Prospects to Determine the Neutrino Mass Hierarchy

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Electroweak Interactions and Unified Theories
Recontres de Moriond, La Thuile, Italy

Plan of talk

- *Current understanding of the neutrino mass hierarchy*

- *Future prospects:*

- *Atmospheric neutrino experiments*

- *Long baseline experiments*

- *Reactor experiments*

- *Conclusions*

Neutrino Mass Hierarchy

normal hierarchy   inverted hierarchy
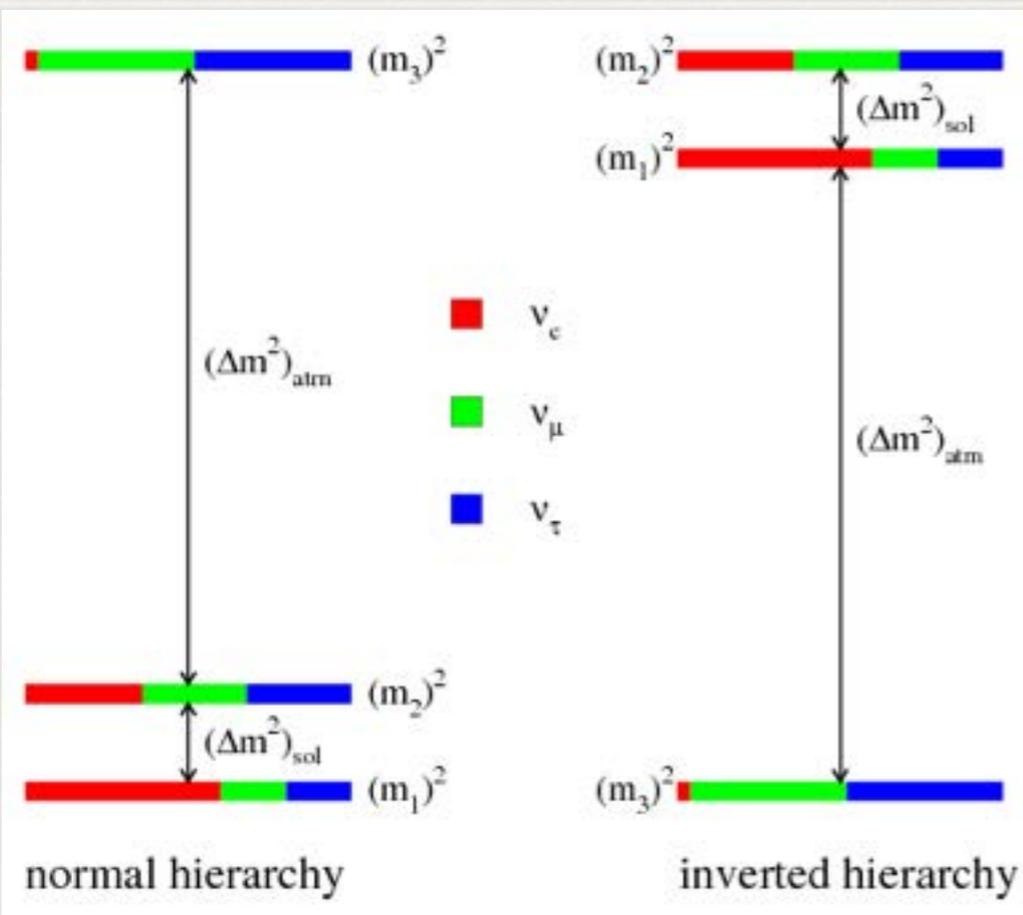
How to measure:

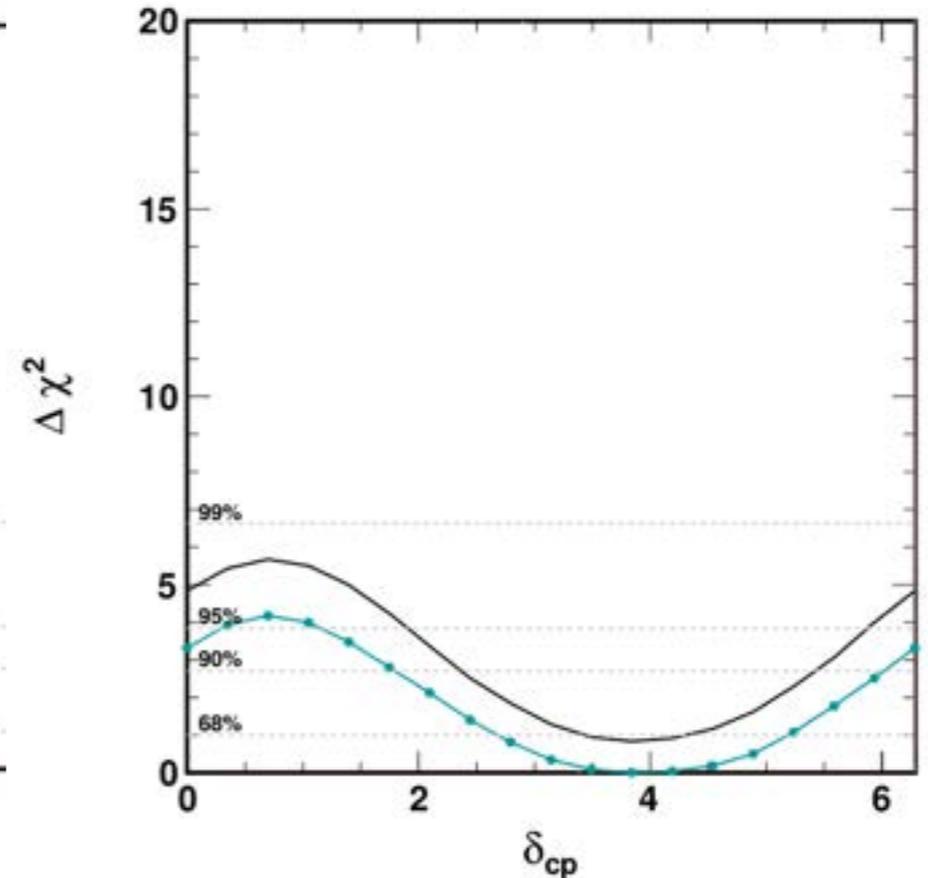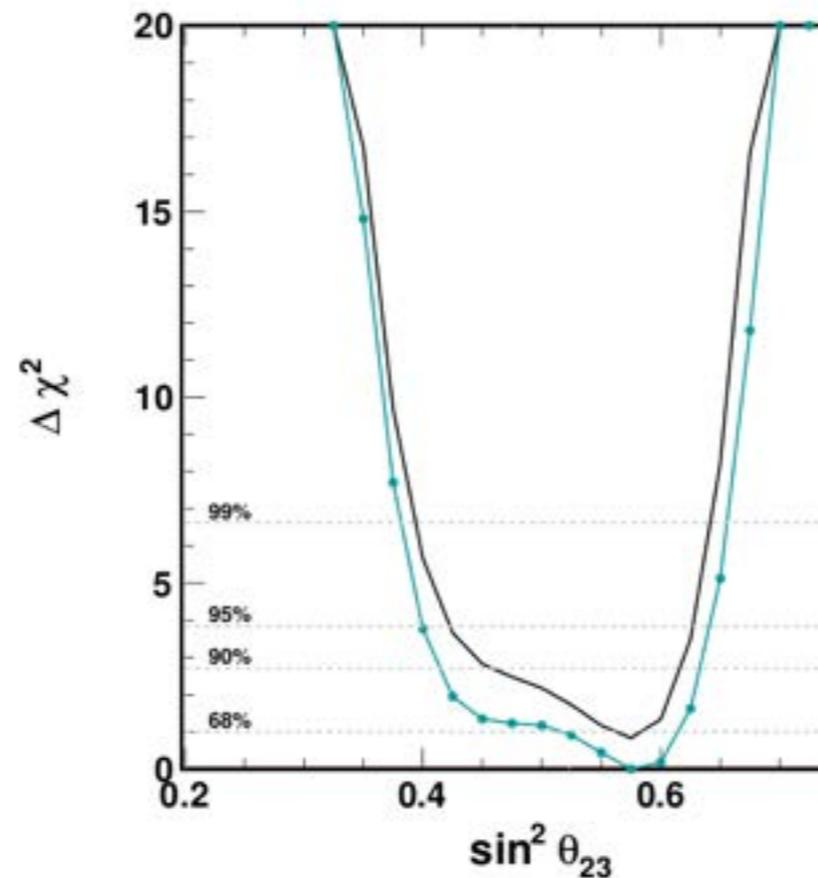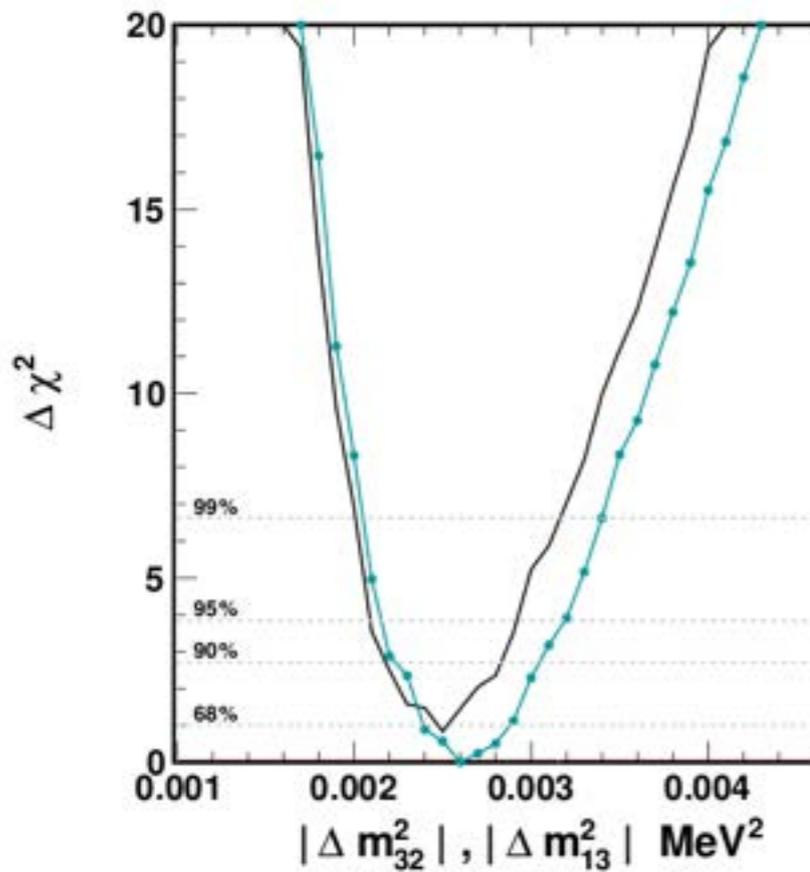### 1. *Matter effects in nu oscillation*

    (i) Long baseline experiments

    (ii) Atmospheric nu experiments

    (iii)Supernova neutrinos

2. *Interference effects in nu oscillation*

    (i) Reactor nu experiments at intermediate baselines
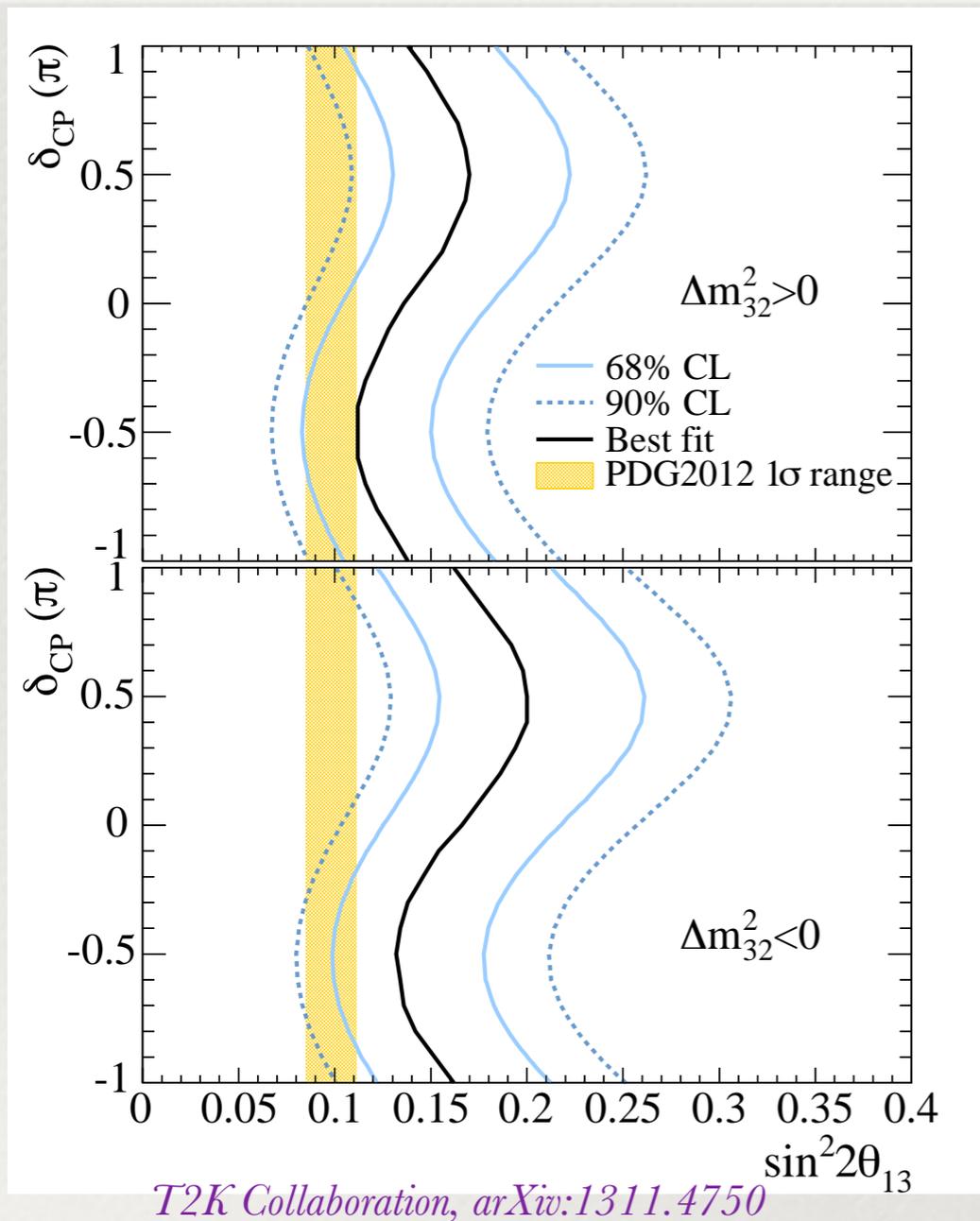
Absolute nu mass: 0vbb,cosmology

Current Status (SK)

Fit (517 dof)	χ^2	θ_{13}	δ_{cp}	θ_{23}	Δm_{23} (x10^{-3})
SK (NH)	559.8	0.025	3.84	0.57	2.6
SK (IH)	560.7	0.025	3.84	0.57	2.5

Statistically insignificant…can they be called hints?

Current Status (T2K)

$\Delta m^2_{32} > 0$

68% CL
90% CL
Best fit
PDG2012 1σ range

$\Delta m^2_{32} < 0$

δ_{CP} (π)

sin²2θ₁₃

T2K Collaboration, arXiv:1311.4750

Is NH favored?

Is delta_cp=-90° favored?

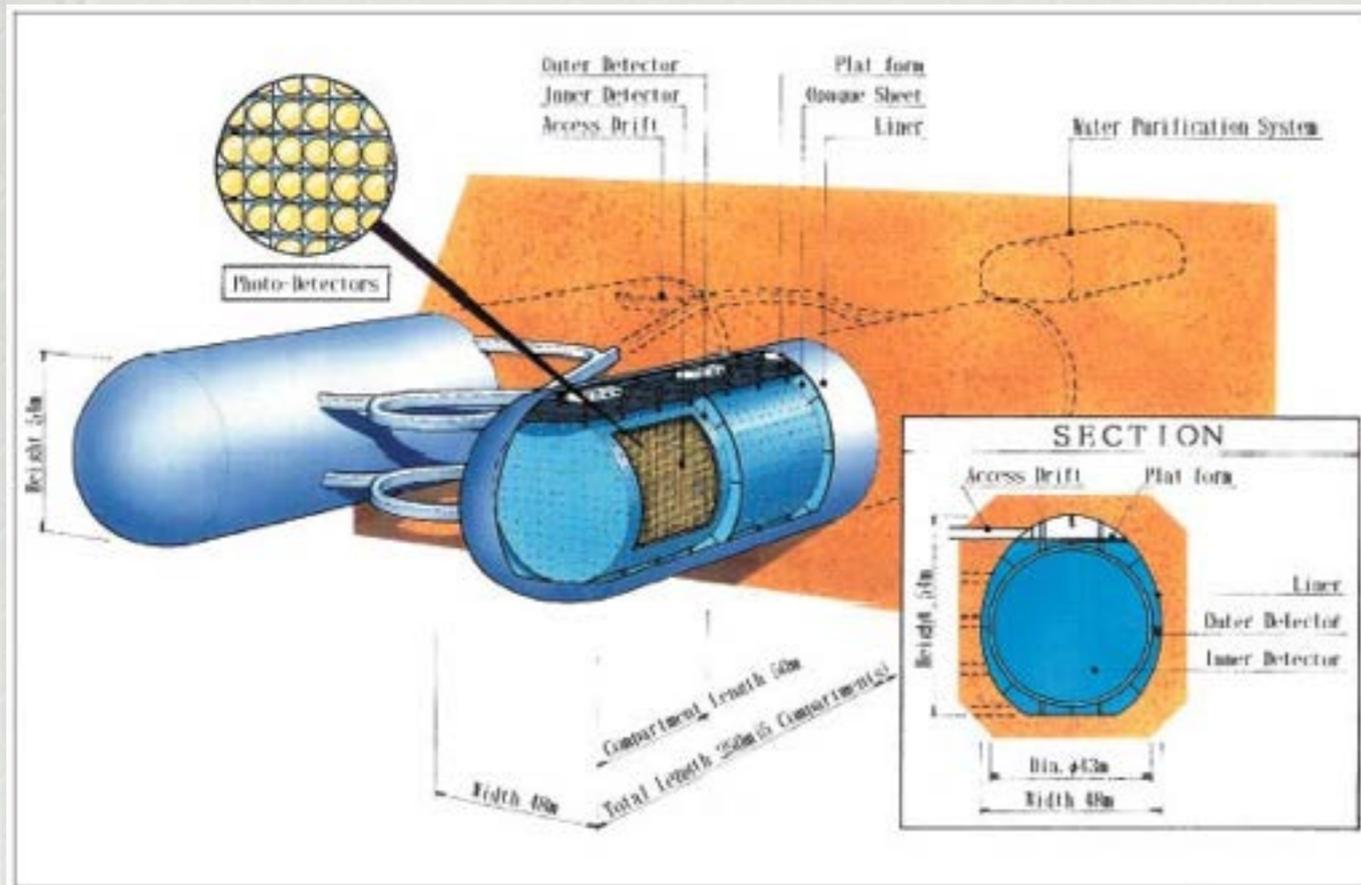*Is non-maximal th23 favored?*

Talk by E.Lisi

Is there NSI?

Gerardi,Meloni,Petcov (2014)

Atmospheric Neutrino Experiments

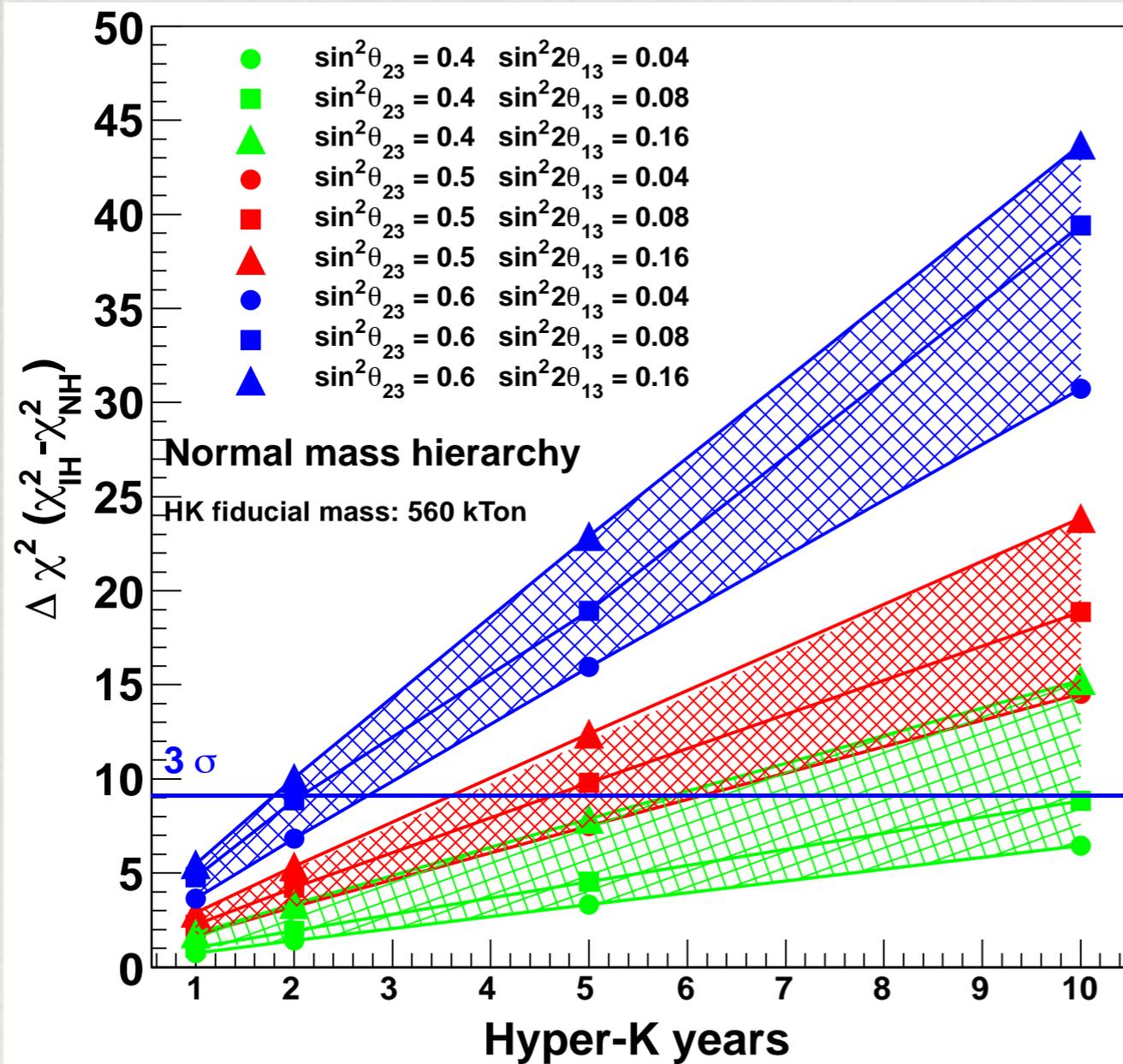## *Megaton-class Water Cerenkov Detectors*

Good zenith angle resoln

e vs mu discrimination

low E threshold

statistical separation of nue vs anti-nue
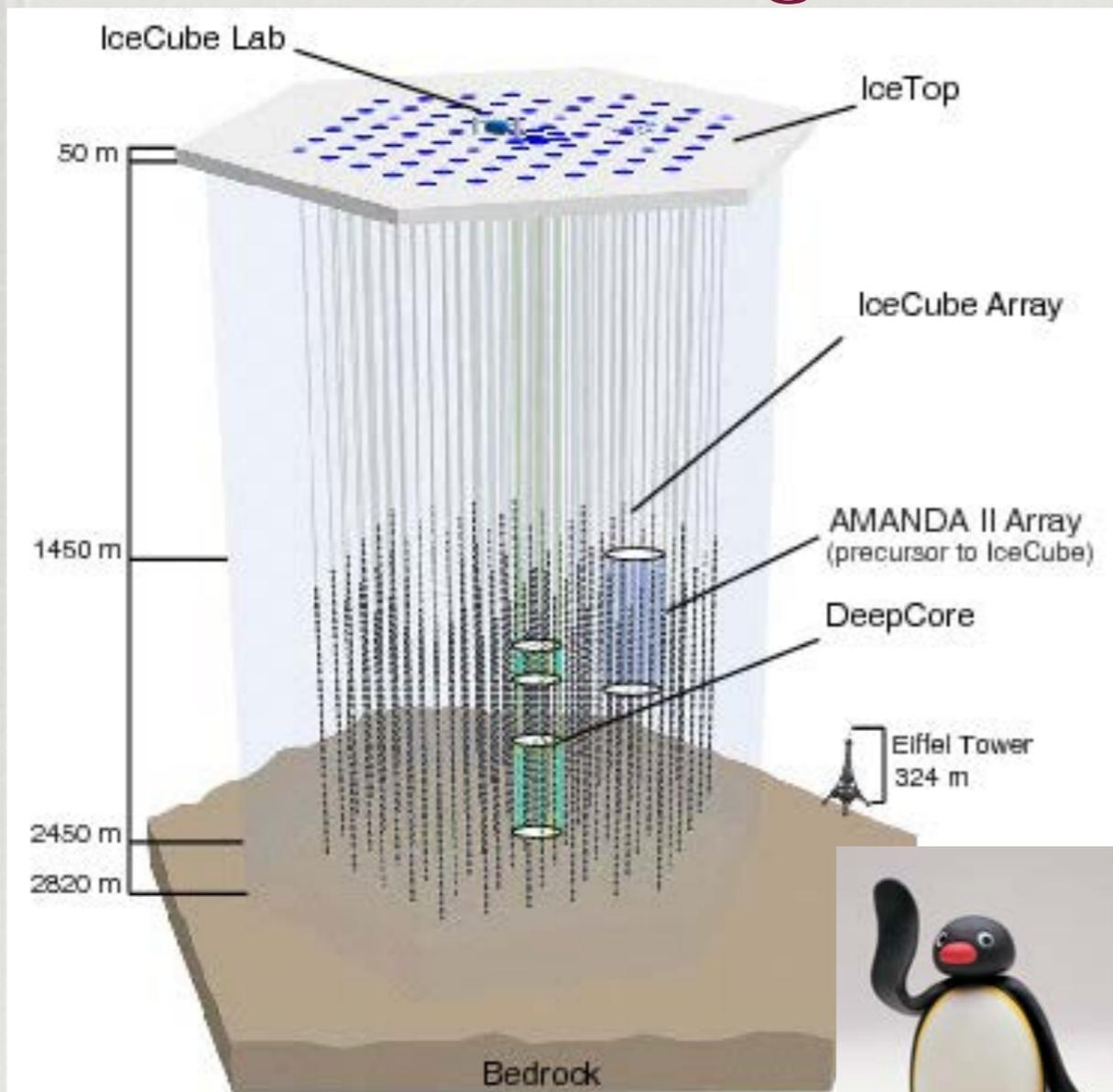
large statistics

Atmospheric Neutrino Experiments

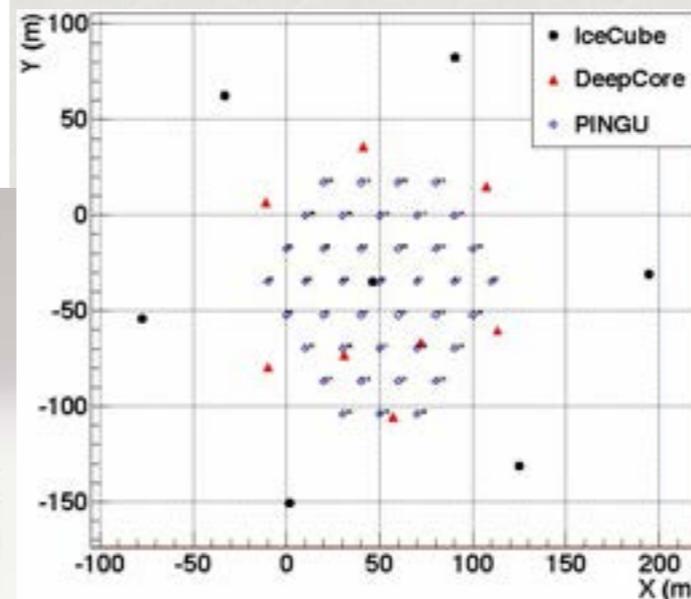*3 sigma discovery in less than 5 years*

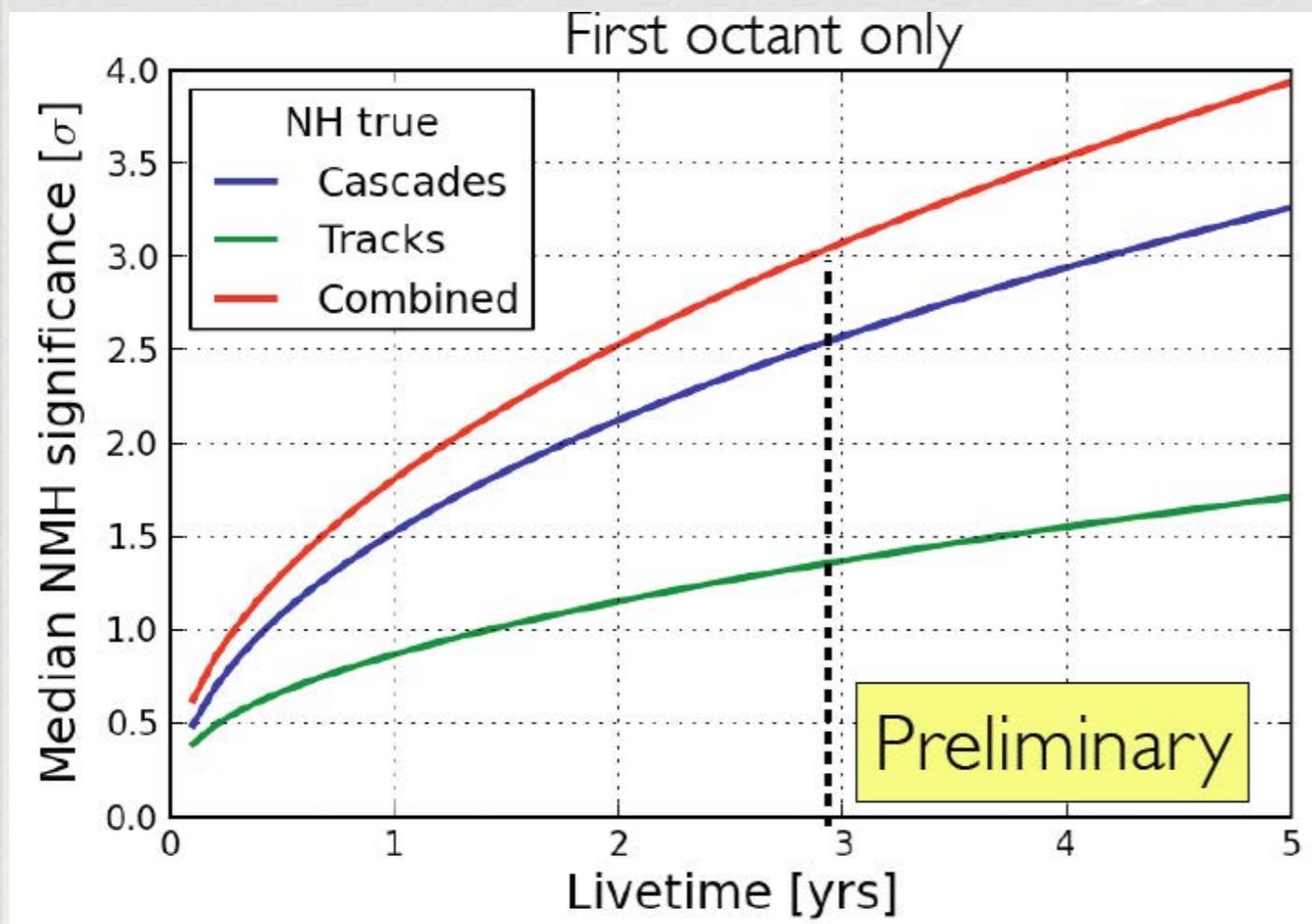# Atmospheric Neutrino Experiments

Multi-megaton Ice/Water Detectors

e vs mu discrimination

very large statistics
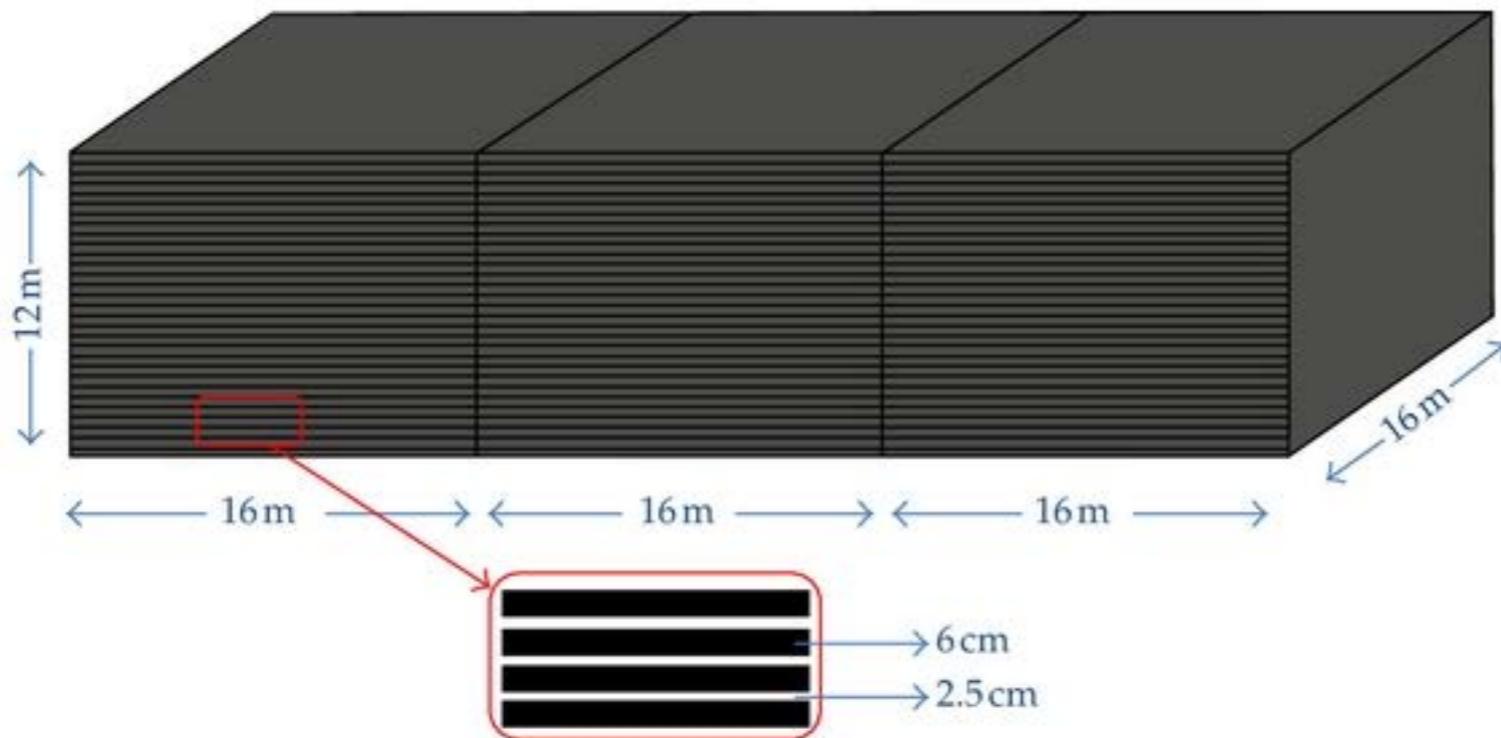
Atmospheric Neutrino Experiments

3 sigma discovery in about 3 years

PINGU LOI, 1401.2046

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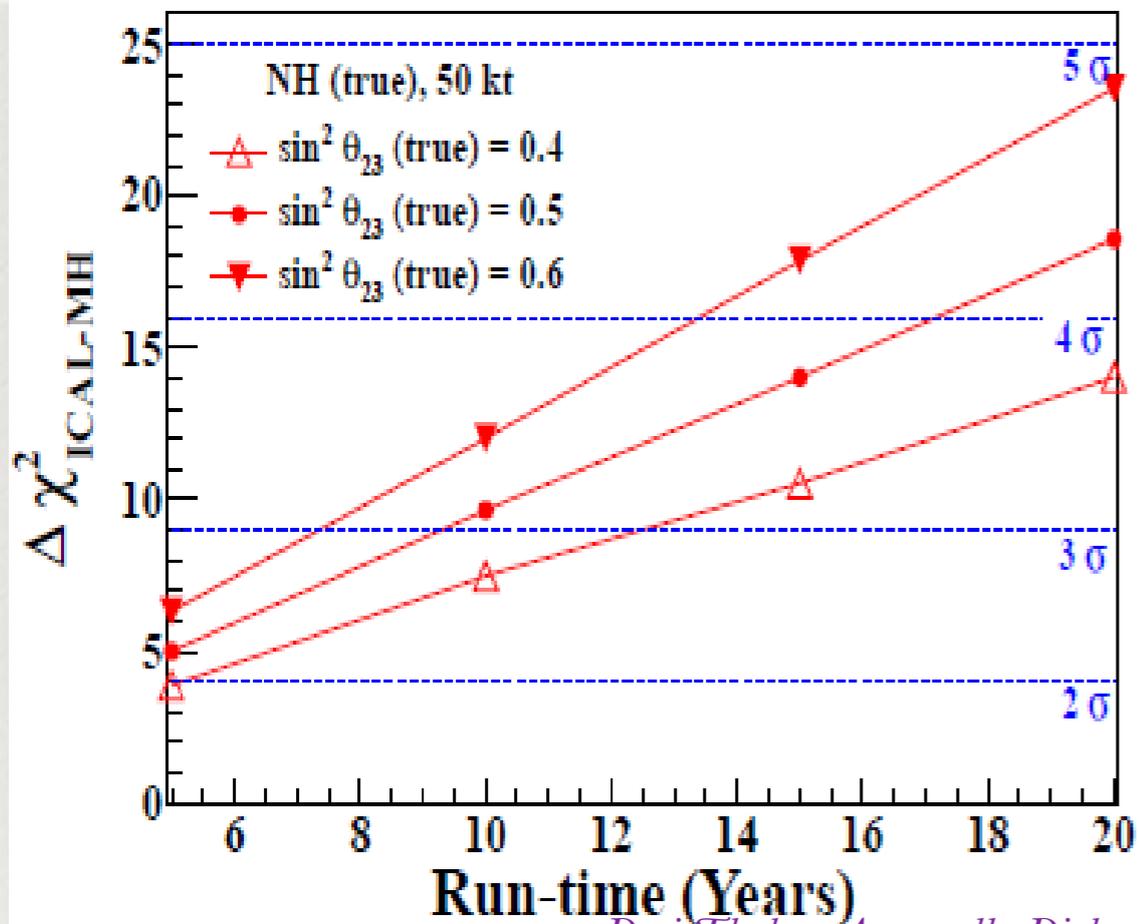# Atmospheric Neutrino Experiments

Large Magnetized Iron Detectors

Good E and θ resoln

99% charge-id

good statistics
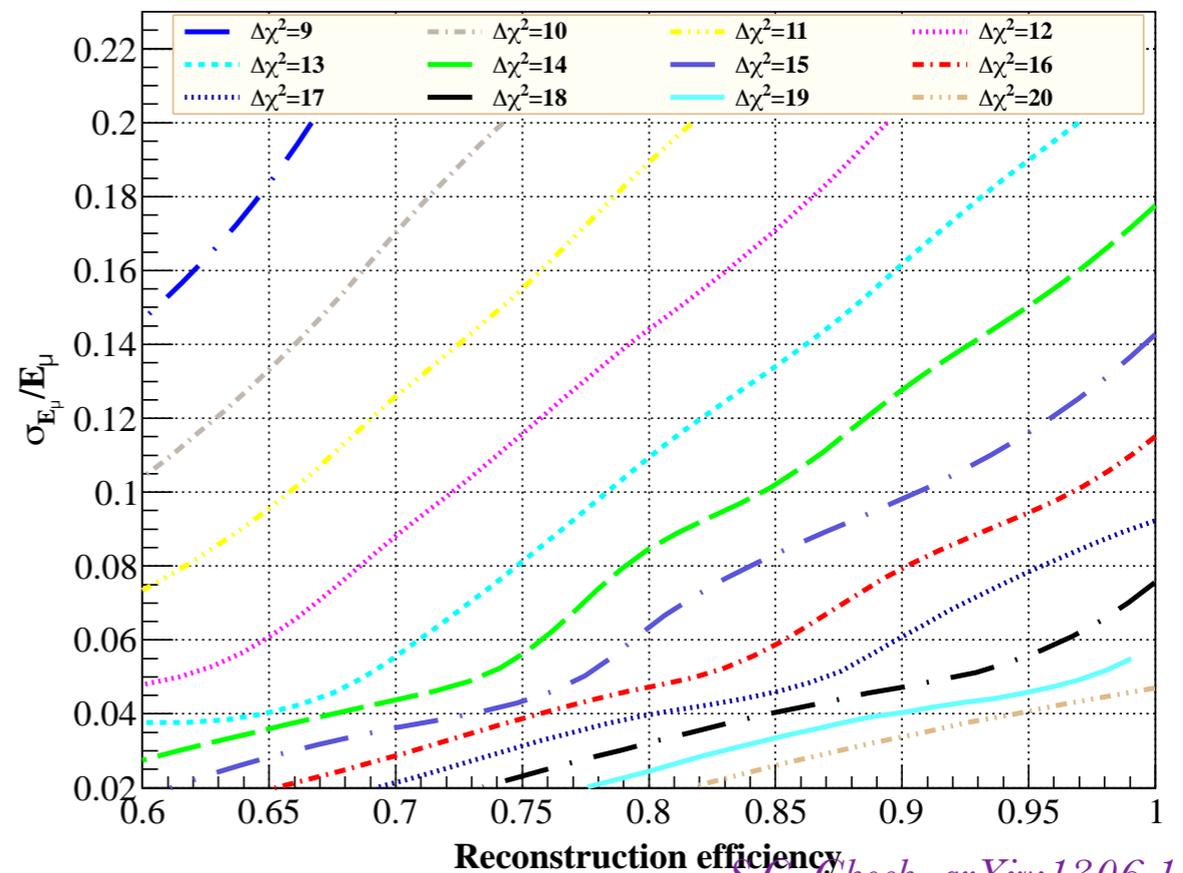
Atmospheric Neutrino Experiments $E_\mu, \cos\theta$

$$\chi^2$$

Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689

S.C., Ghosh, arXiv:1306.1423

Sensitivity can increase if muon energy resolution is improved

3σ *sigma discovery in about 10 years*

40% improvement above muon only analysis

Ghosh, Thakore, S.C., arXiv:1212.1305

$\sin^2 2\theta_{13}$ (true) = 0.1

$P_{e\mu} \sim \sin^2 \theta_{13}$

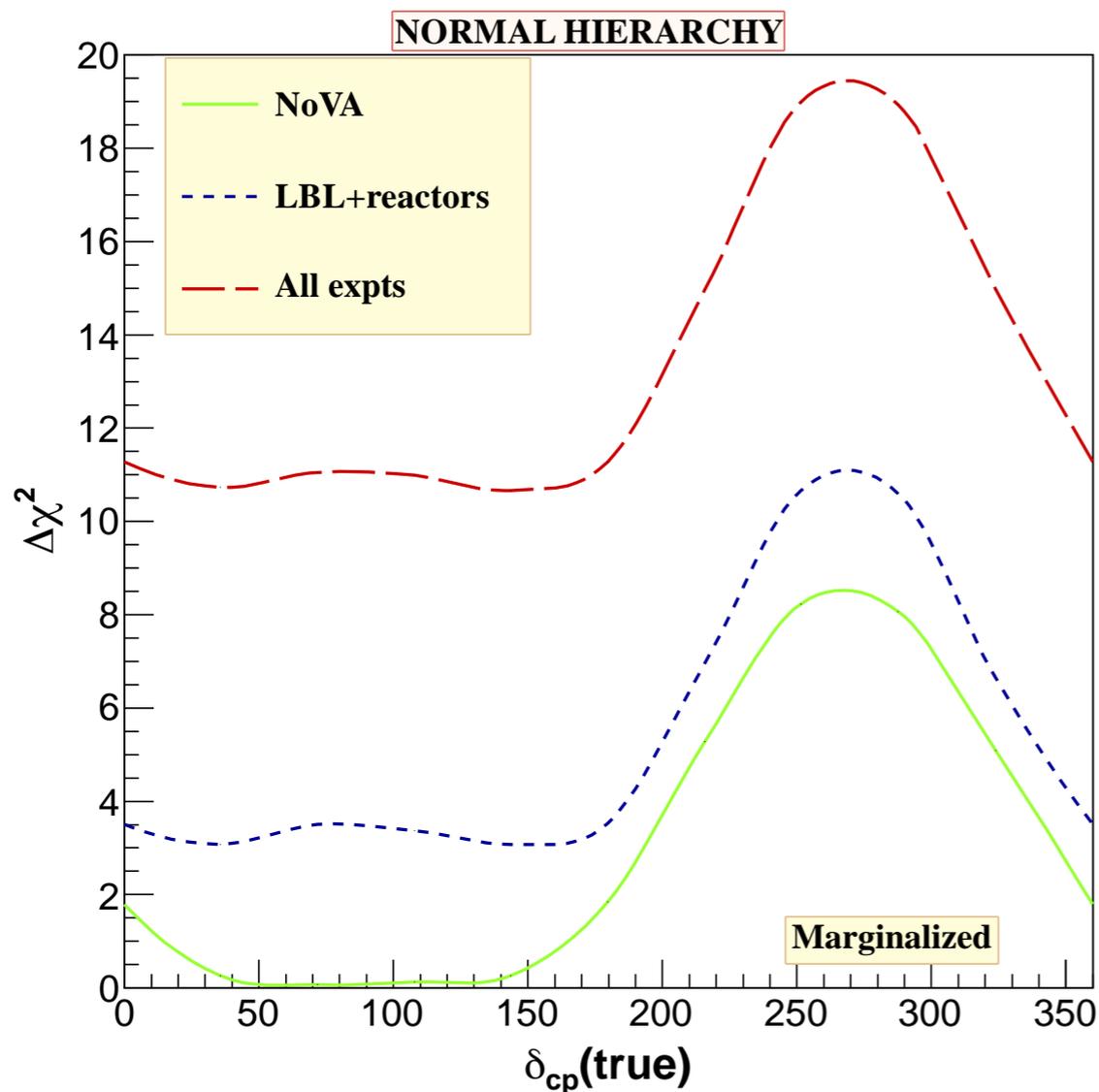*PINGU* ➔ *Ribordy, Smirnov, arXiv:1303.0758*

Include inelasticity y, increase sensitivity by 20-50%

Atmospheric Neutrino Experiments

Hierarchy sensitivity of atmospheric neutrino experiments is almost independent of delta_cp

Prospects at T2K & NOvA

NORMAL HIERARCHY

Legend:
- NoVA
- LBL+reactors
- All expts

Marginalized

Axis labels: $\Delta\chi^2$ vs δ_{cp}(true)

Ghosh, Thakore, S.C., arXiv:1212.1305

$$P_{\mu e} = 4\sin^2\theta_{13}\sin^2\theta_{23}\frac{\sin^2\left[(1-\hat{A})\Delta\right]}{(1-\hat{A})^2}$$

$$+\alpha\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\cos(\Delta+\delta_{CP})\times$$

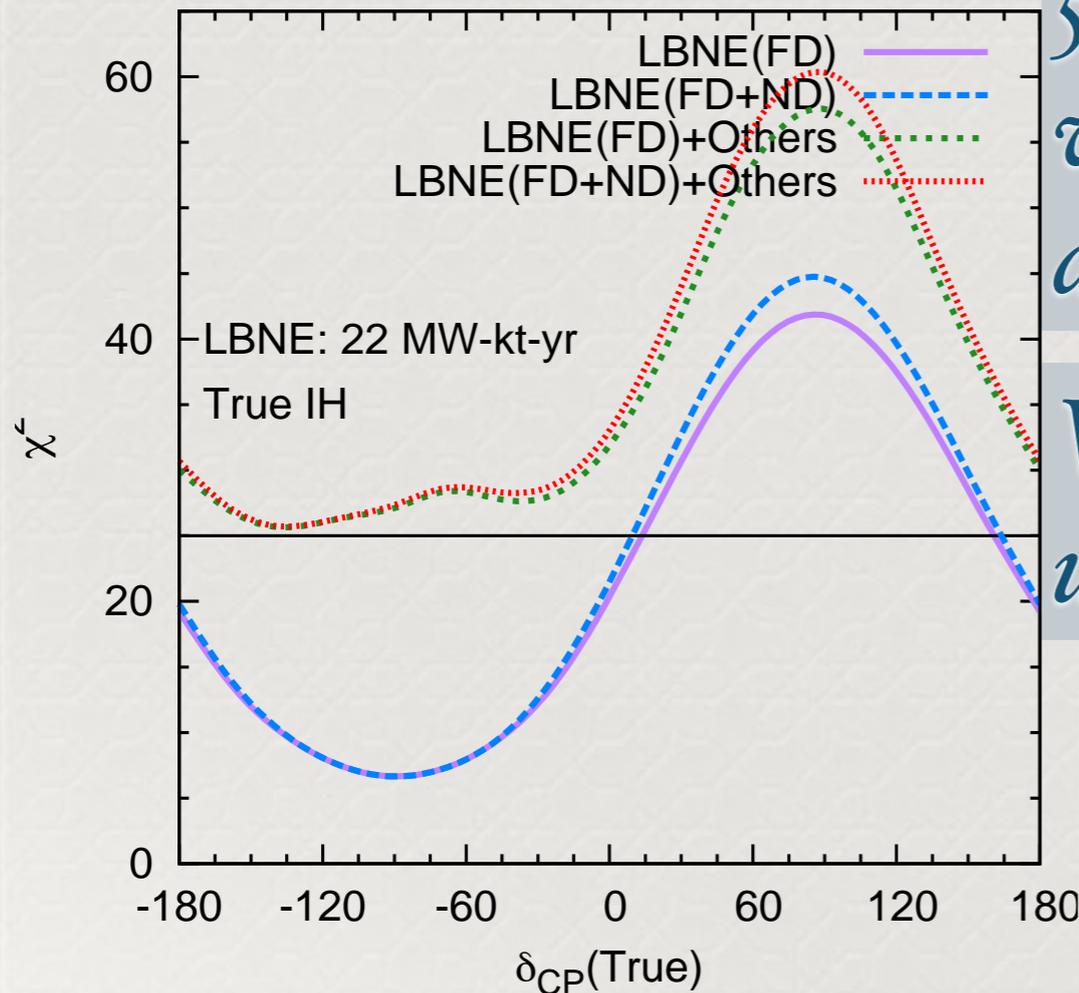$$\frac{\sin\hat{A}\Delta}{\hat{A}}\frac{\sin\left[(1-\hat{A})\Delta\right]}{(1-\hat{A})}+\mathcal{O}(\alpha^2)\,.$$

3 sigma sensitivity expected if NH true and delta_cp is -90 deg or if IH true and delta_cp is 90 deg

Addition of 10 years INO data gives 3 sigma sensitivity for both hierarchies and all delta_cp

Future Long Baseline Experiments

Sensitivity at ELBNF

5 sig sensitivity possible for all values of delta_cp if one adds the data from T2K, NOvA and INO

WO INO, the exposure needs to go up by almost a factor of two (39)
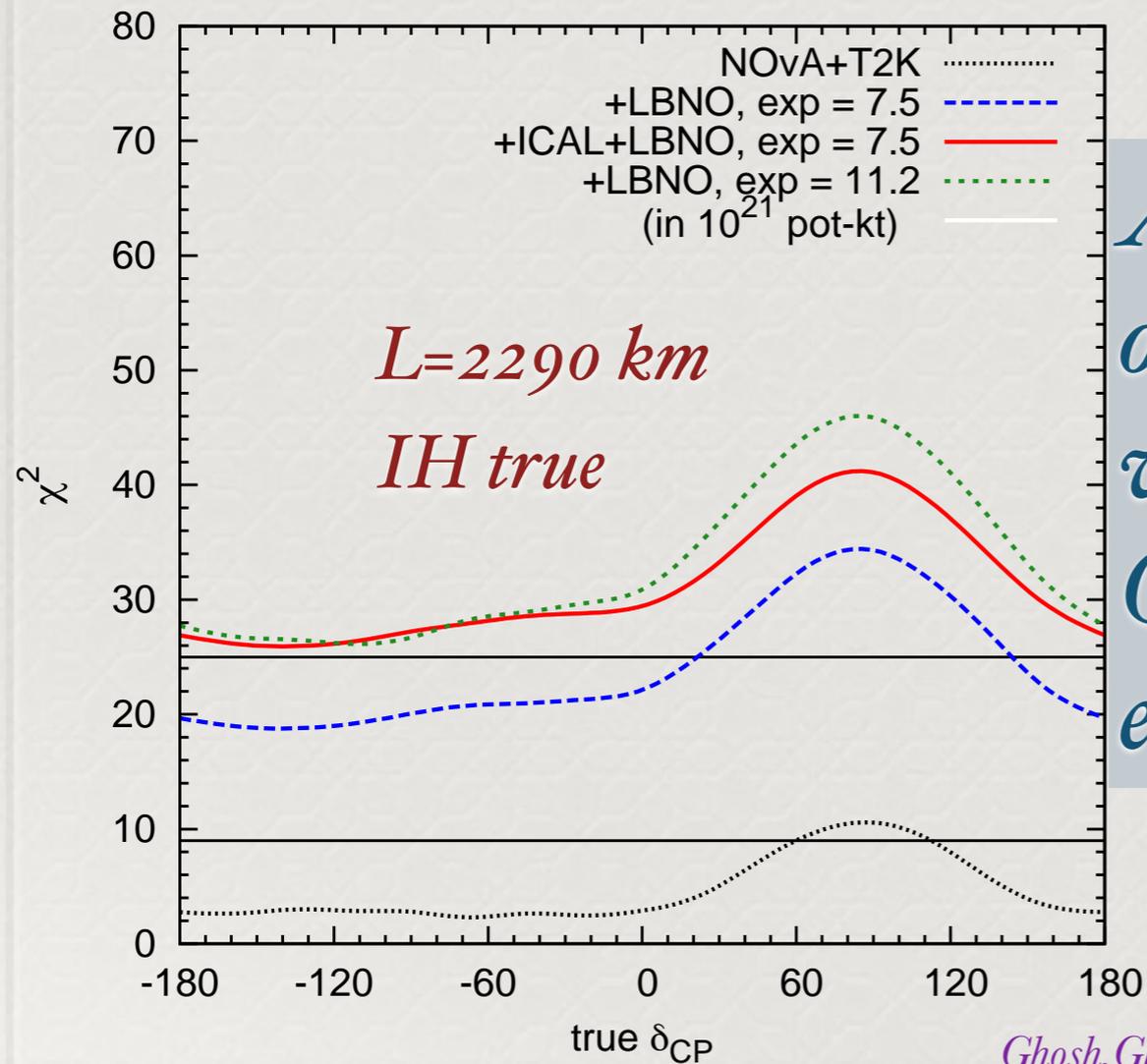
ELBNF alone needs 95 MW-kty data for 5 sigma

Ghosh,Ghoshal,Goswami,Raut, arXiv:1412.1744

Sample figure. I apologise to all whose fig I could not show.

Future Long Baseline Experiments

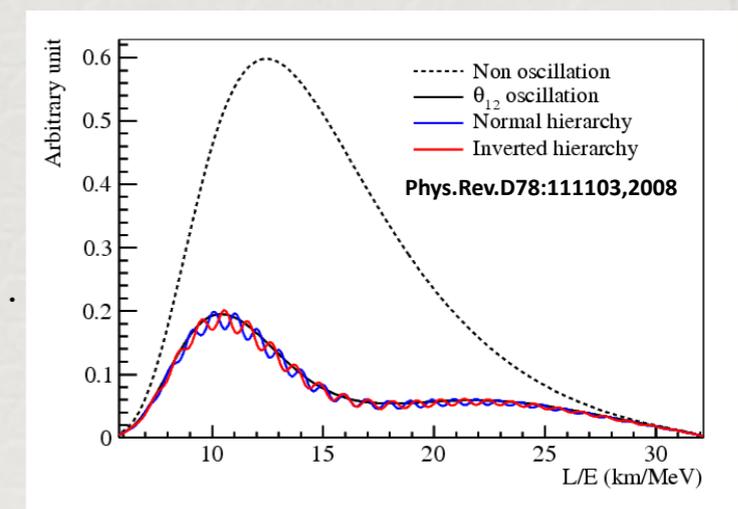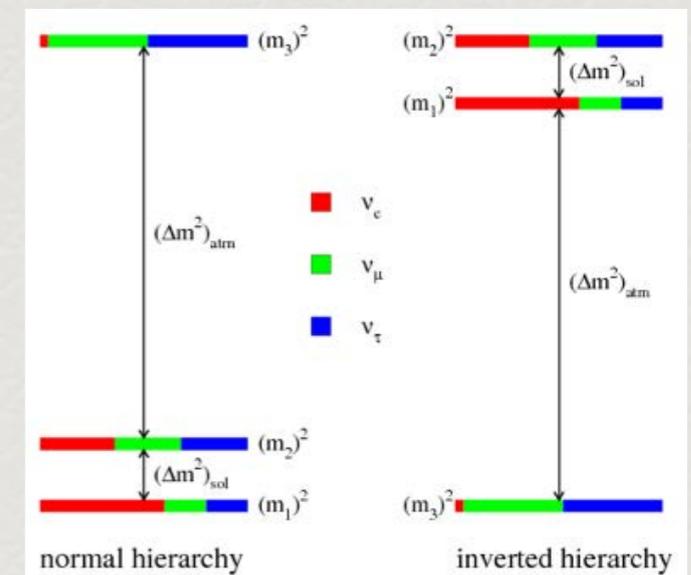*Sample figure. I apologise to all whose fig I could not show.*

Reactor Experiments

$$P_{NH}(\bar{\nu}_e \to \bar{\nu}_e)$$

$$= 1 - 2\sin^2\theta\cos^2\theta\left(1 - \cos\frac{\Delta m^2_{\text{atm}}L}{2E_\nu}\right)$$

$$- \frac{1}{2}\cos^4\theta\sin^2 2\theta_\odot\left(1 - \cos\frac{\Delta m^2_\odot L}{2E_\nu}\right)$$

$$+ 2\sin^2\theta\cos^2\theta\,\boxed{\sin^2\theta_\odot}\left(\cos\left(\frac{\Delta m^2_{\text{atm}}L}{2E_\nu} - \frac{\Delta m^2_\odot L}{2E_\nu}\right) - \cos\frac{\Delta m^2_{\text{atm}}L}{2E_\nu}\right),$$

$$P_{IH}(\bar{\nu}_e \to \bar{\nu}_e)$$

$$= 1 - 2\sin^2\theta\cos^2\theta\left(1 - \cos\frac{\Delta m^2_{\text{atm}}L}{2E_\nu}\right)$$

$$- \frac{1}{2}\cos^4\theta\sin^2 2\theta_\odot\left(1 - \cos\frac{\Delta m^2_\odot L}{2E_\nu}\right)$$

$$+ 2\sin^2\theta\cos^2\theta\,\boxed{\cos^2\theta_\odot}\left(\cos\left(\frac{\Delta m^2_{\text{atm}}L}{2E_\nu} - \frac{\Delta m^2_\odot L}{2E_\nu}\right) - \cos\frac{\Delta m^2_{\text{atm}}L}{2E_\nu}\right).$$

Petcov,Piai (2002),
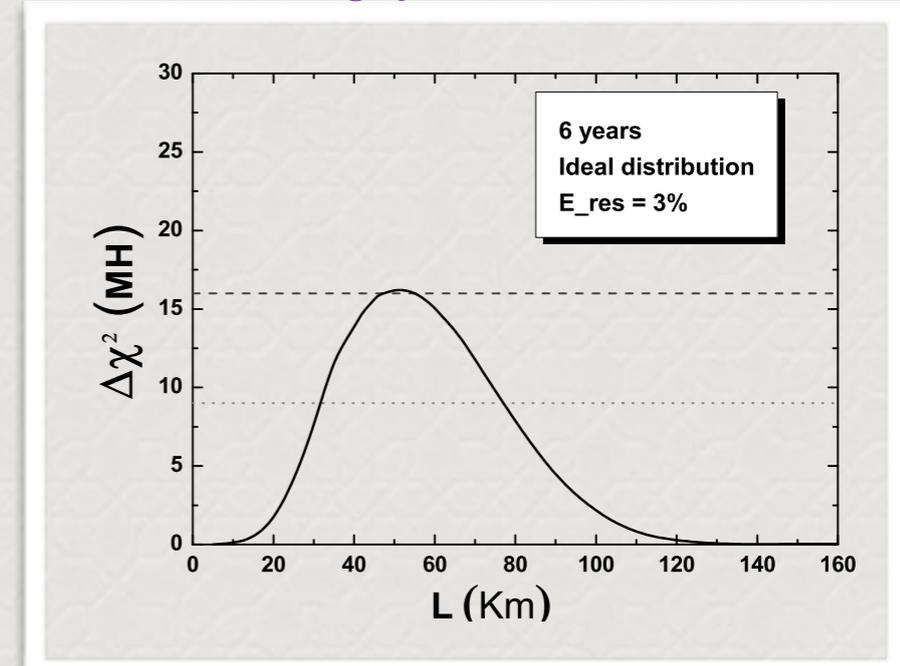*SC,Petcov,Piai (2003),*

normal hierarchy   inverted hierarchy

Phys.Rev.D78:111103,2008

Reactor Expts (JUNO, RENO-50)

Phys.Rev.D78:111103,2008

Li, Cao, Wang, Zhan, PRD88, 013008, 2013

6 years
Ideal distribution
E_res = 3%

Petcov, Piai (2002),
SC, Petcov, Piai (2003),
Learned, Dye, Pakvasa, Svoboda (2008)
Zhan, Wang, Cao, Wen (2008)
Zhan, Wang, Cao, Wen (2009)
Ghoshal, Petcov (2011)
Hagiwara, Okamura, Takaesu (2012)
Capozzi, Lisi, Marrone (2014)

$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$
$$P_{21} = \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21})$$
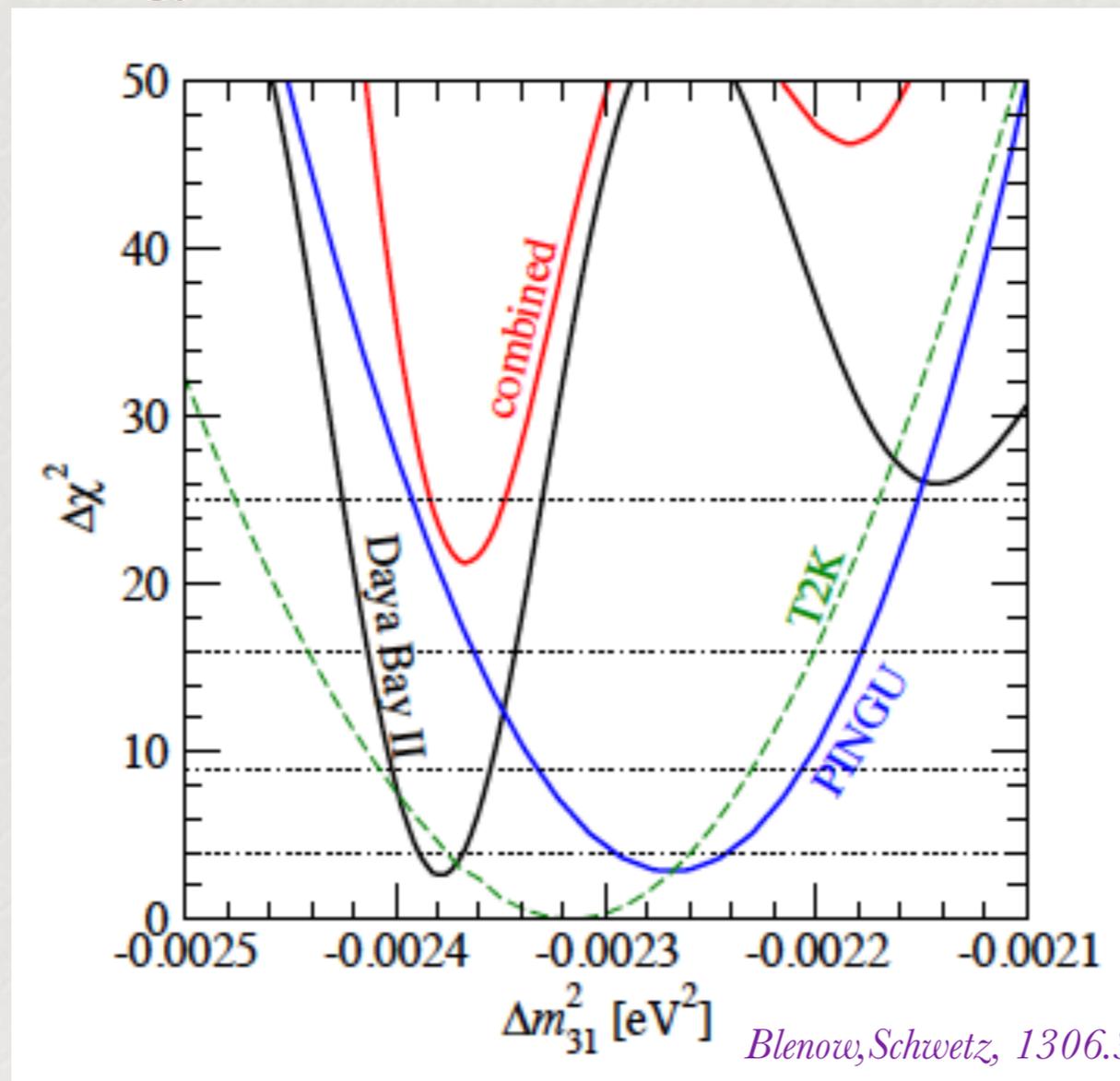$$P_{31} = \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31})$$
$$P_{32} = \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})$$
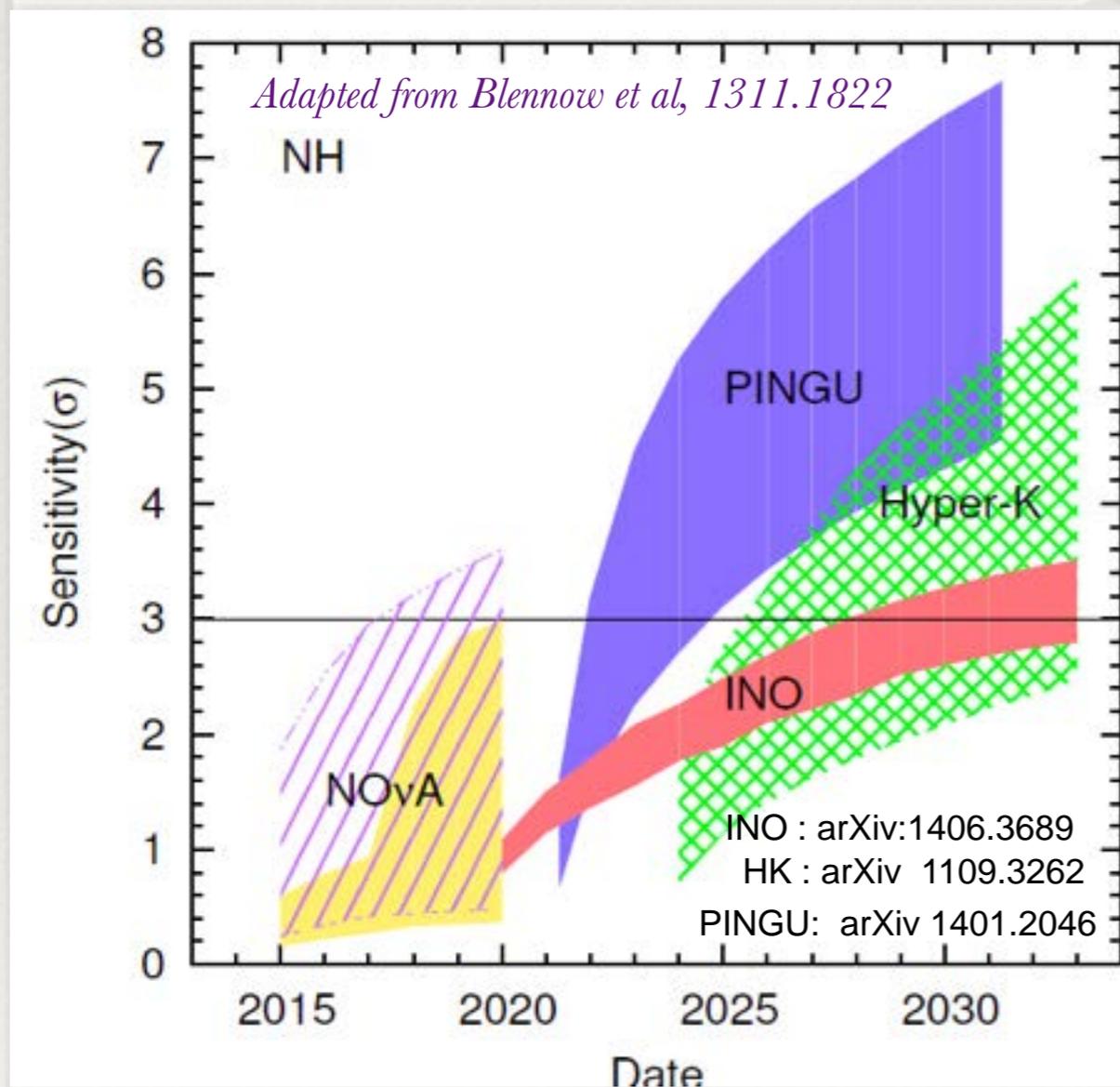
Reactor Expts (JUNO, RENO-50)

Hierarchy sensitivity of reactor neutrino experiments is completely independent of delta_cp as well as theta_23

Reactor Expts (JUNO, RENO-50)

Synergy between PINGU and JUNO

Blenow,Schwetz, 1306.3988
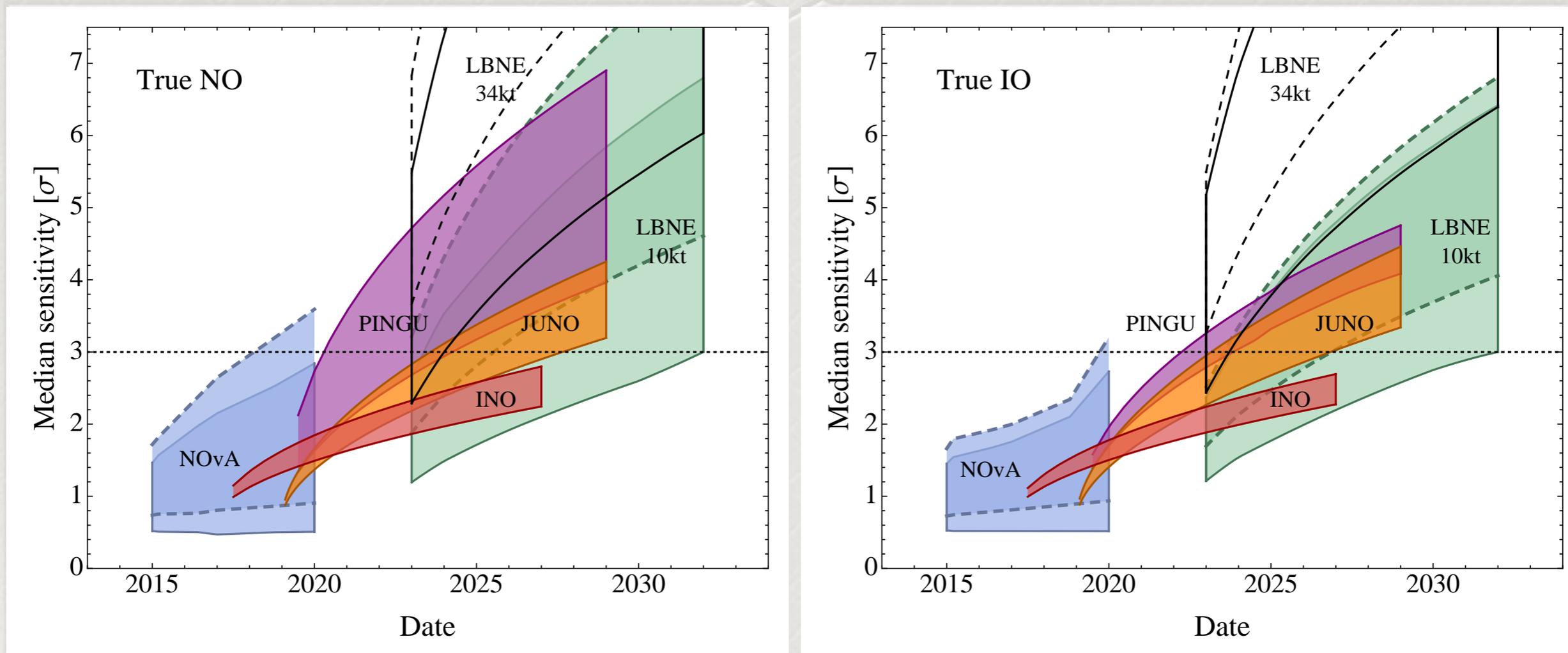
Conclusions

Adapted from Blennow et al, 1311.1822

For favorable deltacp
early hints expected from
NOvA

For unfavorable deltacp values,
early hints expected from
atmospheric expts and/or Juno

Thank you!

Backup Slide

Blennow et al, 1311.1822