Hyper-Kamiokande

goals, status and prospects

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April 30, 2015, Saclay

Super-K is an amazing detector…

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Evidence for Oscillation of Atmospheric Neutrinos

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(Super-Kamiokande Collaboration)

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Discovery of neutrino oscillation (1998)

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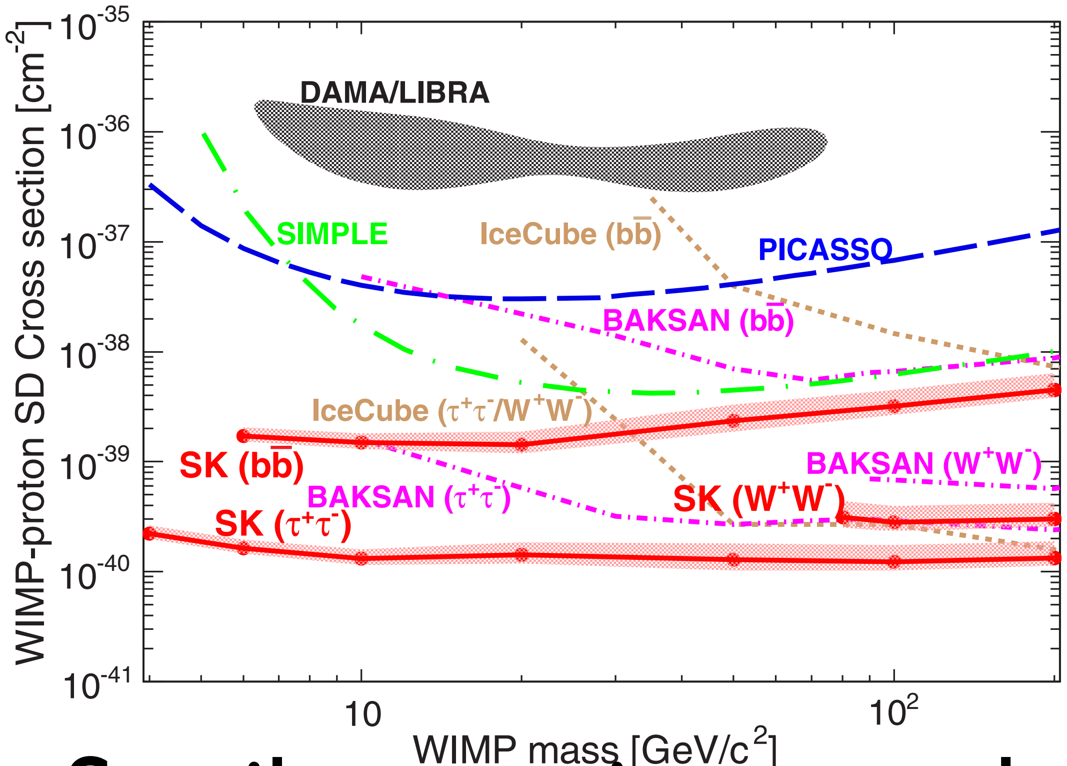
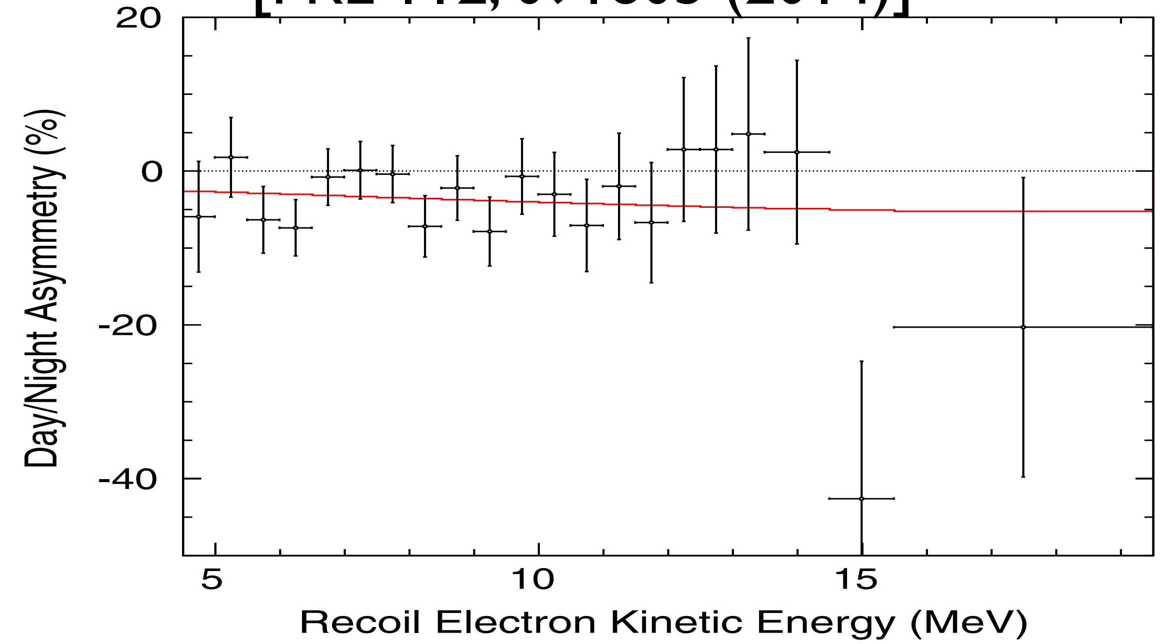
Continue to provide exciting results for 19 years!

WIMP search [PRL 114, 141302 (2015)]



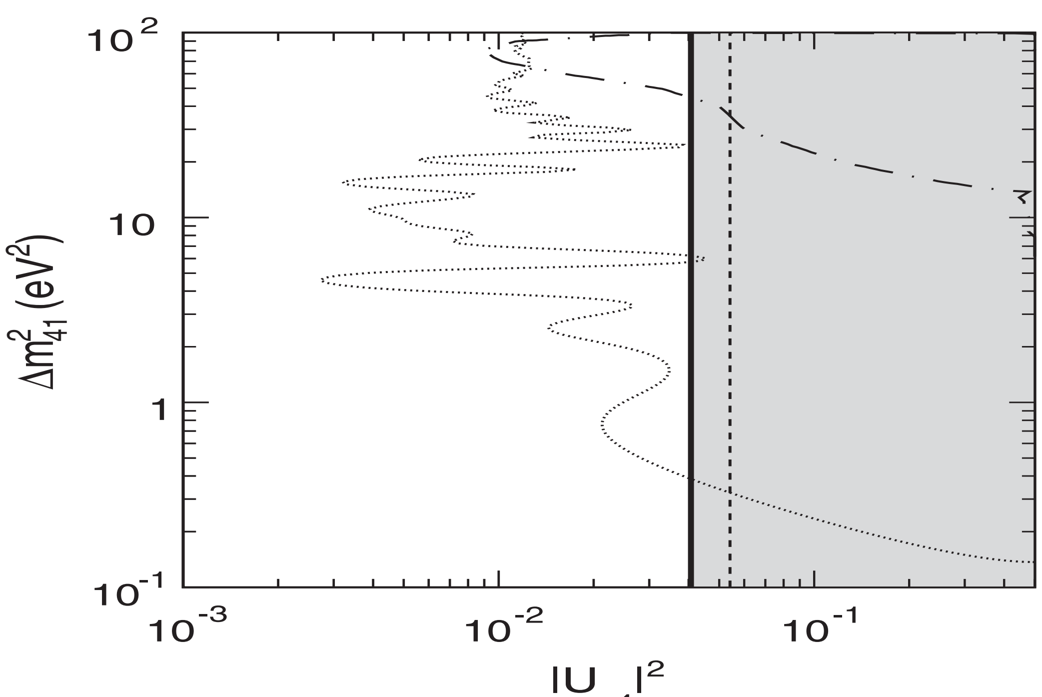
Terrestrial matter effect

[PRL 112, 091805 (2014)]



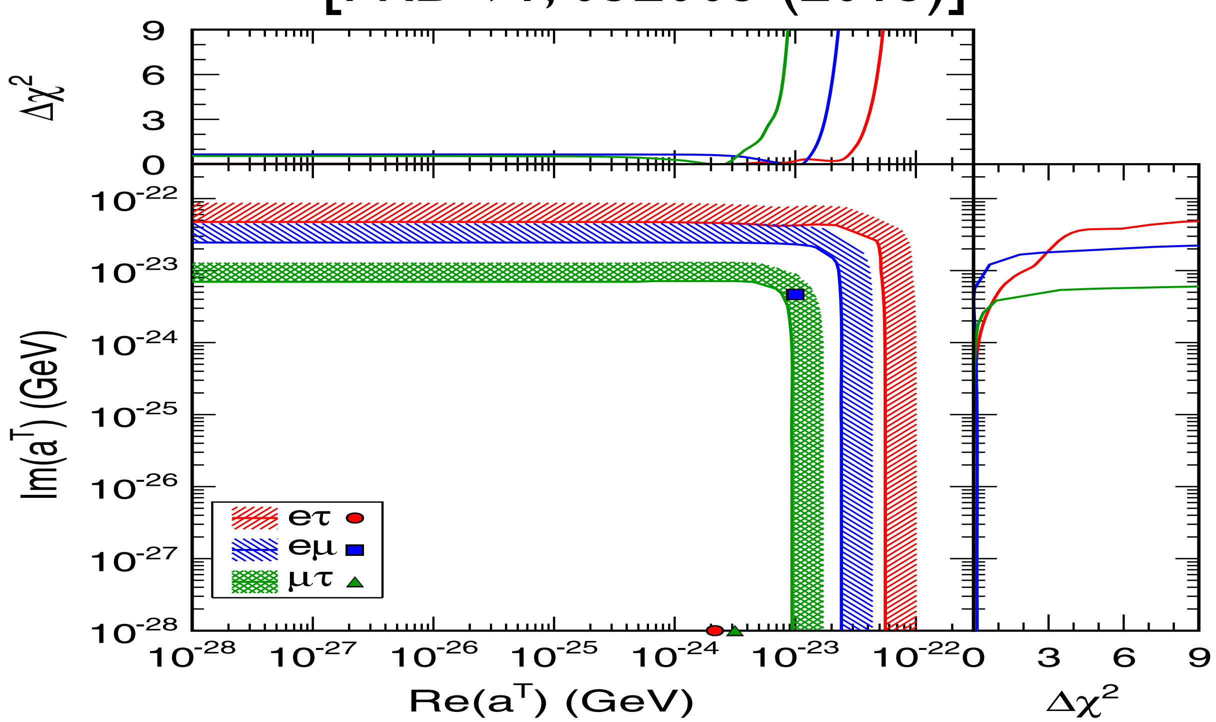
Sterile neutrino search

[PRD 91, 052019 (2015)]



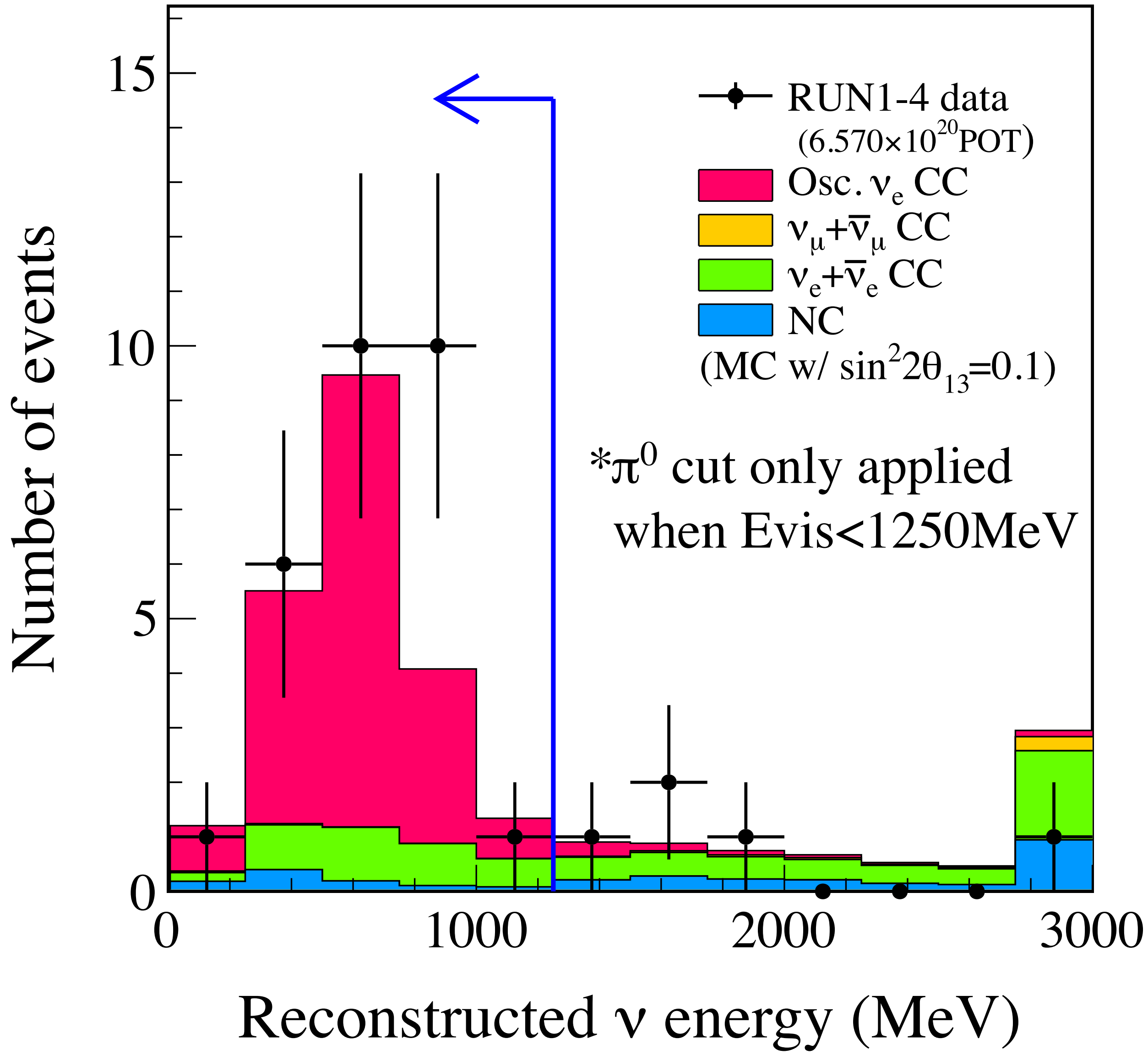
Test of Lorentz invariance

[PRD 91, 052003 (2015)]

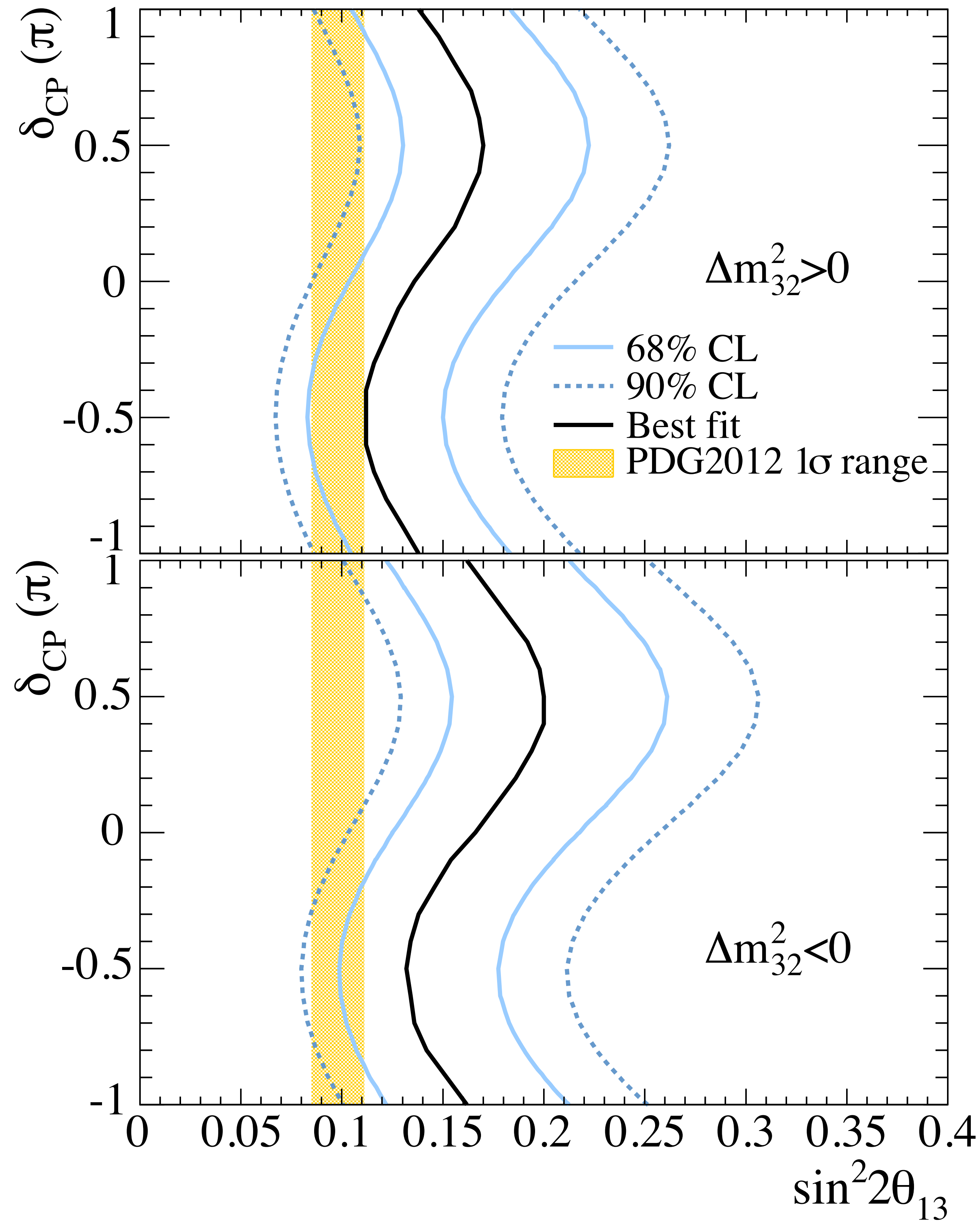


Wide range of relevant energy: from MeV to TeV

Opening a door to new world (again)…



[PRL 112, 061802(2014)]

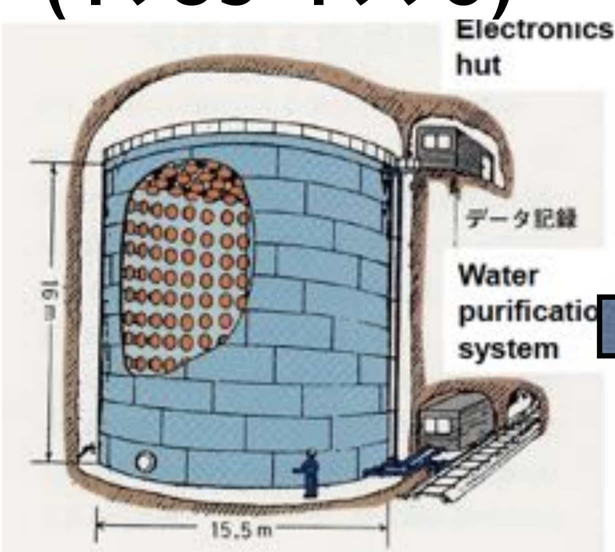


First constraint on leptonic CP violation by T2K (+reactor)

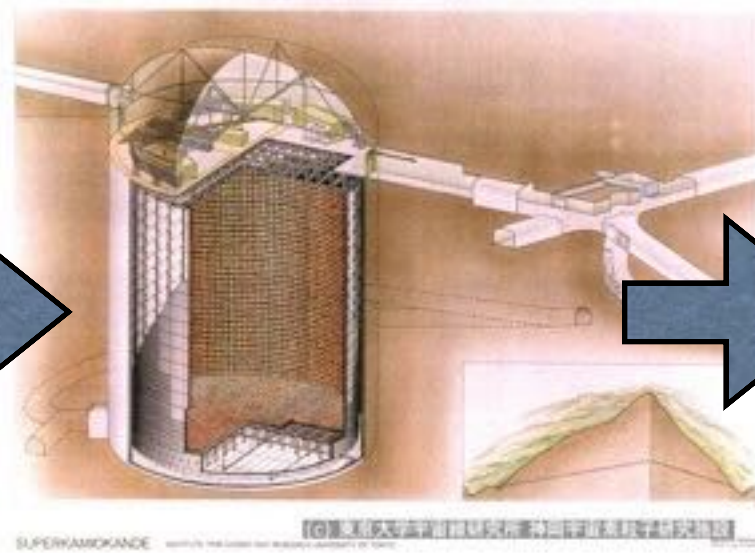
It's time to go to a next step.

Three generation of large water Cherenkov detectors in Kamioka

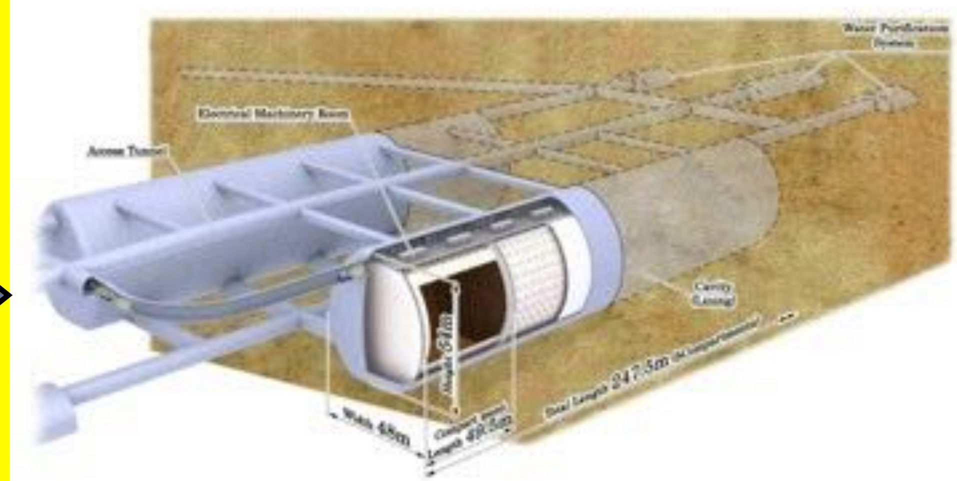
Kamiokande
(1983-1996)



Super-Kamiokande
(1996-)



Hyper-Kamiokande
(202?-)



3kton

50kton

1Mton=1000kton
(560kton fiducial)

x17

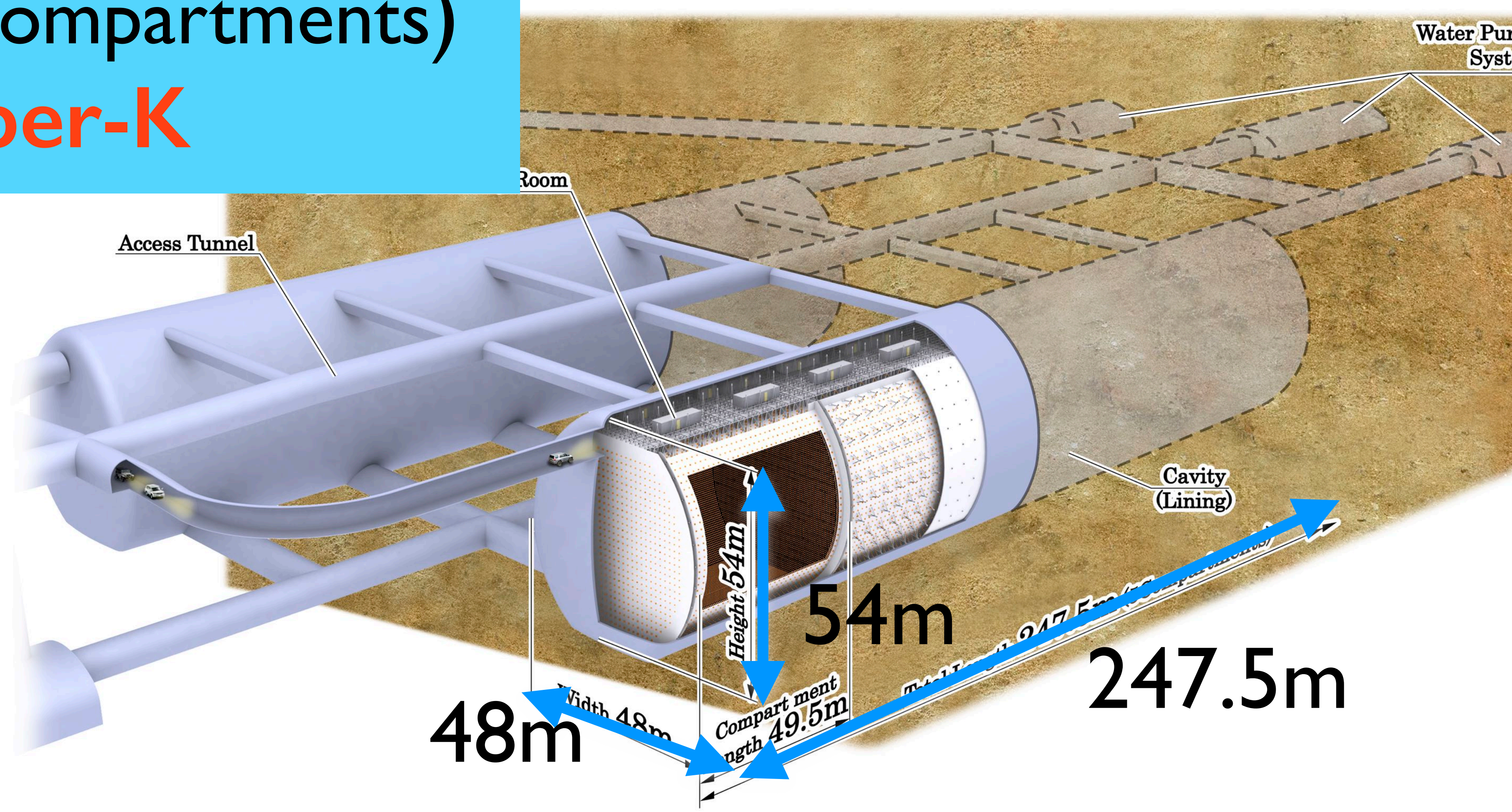
x20
(x25 fiducial mass)

Hyper-Kamiokande Detector

Total volume: 0.99 Mton
Inner volume: 0.74 Mton
Outer volume: 0.2 Mton
Fiducial volume: 0.56 Mton
(0.056Mton × 10 compartments)
x25 of Super-K

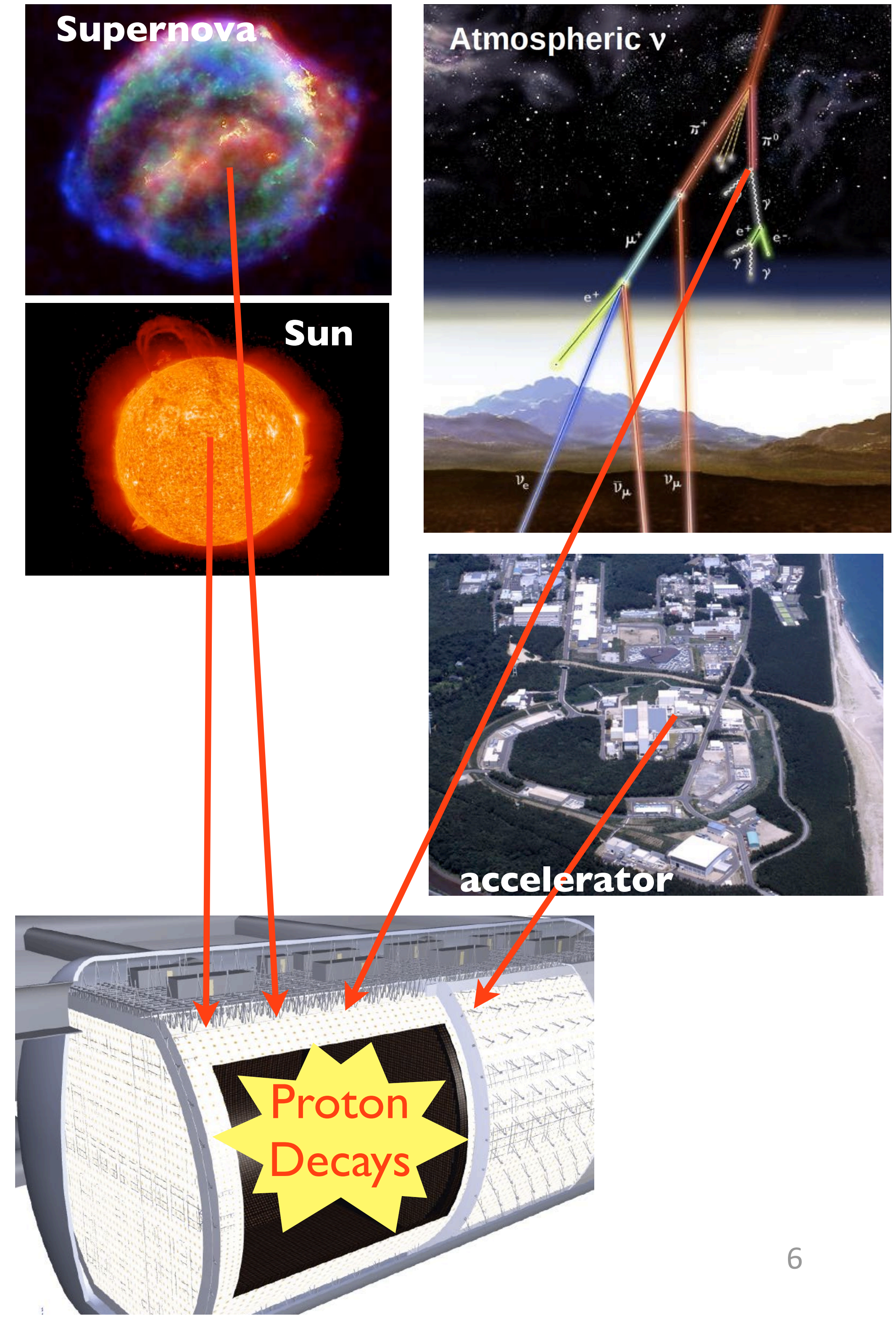
Hyper-K WG,
arXiv:1109.3262
arXiv:1309.0184
arXiv:1502.05199
(to appear in PTEP)

- 99,000 20” PMT for inner-det. (20% coverage)
- 25,000 8” PMT for outer-det.



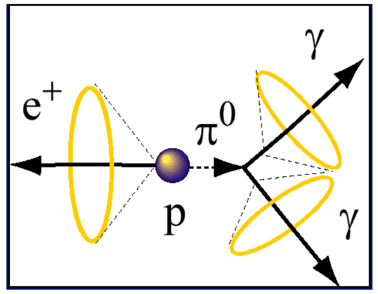
Multi-purpose detector, Hyper-K

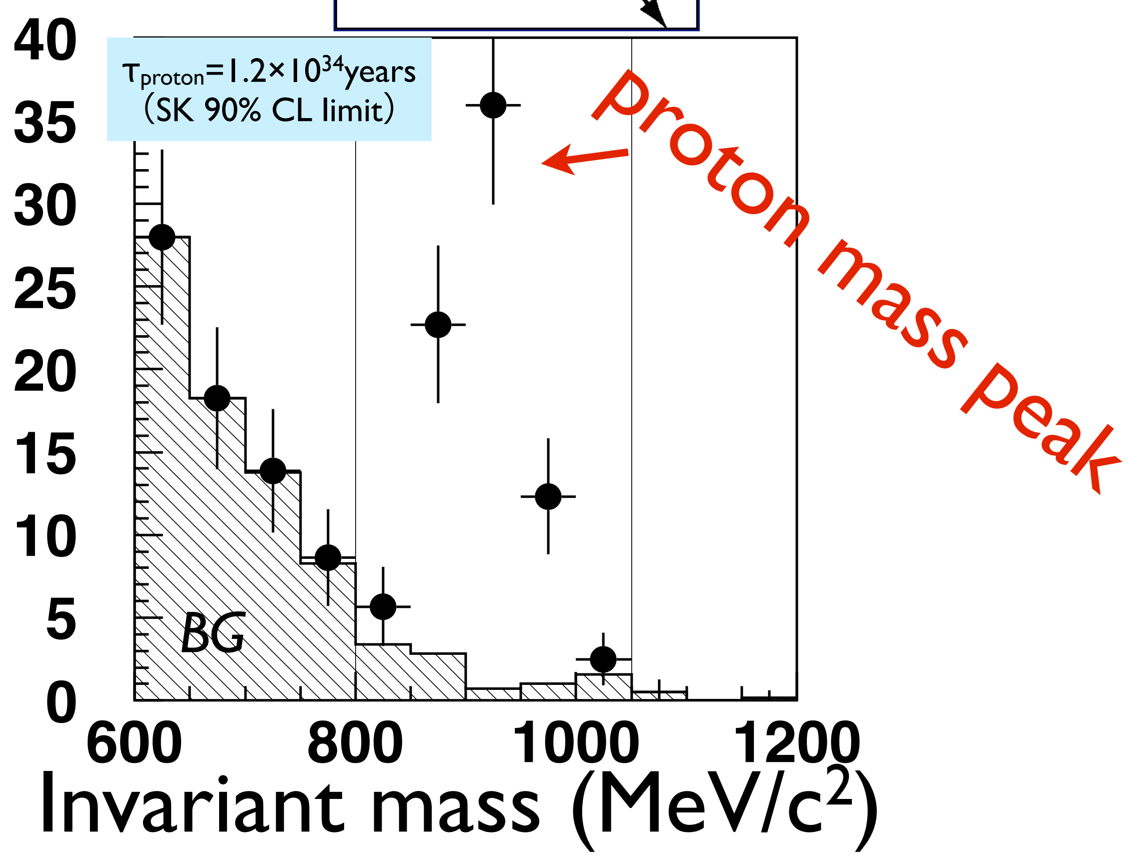
- Comprehensive study of ν oscillation
  - CPV (>3σ for 76% of δ)
  - Mass hierarchy with acc.+atm ν
  - θ_{23} octant
  - Test of exotic scenarios
- Nucleon decay discovery potential
  - $e^{+}\pi^{0}$: 5×10^{34} years,
    νK^{+}: 1×10^{34} years (3σ)
- Neutrino astrophysics
  - Supernova up to 2Mpc, ~1SN/10yrs
  - Relic SN neutrinos (~200ν/10yers)
  - Indirect dark matter search
  - Solar neutrino (~200evts/day)
- Geophysics
- Maybe more / unexpected



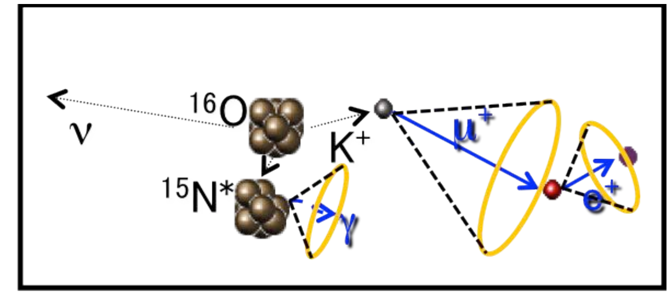
Proton decay sensitivity

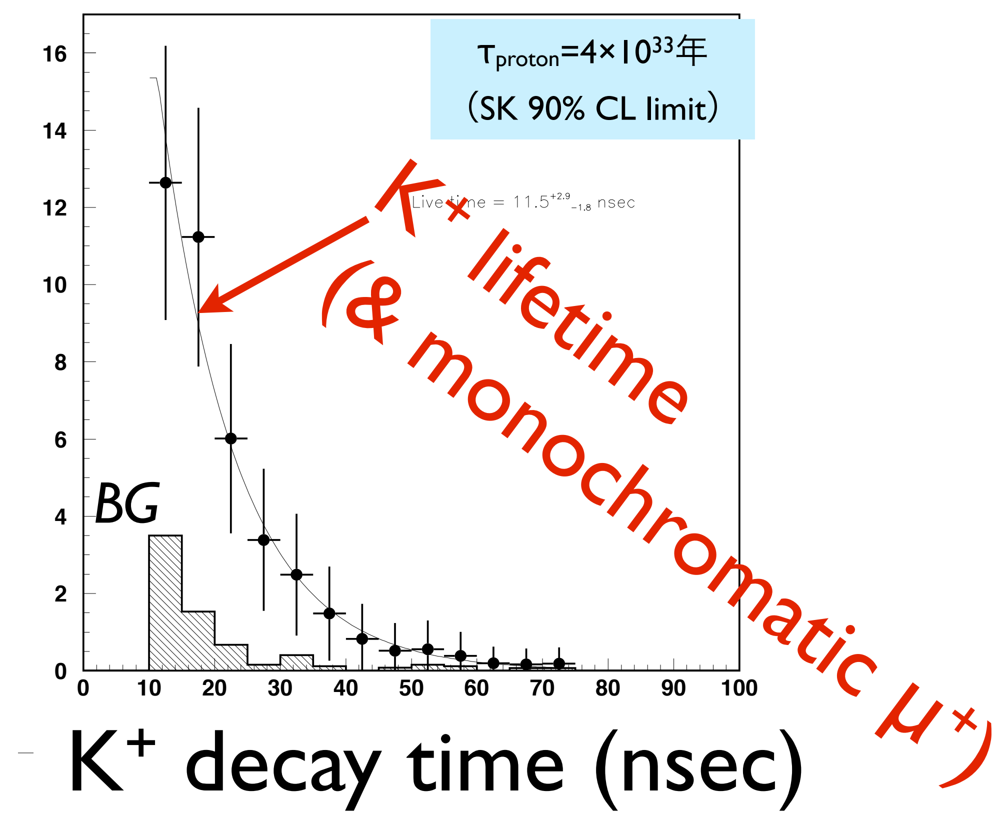
$p \to e^+\pi^0$





$p \to \nu K^+$



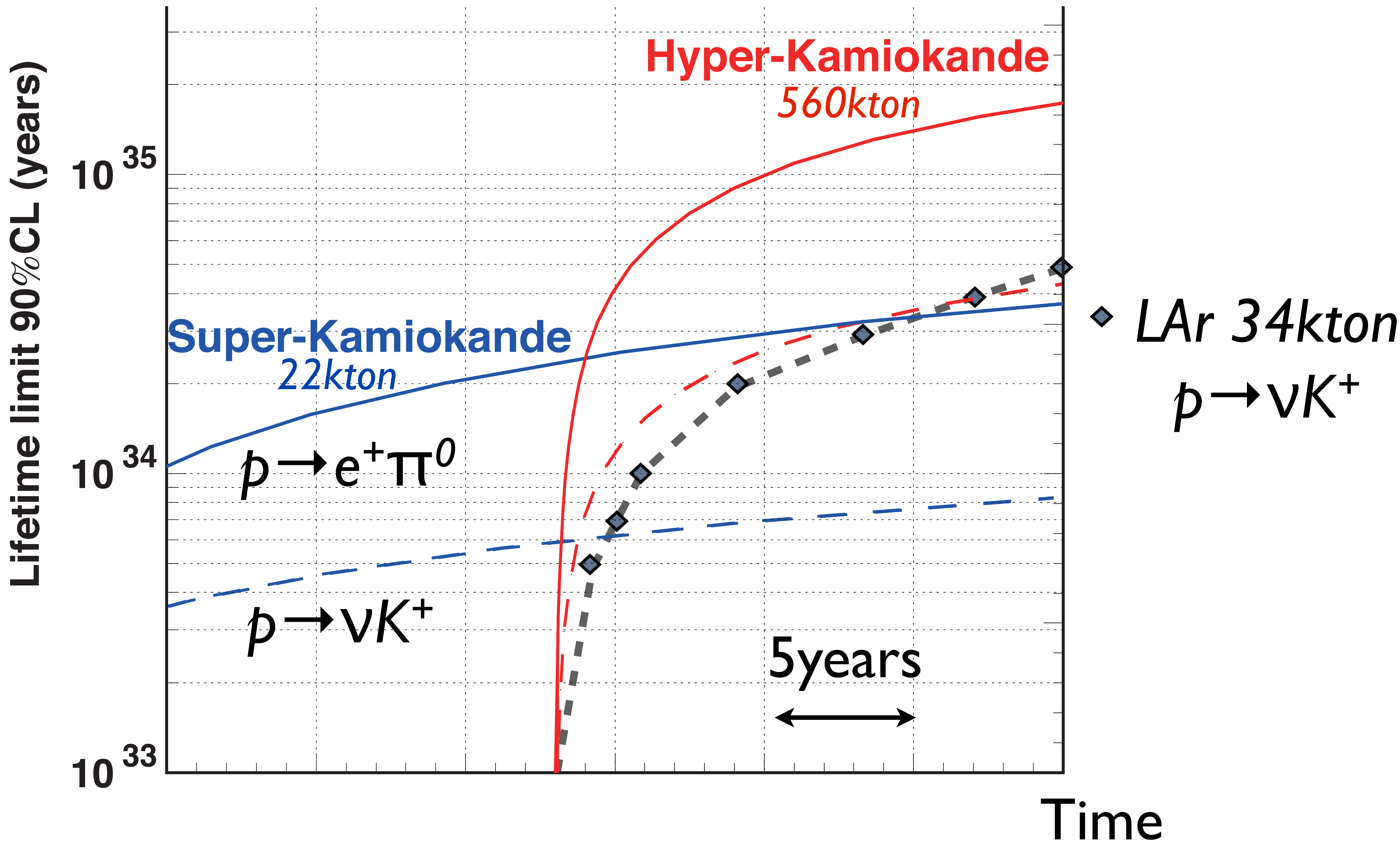


- Discovery reach (3σ)
  - $\tau(p \to e^+\pi^0) \sim 5.4\times10^{34}$years (HK 10yrs)
- Limit (90%CL)
  - $\tau(p \to e^+\pi^0) > 1.3\times10^{35}$years (HK 10yrs)

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

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

Proton decay sensitivity

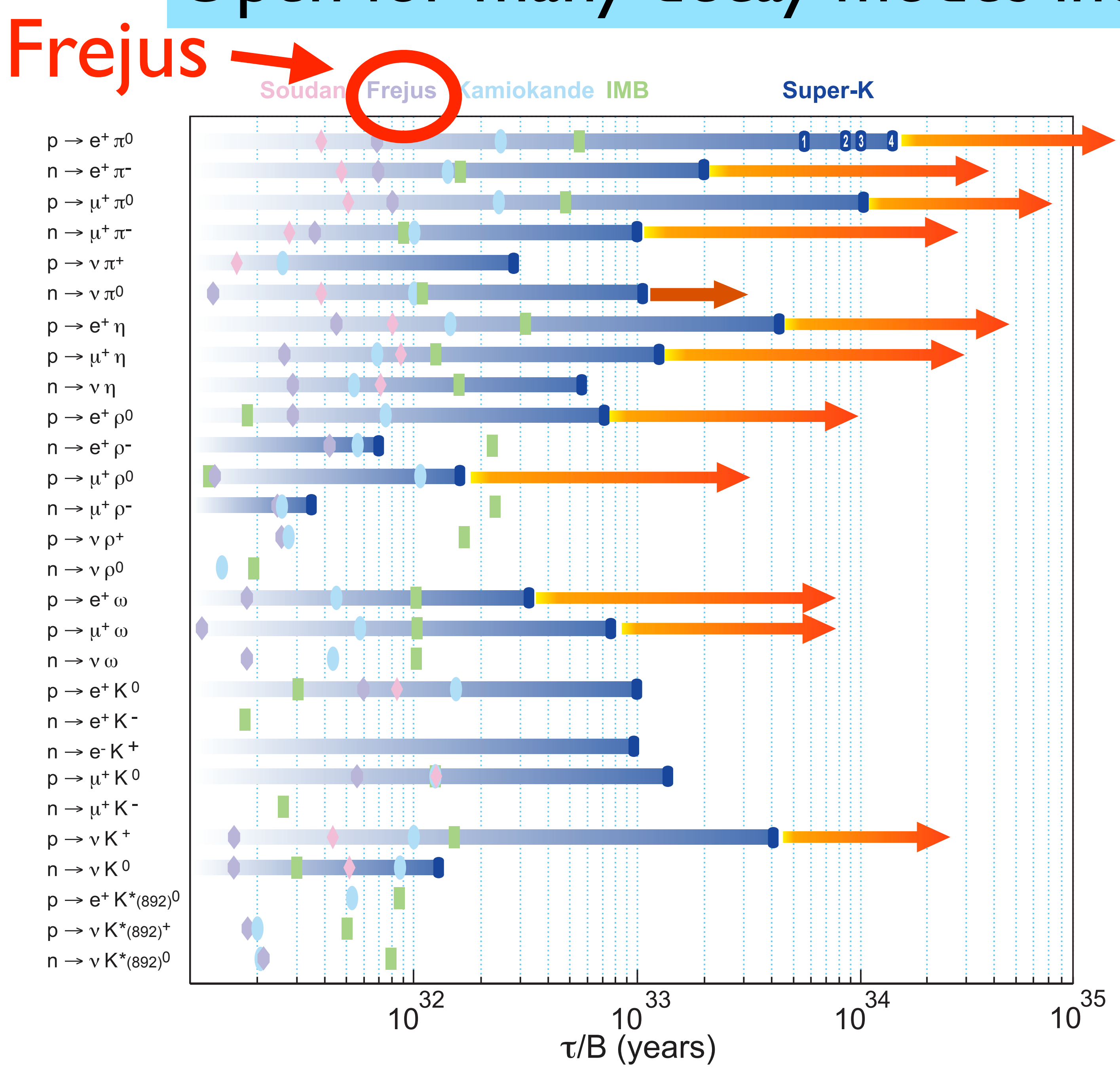


- HK analysis not yet optimized for large exposure
- Analysis still improving with SK data and new technique

Nucleon decay search in Hyper-K

Improvements in many modes by a factor ~10

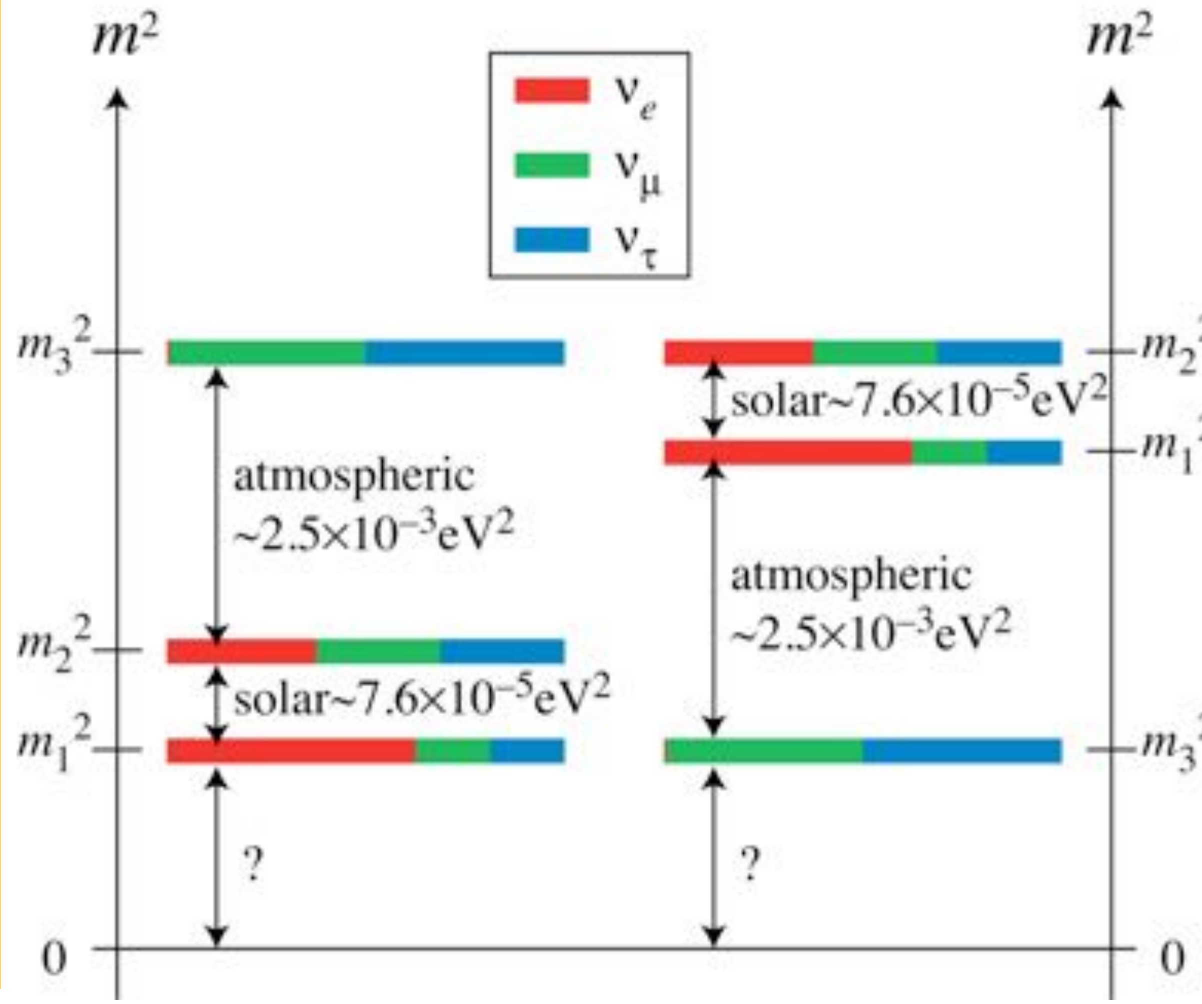
Open for many decay modes including $p \to e^+\pi^0$, $p \to \nu K^+$



- *$p \to e^+ + \pi^0$*
  - $\tau_{proton}/Br > 1\times10^{35}$ years @90%CL
  - 5Mton×years (9 Hyper-K years)
- *$p,n \to (e^+,\mu^+)+(\pi,\rho,\omega,\eta)$*
  - $O(10^{34\sim35})$years
- *SUSY favored $p \to \nu + K^+$*
  - 3×10^{34} years
- K^0 modes, $\nu\pi^0$, $\nu\pi^+$ possible
- Others
  - (B-L) violated modes
  - radiative decays $p \to e^+\gamma$, $\mu^+\gamma$
  - neutron-antineutron oscillations ($|\Delta B|=2$)
  - di-nucleon decays ($|\Delta B|=2$)
    - $pp \to XX\ldots$, $nn \to XX\ldots$

Remaining mysteries of neutrino

- Mass hierarchy (mass ordering) $m_1,m_2<m_3$ or $m_1,m_2>m_3$?
- θ_{23} maximal (45°)? if not, <45° or >45°?
- *CP* symmetry violated?

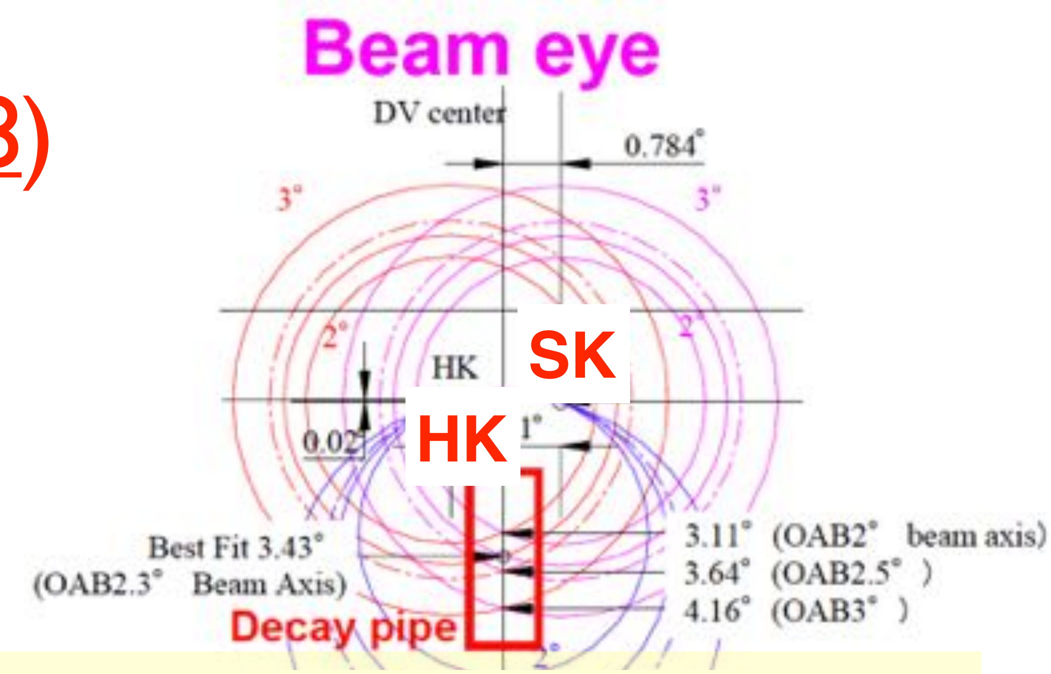


Goals of current and next generation experiments

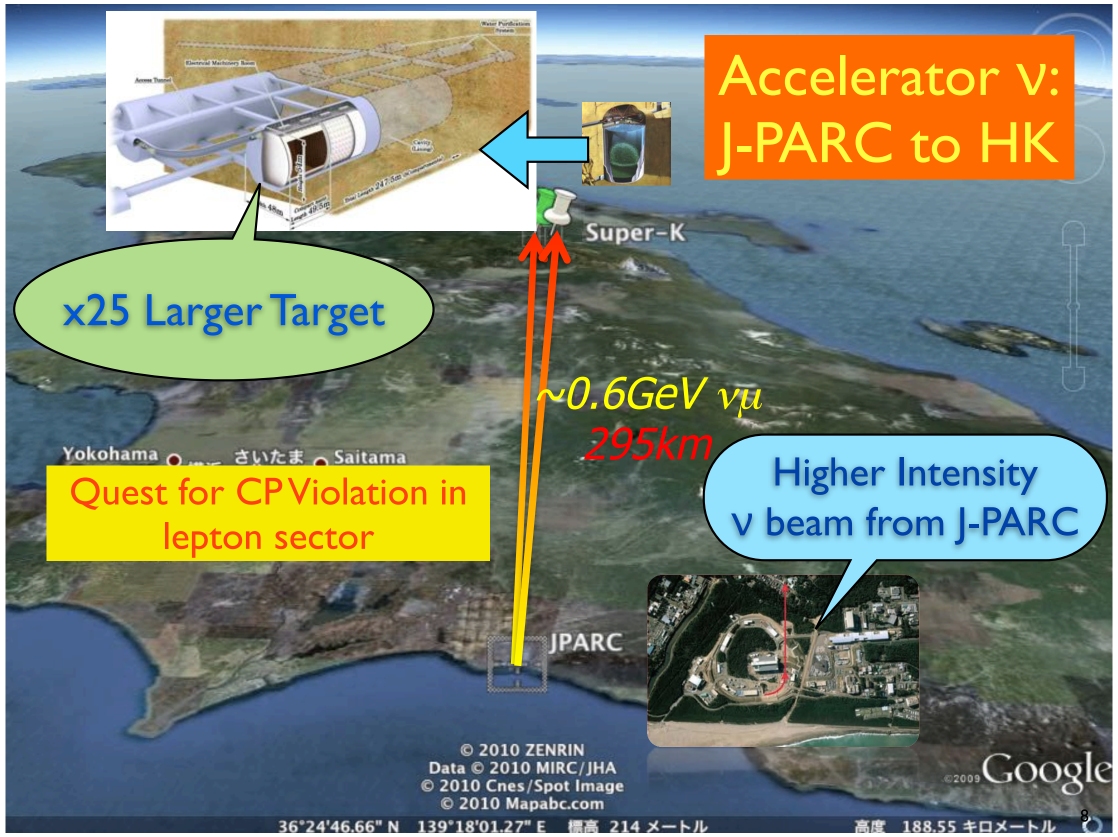
ν oscillation study w/ Hyper-K

- Long baseline experiment with J-PARC neutrino beam (J-PARC P58)
  - Same baseline as T2K
    - Well understood beam and systematics (NA61 etc.)
    - Reliable sensitivity estimate based on T2K results
  - Main focus on CP asymmetry
- Atmospheric neutrino
  - Broad energy and baseline
  - >3σ determination of mass hierarchy and θ_{23} octant

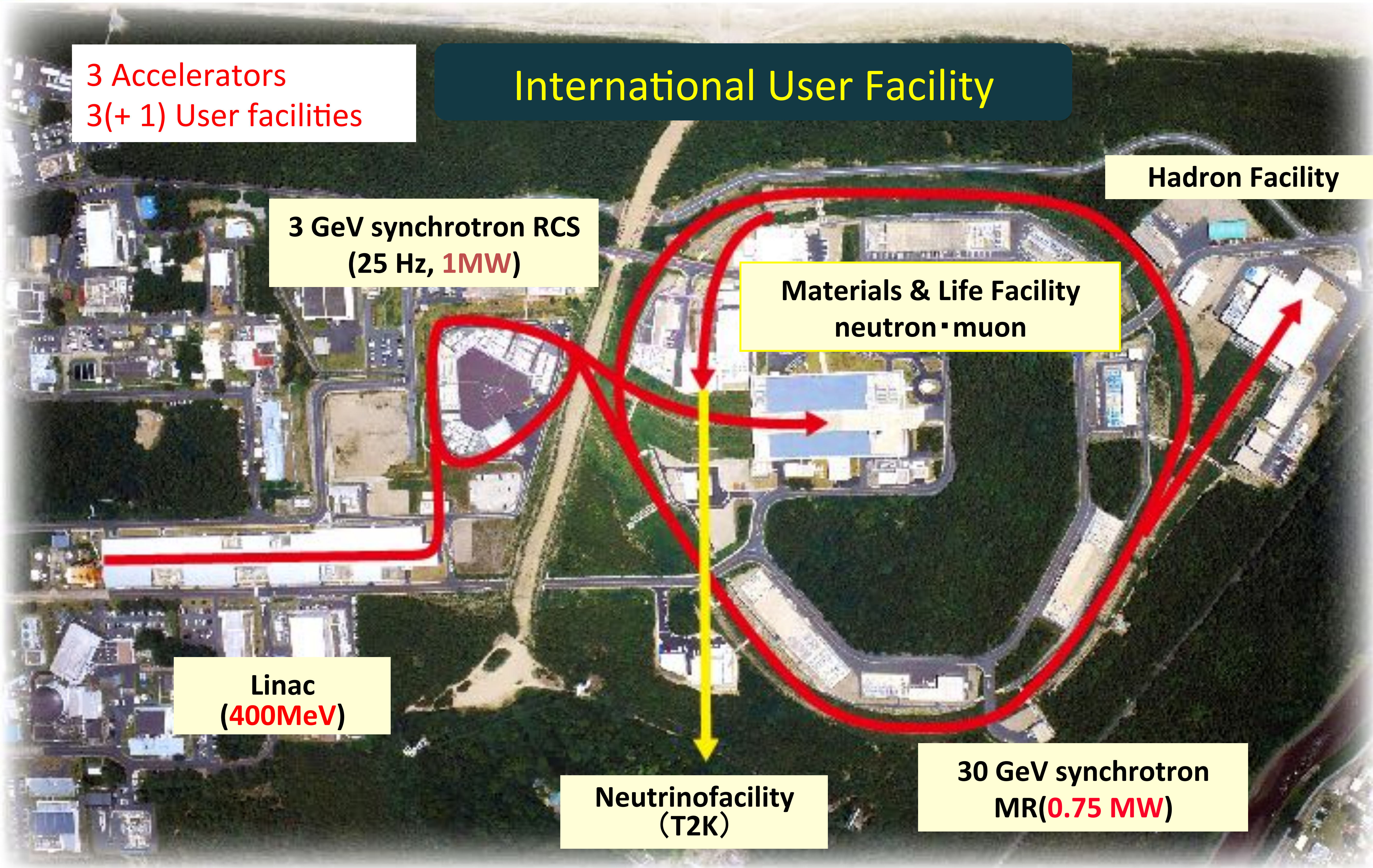
arXiv:1502.05199 (to appear in PTEP)



J-PARC ν beamline designed to have the same off-axis for Super-K & Hyper-K



Japan Proton Accelerator Research Complex



J-PARC MR power mid-term plan

FX: Rep. rate will be increased from ~ 0.4 Hz to ~1 Hz by replacing magnet PS's, rf cavities, ...
SX: Parts of stainless steel ducts are replaced with titanium ducts to reduce residual radiation dose.

JFY	2011	2012	2013	2014	2015	2016	2017
			Li. energy upgrade	Li. current upgrade			
FX power [kW] (study/trial)	150	200	200 - 240	200 –300 (400)	320		750
SX power [kW] (study/trial)	3 (10)	10 (20)	25 (30)	20-50			100
Cycle time of main magnet PS New magnet PS for high rep.	3.04 s	2.56 s R&D	2.48 s		Manufacture installation/test		1.3 s
Present RF system New high gradient rf system	Install. #7,8	Install. #9 R&D		Manufacture installation/test			
Ring collimators	Additional shields	Add.collimato rs and shields (2kW)	Add.collimat ors (3.5kW) C,D,E,F	Back to JFY2012 (2kW)	Add. coll. C,D	Add. coll. E,F	
Injection system FX system	Inj. kicker	Kicker PS improvement, Septa manufacture /test Kicker PS improvement, LF septum, HF septa manufacture /test					
SX collimator / Local shields	SX collimator					Local shields	
Ti ducts and SX devices with Ti chamber		SX septum endplate	Beam ducts	Beam ducts	ESS		

~320kW (Mar. 2015) → 750kW in a few years
with power supply replacement

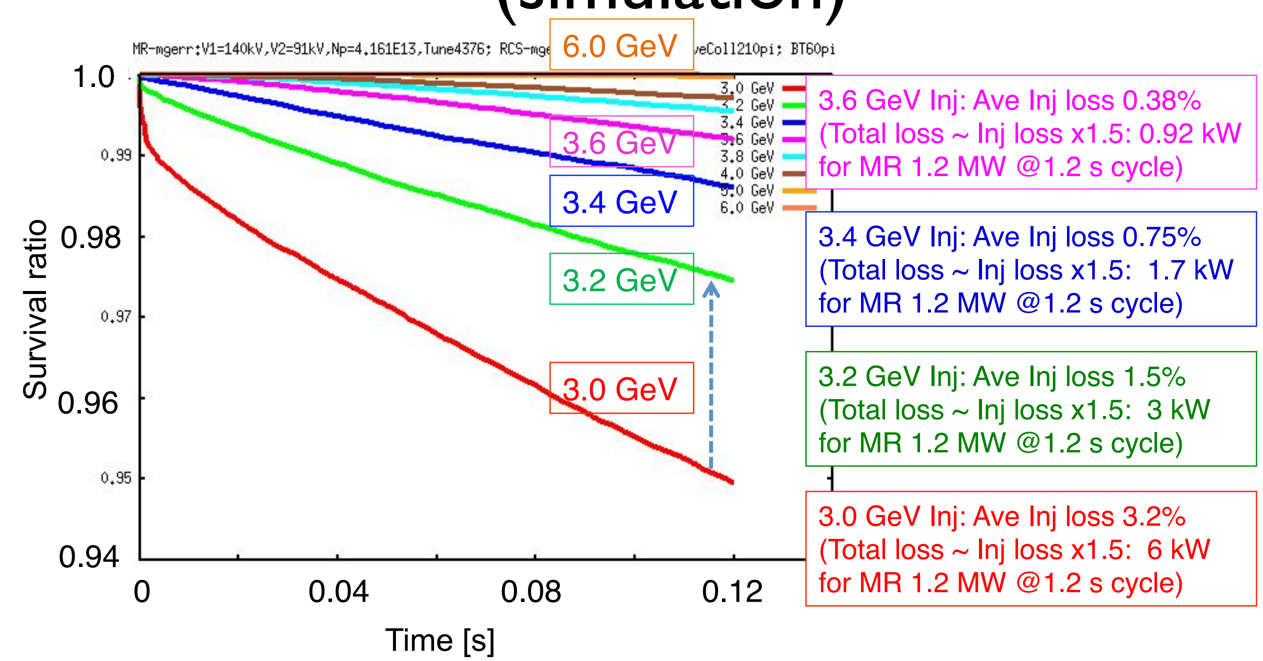
Continue to lead ν physics with T2K while preparing for Hyper-K

J-PARC long-term plan

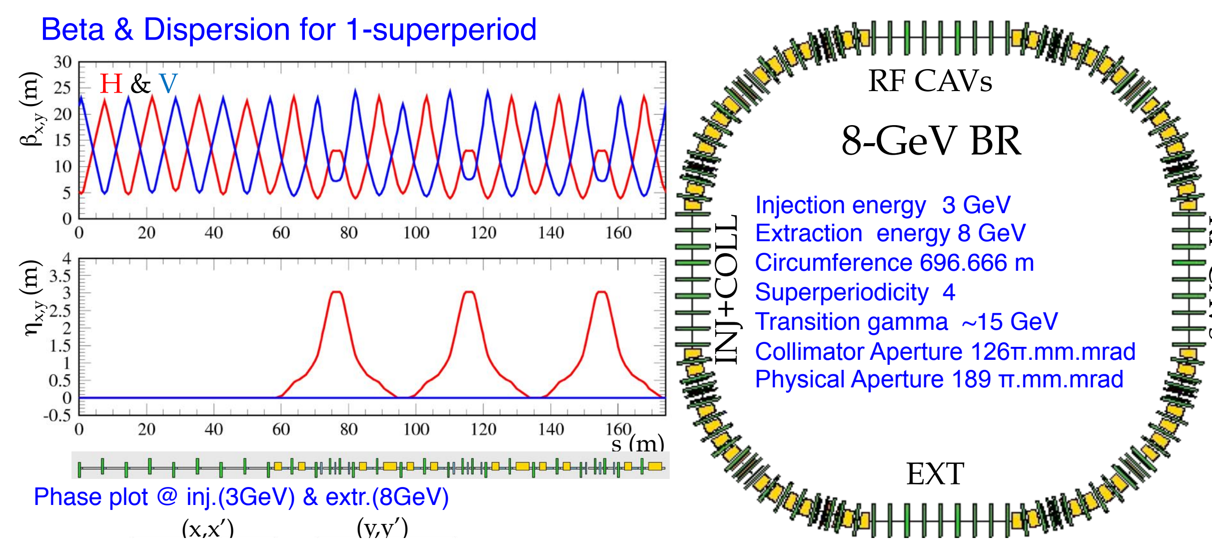
Several ideas under discussion, towards **multi-MW facility**

- RCS energy increase to reduce space charge effect
  - ~1.5MW
- New Booster Ring (8GeV) between RCS &MR
  - >2MW
- New SC proton linac for neutrino beam (Conceptual study)
  - ~9MW linac with >9GeV energy
  - Using KEKB tunnel at Tsukuba?

MR injection energy and beam loss (simulation)



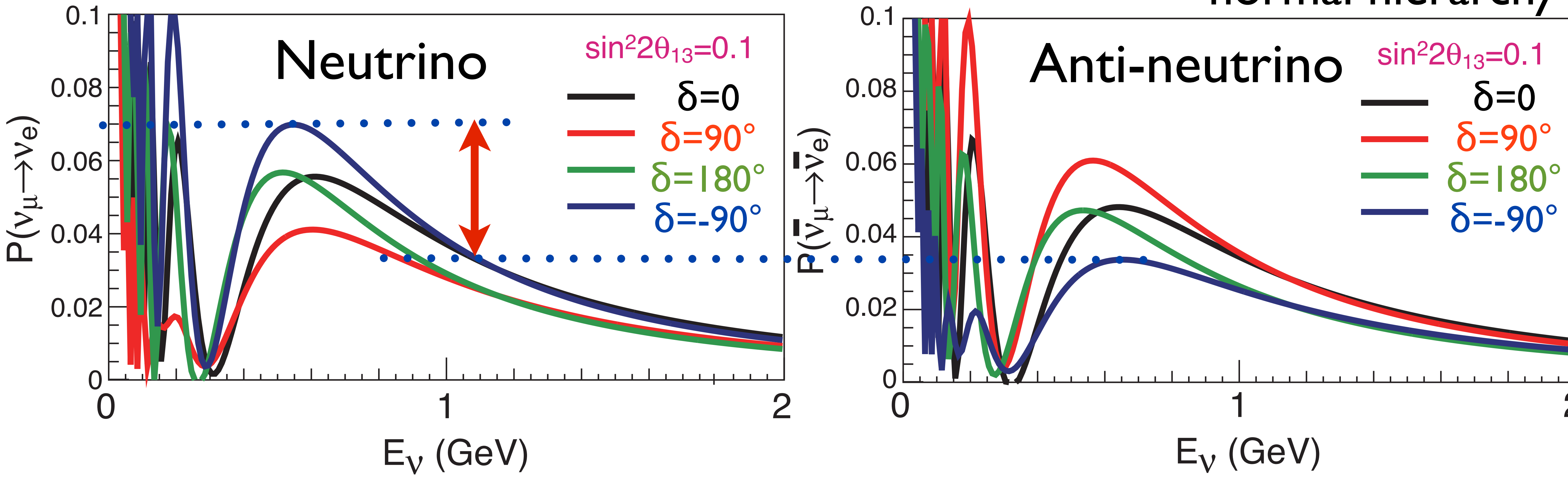
8GeV booster ring



Measurement of *CP* asymmetry with ν beam

$P(\nu_\mu \to \nu_e)$: ν_e appearance probability

for 295km baseline,
normal hierarchy



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

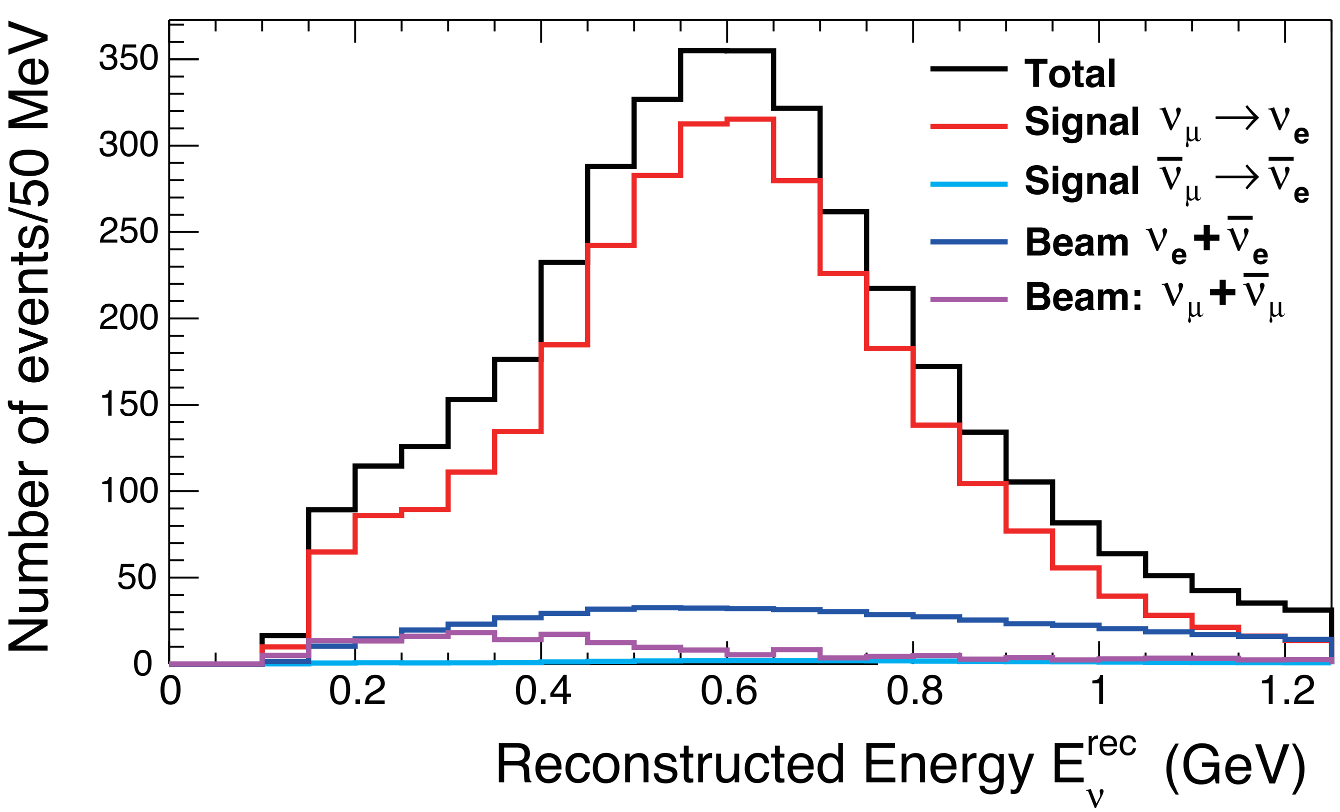
Reconstructed energy distributions

7.5MW×10^7s (1.56×10^{22} POT)

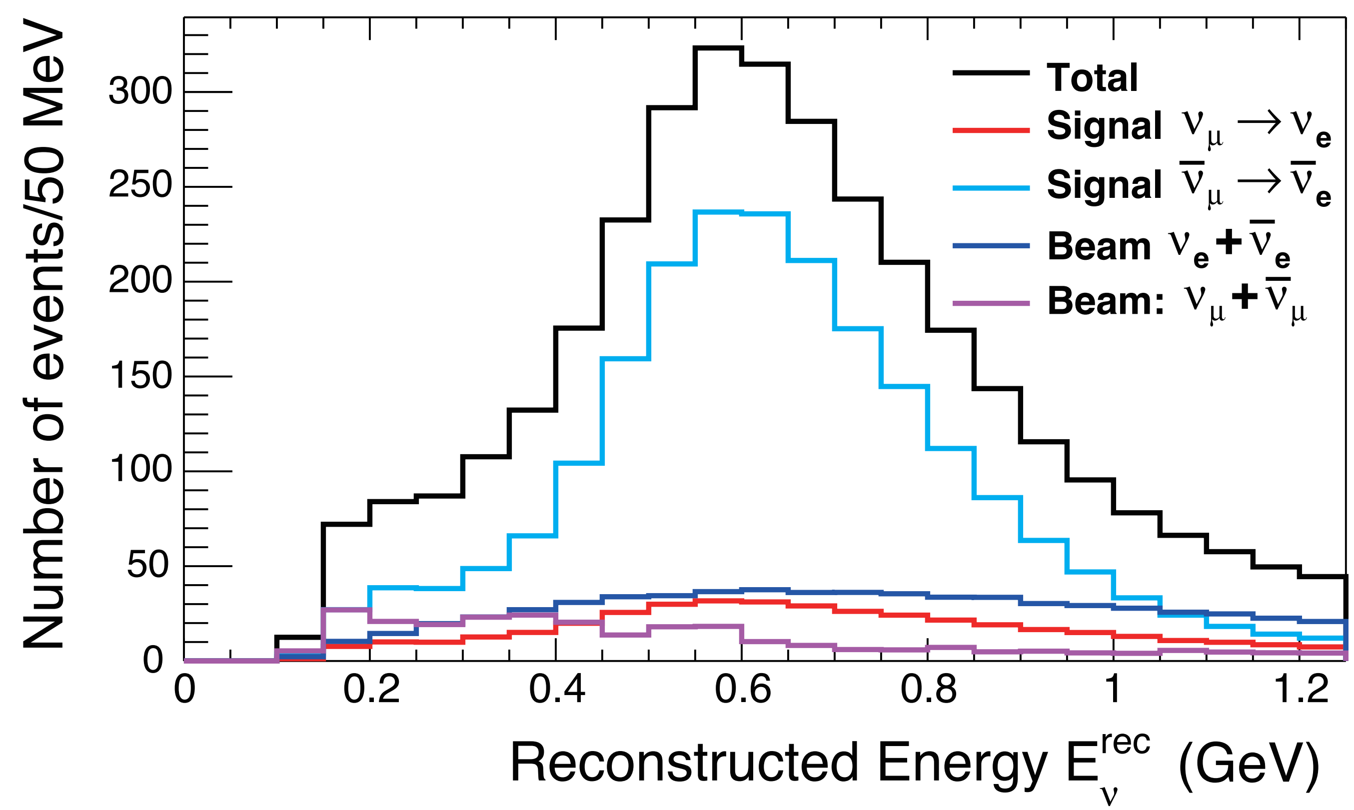
$\sin^2 2\theta_{13}$=0.1,δ=0, normal MH

$\nu:\bar{\nu}$=1:3

Appearance ν mode



Appearance $\bar{\nu}$ mode



	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	3,016	28	11	523	172
$\bar{\nu}$	2,110	396	9	618	265

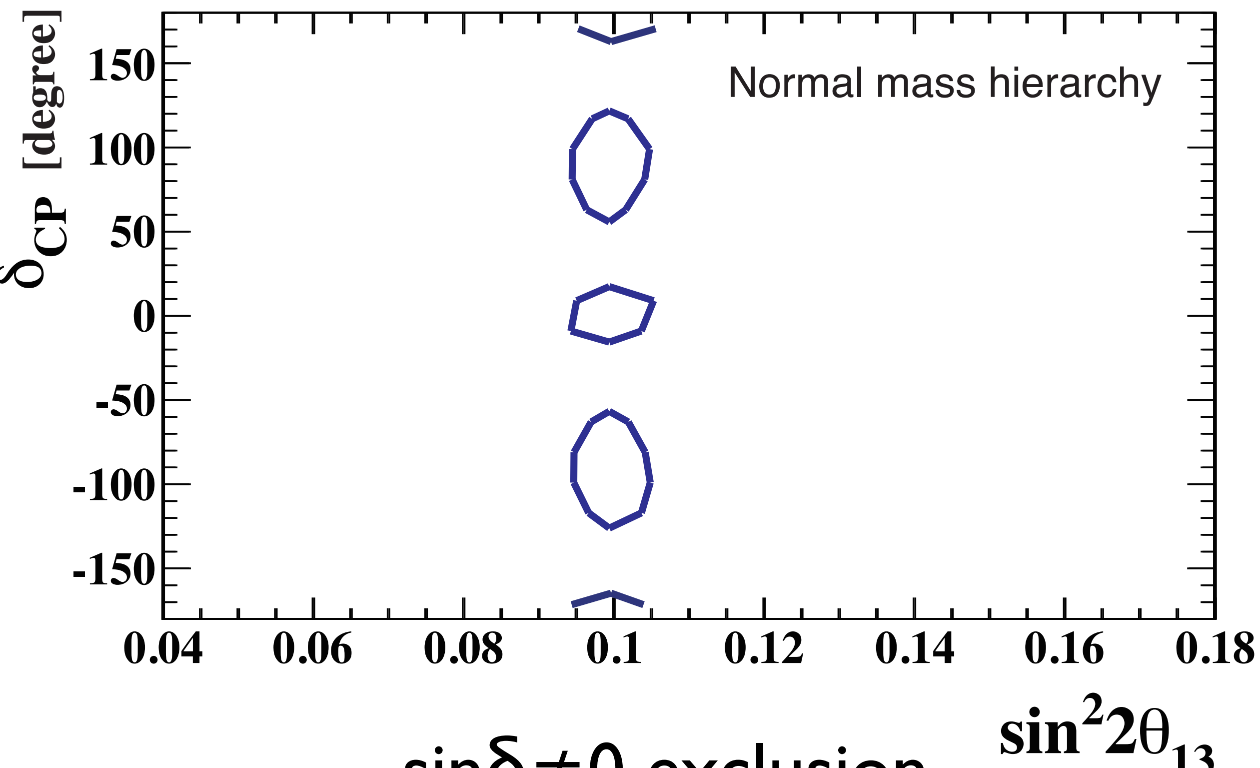
New π^0 rejection (fiTQun) applied

arXiv:1502.05199 (to appear in PTEP)

Expected sensitivity to CP asymmetry

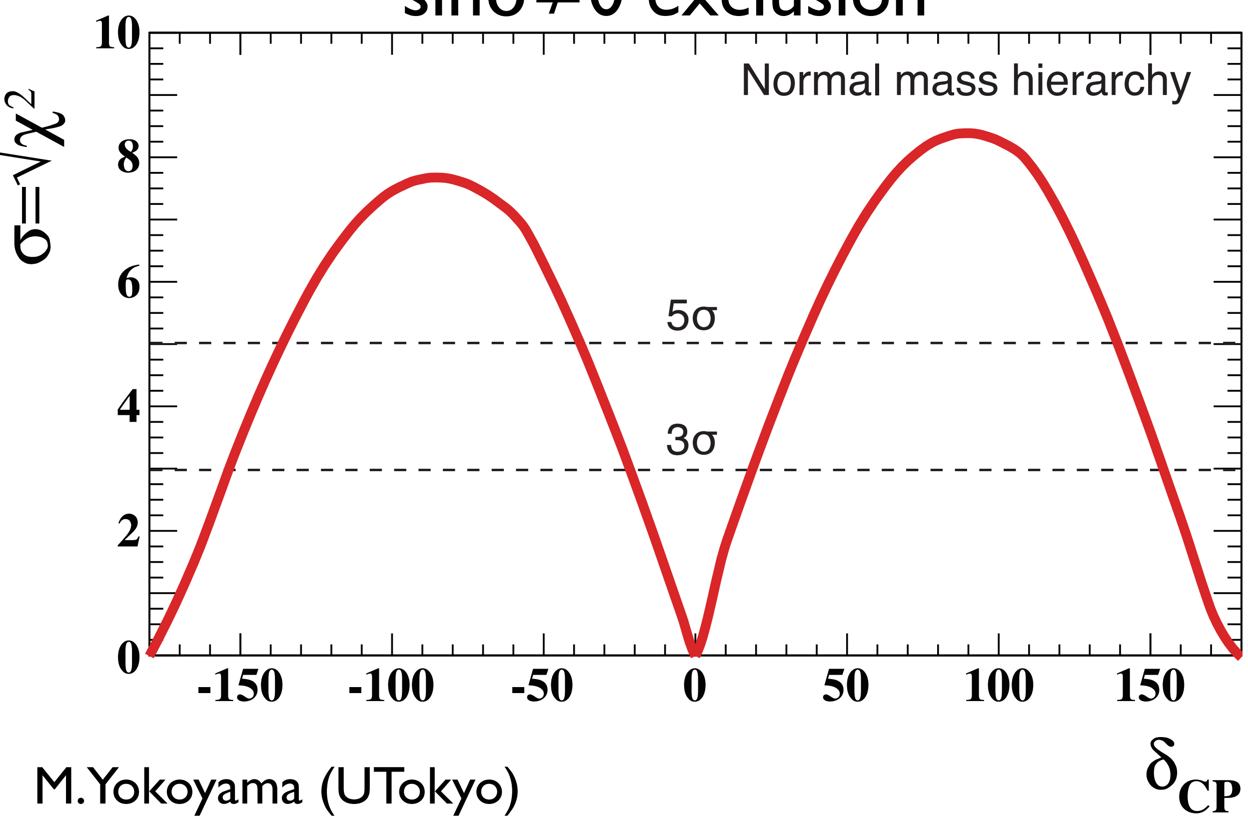
Mass hierarchy assumed to be known

90% CL contour on $\sin^2 2\theta_{13}$-δ plane
(δ=0°, 90°, 180°, -90° overlaid)

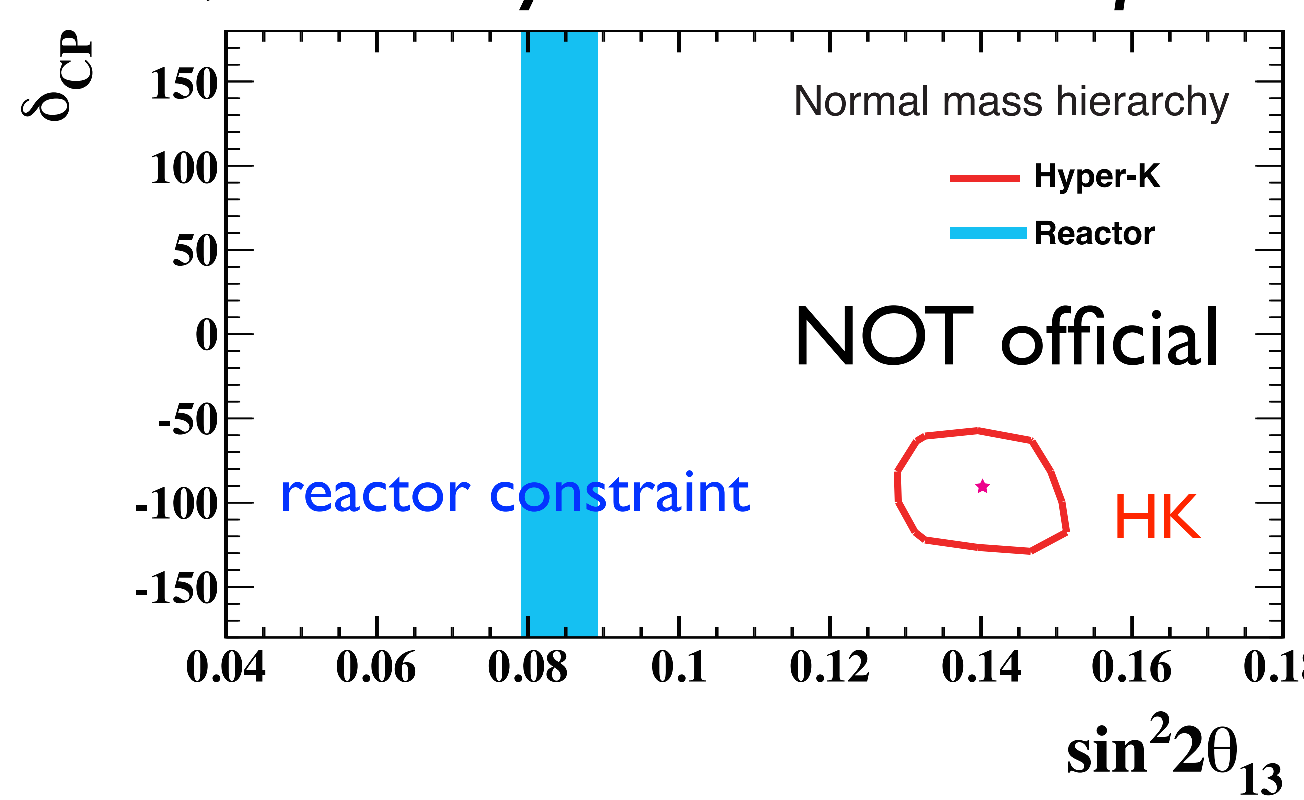


- Exclusion of $\sin\delta=0$
  - >3σ for 76% of δ
  - >5σ for 58% of δ
- Possible to establish CP violation in the lepton sector!

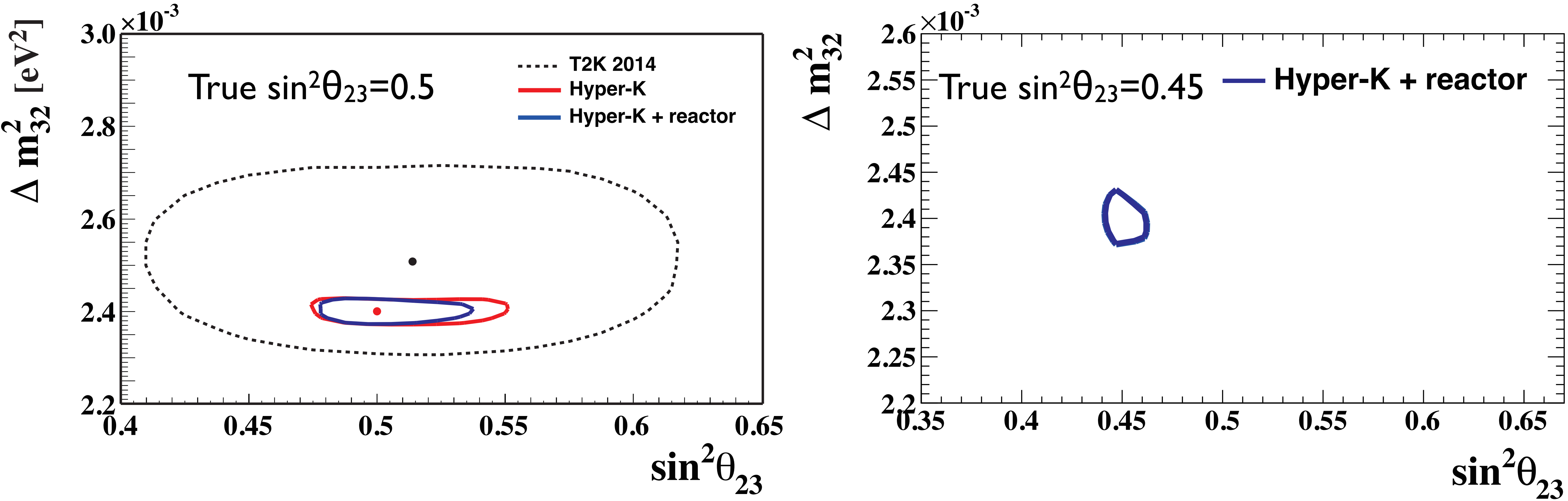
sinδ≠0 exclusion



Or, we may see some surprise



Measurement of $|\Delta m^2_{32}|, \theta_{23}$

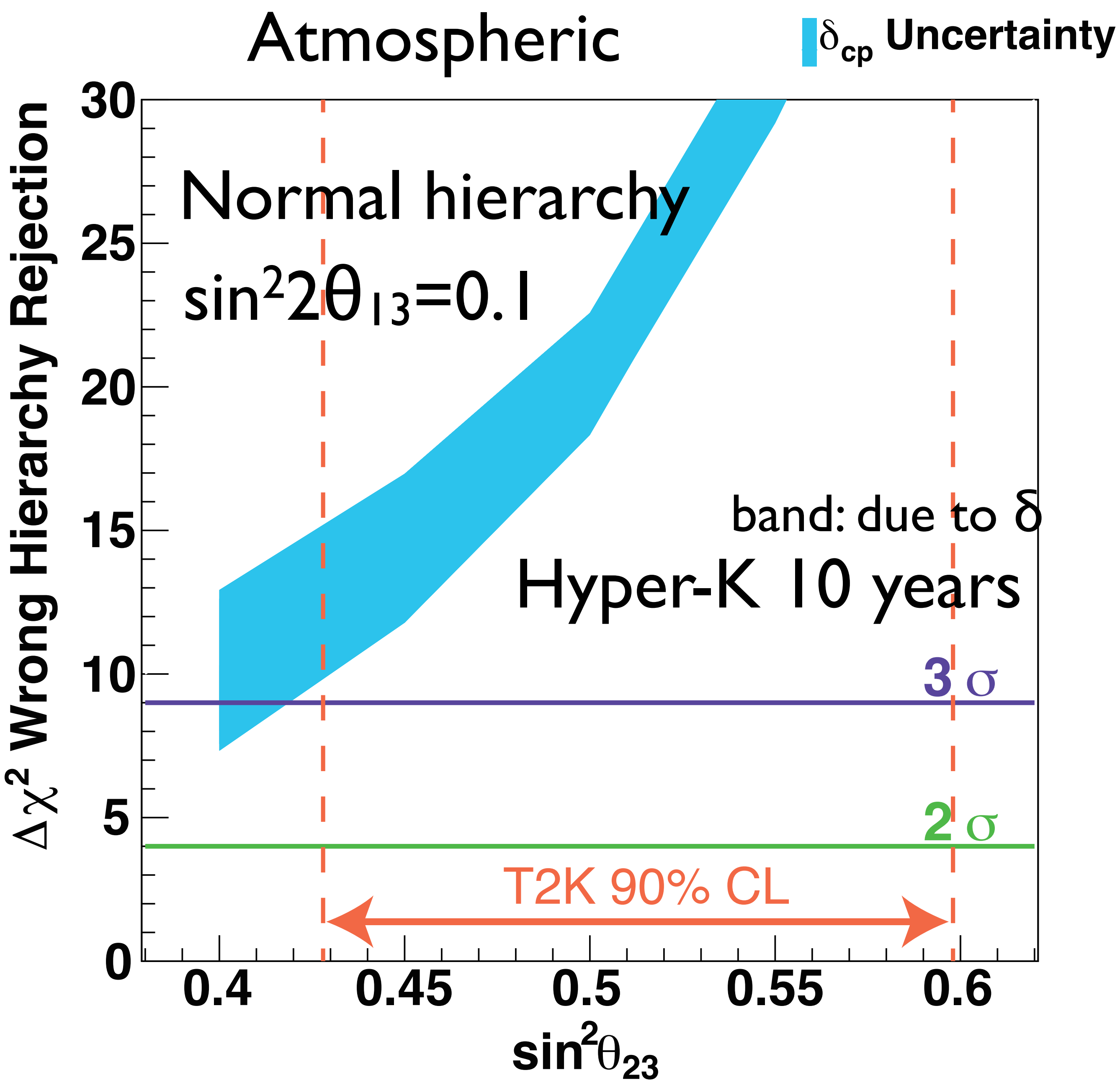


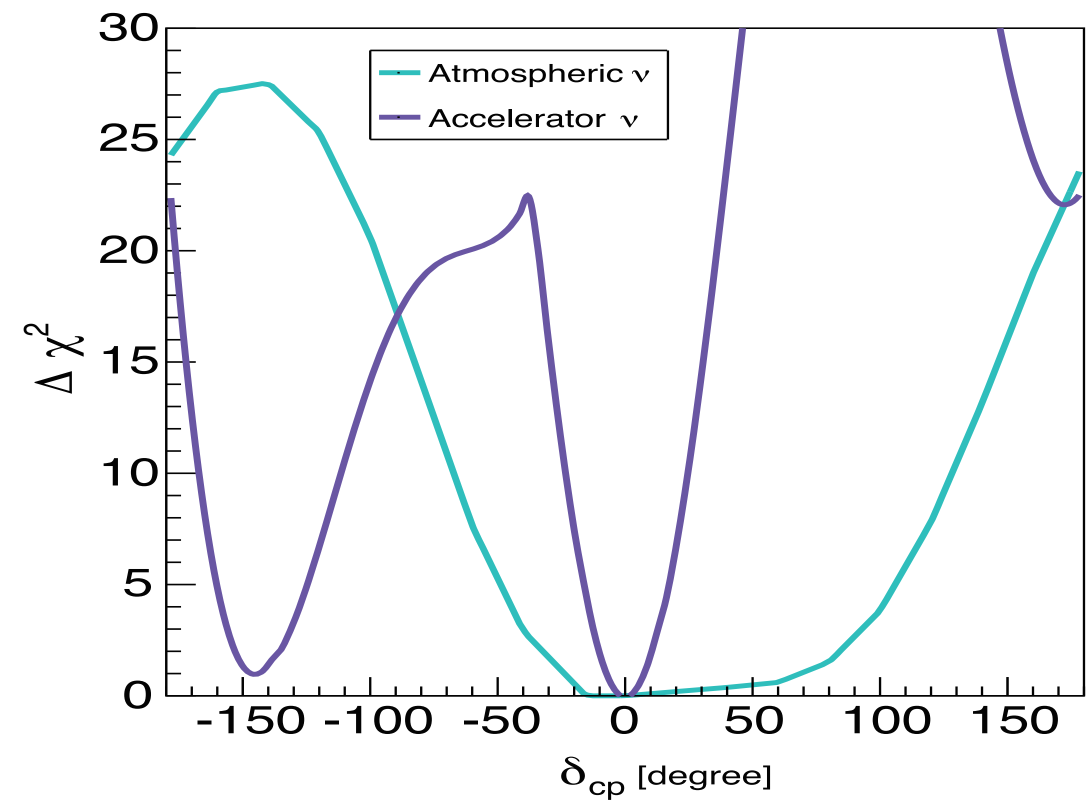
Expected 1σ uncertainty

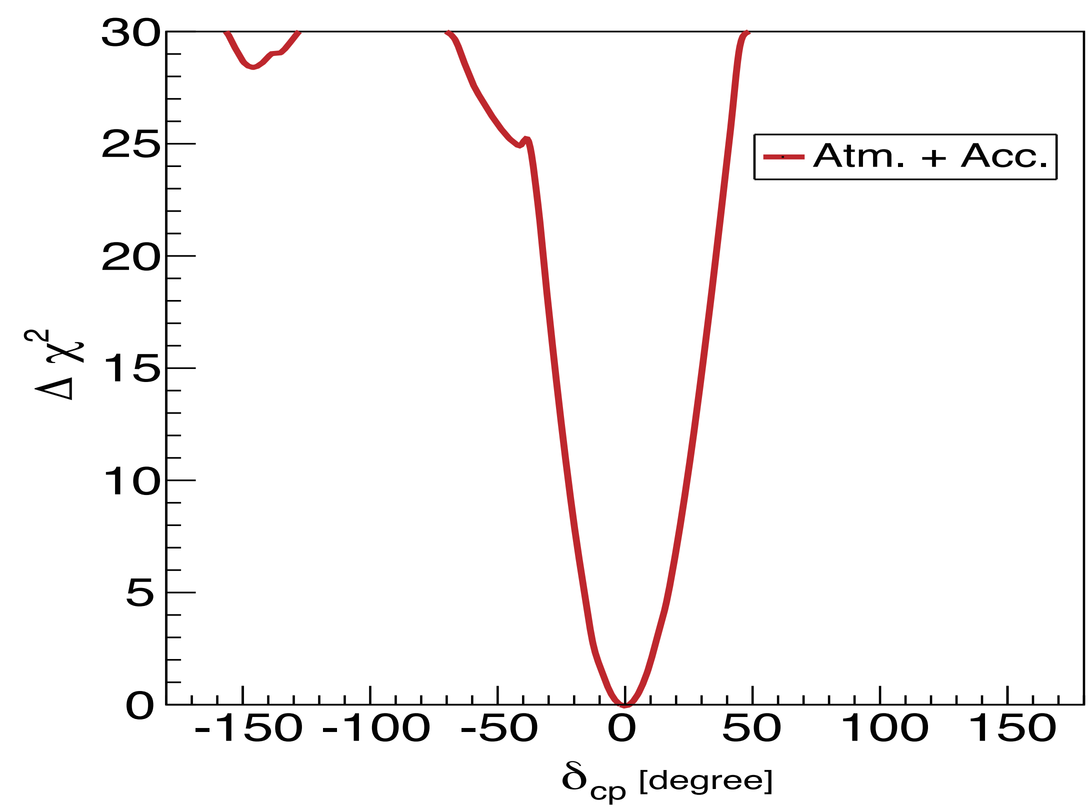
True $\sin^2\theta_{23}$	0.45		0.50		0.55	
Parameter	Δm^2_{32}	$\sin^2\theta_{23}$	Δm^2_{23}	$\sin^2\theta_{23}$	Δm^2_{32}	$\sin^2\theta_{23}$
Normal hierarchy	1.4×10^{-5} eV^2	0.006	1.4×10^{-5} eV^2	0.015	1.5×10^{-5} eV^2	0.009
Inverted hierarchy	1.5×10^{-5} eV^2	0.006	1.4×10^{-5} eV^2	0.015	1.5×10^{-5} eV^2	0.009

cf. T2K 2014 result: $\Delta m^2_{32}=2.51\pm0.10\times10^{-3}$eV^2, $\sin^2\theta_{23}=0.514\pm0.055$

Mass hierarchy determination



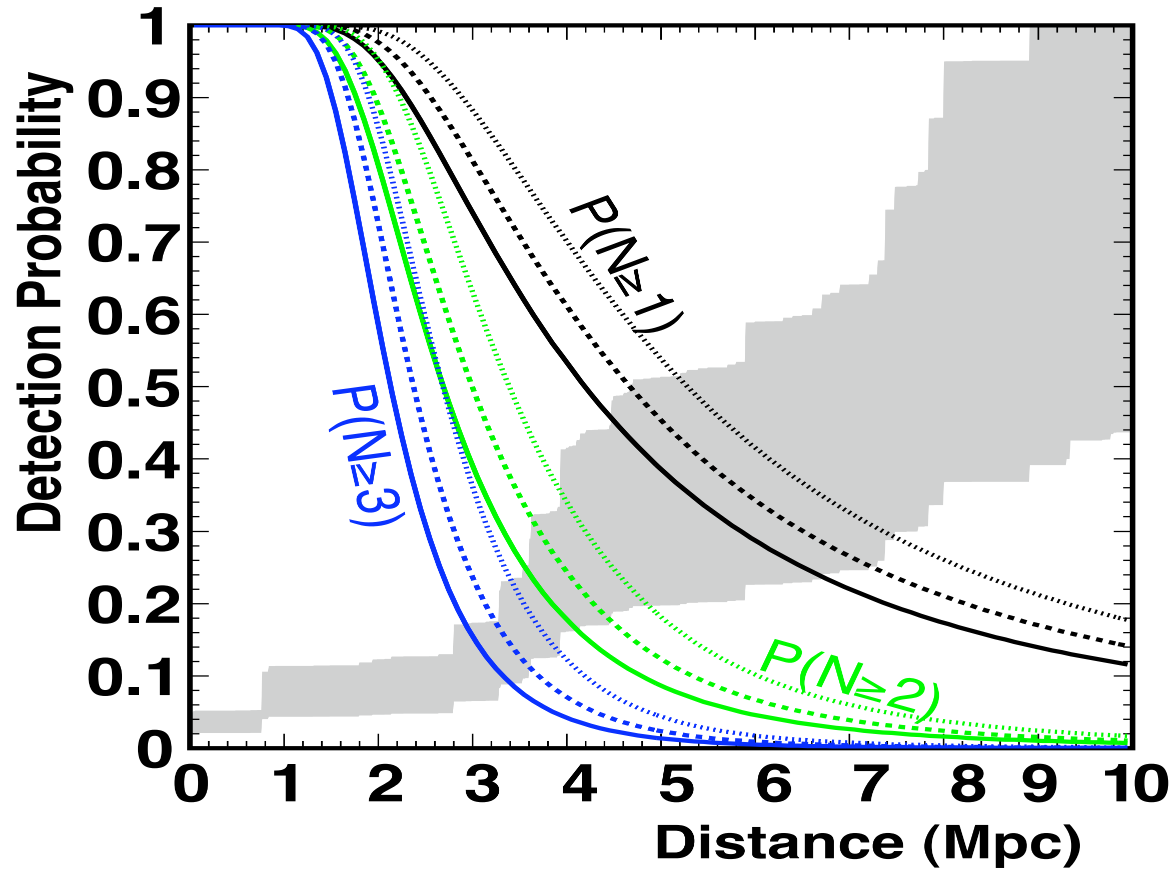


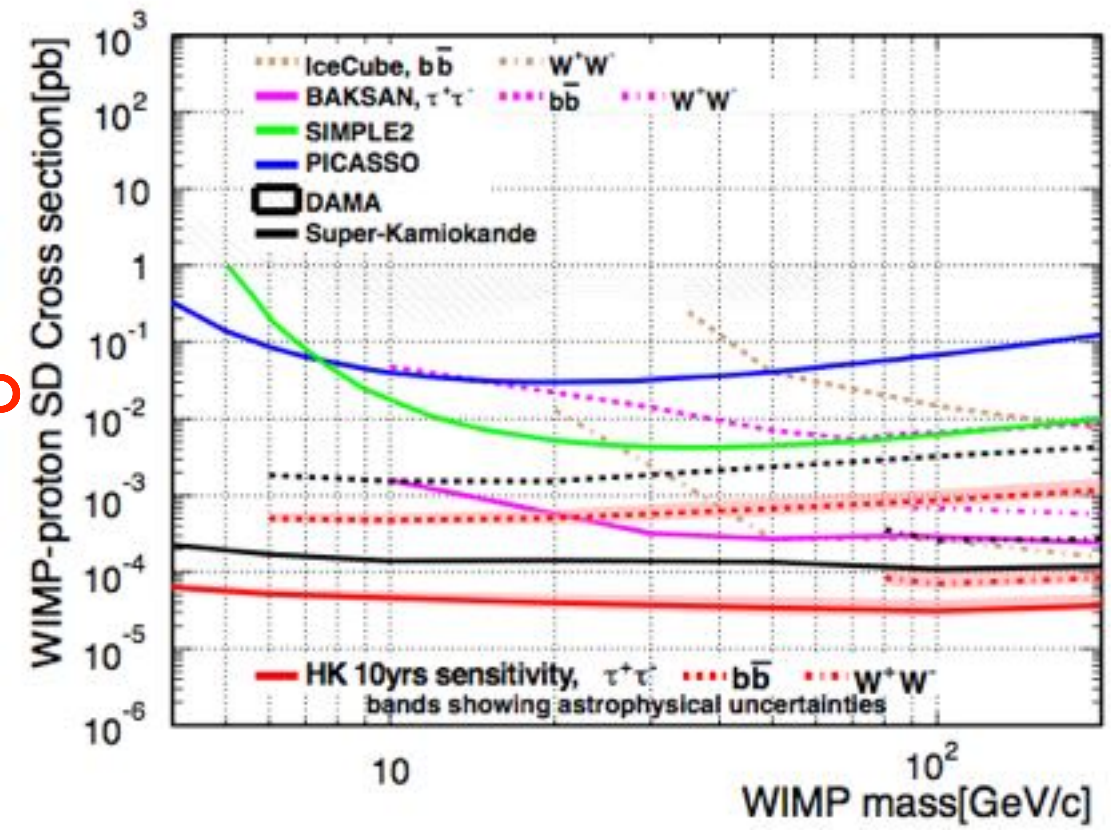


3-5σ determination possible

Neutrino astrophysics

- **Supernova burst neutrino**
  - >50% efficiency with >3 multiplicity for <2Mpc SN (~1/10yrs expected)
  - Huge statistics if SN in our Galaxy
    - ~250k events @ 10kpc
- **Supernova relic neutrino**
  - ~200 events in 10 years
  - History of heavy element synthesis in the universe
- Precision measurements of solar neutrino
  - Spectrum upturn, day/night asymmetry
- **Indirect WIMP Search**





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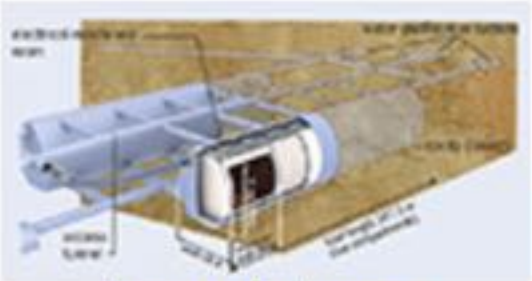
Apr 9, 2015

Proto-collaboration formed to promote Hyper-Kamiokande



Proposed detector

The Inaugural Symposium of the Hyper-Kamiokande Proto-Collaboration, took place in Kashiwa, Japan, on 31 January, attended by more than 100 researchers. The aim was to promote the proto-collaboration and the Hyper-Kamiokande project internationally. In addition, a ceremony to mark the signing of an agreement for the promotion of the project between the Institute for Cosmic Ray Research of the University of Tokyo and KEK took place during the symposium.

The Hyper-Kamiokande project aims both to address the mysteries of the origin and evolution of the universe's matter and to confront theories of elementary-particle unification. To achieve these goals, the project will combine a high-intensity neutrino beam from the Japan Proton Accelerator Research Complex (J-PARC) with a new detector

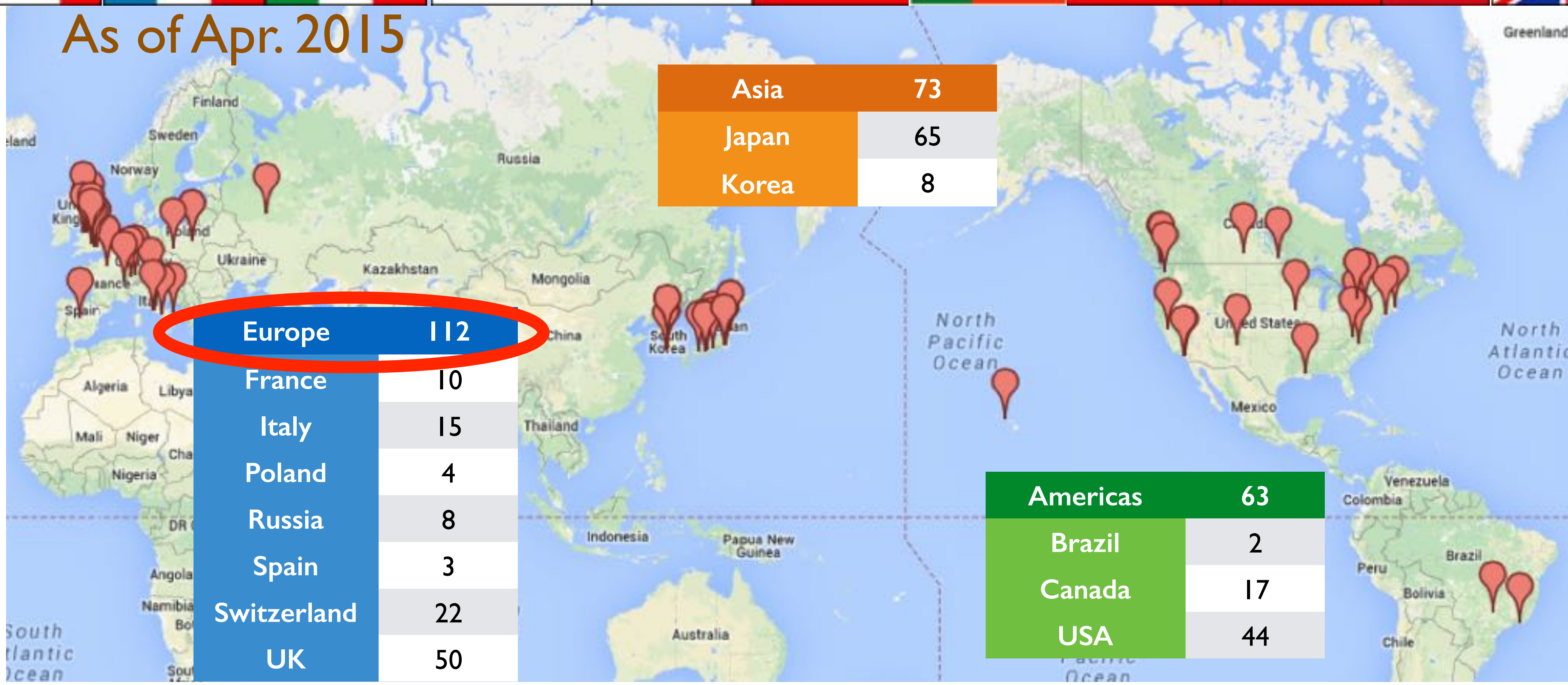
Hyper-K proto-collaboraion

Inaugural Symposium on January 31, 2015

KEK-IPNS and **UTokyo-ICRR** signed a **MoU** for cooperation on the Hyper-Kamiokande project

Hyper-K International Collaboration

As of Apr. 2015



Asia	73
Japan	65
Korea	8

Europe	112
France	10
Italy	15
Poland	4
Russia	8
Spain	3
Switzerland	22
UK	50

Americas	63
Brazil	2
Canada	17
USA	44

- 13 countries, ~250 members and growing
- Governance structure has been defined
  - International Steering Committee, International Board Representatives, and Working Groups, Conveners Board
  - R&D fund and travel budget already secured in some countries, and more in securing processes.

- Just held 3rd Hyper-K EU meeting at CERN this week

http://indico.cern.ch/e/ThirdEUHyperK

Next step

- Design Report is requested by KEK/ICRR.
  - To be prepared in 2015.
    - The next update of Japanese science roadmap (SCJ master-plan and MEXT roadmap) expected in 2016-2017.
  - Optimum design, construction cost&period, beam & near detector, international responsibilities
  - An international review will proceed under KEK/ICRR to promote the project.
- Once the budget is approved, the construction can start in 2018 and the operation will begin in ~2025.

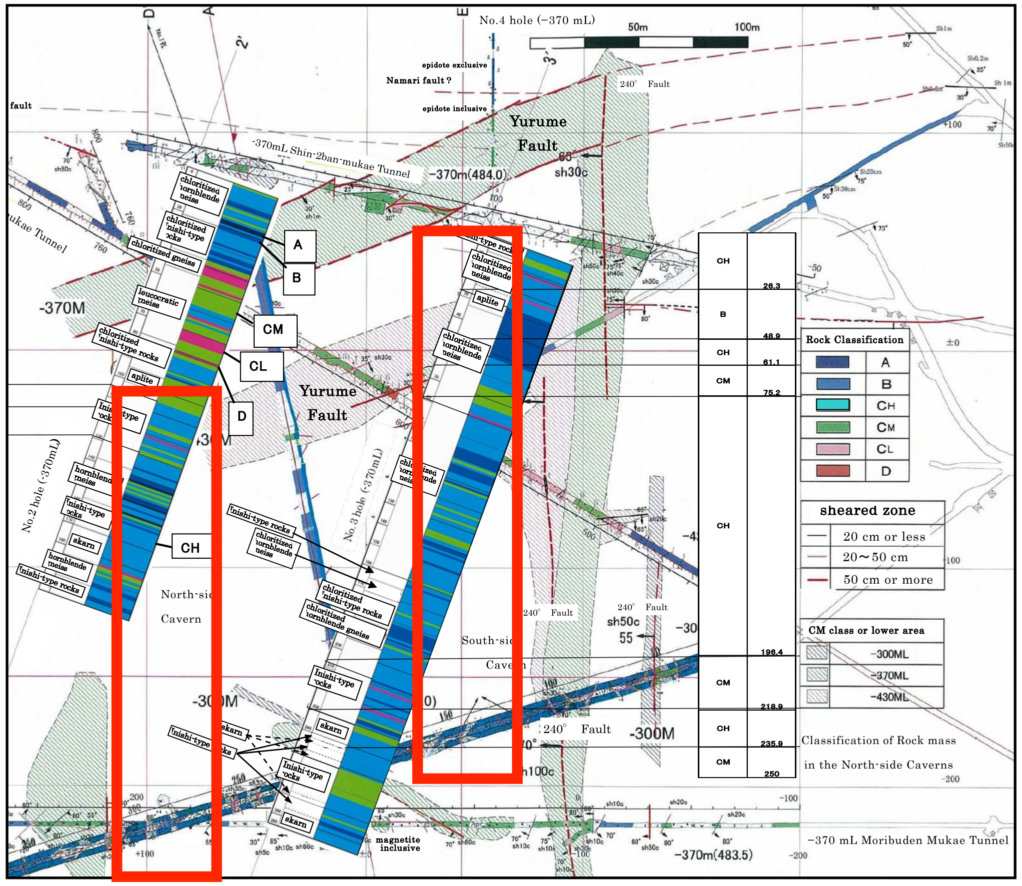
It is a critical time to promote the project

Open for more collaborators !

Next (worldwide) HK Open meeting: June 29-July 1, @Kashiwa/Japan

Geological survey & Cavern stability

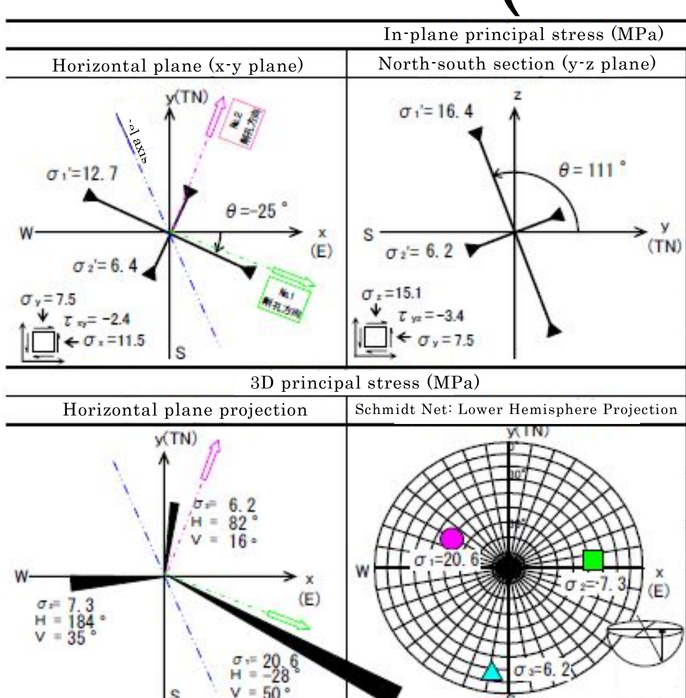
Rock mass characterization



- 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

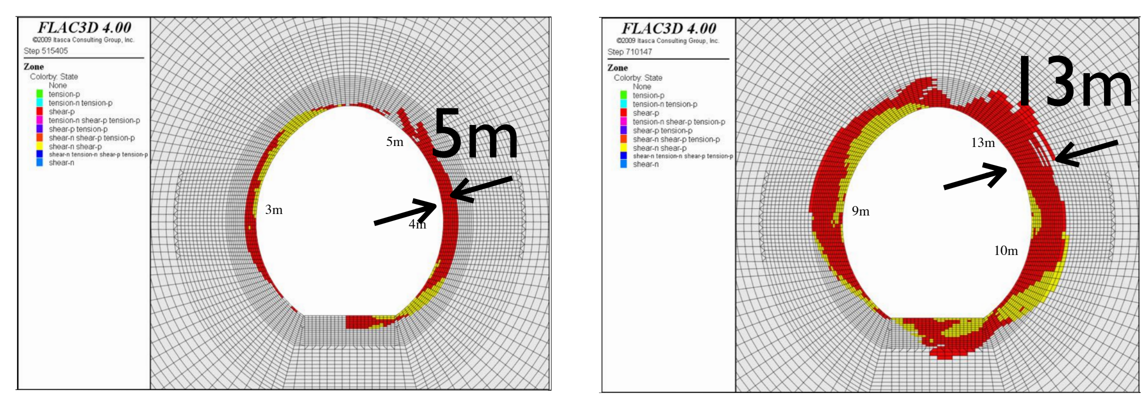
Survey in the Mozumi (Super-K) area is on-going.

Initial stress (in-situ meas.)



Six Stress Components (MPa)	
σ_x	11.5
σ_y	7.5
σ_z	15.1
τ_{xy}	−2.4
τ_{yz}	−3.4
τ_{zx}	5.8

Cavern stability



Excavation steps & supporting method

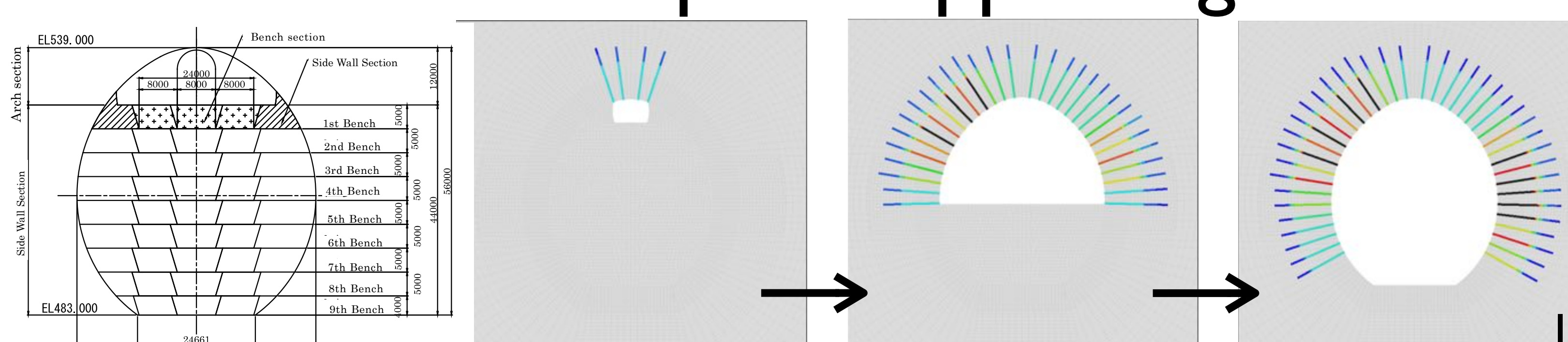
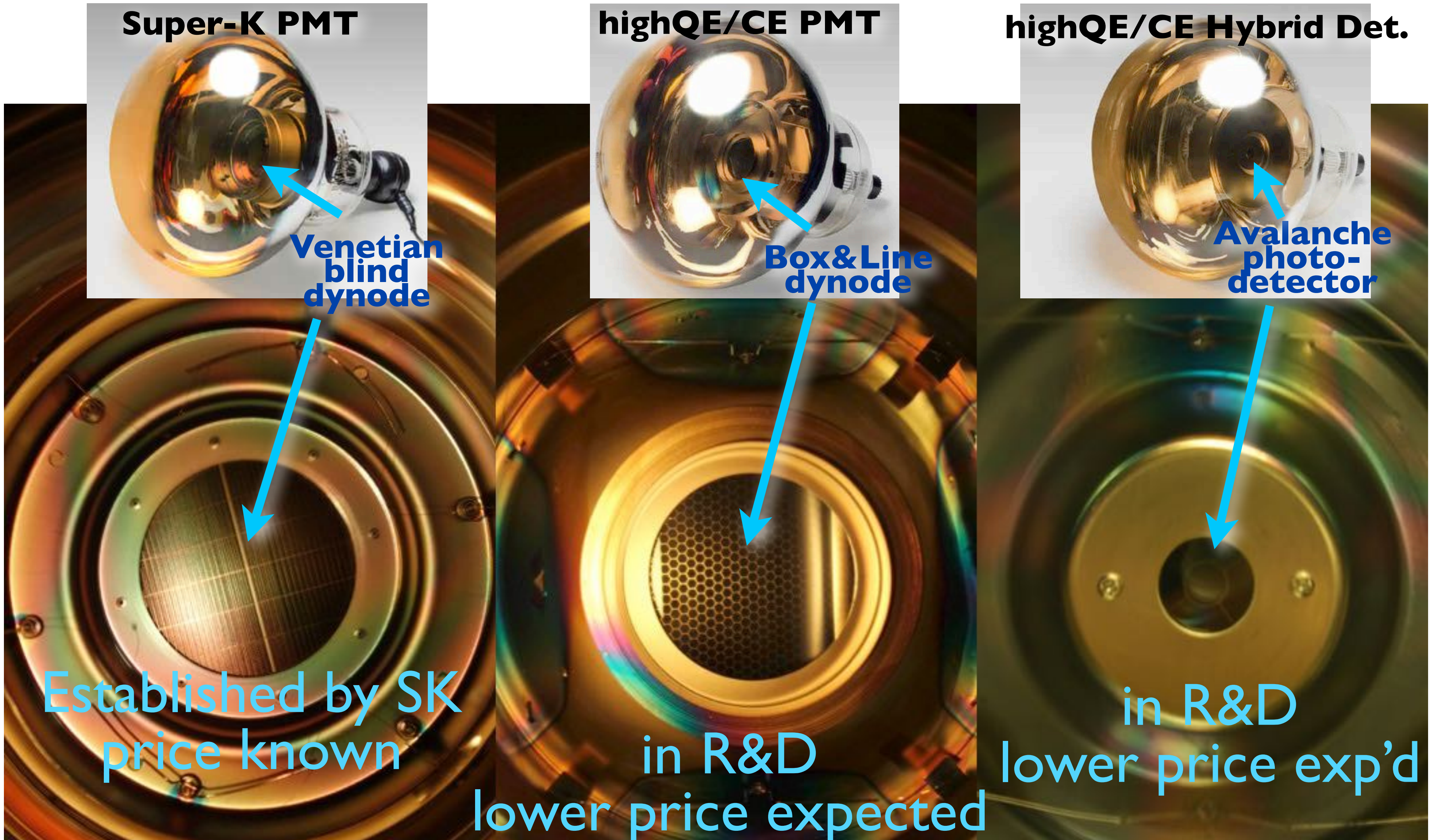


Photo-sensor development in Japan

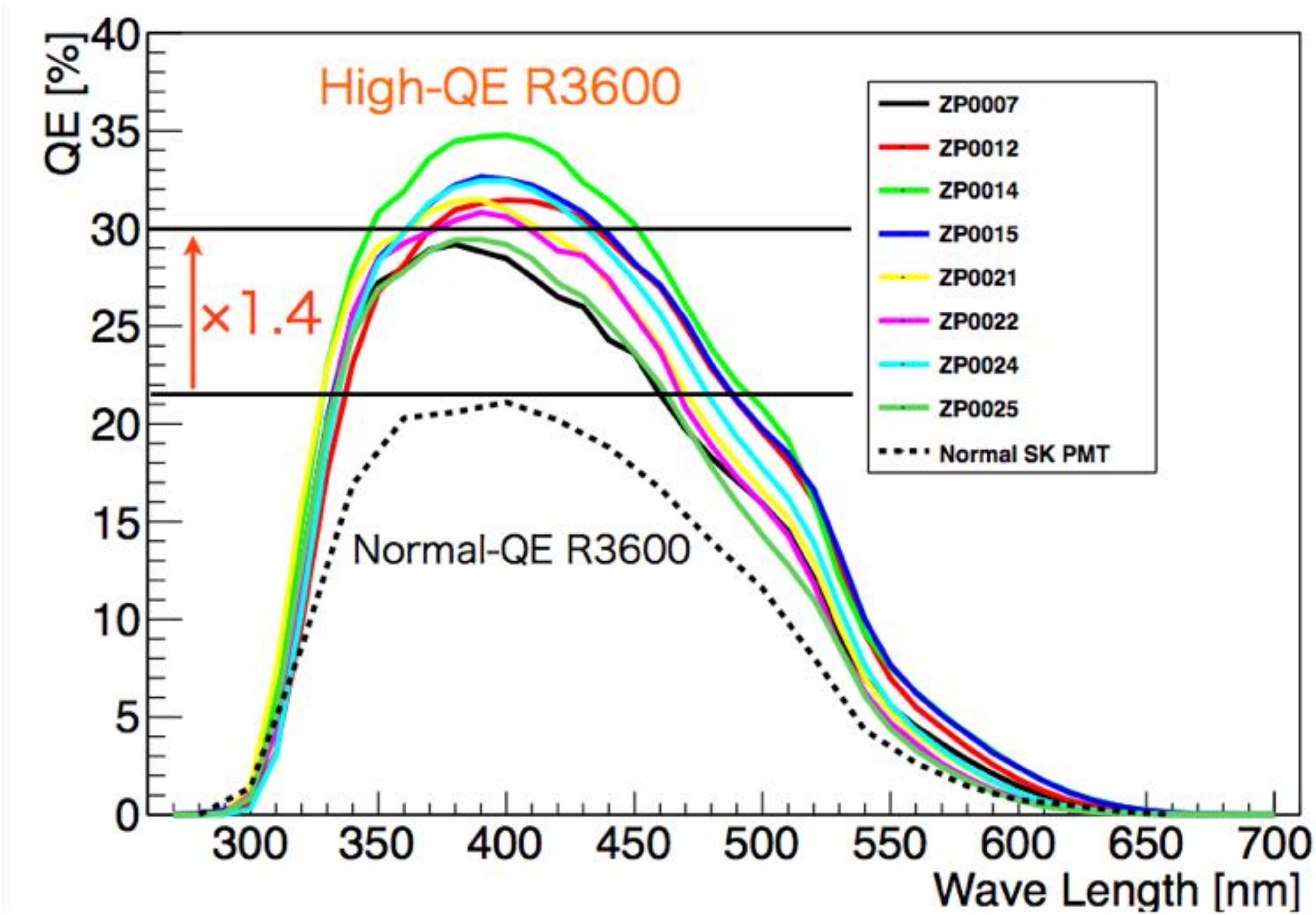


Quantum Efficiency	22%	30%	30%
Collection Efficiency	80%	93%	95%

Open for other photo-sensor options,

for better performance and/or reduced cost

Higher QE achieved



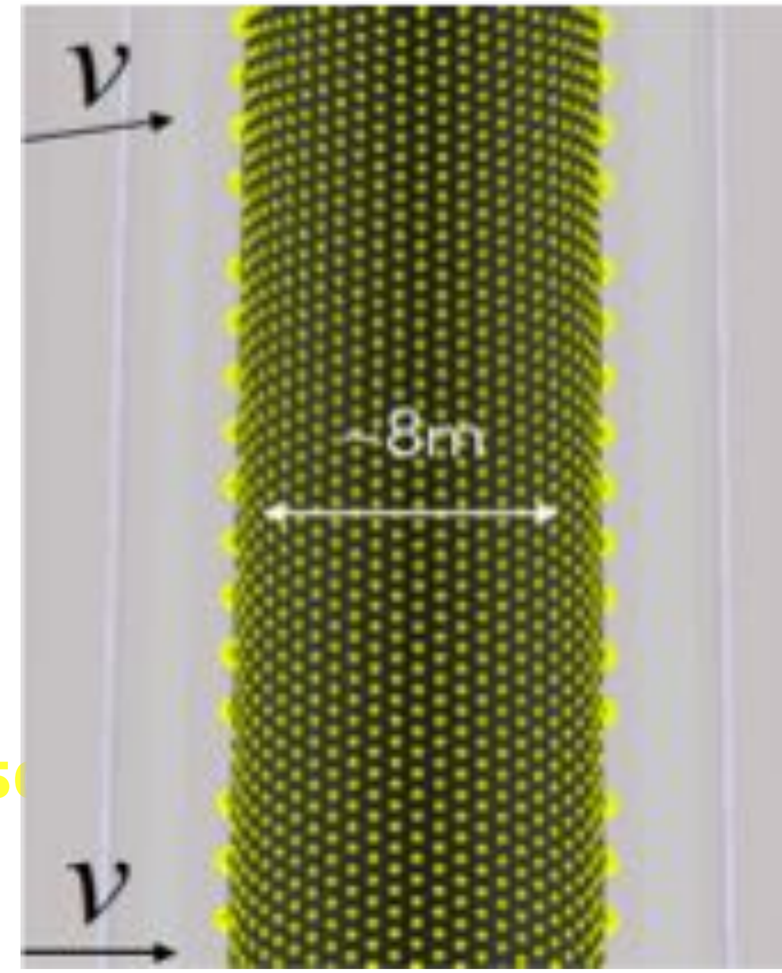
High Quantum Efficiency (QE) of ~30% has been achieved !
for 50cm B&L PMT and HPD

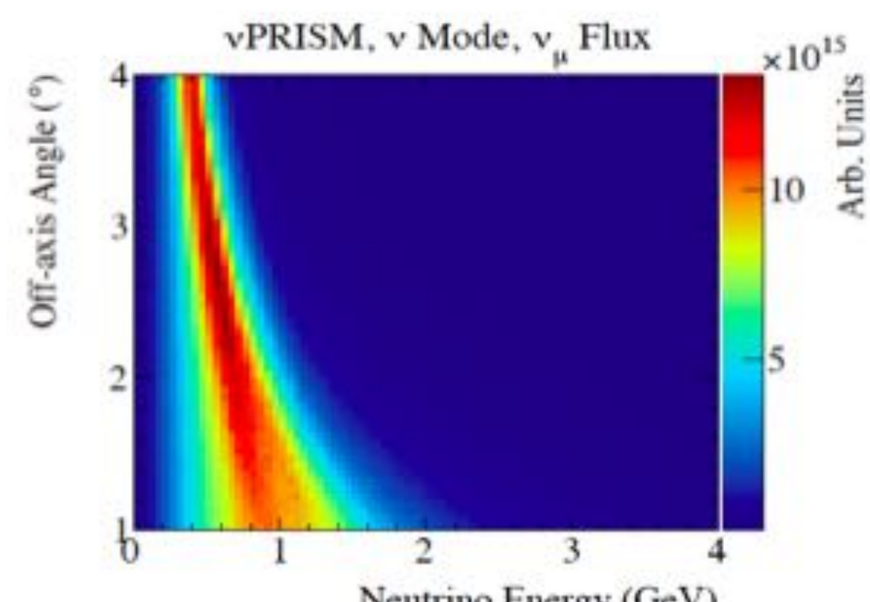
Intermediate detectors

Conceptual design

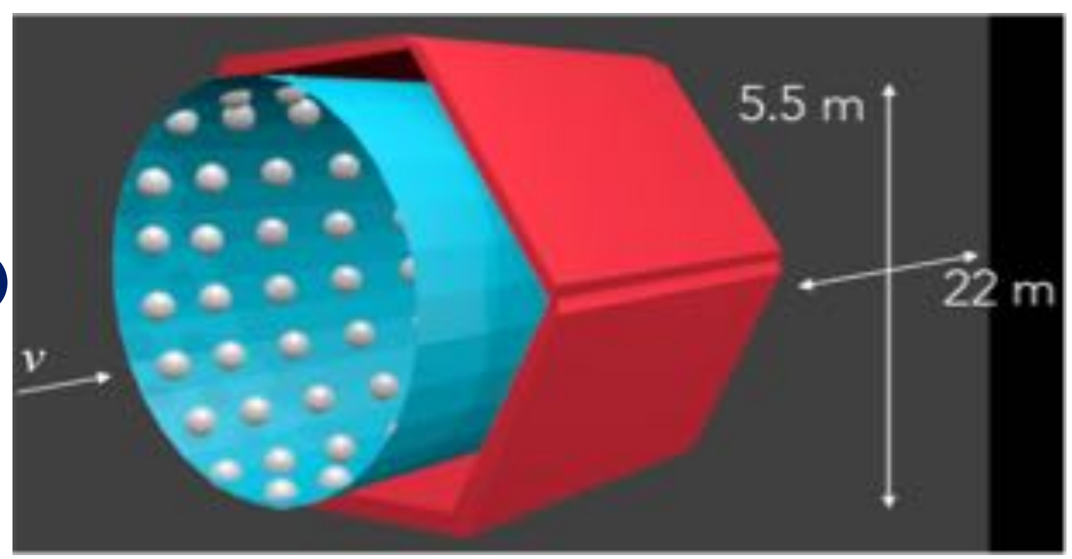
- Oscillation study
  - Water target (same w/ the far detector, minimize nuclear uncertainty)
  - NCπ^0 BG measurement
  - beam νe BG
- Other physics
  - νμ, νe interaction studies
  - Sterile ν searches

νPRISM
50m tall WČ



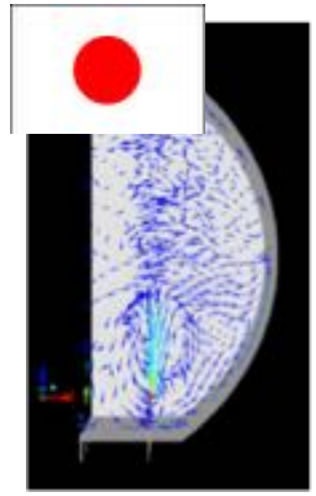


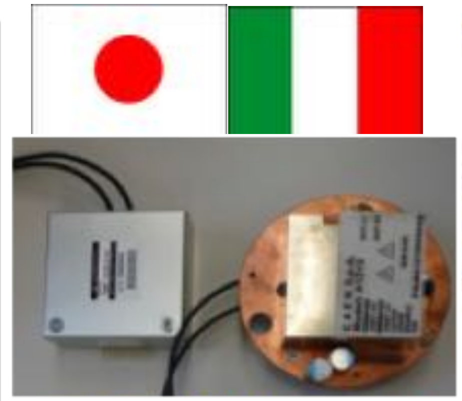
TITUS
WČ+MRD

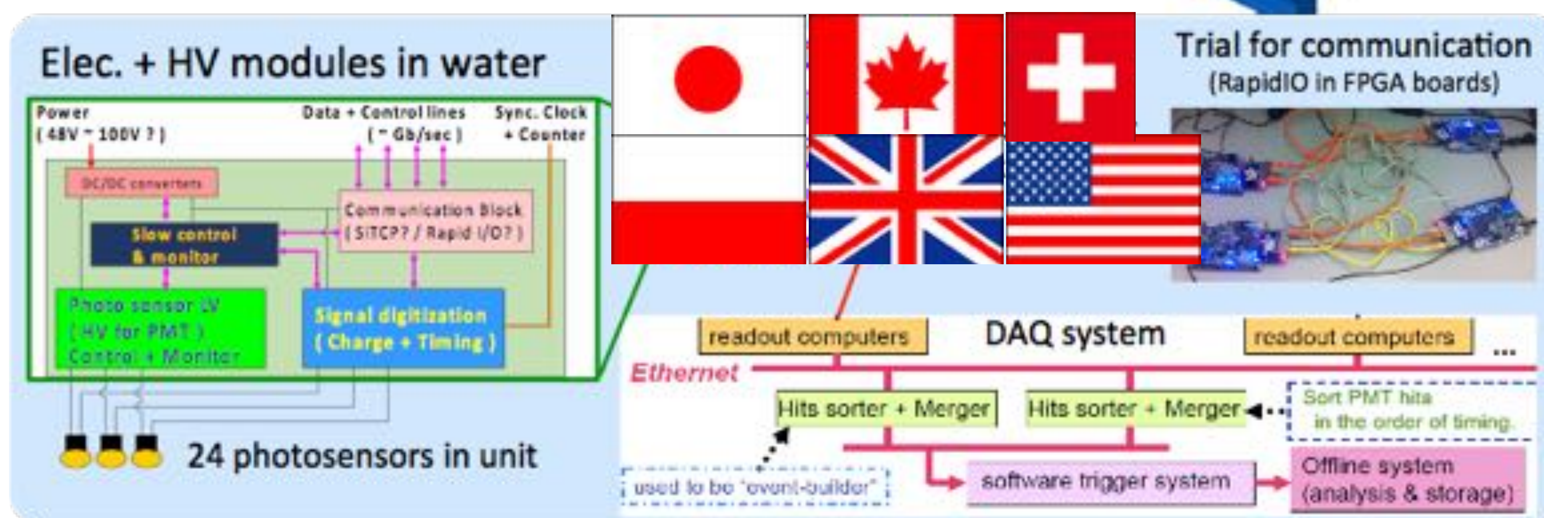


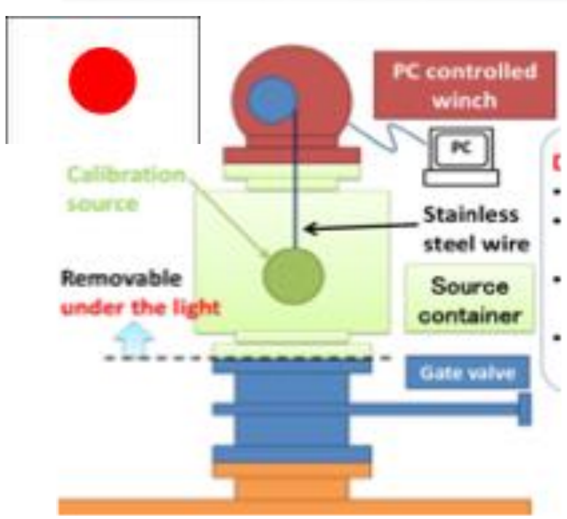
ND280 also assumed as part of ND
Open for more ideas

World wide R&D



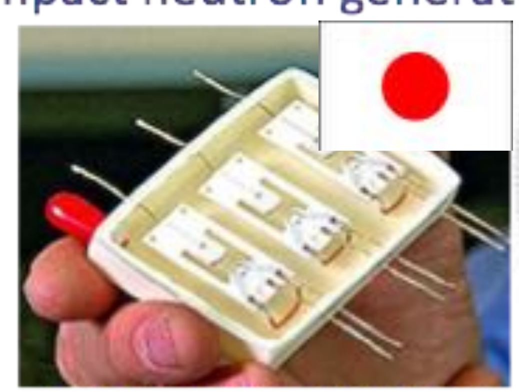






LED

Compact neutron generator



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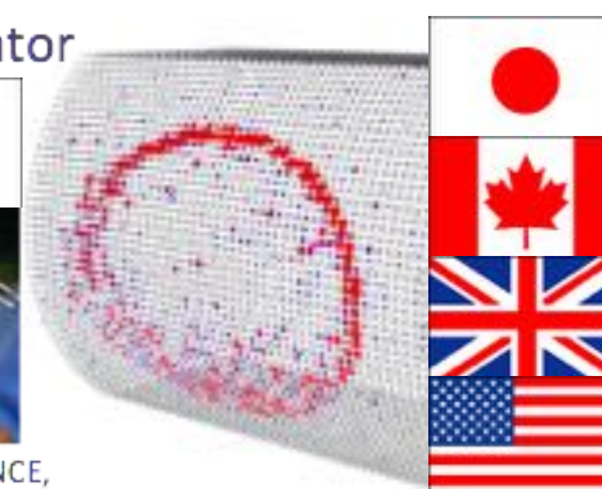

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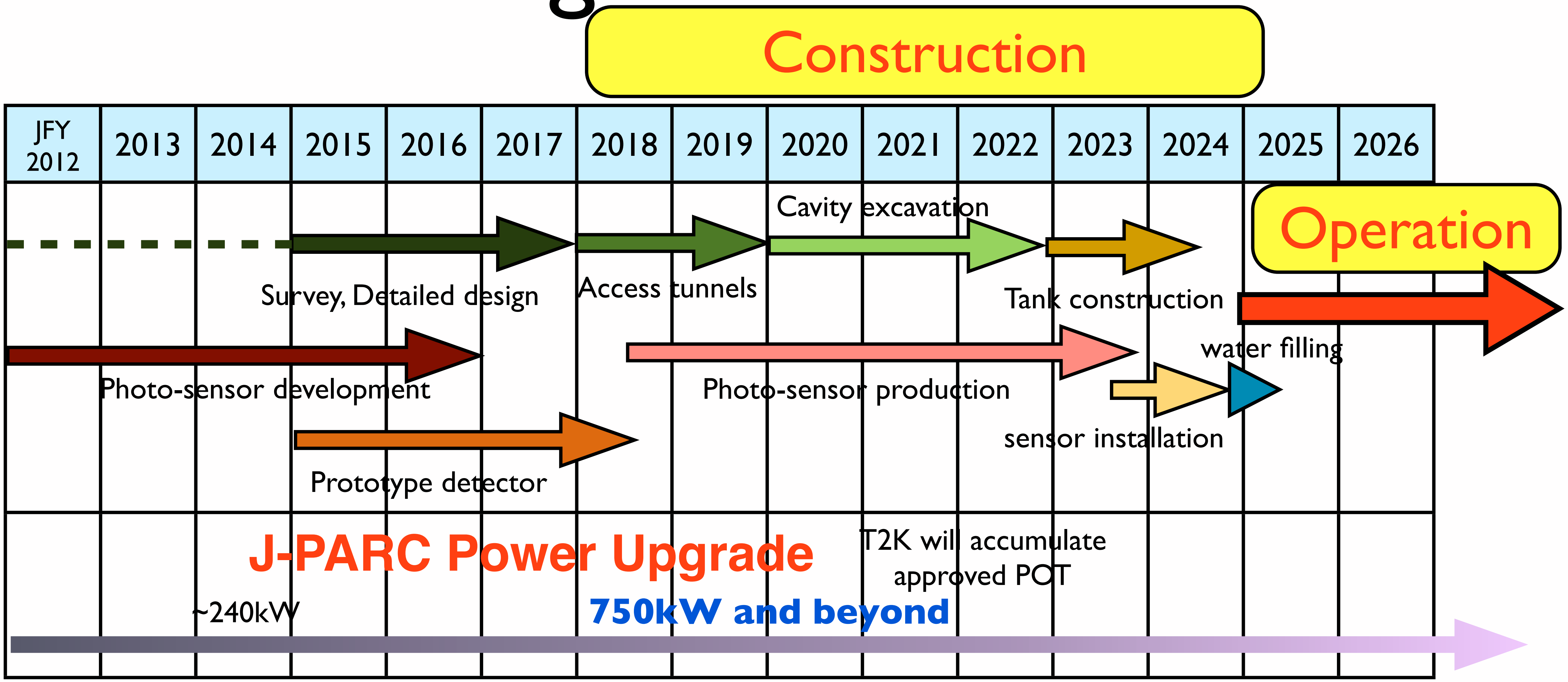
Still a lot to do towards real detector construction…

Target schedule



- -2018 Construction starts
- -2025 Data taking start
  - -2028 Discovery of Neutrino CP violation ?
  - -2030 Discovery of Proton Decay ?
  - -20xx Detection of supernova neutrinos
  - -20xx Discovery of new phenomena

Hyper-K: Summary

- **Wide physics topics with discovery potentials**
  - Proton decay discovery potential for 10^{34}-10^{35} yrs
  - ν CPV(76% of δ space at 3σ), δ precision of <20°
  - SN bursts, relic SN ν, WIMP annihilation ν ...
- **Many good results in development works worldwide**
  - See recent EU Hyper-K meeting for more detail
- **Boost promoting the project**
  - International proto-collaboration has been formed
  - Cooperation with KEK-IPNS/ICRR to develop the project
  - Design Report to be prepared in 2015
  - Open for new collaborators!

Next (worldwide) HK Open meeting: June 29-July 1, @Kashiwa, Japan

Backup

Memberships of the IBR

Chair: D. Wark

Brazil: H. Nunokawa (Rio de Janeiro)
Canada: S. Bhadra (York), A. Konaka (TRIUMF)
France: M. Gonin (Ecole Polytechnique)
Italy: M.G. Catanesi (INFN-Bari)
Japan: T. Kobayashi (KEK), T. Nakaya (Kyoto), M. Shiozawa (ICRR)
Korea: K.K. Joo (CNU)
Poland: E. Rondio (NCBJ, Warsaw)
Russia: Y. Kudenko (INR)
Spain: L. Labarga (Madrid)
Switzerland: A. Blondel (Geneva)
UK: F. Di Lodovico (QM London), D. Wark (STFC, RAL-PPD)
USA: E. Kearns (Boston), C. Walter (Duke)

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International Working Groups

Very active and growing group! Recently added new conveners.

Project Leader:
Masato Shiozawa
Project co-Leader:
Francesca Di Lodovico

- **WG1**: Shiozawa, Smy, H.Tanaka
- **WG2**: Sekiya, Vagins
- **WG3**: Nakayama, Nishimura
- **WG4**: Hayato, Lindner
- **WG5**: Miura, Walter, Di Lodovico
- **WG6**: Koshio, McCauley, Mine, Hide Tanaka, Hiro Tanaka
- **WG7**: Hartz, Wilson
- **WG8**: Hartz, Fuji
- **Phys-WG**: Yokoyama
  - **Phys-WG1**: Yokoyama
  - **Phys-WG2**: Wendell
  - **Phys-WG3**: Shimizu, Takeuchi

WG1: Cavity and Tank
WG2: Water
WG3: Photo-sensors
WG4: Electronics and DAQ
WG5: Software
WG6: Calibration
WG7: Near Detectors
WG8: Beam & Accelerator

Phys-WG1: Accelerator
Phys-WG2: Atmospheric ν+Nucleon decays
Phys-WG3: Astroparticle Physics (SN, Solar ν, etc)

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(International) Steering Committee

Membership

- **Chair: T. Nakaya**
- **IBR chair (co-chair of the iSC)**: D. Wark (UK)
- **ICRR representative**: N. Nakahata (Japan)
- **KEK representative**: T. Kobayashi (Japan)
- **Project leader and co-leader**: M. Shiozawa (Japan), F. Di Lodovico (UK)
- **Physics convener**: M. Yokoyama (Japan)
- **At-large members**:
  - H. Aihara (Japan), A. Blondel (Switzerland), G. Catanesi (Italy), E. Kearns (USA), J.M.Poutissou (Canada)

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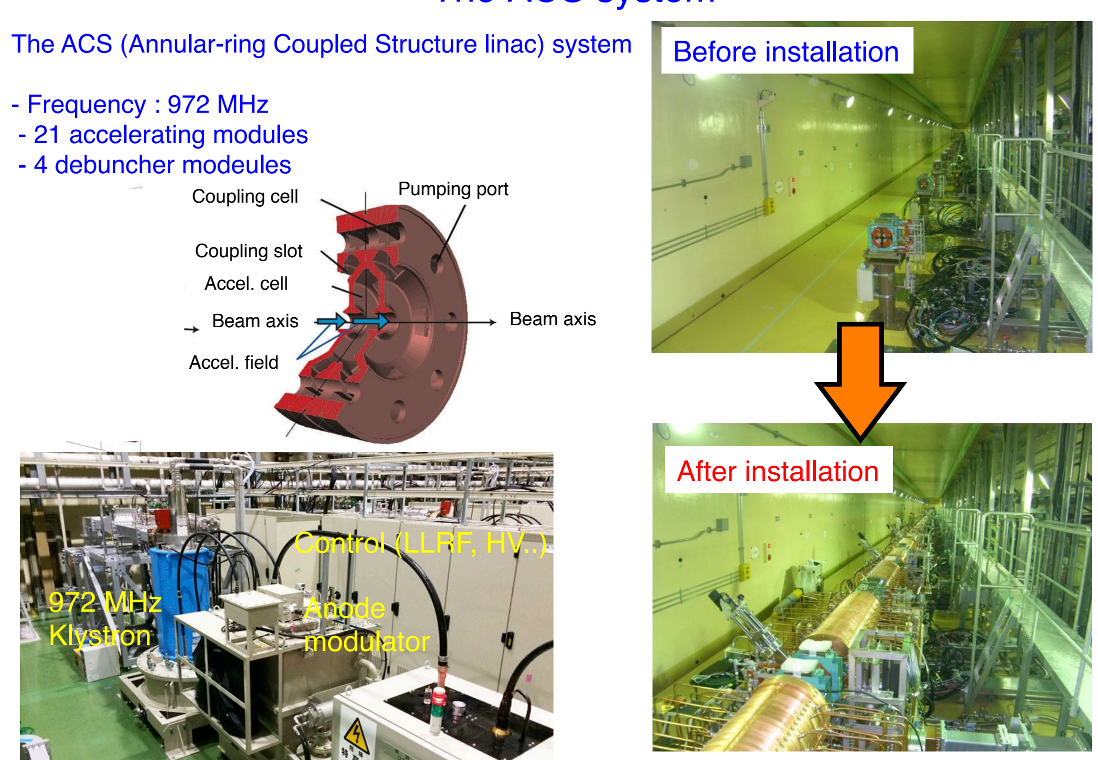
Hyper-K project in Japan

- One of two top priority projects in HEP community (Feb. 2012)
  - http://www.jahep.org/office/doc/201202_hecsubc_report.pdf
- Endorsed by cosmic ray physics community as a next large-scale project
- KEK roadmap includes Hyper-K
  - http://kds.kek.jp/getFile.py/access?sessionId=1&resId=0&materialId=0&confId=11728
- Science Council of Japan selected Hyper-K as one of 27 top priority projects in "Japanese Master Plan of Large Research Projects" (out of 192 projects in all field of science)
  - http://www.scj.go.jp/ja/info/kohyo/pdf/kohyo-22-t188-1.pdf
- Not on the list of MEXT Roadmap 2014.
  - We aim for the next roadmap, which is anticipated in 2017, with addressing comments received (international participation, organization, cost estimate)

LINAC and RCS update

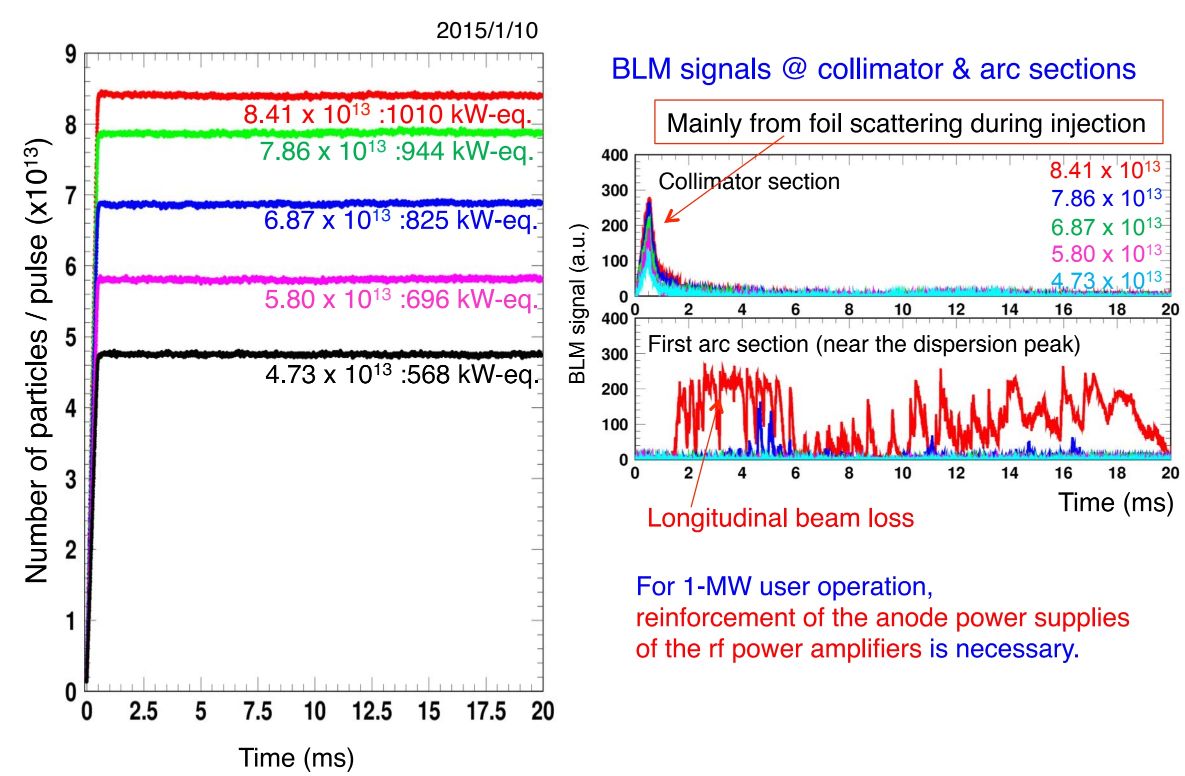
- Linac energy increased with ACS installation in 2013: 181MeV → 400MeV
- Front-end system replaced with a new one to increase the peak current in 2014: 30mA→50mA
- RCS (3GeV) power increased (300→500kW now, 1MW tested)

The ACS system



400-MeV acceleration was achieved on Jan. 17, 2014.

Demonstration of 1 MW-eq. beam



For 1-MW user operation, reinforcement of the anode power supplies of the rf power amplifiers is necessary.

J-PARC ν beamline prospects

- Will be ready to accept 750kW
  - All 3 horns were replaced to upgraded design in 2013-2014
  - Horn PS for high rep purchased
  - Enhancement of radioactive water/air disposal capability ongoing
- NO NEED to reconstruct facility upto ~3MW
  - Inaccessible part (decay volume, beam dump) designed for multi-MW
  - Need buildings for handling radio-active waste (water)
- International cooperation for development of core parts (target, horns, window, …)

Component	beam power / parameter	
	limitation	upgrade
target	3.3×10^{14}ppp	
beam window	3.3×10^{14}ppp	
horn		
cooling for conductors	2MW	
stripline cooling	400kW	1~2MW
hydrogen production	300kW	1~2MW
horn current	250kA	320kA
PS repetition	0.4Hz	1Hz
decay colume	4MW	
hadron absorber / beam dump	3MW	
water cooling facilities	750kW	~2MW
radiation shielding	750kW	4MW
radioactive air leakage to the TS ground floor	500kW	~2MW
radioactive cooling water drainage	600kW	~2MW

Systematic error assumptions

Based on T2K/SK+extrapolation including correlations

- Beam flux + near detector constraint
  - (Conservatively) assumed to be the same
- Cross section uncertainties not constrained by ND
  - Nuclear difference removed assuming water measurements
- Far detector
  - Reduced by increased statistics of atmospheric ν control sample

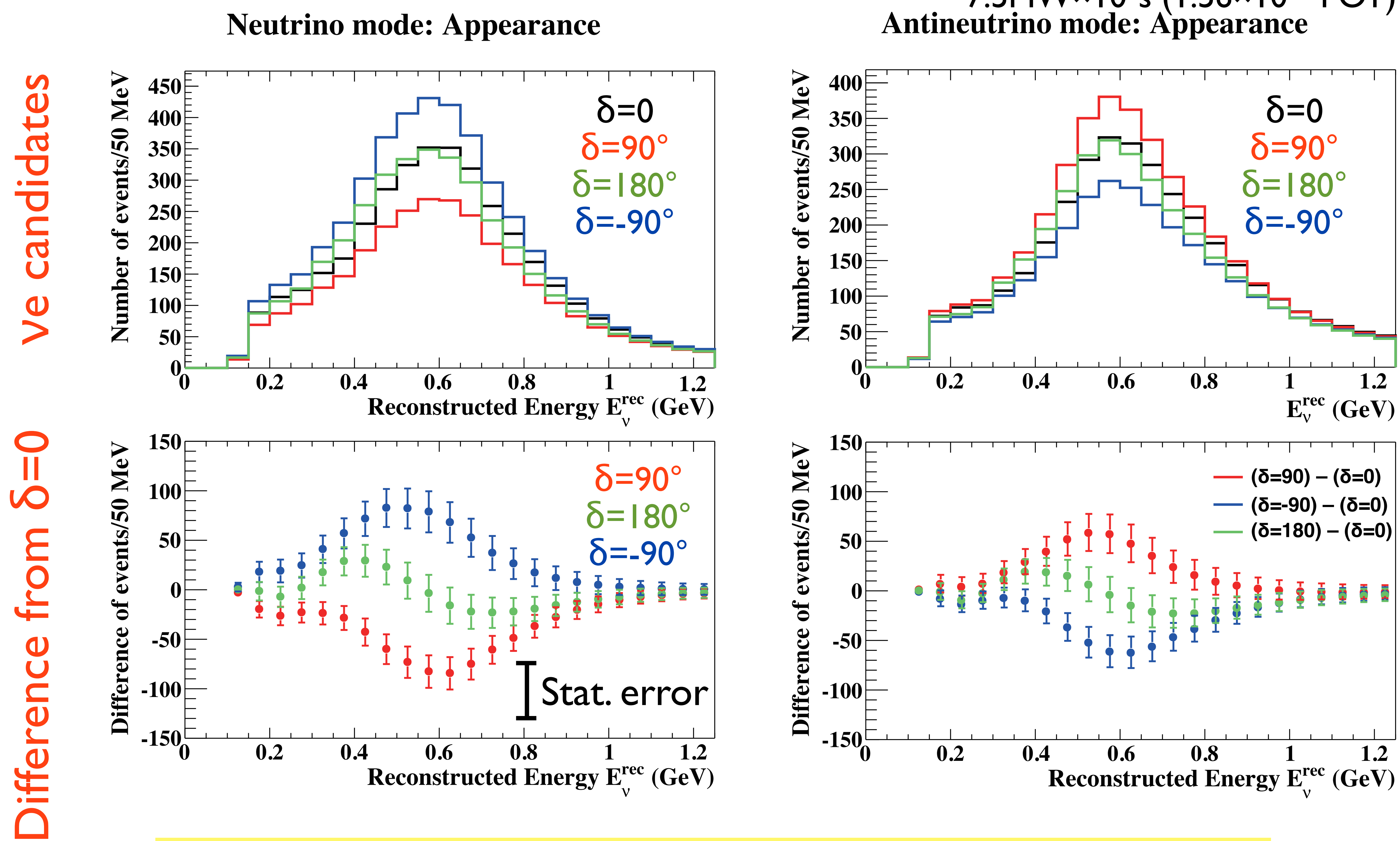
Uncertainty on the expected number of events at Hyper-K (%)

	ν mode		anti-ν mode		(T2K 2014)	
	νe	νμ	νe	νμ	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

- Further reduction by new near detectors under study

δ_{CP} dependence of observables

7.5MW×10^7s (1.56×10^22 POT)



Sensitive to all values of δ with numbers + shape