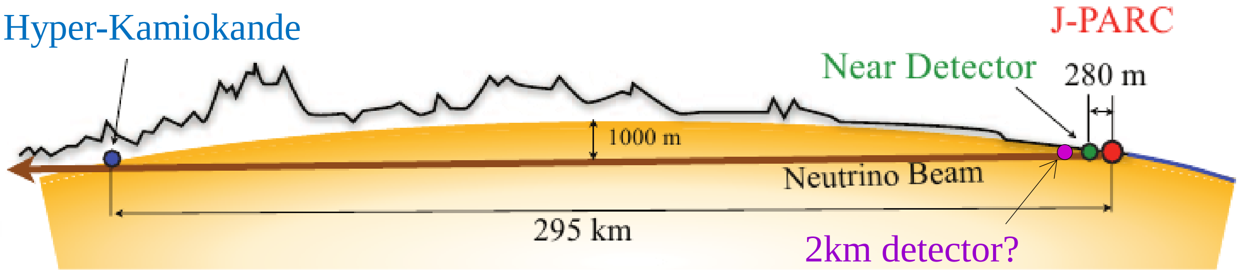


T2HyperK

from hints at CP violation with T2K to <u>discovery</u> in T2HyperK?

(*via* ‘evidence’ from T2K+NOvA…)

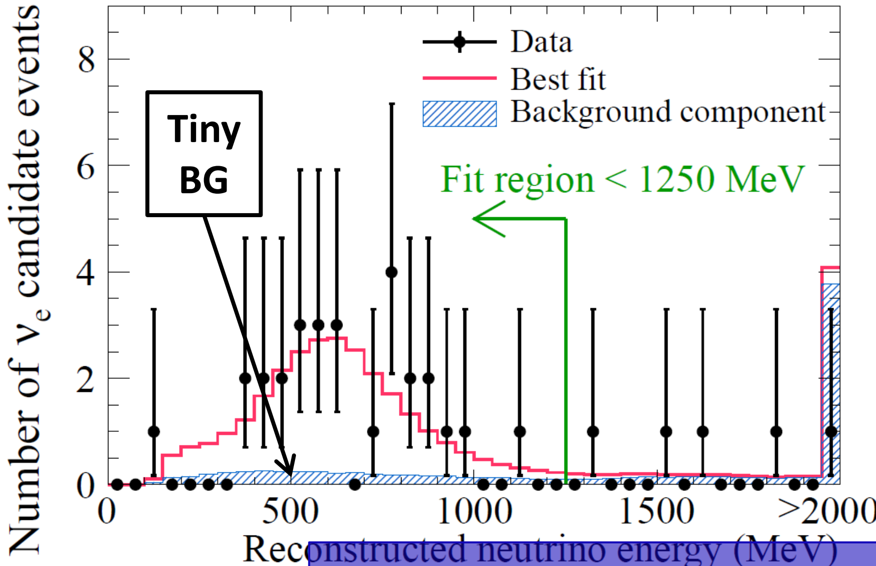
Mark Alastair Rayner

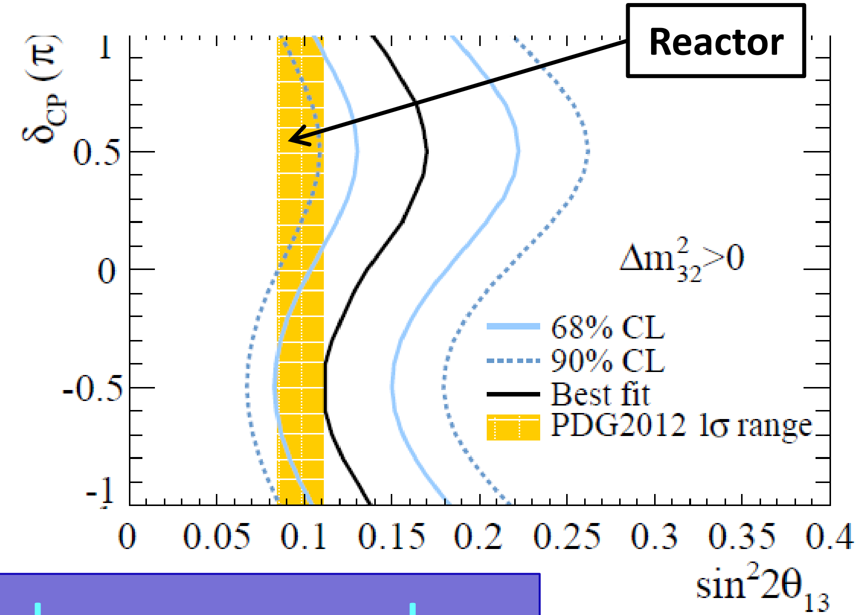
Université de Genève

SINERGIA meeting, 7 January 2014, CERN

N.B. For details on the plots in this talk see the 3rd open meeting, and the 1st European meeting, especially the talks by Nakaya-san and Dave Wark

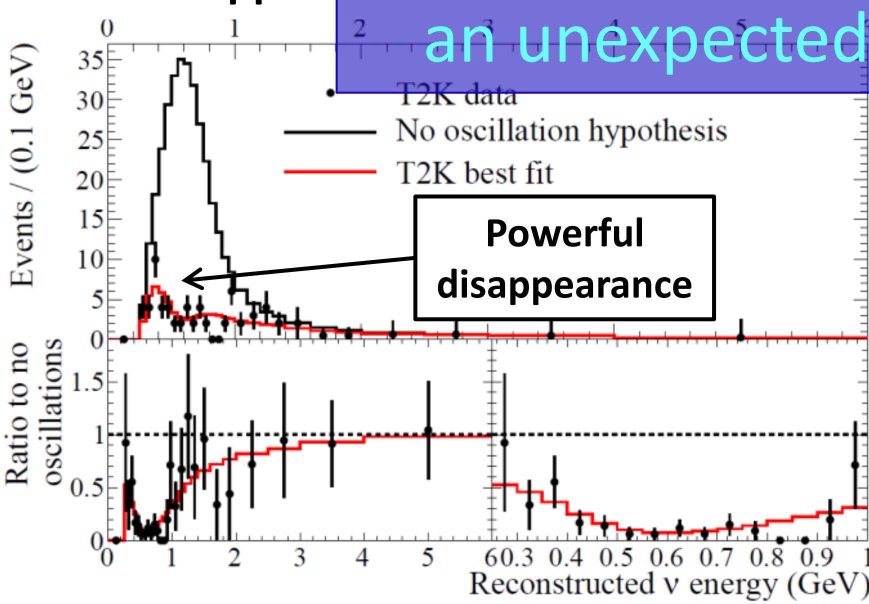
T2K 2013 appearance

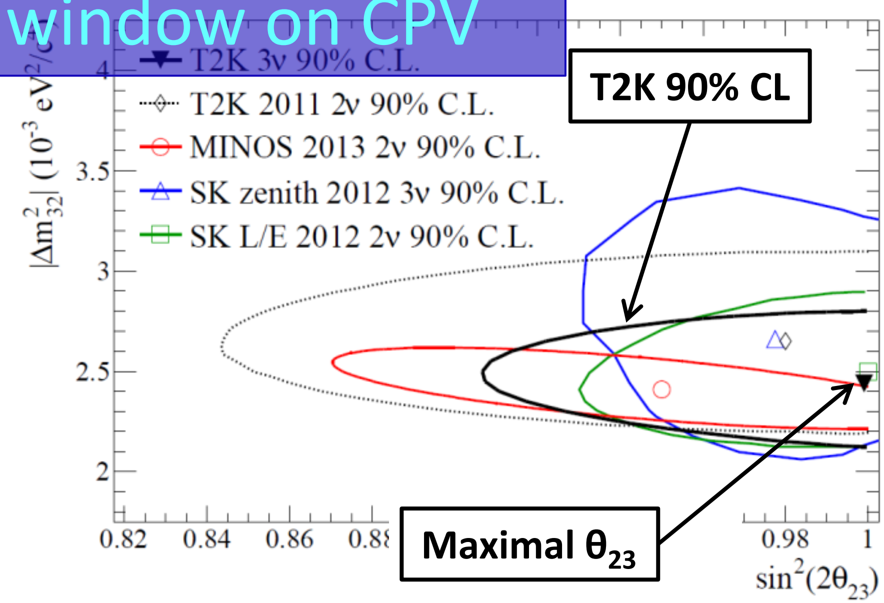




Recent T2K results have opened up an unexpected window on CPV

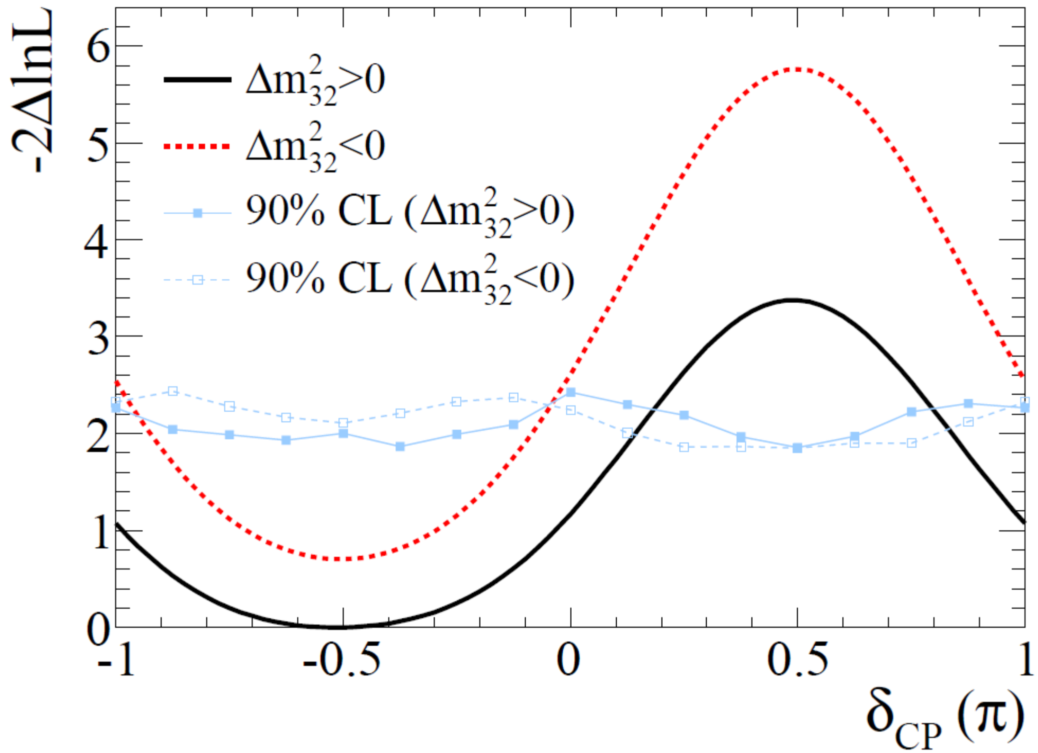
T2K 2013 disappearance





With the reactor constraint, and marginalising…

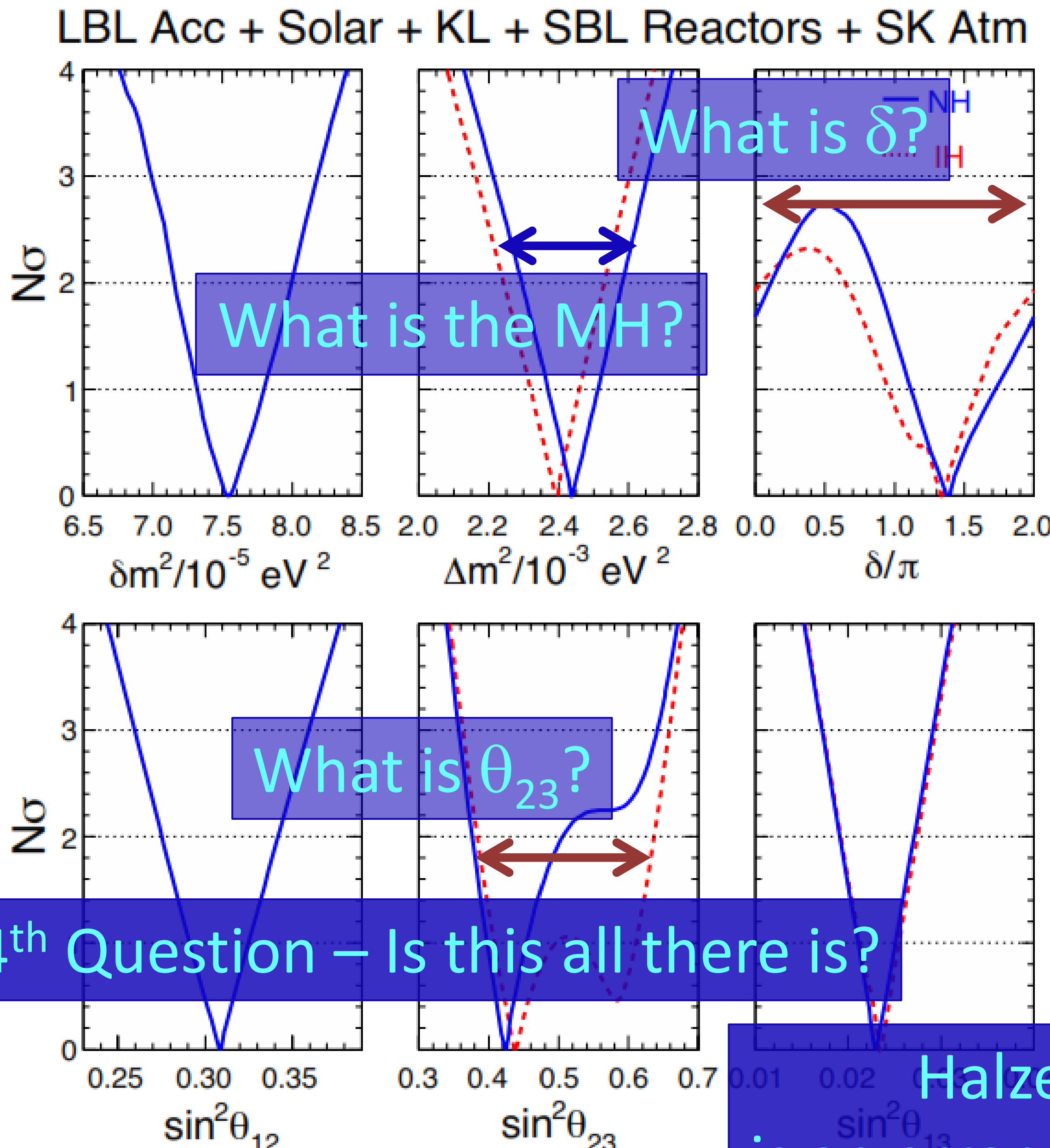
Observation of nue app. in a numu beam T2K, Nov 2013, arXiv:1311.4750v1

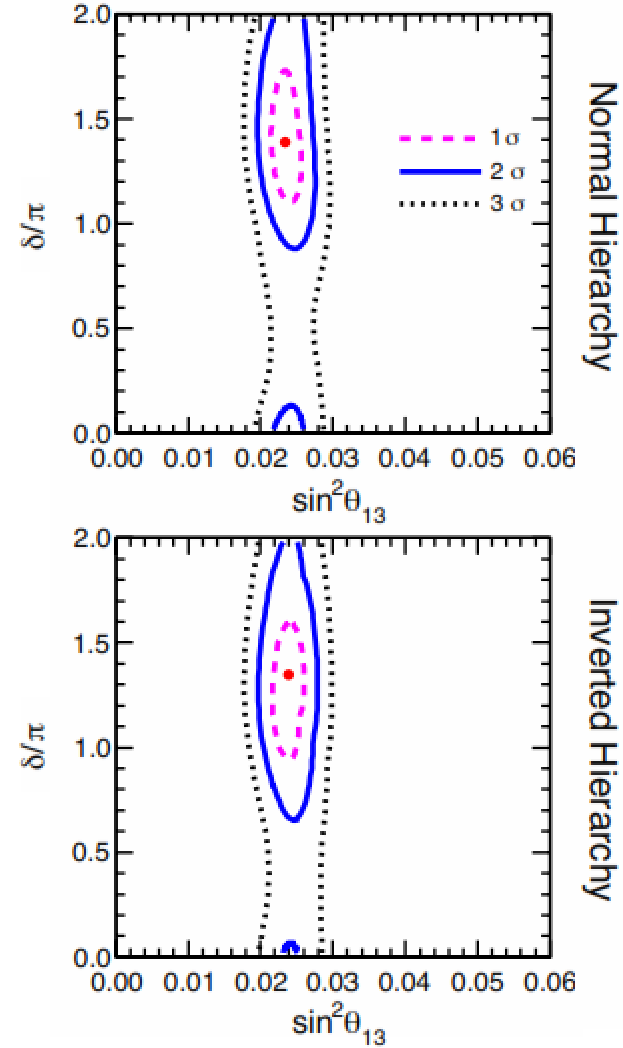


The combined T2K and reactor measurements prefer $\delta_{CP} = -\pi/2$. The 90% CL limits shown in Figure 6 are evaluated by using the Feldman-Cousins method [29] in order to extract the excluded region. The data excludes δ_{CP} between 0.19π and 0.80π ($-\pi$ and -0.97π, and -0.04π and π) with normal (inverted) hierarchy at 90% CL.

We are left with 4 questions for 3ν…

Dave Wark, 1st EU meeting w/ Global fit, Lisi *et al*, Dec 2013





What is δ?

What is the MH?

What is θ_{23}?

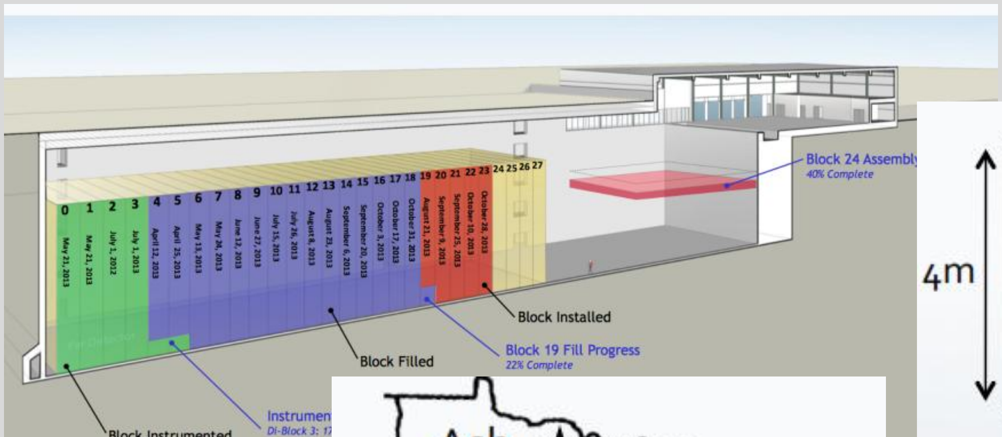
4th Question – Is this all there is?

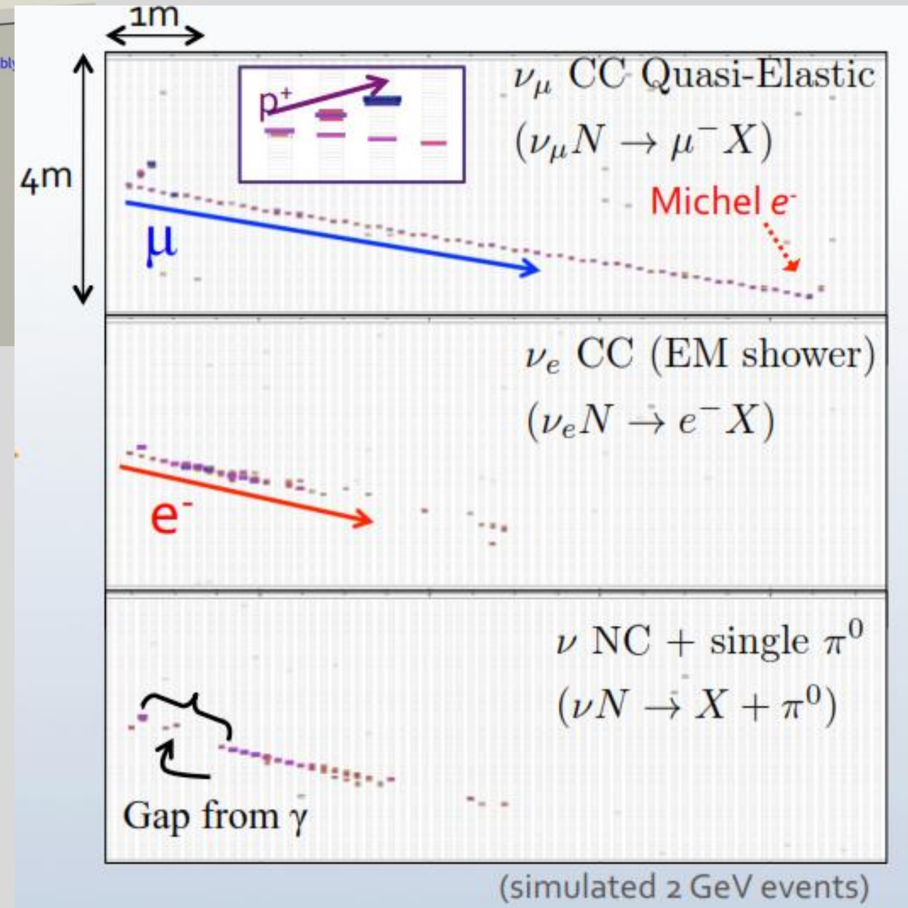
Halzen's Rule – 1σ is an error bar, not a discovery

Where will be by 2020?

If we combine the T2K and NOvA data sets with the reactor fit…

Aside: The NOvA experiment

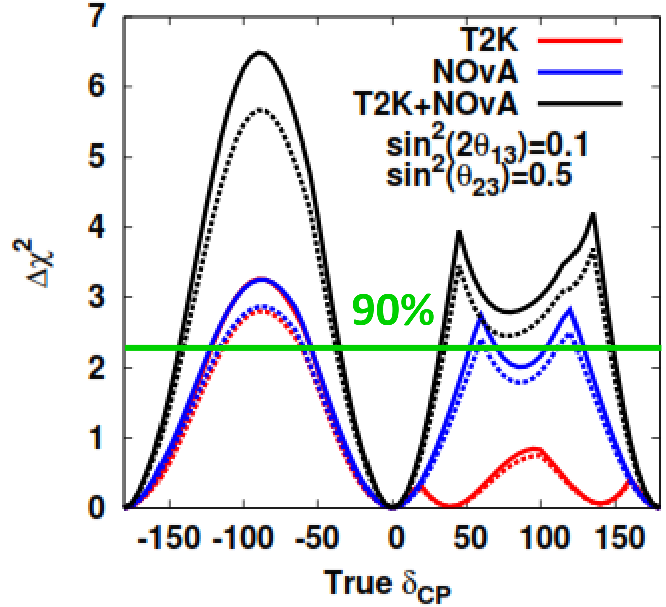


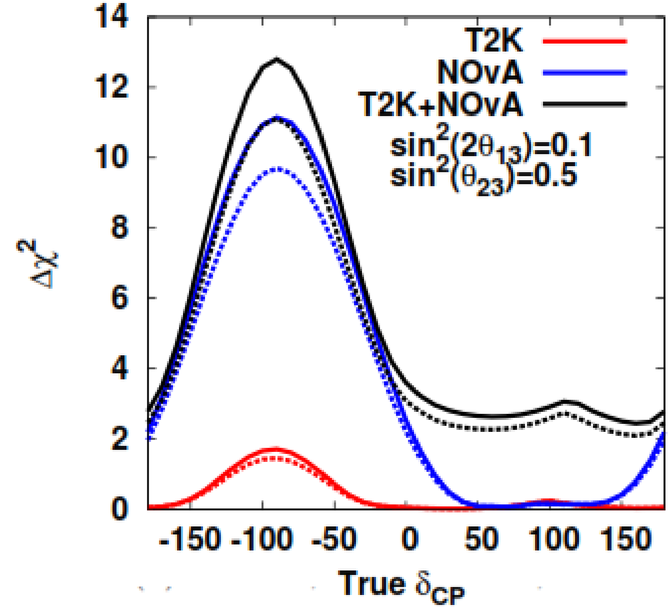


δ_{CP} Sensitivity

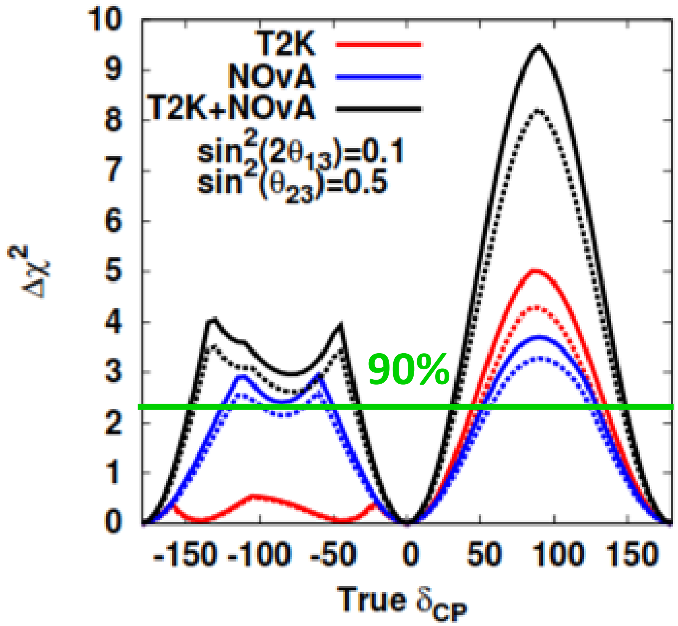
MH Sensitivity

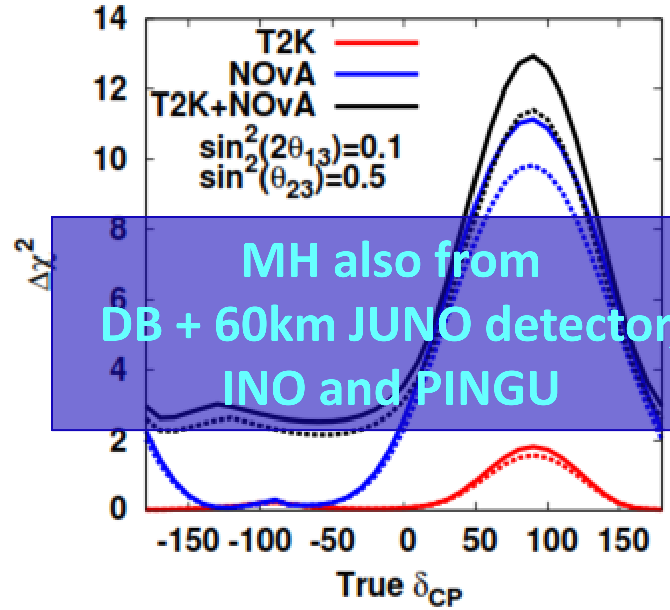
Normal hierarchy





Inverted hierarchy





MH also from DB + 60km JUNO detector, INO and PINGU

Wark, EU meeting

(Assuming T2K and NOvA use 1:1 nu:nubar)

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2(1.27 \frac{\Delta m^2 L}{E})$$

↓

To measure CPV…

Matter effects
➔ Hierarchy ?

$$P(\nu_\mu \rightarrow \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \boxed{\frac{2a}{\Delta m_{31}^2}} (1 - 2S_{13}^2)\right)$$

$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}$$

$$\boxed{-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}}$$

Flip sign for antinu
➔ CP sensitivity

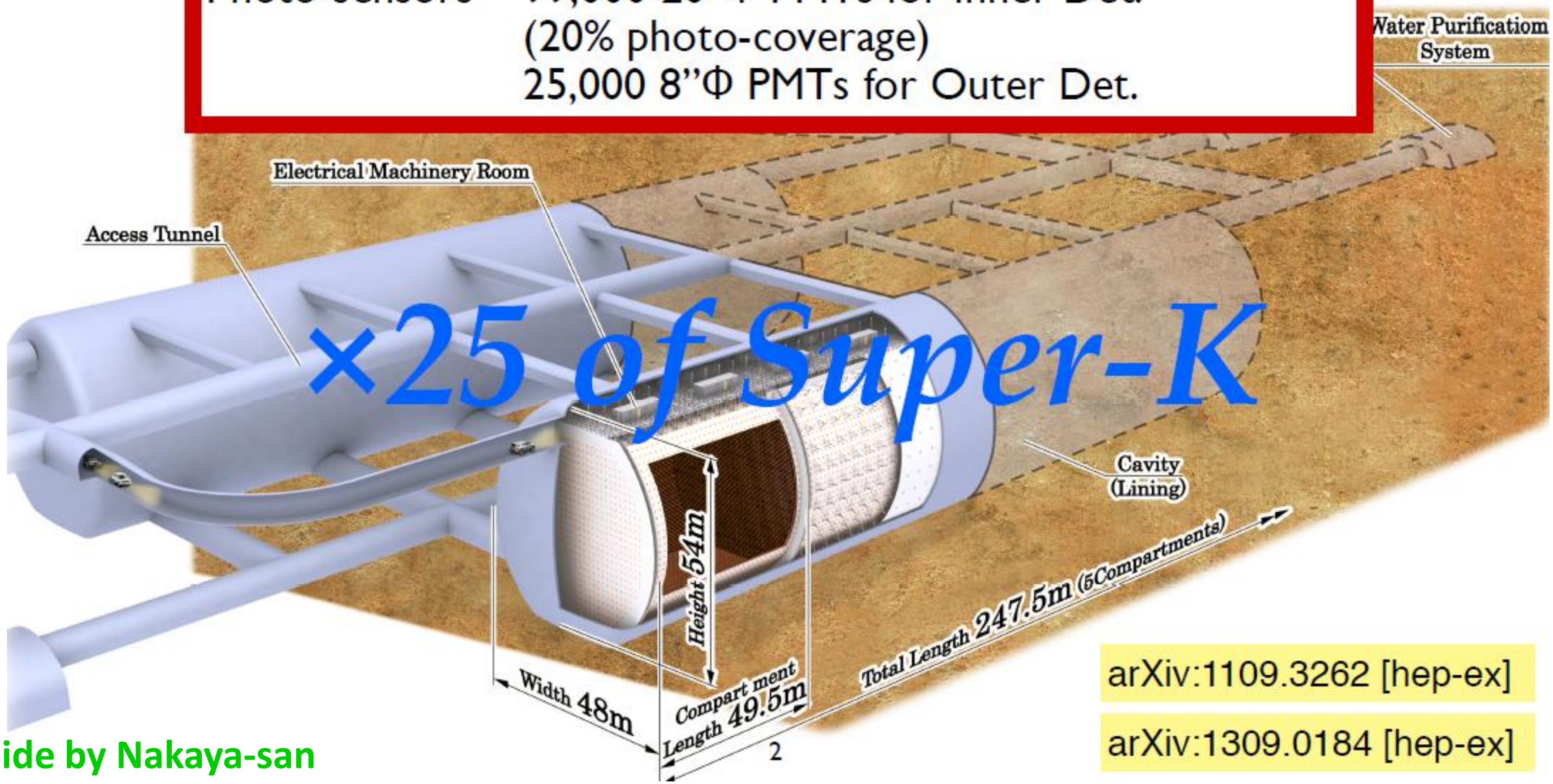
$$+4S_{12}^2 C_{13}^2 \{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\} \sin^2 \frac{\Delta m_{21}^2 L}{4E}$$

$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m_{32}^2 L}{4E} \boxed{\sin \frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E}} (1 - 2S_{13}^2)$$

Challenge: reduce statistical error on signal extraction to 2% and reduce systematics from ~10% to ~2%

Hyper-Kamiokande Overview

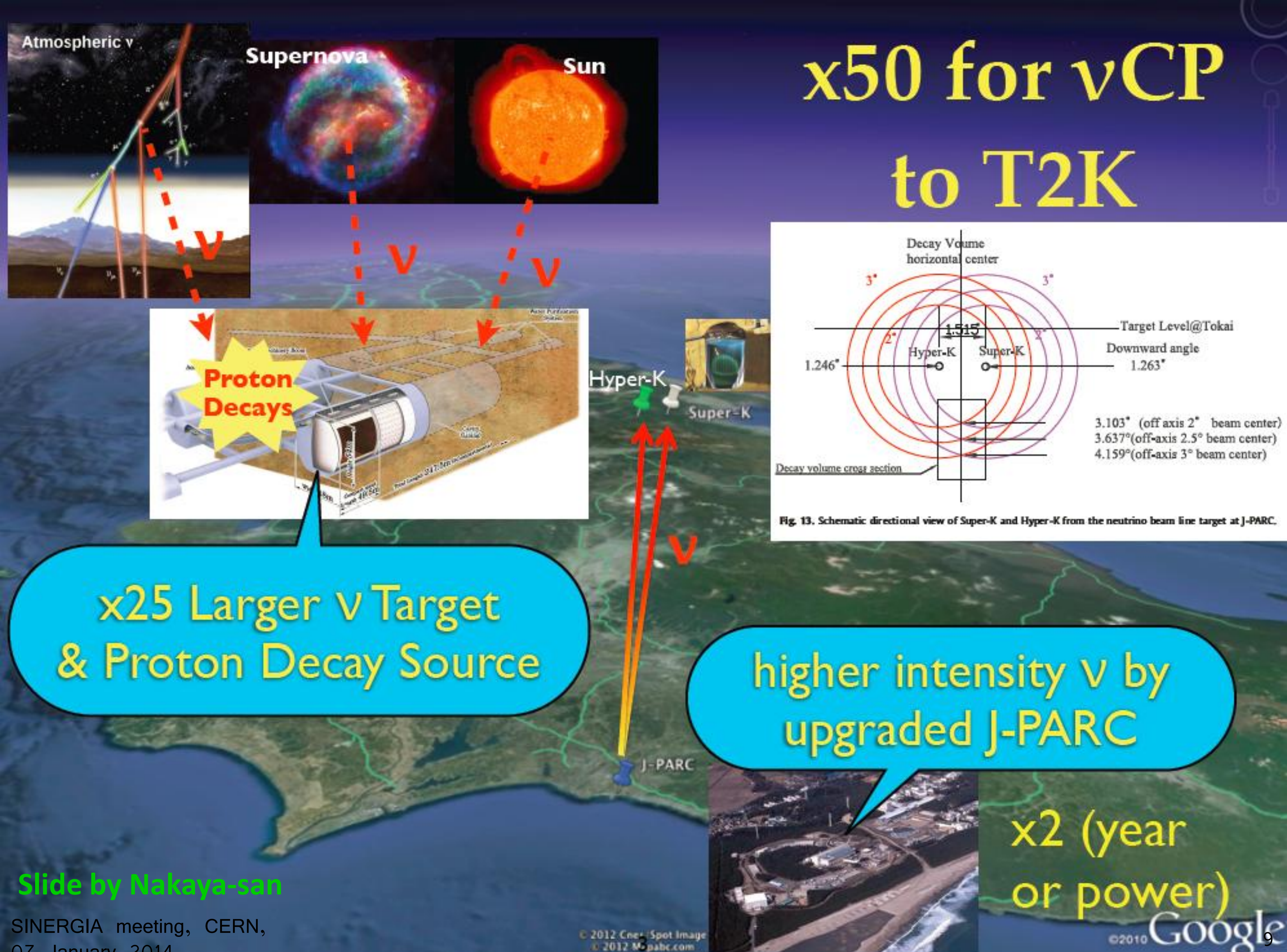
Total Volume	0.99 Megaton
Inner Volume	0.74 Mton
Fiducial Volume	0.56 Mton (0.056 Mton × 10 compartments)
Outer Volume	0.2 Megaton
Photo-sensors	99,000 20”Φ PMTs for Inner Det. (20% photo-coverage)
	25,000 8”Φ PMTs for Outer Det.



arXiv:1109.3262 [hep-ex]

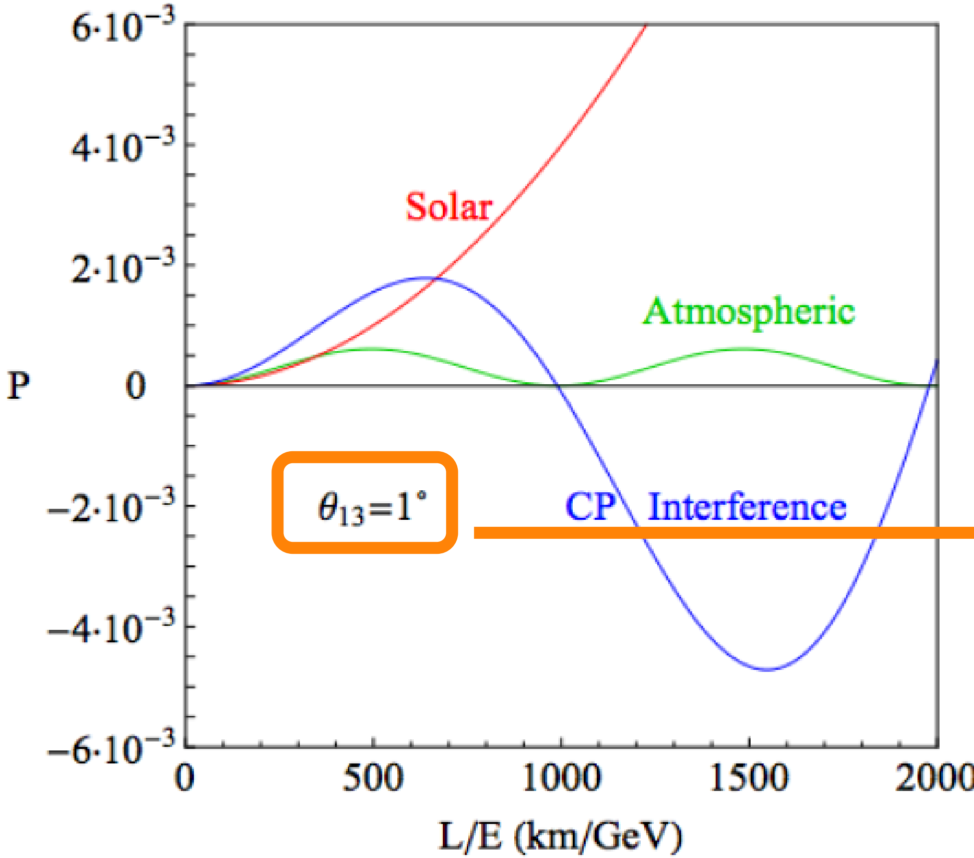
arXiv:1309.0184 [hep-ex]

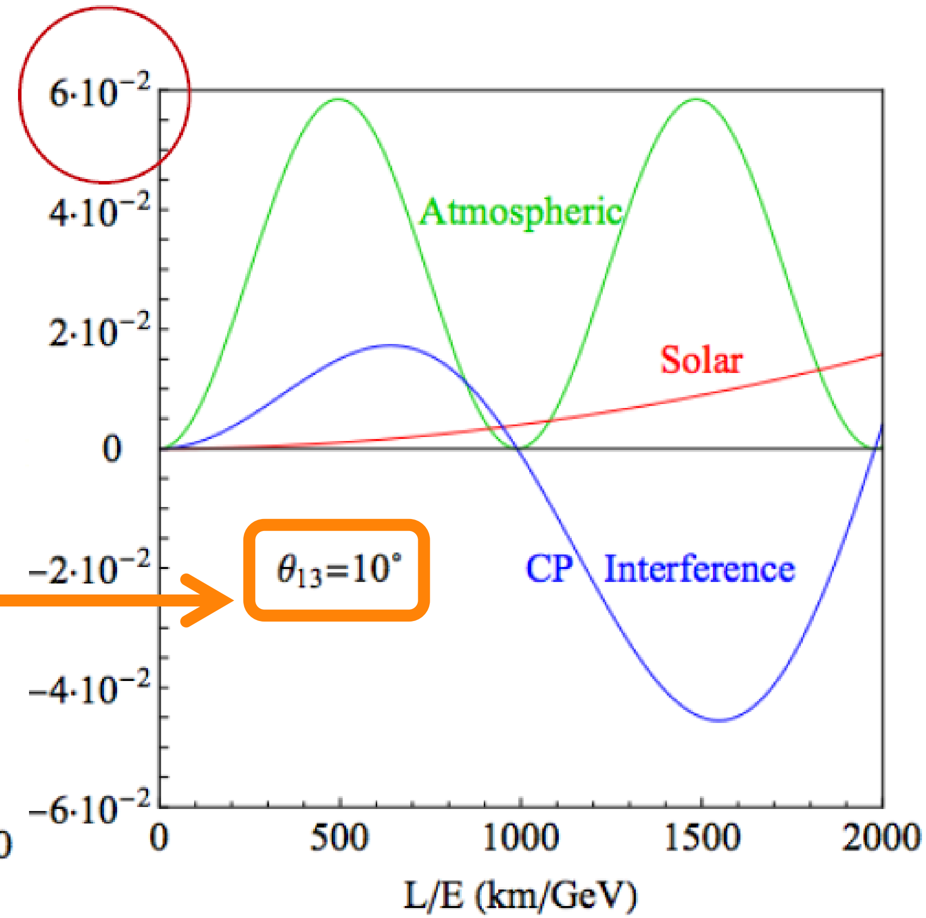
Slide by Nakaya-san


x50 for νCP to T2K
Atmospheric ν
Supernova
Sun
ν
ν
ν
Proton Decays
Hyper-K
Super-K
J-PARC
ν
Decay Volume horizontal center
3°
3°
2°
2°
1.515°
Target Level@Tokai
Downward angle
1.246°
Hyper-K
Super-K
1.263°
3.103° (off axis 2° beam center)
3.637°(off-axis 2.5° beam center)
4.159°(off-axis 3° beam center)
Decay volume cross section
Fig. 13. Schematic directional view of Super-K and Hyper-K from the neutrino beam line target at J-PARC.
x25 Larger ν Target & Proton Decay Source
higher intensity ν by upgraded J-PARC
x2 (year or power)
Slide by Nakaya-san

A wrinkle: CP interference is actually subleading

Appearance probability terms



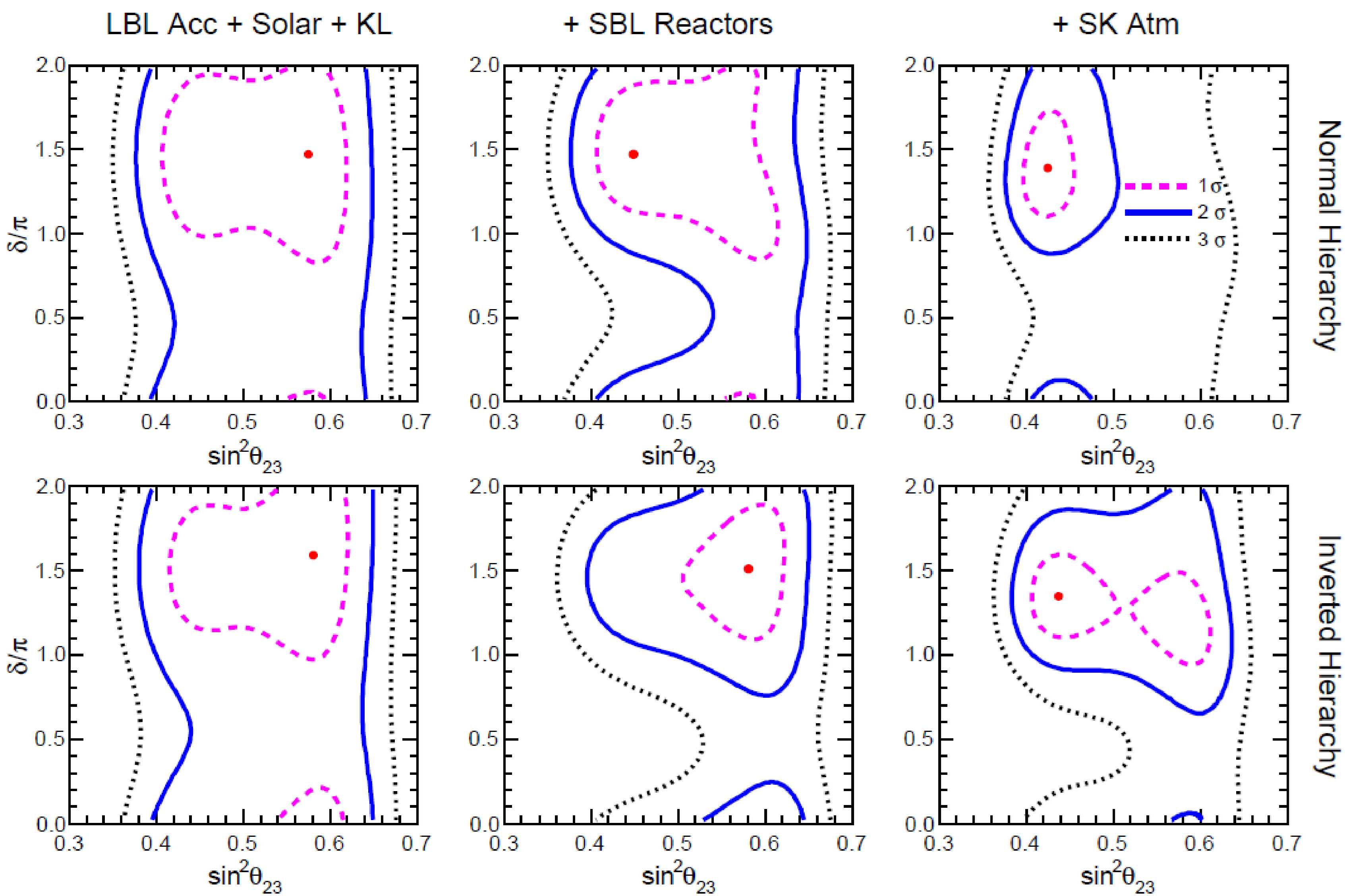


➔ **theta-23 systematics are more important than we previously realized**

Latest global fit in the theta23, deltaCP plane

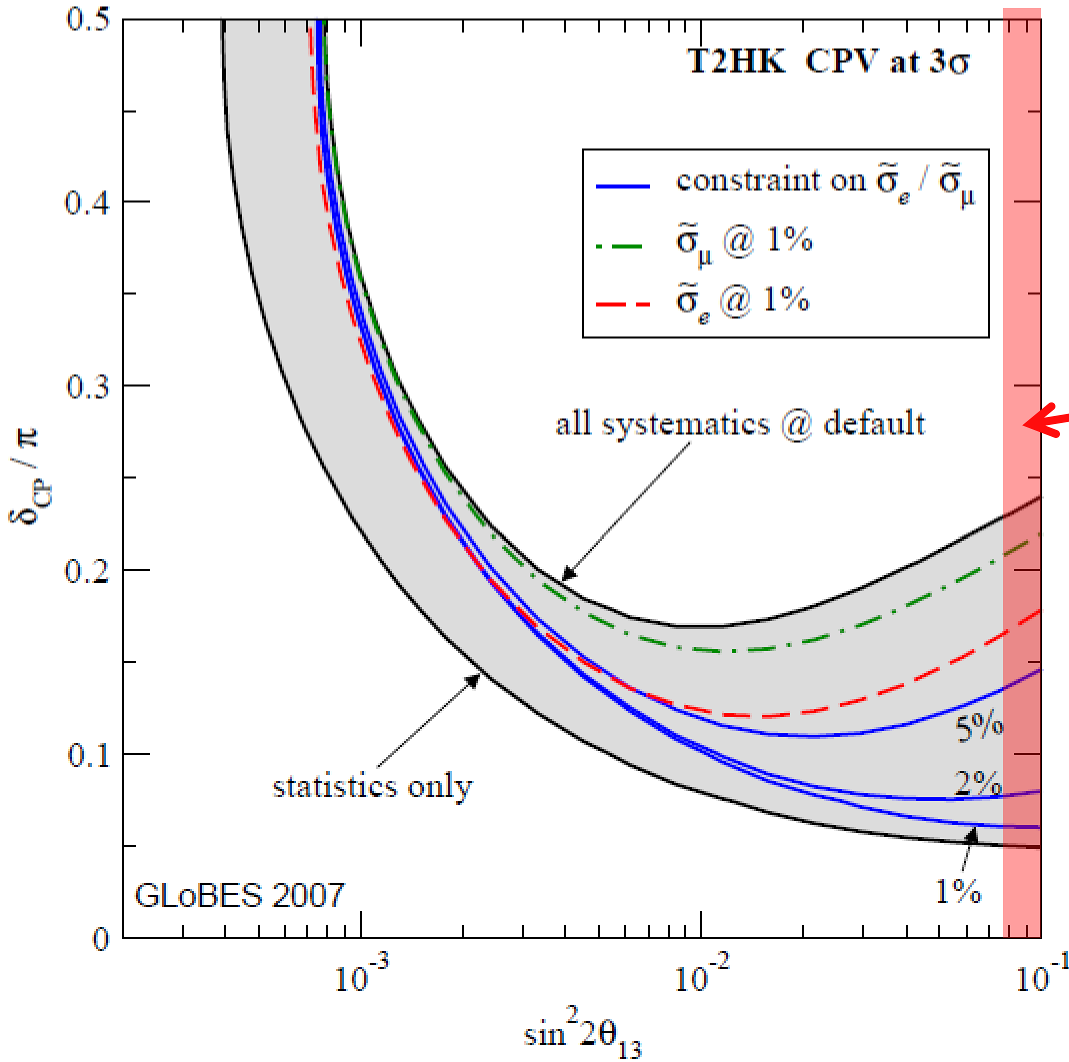
Status of three-neutrino oscillation parameters, circa 2013, arXiv:1312.2878

F. Capozzi, G.L. Fogli, E. Lisi, A. Marrone, D. Montanino, A. Palazzo, Dec 2013



3 sigma sensitivity for T2HyperK (for 0<delta<pi/2)

i.e. the smallest delta you can measure at 3 sigma



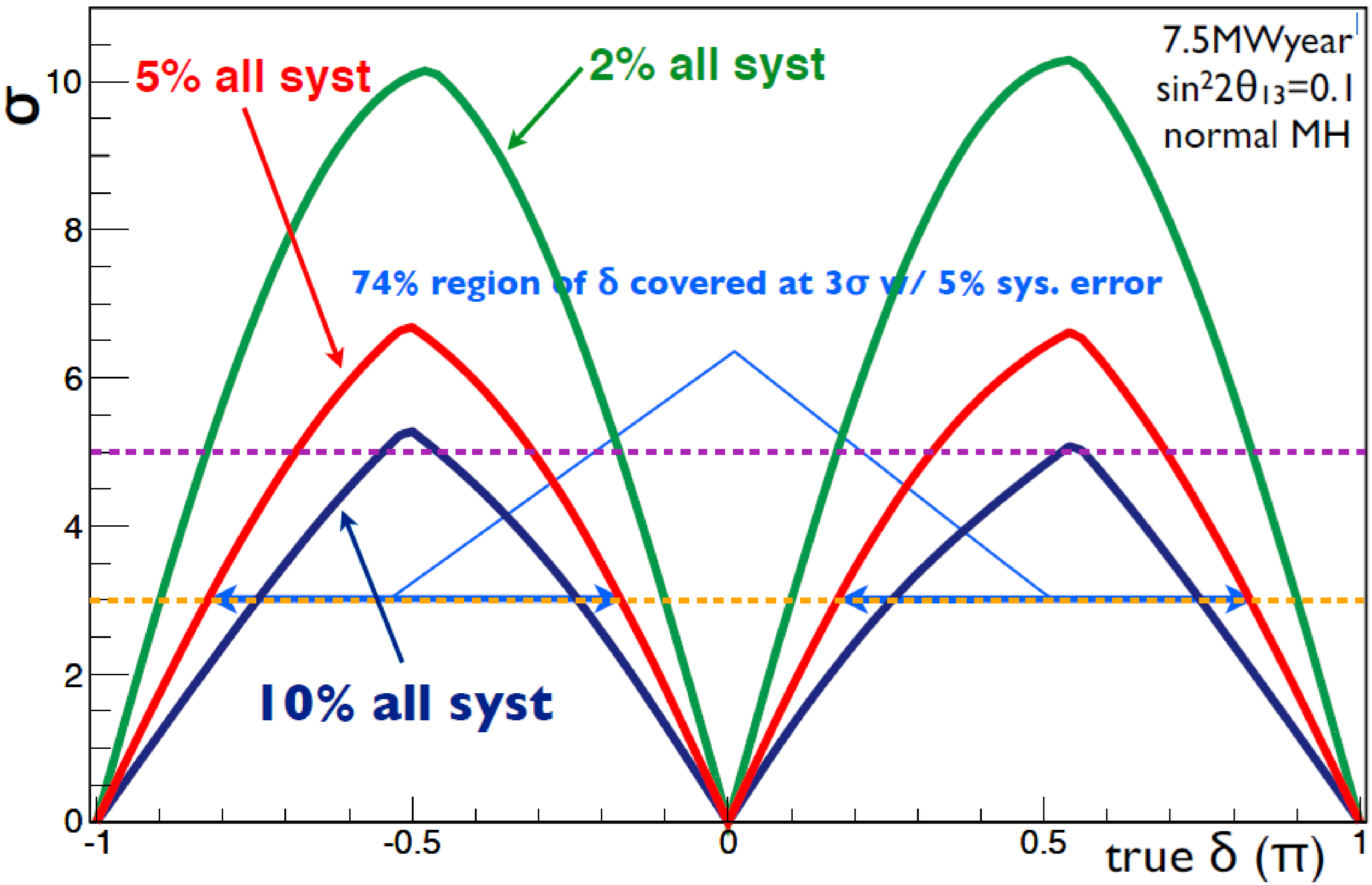
Huber *et al., 2008*
arxiv:0711.2950

Reactor constraint

Appearance experiments are not able to measure final flavor xsecs at the near detector (exception: NuFact)

(➔ nuSTORM?)

T2HyperK CP violation discovery sensitivity (known MH)

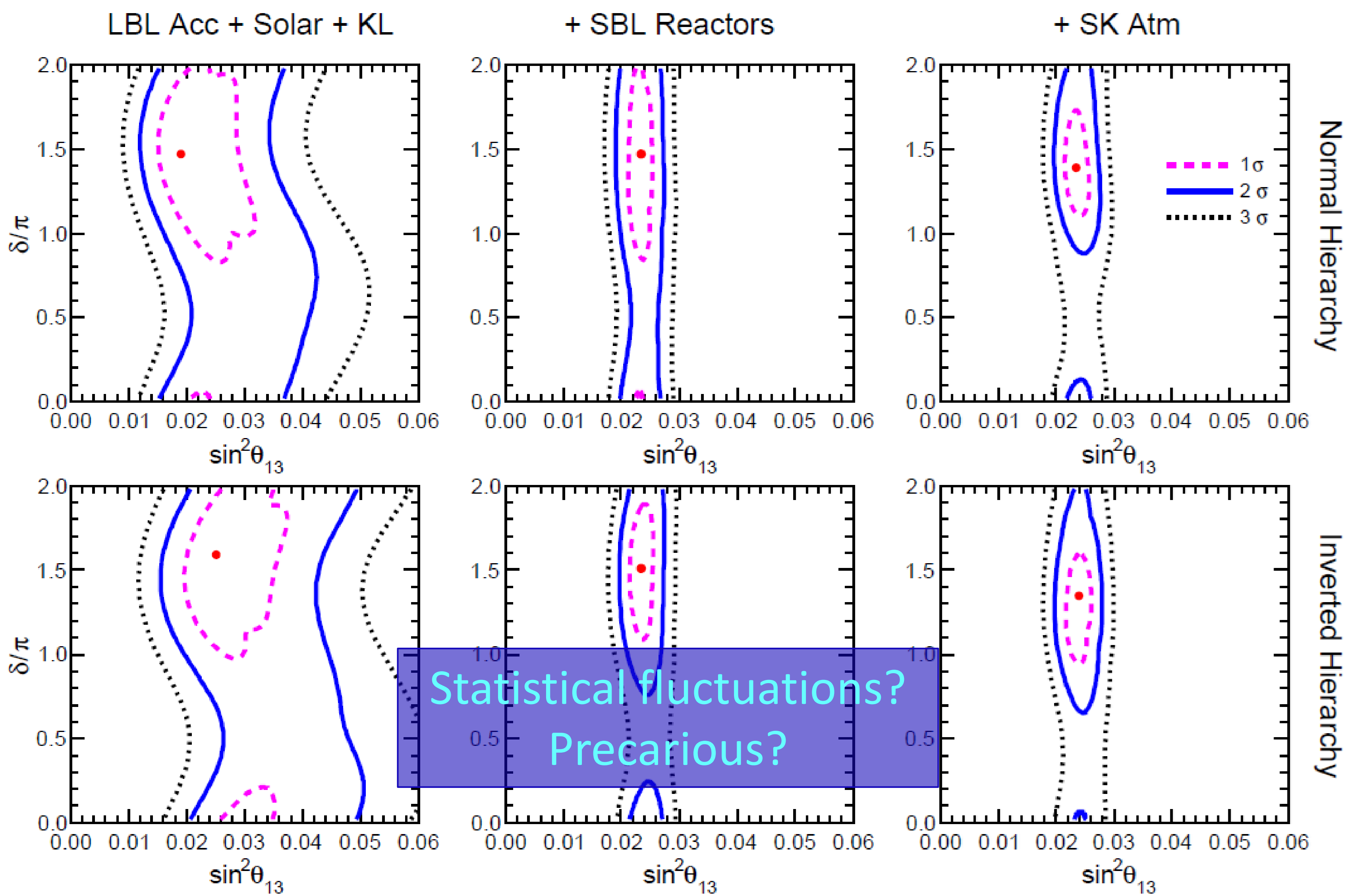


Yokoyama-san, 2nd open meeting

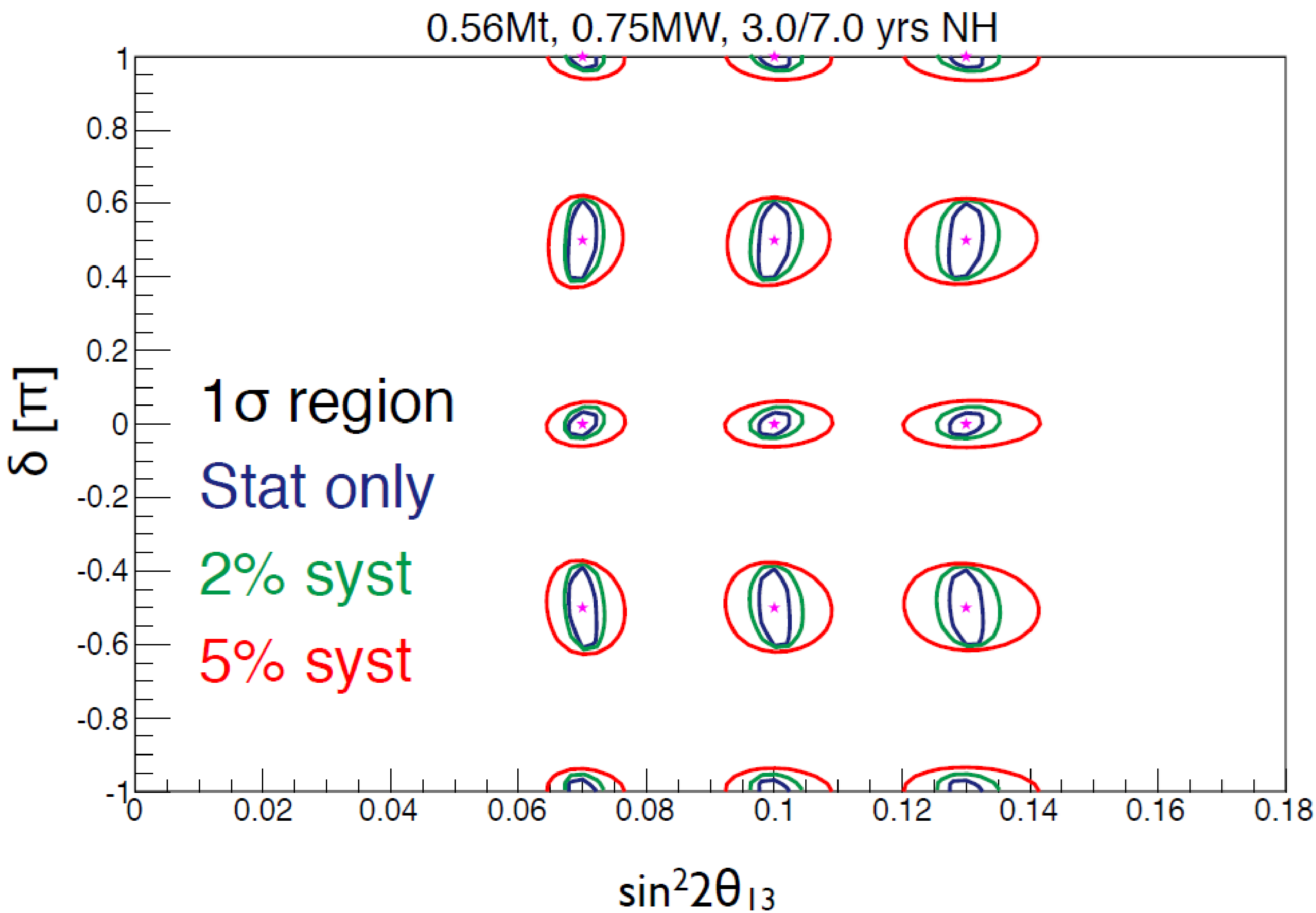
We now see closed 2 sigma (theta13, deltaCP) contours in the latest global fits

Status of three-neutrino oscillation parameters, circa 2013, arXiv:1312.2878

F. Capozzi, G.L. Fogli, E. Lisi, A. Marrone, D. Montanino, A. Palazzo, Dec 2013

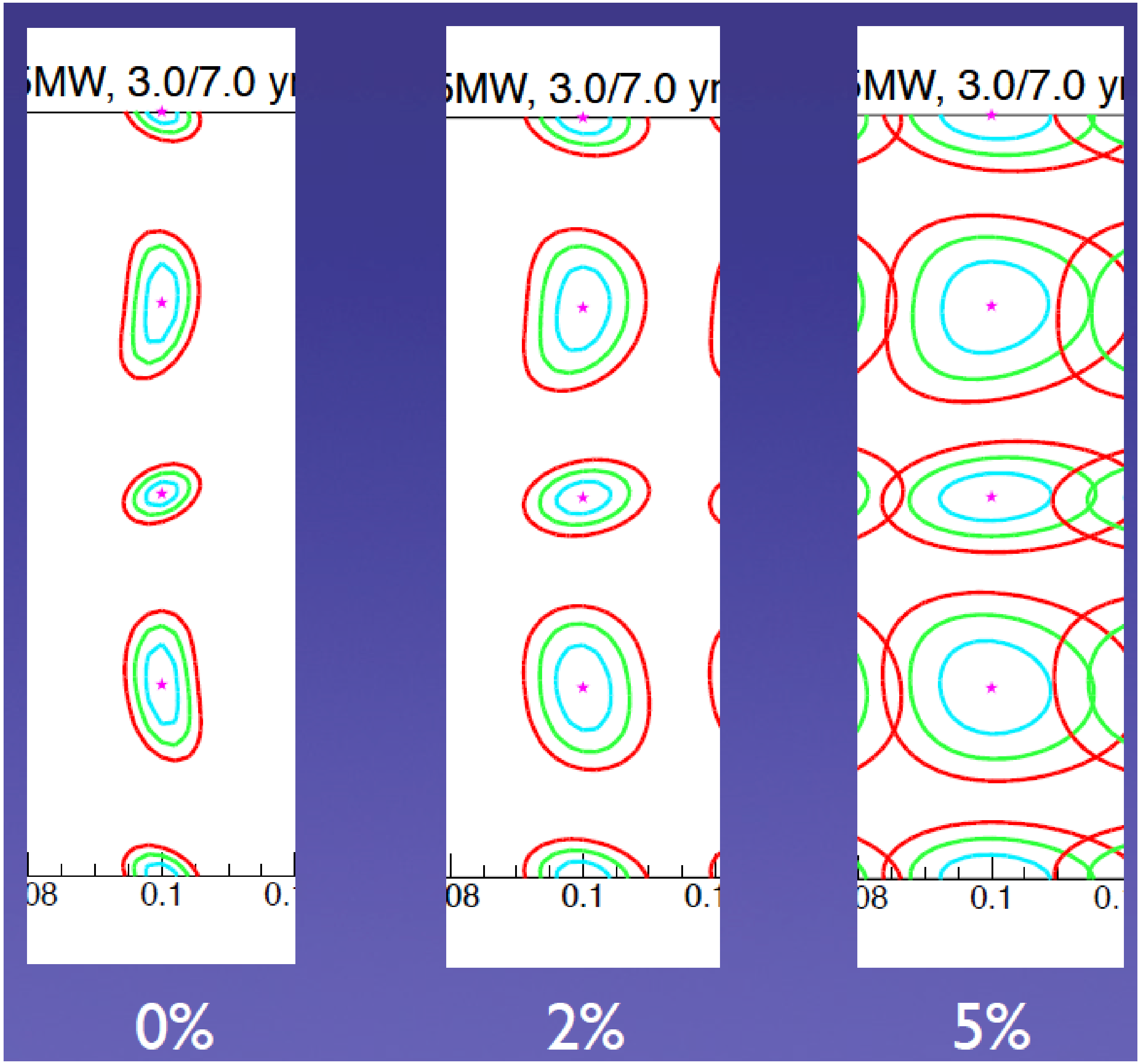


T2HyperK sensitivity



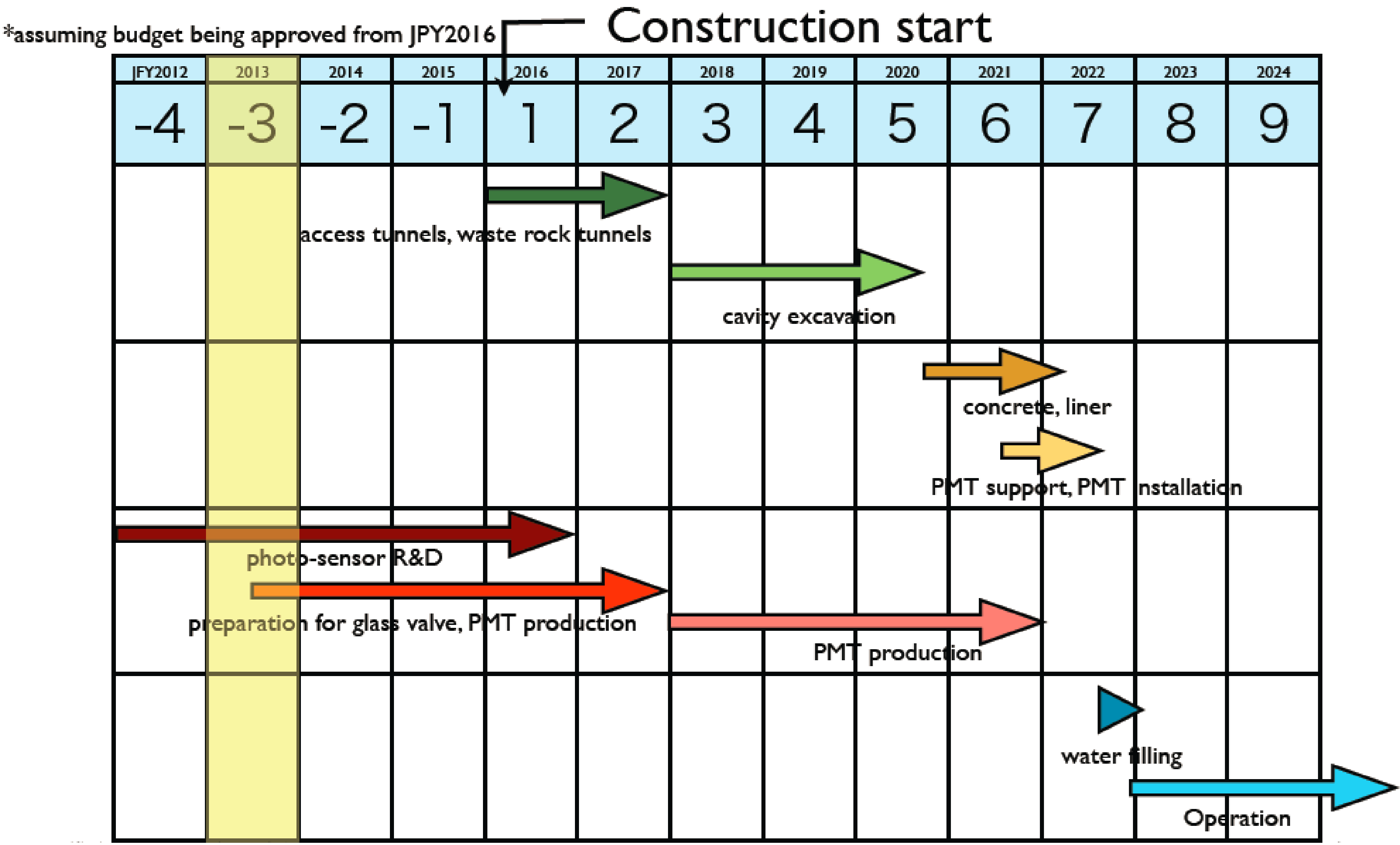
Yokoyama-san, 2[nd] open meeting

Effect of systematic errors



Nakaya-san, EU meeting

TDR in <1 year, construction in 2016



The Hyper Kamiokande collaboration is growing

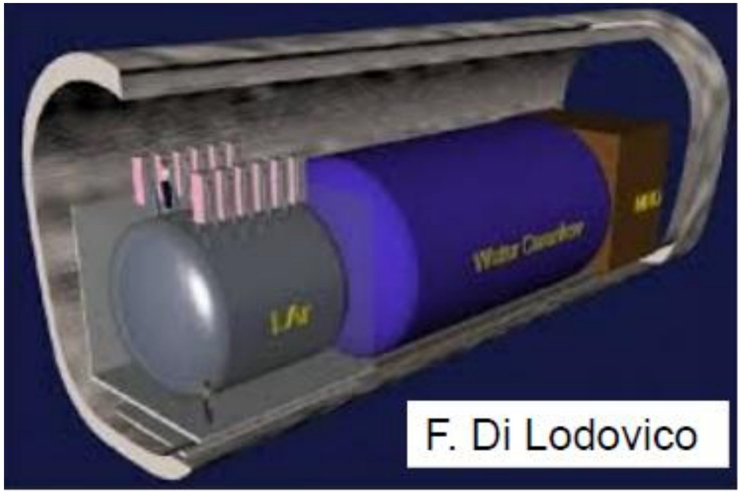
- **49 institutions in 9 countries:** Brazil, Canada, Japan, Korea, Russia, Spain, **Switzerland**, UK, and US
- European leadership of software working group
- 3rd Open Meeting
  - **21-22 June 2013, Tokyo**
- **1st European Open Meeting**
  - **18 December 2013, London**
- 4th Open Meeting
  - **January 27-28 2014, Tokyo**

To give an idea of numbers…

The 3rd open meeting in Tokyo

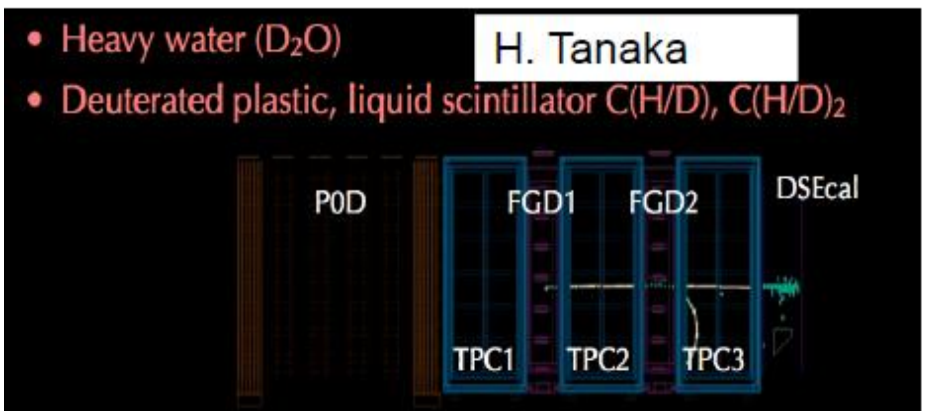
The 1st European meeting last month

T2HyperK near detector ideas from the last CM



Resurrect the 2km proposal

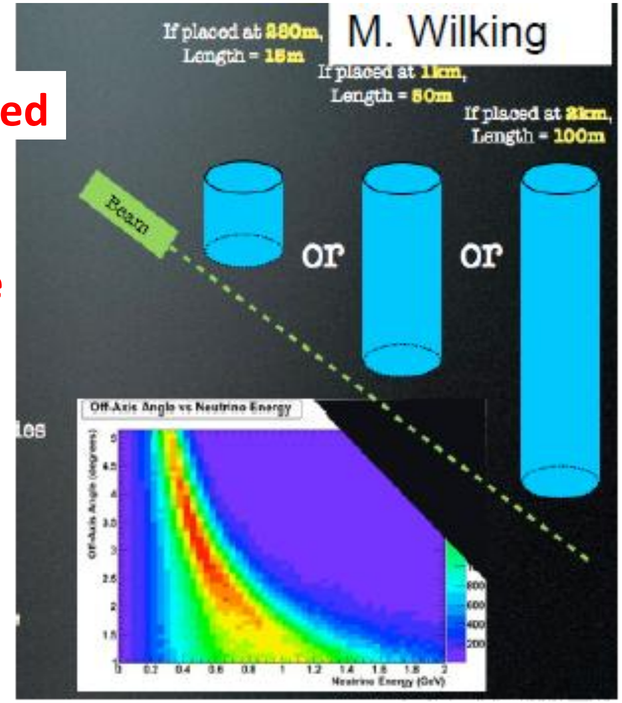
and… Upgrades to ND280



Deuterated plastic, D_2O, liquid scintillator to get at fundamental cross sections

Tall, segmented water ckov:

off-axis angle → energy



100m if at 2km

WC detector covering range of off-axis angles

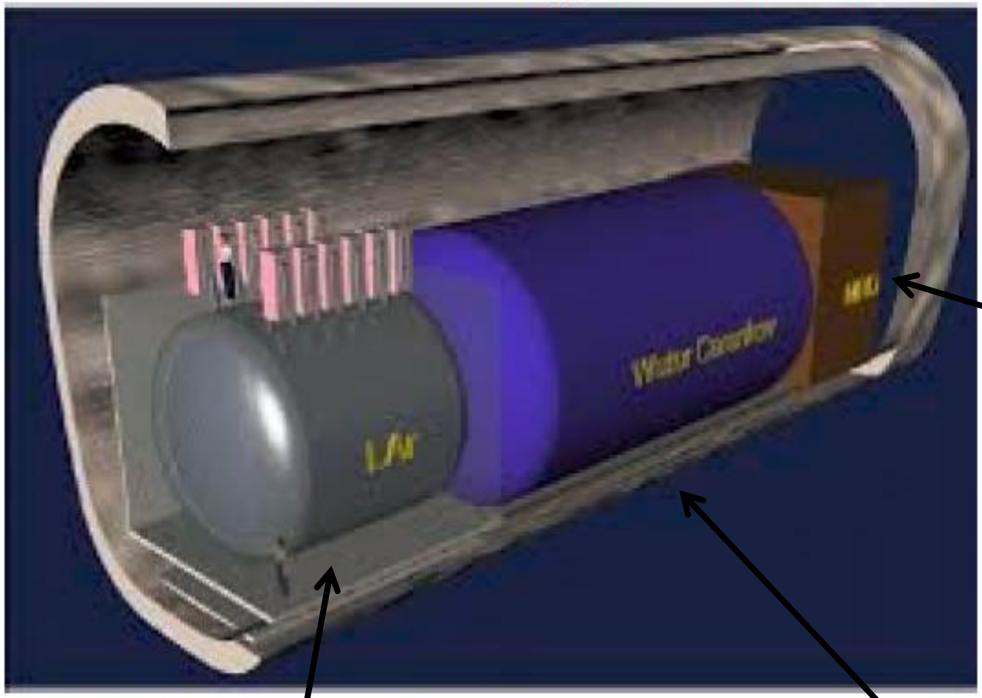
Other ideas:

High pressure Ne TPC
High pressure CO_2 TPC } **Plus interesting TPC concepts!**
Scintillating fiber tracker
Water-based liquid scintillator

A 2km detector was originally proposed for T2K

Original proposal for a 2KM detector for T2K in 2007

A letter of intent to extend T2K with a detector 2 km away from the JPARC neutrino source, June 2007

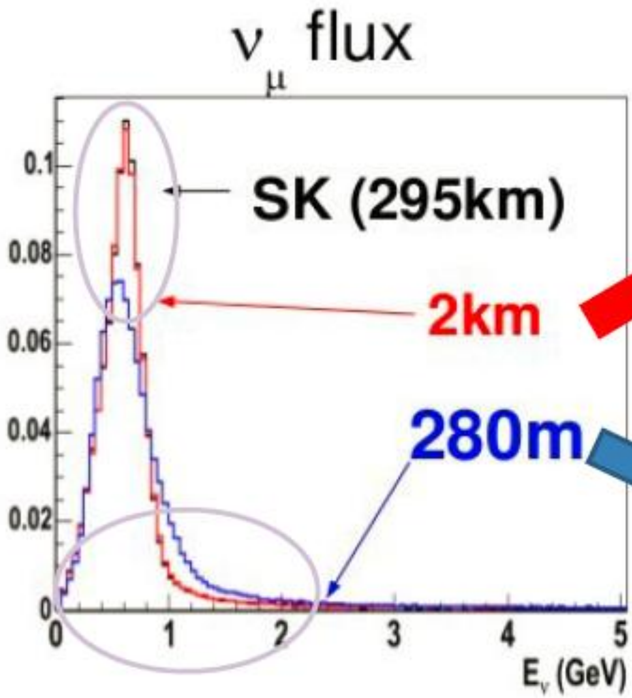


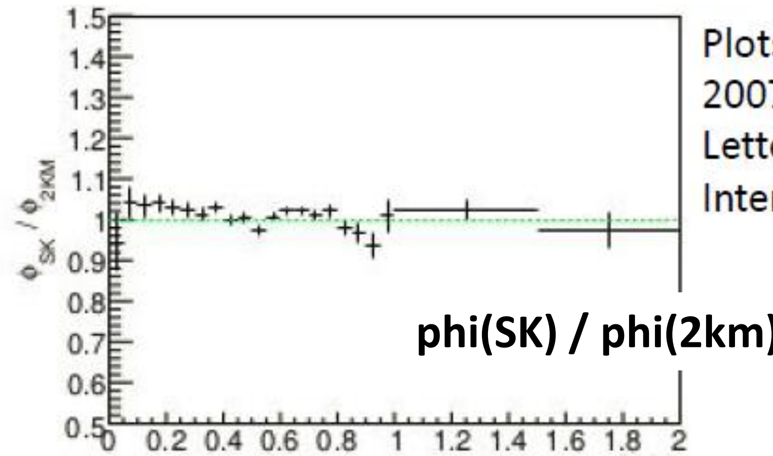
Fe muon range
➔ U. Geneva?

100 ton LAr detector

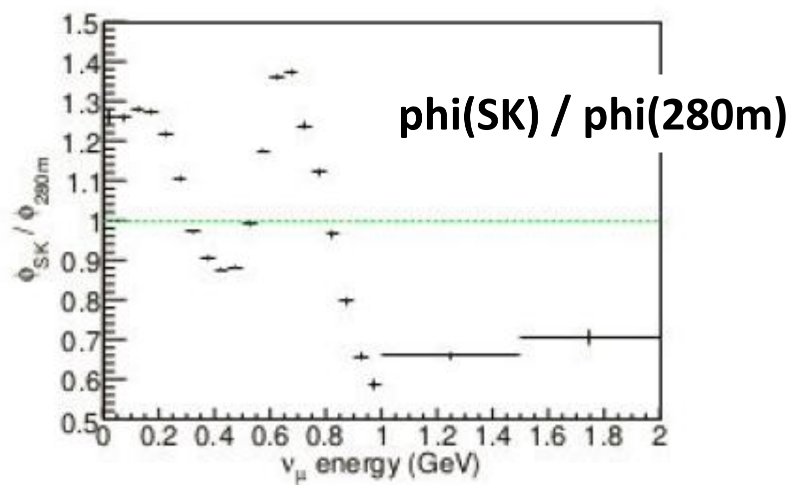
1 kton water Cherenkov
➔ Same nucleus, same energy bias
➔ Also 4pi coverage
➔ 20% of SK events are backwards

2km detector: advantages in flux shape





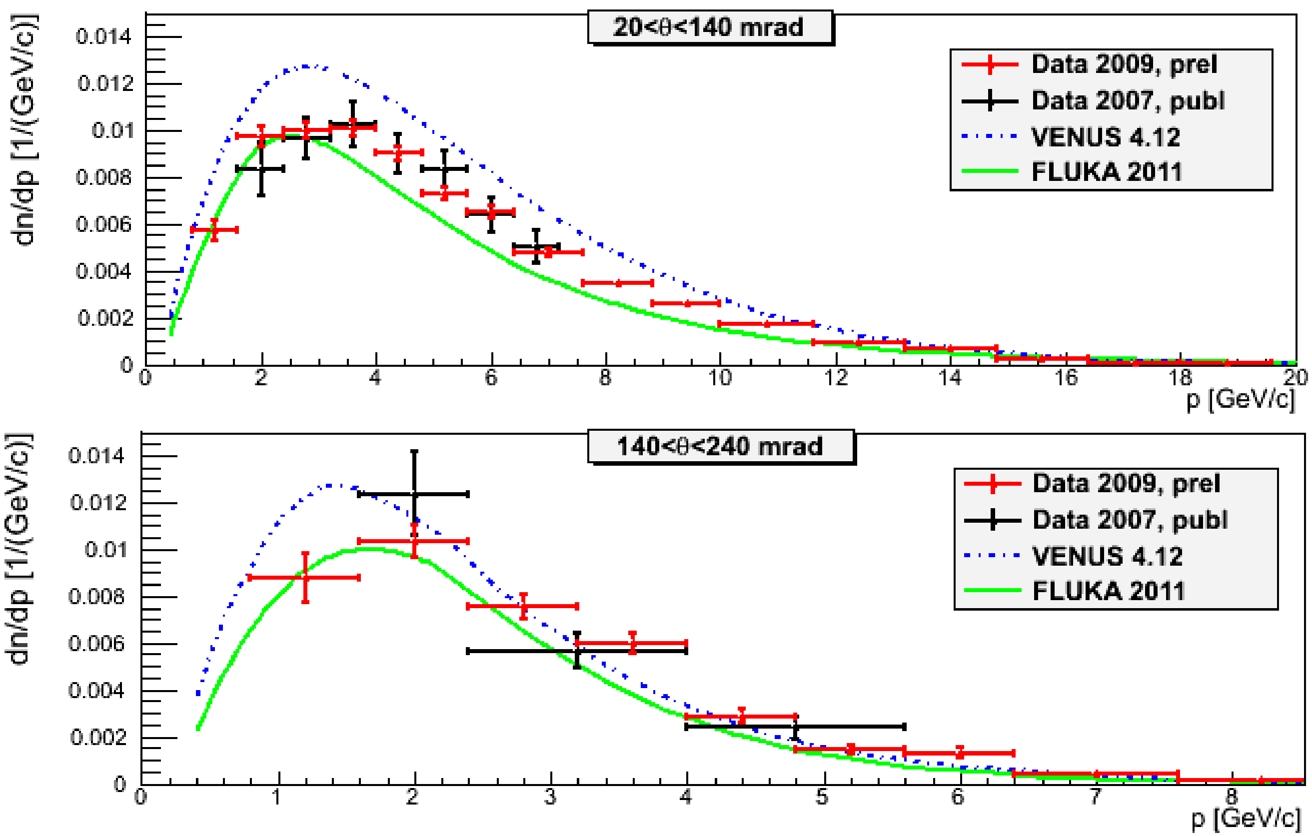
Plots from 2007 2KM Letter of Intent



In addition, NA61 will continue to be crucial

- 2007 results on $p^{\pm}$, K^{+} ➔ beam MC of T2K
- **With data 2009 improvement in precision by a factor 2-3**

Example: K^{+} multiplicities for 2007 & 2009



Korsenev, University of Geneva

More hot topics

- **Cavern design approved in principle, geological survey at Mozumi ongoing**
- **Funding approved for a 1kton prototype**
- **Gadolinium doping is being studied**
  - **80% transmission to 60% neutron absorption, 70% at 90% of neutron absorption**
- **Focusing** by parabolic lens arrays rather than Fresnel
- **B-field shielding** can be passive (mu-metal)
- It's difficult to design a **>20yr experiment** (ultrapure water = ideal acid/base)
- Increase **PMT coverage from** 20% to 40%?
  - **Needed for solar neutrino, geo neutrinos and SNR studies**
- Are geophysics studies really feasible? **Is earth's core Fe or rock?**
  - **Assume** rho(matter) known precisely from seismic tomography
  - **Measure** rho(e) using the matter effect in Hyper Kamiokande
- World best constraint possible on **low mass WIMPs**
- **And of course, proton decay**

In fact T2HyperK lines up nicely with 6/7 'big questions'

Shiozawa-san

"BIG" questions in Snowmass

http://www.symmetrymagazine.org/article/october-2013/the-big-questions

- **The Higgs particle is unlike any other particle we have ever encountered. Why is it different? Are there more?**
- **Neutrinos are very light, elusive particles that change their identity as they travel. How do they fit into our understanding of nature?** ✓ *ν oscillation, supernova*
- **The known particles constitute one-sixth of all the matter in the universe. The rest we call dark matter. But what is it? Can we detect these particles in our labs? Are there other undiscovered particles in nature?** ✓ *indirect DM search*
- **There are four known forces in nature. Are these manifestations of a single unified force? Are there unexpected new forces?** ✓ *proton decays, ν's mass & mixing*
- **Are there new hidden dimensions of space and time?** ✓
- **Both matter and antimatter were produced in the big bang, but today our world is composed only of matter. Why?** ✓ *ν's CPV, proton decays*
- **Why is the expansion of the universe accelerating?**

Summary - a road to CPV discovery

Hyper Kamiokande

- × **25 fiducial volume** compared to Super-K
  - **Proton Decay, Atmospheric neutrinos, Solar neutrinos, Supernova neutrinos, Cosmic neutrinos (and search for dark matter decaying to neutrinos)**
- **240 kW** (T2K now) → ~**1 MW** for T2HyperK (lab is more ambitious)

  → ***×100*** **compared to T2K's data set today**

2km detector

- Given large theta-13, statistical errors on signal extraction = 2%
- To achieve full CPV potential, **require 2% systematics**
  - **Difficult to get this without a 2km detector**

Upgrades to ND280

- Could alternatively/also upgrade the tracker
  - **High pressure TPC doubles as the target to study meson exchange currents and constrain nuclear models**
  - **Or simply a water target surrounded by 4pi TPC tracking**

→ **Lots of potential for significant European contributions**

Post script: The questions posed at the 1st European T2HyperK meeting last month…

EU HK Open Meeting – Round Table

F. di Ludovico

The goal of the round-table is to get an understanding of interest within Europe on Hyper-K and how to ensure mutual support to an effective contribution to the experiment.

- Is it sensible to work towards a relatively coherent strategy for Europe and how to proceed over the next few years?

- Are the timescales for funding from the different Countries complimentary (can other Countries provide support for proposals)?

- How should we communicate to the ICFA panel in Jan 8-10 in Paris?

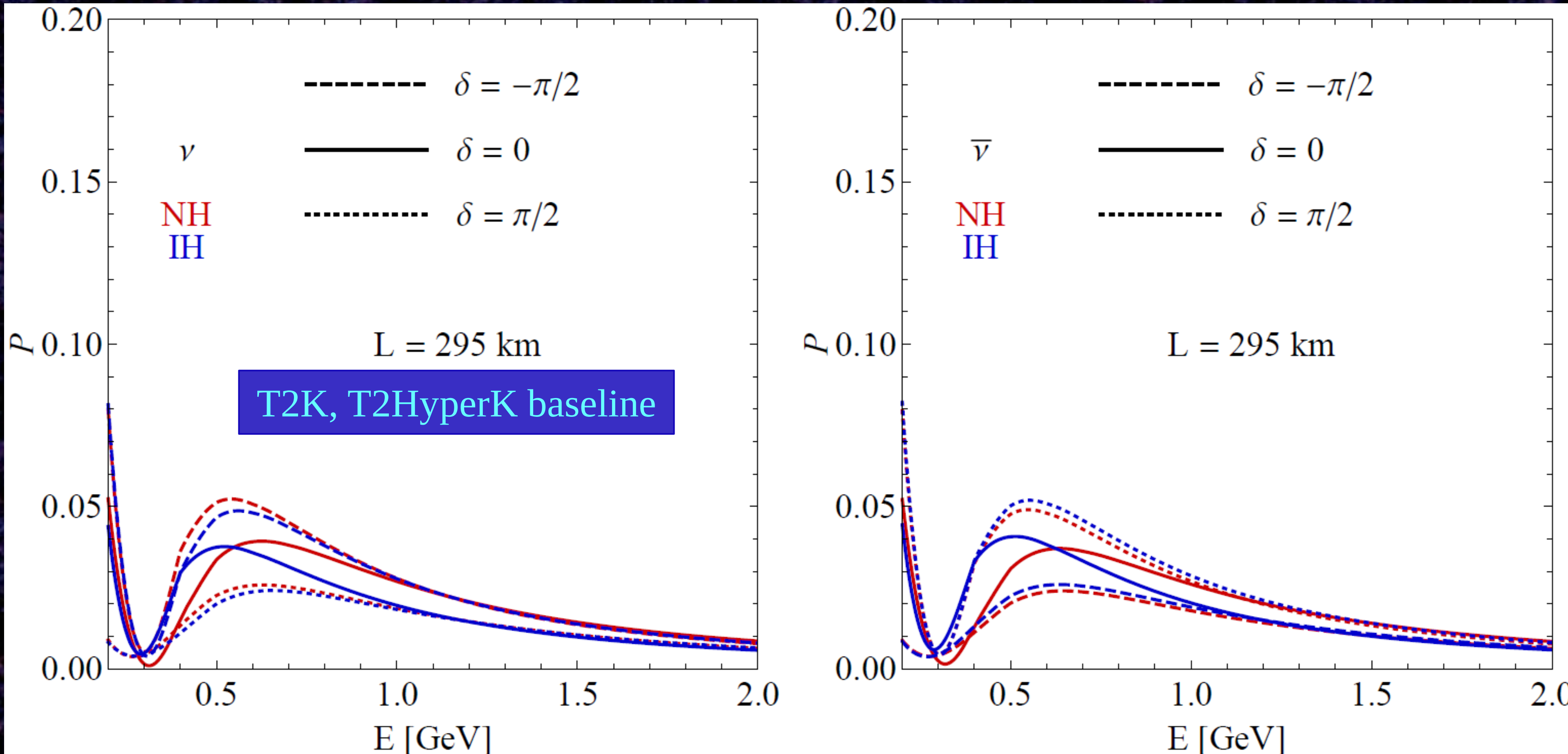
- Are there areas in Hyper-K that are in urgent need of effort?

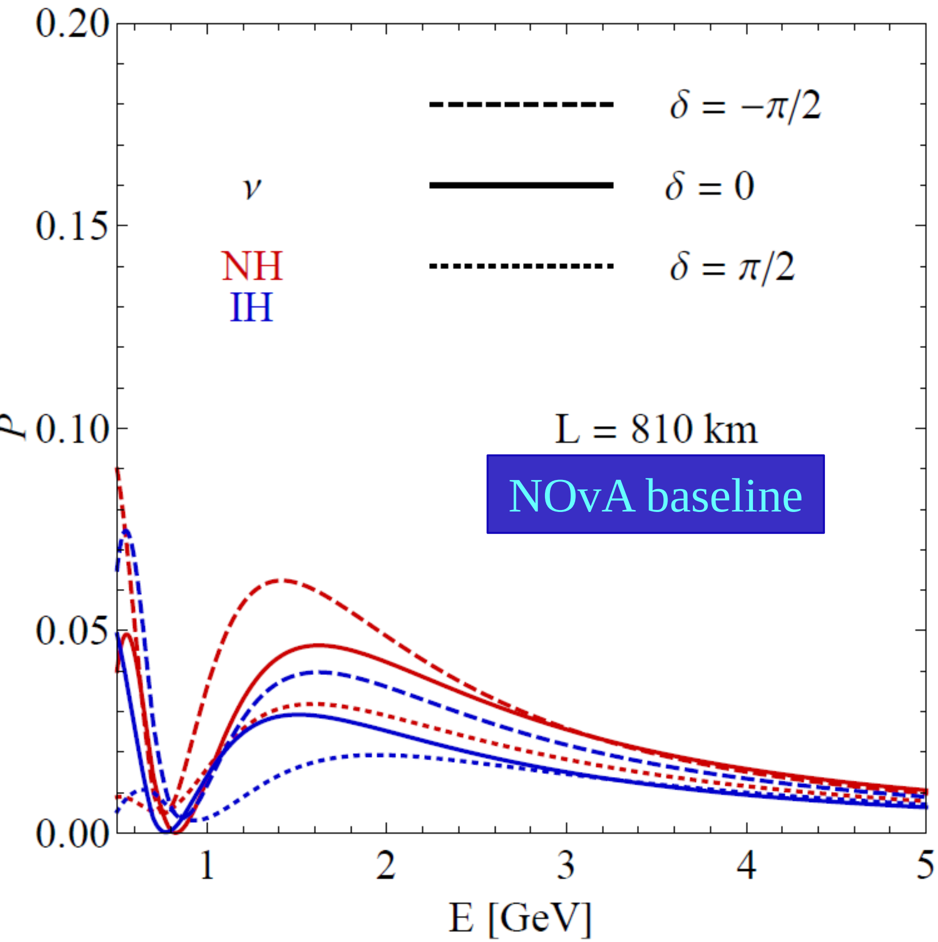
Backup slides

Aside: Dave Wark at the EU meeting

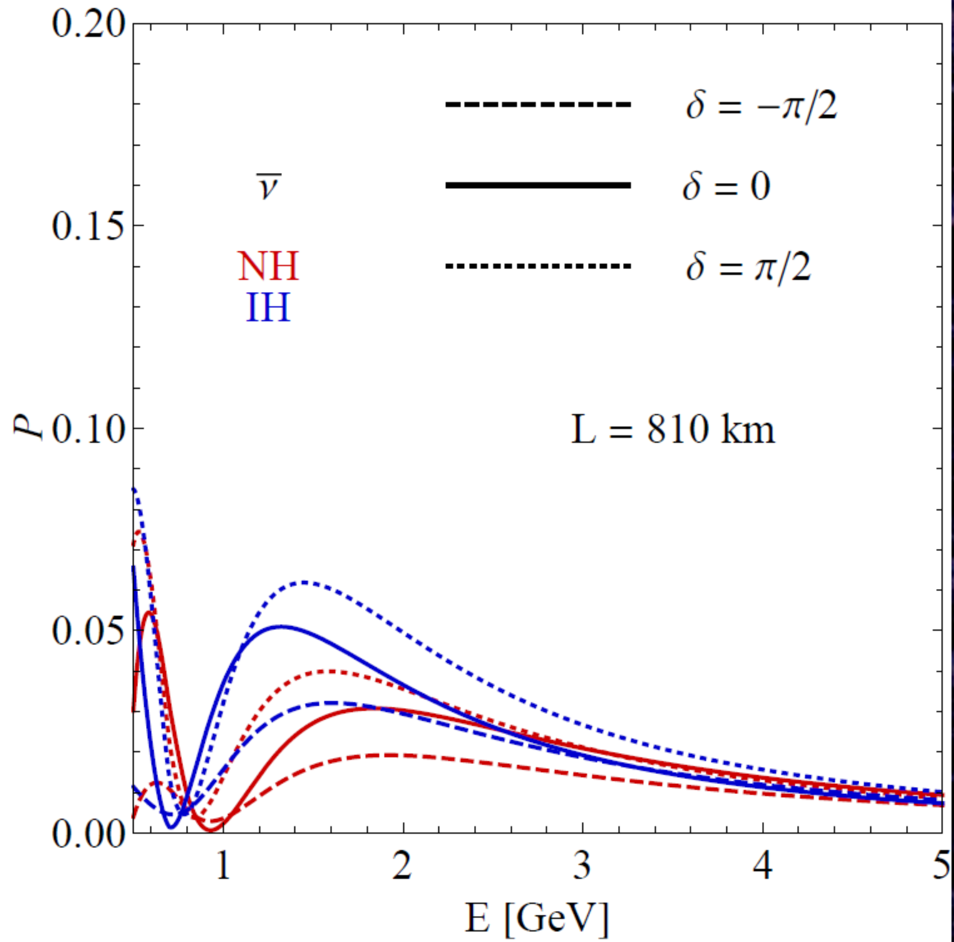
Which experiment should we do?

- I think that is the wrong question.
- The right question is: How many, and which experiments do we need to do to have complementary confirmations for the answers to all the big questions.
- Another thing to emphasize is multiple observables or techniques within each of the experiments (if possible).
- The SNO experiment was never going to be repeated, so we measured the critical NC signal three different ways within the same experiment.
- So what new experiments will help us answer these questions?

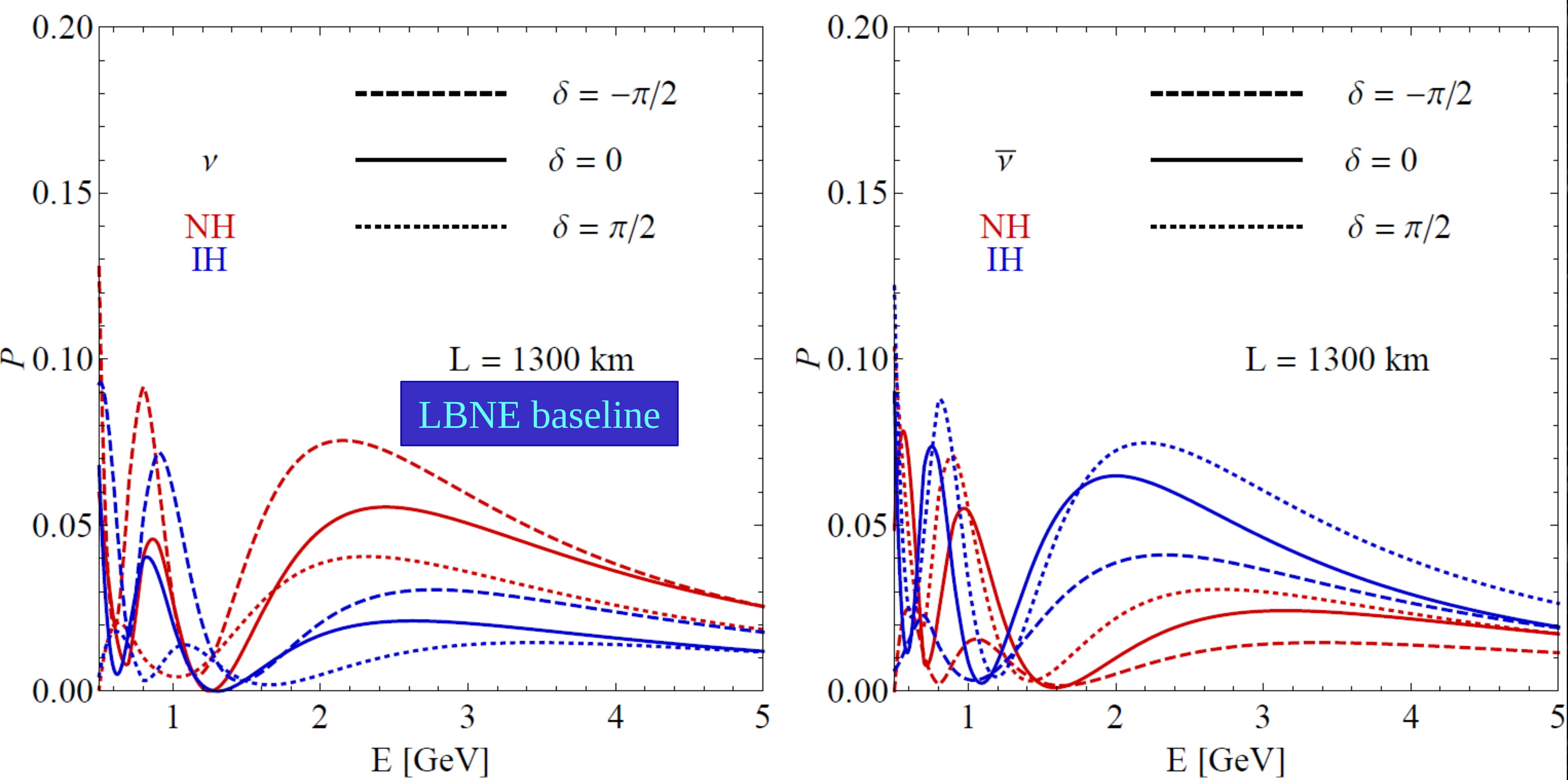

0.20
0.15
0.10
0.05
0.00
P
ν
NH
IH
δ = −π/2
δ = 0
δ = π/2
L = 295 km
T2K, T2HyperK baseline
0.5
1.0
1.5
2.0
E [GeV]
ν̄

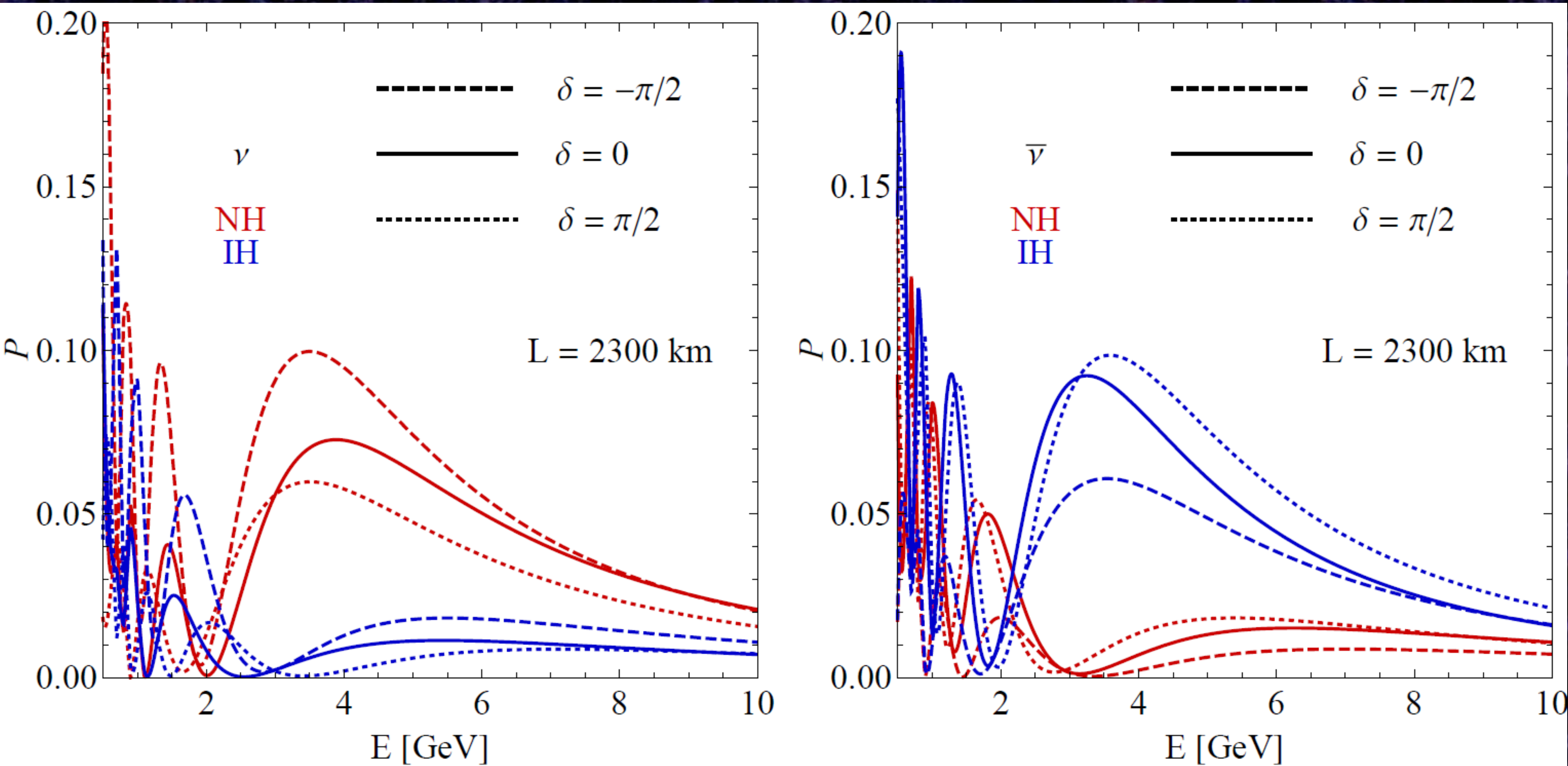


0.20
0.15
0.10
0.05
0.00
P
ν
NH
IH
δ = −π/2
δ = 0
δ = π/2
L = 810 km
NOvA baseline
1
2
3
4
5
E [GeV]



0.20
0.15
0.10
0.05
0.00
P
ν̄
NH
IH
δ = −π/2
δ = 0
δ = π/2
L = 810 km
1
2
3
4
5
E [GeV]


0.20
0.15
0.10
0.05
0.00
P
δ = −π/2
δ = 0
δ = π/2
ν
NH
IH
L = 1300 km
LBNE baseline
1
2
3
4
5
E [GeV]
ν̄



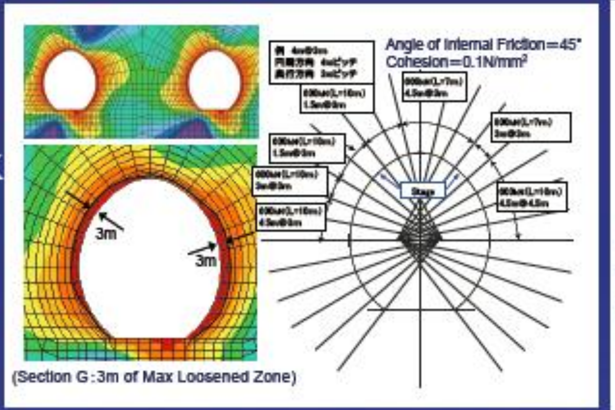
MH effect increases with baseline,
CP effect is ~roughly constant.

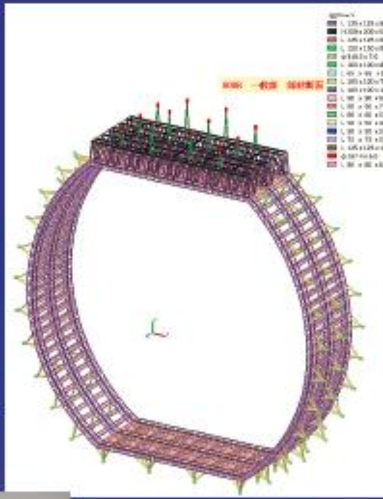
Note size of CP effect in second maximum…

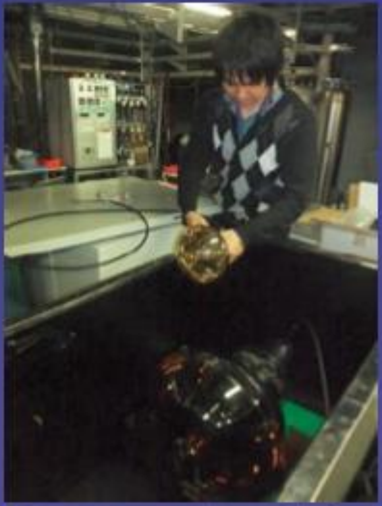
Dave Wark
Oxford U./RAL

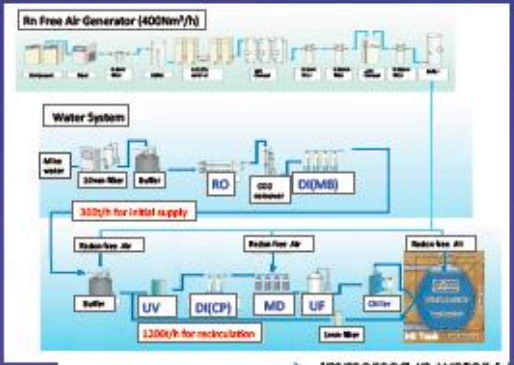
Development works

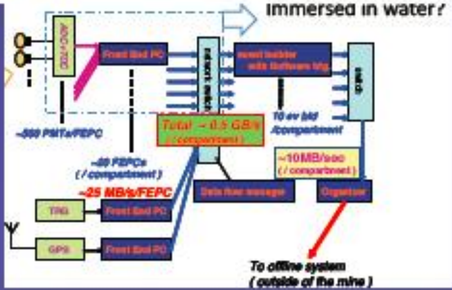
- Detector design optimization
  - tank shape, segmentation wall, tank liner, PMT support structure
- Water purification system, water quality control
- DAQ electronics (under water?)
- Calibration source deployment system
  - automated, 3D control
- Software development
  - Detector geometry optimization, enhance physics capabilities
- Physics potential studies
  - requirements for near detectors











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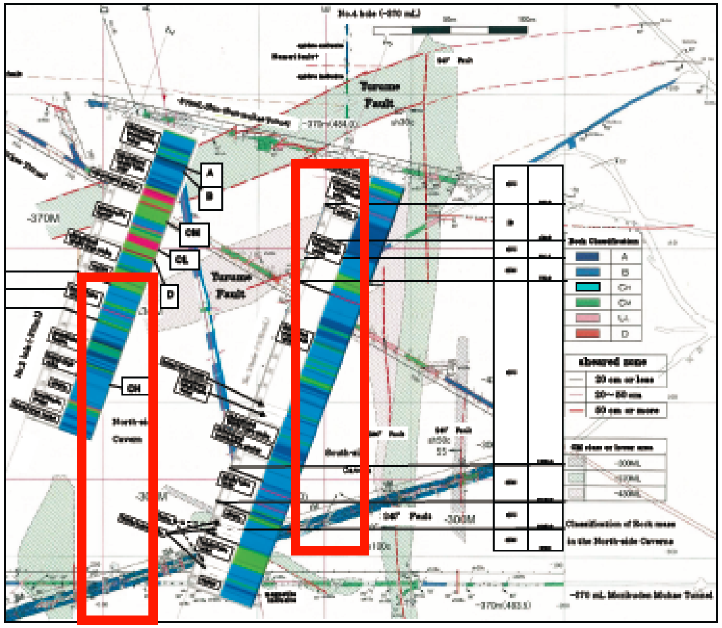
Geological survey & Cavern stability

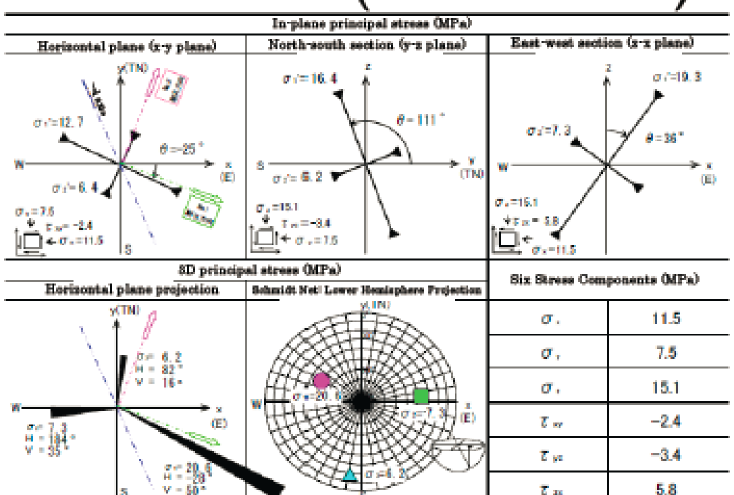
Rock mass characterization



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

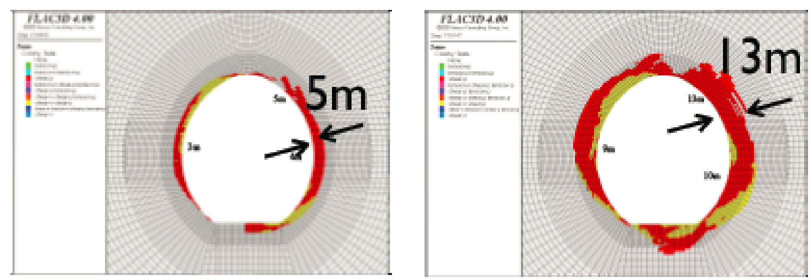
Survey in the Mozumi (Super-K) area is on-going.

Initial stress (in-situ meas.)

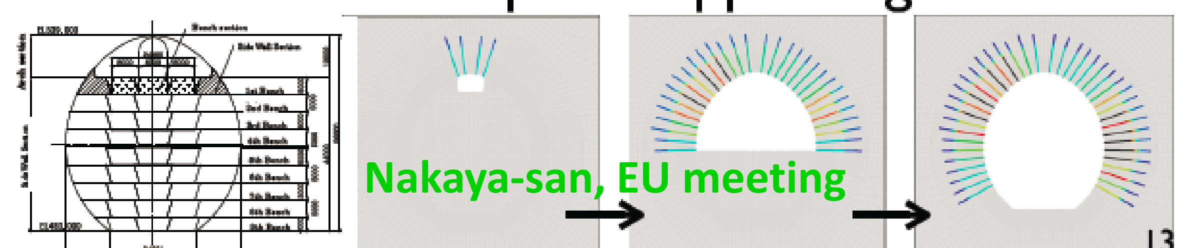


Six Stress Components (MPa)	
σ_x	11.5
σ_y	7.5
σ_z	15.1
τ_{xy}	-2.4
τ_{yz}	-3.4
τ_{zx}	5.8

Cavern stability

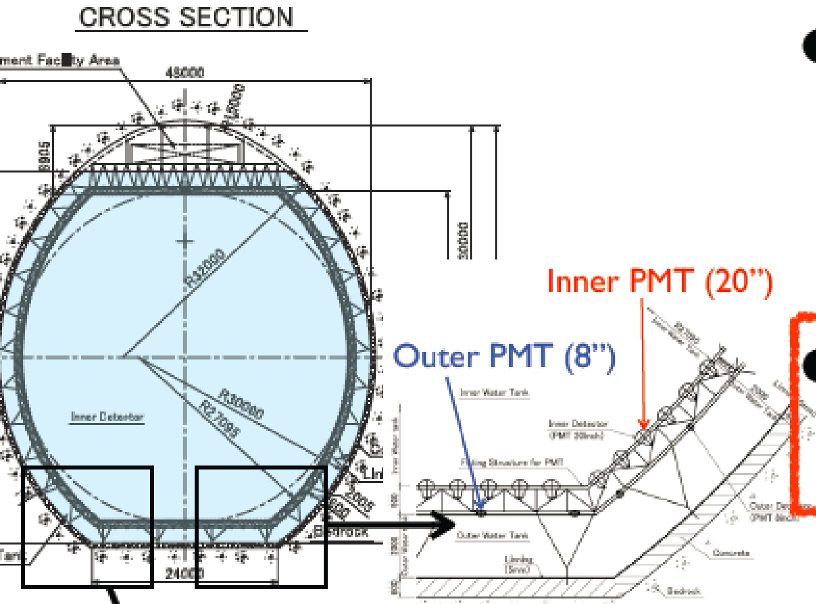


Excavation steps & supporting method

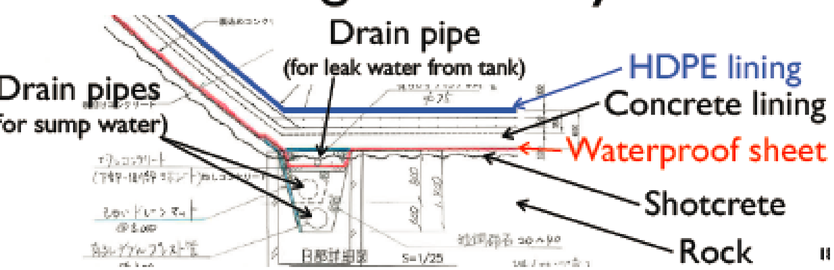


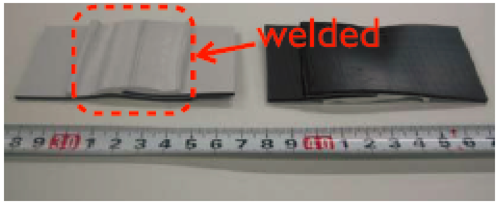
Tank and photo-sensor support

- Baseline designs of the water containment system and photo-sensor support are ready
- Build a prototype detector (1kt)
  - Funding request approved



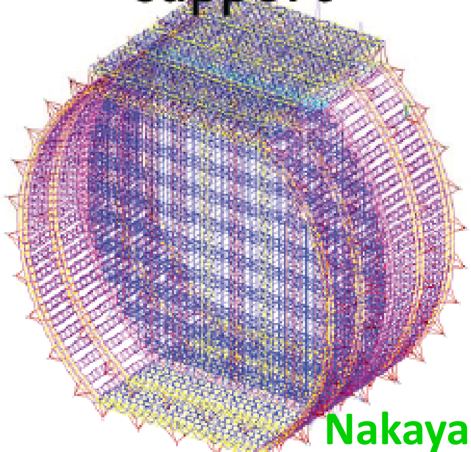
Lining & drain system



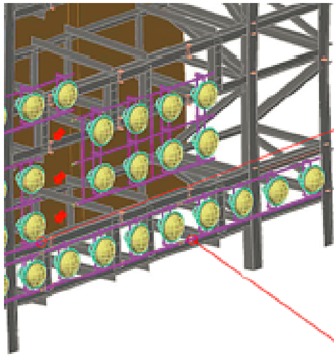


Polyethylene sheet

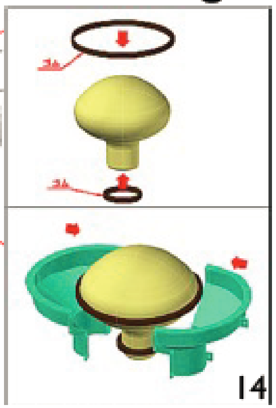
Photo-sensor support



Mounting Photo-sensor



Housing



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New PhotoSensor Development

- High QE 20' PMT (baseline)
- High QE 20' HPD (desired option)
  - Installing the new sensors (8' HPD and 20' High-QE PMT) in EGADS 200 ton tank for a long term test as a Water Cherenkov Detector

8inch HPD Prototype

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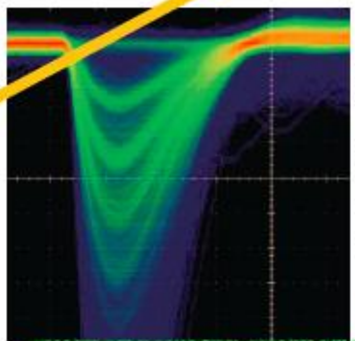
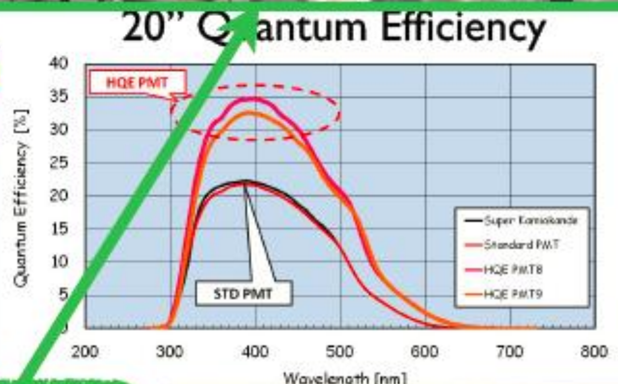
5mmΦ Avalanche Detector



20" Quantum Efficiency

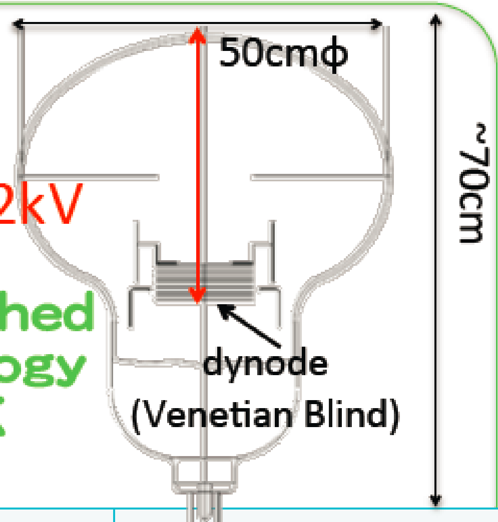


EGADS 200 ton tank @Kamioka

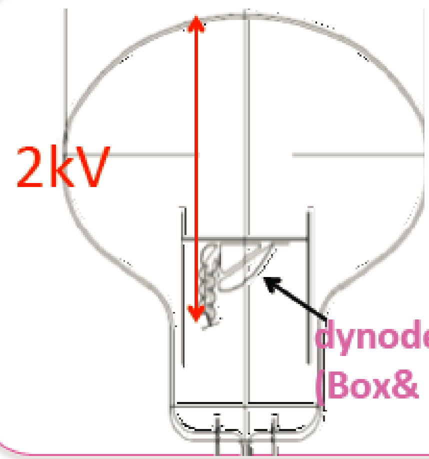
young physicists

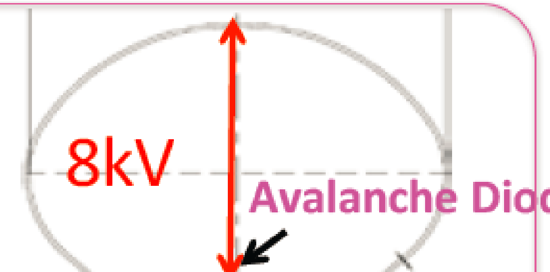
Candidate of HK photo-sensor (50cmϕ)

PMT R3600 (Hamamatsu Photonics K.K.)	PMT R12860 (Hamamatsu Photonics K.K.)	HPD R12850 (Hamamatsu Photonics K.K.)



Established technology in SK





Simple structure!

→Low cost?

New!

	PMT R3600	PMT R12860	HPD R12850
Gain	10^7	10^7	10^4~10^5
T.T.S.(FWHM)	~5.5ns	~2.7ns	~0.75ns
C.E.	80%	93%	95%
P/V @1p.e.	1.4	>2.5	>3

Better (Simulation)

New! **High QE (HQE) option** for all photo-sensors! (22% → 30%)

Expectation of better performance!

- New technology must be verified. → **Proof-test**
- Expected better performance must be confirmed → **Performance evaluation**

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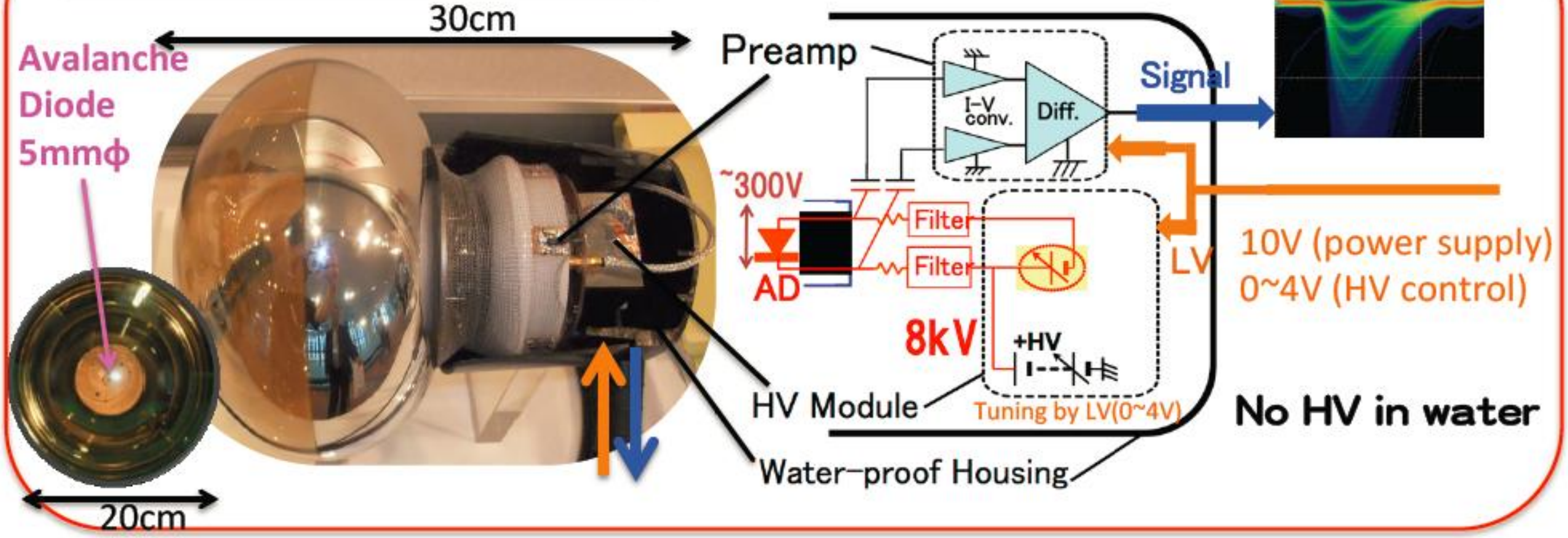
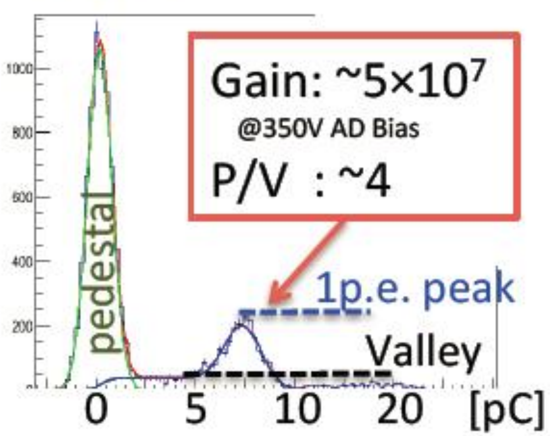
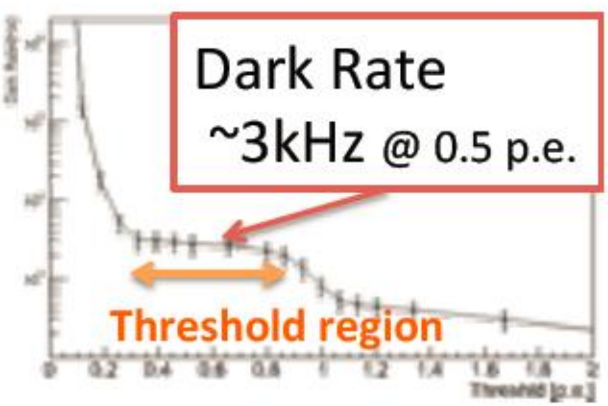
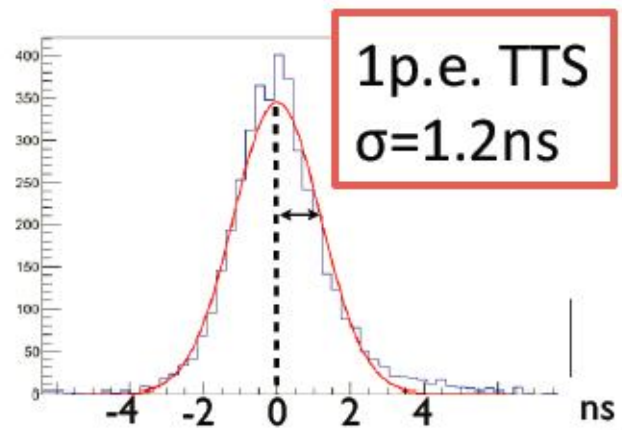
The prototype of 20cmϕ HPD

Prototype of 20cmϕ HPD









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