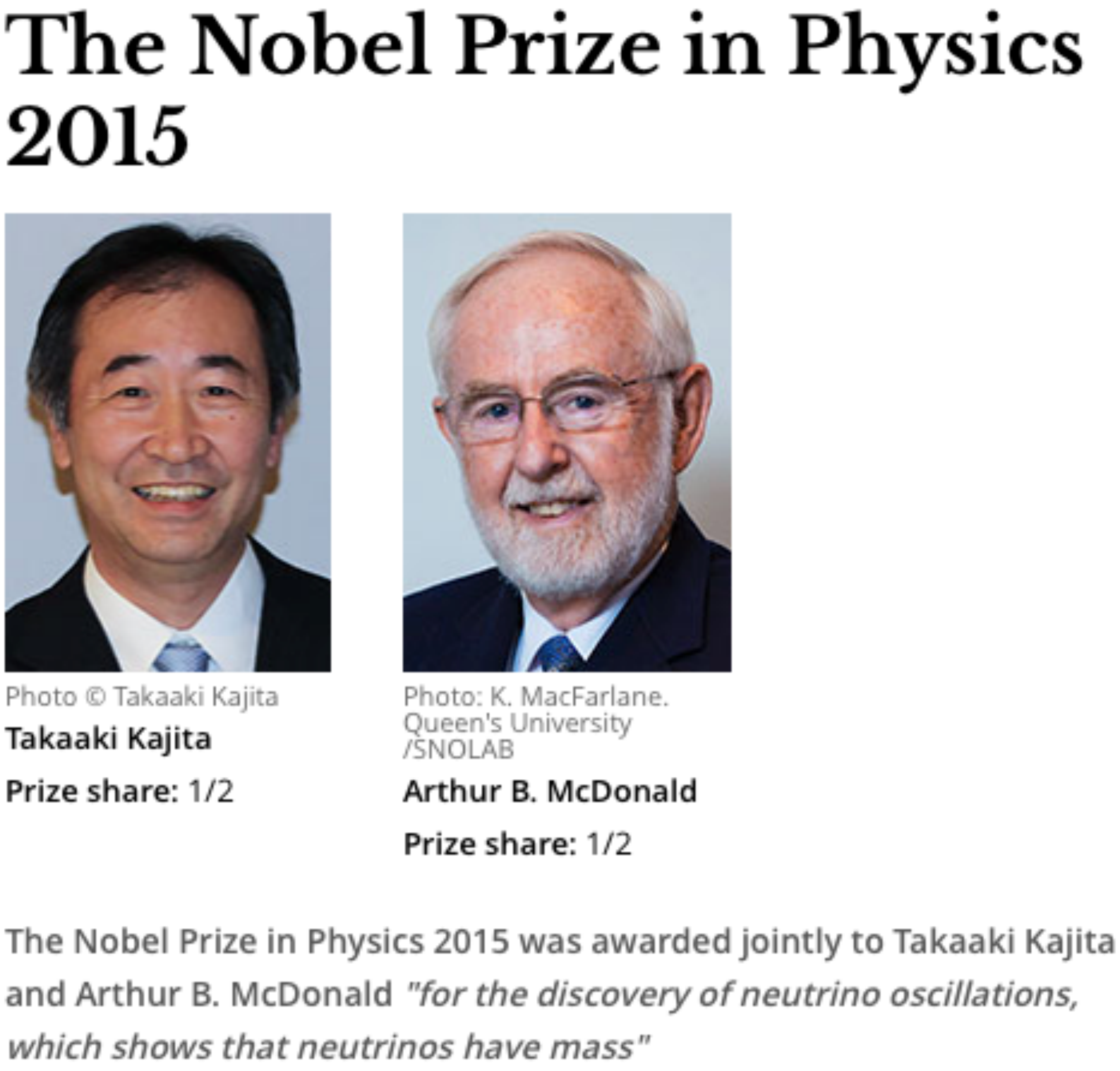
The JUNO and PINGU Experiments

Wei Wang / 王為, Sun Yat-Sen University
The 4th DDMAA, Dec 31, 2016

- ***Neutrino Mixing, Oscillation & Remaining Questions***
- ***The Precision IceCube Next-Generation Upgrade***
- ***The Jiangmen Underground Neutrino Observatory***
- ***Summary and Outlook***

Discovery of Neutrino Oscillations



The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

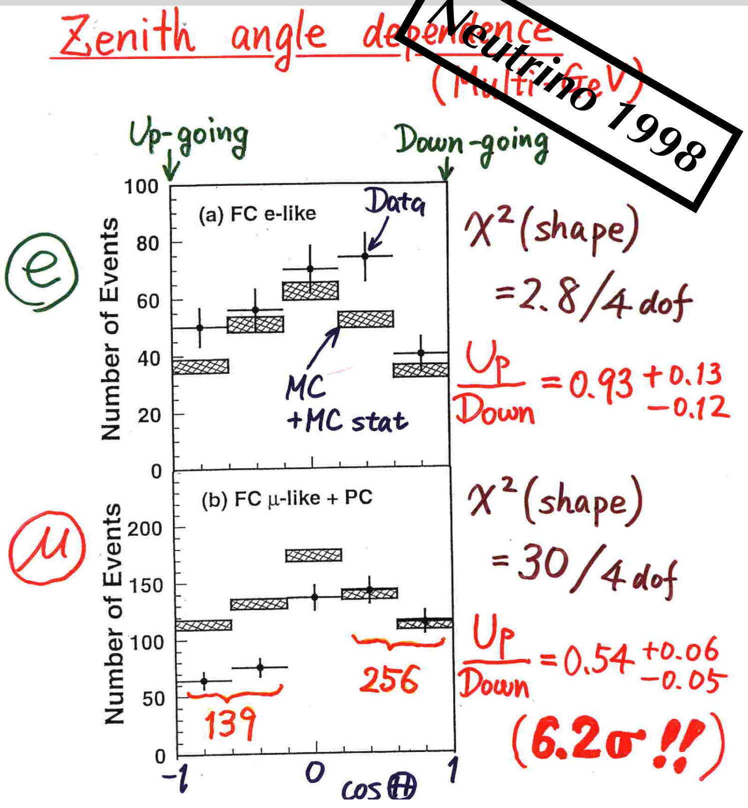
Prize share: 1/2

Photo: K. MacFarlane. Queen's University /SNOLAB

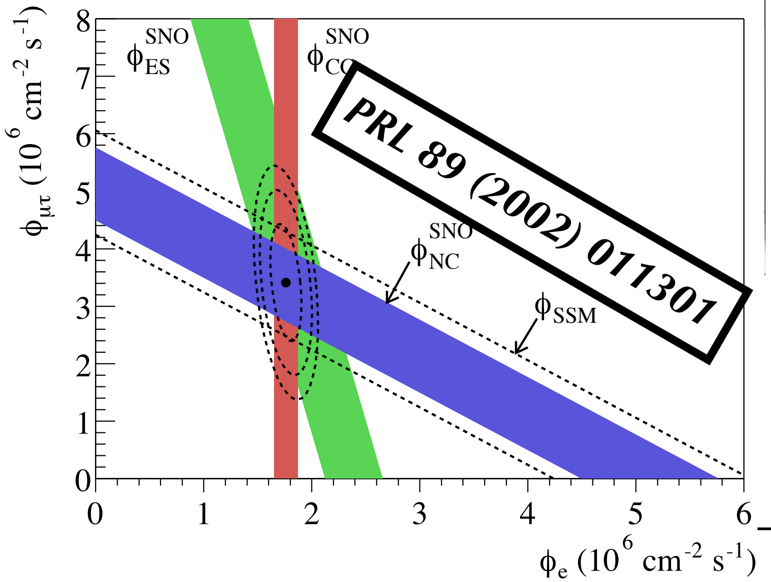
Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*



Neutrino 1998

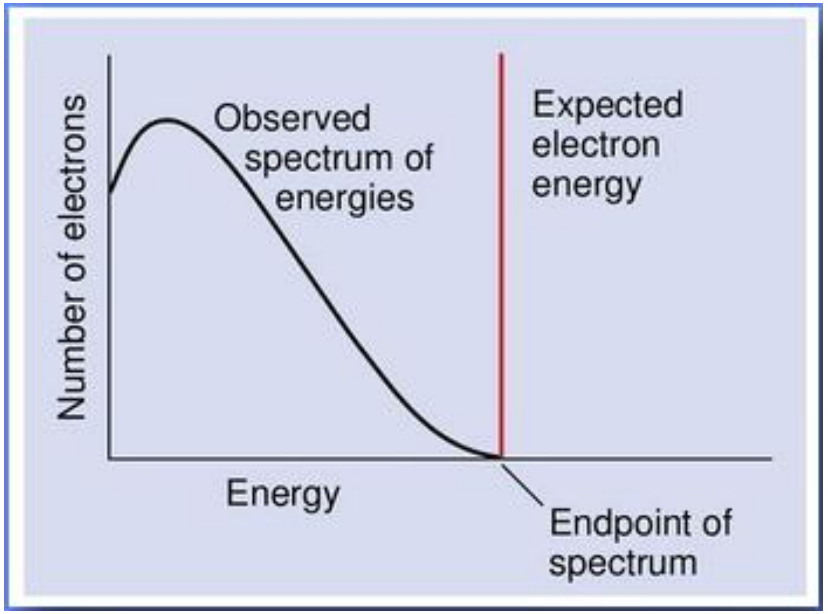


PRL 89 (2002) 011301

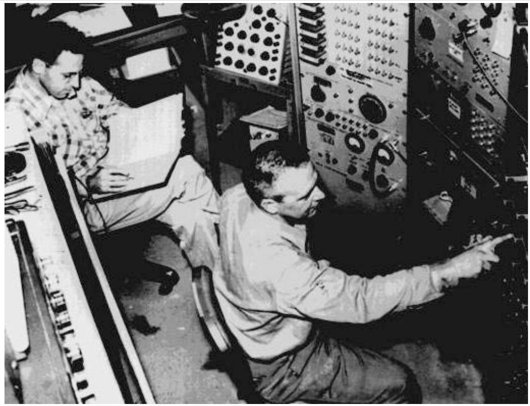

スーパーカミオカンデ観測20周年記念祝賀会
Super-Kamiokande 20th Anniversary Celebration
高級 清酒
満寿泉
芳醇

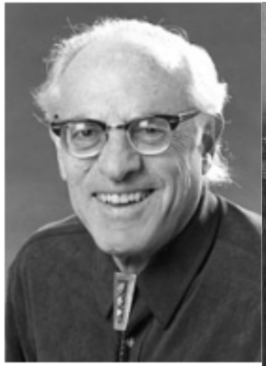
Neutrino 101: Neutrino and Its Discovery

- Neutrino proposed by Pauli to explain beta decay spectrum in 1930.



- First directly detected via Inverse Beta Decay by Reines and Cowan in 1956-1959 at the Savannah River Plant.
- Neutrino oscillation immediately proposed by Pontecorvo after the discovery





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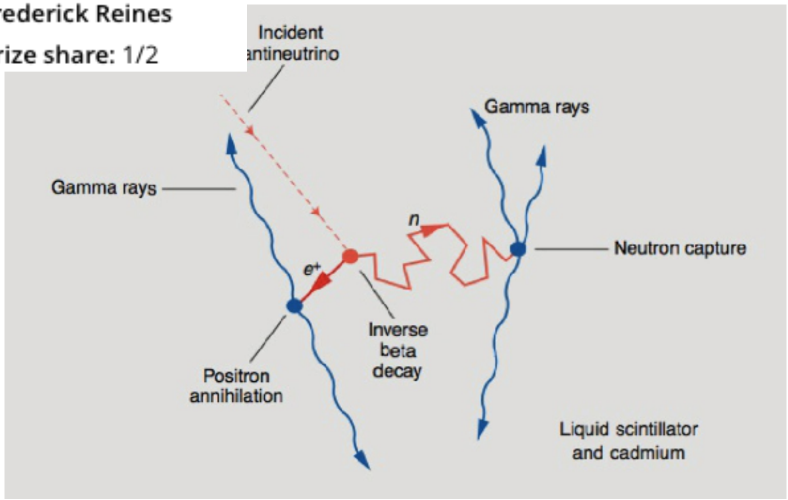
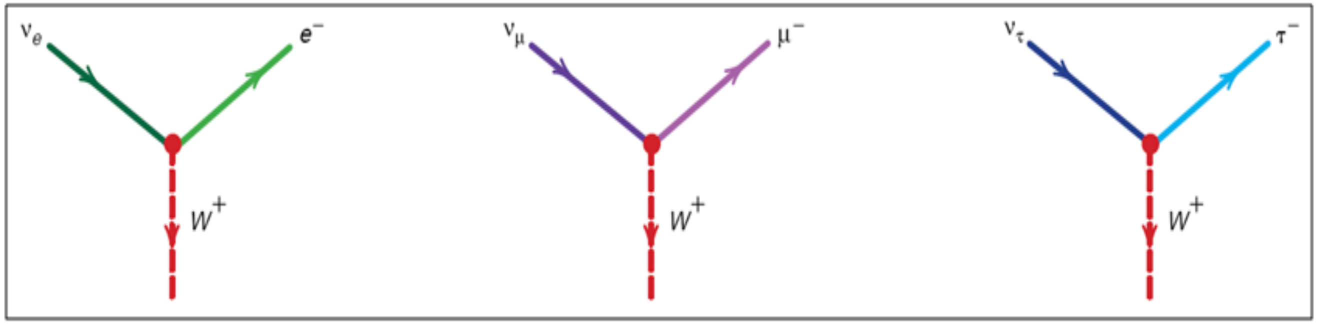
Frederick Reines

Prize share: 1/2



Neutrino 101: Neutrino Mixing and Oscillation



S. Sakata 1911-1970 Z. Maki 1929-2005 M. Nakagawa 1932-2001

Бруно Понтекорво

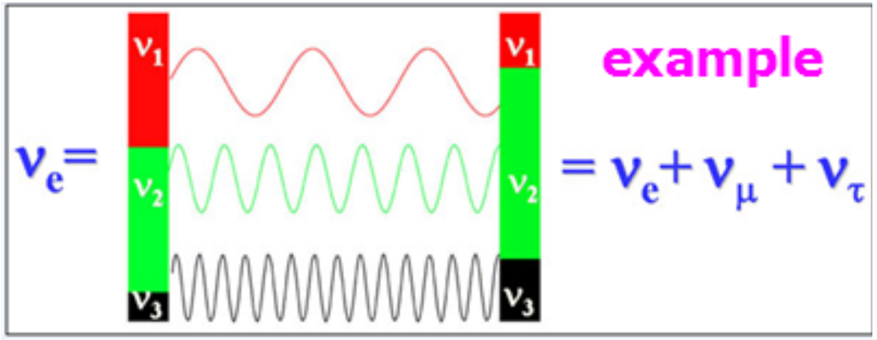
If Mass Eigenstates ≠ Interaction Eigenstates ⇒ Mixing&Oscillating

➡ Extended to 3 flavor mixing by Maki, Nakagawa and Sakata in 1962

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

↓ ↓ ↓

Flavor eigenstates PMNS Matrix Mass eigenstates



$$\Rightarrow \quad P_{\nu_\alpha \to \nu_\beta} = 1 - 4 \sum_{i<j} |V_{\alpha j}|^2 |V_{\beta i}|^2 \sin^2 \frac{\Delta m_{ji}^2 L}{4E}$$

Mixing Angles and Mass-Squared Splittings

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

’98: Neutrino Oscillation discovered
measuring: Δm^2_{atm}, $\sin^2 2\theta_{23}$
K2K/T2K/MINOS/NOvA/DeepCore/**Daya Bay**

$$\times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}$$

> a decade long quest:’98 to ’12
Measuring: $\boldsymbol{\Delta m^2_{atm}(\Delta m^2_{ee})}$, θ_{13}
Daya Bay, RENO, Double Chooz

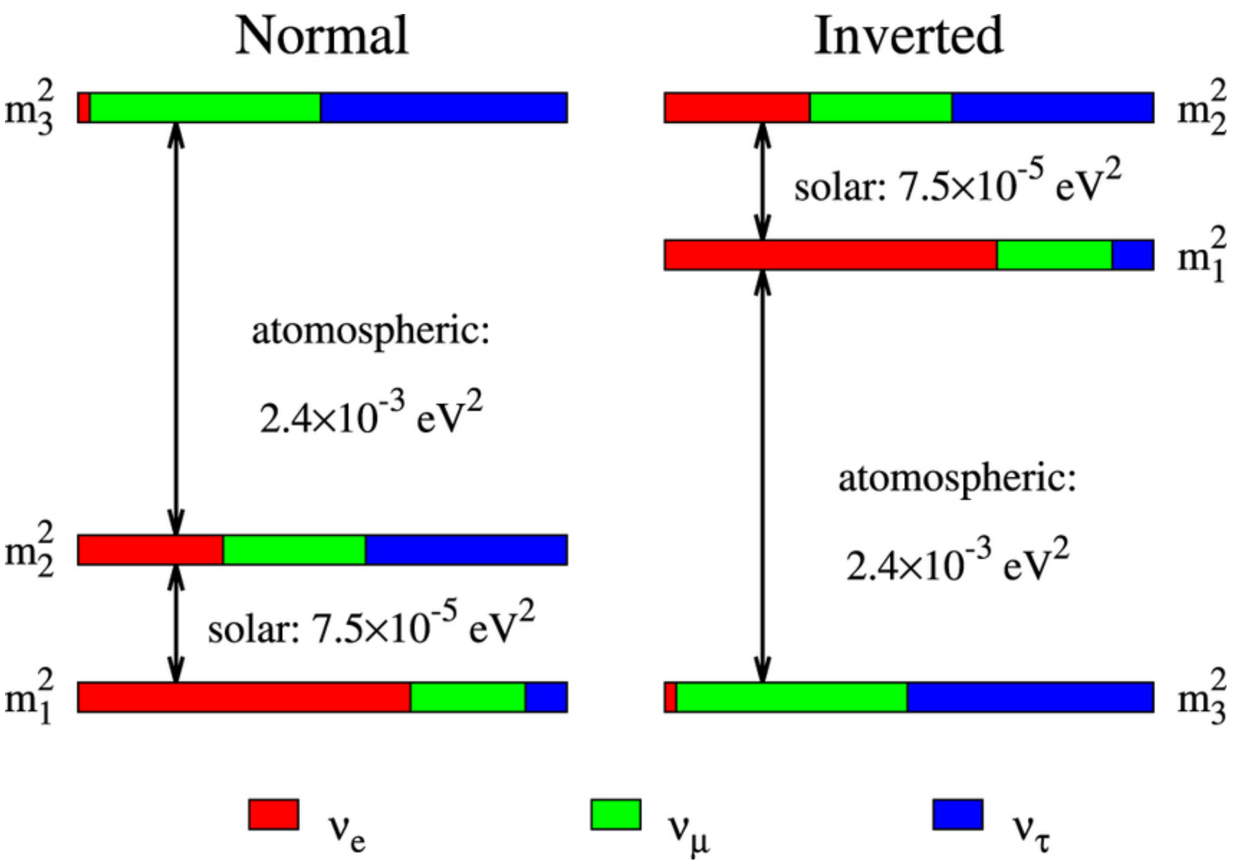
$$\times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

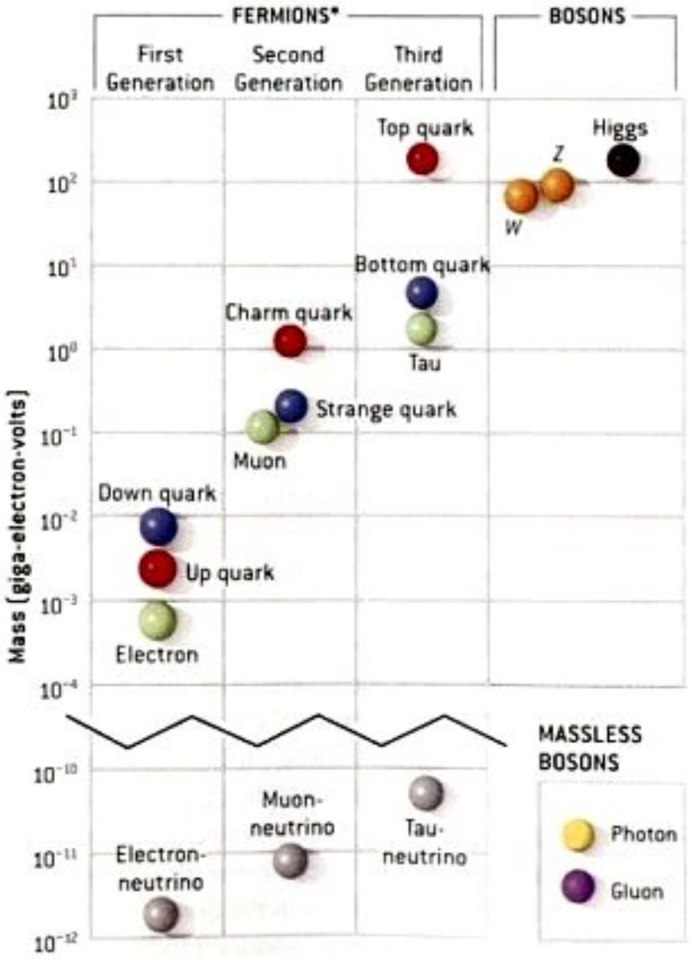
’01-’02: Solar Sector Resolved
SNO, KamLAND, SK
measuring: Δm^2_{solar}, θ_{12}

$$\times \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Thoughts on Majorana Phases?
See Xing, Zhou, 16th Lomonosov Conference on Elementary Particle Physics, Moscow, Russia, 22 – 28 August 2013

Neutrino Mass Hierarchy

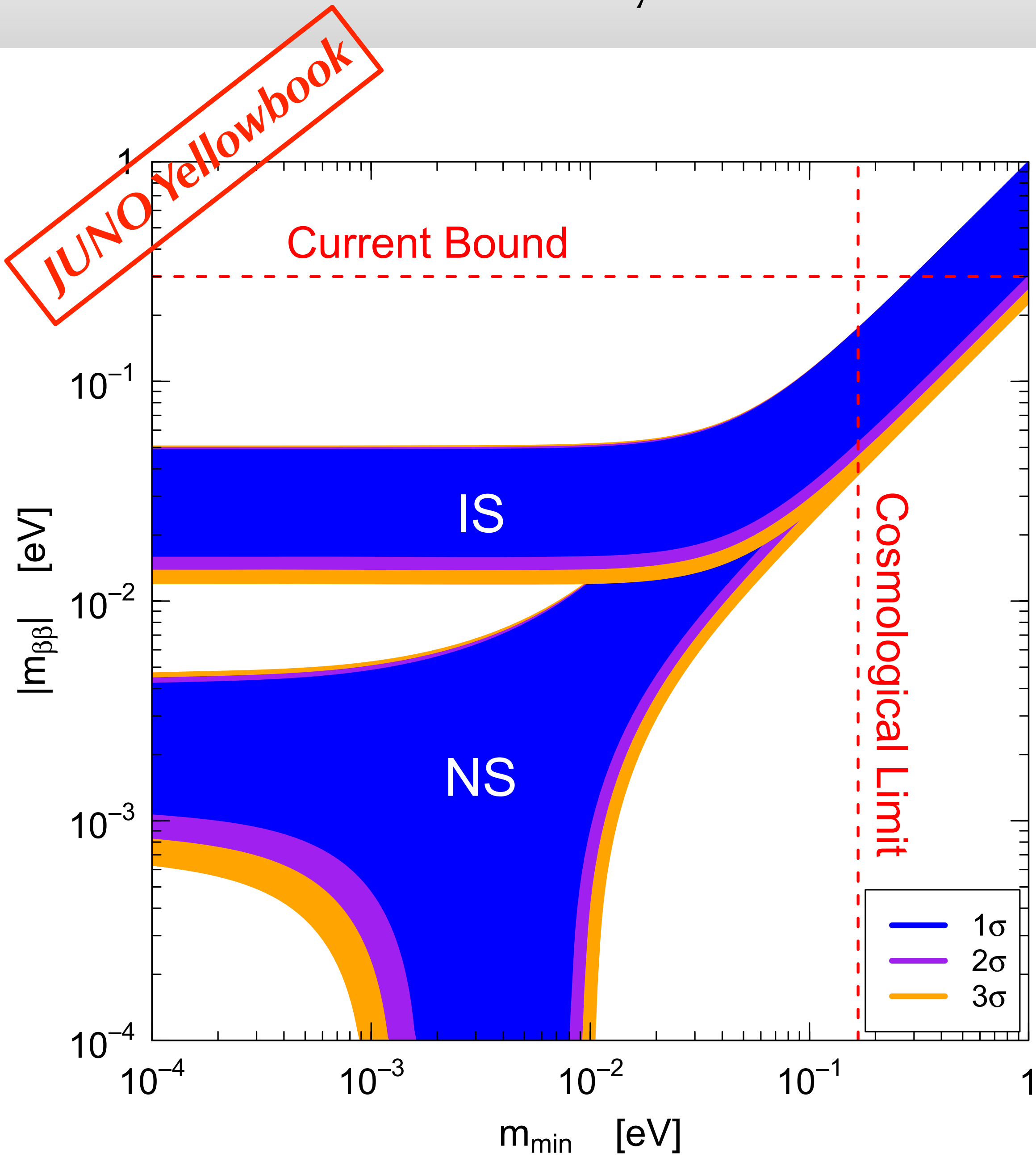




The solar neutrino data tell us that $\Delta m^2_{21}\cos 2\theta_{12} > 0$. In the convention employed by us we have $\Delta m^2_{21} > 0$. Correspondingly, in this convention one must have $\cos 2\theta_{12} > 0$.

MSW Effect tells m_2 from m_1; No clue for the sign of Δm^2_{32}

Neutrino Mass Hierarchy and Neutrinoless Double Beta Decay



- The chance to observe Neutrinoless Double Beta Decay in the next-generation double beta decay experiments is greatly enhanced for an inverted MH and the Majorana nature of massive neutrinos.
- New techniques beyond the next generation are needed to explore the region covered by a normal MH.

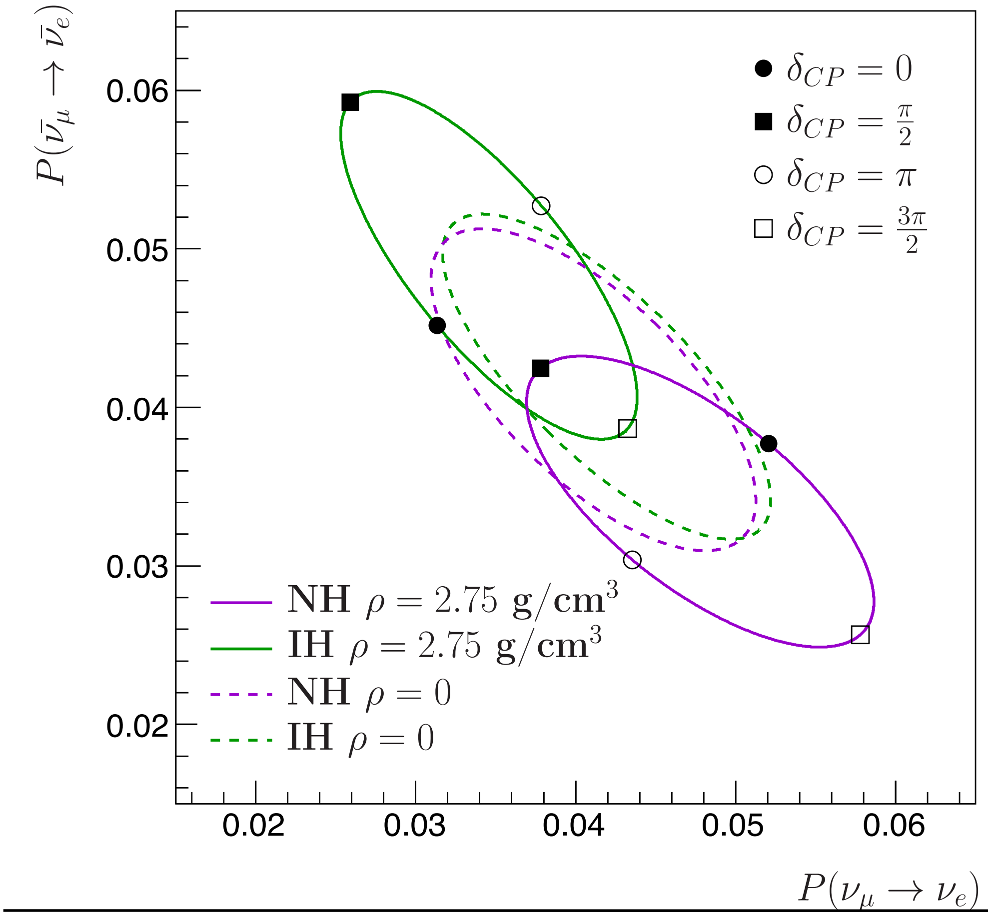
How to Resolve the Neutrino Mass Hierarchy?

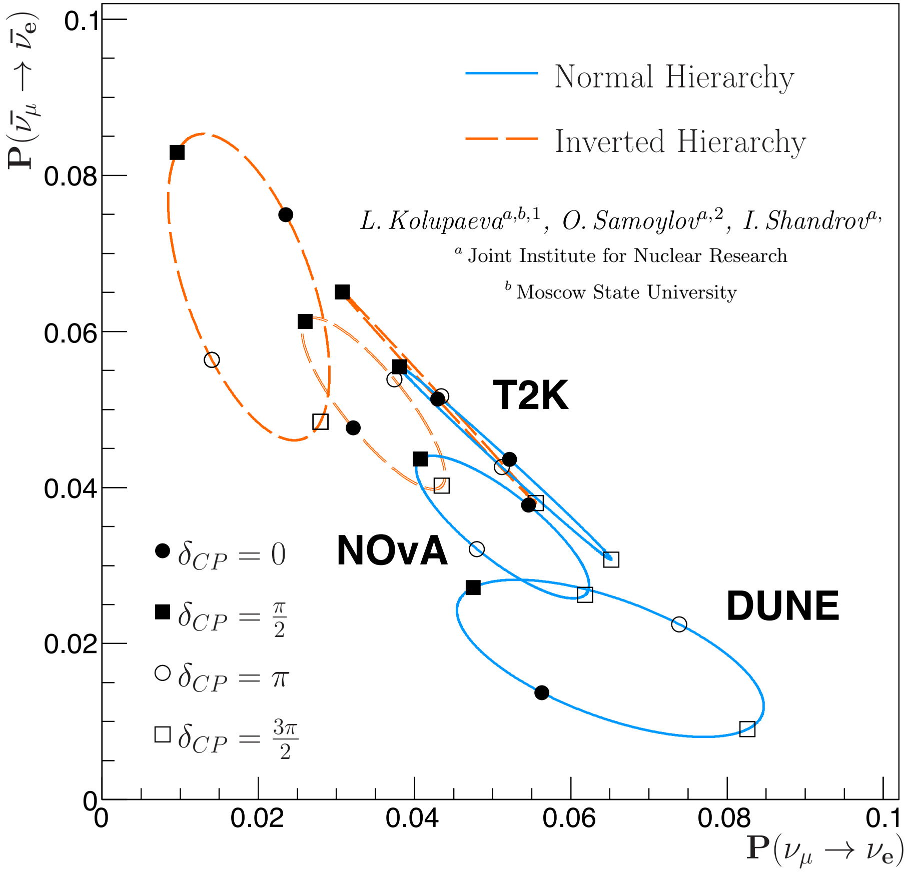
- Matter Effect strength:

$$A = \pm\frac{2\sqrt{2}G_F N_e E}{\Delta m^2}$$

- How to enhance the signal?
  - ➡Increase neutrino energy
  - ➡Increase matter density

NH and IH with δ_{CP} and density



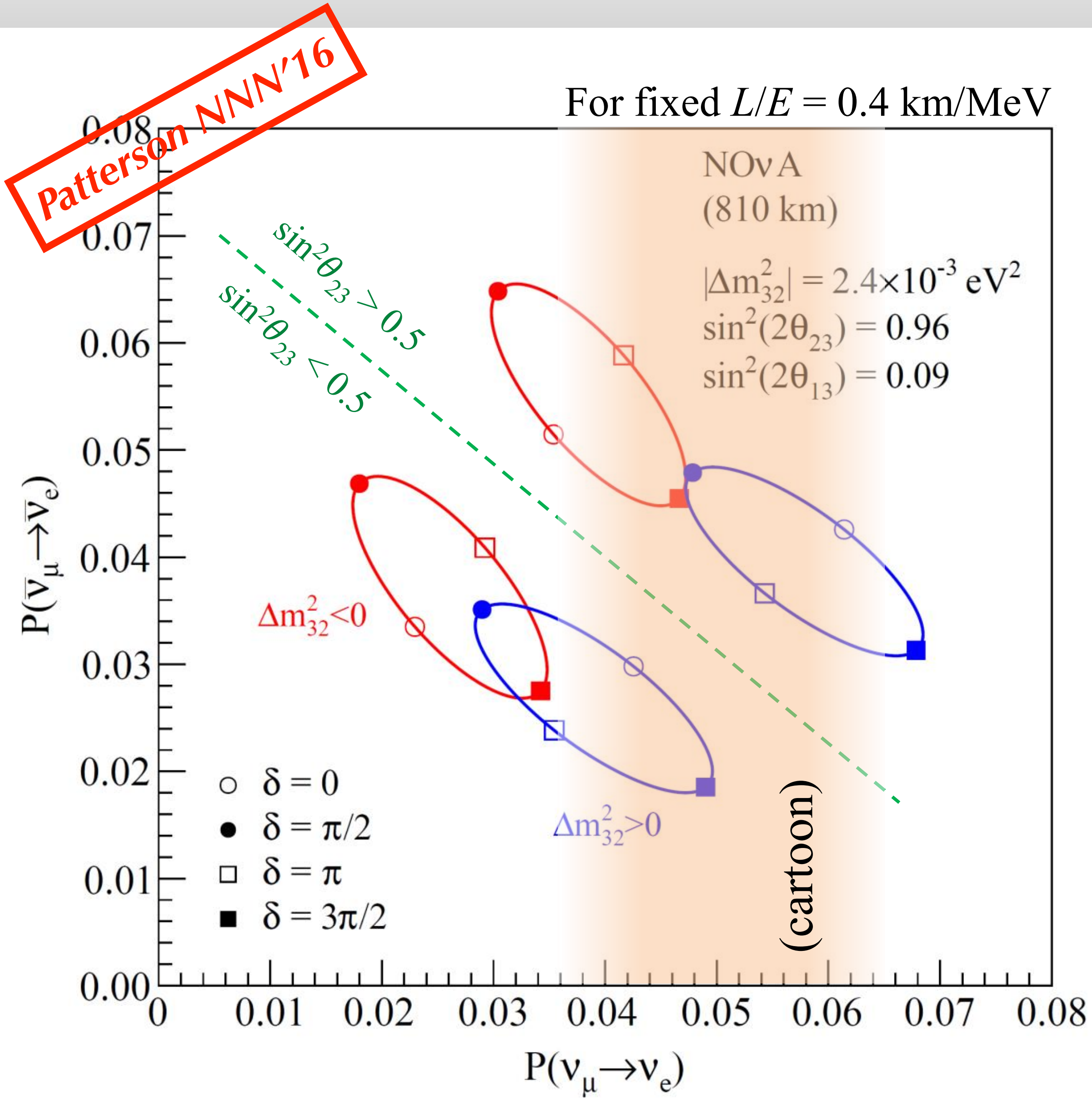


L. Kolupaeva[a,b,1], *O. Samoylov*[a,2], *I. Shandrov*[a],

[a] Joint Institute for Nuclear Research

[b] Moscow State University

Appearance Signals of NOvA



Patterson NNN'16

For fixed L/E = 0.4 km/MeV

$P(\bar{\nu}_\mu\rightarrow\bar{\nu}_e)$ vs. $P(\nu_\mu\rightarrow\nu_e)$

plotted for a single neutrino energy and baseline

→ Strong dependence on δ and **ν mass hierarchy**

→ $P \propto \sin^2\theta_{23}$ *[approx.]*

Total prediction:

~17 to 42 ν_e candidates

(depending on osc. pars.)

Includes **8.2** background

(~independent of osc. pars.)

Syst. uncertainty:

±5% signal

±10% background

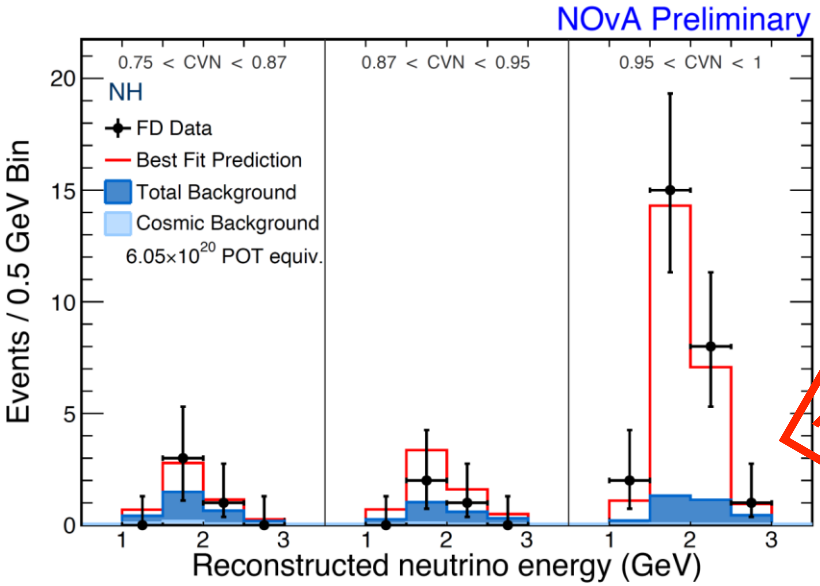
Observed in FD data:

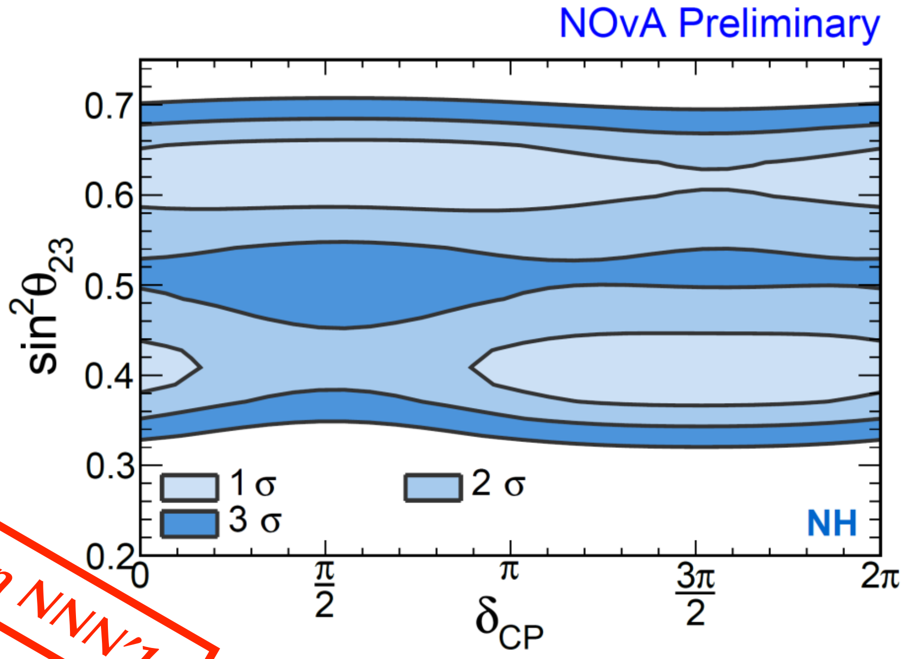
33 ν_e candidates

>8σ observation of ν_e appearance

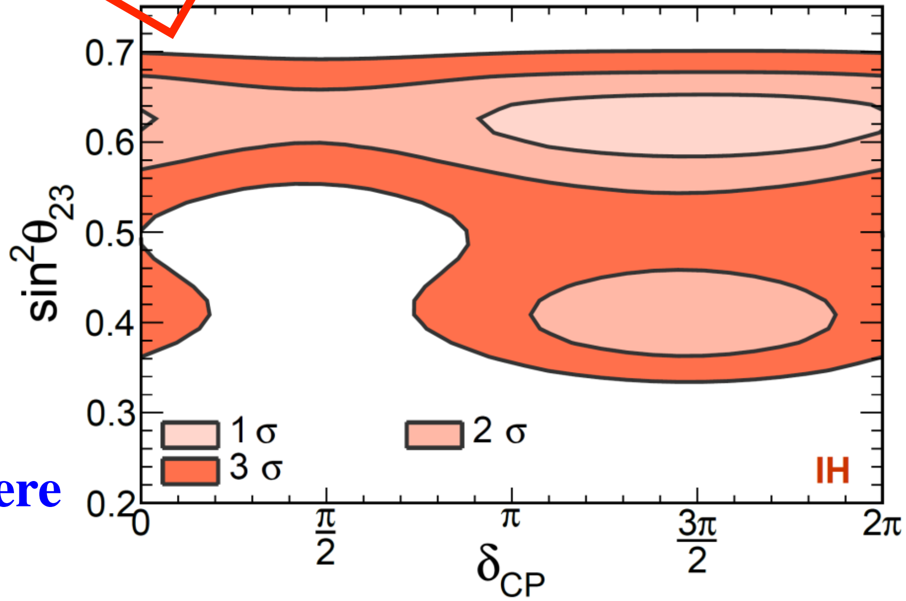
NOvA Preliminary Tries of MH, CP and Octant

Measure signal in 2D bins of E_ν × CVN





Patterson NNN'16



In terms of allowed physical parameters →

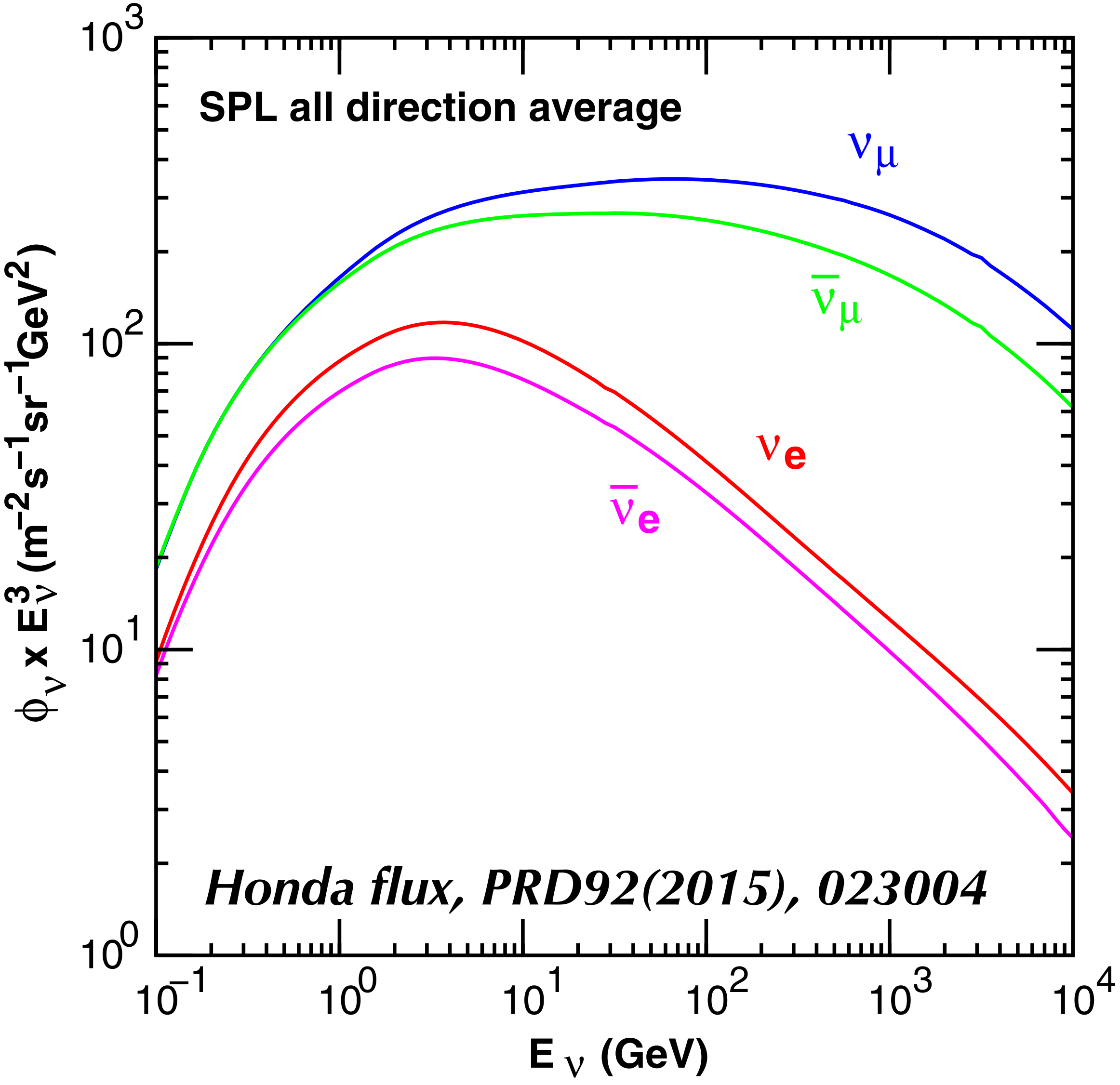
NH preference not signif.: $\Delta\chi^2$=0.46

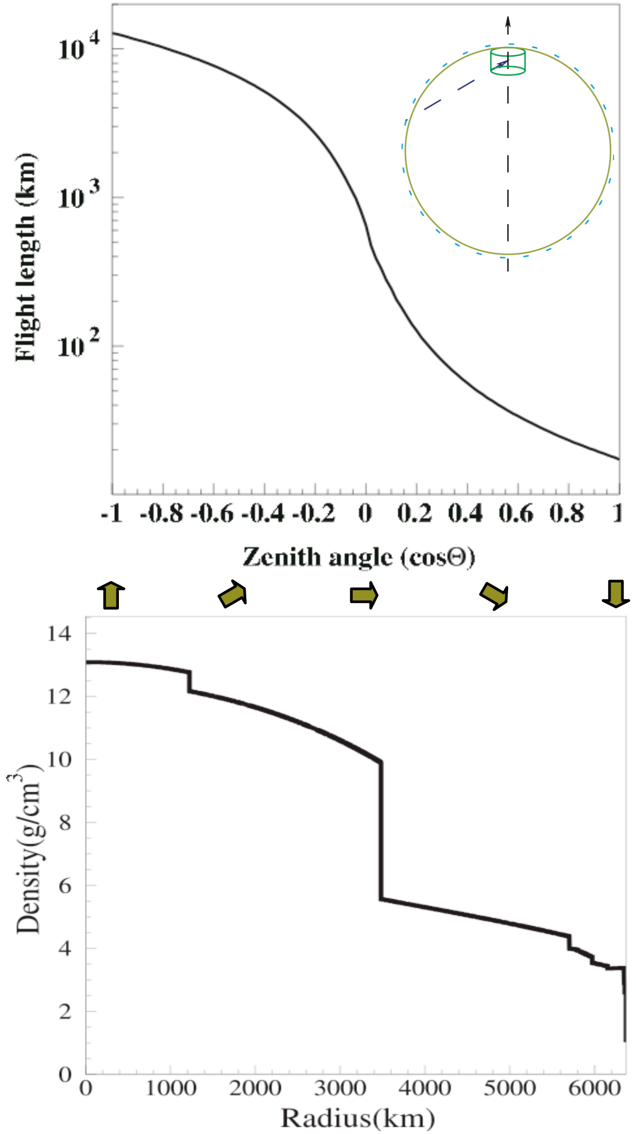
>3σ exclusion of region in

IH, lower octant, around δ=π/2

Feldman-Cousins corrections **not included here**
(*will appear in forthcoming journal article*)

Atmospheric Neutrinos and the Earth



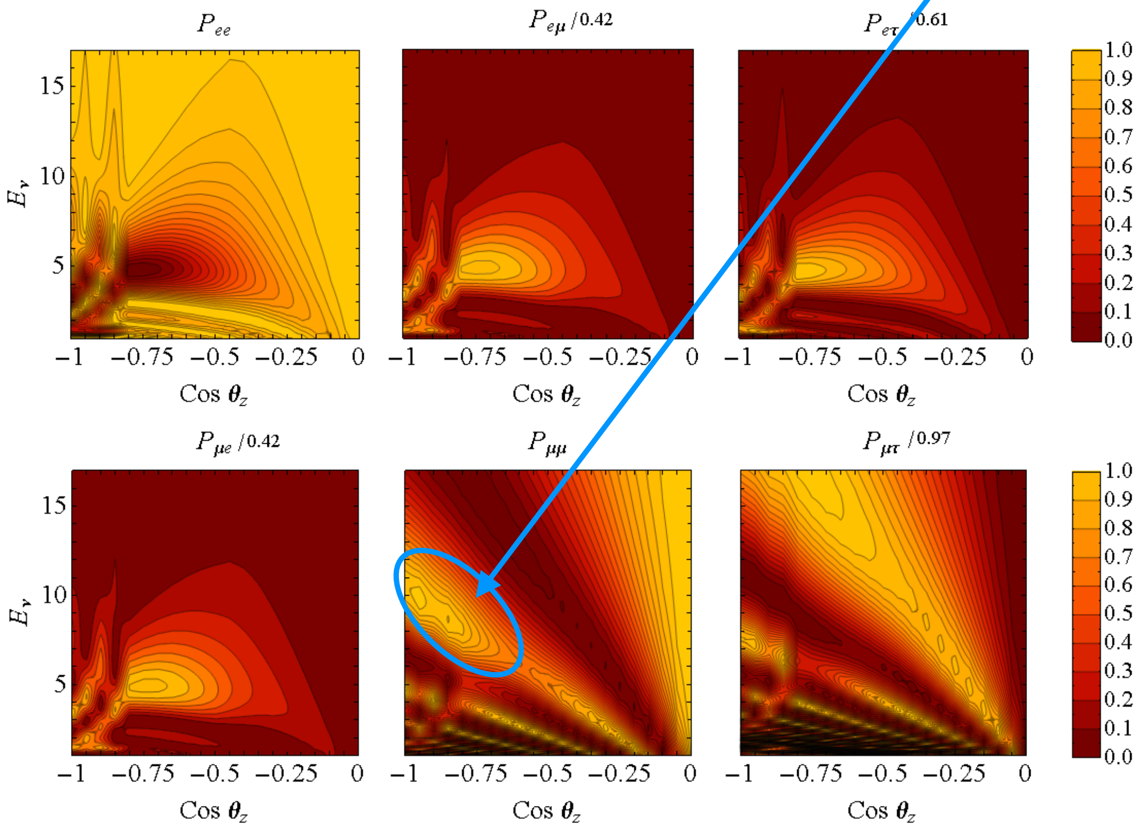


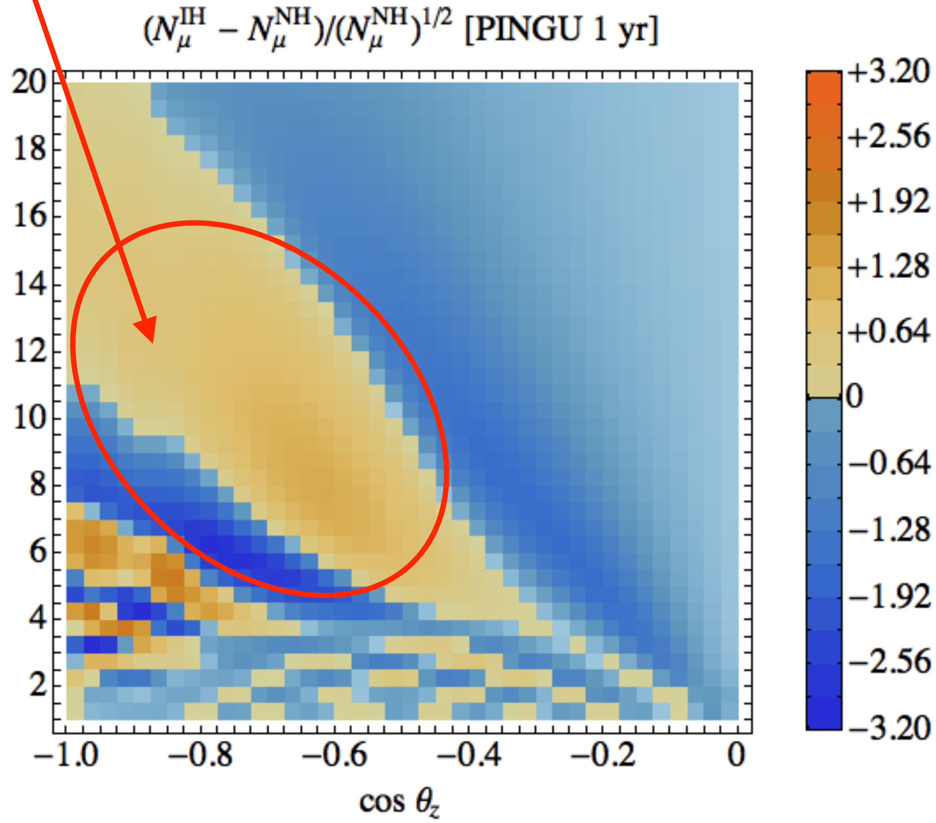
- → Largest E accessible
- → *Biggest* matter densities accessible

→ **A great lab for mass hierarchy!**

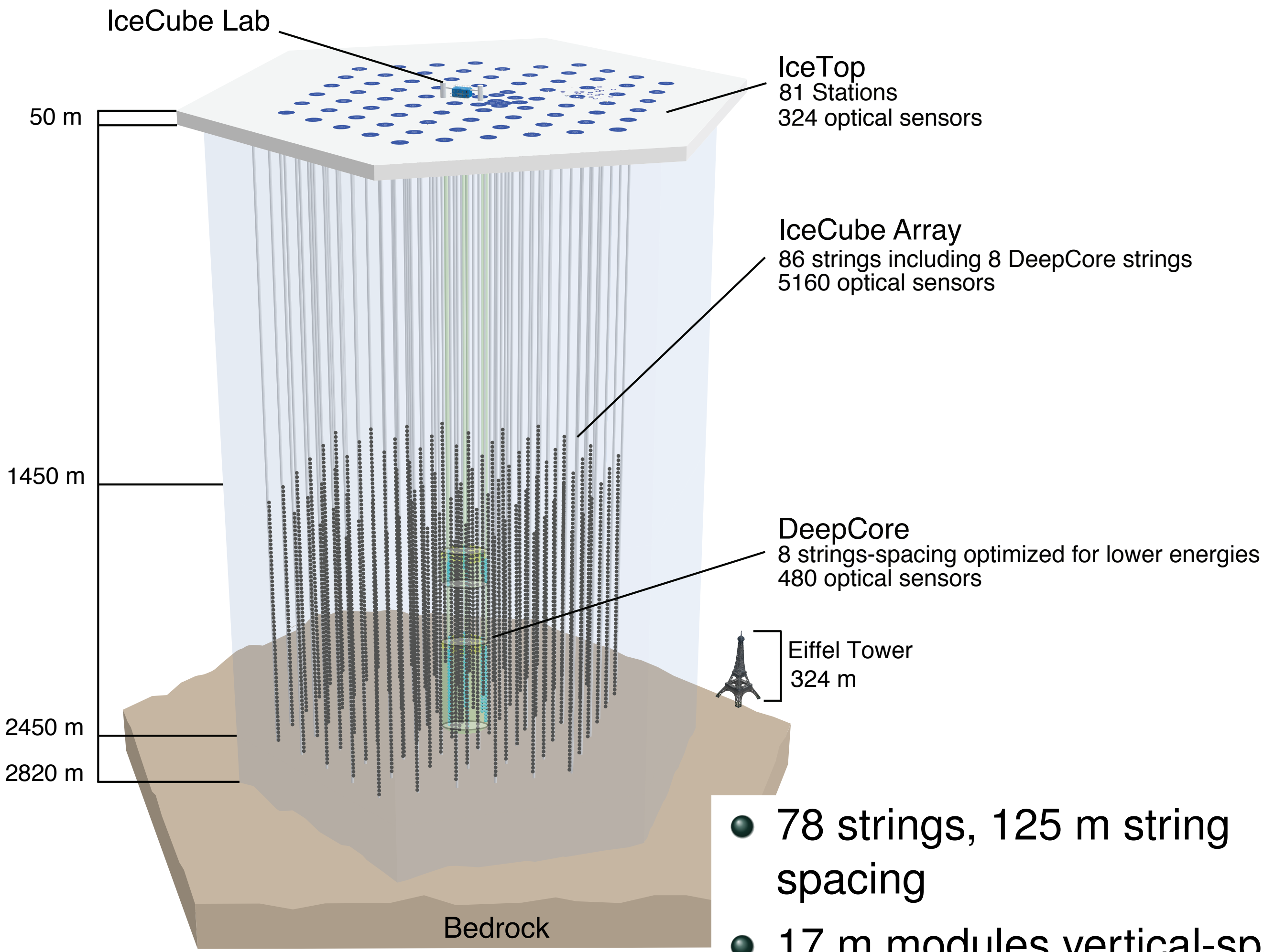
What is Needed to Differentiate Mass Hierarchy?

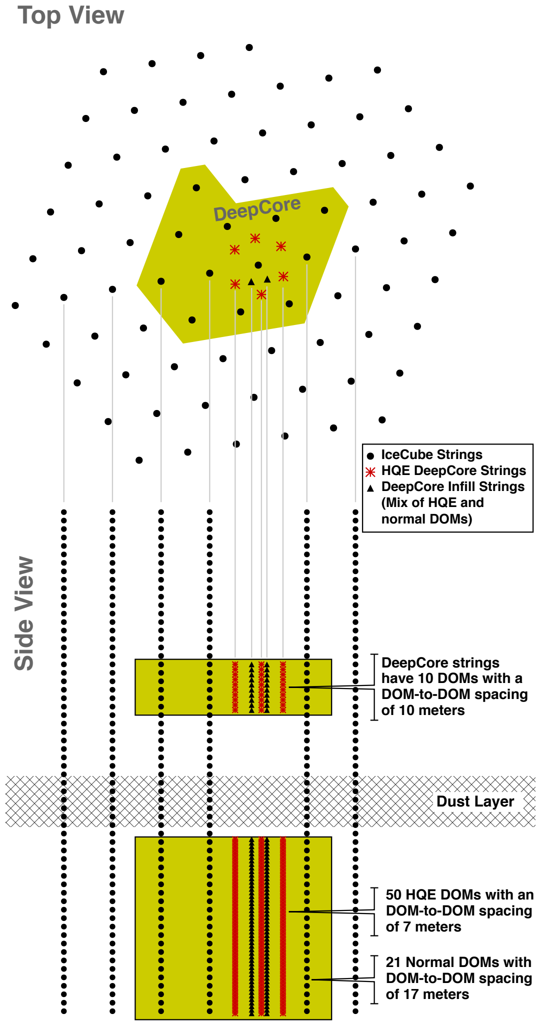
- Resonance oscillation due to MSW effect in Earth for atm neutrinos
- Different mass hierarchies' resonance energies differ $\Longrightarrow$ tells mass hierarchy





IceCube and IceCube-DeepCore





- 78 strings, 125 m string spacing
- 17 m modules vertical-spacing

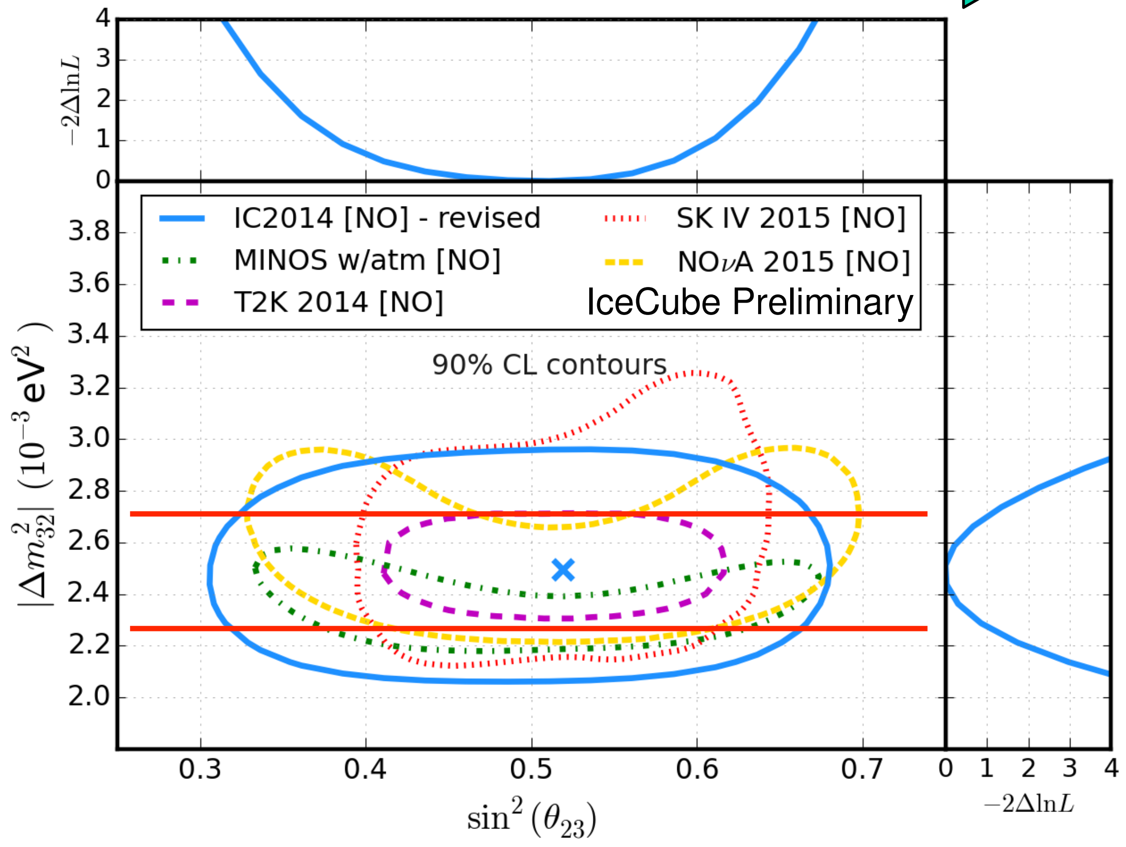
Good for atmospheric oscillation parameters

- 8 strings, 40-75 m string spacing
- 7 m modules vertical-spacing

Threshold energy too high for mass hierarchy

DeepCore “Sees” Atmospheric Neutrino Oscillation

PRD 91, 072004 (2015)



$$|\Delta m^2_{32}| = 2.50^{+0.18}_{-0.24} 10^{-3}\mathrm{eV}^2$$

$$\sin^2(\theta_{23}) = 0.52^{+0.12}_{-0.10}$$

Updates in 2016

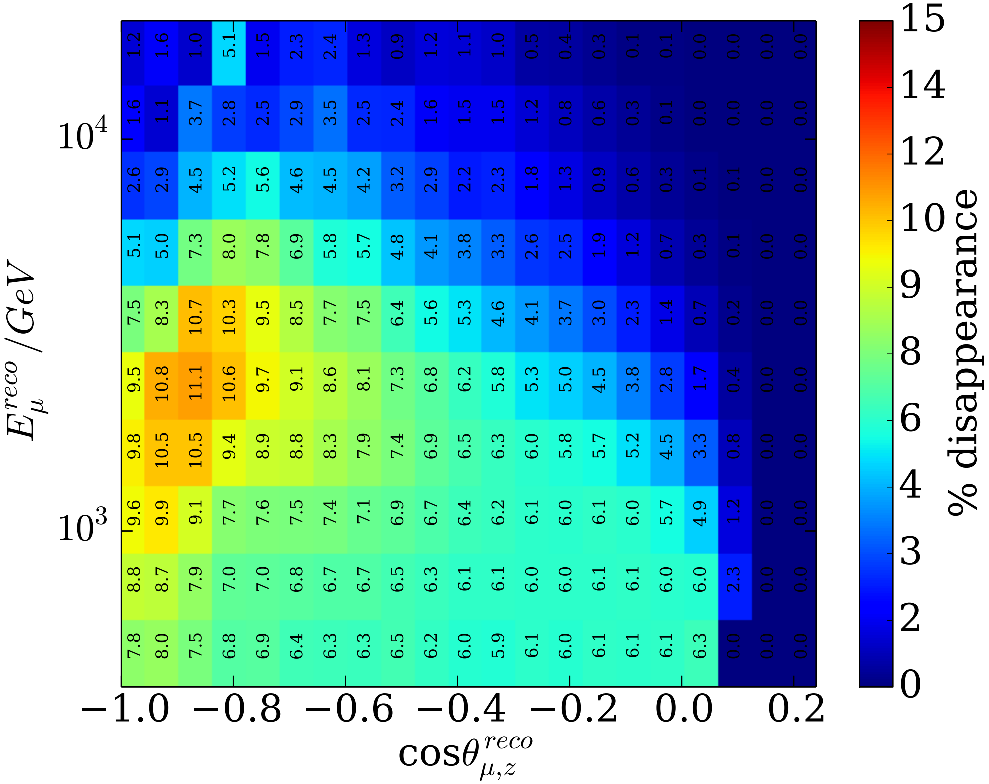
- Improved simulation, systematics, and MC/Data agreement results.
- Improved: detector noise model, tighter cut for atm. muon rejection, flux prediction, PE charge calibration, etc.

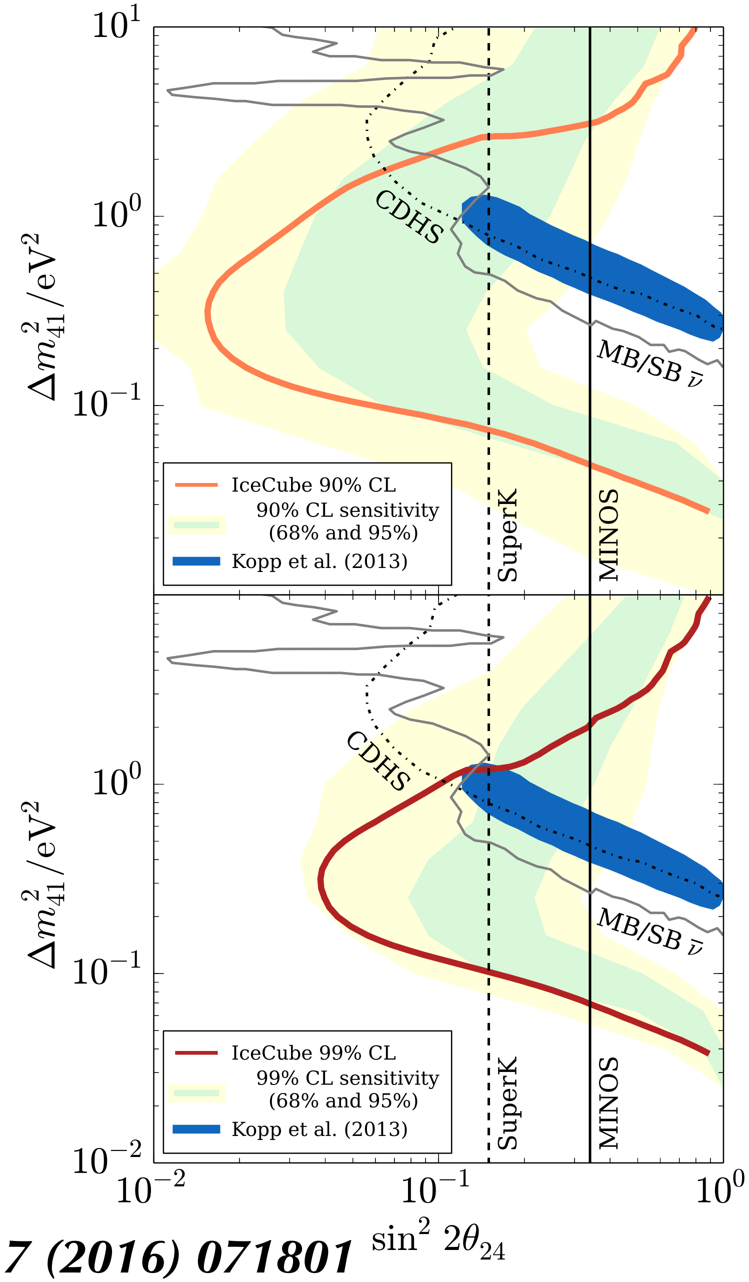
Results competitive w/ SK

- Using only events with $E_{reco} < 56$ GeV
- Fitting to data done in 2D space (E, θ)
  - $\chi^2/ndf = 52.4/56$
- Observed ≈5200 events in 953 days

MSW in Earth at Play: Sterile Neutrinos @ IceCube

Nature, Aug 6, 2016, "Icy telescope throws cold water on sterile neutrino theory"



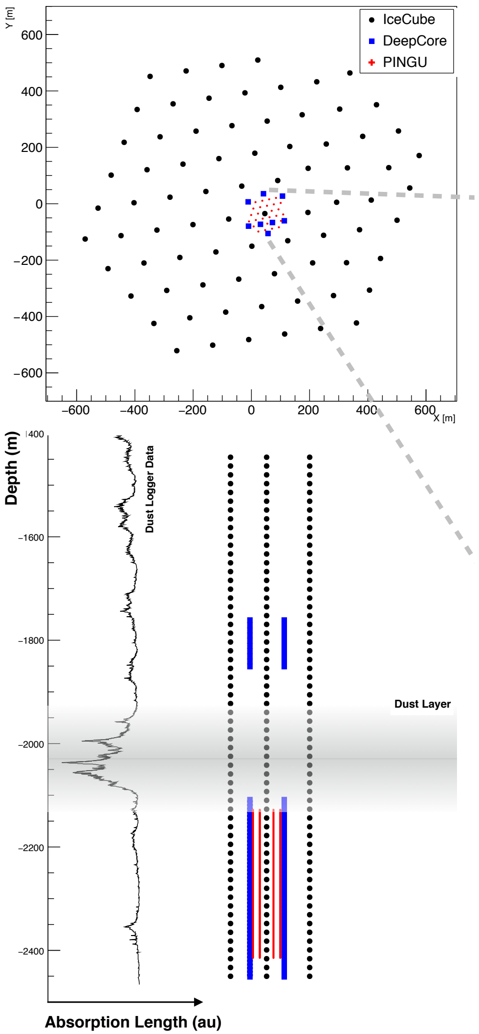


Matter effect causes oscillation resonants for certain sterile neutrino parameters — distinctive signature

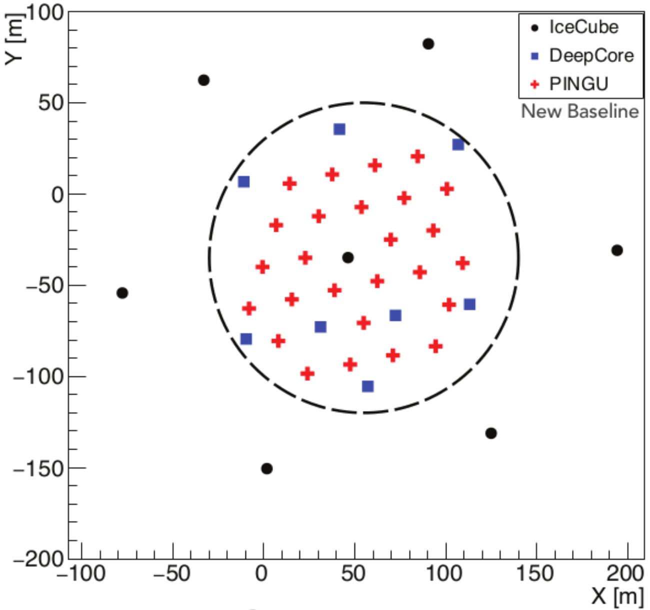
IceCube, PRL117 (2016) 071801

IceCube-Gen2/PINGU

- ➡ Need large statistics ⟹ IceCube
- ➡ Need to lower the energy threshold ⟹ IceCube-Gen2/PINGU

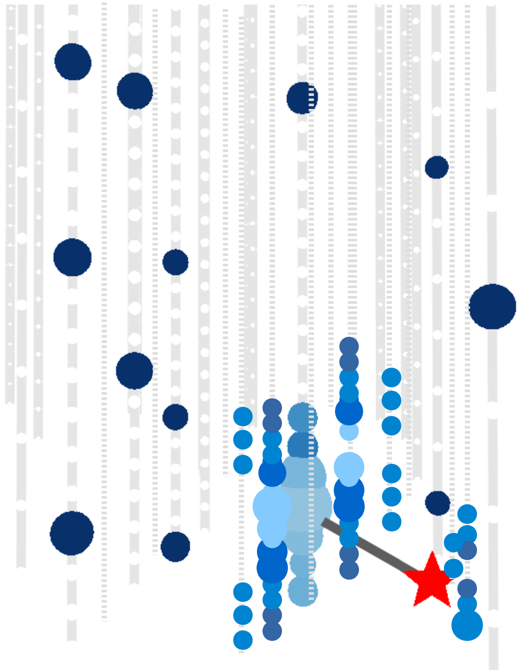


6 Mton "water" Cherenkov detector



Current

26 strings
192 DOMs/string
1.5 m DOM-DOM spacing



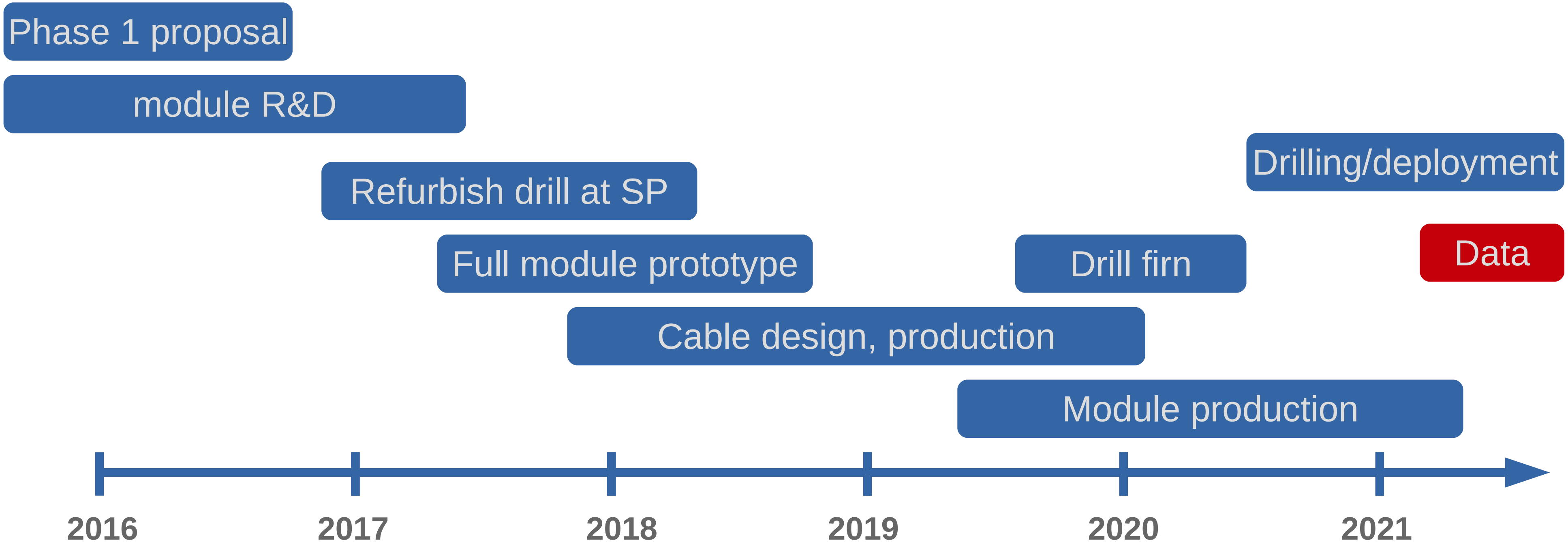
>8GeV: 100% Efficiency

~3GeV: ~50% Efficiency

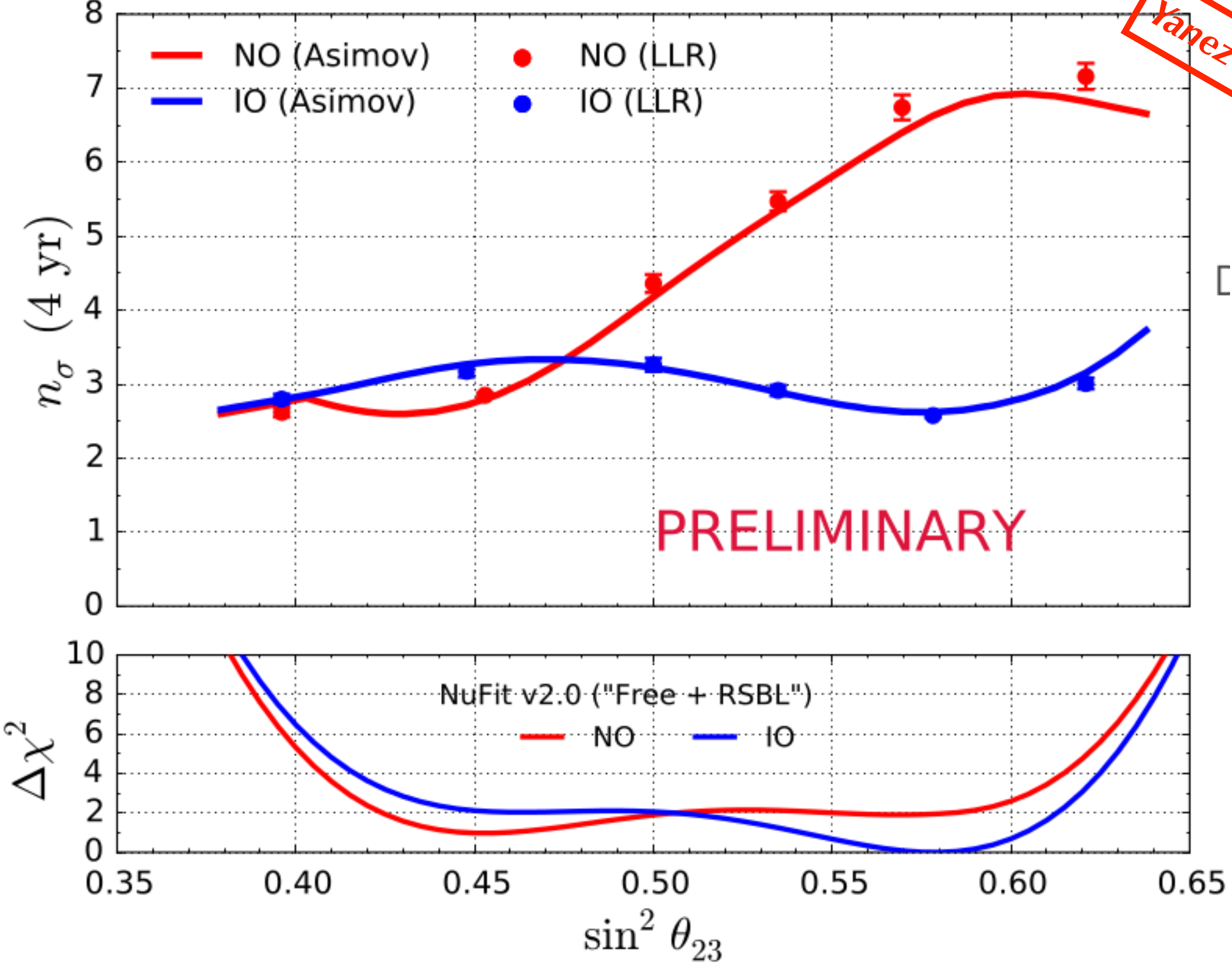
PINGU/IceCube-Gen2 Timeline

Yanez NNN'16

- Phased approach — phase I
- 7 additional strings in DeepCore
- 125 modules per string with additional calibration devices



IceCube-Gen2/PINGU Sensitivity to MH and Octant



Yanez NNN'16

Known θ13 Enables Neutrino Mass Hierarchy at Reactors

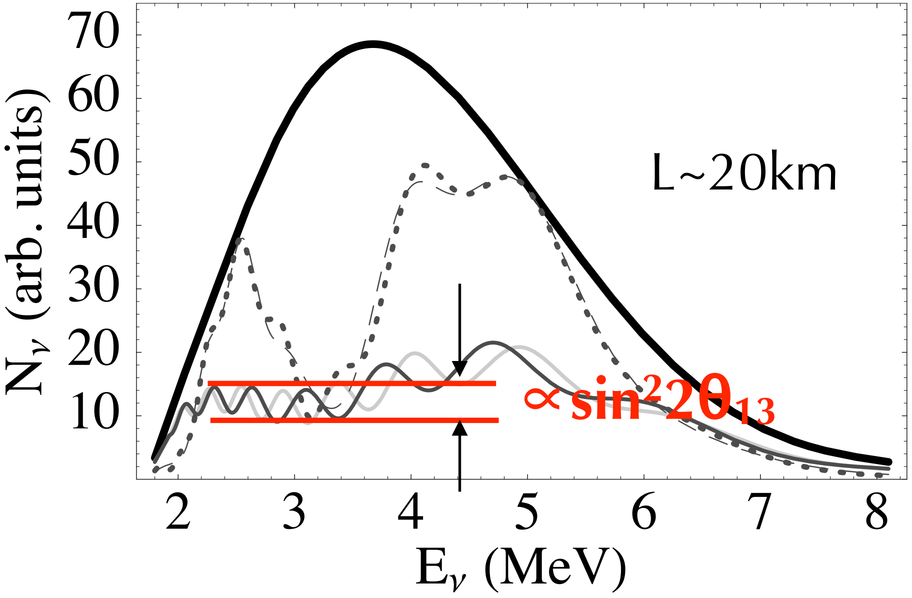
- Recall that reactor neutrinos helped pin down the solar sector

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \boxed{\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}}$$

- Recall that Daya Bay measures the most precise atmospheric mass-squared splitting

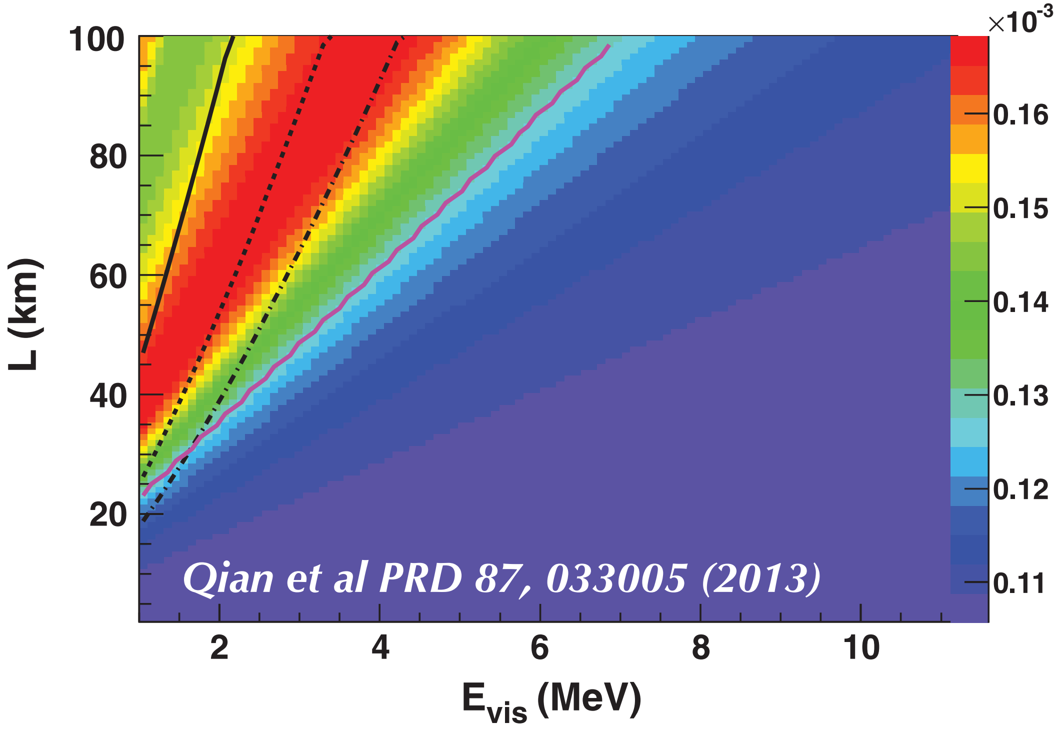
$$-\boxed{\sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})}$$

Petcov&Piai, Phys. Lett. B533 (2002) 94-106

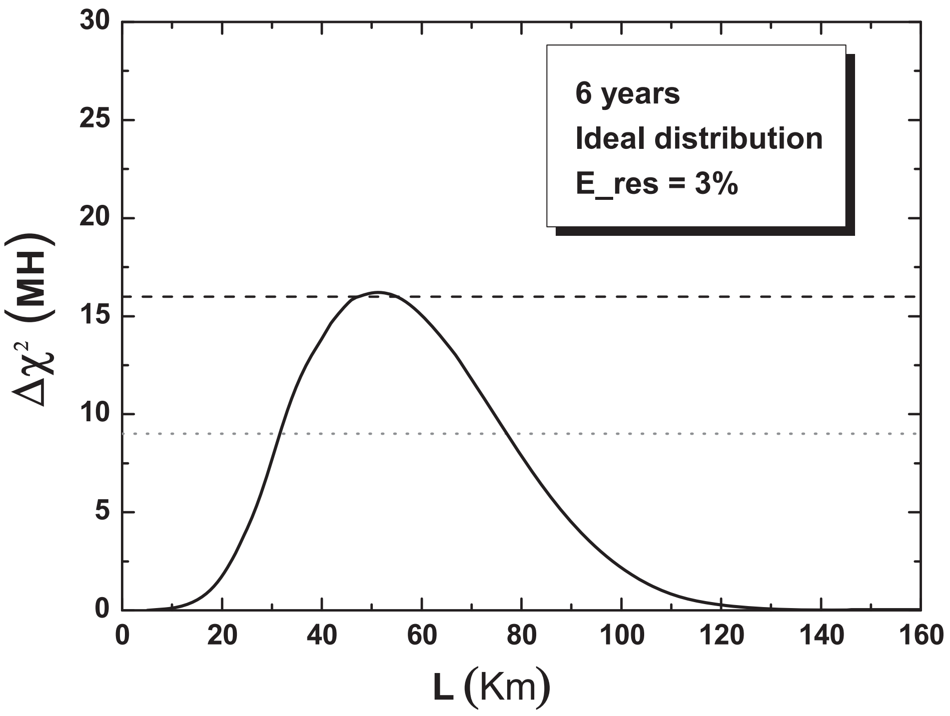


- ✓ Mass hierarchy is reflected in the survival spectrum
- ✓ Proportional to $\sin^2 2\theta_{13}$
- ✓ Signal independent of the unknown CP phase and the value of θ_{23}

A Closer Look at the Reactor Neutrino Case

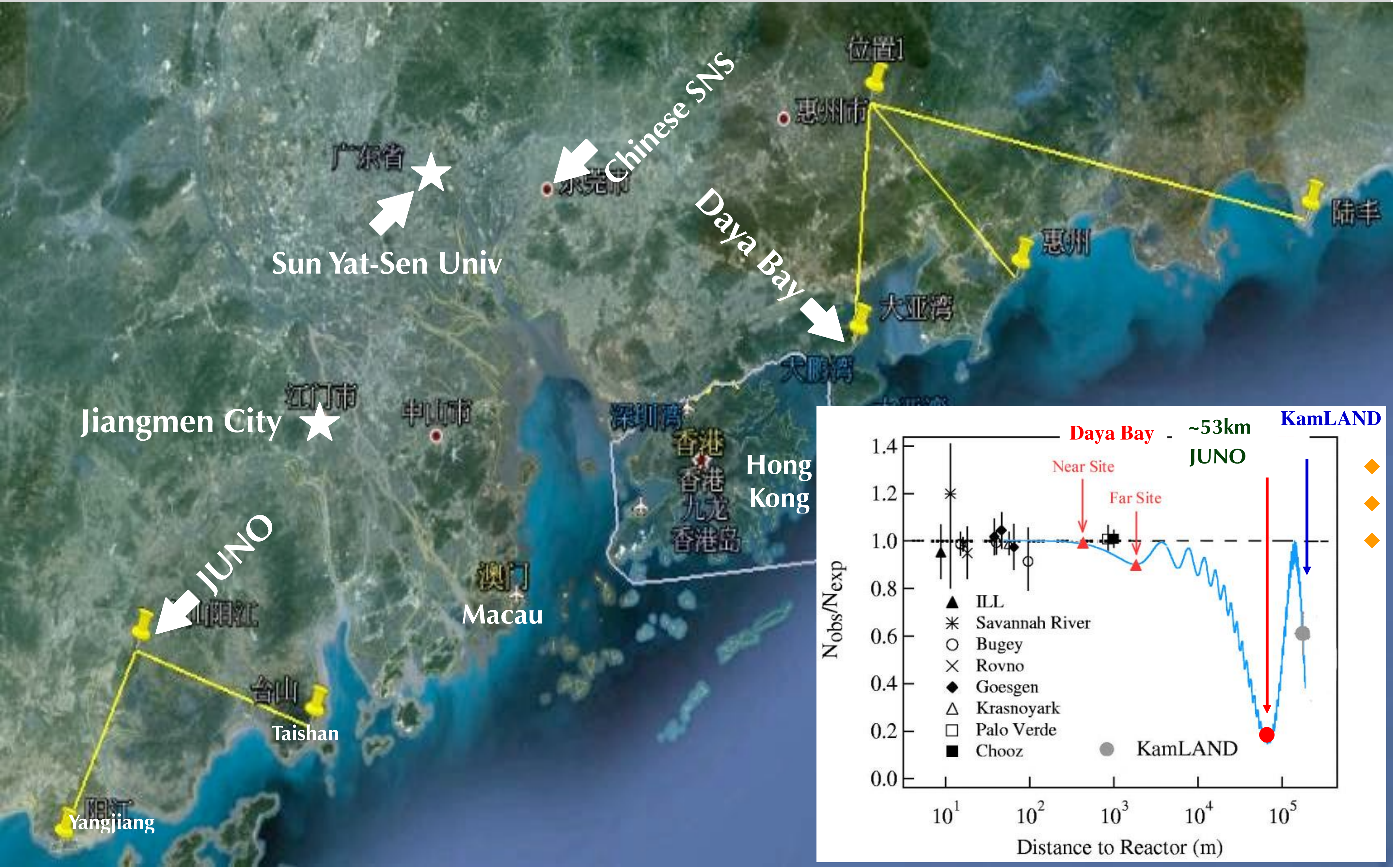


Qian et al PRD 87, 033005 (2013)



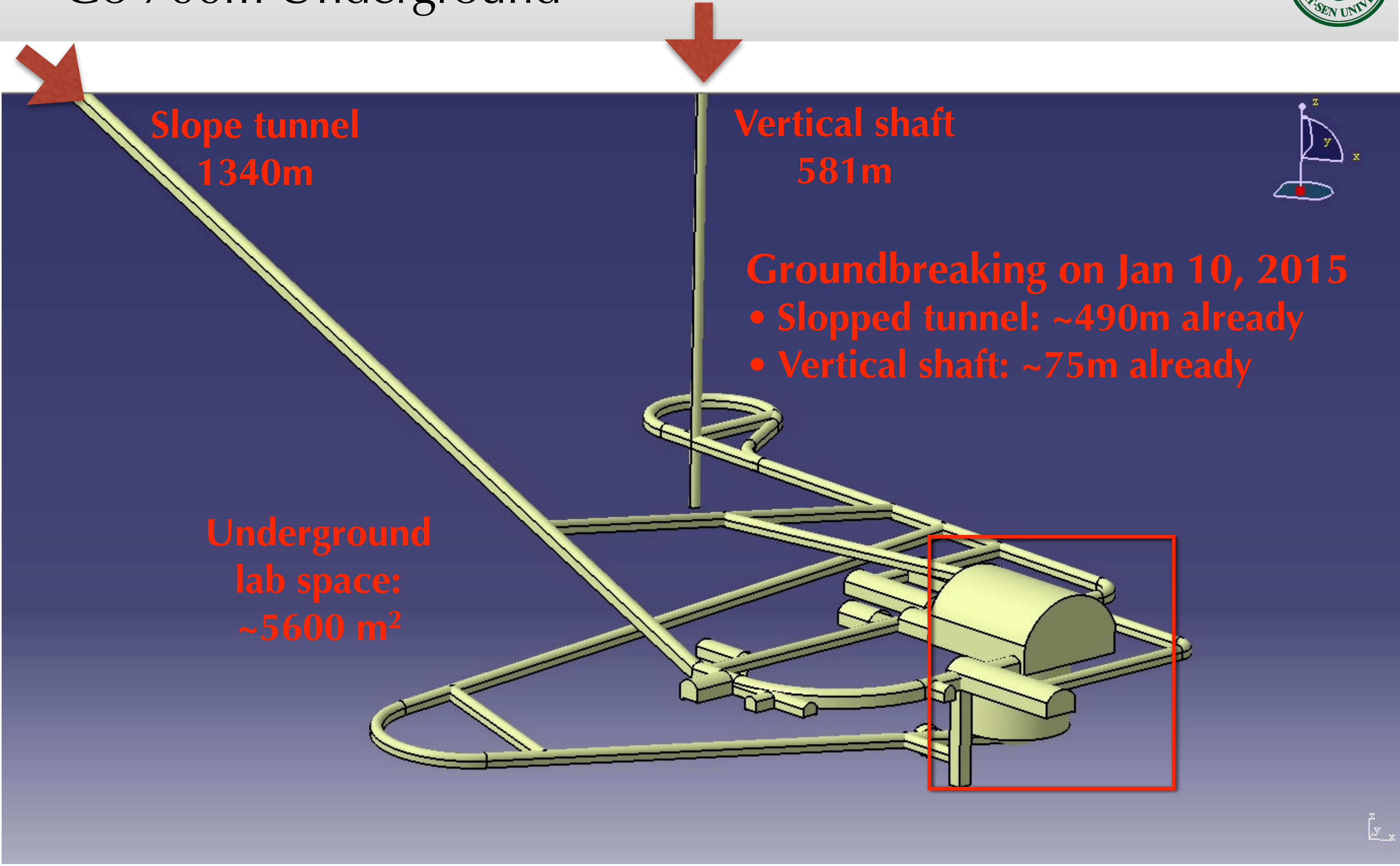
√Suitable baseline is ~60km

Jiangmen Underground Neutrino Observatory as an Example



Surface Facilities: Look into the Near Future……

Go 700m Underground

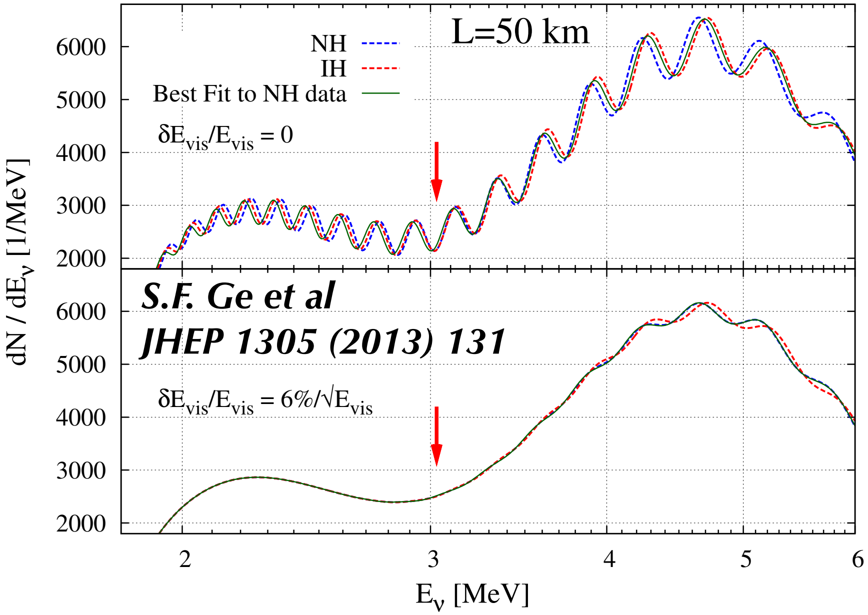


Groundbreaking on Jan 10, 2015

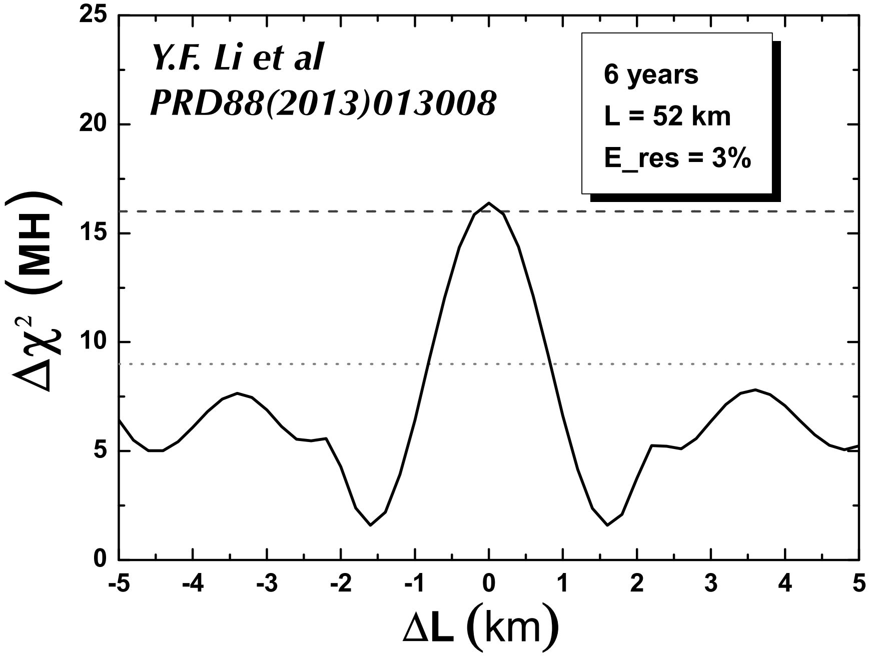
- Slopped tunnel: ~490m already
- Vertical shaft: ~75m already

Challenges in Resolving MH using Reactor Sources

- Energy resolution: ~3%/sqrt(E)
  - Bad resolution leads to smeared spectrum and the MH signal practically disappears
- Energy scale uncertainty: <1%
  - Bad control of energy scale could lead to no answer, or even worse, a wrong answer
- Statistics (who doesn’t like it?)
  - ~36GW thermal power, a 20kt detector plus precise muon tracking to get the best statistics
- Reactor distribution: <~0.5km
  - If too spread out, the signal could go away due to cancellation of different baselines
  - JUNO baseline differences are within half kilometer.

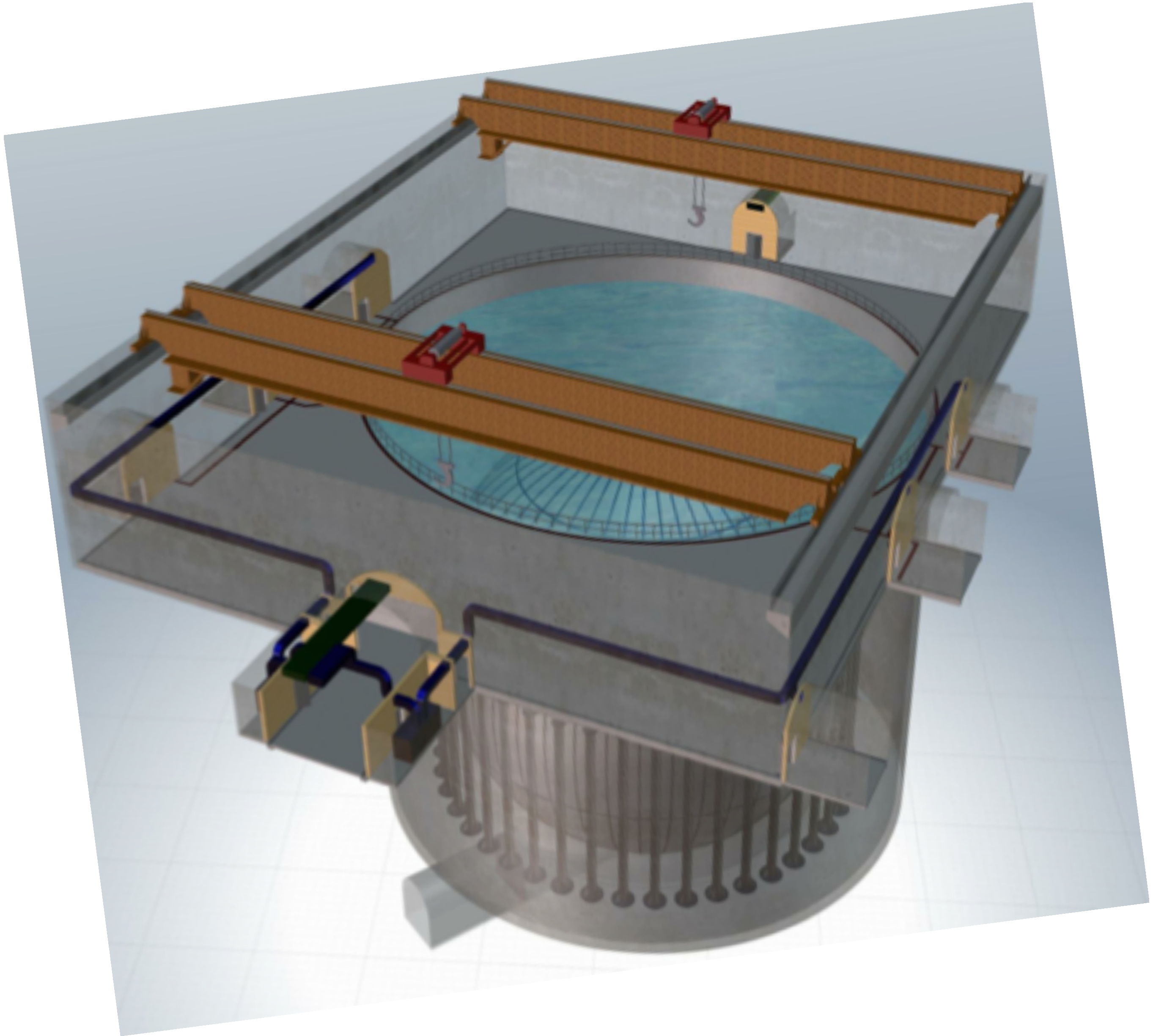


S.F. Ge et al JHEP 1305 (2013) 131



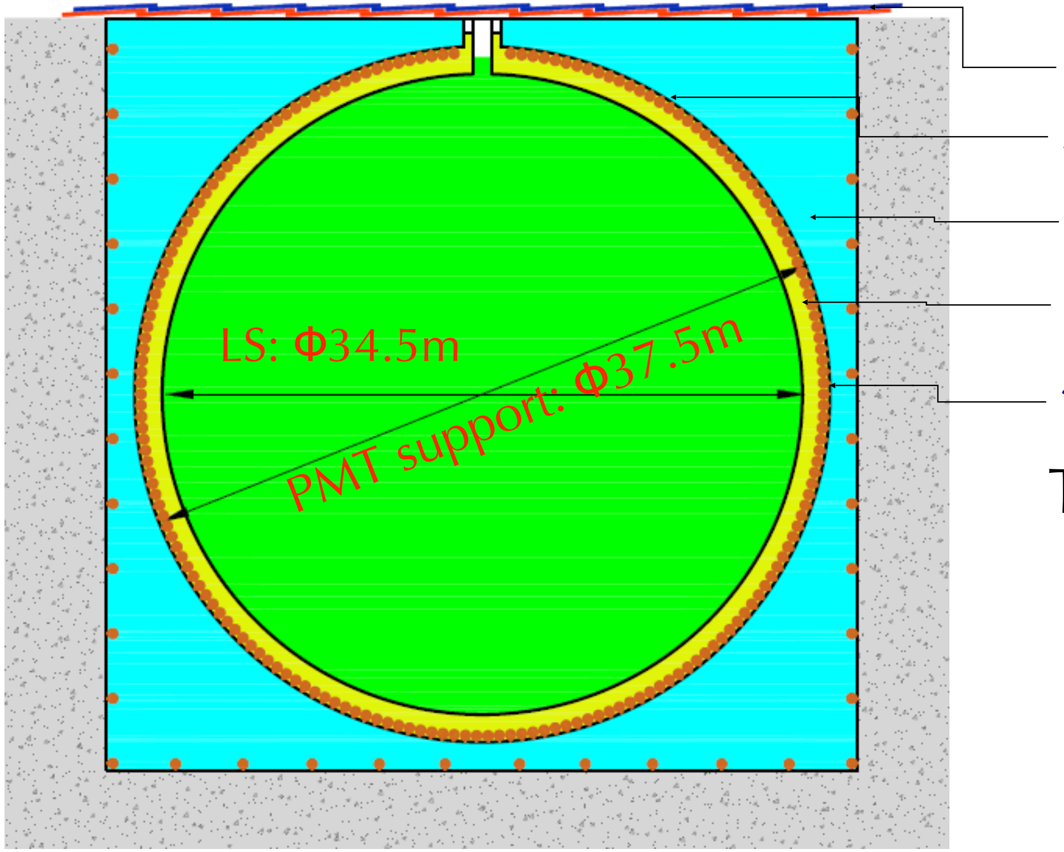
Y.F. Li et al PRD88(2013)013008

The Underground Detector System of JUNO



- A 55x48x27 m^3 main experimental hall and other halls&tunnels for electronics, LS, water, power, refuge and other facility rooms.
- A 20kt spherical liquid scintillator detector
- The muon veto system combines a cylindrical water Cherenkov detector (~42.5m in diameter and depth) and the OPERA calorimeters on the top to provide tracking information

The First Conceptual Design of the Detector



$$\frac{\Delta E}{E} = \sqrt{\underset{\text{Energy leakage \& non-uniformity}}{a^2} + \underset{\text{Photon statistics}}{\frac{b^2}{E}} + \underset{\text{Noise (~background)}}{\frac{c^2}{E^2}}}$$

To reach ~3%/√E energy resolution,

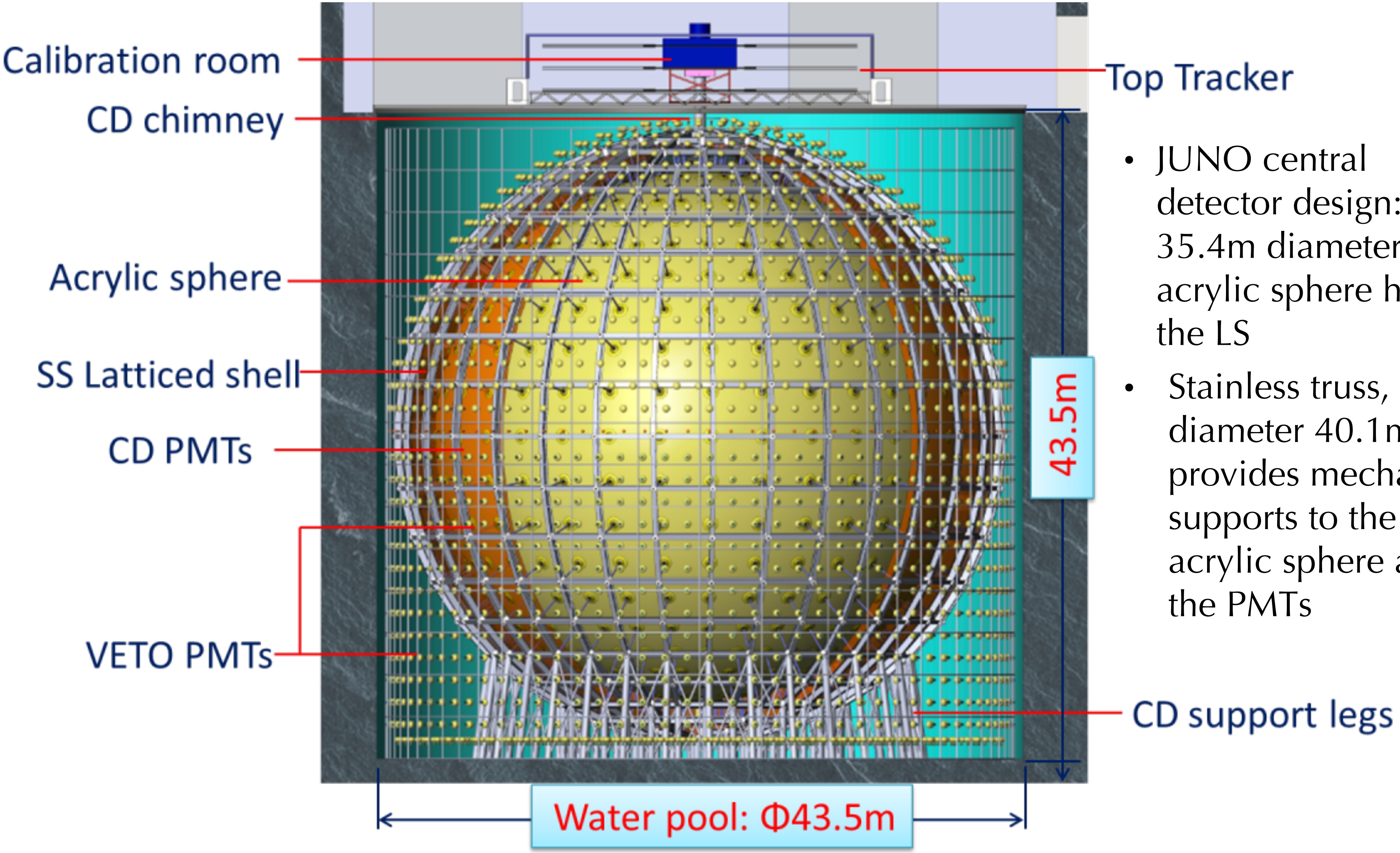
- Obtain as many photons as possible → high light yield scintillator, high photocathode coverage, and high detection efficiency PMTs
- Keep the detector as uniform as possible → a spherical detector
- Keep the noise as low as possible → clean materials and quiet PMTs

The Detector Performance Goals

	Daya Bay	BOREXINO	KamLAND	**JUNO**
Target Mass	20t	~300t	**~1kt**	**~20kt**
PE Collected	~160 PE/MeV	**~500 PE/MeV**	~250 PE/MeV	**~1200 PE/MeV**
Photocathode Coverage	~12%	**~34%**	**~34%**	**~80%**
Energy Resolution	~7.5%/√E	**~5%/√E**	~6%/√E	**3%/√E**
Energy Calibration	~1.5%	**~1%**	~2%	**<1%**

➡ An unprecedented LS detector is under development for the JUNO project —> a great step in detector technology

The JUNO Detector Design



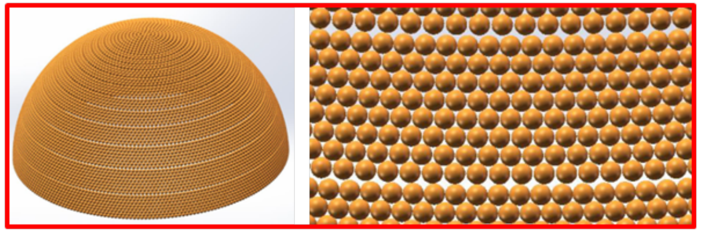
- JUNO central detector design: a 35.4m diameter acrylic sphere holds the LS
- Stainless truss, diameter 40.1m, provides mechanical supports to the acrylic sphere and the PMTs

- Water Cherenkov detector with top tracker functions as the muon veto and reconstruction system; Underwater electronics is the current baseline

PMT Arrangement and Readout

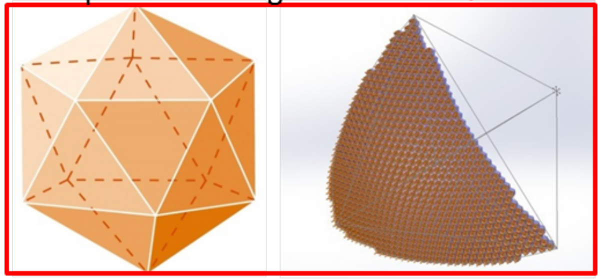
Supper layer arrangement method 77.8%

✓1



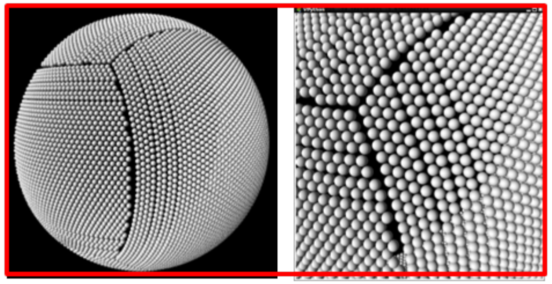
Spherical triangle method 72%

2



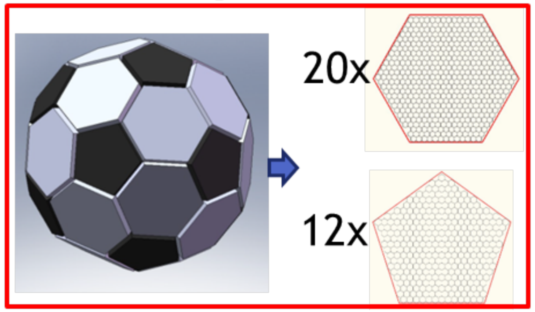
Volleyball arrangement method 75.96%

3



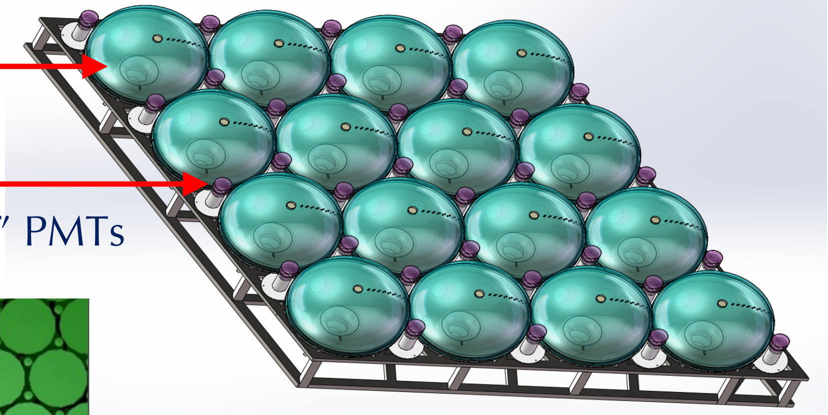
Football arrangement method 74.08%

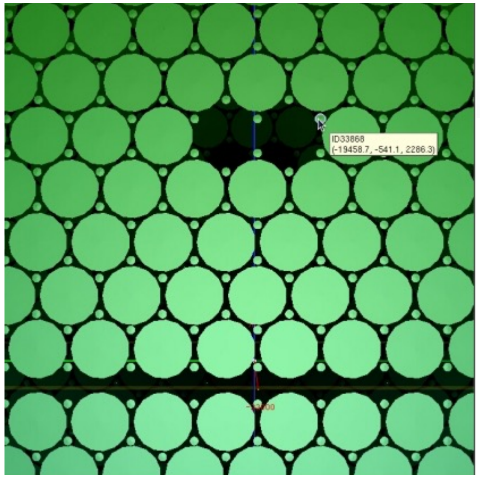
4



20″ PMT(~18000)

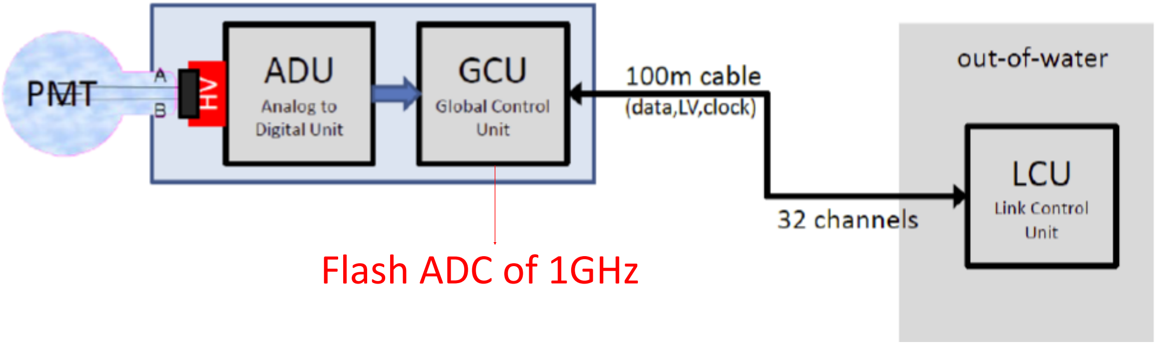
3″ sPMT(~36000)
Arranged between 20″ PMTs





Out of water

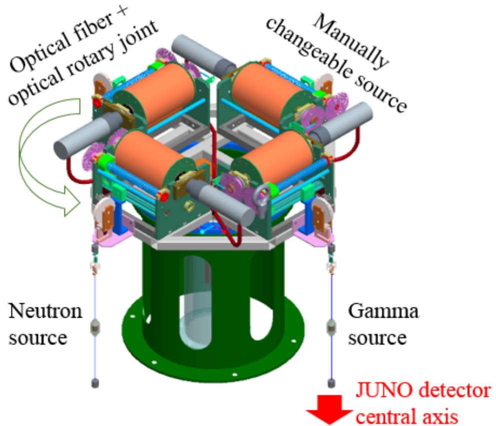
Front part under-water



Flash ADC of 1GHz

Calibration System

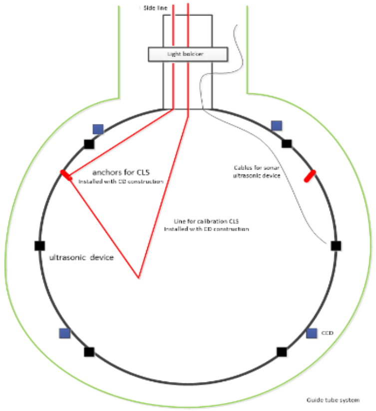
Automatic calibration Unit (ACU) Ø =1.4 m, h=1 m

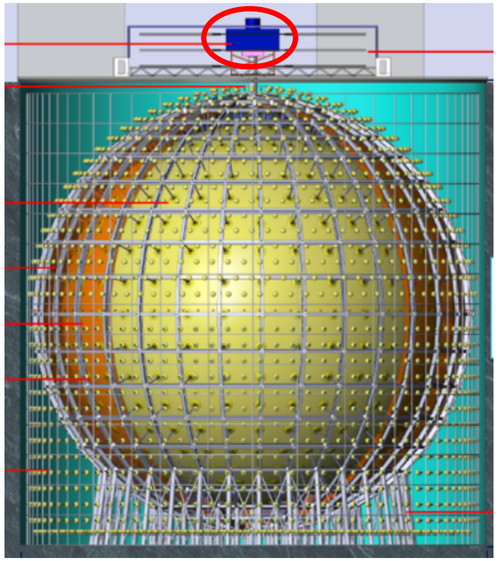


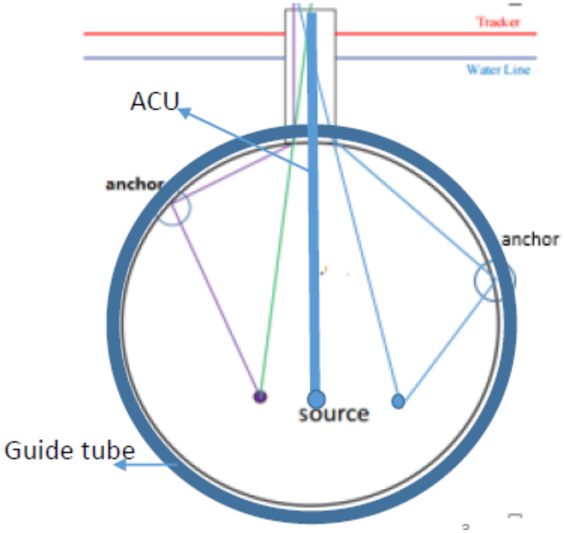
- Regular deployment (every week)

Scan center axis

Cable Loop System (CLS)

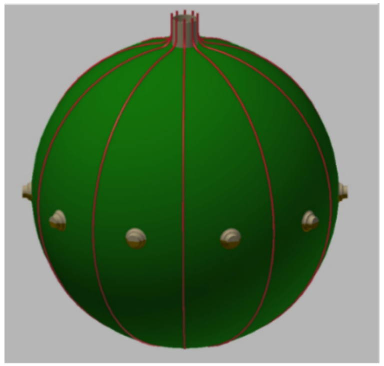






Four units designed

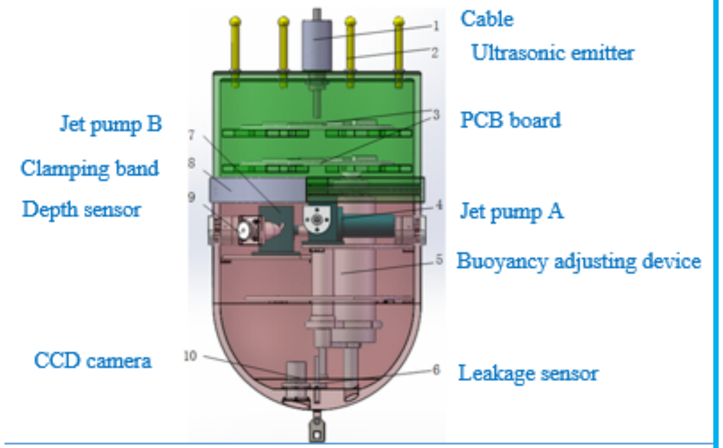
Guide Tube (GT)



Scan outer surface of CD

The source is driven with rope pulled by step motors

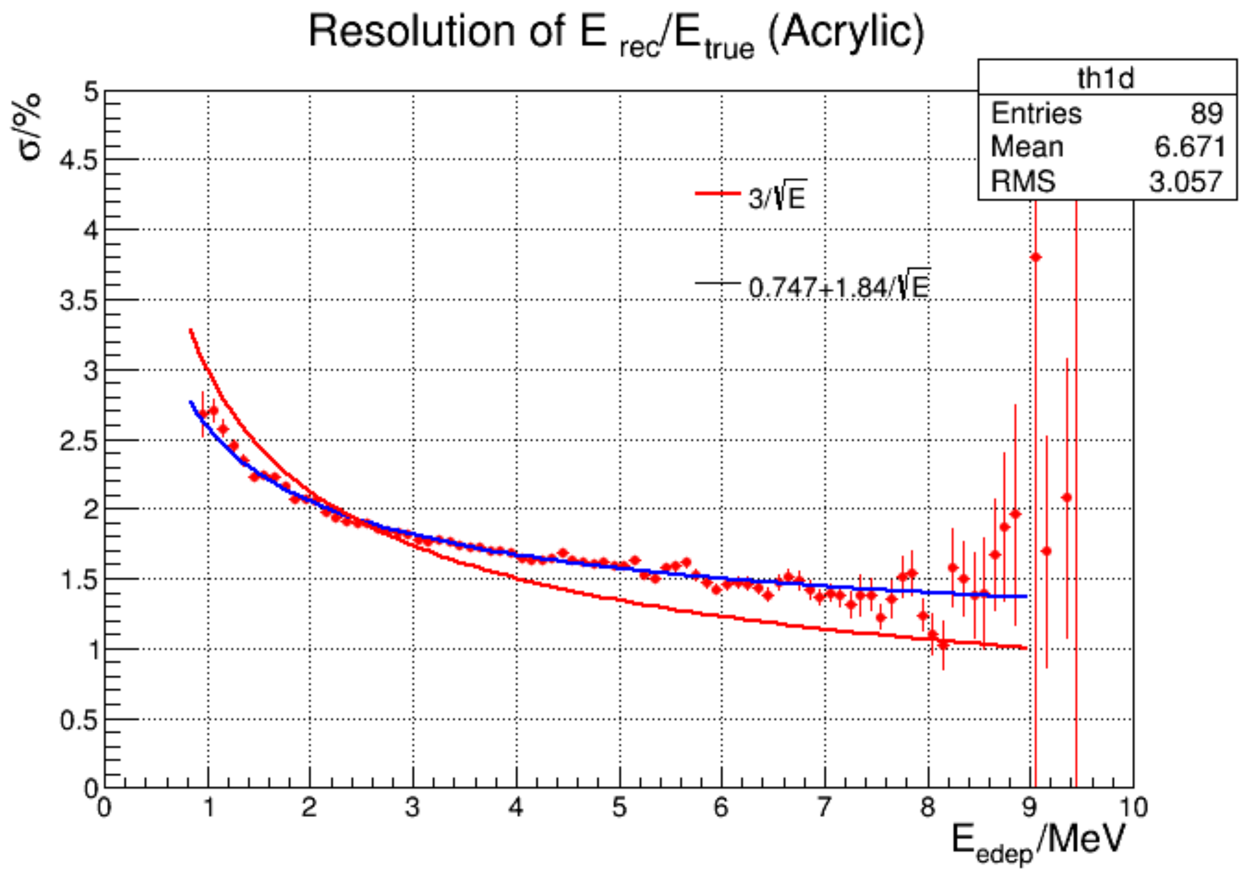
Remotely Operated Vehicle(ROV)



Scan the whole CD if needed

Putting Everything Together (Simulation)

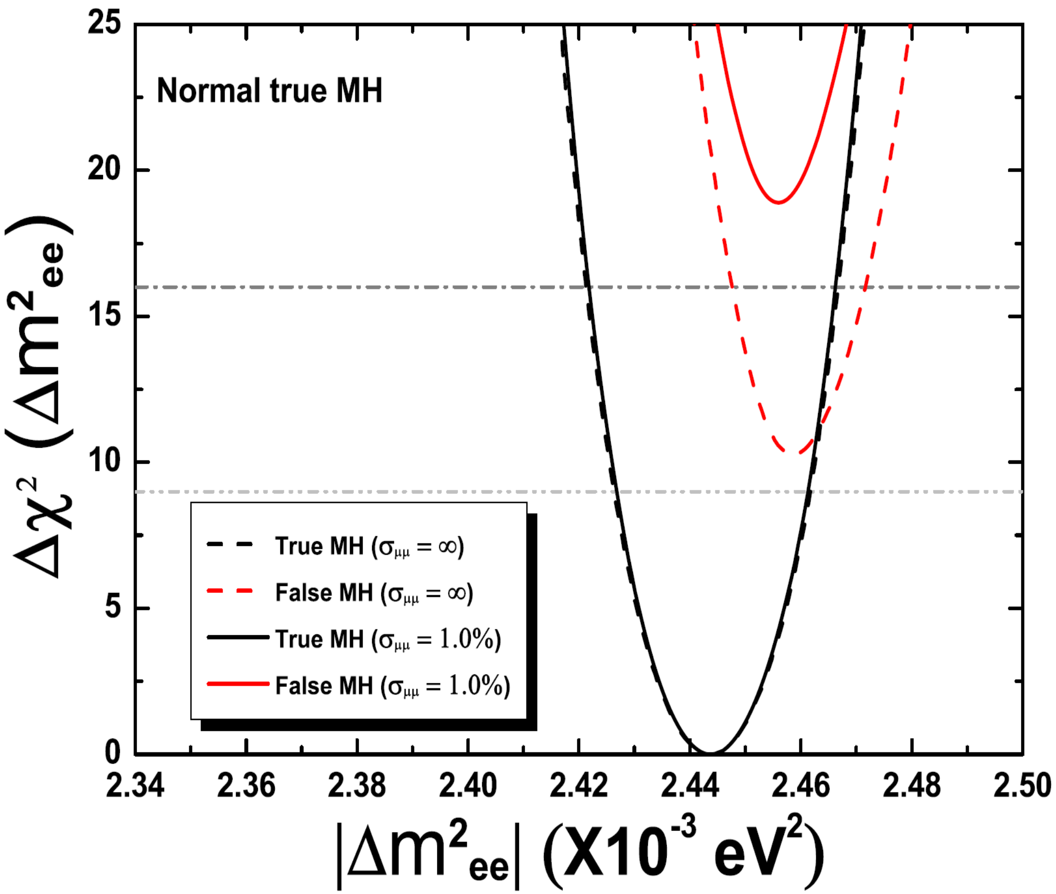
- Assumptions: PMT QE 35%; LS light yield 10.4k photons/MeV and L_{attn} = 20m @430nm



- Simulation suggests that effective photocathode coverage can reach ~75% after considering the (current) support structures.
- A ~3%/√E energy resolution is plausible based on simulation.

The project is planning to start data taking 2020

Expected Significance to Mass Hierarchy



- ~3-sigma if only a relative spectral measurement without external atmospheric mass-squared splitting
- ~4-sigma with an external Δm^2 measured to ~1% level in ν_μ beam oscillation experiments
  - ~1% in Δm^2 is reachable based on the combined T2K+NOvA analysis by
    S.K. Agarwalla, S. Prakash, WW, arXiv:1312.1477

✓Realistic reactor distributions considered

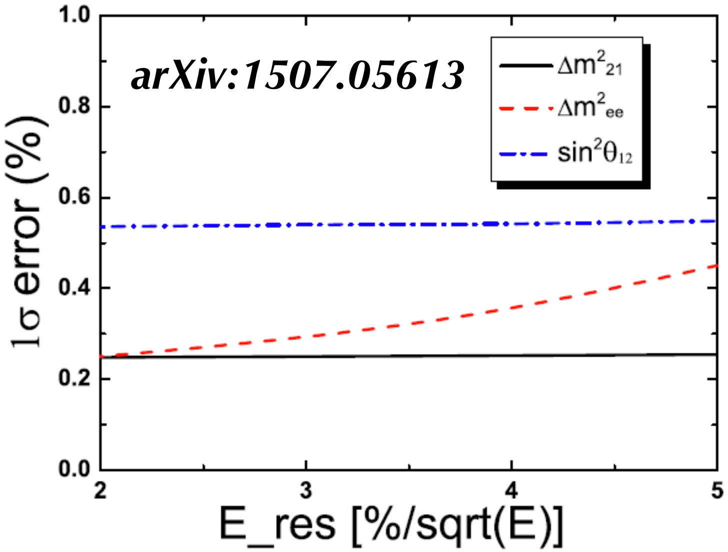
✓20kt valid target mass, 36GW reactor power, 6-year running

✓3% energy resolution and 1% energy scale uncertainty assumed

JUNO Precision Measurements Warranted

Global
arXiv:1507.05613

	Δm^2_{21}	$\|\Delta m^2_{31}\|$	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$
Dominant Exps.	KamLAND	MINOS	SNO	Daya Bay	SK/T2K
Individual 1σ	2.7% [121]	4.1% [123]	6.7% [109]	6% [122]	14% [124,125]
Global 1σ	2.6%	2.7%	4.1%	5.0%	11%



Consistent conclusion from an independent study by A.B. Balantekin et al, Snowmass'13, arXiv:1307.7419

- Precision <1% measurements are warranted in a experiment like JUNO
    - Enable a future ~1% level PMNS unitarity test
    - Neutrinoless double beta decay needs precise θ_{12}

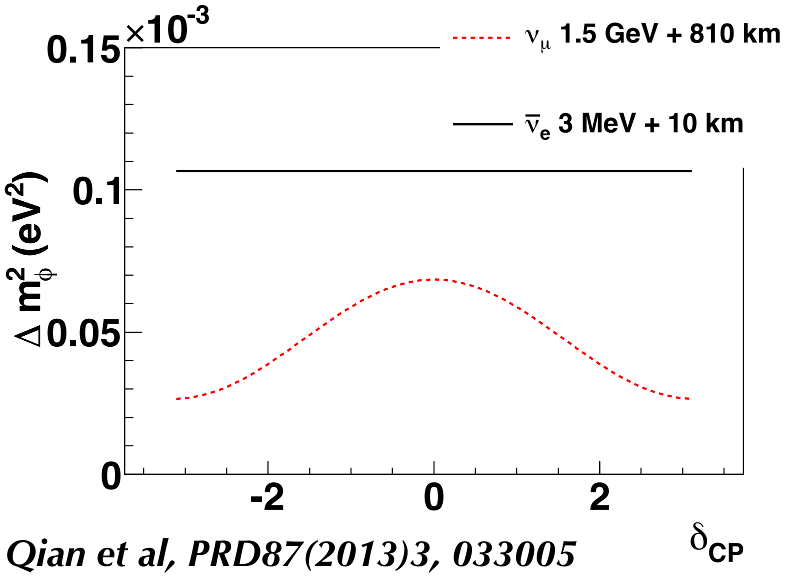
	Nominal	+ B2B (1%)	+ BG	+ EL (1%)	+ NL (1%)
$\sin^2\theta_{12}$	0.54%	0.60%	0.62%	0.64%	0.67%
Δm^2_{21}	0.24%	0.27%	0.29%	0.44%	0.59%
$\|\Delta m^2_{ee}\|$	0.27%	0.31%	0.31%	0.35%	0.44%

JUNO: 100k evts
arXiv:1507.05613

Summary and Outlook

- Exciting and steady progresses have been made in the past 20 years in neutrino experiments since Super-K turned on — ***New physics beyond the Standard Model***
- There are still unknowns in neutrino physics which are essential to the progresses in both theoretical and experimental fronts
- Atmospheric neutrinos and reactor neutrinos provide great potential in resolving the neutrino mass hierarchy, ***and they are complementary and share a very similar schedule***
  - IceCube-Gen2/PINGU phase-I is carrying out R&D
  - JUNO are under construction
- ***Unanswered questions in neutrino physics*** might hold the keys to many profound questions — ***Stay tuned and expect unexpected!***

Why is the Δm^2_{ee} Measurement Interesting?



Qian et al, PRD87(2013)3, 033005

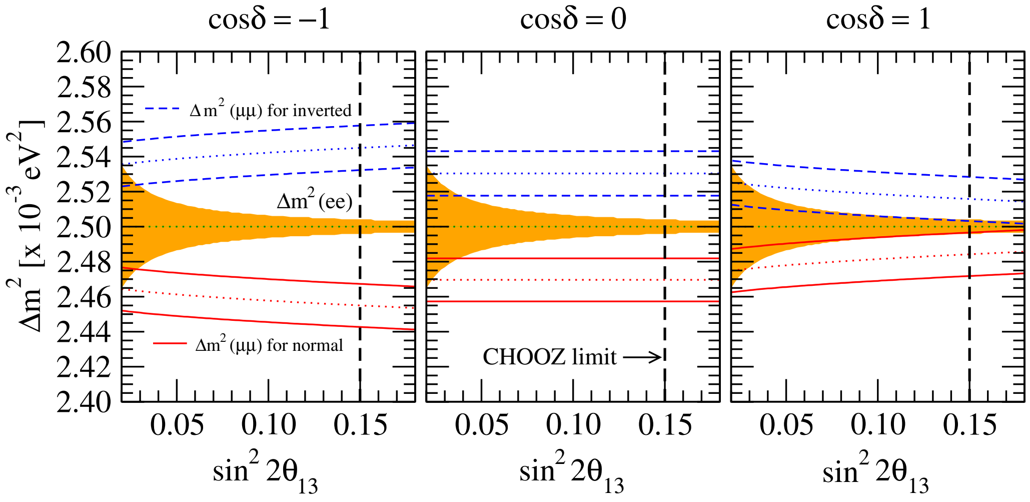
$$\begin{aligned} P(\bar{\nu}_e \to \bar{\nu}_e) &= 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\ &= 1 - 2s^2_{13}c^2_{13} - 4c^4_{13}s^2_{12}c^2_{12}\sin^2\Delta_{21} + 2s^2_{13}c^2_{13}\sqrt{1 - 4s^2_{12}c^2_{12}\sin^2\Delta_{21}}\cos(2\Delta_{32} \pm \phi) \end{aligned}$$

$$P_{\nu_\mu \to \nu_\mu} = 1 - P^\mu_{21} - \cos^2\theta_{13}\sin^2 2\theta_{23}\sin^2\frac{(\Delta m^2_{32} \pm \phi)L}{4E}$$

Because it could, potentially, tell MH!

But it is too hard of a job from this approach.

FIG. 6: The dependence of effective mass-squared difference $\Delta m^2_{ee\phi}$ (solid line) and $\Delta m^2_{\mu\mu\phi}$ (dotted line) w.r.t. the value of δ_{CP} for $\bar{\nu}_e$ and ν_μ disappearance measurements, respectively.



Minakata et al PRD74(2006), 053008

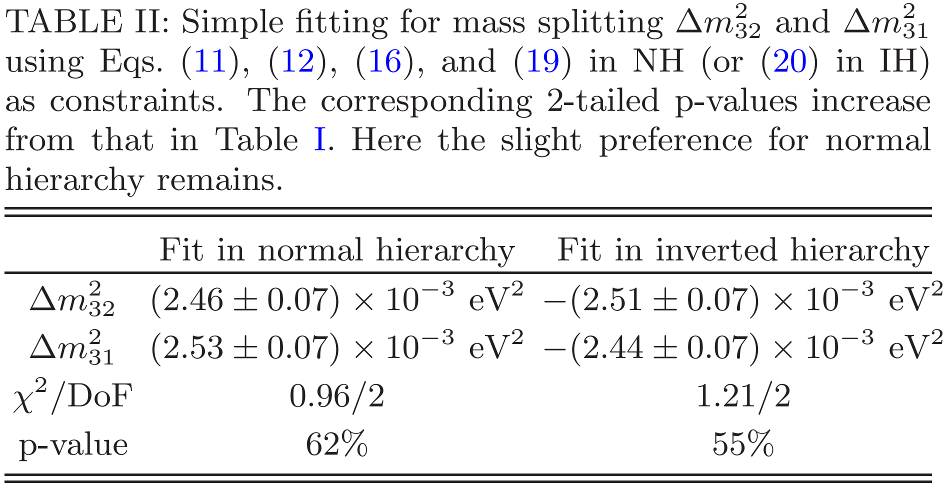
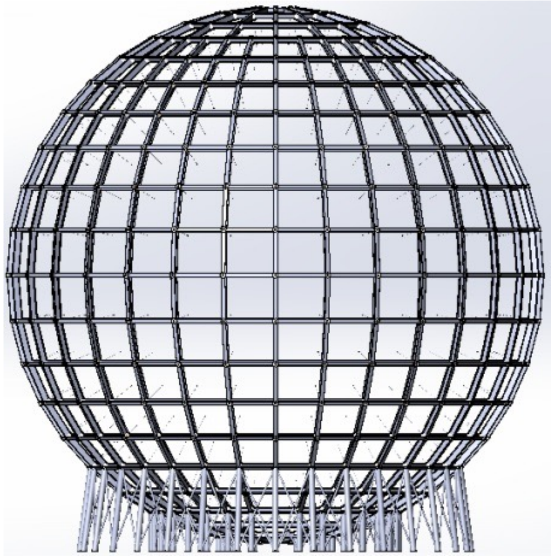


TABLE II: Simple fitting for mass splitting Δm^2_{32} and Δm^2_{31} using Eqs. (11), (12), (16), and (19) in NH (or (20) in IH) as constraints. The corresponding 2-tailed p-values increase from that in Table I. Here the slight preference for normal hierarchy remains.

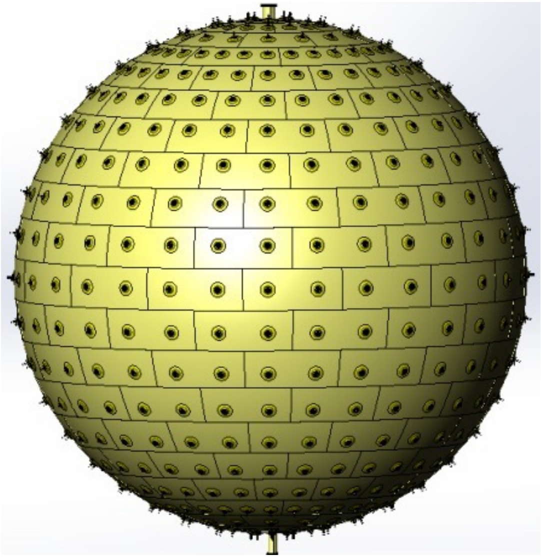
	Fit in normal hierarchy	Fit in inverted hierarchy
Δm^2_{32}	$(2.46 \pm 0.07) \times 10^{-3}$ eV^2	$-(2.51 \pm 0.07) \times 10^{-3}$ eV^2
Δm^2_{31}	$(2.53 \pm 0.07) \times 10^{-3}$ eV^2	$-(2.44 \pm 0.07) \times 10^{-3}$ eV^2
χ^2/DoF	0.96/2	1.21/2
p-value	62%	55%

Zhang&Ma, arXiv:1310.4443

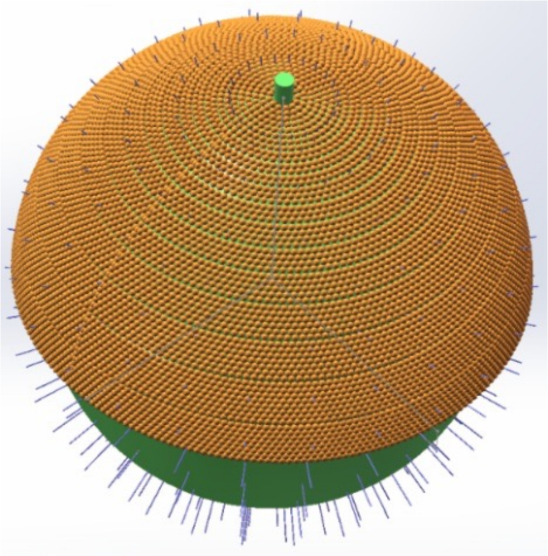
Details of the JUNO Central Detector



Stainless Steel Truss
Inner Diameter:40.1m



Acrylic Sphere
Inner Diameter: 35.4m



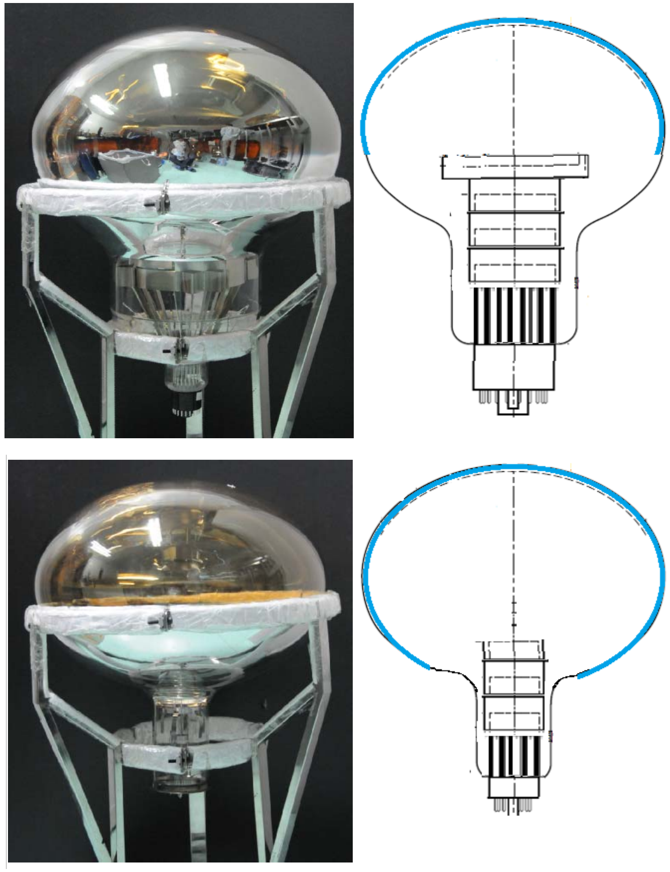
PMT Arrangement
~17,000 (20″)+~34,000 (3″)

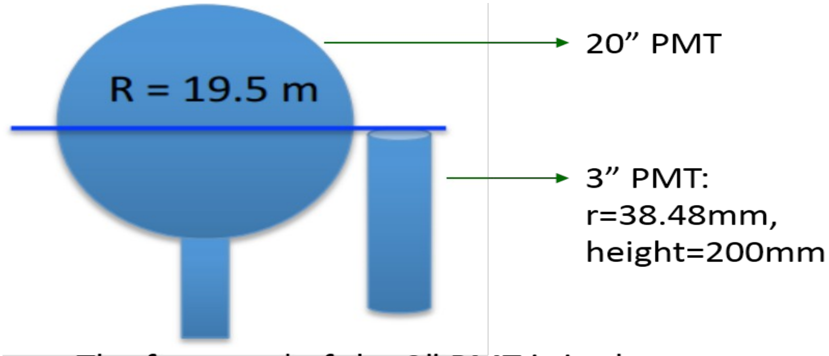
Stainless steel truss
- ID: Ø40.1m
- OD: Ø41.1m
- Weight: ~600t

Acrylic sphere
- ID: Ø35.4m
- Thickness:120mm
- Weight: ~600t

20″ PMT array
- Distance to LS: ~1.6m
- Gap: ~250mm (extremely challenging)

More Light: PMT and Photocathode Coverage

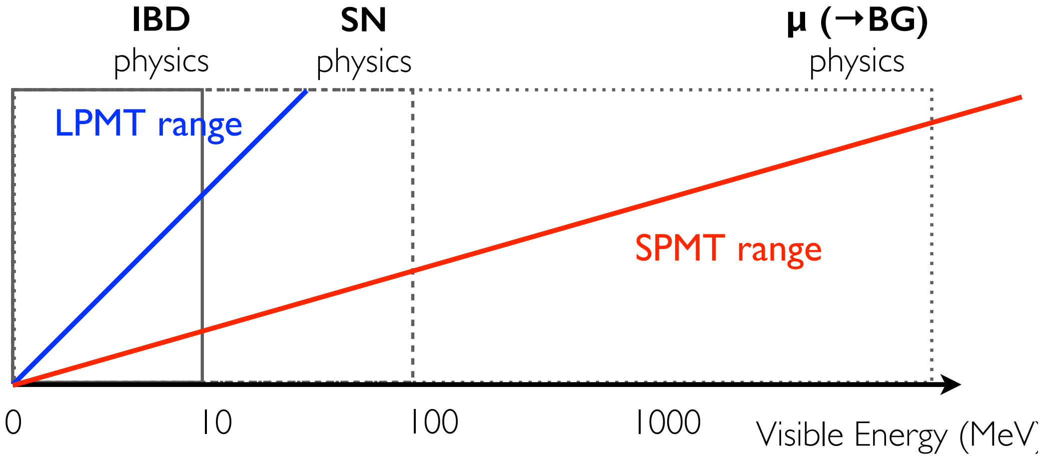




The front end of the 3” PMT is in the same plane as the equatorial plane of 20” PMT

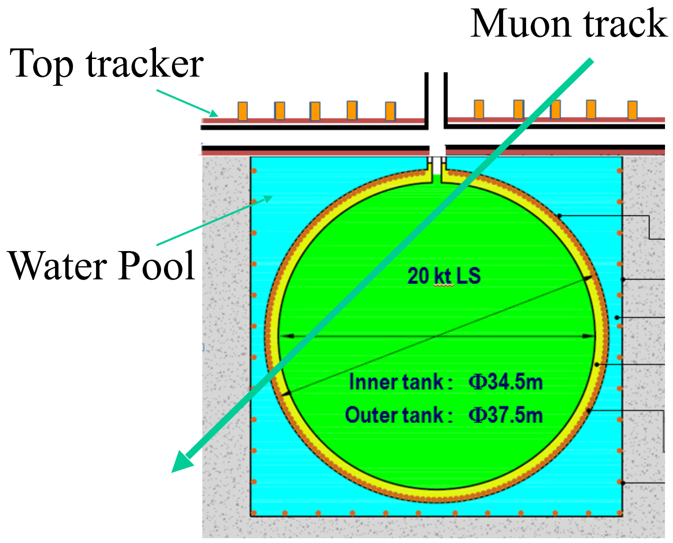
- Large PMTs: 20″ MCP-PMT, ~75%
- Large PMTs: 20″ SBA Hamamatsu, ~25%
- Small PMTs: 3″ PMTs
  - ➡ to further increase the photocathode coverage
  - ➡ to provide a semi-independent calorimetry system for timing
  - ➡ to extend energy dynamic range to avoid saturation, important for high energy events and cosmic muons

Complementary Roles by SPMTs and LPMTs

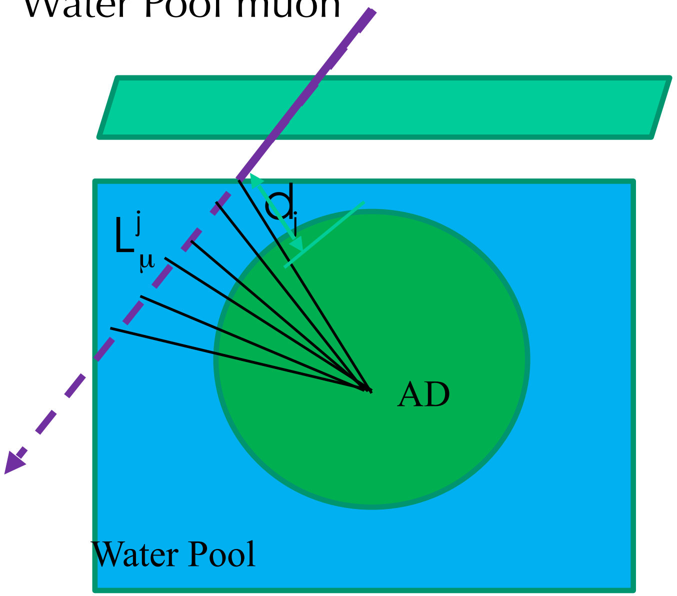


Veto System Considerations and Designs

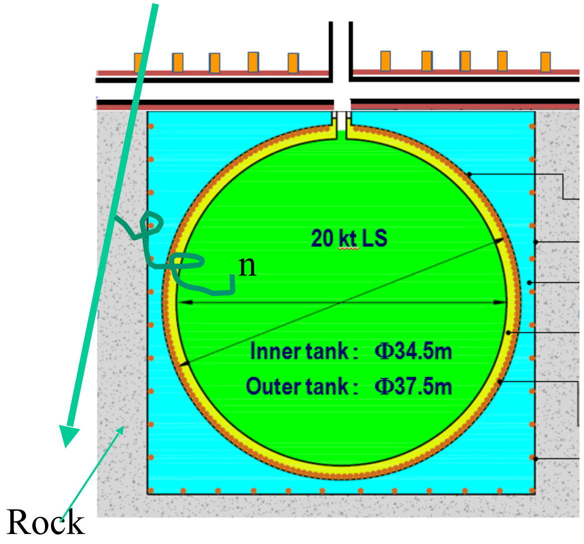
Central Detector muon



Water Pool muon



Rock muon



- Veto is not just a veto. Besides radioactive background shielding, we also need tracking information to better understand and remove cosmogenic backgrounds
  - The main body is the water Cherenkov detector
  - OPERA scintillator calorimeters will be moved to JUNO as the Top Tracker (TT)
- Earth magnetic field compensation coils are being designed together with the veto system design
- Radon removal, control and monitoring are under study