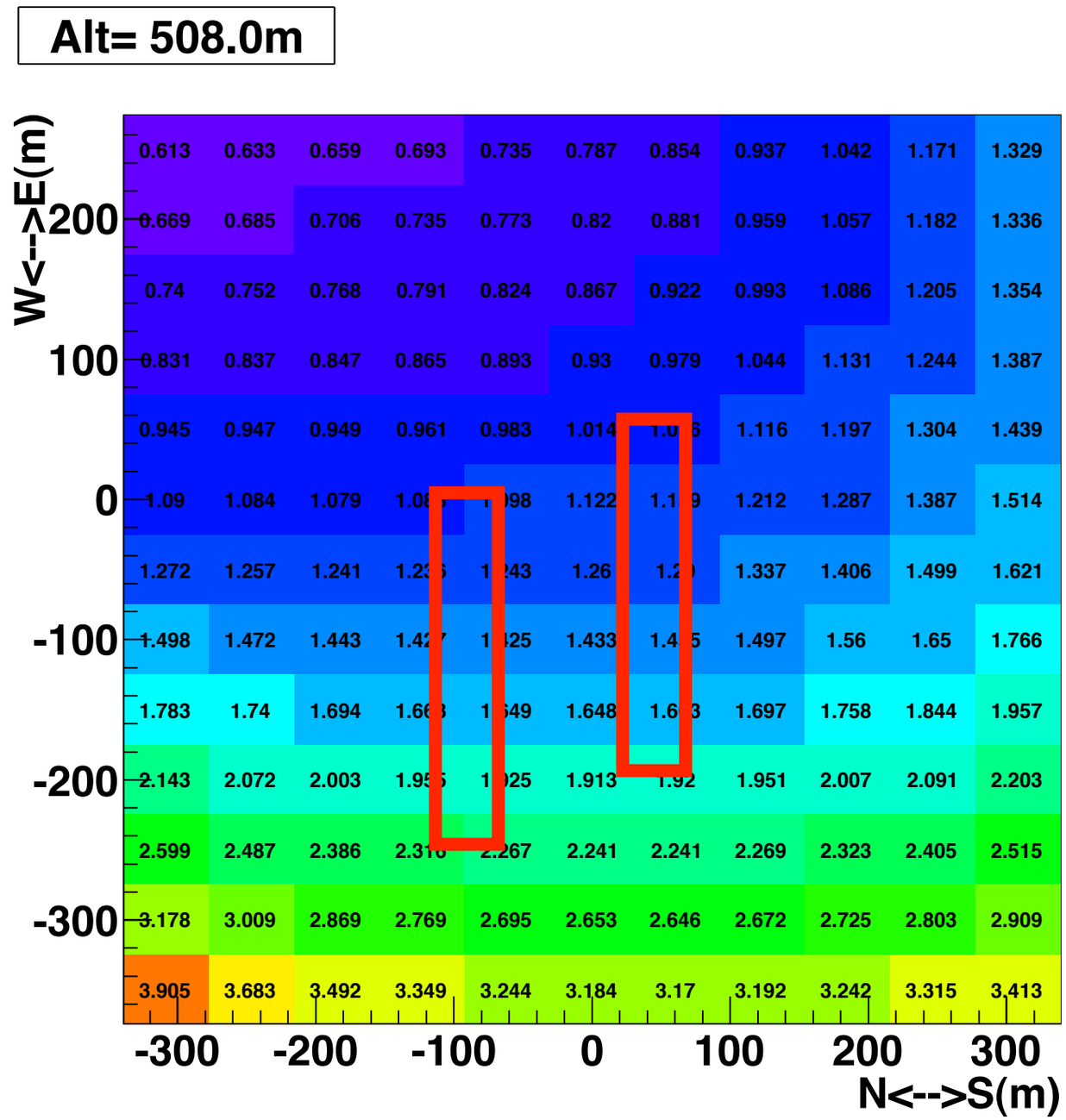




3σ determination with <10 years operation
(sensitivity depends on θ_{23} and δ)

Muon rate at candidate site

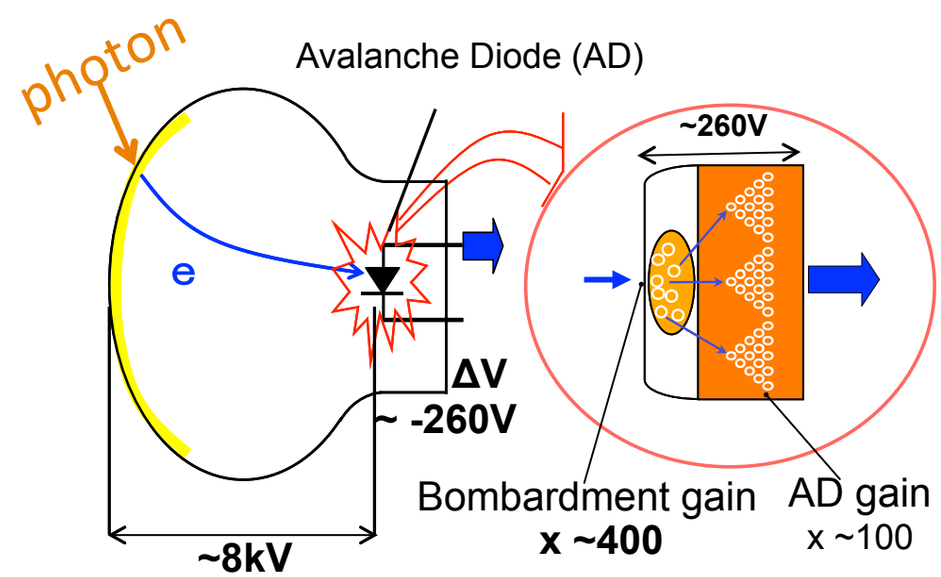
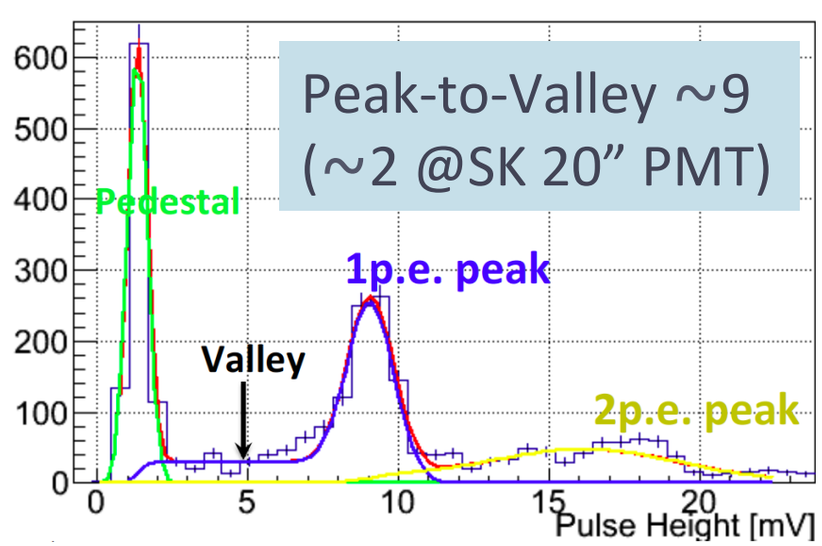
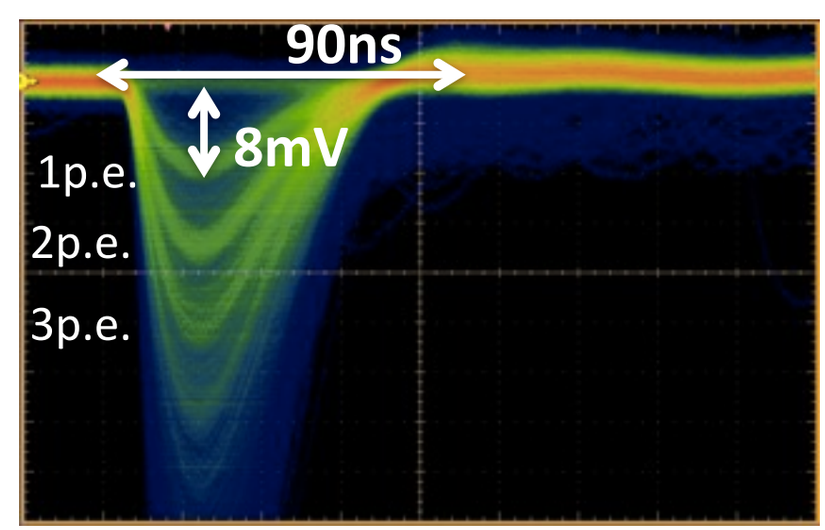
Muon rates at
HK tank floor level
in (cm^{-2} sec^{-1})



- Estimated cosmic-ray muon rate
  - HK candidate site (1755m.w.e.): 1.0~2.3 x 10^{-6} /cm^2/sec
    - cf. SK location (2700m.w.e): ~0.14 x 10^{-6} /cm^2/sec

Photo-sensor R&D

- Candidates for ID photo-sensors
  - 20” Hybrid photo-detector (HPD)
    - Photo-sensor with avalanche diode, replacing metal dynodes
    - Expected better performance than standard PMT in photon counting, timing, collection efficiency, lower cost
  - 20” High QE PMT (~30% QE)
- Long term proof test of 8” HPD (and Hi-QE PMTs) in 200-ton water tank begins in this summer

8” HPD

5mmϕ AD