Karlsruhe Institute of Technology

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

The fate of hints: recent developments in neutrino physics

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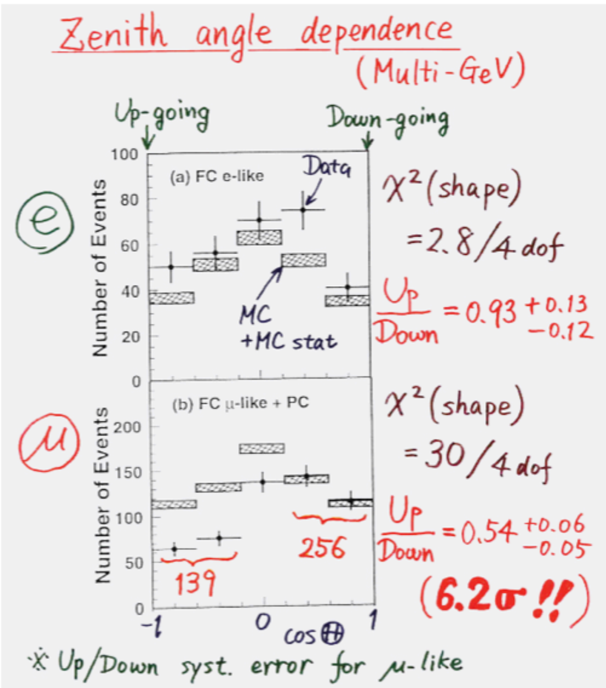
IFT Christmas workshop
Instituto de Física Teórica UAM/CSIC
16-18 Dec 2020

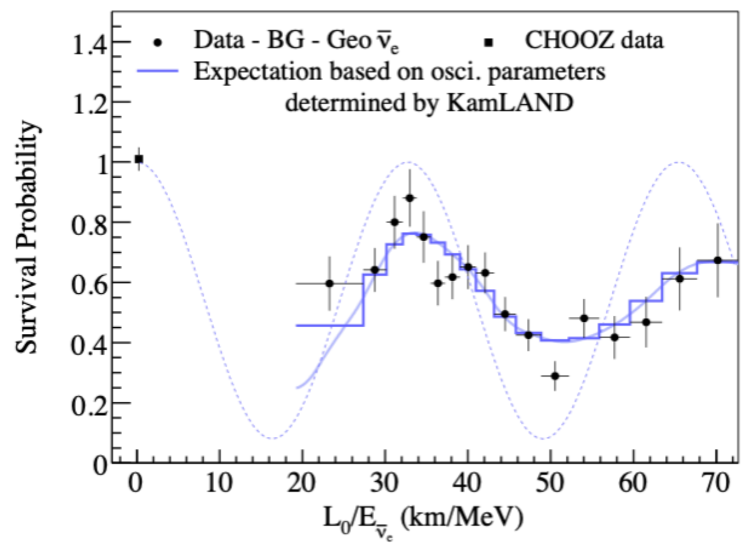
Neutrinos oscillate…

…and therefore have mass!

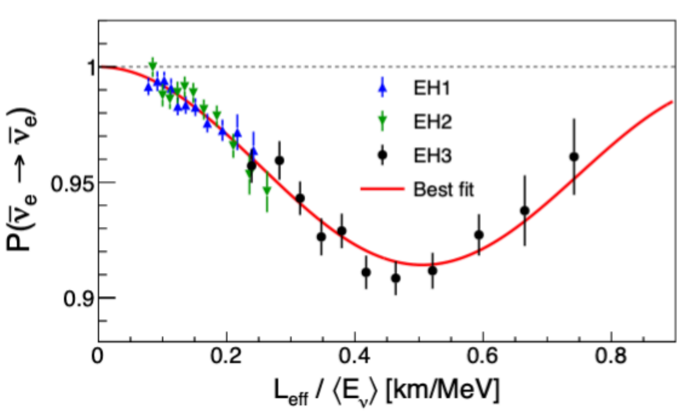
SuperK 1998 atmospheric neutrinos



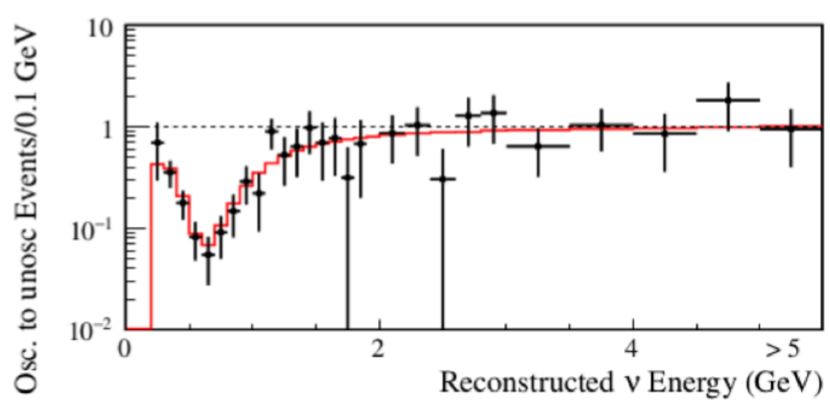
KamLAND 2006
reactor neutrinos ~ 180 km

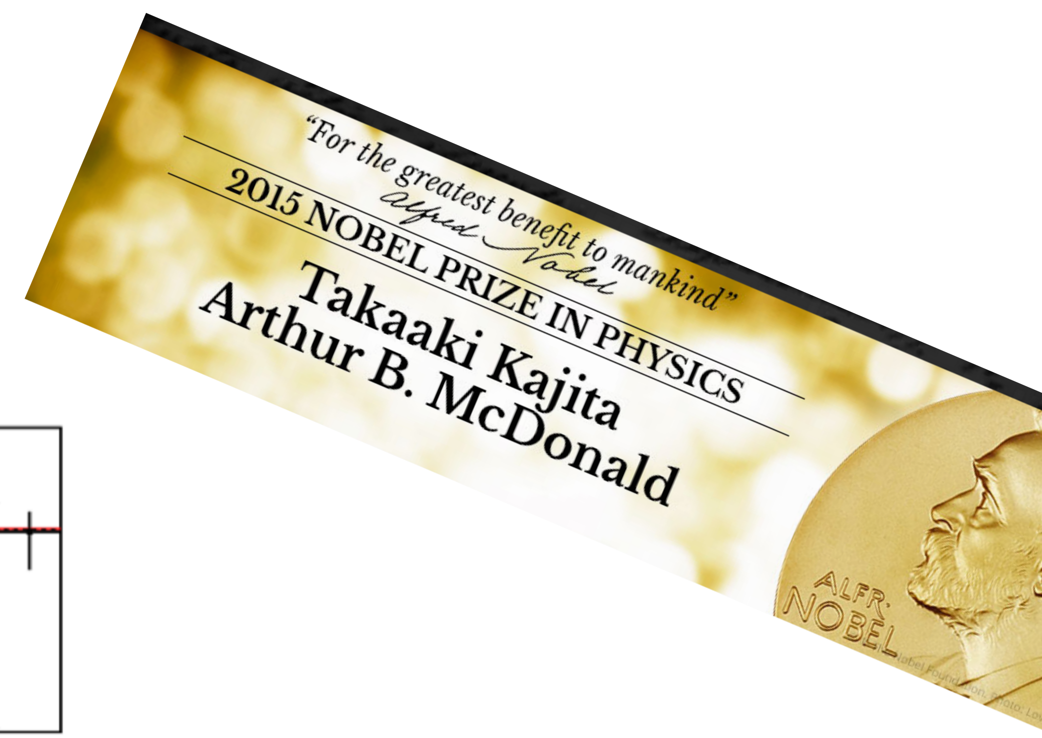


DayaBay, 2015
$\bar{\nu}_e \to \bar{\nu}_e$, $\langle L \rangle \sim 2$ km



T2K, 2015
$\nu_\mu \to \nu_\mu$, $\langle L \rangle \sim 295$ km





In the Standard Model neutrinos are massless

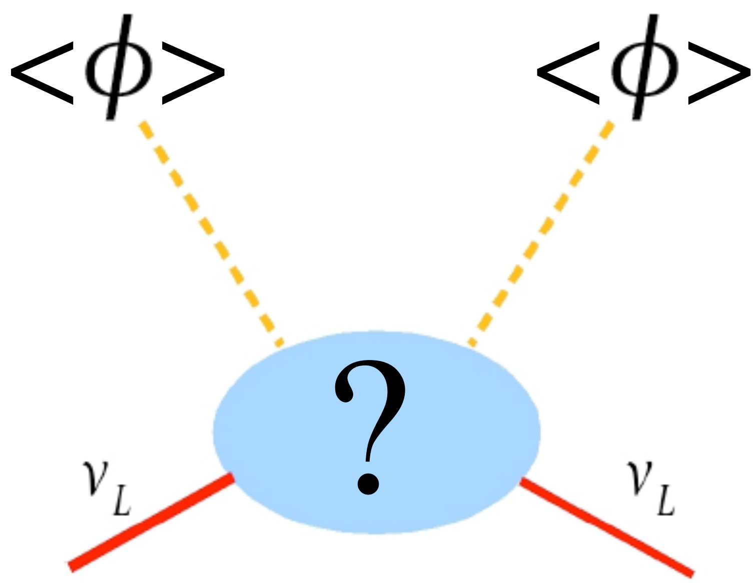
- absence of right-handed neutrinos
  no Dirac mass for neutrinos
- lepton-number is an accidental symmetry at the renormalizable level
  given SM fields and gauge symmetry, lepton number cannot be violated at dim. 4 → no Majorana mass can be generated

⇒ neutrino mass implies physics beyond the SM

Origin of neutrino mass?

Weinberg 1979: there is only one dim-5 operator consistent with the gauge symmetry of the SM, and this operator will lead to a Majorana mass term for neutrinos after EWSB:

$$Y^2 \frac{\overline{L^c}\tilde{\phi}^* \, \tilde{\phi}^\dagger L}{\Lambda} \quad \longrightarrow \quad m_\nu \sim Y^2 \frac{\langle \phi \rangle^2}{\Lambda}$$

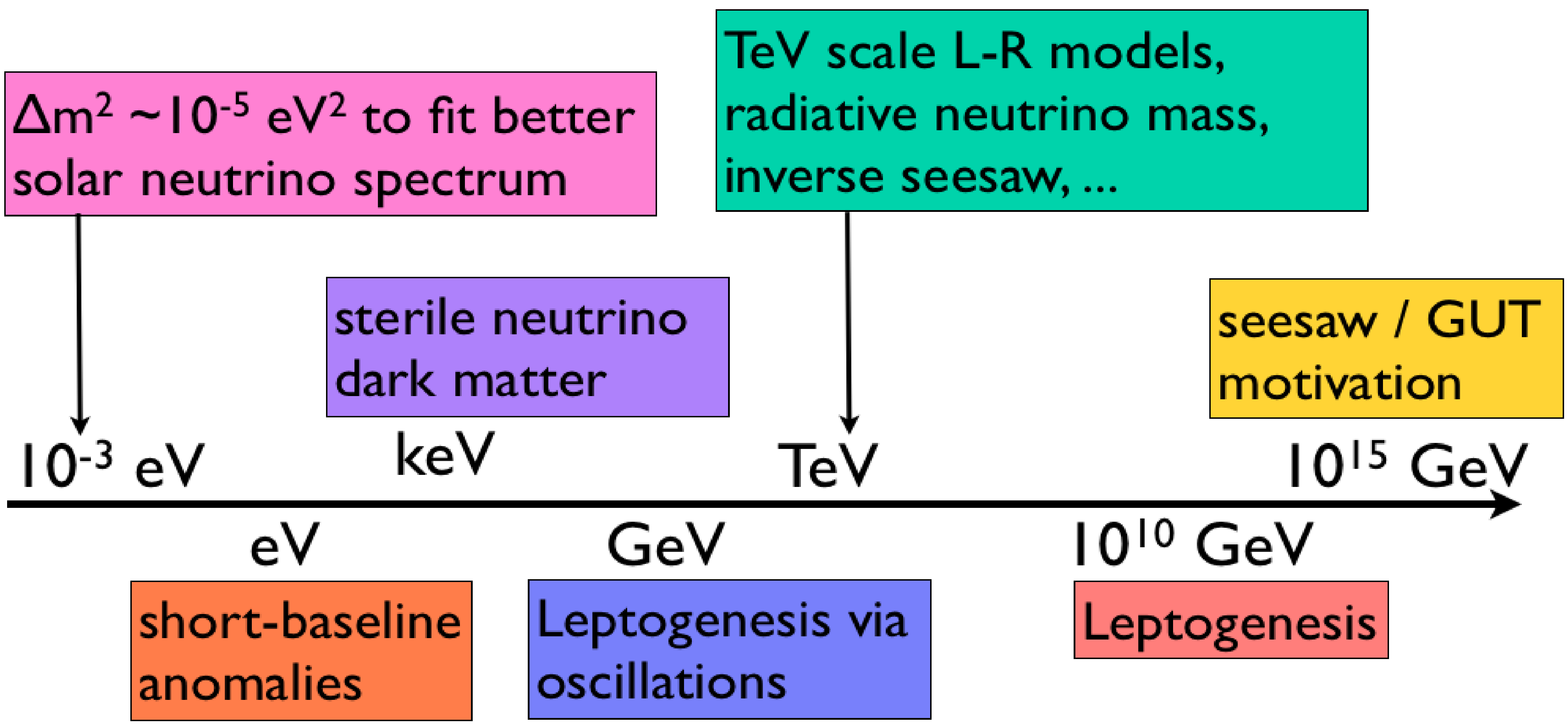


- predicts violation of Lepton number by 2 units (Majorana mass!)
- what is the new physics responsible for that operator?
- what is the energy scale of the new physics?

What is the energy scale of new physics responsible for neutrino mass?

$$m_\nu \sim Y^2 \frac{\langle \phi \rangle^2}{\Lambda} \approx Y^2 \frac{(178\,\mathrm{GeV})^2}{\Lambda}$$

can obtain small neutrino masses by making Λ very large or Y very small (or both)



Outline for the rest of the talk

take a phenomenological approach

- Determination of 3-flavour oscillation parameters
  - Fate of hints for CP violation and mass ordering
- Absolute neutrino mass and searches for lepton number violation
- Fate of hints for exotic neutrino properties
  - Non-standard neutrino interactions
  - sterile neutrinos

3-flavour neutrino parameters

- 3 masses: Δm^2_{21}, Δm^2_{31}, m_0
- 3 mixing angles: $\theta_{12}, \theta_{13}, \theta_{23}$
- 3 phases: 1 Dirac (δ), 2 Majorana (α_1, α_2)

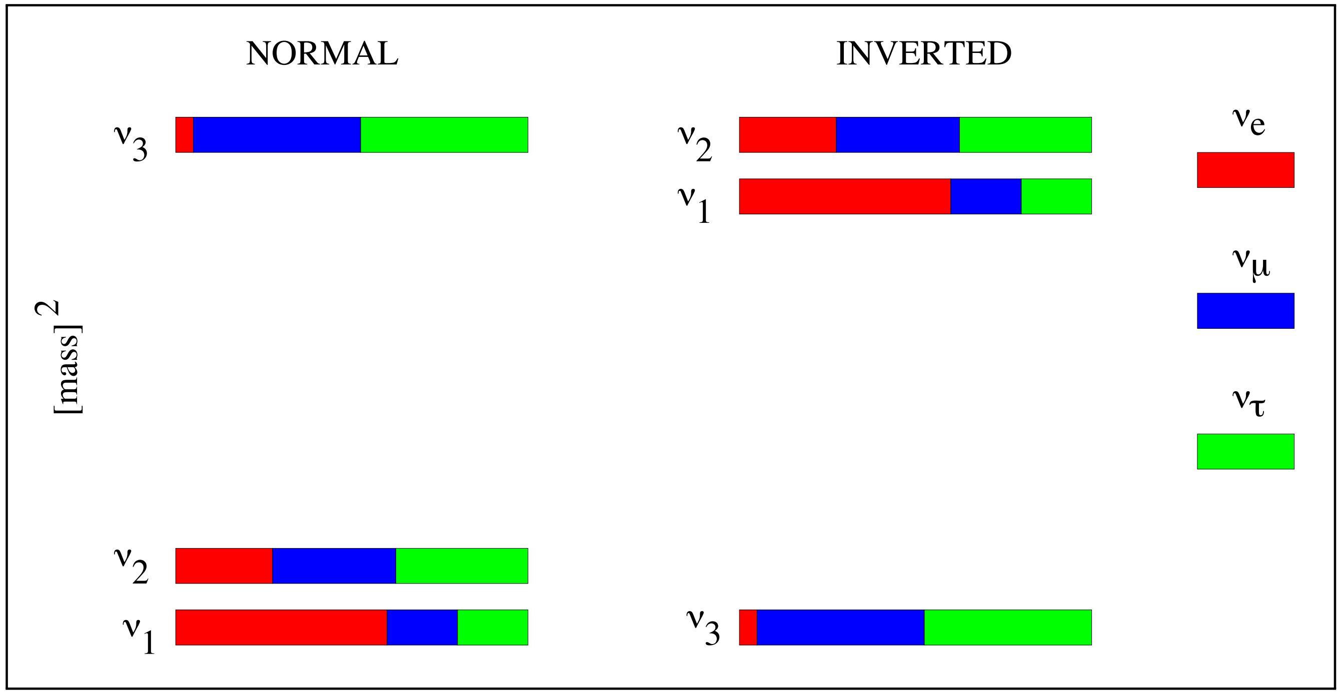
neutrino oscillations
absolute mass observables
lepton-number violation

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atm+LBL(dis)}}^{\Delta m^2_{31}} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix}}_{\text{react+LBL(app)}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar+KamLAND}}^{\Delta m^2_{21}}$$

3-flavour effects are suppressed: $\Delta m^2_{21} \ll \Delta m^2_{31}$ and $\theta_{13} \ll 1$ $(U_{e3} = s_{13} e^{-i\delta})$

$\Rightarrow$ dominant oscillations are well described by effective two-flavour oscillations
$\Rightarrow$ present data is already sensitive to sub-leading effects

The rough picture



- the two mass-squared differences are separated roughly by a factor 30:

$$\Delta m^2_{21} \approx 7 \times 10^{-5} \mathrm{eV}^2 \,, \quad |\Delta m^2_{31}| \approx |\Delta m^2_{32}| \approx 2.4 \times 10^{-3} \mathrm{eV}^2$$

- at least two neutrinos are massive — two possible orderings
- mixing angles are large

$\sin\theta_{13} = \lvert U_{e3}\rvert$	$(\nu_e$ component in $\nu_3) = (\nu_3$ component in $\nu_e)$	$\theta_{13} \approx 9^\circ$
$\tan\theta_{12} = \frac{\lvert U_{e2}\rvert}{\lvert U_{e1}\rvert}$	ratio of ν_2 and ν_1 component in ν_e	$\theta_{12} \approx 33^\circ$
$\tan\theta_{23} = \frac{\lvert U_{\mu 3}\rvert}{\lvert U_{\tau 3}\rvert}$	ratio of ν_μ and ν_τ component in ν_3	$\theta_{23} \approx 45^\circ$

Complementarity of global oscillation data

param	experiment	comment
θ_{12}	SNO, SuperK, (KamLAND)	resonant matter effect in the Sun
θ_{23}	SuperK, T2K, NOvA	ν_μ disappearance atmospheric (accelerator) neutrinos
θ_{13}	DayaBay, RENO, D-Chooz (T2K, NOvA)	$\bar{\nu}_e$ disappearance reactor experiments @ ~ 1 km
Δm^2_{21}	KamLAND, (SNO, SuperK)	$\bar{\nu}_e$ disappearance reactor @ ~ 180 km (spectrum)
$\|\Delta m^2_{31}\|$	MINOS, T2K, NOvA, DayaBay	ν_μ and $\bar{\nu}_e$ disapp (spectrum)
δ	T2K, NOvA + DayaBay	combination of $(\nu_\mu \to \nu_e) + \bar{\nu}_e$ disap

⇒ **global analysis** (especially sub-leading 3-flavour effects)

NuFit collaboration: www.nu-fit.org with M.C. Gonzalez-Garcia, M. Maltoni, et al.
NuFIT 5.0: Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, 2007.14792

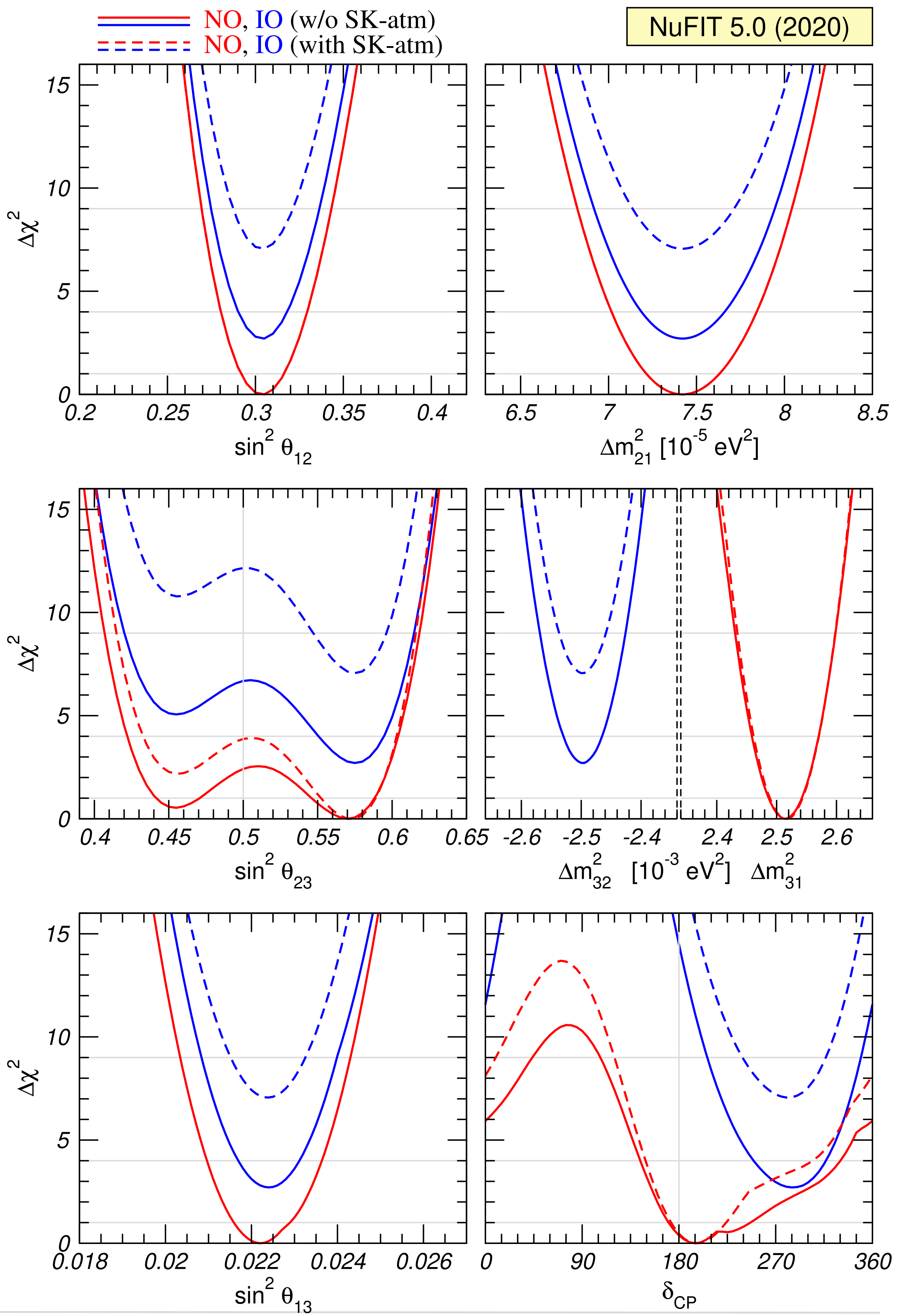
compatible results from Bari (Lisi et al.) and Valencia (Tortola et al.) groups

NuFit 5.0 results

www.nu-fit.org

NuFIT 5.0 (2020)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.7$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.78}_{-0.75}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.570^{+0.018}_{-0.024}$	$0.407 \to 0.618$	$0.575^{+0.017}_{-0.021}$	$0.411 \to 0.621$
	$\theta_{23}/^\circ$	$49.0^{+1.1}_{-1.4}$	$39.6 \to 51.8$	$49.3^{+1.0}_{-1.2}$	$39.9 \to 52.0$
	$\sin^2\theta_{13}$	$0.02221^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02240^{+0.00062}_{-0.00062}$	$0.02053 \to 0.02436$
	$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.61^{+0.12}_{-0.12}$	$8.24 \to 8.98$
	$\delta_{\rm CP}/^\circ$	195^{+51}_{-25}	$107 \to 403$	286^{+27}_{-32}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \rm eV^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \rm eV^2}$	$+2.514^{+0.028}_{-0.027}$	$+2.431 \to +2.598$	$-2.497^{+0.028}_{-0.028}$	$-2.583 \to -2.412$
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
	$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
	$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
	$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
	$\delta_{\rm CP}/^\circ$	197^{+27}_{-24}	$120 \to 369$	282^{+26}_{-30}	$193 \to 352$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \rm eV^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \rm eV^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

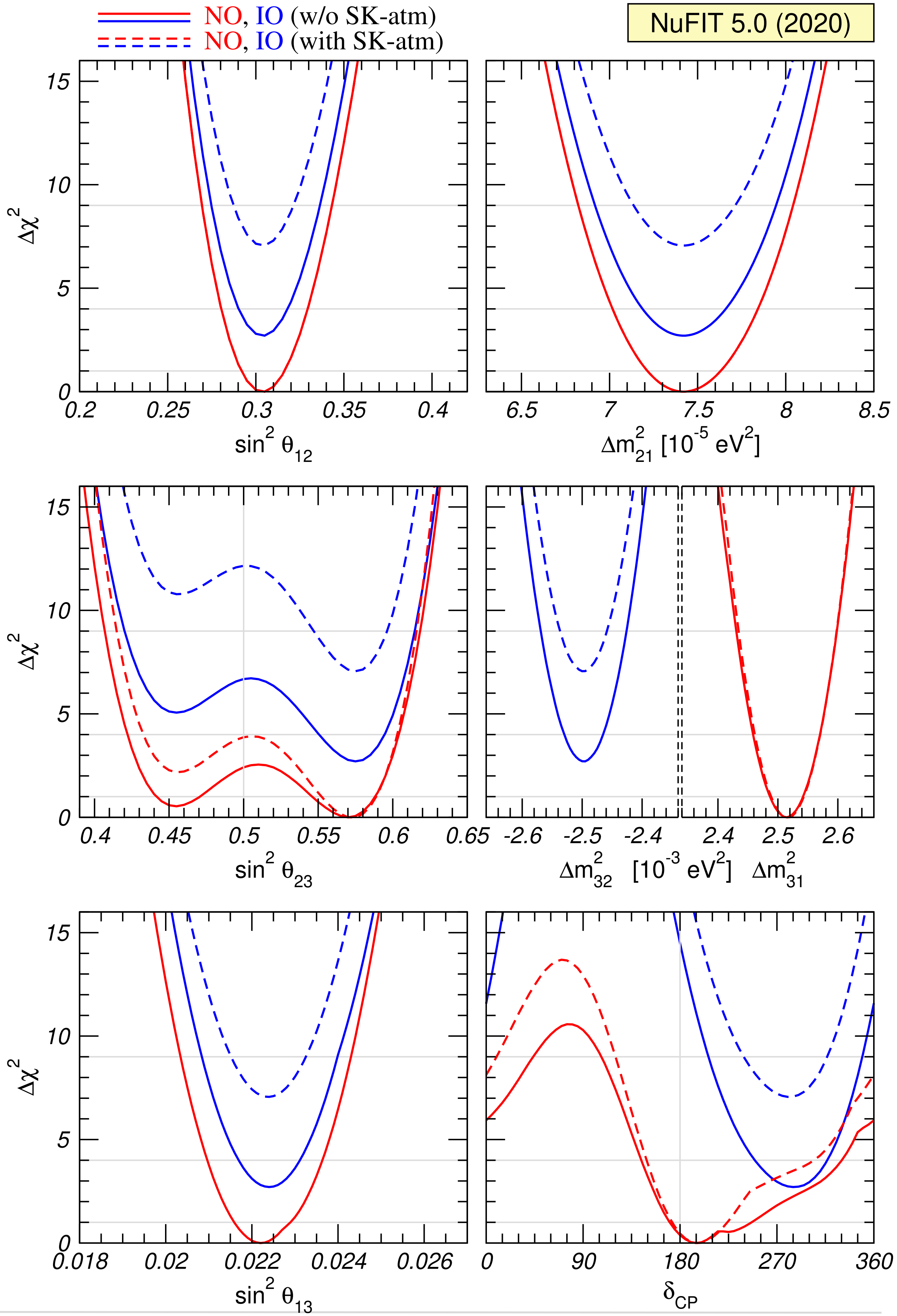


NuFit 5.0 results

- robust determination (relat. precision at 3σ):

$$\theta_{12}\,(14\%)\,,\quad \theta_{13}\,(9\%)$$
$$\Delta m^2_{21}\,(16\%)\,,\quad |\Delta m^2_{3\ell}|\,(6.7\%)$$

- broad allowed range for $\theta_{23}\,(27\%)$, non-significant indications for non-maximality/octant
- ambiguity in sign of $\Delta m^2_{3\ell}$ $\rightarrow$ mass ordering
- values of $\delta_{\rm CP} \simeq 90^\circ$ disfavoured



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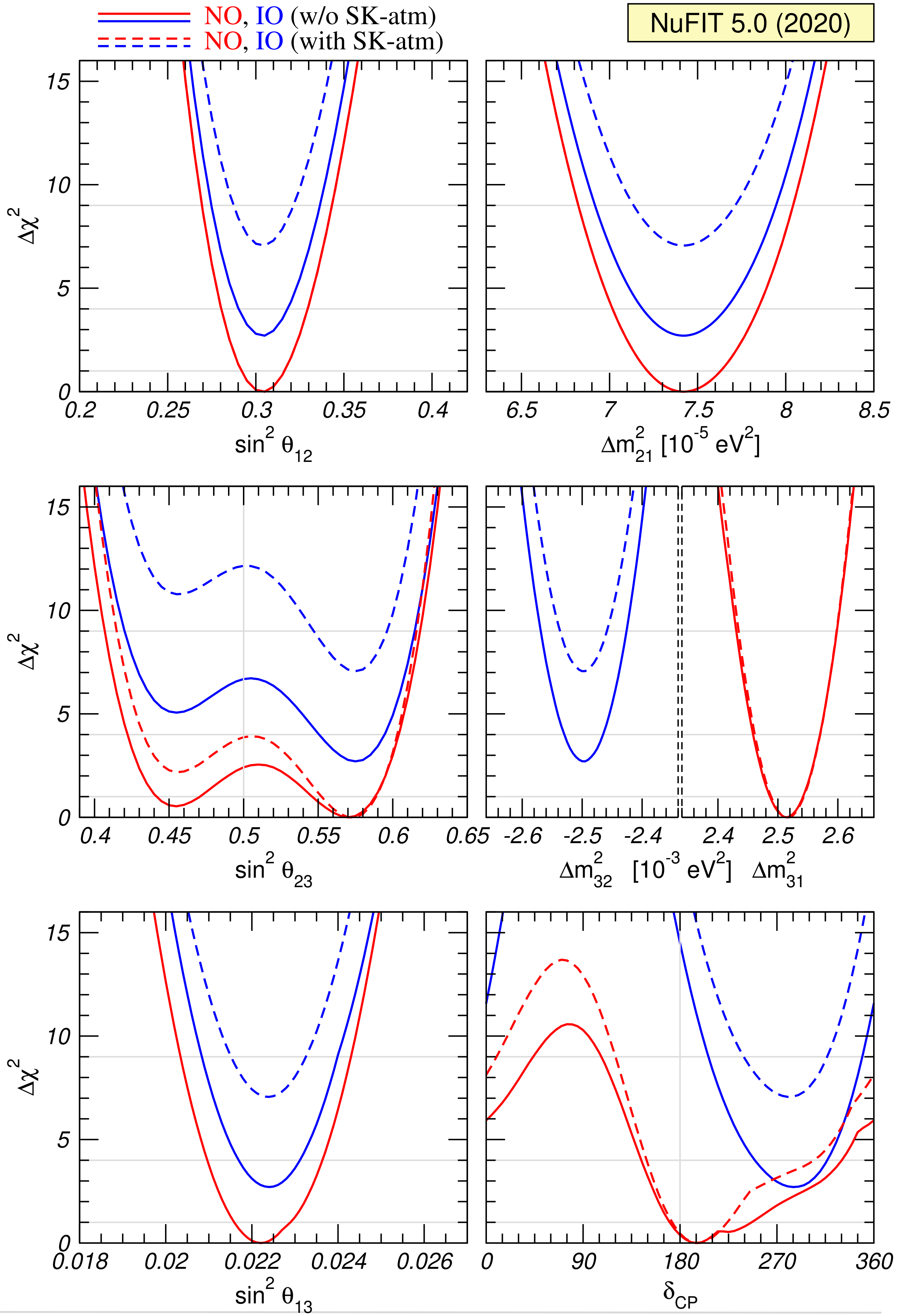


CP violation and mass ordering

status about one year ago:

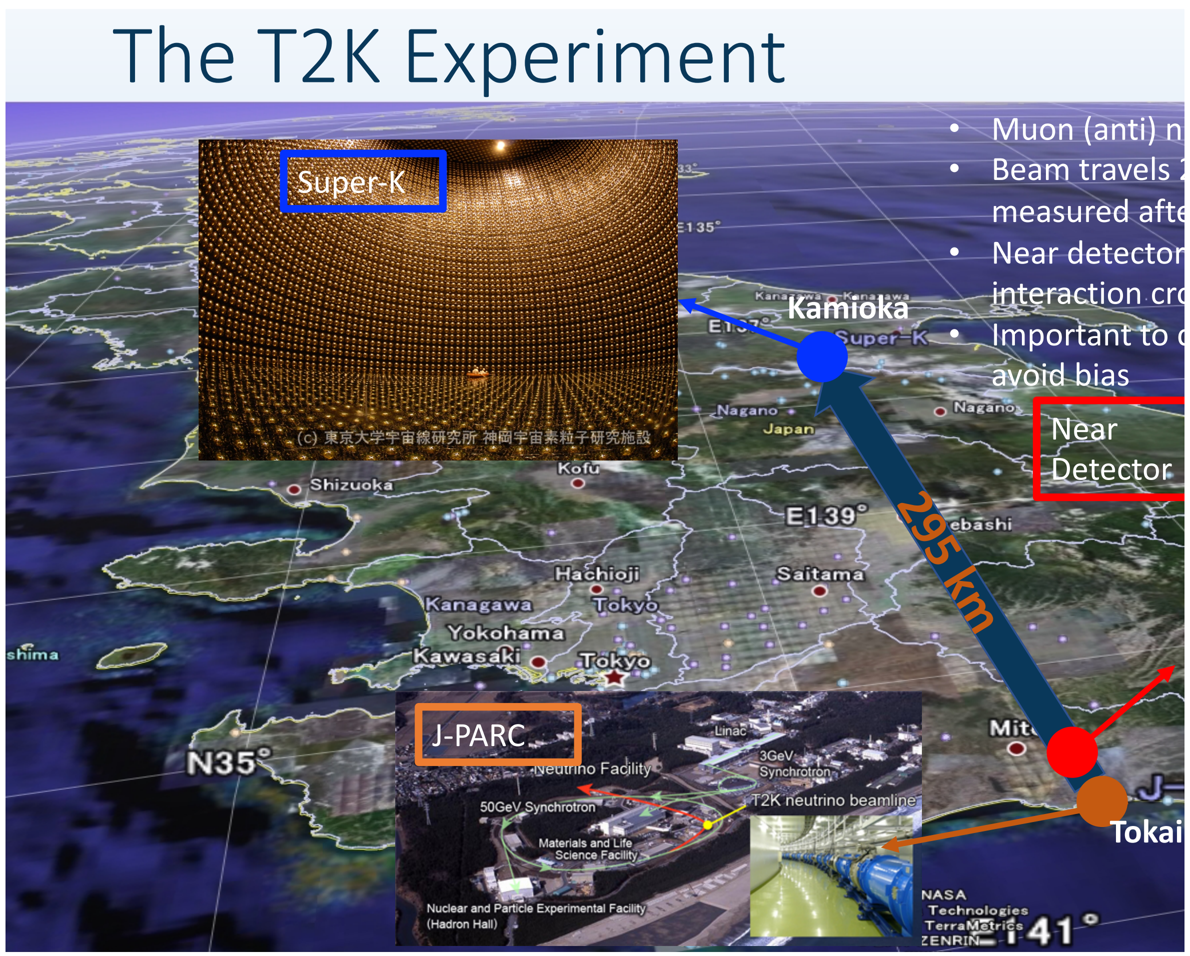
- preference for normal mass ordering ~3σ
  (subtle interplay of global data)
- hints for „large" CP violation ~2-3σ
  (mostly driven by T2K versus DayaBay)

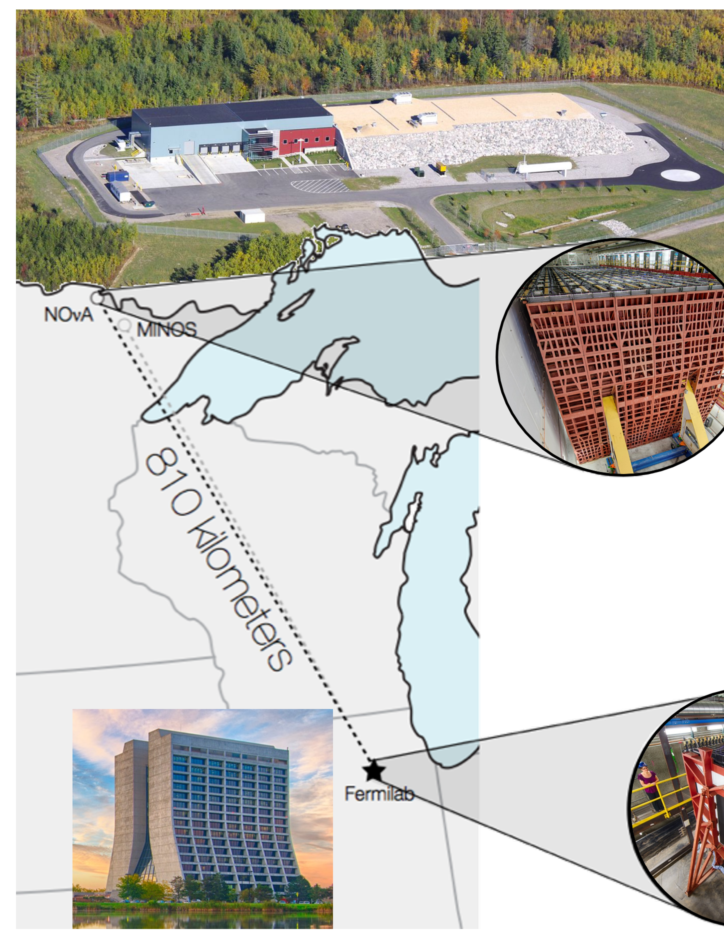
New data from T2K and NOvA at Neutrino20 (June 2020)

neutrino samples increased by 32% / 54% resp.

T2K and NOvA accelerator experiments

- $\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$ disappearance
- $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance





The NOvA Experiment

- Long-baseline neutrino oscillation experiment
- NuMI beam: ν_μ or $\bar{\nu}_\mu$
- 2 functionally identical, tracking calorimeter detectors
  - Near: 300 T underground
  - Far: 14 kT on the surface
  - Placed off-axis to produce a narrow-band spectrum
- 810 km baseline
  - Longest baseline of current experiments.

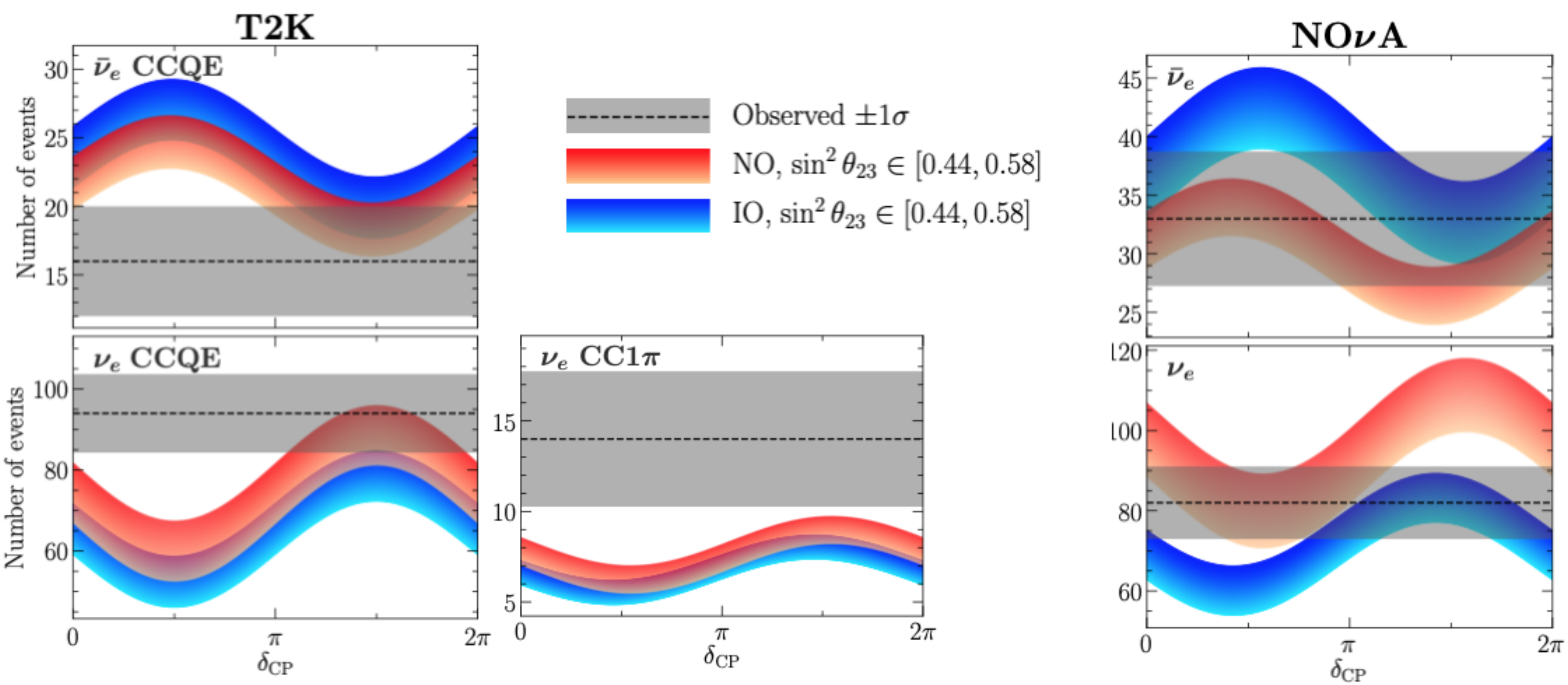
T2K and NOvA Neutrino20 $\nu_\mu \to \nu_e$ appearance results

$$P_{\mu e} \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(1-A)\Delta}{(1-A)^2} + \sin 2\theta_{13}\,\hat{\alpha}\,\sin 2\theta_{23} \frac{\sin(1-A)\Delta}{1-A}\frac{\sin A\Delta}{A}\cos(\Delta+\delta_{CP})$$

$$\Delta \equiv \frac{\Delta m^2_{31} L}{4E_\nu}$$

$$\hat{\alpha} \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \sin 2\theta_{12}$$

$$A \equiv \frac{2E_\nu V}{\Delta m^2_{31}}$$



T2K and NOvA Neutrino20 $\nu_\mu \to \nu_e$ appearance results

determined by DayaBay, RENO, DoubleChooz

$$P_{\mu e} \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(1-A)\Delta}{(1-A)^2} + \sin 2\theta_{13}\, \hat{\alpha}\, \sin 2\theta_{23} \frac{\sin(1-A)\Delta}{1-A} \frac{\sin A\Delta}{A} \cos(\Delta + \delta_{CP})$$

$$\Delta \equiv \frac{\Delta m^2_{31} L}{4E_\nu}$$

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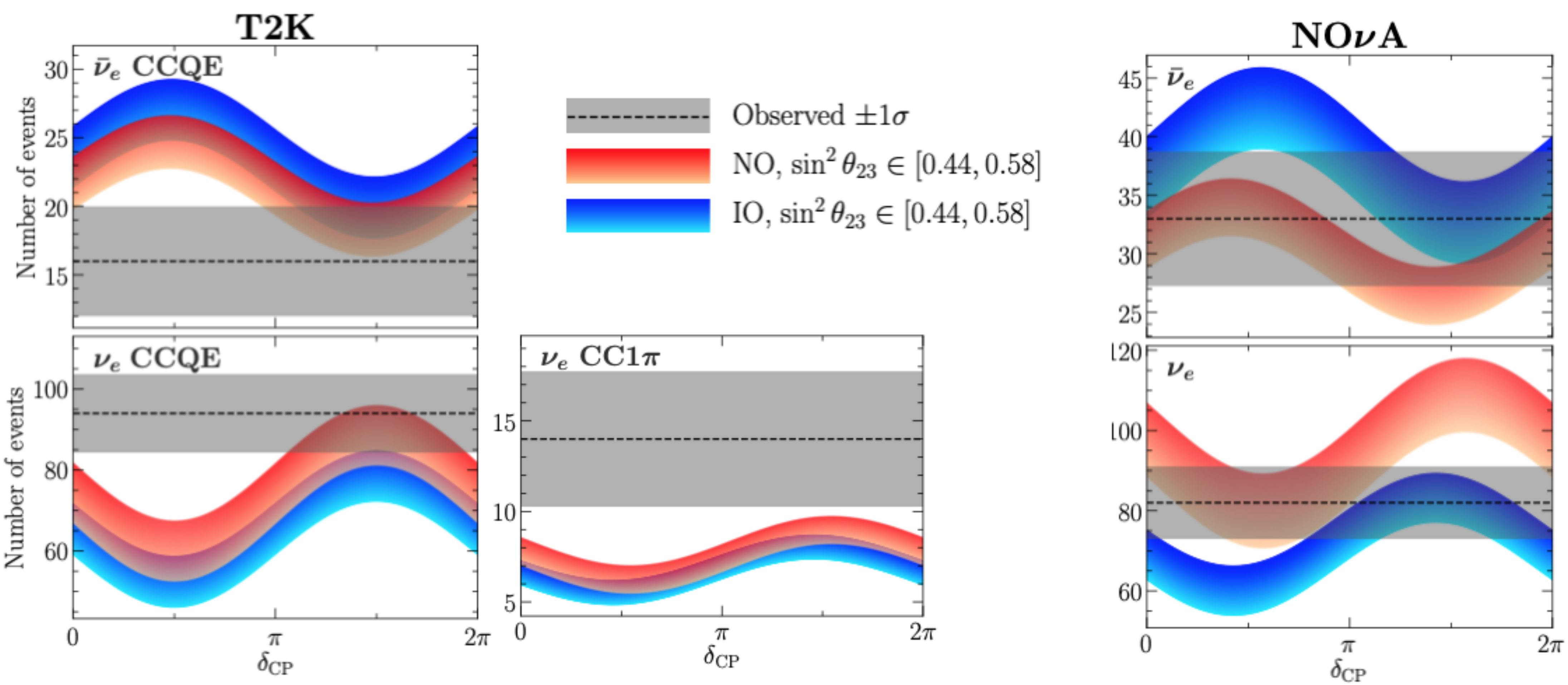
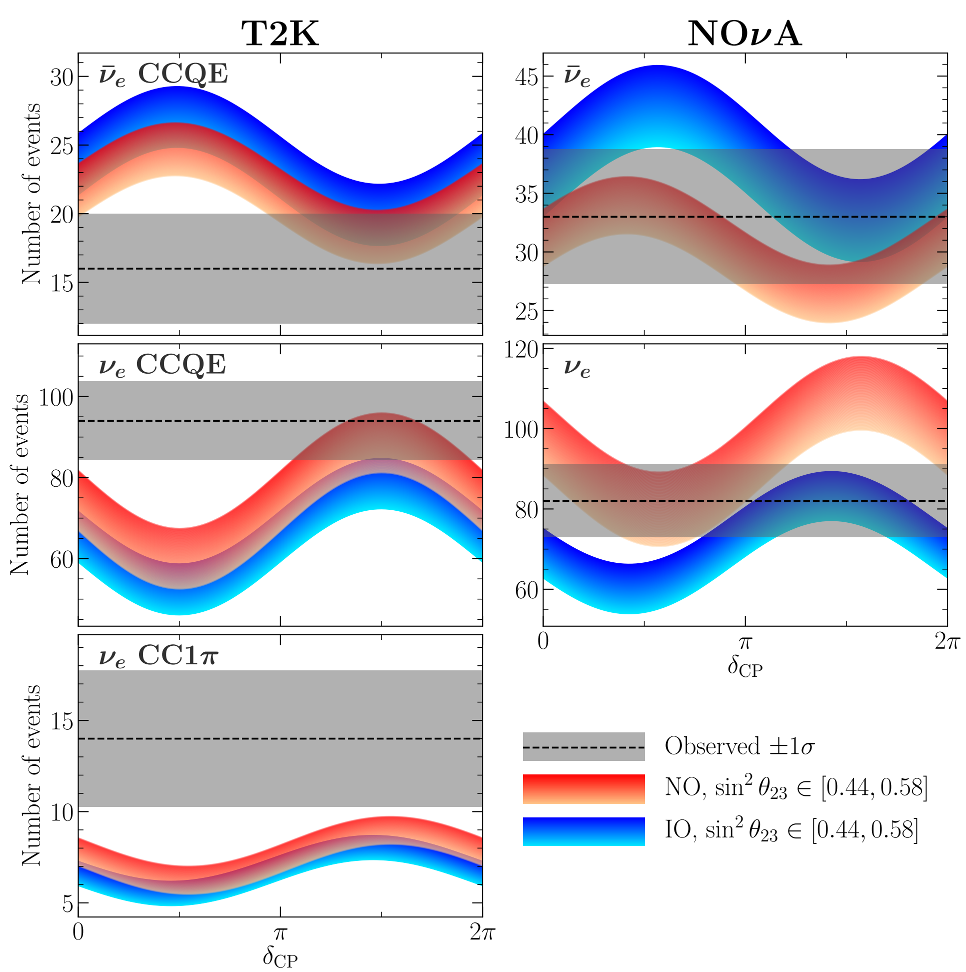
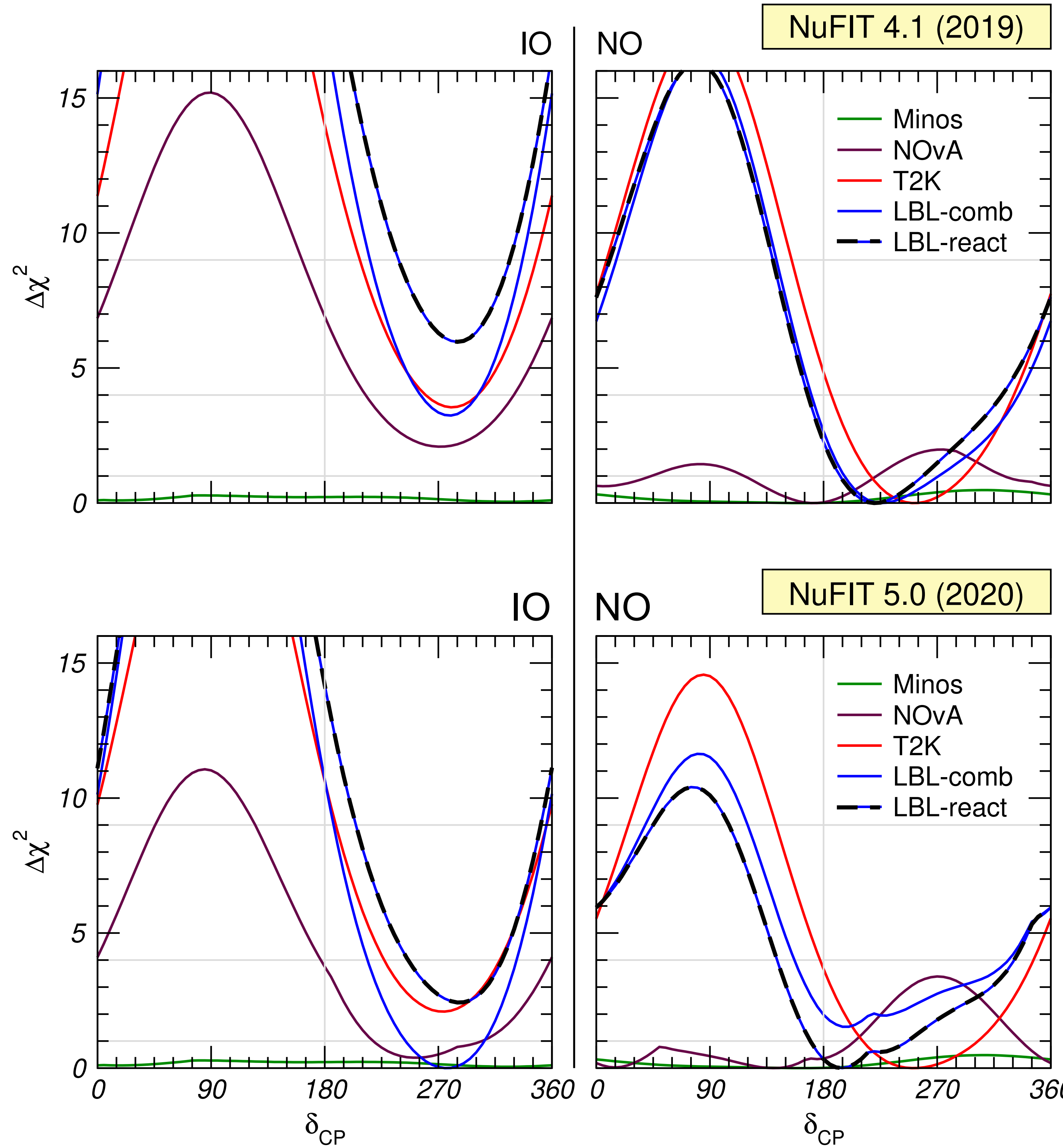
$$A \equiv \frac{2E_\nu V}{\Delta m^2_{31}}$$



Status of mass ordering and CP phase

- T2K and NOvA better compatible for IO → LBL combination best fit for IO

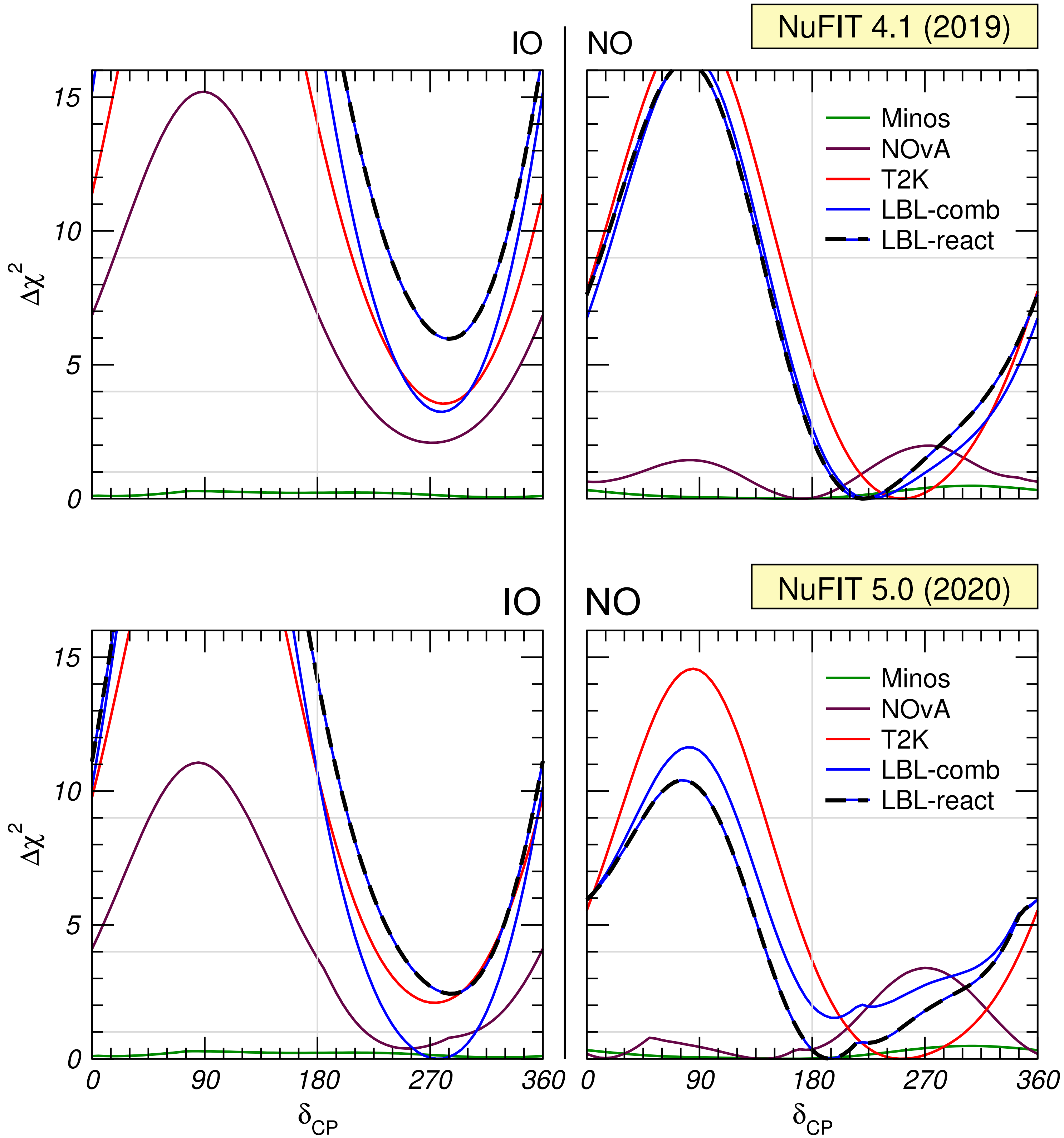




Esteban et al., 2007.14792

Status of mass ordering and CP phase

- T2K and NOvA better compatible for IO → LBL combination best fit for IO
- CP phase best fit at δ=195° (shifted towards 180°) → CP conservation allowed at 0.6σ
- for IO: best fit close to δ=270°, CP conserv. disfavoured at 3σ



Esteban et al., 2007.14792

T2K and NOvA are statistically consistent for both orderings

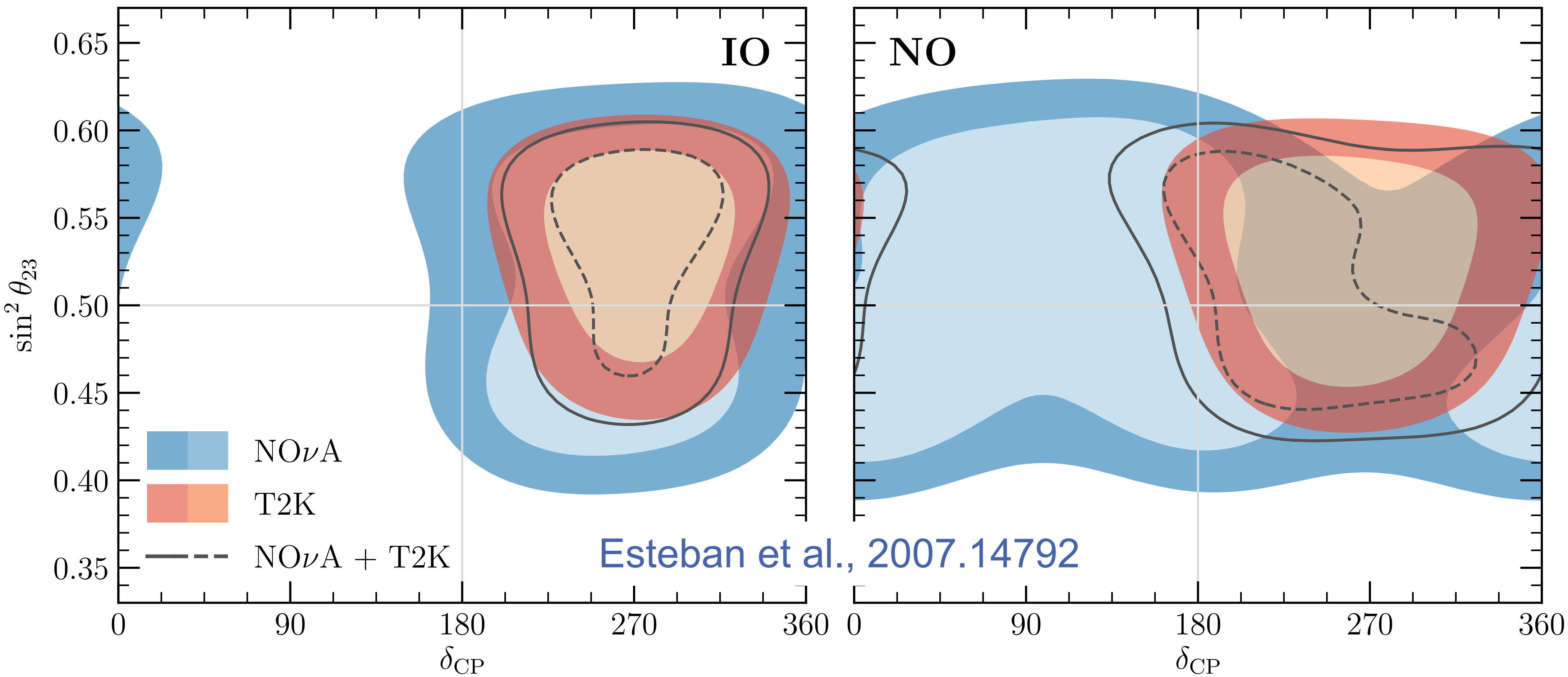


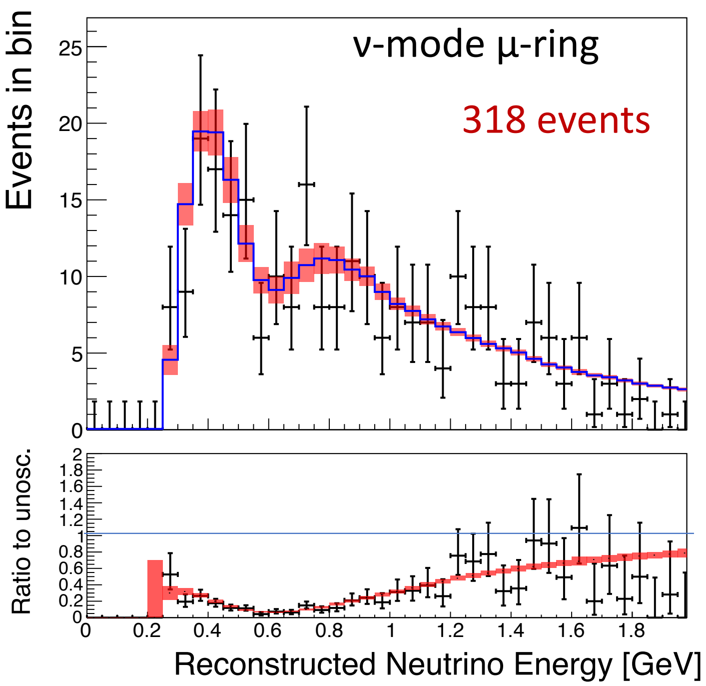
Figure 3. 1σ and 2σ allowed regions (2 dof) for T2K (red shading), NOvA (blue shading) and their combination (black curves). Contours are defined with respect to the local minimum for IO (left) or NO (right). We are fixing $\sin^2\theta_{13} = 0.0224$, $\sin^2\theta_{12} = 0.310$, $\Delta m^2_{21} = 7.40 \times 10^{-5}$ eV^2 and minimize with respect to $|\Delta m^2_{3\ell}|$.

ν_μ disappearance: T2K & NOvA

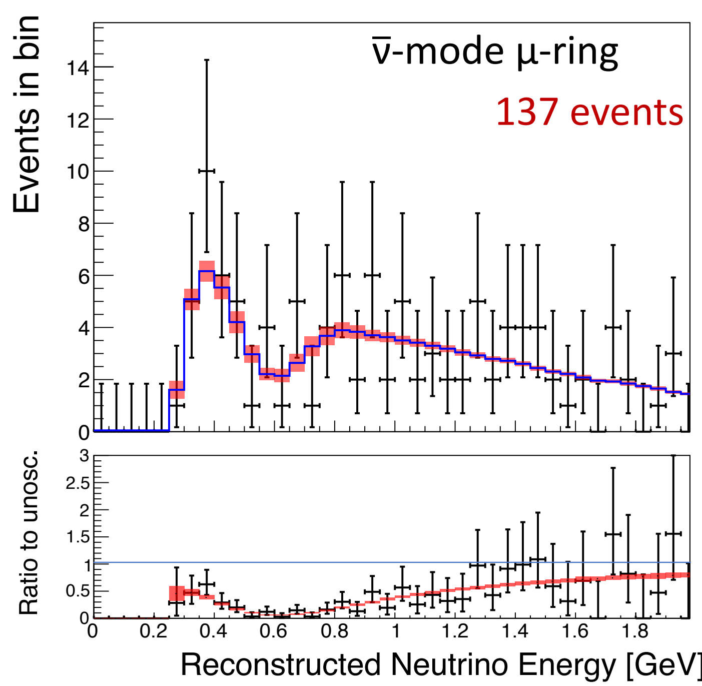
ν_e disappearance: reactor experiments

T2K @ Neutrino20

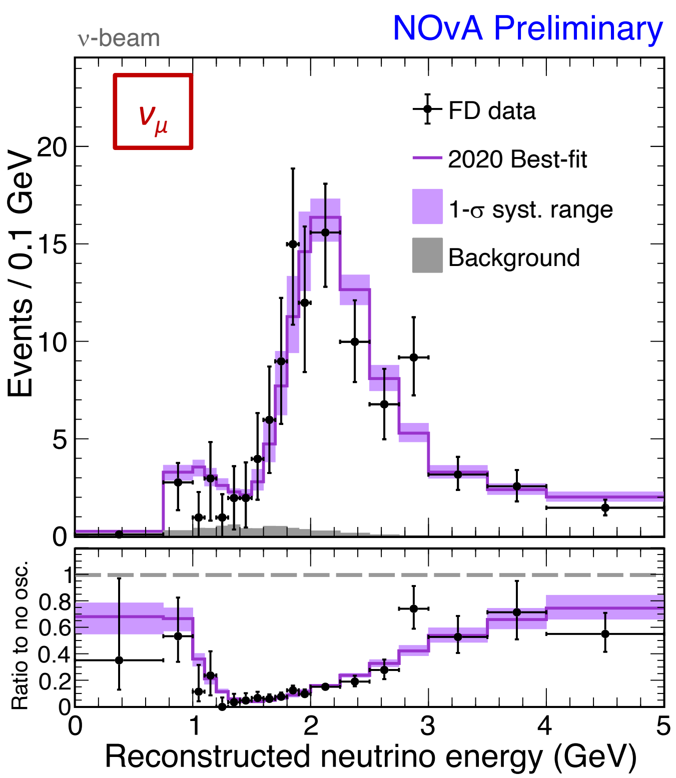
T2K Run 1-10 Preliminary

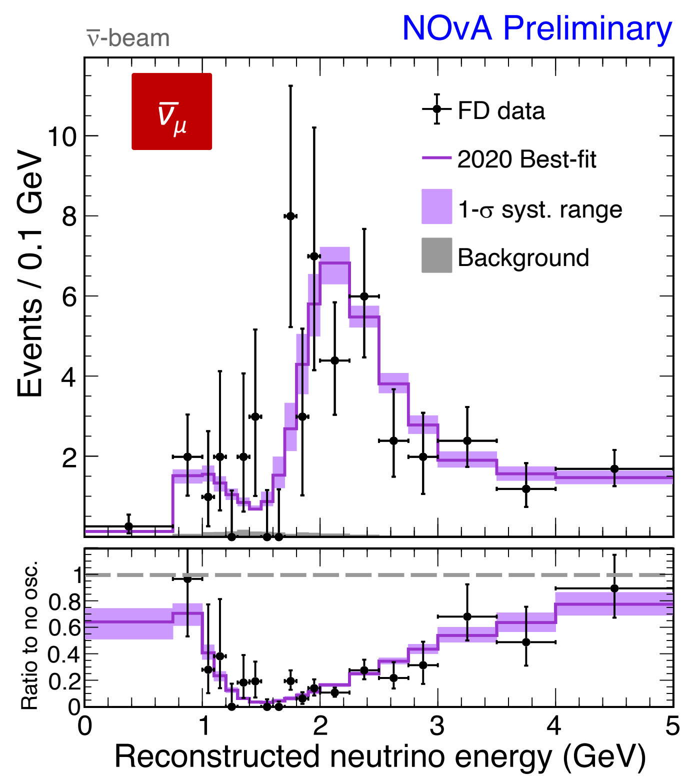


T2K Run 1-10 Preliminary



NOvA @ Neutrino20

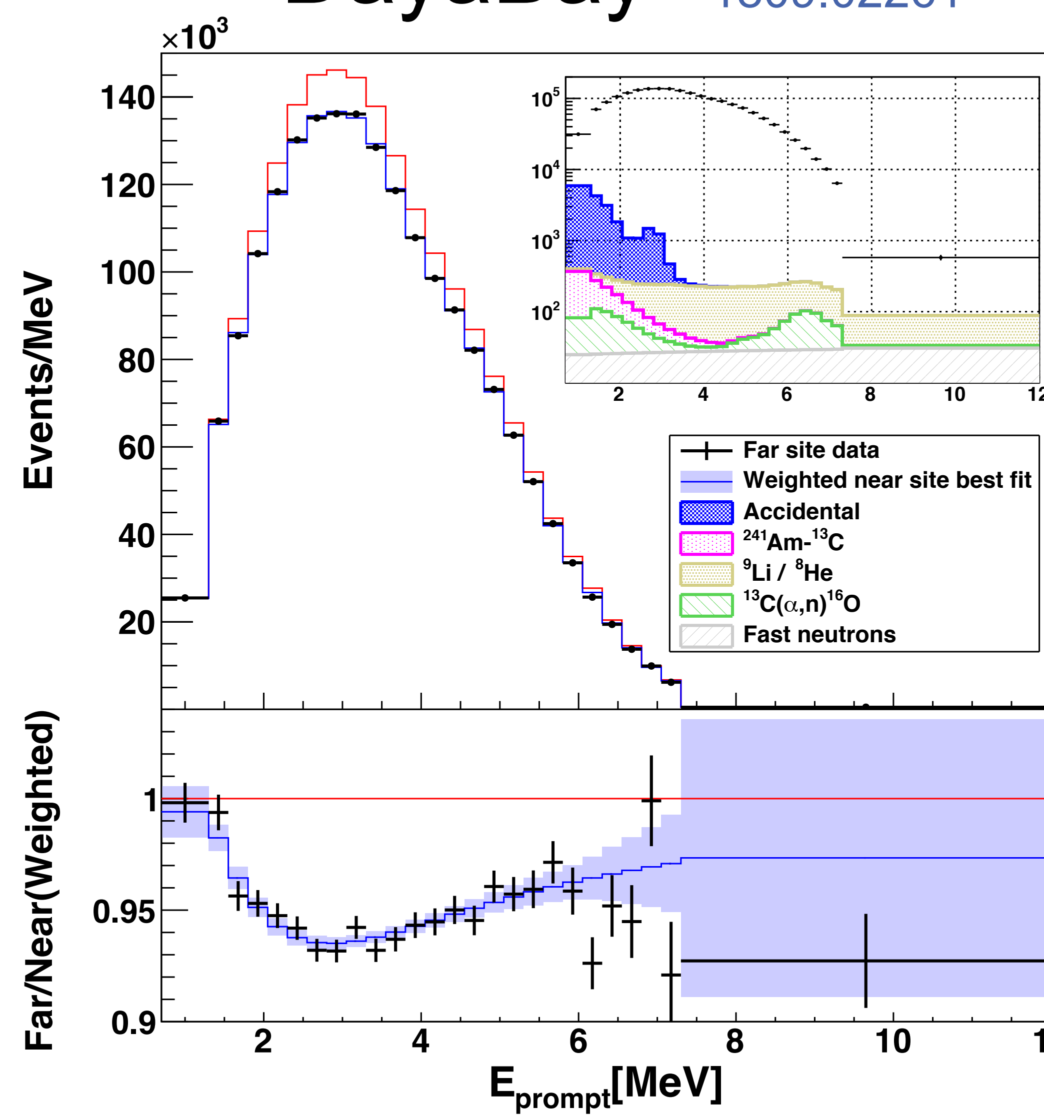




211 events, 8.2 background

105 events, 2.1 background

DayaBay 1809.02261



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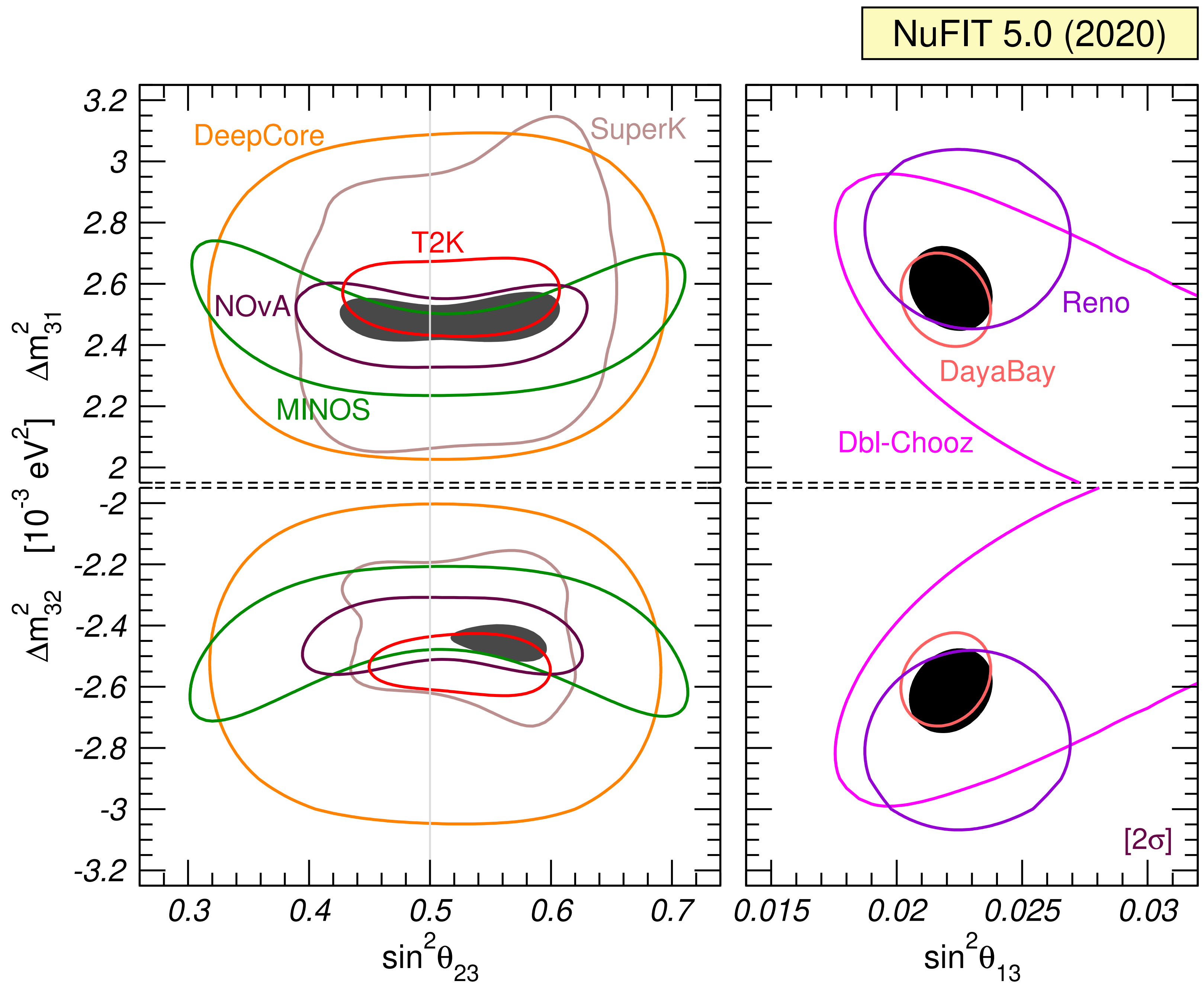
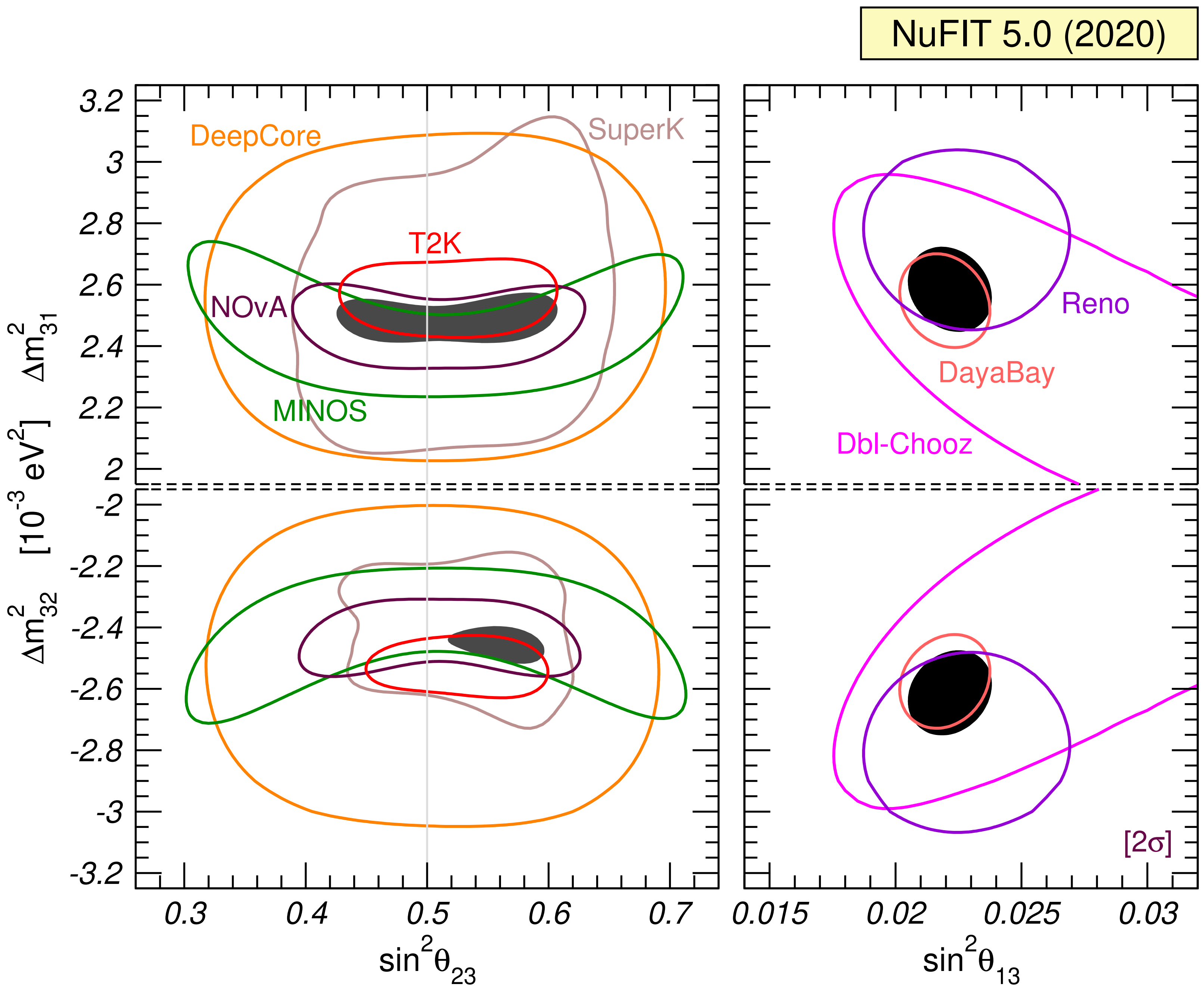
Consistency of μ and e disappearance



Consistency of μ and e disappearance

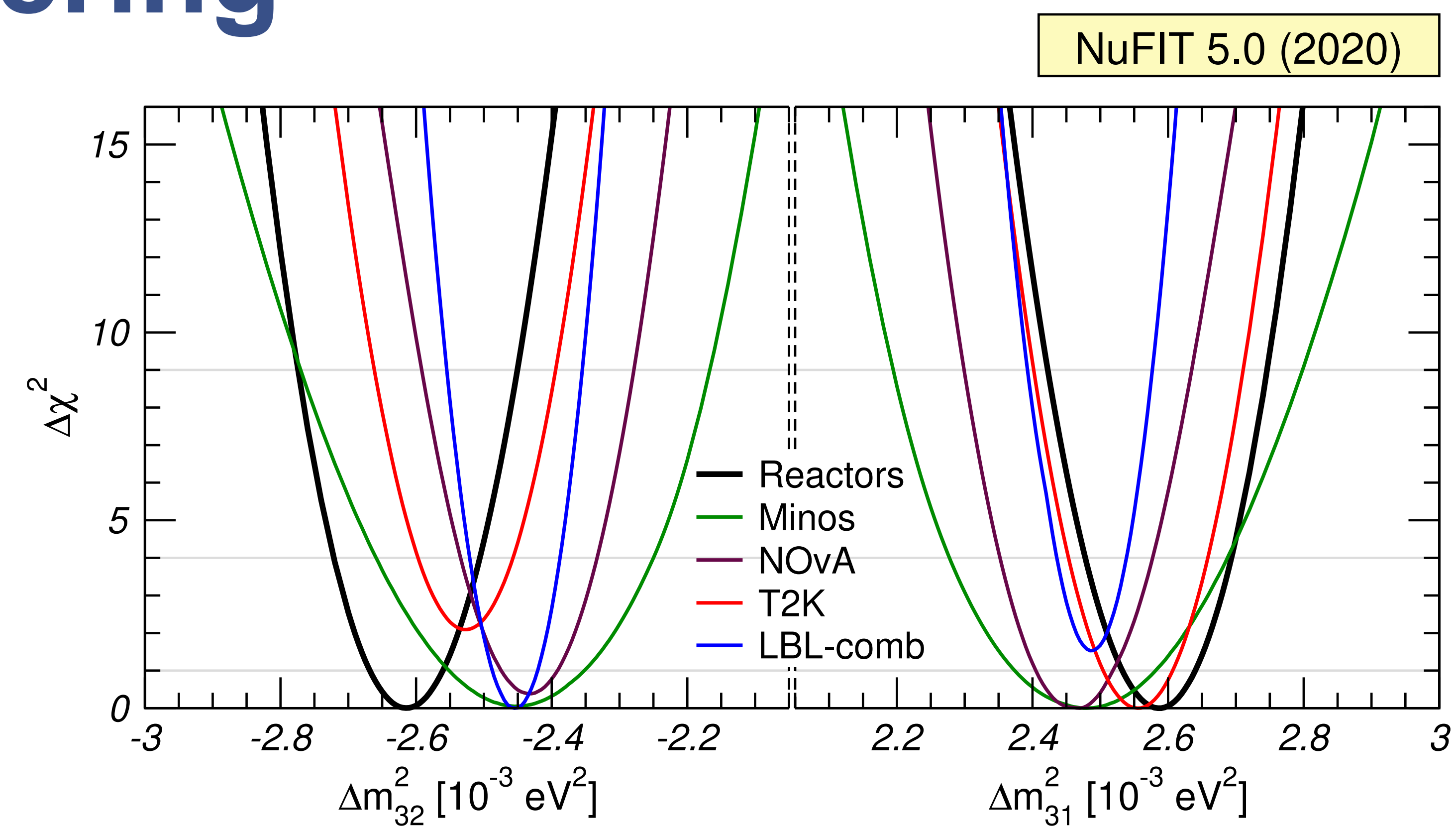


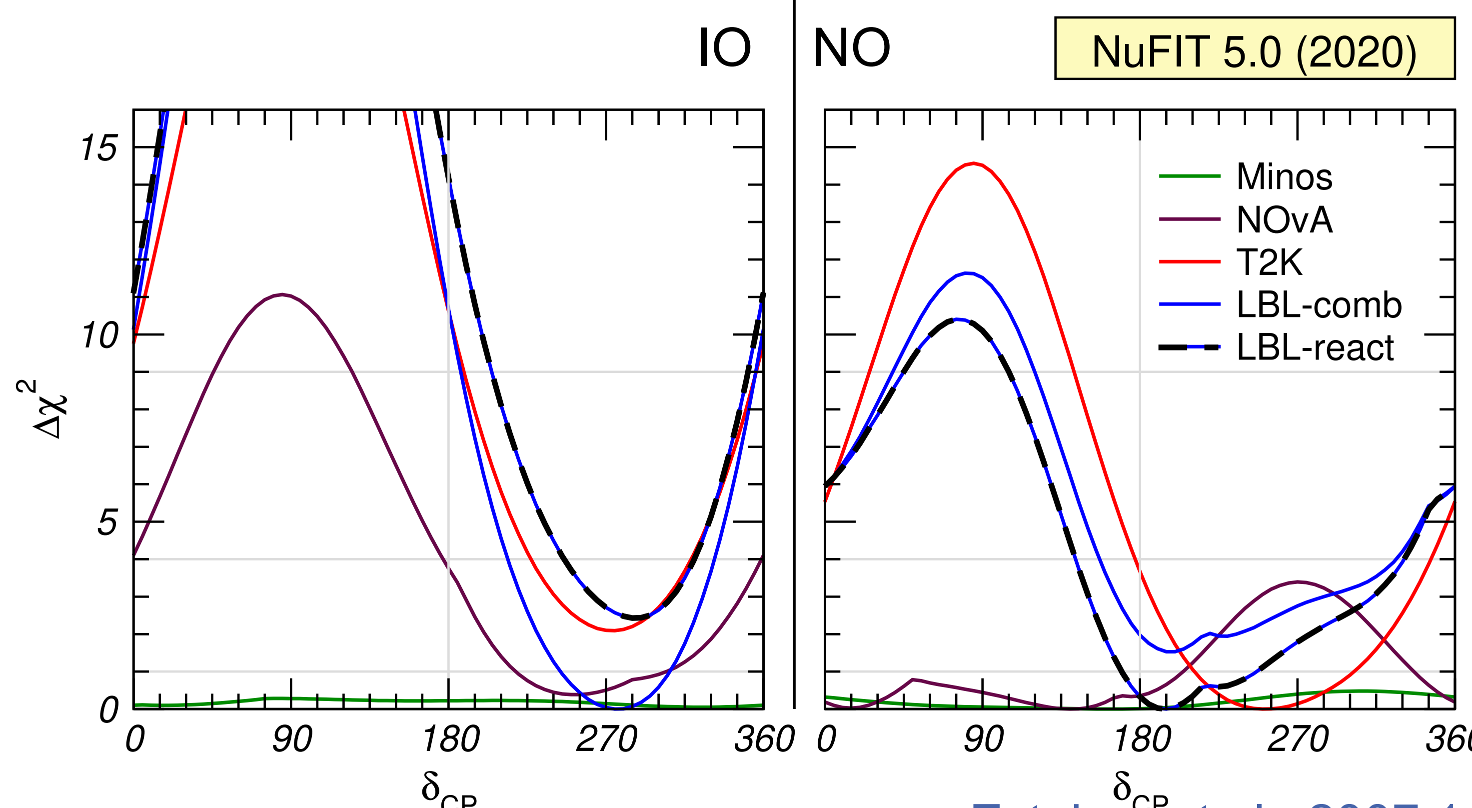
$$|\Delta m^2_{\mu\mu}| = |\Delta m^2_{ee}| \mp \Delta m^2_{21}\,[\cos 2\theta_{12} - \cos\delta \sin\theta_{13} \sin 2\theta_{12} \tan\theta_{23}]$$

slightly different *effective* mass-squared differences: -/+ for NO/IO   Nunokawa, Parke, Zukanovich, 05

Status of mass ordering

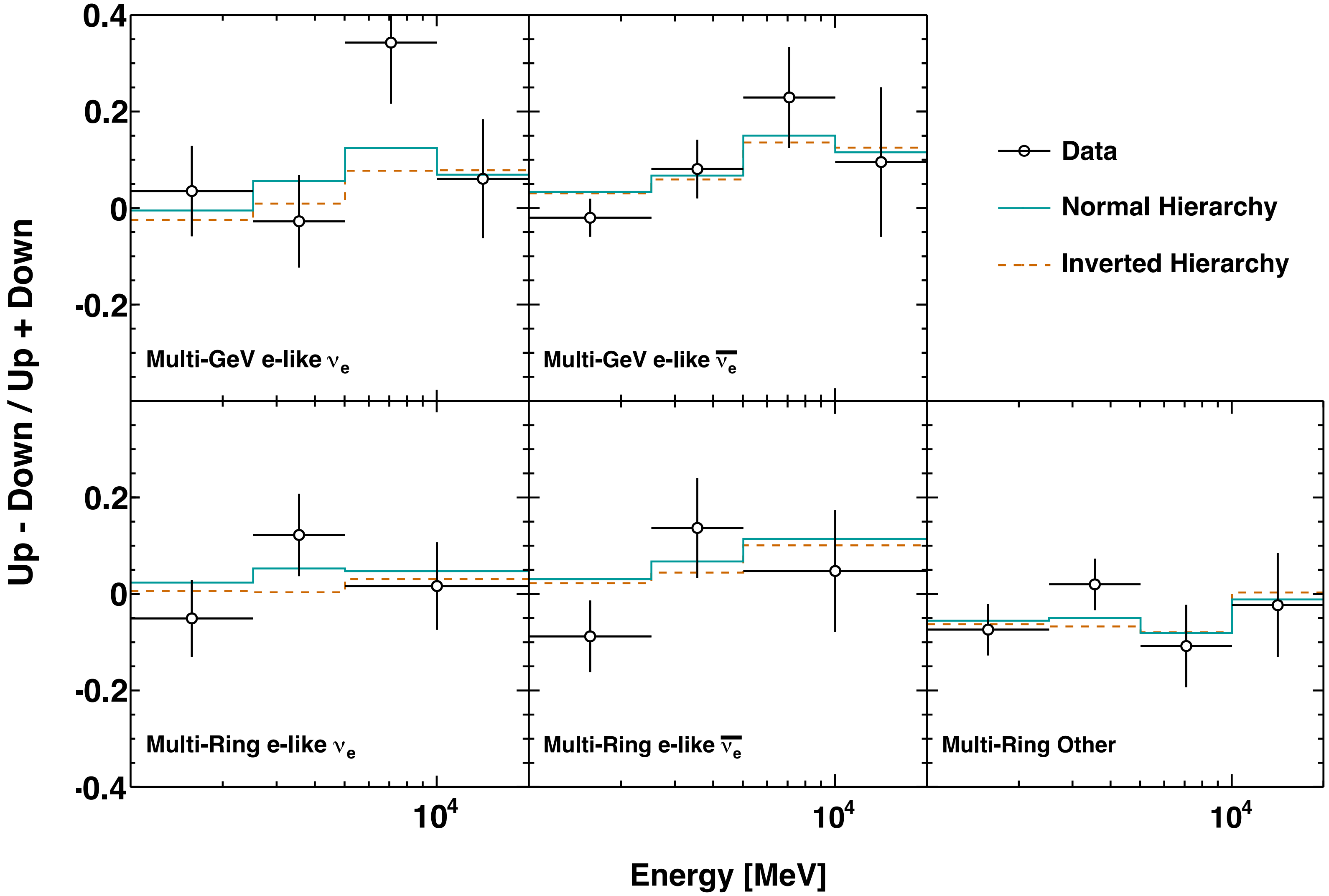
- T2K and NOvA better compatible for IO → LBL combination best fit for IO
- LBL/reactor determ of Δm^2 better for NO →
- overall preference for NO with $\Delta\chi^2 = 2.7$ (was 6.2 in 2019)



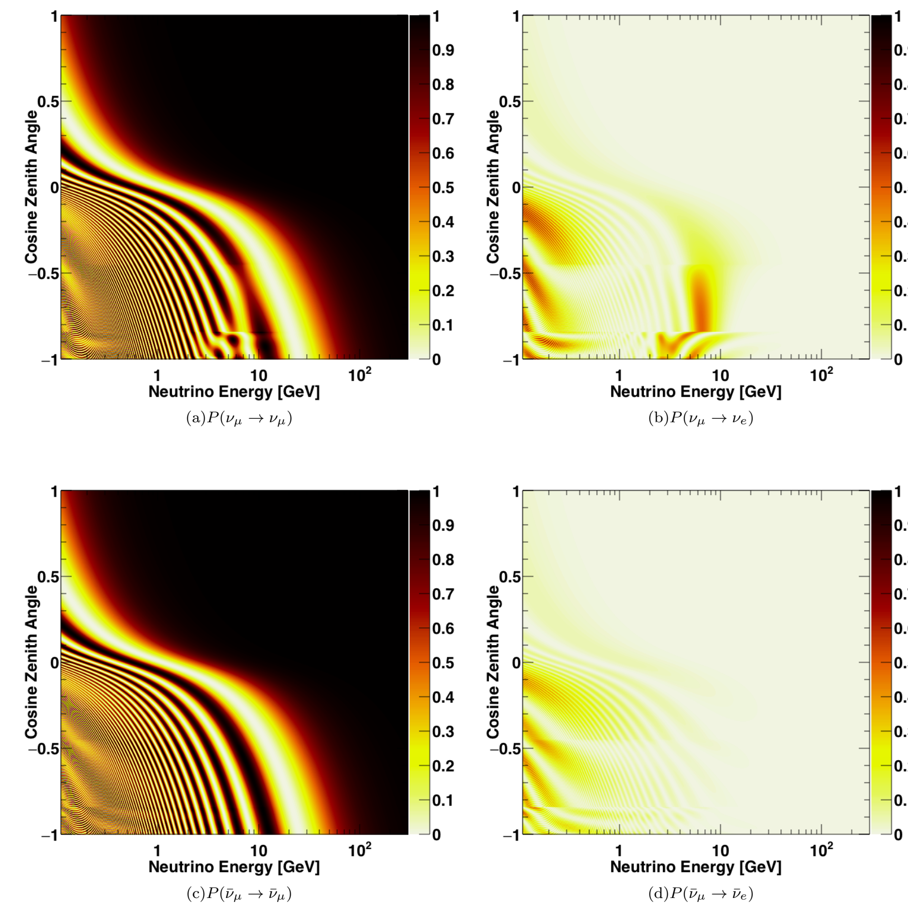


Esteban et al., 2007.14792

Mass ordering - atmospheric neutrinos

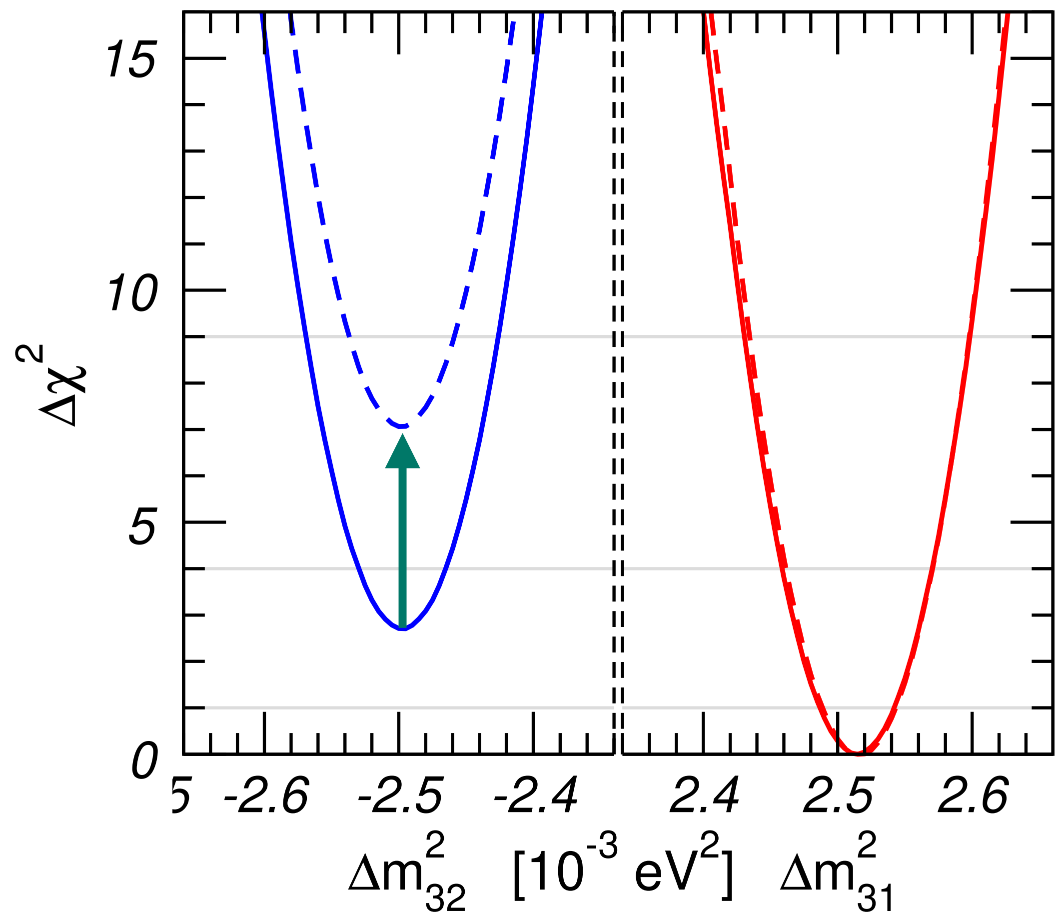


Super-Kamiokande I-IV, 1710.09126



- $\chi^2_{(IO)} - \chi^2_{(NO)} = 4.3$
- analysis not reproducable outside SK
- add χ^2 table to global fit („black box“)

Mass ordering - atmospheric neutrinos



- global analysis (using SK I-IV, 1710.09126):
  χ^2(IO) - χ^2(NO) = 2.7 (no SK) → 7.1 (w SK) 2.7σ was 10.4 (3.2σ) in 2019

- NOTE: recent SK update @ Neutrino20: improved analysis:
  χ^2(IO) - χ^2(NO) = 4.3 → 3.2 (χ^2 table not available yet)

Absolute neutrino mass

- cosmology
- beta-decay endpoint
- double beta-decay

Neutrino mass from cosmology

- finite neutrino mass affects growth of structure in the Universe
- sensitivity of CMB and large-scale structure observables

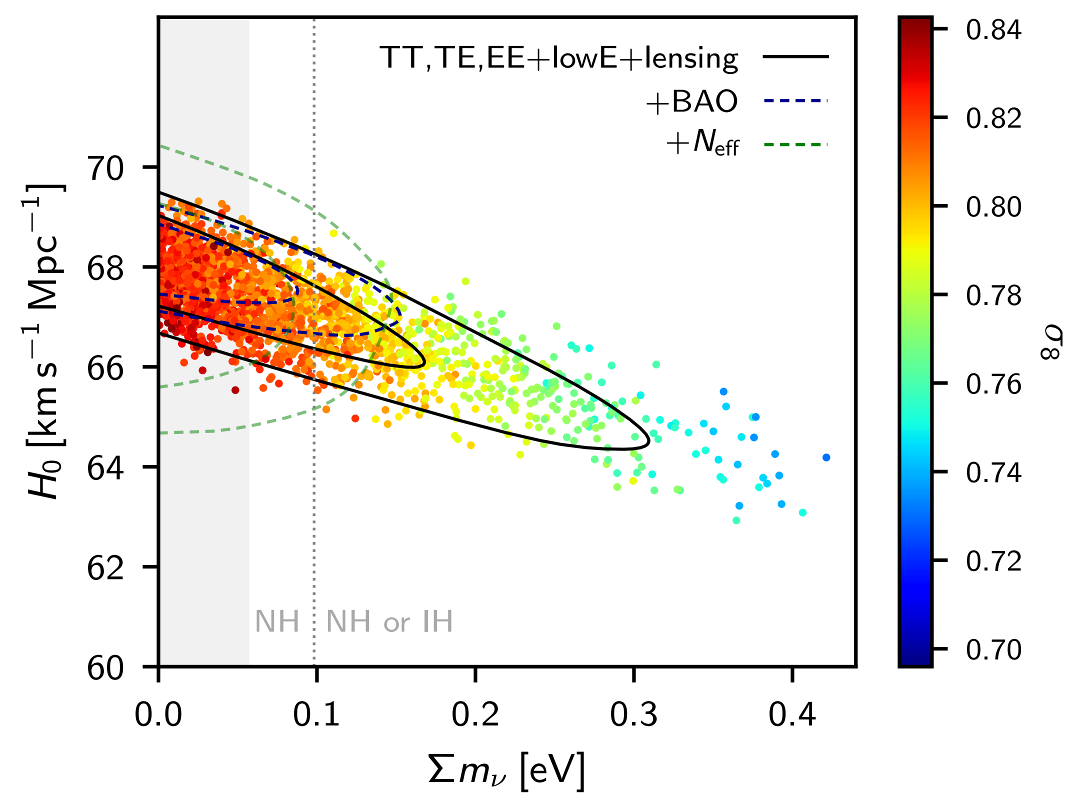
for review, e.g., Lesgourgues, Pastor [astro-ph/0603494]

$$\sum m_\nu < 0.24\,\mathrm{eV}\ (\mathrm{CMB})$$

$$\sum m_\nu < 0.12\,\mathrm{eV}\ (\mathrm{CMB+BAO})$$

limits at 95% CL

Planck 1807.06209



Neutrino mass from cosmology

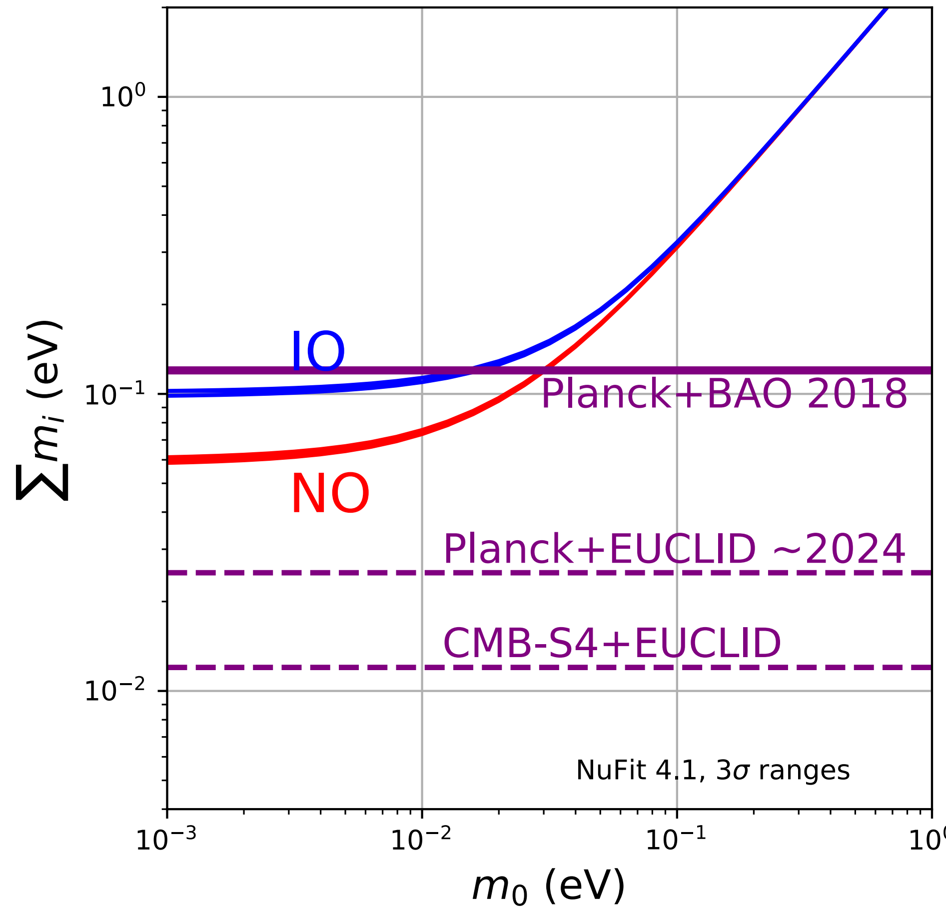
Cosmology is sensitive to the sum of neutrino masses

$$\sum_{i=1}^{3} m_i = \begin{cases} m_0 + \sqrt{\Delta m_{21}^2 + m_0^2} + \sqrt{\Delta m_{31}^2 + m_0^2} & \text{(NO)} \\ m_0 + \sqrt{|\Delta m_{32}^2| + m_0^2} + \sqrt{|\Delta m_{32}^2| - \Delta m_{21}^2 + m_0^2} & \text{(IO)} \end{cases}$$

minimum values for $m_0 = 0$:

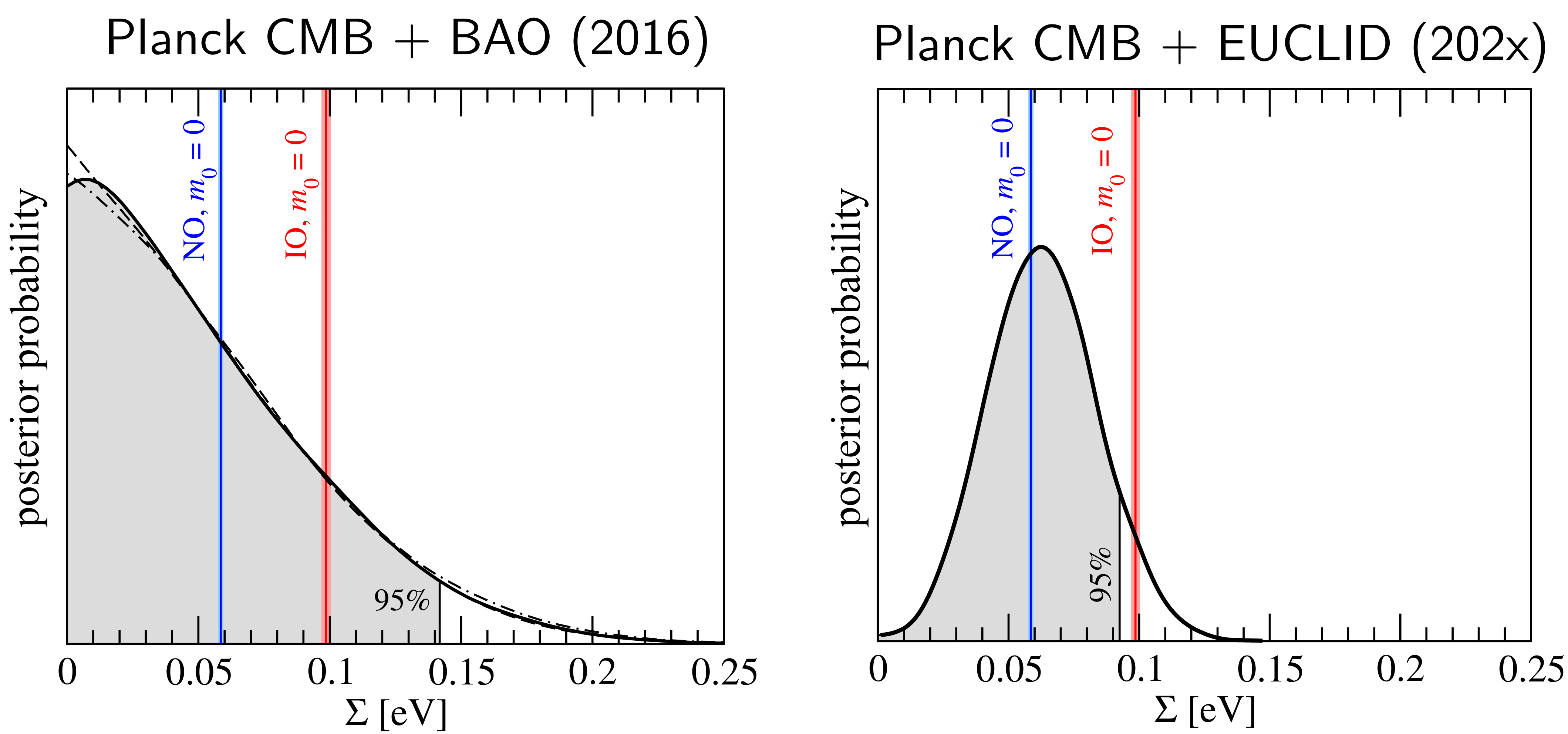
$$\sum m_i \Big|_{\min} = \begin{cases} 58.5 \pm 0.48\,\text{meV} & \text{(NO)} \\ 98.6 \pm 0.85\,\text{meV} & \text{(IO)} \end{cases}$$

- current limit close to IO minimum
- detection of non-zero neutrino mass expected soon!



e.g. Archidiacono et al., 1808.05955

Excluding inverted ordering with cosmology?



Hannestad, Schwetz, 1606.04691

see also: Archidiacono, de Salas, Gariazzo, Mena, Ternes, Tortola, 1801.04946;…

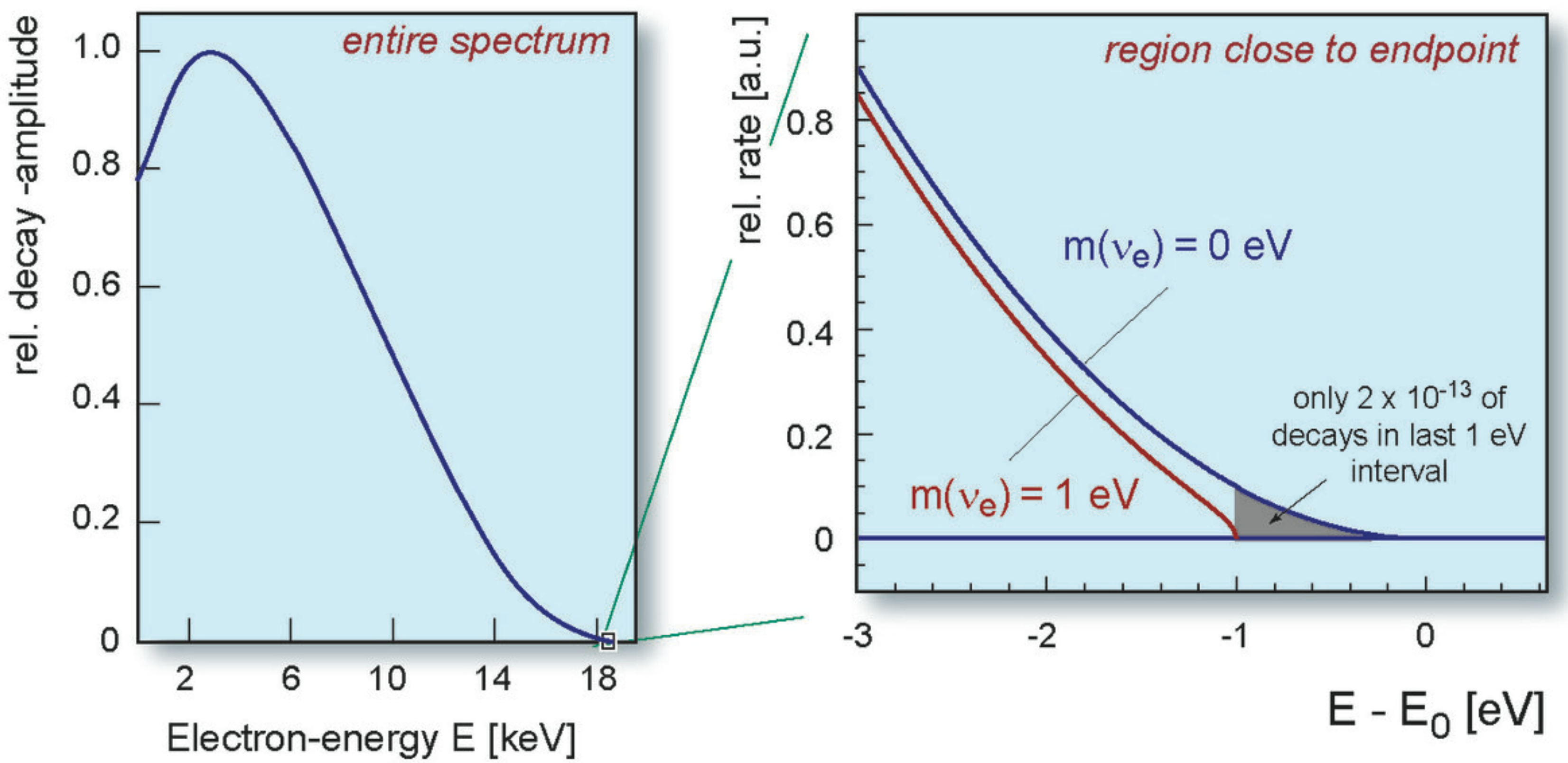
Kinematic mass in β decay

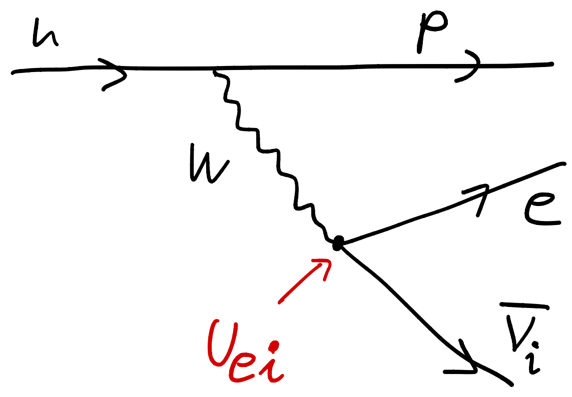
phase space factor close to spectrum endpoint

$$\frac{d\Gamma}{dT} \approx (T_{max,0} - T)\sqrt{(T_{max,0} - T)^2 - \kappa^2 m_\beta^2}$$

$$m_\beta^2 \equiv \sum_i |U_{ei}|^2 m_i^2$$

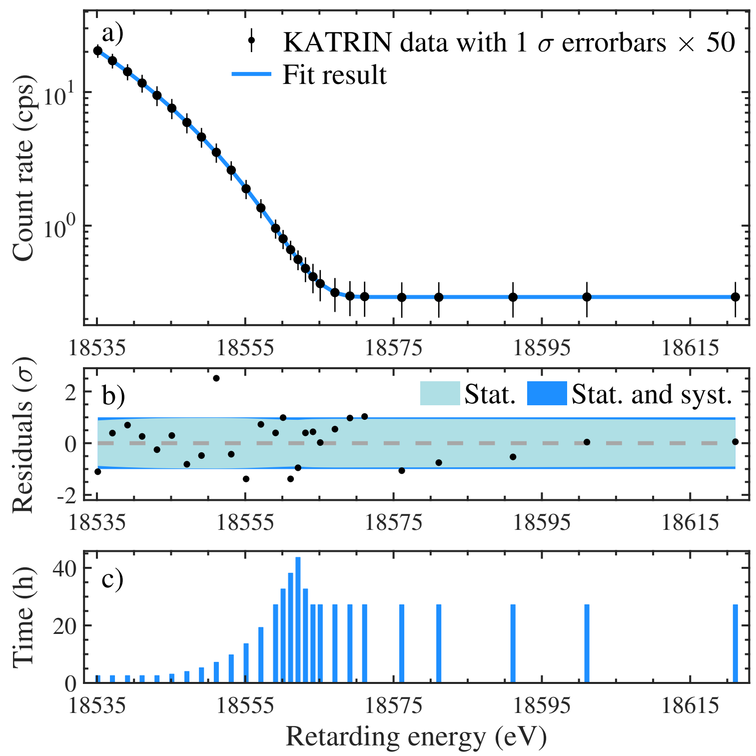
effective mass: incoherent sum of mass states

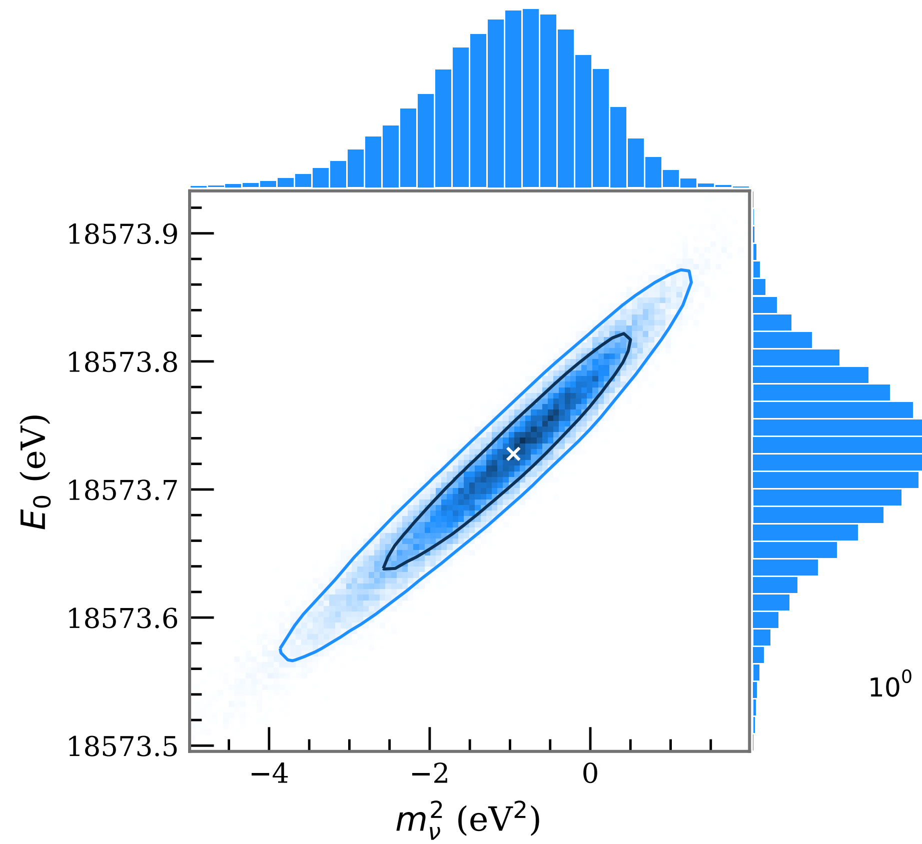




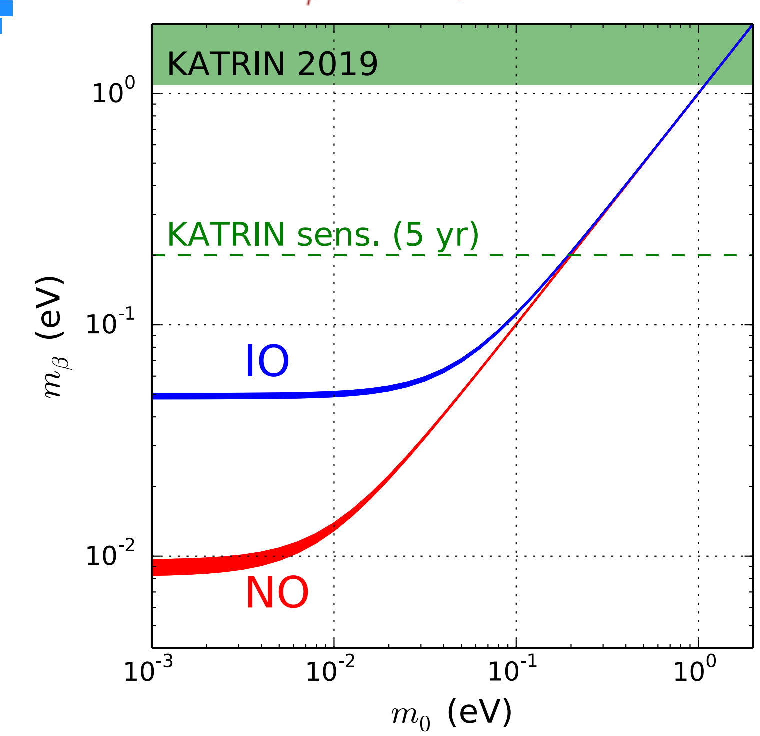
Kinematic mass in β decay

KATRIN 2019 Aker et al., 1909.06048





$m_\beta^2 = \sum_i |U_{ei}^2| m_i^2$



$m_\beta^2 = -1.0^{+0.9}_{-1.1}\,\mathrm{eV}^2$ $\qquad$ $m_\beta < 1.1\,\mathrm{eV}\ (90\%\ \mathrm{CL})$

based on ~3 weeks data
updated results expected soon!

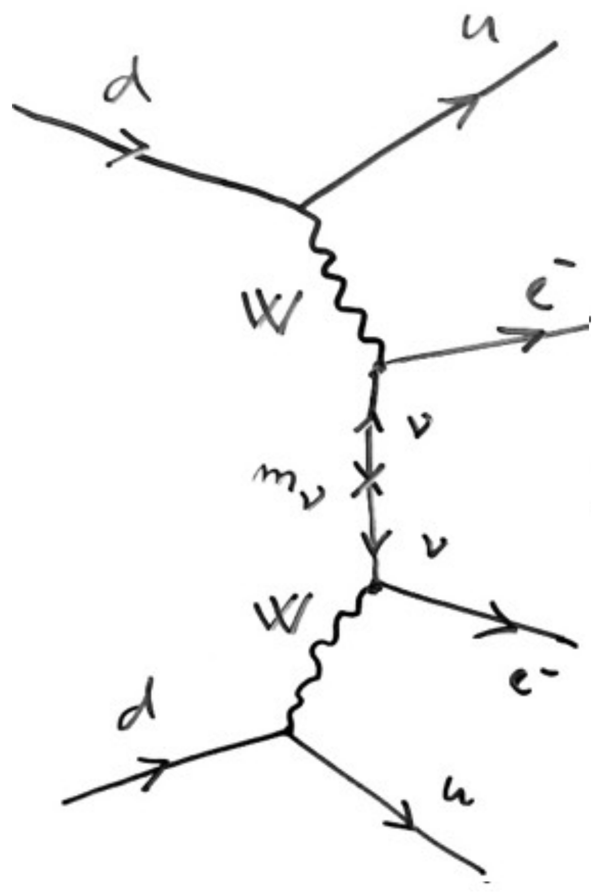
Neutrinoless double-beta decay

$$(A,Z) \to (A,Z+2) + 2e^-$$

effective mass:

$$m_{ee} = |\sum_i U_{ei}^2 m_i|$$

coherent sum over
mass states

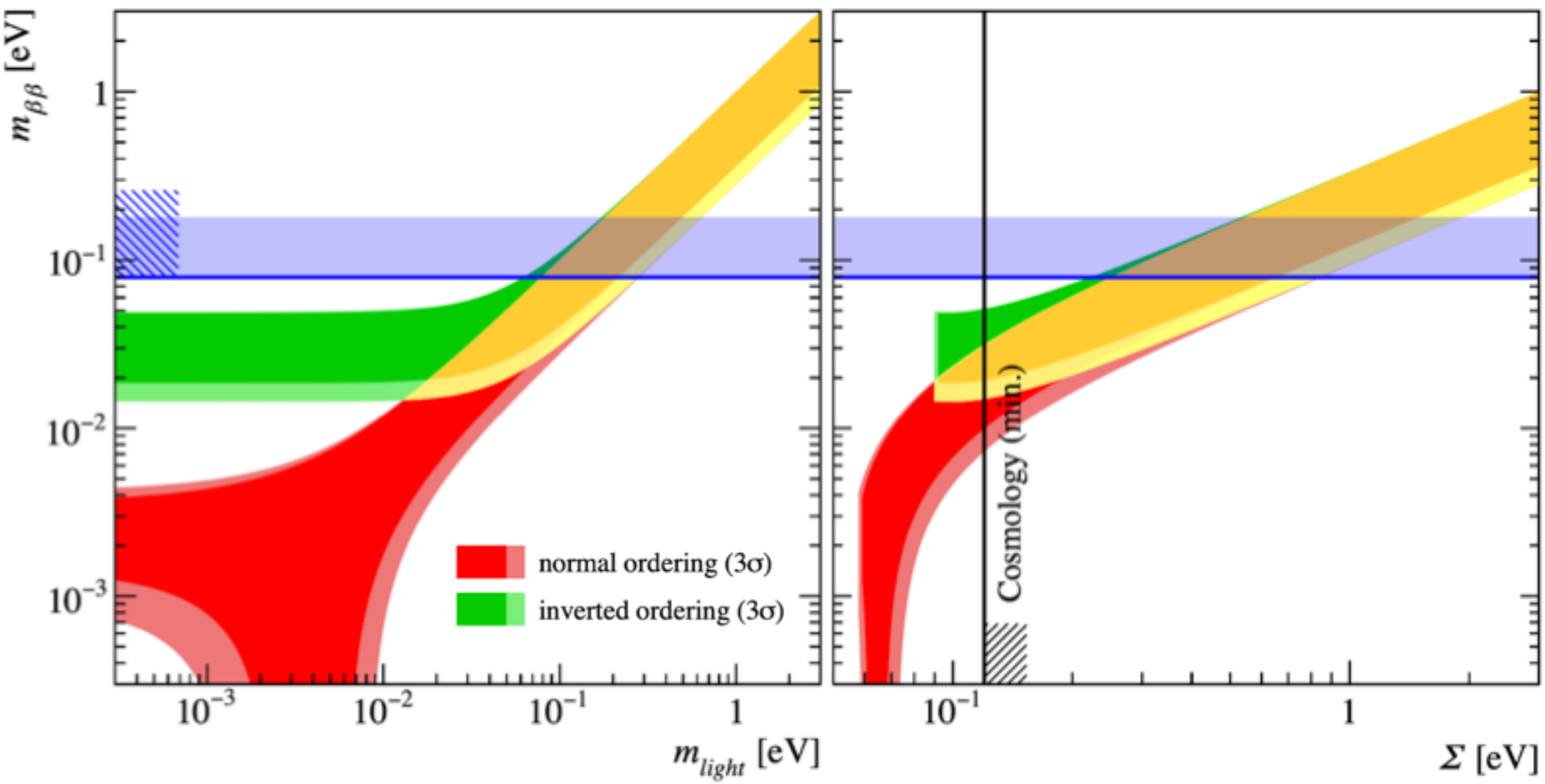


neutrino mass interpretation affected by nuclear matrix elements and Majorana phases

Neutrinoless double-beta decay

neutrino mass interpretation affected by nuclear matrix elements and Majorana phases

three flavour oscillation parameters from [Esteban et al., JHEP 09 (2020) 178]

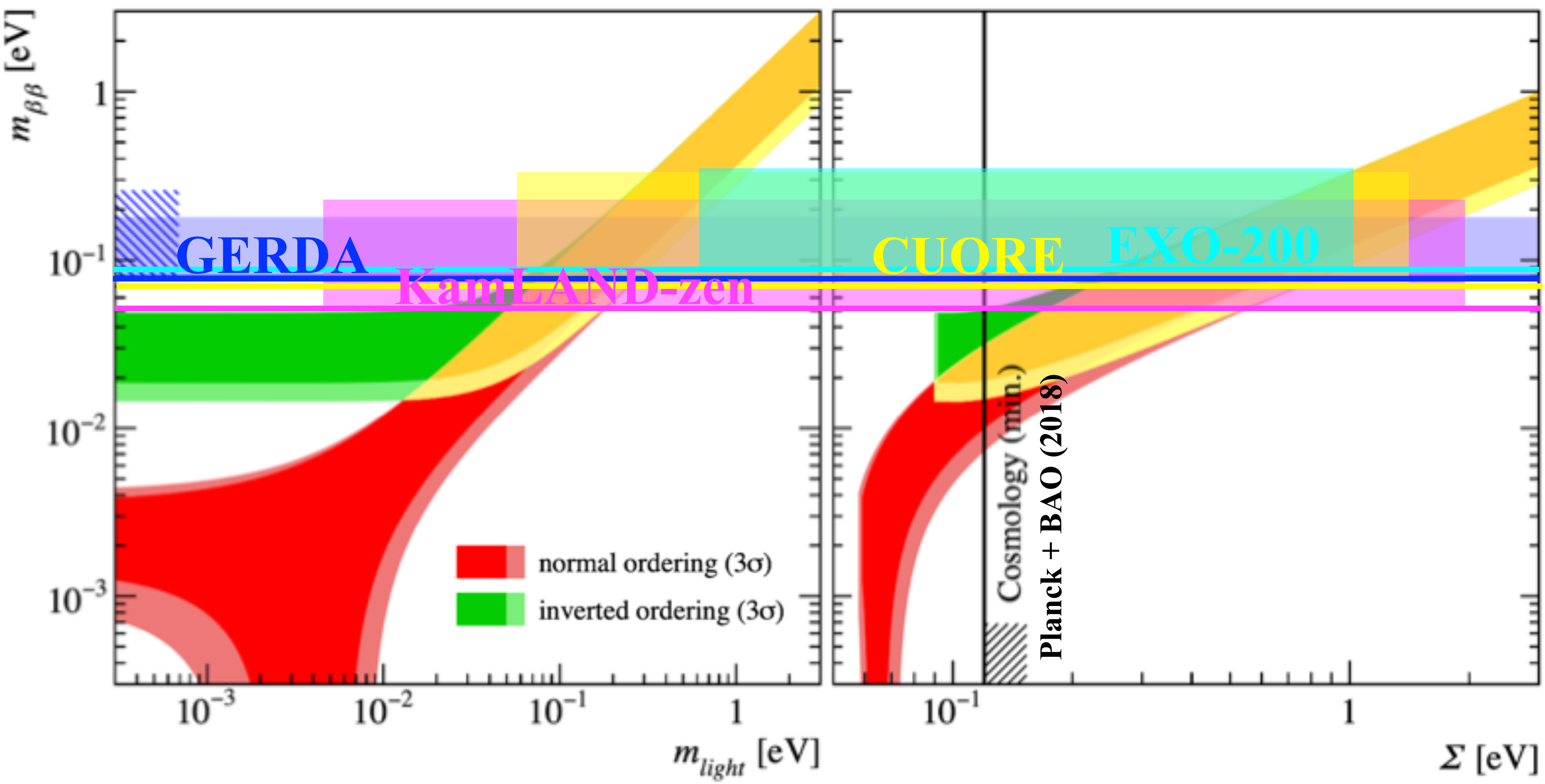


plot adapted from S. Schönert

Neutrinoless double-beta decay

neutrino mass interpretation affected by nuclear matrix elements and Majorana phases

three flavour oscillation parameters from [Esteban et al., JHEP 09 (2020) 178]



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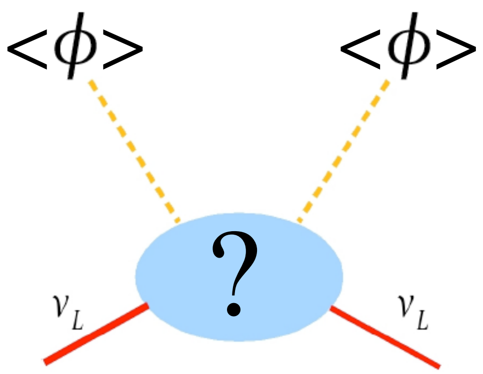
Neutrinoless double-beta decay

$$(A, Z) \to (A, Z+2) + 2e^-$$

Lepton number violation!

Weinberg operator:

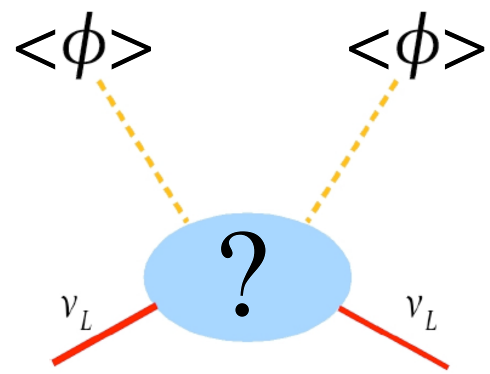
$$Y^2 \frac{\overline{L^c}\tilde{\phi}^* \tilde{\phi}^\dagger L}{\Lambda}$$



- what is the new physics responsible for that operator?
- what is the energy scale of the new physics?

- a unique prediction is the Majorana nature of neutrinos, which implies breaking of lepton number
- observation of neutrinoless double beta decay would prove that lepton number is violated by 2 units, as predicted by the Weinberg operator
- Majorana mass term will be induced at some level

Schechter, Valle, 1982, Takasugi, 1984



- what is the new physics responsible for that operator?
- what is the energy scale of the new physics?

- need signs of „new physics“ related to neutrinos (little guidance from theory)
- phenomenological approach:
  search for signals beyond standard 3-flavour paradigm

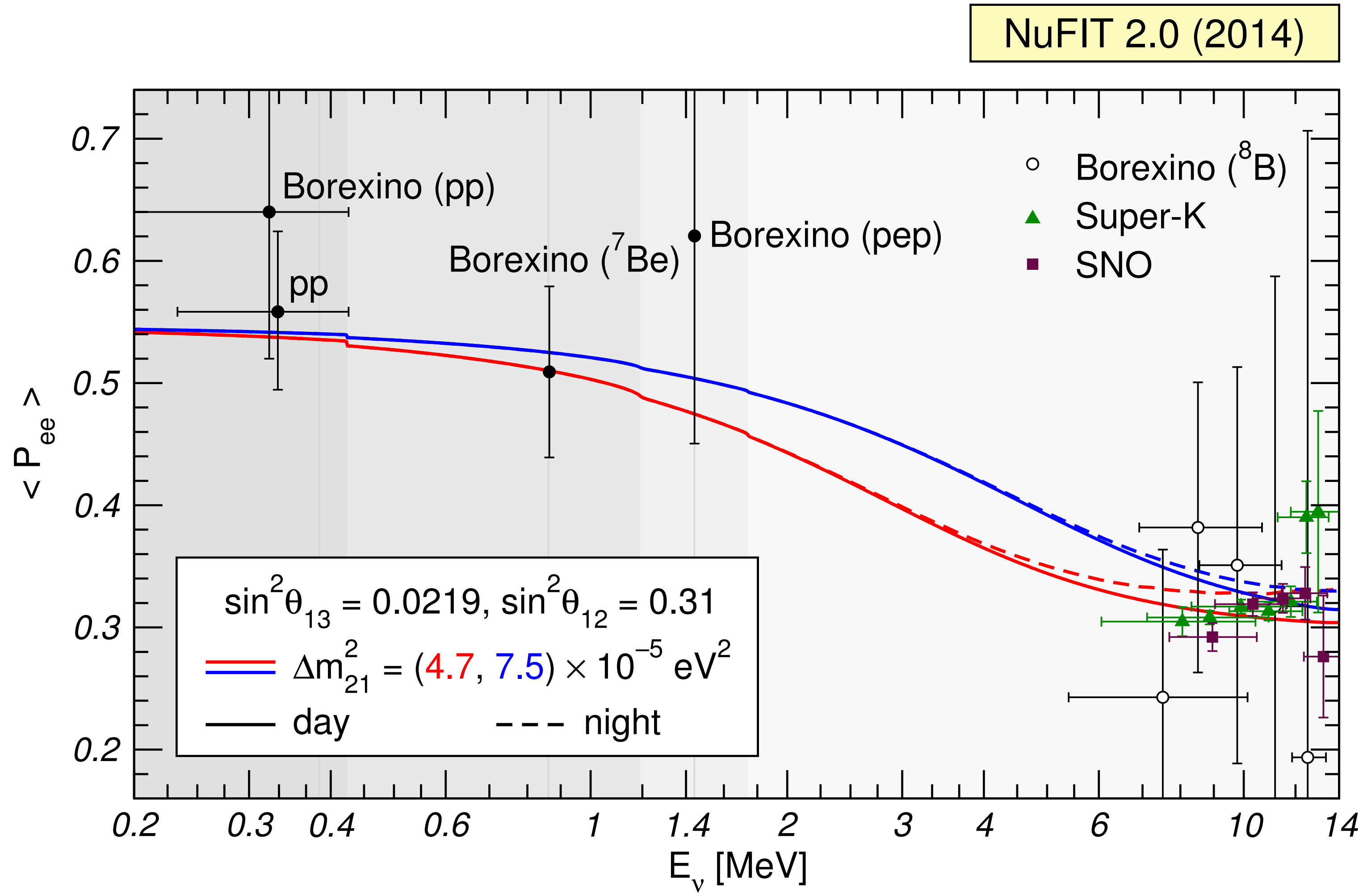
Anomalies inconsistent with 3-flavour paradigm

Anomalies inconsistent with 3-flavour paradigm

- slight tension between solar neutrino data and the KamLAND reactor experiment in determination of Δm^2_{21} (non-standard interactions?)

- short-baseline anomalies:
  LSND, MiniBOONE, reactor, Gallium
  (sterile neutrinos?)

Small „tension“ (2σ) in 12 sector

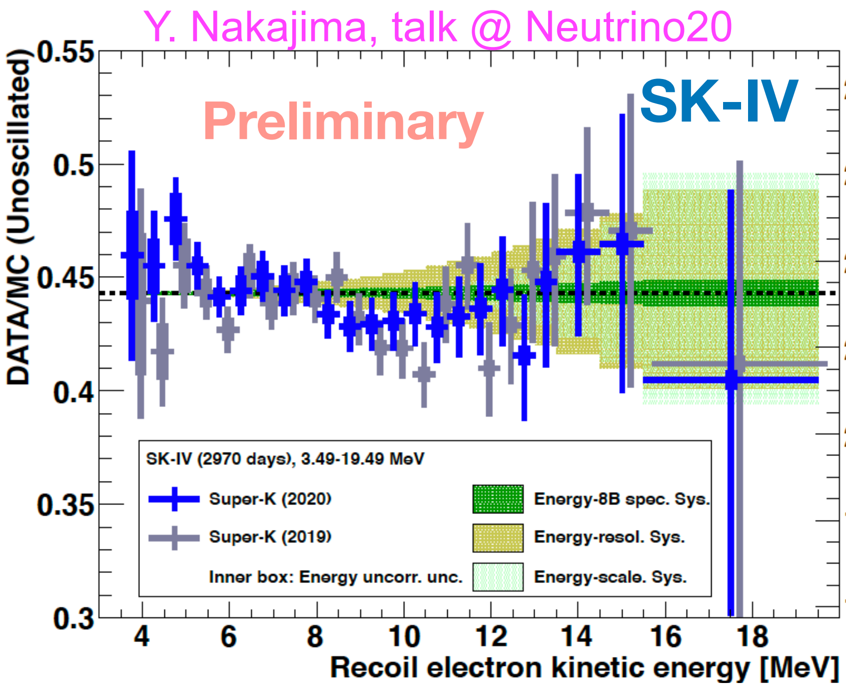


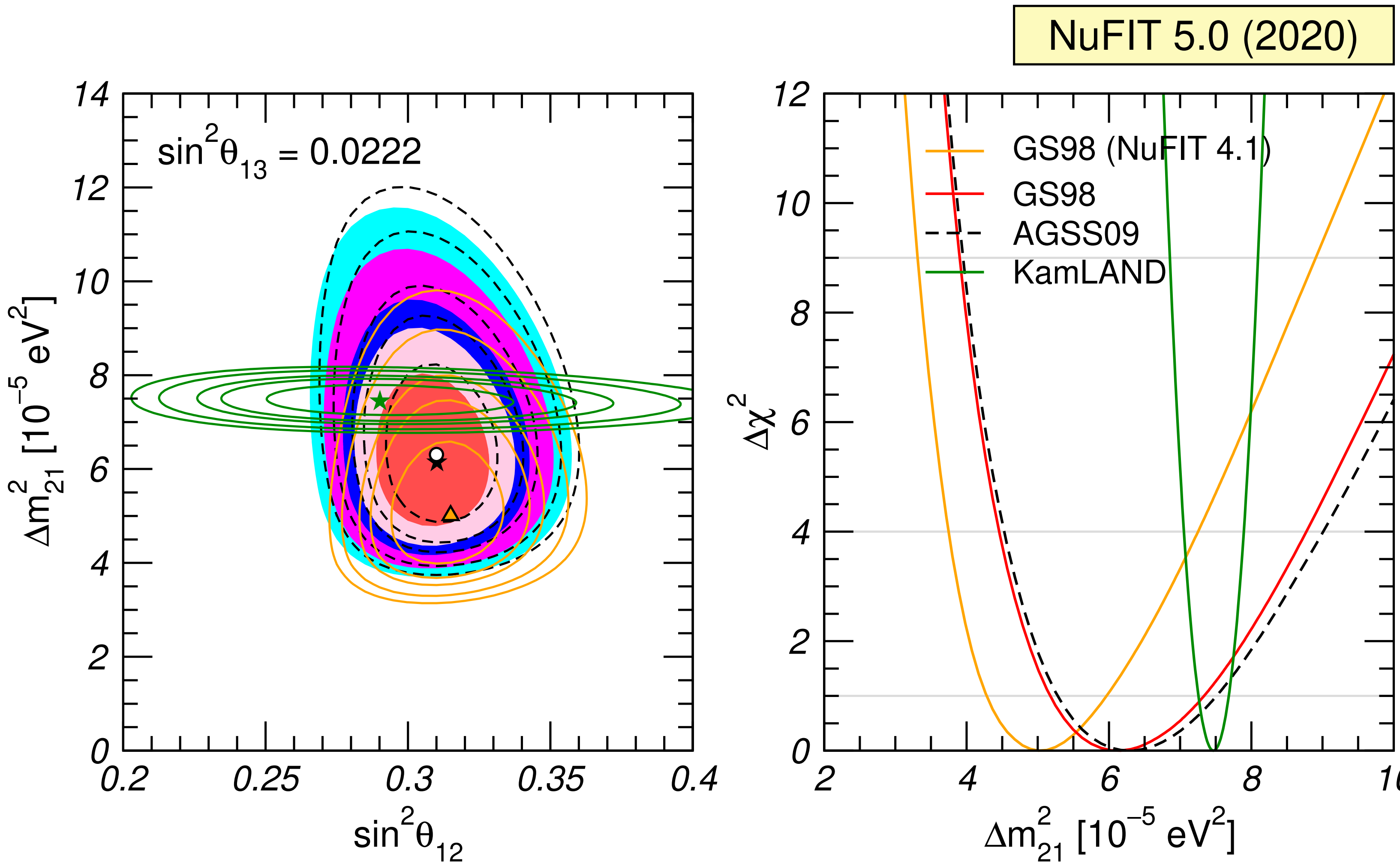
long-standing tension between Δm^2 from KamLAND and solar neutrinos:

- missing up-turn of high-energy solar neutrino spectrum
- too large day-night effect

KIT Karlsruhe Institute of Technology

Small „tension“ (2σ) in 12 sector: RESOLVED



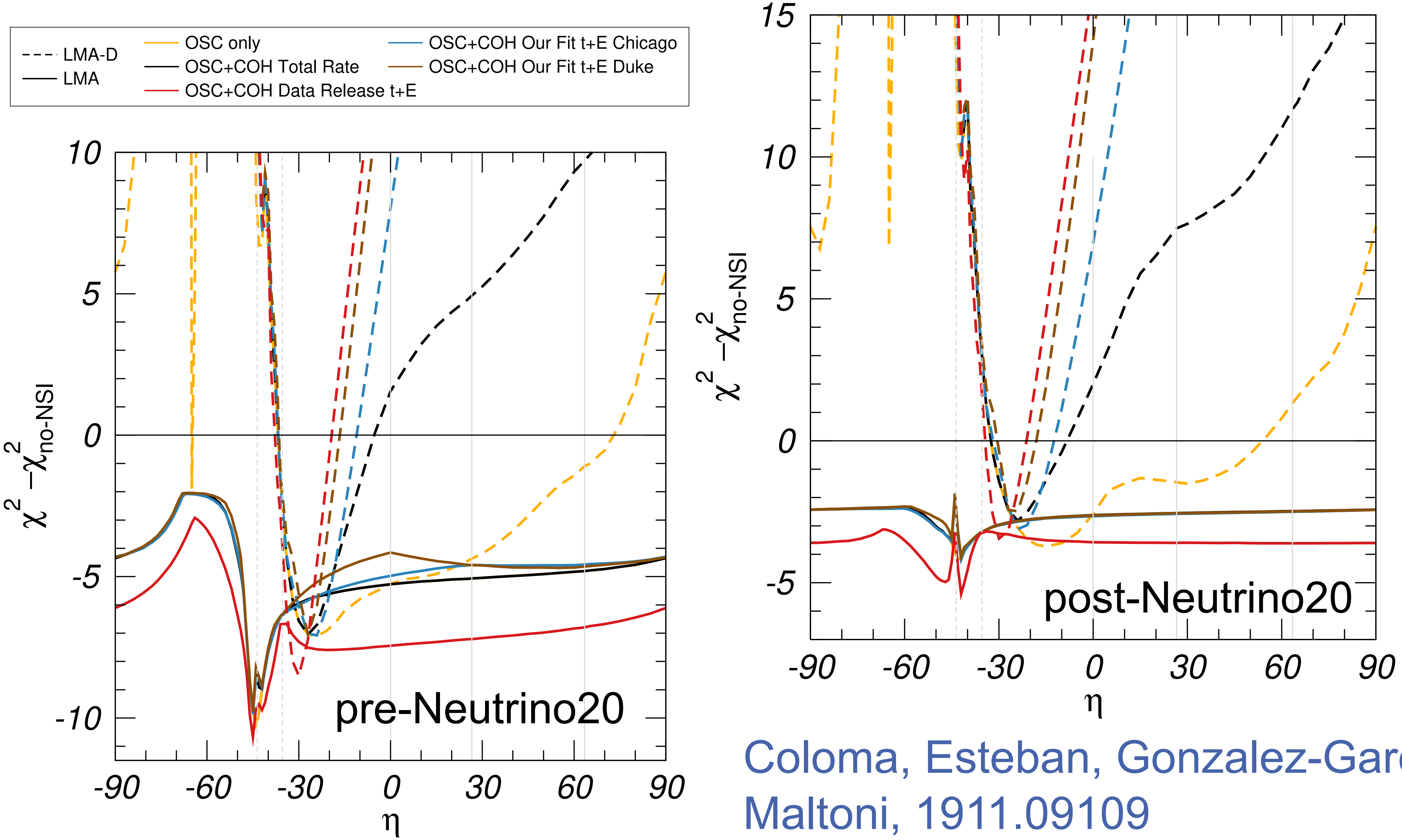


- new SuperK solar neutrino data @ Neutrino20:
  - spectrum better compatible with KamLAND prediction
  - day/night asym.: $A_{DN}^{Fit} = (-3.6 \pm 1.6(stat) \pm 0.6(syst))\,\%$ $\rightarrow$ $A_{DN}^{Fit} = (-2.1 \pm 1.1)\,\%$
- solar neutrino and KamLAND data compatible at 1.1σ

Hints for non-standard neutrino interactions?

$$\mathcal{L}_{\mathrm{NSI,NC}} = \sum_{f,\alpha,\beta} 2\sqrt{2} G_F \varepsilon_{\alpha\beta}^{f,P} (\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta)(\bar{f}\gamma^\mu P f) + \mathrm{h.c.}$$

global fit of osc + NC NSI (5+7 params.), oscillation data + COHERENT



Coloma, Esteban, Gonzalez-Garcia, Maltoni, 1911.09109

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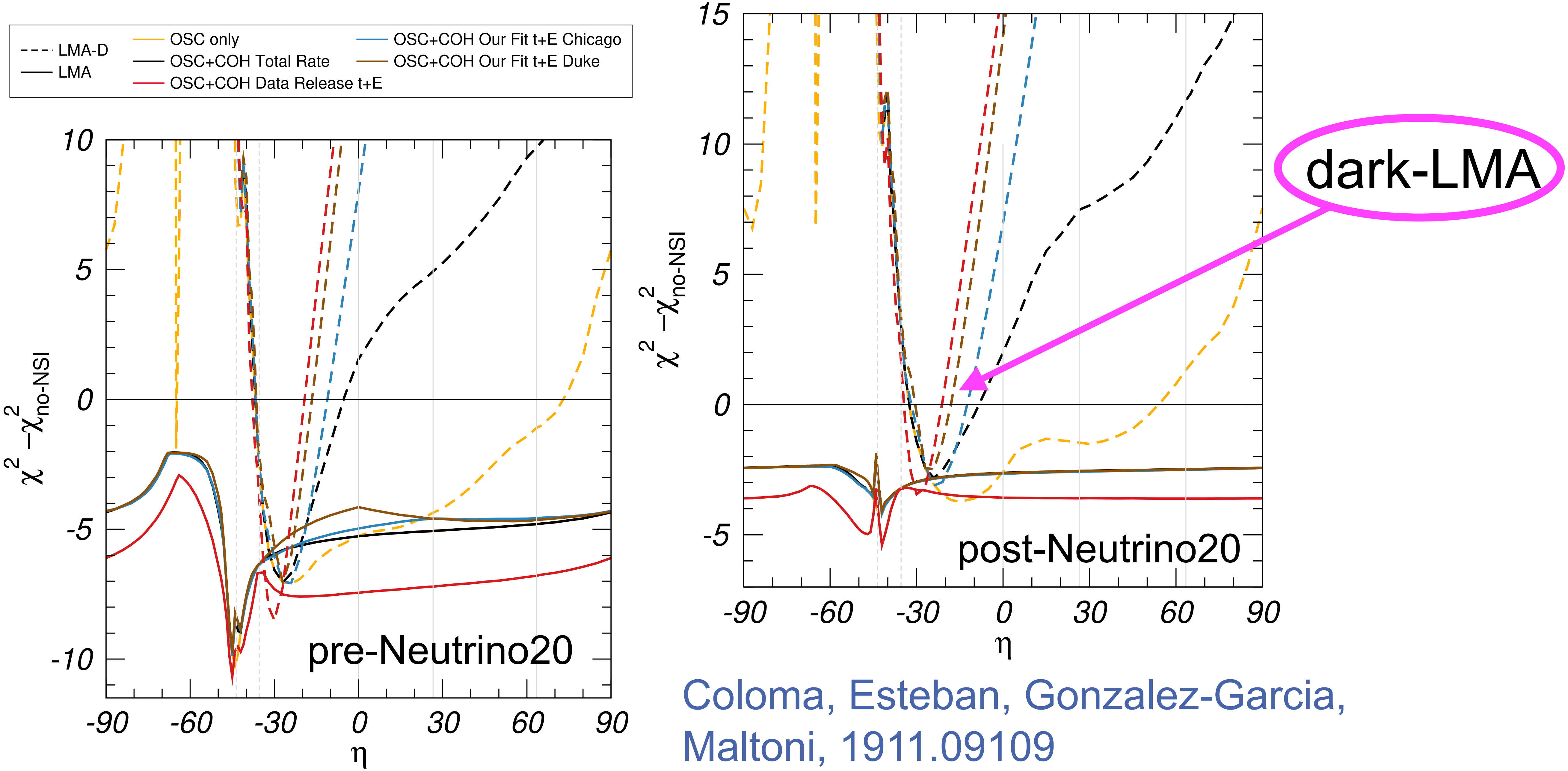


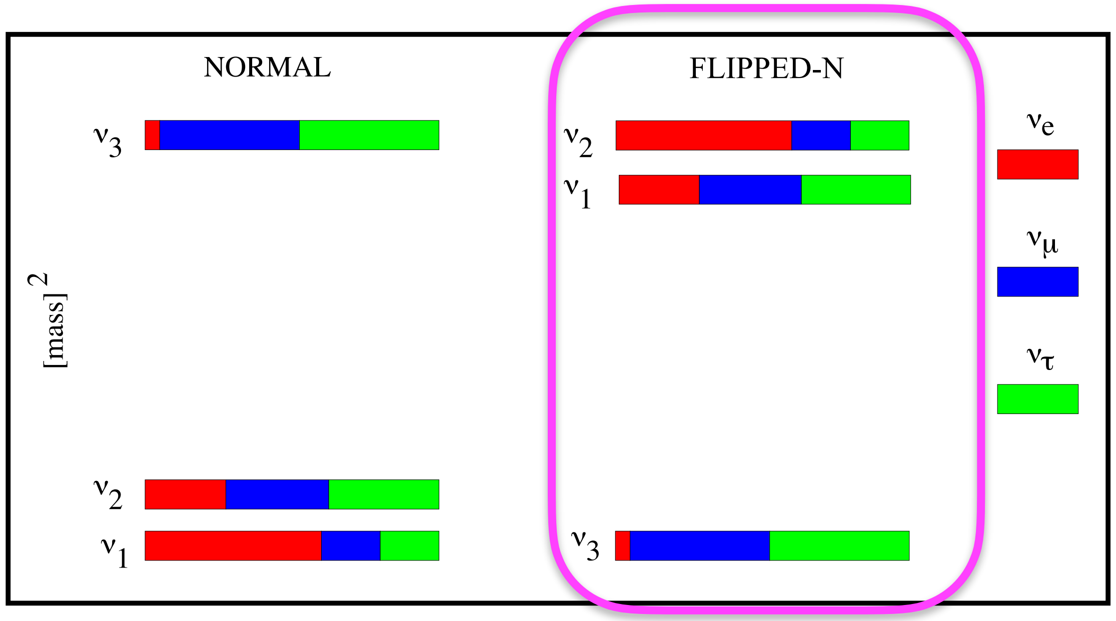
Coloma, Esteban, Gonzalez-Garcia, Maltoni, 1911.09109

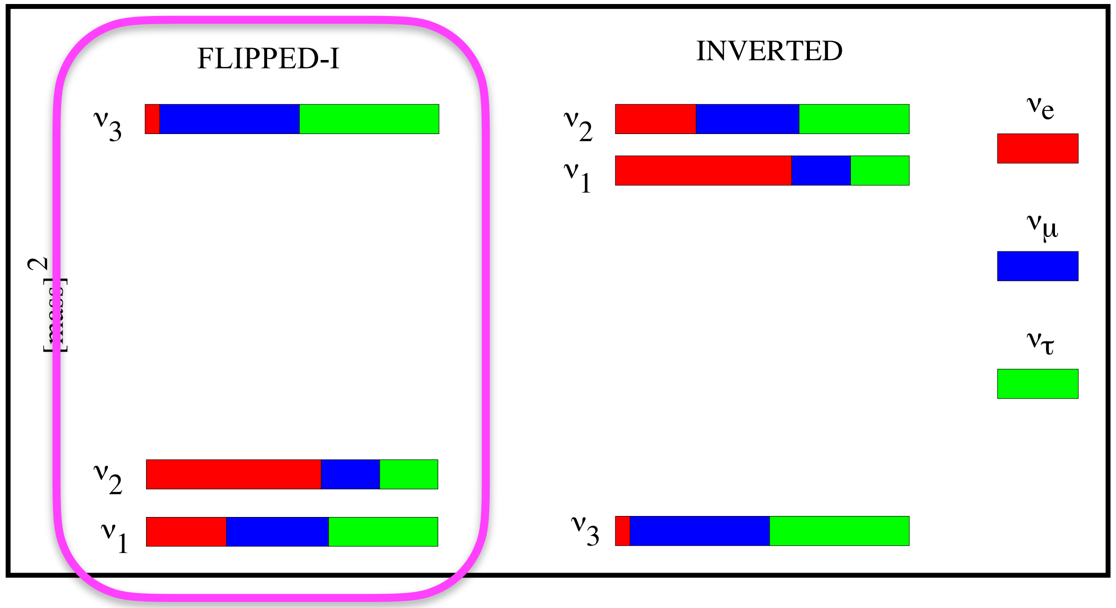
Dark-LMA / generalised MO degeneracy

- solution with $\theta_{12} > 45°$: „dark-LMA“
  Miranda, Tortola, Valle, hep-ph/0406280
- implies flipping of the mass ordering: „generalised MO degeneracy“ Coloma, TS, 06

$\Rightarrow$

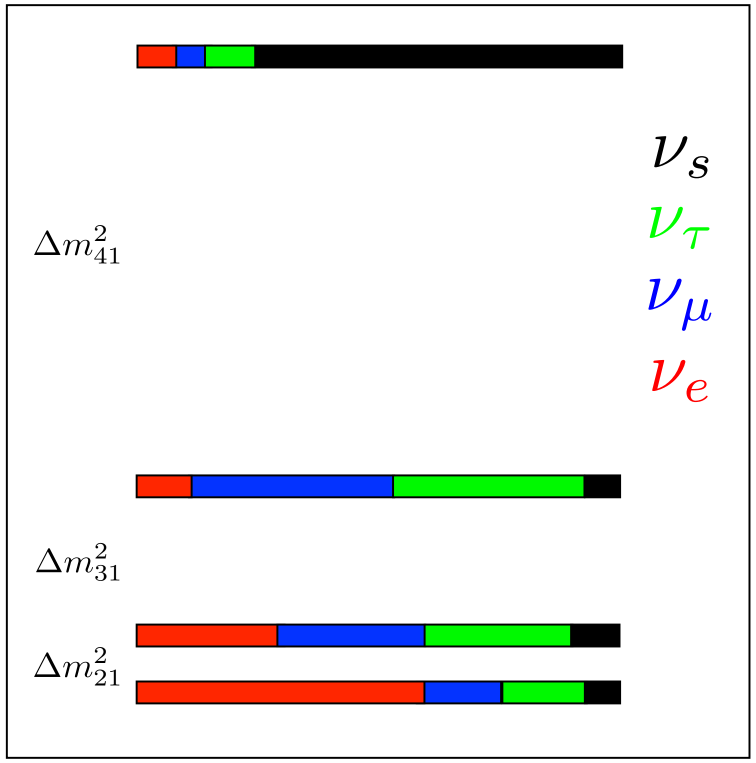
- requires NSI ~ G_F
- O(1) modification of mixing pattern
- makes determination of MO by oscillation experiments impossible





Sterile neutrinos at the eV scale?

- Reactor anomaly ($\bar{\nu}_e$ disappearance)
  - predicted vs measured rate
  - distance dependent spectral distortions
- Gallium anomaly (ν_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)



Reactor anomaly

- tension between „predicted“ and observed neutrino rates at nuclear reactors
- dominated by systematic/theoretical uncertainty, status „unclear“

Berryman, Huber, 1909.09267

Huber, Muller, 2011 → HM Rates

Estienne et al., 1904.09358 → *Ab Initio* Rates

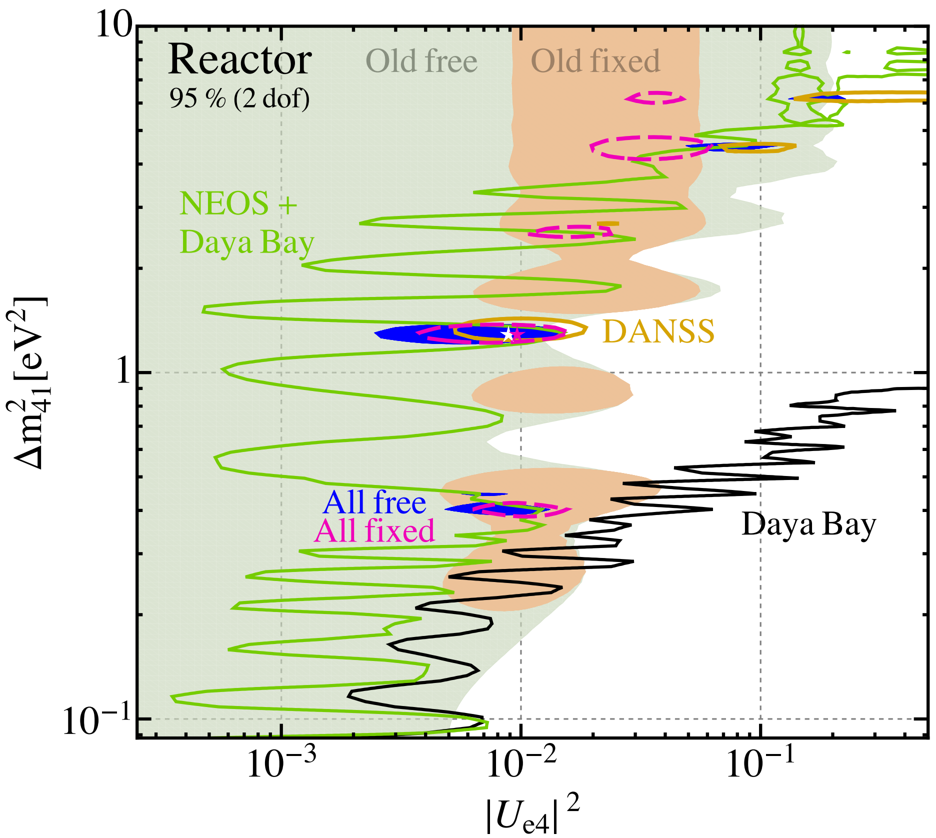
Hayen et al., 1908.08302 → HKSS Rates

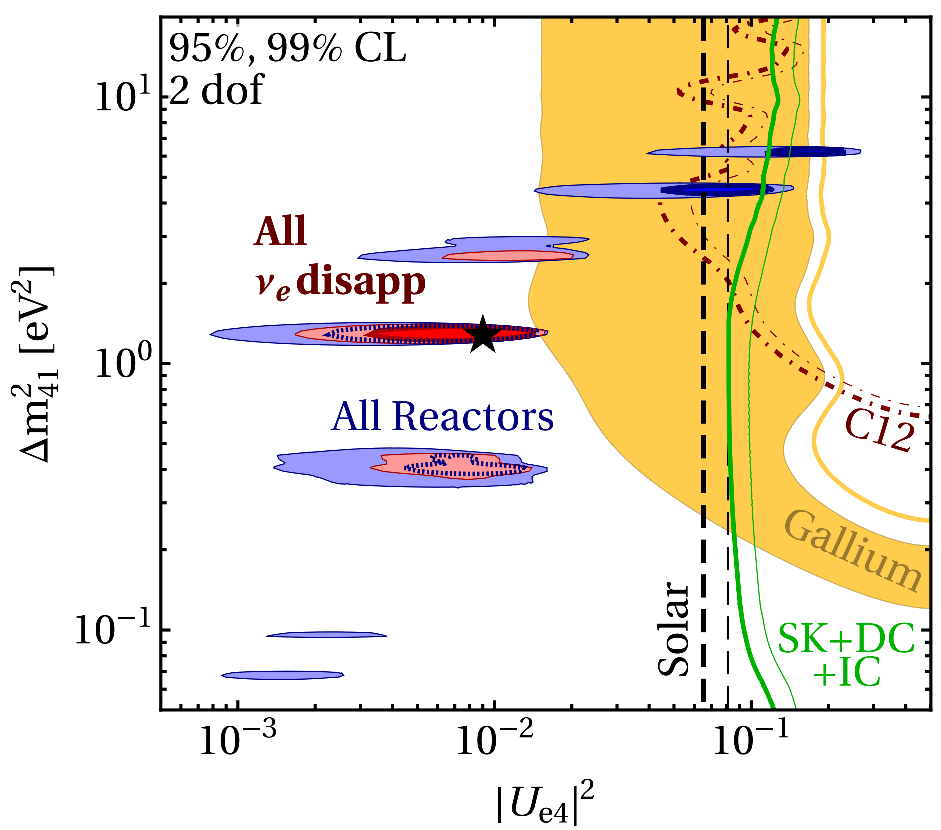
Analysis	$\chi^2_{3\nu}$	$\chi^2_{\rm min}$	$n_{\rm data}$	p	$n\sigma$
HM Rates	41.4	33.5	40	2.0×10^{-2}	2.3
Ab Initio Rates	39.2	37.0	40	0.34	0.95
HKSS Rates	58.1	47.5	40	5.0×10^{-3}	2.8
Spectra	184.9	172.2	212	1.8×10^{-3}	3.1
DANSS + NEOS	98.9	84.7	84	8.1×10^{-4}	3.3

Hints from relative shape measurements — 2018 status

Analysis	Δm^2_{41} [eV^2]	$\lvert U^2_{e4}\rvert$	$\chi^2_{\rm min}$/dof	$\Delta\chi^2$(no-osc)	significance
DANSS+NEOS	1.3	0.00964	74.4/(84 – 2)	13.6	3.3σ
all reactor (flux-free)	1.3	0.00887	185.8/(233 – 5)	11.5	2.9σ
all reactor (flux-fixed)	1.3	0.00964	196.0/(233 – 3)	15.5	3.5σ
$\overset{(-)}{\nu}_e$ disap. (flux-free)	1.3	0.00901	542.9/(594 – 8)	13.4	3.2σ
$\overset{(-)}{\nu}_e$ disap. (flux-fixed)	1.3	0.0102	552.8/(594 – 6)	17.5	3.8σ

assuming Wilks theorem

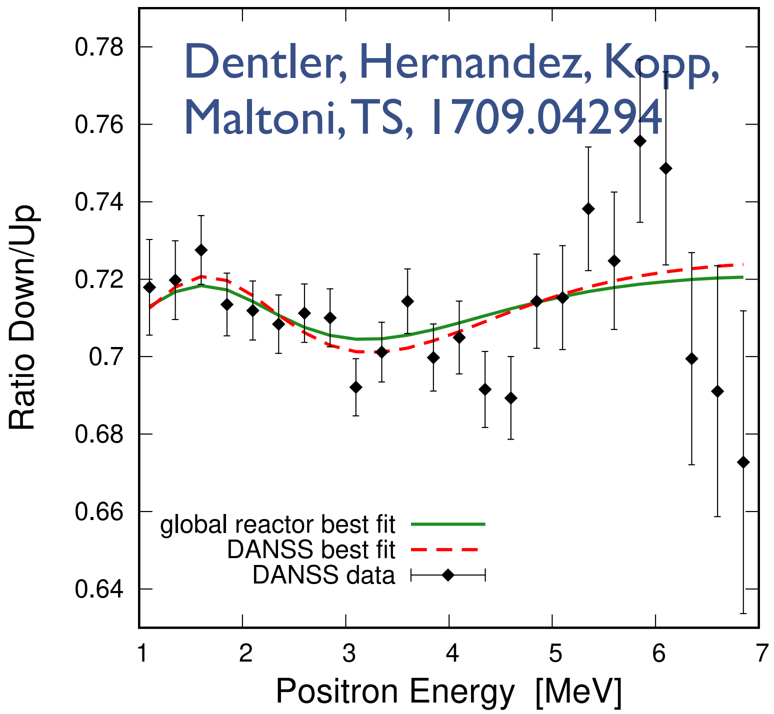




Dentler et al., 1803.10661

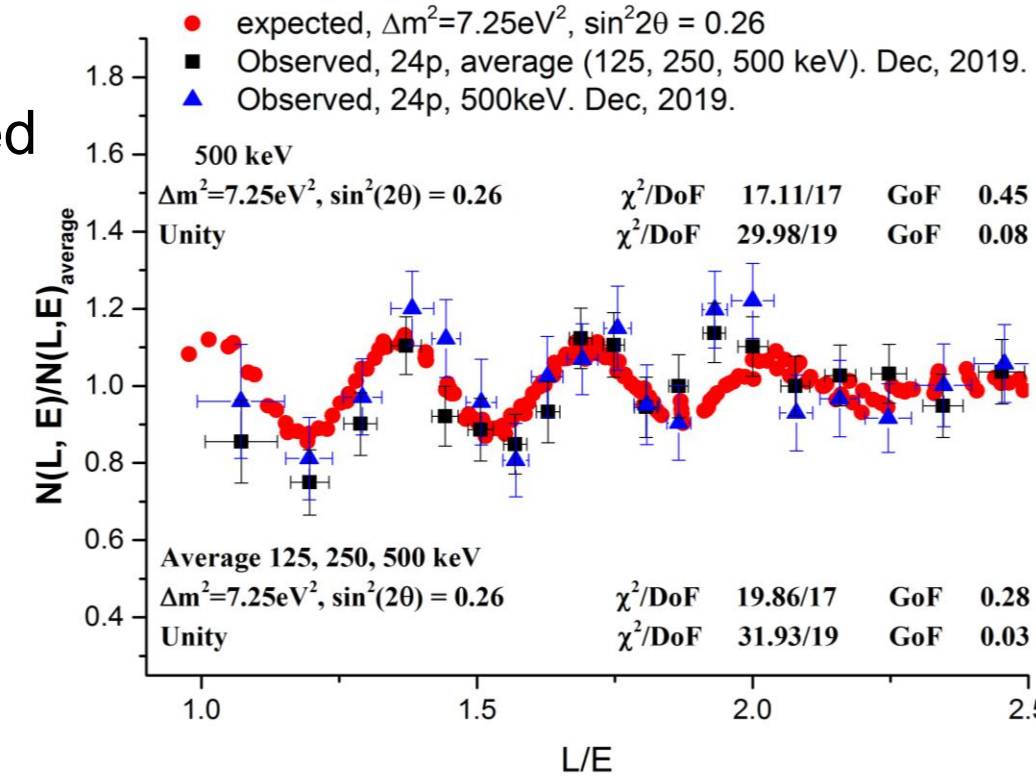
hint for sterile neutrino oscillations, independent of reactor flux calculations!

Recent relative spectral measurments



Neutrino4: segmented detector, L = 6.25 to 11.9 m, 216 bins in L/E „3σ“ indication

Neutrino4 2005.05301

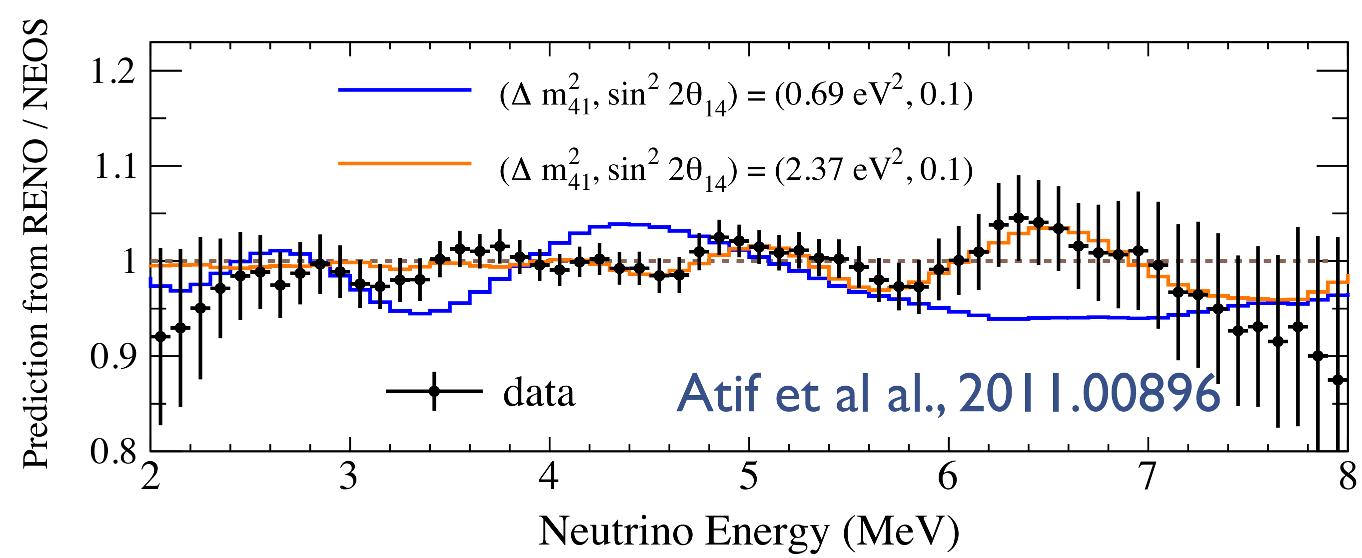


DANSS: relative spectra @ L = 10.7 and 12.7 m
prev. ~ 2σ hint decr. ~1.5σ
DANSS talk @ ICHEP20

segmented detectors:

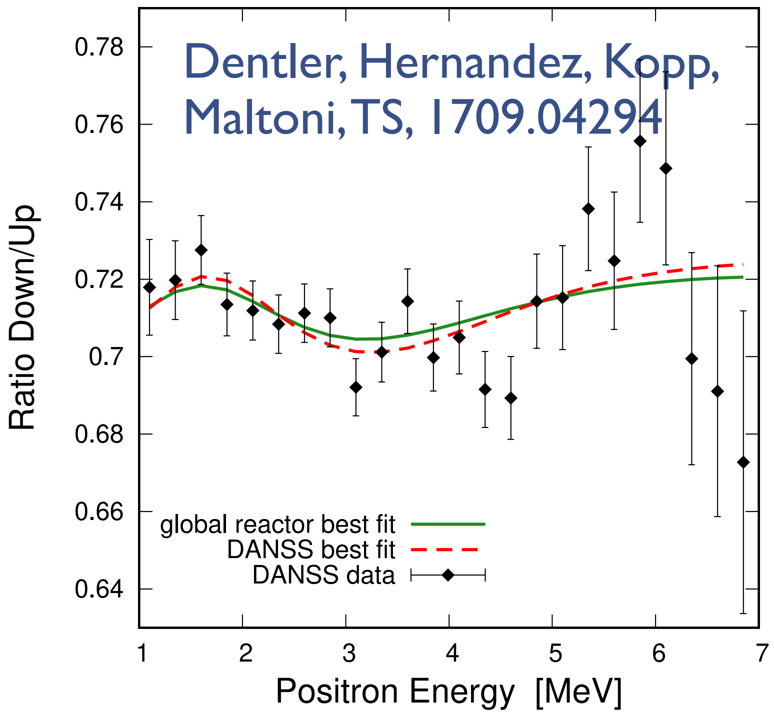
STEREO [arXiv:1912.06582]
L = 9 to 11 m $\Delta\chi^2$(no osc) ≈ 9

PROSPECT [arXiv:2006.11210]
L = 6.7 to 9.2 m



NEOS: spectrum at L = 24 m, relative to RENO (or DayaBay) near detectors: $\Delta\chi^2$(no osc) = 11.7

Recent relative spectral measurments



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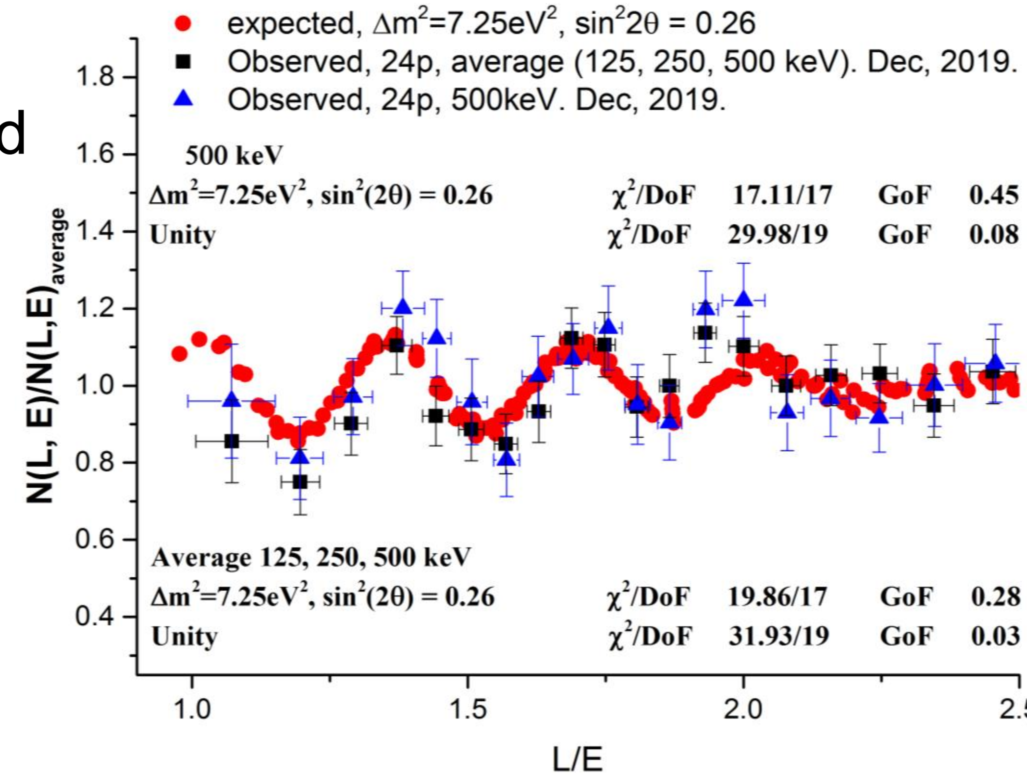

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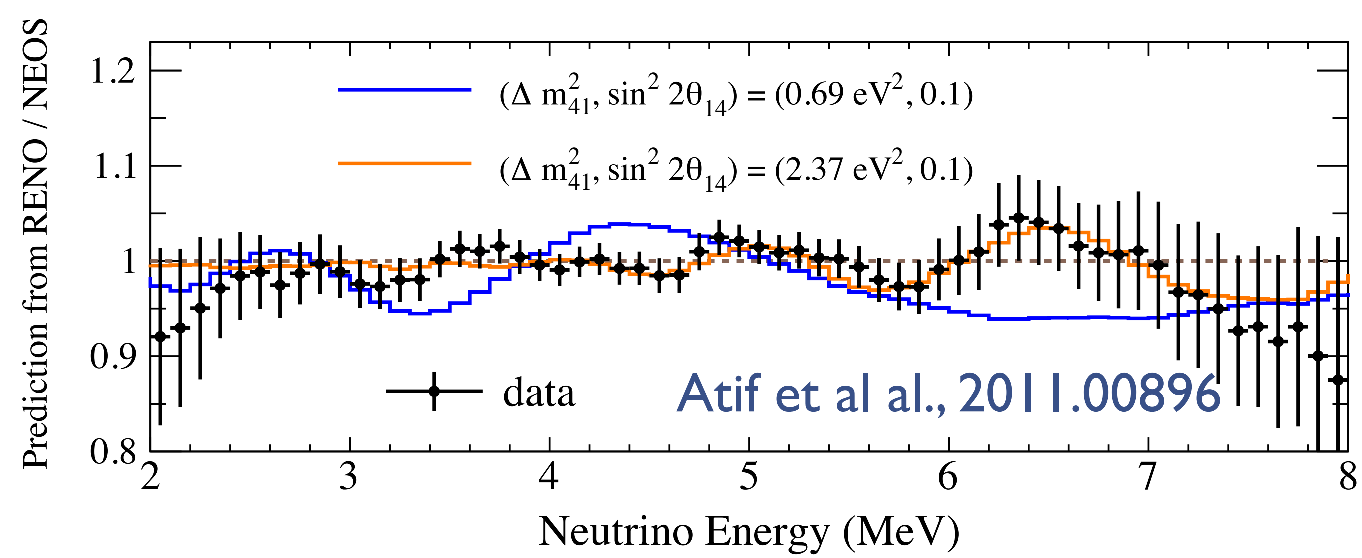

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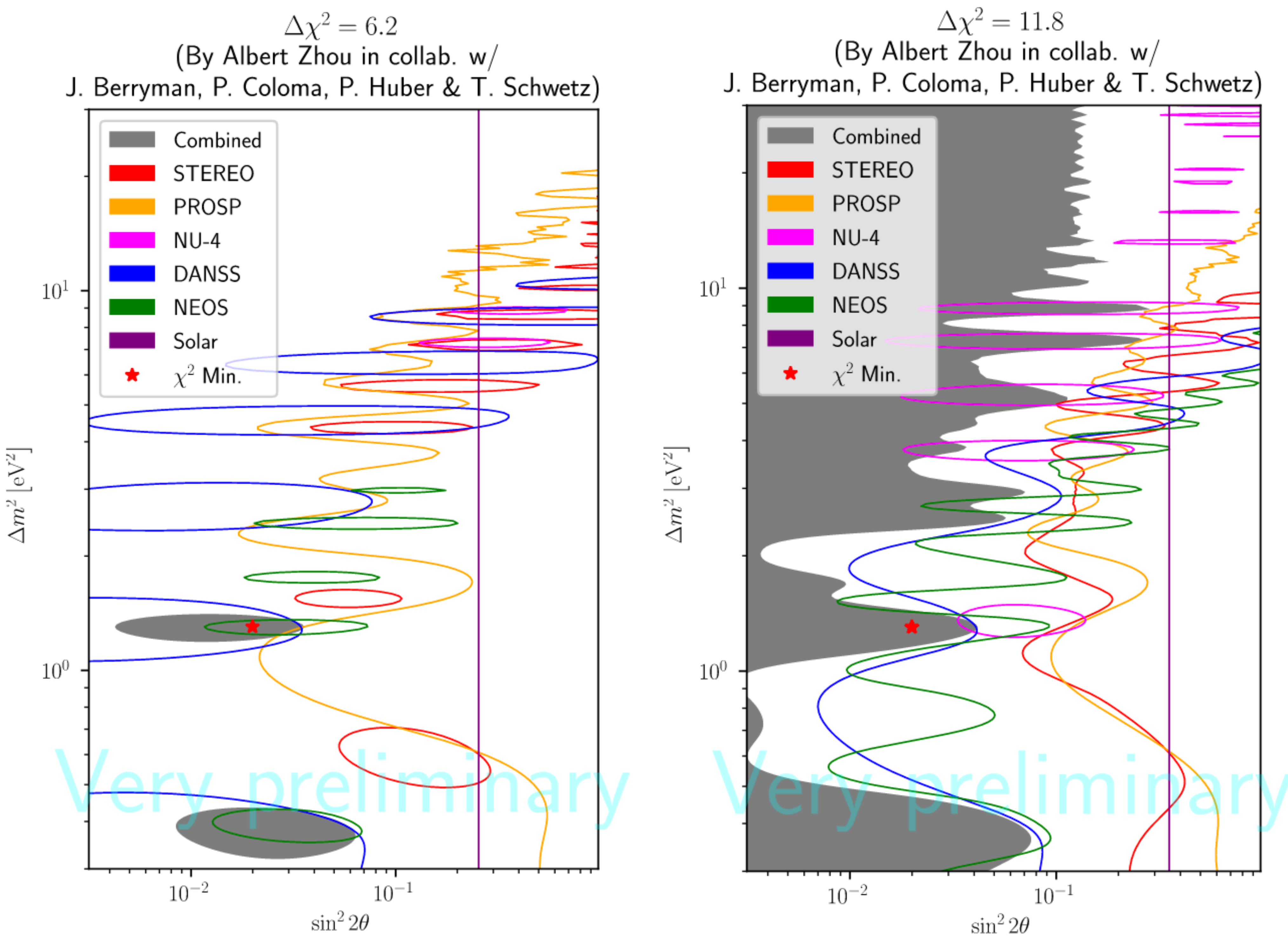
Are hints consistent with each other?



global best fit:

$\Delta\chi^2$(no osc) = 9.9

$\Delta m^2 = 1.3$ eV^2

$\sin^2 2\theta = 0.02$

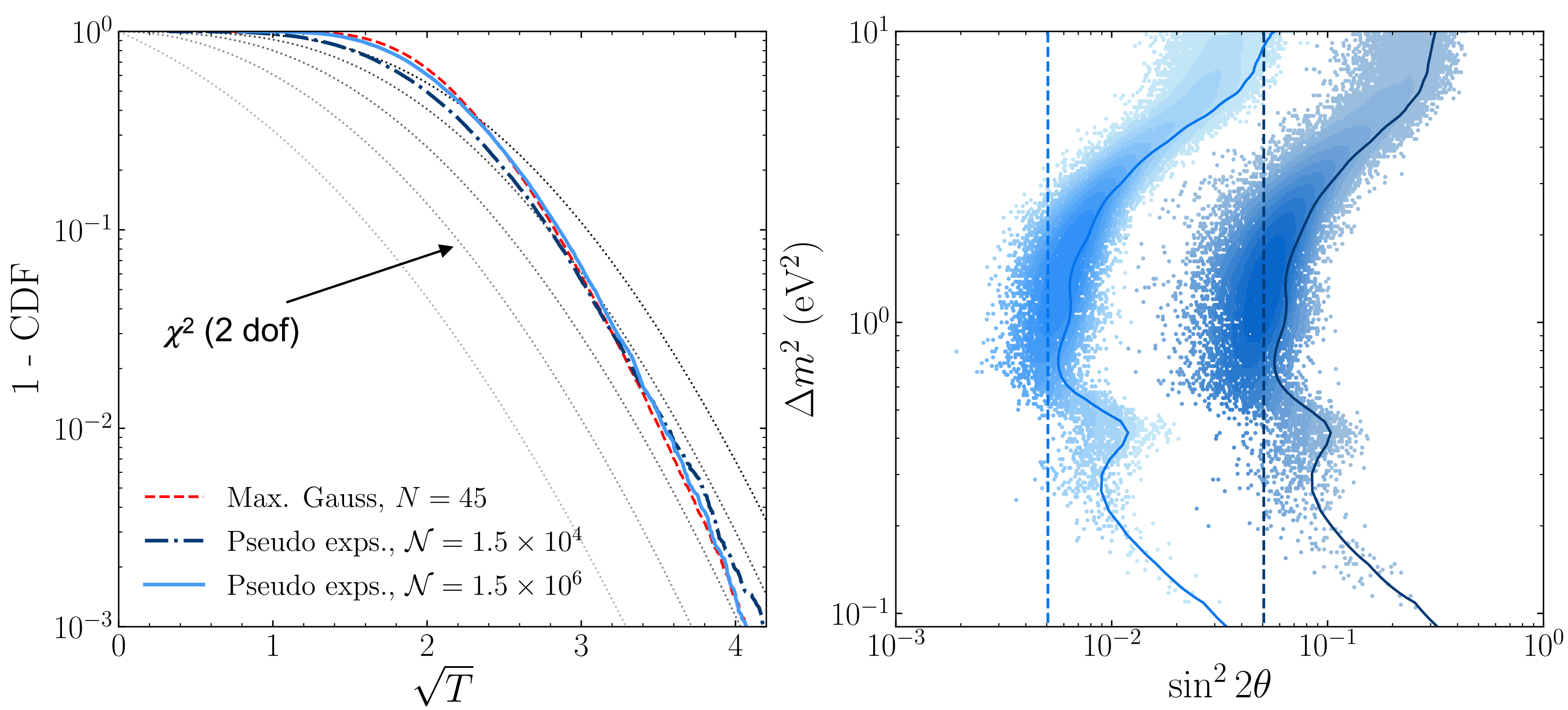
NEOS analysis to be updated

Evaluating significances is tricky

$$\chi^2(s,\kappa) = \sum_{i=1}^{N} \left[n_i - s\cos\varphi_{\kappa i}\right]^2$$

- sterile osc. search is similar to fitting white noise with cosine of arbitrary amplitude and frequency
- → it is very likely to find *some* frequency which fits random fluctuations

Coloma, Huber, Schwetz, 2008.06083



Wilks theorem does not apply

see also, Feldman, Cousins, 98; Agostini, Neumair, 1906.11854; Giunti, 2004.07577; PROSPECT&STEREO colls. 2006.13147

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- → it is very likely to find *some* frequency which fits random fluctuations

Neutrino4 case study:

significance for signal is reduced from

3.2σ (*p*=0.0016) to 2.6σ (*p*=0.0091)

based on stat. errors only

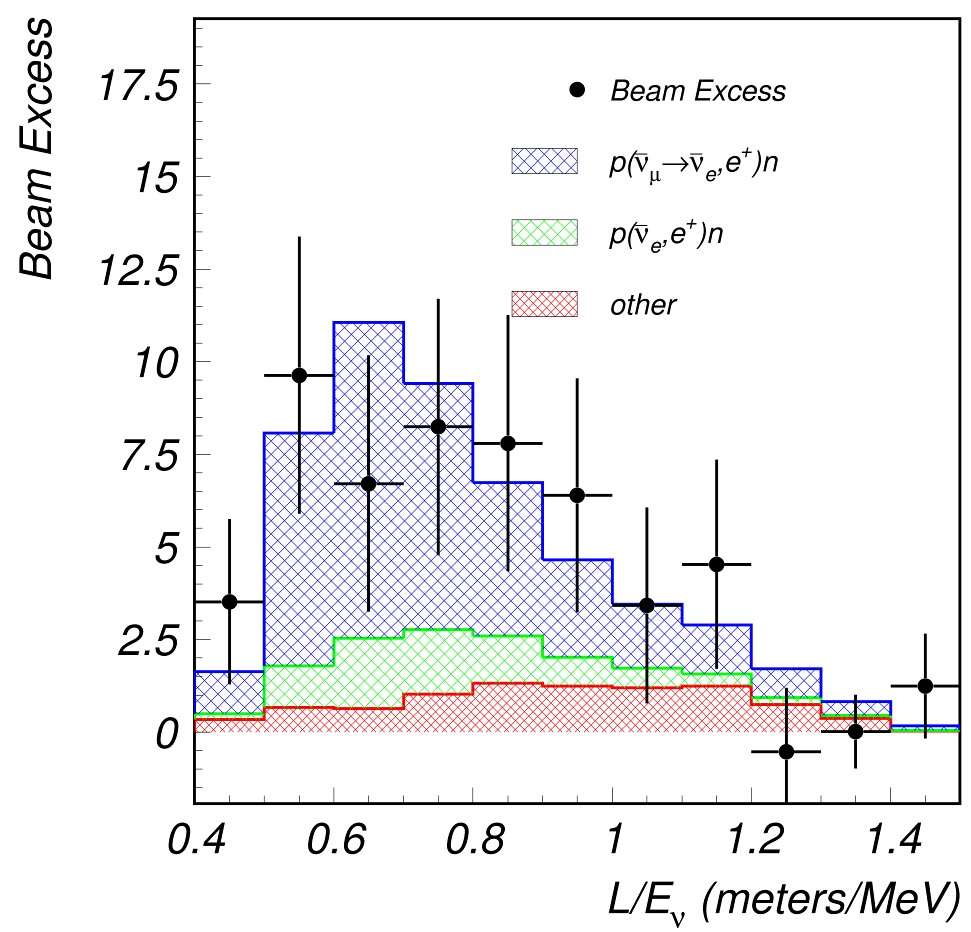
Coloma, Huber, Schwetz, 2008.06083

Wilks theorem does not apply

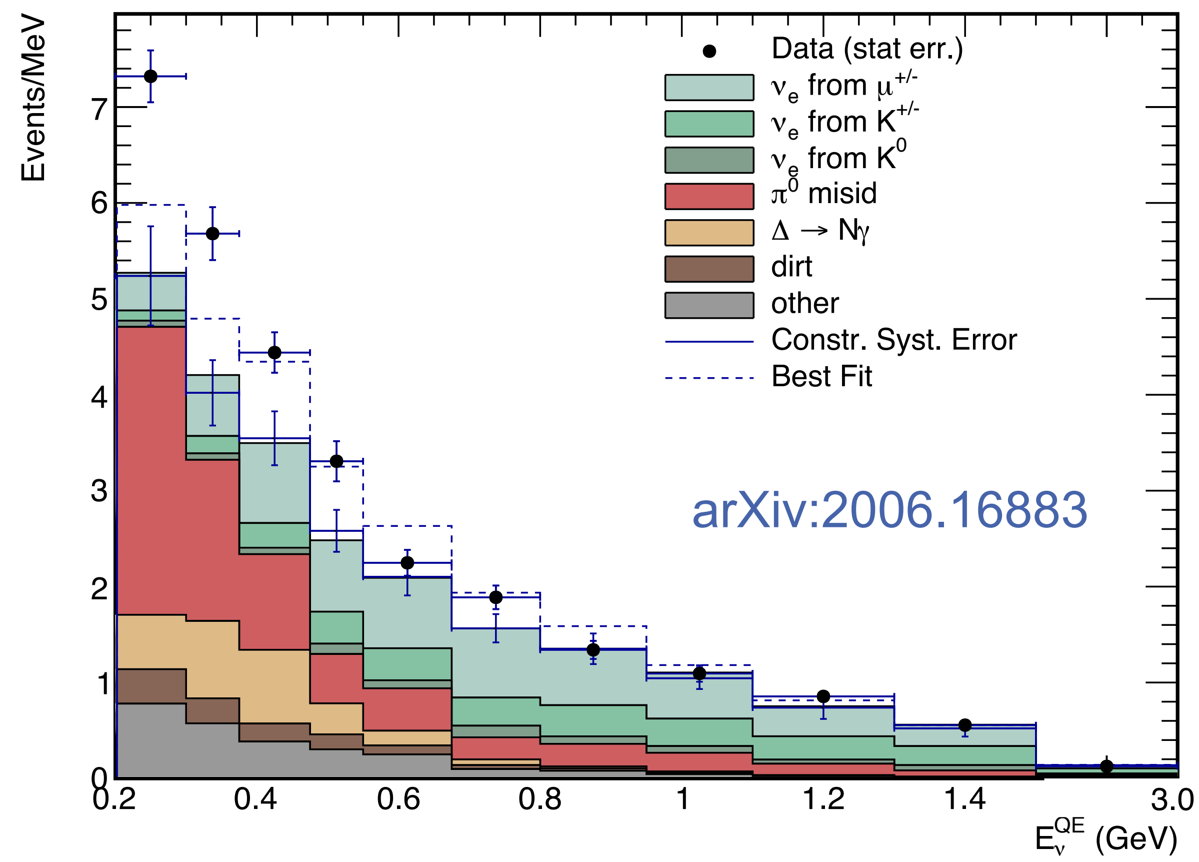
see also, Feldman, Cousins, 98; Agostini, Neumair, 1906.11854; Giunti, 2004.07577; PROSPECT&STEREO colls. 2006.13147

Hints for $\nu_\mu \to \nu_e$ appearance

LSND, 2001



MiniBooNE 2020

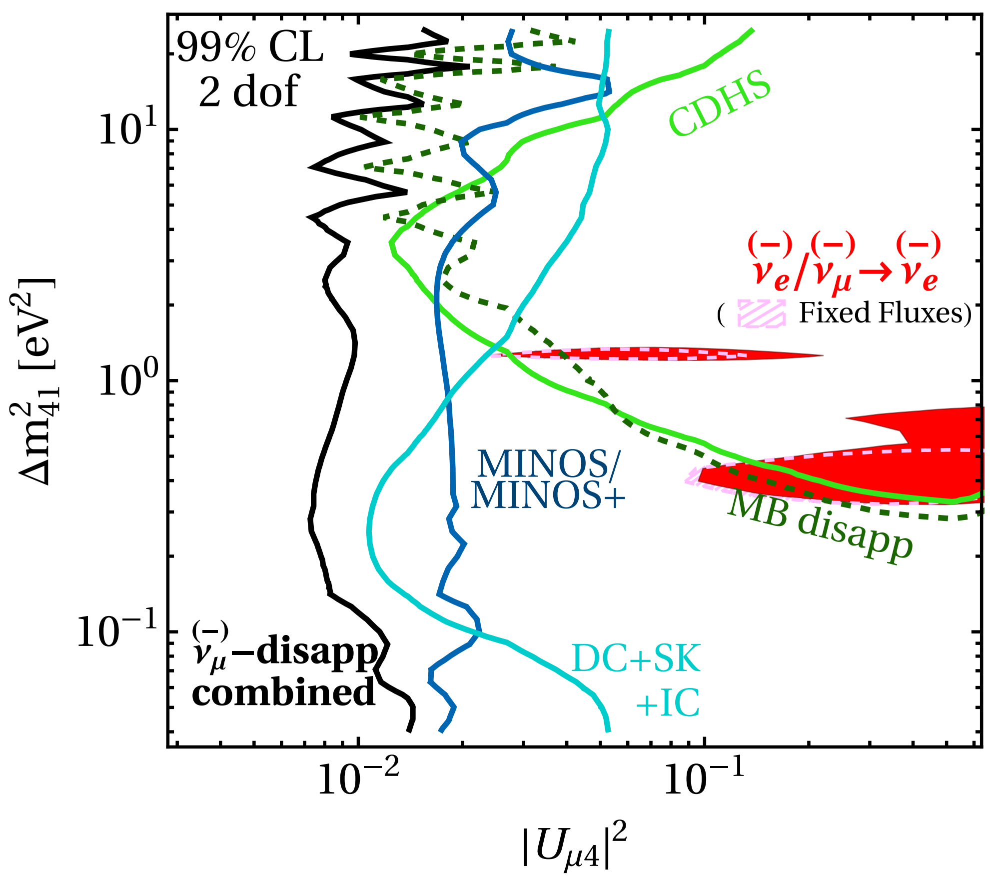


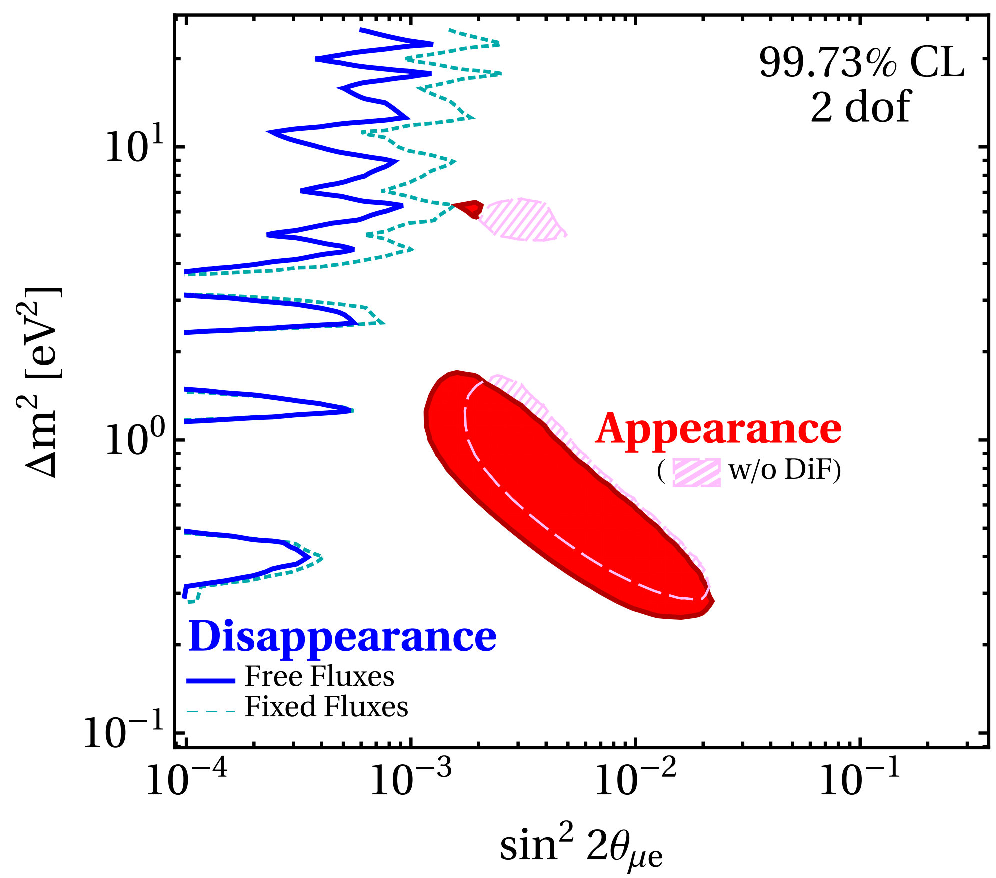
- signal for $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions (3.8σ)

combined neutrino+antineutrino excess: 638.0±132.8 events (4.8σ)

Strong tension btw appearance and disappearance

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





non-observation of oscillations in ν_μ disappearance (CDHS, MiniB, MINOS+, SK, IceCube)

consistency of appearance and disapp. data with a p-value $< 10^{-6}$

Dentler et al, 1803.10661

Strong tension btw appearance and disappearance

→ sterile neutrino oscillation explanation of LSND/MB excluded

… robust result wrt to individual experiments

Analysis	$\chi^2_{\text{min,global}}$	$\chi^2_{\text{min,app}}$	$\Delta\chi^2_{\text{app}}$	$\chi^2_{\text{min,disapp}}$	$\Delta\chi^2_{\text{disapp}}$	$\chi^2_{\text{PG}}/\text{dof}$	PG
Global	1120.9	79.1	11.9	1012.2	17.7	29.6/2	3.71×10^{-7}
Removing anomalous data sets							
w/o LSND	1099.2	86.8	12.8	1012.2	0.1	12.9/2	1.6×10^{-3}
w/o MiniBooNE	1012.2	40.7	8.3	947.2	16.1	24.4/2	5.2×10^{-6}
w/o reactors	925.1	79.1	12.2	833.8	8.1	20.3/2	3.8×10^{-5}
w/o gallium	1116.0	79.1	13.8	1003.1	20.1	33.9/2	4.4×10^{-8}
Removing constraints							
w/o IceCube	920.8	79.1	11.9	812.4	17.5	29.4/2	4.2×10^{-7}
w/o MINOS(+)	1052.1	79.1	15.6	948.6	8.94	24.5/2	4.7×10^{-6}
w/o MB disapp	1054.9	79.1	14.7	947.2	13.9	28.7/2	6.0×10^{-7}
w/o CDHS	1104.8	79.1	11.9	997.5	16.3	28.2/2	7.5×10^{-7}
Removing classes of data							
$\overset{(-)}{\nu}_e$ dis vs app	628.6	79.1	0.8	542.9	5.8	6.6/2	3.6×10^{-2}
$\overset{(-)}{\nu}_\mu$ dis vs app	564.7	79.1	12.0	468.9	4.7	16.7/2	2.3×10^{-4}
$\overset{(-)}{\nu}_\mu$ dis + solar vs app	884.4	79.1	13.9	781.7	9.7	23.6/2	7.4×10^{-6}

reactor flux-free analysis

Dentler et al, 1803.10661

results for 2018 MiniB very similar (tension gets slightly worse)

Other BSM explanations? incomplete and outdated list:

- 3-neutrinos and CPT violation Murayama, Yanagida 01; Barenboim, Borissov, Lykken 02; Gonzalez-Garcia, Maltoni, TS 03
- 4-neutrinos and CPT violation Barger, Marfatia, Whisnant 03
- Exotic muon-decay Babu, Pakvasa 02
- CPT viol. quantum decoherence Barenboim, Mavromatos 04
- Lorentz violation Kostelecky et al., 04, 06; Gouvea, Grossman 06
- mass varying ν Kaplan,Nelson,Weiner 04; Zurek 04; Barger,Marfatia,Whisnant 05
- shortcuts of sterile νs in extra dim Paes, Pakvasa, Weiler 05; Doring, Pas, Sicking, Weiler, 18
- decaying sterile neutrino Palomares-Riuz, Pascoli, TS 05; Gninenko 09, 10; Bertuzzo, Jana, Machado, Zukanovich, 18; Ballett, Pascoli, Ross-Lonergan, 18
- energy dependent quantum decoherence Farzan, TS, Smirnov 07; Bakhti, Farzan, TS, 15
- sterile neutrinos and new gauge boson Nelson, Walsh 07
- sterile ν with energy dep. mass or mixing TS 07
- sterile ν with nonstandard interactions Akhmedov, TS 10; Conrad, Karagiorgi, Shaevitz, 12; Liao, Marfatia, Whisnant 18

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- mass varying ν Kaplan,Nel[illegible] Barger,Marfatia,Whisnant 05
- shortcuts of [illegible] P[illegible] 05; Doring, Pas, Sicking, Weiler, 18
- de[illegible] sterile neutrino Palomares-Riuz, Pascoli, TS 05; Gninenko 09, 10; Bertuzzo, Jana, Machado, Zukanovich, 18; Ballett, Pascoli, Ross-Lonergan, 18
- energy dependent quantum decoherence Farzan, TS, Smirnov 07; Bakhti, Farzan, TS, 15
- sterile neutrinos and new gauge boson Nelson, Walsh 07
- sterile ν with energy dep. mass or mixing TS 07
- sterile ν with nonstandard interactions Akhmedov, TS 10; Conrad, Karagiorgi, Shaevitz, 12; Liao, Marfatia, Whisnant 18

many of them excluded by some data

MiniBooNE and a decaying sterile neutrino

Palomares, Pascoli, TS, hep-ph/0505216; Gninenko, 0902.3802, 1009.5536;
Bertuzzo, Jana, Machado, Zukanovich, 1807.09877; Ballett, Pascoli, Ross-Lonergan, 1808.2915;
Arguelles, Hostert, Tsai, 1812.08768; Fischer, Hernandez, TS, 1909.09561;
Dentler, Esteban, Kopp, Machado, 1911.01427; deGouvea, Peres, Prakash, Stenico, 1911.01447;
Brdar, Fischer, Smirnov, 2007.14411, …

- sterile neutrino N with m_N ~ keV to ~500 MeV
- produce N either by mixing or by up-scattering
- decay:
  - N → Φ ν_e with standard neutrino interact in detector
  - electromagn. decay inside MB detector N → $\nu\gamma$ / $\nu e^\pm$ (no LSND explanation)

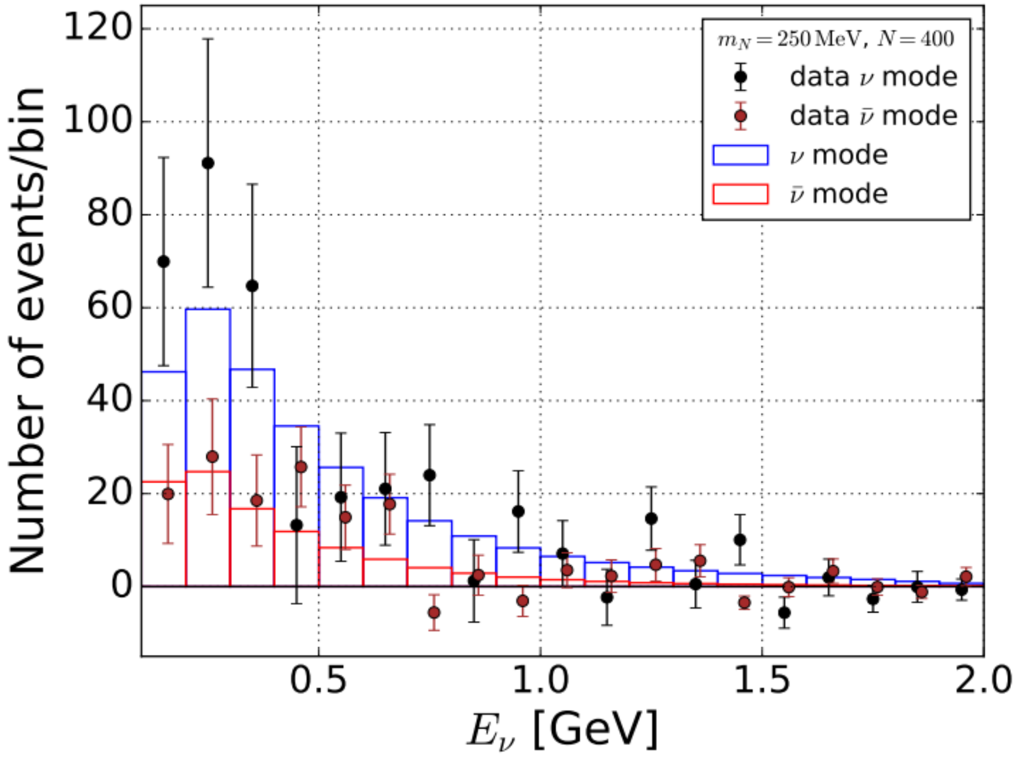
MiniBooNE and a decaying sterile neutrino — example:

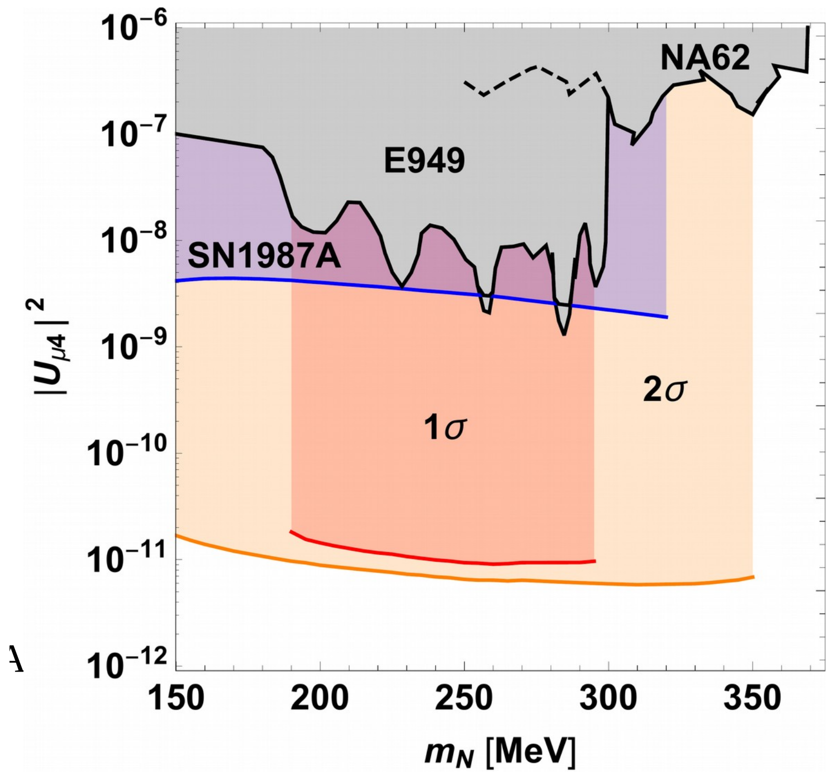
$$K \to N\mu$$

Fischer, Hernandez, TS, 1909.09561

- sterile neutrino N with m_N ~ 250 MeV ($m_\pi < m_N < m_K$)
- produce N in kaon decays via mixing K → N μ/e
- decay inside MB detector N →νγ via

$$\mathcal{O}_{N\to\gamma\nu} = \frac{1}{\Lambda}\bar{N}\sigma^{\alpha\beta}\nu F_{\alpha\beta}$$





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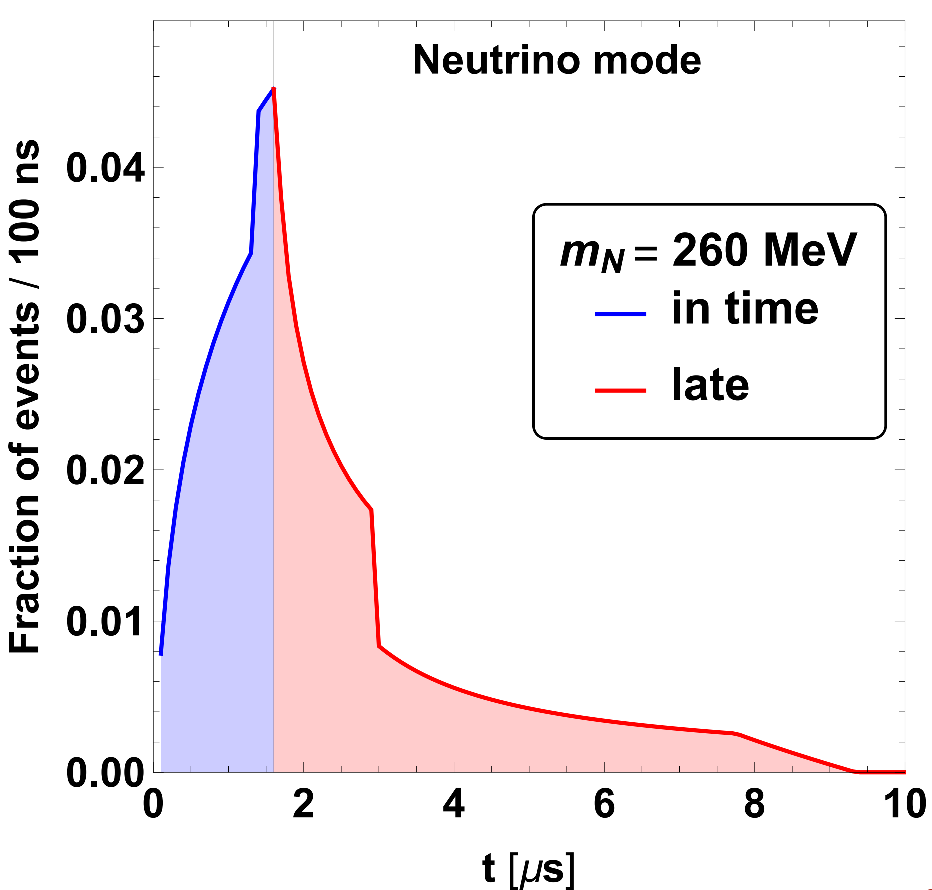

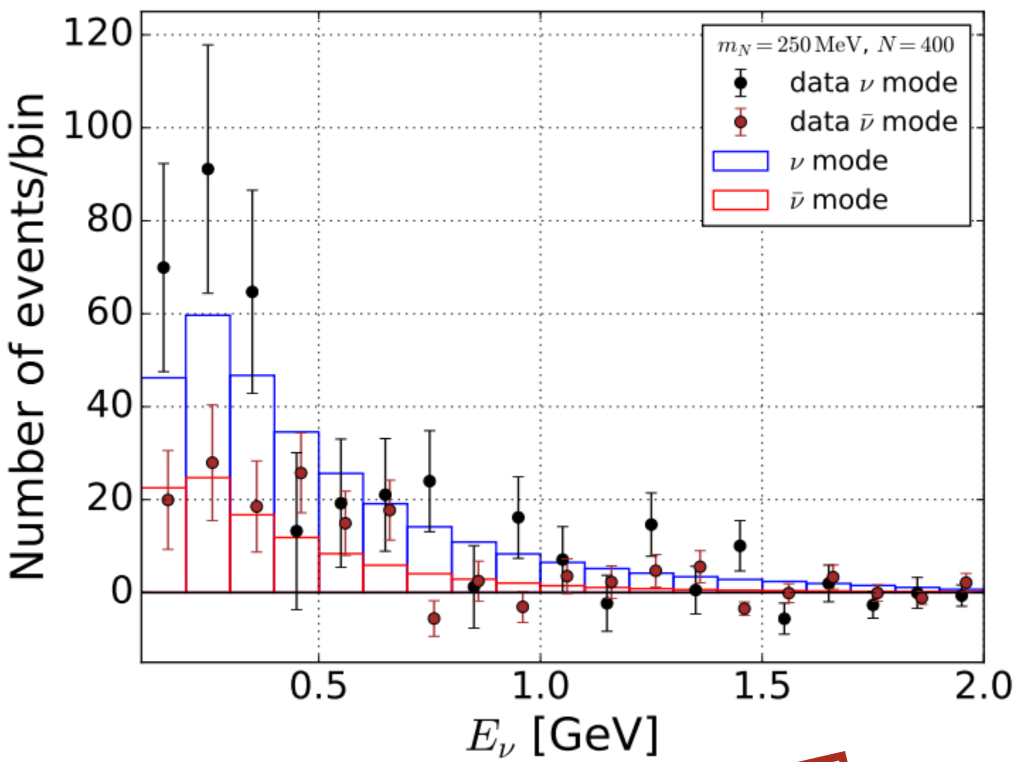

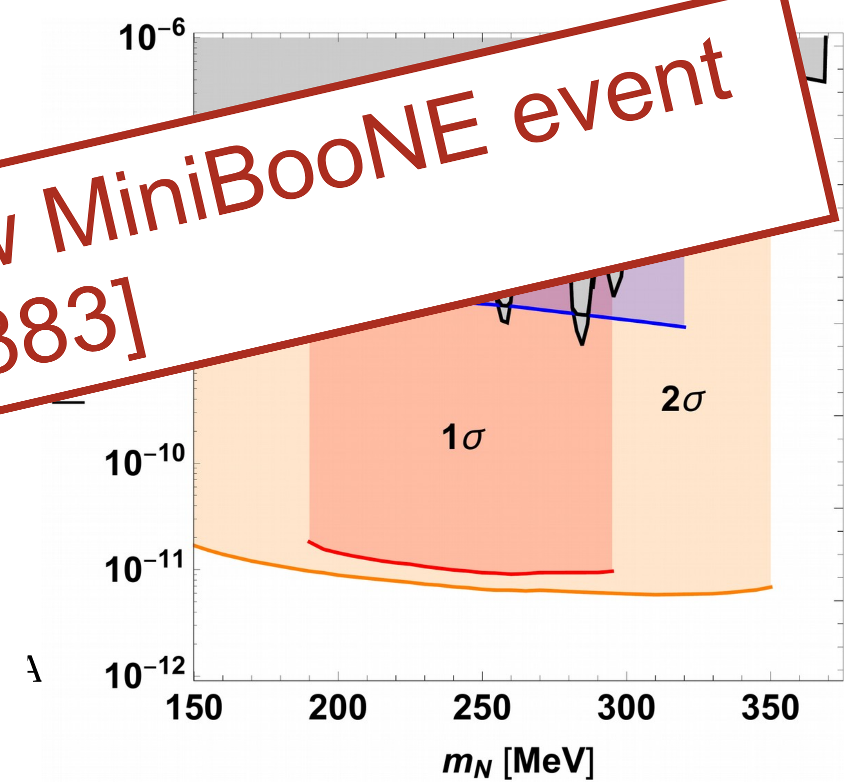

disfavoured (excluded?) by new MiniBooNE event timing analysis [arXiv:2006.16883]

MiniBooNE and a decaying sterile neutrino

Palomares, Pascoli, TS, hep-ph/0505216; Gninenko, 0902.3802, 1009.5536;
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Fischer, Hernandez, TS, 1909.09561; Dentler, Esteban, Kopp, Machado, 1911.01427;
deGouvea, Peres, Prakash, Stenico, 1911.01447; …

- exciting new physics
- rich phenomenology: timing / angular event distributions
- most cannot explain LSND / reactor anomalies
- predict signatures in existing (near detectors) and/or upcoming experiments (Fermilab SBN)

Jordan et al., 1810.07185; Arguelles, Hostert, Tsai, 1812.08768;
Brdar, Fischer, Smirnov, 2007.14411

Summary - fate of hints:

Hint	Fate

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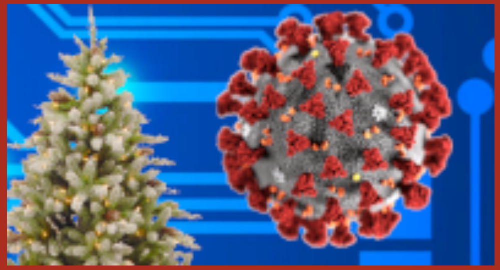
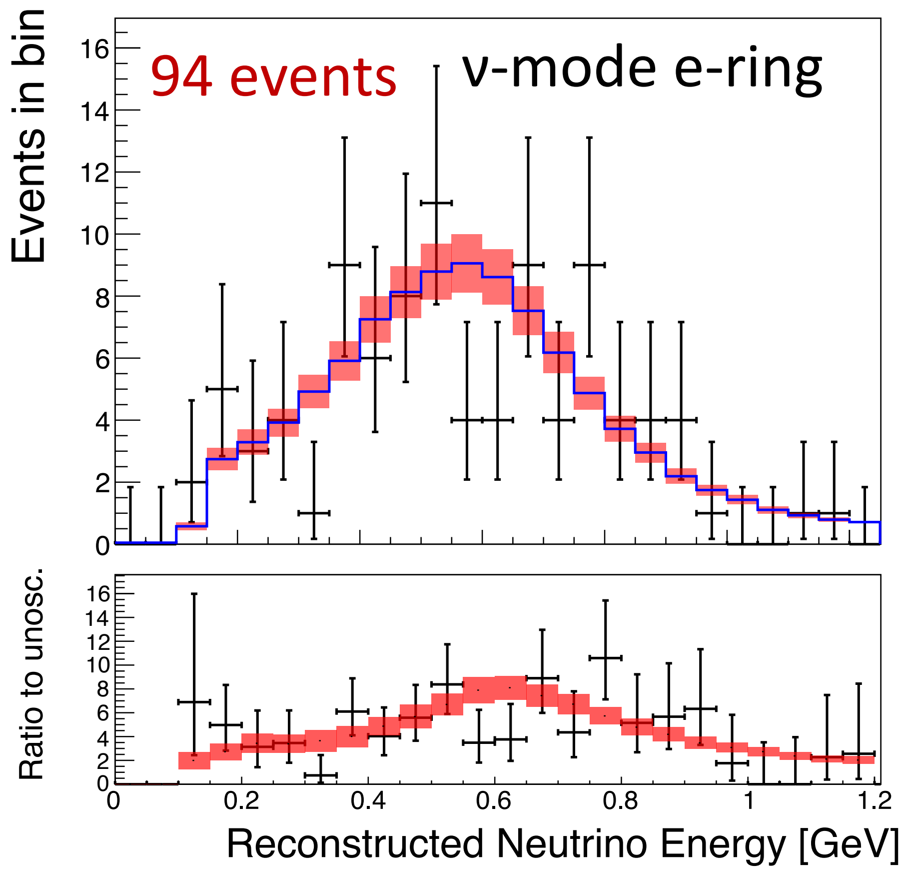
Thank you!

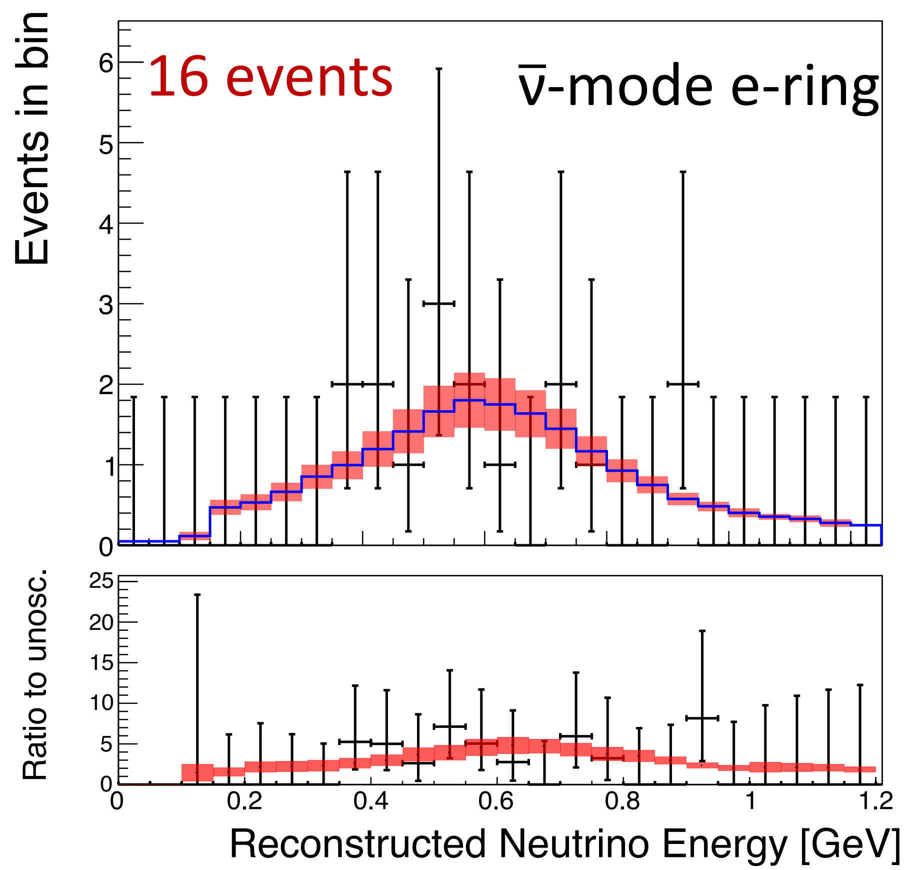


Karlsruhe Institute of Technology

Supplementary slides

T2K and NOvA Neutrino20 $\nu_\mu \rightarrow \nu_e$ appearance results





NOvA neutrino

Total Observed	82	Range
Total Prediction	85.8	52-110
Wrong-sign	1.0	0.6-1.7
Beam Bkgd.	22.7	
Cosmic Bkgd.	3.1	
Total Bkgd.	26.8	26-28

NOvA anti-neutrino

Total Observed	33	Range
Total Prediction	33.2	25-45
Wrong-sign	2.3	1.0-3.2
Beam Bkgd.	10.2	
Cosmic Bkgd.	1.6	
Total Bkgd.	14.0	13-15

>4σ evidence of $\bar{\nu}_e$ appearance

T2K, NOvA, and reactors are consistent with each others

data sets	normal ordering			inverted ordering		
	$\chi^2_{\rm PG}/n$	p-value	$\#\sigma$	$\chi^2_{\rm PG}/n$	p-value	$\#\sigma$
T2K vs NOvA	6.7/4	0.15	1.4σ	3.6/4	0.46	0.7σ
T2K vs React	0.3/2	0.87	0.2σ	2.5/2	0.29	1.1σ
NOvA vs React	3.0/2	0.23	1.2σ	6.2/2	0.045	2.0σ
T2K vs NOvA vs React	8.4/6	0.21	1.3σ	8.9/6	0.18	1.3σ
T2K vs NOvA	6.5/3	0.088	1.7σ	2.8/3	0.42	0.8σ
T2K vs NOvA vs React	7.8/4	0.098	1.7σ	7.2/4	0.13	1.5σ

Table 2. Testing the consistency of different data sets shown in the first column assuming either normal or inverted ordering. "React" includes Daya-Bay, RENO and Double-Chooz. In the analyses above the horizontal line, θ_{13} is a free parameter, whereas below the line we have fixed $\sin^2\theta_{13} = 0.0224$. See text for more details.

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, 2007.14792

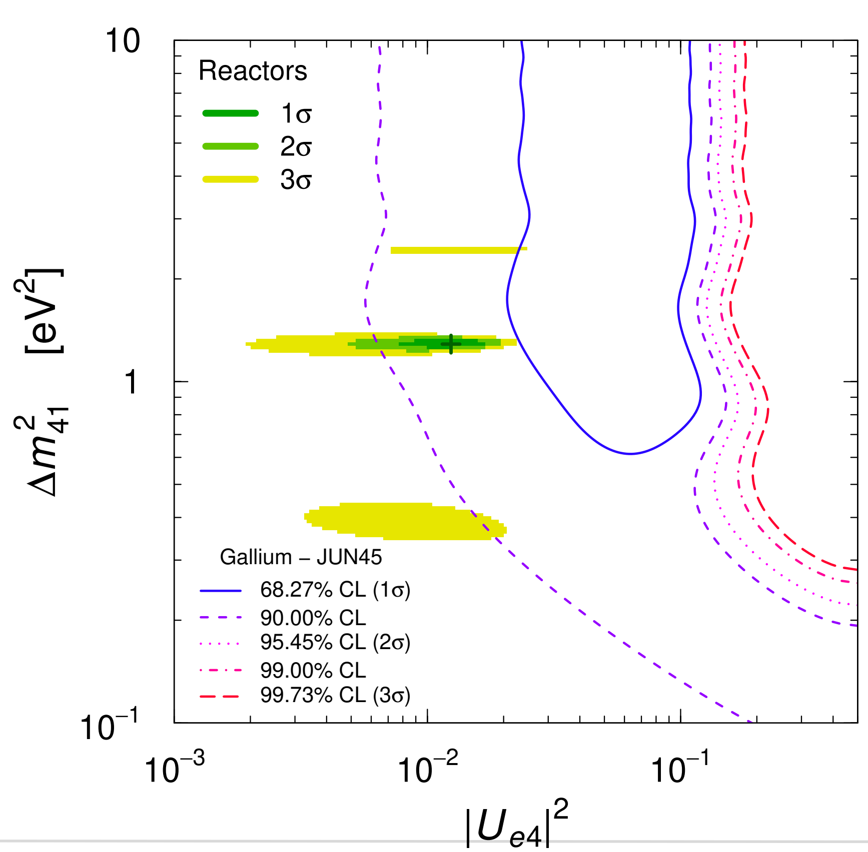
Update on Gallium anomaly

Kostensalo, Suhonen, Giunti, Srivastava, 1906.10980

Table 7: Ratios of measured and expected ^{71}Ge event rates in the four radioactive source experiments, their correlated average, and the statistical significance of the gallium anomaly obtained with the cross sections in Table 5.

	GALLEX-1	GALLEX-2	SAGE-1	SAGE-2	Average	Anomaly
R_{Bahcall}	0.95 ± 0.11	0.81 ± 0.11	0.95 ± 0.12	0.79 ± 0.08	0.85 ± 0.06	2.6σ
R_{Haxton}	0.86 ± 0.13	0.74 ± 0.12	0.86 ± 0.14	0.72 ± 0.10	0.76 ± 0.10	2.5σ
R_{Frekers}	0.93 ± 0.11	0.79 ± 0.11	0.93 ± 0.12	0.77 ± 0.08	0.84 ± 0.05	3.0σ
R_{JUN45}	0.97 ± 0.11	0.83 ± 0.11	0.97 ± 0.12	0.81 ± 0.08	0.88 ± 0.05	2.3σ

- improved shell-model cross section calculations
- significance decreases $3.0\sigma \rightarrow 2.3\sigma$



Summary — fate of hints 1

- Neutrino oscillations well established
  3-flavour paradigm very successful

- previous hints for CP violation disappeared:
  - CP cons. @ 0.6σ
  - if restricted to inverted ordering: CPV preferred at ~3σ

- previous hints for normal ordering decreased:
  - $\Delta\chi^2_{(IO)}$ = 2.7 (no SK atm) / 7.1 (w SK atm)

    opposite tendencies in different sets of experiments
  - preference for NO from SK atm is decreasing

Summary — fate of hints 2

- previous tension between solar and KamLAND data disappeared
  - no hint for non-standard interactions
  - but Dark-LMA still allowed: O(1) perturbation, MO degeneracy
- eV sterile @ reactors:
  - reactor flux predictions: situation unclear, dominated by theory uncertainties
  - spectral distortions at reactors: a number of 2-3σ hints,
    no clear best fit emerging, statistical interpretation non-trivial
- Gallium anomaly: significance decreases from 3.0σ → 2.3σ due to new shell-model cross section calculations [Kostensalo et al., 1906.10980]
- LSND and MiniBooNE
  - sterile neutrino oscillation interpretation strongly disfavoured
  - no clear hints for more exotic explanations (but testable predictions)