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Prospects on neutrino mass hierarchy determination

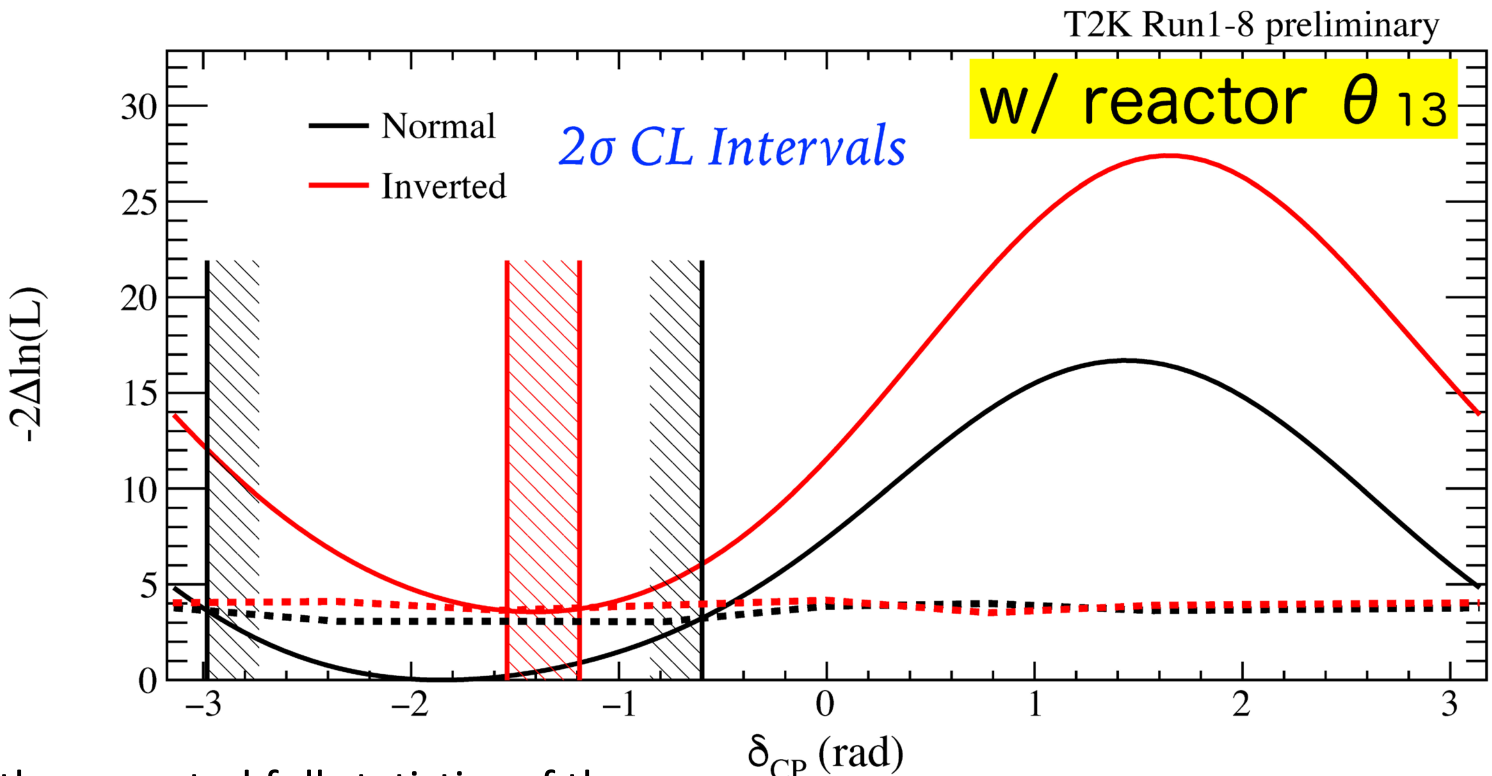
- Experimental possibilities
- Present status
- Medium term
- Long term
- Conclusions

RECENT DEVELOPMENTS IN NEUTRINO PHYSICS AND ASTROPHYSICS, LNGS, 4-7 September 2017

… before addressing MH

New T2K results: KEK seminar on 4 August 2017

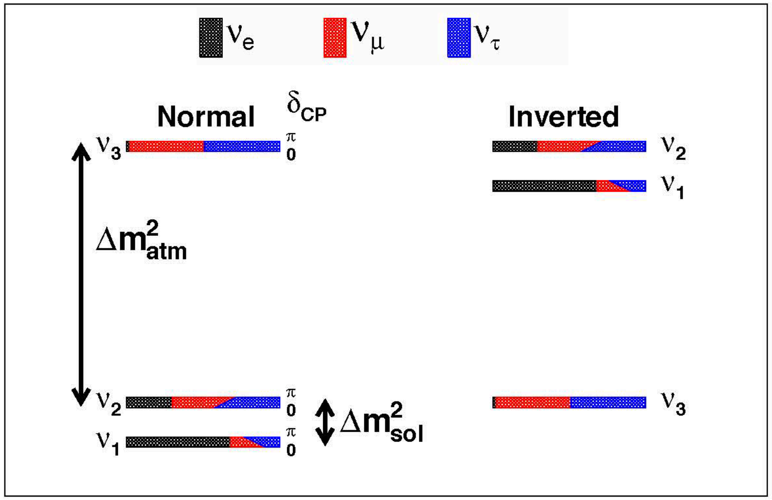
Based on 89 ν_e and 7 $\overline{\nu}_e$ events



- 30% of the expected full statistics of the experiment
- 30% improvement in efficiency x acceptance
- Important improvements in neutrino interactions modelling

- δ_{CP} determination is very important for future searches of MH in long baseline experiments

Neutrino Mass Hierarchy
(aka Neutrino Mass Ordering)



A degree of freedom in neutrino mass spectrum: neutrino masses can be ordered following the generations (normal hierarchy) or not (inverted hierarchy).
Related to

sign of $\Delta m^2_{31}=m_3^2-m_1^2$

One of the key objectives in neutrino physics:

- Important phenomenological consequences in neutrino oscillations, supernova neutrinos, cosmology, neutrinoless double beta decays, ...
- Important consequences in neutrino theory: model building, symmetries etc.

Neutrino oscillations effects

(see f.i. Capozzi, Lisi, Marrone, arXiv:1708.03022)

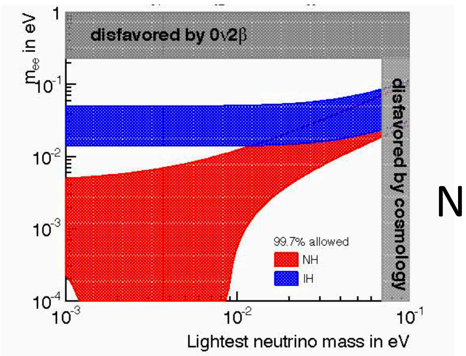
Look for interferences of Δm^2-driven oscillations with oscillations driven by a different quantity, say Q, having a known sign. The interference can reveal the sign of Δm^2.

- $Q=\delta m^2$ → medium-baseline reactor ν oscillations in vacuum
- $Q = V_e = \sqrt{2} G_F N_e$ → earth matter effects: both atmospheric and long-baseline neutrinos
- $Q=V_\nu$ →core-collapse events of a galactic supernova

Had θ_{13} been smaller none of the above methods would have worked, except for long baseline neutrinos

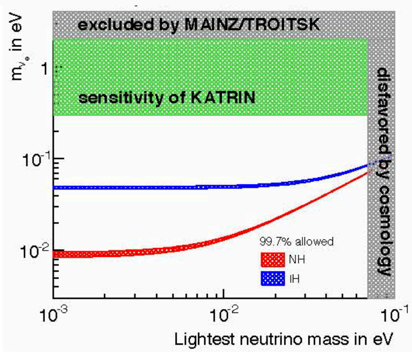
Neutrino mass effects

Mass hierarchy has a direct effect on the different ways of adding up neutrino masses (gray regions purely indicative):



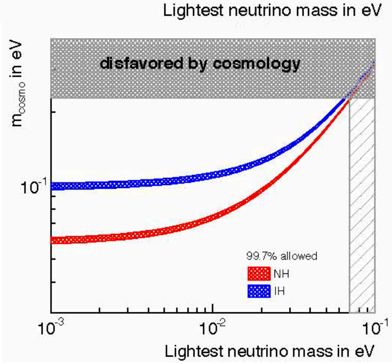
$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right|$$

Neutrinoless double beta decays



$$m_\beta^2 = \sum_i |U_{ei}|^2 m_i^2$$

Neutrino mass via beta decays



$$\Sigma = \sum_i m_i$$

Sum of neutrino masses via cosmology

Electron neutrino vacuum oscillations

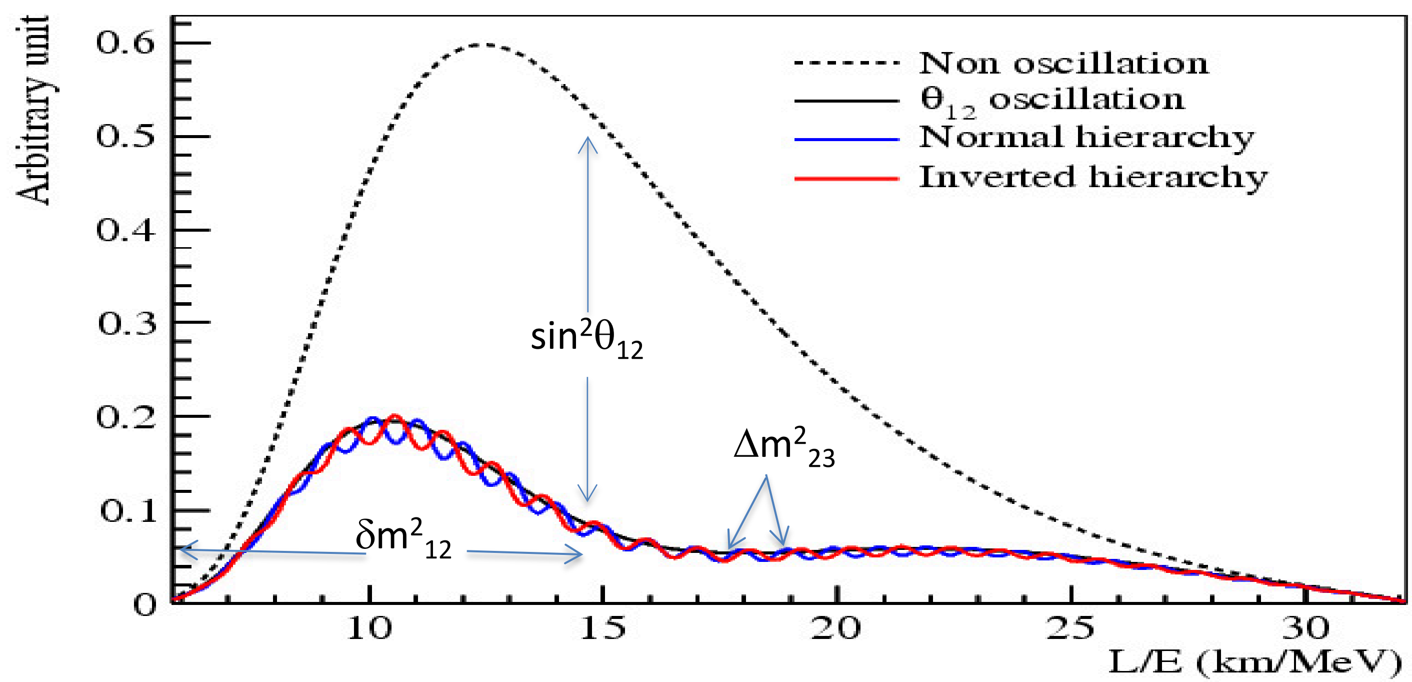
Phys.Lett. B533 (2002) 94-106
Astroparticle Phys.18 (2003) 565-579

$$
\begin{aligned}
P_{\bar{\nu}_e\to\bar{\nu}_e} = {} & 1 - 2|U_{e3}|^2(1-|U_{e3}|^2)\left(1-\cos\frac{\Delta m^2_{31}L}{2E}\right) \\
& -\frac{1}{2}(1-|U_{e3}|^2)^2\sin^2 2\Theta_{12}\left(1-\cos\frac{\Delta m^2_{21}L}{2E}\right) \\
& +2|U_{e3}|^2(1-|U_{e3}|^2)\sin^2\Theta_{12}\left(\cos\left(\frac{\Delta m^2_{31}L}{2E}-\frac{\Delta m^2_{21}L}{2E}\right)-\cos\frac{\Delta m^2_{31}L}{2E}\right).
\end{aligned}
$$

Atmospheric

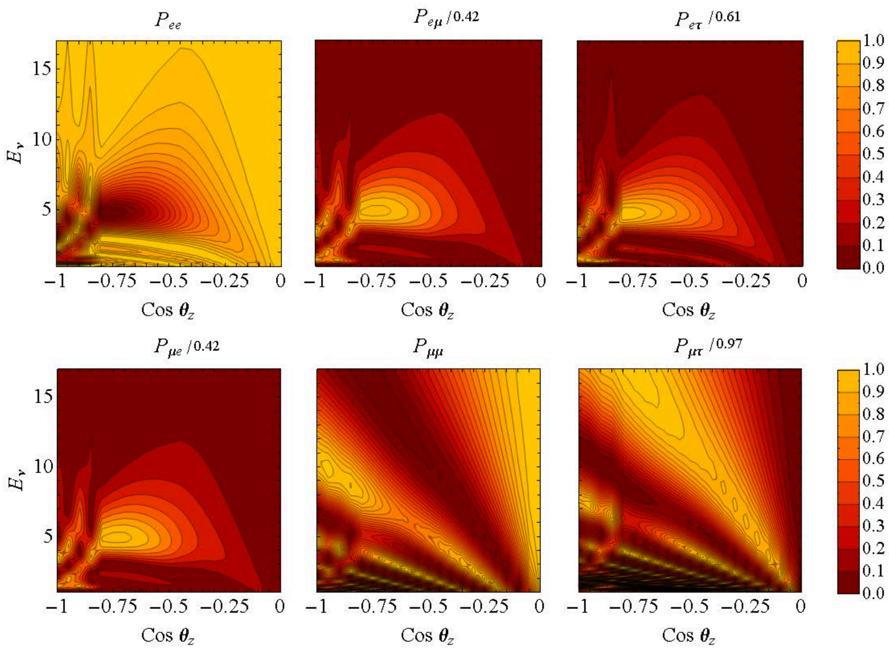
Solar

Interference



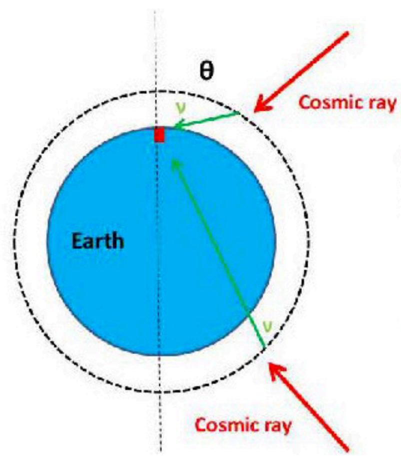
Matter effects through the Earth

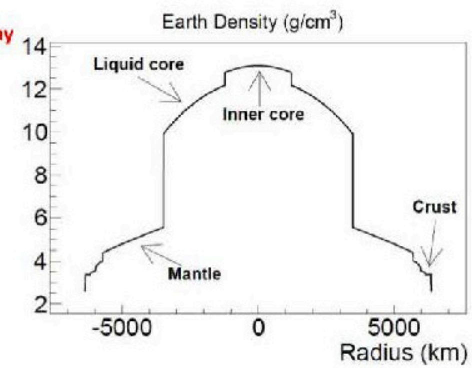
E. K. Akhmedov, S. Razzaque and A. Y. Smirnov, JHEP 1302 (2013) 082



Key features

- The resonance peak (for $P_{e\mu}$, $P_{e\tau}$, $P_{\mu e}$) or dip (for P_{ee}) in the mantle domain ($\cos\theta_z > -0.83$) at $E_\nu \approx 6$ GeV and $\cos\theta_z = -0.8$;
- Three parametric ridges in the core domain ($\cos\theta z < -0{:}83$) at $E_\nu \approx (2 - 10)$ GeV.





Opposite effects for ν and $\bar{\nu}$
Different effects for the different ν flavors

↓

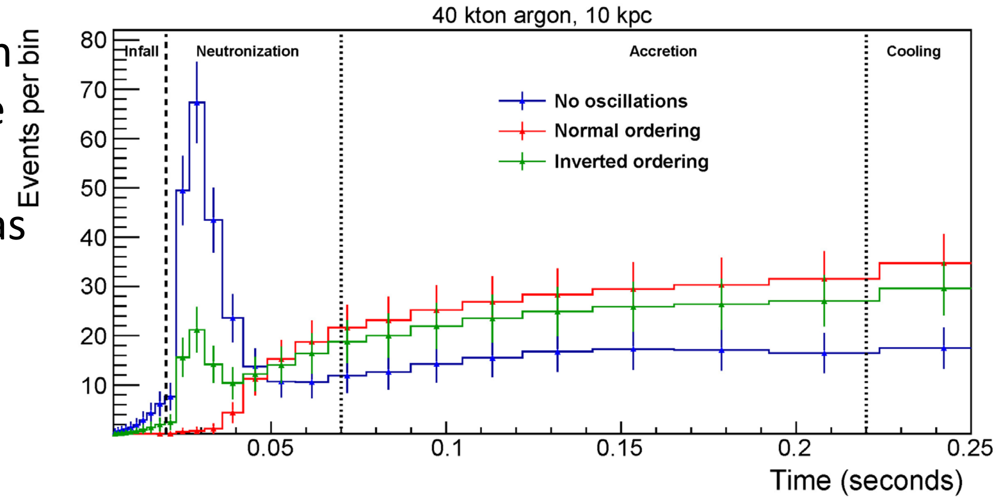
- Flavor identification
- Smearing over energies and directions
- Degeneracy of osc. Parameters
- Statistics
- Systematics

Supernova MH Signatures

Mirizzi et al. Riv. Nuovo Cim. 39, 1 (2016); K. Scholberg, arXiv:1708.03022

Supernovae explosion mechanisms (and neutrino collective effects) are not known enough to compute a solid prediction of neutrino spectra for NH and IH.

A promising "candle" is the observation of the neutronization because the time dependence of its luminosity is nearly model independent: self-interaction has a negligible effect and the burst to be processed by MSW effects only.
Its flavor is strongly dominated by ν_e.



It is anyway important to separately measure neutrino-antineutrino flavors and accumulate a large statistics, this is possible only combining different detection technologies (water, Lar, scintillator etc.)

Present and future experiments with sensitivity to SN events

K.Scholberg, arXiv:1707.06384. normalized to a 10 kpc SN2a explosion

Detector	Type	Mass (kt)	Location	Events	Status
Super-Kamiokande	H_2O	32	Japan	7,000	Running
LVD	C_nH_{2n}	1	Italy	300	Running
KamLAND	C_nH_{2n}	1	Japan	300	Running
Borexino	C_nH_{2n}	0.3	Italy	100	Running
IceCube	Long string	(600)	South Pole	(10^6)	Running
Baksan	C_nH_{2n}	0.33	Russia	50	Running
HALO	Pb	0.08	Canada	30	Running
Daya Bay	C_nH_{2n}	0.33	China	100	Running
NOνA*	C_nH_{2n}	15	USA	4,000	Running
MicroBooNE*	Ar	0.17	USA	17	Running
SNO+	C_nH_{2n}	0.8	Canada	300	Near future
DUNE	Ar	40	USA	3,000	Future
Hyper-Kamiokande	H_2O	374	Japan	75,000	Future
JUNO	C_nH_{2n}	20	China	6000	Future
RENO-50	C_nH_{2n}	18	Korea	5400	Future
PINGU	Long string	(600)	South Pole	(10^6)	Future

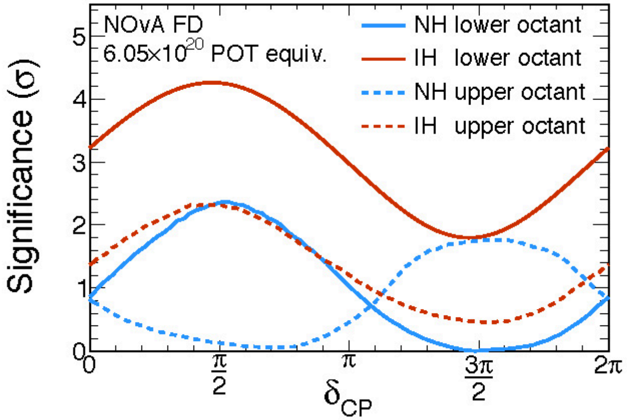
Statistical Methods

MH can have only two values (of course) and their are a priori known. One could question if the ΔX^2 method is adequate: this discussion is indeed quite animate in literature (the following list could be incomplete):

- Qian X. *et al.* Phys.Rev. D86 (2012) 113011
- E. Ciuffoli, J. Evslin and X. Zhang, JHEP 1303 (2013), Phys. Rev. D 88 (2013) 033017
- A. Tonazzo, PoS EPS-HEP2015 (2015) 085
- L. Stanco et al. Phys.Rev. D95 (2017) no.5, 053002
- LBNO coll. J.Phys.Conf.Ser. 598 (2015) no.1, 012005
- X. Qian et al, Nucl.Instrum.Meth. A827 (2016) 63-78
- Vitells and Read, arXiv:1311.4076
- M. Blennow , JHEP 1401 (2014) 139
- M. Blennow et al., JHEP 1403 (2014) 028
- Y. Zhang et al., Mod.Phys.Lett. A29 (2014) 1450096
- J. Evslin, arXiv:1310.4007.
- L.Stanco et al., arXiv:1707.07651.

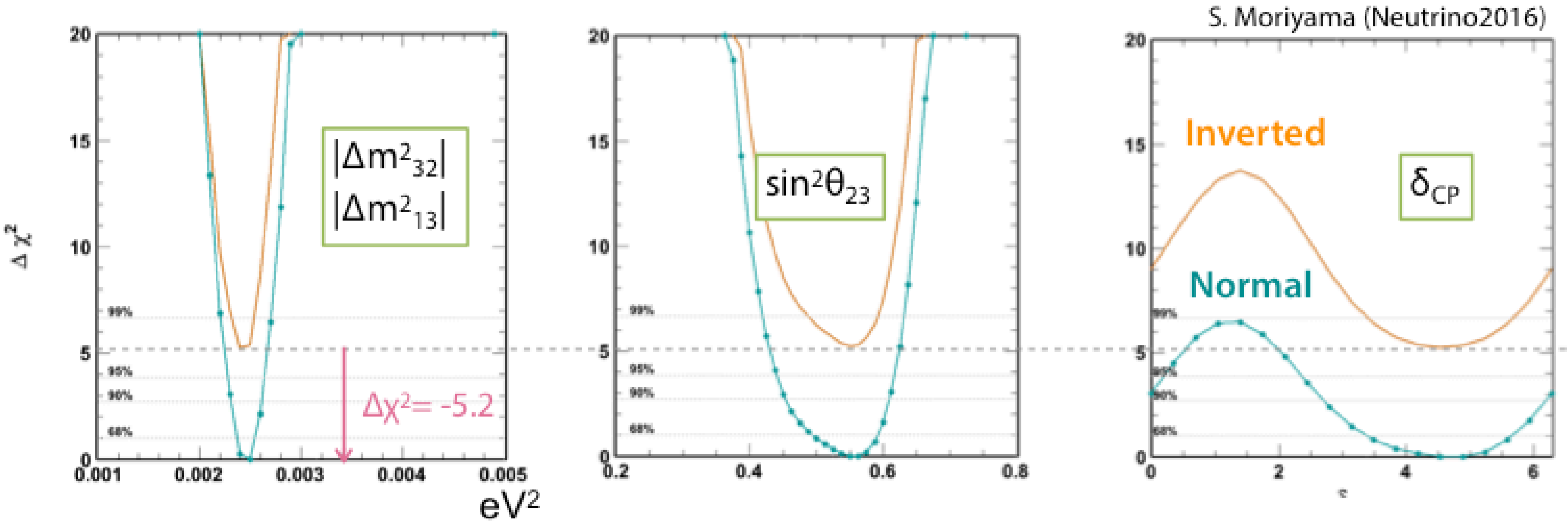
Present Status

- SK alone: ΔX^2 (NH-IH)= -5.2
- T2K alone: (too short baseline): IH favored (posterior probability 0.86)
- NOνA alone (PRL 118, 231801 (2017)):
  ΔX^2 (NH-IH)= - 0.2 (upper octant)
  ΔX^2 (NH-IH)= - 3.2 (lower octant)



- Global fits (not including 2017 data or full SK data set, see also previous talk):
  Capozzi et al, Nucl.Phys. B908 (2016) 218, ΔX^2 (NH-IH)= -0.98
  nu-fit.org, ΔX^2 (NH-IH)= -0.83
  de Salas et al., arXiv:1708.01186, ΔX^2 (NH-IH)= -2.7

Three Flavor Fit (w/ reactor and T2K constraints)

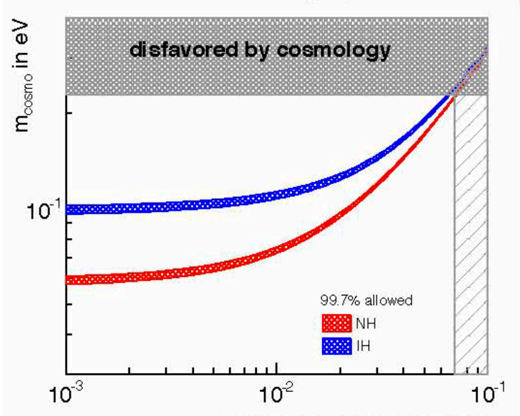


- Include constraint from T2K public data.
- **Normal hierarchy is slightly preferred:** $\Delta\chi^2 = \chi^2_{NH}-\chi^2_{IH} = -5.2$ (-3.8 exp. for SK best, -3.1 for combined best)
- p-value of Inverted hypothesis is 0.024 ($\sin^2\theta_{23}$=0.6) and 0.001 ($\sin^2\theta_{23}$=0.4).

	δ_{CP}	$\sin^2\theta_{23}$	$\|\Delta m^2_{32}\|$ (eV²)
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

Cosmology



See next talk by R. Battye

S. Vagnozzi et al. arXiv: 1701.08172
CMB+BAO+τ (optical depth to reionization)
→ $M\nu$ < 0.151 eV (95%CL) → IH excluded at ~64% C.L.

CMB+BAO+τ+Planck high-polarization data
→ $M\nu$ < 0.118 eV (95%CL) → IH excluded at ~71% C.L.

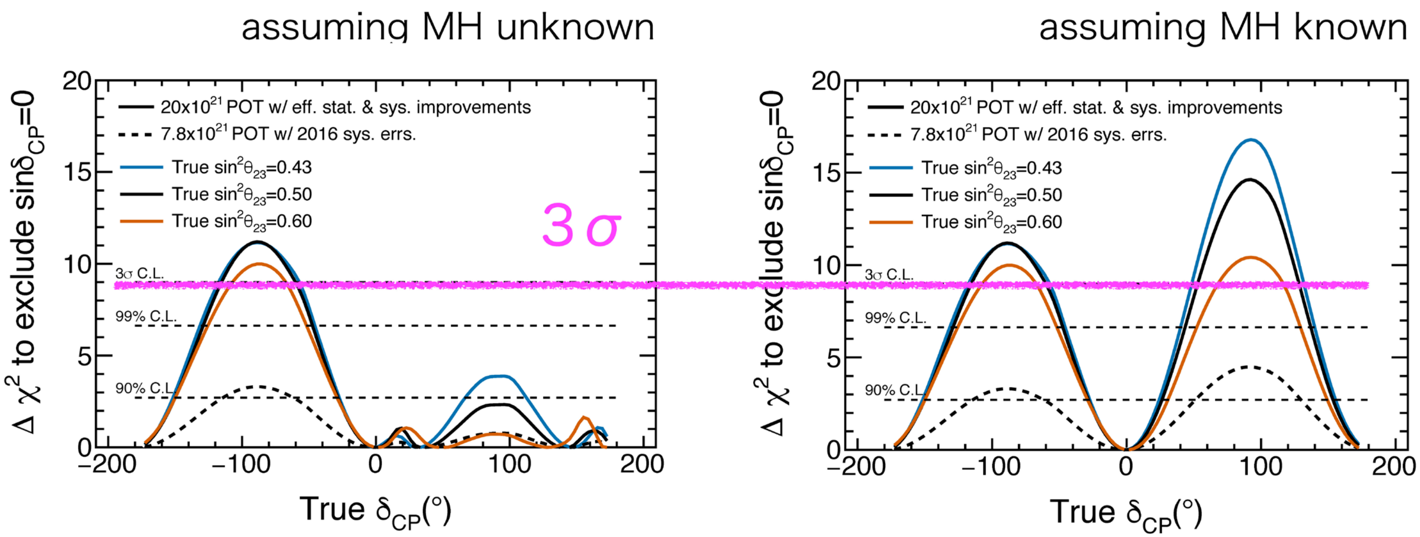
CMB+BAO+τ+Planck high-polarization data+[H_0 = (73.02+/- 1.79) km $s^{-1}Mpc^{-1}$]
→ $M\nu$ < 0.090 eV (95%CL) → IH excluded at ~77% C.L.

Simpson, Jimenez, Pena-Garay, Verde, “Strong Evidence for the Normal Neutrino Hierarchy”, 1703.03425: “... we infer odds of 42:1 in favour of the normal hierarchy” (Bayesian odds)

T.Schwetz et al., arXiv:1703.04585: " We argue that the claimed evidence for normal ordering is almost entirely driven by the adopted prior and not due to the data itself”

Near Future
(extrapolation of running experiments)

- T2K-II: MH sensitivity not quoted but …

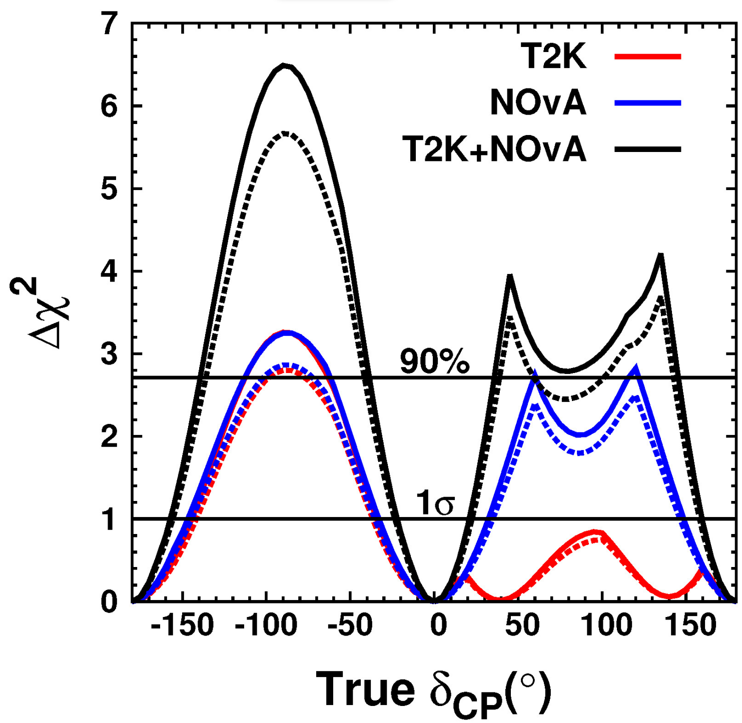


- SK: could improve its sensitivity thanks to the event reconstruction developments by the T2K collaboration
- Nova: see also next slides

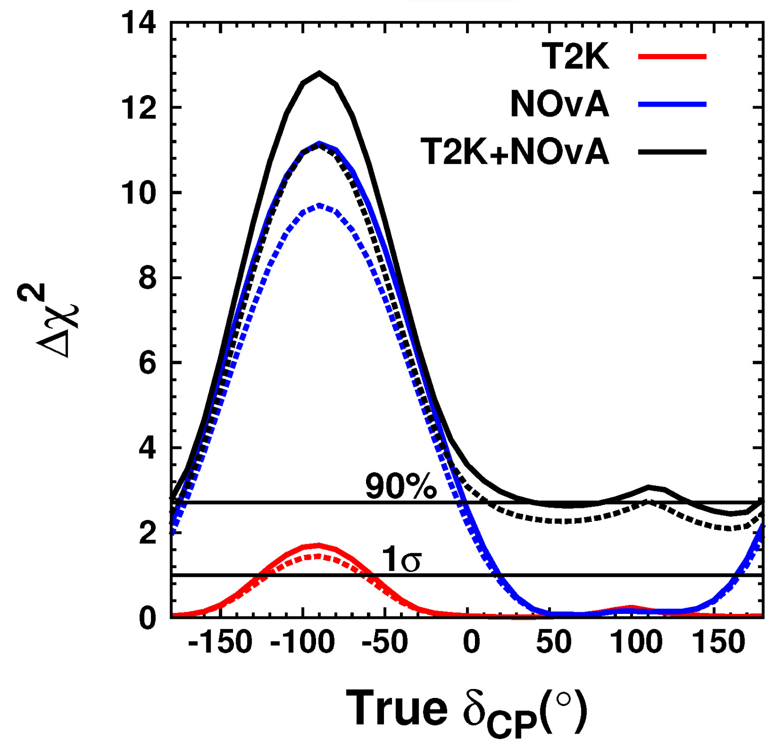
Projection of T2K+Nova at full statistics

From T2K collaboration: PTEP 2015 (2015) 4, 043C01. Recent improvements of both T2K and Nova reconstruction not considered and T2K-II not included

CP

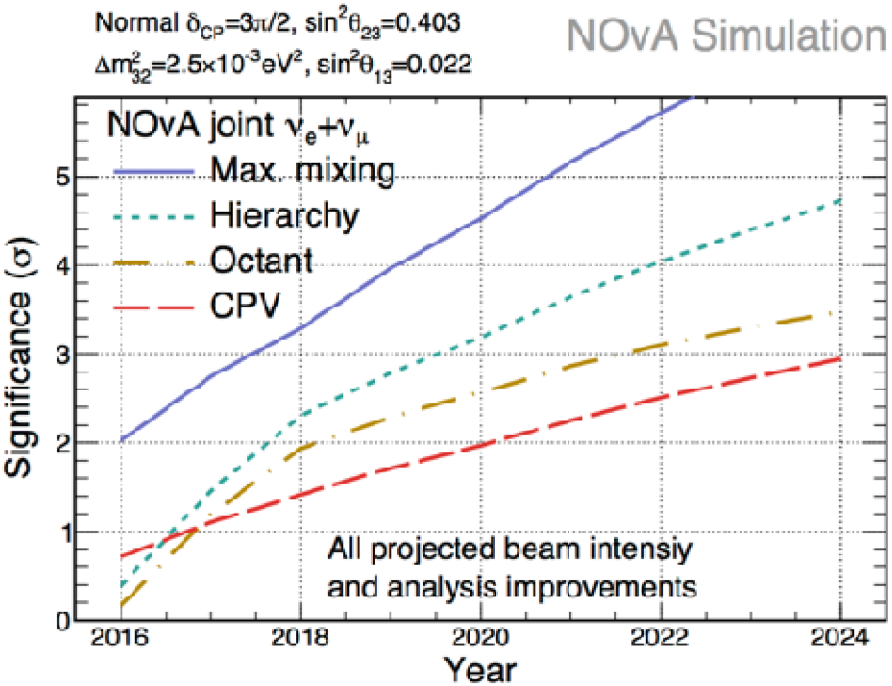


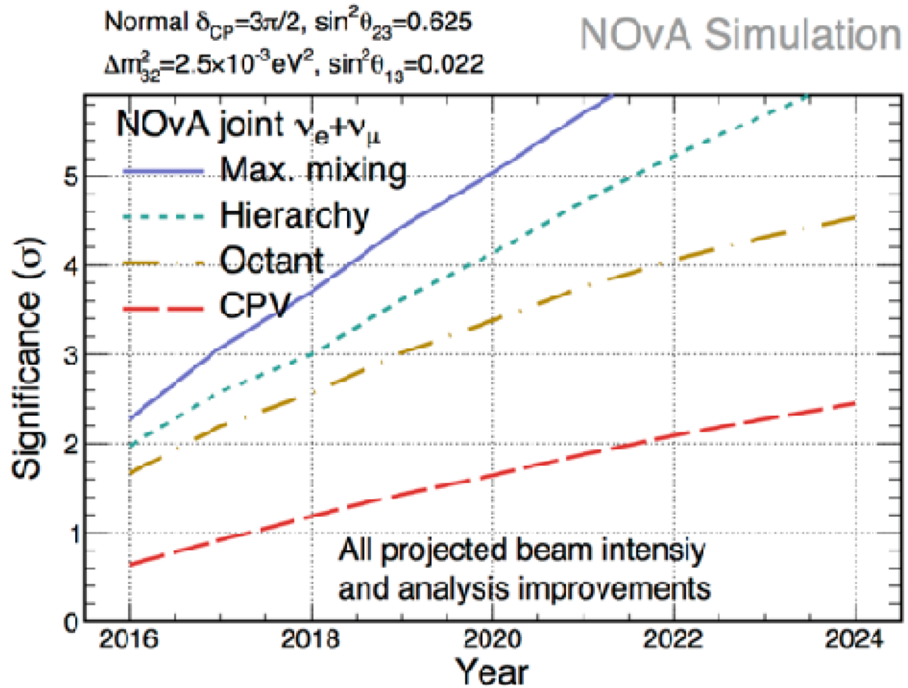
MH

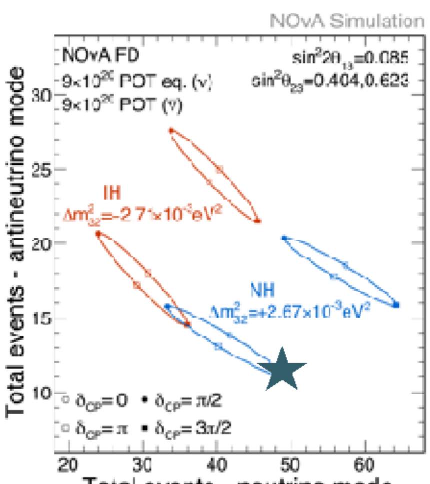


Full statistics of the running experiments: T2K and Nova, equal ν and $\bar{\nu}$ runs, dashed lines: including systematics

NOvA future reach



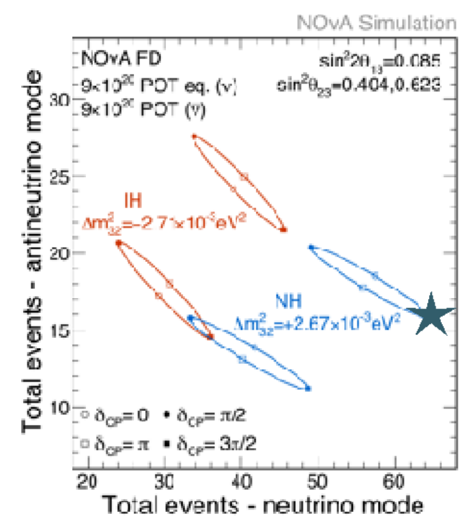




NOVA Switched to anti-neutrino running in February 2017

Plan to run 50% neutrino, 50% anti-neutrino after 2018

- 3 σ sensitivity to maximal mixing of θ_{23} in 2018
- 3 σ sensitivity to mass hierarchy in 2020
- 3 σ sensitivity to θ_{23} octant by 2022
- 2-3 σ sensitivity to δ_{CP} by 2024



Future experiments

Atmospheric neutrinos

- INO
- Orca
- Pingu
- Hyper-Kamiokande

Long Baseline

- Dune
- Hyper-Kamiokande (T2KK)

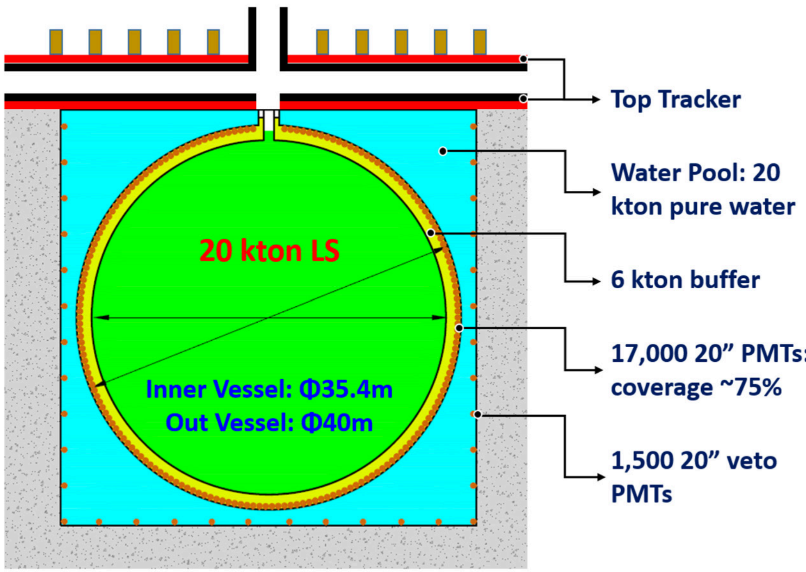
Vacuum oscillations

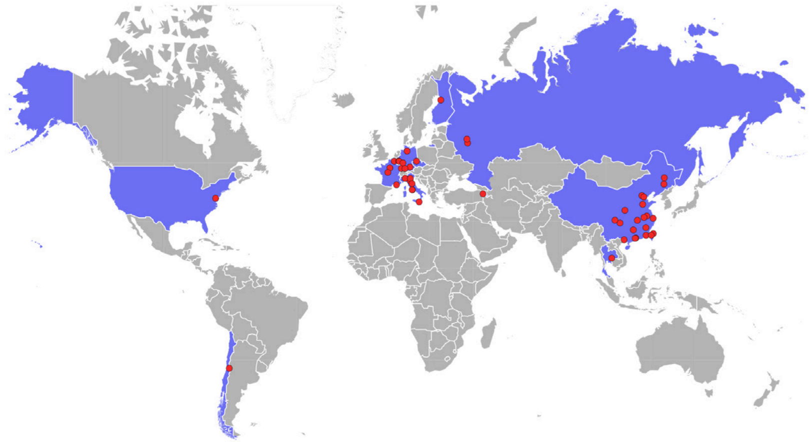
- Juno

JUNO (Jiangmen Underground Neutrino Observatory)

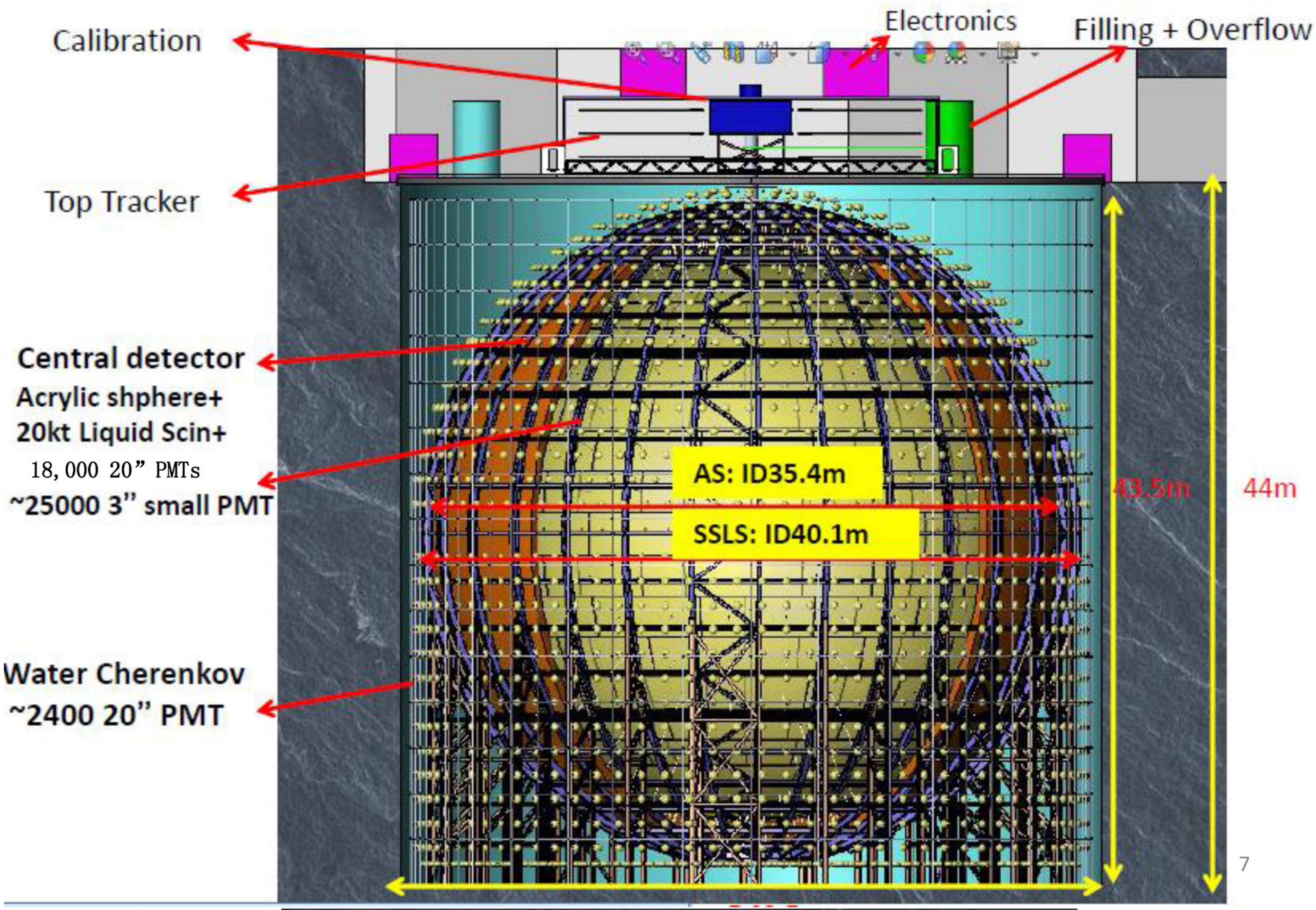
CDR: arXiv:1508.07166,
Physics: J.Phys. G43 (2016) no.3, 030401

- Funded, under construction
- Data taking expected by 2020
- Reactors power: 36 GW (26.6 GW by 2020)
- Aimed to measure MH, precision measurement of $\sin^2\theta_{12}$, δm^2_{12},Δm^2_{23} and also SuperNovae, solar, atmospheric, geo neutrinos, proton decay, indirect DM searches ..





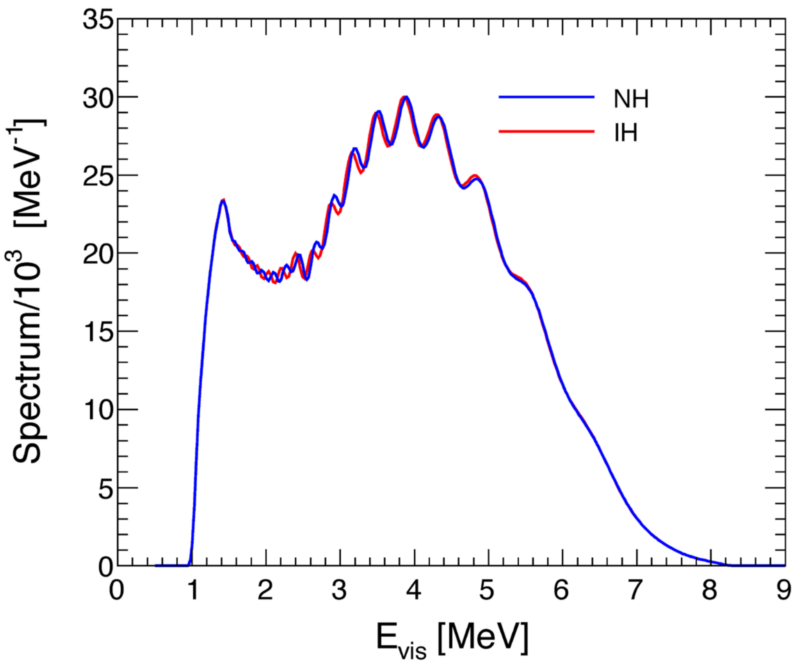
Juno detector

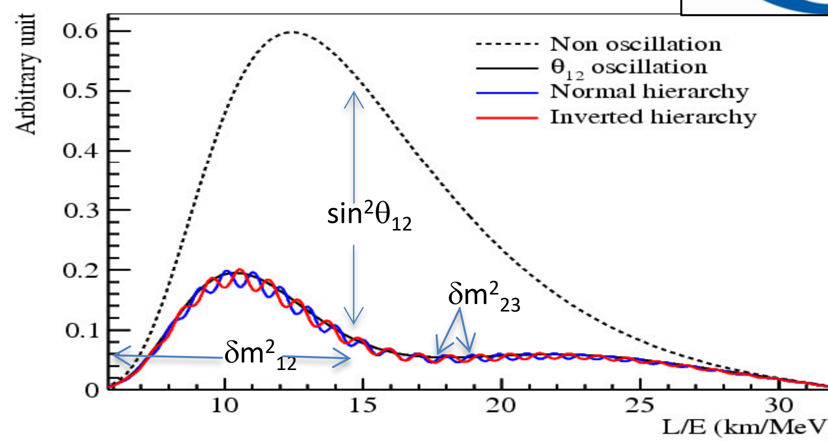


Experiment	Daya Bay	BOREXINO	KamLAND	JUNO
LS mass	20 ton	~300 ton	~1 kton	20 kton
Coverage	~12%	~34%	~34%	~80%
Energy resolution	~7.5%/√E	~5%/√E	~6%/√E	~3%/√E
Light yield	~ 160 p.e. / MeV	~ 500 p.e. / MeV	~ 250 p.e. / MeV	~ 1200 p.e. / MeV

JUNO

As hard as to disentangle the two curves below
Requires extreme control of detector response





Impressive performances in measuring osc parameters

	Current	JUNO
Δm^2_{12}	3%	0.6%
Δm^2_{23}	5%	0.6%
$\sin^2\theta_{12}$	6%	0.7%
$\sin^2\theta_{23}$	20%	N/A
$\sin^2\theta_{13}$	5%	~15%

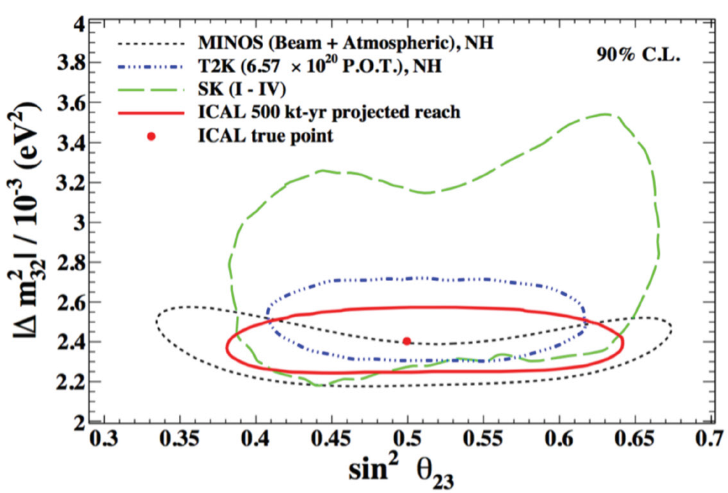
MH sensitivity in 6 years. External measure of Δm^2_{ee} could be crucial

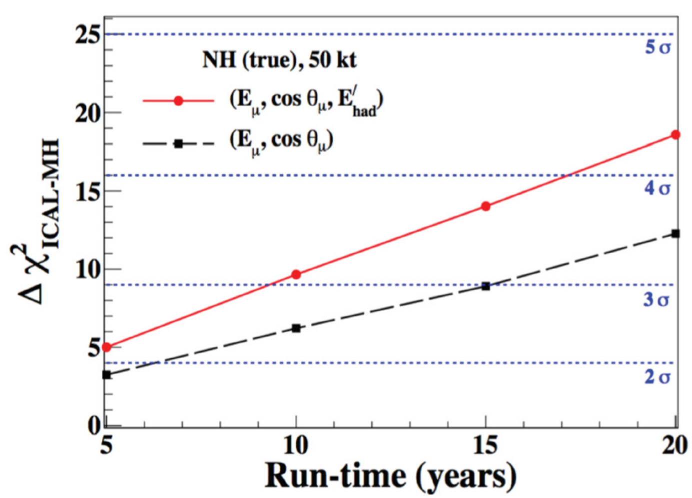
	Stat.	Core dist.	DYB & HZ	Shape	B/S (stat.)	B/S (shape)	$\lvert\Delta m^2_{\mu\mu}\rvert$
Size	52.5 km	Tab. 1-2	Tab. 1-2	1%	6.3%	0.4%	1%
$\Delta\chi^2_{MH}$	+16	−3	−1.7	−1	−0.6	−0.1	+(4 − 12)

INO/ICAL

Pramana - J. Phys. (2017) 88 : 79

- **Magnetized Iron Calorimeter** (ICAL) composed of resistive plate chamber (RPC) in India
  - 48x16x14.5 m, 50 kton mass
- **ν and $\overline{\nu}$ separation** by muon charge
- Expect MH determination at **2.2σ using 10 yr data** (3σ if hadron information is introduced)





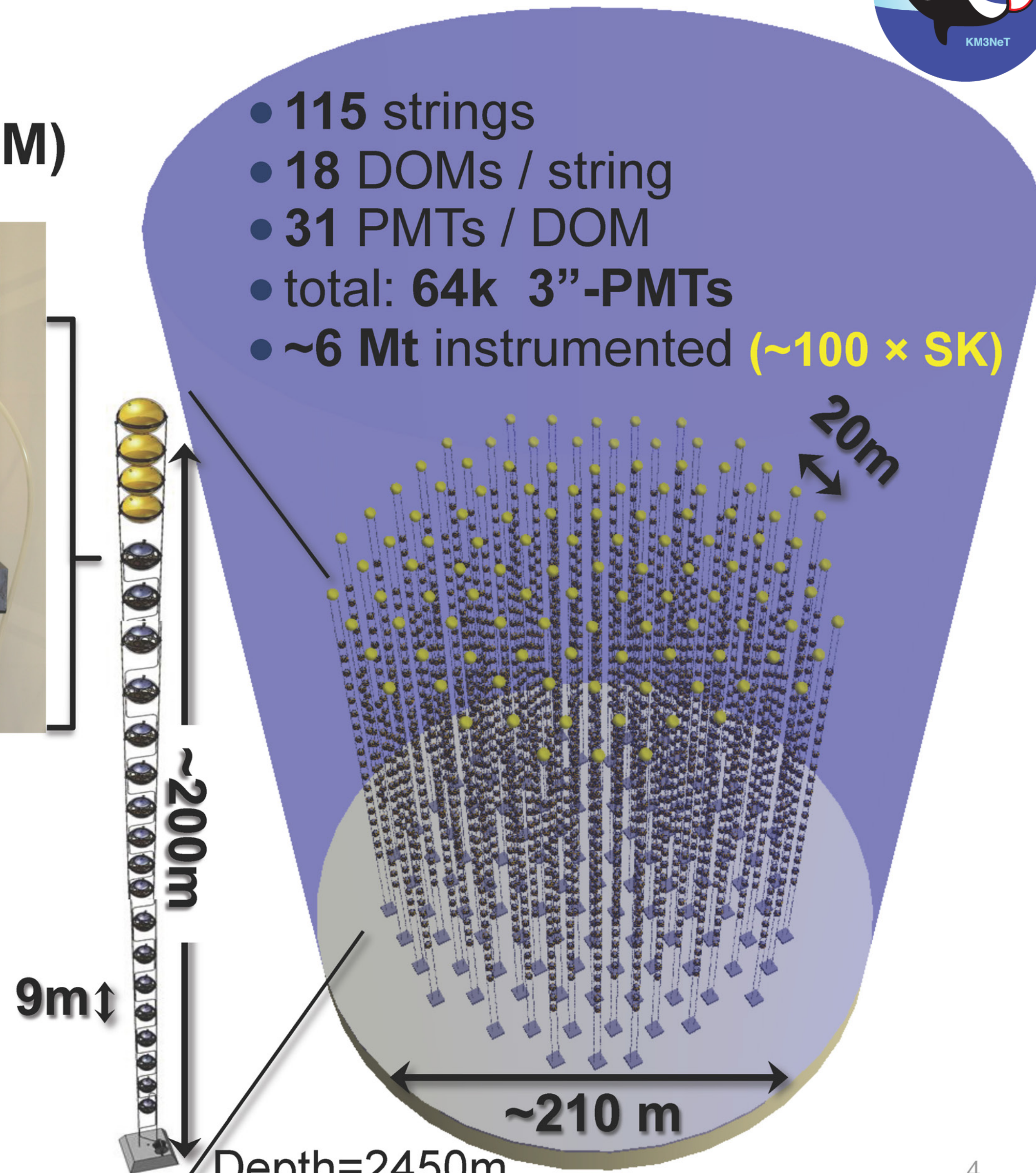
ORCA (Oscillation Research with Cosmics in the Abyss)

J.Phys G43 (2016) n.8, 084001

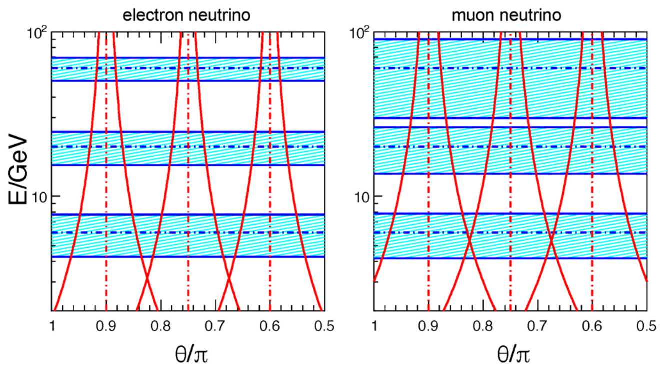
Digital Optical Module (DOM)

31 x 3”-PMTs
(19↓, 12↑)

- Uniform angular coverage
- Directional information
- Single photon counting



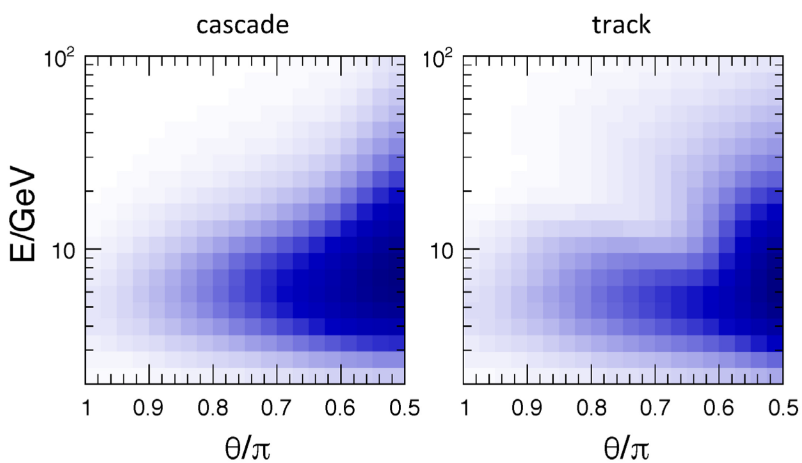
ORCA



1 σ Energy-Direction resolution curves

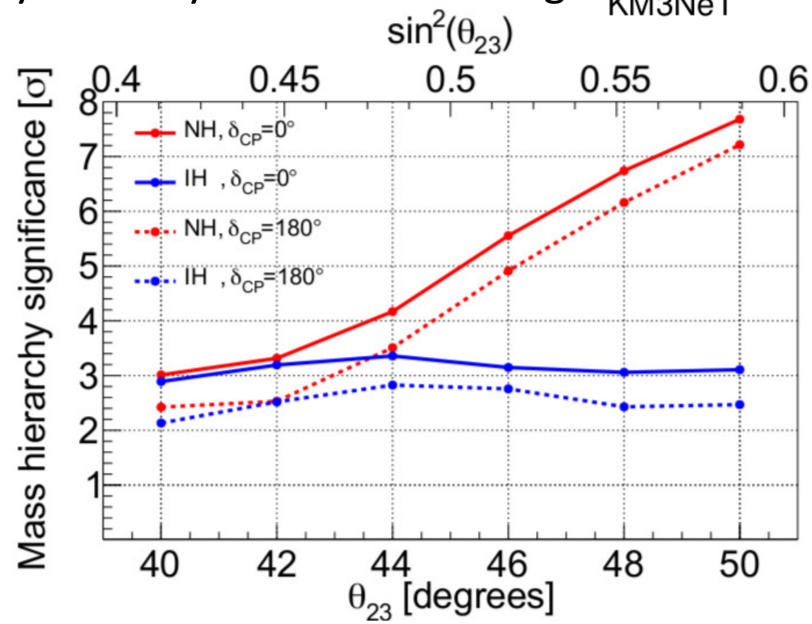
- neutrino and antineutrino events cannot be distinguished
- electron and muon flavors are only probed via the categories of "shower" and "track" events.

Capozzi, Lisi, Marrone arXiv:1708.03022



" … the corresponding distributions for IO (not shown) would be visually indistinguishable."

Sensitivity after 3 years of data taking

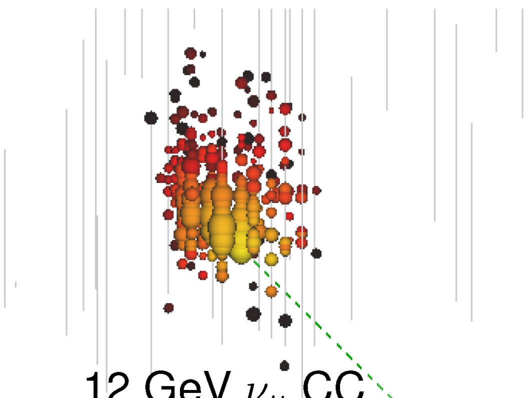


Aimed to be in data taking by mid 2020 (but not yet fully funded)

PINGU (Precision IceCube Next Generation Upgrade)

J.Phys. G44 (2017) no.5, 054006

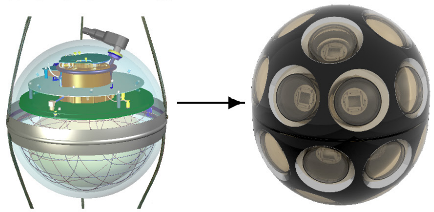
IceCube-Gen2 PINGU



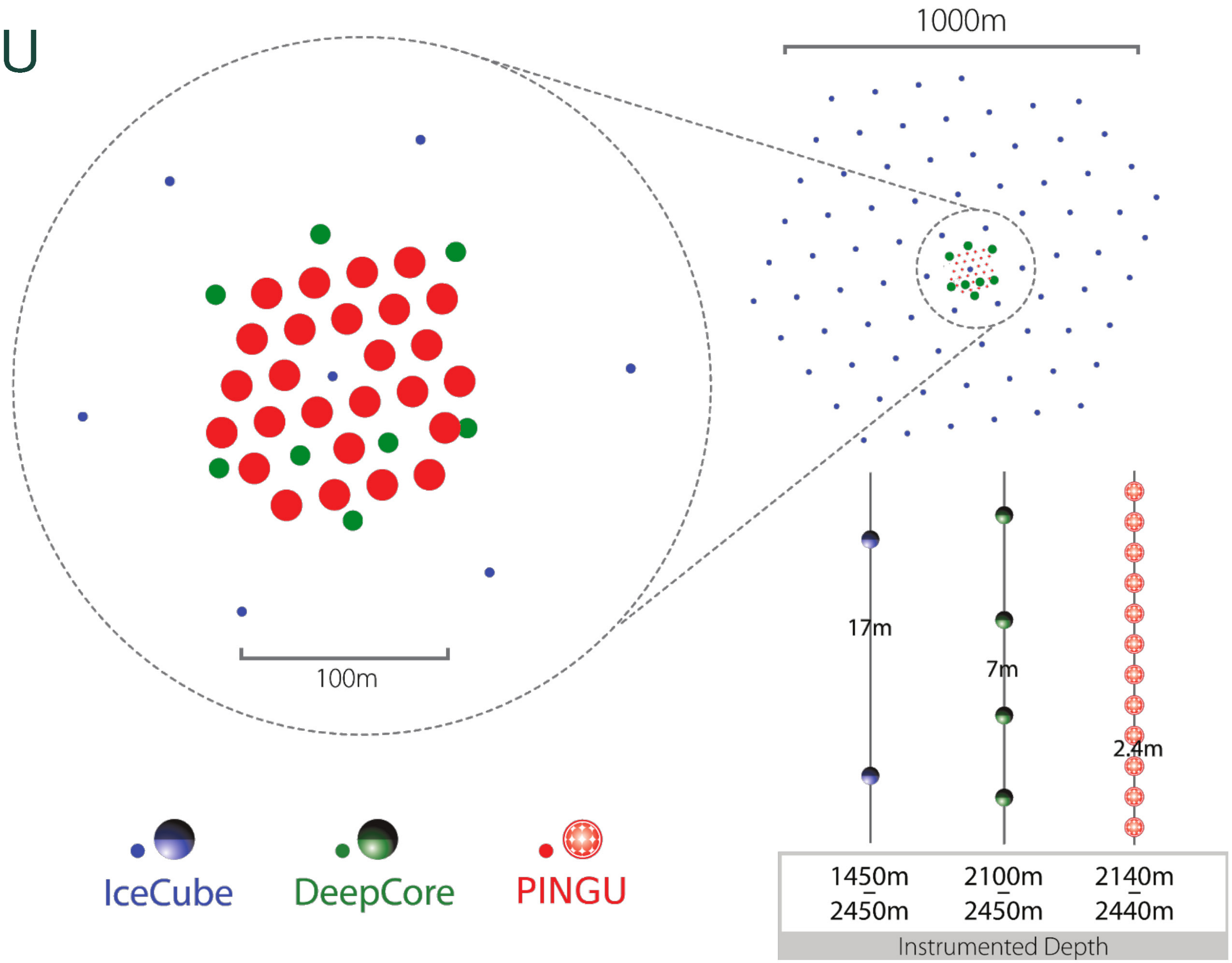
12 GeV ν_μ CC

color $\rightarrow$ hit time
size $\rightarrow$ hit charge

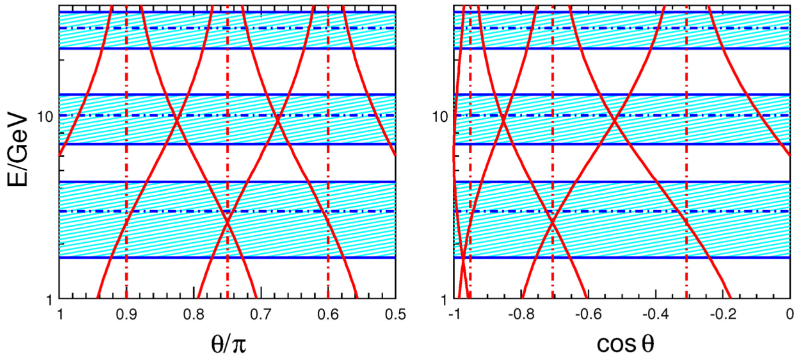
IceCube DOM　　mDOM



in LoI　　plan to use

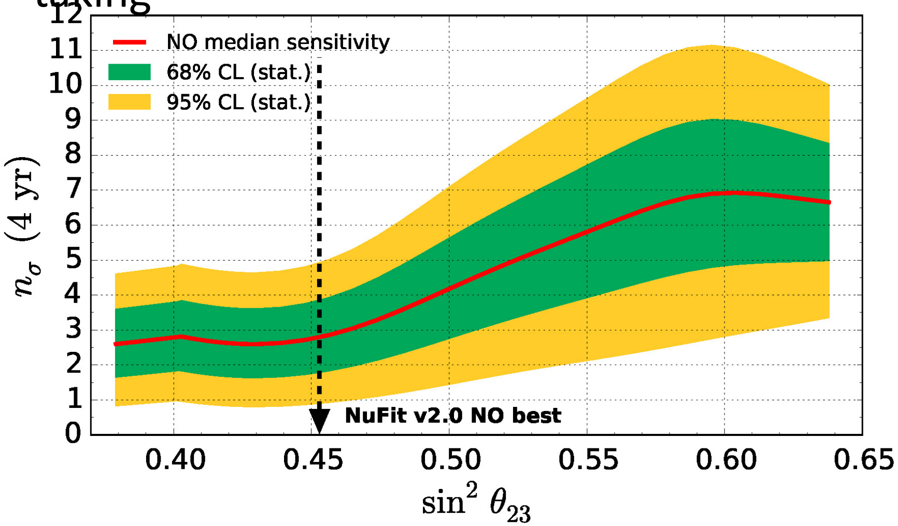


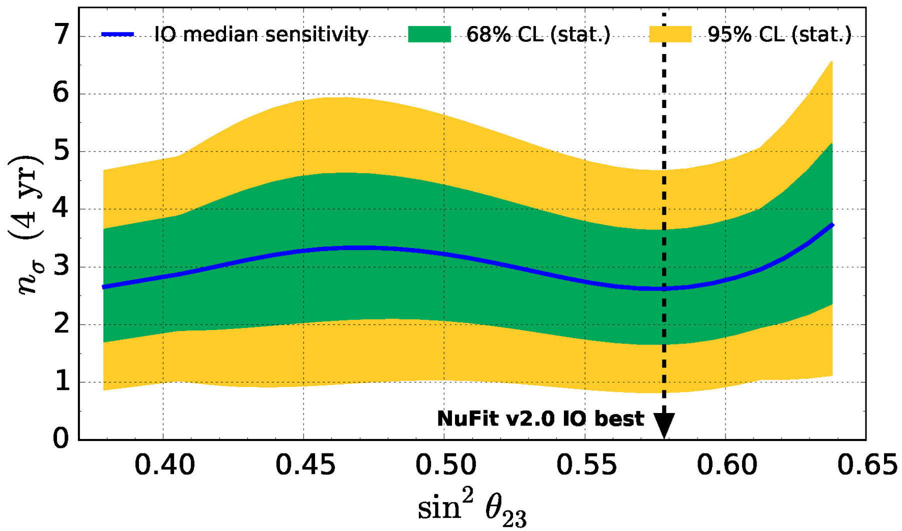
PINGU



1 σ Energy-Direction resolution curves

MH sensitivity after 4 years of data taking

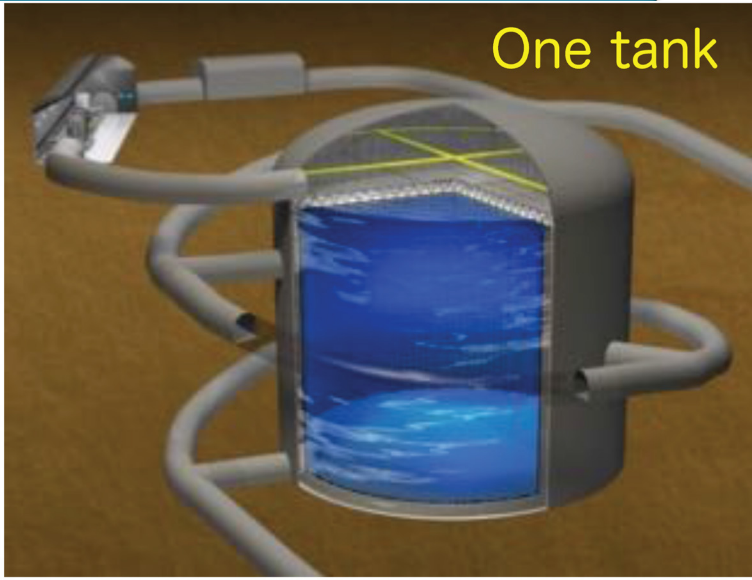




4 years to be completed, start in 2018?

Hyper-Kamiokande

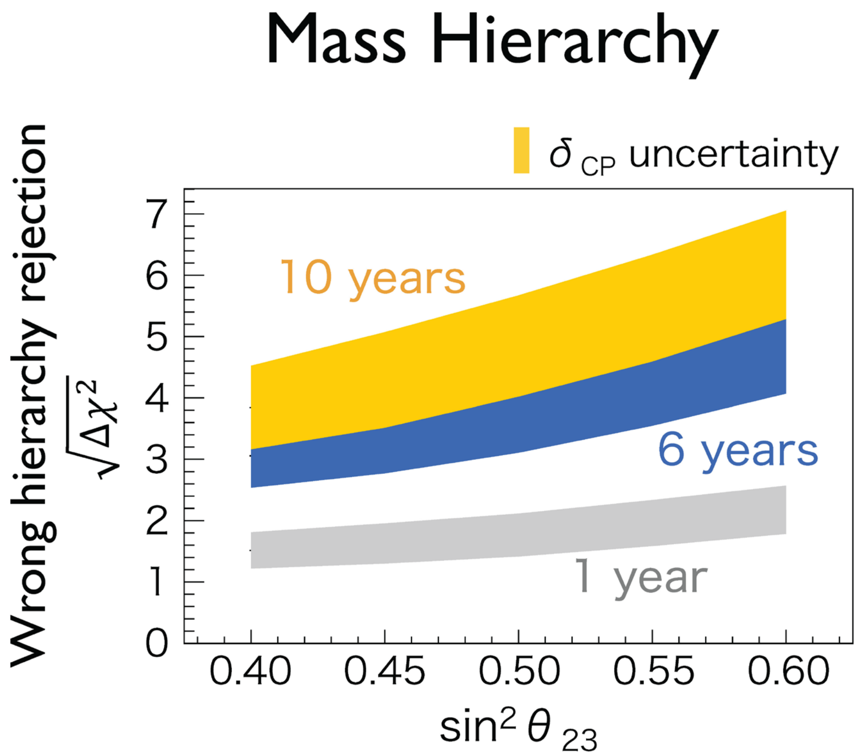
arXiv:1412.4673, Kek preprint 2016-21

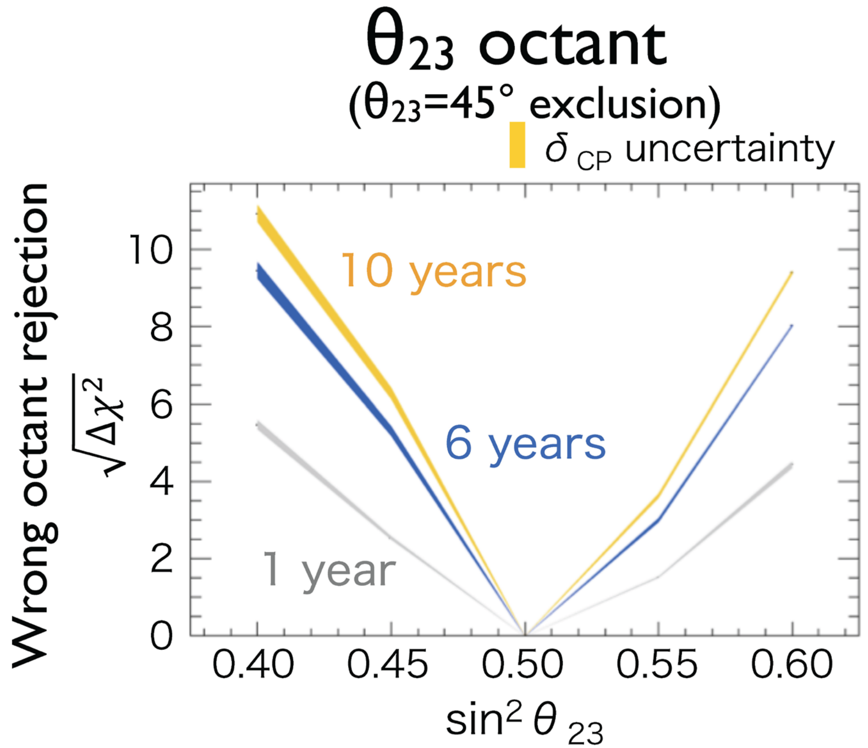


	SK	HK
Total Volume (Fiducial)	0.05 Mton (0.022)	0.26 Mton (0.19)
Dimension	39 m (ϕ) 42 m (H)	74 m (ϕ) 60 m (H)
No. Of PMT (coverage)	11 k (40%)	80 k (new gen.) (40%)
Single photon detection eff.	12%	24%
Photon yield	1	2
Timing resolution (single photon)	2 ns	1 ns
Beam Power	0.75 MW (goal T2K)	1.3 MW

HK sensitivity on MH

By combining atmospherics with beam data

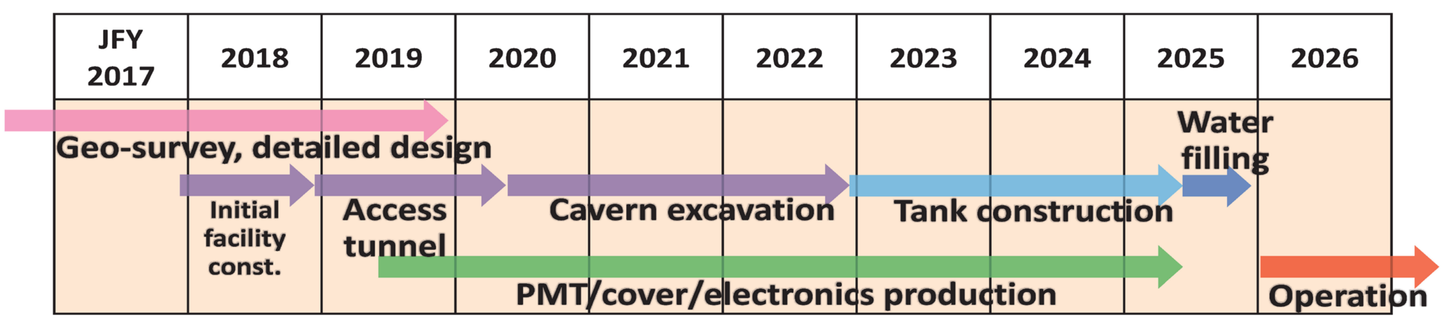




Project status in Japan

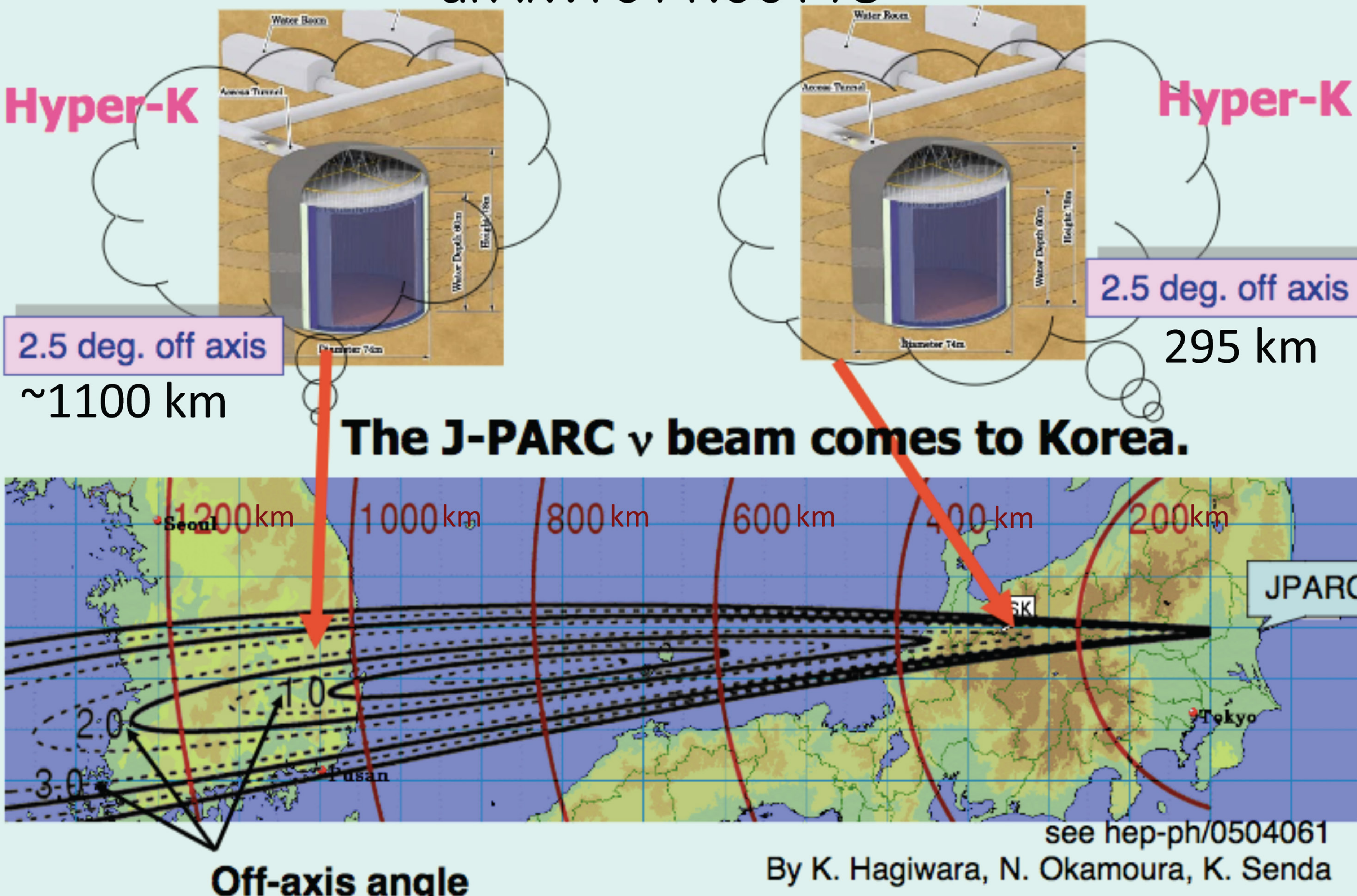
T. Nakaya @ Lepton Photon 2017

- Strong support from communities: Cosmic-Ray and High Energy
- Strong Commitment from host institutes: ICRR, U. Tokyo and KEK
  - MoU between ICRR and KEK/IPNS for Hyper-K
  - U.Tokyo will launch new institute for Hyper-K in October 2017
  - ICRR future project committee: Hyper-K should be the laboratory’s next main project
  - KEK project implementation plan: the first priority to the J-PARC upgrade for Hyper-K
- Science Council of Japan selects Hyper-K as one of the top priority large-scale projects in “Master Plan 2017” (28 among 163)
- Hyper-K is listed in the MEXT (funding agency) Large Projects Roadmap.
- Budget is requested to start in 2018 toward the operation from 2026.



The 2nd Hyper-K Detector in Korea

arXiv:1611.06118



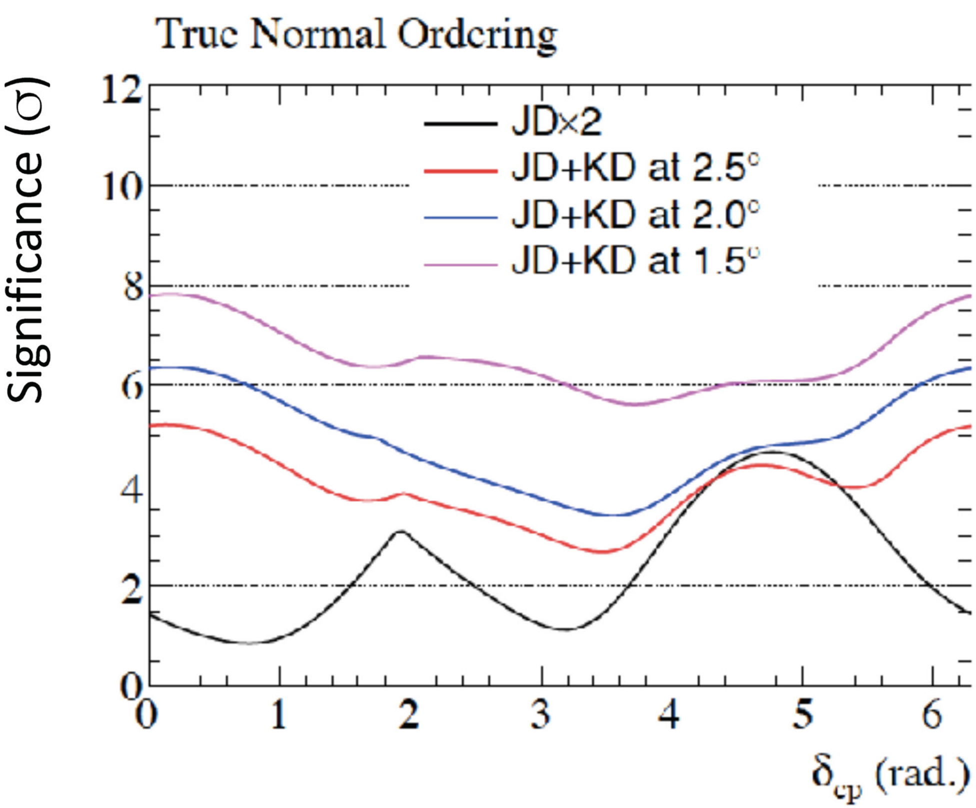
T2KK MH Sensitivity

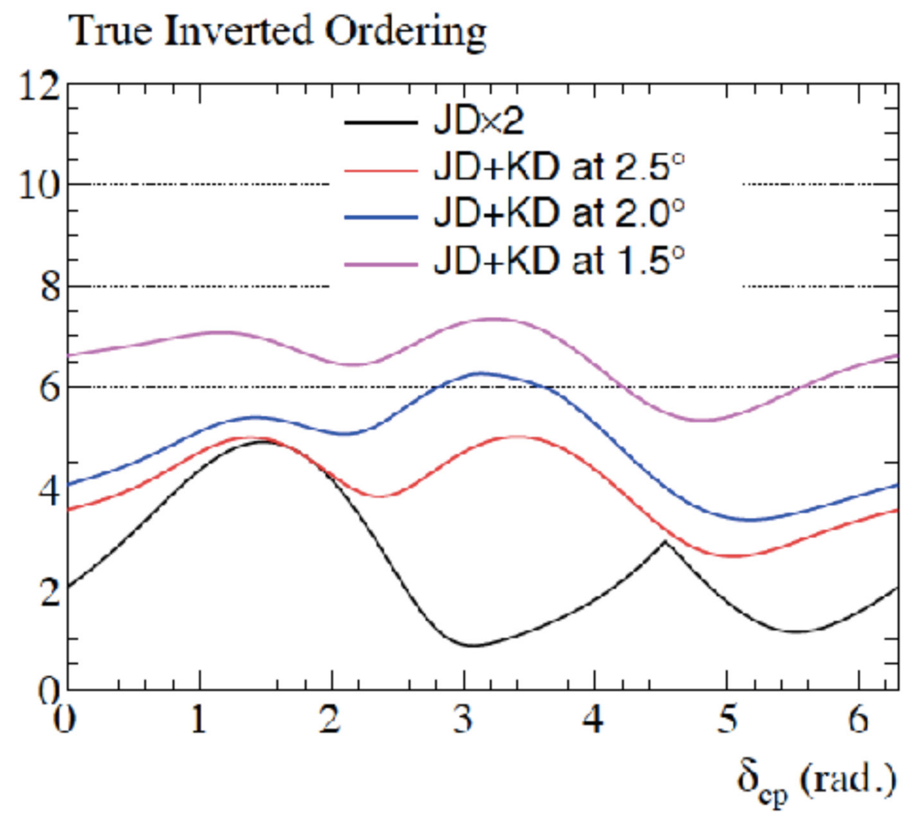
Beam only.

Normal

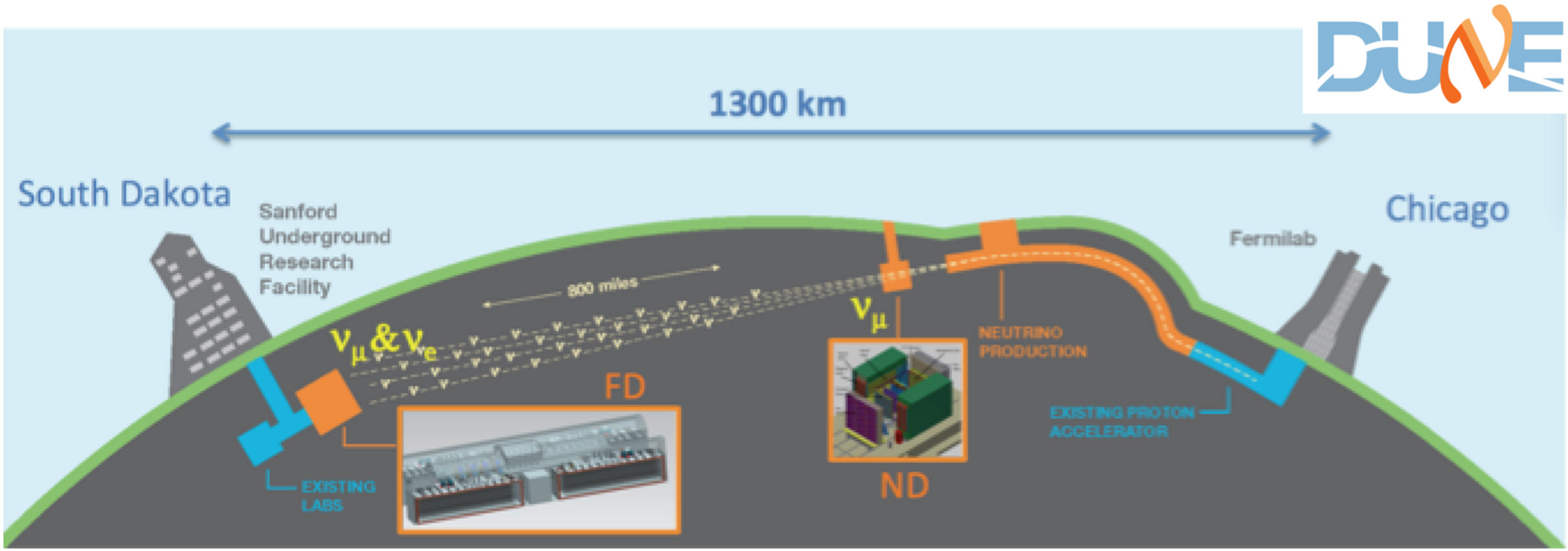
arXiv:1611.06118

Inverted





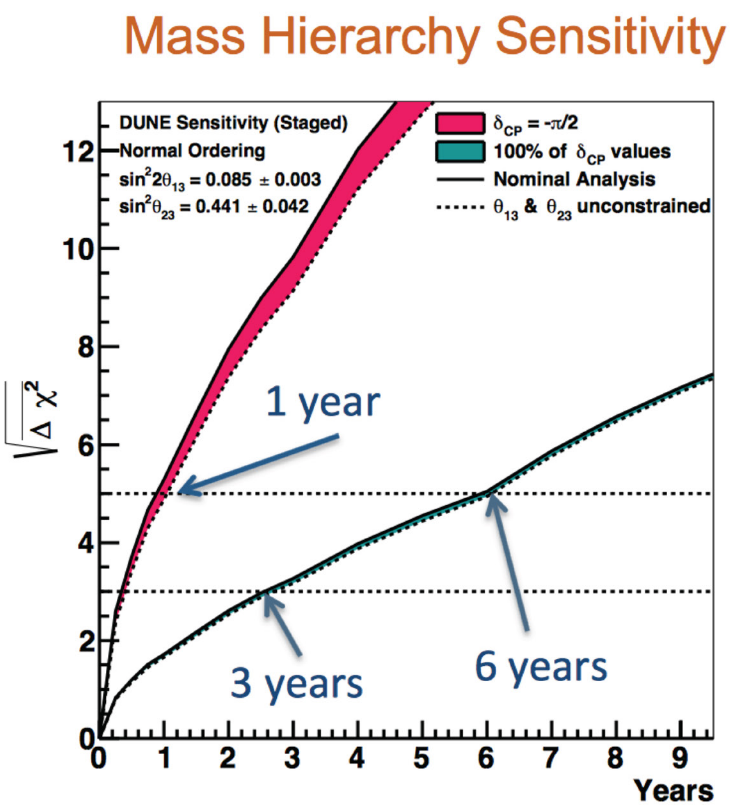
Dune (Deep Underground Neutrino Experiment)

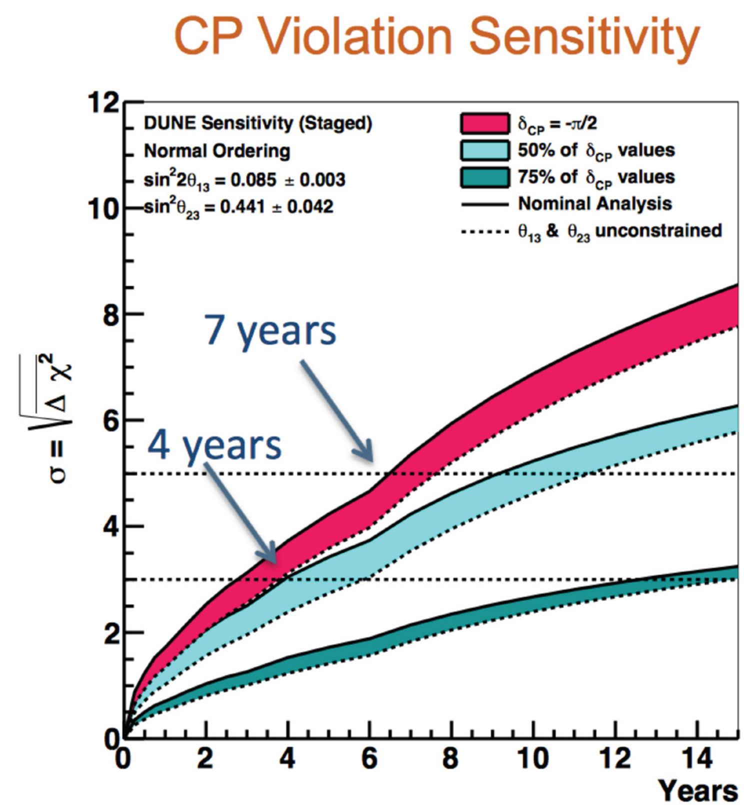


- Muon neutrinos/antineutrinos from high power proton beam:
  1.2 MW from day one, upgradeable to 2.4 MW
- Massive underground Liquid Argon TPC, 4 x 17 kton modules for a
  total fiducial mass > 40 kton
- Near detector to characterize the beam and measure neutrino cross sections in Argon

Dune MH sensitivity

Dune is the ultimate experiment as far as regards MH sensitivity



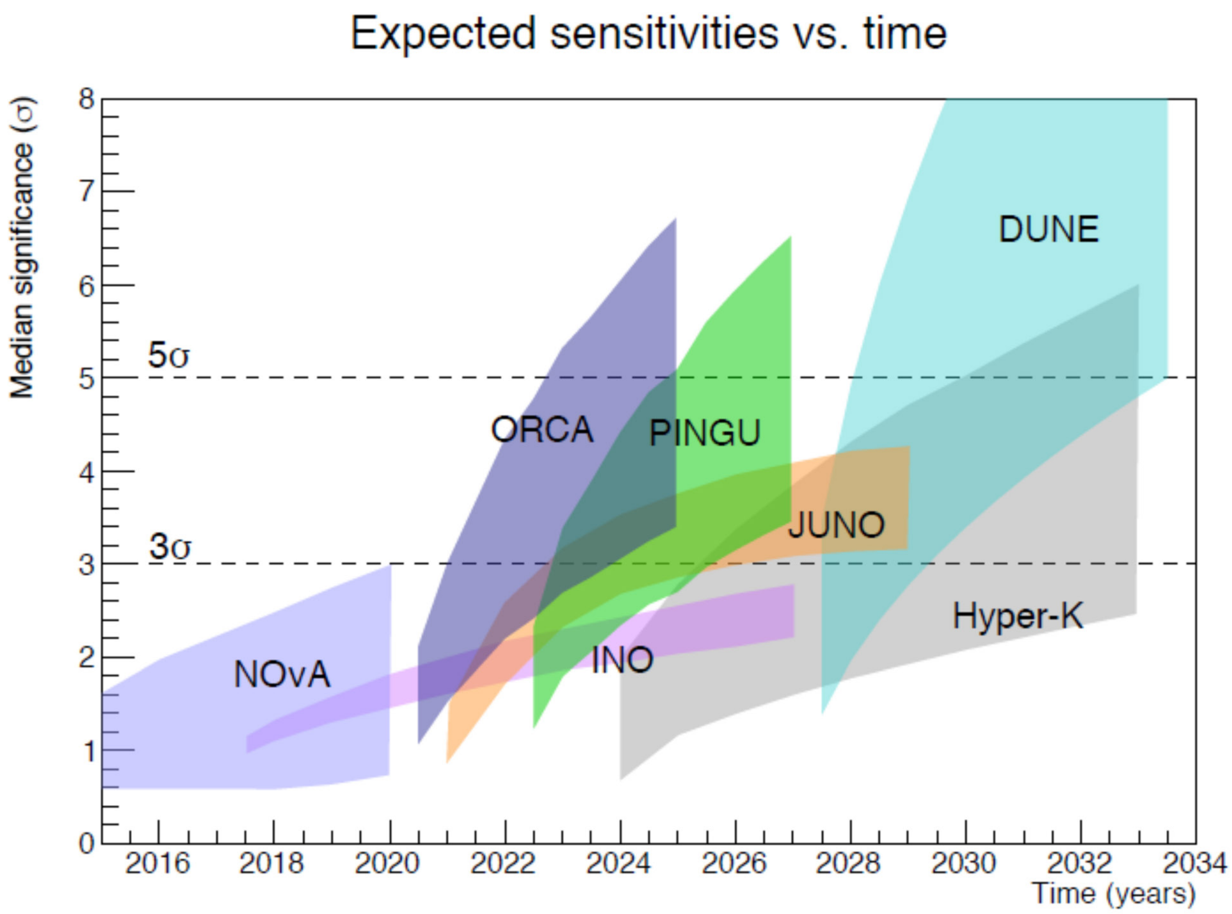


A. De Roeck@Lepton Photon 2017:

"… We look forward to start operation of the first far detector module in 2024 and first data with beam, near detector and first two far detector modules in 2026."

… to guide the eye

Originally published in Blennow et al., JHEP 1403 (2014) 028



Conclusions

- Running experiments could reach a 3σ sensitivity on MH already in 2020
- Around 2020 several new experiments will start with a target sensitivity of 3-5 σ
- In the late 20's new generation Long Baseline Experiments will surpass the 5σ sensitivity
- As a very welcome bonus all those experiments will bring important improvements in
  - Proton decay searches
  - Precision in neutrino oscillation parameters
  - Supernovae physics
  - Indirect Dark Matter searches
  - Neutrino astronomy, etc.