Neutrino Physics and Detectors

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What we have learned?

Standard Parametrization of the PMNS Matrix

$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\boldsymbol{\theta_{23} \sim 45^\circ}$

$\boldsymbol{|\Delta m^2_{32}| \sim 2.5 \times 10^{-3}\ \mathrm{eV}^2}$

Atmospheric,
LBL accelerator

$\boldsymbol{\theta_{13} \sim 9^\circ}$

$\boldsymbol{\delta \sim ?}$

Reactor,
LBL accelerator

$\boldsymbol{\theta_{12} \sim 34^\circ}$

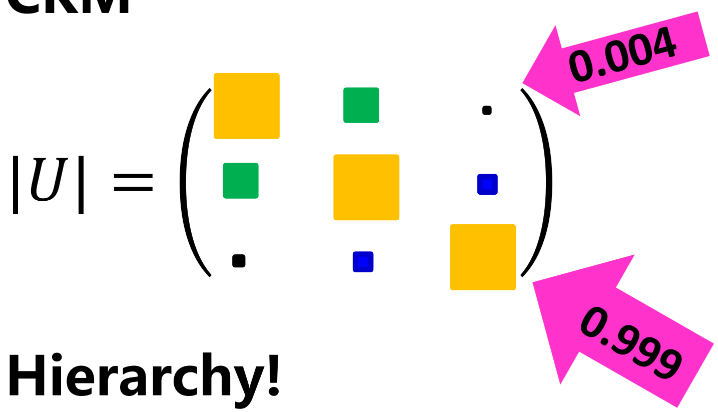
$\boldsymbol{\Delta m^2_{21} \sim 8 \times 10^{-5}\ \mathrm{eV}^2}$

Solar,
KamLAND

0ν2β, LNV?

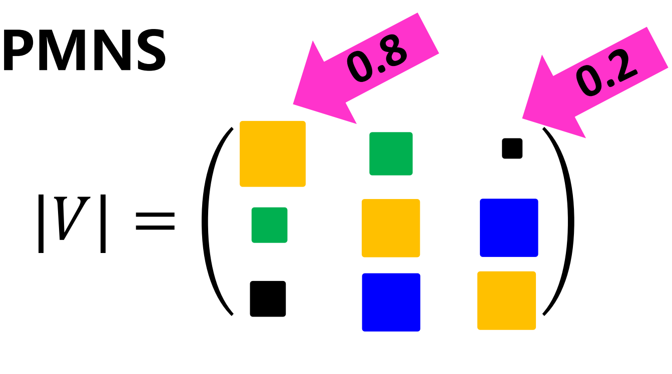
Quarks vs. Leptons: A big puzzle of fermion flavor mixings

CKM



Hierarchy!

PMNS



Approximate μ-τ symmetry?

Future Neutrino Puzzles

$\Delta m^2_{31}>0$?

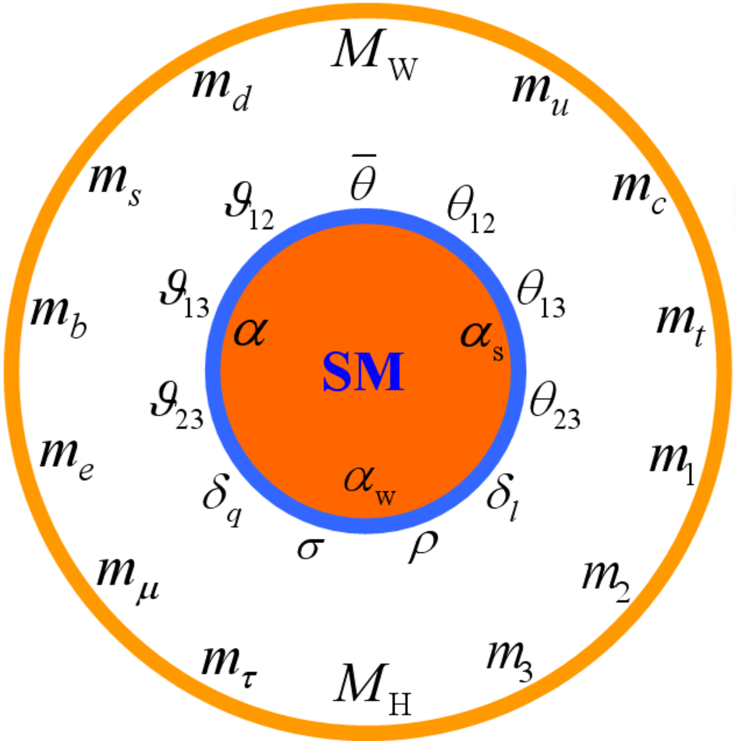
δ_{CP} ?

$\nu=\bar{\nu}$?

$U_{PMNS}U^{+}_{PMNS} = I$?

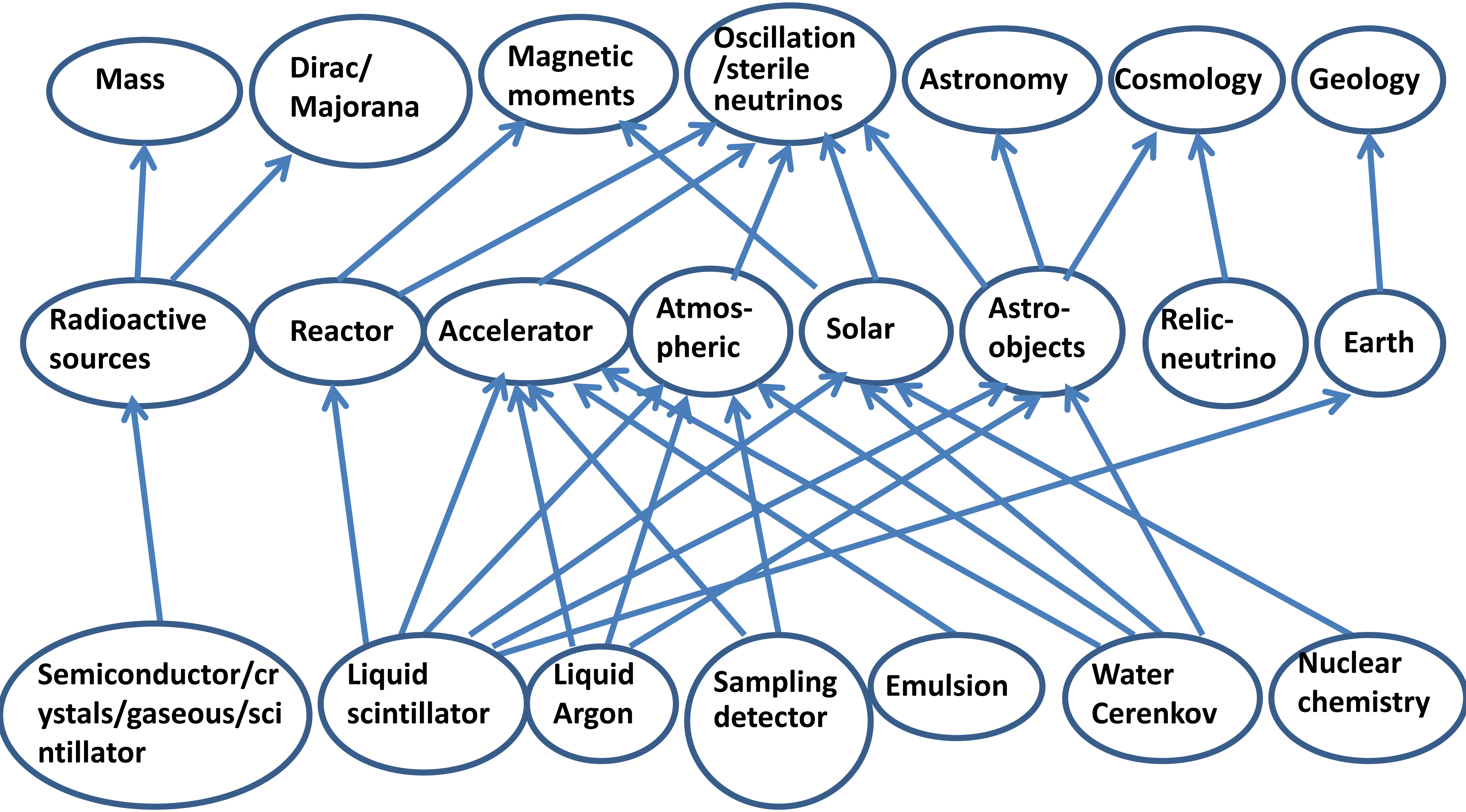
ν_s exists ?

…



Fritzsch-Xing Plot

Neutrino physics： problems and methods



Y.F. Wang @ TIPP2011

Selected Topics

- Neutrino oscillations (running & future)
  - Reactor neutrinos: Daya Bay, Double Chooz, RENO, JUNO, RENO-50, …
  - Accelerator neutrinos: T2K, NoVA, LBNF/DUNE
  - Atmospheric neutrinos: ORCA, Hyper-K, PINGU, INO, …
  - Solar neutrinos: SuperK, SNO, Borexino, …
  - Sterile neutrinos
- NLDBD searches
  - KamLAND-Zen, EXO, Gerda, Majorana, CUORE/CUPID, SNO+, NEXT, SuperNEMO, PandaX-III, AMoRE, CANDLES, COBRA, …
- Neutrino astronomy
  - Supernova → in combination with solar/atmospheric/reactor neutrino detectors
  - Geo-neutrinos → in combination with solar/reactor neutrinos
  - High energy neutrinos *(not covered in this talk)*

Precision Measurements

$\Delta m_{31}>0$?

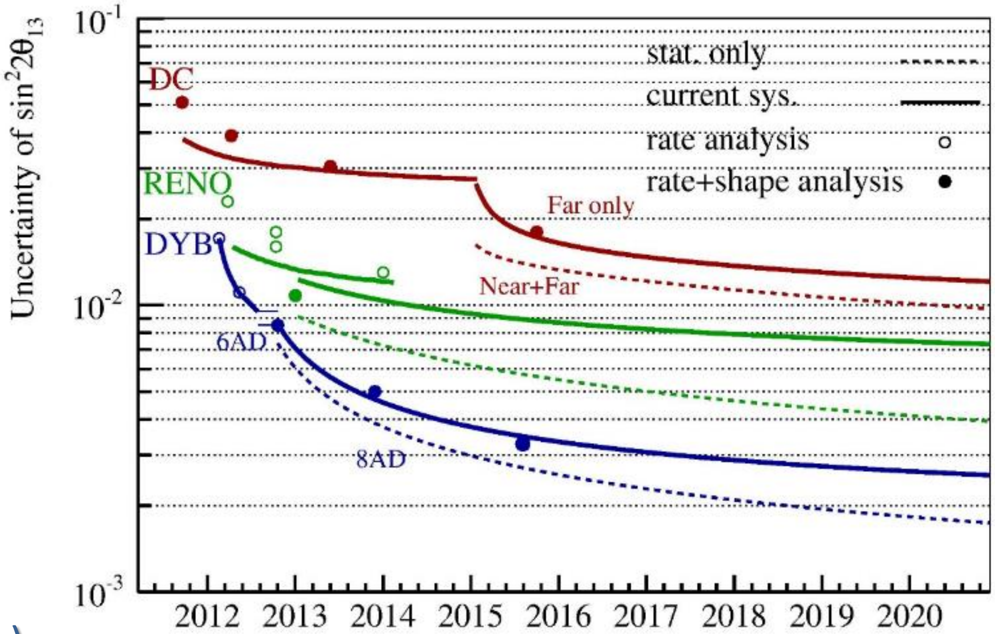
$\delta_{CP}=?$

$\nu=\nu$?

Apologies for incompleteness, bias and mis-handling

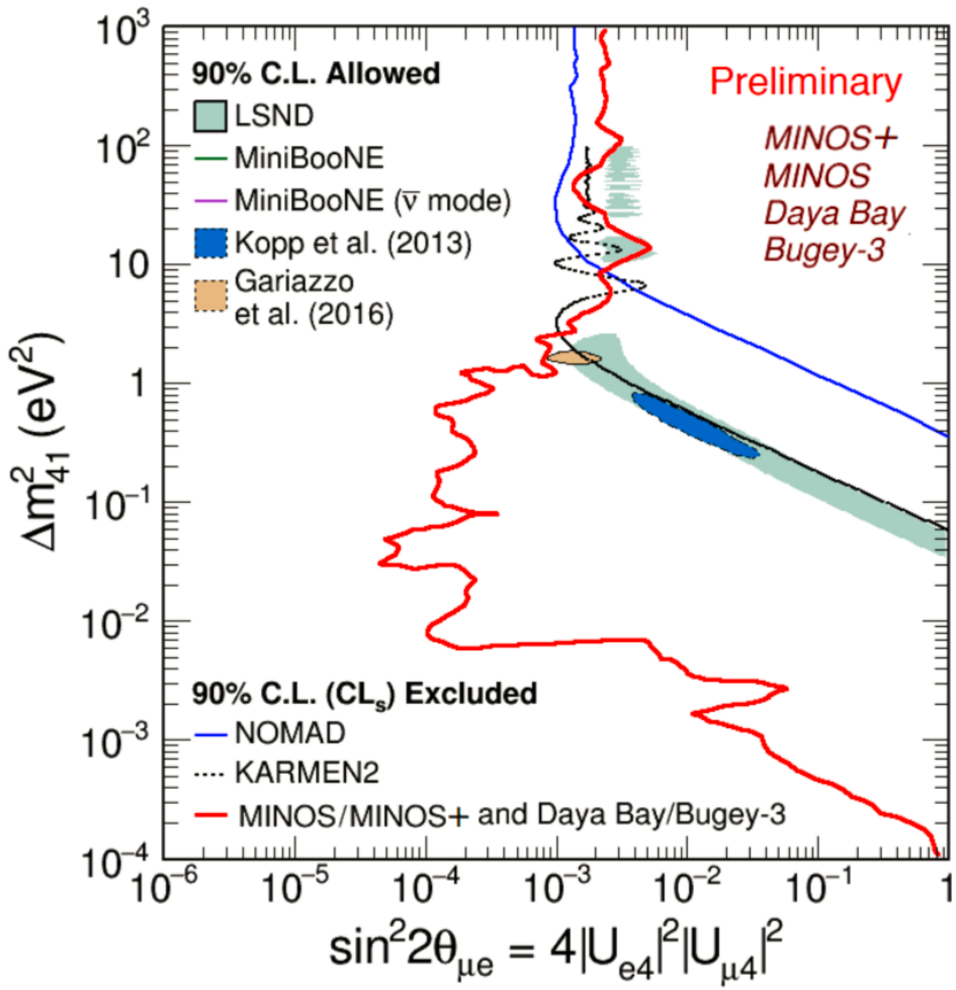
Reactor Experiments

- Daya Bay
  - $\Delta(\sin^2 2\theta_{13}) \sim 0.003 \rightarrow$ **~3%**
  - $\Delta(\Delta m^2_{ee}) \sim 0.07 \rightarrow$ **~ 3%**
  - operation till 2020
- RENO: ~5%.
  - operation funding secured until Feb. 2019
- Double Chooz: ~10%
  - secured to Jan. 2018 (may change)



by J. Zhao

Sterile ν exists?

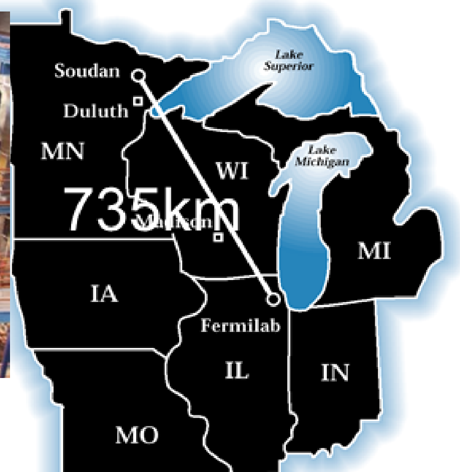


Parameter space allowed by LSND and MiniBooNE is excluded by the combination of MINOS(+), Daya Bay and Bugey-3

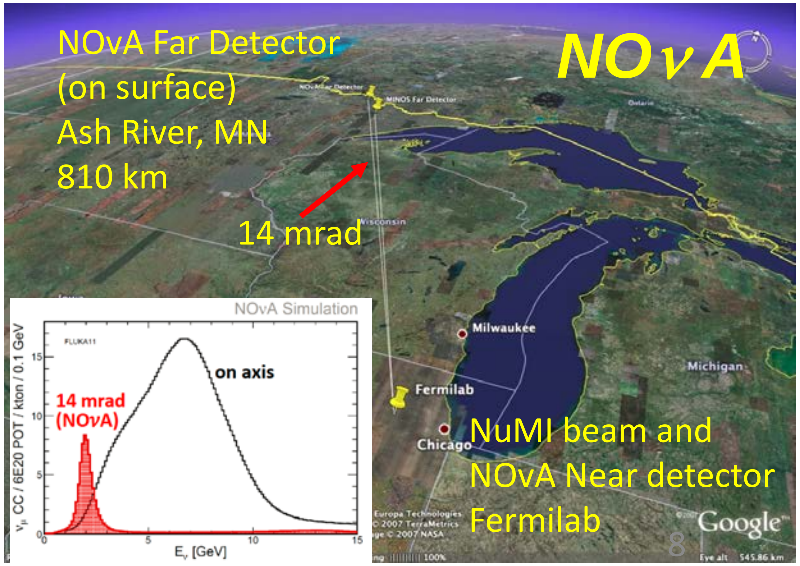
Next generation sterile experiments are almost ready

(SOX, PROSPECT, SoLid, Chandler, NEOS, Neurino4, DANSS, nuLat, …)

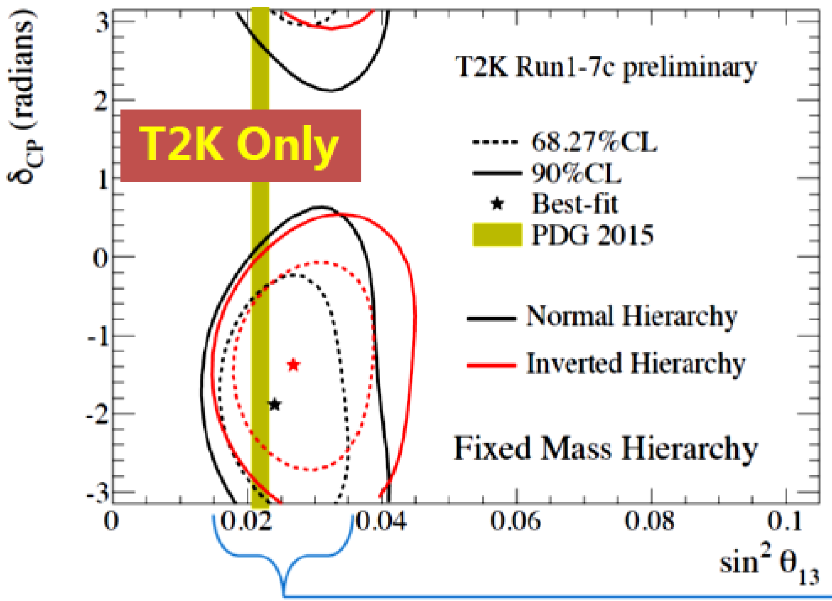
Accelerator Experiments

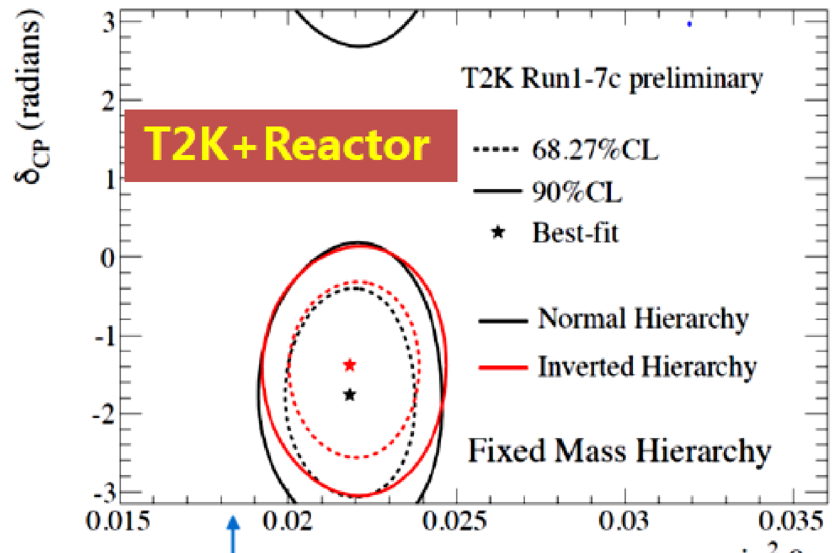


First generation LBL experiments ended

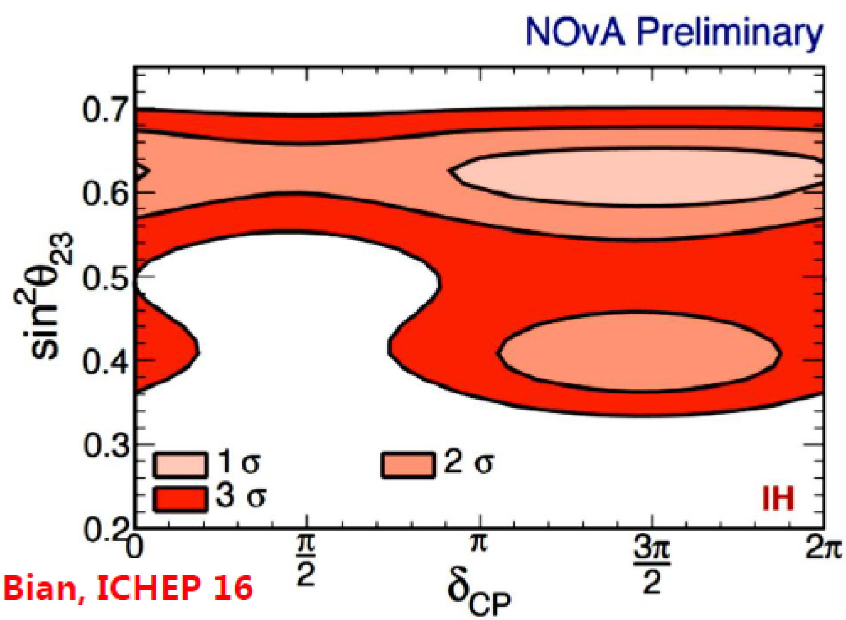


Hits on δ_{CP}





Iwamoto, ICHEP 16



Bian, ICHEP 16

T2K Results

- T2K-only consistent reactor data
- maximal mixing $\theta_{23} = 45^\circ$ favored
- maximal CP phase $\delta = -90^\circ$ favored

NOνA Results

- maximal mixing $\theta_{23} = 45^\circ$ excluded @ 2.5σ
- NH, $\delta \sim -90^\circ$ and $\theta_{23} \sim 39^\circ$ favored
- IH and $\delta \sim 90^\circ$ for $\theta_{23} < 45^\circ$ excluded @ 3σ

Future Neutrino Detectors for neutrino mass ordering and δ_{CP}

JUNO

RENO-50

Liquid scintillator

HYPER K

ORCA KM3NeT

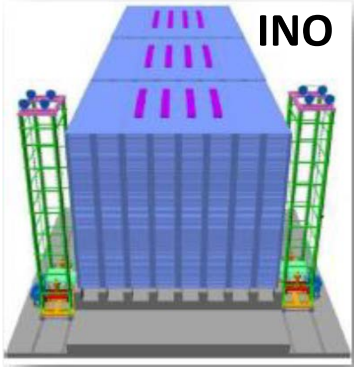
ICECUBE GEN2

Water/Ice

DUNE

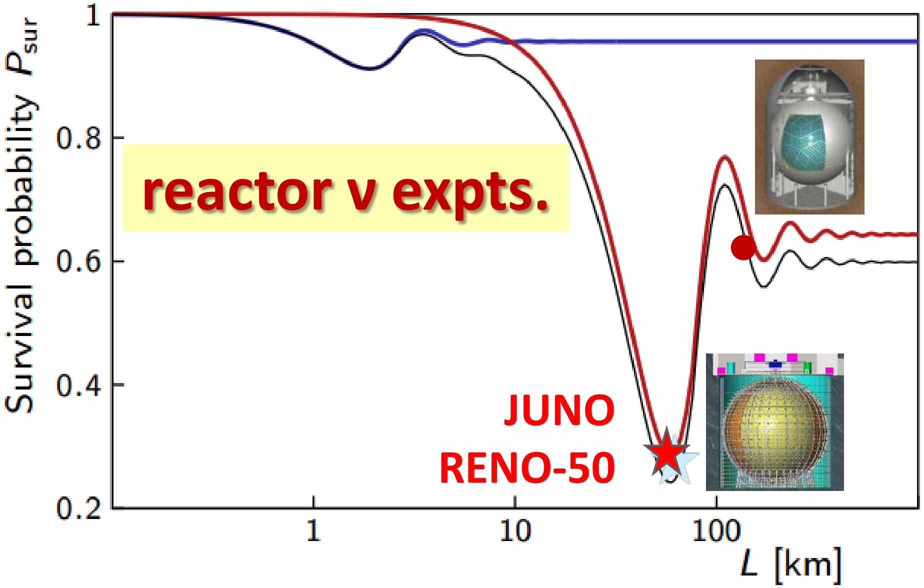
(protoDUNE,
MicroBooNE,
ICARUS-T600,
SBND)

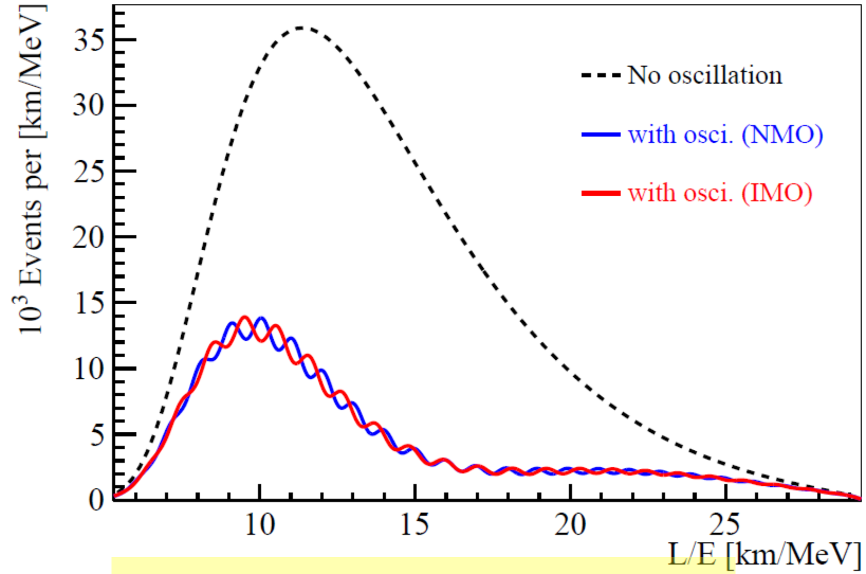
Liquid Argon



RPC/Ion

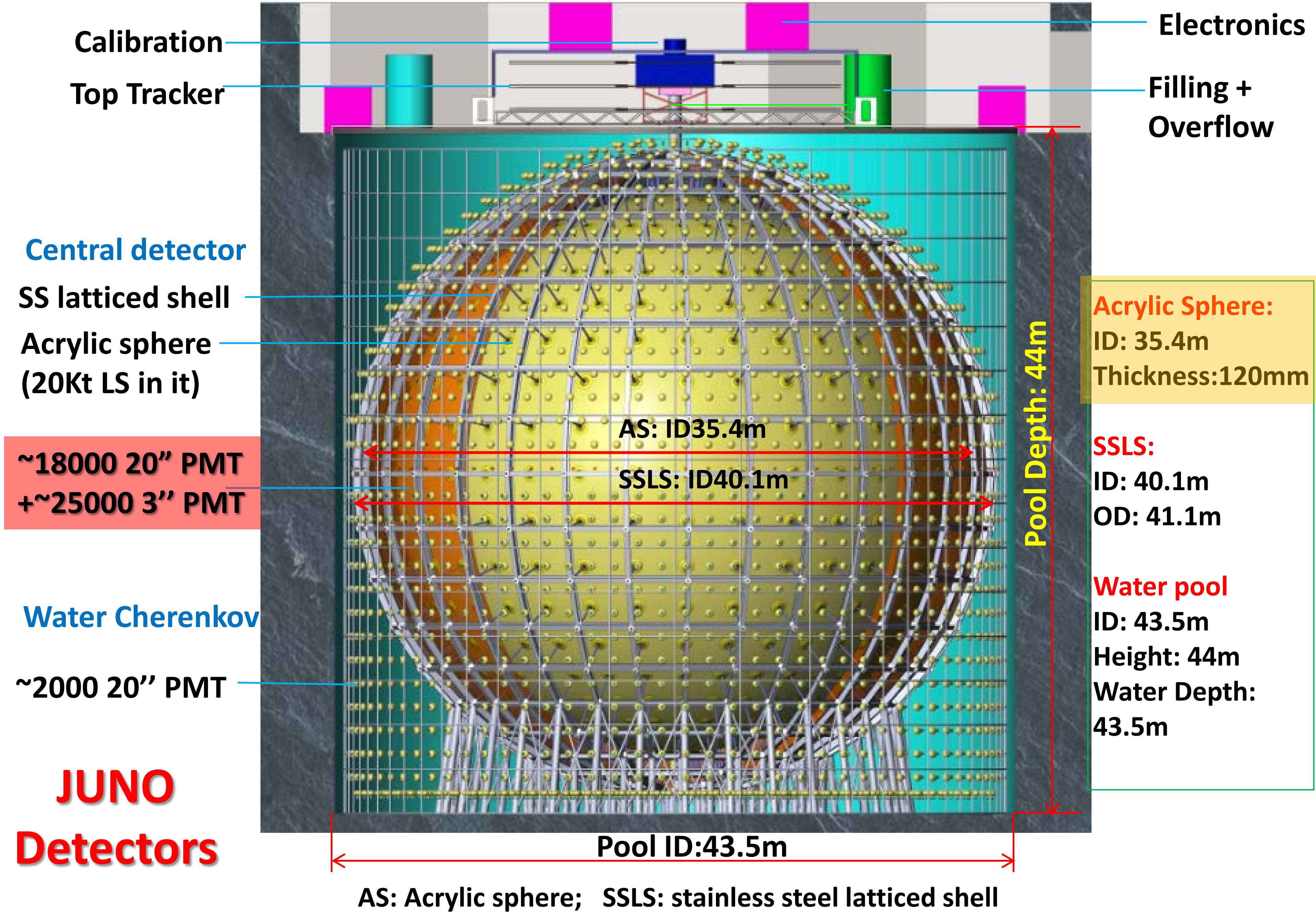
NMO determination at JUNO





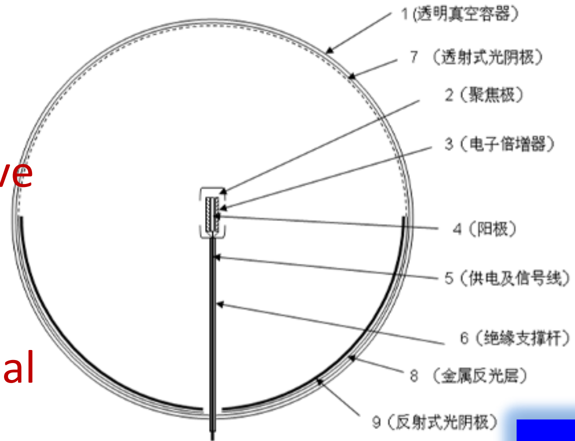
Independent on CP phase and θ_{23} (Acc. & Atm. do). Energy Resolution is the key

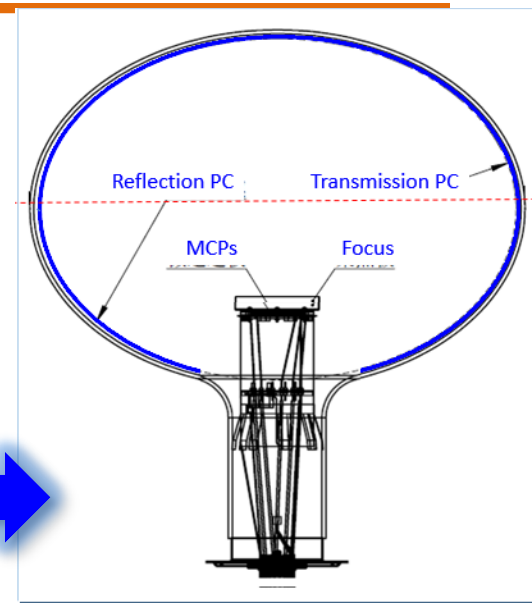
- **Physics** J. Phys. G43:030401 (2016)
  - NMO determination: 3-4σ in 2026
  - Precision measurement of 3/6 mixing parameters
  - Rich physics: supernova-ν, geo-ν, atmospheric-ν, solar-ν, exotics, etc
- **Key: get max. photons in a 20 kton LS detector**
  - High QE PMT, high coverage
  - High transparent LS (> 20m A.L @430nm)
  - Low radioactivity (< 10^{-15} g/g (U, Th))


Calibration
Top Tracker
Electronics
Filling +
Overflow
Central detector
SS latticed shell
Acrylic sphere
(20Kt LS in it)
~18000 20" PMT
+~25000 3" PMT
Water Cherenkov
~2000 20'' PMT
AS: ID35.4m
SSLS: ID40.1m
Pool Depth: 44m
Acrylic Sphere:
ID: 35.4m
Thickness:120mm
SSLS:
ID: 40.1m
OD: 41.1m
Water pool
ID: 43.5m
Height: 44m
Water Depth:
43.5m
Pool ID:43.5m
JUNO
Detectors
AS: Acrylic sphere; SSLS: stainless steel latticed shell

Success: 20” MCP-PMT

- Advantages:
  - Higher QE: transmissive photocathode at top + reflective photocathode at bottom
  - High CE: less shadowing effect
  - Easy for production: less manual operation and steps





Project Team

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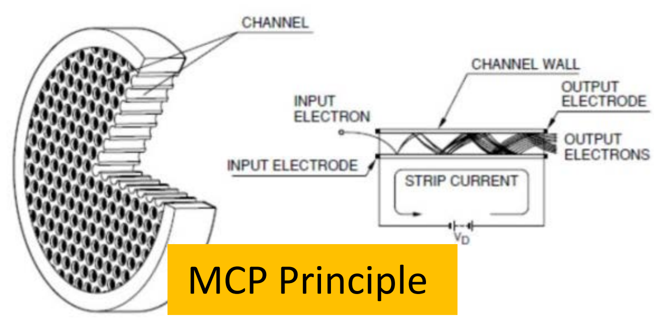
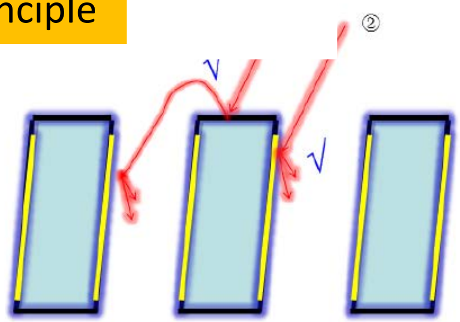
中国科学院西安光学精密机械研究所 XI'AN INSTITUTE OF OPTICS AND PRECISION MECHANICS OF CAS

中核（北京）核仪器厂 CNNC Beijing Nuclear Instrument Factory





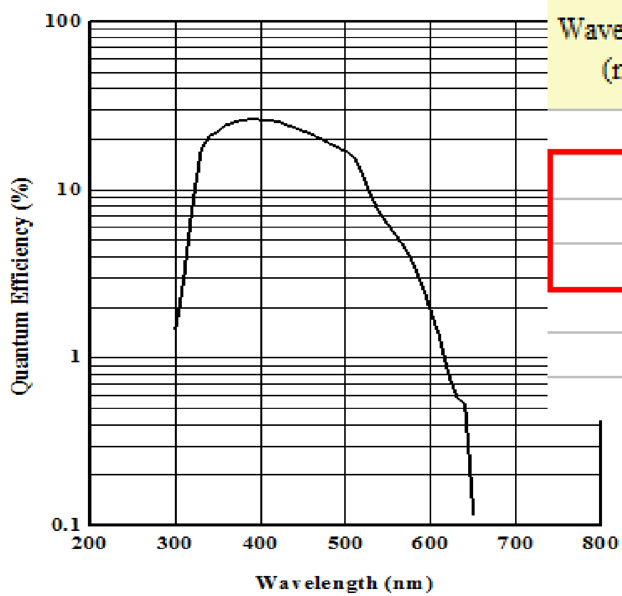
Design — 2009

5”(8”) Prototype — 2010~2013

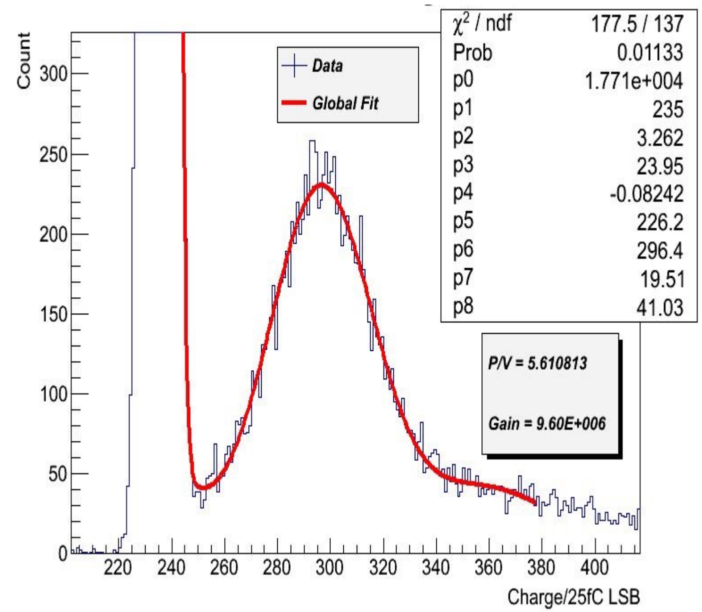
20” Prototype — 2013~2015

Production — 2016~2019

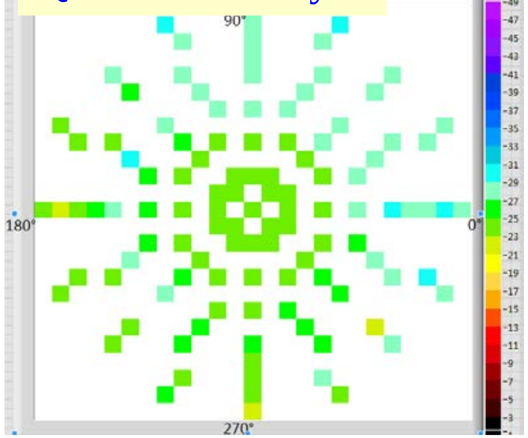
MCP-PMT Performance



Wavelength (nm)	79#
390	26.32155
400	26.18978
410	26.058
420	25.4807
430	24.47675
440	23.4516
450	22.37645

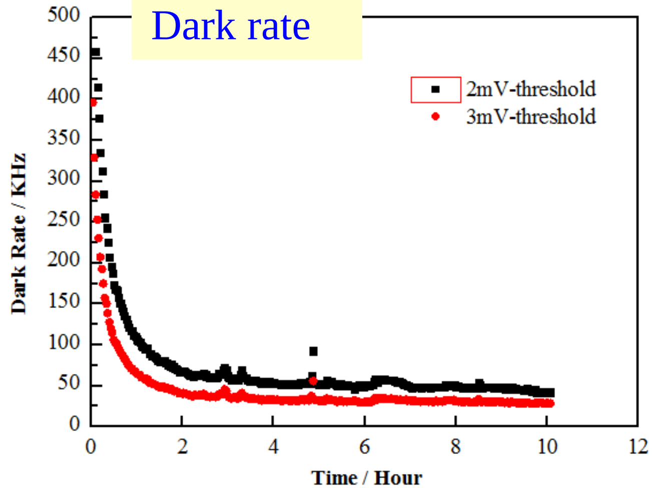


QE & uniformity

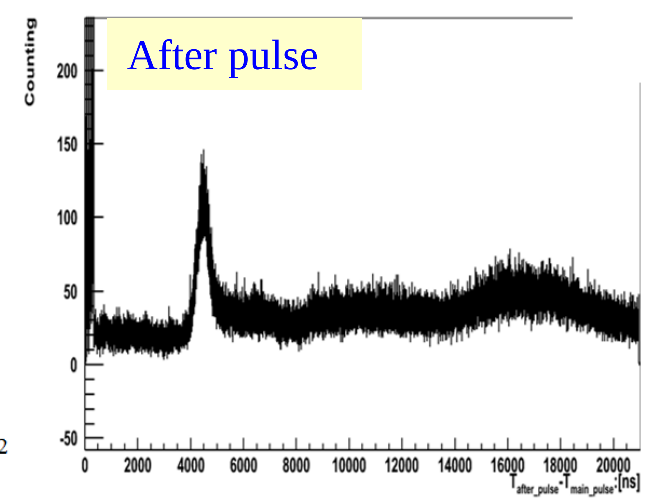


Min:24.5%; Max:29%
Average:26.5%

Dark rate



After pulse



PMT Purchasing of JUNO

Characteristics	unit	MCP-PMT（NNVC）	R12860（Hamamatsu）
Detection Efficiency (QE*CE*area)	%	27%, >24%	27%, >24%
P/V of SPE		3.5, > 2.8	3, > 2.5
TTS on the top point	ns	~12, < 15	2.7, < 3.5
Rise time/ Fall time	ns	R~2, F~12	R~5,F~9
Anode Dark Count	Hz	20K, < 30K	10K, < 50K
After Pulse Rate	%	1, <2	10, < 15
Radioactivity of glass	ppb	238U:50 232Th:50 40K: 20	238U:400 232Th:400 40K: 40

15k MCP-PMT (75%) from NNVT
5k Dynode(25%) from Hamamatzu

By Scaling PMT Spec for LS quantity to reach 3σ@ 6year ➔

Decision based on risk, price, performance merit for physics

Challenge: LS Purification

- Extremely clean LS in Borexino, relatively mature technology
- Technologies
  - Al_2O_3 column, distillation, gas striping, water extraction

$^{14}C/^{12}C \sim 2.7 \times 10^{-18}$

^{238}U (Bi-Po 214)
$< 9.7 \times 10^{-19}$ g/g (95% CL)

^{232}Th (Bi-Po 212)
$< 1.2 \times 10^{-18}$ g/g (95% CL)

^{40}K no evidence (TBD)

$^{39}Ar << {}^{85}Kr$

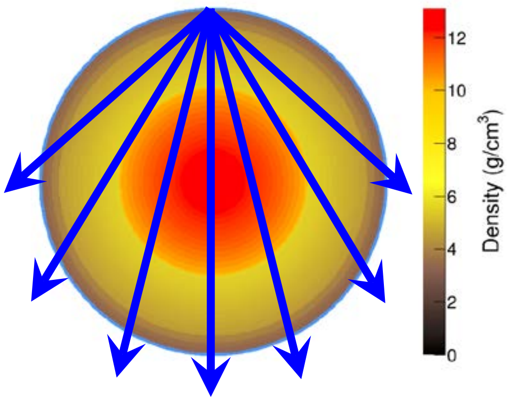
Borexino, N. Rossi @ Neutrino2016

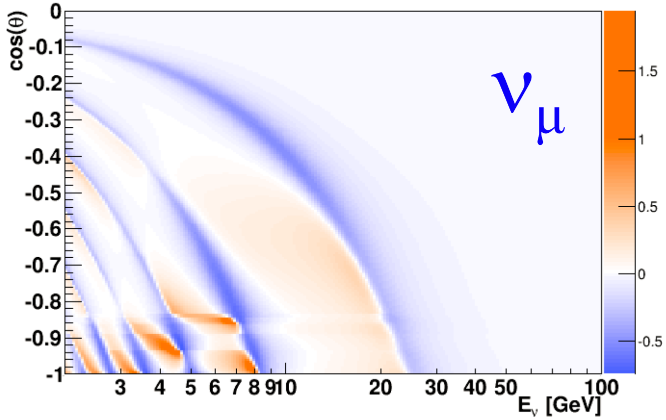
LS pilot plant in Daya Bay LS hall.

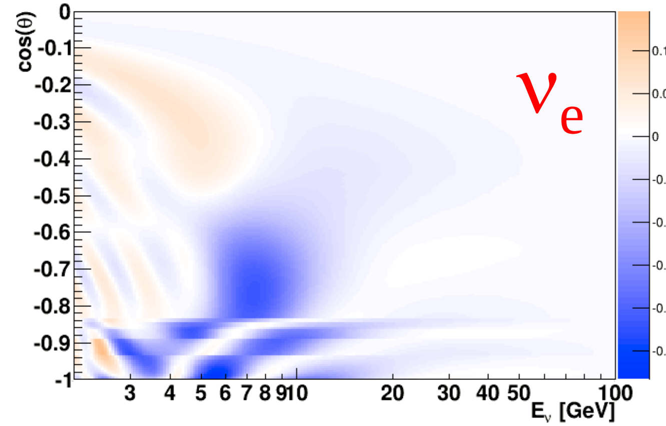
A new batch of purified LS was produced and filled into DYB-AD1.
→ evaluate radioactivity
→ optimize LS recipe

NMO & δ_{CP} determination via Matter Effects

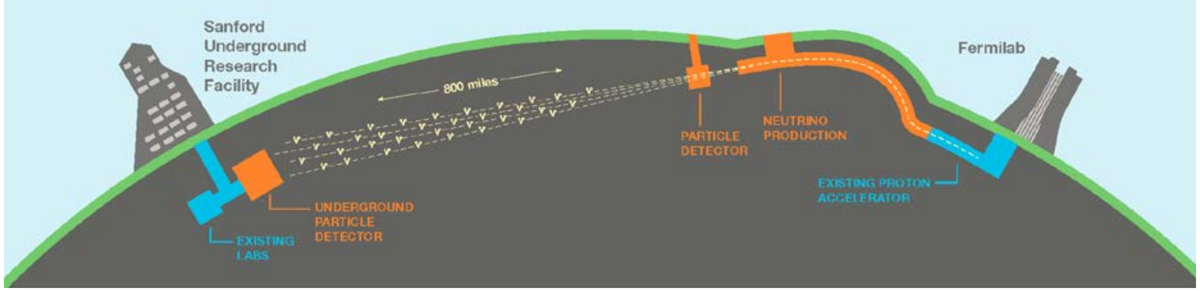
Atmospheric ν

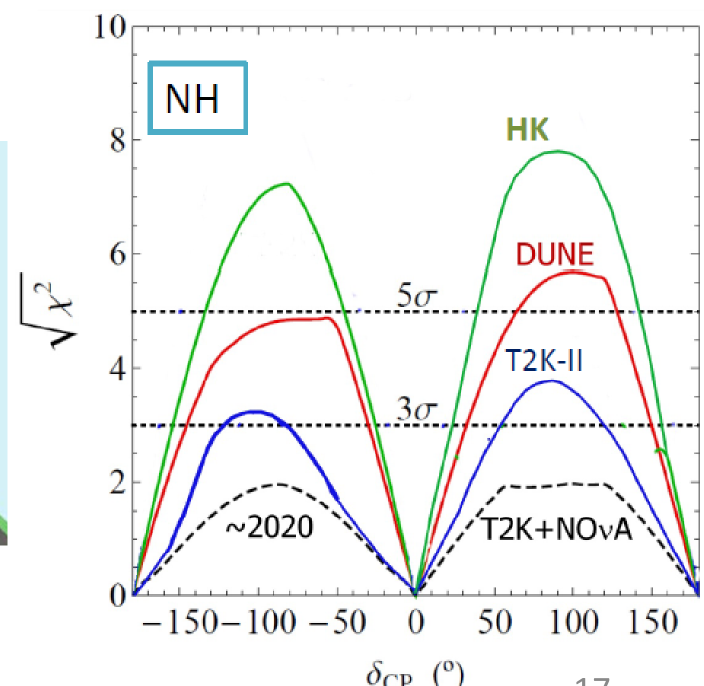




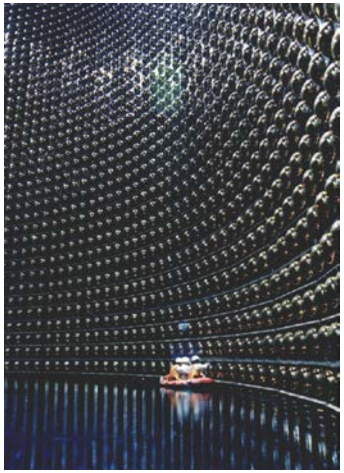


Accelerator ν





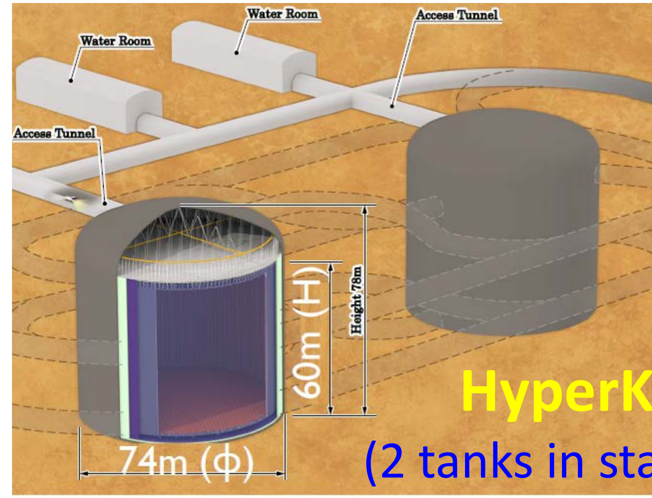
Hyper Kamiokande



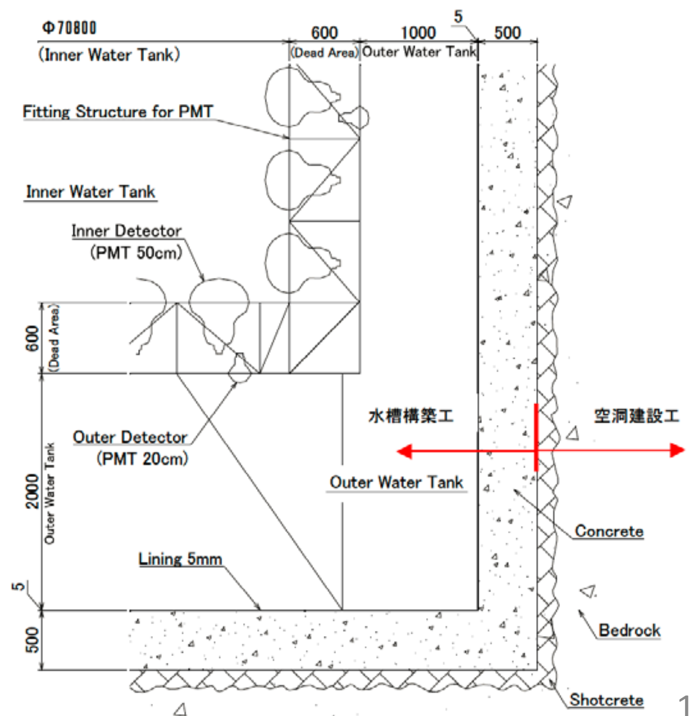
SuperK

50 kt, PMT coverage: ~40%
Threshold: ~4 MeV
Light yield: 6 PE/MeV

20x larger,
same photo-coverage
better PMTs



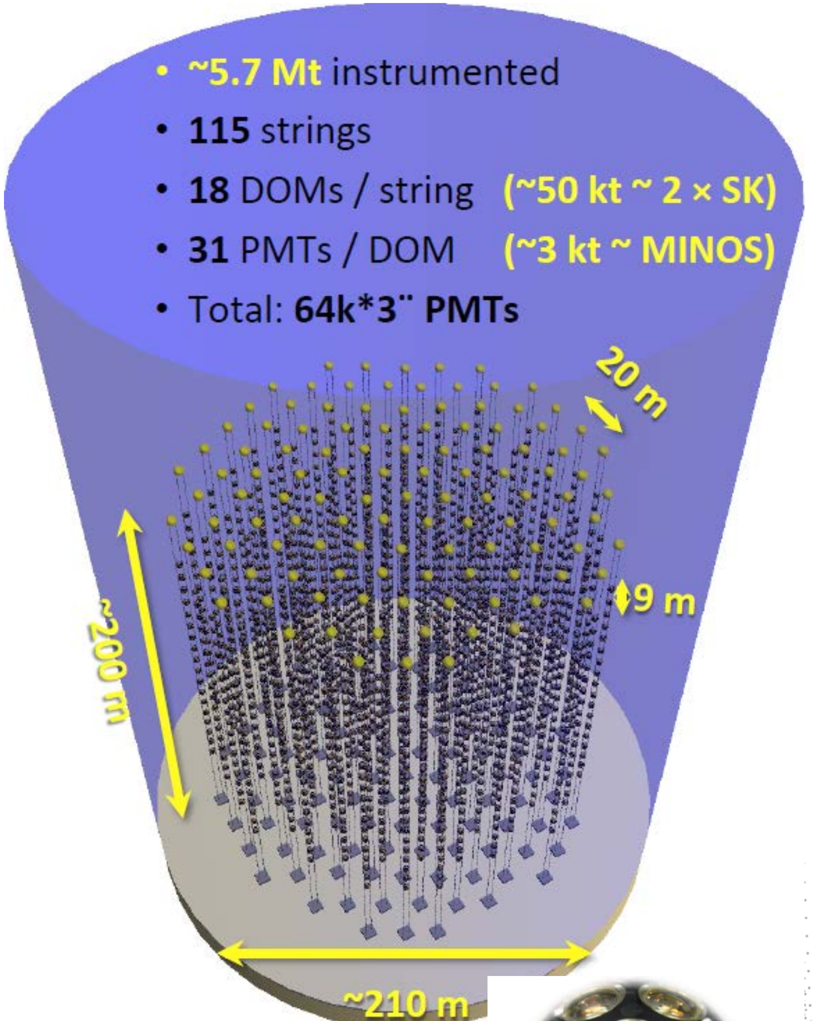
(2 tanks in stages)



- Technical issues
  - PMTs protection under pressure (60 m)
  - Water circulation system
  - High eff. PMT

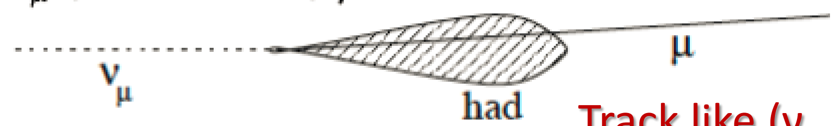
ORCA

- **~5.7 Mt** instrumented
- **115** strings
- **18** DOMs / string (~50 kt ~ 2 × SK)
- **31** PMTs / DOM (~3 kt ~ MINOS)
- Total: **64k*3¨ PMTs**



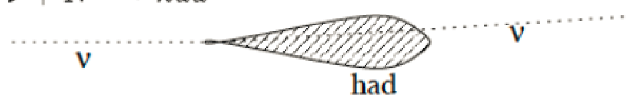
Depth=2475m

$$\nu_\mu + N \xrightarrow{cc} had + \mu$$



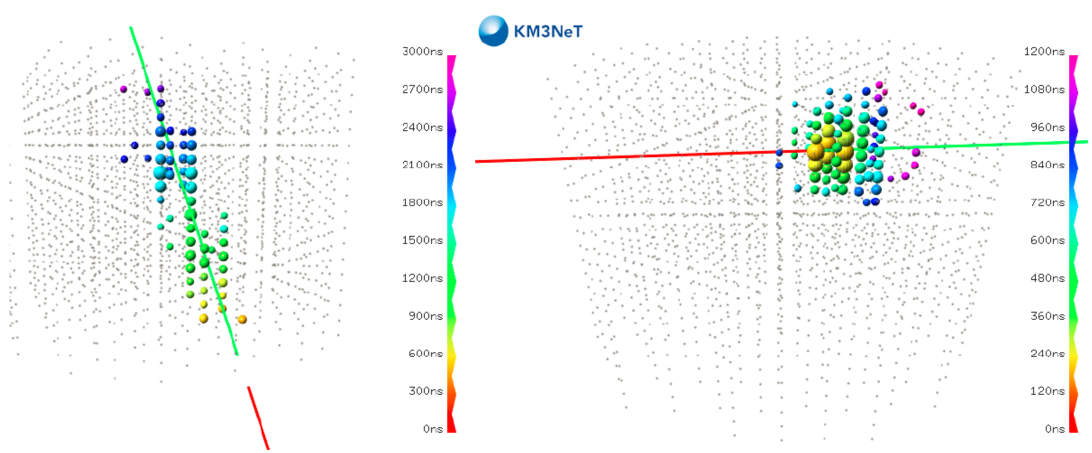
Track like (ν_μ CC)

$$\nu + N \xrightarrow{cn} had$$



Shower like (ν NC, ν_e CC)

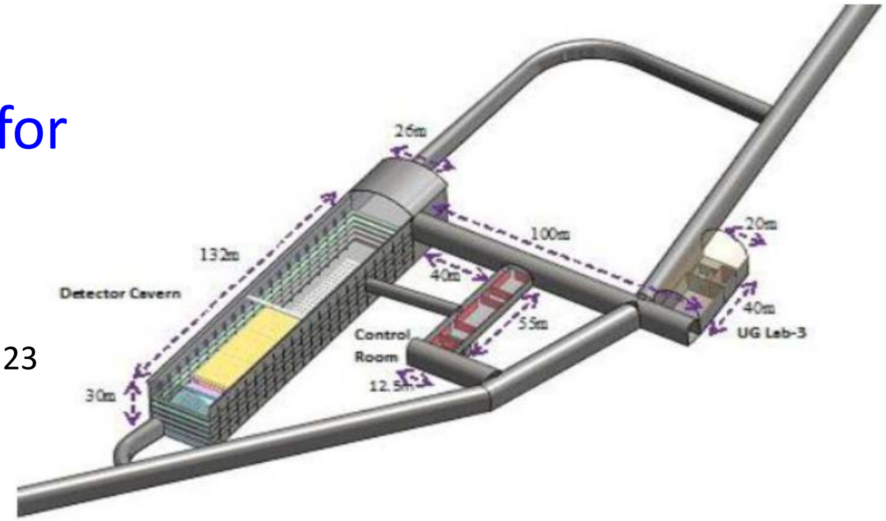
$$\nu_e + N \xrightarrow{cc} had + em$$



Optical module
31 x 3" PMTs

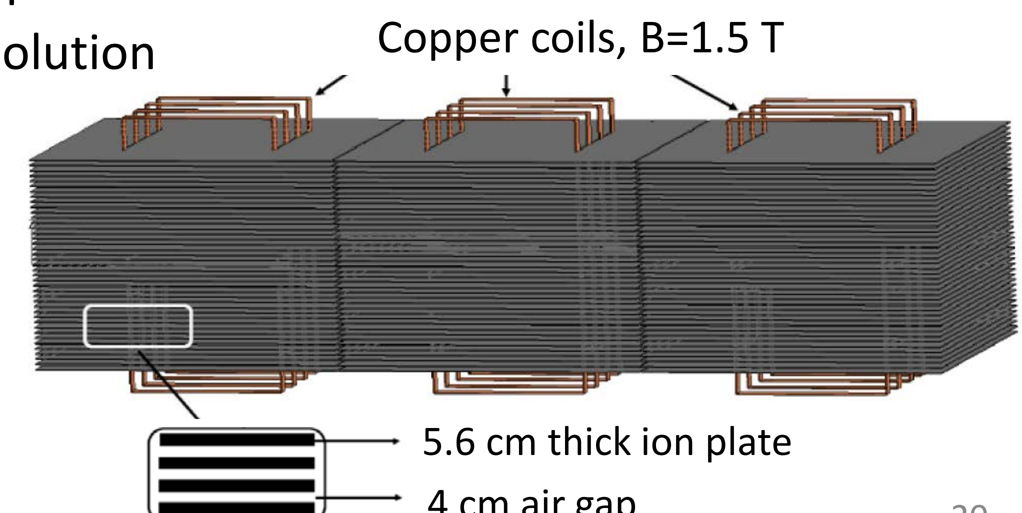
Indian Neutrino Observatory: INO

- 50kt magnetized Iron CALorimeter detector (ICAL) interleaved by RPC for detecting atmospheric neutrinos
  - Neutrino mass ordering
  - Octant and precision of $|\Delta m^2_{31}|$ and θ_{23}
  - New physics
  - Magnetic monopole search
- Features:
  - Muons fully contained up to 20 GeV
  - Good charge resolution, B=1.5 T
  - Good tracking/Energy/time resolution



3 modules, 151 layers

One module:
16 m x 16 m x 14.5 m



EGADS and SK-Gd

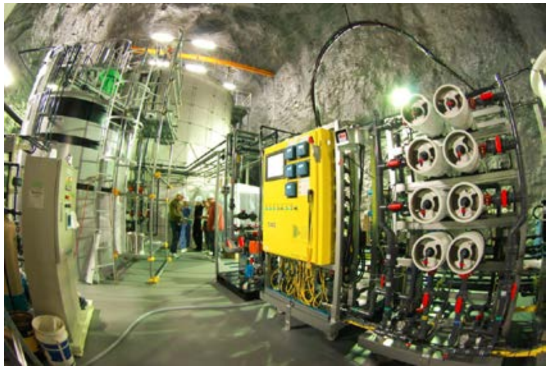
- Gd in water:
  - $GdCl_3$ highly soluble in water
  - Improve low energy detection capabilities
  - flavor sensitive
  - Good for LBNE, supernova, reactor and geo-neutrinos, …
- A 200 ton-scale R&D project, EGADS – is under construction at Kamioka

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

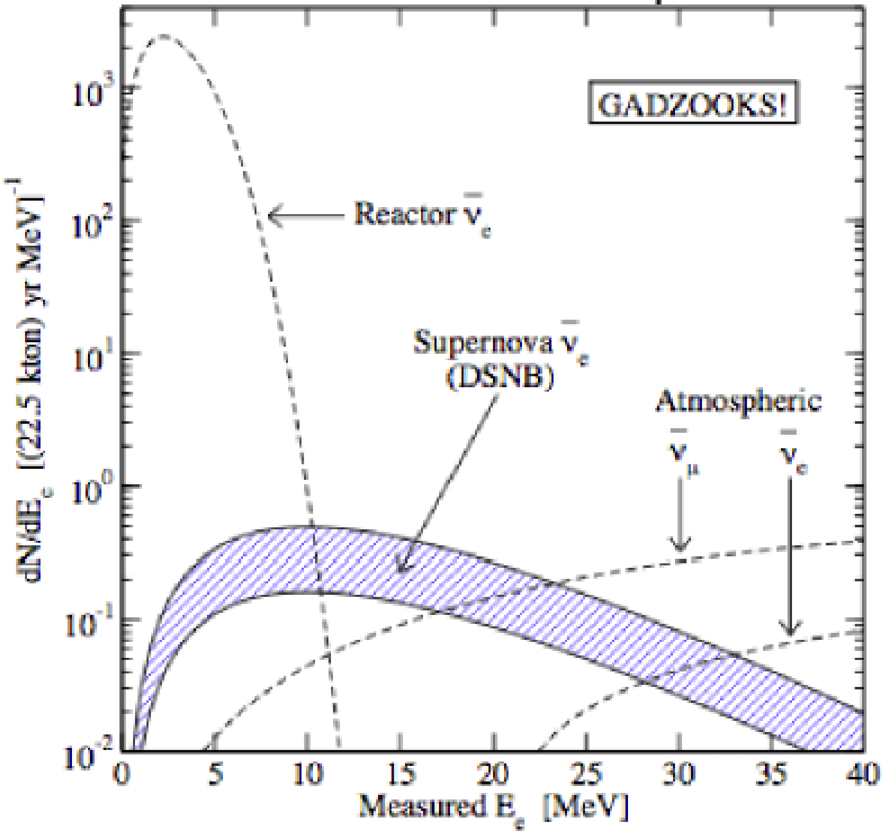
$$n + p \rightarrow d + \gamma\ (2.2\ \text{MeV})$$

$$n + Gd \rightarrow Gd^* + \gamma\ (8\ \text{MeV})$$

$$\tau \approx 28\ \mu s\ (0.1\%\ Gd)$$

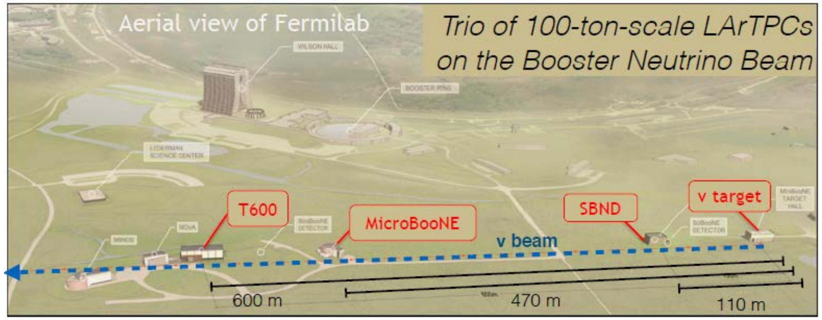


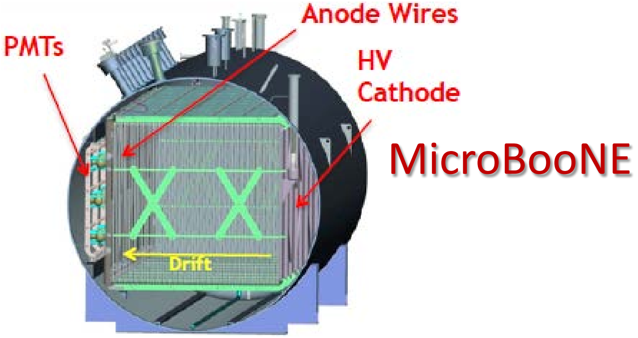
Gd in SuperK:

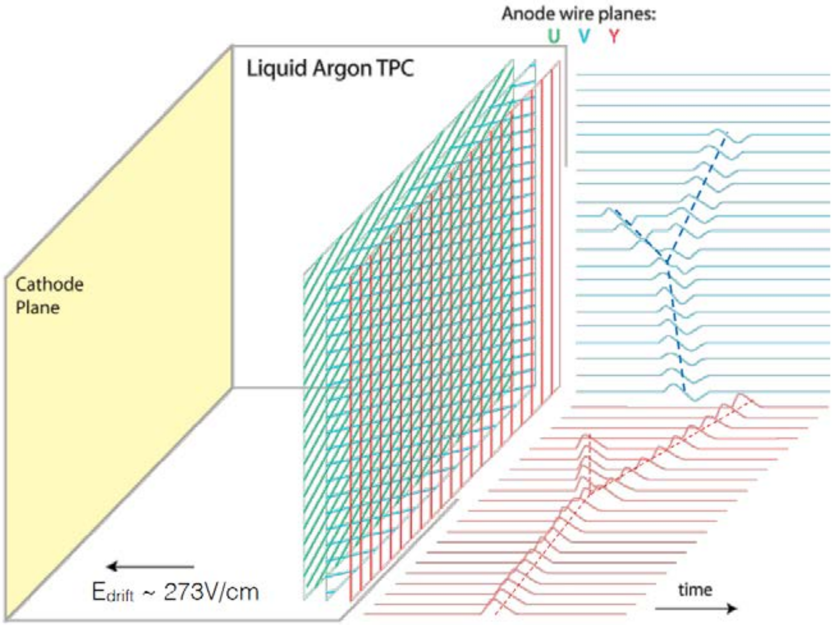


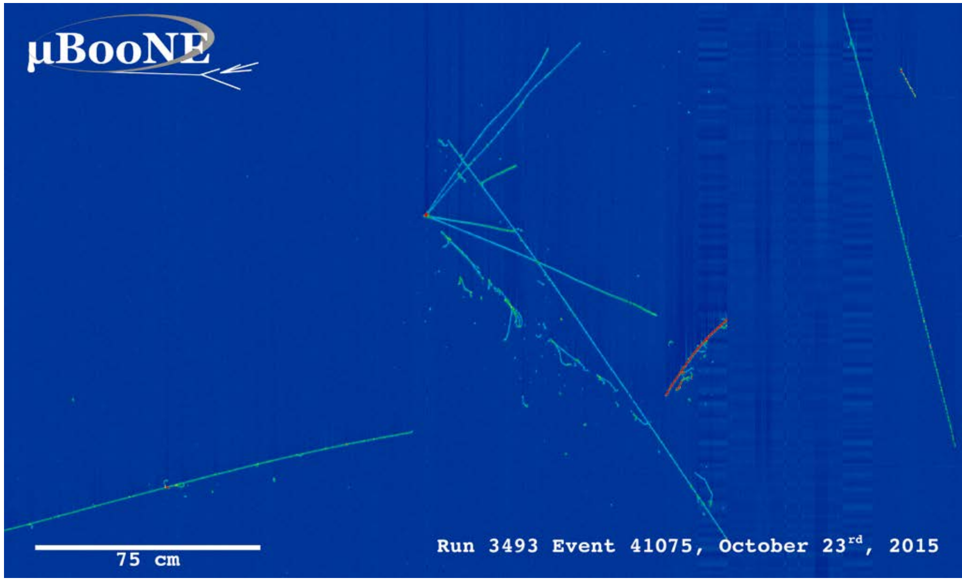
Liquid Ar TPC

- Idea first proposed in 1985
  - Dense target
  - ample Ionization & scintillation:
    good energy resolution & Low threshold
  - Excellent tracking and PID capabilities
- Challenges
  - LAr purity (long-drift)
  - Readout wires or large electron multipliers
  - Cold electronics
  - Cryostat for multi-kiloton TPC



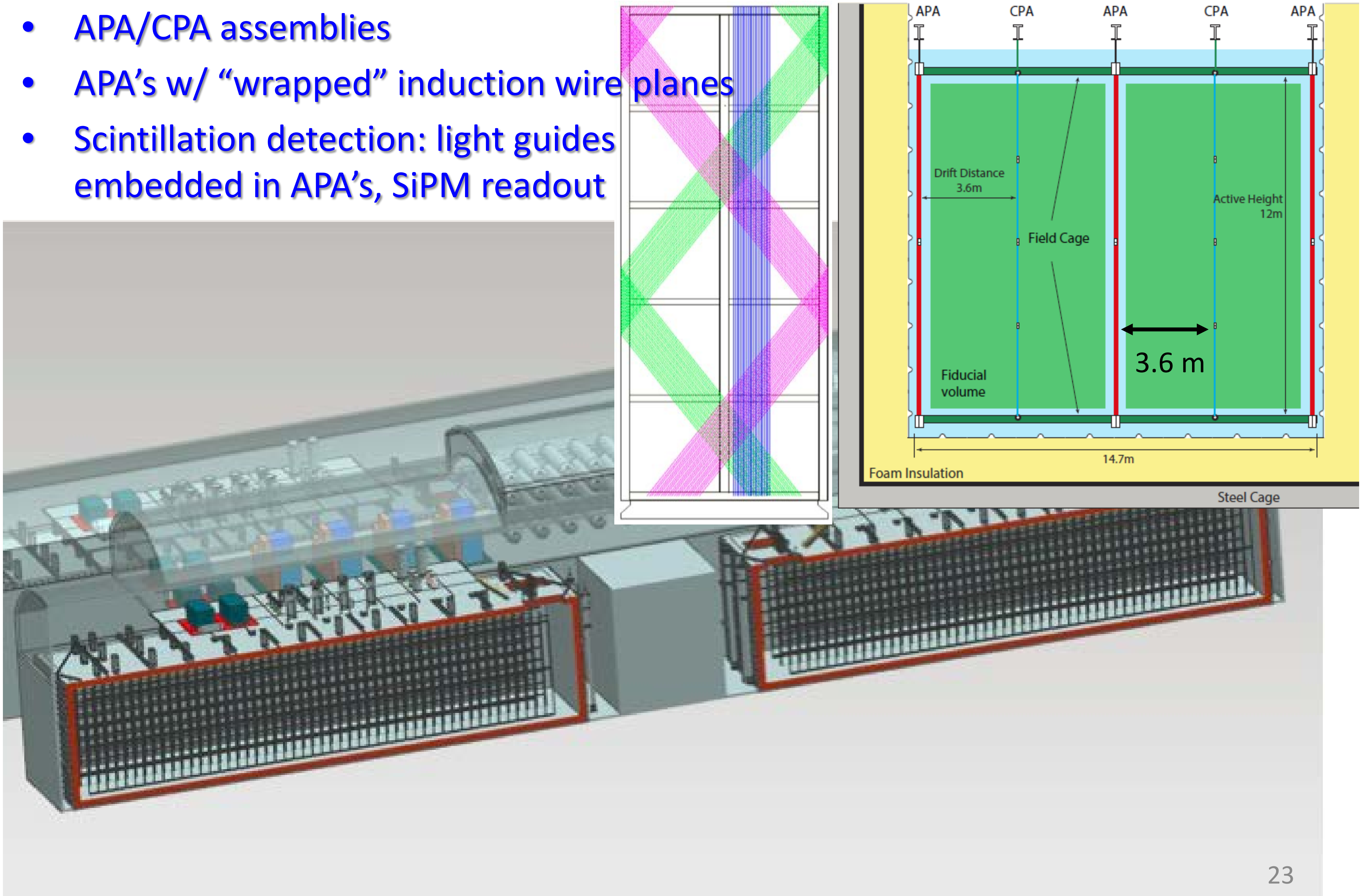






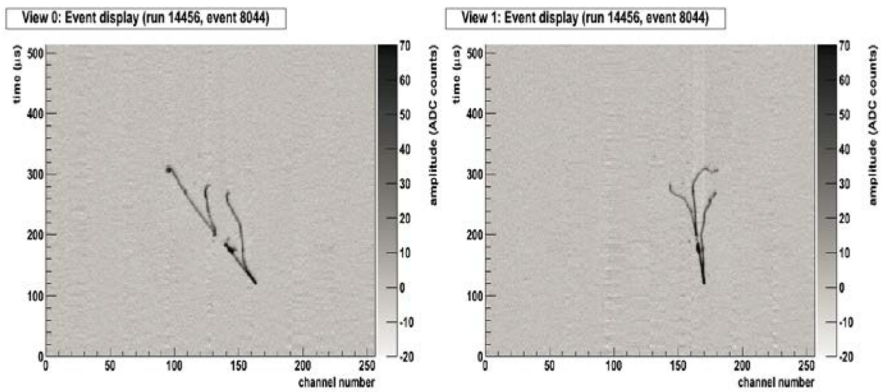
DUNE LArTPC R&D: Single-Phase

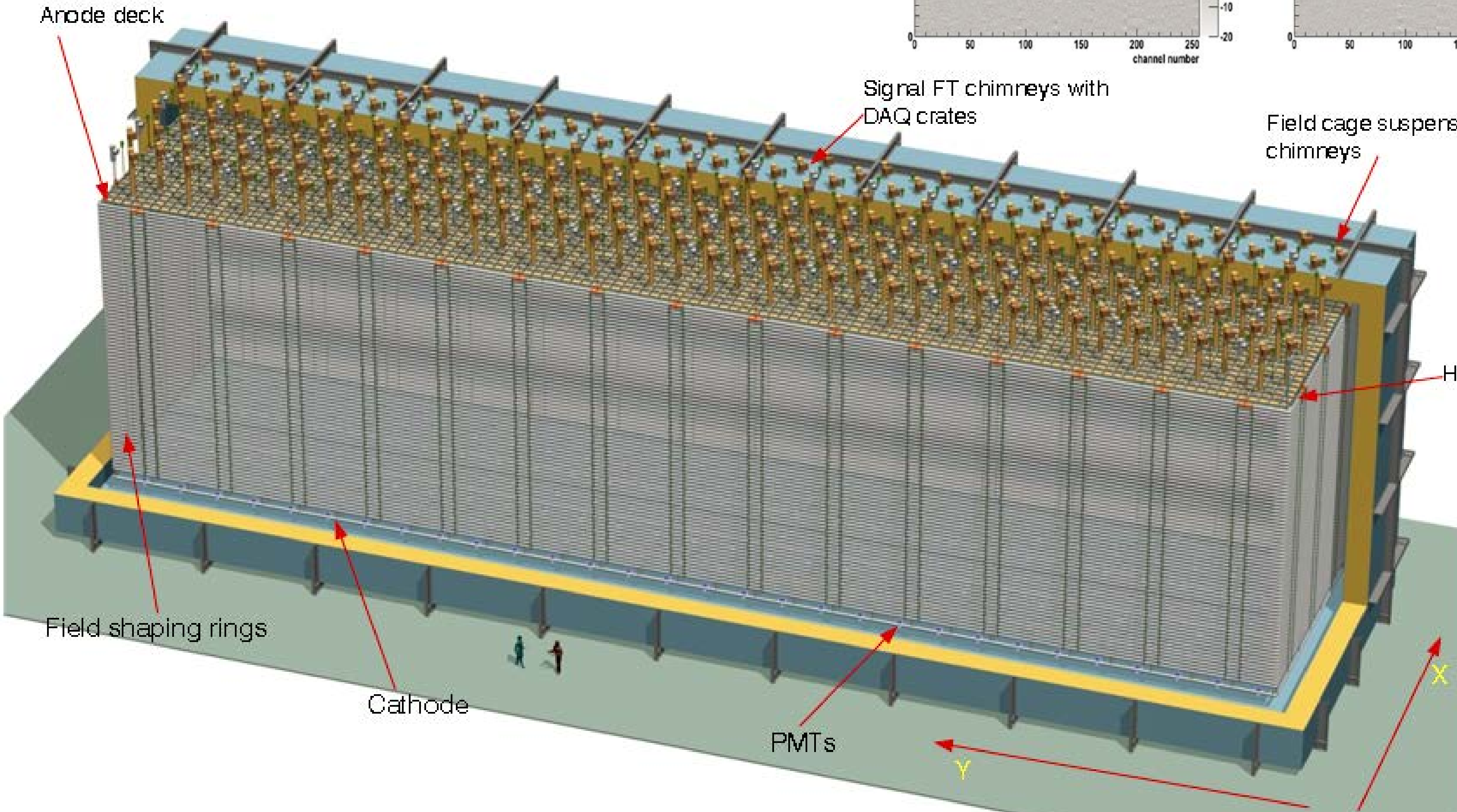
- APA/CPA assemblies
- APA's w/ "wrapped" induction wire planes
- Scintillation detection: light guides embedded in APA's, SiPM readout



DUNE LArTPC R&D: Dual-Phase

- 12m max drift (vertical), LEM readout
- S/N: ~100/1
- Scintillation via PMT's below cathode

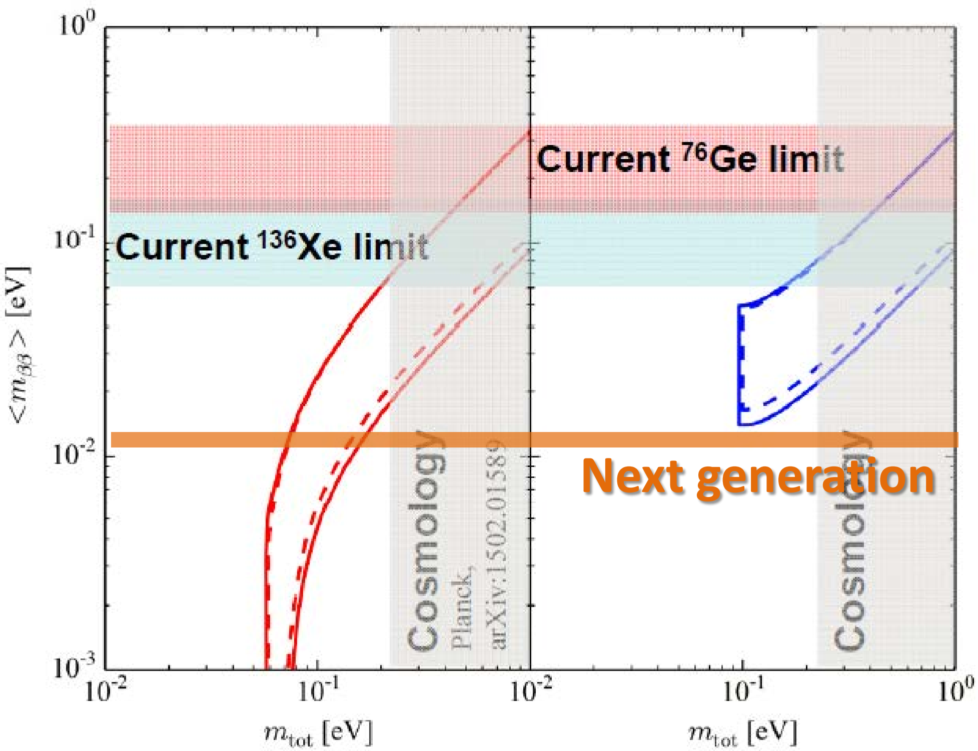


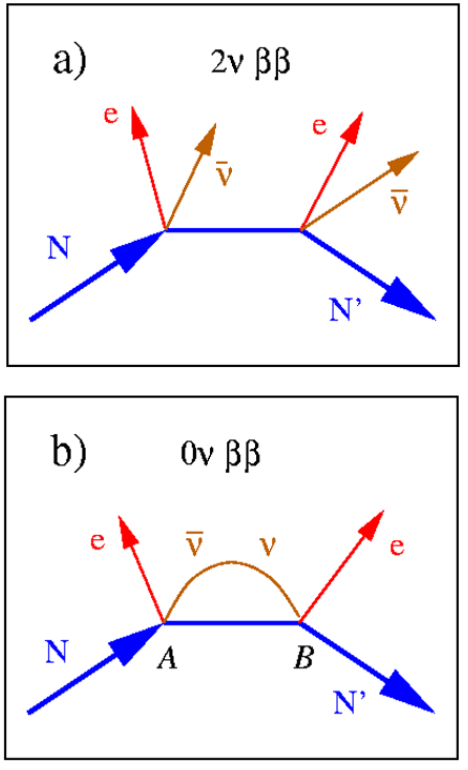


NLDBD experiments

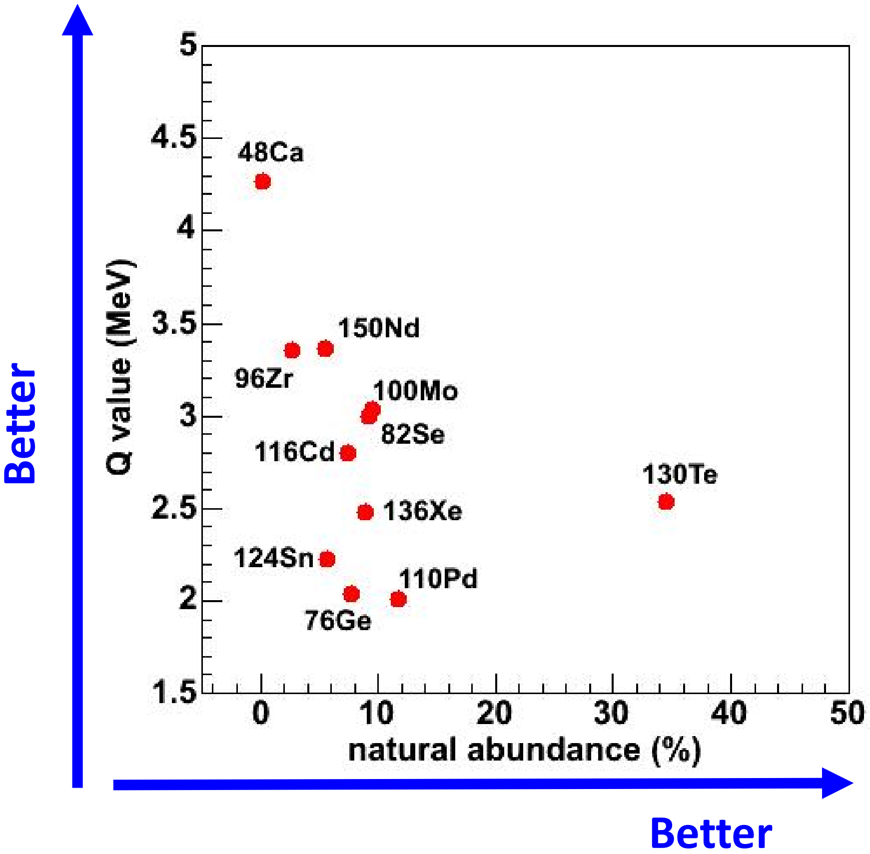
0νββ Decay

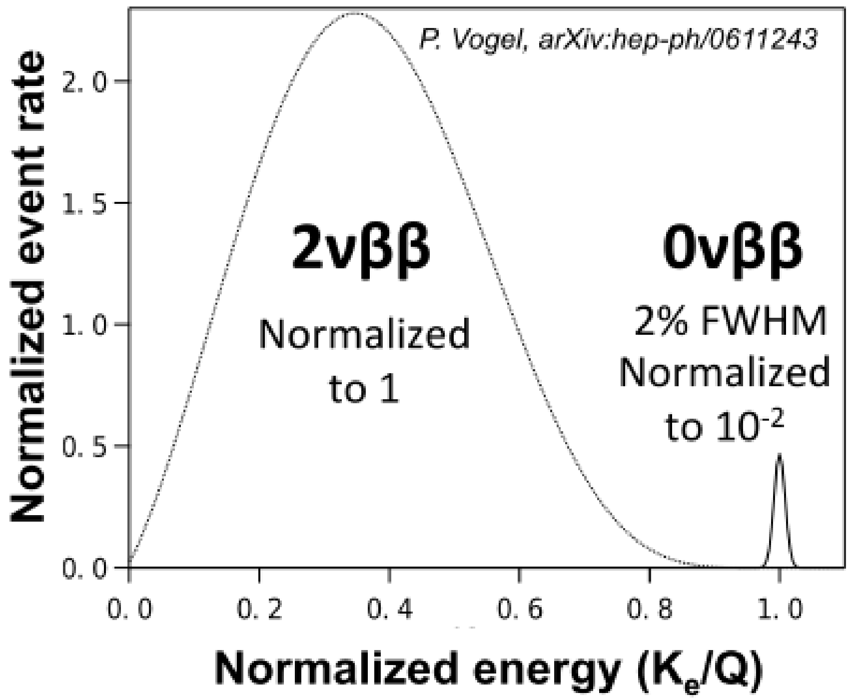
- Unique feasible way to determine the Majorana nature of ν. Possible to pin down mass ordering
- Lepton number violation process
- If Majorana: a natural way to understand tiny ν masses (seesaw)
- Set constraints on 2 Majorana-type CP-violating phases





0νββ Decay





Different isotopes correspond to vastly different experimental techniques

- Ultra-low external background
- Good energy resolution
- Large detector volume

Technologies

^{136}Xe

supernemo collaboration

Feature: Topological information
Challenge: very large size

^{82}Se (^{130}Te, ^{116}Cd, ^{48}Ca, ^{96}Zr, ^{150}Nd, ^{100}Mo)

^{136}Xe ^{130}Te

Feature: existing large clean detector; self-shielding
Challenge: 2νββ background, internal purity

^{76}Ge ^{130}Te

Feature: excellent energy resolution
Challenge: very large size; segmented

Enriched Xenon Observatory for double beta decay

^{136}Xe

Feature: homogeneous; decent energy resolution; 3D toponology
Challenge: 2νββ background, internal purity

CUPID ($Zn^{82}Se$, $Li_2{}^{100}MoO_4$, TeO_2), **AMoRE** (^{100}Mo), **CANDLES** (^{48}Ca), **ZICOS** (^{96}Zr), **AXEL** (^{136}Xe), **DCBA** (^{100}Mo/ ^{150}Nd), **COBRA** (CdZnTe), …

Sensitivity vs. Background and Exposure

For a none background-free experiment, the sensitivity (1st order) of 0vββ decay half-life.

Detector Exposure

Detector efficiency

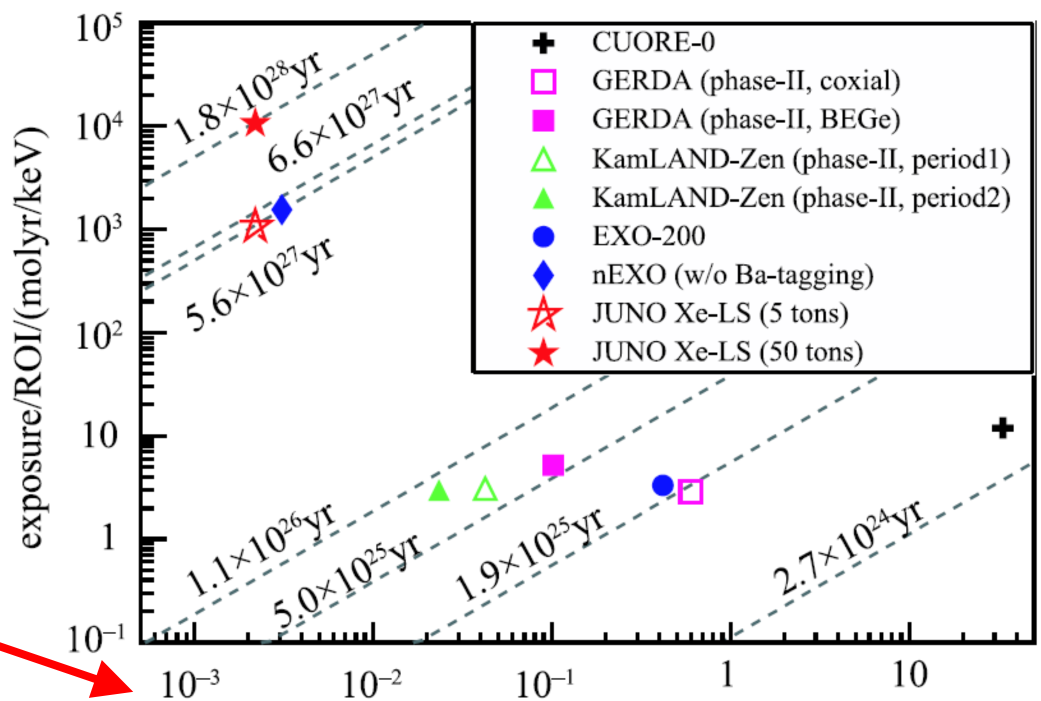
$$T^{0\nu\beta\beta}_{1/2} = \frac{\ln 2 \cdot N_A}{M_{isotope}} \cdot \frac{Mt \cdot \epsilon \cdot \eta}{\alpha \cdot \sqrt{b}}$$

Isotope abundance

Background in ROI

* For 90% C.L, α=1.64

$$T^{0\nu\beta\beta}_{1/2} \cdot \frac{\alpha M_{isotope}}{\ln 2 \cdot N_A} = \frac{\sqrt{Mt/\mathrm{ROI}} \cdot \epsilon \cdot \eta}{\sqrt{b/(Mt)/\mathrm{ROI}}}$$



background index in ROI/(10^{-3} cnts/keV/mol/yr)

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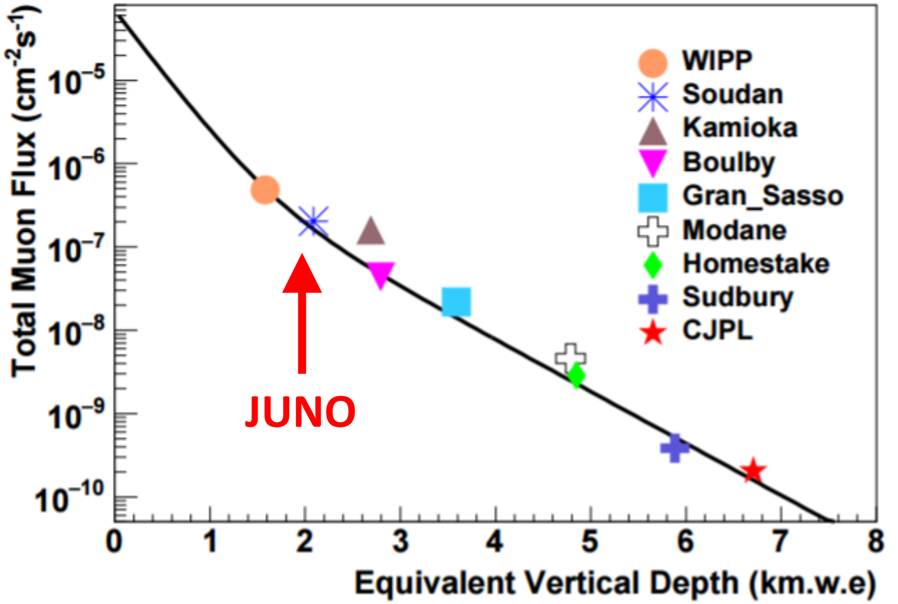
Fundamental Requirements

- Enrichment of the source material
  - 10 kg/100 kg scale → ton scale

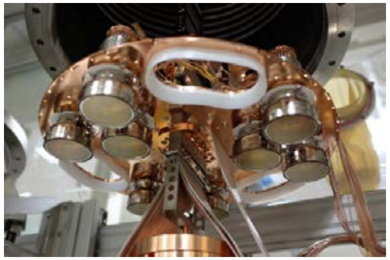
- Deep underground location to shield cosmogenic backgrounds

Several underground labs around the world,
next round of experiments 1-2 km deep.



Fundamental Requirements

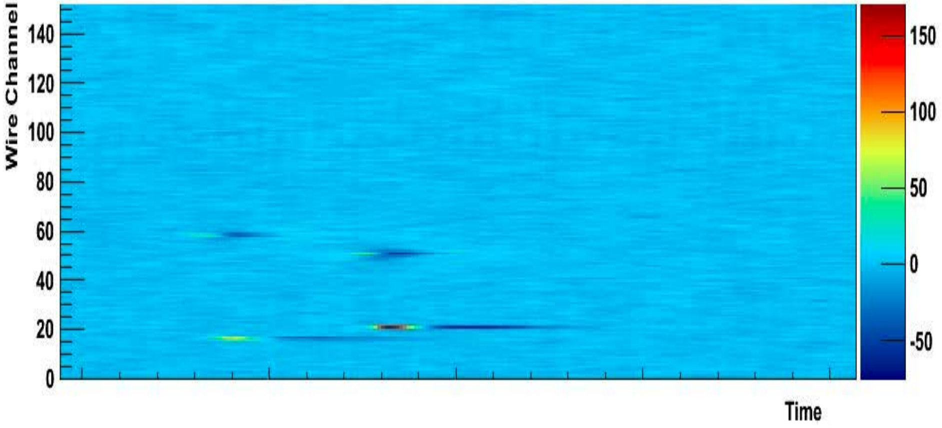
- Ultra-low radioactive contamination during detector construction



Materials used ≈$<10^{-15}$ in U, Th
(U, Th in the earth crust ~ ppm)

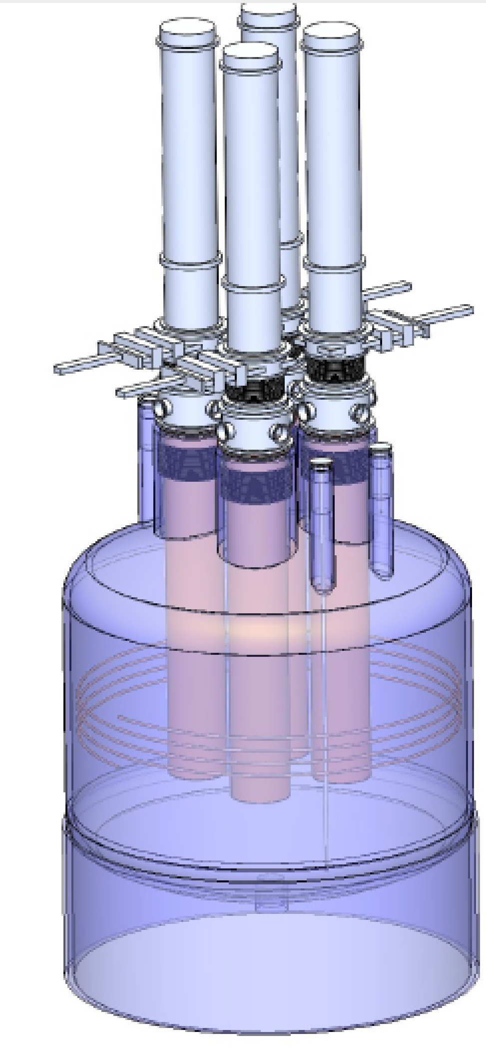
- New Techniques to discrimination signal from background

Non trivial for E ~ 1 MeV
This gets easier in larger detectors



Future Concepts

LEGEND



cryostat sketch for 4x250 kg

new collaboration formed in October 2016, members of GERDA, Majorana and other groups

LEGEND = Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay

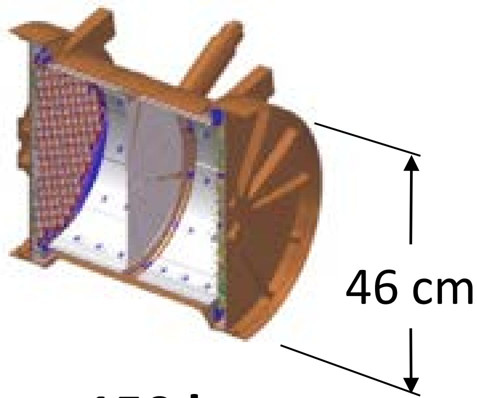
(up to) 200 kg in existing infrastructure at LNGS starting ~2020, background reduced by ~5 relative to GERDA

1000 kg if Ge is chosen in US down-select process, background reduced by ~30 relative to GERDA

B. Schwingenheuer @ CERN EP seminar, Jan 2017

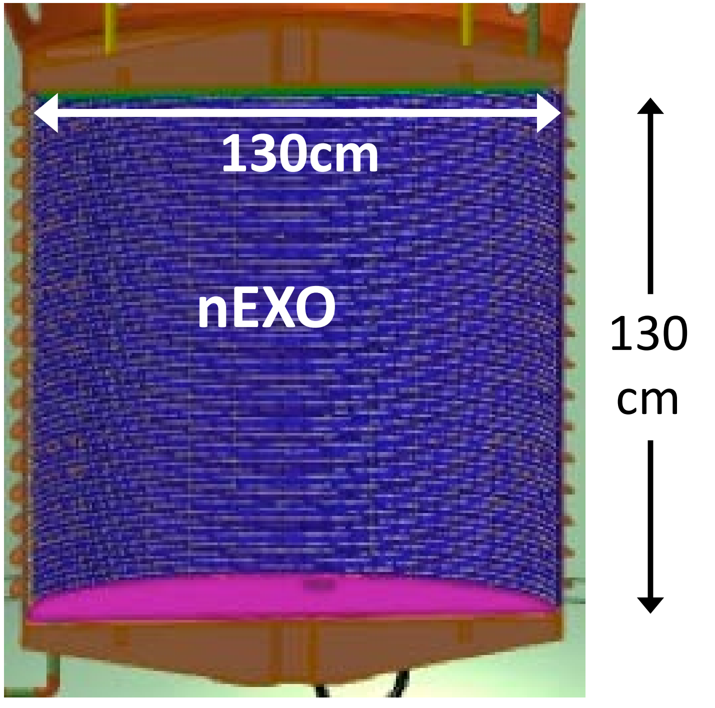
Future Concepts

EXO-200

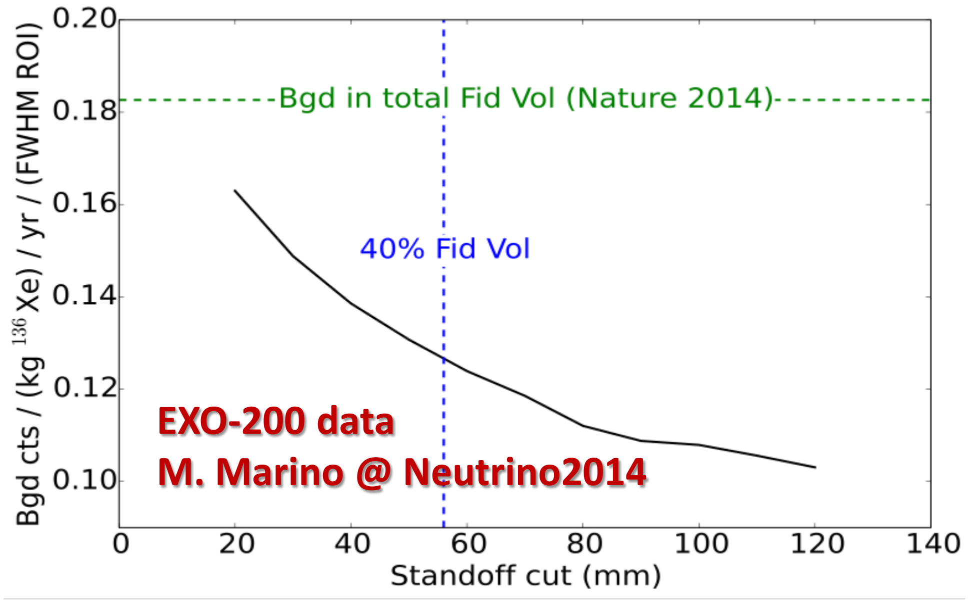


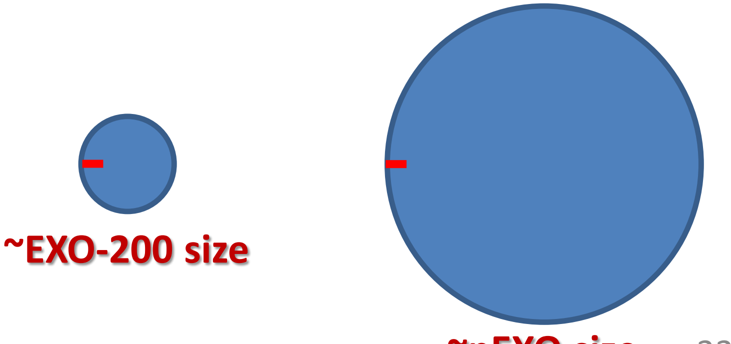
~ 150 kg

A 5000 kg enriched LXe TPC, directly extrapolated from EXO-200

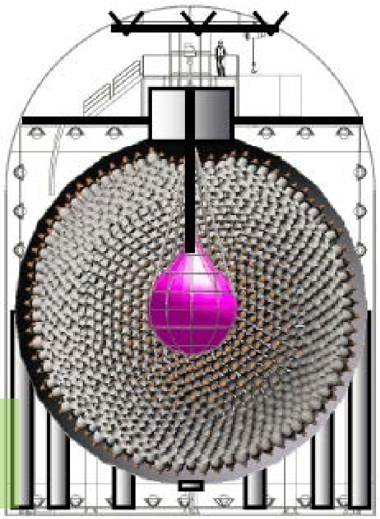


~ 5000 kg





Future Concepts

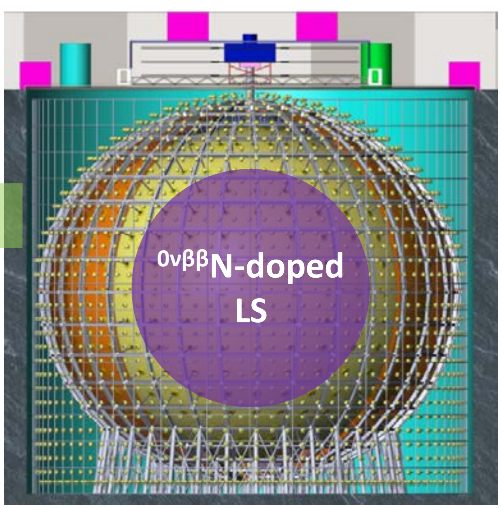


Existing
1 kton LS

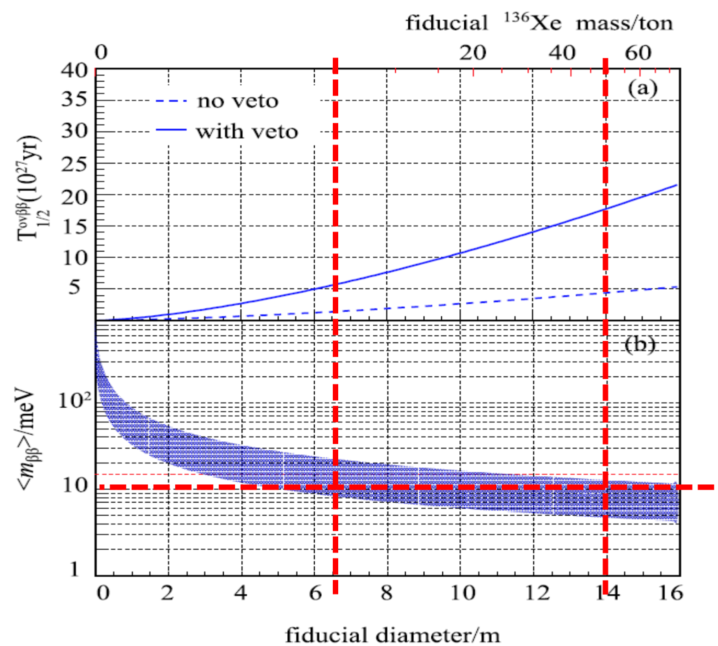
Running "KamLAND-Zen 800" →
Future "KamLAND2-Zen" with 1000 kg enriched Xe.
Assumptions:

winston cones:	x 1.8
Higher Q.E. PMTs:	x 1.9
LAB-based liquid scint.:	x 1.4
Overall:	x 4.8

Expected resolution (2.6 MeV):
4% → ~2%
Target sensitivity 20 meV



20 kton LS



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Beyond JUNO: possible < 10 meV

Summary

- Few significant advances of neutrino physics. Hints on δ_{CP}
- Many technological progresses → preparation for the next generation experiments
  - larger mass →10~20 times in general, comparing to the previous generation
  - better resolution, precision, S/N ratio, etc
- New discoveries ahead of us, probably in 10 - 20 yrs
  - Neutrino mass ordering
  - Neutrino is Majorana?
  - δ_{CP}

Thanks

Acknowledgements

Many Information from relevant talks given at Neutrino2016, ICHEP2016, NeuTel2017, NNN16, DBD16, etc.