Tensions in flavor measurements: A path towards BSM physics - Naples, 24 May 2017

3ν masses, mixings and CPV phases: status and prospects

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Main results 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 [PRD in press]

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]

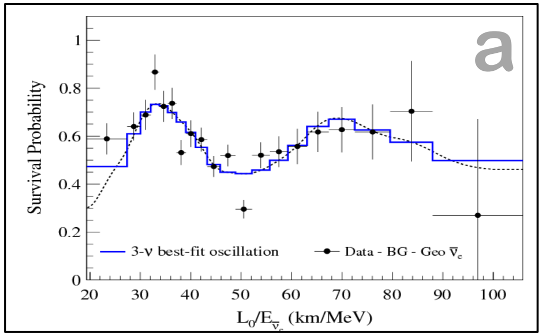
OUTLINE:

- Introduction
- Knowns and unknowns from 3ν oscillations
- Nonoscillation constraints from $0\nu\beta\beta$ & Cosmology
- Combining oscillation + nonoscillation data
- Summary and prospects

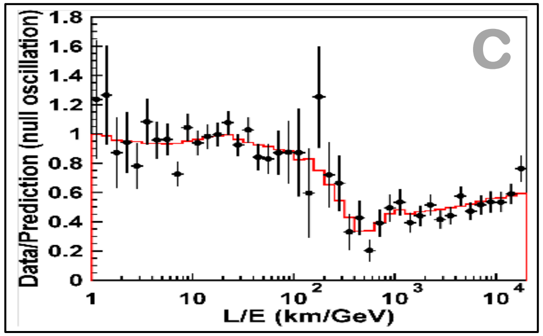
Introduction

Established facts: $\alpha \rightarrow \beta$ oscillations in vacuum and matter…

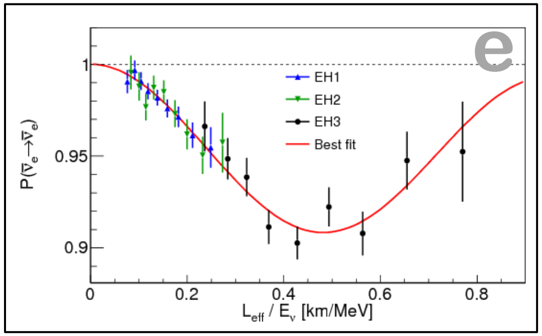
e→e



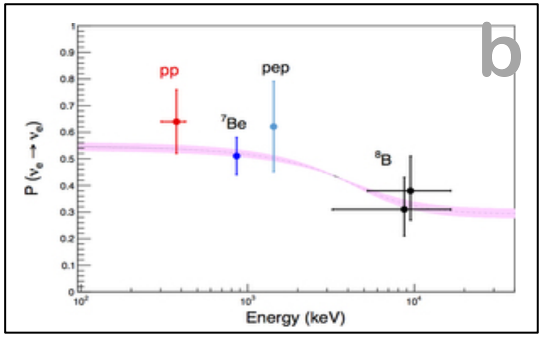
μ→μ



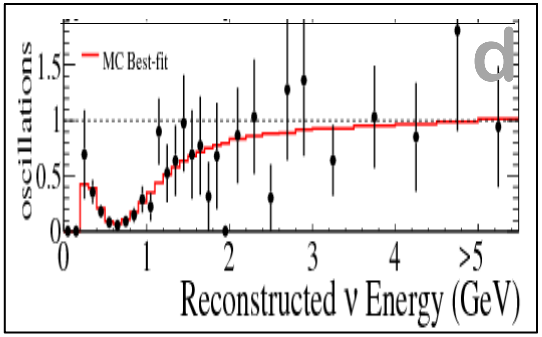
e→e



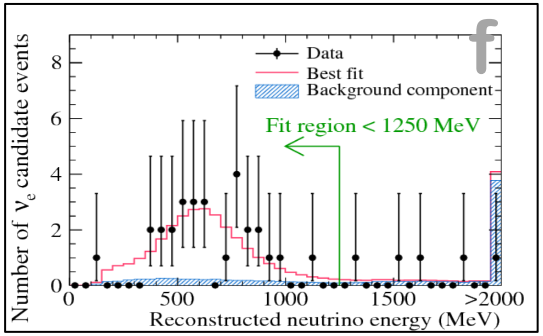
e→e



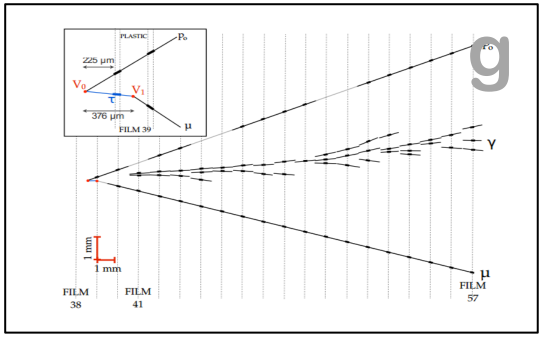
μ→μ



μ→e



μ→τ

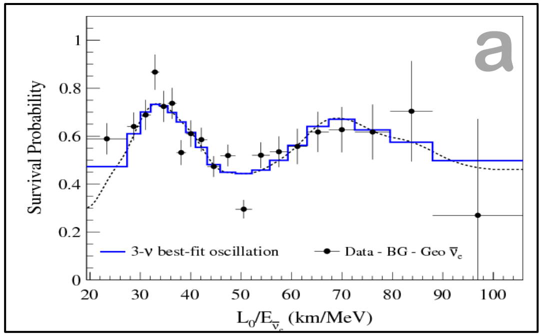


Data from various types of neutrino experiments: (a) solar, (b) long-baseline reactor, (c) atmospheric, (d) long-baseline accelerator, (e) short-baseline reactor, (f,g) long baseline accelerator (and, in part, atmospheric).

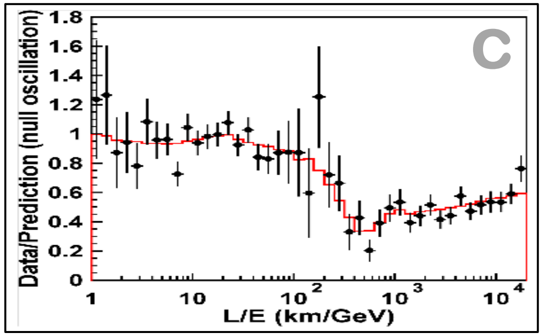
(a) KamLAND [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], DeepCore, MACRO, MINOS etc.; (d) T2K (plot), MINOS, K2K; (e) Daya Bay [plot], RENO, Double Chooz; (f) T2K [plot], MINOS, NOvA; (g) OPERA [plot], Super-K atmospheric.

...can be interpreted in a simple 3ν theoretical framework

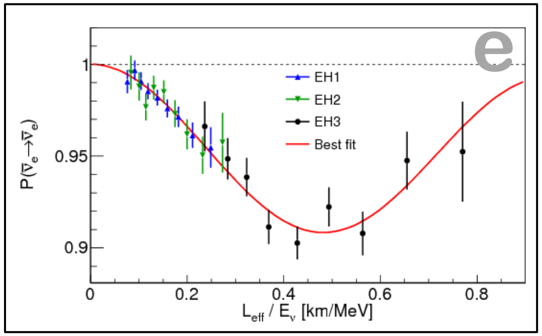
e→e (δm^2 , θ_{12})



μ→μ (Δm^2 , θ_{23})



e→e (Δm^2 , θ_{13})



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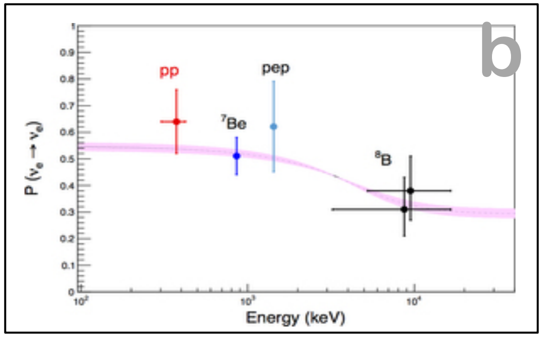
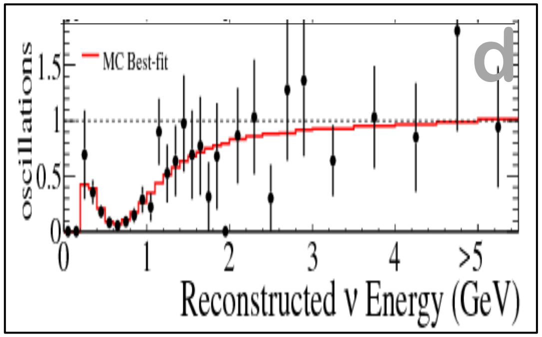
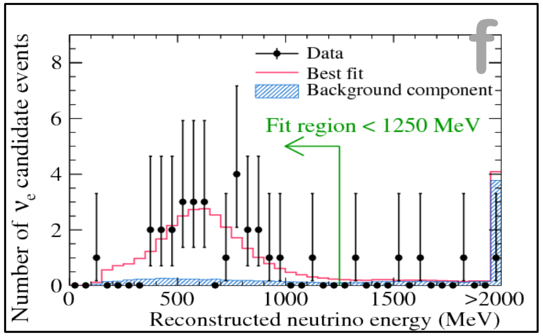


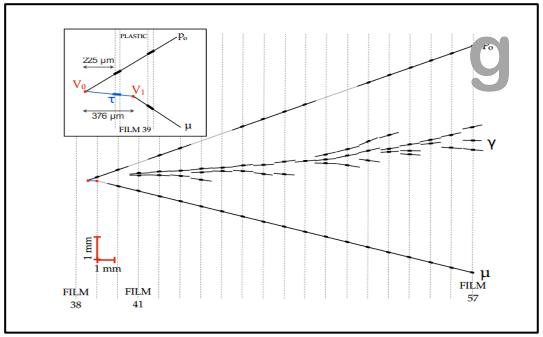
μ→μ (Δm^2 , θ_{23})



μ→e (Δm^2 , θ_{13} , θ_{23})



μ→τ (Δm^2 , θ_{23})



Five parameters measured so far:

δm^2 $|\Delta m^2|$ θ_{12} θ_{23} θ_{13}

Parameters of the 3ν theoretical framework

Pontecorvo-Maki-Nakagawa-Sakata (**PMNS**) matrix

$$U_{\alpha i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\beta/2} \end{bmatrix}$$

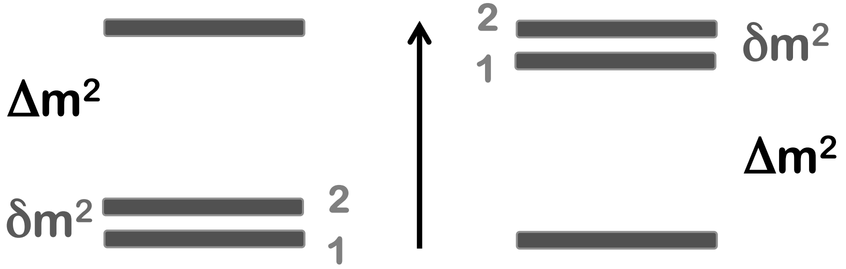
[only if Majorana]

Mixing angles θ_{23}, θ_{13}, θ_{12}

CP-violat. phase(s) δ (α, β)

Mass (squared) spectrum

"Normal"
Hierarchy
or Ordering



"Inverted"
Hierarchy
or Ordering

Squared mass splittings δm^2, $|\Delta m^2|$ Ordering = sign(Δm^2) **[+ abs. mass scale]**

+ matter effects ~ $G_F \cdot E \cdot$ density

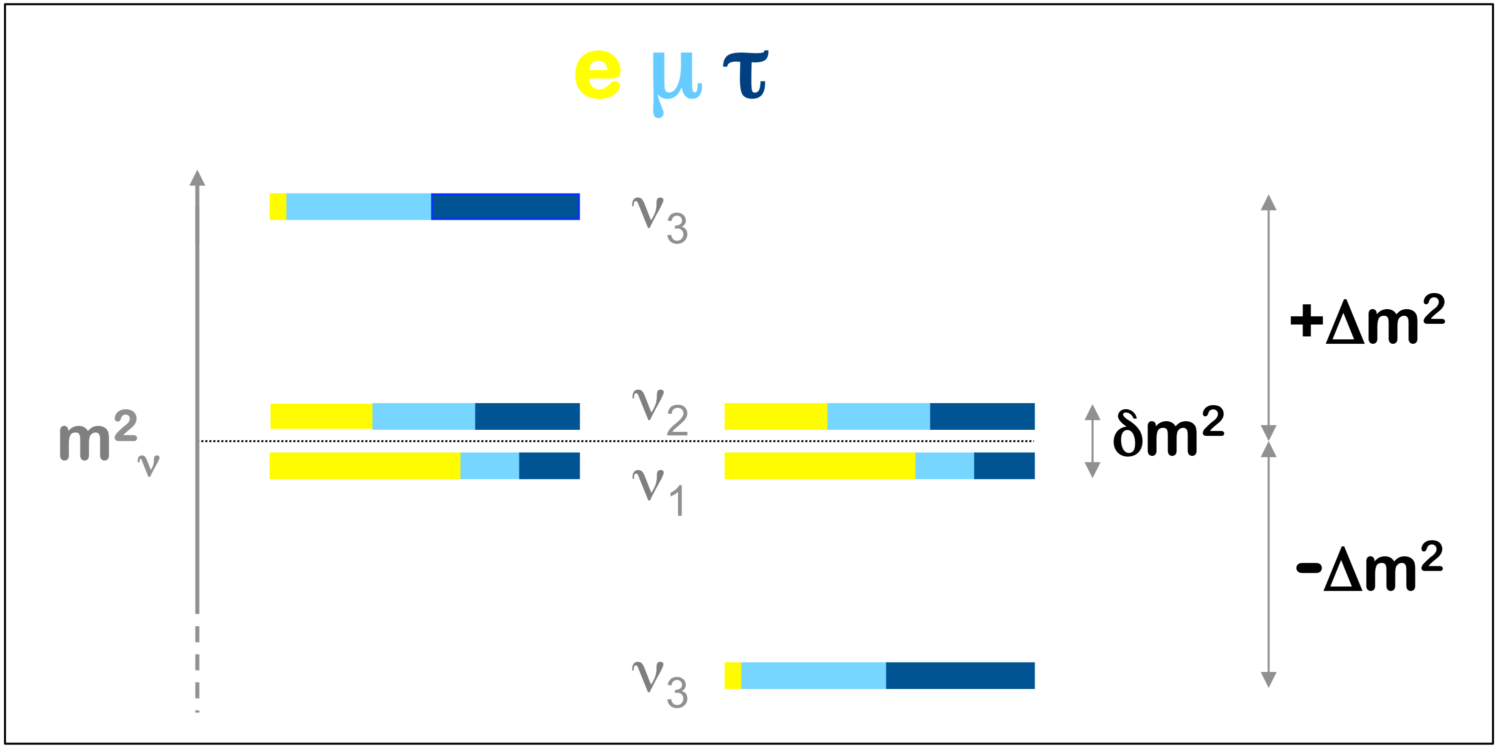
"Broad-brush" 3ν picture (with 1-digit accuracy)

Knowns:

$\delta m^2 \sim 7 \times 10^{-5}\ \mathrm{eV}^2$
$\Delta m^2 \sim 2 \times 10^{-3}\ \mathrm{eV}^2$
$\sin^2\theta_{12} \sim 0.3$
$\sin^2\theta_{23} \sim 0.5$
$\sin^2\theta_{13} \sim 0.02$

Unknowns:

δ (CP)
sign(Δm^2) = ordering
octant(θ_{23})
absolute mass scale
Dirac/Majorana nature



Remark

CPV: In ν oscillations, driven only by δ (Majorana phases -if any- decouple)

$$\boxed{P(\nu_\alpha \to \nu_\beta) - P(\overline{\nu}_\alpha \to \overline{\nu}_\beta) \propto J_{\rm PMNS}}$$

[Valid in vacuum. In matter, oscillation pick up further (background) CPV effects]

$$J_{\rm PMNS} = \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin\delta$$

$$\simeq 3 \times 10^{-2} \sin\delta$$ = known x unknown

$$[J_{\rm CKM} \simeq 3 \times 10^{-5}]$$

If $|\sin\delta| \sim 1$ (maximal CPV) → $J_{\rm PMNS} \sim 10^3\, J_{\rm CKM}$

more on...

Knowns and unknowns from 3ν oscillations

From a "broad-brush" to a more detailed picture, circa 2017

Global analysis includes increasingly rich oscillation data sets:

LBL Acc + Solar + KL $(\Delta m^2, \theta_{13}, \theta_{23}) + (\delta m^2, \theta_{12})$ + sublead.

LBL Acc + Solar + KL + SBL Reactor ...$+(\Delta m^2, \theta_{13})$

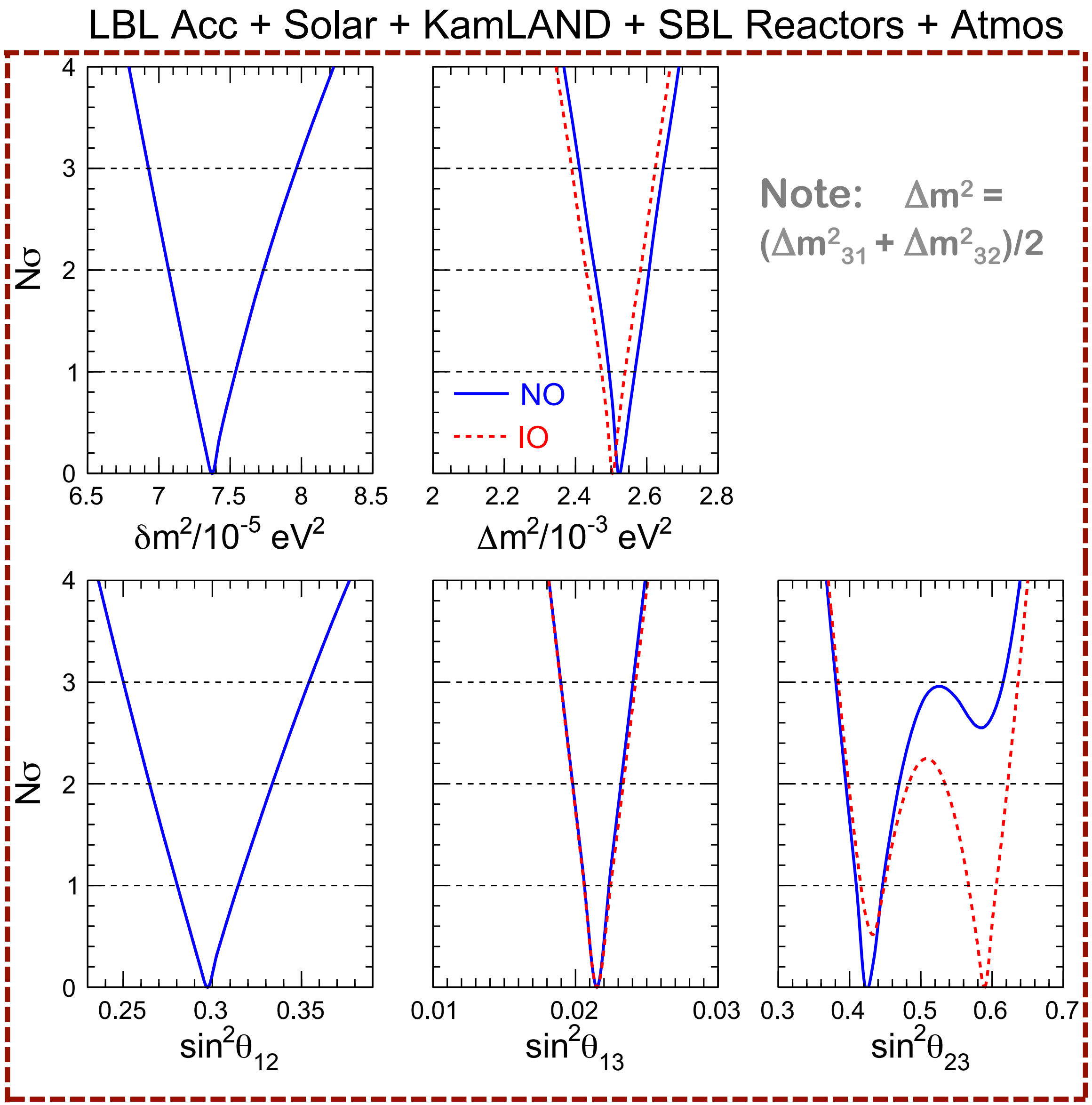
LBL Acc + Solar + KL + SBL Reactor + Atmosph.

Parameters not shown are marginalized away

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

NO / IO = Normal / Inverted Ordering

Five known oscillation parameters:



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

Current 1σ errors
(1/6 of ±3σ range):

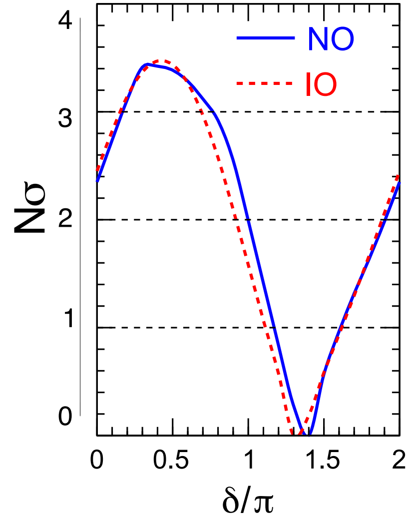
δm^2	2.3 %
Δm^2	1.6 %
$\sin^2\theta_{12}$	5.8 %
$\sin^2\theta_{13}$	4.0 %
$\sin^2\theta_{23}$	~ 9 %

all < 10%...

Precision Era!

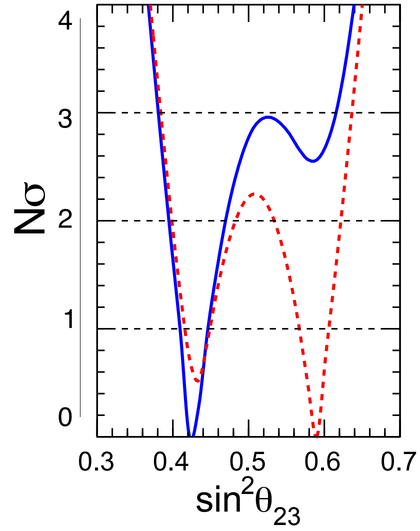
[but PMNS still very far from CKM accuracy]

Three unknown oscillation parameters



δ_{CP}

$P(\nu_\alpha \to \nu_\beta) - P(\overline{\nu}_\alpha \to \overline{\nu}_\beta)$

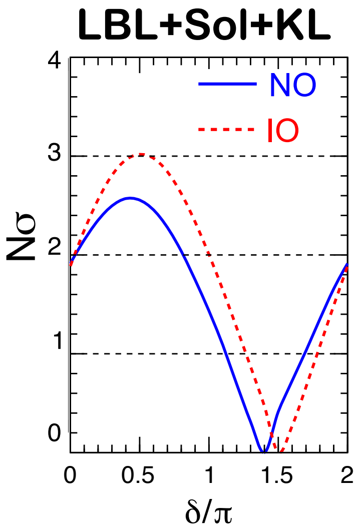


θ_{23} octant

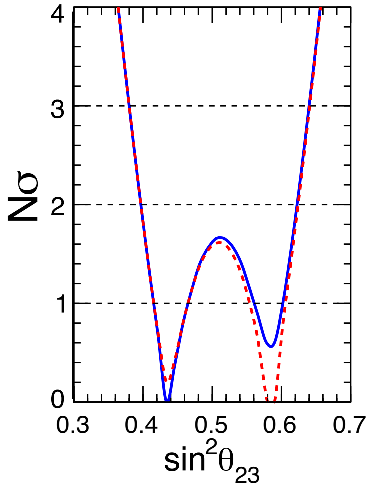
NO or IO

More on unknown oscillation parameters:

δ_{CP}



θ_{23} **octant**

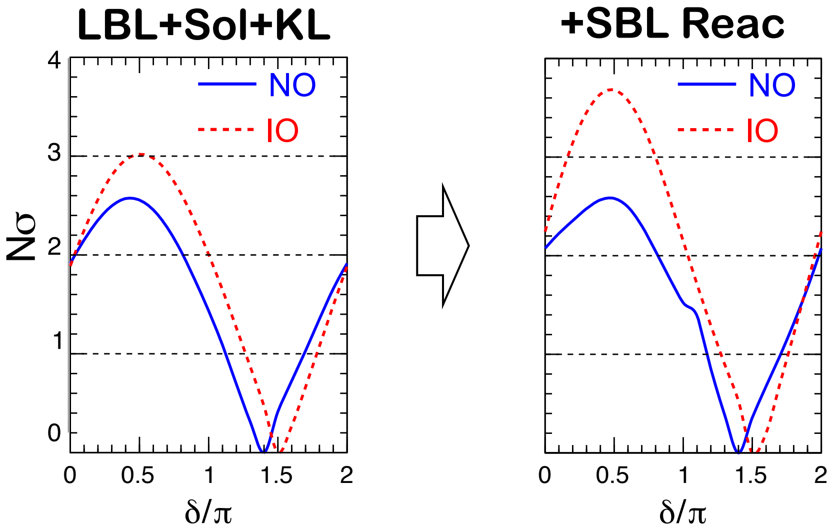


$\Delta\chi^2$ **(IO-NO)**

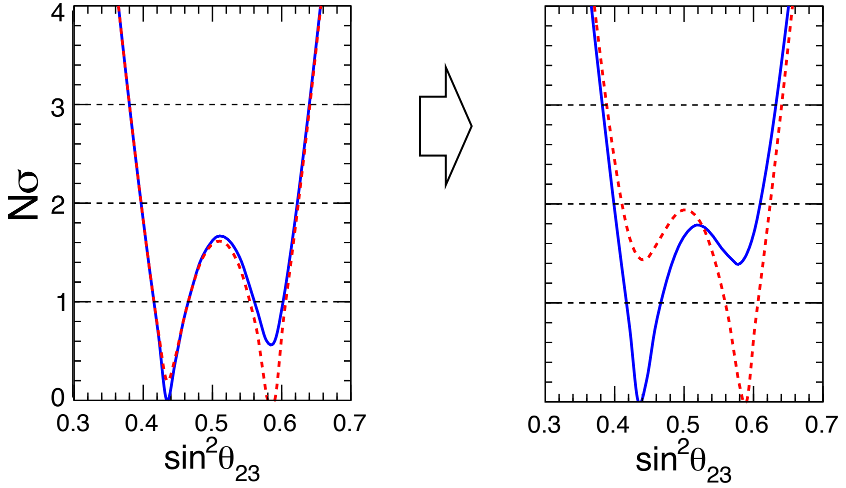
+1.1

More on unknown oscillation parameters:

δ_{CP}



θ_{23}
octant



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

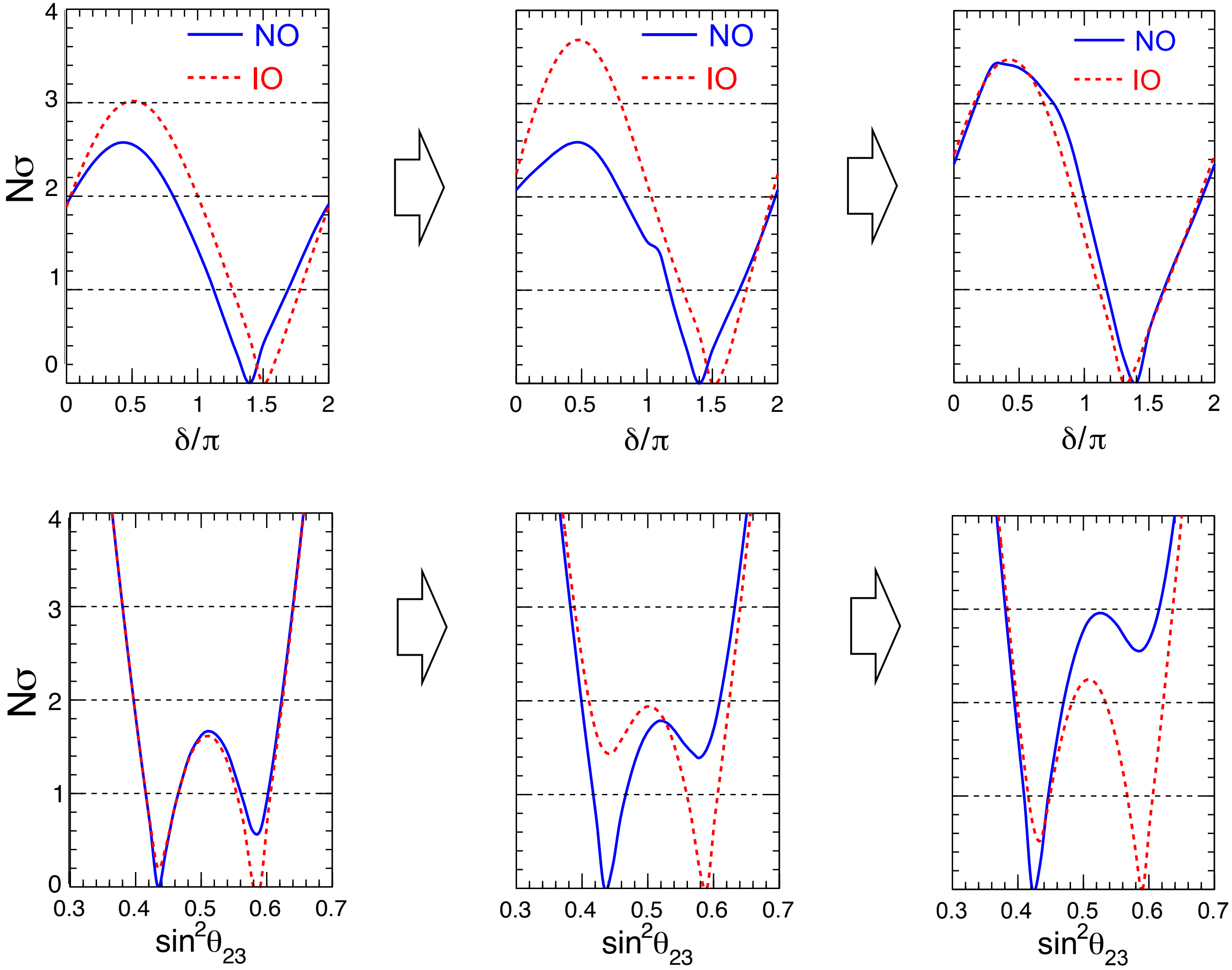
+1.1 **+1.1**

More on unknown oscillation parameters:

LBL+Sol+KL ⇨ **+SBL Reac** ⇨ **+Atmos**

δ_{CP}

θ_{23} octant



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

[next talk;
stay tuned!]

Max-mixing
disfavored;
octant flips
with NO/IO

[difficult
to solve the
ambiguity]

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

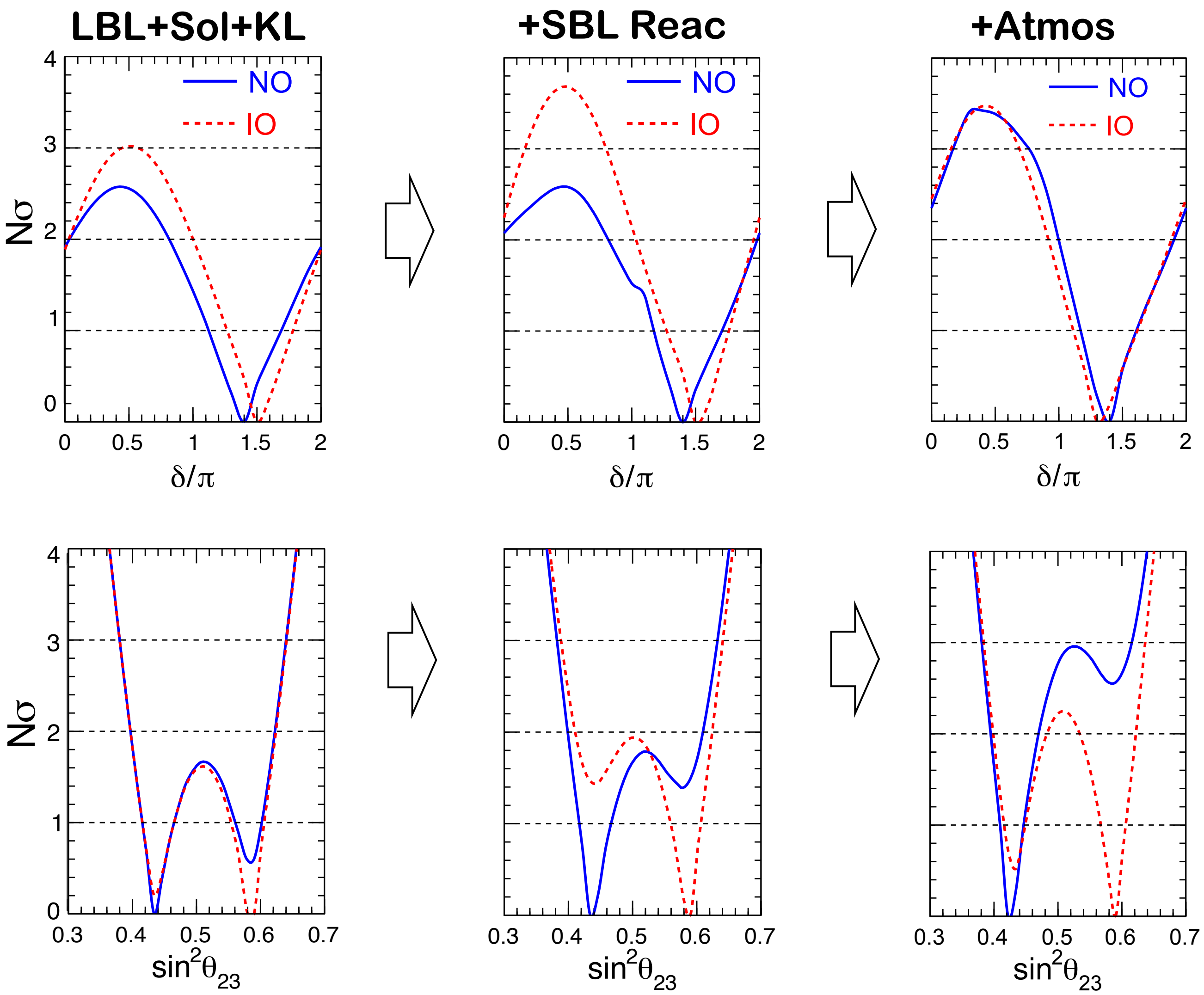
+1.1 ⇨ **+1.1** ⇨ **+3.6**

Intriguing!
NO favored

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

δ_{CP}

θ_{23} octant



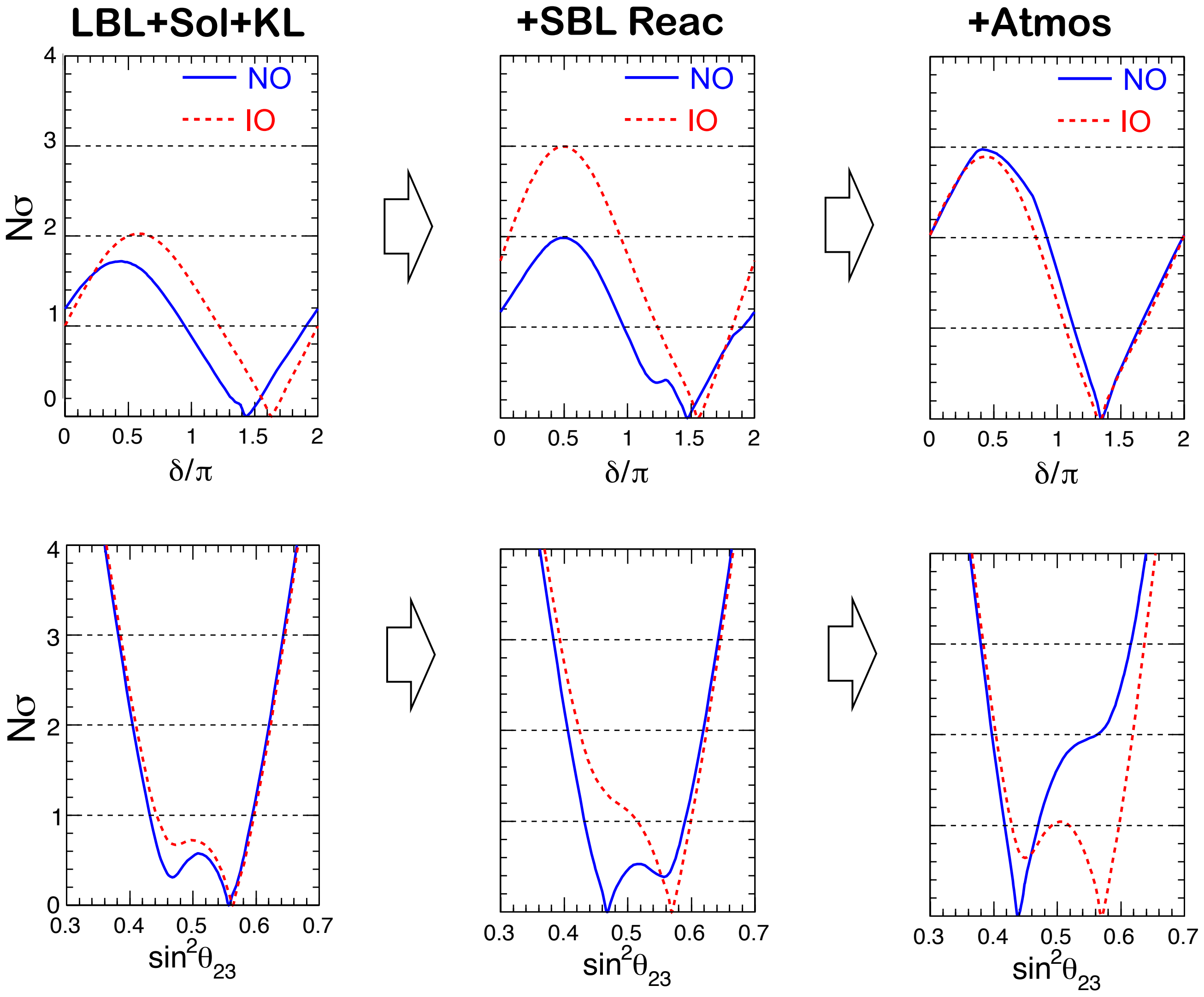
$\Delta\chi^2$ (IO-NO)

+1.1	+1.1	+3.6

… 1yr ago, 2016: trends were somewhat weaker

δ_{CP}

θ_{23} **octant**

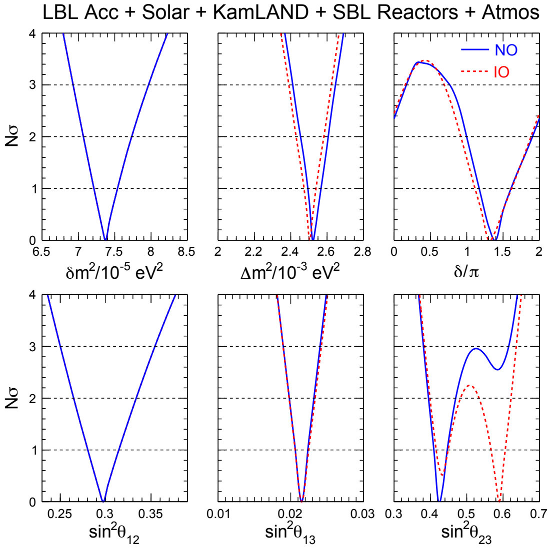


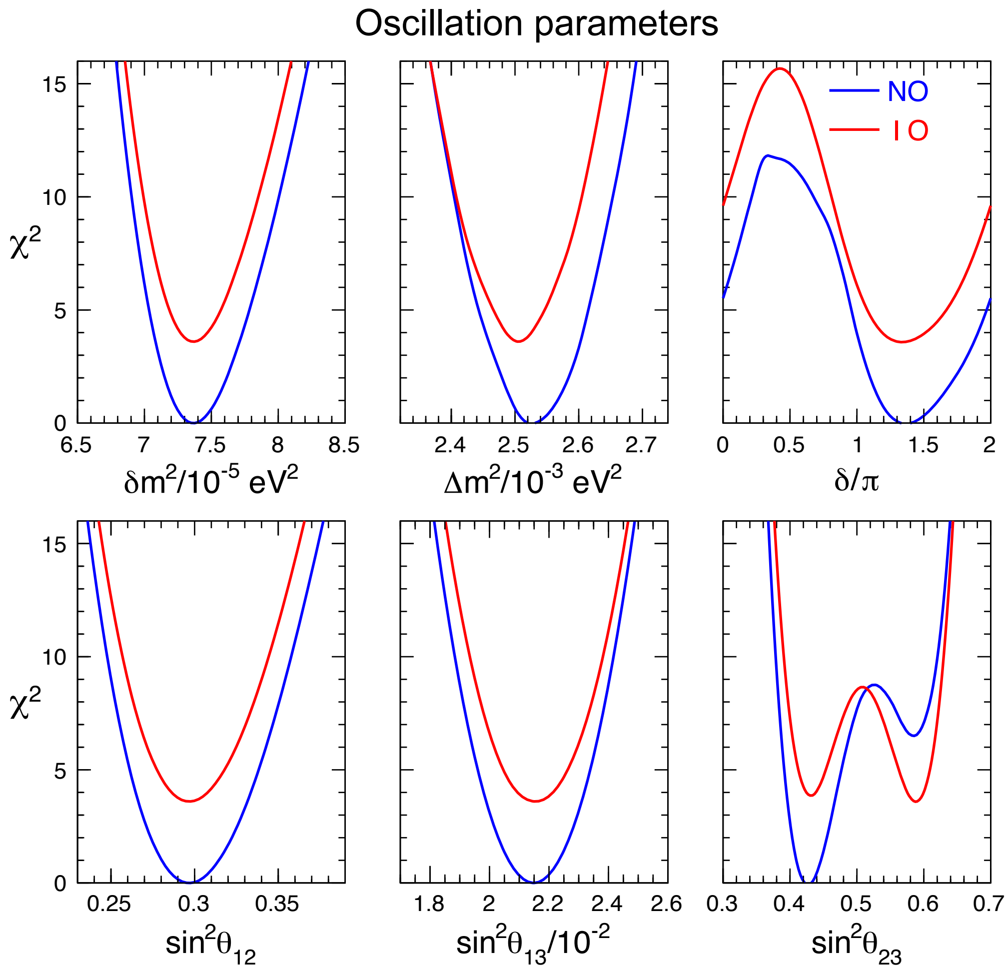
$\Delta\chi^2$ **(IO-NO)**

-1.2 → **-0.9** → **+1.0**

Current indication $\Delta\chi^2_{IO-NO} = 3.6$ from oscill. data starts to be interesting.

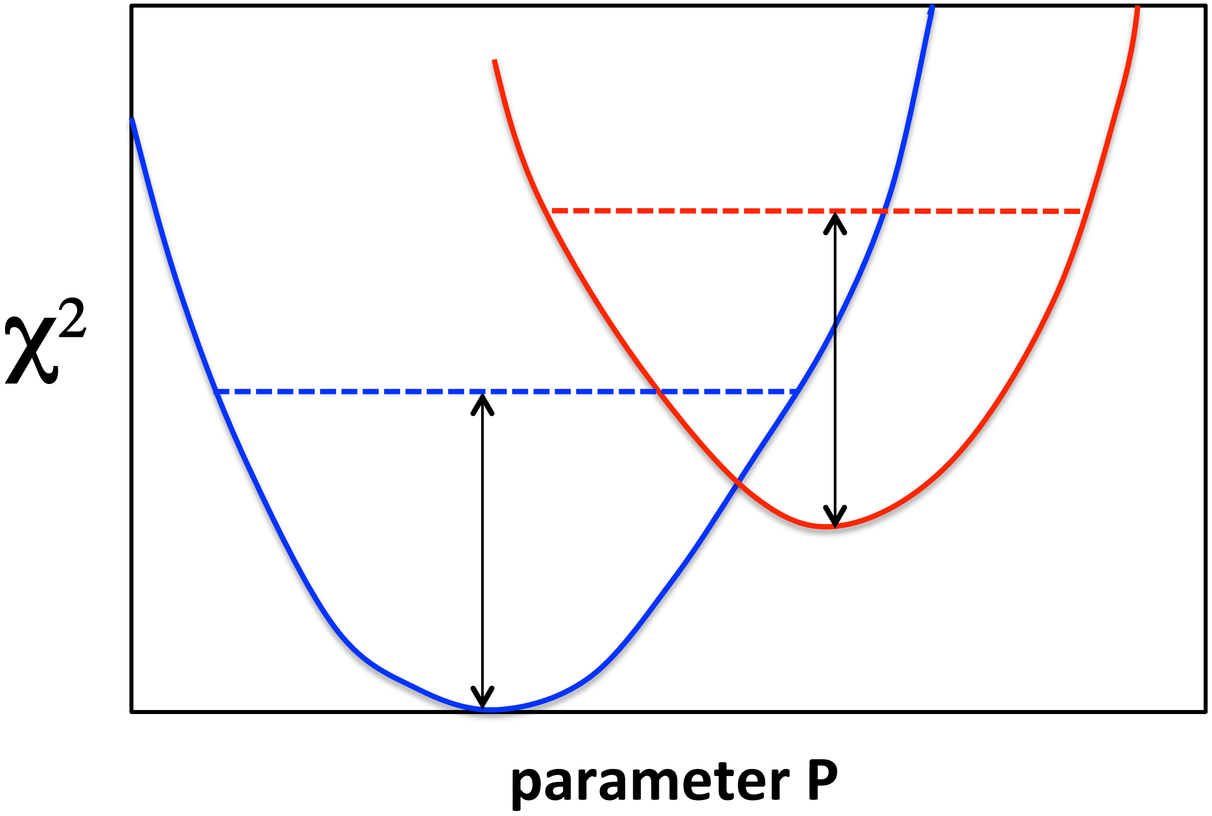
Useful to see the effect of excluding/including this offset in the analysis:





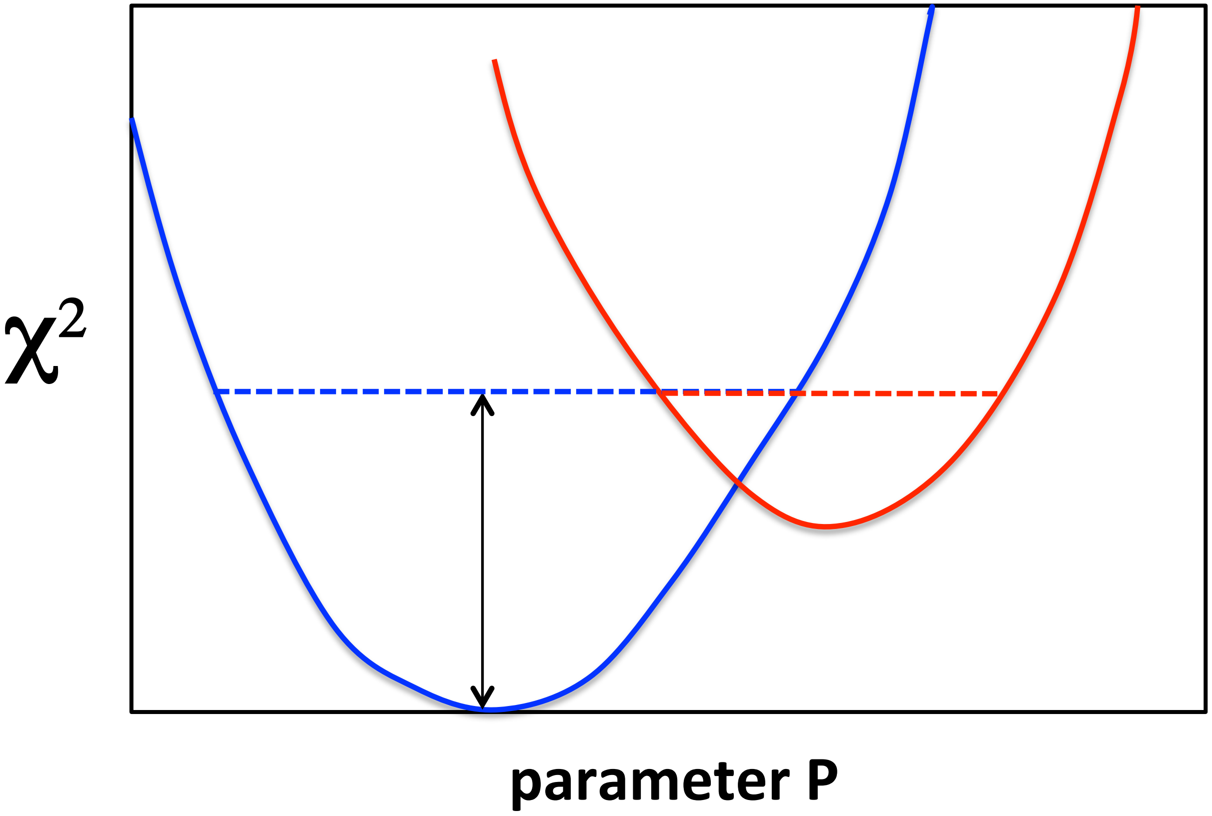
Two different ways of marginalizing over mass ordering(s) →

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



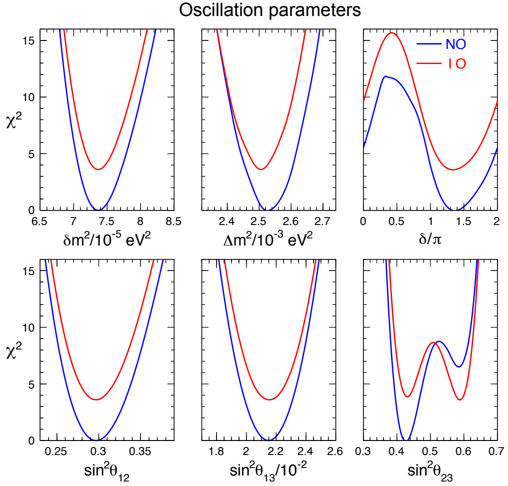
(does not include IO-NO offset information)

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



(includes IO-NO offset information)

Oscillation parameter ranges



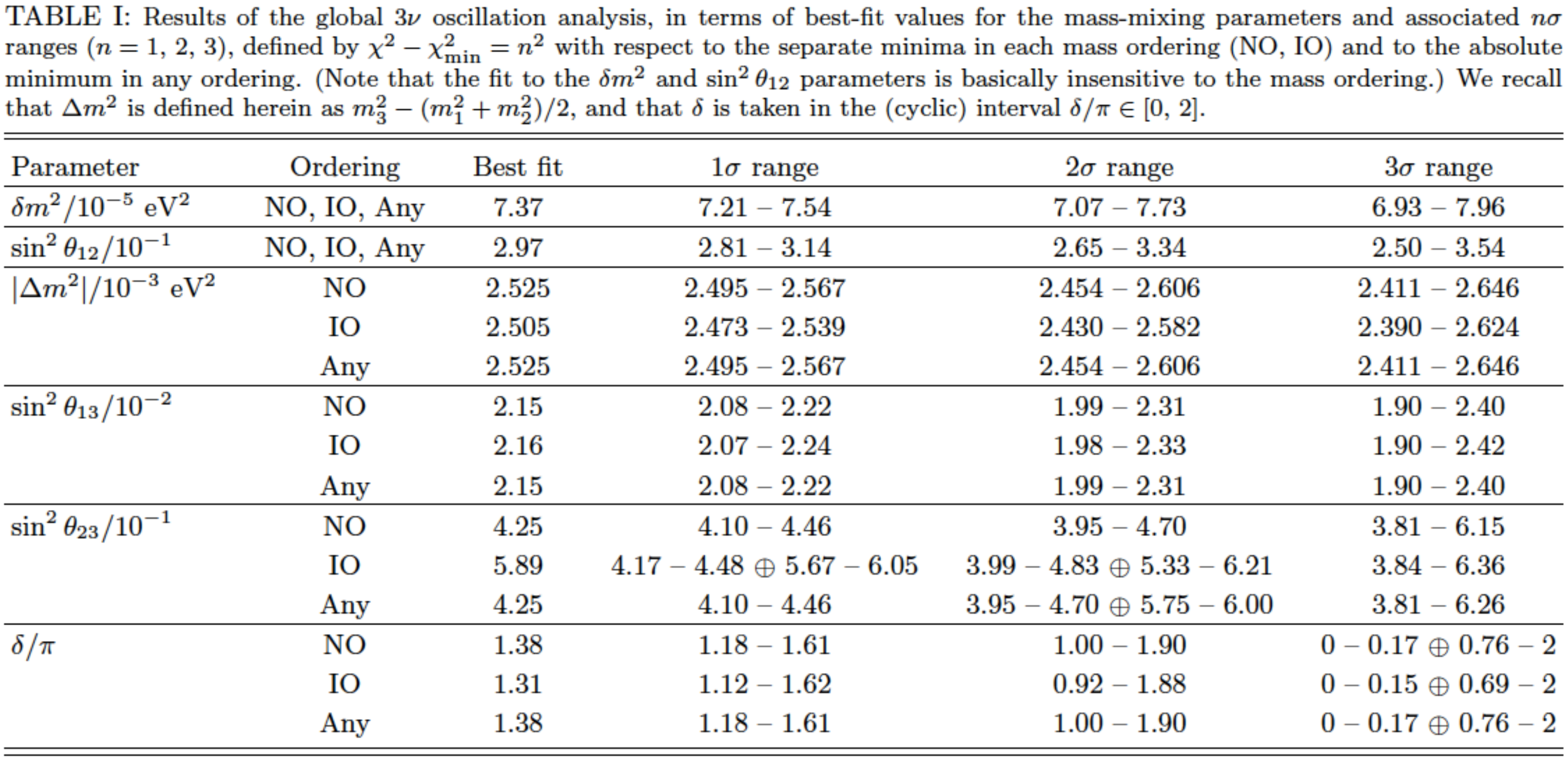
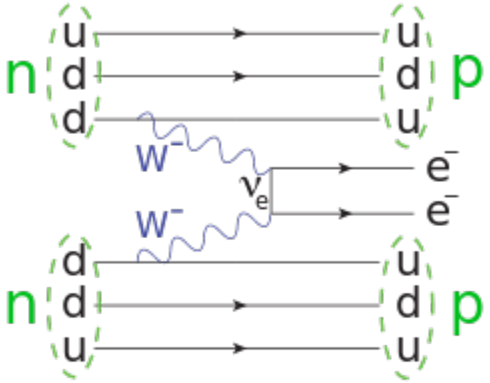
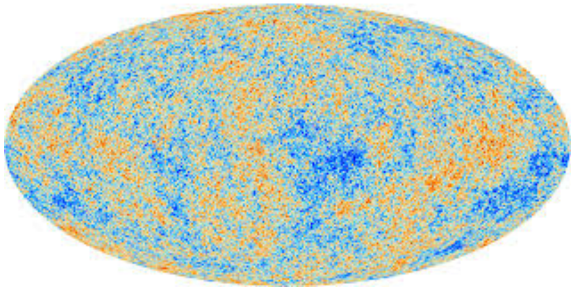


TABLE I: Results of the global 3ν oscillation analysis, in terms of best-fit values for the mass-mixing parameters and associated $n\sigma$ ranges ($n = 1, 2, 3$), defined by $\chi^2 - \chi^2_{\rm min} = n^2$ with respect to the separate minima in each mass ordering (NO, IO) and to the absolute minimum 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
$\lvert\Delta m^2\rvert/10^{-3}$ 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

Non-oscillation constraints from $0\nu\beta\beta$ & Cosmology





Three observables sensitive to absolute ν masses:

(m_β , $m_{\beta\beta}$, Σ)

Limits:

β decay, sensitive to the "effective electron neutrino mass":

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$

~ 2 eV

0νββ decay: only if Majorana. "Effective Majorana mass":

$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

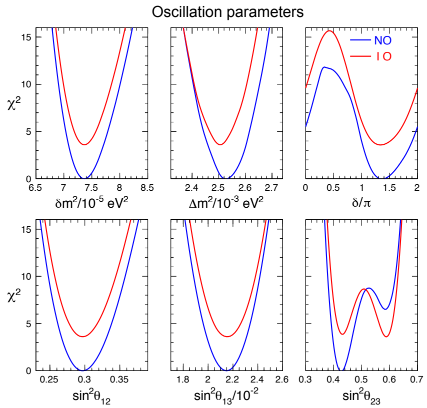
sub-eV

Cosmology: Dominantly sensitive to sum of neutrino masses:

$$\Sigma = m_1 + m_2 + m_3$$

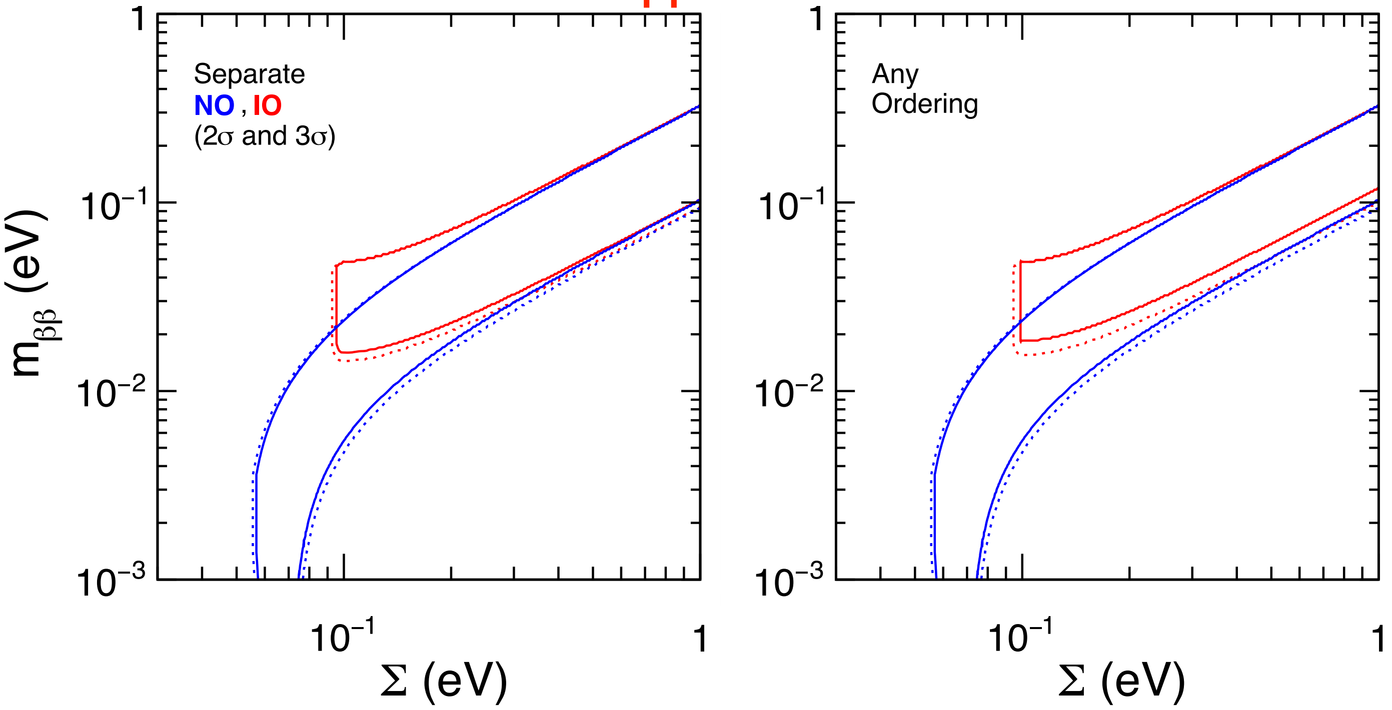
sub-eV

Note 1: They may provide handles to distinguish NO/IO.
Note 2: Majorana case may provide a new source of CPV
Note 3: Available phase space constrained by oscillations →



($m_{\beta\beta}$, Σ) plane

Effective Majorana Mass (DBD)



Sum of neutrino masses (Cosmology)

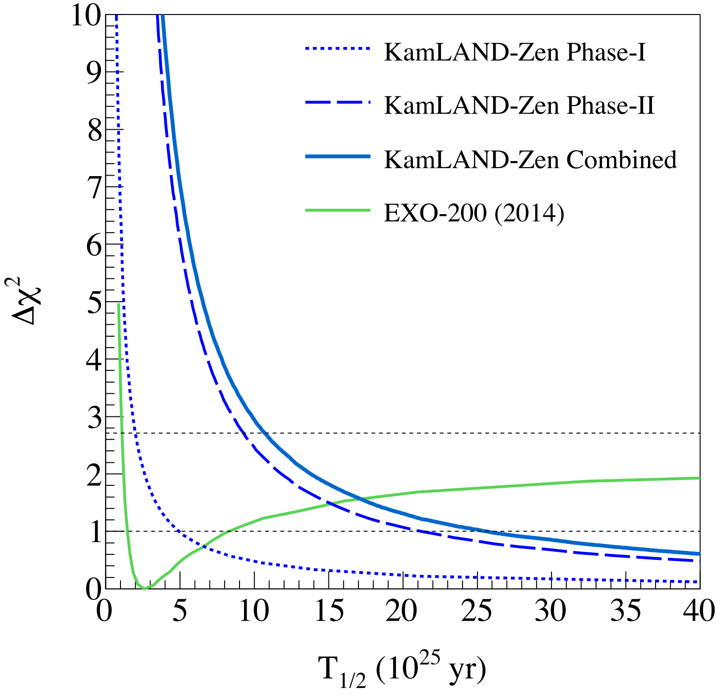
↕ spread from Majorana CPV phases

↑ = constructive interference

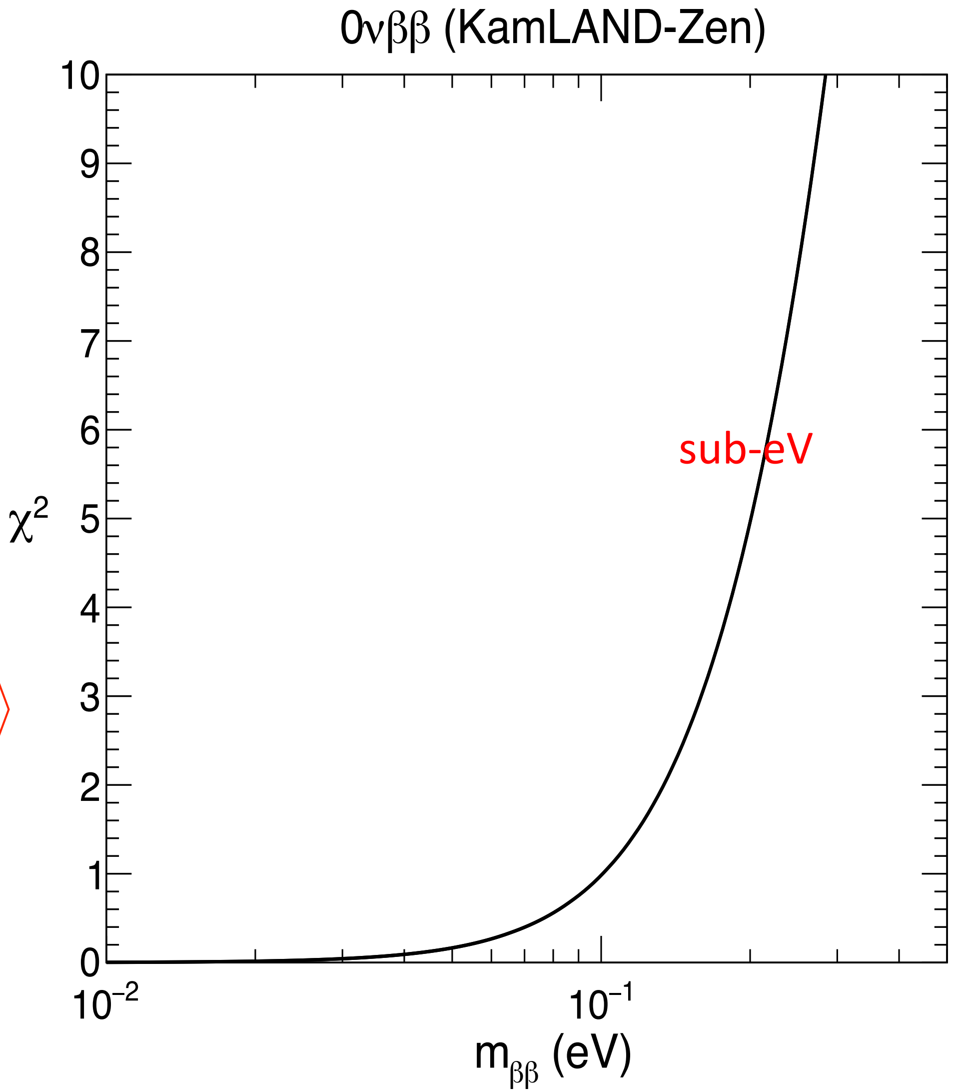
↓ = destructive interference

Representative (leading) $0\nu\beta\beta$ limits

KamLAND-Zen half-life limits



+ theoretical estimates of nuclear matrix element for 136-Xe



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)

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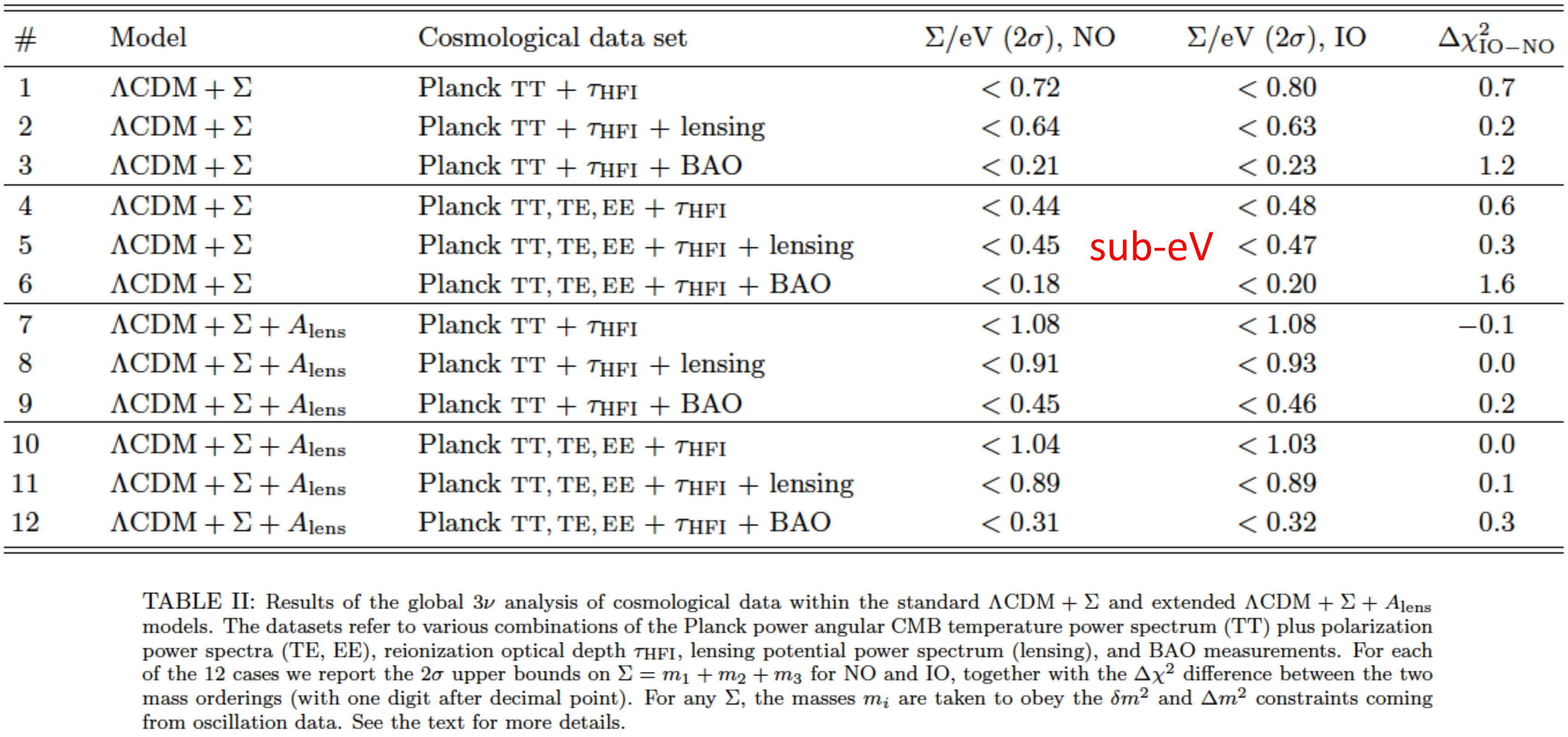
Results on Σ (upper bounds) **and on $\Delta\chi^2_{\mathrm{IO-NO}}$:**

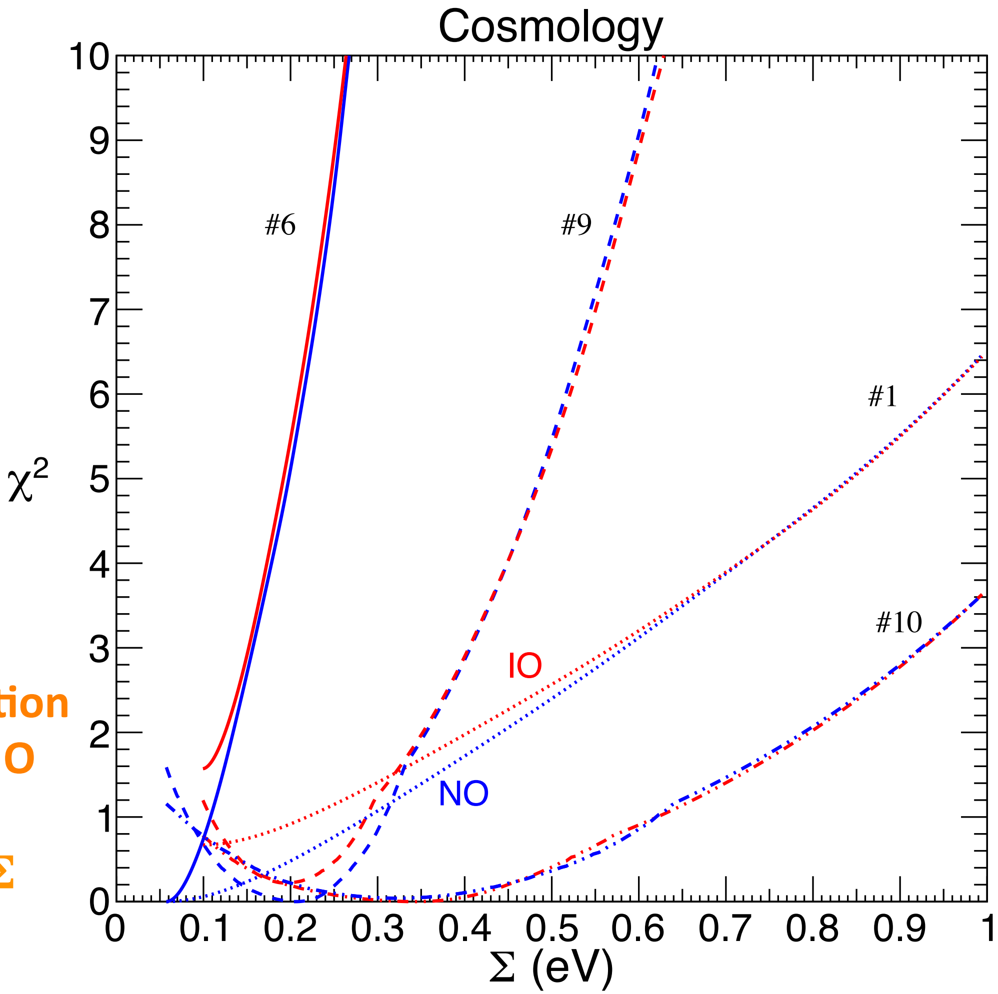


#	Model	Cosmological data set	Σ/eV (2σ), NO	Σ/eV (2σ), IO	$\Delta\chi^2_{\mathrm{IO-NO}}$
1	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT + τ_{HFI}	< 0.72	< 0.80	0.7
2	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT + τ_{HFI} + lensing	< 0.64	< 0.63	0.2
3	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT + τ_{HFI} + BAO	< 0.21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

sub-eV

TABLE II: Results of the global 3ν analysis of cosmological data within the standard $\Lambda\mathrm{CDM}+\Sigma$ and extended $\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$ 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.

χ^2 profile for NO, IO in representative cases



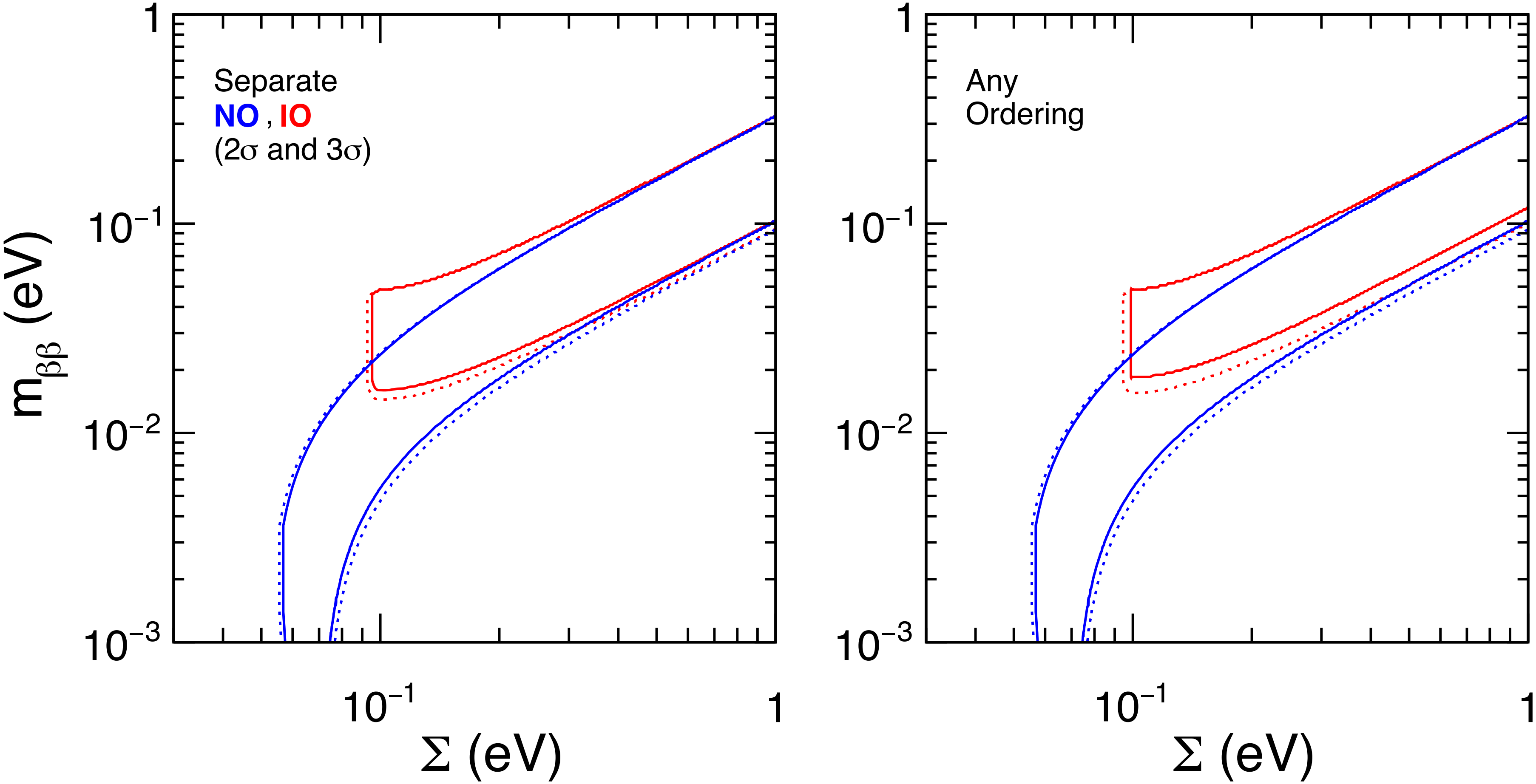
convergence of NO, IO curves at high Σ

bifurcation of NO, IO curves at low Σ

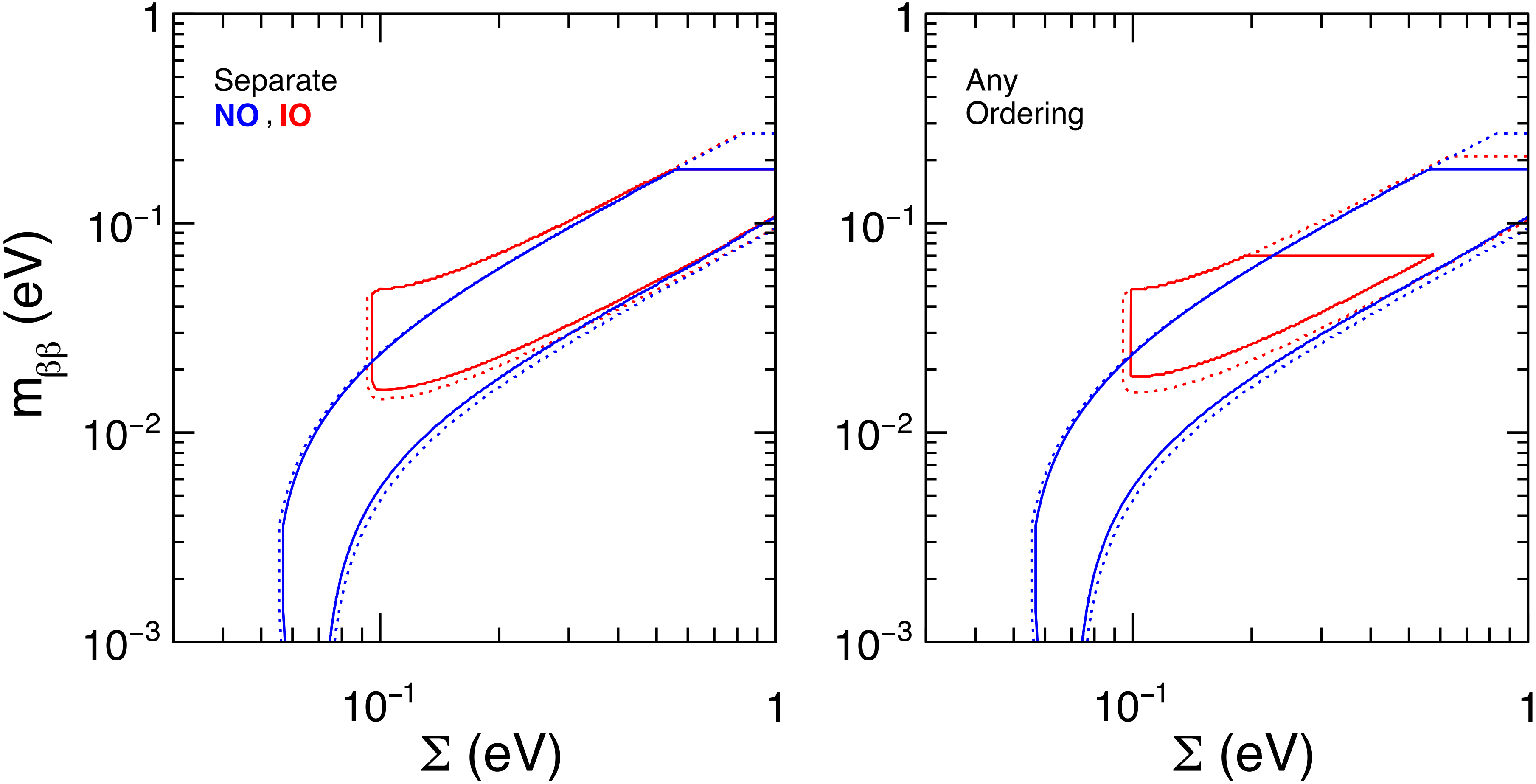
Note: Σ > 0.06 eV (NO)
Σ > 0.10 eV (IO)

Combining oscillation + nonoscillation data

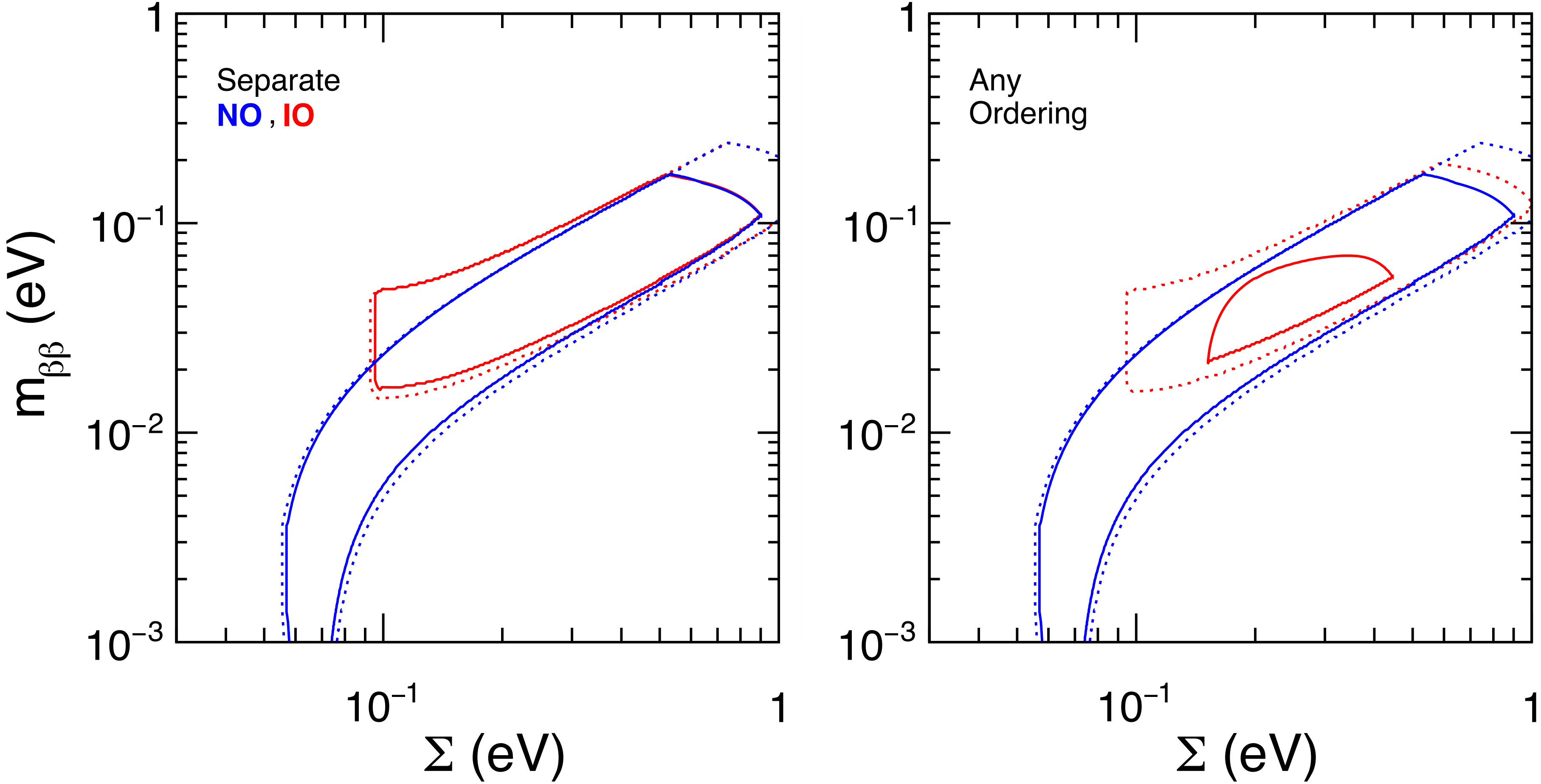
Oscillations



Oscill. + 0νββ

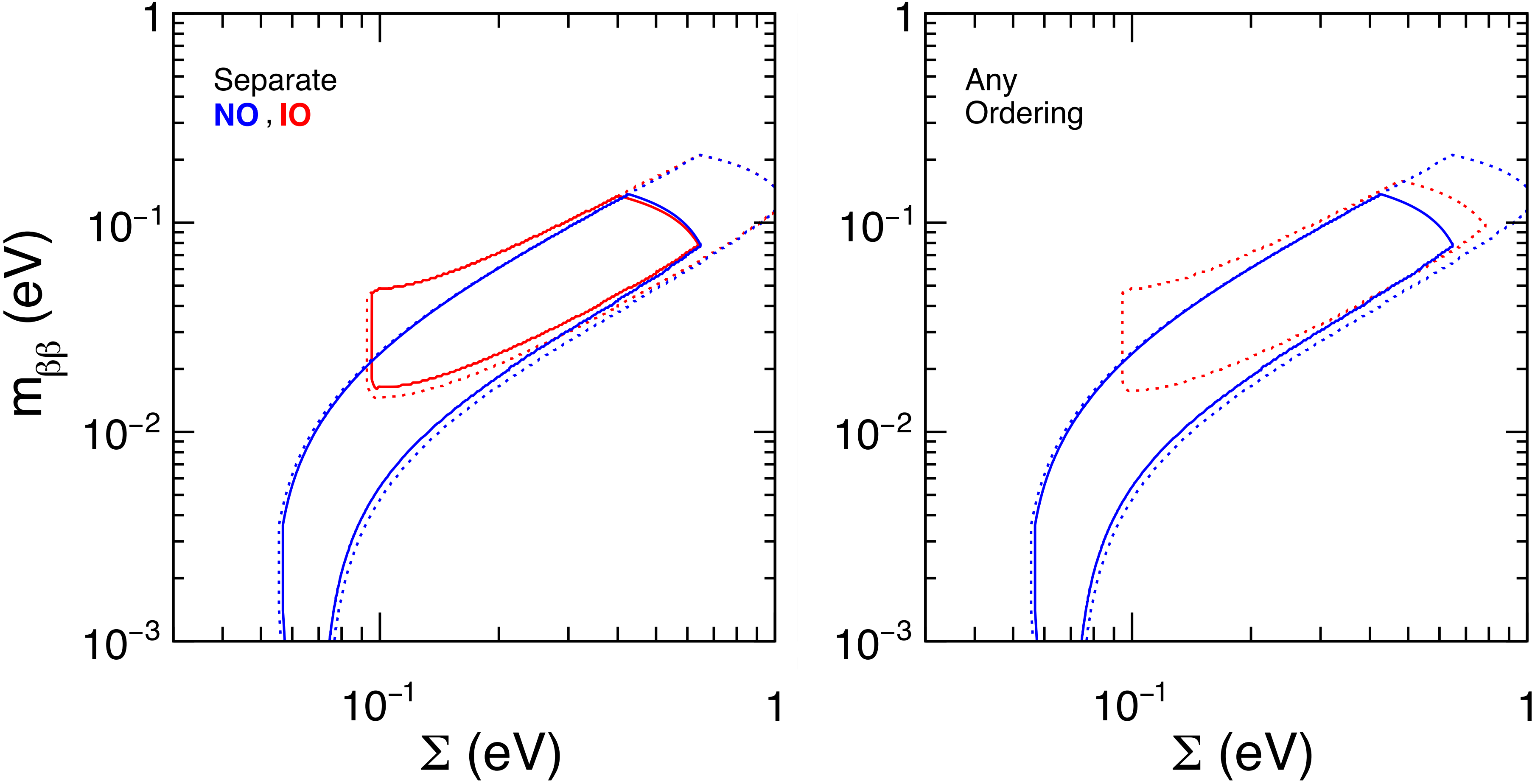

Separate
NO , IO
Any
Ordering
$m_{\beta\beta}$ (eV)
1
10^{-1}
10^{-2}
10^{-3}
Σ (eV)
10^{-1}
1

Oscill. + 0νββ + Cosmo #10

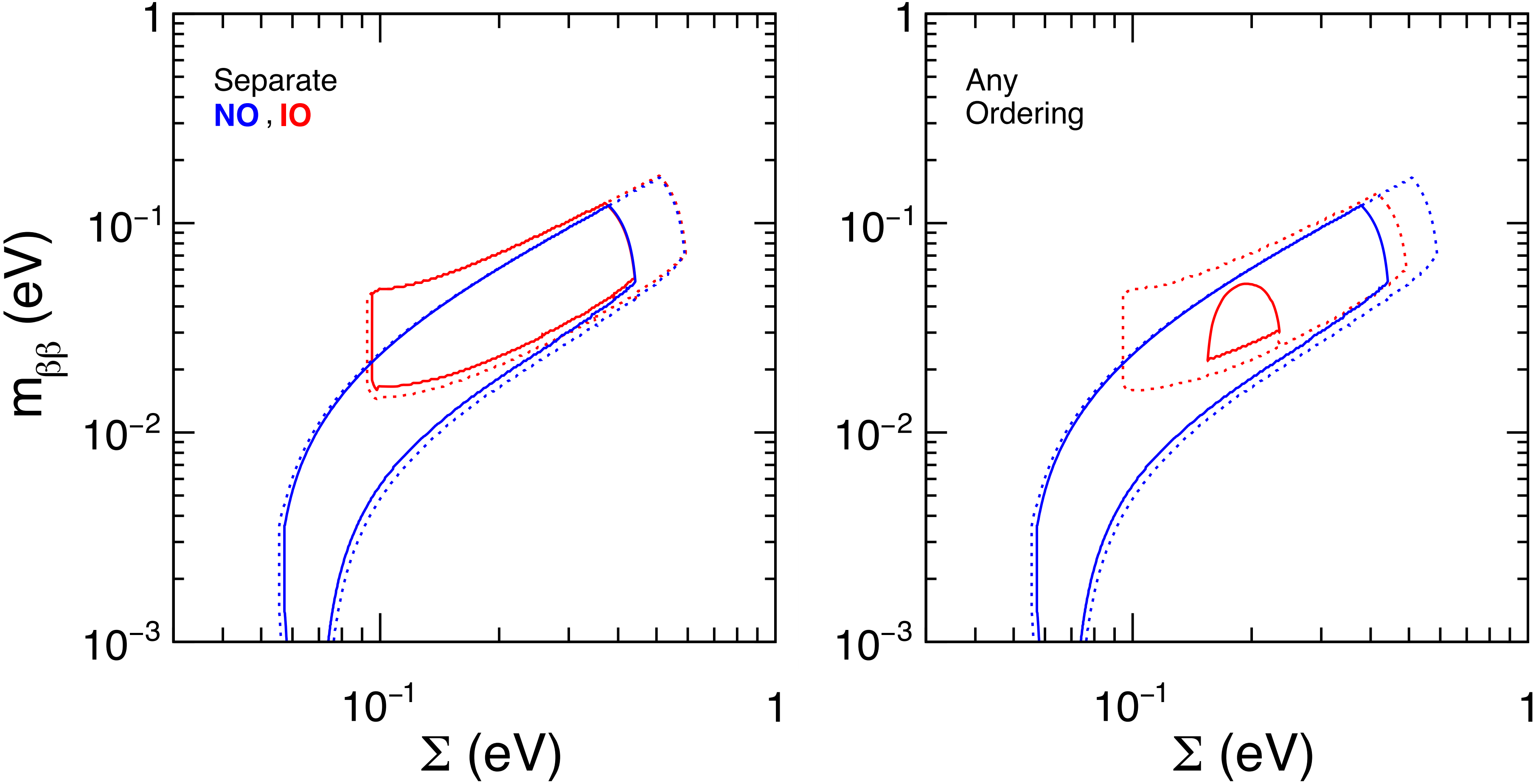


[Case with “conservative” bounds from cosmology]

Oscill. + 0νββ + Cosmo #1

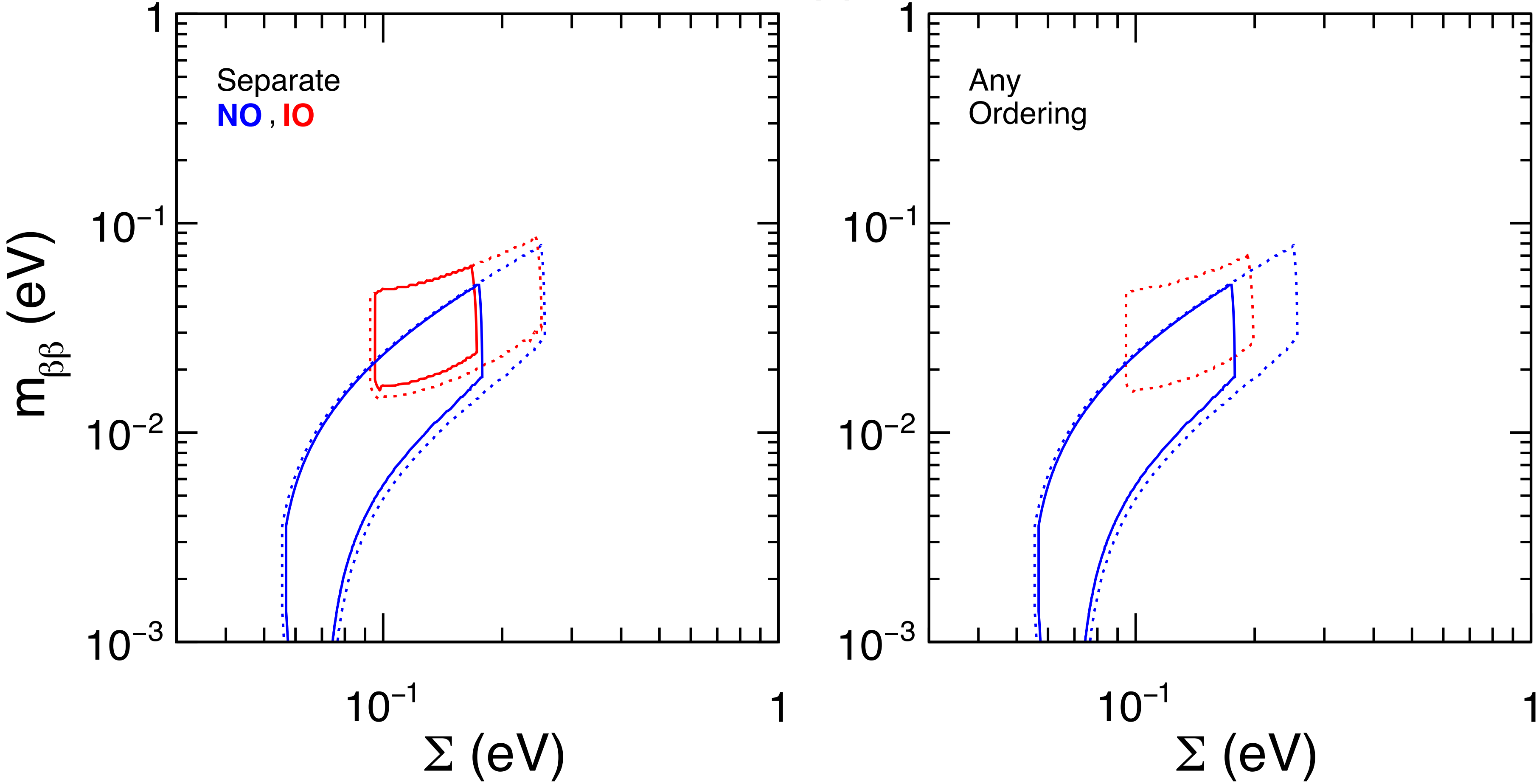


Oscill. + 0νββ + Cosmo #9



[RHS plot (inner red curve) shows how a cosmological "claim" of Σ>0 could look like]

Oscill. + 0νββ + Cosmo #6



[Case with “aggressive” bounds from cosmology]

Recap of IO-NO differences:

	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

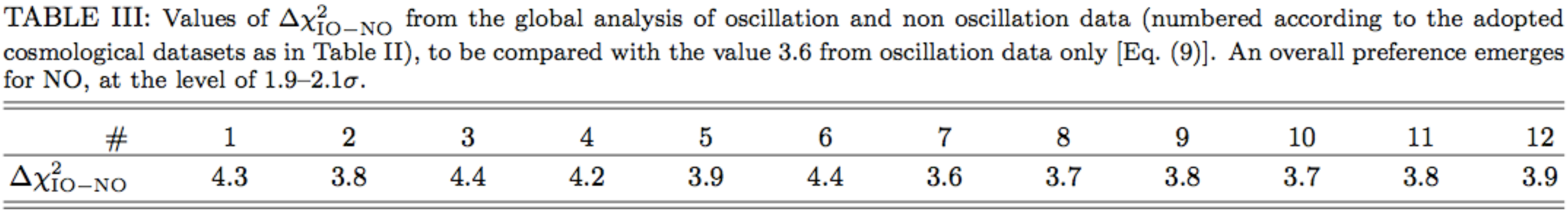


TABLE III: Values of $\Delta\chi^2_{\mathrm{IO-NO}}$ from the global analysis of oscillation and non oscillation data (numbered according to the adopted cosmological datasets as in Table II), to be compared with the value 3.6 from oscillation data only [Eq. (9)]. An overall preference emerges for NO,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

#	1	2	3	4	5	6	7	8	9	10	11	12
$\Delta\chi^2_{\mathrm{IO-NO}}$	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 and prospects

SUMMARY

- **Status of known 3ν oscillation parameters:**
  Precision era (but PMNS accuracy far from CKM)

- **Trends of unknown oscillation parameters:**
  Favoring **CPV** with $\sin\delta<0$, nonmax θ_{23}, and NO

- **Status of constraints from $0\nu\beta\beta$ & Cosmology:**
  Sub-eV sensitivity; Cosmo analysis with NO vs IO

- **Oscillation + nonoscillation global analysis:**
  Corroborates **NO with respect to IO** at $\sim 2\sigma$ level

PROSPECTS - oscillations

- **Known 3ν oscillation parameters:**

  Higher accuracy with LBL acceler., JUNO react. + others

- **CPV:**

  If **sinδ ~ -1**, then **T2K+NOvA may probe CPV** at ~3σ

  Higher C.L. requires future LBL acc. (DUNE, Hyper-K)

- **Hierarchy:**

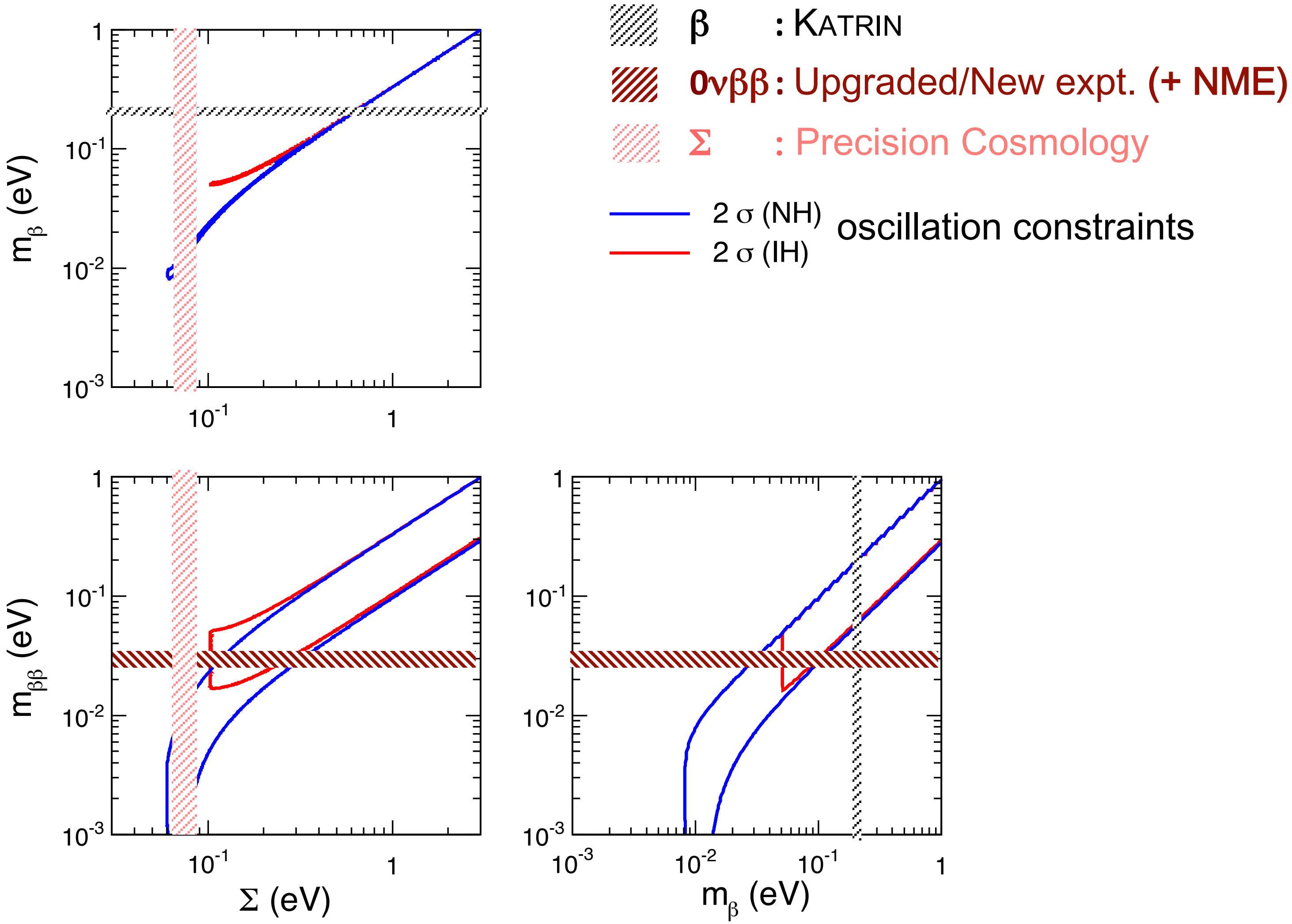
  Expect progress from T2K+NOvA and future expts:

  JUNO reactor, LBL acceler., Large-volume atmospheric

- **Octant of θ_{23}:**

  Lifting degeneracy **possible, but not easy** at high CL

Non-oscillations: Upper limits on m_β, $m_{\beta\beta}$, Σ in ~10 years ?



Large phase space for discoveries... and surprises (beyond 3ν?)

[Debated “tensions” for a 4th eV-mass sterile neutrino would require a separate talk]

ν physics … is ready to sail towards new horizons!