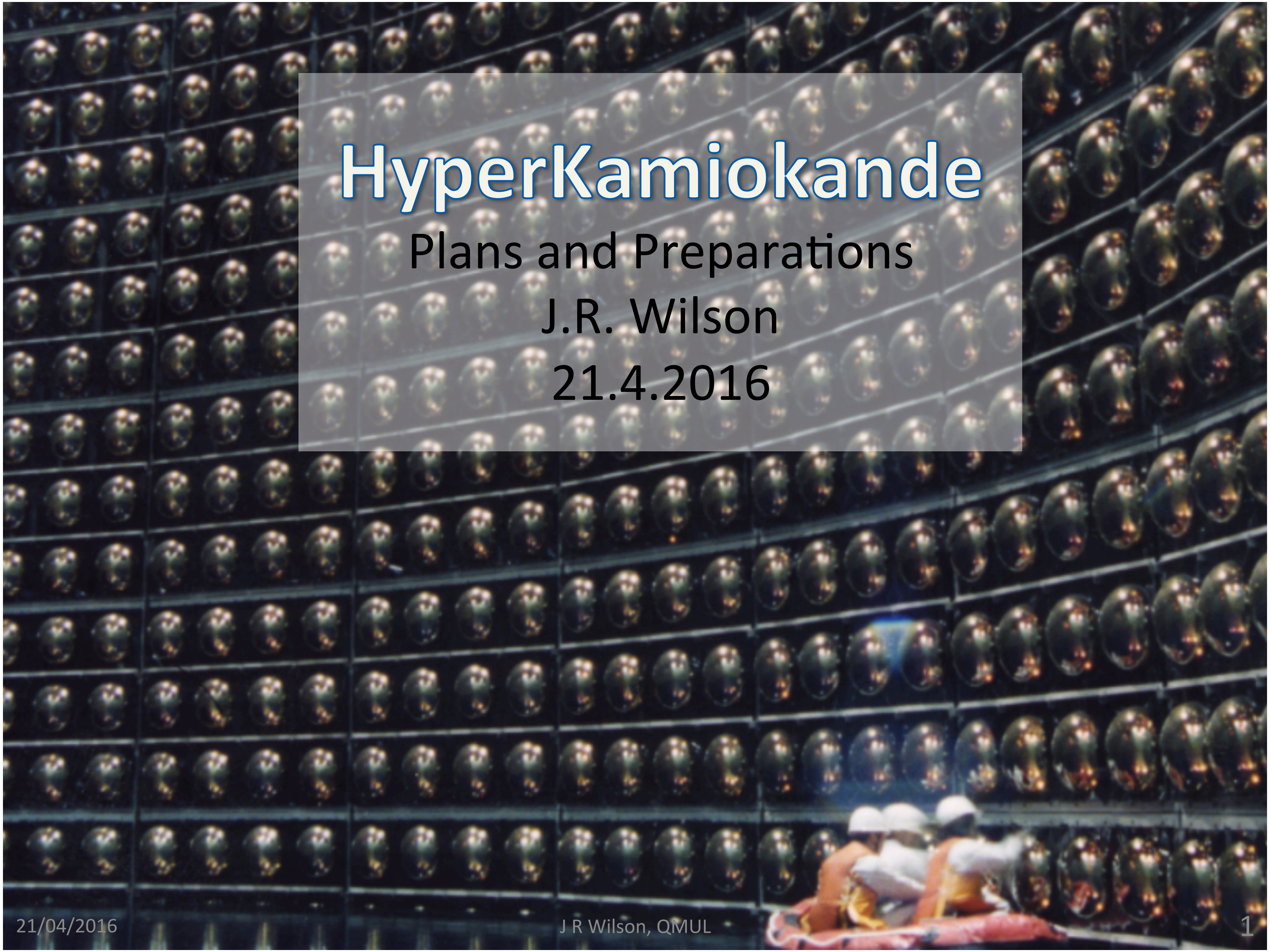


HyperKamiokande

Plans and Preparations

J.R. Wilson

21.4.2016

Contents

- Neutrinos – what we know and what we don't
- Designing an experiment to measure δ_{CP}
- Hyper-K concept
  - JPARC beam
  - Far detector design
    - Location, size, PMTs, DAQ
  - Near detectors
    - ND280, νPRISM, **TITUS**
- Hyper-K physics
  - δ_{CP} sensitivity
  - Proton decay
  - Atmospheric neutrinos
  - Solar neutrinos
  - Supernovae

Neutrinos – What we know

$S_{ab} = \sin(\theta_{ab})$
$c_{ab} = \cos(\theta_{ab})$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & e^{i\delta_3} \end{pmatrix}$$

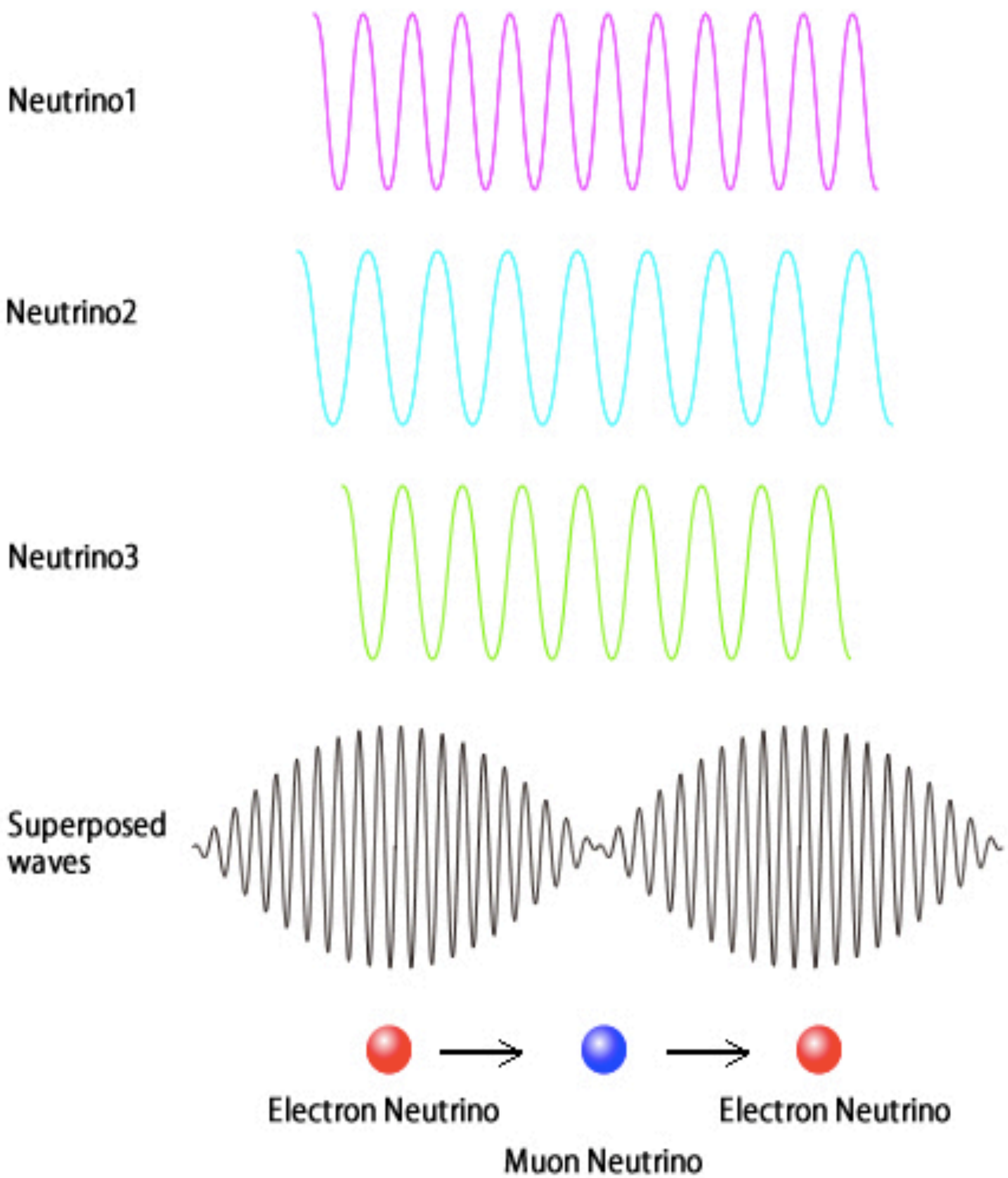
ν_μ disappearance
Atmospheric, Beam

ν_e appearance in ν_μ beam
or
$\overline{\nu}_e$ disappearance in reactor experiments

Solar neutrinos

ν–less double beta decay

Neutrino Oscillations



http://www.hyper-k.org/en/img/waves.jpg

Mass differences: $\mathbf{\Delta m_{12}, \Delta m_{23}}$
Govern at what distance/energy you see the maximum effect.

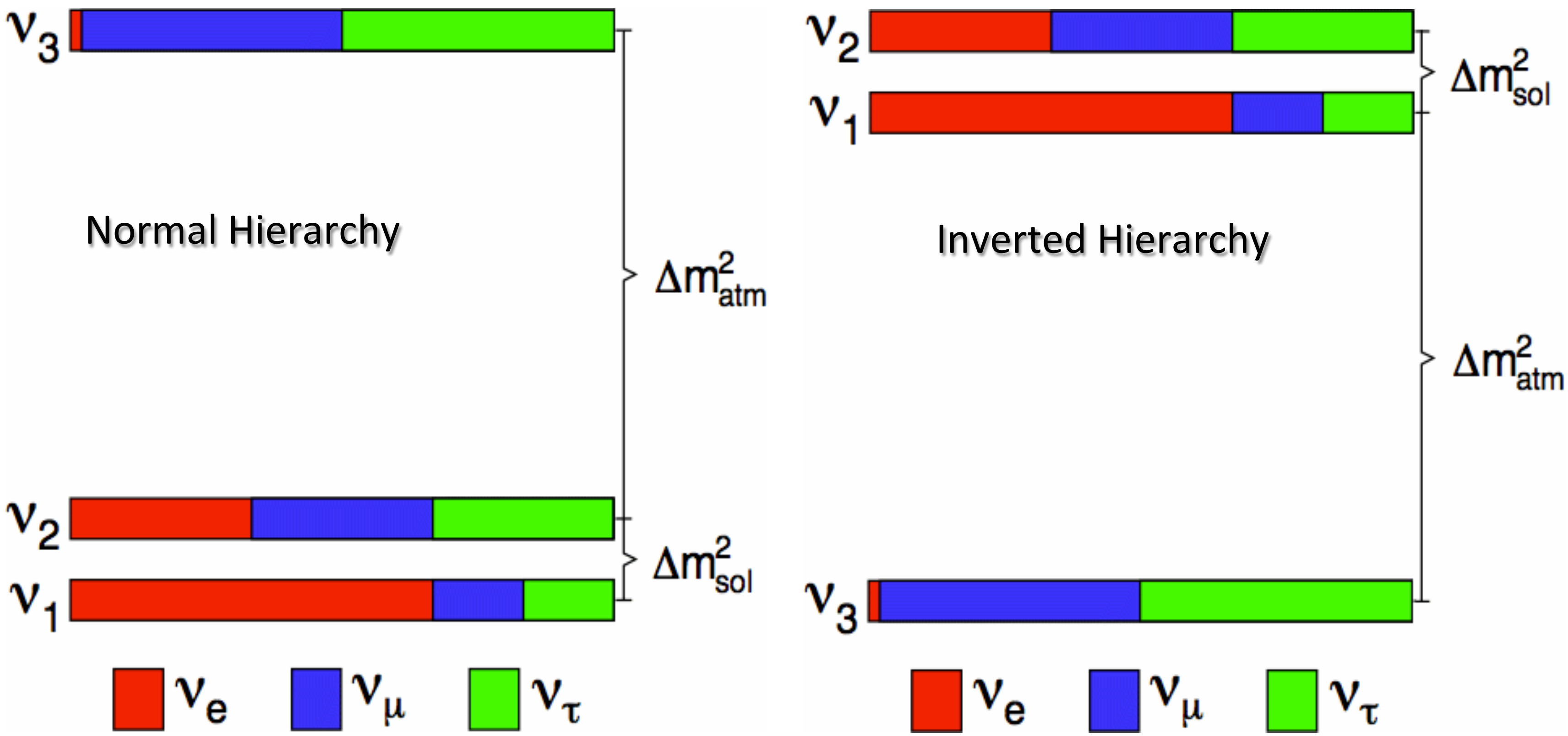
Mixing angles: $\boldsymbol{\theta_{12}, \theta_{23}, \theta_{13}}$
The relative contributions of mass states to flavour states. Govern the amplitude of the effect

Atmospheric Neutrinos:
$\mathbf{\Delta m_{23},} \boldsymbol{\theta_{23}}$

Solar Neutrinos:
$\mathbf{\Delta m_{12},} \boldsymbol{\theta_{12}}$

Beam Neutrinos:
$\boldsymbol{\theta_{13}, \theta_{23},}$

Neutrino Masses



Neutrinos – the known unknowns

- Are neutrinos DIRAC or Majorana?
- Is CP violated in the lepton sector? $(\delta \neq 0)$
- What is the neutrino Mass Hierarchy?
- What is the absolute scale of neutrino masses?
- Is θ_{23} maximal?
- Is there new physics?
  - Sterile neutrinos?
  - Non-standard interactions?
  - ....?

* Other double beta experiments are available

Neutrinos – the known unknowns

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- Is CP violated in the lepton sector? ($\delta \neq 0$)
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- What is the absolute scale of neutrino mass?
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  - Sterile neutrinos?
  - Non-standard interactions?
  - ….?

Why are we here?

- CP violation is needed to explain the baryon asymmetry of the Universe.

- Different rates for $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations
- Measurement require large statistics and well controlled systematics
- …and its complicated…

CP violation

$S_{ab} = \sin(\theta_{ab})$
$c_{ab} = \cos(\theta_{ab})$
$\Delta_{ab} = \Delta m^2_{ab} L/4E_\nu$

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = {} & 4c_{13}^2 s_{13}^2 s_{23}^2 \cdot \sin^2 \Delta_{31} \\
& + 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta_{CP} - s_{12} s_{13} s_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& \underline{- 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta_{CP} \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}} \\
& + 4s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta_{CP}) \cdot \sin^2\Delta_{21} \\
& - 8c_{13}^2 s_{13}^2 s_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2s_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\
& + 8c_{13}^2 s_{13}^2 s_{23}^2 \frac{a}{\Delta m_{31}^2} (1 - 2s_{13}^2) \cdot \sin^2\Delta_{31},
\end{aligned}
$$

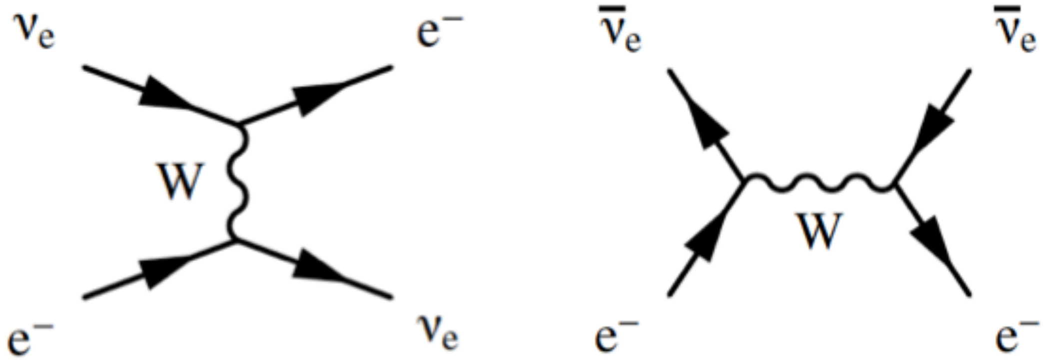
cp violating term

$a = 2\sqrt{2} G F n_e E_\nu$
matter effects

For $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$:
$\delta_{cp} \rightarrow -\delta_{cp}$
$a \rightarrow -a$

Matter Effects

- Neutrinos travel through material that is not CP symmetric, i.e. matter not antimatter
- effective potential due to the forward weak scattering processes:



$$V = \pm\sqrt{2}G_{\mathrm{F}}n_{\mathrm{e}}$$

Different sign for ν_e vs $\bar{\nu}_e$

$$\mathcal{H}(n_e) = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{pmatrix} U^\dagger + \begin{pmatrix} V(n_e) & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$V_\nu = +\sqrt{2}G_F n_e,\ V_{\bar{\nu}} = -\sqrt{2}G_F n_e,\ n_e = Y\rho_j/m_N$$

CP violation

$S_{ab} = \sin(\theta_{ab})$
$c_{ab} = \cos(\theta_{ab})$
$\Delta_{ab} = \Delta m^2_{ab} L/4E_\nu$

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = {} & 4c_{13}^2 s_{13}^2 s_{23}^2 \cdot \sin^2 \Delta_{31} \\
& + 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta_{CP} - s_{12} s_{13} s_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& - 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta_{CP} \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& + 4s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta_{CP}) \cdot \sin^2\Delta_{21} \\
& - 8c_{13}^2 s_{13}^2 s_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2s_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\
& + 8c_{13}^2 s_{13}^2 s_{23}^2 \frac{a}{\Delta m_{31}^2} (1 - 2s_{13}^2) \cdot \sin^2\Delta_{31},
\end{aligned}
$$

cp violating term

For $\nu_\mu \to \nu_e$:
δ_{cp} -> $-\delta_{cp}$
a -> -a

$a = 2\sqrt{2} G F n_e E_\nu$
matter effects

You also need to know θ_{12}, θ_{23}, Δm_{12}, Δm_{23} precisely to start with

Neutrinos – the known unknowns

- Are neutrinos DIRAC or Majorana?
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- What is the neutrino Mass Hierarchy?
- What is the absolute scale of neutrino mass?
- Is θ_{23} maximal?
- Is there new physics?
  – Sterile neutrinos?
  – Non-standard interactions?
  – ….?

Mass Hierarchy

The race is on....

- T2K + Nova + reactor
  - Compare the absolute values of the effective Δm^2 determined by reactor ($\bar{\nu}_e$ disappearance) and accelerator (ν_μ disappearance) with high precision
- DUNE
  - Oscillation probability around the first oscillation maximum, $O(L/E_\nu) \sim 1$, tends to be enhanced (suppressed) if the mass hierarchy is normal (inverted) due to the matter effects
- JUNO/RENO-50
  - Look for the small interference effects caused by Δm^2_{31} and Δm^2_{32} in the medium baseline (L ~ 50 km) reactor neutrino oscillation experiment
- PINGU/ORCA/ICAL/HyperK
  - Atmospheric neutrinos. significant enhancement of the $\nu_\mu \rightarrow \nu_e$ appearance probability for upward-going neutrino in normal hierarchy and for anti-neutrino in inverted hierarchy

Neutrinos – the known unknowns

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Is sinθ$_{23}$ maximal?

- Currently measured value of θ_{23} is consistent with maximal mixing, $\theta_{23} \approx \pi/4$, measured from

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4c_{13}^2 s_{23}^2 [1 - c_{13}^2 s_{23}^2] \sin^2(\Delta m_{32}^2 \, L/4E_\nu)$$
$$\simeq 1 - \sin^2 2\theta_{23} \sin^2(\Delta m_{32}^2 \, L/4E_\nu), \qquad \text{(for } c_{13} \simeq 1\text{)}$$

- Whether θ_{23} is less or greater than $\pi/4$, could constrain models of neutrino mass generation and quark-lepton unification
- ν_e appearance can determine $\sin^2\theta_{23}\sin^2 2\theta_{13}$
- Reactor experiments determine $\sin^2 2\theta_{13}$
  - Resolve degeneracy with combination

Neutrinos – the known unknowns

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- What is the absolute scale of neutrino mass?
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  - ….?

Experimental Strategy

Two possible approaches to probe $\delta_{CP:}$

- Short baseline (~200km) – less sensitive to matter effects -> Increased sensitivity to CP effects
- To maximise oscillation effect need $E_\nu < 1$GeV
- Use off-axis narrow band beam

OR

- Long baseline (>1000km) – measure matter effects
- To maximise oscillation effect need $E_\nu > 2$GeV
- Unfold CPV from matter effects through E dependence using wide range of neutrino energies from On-axis beam
  - Matter effects amplitude proportional to L×E
  - CP effects amplitude proportional to L/E

Experimental Strategy

Two possible approaches to probe δ_{CP}:

- Short baseline (~200km) – less sensitive to matter effects -> Increased sensitivity to CP effects
- To maximise oscillation effect need E_ν < 1GeV
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OR

- Long baseline (>1000km) – measure matter effects
- To maximise oscillation effect need E_ν > 2GeV
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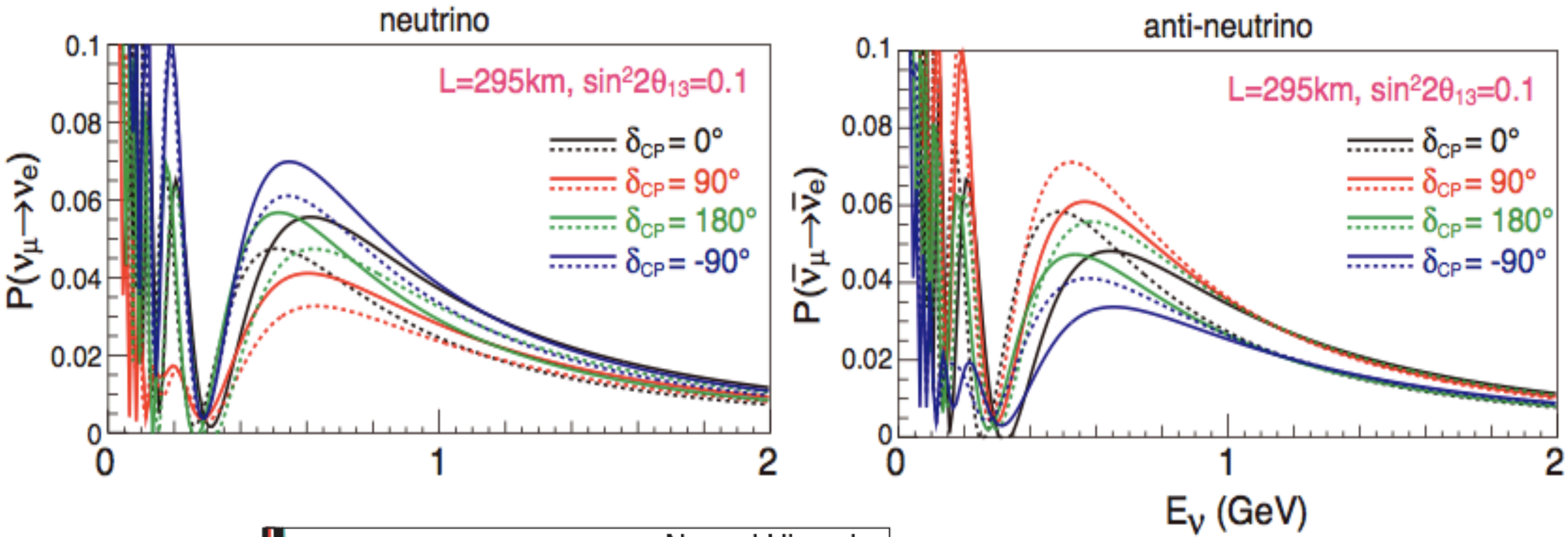
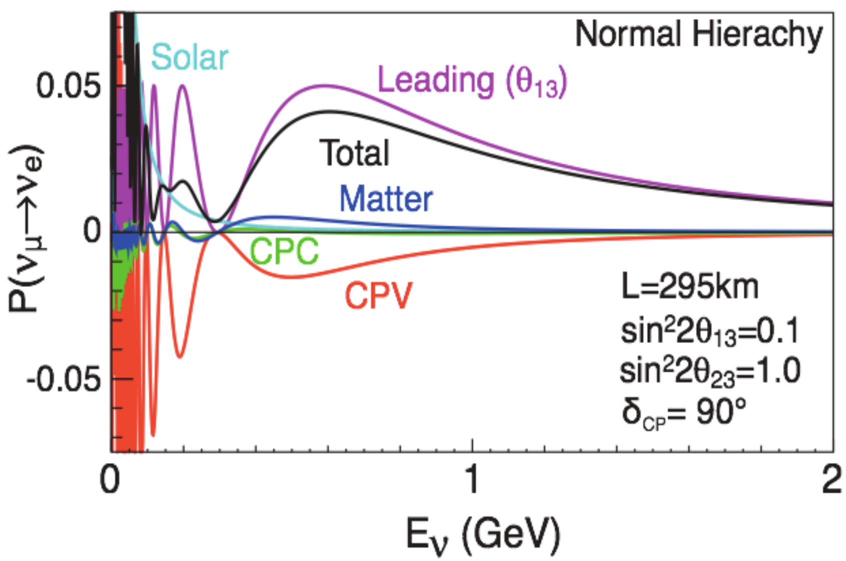
Oscillation Probabilities

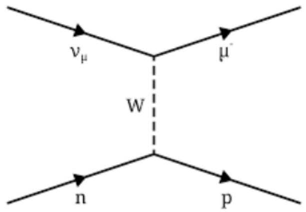


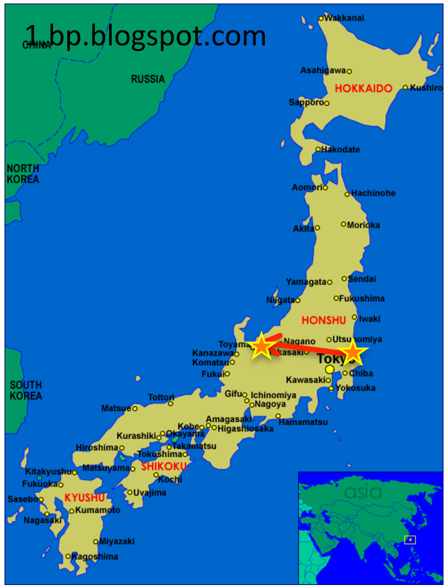


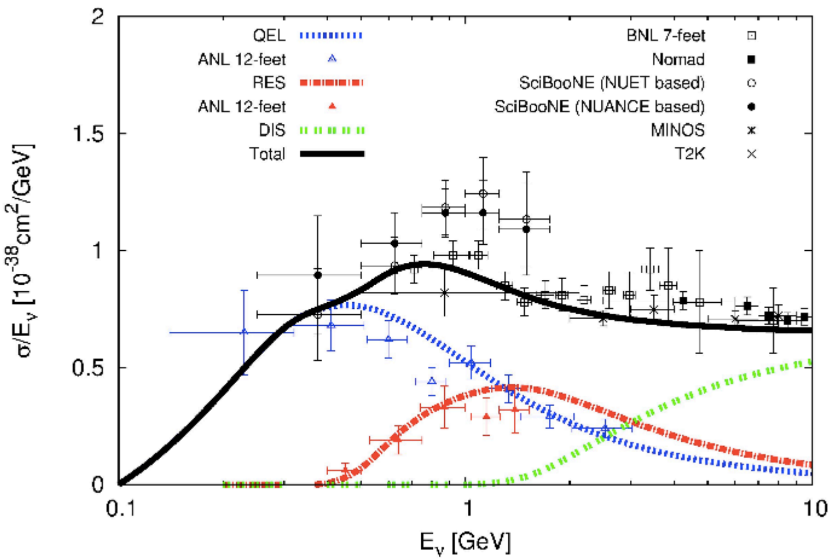
The effect of CP violating term can be as large as 28%, while that of the matter effect is 7%

Hyper Kamiokande

- 295km baseline from JPARC to Tochibora
- >1MW 600MeV off-axis beam
- 0.5Mton Water Cerenkov far Detector
  - Excellent e/μ separation capability
  - High background rejection efficiency
  - High signal efficiency for sub-GeV neutrino events (CCQE)







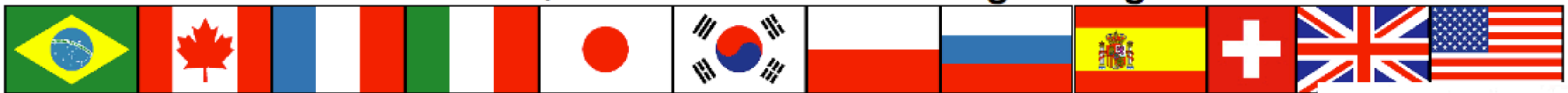
http://arxiv.org/pdf/1209.6586.pdf

Physics Potential

- CP violation
  - Explain the Baryon asymmetry of the Universe
- Proton Decay
- Atmospheric Neutrinos
  - Mass ordering,
  - + Beam: test 3 flavour paradigm precisely
  - search for new physics: NSI, Lorentz invariance, sterile neutrinos
- Solar Neutrinos
- Indirect dark matter
- Astronomical Sources
  - Galactic supernovae
  - dark matter annihilation, gamma ray burst jets, and pulsar winds

Inaugural Symposium of the HK proto-collaboration@Kashiwa, Jan-2015

12 countries, ~250 members and growing



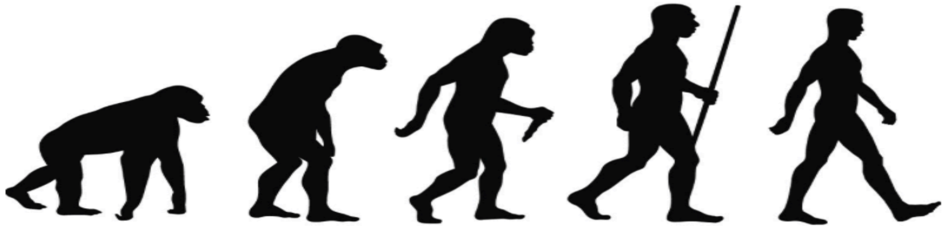
- Proto-collaboration formed in Jan-2015
- International Steering Committee
- More international conveners
- International chair for international board of representative (IBR)

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

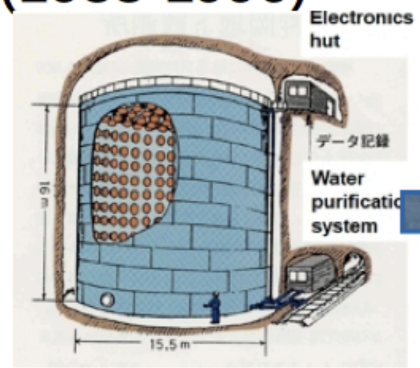
IPNS=Institute for Particle and Nuclear Studies

ICRR=Instituted for Cosmic Ray Research

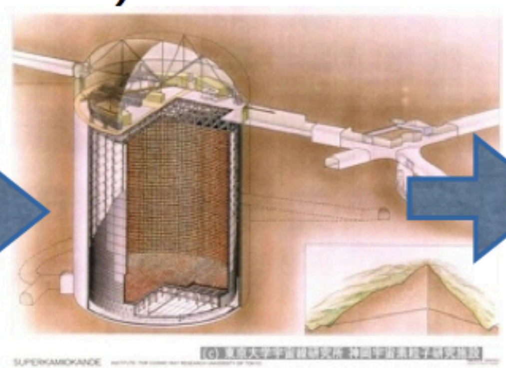
Kamiokande Evolution



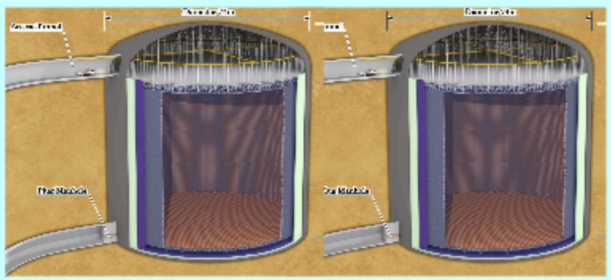
Kamiokande
(1983-1996)



Super-Kamiokande
(1996-)



Hyper-Kamiokande
(2025-)



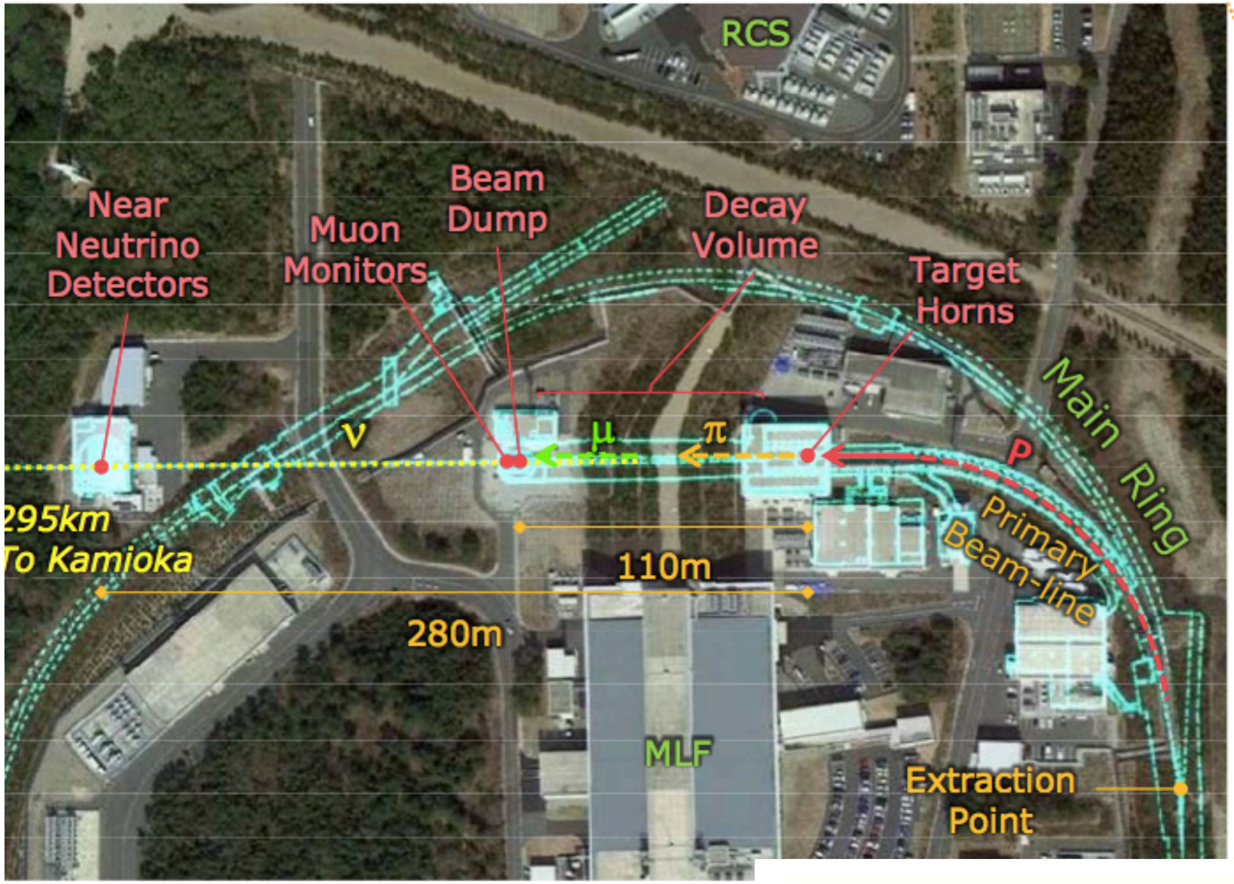
3kton

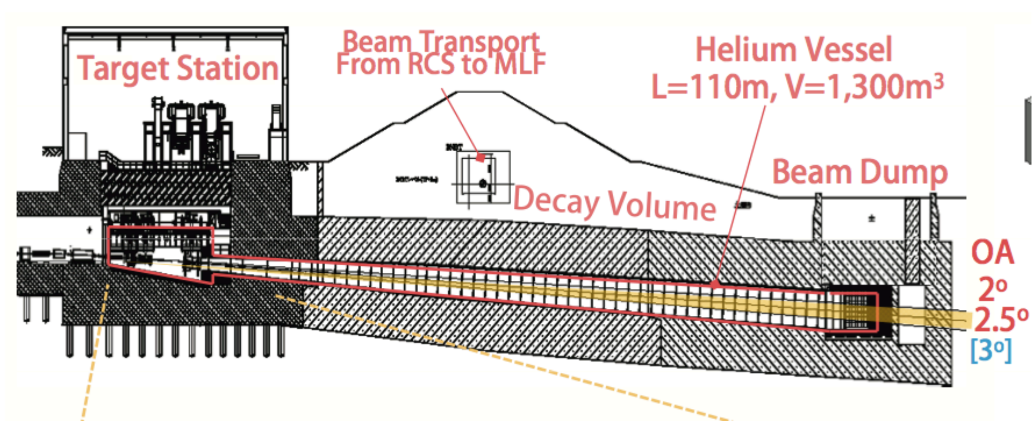
50kton

0.52Mton=520kton

(380kton fiducial)

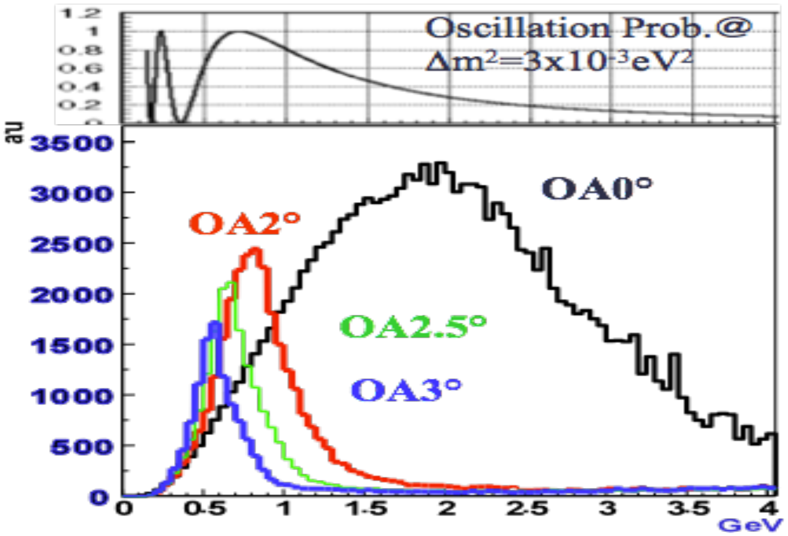
JPARC and Beam

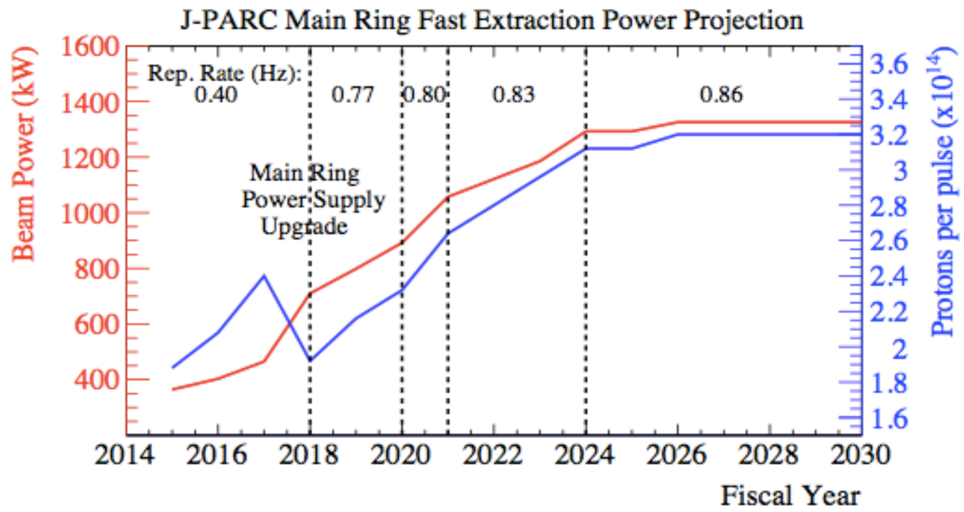




JPARC and beam

- Beam energy spectrum tuned to oscillation maximum with off-axis technique
  - Reduces HE component background events
  - 600MeV well matched to Cerenkov detector

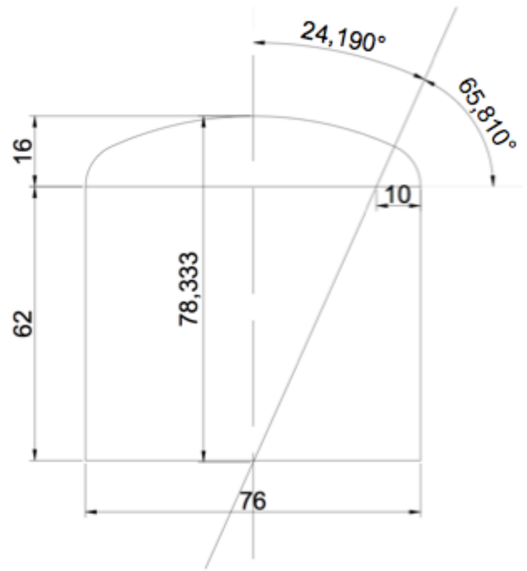


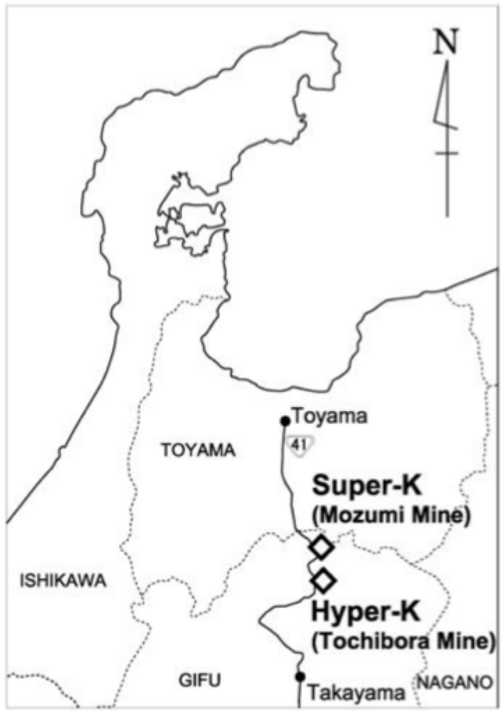


- T2K approved for 7.8×10^{21} protons-on-target (POT) -> 2020
- Proposal for T2K-II running: extend to 20×10^{21} POT -> 2026
- Upgrades to existing accelerators – reach 1MW by start of HyperK experiment (2026) – 1.3MW planned

Far Detector

- Tochibora mine, 295km away
- 650m rock overburden, 1750 MWE
- 2.5km horizontal access
- Surveys of rock quality and known fault lines to optimize cavern location

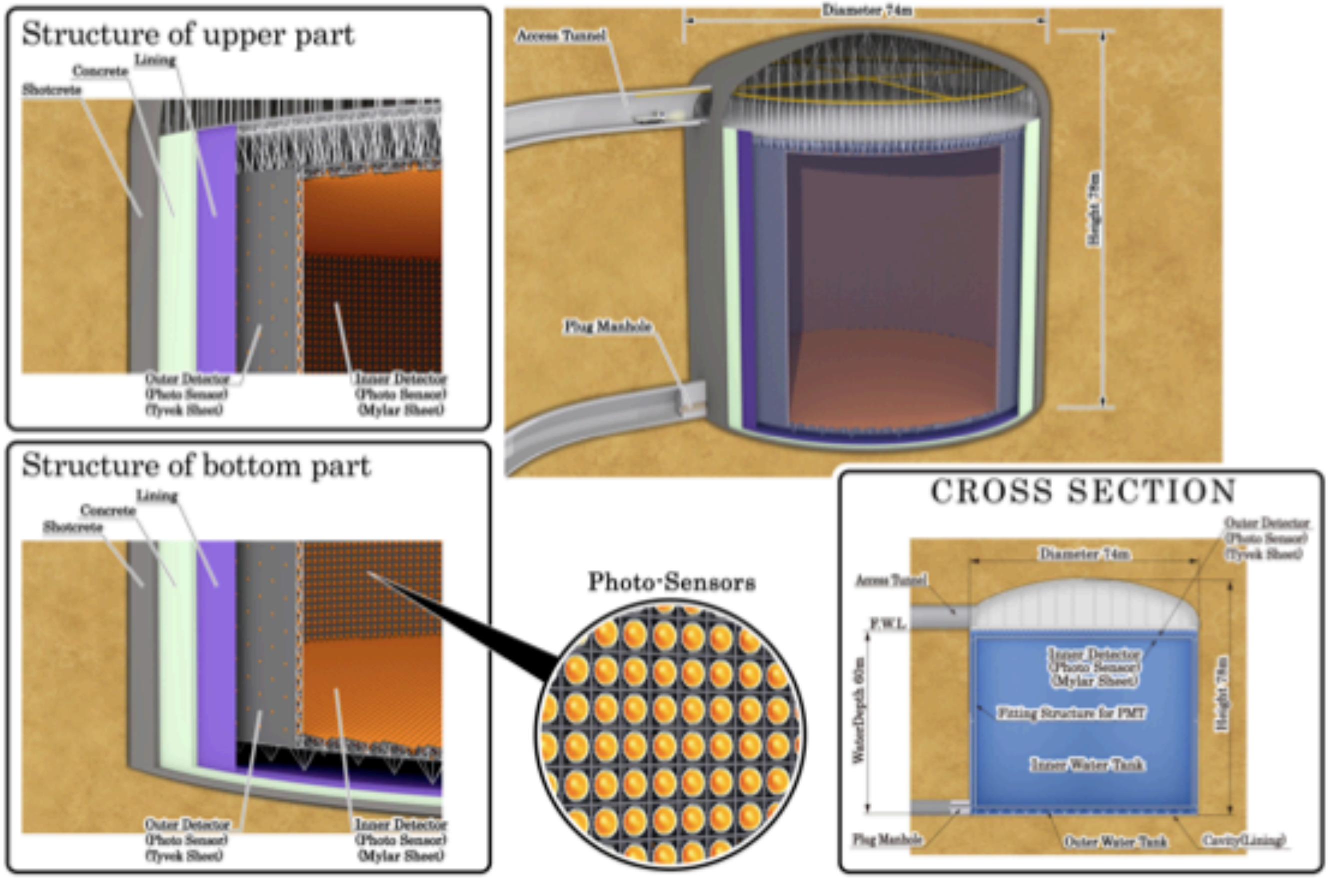




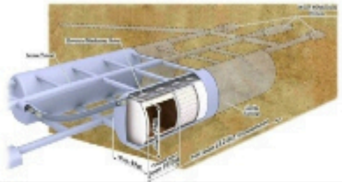
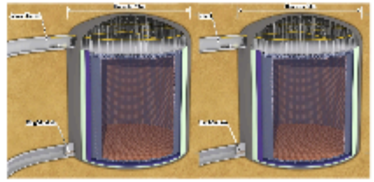
Detector Design

2 × 74m diameter, 60m high cylindrical tanks, 40% Photo-coverage

- ~40, 000 50 cm diameter inward-facing photo-sensors per tank
- ~6,700 20 cm diameter outward-facing photo-sensors per tank

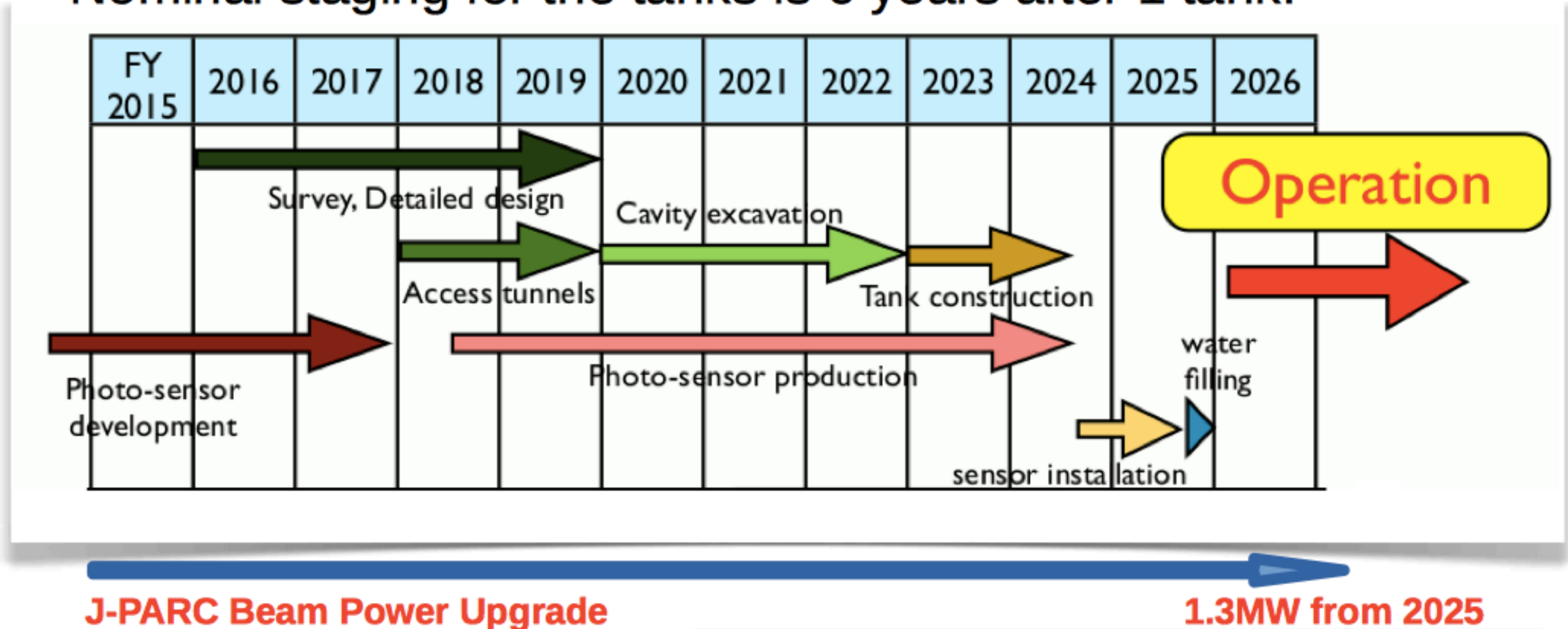


Tank Optimisation

	Super-K (SK)	Letter-of-Intent 2011 (LOI)	2 Tanks w/ High Photodetector density (2HD)
			
Total Volume (Fiducial Volume)	0.05Mton (0.022Mt)	1Mt (0.56Mt)	0.52Mt (0.38Mt)
Dimension	39mΦ × 42m (H)	48 (W) × 54 (H) × 250 (L) m^3 ×2	74mΦ × 60m(H) ×2
ID #of Photo-sensors (coverage)	11k (Super-K PMT) (40%)	99k (Super-K PMT) (20%)	80k (B&L) (40%)
Single-photon detection efficiency	12%	12%	24%
Photon-yield	1	0.5	2
single-photon timing resolution	~2nsec	~2nsec	1nsec

Timeline

- Nominal staging for the tanks is 6 years after 1 tank.



Detailed timeline:

- Geological survey
- Access tunnel: 2 years
- Cavity excavation: 3 years
- Tank (liner, photosensor support): 2.7 years
- Water filling: 0.4 years
- **Exact cavern location(s) and its design will be finalized during the geological survey.**

Schedule: FY2018~2045
FY2018:start of 1st phase construction (8y)
FY2026: start (1st tank) operation
FY2032 (nominal): start (2nd tank) operation
FY2026~2035: Neutrino CP measurement
FY2026~2045:proton decay searches, solar/atm/SN neutrino observations 13

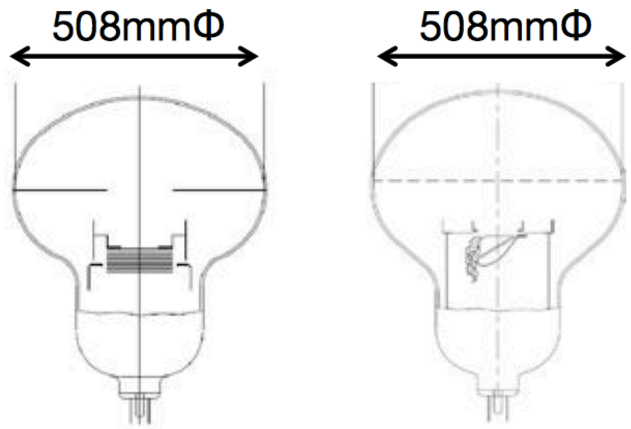
PMTs

Y. Suda, U. Tokyo,
http://www.hyper-k.org/doc/mth2013_suda.pdf

- Newly developed high-efficiency and high-resolution PMTs (Hamamatsu R12860)
- At 60m depth in Hyper-K cavern applied pressure is close to the manufacturers upper specification of the Super-K R3600 PMT

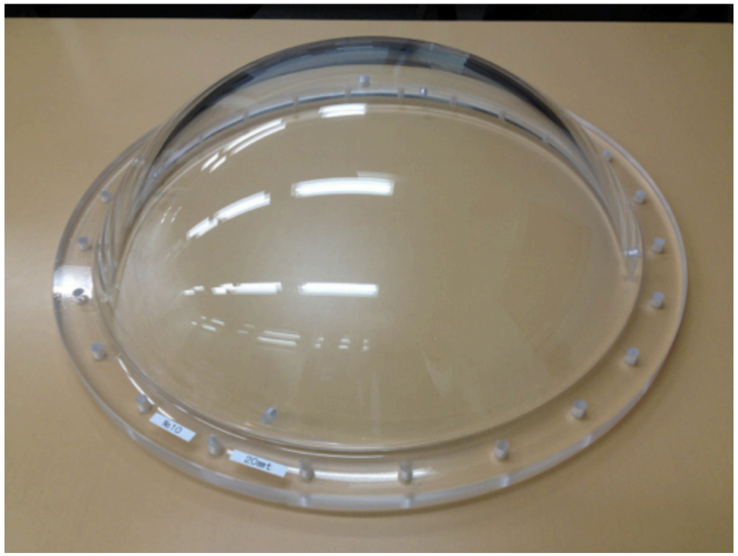
  0.65 MPa!

  – Optimised shape
  – Plastic cases
  – Pressure tests
  – Rigorous QA

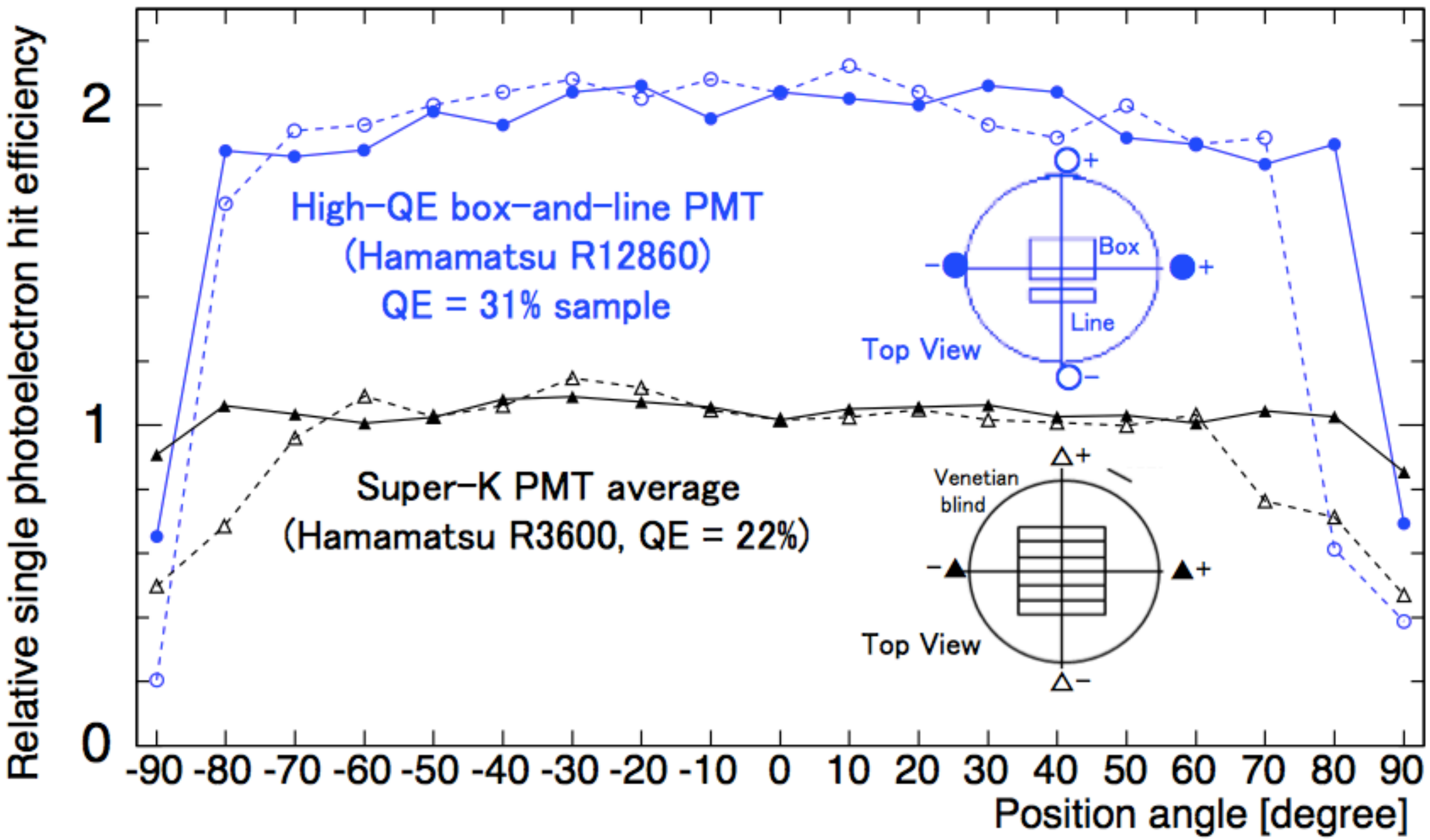


20-inch Venetian Blind dynode type PMT (R3600)

20-inch Box & Line dynode type PMT



PMTs



A HQE Box and Line PMT with a 31% QE sample shows twice the efficiency of normal QE Super-K PMTs (QE = 22%, based on an average of four samples).

DAQ

- The overall rate of hits (mostly from dark noise) from the inner detector will be about 460MHz, leading to a total input data rate of 5GB/s including additional data, in the absence of waveform information
- SK-like trigger:
  - trigger will be generated when the total number of hits seen (NHITS) in a sliding time-window exceeds a certain threshold (e.g. 27 hits)
  - Require no dead time. Important to observed delayed events: Michel e^-s and neutron captures.
- Required to handle Galactic Supernova events
  - 100,000s events per second

Reducing Uncertainties

$$N_{FD} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{FD}P(\nu_\mu \rightarrow \nu_e)$$

Neutrino flux prediction

Neutrino cross section model

Far Detector selection, efficiency

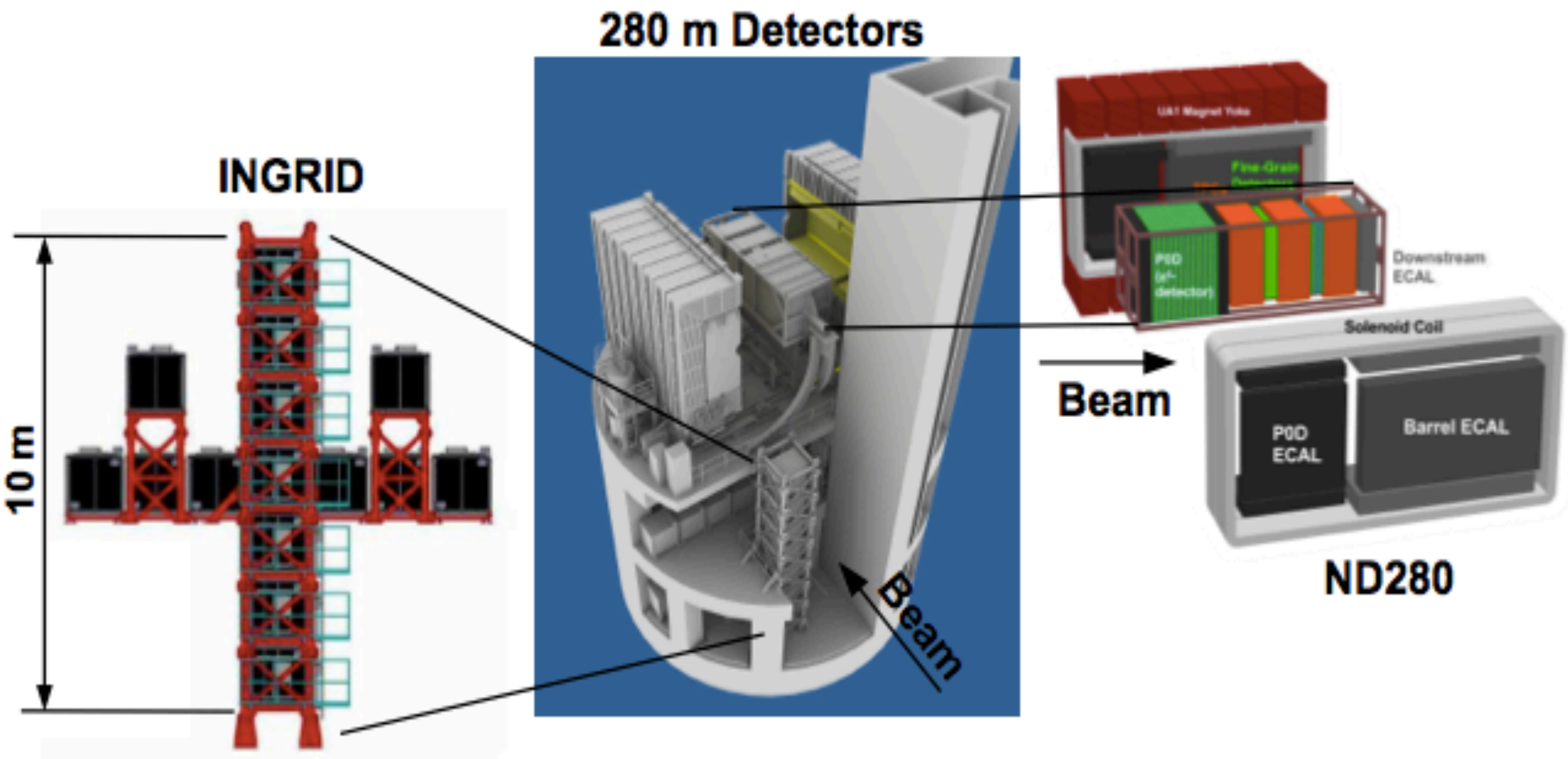
Oscillation Probability

$$N_{ND} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{ND}$$

Near Detector selection, efficiency

Near Detectors

Inherit T2K Near Detectors *



* They weren't designed to last to 2030+

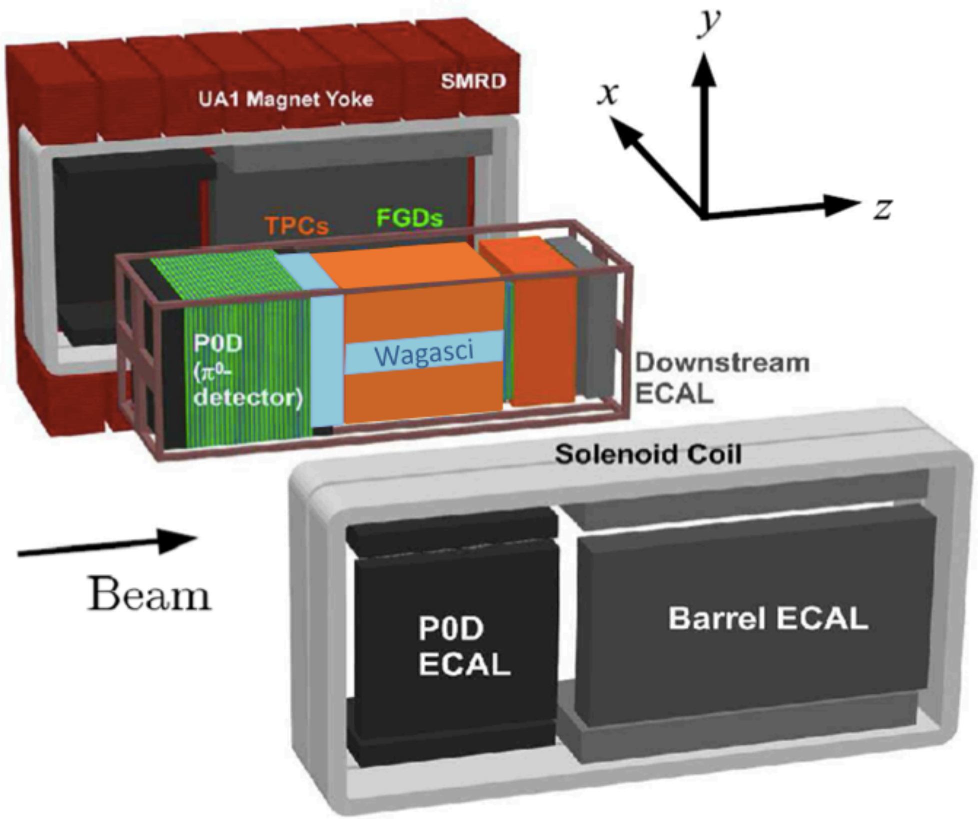
ND280 Limitations

Source of uncertainty	ν_μ CC	ν_e CC
Flux and common cross sections		
(w/o ND280 constraint)	21.7%	26.0%
(w/ ND280 constraint)	2.7%	3.2%
Independent cross sections	5.0%	4.7%
SK	4.0%	2.7%
FSI + SI(+ PN)	3.0%	2.5%
Total		
(w/o ND280 constraint)	23.5%	26.8%
(w/ ND280 constraint)	7.7%	6.8%

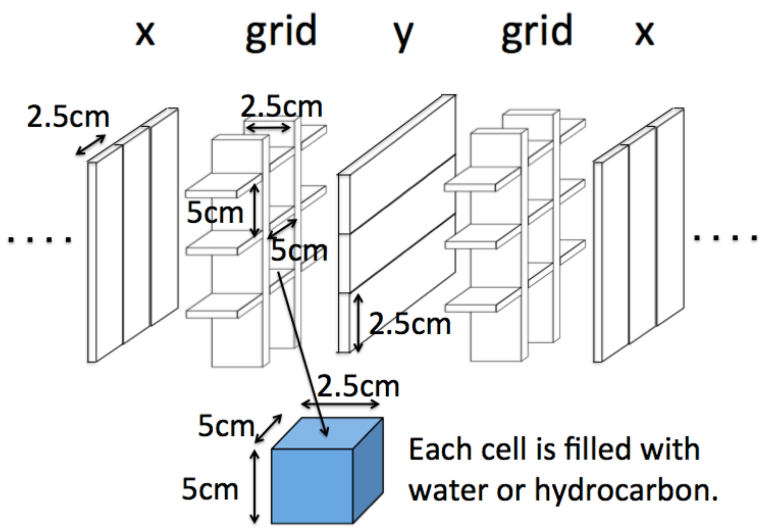
K. Abe et al. (T2K), Phys. Rev. D91, 072010 (2015)

ND280	Far Detector
Forward Tracking	4π coverage
Scintillator and water targets (subtraction method)	Water target
Unoscillated spectrum	Oscillated spectrum

Near Detector Upgrade Possibilities



- Reconfiguration to increase angular acceptance
- WAGASCI – water target approach
- Emulsion Detectors
- High Pressure TPC



Intermediate Water Cerenkov Detector

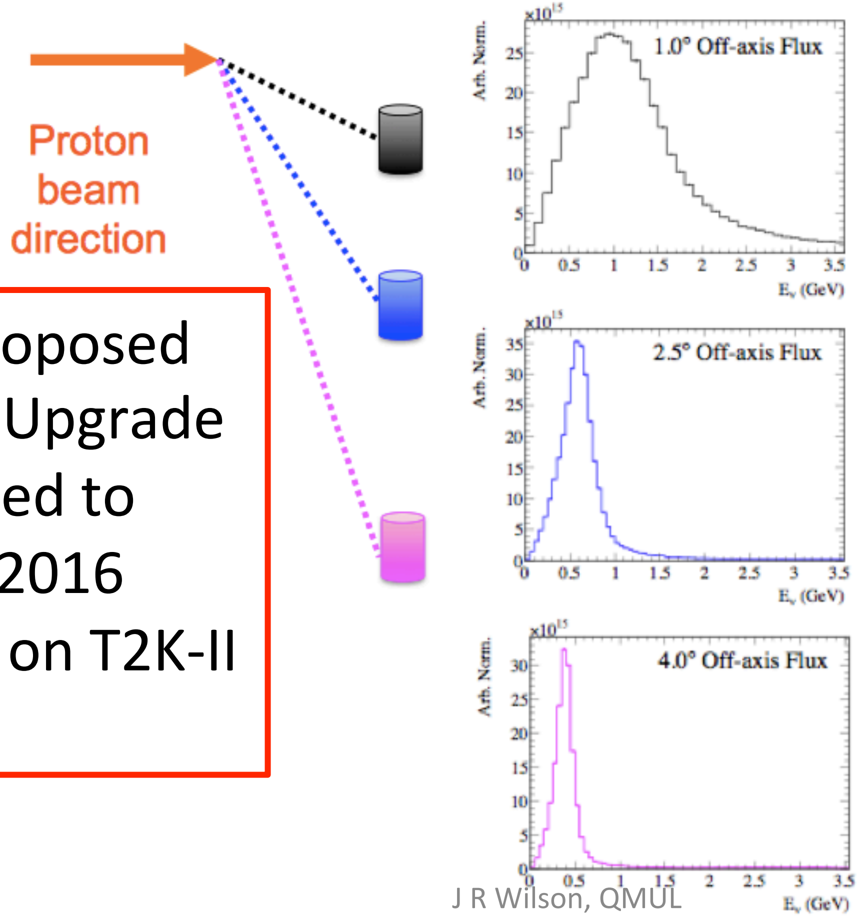
- Large enough to contain muons across oscillation peak energies
- Far enough from beam for minimal pile-up of events in same beam timing bunch

➢ 1-2km from Beam target

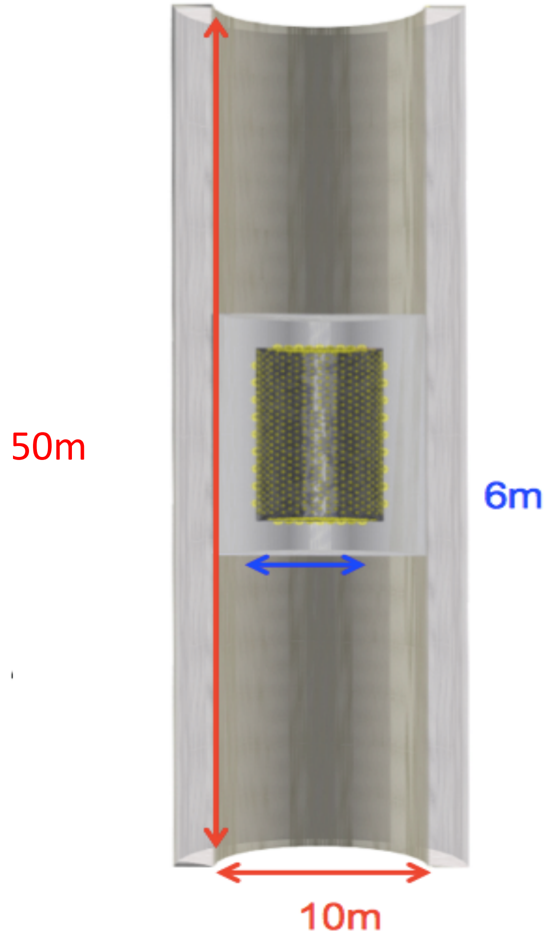
- Off-axis span of 1°-4° to measure the final state leptonic response over a range of neutrino spectra peaked at different energies
- Gd Loading to tag neutrons and statistical separate ν and $\bar{\nu}$ and different interaction modes
- Magnetised Muon Range Detector (MRD) to extend muon energy range and for charge identification

Proposals - νPRISM

Aims: Direct measure of lepton kinematics for any given set of oscillation parameters -> remove neutrino interaction modelling uncertainties.

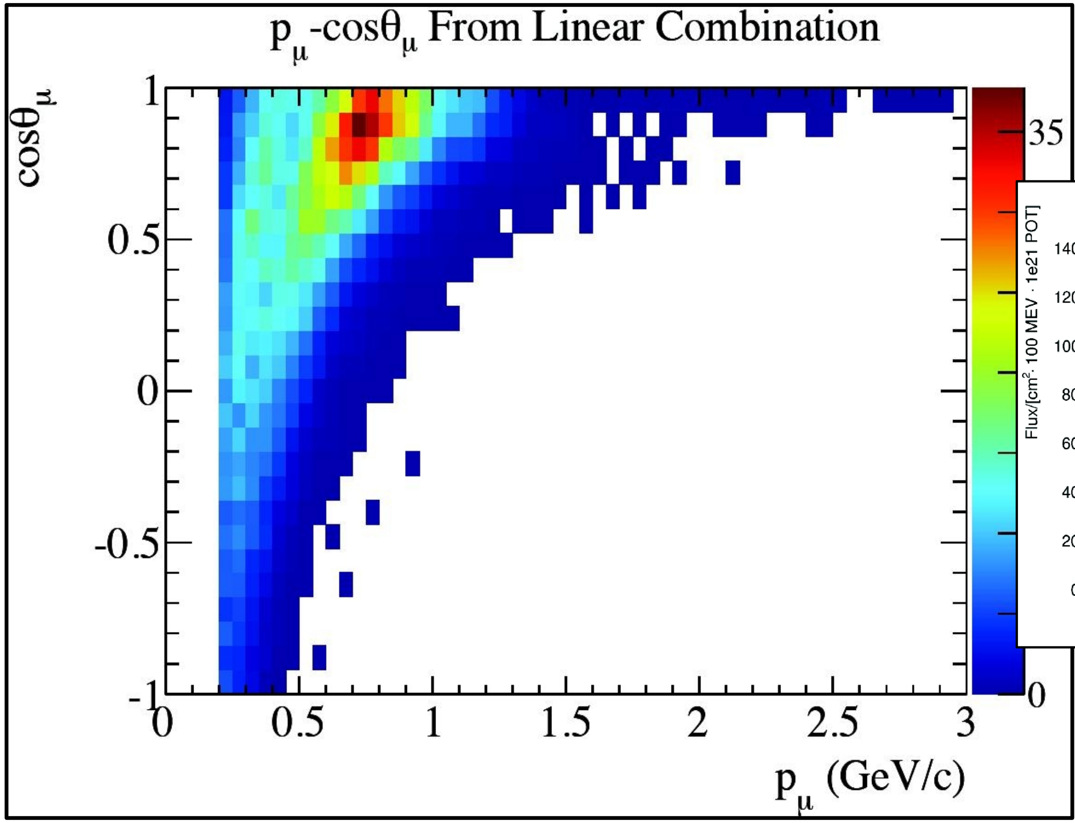


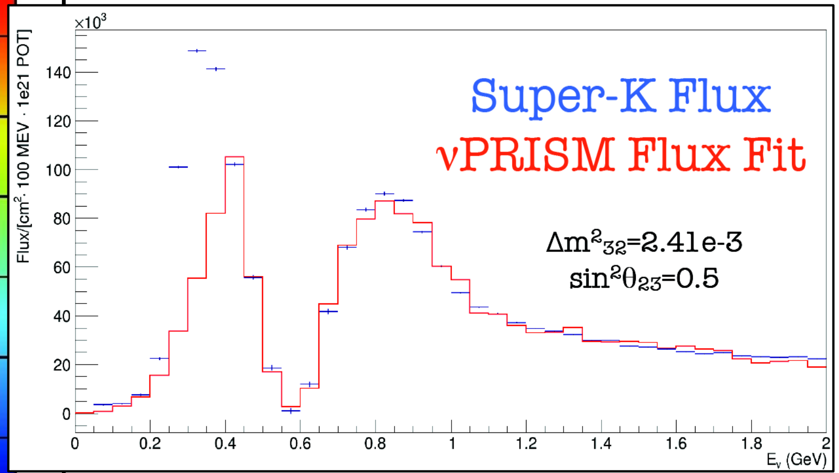
νPRISM-lite proposed as part of T2K Upgrade
- LOI submitted to JPARC PAC 2016
- Dependent on T2K-II approval



M. Scott, Triumf

νPRISM Analysis Concept





Recreate oscillated neutrino flux at SK using near detector

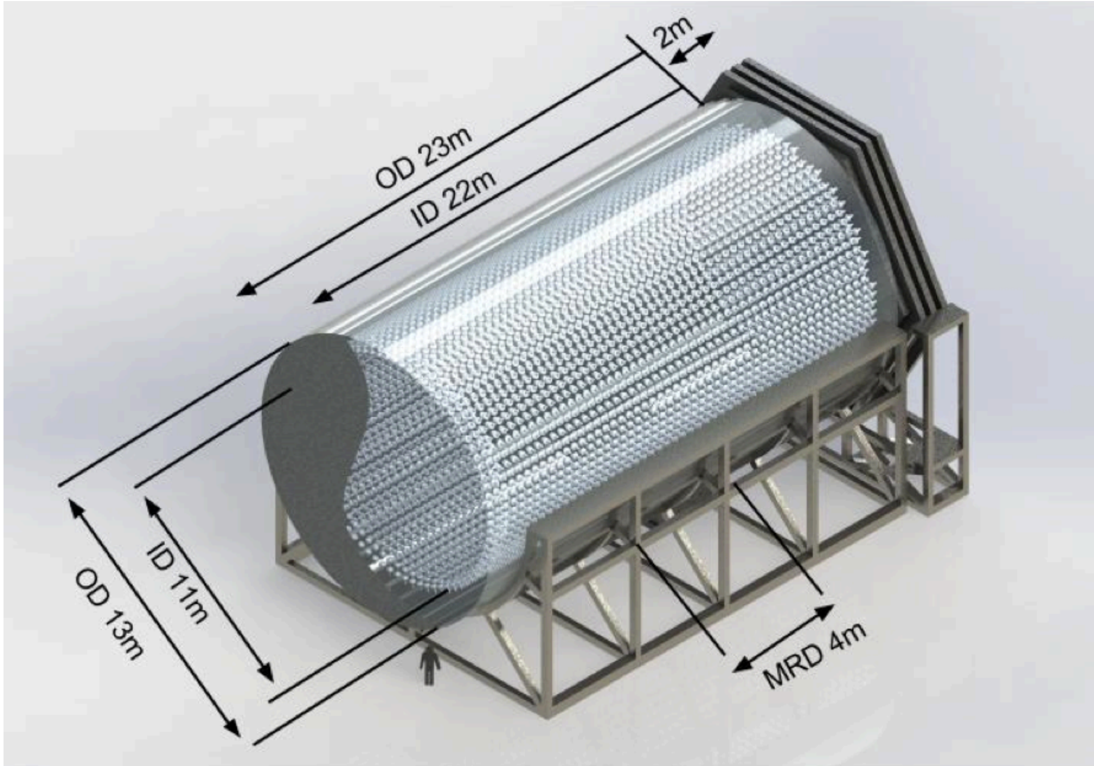
Directly measure muon p-θ for given value of oscillation parameters

Analysis becomes less sensitive to cross-section modelling

TITUS Proposal

2kton Gadolinium doped water Cherenkov detector

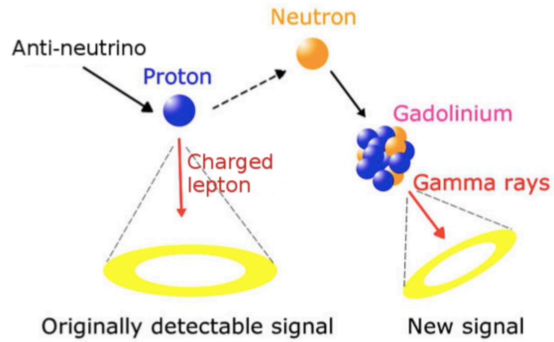
UK-Driven



- ~2km from J-PARC
- 2.5° Off Axis
- 22m long, 11m diameter
- 0.1% Gadolinium doping
- Magnetized Muon Range Detector at downstream end
- Small side MRD

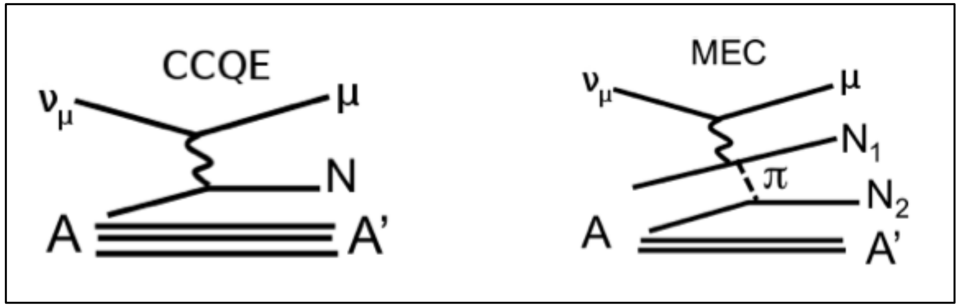
Gadolinium Doping

- Neutron capture on Gadolinium:
  - Cross section of 49,000b compared to 0.3b for H
  - 8MeV gamma cascade with 4-5MeV visible energy
  - 0.1% Gd doping: ~90% of neutrons capture on Gd



- New signal to distinguish ν / $\bar{\nu}$ events and different interaction modes:
  - ν_μ CCQE: $\nu_\mu + n \rightarrow \mu^- + p$ — 0 neutrons
  - $\bar{\nu}_\mu$ CCQE: $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ — 1 neutron
  - ν_μ MEC: $\nu_\mu + (n+n) \rightarrow \mu^- + p + n$ — 0.2 neutrons on average
  - $\bar{\nu}_\mu$ MEC: $\bar{\nu}_\mu + (p + p/n) \rightarrow \mu^+ + n + p/n$ — 1.8 neutrons on average

- Greatly enhanced sample purities:
  - ν_μ CCQE: 36% → 67%
  - $\bar{\nu}_\mu$ CCQE: 63% → 88%



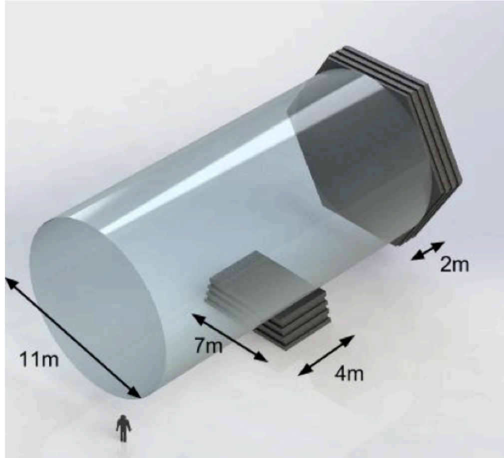
- Feasibility of Gd in water Cherenkov detector being tested in EGADS arXiv: 1201.1017. Gd addition to SuperK approved.

Magnetized Muon Range Detector

- 18% of muons escape tank
- Magnetized (1.5T) iron tracking detector
  - Range out forward muons -> 2GeV, increased statistics
  - Measure charge (~95% efficiency average) -> direct constraint on wrong-sign contamination
  - Calibration of the complementary gadolinium charge reconstruction technique
- Optimize @0.6GeV peak (~90%)
  - Double scintillator planes and 10cm air gaps between first 3 iron layers.

Combined MRD & Gd techniques give 96% pure ν_μ and $\bar{\nu}_\mu$ samples from events in the oscillation peak in TITUS.

Side MRD – Baby MIND



- Side magnetized-MRD.
  - Higher Q^2 region: This part of phase space is poorly understood -> useful for testing and discriminating cross-section models.
  - Muons have different angular distributions for ν and ν̄ interactions -> useful for measuring wrong sign background.
- Proof of Principle: Baby-MIND (University of Geneva)
  - Will be actively used in WAGASCI (forward MRD)

Event Rate Considerations

- To successfully match a neutrino interaction and a captured neutron from the same interaction for a Gd-doped detector, it is useful to have roughly one interaction per spill in the TITUS ID with minimal penetration of external particles.
- 2.2×10^{14} POT/spill

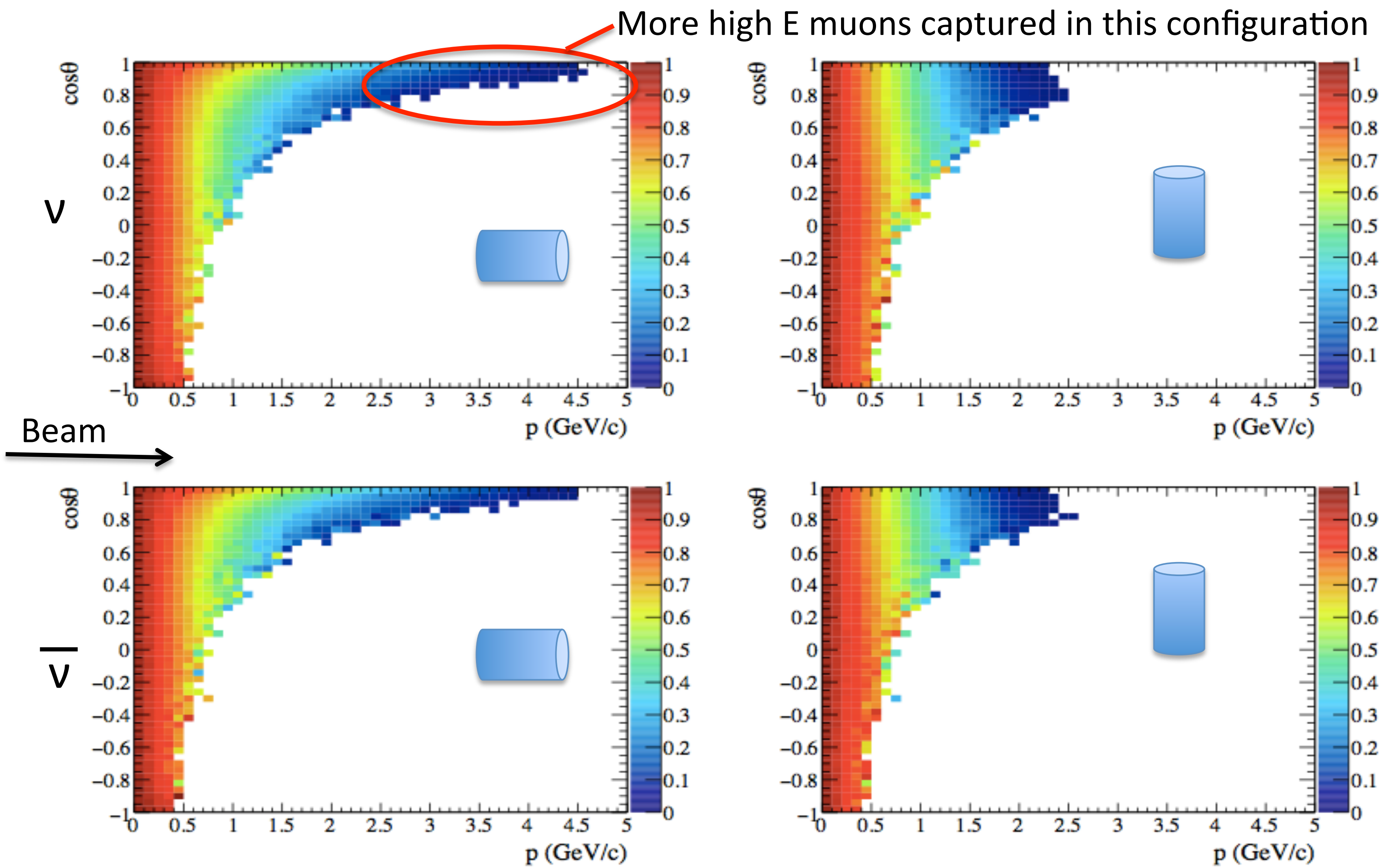
Number of neutrino interactions per kT per spill

Baseline (m)	FHC	RHC
1000m	1.48	0.50
1838m	0.42	0.14
2036m	0.33	0.11

FHC: consider SK-style OD (1m) and FV cut 1m from wall (1.27kT FV)

Baseline (m)	Tank ev/spill	Tank ev/bunch	ID ev/spill	ID ev/bunch	FV ev/spill	FV ev/bunch
1000	39.17	4.87	3.92	0.47	2.41	0.28
1838	11.19	1.37	1.25	0.14	0.79	0.08
2036	8.91	1.09	1.04	0.11	0.66	0.07

Inner Detector Volume



Nominal Tank, 2036m downstream, 22m long ✕ 5.5m radius, 1m FV cut

Event Selection

- Super-K single-ring muon (1Rμ) and single-ring electron (1Re) selections applied to TITUS
- Vertex > 2m from wall (scope to optimise)

<u>1 Ring μ (1Rμ)</u>
Muon-PID
Fully contained
No other rings
p_{recon} > 200MeV

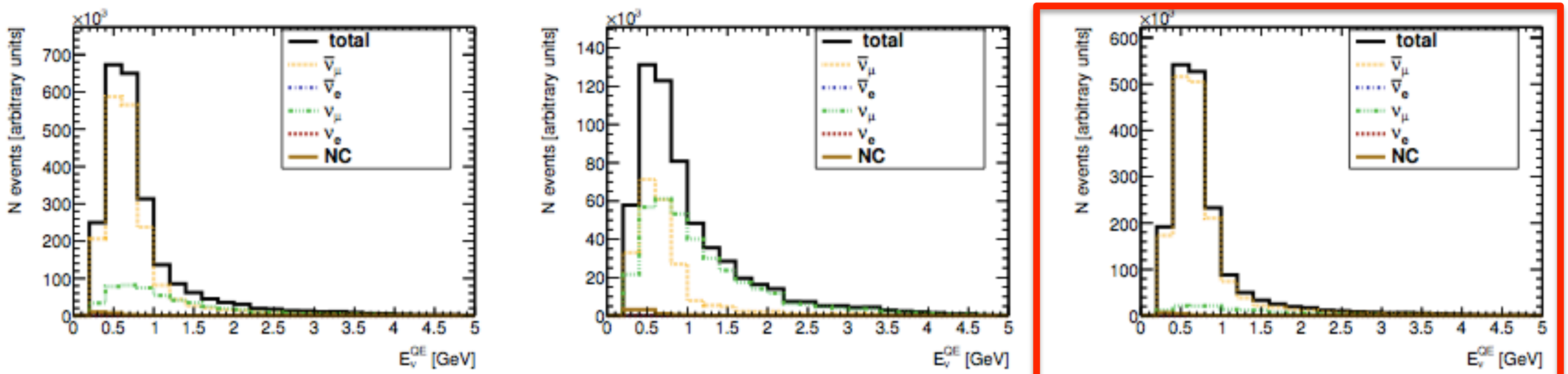
<u>1 Ring electron (1Re)</u>
Electron-PID
p_{recon} > 100MeV
P_{ve_recon} < 1250MeV
Michel e- and π^0 veto cuts

Resolutions:

	Electron	Muon
Visible energy [GeV]	0.075	0.042
Visible energy [%]	9.0	6.0
Lepton Angle [degress]	2.4	1.7
Vertex Position [m]	0.21	0.12
E_ν^{QE} [GeV]	0.17	0.09
E_ν^{QE} [%]	24.0	8.0

Selection + Neutron tagging

- In RHC, 23% wrong-sign in 1Rμ selection
  - Reduce to 8% by requiring ≥1 tagged neutron
  - Signal:Background increases 1.5->2.7

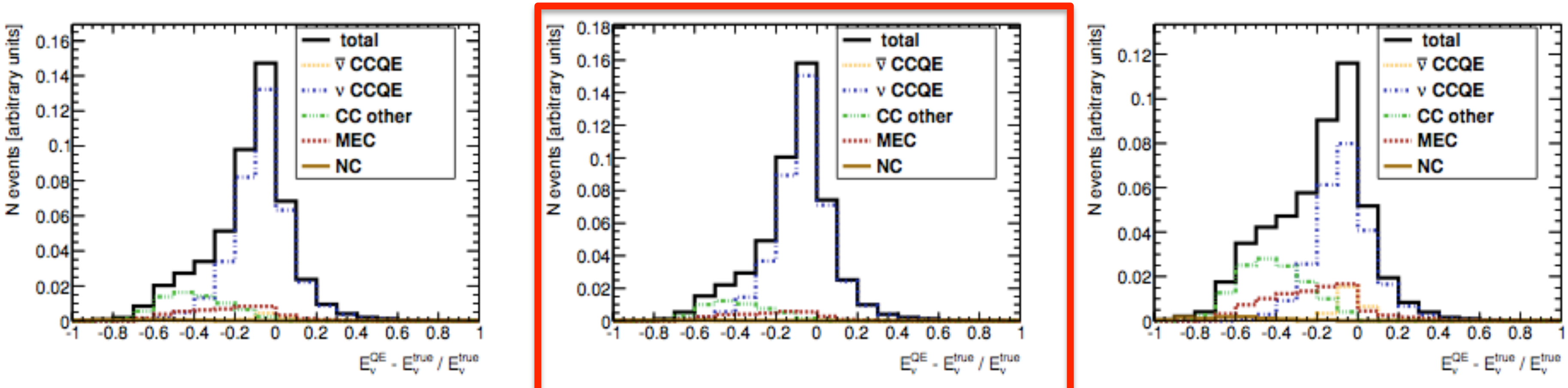


(a) Any $N_{neutrons}$ (b) $N_{neutrons} = 0$ (c) $N_{neutrons} \geq 1$

Anti-neutrino Mode

Selection + Neutron tagging

- In FHC, 24% CCother in 1Rμ selection
  - Reduce by requiring 0 tagged neutrons
  - Signal:Background increases 2.9->4.8
  - Improved neutrino energy reconstruction (QE assumption)



(a) Any N_{neutrons} (b) $N_{\mathrm{neutrons}} = 0$ (c) $N_{\mathrm{neutrons}} \geq 1$

Neutrino Mode

Systematic Uncertainties

- Flux systematic based on T2K error model. Assume:
  - 6% prior uncertainty (flux model and replica target data)
  - Correlations between TITUS and HK flux (100%)
  - Correlations between FHC and RHC flux (60%)
- Interaction uncertainty based on T2K prior input to pre2015 analyses
  - + 50% uncertainty on normalisation of MEC events
  - + $\nu - \overline{\nu}$ cross-section ratio uncertainty = 20%
- Near-to-far ratio important for oscillation analyses
- Double ratio relevant for δ_{cp} analysis

Systematic	N^{HK}_{FHC}	N^{TITUS}_{FHC}	N^{HK}_{RHC}	N^{TITUS}_{RHC}	R_{FHC}	R_{RHC}	$\frac{(R_{RHC})}{(R_{FHC})}$
Interaction Syst.	24.1	24.4	11.4	12.0	4.2	4.5	1.9
Flux Syst.	6.5	6.6	6.0	6.3	0.9	1.0	1.3
Total Syst.	21.8	21.9	14.2	14.4	4.5	4.3	2.4
Statistical	2.5	0.1	3.2	0.2	2.5	3.1	4.3
Stat. + Syst.	21.4	21.4	11.8	11.2	5.1	5.6	4.9

Intermediate WC Detector

- In reality, we will not build 2 new intermediate detectors!
- Work towards hybrid detector concept that merges three main design features
  - Off-axis spanning
  - Gd neutron capture information
  - Muon Range Detector

Hyper-K Physics Potential

- CP violation
  - Explain the Baryon asymmetry of the Universe
- Proton Decay
- Atmospheric Neutrinos
  - Mass ordering,
  - + Beam: test 3 flavour paradigm precisely
  - search for new physics: NSI, Lorentz invariance, sterile neutrinos
- Solar Neutrinos
- Indirect dark matter
- Astronomical Sources
  - Galactic supernovae
  - dark matter annihilation, gamma ray burst jets, and pulsar winds

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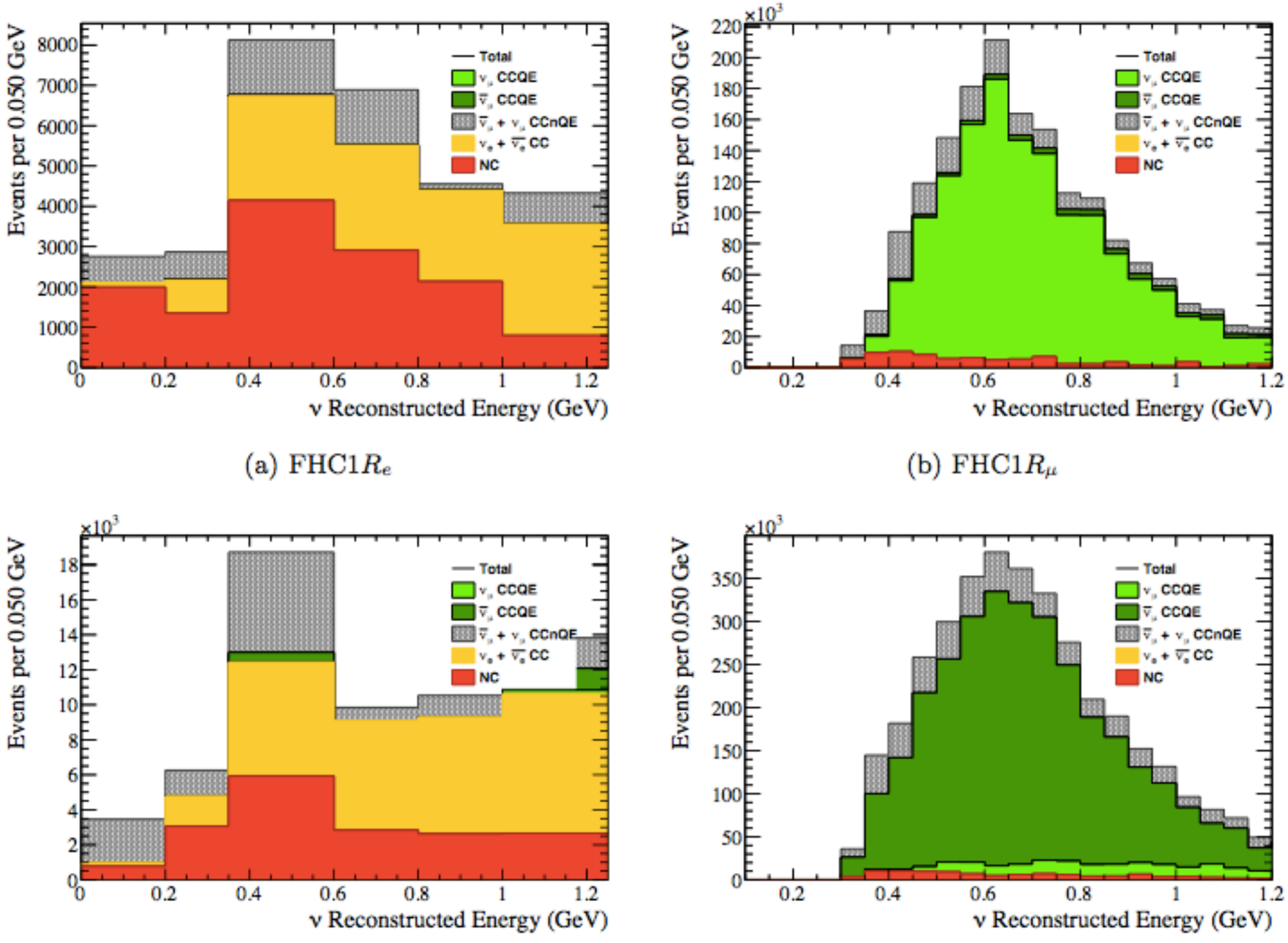
δ_{CP} Sensitivity

- Fit reconstructed MC for TITUS and HK simulations using VALOR framework
- Minimise global poisson log likelihood constructed from the expected (nexp) and observed (nobs) number of events in each reconstructed energy bin
- Use Asimov data set: nominal MC = fake data
- Apply systematic parameter weights to nexp (MC)

Predicted TITUS spectra



(a) FHC1R_e (b) FHC1R_μ

(c) RHC1R_e (d) RHC1R_μ

Predicted HK spectra - reconstructed

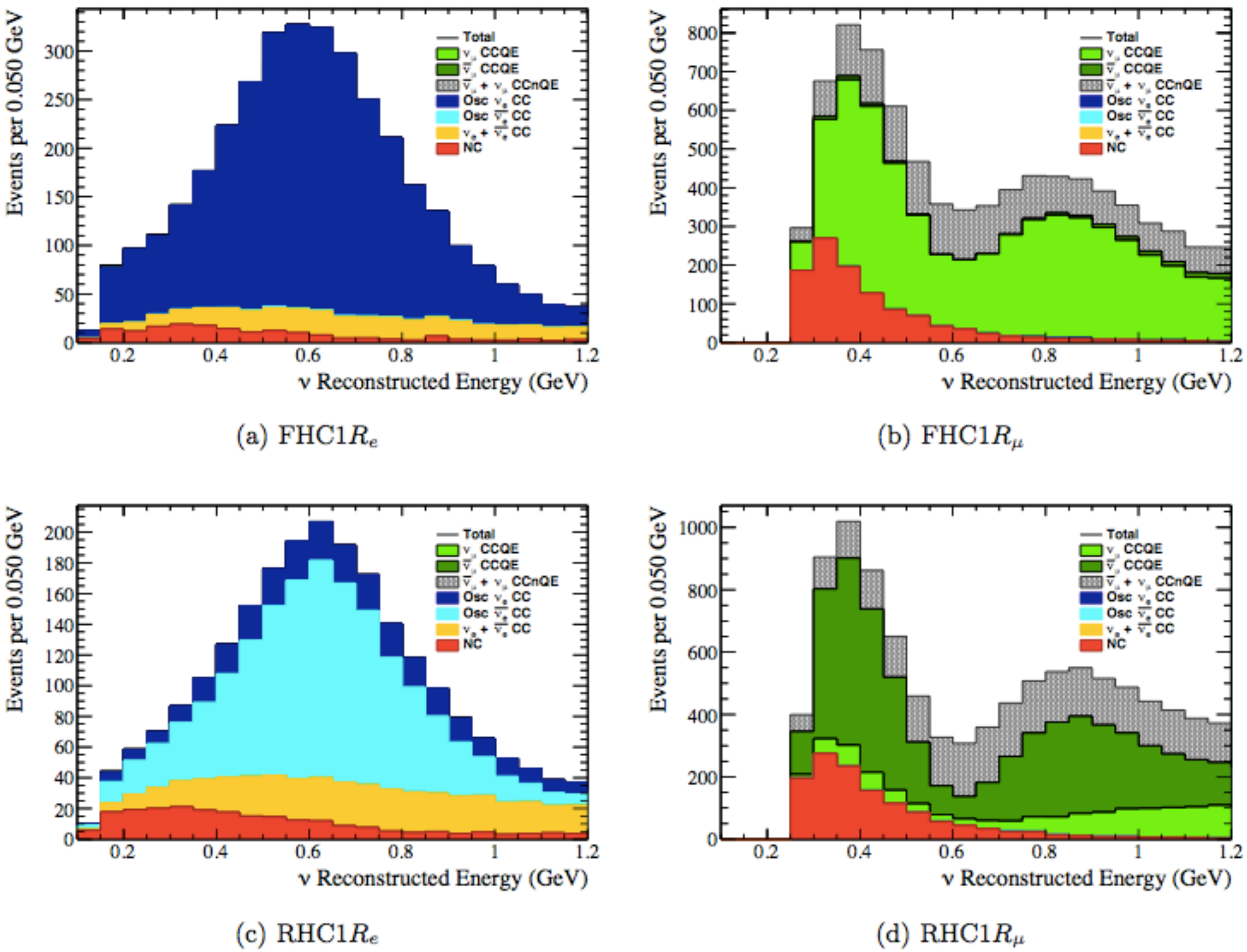
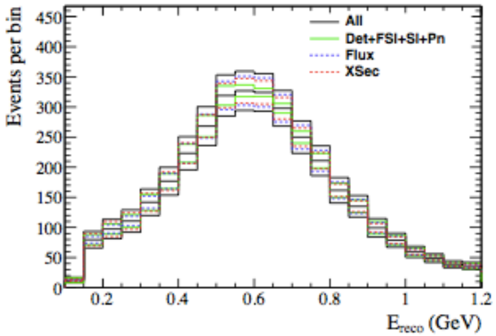
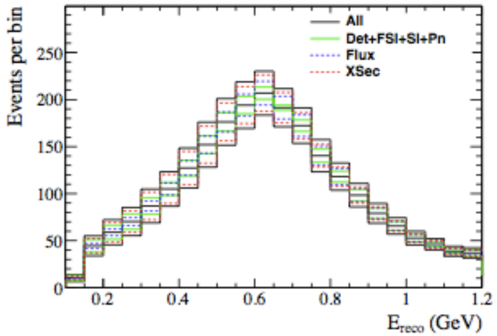


Figure 28: Predicted Hyper-K spectra for oscillation parameters $sin^2(\theta_{23}) = 0.528$, $sin^2(\theta_{12}) = 0.306$, $sin^2(\theta_{13}) = 0.025$, $\delta_{cp} = -1.601$, $\Delta m^2_{32} = 2.5 \cdot 10^{-3} eV^2$, $\Delta m^2_{12} = 7.5 \cdot 10^{-5} eV^2$, hierarchy=normal

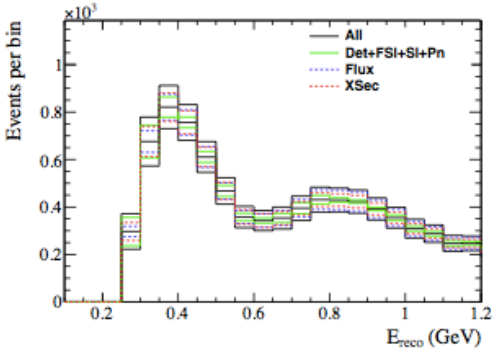
Systematic Uncertainties



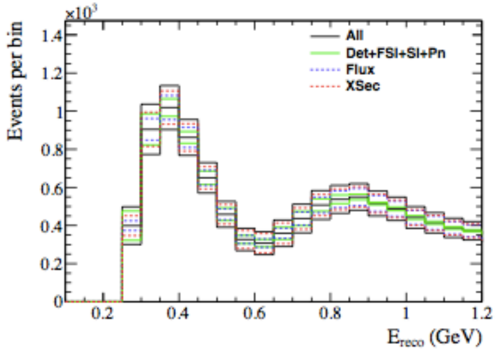
(a) FHC1R_e



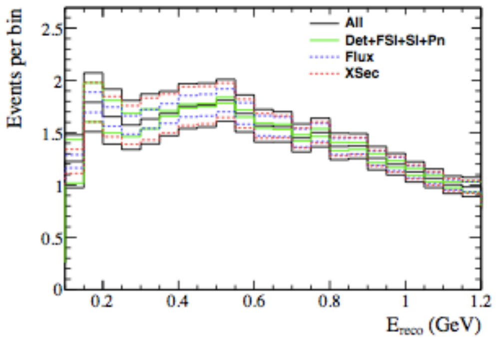
(b) RHC1R_e



(c) FHC1R_μ

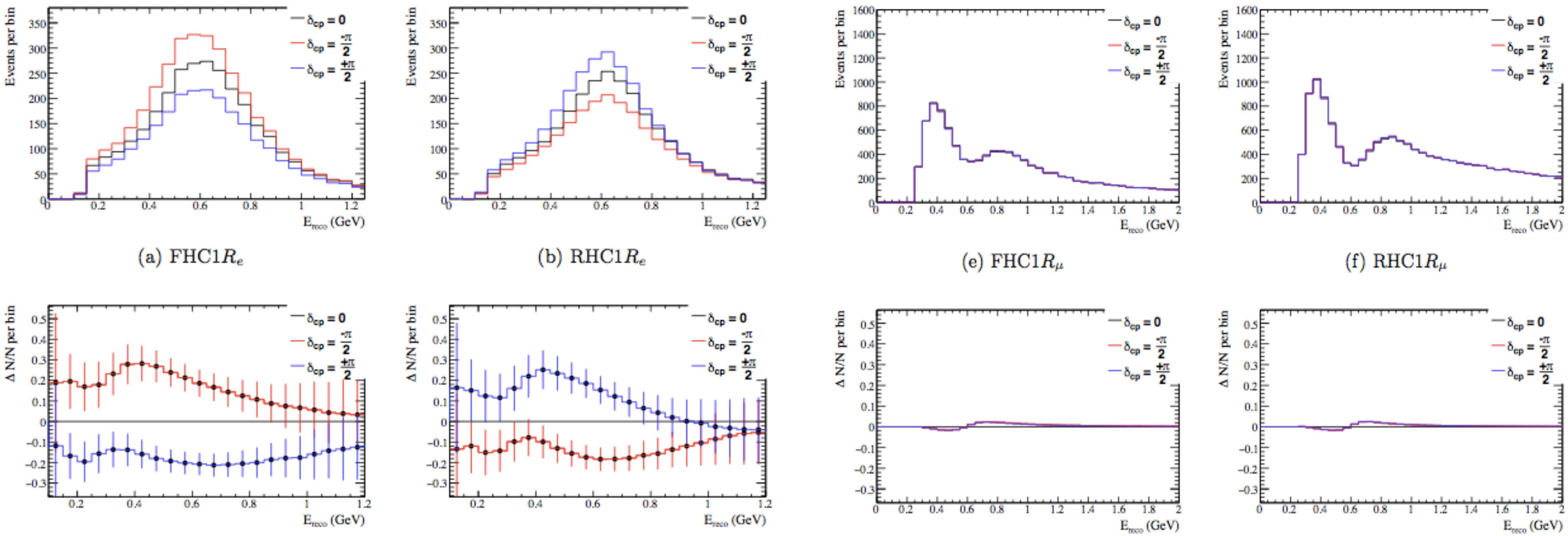


(d) RHC1R_μ



(e) Ratio FHC1R_e/RHC1R_e

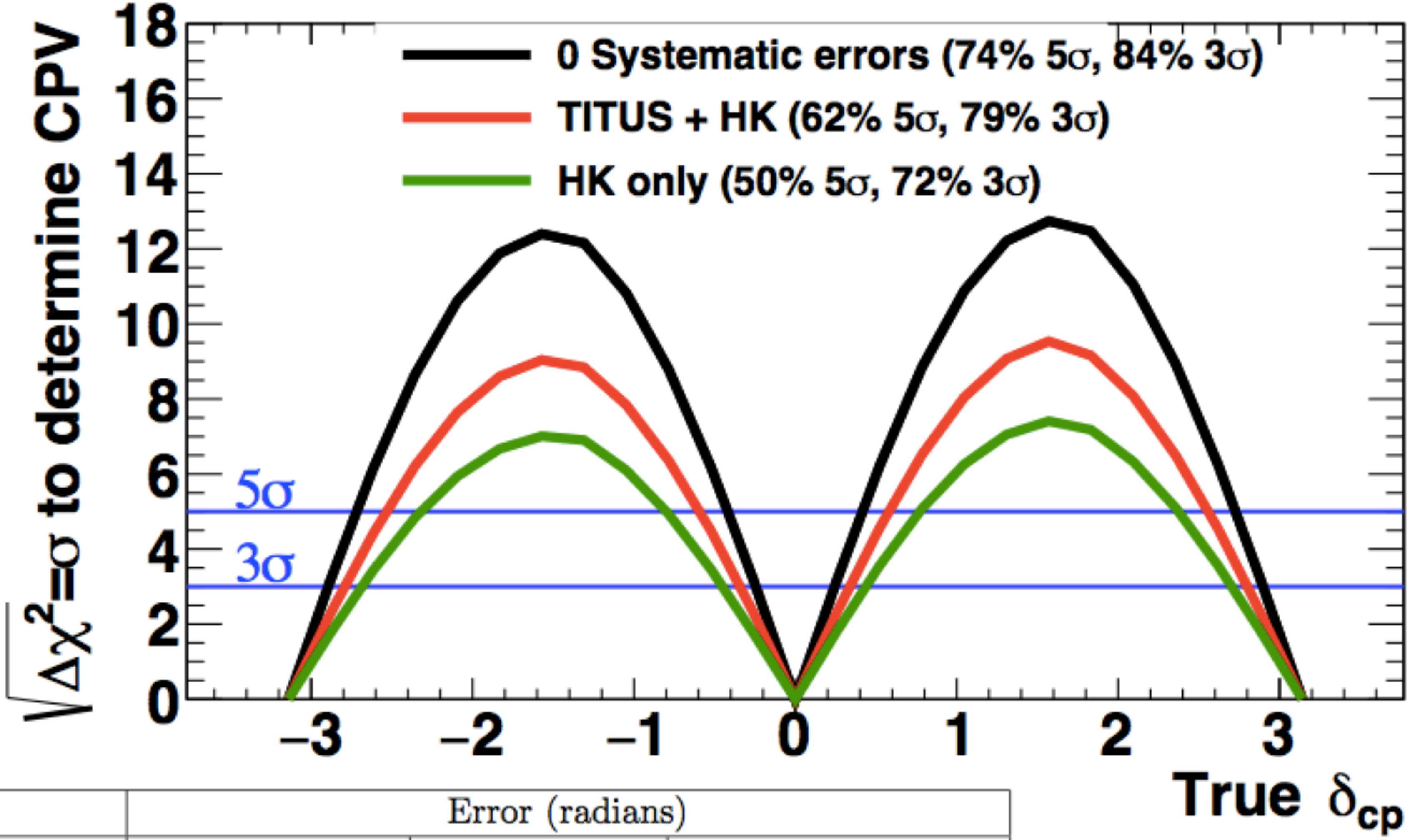
Affect of δ_{CP} on HK Spectra



(a) FHC1R_e (b) RHC1R_e (e) FHC1R_μ (f) RHC1R_μ

(c) FHC1R_e fractional change (d) RHC1R_e fractional change (g) FHC1R_μ fractional change (h) RHC1R_μ fractional change

δ_{CP} Sensitivity



	Error (radians)		
True δ_{cp}	No Systematics	Hyper-K only	TITUS + Hyper-K
0	0.08	0.15	0.11
$\frac{\pi}{4}$	0.13	0.23	0.17
$-\frac{\pi}{2}$	0.29	0.38	0.33

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  - search for new physics: NSI, Lorentz invariance, sterile neutrinos
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  - Galactic supernovae
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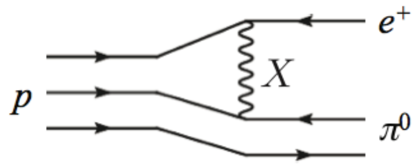
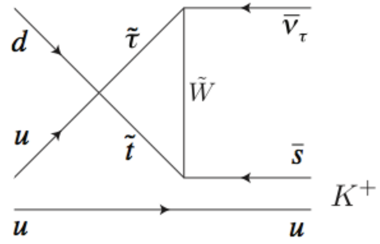
Proton Decay

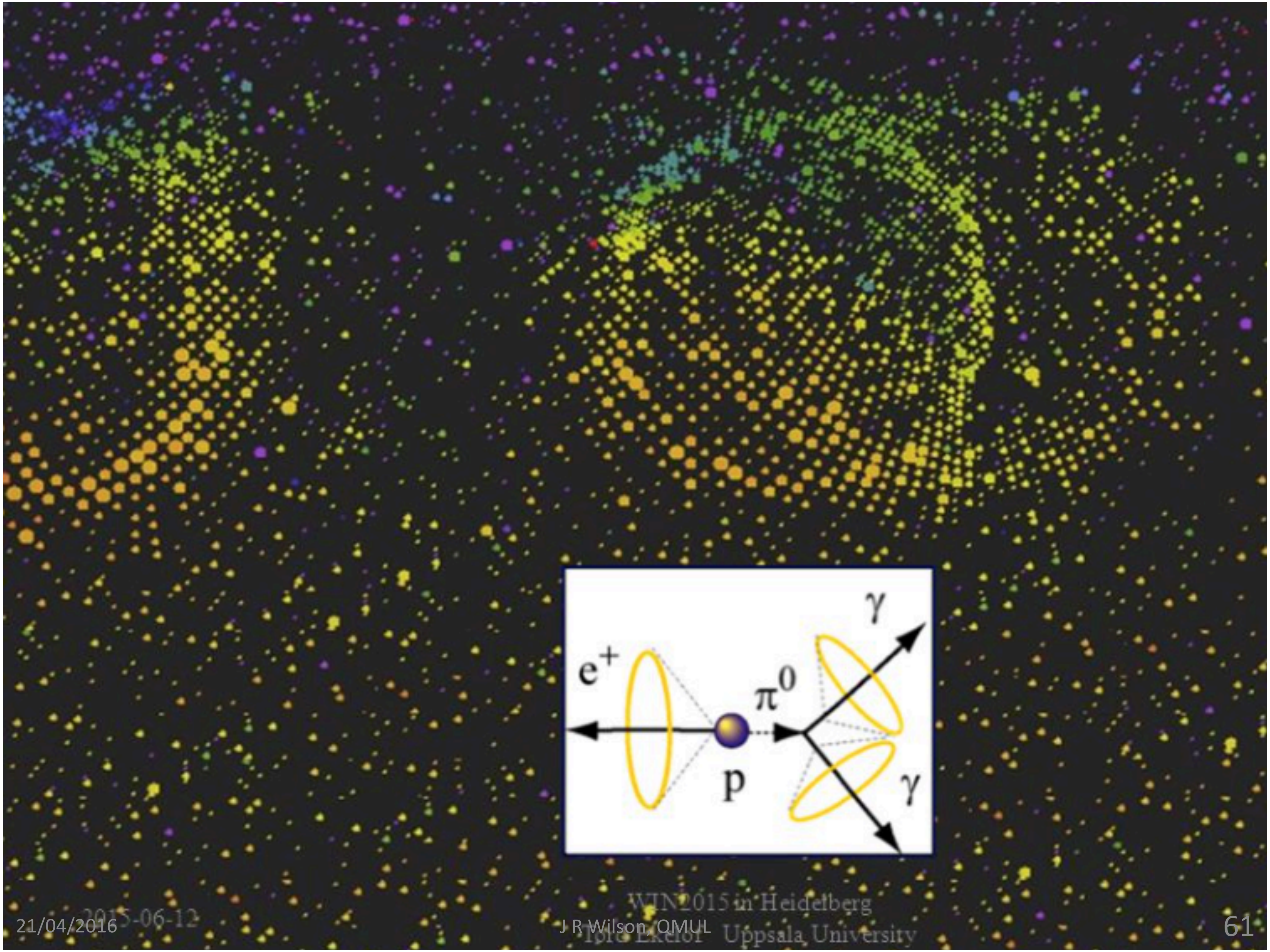




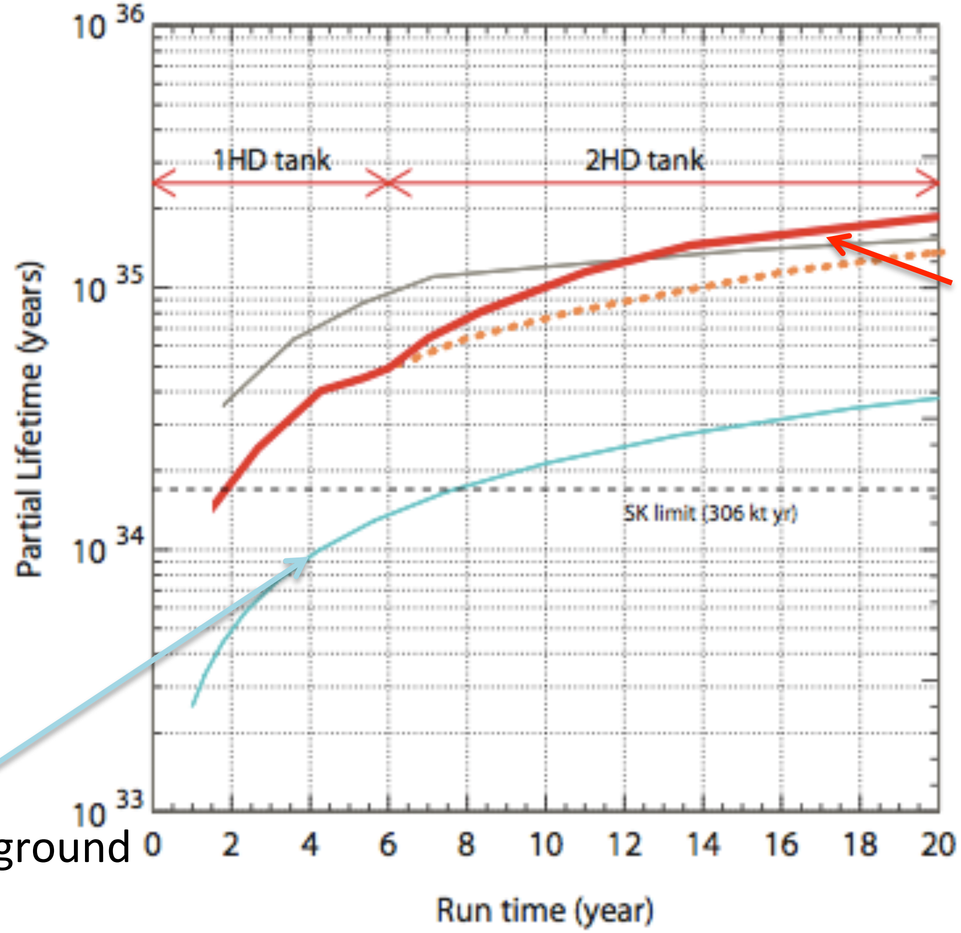
Baryon number violation is believed to have played an important role during the formation of the universe: one of the famous Sakharov Conditions to explain the baryon asymmetry of the universe.

Proton decay is an observable consequence of the violation of baryon number.

- Requirements:
  - Large number of nucleons
  - Reconstruction to extract signals and suppress backgrounds
- Strength of WC: sensitive to wide variety of modes


e^+
π^0
p
γ
γ
2015-06-12
WIN2015 in Heidelberg
Tord Ekelof Uppsala University

p -> $e^+ + \pi^0$

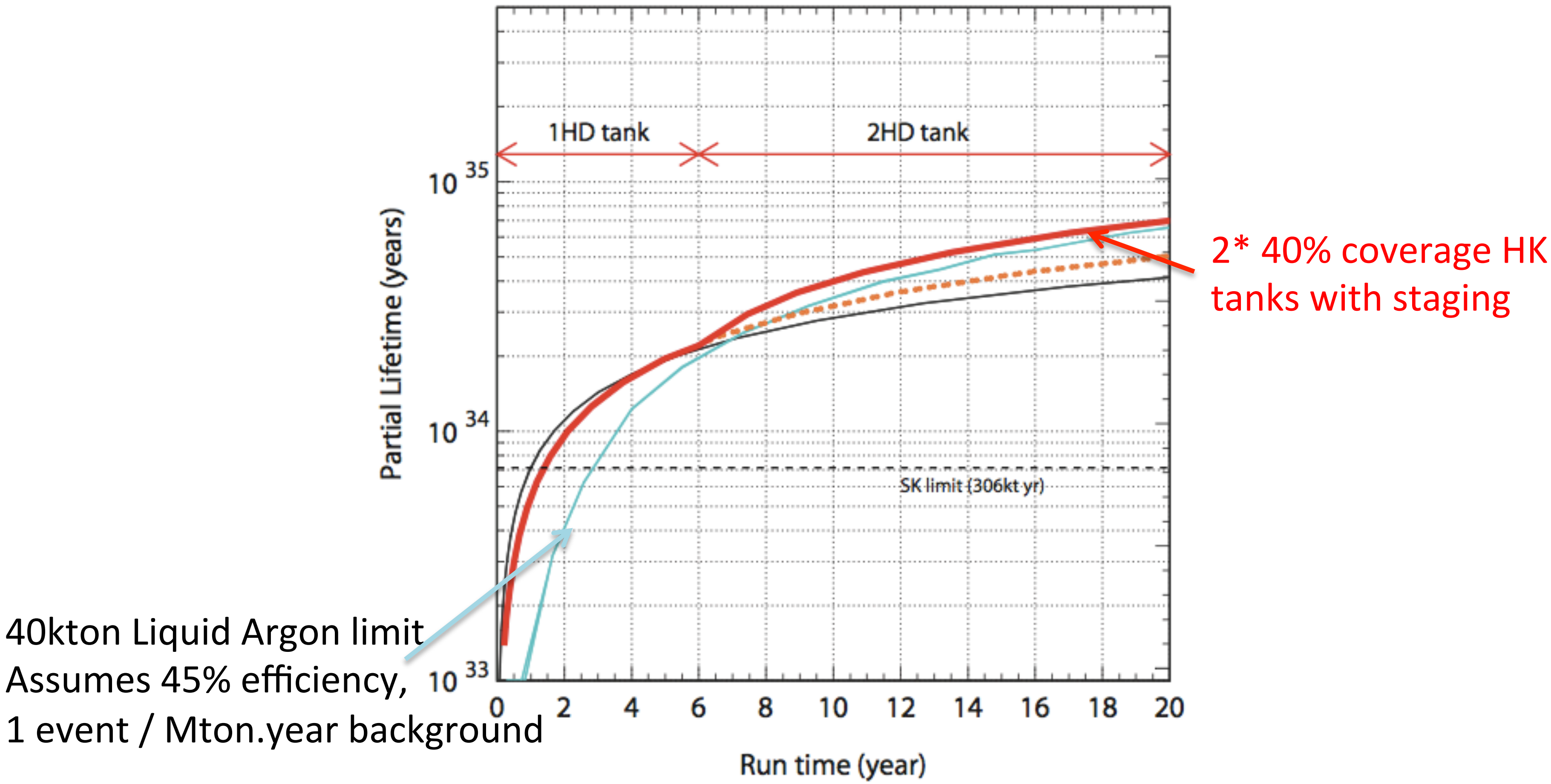


2* 40% coverage HK tanks with staging

40kton Liquid Argon limit
Assumes 45% efficiency,
1 event / Mton.year background

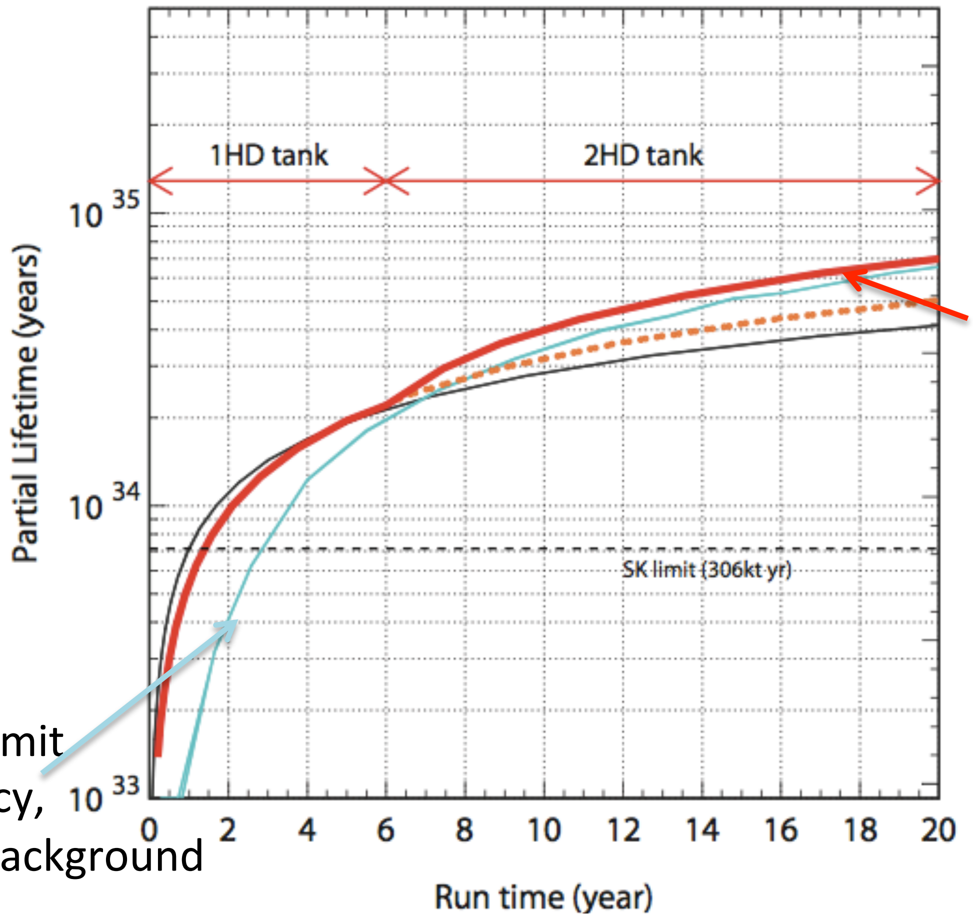
- Mode preferred by most GUTs
- Clean Topology
  - No invisible final state particles. Reconstruct p invariant mass
- Selection = 2 or 3 e-like rings
- Low Backgrounds from atmospheric neutrinos ($Cc\nu_e\pi$)

p-> $\bar{\nu}$ + K^+



- Mode preferred by SUSY GUTs
- K^+ produced with 340MeV/c : below Cherenkov threshold
- See prompt γ from p hole de-excitation and $K^+ \to \mu^+ + \nu$ (64%) or $K^+ \to \pi^+ + \pi^0$ (21%)

p-> $\overline{\nu}$ + K^+



2* 40% coverage HK tanks with staging

40kton Liquid Argon limit
Assumes 45% efficiency,
1 event / Mton.year background

	Prompt γ				$\pi^+\pi^0$				p_μ Spectrum		
Design	ϵ_{sig} [%]	σ_ϵ [%]	Bkg	σ_{Bkg} [%]	ϵ_{sig} [%]	σ_ϵ [%]	Bkg	σ_{Bkg} [%]	ϵ_{sig} [%]	Bkg	σ_{fit} [%]
1TankHD	12.7	19.0	0.9	27.0	10.8	10.0	0.7	31.0	31.0	1916.0	8.0

Other Modes p decay

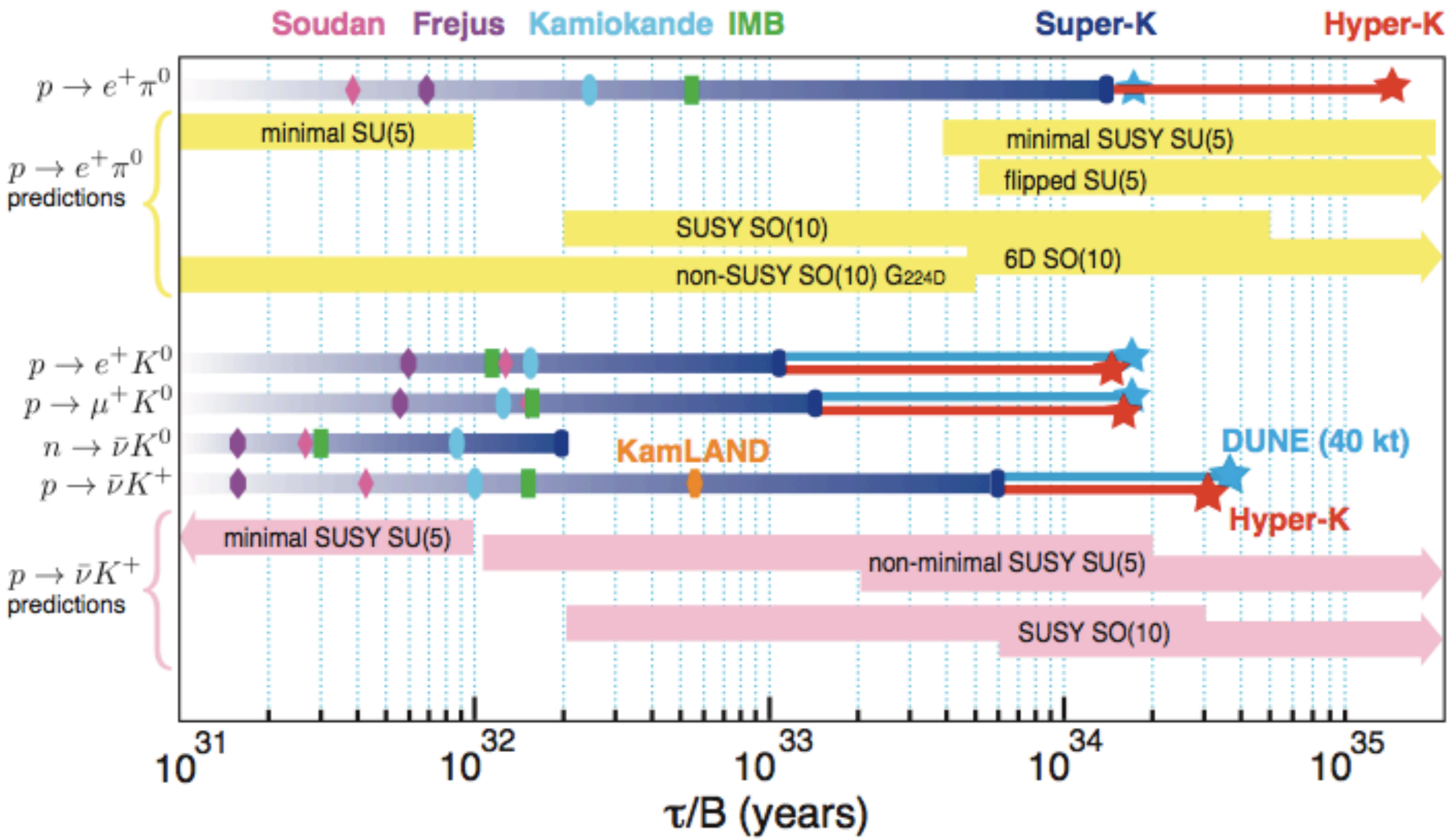


FIG. 3. A comparison of historical experimental limits on the rate of nucleon decay for several key modes to indicative ranges of theoretical prediction. Included in the figure are projected limits for Hyper-Kamiokande and DUNE based on 10 years of exposure.

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  - Mass ordering,
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  - search for new physics: NSI, Lorentz invariance, sterile neutrinos
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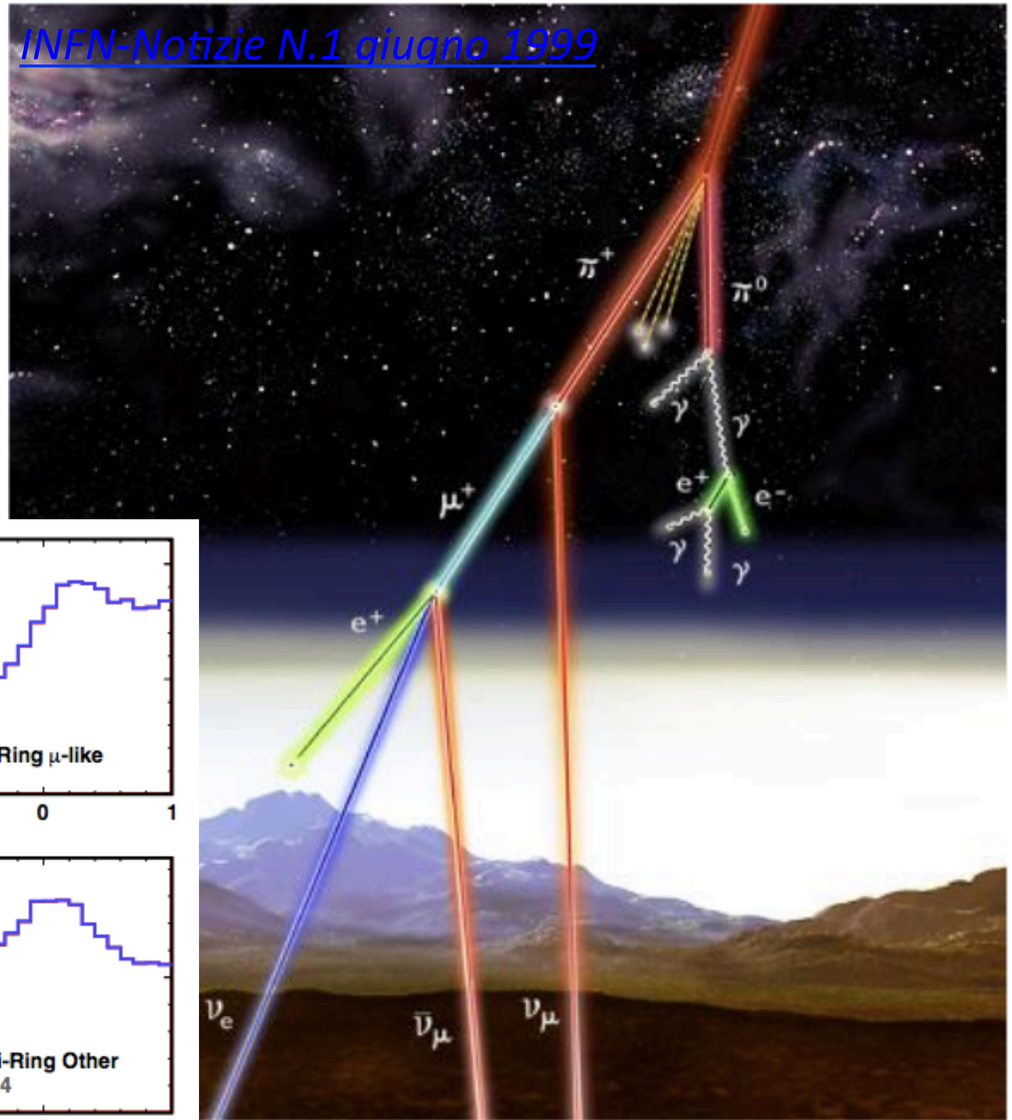
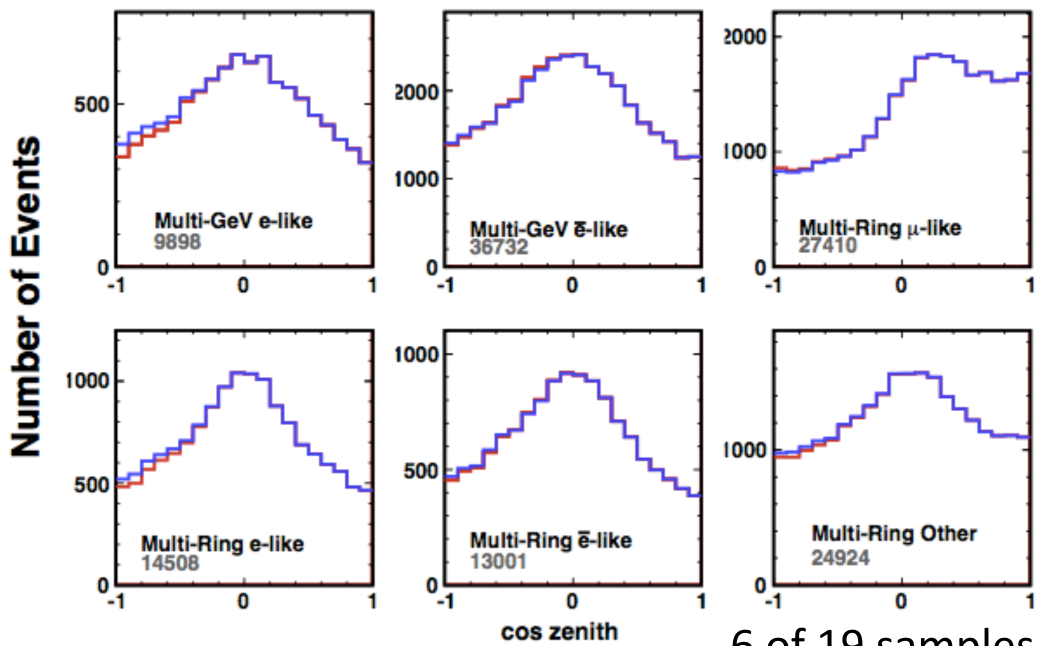
Atmospheric neutrinos

- Provides both neutrino and anti-neutrino fluxes
- Spanning a few orders of magnitude in energy.
- Spanning path lengths O(10) – O(10^4)km



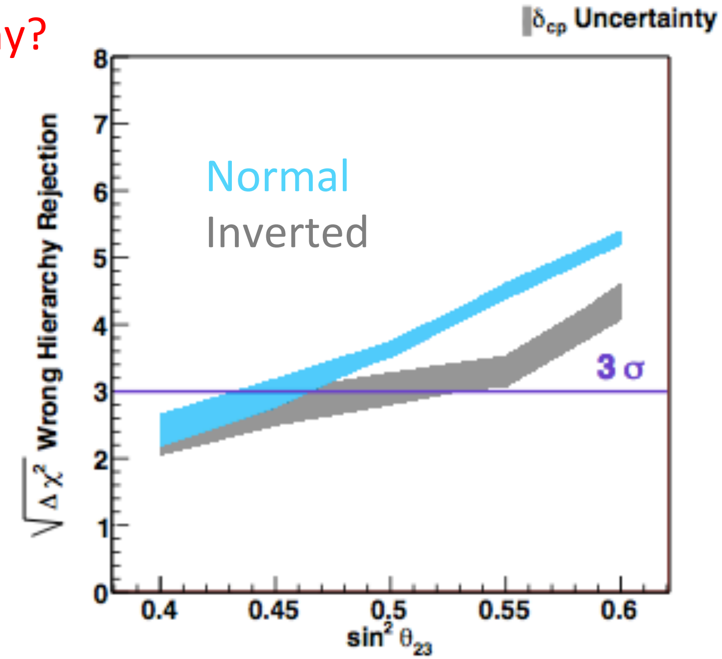


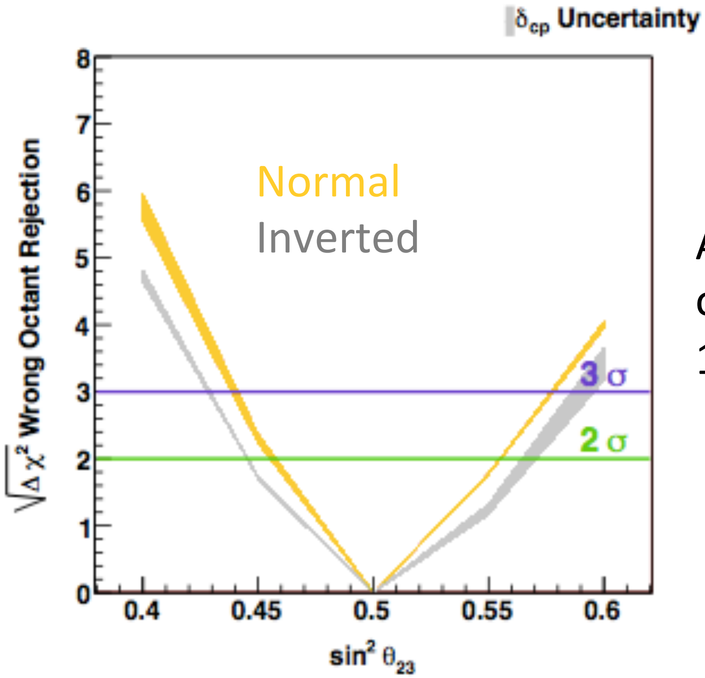
6 of 19 samples

Normal, inverted hierarchy

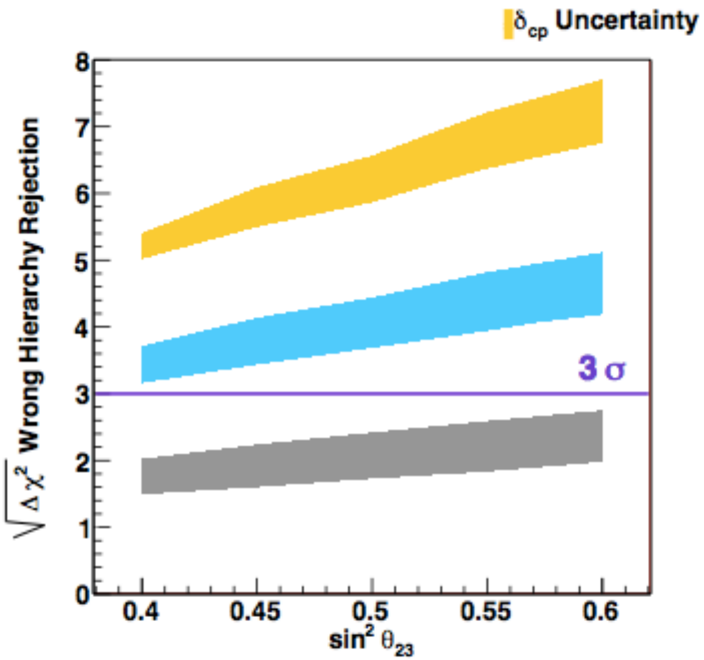
Hierarchy?

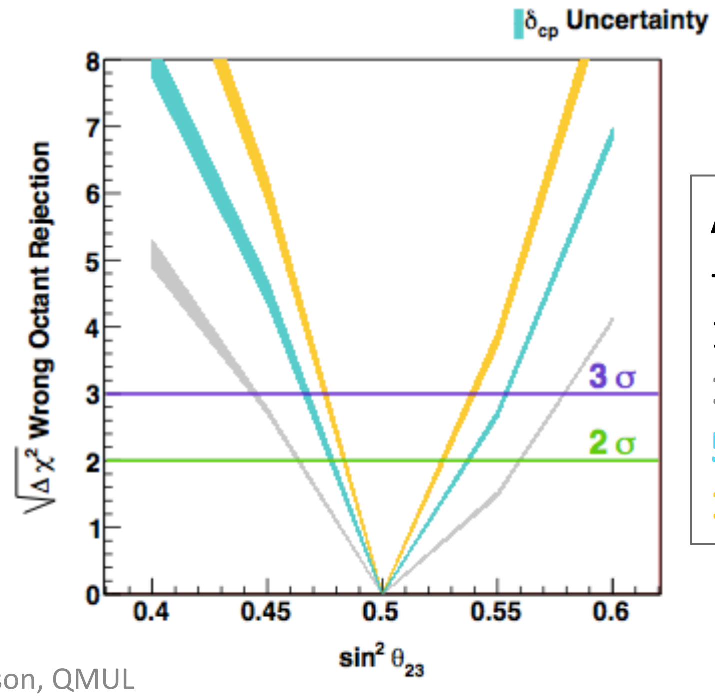
Octant?





Atmospheric only
10 years





Atmospheric
+ Beam
1 tank
1 year
5 years
10 years

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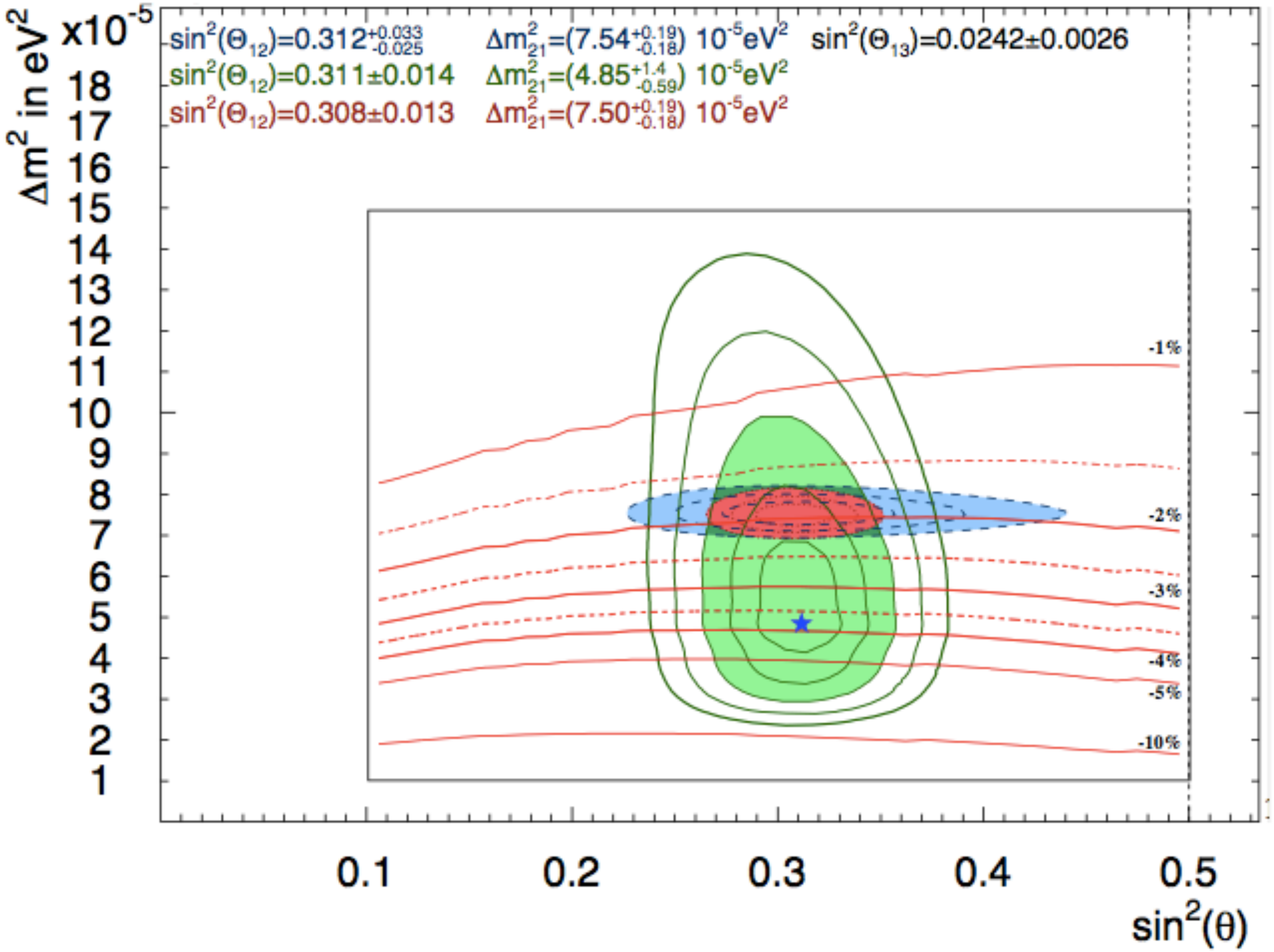
Solar Neutrino Oscillations

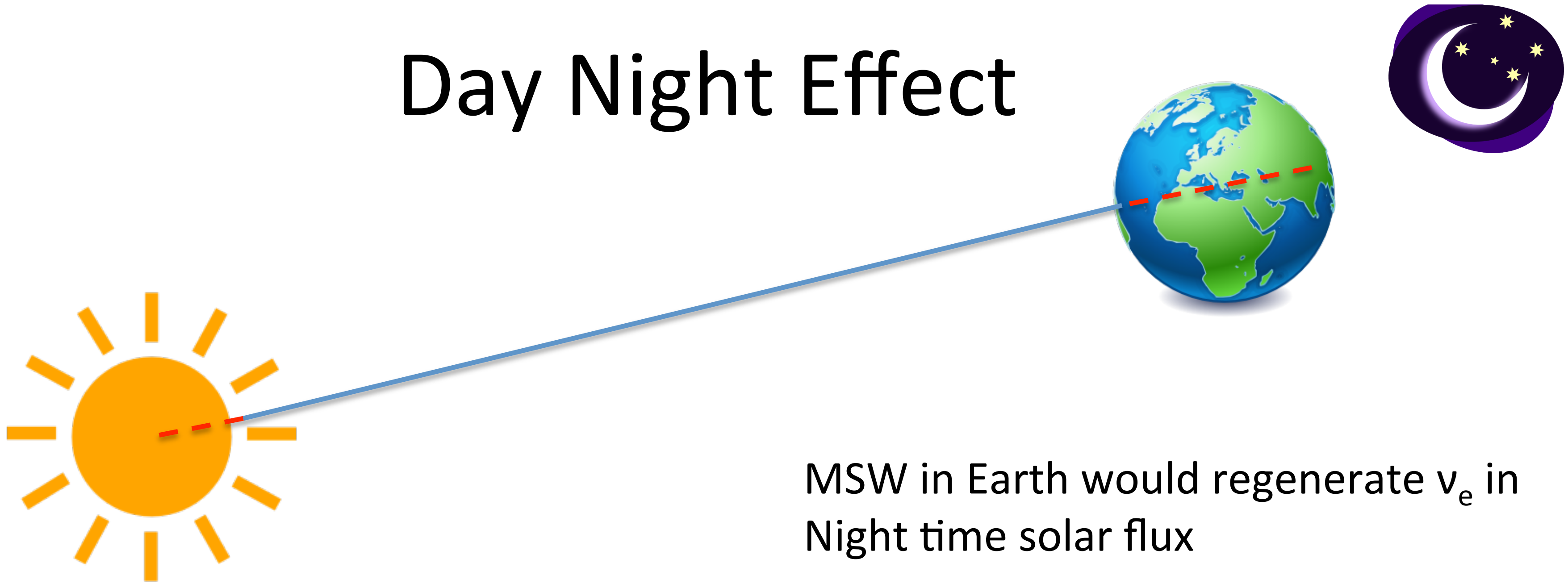
KamLAND
Solar Neutrino Experiments
Combined



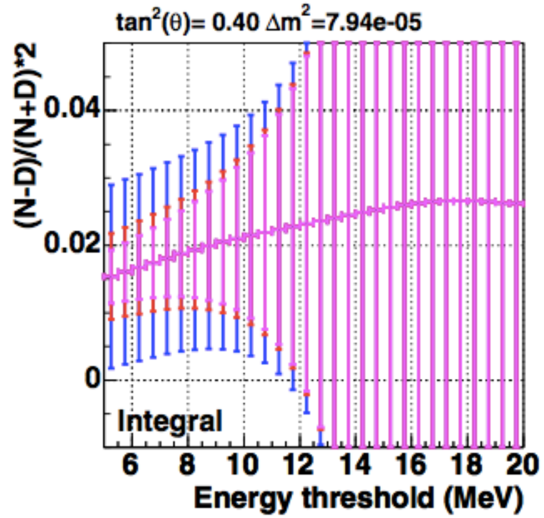
Δm^2_{12} 2σ tension between Super-K Day-Night and KamLAND

Θ_{12} in good agreement

Day Night Effect

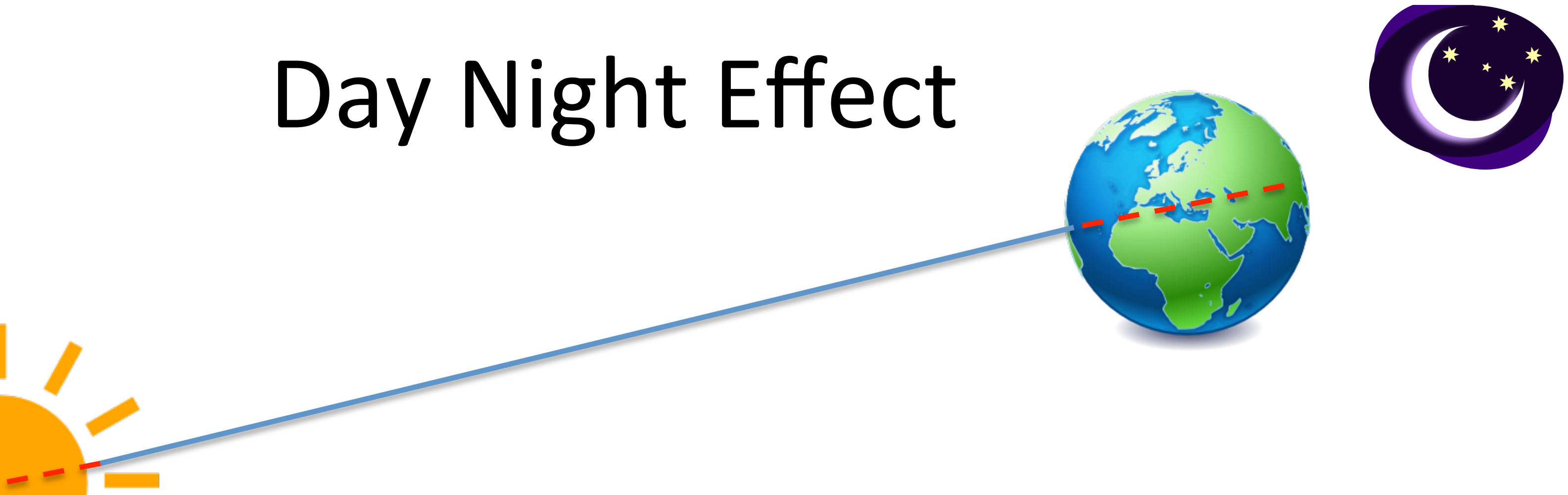


MSW in Earth would regenerate ν_e in Night time solar flux

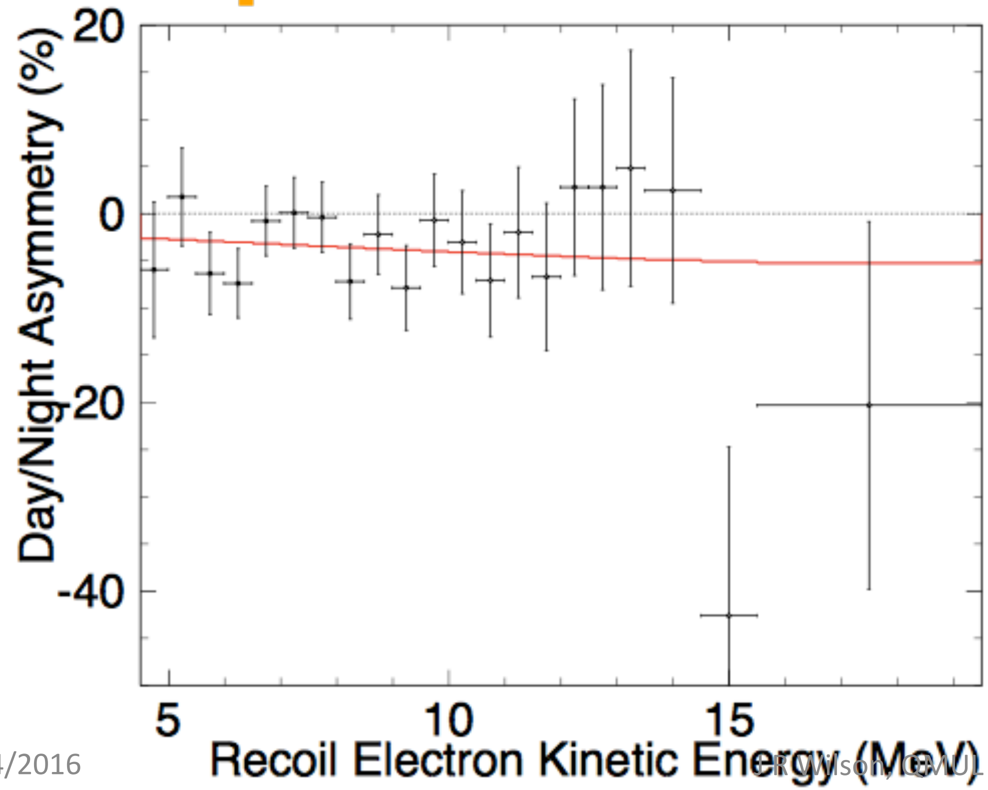


- Expected asymmetry ≈1%
- Tight control of up/down systematic
- High statistics in higher energy region

Day Night Effect

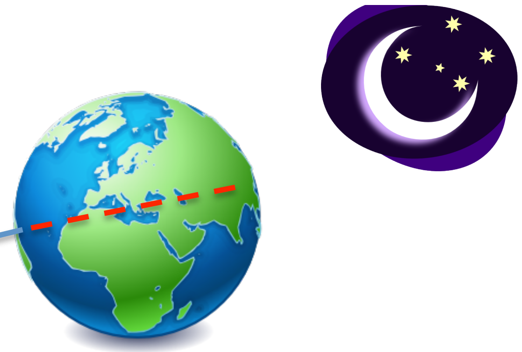


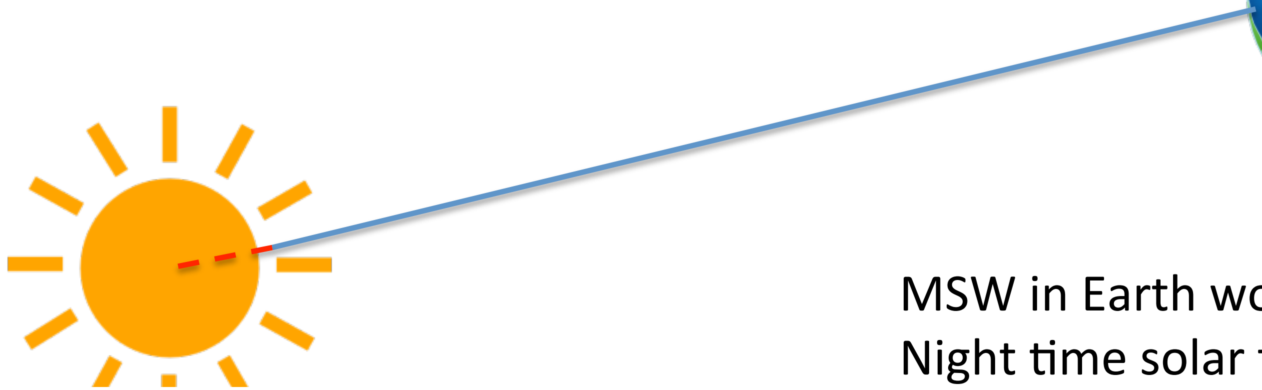
MSW in Earth would regenerate ν_e in Night time solar flux



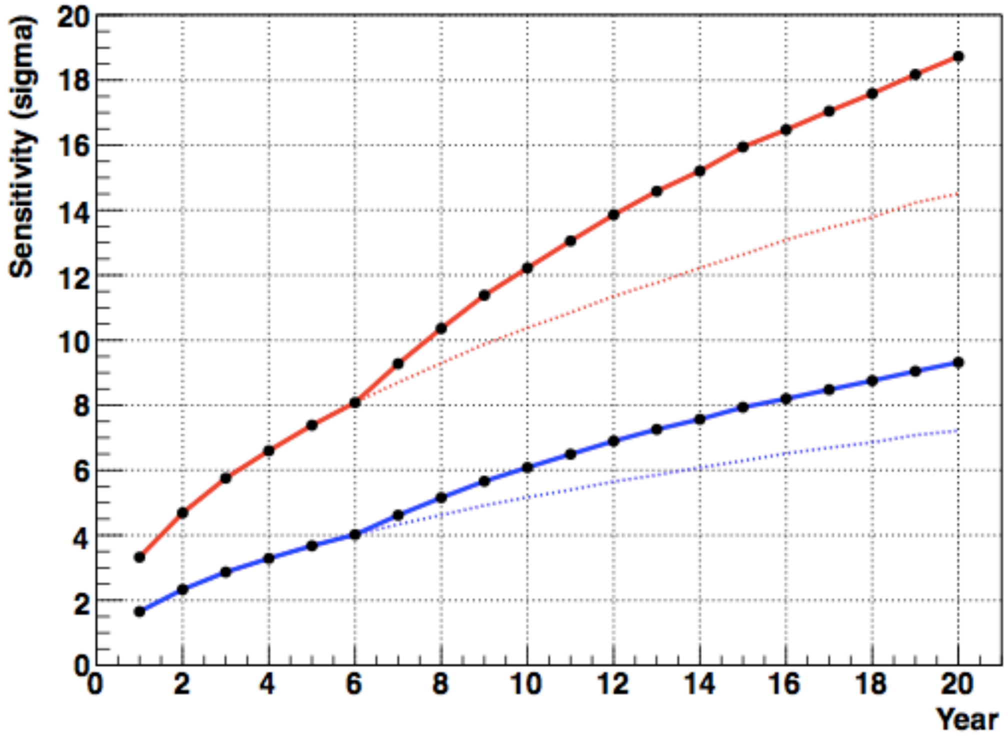
SuperKamiokande
Phys. Rev. Lett. 112, 091805 (2014)
$A_{d/n}$ =(−3.2 ± 1.1(stat) ± 0.5(syst))%, deviates from zero by 2.7 σ

Day Night Effect





MSW in Earth would regenerate ν_e in Night time solar flux



No asymmetry

Asymmetry expected from reactor neutrino oscillation

Hyper-K Physics Potential

- CP violation
  - Explain the Baryon asymmetry of the Universe
- Proton Decay
- Atmospheric Neutrinos
  - Mass ordering,
  - + Beam: test 3 flavour paradigm precisely
  - search for new physics: NSI, Lorentz invariance, sterile neutrinos
- Solar Neutrinos
- Indirect dark matter
- Astronomical Sources
  - Galactic supernovae
  - dark matter annihilation, gamma ray burst jets, and pulsar winds

Supernovae

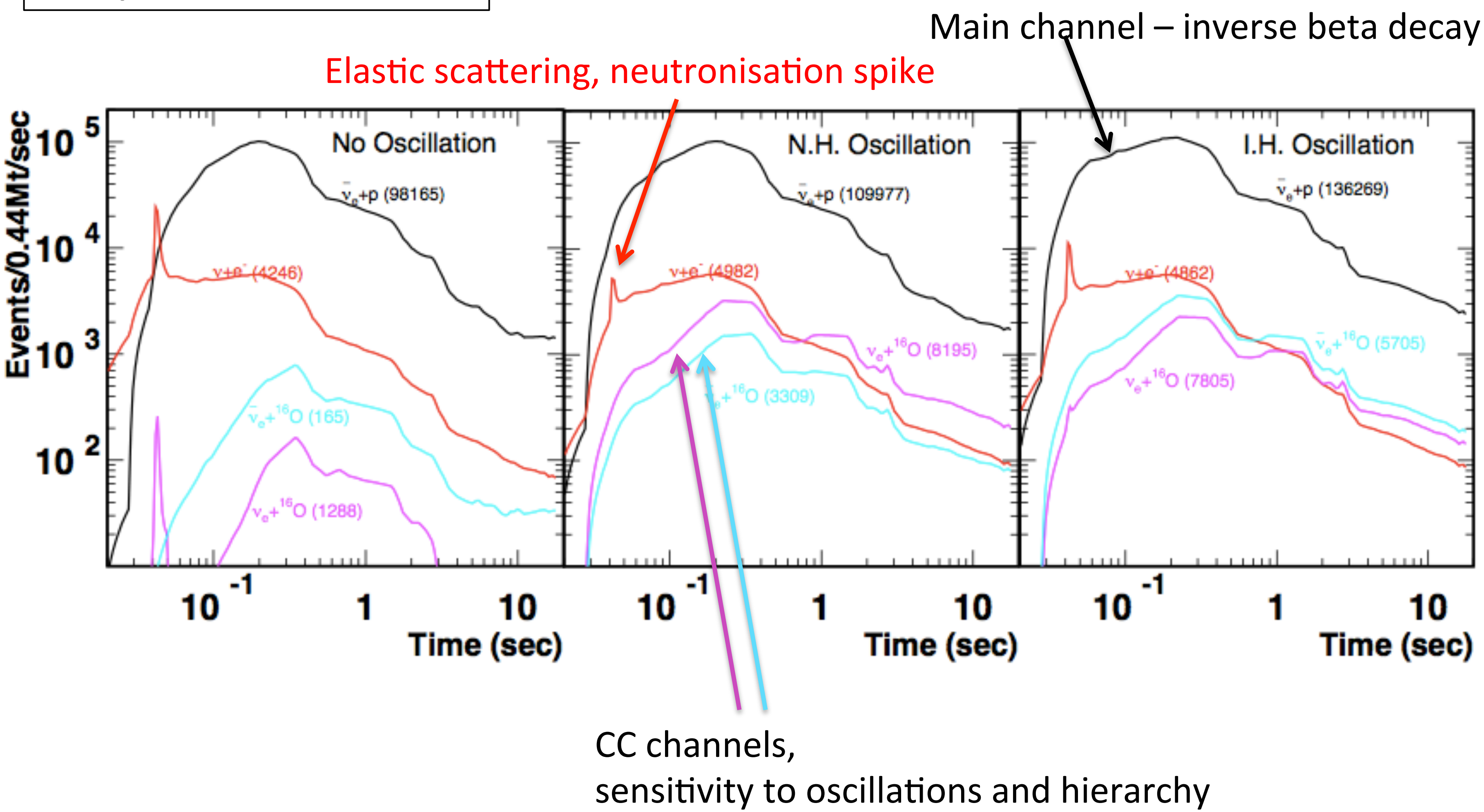
- Core Collapse Super Nova: Death of $>8M_{\odot}$ star, releases $\sim 3\times10^{53}$ergs
  - 99% energy release carried by νs
  - Neutronisation burst: ~10ms of electron captures ($p + e^- \rightarrow n + \bar{\nu}_e$) releases $\sim 10^{51}$ergs
  - Accretion phase <~1s
  - Cooling phase: several seconds in which all ν types emitted

- Understanding of supernova process
- Probe neutrino
  - Measure direction, energy, type and arrival times
  - Low background as short burst

If a CCSN explosion were to take place halfway across our Galaxy, Hyper-K would observe ~52,000 - 79,000 neutrino interactions per tank!

Hyper-K SN signals

10kpc SN, two tanks



DUNE main sensitivity to ν_e through $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$ Good Complementarity

Summary

- Hyper-K is the proposed next generation Water Cherenkov Detector
  - Leptonic CP Violation
  - Precision Neutrino Oscillation Measurements
  - Proton Decay Searches
  - Supernova sensitivity
  - +++ more Physics

- Proposal submitted to Science Council of Japan by Prof. T. Kajita on behalf of Hyper-K in March 2016.