Neutrino detectors for oscillation experiments

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INSTR17, Novosibirsk, Russia, 1 March 2017

OUTLINE

- Neutrino oscillations
- Current experiments
  - Accelerators: T2K, NOVA
  - Plans for upgrade
  - Reactors: Daya Bay, RENO, Double Chooz
- Future projects
  - JUNO
  - DUNE
  - HyperKamiokande

Talks

W. H. Trzaska
WA105 experiment at CERN: large demonstrator of Dual Phase Liquid Argon TPC detector for DUNE

V.Berardi
The Hyper-Kamiokande detector: R&D studies of a new generation of Photosensors

Y.Heng
The Instrumentation of JUNO

Posters

I.Anfimov
Testing methods for 20 inches PMTs of the JUNO experiment

Z.Wang
JUNO PMT system

A. Mefodiev

B. Developing of segmented neutrino detector Baby-MIND

ν oscillations and mixing

Standard Model: neutrinos are *massless* particles

3 families

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$U = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}$$

***U* parameterization:**

three mixing angles θ_{12} θ_{23} θ_{13}

CP violating phase δ_{CP}

atmospheric — link between atmospheric and solar — solar

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

SuperK, K2K, MINOS, T2K

$\theta_{23} \sim 45^0$

$$|\Delta m^2_{32}| \cong |\Delta m^2_{31}| = |\Delta m^2_{atm}| \approx 2.4\times10^{-3}\,\text{eV}^2$$

T2K
MINOS

Daya Bay, RENO
Double Chooz

$\theta_{13} \approx 9^0$

$$\Delta m^2_{ij} = m_i^2 - m_j^2$$

$$\Delta m^2_{12} + \Delta m^2_{23} + \Delta m^2_{31} = 0$$

Solar experiments, SuperK
KamLAND

$\theta_{12} \approx 34^0$

$$\Delta m^2_{21} = \Delta m^2_{sol} \approx 7.5\times10^{-5}\,\text{eV}^2$$

two independent Δm^2

Main goals of accelerator and reactor LBL experiments

- CP violation in lepton sector

Strength of CP violation in neutrino oscillations

neutrinos

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

quarks

$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

$$J_{CP} = \mathrm{Im}(U_{e1}U_{\mu2}U^*_{e2}U^*_{\mu1}) = \mathrm{Im}(U_{e2}U_{\mu3}U^*_{e3}U^*_{\mu2})$$
$$= \cos\theta_{12}\sin\theta_{12}\cos^2\theta_{13}\sin\theta_{13}\cos\theta_{23}\sin\theta_{23}\sin\delta_{CP}$$

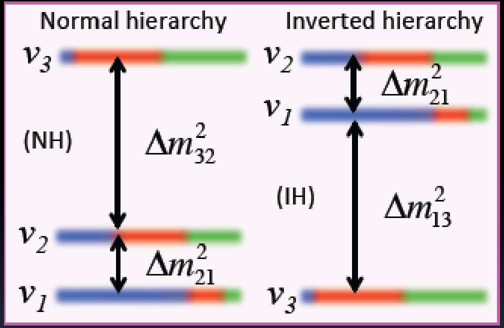
Quark sector $J_{CP} \approx 3\times10^{-5}$

Lepton sector $J_{CP} \sim 0.02\times\sin\delta_{CP}$

all mixing angles $\neq 0$ $\rightarrow$
$\rightarrow J_{CP} \neq 0$ if $\delta_{CP} \neq 0$

First indication from T2K: $\delta_{CP} = -\pi/2$??

- Neutrino mass hierarchy



- θ_{23} – maximal? If not, what octant ($\theta_{23} > \pi/4$ or $\theta_{23} < \pi/4$)?

- Neutrino cross sections
- Sterile neutrinos

CERN Neutrino Platform

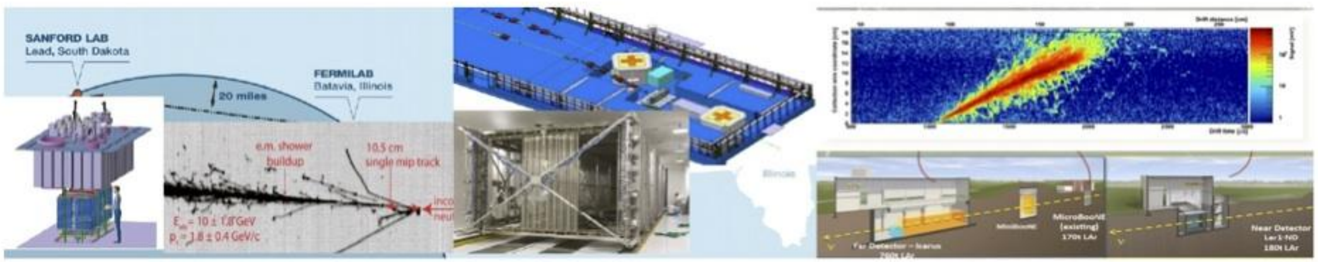
Following 2013 European Strategy for Particle Physics recommendations

Initial Mandate

…assist various groups in their R&D phase (detectors and components)….

…bring R&D at the level of technology demonstrators…

… support the long and short baseline activities (infrastructure & detectors)



Welcome to CENF : CERN Neutrino Platform

Home | About CENF | Organization | Projects/R&D | Facilities | Education&Outreach | Useful Links

CERN Neutrino Platform - CENF (http://cenf.web.cern.ch/) - represents an effort of CERN (http://home.web.cern.ch/)to foster fundamental research in the field of Neutrino Accelerator Physics as decided by CERN Council (http://council.web.cern.ch/council/en/Welcome.html) in framework of the 2013 European Strategy (http://council.web.cern.ch/council/en/EuropeanStrategy/ESParticlePhysics.html).

CENF-Project coordinator (https://phonebook.cern.ch/phonebook/#personDetails/?id=417906) works in close collaboration with:

- CERN-EP Neutrino group (http://ep-dep.web.cern.ch/organisation/nu) and
- CERN Neutrino Platform - Theory working group (CENF-TH) (http://th-dep.web.cern.ch/neutrino-platform-theory)

Current experiments

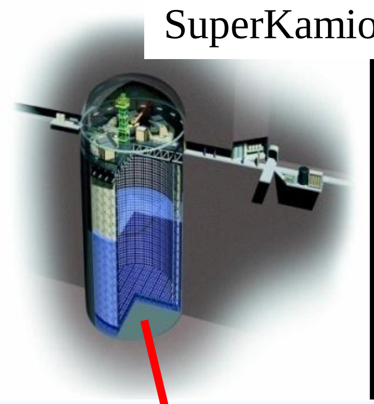
T2K

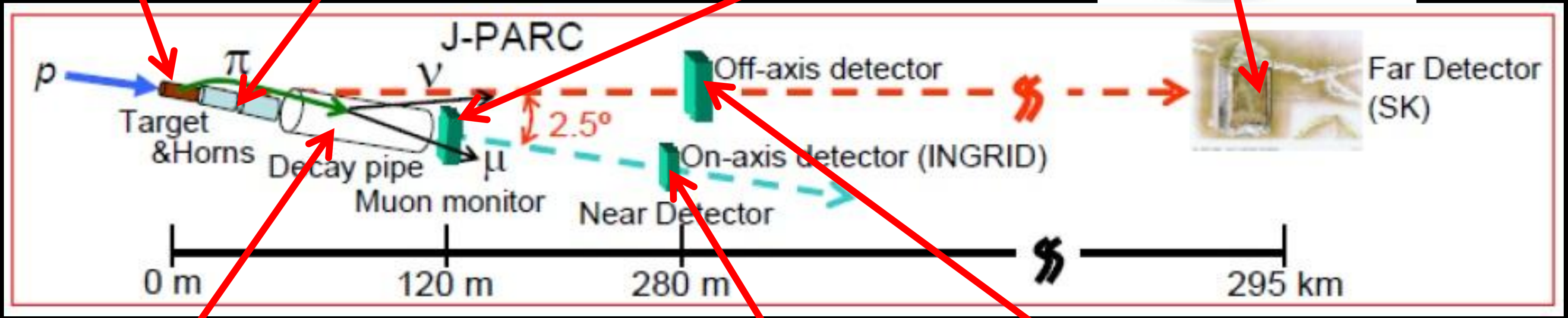
about 500 members
59 institutions
from 11 countries

LONG-BASELINE NEUTRINO OSCILLATION EXPERIMENT

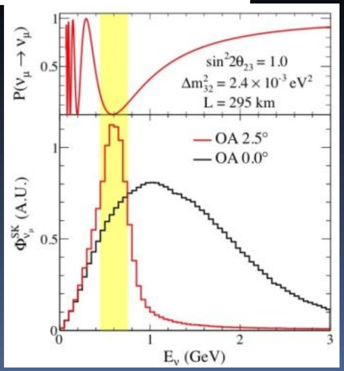
T2K experiment

Far neutrino detector
SuperKamiokande

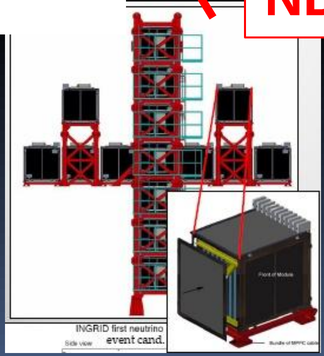




Off-axis neutrino
beam

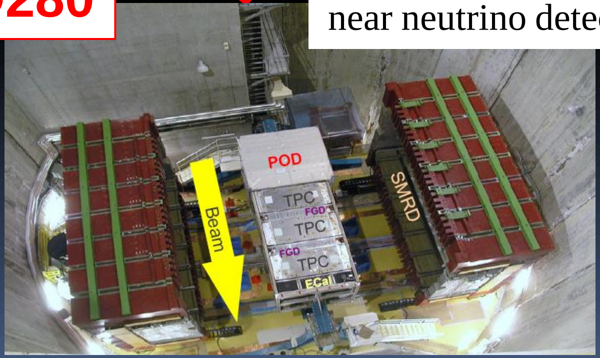


Neutrino monitor
INGRID



ND280

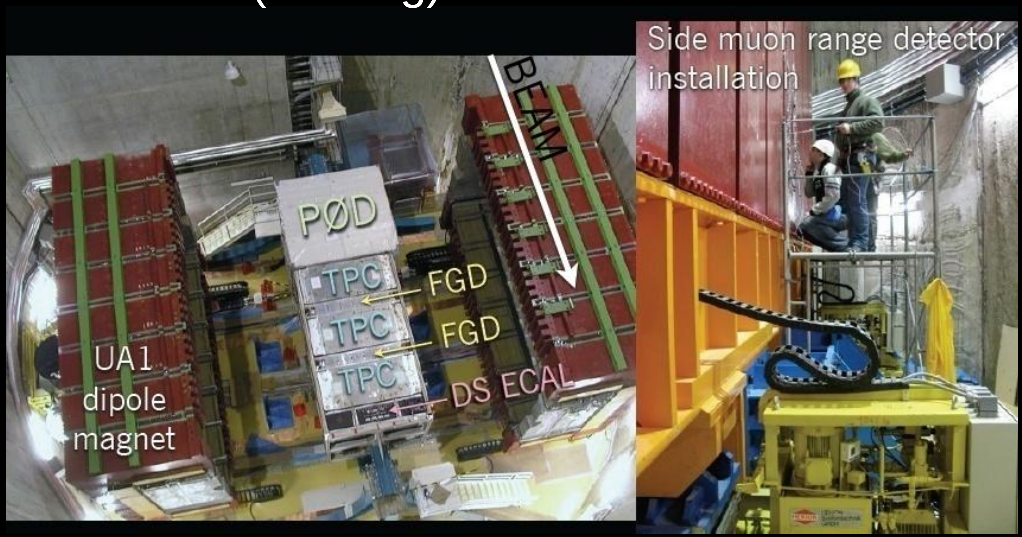
Off-axis
near neutrino detector



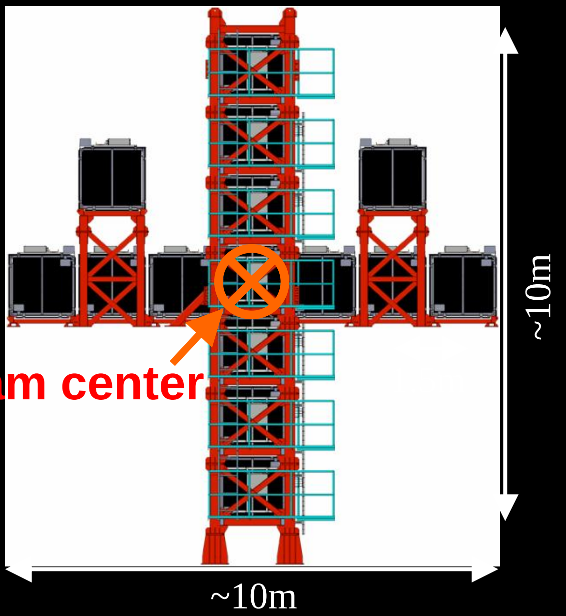
T2K near detector ND280

280 meters from pion production target

Off-axis (2.5 deg)



On-axis



- Tracker: 2 FGD + 3 TPC
- POD, ECAL
- SMRD

Measurement of unoscillated ν beam

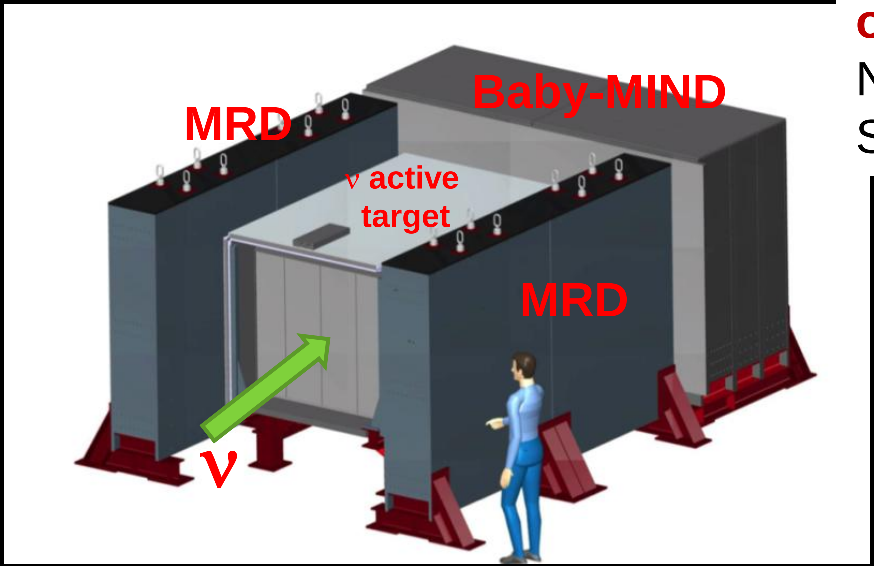
- 16 identical modules (14 in cross)
- Iron/scintillator layers
- Monitor ν beam direction, profile, rate

T2K Systematics (ν mode)	w/o ND280	with ND280
Appearance	11.9%	5.4%
Disappearance	12.0%	5.0%

2-3%

WAGASCI + Baby-MIND

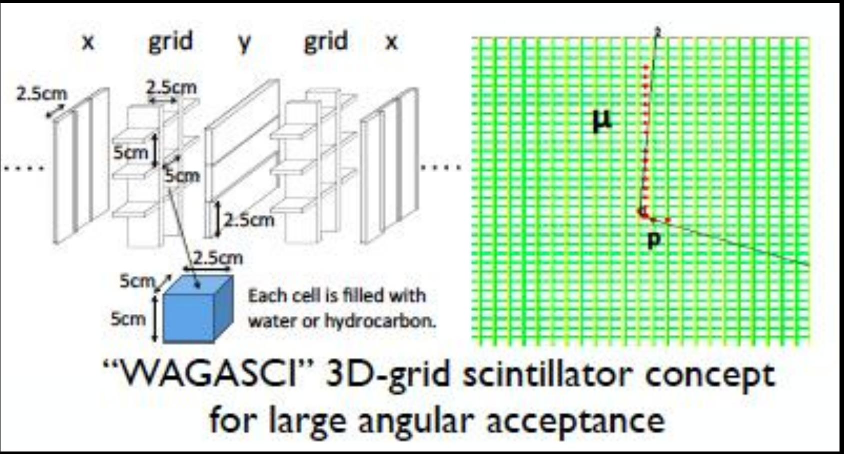
WAGASCI detector



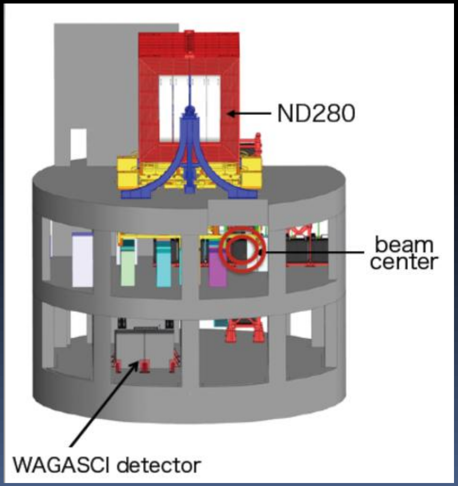
Neutrino cross sections – the main source of systematic uncertainties

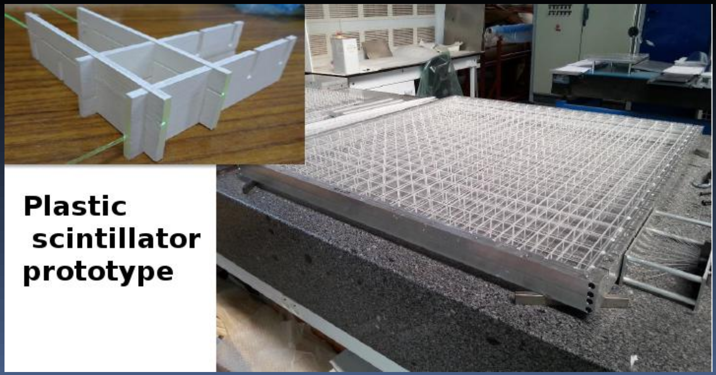
ND280 → CH neutrino target

SuperKamiokande → H_2O neutrino target



"WAGASCI" 3D-grid scintillator concept for large angular acceptance

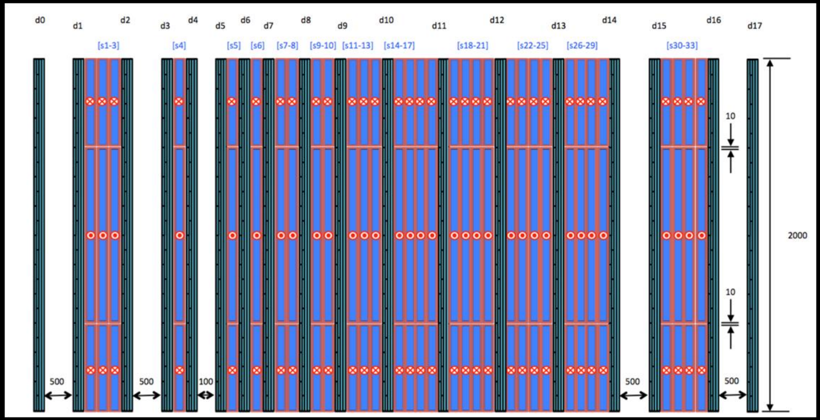




active target filled with H_2O and scintillator 80%:20% (H_20:CH)

Baby-MIND

Neutrino magnetized detector Baby-MIND - NP05 project in framework of CERN Neutrino Platform

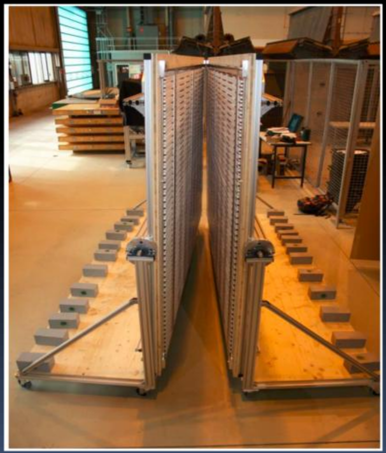


A spectrometer to measure muon momentum and charge identification.

Baby-MIND has 18 active modules
Active elements – scintillator detectors with WLS/SiPM readout
Each module: 95 horizontal bars and 16 vertical bars
Horizontal bar: 2900(L)x30(W)x7(t) mm^3
Vertical bar: 1950(L)x210(W)x7(t) mm^3
In total ~1800 horiz and 250 vert sci bars
and 3-cm thick 33 magnetized iron plates

Scintillator plane

Two half-modules



Complete module

Magnetized iron plate

Reconstruction efficiency > 95%
Charge identification > 90%

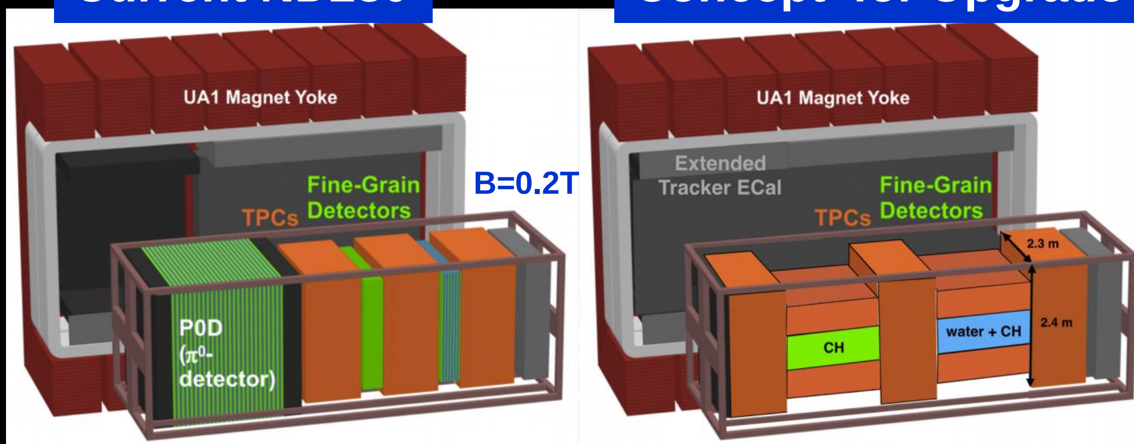
Start data taking with WAGASCI target in Autumn 2017

Upgrade of T2K near detectors

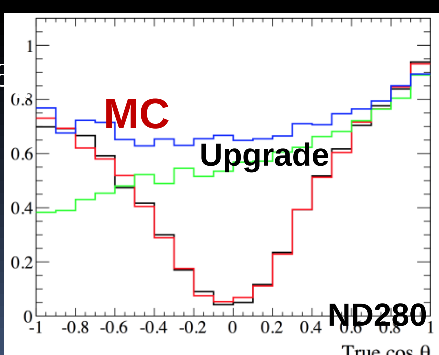
For T2K-II phase and HyperKamiokande

T2K systematic errors of ~ 5-6%
Need to improve to ≤3%

Current ND280 | **Concept for Upgrade**

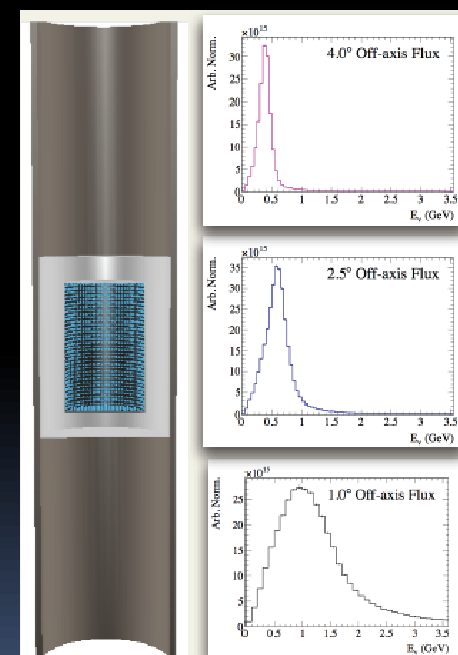


- new tracking target
- new TPS for high angle tracks



NuPRISM: arXiv:1412.3086

Intermediate (~1 km) Water Cherenkov detector NuPRISM
Span several off-axis angles

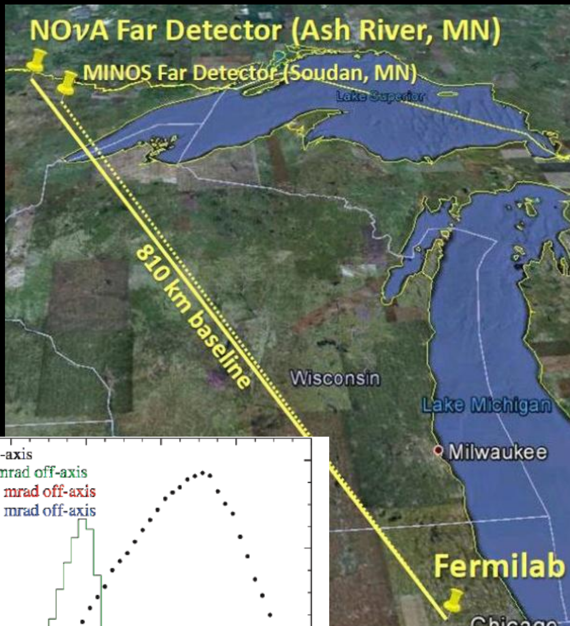


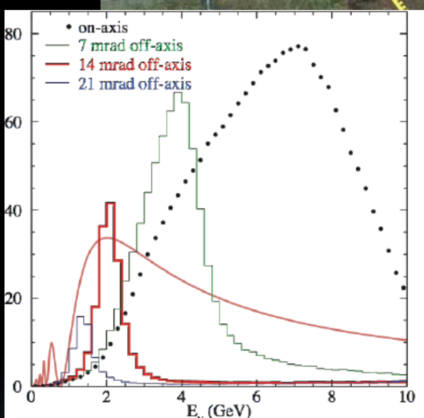
Measurement of $\sigma(E\nu)$

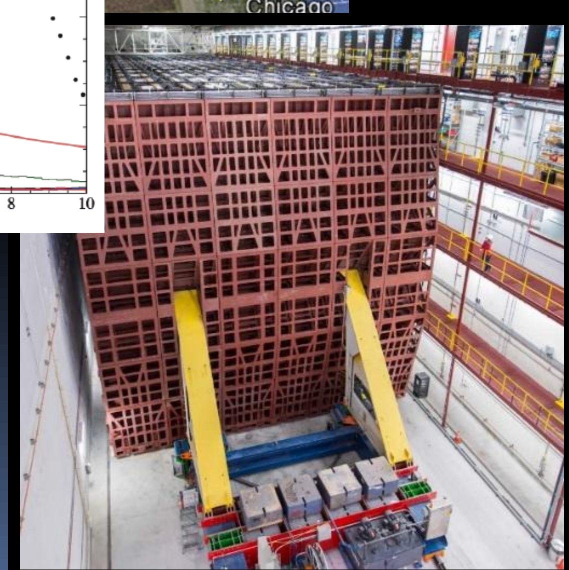
Plan: TDR -2017, Commissioning -2020

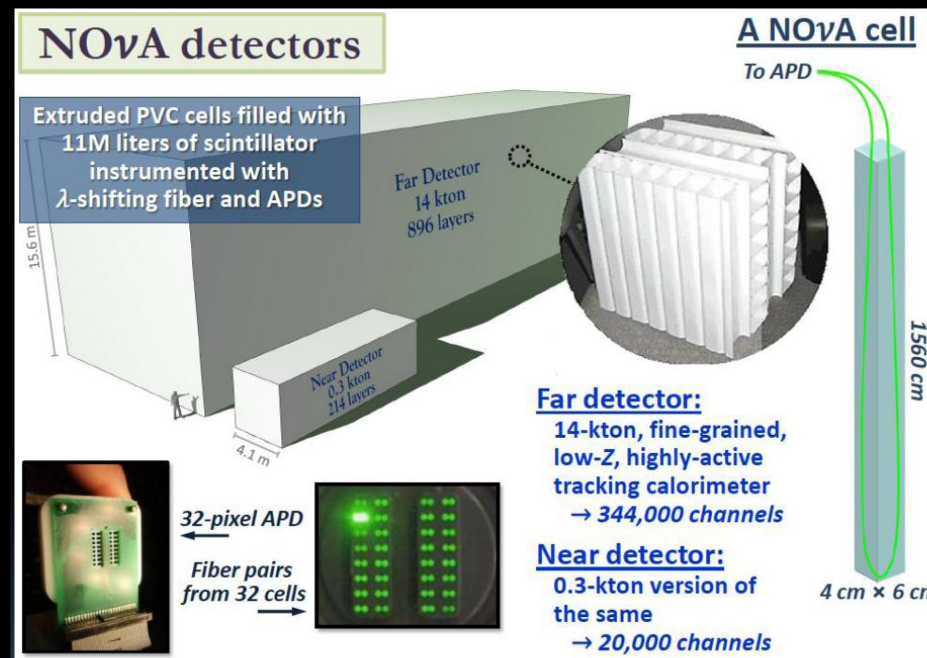
NOVA

Neutrino beam from FNAL to Ash River
Baseline 810 km
Neutrino beam 14 mrad off-axis
Far detector : 14 kt fine-grained calorimeter
65% active mass
Near Detector: 0.3 kt fine-grained calorimeter









Taking data since Summer 2014
Study of $\nu_\mu \to \nu_\mu$ and $\nu_\mu \to \nu_e$ oscillations

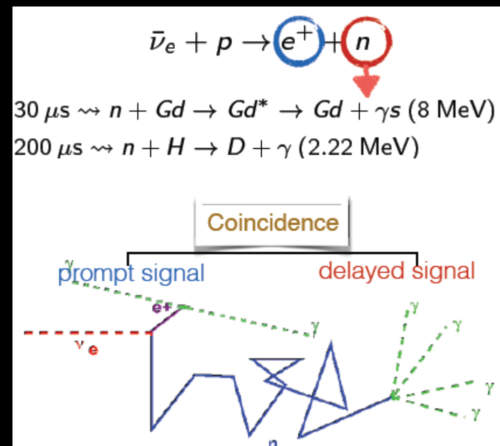
Reactor experiments

Daya Bay, China

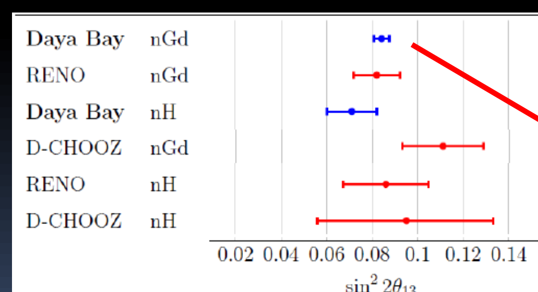
RENO, Korea

Double Chooz, France

Principle

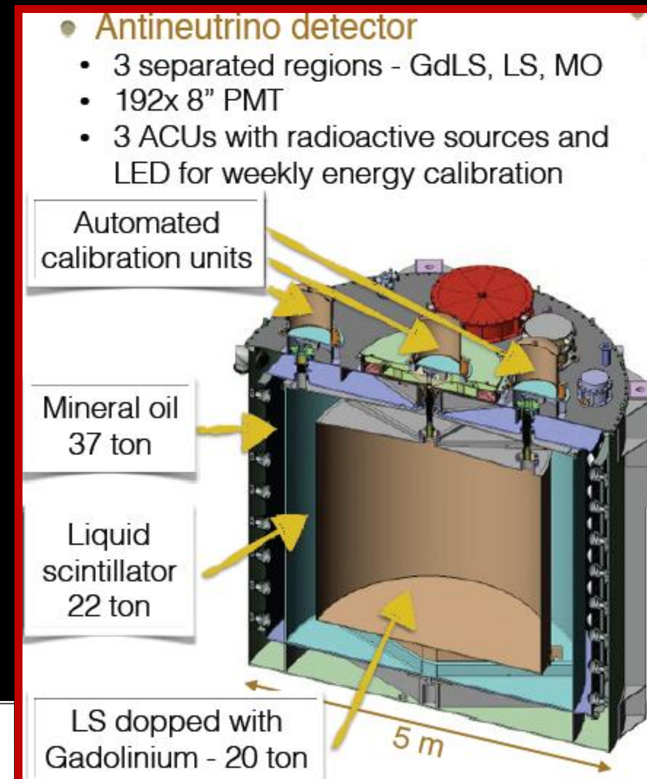


Typical energy resolution
$\sigma E \sim (6\text{-}8)\%/\sqrt{E}$



θ_{13} = 8.4 deg

Detector Daya Bay



Next generation: experiment JUNO

Future LBL Projects

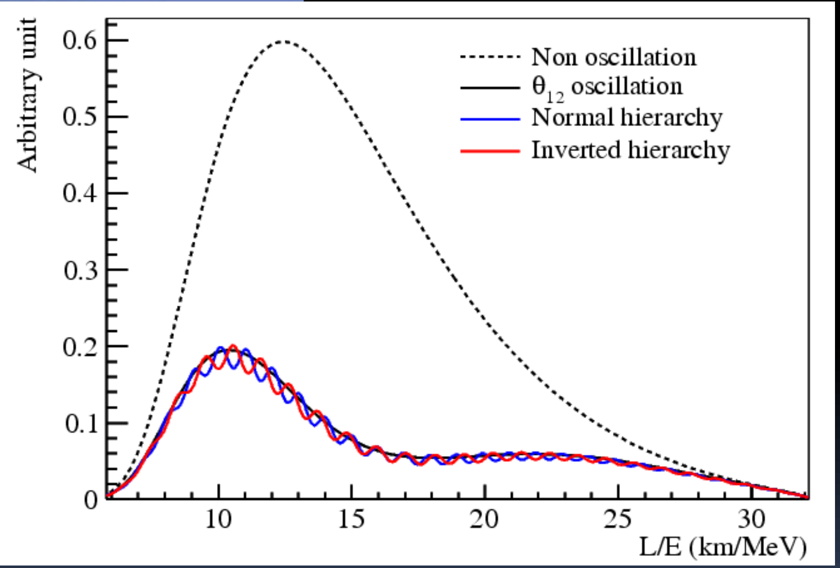
- Reactor experiment JUNO
- Accelerator LBL experiment DUNE
- HyperKamiokande and T2HK

Reactor experiment JUNO

China

66 institutions
> 400 collaborators

Main target:
Measurement of neutrino mass hierarchy



- 700 m deep underground
- 36 GW reactor power
- 53 km baseline -> oscillation maximum θ_{12}
- 20 kton LS detector
- 3% energy resolution at 1MeV
- <1% energy scale uncertainty

!?

Start data taking in 2020

Detector JUNO

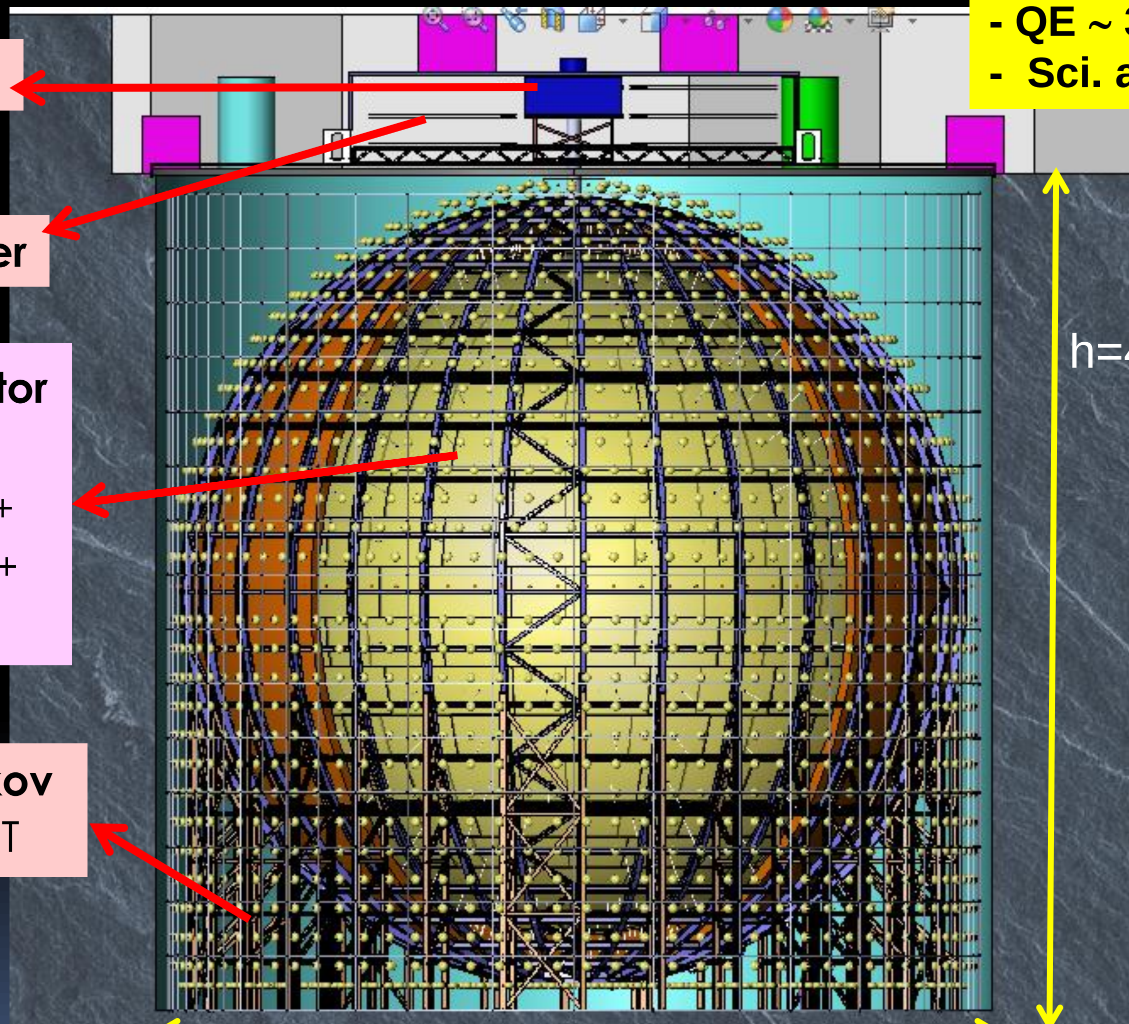
Requirements:
- **PMT coverage 75% of total surface**
- **QE ~ 35%**
- **Sci. att. length >20 m**

Calibration

Top Tracker

Central detector
Acrylic sphere+
20kt Liquid Scin+
~17000 20'' PMT+
~36000 3'' PMT

Water Cherenkov
~2000 20'' PMT



h=44 m

d=43.5 m

3" PMT

20" PMT

PMT's for JUNO

20" PMT's

NNVT MCP-PMT

15000

Transmission and reflection photocathode:
QE (400 nm) ~ 30%

Sen Qian, talk at NNN16

Hamamatsu R12860

5000

Characteristics	unit	MCP-PMT (IHEP)	R12860 (Hamamatsu)
Electron Multiplier	--	MCP	Dynode
Photocathode mode	--	reflection+ transmission	transmission
Quantum Efficiency (400nm)	%	26 (T), 30 (T+R)	30(T)
Relativity Detection Efficiency	%	~ 110%	~ 100%
P/V of SPE		> 3	> 3
TTS on the top point	ns	~12	~3
Rise time/ Fall time	ns	R~2 , F~10	R~7 , F~17
Anode Dark Count	Hz	~30K	~30K
After Pulse Time distribution	us	4.5	4, 17
After Pulse Rate	%	3	10
Glass	--	Low-Potassium Glass	HARIO-32

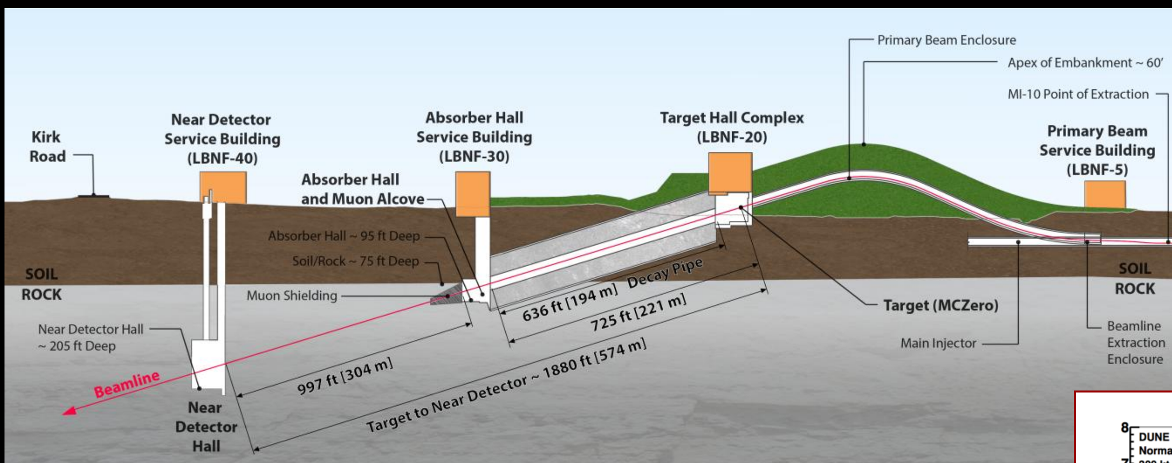
LBNF/DUNE Project

Flagship FNAL project

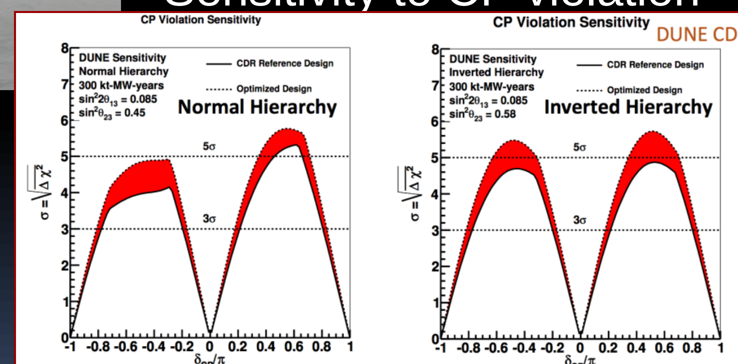
Main goals: **- discovery of CP violation in leptonic sector**
- neutrino mass hierarchy at >5σ level
- neutrino astronomy
- proton decay search

30 countries
161 institutions
~1000 collaborators

E_p = 60-120 GeV
Beam power 1.2 -> 2.4 MW
On axis neutrino beam
Eν ~ 1- 6 GeV
L=1300 km from FNAL to SURF, S.Dakota

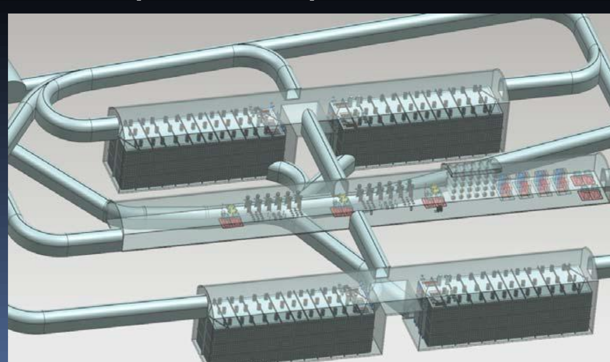


Sensitivity to CP violation



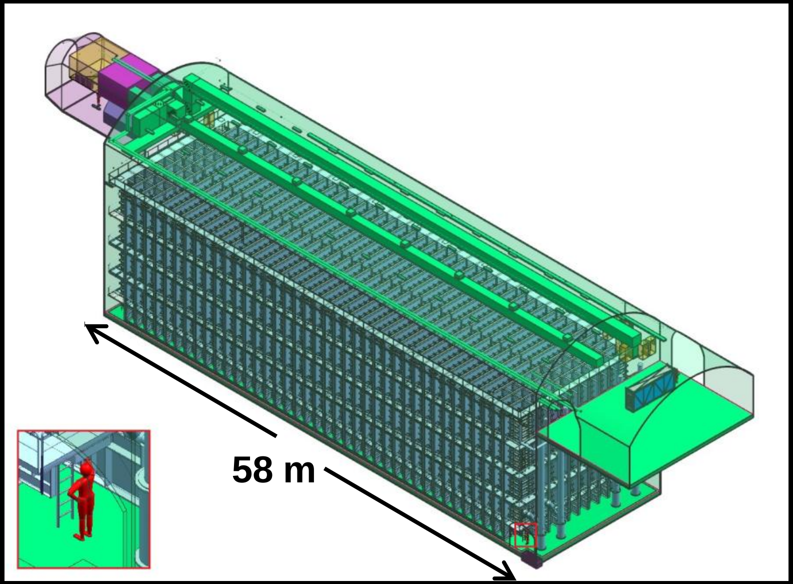
Far detector 40 kt (4 x 10kt) LAr TPC

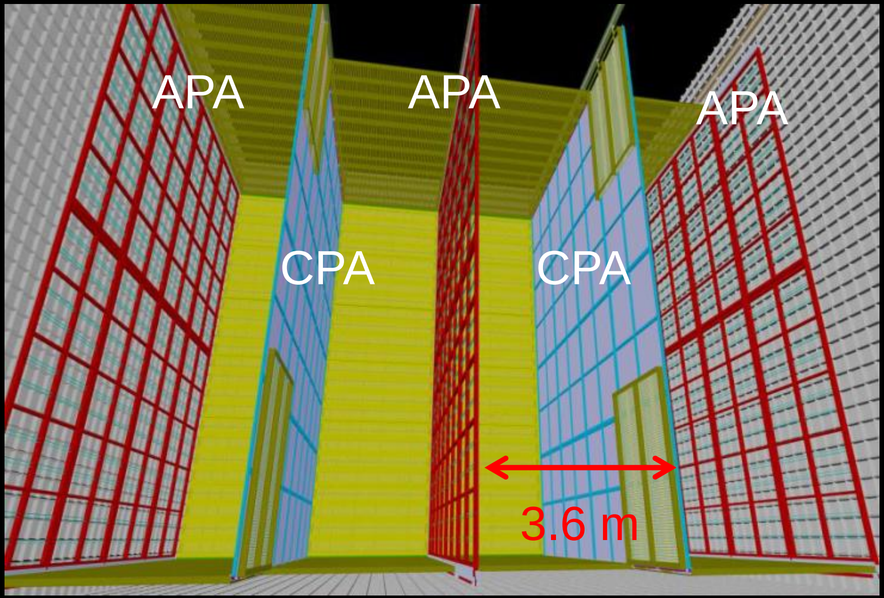
Single
and
Dual
phase
detectors



2021 – installation of 1st far detector
2024 – 2 modules operational
2026 – deliver neutrino beam

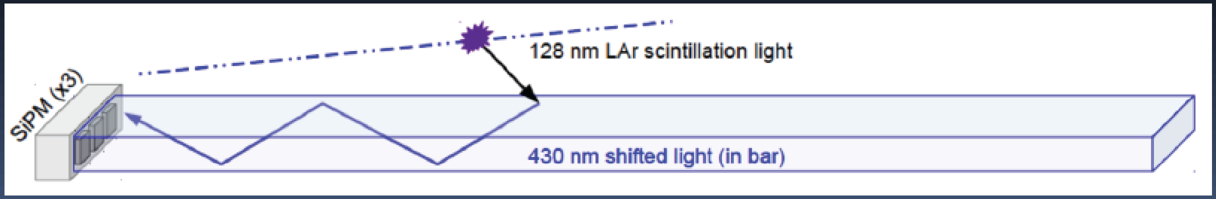
Single-phase LAr TPC



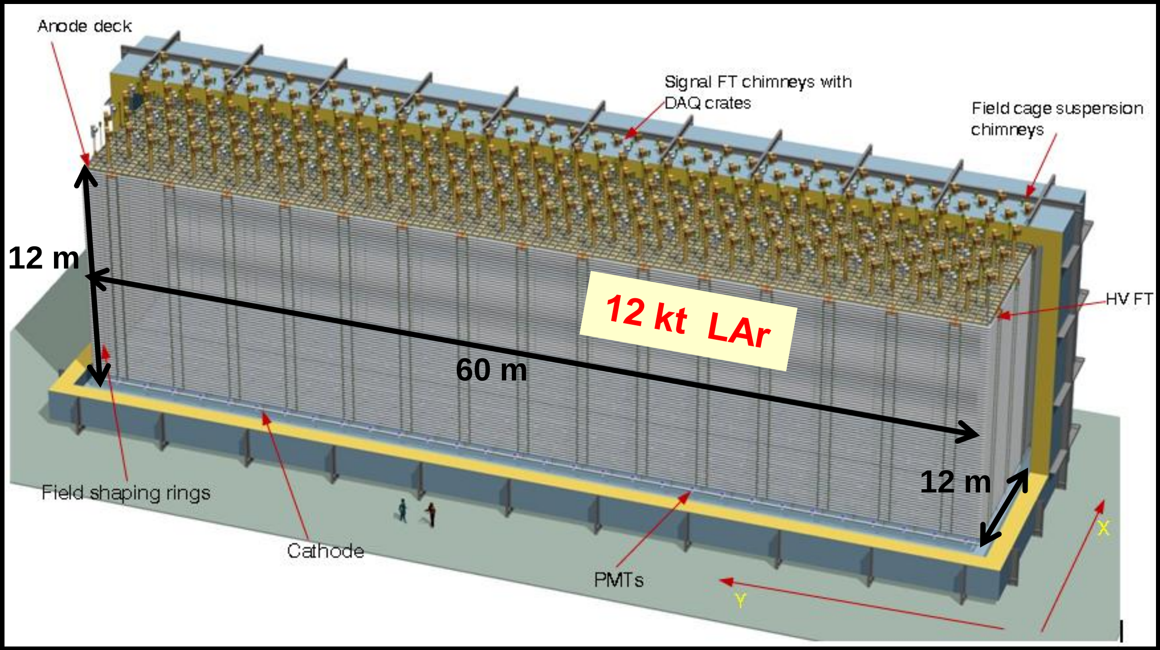


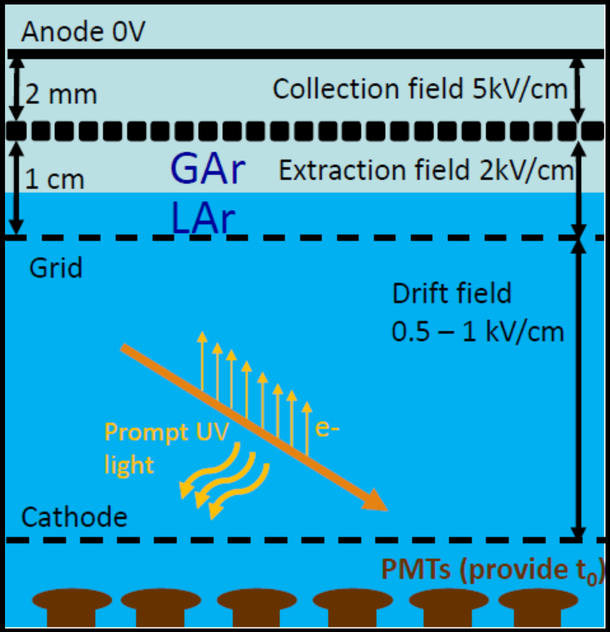
1st 10 kt module of DUNE - single-phase TPC
6m x 2.3 m anode and cathode planes 3.6 m spacing
Photon detectors – light guides + SiPMs embedded in APAs

J.Insler, talk at LLWI2017



Dual-phase LAr TPC



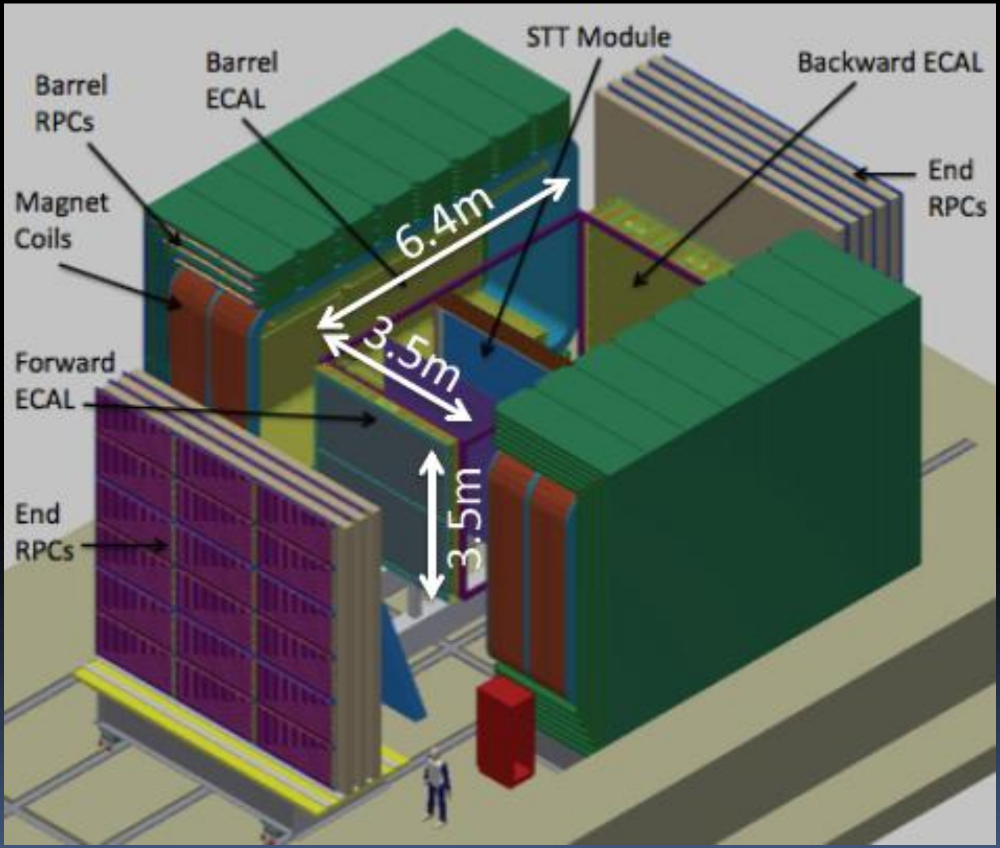


- Electrons extracted from LAr to gaseous volume
- Signal amplified by LEM
- Drift (vertical) 12 m
- Signal/Noise 100:1
- Photon detectors: PMTs + WLS
- Small number of channels
- No dead material inside the active volume

DUNE Near Detector

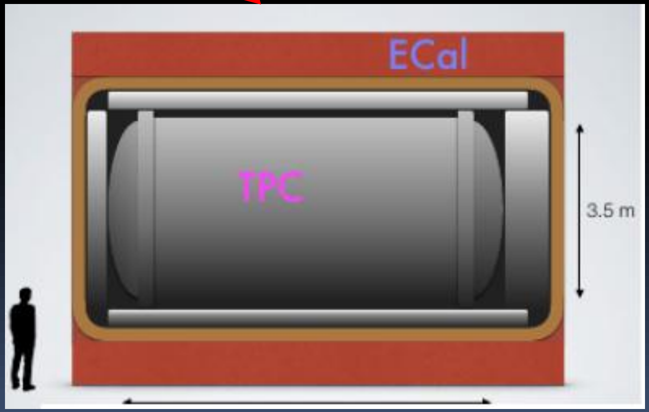
T.Kutter, talk at HINT2016

Fine Grained Tracker inside 0.4 T magnetic field : straw-tube tracker
Surrounded by lead-scintillator ECal and RPC muon tracker



Multiple nuclear targets:
Ar, C, Ca, Fe, ...

Other designs under consideration:
- Magnetized LAr TPC
- High-pressure GAr TPC

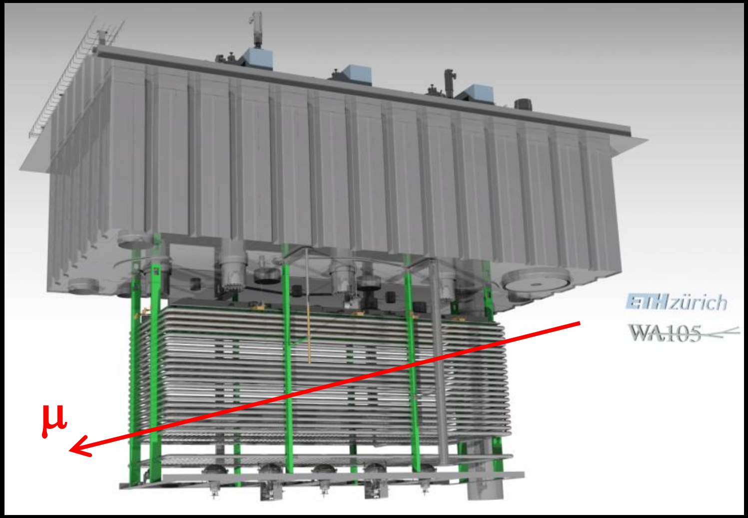


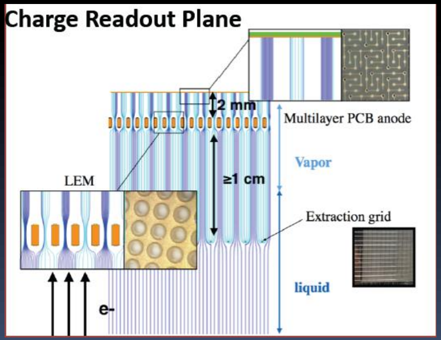
LAr detectors at CERN Neutrino Platform

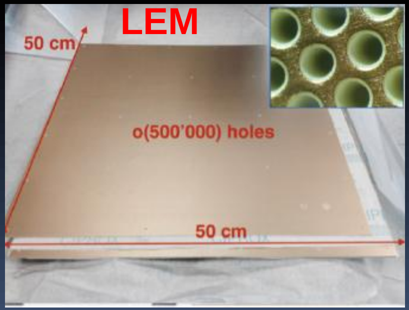
NP02: WA105, DP demonstrator + ProtoDUNE DP

S.Murthy, talk at TPC-2016

Demonstrator: 3x1x1 m^3 – 5 tons

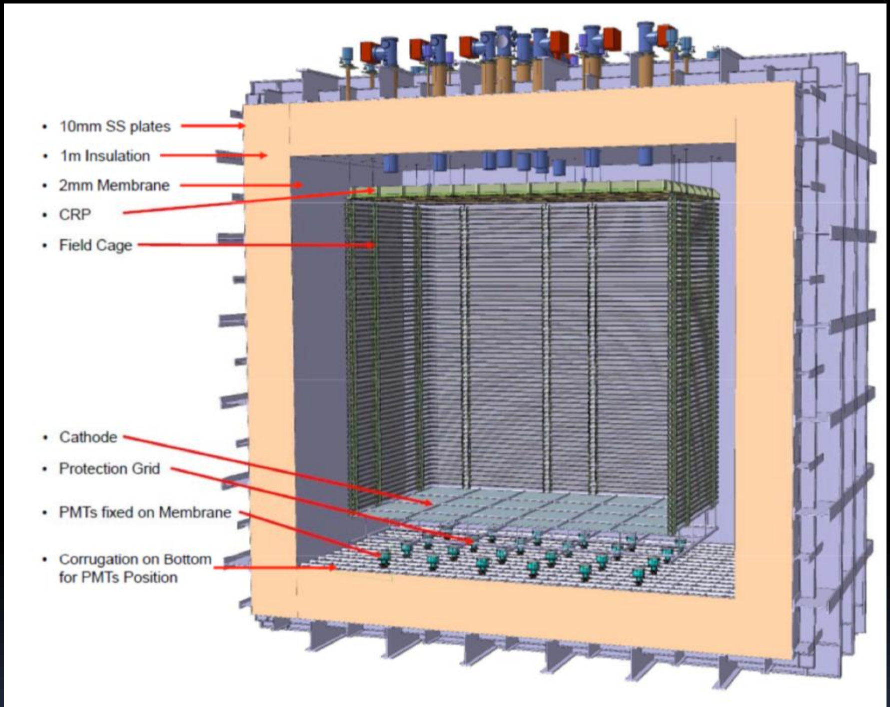






ProtoDUNE DP: 6x6x6 m^3

300 tons active mass



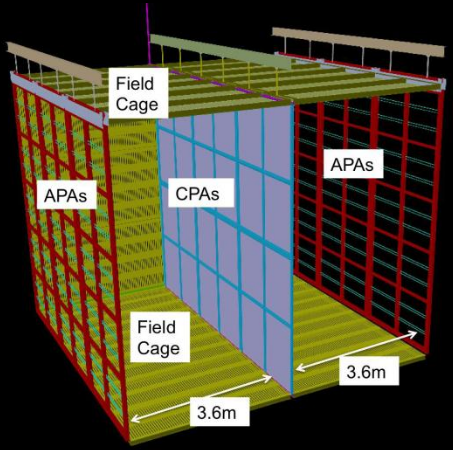
Measurements with test beam in 2018

Cosmic data taking gas begun

LAr detectors at CERN Neutrino Platform

NP04: ProtoDUNE SP

400 tons active mass



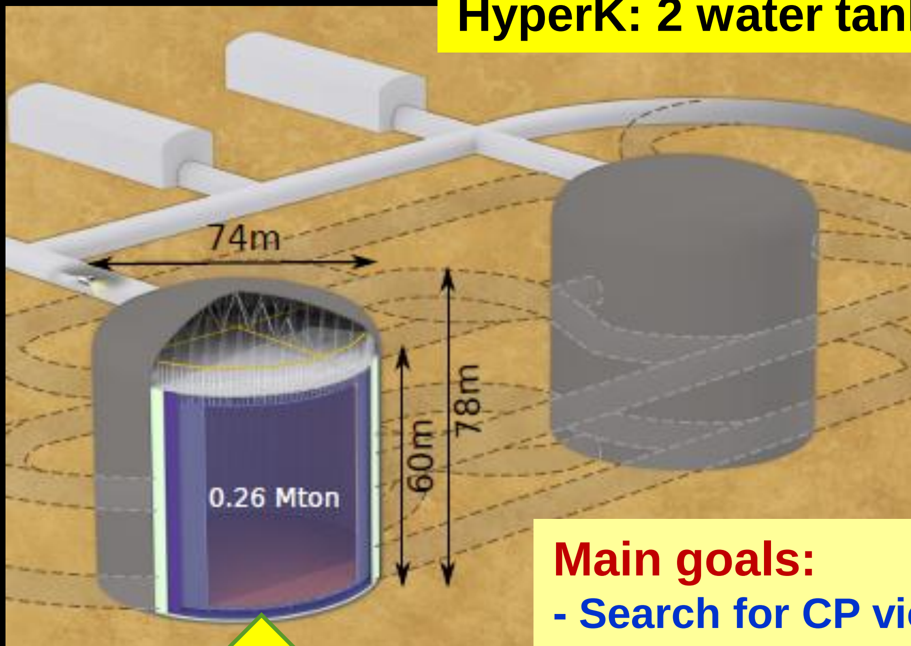
Tests:
- Full size of APAs, CPAs
- Drift regions
- >15000 TPC channels
- Photon detectors

HyperKamiokande

Japan

12 countries
70 institutes
~300 members
Expected data taking start 2026

HyperK: 2 water tanks



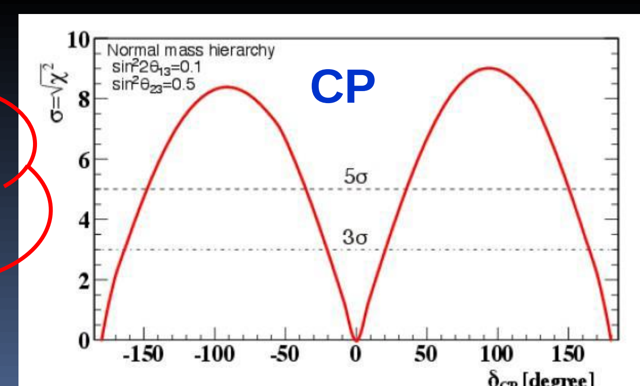
- **Upgrade of JPARC to 1.3 MW beam power**
- **New/upgrade of near neutrino detectors**

Main goals:
- **Search for CP violation**
- **Proton decay**
- **Neutrino astrophysics**

1 tank
60 m(H)x74m(D)
Total volume 260 kt
Fiducial volume 190 kt
~10xSuperK
PMT coverage 40%
40000 PMTs

10 years of running:
- 8σ for $\delta_{CP} = -\pi/2$
- 80% coverage of δ_{CP} parameter space with $>3\sigma$

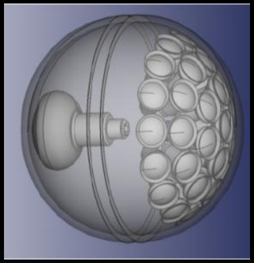
$p \to \pi^0 e^+$ $>10^{35}$ y



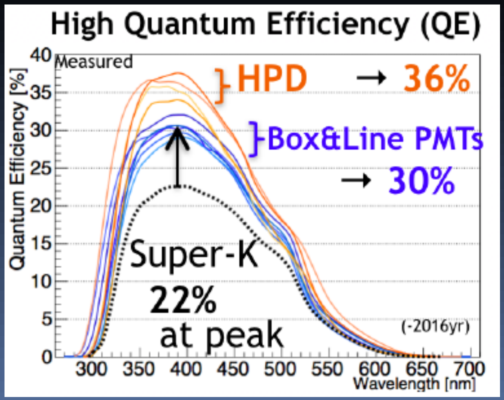
PMTs for HyperKamiokande

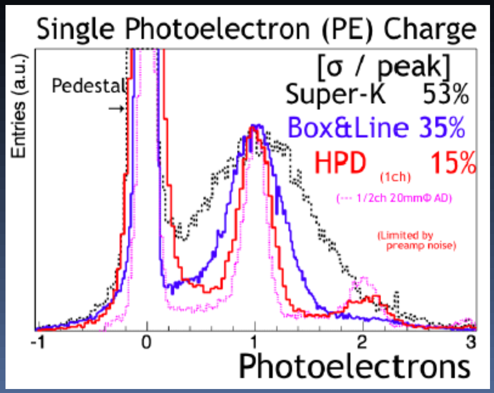
Implosion tests
at 60 and 80 m depth
No chain implosion observed

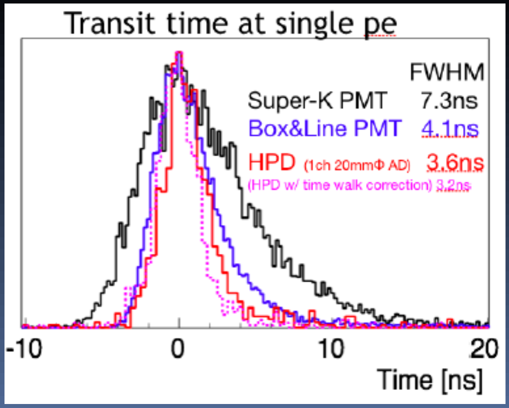
Multi-PMT option
KM3NeT module



Performance of new photosensors







Conclusion

Very intense R&D for neutrino detectors

Current experiments: ***detector upgrades to reduce systematics***

- active neutrino targets

- Cherenkov detectors

- magnetized detectors

Main goals of new projects: **CP violation, MH**
oscillation parameters
proton decay

Next generation detectors

Reactor experiment JUNO	***under construction***
Accelerator experiment DUNE	***approved***
HyperKamiokande and T2HK	***approval in progress***

Thank you!