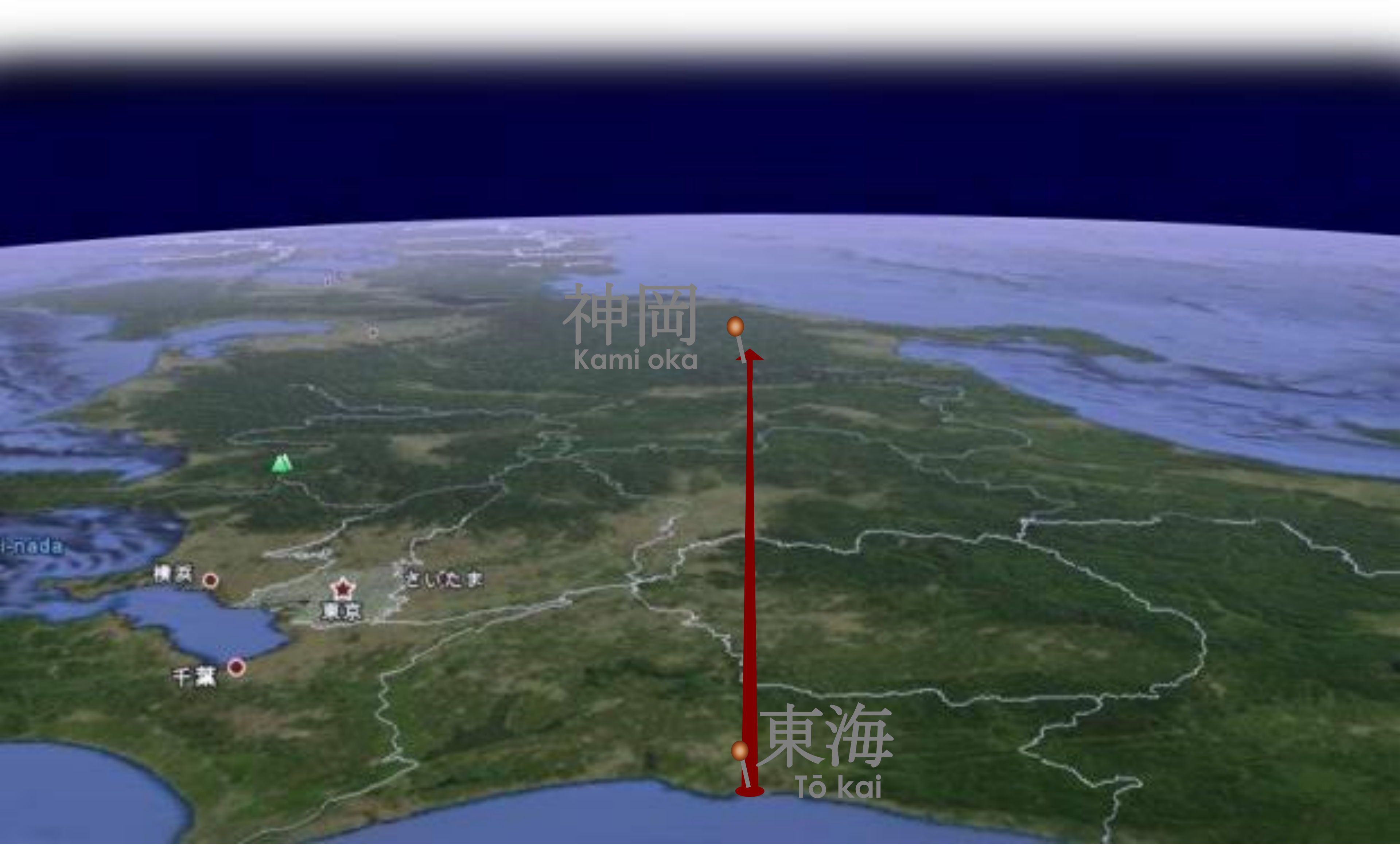
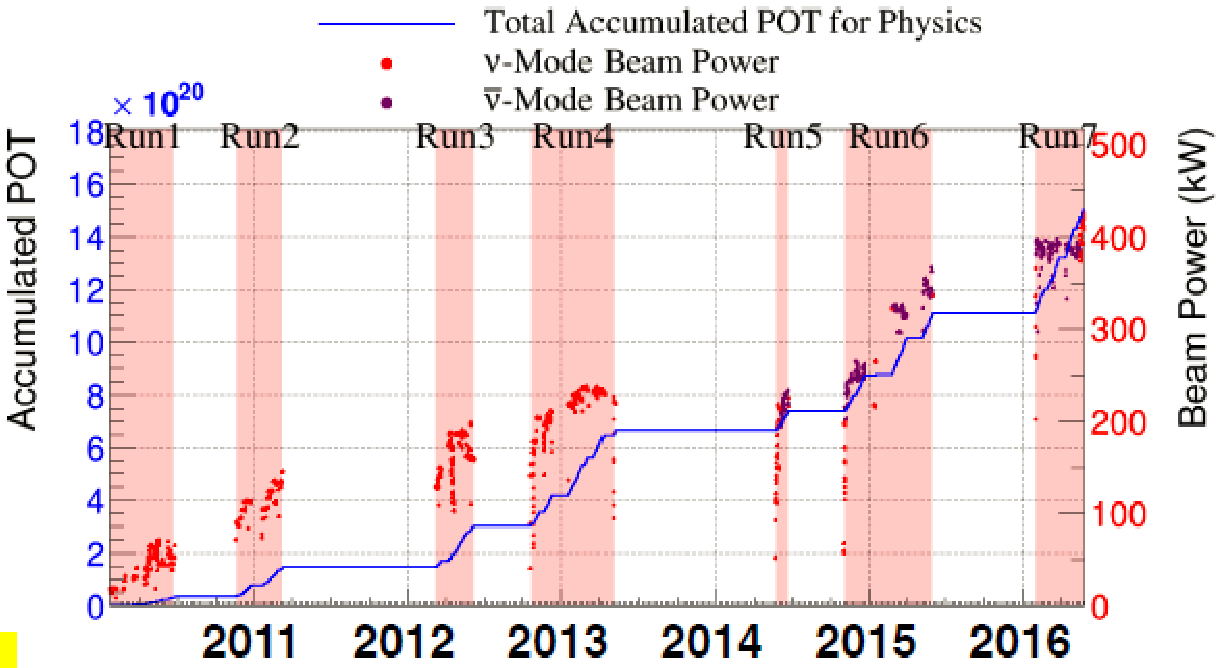
T2K, T2K-II and HyperK





only 20% of initial request

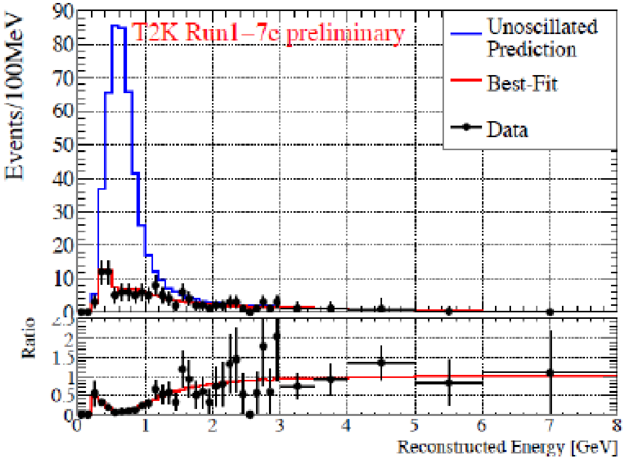
27 May 2016
POT total: 1.510×10^{21}
(POT = Proton on target)

ν-mode POT: 7.57×10^{20} (50.14%)
ν̄-mode POT: 7.53×10^{20} (49.86%)

Steady improvements since start in 2010 … and many interruptions
earthquake+ tsunami (2011), safety incident in hadron hall (2013-14)
now running at 415kW average beam @ 2.6 sec. rep. rate.
Planned improvements: beam feedbacks and optics → 600MW
upgrade of power supply and RF system → rep rate to 1.15 s.
Aim towards 1.3 MW by early 2020's

T2K fit to $\nu_\mu \rightarrow \nu_\mu$ and $\overline{\nu_\mu} \rightarrow \overline{\nu_\mu}$ disappearance

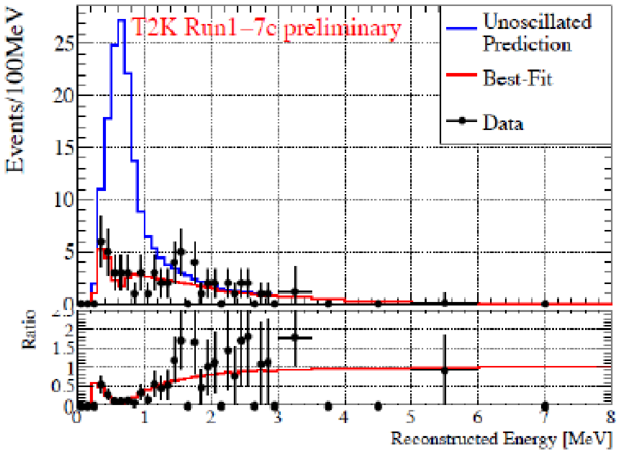
Neutrino



$\Delta m^2_{32} = [2.34, 2.75]\times10^{-3}eV^2(NH)$ at 90% CL

$\sin^2\theta_{23} = [0.42,0.61](NH)$ at 90% CL

Antineutrino



$\Delta \overline{m}^2_{32} = [2.16, 3.02]\times10^{-3}eV^2(NH)$ at 90% CL

$\sin^2\overline{\theta}_{23} = [0.32,0.70](NH)$ at 90% CL

Neutrino and antineutrino parameters are consistent

No evidence of CPT violation, NSI, etc

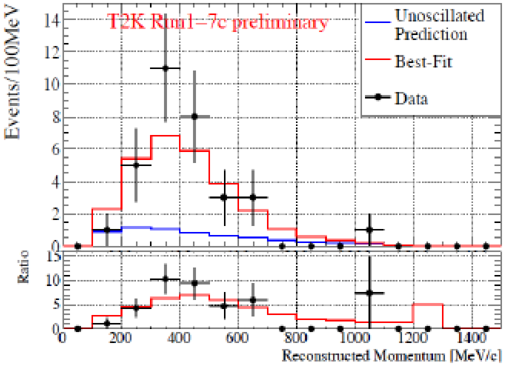
T2K fit to $\nu_\mu \longrightarrow \nu_e$ and $\overline{\nu_\mu} \longrightarrow \overline{\nu_e}$ appearance

Predictions:

ν_e: 19.6 events (NH, $\delta_{CP} = \pi/2$) to 28.7 events (NH, $\delta_{CP} = -\pi/2$)

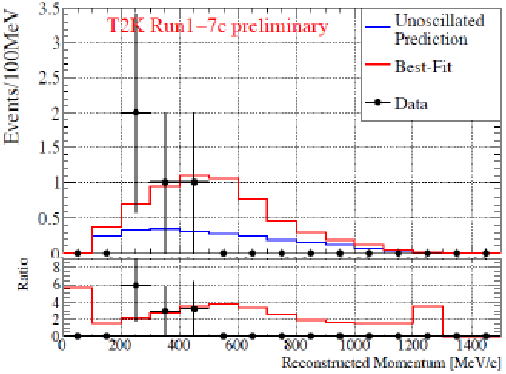
$\overline{\nu_e}$: 7.7 events (NH, $\delta_{CP} = \pi/2$) to 6.0 events (NH, $\delta_{CP} = -\pi/2$)

Neutrino



Observed 32 events

Antineutrino



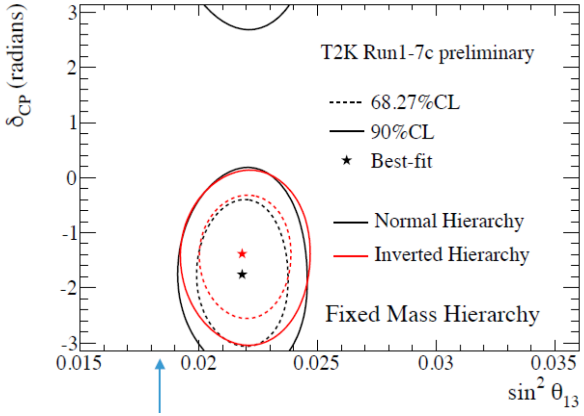
Observed 4 events

Excess of ν_e events above prediction favors NH and $\delta_{CP} = -\pi/2$ ($3\pi/2$)

Deficit of $\overline{\nu}_e$ events below prediction favors NH and $\delta_{CP} = -\pi/2$ ($3\pi/2$)

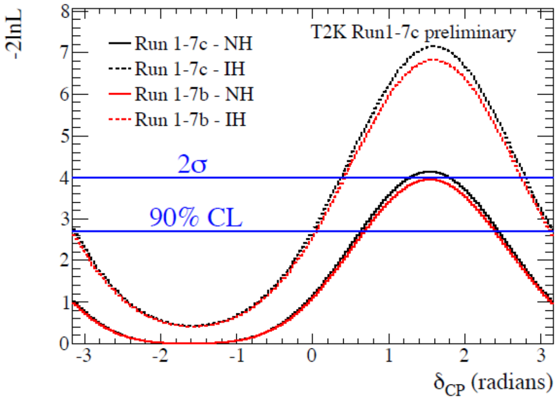
θ_{13} and δ_{cp}

T2K Result with Reactor Constraint
($sin^2 2\theta_{13} = 0.085 \pm 0.005$)

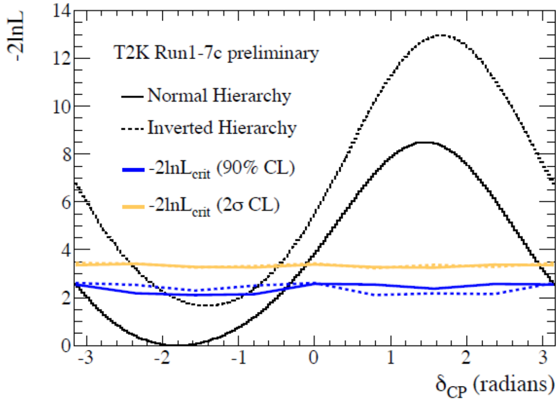


- T2K result with reactor constraint ($\sin^2 2\theta_{13} = 0.085 \pm 0.005$)

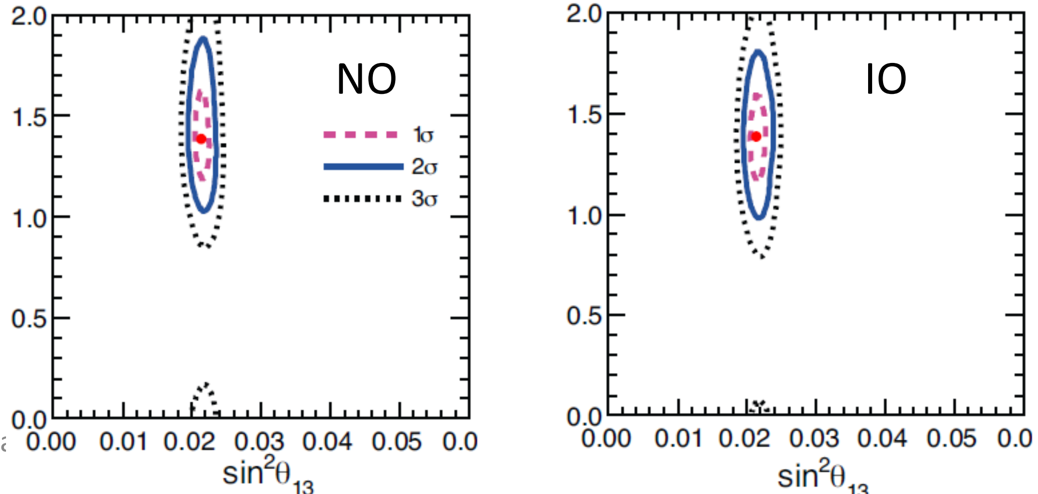
Sensitivity (Simulation)



Measurement (Data)



$$\delta_{cp} = [-3.13, -0.39](NH), [-2.09, -0.74]\ (IH) \text{ at } 90\% \text{ CL}$$

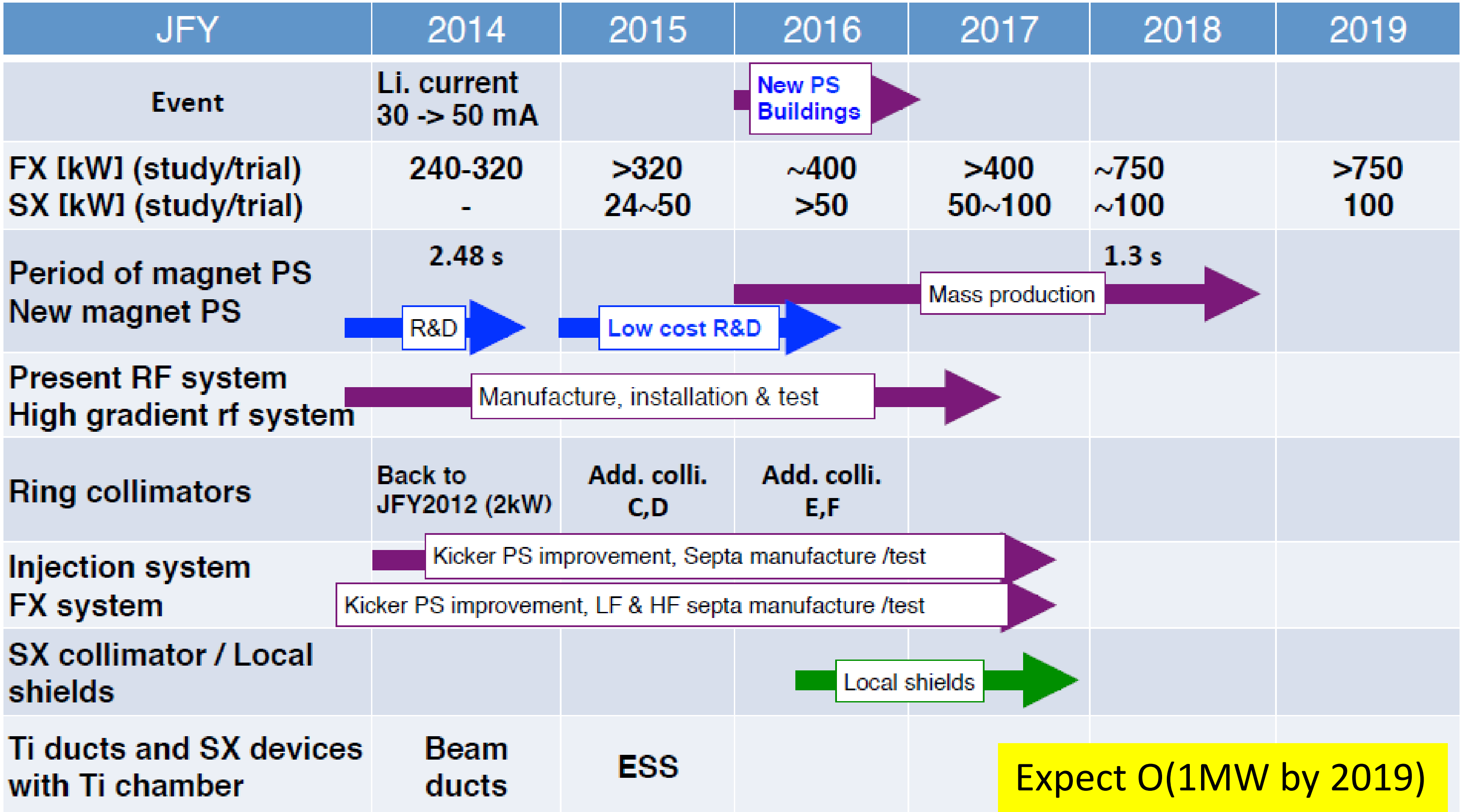


Similar (but less significant) effects seen in NOvA and SuperK)
➔ 2.5 σ CP violation
average by Marrone (neutrino2016)
Regardless of Hierarchy

Power upgrade plan of MR

FX: The high rep. 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 and RF cavities.

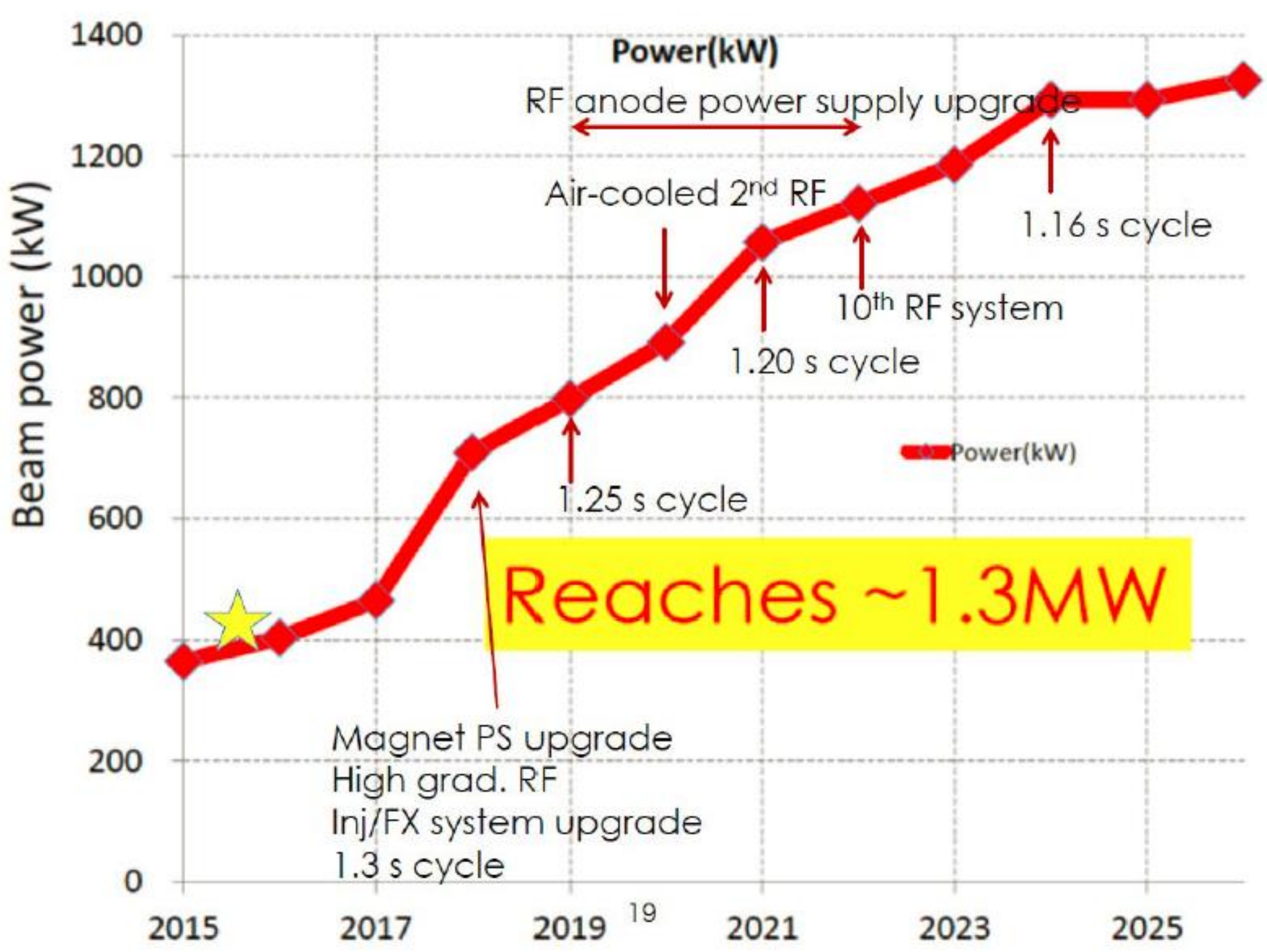
SX: After replacement of stainless steel ducts to titanium ducts to reduce residual radiation dose, 50 kW operation for users will be started. Beam power will be gradually increased toward 100 kW carefully watching the residual activity. Local shields will also be installed if necessary.



JFY	2014	2015	2016	2017	2018	2019
Event	Li. current 30 -> 50 mA		New PS Buildings			
FX [kW] (study/trial) SX [kW] (study/trial)	240-320 -	>320 24~50	~400 >50	>400 50~100	~750 ~100	>750 100
Period of magnet PS New magnet PS	2.48 s R&D	Low cost R&D		Mass production	1.3 s	
Present RF system High gradient rf system		Manufacture, installation & test				
Ring collimators	Back to JFY2012 (2kW)	Add. colli. C,D	Add. colli. E,F			
Injection system FX system	Kicker PS improvement, Septa manufacture /test Kicker PS improvement, LF & HF septa manufacture /test					
SX collimator / Local shields			Local shields			
Ti ducts and SX devices with Ti chamber	Beam ducts	ESS				

Expect O(1MW by 2019)
original beam request:
5 yrs @750kW

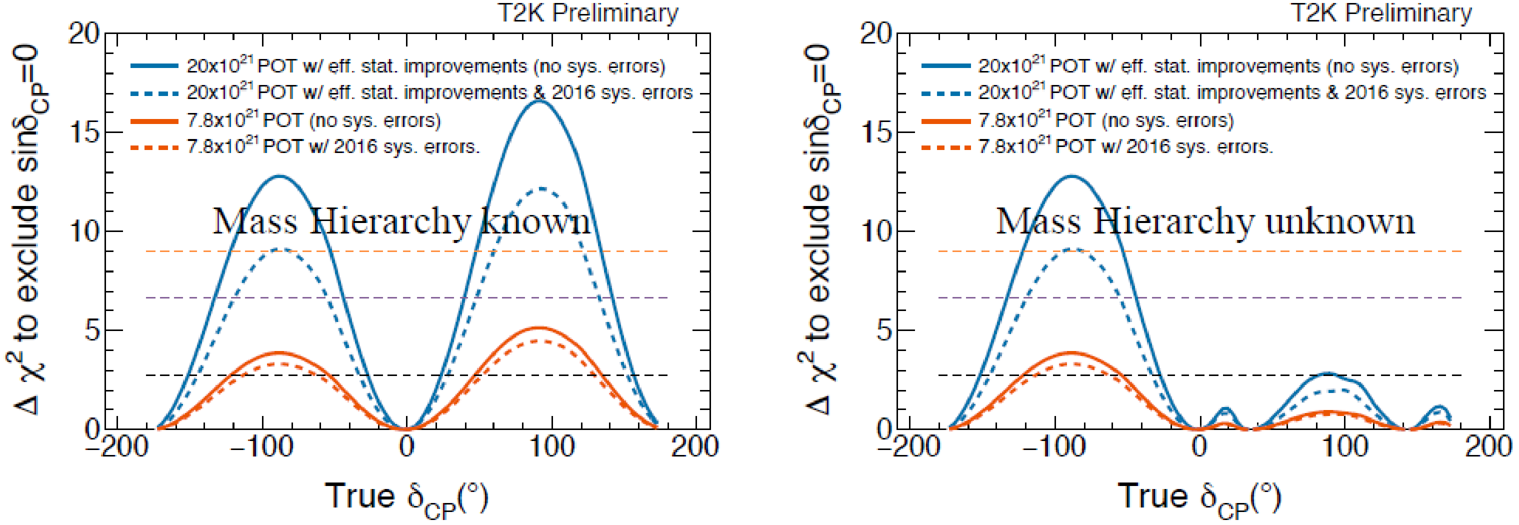
Timeline toward MW beam

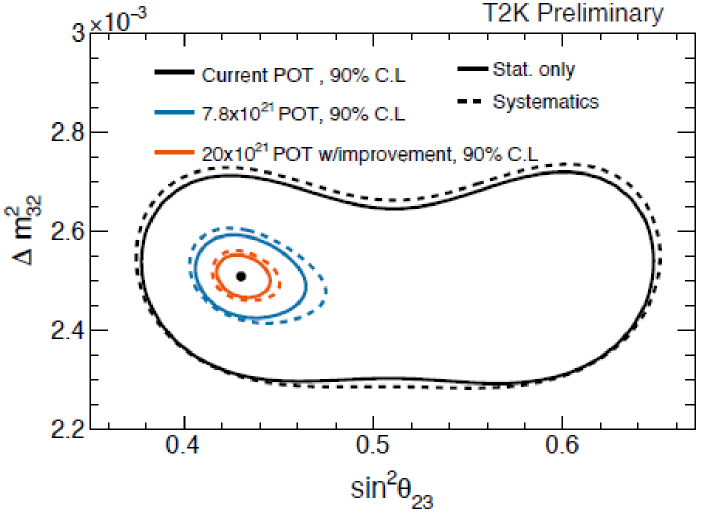


Realizing 1.3MW operation before 2025

Stage-I approved by JPARC PAC needs convincing reduction of syst!

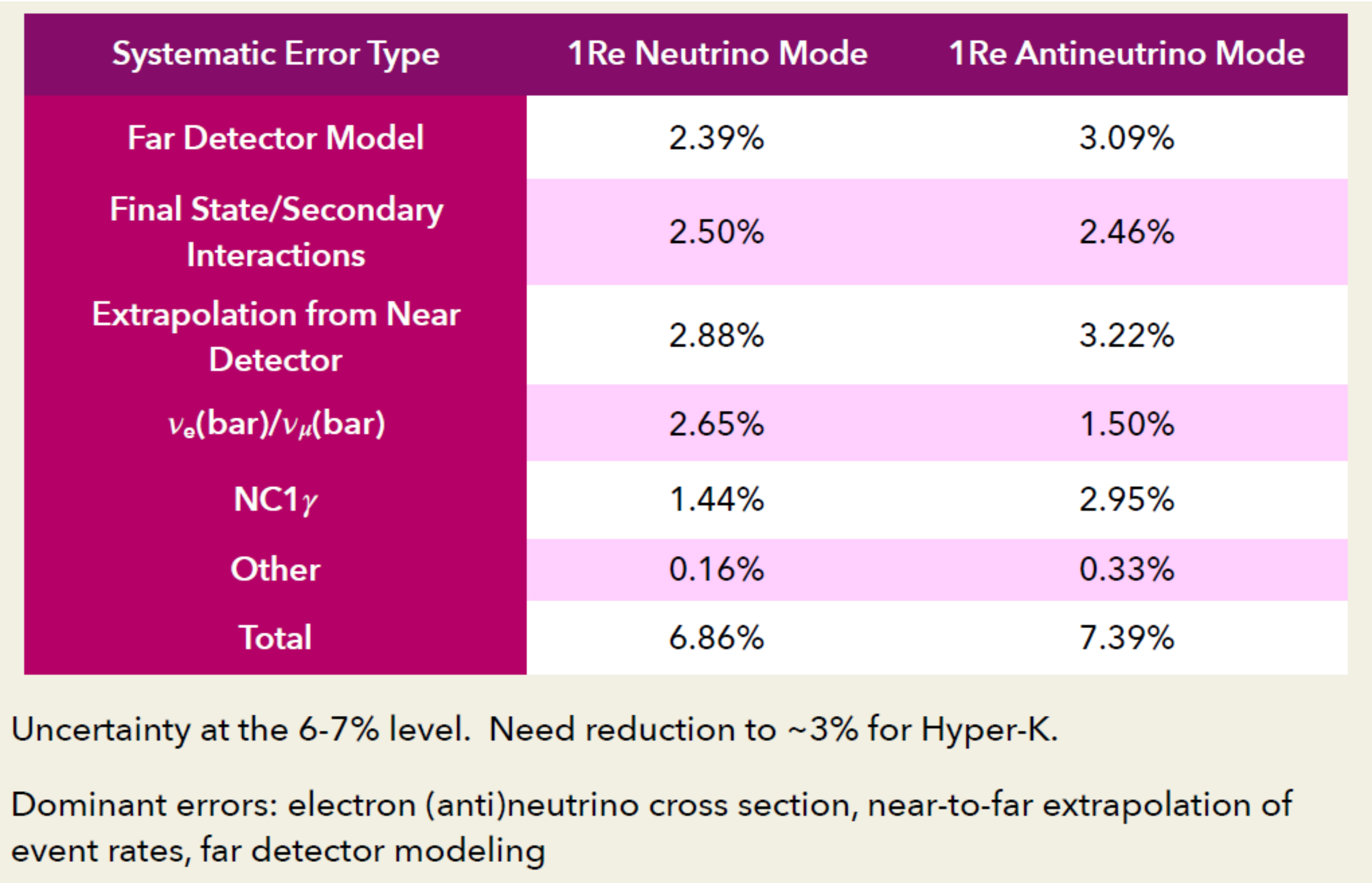
Physics Potential of T2K-II





- ~50% increase in effective POT
- ~3σ sensitivity to δ_{cp}
- Precise measurement of θ_{23}
  - resolution of 1.7%

arXiv:1609.04111v1 [hep-ex] 14 Sep 2016



Systematic Error Type	1Re Neutrino Mode	1Re Antineutrino Mode
Far Detector Model	2.39%	3.09%
Final State/Secondary Interactions	2.50%	2.46%
Extrapolation from Near Detector	2.88%	3.22%
ν_e(bar)/ν_μ(bar)	2.65%	1.50%
NC1γ	1.44%	2.95%
Other	0.16%	0.33%
Total	6.86%	7.39%

Uncertainty at the 6-7% level. Need reduction to ~3% for Hyper-K.

Dominant errors: electron (anti)neutrino cross section, near-to-far extrapolation of event rates, far detector modeling

Improvements on three fronts:

- near detector acceptance
- enery response ($E^{\text{rec vs}}$ E^{true})
- fake CP violation from (ν_e/ν_μ) / $(\bar{\nu}_e/\bar{\nu}_\mu)$
  - aim at larger samples of electron neutrinos
- Magnetic and non-magnetic detectors

Near detector upgrade for T2K-II

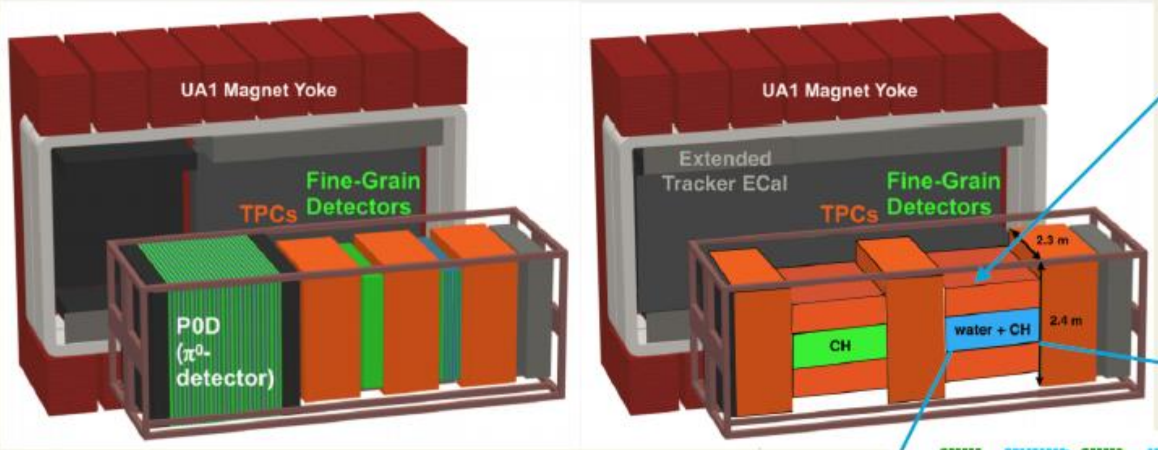
Near and intermediate detectors for Hyper-K are being developed to control flux and cross-section systematic errors

Will continue using the INGRID on -axis and magnetized ND280 detectors

Work within T2K to upgrade ND280 detector

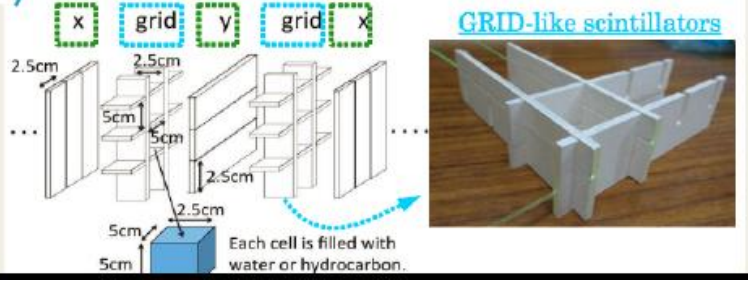
Current ND280 Detectors

Concept for Upgrade

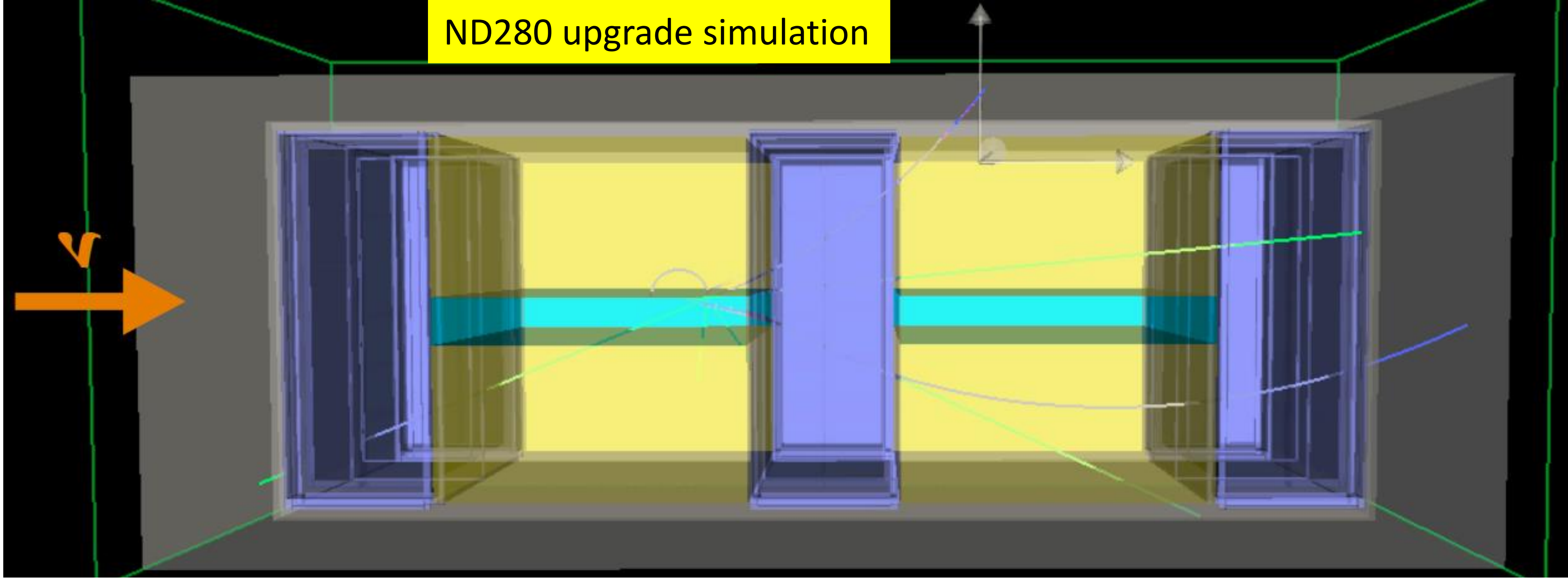


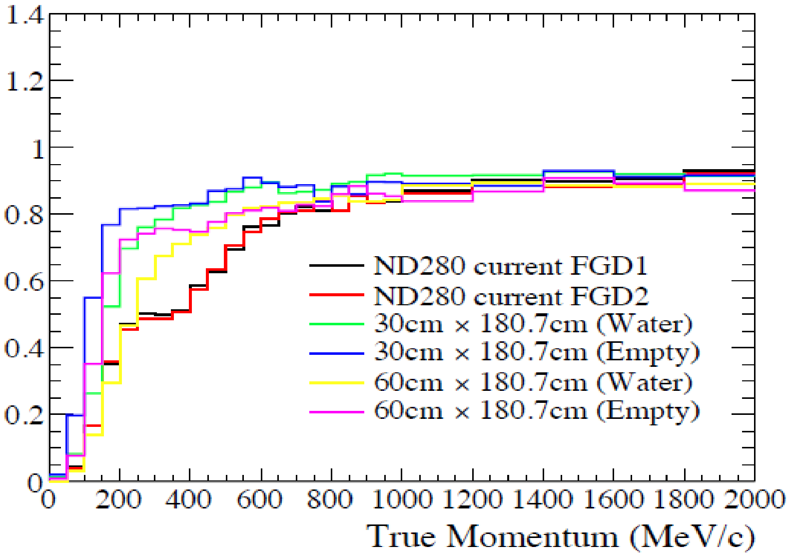
TPC reconfiguration for high angle track reconstruction

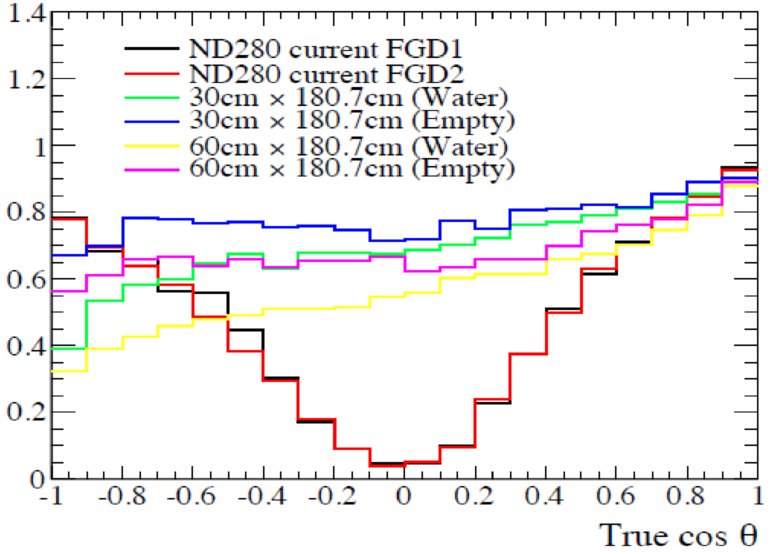
Potential upgrade for tracking target is WAGASCI tracker



Each cell is filled with water or hydrocarbon.



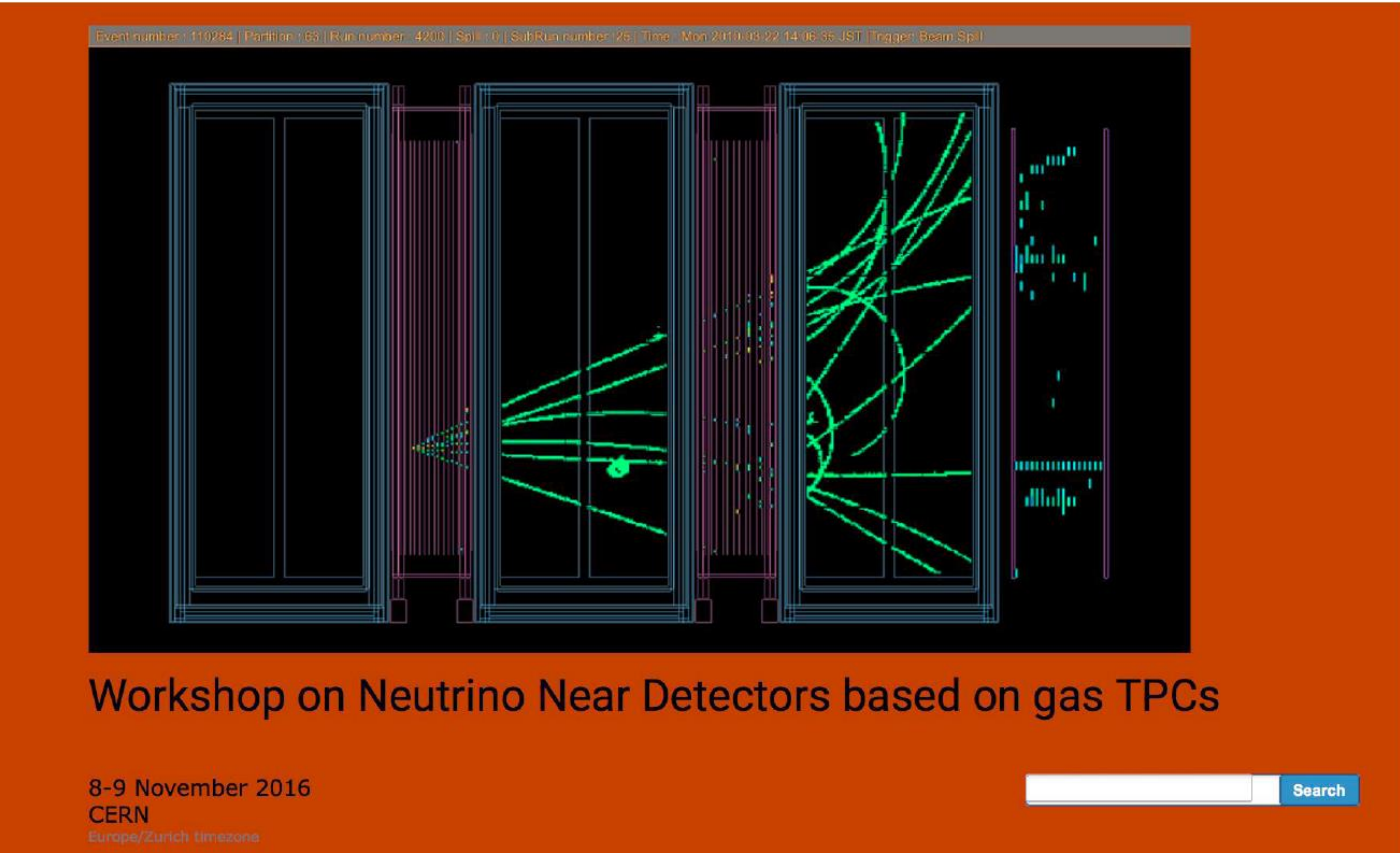




- Thickness 60cm provides x2 mass but lower efficiency
- New detector configuration provide a much better acceptance at high angles

CERN workshop

https://indico.cern.ch/event/568177/



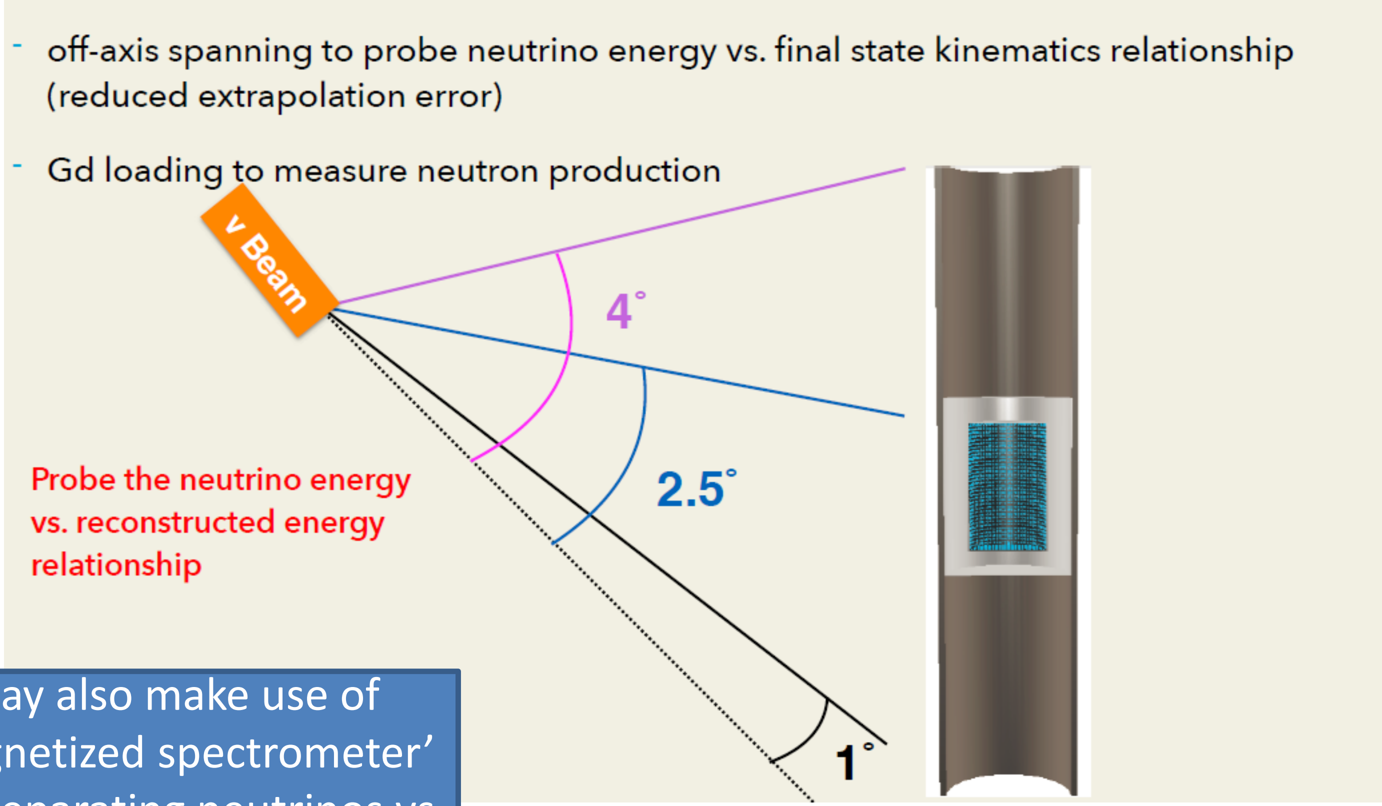
Workshop on Neutrino Near Detectors based on gas TPCs

8-9 November 2016
CERN
Europe/Zurich timezone

Testing the energy response of the near and far detector system

Energy response is biased by

- -- energy absorbed in nuclei
- -- missing reconstructed particles (below Cherenkov threshold)
- -- need monochromatic neutrino beam (but we dont have that)
  - ➔ can make one using off-axis neutrino kinematics



- off-axis spanning to probe neutrino energy vs. final state kinematics relationship (reduced extrapolation error)
- Gd loading to measure neutron production

Probe the neutrino energy vs. reconstructed energy relationship

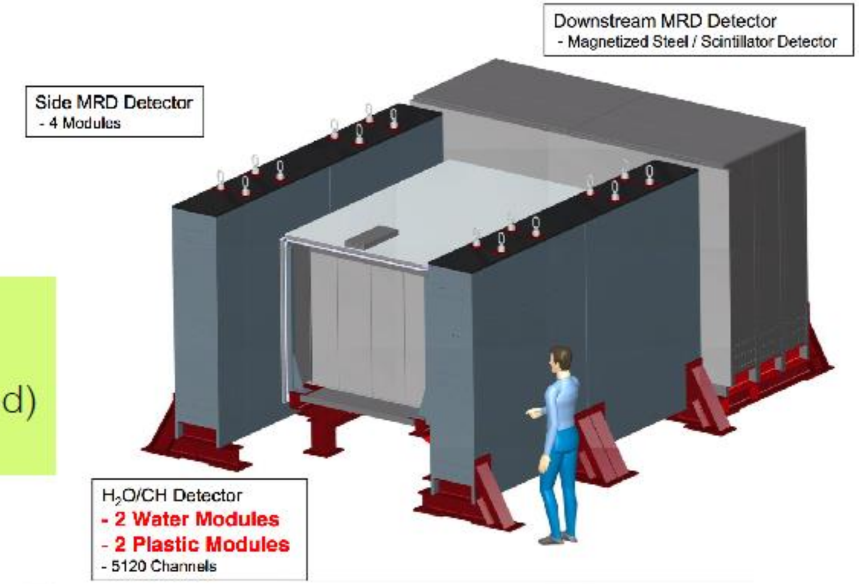
May also make use of ‘Magnetized spectrometer’ for separating neutrinos vs antineutrinos (Baby-MIND

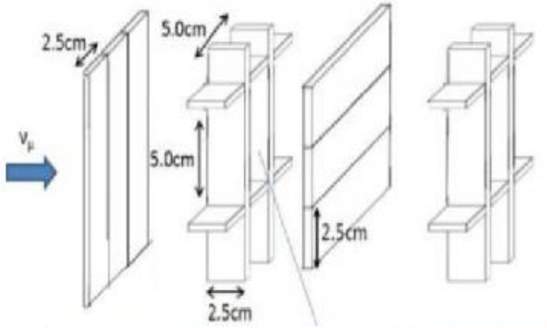
3% precision H_2O / CH x-section ratio

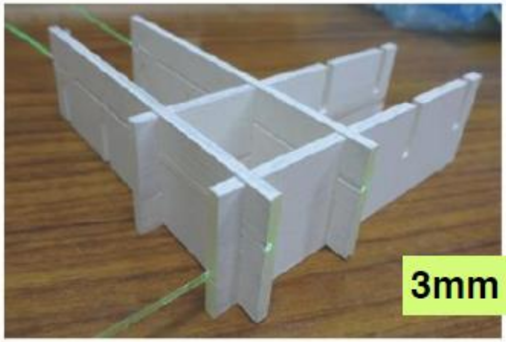
Wagasci

Wagasci collaboration

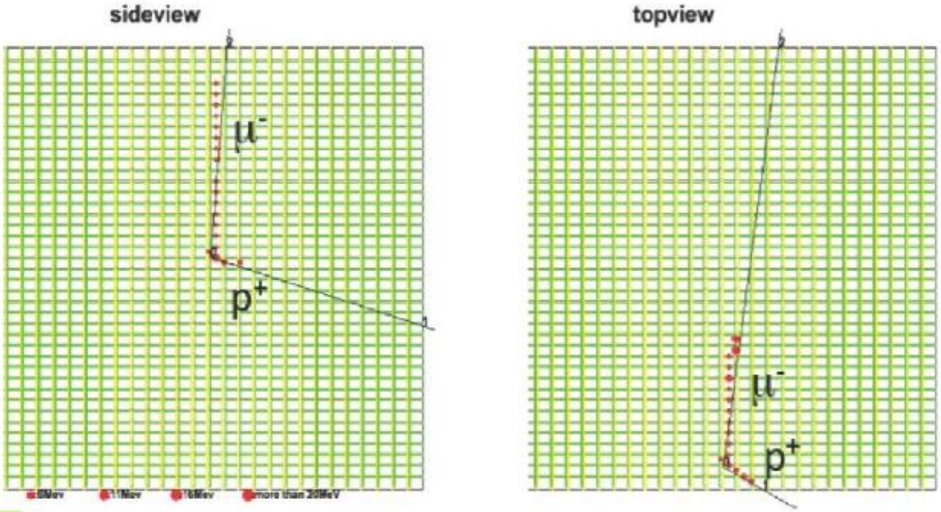
'The B2 experiment'
- 3D scintillator grid filled with water
- Side MRDs and end MRD (magnetized)
- Excellent phase space coverage







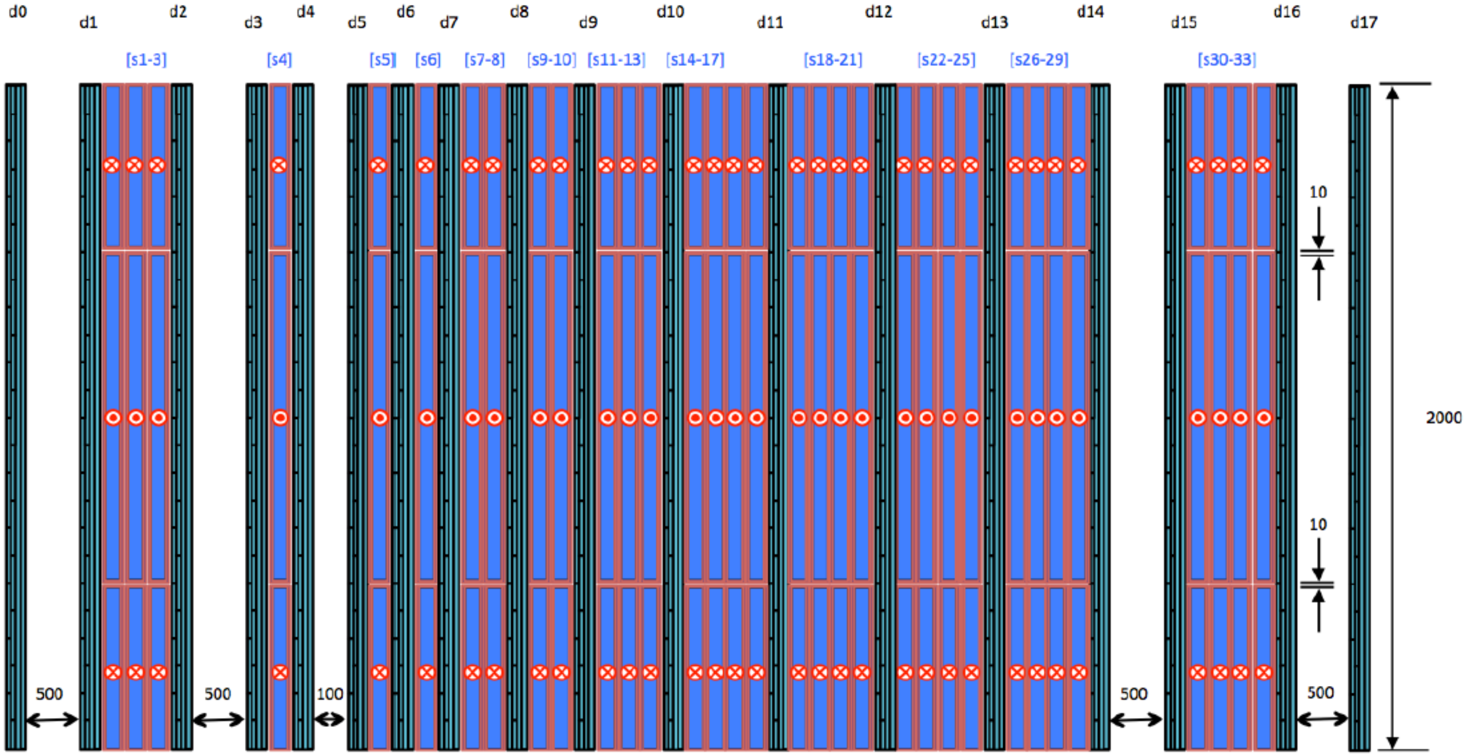
3mm thick



WAGASCI/Baby-MIND are part of T2K phase-I !

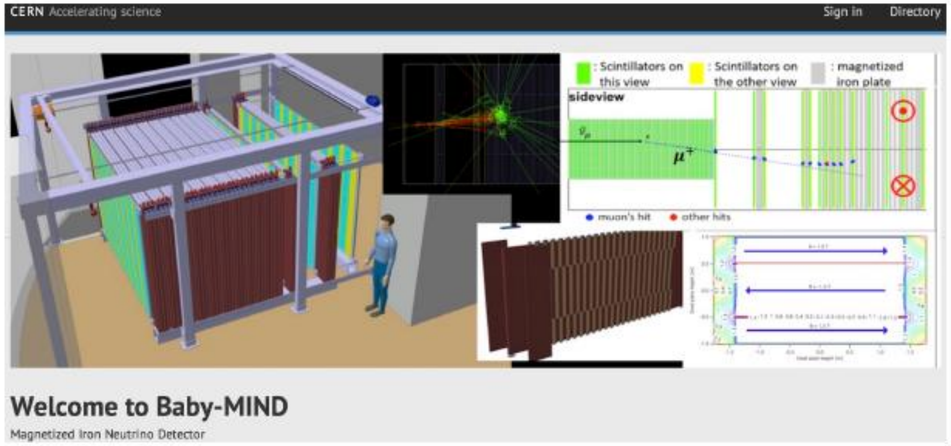
Baby MIND layout

- Magnet module thickness: 50 mm (30 mm Fe) (envelope: 60 mm).
- Detector module thickness: 38 mm (31 mm CH).
- Finalization of the layout will be done with T9 and simulation info.



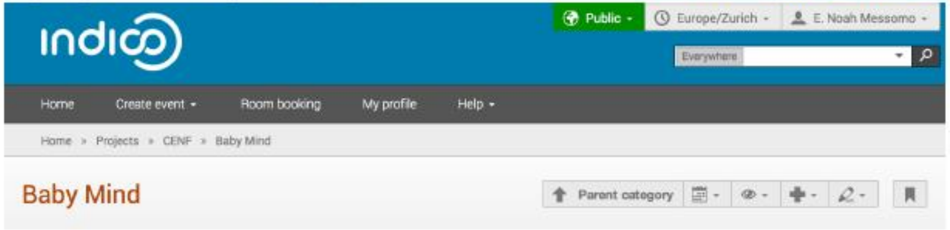
Working within CERN Neutrino Platform Framework

- NP funding for magnet design and construction.
- Access to NP manpower for technical, administrative assistance.
- Use of everyday working tools within NP framework:
  - bMIND website
  - bMIND edms
  - bMIND indico

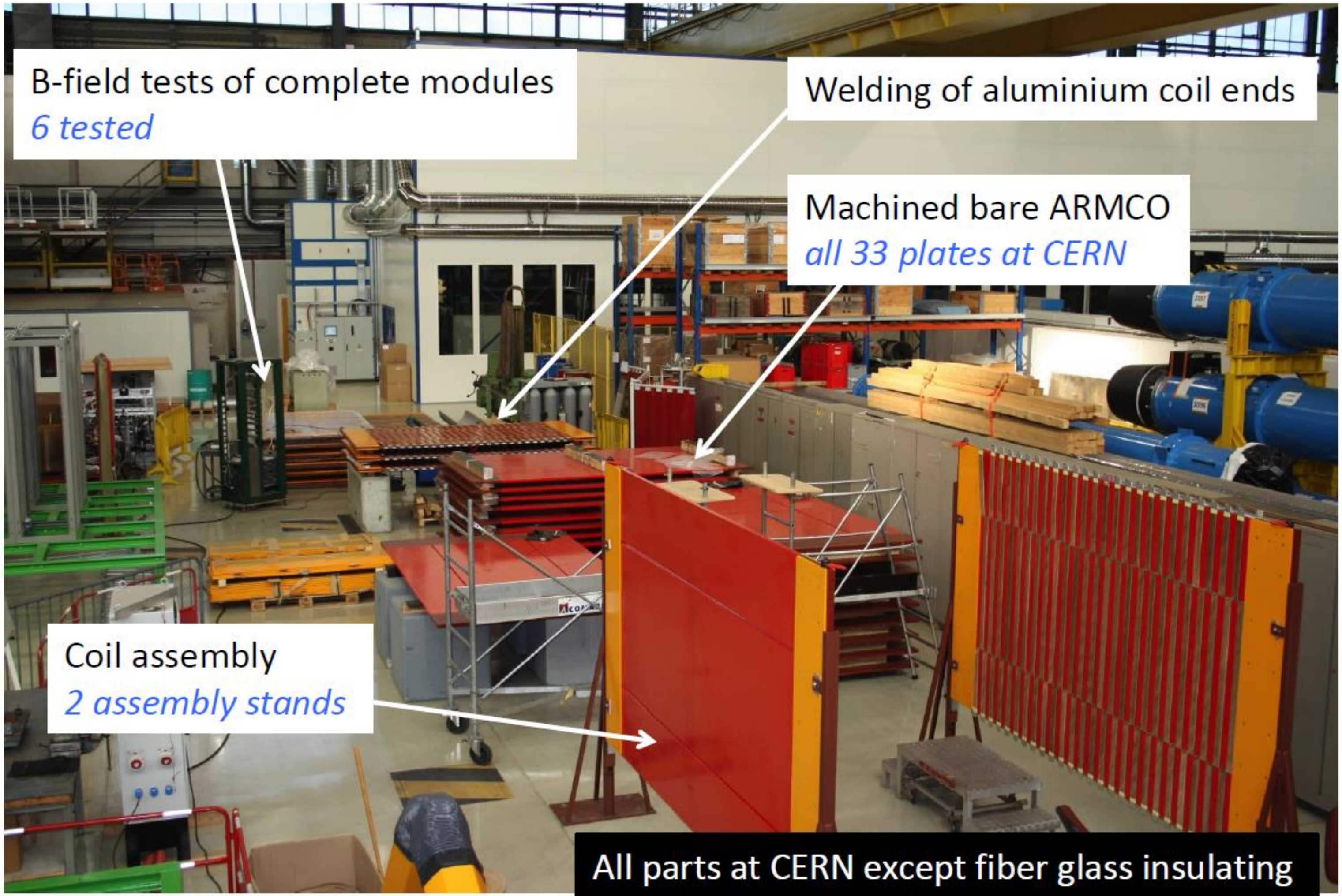


Welcome to Baby-MIND

Magnetized Iron Neutrino Detector



Magnet production



B-field tests of complete modules
6 tested

Welding of aluminium coil ends

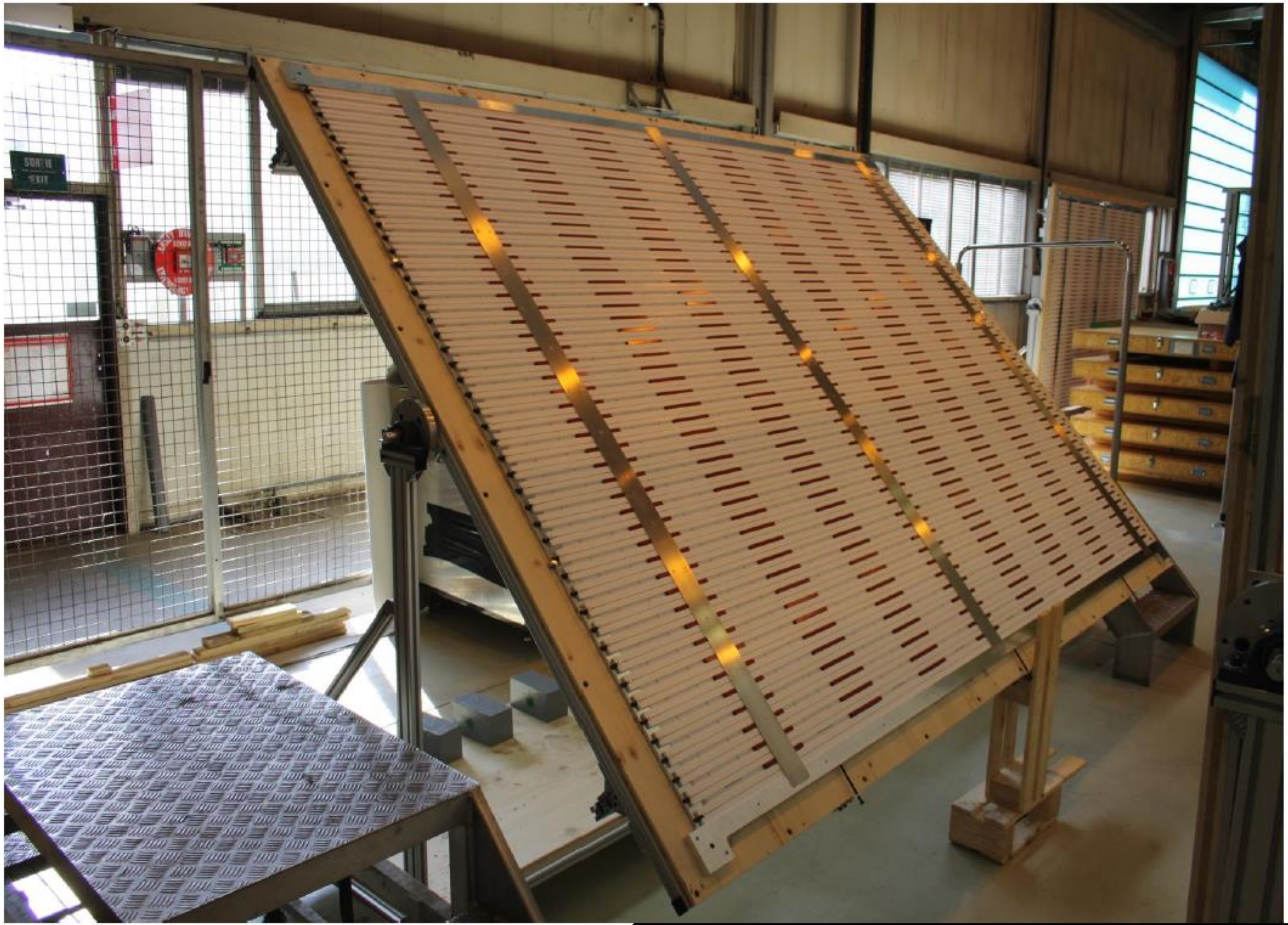
Machined bare ARMCO
all 33 plates at CERN

Coil assembly
2 assembly stands

All parts at CERN except fiber glass insulating sheath (delivery end November for extra)
... enough for 6 modules

2 magnet modules every 7 days
10 done, 23 to go: 20 done by end 2016

Scintillator module production

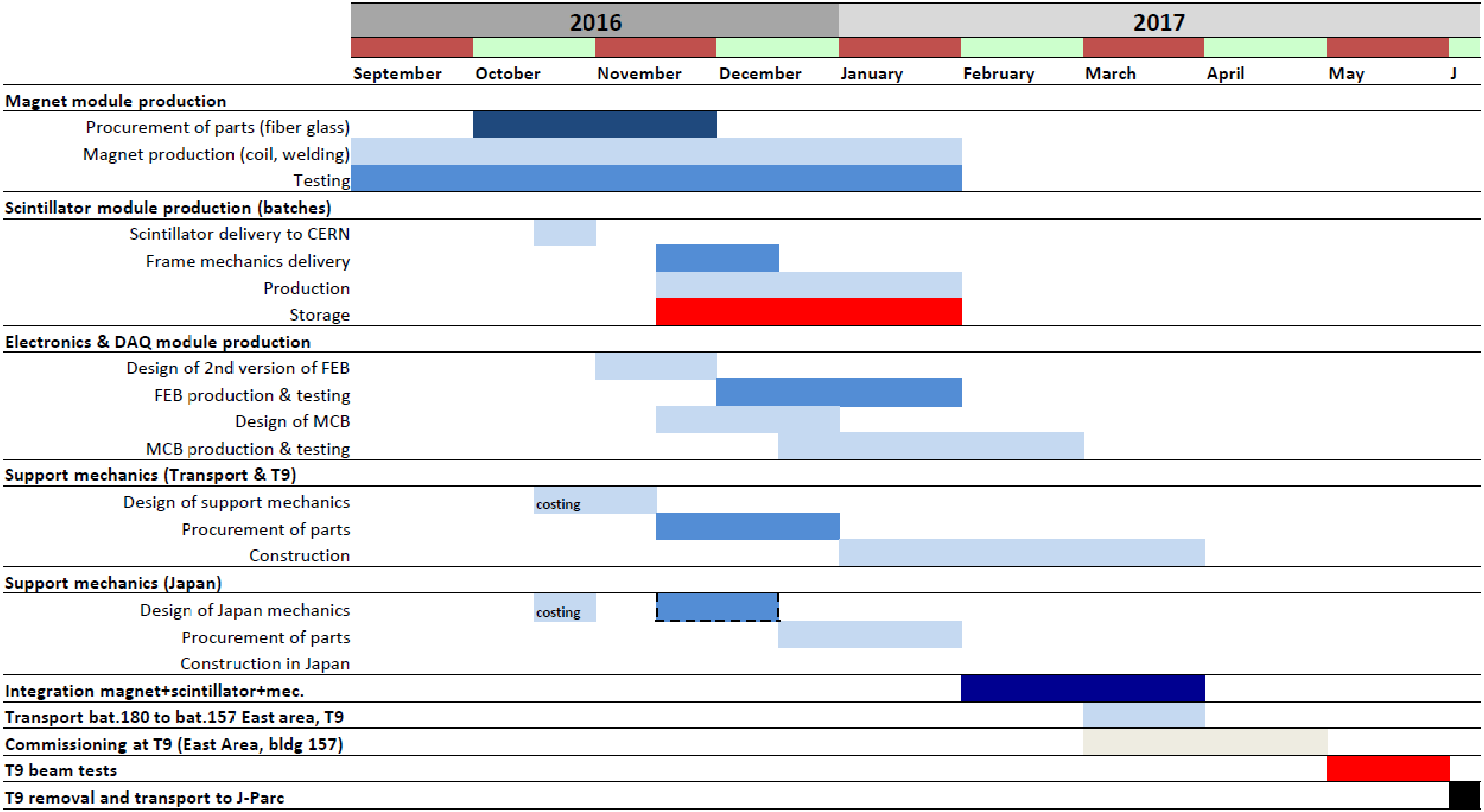


2 to 3 modules every 5 days
1 done, 18 to go: 10 done by end 2016

Scintillator from Moscow: end October
Support mechanics from CH: ??

Schedule

NB: there is a Transnational access program in AIDA2 for participation in the test beam



T2K = Tokai to KamioKa neutrino experiment

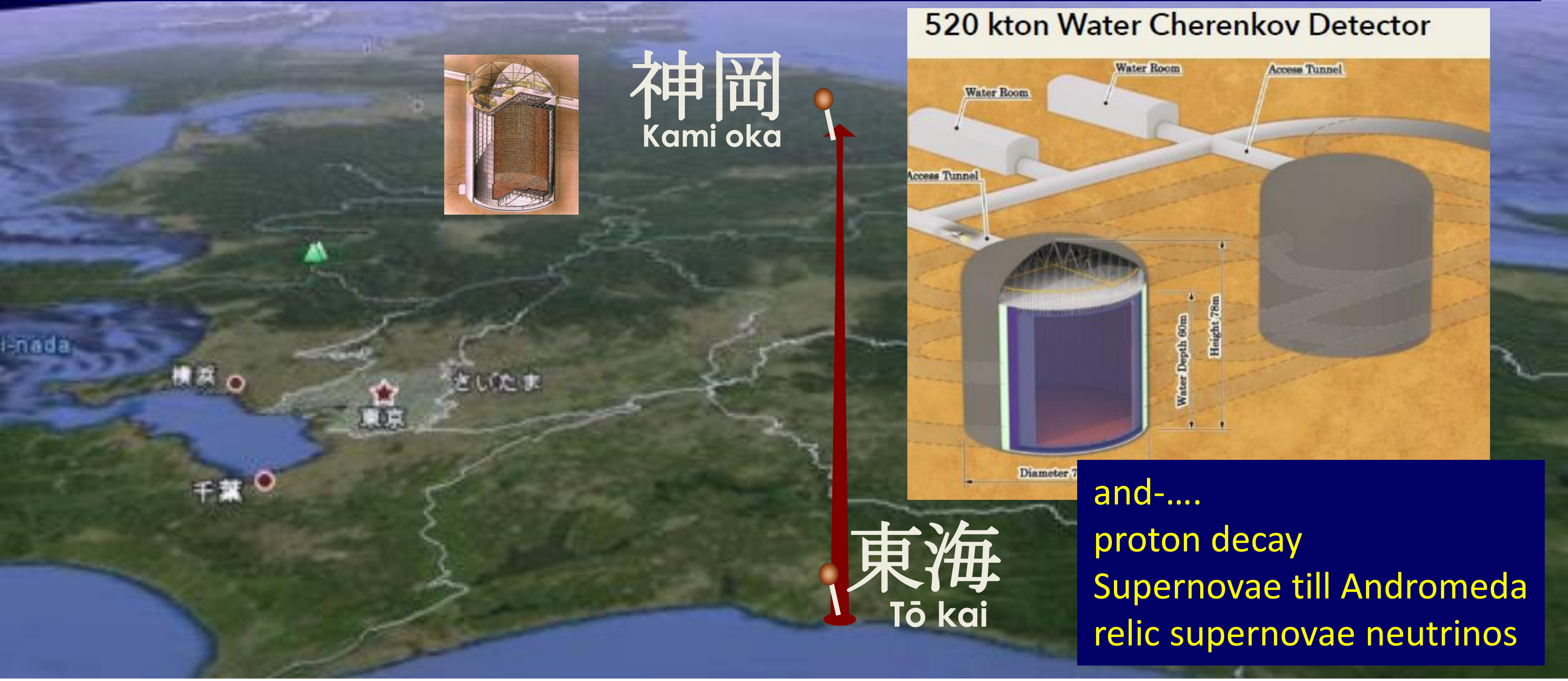
2015 Breakthrough prize for discovery of $\nu_\mu \rightarrow \nu_e$ Oscillation

2016 0.45 MW (proton+C-> neutrinos) beam → 50 ton SuperKamionande WC detector

2σ indication of CP violation

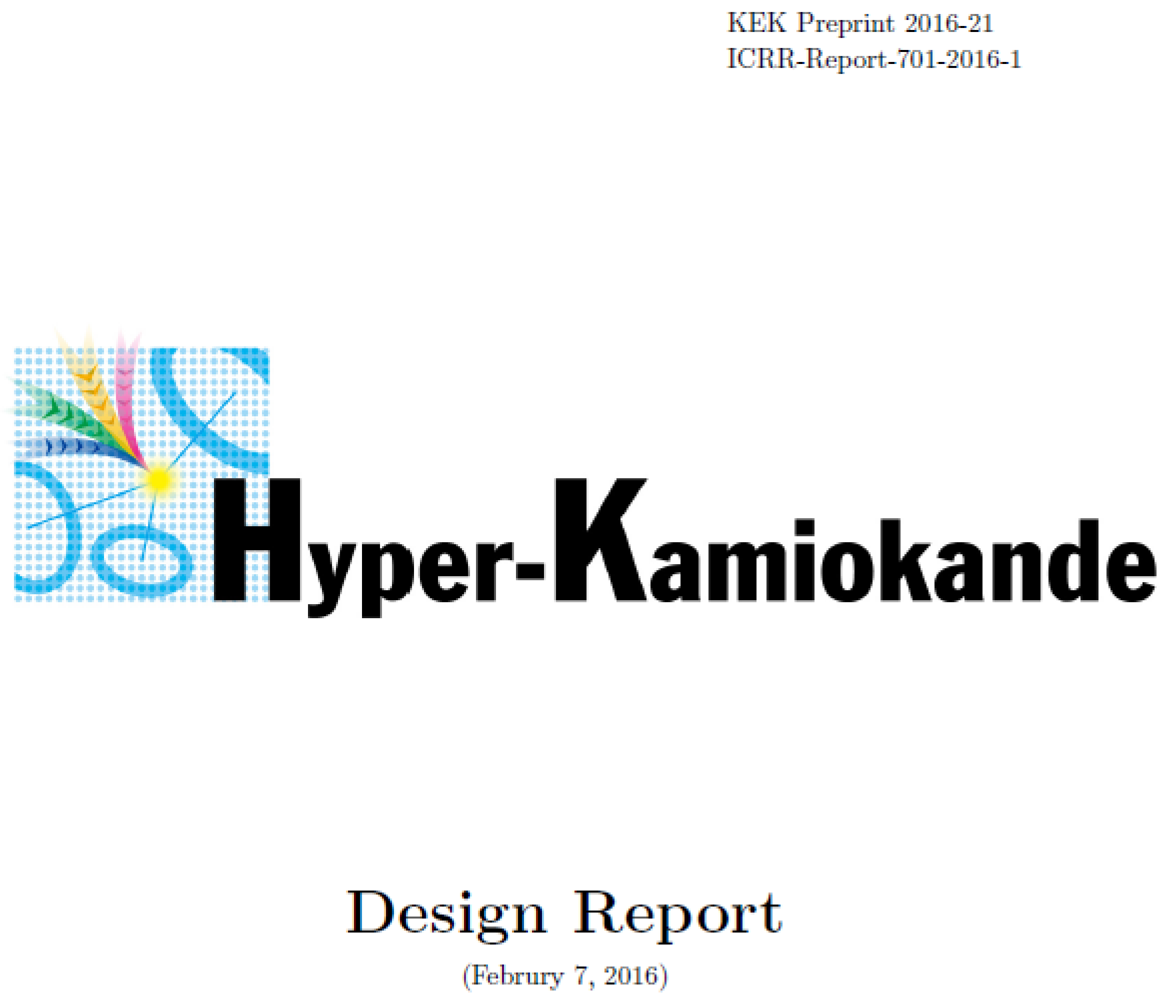
2016-2026 upgrades to reach 1.3 MW beam power → up to 4σ evidence for CP violation

2016 300-600 kton HyperKamiokande WC detector → precise measurements (5-10°)



520 kton Water Cherenkov Detector

and-....
proton decay
Supernovae till Andromeda
relic supernovae neutrinos



KEK Preprint 2016-21
ICRR-Report-701-2016-1

Hyper-Kamiokande

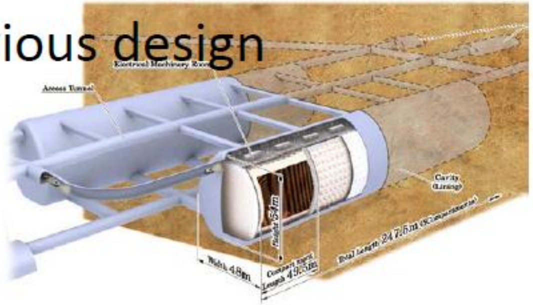
Design Report

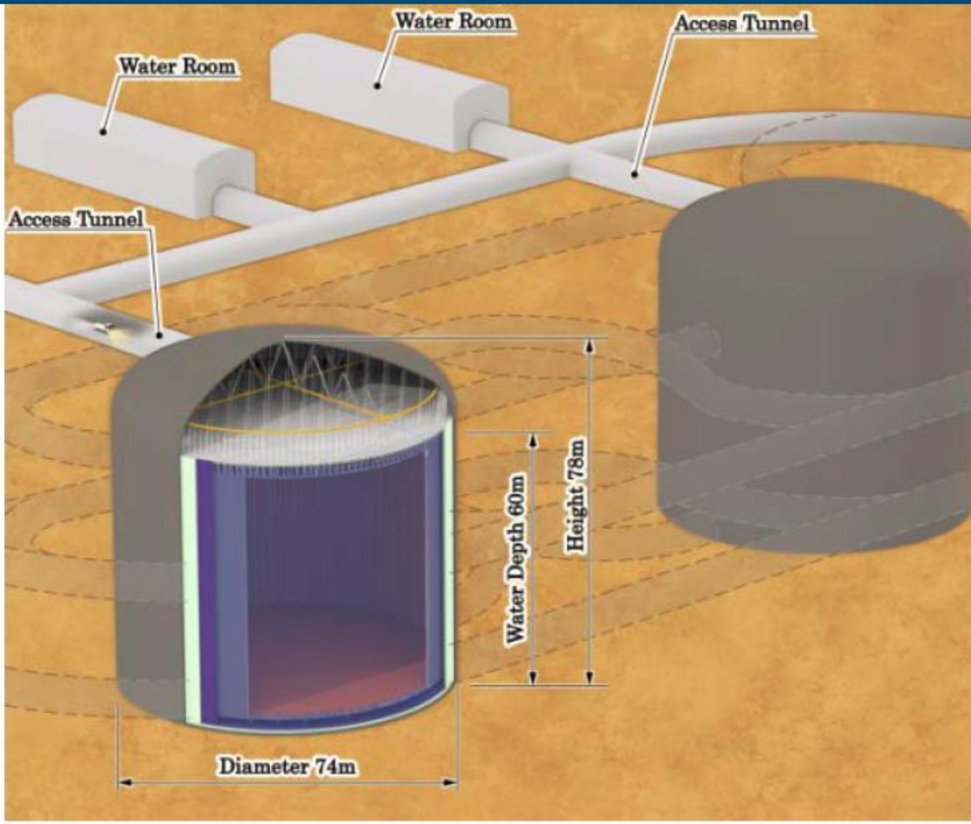
(Februry 7, 2016)

https://lib-extopc.kek.jp/preprints/PDF/2016/1627/1627021.pdf

Present design of Hyper-K

Previous design





✓Super-K-like structure

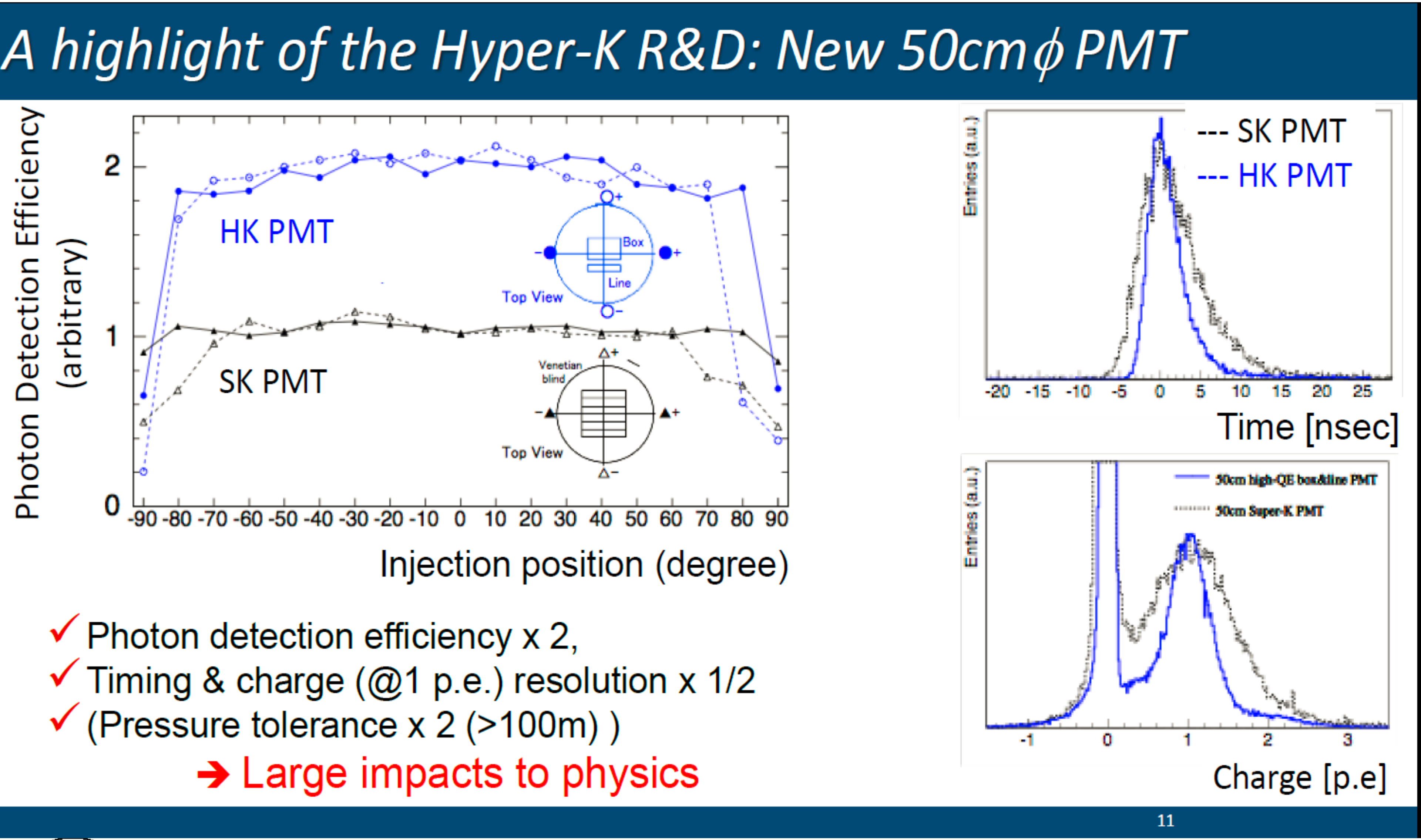
✓2 tanks with staging

(2nd tank assumed to be ready 6 years later)

✓1 tank will be;

- 60m(H)×74m(D)
- Total volume: 260 kton
- Fiducial volume(FV): 190 kton
  ~10 x Super-K FV
- PMT coverage 40%, 40,000 ID-PMT, 6,700 OD-PMT

✓ The candidate site is ~8km south of SK (2.5 degree off axis beam, L=295km)



A highlight of the Hyper-K R&D: New 50cmϕ PMT

- ✓ Photon detection efficiency x 2,
- ✓ Timing & charge (@1 p.e.) resolution x 1/2
- ✓ (Pressure tolerance x 2 (>100m))

➔ Large impacts to physics

with 40% coverage threshold is around 2-3 MeV

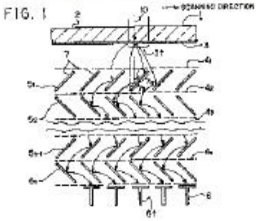
Photosensor Improvements

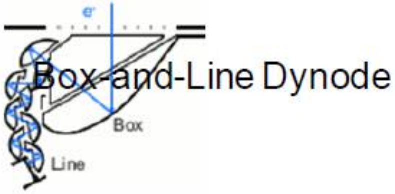
Photo Multipliers (PMTs)

Super-K PMT

50cm HQE Box&Line PMT

Venetian Blind



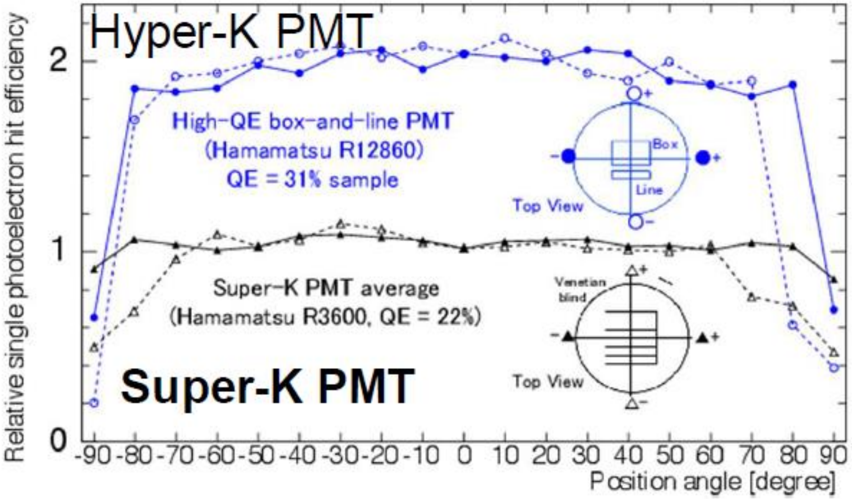


Box-and-Line Dynode

- Efficiency x 2, Timing resolution x 1/2

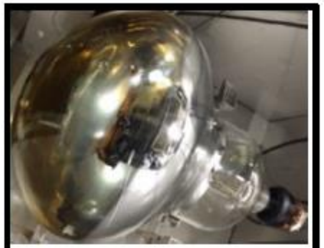
  Pressure tolerance x 2 (>100m)

  Enhance p→$\bar{\nu}K^+$ signal, solar ν, neutron signature of np→d+γ(2.2MeV),..

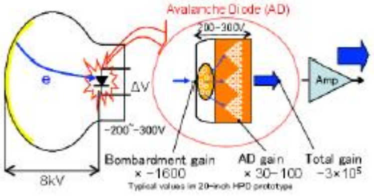


Other Developments:

Hybrid Photo Detectors (HPDs)

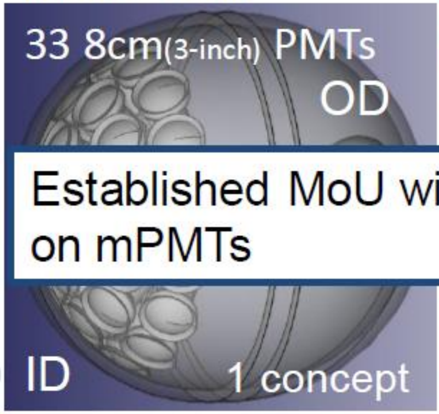


50cm HQE HPD w/ 20mm ϕ AD



Under viability study

Multi-PMTs



Working concept from KM3NeT but:

- peripheral ID/OD
- ultrapure water.

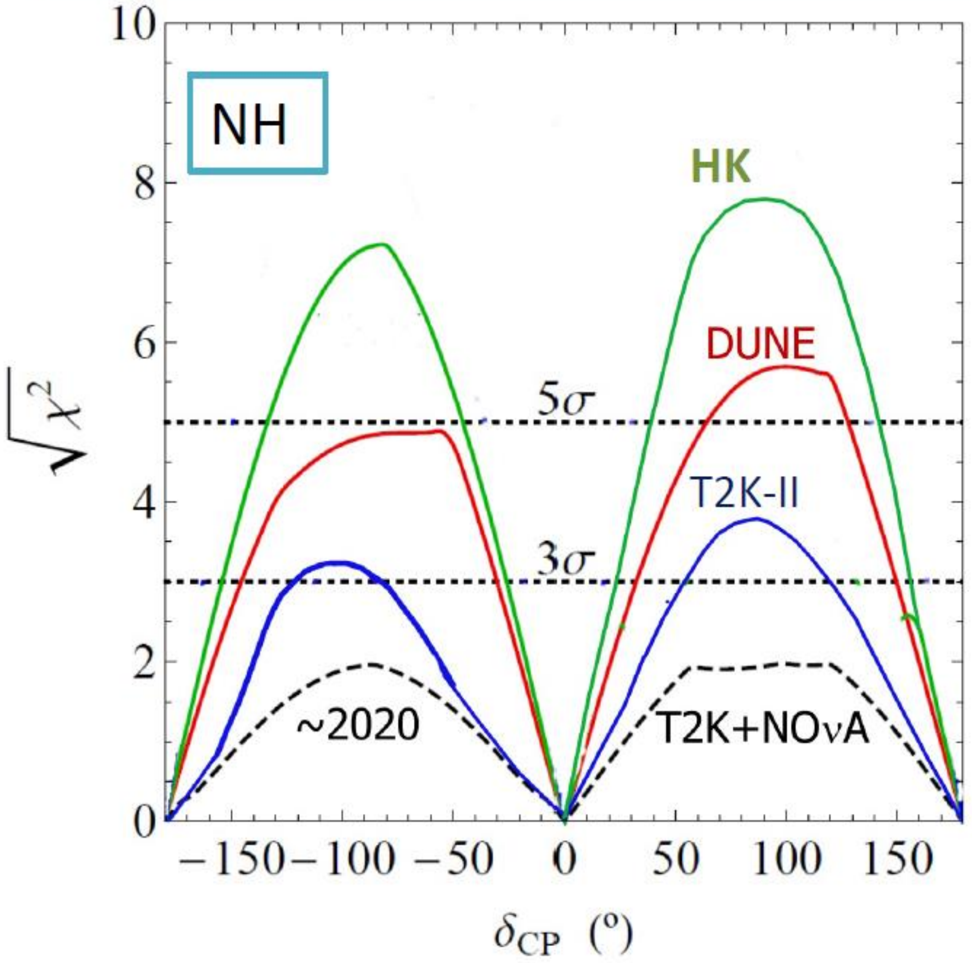
International contribut.

Established MoU with KM3Net to collaborate on mPMTs

Hamamatsu new plant for mass production

- **New large plant for mass production for HK built by Hamamatsu.**
- The PMT division is moving there.
- Around 6 years for mass production.

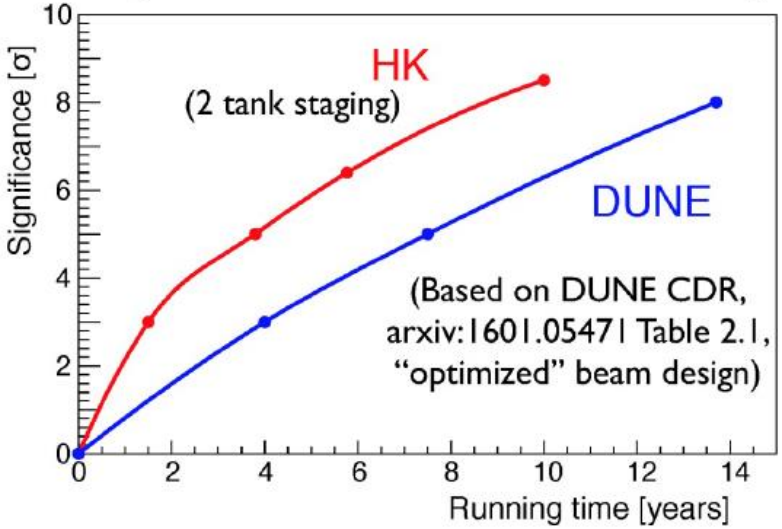
Next on CP



Mezzetto Neutrino 2016

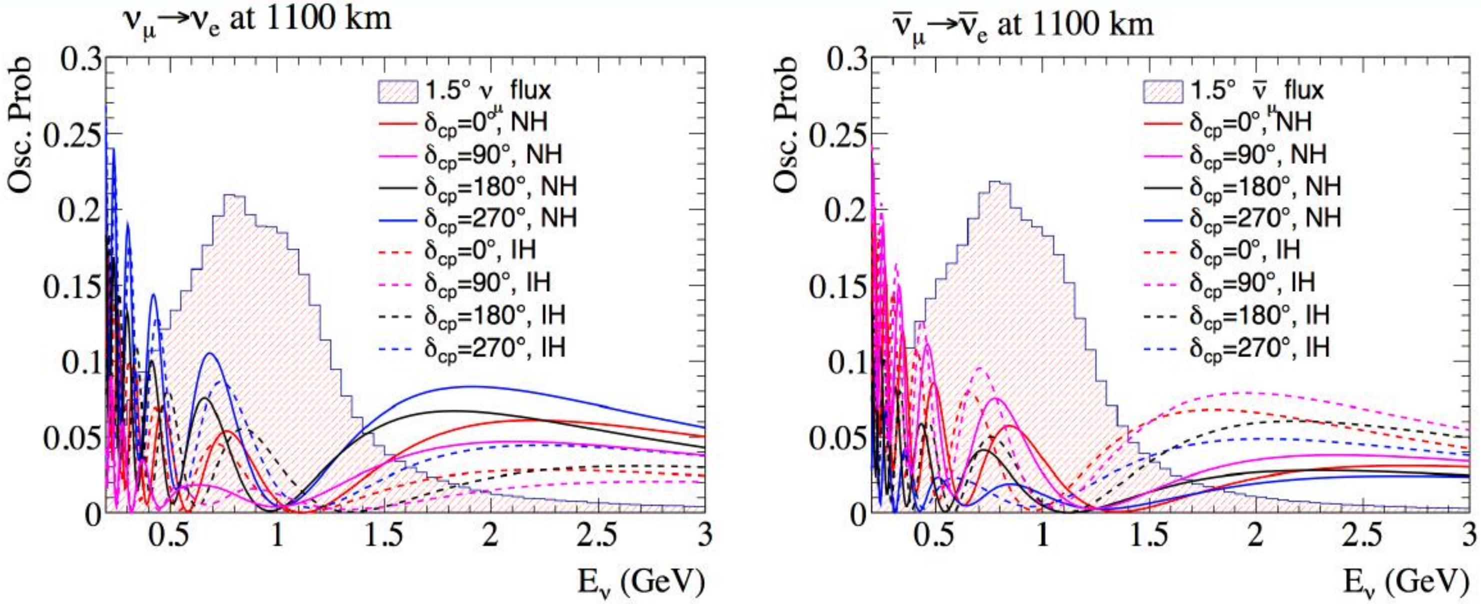
- HK: 10 years, staged
- Dune: 7 years full conf.
- T2K-II: 3 times T2K stats and several improvements in beam configuration and data analysis
- T2K+Nova: full stats, basically already achieved
- What about Nova-II?

CPV significance for δ=-90°, normal hierarchy

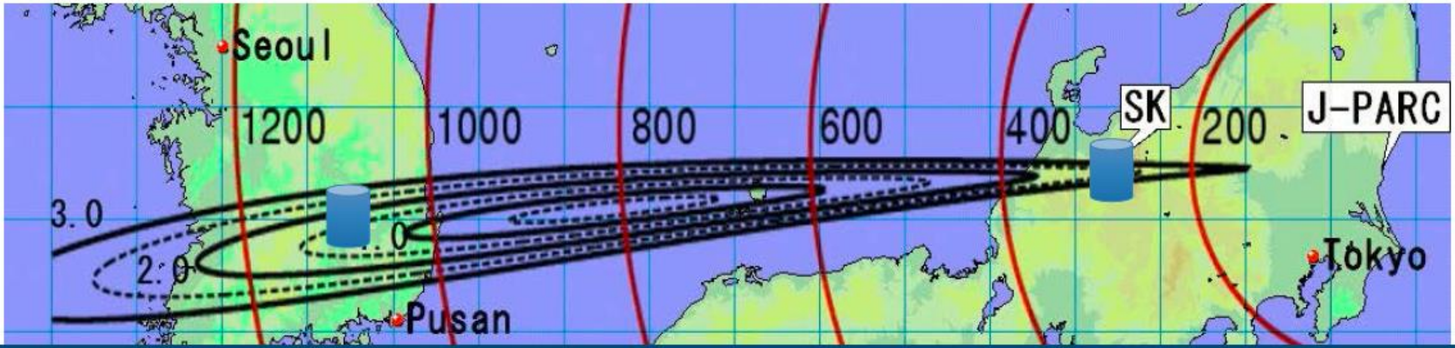


CAREFUL THAT THERE ARE UNCERTAINTIES IN THE STARTING DATE OF BOTH DUNE AND HYPERK

2nd Hyper-K detector in Korea ?

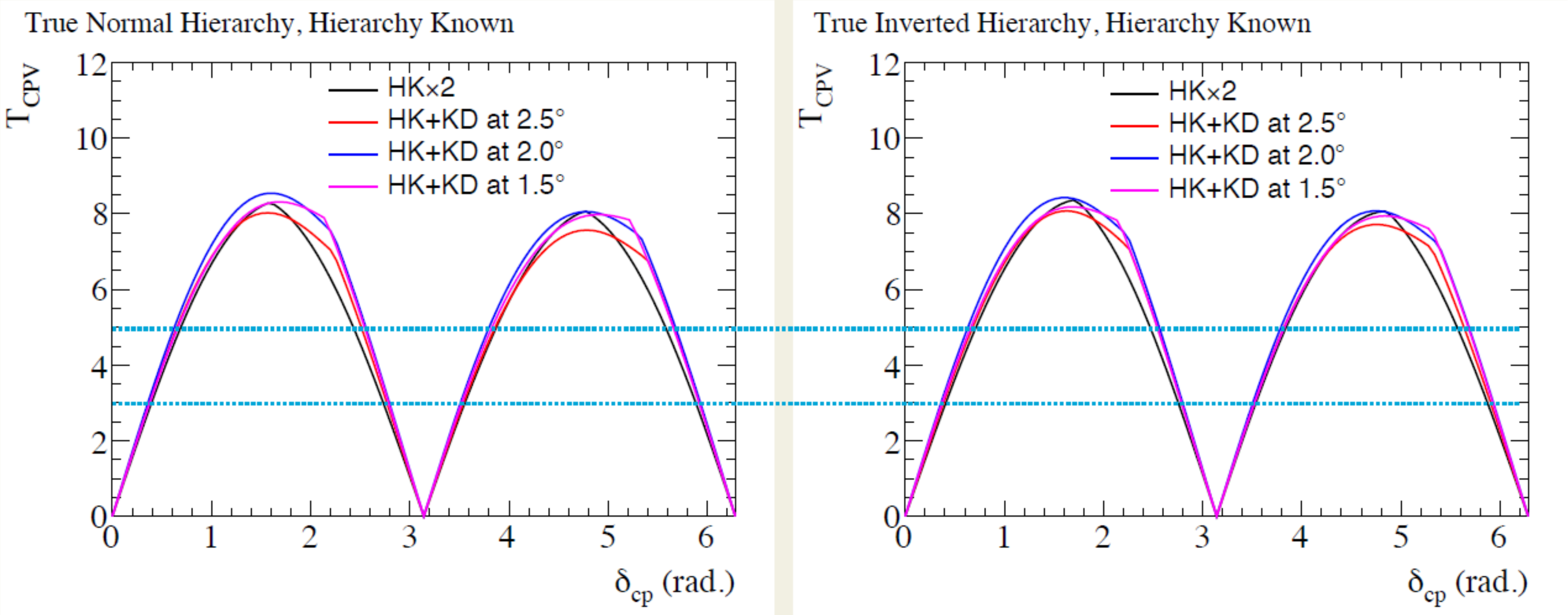


Phys.Rev.D72:033003,2005
Phys.Lett.B637:266-273,2006
Phys. Rev. D81, 093001, 2010



- The 2nd HK tank can be located some other place.
- About 10 years ago, this possibility was discussed.
- Now this possibility is revisited...

CP VIOLATION DISCOVERY



- The configurations with the detector in Korea have a 5 sigma discovery potential for a broader range of δ_{cp} values

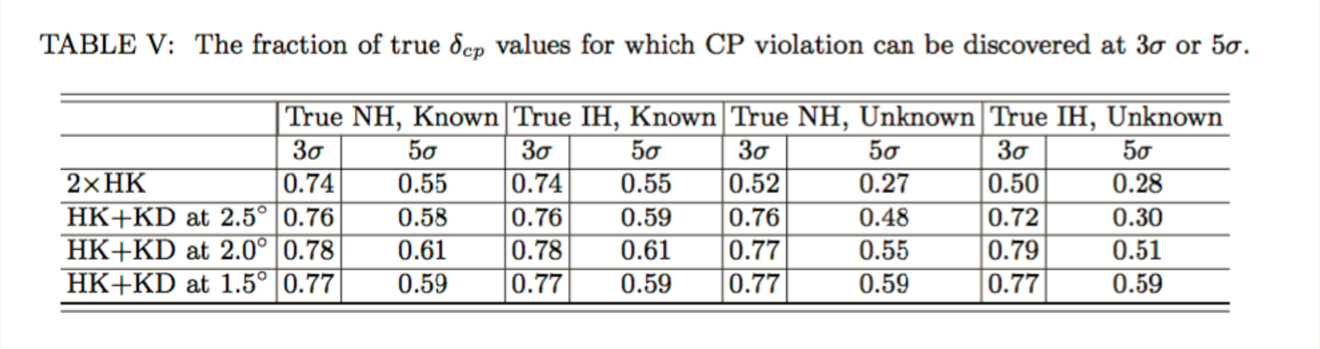
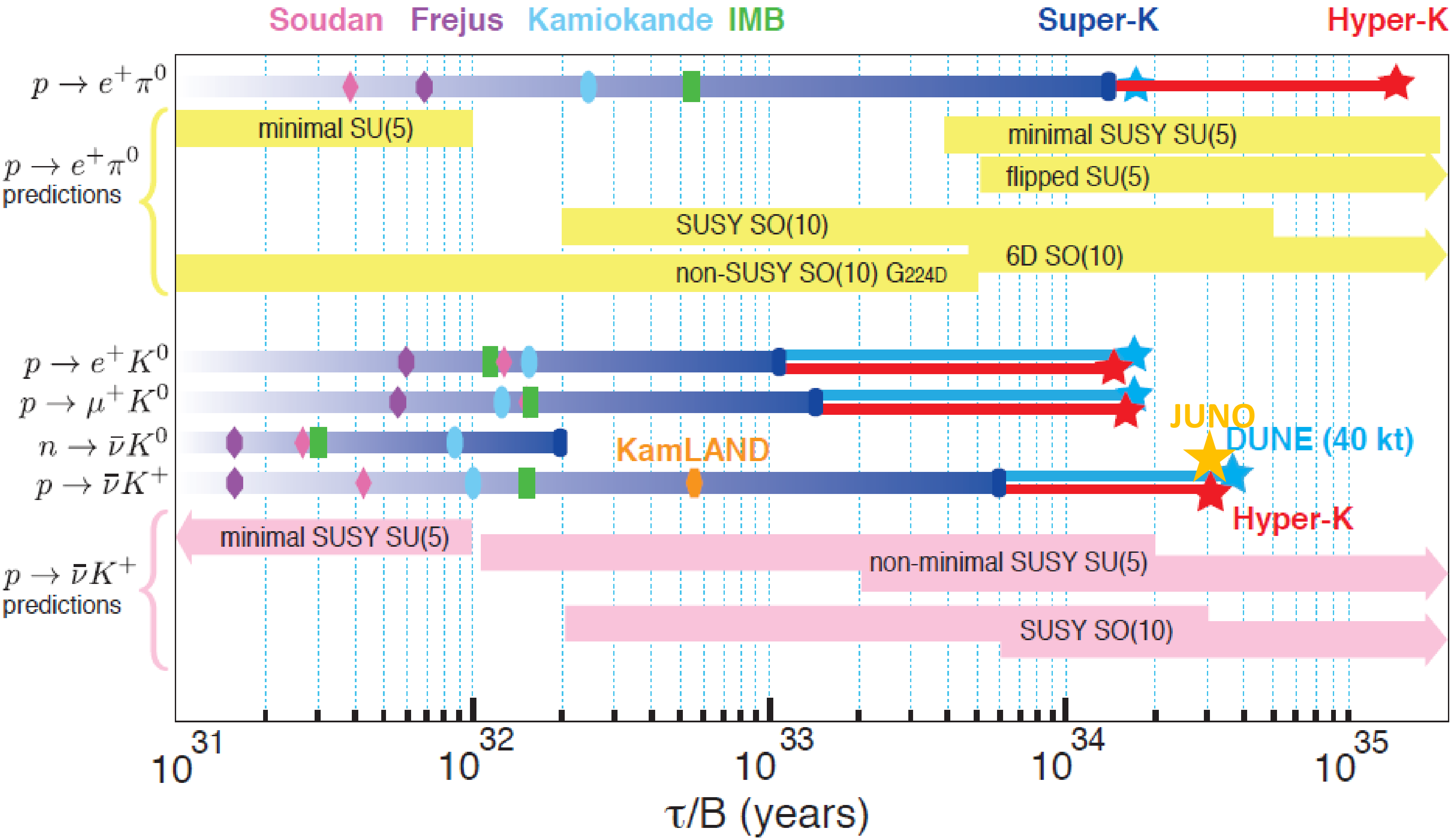


TABLE V: The fraction of true δ_{cp} values for which CP violation can be discovered at 3σ or 5σ.

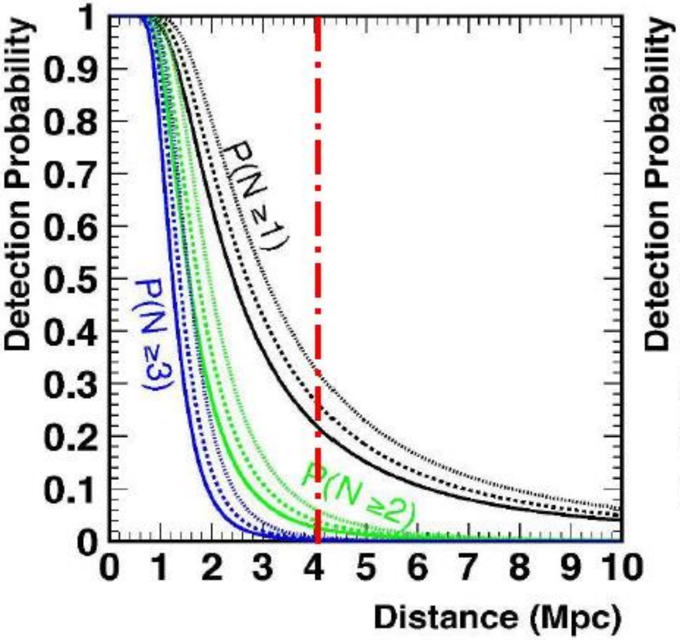
	True NH, Known		True IH, Known		True NH, Unknown		True IH, Unknown	
	3σ	5σ	3σ	5σ	3σ	5σ	3σ	5σ
2×HK	0.74	0.55	0.74	0.55	0.52	0.27	0.50	0.28
HK+KD at 2.5°	0.76	0.58	0.76	0.59	0.76	0.48	0.72	0.30
HK+KD at 2.0°	0.78	0.61	0.78	0.61	0.77	0.55	0.79	0.51
HK+KD at 1.5°	0.77	0.59	0.77	0.59	0.77	0.59	0.77	0.59

Proton decay

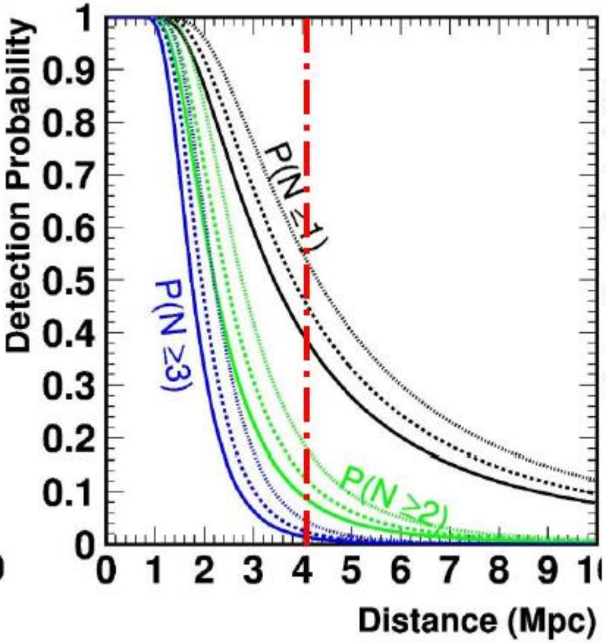


ν detection probability for ~Mpc SN

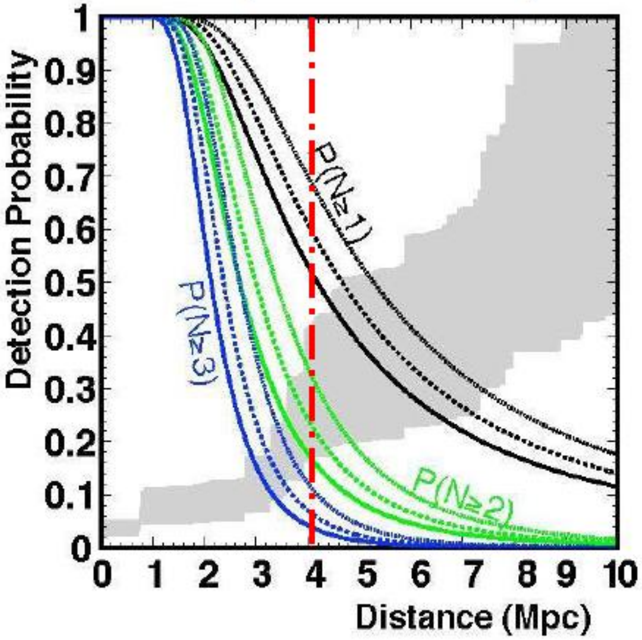
1 tank (0.19Mt FV)



2tank staged (0.37Mt FV)



LOI (0.56Mt FV)



For 4Mpc supernova

3-6% for P(N >= 2)

10-20 % for P(N >= 2)

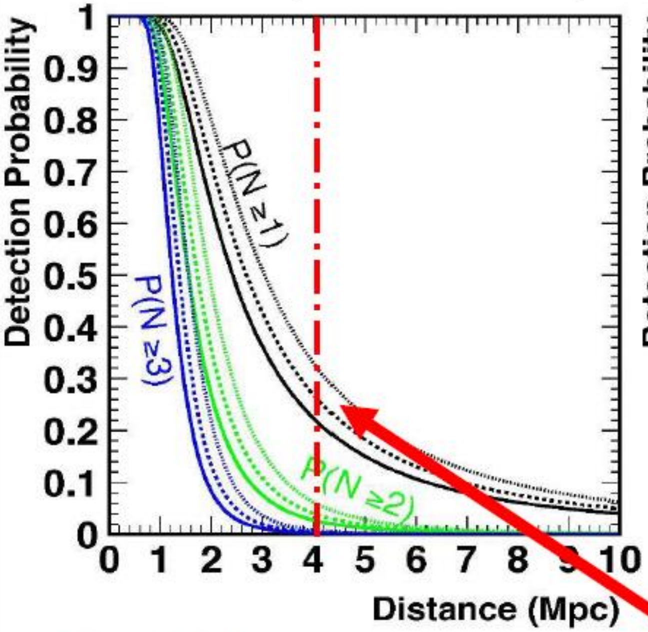
17-32% for P(N >=2)

Conditions:

- Livermore simulation
- 10MeV threshold
- # range for no osc., N.H. and I.H.

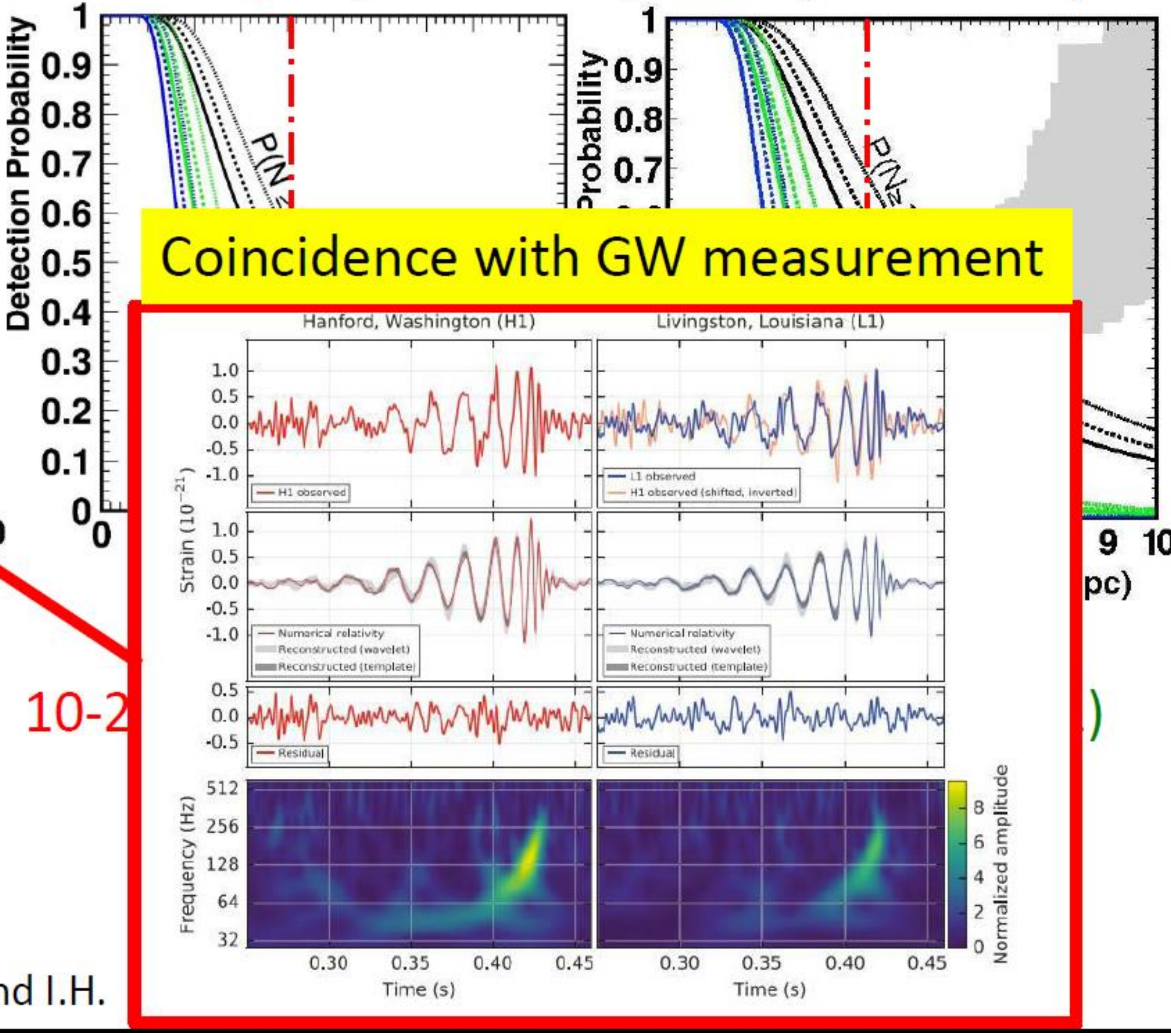
ν detection probability for ~Mpc SN

1 tank (0.19Mt FV)



2tank staged (0.37Mt FV)

LOI (0.56Mt FV)



Coincidence with GW measurement

For 4Mpc supernova

3-6% for P(N >= 2)

10-2

)

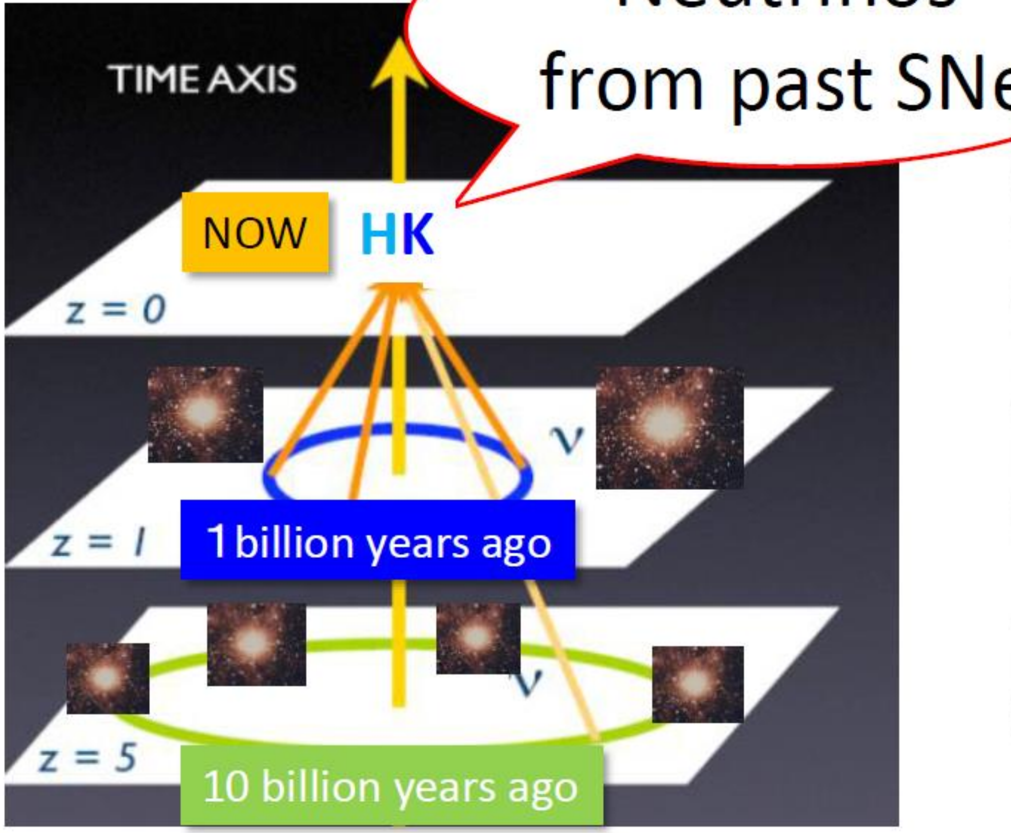
Conditions:

- Livermore simulation
- 10MeV threshold
- # range for no osc., N.H. and I.H.

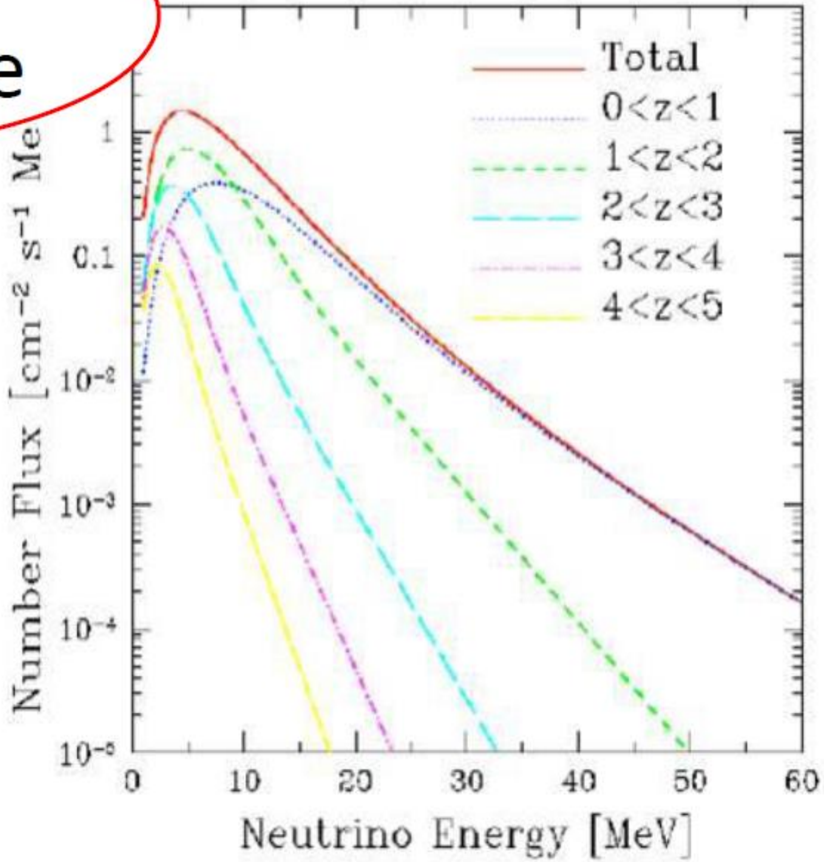
Supernova Relic Neutrino (SRN)

10^{10} stellar/galaxy × 10^{10} galaxy × 0.3%(become SNe) ~$O(10^{17})$SNe

Neutrinos from past SNe



Beginning of the universe



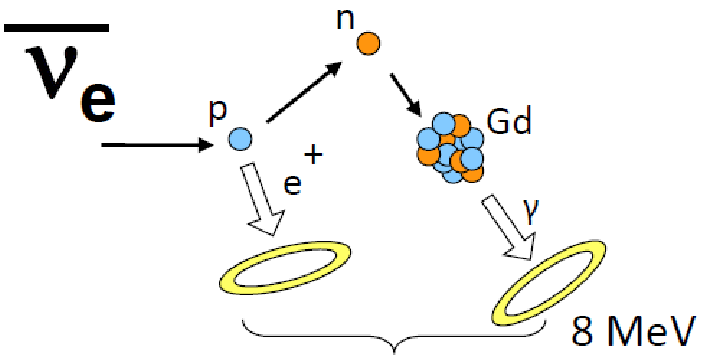
S.Ando, Astrophys.J. 607, 20(2004)

Theoretical flux prediction : 0.3~1.5 /cm2/s (17.3MeV threshold)

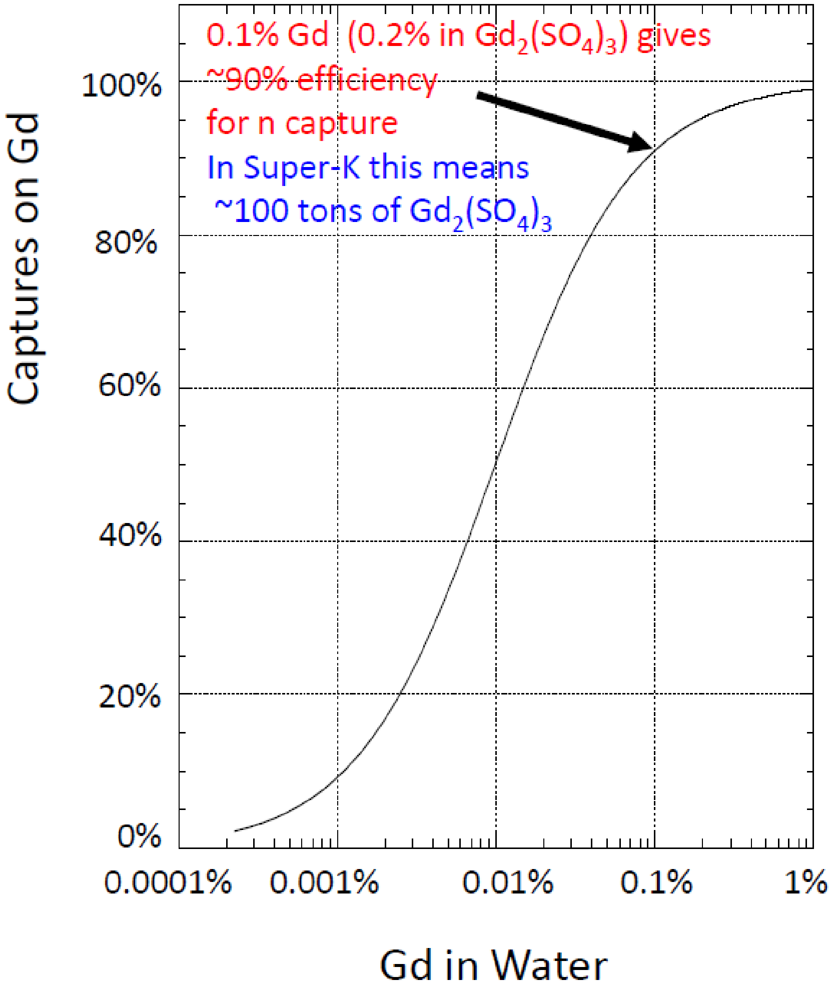
GADZOOKS! project

Identify $\overline{\nu}_e p$ events by neutron tagging with Gadolinium.

Gadolinium has large neutron capture cross section and emit 8MeV gamma cascade.



ΔT~30μs
Vertices within 50cm



0.1% Gd (0.2% in $Gd_2(SO_4)_3$) gives ~90% efficiency for n capture

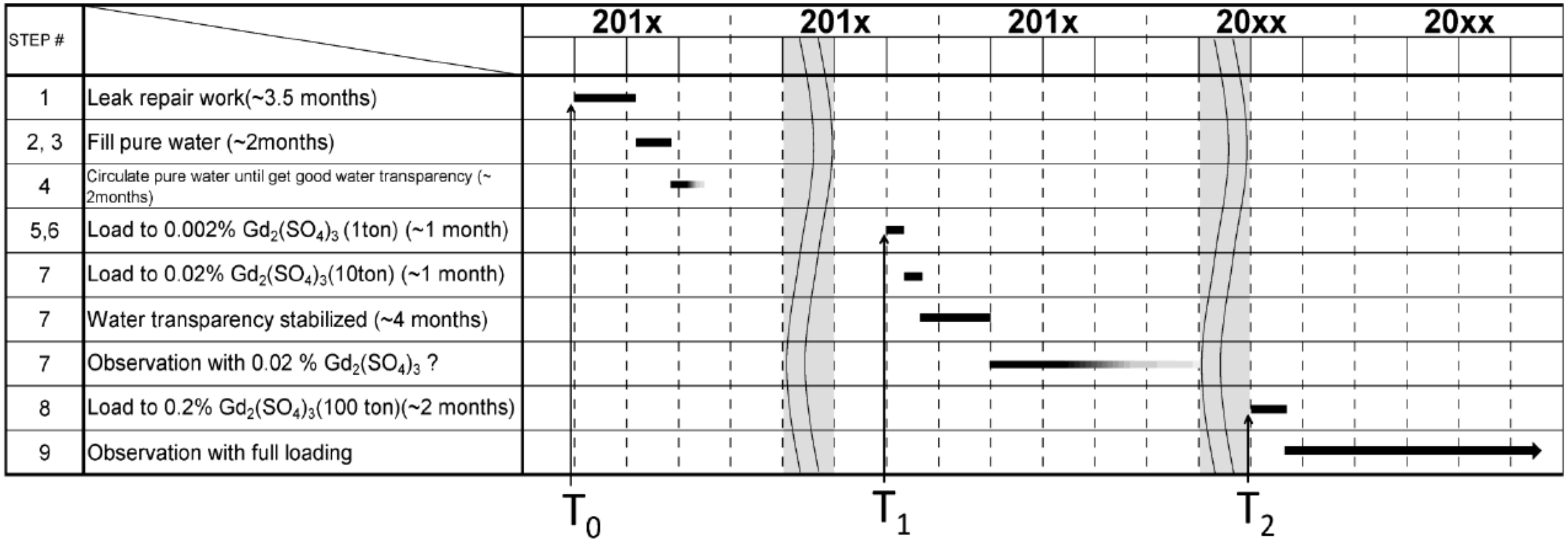
In Super-K this means ~100 tons of $Gd_2(SO_4)_3$

Physics targets:

(1) Supernova relic neutrino (SRN)
(2) Improve pointing accuracy for galactic supernova
(3) Precursor of nearby supernova by Si-burning neutrinos
(4) Reduce proton decay background
(5) Neutrino/anti-neutrino discrimination
(6) Reactor neutrinos

GADZOOKS Timeline

Preliminary



STEP #	
1	Leak repair work(~3.5 months)
2, 3	Fill pure water (~2months)
4	Circulate pure water until get good water transparency (~2months)
5,6	Load to 0.002% $Gd_2(SO_4)_3$ (1ton) (~1 month)
7	Load to 0.02% $Gd_2(SO_4)_3$(10ton) (~1 month)
7	Water transparency stabilized (~4 months)
7	Observation with 0.02 % $Gd_2(SO_4)_3$?
8	Load to 0.2% $Gd_2(SO_4)_3$(100 ton)(~2 months)
9	Observation with full loading

The introduction of Gadolinium $GdSO_4$ in SuperK will require 8 months interruption of SuperK operation. Should be planned at the same time as accelerator stop and ND280 upgrade installation. Schedule not fixed yet.

A few words about politics/organization

-1- While T2K and SuperK are separate collaborations it is planned that **HyperK will be a single collaboration** addressing both

-- with neutrino beam: cross-section and oscillation measurements. δ_{CP}

-- without the beam:

-- proton decays

-- solar neutrinos and geo-neutrinos

-- amospheric neutrinos

-- Supernovae, SN relics neutrinos

A few words about politics/organization

-2- The T2K-II proposal (including the notion of near detector upgrades) has received stage 1 approval from the JPARC PAC*).
Needs to come up with more precise scenario to improve systematics.

The accelerator upgrade (doubling frequency, and increasing intensity) is already started. (it benefits everyone at JPARC)

*) Program advisory committee

PAC minutes: T2K extension (2)

The SK collabor

neutron detect

physics (relic

program has not been fully evaluated.

Technical Reviews for
1. Beam line upgrades : Homework for IPNS/J-PARC
2. Near detector: Homework for you

The PAC endorses the physics program to attempt to establish evidence of non-zero CP violation in the lepton sector outlined by this proposal and recommends stage-1 status. To both complete the current T2K program and meet T2K-II goals significant upgrades of the J-PARC accelerator complex must be completed and done so in a timely manner. Before this proposal is to receive stage-2 approval detailed technical reviews should be held to examine the beam line upgrades necessary to achieve 1.3 MW operation and near detector upgrades. The PAC would like to see a demonstration of the proposed analysis improvements, in order to understand better how the systematic uncertainties change in the new higher acceptance analysis.

Katsuo Tokushuku KEK IPNS director

A few words about politics/organization

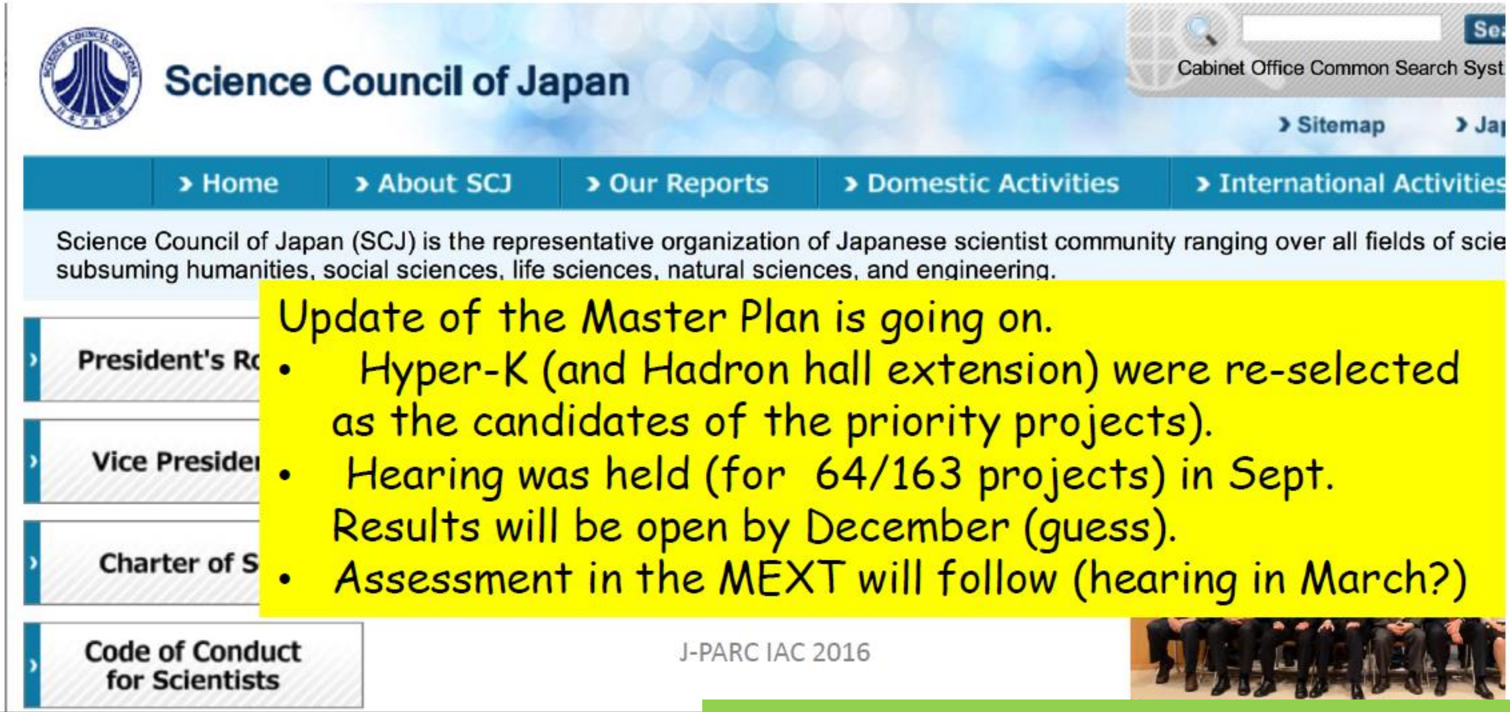
-3- The HyperK proposal was submitted in 1st quarter 2016 for one tank of 500M$

It has been accepted among the 27 ‘important’ (priority) projects on the MEXT road map.
The review process will continue end-2016 - 2017.
Approval could happen in second half of 2017.

Master Plan of Science Council of Japan for “Large Scale Research Project”

Saito-san’s Slide in May

- J-PARC upgrades and Hyper-K are selected as 27 important projects among 209 proposals under Japan Science Council !



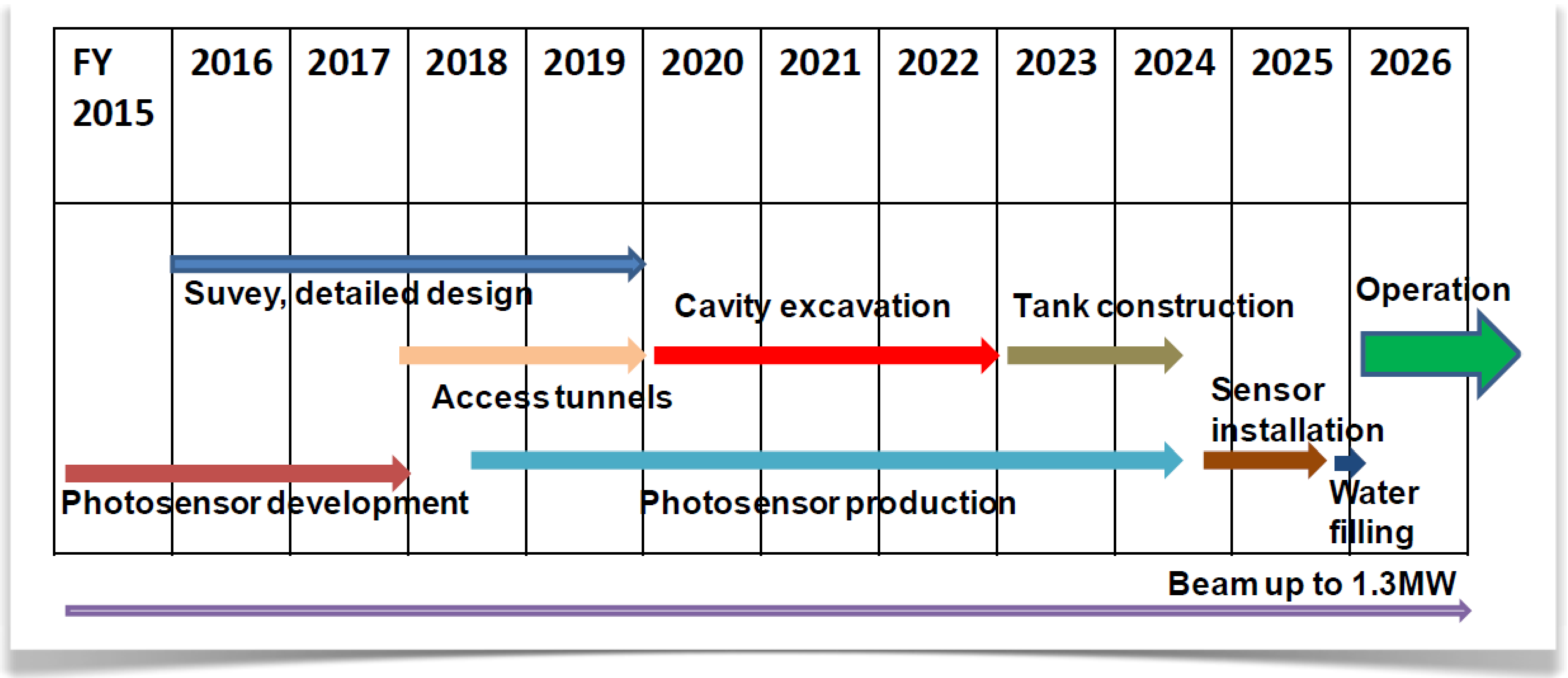
Science Council of Japan (SCJ) is the representative organization of Japanese scientist community ranging over all fields of scie subsuming humanities, social sciences, life sciences, natural sciences, and engineering.

Update of the Master Plan is going on.

- Hyper-K (and Hadron hall extension) were re-selected as the candidates of the priority projects).
- Hearing was held (for 64/163 projects) in Sept. Results will be open by December (guess).
- Assessment in the MEXT will follow (hearing in March?)

Katsuo Tokushuku KEK IPNS director

The Hyper-Kamiokande Timeline



- 2018 - 2025 HK construction
- 2026 onwards CPV study, Atm, Solar, Supernova ν study, Proton decay searches

The second (identical) tank start starts operation 6y after the first one.

A few words about politics/organization

-4- For the moment there is an official ‘protocollaboration’.
Expect that it will change very soon into a ‘construction collaboration’

There will be a lot to do and there are many «holes».

IT IS VERY TIMELY TO JOIN THE COLLABORATION

CONCLUSIONS

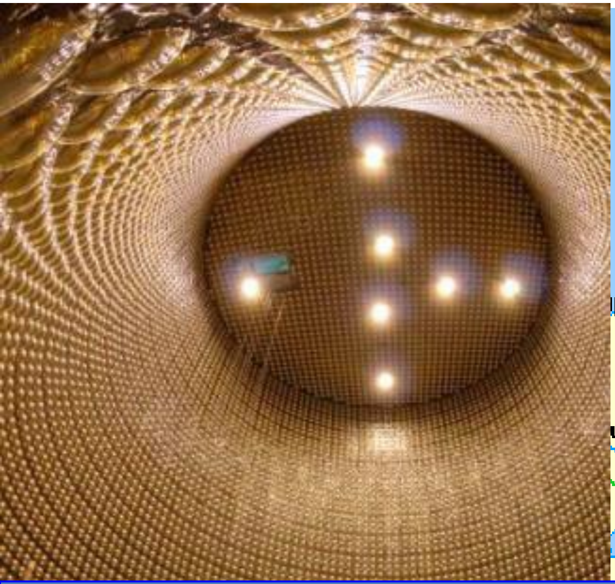
The T2K (+NA61) experiment is extremely successful → discovery of $\nu_\mu \rightarrow \nu_e$ oscillation!
this opens the way towards CP violation.

JPARC accelerator improvements and prospects are now impressive.
Experiment is approved for another factor 5 more data .
Extension (T2K-II) for an additional 2.5 times more until 2025.
The upgrade program is first priority of JPARC/KEK
→ more precise parameters and possibly first 3-4 σ observation for CP Violation
this requires continued improvement of systematics!
Upgrade of near detector organized: magnetic detector + intermediate Water Cherenkov

HyperK is an upgrade by a further factor 10-20. It is highly placed on Japan road map.
-- It has been submitted to MEXT for approval
-- CDR has been published and reviewed favorably by the HK advisory committee.
-- Seeking approval towards the end of 2017 for a start of exploitation in 2026.

HYPERK is a highly competitive for the study of neutrino oscillations (discovery of CPV)
+ unparalleled program for proton decay, supernovae observations (near and relic)
and other astrophysical sources.

The complemetarity with NOvA, JUNO, Atmospheric programs PINGU and ORCA,
and with DUNE, is compelling.



Idea of T2K was born 1999-2001 hep-ex/0106019 combining:

-- existing SuperKamiokande detector (50kton W.Č., 22.5 kton fiducial)

-- JAERI-KEK Japanese Proton Accelerator Research Complex (JPARC) at TOKAI including a high power, 0.75MW/30GeV Proton Synchrotron neutrino beam from pion decay $\pi^+ \rightarrow \mu^+ \nu_\mu$

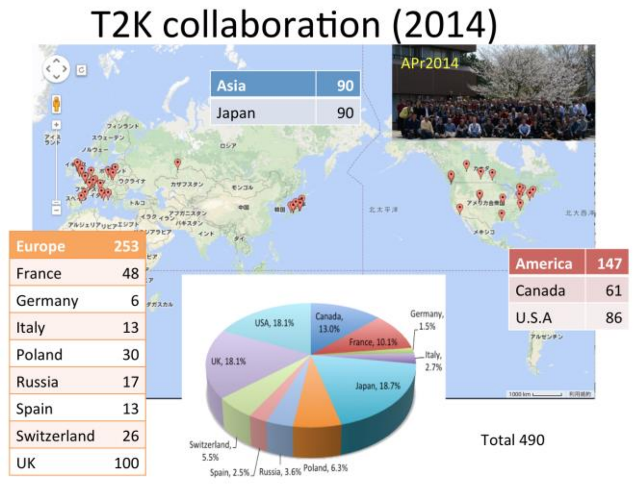
-- baseline 295 km ➔ neutrino energy for first maximum is ~650 MeV achievable by pion-decay beam at 2.5 degrees off-axis

T2K Long Baseline Neutrino Oscillation Experiment

Attack fundamental questions of nature, eg,

- How matter (us) was created in the Universe
- What is the ultimate law to govern extreme microscopic world

through exploring most elusive elementally particle called "neutrino"



T2K collaboration (2014)

Asia	90
Japan	90

Europe	253
France	48
Germany	6
Italy	13
Poland	30
Russia	17
Spain	13
Switzerland	26
UK	100

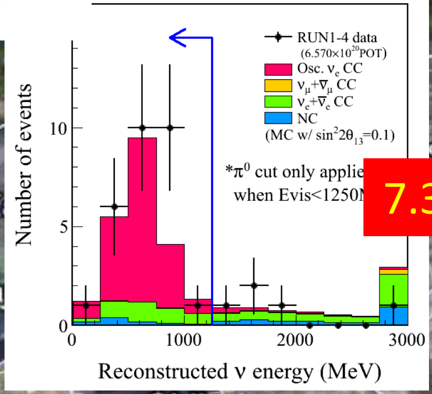
America	147
Canada	61
U.S.A	86

Total 490

Super-Kamiokande

$40m^{\phi}$x$40m^{H}$
50kt Water Cherenkov det.

Discovery of appearance of electron neutrino

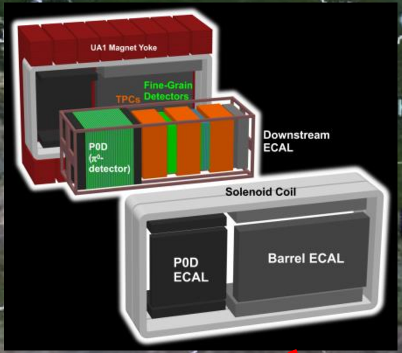


7.3σ

Muon neutrino beam

295km

Near neutrino detector



- T2K collaboration ~500 collaborators from 59 institutions, 11 countries
- Funded in FY2004, Started measurements in 2010
- First discovery of ν_e appearance in ν_μ beam
- Best measurement of ν_μ disappearance
- Opens the door for CP violation measurements
  - Could be the key to matter in the universe!

The HyperK physics list

-- PMNS matrix
  -- Mass Hierarchy
  -- CP violation and CP phase determination
  -- precision determination of theta_23

-- Beyond PMNS (unitarity, sterile neutrinos etc..)

-- Astrophysical neutrinos
  -- SuperNovae signals
  -- solar neutrinos

-- proton decay
  -- e+ π^0 and other 1st family decays
  -- decays with Kaons

Main actors in the global scene

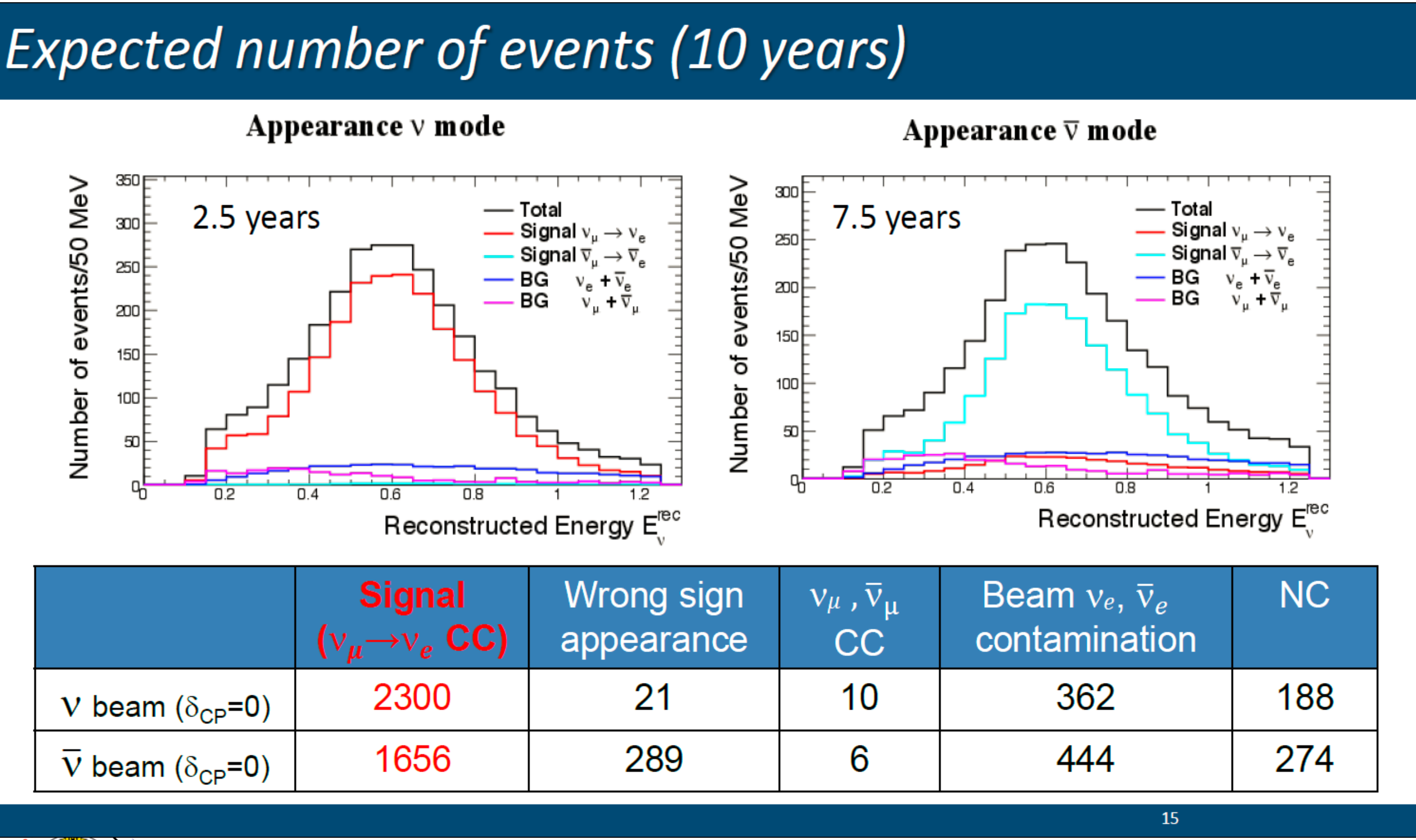
T2K,T2KII, SK-Gd, NOvA, JUNO/RENO50, PINGU, ORCA, DUNE

A very large program for the LSND eV region (will not discuss here) and towards future (SHIP, FCC…)

SK-Gd, JUNO/RENO50, DUNE
JUNO/RENO50

JUNO/RENO50, DUNE

(13 years for just one tank)



Expected number of events (10 years)

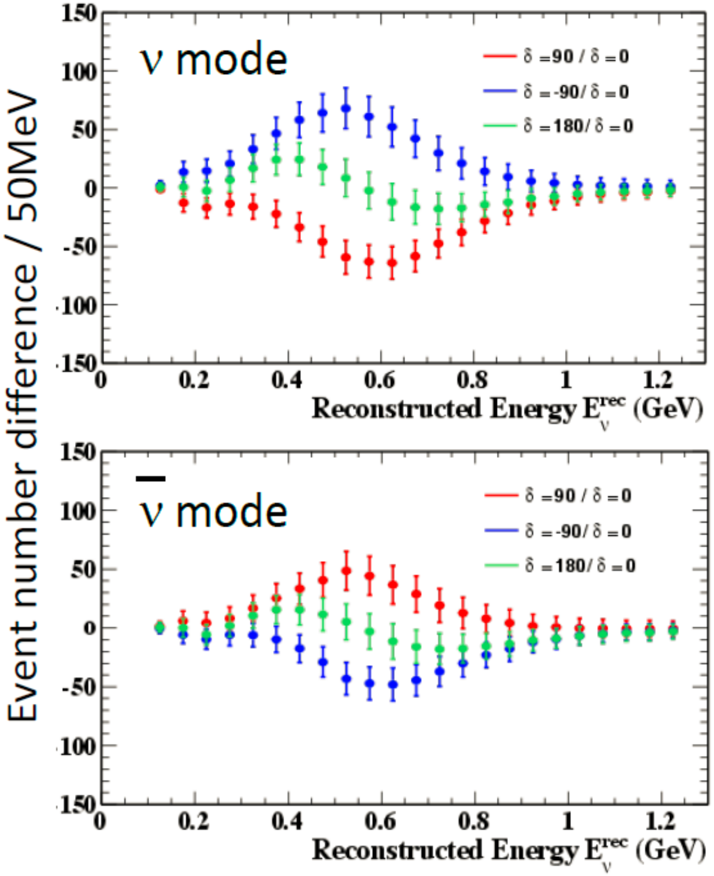
Appearance ν mode

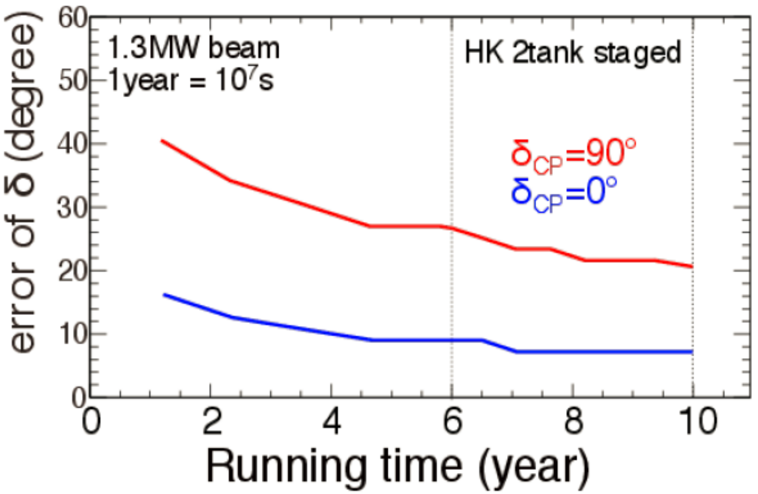
Appearance $\bar{\nu}$ mode

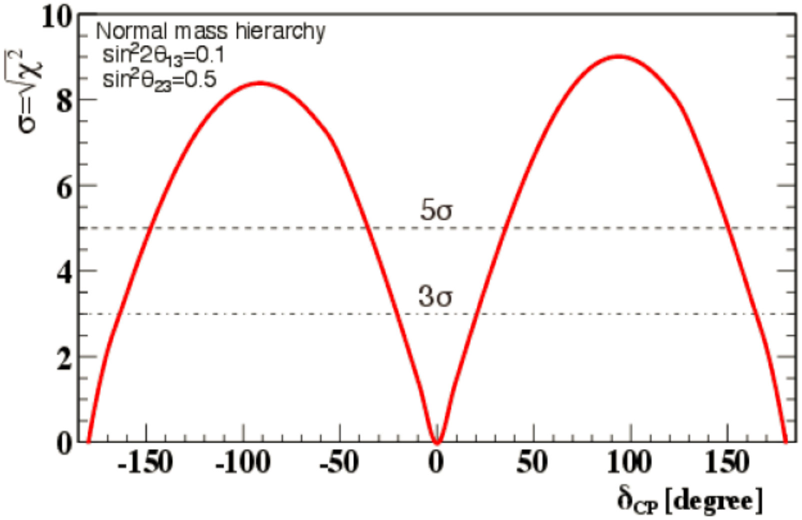
	Signal ($\nu_\mu \rightarrow \nu_e$ CC)	Wrong sign appearance	ν_μ , $\bar{\nu}_\mu$ CC	Beam ν_e, $\bar{\nu}_e$ contamination	NC
ν beam (δ_{CP}=0)	2300	21	10	362	188
$\bar{\nu}$ beam (δ_{CP}=0)	1656	289	6	444	274

δ_{CP} sensitivity

Difference from δ_{CP}=0

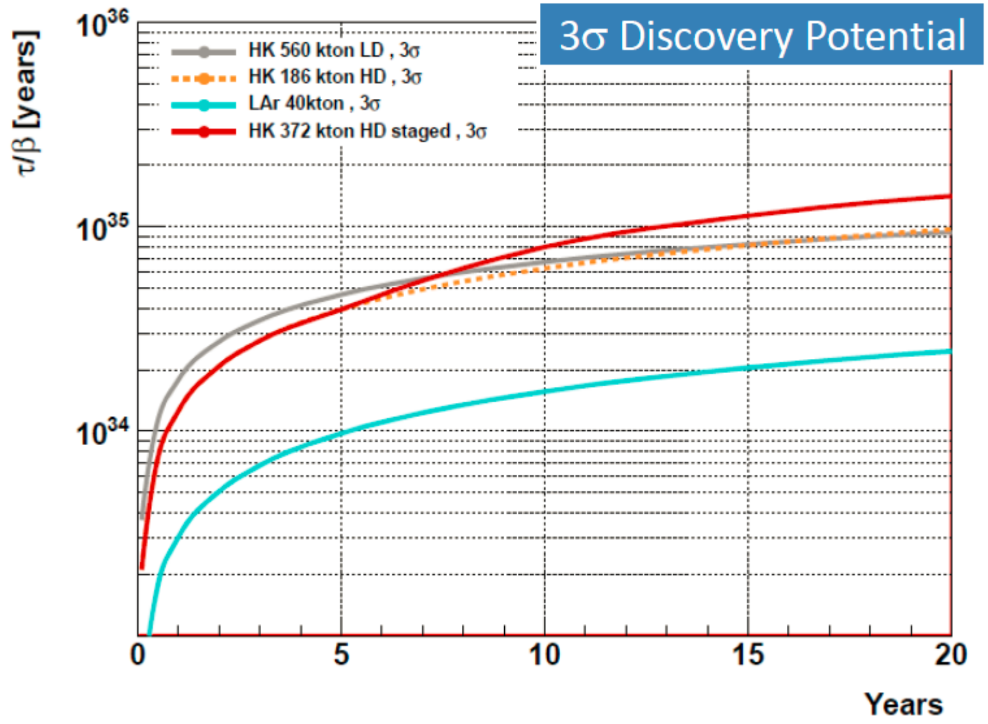


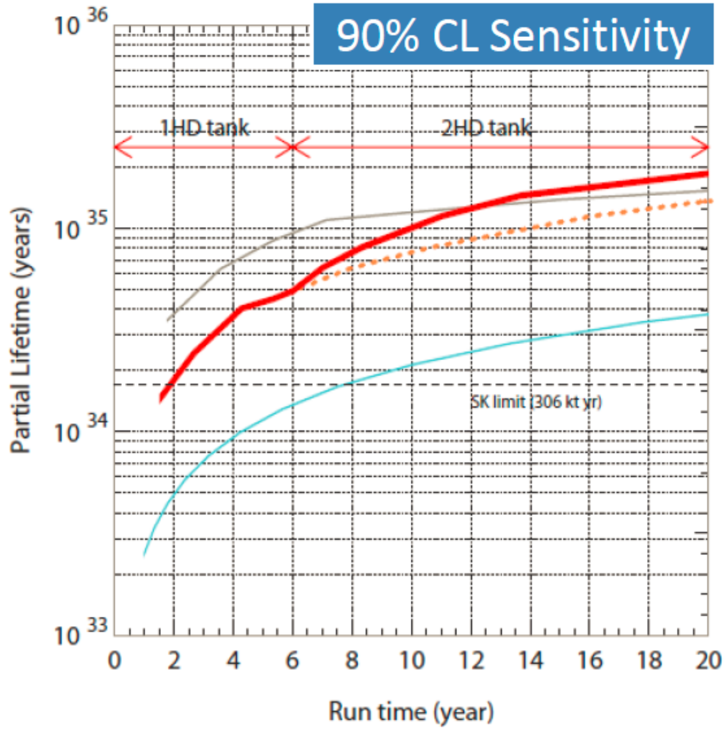




Proton decay

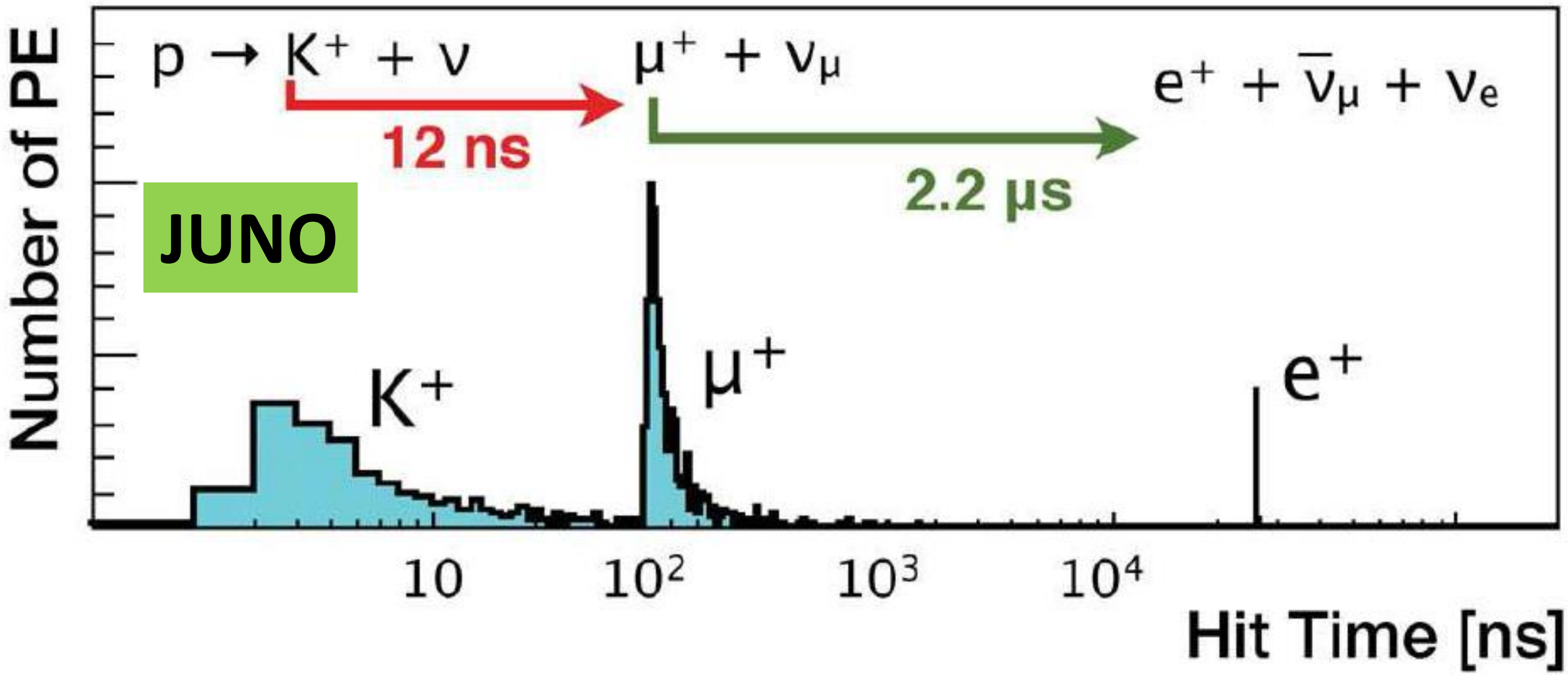
$P \rightarrow e^+ \pi^0$: sensitivity





- ✓ > 1×10^{35} years after 2.7 Mton yr (90%CL) or 3σ discovery with 4.0 Mtonyr.
- ✓ If proton lifetime is near the current Super-K limit of 1.7×10^{34} years Hyper-K will observe a positive signal at 8.9σ in 2.7 Mtonyr exposure.

(Lines for the liquid argon experiment have been generated based on numbers in the literature (efficiency: 45% bkg: 1 event/Mtonyr).)



LAr numbers taken
from DUNE CDR 2015

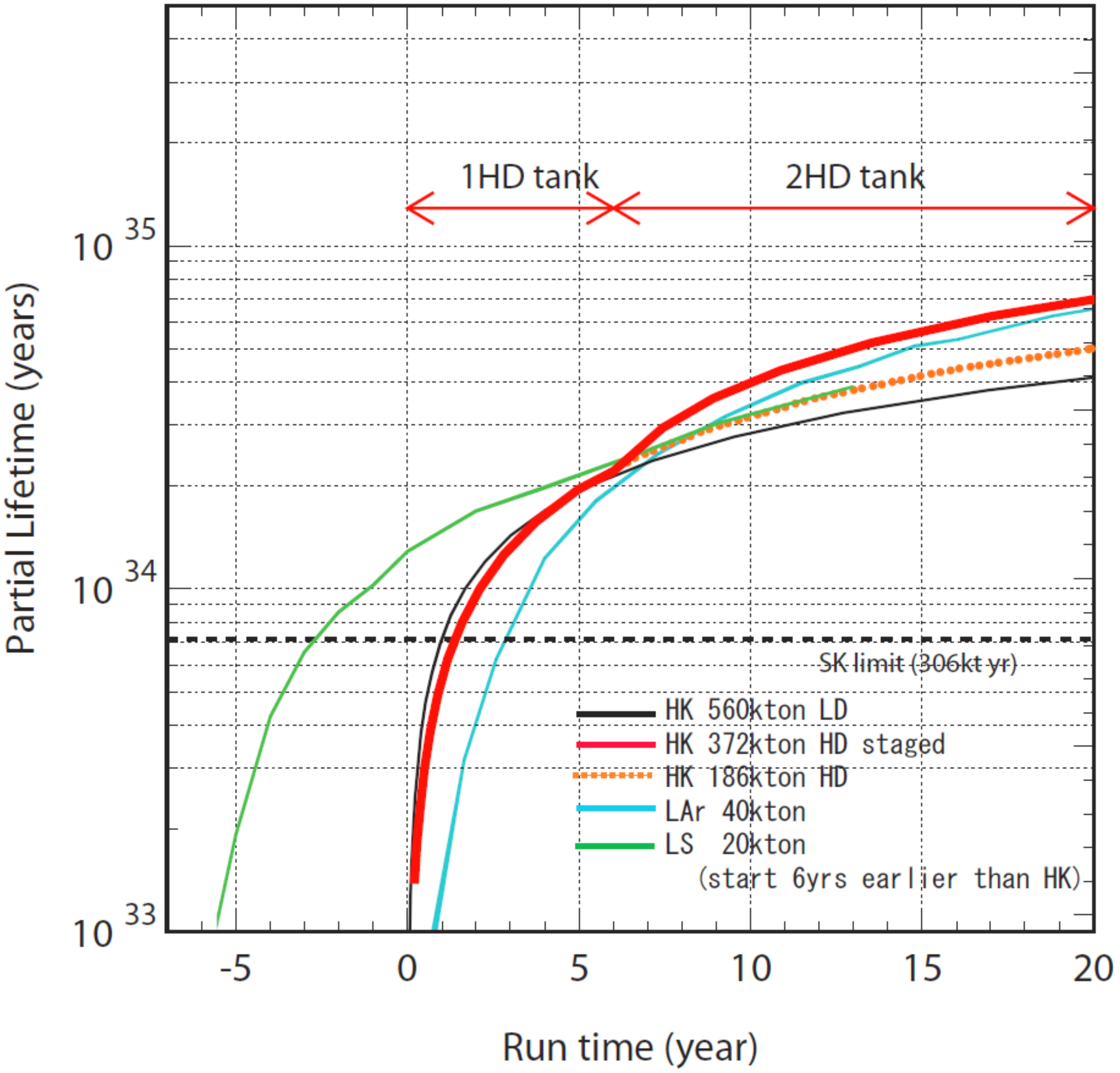
BG / Mton yr	0.7,0.9,1916	~1
10yr. Sens. 90%	4.0×10^{34}	3.3×10^{34}

- LAr exhibits good sensitivity to decay modes with a Kaon present
  - Significant advantage over water Cherenkov detectors
- Most complementary physics
  - If a signal is present, it should be discernible at both HK and a LAr detector
  - In-situ measurements of BG kaon processes with LAr will help HK

But JUNO might be there first

$p \rightarrow K^+ \nu$ sensitivity

Here, JUNO expt (liquid Scintillator (LS) is competitive and will be earlier.



Atmospheric neutrinos

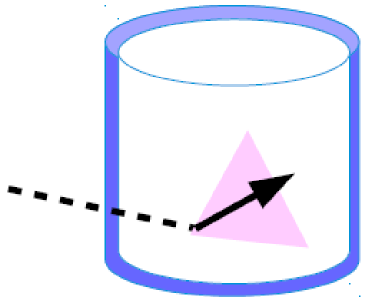
Comparison to Current Super-K Exposure

	Hyper-K **HD**	SK-IV
Fiducial Vol.	**186 kton**	22.5 kton
Eff. Area	**6,430 m^2**	1500 m^2
Protons	**6.0×10^{34}**	7.5×10^{33}
Neutrons	**5.0×10^{34}**	6.0×10^{33}
Fully Contained μ-/e-like	**246,600**	41,000
Partially Contained μ-like	**21,300**	3,100
Upward-Going μ	**24,300**	7,400

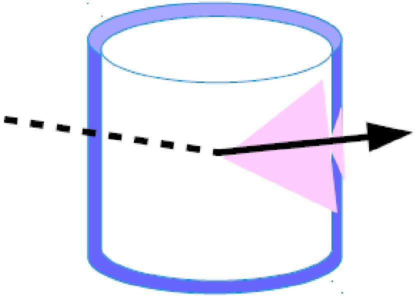
- Hyper-K sensitivity studies are based on Super-K simulation and reconstruction
  - Analyses exposures have been adjusted to account for difference in fiducial volume and effective area between Hyper-K and Super-K
- Event rates compare 10 years of Hyper-K and 12.8 years of SK

Hyper-K Atmospheric ν Analysis Samples

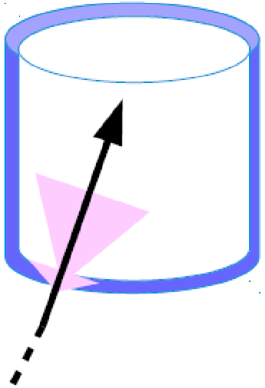
Fully Contained (FC)

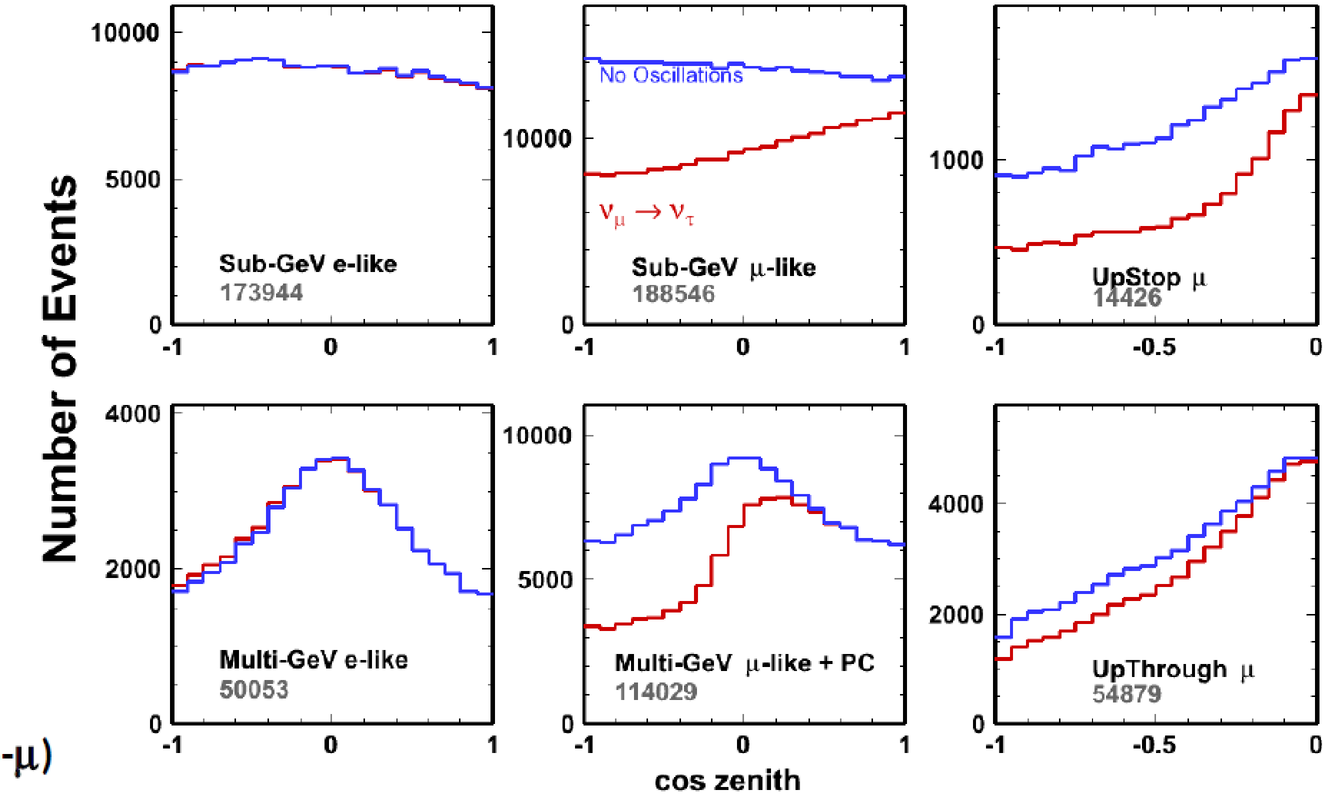


Partially Contained (PC)



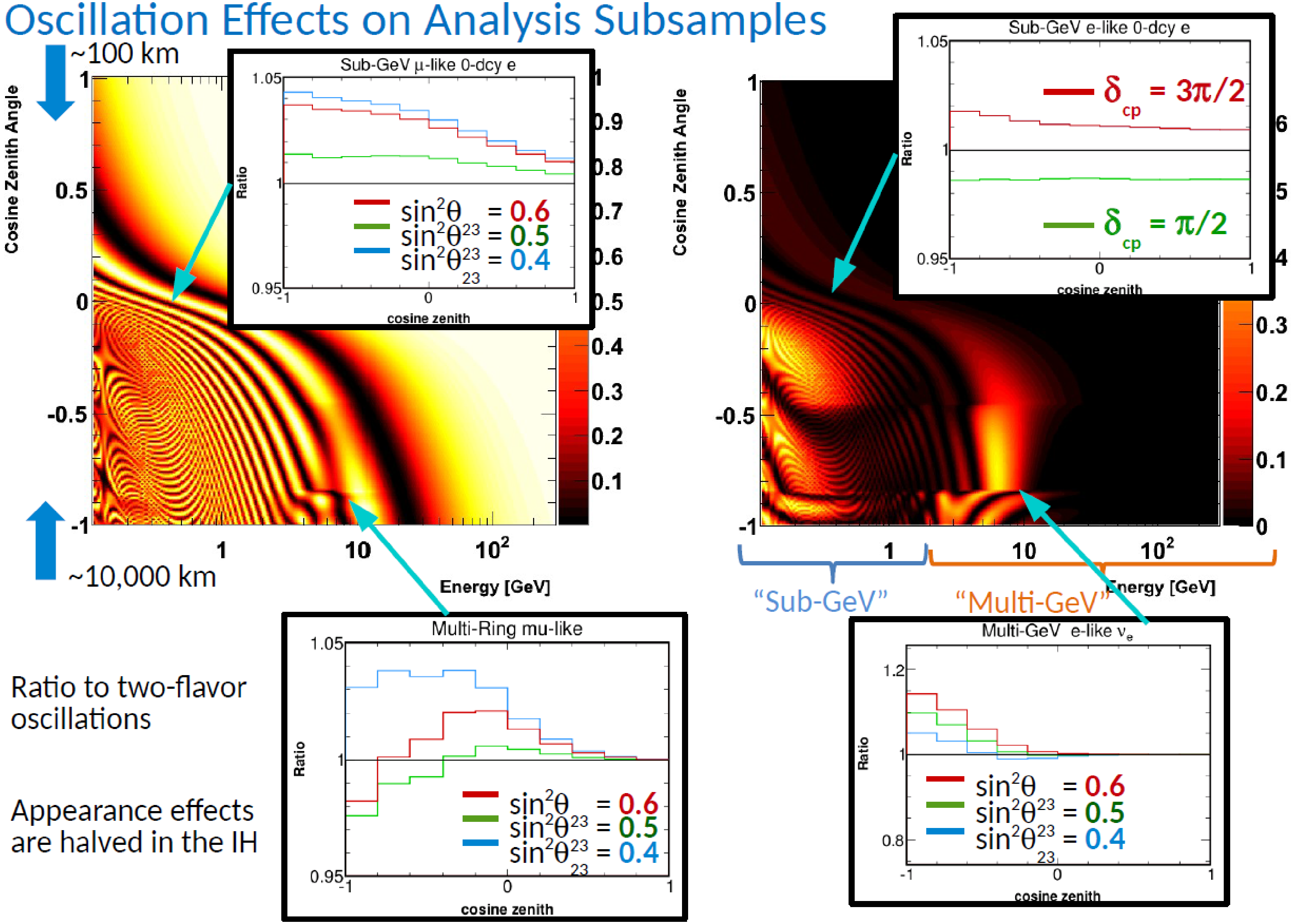
Upward-going Muons (Up-μ)





- In total **19** analysis samples: multi-GeV e-like samples are divided into ν-like and $\bar{\nu}$-like subsamples
- Dominated by ν_μ->ν_τ oscillations
- Interested in subdominant contributions to this picture
  - Ie three-flavor effects, Sterile Neutrinos, LIV, etc.

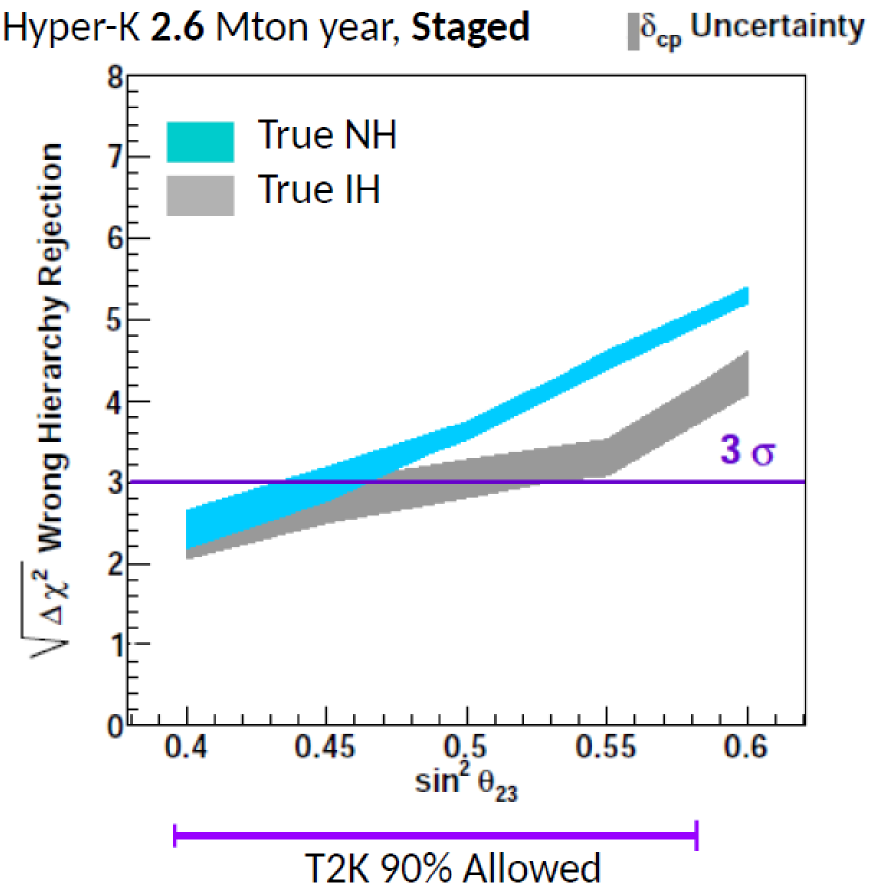
Oscillation Effects on Analysis Subsamples

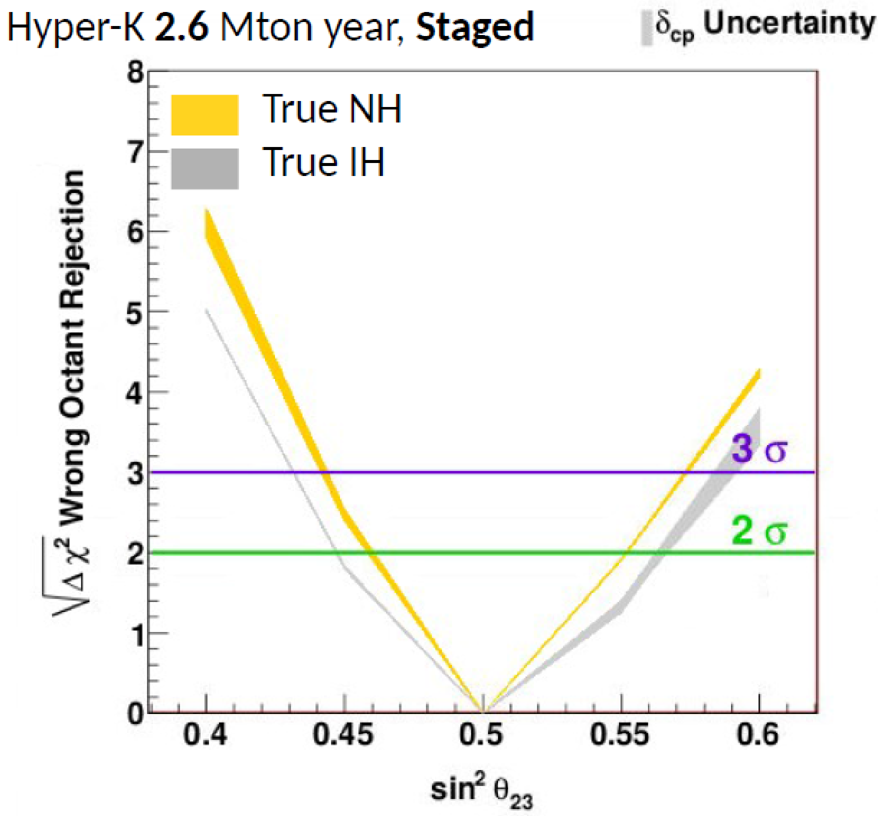


Ratio to two-flavor oscillations

Appearance effects are halved in the IH

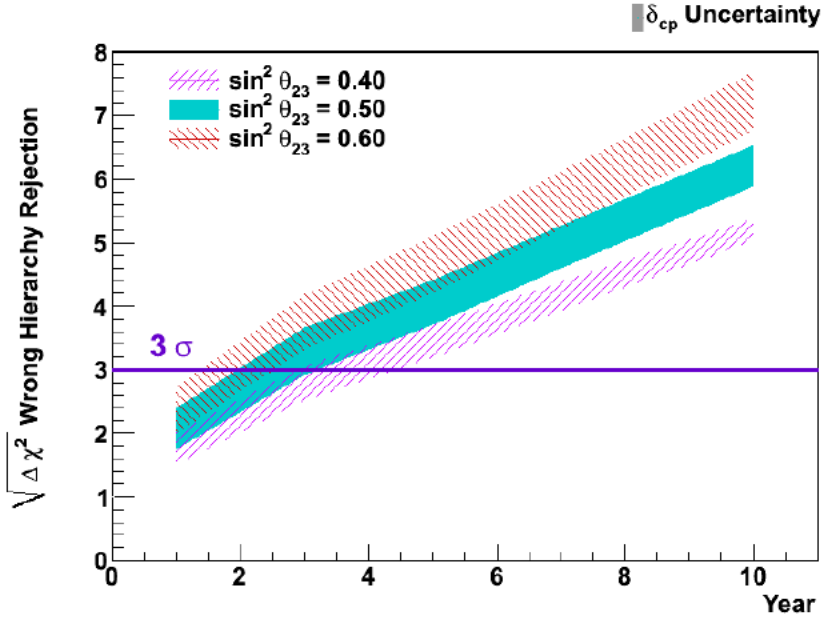
Hyper-K Sensitivity 10 Years, Staging Scenario

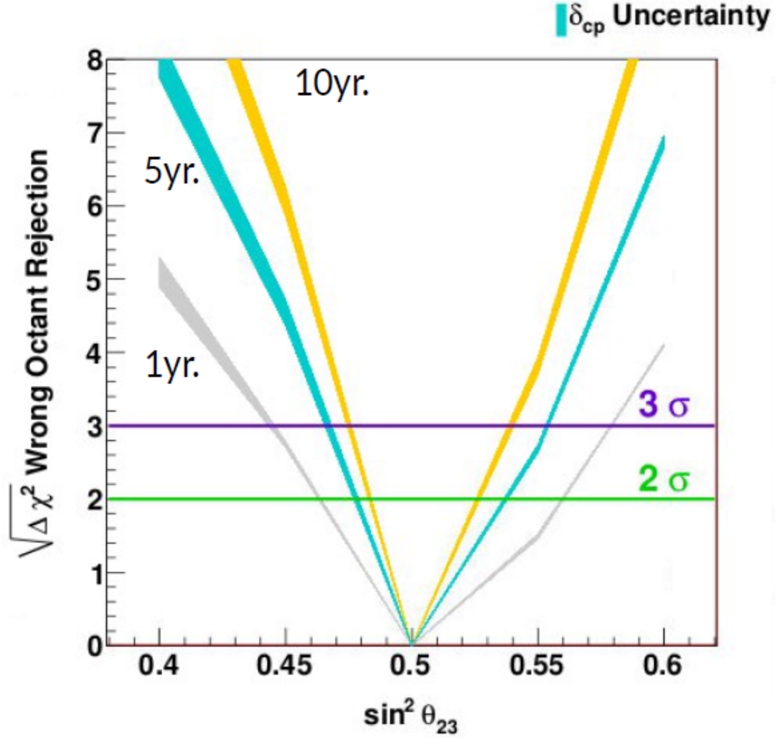




- Expect better than ~3σ sensitivity to the mass hierarchy using atmospheric neutrinos alone
- 3σ Octant determination possible if $|\theta_{23} - 45°| > 4°$

Combination with Beam Neutrinos : Hierarchy and Octant

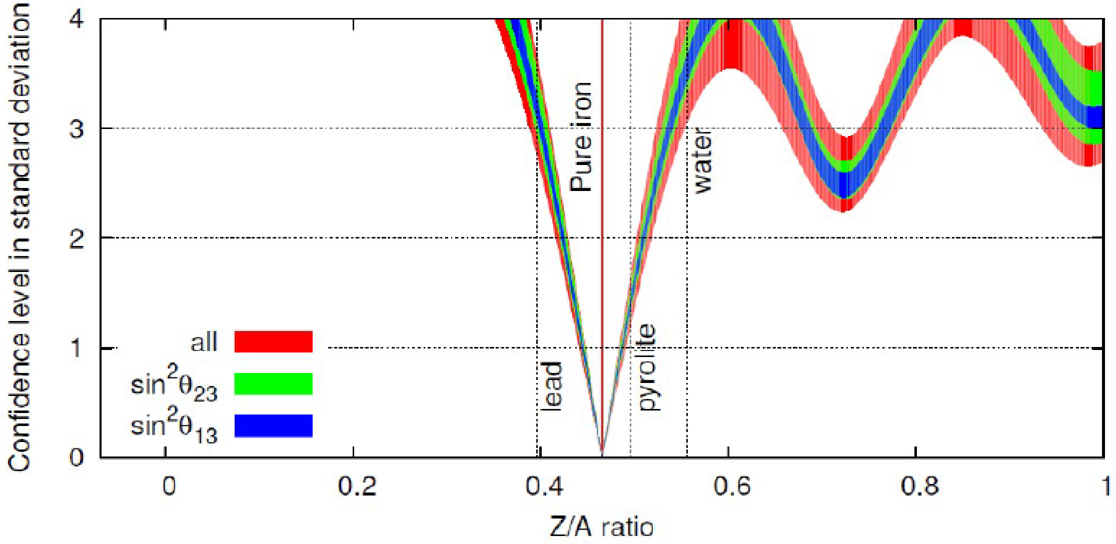


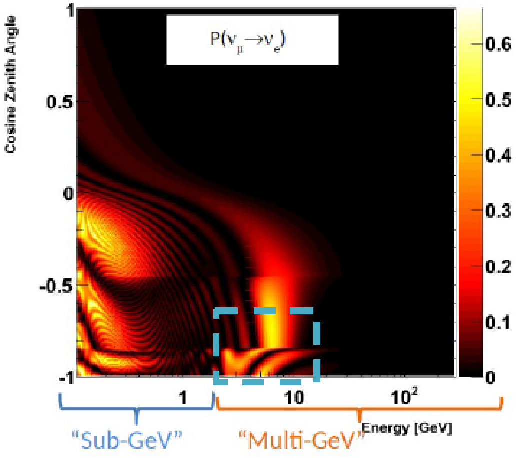


- For the optimal (worst) set of parameters the combined measurement can determine the mass hierarchy with ~1.5 (4.0) years of data
- Here the beam exposure after 10 years is assumed to be $2.7\text{x}10^{22}$ POT , divided in a 1:3 ratio between neutrinos and antineutrinos
  - POT have been scaled evenly for shorter run periods
- 3σ Octant determination possible if $|\theta_{23} - 45°| > 3°$

Geophysics: Chemical composition of Earth’s Outer Core

Sensitivity to Outer Core Chemical Composition, 10 Mton yr





- Density profile of the Earth is well known from seismology
  - Outer core is thoughts to be made of Fe+Ni and some other light element (unknown)
- Chemical composition of the Earth’s core (Z/A ratio) is essential to understanding the formation of the Earth and its magnetic field
- Hyper-K can begin making measurements in this as yet unopened field
- <u>Any measurement</u> is of interest to the geophysics community , even if errors are large
- With a 10 Mton year exposure Hyper-K can exclude a lead- and water-based cores
- Technique is complementary to that of large neutrino telescopes

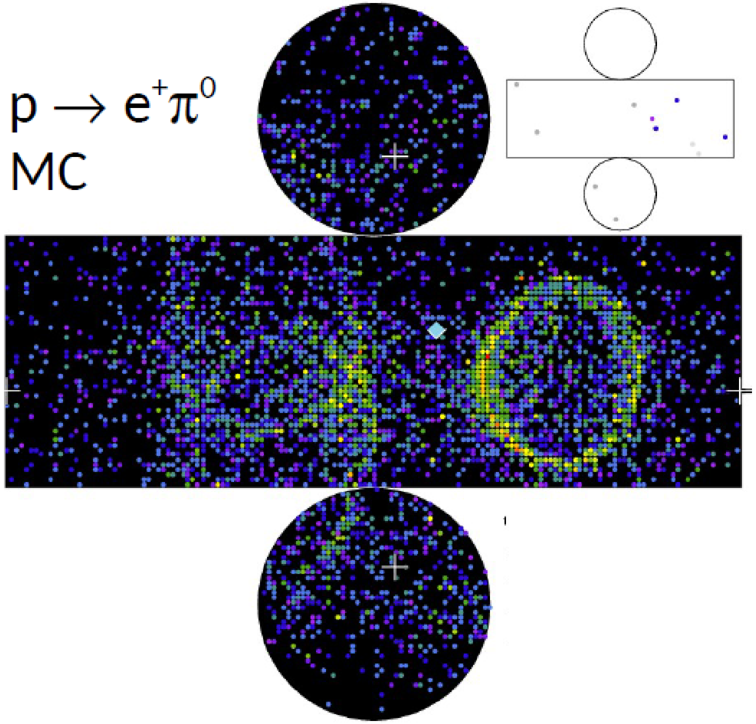
Proton Decay: p → e+π0

Hyper-K Selection

- 2 or 3 e-like rings
- No decay-e
- $85 < M_{\pi^0} < 185$ MeV/c² (3ring)
- $800 < M_p < 1050$ MeV/c²
- $p_{tot} < 250$MeV/c

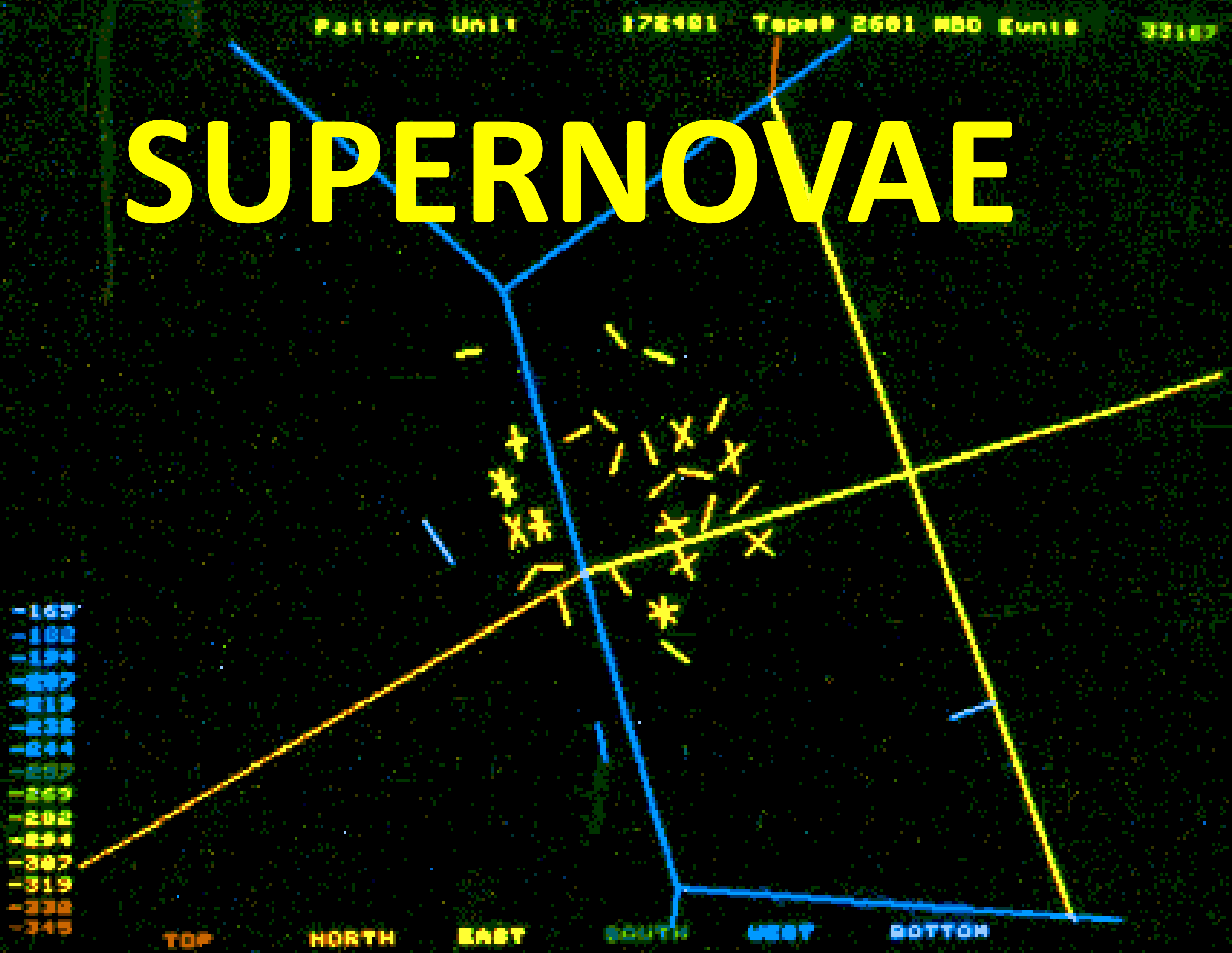
	Hyper-K	LAr
Signal ε	~39%	45%
BG / Mton yr	0.7	~1
10yr. Sens. 90%	**1.0×10^{35} yr**	$\sim 10^{34}$

* LAr numbers from JHEP 0704 (2007) 041



- Efficiency and background rates are similar for Hyper-K and LAr detector
  - This is basically true for other lepton + π modes as well
  - Smaller size of LAr detector makes it less competitive, generally nuclear effects are expected to be larger
- **Hyper-K** is the only effective way to probe this decay beyond existing limits
  - A 40 kton LAr detector would provide supporting evidence if $\tau \sim 10^{34}$ years

SUPERNOVAE


Pattern Unit 178401 Tape# 2601 NBD Evnt# 33167
-169
-182
-194
-207
-219
-232
-244
-257
-269
-282
-294
-307
-319
-332
-345
TOP
NORTH
EAST
SOUTH
WEST
BOTTOM

Galactic SN Burst Neutrino Events

Neutrino source	1 Tank HD	2 Tank HD	LOI
$\bar{\nu}_e + p$	49,000～68,000	98,000～136,000	165,000～230,000
$\nu_e + e^-$	2,100～2,500	4,200～5,000	7,000～8,000
$\nu_e + {}^{16}O$ CC	80～4,100	160～8,200	300～14,000
$\bar{\nu}_e + {}^{16}O$ CC	650～3,900	1,300～7,800	2,000～13,000
NC γ	～2,500	～5,000	～7,500
$\nu_e + e^-$ (Neutronization)	6～40	12～80	20～130
Total events.	52,000～79,000	104,000～158,000	170,000～260,000

Energy threshold is 5MeV in all cases.
NC is roughly scaled from Langanke et al. PRL 76 2629, 1996

10kpc, Livermore model

Large statistics will make it possible to study SN mechanism in detail

3σ CPV sensitivity over 75% of δ after 13 yrs.

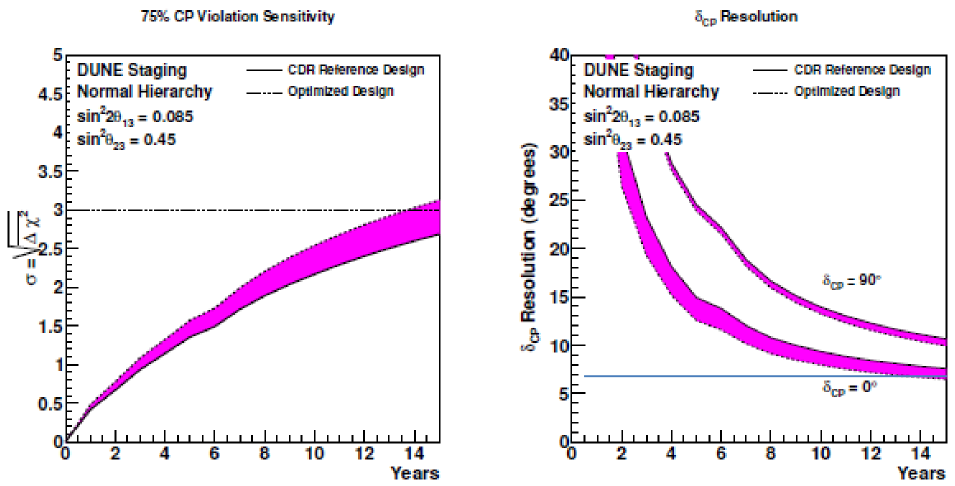
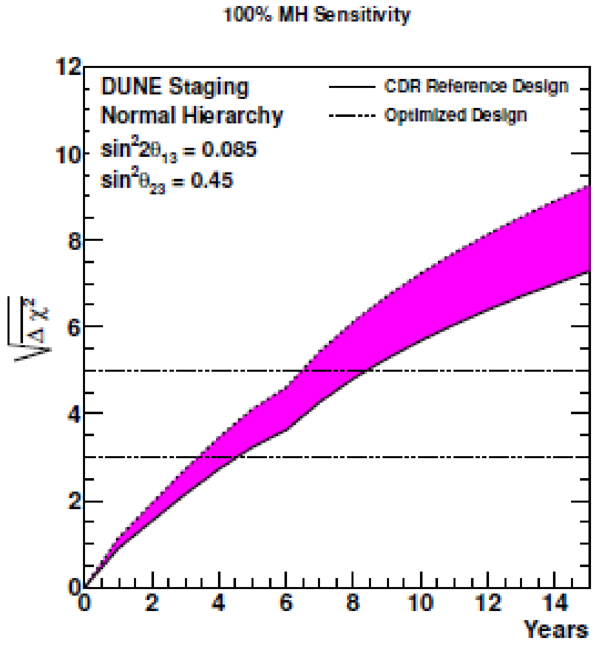
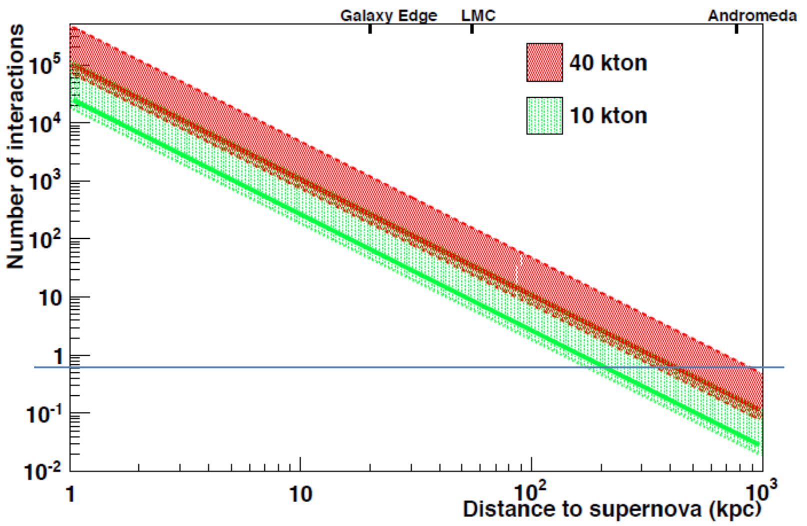


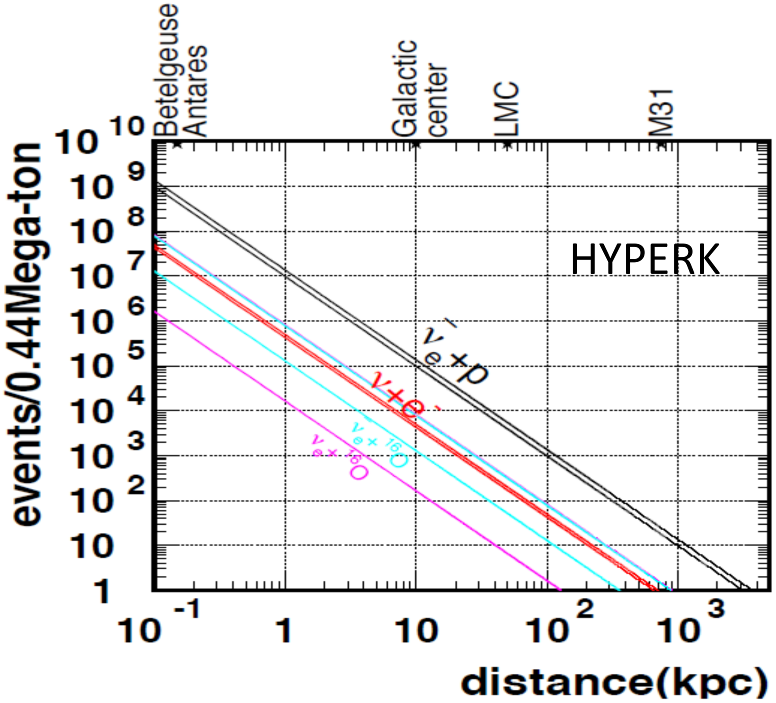
Figure 2.2: The significance with which CP violation can be determined for 75% of δ_{CP} values (left) and the expected 1σ resolution (right) as a function of exposure in years using the proposed staging plan outlined in this chapter. The shaded regions represent the range in sensitivity due to potential variations in the beam design. The plots assume normal mass hierarchy.



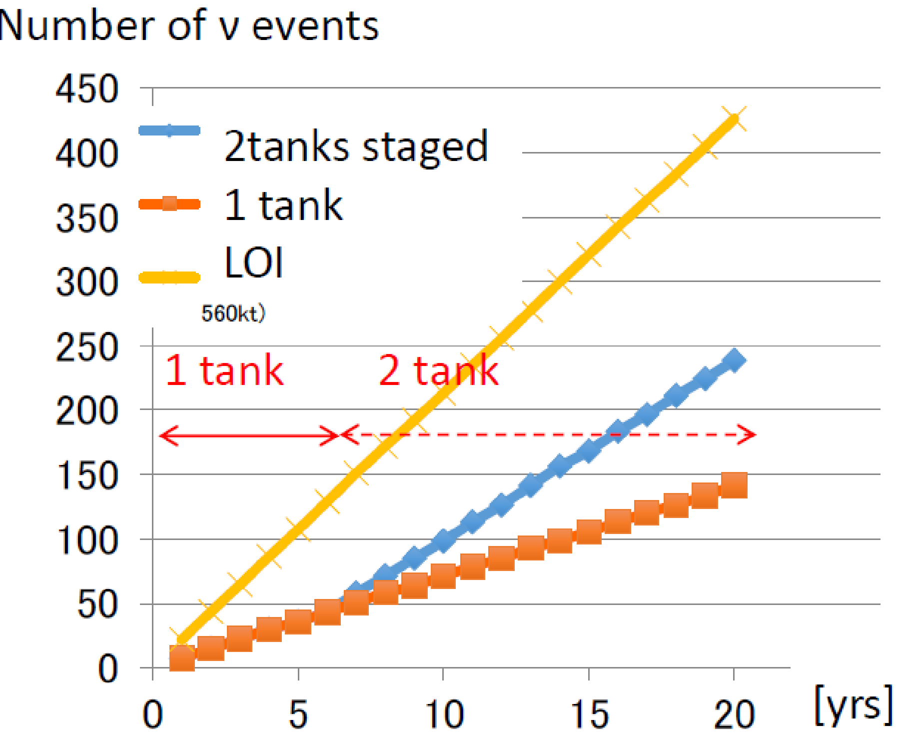
SUPERNOVAE

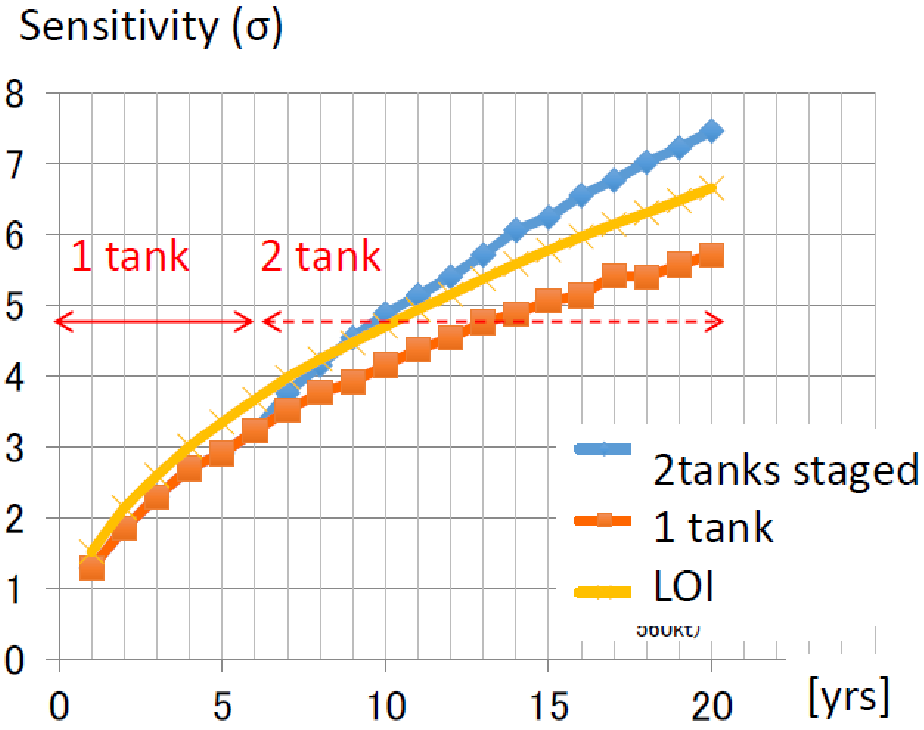
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$





Supernova Relic Neutrino Sensitivity



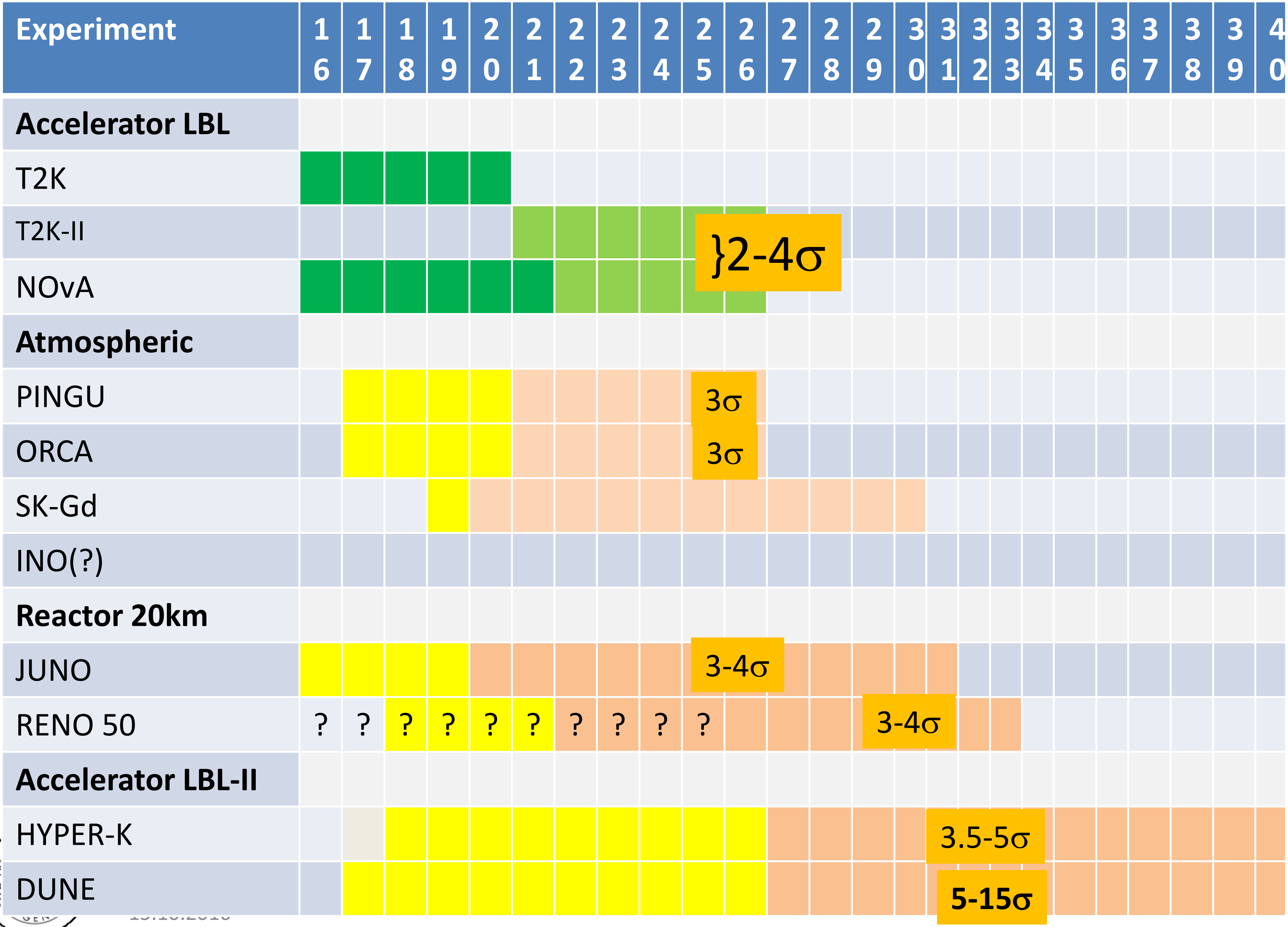


- 2 tanks staged : ~100 events / 10 yrs. ~4.8 σ non-0 significance.
- 1 tank : ~70 events / 10 yrs. ~4.2 σ
  - Neutron tagging efficiency 70% is assumed
- LOI : ~200 events / 10 yrs. ~4.7 σ

SRN flux uncertainty will be ±15% after 20y with 2 tanks staged.

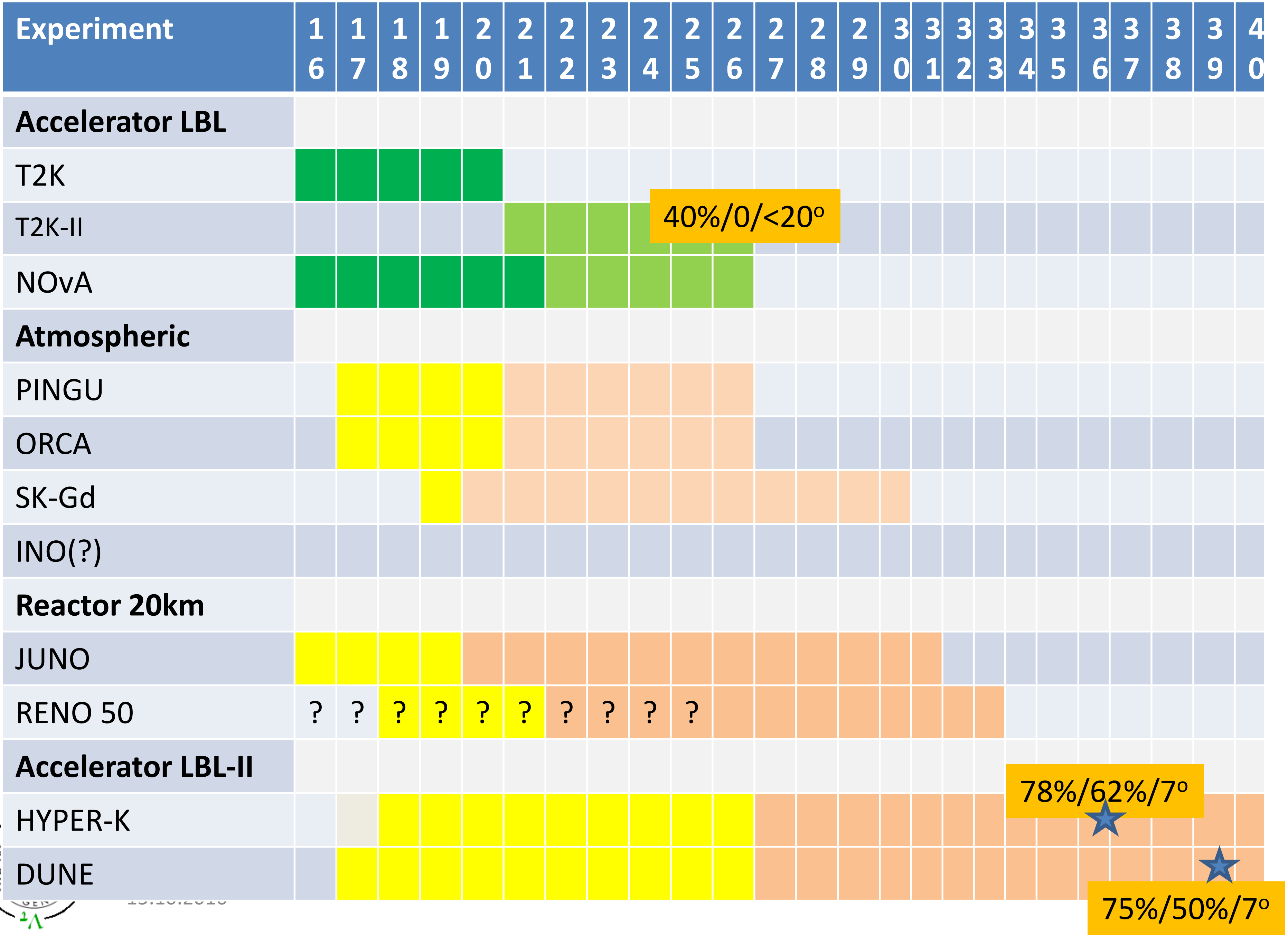
Model definition and further spectrum analysis will be possible.

The players Mass Ordering



Experiment	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Accelerator LBL																									
T2K	🟩	🟩	🟩	🟩	🟩																				
T2K-II						🟩	🟩	🟩	🟩	🟩 }2-4σ	🟩														
NOvA	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩														
Atmospheric																									
PINGU		🟨	🟨	🟨	🟨	🟧	🟧	🟧	🟧	🟧 3σ	🟧														
ORCA		🟨	🟨	🟨	🟨	🟧	🟧	🟧	🟧	🟧 3σ	🟧														
SK-Gd				🟨	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧										
INO(?)																									
Reactor 20km																									
JUNO	🟨	🟨	🟨	🟨	🟧	🟧	🟧	🟧	🟧	🟧 3-4σ	🟧	🟧	🟧	🟧	🟧	🟧									
RENO 50	?	?	🟨 ?	🟨 ?	🟨 ?	🟨 ?	🟧 ?	🟧 ?	🟧 ?	🟧 ?	🟧	🟧	🟧	🟧 3-4σ	🟧	🟧	🟧	🟧							
Accelerator LBL-II																									
HYPER-K			🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟧	🟧	🟧	🟧	🟧 3.5-5σ	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
DUNE		🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟧	🟧	🟧	🟧	🟧 **5-15σ**	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧

The players CP Violation fraction at 3σ /5σ /(1σ error at δ=0)



Experiment	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Accelerator LBL																									
T2K	🟩	🟩	🟩	🟩	🟩																				
T2K-II						▩	▩	▩	▩	▩	▩														
NOvA	🟩	🟩	🟩	🟩	🟩	🟩	▩	▩	▩	▩	▩														
Atmospheric																									
PINGU		🟨	🟨	🟨	🟨	▨	▨	▨	▨	▨	▨														
ORCA		🟨	🟨	🟨	🟨	▨	▨	▨	▨	▨	▨														
SK-Gd				🟨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨										
INO(?)																									
Reactor 20km																									
JUNO	🟨	🟨	🟨	🟨	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧									
RENO 50	?	?	🟨 ?	🟨 ?	🟨 ?	🟨 ?	🟧 ?	🟧 ?	🟧 ?	🟧 ?	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧							
Accelerator LBL-II																									
HYPER-K			🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧 ★	🟧	🟧	🟧	🟧
DUNE		🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧 ★	🟧

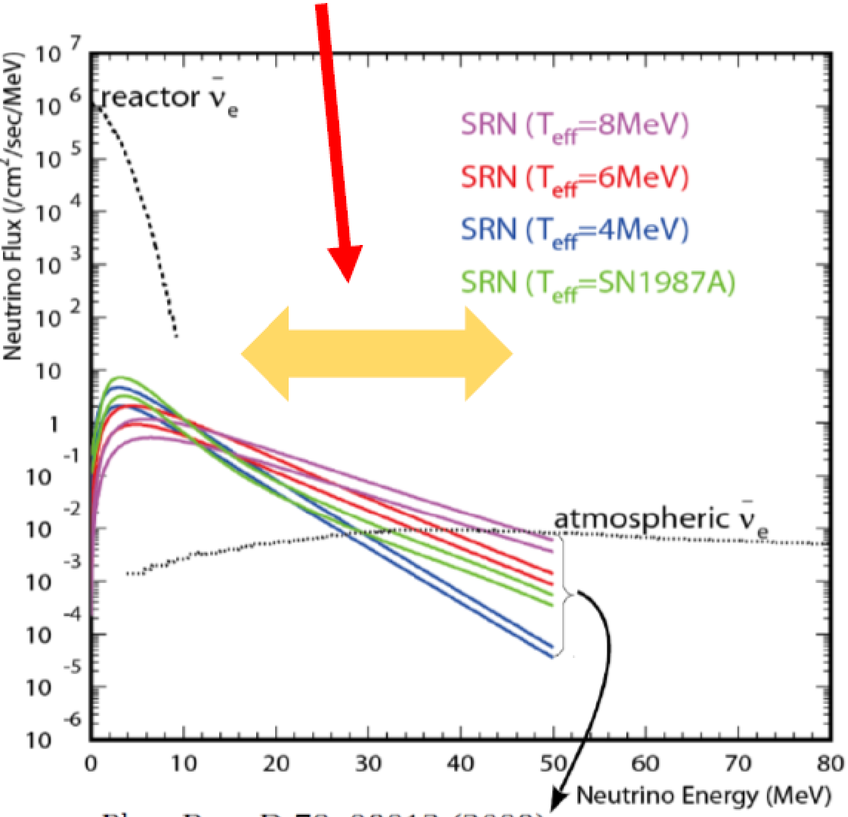
40%/0/<20º

78%/62%/7º

75%/50%/7º

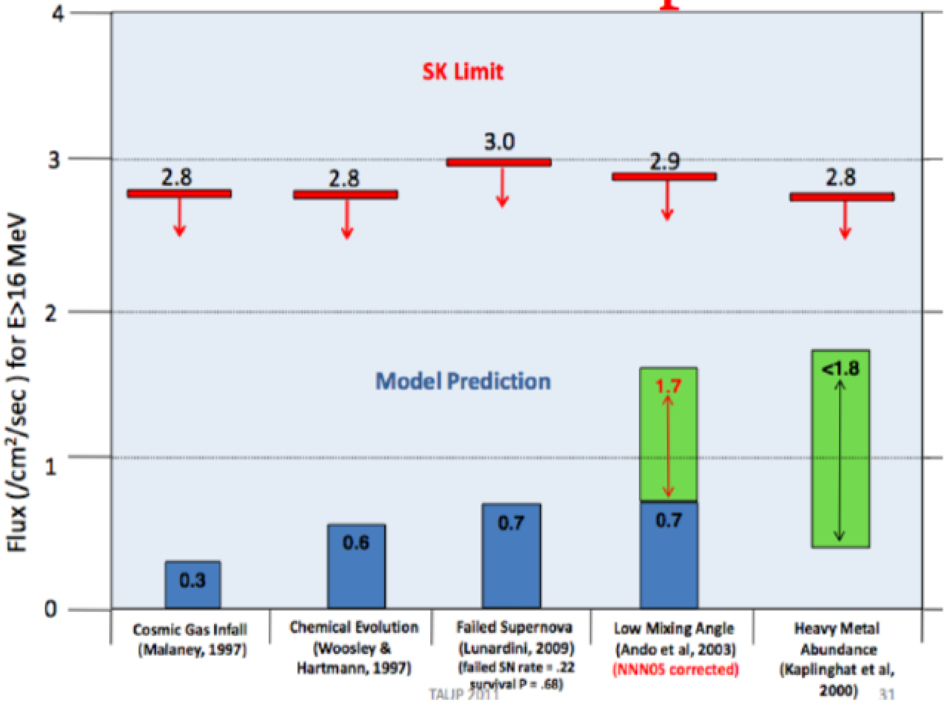
Search for SRN at Super-K

Search window for SRN at SK : From ~10MeV to ~30MeV



Phys.Rev. D 79, 08013 (2009)

Flux limit at Super-K



Phys. Rev. D 85, 052007 (2012)

Now SRN search is limited by statistics and BG.

HD option will help BG reduction by the neutron tagging.