Hyper-Kamiokande

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International Meeting for Large Neutrino Infrastructures
June 23-24, 2014

Five Questions from the organizer

Q1. (Theoretical relevance) What is according to you the theoretical relative urgency of the determination of the

- neutrino mass hierarchy,
- PMNS CP violating phase δ,
- θ_{23} octant
- existence of sterile neutrinos
- Dirac vs Majorana nature of the neutrino

Compare, if relevant, to other attempts of measurement direct or indirect (e.g. in cosmology). Describe also synergies with other topics of science e.g. proton decay or neutrino astrophysics (supernova burst and relic, solar neutrinos,…).

Q2. (Experimental Strategy) What is according to you the experimental strategy that needs to be deployed worldwide in order to answer the above questions? And in particular, how many experiments should there be worldwide, what complementarities or double check features should they exhibit? In this world-wide context describe the phases of your project, its timeline and the expected statistical significance per phase. Discuss the relevant systematics, how well you know them and in particular do you need any supporting measurements to further determine them?

Q3. (Experimental readiness) Evaluate the readiness of the technology you are planning to use. Describe the phases (or R&D) towards its final validation. What are the risks associated. Is there place for global sharing and coordination of the R&D or validation effort? Are there industrial issues e.g. in procurement?

Q4. (Site issues) What are the optimisation criteria for the site you propose? What is the regional support for the site you propose? Is your proposal site specific? Could the same or better performances be obtained in another site in the same continent or some other region?

Q5. (Financial and internationalisation issues) What is the cost of the experimental configuration (beam where relevant and detector)? What is your financial plan? What is the current level of international participation and what level of participation would be necessary to move to a construction decision? What models would you propose for international participation and at which parts of the beam or detectors? What would be the parts of the configuration whose leadership you would be willing to negotiate in exchange of international participation ?

Quick answer to the Questions

Q1, Theoretical relevance

A1, Rich physics topics can be covered by the Hyper-K

- Proton decay searches extends to discovery region (e.g 10^{35} years for $p \to e^+\pi^0$ (dominant decay mode in simple GUTs), 0.5×10^{35} years for $p \to \nu K^+$ (SUSY favored by Supersymmetric GUTs))

- Studies toward understanding full picture of neutrino oscillations
  - CPV (76% of δ space at 3σ), δ precision of <20° by 7.5MW×yrs
  - MH determination for any δ w/ accelerator/atmospheric neutrino study
  - θ_{23} octant determination: $\sin^2\theta_{23}<0.47$ or $\sin^2\theta_{23}>0.53$ or $\sin^2\theta_{23}\sim0.5$
  - precision (<1%) measurement of Δm^2_{32}
  - test of exotic scenarios (sterile, LIV etc.) at 300km and O(100m~1km)

- Astrophysical neutrino observatory
  - Supernova explosion mechanism, ν spectrum, rate (visible and invisible SN)
    - Supernova burst detection to 2Mpc distance, ~1SN /10 years
    - guaranteed Supernova relic ν signal (~300ν events/10yrs)
  - Search for neutrinos induced by dark matter captured in the Sun, Galaxy, and Earth
  - Solar neutrino monitoring and oscillation study (~200ν events/day)

Q2, Experimental strategy

A2, Hyper-K would be most quick approach to neutrino's CP δ and proton decays

- technology is ready
- high statistical study is possible (~3000 νe and ~2000 anti-νe appearance signals)
- realistic systematic errors of ~5% estimated based on SK/T2K experiences
- Notional timeline
  - 2025 *Start Hyper-K data taking*
  - 2028 Discovery of leptonic CPV w/ >5σ (MH at the same time or earlier)
  - 2030 Discovery of proton decays

In the world;

- collaboration on accelerator and beamline intensity upgrade
- hadron (pion/Kaon) production measurement, ν interaction measurements would help
- LBL experiments at different distance and/or energy (e.g. 2nd oscillation maximum) would provide complemental information toward full understanding of three generation framework
- Once proton decays are discovered, design of ultimate detectors (target mass and necessary detector technology) would become possible for pinning down the grand unification picture.

Q3, Experimental readiness

A3, technology is ready, baseline design exists. We are open to ideas toward better/low-cost design.

- Such development works can be done during preparation work (full site survey, access tunnels constructions) for the cavern excavation.

Q4, Site issues

A4, Hyper-K and J-PARC realize a good experimental setup

- J-PARC exists.
- Kamioka underground lab. exists. Support by the mine company.

- good quality bedrock enables 1 million tons detector cavities

- 300 km distance
  - neutrino energy ~600MeV → first oscillation maximum (high oscillation probability)
  - ~600MeV provides simple neutrino interaction topology (Quasi Elastic scattering)
    - high signal efficiency (60% for νe appearance)
    - very low background (10% at the peak energy (beam νe dominated))

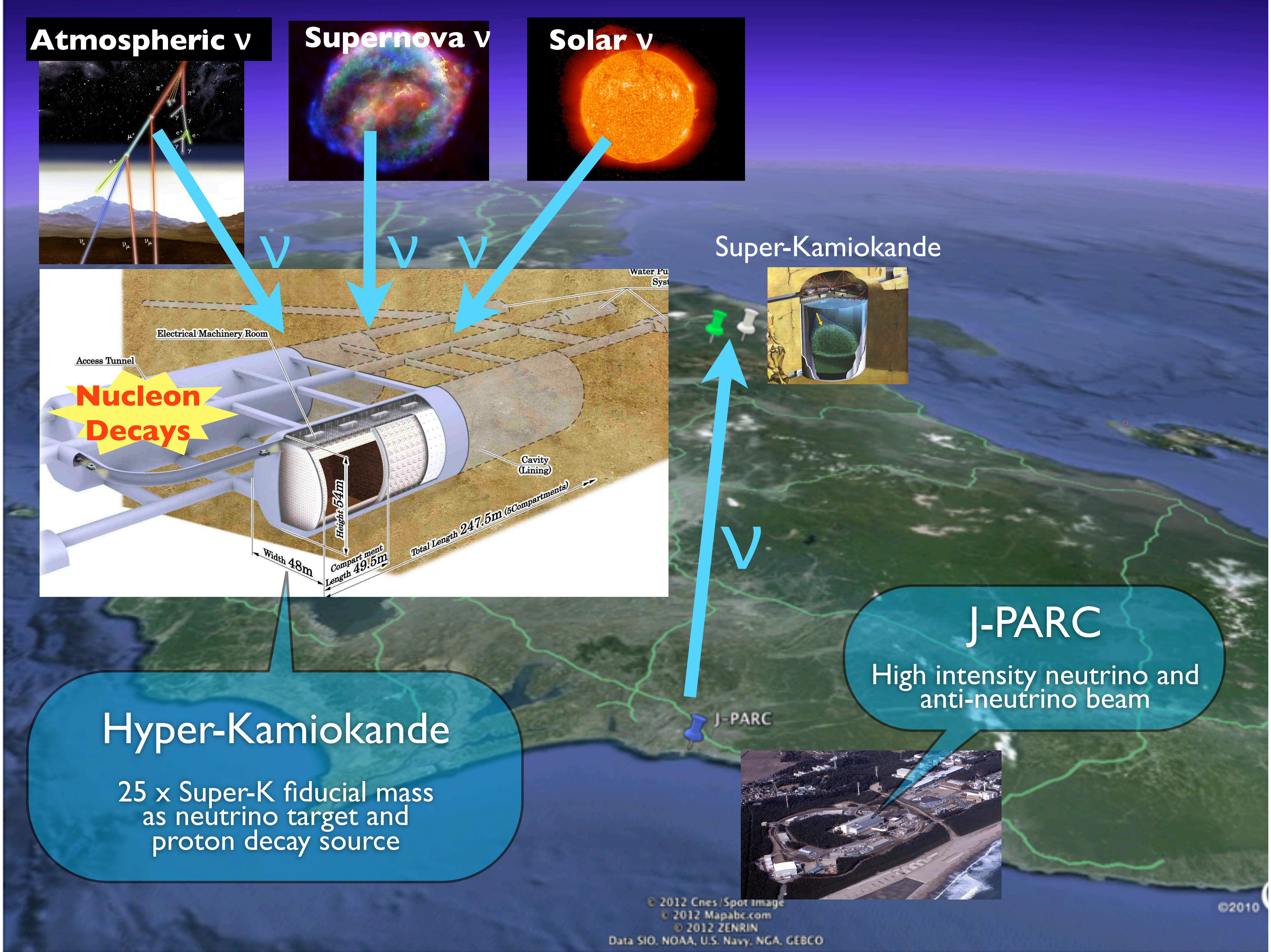
Q5, Financial and internationalisation issues
A5,

- 800M$ for Hyper-K construction
- Selected as one of 27 top large-scale projects by the "Master plan 2014" of Science Council of Japan
- discussions w/ MEXT (funding agency) toward budget request

- 5 yrs Grant-in-Aid for Hyper-K R&D and design was approved and budget requests under way in foreign countries (e.g. Canada, UK)
- Prototype detector project was launched as a seed of a real detector project

- Hyper-K is open to the international community
  - face-to-face group meetings were open to the community
- starting forming international Hyper-K proto-collaboration
- expect foreign contributions to various items such as photo-sensors, electronics, calibration, water system, near detectors, and J-PARC/beamline upgrade

Project overview



Atmospheric ν
Supernova ν
Solar ν
ν
ν
ν
Super-Kamiokande
Electrical Machinery Room
Access Tunnel
Nucleon Decays
Cavity (Lining)
Height 54m
Total Length 247.5m (5Compartments)
Width 48m
Compart ment Length 49.5m
ν
J-PARC
High intensity neutrino and anti-neutrino beam
J-PARC
Hyper-Kamiokande
25 x Super-K fiducial mass as neutrino target and proton decay source
© 2012 Cnes/Spot Image
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Data SIO, NOAA, U.S. Navy, NGA, GEBCO
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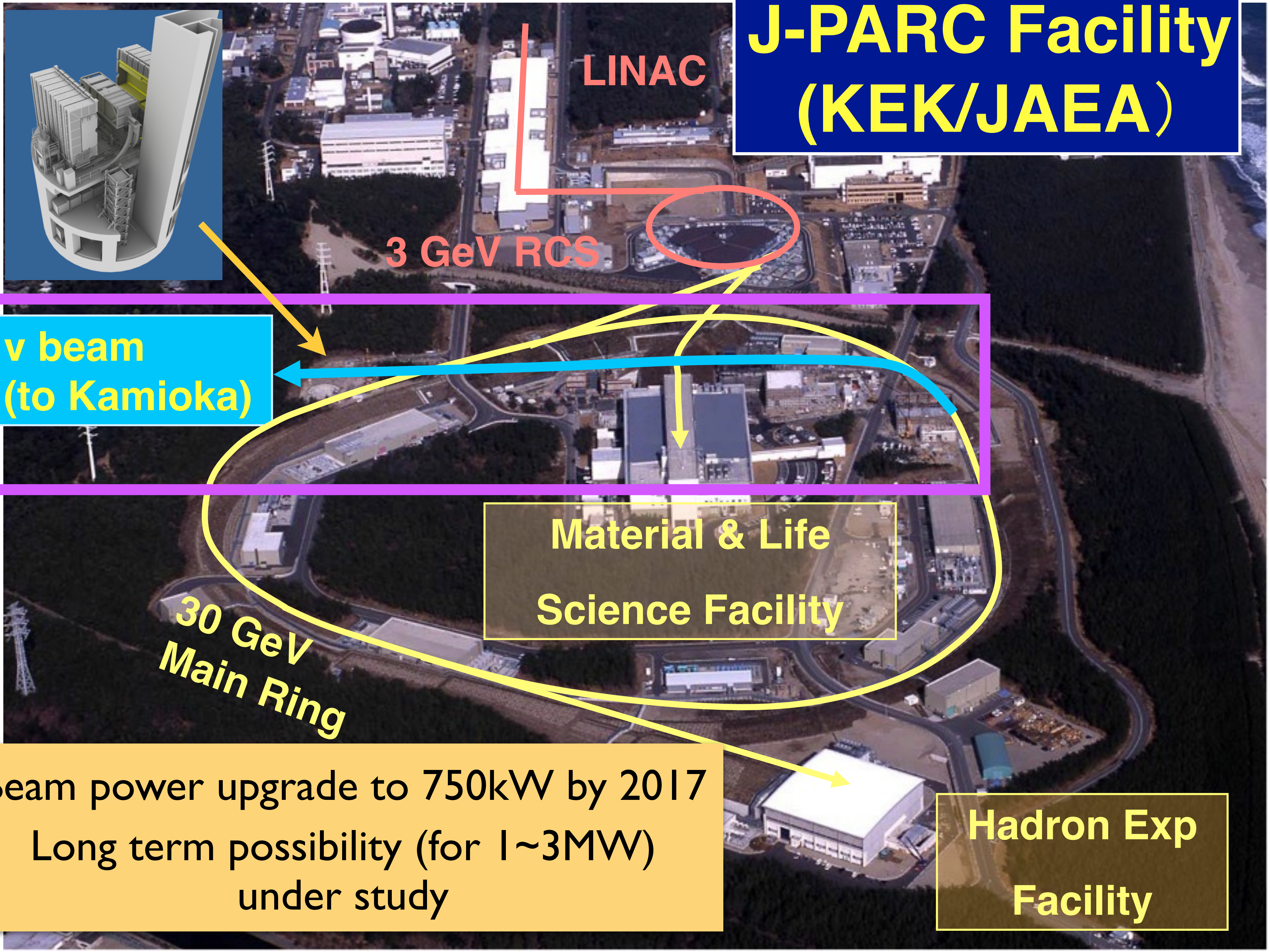
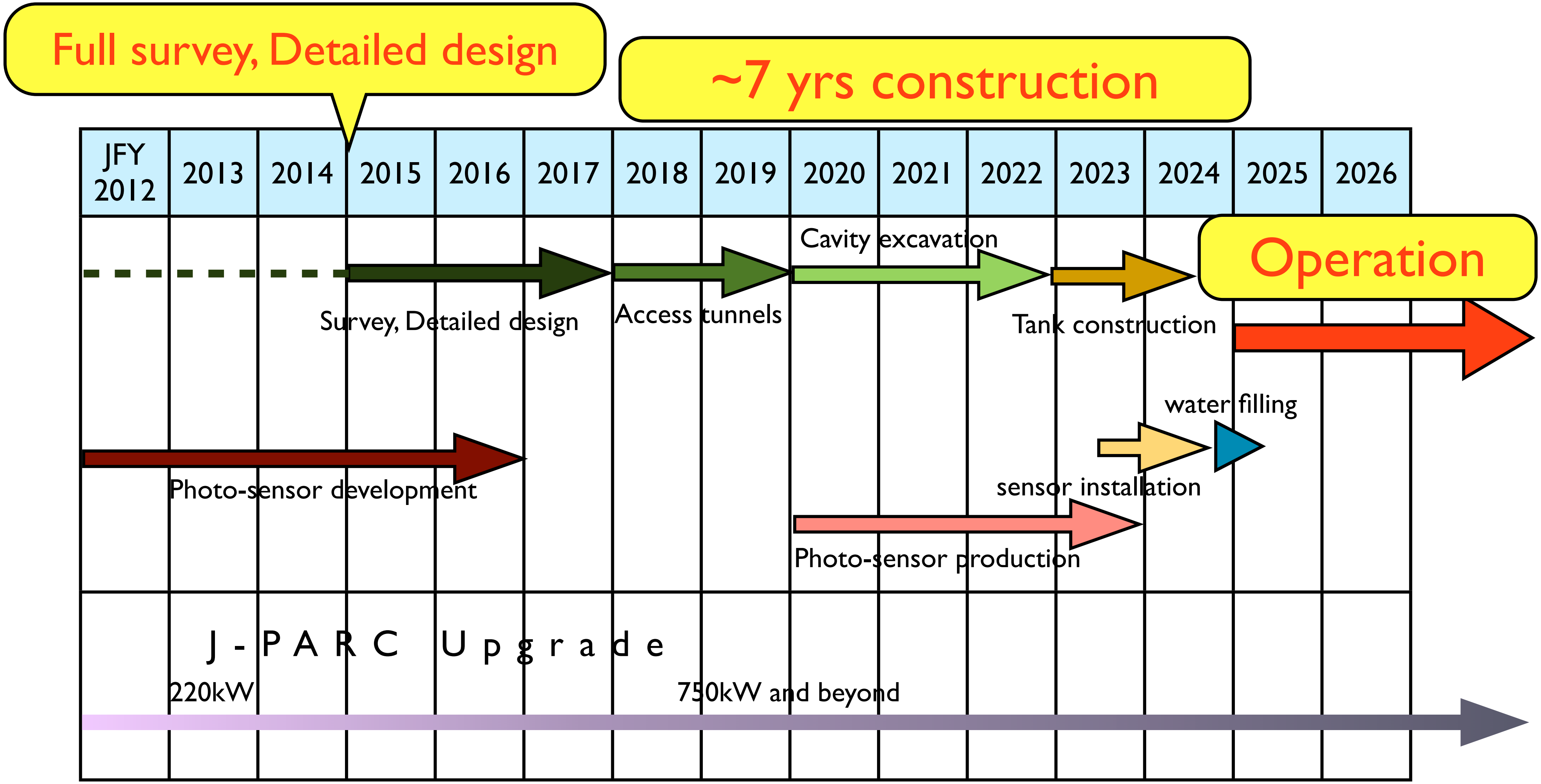
J-PARC Facility (KEK/JAEA）



Beam power upgrade to 750kW by 2017
Long term possibility (for 1~3MW)
under study

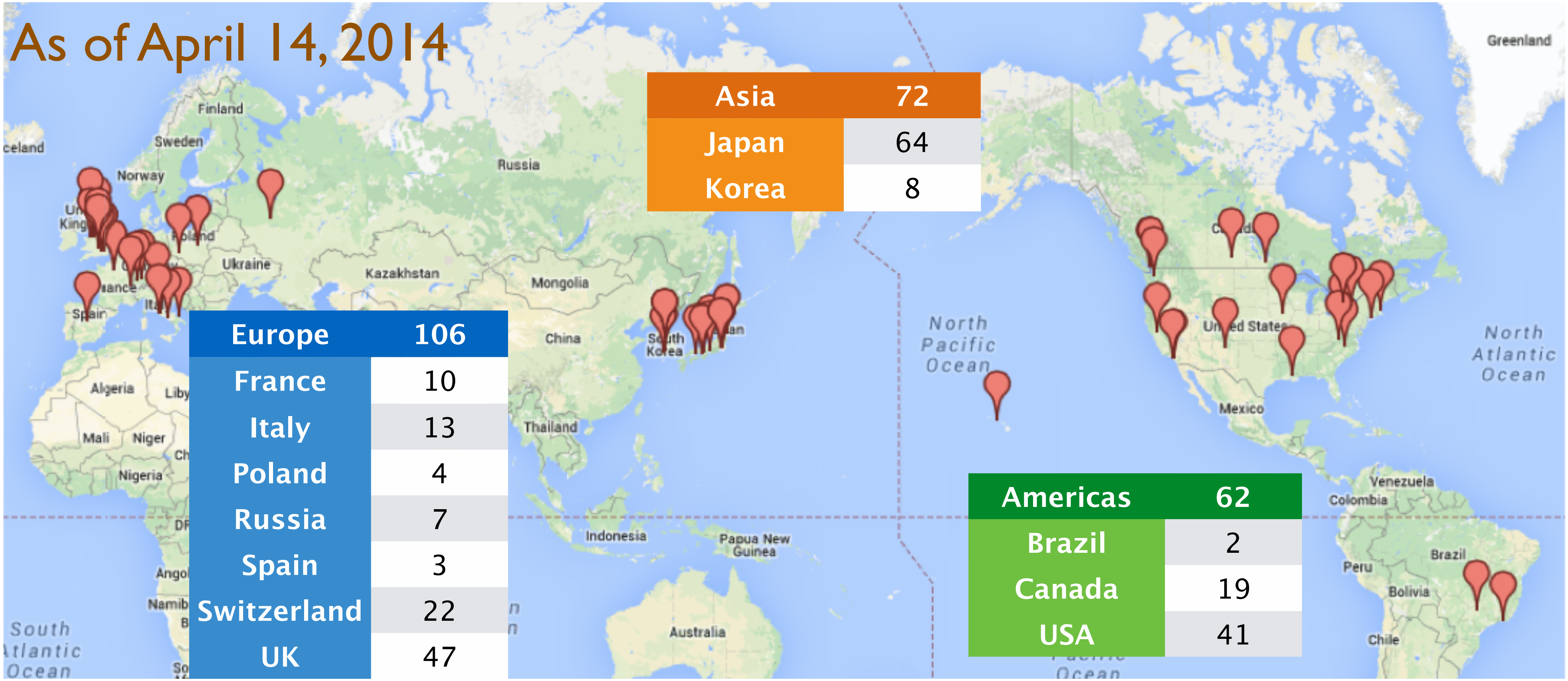
Notional Timeline



-2015 Full survey, Detailed design (3 years)
-2018 Excavation start (7 years)
-2025 Start operation

Hyper-Kamiokande International Working Group

As of April 14, 2014

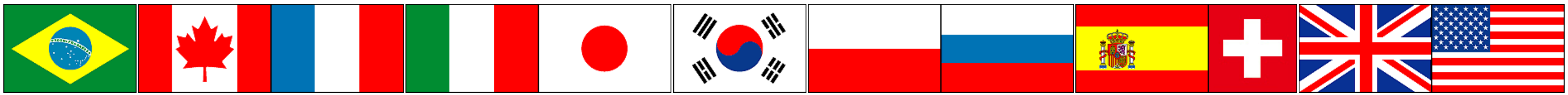


Europe	106
France	10
Italy	13
Poland	4
Russia	7
Spain	3
Switzerland	22
UK	47

Asia	72
Japan	64
Korea	8

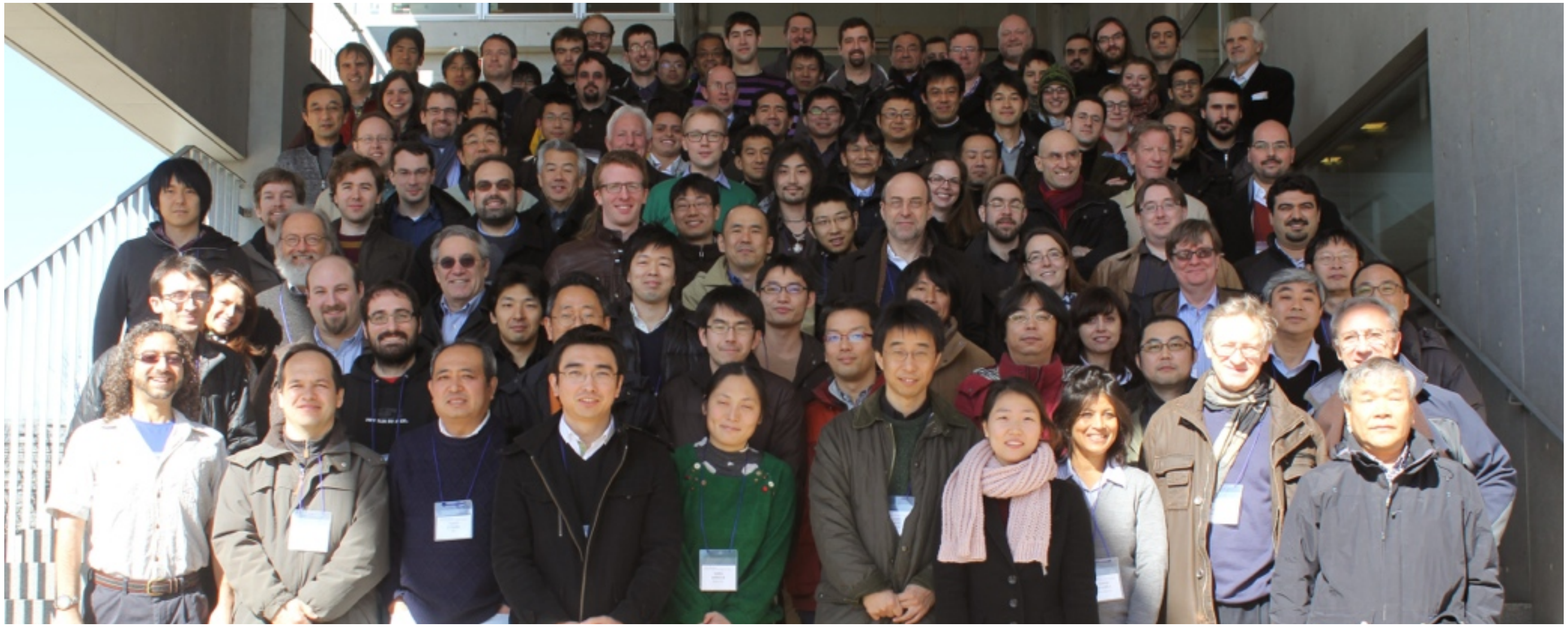
Americas	62
Brazil	2
Canada	19
USA	41

12 countries, 67 institutes, 240 people



International Hyper-K Working Group

4th Open Hyper-K meeting



- International open Hyper-K meetings: twice every year
- Next meeting: July 19-22, 2014 in Vancouver, CANADA

  http://bit.ly/5th-hyperk
- International Board of Representative
  - Representatives from 13 countries: Brazil, Canada, France, Italy, Japan, Korea, Poland, Portugal, Russia, Spain, Switzerland, UK, USA
  - Discussing contributions, cost-sharing, and budget requests

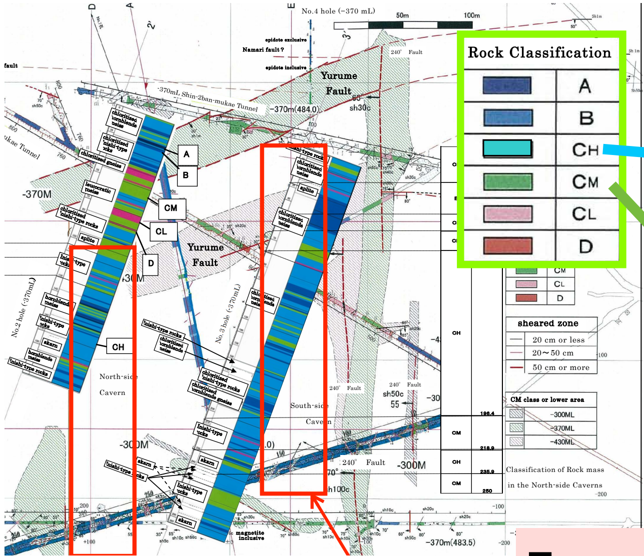
International Hyper-K Working Group

- In Japan
  - Selected as one of 27 top large-scale projects by the "Master plan 2014" of Science Council of Japan

No.	Scien-tific Field No.	Project Name	Project Summary	Scientific Significance	Social Value	Project Duration	Financial Requirement (1billion yen)
85	23-2	Nucleon decay and neutrino oscillation experiment with a large advanced detector	The project is to construct an 1 million ton scale water Cherenkov detector Hyper-Kamiokande as a successor of Super-Kamiokande and to perform world leading studies of nucleon decays and neutrinos with the J-PARC accelerator facility.	The project will explore CP violation (matter-antimatter asymmetry) of neutrinos to help understand the evolution of the universe. Along with world best nucleon decay searches, it aims to establish unification of elementaly particles and their forces.	I will challenge to solve profound problems on particle unification and universe which should appeal to intellectual curiocities of human being. It will also represent dreams of basic science by advancing the world leading project in Japan.	2015 to 2038	Total:1,880 Construction of Hyper-Kamiokande800, Operating cost of Hyper-Kamiokande450, Operating cost of J-PARC600, Neutrino monitor30

  - discussions w/ MEXT (funding agency) toward budget request
  - 5 yrs Grant-in-Aid for Hyper-K R&D and design from 2013
    - Prototype detector project was launched
- Budget request for Hyper-K R&D projects being submitted in Canada and UK
- In Switzerland, included in the SERI inventory of planned research infrastructures
- Travel grant request submitted in EU (UK,France,Italy,Poland, Spain)

Geological survey

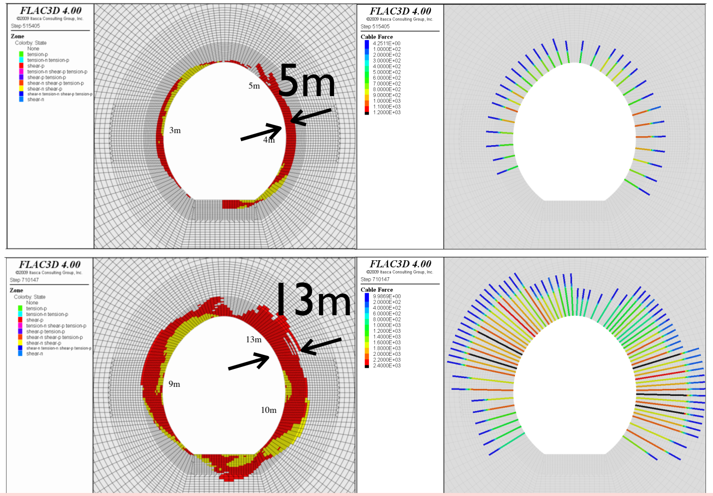


Cavern Design and Analysis

Plasticity region depth PS-anchor tension

CH class

CM class



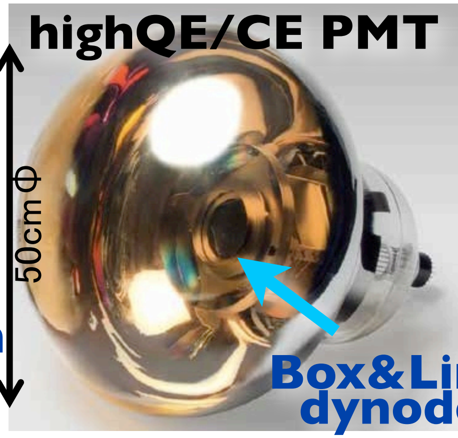
For dominant rock classes (B,CH,CM), the cavern construction is feasible, made baseline design of cavern and its supports.

Photo-detectors

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

established

R&D

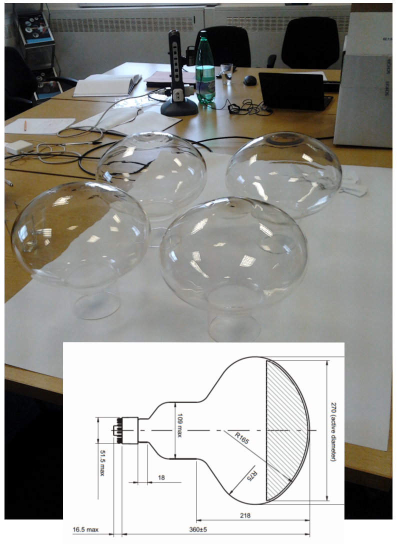


R&D

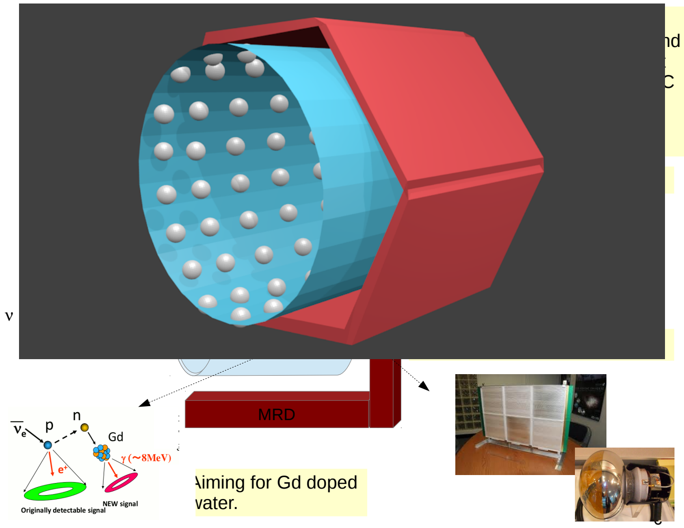
quantum eff. (QE)	22%	30%	30%
collection eff. (CE)	80%	93%	95%
timing resolution (FWHM)	5.5 nsec	2.7 nsec	1 nsec

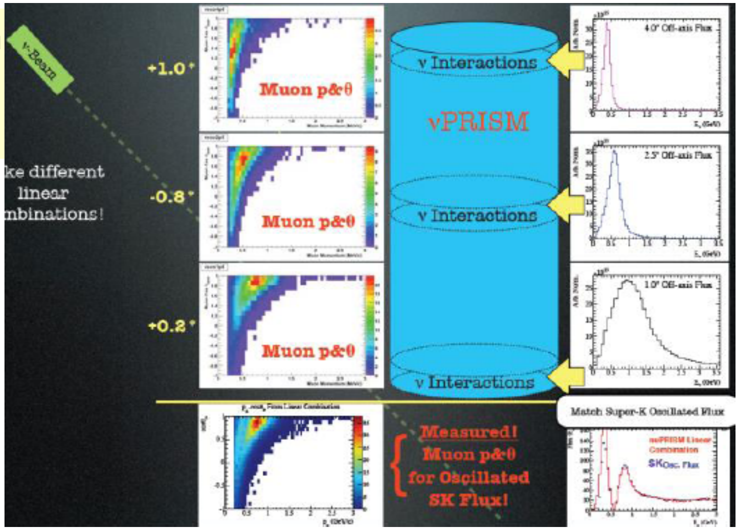
Collaborative R&D works

US : PMT development



UK, CANADA, etc. : New Near Detectors



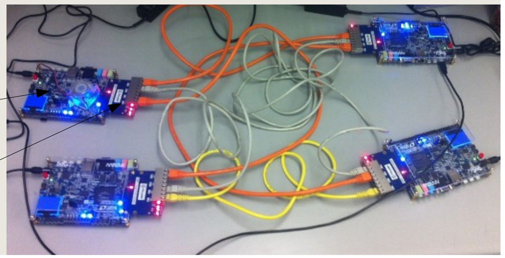


CANADA : Network I/O for DAQ

TRIUMF

RapidIO Test II

- Implemented 4 RapidIO cores in FPGA on each board; each RapidIO core has associated DMA engine.
- Managed to get each of 4 links running at 135MB/s; can also run faster, near 250MB/s, but needs to tweak DMA.
- Starting to work on the routing functionality; did some tests already, checking fail-over when cables are detached.



Terasic Board

Extension Card

CANADA : PMT test facility

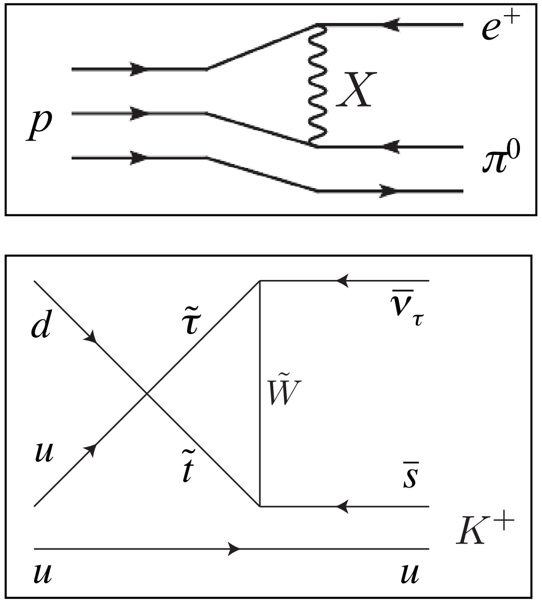
Physics Potentials

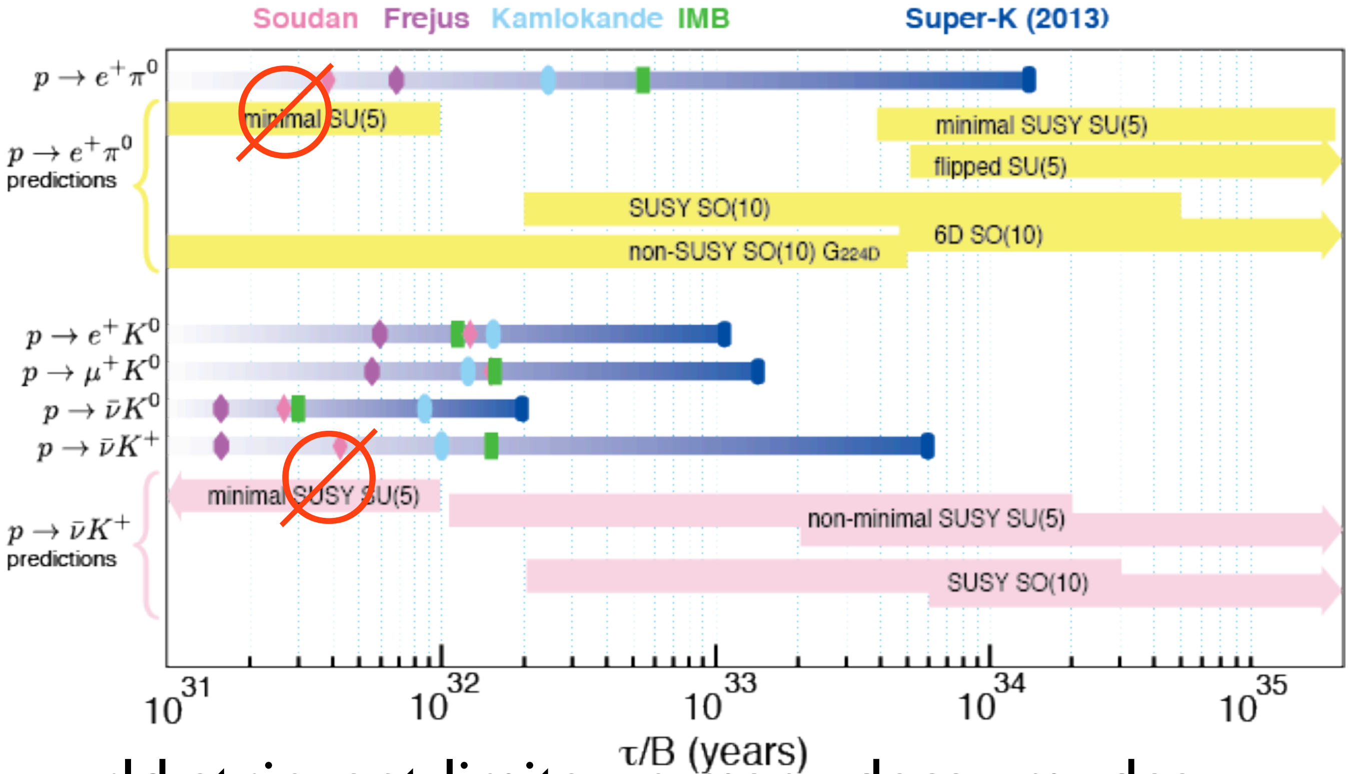
-Proton Decay Searches

-Accelerator ν oscillation study
-Atmospheric ν study

-Supernova ν observatory
-Search for ν's from dark matters

Upper bounds on the proton decay



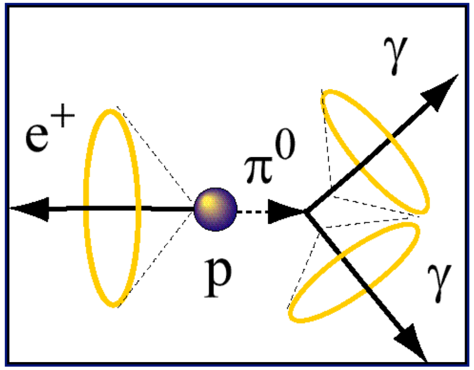


- Super-K provides world stringent limits on many decay modes
  - $\tau(p \to e^+\pi^0) > 1.4\times10^{34}$ years (90%C.L., 260kton・years)
  - $\tau(p \to \nu K^+) > 5.9\times10^{33}$ years (90%C.L., 260kton・years)
- No significant signal excess so far ➡ Giving constraints on GUT models
  - Constraints on SUSY models (e.g. R-parity conservation)
  - minimal *SU(5) and* minimal SUSY *SU(5) are considered to be excluded.*

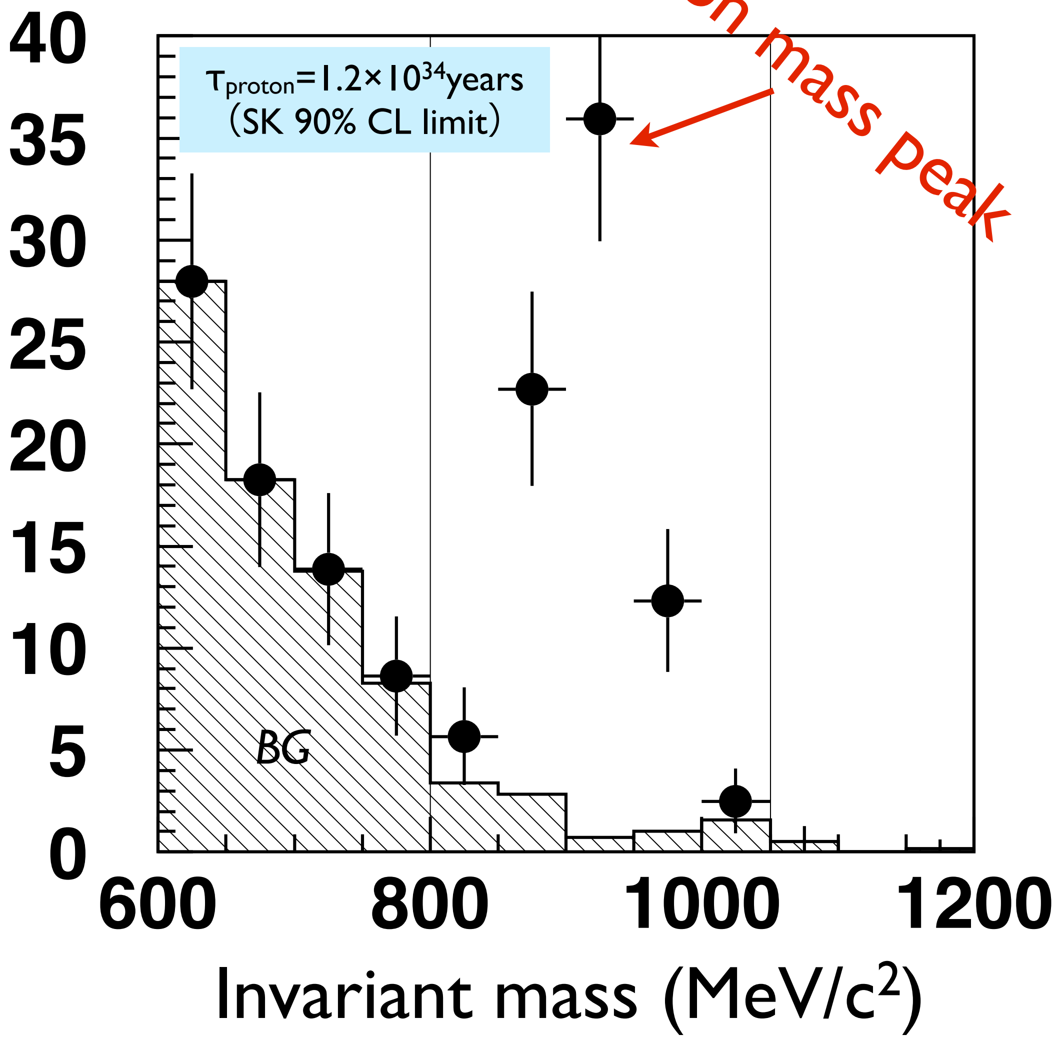
Discovery could be around corner!

Discovery potential in Hyper-K

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



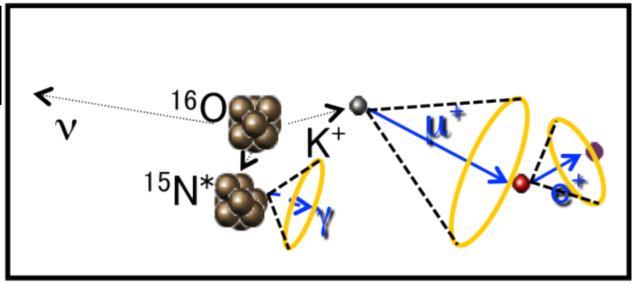
- Discovery reach (3σ)
  - $\tau(p \rightarrow e^+\pi^0) \sim 5\times10^{34}$ years (HK 10yrs)
- Limit (90%CL)
  - $\tau(p \rightarrow e^+\pi^0) > 1\times10^{35}$ years (HK 10yrs)



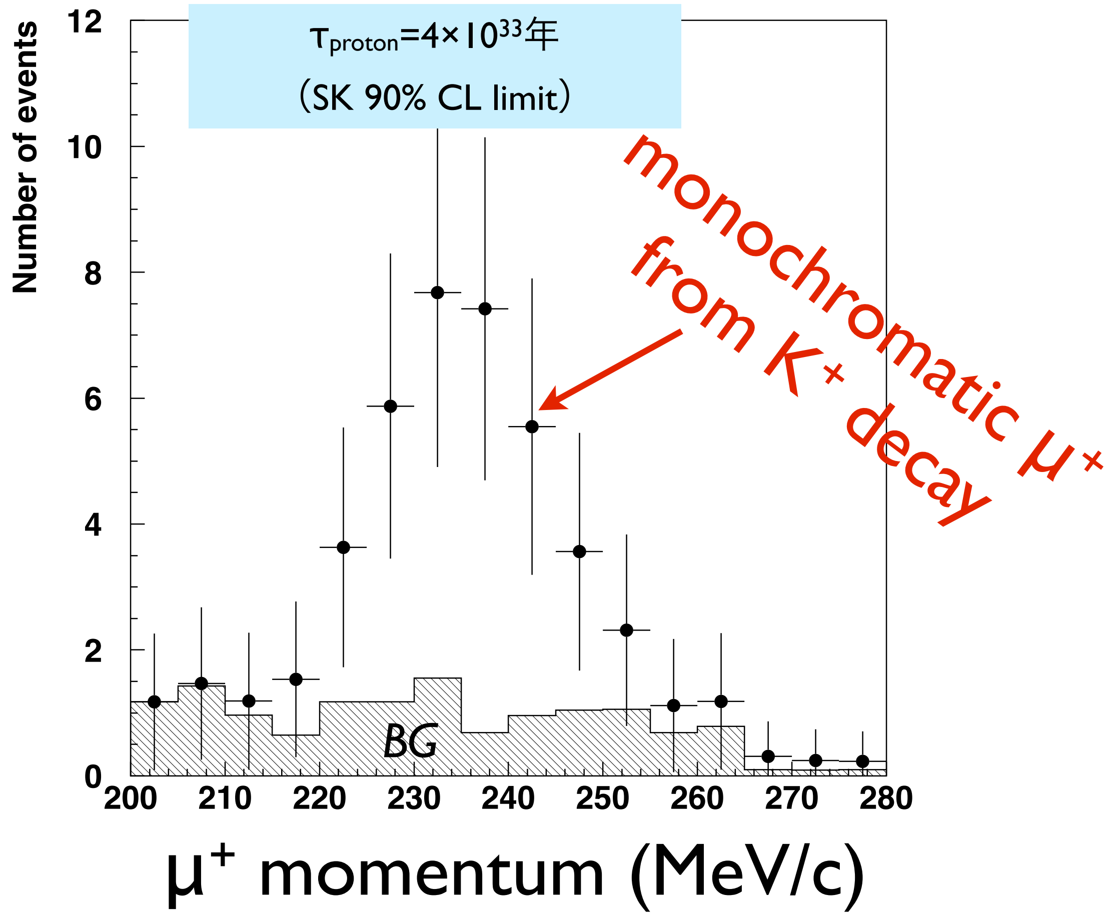
Only realistic proposal to reach the lifetime of 10^{35} years for $p \rightarrow e^+\pi^0$

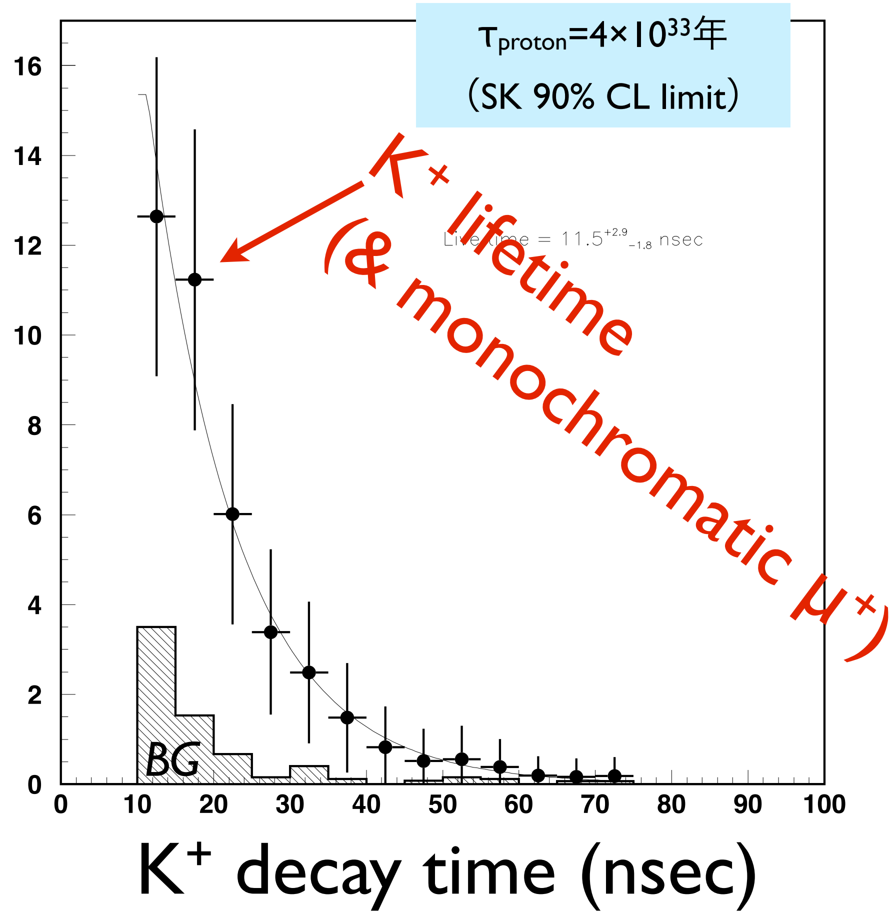
Discovery potential (2)

$p \to \nu K^+$

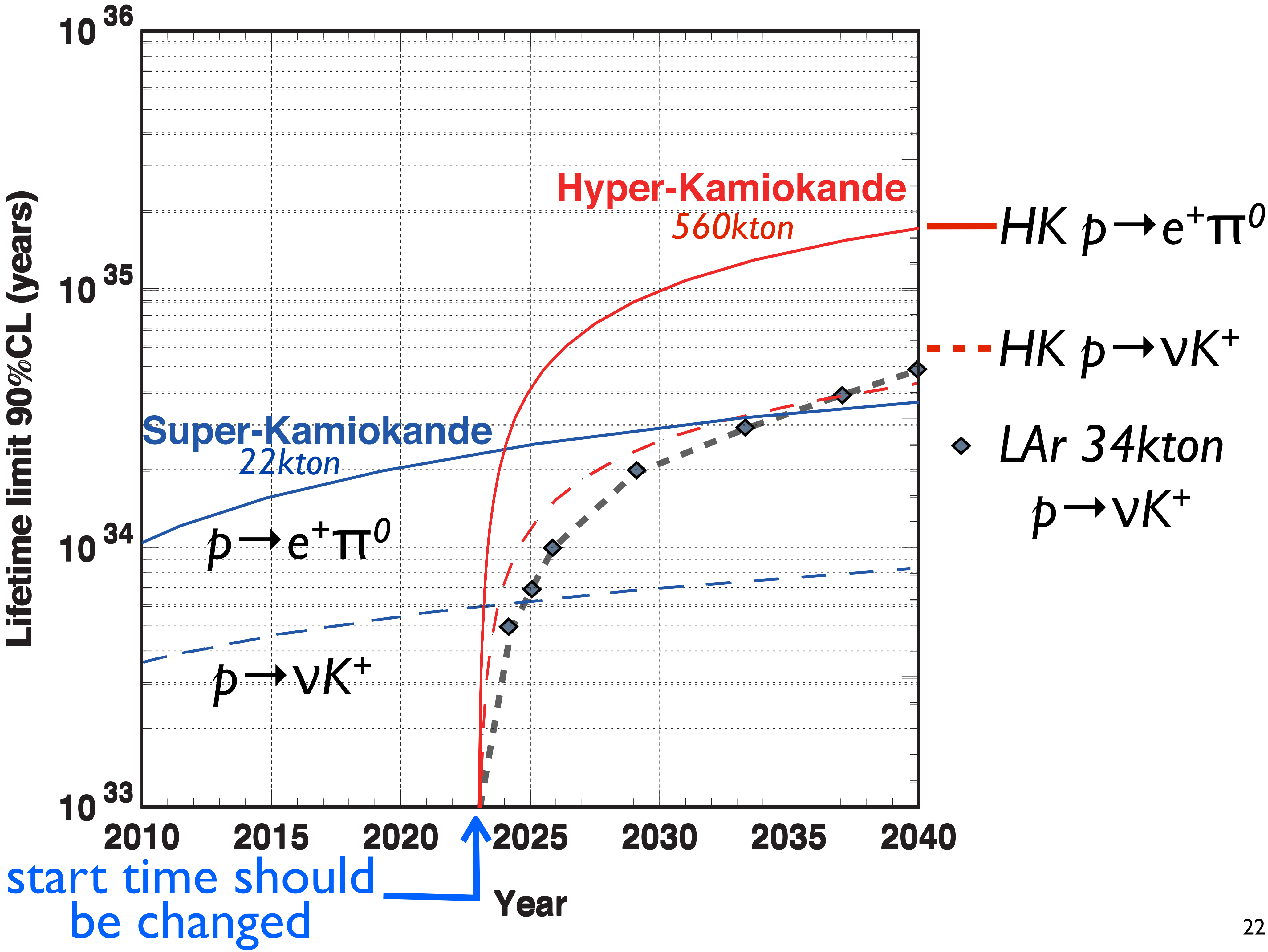


- Discovery reach (3σ)
  - $\tau(p \to \nu K^+) \sim 1 \times 10^{34}$ years (HK 10yrs)
- Limit (90%CL)
  - $\tau(p \to \nu K^+) > 3 \times 10^{34}$ years (HK 10yrs)



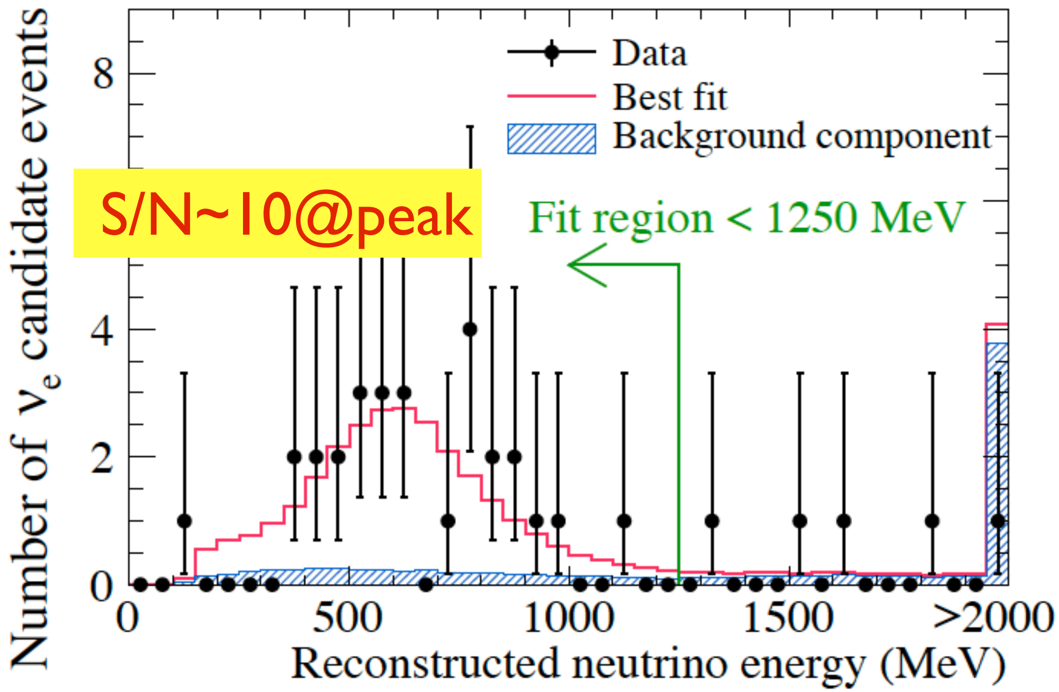


Experimental test on Supersymmetry


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
$p \to \nu K^+$
Lifetime limit 90%CL (years)
Year
start time should be changed

T2K (JPARC ν+Super-K)

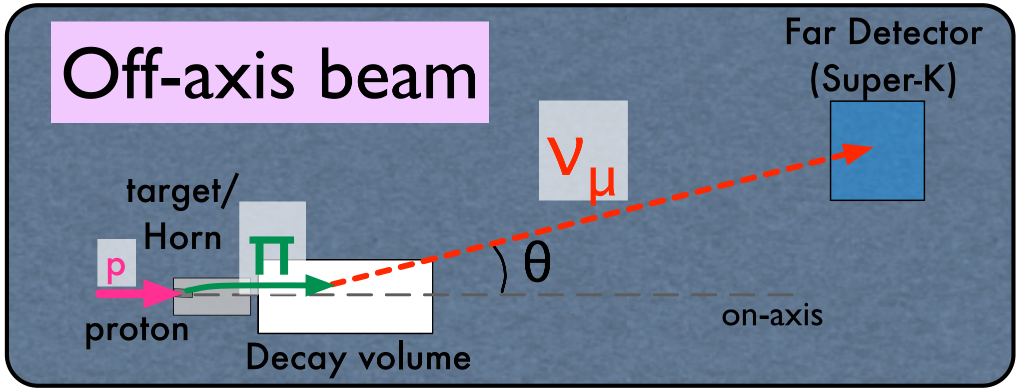
N_{obs} : 28 νe candidates
N_{exp} : 4.9±0.6(syst)
for $\sin^2 2\theta_{13}=0$
(6.57×10^{20} POT)

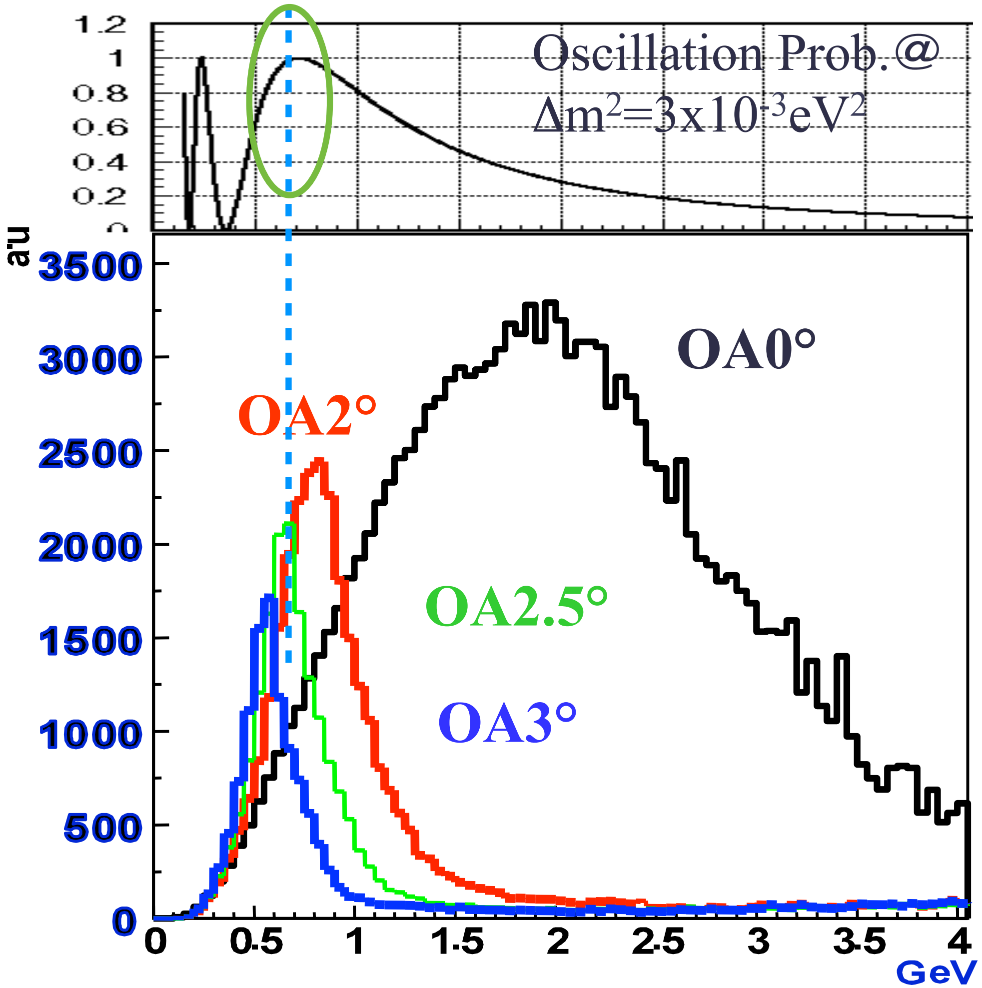


CPV test can be performed by the established $\nu_\mu \rightarrow \nu_e$ appearance measurement with high S/N

Key elements are (i) 300km baseline,
(ii) narrow-band sub-GeV ν beam, and
(iii) large water Cherenkov detector

JPARC ν: off-axis sub-GeV narrow-band beam

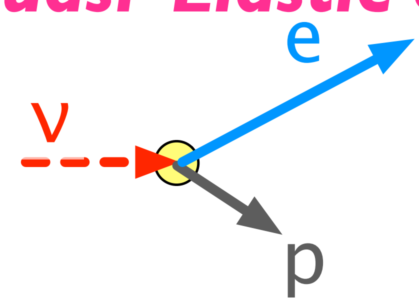




E_ν~0.6GeV and L=295km provide us maximal oscillation probability (First oscillation maximum)

JPARC ν: off-axis sub-GeV narrow-band beam

→ ***CC Quasi-Elastic dominant***



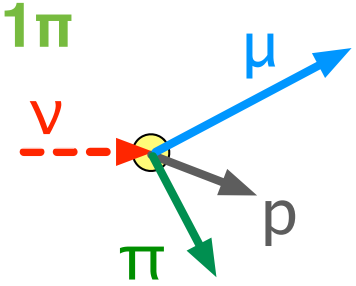
CCQE: $\nu_{e(\mu)} + n \rightarrow e(\mu) + p$

(ve appearance signal)

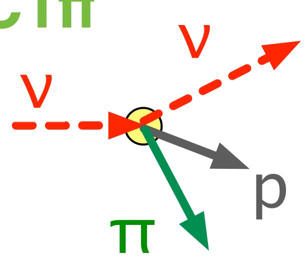
High signal efficiency

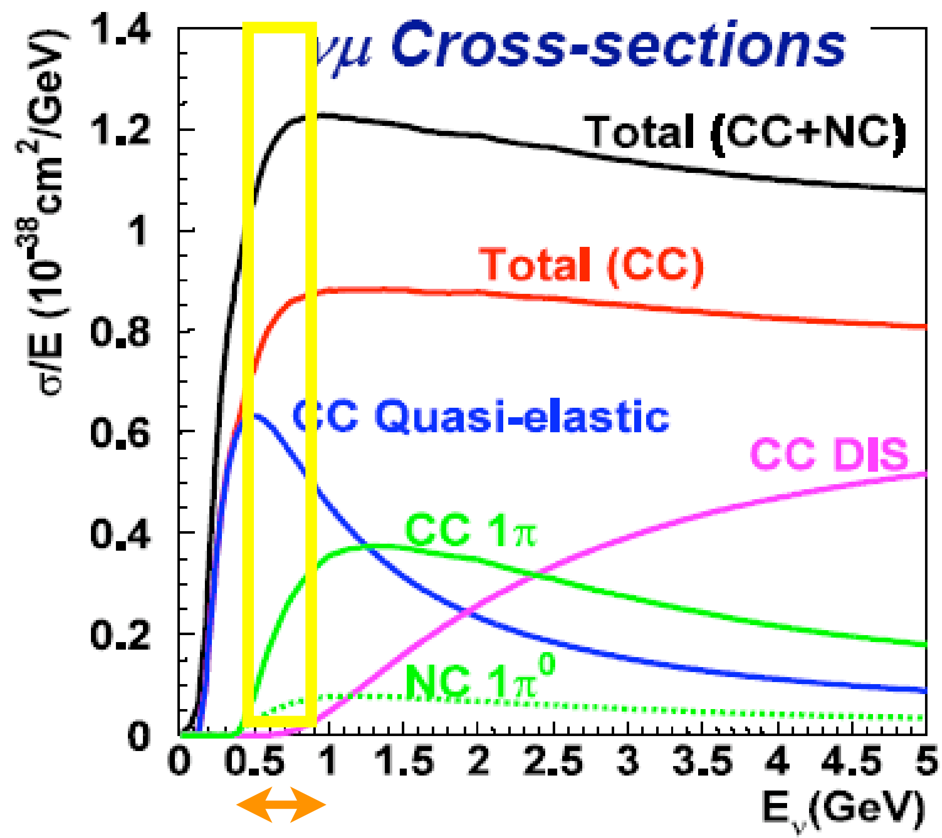
→ ***reduce high energy ν***

CC1π



NC1π



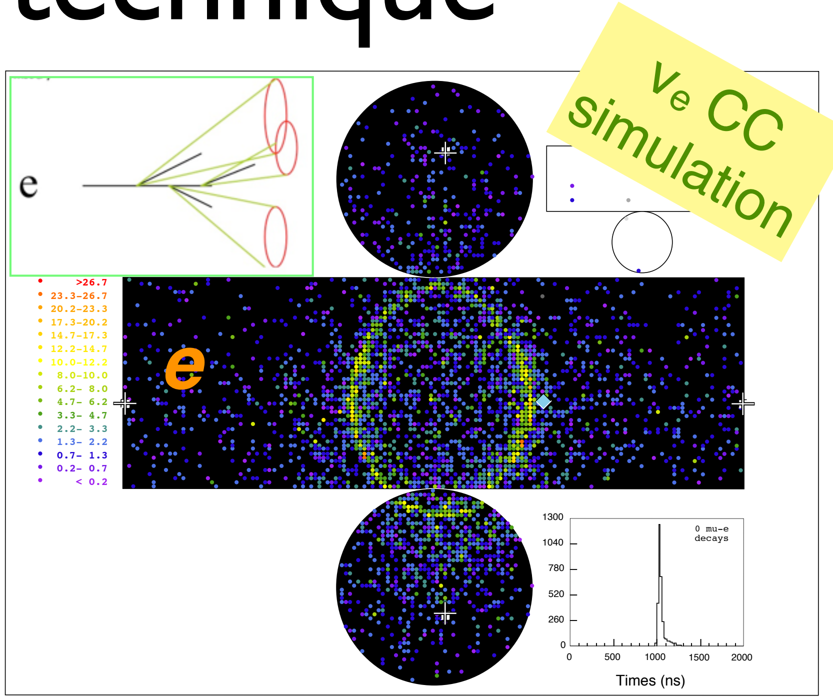


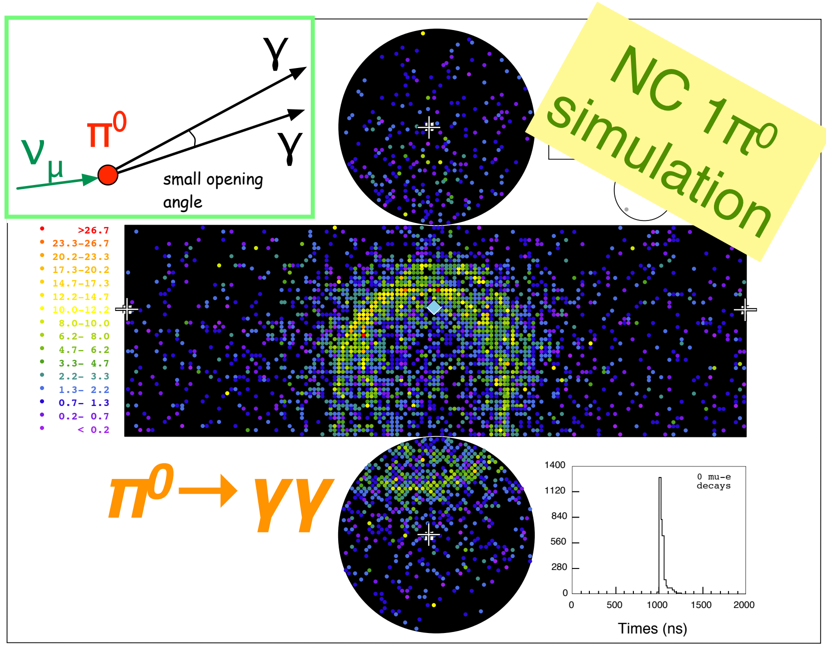
Off-axis 2.5° beam

Water Cherenkov technique

- For νe appearance in T2K (J-PARC beam)
  - νe signal efficiency ~60%
  - BG ν_μ+antiν_μCC<0.1%, NCπ^0~1%
  (0.1<E^{rec}_ν<1.25GeV, can be optimized in future)

- Good imaging capability at ~1GeV
  - accelerator ν, atmospheric ν, proton decays
- Excellent particle ID capability > 99%
- Energy resolution for e and μ ~3%
- Energy threshold ~5MeV
  - Supernova ν, solar ν…
- Stable operation
  - energy scale stability ~1%
  - livetime for physics analyses > 90%

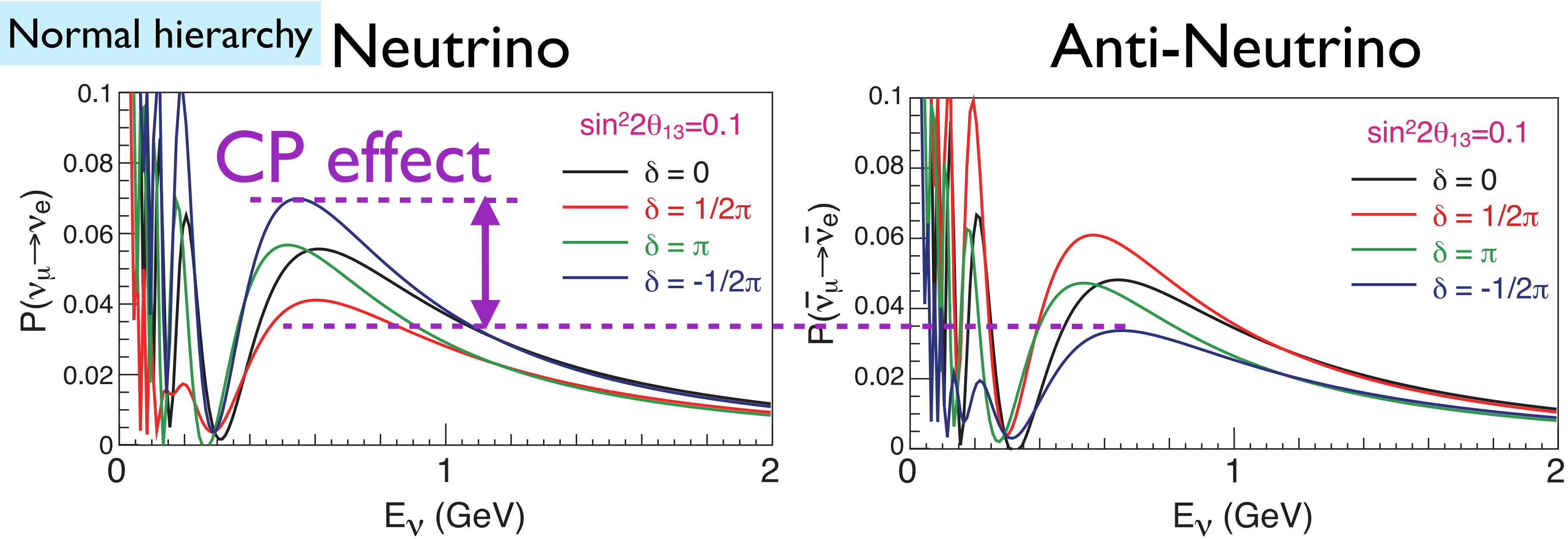




Excellent detector performance
&
High Mass (Million ton scale)

CP measurement w/ Hyper-K/J-PARCν

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



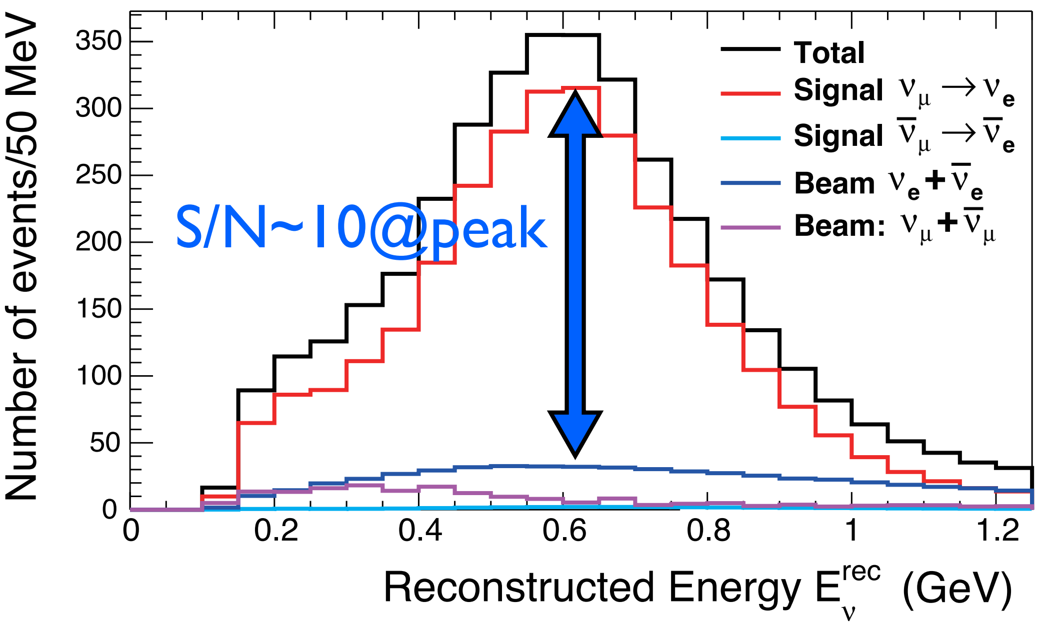
- Direct CPV test by comparing $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$.
  - $>3\sigma$ for 76% of δ space by 7.5MW×years.
  - Test of (exotic) CPV origin
- δ measurement (w/ precision of 10°~20°),
- Good chance to determine MH by J-PARC ν alone (50% of δ space) and High statistic atmospheric ν data enables us to determine MH for any δ.

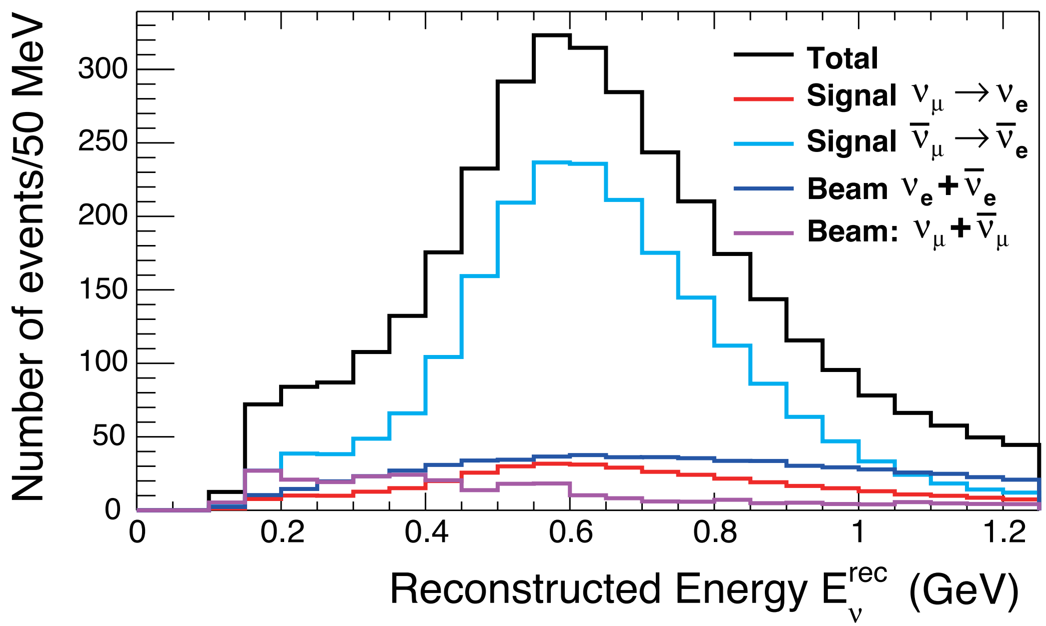
Reconstructed energy distributions

$7.5\text{MW}\times 10^7\text{s}$ (1.56×10^{22} POT)

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

Appearance ν mode $\nu:\bar{\nu}=1:3$ **Appearance $\bar{\nu}$ mode**



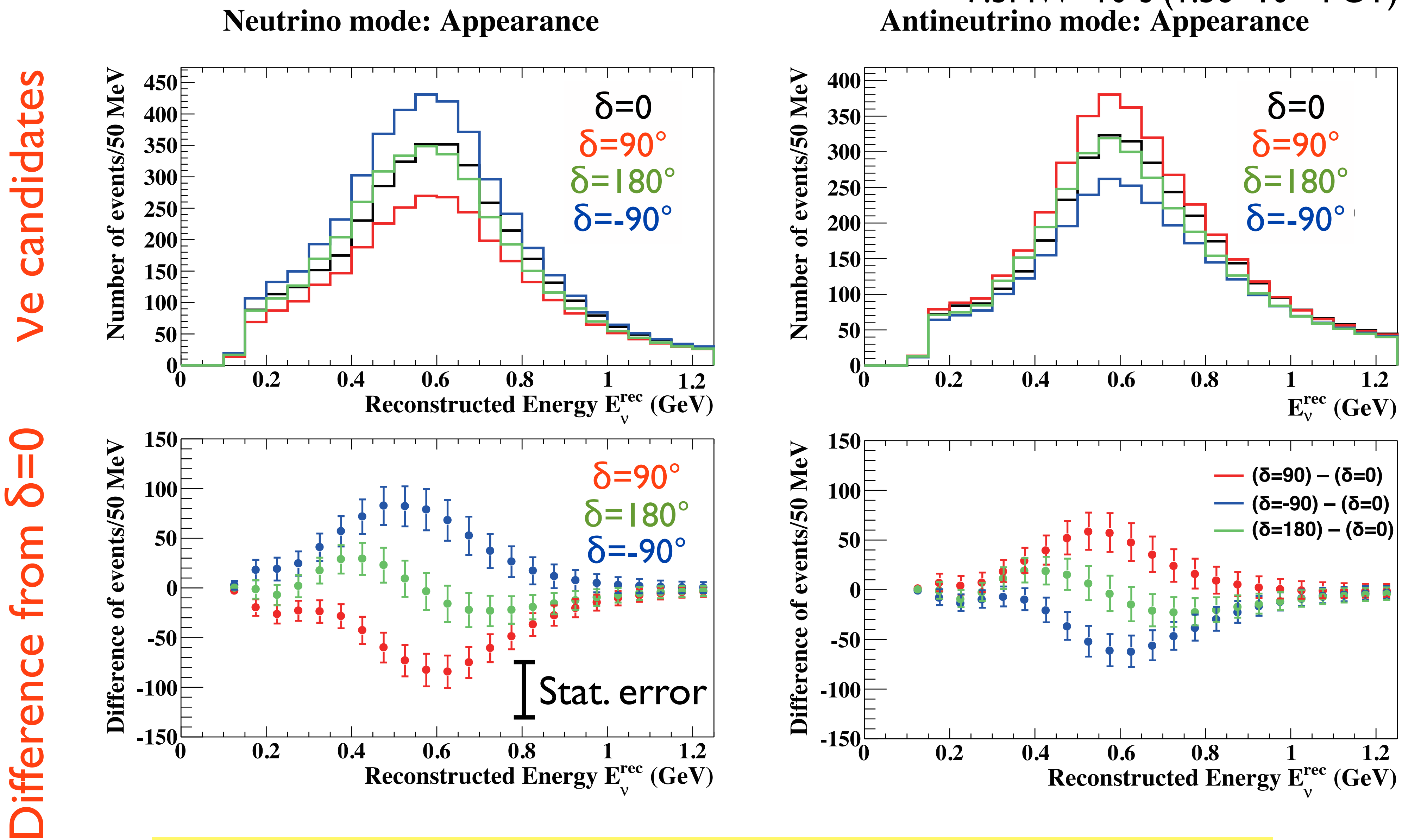


	Signal ($\nu_\mu \to \nu_e$ CC)	Wrong sign appearance	$\nu_\mu/\bar{\nu}_\mu$ CC	beam $\nu_e/\bar{\nu}_e$ contamination	NC
ν	3,016	28	11	523	172
$\bar{\nu}$	2,110	396	9	618	265

High signal statistics and High S/N ratio

δ_{CP} dependence of observables

7.5MW×10^7s (1.56×10^{22} POT)



Sensitive to all values of δ with numbers + shape

Assumed systematic uncertainties

Realistic estimation based on SK/T2K

- 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 (%)

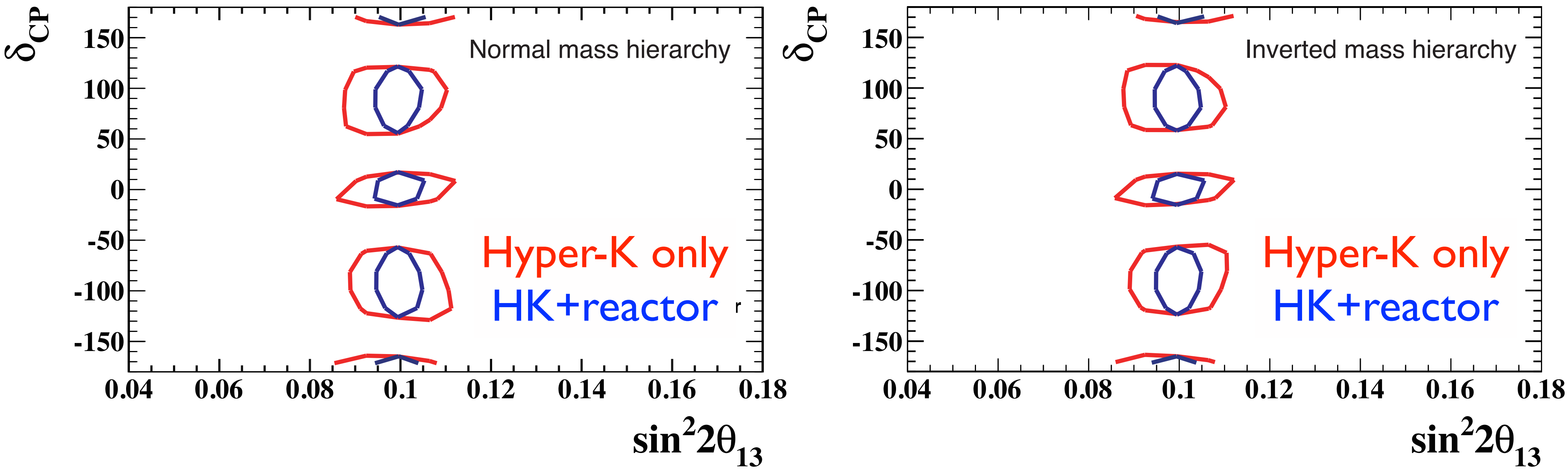
	ν mode		anti-ν mode		(T2K 2014)	
	νe	νμ	νe	νμ	νe	νμ
Flux&ND	3.0	2.8	5.6	4.2	3.1	2.7
XSEC model	1.2	1.5	2.0	1.4	4.7	5.0
Far Det. +FSI	0.7	1.0	1.7	1.1	3.7	5.0
Total	3.3	3.3	6.2	4.5	6.8	7.6

- Further reduction by new near detectors under study

Expected sensitivity to CP asymmetry

Mass hierarchy assumed to be known

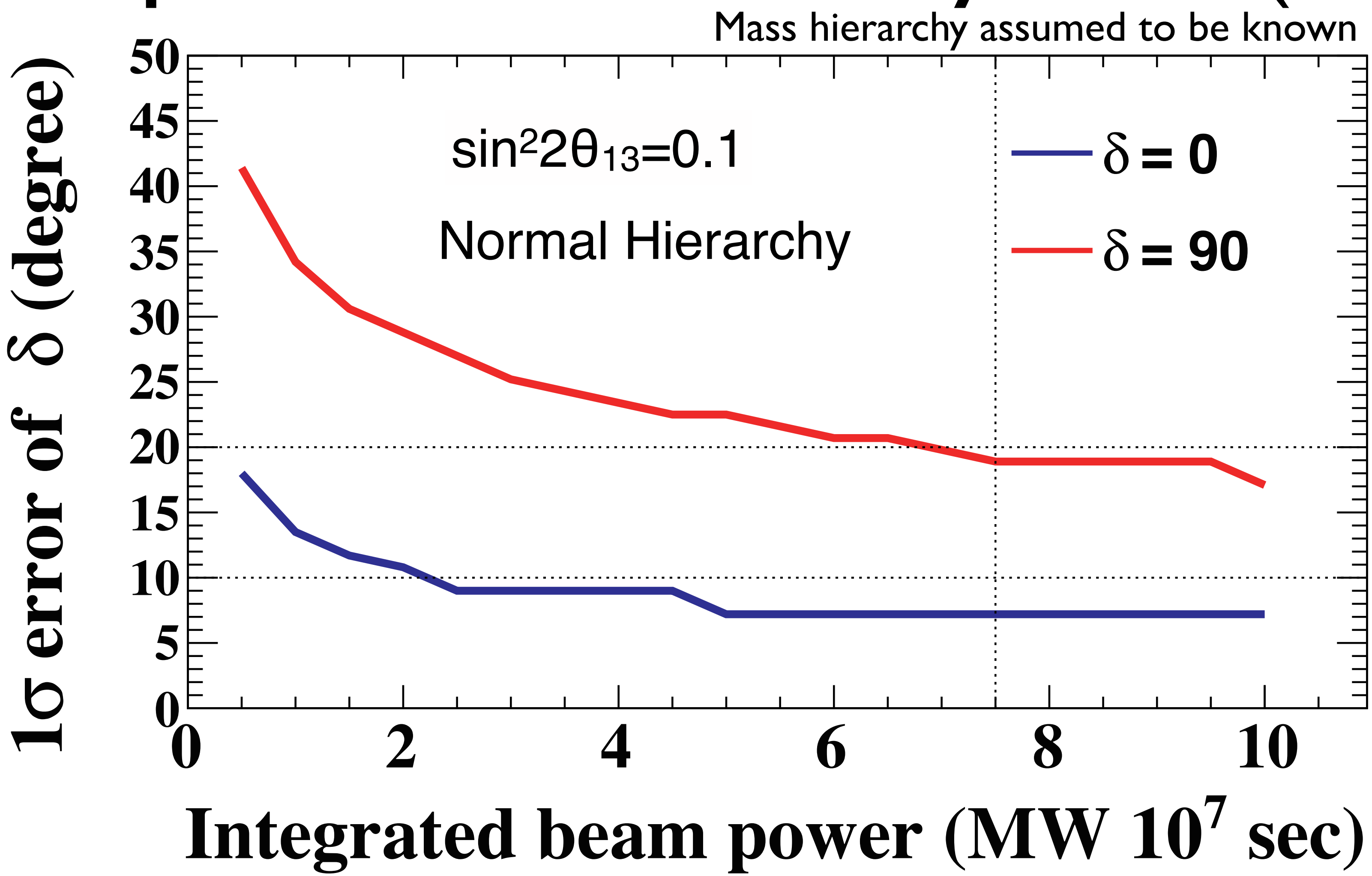
90% CL contour on $\sin^2 2\theta_{13}$-δ plane
(δ=0°, 90°, 180°, -90° overlaid)



7.5MW×10^7s (1.56×10^{22} POT)

- Excellent δ_{CP} measurement capability

Expected uncertainty of δ (1σ)

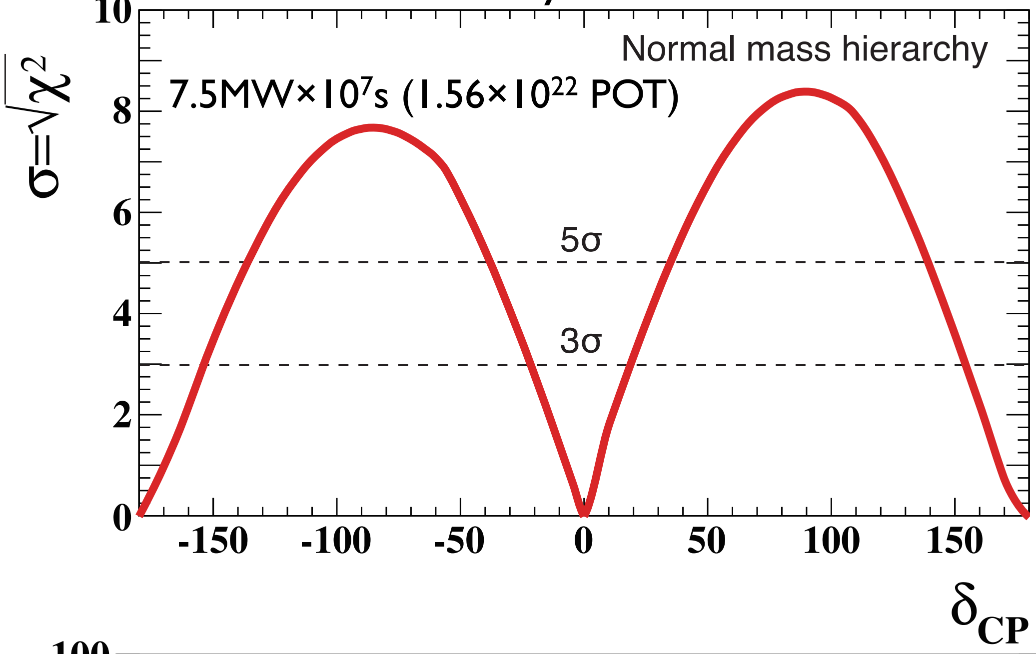


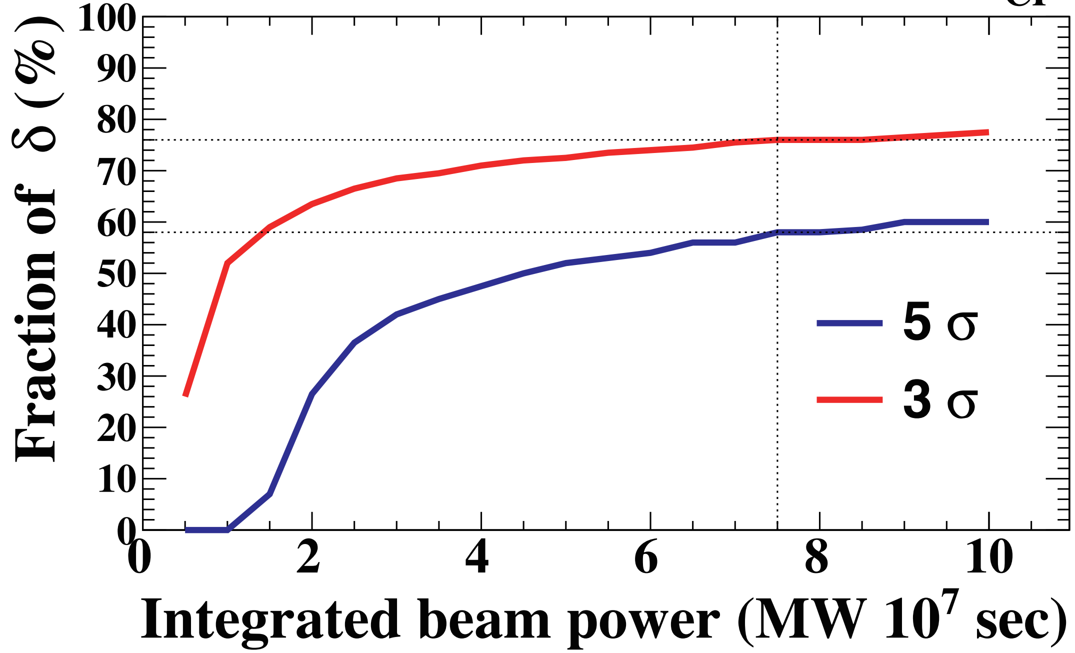
- 8°-19° depending on the true value of δ

Sensitivity to CP violation

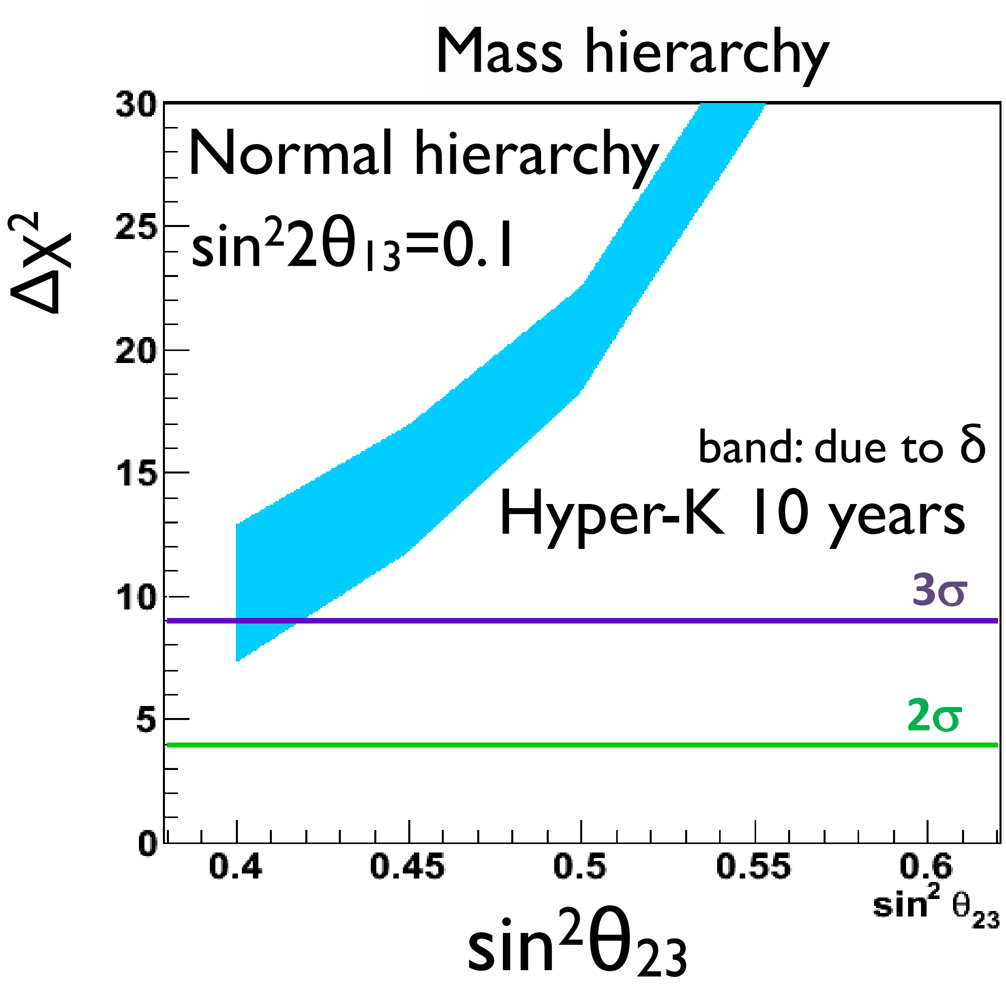
- Exclusion of sinδ=0
  - >3σ for 76% of δ
  - >5σ for 58% of δ
- Possible to establish CP violation in the lepton sector!

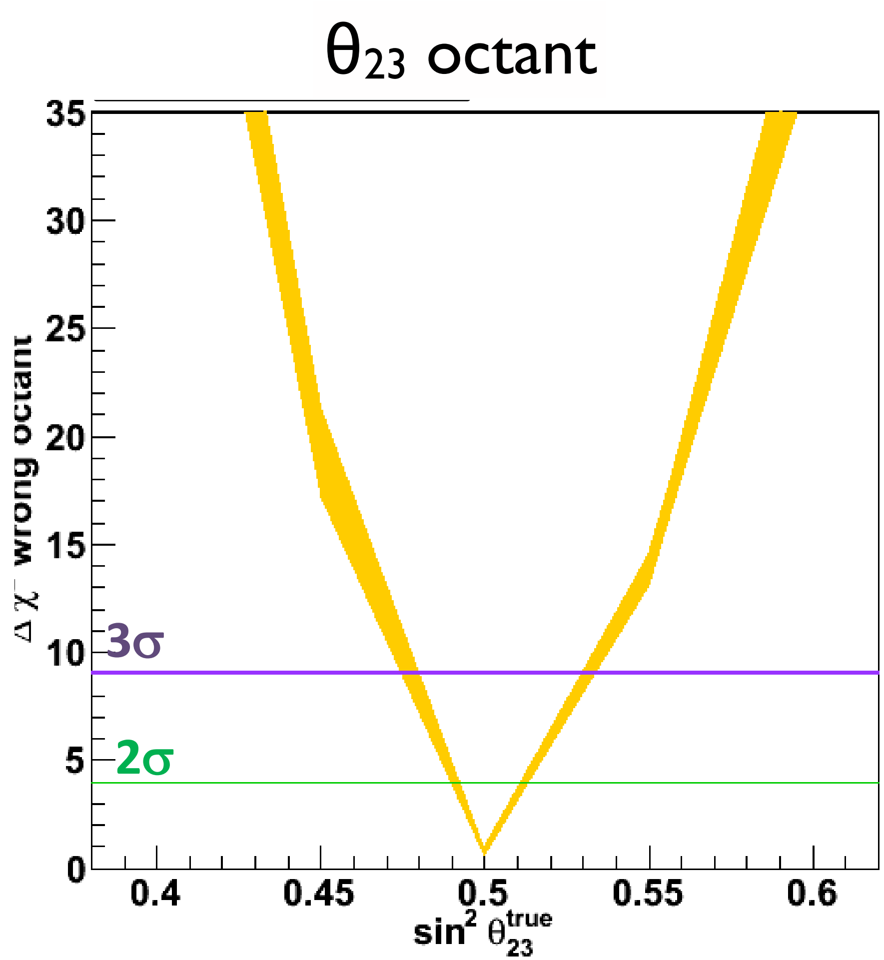
Mass hierarchy assumed to be known





Atmospheric ν

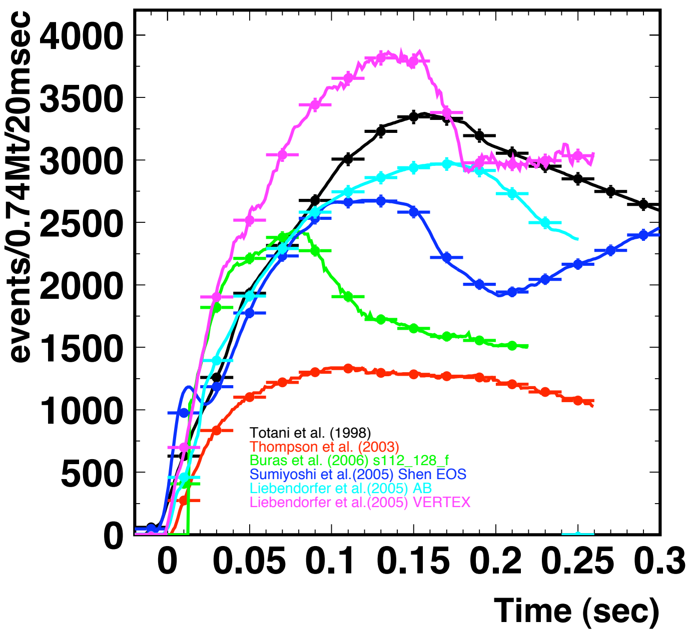


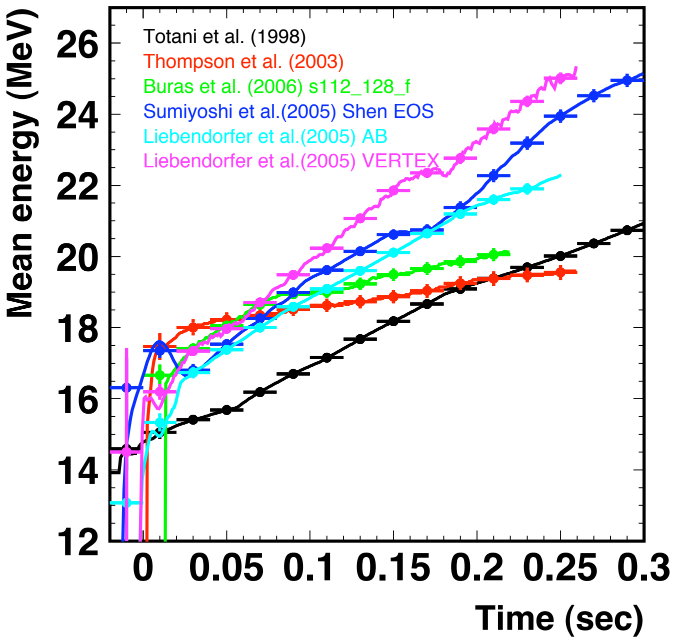


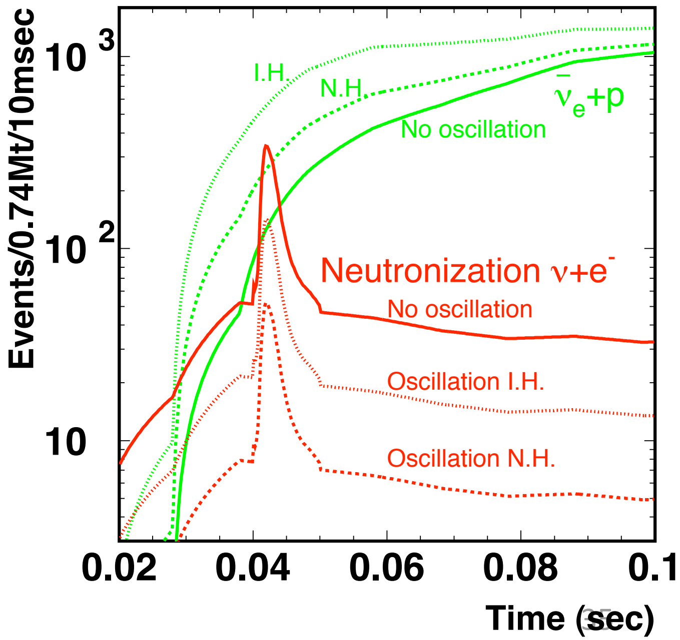
Complementary measurements to accelerator ν
Combined analysis of acc + atm ν will enhance capability

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

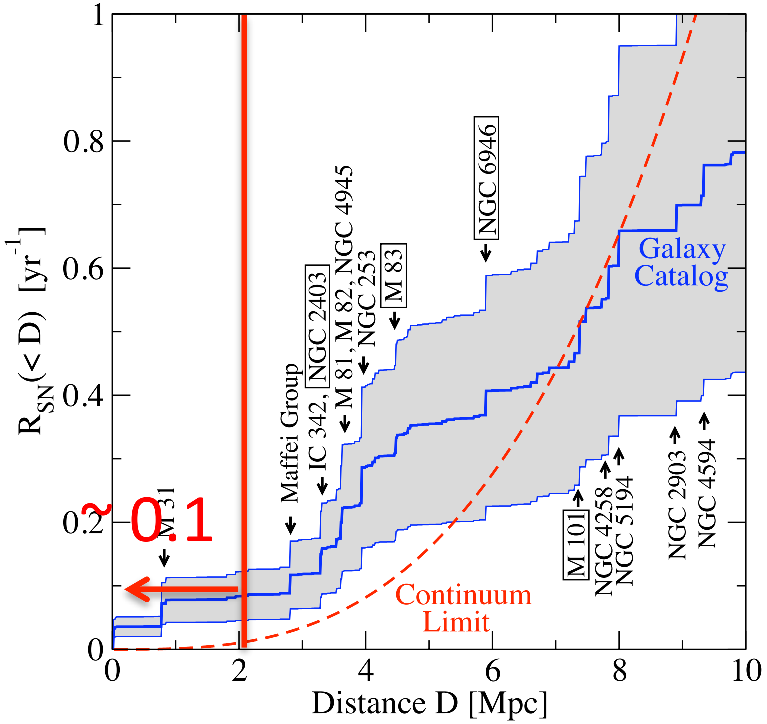




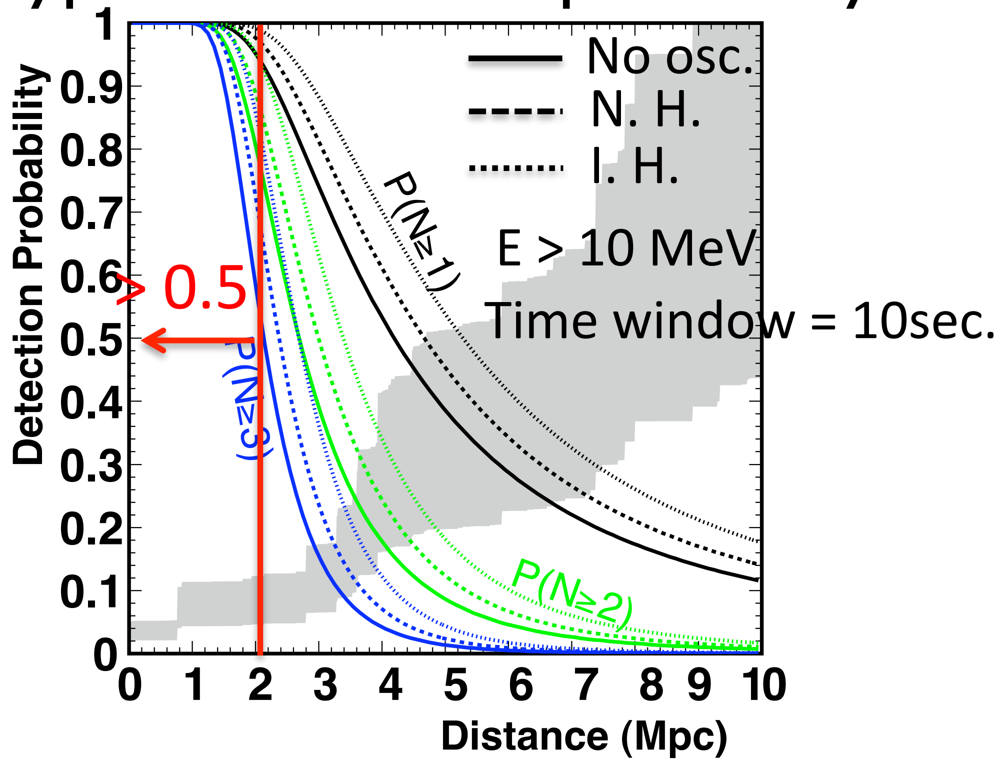


Supernova in nearby galaxies

Cumulative supernova rate



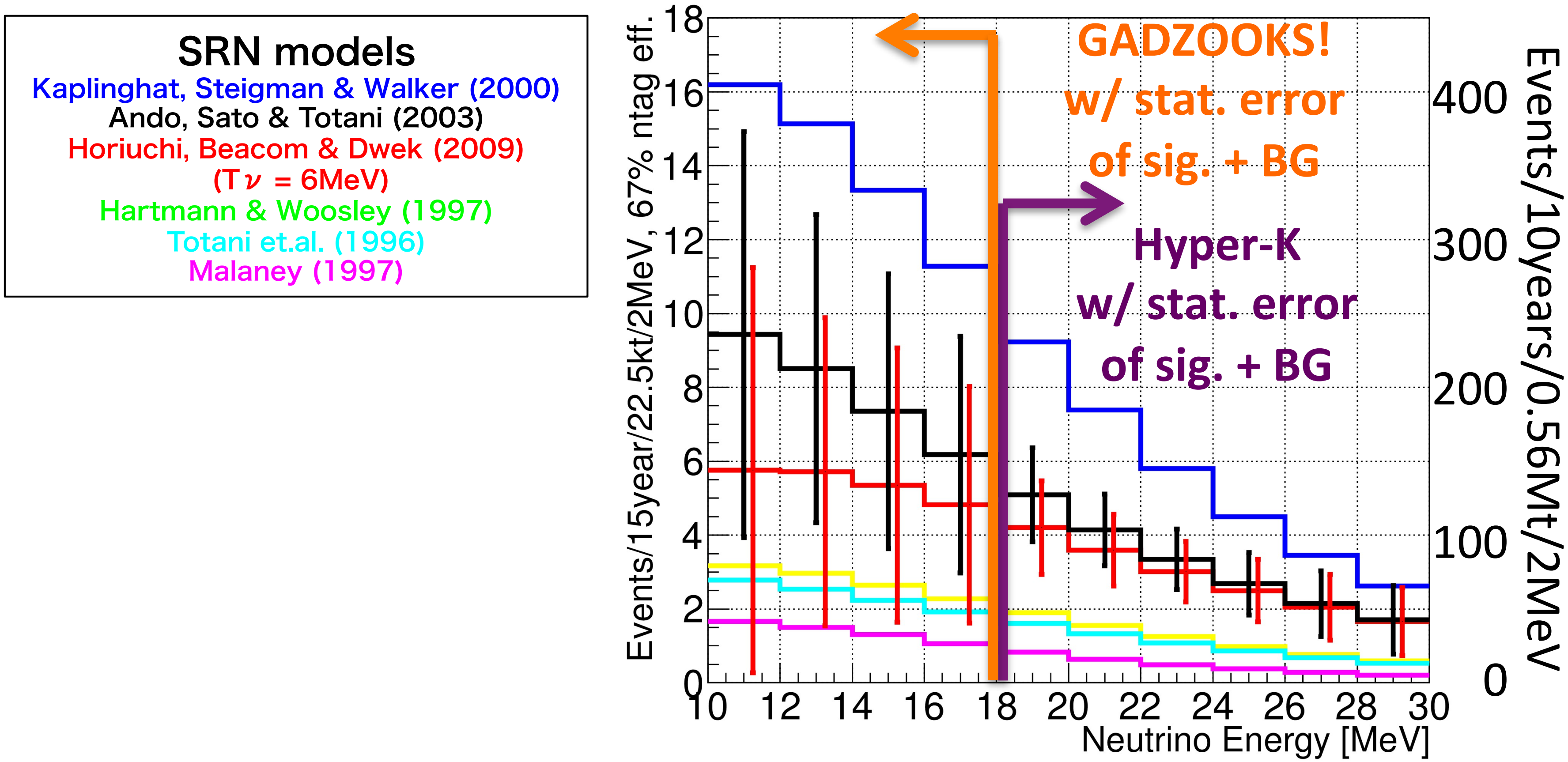
Hyper-K detection probability



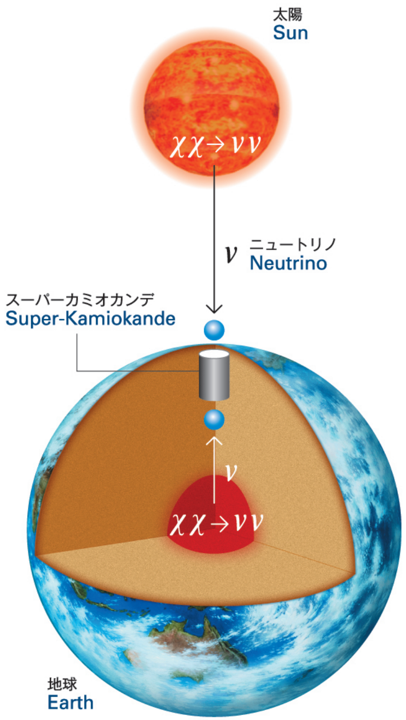
- >50% efficiency is expected within 2 Mpc for requiring signal triplets (N>=3)
- 1 SN about every 10 yrs is expected

Supernova relic ν (SRN)

- SRN is guaranteed signal which will provide precious information on SN rate and SN ν spectrum



- ~300 SRN / 10 years (>17.5MeV) is expected

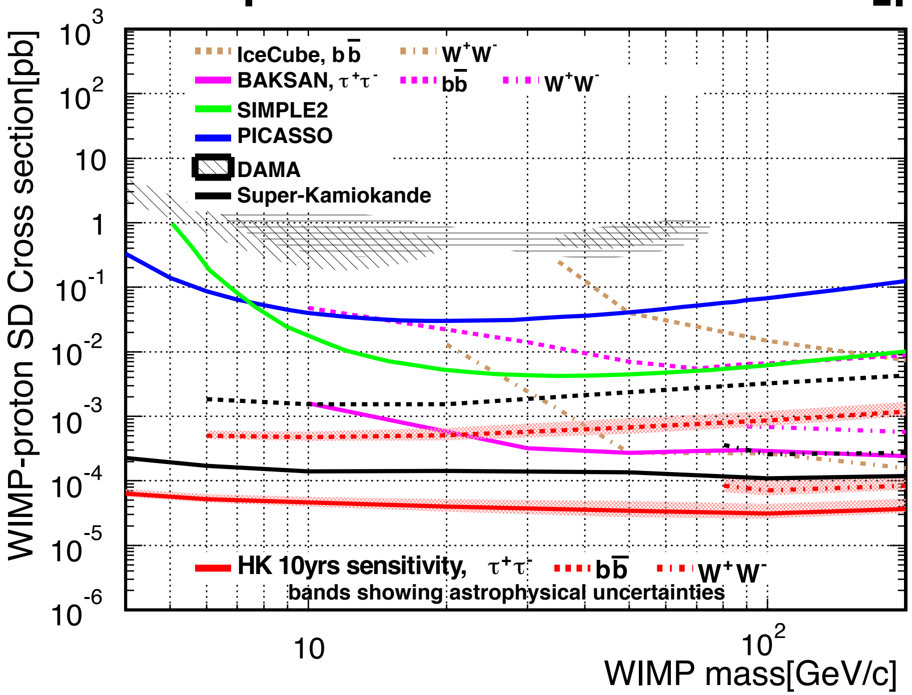


Search for ν's induced by dark matters

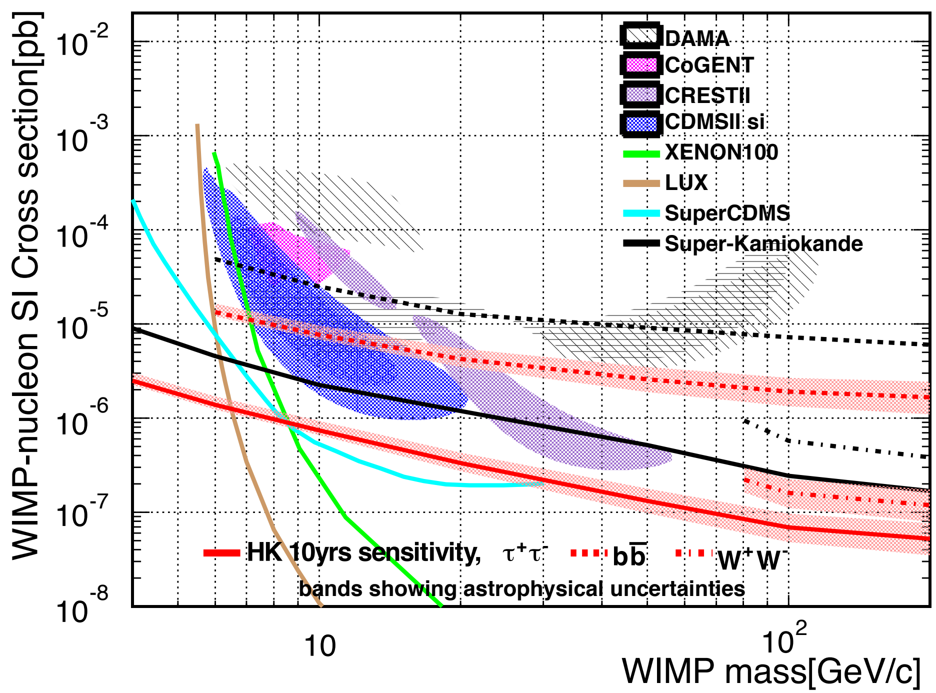
- provide complemental information w/ direct detection experiments
- Sensitive to low mass (GeV/c^2) WIMPs

Expected sensitivity for Solar WIMPs

WIMP-proton cross section[pb]



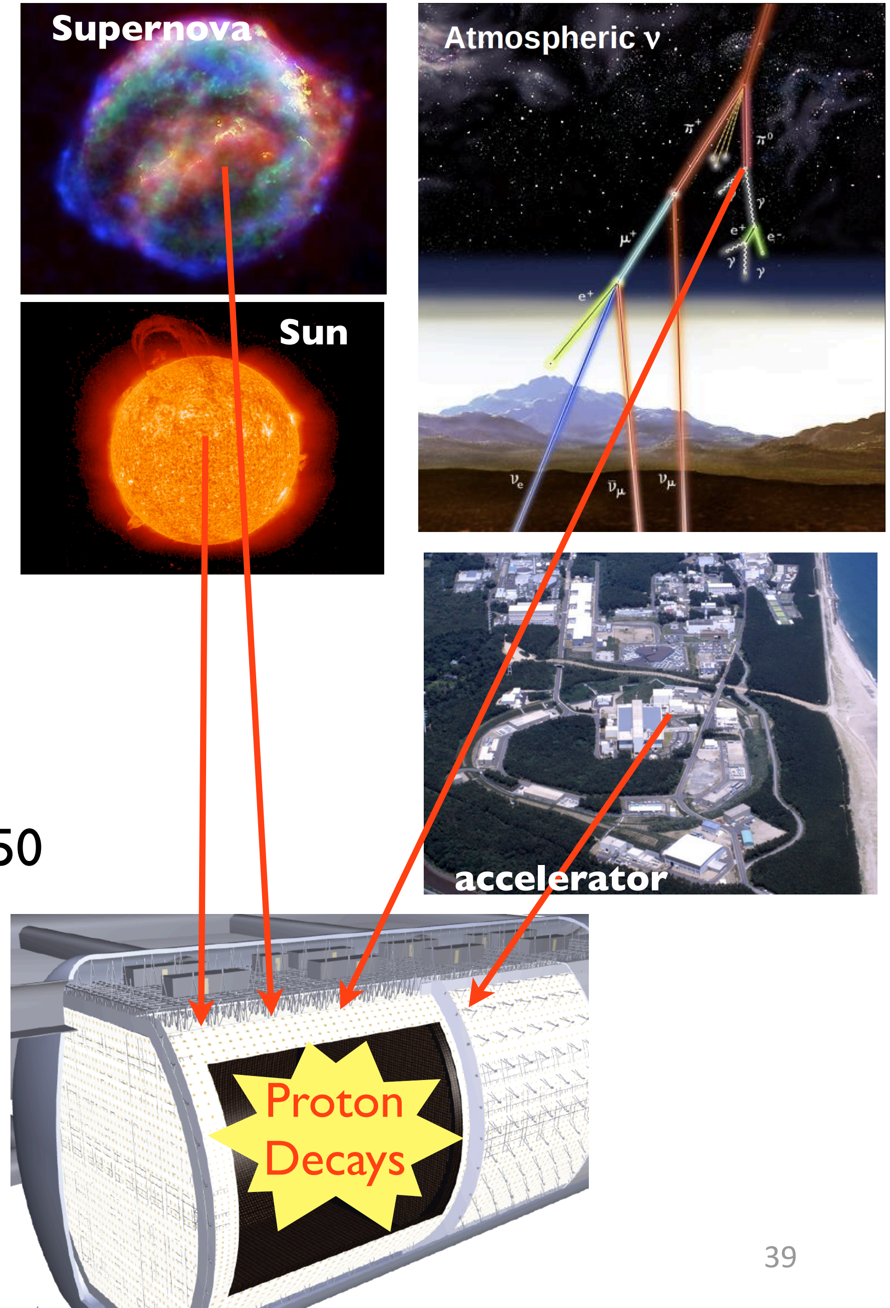
WIMP-nucleon cross section[pb]



Multi-purpose detector, Hyper-K

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

- 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($\Delta m^2_{32}>0$ 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



Summary

- Proton decay searches extends to discovery region
  - e.g 10^{35} years for $p \rightarrow e^+\pi^0$, 0.5×10^{34} years for $p \rightarrow \nu K^+$

- CPV test by extending the JPARC-SK experimental setup
  - J-PARC is expected to be upgraded to ~700kW and beyond
  - $\nu\mu \rightarrow \nu e$ efficiency~60%, 99% rejection of π^0 BG
    $\rightarrow$high S/N~10 at the oscillation maximum
  - 1Megaton → 2000~3000 signals for νe and νe-bar each
  - CPV (76% of δ space at 3σ), δ precision of <20°

- Rich physics topics can be covered
  - high statistics atmospheric neutrino study
  - Supernova ν (guaranteed signal)
  - indirect dark-matter searches etc

- Top large-scale project by the "Master plan 2014" of Science Council of Japan

- Hyper-K project is completely open to the international community. We'd like to contribute to the world-wide effort to make a strong neutrino physics program.