Neutrino Properties

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elusives
neutrinos, dark matter &

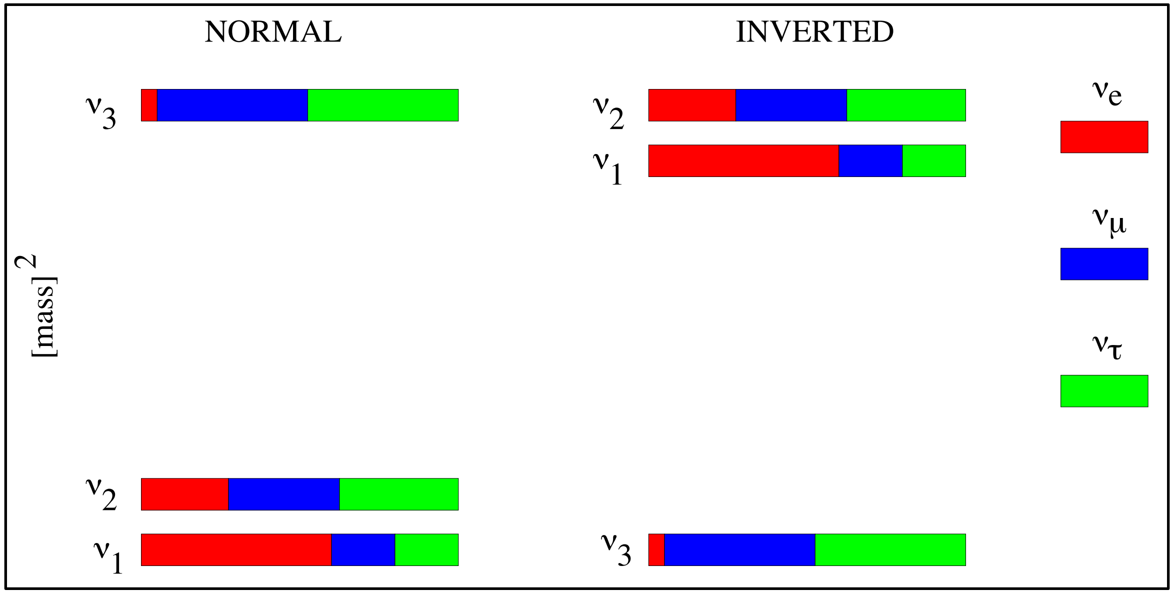
COSMO 2017, Aug. 27 - Sept. 1, 2017, Paris, France

Outline

- Three-flavour neutrino parameters
- Beyond Standard Model neutrino interactions
- Hints for sterile neutrinos at the eV scale

3-neutrino parameters

- 3 masses: Δm^2_{21} , Δm^2_{31}, m_0
- 3 mixing angles θ_{12} θ_{13} θ_{23}
- 3 phases (1 Dirac, 2 Majorana)



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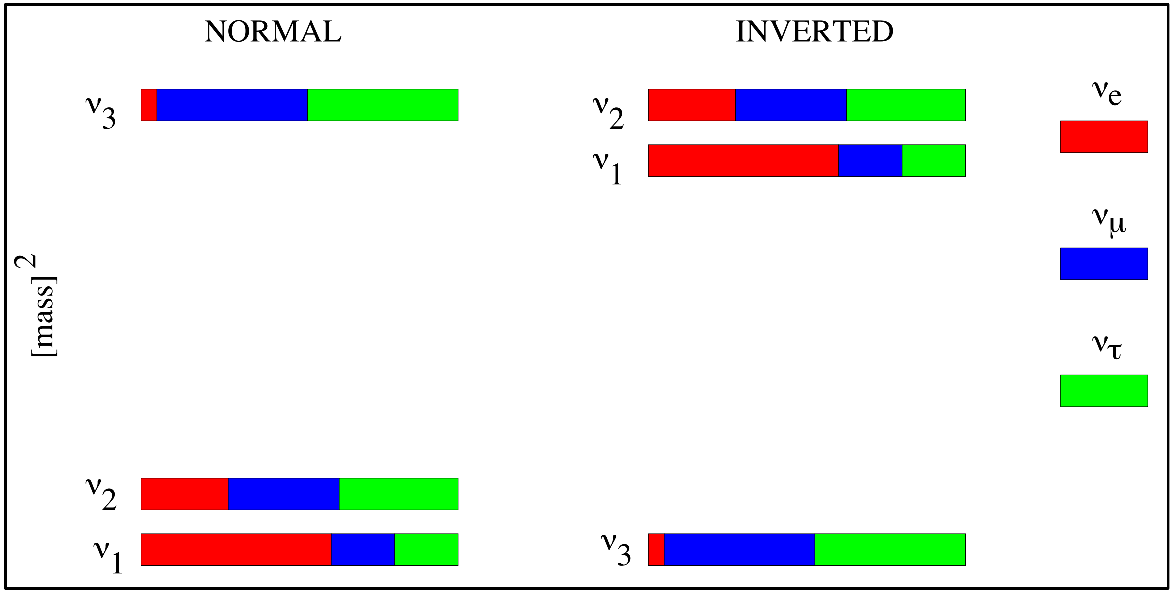
← neutrino oscillations

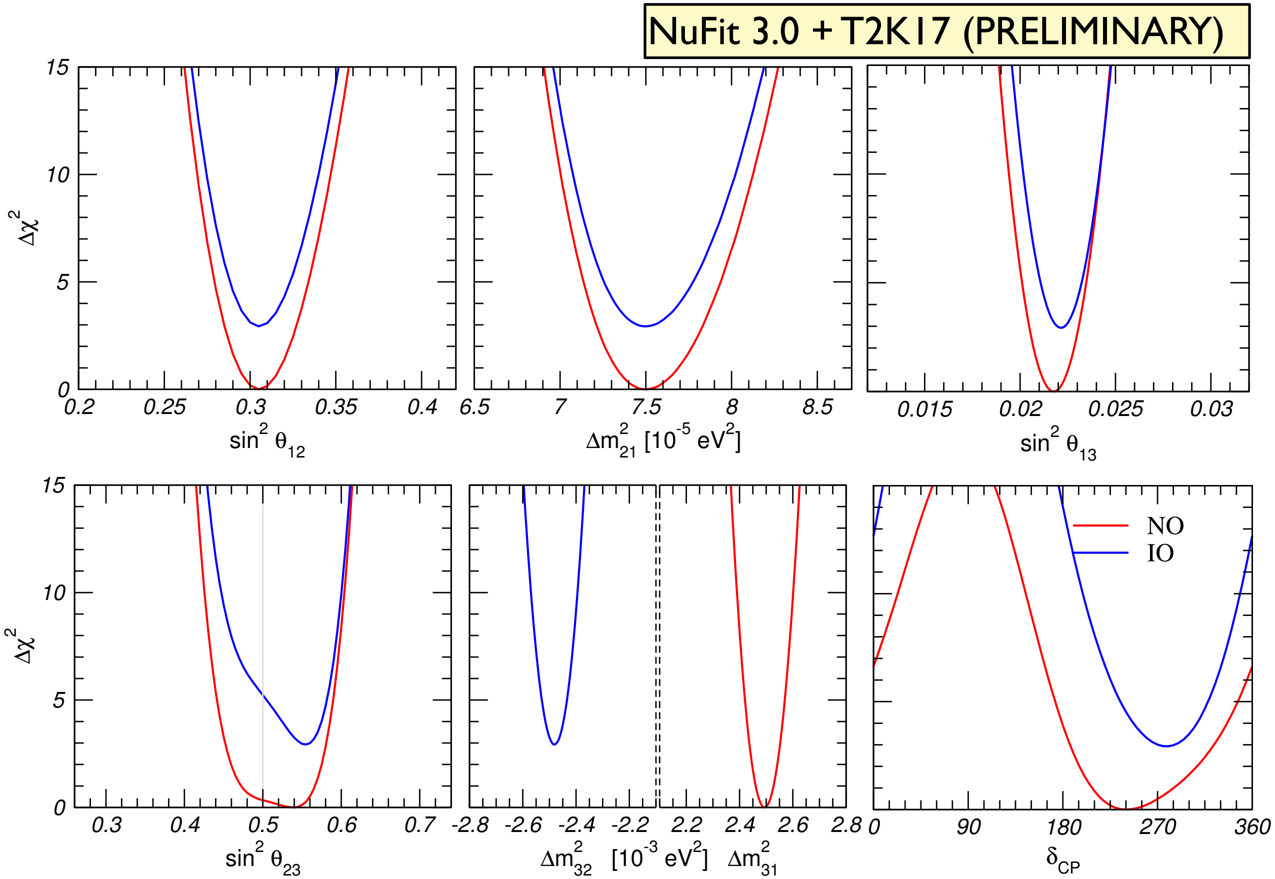


3-flavour mixing - global fit

www.nu-fit.org

- NuFit: www.nu-fit.org
- MC Gonzalez-Garcia, M Maltoni, et al
- updated global fit results including 2-dim chi^2 maps
- last release NuFit-3.0 Esteban et al., 1611.01514
  NuFit-3.1 in preparation
- this talk: preliminary results from NuFit-3.0 + summer 2017 results from T2K

3-flavour mixing - global fit



- well determined parameters

$\theta_{12}\ \theta_{13}\ \Delta m^2_{21}\ |\Delta m^2_{31}|$

open issues:

- θ_{23}: octant/maximality
- mass ordering
- δ_{CP} : preference for $180° < \delta_{CP} < 360°$

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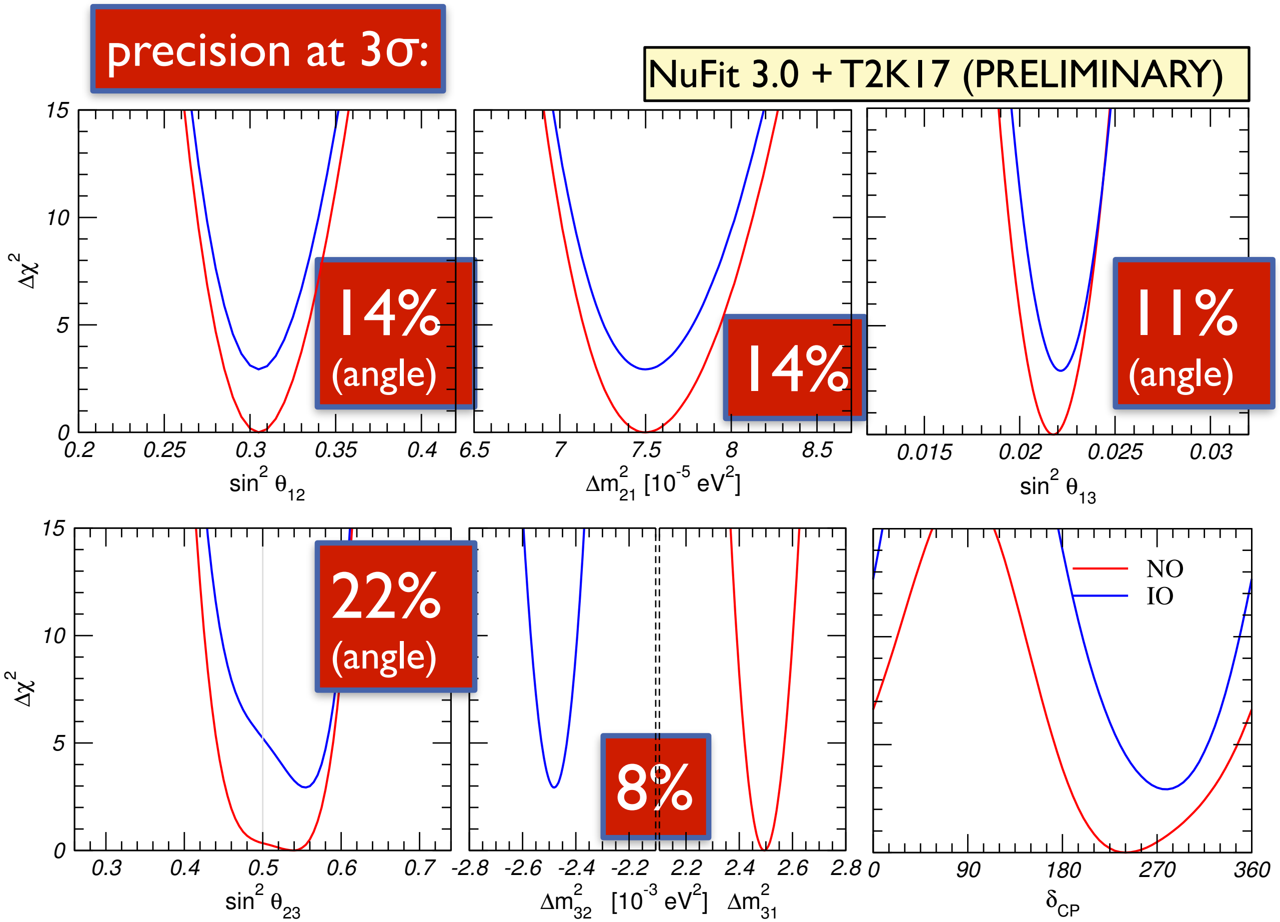

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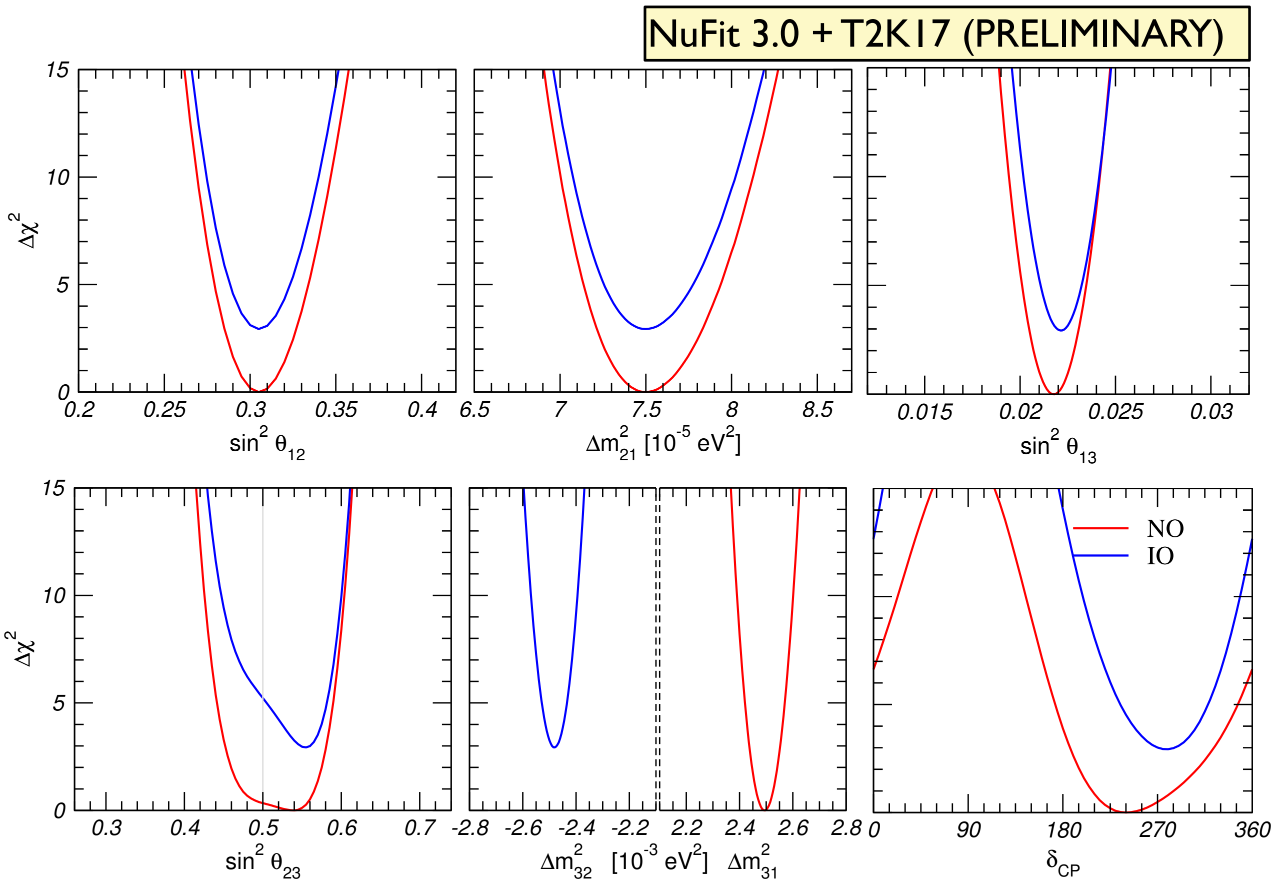

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Leptonic CP violation

Leptonic CP violation will manifest itself in a difference of the vacuum oscillation probabilities for neutrinos and anti-neutrinos

Cabibbo, 1977; Bilenky, Hosek, Petcov, 1980, Barger, Whisnant, Phillips, 1980

$$P_{\nu_\alpha \to \nu_\beta} - P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta} \propto J \,, \qquad J = |\mathrm{Im}(U_{\alpha 1} U^*_{\alpha 2} U^*_{\beta 1} U_{\beta 2})|$$

J: leptonic analogue to Jarlskog-invariant Jarlskog, 1985

standard parameterization: $J = s_{12} c_{12} s_{23} c_{23} s_{13} c_{13}^2 \sin\delta \equiv J^{\max} \sin\delta$

NuFit 3.0: $$J_{\mathrm{CP}}^{\max} = 0.0329 \pm 0.0007$$

compare with Jarlskog invariant in the quark sector:

$$J_{\mathrm{CKM}} = (3.06^{+0.21}_{-0.20}) \times 10^{-5}$$

- CPV for leptons might be a factor 1000 larger than for quarks
- OBS: for quarks we know J, for leptons only $J^{\max}$ (do not know δ!)

Leptonic CP violation

Comment on Leptogenesis:

- CPV is a necessary condition for Leptogenesis
- CPV observable in oscillations can be related to Leptogenesis only within a specific model
- observation of CPV cannot be a „prove“ of Leptogenesis — only „circumstantial evidence“

Dirac CP phase — recent T2K results

M. Hartz, KEK colloquium, August 4, 2017

Accumulated **14.7x10^{20}** protons-on-target (POT) in neutrino mode and **7.6x10^{20}** POT in antineutrino mode - full data set presented here

- **29% of the approved** T2K POT

		Predicted Rates				Observed
	Sample	$\delta_{cp}=-\pi/2$	$\delta_{cp}=0$	$\delta_{cp}=\pi/2$	$\delta_{cp}=\pi$	Rates
neutrino	CCQE 1-Ring e-like FHC	73.5	61.5	49.9	62.0	74
neutrino	CC1π 1-Ring e-like FHC	6.92	6.01	4.87	5.78	15
anti-neutrino	CCQE 1-Ring e-like RHC	7.93	9.04	10.04	8.93	7
neutrino	CCQE 1-Ring μ-like FHC	267.8	267.4	267.7	268.2	240
anti-neutrino	CCQE 1-Ring μ-like RHC	63.1	62.9	63.1	63.1	68

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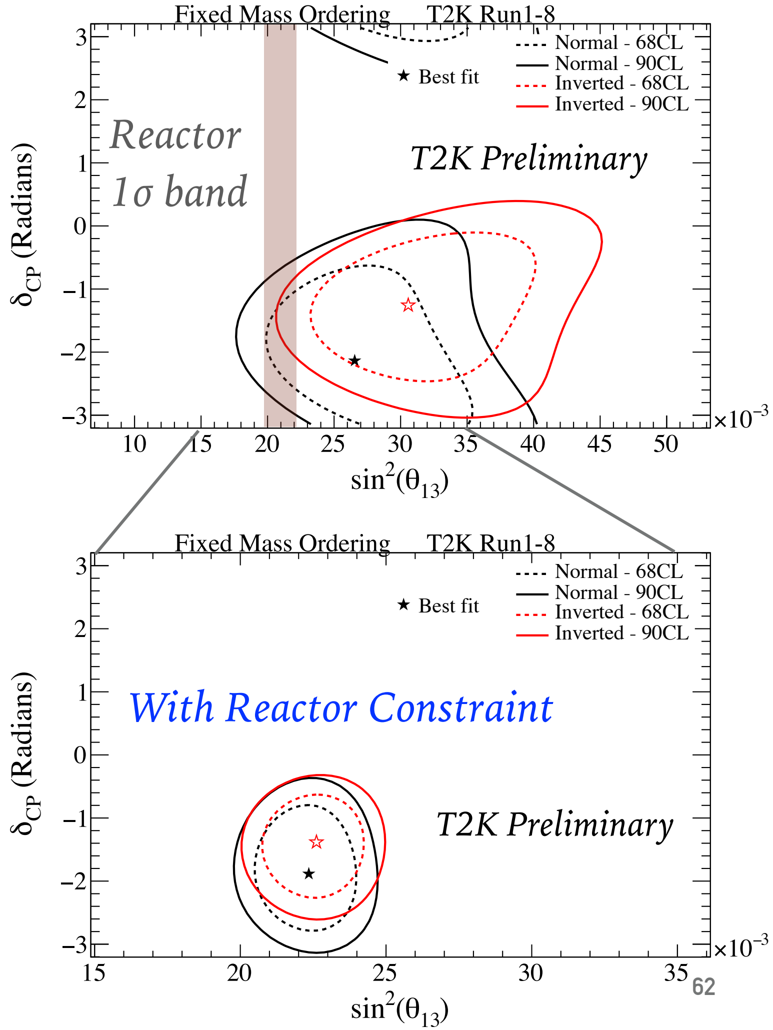

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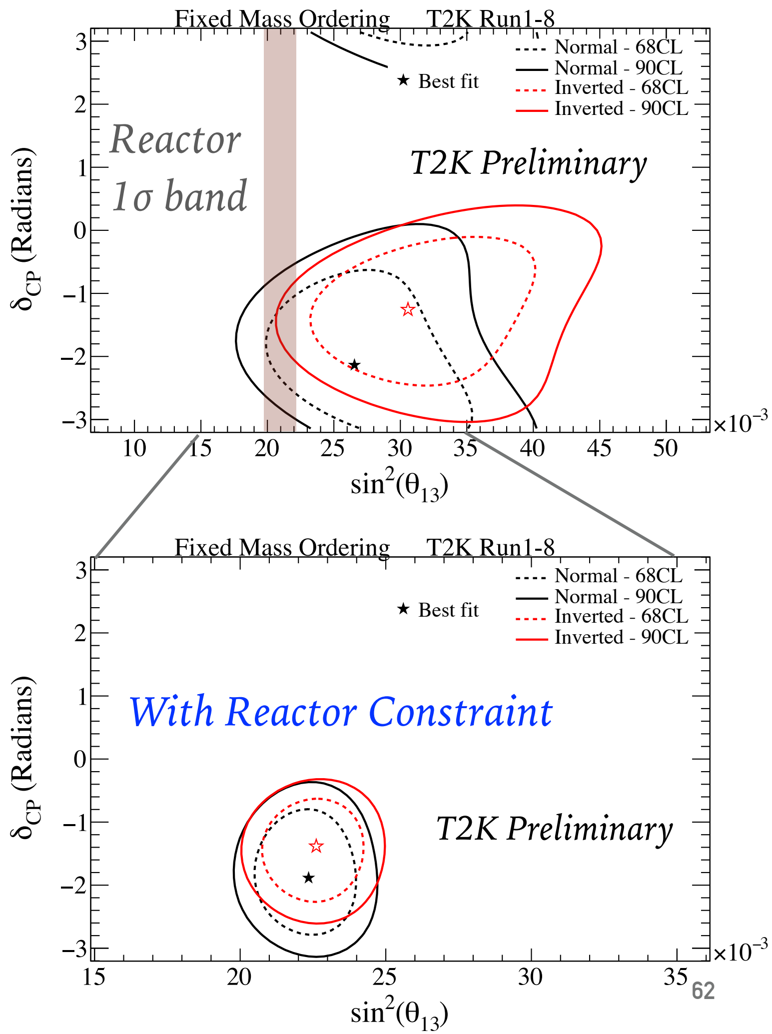
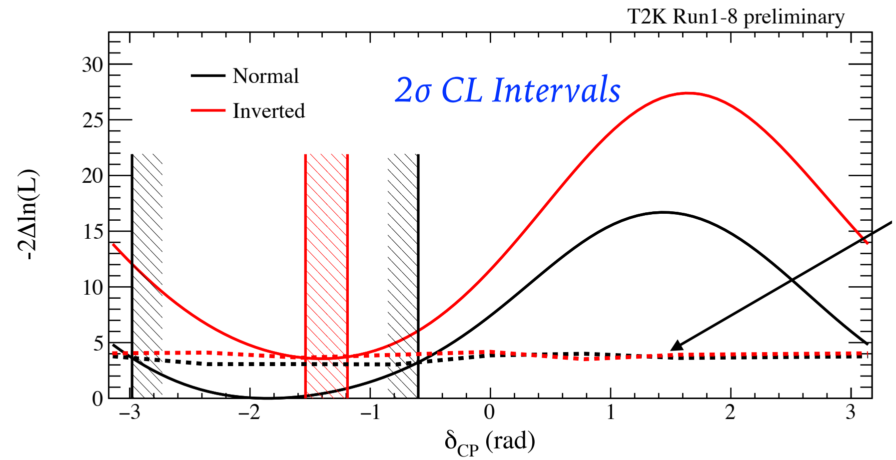
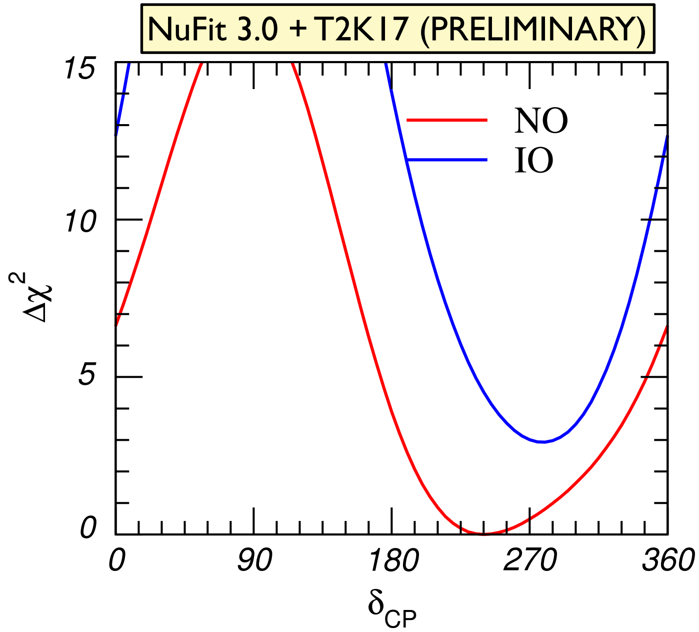




CP conserving values 0 and π are outside the 2σ CL intervals!

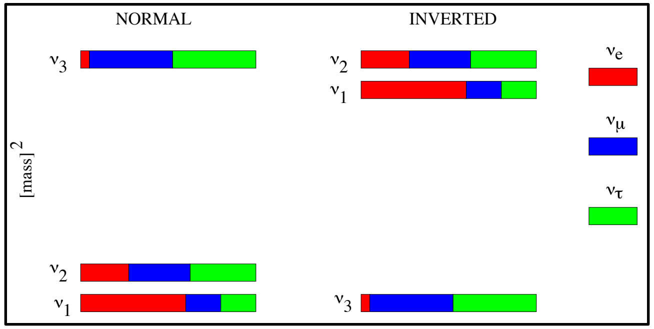
Dirac CP phase — global fit

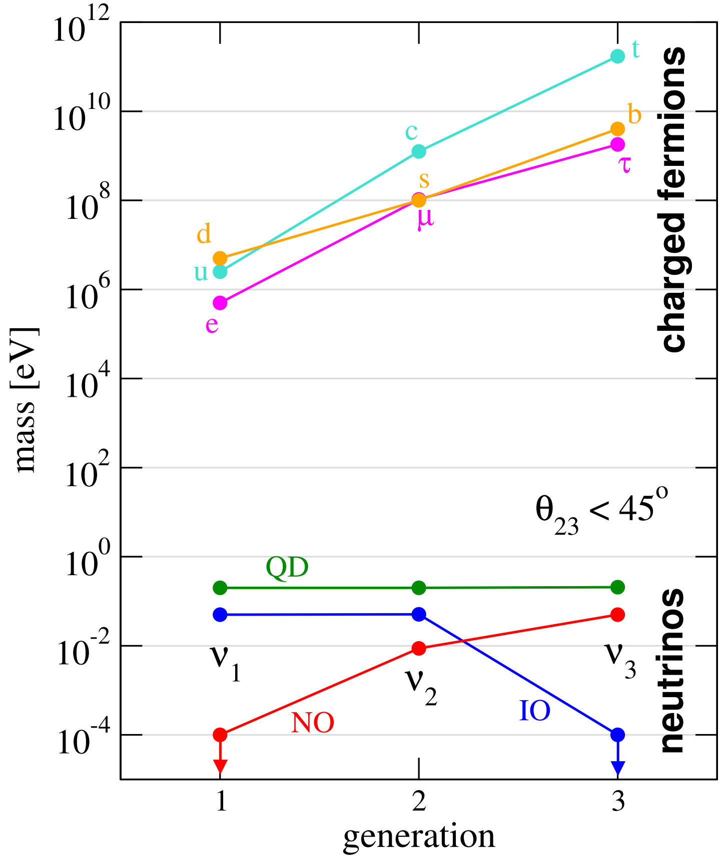


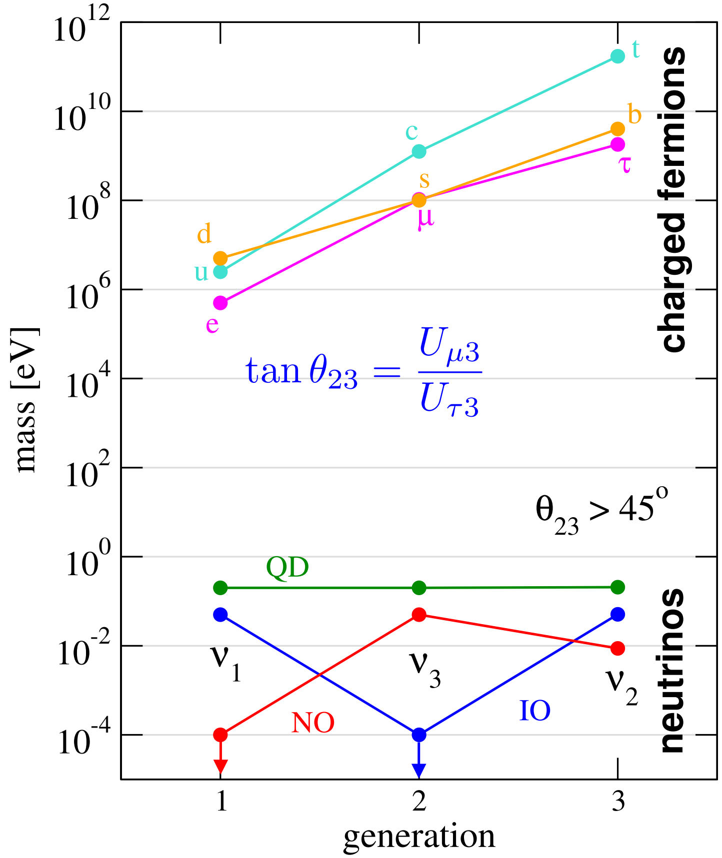
- best fit at $\delta_{CP} \approx 240°$
- CP conservation allowed with $\Delta\chi^2 \approx 4$
- region between 16° and 150° disfavoured with $\Delta\chi^2 > 9$

Neutrino mass spectrum

for inverted ordering and/or $\theta_{23} > 45°$
lepton mixing is very different from quarks







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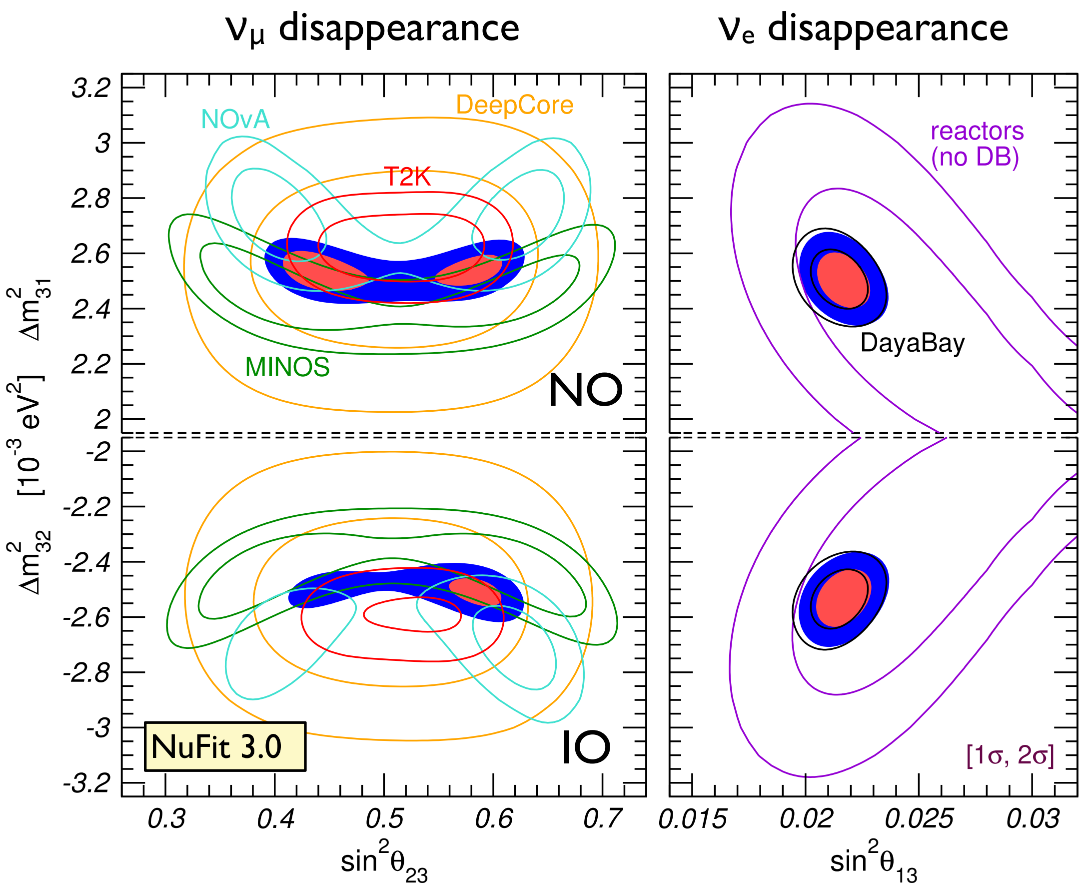
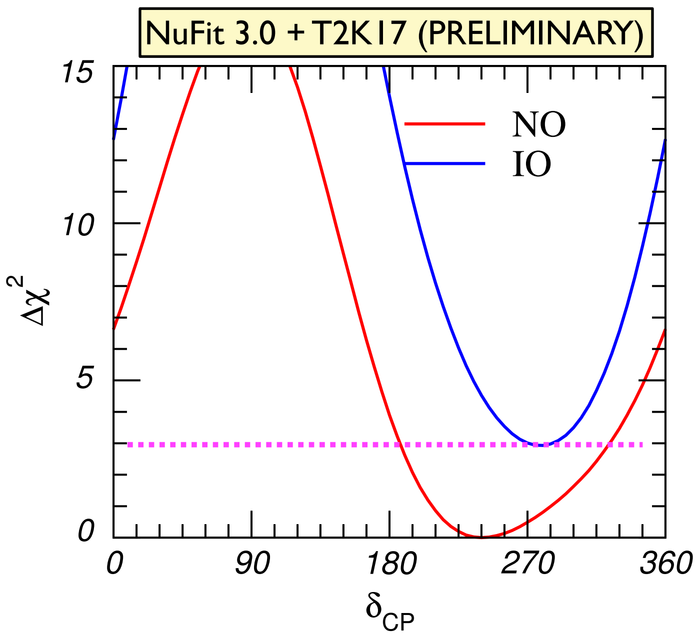
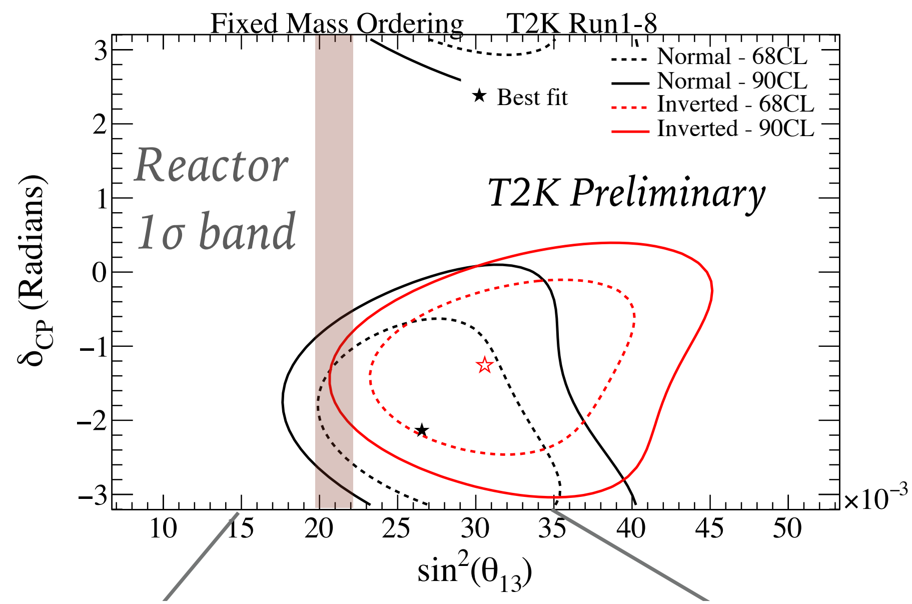
Entering the era of redundancy



- consistent results in ν_e and ν_μ disappearance searches
- several consistent results in ν_μ disappearance

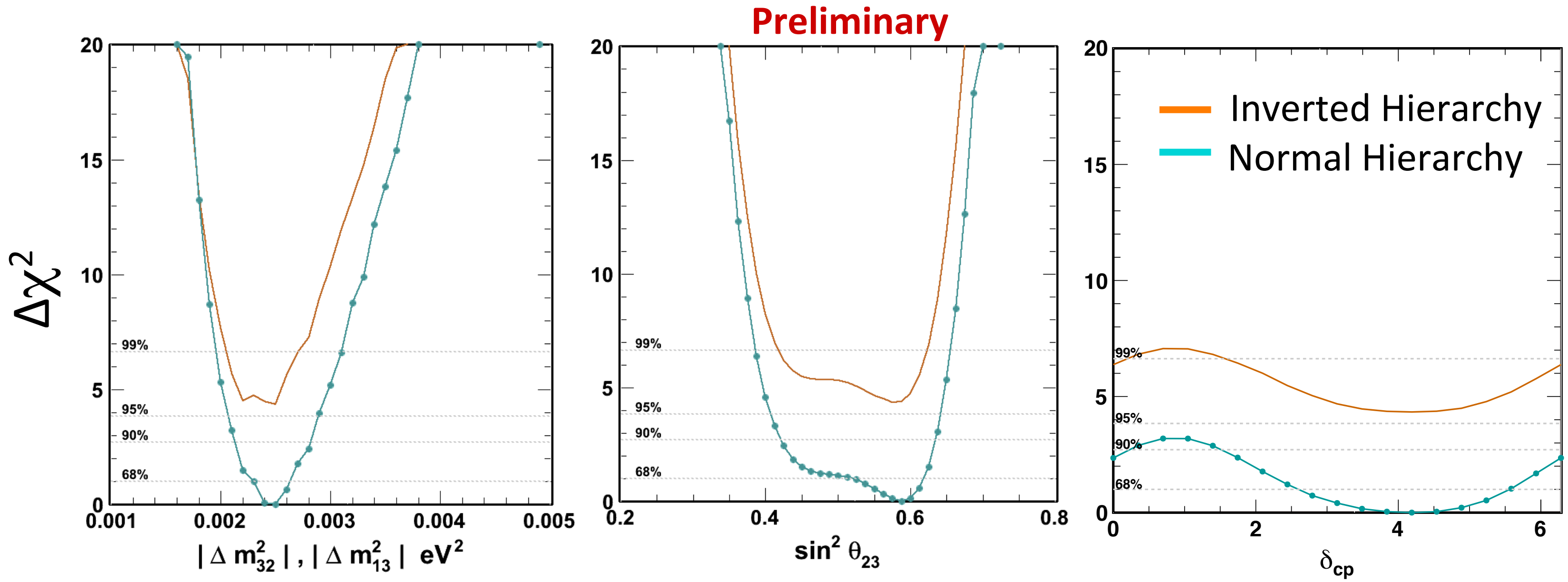
Mass ordering





- Preference for NO with $\Delta\chi^2 \approx 3$
- mostly driven by T2K vs Reactor

Three flavor ν oscillation analysis Super-K atm.ν only



Fit (517 d.o.f.)	$\chi2$	δ_{cp}	θ_{23}	Δm_{23} ($\times 10^{-3}$)
Normal Hierarchy	571.74	4.189	0.587	2.5
Inverted Hierarchy	576.08	4.19	0.575	2.5

- $\chi^2_{NH} - \chi^2_{IH}$ = **-4.3 (-3.1 expected)**
- The probability to obtain $\Delta\chi2$ of -4.3 or less for IH is 0.03 ($\sin^2\theta_{23}$=0.6), 0.007 ($\sin^2\theta_{23}$=0.4). NH hypothesis : 0.45 ($\sin^2\theta_{23}$=0.6)
- θ_{13} fixed to PDG average and its uncertainty is included as a systematic error.

12

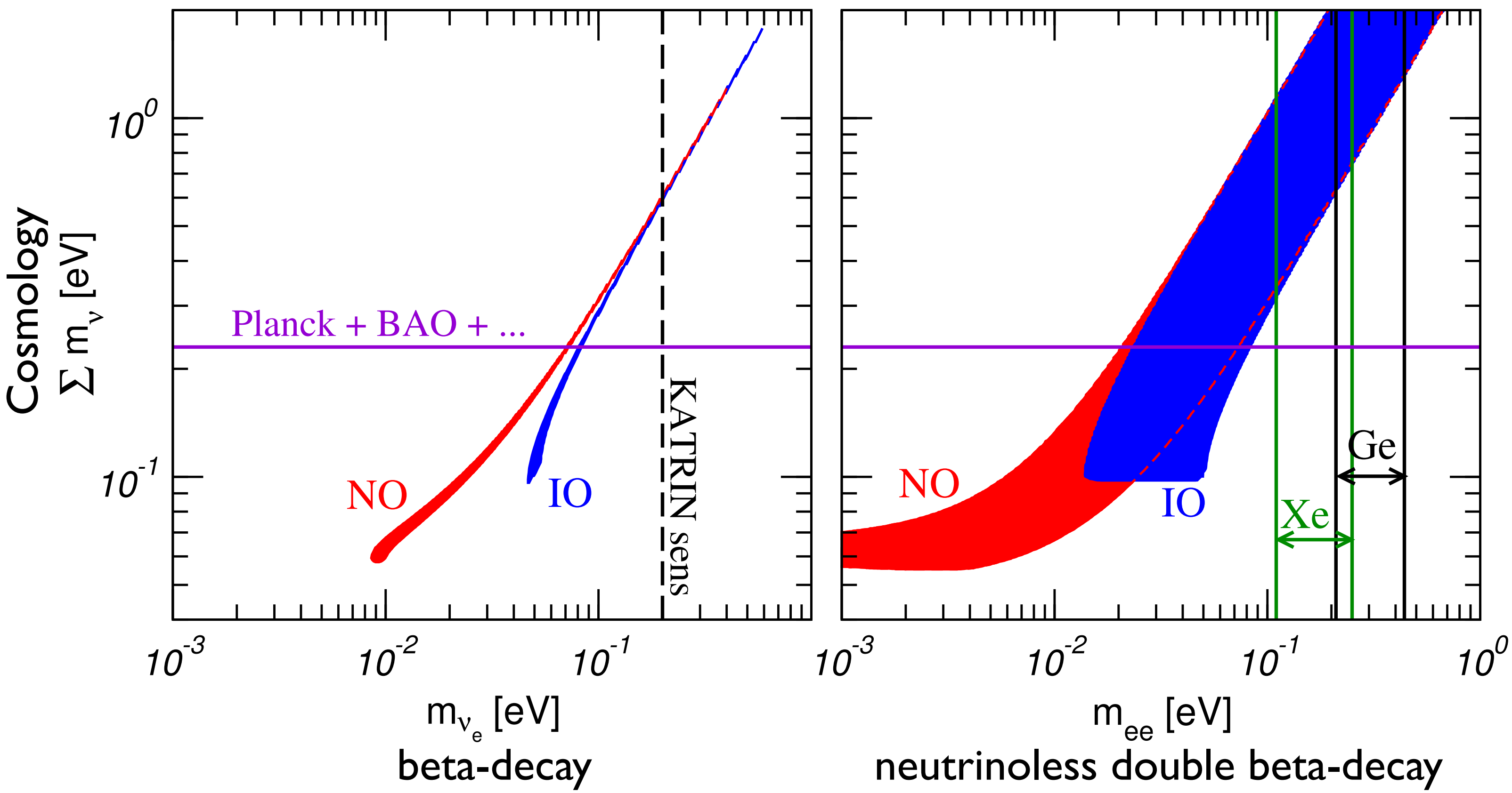
SK coll., talk by J. Kameda, NuFact 2016, Vietnam

Absolute neutrino mass

Three ways to measure absolute neutrino mass:
sensitive to different quantities

- Neutrinoless double beta-decay: $(A, Z) \to (A, Z+2) + 2e^-$
  (with caveats: lepton number violation)
  $m_{ee} = |\sum_i U_{ei}^2 m_i|$
- Endpoint of beta spectrum: $^3\text{H} \to ^3\text{He} + e^- + \bar{\nu}_e$
  (experimentally challenging $\to$ KATRIN)
  $m_\beta^2 = \sum_i |U_{ei}^2| m_i^2$
- Cosmology
  (with caveats: cosmological model/data selection)
  $\sum_i m_i$

Absolute neutrino mass



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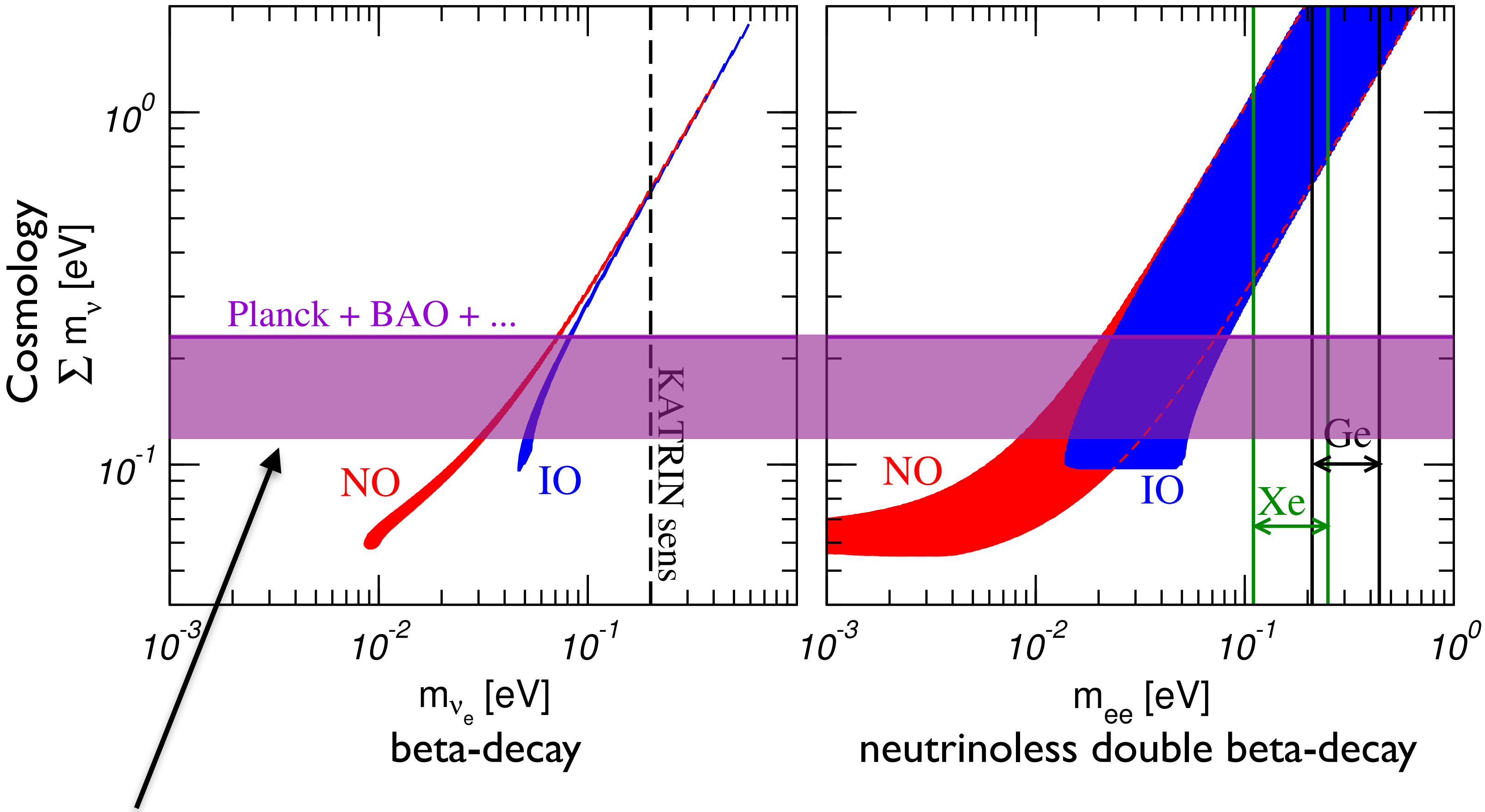


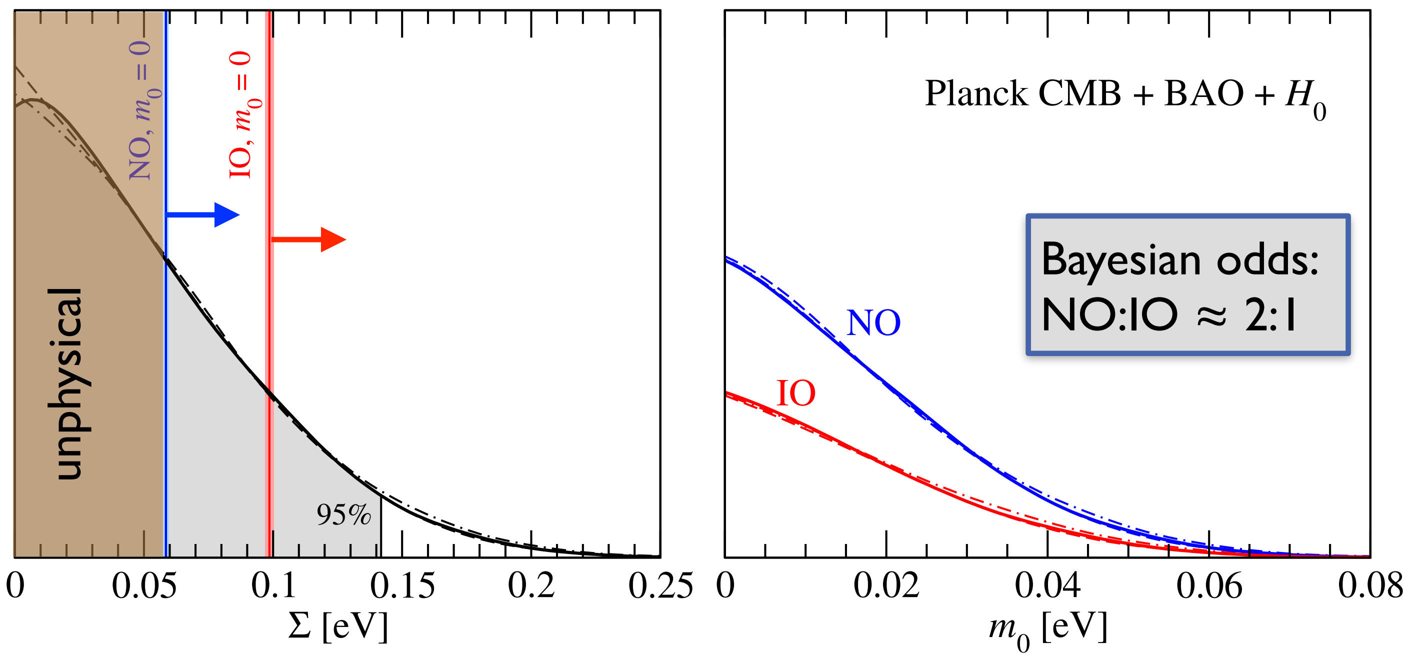
incl. Lyman-α

Baur et al., 1506.05976

Excluding inverted ordering with cosmology?

Hannestad, Schwetz, 1606.04691

minimal values:
$$\Sigma = \begin{cases} 58.5 \pm 0.48\,\text{meV} & \text{(NO)} \\ 98.6 \pm 0.85\,\text{meV} & \text{(IO)} \end{cases} \qquad (m_0 = 0)\,.$$



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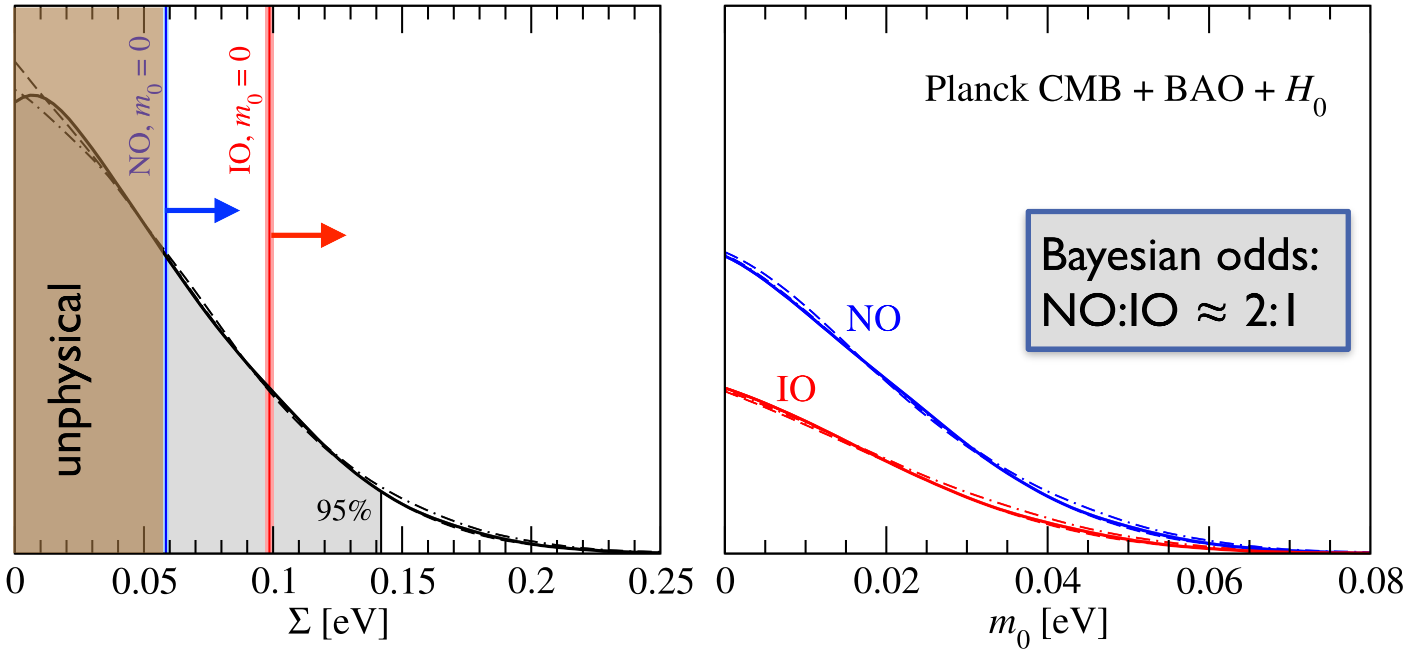

„Strong evidence" for NO claimed in Simpson et al. 1703.03425
→ be aware of Bayesian priors [TS et al. 1703.04585]

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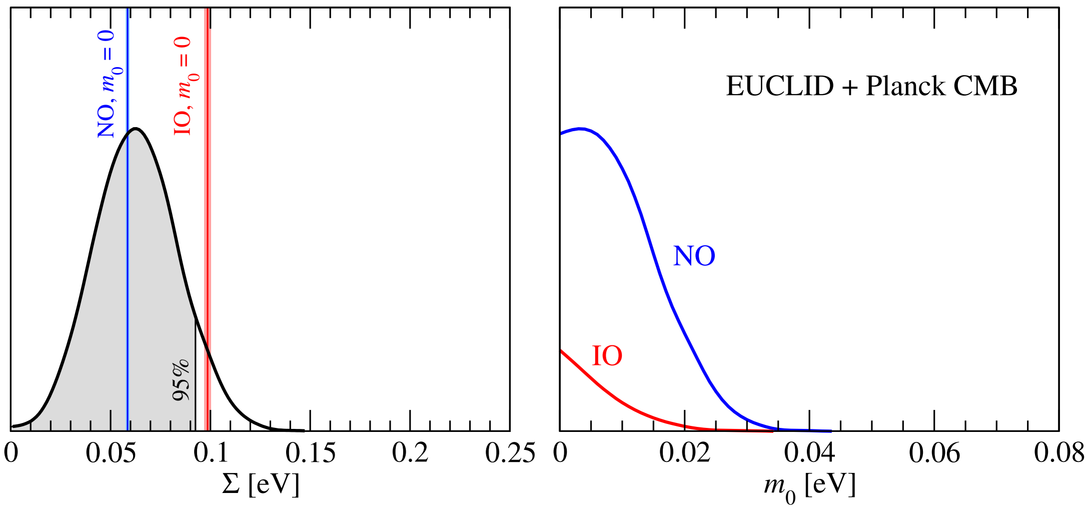
simulated future data:
2 yrs of EUCLID data, available ~2023-24



- need accuracy better than 0.02 eV to exclude 0.1 eV against 0.06 eV at 2σ
- this would imply a 3σ evidence for non-zero neutrino mass (for Sum = 0.06 eV)

Neutrino properties beyond 3-flavour oscillations

Neutrino properties beyond 3-flavour oscillations

- three-flavour scenario very robust
- most extensions lead to sub-leading perturbations ex.: non-unitarity, eV-scale sterile neutrinos
- counter example: non-standard interactions (until last month!)

Non-standard neutrino interactions

assume presence of NC-like dim-6 effective operators:

$$H_{\mathrm{NSI}} = \frac{G_F}{\sqrt{2}} \bar{\nu}_\alpha \gamma_\mu (1 - \gamma_5) \nu_\beta \sum_f \bar{f} \gamma^\mu \epsilon^f_{\alpha\beta} f$$

- $\epsilon^f_{\alpha\beta}$ parametrizes strength of NSI relative to G_F
- restrict to vector-type interactions (matter potential)
- NSI can be non-universal ($\alpha = \beta$) or flavour-changing ($\alpha \neq \beta$)
- in general not directly related to neutrino mass (dim-6) but generically expected at some level

NSI constraints from oscillation data

Gonzalez-Garcia, Maltoni, 1307.3092

		90% CL	
Param.	best-fit	LMA	LMA $\oplus$ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$+0.298$	$[+0.00, +0.51]$	$\oplus\ [-1.19, -0.81]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$+0.001$	$[-0.01, +0.03]$	$[-0.03, +0.03]$
$\varepsilon^u_{e\mu}$	-0.021	$[-0.09, +0.04]$	$[-0.09, +0.10]$
$\varepsilon^u_{e\tau}$	$+0.021$	$[-0.14, +0.14]$	$[-0.15, +0.14]$
$\varepsilon^u_{\mu\tau}$	-0.001	$[-0.01, +0.01]$	$[-0.01, +0.01]$
$\varepsilon^d_{ee} - \varepsilon^d_{\mu\mu}$	$+0.310$	$[+0.02, +0.51]$	$\oplus\ [-1.17, -1.03]$
$\varepsilon^d_{\tau\tau} - \varepsilon^d_{\mu\mu}$	$+0.001$	$[-0.01, +0.03]$	$[-0.01, +0.03]$
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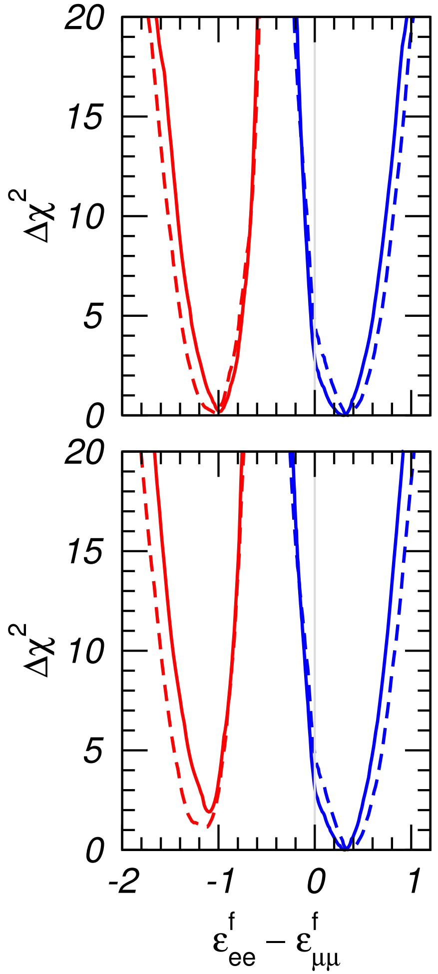

- limits of few %,
- exceptions: $\varepsilon_{e\tau}$, ε_{ee}-$\varepsilon_{\mu\mu}$

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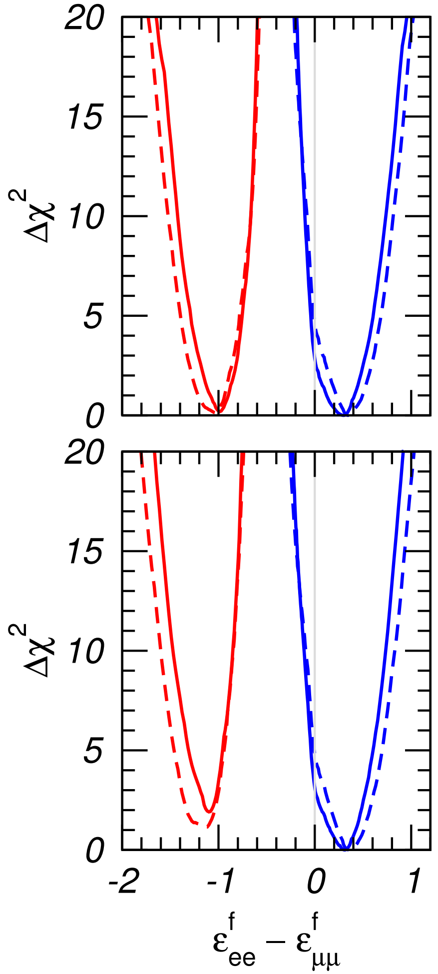

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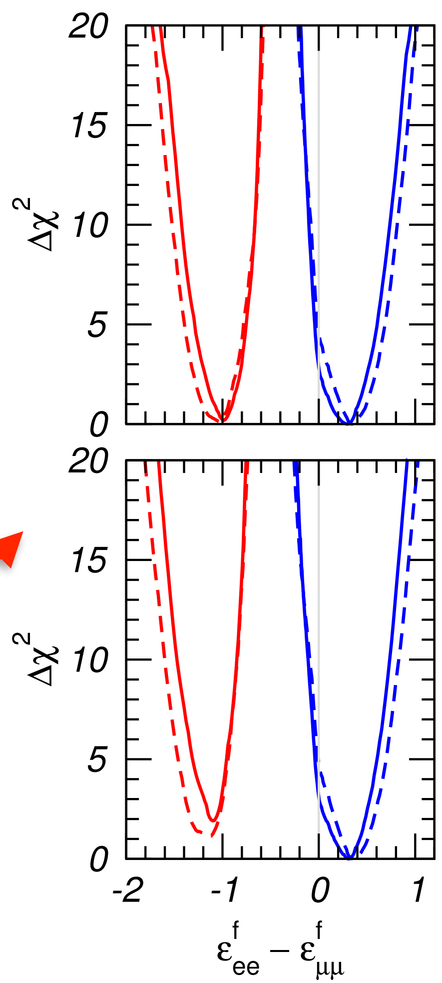

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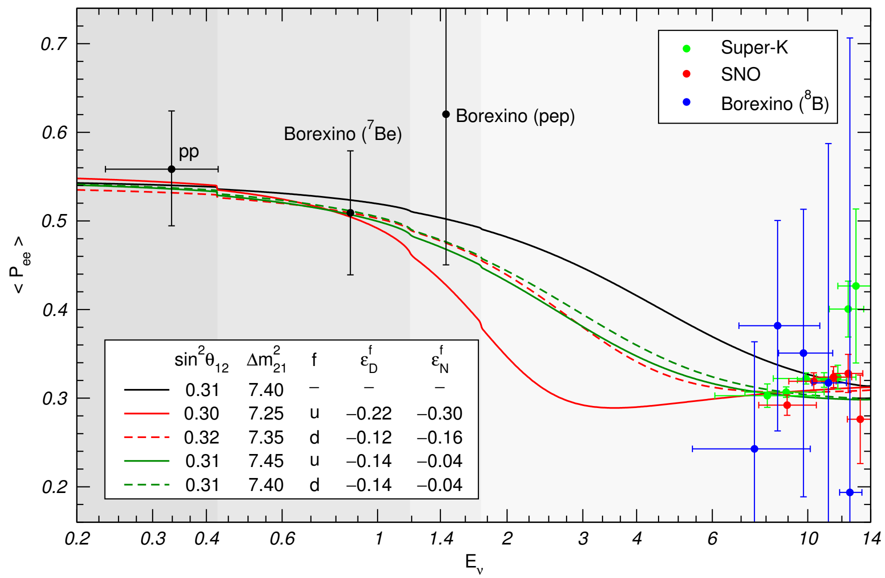
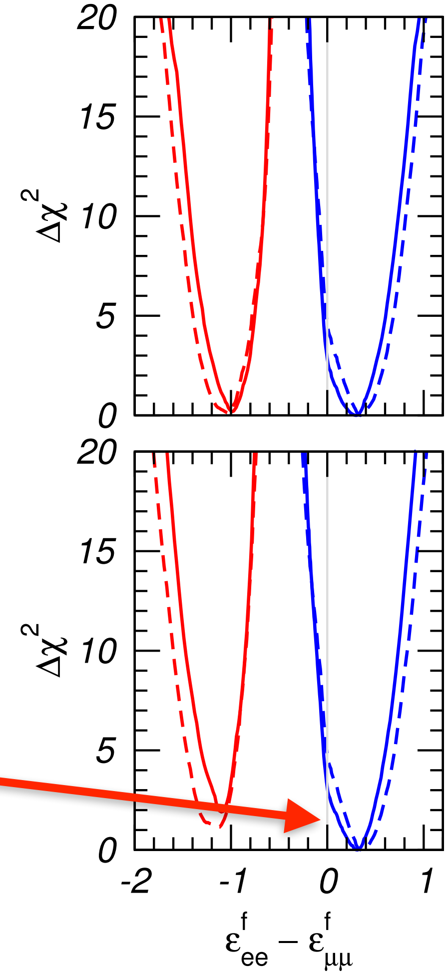
NSI constraints from oscillation data

Gonzalez-Garcia, Maltoni, 1307.3092



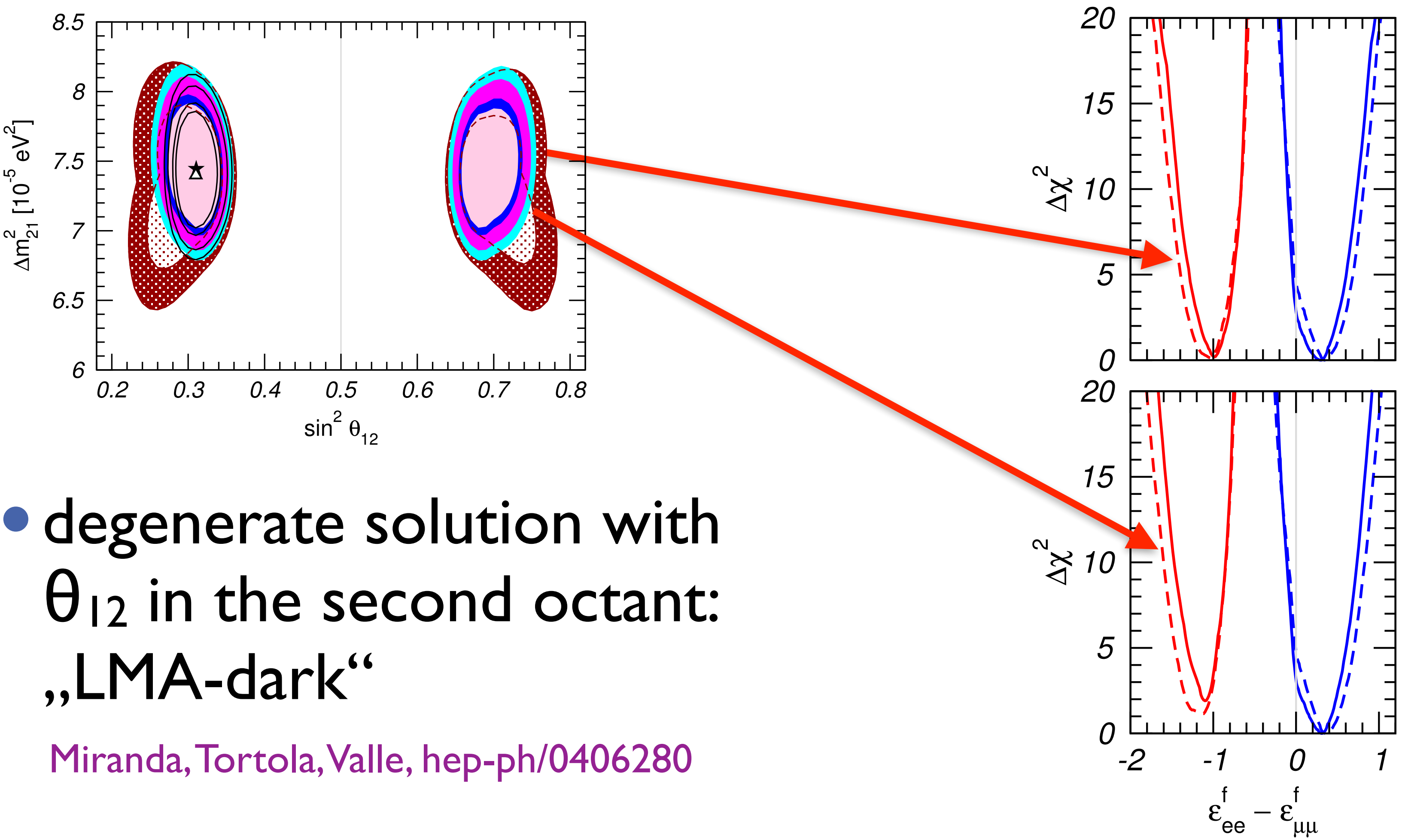
	$\sin^2\theta_{12}$	Δm^2_{21}	f	ε^f_D	ε^f_N
black solid	0.31	7.40	–	–	–
red solid	0.30	7.25	u	−0.22	−0.30
red dashed	0.32	7.35	d	−0.12	−0.16
green solid	0.31	7.45	u	−0.14	−0.04
green dashed	0.31	7.40	d	−0.14	−0.04



- slightly improved fit to solar neutrino data

LMA-dark degeneracy

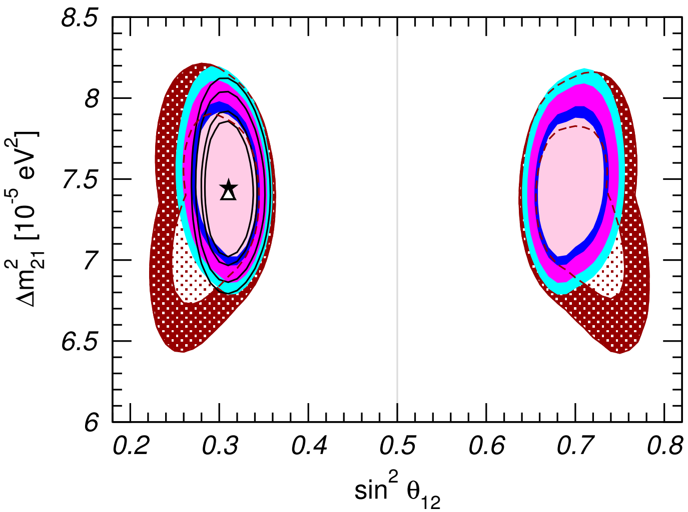
Gonzalez-Garcia, Maltoni, 1307.3092

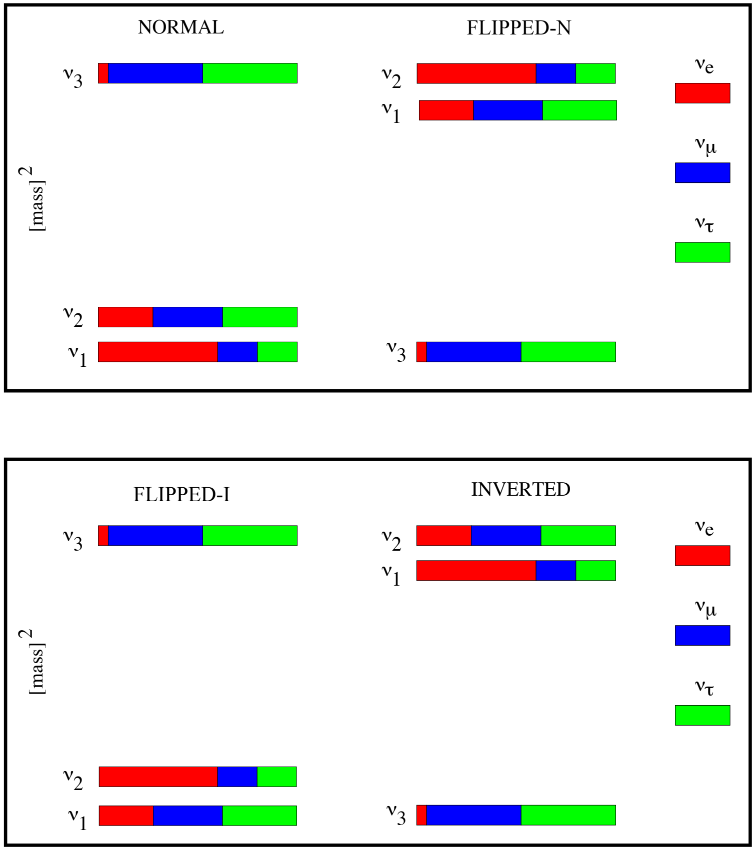


- degenerate solution with θ_{12} in the second octant: „LMA-dark"

Miranda, Tortola, Valle, hep-ph/0406280

LMA-dark degeneracy

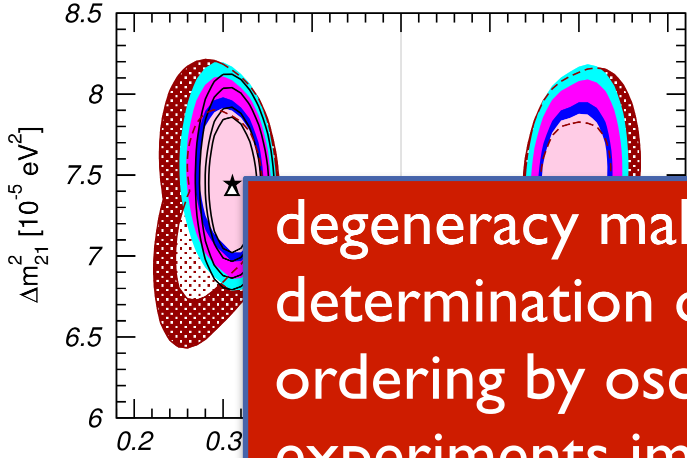




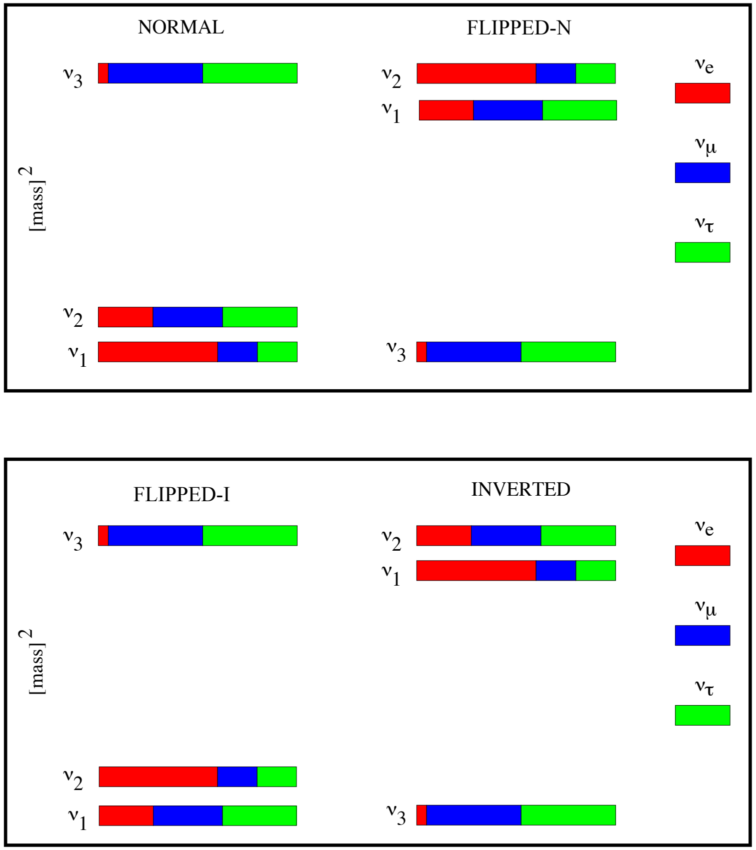
- degenerate solution with θ_{12} in the second octant: „LMA-dark"
- related to a sign-flip in Δm^2_{31}

Coloma, Schwetz, 16

LMA-dark degeneracy



degeneracy makes determination of mass ordering by oscillation experiments impossible!



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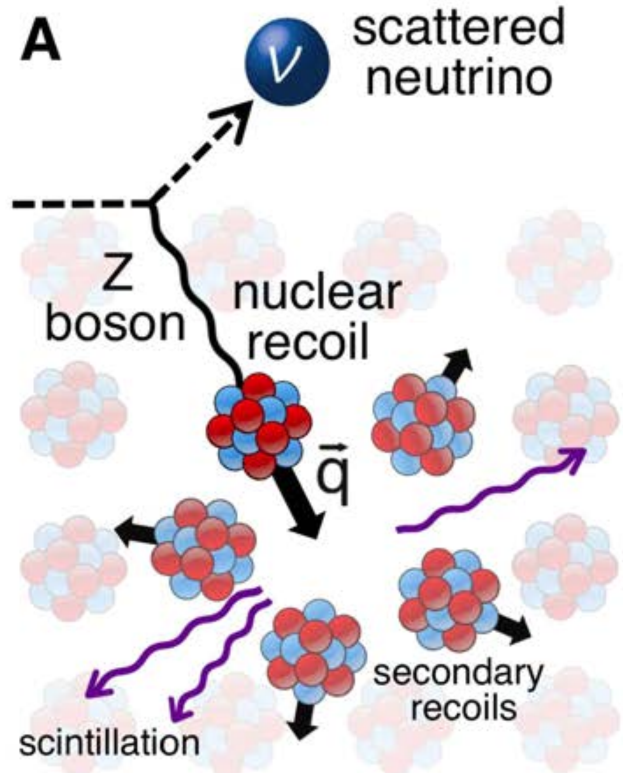
Coloma, Schwetz, 16

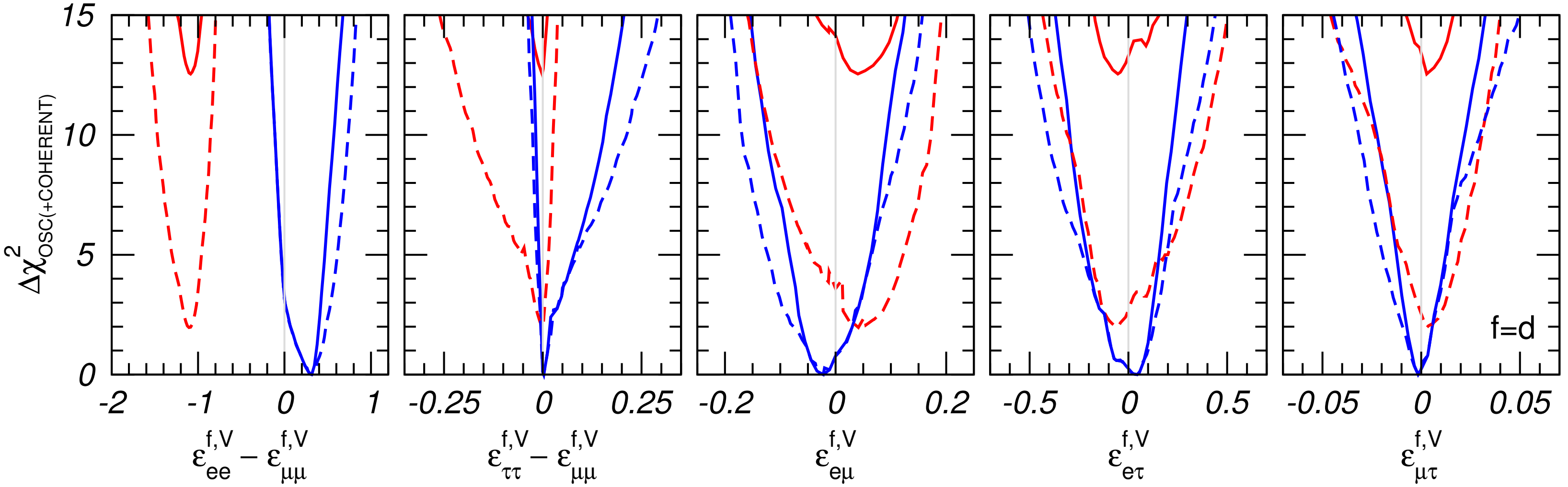
COHERENT results Science 2017 [arXiv:1708.01294]

- observation of coherent neutrino-nucleus scattering at 6.7σ at CsI[Na] detector
- neutrinos from stopped pion source at Oak Ridge NL
- 142 events observed, in agreement with Standard Model



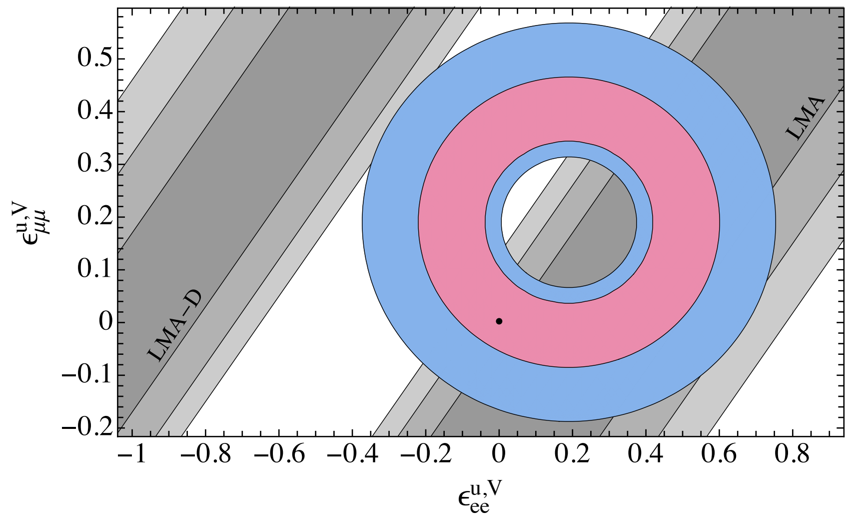
COHERENT results

Science 2017 [arXiv:1708.01294]



- COHERENT data exclude LMA-D degeneracy at more than 3σ

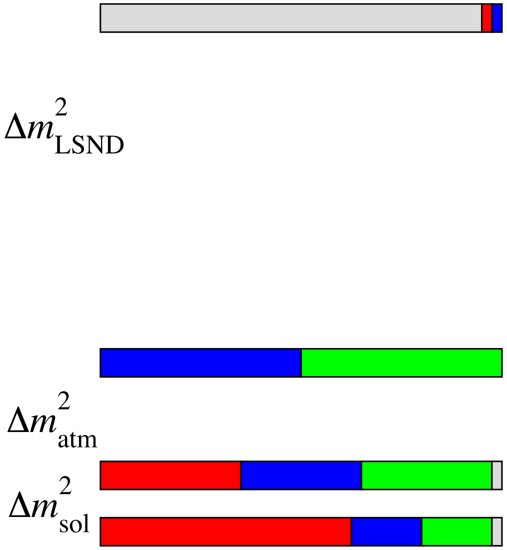
Coloma, Gonzalez-Garcia, Maltoni, Schwetz 1708.02899



Hints for neutrino mass state at eV scale

few hints at ~3σ

- reactor anomaly ($\bar{\nu}_e$ disappearance)
- Gallium anomaly ($\bar{\nu}_e$ disappearance)
- LSND ($\bar{\nu}_\mu \to \bar{\nu}_e$ appearance)
- MiniBooNE
  ($\nu_\mu \to \nu_e, \bar{\nu}_\mu \to \bar{\nu}_e$ appearance)



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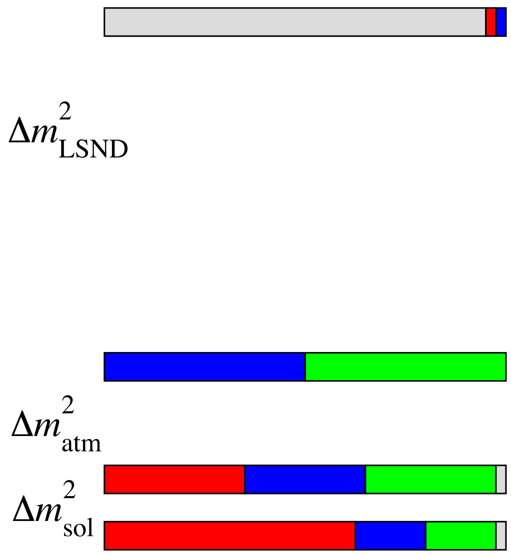
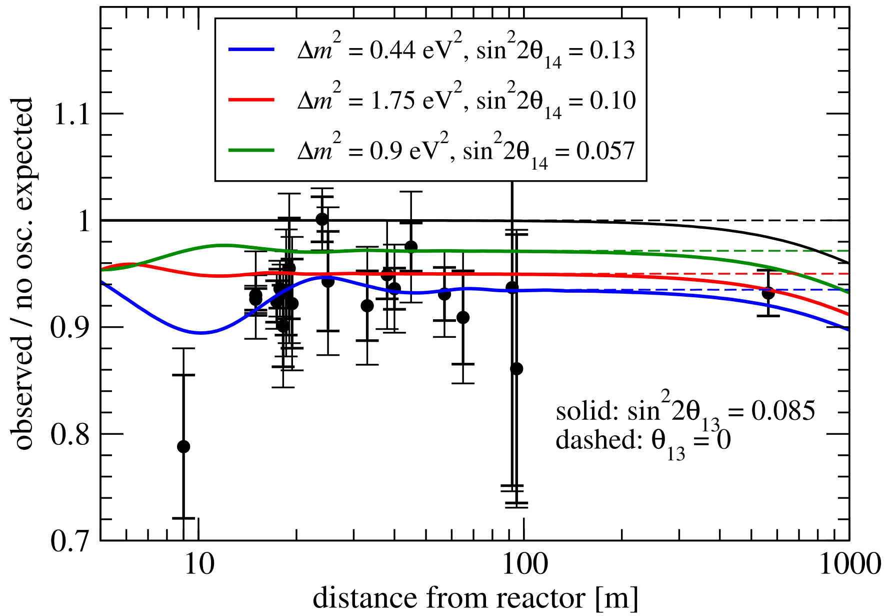


Reactor anomaly

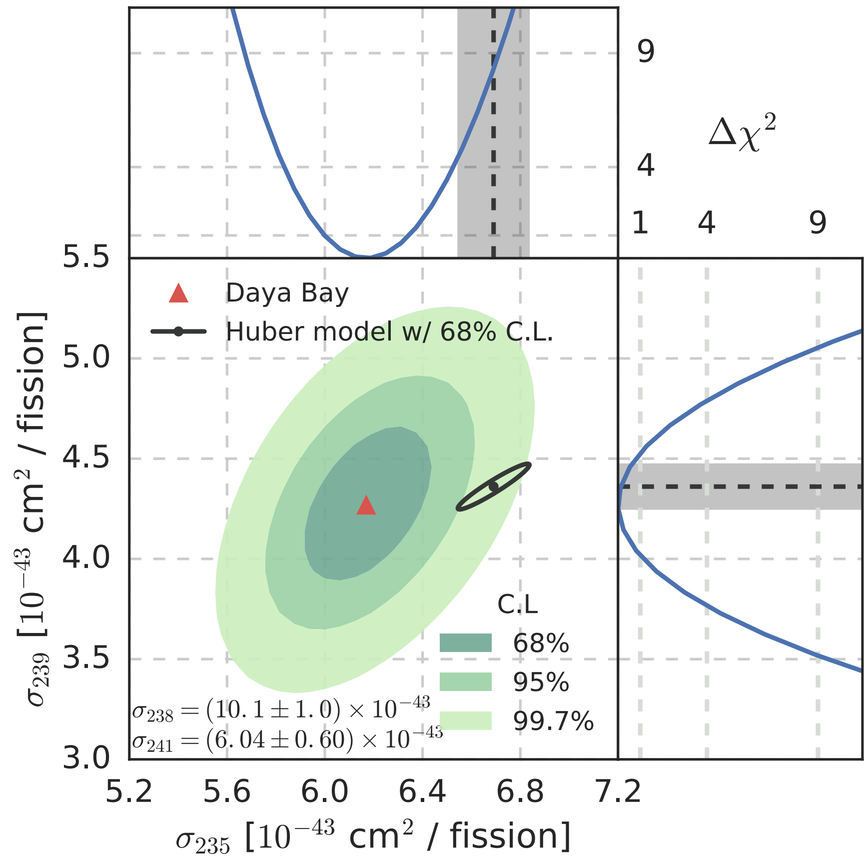


- predicted neutrino fluxes from nuclear reactors are larger than observed Huber 11, Mueller et al 11
- can be explained by oscillations at eV scale
- calculations depend on difficult nuclear physics

Recent developments on reactor anomaly

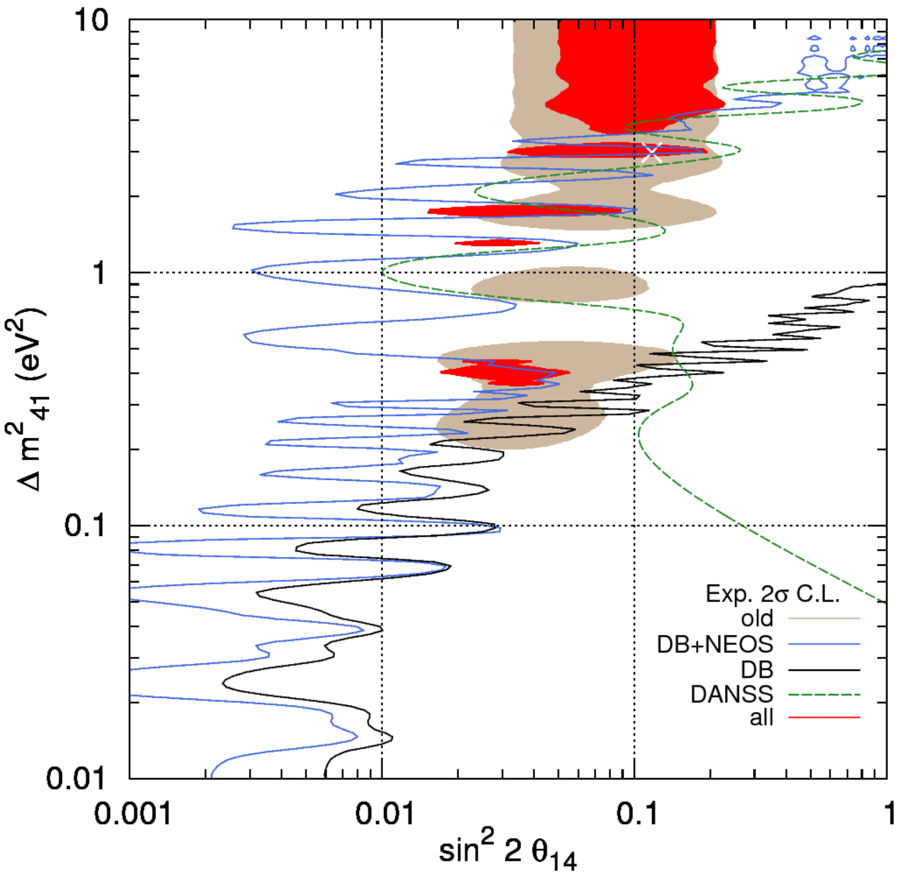
- Daya Bay 17 determines flux of 4 leading isotopes by using time evolution of reactor fuel → ~2.7σ hint for deficit dominated by ^{235}U (disfavours sterile neutrinos)

- But significance of this result goes down in global analysis of reactor data
  Giunti, Ji, Laveder, Li, Littlejohn, 17;
  Dentler, Hernandez, Kopp, Maltoni, Schwetz, in prep



Recent developments on reactor anomaly

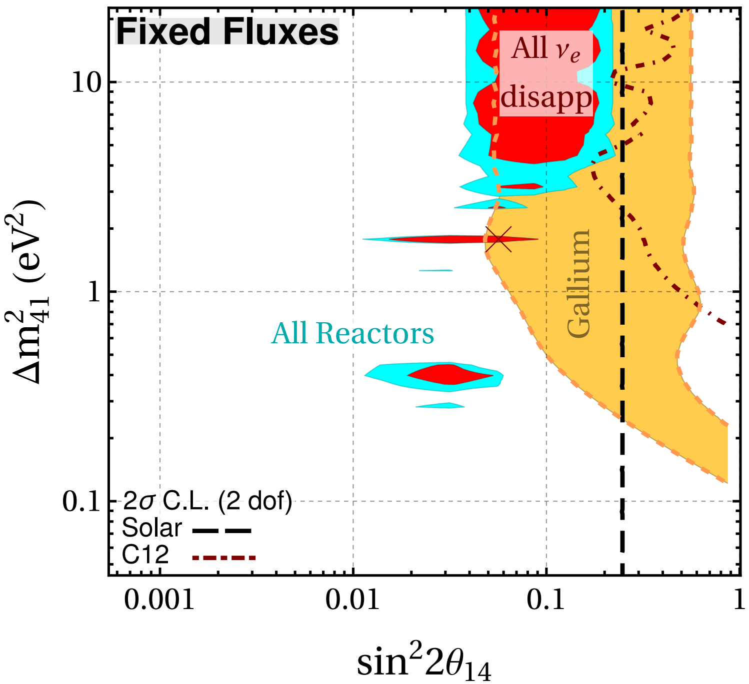
- first results from NEOS and DANSS cut into parameter region
- data show „wiggles“ consistent between NEOS and DANSS and the anomaly



Dentler, Hernandez, Kopp, Maltoni, Schwetz, in prep

Global data on ν_e disappearance

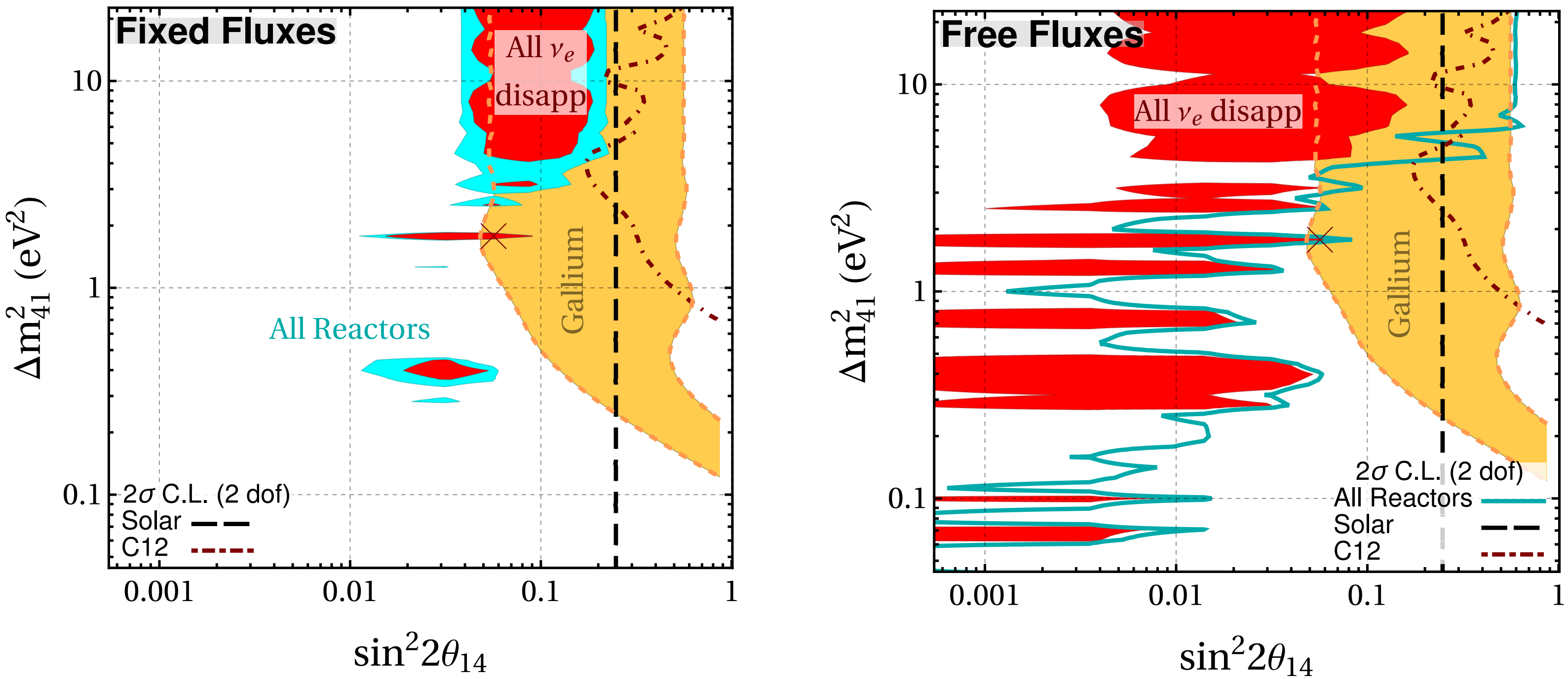
Dentler, Hernandez, Kopp, Maltoni, Schwetz, in prep



- significance at slightly below 3σ

Global data on ν_e disappearance

Dentler, Hernandez, Kopp, Maltoni, Schwetz, in prep



- significance at slightly below 3σ
- even for flux-free analysis hint remains at ~2σ

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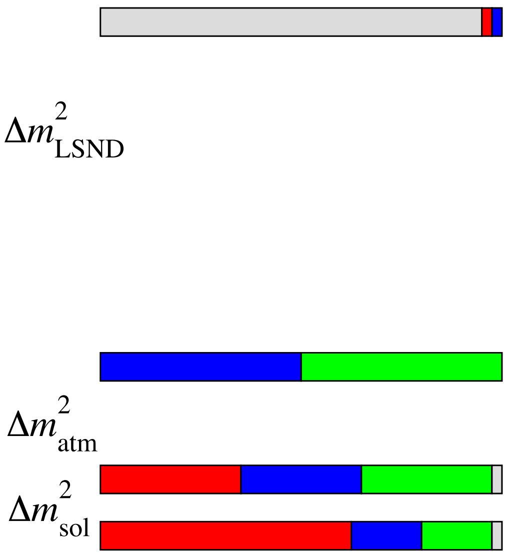

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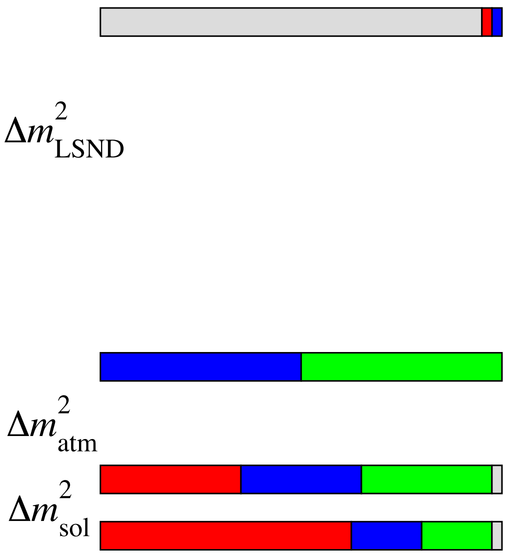
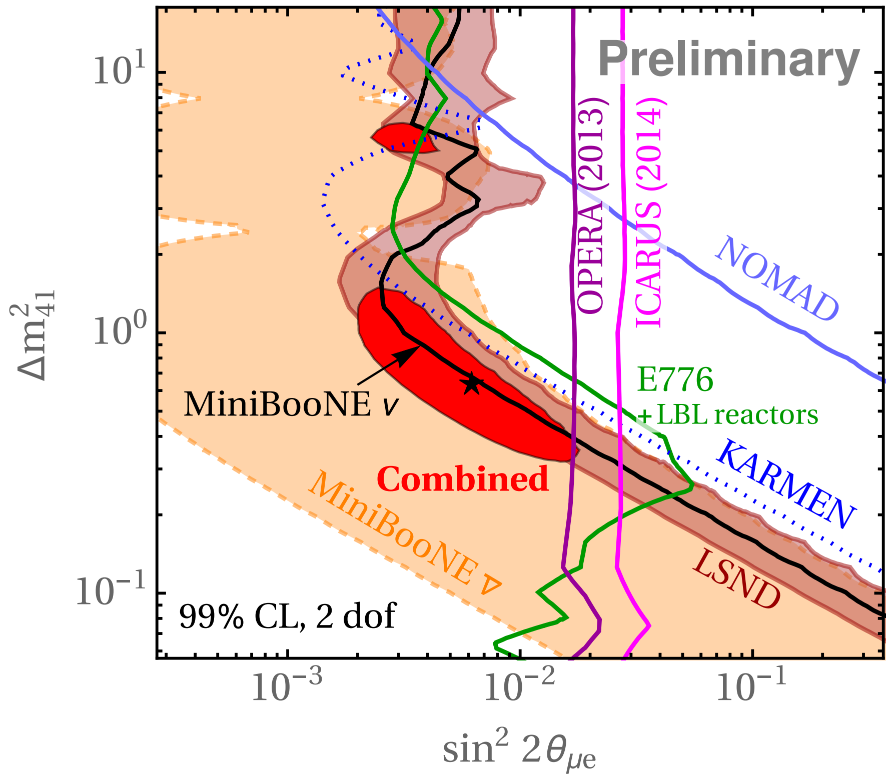


Global data on appearance

- LSND signal at 3.8σ
- MB antineutrino excess (2.8σ) consistent with oscillations
- MB neutrino excess (3.4σ) marginally consistent with osc. (p-value 6.1%)



Dentler, et al, in prep

Fitting all together?

appearance

$$P_{\mu e} = \sin^2 2\theta_{\mu e} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

disappearance ($\alpha = e, \mu$)

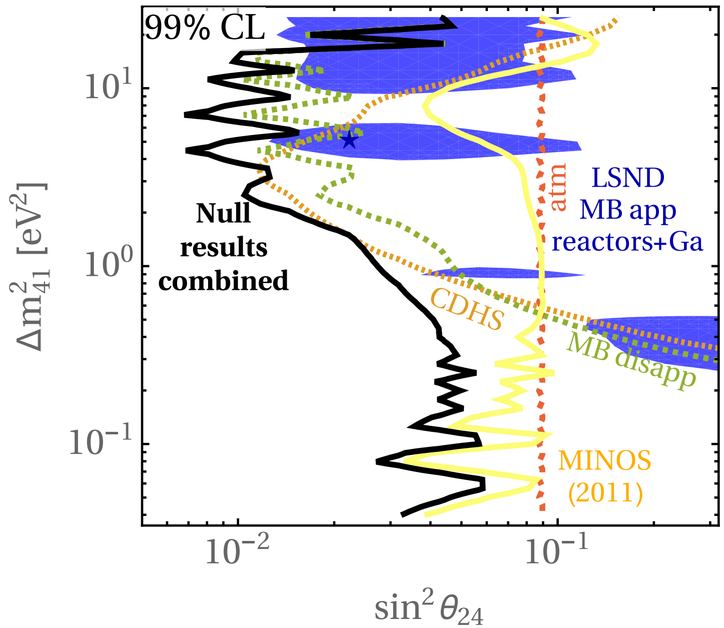
$$P_{\alpha\alpha} = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\alpha\alpha} = 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)$$

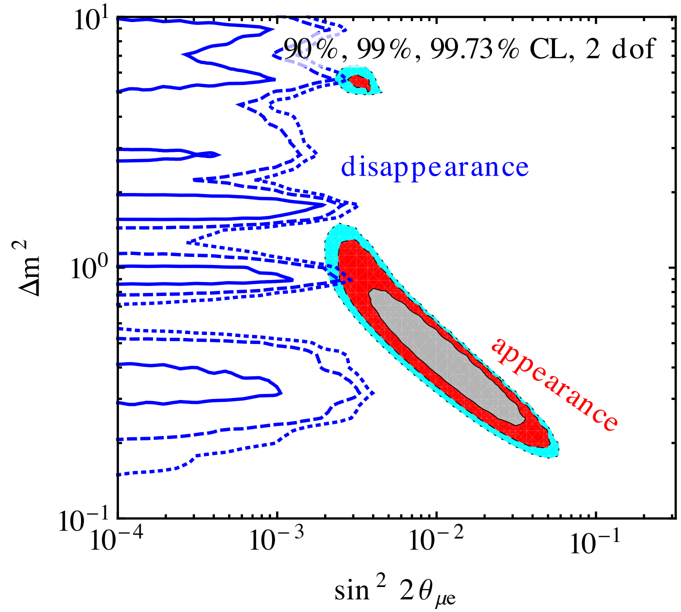
$$\boxed{\sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}}$$

$\nu_\mu \to \nu_e$ app. signal requires also signal in both, ν_e and ν_μ disappearance (appearance mixing angle quadratically suppressed)

Fitting all together?

non-observation of ν_μ disappearance leads to tension between appearance and disappearance data



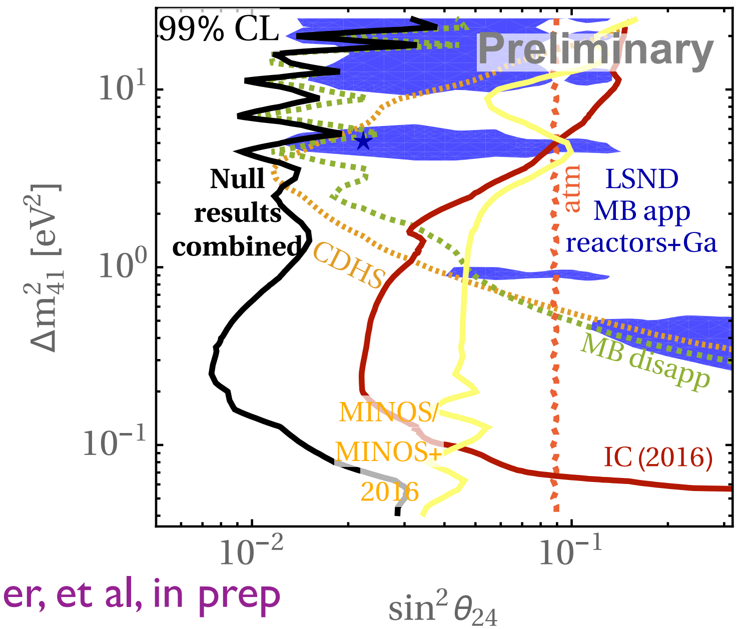


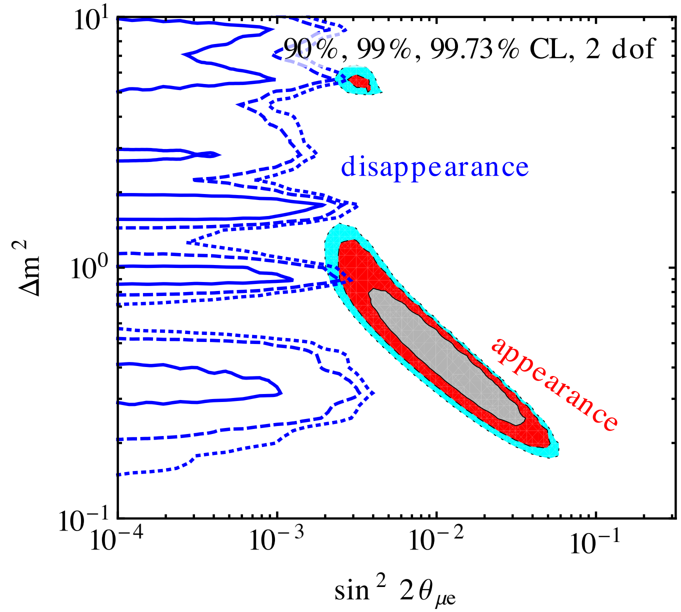
consistency of appearance vs disappearance $\chi^2_{\rm PG} = 18/2,\ P \approx 10^{-4}$

Kopp, Machado, Maltoni, Schwetz, 1303.3011

Fitting all together?

non-observation of ν_μ disappearance leads to tension between appearance and disappearance data





Dentler, et al, in prep

consistency of appearance vs disappearance $\chi^2_{\rm PG} = 18/2,\ P \approx 10^{-4}$

tension is expected to become even more severe

Cosmology

3+1 SBL osc

PLANCK coll., 1502.01589

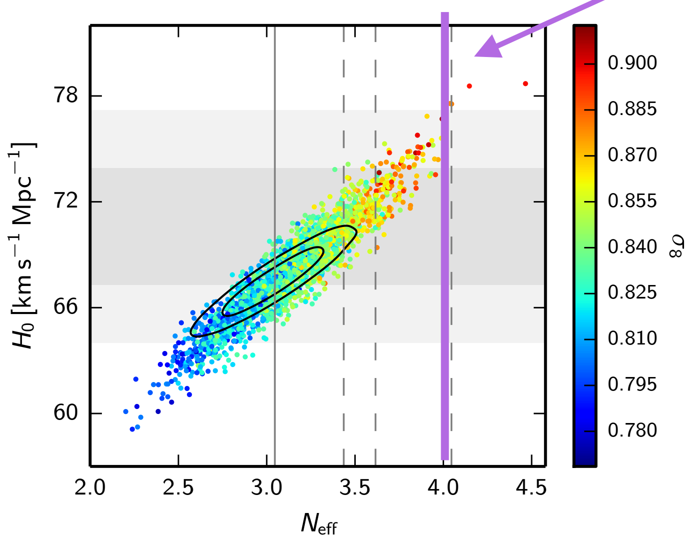


Fig. 31. Samples from *Planck* TT+lowP chains in the $N_{\rm eff}$–H_0 plane, colour-coded by σ_8. The grey bands show the constraint $H_0 = (70.6 \pm 3.3)$ km s^{-1}Mpc^{-1} of Eq. (30). Note that higher $N_{\rm eff}$ brings H_0 into better consistency with direct measurements, but increases σ_8. Solid black contours show the constraints from *Planck* TT,TE,EE+lowP+BAO. Models with $N_{\rm eff} < 3.046$ (left

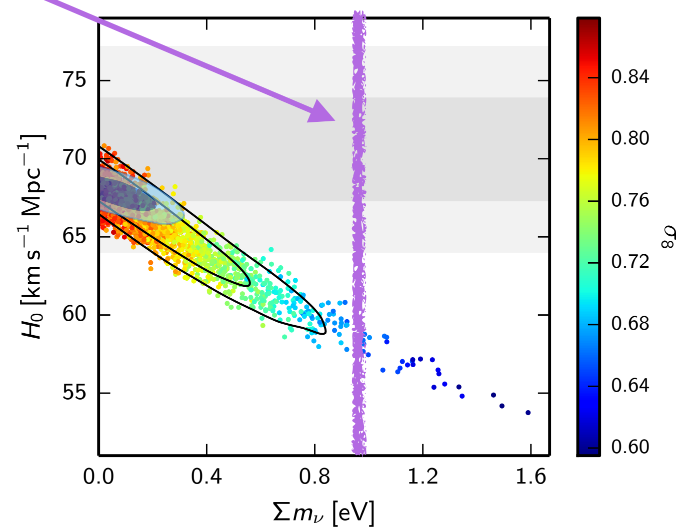


Fig. 29. Samples from the *Planck* TT+lowP posterior in the $\sum m_\nu$–H_0 plane, colour-coded by σ_8. Higher $\sum m_\nu$ damps the matter fluctuation amplitude σ_8, but also decreases H_0 (grey bands show the direct measurement $H_0 = (70.6 \pm 3.3)$ km s^{-1}Mpc^{-1}, Eq. 30). Solid black contours show the constraint from *Planck* TT+lowP+lensing (which mildly prefers larger masses), and filled contours show the constraints from *Planck* TT+lowP+lensing+BAO.

$$N_{\rm eff} = 3.04 \pm 0.18\,(68\%\ {\rm CL})$$

Planck TT,TE,EE+lowP+BAO

$$\sum m_\nu < 0.23\,{\rm eV}\,(95\%\ {\rm CL})$$

Planck+BAO+H_0+...

Cosmology

3+1 SBL osc

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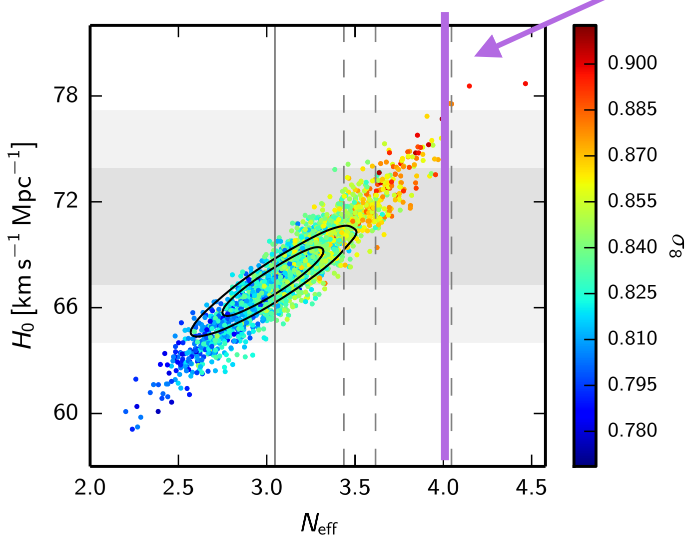

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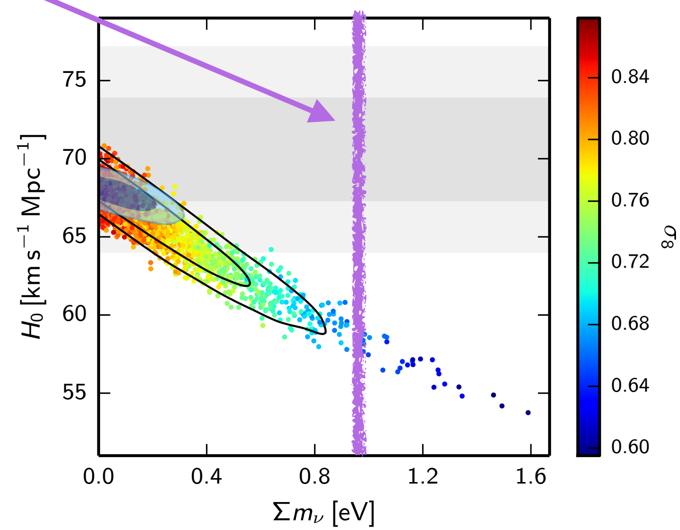

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need to invoke mechanism to prevent equilibration of sterile neutrino (e.g., large L-asymmetry, large interactions in the dark sector)

$$N_{\rm eff} = 3.04 \pm 0.18\,(68\%\ {\rm CL})$$

Planck TT,TE,EE+lowP+BAO

$$\sum m_\nu < 0.23\,{\rm eV}\,(95\%\ {\rm CL})$$

Planck+BAO+H_0+...

Summary

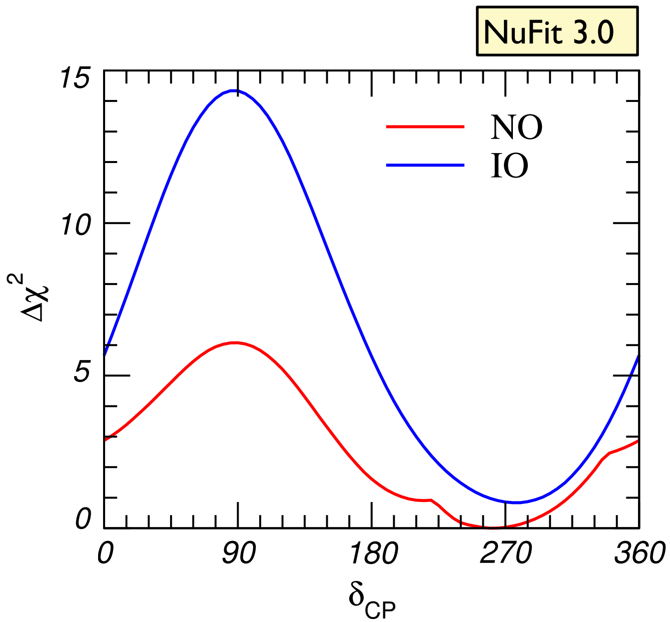
- 3-flavour properties:
  CP phase: values of $\pi < \delta < 2\pi$ preferred over $0 < \delta < \pi$
  CP conservation excluded at 2σ CL
  hints for normal mass ordering emerging (not yet significant)

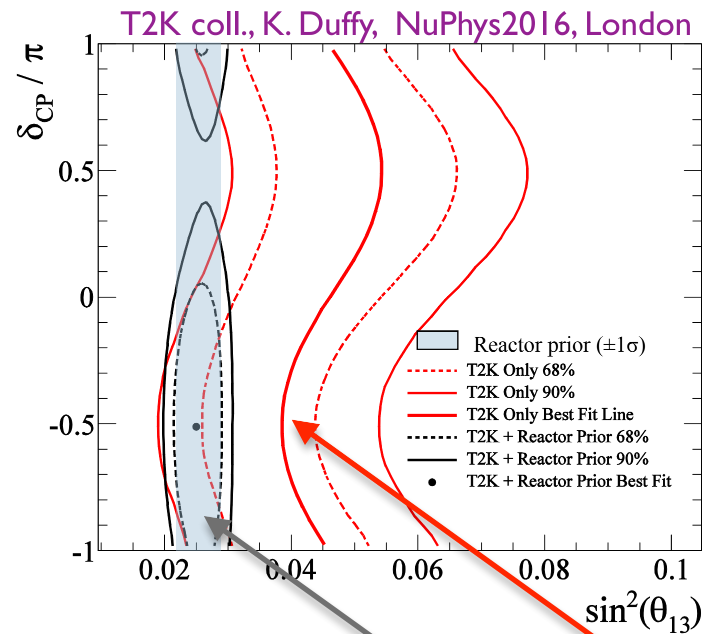
- non-standard interactions:
  COHERENT result excludes LMA-dark degeneracy
  limits at few % level (few exceptions depending on flavour)

- eV scale sterile neutrinos:
  reactor anomaly still around — progress expected soon
  sterile neutrino explanation of LSND keeps getting worse

supplementary slides

CP phase — 2016 data



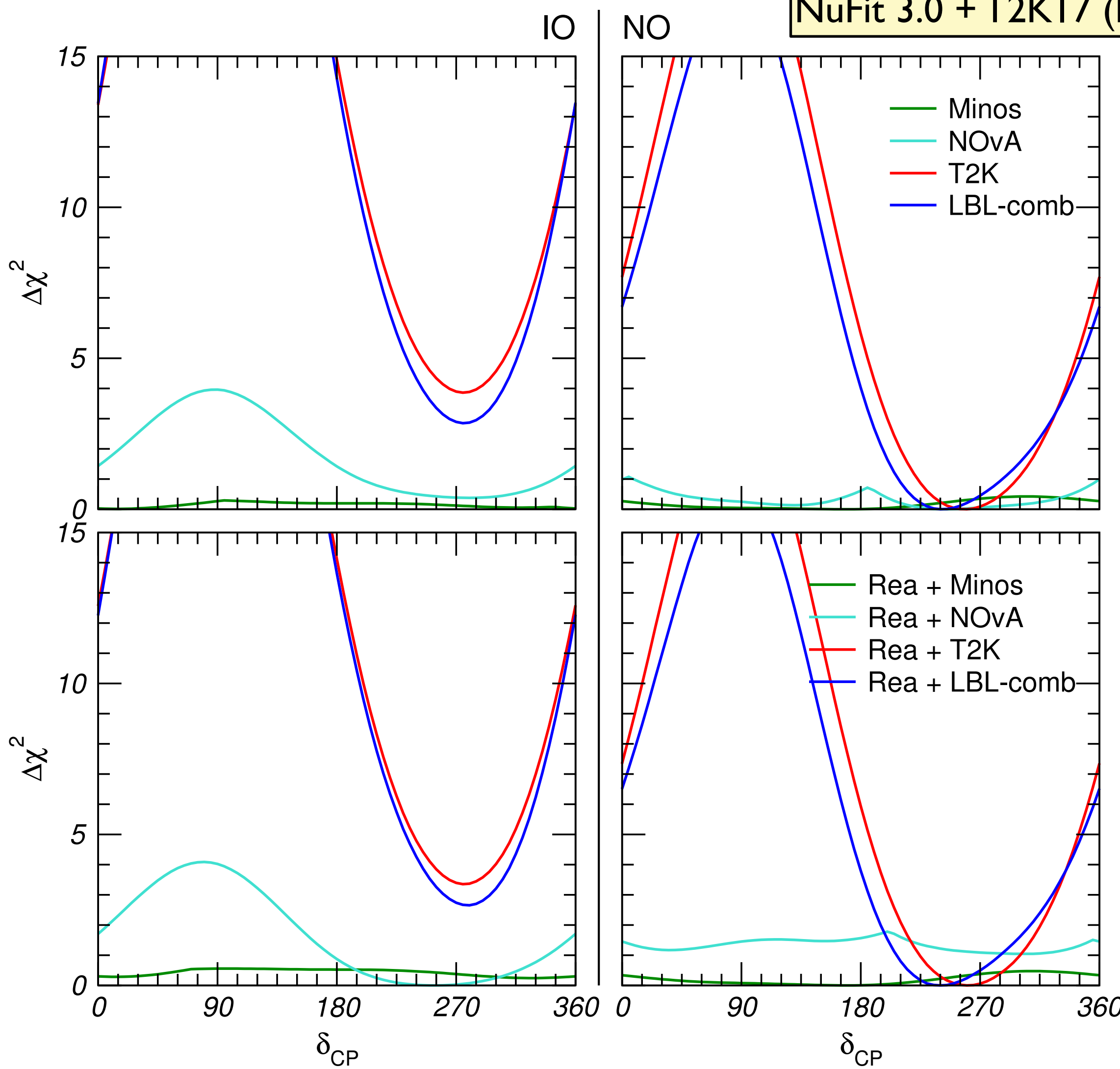


complementarity of reactor and accelerator

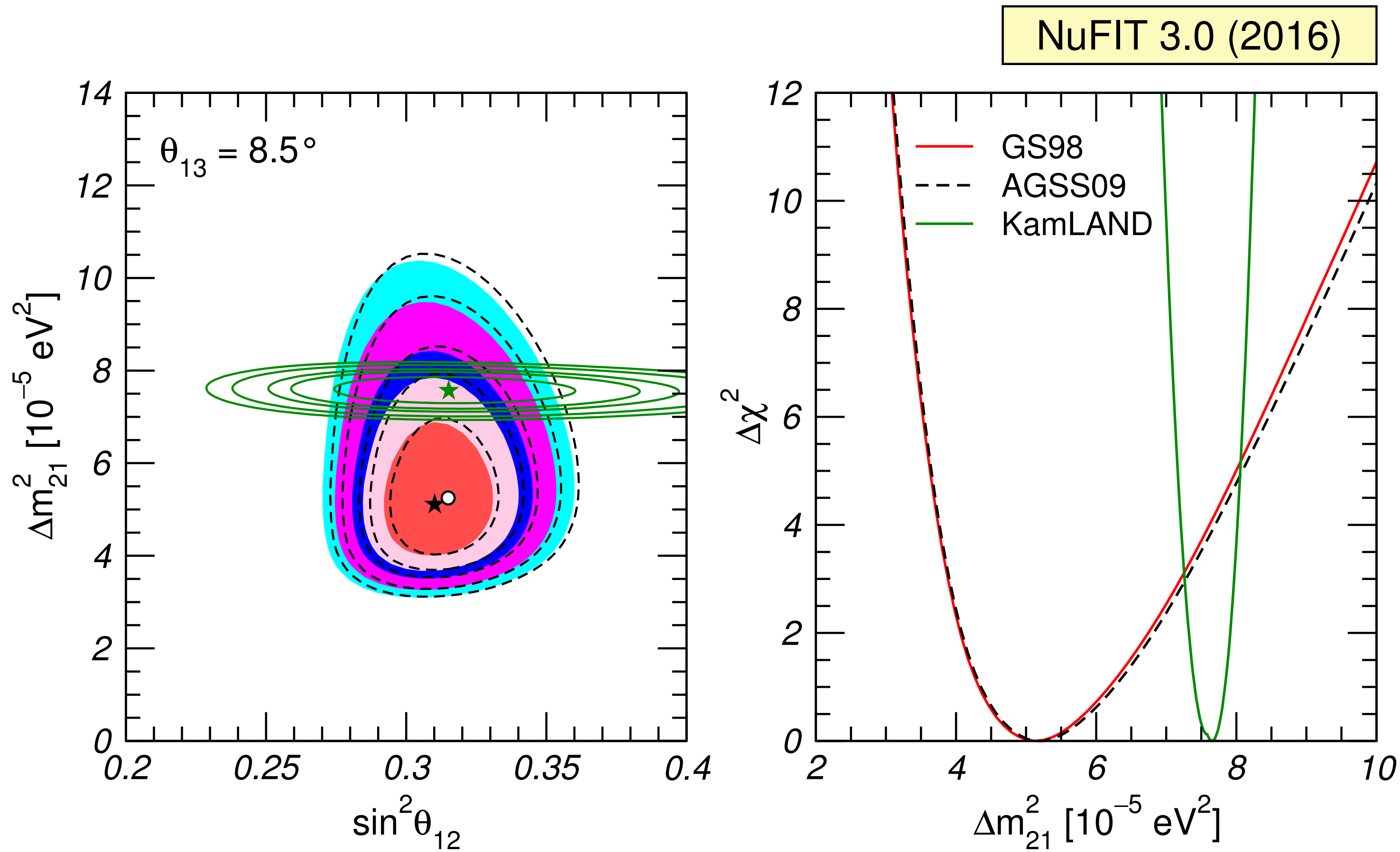
- best fit at $\delta_{CP} \approx 270°$
- correlations with θ_{23}
- CP conservation allowed at 70% CL (NO), 97% CL (IO)
- $\delta_{CP} \approx 90°$ disfavoured with $\Delta\chi^2 \approx 6$ (14) for NO (IO)

CP - MO contributions

NuFit 3.0 + T2K17 (PRELIMINARY)

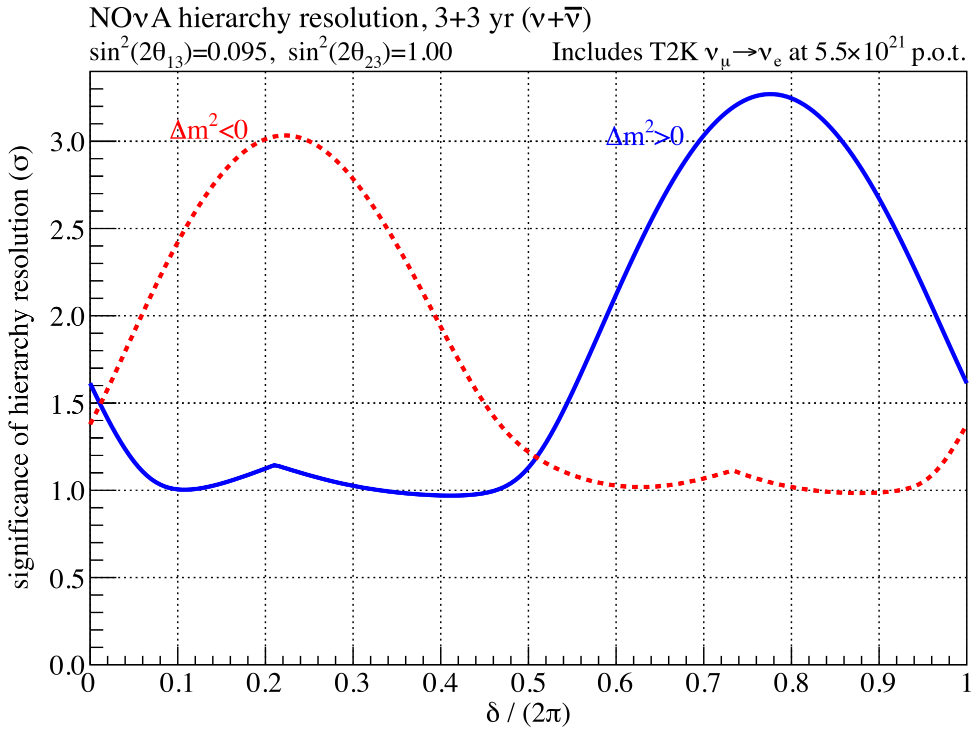


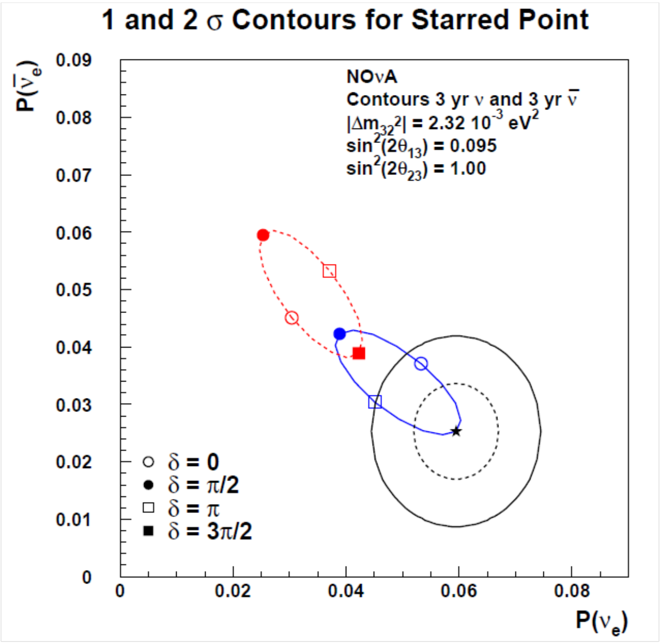
Minor tension between solar neutrinos and KamLAND



MO sensitivity of existing experiments

- strong dependence on true ordering and δ_{CP}
- 3σ possible for the most favourable combinations





http://www-nova.fnal.gov/plots_and_figures/plots_and_figures.html

MO - compilation of upcoming experiments

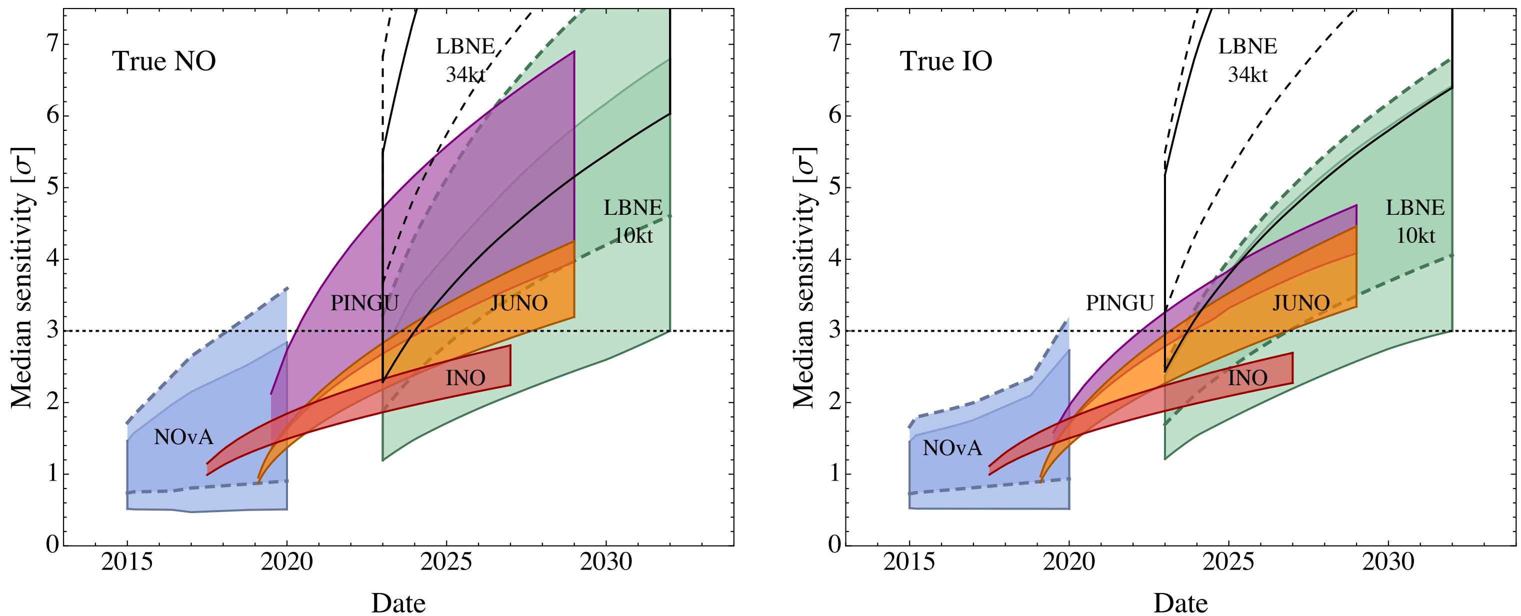


FIG. 12: The left (right) panel shows the median sensitivity in number of sigmas for rejecting the IO (NO) if the NO (IO) is true for different facilities as a function of the date. The width of the bands correspond to different true values of the CP phase δ for NOνA and LBNE, different true values of θ_{23} between 40° and 50° for INO and PINGU, and energy resolution between $3\%\sqrt{1\ \text{MeV}/E}$ and $3.5\%\sqrt{1\ \text{MeV}/E}$ for JUNO. For the long baseline experiments, the bands with solid (dashed) contours correspond to a true value for θ_{23} of 40° (50°). In all cases, octant degeneracies are fully searched for.

[not shown: ORCA and HyperK (atm)]

Blennow, Coloma, Huber, TS, 1311.1822