ν Parameters in Fall 2016

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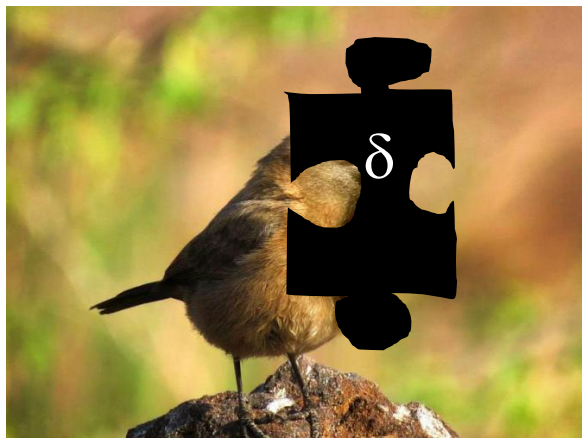
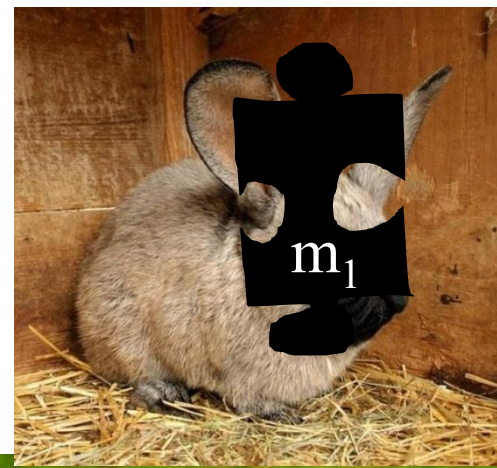
Latest Results

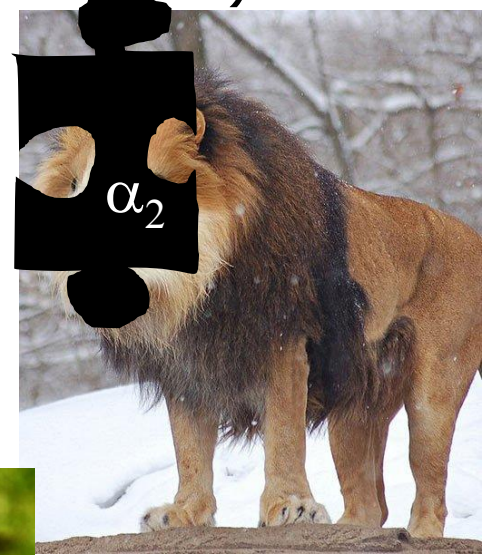
- Results have been presented at Nu 2016 (London):
  - http://neutrino2016.iopconfs.org/programme
- New (ν property) results from:
  - Super-Kamiokande
  - **Daya Bay**
  - RENO
  - **T2K**
  - **NOvA**
  - **KamLAND Zen**
- Skipping sterile neutrinos (no evidence)

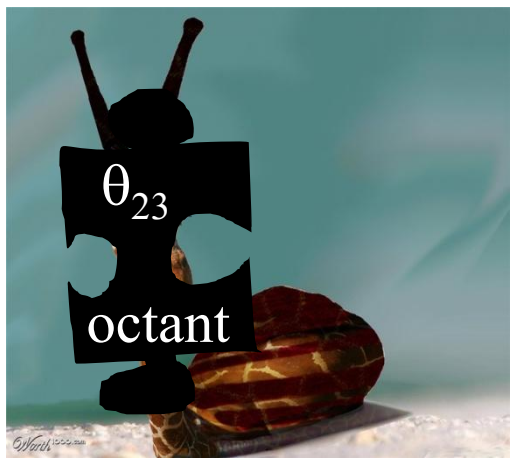
Neutrinos and the flavour puzzle

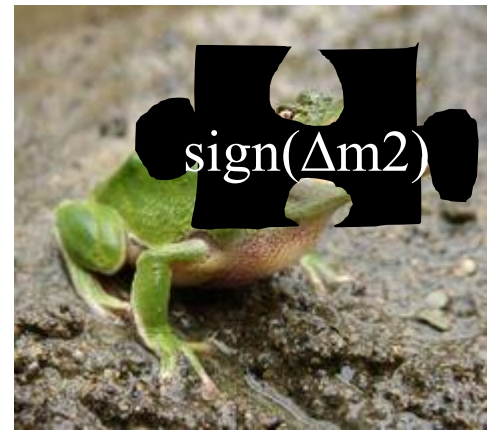
The ν sector is, at least, half of the flavour puzzle and we are still missing several pieces!! (that we know of)











E.F. Martinez

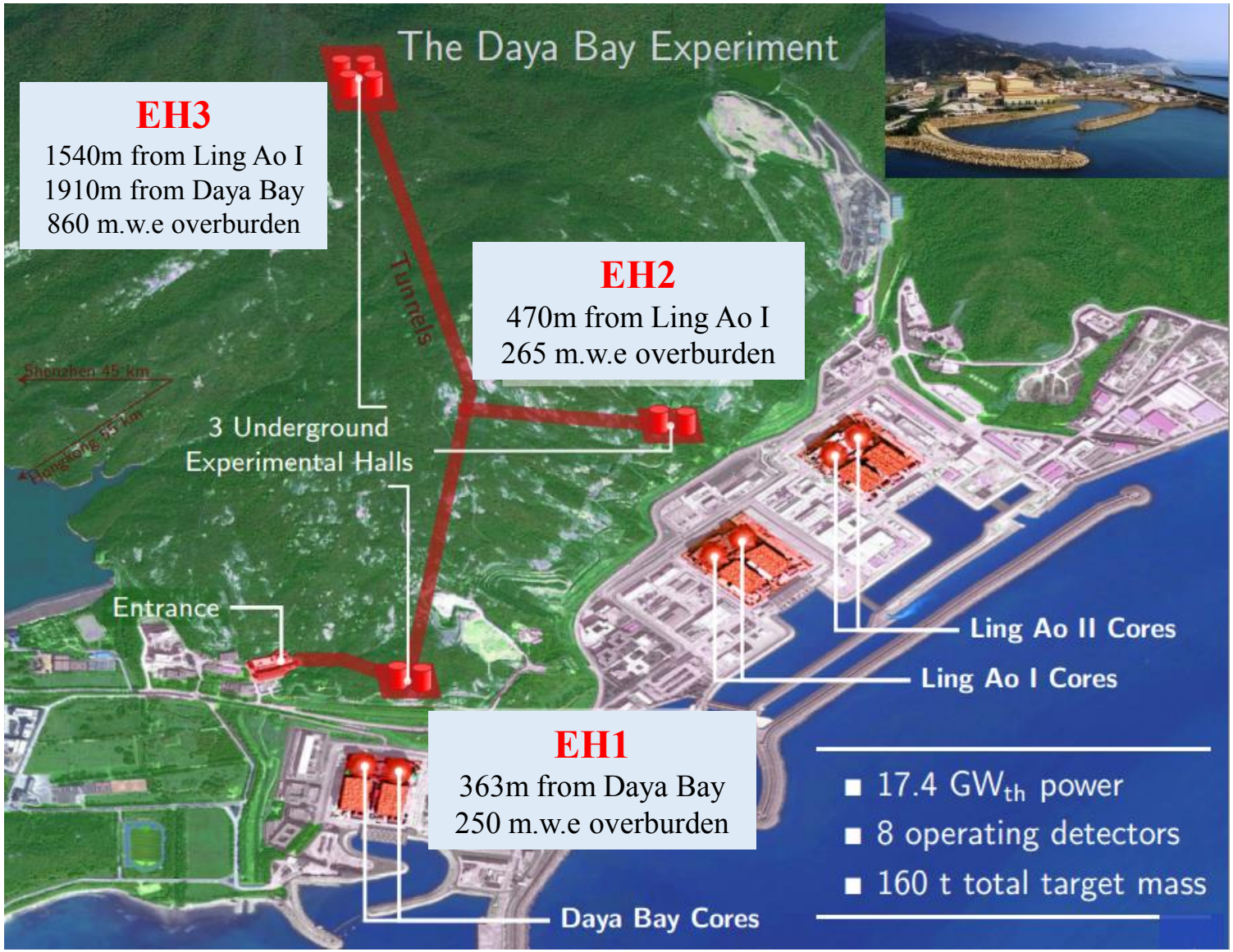
Neutrinos and the flavour puzzle

The ν sector is, at least, half of the flavour puzzle and we are still missing several pieces!! (that we know of)






Experimental site

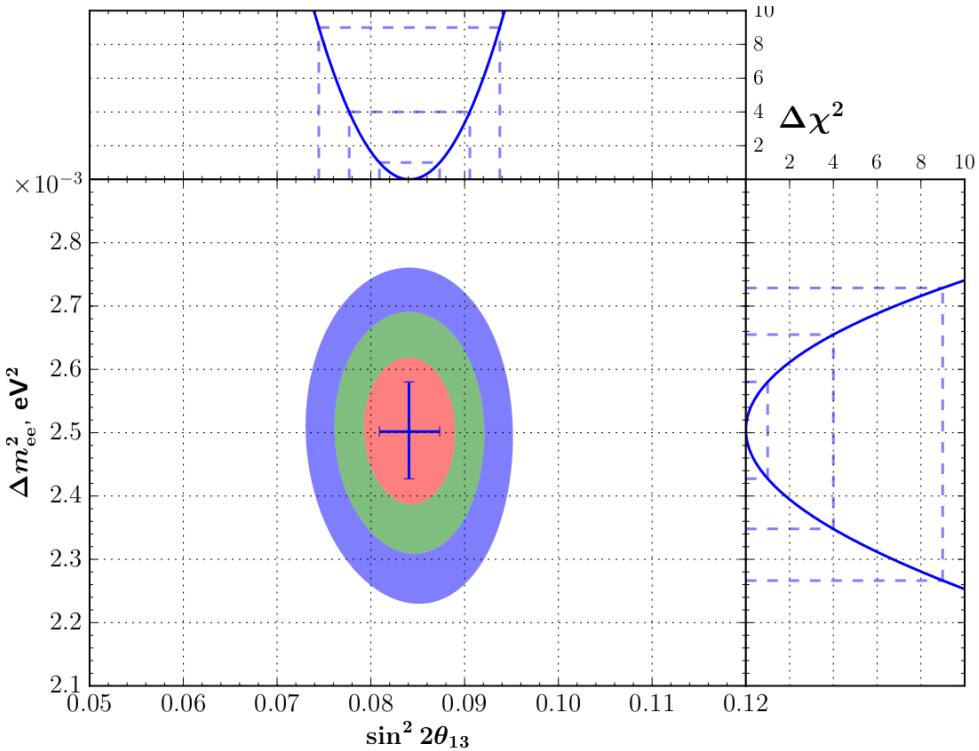


Z.Yu

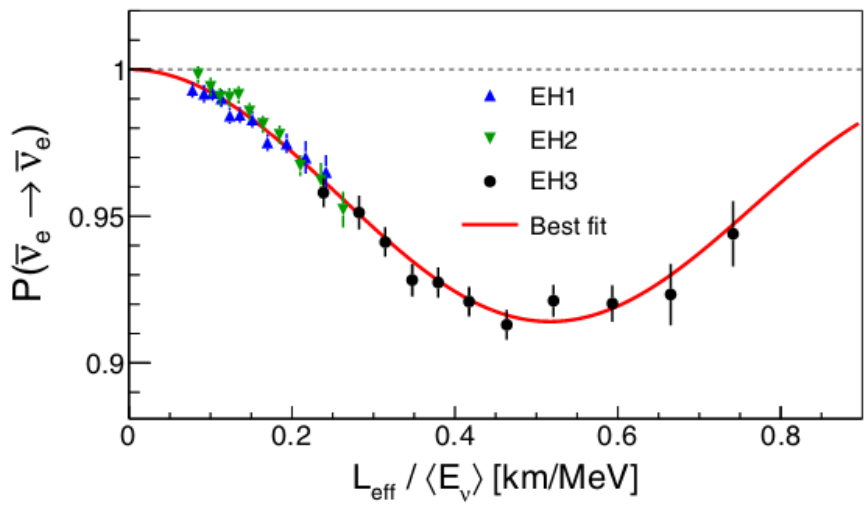
Poster Id: P2.063 by Maxim Gonchar

Oscillation results

1230 days data



$$P = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{1.267\Delta m^2_{21}L}{E} - \sin^2 2\theta_{13}\sin^2\frac{1.267\Delta m^2_{ee}L}{E}.$$



$\sin^2 2\theta_{13} = [8.41 \pm 0.27(\text{stat.}) \pm 0.19(\text{syst.})] \times 10^{-2}$

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

$\chi^2/\text{NDF} = 232.6/263$

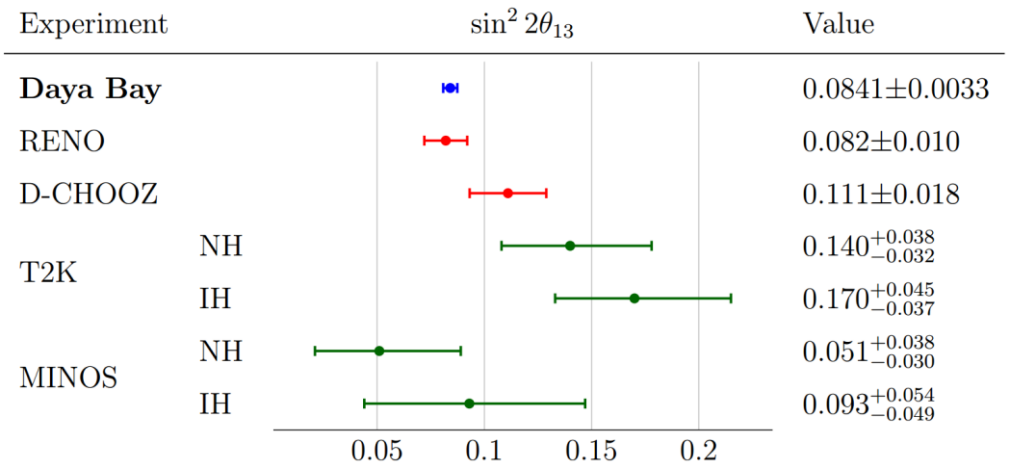
Last publication:	$\sin^2 2\theta_{13} =$	$[8.4 \pm 0.5] \times 10^{-2}$
P. R. L. 115, 111802 (2015)	$\lvert\Delta m^2_{ee}\rvert =$	$]2.42 \pm 0.11] \times 10^{-3}\text{eV}^2$

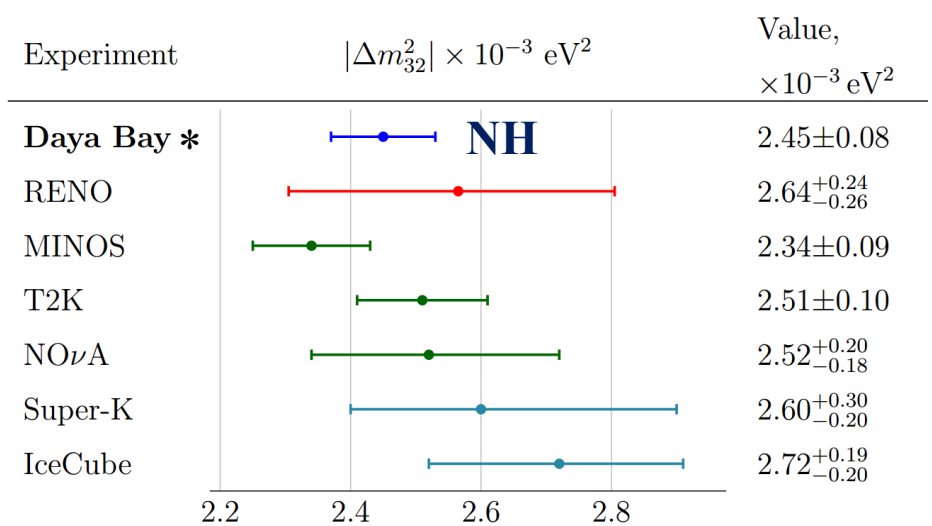
Z.Yu

Oscillation results

1230 days data

- **Most precise measurement**
  - **$\sin^2 2\theta_{13}$ and $|\Delta m^2_{32}|$**
- Consistent results among
  - The MeV-scale reactor
  - The GeV-scale accelerator and atmospheric experiments





$$P_{\rm sur} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$

Δm^2_{32} (NH)=[2.45$\pm$0.08]$\times10^{-3}$eV^2

Δm^2_{32} (IH) =[-2.55$\pm$0.08]$\times10^{-3}$eV^2

*** Fit with full 3-flavor oscillation formula assuming normal mass hierarchy.**

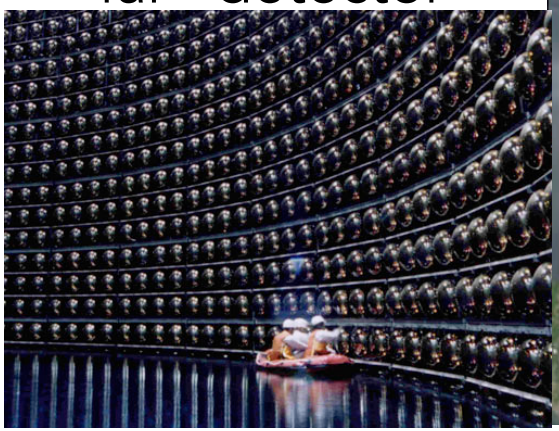
Z.Yu

T2K:

ND280
"near" detectors

J-PARC

Super-Kamiokande
"far" detector



~400 collaborators
59 institutions
11 nations

- Intense muon (anti)neutrino beam from J-PARC to Super-K to study:
  - muon (anti) neutrino disappearance ($\nu_\mu \nrightarrow \nu_\mu$, $\bar{\nu}_\mu \nrightarrow \bar{\nu}_\mu$)
  - electron (anti)neutrino appearance ($\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)
  - rich program of
    - neutrino-nucleus interaction studies with near detectors
    - "exotic" physics: Lorentz violation, sterile neutrinos, heavy leptons, etc.
    - Will not be able to discuss these other interesting topics.

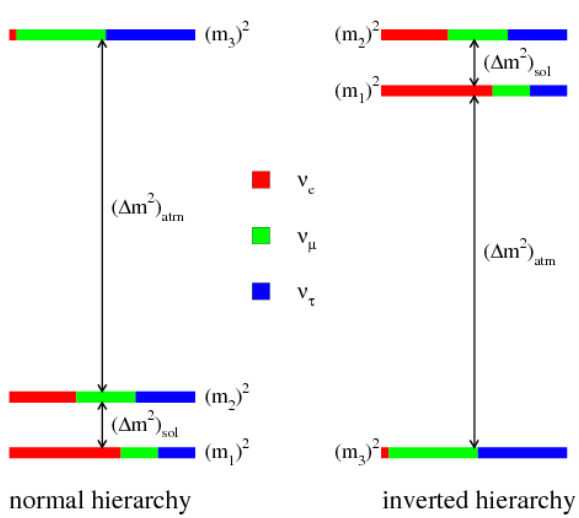
QUICK SUMMARY

- **$\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$**
  - enhance/suppress both $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- **CP violating parameter δ_{CP}** *up to ±30% effect at T2K*
  - δ_{CP}=0,π: no CP violation: vacuum oscillation probabilities equal
  - δ_{CP} ~-π/2: enhance $\nu_\mu \rightarrow \nu_e$, suppress $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - δ_{CP} ~+π/2: suppress $\nu_\mu \rightarrow \nu_e$, enhance $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

"normal" hierarchy (NH):

- enhance $\nu_\mu \rightarrow \nu_e$
- suppresses $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

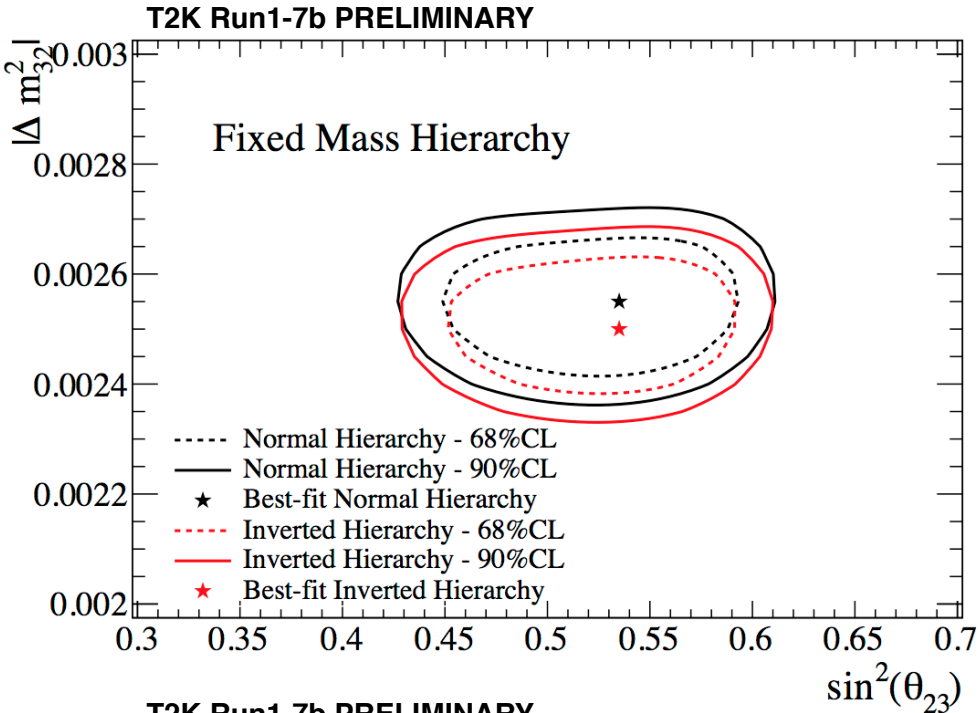
±10% effect at T2K

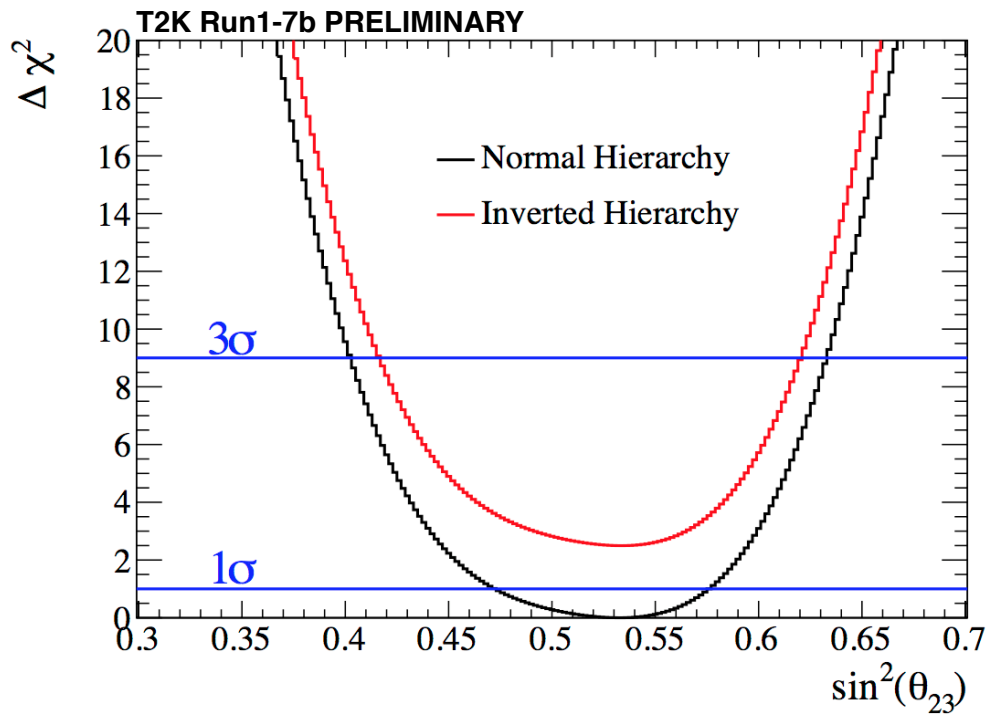


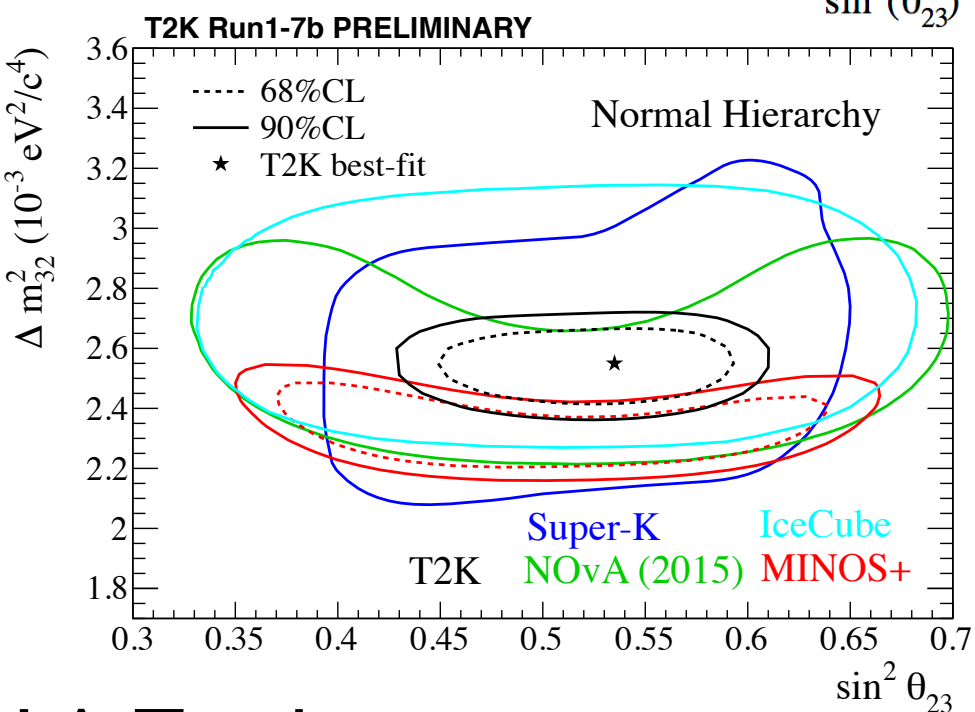
"inverted" hierarchy: (IH)

- suppress $\nu_\mu \rightarrow \nu_e$
- enhance $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$\sin^2\theta_{23}$ AND Δm^2_{32}





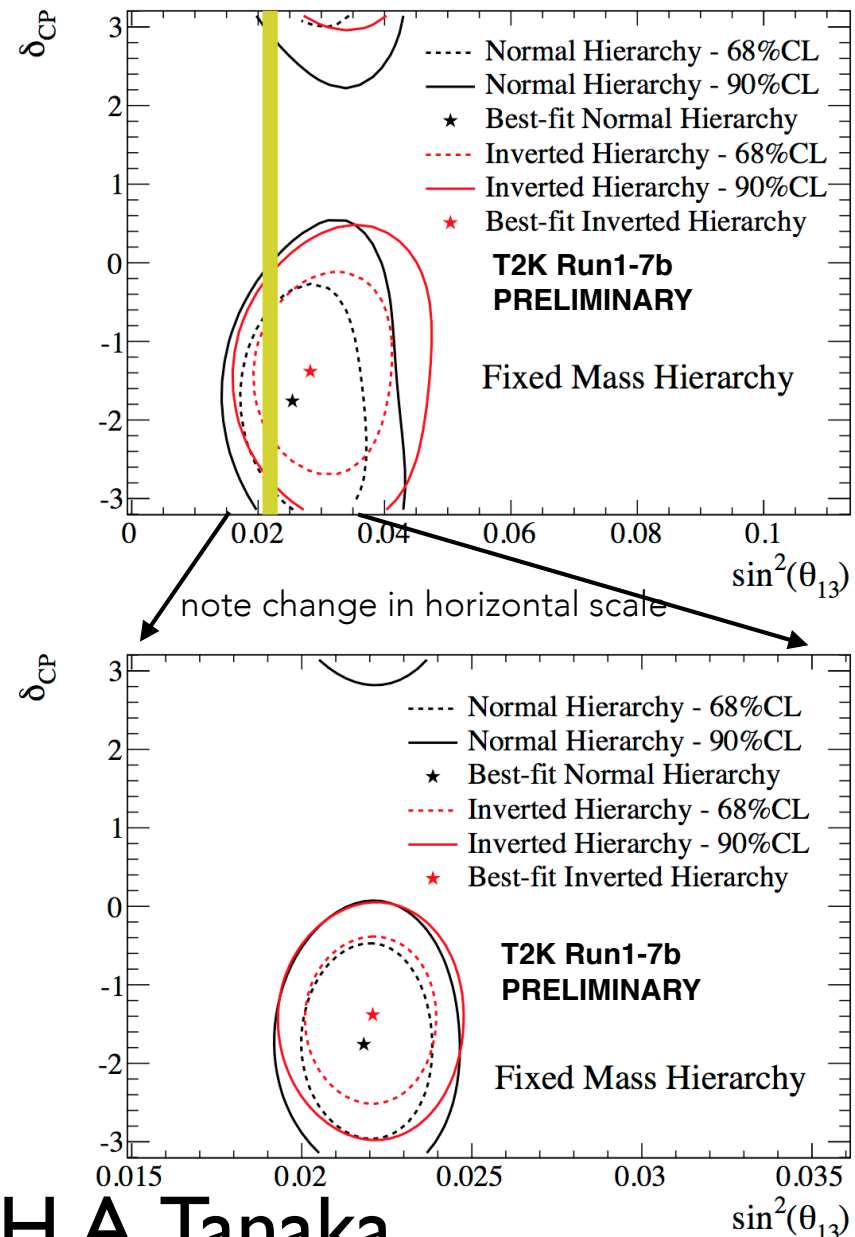


	NH	IH
$\sin^2\theta_{23}$	$0.532^{+0.044}_{-0.060}$	$0.534^{+0.041}_{-0.059}$
$\lvert\Delta m^2_{32}\rvert$ ($/10^{-3}$eV^2)	$2.545^{+0.084}_{-0.082}$	$2.510^{+0.082}_{-0.083}$

- Results continue to be consistent with maximal mixing/oscillation

δ_{CP} vs. θ_{13}

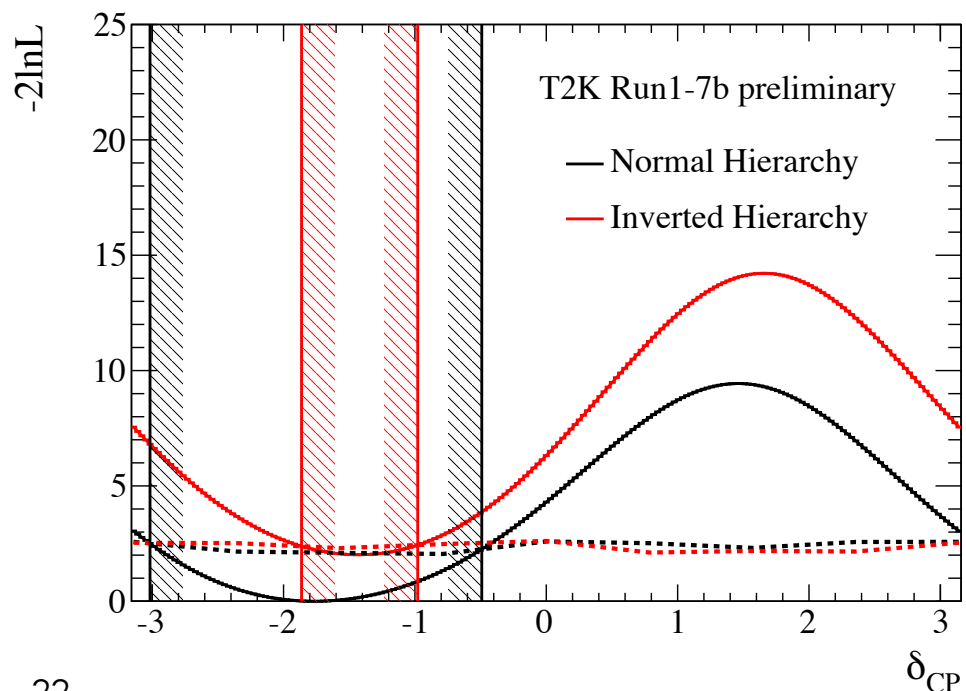
20% of full statistics ν:anti-ν = 1:1



Left: δ_{CP} vs. θ_{13} (fixed $\Delta\chi^2$, fixed hierarchy)

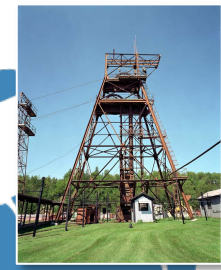
- T2K-only
- T2K with reactor $\sin^2 2\theta_{13} = 0.085 \pm 0.005$

Below: δ_{CP} with Feldman-Cousins critical values and reactor θ_{13}



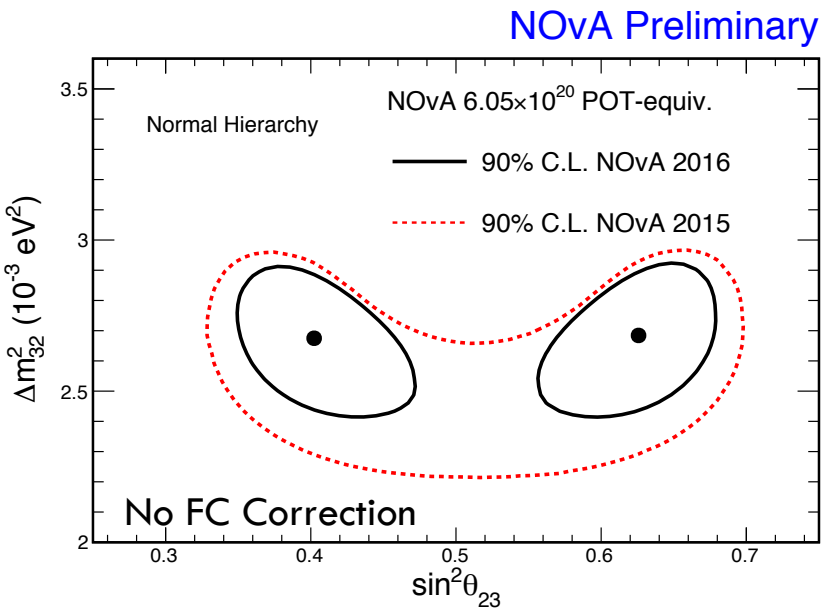
H.A. Tanaka

NOvA



- Long-baseline, off-axis neutrino oscillation experiment
- Study neutrinos from NuMI beam at Fermilab
- At 14 mrad off-axis, energy peaked at 2 GeV
- Functionally identical detectors
  - ND on site at Fermilab
  - FD 810 km away in Ash River, MN
  - Measurement at ND is directly used to predict FD

Contours



- Fit for Δm^2 and $\sin^2\theta_{23}$
- Dominant systematic effects included in fit:
  - Normalization
  - NC background
  - Flux
  - Muon and hadronic energy scales
  - Cross section
  - Detector response and noise

Best Fit (in NH):

$$|\Delta m^2_{32}| = 2.67 \pm 0.12 \times 10^{-3}\text{eV}^2$$
$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02}(0.63^{+0.02}_{-0.03})$$

Maximal mixing excluded at 2.5σ

See Poster P1.029 by L. Vinton and B. Zamorano for more detail on systematics

15% of full statistics ν:anti-ν = 1:0

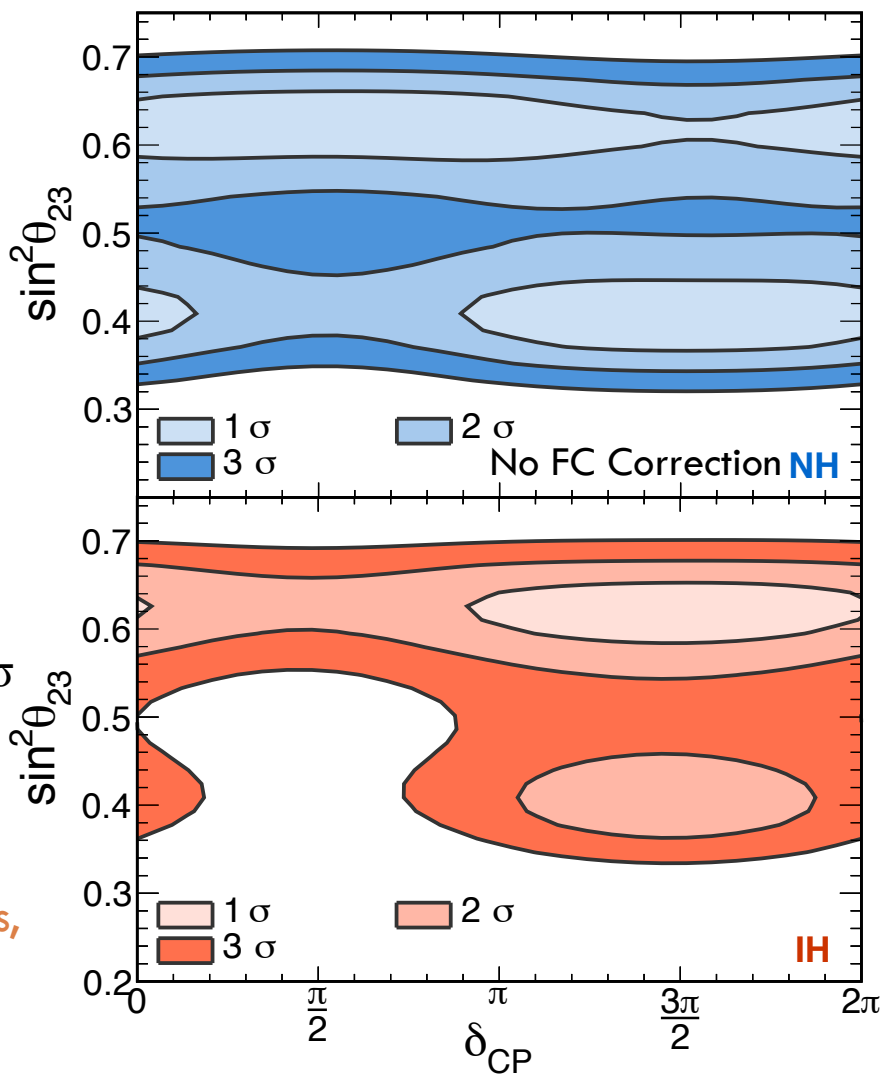
Contours

- Fit for hierarchy, δ_{CP}, $\sin^2\theta_{23}$
  - Constrain Δm^2 and $\sin^2\theta_{23}$ with NOvA disappearance results
  - Not a full joint fit, systematics and other oscillation parameters not correlated
- Global best fit Normal Hierarchy

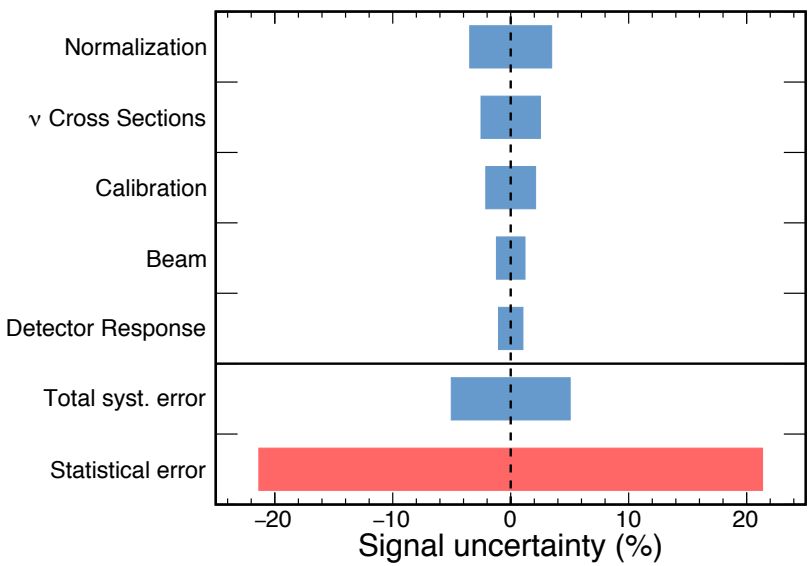
$$\delta_{CP} = 1.49\pi$$
$$\sin^2(\theta_{23}) = 0.40$$

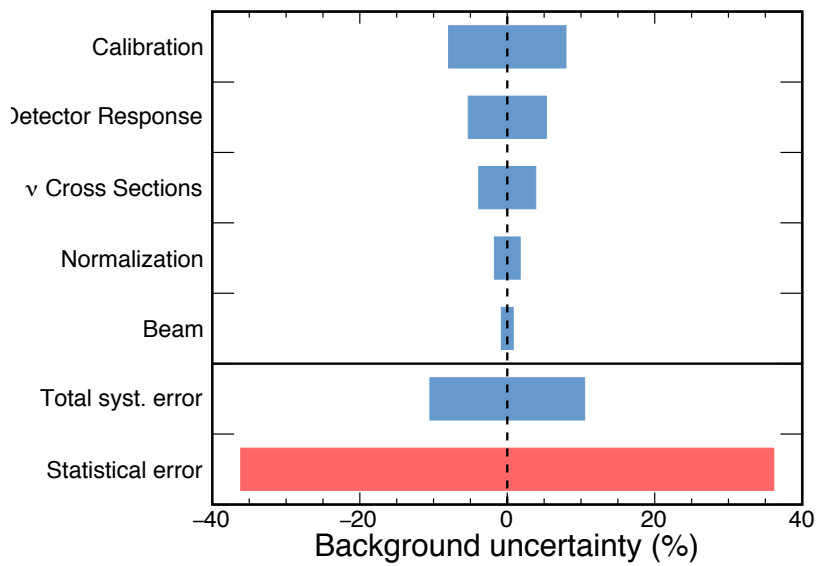
  - best fit IH-NH, $\Delta\chi^2$=0.47
  - both octants and hierarchies allowed at 1σ
  - 3σ exclusion in IH, lower octant around δ_{CP}=π/2

Antineutrino data will help resolve degeneracies, particularly for non-maximal mixing
Planned for Spring 2017



Appearance Systematics





Global Analysis: NuFit Collaboration

Esteban et al., arXiv:1611.01514v1

Solar experiments

- Chlorine total rate [15], 1 data point.
- Gallex & GNO total rates [16], 2 data points.
- SAGE total rate [17], 1 data point.
- SK1 full energy and zenith spectrum [18], 44 data points.
- SK2 full energy and day/night spectrum [19], 33 data points.
- SK3 full energy and day/night spectrum [20], 42 data points.
- SK4 2055-day day-night asymmetry [21] and 2365-day energy spectrum [22], 24 data points.
- SNO combined analysis [23], 7 data points.
- Borexino Phase-I 740.7-day low-energy data [24], 33 data points.
- Borexino Phase-I 246-day high-energy data [25], 6 data points.
- Borexino Phase-II 408-day low-energy data [26], 42 data points.

Atmospheric experiments

- IceCube/DeepCore 3-year data [48, 70], 64 data points.

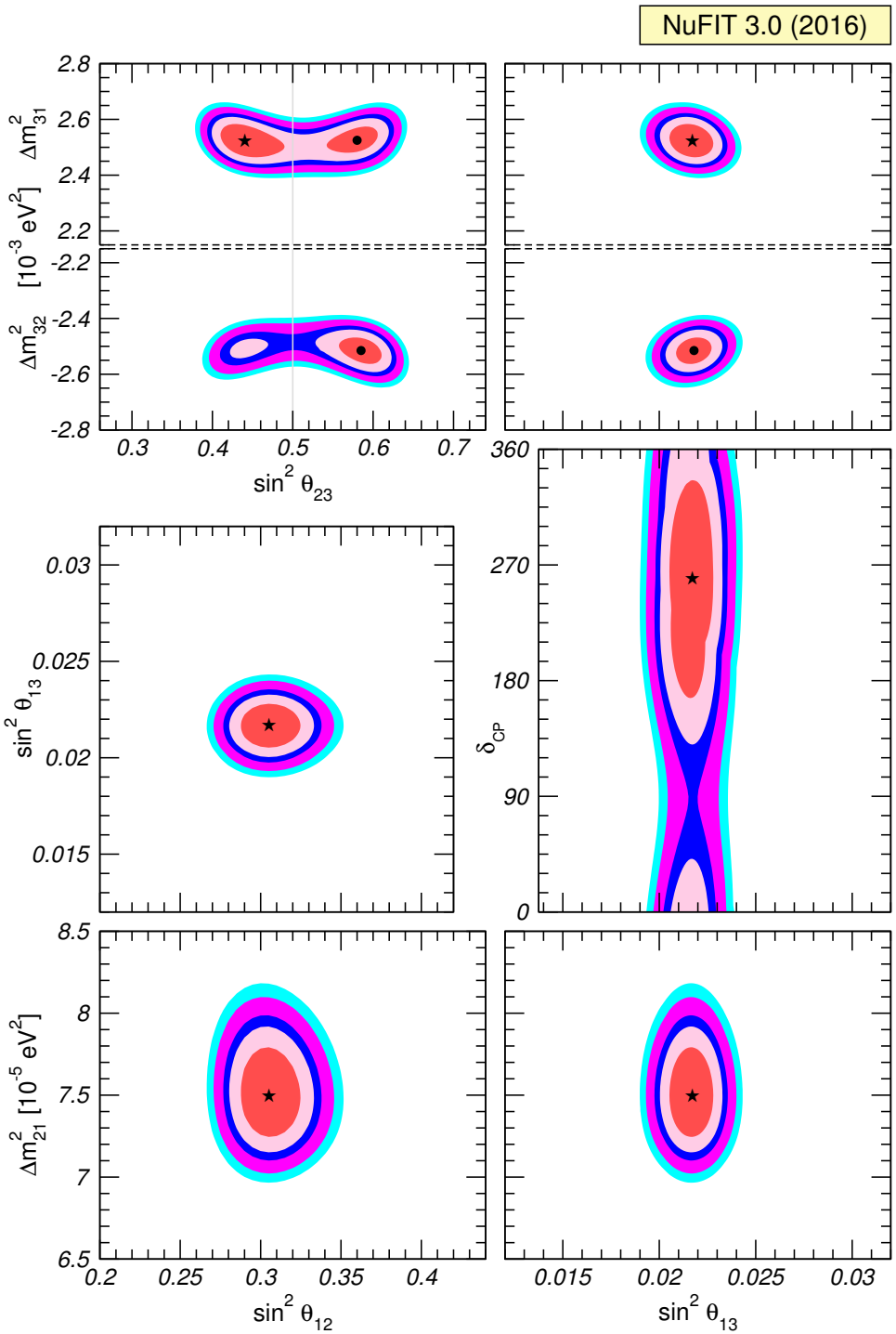
Reactor experiments

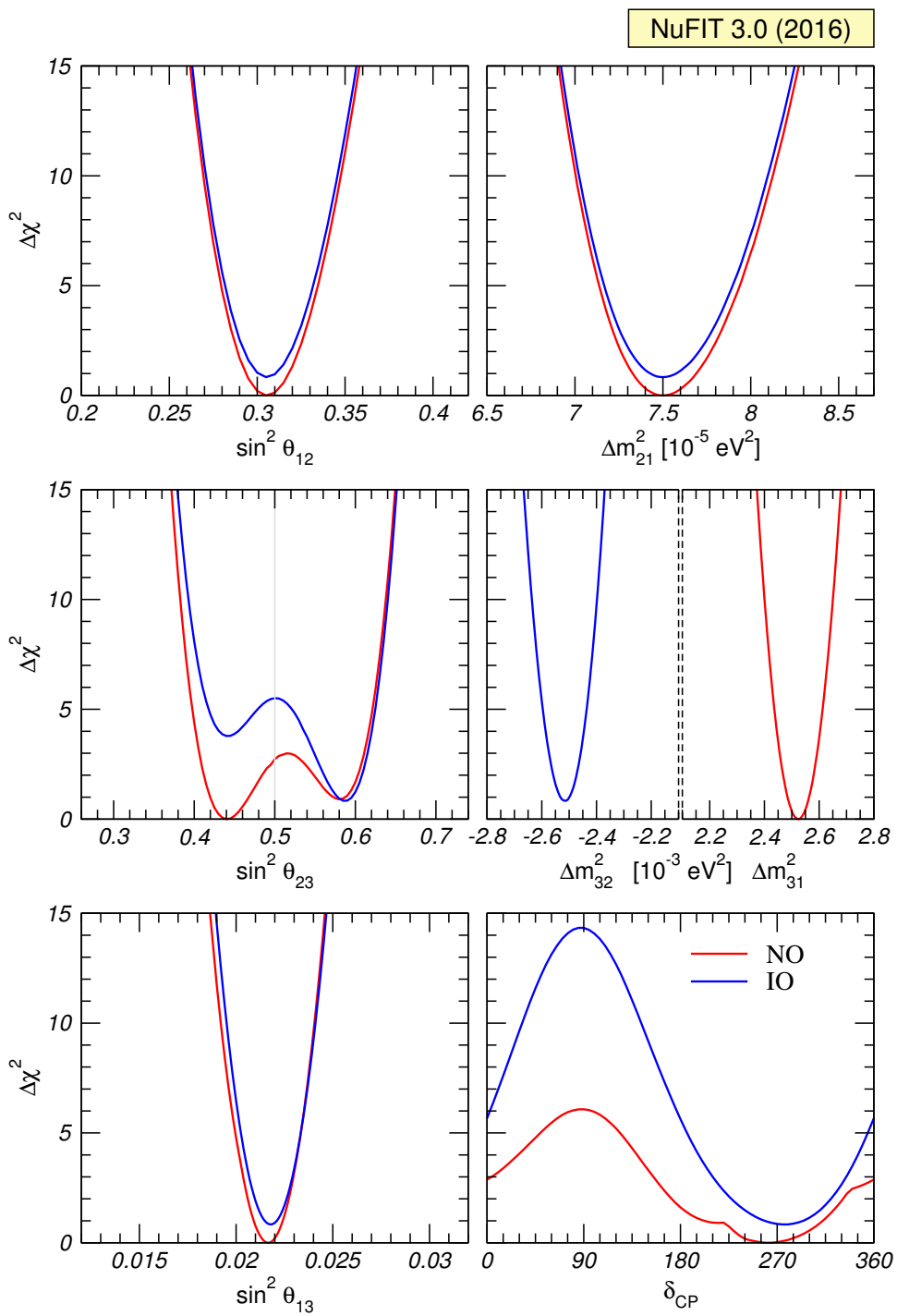
- KamLAND combined DS1 & DS2 spectrum [32], 17 data points.
- CHOOZ energy spectrum [33], 14 data points.
- Palo-Verde total rate [34], 1 data point.
- Double-Chooz FD-I (461 days) and FD-II (212 days) spectra [35], 54 data points.
- Daya-Bay 1230-day spectrum [36], 34 data points.
- Reno 800-day near & far total rates [37], 2 data points (with free normalization).
- SBL reactor data (including Daya-Bay total flux at near detector), 77 data points [38, 71].

Accelerator experiments

- MINOS 10.71×10^{20} pot ν_μ-disappearance data [27], 39 data points.
- MINOS 3.36×10^{20} pot $\bar{\nu}_\mu$-disappearance data [27], 14 data points.
- MINOS 10.6×10^{20} pot ν_e-appearance data [28], 5 data points.
- MINOS 3.3×10^{20} pot $\bar{\nu}_e$-appearance data [28], 5 data points.
- T2K 7.48×10^{20} pot ν_μ-disappearance data [29, 30], 28 data points.
- T2K 7.48×10^{20} pot ν_e-appearance data [29, 30], 5 data points.
- T2K 7.47×10^{20} pot $\bar{\nu}_\mu$-disappearance data [29, 30], 63 data points.
- T2K 7.47×10^{20} pot $\bar{\nu}_e$-appearance data [29, 30], 1 data point.
- NOνA 6.05×10^{20} pot ν_μ-disappearance data [31], 18 data points.
- NOνA 6.05×10^{20} pot ν_e-appearance data [31], 10 data points.

Global Fit





Esteban et al., arXiv:1611.01514v1

Global Fit: NuFIT 3.0

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 0.83$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.271 \to 0.345$
$\theta_{12}/^\circ$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$31.38 \to 35.99$
$\sin^2\theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.385 \to 0.635$	$0.587^{+0.020}_{-0.024}$	$0.393 \to 0.640$	$0.385 \to 0.638$
$\theta_{23}/^\circ$	$41.6^{+1.5}_{-1.2}$	$38.4 \to 52.8$	$50.0^{+1.1}_{-1.4}$	$38.8 \to 53.1$	$38.4 \to 53.0$
$\sin^2\theta_{13}$	$0.02166^{+0.00075}_{-0.00075}$	$0.01934 \to 0.02392$	$0.02179^{+0.00076}_{-0.00076}$	$0.01953 \to 0.02408$	$0.01934 \to 0.02397$
$\theta_{13}/^\circ$	$8.46^{+0.15}_{-0.15}$	$7.99 \to 8.90$	$8.49^{+0.15}_{-0.15}$	$8.03 \to 8.93$	$7.99 \to 8.91$
$\delta_{\rm CP}/^\circ$	261^{+51}_{-59}	$0 \to 360$	277^{+40}_{-46}	$145 \to 391$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.03 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.524^{+0.039}_{-0.040}$	$+2.407 \to +2.643$	$-2.514^{+0.038}_{-0.041}$	$-2.635 \to -2.399$	$\begin{bmatrix} +2.407 \to +2.643 \\ -2.629 \to -2.405 \end{bmatrix}$

Esteban et al., arXiv:1611.01514v1

Combination LBL & Reactor

$$\Delta\chi^2_{\mathrm{LBL}+\theta_{13}^{\mathrm{REA}}}(\theta_{23},\delta_{\mathrm{CP}},\Delta m^2_{3\ell})$$

$$= \min_{\theta_{13}}\left[\chi^2_{\mathrm{LBL}}(\theta_{13},\theta_{23},\delta_{\mathrm{CP}},\Delta m^2_{3\ell}) + \min_{\Delta m^2_{3\ell}}\chi^2_{\mathrm{REA}}(\theta_{13},\Delta m^2_{3\ell})\right] - \chi^2_{\mathrm{min}}$$

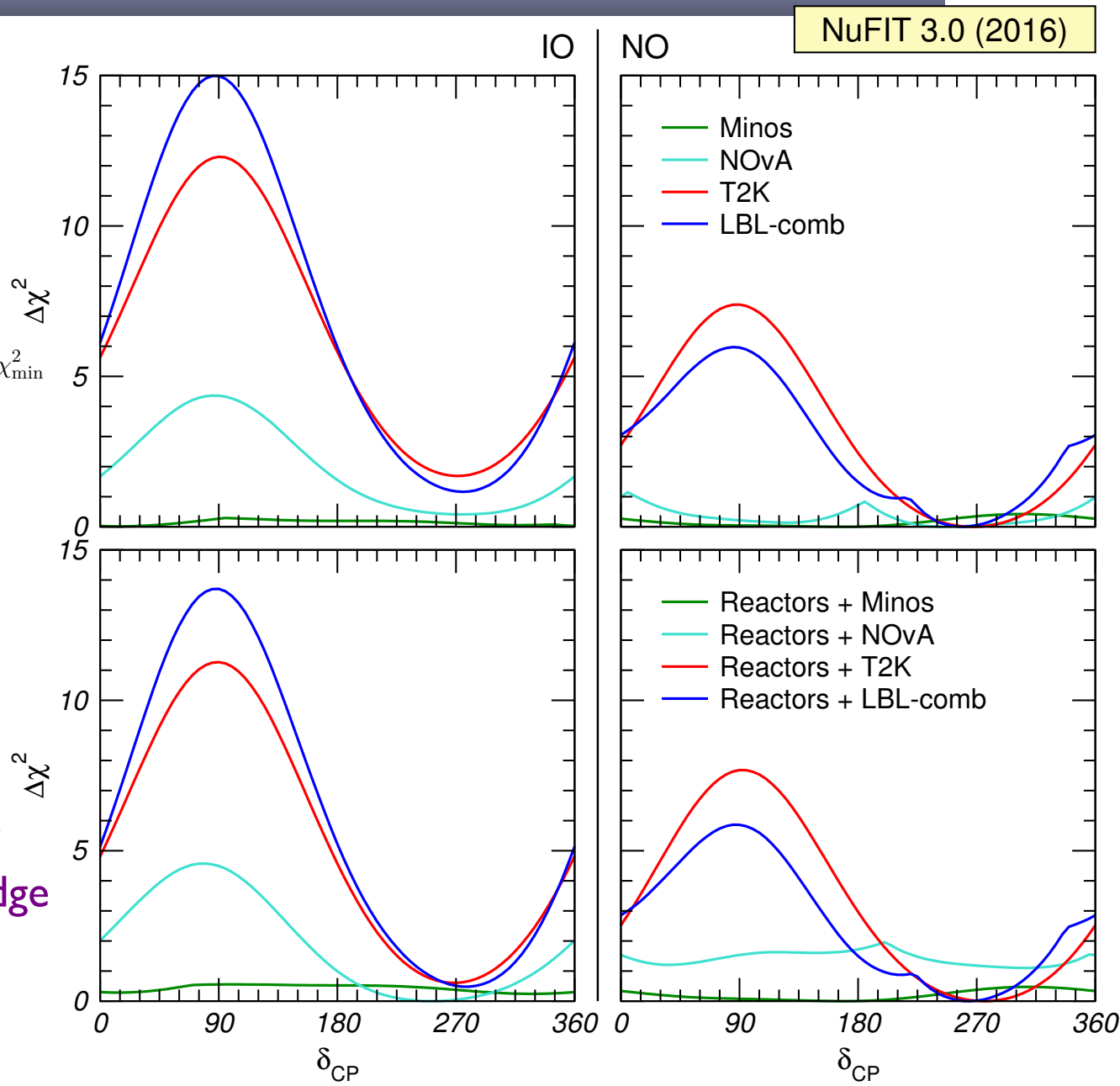
only Reactor θ_{13}

VS

$$\Delta\chi^2_{\mathrm{LBL+REA}}(\theta_{23},\delta_{\mathrm{CP}},\Delta m^2_{3\ell})$$

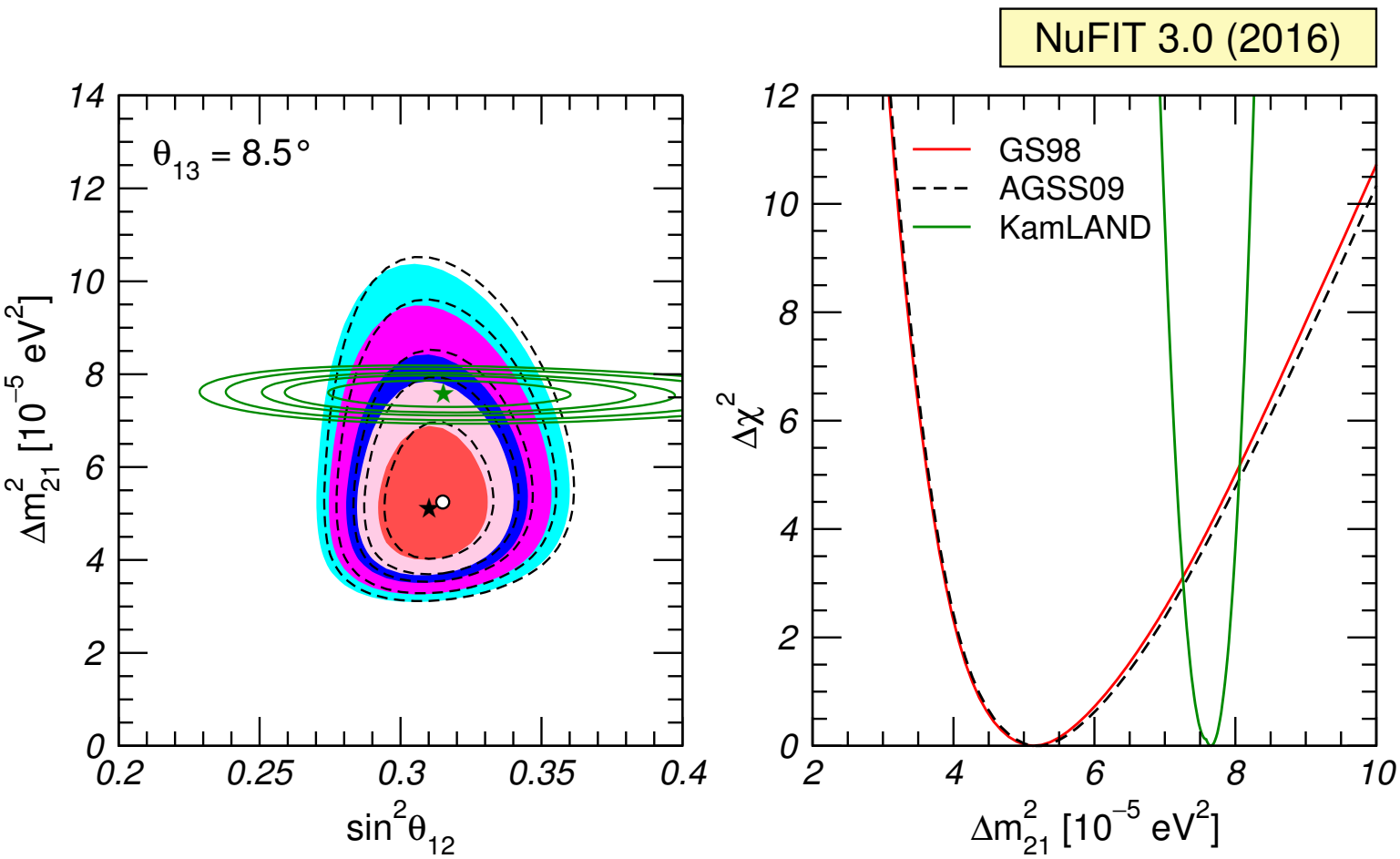
$$= \min_{\theta_{13}}\left[\chi^2_{\mathrm{LBL}}(\theta_{13},\theta_{23},\delta_{\mathrm{CP}},\Delta m^2_{3\ell}) + \chi^2_{\mathrm{REA}}(\theta_{13},\Delta m^2_{3\ell})\right] - \chi^2_{\mathrm{min}}$$

Reactor θ_{13} and Δm^2_{3L} knowledge



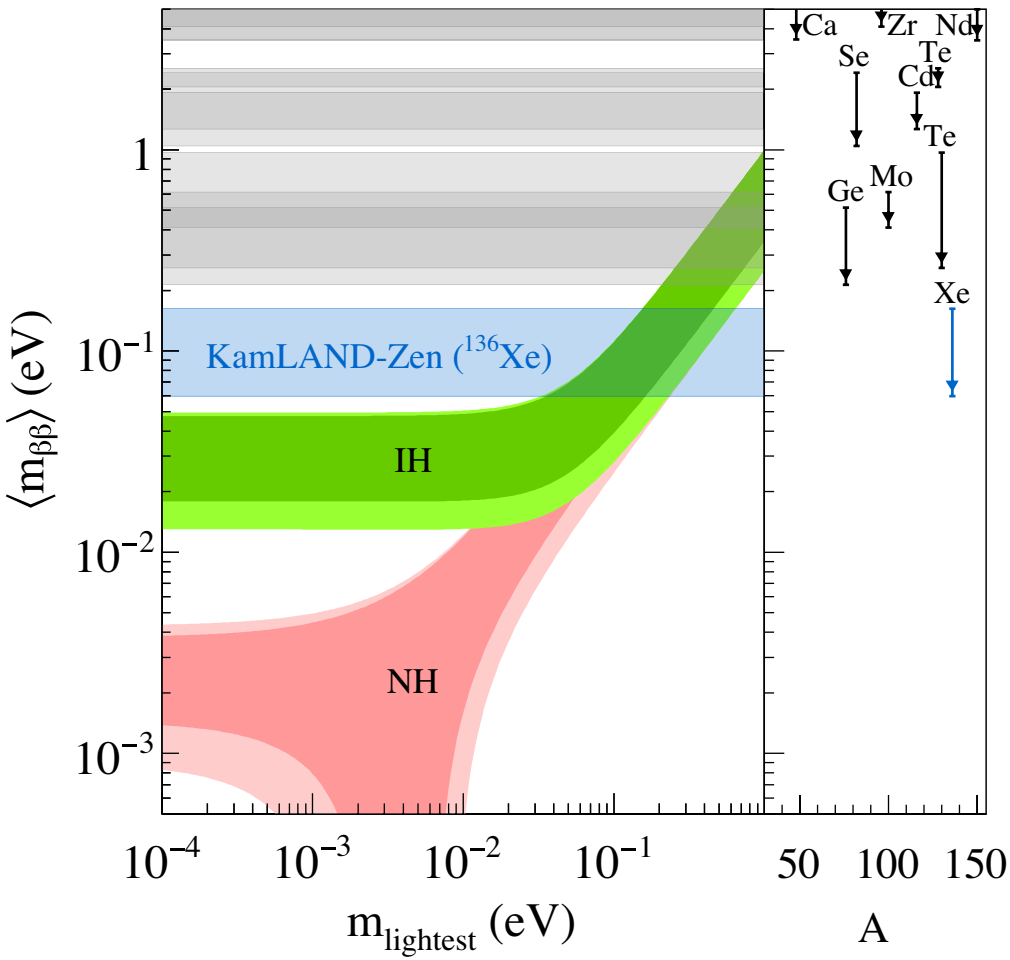
Hint for NO below 1σ

Solar Osc Parameters

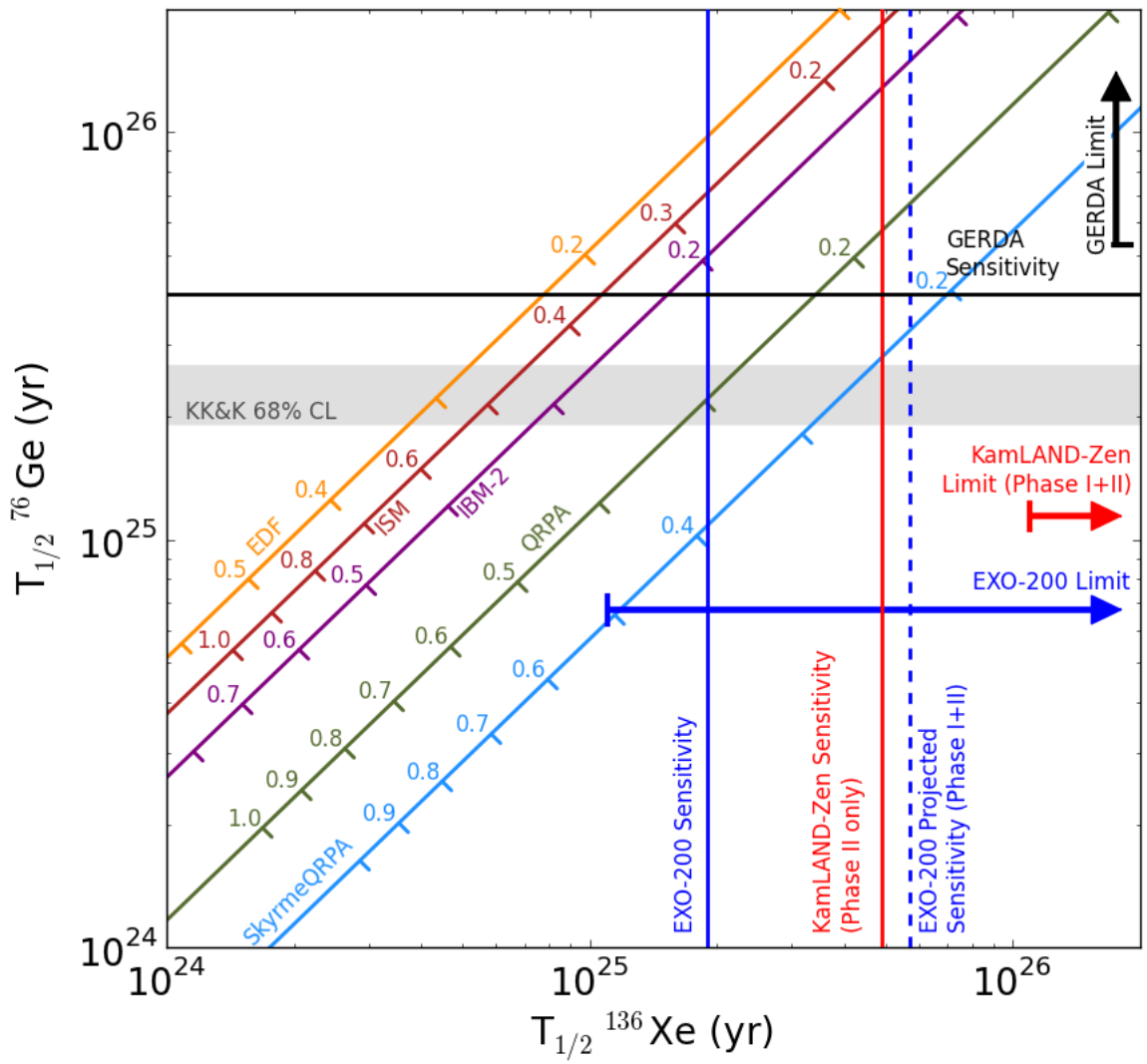


Δm^2_{21}: 2σ "tension"

0ν2β



- EXO-200 running again
- CUORE about to start
- GERDA taking a run
- KamLAND-Zen 800 will not start for another year…


10^{26}
10^{25}
10^{24}
10^{24}
10^{25}
10^{26}
$T_{1/2}$ ^{76}Ge (yr)
$T_{1/2}$ ^{136}Xe (yr)
GERDA Limit
GERDA Sensitivity
KK&K 68% CL
KamLAND-Zen Limit (Phase I+II)
EXO-200 Limit
EXO-200 Sensitivity
KamLAND-Zen Sensitivity (Phase II only)
EXO-200 Projected Sensitivity (Phase I+II)
EDF
ISM
IBM-2
QRPA
SkyrmeQRPA
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0