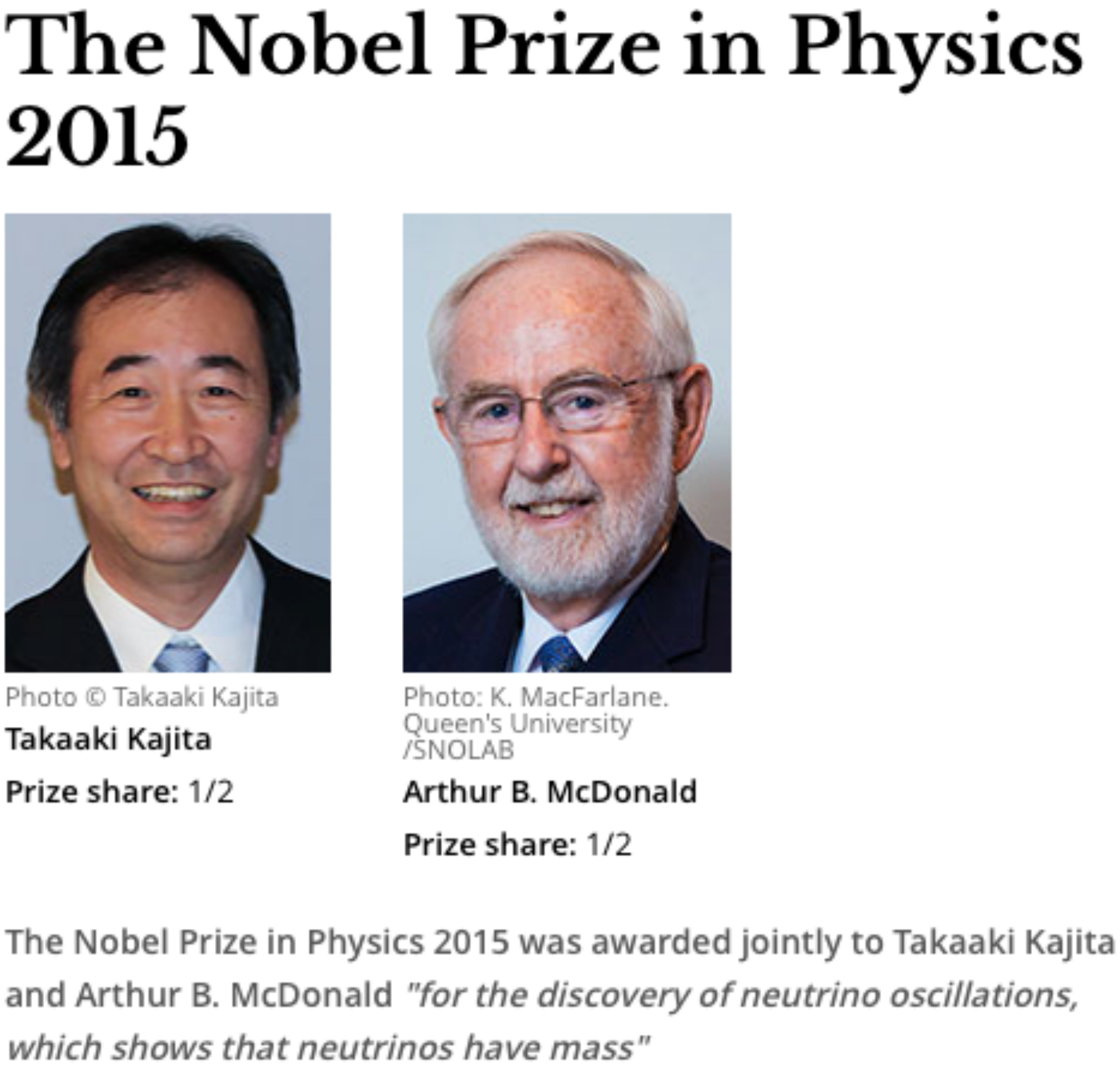
Search for ν MH & ν Physics @ JUNO

Wei Wang / 王為, Sun Yat-Sen University
39th Erice Summer School 2017, Sep 21, 2017

- *Opportunities&Challenges in ν Mixings&Oscillations*
- *The Quest for the ν Mass Hierarchy*
- *Jiangmen Underground Neutrino Observatory*
- *Summary and Outlook*

Discovery of Neutrino Oscillations



The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

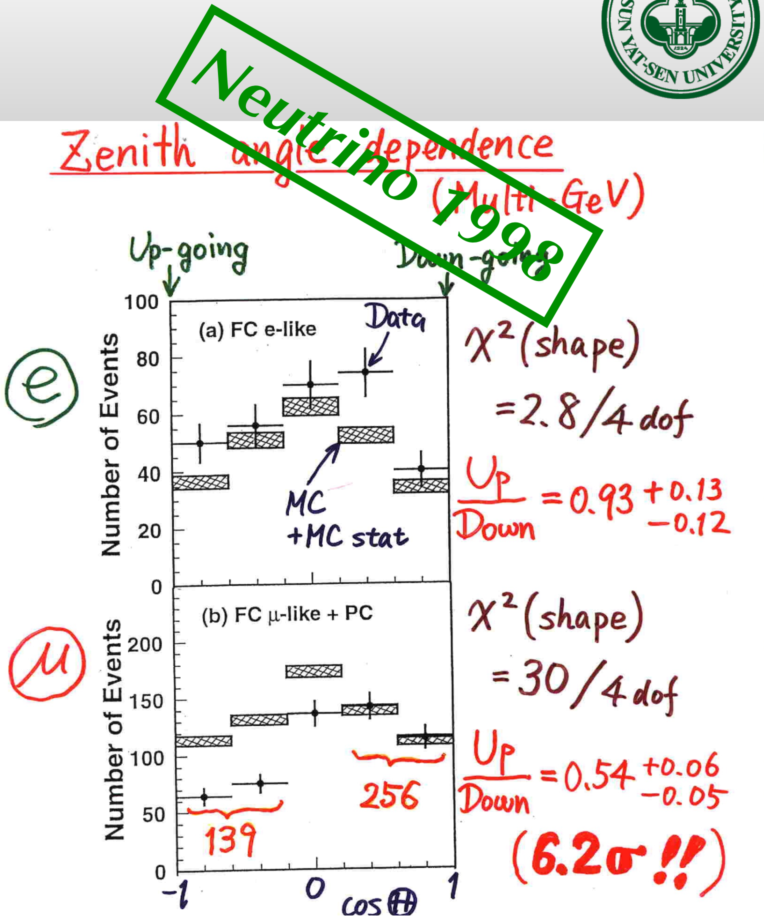
Prize share: 1/2

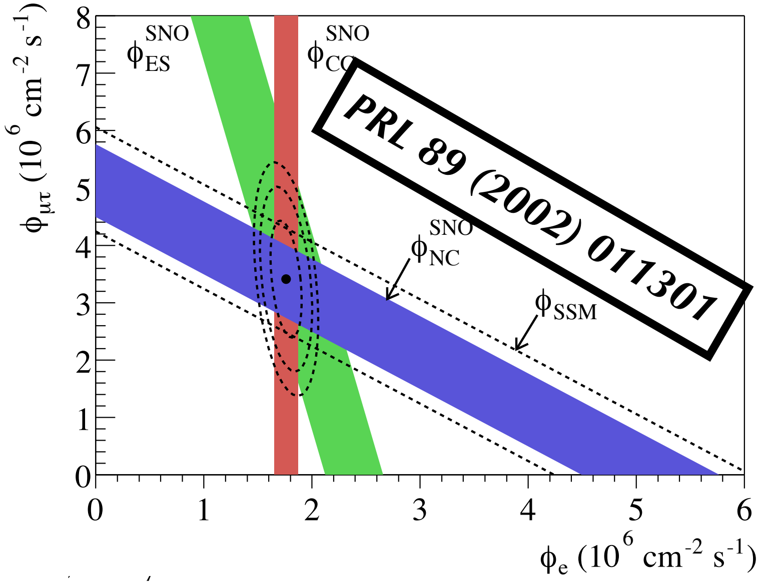
Photo: K. MacFarlane. Queen's University /SNOLAB

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"*





PRL 89 (2002) 011301

Neutrino Mixing Parameters

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

’98: Neutrino Oscillation discovered

Measured: 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 quest of 10+ years (’98-’12):

Measured: $\boldsymbol{\Delta m^2_{atm}(\Delta m^2_{ee})}$, 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

Measured: Δm^2_{solar}, θ_{12}

SNO, KamLAND, SK

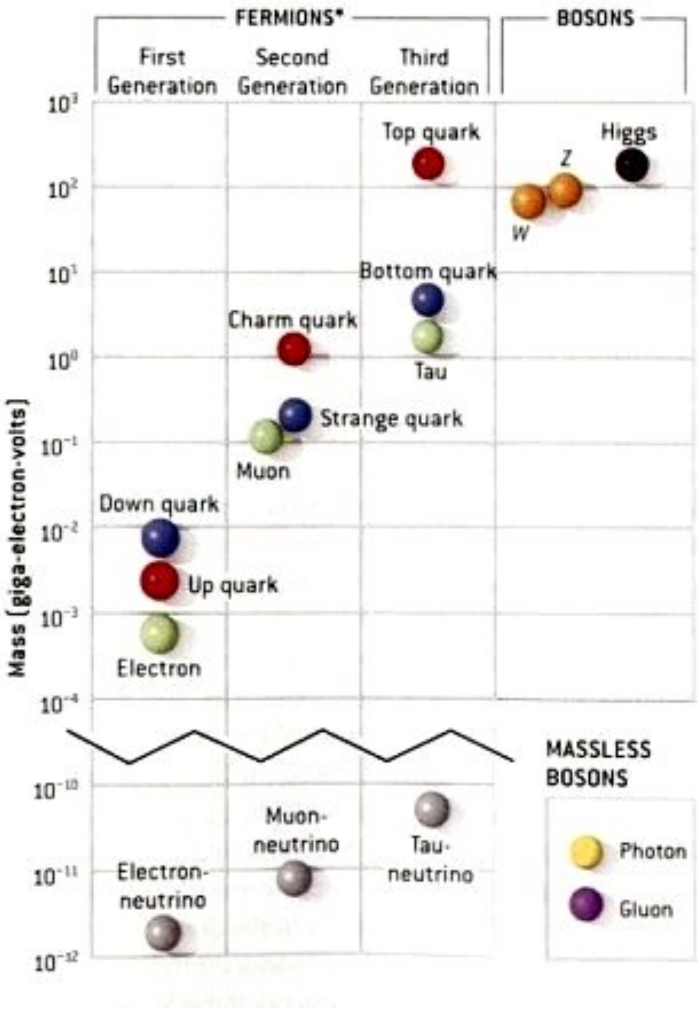
$$\times \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

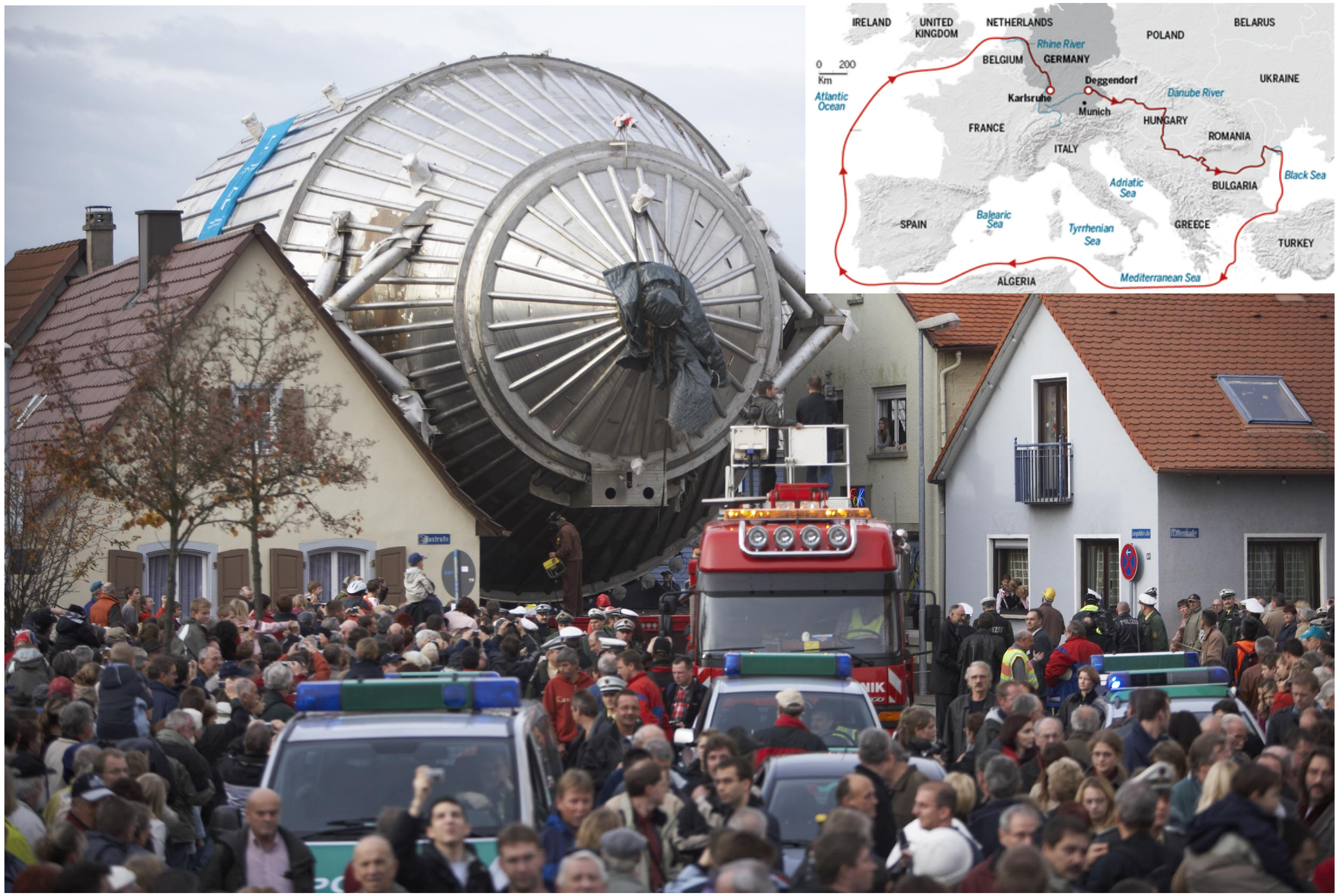
Thoughts on Majorana Phases?

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

A Great Discovery Opportunity beyond the SM

- The keyword in this opportunity is “mass”. Neutrino mass is really really hard. And this is an understatement.

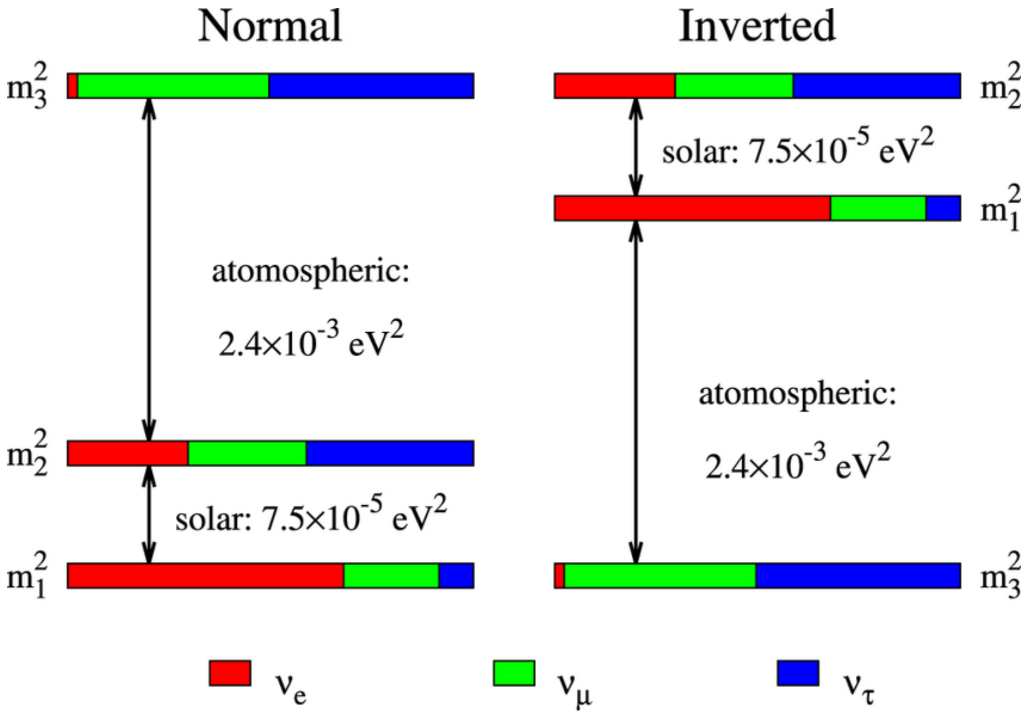




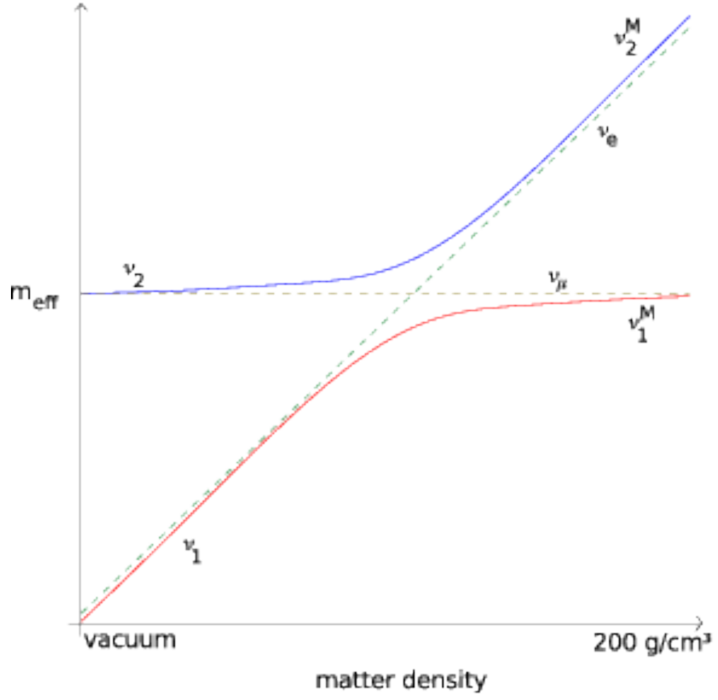
“KATRIN might be the last of its kind”

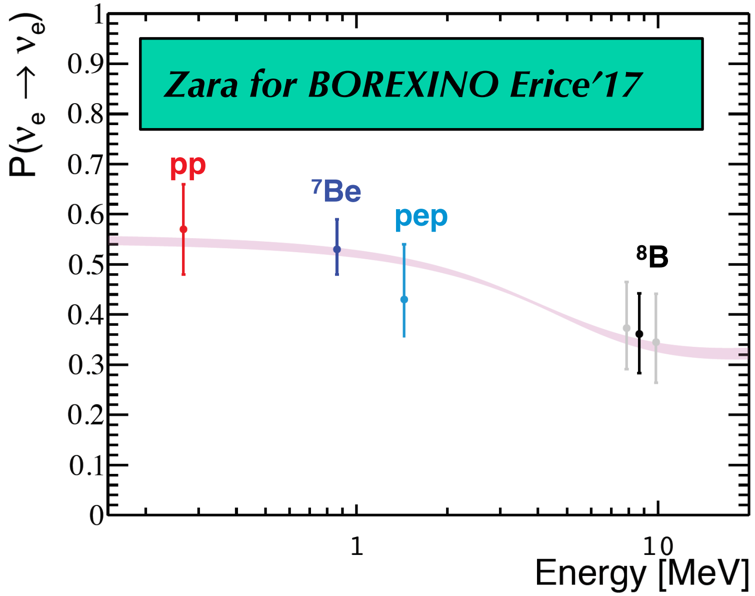
Neutrino Mass Hierarchy Must be Resolved

- Even if KATRIN would measure, we STILL have no clue about its mass ordering

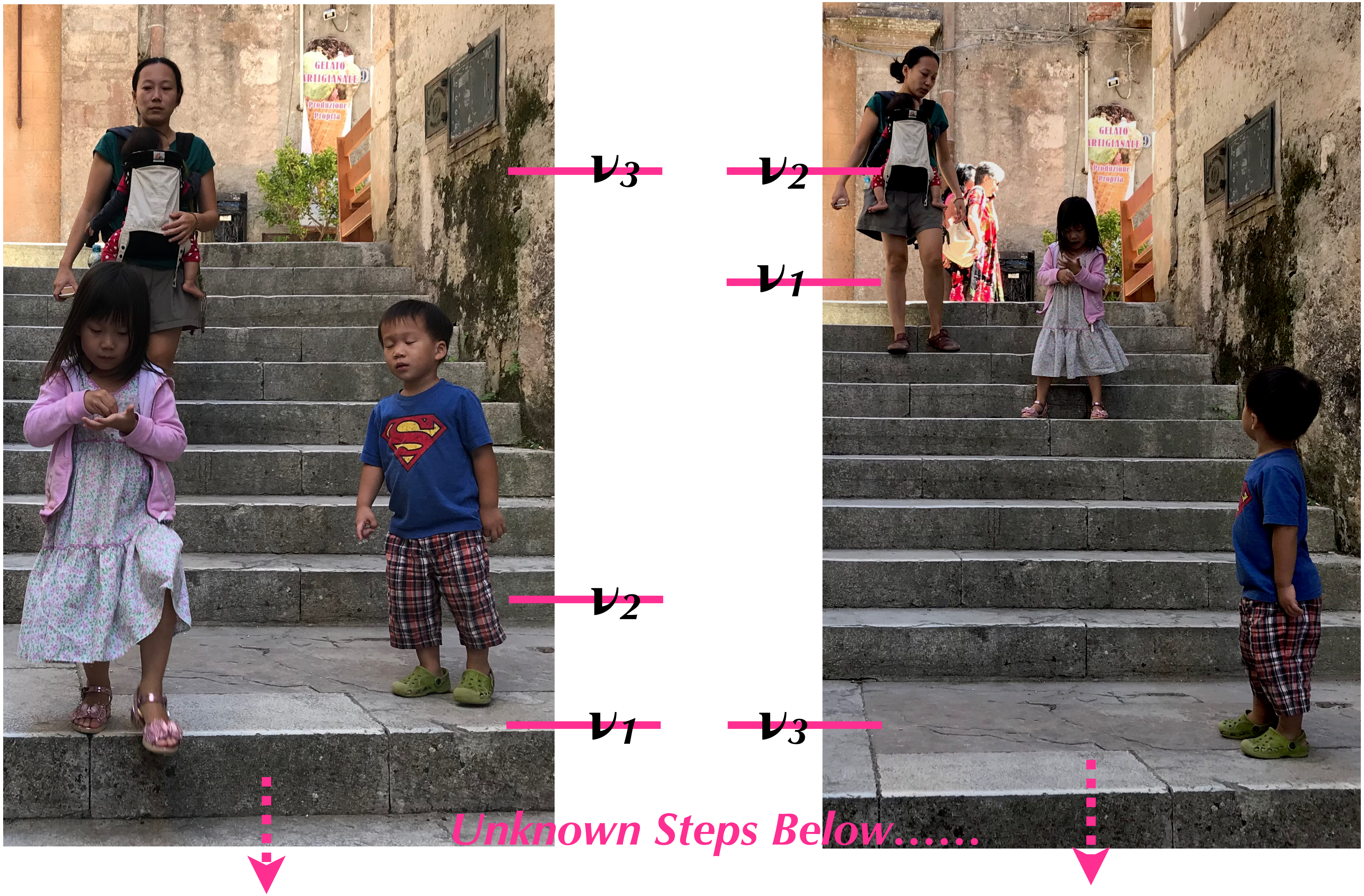


MSW Effect tells m_2 from m_1;
No clue for the sign of Δm^2_{32}

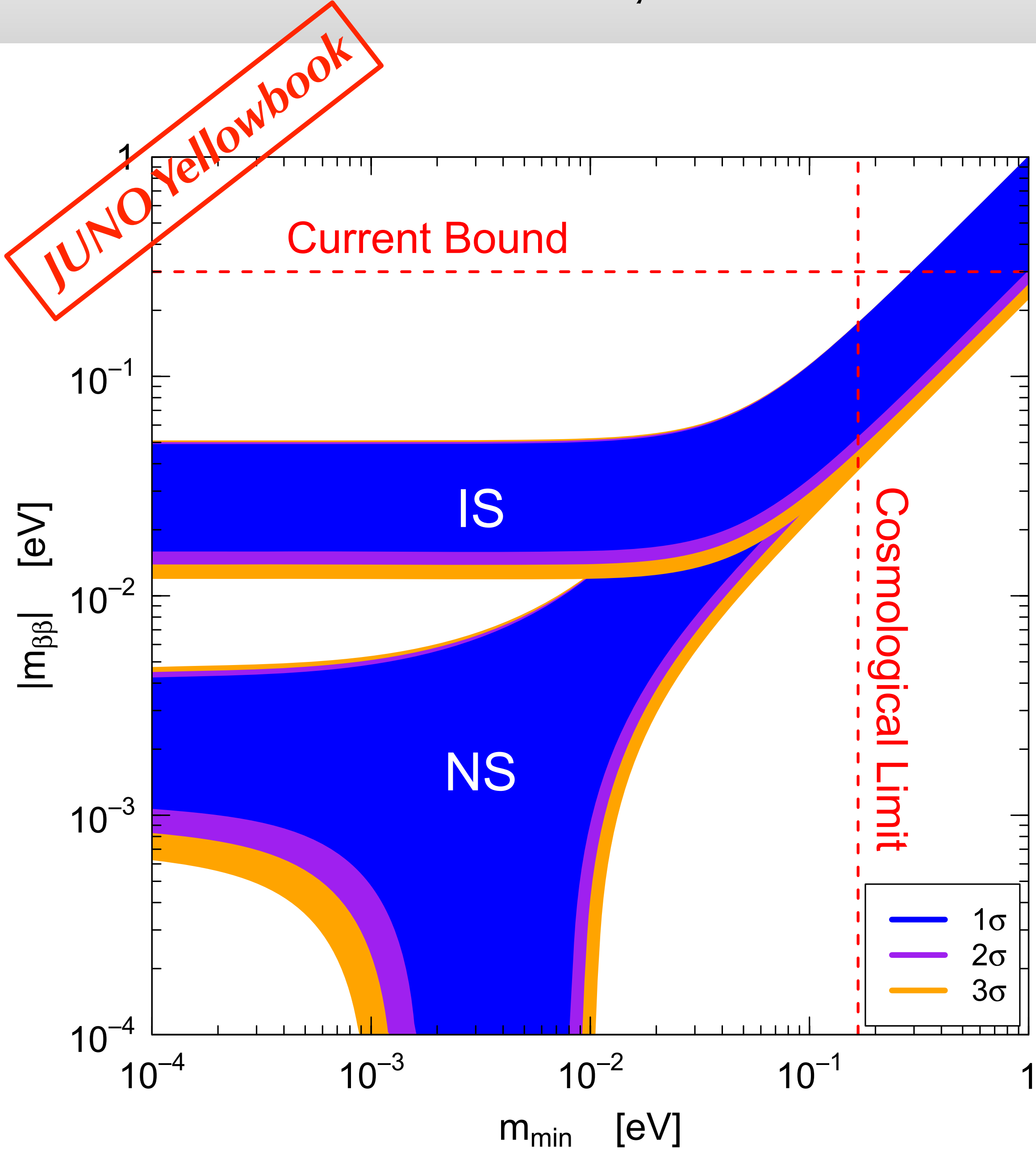




Normal Hierarchy vs. Inverted Hierarchy



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 if nature chooses to be the inverted case
- New techniques beyond the next generation are needed to explore the parameter space in the normal mass ordering case

Strategies and Methods Resolving MH

- **Our familiar tool that has helped us telling the m_2 state from m_1 using solar neutrino data: Matter Effect**
- **Interference between the solar and the atmospheric oscillation terms**
- Cosmological data: limiting the total mass of the neutrino eigenstates → information on MH by combining with the mass-squared differences
- Supernova neutrinos: collective oscillation on the detected neutrino arrival time profile and their spectra

Matter Effect to Resolve Mass Hierarchy

- Matter Effect strength:

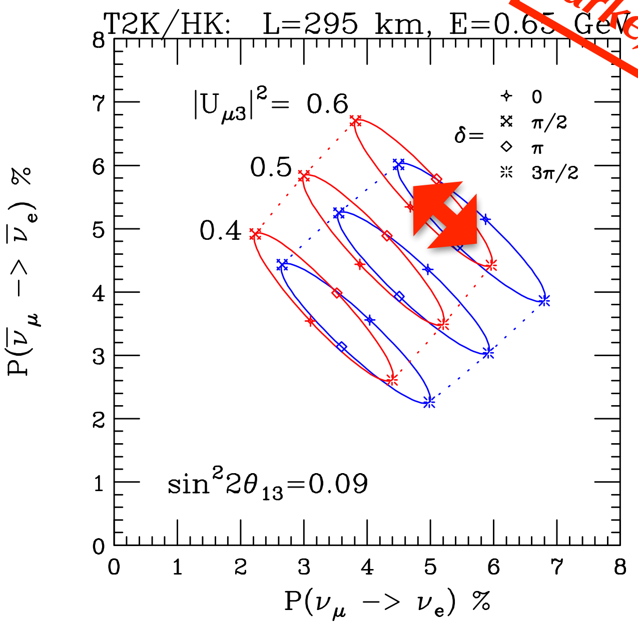
$$A = \pm \frac{2\sqrt{2} G_F N_e E}{\Delta m^2}$$

$\propto \rho L \ \sin^2 \theta_{23}$

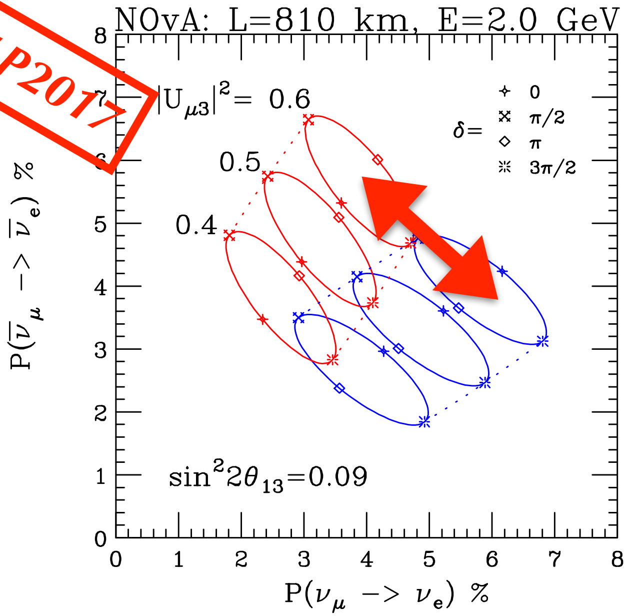
- How to enhance the signature?
  - ➡Increase neutrino energy
  - ➡Increase matter density
  - ➡Hope θ_{23}>45°

Parke, LP2017

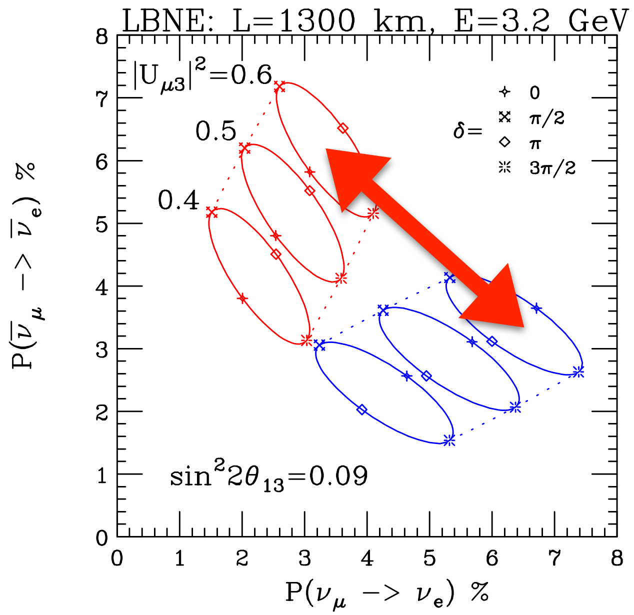
T2K/HK



NOvA



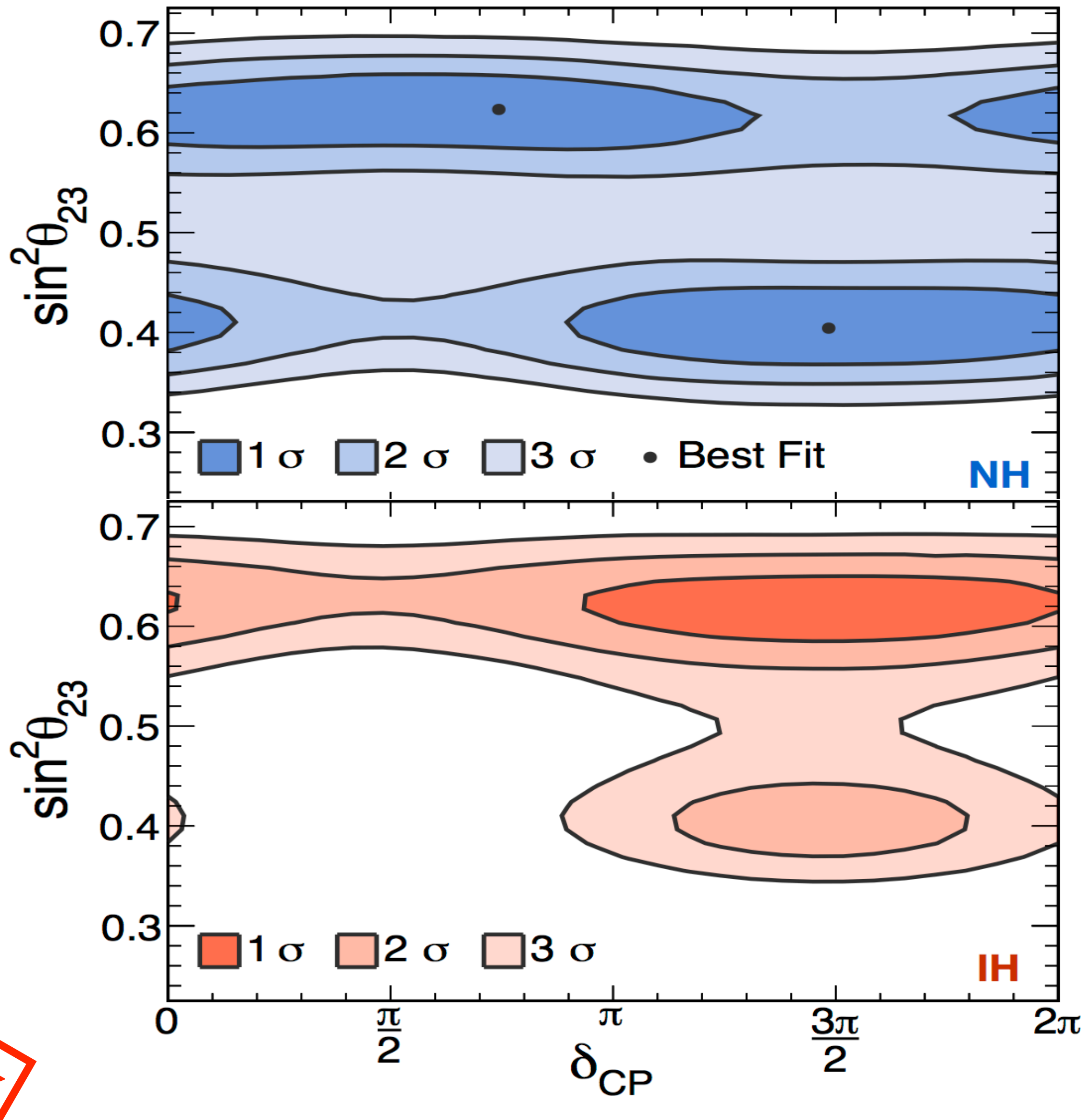
DUNE Same L/E as NOνA



NOvA First Try on MH, CP and Octant

ν_e Appearance Results

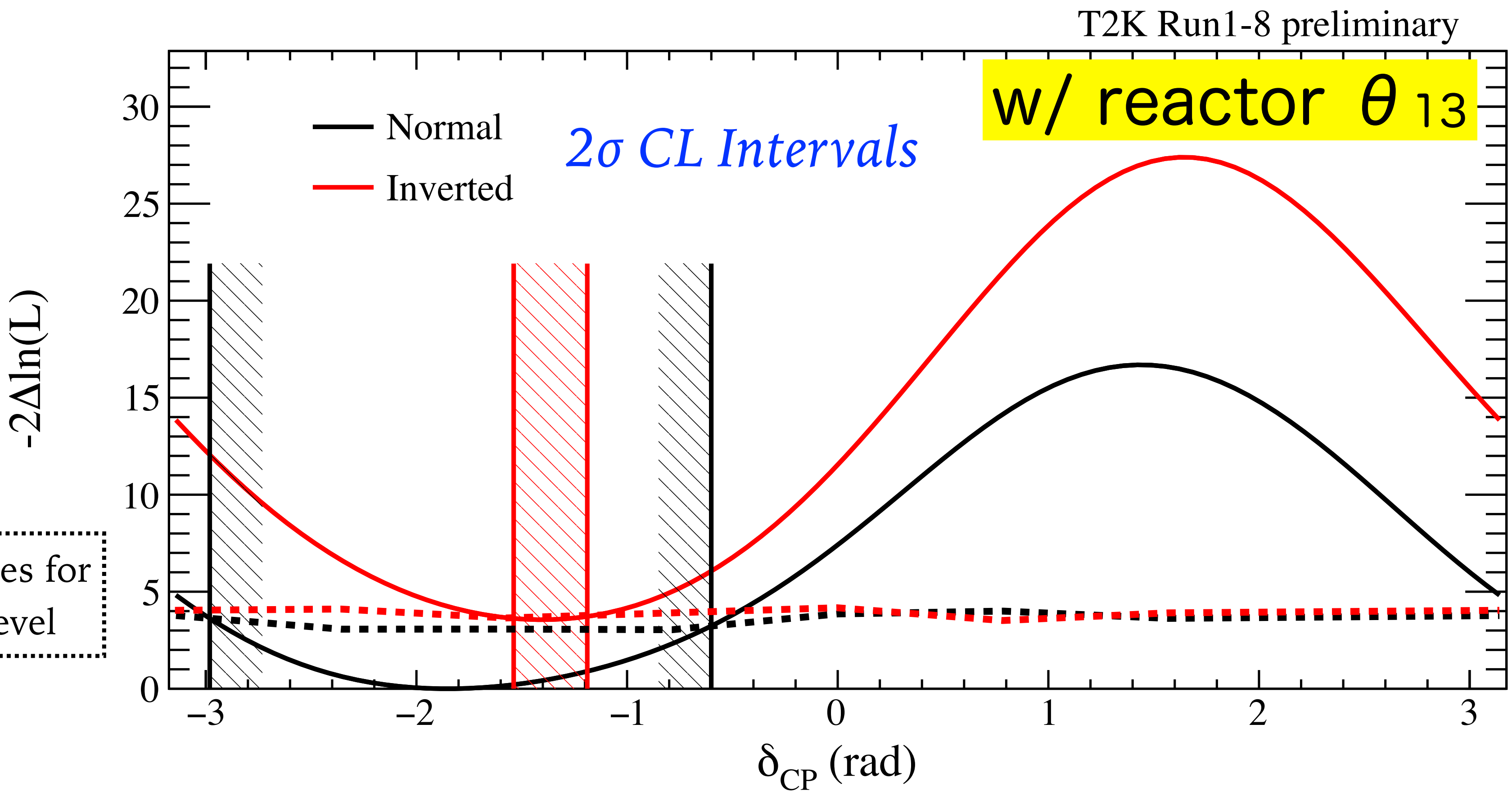
- Combine with ν_μ disappearance result to better constraint Mass Hierarchy, δ_{CP}, θ_{23}
  - Fit ν_e in bins of E_ν and selection parameter
  - Two effectively degenerate best fits, Normal Hierarchy
  - Lower octant in Inverted Hierarchy disfavored at 93% CL for all δ_{CP}
  - Large region of parameter space disfavored at 3 σ for Inverted Hierarchy



P. Shanahan Erice'17

Mass Hierarchy Analysis of T2K

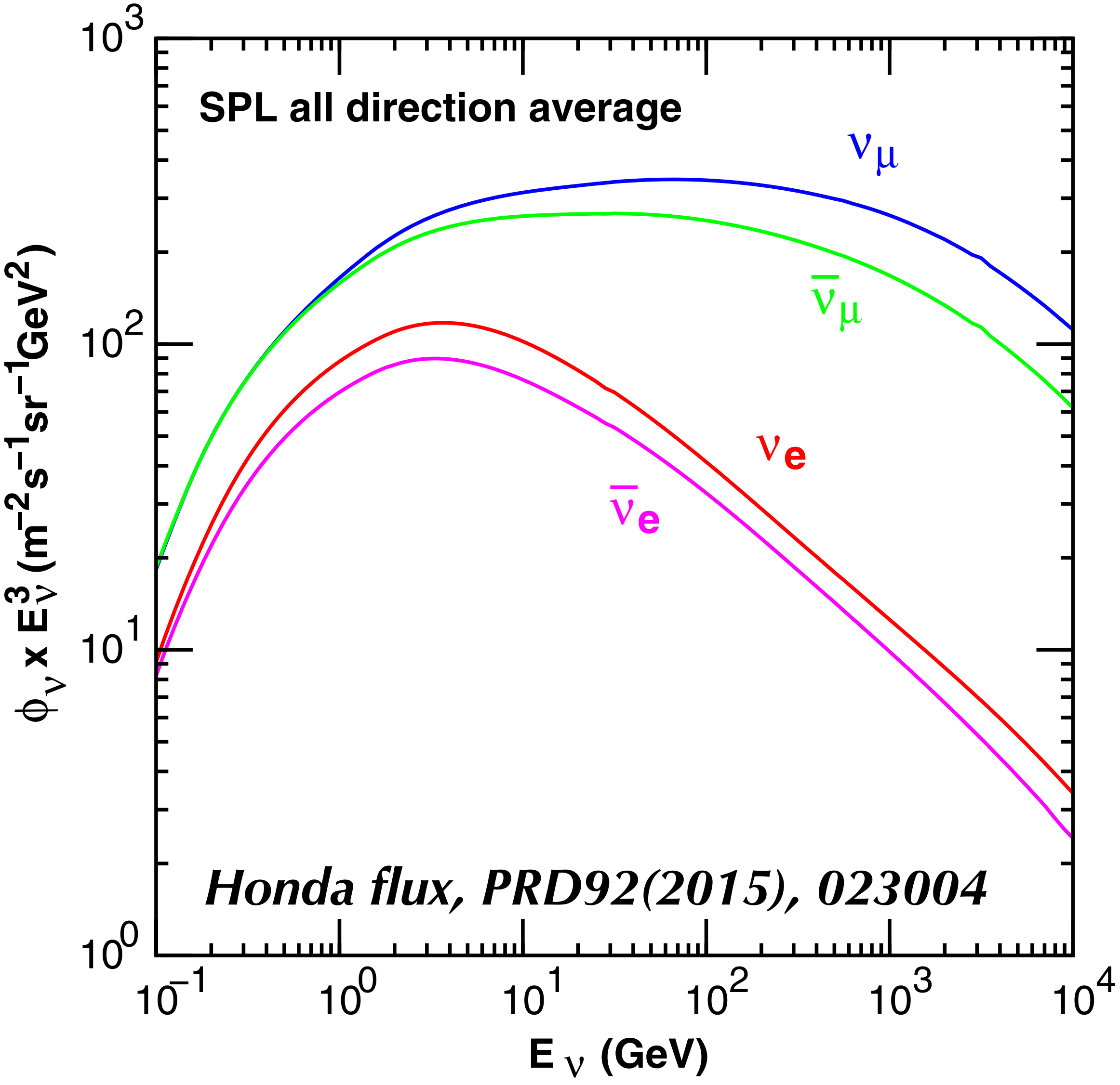
Based on 89 ν_e and 7 $\overline{\nu}_e$ events

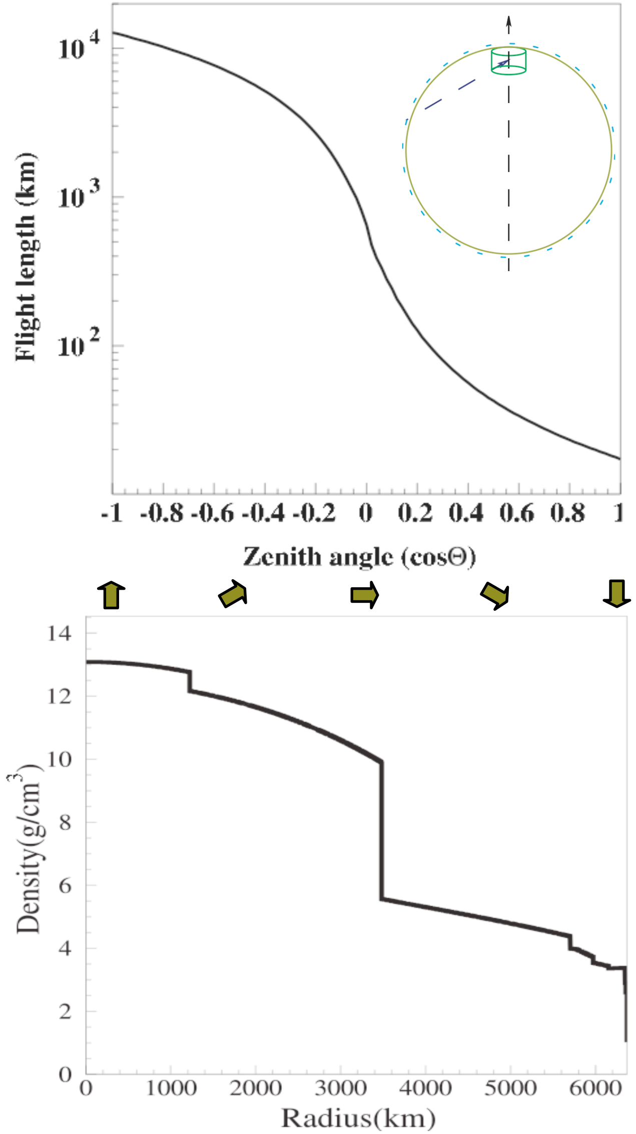


critical $\Delta\chi^2$ values for 2σ confidence level

Best fit: $\delta_{CP}=-1.83^{+0.60}_{-0.66}$ in Normal Hierarchy

Atmospheric Neutrinos and the Earth



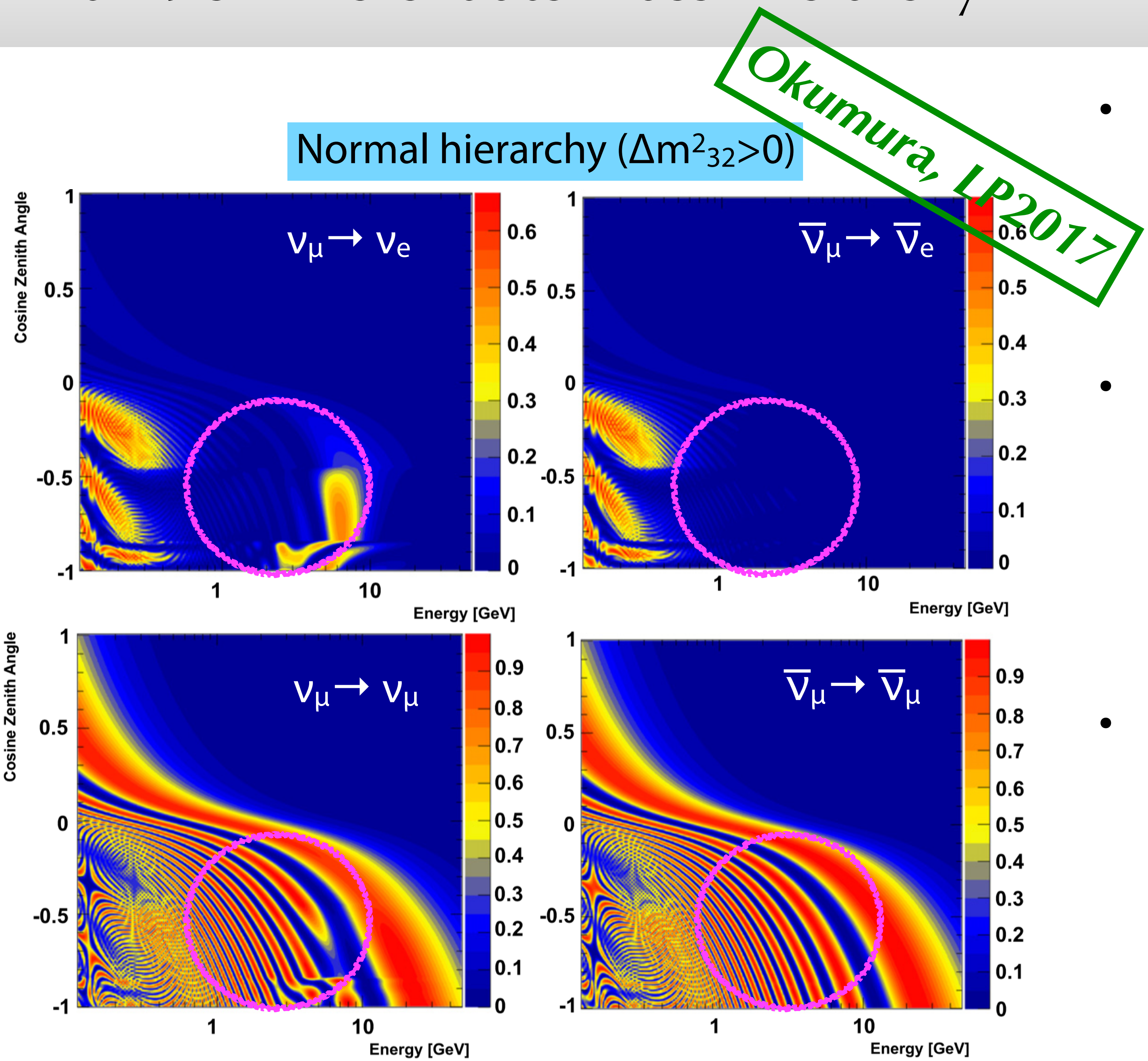


➔Largest E accessible

➔*Biggest* matter densities accessible

➔A great lab for mass hierarchy!

Atm ν's Differentiate Mass Hierarchy

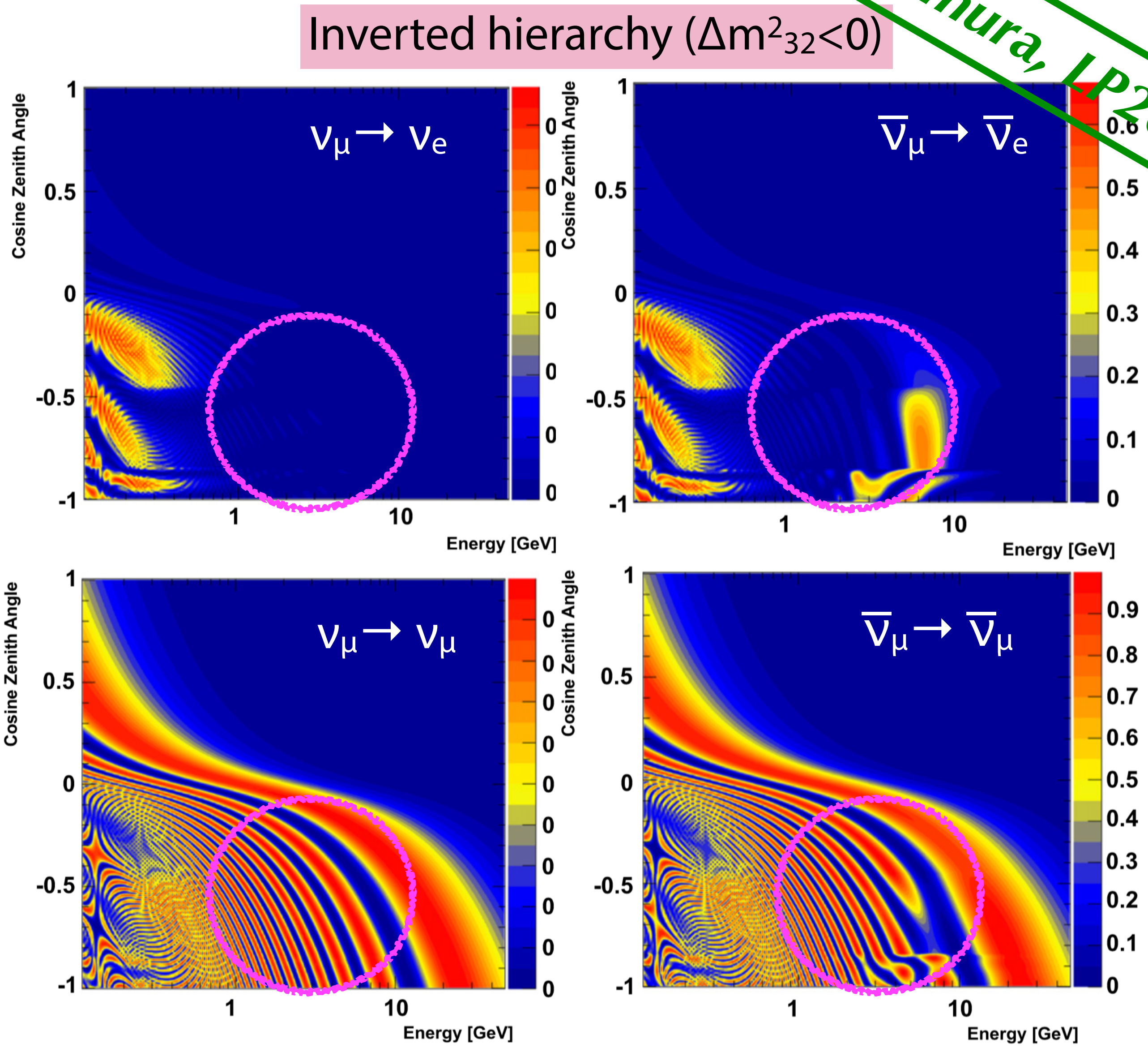


- Resonance oscillation due to MSW effect in Earth for atm neutrinos
- Different mass hierarchies' resonance energies flips for neutrino and antineutrinos
- Tell neutrino events from antineutrino events?

➡ Yes

➡ No

Atm ν's Differentiate Mass Hierarchy



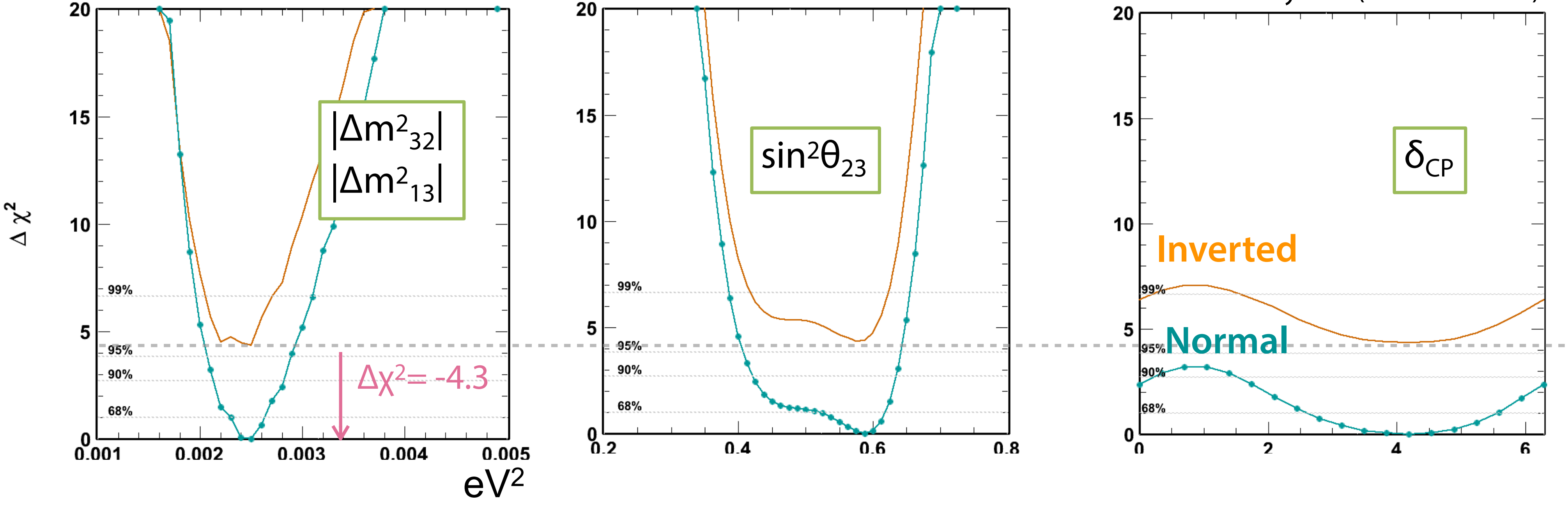
Okumura, LP2017

- Resonance oscillation due to MSW effect in Earth for atm neutrinos
- Different mass hierarchies' resonance energies flips for neutrino and antineutrinos
- Tell neutrino events from antineutrino events?

➡ Yes

➡ No

The Performance of Super-K in MH

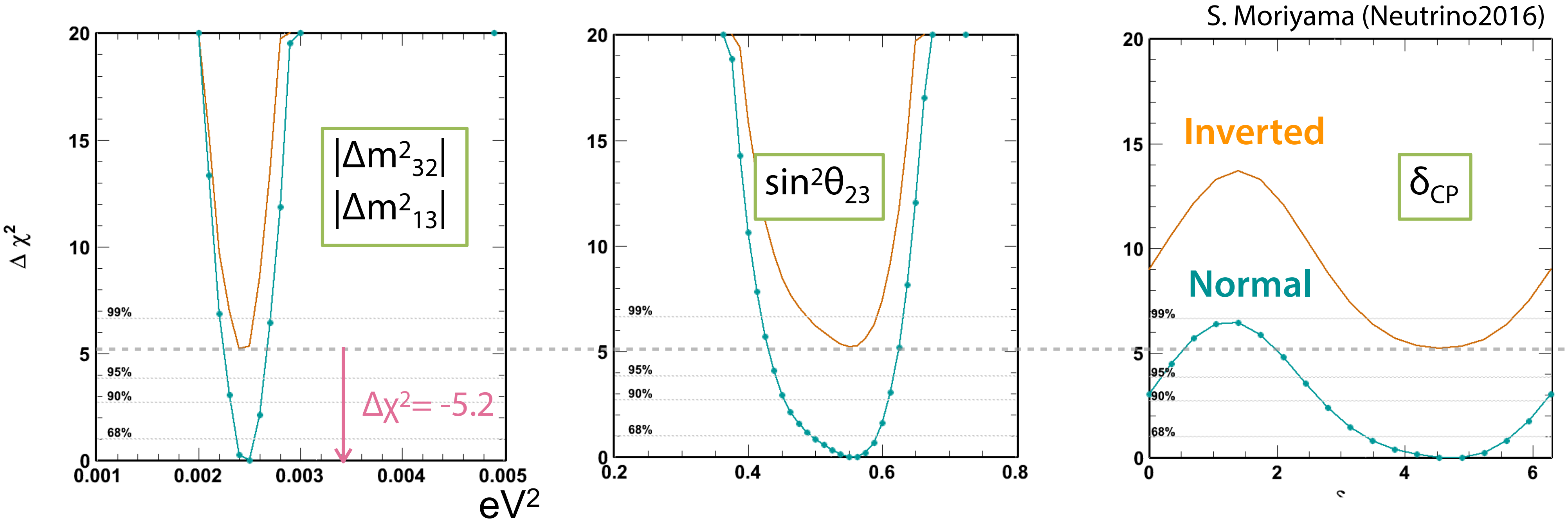


S. Moriyama (Neutrino2016)

- Perform full parameter fit with additional constraints from reactor ($\sin^2\theta_{13}$=0.0219):
  $\Delta\chi^2 = \chi^2_{NH}-\chi^2_{IH} = -4.3$ (-3.1 expected)
- Under IH hypothesis, the probability to obtain $\Delta\chi^2$ of -4.3 or less is 0.031 ($\sin^2\theta_{23}$=0.6) and 0.007 ($\sin^2\theta_{23}$=0.4). Under NH hypothesis, the probability is 0.45 ($\sin^2\theta_{23}$=0.6).

	δ_{CP}	$\sin^2\theta_{23}$	$\lvert\Delta m^2_{32}\rvert$ (eV^2)
Inverted	4.189	0.575	2.5×10^{-3}
Normal	4.189	0.587	2.5×10^{-3}

The Performance of Super-K+T2K in MH



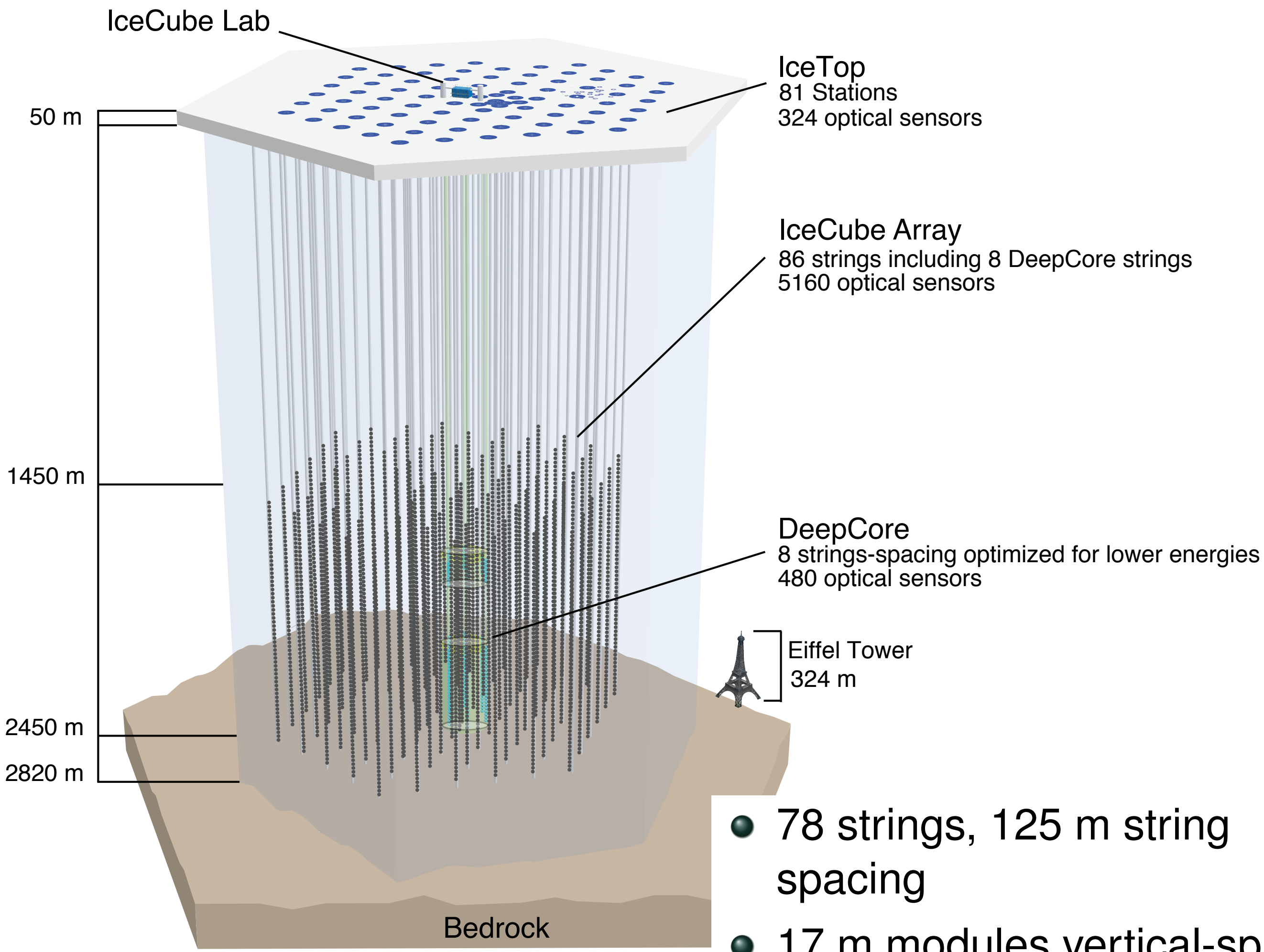
S. Moriyama (Neutrino2016)

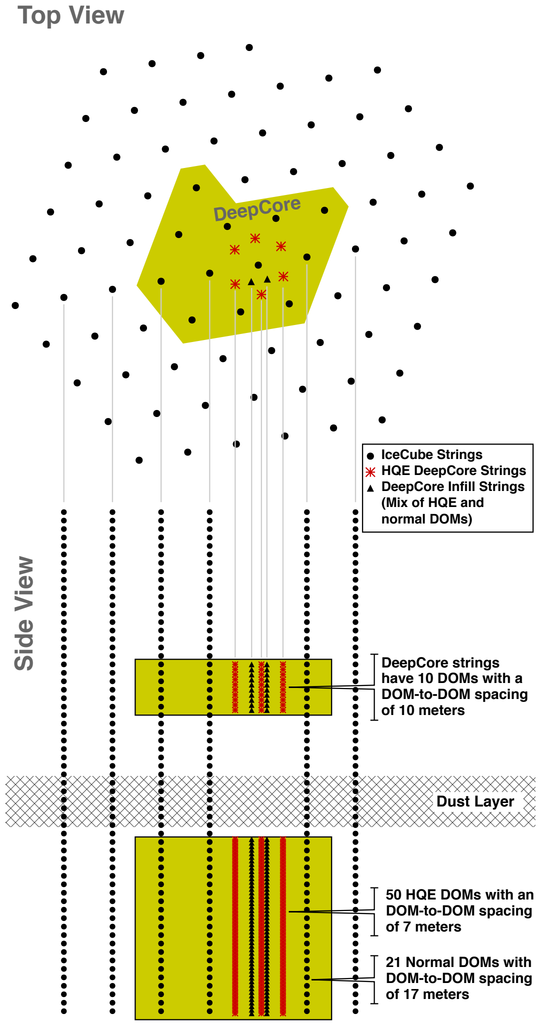
- Include constraint from T2K public data.
- **Normal hierarchy is slightly preferred:** $\Delta\chi^2 = \chi^2_{NH}-\chi^2_{IH} = -5.2$ (-3.8 exp. for SK best, -3.1 for combined best)
- p-value of Inverted hypothesis is 0.024 ($\sin^2\theta_{23}=0.6$) and 0.001 ($\sin^2\theta_{23}=0.4$).

	δ_{CP}	$\sin^2\theta_{23}$	$\lvert\Delta m^2_{32}\rvert$ (eV^2)
Inverted	4.189	0.575	2.5×10^{-3}
Normal	4.189	0.587	2.5×10^{-3}
Inverted	4.538	0.55	2.5×10^{-3}
Normal	4.887	0.55	2.4×10^{-3}

w/ T2K constraint

IceCube and IceCube-DeepCore





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

Good for atmospheric oscillation parameters

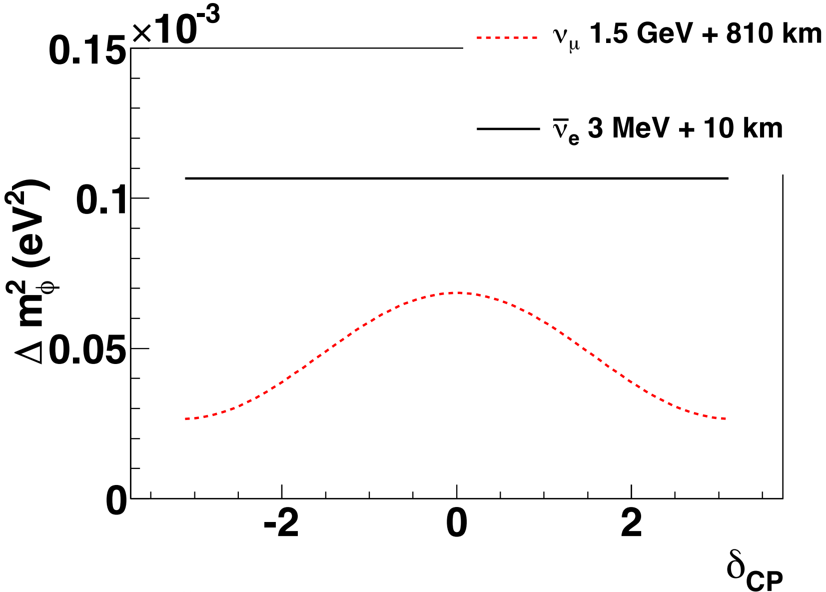
- 8 strings, 40-75 m string spacing
- 7 m modules vertical-spacing

Threshold energy too high for mass hierarchy

Mass Hierarchy by Comparing $\boldsymbol{\Delta} m^2{}_{\mu\mu}$ and $\boldsymbol{\Delta} m^2{}_{ee}$

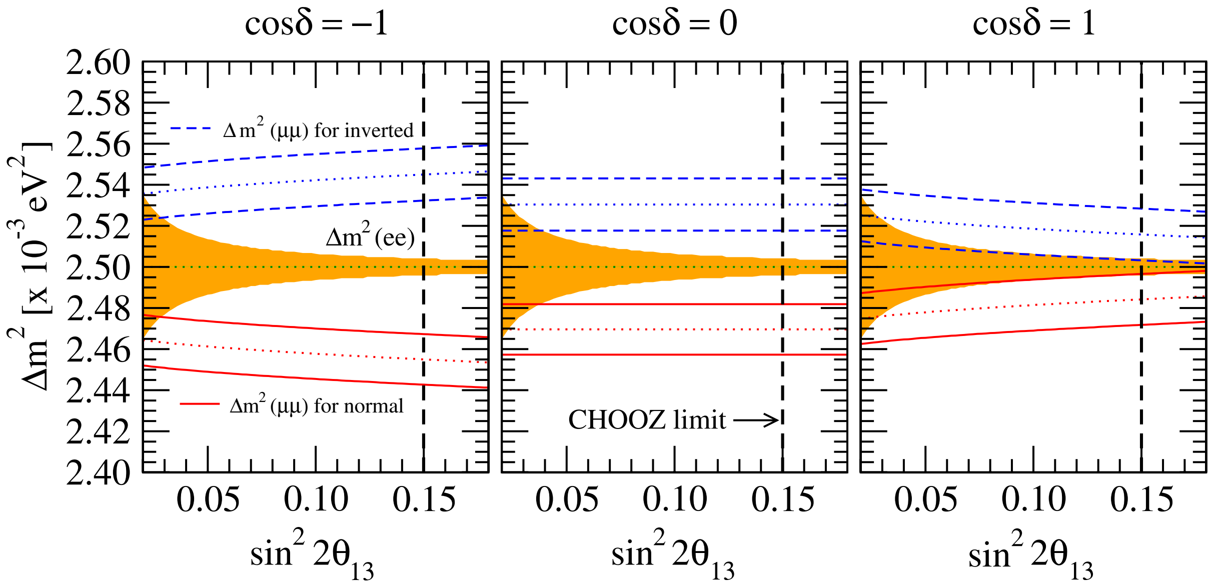
$$\begin{aligned} P(\bar{\nu_e} \to \bar{\nu_e}) &= 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\ &= 1 - 2s_{13}^2c_{13}^2 - 4c_{13}^4s_{12}^2c_{12}^2\sin^2\Delta_{21} + 2s_{13}^2c_{13}^2\sqrt{1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

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



Qian et al, PRD87(2013)3, 033005

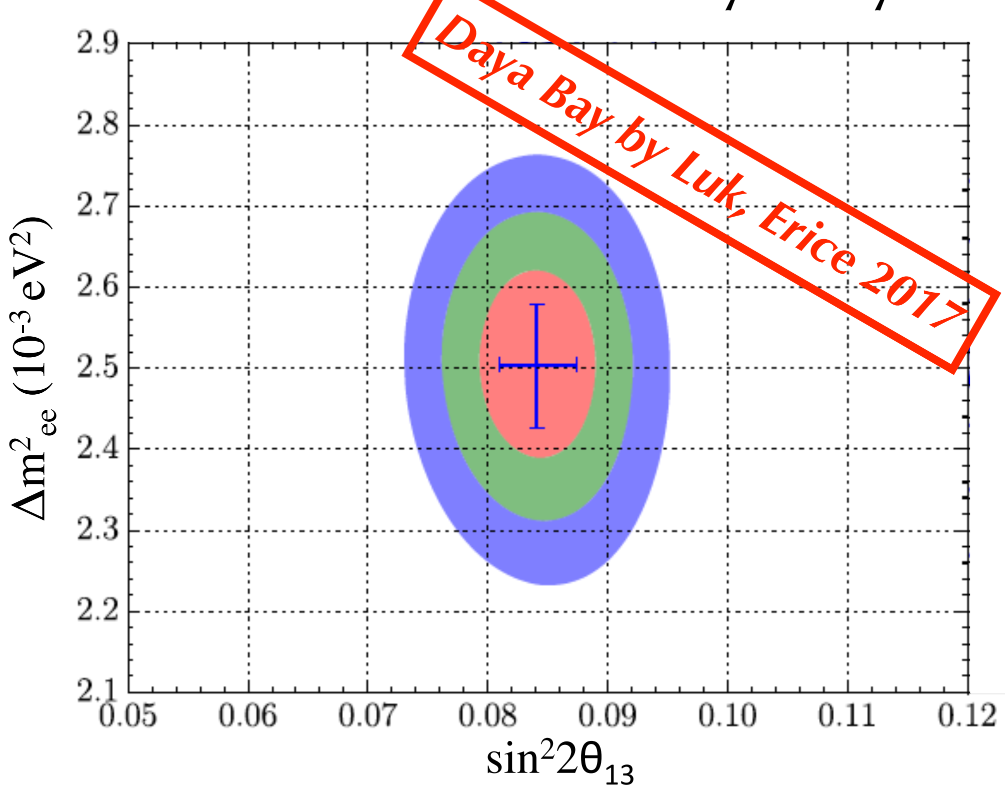
FIG. 6: The dependence of effective mass-squared difference $\Delta m^2_{ee\phi}$ (solid line) and $\Delta m^2_{\mu\mu\phi}$ (dotted line) w.r.t. the value of δ_{CP} for $\bar{\nu}_e$ and ν_μ disappearance measurements, respectively.



Minakata et al PRD74(2006), 053008

Mass Hierarchy by Comparing $\Delta m^2_{\mu\mu}$ and Δm^2_{ee}

e-flavor ν Survival: Daya Bay


Daya Bay by Luk, Erice 2017

$$\sin^2 2\theta_{13} = 0.0841 \pm 0.0027 \pm 0.0019$$

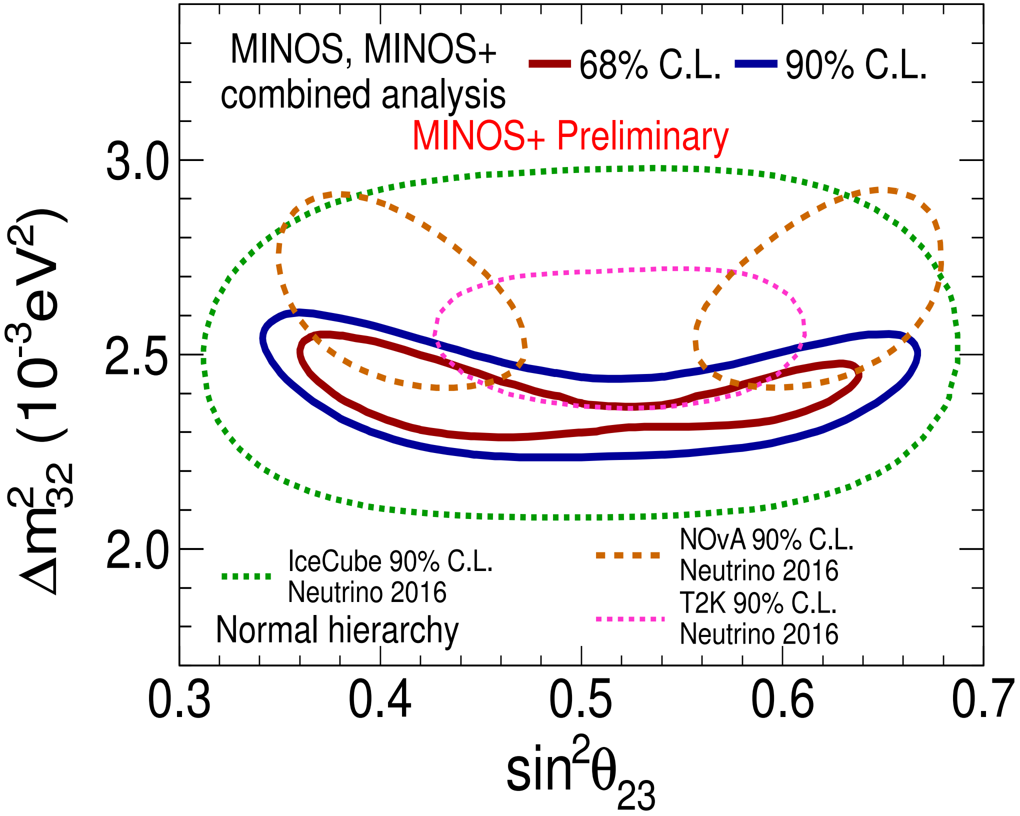
$$|\Delta m^2_{ee}| = (2.50 \pm 0.06 \pm 0.06) \times 10^{-3}\ \text{eV}^2$$

$$\Delta m^2_{32} = (2.45 \pm 0.06 \pm 0.06) \times 10^{-3}\ \text{eV}^2 \quad \text{(NH)}$$

$$\Delta m^2_{32} = (-2.56 \pm 0.06 \pm 0.06) \times 10^{-3}\ \text{eV}^2 \quad \text{(IH)}$$

$$\chi^2/\text{NDF} = 235/263$$

μ-flavor ν Survival: MINOS+



$$\Delta m^2_{32} = (2.42 \pm 0.09) \times 10^{-3}\,\text{eV}^2$$

$$\Delta m^2_{32} = -(2.48^{+0.09}_{-0.11}) \times 10^{-3}\,\text{eV}^2$$

Known θ_{13} Enables Neutrino Mass Hierarchy at Reactors

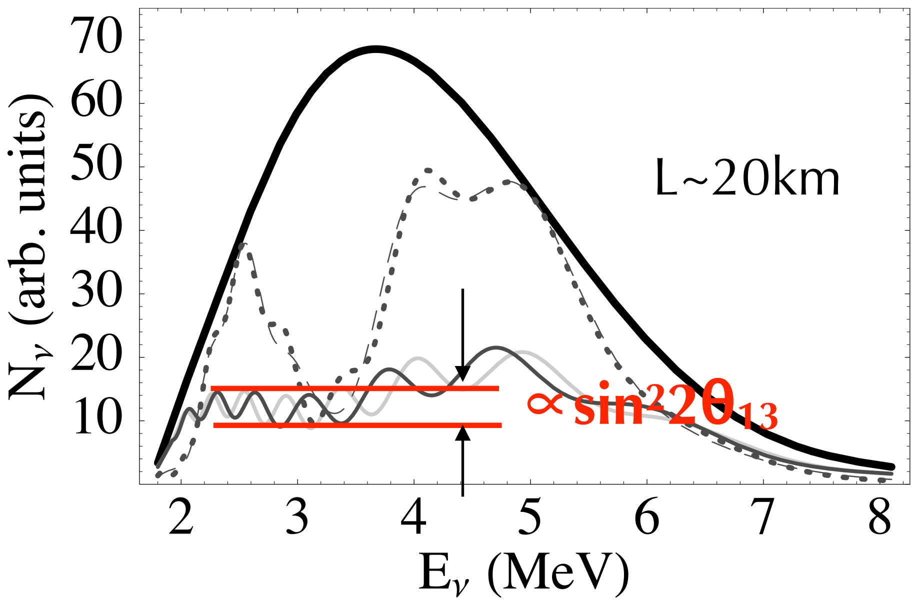
- Recall that reactor neutrinos helped pin down ***the solar sector***

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

- 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

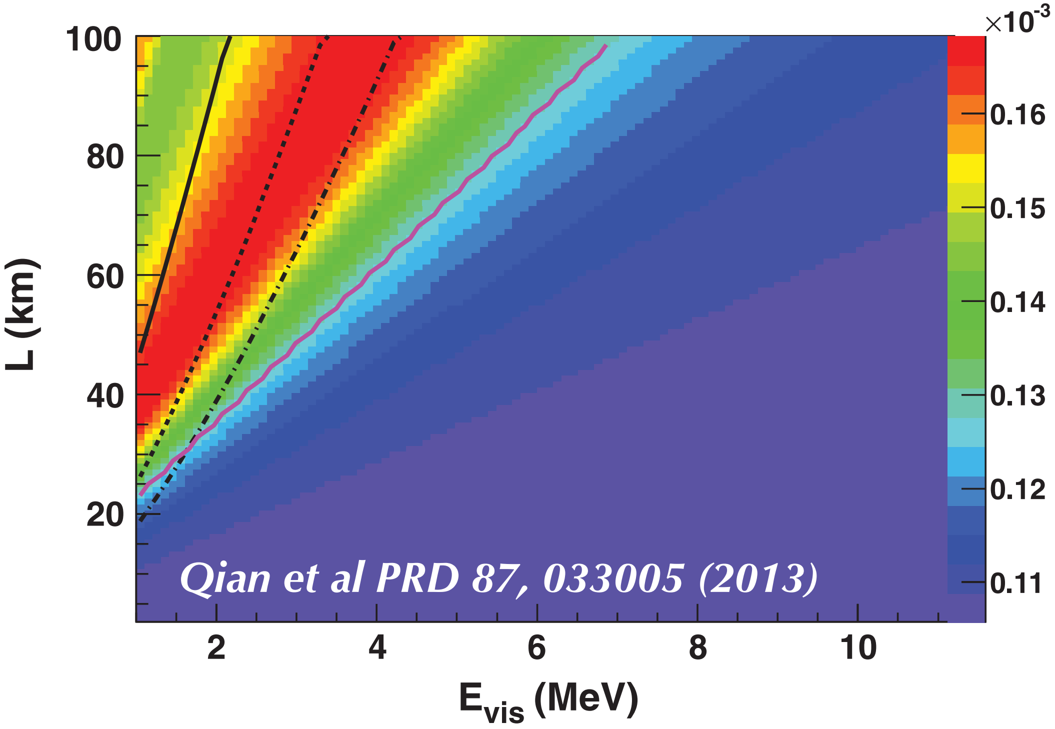


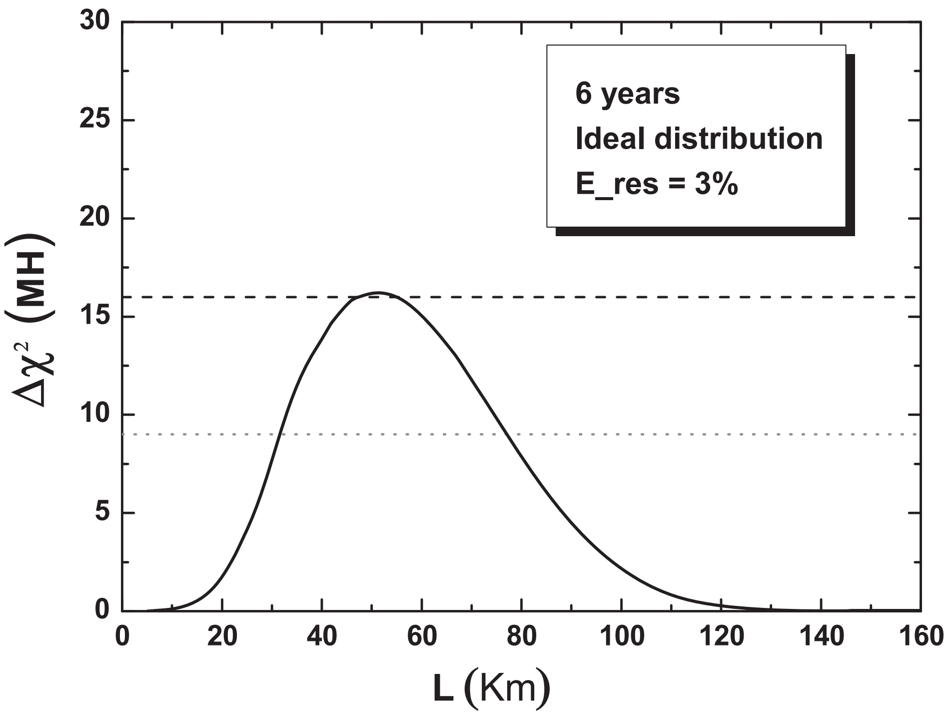
✓ Mass hierarchy is reflected in the survival spectrum

✓ Proportional to $\sin^2 2\theta_{13}$

✓ Independent of the unknown CP phase and the θ_{23} octant

A Closer Look at the Reactor Neutrino Case

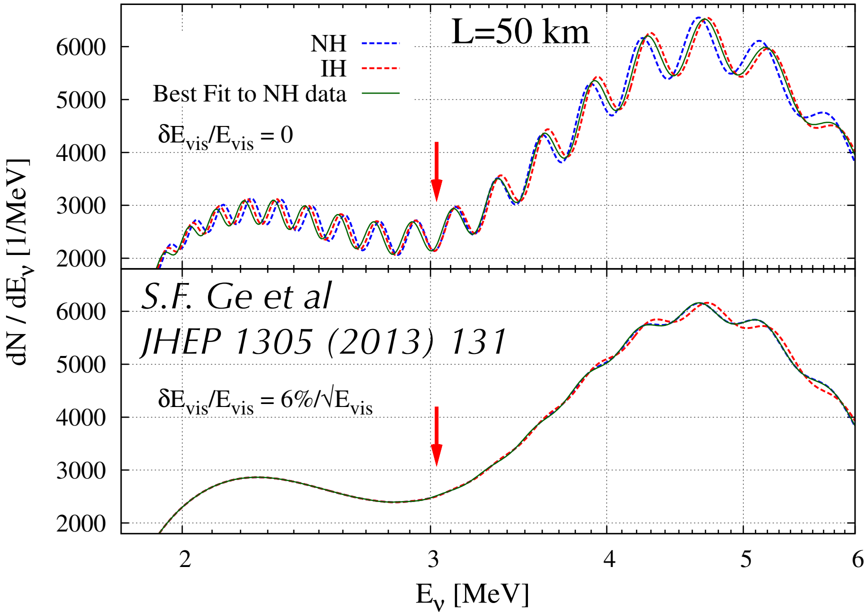




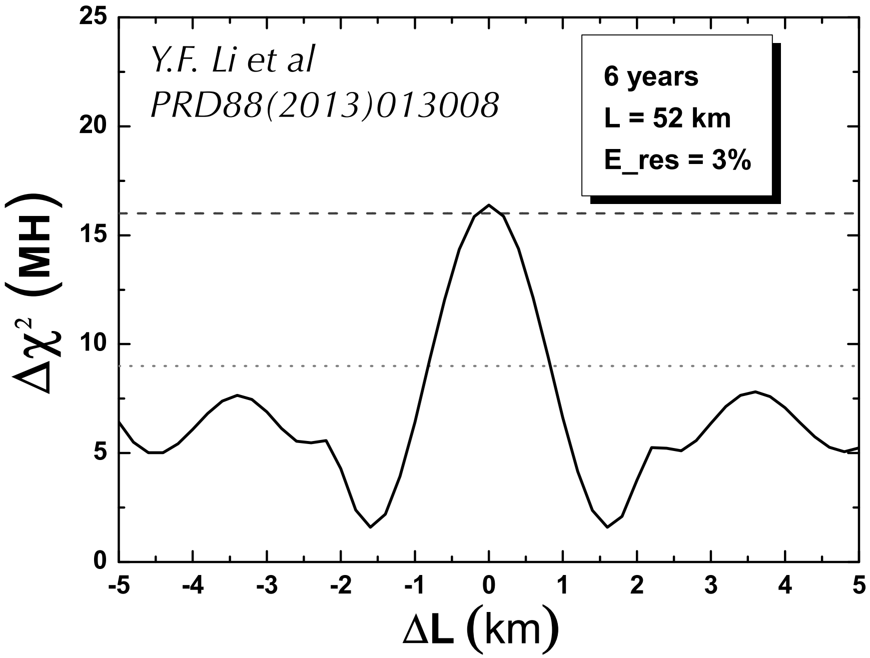
✓Suitable baseline is ~60km

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.

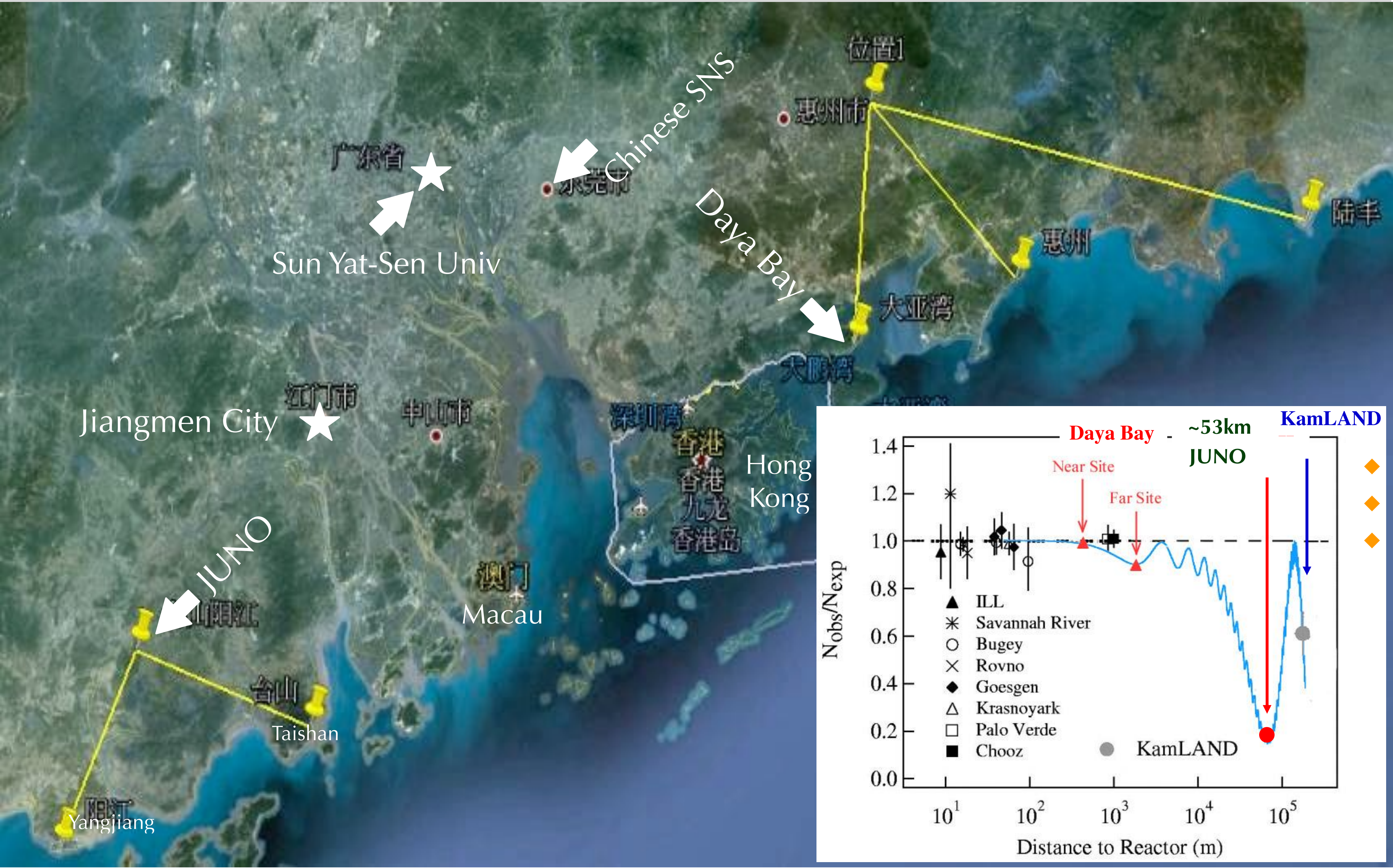


S.F. Ge et al JHEP 1305 (2013) 131



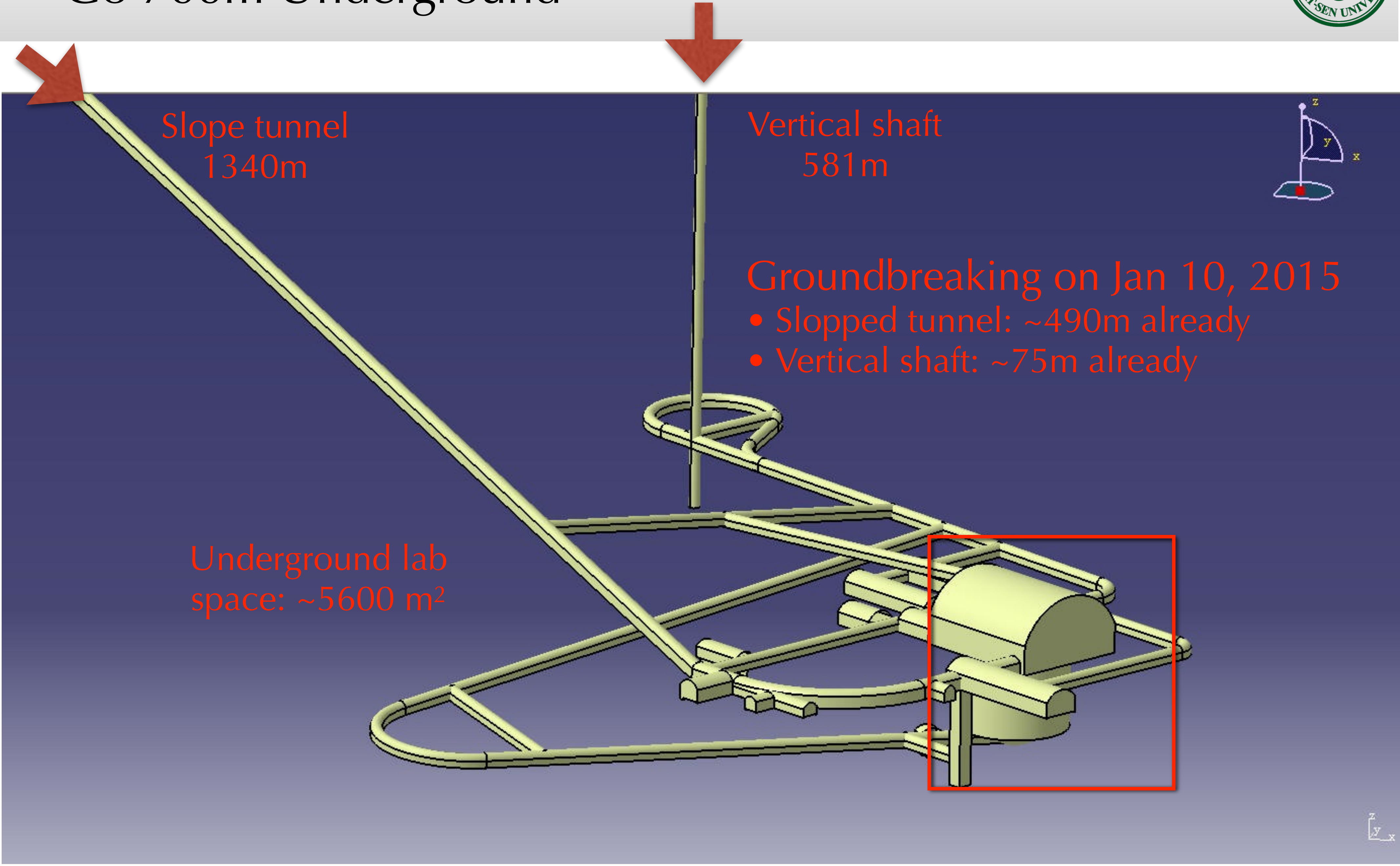
Y.F. Li et al PRD88(2013)013008

Jiangmen Underground Neutrino Observatory as an Example



Surface Facilities: Look into the Near Future……

Go 700m Underground



Slope tunnel
1340m

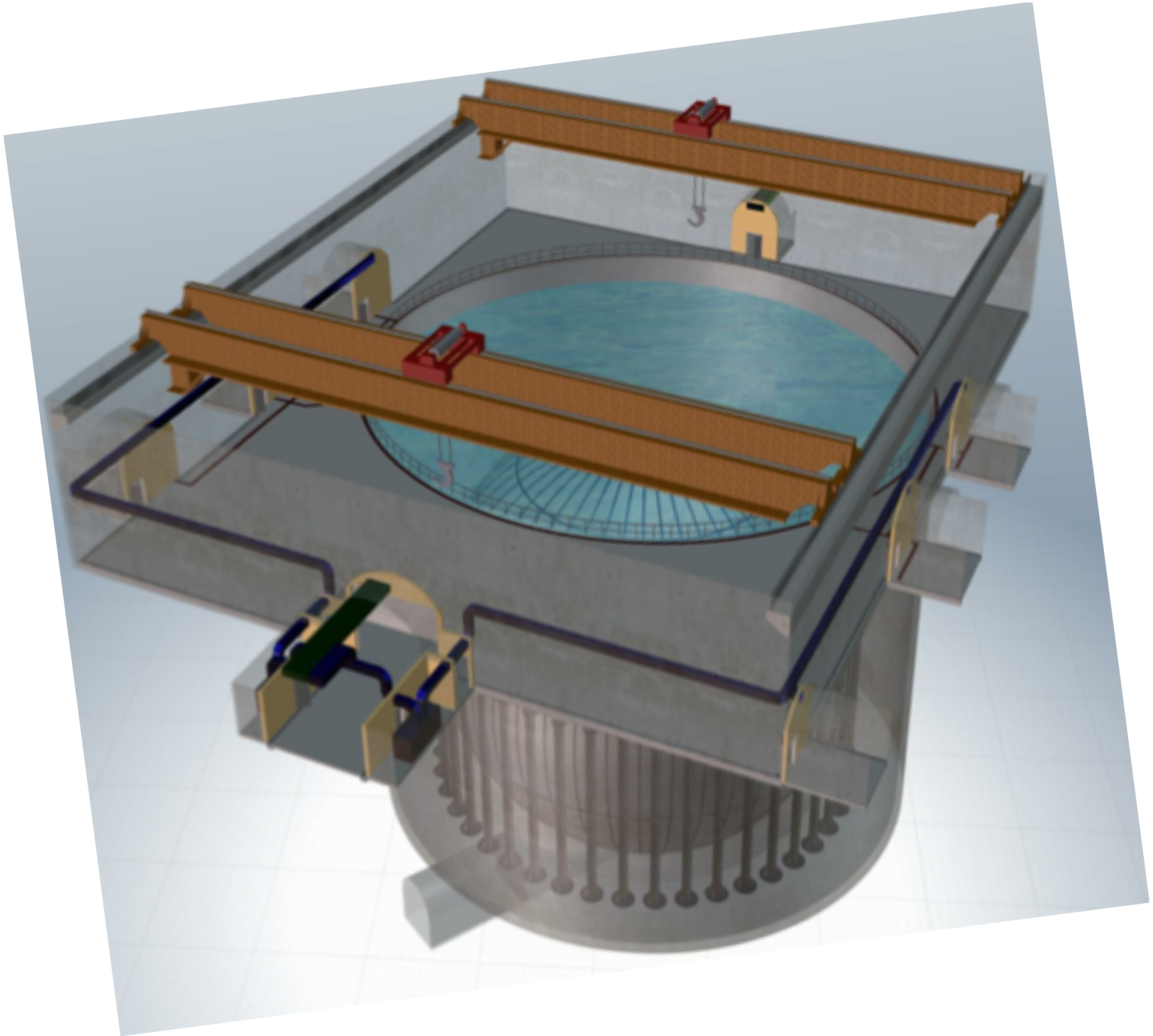
Vertical shaft
581m

Groundbreaking on Jan 10, 2015

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

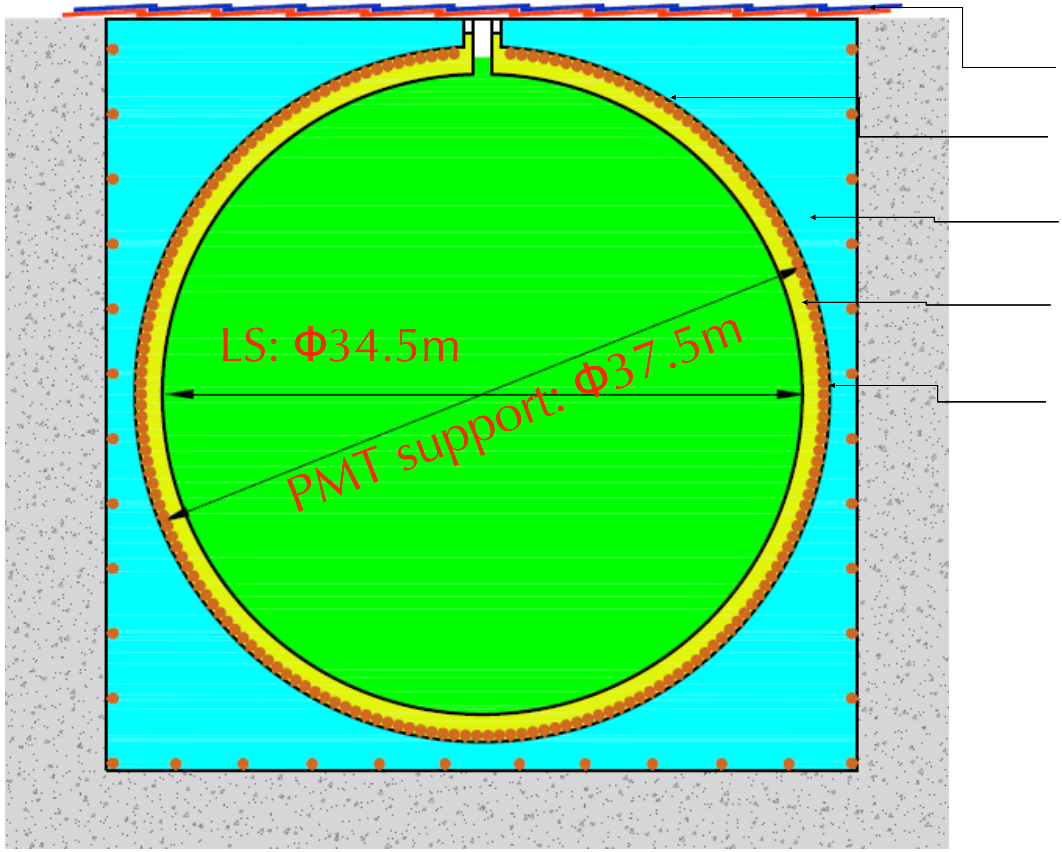
Underground lab
space: ~5600 m²

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



Muon detector

Stainless steel tank or truss

Water Cherenkov veto and radioactive

Mineral oil or water buffer

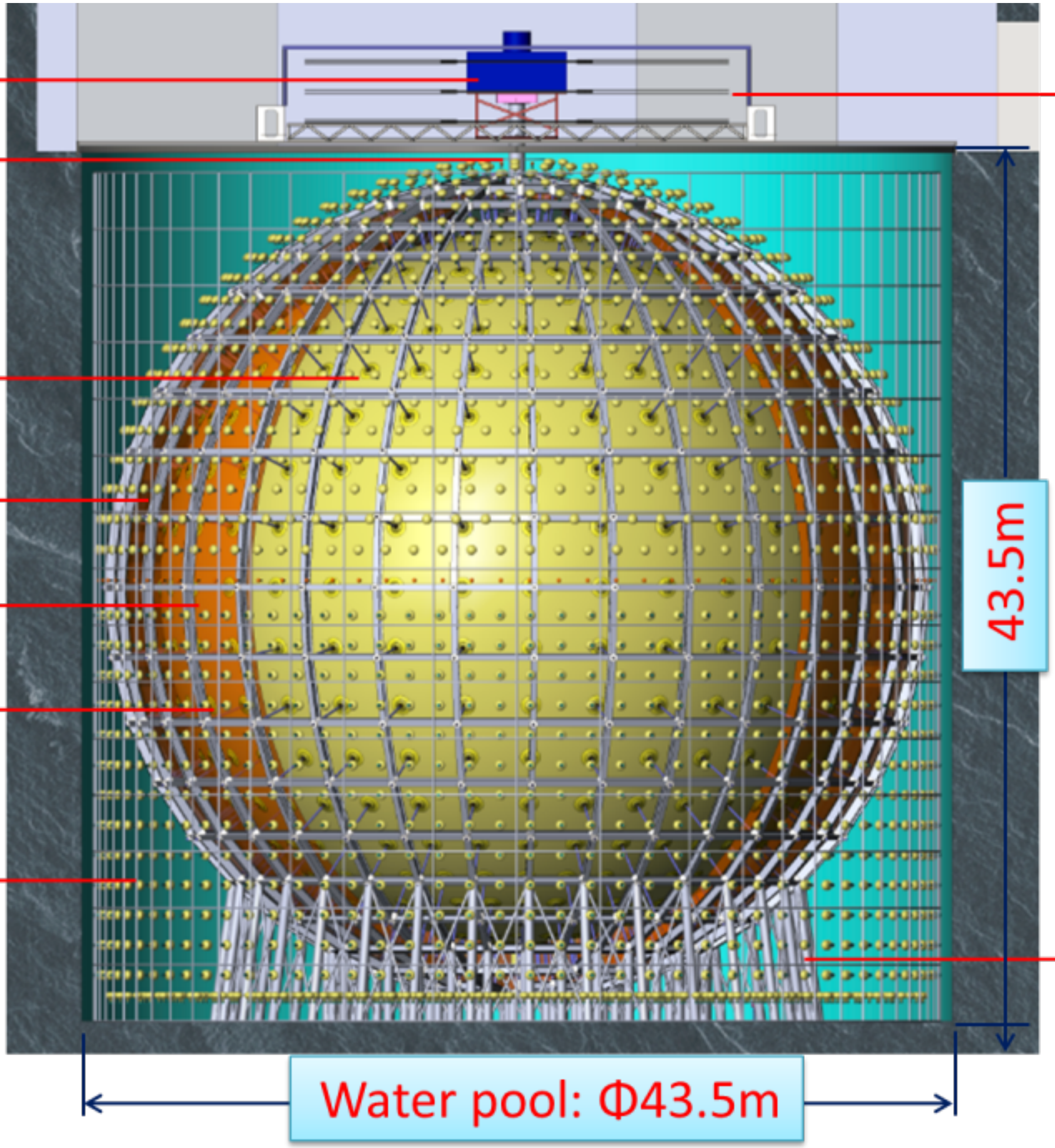
~18000 20″ PMTs coverage: ~80%

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

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 JUNO Detector Design



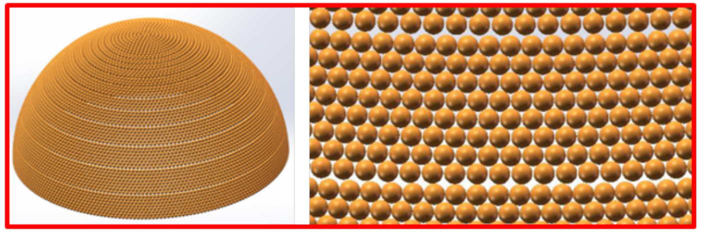
- JUNO central detector design: a 35.4m diameter acrylic sphere holds the LS
- Stainless truss, diameter 40.1m, provides mechanical supports to the acrylic sphere and the PMTs

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

Generate Light ➛ Collect Light ➛ Convert Light

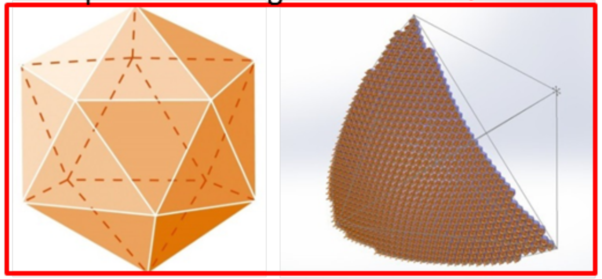
✓1

Supper layer arrangement method 77.8%



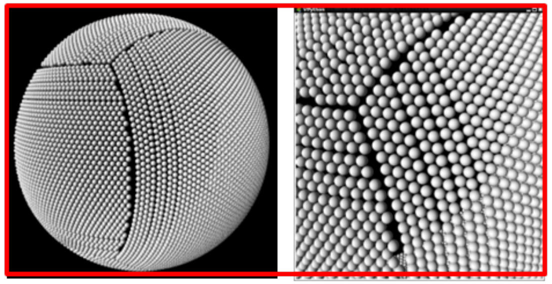
2

Spherical triangle method 72%



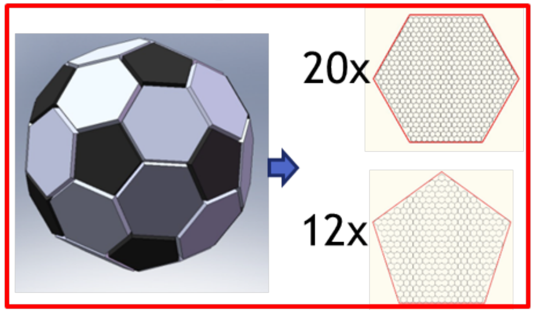
3

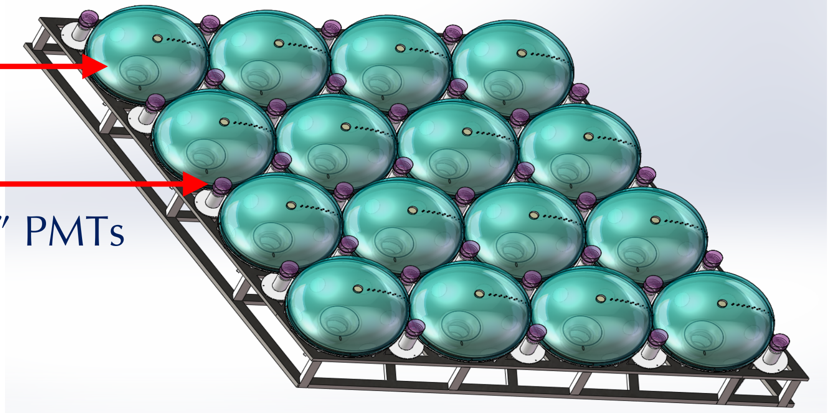
Volleyball arrangement method 75.96%



4

Football arrangement method 74.08%



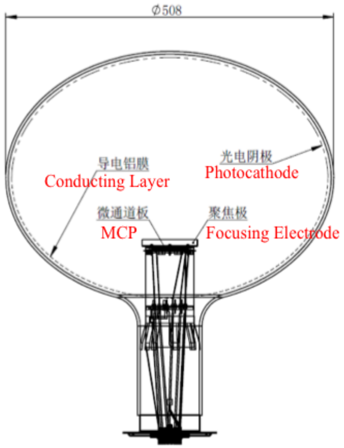


20″
PMT(~17000)

3″ sPMT(~25000)
Arranged between 20″ PMTs

- LAB-based Liquid Scintillator 10k photon/MeV
- Transparency reaches ~20m
- High DE PMTs coverage: ~75%

➡ ~3%/√E energy resolution plausible



Structure of MCP-PMT

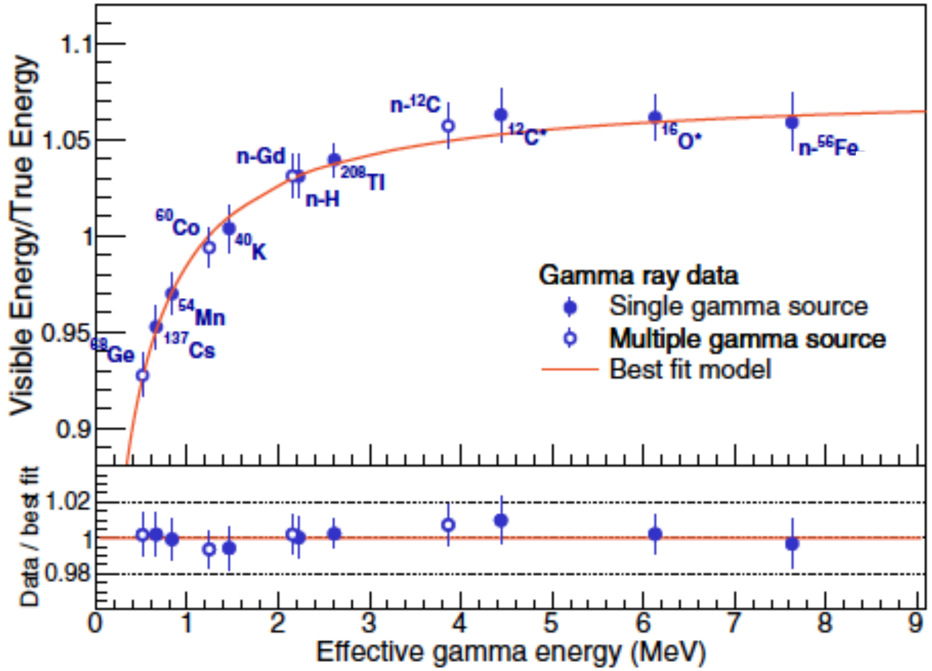
Photograph of MCP-PMT

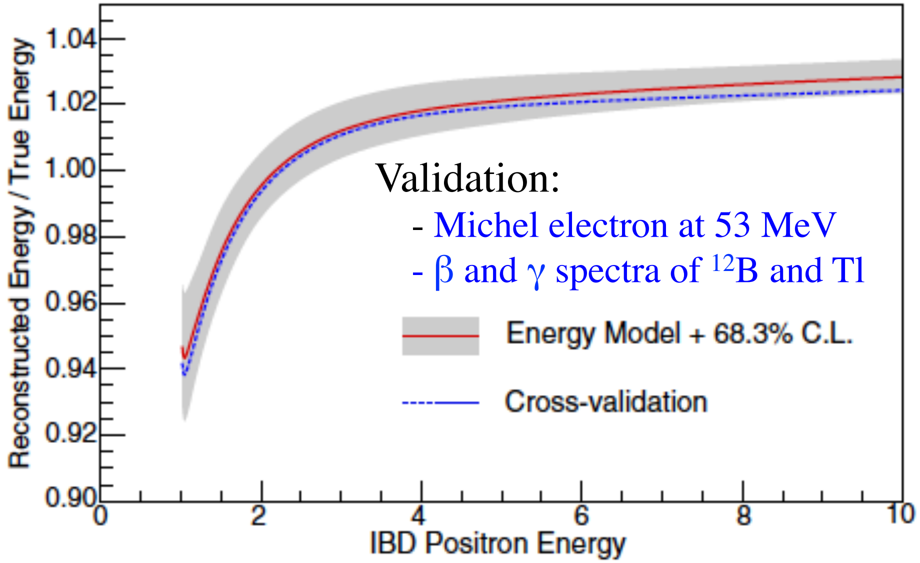
Hamamatsu R12860-50

Can One Calibrate Energy to 1%?

Daya Bay by Luk, Erice 2017

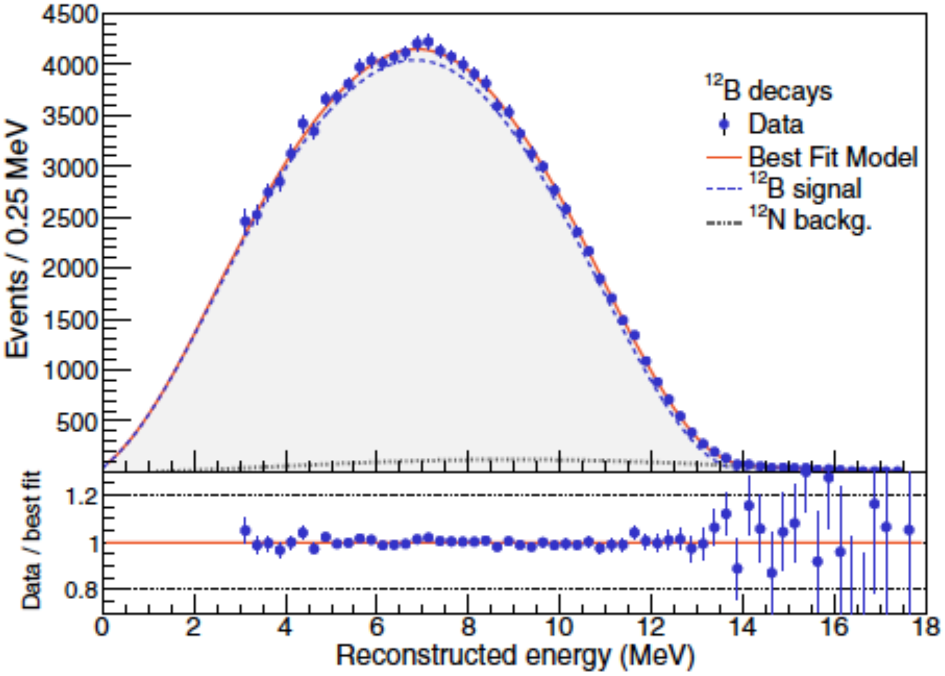
Also use electrons from Compton scattering to determine energy non-linearity of liquid scintillator in labs





Validation:

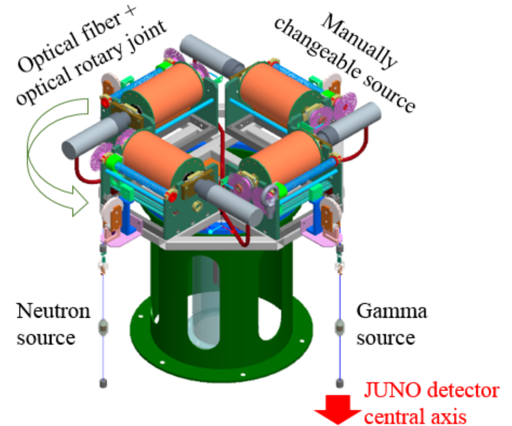
- Michel electron at 53 MeV
- β and γ spectra of ^{12}B and Tl



E_{obs}/E_{true} is known to <1% for $1\ \mathrm{MeV} < E_{e+} < 10\ \mathrm{MeV}$

Calibration System

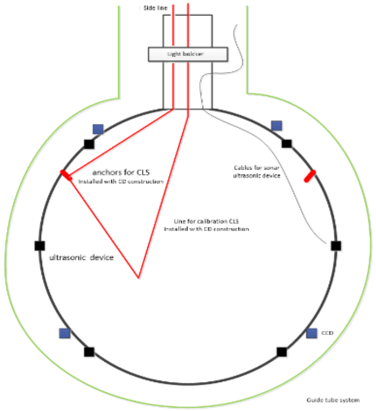
Automatic calibration Unit (ACU) Ø =1.4 m, h=1 m

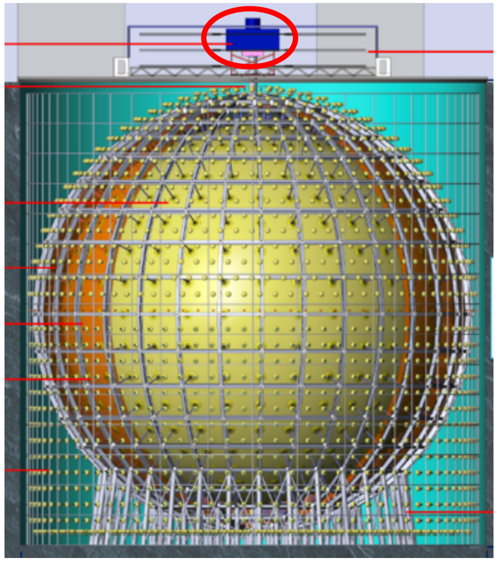


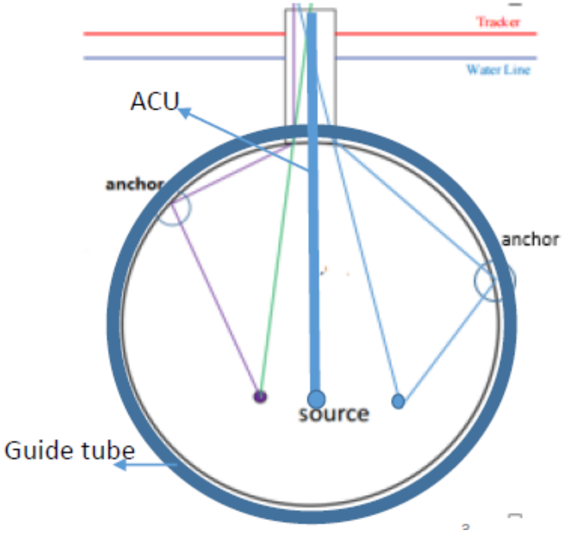
- Regular deployment (every week)

Scan center axis

Cable Loop System (CLS)

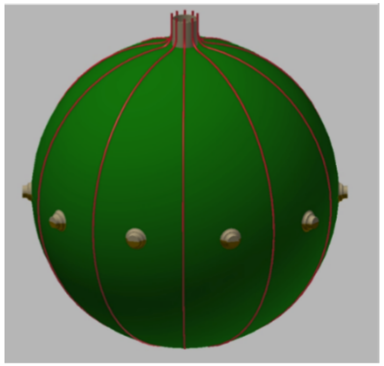






Four units designed

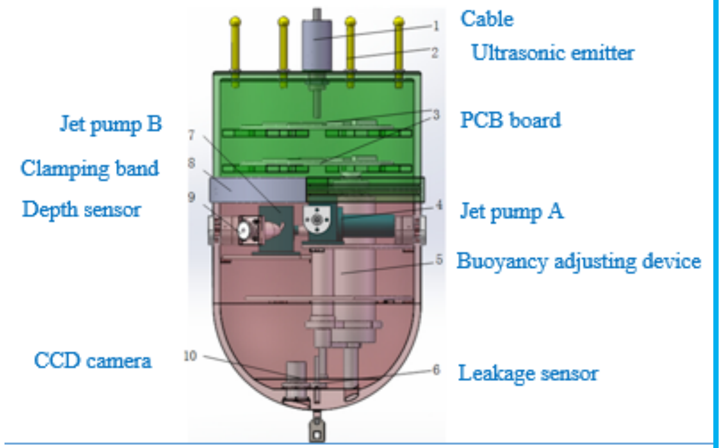
Guide Tube (GT)



Scan outer surface of CD

The source is driven with rope pulled by step motors

Remotely Operated Vehicle(ROV)



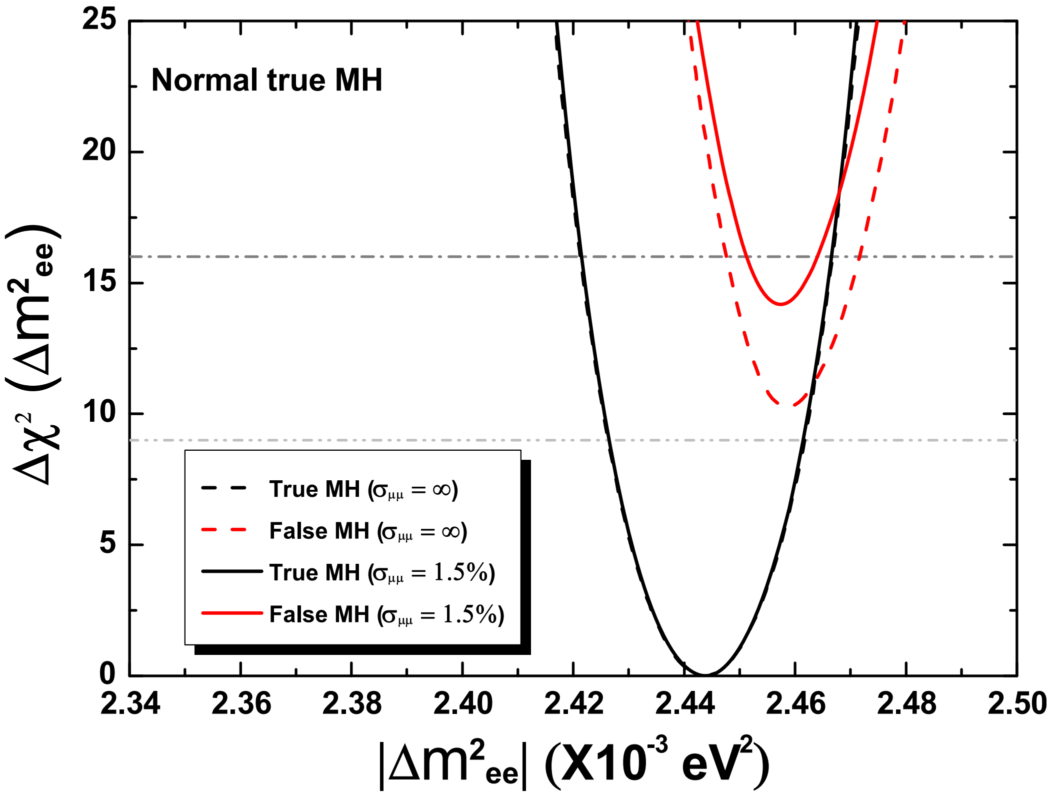
Scan the whole CD if needed

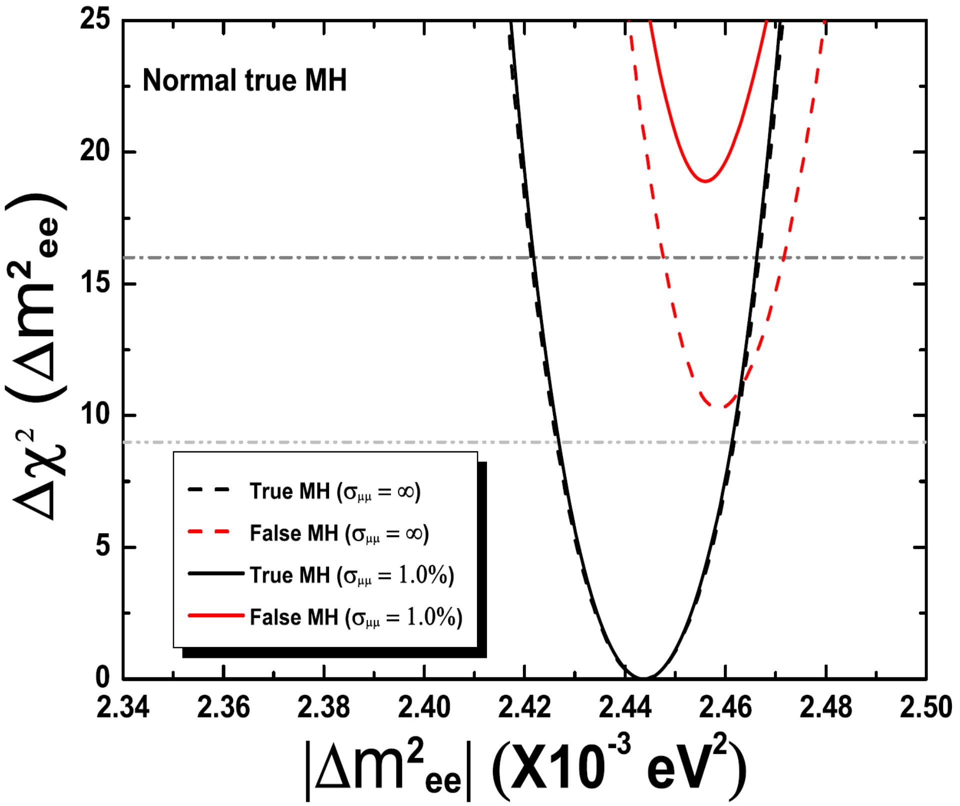
The Detector Performance Goals

	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

Expected Significance to Mass Hierarchy

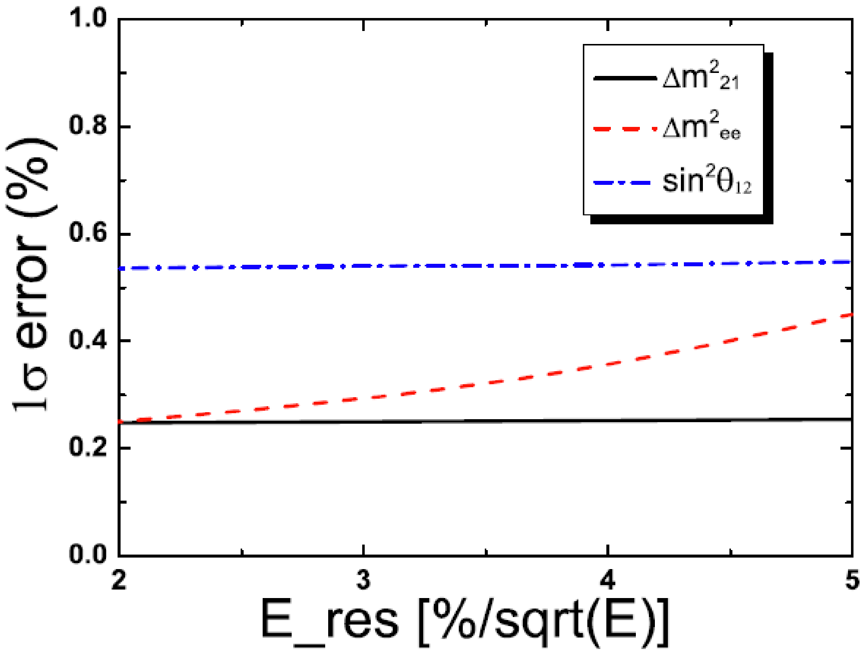




- Reactor neutrino survival spectrum can tell MH to ~3σ
- JUNO can use help: If T2K+NOvA tells $\Delta m^2_{\mu\mu}$ ~1%, ~4σ
  - *T2K+NOvA $\Delta m^2_{\mu\mu}$ ~1%, S.K. Agarwalla, S. Prakash, WW, arXiv:1312.1477*

JUNO Precision Neutrino Physics Warranted

	Δm^2_{21}	$\lvert\Delta m^2_{31}\rvert$	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$
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%



arXiv:1507.05613

- Subpercent precision measurements warranted @ JUNO

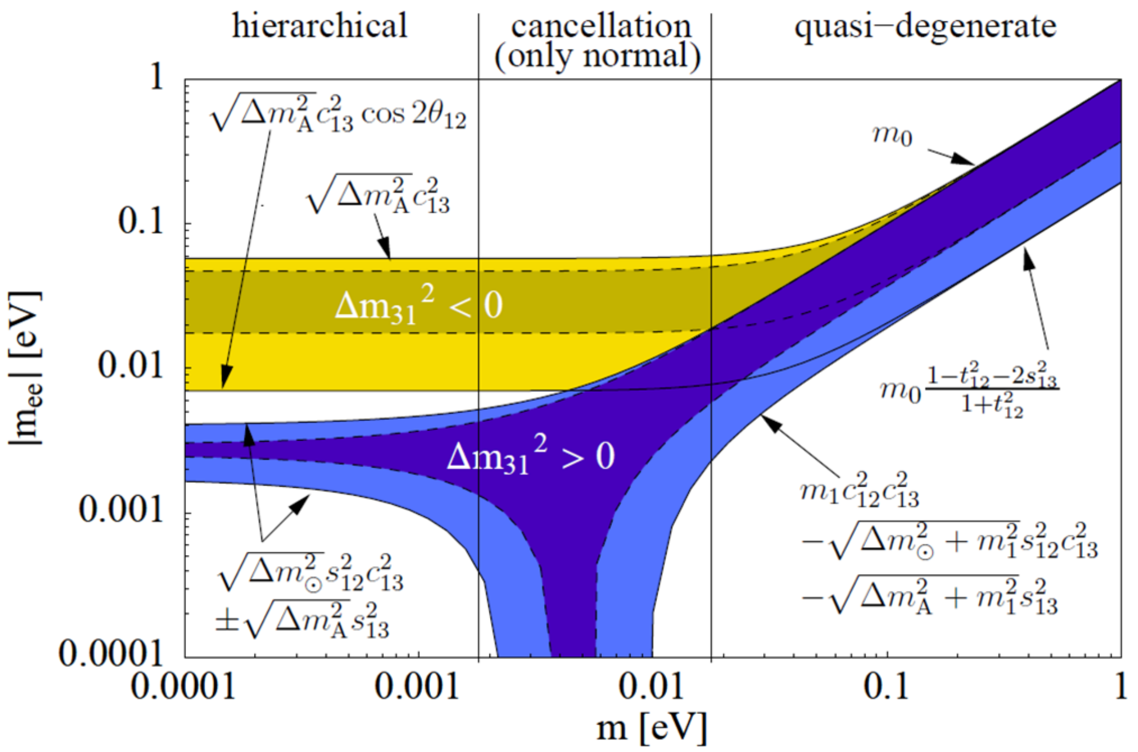
JUNO: 100k evts, arXiv:1507.05613

	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%
$\lvert\Delta m^2_{ee}\rvert$	0.27%	0.31%	0.31%	0.35%	0.44%

Why Precise Solar Mixing Angle Measurements

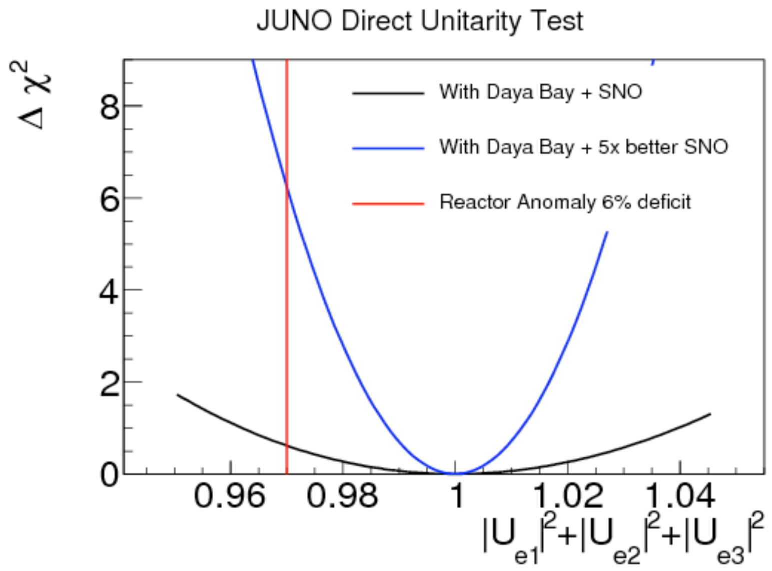
- Best solar angle in the foreseeable future
- Valuable input to the neutrinoless double beta decay

W. Rodejohann, J. Phys. G **39**, 124008 (2012)



- Three-neutrino paradigm test

Direct unitarity test of $|U_{e1}|^2+|U_{e2}|^2+|U_{e3}|^2=1$



Qian, X. et al. arXiv:1308.5700

Global Efforts Resolving ν Mass Hierarchy

Source / Principle	Matter Effect	Interference of Solar&Atm Osc. Terms	Collective Oscillation on Detected Spec.	Constraining Total Mass
Atmospheric ν	Super-K, Hyper-K, PINGU/IceCUBE, ICAL/INO, ORCA/KM3NeT, DUNE	Atm ν_μ + JUNO		
Beam ν_μ	T2K, NOνA, T2HKK, DUNE	Beam ν_μ + JUNO		
Reactor ν		JUNO, JUNO+Beam ν_μ		
Supernova Burst ν			Super-K, Hyper-K, PINGU/IceCUBE, ORCA/KM3NeT, DUNE, JUNO	
ν during Struc. Form.				Cosmological Data

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***

- Mass hierarchy is one of the center focuses and reactor neutrinos provide great potential in resolving the neutrino mass hierarchy, ***complementary to other efforts***

    - ➡ Pure e-flavor: JUNO is being constructed — 2020 data taking

    - ➡ Matter Effect: Hyper-K/T2HK/T2HKK/IceCube-Gen2/PINGU KM3NeT/ORCA

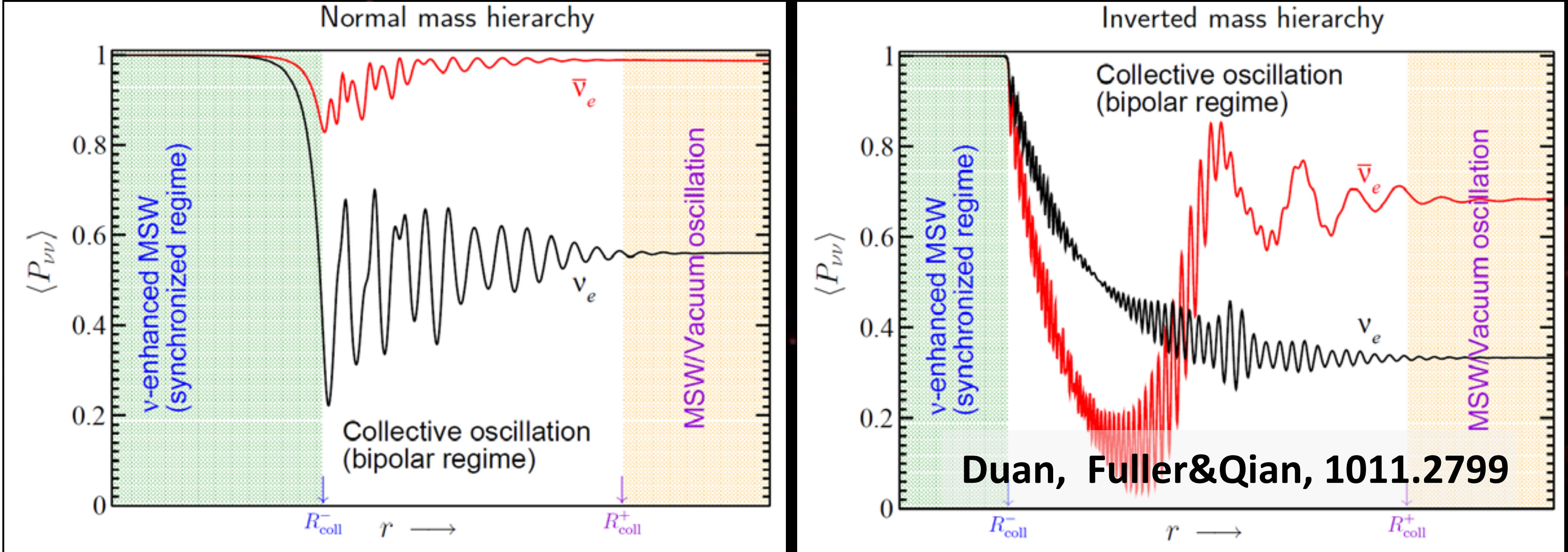
    - ➡ Extraterrestrial sources: be prepared……

- ***Neutrino physics*** might hold the keys to many profound questions — ***Stay tuned and let us expect unexpected!***

Supernova Neutrinos Tell MH?

Zhou for JUNO
@ FCPPL 2015

■ 中微子味转变和物质效应：集体效应（吸积阶段）

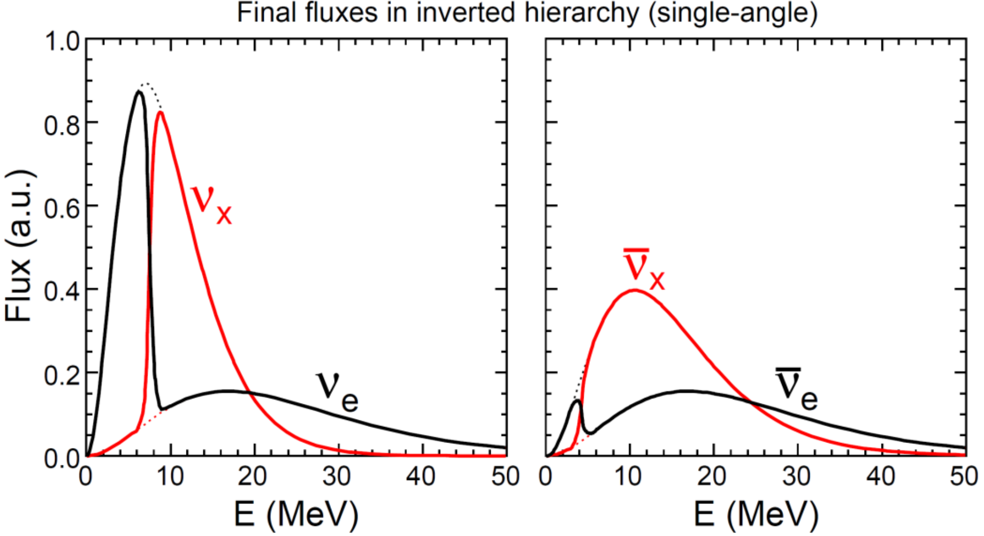


Duan, Fuller&Qian, 1011.2799

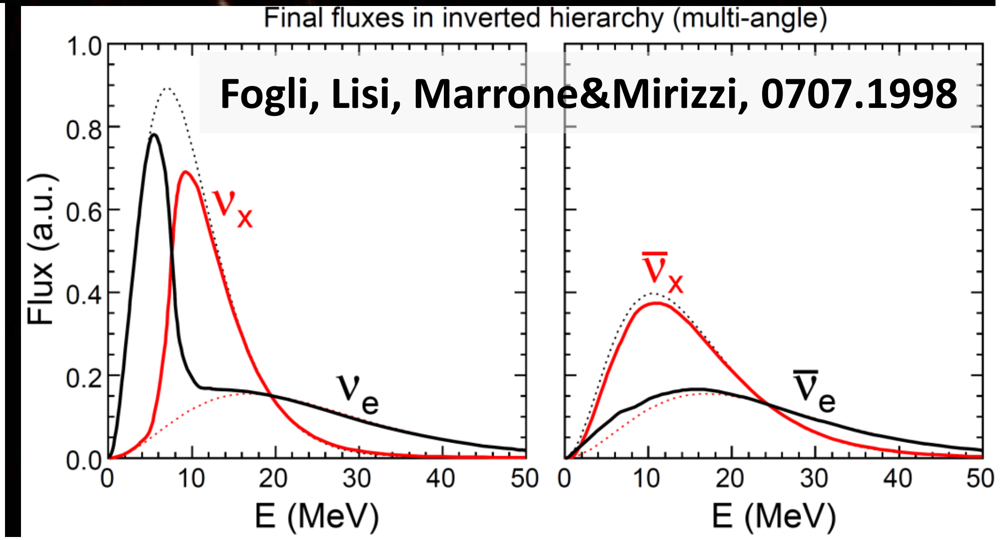
左二图：味转化示意图

下二图：倒质量等级+吸积

Final fluxes in inverted hierarchy (single-angle)

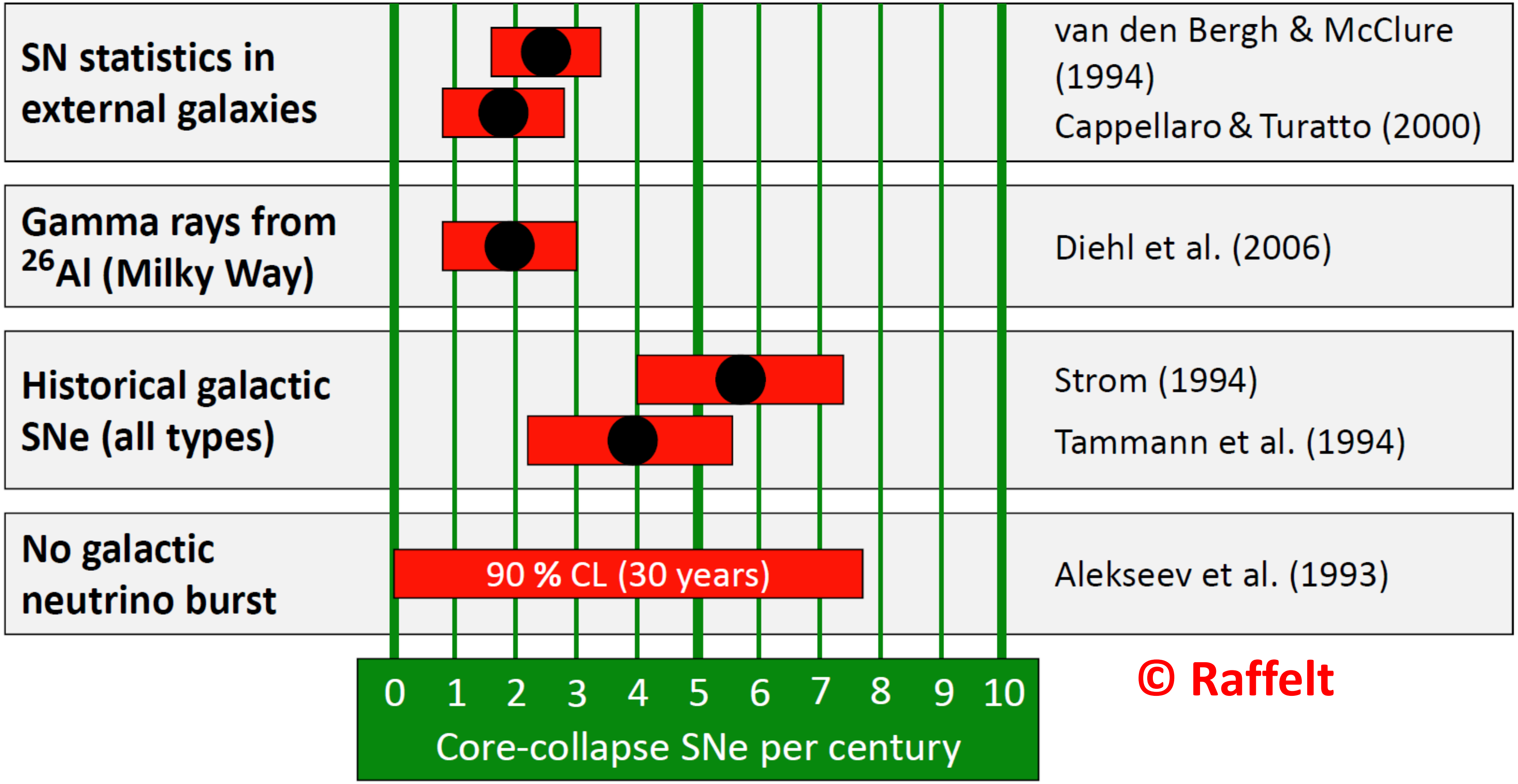


Final fluxes in inverted hierarchy (multi-angle)



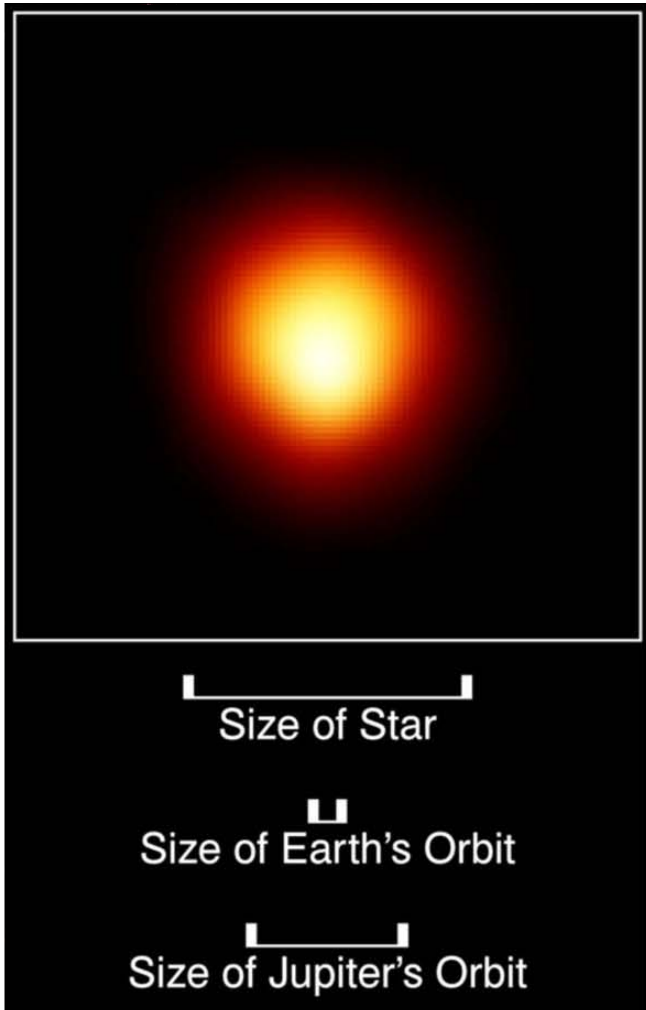
Fogli, Lisi, Marrone&Mirizzi, 0707.1998

SN: When and Where?

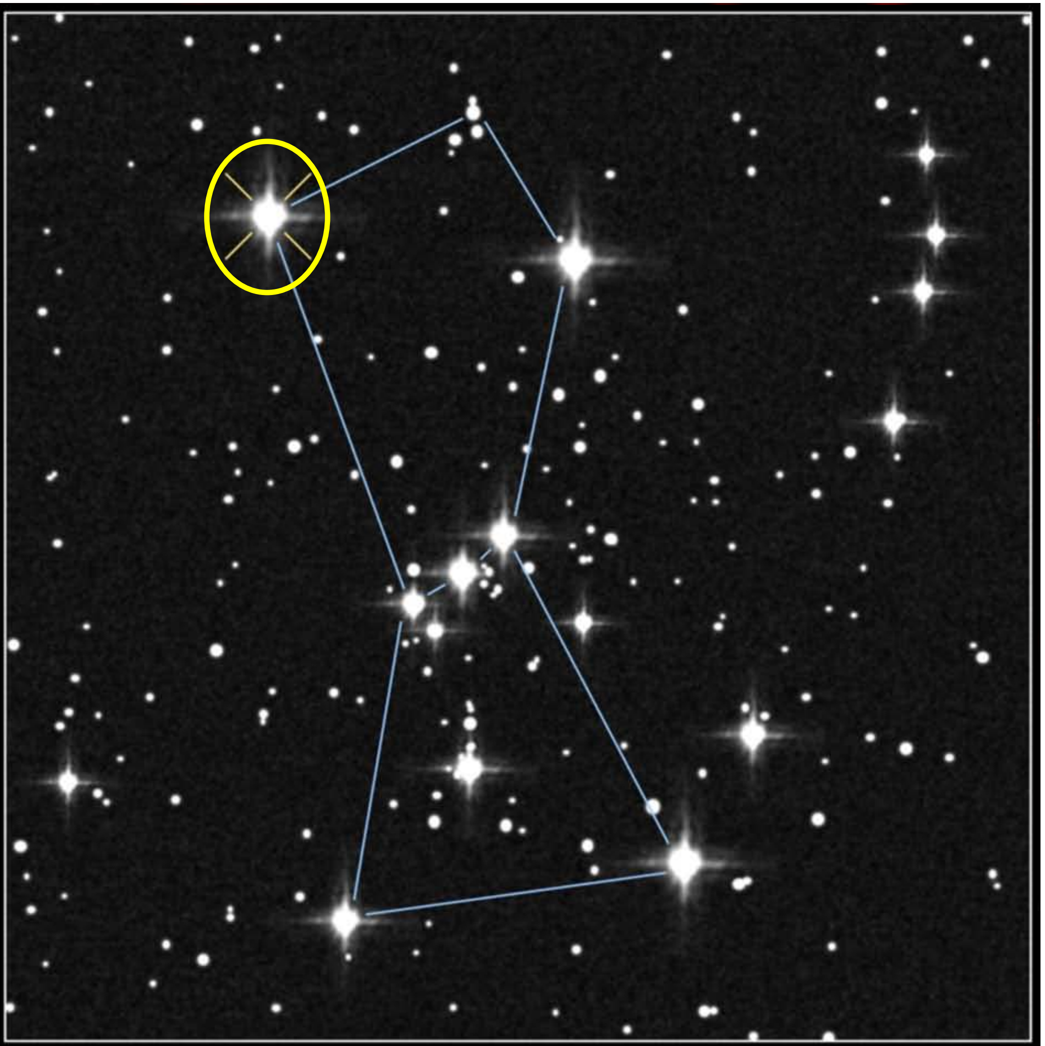


© Raffelt

Alpha Orionis

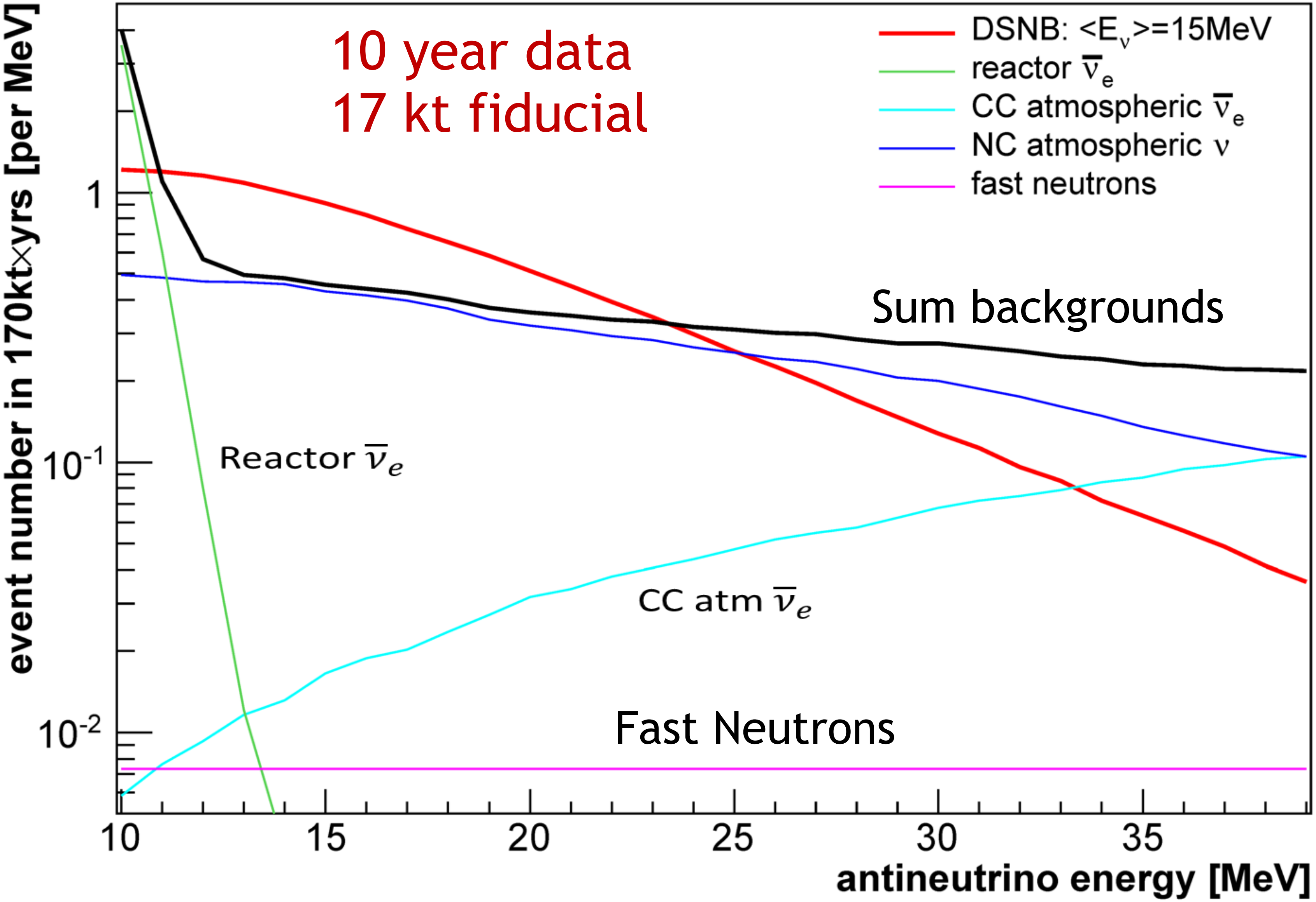


距离：425光年(130 pc)
类型：红超巨星
质量：~ 18倍太阳质量



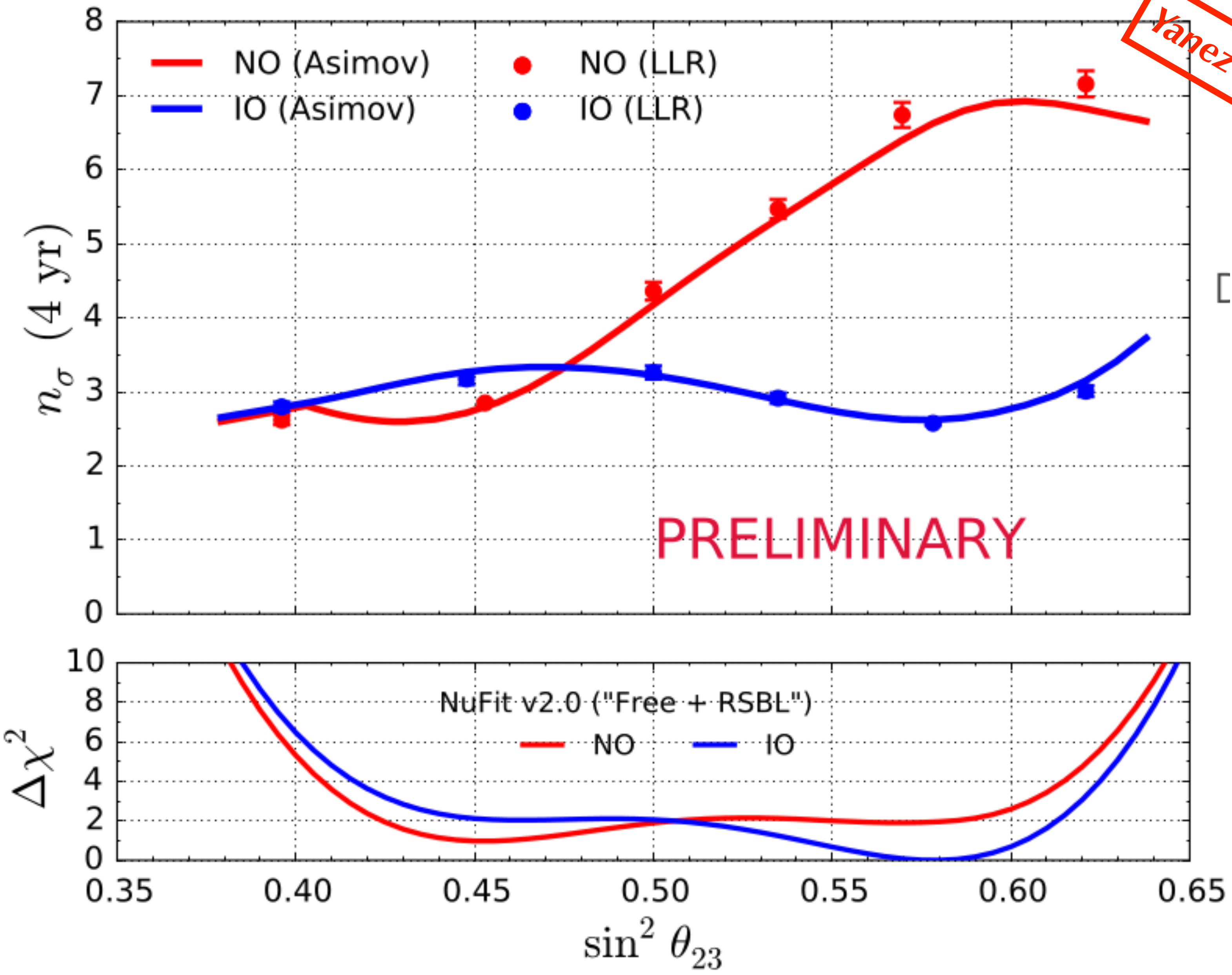
预期以II型超新星爆发结束(或已爆发?)：
在 Super-K 产生 6×10^7 个事例

JUNO Sensitivity to DSNB



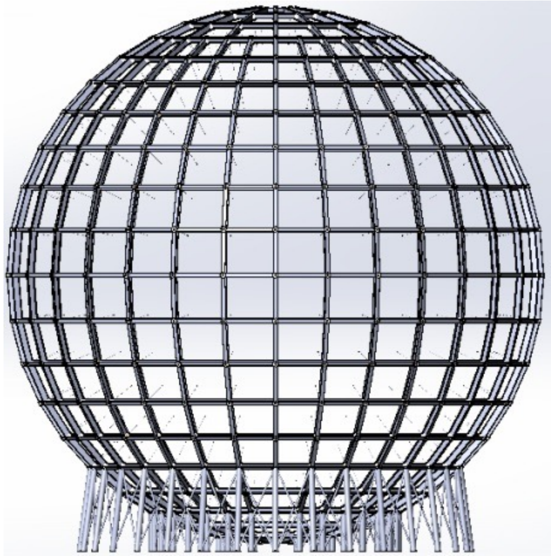
JUNO Yellow Book, in preparation 2015

IceCube-Gen2/PINGU Sensitivity to MH and Octant

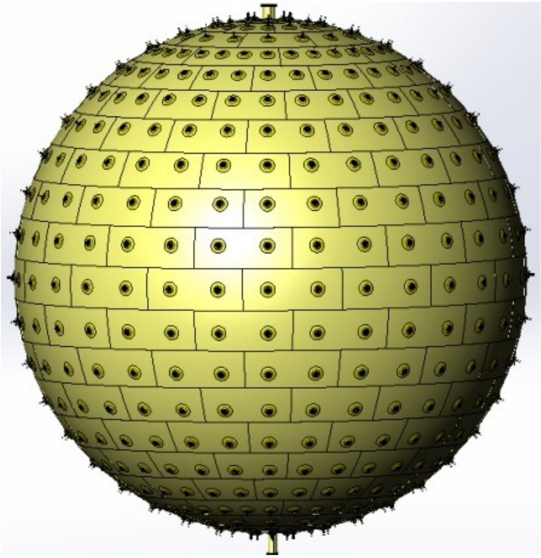


Yanez NNN'16

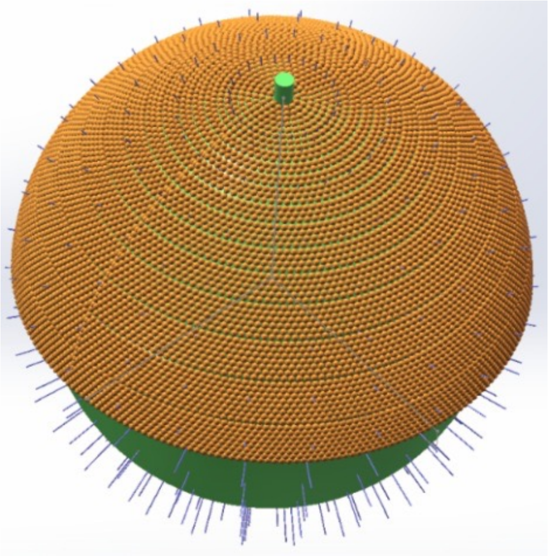
Details of the JUNO Central Detector



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

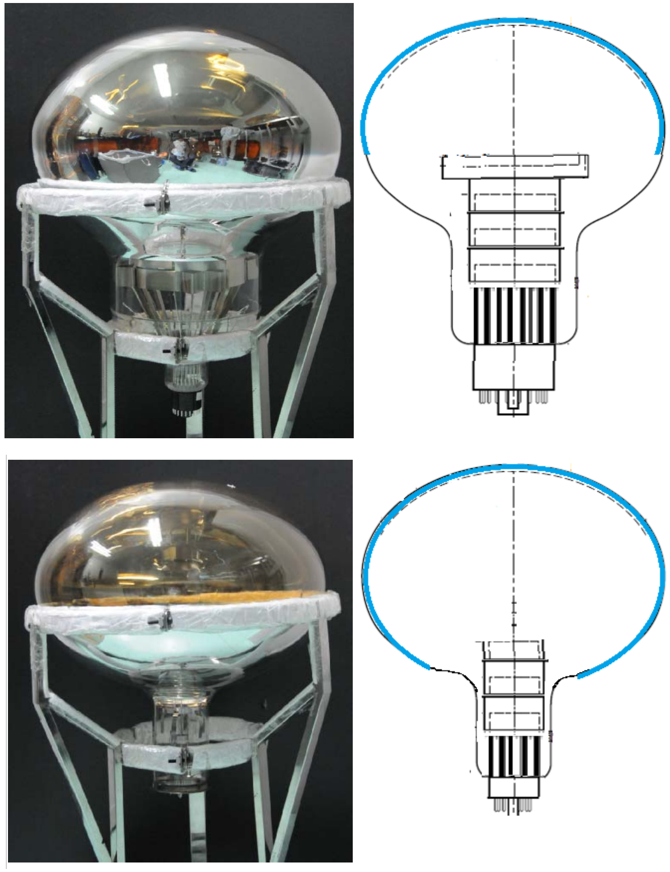
Acrylic sphere

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

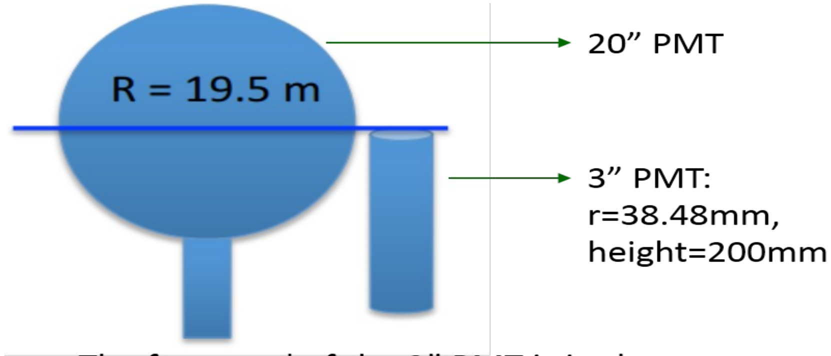
20″ PMT array

- Distance to LS: ~1.6m
- Gap: ~250mm (extremely challenging)

More Light: PMT and Photocathode Coverage

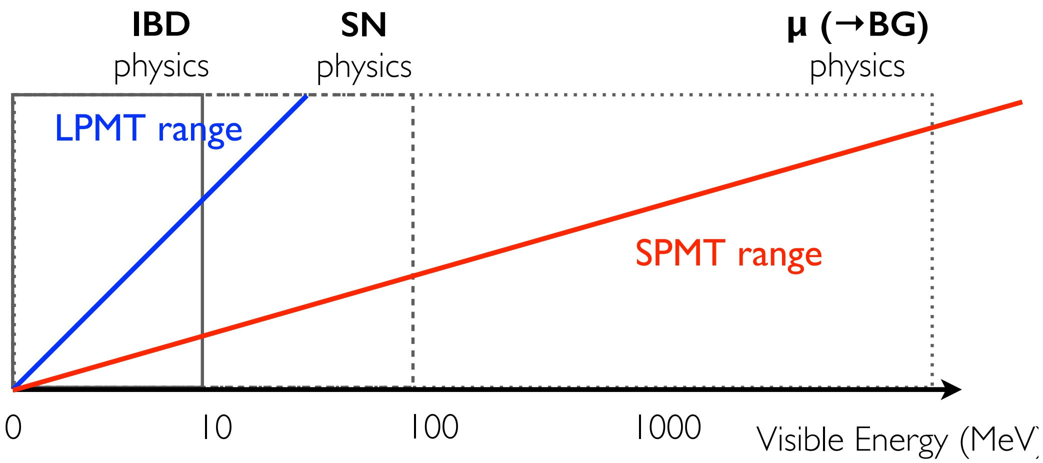


- Large PMTs: 20″ MCP-PMT, ~75%
- Large PMTs: 20″ SBA Hamamatsu, ~25%
- Small PMTs: 3″ PMTs
  - ➡ to further increase the photocathode coverage
  - ➡ to provide a semi-independent calorimetry system for timing
  - ➡ to extend energy dynamic range to avoid saturation, important for high energy events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



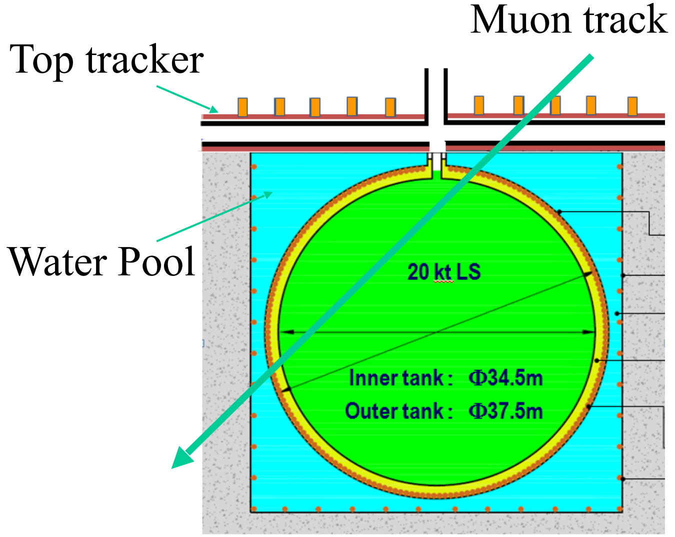
The front end of the 3” PMT is in the same plane as the equatorial plane of 20” PMT

Complementary Roles by SPMTs and LPMTs

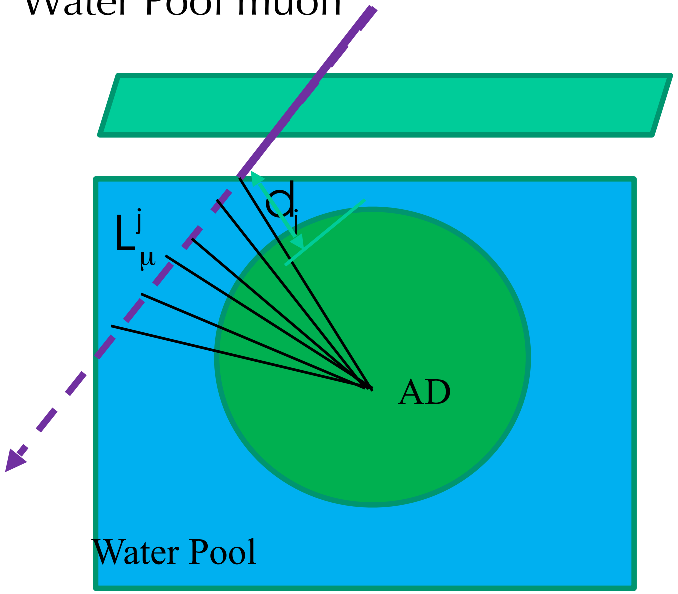


Veto System Considerations and Designs

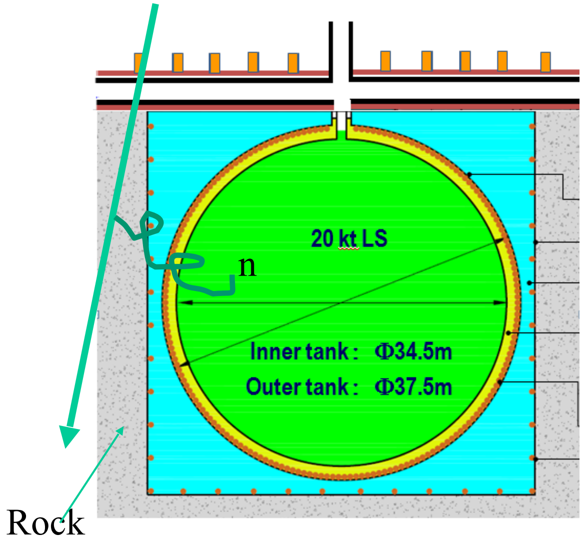
Central Detector muon



Water Pool muon



Rock muon

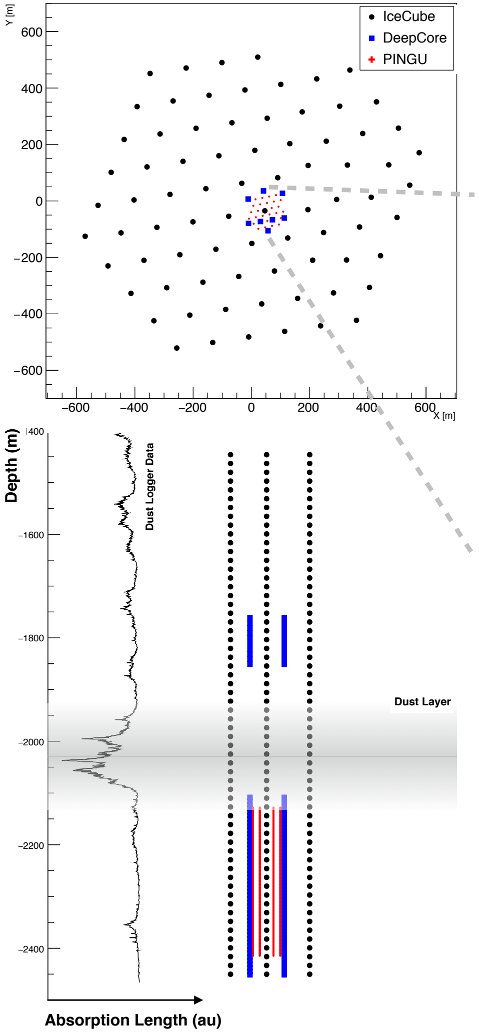


- Veto is not just a veto. Besides radioactive background shielding, we also need tracking information to better understand and remove cosmogenic backgrounds
  - The main body is the water Cherenkov detector
  - OPERA scintillator calorimeters will be moved to JUNO as the Top Tracker (TT)
- Earth magnetic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

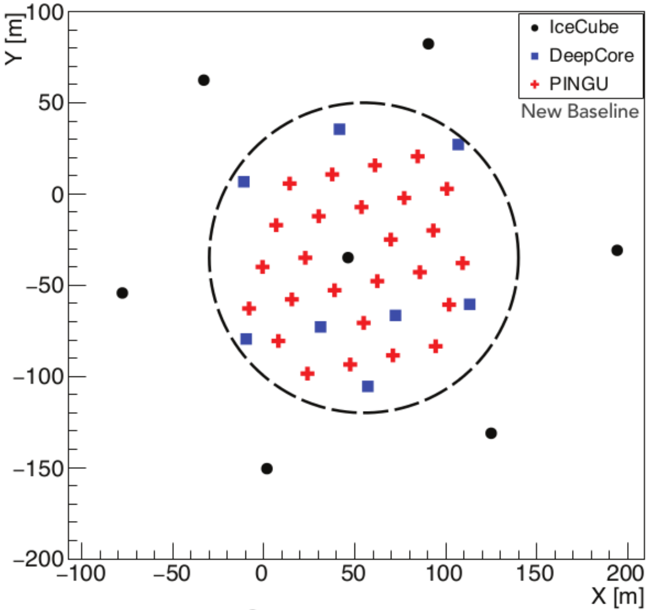
IceCube-Gen2/PINGU

➡ Need large statistics ⟹ IceCube

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

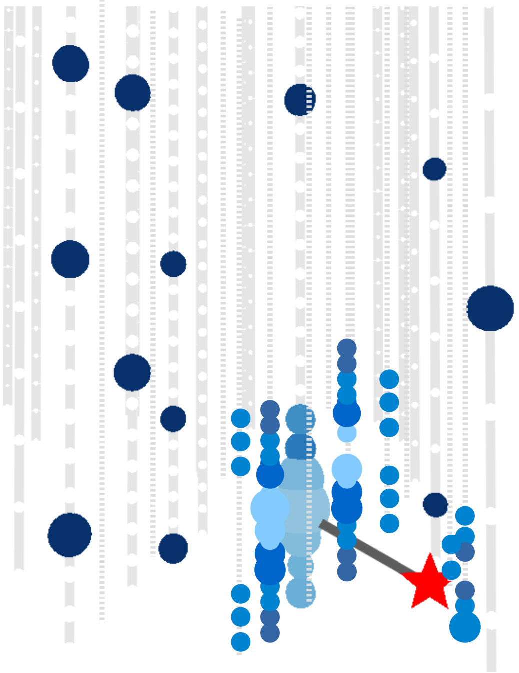


6 Mton “water” Cherenkov detector



Current

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



>8GeV: 100% Efficiency

~3GeV: ~50% Efficiency


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