IFD2015

INFN Workshop on Future Detectors

16-18 December 2015 - Torino - Italy

Future large neutrino detectors

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Motivation

- **ν masses from ν oscillation are a clear signature of physics beyond SM** ➡ **access to very high new physics scale (M_{NP})**

$$m_\nu \simeq \frac{g}{M_{NP}}$$

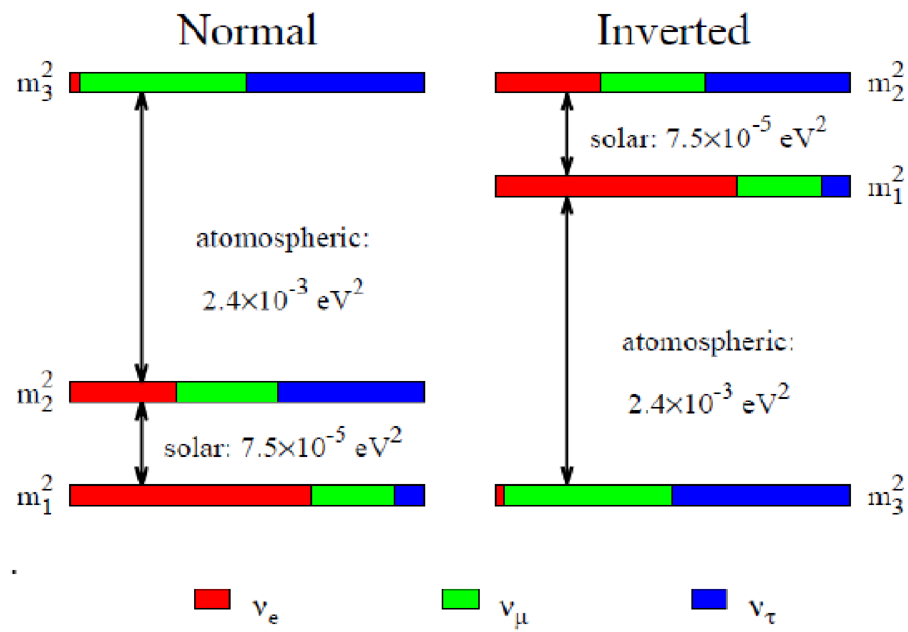
- Oscillation parametrized with neutrino mixing PMNS matrix + 2 mass differences

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}.$$

3 angles (θ_{12}, θ_{23}, θ_{13}) and 1 phase δ_{CP}

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta CP} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta CP} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta CP} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta CP} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta CP} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta CP} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta CP} & c_{23}c_{13} \end{bmatrix}.$$



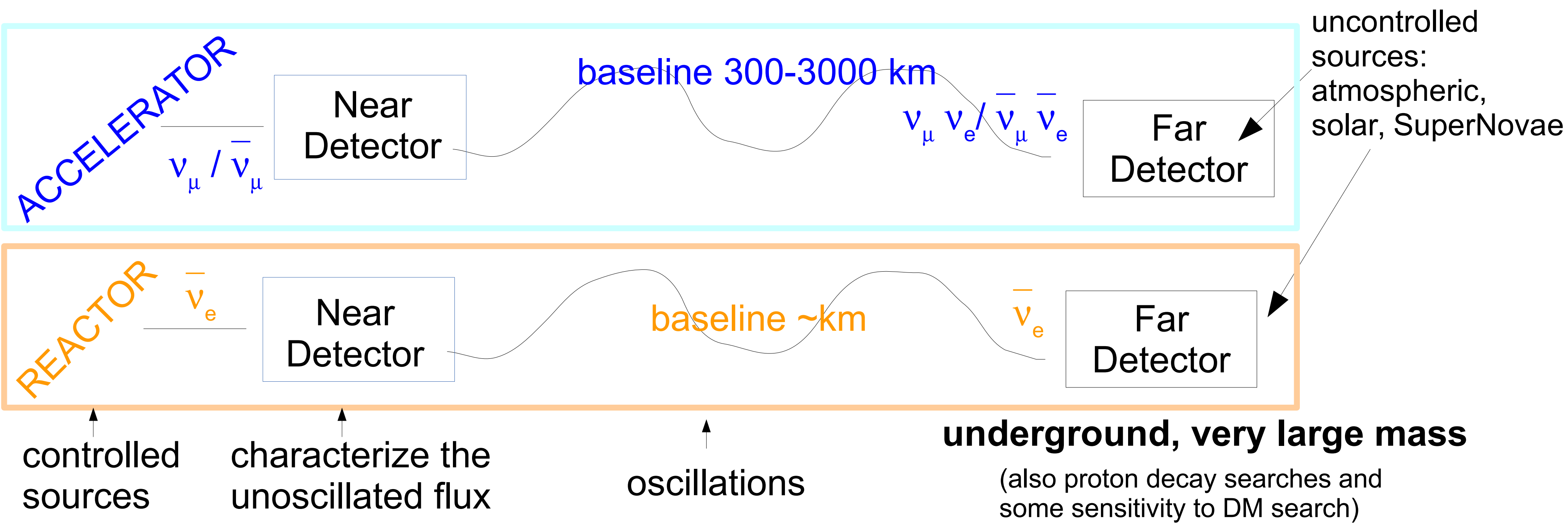
→ precise determination of parameters allow to constraint models explaining oscillation. Open questions:

- mass hierarchy (MH) ?
- θ_{23} maximal (> or <45deg) ?
- δ_{CP} ?

- **Not zero δ_{CP} would be first observation in CP violation in lepton sector!**

  → important piece of the puzzle of matter/antimatter asymmetry

Oscillation experiments



Measurements:

- $\bar{\nu}_e \rightarrow \bar{\nu}_e$ disapp. $\rightarrow \theta_{12}, \Delta m_{12}$ (Kamland: 180 km)
- $\nu_\mu \rightarrow \nu_\mu$ disappearance $\rightarrow \theta_{23}, \Delta m_{23}$
- $\bar{\nu}_e \rightarrow \bar{\nu}_e$ disappearance $\rightarrow \theta_{13}$
- $\nu_\mu \rightarrow \nu_e$ appearance $\rightarrow \theta_{13}$

  δ_{CP}
- $\nu_\mu \rightarrow \nu_\mu$ VS $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ disappearance

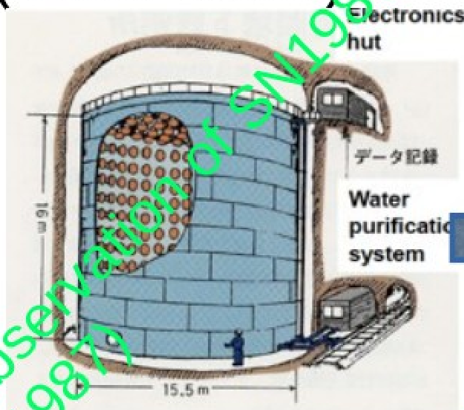
  $\nu_\mu \rightarrow \nu_e$ VS $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance

  δ_{CP}, MH

PRESENT	FUTURE
SuperKamiokande (T2K): water cherenkov	**HyperKamiokande (T2HK)**: water cherenkov
NOVA: plastic scintillator	**DUNE**: Liquid Argon TPC
Daya Bay, Double Chooz, RENO Gadolinium doped liquid scintillator	**JUNO:** doped liquid scintillator (50 km baseline $\rightarrow$ MH)

Water cherenkov ν detectors

Kamiokande
(1983-1996)



Observation of SN1987A
(1987)

3kton

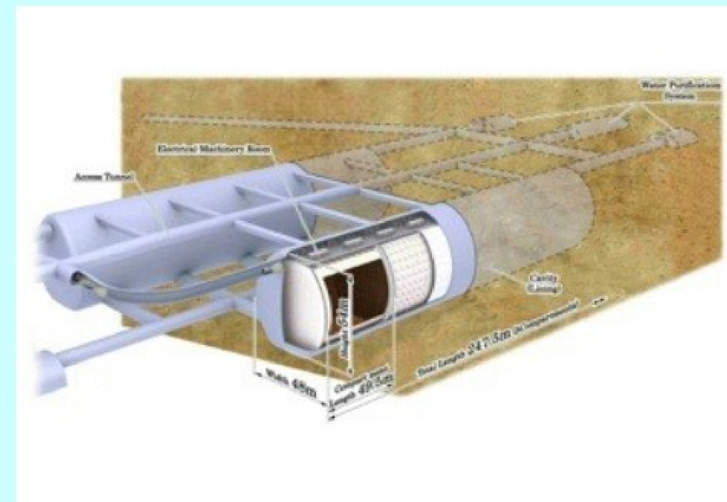
Super-Kamiokande
(1996-)

Discovery of neutrino oscillation (1998)

Observation of electron neutrino appearance
(w/ beam, T2K, 2013)

50kton

Hyper-Kamiokande
(202?-)



1Mton=1000kton

(560kton fiducial)

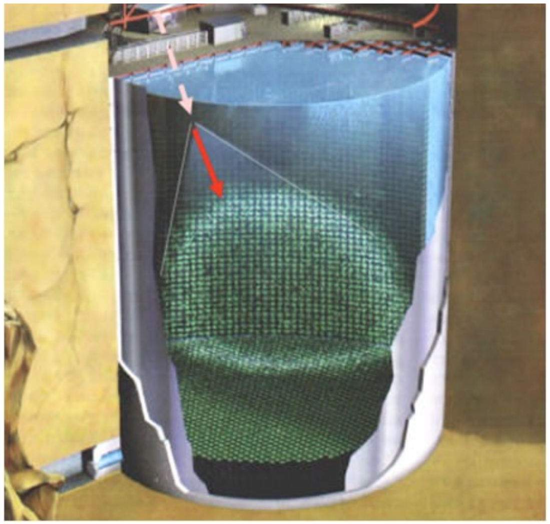
x17

x20
(x25 fiducial mass)

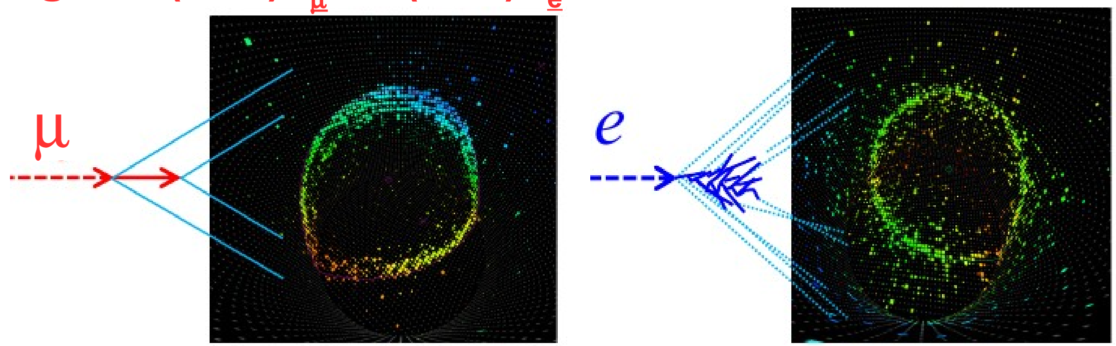
2

How does it work?

SUPERKAMIOKANDE



- **Signal: (anti)$\nu_\mu \rightarrow$ (anti)ν_e oscillation**



clear ring **fuzzy ring**

- Lepton momentum and angle → neutrino energy
- Select events with no outgoing pions (1 ring) (Quasi-Elastic interactions) $\nu n \rightarrow l^- p$ (outgoing nucleon undetected)

- **Backgrounds:**

- Outer volume with outward facing PMT to veto external background
- **PMT timing** to select beam bunches and reconstruct vertex position in fiducial volume

ν interactions from beam:

- intrinsic ν_e component in the beam
- pions: **$\pi^{+/-}$ undetected** and $\pi^0 \rightarrow \gamma\gamma \rightarrow$ e-like ring + **γ undetected**
- $\bar{\nu}$ oscillations: intrinsic ν component in the beam

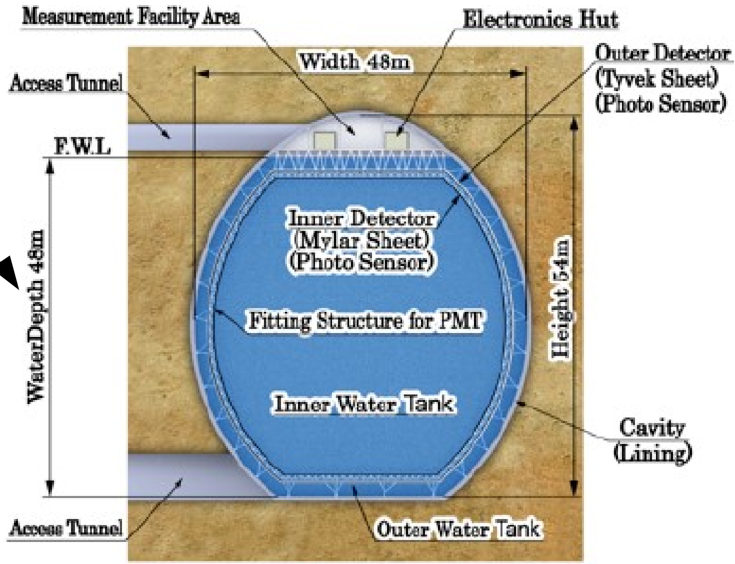
No magnetic field → no charge measurement ($\nu/\bar{\nu}$)

R&D: Gd doping to tag neutrons to distinguish: $\nu n \rightarrow l^- p$ from $\bar{\nu} p \rightarrow l^+ n$

HYPERKAMIOKANDE: Working to improve PMTs and on Gd doping.
Electronics and calibration system very similar to SuperK

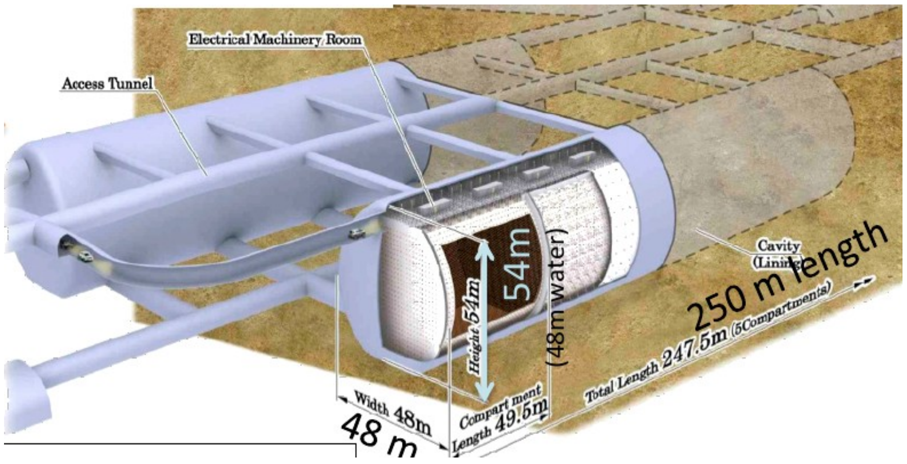
From SuperK to HyperK

		SuperK	HyperK
Total volume		50 kTon	990 kTon
Fiducial volume		22.5 kTon	**560 kTon**
Tanks		1 cylindrical 41.4m (h) x 39.3m (d)	2 egg-shape tanks 48m (w) x 50m (h) x 250m (l)
PMTs	inner detector	11.129	50.000
	outer detector	1885	25.000
Photocoverage		40%	**20%**
Sensor efficiency (Collection x Quantum eff.)		18% (22x80%)	**29%** (30x95%)



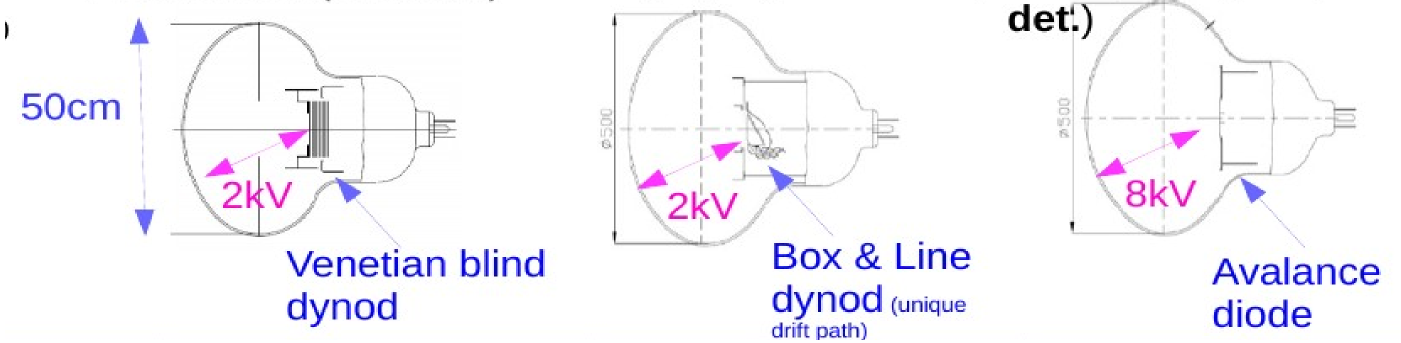
Tanks and PMT design under discussion:

- minimize risk due to pressure on PMTs (avoid cascade implosion as in SK 2001 incident)
- minimize cost (volume vs #PMTs)
- need PMT R&D (next slide)



R&D on PMTs

Lower Risk ⟷ Higher Performance

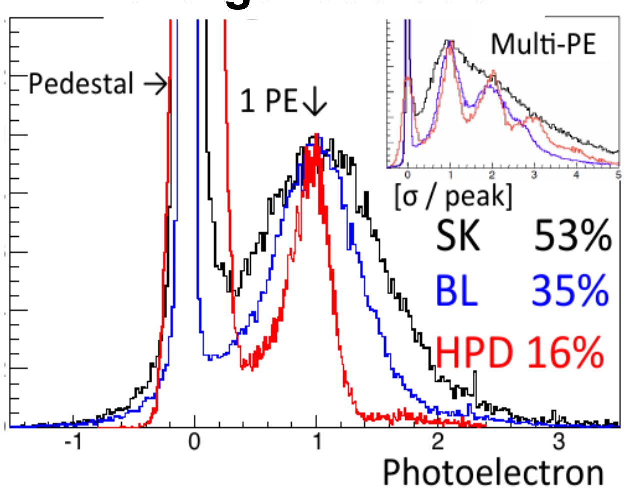


	Established (**SK PMT**)	R&D (**HighQE/CE PMT**)	R&D (**HighQE hybrid det.**)
Quantum Eff. (QE)	22%	30%	30%
Collection Eff. (CE)	80%	93%	95%
Timing resol (FWHM)	5.5 nsec	2.7nsec	1nsec

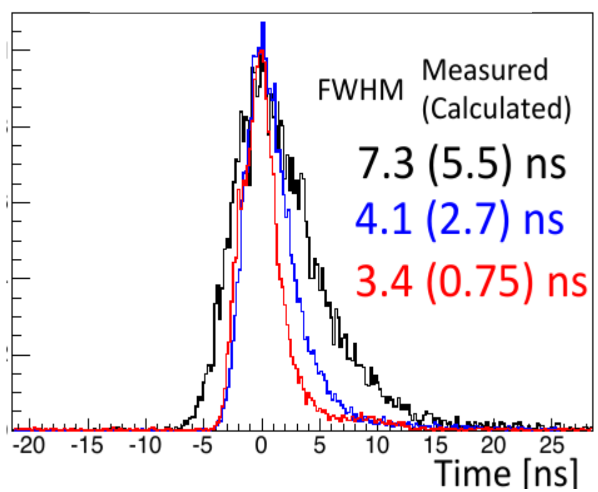
- Optimization should include **pressure resistance**
  possible to put protective cover → need precise control of glass quality

- Response to single photoelectron:

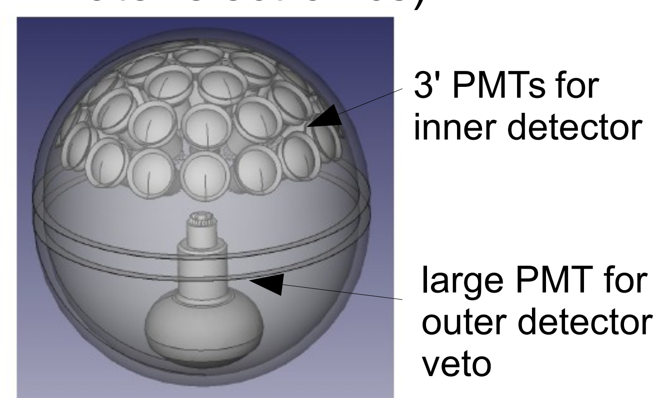
charge resolution



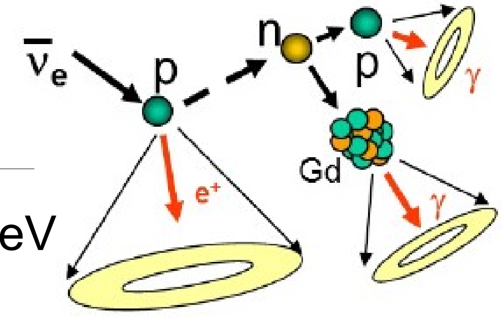
time resolution



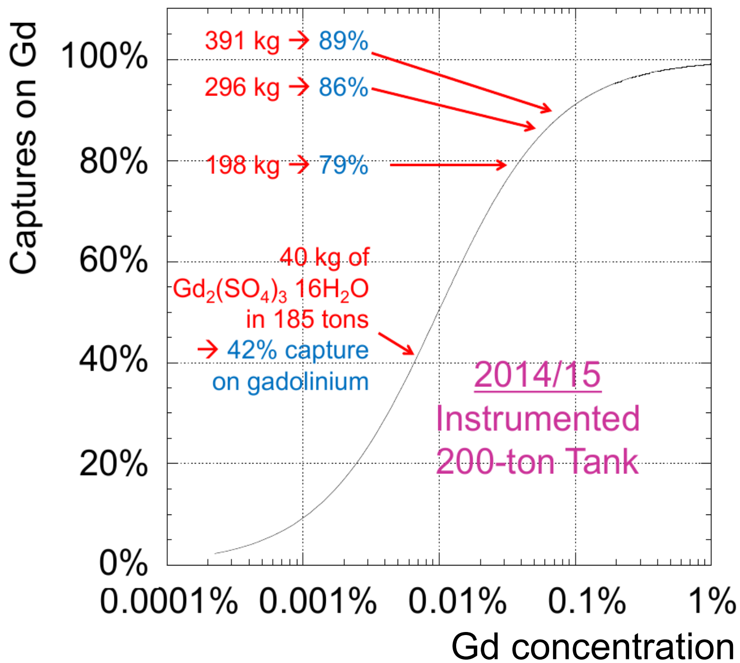
Integrated system of inner and outer PMTs under study (solve problems of pressure and in-water electronics)



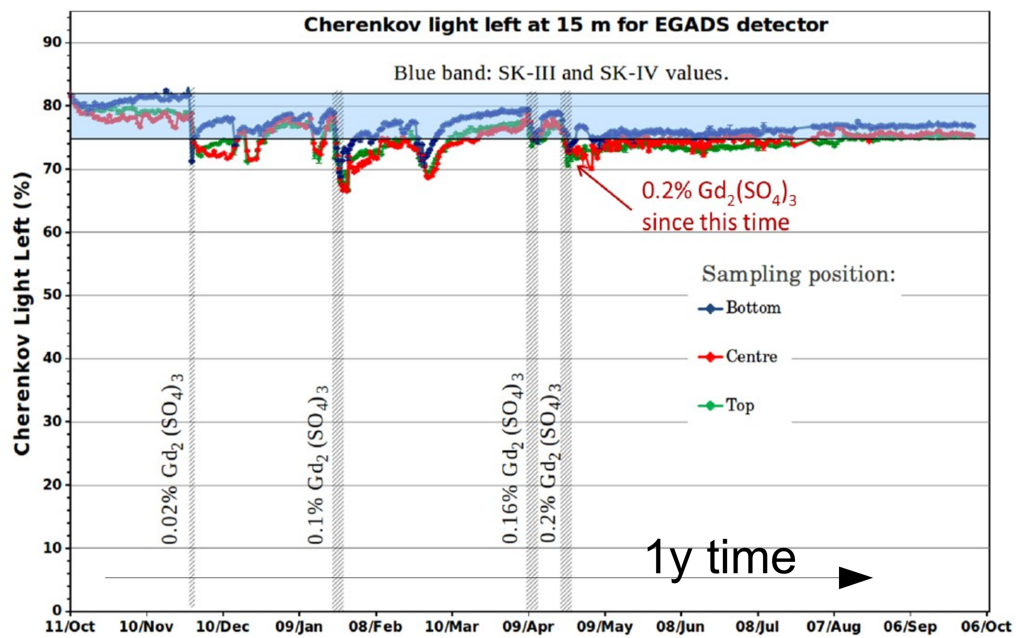
Gadolinium doping



- $\bar{\nu}p \rightarrow l^+n \rightarrow$ n get captured in Gd with emission of few γ ~8MeV
$\rightarrow$ for beam neutrino physics: ν vs $\bar{\nu}$ separation,
but also useful to enhance sensitivity to SuperNova ν and proton decay
- R&D studies (eg, WATCHMAN) as reactor monitoring
- **EGADS: 200 ton scale model of SuperK fully operative in Kamioka mine**



Neutron capture time tested with Am/Be source: data-MC perfect agreement



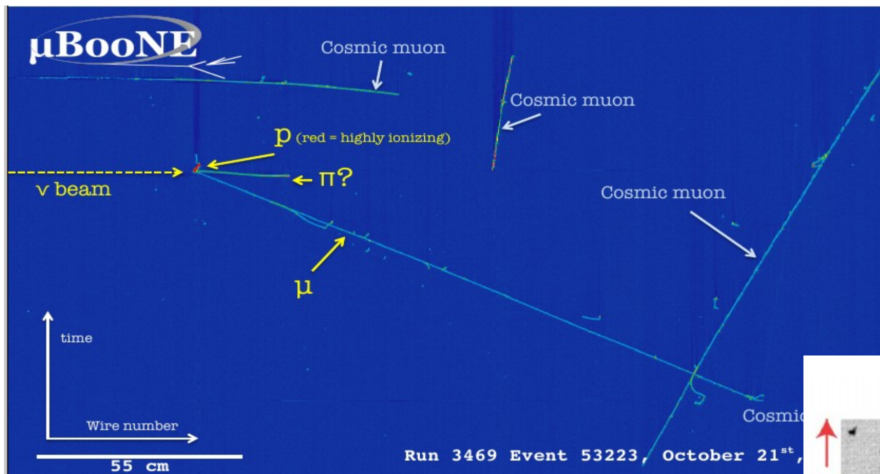
All the trick is about keeping water pure and transparent without loosing Gd (dedicated filtration system)

- SuperKamiokande will run with loaded Gd in next years!

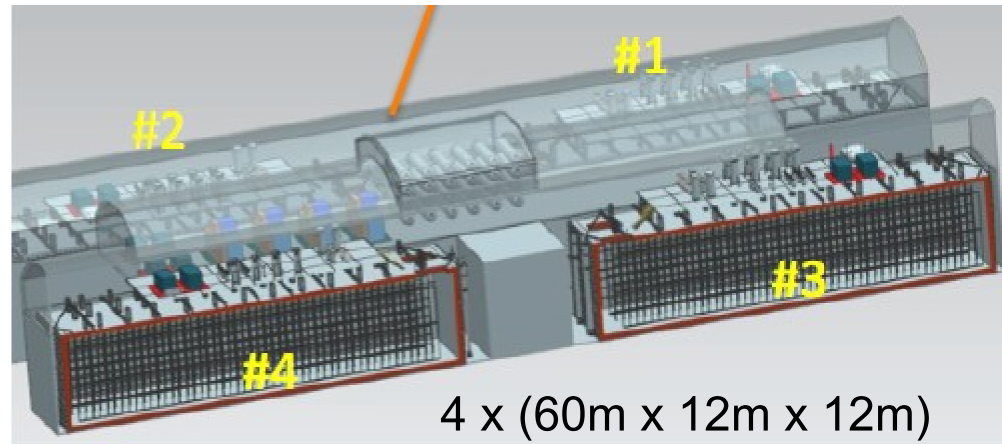
Liquid Argon technology

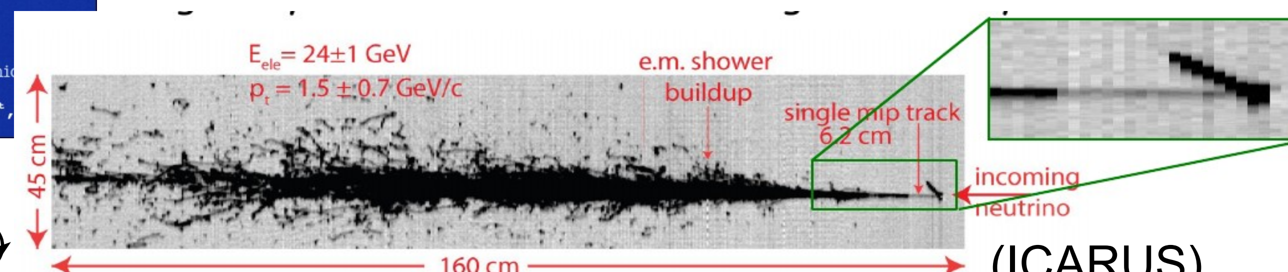
Ionizing particle in LAr → 2 measurements:

- **charge from ionization**
  → tracking and calorimetry
- **scintillation light** → trigger and t_0
  (drift time → third coordinate for non-beam events)



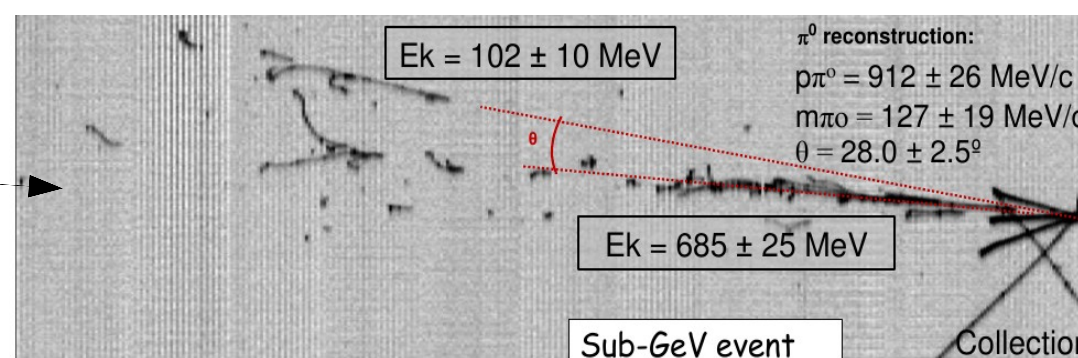
DUNE: staged approach with 4 modules of ~10kTon fiducial mass each



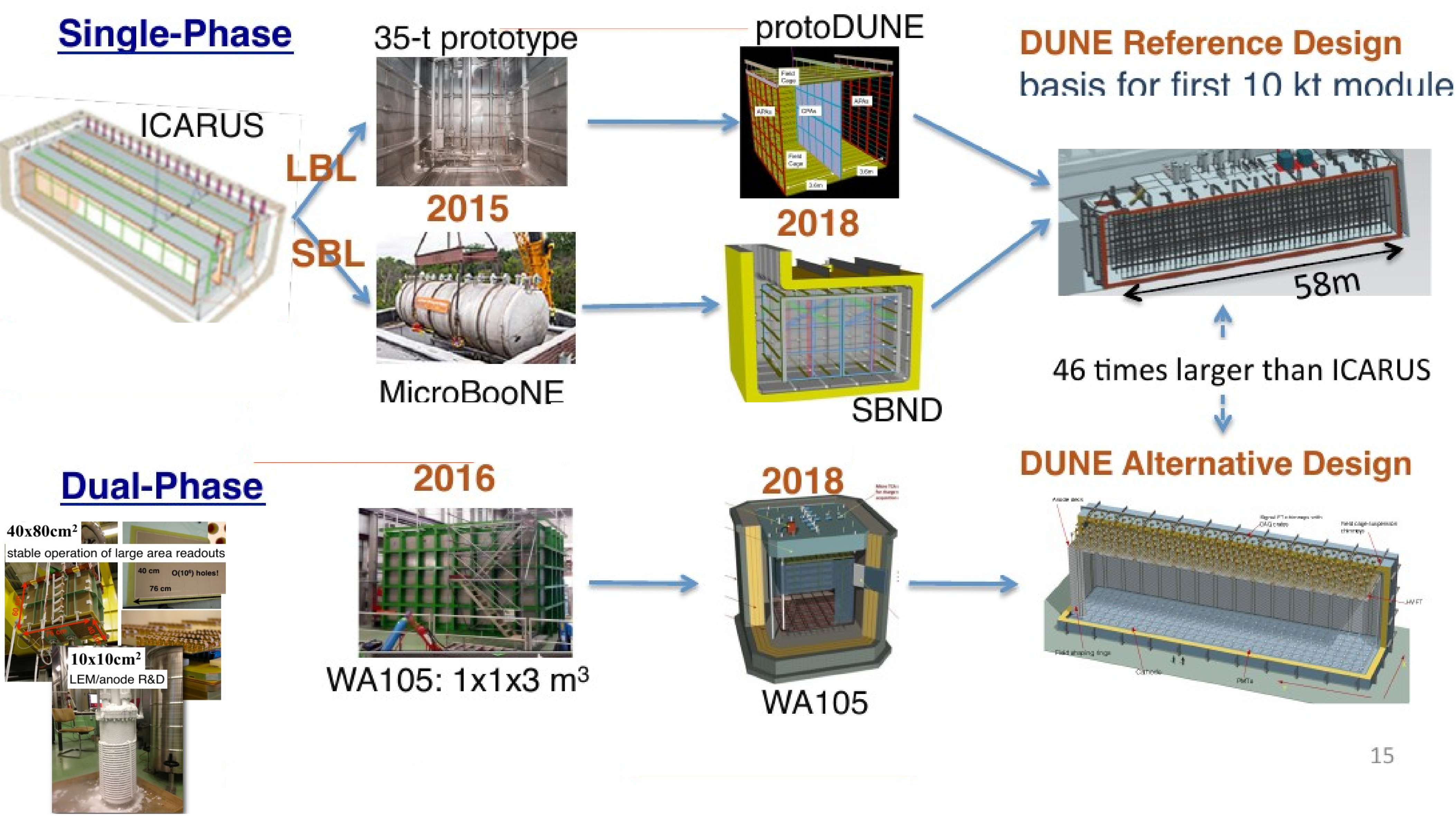


(ICARUS)

- μ track momentum from range
  (or from multiple scattering if not contained)
- PID from dE/dx
- Very good electron/γ ID and π^0 reconstruction
- Calorimetric energy from total collected charge (+ light)



Result of years of R&D

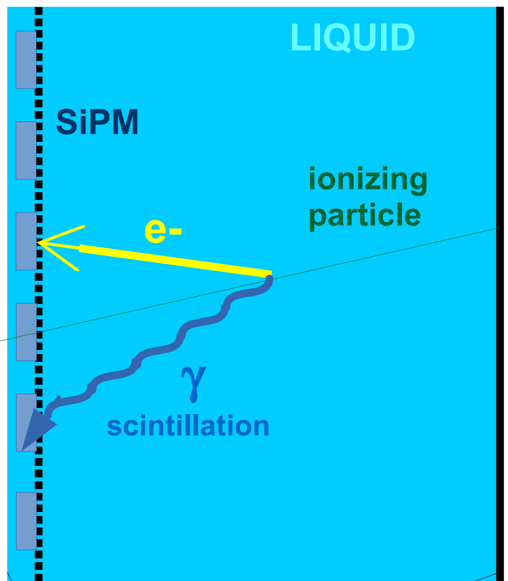


Single-phase VS Double-phase

- **Very long charge drift path → diffusion and attenuation**

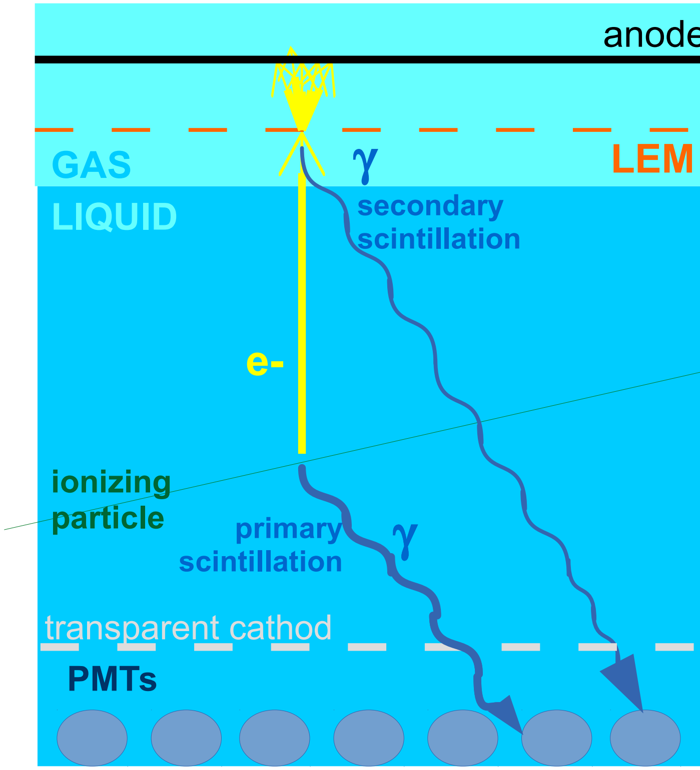
anode wires

cathode

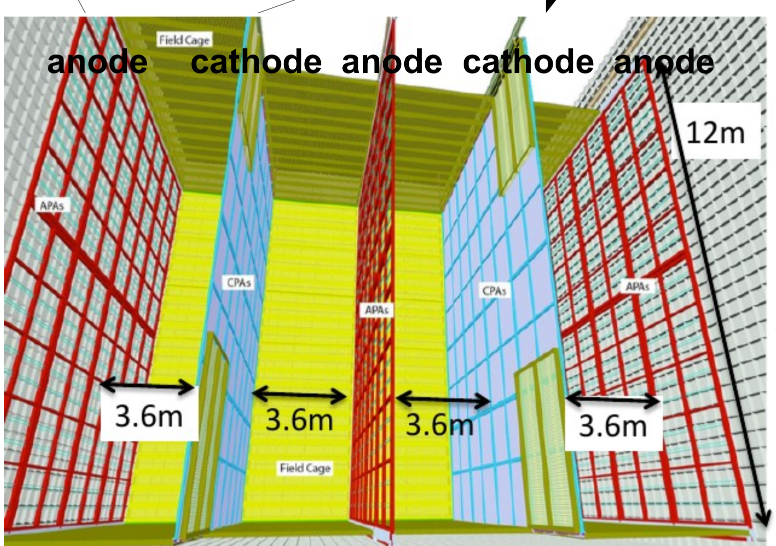


Single Phase charge readout
→ limited to short drift distances:
4 drift regions of 3.6m each

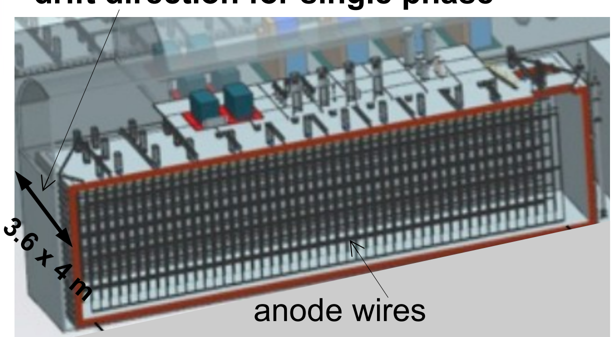
Double Phase charge readout



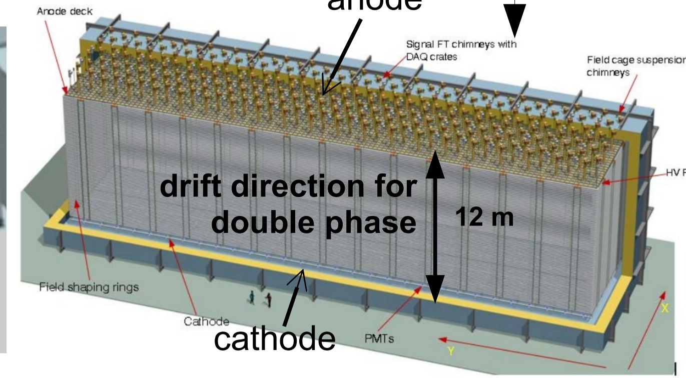
→ high signal/noise thanks to avalanche multiplication in gas



drift direction for single phase



anode

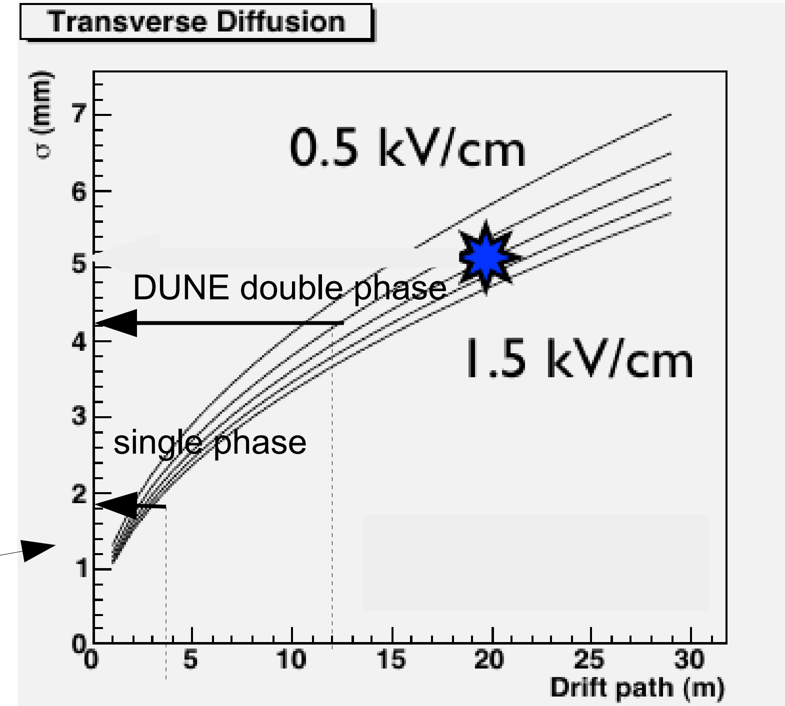


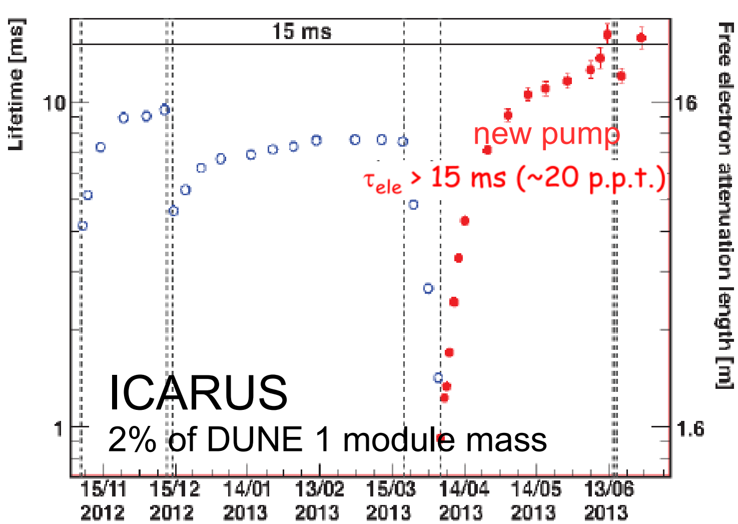
Charge signal

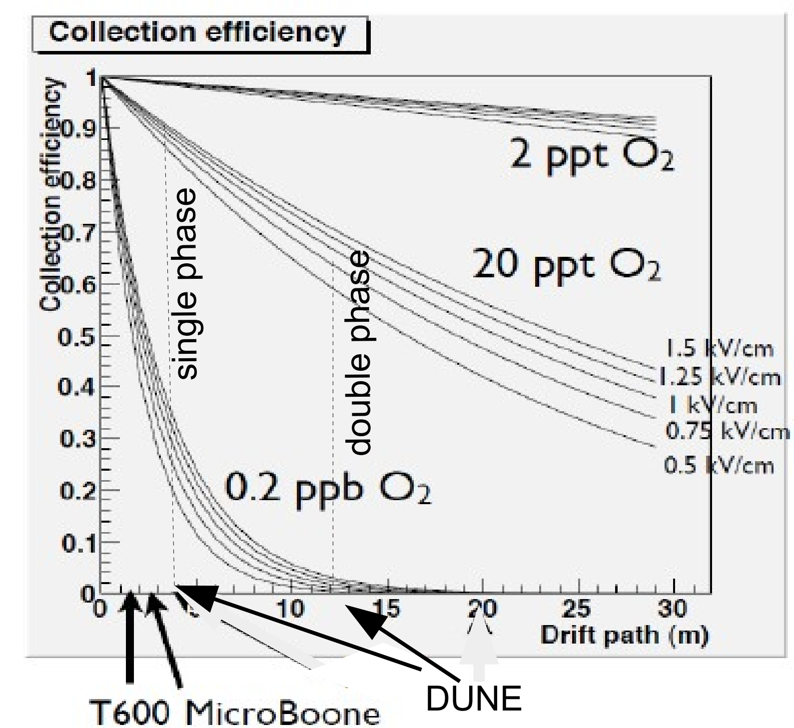
- W_e = 23.6 eV → mip produces ~ 100k e- per cm → 60k e- after recombination
- dirft velocity ~mm/µs (→ total drift time ~10 ms)

- **Very long drift path → diffusion and attachment**
  - diffusion ~few mm with 1-0.5 kV/cm (→ pitch readout few mm)
  - O_2 pollution captures ionization electrons → charge attenuation

  (→ impurity ~20 ppt O_2 needed)

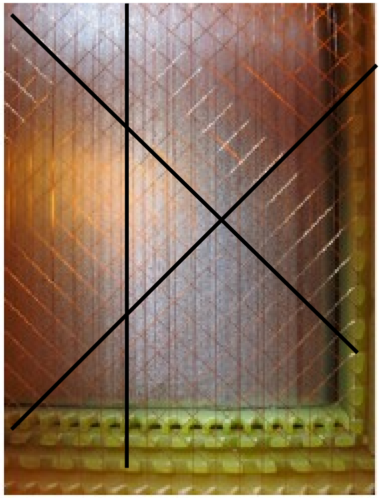


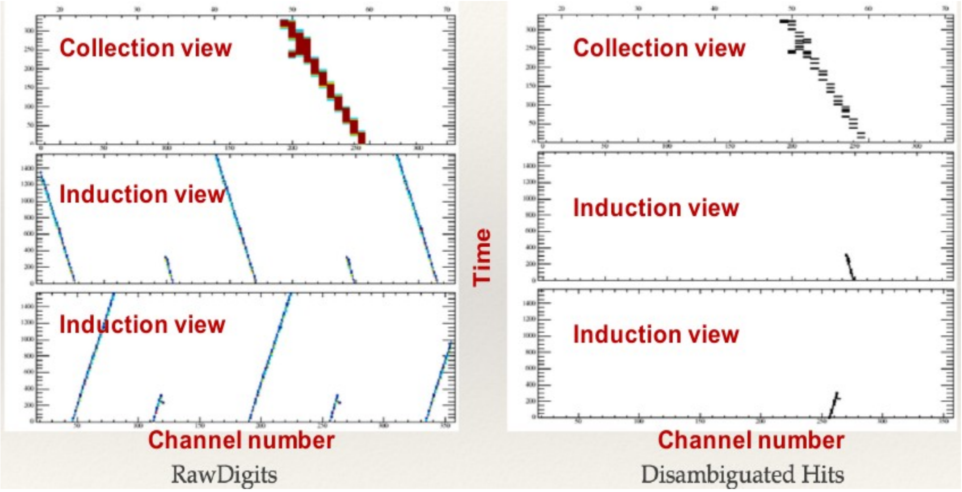




Charge readout plane (CRP)

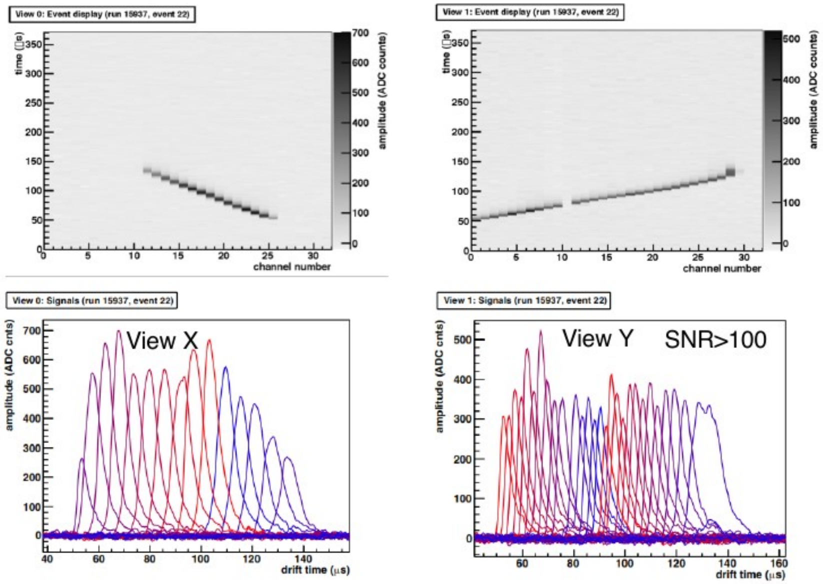
- **Single Phase**
  - no gain
  - 3 views
  - uniform CRP design

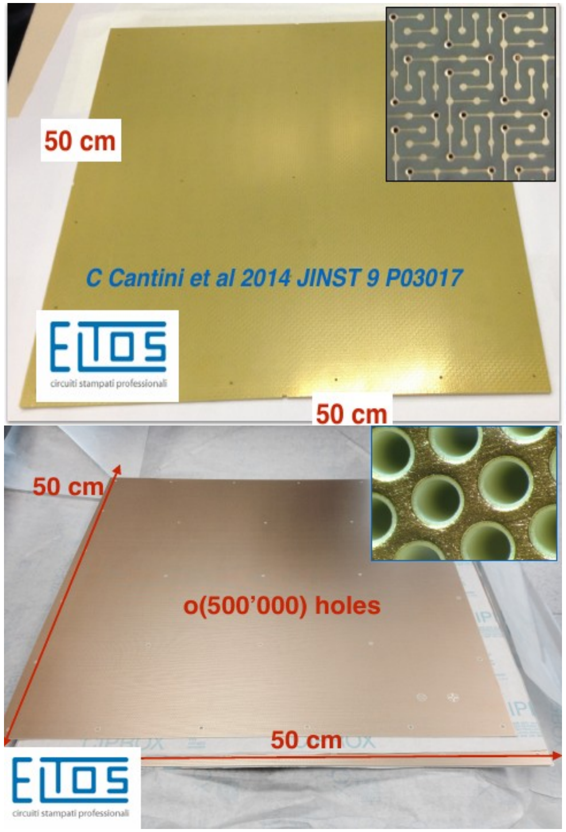


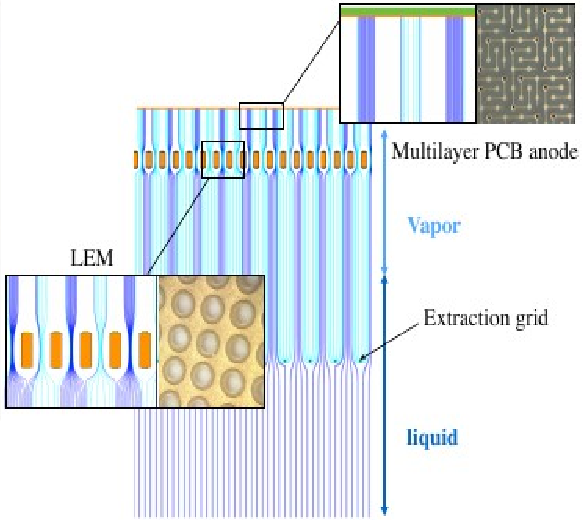


- **Double Phase**
  - stable gain of 20 on 10x10cm LEM
  - 2 views (x,y) of equal quality
  - to scale up: CRP segmented in 50x50cm modules

Cosmic event in double phase TPC at effective gain~20







Many other challenges

- **scintillation light:** single phase: first test of wavelenght shifting bars to SiPM integrated with a TPC

  double phase: standard PMTs (with coating),

- **high voltage on large surfaces:** cathode-anode ΔV ~few hundreds V (double phase)

  ~180 V (single phase)

- **large number of channels**

  → electronics in gas accessible only in double phase design

  → calibration and uniformity

  (eg: flattening of cathode and of charge readout plane, E field between different modules of charge readout ...)

- **software for automatic reconstruction**

  huge amount of info (efficient zero suppression)

- **LAr TPC as calorimeter**

  fully omogeneus with very low threshold

  very good resolution and detailed tracking inside shower → potential to improve shower models!

ICARUS:

- Low energy electrons: $\sigma(E)/E = 11\%/\sqrt{E(MeV)}+2\%$
- Electromagnetic showers: $\sigma(E)/E = 3\%/\sqrt{E(GeV)}$
- Hadron shower (pure LAr): $\sigma(E)/E \approx 30\%/\sqrt{E(GeV)}$

Water Cherenkov vs Liquid Argon

- Hyperkamiokande much more sensitive to CP violation while DUNE much more sensitive to Mass Herarchy (see backup).

But sensitivities depend on assumed beam power, detector mass and on baseline.

- Comparison of technologies:

WATER CHERENKOV

- well known and solid technology
- very large mass (~MTon)
- info only about particles above Cherenkov threshold

→ model dependent assumptions to reconstruct E_ν

→ no need of precise E_ν shape: **mainly a counting experiment**

LIQUID ARGON

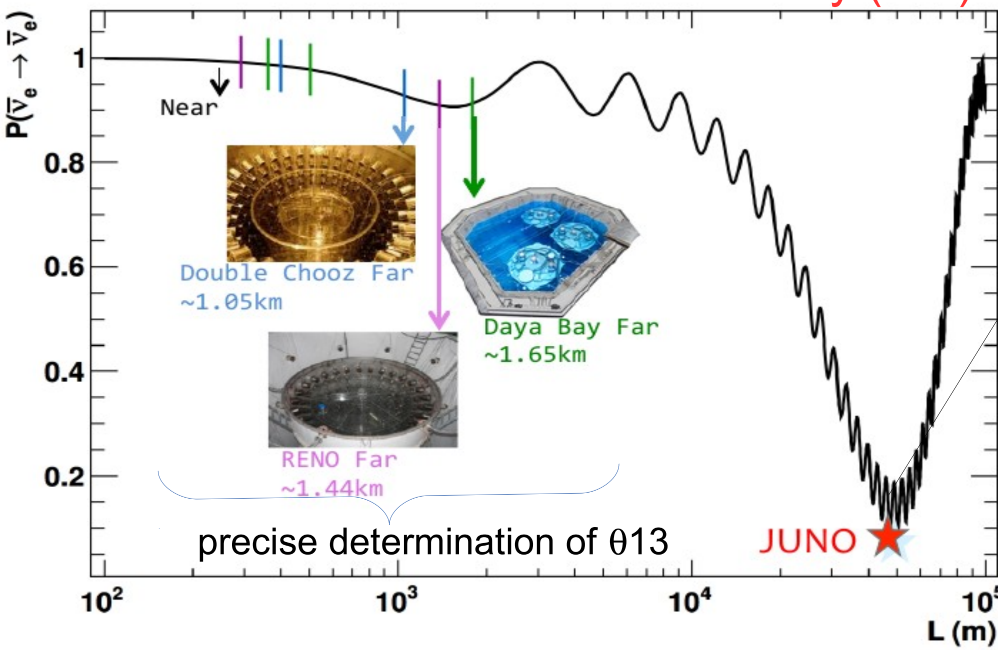
- successfull R&D → first very large scale realization
- size limited by drift length (~40KTon)
- full reconstruction of tracks and showers down to very low threshold, very good particle ID

→ precise E_ν shape accessible and needed for good sensitivity

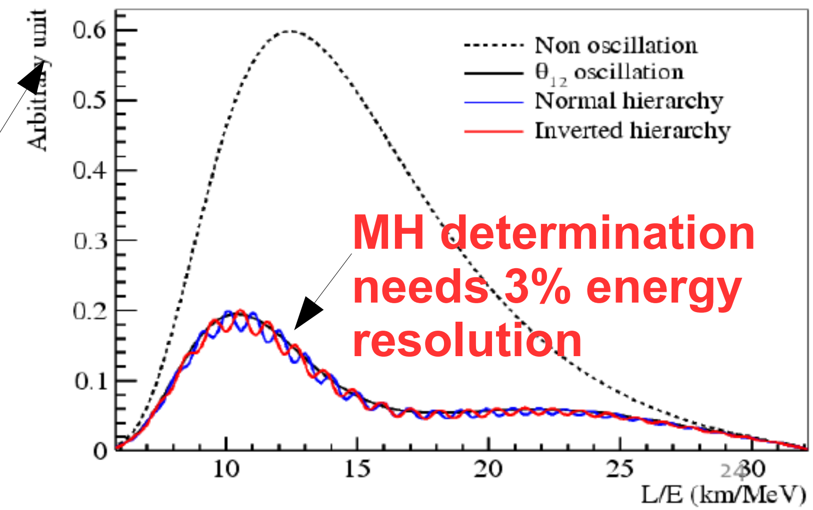
→ **need to reach very good control on detector calibration/uniformity and on neutrino interaction modelling**

JUNO concept

- **New attempt:** use $\bar{\nu}_e$ disappearance from reactors to measure mass hierarchy (MH)



MH corresponds to a change of phase in the oscillation



- $\bar{\nu}_e$ detected through inverse beta decay:

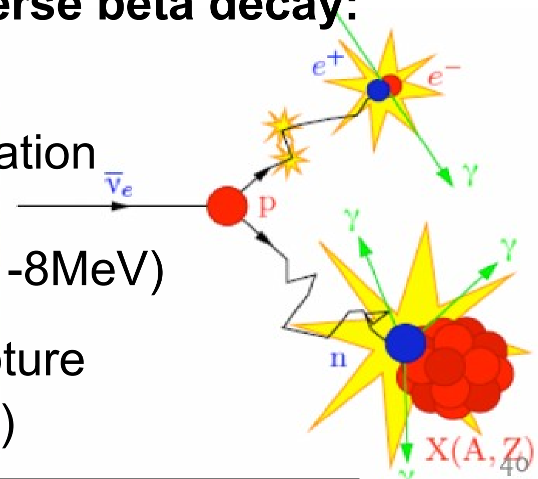
  $\bar{\nu}_e p \to e^+ n$

  - prompt γ from e^+ ionization and annihilation

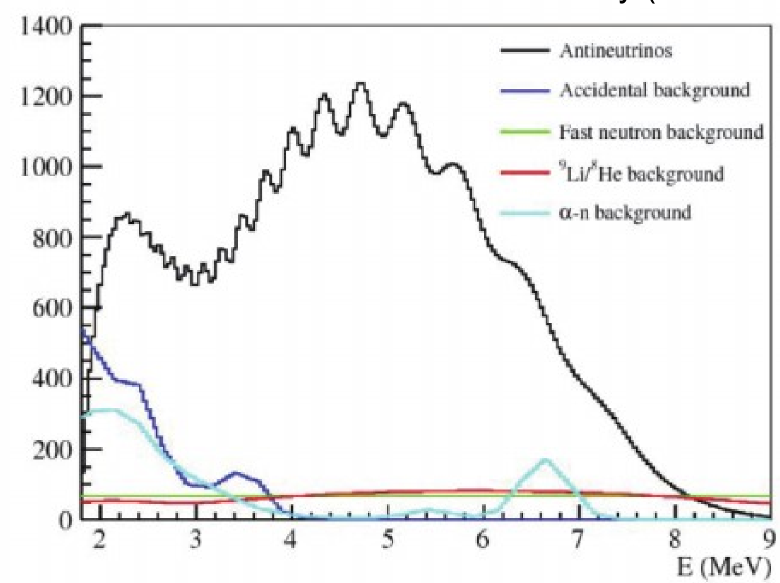
    $E_{VIS} = E_\nu - (M_n - M_p) + m_e$ (1-8MeV)

  - delayed γ's from n capture

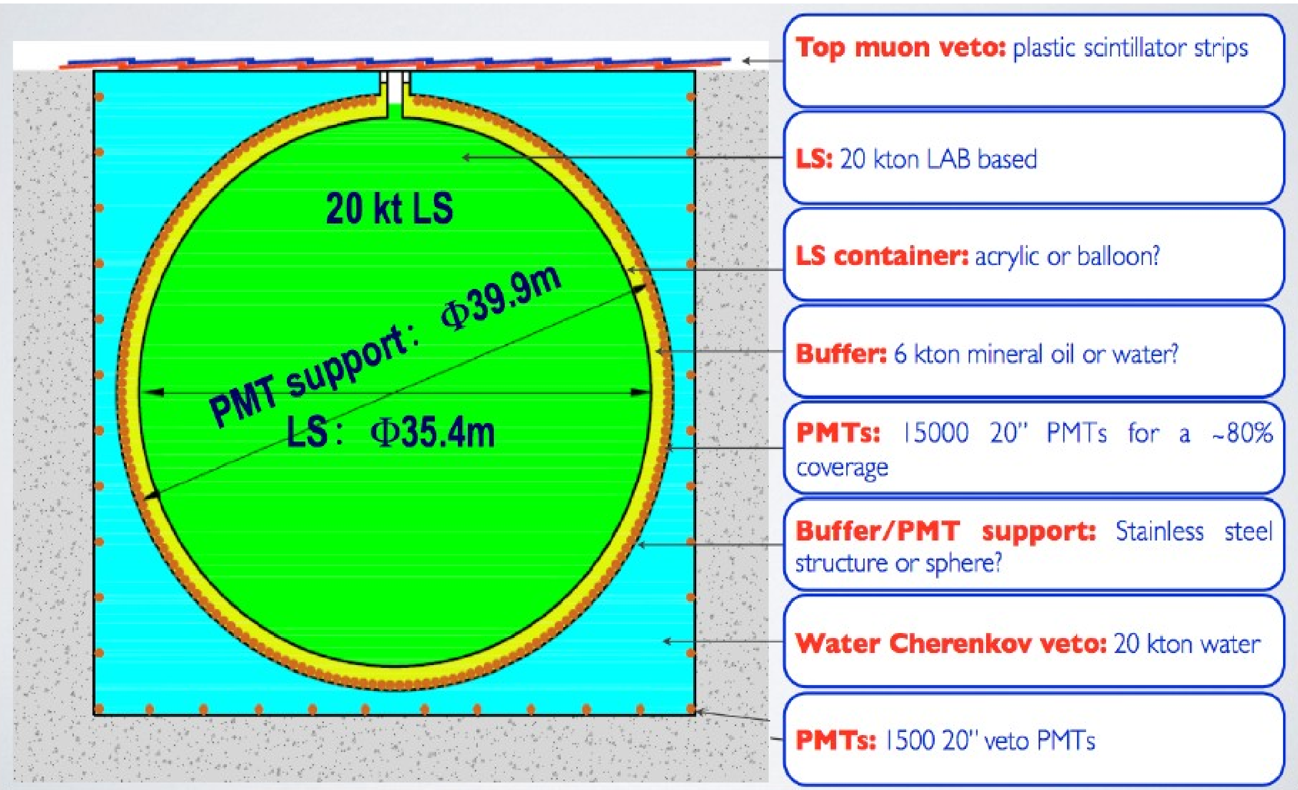
    (Δt~200μs, E=2.2MeV)



IBD events before selection: ~80/day (eff~83%)



JUNO requirements



	KamLAND	Borexino	Daya Bay	JUNO
Mass [t]	~1000	~300	~170	20000
Energy resolution	6%/√E	5%/√E	7.5%/√E	3%/√E
Light yield [p.e./MeV]	250	500	200	1200

$$\frac{\sigma}{E_{vis}} = \sqrt{\boxed{\frac{a^2}{E_{vis}}} + \boxed{b^2 + \frac{c^2}{E_{vis}^2}}}$$

< 3% @1MeV

1) stochastic term 2) non-stochastic term (systematics)

1) Large **light yield**:
10000 pe/MeV created

- attenutation length >20m
- photocoverage 80%
- detection efficiency 35%

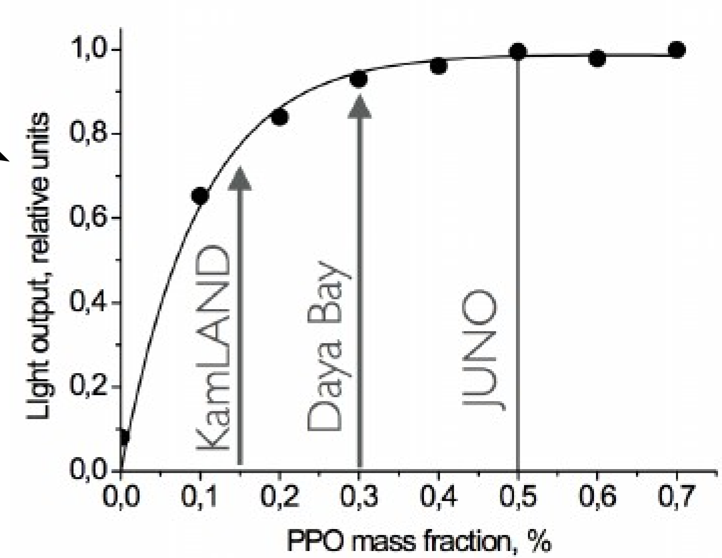
→ detected 1200 pe/MeV

2) **Non-uniformity and linearity** (geometry, electronics, noise...) **need to be 6 times better than Double Chooz**

Stochastic term

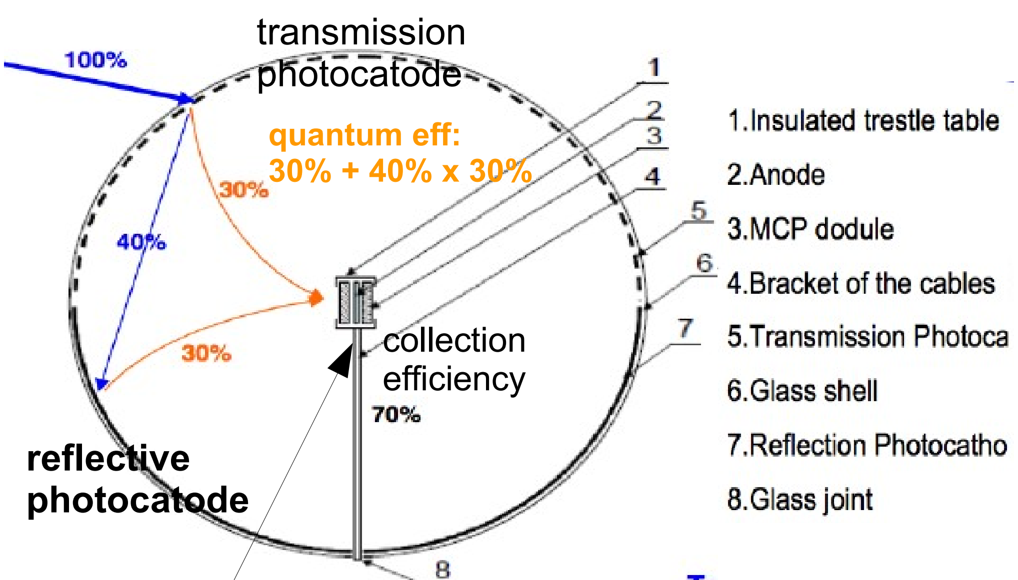
- Increase light yield

  liquid scintillator with increased doping and better purity (→ attenuation length 25 m atteined in lab.)



- 15k PMTs with detection efficiency (quantum eff x collection eff) ~35%

  R&D on PMTs with 4π acceptance



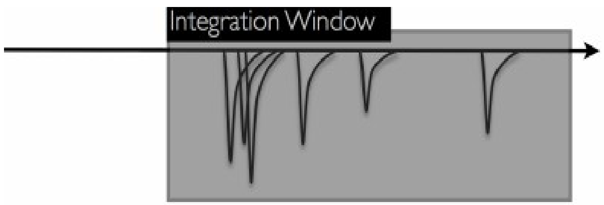
to collect electrons from all directions: Microchannel plates (instead of dynode chain)

(still in R&D phase)

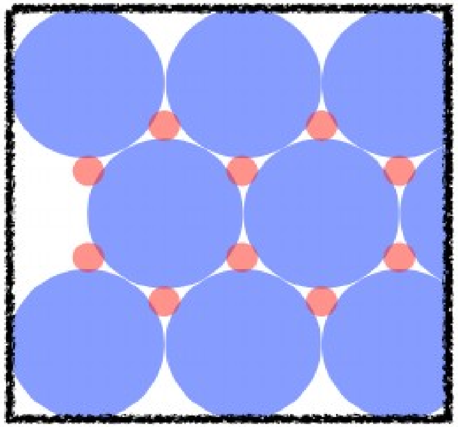
	8" MPC-PMT	20" MPC-PMT
photocathode uniformity	✓ (under investigation→ quantification)	
QE⊗CE estimation	~25% ✓ (goal→ ~35%)	~22% ✓ (goal→ ~35%)
CE estimation	~60% (goal→ ~80%)	
MPC status	✓	✓
gain	10^7 @ ~2kV	
single-PE (P/V)	~2.5 (→improving)	~1.7 (goal→>2.5)
linearity studies	better than dynode-PMT (→ MPC)	
dark noise rate	$O(5k\ s^{-1})$	$O(50k\ s^{-1})$

Non-uniformity and non-linearity

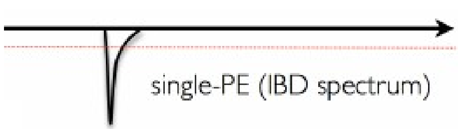
- Beyond electronics and noise, there is an **intrinsic non uniformity** in a huge volume with very large light yield:
  - the light yield per PMT change by a factor of 100 between events in the center and near the edges
  - events near the edge may give up to 100 pe/PMT → energy estimation via charge integral become very complicated with 100 signal superimposed



- Detailed system of radioactive sources deployment for calibration
  - sources only up to 5 GeV
  - very difficult to map all the huge volume (especially near edges)



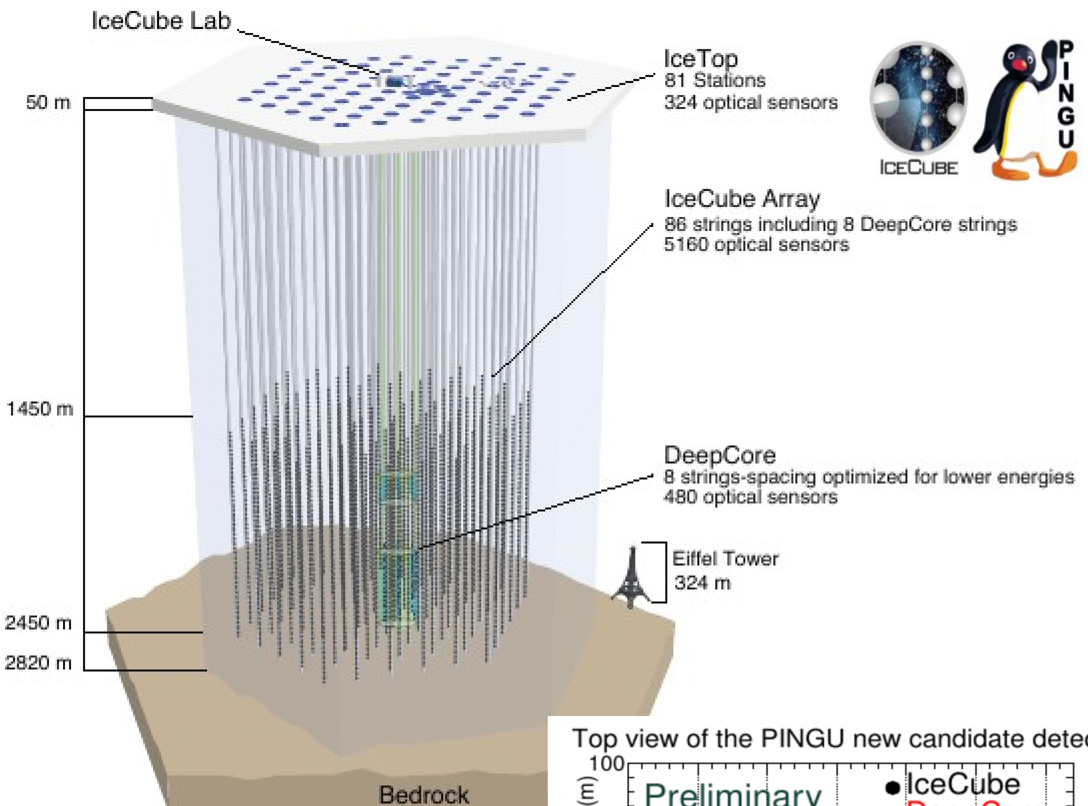
- Adding 3' small PMTs in the space between large PMTs
  - much smaller light yield: 10% coverage → 50pe/MeV → <4 pe/PMT → energy via photon counting

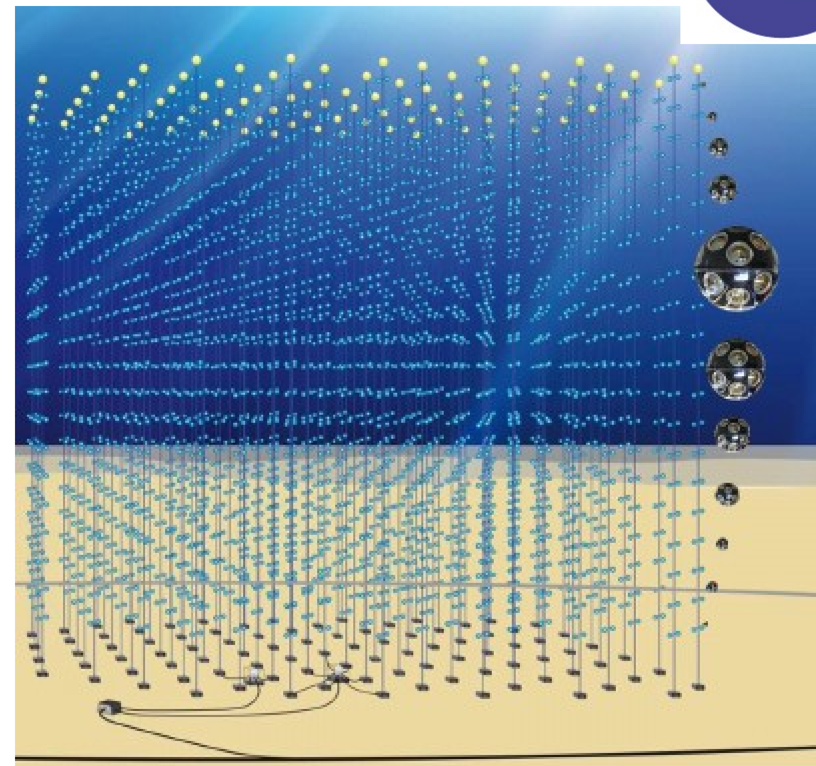


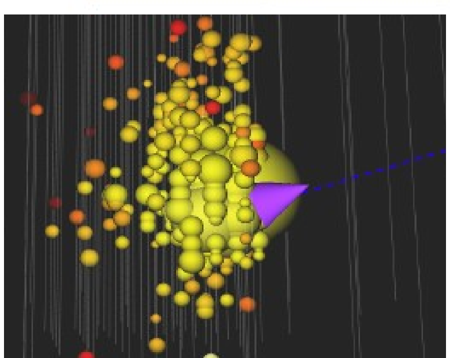
  - larger stochastic term but same response also for high energy events and events near border
  - during source calibration campaign cross-check uniformity and linearity with small PMTs (possibility of x-checking ev. by ev. under study)

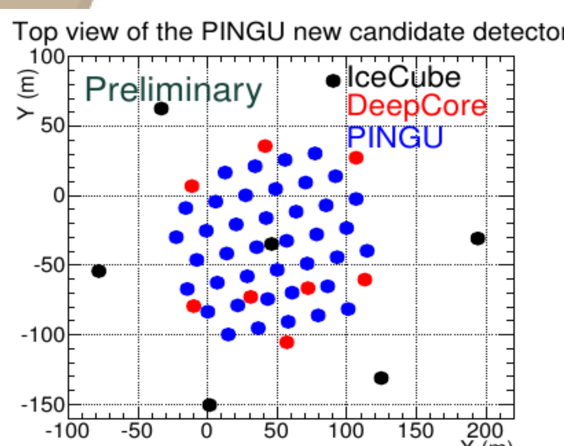
PINGU/ORCA

Huge volume in South Pole ice (PINGU) or in Mediterranean sea (ORCA) instrumented with PMTs









The KM3NeT Digital Optical Module.

Summary

- **Target: measurement of neutrino oscillation parameters → focus on MH and δ_{CP}**

- **Working on 3 technologies:**
  - **water cherenkov** : **HK** ~25 times SK(mainly limited by cost of civil engeneering given the huge size)
    → increase PMT light collection to minimize number of PMTs
    → possibly Gd doping
    (water Cherencov in sea or ice)
  - **LAr** (DUNE): scale up to large volumes and large charge readout surface
  - **liquid scinitillator** (JUNO): unprecedented energy resolution to measure MH at reactors

- Other experiments and R&D:
  water based liquid scintillators (beyond Gd)
  SNO+
  double beta experiments ...

IFD2015

INFN Workshop on Future Detectors

16-18 December 2015 - Torino - Italy

BACKUP

Future large neutrino detectors

50cmΦ Photosenor Candidates

By Hamamatsu Photonics K.K.

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

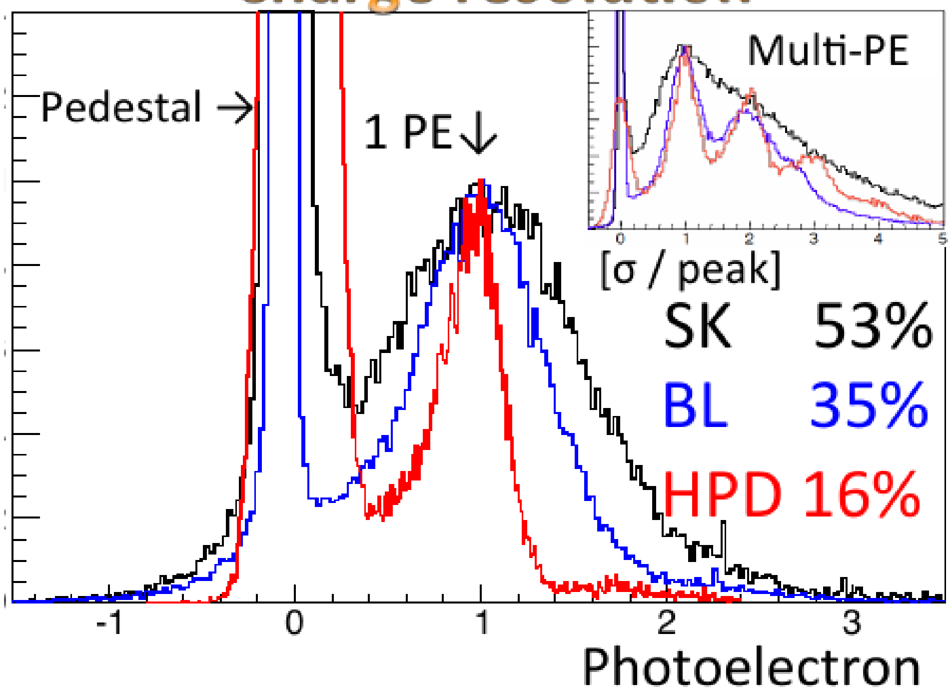
Model	R3600 (Established)	R12860	R12850 † still in R&D
Amplification	Venetian blind dynode	Box and line dynode	20mmΦ Avalanche diode
Q.E.	~22% (or ~30% in HQE)	~30%	~30%
C.E. Φ46 (Φ50)	67% (61%)	95% (85%)†	93% (76%) w/ 5ch AD†
T.T.S. (FWHM)	5.5 ns	2.7 ns	0.75ns (w/o Preamp.)
Bias voltage	2 kV bias	2 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

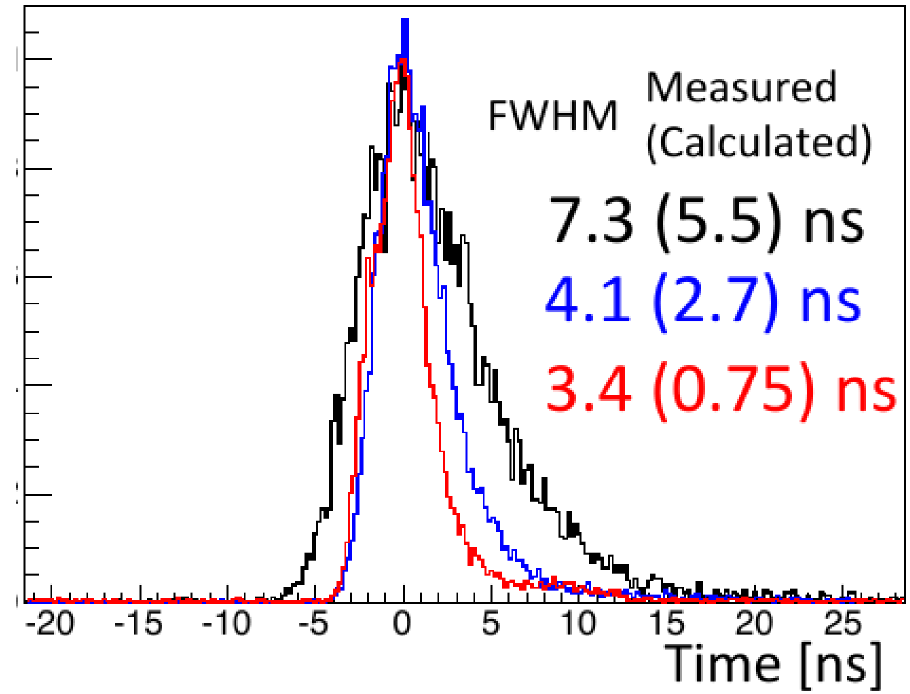
1 PE Detection in 50cmΦ Photodetector

Results shown in NNN14

Charge resolution



Time resolution



	Charge σ / peak	Time σ (left)	Time FWHM
Super-K PMT	53%	2.1 ns	7.3 ns
Box&Line PMT	35%	1.1 ns	4.1 ns
HPD (w/5mmΦ AD†)	16%	1.4 ns	3.4 ns
(20cmΦ HPD)	(12%)	(1.1 ns)	(3.3 ns)

More details will be reported by D.Fukuda in poster presentation.

† 20mmΦ Avalanche Diode in final design with full efficiency

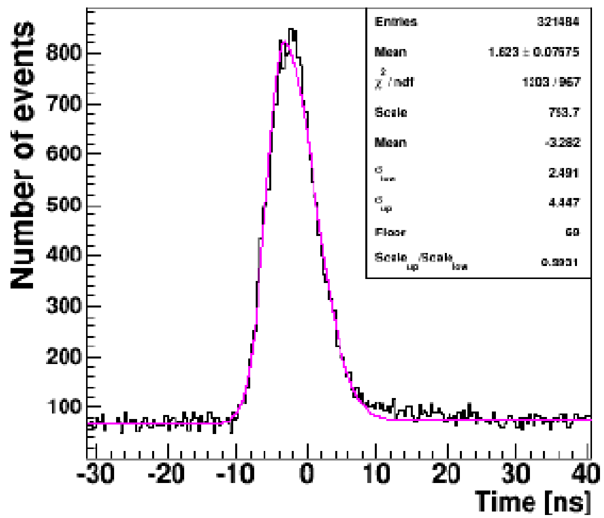
w/ preamplifier (intrinsic resolution is better, less than 1ns)

Single p.e. charge and time resolutions are better for both new photodetectors.

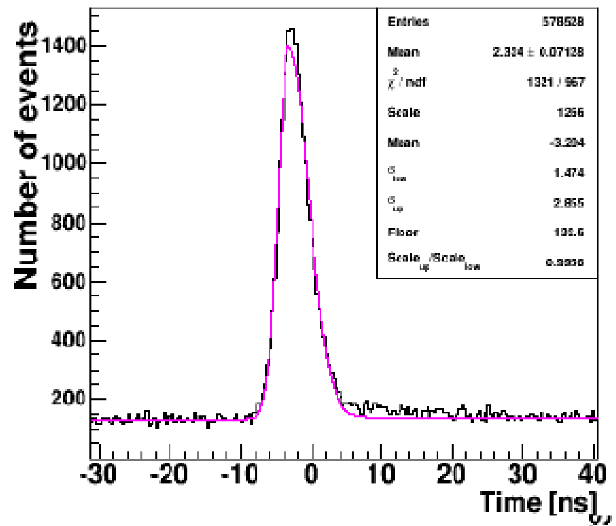
Single PE Time in Water

Transit Time Distribution

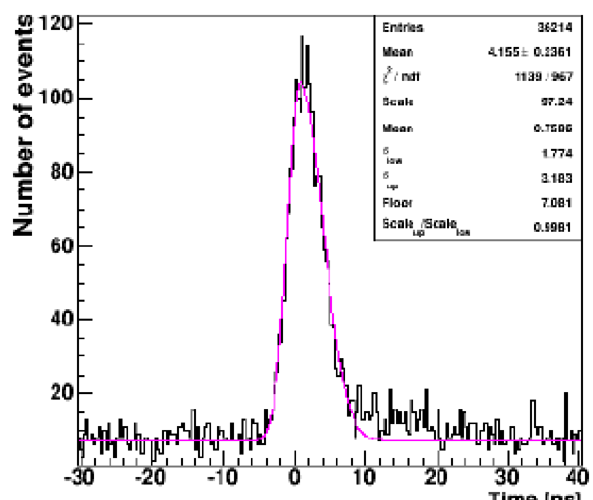
HQE SK PMT



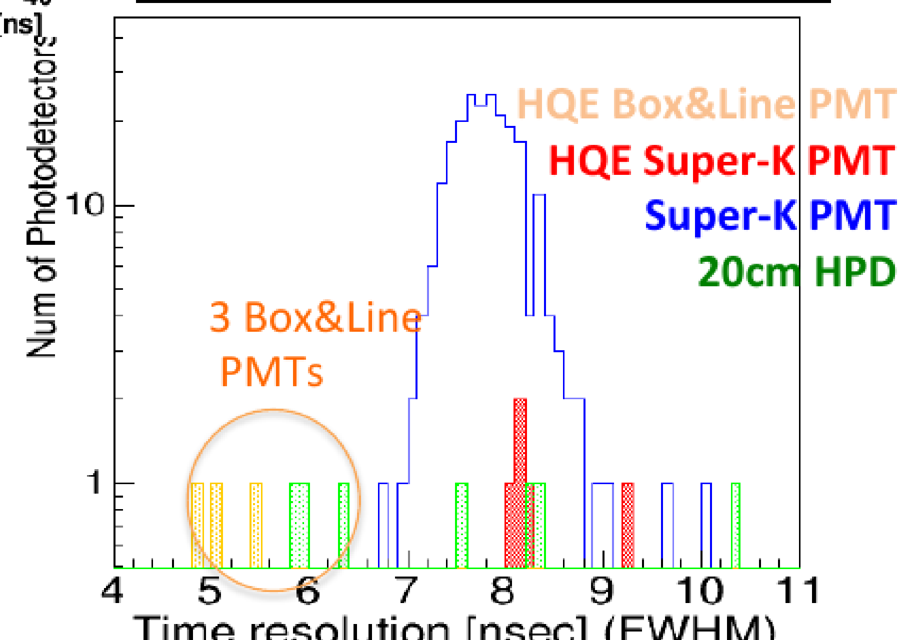
HQE Box&Line PMT



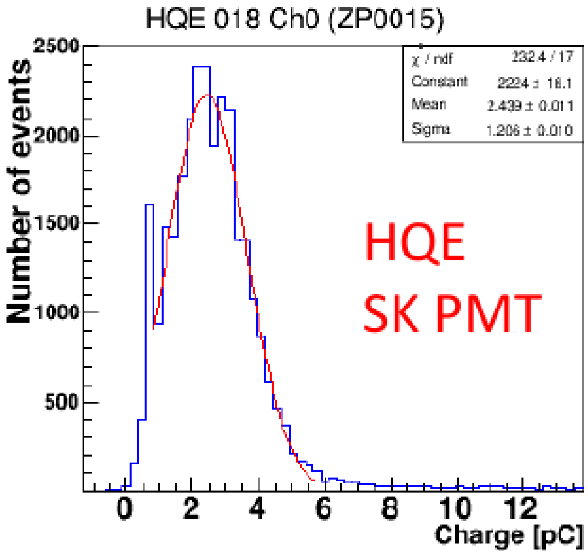
20cm HPD

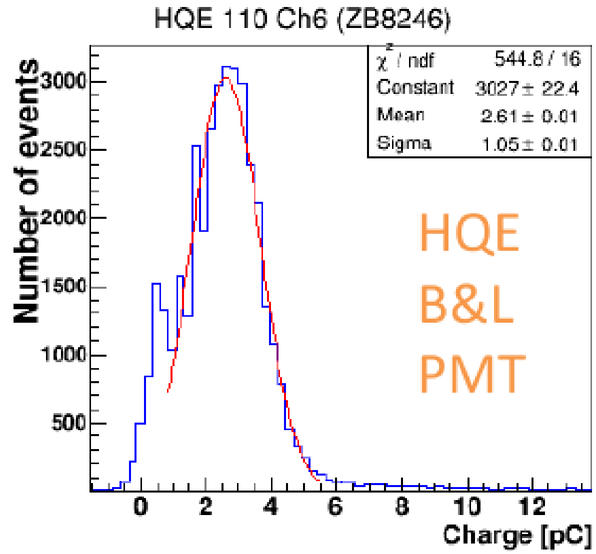


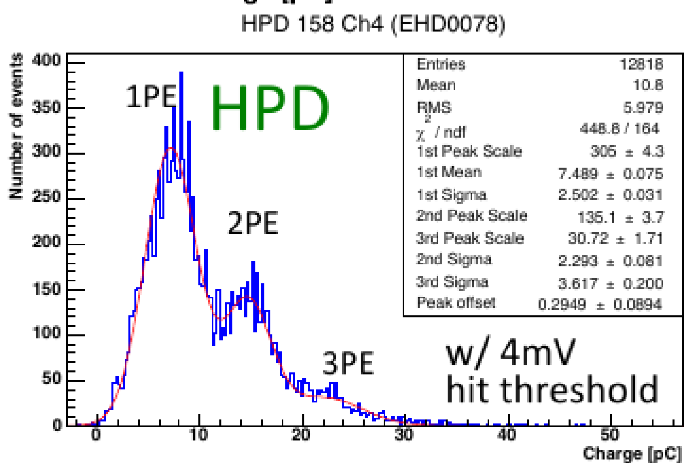
Time resolution at 1 p.e.



Single PE Charge in Water

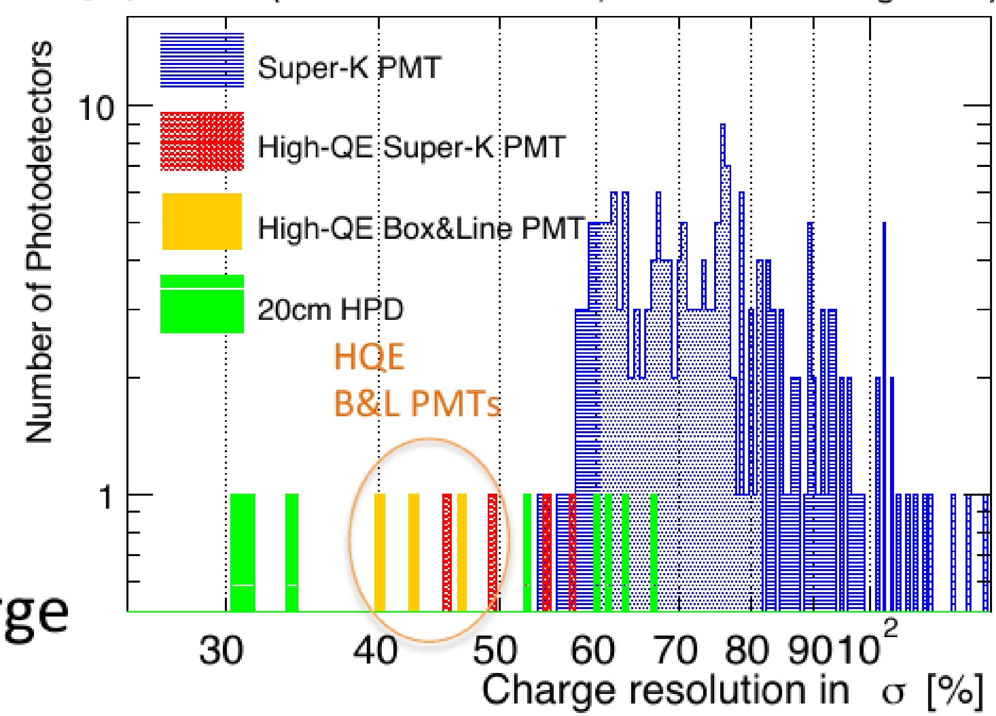






Charge resolution at 1 p.e.

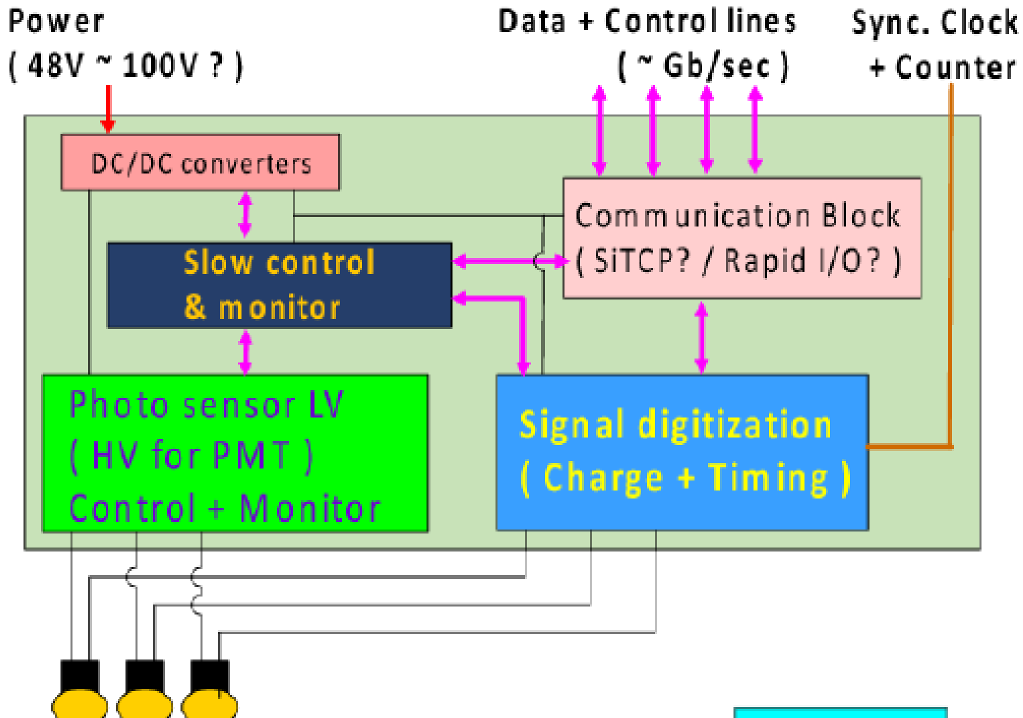
(Low resolution of HPD/PMT is due to low gain set)



High-QE Box&Line PMTs clearly showed better time and charge resolutions in water.

Electronics/DAQ

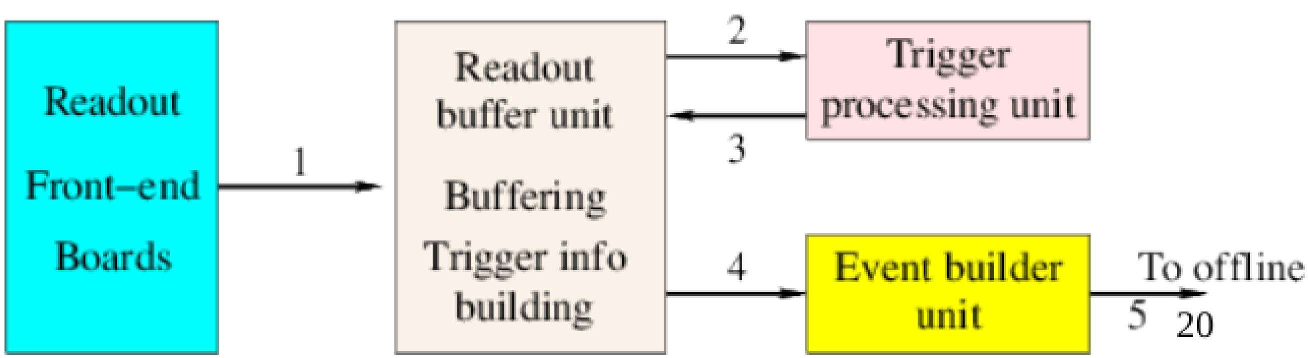
- Front-end electronics module with the power supply for the photo-sensor in the detector water, close to the photo-sensor.
- Schematic diagram of the front end module:



The signal digitization block accept the signals from the photo sensors and convert them to the digital timing and charge data.
Two options:

- Charge to time conversion (QTC) chips
- Flash ADC (FADC) chips

DAQ & triggering simplified block diagram:



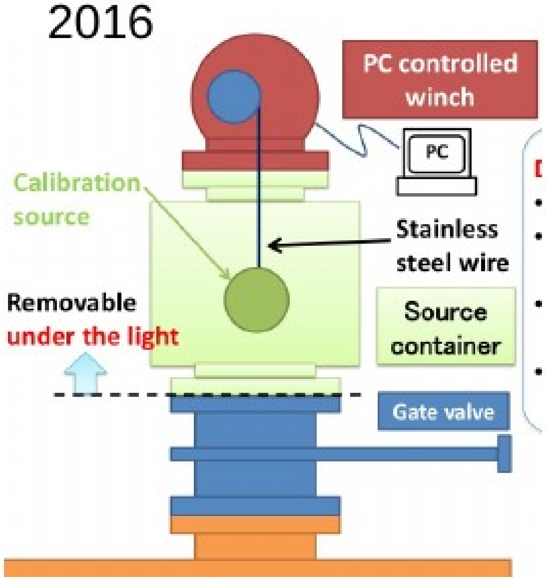
Calibrations

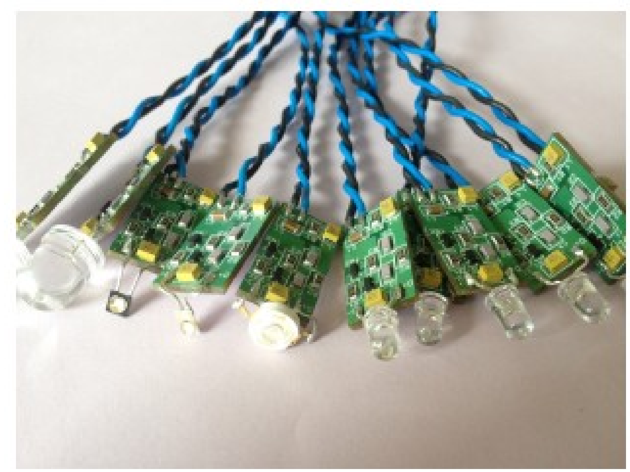
Nominal methods as in Super-K, but with 3D automated deployment systems. Further additions: external PMT calibration, integrated light injection system.

- Simple semi-automated calibration system (to be deployed in SK)
- Computed controlled.
- Compact and light-shielded.
- R&D (3D) for HK in 2015-2016

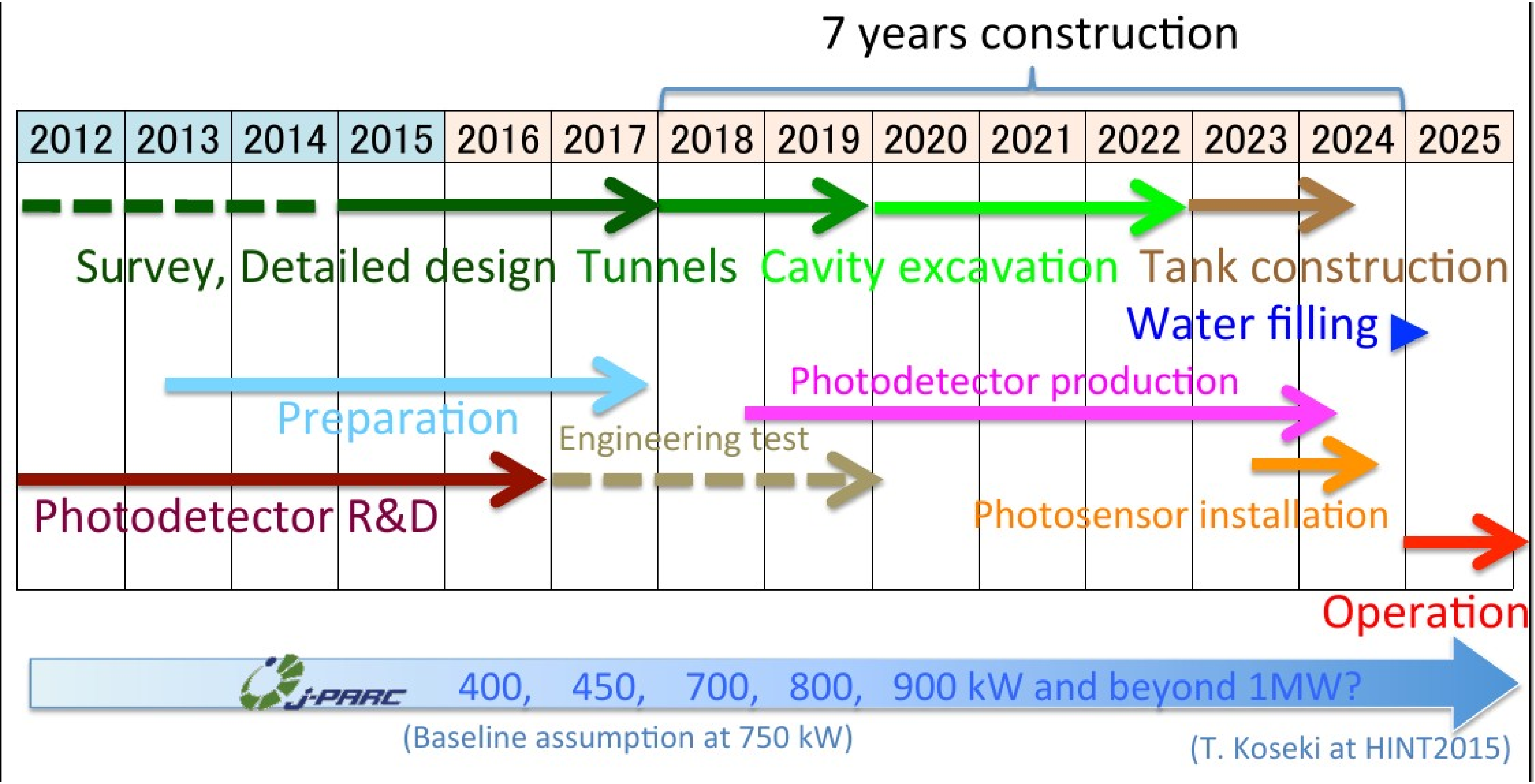
- Study response & reflection of large photosensors in water (Photosensor Testing Facility at TRIUMF)
- Optical system with laser, monitor and receiver PMTs in place and tested.

- Use LED as a light source for optical calibration.
- Can build an automated system that can illuminate each PMT with known sources
- Tests of LEDs underway





Timeline


7 years construction
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
Survey, Detailed design
Tunnels
Cavity excavation
Tank construction
Water filling
Photodetector production
Preparation
Engineering test
Photodetector R&D
Photosensor installation
Operation
J-PARC
400, 450, 700, 800, 900 kW and beyond 1MW?
(Baseline assumption at 750 kW)
(T. Koseki at HINT2015)

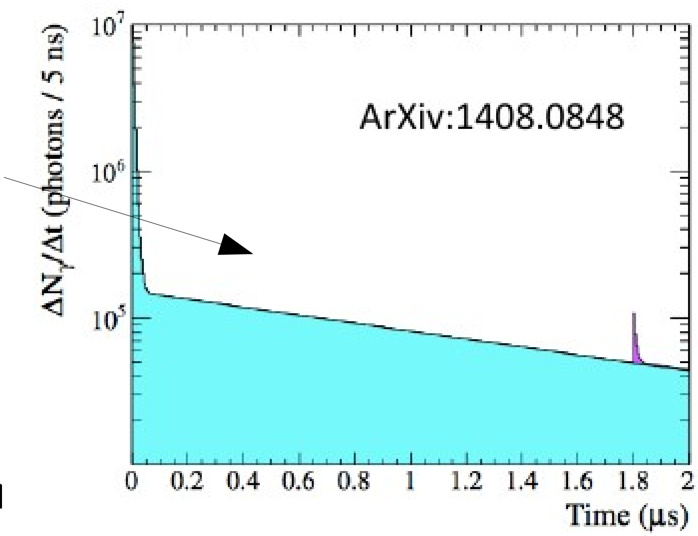
Scintillation in LAr

- Peak of emitted light in Ar at **128 nm** → need coating to shift into PMT wavelength

- W_γ = 19.5 eV → **few 10^7 γ per GeV**
  one 8" PMT per sq. meter inside LAr
  (QE~10 % → collection efficiency few 10^{-4})

  ➡ few 1000 PE/PMT dynamic range

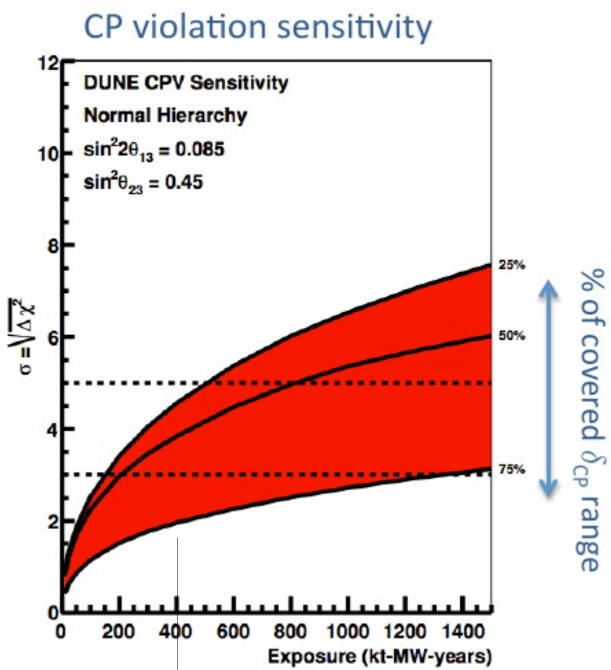
- Scintillation signal shape :
  - **fast component** (singlet): τ_1 ~10 ns (~23% for mip)
  - **slow component** (triplet): τ_2 ~1 μs (~77% for mip)

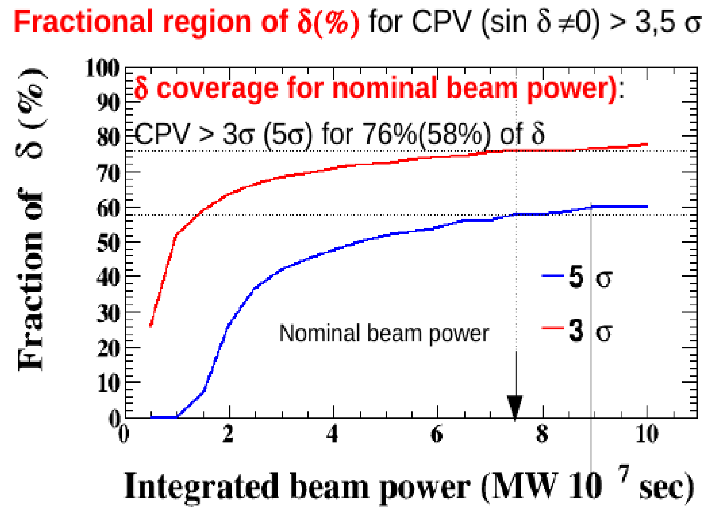


- Background from 7kHz cosmics
  - **primary scintillation** → deadtime < 100μs
  - continuous background of **secondary scintillation (from avalanche in gas)**

➡ (S+B)/B ~ 50 (20 ns) → 1 (1 μs) use signal shape to isolate signal over background

Sensitivities

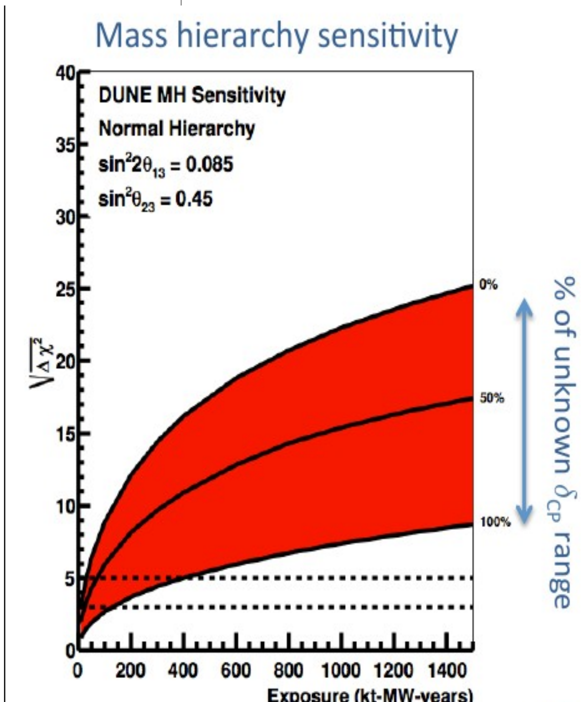




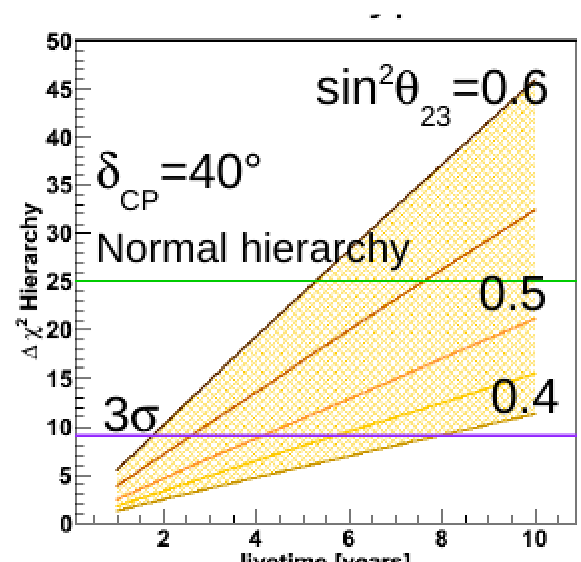
Assuming 1MW beam

HK 3 years (1MTon): CPV measured at 3s(5s) for 75% (60%) of dCP values

DUNE 10 years (40 kTon): CPV measured at 3s (5s) for >50% (~25%) of dCP values



DUNE 10 years: definitive determination of MH



HK 10 years: wrong MH excluded at 3s

JUNO

3 oscillation frequencies:

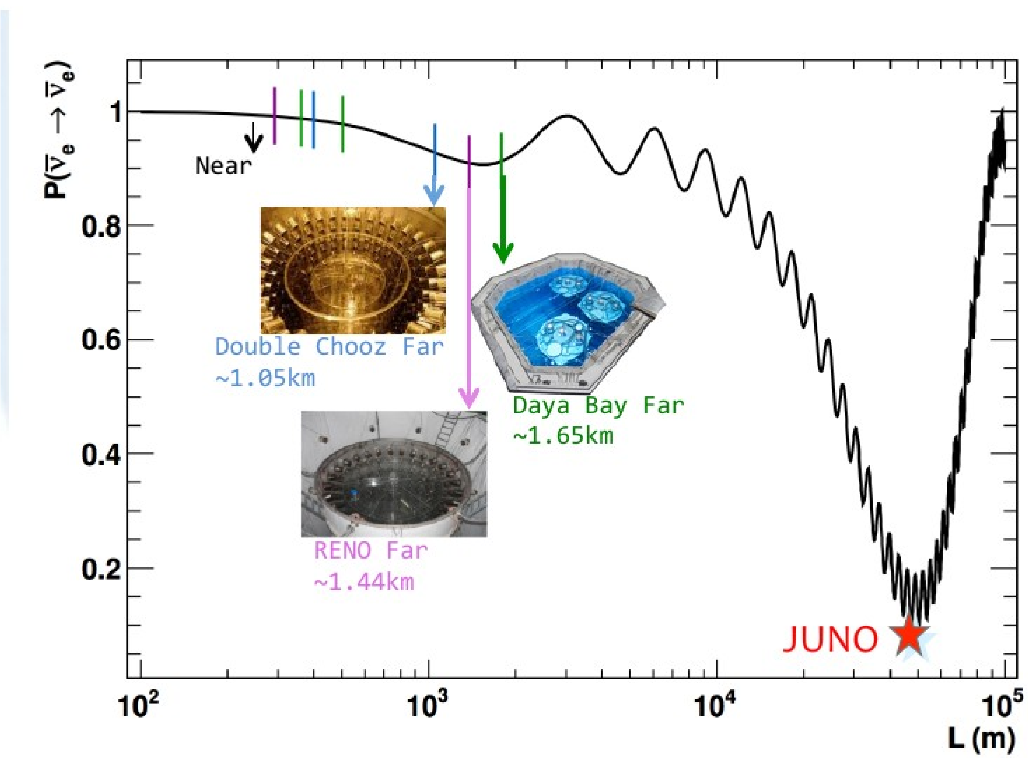
- Low frequency Δm^2_{21} (~ 7.54 x10^{-5} eV^2)
- High frequencies: Δm^2_{31} and Δm^2_{32} (2.43 x10^{-3} eV^2)

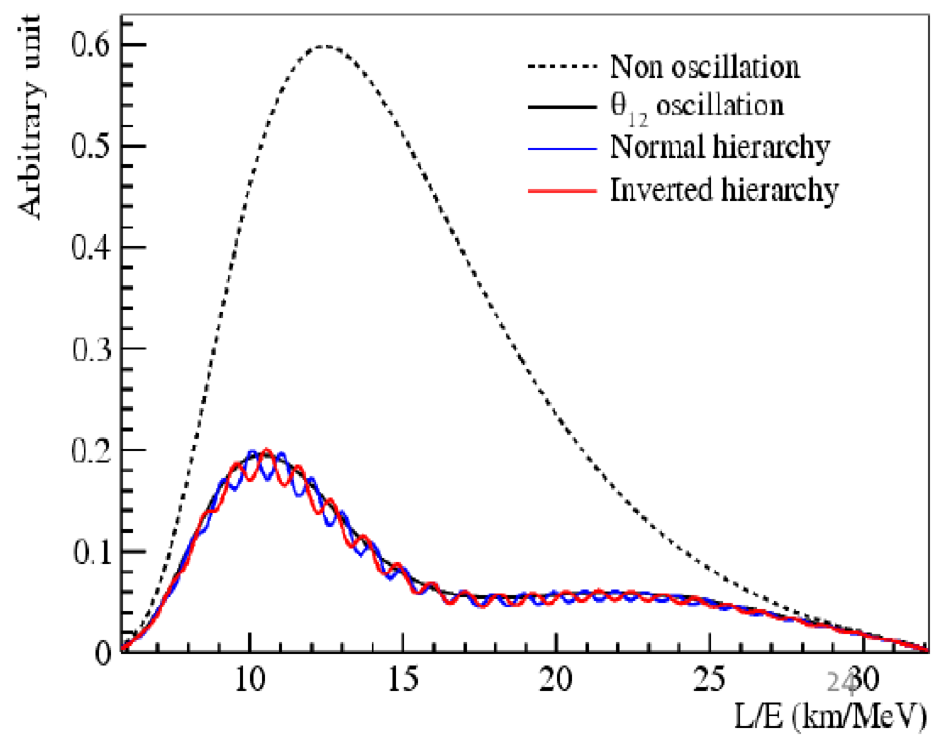
If $\mathrm{NH}: \Delta m^2_{32} > 0 \quad \Longrightarrow \quad |\Delta m^2_{31}| > |\Delta m^2_{32}|;$

if $\mathrm{IH}: \Delta m^2_{32} < 0 \quad \Longrightarrow \quad |\Delta m^2_{31}| < |\Delta m^2_{32}|.$

corresponds to a change of phase in the oscillation

$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L,E) = 1 - \sin^2 2\theta_{12}\cos^4\theta_{13}\sin^2\frac{\Delta m^2_{21}L}{4E} - \sin^2 2\theta_{13}\left[\cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E} + \sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E}\right]$$





JUNO backgrounds

Accidental BG

e^+-like signal: radioactivity from materials, PMTs, surrounding rock.

n signal: n from cosmic μ spallation, thermalised in detector and captured on H or radioactivity gamma.

Correlated BG

- Fast n (by cosmic μ) gives recoil protons (low energy) and are captured on H.
- Long-lived (^9Li, ^8He) β+n-decaying isotopes induced by μ.

Estimated IBD events before selection cut: ~80/day (estimated efficiency ~ 83%)