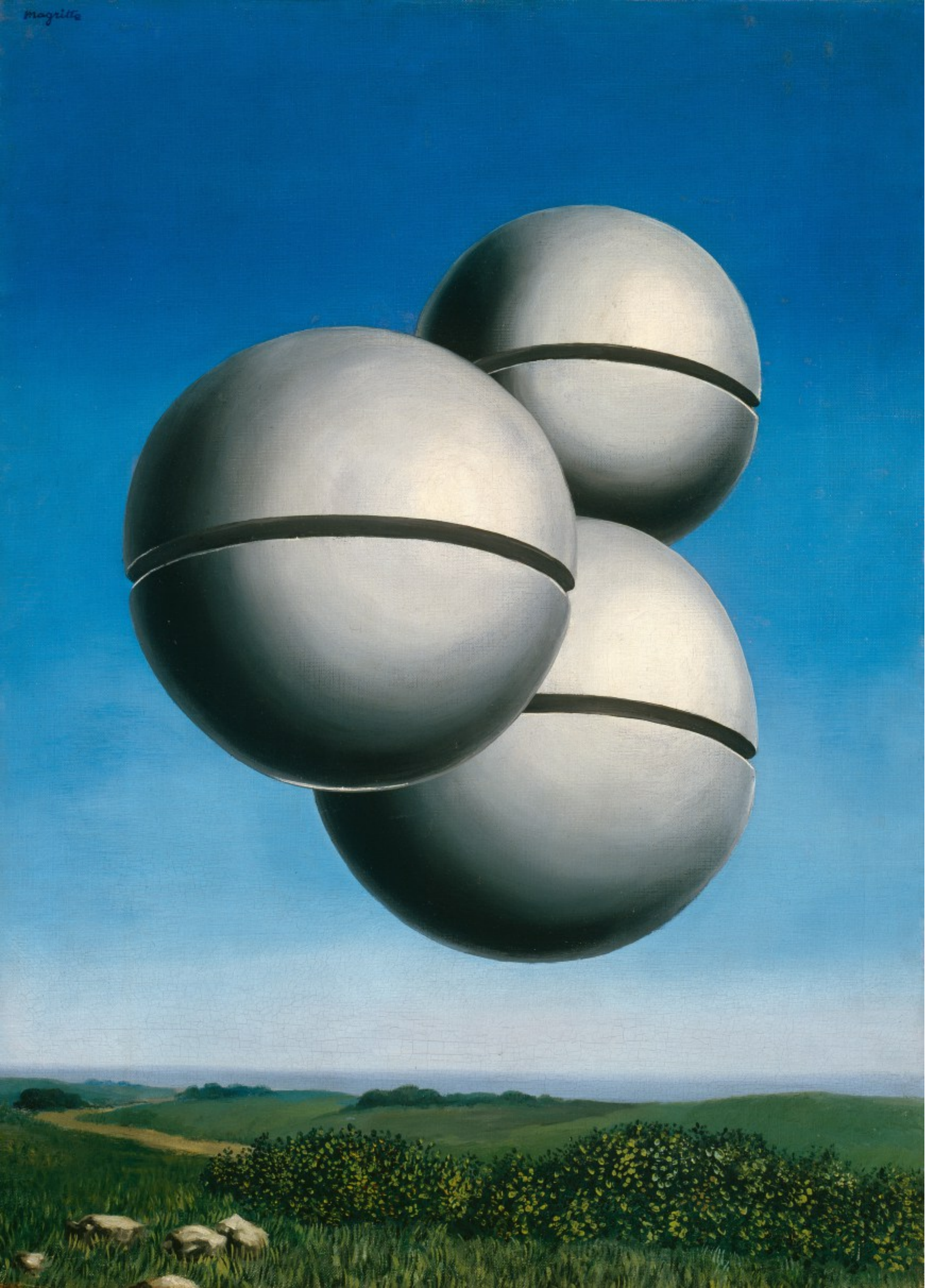


Neutrino Mass Ordering: Hints and Challenges

Eligio Lisi

(INFN, Bari, Italy)

Solvay ν Workshop, Brussels, 2017

← René Magritte, Voice of Space (1931)

OUTLINE:

- Prologue: 3ν knowns and unknowns
- Global 3ν oscillation analysis and mass ordering
- Combination with nonoscillation constraints
- Future challenges
- Epilogue

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 [PRD 95, 096014 (2017)]

For independent analyses, see also Esteban+ 1611.01514; de Salas+ 1708.01186

Prologue: 3ν paradigm - parameters

Mixings and phases: CKM→ PMNS (Pontecorvo-Maki-Nakagawa-Sakata)

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

2-3 rotation

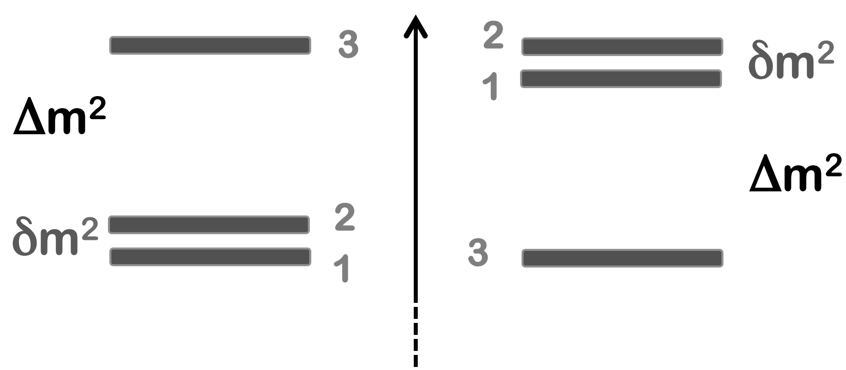
1-3 rotation
+ CPV "Dirac" phase

1-2 rotation

Extra CPV phases
[if Majorana]
not tested in oscillat.

Mass [squared] spectrum (E ~ p + $m^2/2E$ + "interaction energy")

"Normal"
Ordering
NO

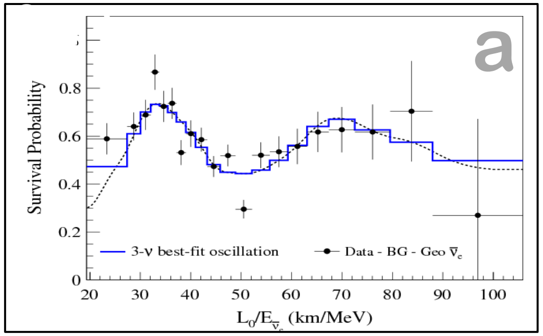


"Inverted"
Ordering
IO

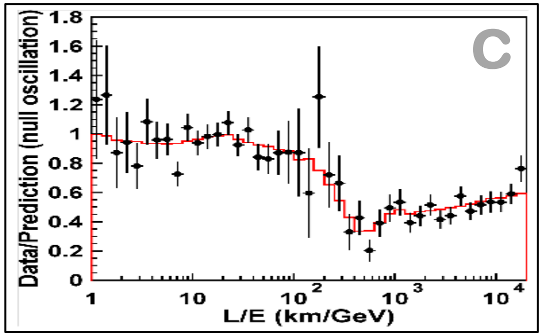
+ interactions in matter → effective terms ~ $G_F \cdot E \cdot$ density
+ absolute mass scale (not tested in oscillations)

ν flavor oscillation experiments: α → β in vacuum and matter

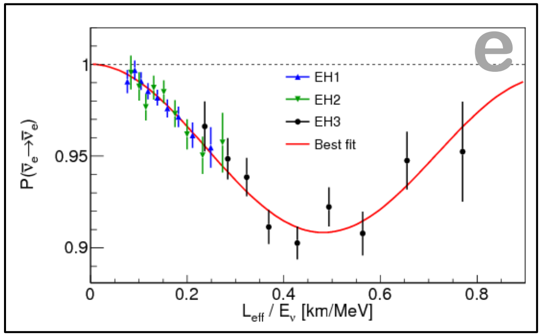
e→e (KamLAND)



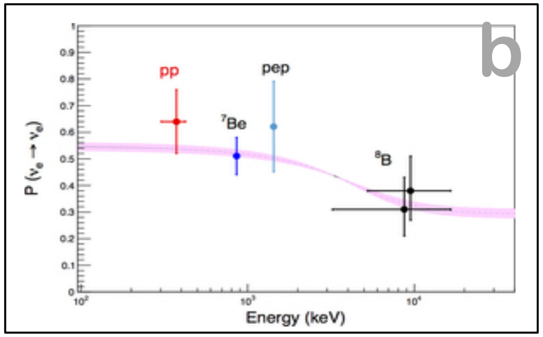
μ→μ (Atmospheric)



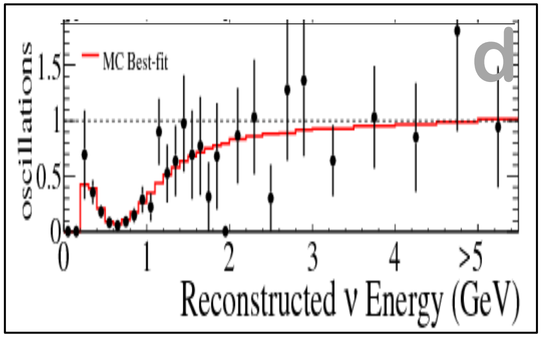
e→e (SBL Reac.)



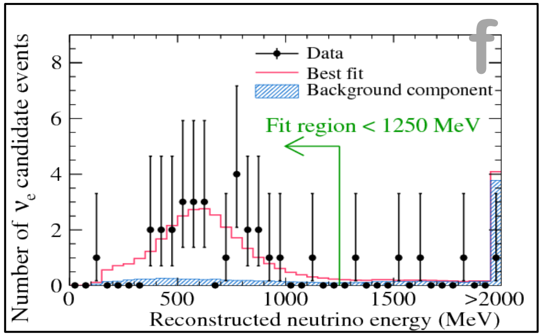
e→e (Solar)



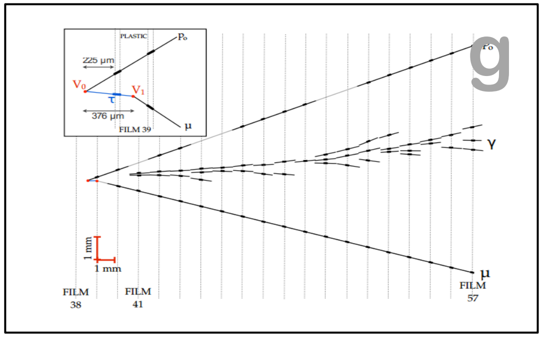
μ→μ (LBL Accel)



μ→e (LBL Accel)



μ→τ (OPERA, SK)

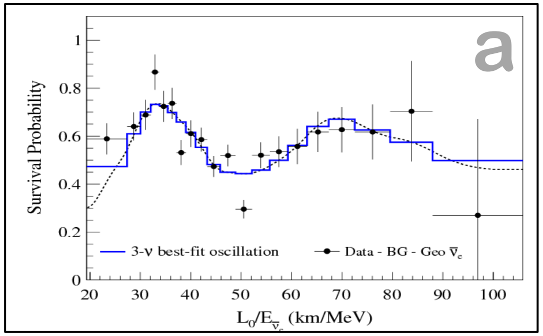


Data from various types of neutrino experiments: (a) solar, (b) long-baseline reactor, (c) atmospheric, (d) long-baseline accelerator, (e) short-baseline reactor, (f,g) long baseline accelerator (and, in part, atmospheric).

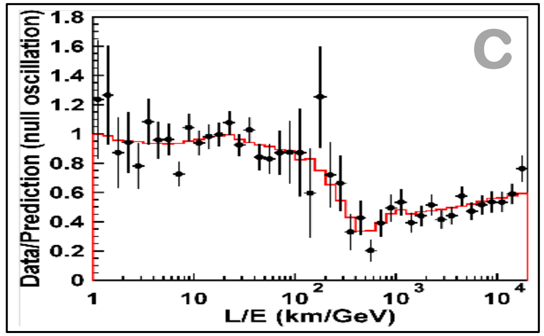
(a) KamLAND [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], DeepCore, MACRO, MINOS etc.; (d) T2K (plot), MINOS, K2K; (e) Daya Bay [plot], RENO, Double Chooz; (f) T2K [plot], MINOS, NOvA; (g) OPERA [plot], Super-K atmospheric.

Leading sensitivities to 3ν oscillation parameters:

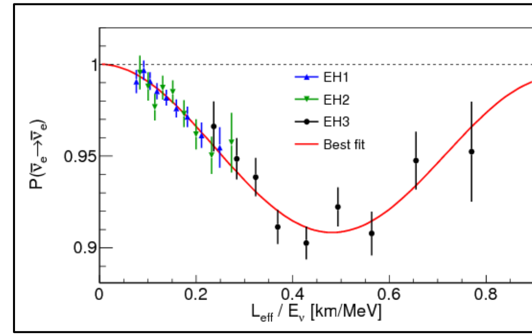
e→e (δm^2 , θ_{12})



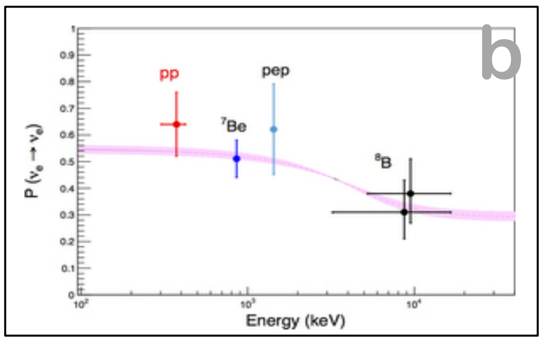
μ→μ (Δm^2 , θ_{23})



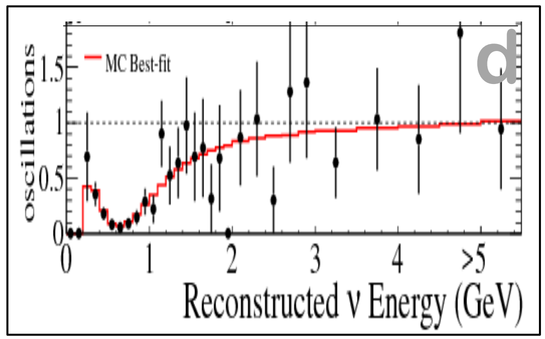
e→e (Δm^2 , θ_{13})



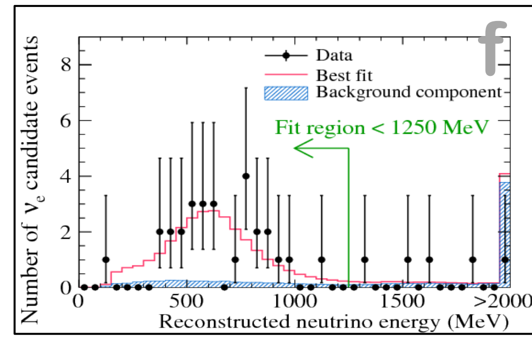
e→e (δm^2 , θ_{12})



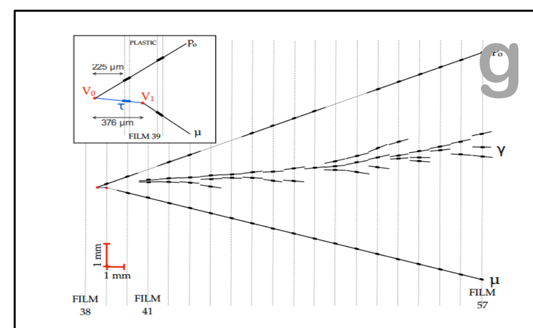
μ→μ (Δm^2 , θ_{23})



μ→e (Δm^2 , θ_{13} , θ_{23})



μ→τ (Δm^2 , θ_{23})



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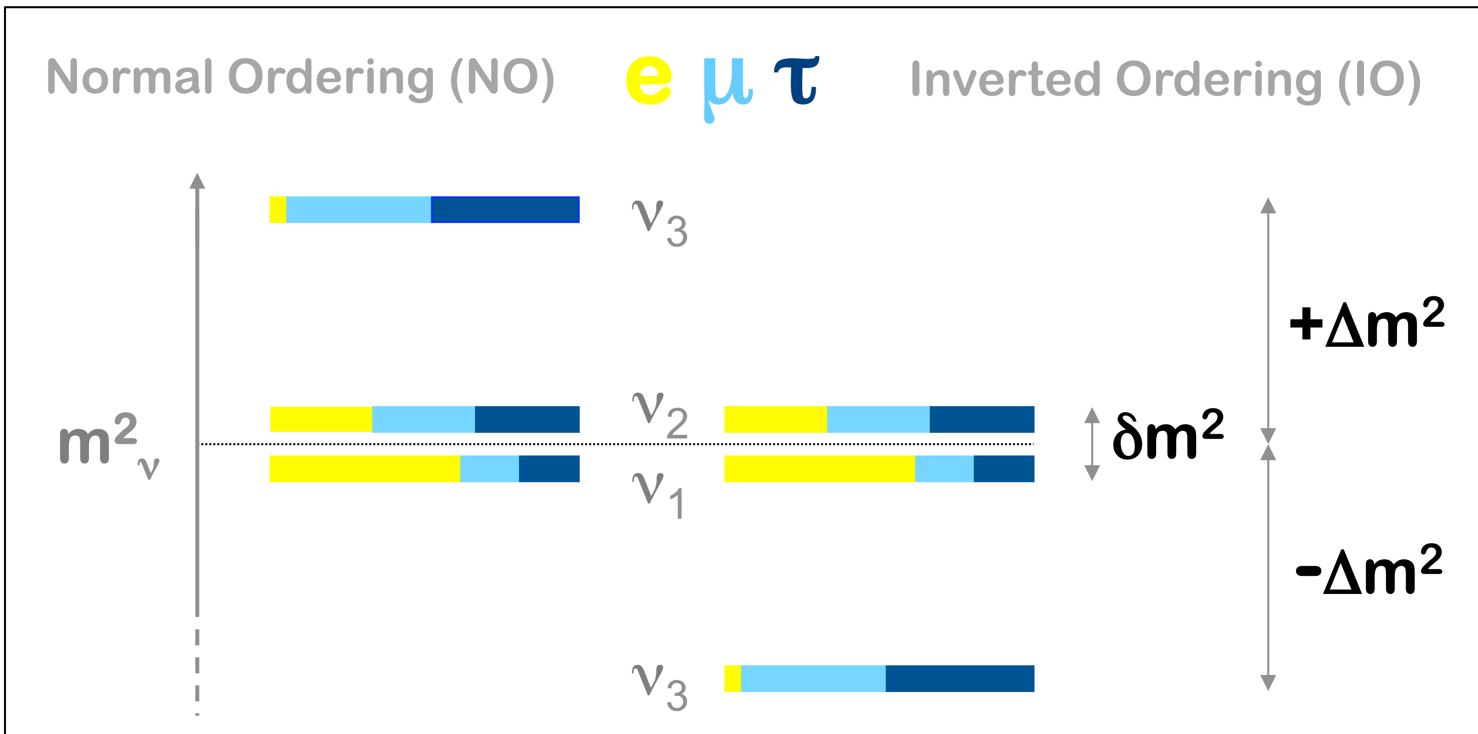
"Broad-brush" 3ν picture (with 1-digit accuracy)

Knowns:

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

Unknowns:

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



Hi-res and larger picture → Global analysis of ν oscill. data

Analysis includes increasingly rich oscillation data sets:

LBL Acc + Solar + KL

LBL Acc + Solar + KL + SBL Reactor

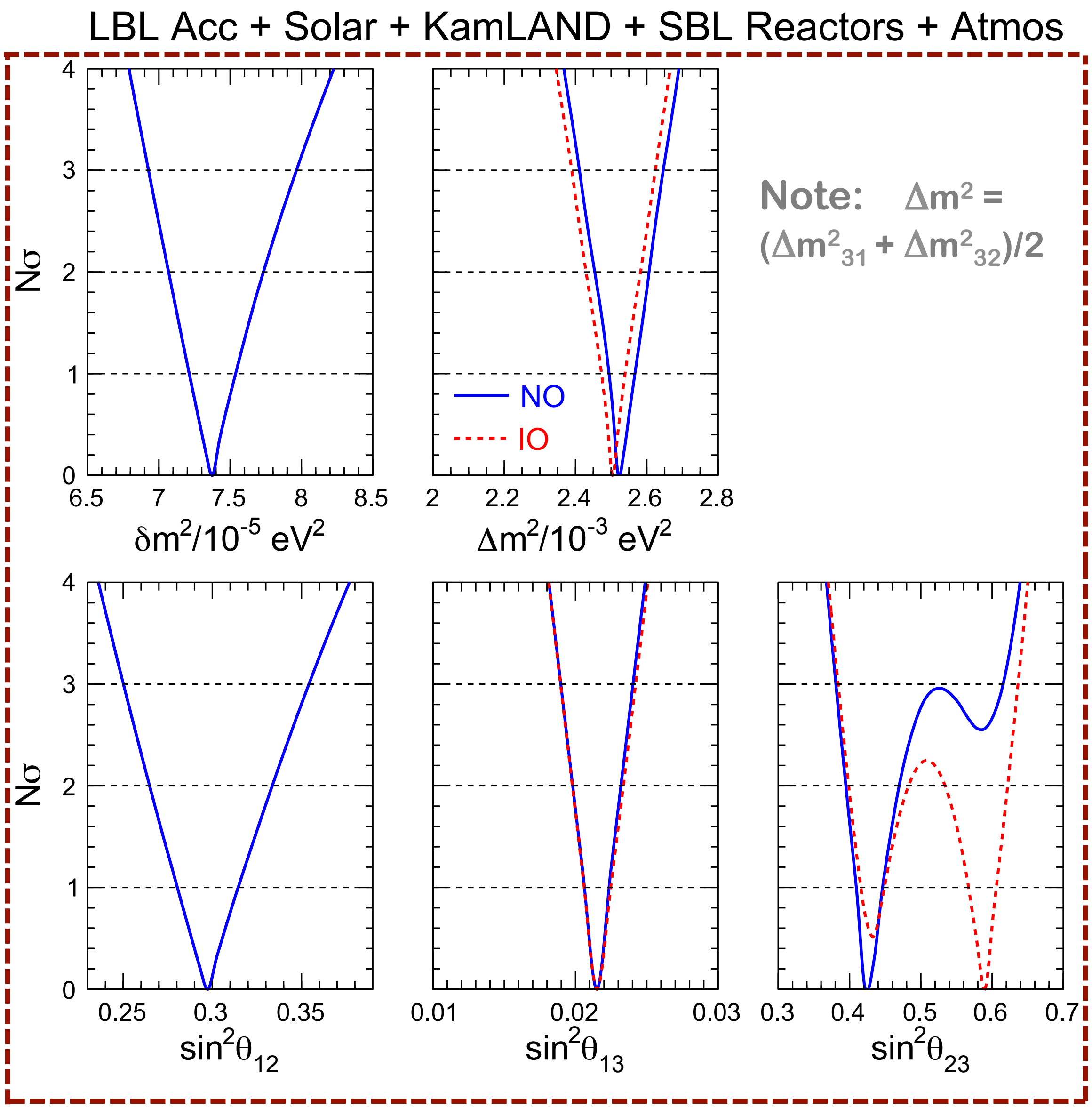
LBL Acc + Solar + KL + SBL Reactor + Atmosph.

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

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

Global fit results taken from 1703.04471 . Note: KL=KamLAND.

Five known oscillation parameters:



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%...

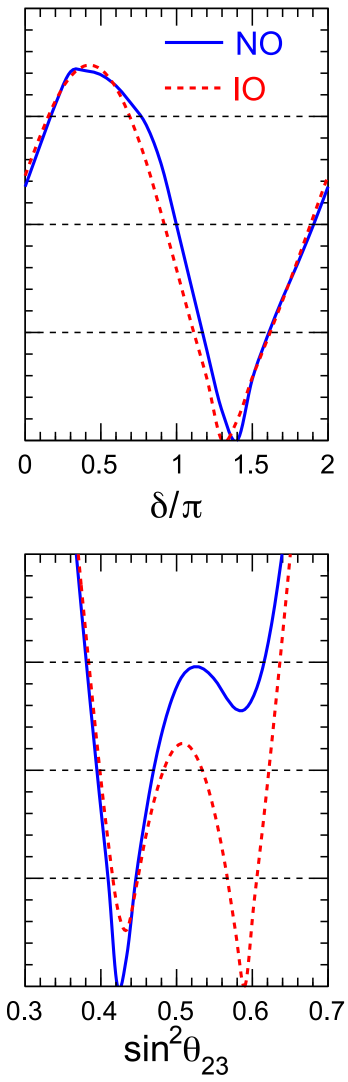
2 - 3 digits needed

→ Precision Era!

[but: PMNS still very far from CKM accuracy]

→ novel expt+theo challenges (fluxes, cross sections, ...) in nuclear physics

Three unknown oscillation parameters



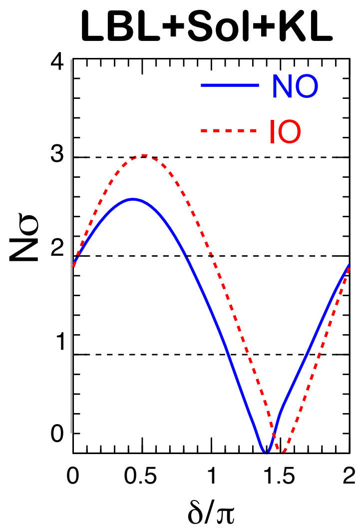
δ_{CP}

θ_{23} octant

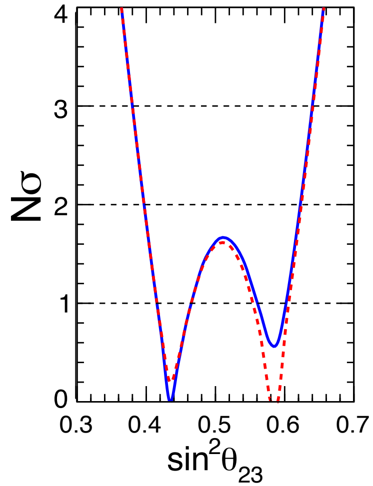
NO or IO

More on unknown oscillation parameters:

δ_{CP}



θ_{23} octant



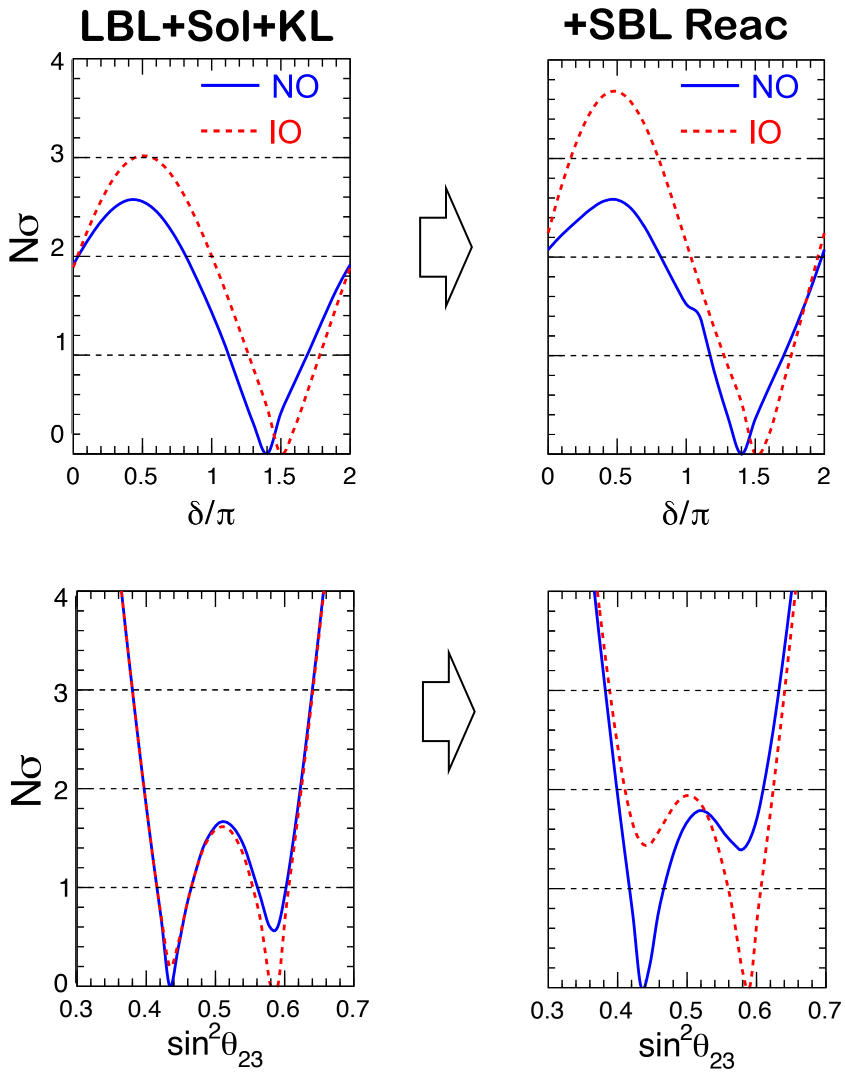
$\Delta\chi^2$ (IO-NO)

+1.1

More on unknown oscillation parameters:

δ_{CP}

θ_{23} octant



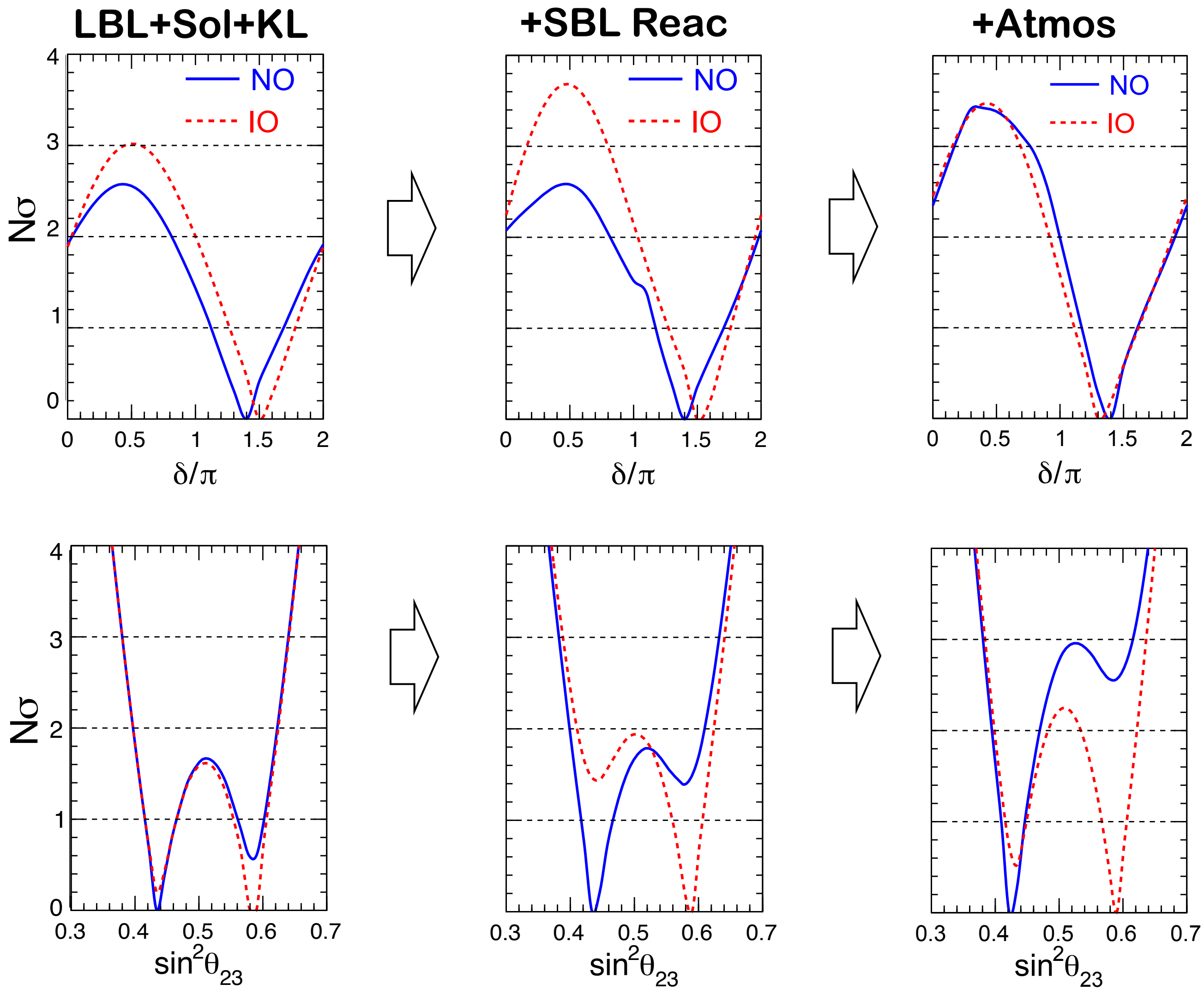
$\Delta\chi^2$ (IO-NO)

+1.1 → +1.1

More on unknown oscillation parameters:

δ_{CP}

θ_{23} octant



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

Max-mixing disfavored;
octant flips with NO/IO

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

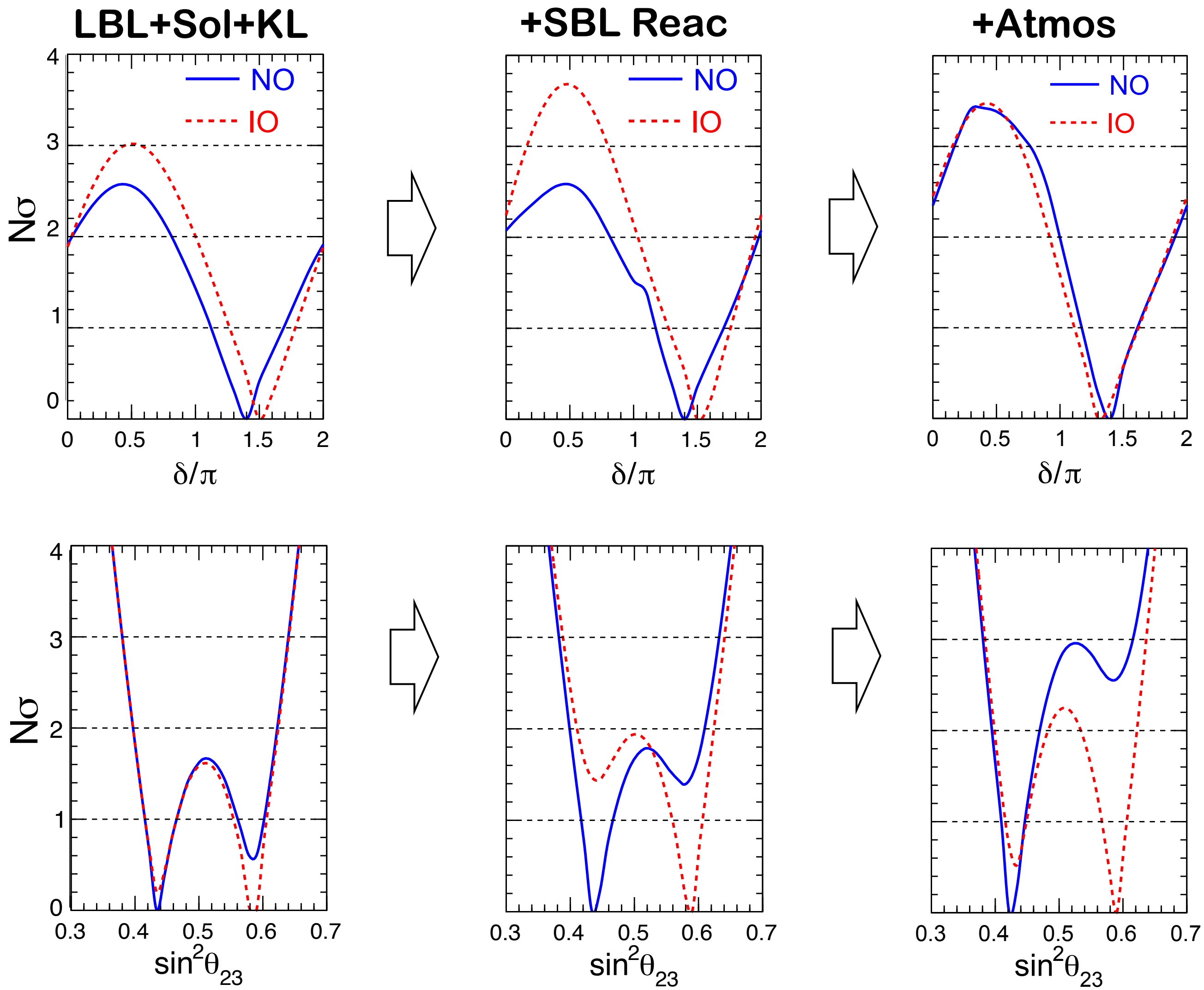
LBL+Sol+KL	+SBL Reac	+Atmos
+1.1	+1.1	+3.6

Intriguing!
NO favored

Compare the current results (circa 2017) with…

δ_{CP}

θ_{23} octant

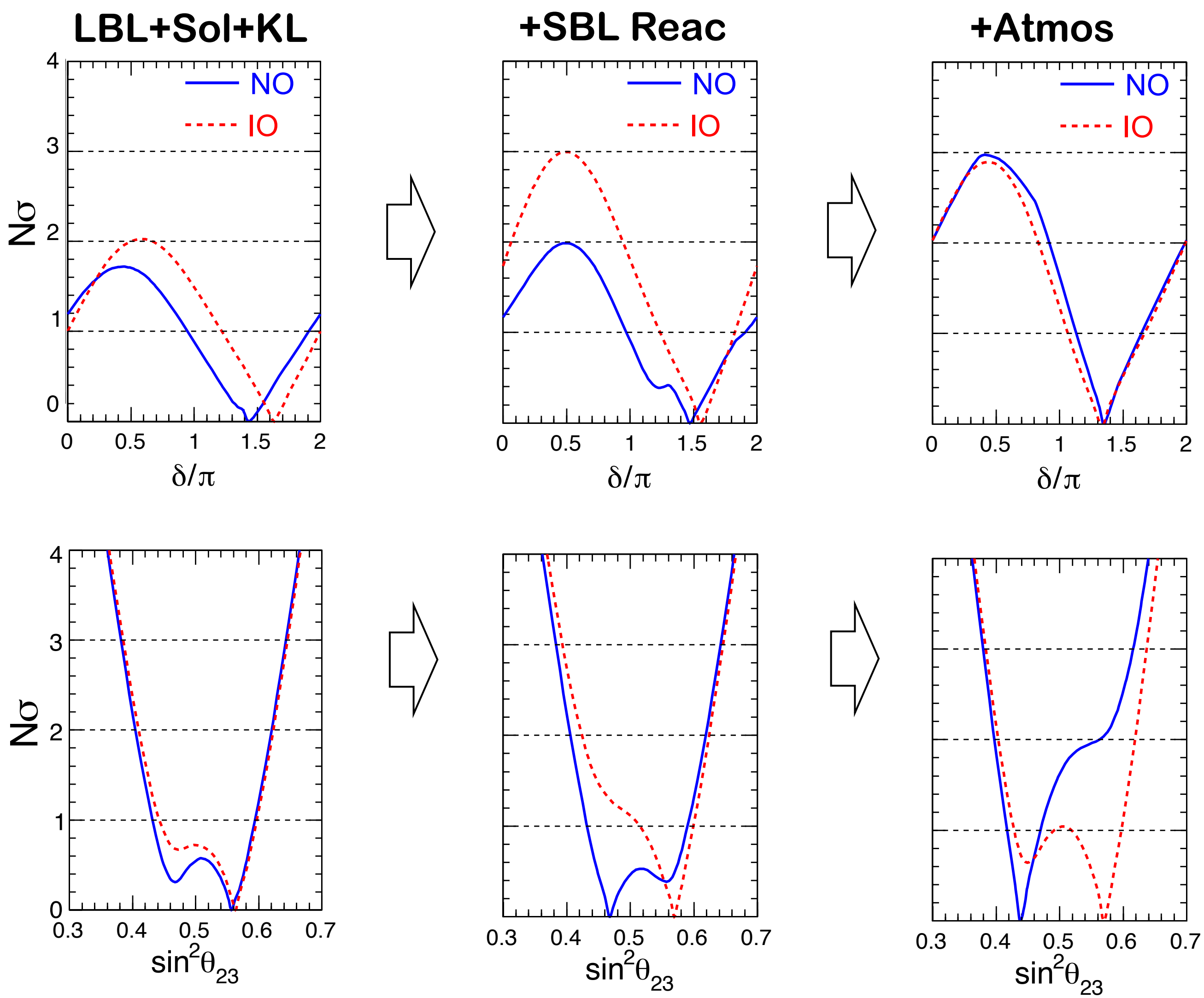


$\Delta\chi^2$ (IO-NO)	+1.1	+1.1	+3.6

… 1yr ago, 2016: trends were somewhat weaker

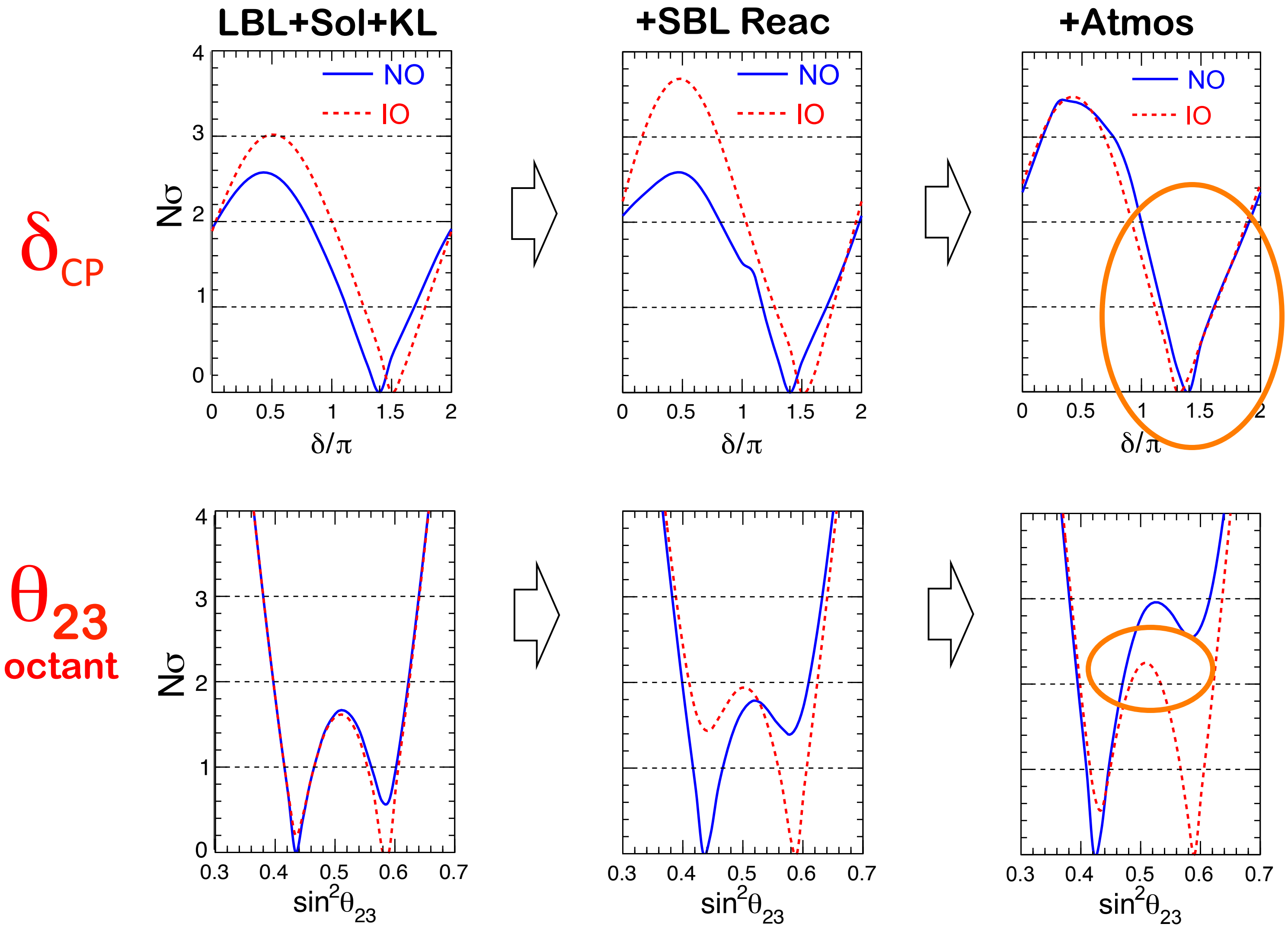
δ_{CP}

θ_{23} octant



	LBL+Sol+KL		+SBL Reac		+Atmos
$\Delta\chi^2$ (IO-NO)	-1.2	⇨	-0.9	⇨	+1.0

Currently: ~2σ hints in favor of Dirac CPV, NO, and non-maximal θ_{23} (*)



$\Delta\chi^2$ (IO-NO): +1.1 → +1.1 → +3.6

Time will tell if these hints will grow up!

(*) Latest T2K data (Aug. 2017) not yet included in this fit.

Update (2018) of the global analysis with these and other data is in progress

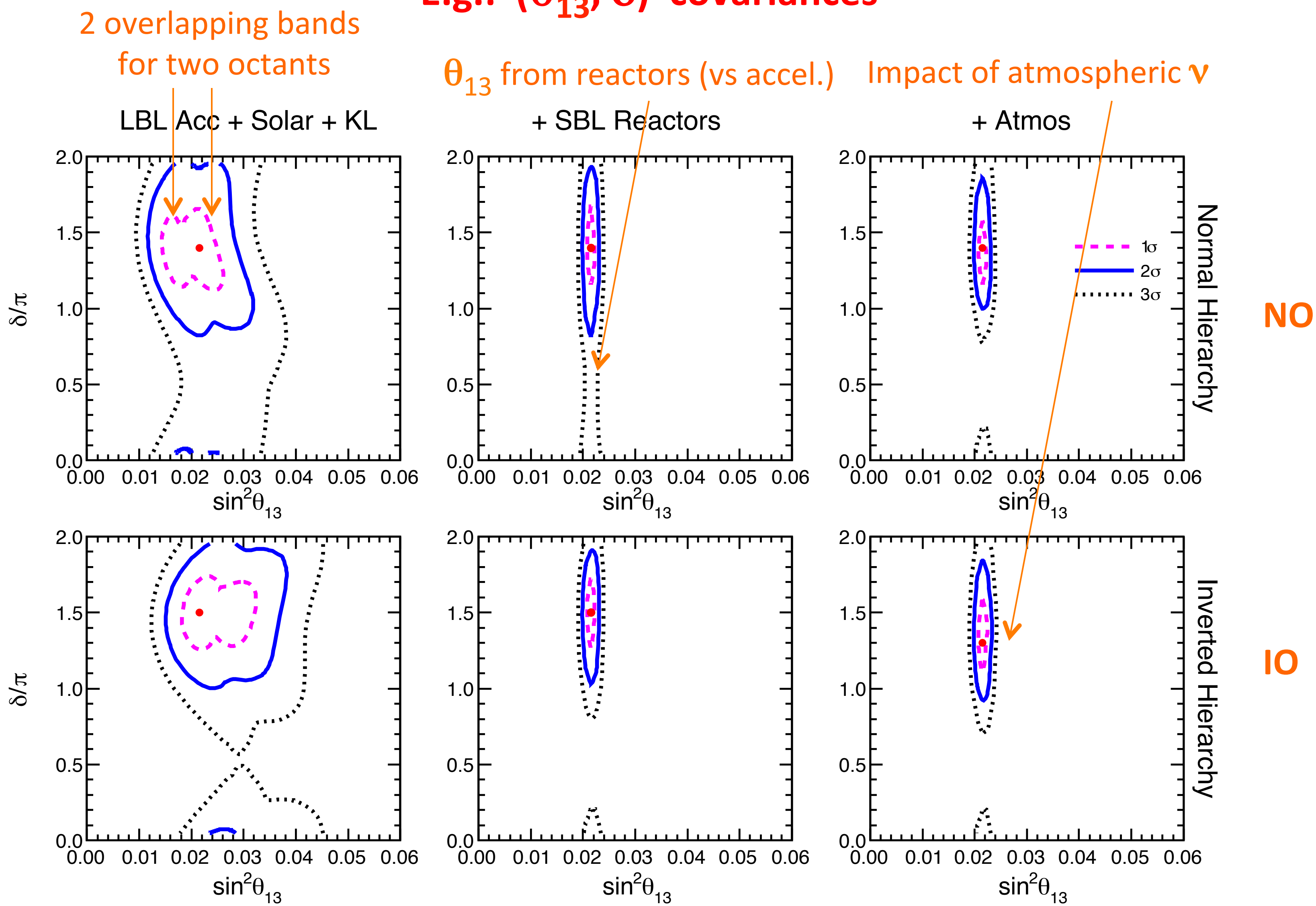
Very personal and subjective rating of such ~2σ hints:

δ_{CP}	* * *	*ν_e / $\overline{\nu}_e$ appearance probab. seem to differ by CPV:* *Very interesting! [Akin to θ_{13} hints before 2012]*
$\Delta\chi^2$ **(IO-NO)**	* *	*Mass-ordering information rather "diluted" in data:* *Still vague, but starts to be interesting*
θ_{23} **octant + (non)max**	*	*Fragile - different experiments not yet converging:* *Degeneracy might stay with us for quite some time...*

Hints are "entangled" as subleading effects in ν_e appearance channel

[They might also be entangled with BSM neutrino physics, if any]

E.g.: (θ_{13}, δ) covariances

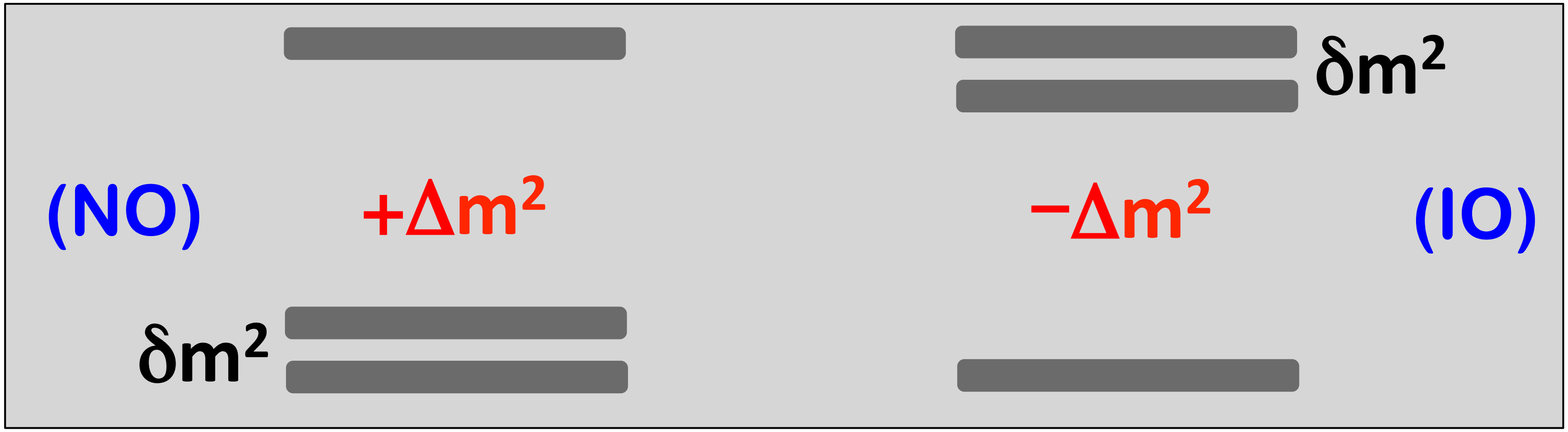


Hints may (not) converge better in one mass ordering wrt the other

[Supplementary to arXiv:1703.04471]

Mass ordering via oscillations

Oscillation experiments can determine the sign of $\pm\Delta m^2$ ...



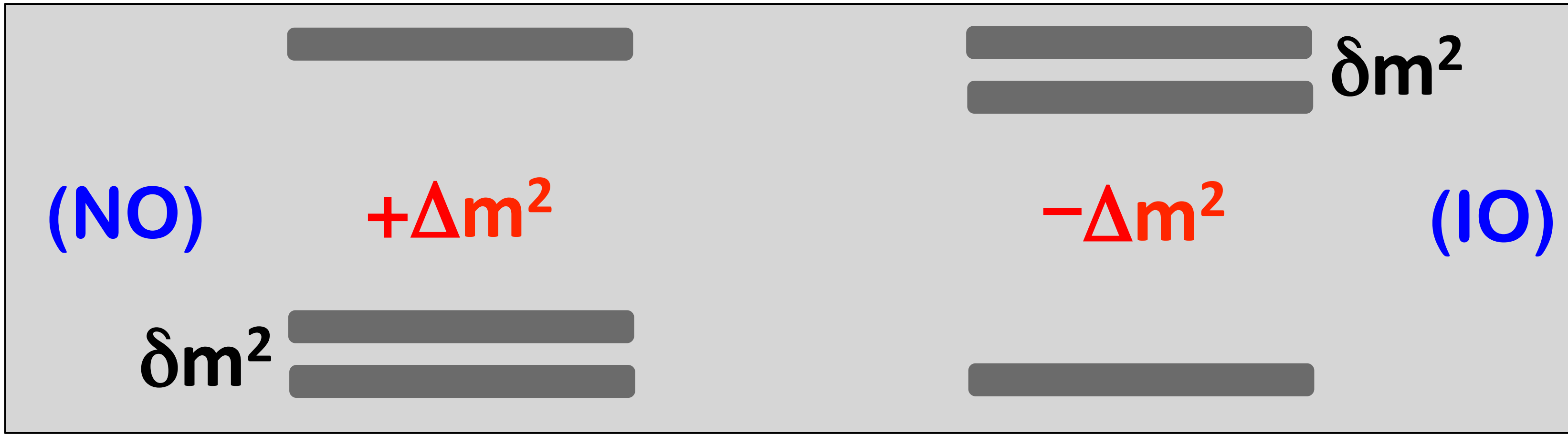
...if they can observe interference of oscill. driven by $\pm\Delta m^2$ with oscill. driven by a quantity Q having known sign. Three options:

$Q \sim \delta m^2$	medium-baseline reactors [(a)]
$Q \sim G_F\, E\, N_e$	matter effects in accel./atmosph. ν [(b)]
$Q \sim G_F\, E\, N_\nu$	self-interaction effects in supernovae [(c)]

(a) JUNO
(b) Atmos: KM3NeT-ORCA, PINGU, HyperK...; Accel.: DUNE, T2HK, ...
(c) All operating low-E detectors

Mass ordering via oscillations

Oscillation experiments can determine the sign of $\pm\Delta m^2$ ...



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Nonoscillation searches may provide further probes of ordering →

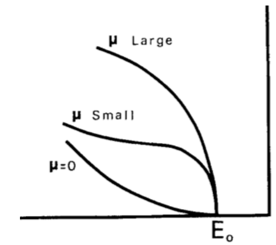
[independently on δ_{CP} and on θ_{23}]

3ν paradigm: absolute ν masses and observables

(m_β , $m_{\beta\beta}$, Σ)

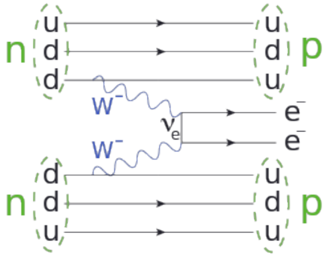
β decay, sensitive to the "effective electron neutrino mass":

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



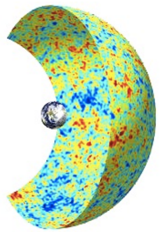
0νββ decay: only if Majorana. "Effective Majorana mass":

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



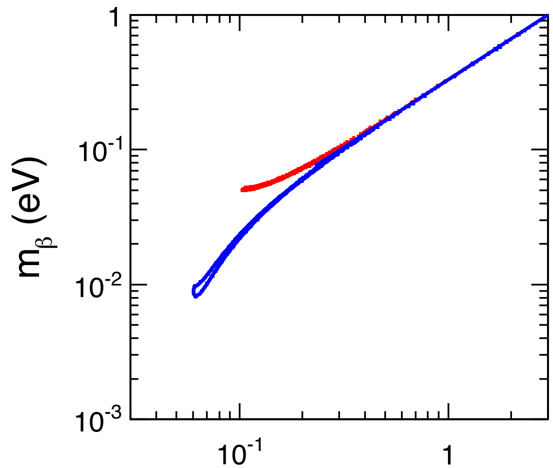
Cosmology: Dominantly sensitive to sum of neutrino masses:

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



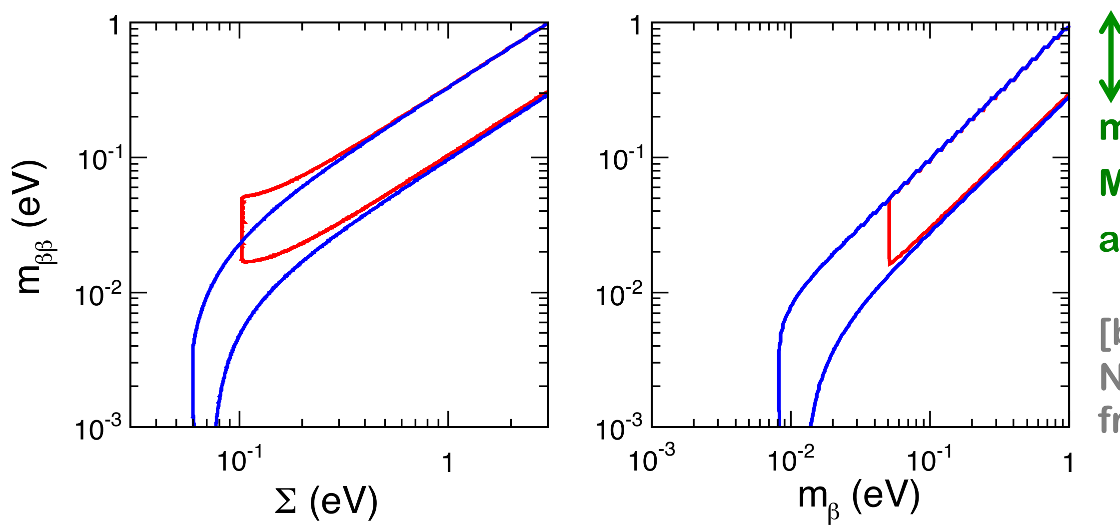
Note 1: These observables may provide handles to distinguish NO/IO.
Note 2: Majorana case gives a new source of CPV (unconstrained)
Note 2: The three observables are correlated by oscillation data→

Constraints on nonoscillation observables from oscillation data



NO
IO

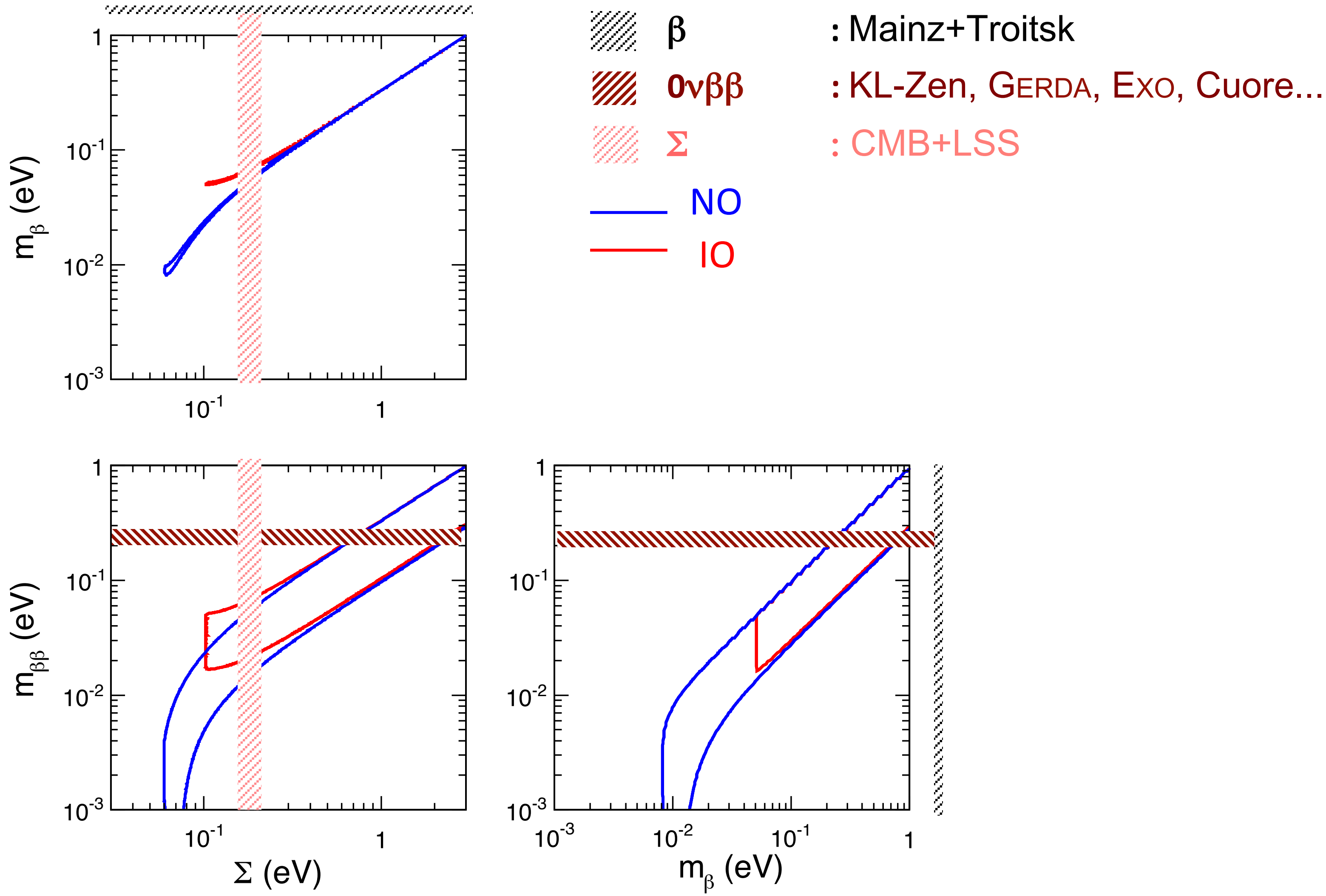
~degenerate for relatively large neutrino masses



$m_{\beta\beta}$ spread due to Majorana CP phase(s): accessible in principle

[but: large errors on Nuclear Matrix Elements from nuclear modeling]

Upper limits on m_β, $m_{\beta\beta}$, Σ (up to some syst.) + osc. constraints



Cosmological data generally prefer the smallest values for the total neutrino mass, and already **contribute to put IO "under pressure"** →

Grand total 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 but coherent steps: **N.O. favored**... Overall preference at $1.9\sigma - 2.1\sigma$

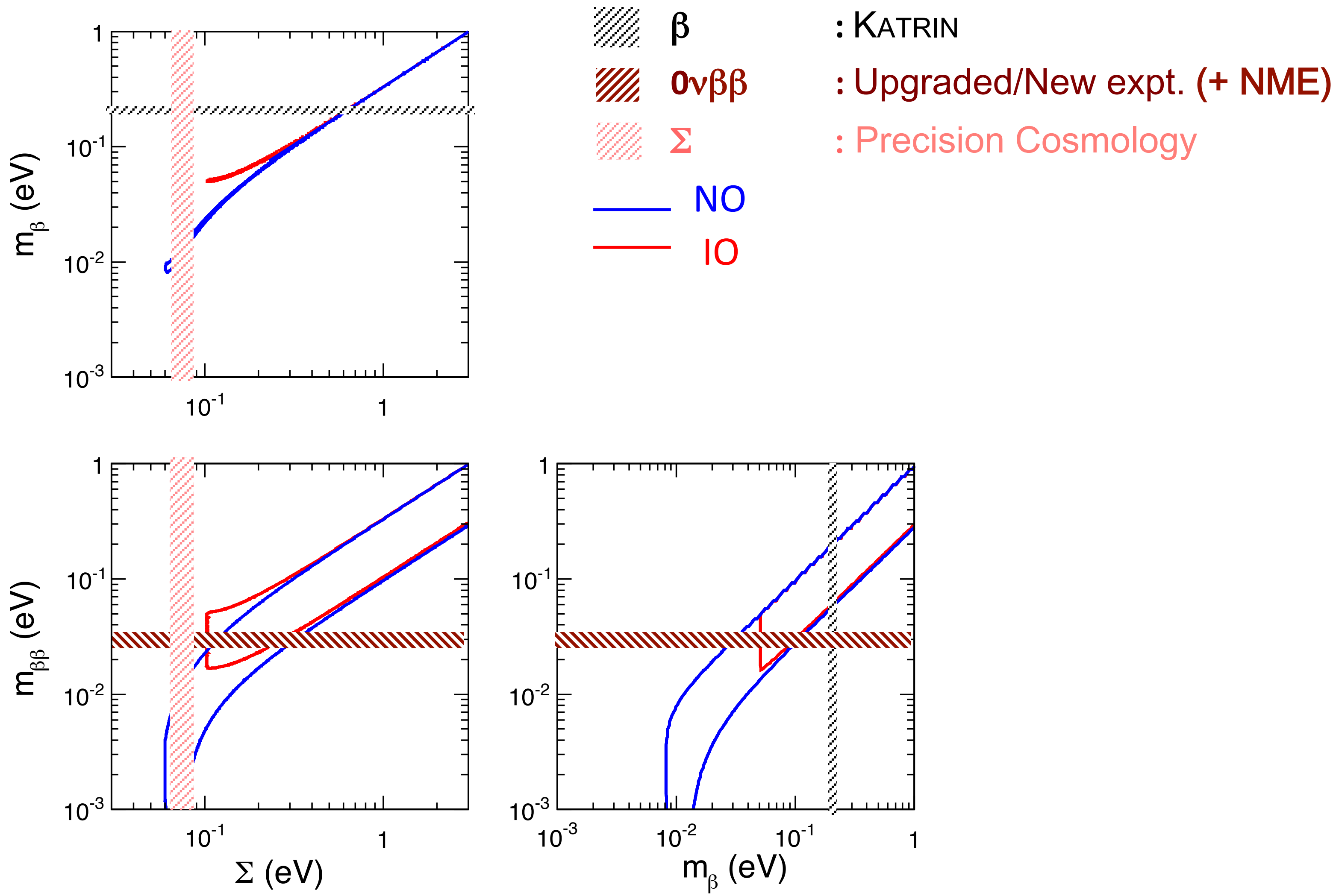
[See 1703.04471 for detailed discussion]

The statistical significance of possible hints about ordering is currently debated.

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

Dedicated projects are planned with reactor, atmospheric, accel. neutrinos...

… and on absolute masses. Upper limits on m_β, $m_{\beta\beta}$, Σ in ~10 years ?



Large phase space for discoveries about ν mass and nature.

Theoretical challenges: cosmo high accuracy calculations/simulations, NME uncertainties

Oscillations: A glimpse of upcoming challenges...

Once upon a time... all neutrino observations were limited by stat's, and systematics could be treated as numbers (normalization, bias ...)

Now we have as many as O(10^6) events collected in SBL reactors, and we expect O(10^5) events in each of JUNO, ORCA, PINGU etc.

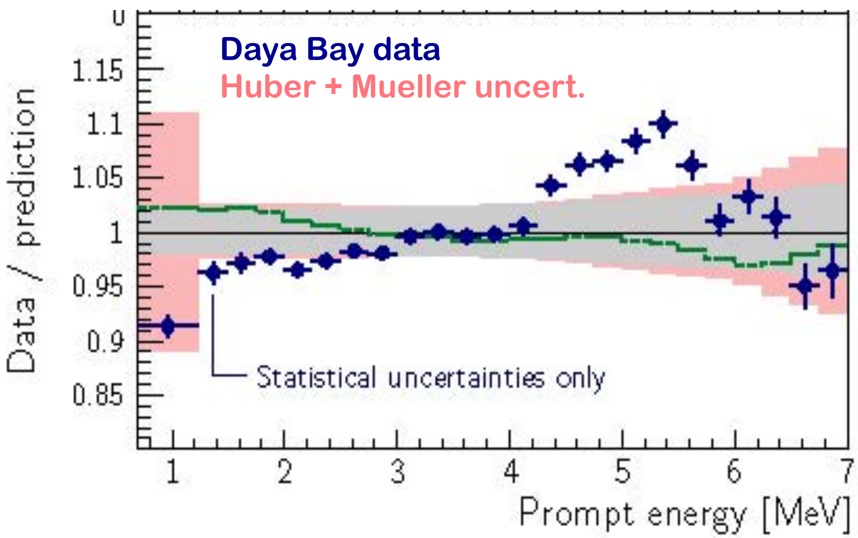
Systematic errors are no longer "numbers" but become "functions". Dedicated approaches are needed to deal with such uncertainties.

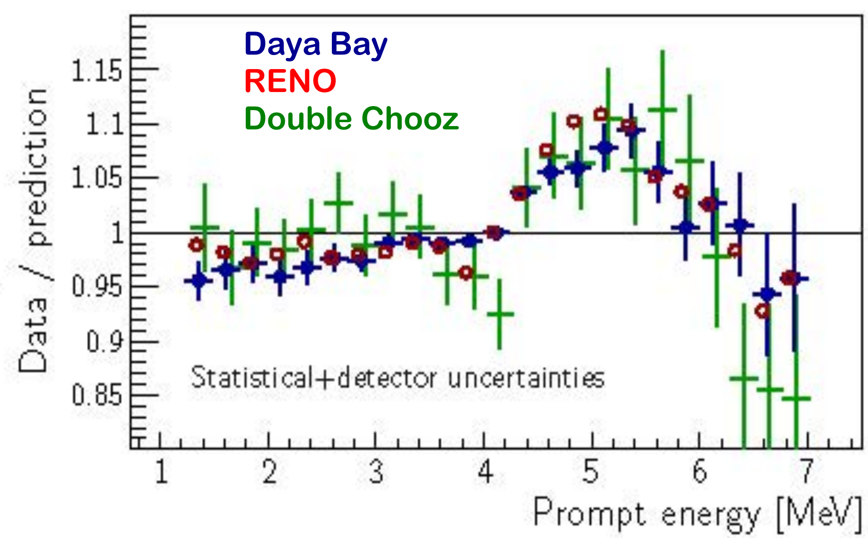
[This transition has already taken place in other fields, such as in parton distribution function fits and precision cosmology forecasts.]

Unprecedented challenges are awaiting us in neutrino data analyses:

We must be prepared to deal with "functions" which *ideally* should be known in size, shape, correlations and probability distributions, but *in practice* may also be partly (if not completely!) unknown.

Hard lesson learned from current reactor experiments:
An unknown systematic error source (function) δΦ(E),
well beyond supposedly-known shape uncertainties!





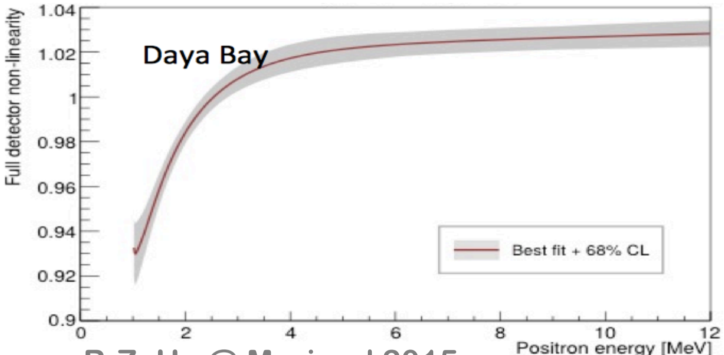
From S. Jetter (TAU 2014) & J. Cao (TAUP 2015)

Now we know its shape, and can correct for it, but residuals do remain:

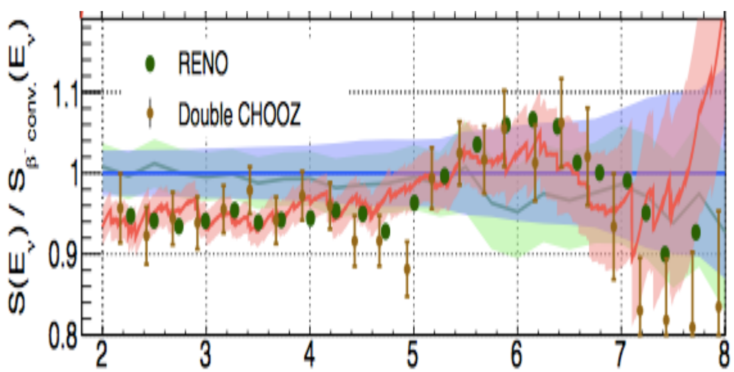
energy-scale uncertainties	E → E'(E)	(x-axis "stretch")
flux-shape uncertainties	Φ (E) → Φ'(E)	(y-axis "stretch")

Recent evaluations of energy-scale and flux-shape errors (reactors)

E'(E) and Φ'(E) models



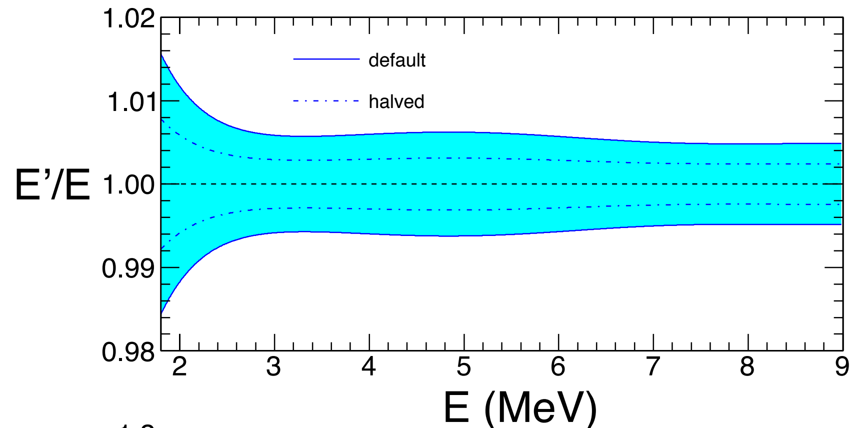
B-Z. Hu @ Moriond 2015

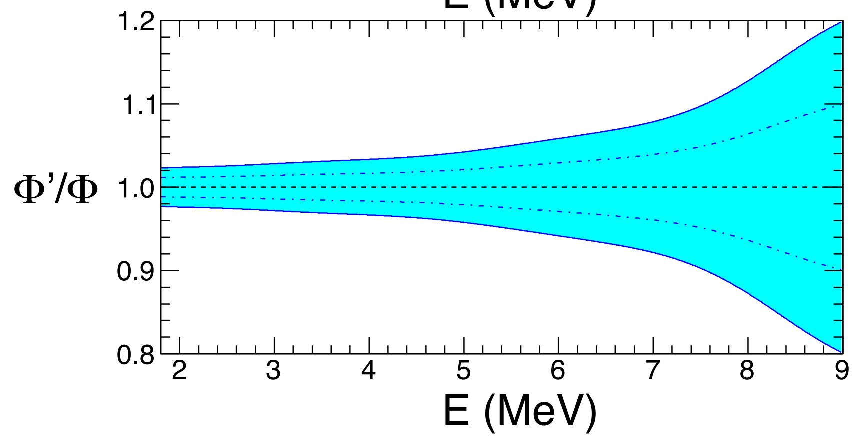


Dwyer & Langford 2014

[Note sawtooth-like spectrum]

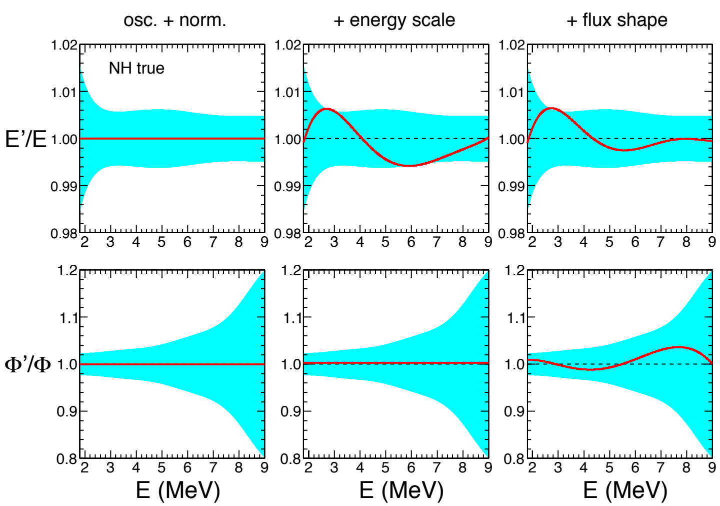
Relative 1σ error bands



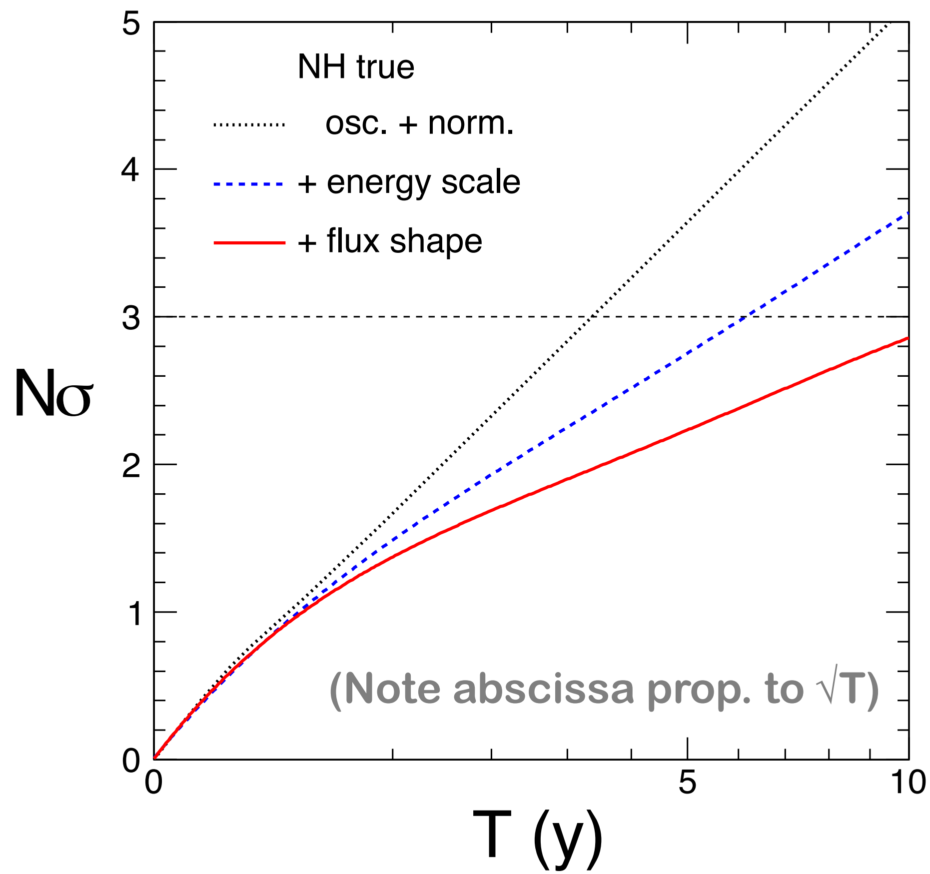


Smoothed errors assumed to be linear and symmetric (gaussian)

Energy-scale and flux-shape errors with constrained "size" but unconstrained "shape" can noticeably lower JUNO sensitivity

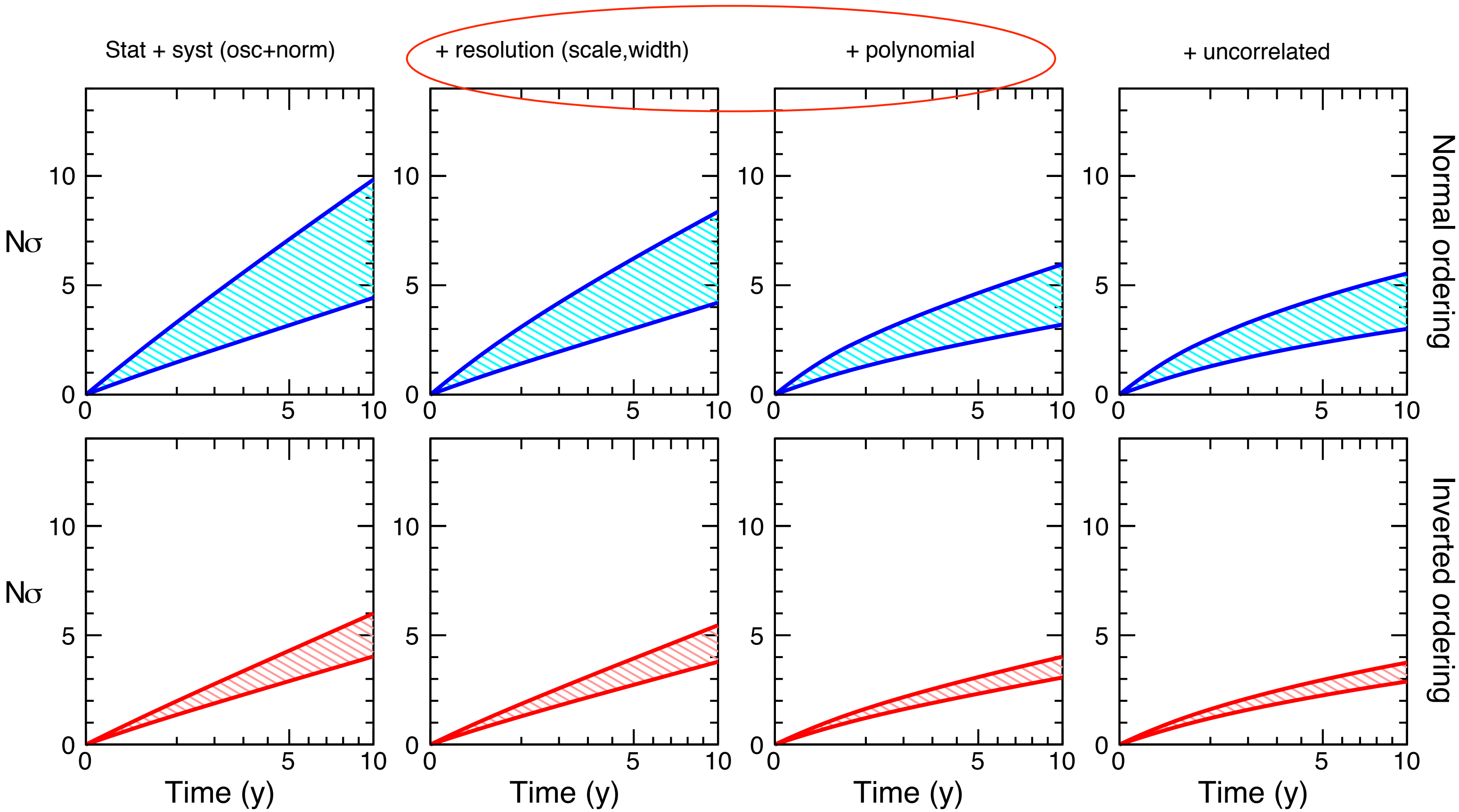


[See arXiv:1508.01392]



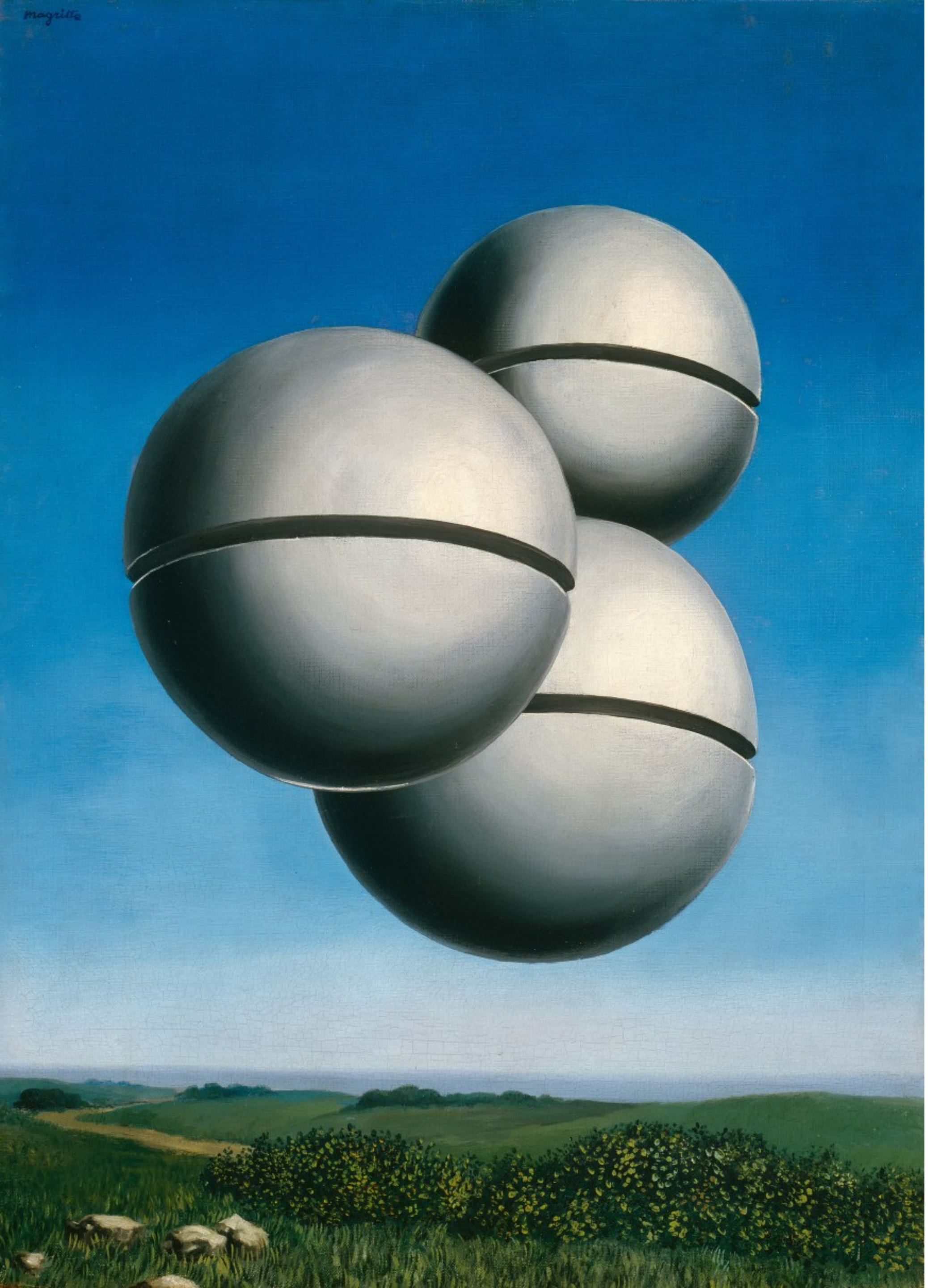
In addition: sawtooth-like fluctuations may further affect and challenge JUNO performances! Near detector needed? [See next reactor talks]

Another example: effect of shape uncertainties on energy-angle spectra in ORCA



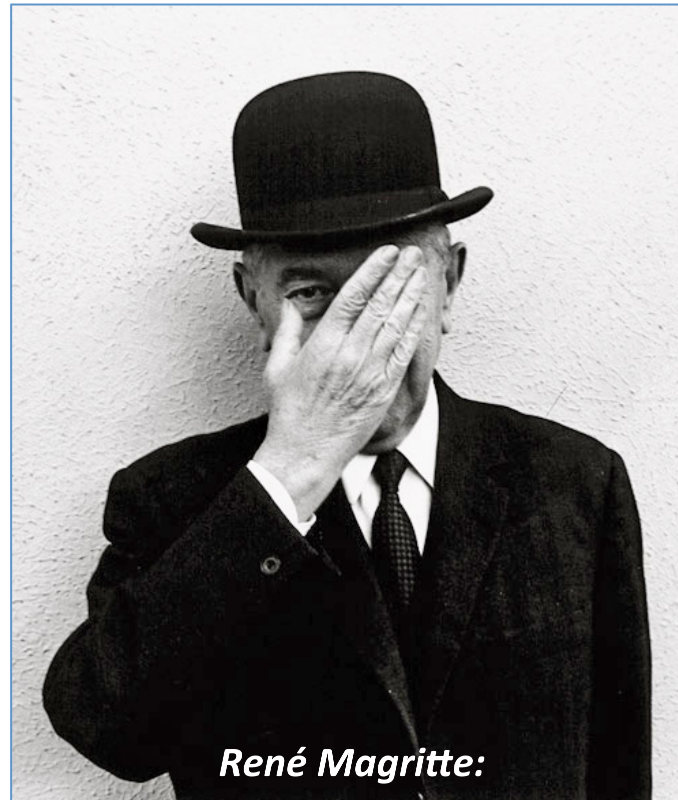
See arXiv:1708.03022

Other functional uncertainties in future expts: differential neutrino cross-sections, nuclear form factors (including M_A , g_A), inhomogeneities of large-volume detectors, ...



Epilogue

Start to have some **hints** on ν mass ordering. But: unprecedented **challenges** before we can really "see" it! **Surprises?**

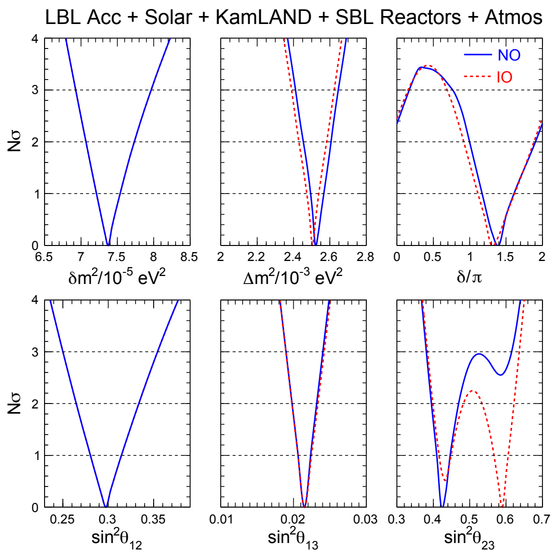


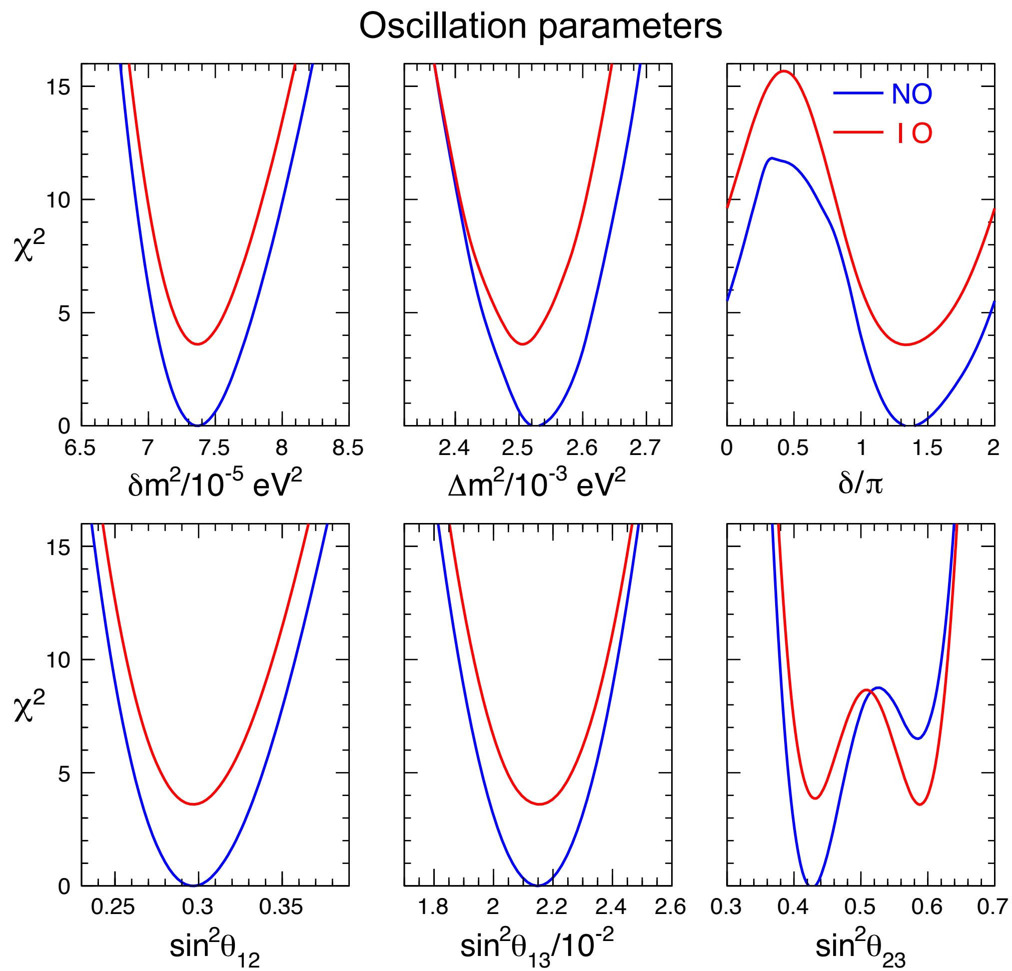
"Everything we see hides another thing, we always want to see what is hidden by what we see."

Extra slides

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

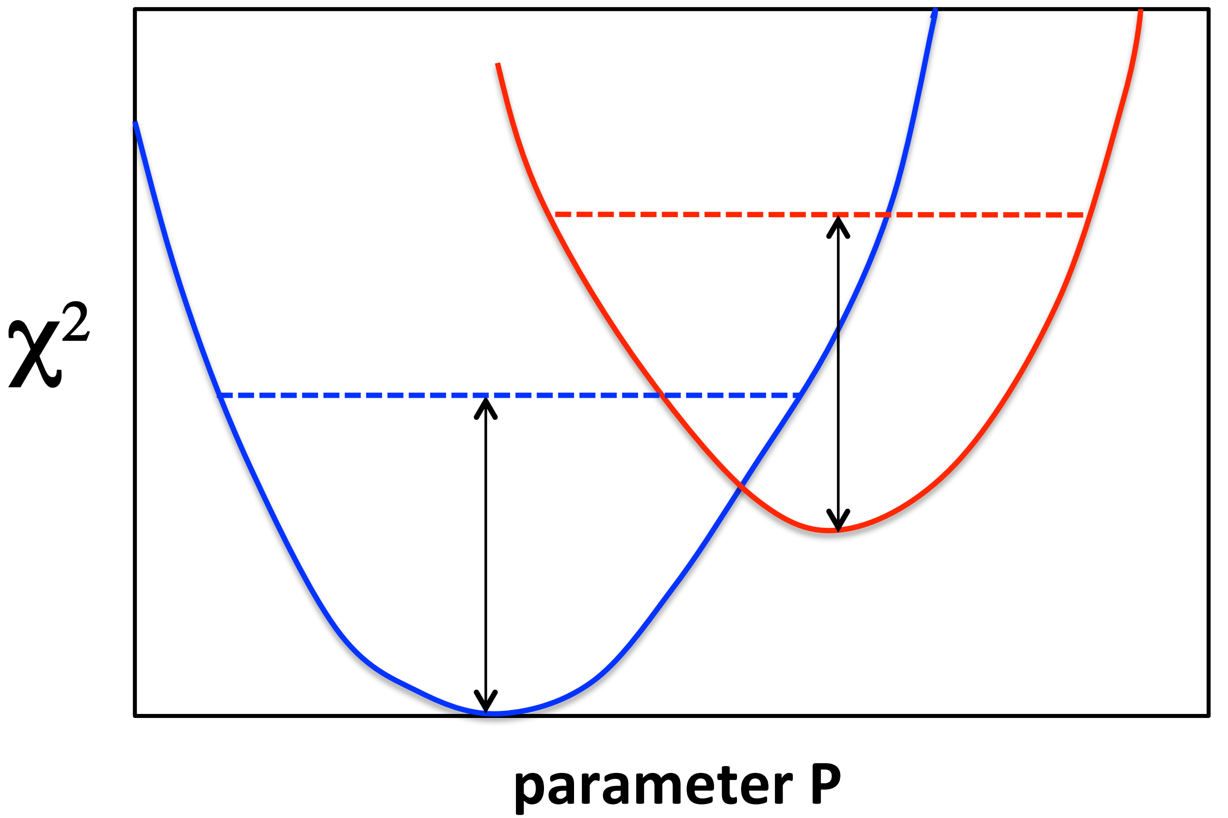
Useful to see the effect of excluding/including this offset in the analysis:





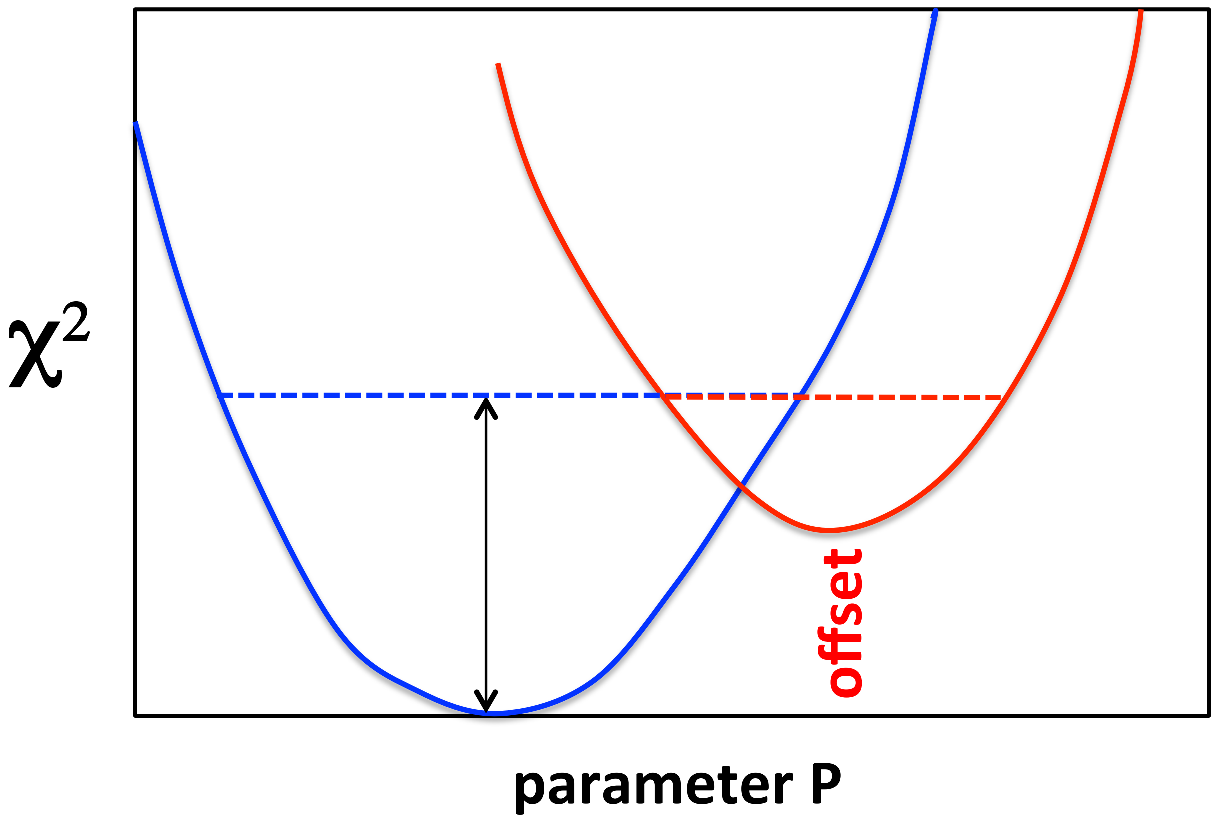
Two different ways of marginalizing over mass ordering(s) →

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

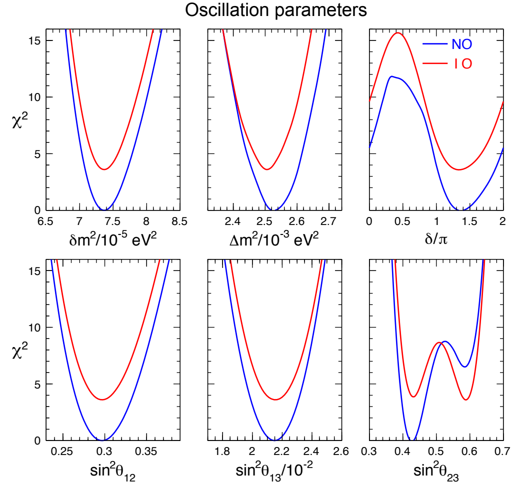


(does **not** include **IO-NO offset** information)

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



(includes **IO-NO offset** information)



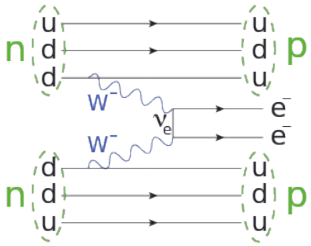
Oscillation parameter ranges

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 $\oplus$ 5.67 – 6.05	3.99 – 4.83 $\oplus$ 5.33 – 6.21	3.84 – 6.36
	Any	4.25	4.10 – 4.46	3.95 – 4.70 $\oplus$ 5.75 – 6.00	3.81 – 6.26
δ/π	NO	1.38	1.18 – 1.61	1.00 – 1.90	0 – 0.17 $\oplus$ 0.76 – 2
	IO	1.31	1.12 – 1.62	0.92 – 1.88	0 – 0.15 $\oplus$ 0.69 – 2
	Any	1.38	1.18 – 1.61	1.00 – 1.90	0 – 0.17 $\oplus$ 0.76 – 2

Absolute neutrino mass observables

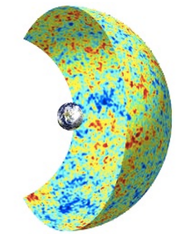
0νββ



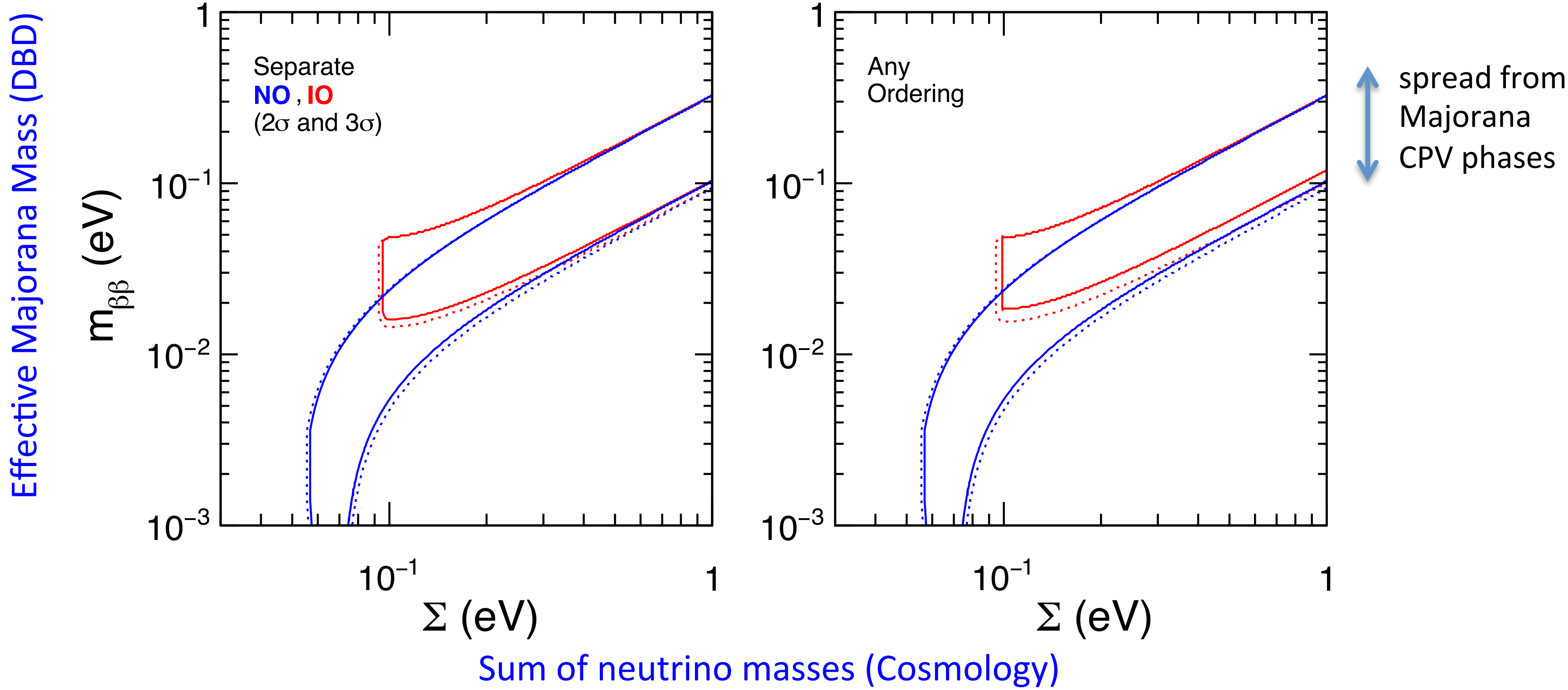
$$m_{\beta\beta} = \left| c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \right|$$

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

Cosmo

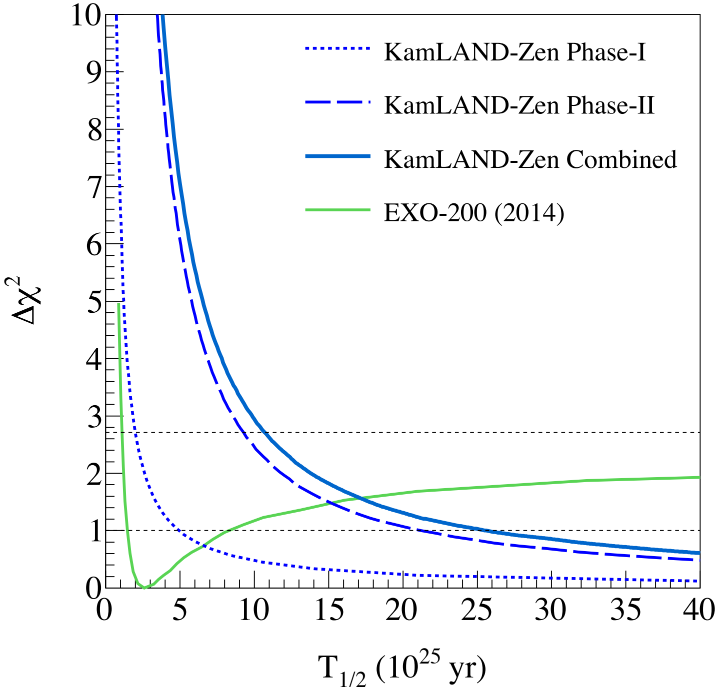


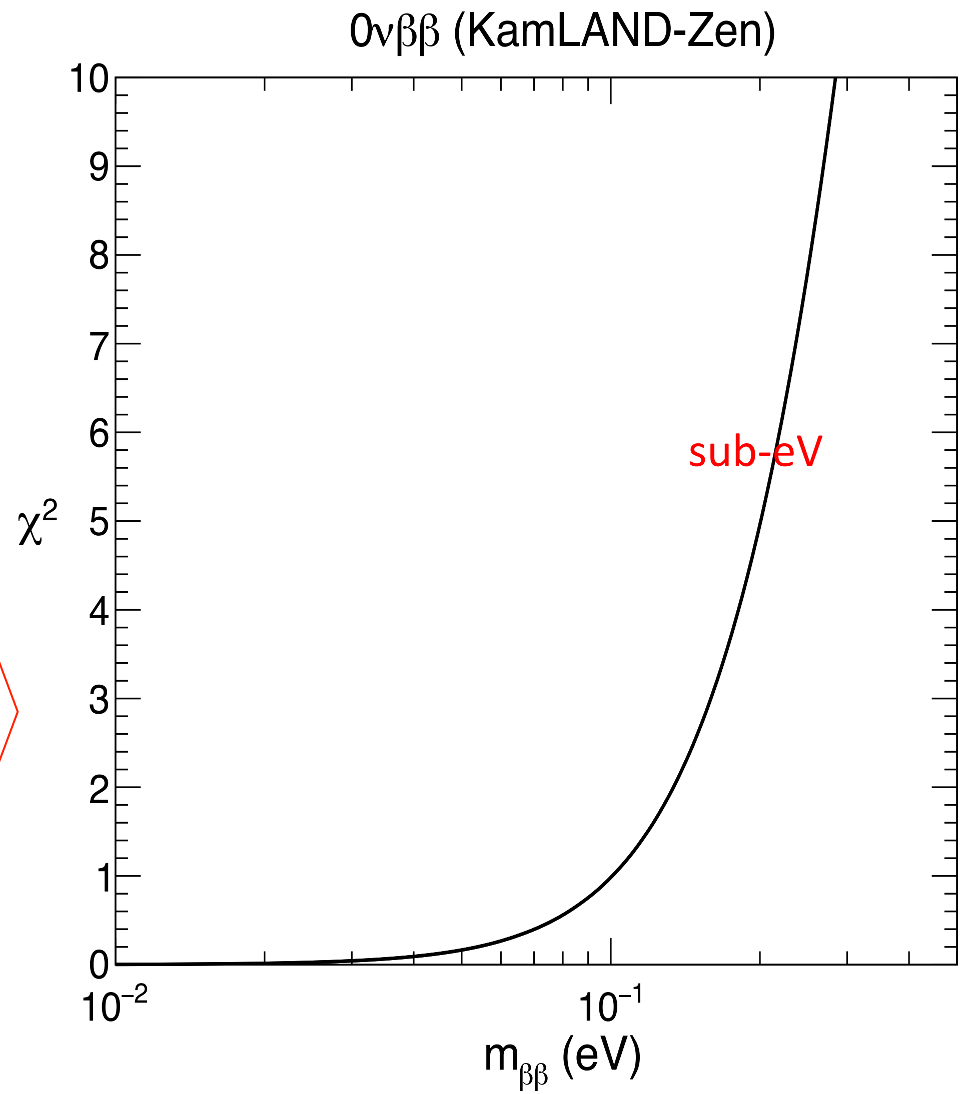
Oscillations



Current leading $0\nu\beta\beta$ constraints

KamLAND-Zen half-life limits

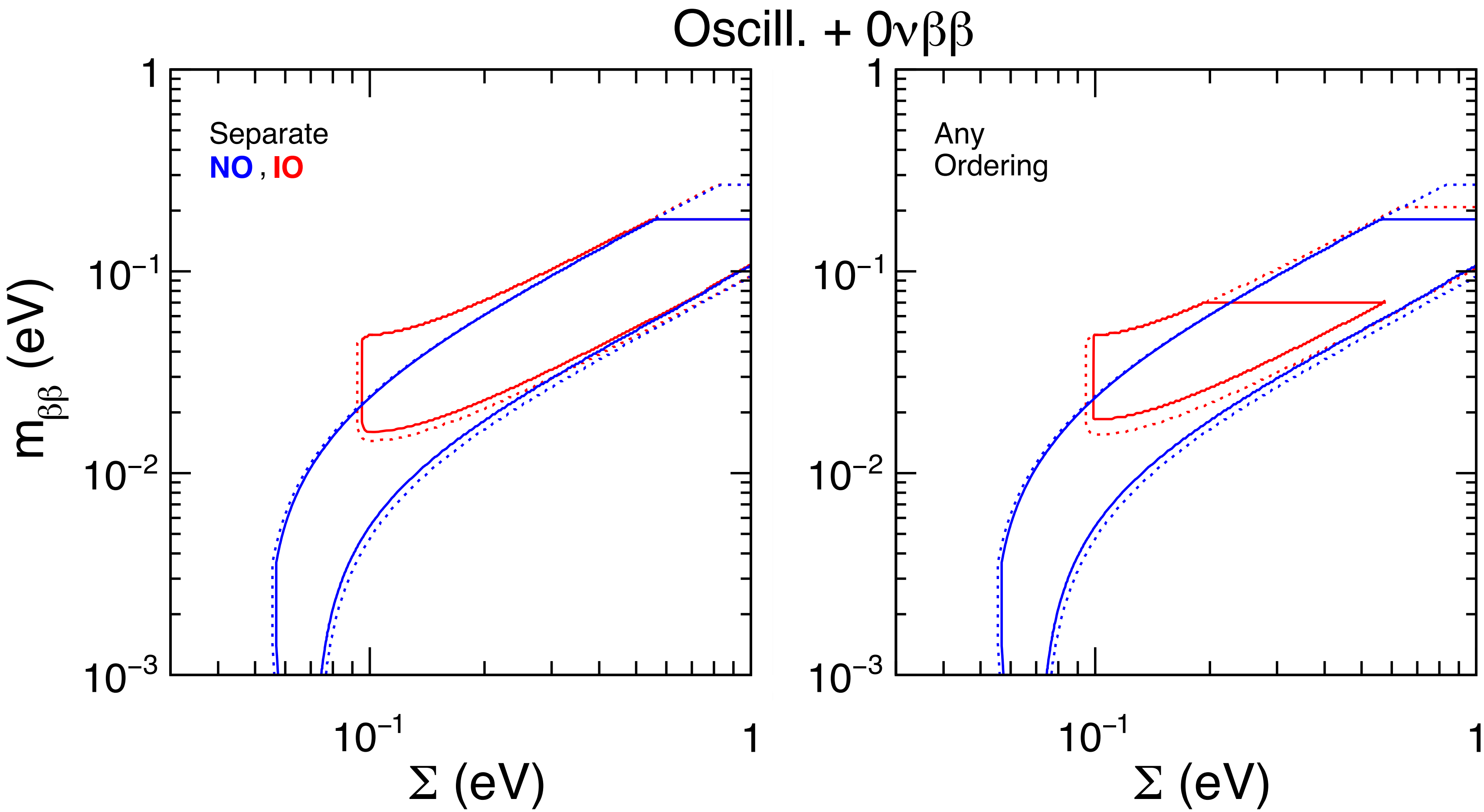




+NME Likelihood based on:

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

arXiv:1506.04058



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

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
[**A_{lens}** > 1 may be typically traded for higher values of the sum of neutrino mass **Σ**]

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) not allowed by construction.
→ expect small NO-IO differences at low Σ, but vanishing at high Σ (degenerate spectrum)

Cosmological constraints (circa 2017)

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plus one possible 1 extra parameter $\mathbf{A_{lens}}$, to account for syst's or nonstandard effects
[$\mathbf{A_{lens}}$ > 1 may be typically traded for higher values of the sum of neutrino mass **Σ**]

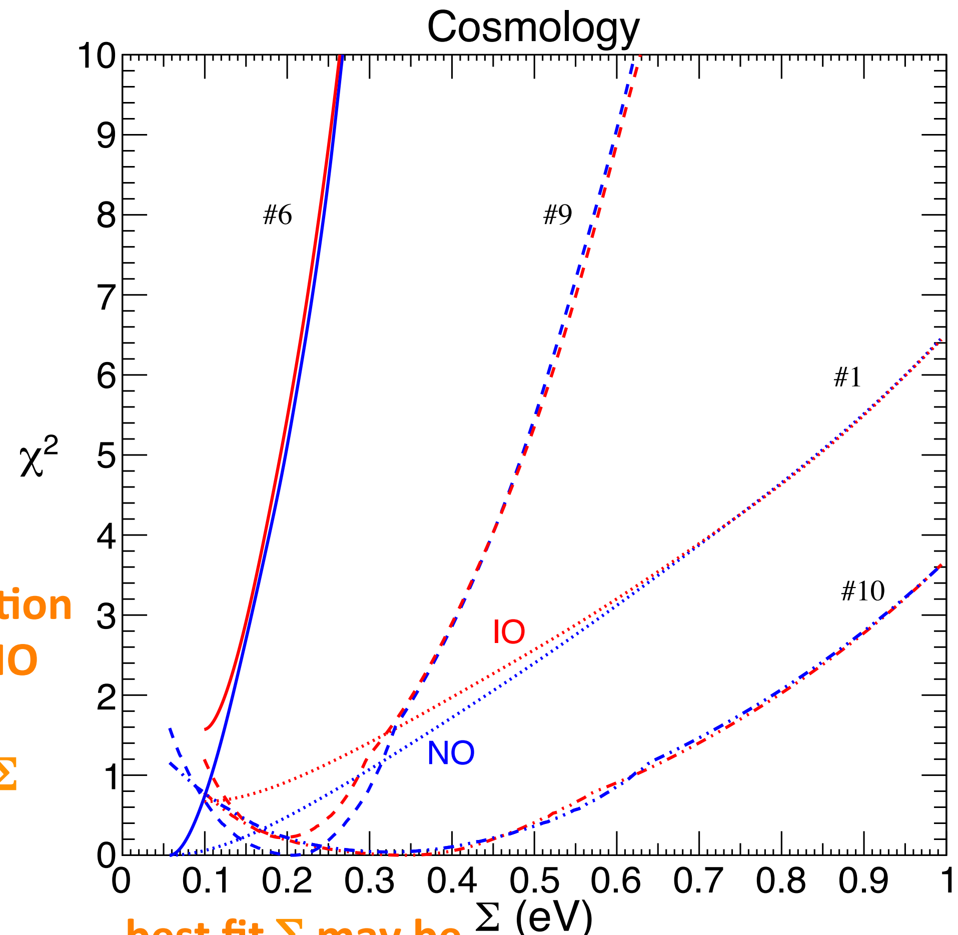
Code: **CosmoMC with NO / IO options explicitly included in Σ,** via the two mass^2 differences
→ unphysical spectra of neutrino masses (e.g., **Σ** = 0) not allowed by construction.
→ expect small NO-IO differences at low Σ, but vanishing at high Σ (degenerate spectrum)

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

χ^2 profile for NO, IO in representative cases



convergence of NO, IO curves at high Σ

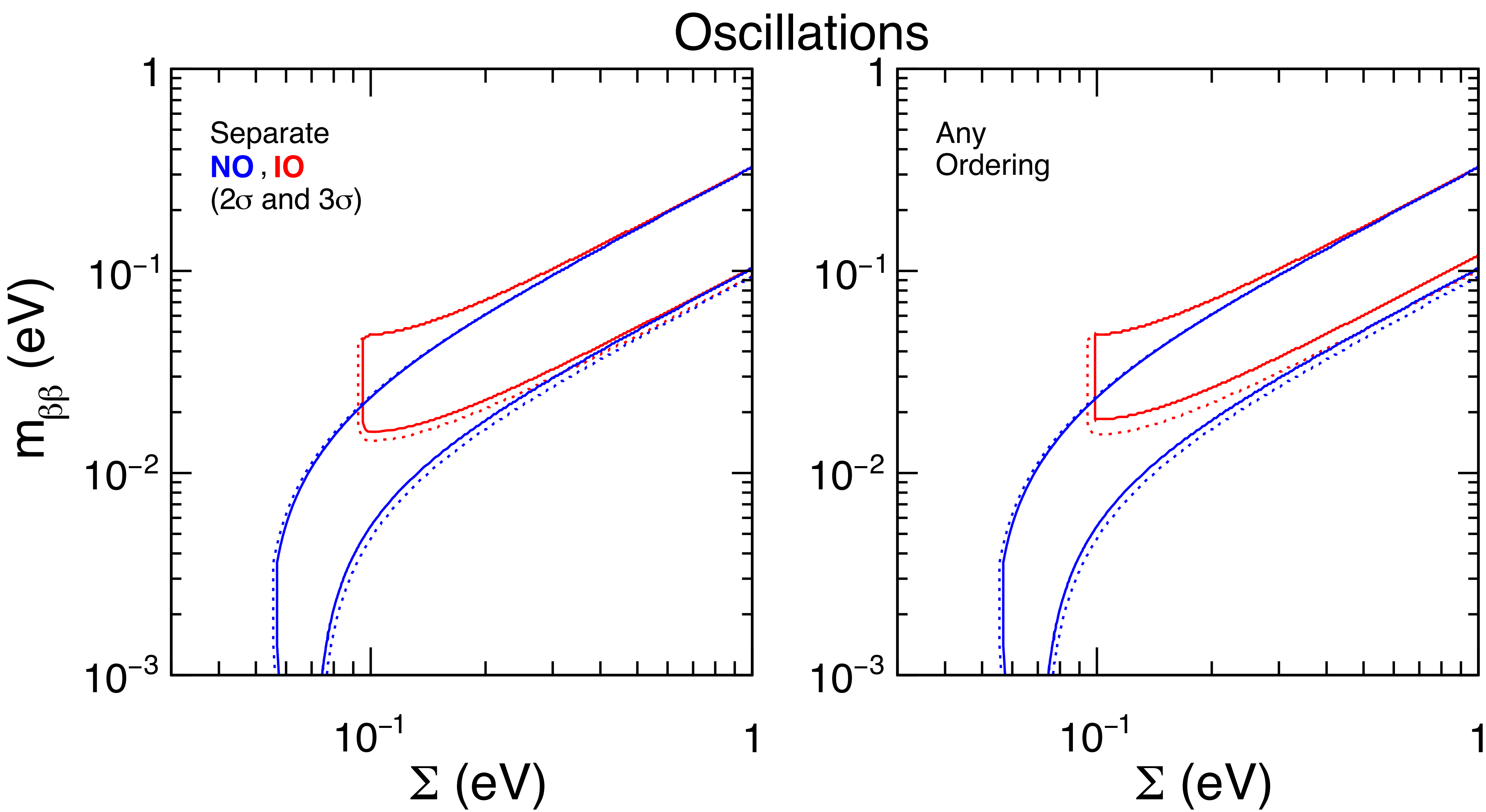
bifurcation of NO, IO curves at low Σ

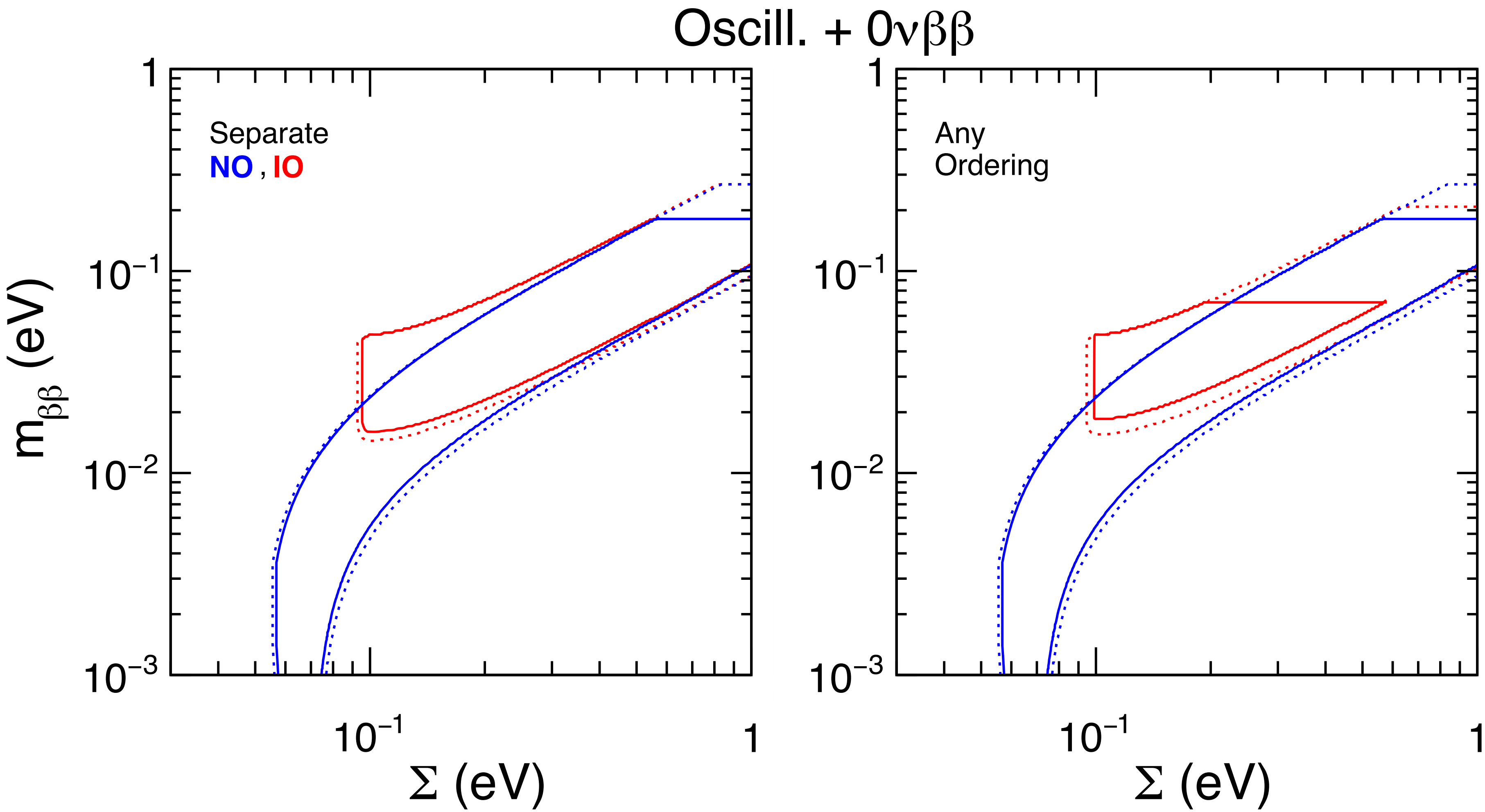
best fit Σ may be above threshold

Thresholds: Σ > 0.06 eV (NO)
Σ > 0.10 eV (IO)
Σ = 0: not allowed

Grand total: combination of oscillation + nonoscillation data

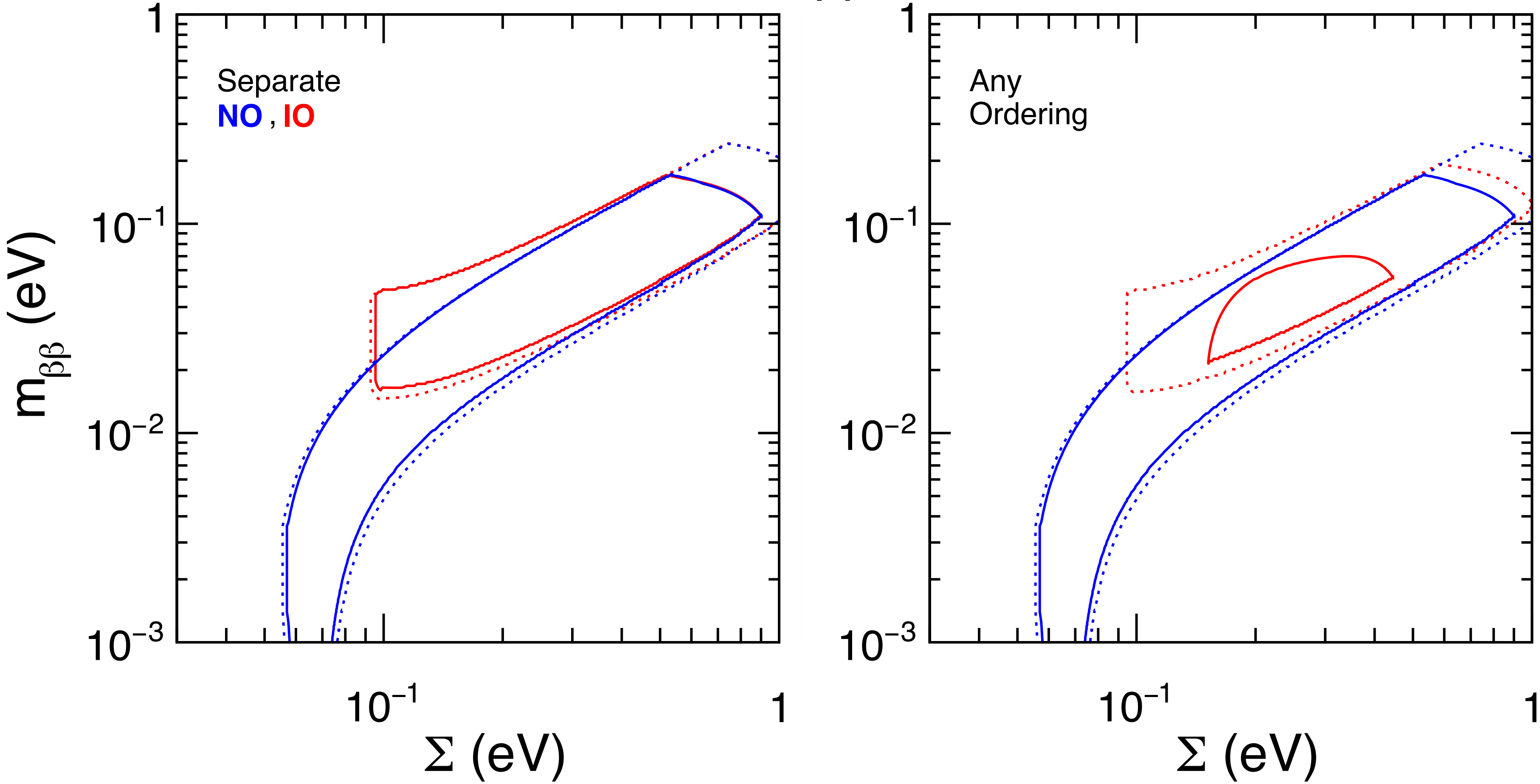
(with increasingly strong cosmological constraints)





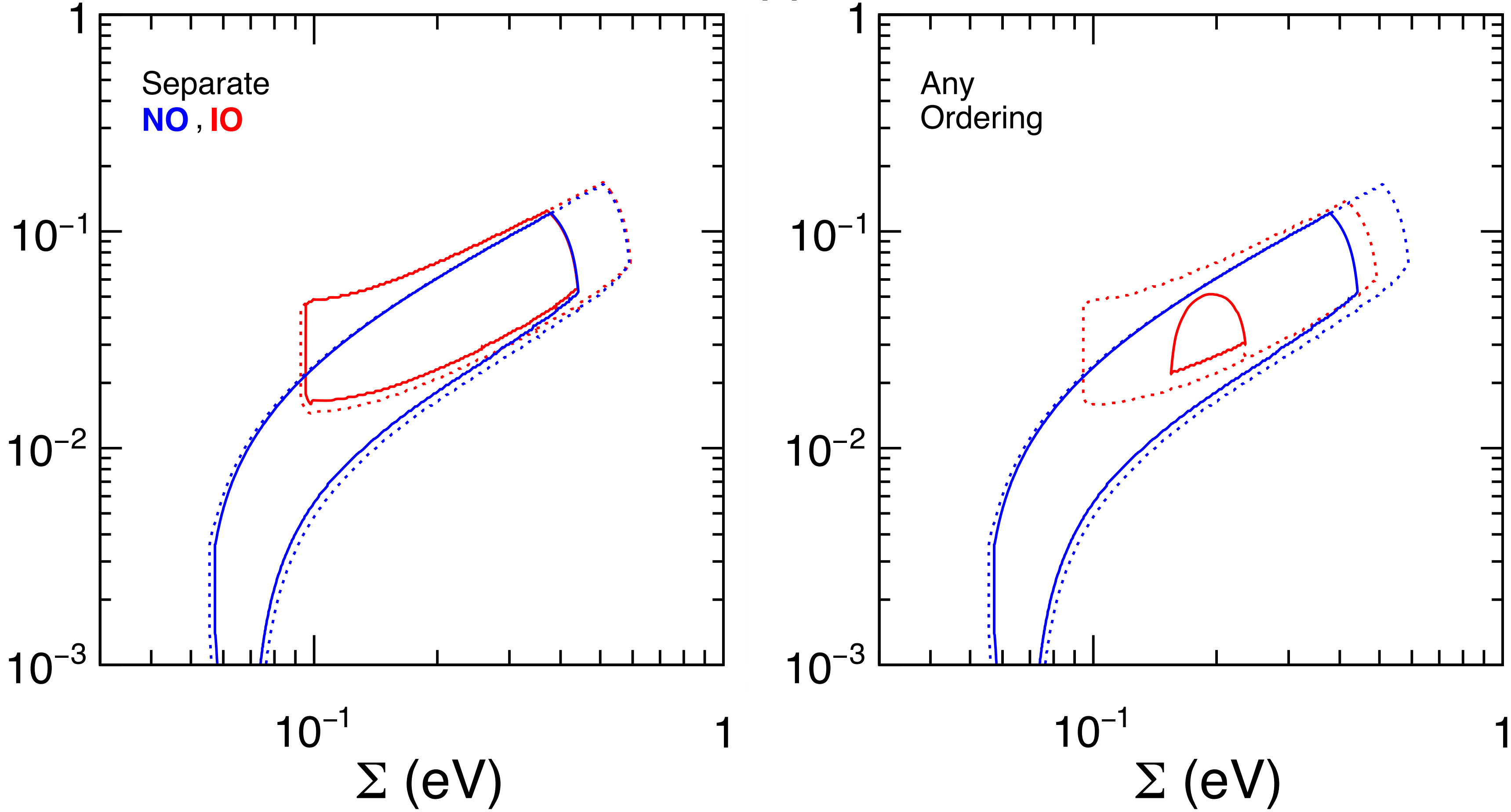
Oscill. + 0νββ
1
10−1
10−2
10−3
mββ (eV)
Separate
NO , IO
10−1
1
Σ (eV)
1
10−1
10−2
10−3
Any
Ordering
10−1
1
Σ (eV)

Oscill. + 0νββ + Cosmo #10



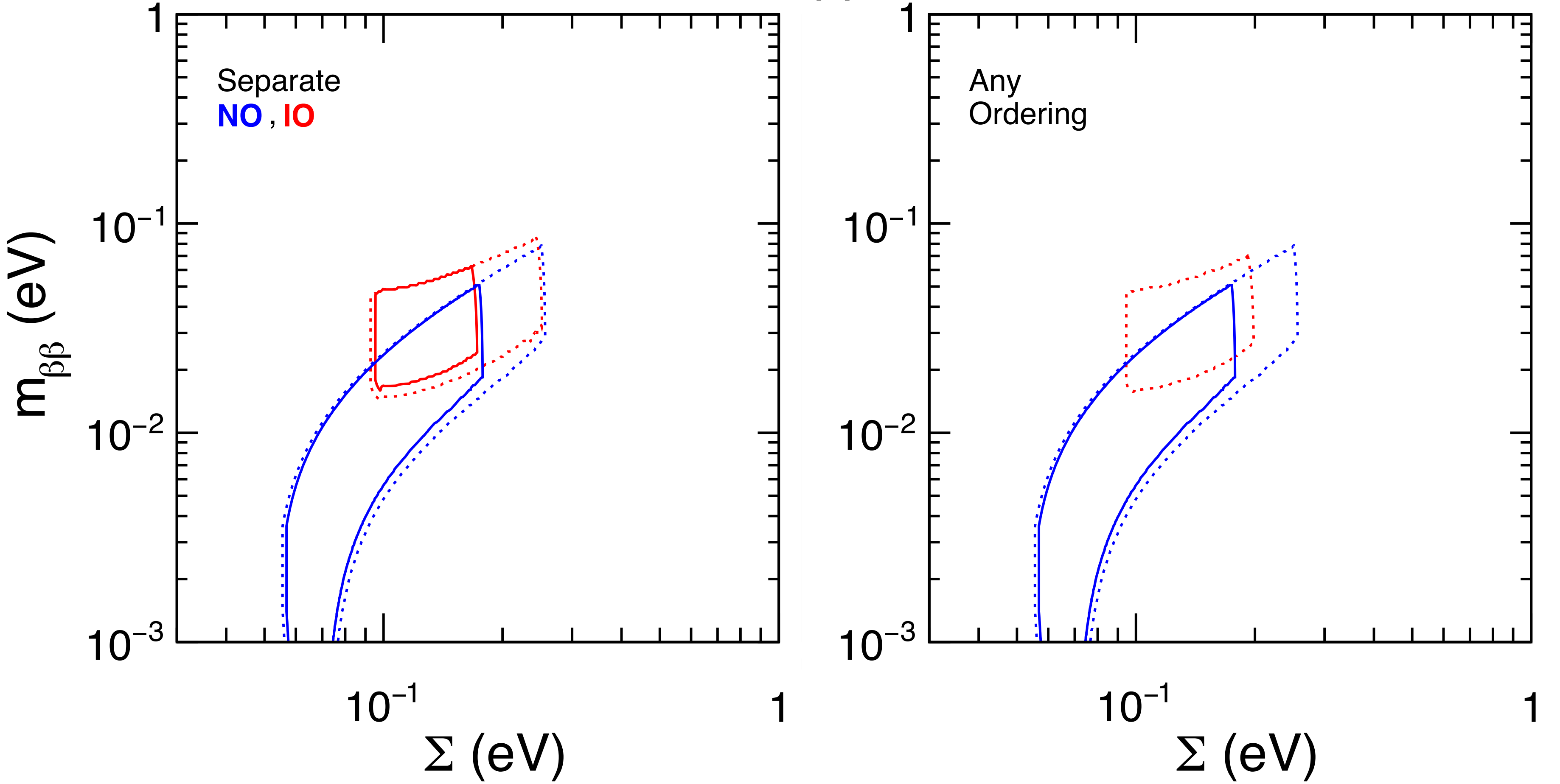
[Case with "conservative" bounds from cosmology]

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]

Grand total 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 but coherent steps: **N.O. favored**... Overall preference at $1.9\sigma - 2.1\sigma$

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

The statistical significance of possible hints about ordering is currently debated.
If they are not fluctuations, expect (fractional) improvements in upcoming years
Dedicated projects are planned with reactor, atmospheric, accelerator neutrinos

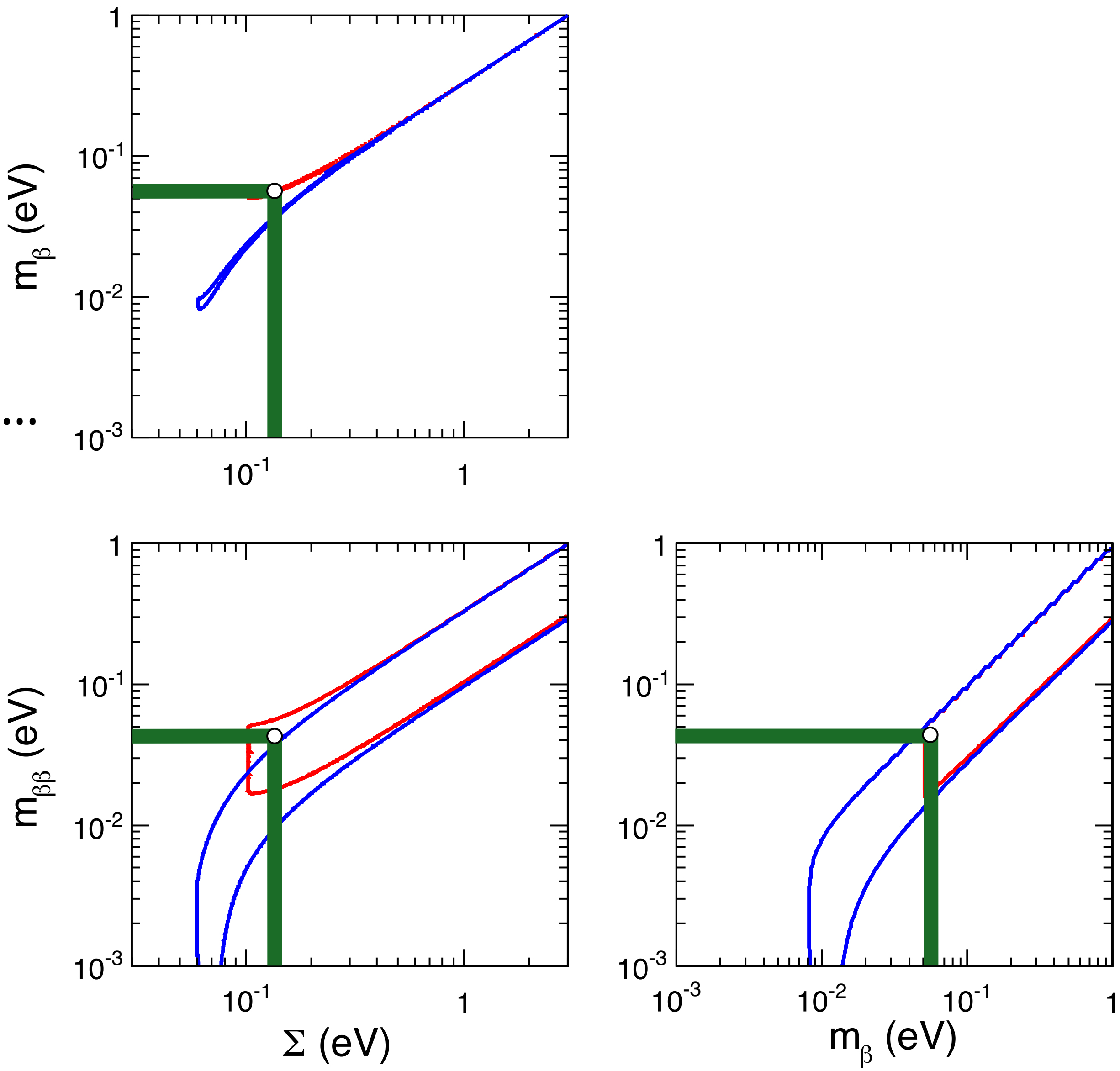
With "dreamlike" and converging data one could, e.g.

Determine the mass scale…

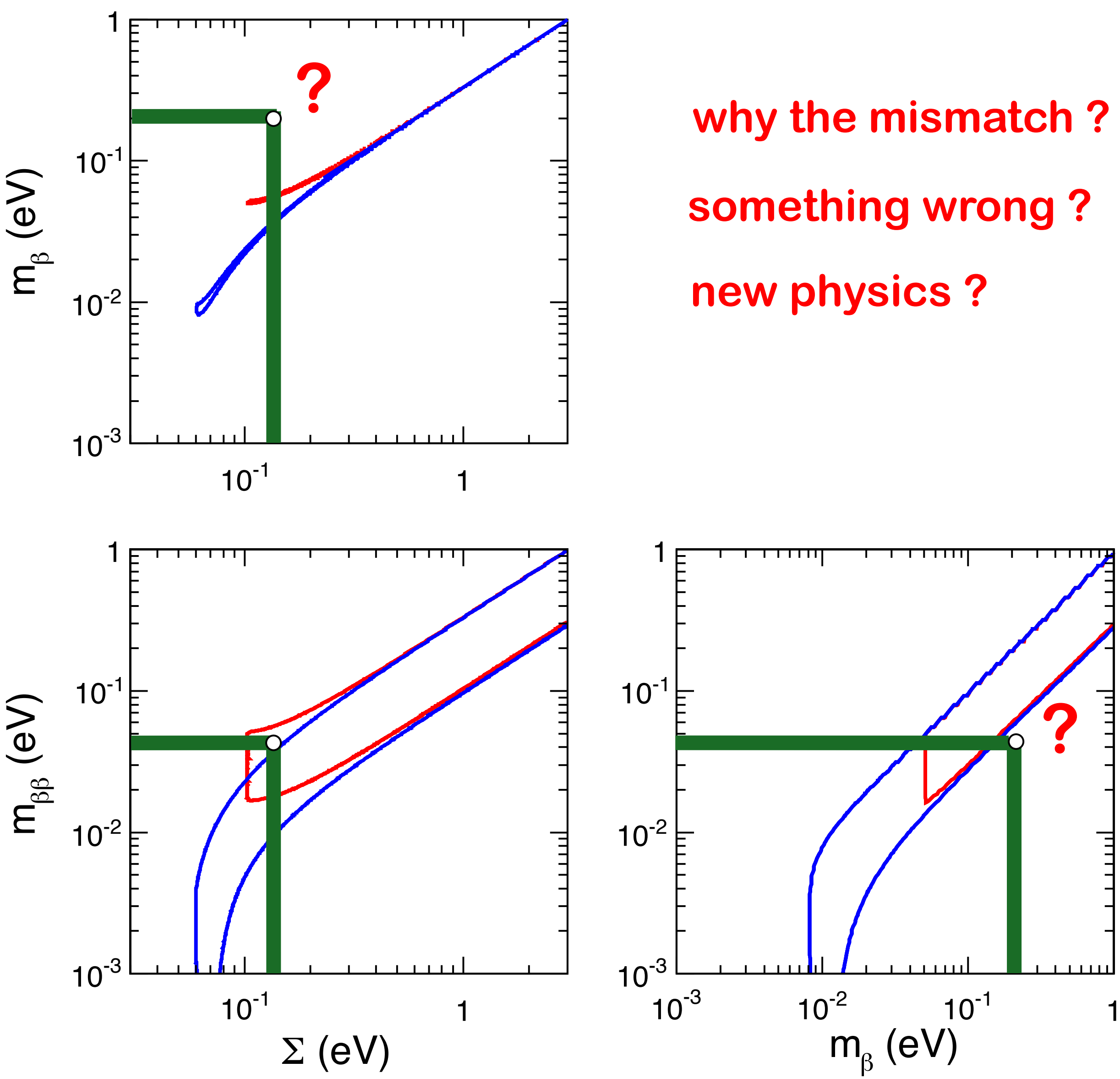
Check 3ν consistency …

Identify the hierarchy …

Probe the Majorana phase(s) …



But alternative situations (surprises!) might also occur….



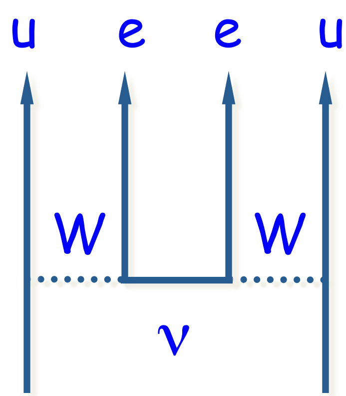
why the mismatch ?

something wrong ?

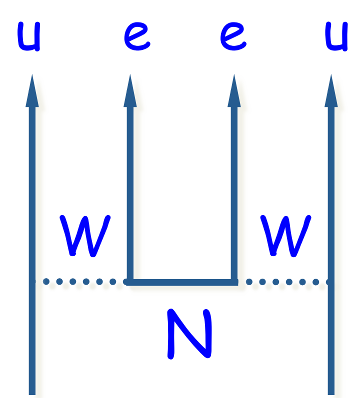
new physics ?

Physics beyond "3 light ν" should always be kept in mind,

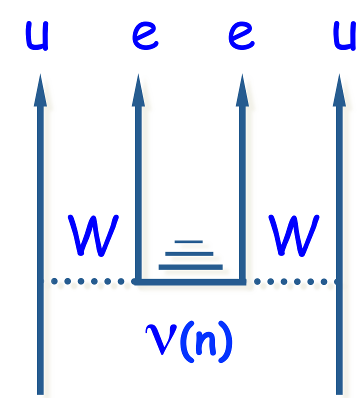
e.g., in neutrinoless double beta decay:



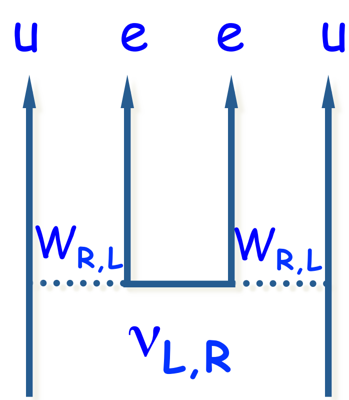
Standard



Heavy ν

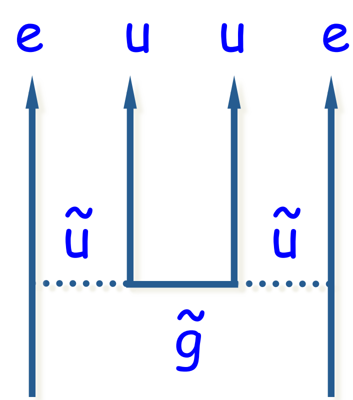


Kaluza-Klein

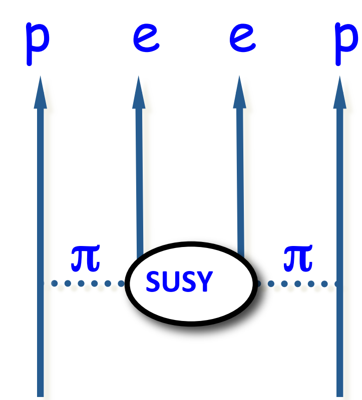


RHC λ,η

λ=RH had, η=LH had

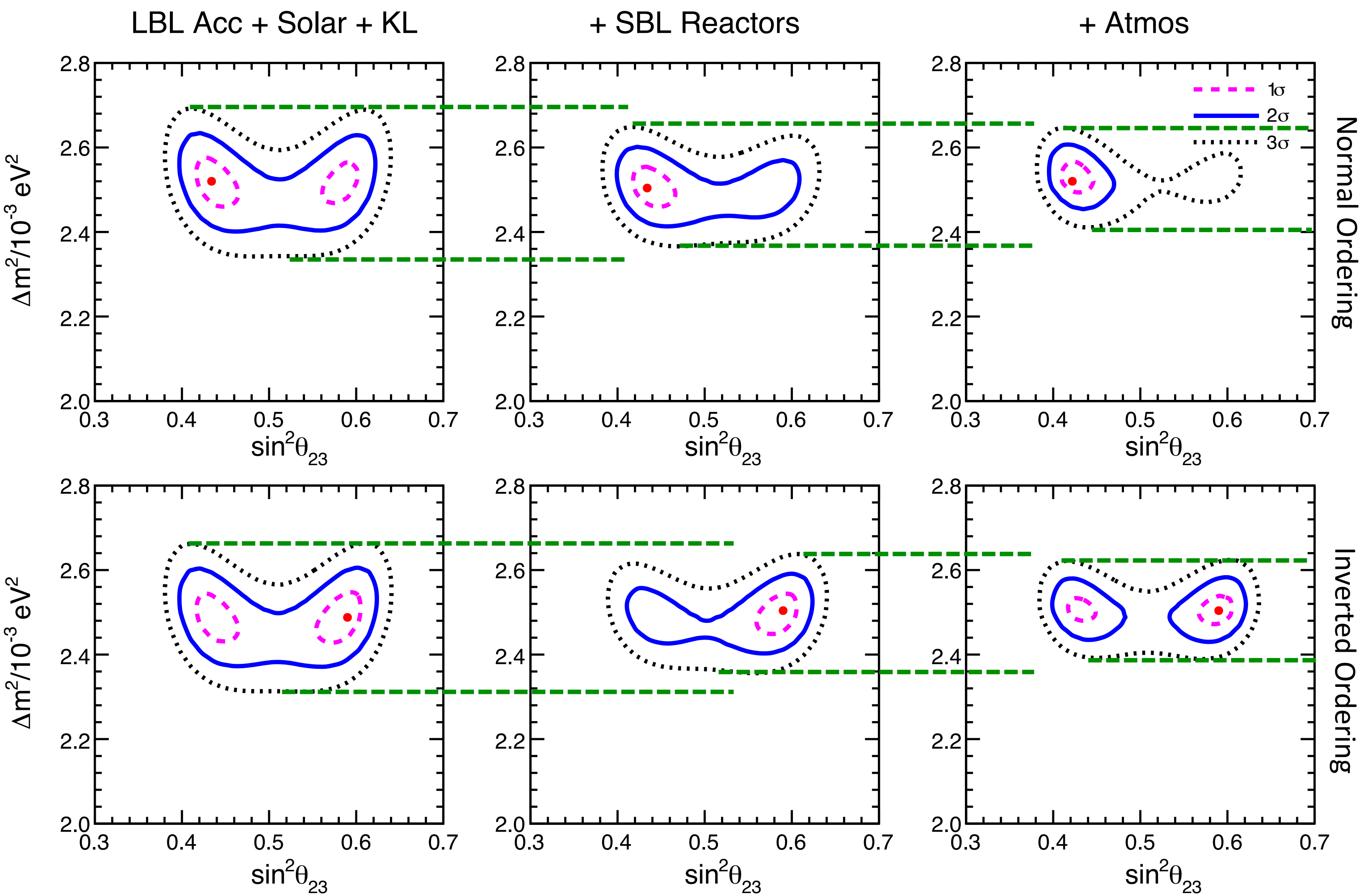


SUSY $\tilde{g}$



SUSY π

More on known oscillation parameters: sinergy on Δm^2



Each of these three data sets contributes to constrain Δm^2

Supplementary to arXiv:1703.04471