Phenomenology of 3ν masses and mixings, circa 2017

- Steps towards the neutrino mass ordering -

XVII International Workshop on Neutrino Telescopes, Venice, Italy, 13-17 March 2017

Eligio Lisi

INFN, Bari, Italy

Mainly based on:

F. Capozzi, E. Di Valentino, E. Lisi, A. Marrone, A. Melchiorri, A. Palazzo,
"Global constraints on absolute neutrino masses and their ordering"
arXiv:1703/04471 [today on arXiv]

See also:

F. Capozzi, E. Lisi, A. Marrone, D. Montanino, A. Palazzo, arXiv:1601/07777
[Special Issue of NPB celebrating the 2015 Nobel Prize for neutrino oscillations]

+ presentation by A. Marrone at Neutrino 2016 (in the Proceedings)

[For an independent analysis of recent oscillation data, see I. Esteban *et al.*, 1611.01514]

OUTLINE:

- Knowns and unknowns from 3ν oscillations
- Nonoscillation constraints from $0\nu\beta\beta$ & Cosmology
- Global analysis of oscillation + nonoscillation data
- Conclusions

Neutrino Oscillation Data – circa 2017

Analysis includes increasingly rich oscillation data sets:

LBL Acc + Solar + KL

LBL Acc + Solar + KL + SBL Reactor

LBL Acc + Solar + KL + SBL Reactor + Atmosph.

χ^2 metric adopted. Parameters not shown are marginalized away:

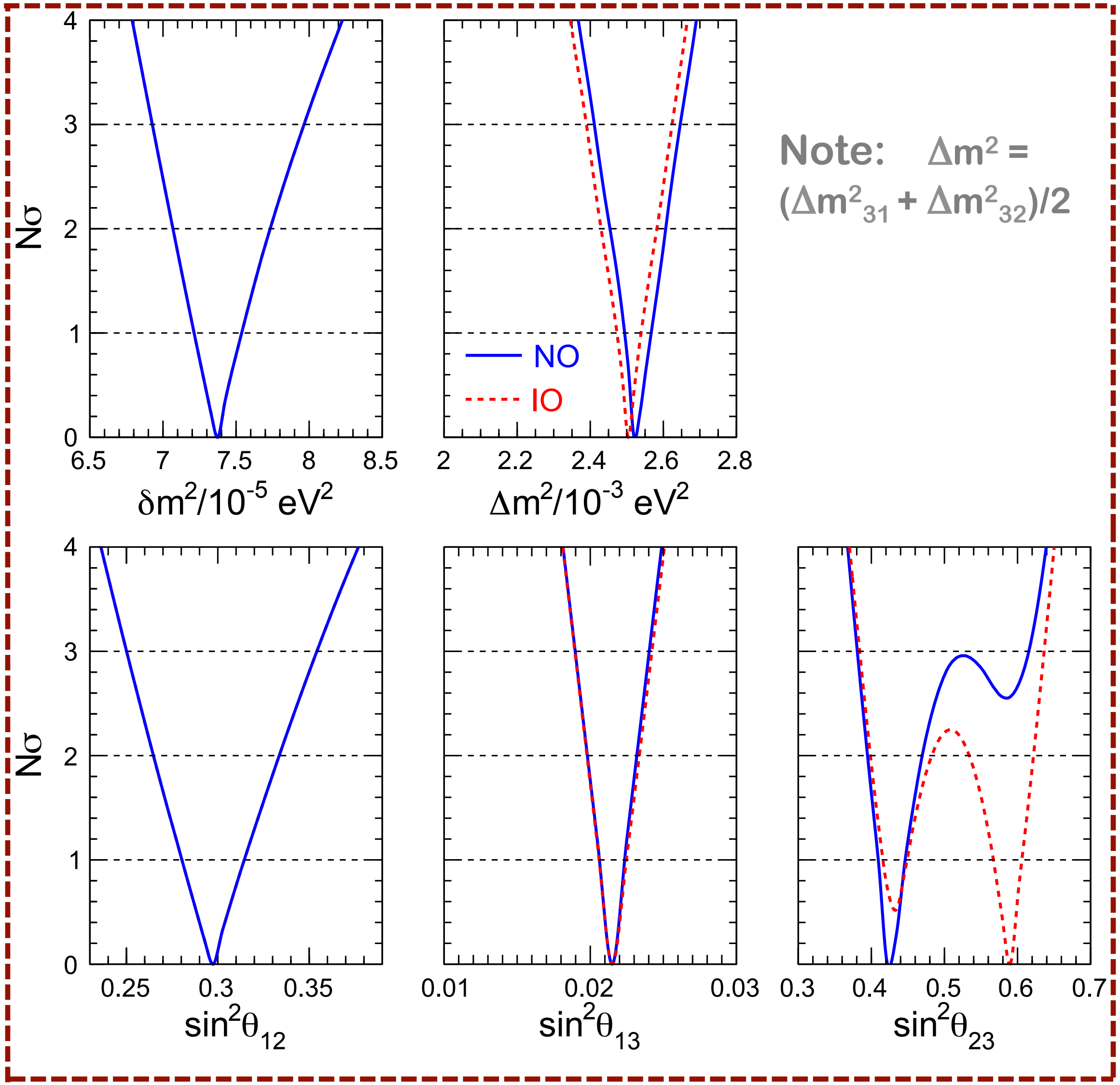
C.L.'s refer to $N\sigma = \sqrt{\Delta\chi^2} = 1, 2, 3, \ldots$

NO = Normal Ordering

IO = Inverted Ordering

Five known oscillation parameters:

LBL Acc + Solar + KamLAND + SBL Reactors + Atmos



Note: $\Delta m^2 = (\Delta m^2_{31} + \Delta m^2_{32})/2$

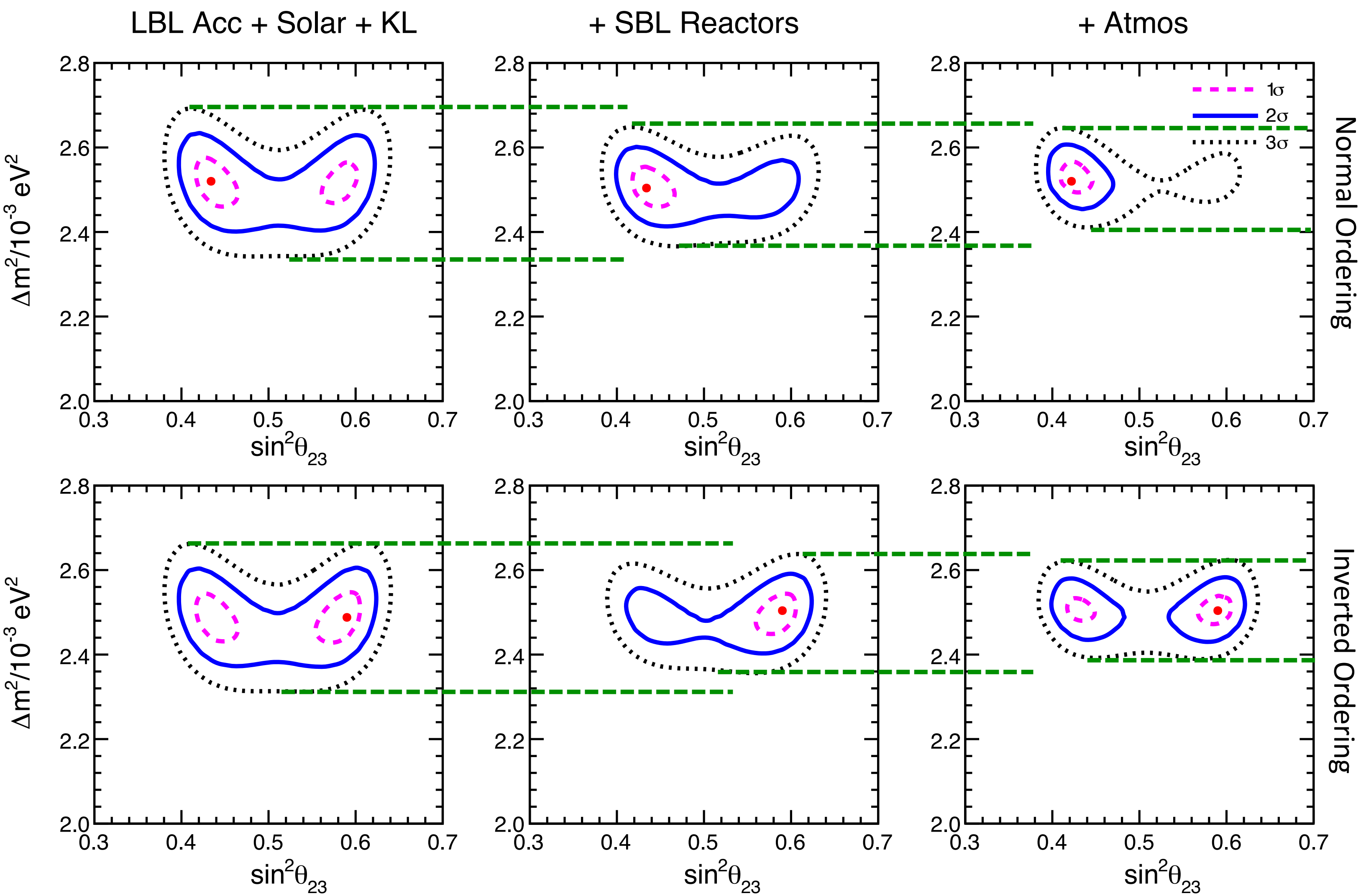
Current 1σ errors (1/6 of ±3σ range):

δm^2	2.3 %
Δm^2	1.6 %
$\sin^2\theta_{12}$	5.8 %
$\sin^2\theta_{13}$	4.0 %
$\sin^2\theta_{23}$	~ 9 %

all < 10%...

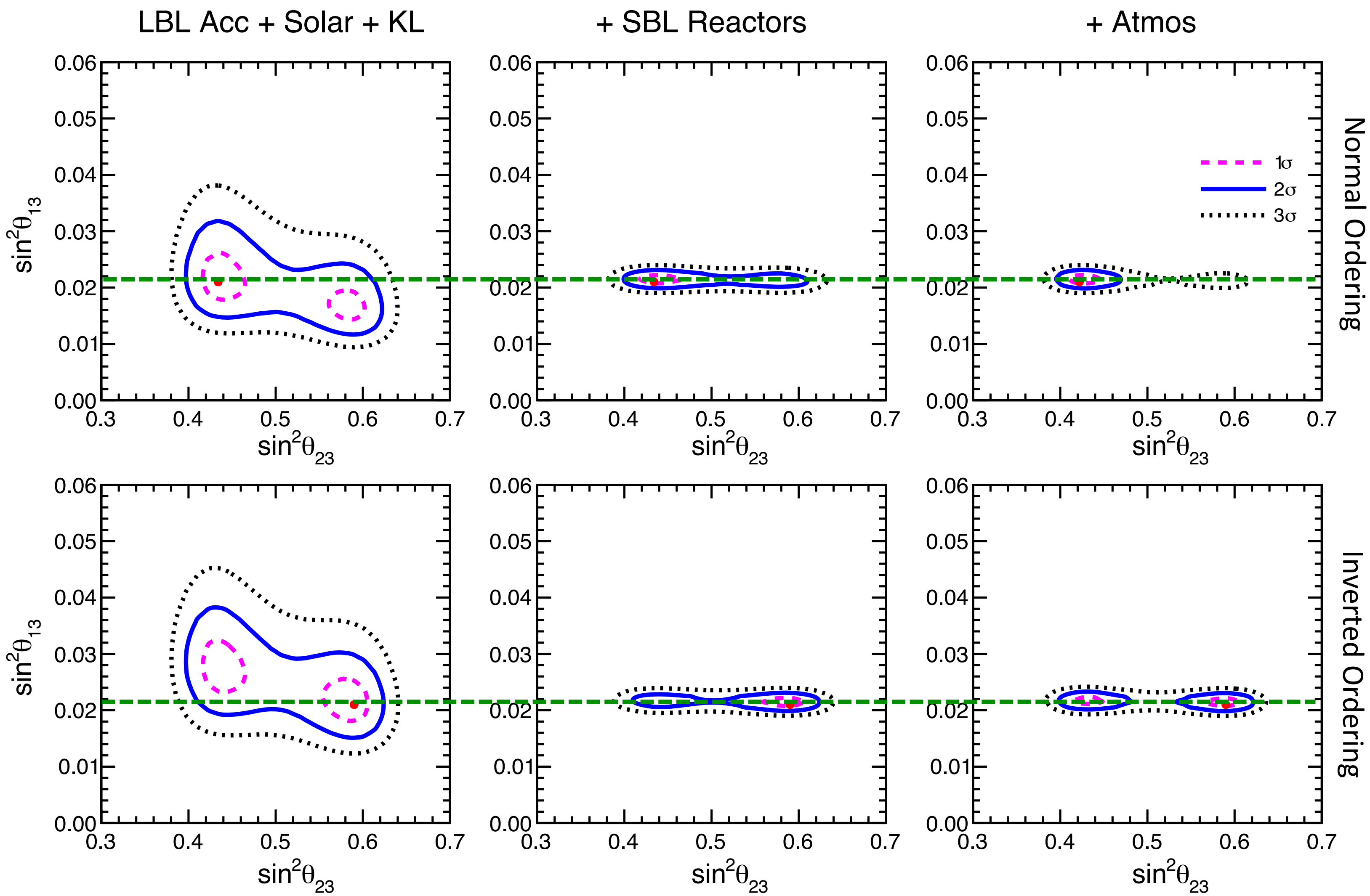
Precision Era!

More on known oscillation parameters: sinergy on Δm^2



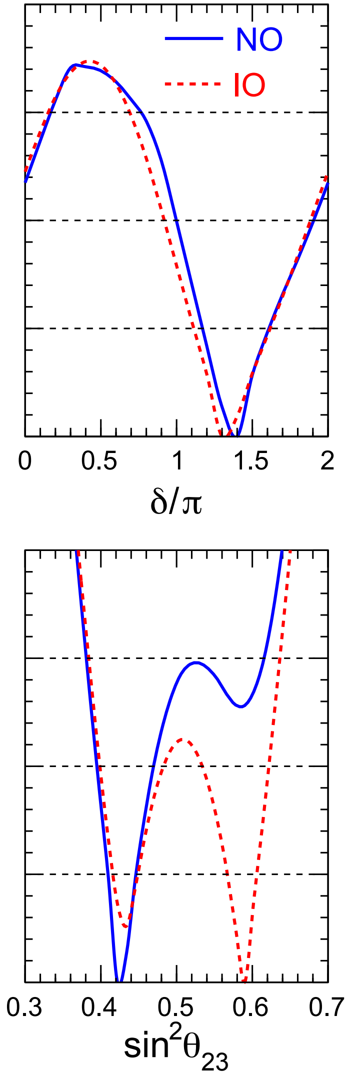
All data sets contribute to Δm^2

More on known oscillation parameters: sinergy on θ_{13}



LBL + solar + KL prefer the same θ_{13} as reactors (within large uncertainties)

Three unknown oscillation parameters



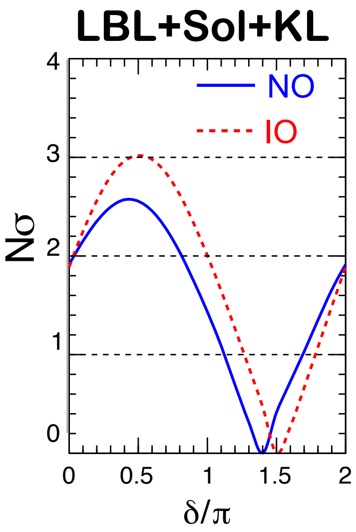
δ_{CP}

θ_{23} octant

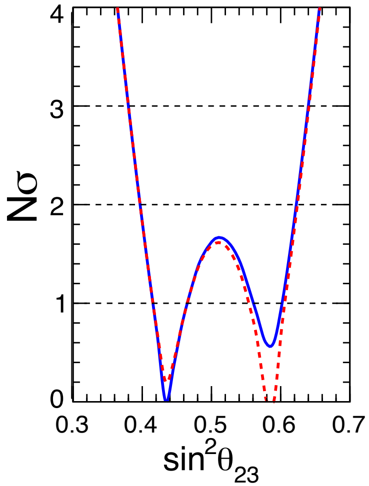
NO or IO

More on unknown oscillation parameters:

δ_{CP}



θ_{23} **octant**



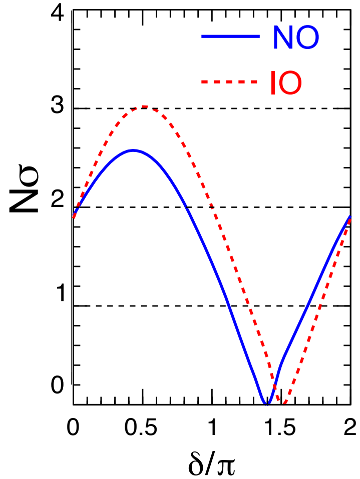
$\Delta\chi^2$ **(IO-NO)**

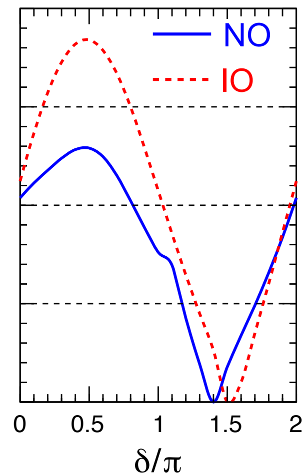
+1.1

More on unknown oscillation parameters:

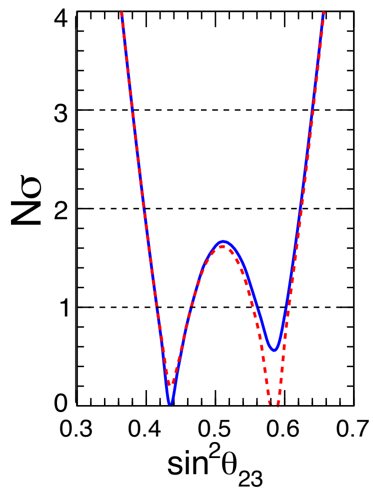
LBL+Sol+KL | +SBL Reac

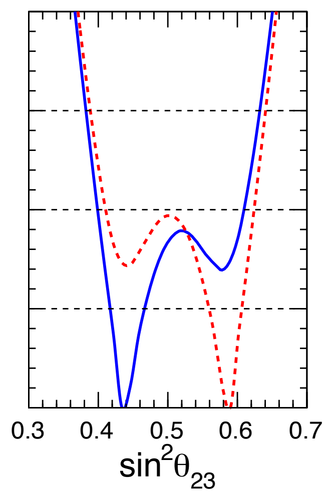
δ_{CP}





θ_{23} octant



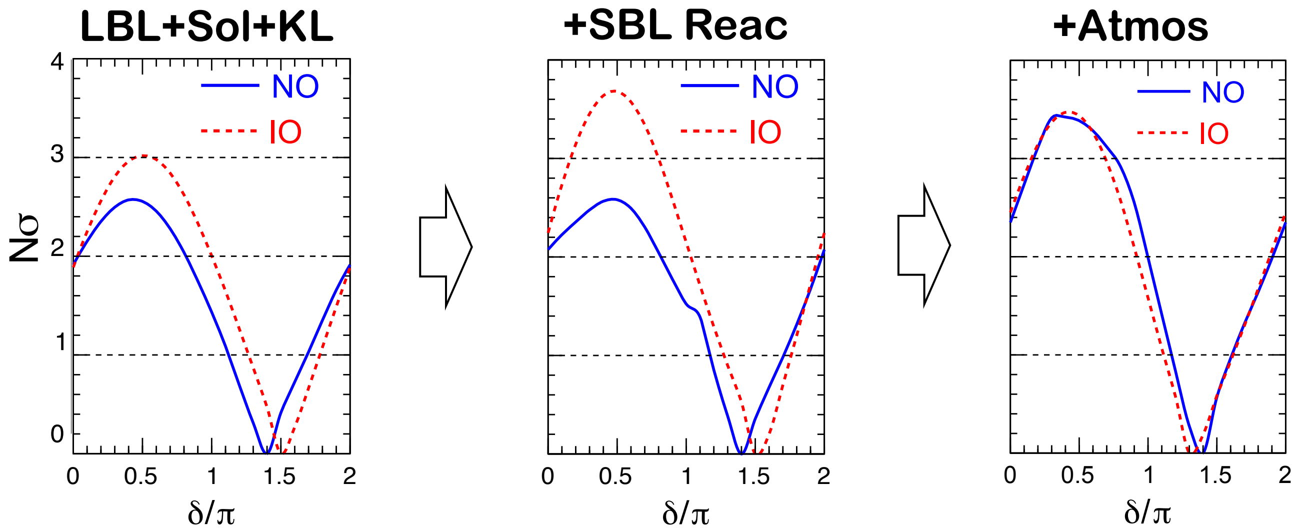


$\Delta\chi^2$ (IO-NO)

+1.1 → +1.1

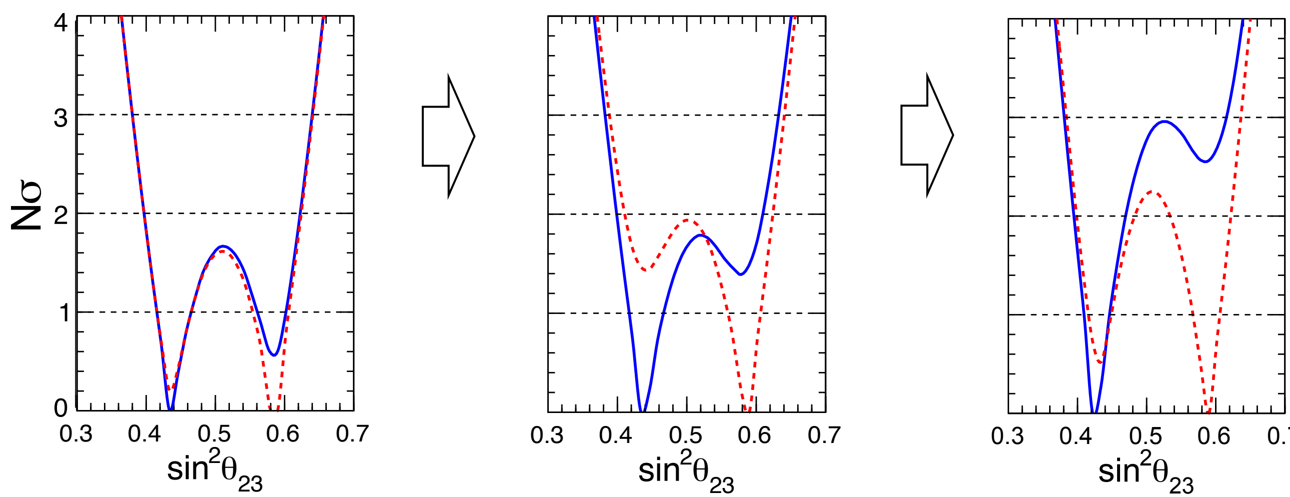
More on unknown oscillation parameters:

δ_{CP}



sin δ ~ -1
(or sin δ < 0)
favored;
sin δ ~ +1
excluded

θ_{23}
octant



Max-mixing disfavored;
octant flips with NO/IO

$\Delta\chi^2$
(IO-NO)

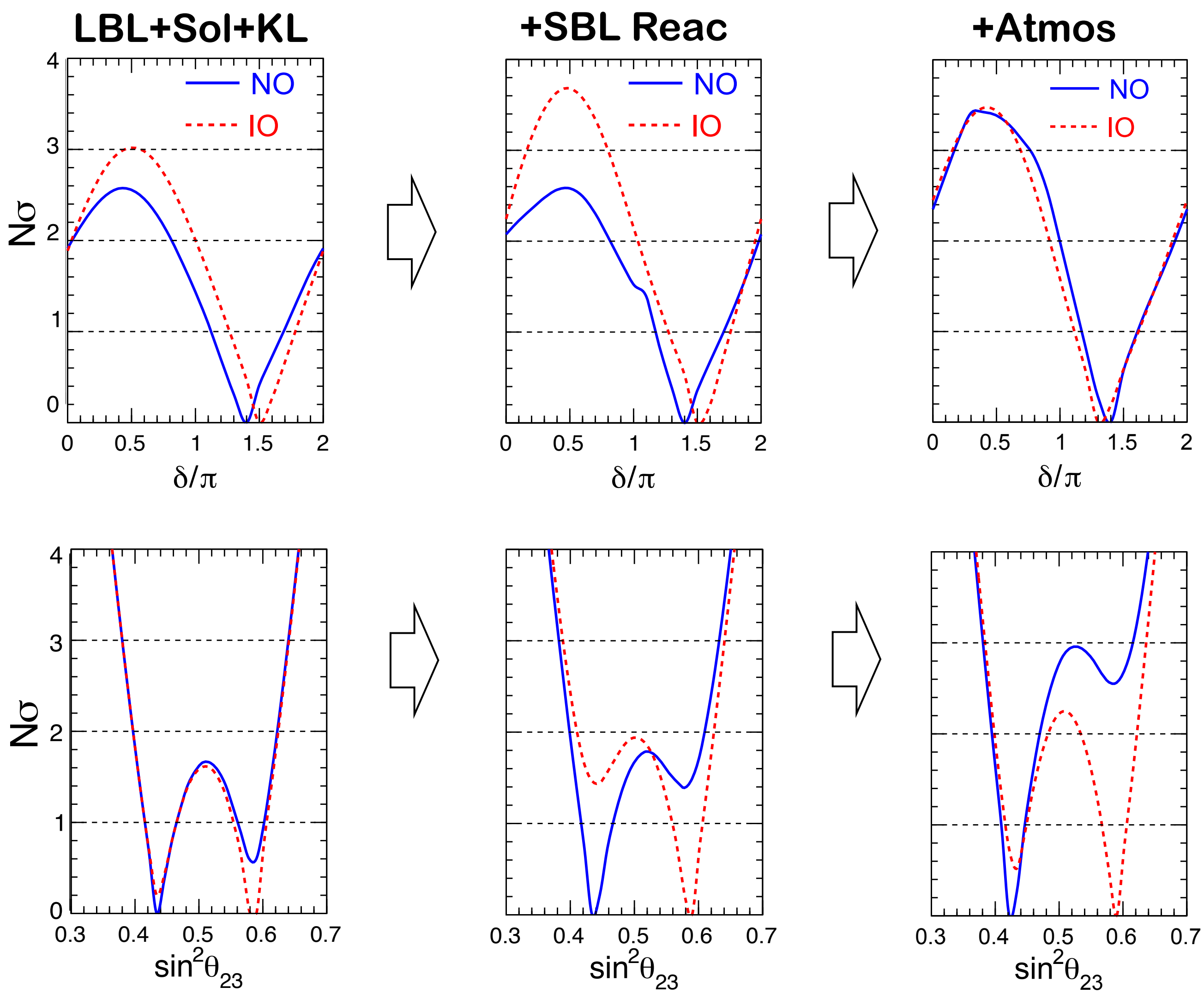
+1.1 ⇒ **+1.1** ⇒ **+3.6**

Intriguing!
NO favored

Compare the current results (circa 2017) with...

δ_{CP}

θ_{23} octant



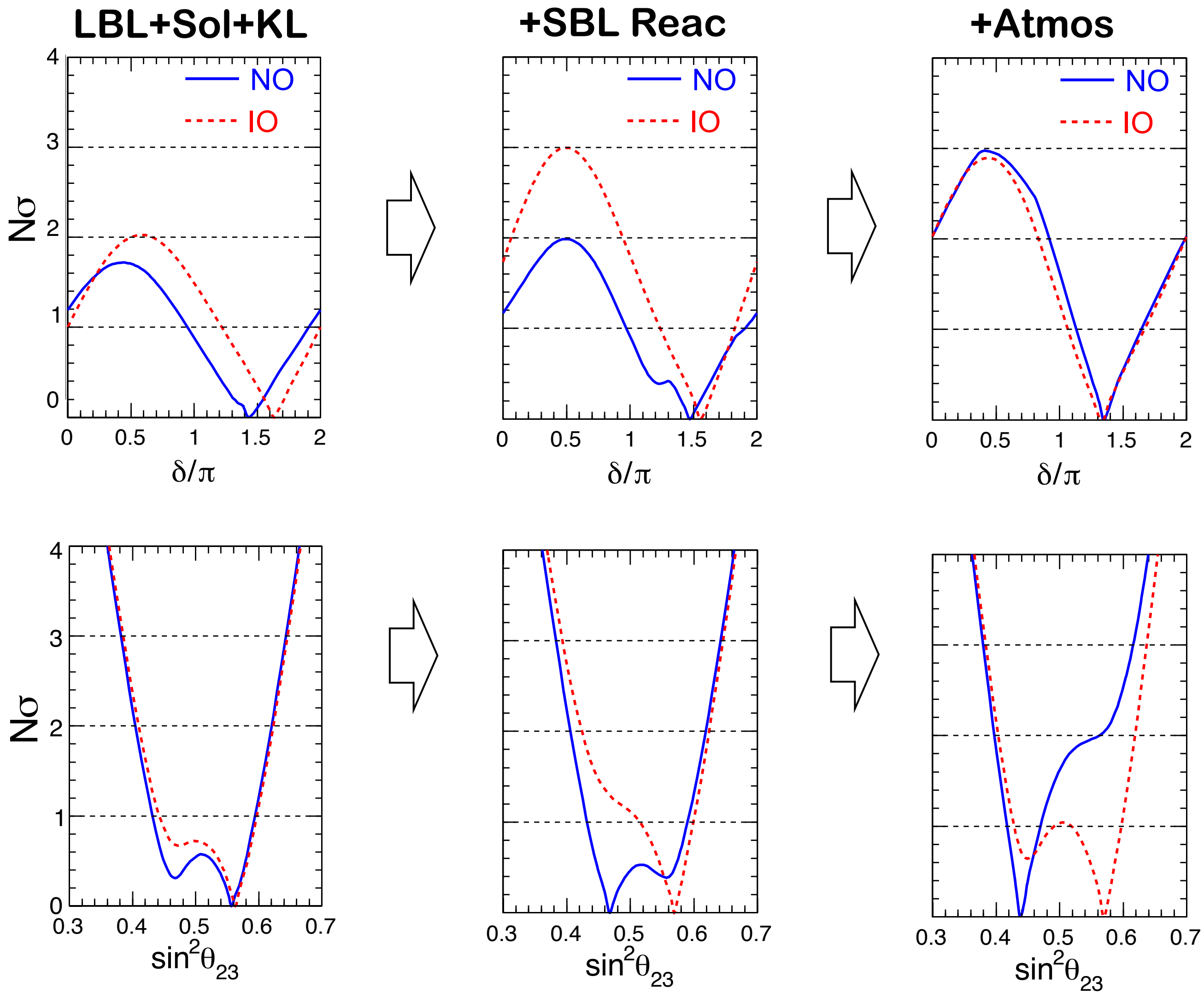
$\Delta\chi^2$ (IO-NO)

+1.1 → +1.1 → +3.6

... 1yr ago, 2016: trends were somewhat weaker

δ_{CP}

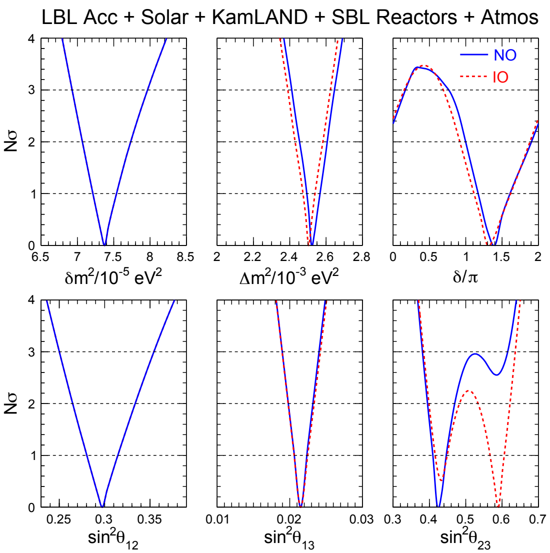
θ_{23} octant

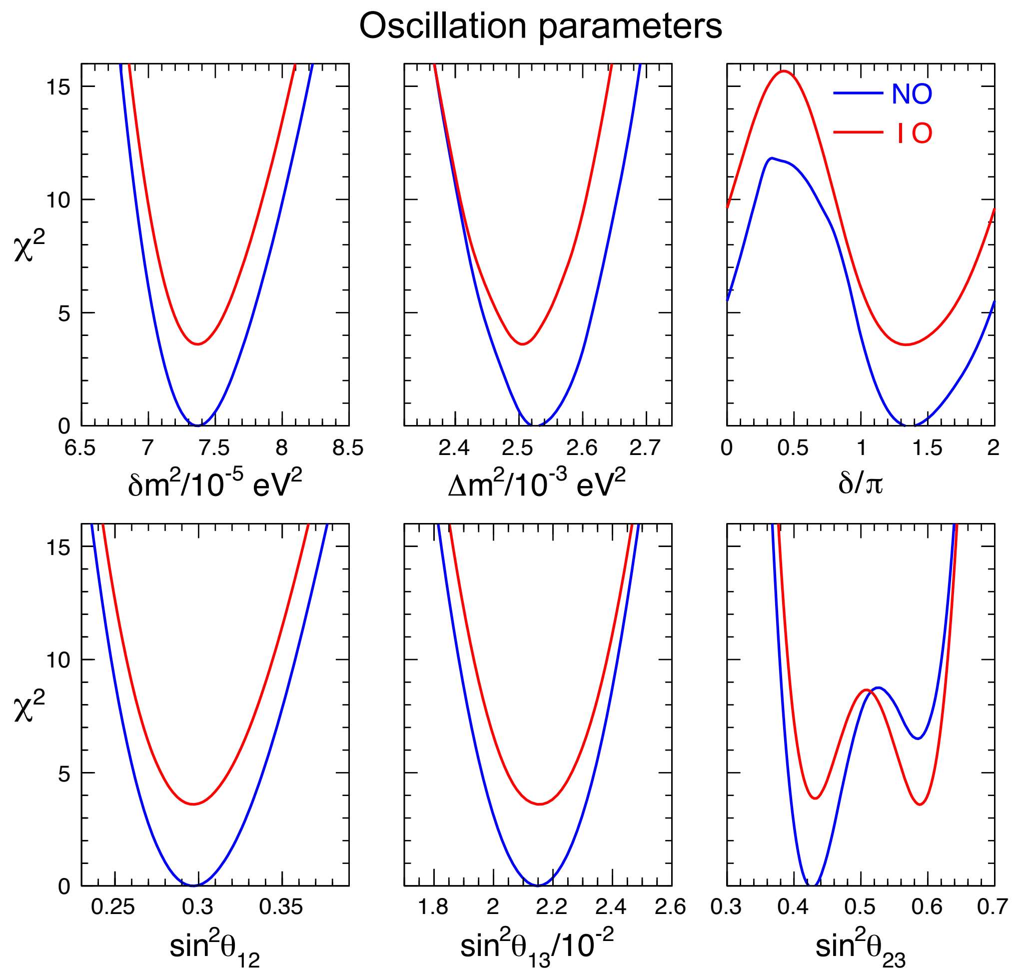


$\Delta\chi^2$ (IO-NO)

-1.2 → -0.9 → +1.0

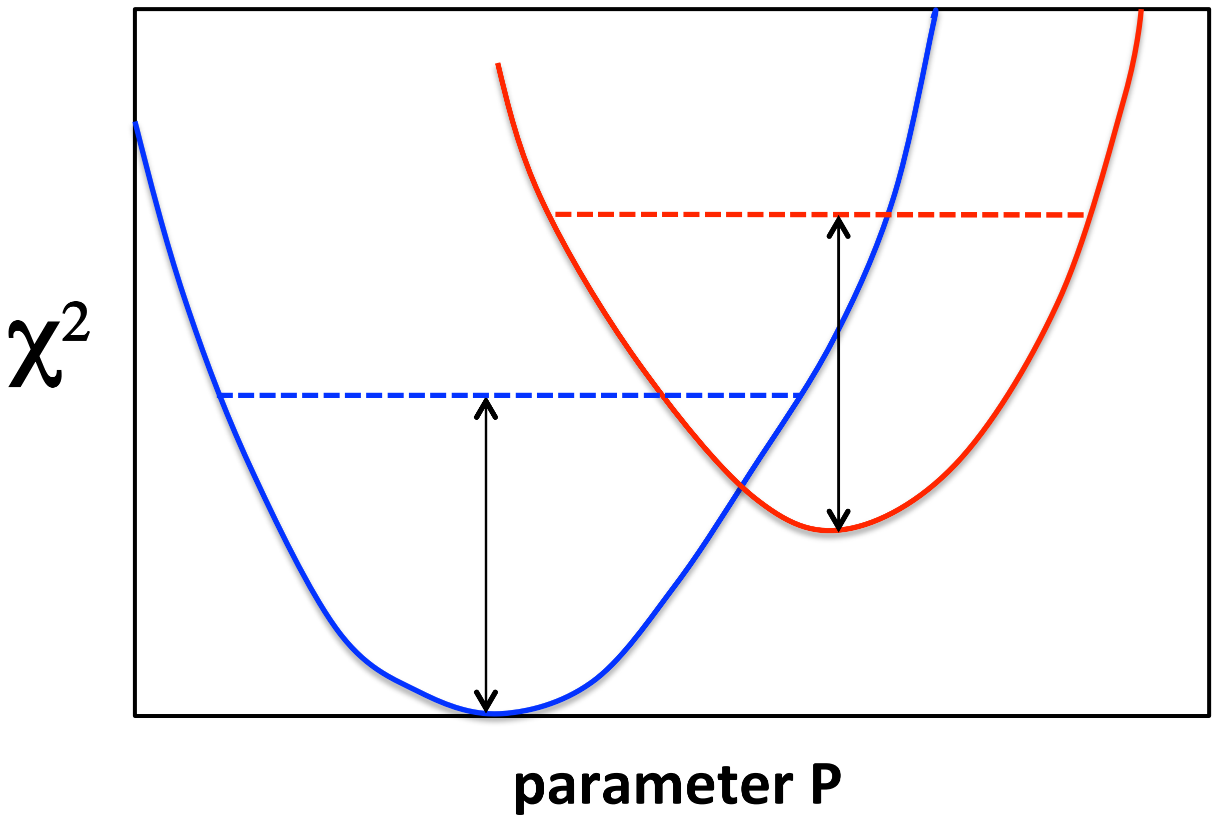
Current indication $\Delta\chi^2_{IO-NO} = 3.6$ from oscill. data starts to be interesting.
Useful to see the effect of excluding/including this offset in the analysis:





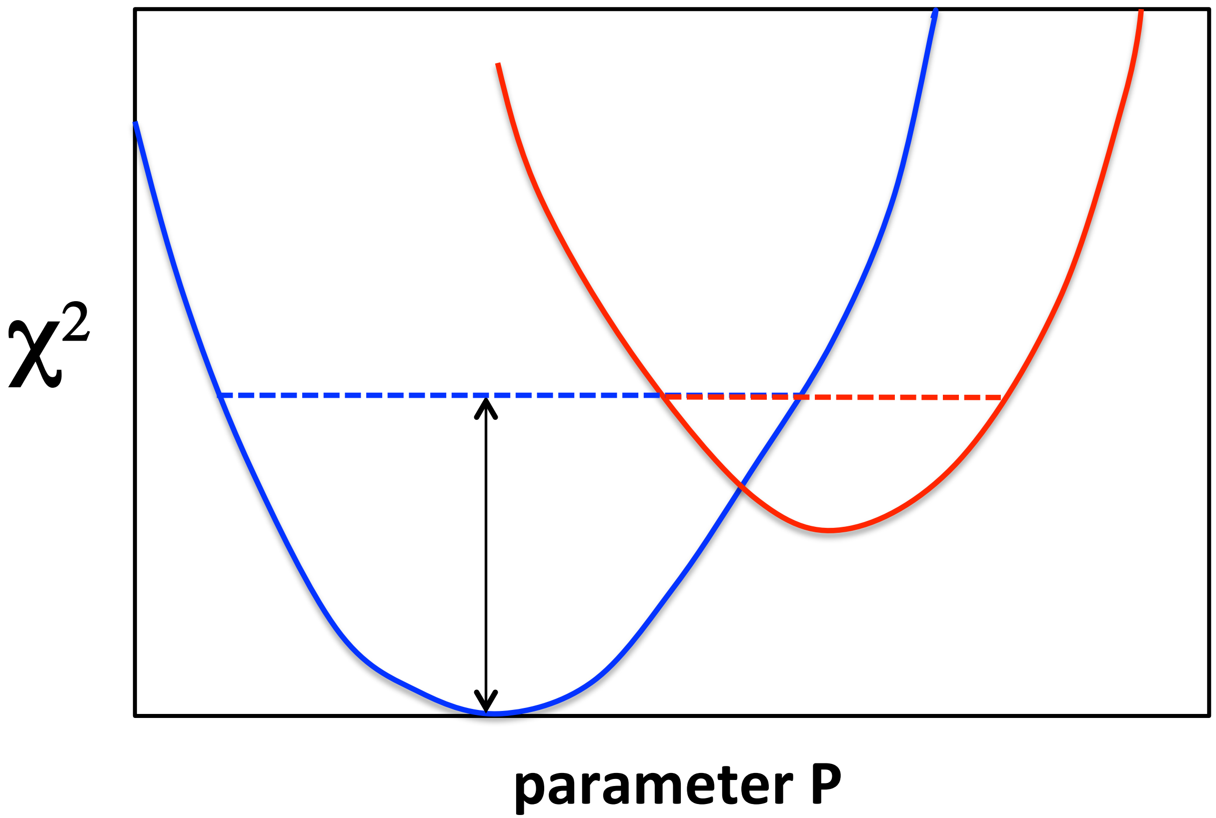
Two different ways of marginalizing over mass ordering(s) →

Apply a “$\Delta\chi^2$ cut” to **SEPARATE** minima in **NO**, **IO**....

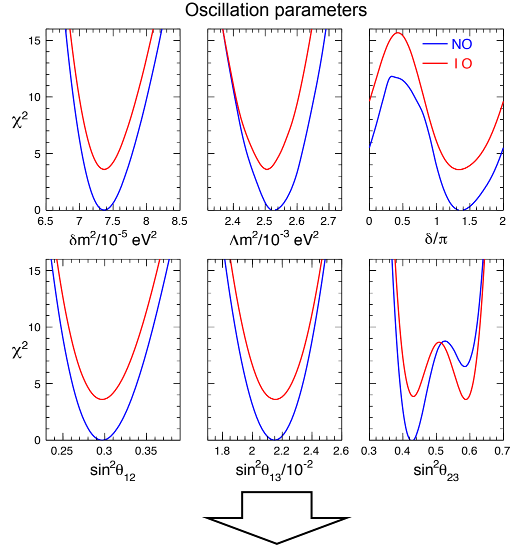


(does not include IO-NO offset information)

...or minimize and expand over **ANY ORDERING**



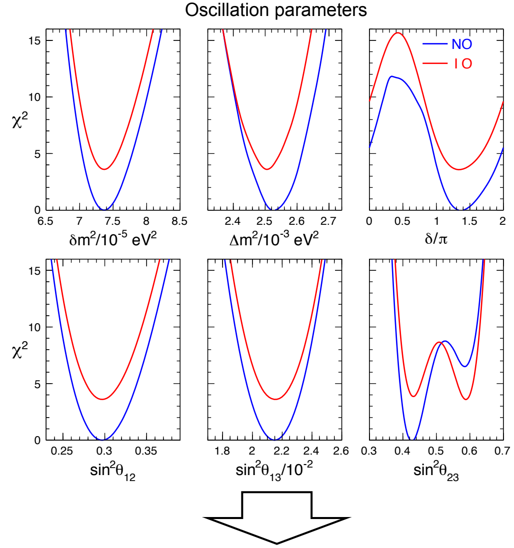
(includes IO-NO offset information)



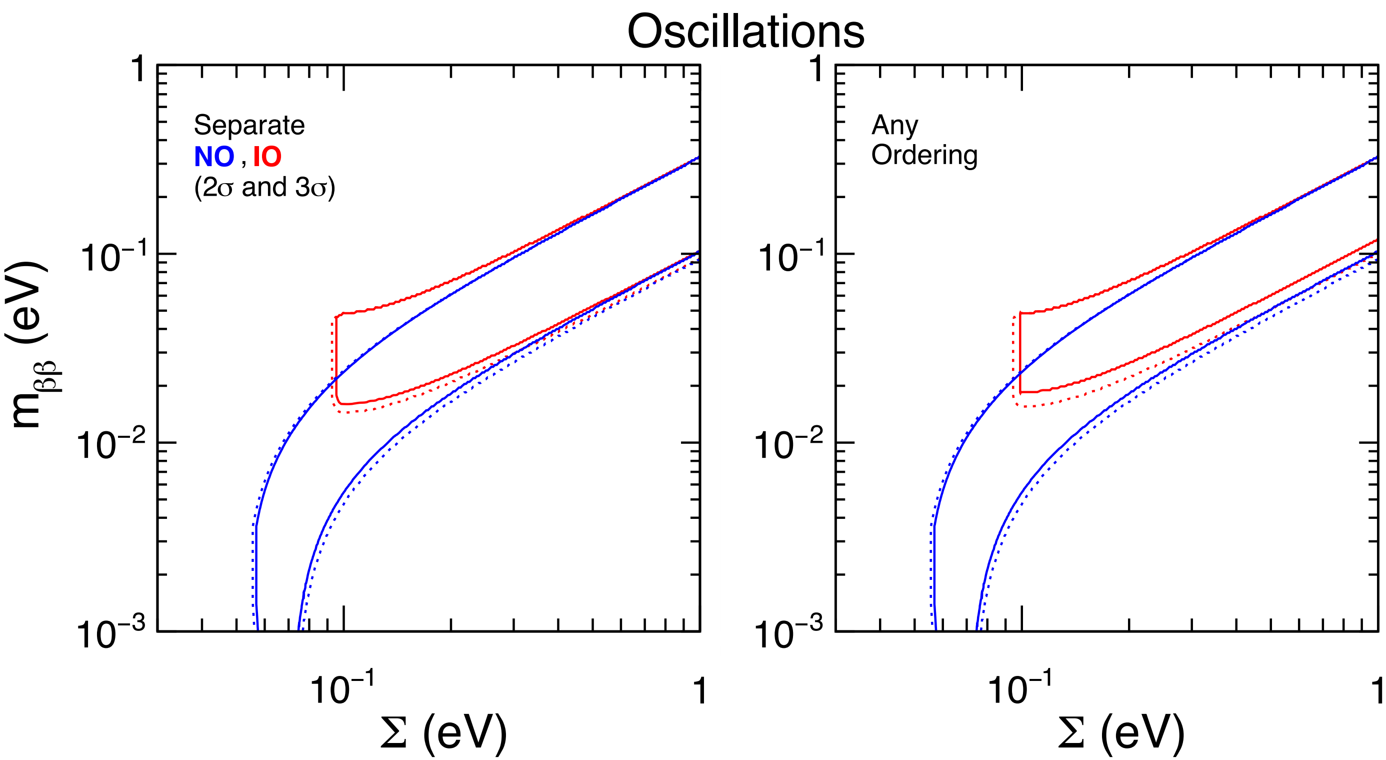
Oscillation parameter ranges

TABLE I: Results of the global 3ν oscillation analysis, in terms of best-fit values for the mass-mixing parameters and associated $n\sigma$ ranges ($n = 1, 2, 3$), defined by $\chi^2 - \chi^2_{\rm min} = n^2$ with respect to the separate minima in each mass ordering (NO, IO) and to the absolute minimum in any ordering. (Note that the fit to the δm^2 and $\sin^2\theta_{12}$ parameters is basically insensitive to the mass ordering.) We recall that Δm^2 is defined herein as $m_3^2 - (m_1^2 + m_2^2)/2$, and that δ is taken in the (cyclic) interval $\delta/\pi \in [0, 2]$.

Parameter	Ordering	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2	NO, IO, Any	7.37	7.21 – 7.54	7.07 – 7.73	6.93 – 7.96
$\sin^2\theta_{12}/10^{-1}$	NO, IO, Any	2.97	2.81 – 3.14	2.65 – 3.34	2.50 – 3.54
$\|\Delta m^2\|/10^{-3}$ eV^2	NO	2.525	2.495 – 2.567	2.454 – 2.606	2.411 – 2.646
	IO	2.505	2.473 – 2.539	2.430 – 2.582	2.390 – 2.624
	Any	2.525	2.495 – 2.567	2.454 – 2.606	2.411 – 2.646
$\sin^2\theta_{13}/10^{-2}$	NO	2.15	2.08 – 2.22	1.99 – 2.31	1.90 – 2.40
	IO	2.16	2.07 – 2.24	1.98 – 2.33	1.90 – 2.42
	Any	2.15	2.08 – 2.22	1.99 – 2.31	1.90 – 2.40
$\sin^2\theta_{23}/10^{-1}$	NO	4.25	4.10 – 4.46	3.95 – 4.70	3.81 – 6.15
	IO	5.89	4.17 – 4.48 ⊕ 5.67 – 6.05	3.99 – 4.83 ⊕ 5.33 – 6.21	3.84 – 6.36
	Any	4.25	4.10 – 4.46	3.95 – 4.70 ⊕ 5.75 – 6.00	3.81 – 6.26
δ/π	NO	1.38	1.18 – 1.61	1.00 – 1.90	0 – 0.17 ⊕ 0.76 – 2
	IO	1.31	1.12 – 1.62	0.92 – 1.88	0 – 0.15 ⊕ 0.69 – 2
	Any	1.38	1.18 – 1.61	1.00 – 1.90	0 – 0.17 ⊕ 0.76 – 2



Absolute neutrino mass observables

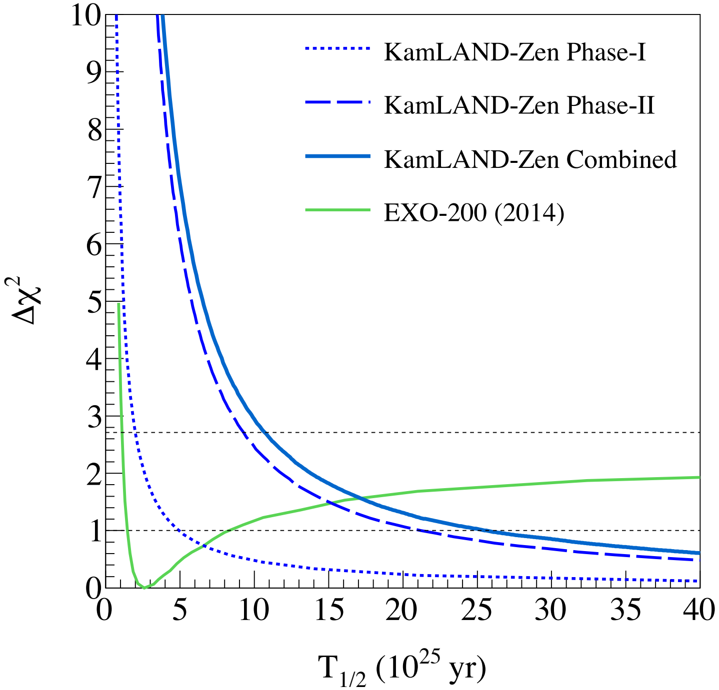


Effective Majorana Mass (DBD)

Sum of neutrino masses (Cosmology)

Dominant $0\nu\beta\beta$ constraints

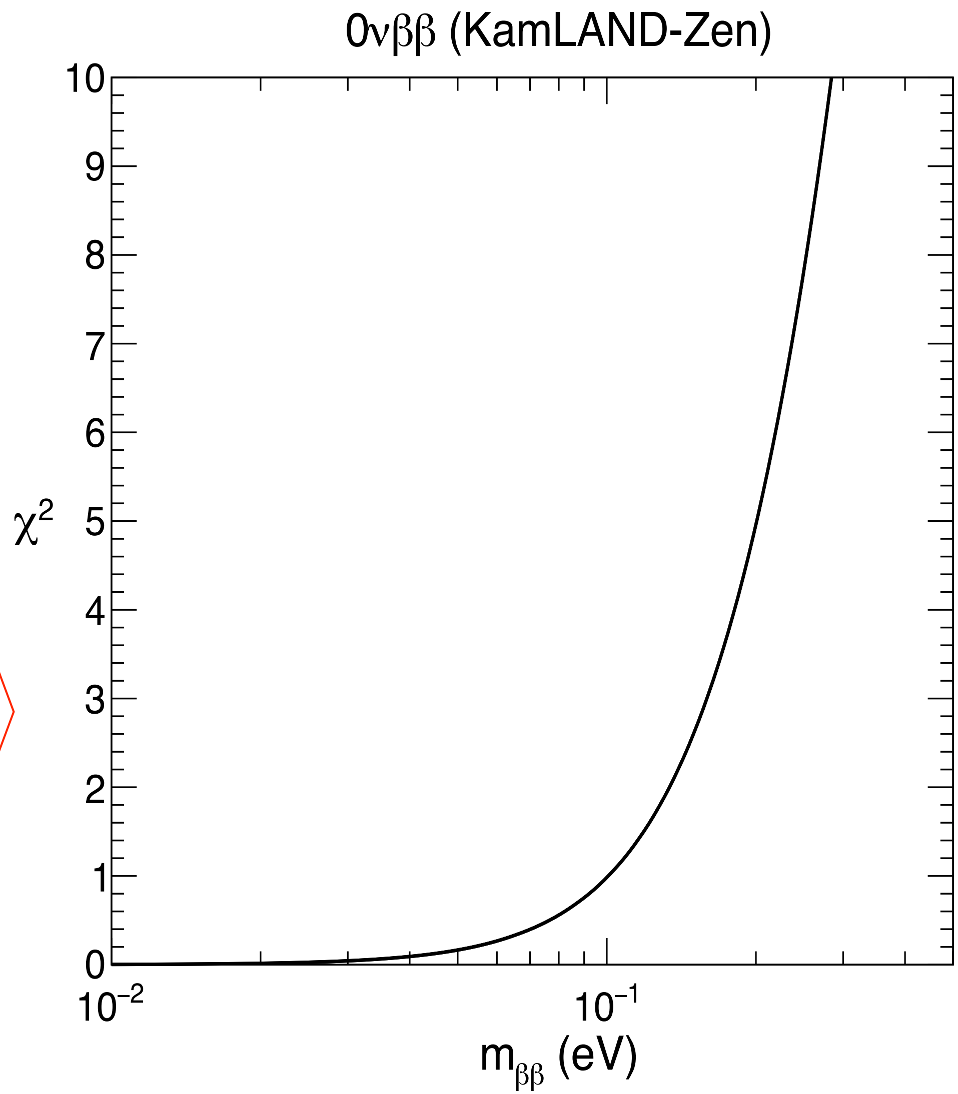
KamLAND-Zen half-life limits

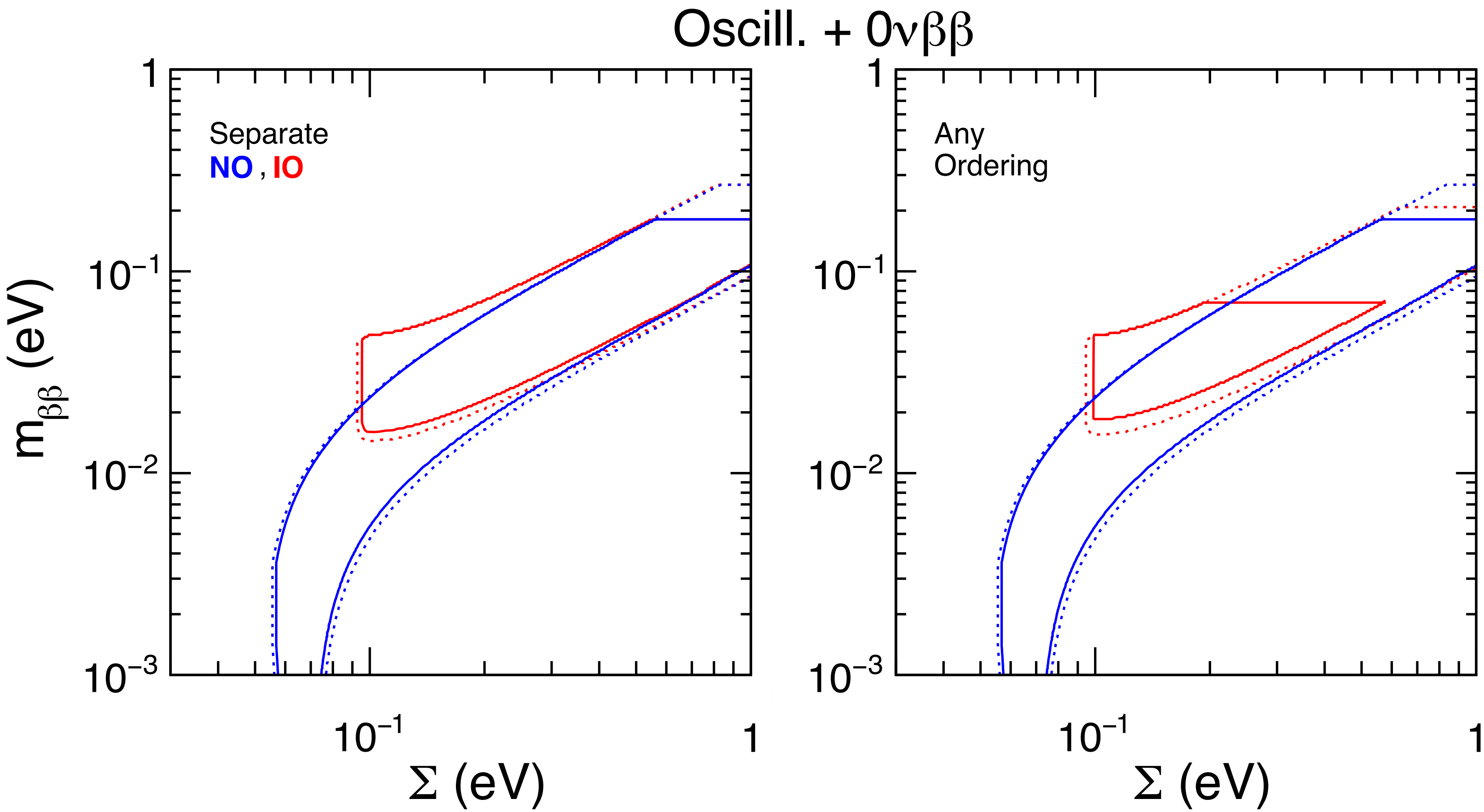


+NME Likelihood based on:

E.L., A. Rotunno, F. Simkovic,

arXiv:1506.04058





Oscill. + 0νββ
Separate
NO , IO
Any
Ordering
m_ββ (eV)
Σ (eV)
1
10^−1
10^−2
10^−3
10^−1
1

Cosmological constraints (circa 2017)

Analysis of various **datasets** within standard (6-param.) Λ**CDM model** augmented with $\boldsymbol{\Sigma}$ (plus one possible 1 extra parameter $\mathbf{A_{lens}}$, to account for syst's or nonstandard effects)

Code: **CosmoMC with NO / IO options explicitly included in Σ,** via the two mass^2 differences
→ unphysical spectra of neutrino masses (e.g., $\boldsymbol{\Sigma}$ = 0) excluded by construction.
→ expect small NO-IO differences at low Σ, but vanishing at high Σ (degenerate spectrum)

Cosmological constraints (circa 2017)

Analysis of various **datasets** within standard (6-param.) **ΛCDM model** augmented with **Σ** (plus one possible 1 extra parameter **A_{lens}**, to account for syst's or nonstandard effects)

Code: **CosmoMC with NO / IO options explicitly included in Σ**, via the two mass^2 differences
→ unphysical spectra of neutrino masses (e.g., Σ = 0) excluded by construction.
→ expect small NO-IO differences at low Σ, but vanishing at high Σ (degenerate spectrum)

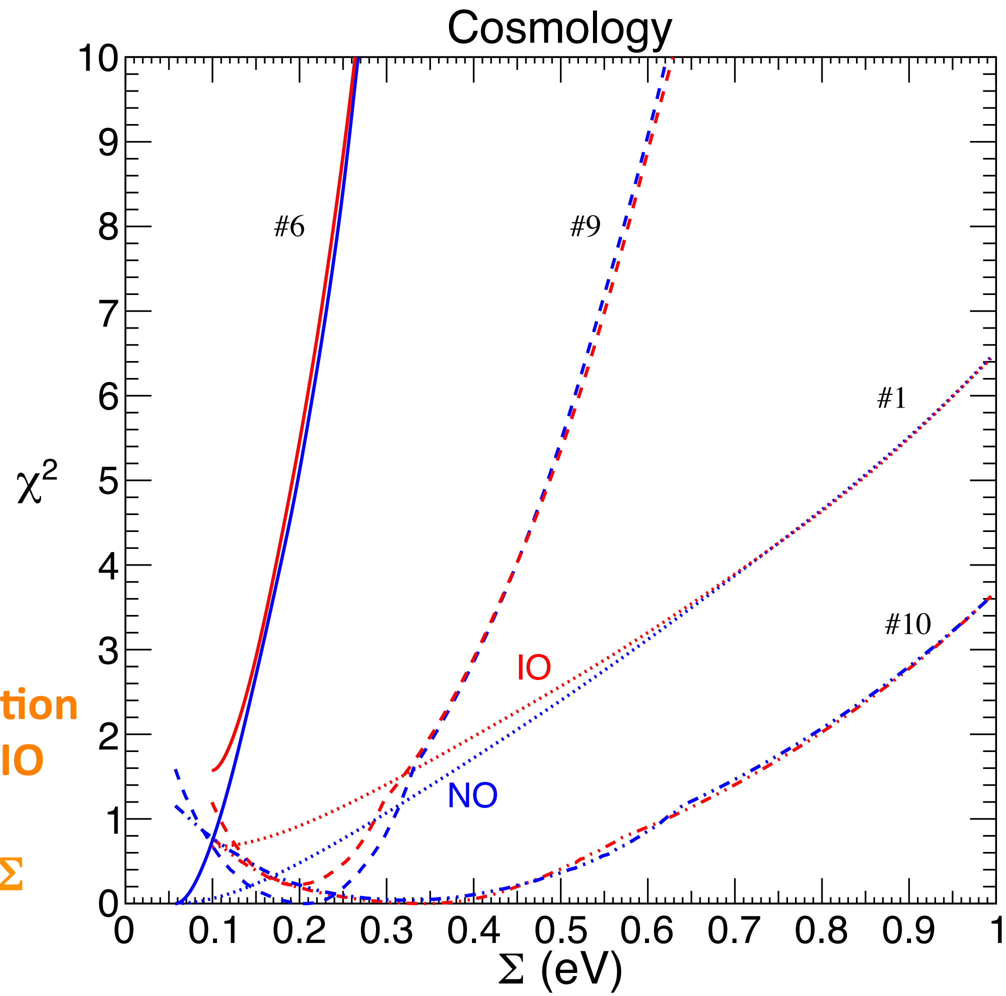
Results on Σ (upper bounds) and on $\Delta\chi^2_{IO-NO}$

TABLE II: Results of the global 3ν analysis of cosmological data within the standard $\Lambda\text{CDM} + \Sigma$ and extended $\Lambda\text{CDM} + \Sigma + A_{\text{lens}}$ models. The datasets refer to various combinations of the Planck power angular CMB temperature power spectrum (TT) plus polarization power spectra (TE, EE), reionization optical depth τ_{HFI}, lensing potential power spectrum (lensing), and BAO measurements. For each of the 12 cases we report the 2σ upper bounds on $\Sigma = m_1 + m_2 + m_3$ for NO and IO, together with the $\Delta\chi^2$ difference between the two mass orderings (with one digit after decimal point). For any Σ, the masses m_i are taken to obey the δm^2 and Δm^2 constraints coming from oscillation data. See the text for more details.

#	Model	Cosmological data set	Σ/eV (2σ), NO	Σ/eV (2σ), IO	$\Delta\chi^2_{\text{IO-NO}}$
1	$\Lambda\text{CDM} + \Sigma$	Planck TT + τ_{HFI}	< 0.72	< 0.80	0.7
2	$\Lambda\text{CDM} + \Sigma$	Planck TT + τ_{HFI} + lensing	< 0.64	< 0.63	0.2
3	$\Lambda\text{CDM} + \Sigma$	Planck TT + τ_{HFI} + BAO	< 0.21	< 0.23	1.2
4	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + τ_{HFI}	< 0.44	< 0.48	0.6
5	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + τ_{HFI} + lensing	< 0.45	< 0.47	0.3
6	$\Lambda\text{CDM} + \Sigma$	Planck TT, TE, EE + τ_{HFI} + BAO	< 0.18	< 0.20	1.6
7	$\Lambda\text{CDM} + \Sigma + A_{\text{lens}}$	Planck TT + τ_{HFI}	< 1.08	< 1.08	−0.1
8	$\Lambda\text{CDM} + \Sigma + A_{\text{lens}}$	Planck TT + τ_{HFI} + lensing	< 0.91	< 0.93	0.0
9	$\Lambda\text{CDM} + \Sigma + A_{\text{lens}}$	Planck TT + τ_{HFI} + BAO	< 0.45	< 0.46	0.2
10	$\Lambda\text{CDM} + \Sigma + A_{\text{lens}}$	Planck TT, TE, EE + τ_{HFI}	< 1.04	< 1.03	0.0
11	$\Lambda\text{CDM} + \Sigma + A_{\text{lens}}$	Planck TT, TE, EE + τ_{HFI} + lensing	< 0.89	< 0.89	0.1
12	$\Lambda\text{CDM} + \Sigma + A_{\text{lens}}$	Planck TT, TE, EE + τ_{HFI} + BAO	< 0.31	< 0.32	0.3

χ^2 profile for NO, IO in representative cases

bifurcation of NO, IO curves at low Σ

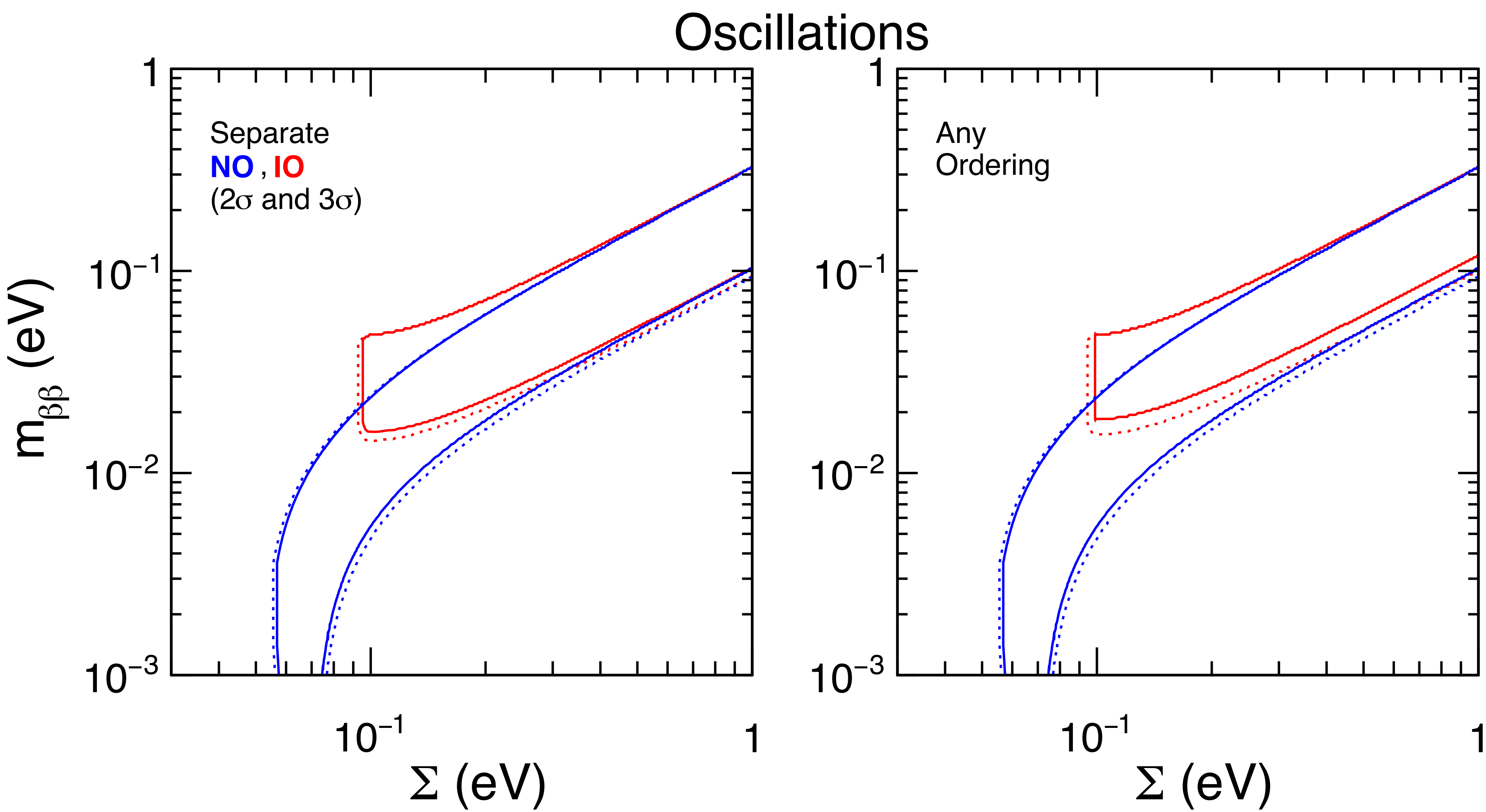


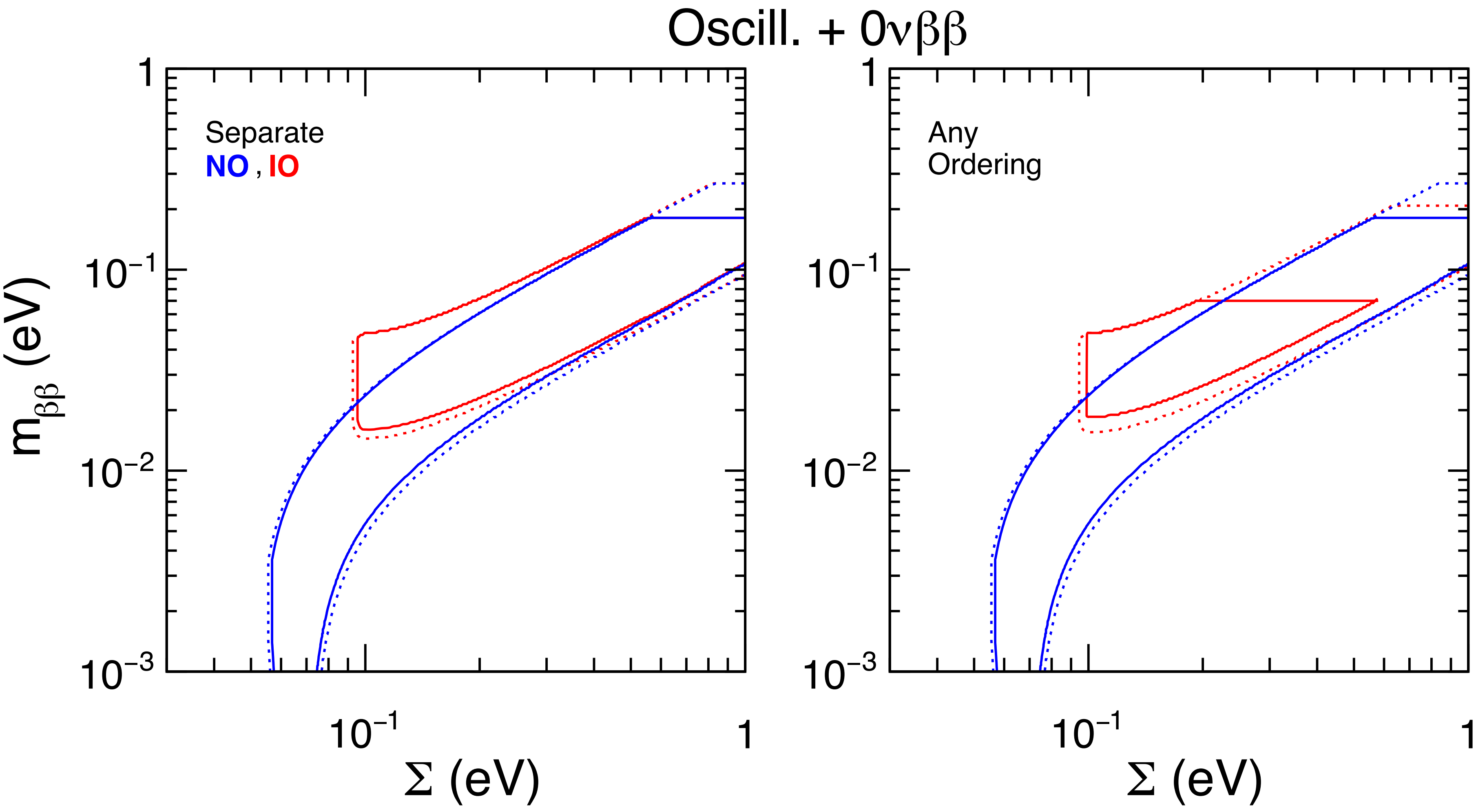
convergence of NO, IO curves at high Σ

Note: Σ > 0.06 eV (NO)
Σ > 0.10 eV (IO)

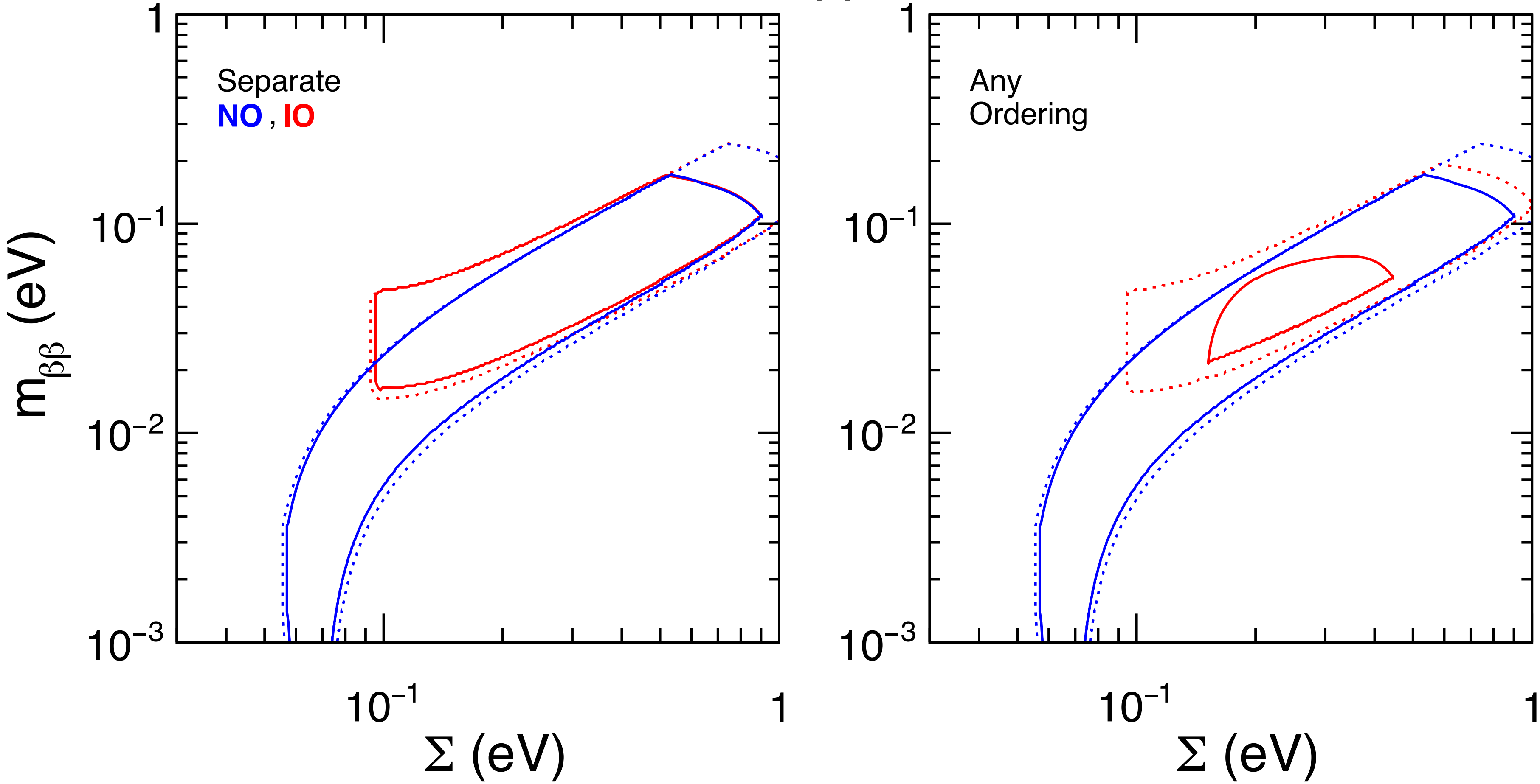
Grand total: combination of oscillation + nonoscillation data

(with increasingly strong cosmological constraints)

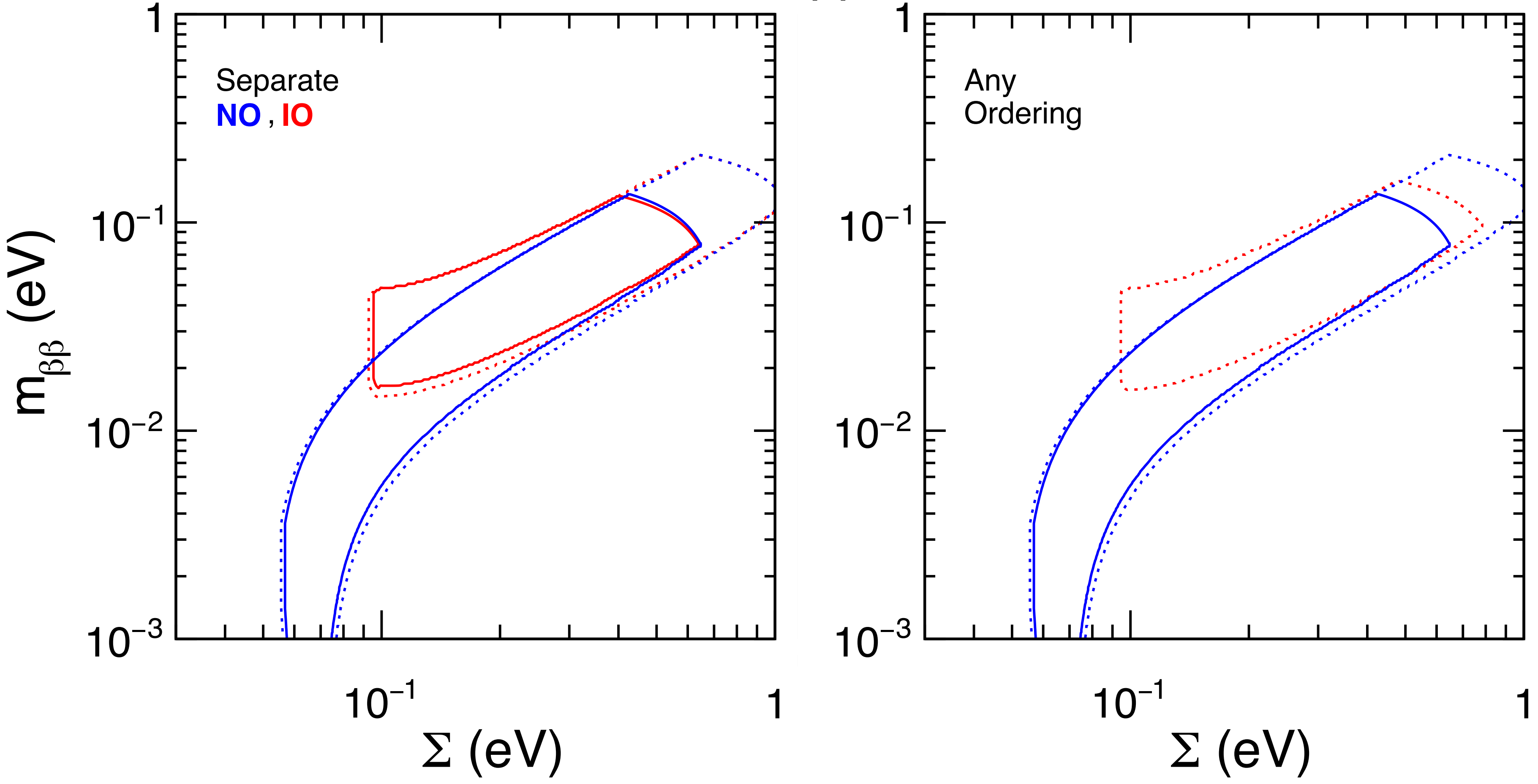



Oscill. + 0νββ
Separate
NO , IO
Any
Ordering
m_ββ (eV)
Σ (eV)
1
10^−1
10^−2
10^−3
1
10^−1
10^−2
10^−3
10^−1
1
10^−1
1

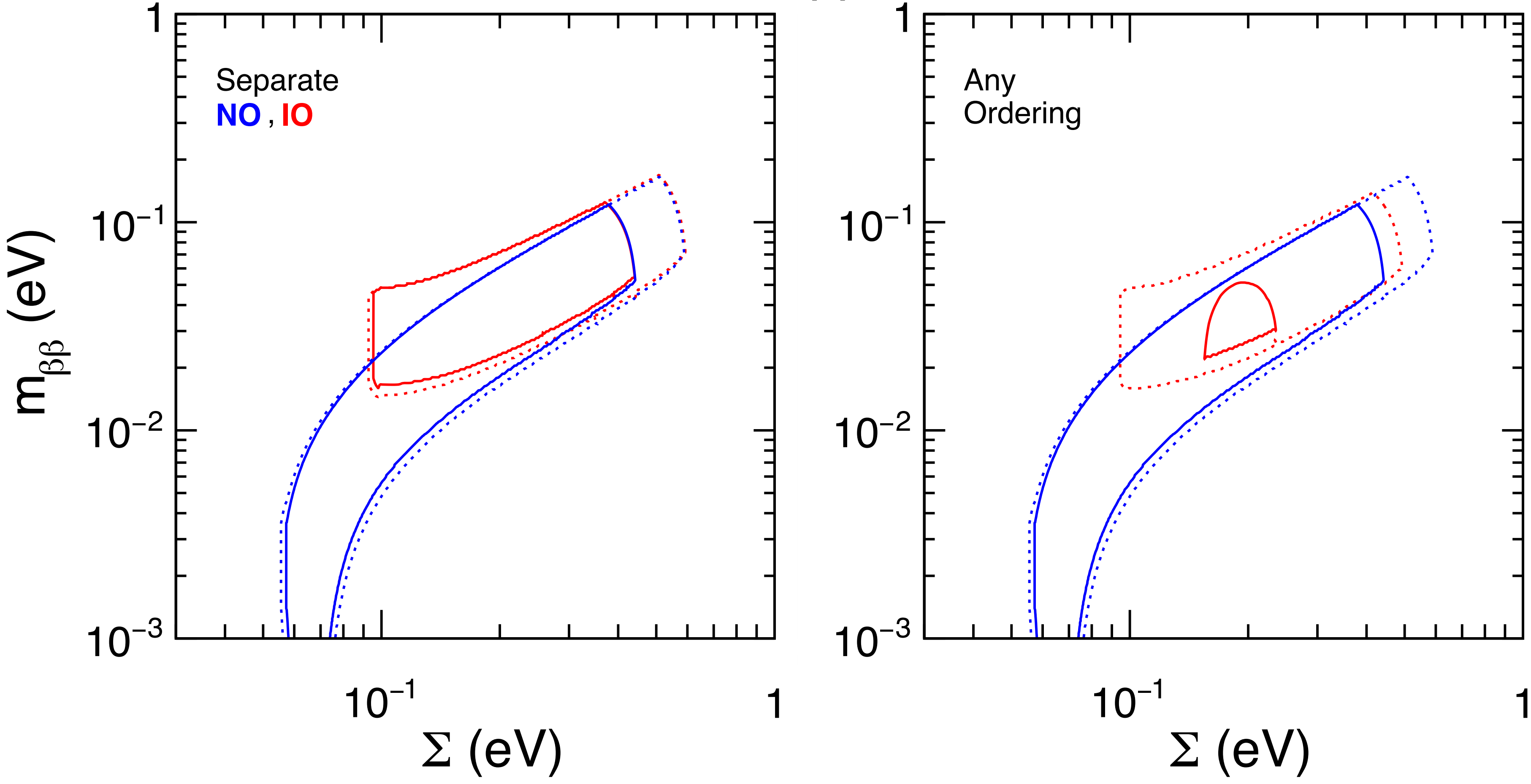
Oscill. + 0νββ + Cosmo #10



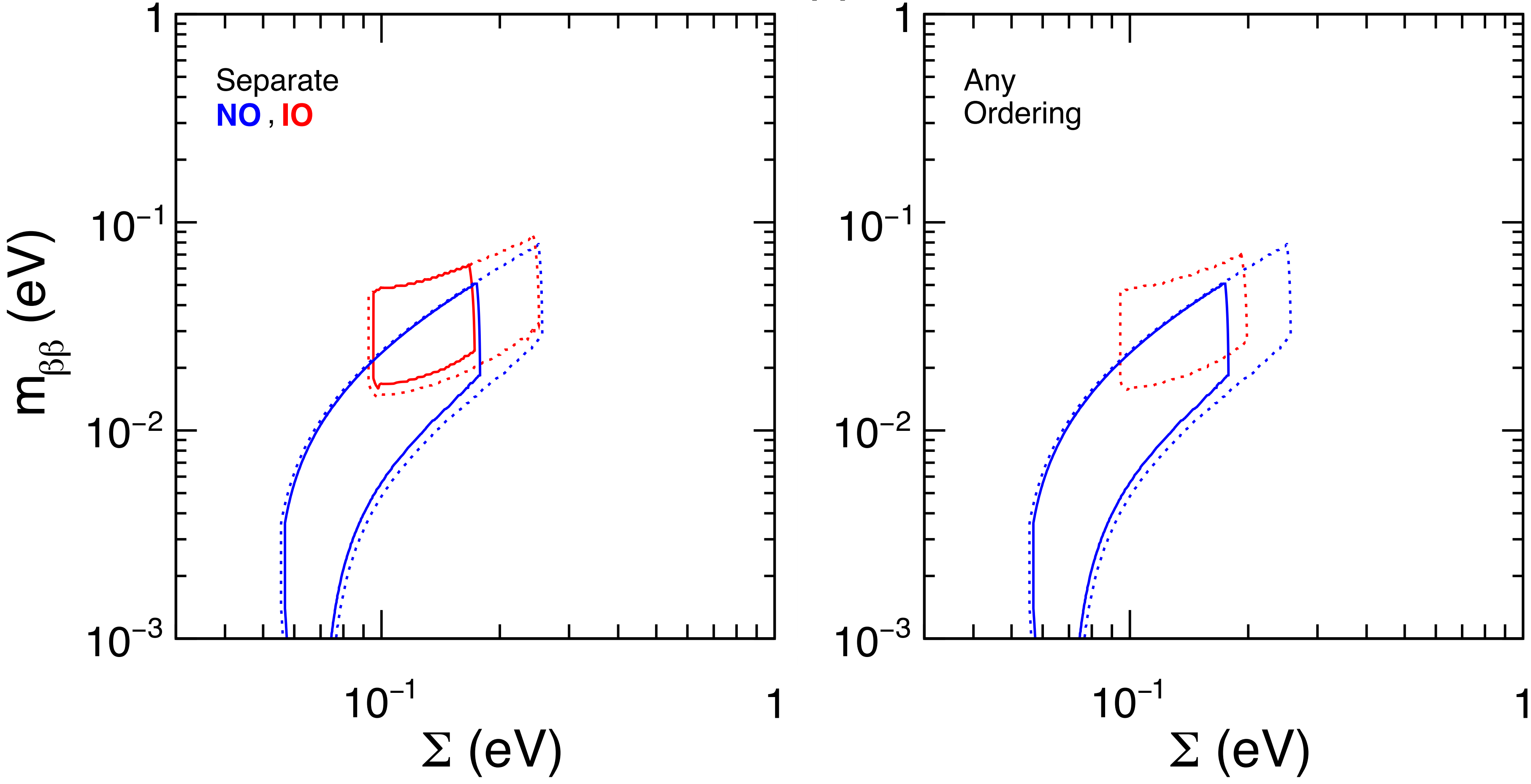
Oscill. + 0νββ + Cosmo #1



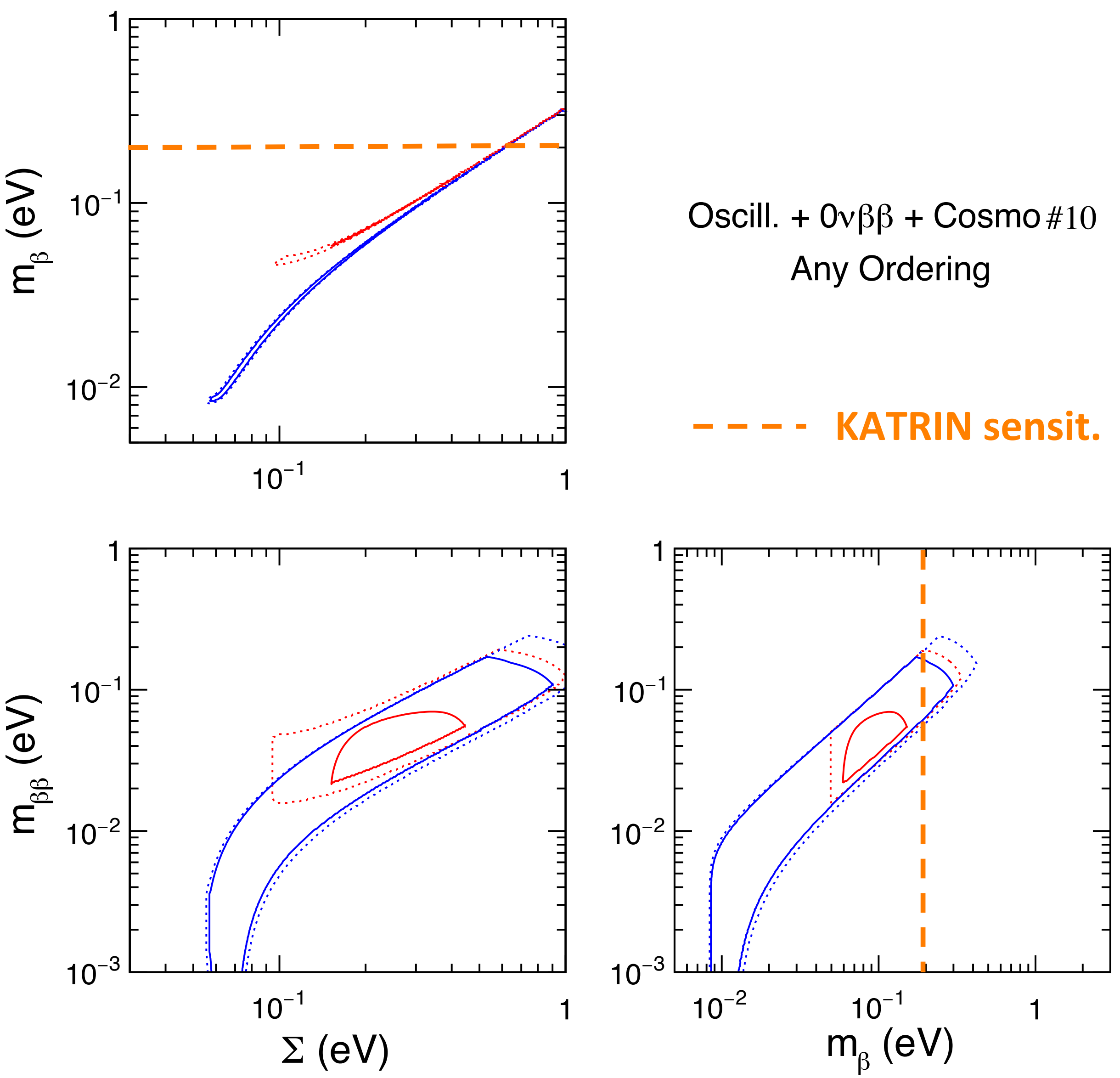
Oscill. + 0νββ + Cosmo #9



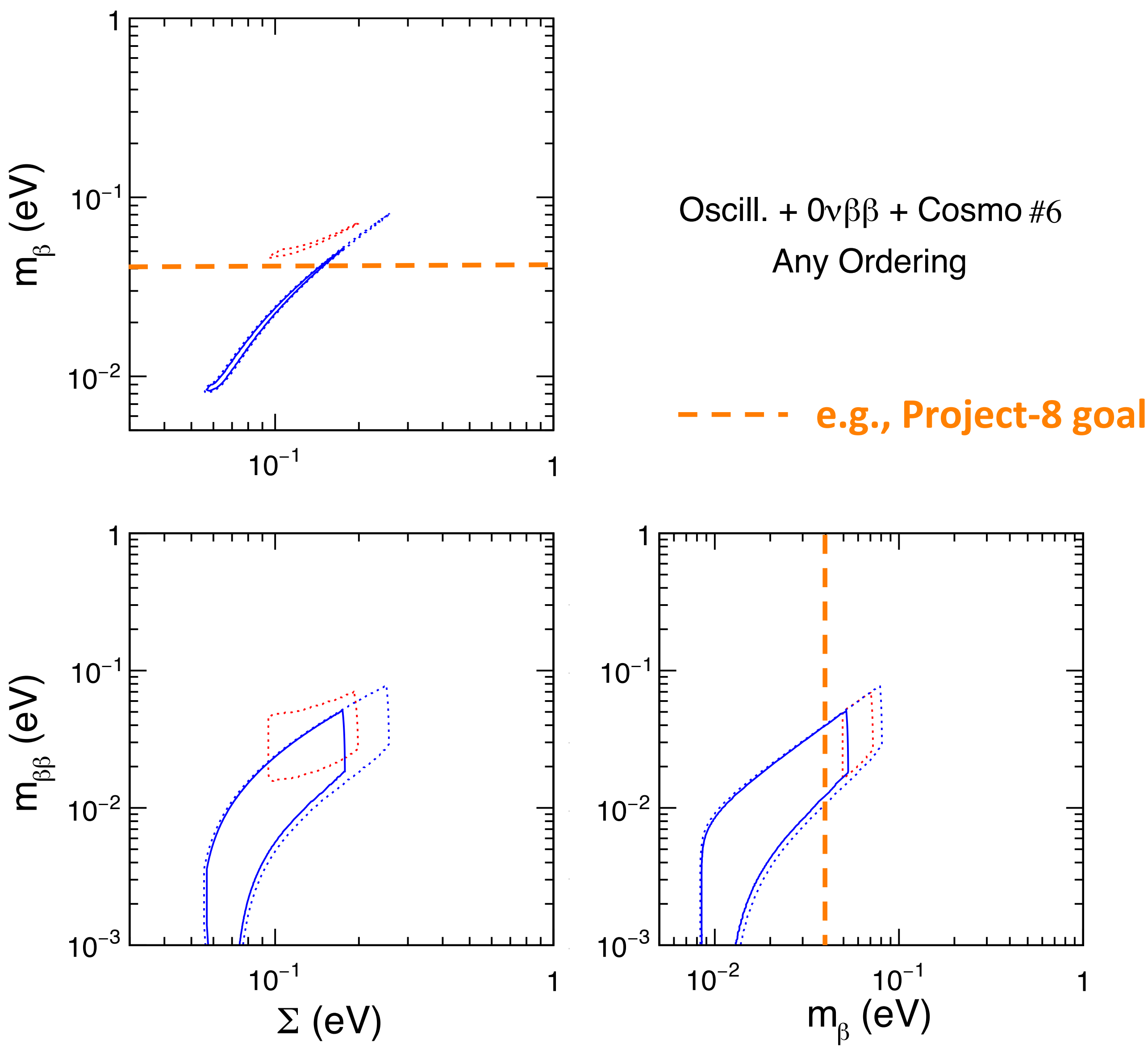
Oscill. + 0νββ + Cosmo #6



Implications for β-decay (weak cosmo bounds)



Implications for β-decay (strong cosmo bounds)



Summary of IO-NO difference:

	LBL+Sol+KL		+SBL Reac		+Atmos		+DBD, Cosmo
$\Delta\chi^2$ (IO-NO)	+1.1	⇒	+1.1	⇒	+3.6	⇒	+3.6 ... +4.4

Small steps in one direction: **N.O. favored**... Overall preference at $1.9\sigma - 2.1\sigma$

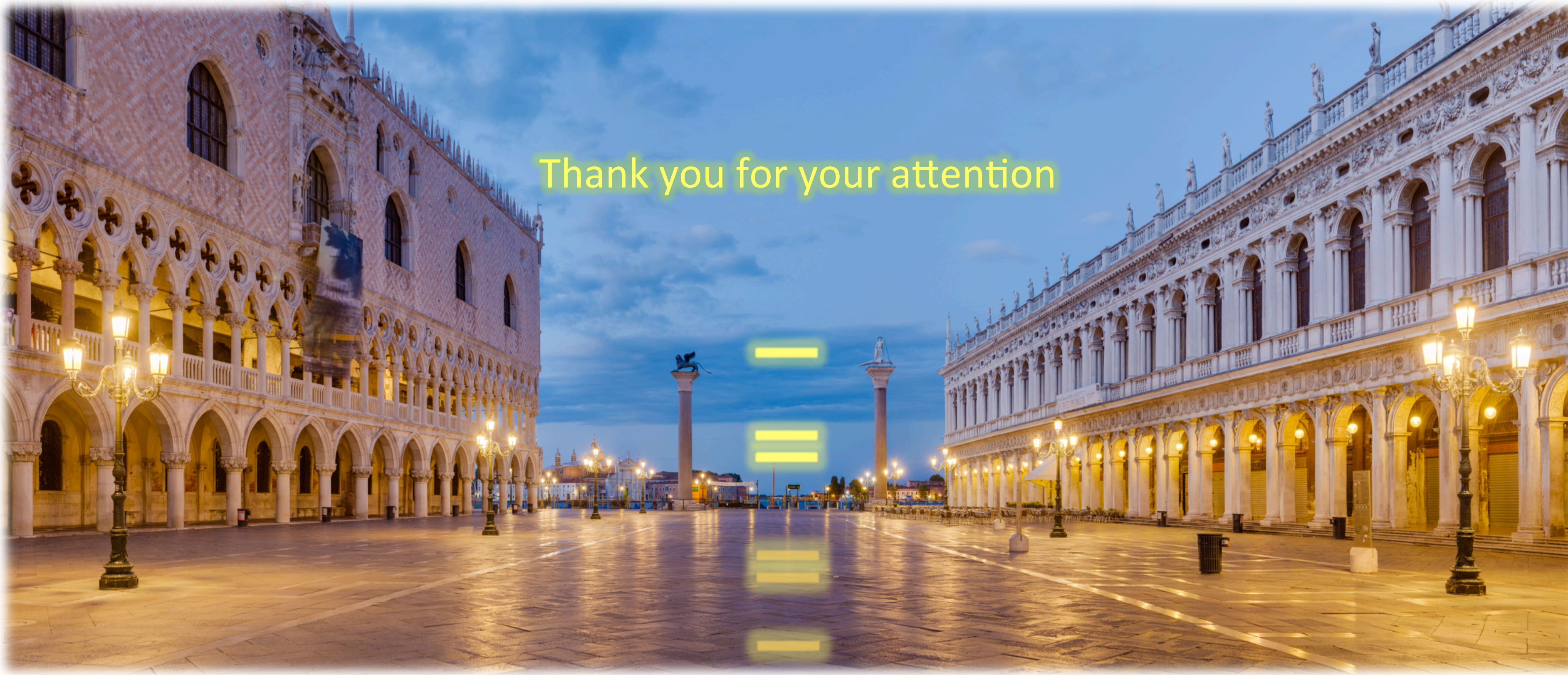
If these are not fluctuations, expect (fractional) improvements in upcoming years

TABLE III: Values of $\Delta\chi^2_{\rm IO-NO}$ from the global analysis of oscillation and non oscillation data (numbered according to the adopted cosmological datasets as in Table II), to be compared with the value 3.6 from oscillation data only [Eq. (9)]. An overall preference emerges for NO, at the level of 1.9–2.1σ.

#	1	2	3	4	5	6	7	8	9	10	11	12
$\Delta\chi^2_{\rm IO-NO}$	4.3	3.8	4.4	4.2	3.9	4.4	3.6	3.7	3.8	3.7	3.8	3.9

SUMMARY:

- **Status of known 3ν oscillation parameters:**
  Precision era, sinergies
- **Trends of unknown oscillation parameters:**
  favoring negative sinδ, nonmax θ_{23}, and NO
- **Status of constraints from 0$\nu\beta\beta$ & Cosmology:**
  Cosmo analysis including NO, IO mass spectra
- **Oscillation + nonoscillation global analysis:**
  corroborate NO; room for improvements


Thank you for your attention