Session summary

Water Cherenkov and Liquid Scintillator detectors

D. Grant, M. He, H. Tanaka, R. Wendell

NNN15

October 28-31, 2015, Stony Brook University

Organization

Time	Contribution	Speaker
14:00	**Liquid Scintillator technologies (including water based and achi...**	*DENG, Ziyan*
	Gd doping (EGADs, Watchmen, ANNIE)	*VAGINS, Mark*
15:00	**Developments in photosensors (LAPPDs)**	*WETSTEIN, Matthew*
	Developments in photosensors (broad sc...	*WENDELL, Roger et al.*
	Coffee Break *Math Common Room, 4-125 (4 th -5 th floor)*	
16:00	**JUNO (R&D detector focus)** *Math Common Room, 4-125 (4 th -5 th floor)*	*ZHAO, Jie*
	HyperK (R&D focus) *Math Common Room, 4-125 (4 th -5 th floor)*	*NISHIMURA, Yasuhiro*
17:00	**SNO+ status and prospects** *Math Common Room, 4-125 (4 th -5 th floor)*	*COULTER, Ian*
	PINGU *Math Common Room, 4-125 (4 th -5 th floor)*	*HIGHNIGHT, Joshua*
	ORCA *Math Common Room, 4-125 (4 th -5 th floor)*	*JONGEN, Martijn*
18:00	**Physics with a very large WBLSn experiment**	*KLEIN, Josh*

Part1

Technology sub-session which contains general level talks on the status of R&D towards future detectors

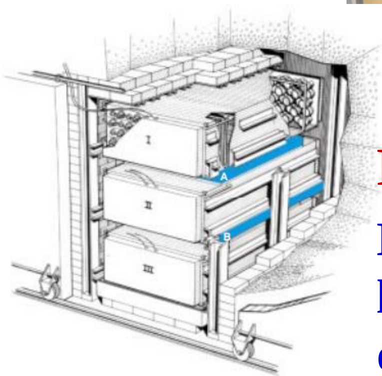
Part2

Experiment sub-session which contains detailed talks on the specific experiment R&D and sensitivity studies

History of WC and LS detectors

Glorious history!

Only an incomplete list.



Reines-Cowan

Mixture of water and liquid scintillator, first detection of neutrinos

Kamiokande

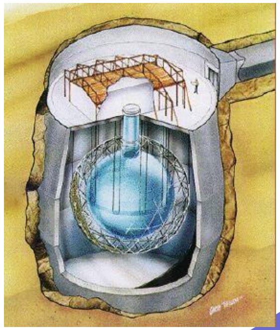
Supernova neutrinos

SuperK

Atmospheric neutrinos' oscillation

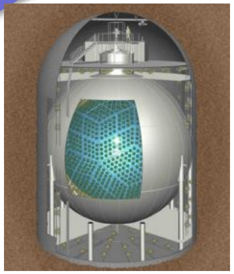
SNO

Solar neutrinos' oscillation



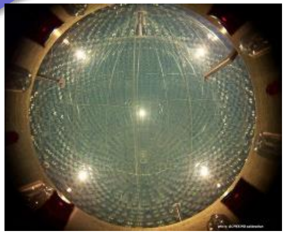
IceCube

PeV neutrinos



KamLAND

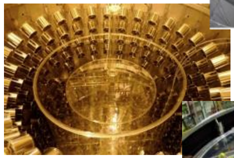
Reactor neutrinos and θ_{12}, Geoneutrinos



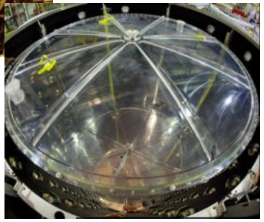
Borexino

Solar neutrinos, Geoneutrinos

Double Chooz



RENO



Daya Bay

Reactor neutrinos and θ_{13}

What's next

Water Cherenkov Detector

Liquid Scintillator Detector

CP-violation

Atmospheric neutrino and θ_{23}

Mass Hierarchy

Nucleon decay

Supernova

Solar neutrino

Geo-neutrino

Reactor neutrino and θ_{12}

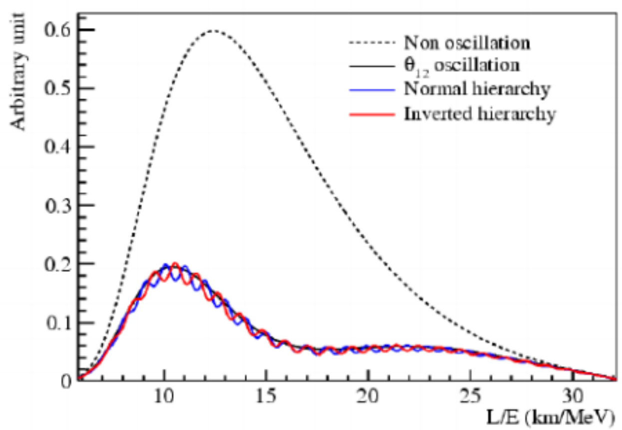
$0\nu\beta\beta$ decay

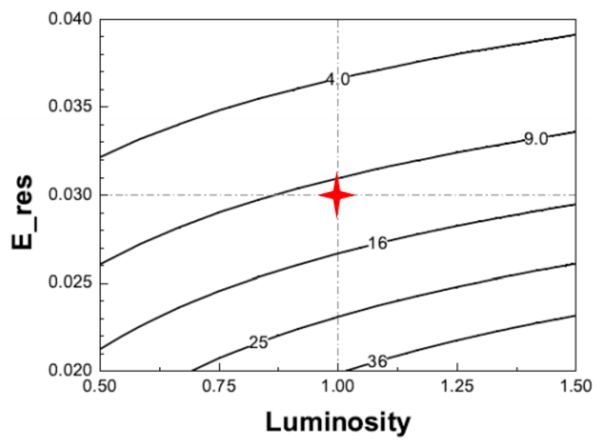
Sterile neutrino

Large LS detector technique and performance

Ziyan Deng

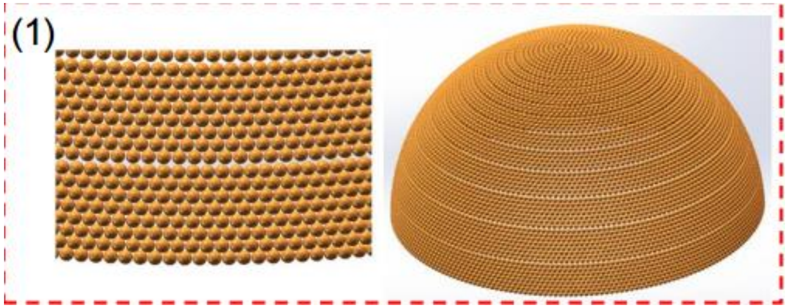
- **Determine mass hierarchy with reactor antineutrinos**
  - Interference between Δm^2_{31} and Δm^2_{32}
  - Requirement to the experiment
    - ✓ High statistics → large detector and long exposure
    - ✓ Good energy resolution → increase photoelectrons and control systematics

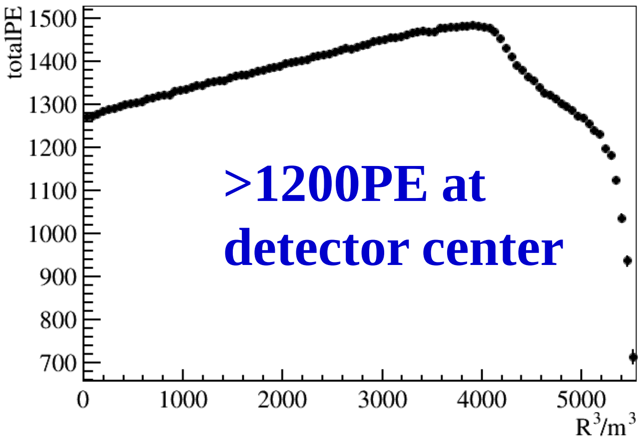




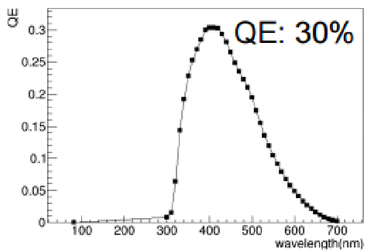
- **How to design a detector with 3% energy resolution?**
  - Scale light yield from running liquid scintillator detectors
  - Study detector performance with full detector simulation
    - Based on reliable MC simulation package, p.e. tuned to data
  - With expected geometry and optical parameters as input

Increase number of photoelectrons

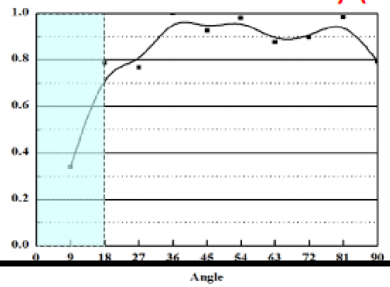




PMT quantum efficiency (QE)



PMT collection efficiency (CE)



Achieve $\sigma_E/E=3\%$

	Daya Bay MC simulation	NEW MC simulation
PMT coverage	~12% (effective)	75%
PMT quantum efficiency@430nm	0.2	0.29
absorption length@430nm	25m	77m
Rayleigh scattering length@430nm	40m	27m
LS radius	2m	17.7m
p.e./1MeV	163	1270

Control systematics

$$\frac{\sigma_E}{E} = \sqrt{\left(\frac{A}{\sqrt{E}}\right)^2 + B^2 + \left(\frac{C}{E}\right)^2} \approx \sqrt{\left(\frac{A}{\sqrt{E}}\right)^2 + \left(\frac{1.6B}{\sqrt{E}}\right)^2 + \left(\frac{C}{1.6\sqrt{E}}\right)^2}$$

Detector energy resolution

Effective energy resolution to MH sensitivity

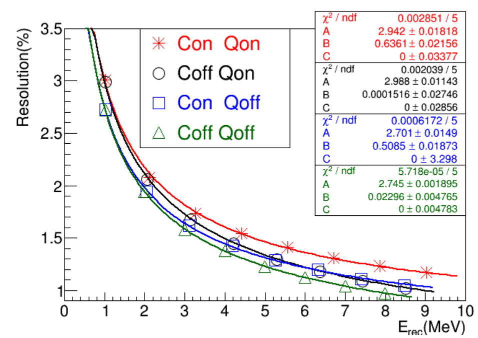
A: Stochastic term

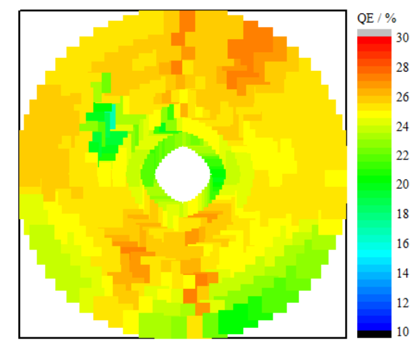
B: Constant term

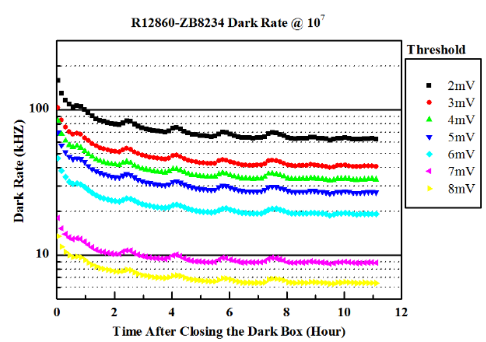
C: Noise term

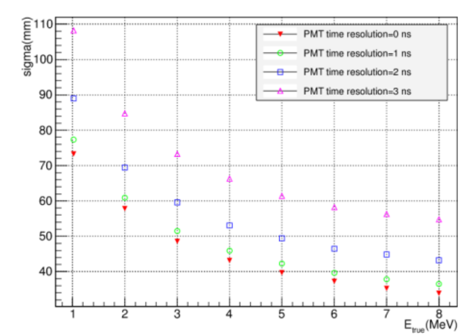
Reduce non-stochastic term is important!

- To get effective energy resolution: 3%/√E
  - LS attenuation length: >20m @430nm
  - PMT QE: >30%@430nm
  - PMT photocathode coverage: >75%
  - PMT charge resolution: <30%
  - PMT QE non-uniformity: <20%
  - PMT time resolution: <3ns
  - PMT dark noise: <50kHz/PMT



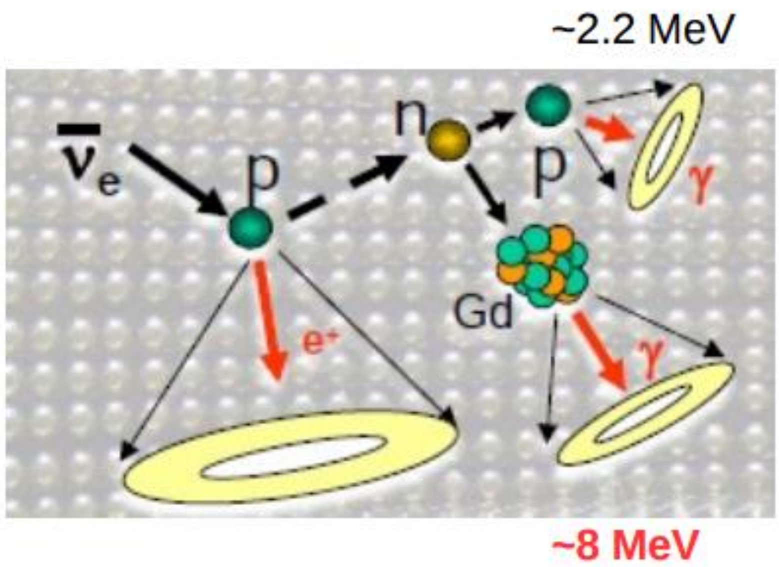


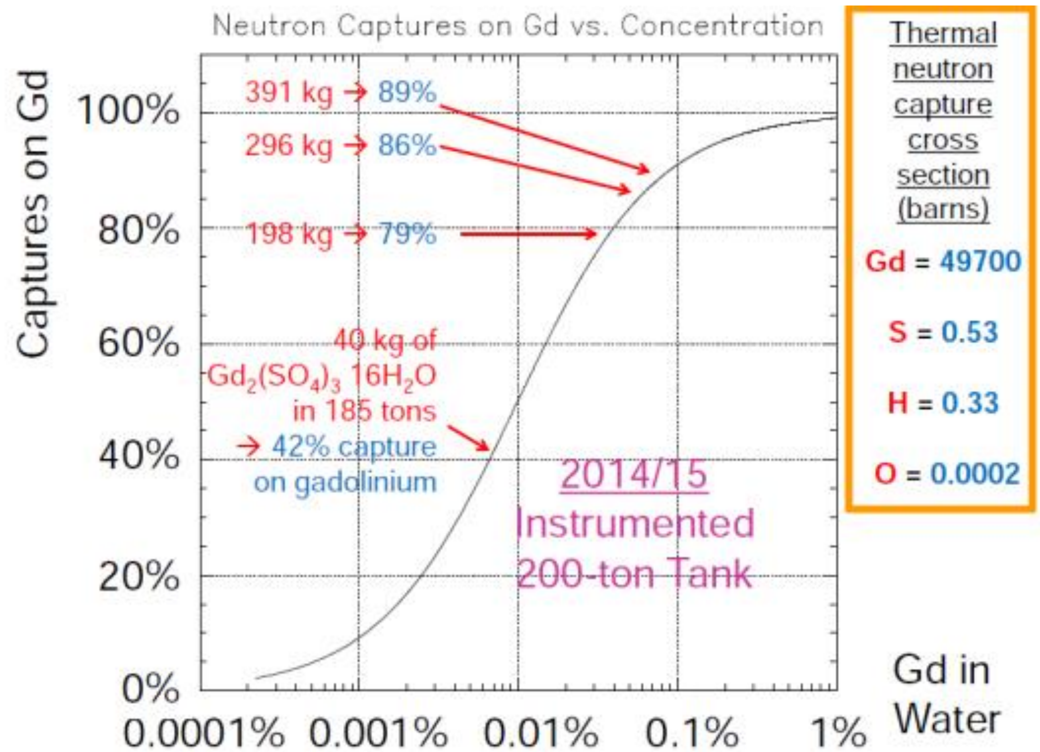




Gd doping in water

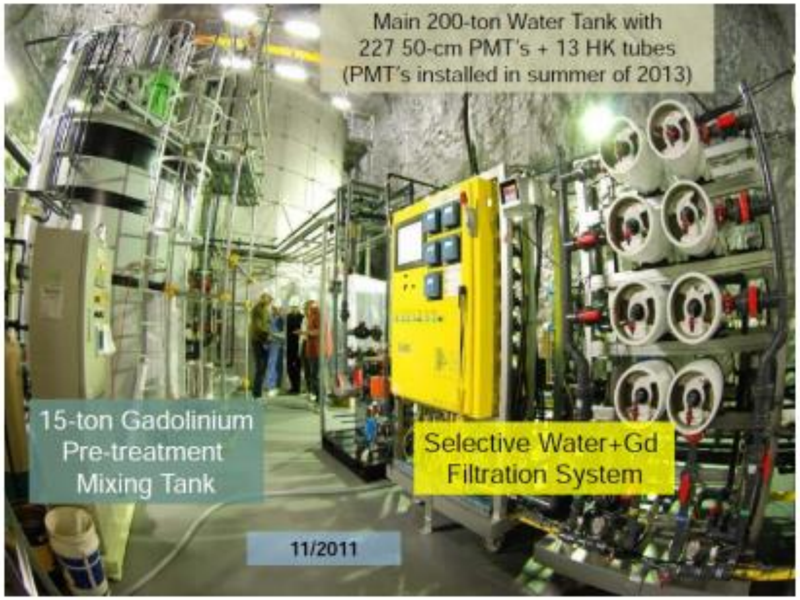
Mark Vagins



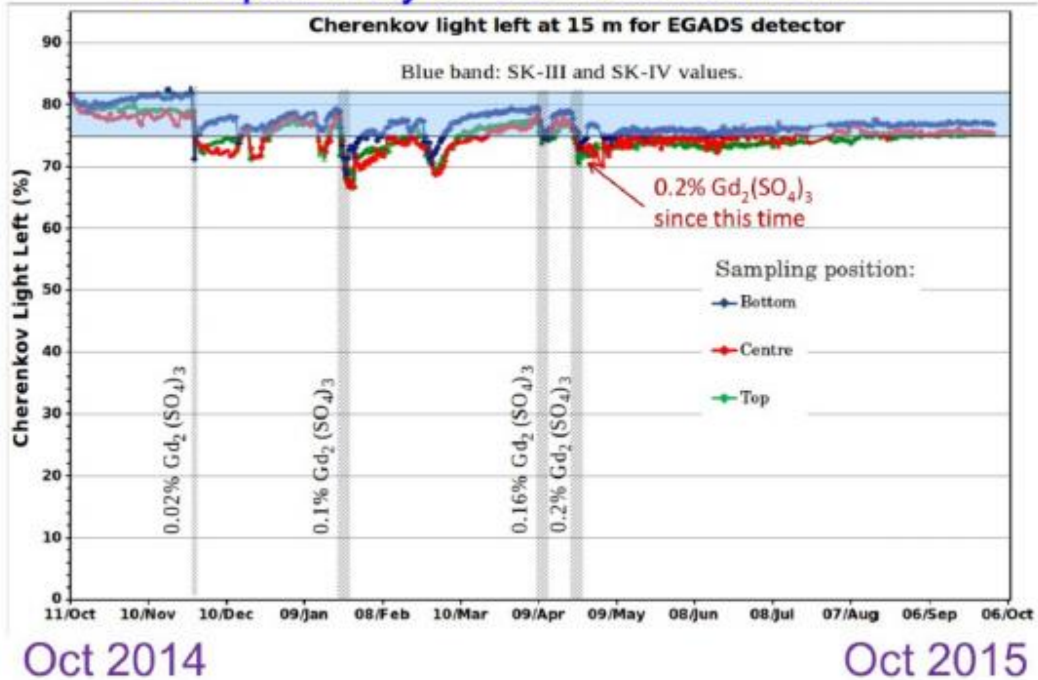


- Adding water soluble gadolinium to water Cherenkov detectors enhances sensitivity to a variety of physics channels by providing a neutron tag
  - Provide enhanced sensitivity to inverse beta decay → Supernova relic ν
    - Remote nuclear reactor monitoring
  - Proton decay searches: Suppress atmospheric neutrino backgrounds since they are often accompanied by (multiple) neutrons while signals are not
  - Improved ν / $\bar{\nu}$ discrimination in atmospheric and LBL neutrino experiments

EGADS Gd-Doping Demonstrator



Transparency of Gd-loaded water



- 200 Ton demonstrator experiment designed to mimic Super-Kamiokande, EGADs, operating with Gd loading at various concentrations since 2014
- Even with the full loading, 0.2% Gd by mass, use of selective filtration system effectively cleans the detector water, without loss of Gadolinium
  - Super-K-level water transparency achieved!
- Neutron's from an Am/Be-BGO calibration source have been seen in the detector
  - Measured capture times shouw good agreement between data and MC

p_1 : average capture time of neutron (μsec)

	2178±76ppm	1055±37ppm	225±8ppm
Data	29.89 ± 0.33	51.48 ± 0.52	130.1 ± 1.7
MC	30.05 ± 1.14	53.47 ± 1.77	126.2 ± 2.8

As a result ....

After years of testing and study
– culminating in these powerful EGADS results –
no technical showstoppers have been encountered. Therefore:

On June 27, 2015, the Super-Kamiokande collaboration approved the SuperK-Gd project which will enhance anti-neutrino detectability by dissolving gadolinium to the Super-K water.

The actual schedule of the project including refurbishment of the tank and Gd-loading time will be determined soon taking into account the T2K schedule.

- In addition, Gd-doping is also planned (or under consideration) for other current- and next-generation detectors:

Other Upcoming Gd-loaded detectors

May 28 2015 - DOE-SC-HEP decision not to support WATCHMAN deployment

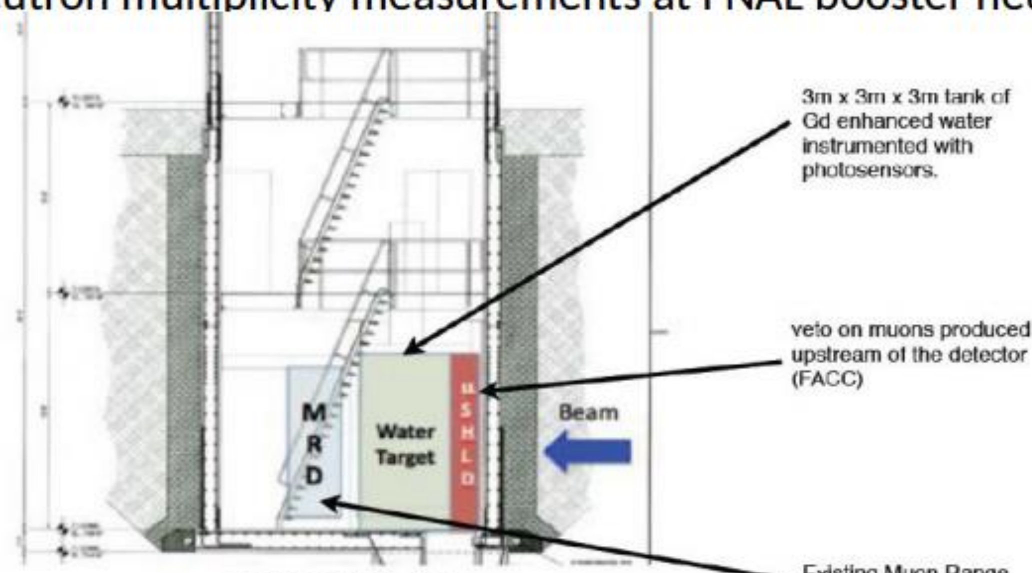
- Reactor monitoring with WATCHMAN

Baseline WATCHMAN Detector Design

N.B: DNN is still supportive and claims ~$20M-$30M is set aside

- Stainless cylindrical tank, assembled in place in existing IMB cavern
- 3.5 kilotons total volume Gd-H_2O, 1 kton fiducial
- 4810 inner 12" PMTs, 40% + HQE → 50% more light collection than Super-K
  - Largest cost item, main schedule determinant

- Neutron multiplicity measurements at FNAL booster neutrino beam with ANNIE



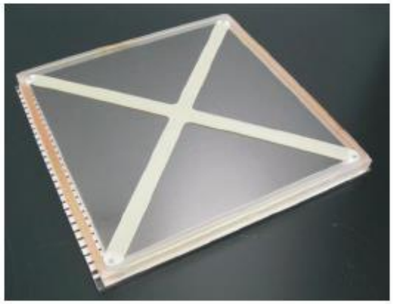
"ANNIE Hall"

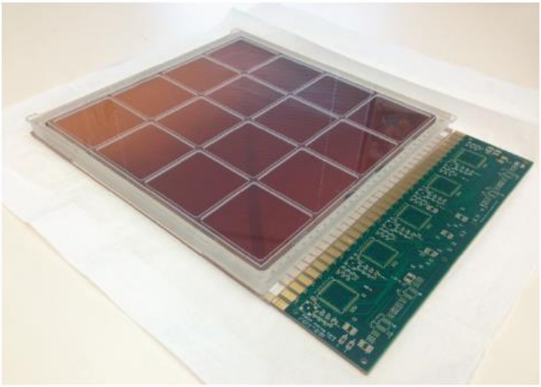
- And more:
  - Hyper-Kamiokande
  - nuPRISM
  - TITUS
  - IceCube

LAPPD

Matt Wetstein

Reinventing the unit-cell of light-based neutrino detectors





LAPPD detectors:

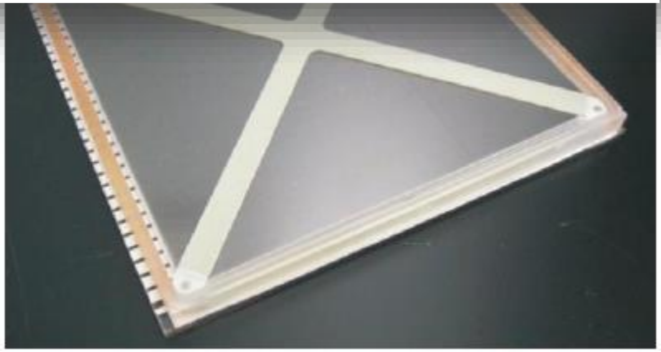
- Thin-films on borosilicate glass
- Glass vacuum assembly
- Simple, pure materials
- Scalable electronics
- Designed to cover large areas

- single pixel (poor spatial granularity)
- nanosecond time resolution
- bulky
- blown glass
- sensitive to magnetic fields

- millimeter-level spatial resolution
- <100 picosecond time resolution
- compact
- standard sheet glass
- operable in a magnetic field

Commercialization status

- Now moving along in the commercialization phase.
- Limited numbers soon available for early adopters.
- Volume and markets will bring down the price, gen-II research could make an even bigger dent.



Milestones

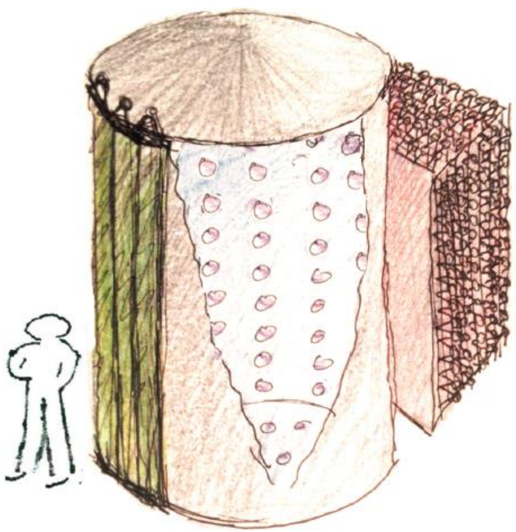
- Early-November: seal 1st LAPPD tile at UC Berkeley, Space Sciences Laboratory
- Mid-November: seal a mock tile at Incom that includes anode/ sidewall, glass capillary arrays (not MCPs), X-spacers, top window, no photocathode
- Mid-December: seal 1st LAPPD tile at Incom
- End-December: seal 2nd LAPPD tile at UC Berkeley, Space Sciences Laboratory
- Mid-January: seal 2nd LAPPD tile at Incom

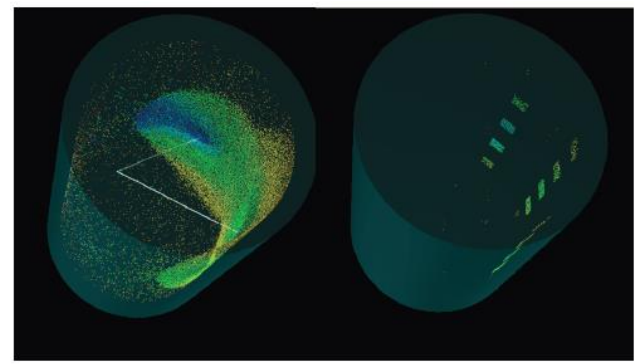
1

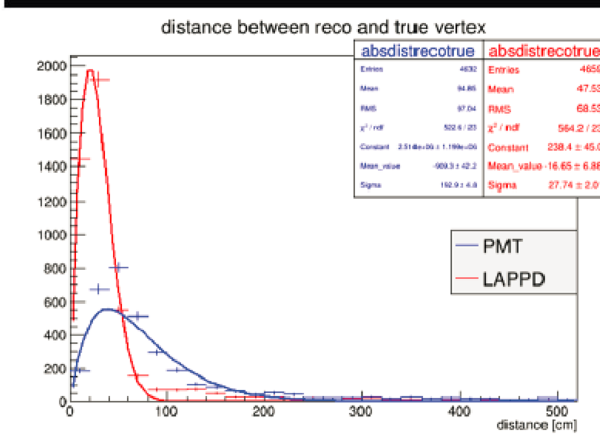
ANNIE

- Accelerator Neutrino Neutron Interaction Experiment
- A US based R&D water Cherenkov facility

> - Demonstration of LAPPDs in a neutrino experiment
> - Application of fast, waveform sampling (PSEC) electronics
> - First use of Gd on a high energy neutrino beam





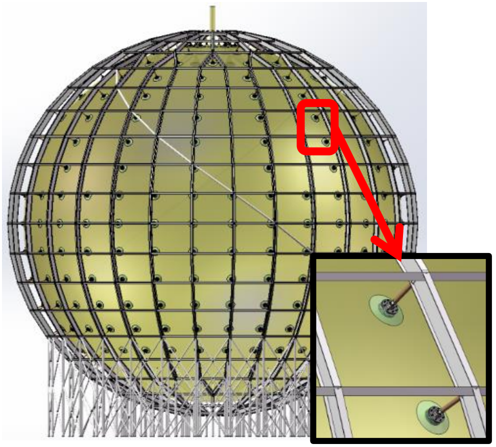


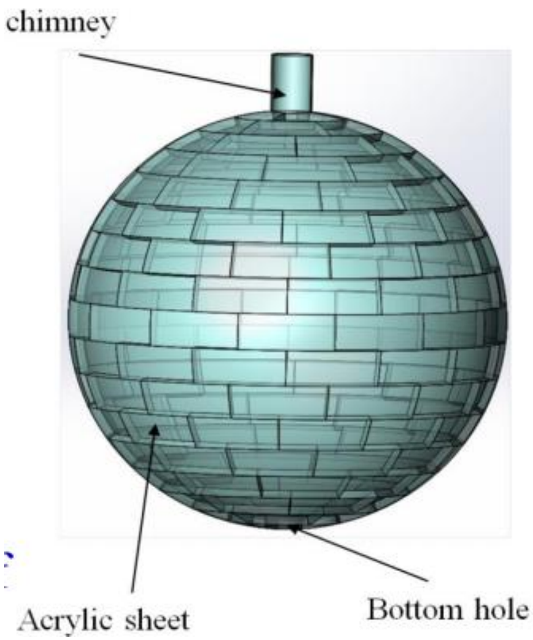
- Phase I – test runs: ~2016
- Phase II – first physics run: ~2018
- Phase II – second physics run: ~2021

JUNO central detector R&D

Jie Zhao

- **Composition**
  - **Acrylic sphere**: Φ35.4m, 600t
  - **Stainless steel frame**: Φ40m, ~400t
    - ✓ Connecting nodes: ~500
    - ✓ Diagonal brace: increasing stability
  - **20 inch PMT**: ~17,000

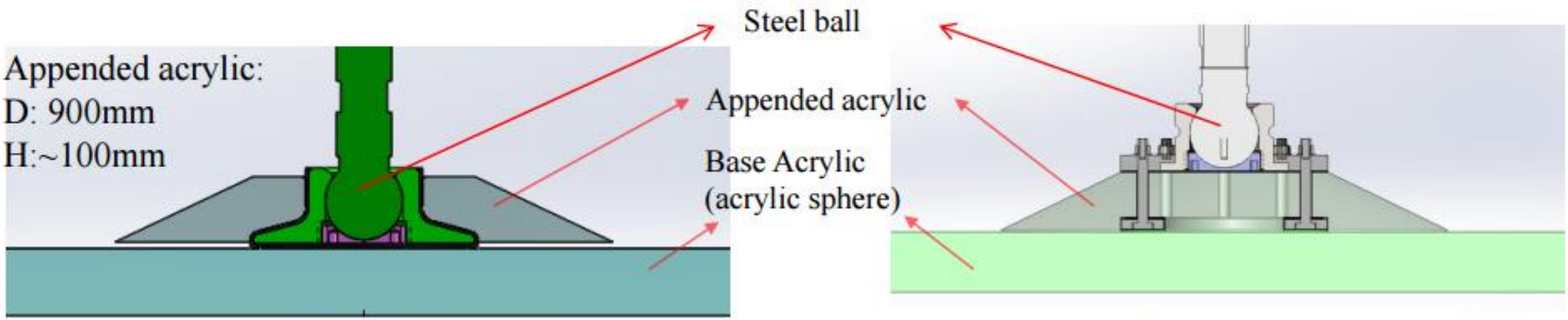




- **Acrylic sphere**
  - More than 170 pieces of acrylic, ~ 3m x 8m x 120mm for each piece
  - Sample pieces are made
  - Quick bonding (~6h for curing)

Mechanics design and strength analysis

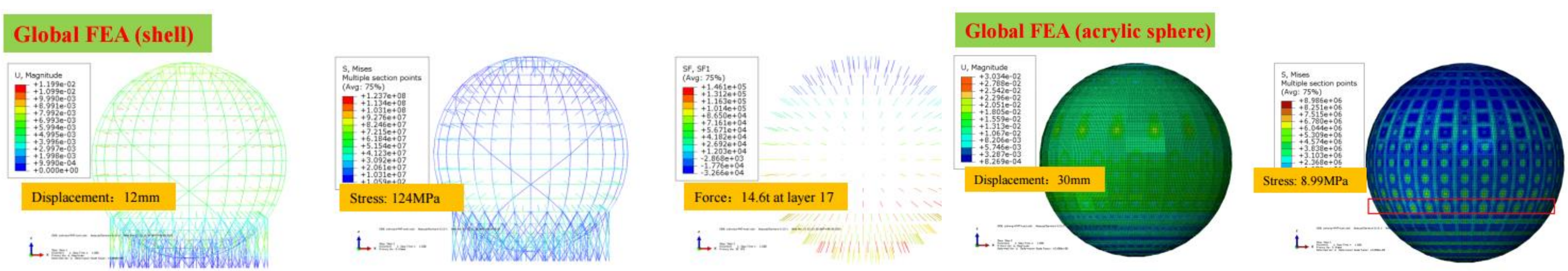
- **Joint of the Acrylic and Truss**
  - ⇨ The maximum breaking strength of scaled node is above 51tons



Node A

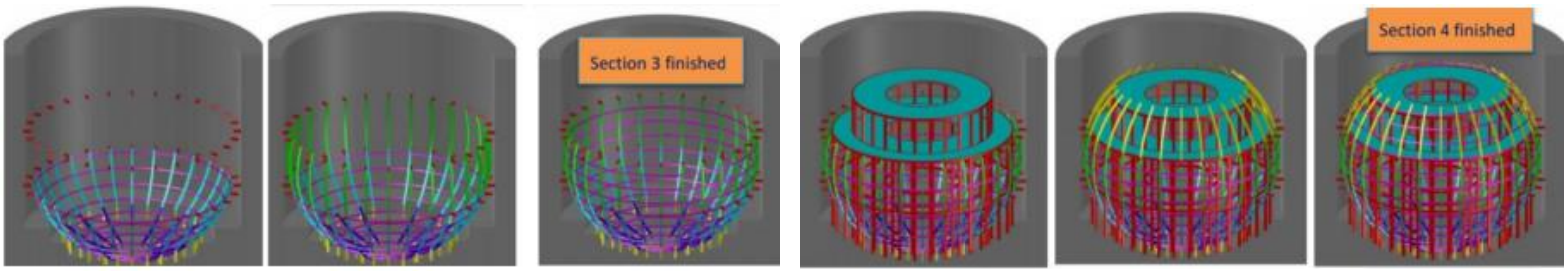
Node B

- **Shell is strong enough to support acrylic sphere**
- **Acrylic sphere's stress is less than 5 MPa**

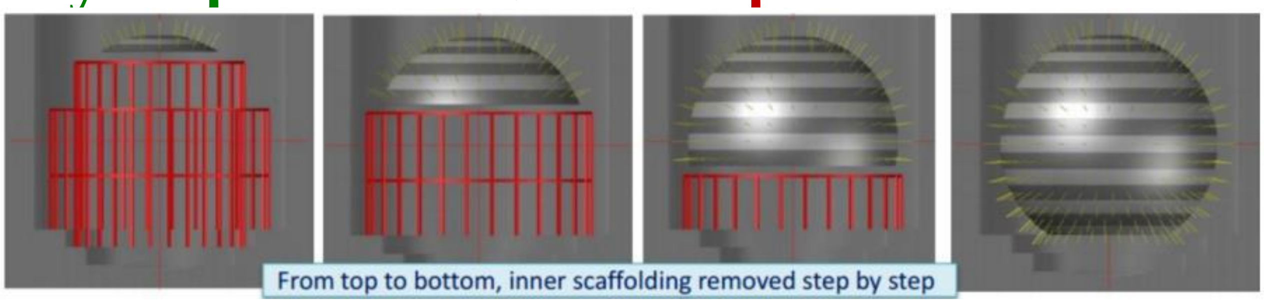


Installation

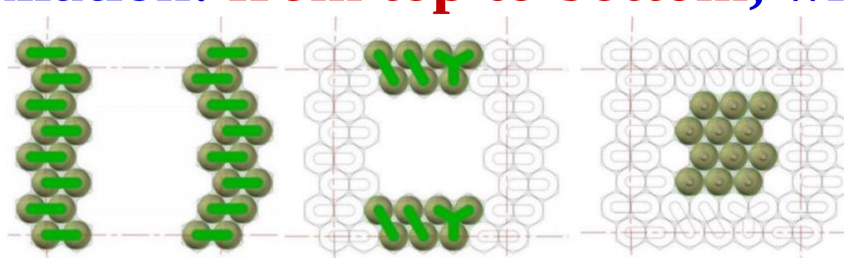
- **Building sequence: steel frame—Acrylic sphere—PMT installation**
- **Steel frame built: from bottom to top**



- **Acrylic sphere built: from top to bottom**



- **PMT installation: from top to bottom, window element**



Schedule and milestones

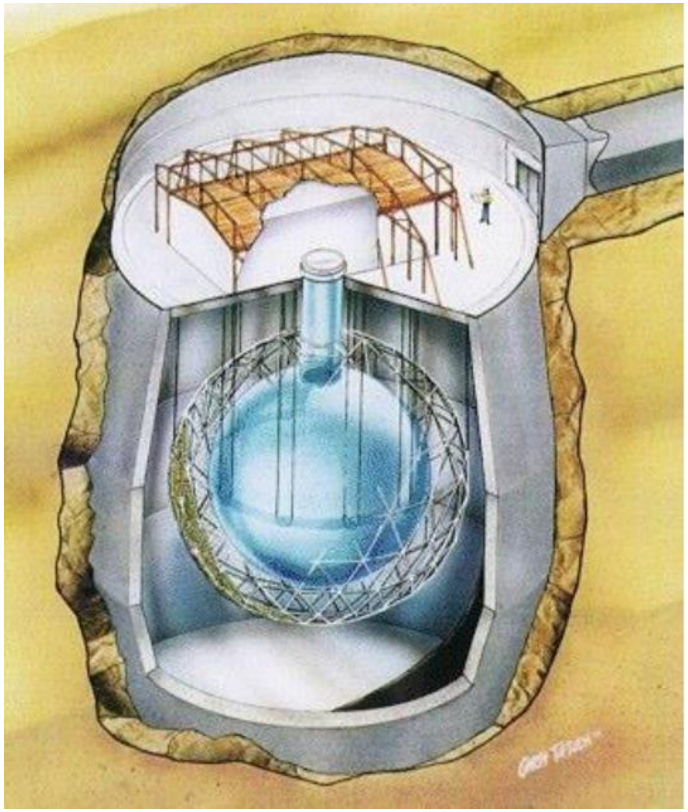
- Integration drawing of engineering: 2016.7
- Truss assembly onsite: 2018.4.1 ~2018.6.30
- Acrylic assembly onsite: 2018.7.1~2019.3.31
- PMT installing: 2019.4.1~2019.6.30
  - ⇨ Including PMT and electronics installing and check
- Filling: 2019.8.1~2019.12.31
  - ⇨ Filling water both in water pool and CD: 2 months
  - ⇨ Replacing water with LS in CD: 3 months
- Data taking: 2020 beginning

SNO+ Ian Coulter

Detector

- SNO+ will use an upgraded version of the SNO detector:
  - 780t scintillator contained within 6m radius acrylic sphere
  - Shielded by 7kt of ultrapure water
  - Surrounded by ~9300 PMTs mounted on a stainless steel support structure

6000 mwe underground



Physics

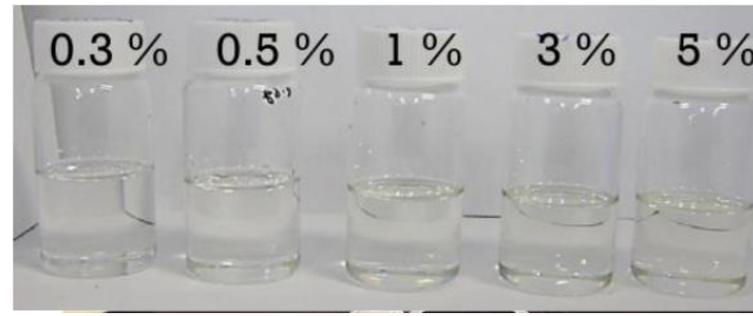
- Neutrinoless double beta decay
- Low energy solar neutrinos
- Supernova neutrinos
- Reactor anti-neutrinos
- Geo-neutrinos
- Invisible nucleon decay
- Other exotics

Phase I: $m_{\beta\beta}$ ~ 55-133 meV

Phase II: $m_{\beta\beta}$ ~ 19-46 meV

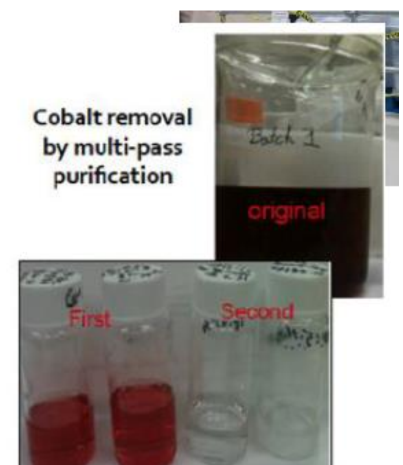
Tellurium Loading

- SNO+ will search for neutrinoless double beta decay using tellurium loaded into the scintillator
  - Initially 0.3% in Phase 1 then onto higher loadings



- 0.3% loading has been produced in larger batches of 30L and its properties measured
- Higher loadings of over 5% have been tested on a smaller scale

- Challenges
  - Backgrounds must be well understood
  - Purification techniques have been developed
  - Ability to tag backgrounds with beta-alpha discrimination
  - Several phase model gives ability to see how backgrounds



- Will be purified underground using a water/acid rinse cycle
- Tests show reduction factor of 10^3 per pass, 10^6 for two passes for Co60 as well as reduction of optical impurities

Current Status

- Currently preparing for water-fill
  - Tests of new ropes using the buoyancy of AV
  - Installing calibration fibres
  - Replacing PMTs
  - Inspections of cavity
- Tellurium development
  - Finalising plans for the loading of 0.3%
  - Further development of higher loadings

- **Detector upgrades**
  - ⇨ Improved electronics
  - ⇨ New optical fibre calibration systems
  - ⇨ Repaired PMTs
  - ⇨ Hold-down ropes installed
  - ⇨ New scintillator plant constructed
- Phase of SNO+
  - ⇨ Water phase
  - ⇨ Pure scintillator
  - ⇨ Te-Loaded scintillator

- DAQ, electronics and data flow have been tested during “air fill” runs
  - Initial commissioning of calibration systems

Hyper-Kamiokande

Yasuhiro NISHIMURA

Super-Kamiokande

(since 1995)

0.0225 (0.05) Mton

Fiducial (Total)

x 25(20)

Hyper-Kamiokande

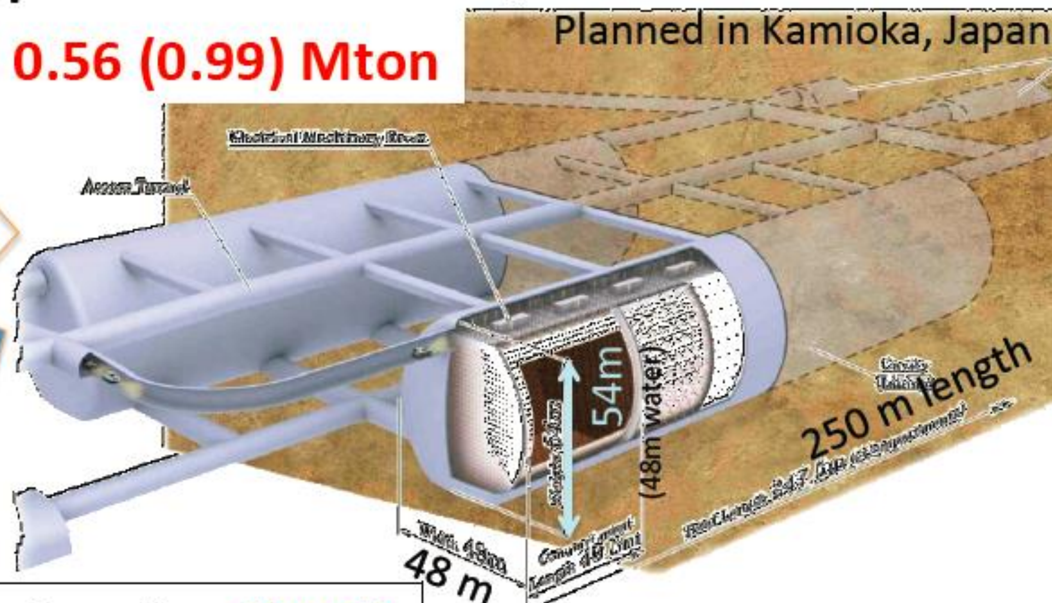
Large water Cherenkov detector

Planned in Kamioka, Japan

0.56 (0.99) Mton

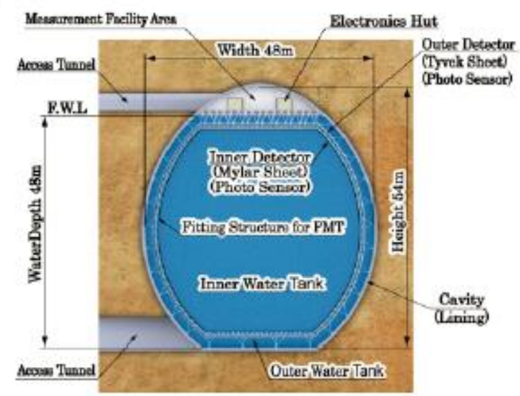
Based on established technologies

+ Improvement with new technologies



Photosensors

Photo-sensor	Super-K	Hyper-K
Inner detector (for ν detection)	11,129 (50cmΦ)	99,000 (50cmΦ)
Outer detector (for cosmic-ray veto)	1,885 (20cmΦ)	25,000 (20cmΦ)
Photo-coverage	40%	20%
Sensor efficiency (Quantum × Collection Eff.)	18% (22%×80%)	29% (30%×95%)



Expected in new photo-sensor R&D

HyperK R&D

Construction : Super-K 1993 – 1996 ~25 yrs → Hyper-K 2018 – 2023 (?)

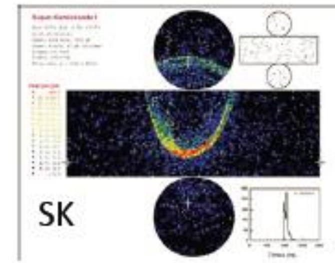
- Studying Hyper-K design based on well-established Super-K by 8 Detector R&D working groups to construct Hyper-K.

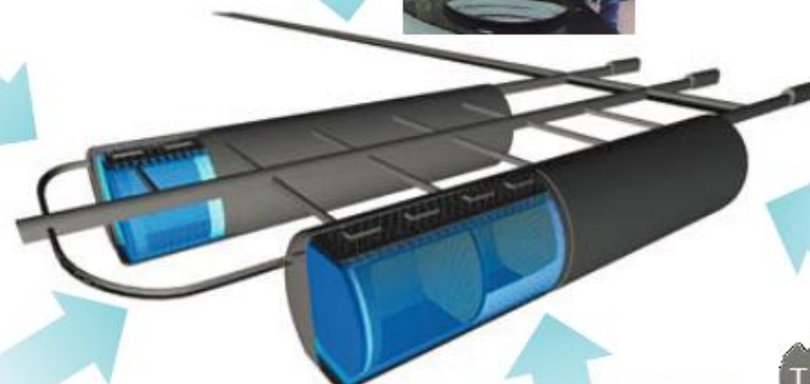
1. Cavity & Tank

2. Water

3. Photo-sensor

5. Software

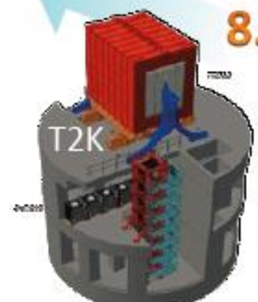




6. Calibration

8. Beam&Accelerator

4. Electronics & DAQ



7. Near detector

and physics working groups

Various R&D groups are actively working for further improvement.

50cmΦ photosensor candidates

- 2 types of new 50 cm Φ photodetectors are developed.

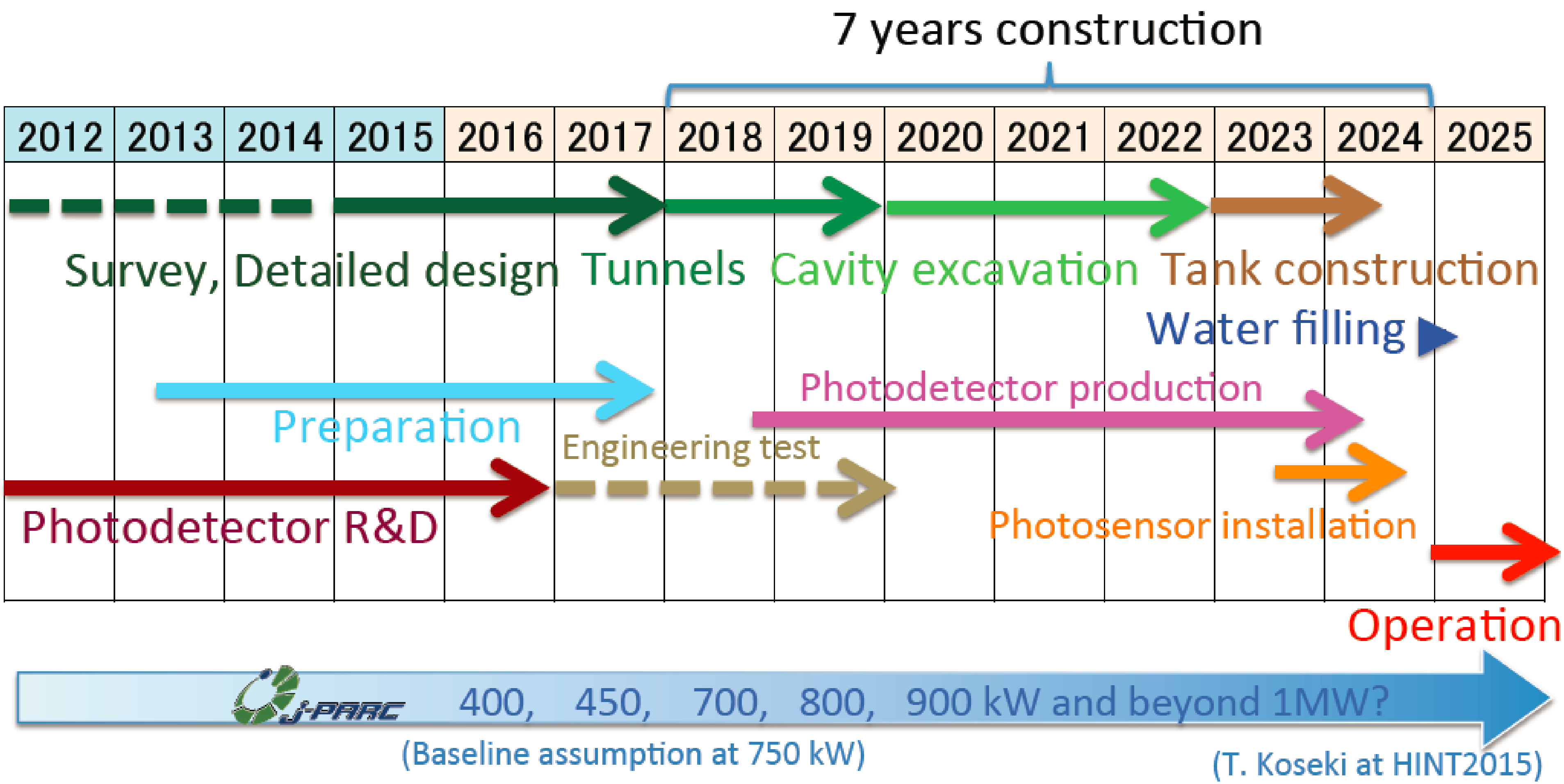
† still in R&D

Model	R3600 (Established)	R12860	R12850
Amplification	Venetian blind dynode	Box and line dynode	20mmΦ Avalanche diode
Q.E.	~22% (or ~30% in HQE)	~30%	~30%
C.E. Φ46 (Φ50)	67% (61%)	95% (85%)†	93% (76%) w/ 5ch AD†
T.T.S. (FWHM)	5.5 ns	2.7 ns	0.75ns (w/o Preamp.)
Bias voltage	2 kV bias	2 kV bias	8 kV bias + AD bias (<1kV)
Proof test	2 yrs for HQE (19yrs in SK)	1 yrs now from Sep.2014	> 0.5 yrs expected

C.E. = Collection efficiency of 1 photoelectron, T.T.S. = Transit Time Spread, by calculation

Timeline

(Assuming budget approval, not determined yet)



KM3NeT/ORCA

Martijn Jongen

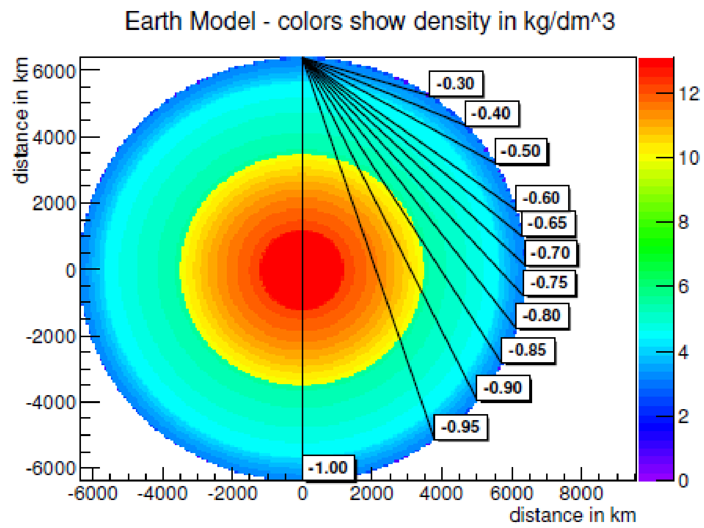
- Measure the mass hierarchy with atmospheric neutrinos

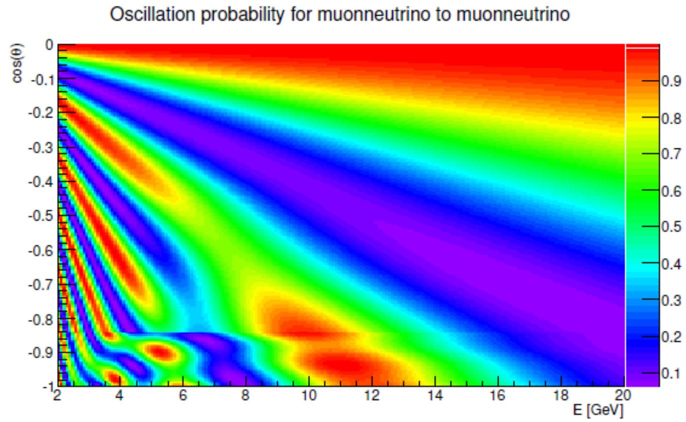
Charged Current (CC)

$$\nu_\ell + X \xrightarrow{\text{via } W^\pm} \ell + \text{hadronic cascade}$$

- $\ell = e \Rightarrow$ electromagnetic **cascade**
- $\ell = \mu \Rightarrow$ several meters long **track**
- $\ell = \tau \Rightarrow$ immediately decays (strongly suppressed) **cascade**

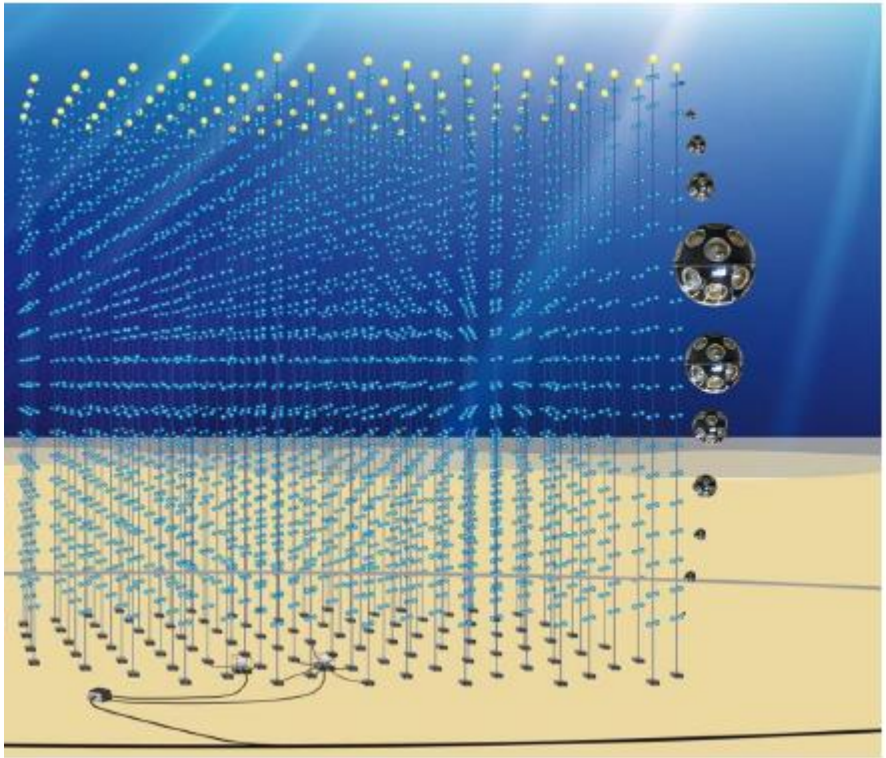
Particle ID by distinguishing `track-like' events from 'cascade-like' events.

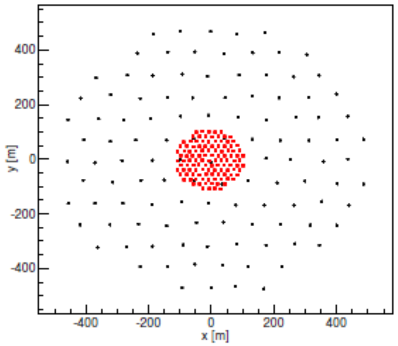




Zenith-energy plot of the $\nu_\mu \rightarrow \nu_\mu$ oscillation probability **with the MSW-effect**.

Detectors





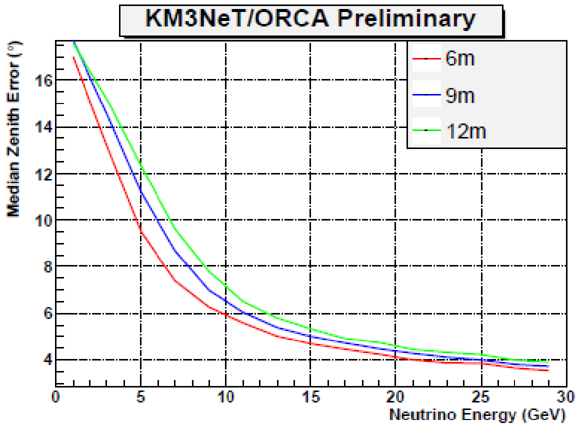
Detector footprint of ORCA (red) and ARCA (black)

The KM3NeT Digital Optical Module.

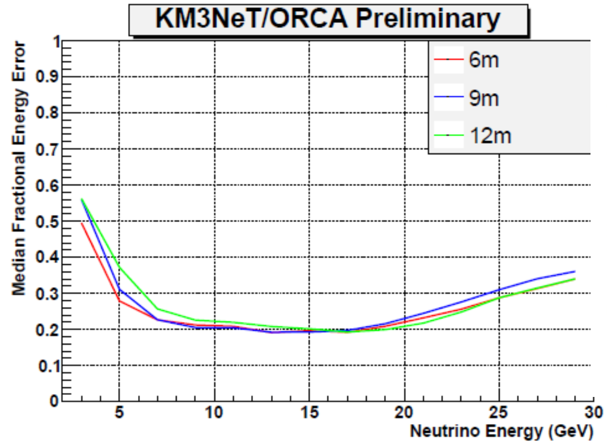
Second completed KM3NeT string at Nikhef.

- Six ORCA-style strings already funded
- First to be deployed before end of 2016
- String production started: 2 ARCA strings completed
- Deployment December 2015 and early 2016

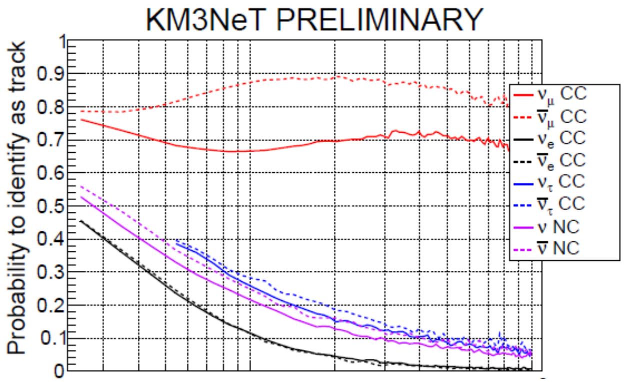
Performance



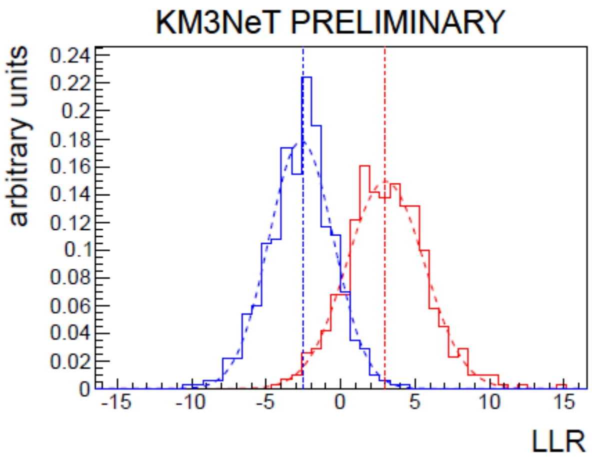
Median direction resolution for μ-typ events.



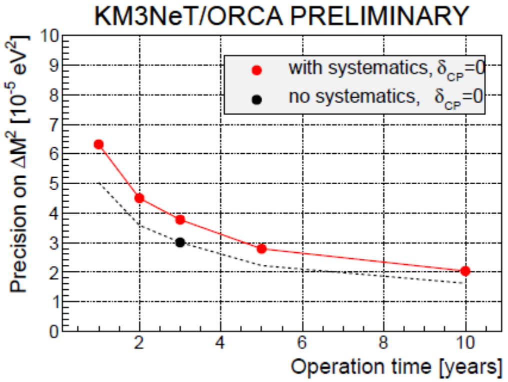
Median fractional energy resolution for ν_μ CC events.



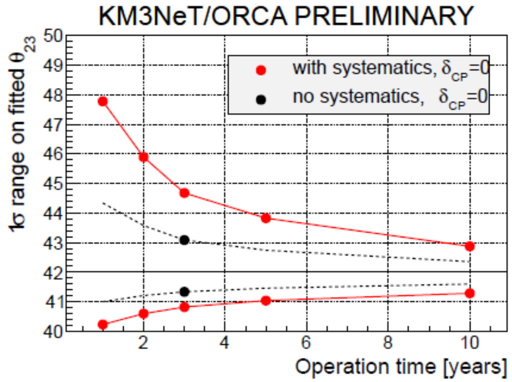
- e-like CC events better than 90% above 10 GeV
- mu-like CC events around 80% (better for $\bar{\nu}_\mu$, worse for ν_μ).



~3σ in 3 years of full detector operation



Expected precision on ΔM^2 as a function of operation time.

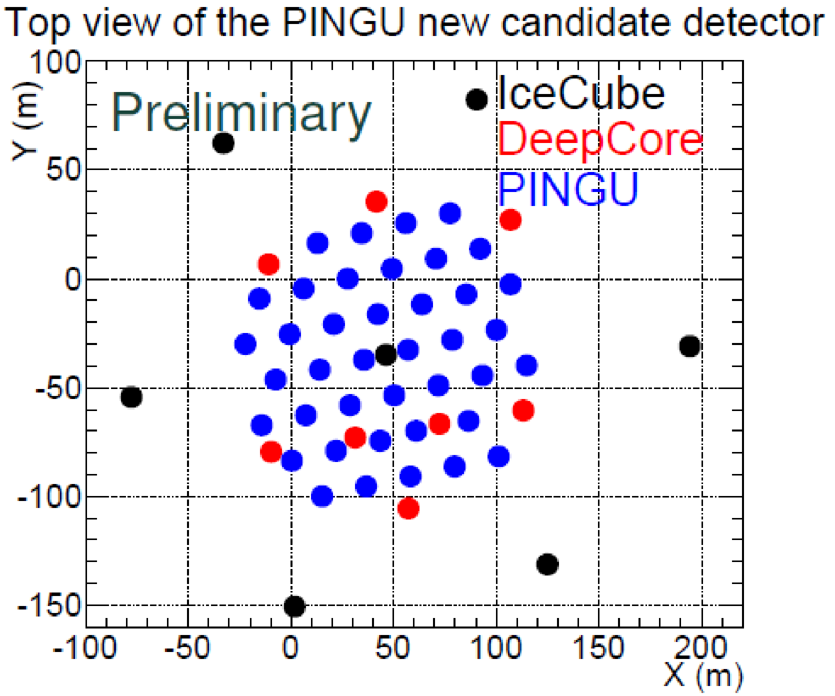


Expected precision on θ_{23} as a function of operation time.

PINGU

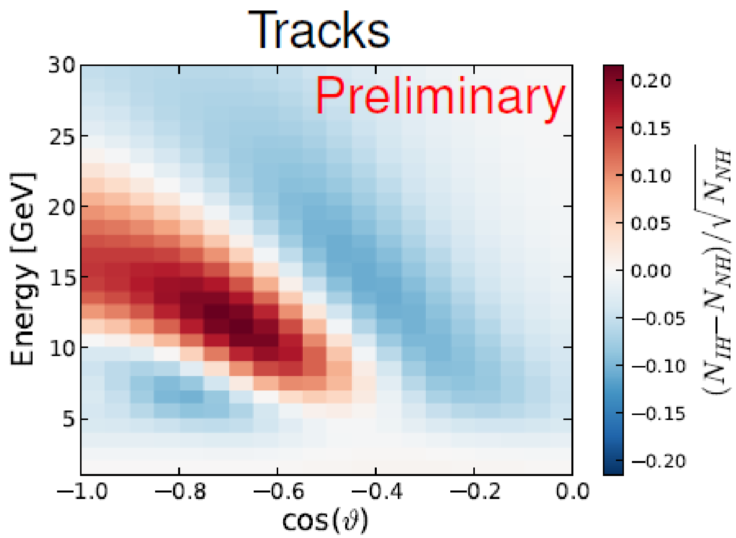
Joshua Hignight

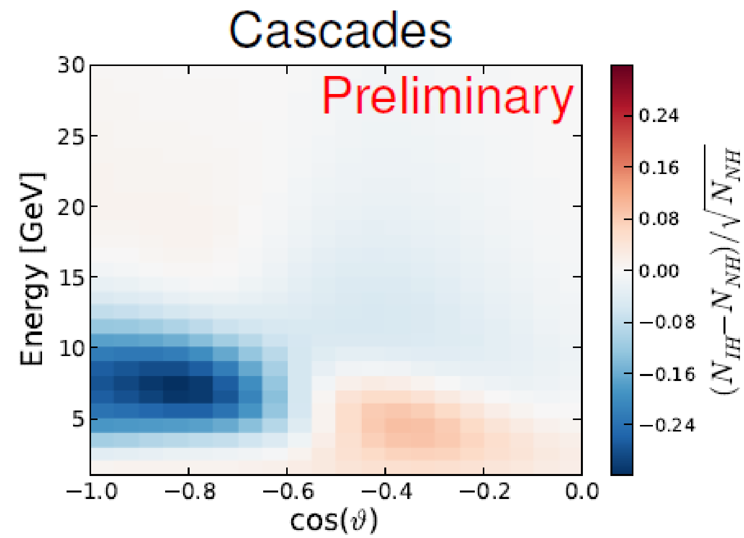
- 78 strings, 125 m string spacing
- 17 m modules vertical-spacing
- 8 strings, 75 m string spacing
- 7 m modules vertical-spacing
- 40 strings, 22 m string spacing
- 3 m modules vertical-spacing
  - all optical modules in clearest ice

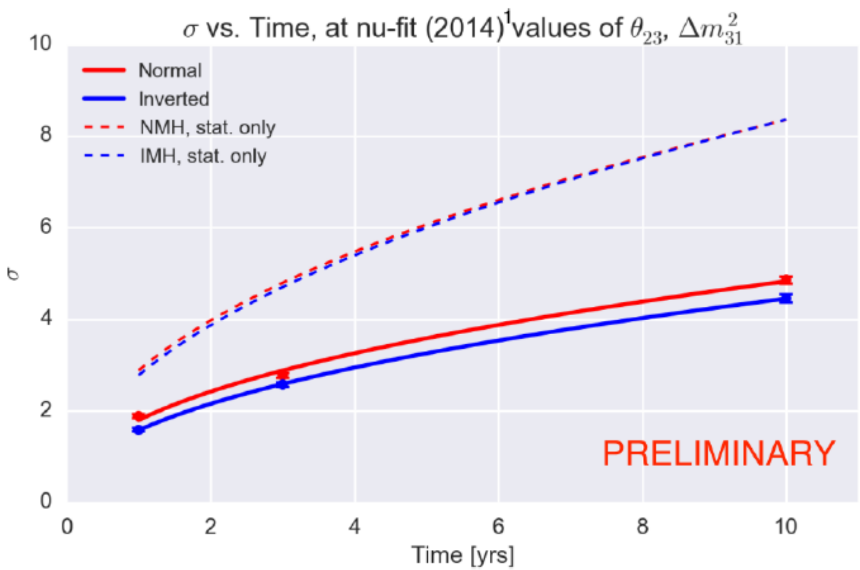


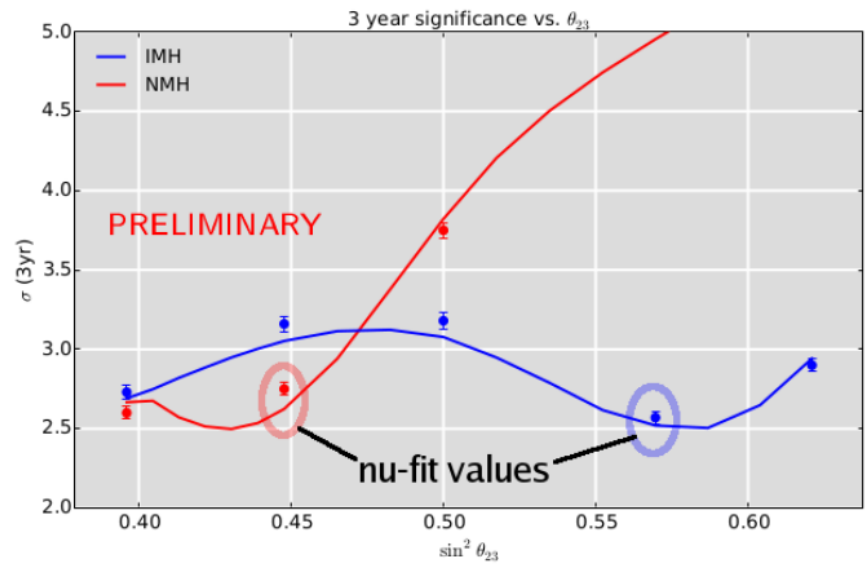
- Precision measurements of atmospheric neutrino oscillation at a few GeV with very high statistics
  - Measure Neutrino Mass Hierarchy (NMH)
  - Precise measurement of Δm^2_{23}, θ_{23}
  - High statistics measurement of ν_τ appearance

Mass hierarchy







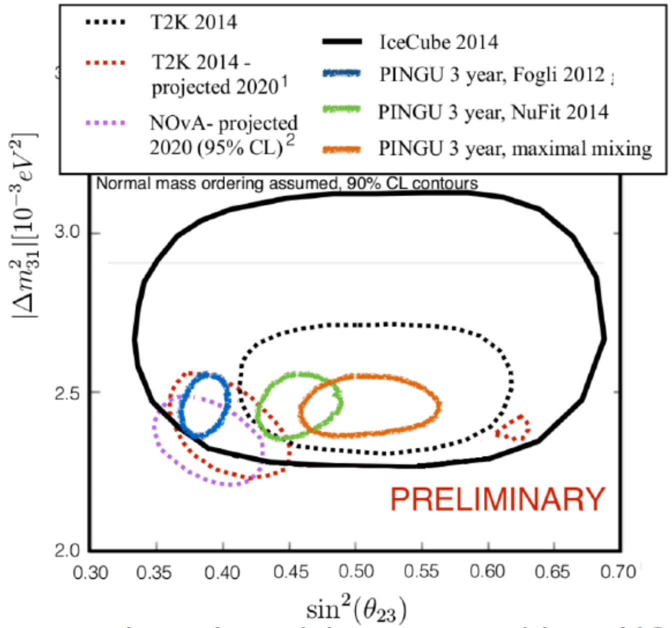


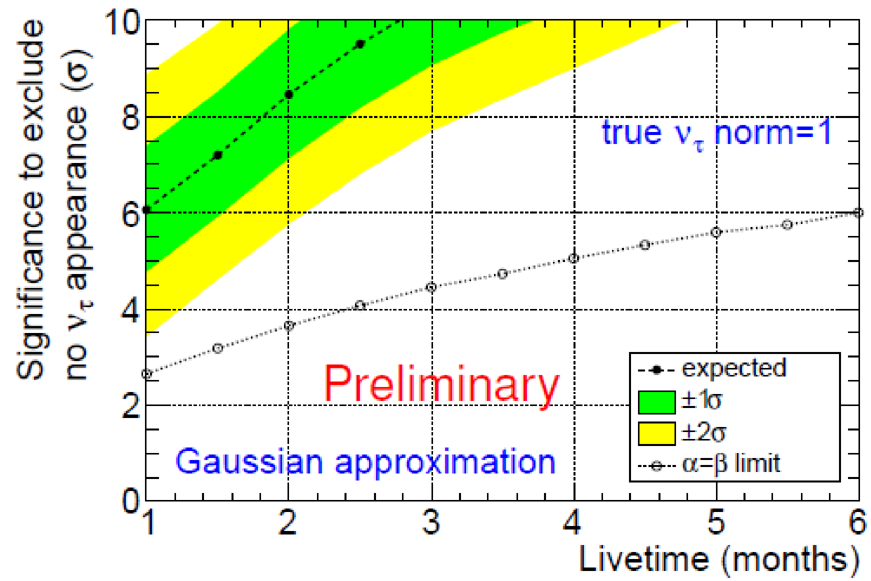
3σ determination of mass hierarchy with 3-4 years of data

NMH sensitivity strongly dependent on true value of θ_{23}

Others physics in PINGU

PINGU sensitivity to θ_{23}





- Expected constraints of precision comparable to NOνA and T2K (projected)

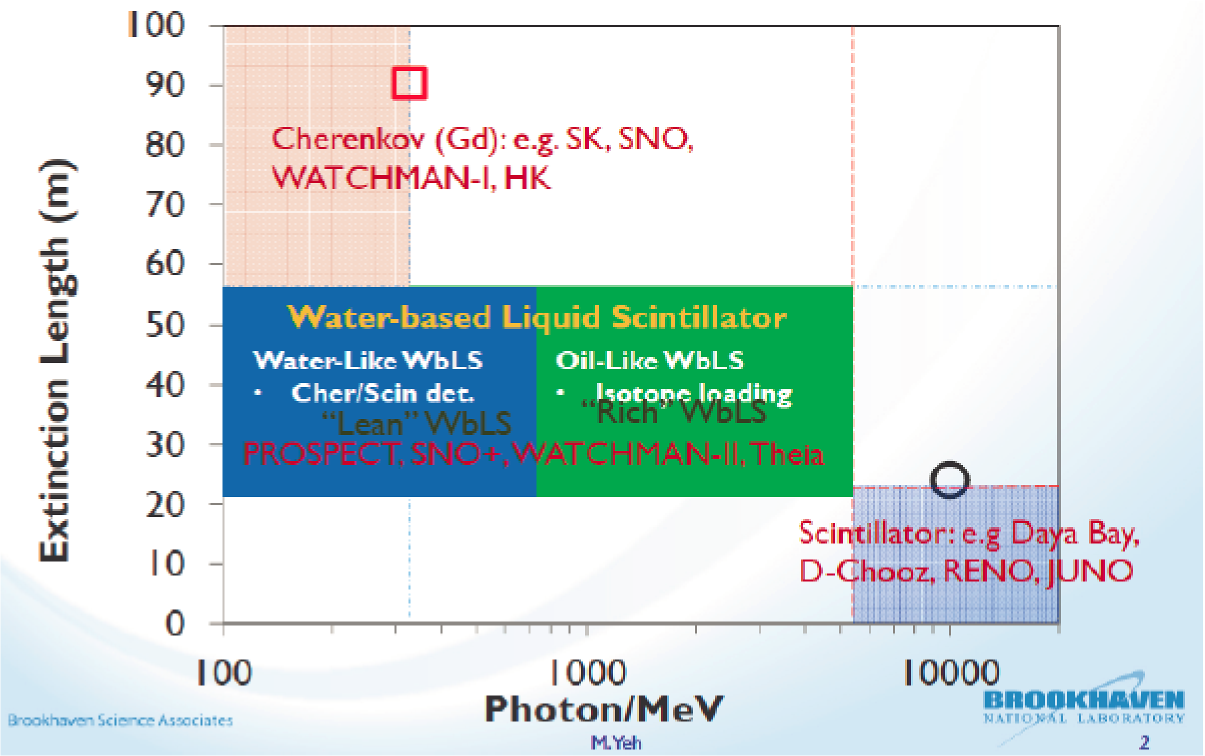
- 5σ exclusion of no ν_τ appearance after 1 month of data
- 10% precision in the ν_τ normalization after 6 months
  - Test of the unitarity of the ν mixing matrix

Water-based Liquid Scintillator Detector

Josh, Klein

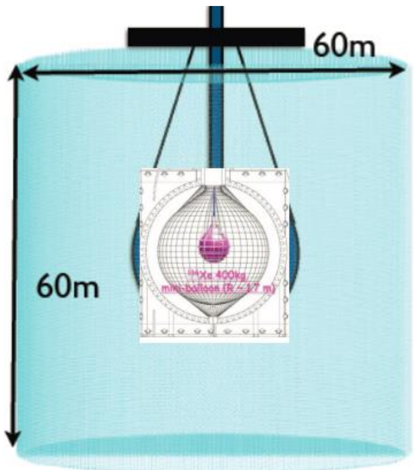
Physics	Size	Cherenkov Priority	Scintillation Priority	Cleanliness Priority
0νββ	~few ktonne	Medium	Very high	Very High
Low E Solar νs (< 1MeV)	~10 ktonne	High	Very high	Very High
High E Solar νs (> 1 MeV)	>50 ktonne	High	Low	High
Geo/reactor anti-νs	~10 ktonne	Low	High	Medium
DSNB anti-ns	>50 ktonne	Low	High	Medium
Long-baseline νs	> 50 ktonne	Very high	Low	Low
Nucleon decay (K+ anti-ν)	> 100 ktonne	High	High	Low

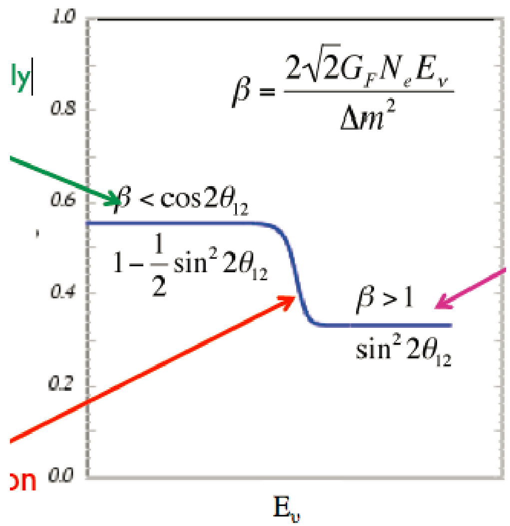
- Low-energy physics wants a clean detector with a lot of light
- High-energy physics wants a big detector with direction reconstruction

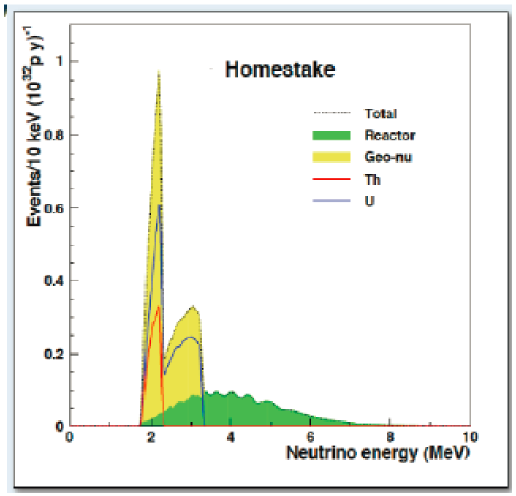


- Long attenuation length compared to scintillator=bigger detector
- Higher light yield=low threshold, good energy resolution
- High Cherlight/scintlight ratio makes directionality and background rejection possible

Plenty of physics possibilities







0νββ decay: a larger KamLAND-Zen (best limit so far)

Solar neutrino: need "statistics of Super-K with light yield of BOREXINO" to measure transition region

Geo-neutrinos

Supernova burst and diffuse

- **Nucleon decay**
- **Sterile neutrinos**
- **Long baseline program**
- **…**

Summary

- **Glorious history of Water Cherenkov and Liquid Scintillator detectors in the neutrino detection**
- **Future WC and LS detectors: larger, better**
- **Rich physics possibilities**
- **Technical challenges exist**