Resolving the Mass Hierarchy

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Neutrino Mixing

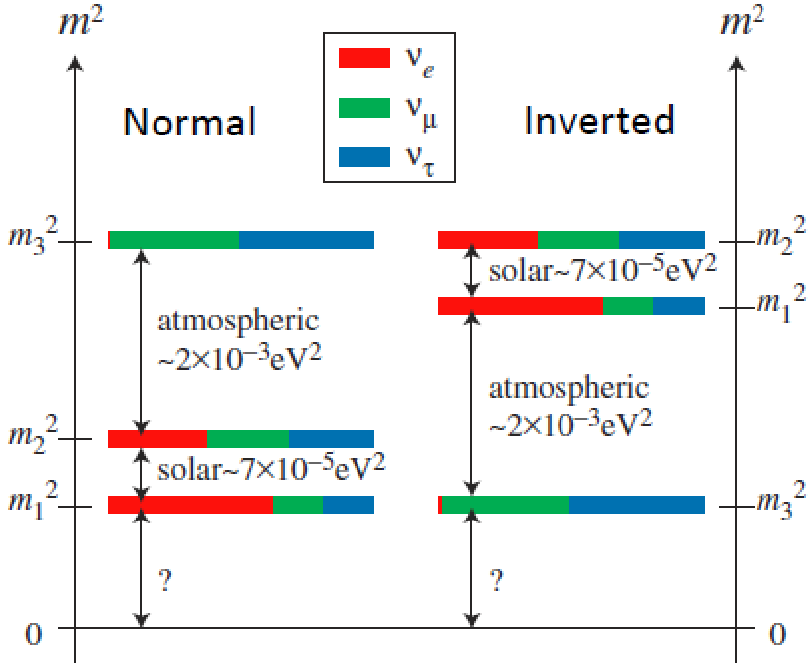
2-neutrino oscillation: Δm^2 θ

3-neutrino oscillation:

→ 6 oscillation parameters

Known: $|\Delta m^2_{32}|$ θ_{23} Δm^2_{21} θ_{12} θ_{13}

Unknown: δ_{CP} **Sign of** Δm^2_{32}



$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{-i\alpha_1/2} & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$c_{ij} \equiv \cos\theta_{ij}$

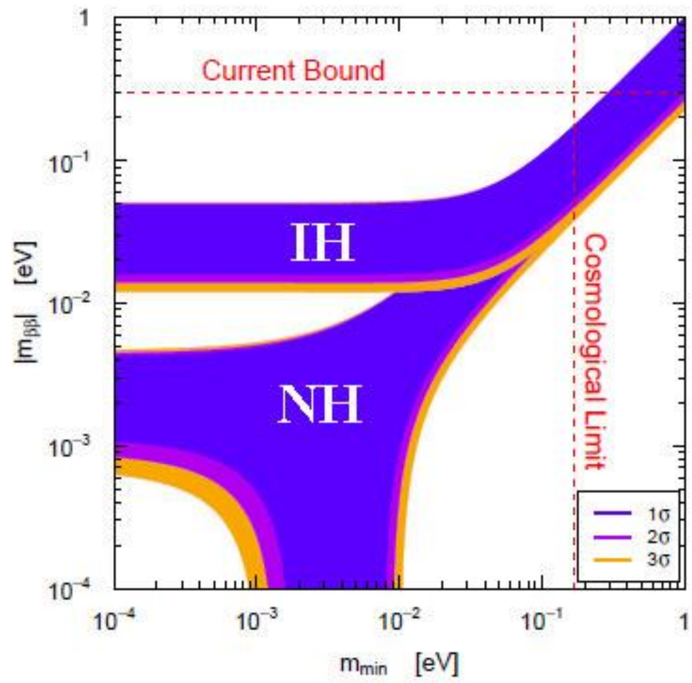
$s_{ij} \equiv \sin\theta_{ij}$

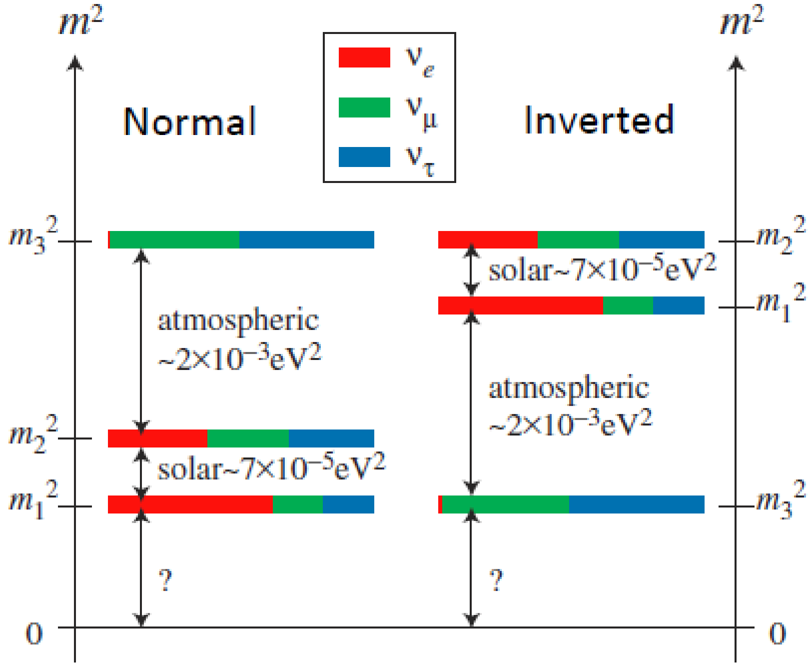
Atmospheric	"CP" sector	Solar	Majorana
$\theta_{23} \approx 45°$	$\theta_{13} = 9°$	$\theta_{12} \approx 34°$	

$|\Delta m^2_{32}| \approx |\Delta m^2_{31}| \approx 2.4 \times 10^{-3}$ eV^2

$\Delta m^2_{21} \approx 7.6 \times 10^{-5}$ eV^2

Mass Hierarchy





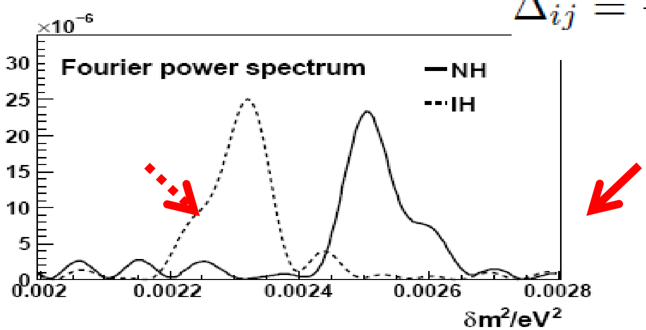
Mass hierarchy: Which neutrino is the lightest?

- **Impacts on oscillation probability, MH and CP degeneracy.**
- **Roadmap for 0νββ experiment**
- **Understanding the mass origin and neutrino mixing in theory**
  Some GUT theories predict normal MH
- **Nucleosynthesis in supernova, neutrino mass scale … …**

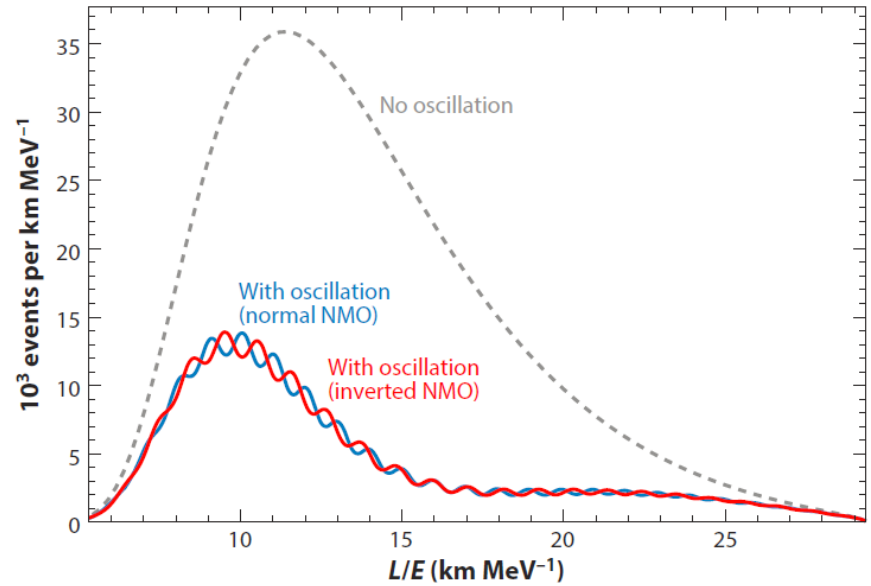
MH with Reactors

$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$
$$P_{21} = \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21})$$
$$P_{31} = \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31})$$
$$P_{32} = \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})$$

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$



Petcov et al., PLB533(2002)94, J. Learned et al., PRD78, 071302 (2008), L. Zhan, Y. Wang, J. Cao, L. Wen, PRD78:111103, 2008, PRD79:073007, 2009



- **Relative measurement**
- **Not rely on δ_{CP} and θ_{23}**
- **JUNO energy resolution: $3\%/\sqrt{E}$**

Δm^2_{31} and Δm^2_{32} Interplay (ϕ)	Δm^2_{ee} and $\Delta m^2_{\mu\mu}$ difference	Matter Effect

Reactor

Atmospheric

Accelerator

MH with Matter Effect

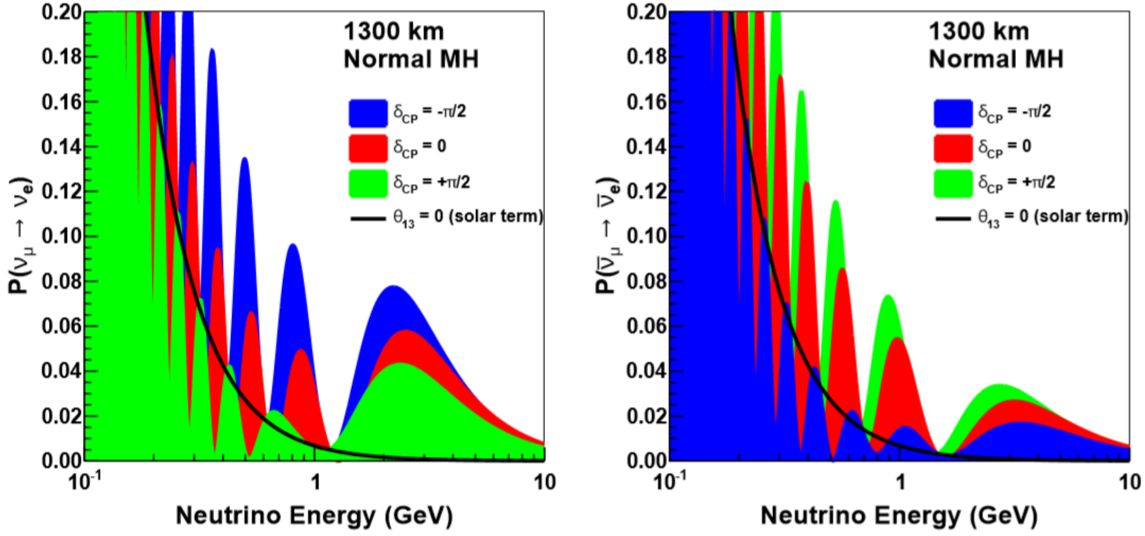
- **Both ν_e appearance channel and ν_μ disappearance channel.**
- **Matter effect (aL) and CP asymmetry for neutrino and anti-neutrino due to electron in matter. Large effect at long distance.**
- **DUNE at 1300 km resolves degeneracy of MH and δ_{CP}**

$$P_{vac}(\nu_\mu \to \nu_e) = P_{atm} + P_{sol} + P_{int}$$

$$\sin \Delta_{ij} \to \frac{\Delta_{ij}}{\Delta_{ij} \pm aL} \sin(\Delta_{31} \pm aL)$$

$$P_{mat}(\nu_\mu \to \nu_e) \approx (1 \pm 2\frac{E}{12\ GeV}) P_{vac}(\nu_\mu \to \nu_e)$$

Appearance channel: Accelerator w/ ν and $\bar{\nu}$
NOvA, DUNE



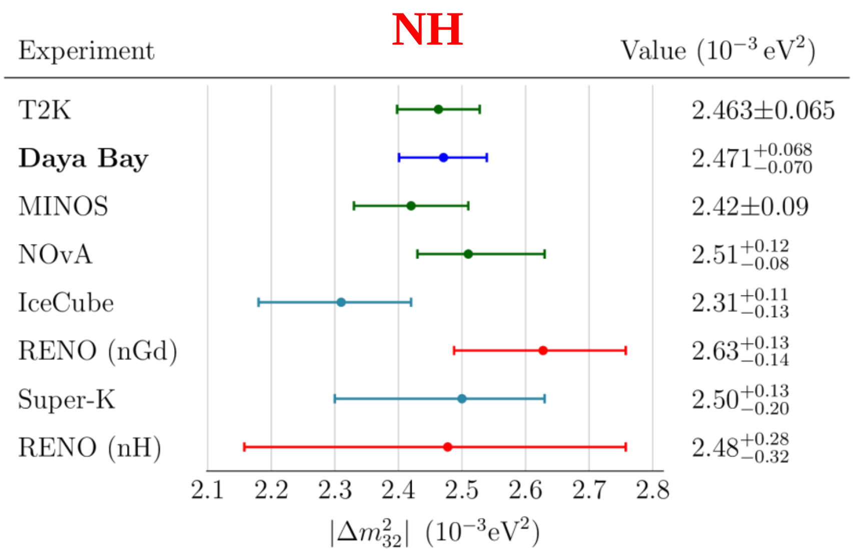
MH with absolute Δm^2

NH: $|\Delta m^2_{31}| - |\Delta m^2_{32}| = +\Delta m^2_{21}$

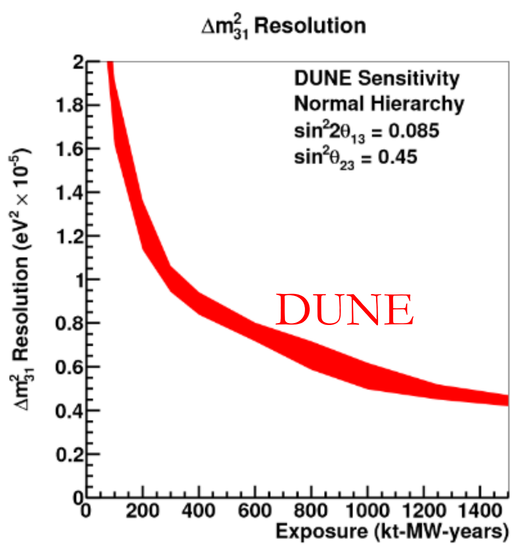
IH: $|\Delta m^2_{31}| - |\Delta m^2_{32}| = -\Delta m^2_{21}$

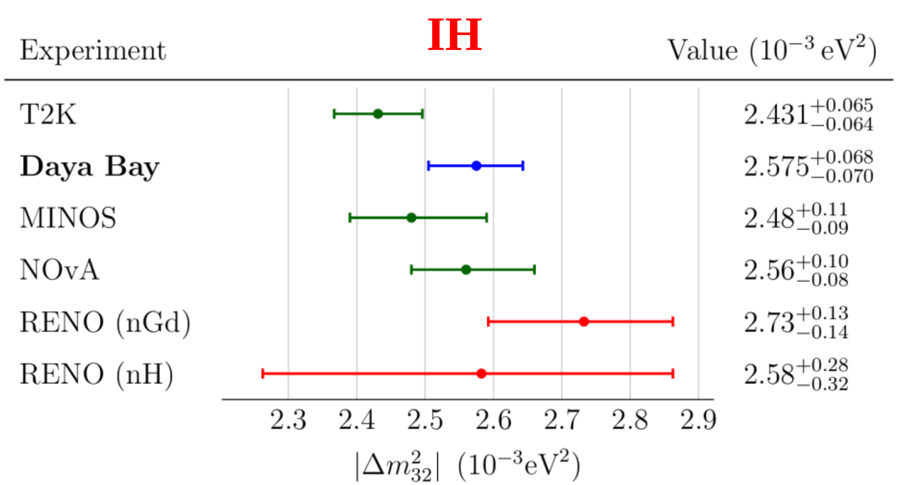
$\Delta m^2_{21} \sim 3\% \, |\Delta m^2_{31}|$

JUNO	Statistics	+BG +1% b2b +1% EScale +1% EnonL
$\sin^2\theta_{12}$	0.54%	0.67%
Δm^2_{21}	0.24%	0.59%
Δm^2_{31}	0.27%	**0.44%**

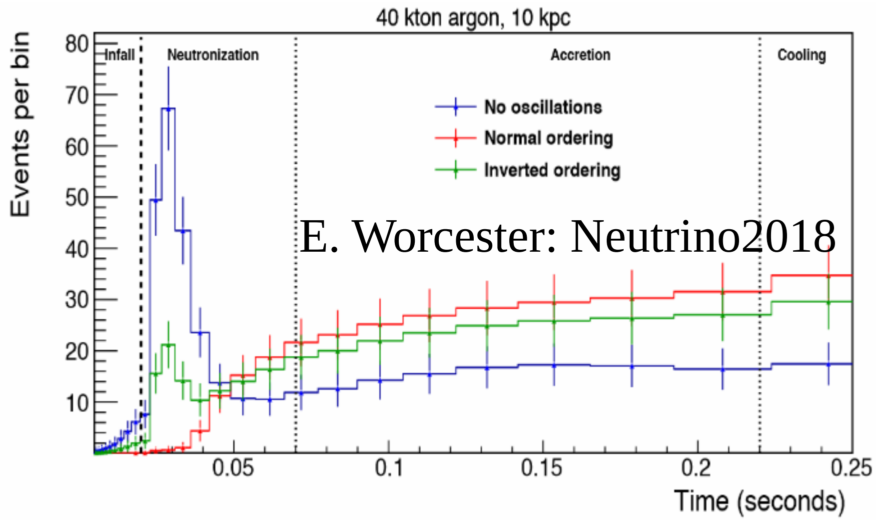


- **T2K, NOvA**
  - **~ 1%**
- **T2HK**
  - **~ 0.6% (10y)**





MH with Supernova/Cosmology

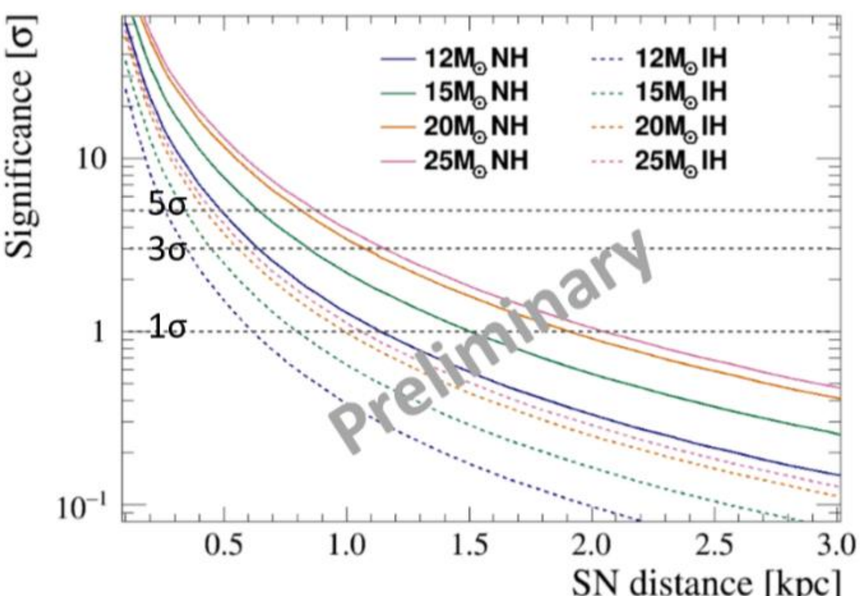


E. Worcester: Neutrino2018

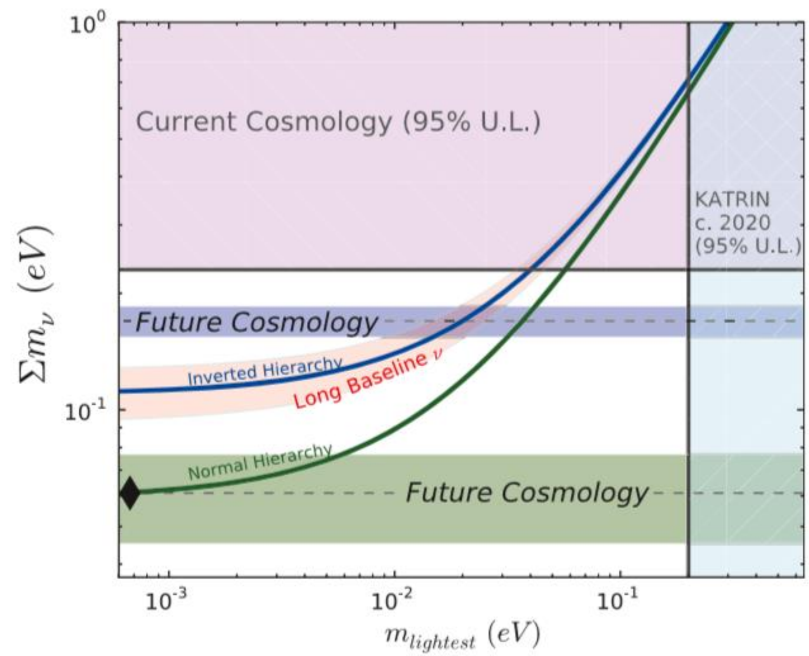
- **Supernova burst**
- **Pre-Supernova**
- **Cosmology determine ($\Sigma m = m_1 + m_2 + m_3$) to 0.1 eV**

$|\Delta m^2_{32}| \sim 2.5\times10^{-3}$ eV^2

$\Delta m^2_{21} \sim 7\times10^{-5}$ eV^2

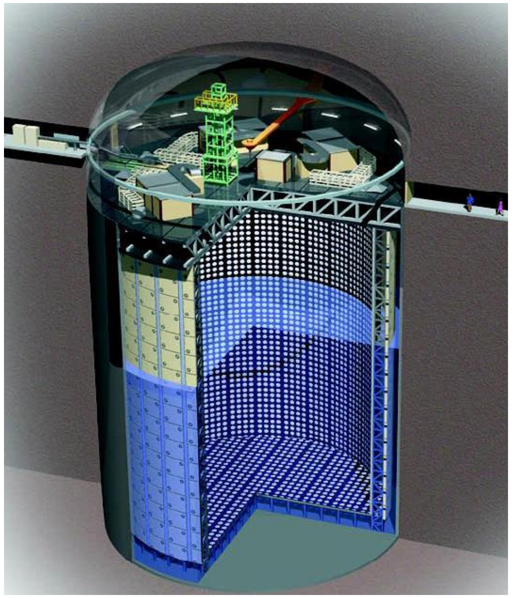


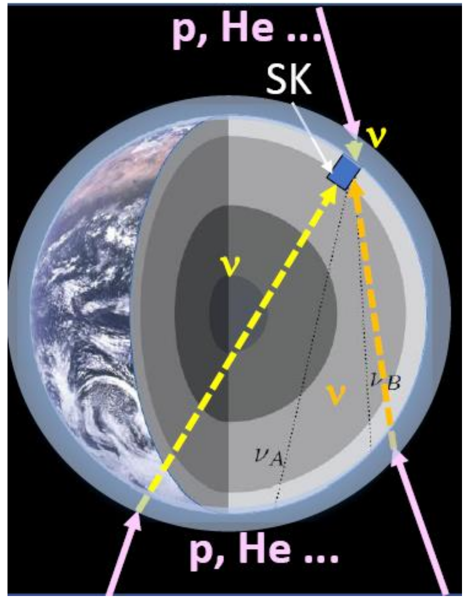
Huiling Li, SNEWS, 2019

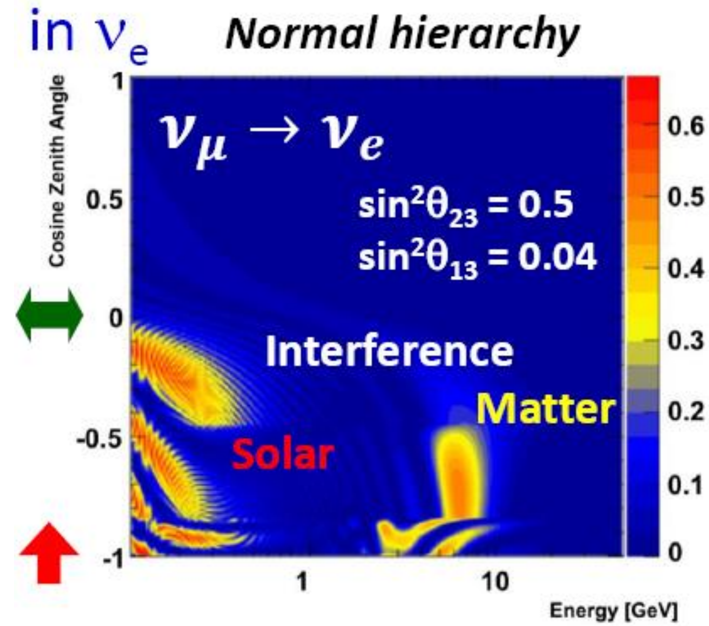


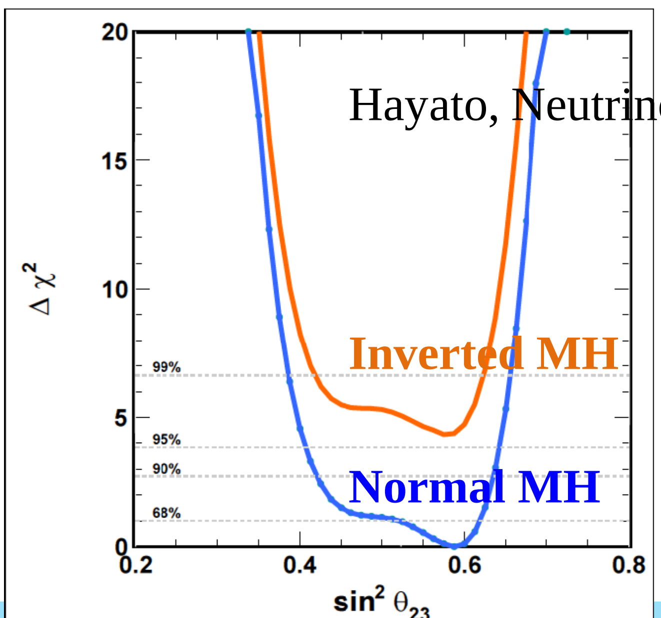
K.N.Abazajian 2015 Astropart. Phys. 63 66

Current Experiment – Super-K









Hayato, Neutrino2018

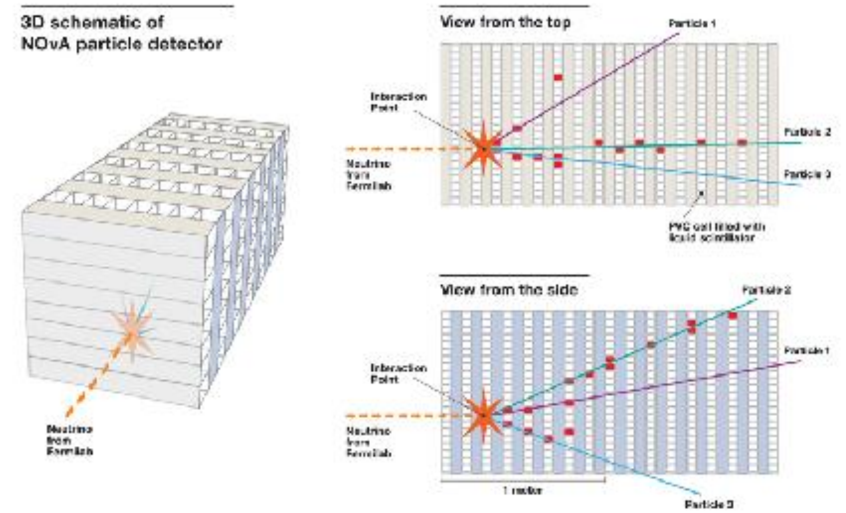
Difference in # of electron events:

$$\Delta_e \equiv \frac{N_e}{N_e^0} \cong \Delta_1(\theta_{13}) + \Delta_2(\Delta m_{12}^2) + \Delta_3(\theta_{13}, \Delta m_{12}^2, \delta)$$

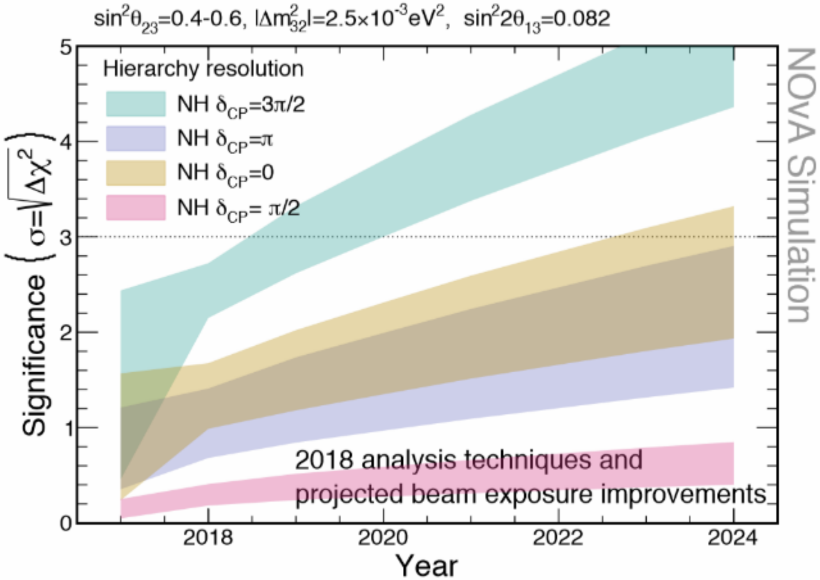
- Matter effect
- Solar term
- Interference

- **5326 days, 328 kt.yr**
- **$\Delta\chi^2 = 4.34$**
- **CLs: Inverted MH rejection 80.6-96.7%**

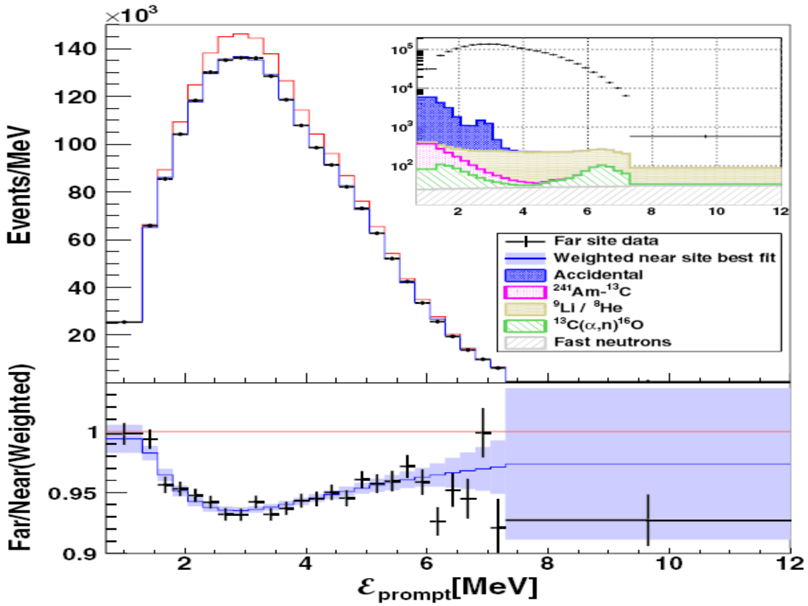
Current Experiment - NOvA

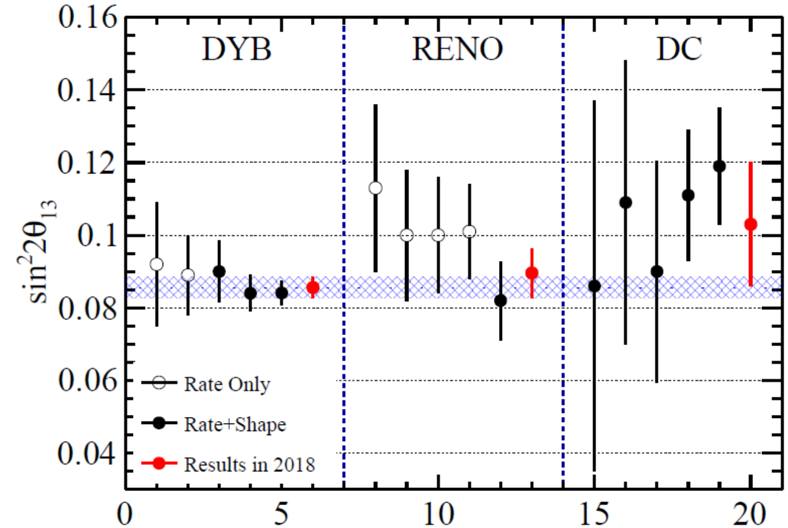


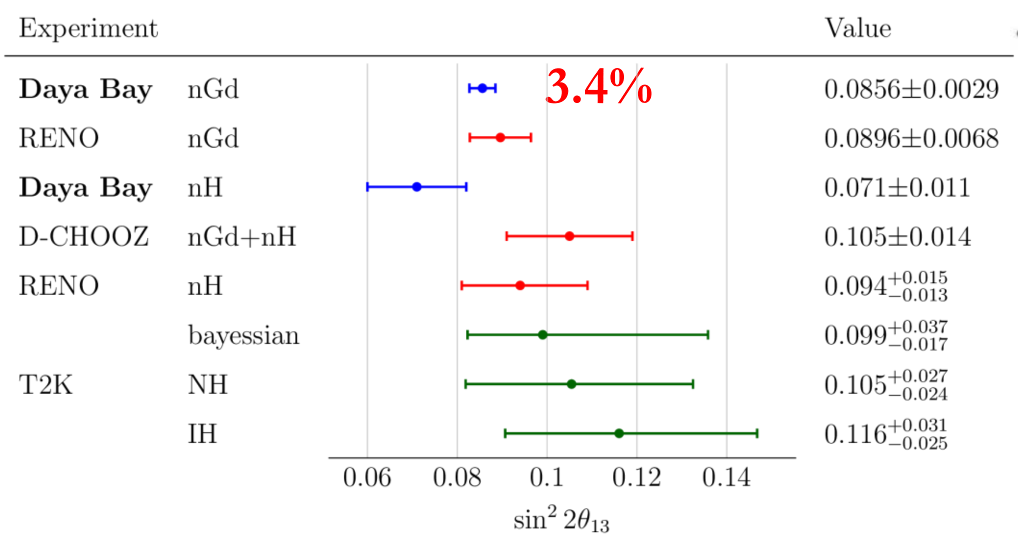
- Fermilab (700kW) to Minnesota (810 km). 14 kt LS detector
- Prefer NH at 1.8σ
- Extended running through 2024, proposed accelerator improvement
  - 3σ (if NH and $\delta_{CP}=3\pi/2$) for allowed range of θ_{23} by 2020
  - 3σ for 30-50% (depending on octant) of δ_{CP} range by 2024.

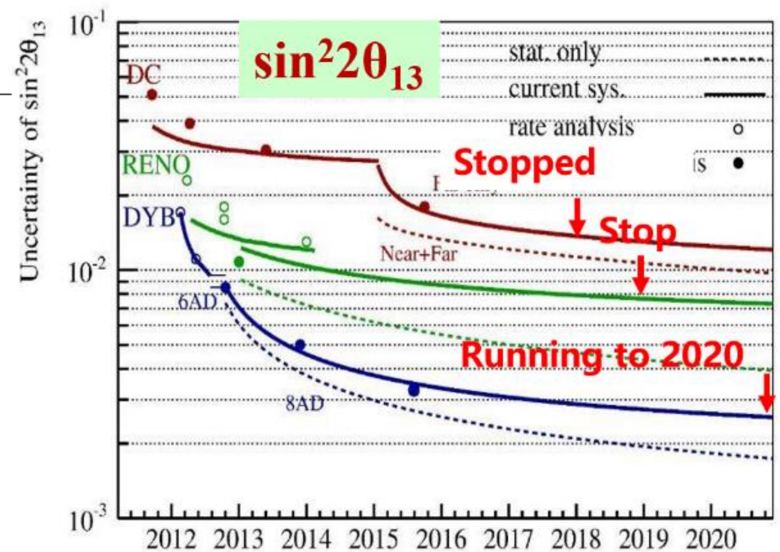


Large θ_{13} enables MH determination

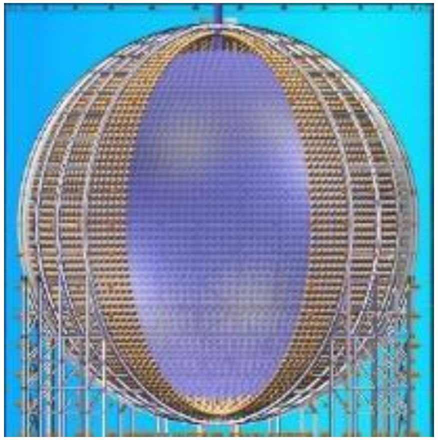


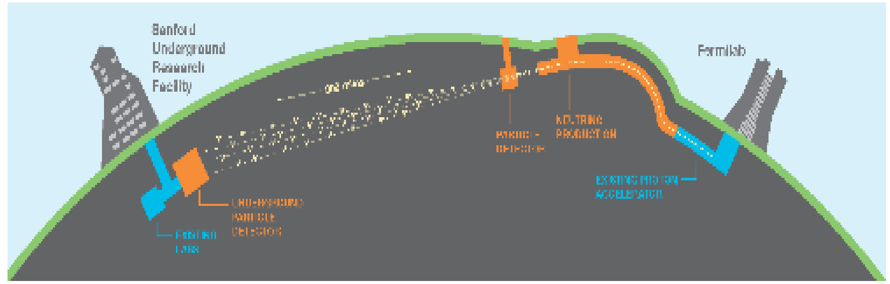




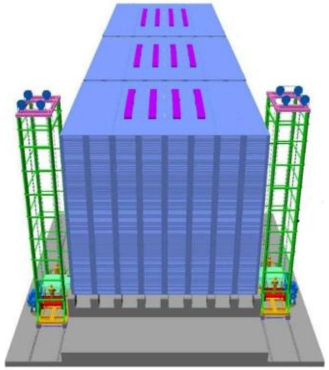


Next Generation Oscillation Exp





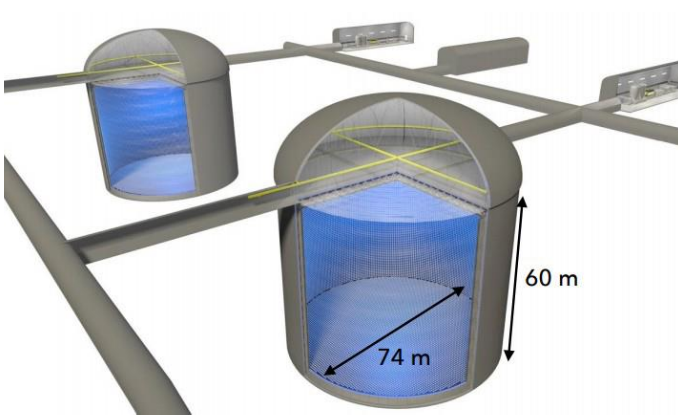
DUNE in US, 10-40 kton Liquid Argon

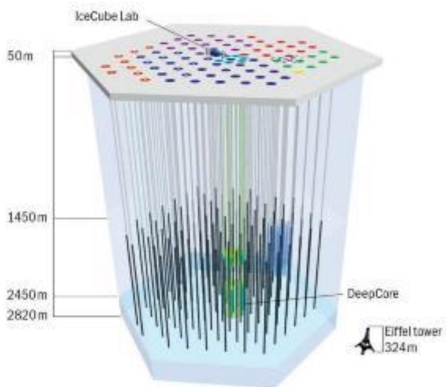


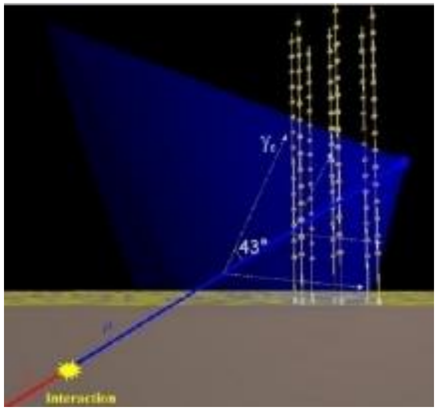
JUNO: 20 kton Liquid Scintillator

INO in India, 50 kton Iron+RPC

PINGU at South Pole







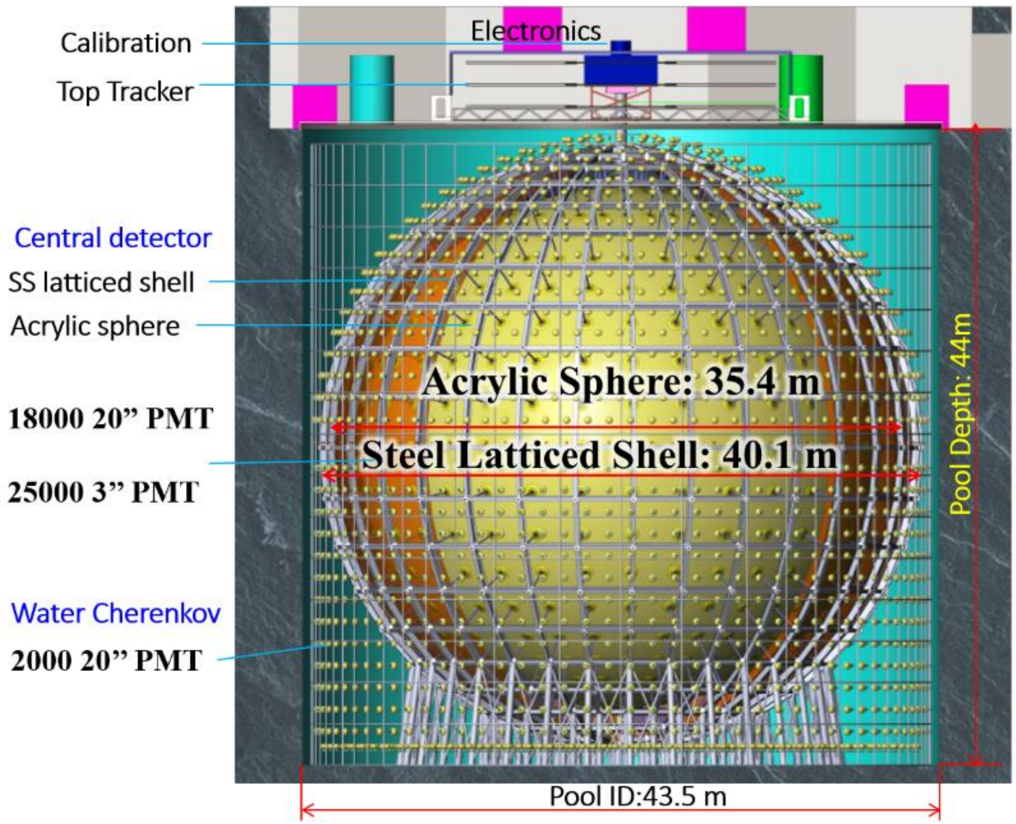
Hyper-K, T2HK in Japan, 260 kton water

ORCA in Mediterranean

JUNO Detector

Jiangmen Underground Neutrino Observatory, a multiple-purpose neutrino experiment, proposed in 2008, approved in 2013, online in 2021

LS | 12cm acrylic | 2.35m water | SS lattice+PMTs | 1.2m water+PMT | HDPE

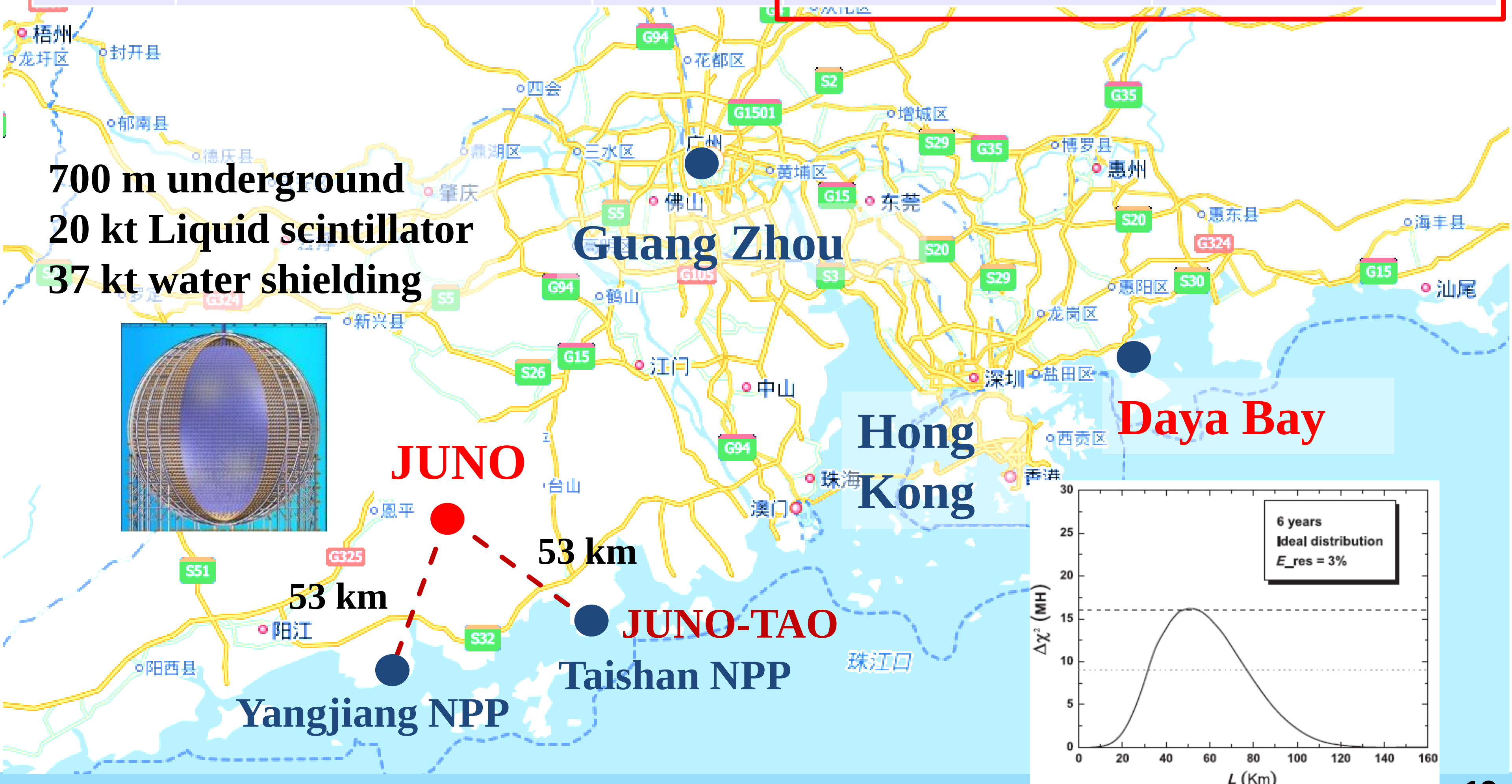


- **20 kton LS detector**
- **$3\%/\sqrt{E}$ energy resolution**
- **Rich physics possibilities**
  - Reactor neutrino for Mass hierarchy and precision measurement of 3 oscillation parameters
  - Supernova neutrino
  - Geo-neutrino
  - Solar neutrino
  - Proton decay
  - Exotic searches

Location of JUNO

NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	9.2 + 9.2 GW

700 m underground
20 kt Liquid scintillator
37 kt water shielding



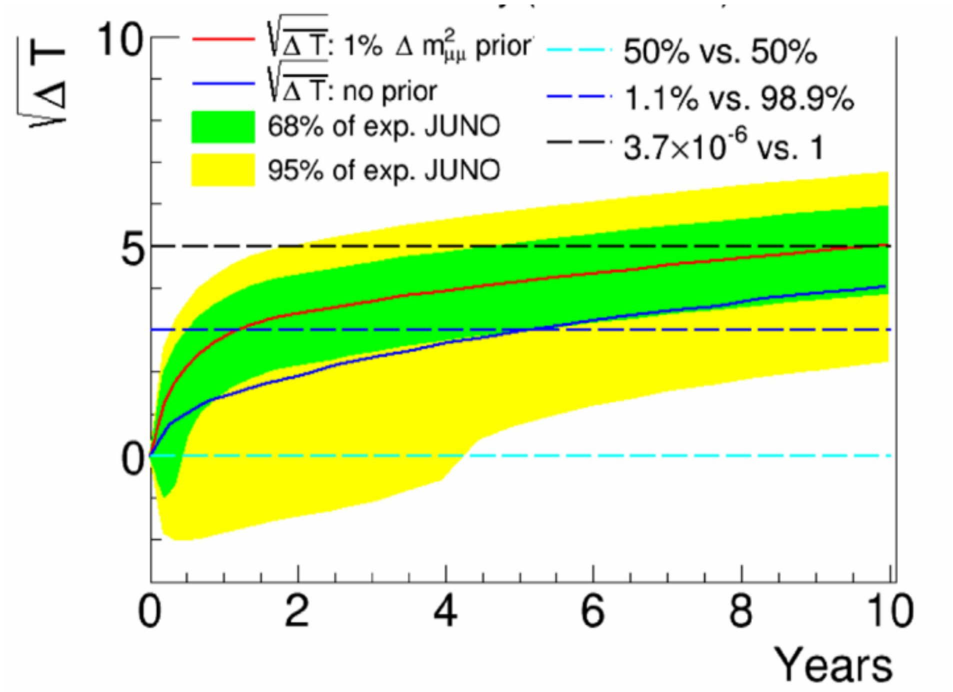
State-of-Art LS Detector

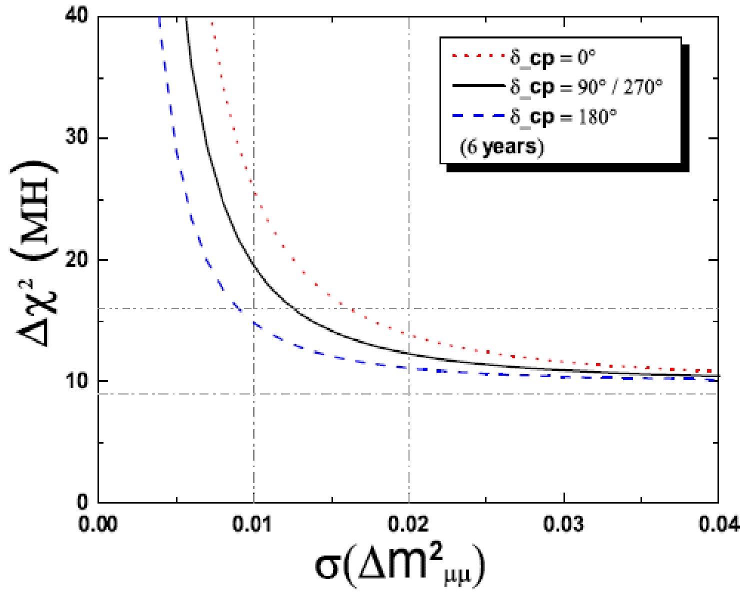
	Daya Bay	BOREXINO	KamLAND	**JUNO**
Target Mass	~20 t	~300 t	~1 kt	**~20 kt**
Photoelectron Yield (PE/MeV)	~160	~500	~250	**~1200**
Photocathode Coverage	~12%	~34%	~34%	**~78%**
Energy Resolution	~8%/√E	~5%/√E	~6%/√E	**3%/√E**

- **Unprecedented energy resolution (3%)**
  - **PMT Coverage 78%**
  - **PMT Detection Eff. > 27%**
  - **LS attenuation length > 20 m**
  - **Calibration**
- **Low background (e.g. 1 ppt for acrylic, 10^{-15} to 10^{-17} for LS)**
- **20 times more statistics, mechanical challenges**

→ **Refresh many studies by an order**

Mass Hierarchy Sensitivity





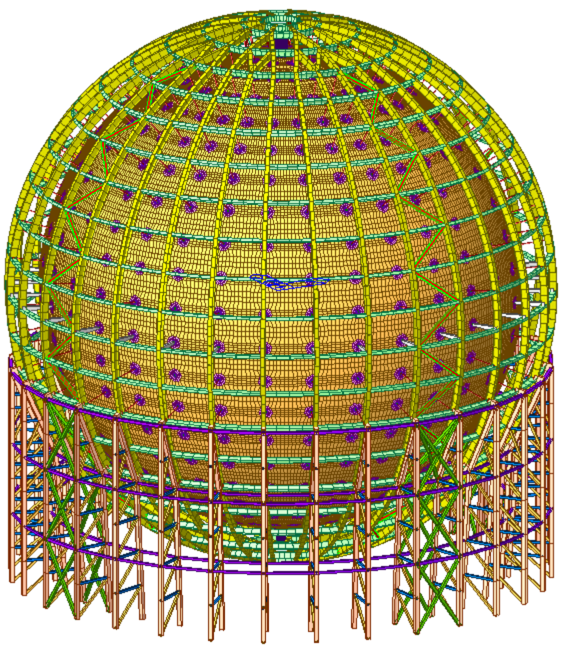
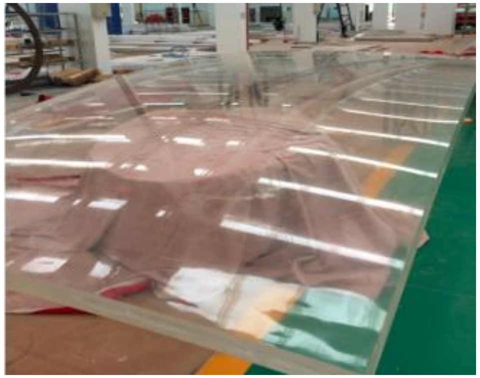
3-4σ in 6y, 4-5σ in 10y

6 Years	Relative	w/ abs. Δm^2
Statistics only	4σ	5σ
Realistic case	3σ	4σ

	Ideal	Core distr.	Shape	B/S (stat.)	B/S (shape)	$\lvert\Delta m^2_{\mu\mu}\rvert$
Size	52.5 km	Real	1%	4.5%	0.3%	1%
$\Delta\chi^2_{MH}$	+16	−4	−1	−0.5	−0.1	+8

JUNO Progress

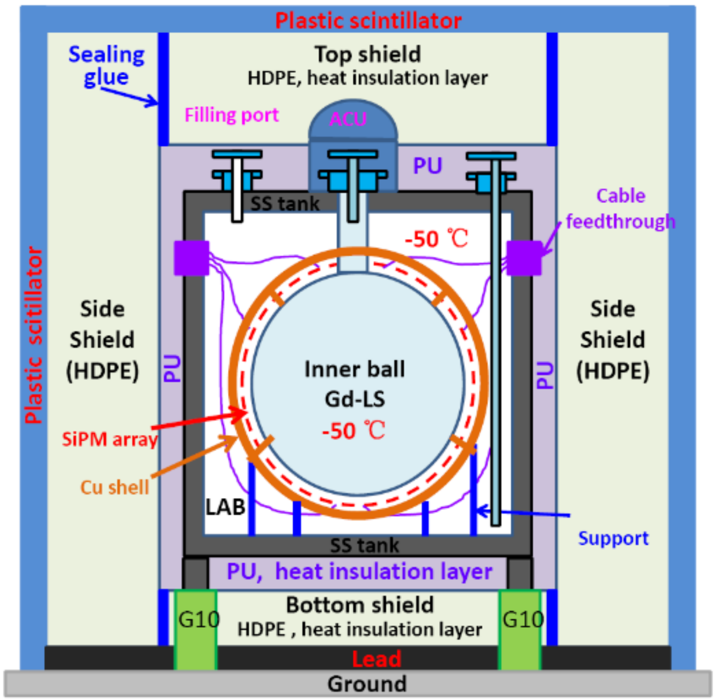
- **Completed slope and vertical tunnel. Excavating exp. hall. Delay due to unexpected underground water.**
- **Detector R&D and fabrication on schedule**
  - **Most major components contracted**
  - **15k 20-in PMTs (PDE 28%, 30%) and 18k 3-in PMTs received.**
  - **1st acrylic panel (8x3x0.12m) qualified. Start batch production**



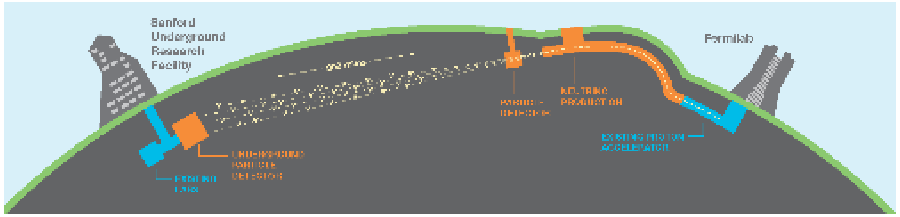
JUNO-TAO

- Taishan Antineutrino Observatory (TAO), a ton-level, high energy resolution LS detector at 30 m from the core, a satellite exp. of JUNO.
- Measure reactor neutrino spectrum w/ sub-percent E resolution.
  - ⇨ Model-independent reference spectrum for JUNO
  - ⇨ Benchmark for investigation of the nuclear database
- Ton-level Liquid Scintillator (Gd-LS)
- Full coverage of SiPM w/ PDE > 50%
- Operate at -50 ℃ (SiPM dark noise)
- 4500 p.e./MeV
- Taishan Nuclear Power Plant, 30-35 m from a 4.6 GW_th core
- 2000 IBD/day (4000)
- Online in 2021



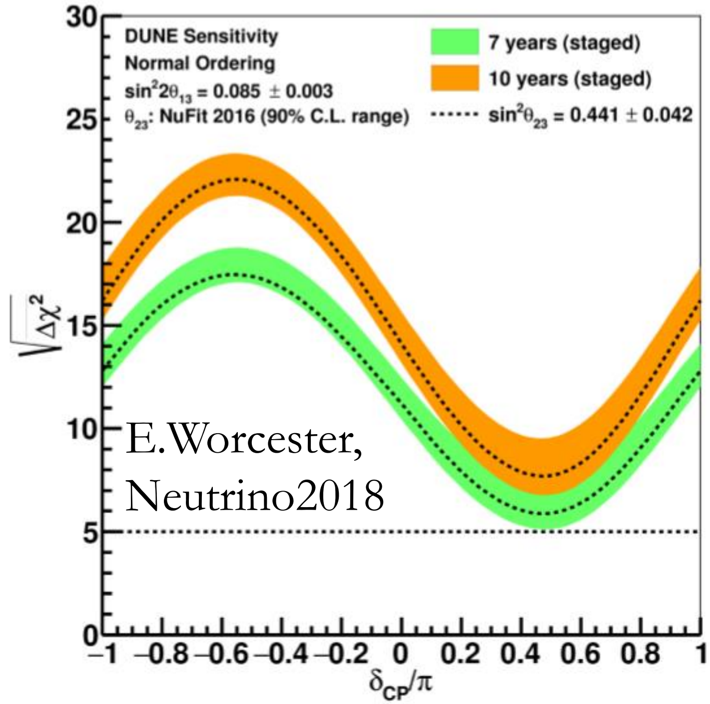
DUNE/LBNF

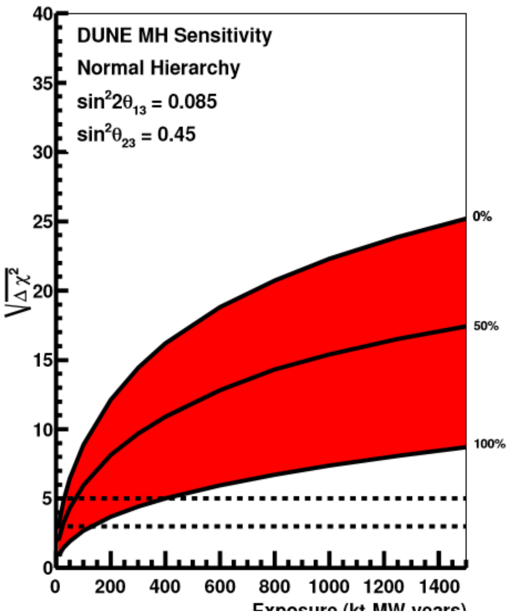
- **1300 km FNAL-SURF**
- **1.2 MW upgradable to 2.4MW**
- **4 10-kt LAr TPC modules, staged**
- **2024 first module, 2026 beam on**
- **> 5σ for all CP in 7 years**

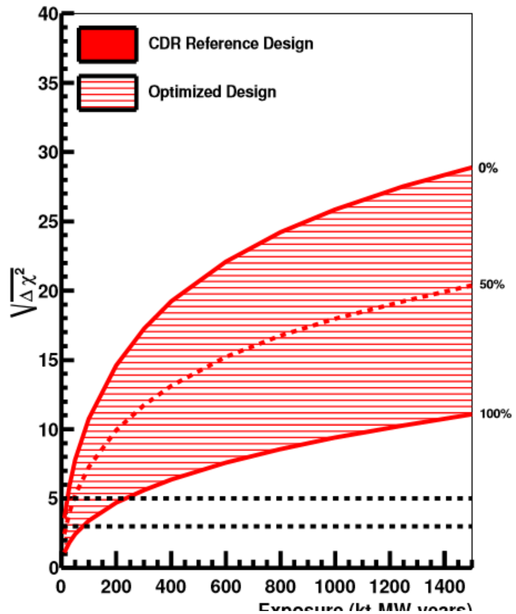


60-120 GeV proton beam

Mass Ordering

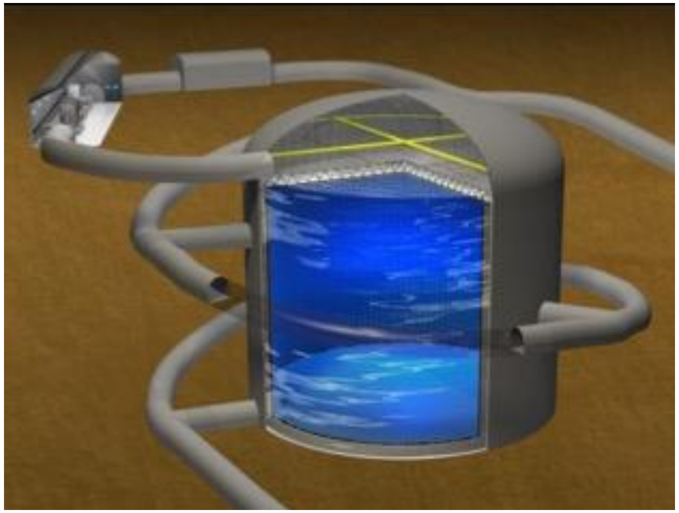




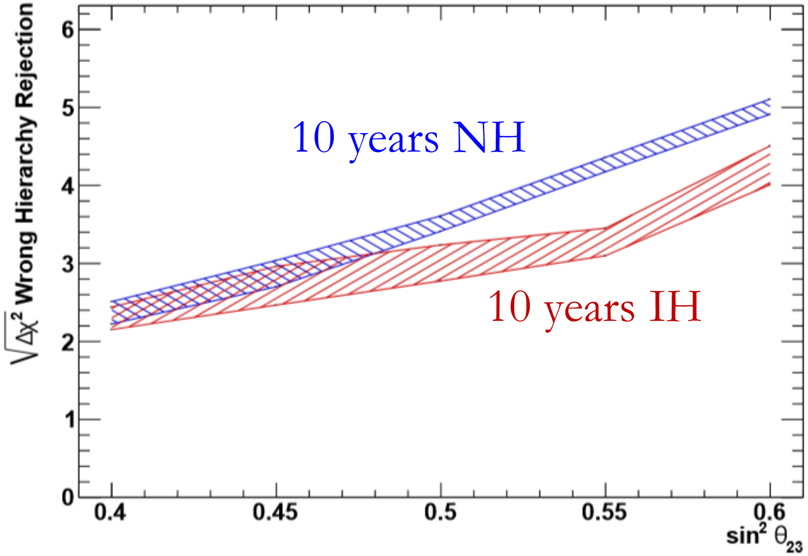


Hyper-K

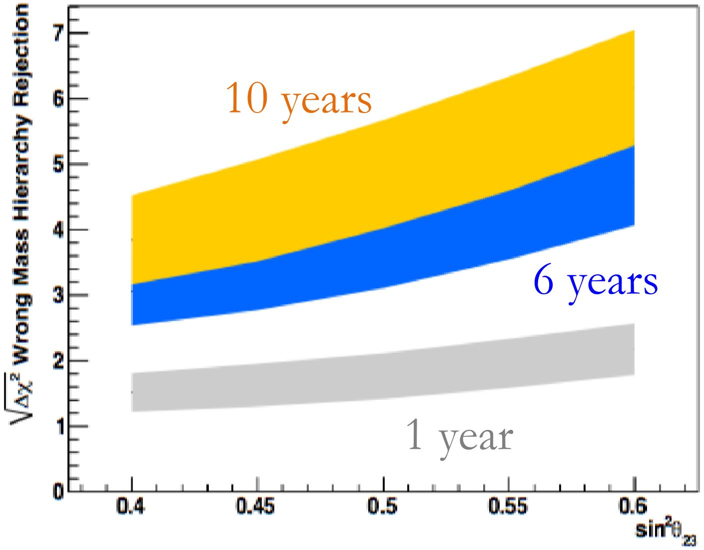
- **260 kt water Cherenkov detector**
- **186 kt fiducial, 10× Super-K**
- **Photon sensitivity 2× Super-K**
- **Construction 2020, complete 2027**
- **Possible 2nd detector in Korea**



Atmospheric

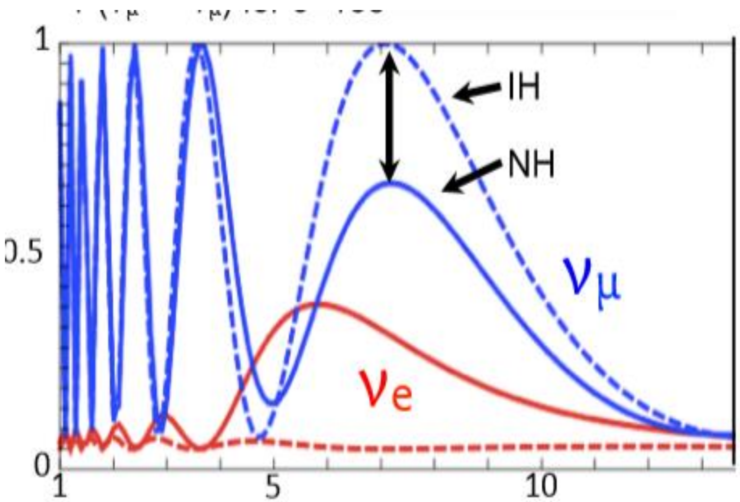


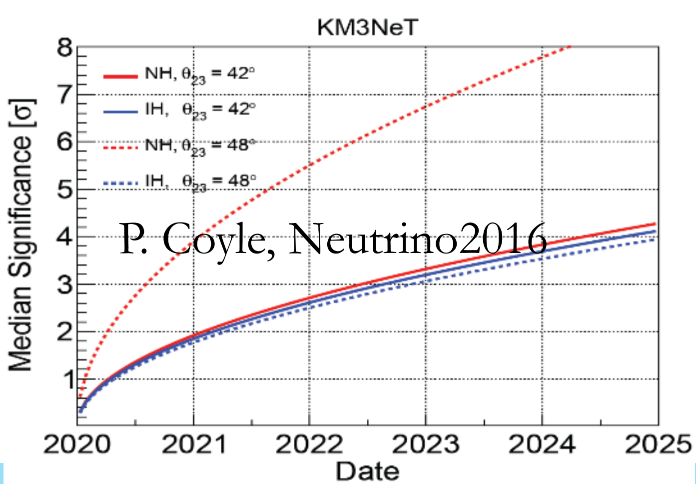
M. Shiozawa, neutrino2018

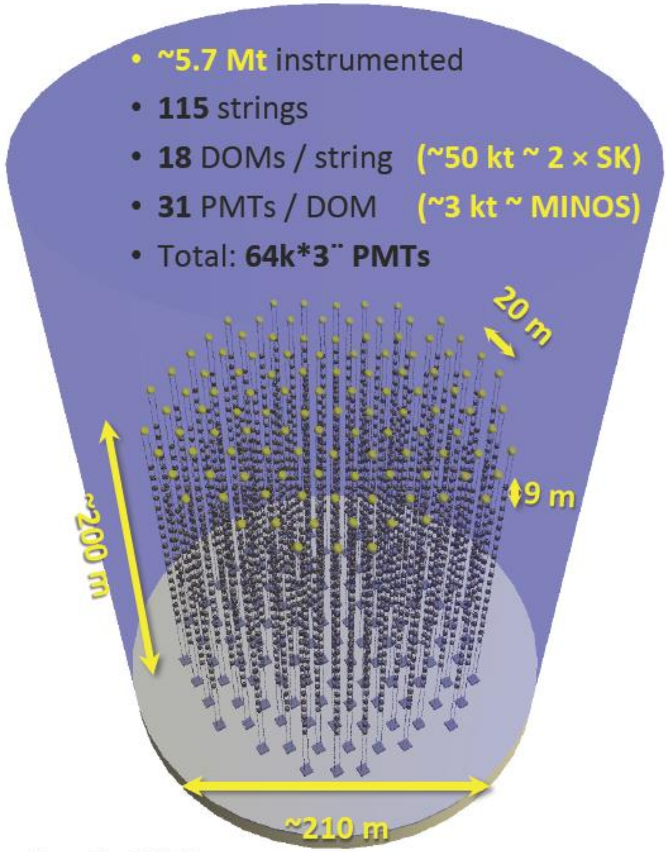


ORCA

Earth matter effect maximum difference IH↔NH at θ=130° (7645 km) and Eν = 7 GeV





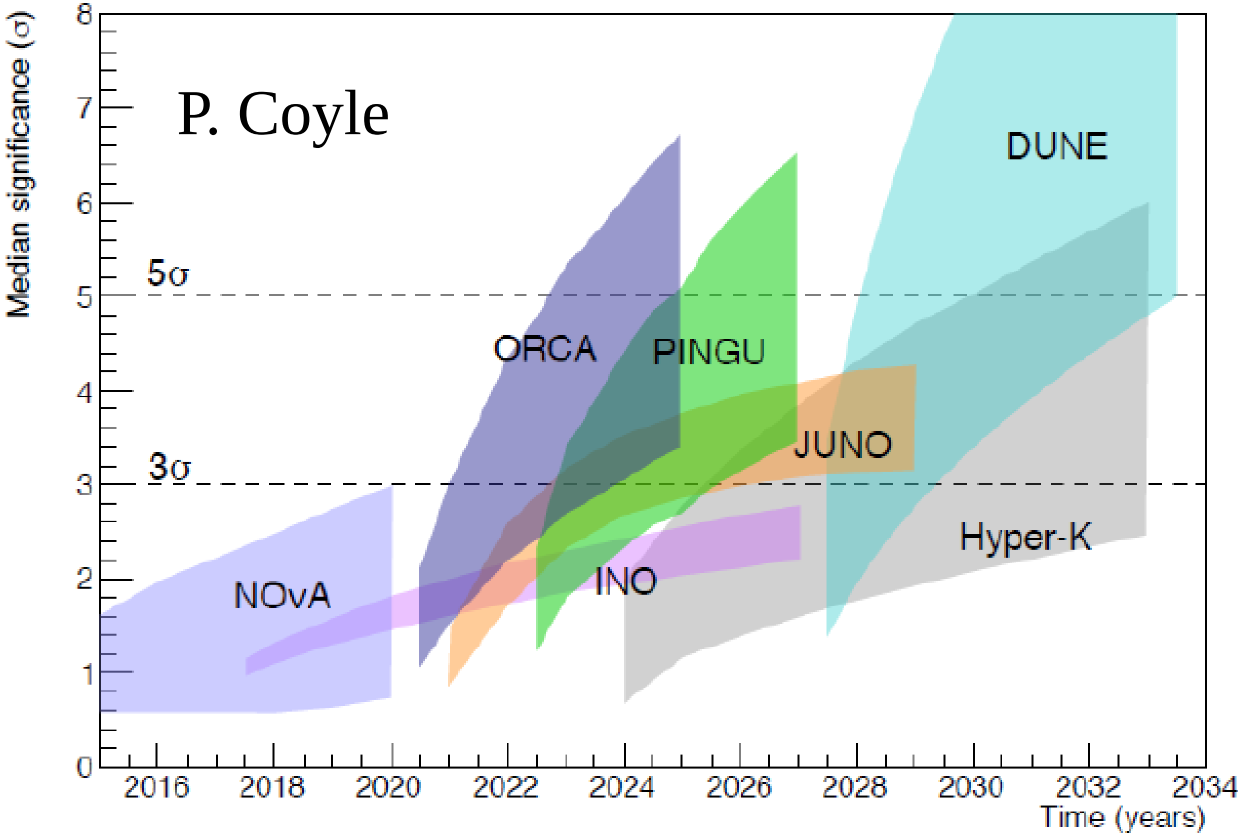


Depth=2475m

Systematics

- **PID 90% correct for e, 70% correct for μ at 10 GeV**
- **Angular resolution, energy resolution**

Mass Hierarchy



NOvA: certain chance

JUNO: 2021, 3-4σ in 6y

DUNE: 2026

Hyper-K: 2027

ORCA: 202x, 3σ in 4y

PINGU: 202x

INO: Paused

Just for demonstration. It depends on real schedule, real value of parameters, operation assumption, systematic assumption, etc.

Summary

- **Neutrino Mass Hierarchy has profound impacts to neutrino physics, GUT, astrophysics and cosmology**
- **Current measurements ~2σ**
- **Several coming experiments will firmly determine the MH with different sources (reactor, accelerator, atmospheric) and different technologies (liquid scintillator, liquid Argon TPC, water, etc.), and with astrophysics.**

Thank you for you attention!