Future prospects of neutrino oscillation study

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April 27, 2016 @ IPMU

1. Introduction

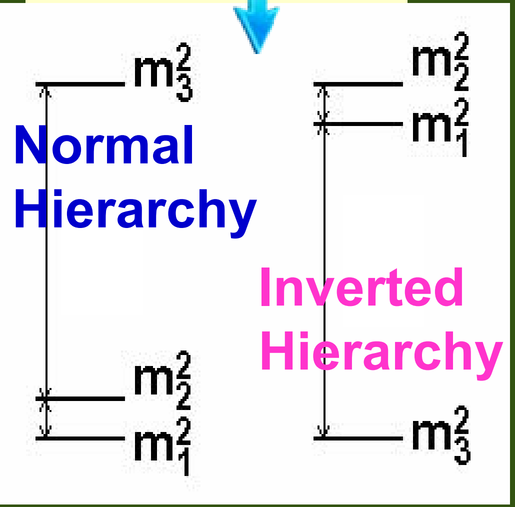
2. New Physics probed by ν experiments

3. Conclusions

1. Introduction

Framework of 3 flavor ν oscillation

Both hierarchy patterns are allowed



Mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Functions of mixing angles θ_{12}, θ_{23}, θ_{13}, and CP phase δ

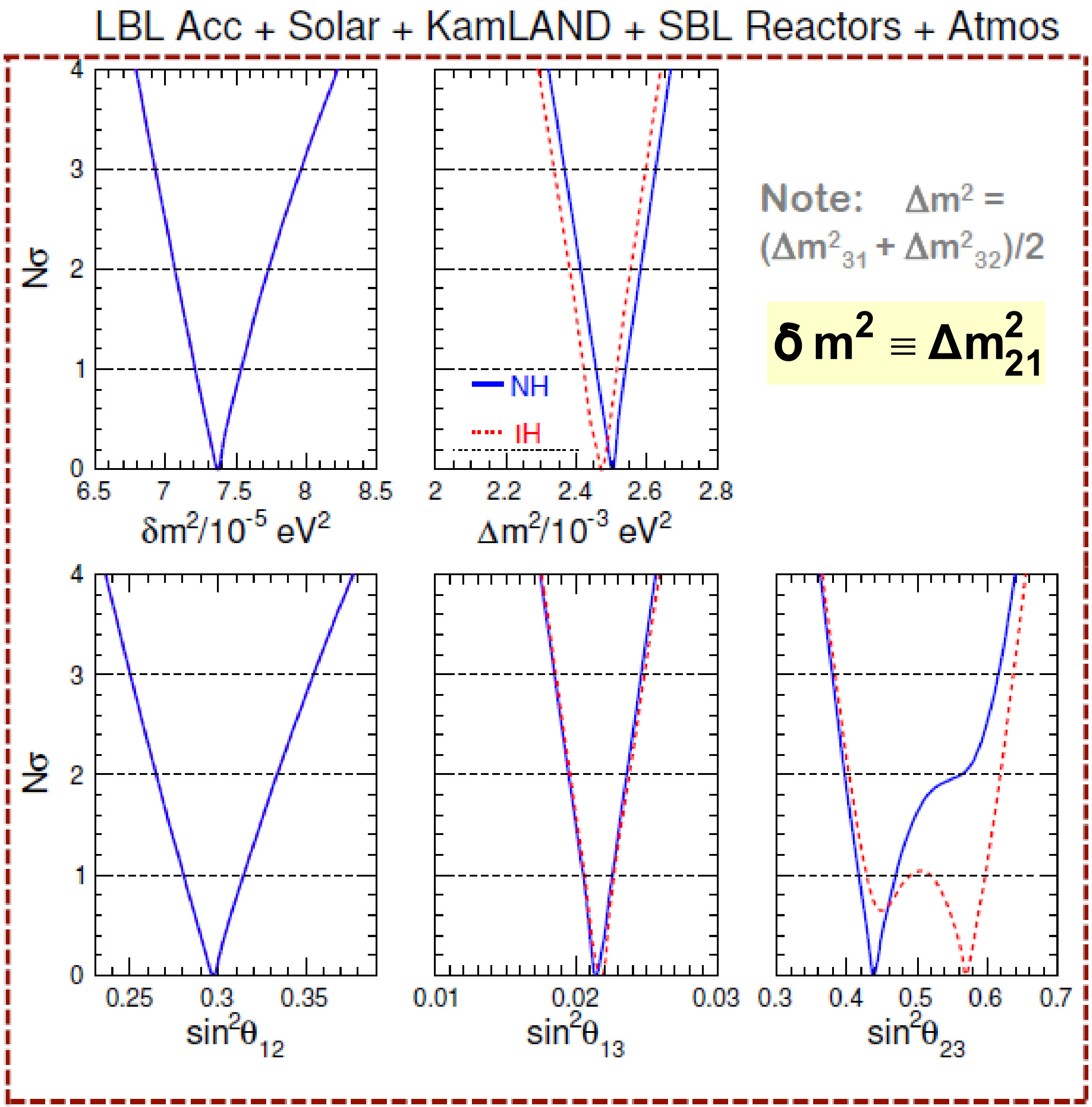
3 mixing angles & 2 Δm^2_{jk} have been measured:

ν_{solar}+KamLAND (reactor) → $\theta_{12} \cong \frac{\pi}{6}, \Delta m^2_{21} \cong 8\times10^{-5}\,\mathrm{eV}^2$

ν_{atm}+K2K,MINOS(accelerators) → $\theta_{23} \cong \frac{\pi}{4}, |\Delta m^2_{32}| \cong 2.5\times10^{-3}\,\mathrm{eV}^2$

D-CHOOZ+Daya Bay+RENO (reactors), T2K+MINOS+NOvA etc → $\theta_{13} \cong \pi/20$

Single (known) oscillation parameters



Current 1σ errors (1/6 of ±3σ range):

δm^2	2.4 %
Δm^2	1.8 %
$\sin^2\theta_{12}$	5.8 %
$\sin^2\theta_{13}$	4.7 %
$\sin^2\theta_{23}$	~ 9 %

all < 10%...

Precision Era!

Lisi@BSM in Okinawa 2016

Oscillation vs non-oscillation experiments

- **neutrino oscillation**

$$\Delta m^2_{jk}=m^2_j - m^2_k$$

- **neutrinoless double beta decay**

$$m_{ee}=|\Sigma(U_{ej})^2 m_j \exp(i\phi_j)|$$

Majorana phases

- **direct measurement**

$$m_\beta=(\Sigma|U_{ej}|^2 m^2_j)^{1/2}$$

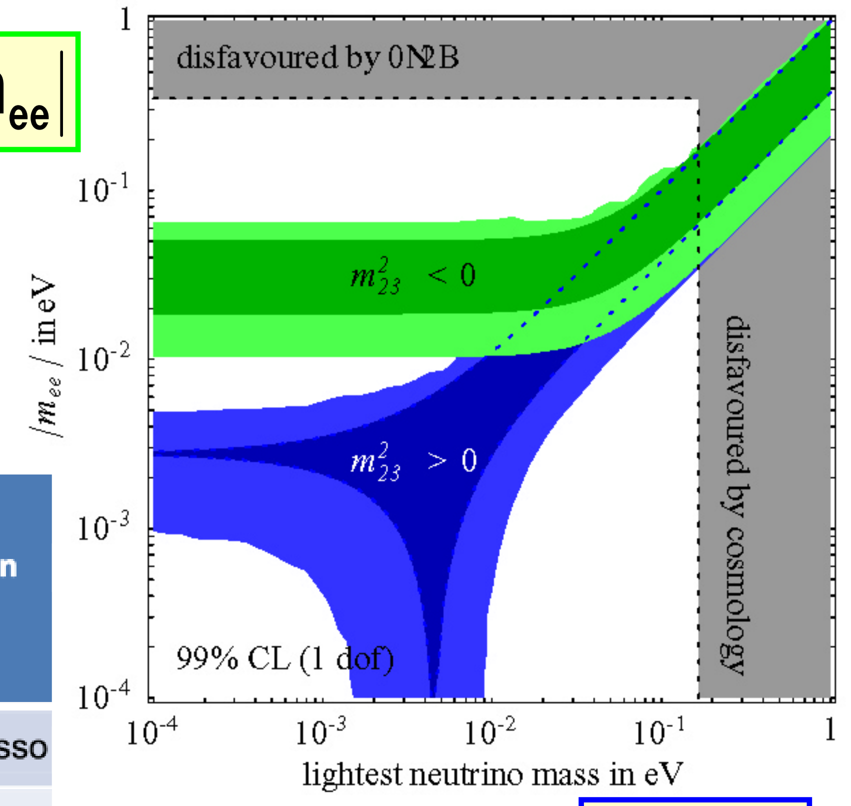
- **cosmology**

$$\Sigma m_j$$

neutrinoless double beta decay

$$m_{ee}=|\Sigma(U_{ej})^2 m_j \exp(i\phi_j)|$$

$|m_{ee}|$



min (m_j)

Strumia-Vissani: hep-ph/0606054

Biller@NuPhys2015

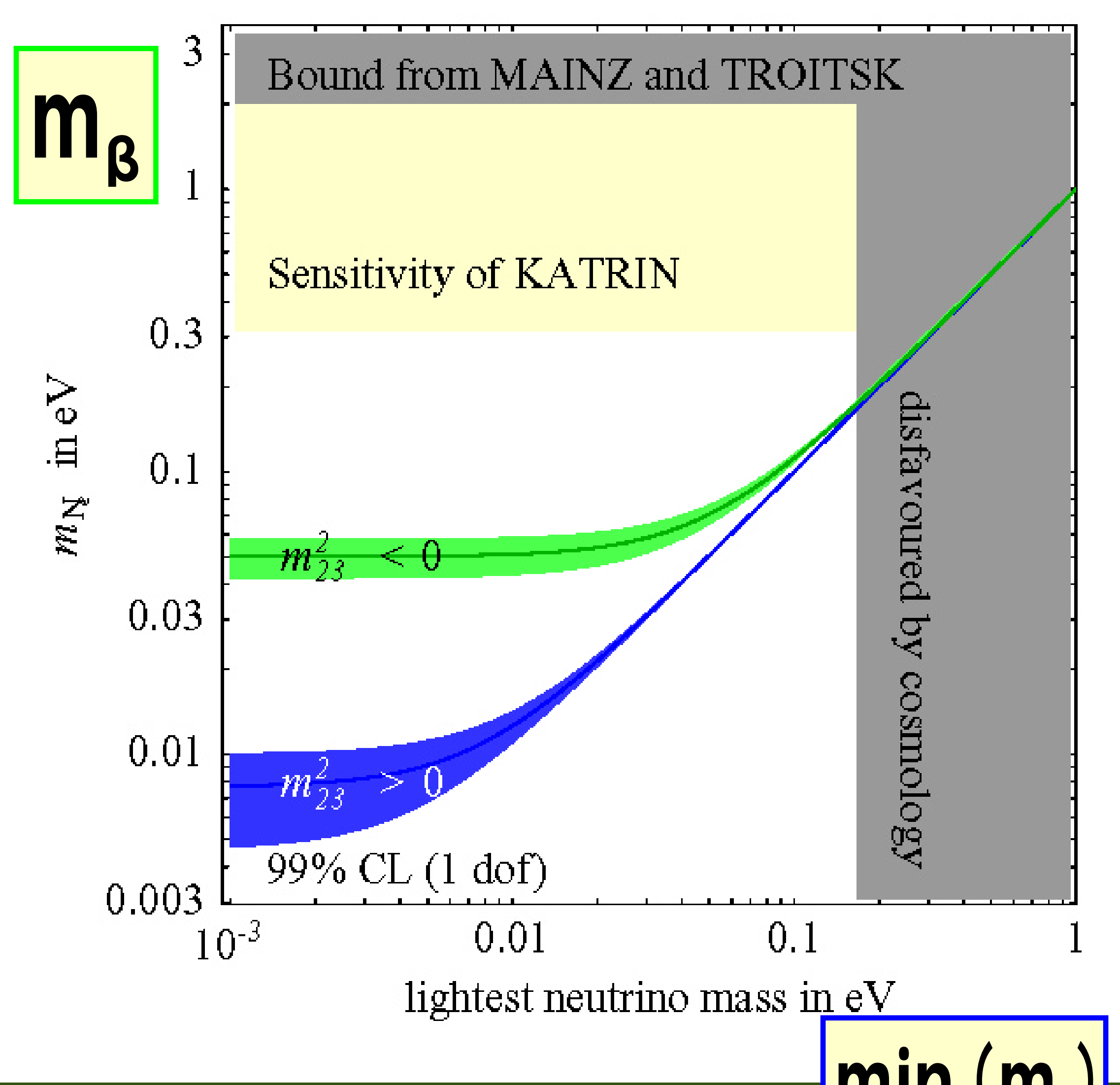
Project	Isotope	Isotope Mass (kg fiducial)	Currently Achieved (10^{26} yr)	Location
CUORE	^{130}Te	206	>0.028	Gran Sasso
MAJORANA	^{76}Ge	24.8		SURF
GERDA	^{76}Ge	31	>0.21	Gran Sasso
EXO-200	^{136}Xe	79	>0.11	WIPP
NEXT	^{136}Xe	10→100		Canfranc
SuperNEMO	^{82}Se+	7→100 7	(NEMO3) >0.001	LSM ~~Frejus~~
KamLAND-Zen	^{136}Xe	434	>0.19	Kamioka
SNO+	^{130}Te	~~160~~ 445		SNOLAB
PANDAX-III	^{136}Xe	200		Jinping

● **direct measurement**

Strumia-Vissani: hep-ph/0606054

$$m_\beta = \left(\Sigma |U_{ej}|^2 m_j^2\right)^{1/2}$$

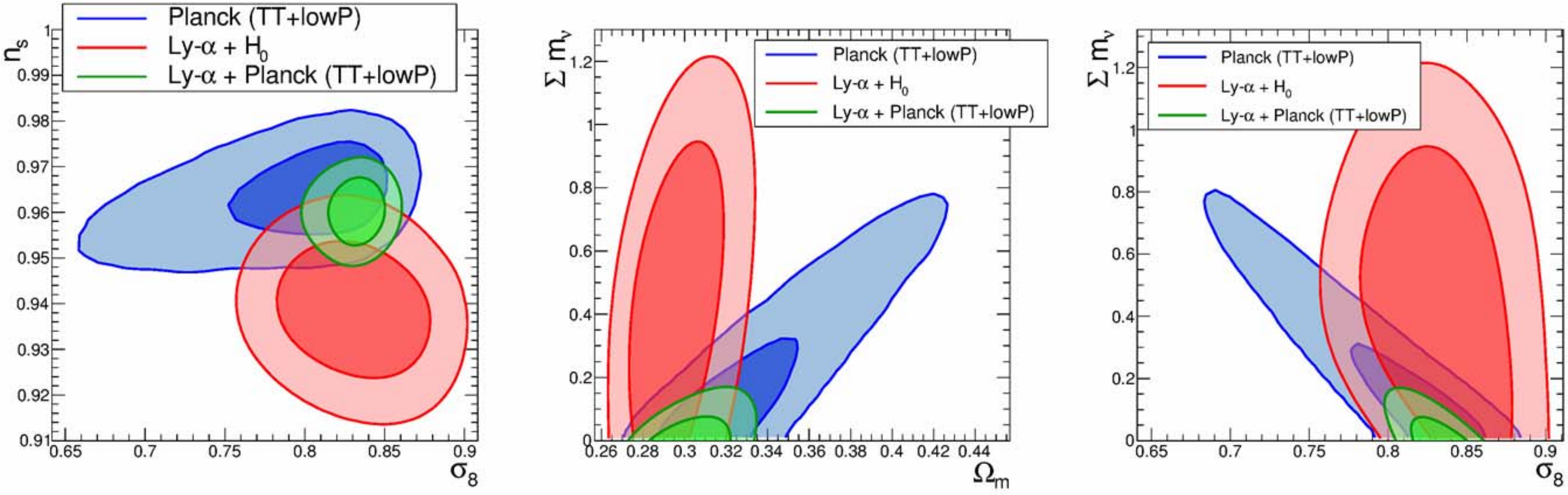
m_β



min (m_j)

Cosmology

THE STRONGEST BOUND IS CURRENTLY $\sum m_\nu < 0.12$ eV BUT THIS IS DERIVED FROM THE COMBINATION OF CMB AND LYMAN-α DATA AND PERHAPS NOT VERY ROBUST



Palanque-Delabrouille et al. 1506.05976

HANNESTAD @ NUPHYS2015

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cong \begin{pmatrix} c_{12} & s_{12} & \varepsilon \\ -s_{12}/\sqrt{2} & c_{12}/\sqrt{2} & 1/\sqrt{2} \\ s_{12}/\sqrt{2} & -c_{12}/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}$$

Next task is to measure sign(Δm^2_{31}), $\pi/4-\theta_{23}$ and δ

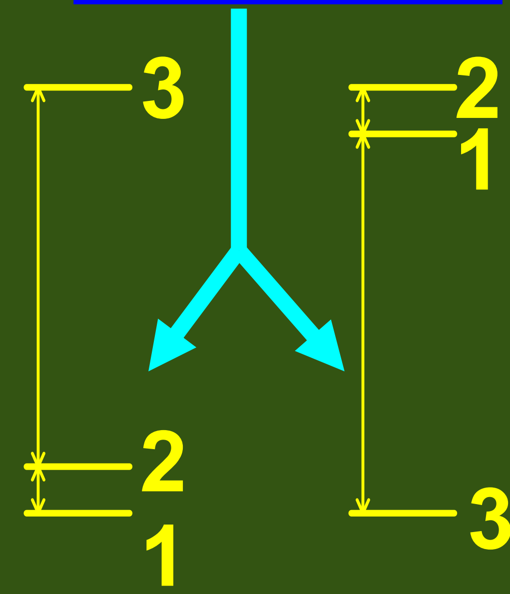
sign(Δm^2_{31}) : mass hierarchy

$\pi/4-\theta_{23}$: octant

δ : CP phase

→ These quantities are expected to be determined in future experiments with huge detectors.

- **Both mass hierarchies are allowed**



normal hierarchy	inverted hierarchy
$\Delta m^2_{32} > 0$	$\Delta m^2_{32} < 0$

(1) Determination of $\mathrm{sgn}(\Delta m^2_{31})$

$$P(\nu_\mu \to \nu_e) \cong s^2_{23}\sin^2 2\theta_{13} \frac{\Delta E^2_{31}}{\Delta \tilde{E}^2_{31}} \sin^2\left(\frac{\Delta \tilde{E}_{31} L}{2}\right)$$

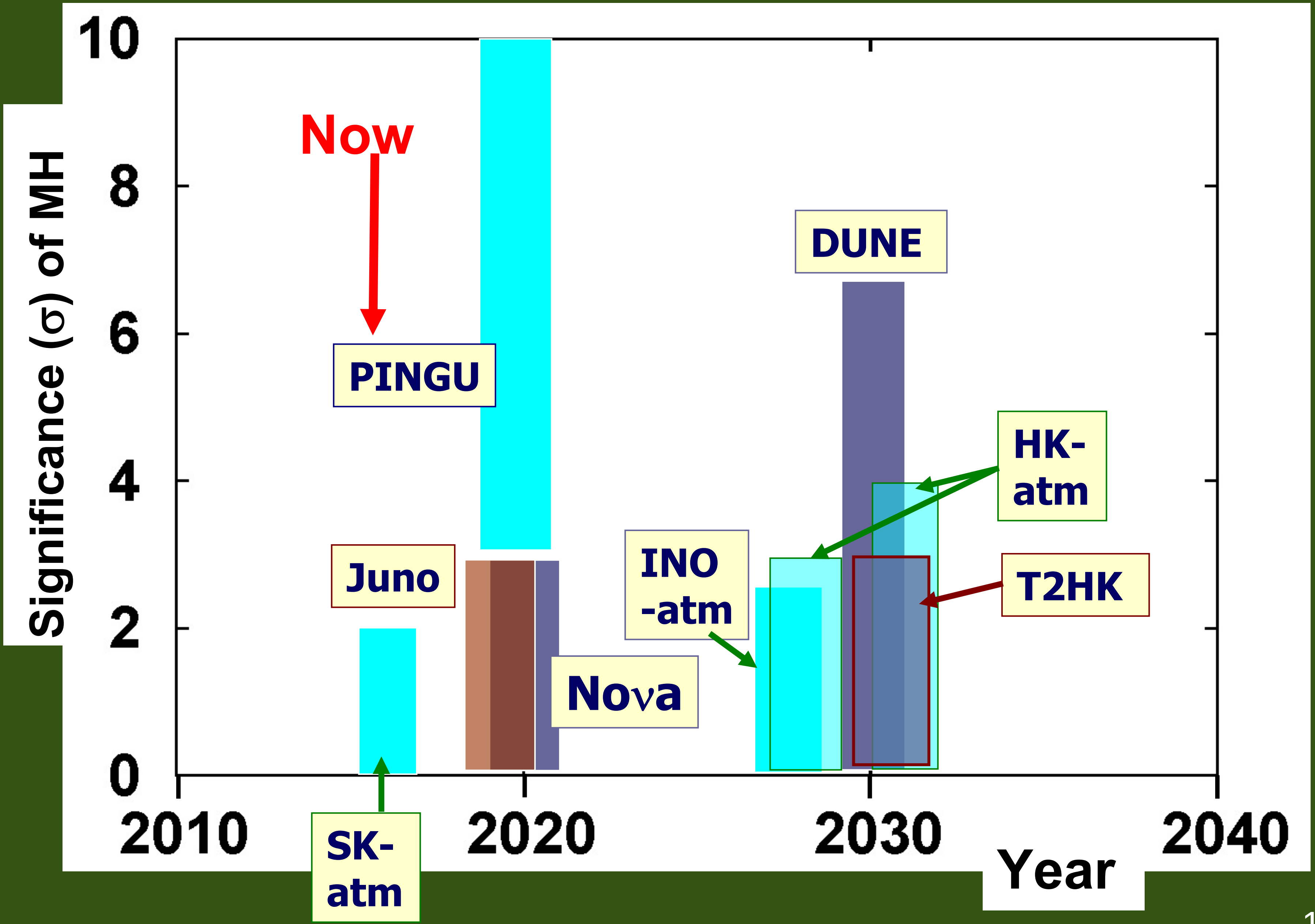
$\mathrm{sgn}(\Delta m^2_{31})$ can be deduced

$$\Delta \tilde{E}_{31} \equiv \left[(\Delta E_{31}\cos 2\theta_{13} - A)^2 + (\Delta E_{31}\sin 2\theta_{13})^2\right]^{1/2}$$

$$\Delta E_{31} \equiv \Delta m^2_{31}/2E, \quad A \equiv \sqrt{2} G_F N_e \cong 1/2000\mathrm{km} > 0$$

To identify $\mathrm{sgn}(\Delta m^2_{31})$, a longer baseline (L>1000km) will be necessary, because AL∼O(1) is necessary.

Future exp. vs Mass Hierarchy



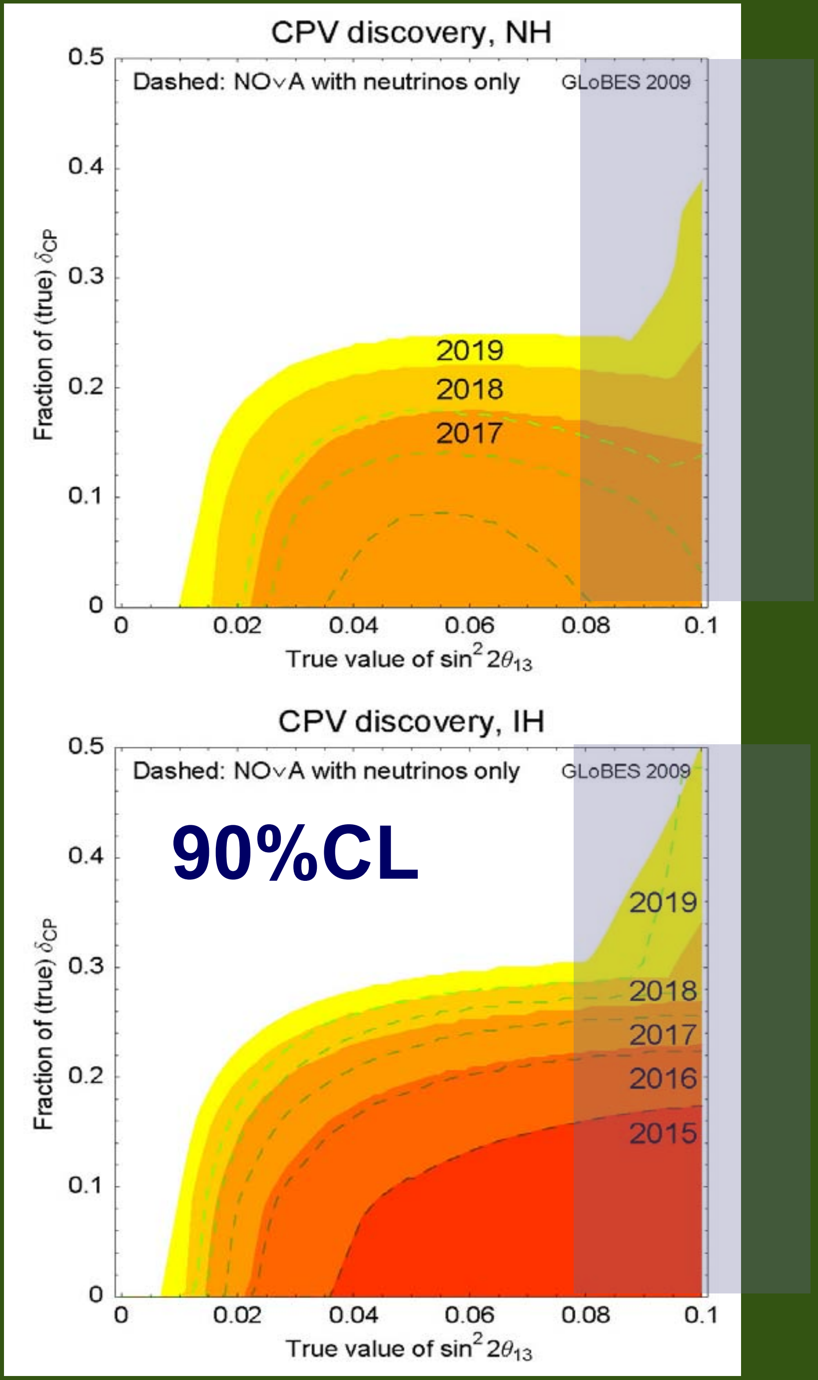
(2) Measurement of δ

$$\sin^2 2\theta_{13} = 0.09$$

Contribution of δ always comes with $\sin\theta_{13}$
→ Measurement of δ is difficult

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Sensitivity to δ at T2K & Nova



Huber et al., arXiv:0907.1896 v1

Proposed experiments

$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu + \overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$

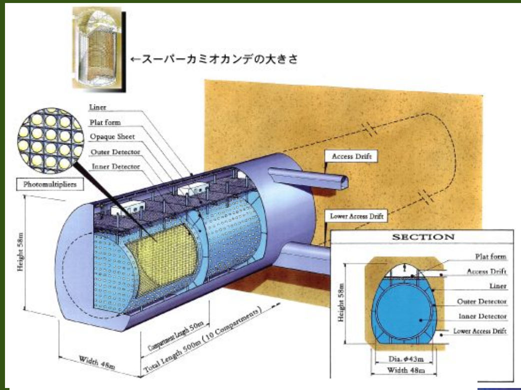
- **T2HK (JP, JPARC→HK) L=295km, E～0.6GeV**
- **DUNE (US, FNAL→Homestake, SD), E ～ 2GeV, L ～ 1300km**

Future plan: T2HK

- **Extension of T2K (large #(events))**

1.66MW ν beam ⇒ Hyperkamiokande
(300 times K2K) (20 times SK)

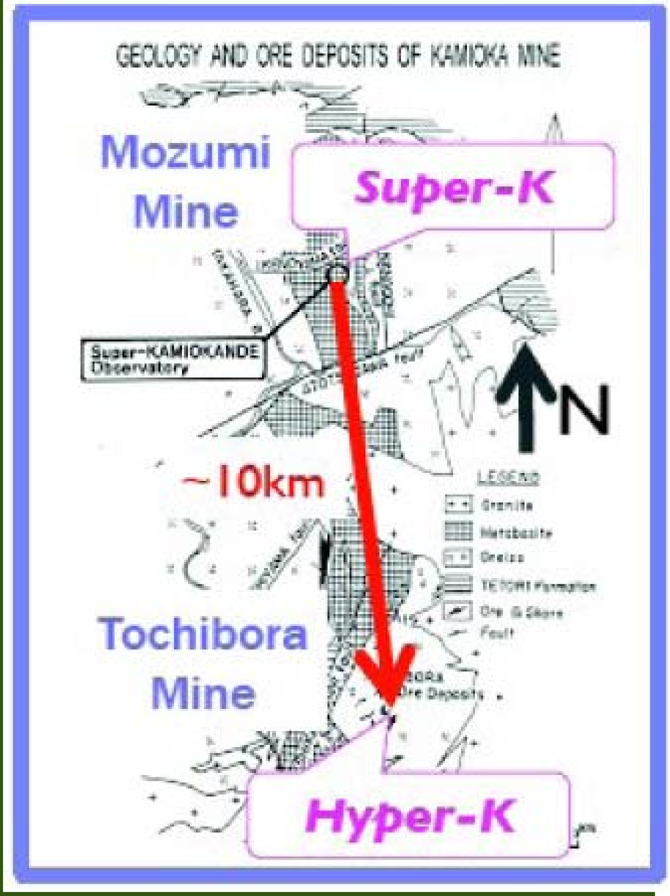
- **Main purpose: Measurement of CP phase δ**

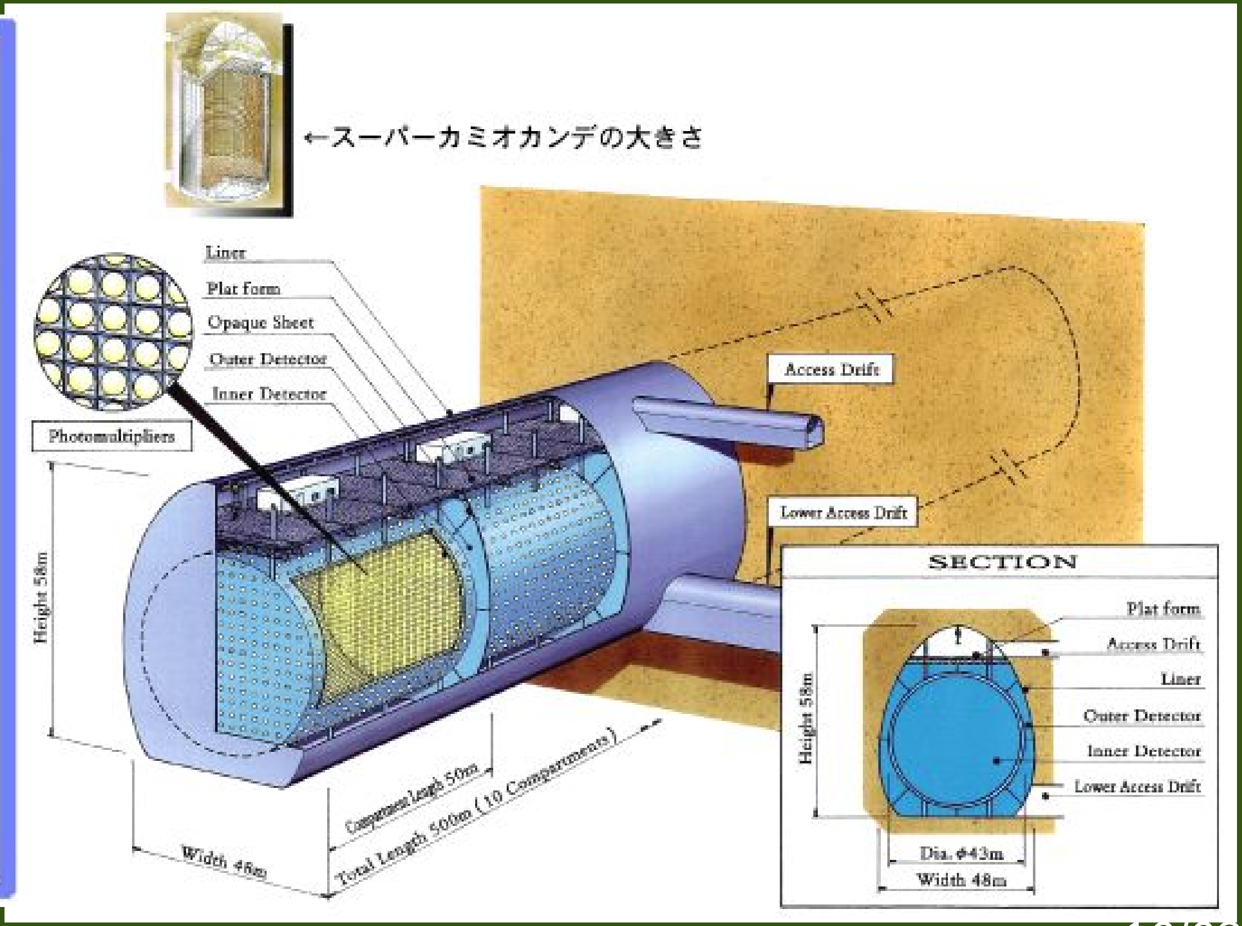


Hyper-kamiokande

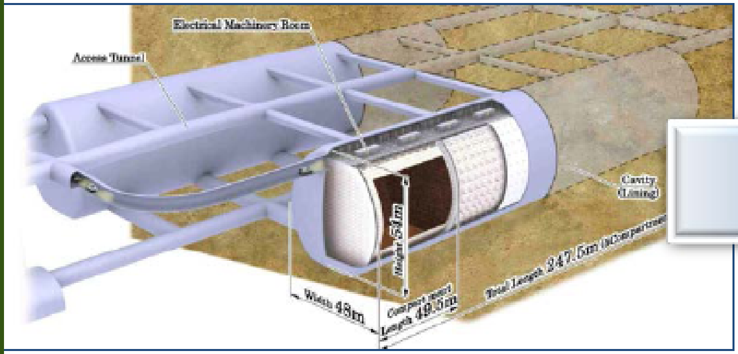
Hyperkamiokande (H_2O:0.5Mt=SKx10, 2025(?)-)

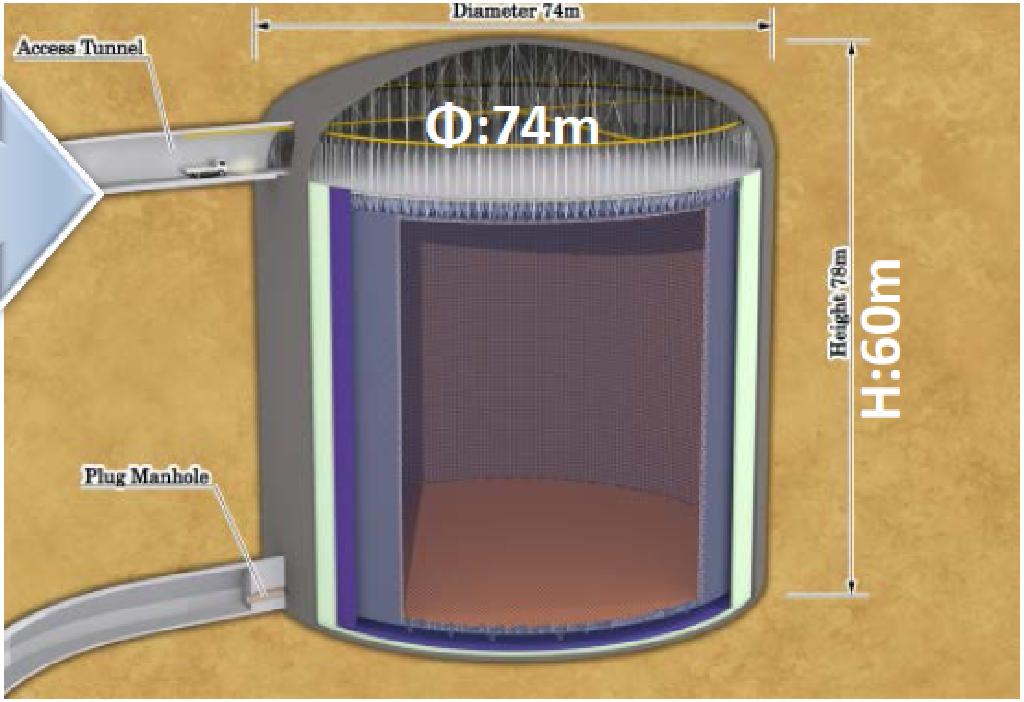
- Precision measurement of ν oscillation
- Further search for nucleon decays
- Precision measurement of supernova ν (if any)





New Hyper-K design





- New design similar to the present Super-K tank.
- 2 tanks with the staging construction.
- Cylindrical tank with Φ 74 meters and H 60 meters.
- The total and fiducial volumes (for one tank) are 0.26 and 0.19 Mtons, resp.
- Photo-cathode coverage is 40%. 40,000 ID PMTs and 6700 OD PMTs per tank.
- Planned time line: Project approval 2018, experiment 2026 (1st tank).

Kajita @ Atmospheric ν w/s, MIAPP, Feb. 2016

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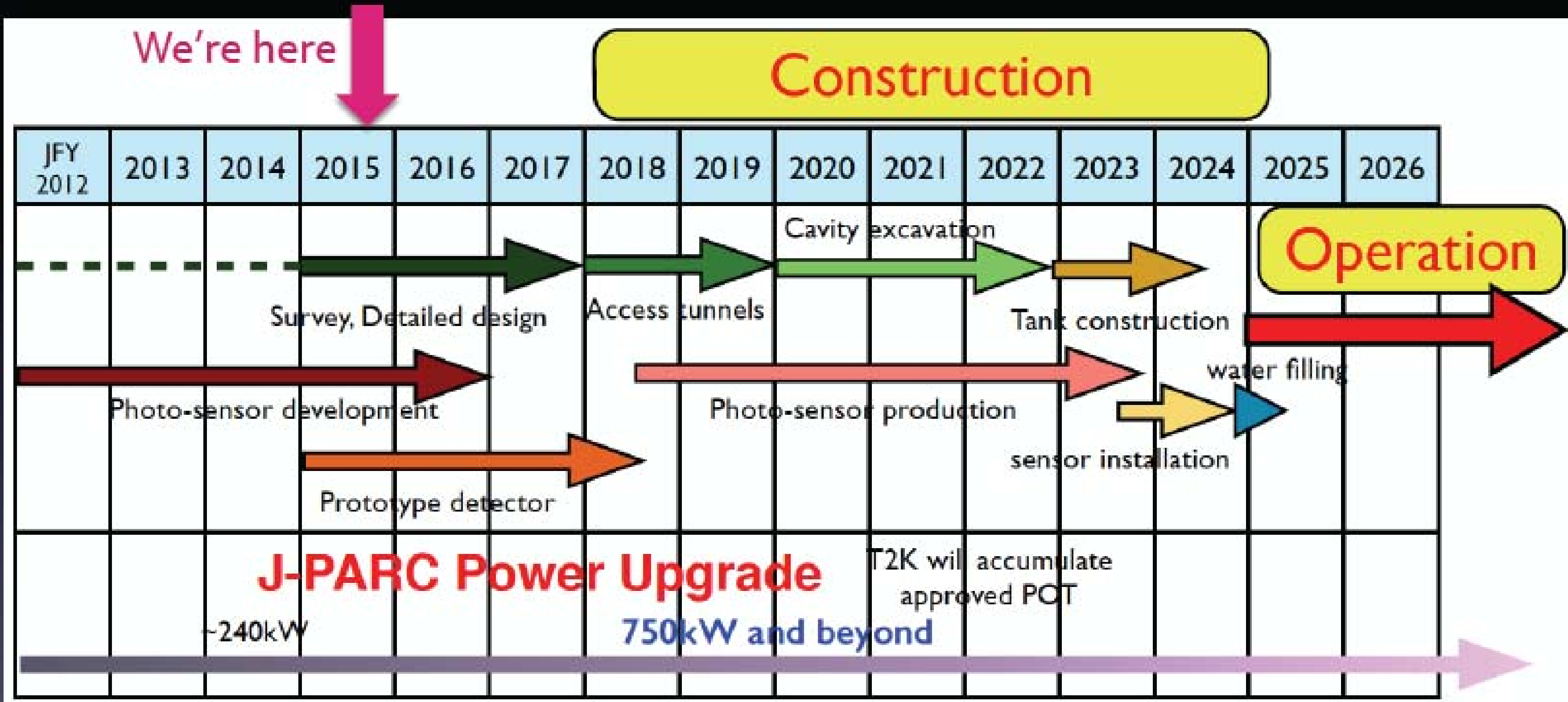
Notional (or Target) Timeline



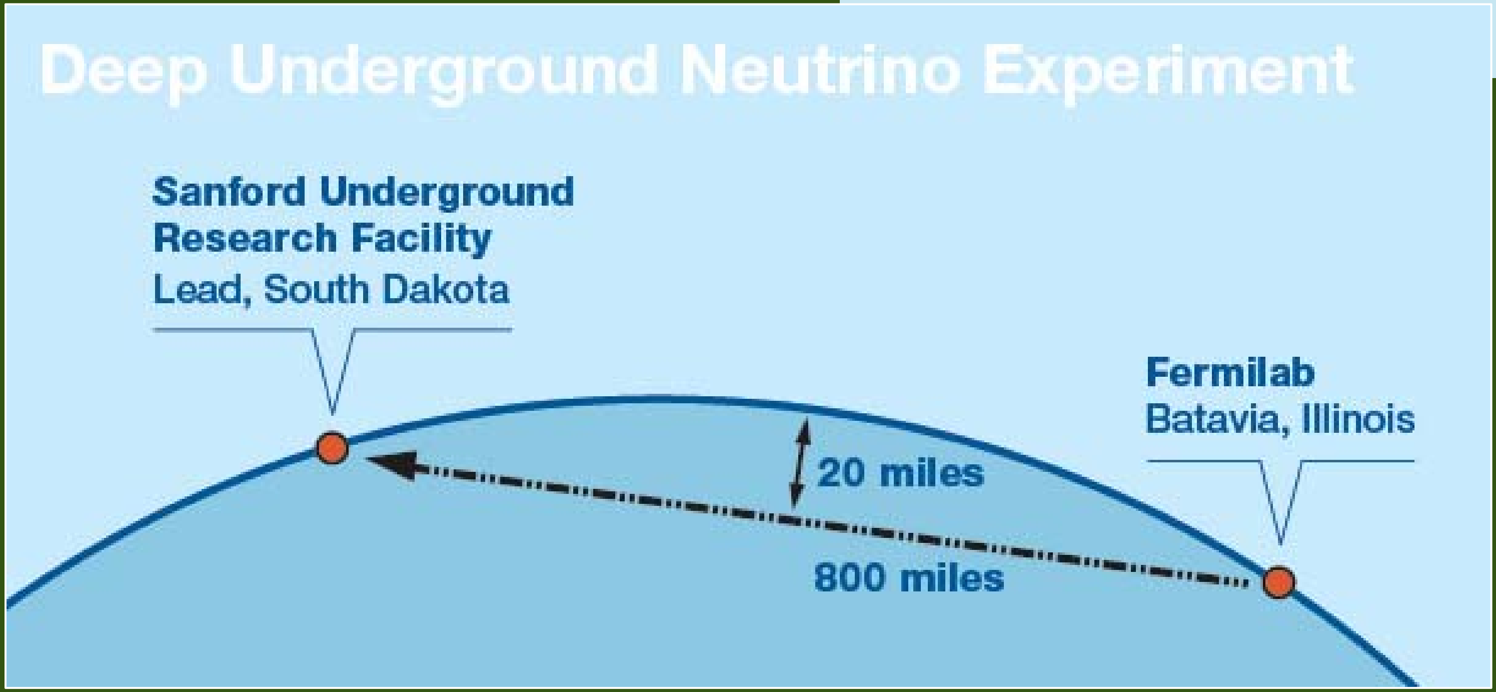
2016 Start making the detailed design
2018 Start the excavation
2025 Start the operation

Nakayama @ Nu Frontier W/S , Dec. 2015

Future plan: DUNE

2.3MW ν beam@Fermilab
⇒ 40-kt Liquid Argon detector @ Sanford Underground RF

E ∼ 2GeV, L ∼ 1300km



Schedule and Outlook

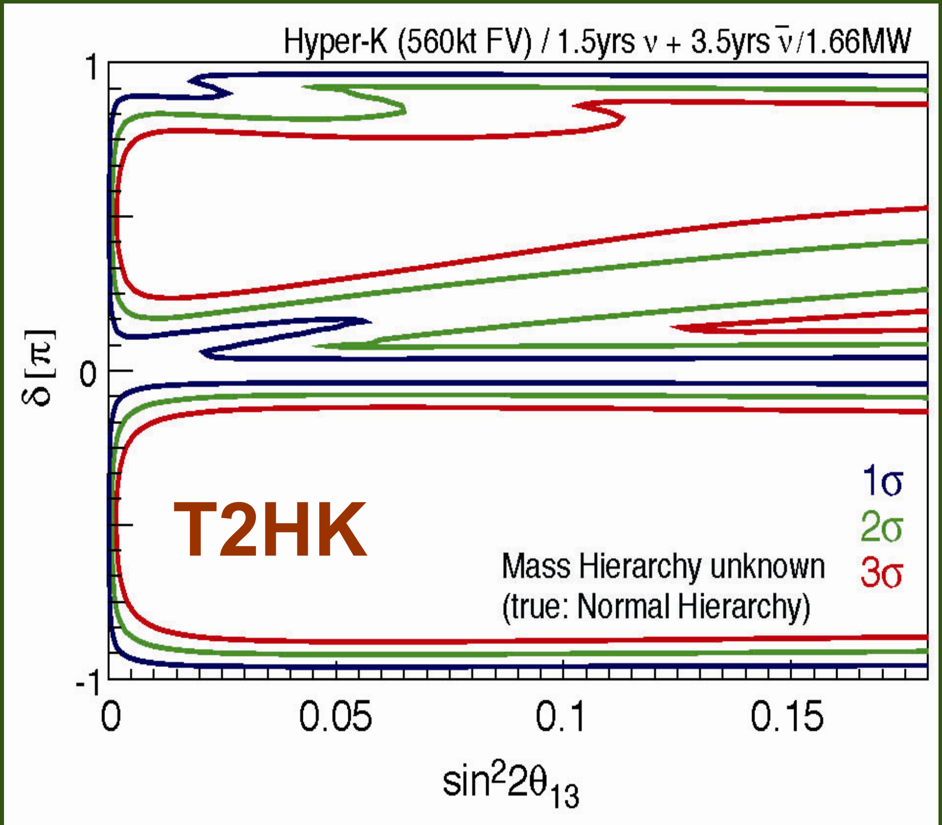
- DUNE has excellent prospect for major scientific discoveries such as leptonic CP-violation and MH, along with precision measurement of neutrino oscillation parameters.
- Deep underground location enables search for proton decay, supernova neutrinos and other astrophysics topics.

- *Schedule strongly dependent on funding profile from DOE and other agencies.*
- High level agreement negotiated between CERN, US DOE, India, etc.

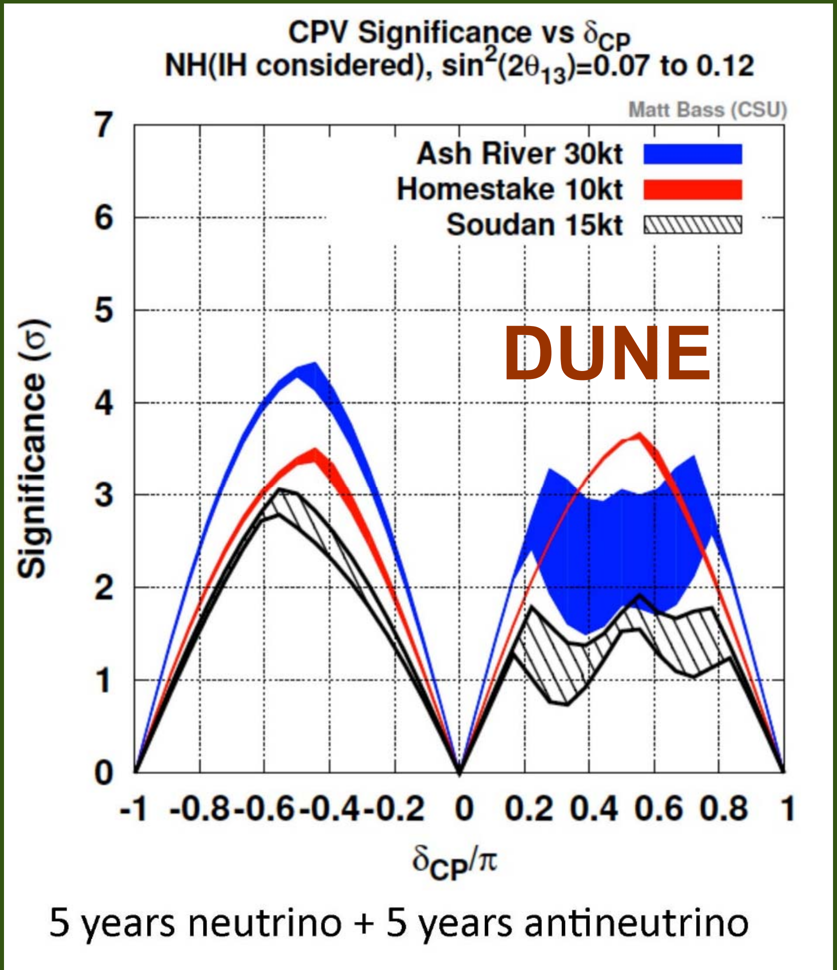
- Cavern excavation 2016-2017.
- First 10 kton FD module in 2021 with 1.2 MW beam.
- All four 10 kton modules by 20124 with upgraded

  2.4 MW neutrino beam.
- Final sensitivity goals can be achieved by 2035.

Sensitivity to δ at Future LBL experiments



Hyper-Kamiokande LOI, arXiv:1109.3262v1 [hep-ex]

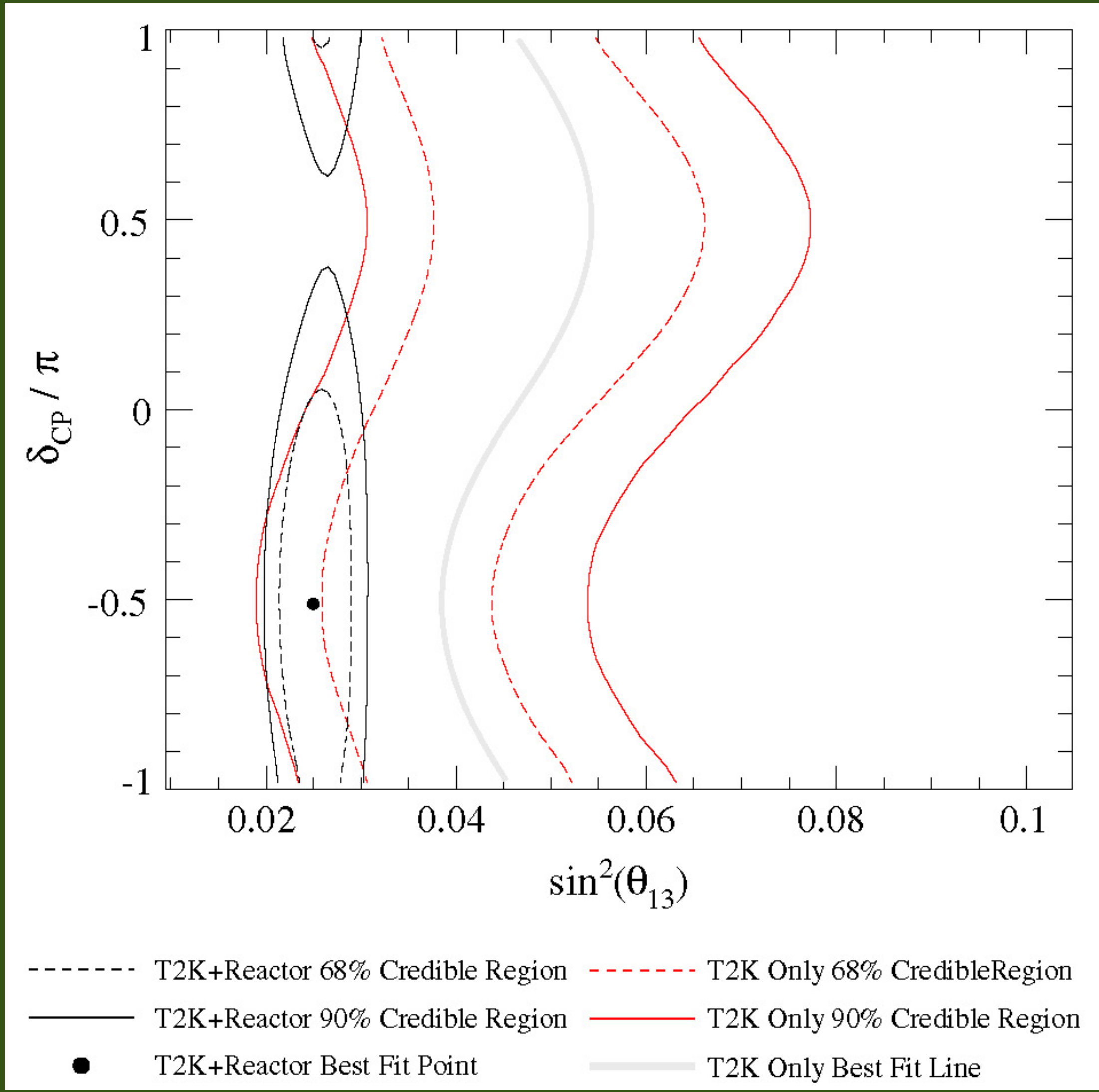


Svoboda@ν2012

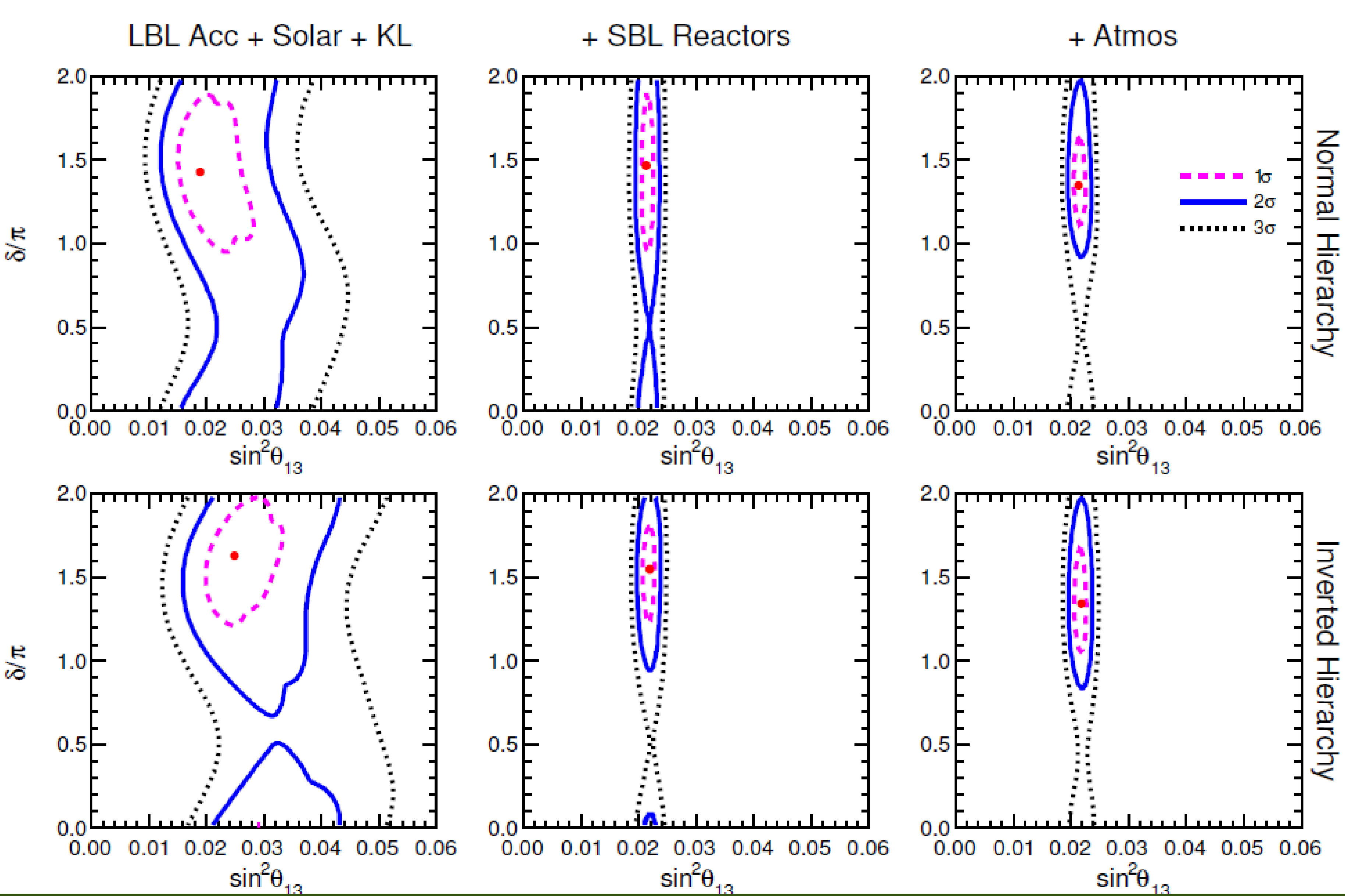
In the mean time,

T2K found ν_e appearance

T2K Collaboration, Phys.Rev. D91 (2015) 7, 072010 (Received 6 February 2015)



Result of global analysis



We even already have a hint on the value of δ: $\delta = -\pi/2$ seems to be favored

↓

Things are moving faster than we expected!

↓

In addition to the standard oscillation scenario, research on New Physics is important to give further motivations for future long baseline experiments.

2. New Physics probed by ν experiments

Motivation for research on New Physics

High precision measurements of ν oscillation in future experiments can be used to probe physics beyond SM by looking at deviation from SM+m_ν (like at B factories).
→ Research on New Physics is important.
It would give further motivations for T2HK & DUNE.

Scenario	3 flavor unitarity	Phenomenological constraints on the magnitude of the effects
Light sterile ν	×	O(10%)
NSI at production / detection	×	O(1%)
NSI in propagation	✓	e-τ: O(100%) Others: O(1%)
Unitarity violation due to heavy particles	×	O(0.1%)

2.1 Light sterile neutrinos (ν_s)

2.1.1 Motivation for ν_s

Sterile neutrinos have been phenomenologically motivated by the following:

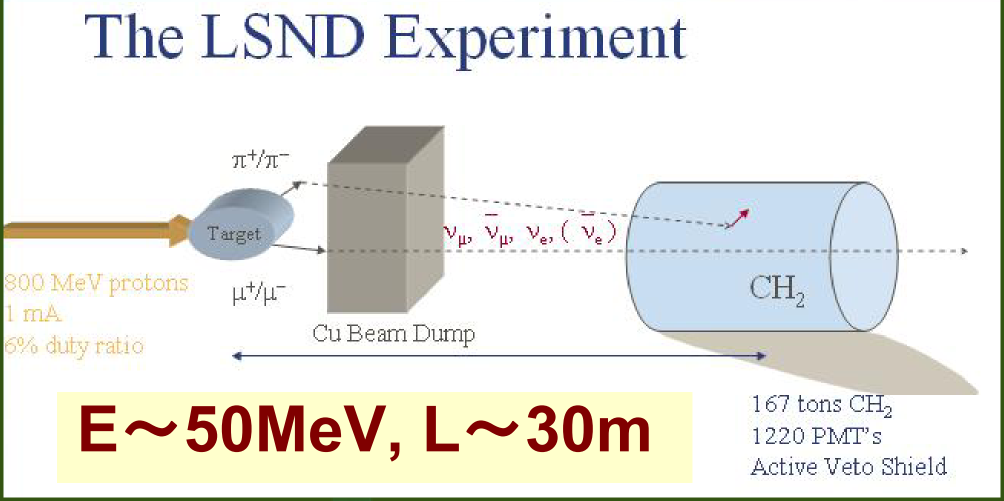
- **LSND anomaly**
- **Reactor anomaly**
- **Galium anomaly**
- **Some hint for ν_s from cosmological observations**

Sterile ν is not necessarily required from theory

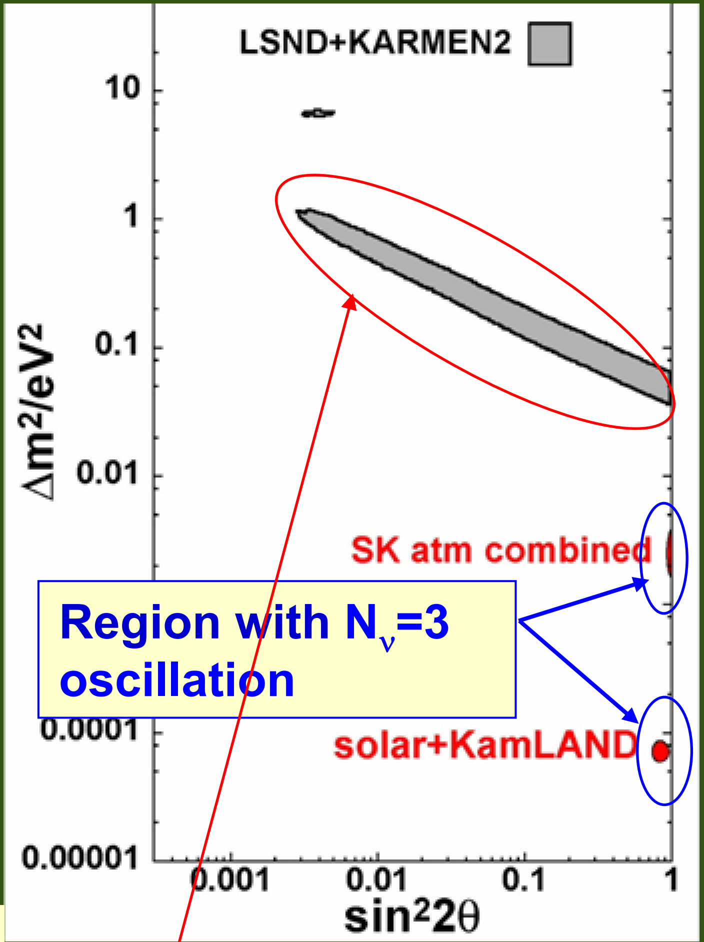
2.1.2 LSND anomaly

● LNSD experiment (1993-1998@LANL)

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



E～50MeV, L～30m



$$\Delta m^2 \cong O(1)eV^2, \sin^2 2\theta \cong O(10^{-2})$$??

It cannot be explained by N_ν=3 oscillation

→ LEP data

→ N_ν=3 active light ν

→ 4th ν must be sterile

2.1.3 MiniBooNE(2002-, FNAL)

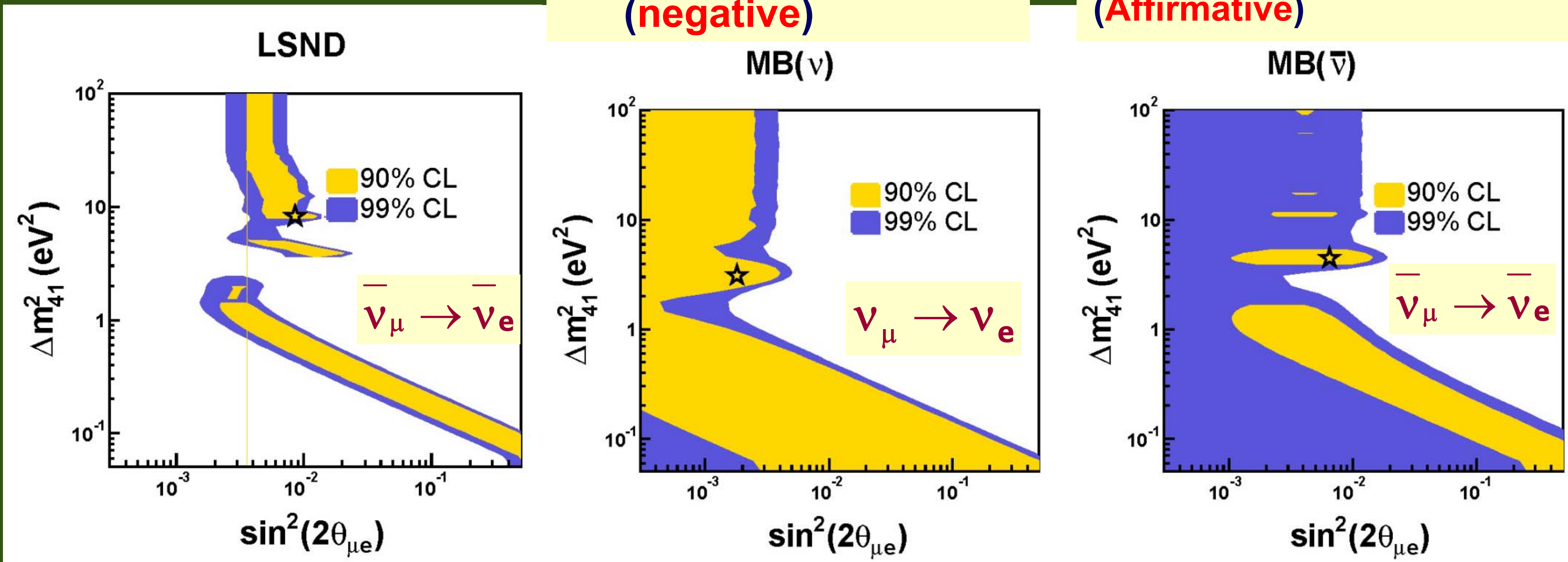
Aim was to check LSND

Karagiorgi, Djurcic, Conrad, Shaevitz, Sorel, Phys.Rev.D80:073001,2009.

E～1GeV, L～1km, $(L/E)_{MB}=(L/E)_{LSND}$

Neutrino mode(2007) (negative)

Antineutrino mode(2010) (Affirmative)



1995
Is LSND true?

2007
LSND was wrong!

2010
LSND was true?

Sterile neutrino oscillation!?

2.1.4 Reactor ν anomaly

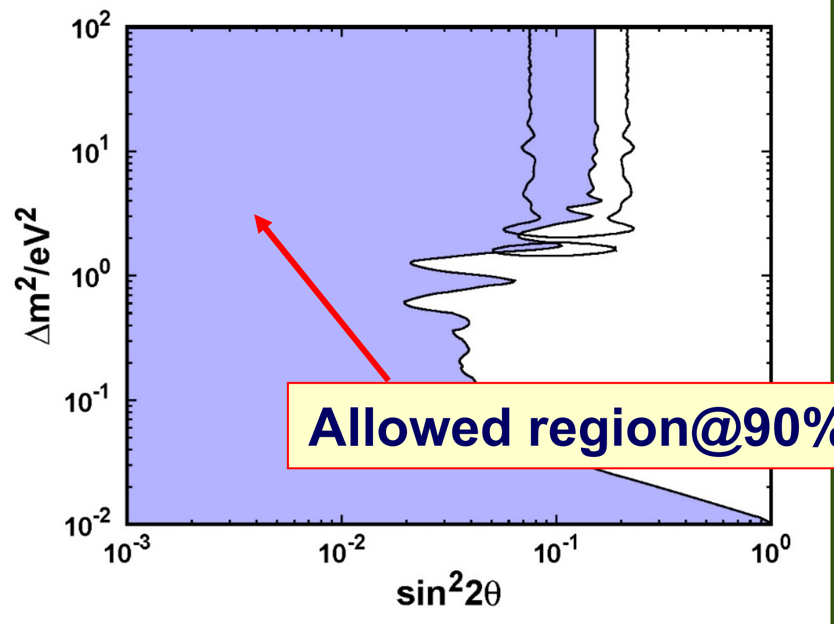
Mention et al, PRD83 (2011) 073006

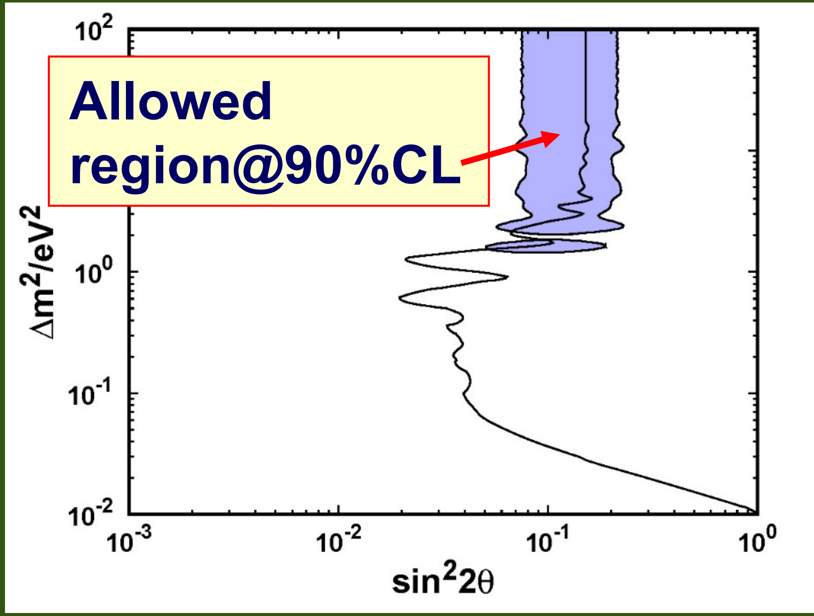
Recent reevaluation of reactor ν flux suggests affirmative interpretation of $\bar{\nu}_e \rightarrow \bar{\nu}_e$ oscillation

(new flux)= (old flux) x 1.03

Bugey(reactor $\bar{\nu}_e \rightarrow \bar{\nu}_e$):
Negative w/ old flux

Bugey(reactor)+etc:
Affirmative w/ new flux?



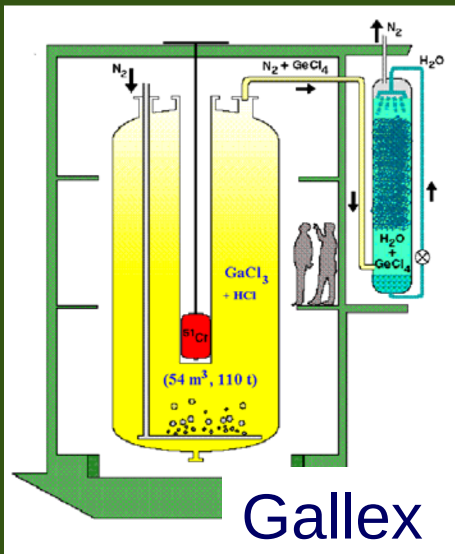


No ν oscillation for $\Delta m^2_{41} = O(1)\, eV^2$

ν oscillation may exist for $\Delta m^2_{41} = O(1)\, eV^2$

2.1.5 Galium anomaly

Calibration of Ga solar ν experiments

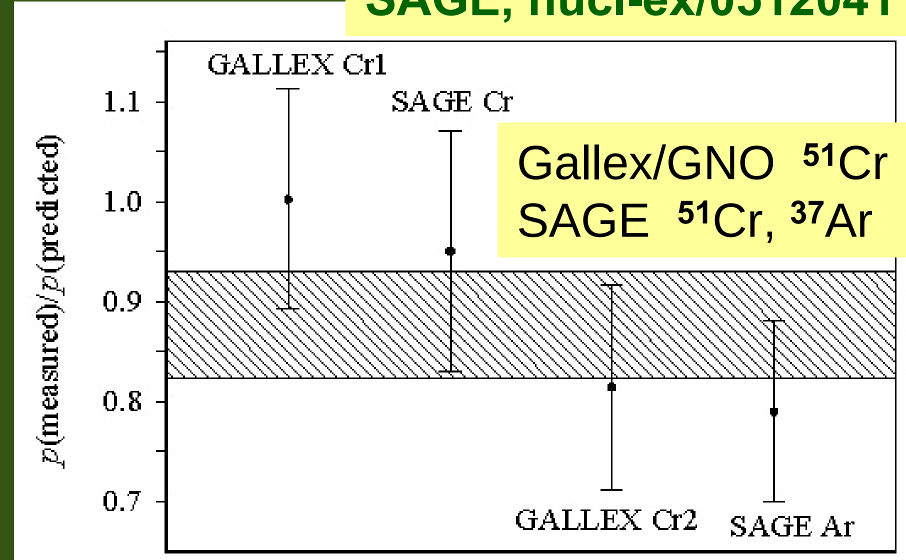


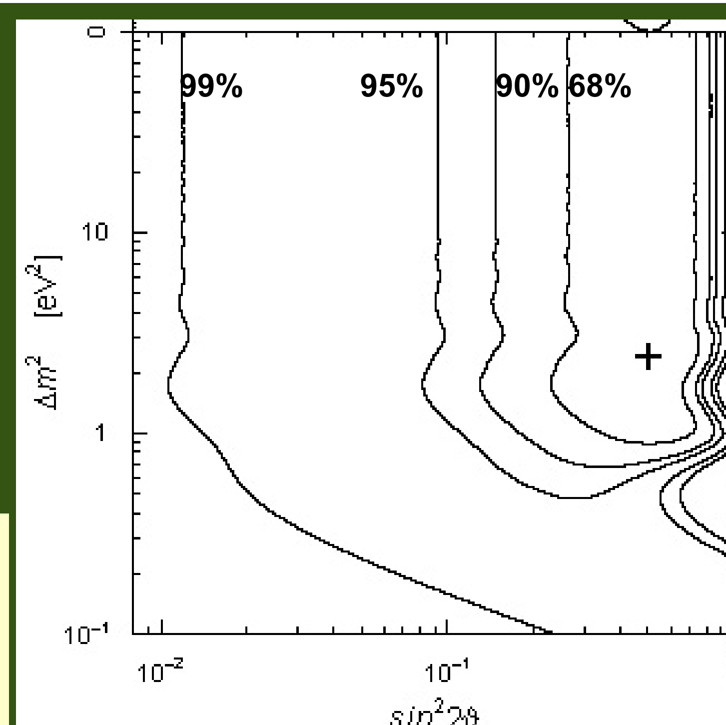
$$R \equiv \frac{\mathrm{p(measured)}}{\mathrm{p(predicted)}} = 0.88 \pm 0.05 (1\sigma)$$

Giunti-Laveder, 1006.3244v3 [hep-ph]

Results of Ga solar ν exp. can be interpreted as ν_e disappearance due to active-sterile ν oscillation

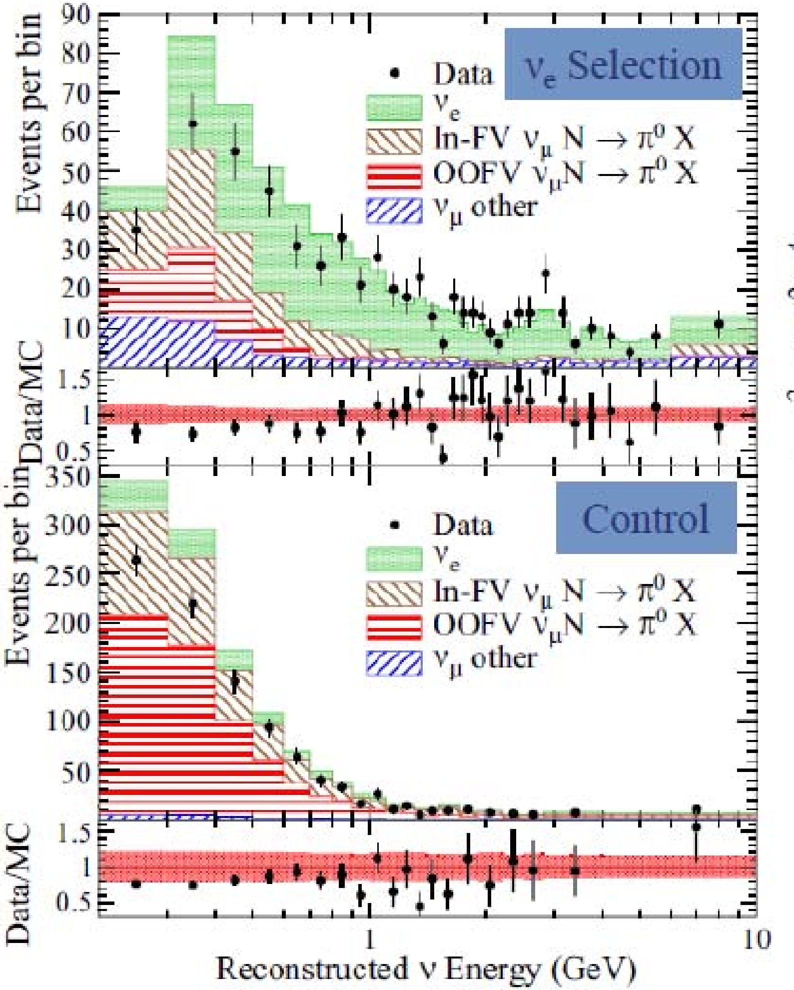
SAGE, nucl-ex/0512041



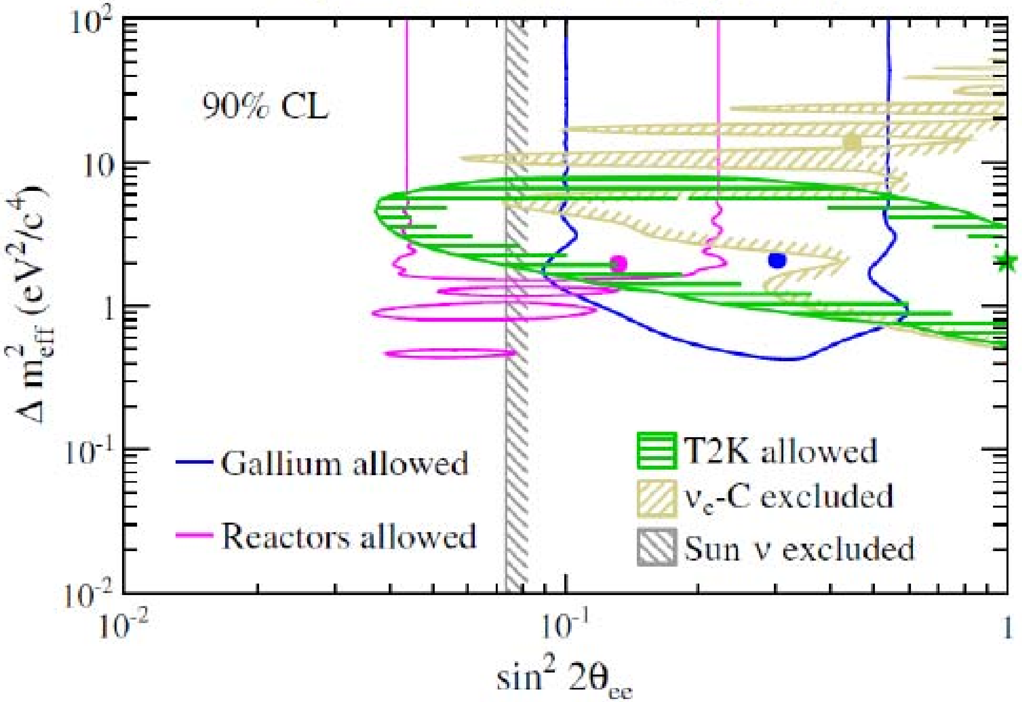


T2K Near Detector (ν_e Disappearance)

Although the T2K beam is predominantly a ν_μ beam, the small ν_e component can be used in the near detector for a ν_e disappearance search.

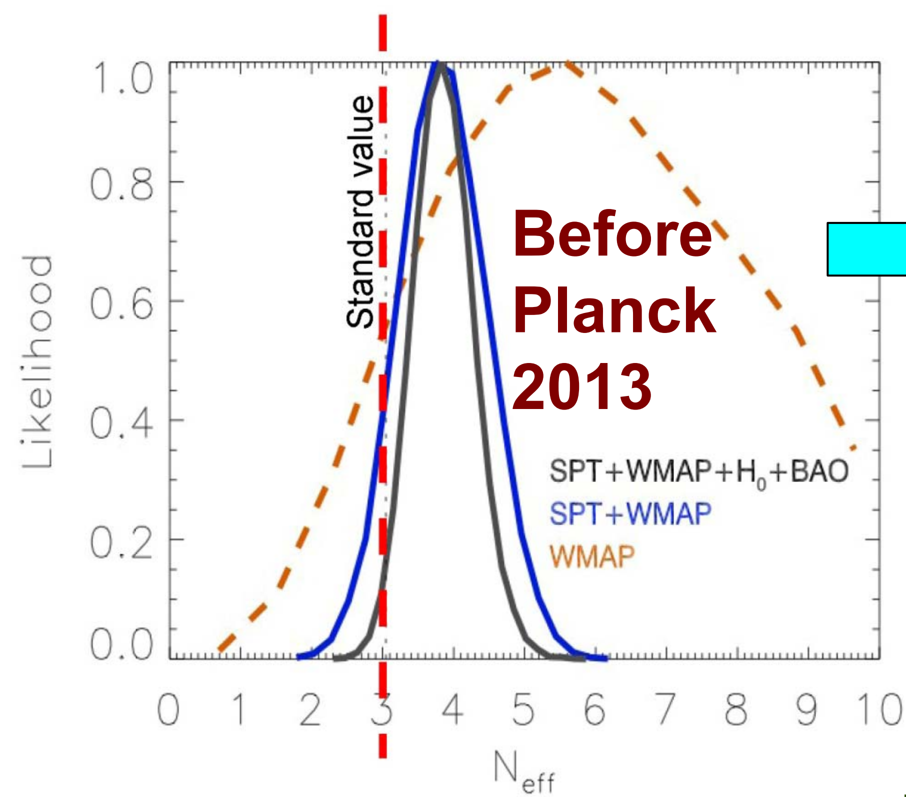


Phys.Rev. D91, 051102(R) (2015)

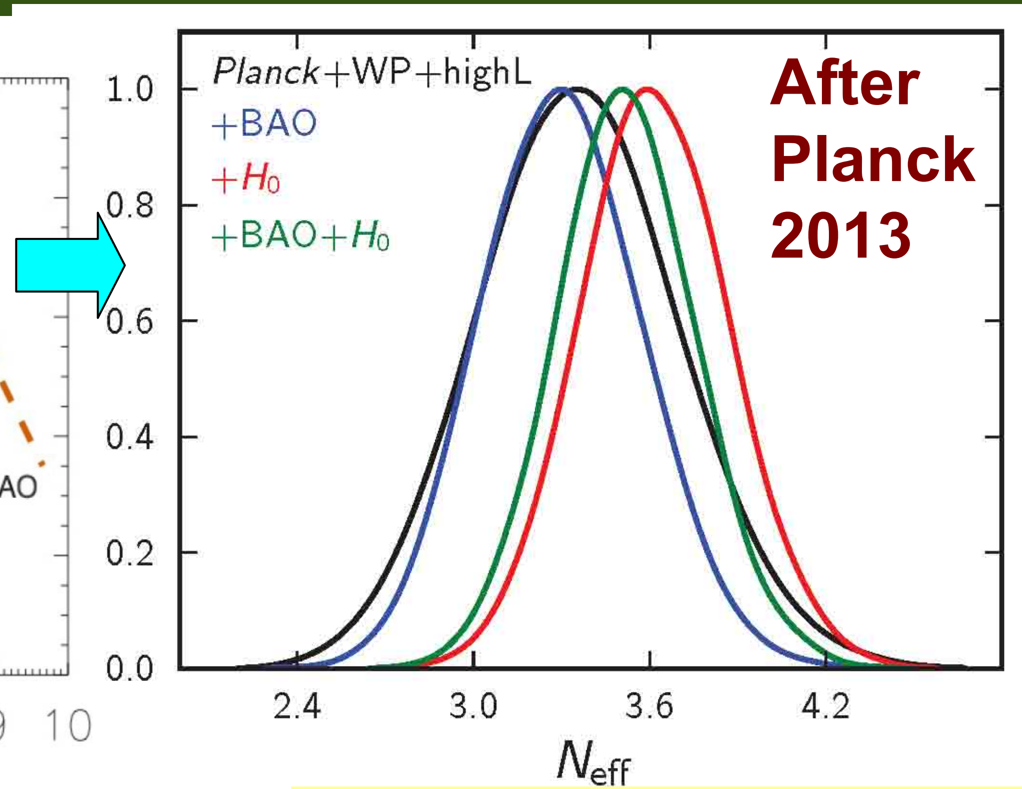


Short-baseline ν_e appearance from the much larger ν_μ component of the beam could fill in the exact region depleted by disappearance, so it is assumed to be zero in this analysis.

2.1.7 Cosmological Observation (CMB+LSS)→N_ν > 3 ?



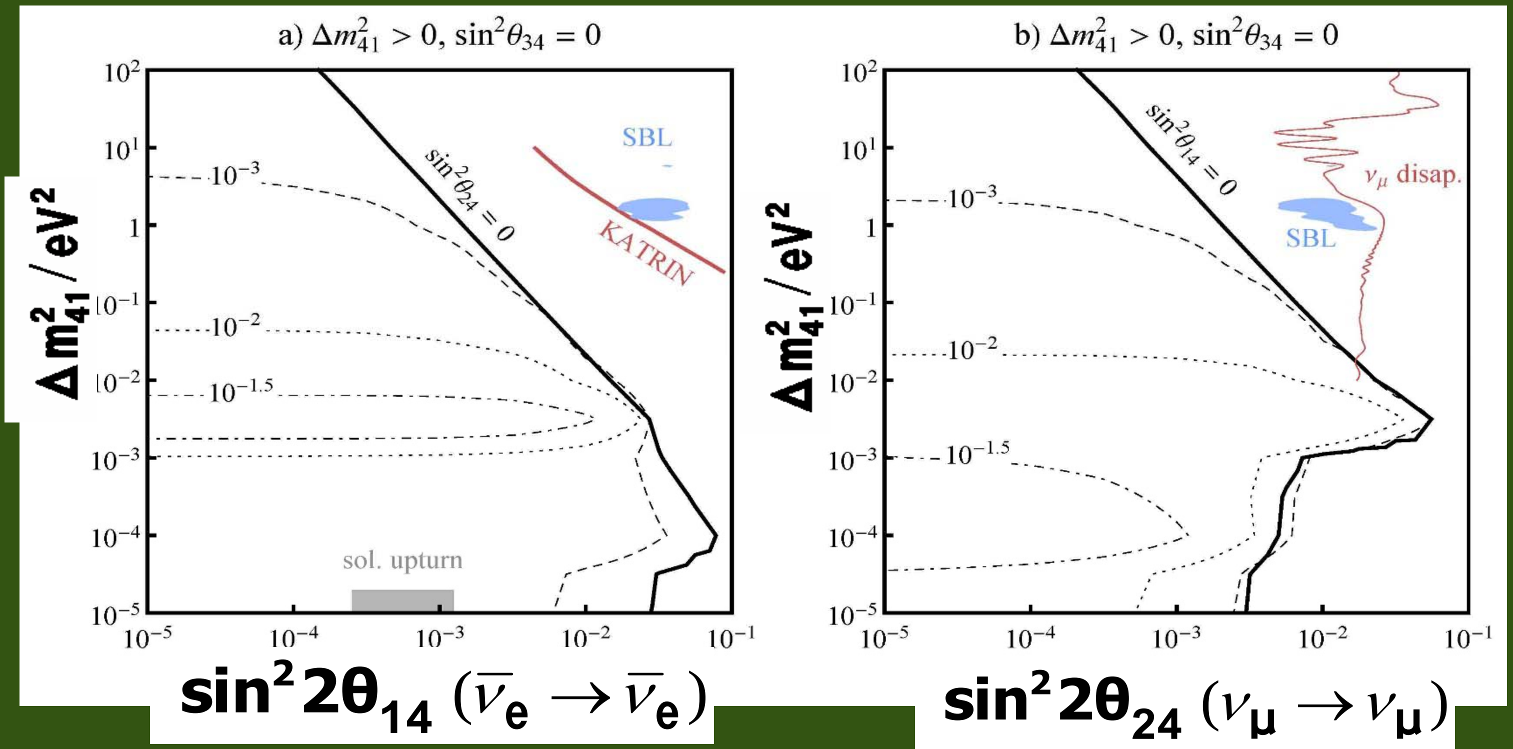
Keisler et al. [South Pole Telescope] 2011



Planck 2013 results. XVI, Cosmological parameters, arXiv:1303.5076v1

There seems to be conflict between cosmological observations → It may be premature to conclude $N_\nu = 3$ (or $N_\nu > 3$).

2.1.7' Cosmological Observation(Planck2013) → Is ν_s oscillation dead？



Mirizzi, Mangano, Saviano, Borriello, Giunti, Miele, Pisanti, arXiv:1303.5368

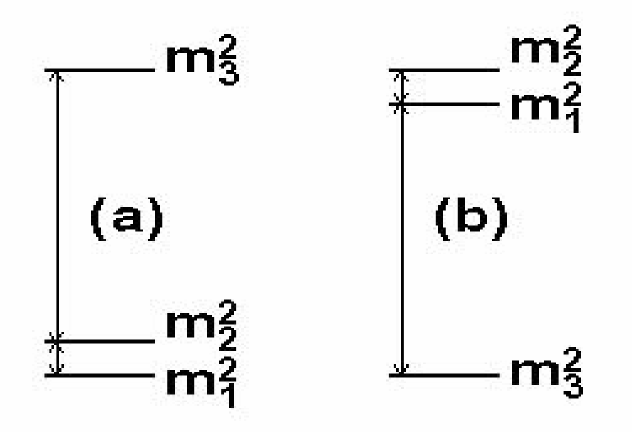
→Even if the negative result of Planck2013 is confirmed, it is still possible that ν_s has never been in thermal equilibrium due to lepton asymmetry → ν_s oscillation is still possible

2.1.8 Oscillation with N_ν=4 schemes

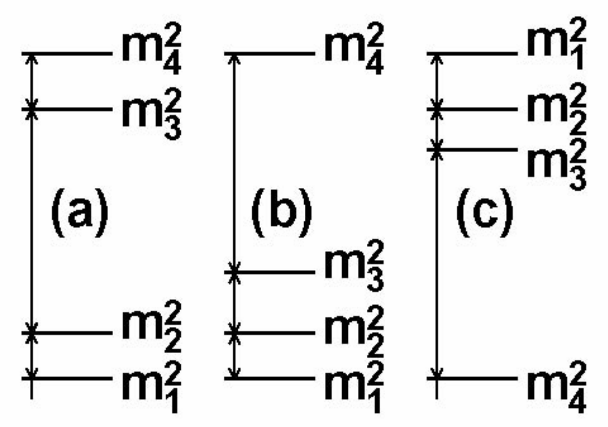
Because of the hierarchy: $\Delta m^2_{sol} << \Delta m^2_{atm} << \Delta m^2_{LSND}$

N_ν=3 schemes can't explain LSND.

$$\Delta m^2_{21} = \Delta m^2_{sol}, \Delta m^2_{32} = \Delta m^2_{atm}$$



N_ν=4 schemes may be able to explain all.



LEP ➔ 4th ν has to be sterile

$$\Delta m^2_{21} = \Delta m^2_{sol}, \Delta m^2_{32} = \Delta m^2_{atm}, \Delta m^2_{43} = \Delta m^2_{LSND}$$

Matter effects of neutrinos

$$i\frac{\partial}{\partial t}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} = \left[U\begin{pmatrix}E_1 & 0 & 0 & 0\\ 0 & E_2 & 0 & 0\\ 0 & 0 & E_3 & 0\\ 0 & 0 & 0 & E_4\end{pmatrix}U^{-1} + \begin{pmatrix}A_e + A_n & 0 & 0 & 0\\ 0 & A_n & 0 & 0\\ 0 & 0 & A_n & 0\\ 0 & 0 & 0 & 0\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix}$$

$$A_e \equiv \sqrt{2}G_F N_e, \quad A_n \equiv -\frac{G_F N_n}{\sqrt{2}}$$

The term which is proportional to identity can be ignored

$$i\frac{\partial}{\partial t}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} = \left[U\begin{pmatrix}0 & 0 & 0 & 0\\ 0 & \Delta E_{21} & 0 & 0\\ 0 & 0 & \Delta E_{31} & 0\\ 0 & 0 & 0 & \Delta E_{41}\end{pmatrix}U^{-1} + \begin{pmatrix}A_e & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & -A_n\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix}$$

Matter effects of neutrinos

	ν_e	ν_μ, ν_τ	ν_s
CC	✓	×	×
NC	✓	✓	×
V	$A_e + A_n$	A_n	0

$$A_e = \sqrt{2} G_F N_e$$

$$A_n = -(1/\sqrt{2}) G_F N_n$$

N_ν=2 framework

$\nu_e \leftrightarrow \nu_\mu \quad \Delta A = A_e$

$\nu_\mu \leftrightarrow \nu_\tau \quad \Delta A = 0$

$\nu_\mu \leftrightarrow \nu_s \quad \Delta A = A_n$

2.1.8.1 (2+2)-scheme

Maltoni et al., hep-ph/0405172

$$\eta_s \equiv |U_{s1}|^2 + |U_{s2}|^2 \to 0$$

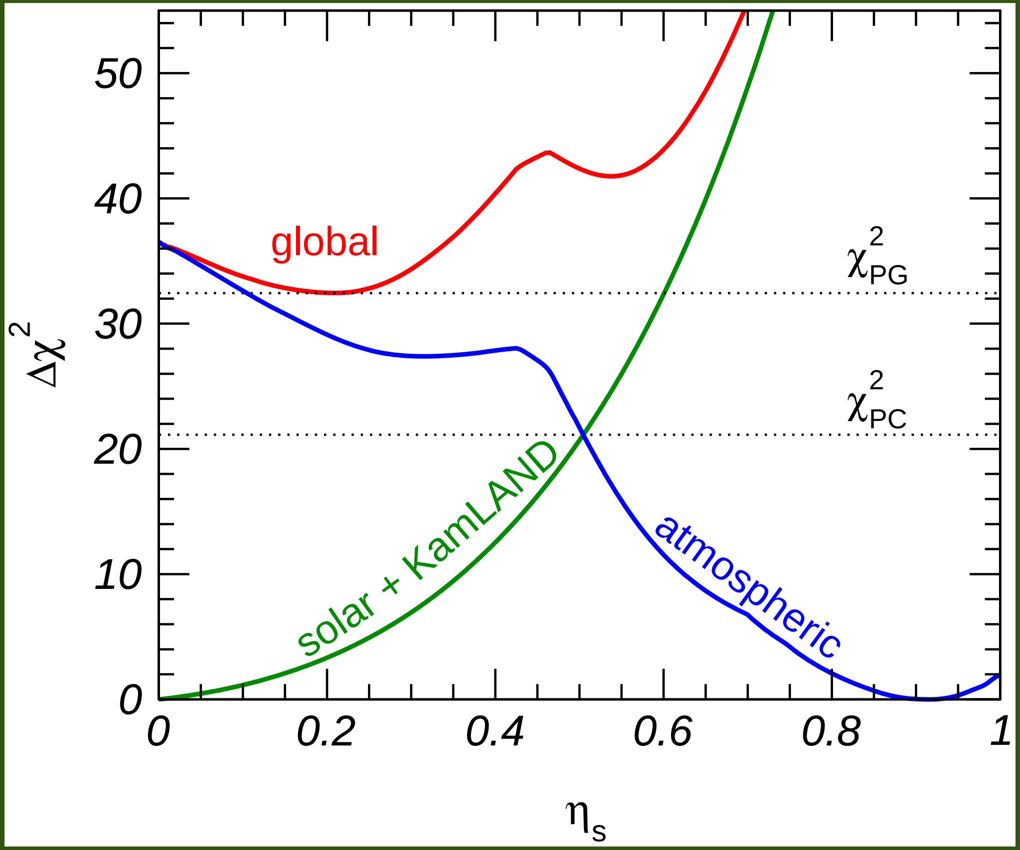
$$\nu_{atm} : \nu_\mu \to \nu_s (100\%)$$

Strongly disfavored by SK ν_{atm} data

$$\eta_s \equiv |U_{s1}|^2 + |U_{s2}|^2 \to 1$$

$$\nu_{sol} : \nu_e \to \nu_s (100\%)$$

Strongly disfavored by SNO ν_{sol} data



PC: parameter consistency test
PG: parameter goodness-of-fit test

For any value of $|U_{s1}|^2 + |U_{s2}|^2$, fit to sol+atm data is bad.

2.1.8.2 (3+1)-scheme

Bugey (reactor): negative

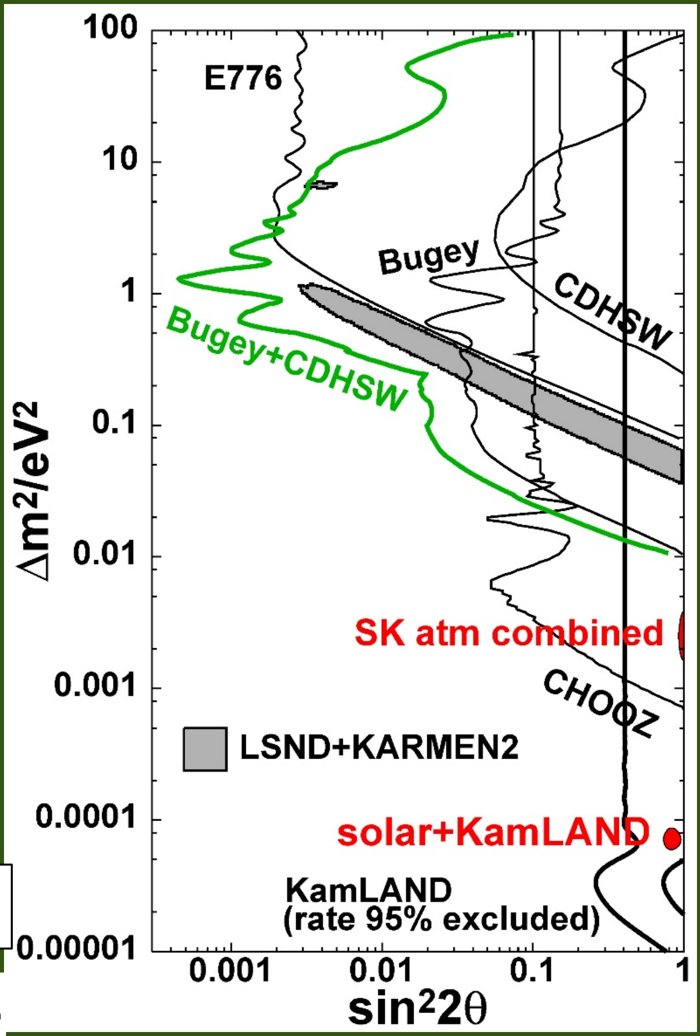
$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - 4|U_{e4}|^2(1-|U_{e4}|^2)\sin^2(\Delta m^2_{41}L/4E)$$

$$\sin^2 2\theta_{\rm Bugey} > 4|U_{e4}|^2(1-|U_{e4}|^2) \cong 4|U_{e4}|^2$$

CDHSW (accelerator): negative

$$P(\nu_\mu \to \nu_\mu) = 1 - 4|U_{\mu4}|^2(1-|U_{\mu4}|^2)\sin^2(\Delta m^2_{41}L/4E)$$

$$\sin^2 2\theta_{\rm CDHSW} > 4|U_{\mu4}|^2(1-|U_{\mu4}|^2) \cong 4|U_{\mu4}|^2$$



LSND (accelerator): affirmaive

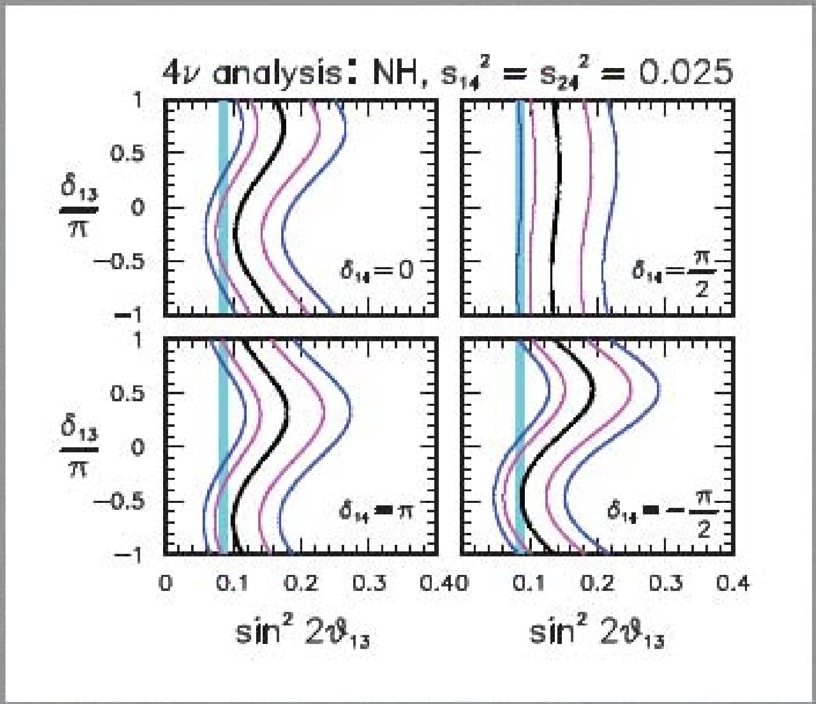
$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = 4|U_{e4}|^2|U_{\mu4}|^2\sin^2(\Delta m^2_{41}L/4E)$$

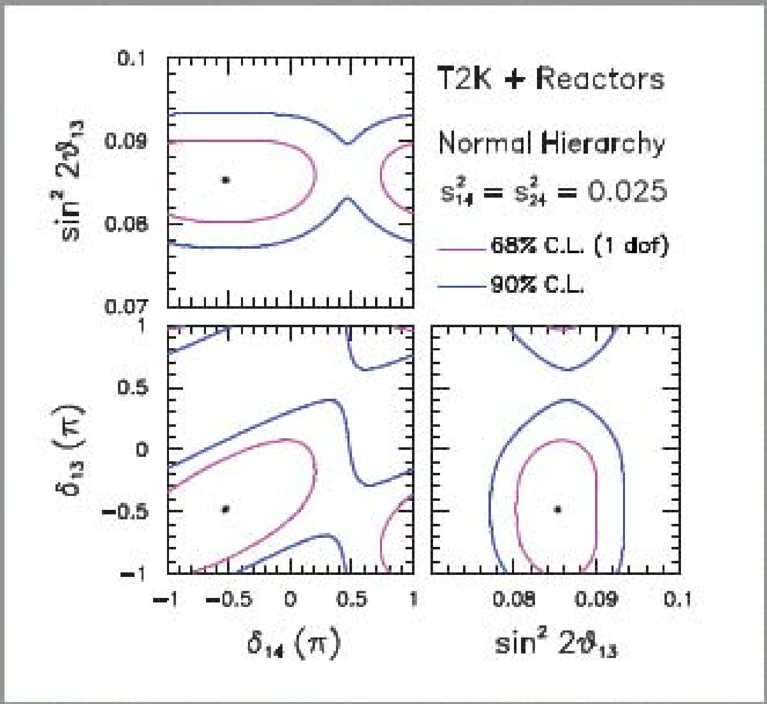
$$\sin^2 2\theta_{\rm LSND} = 4|U_{e4}|^2|U_{\mu4}|^2$$

$$\sin^2 2\theta_{\rm LSND}(\Delta m^2) < \frac{1}{4}\sin^2 2\theta_{\rm Bugey}(\Delta m^2)\sin^2 2\theta_{\rm CDHSW}(\Delta m^2)$$

must be satisfied but there is no overlap between the left side of Bugey+CDHSW and the inside of LSND (Okada-OY Int.J.Mod.Phys.A12:3669,1997)

Results of the 4ν analysis (NH)





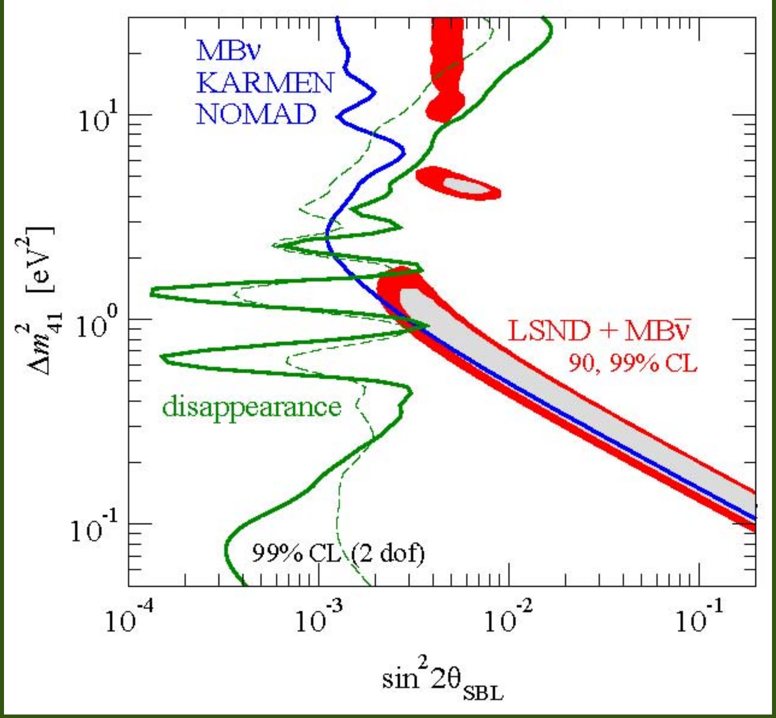
Similar findings in IH

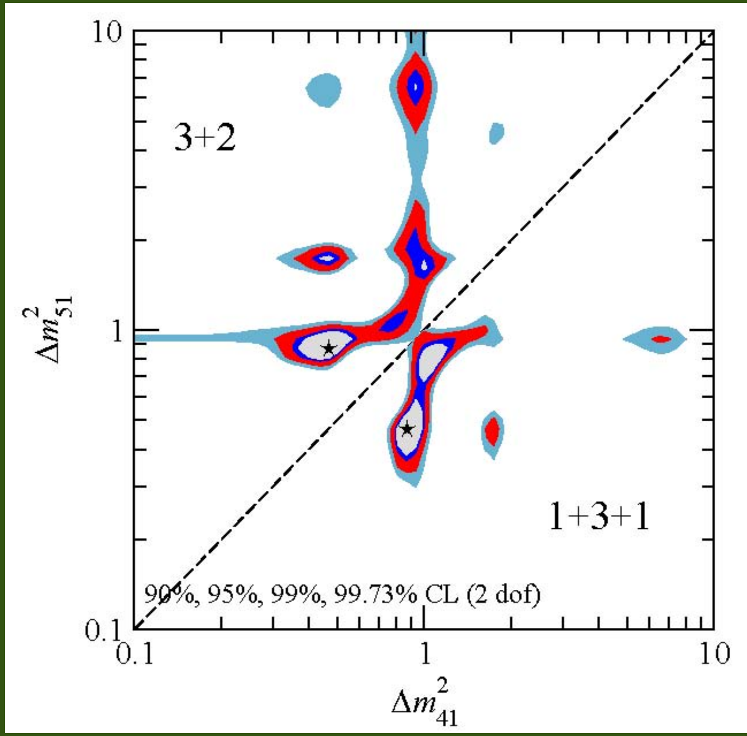
- Big impact on T2K "wiggles"
- Comparable sensitivity to δ_{13} & δ_{14}
- Best fit values: $\delta_{13} \sim \delta_{14} \sim -\pi/2$
- 4ν gives better agreement of T2K & Reactors

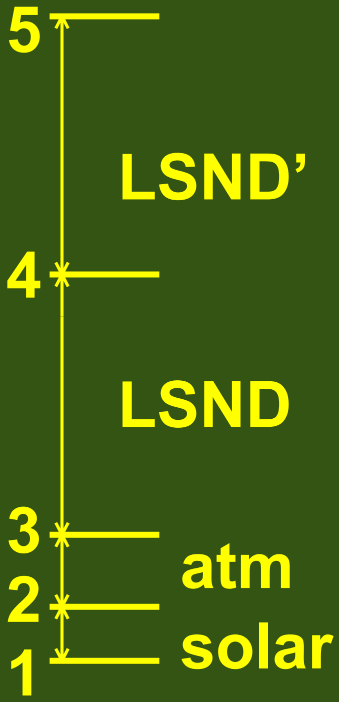
Palazzo, Nu@Fermilab, July 2015

2.1.8.3 (3+2)-scheme: With 2 kinds sterile ν, fit improves a little, but not much.

Kopp-Maltoni-Schwetz, arXiv:1103.4570v2 [hep-ph]







(3+2)-scheme is consistent w/ all the data @3% (excluded @ 97%CL; other scenarios fit even worse)

Ongoing & Future Short-Baseline Experiments

TAUP Presentations: Talks Posters

Accelerator Decay-in-Flight:

Fermilab Short-Baseline (SBND, MicroBooNE (Toups), ICARUS (Varanini))

T2K Near Detector nuSTORM

Accelerator Decay-at-Rest:

JSNS2@J-PARC, MLF

OscSNS IsoDAR KDAR/KPipe

Reactor Experiments:

Nucifer	Stereo (Haser)	Solid (Yarmia)
DANSS	POSIDON	Neutrino-4
CARR	Korean SBL	Prospect (Heeger)
NuLAT	CHANDLER	…

Radioactive Neutrino Sources:

SOX (Vivier) LZ-Cr (McKinsey) RICCOCHET

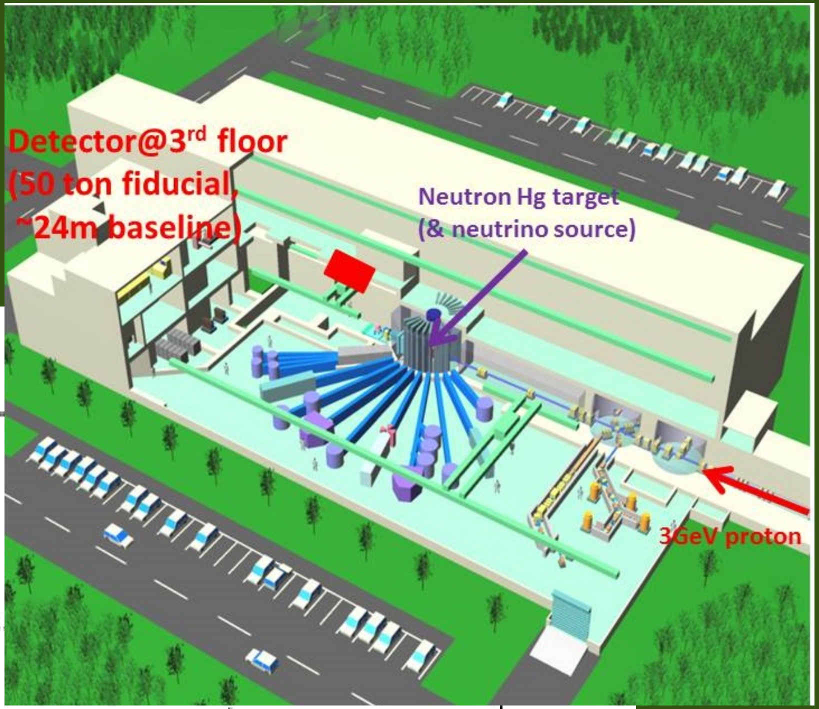
Sterile Searches that are not Short-Basline:

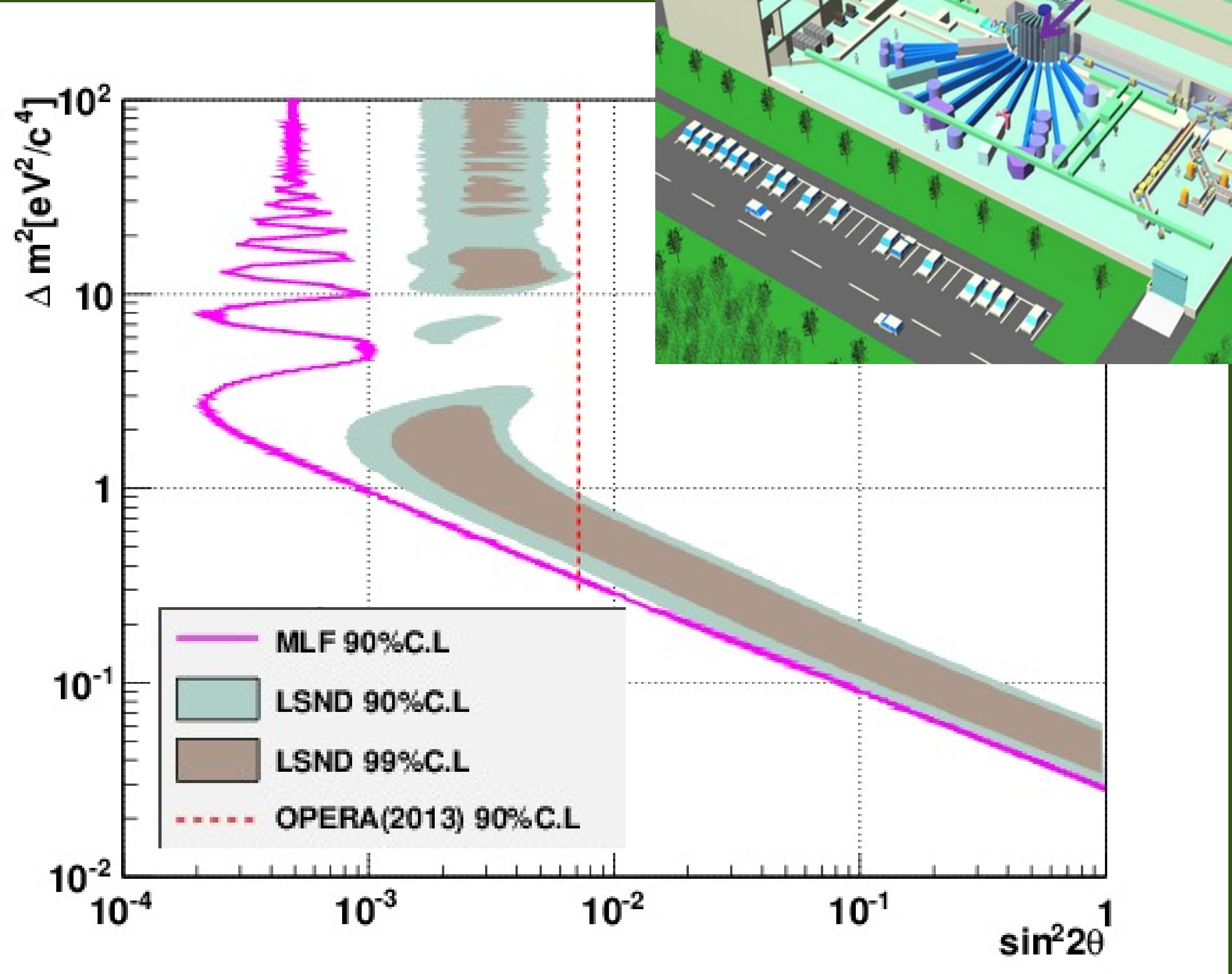
OPERA (Di Crescenzo)	IceCube (Salvado)	SHiP (De Serio)
MINOS+ (Holin)	Plank (Lattanzi)	KATRIN (Mertens)

Link@TAUP2015

JSNS2@J-PARC, MLF

Spokesperson: Takasumi Maruyama





2.1.9 Deficit due to ν_s oscillations

In 2 flavor ν_s oscillation framework

$$i\frac{d}{dx}\begin{pmatrix}\nu_\mu \\ \nu_s\end{pmatrix} = \left[U\begin{pmatrix}E_1 & 0 \\ 0 & E_2\end{pmatrix}U^{-1} + \begin{pmatrix}0 & 0 \\ 0 & A_n\end{pmatrix}\right]\begin{pmatrix}\nu_\mu \\ \nu_s\end{pmatrix}$$

$$U = \begin{pmatrix}\cos\theta & -\sin\theta \\ \sin\theta & \cos\theta\end{pmatrix} = \exp(-i\sigma_2\theta)$$

$$A_n = -(1/\sqrt{2})G_F N_n$$

If N_n=const.

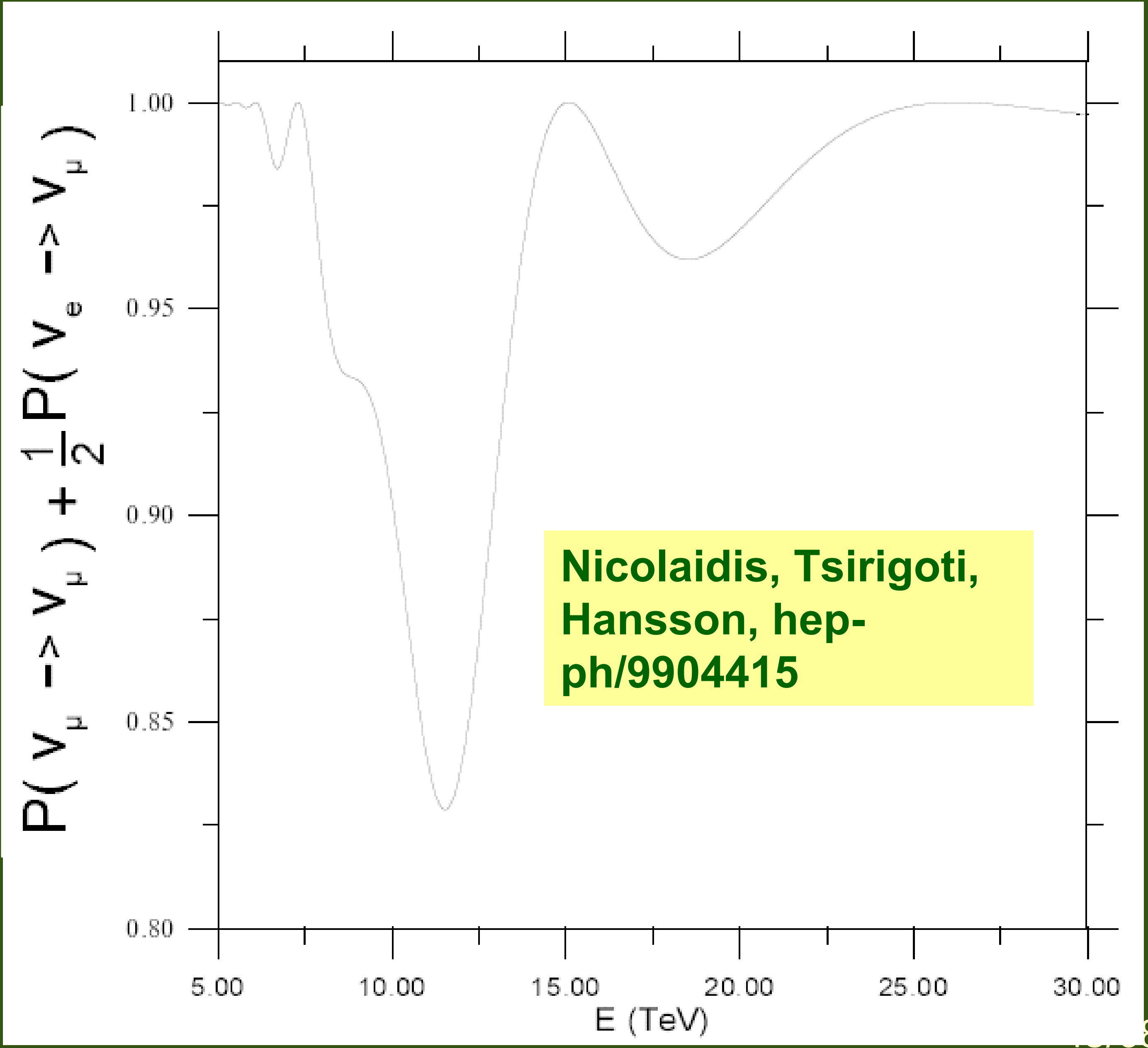
$$P(\nu_\mu \to \nu_s) = \sin^2 2\tilde{\theta}\,\sin^2\left(\frac{\Delta\tilde{E}L}{2}\right)$$

$$\Delta\tilde{E} \equiv \left[(\Delta E\cos 2\theta + A_n)^2 + (\Delta E\sin 2\theta)^2\right]^{1/2}$$

$$\tan 2\tilde{\theta} \equiv \frac{\Delta E\sin 2\theta}{\Delta E\cos 2\theta + A_n}$$

For $\Delta m^2 \sim 10\,\mathrm{eV}^2$,
$\tilde{\theta} = \pi/4$ at $E \sim 10\,\mathrm{TeV}$

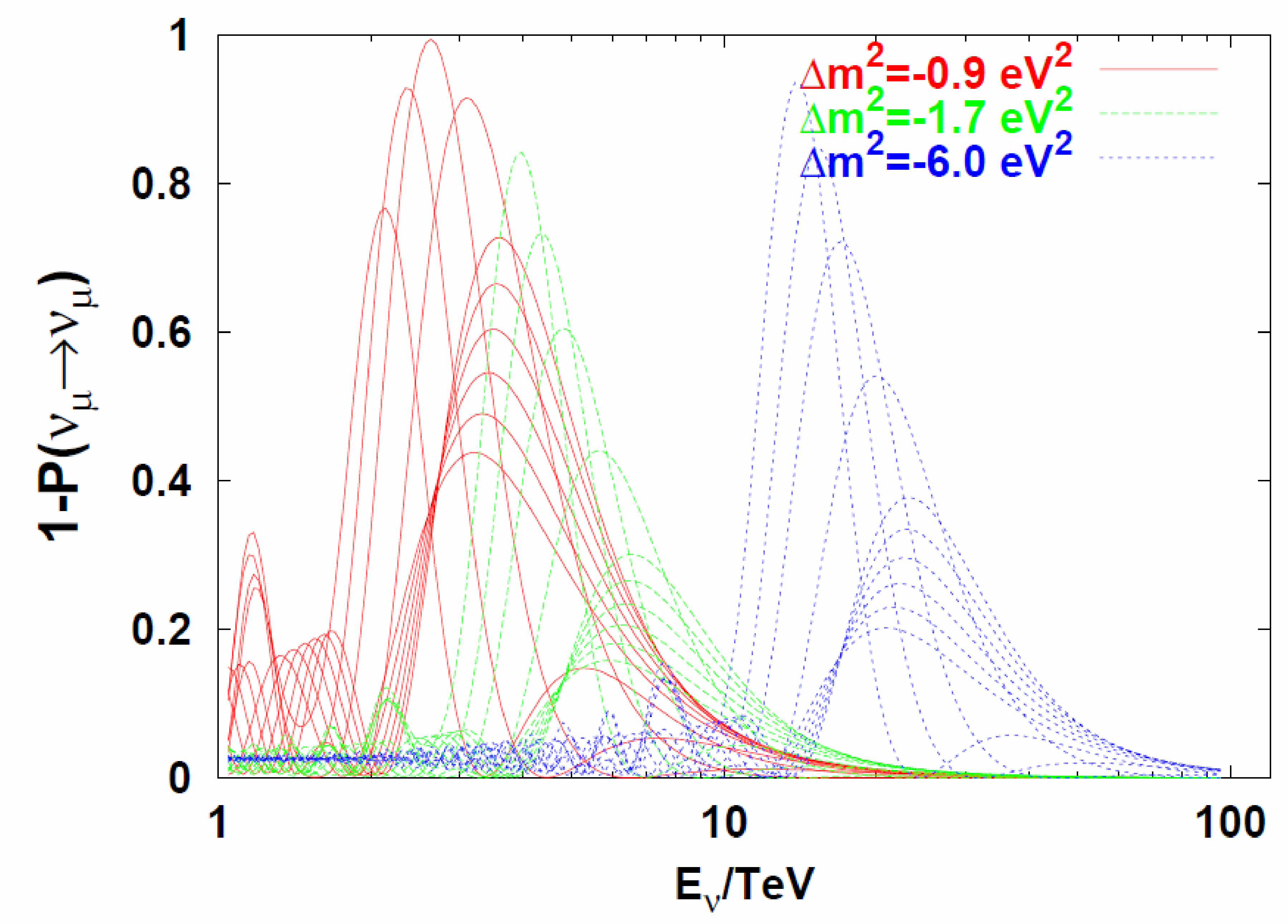
2 flavor ν_s oscillation framework



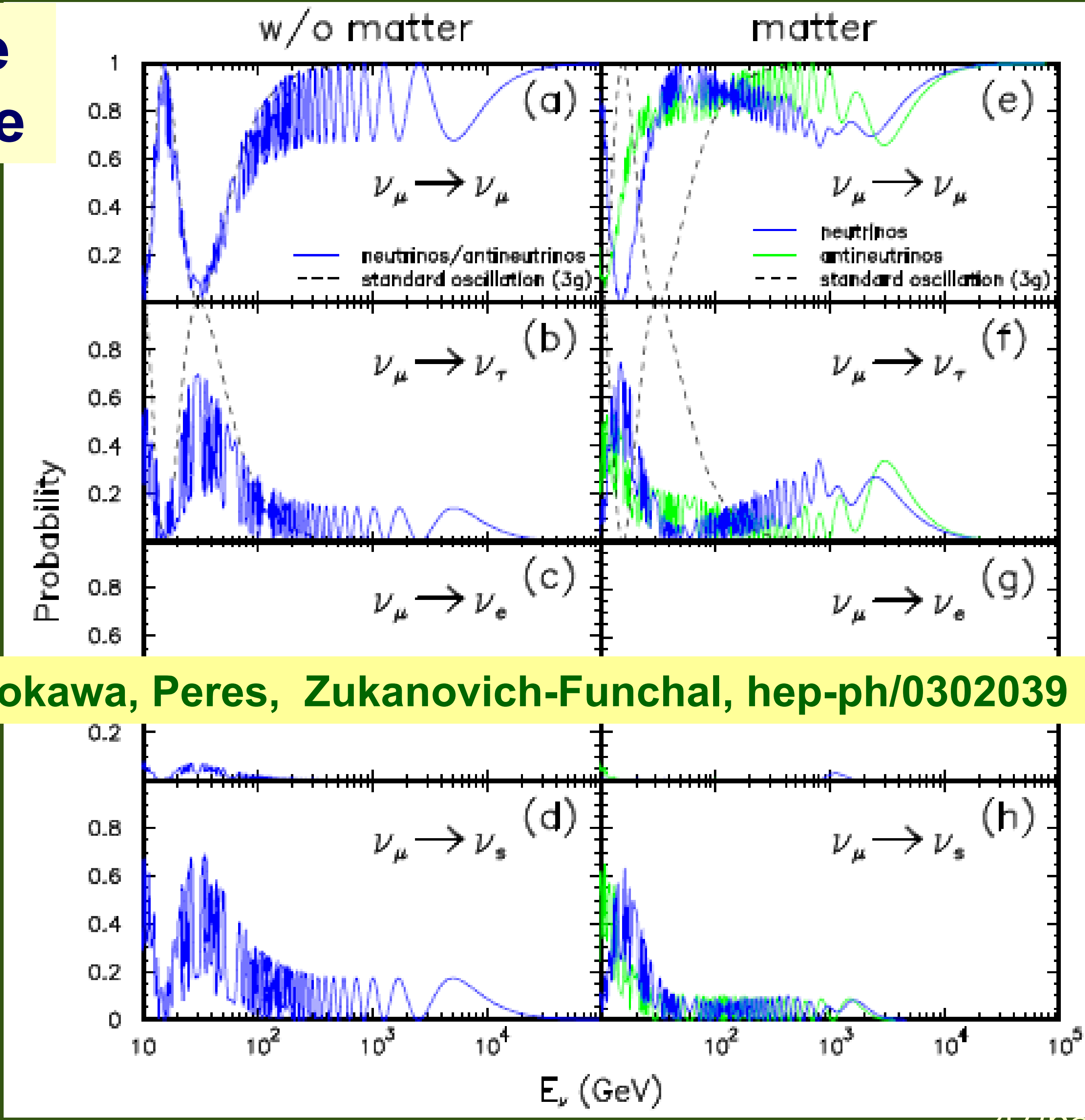
Nicolaidis, Tsirigoti, Hansson, hep-ph/9904415

●(2+2)-scheme

OY, hep-ph/0102166



●(2+2)-scheme & (3+1)-scheme



Nunokawa, Peres, Zukanovich-Funchal, hep-ph/0302039

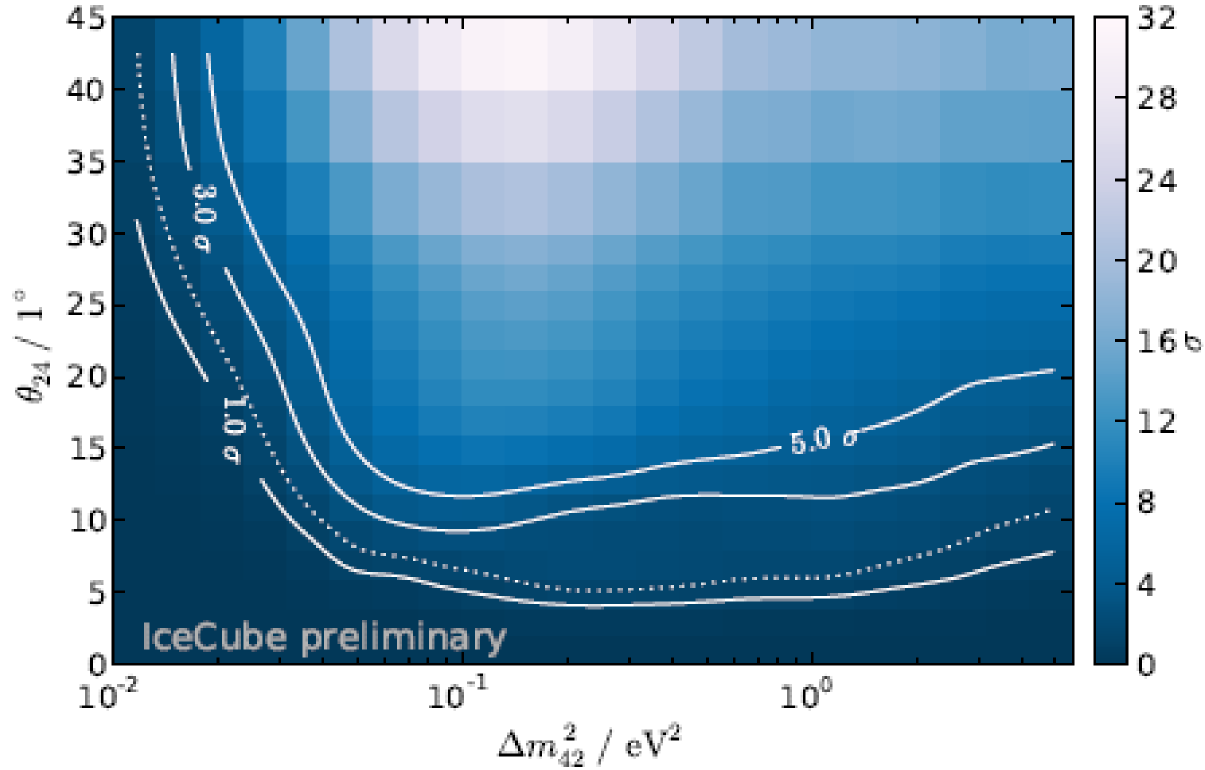


Figure 6: Estimated sensitivity for the exclusion of oscillation parameters with five years of IC86 data, given the null hypothesis and the same event selection. The dotted line indicates the 90% confidence level. Systematic uncertainties mentioned in the text have been taken into account (without priors), except for the ice model.

2.2 Nonstandard scenarios (2)

● Motivation for Non Standard Interactions

- Theoretical motivation is phenomenological, but its discovery would give a clue to physics beyond Standard Model.
- There seems to be slight tension between the solar ν and KamLAND ; another tension between recent measurement of θ_{13} of D-CHOOZ & Daya Bay + RENO.

→ it may be a hint for either **NSI in propagation (production/detection)** or ν_s

Some models exist: NSI due exchange by light (MeV scale mass) mediators with small couplings allow to avoid existing bounds

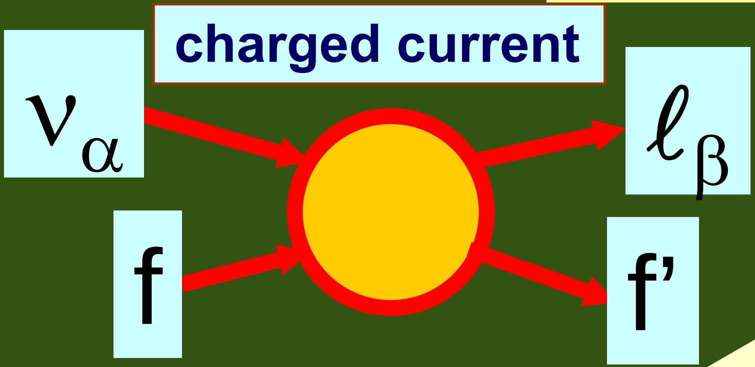
Farzan, Shoemaker, arXiv:1512.09147

2.2.1 New Physics at source and detector

Grossman, Phys. Lett. B359, 141 (1995)

Possible processes with

$$\mathcal{L}_{\rm eff} = G_F\, \epsilon^{ff'}_{\alpha\beta}\, \bar{\nu}_\alpha \gamma^\rho \ell_\beta \bar{f} \gamma_\rho f'$$



- **NSI at production**

$$\mu^+ \to e^+ + \overline{\nu}_\mu + \nu^s_\mu$$

$$\nu^s_e = \nu_e + \epsilon^s_{e\mu} \nu_\mu$$

Effective eigenstate $\equiv U^s$

$$\begin{pmatrix} \nu^s_e \\ \nu^s_\mu \end{pmatrix} = \begin{pmatrix} 1 & \epsilon^s_{e\mu} \\ -\epsilon^s_{e\mu} & 1 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

SM: U → NP: U^sU

- **NSI at detection**

$$\nu^d_\mu + n \to \mu^- + p$$

$$\nu^d_\mu = \nu_\mu - \epsilon^d_{e\mu} \nu_e$$

Effective eigenstate $\equiv U^d$

$$\begin{pmatrix} \nu^d_e \\ \nu^d_\mu \end{pmatrix} = \begin{pmatrix} 1 & \epsilon^d_{e\mu} \\ -\epsilon^d_{e\mu} & 1 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

SM: U → NP: U^dU

Direct bounds on prod/det NSI

From μ, β, π decays and zero distance oscillations

$$2\sqrt{2}G_F\varepsilon^{ud}_{\alpha\beta}\left(\bar{l}_\beta\gamma^\mu P_L\nu_\alpha\right)\left(\bar{u}\gamma_\mu P_{L,R}d\right)$$

$$2\sqrt{2}G_F\varepsilon^{\mu e}_{\alpha\beta}\left(\bar{\mu}\gamma^\mu P_L\nu_\beta\right)\left(\bar{\nu}_\alpha\gamma_\mu P_L e\right)$$

$$\left|\varepsilon^{ud}\right| < \begin{pmatrix} 0.042 & 0.025 & 0.042 \\ 2.6\cdot 10^{-5} & 0.1 & 0.013 \\ 0.087 & 0.013 & 0.13 \end{pmatrix}$$

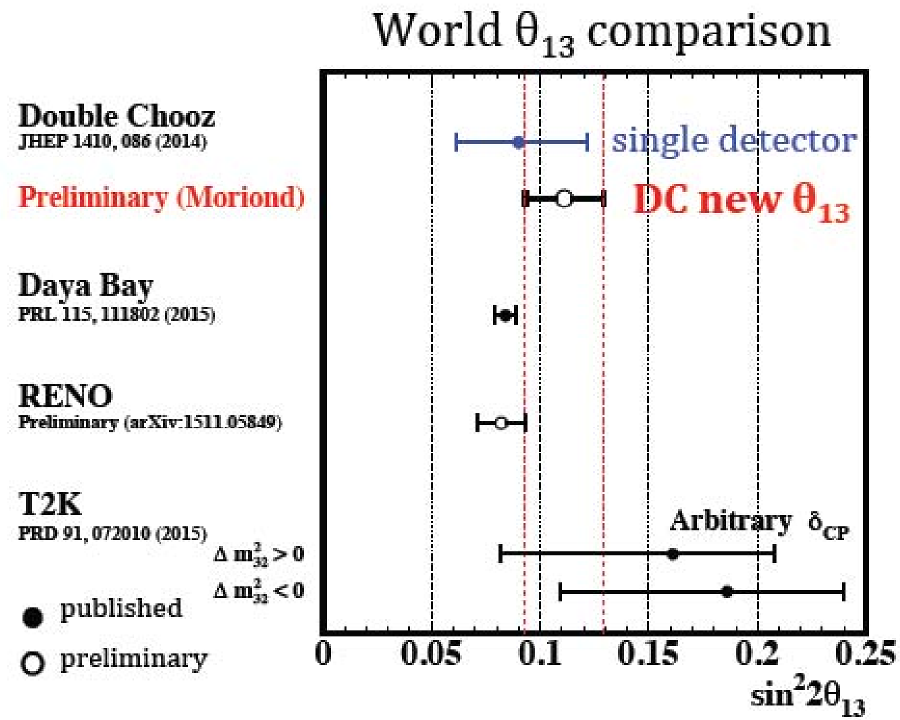
$$\left|\varepsilon^{\mu e}\right| < \begin{pmatrix} 0.025 & 0.03 & 0.03 \\ 0.025 & 0.03 & 0.03 \\ 0.025 & 0.03 & 0.03 \end{pmatrix}$$

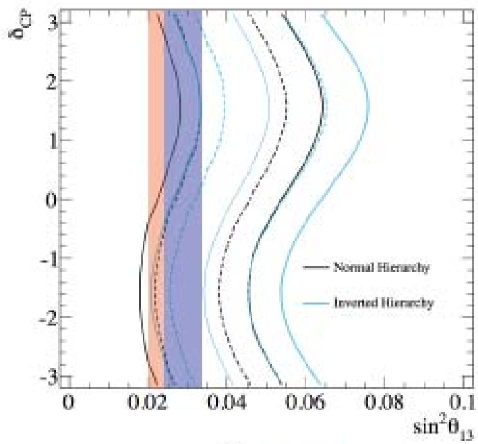
Bounds ~O(10^{-2})

C. Biggio, M. Blennow and EFM 0907.0097

Double Chooz θ_{13} in the world

Ishitsuka @ Moriond2016





Reactor vs. T2K

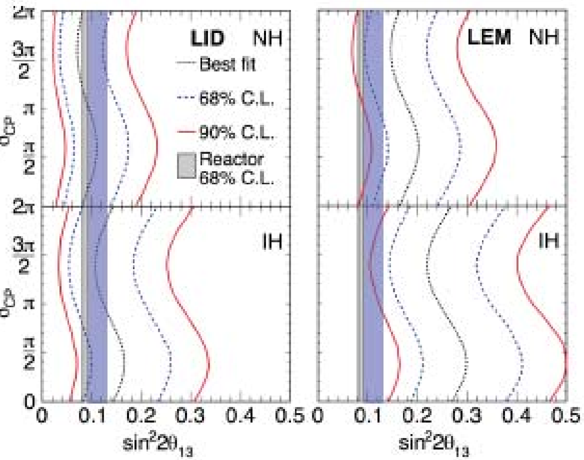
PRD91 072010 (2015)

Double Chooz 1σ

Daya Bay 1σ

Reactor vs. NOvA

arXivL1601.05522 (accepted by PRL)



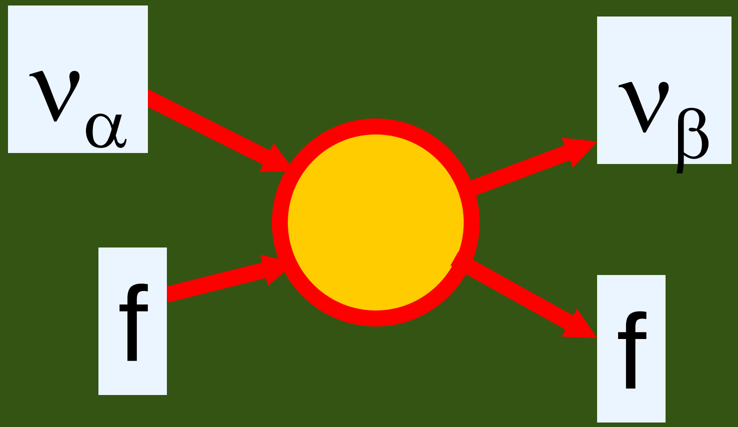
- DC θ_{13} is higher than other reactor θ_{13} by ~30% (1.4σ wrt Daya Bay)
- Long baseline (T2K, NOvA) weakly favors higher θ_{13} than reactor average
- Reactor θ_{13} is key parameter to solve CP-violation and mass hierarchy

27

→ This may be a hint for NSI in production / detection or ν_s

2.2.2 New Physics in propagation (matter effect)

$$\mathcal{L}_{eff} = G_{NP}^{\alpha\beta}\,\bar{\nu}_\alpha \gamma^\mu \nu_\beta\, \bar{f}\gamma_\mu f'$$



SM potential due to W exchange is modified by NP

$$\textbf{SM}\quad \mathcal{A}_0 \equiv A\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \rightarrow \textbf{NP}\quad \mathcal{A} \equiv A\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix}$$

$A \equiv \sqrt{2}G_F N_e$ $\quad N_e \equiv$ electron density

• Constraints on $\varepsilon_{\alpha\beta}$ for experiments on Earth

Davidson et al., JHEP 0303:011,2003; Berezhiani, Rossi, PLB535 ('02) 207; Barranco et al., PRD73 ('06) 113001; Barranco et al., arXiv:0711.0698

Biggio et al., JHEP 0908, 090 (2009) w/o 1-loop arguments

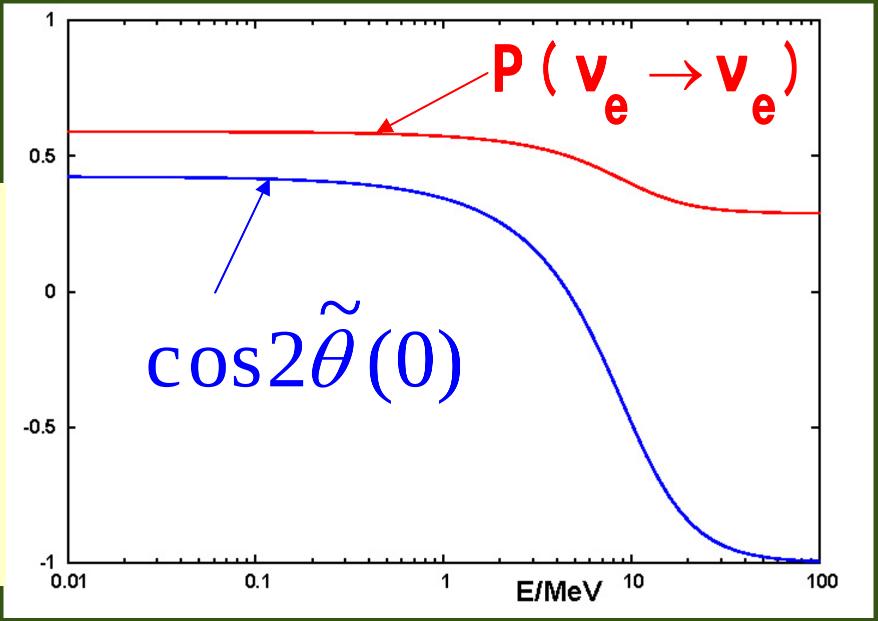
Constraints are weak

$$\begin{pmatrix} |\epsilon_{ee}| \lesssim 4 \times 10^{0} & |\epsilon_{e\mu}| \lesssim 3 \times 10^{-1} & |\epsilon_{e\tau}| \lesssim 3 \times 10^{0} \\ & |\epsilon_{\mu\mu}| \lesssim 7 \times 10^{-2} & |\epsilon_{\mu\tau}| \lesssim 3 \times 10^{-1} \\ & & |\epsilon_{\tau\tau}| \lesssim 2 \times 10^{1} \end{pmatrix}$$

ε_{ee} , $\varepsilon_{e\tau}$, $\varepsilon_{\tau\tau}$ **~O(1)** **are consistent with accelerator experiments data**

Probability for solar ν

Probability for solar ν is expressed in terms of the initial and final mixing angles, and depends on E_ν through the initial mixing angle.



$$P(\nu_e \to \nu_e) = \frac{1}{2}\left[1 + \cos 2\theta \; \cos 2\tilde{\theta}(0)\right]$$

$$\Delta E \equiv \Delta m^2 / 2E$$

$$A \equiv \sqrt{2} G_F n_e(x)$$

$$\tan 2\tilde{\theta}(0) \equiv \frac{\Delta E \sin 2\theta}{\Delta E \cos 2\theta - A(0)}$$

Mixing angle at production point (t=0)

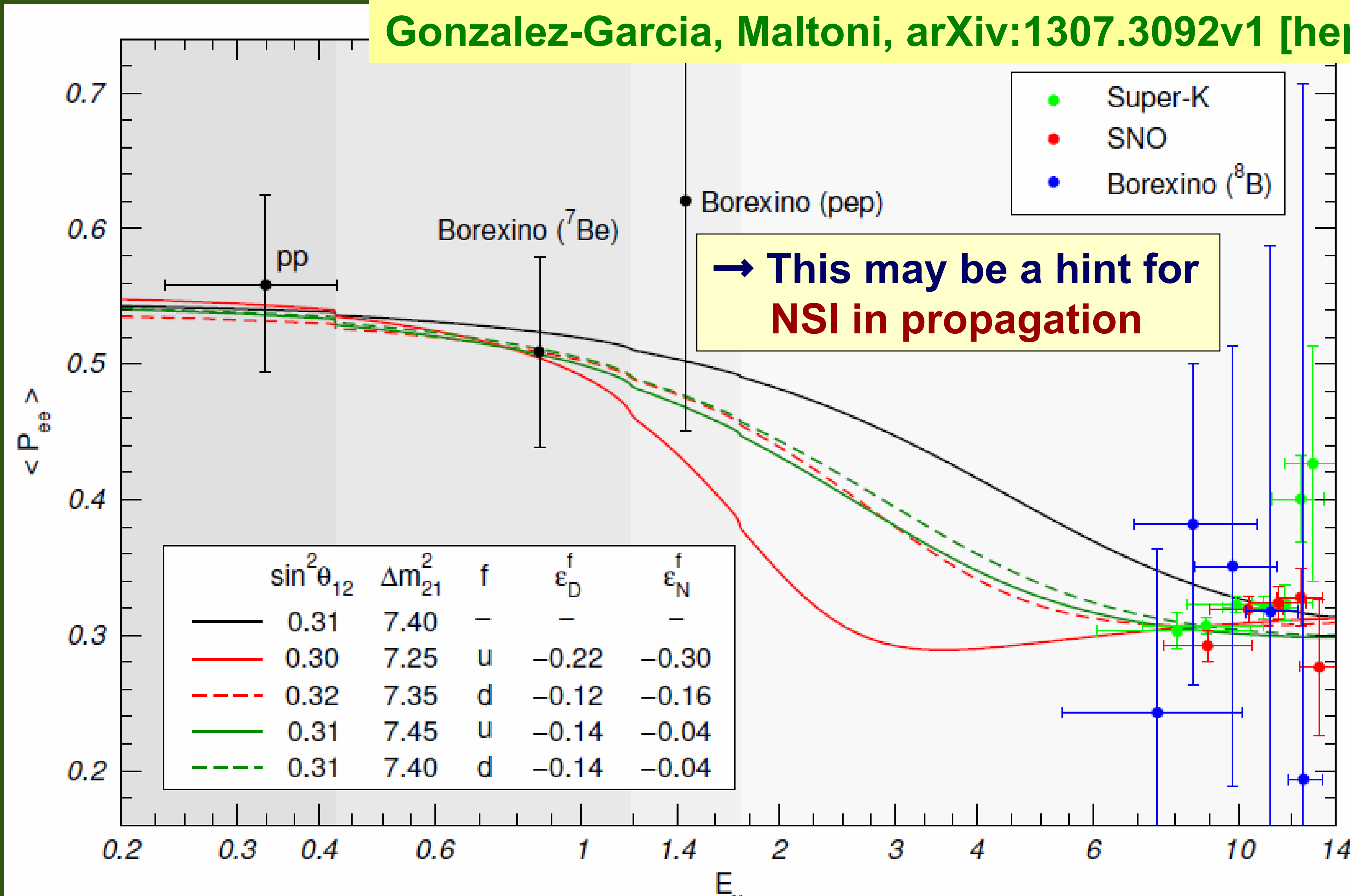
Matter potential at production point (t=0, i.e., in the center on the Sun)

up-turn of solar ν

Better fit with NSI ($\Delta\chi^2_{\rm OSC} \simeq 5$–$7$)

Due to no observation of MSW up-turn of solar ν

Gonzalez-Garcia, Maltoni, arXiv:1307.3092v1 [hep-ph]

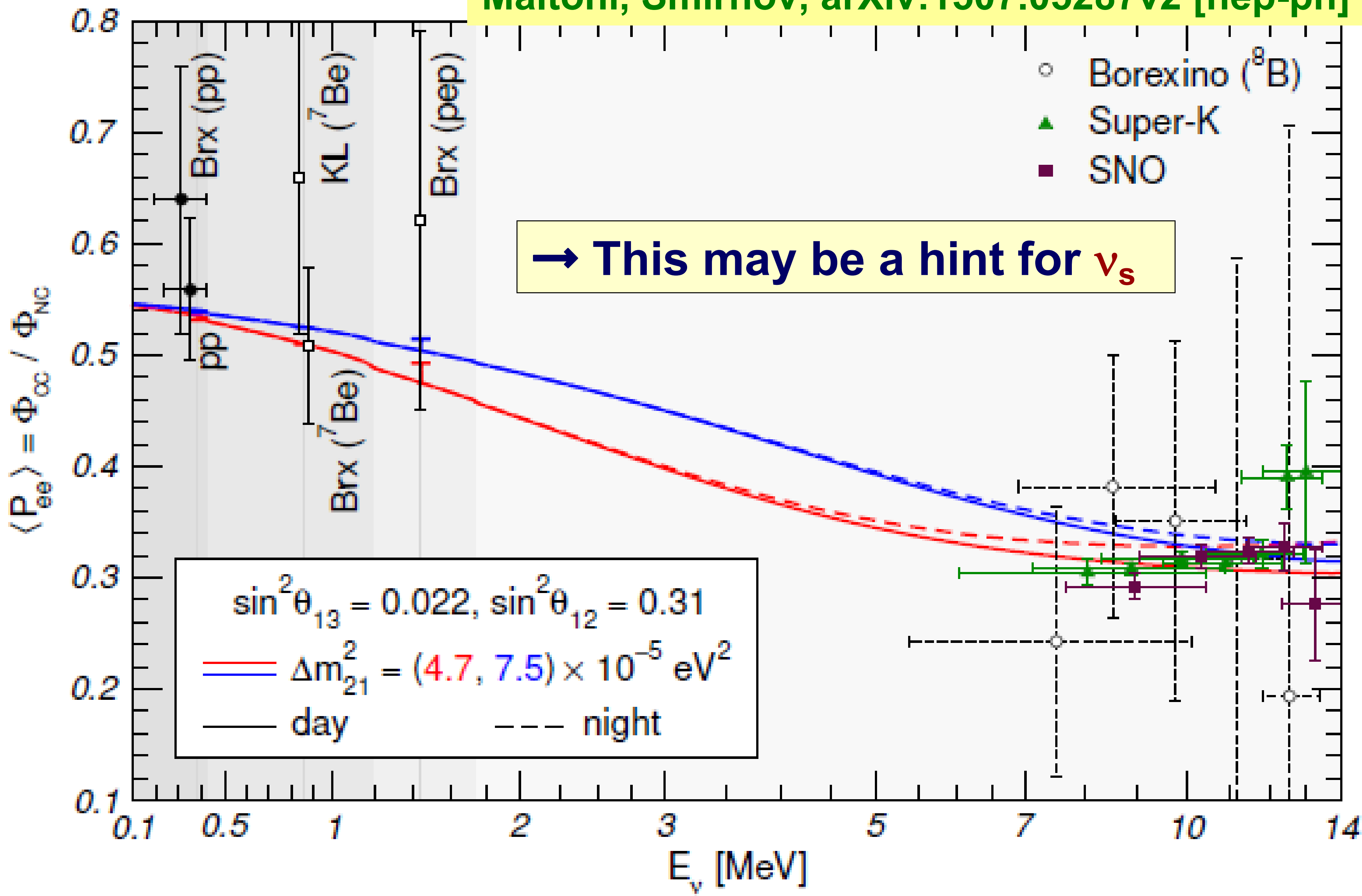


→ This may be a hint for NSI in propagation

up-turn of solar ν

Better fit with sterile ν

Maltoni, Smirnov, arXiv:1507.05287v2 [hep-ph]



→ This may be a hint for ν_s

Constraints on NSI from high energy behavior of ν_{atm} data

Oki-OY PRD82 ('10) 073009

- **Standard case with N_ν=2**

$$1 - P(\nu_\mu \to \nu_\mu) = \sin^2 2\theta_{\rm atm} \sin^2\left(\frac{\Delta m^2_{\rm atm} L}{4E}\right) \propto \frac{1}{E^2}$$

- **Standard case with N_ν=3**

$$1 - P(\nu_\mu \to \nu_\mu) \sim \left(\frac{\Delta m^2_{31}}{2AE}\right)^2 \left[\sin^2 2\theta_{23} \left(\frac{c^2_{13} AL}{2}\right)^2 + s^2_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{AL}{2}\right)\right] \propto \frac{1}{E^2}$$

- **Deviation of 1-P($\nu_\mu \to \nu_\mu$) due to NSI contradicts with data**

$$1 - P(\nu_\mu \to \nu_\mu) \simeq c_0 + \frac{c_1}{E} + \frac{c_{20} L^2 + c_{21} \sin^2(c_{22} L)}{E^2}$$

High energy ν_{atm} data is well described by standard scheme
→ constraints on NSI: $|c_0| \ll 1, \ |c_1| \ll 1$

● with **NSI**

$$1 - P(\nu_\mu \to \nu_\mu) \simeq c_0 + \frac{c_1}{E} + \frac{c_{20}L^2 + c_{21}\sin^2(c_{22}L)}{E^2}$$

$|c_0| \ll 1 \to$ $|\varepsilon_{e\mu}| << 1$, $|\varepsilon_{\mu\mu}| << 1$, $|\varepsilon_{\mu\tau}| << 1$

$|\varepsilon_{\mu\tau}| << 1$: Shown by Fornengo et al. PRD65, 013010, '02; Gonzalez-Garcia&Maltoni, PRD70, 033010, '04; Mitsuka@nufact08

$|\varepsilon_{\mu\mu}| << 1$: Shown from other expts. by Davidson et al. JHEP 0303:011, '03

$|\varepsilon_{e\mu}| << 1$: Shown by Oki-OY PRD82 ('10) 073009

$|c_1| \ll 1 \to$ $\left| \varepsilon_{\tau\tau} - \frac{|\varepsilon_{e\tau}|^2}{1+\varepsilon_{ee}} \right| << 1$

Shown by Friedland-Lunardini, PRD72:053009,'05

Summary of the constraints on $\varepsilon_{\alpha\beta}$

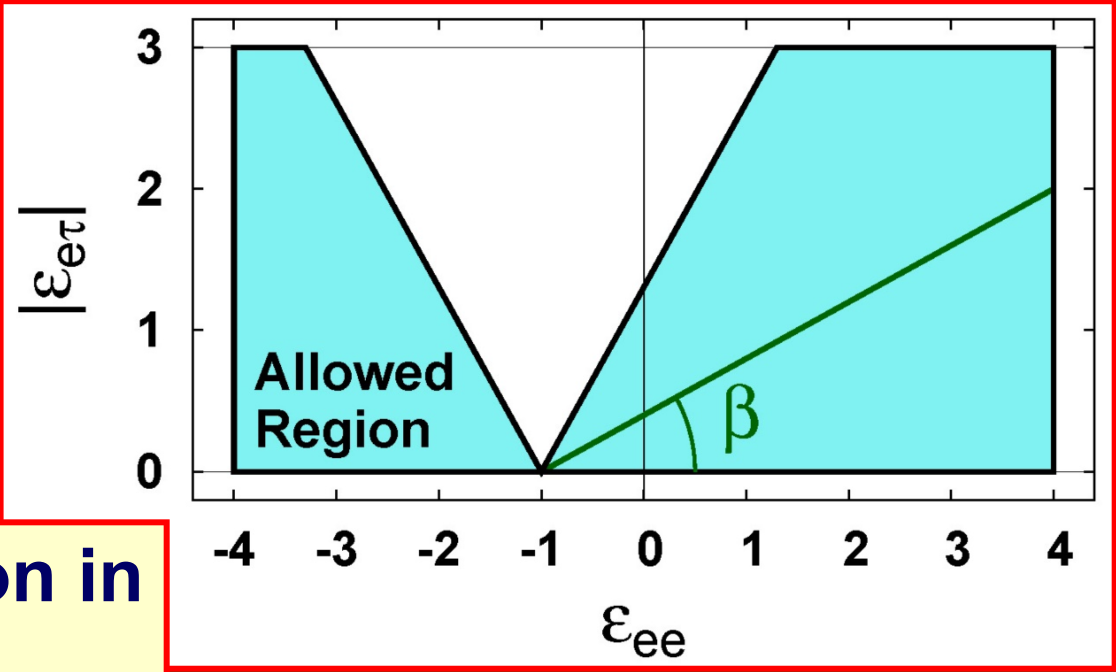
To a good approximation, we are left with 3 independent variables ε_{ee}, $|\varepsilon_{e\tau}|$, $\arg(\varepsilon_{e\tau})$:

$$A\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix} \Rightarrow A\begin{pmatrix} 1+\epsilon_{ee} & 0 & \epsilon_{e\tau} \\ 0 & 0 & 0 \\ \epsilon^*_{e\tau} & 0 & |\epsilon_{e\tau}|^2/(1+\epsilon_{ee}) \end{pmatrix}$$

Furthermore, ν_{atm} data implies

$\tan\beta = |\varepsilon_{e\tau}|/(1+\varepsilon_{ee}) < 1.5$ @2.5σCL

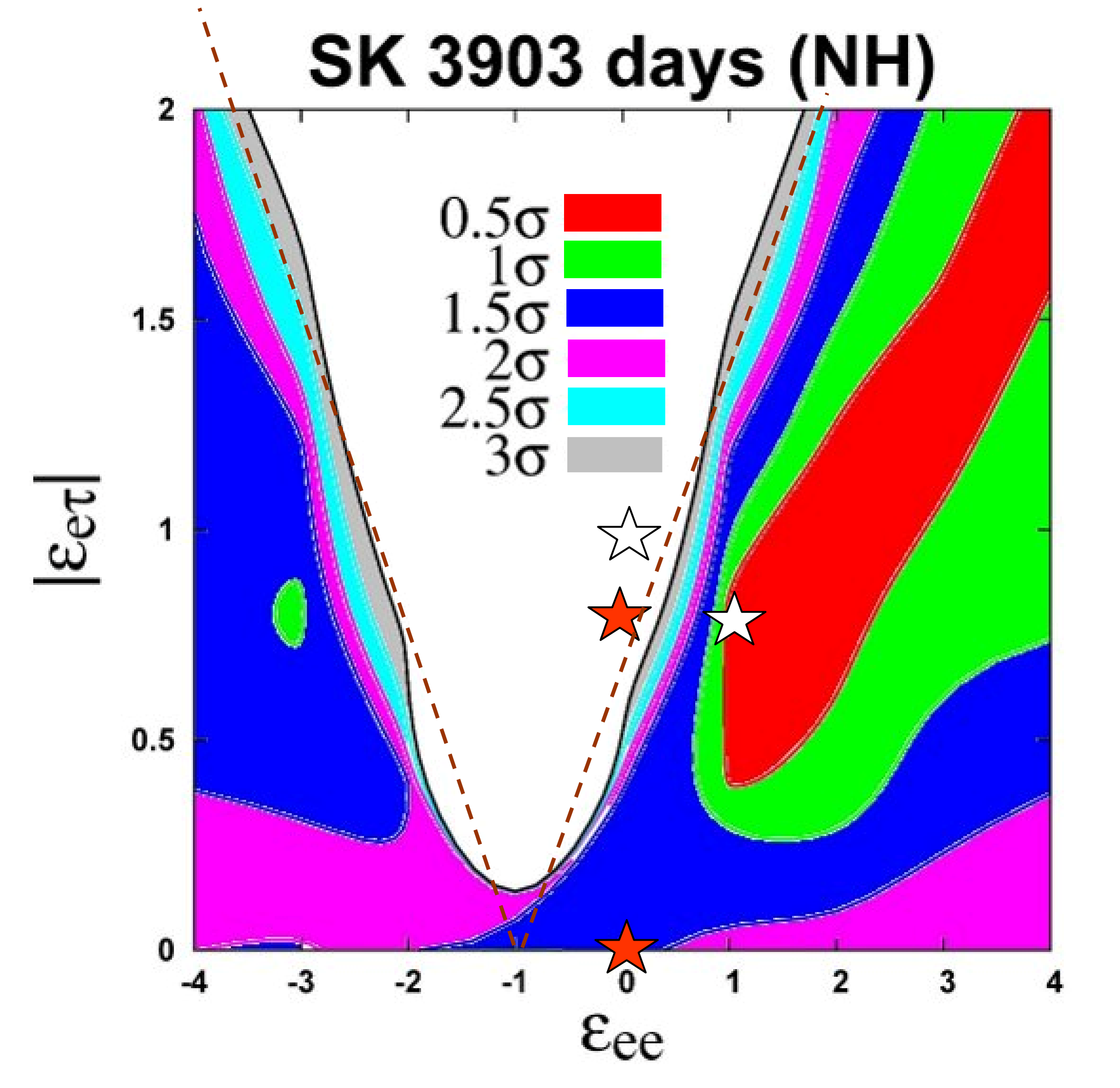
Friedland-Lunardini, PRD72:053009,'05



Allowed region in (ε_{ee}, $|\varepsilon_{e\tau}|$)

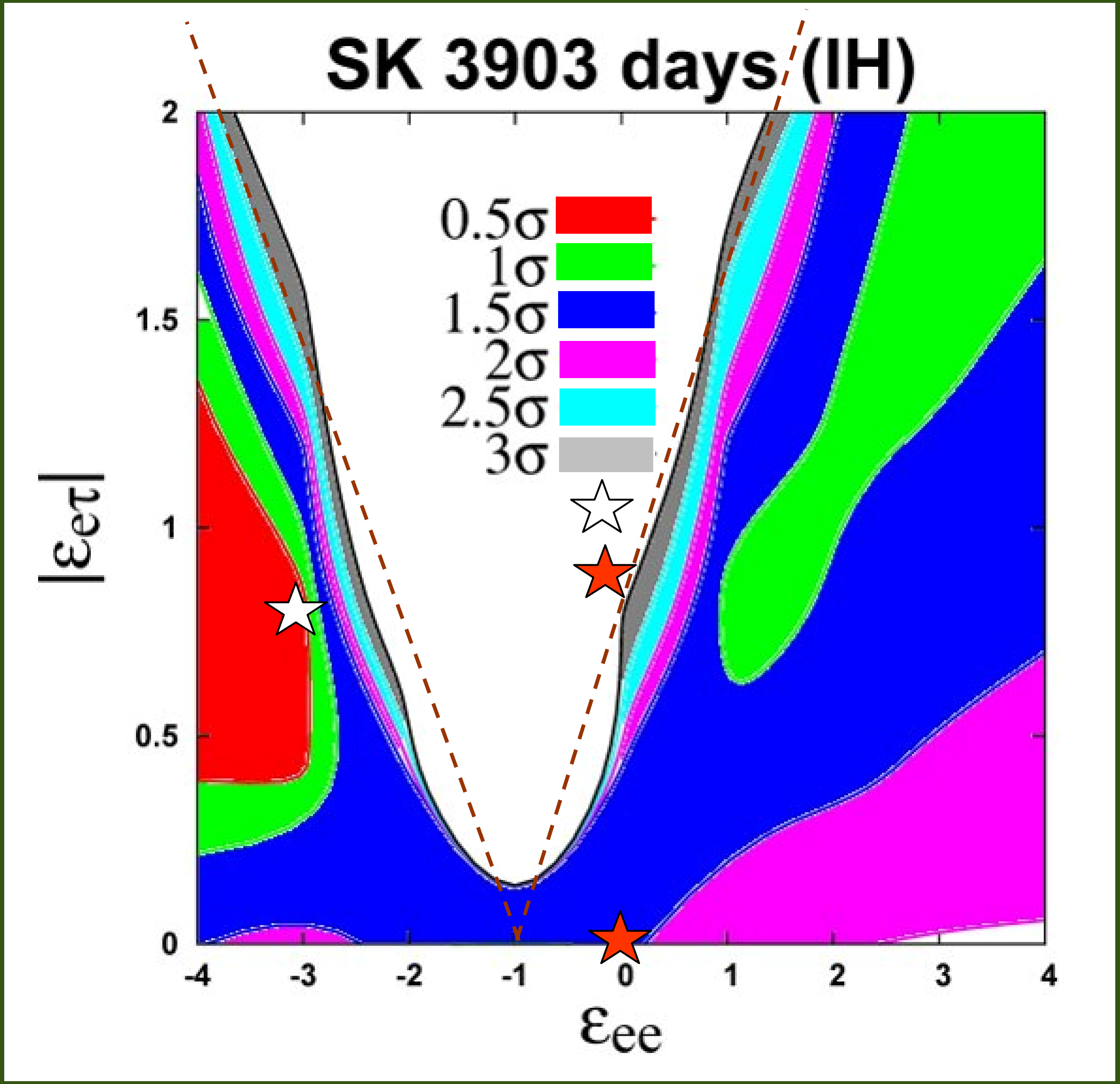
Constraint by SK ν_{atm} on ε_{ee}, $|\varepsilon_{e\tau}|$

Fukasawa-OY
(arXiv:1503.08056)



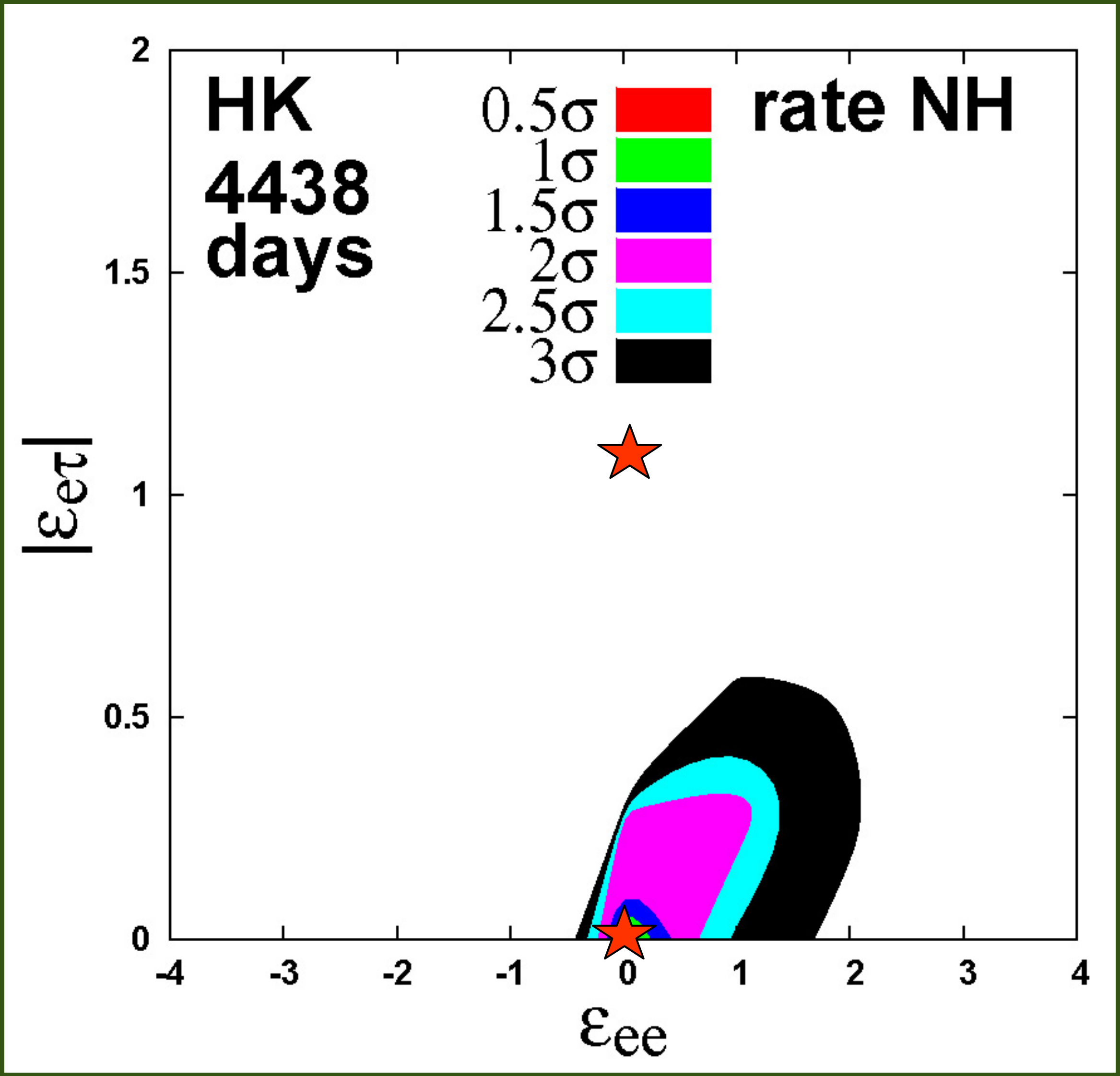
- The standard case ($\varepsilon_{\alpha\beta}$=0) is not best fit point (1.4σ). This may be because we have been unable to reproduce SK MC results completely.
- The 2.5σ excluded region (tanβ<0.8) improves the old one (tanβ<1.5) by Friedland-Lunardini in 2005.

Fukasawa-OY
(arXiv:1503.08056)



Sensitivity of HK ν_{atm} to ε_{ee}, $|\varepsilon_{e\tau}|$

(1) Rate analysis

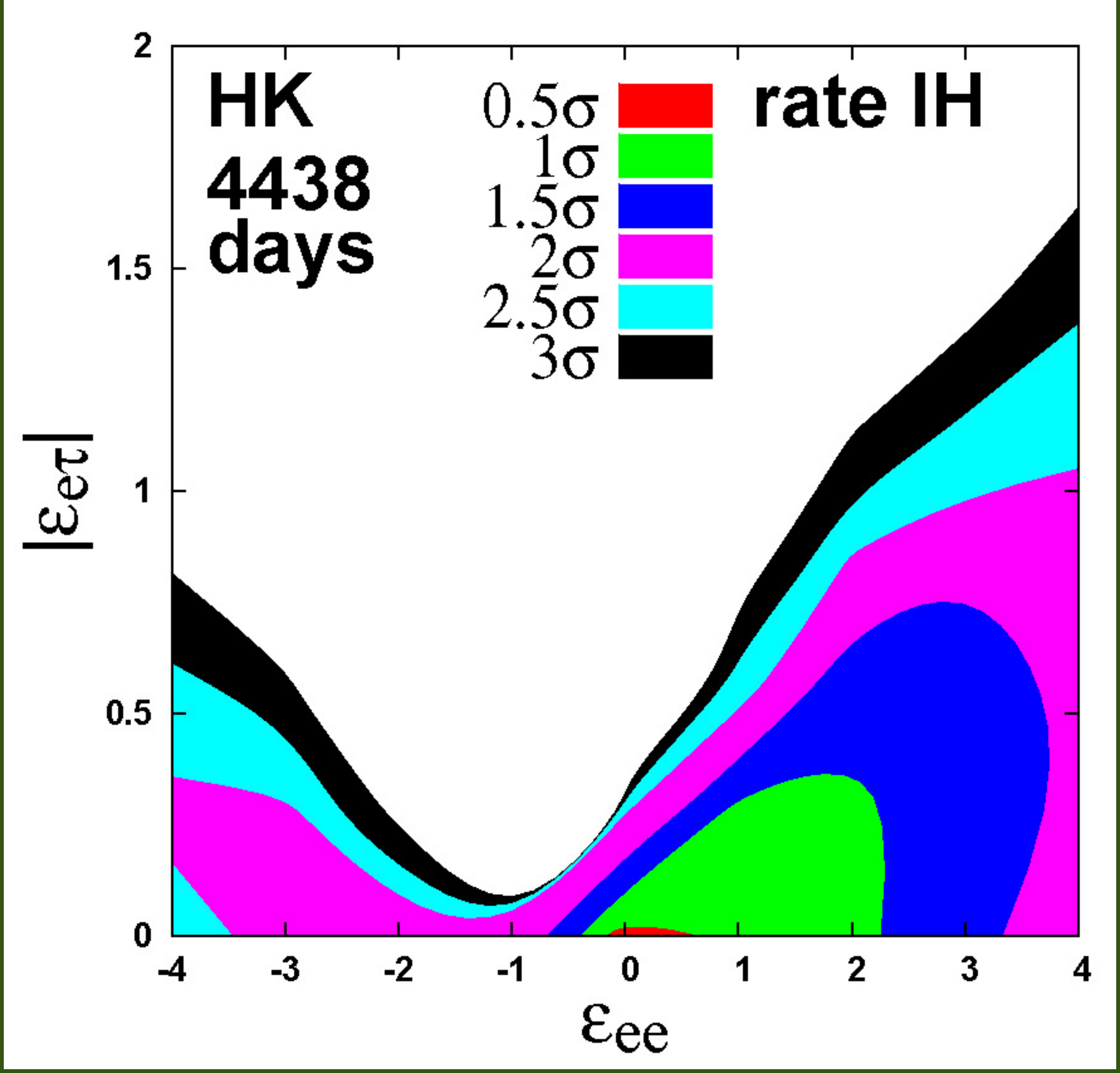


**Fukasawa-OY
arXiv.1503.08056**

**#(events)$_{HK}$
= 20 x #(events)$_{SK}$**

- **The region $|\varepsilon_{e\tau}|$ >1.5 is excluded. The 2.5σ excluded region is $|\tan\beta|<0.4$.**

Fukasawa-OY
arXiv.1503.08056

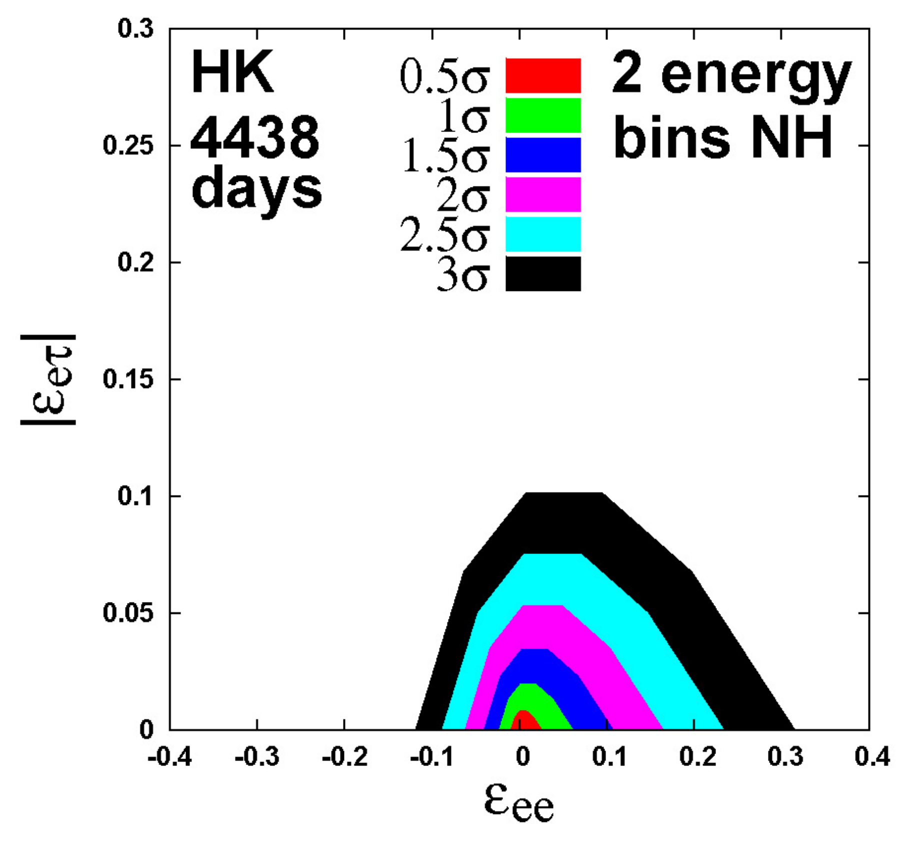


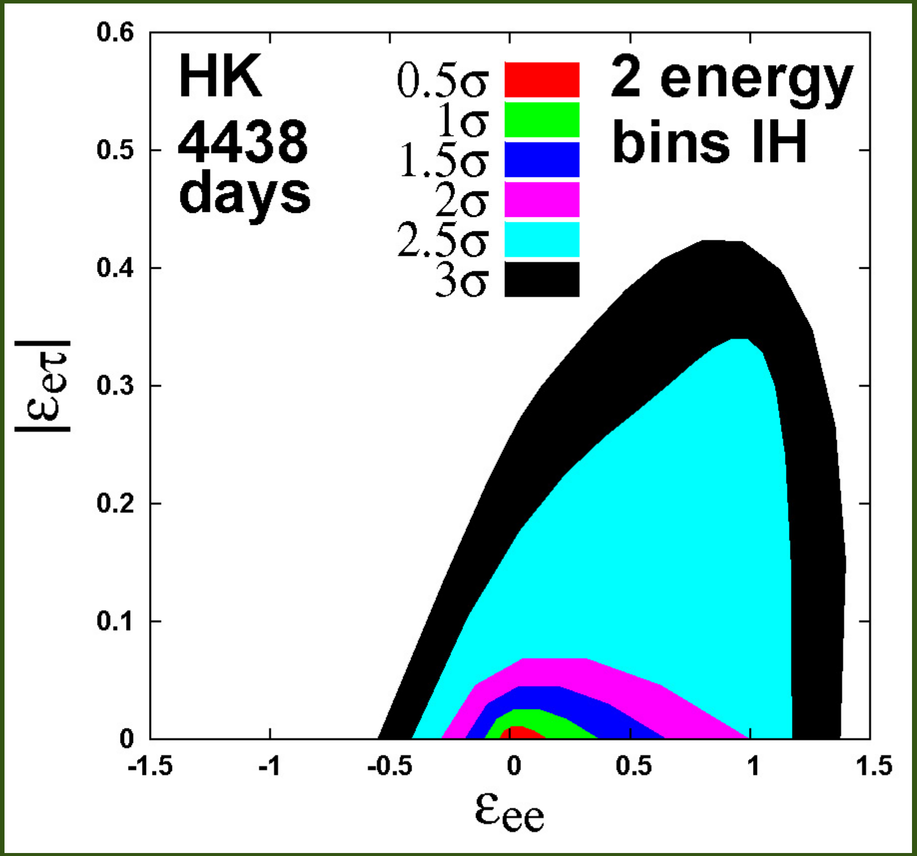
- The case of IH has a much larger allowed region. This may be because the resonance occurs for the $\bar{\nu}$ channel which has less #(events) than ν.

Sensitivity of HK ν_{atm}

(2) Spectrum analysis

Fukasawa-OY
arXiv.1503.08056





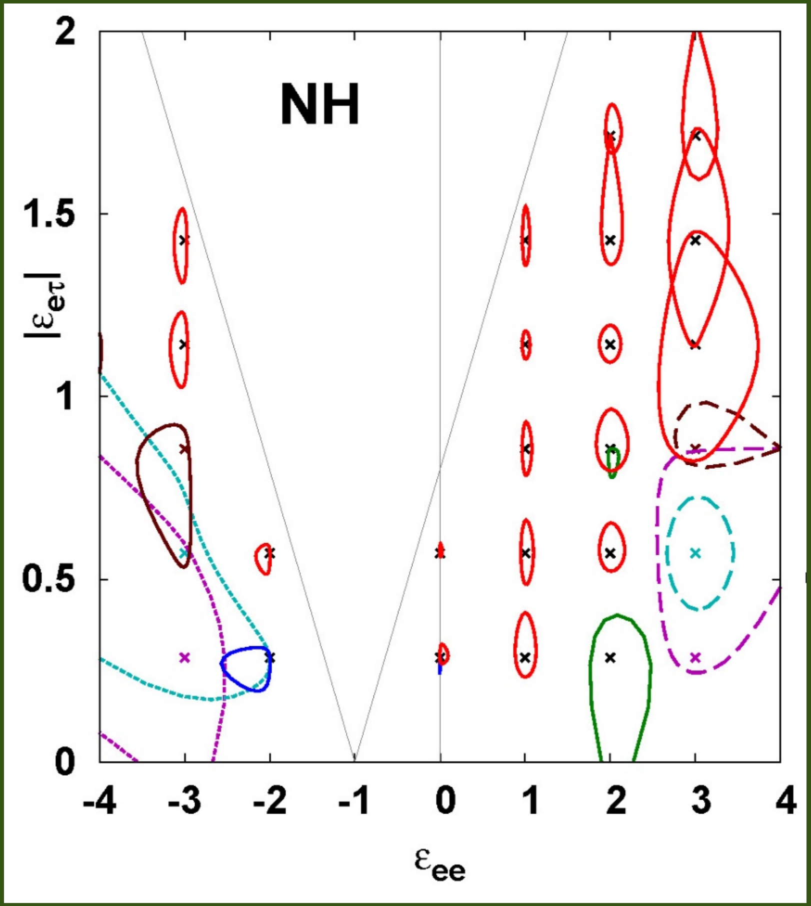
- With the information of the energy spectrum, the allowed region becomes much smaller (Note the difference in scale). The 2.5σ excluded region is $|\tan\beta|<0.1$.

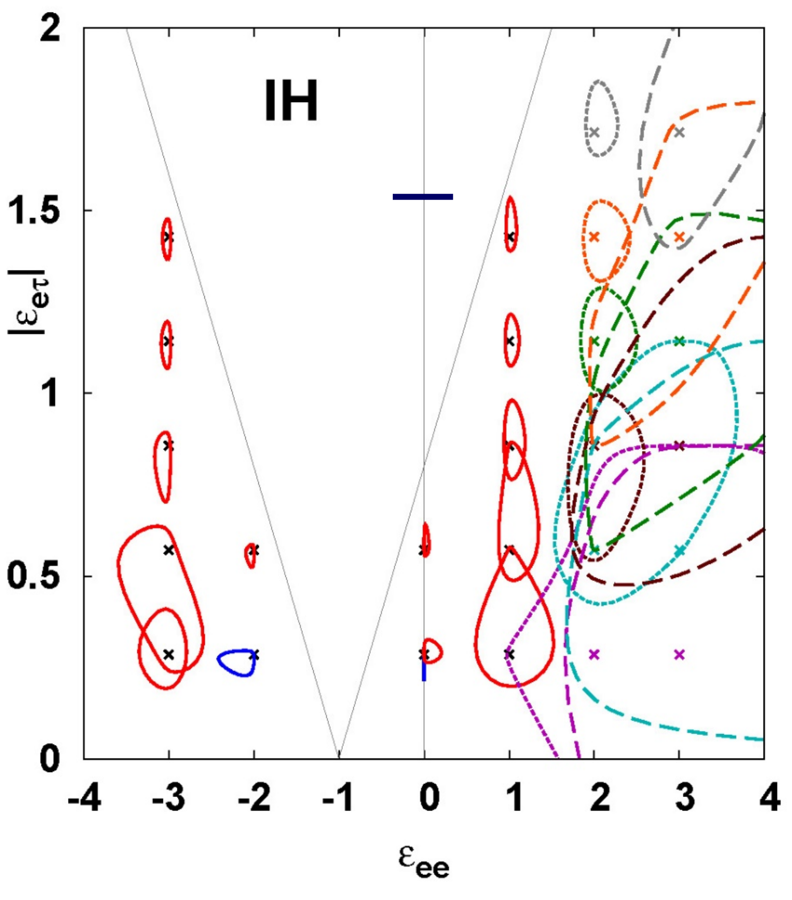
Sensitivity of HK ν_{atm}

Fukasawa-OY
arXiv.1503.08056

(3) Spectrum analysis in the presence of NSI

Relatively good sensitivity to NSI for $|\varepsilon_{ee}|<2$





Sensitivity of HK ν_{atm}

(4) Implication to solar ν

If the deviation of the up-turn behavior of the solar ν is due to NSI in ν propagation, there is a chance to see it in atmospheric ν observation at HK with great significance.

Fukasawa-OY
work in progress

6. Summary (1)

- From various ν oscillation experiments, 3 mixing angles and 2 mass squared difference have been determined. Undetermined parameters are δ & sign(Δm^2_{31}).
- Future experiments are planned to determine δ & sign(Δm^2_{31}) .
- Just like the B factories, we can probe physics beyond SM by looking at deviation from SM+m_ν

6. Summary (2)

- New physics beyond SM includes sterile ν, NSI, unitarity violation.
- At present there are a few anomalies:

  (i) LSND-MiniBooNE-reactor-Gallium anomaly

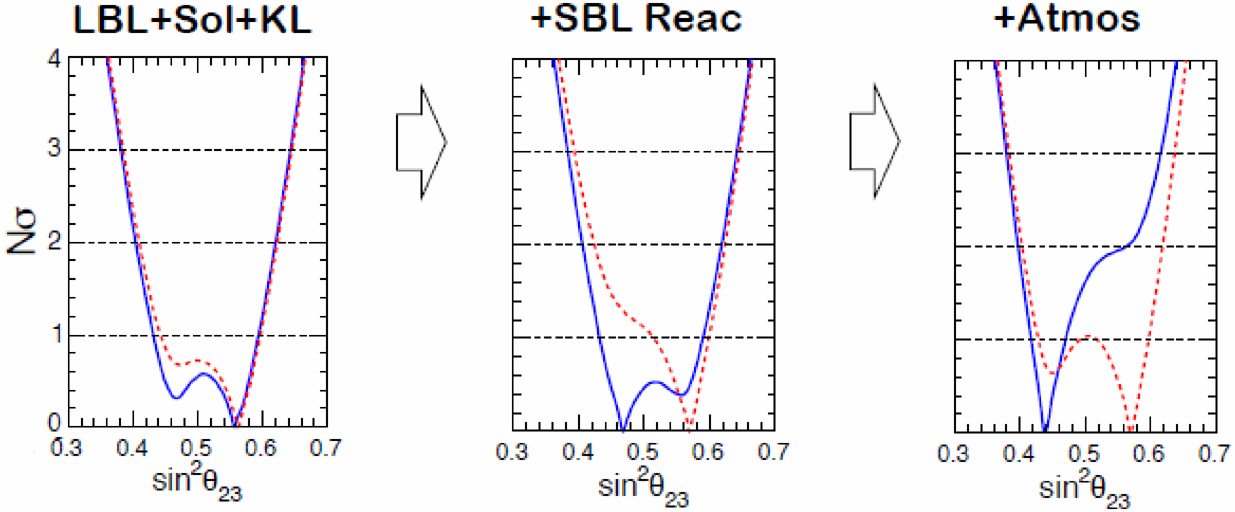
  (ii) Tension between solar ν & KamLAND

  (iii) Tension between D-CHOOZ &DB+RENO
- These anomalies can be tested in the future experiments.

Backup slides

More on single (unknown) parameters:

θ_{23} octant



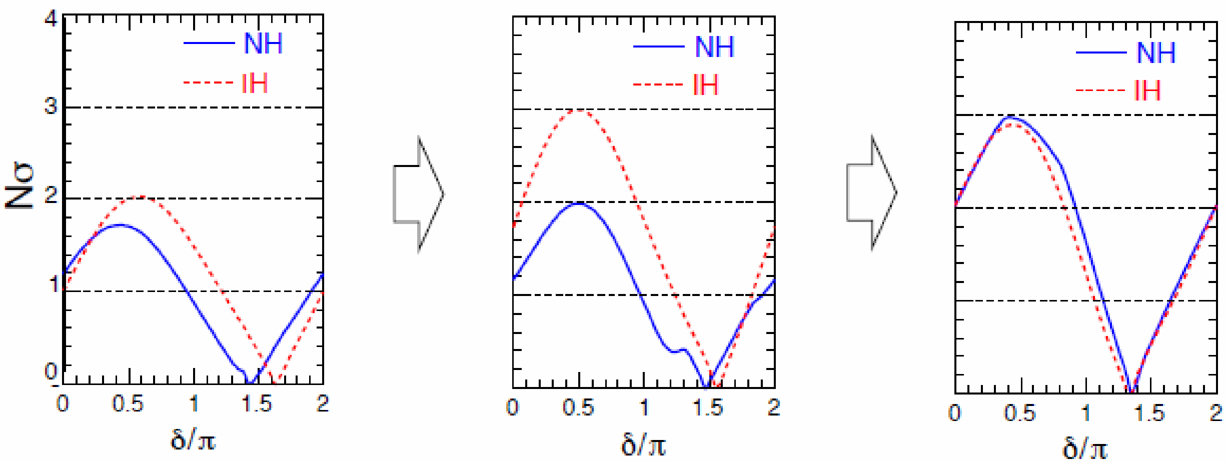
currently unstable, fragile

$\Delta\chi^2$ (IH-NH)

-1.2 → -0.88 → +0.98

negligible

δ_{CP}

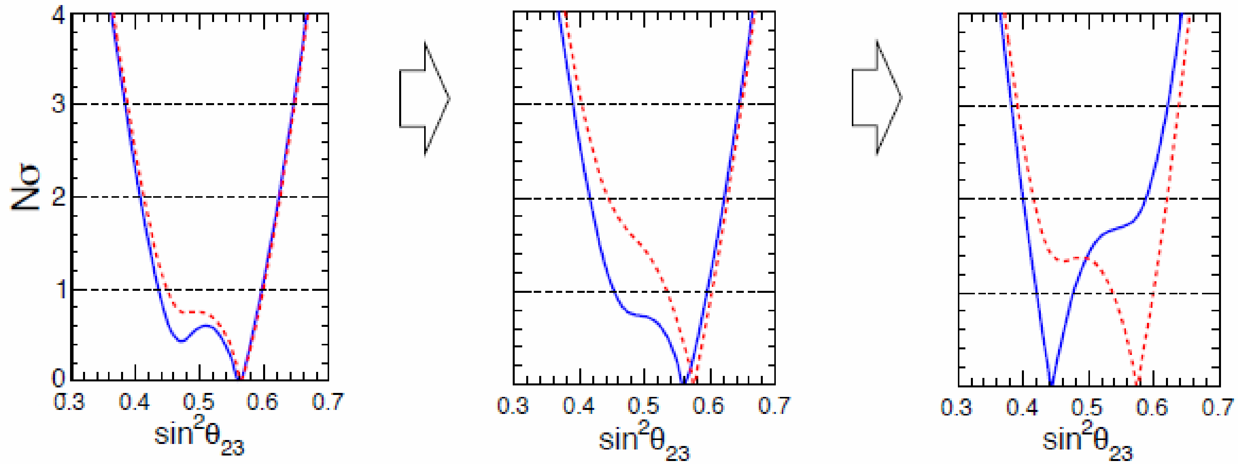


intriguing, $\sin\delta \sim -1$ (or $\sin\delta < 0$) favored

Lisi@BSM in Okinawa 2016

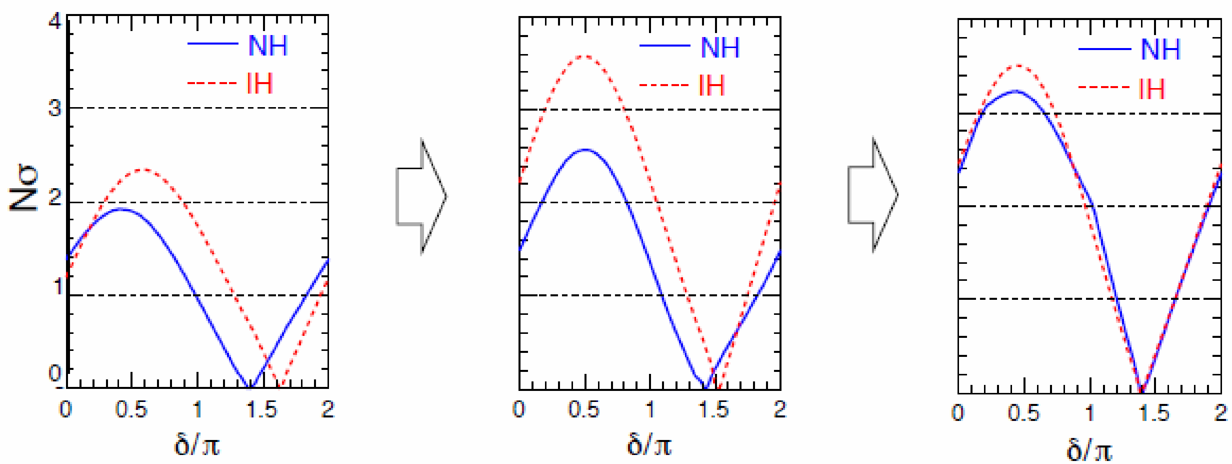
More on single (unknown) parameters: NOvA analysis LID → LEM

	LBL+Sol+KL		+SBL Reac		+Atmos	
θ_{23} octant						currently unstable, fragile



$\Delta\chi^2$ (IH-NH)	+0.61	⇨	+2.2	⇨	+2.8	negligible ?

δ_{CP}



intriguing, sin δ ~ -1 (or sin δ < 0) favored

sin δ ~ +1 ~excluded

NOvA analysis

LID: a likelihood-based selector

LEM: Library Event Matching

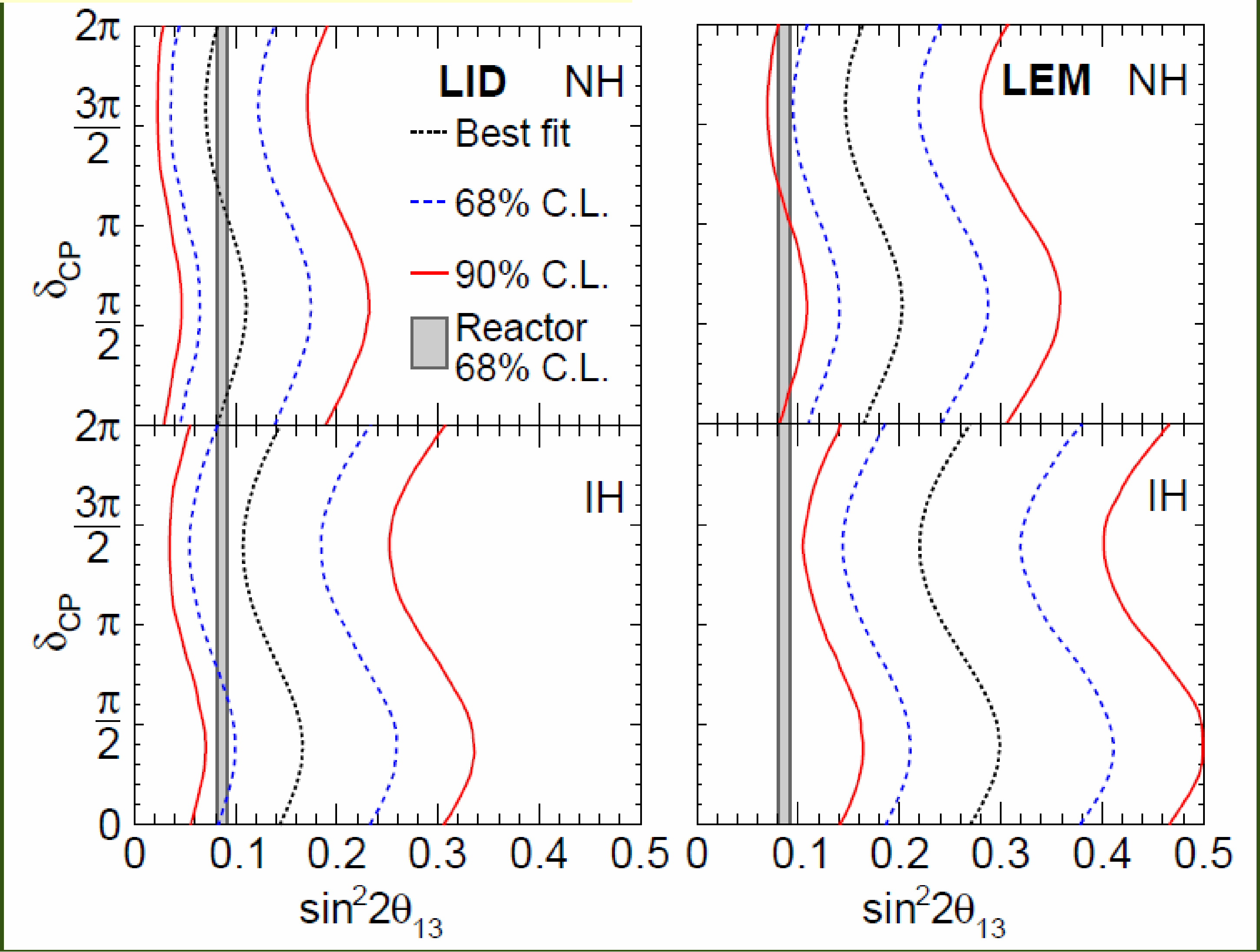
Nova appearance: 2.74 × 10^{20} POT

6 events observed

Nova Collaboration, Phys.Rev.Lett. 116 (2016) 151806

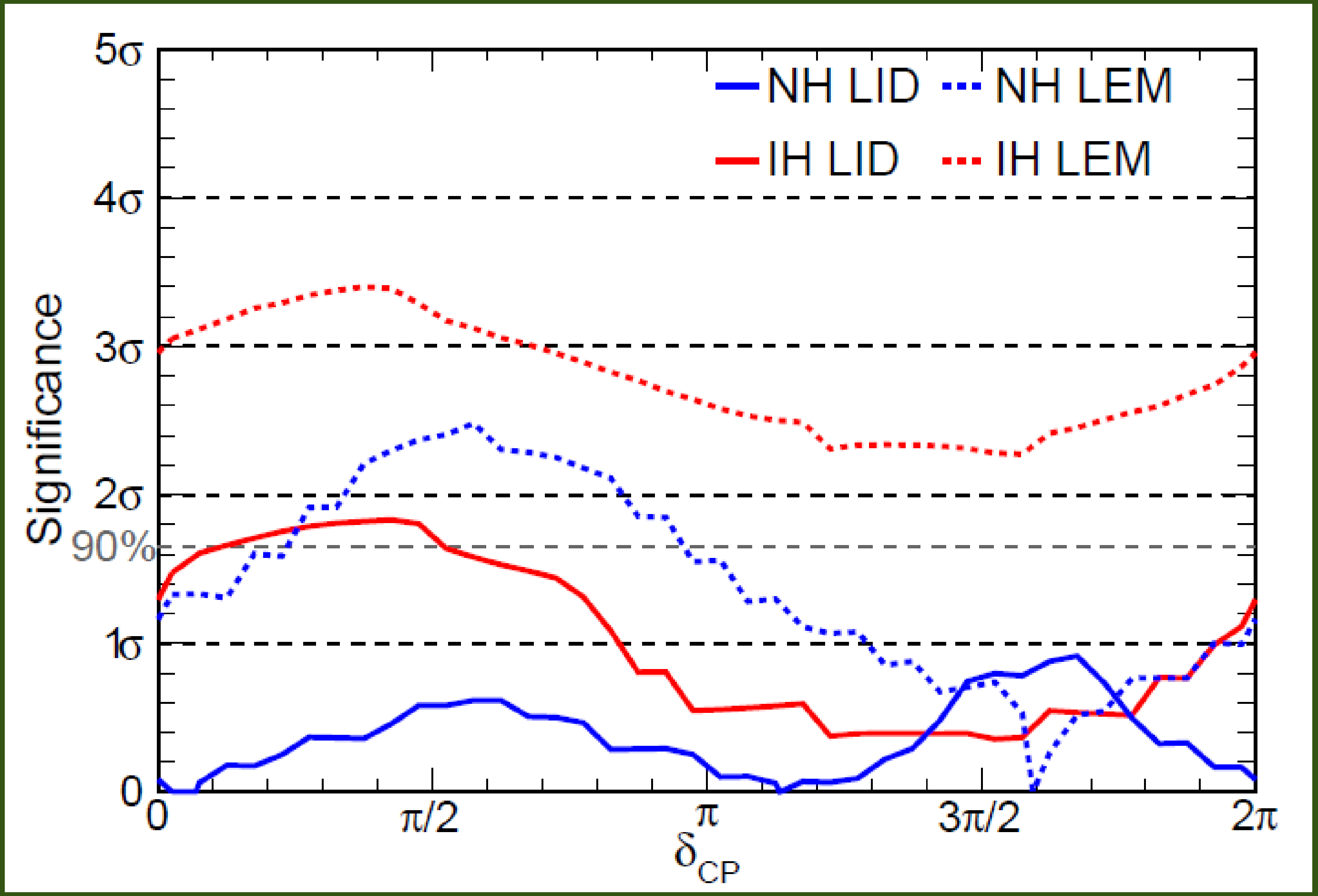
LID: a likelihood-based selector

LEM: Library Event Matching



Nova appearance: 2.74×10^{20} POT

6 events observed

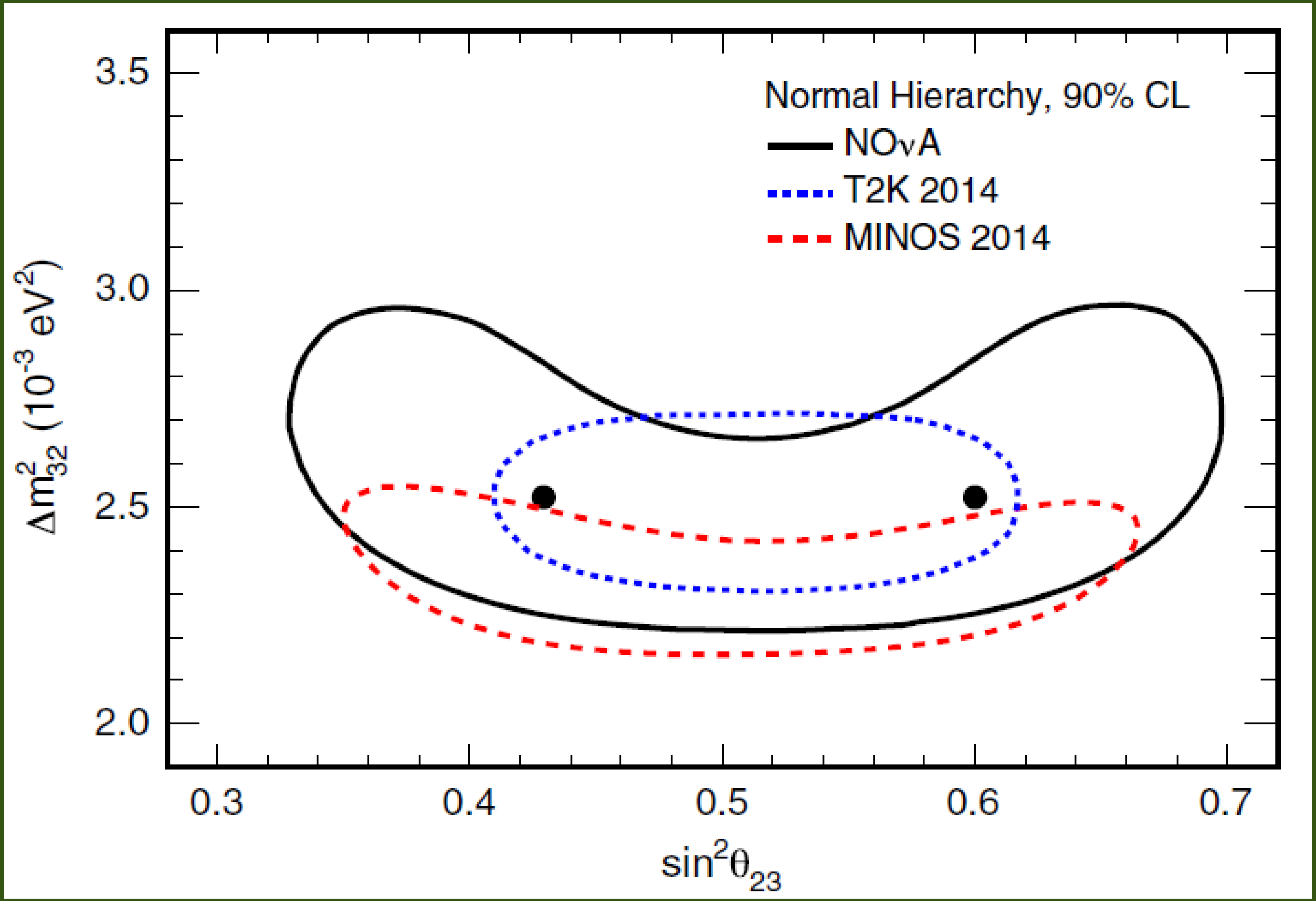


Nova Collaboration, Phys.Rev.Lett. 116 (2016)

A likelihood-based selector (LID): compares the longitudinal and transverse energy deposition in the primary shower to template histograms for various simulated particles The likelihood differences among different particle hypotheses and other topological variables are used as input to an articial neural network to construct the primary classier. The energy range of events selected with this primary method is further restricted to 1.5 to 2.7 GeV to remove additional backgrounds from cosmic radiation.

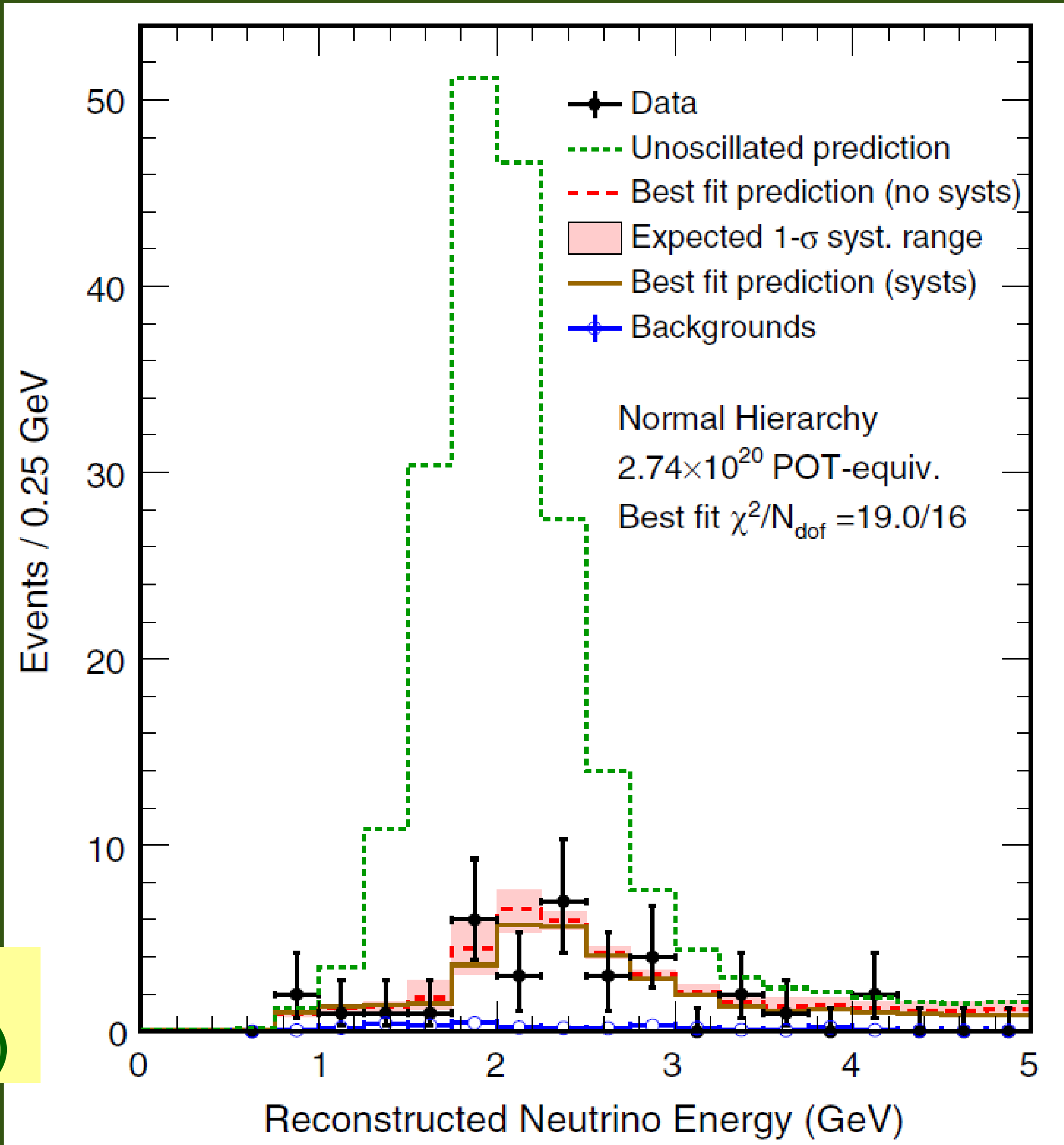
Library Event Matching (LEM): compares an input event from either data or simulation to a large and independent library of simulated events. The properties of the library events that are most similar to the input event provide information about the most likely identity of the neutrino interaction. This and additional identifying information from the best matches in the library is fed into an ensemble decision tree that gives the nal classier for this technique.

Nova disappearance: 2.74×10^{20} POT



Nova Collaboration, Phys. Rev. D 93, 051104(R) (2016)

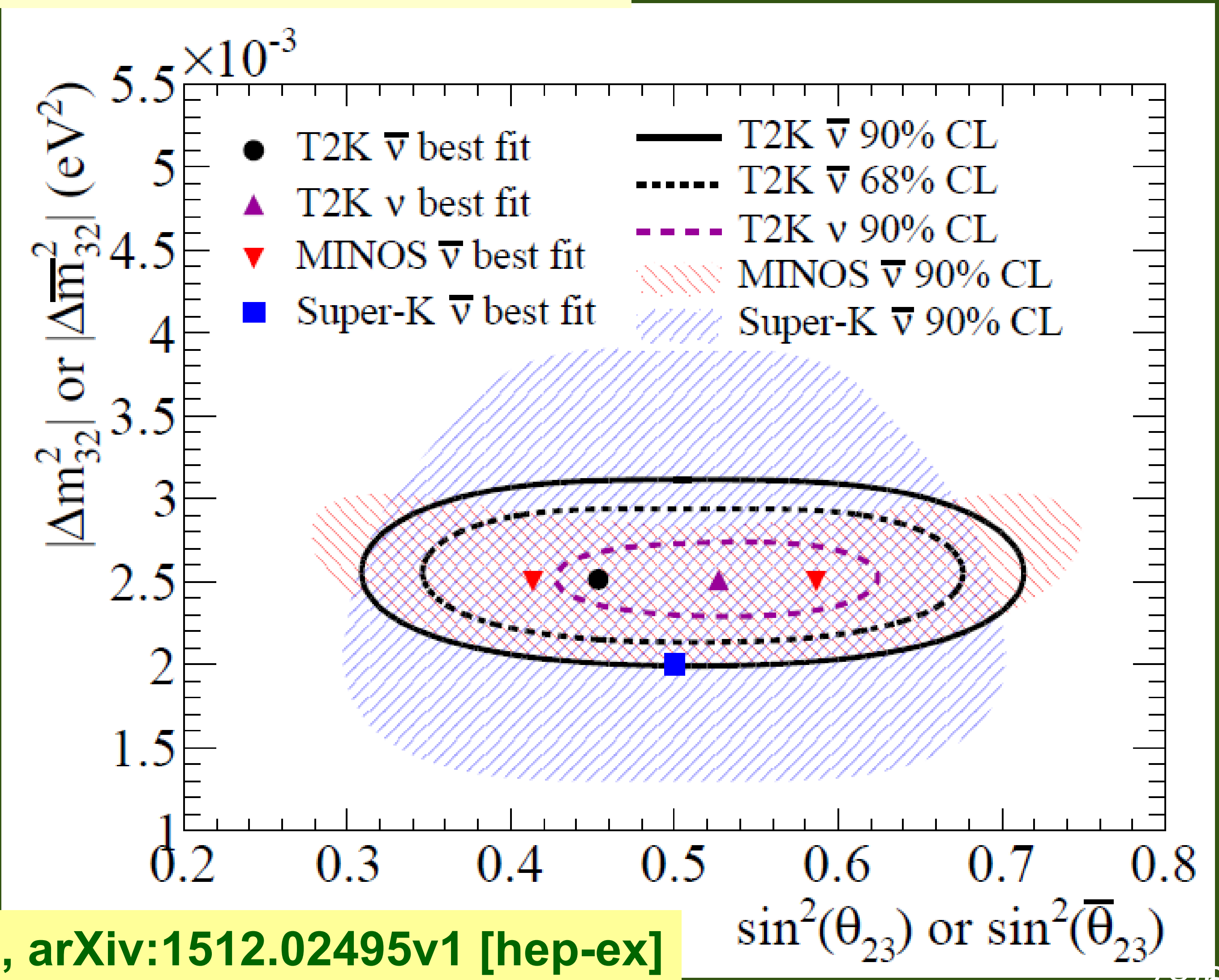
Nova disappearance: 2.74 × 10^{20} POT



Nova Collaboration, Phys. Rev. D 93, 051104(R) (2016)

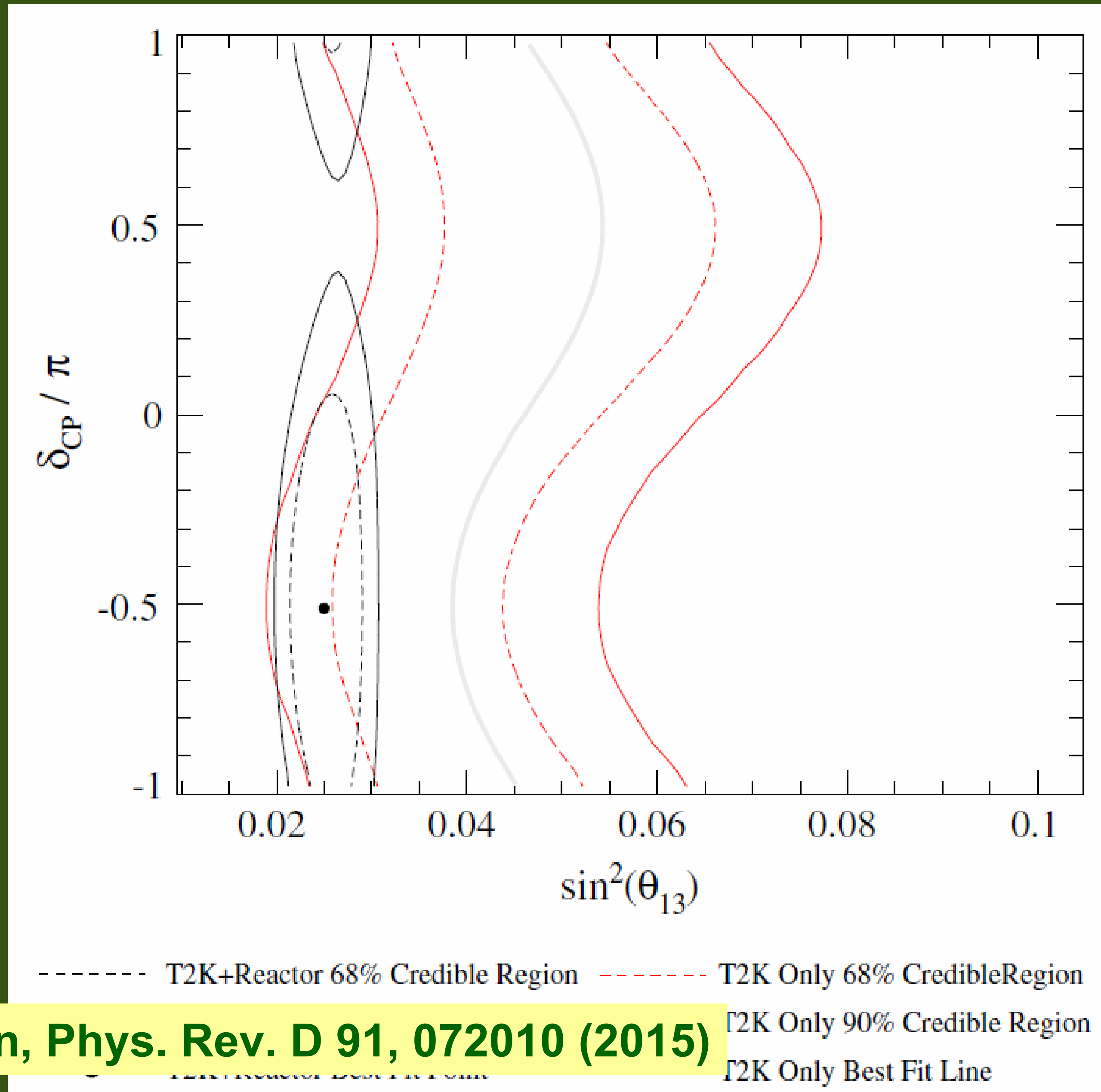
T2K $\bar{\nu}$ disappearance: 4.01 × 10^{20} POT

34 fully contained -like events



T2K Collaboration, arXiv:1512.02495v1 [hep-ex]

T2K ν appearance/disappearance: 6.57 × 10^{20} POT



T2K Collaboration, Phys. Rev. D 91, 072010 (2015)