Global analysis of neutrino oscillation experiments

Christoph Andreas Ternes
IFIC, Universitat de València/CSIC

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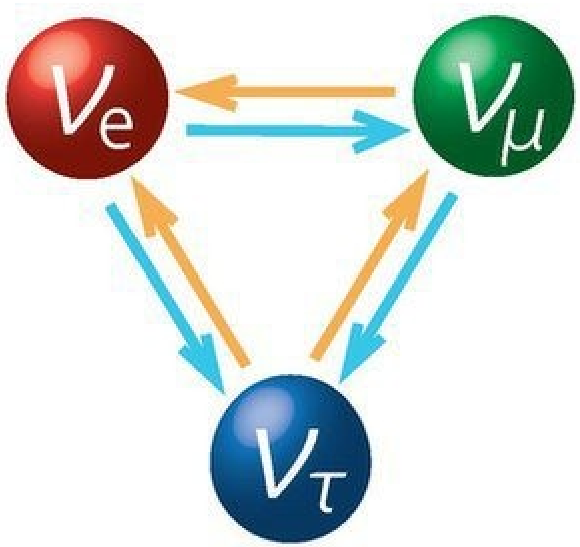
Neutrino oscillations



Parametrization of the mixing matrix

- Neutrino oscillation probability is given by

$$P(\alpha \to \beta; E, L) = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} e^{i \frac{\Delta m^2_{kj}}{2E} L}$$

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- For a given energy E and distance L the probability depends on:
  - Two mass splittings Δm^2_{21} , Δm^2_{31}
  - The entries of the matrix U

Parametrization of the mixing matrix

- The mixing matrix can be parametrized as

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

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- There are also two more majorana phases, but oscillation experiments are blind to them
- Different types of experiments are sensitive to different parameters

Experiment	Dominant parameters	Sub-dominant parameters
Solar Experiments + LBL reactors	θ_{12}, Δm^2_{21}	θ_{13}
Short baseline Reactors	θ_{13}, Δm^2_{31}	θ_{12}, Δm^2_{21}
Atmospheric experiments	θ_{23}, Δm^2_{31}	θ_{13}, δ
LBL accelerator disappearance	θ_{23}, Δm^2_{31}	θ_{13}
LBL accelerator appearance	θ_{13}, δ	θ_{23}

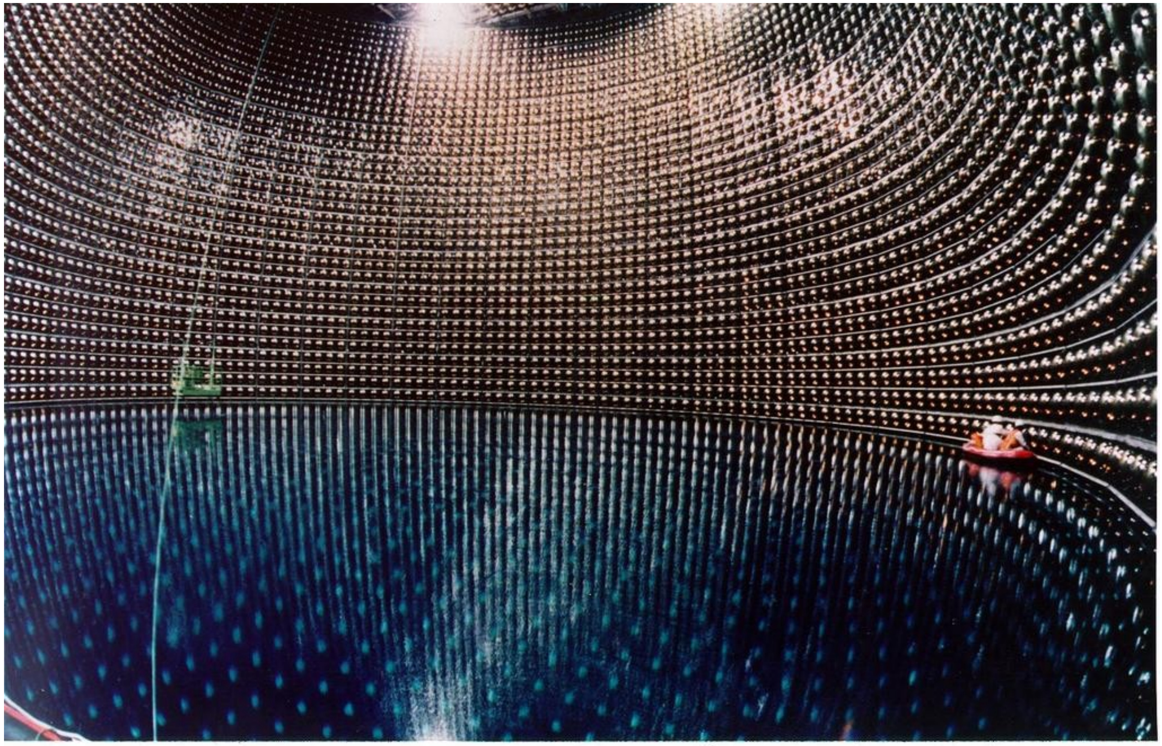
Global fit to neutrino oscillations

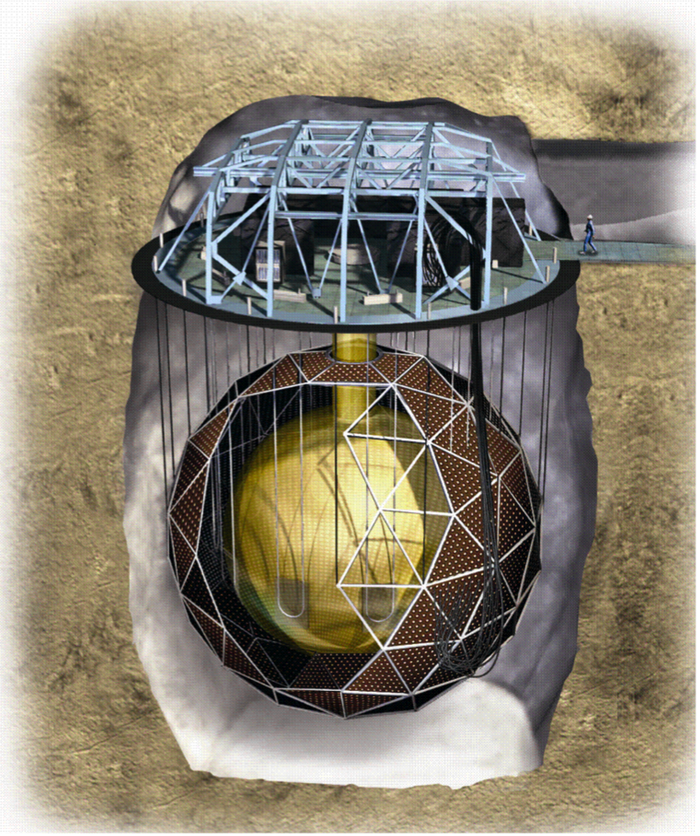
Phys.Lett. B782 (2018) 633-640, P.F. de Salas, D.V. Forero, CAT, M. Tórtola, J.W.F. Valle

https://globalfit.astroparticles.es/

Global fit to neutrino oscillations

- Solar experiments measure disappearance (P_{ee}) and conversion (P_{ex}) of electron neutrinos created in the sun





Global fit to neutrino oscillations

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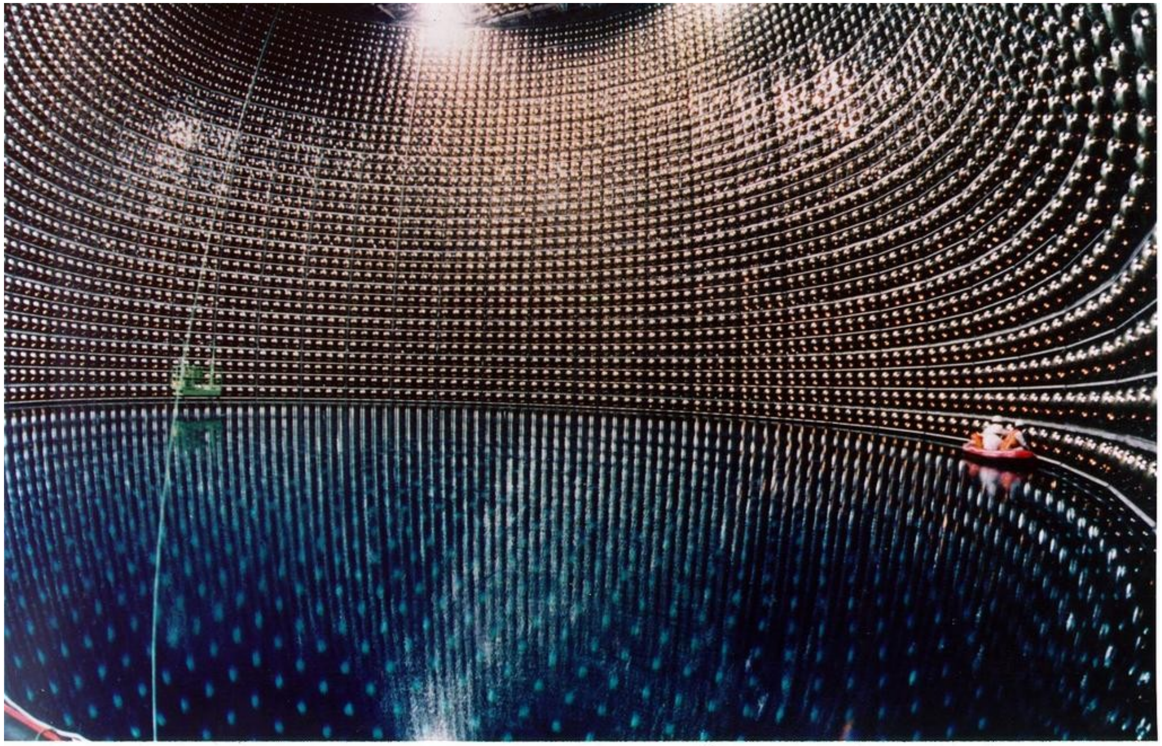

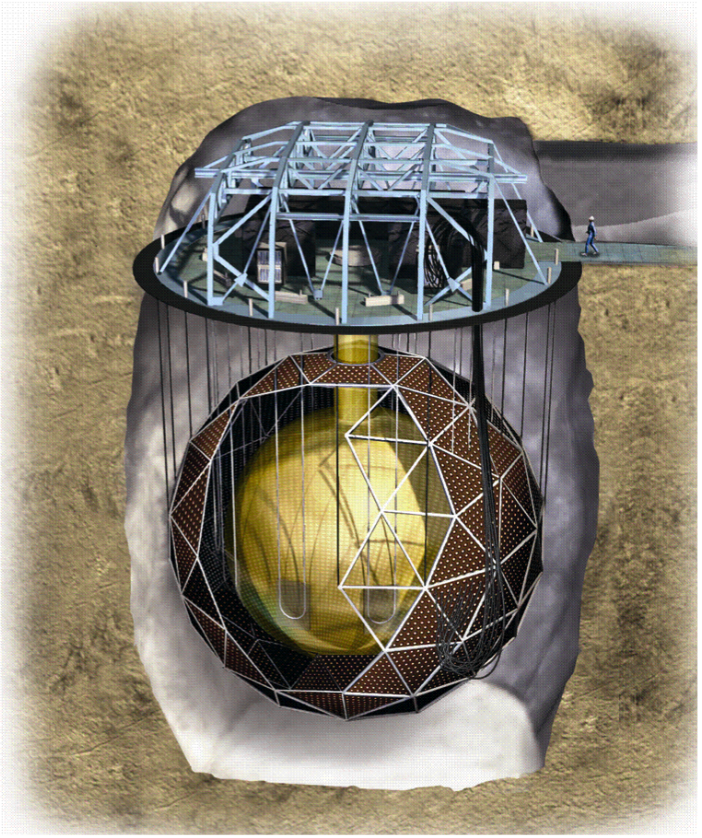

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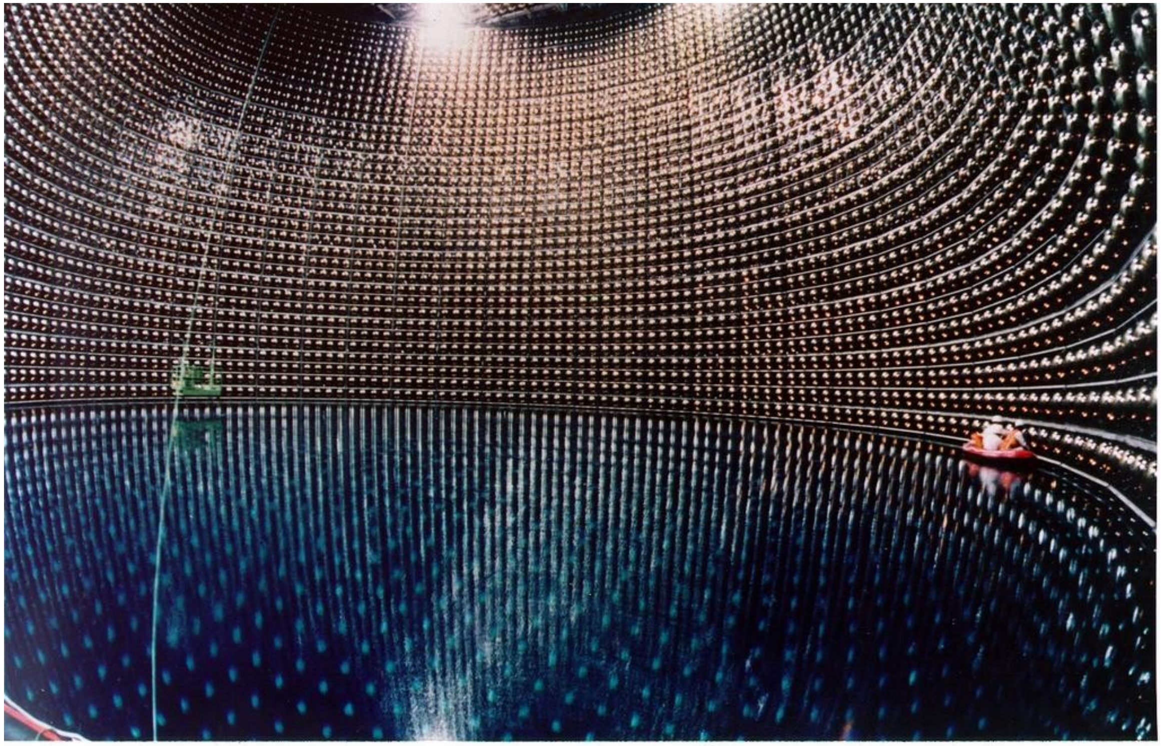
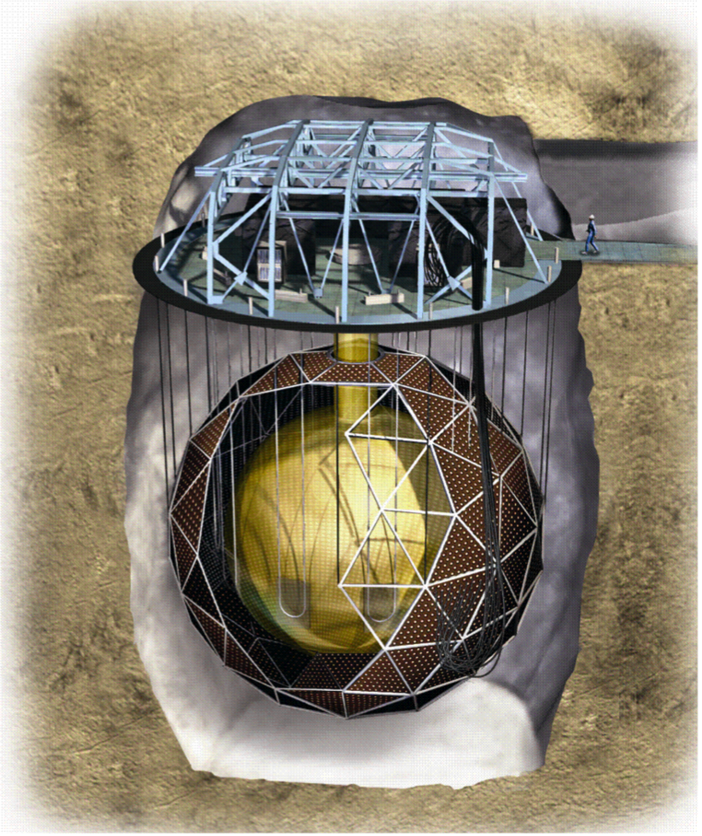
- The solar parameters are measured also by the long baseline reactor experiment KamLAND



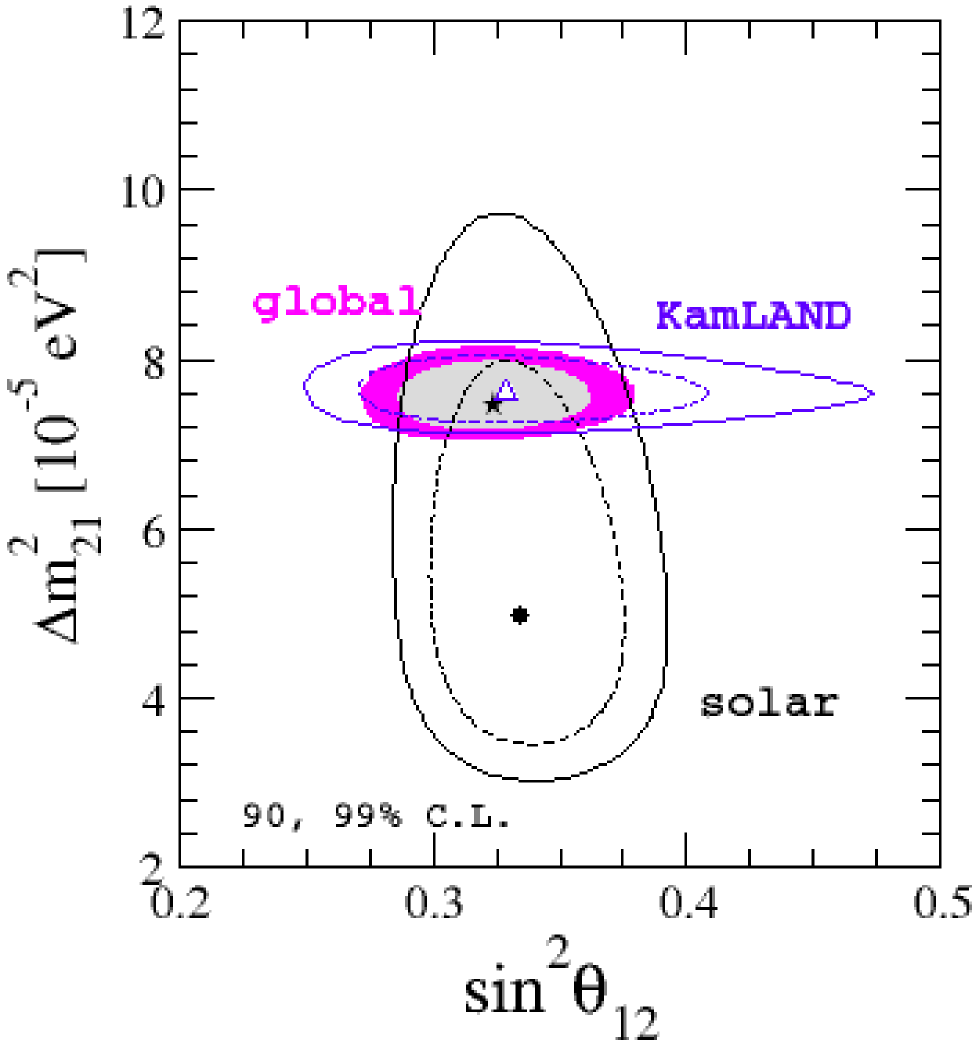


Global fit to neutrino oscillations

- Data included:
  - SK I-IV
  - Borexino: Beryllium data
  - SNO I-III
  - Sage
  - Gallex+GNO
  - Chlorine
  - KamLAND

Global fit to neutrino oscillations

- Result of solar experiments and KamLAND



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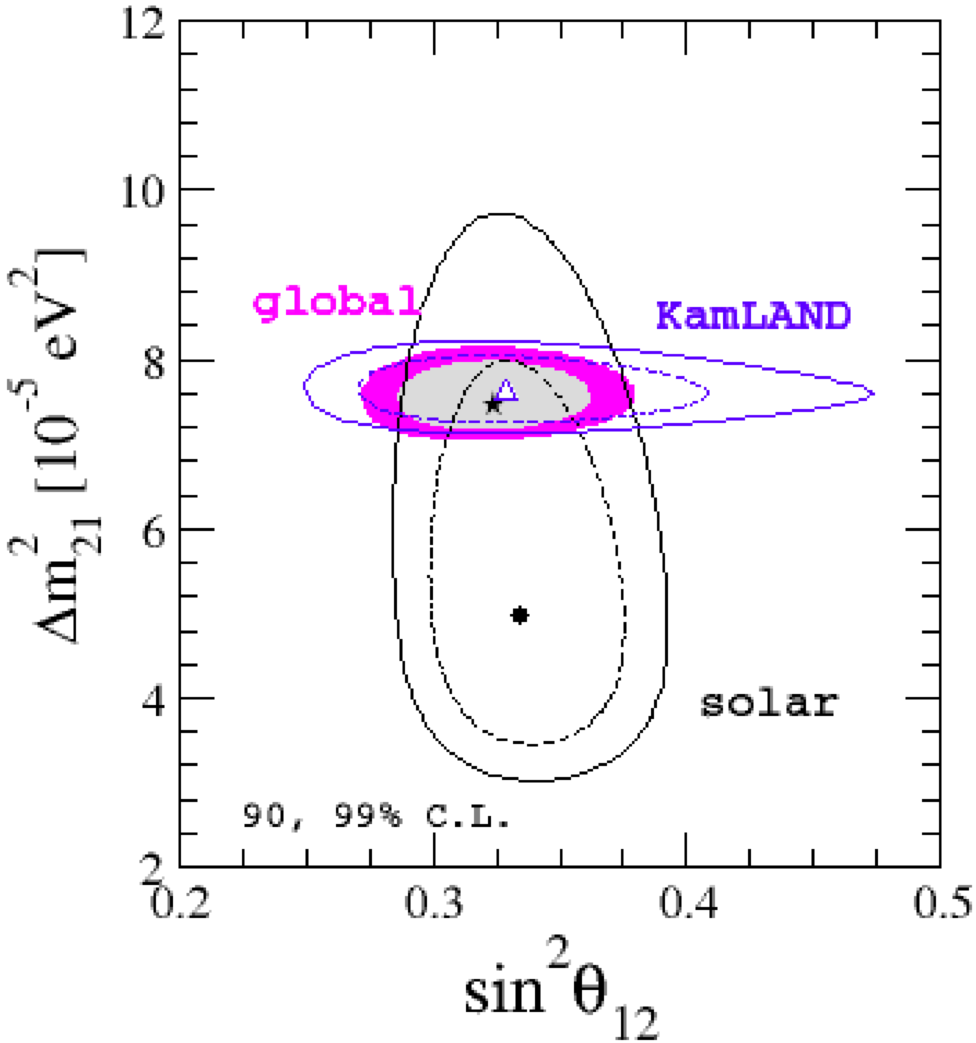

- θ_{12} better measured by solar data

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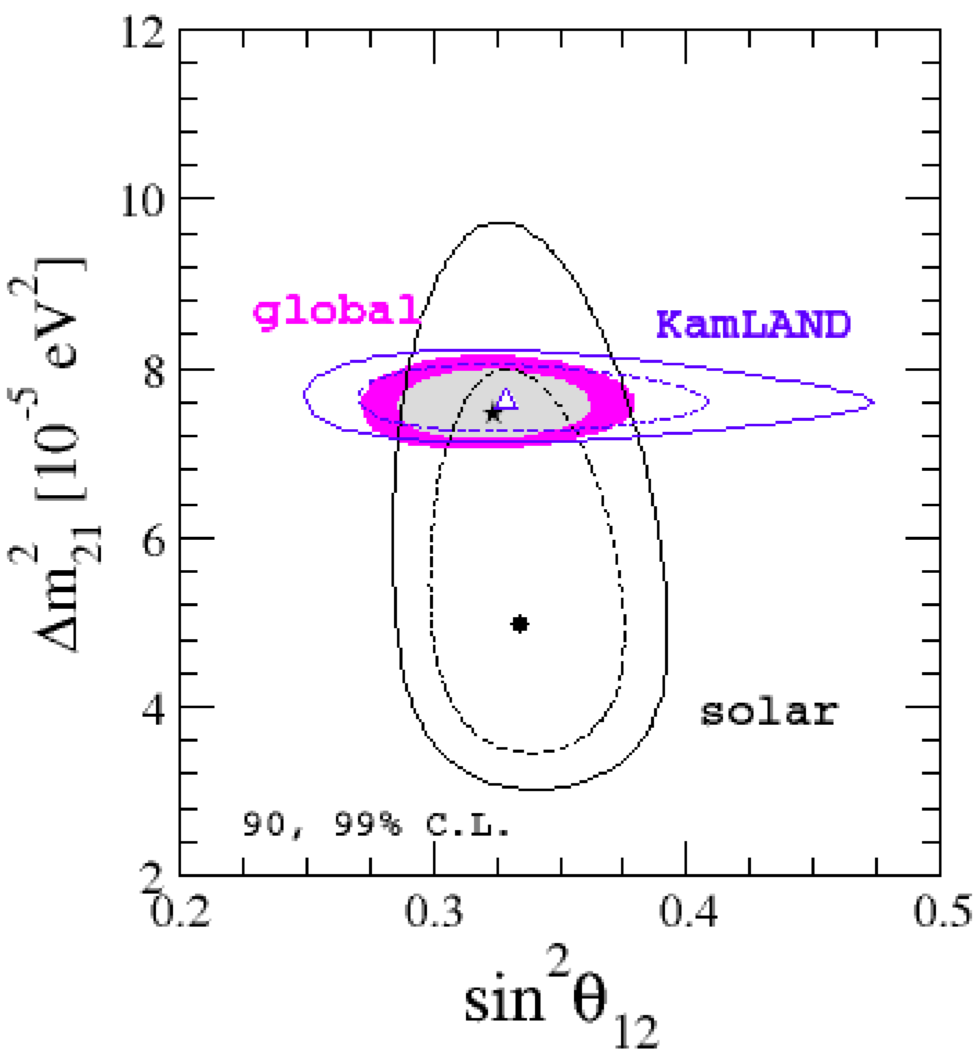

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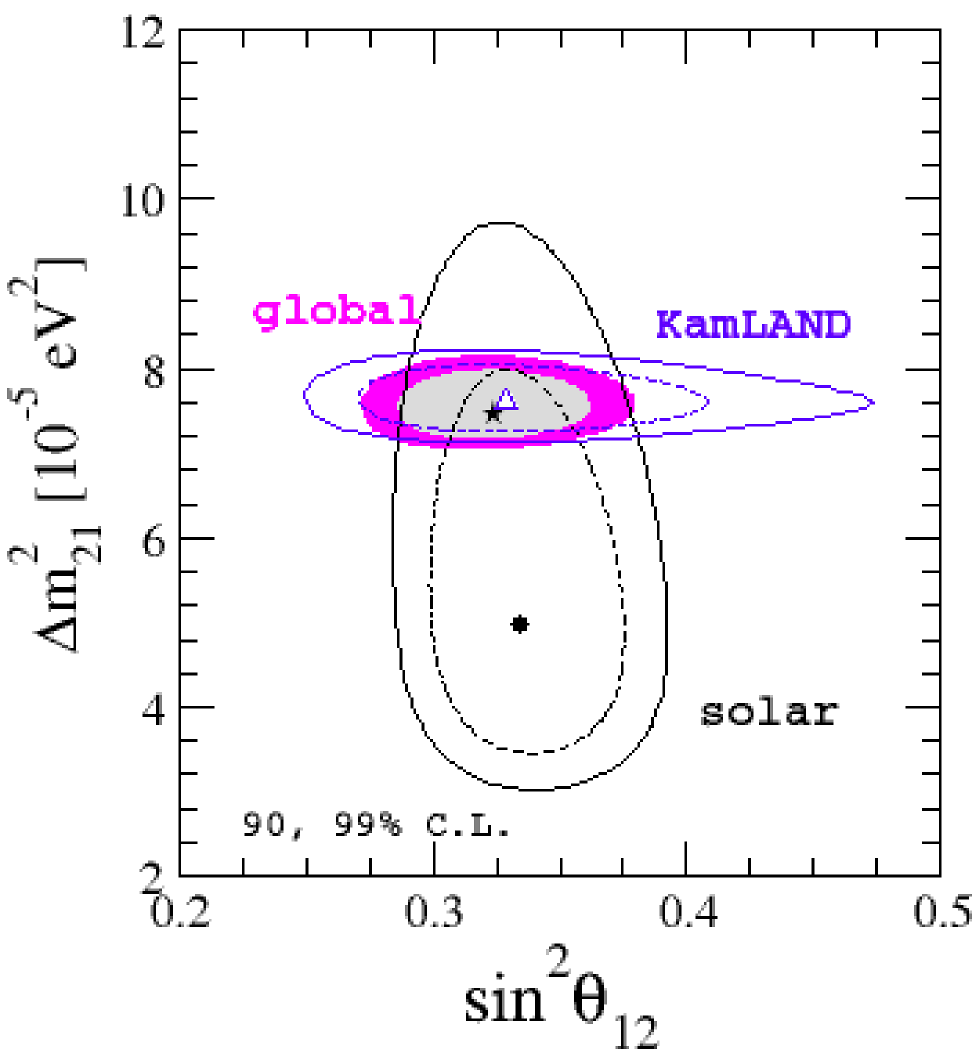

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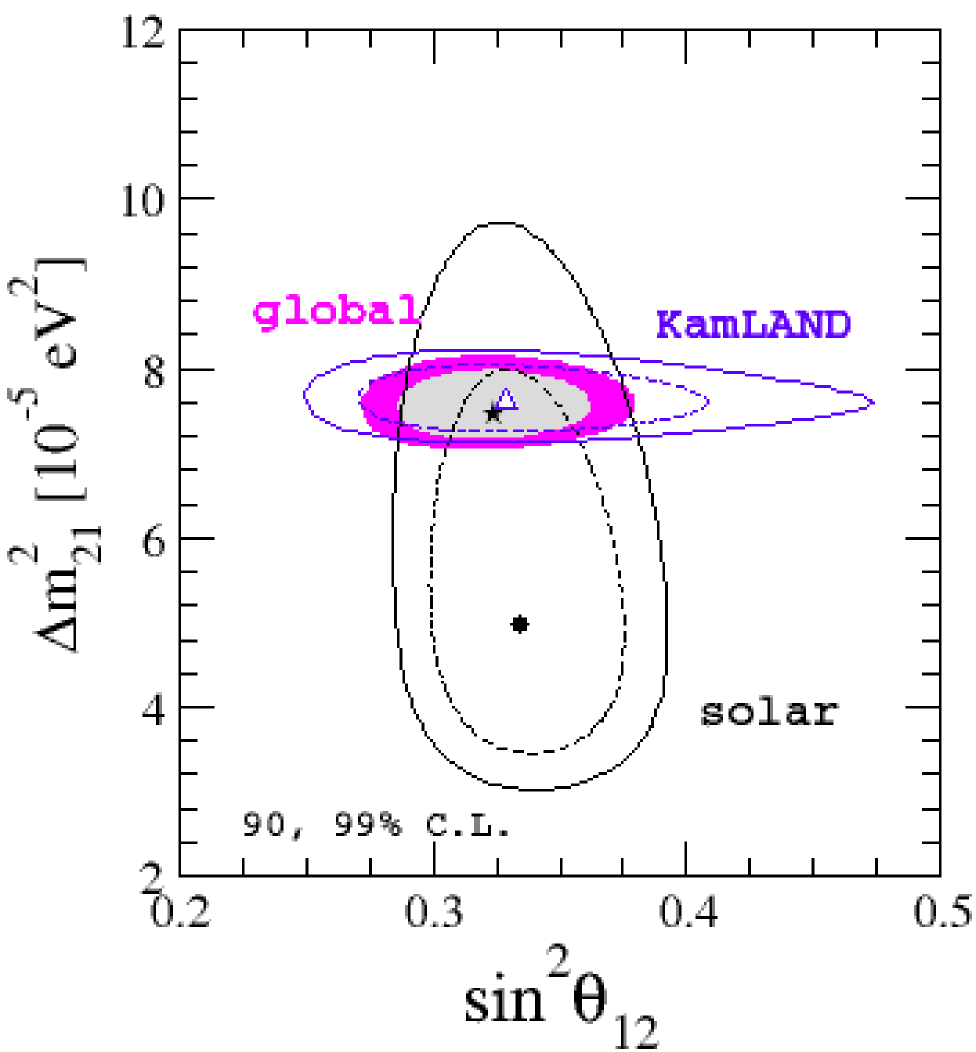

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- Δm^2_{21} better measured by KamLAND
- Maximal mixing is highly disfavored
- Mismatch between solar and KamLAND data for mass splitting

Global fit to neutrino oscillations

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Global fit to neutrino oscillations

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- The main dependence of short baseline reactors is on θ_{13} and Δm^2_{31}

Global fit to neutrino oscillations

- Data included:
  - 1230 day Daya Bay spectrum
  - 1500 day RENO spectrum
  - 461 day (FI) and 212 day (FII) Double Chooz spectrum

Global fit to neutrino oscillations

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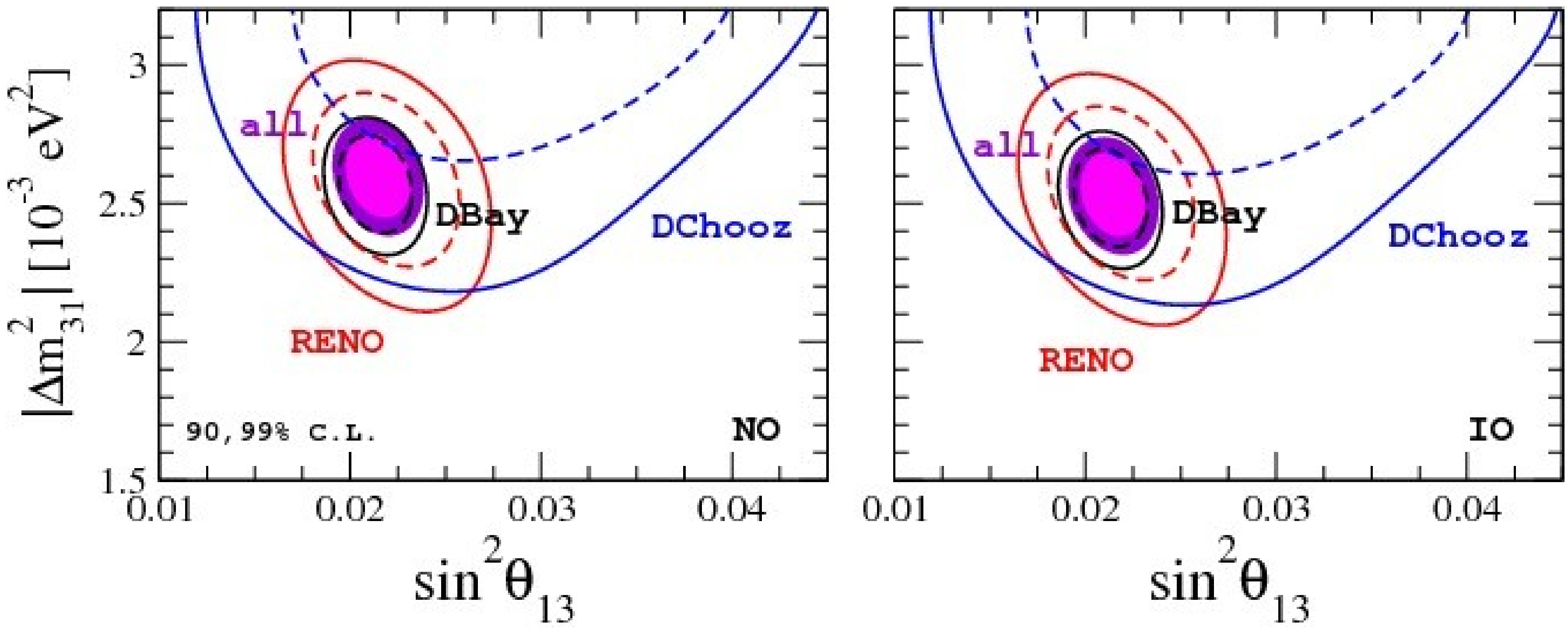
  - 1230 day Daya Bay spectrum
  - 1500 day RENO spectrum
  - 461 day (FI) and 212 day (FII) Double Chooz spectrum
- Older reactors are not included, because they only provide upper limits on θ_{13}

Global fit to neutrino oscillations

- Result of reactor experiments



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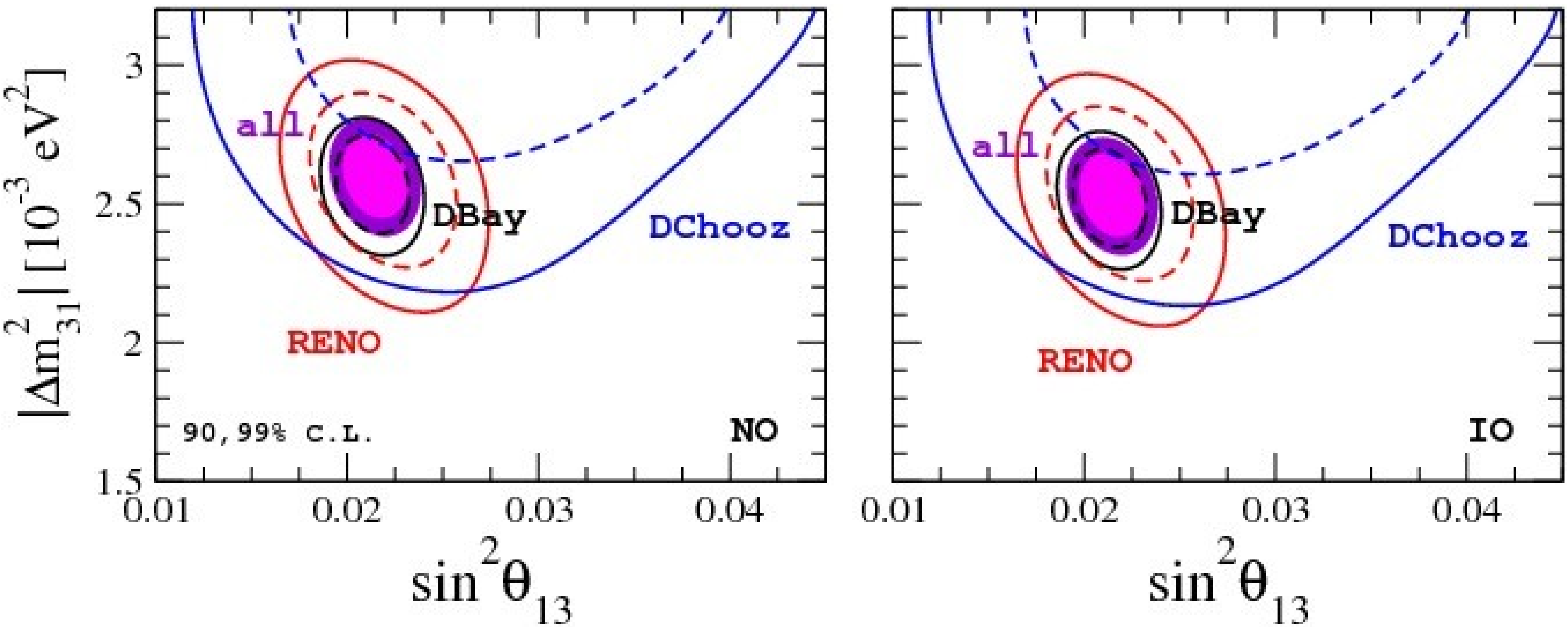

- Reactor analysis is dominated by Daya Bay

Global fit to neutrino oscillations

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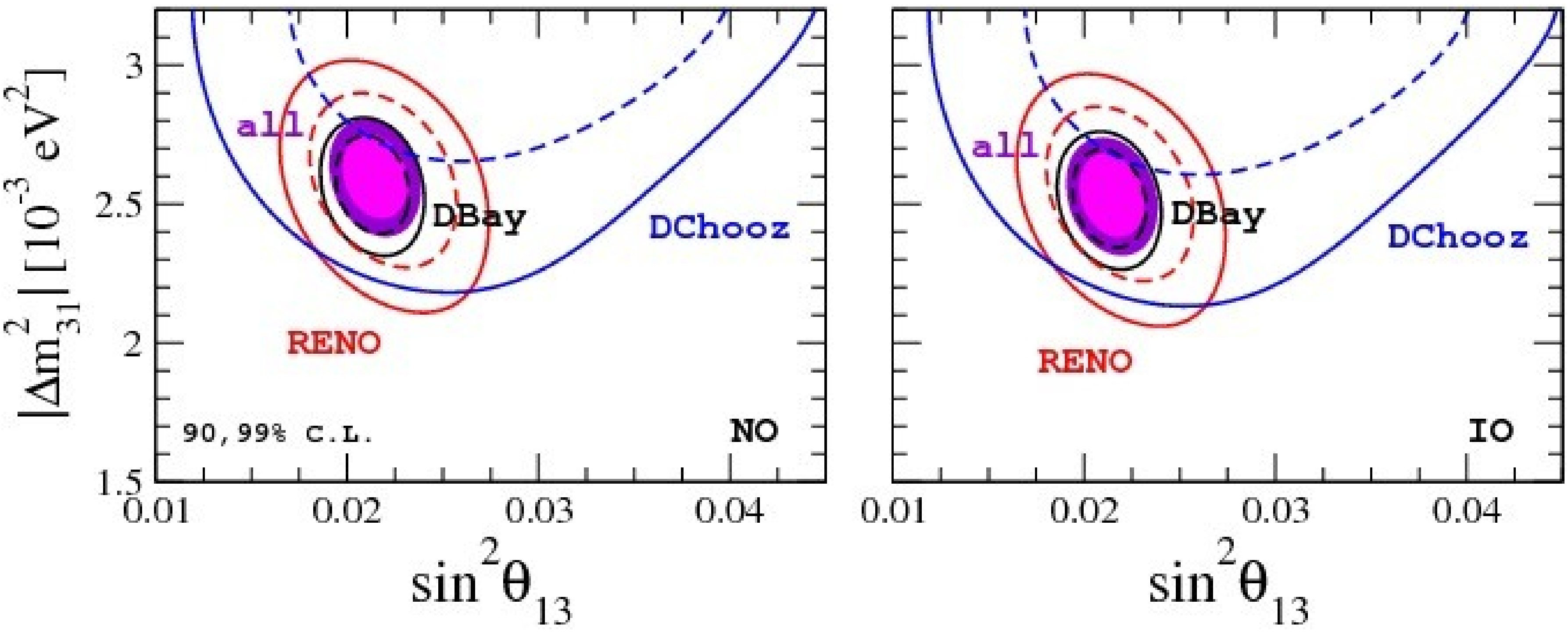
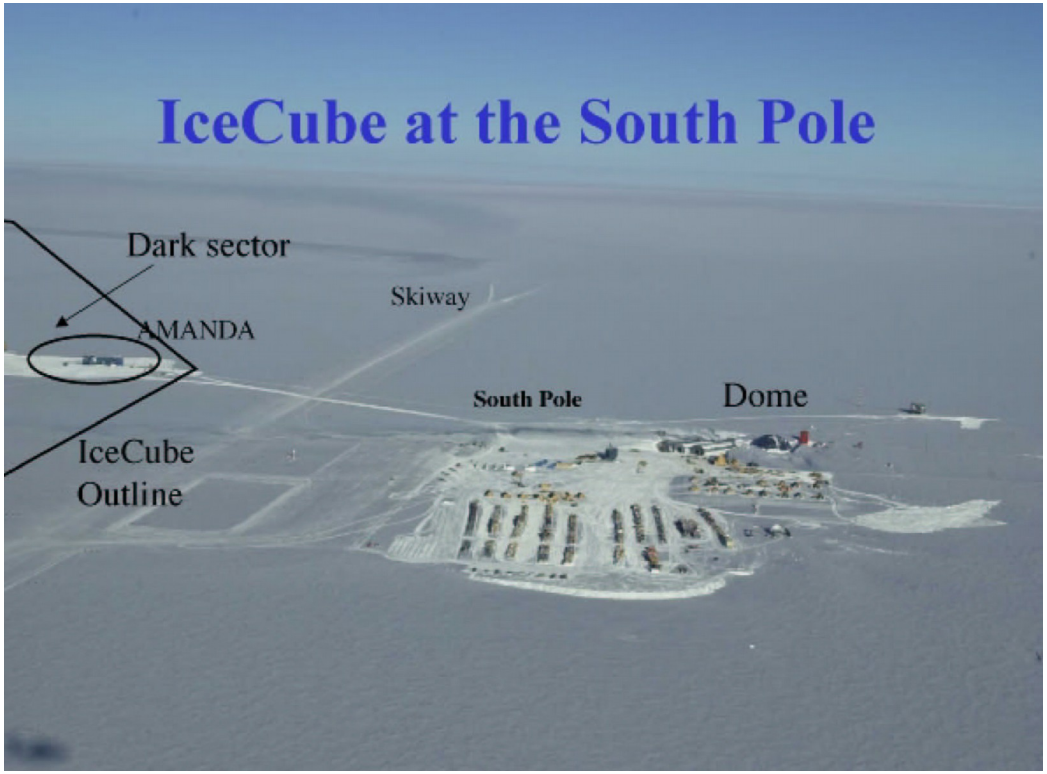
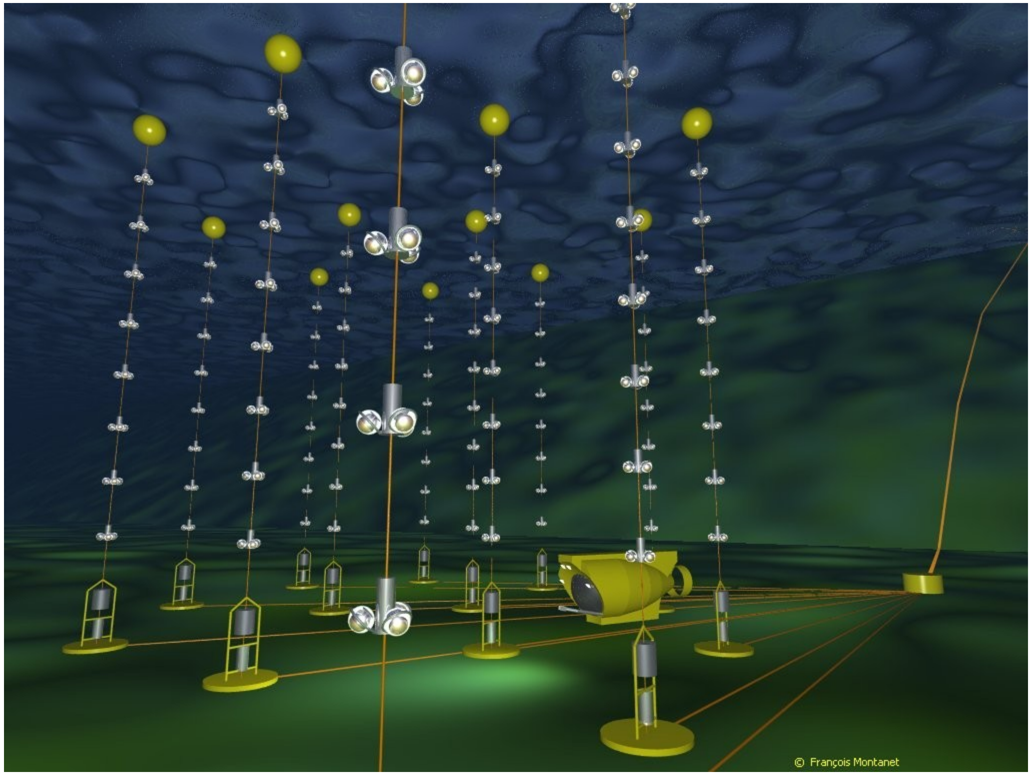


- Reactor analysis is dominated by Daya Bay
- RENO starts being competitive

Global fit to neutrino oscillations

- Atmospheric neutrino experiments are mostly focused on the disappearance of muon neutrinos $(P_{\mu\mu})$ and antineutrinos $(P_{\bar{\mu}\bar{\mu}})$ created in the atmosphere





Global fit to neutrino oscillations

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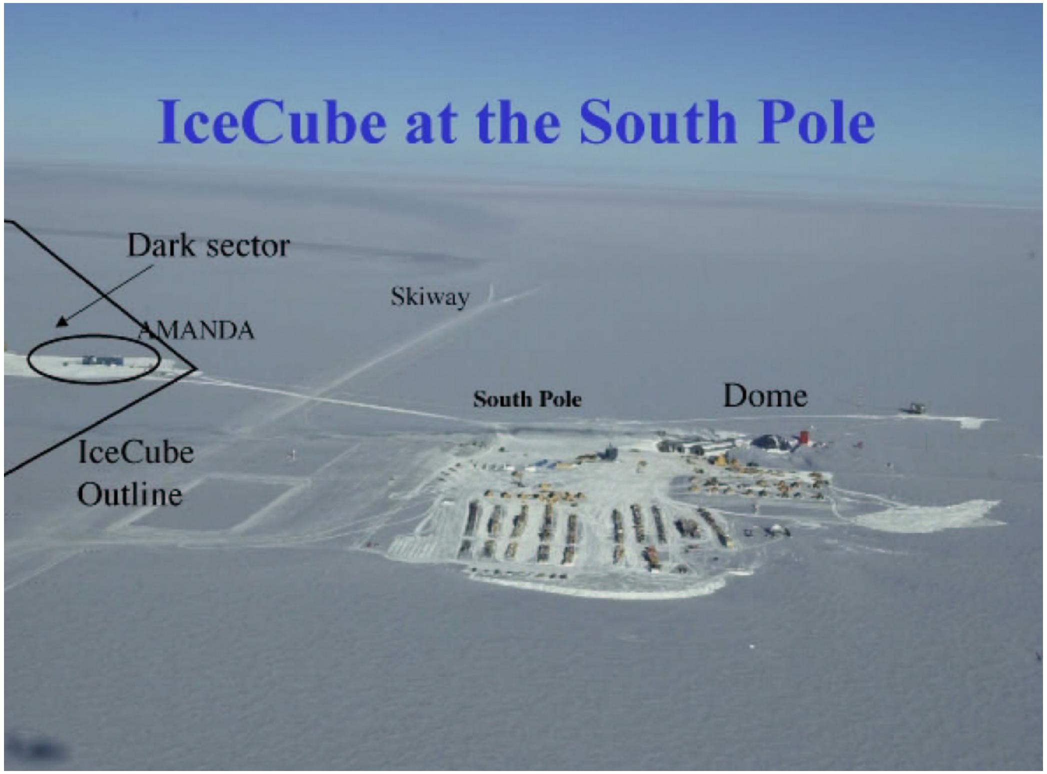
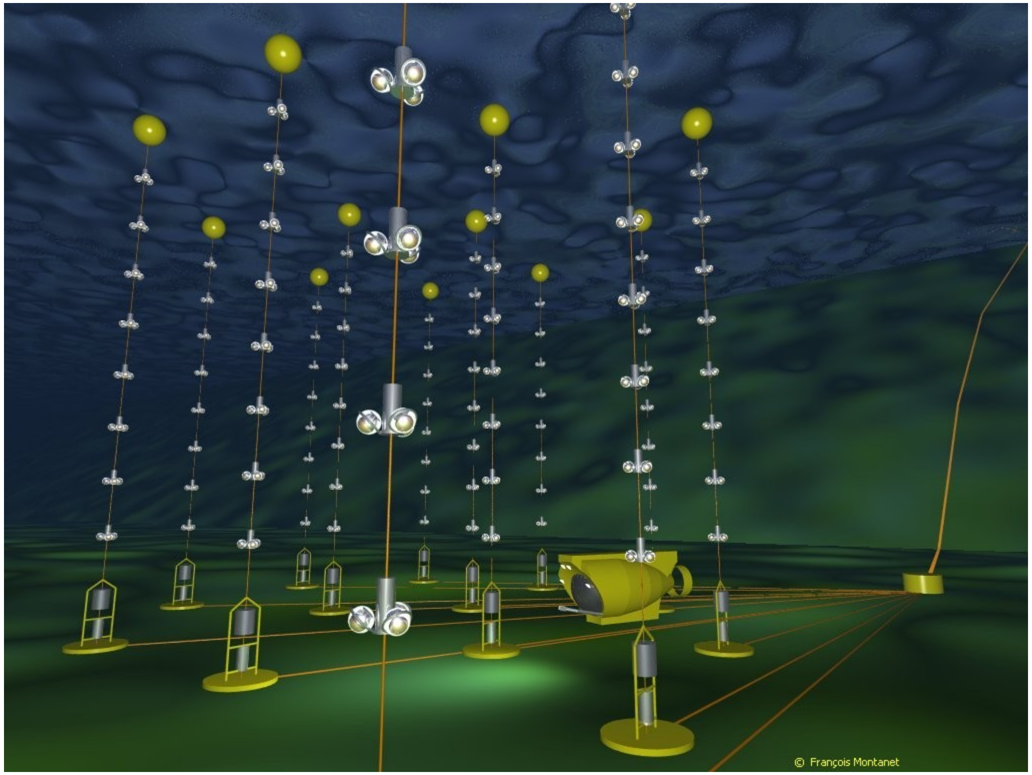
- They measure the atmospheric parameters Δm^2_{31} and θ_{23}





Global fit to neutrino oscillations

- Data included:
  - 863 days of ANTARES data
  - 953 days of IceCube DeepCore data
  - SK I-IV

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Global fit to neutrino oscillations

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  - 953 days of IceCube DeepCore data
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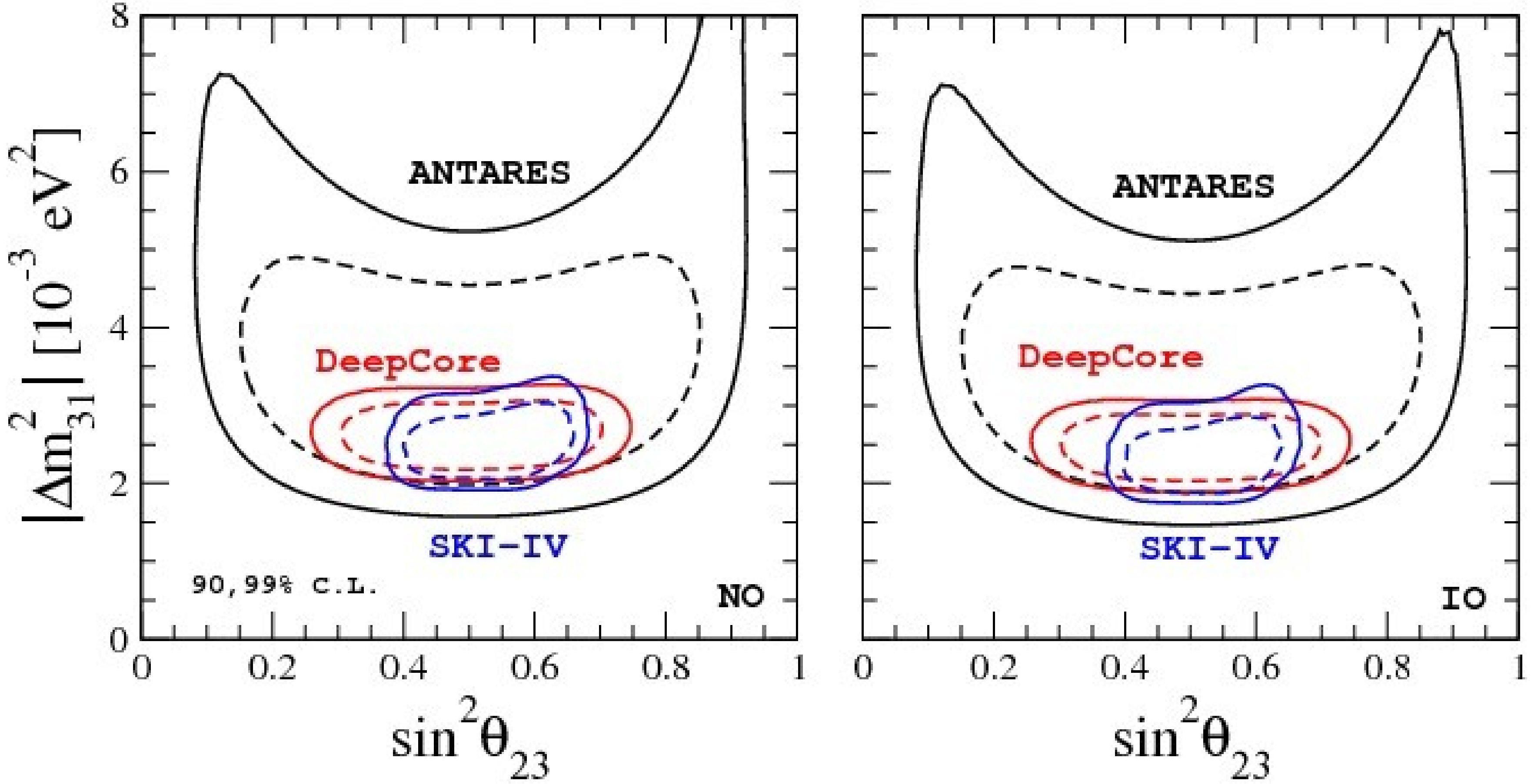
- In the case of SK we add the grid provided by the collaboration
  - 14 datasets, 4 times 520 bins and 155 systematic errors with possible correlations among them, make it impossible to reproduce the results outside the collaboration

Global fit to neutrino oscillations

- Result of atmospheric experiments



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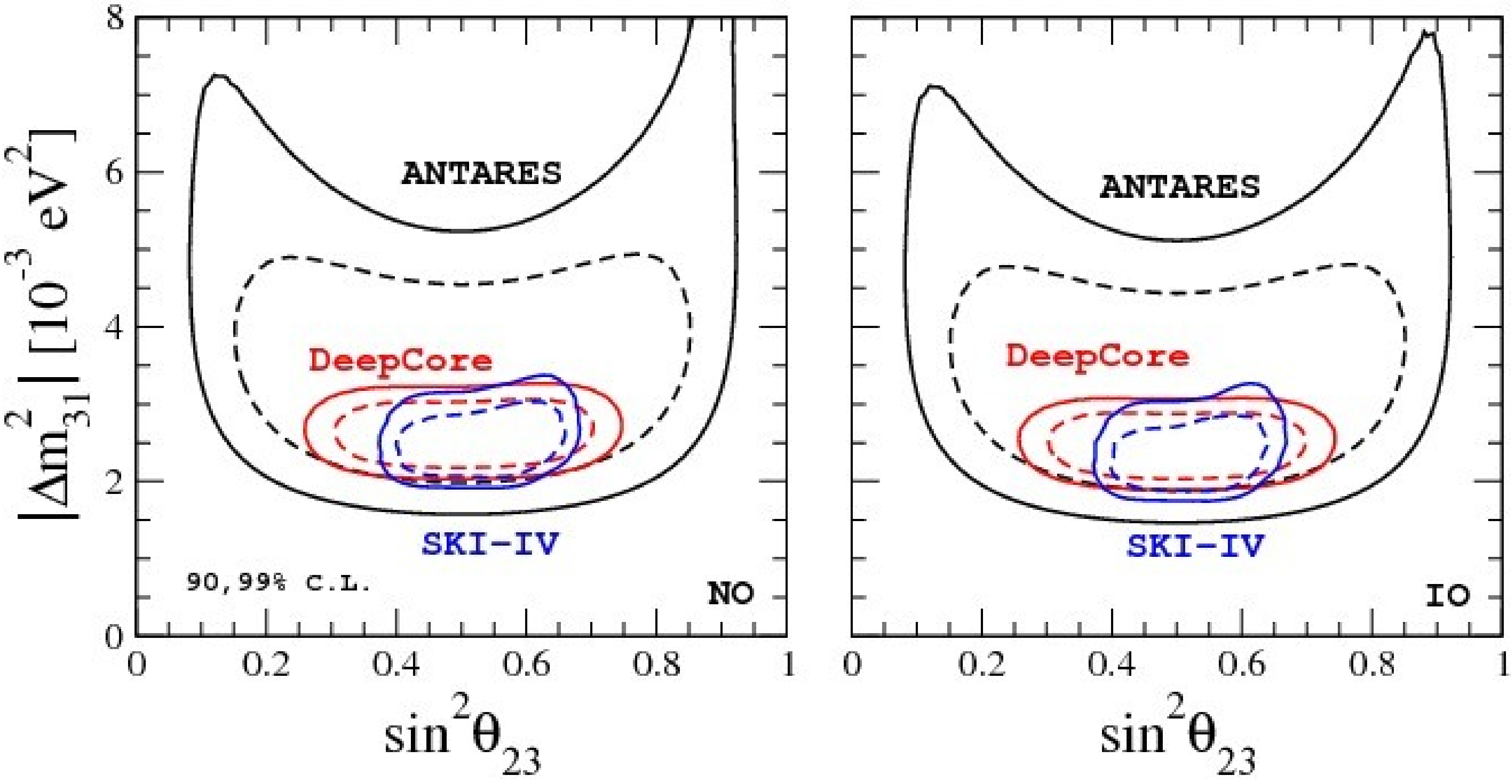
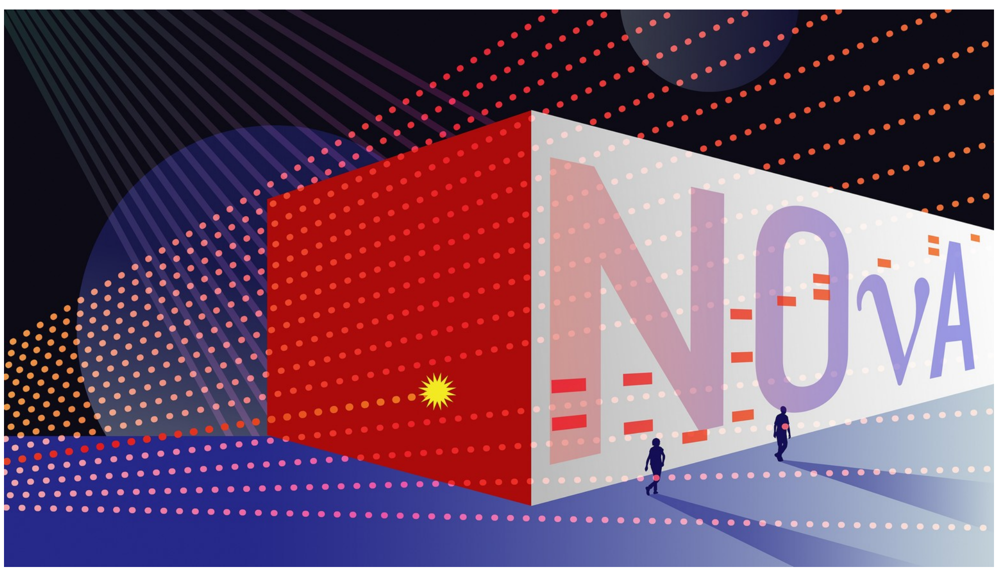
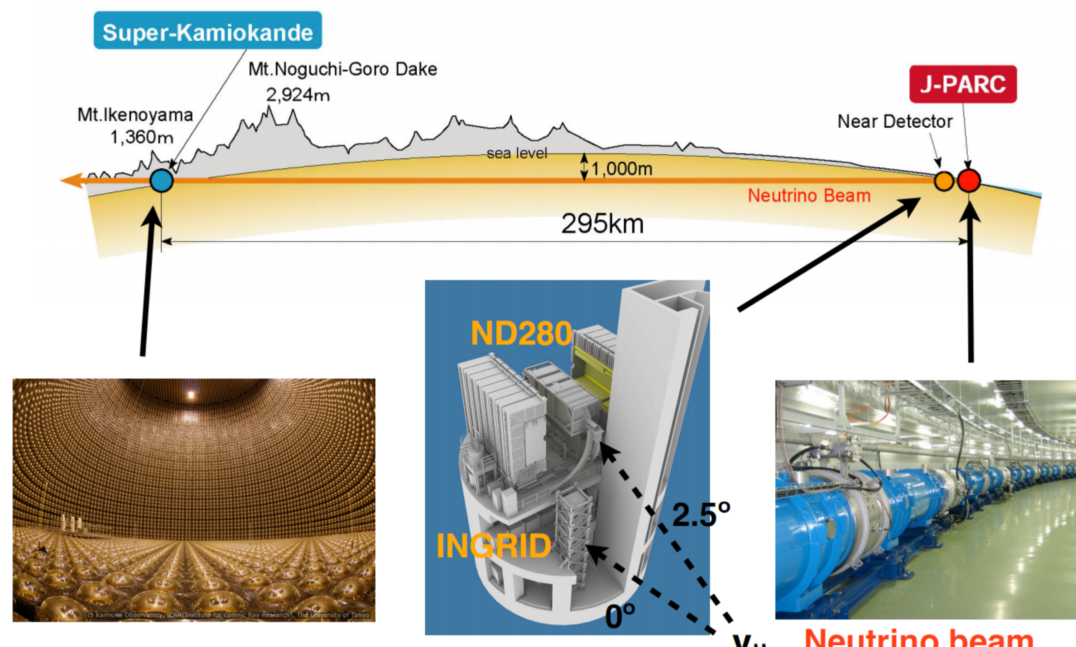


- Atmospheric experiments start to be competitive with long baseline experiments as we will see now

Global fit to neutrino oscillations

- Long baseline experiments measure disappearance of muon neutrinos $(P_{\mu\mu})$ and antineutrinos $(P_{\bar{\mu}\bar{\mu}})$ and appearance of electron neutrinos $(P_{\mu e})$ and antineutrinos $(P_{\bar{\mu}\bar{e}})$ created at accelerator experiments





Super-Kamiokande

INGRID (on-axis) and ND280 (off-axis)

Neutrino beam created at J-PARC main ring

Global fit to neutrino oscillations

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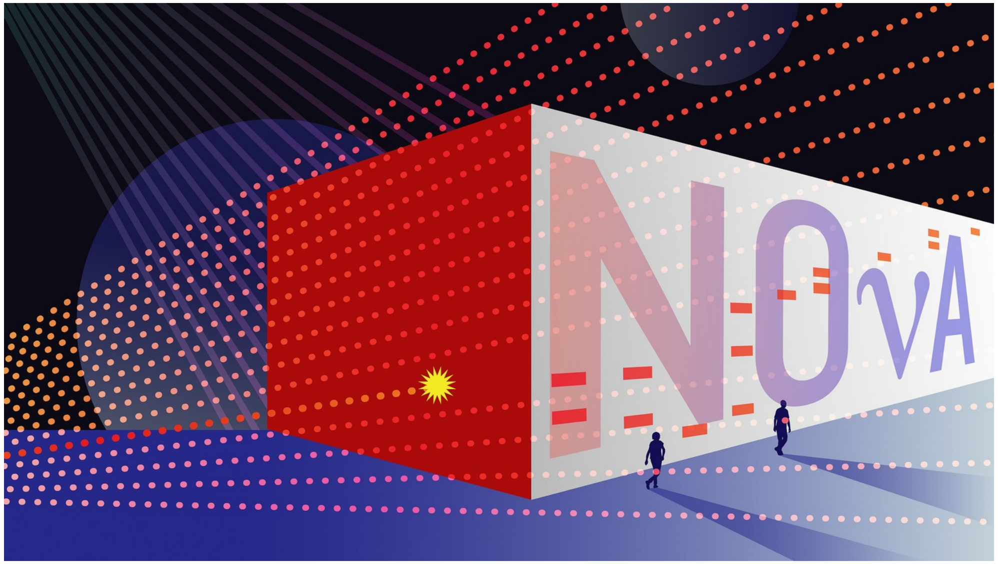
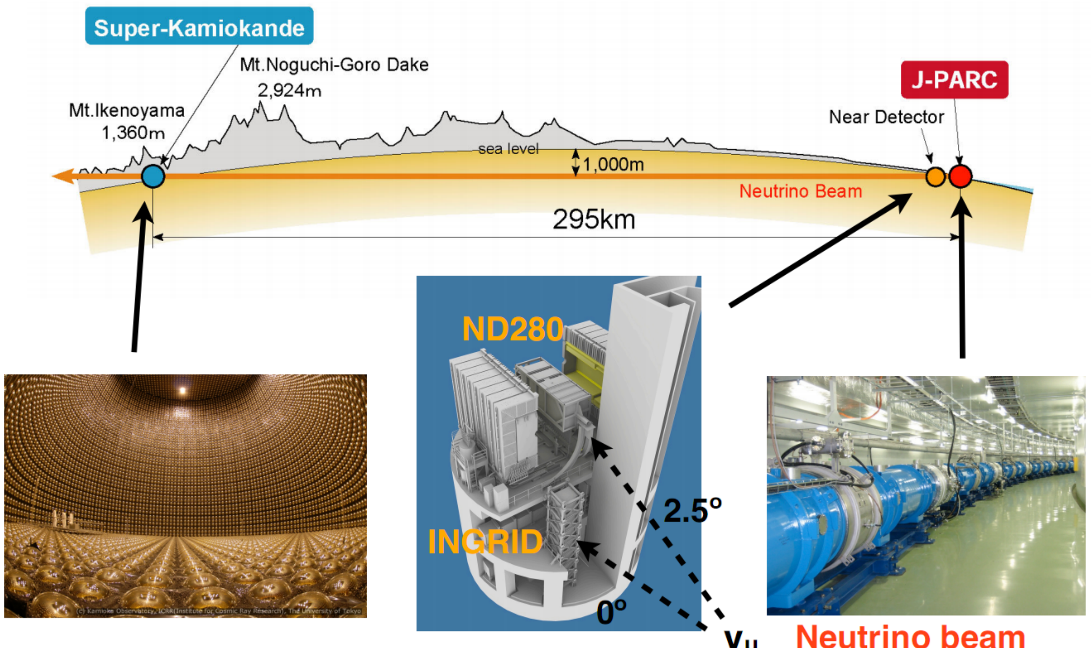
- They measure the parameters Δm^2_{31}, θ_{23}, θ_{13} and δ





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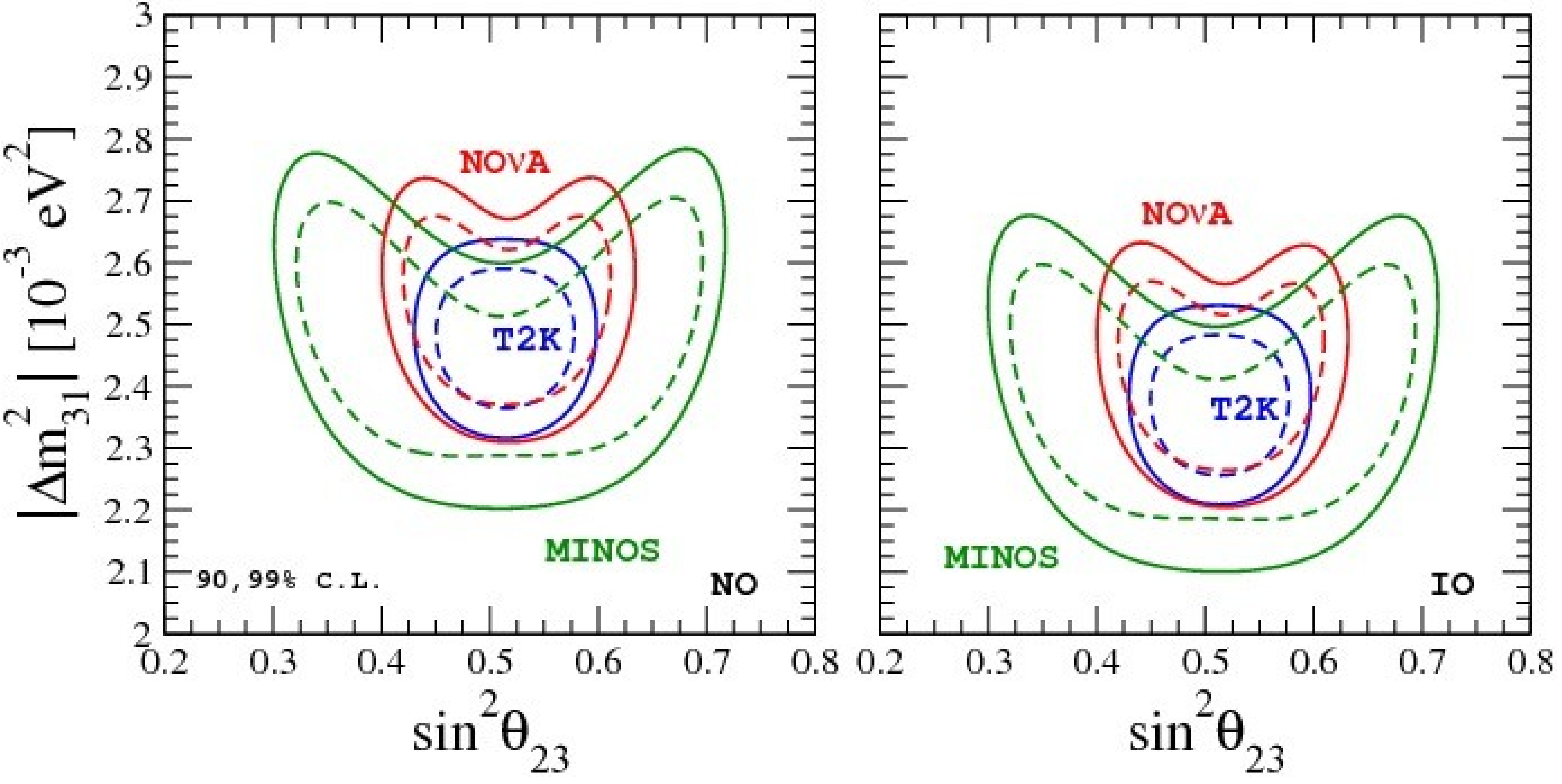
Neutrino beam created at J-PARC main ring

Global fit to neutrino oscillations

- Data included:
  - 14.7 x 10^{20} POT in neutrino mode at T2K
  - 7.6 x 10^{20} POT in antineutrino mode at T2K
  - 8.85 x 10^{20} POT in neutrino mode at NOνA
  - MINOS: full accelerator data set
  - K2K: full data set

Global fit to neutrino oscillations

- Result of long-baseline experiments



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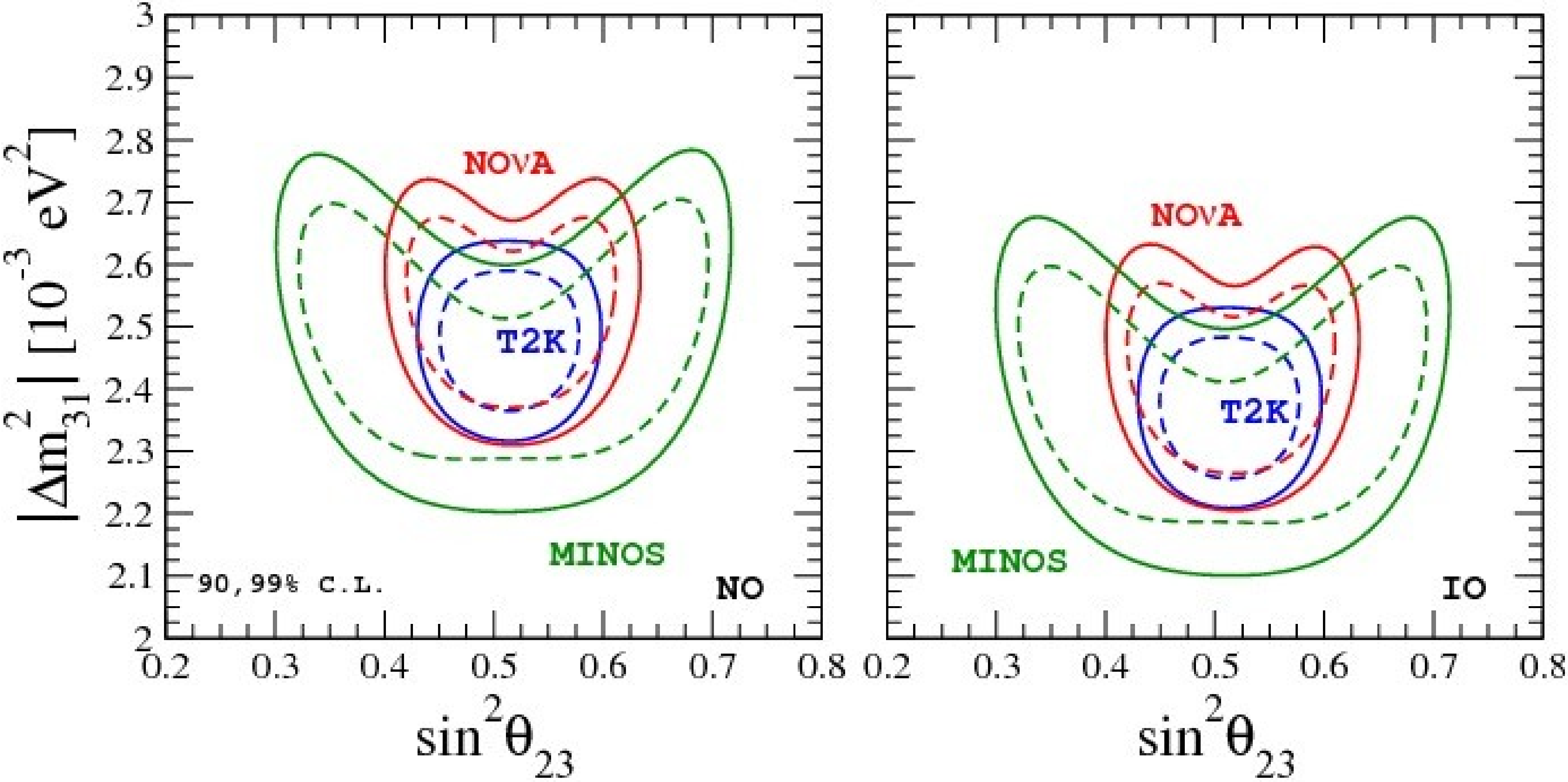
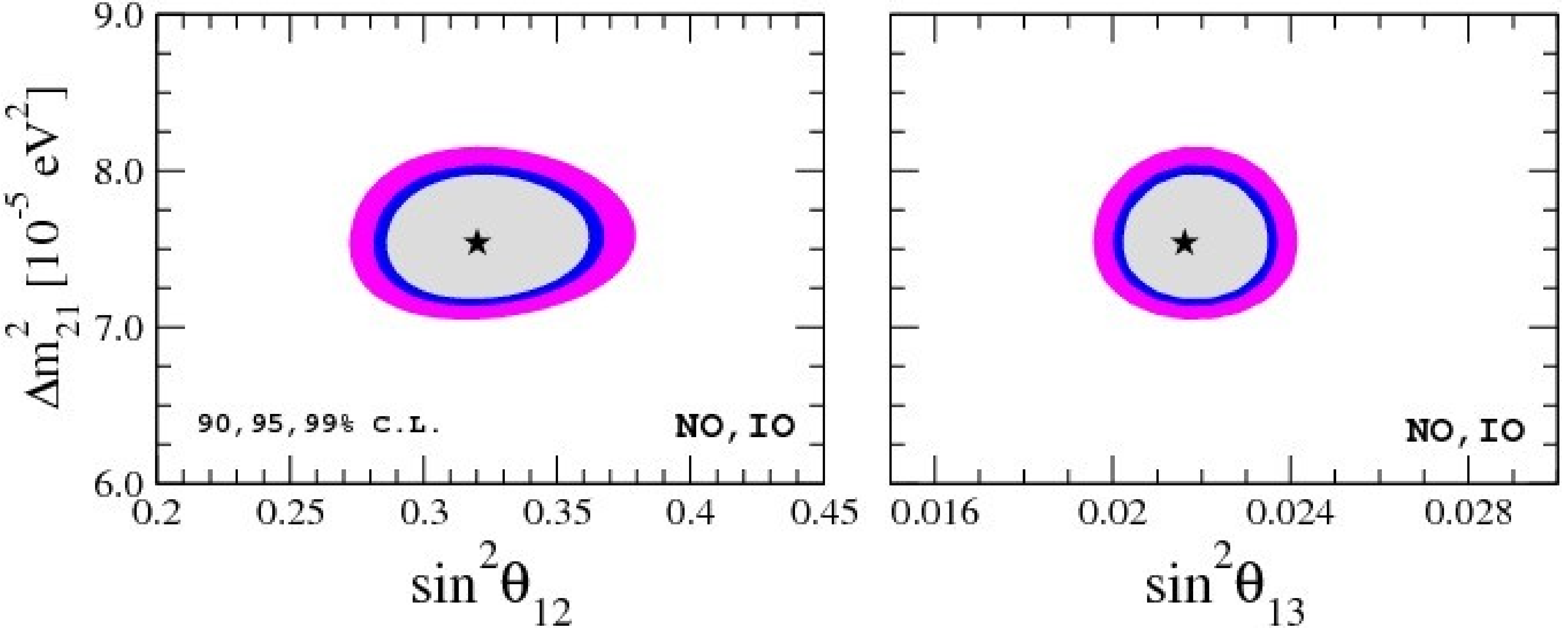


- Analysis dominated by T2K and NOνA

Results of the combined analysis

The solar plane

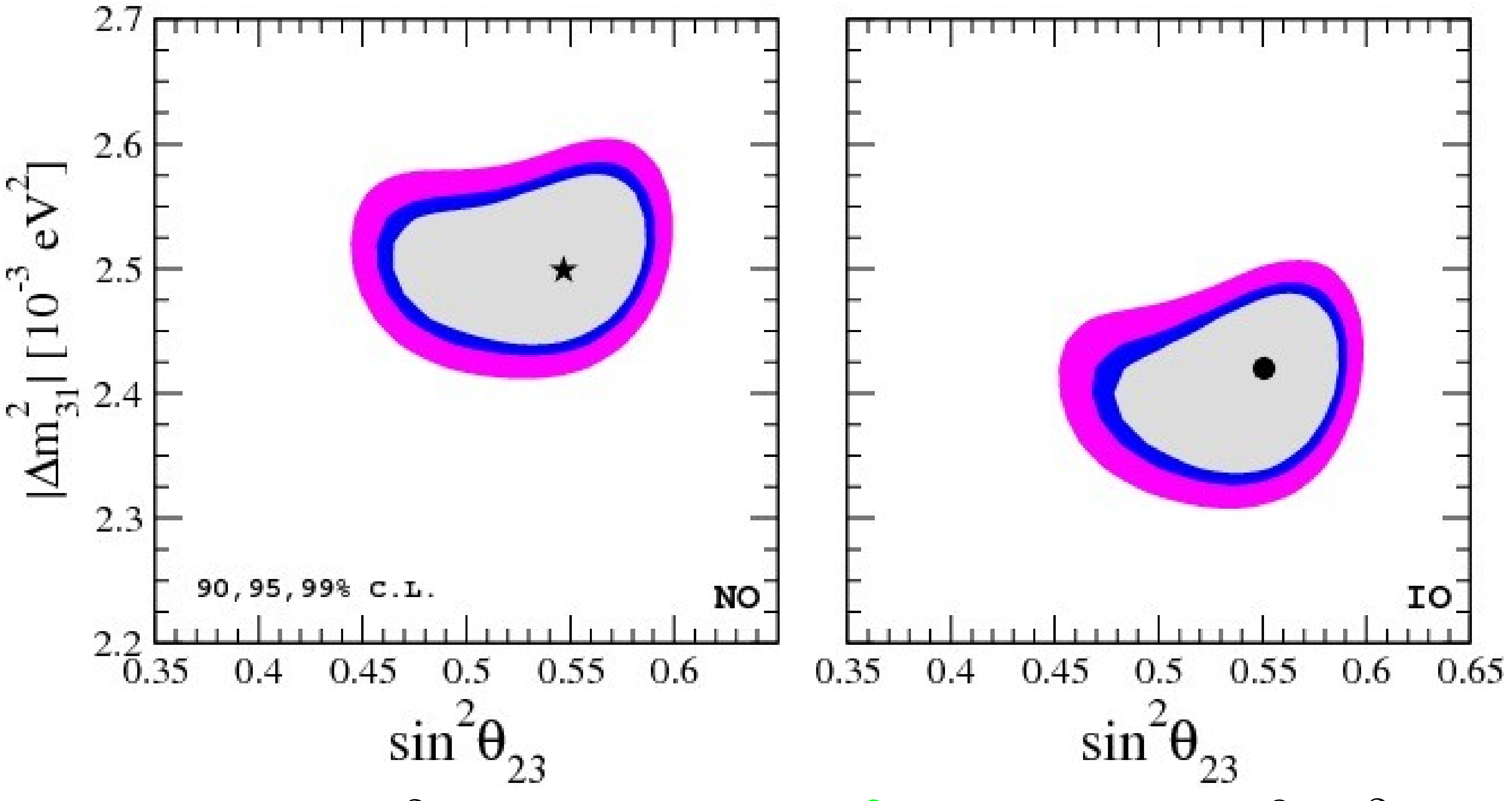
- The solar parameters are measured by solar experiments and KamLAND



- Best fit: $\sin^2\theta_{12} = 0.320, \Delta m^2_{21} = 7.55 \times 10^{-5} \mathrm{eV}^2$

The atmospheric plane

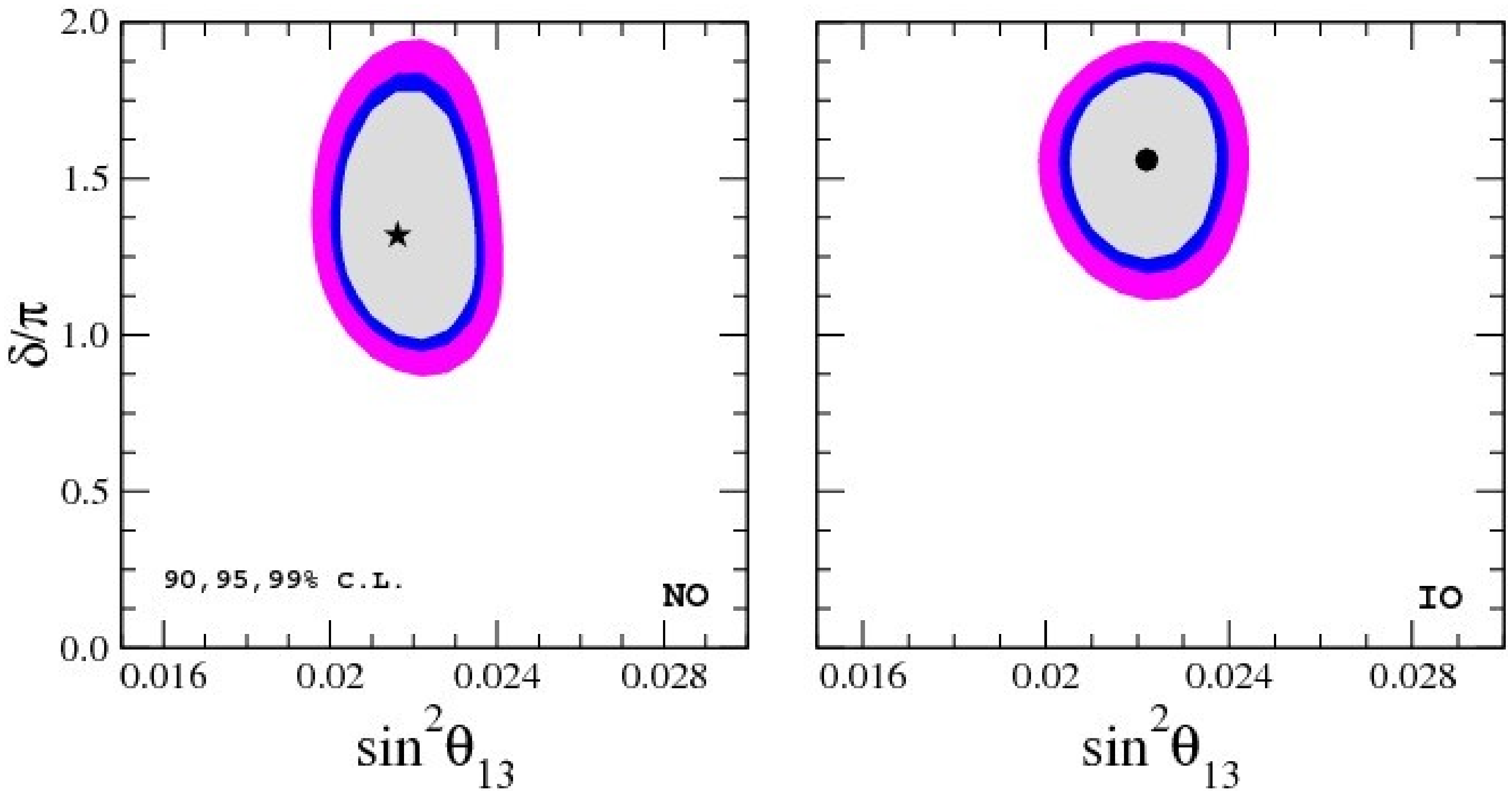
- Measurement of atmospheric parameters dominated by the combination of LBL and reactor experiments



- Best fit: $\sin^2\theta_{23} = 0.547, \Delta m^2_{31} = 2.50 \times 10^{-3}\mathrm{eV}^2(\mathrm{NO})$
  $\sin^2\theta_{23} = 0.551, \Delta m^2_{31} = -2.42 \times 10^{-3}\mathrm{eV}^2(\mathrm{IO})$

The reactor angle and the CP phase

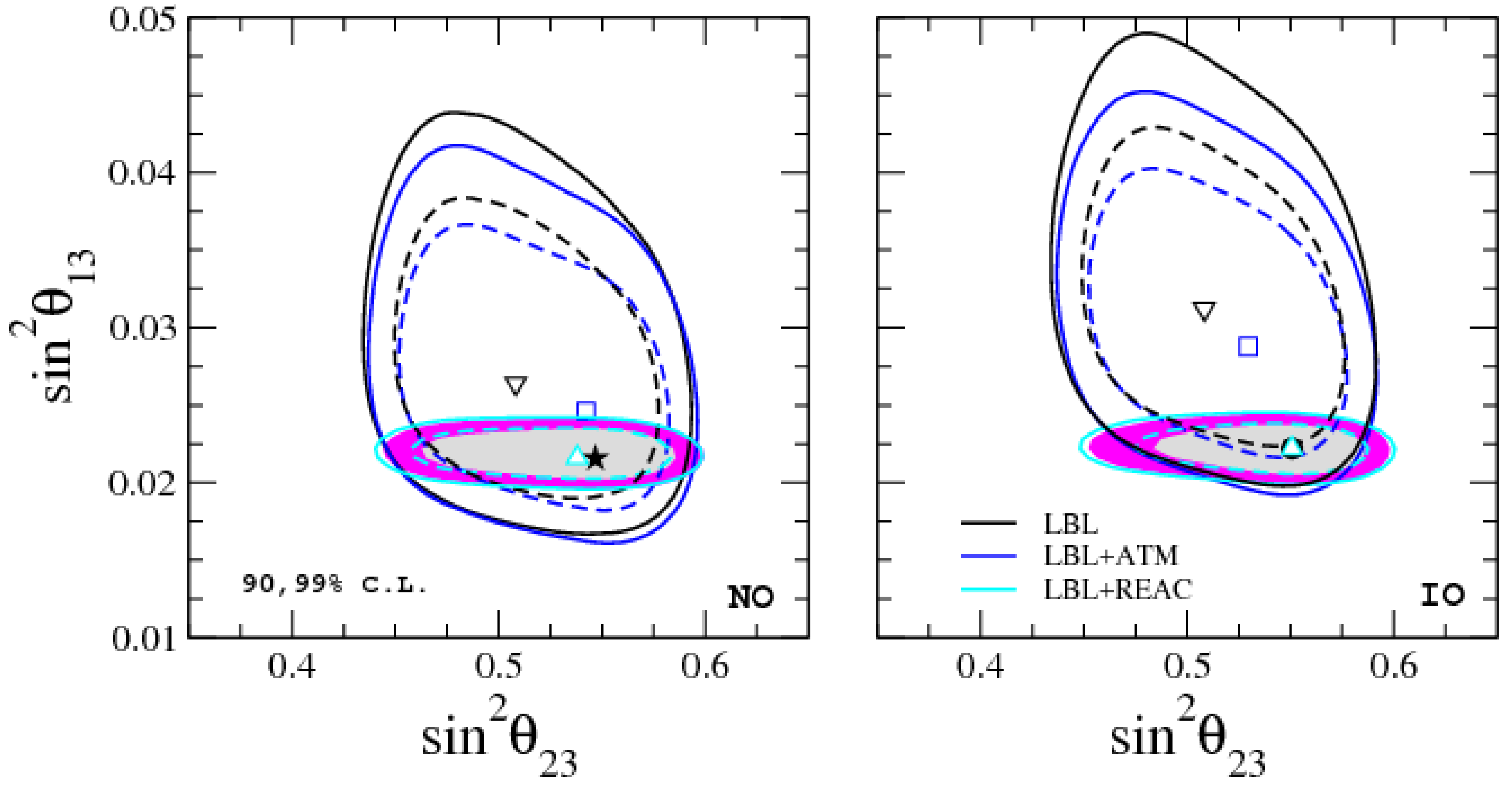
- For the first time we can exclude big part of the parameter space for δ



- Best fit: $\sin^2\theta_{13} = 0.02160, \delta = 1.32\pi(\text{NO})$
  $\sin^2\theta_{13} = 0.02220, \delta = 1.56\pi(\text{IO})$

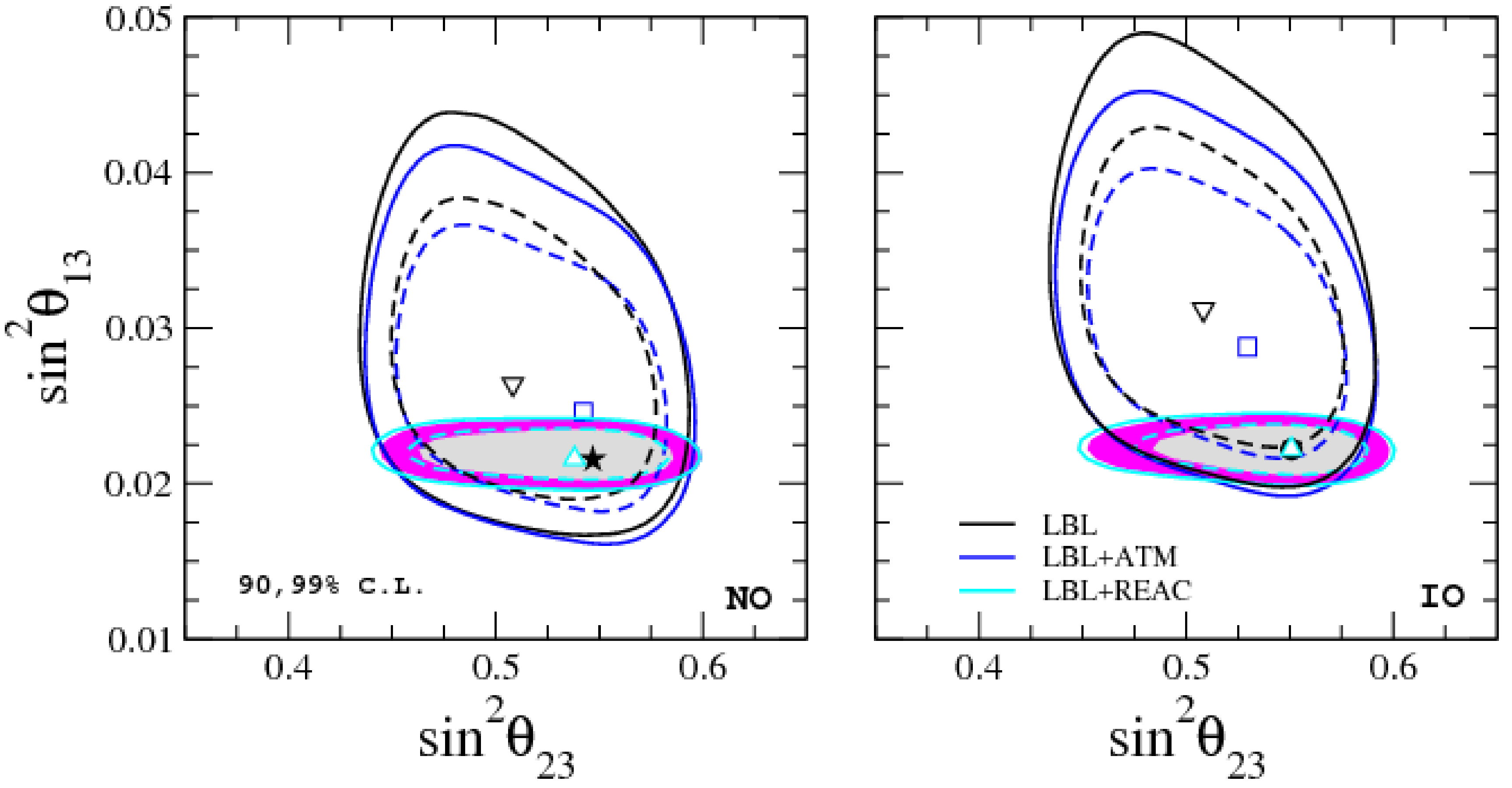
The reactor angle

- The measurement of the reactor angle is dominated by the short baseline reactors



The reactor angle

- The measurement of the reactor angle is dominated by the short baseline reactors
- LBL+ATM might start being competitive in the near future



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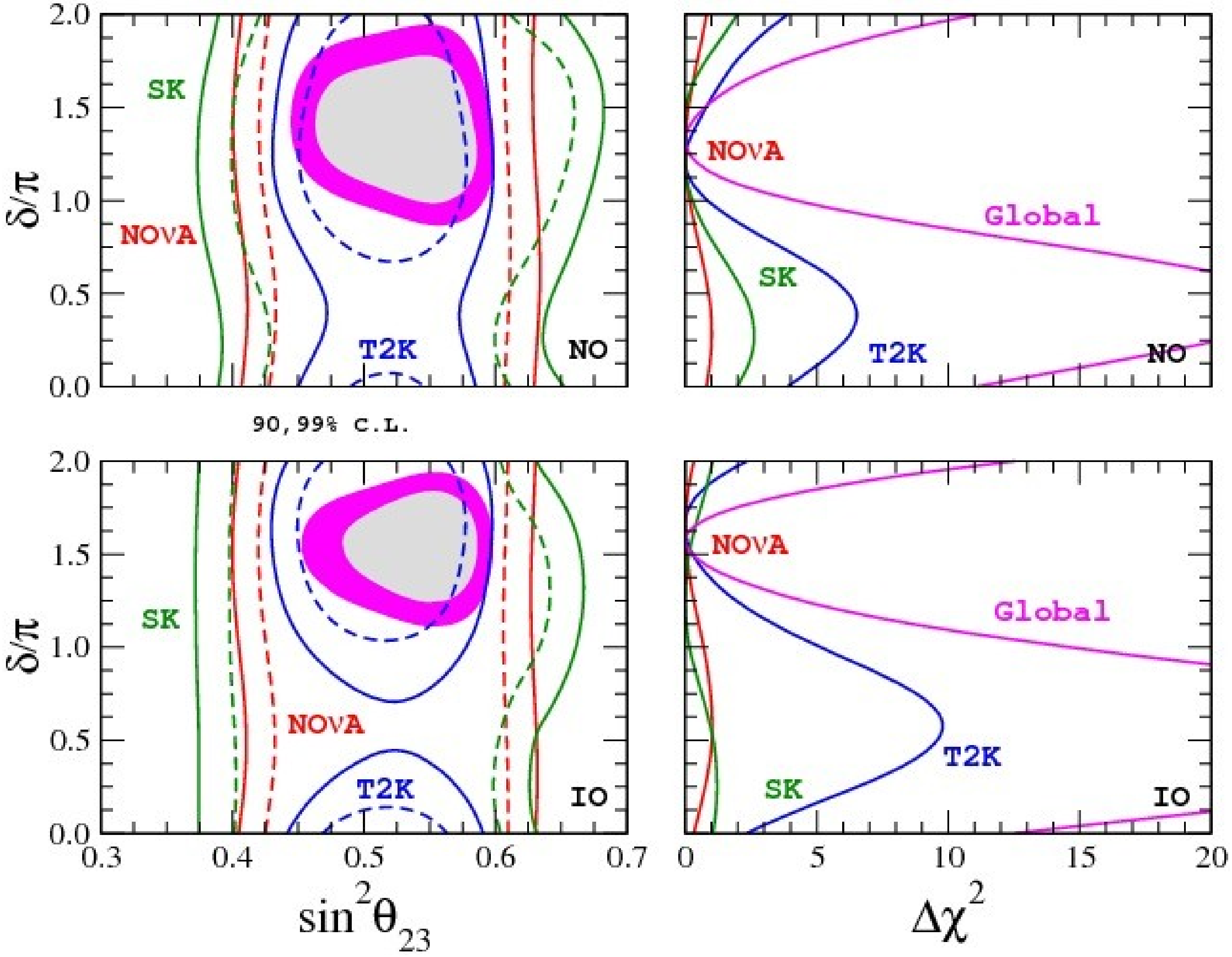

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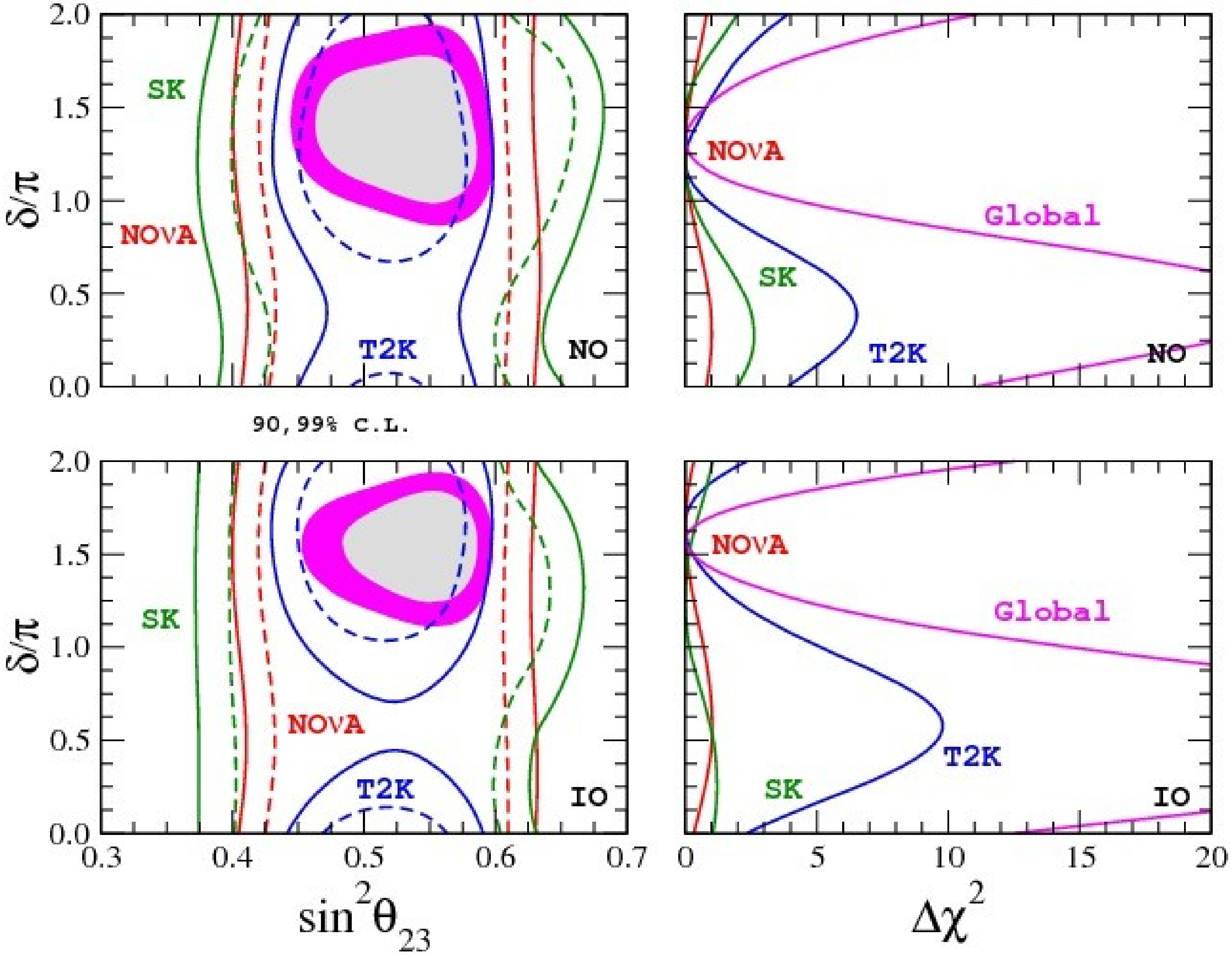
The CP phase



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- Constraint on θ_{13} improves sensitivity to δ at all experiments significantly

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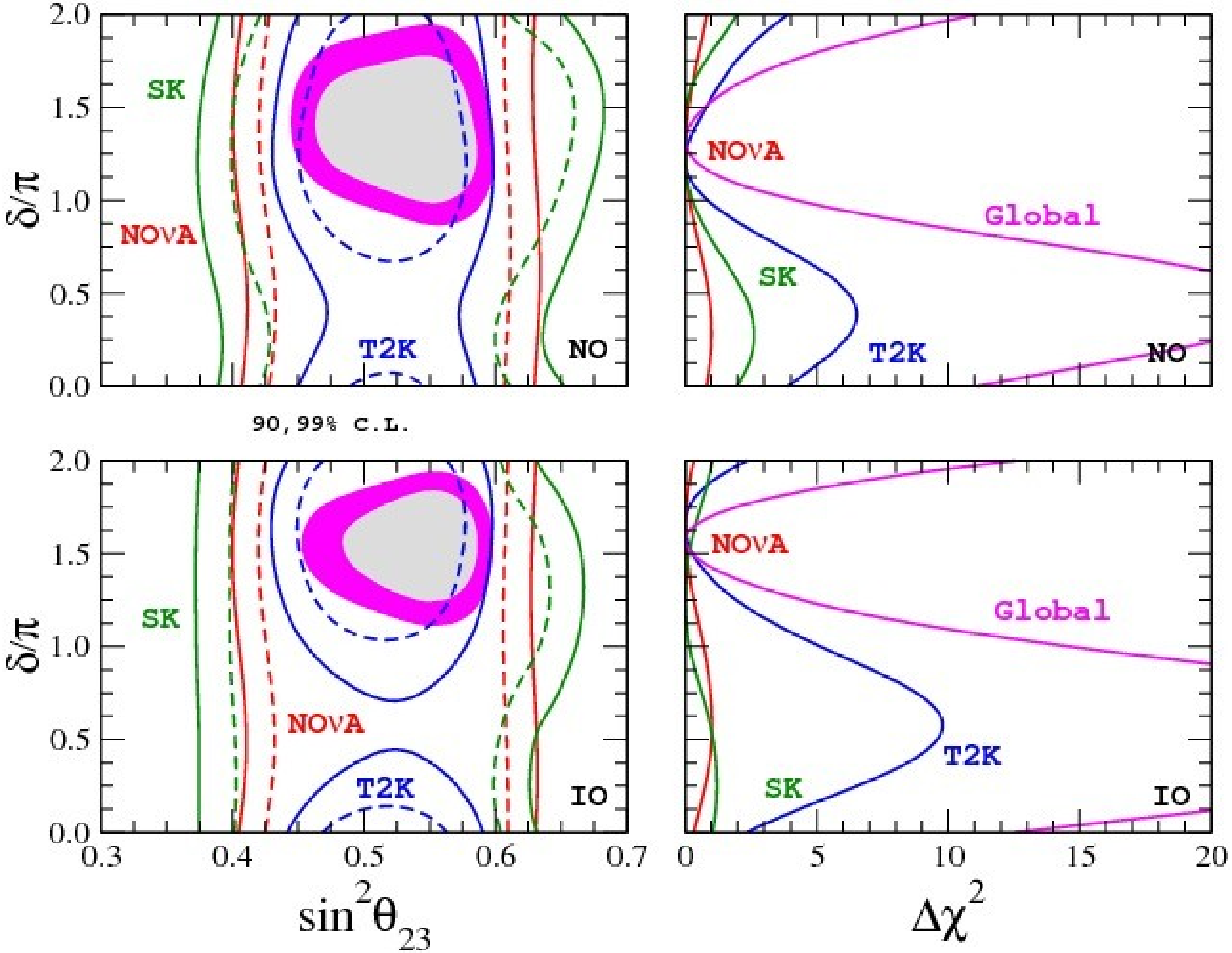
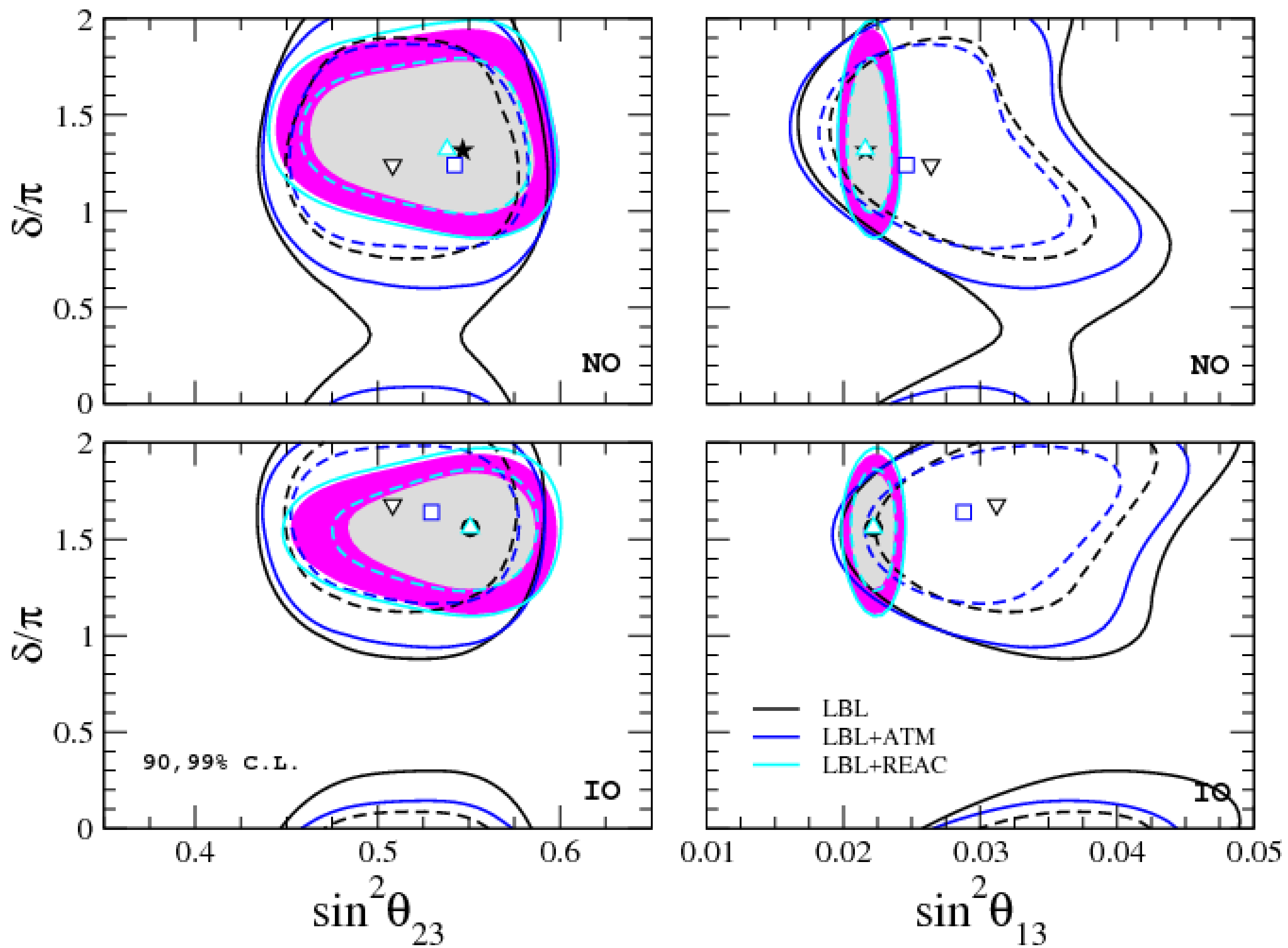


- Best sensitivity to δ comes from T2K
- Constraint on θ_{13} improves sensitivity to δ at all experiments significantly
- This results in exclusion of values around 0.5π at > 4σ

The mass ordering and the role of SK

- Inverted mass ordering is now disfavored at more than 3σ, with $\Delta\chi^2 = 11.7$

SK does not change regions:



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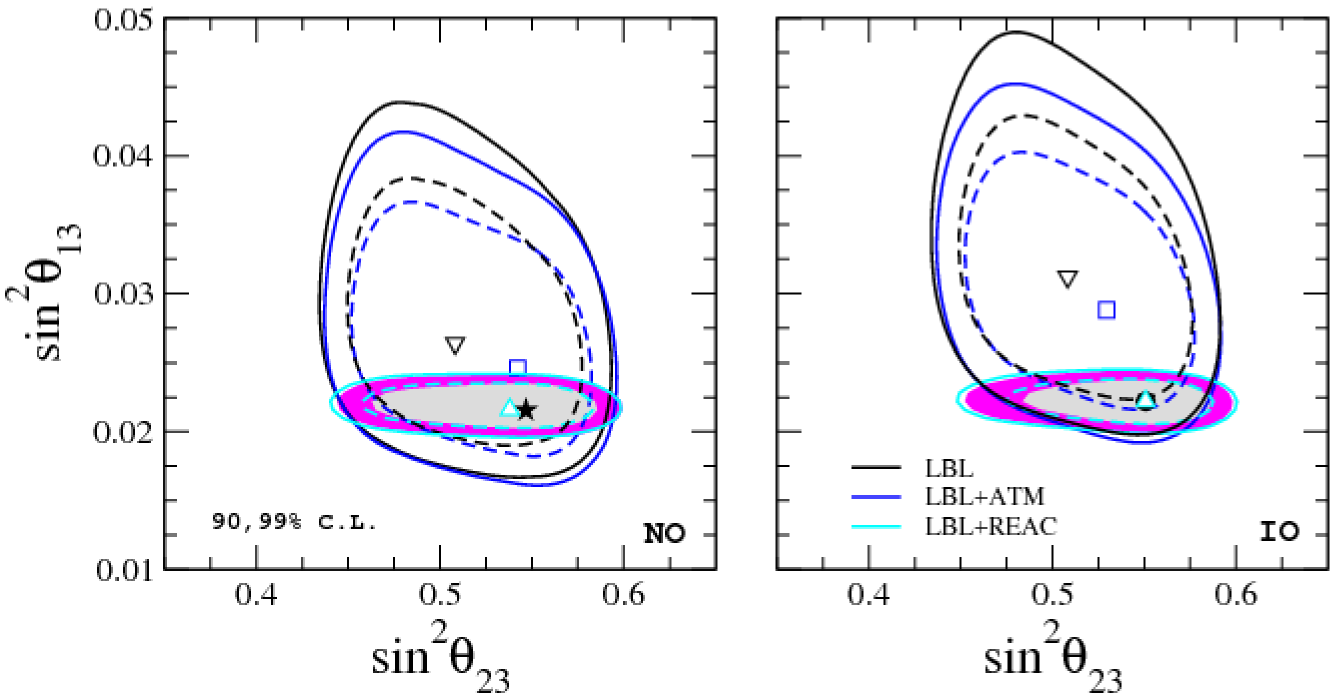

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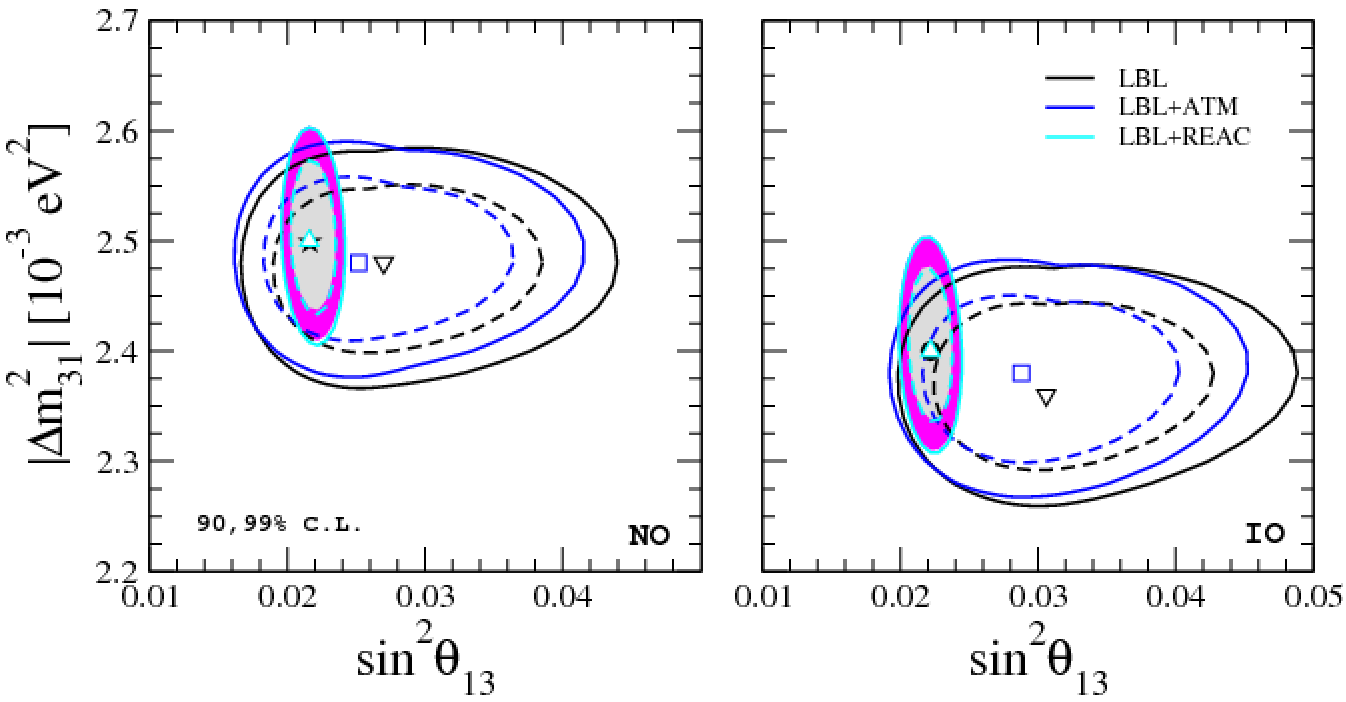

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- SK "only" improves the sensitivity to the mass ordering

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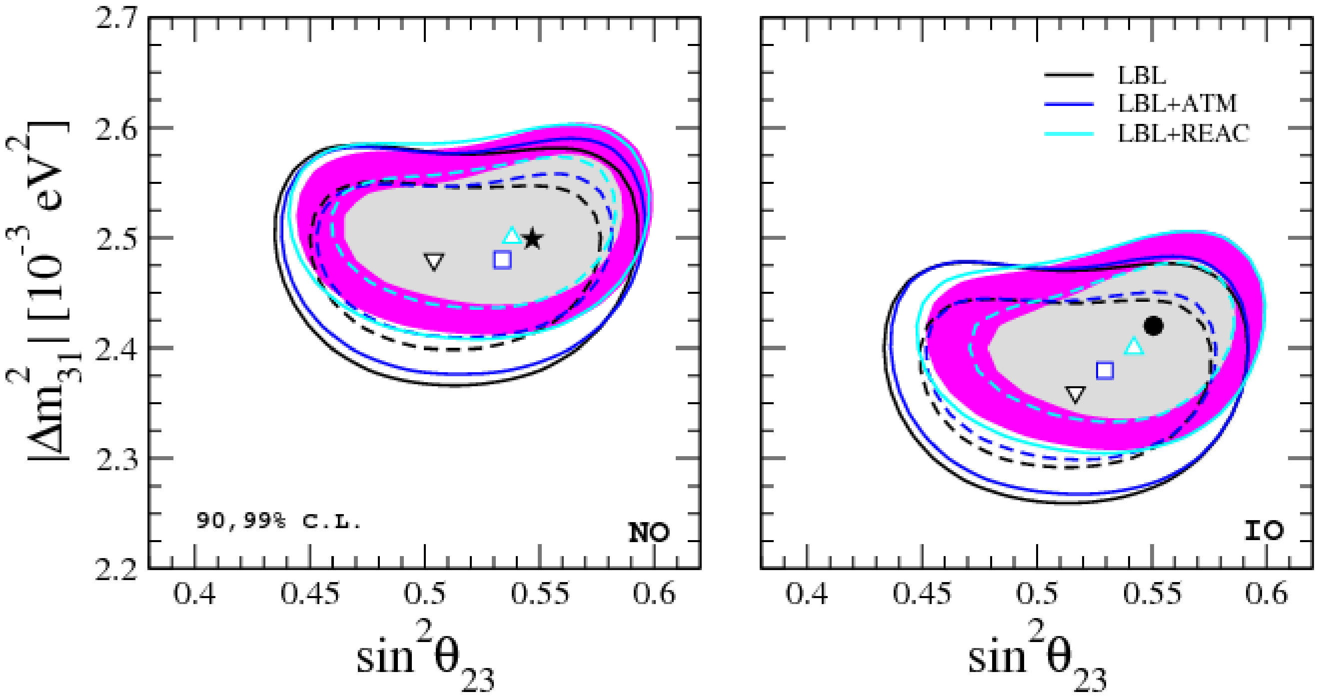
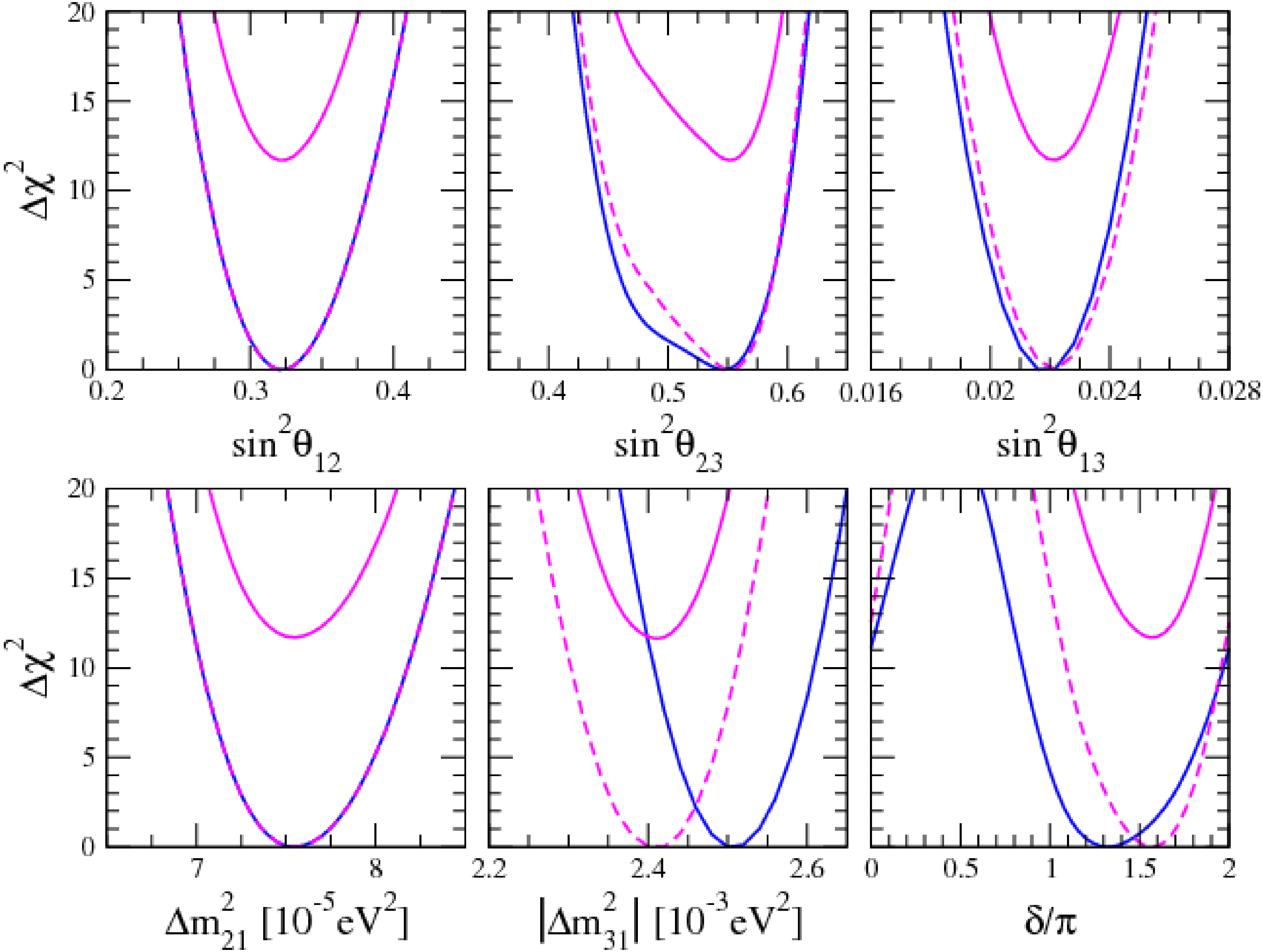


Summary of the global fit



Summary of the global fit

parameter	best fit $\pm$ 1σ	3σ range
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.55^{+0.20}_{-0.16}$	7.05–8.14
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (NO)	2.50$\pm$0.03	2.41–2.60
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94

More on mass ordering

JCAP 1803 (2018) no.03, 011, S. Gariazzo, M. Archidiacono, P.F. de Salas, O. Mena, CAT, M. Tórtola

arXiv:1806.11051, P.F. de Salas, S. Gariazzo, O. Mena, CAT, M. Tórtola

More on mass ordering

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- We calculate the Bayesian evidence for both mass orderings

$$Z = p(d|\mathcal{M}) = \int_{\Omega_{\mathcal{M}}} p(d|\theta, \mathcal{M})p(\theta|\mathcal{M})d\theta$$

More on mass ordering

- We can perform a Bayesian analysis combining several datasets
- In this case we compare NO and IO by means of model selection techniques
- We calculate the Bayesian evidence for both mass orderings

$$Z = p(d|\mathcal{M}) = \int_{\Omega_{\mathcal{M}}} p(d|\theta, \mathcal{M}) p(\theta|\mathcal{M}) d\theta$$

- Then we compute the Bayes factor

$$B_{\rm NO,IO} = \frac{Z_{\rm NO}}{Z_{\rm IO}} \Rightarrow \ln B_{\rm NO,IO} = \ln Z_{\rm NO} - \ln Z_{\rm IO}$$

More on mass ordering

- The preference for one ordering is then given by the Jeffreys' scale

$\vert \ln B_{\mathrm{NO,IO}} \vert$	Odds	strength of evidence	$N\sigma$ for the mass ordering
< 1.0	$\lesssim 3:1$	inconclusive	$< 1.1\sigma$
$\in [1.0, 2.5]$	$(3-12):1$	weak	$1.1-1.7\sigma$
$\in [2.5, 5.0]$	$(12-150):1$	moderate	$1.7-2.7\sigma$
$\in [5.0, 10]$	$(150-2.2\times 10^4):1$	strong	$2.7-4.1\sigma$
$\in [10, 15]$	$(2.2\times 10^4-3.3\times 10^6):1$	very strong	$4.1-5.1\sigma$
> 15	$> 3.3\times 10^6:1$	decisive	$> 5.1\sigma$

Parameterization and data

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- Also included is data from the decay experiments: KamLAND-ZEN, EXO200 and GERDA

Parameterization and data

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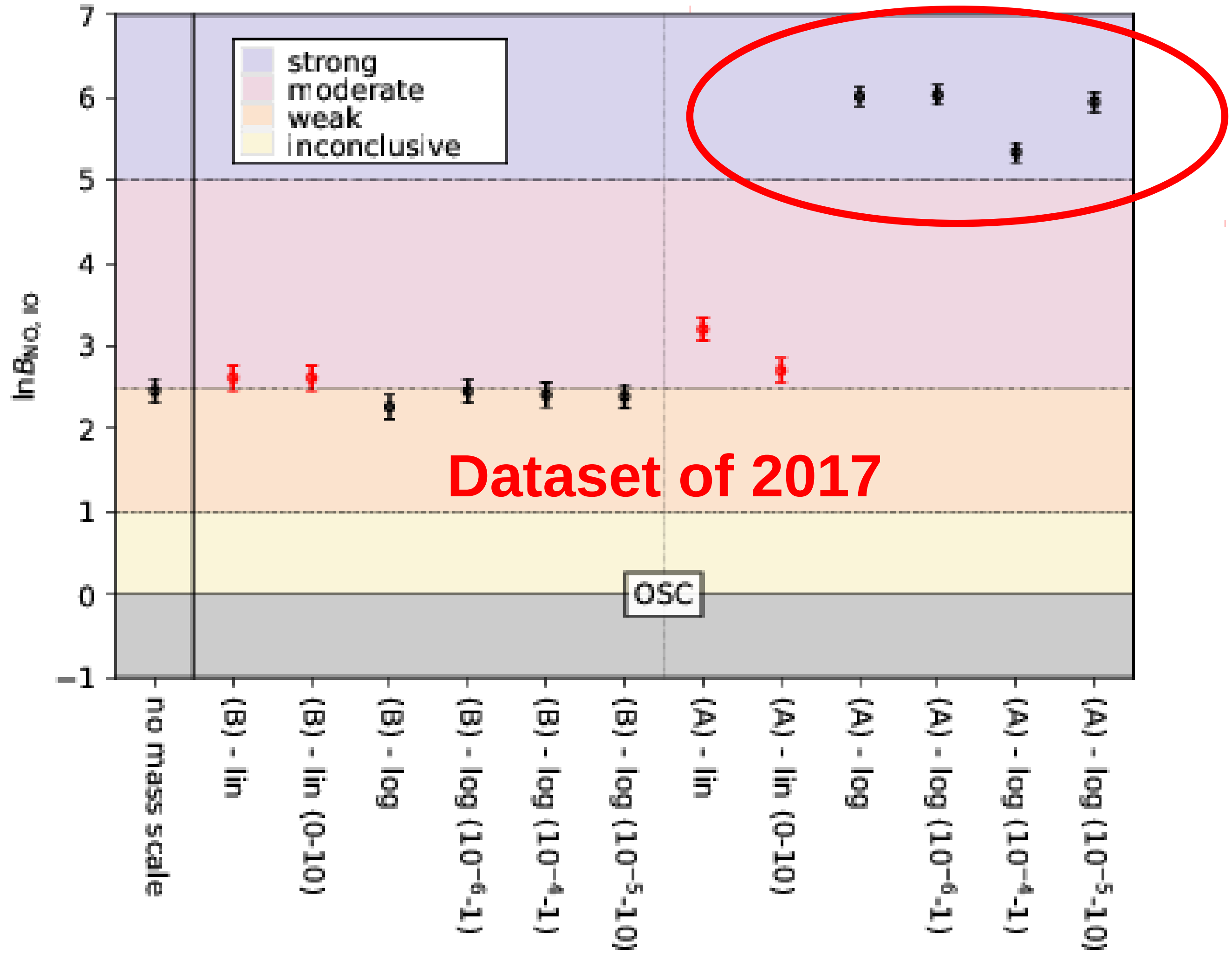
- There are for example several ways to parametrize the neutrino masses

Model A			Model B		
Parameter	Prior	Range	Parameter	Prior	Range
m_1/eV	linear log	$0 - 1$ $10^{-5} - 1$	$m_{\text{lightest}}/\text{eV}$	linear log	$0 - 1$ $10^{-5} - 1$
m_2/eV	linear log	$0 - 1$ $10^{-5} - 1$	$\Delta m^2_{21}/\text{eV}^2$	linear	$5 \times 10^{-5} - 10^{-4}$
m_3/eV	linear log	$0 - 1$ $10^{-5} - 1$	$\lvert\Delta m^2_{31}\rvert/\text{eV}^2$	linear	$1.5 \times 10^{-3} - 3.5 \times 10^{-3}$

JCAP 1803 (2018) no.03, 011, S. Gariazzo, M. Archidiacono, P.F. de Salas, O. Mena, CAT, M. Tórtola

Parameterization and data

- This can give a biased preference for normal ordering



JCAP 1803 (2018) no.03, 011, S. Gariazzo, M. Archidiacono, P.F. de Salas, O. Mena, CAT, M. Tórtola

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Neutrino mixing and masses		Cosmological		$0\nu\beta\beta$	
Parameter	Prior	Parameter	Prior	Parameter	Prior
$\sin^2\theta_{12}$	$0.1 - 0.6$	$\Omega_b h^2$	$0.019 - 0.025$	α_2	$0 - 2\pi$
$\sin^2\theta_{13}$	$0.00 - 0.06$	$\Omega_c h^2$	$0.095 - 0.145$	α_3	$0 - 2\pi$
$\sin^2\theta_{23}$	$0.25 - 0.75$	Θ_s	$1.03 - 1.05$	$\mathcal{M}^{0\nu}_{^{76}\mathrm{Ge}}$	$3.3 - 5.7$
δ_{CP}/π	$0 - 2$	τ	$0.01 - 0.4$	$\mathcal{M}^{0\nu}_{^{136}\mathrm{Xe}}$	$1.5 - 3.7$
$\Delta m^2_{21}/\mathrm{eV}^2$	$5\times10^{-5} - 10^{-4}$	n_s	$0.885 - 1.04$		
$\Delta m^2_{31}/\mathrm{eV}^2$	$1.5\times10^{-3} - 3.5\times10^{-3}$	$\log(10^{10}A_s)$	$2.5 - 3.7$		
$\log_{10}(m_{\mathrm{lightest}}/\mathrm{eV})$	-5 – 0				

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- with a logarithmic prior on the lightest neutrino mass

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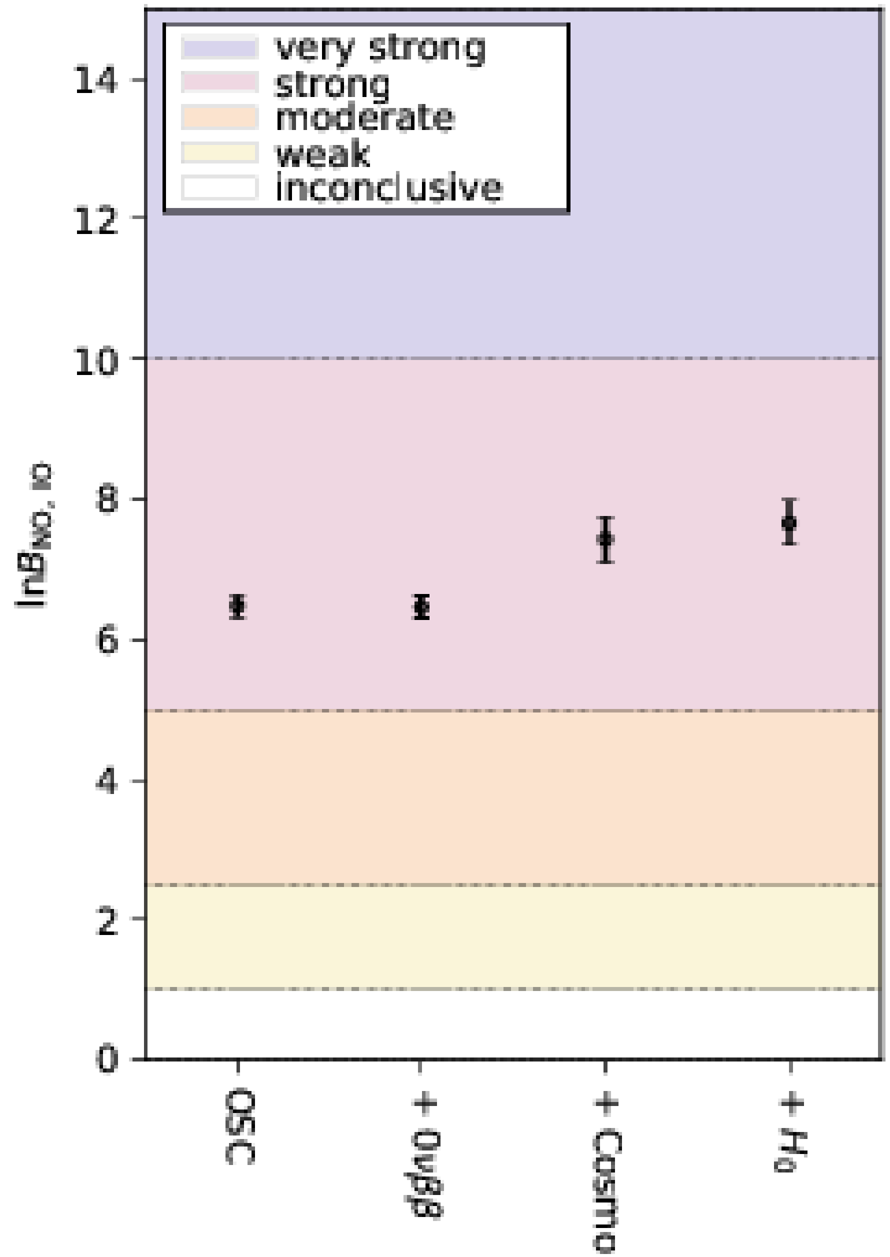

arXiv:1806.11051, P.F. de Salas, S. Gariazzo, O. Mena, CAT, M. Tórtola

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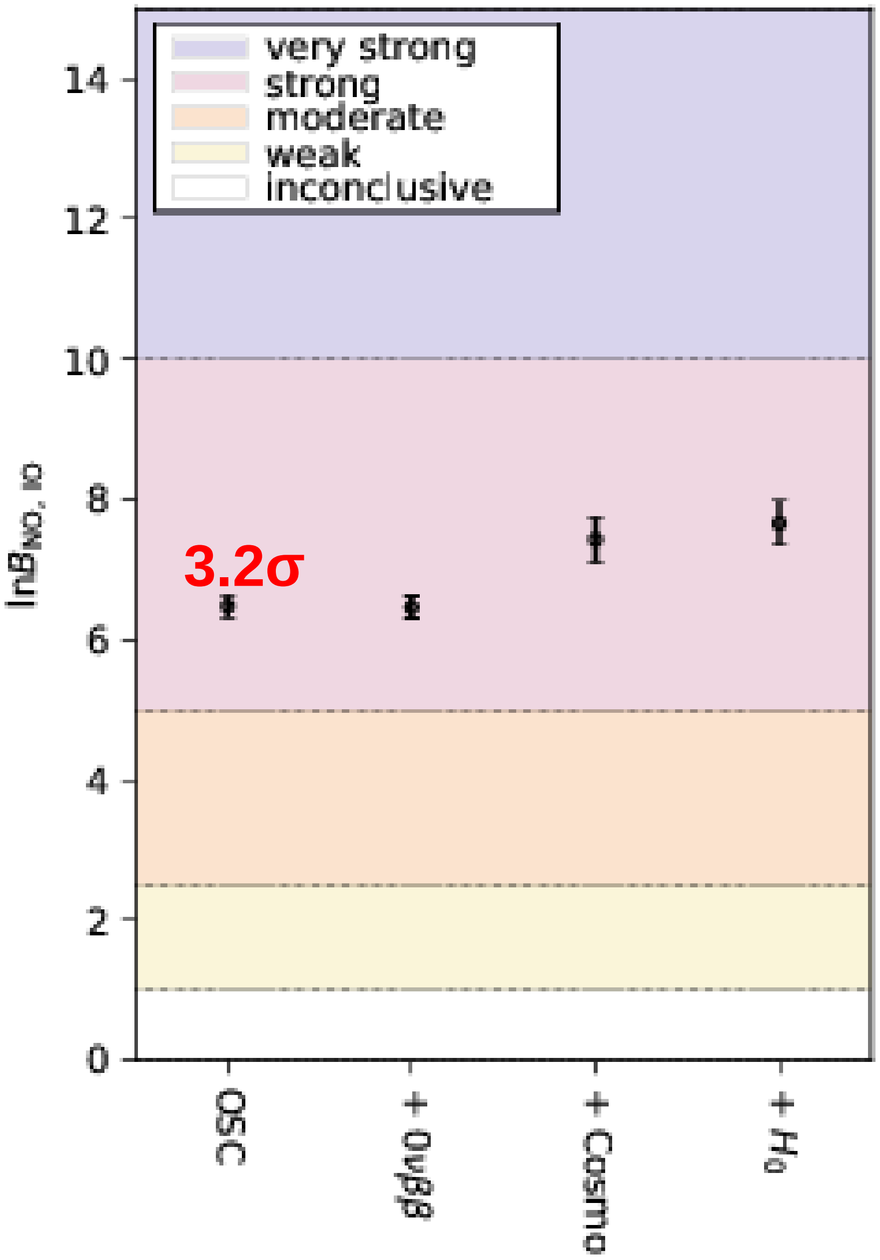

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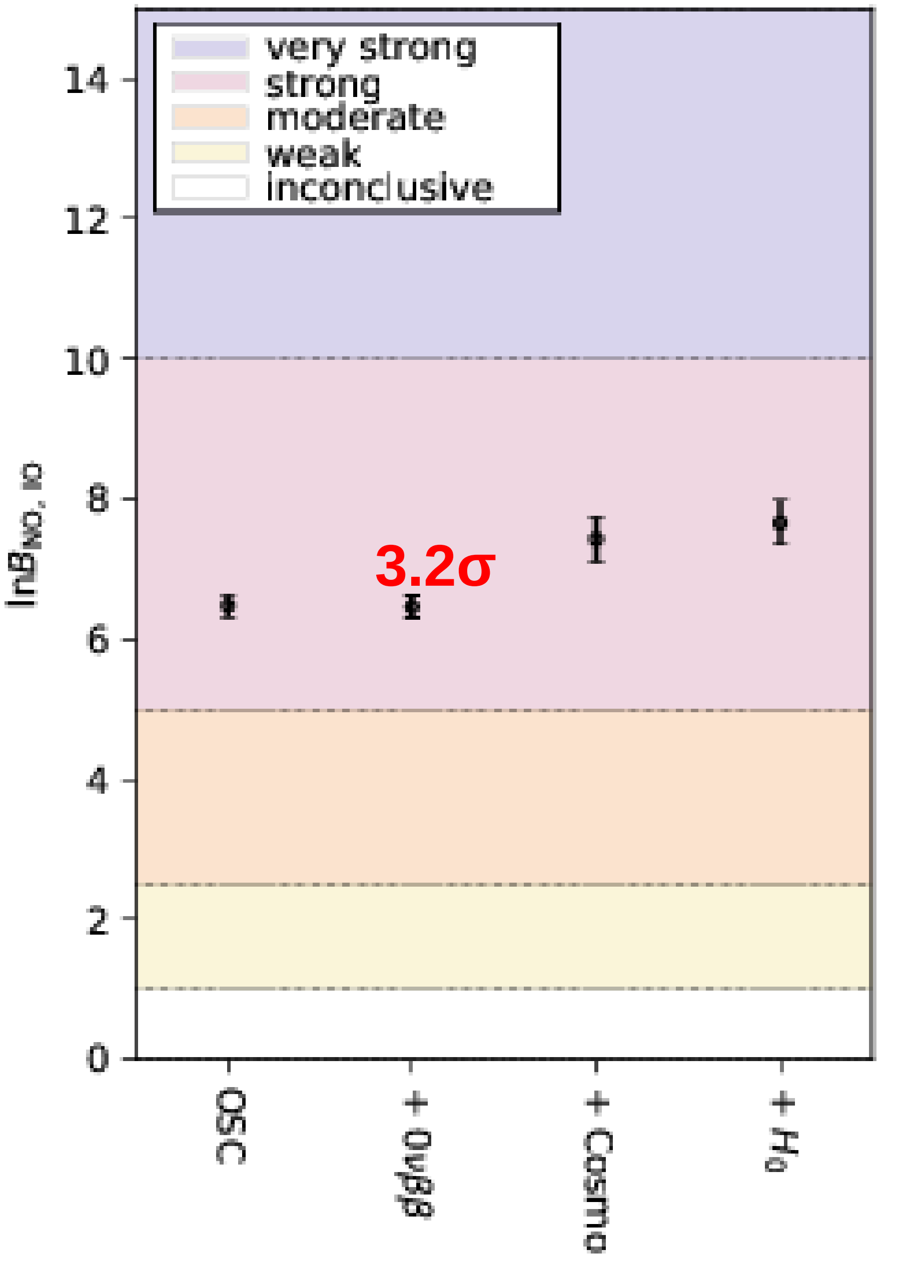

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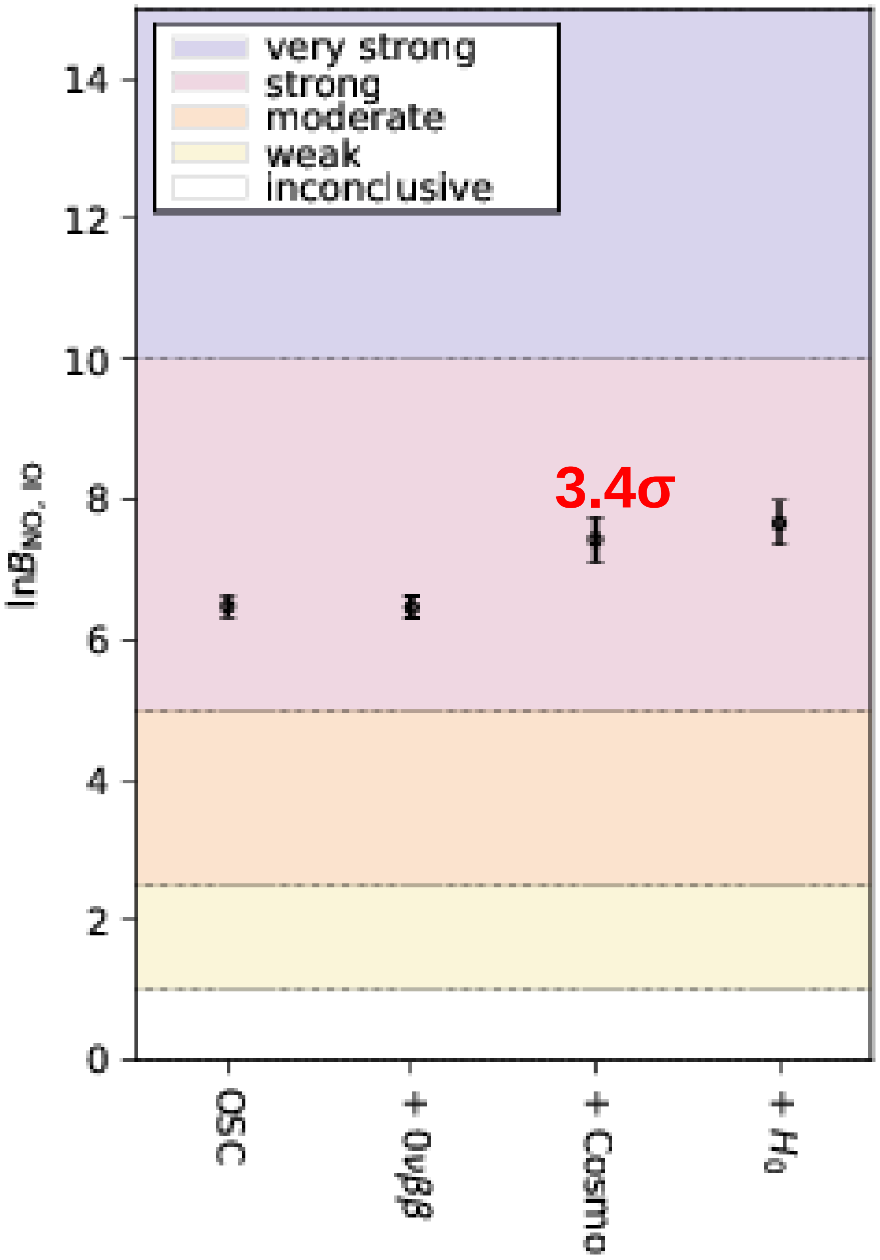

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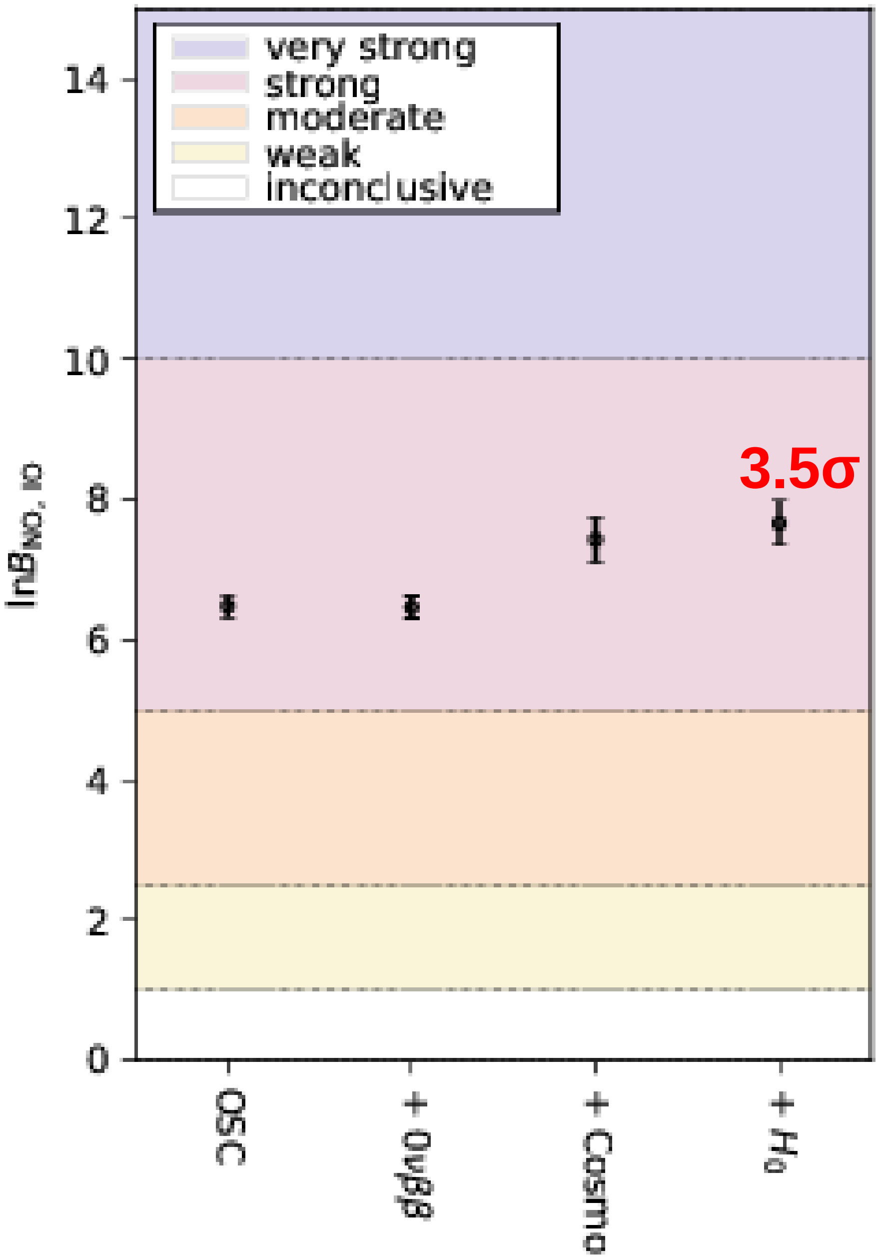

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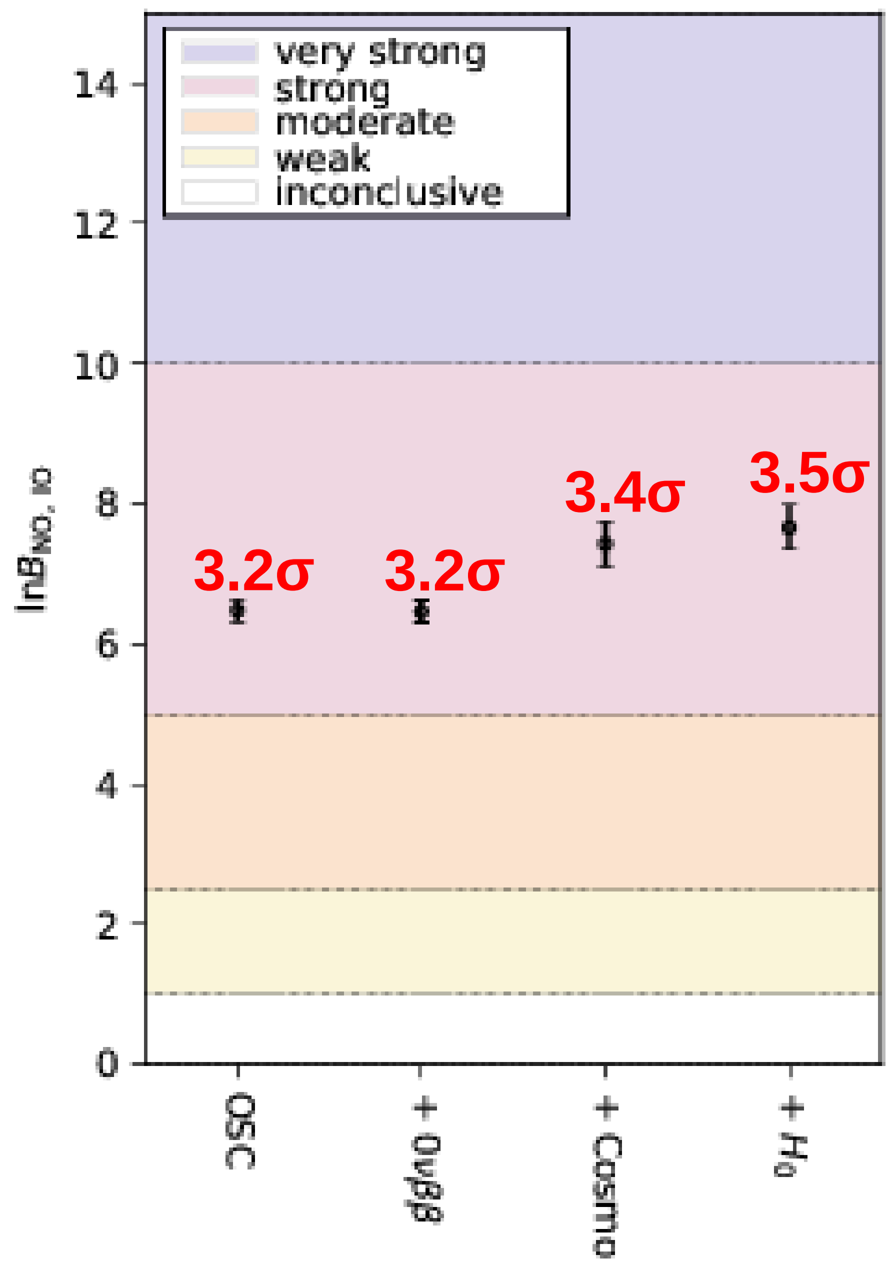
- Strong preference for NO in all cases (driven by oscillation data)



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- We exclude a large part for of the parameter space for the CP phase
- The octant problem remains unsolved, although the value now tends towards the second octant
- By combining several datasets, including cosmological observations and $0\nu\beta\beta$-data we disfavor inverted mass ordering with 3.5σ

Stay tuned for the future!

RENO-50

DUNE

JUNO

INO

ORCA
KM3NeT

HYPER K


Thank you!
muon neutrino