Up-to-date status of neutrino mass and mixing parameters

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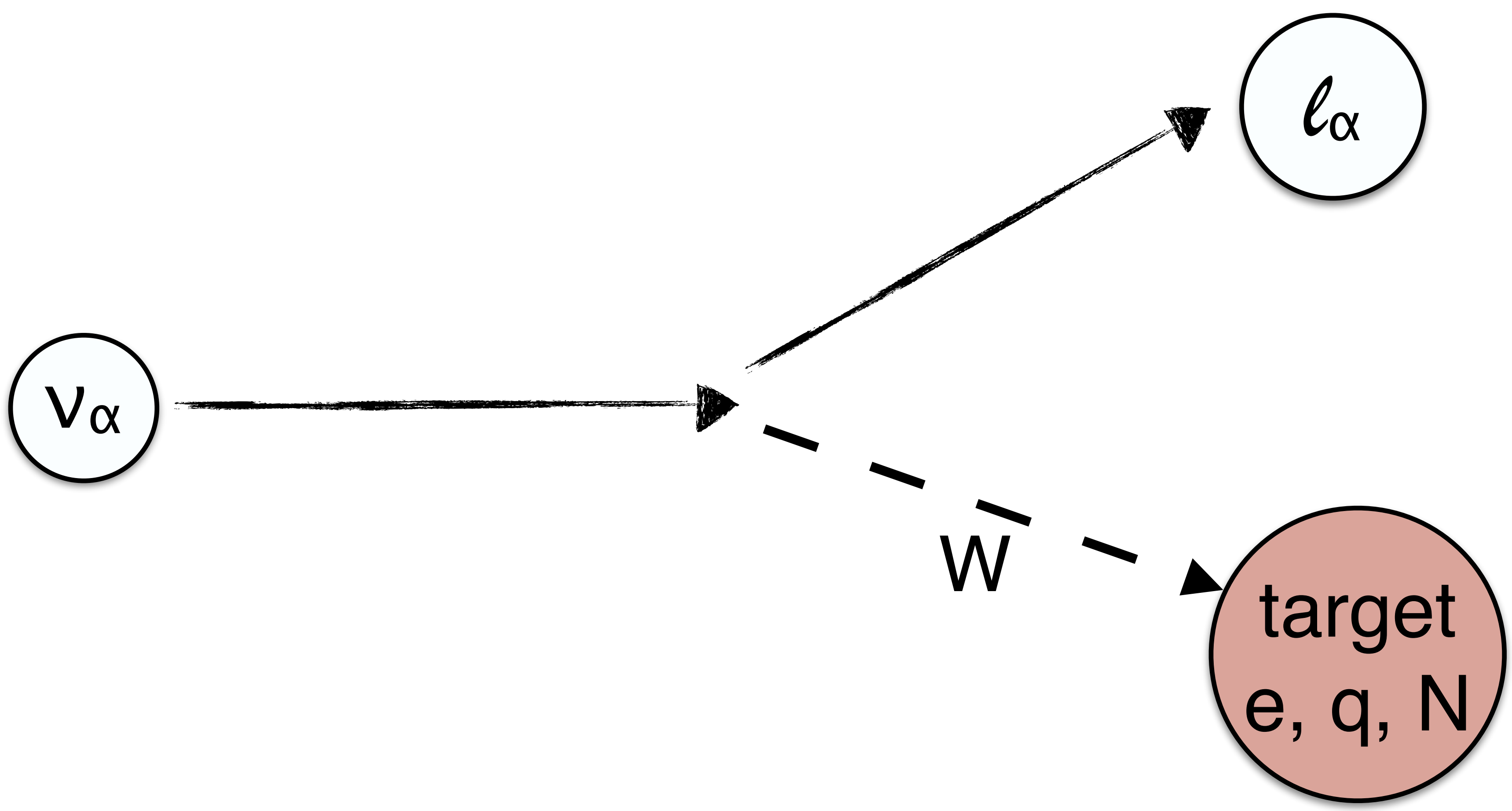
VIRGINIA TECH™

Neutrinos

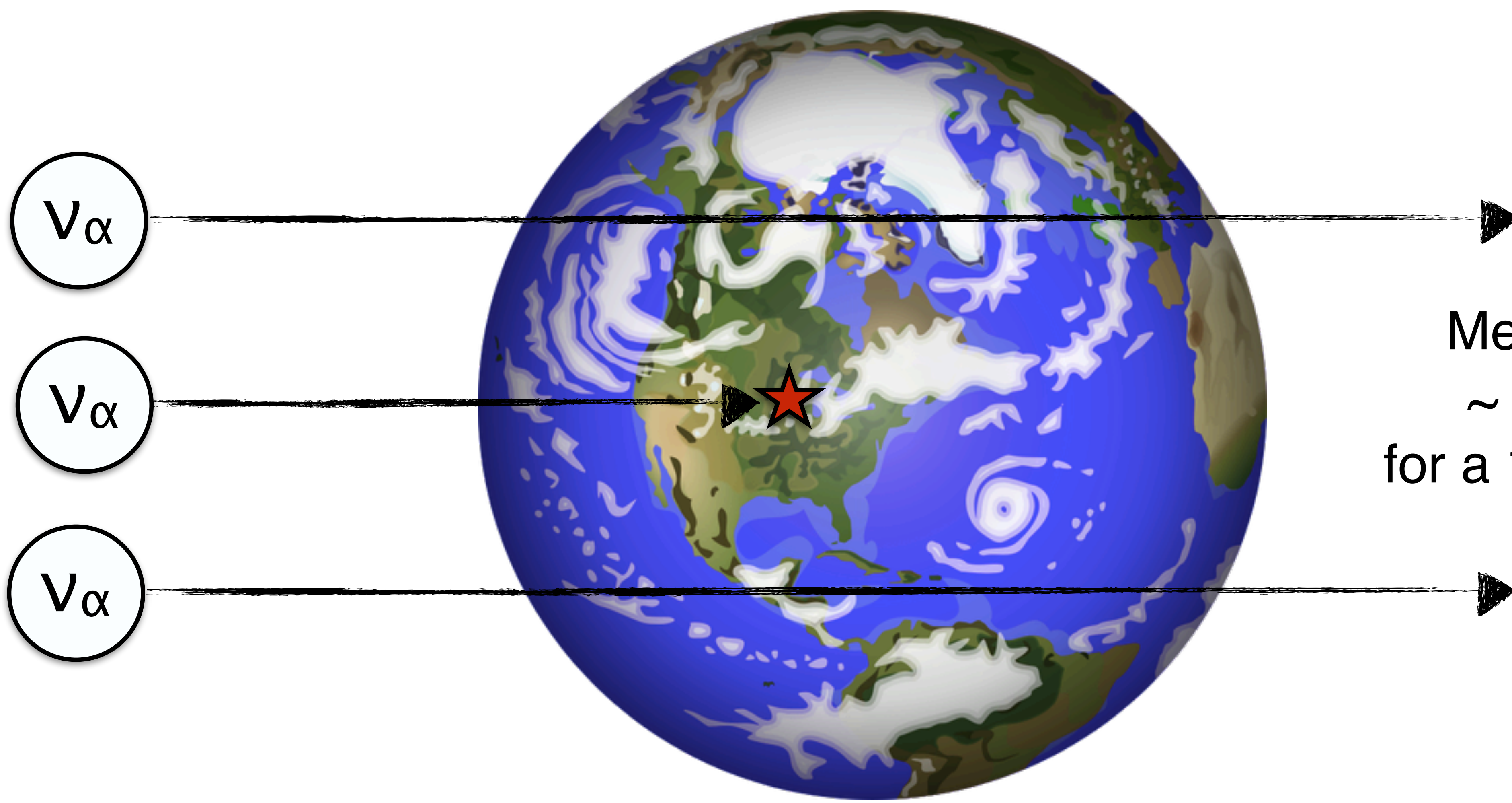
Neutrinos are very light, weakly interacting particles without electric charge



Three flavours $\alpha = e,\mu,\tau$, each identified by the corresponding lepton

Neutrinos

Neutrinos hardly interact with matter

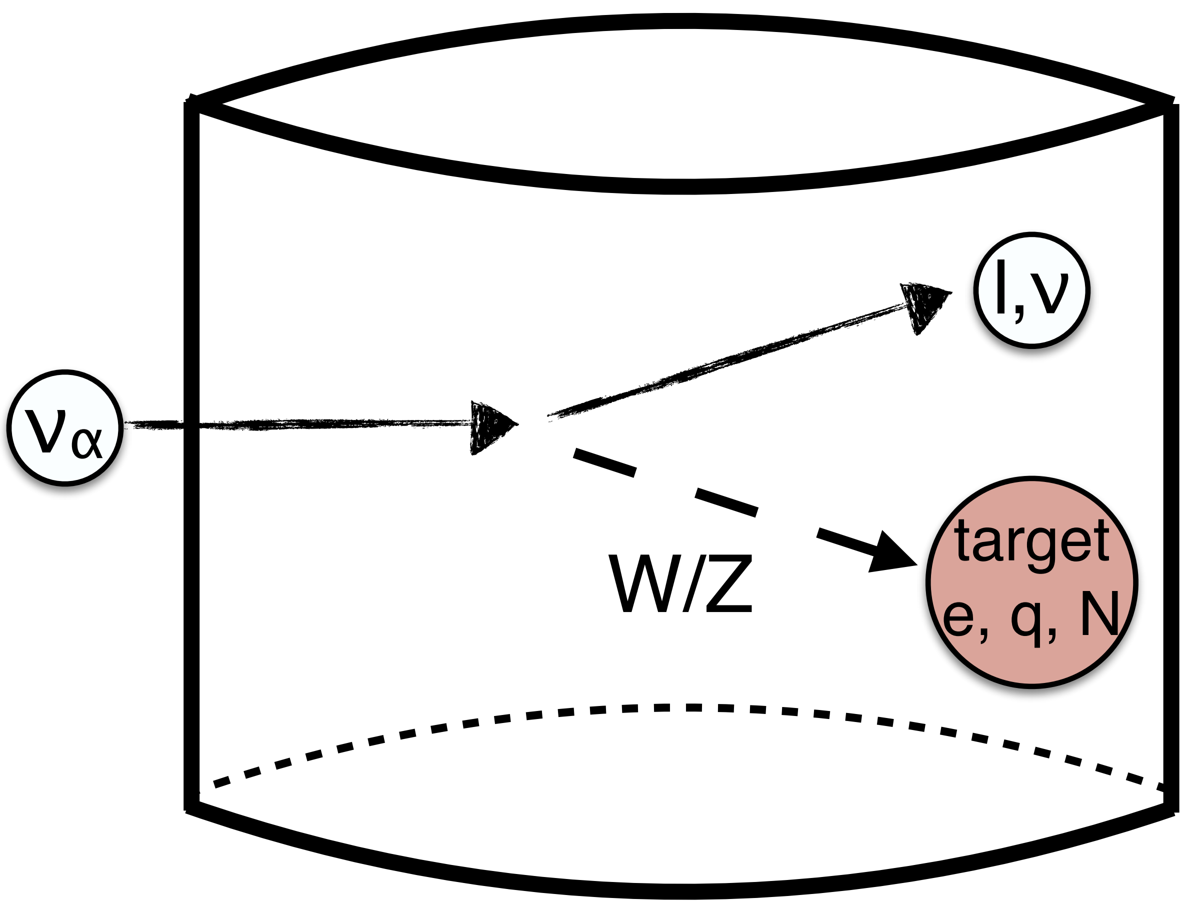


Mean free path
$\sim 6 \times 10^{19}$ cm
for a 1 MeV neutrino

Only 1 neutrino (1 MeV) in 10^{11} interacts with the Earth

Neutrinos

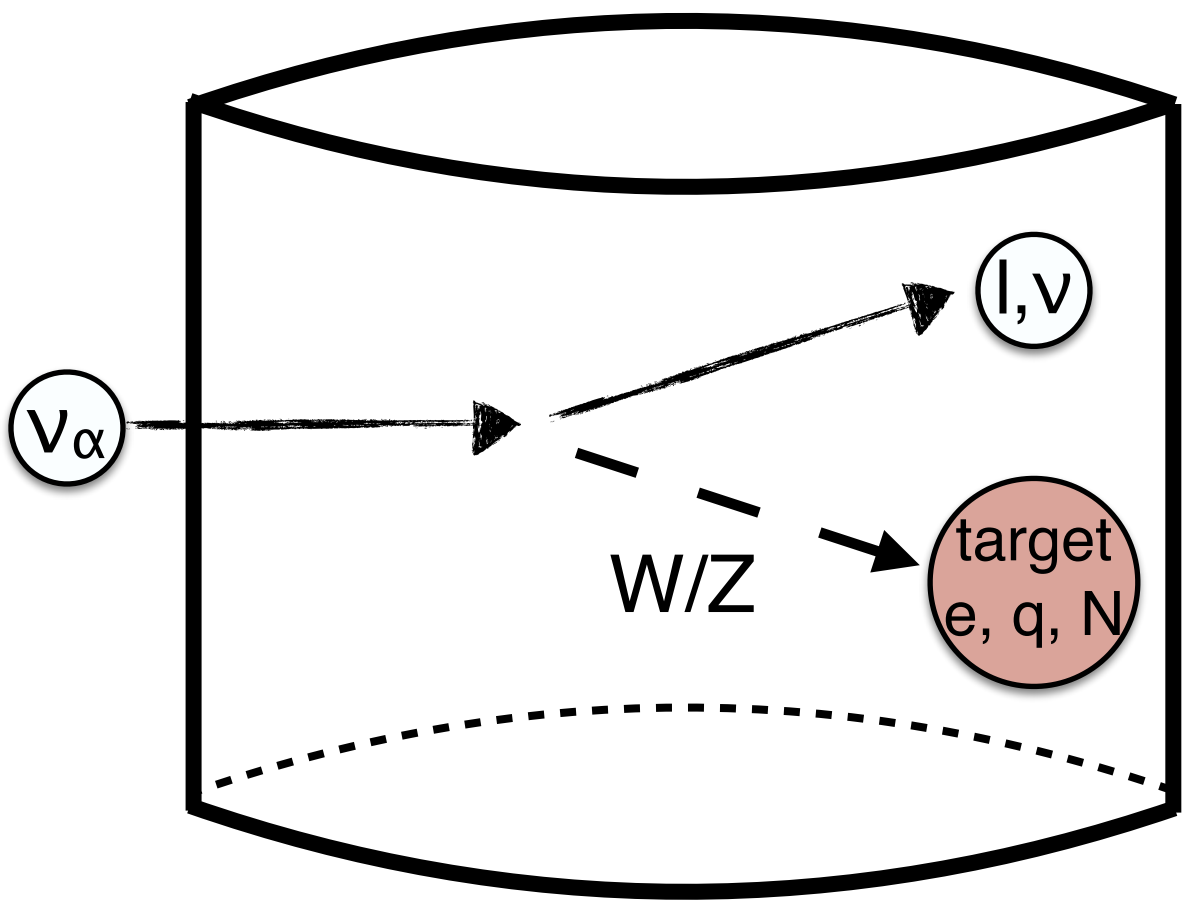
Downside: need very large detectors to collect a reasonable statistics

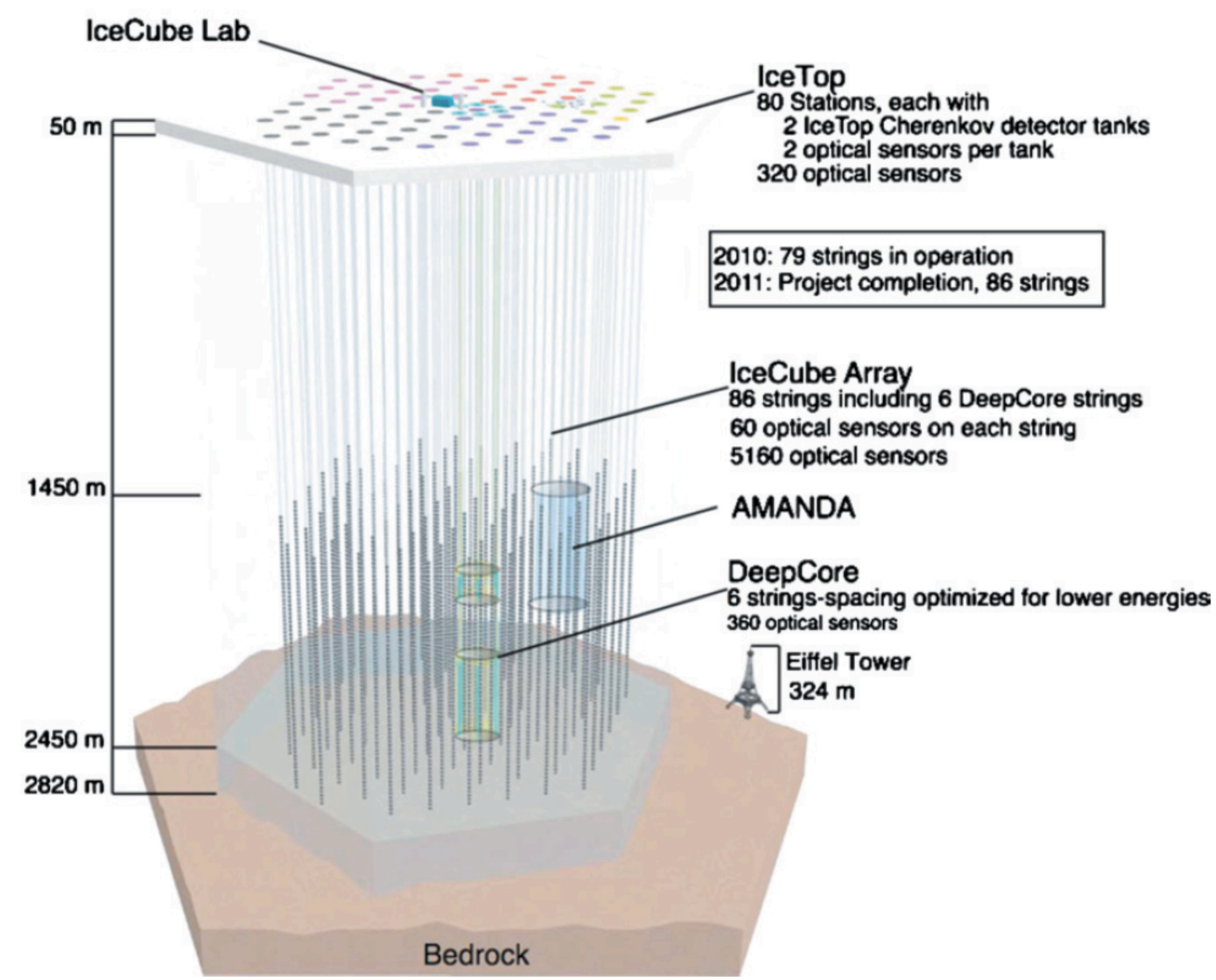


We only see the products of interactions

Neutrinos

Downside: need very large detectors to collect a reasonable statistics



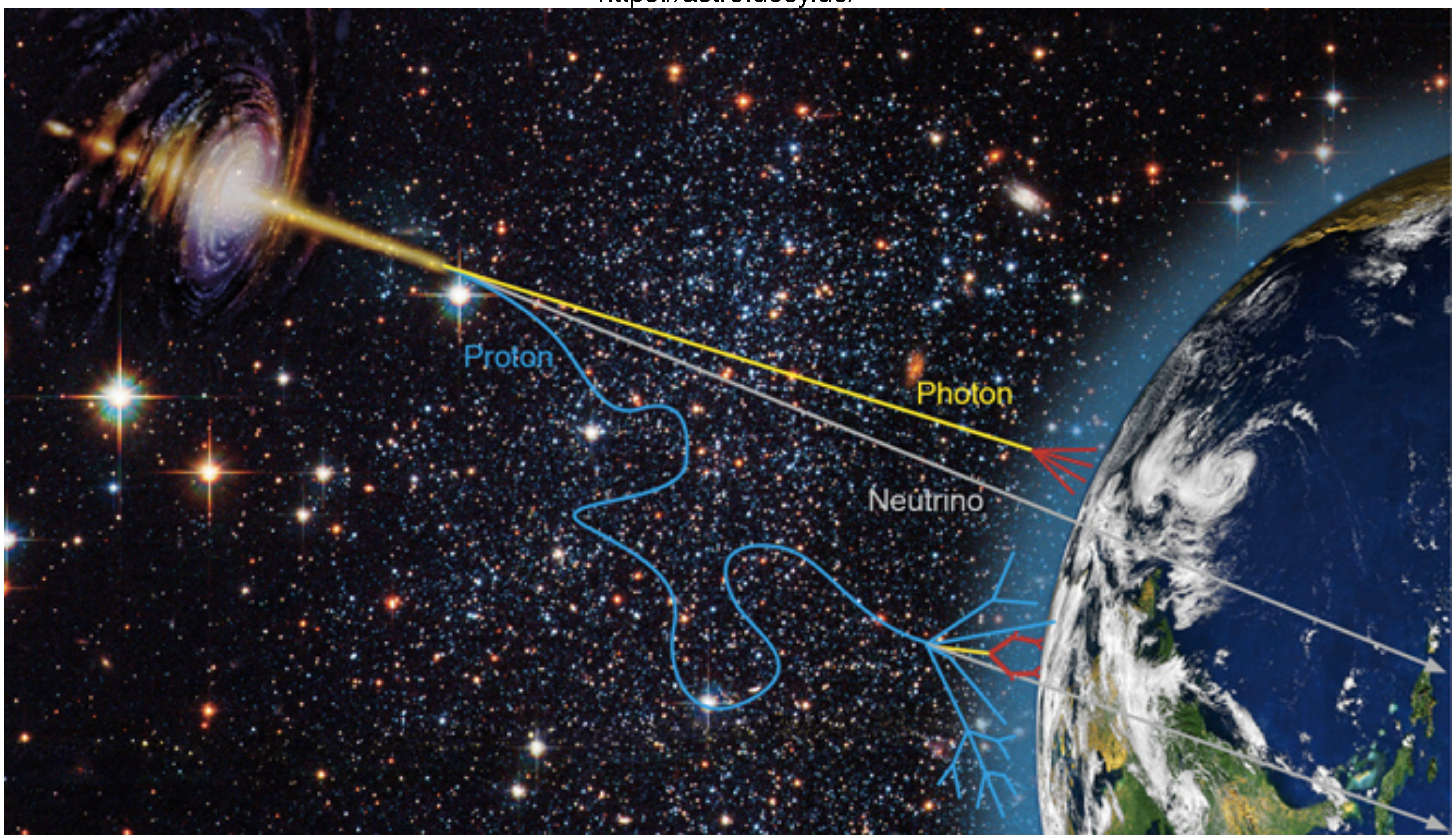


Example: IceCUBE with 1 km^3 of ice

Neutrinos

Upside: neutrinos travel unimpeded through the universe

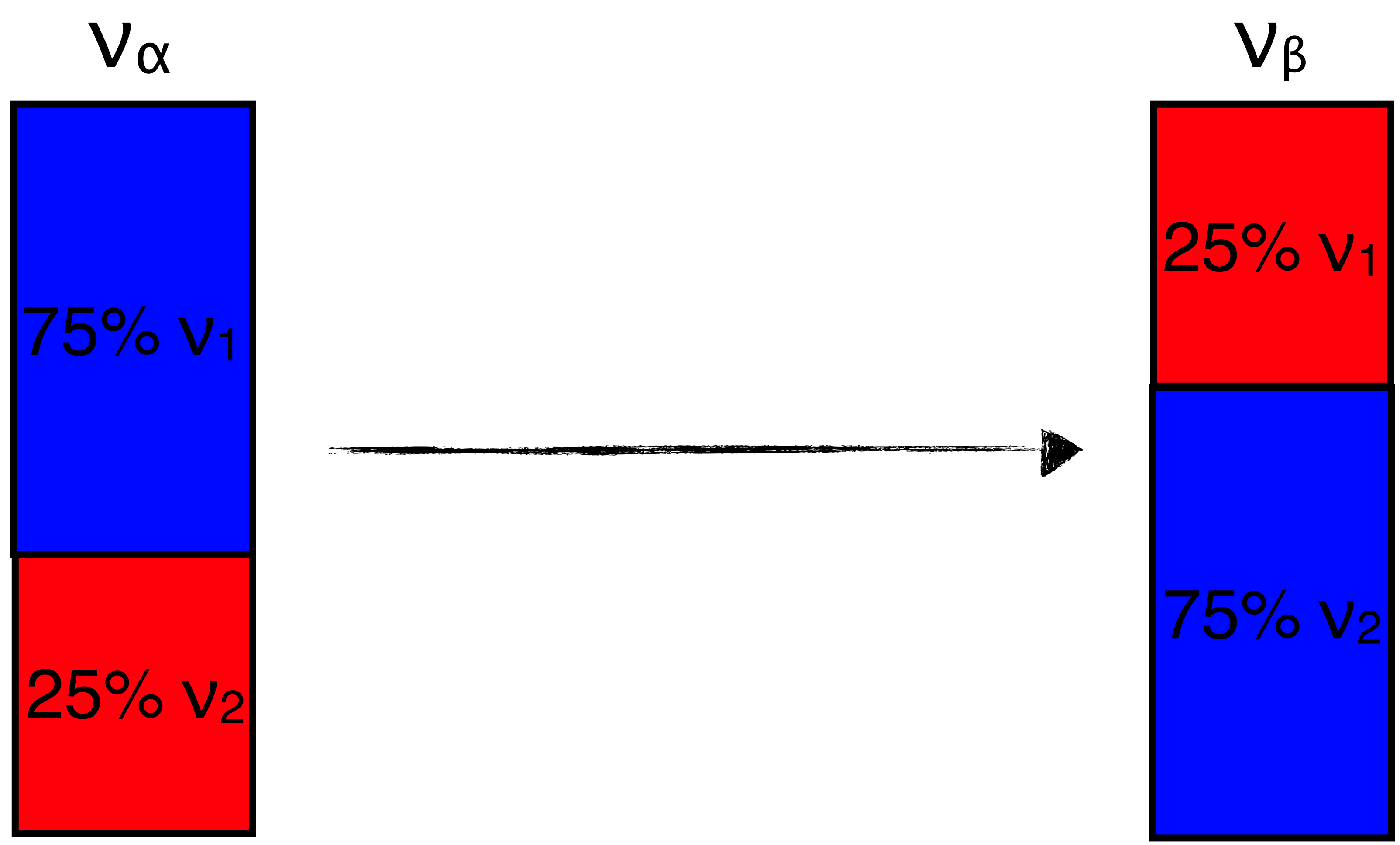
https://astro.desy.de/



Upside: neutrinos are messengers from astrophysical sources and a remnant of the Big Bang (affecting the evolution of the Universe)

Neutrino Oscillations

Neutrinos with a given flavour are a superposition of mass eigenstates



Mass eigenstates propagate with different phases, inducing oscillations

Neutrino Oscillations

Neutrinos produced in flavour states are a superposition of mass states

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

θ = “mixing angle” $\Delta m^2 = m_2^2 - m_1^2$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Oscillations are only possible if neutrinos are massive particles $(\Delta m^2 \neq 0)$

Neutrino Oscillations

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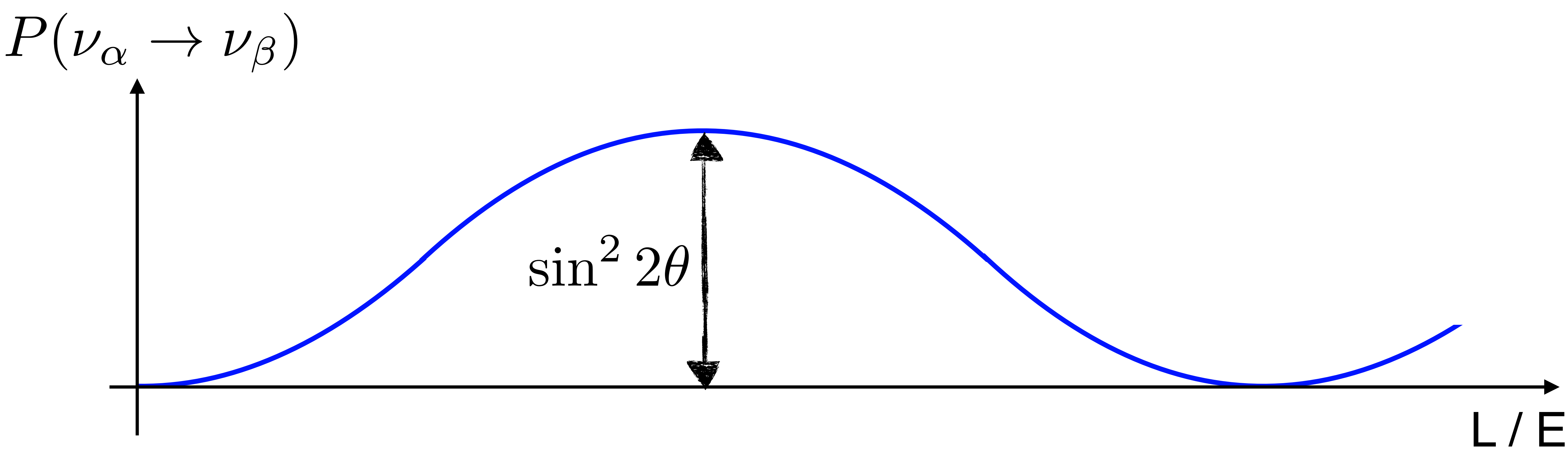

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Neutrino Oscillations

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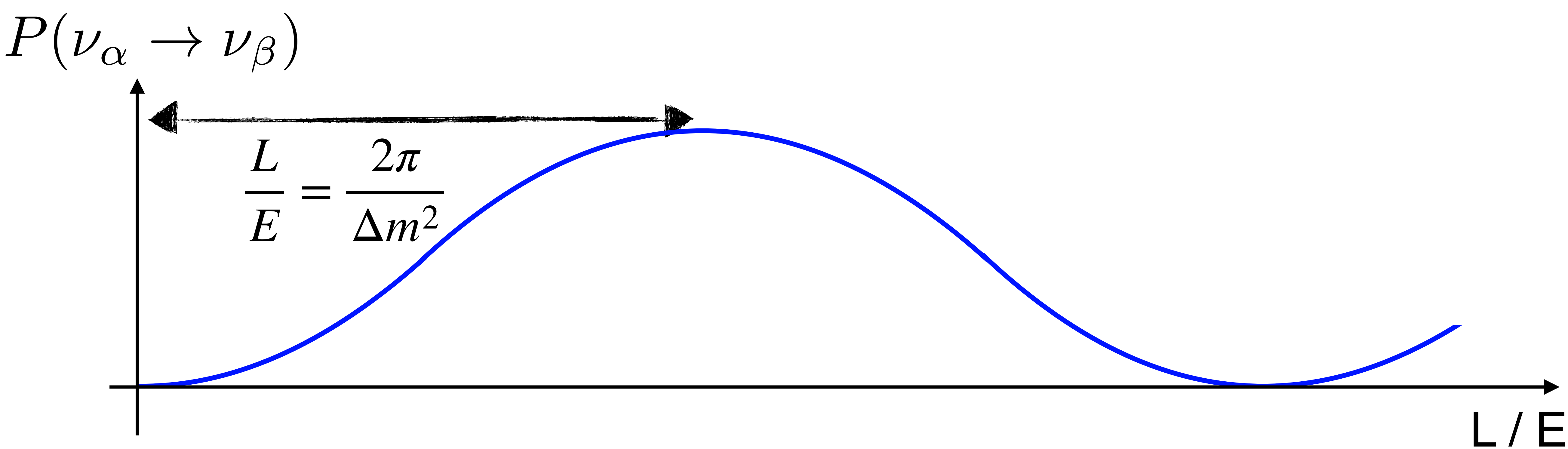

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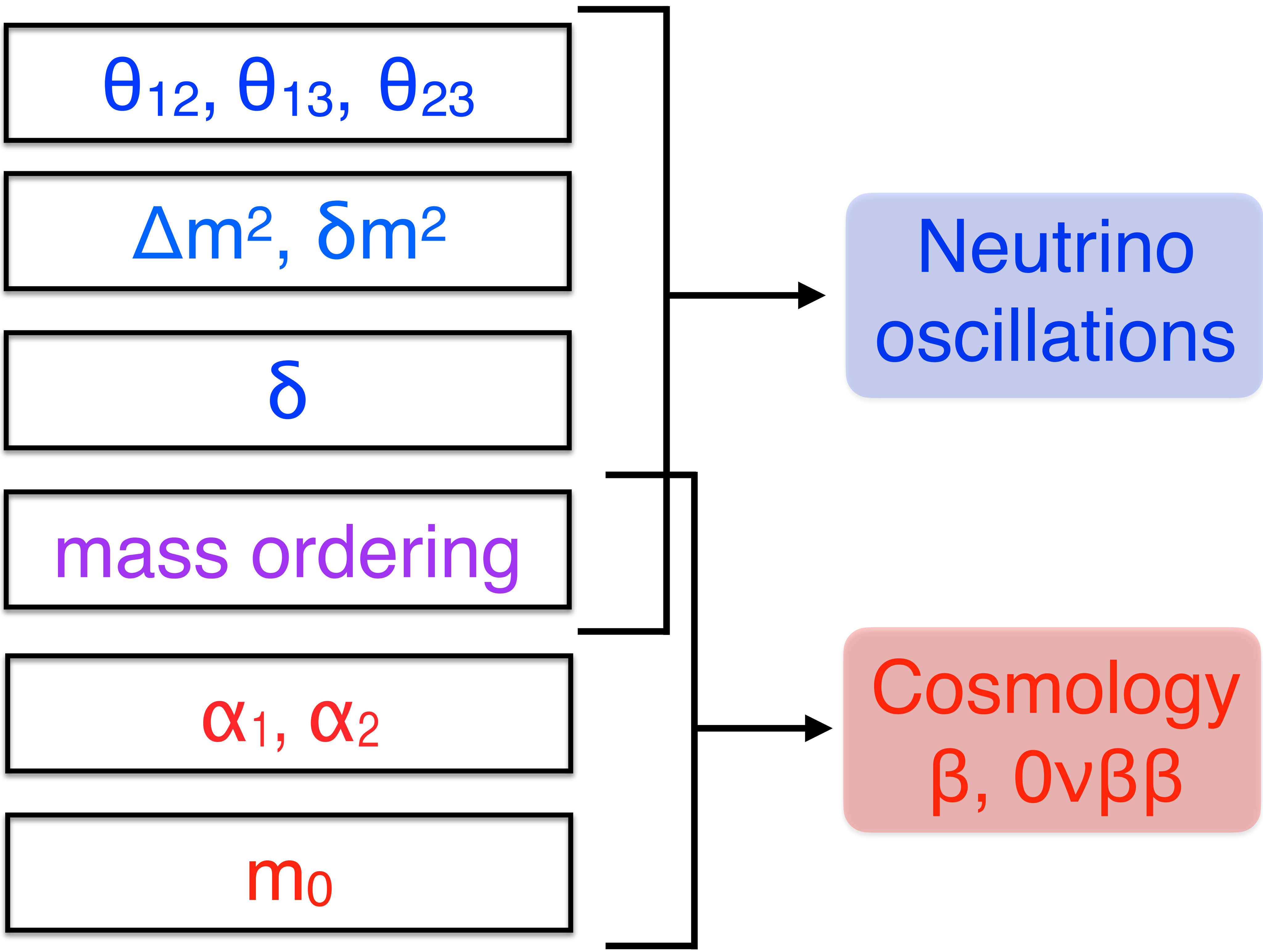
Neutrino Properties

In a 3-neutrino framework we have 10 mass and mixing parameters

$\theta_{12}, \theta_{13}, \theta_{23}$	3 mixing angles
δ	1 Dirac phase
$\Delta m^2, \delta m^2$	2 mass differences $\Delta m^2 = m^2{}_3 - m^2{}_1$ $\delta m^2 = m^2{}_2 - m^2{}_1 > 0$
mass ordering	Normal (NO) if $\Delta m^2 > 0$ Inverted (IO) if $\Delta m^2 < 0$
α_1, α_2	2 Majorana phases (only if $\nu = \overline{\nu}$)
m_0	absolute mass scale

What do we need?

We need oscillation and non-oscillation probes



What do we need?

A Global Analysis gives the best precision and information on unknowns

- θ_{12}, θ_{13}, θ_{23}
- Δm^2, δm^2
- δ
- mass ordering
- α_1, α_2
- m_0

→ **GLOBAL ANALYSIS**

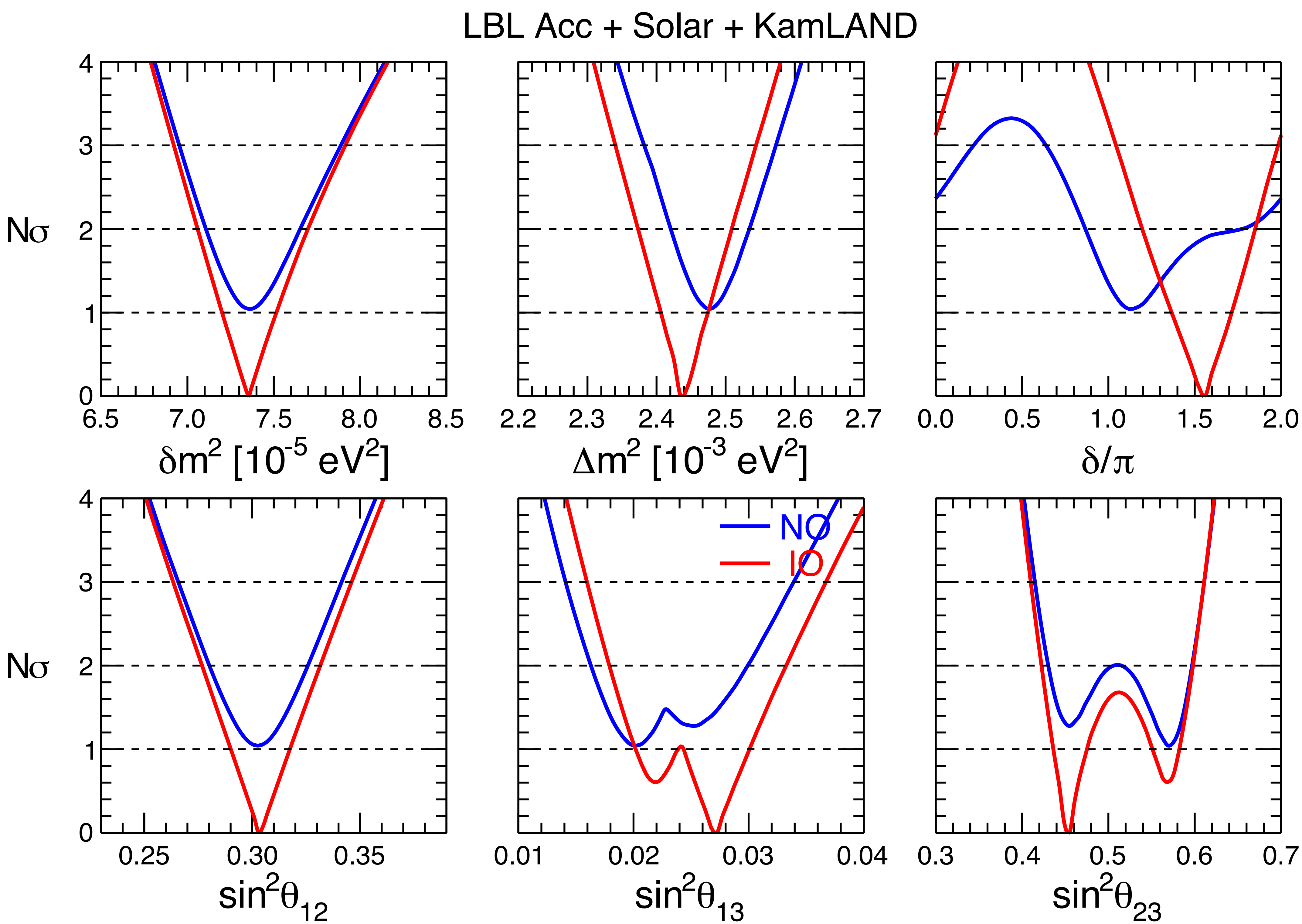
Global analysis of oscillation data

Plethora of experiments: very rich phenomenology

Experiment Type	Oscillation Channel(s)	Sensitive to
Solar (Homestake,Gallex,GNO, Borexino,SNO,SK)	$\nu_e \longrightarrow \nu_e$	$(\theta_{12}, \delta m^2, \theta_{13})$
Long baseline reactors (KamLAND)	$\bar{\nu}_e \longrightarrow \bar{\nu}_e$	$(\theta_{12}, \delta m^2, \theta_{13})$
Long baseline accelerator (T2K, NOvA, MINOS)	$\bar{\nu}_\mu \longrightarrow \bar{\nu}_{\mu,e}$, $\nu_\mu \longrightarrow \nu_{\mu,e}$	$(\theta_{23}, \Delta m^2, \delta, MO, \theta_{13})$

Global analysis of oscillation data

F. Capozzi, E. Di Valentino, E. Lisi, A. Marrone, A. Melchiorri and A. Palazzo, arXiv:2107.00532



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Plethora of experiments: very rich phenomenology

Experiment Type	Oscillation Channel(s)	Sensitive to
Short baseline reactors (Daya Bay, Double Chooz, RENO)	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	$(\theta_{13}, \Delta m^2)$

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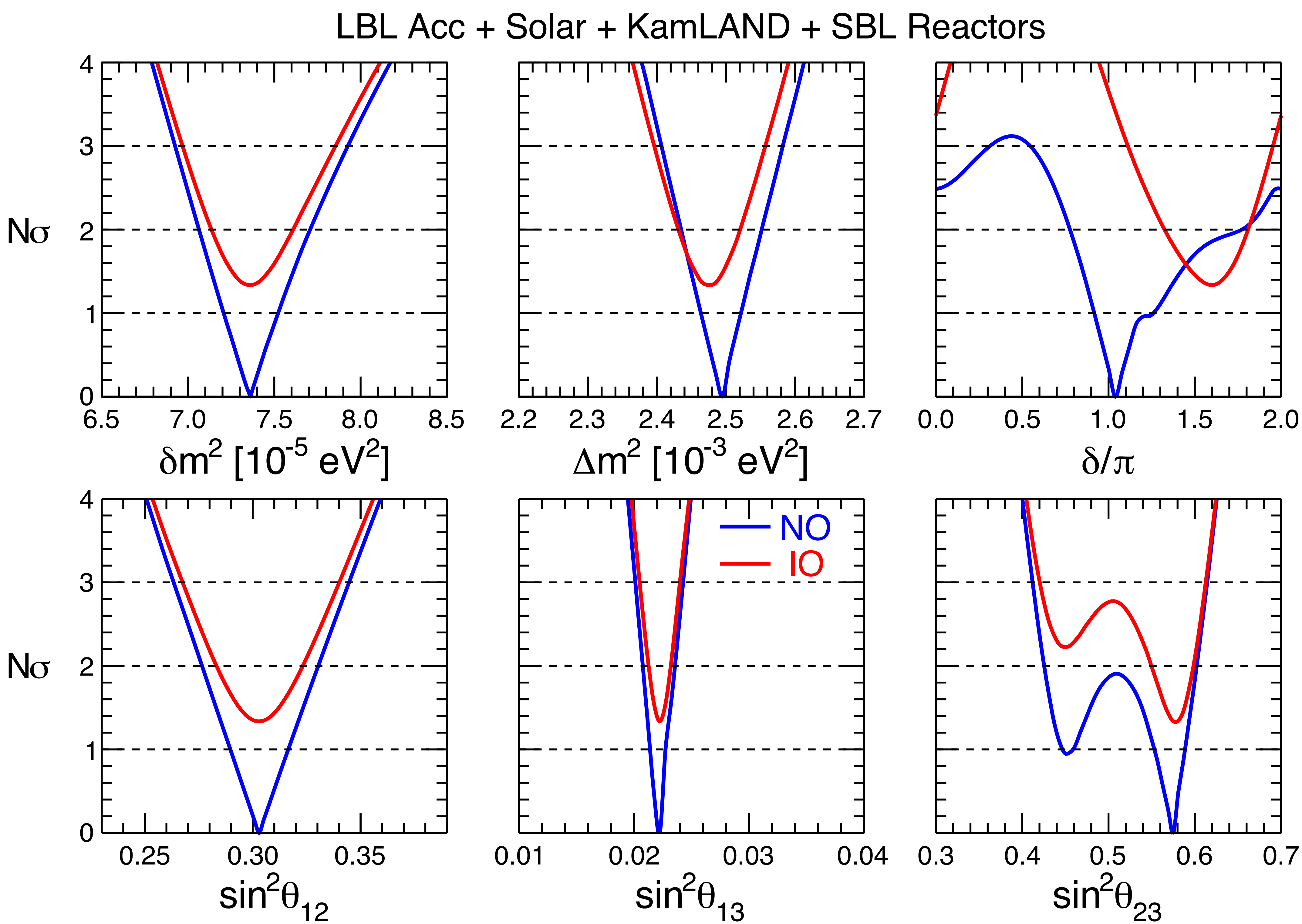

Global analysis of oscillation data

Plethora of experiments: very rich phenomenology

Experiment Type	Oscillation Channel(s)	Sensitive to
Short baseline reactors (Daya Bay, Double Chooz, RENO)	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	(θ_{13}, Δm^2)
Atmospheric (Super-Kamiokande, IceCube-Deepcore)	$\bar{\nu}_\mu \rightarrow \bar{\nu}_{\mu,e}$, $\nu_\mu \rightarrow \nu_{\mu,e}$	(θ_{23}, Δm^2, MO, δ, θ_{13})

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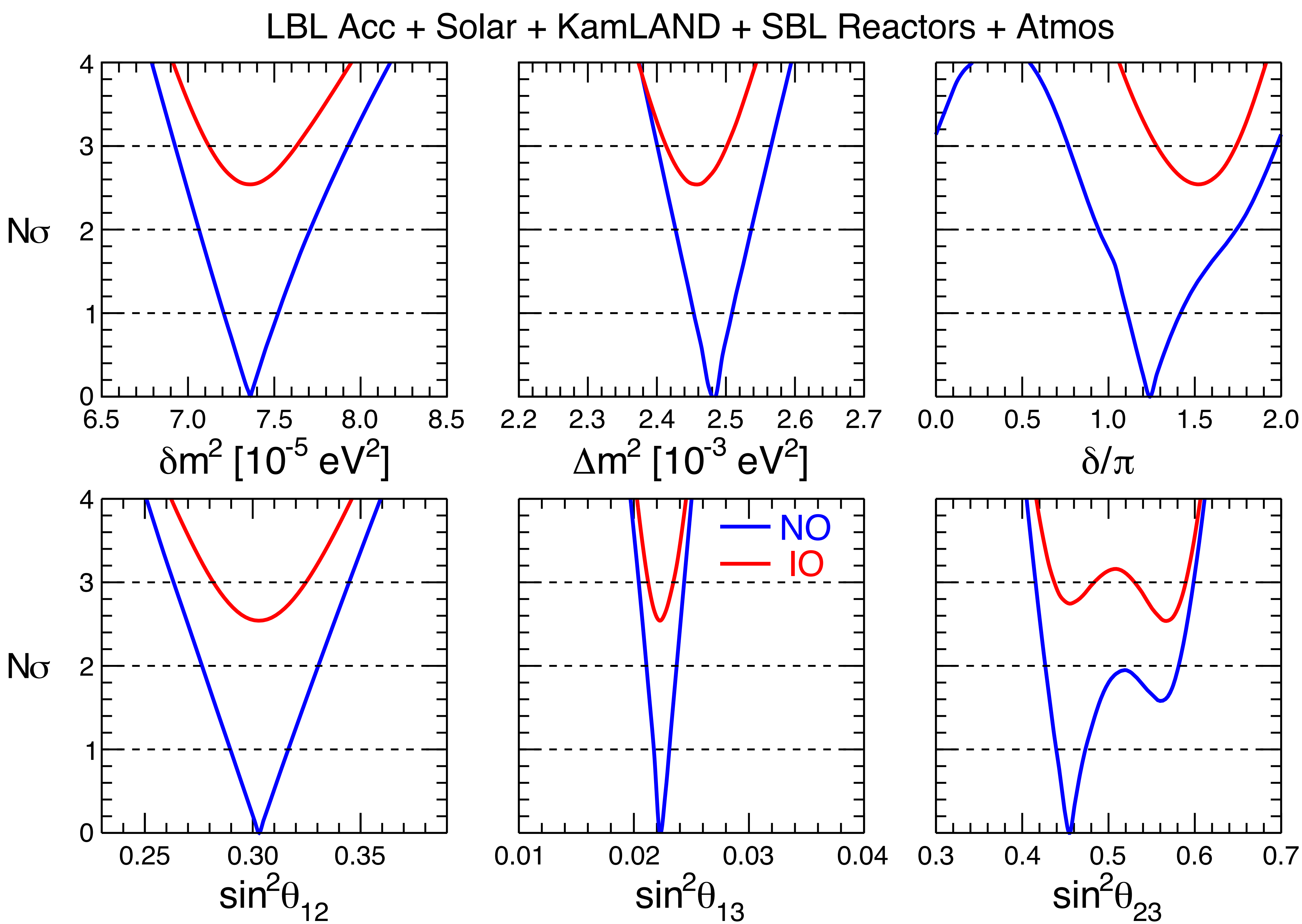

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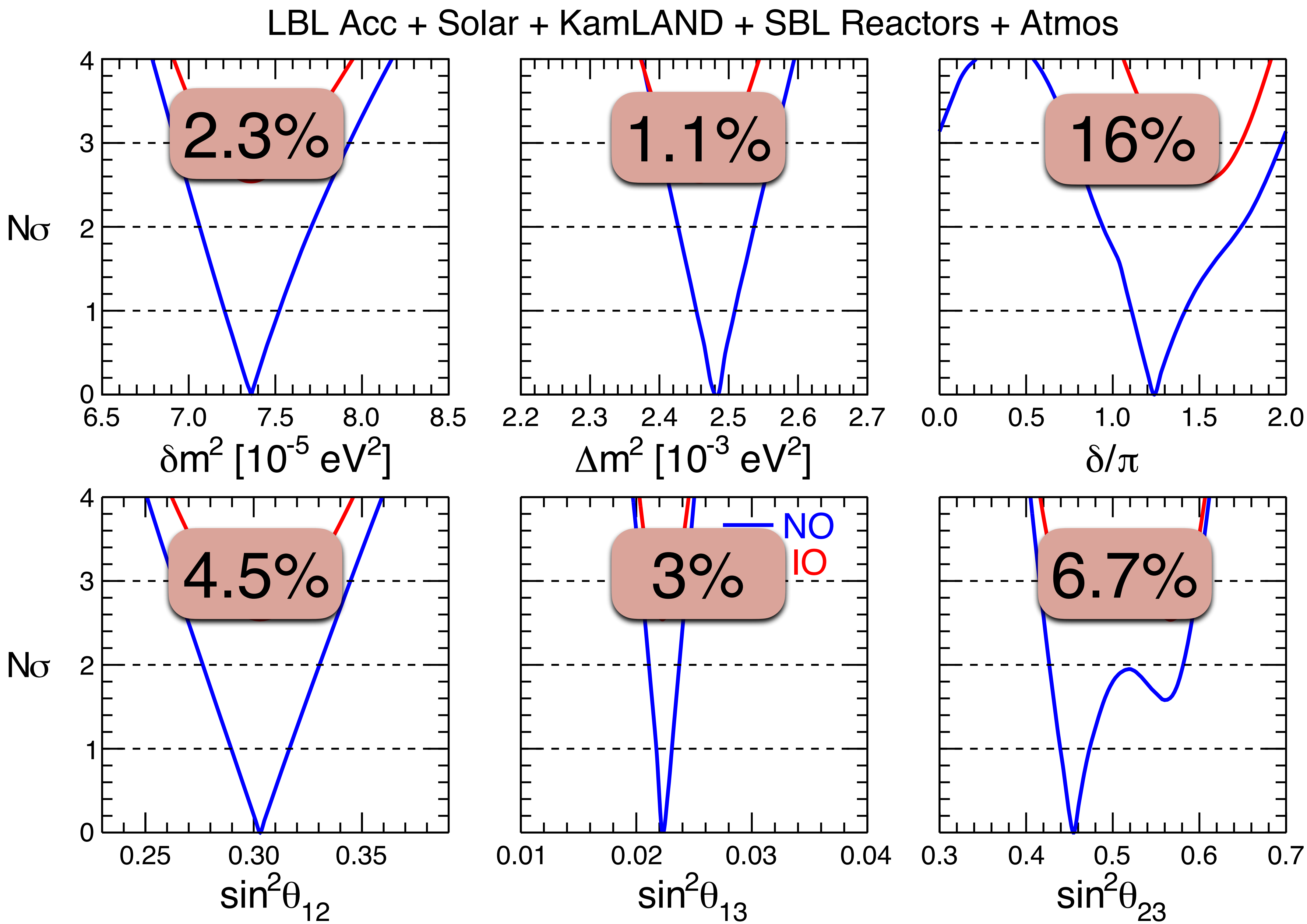

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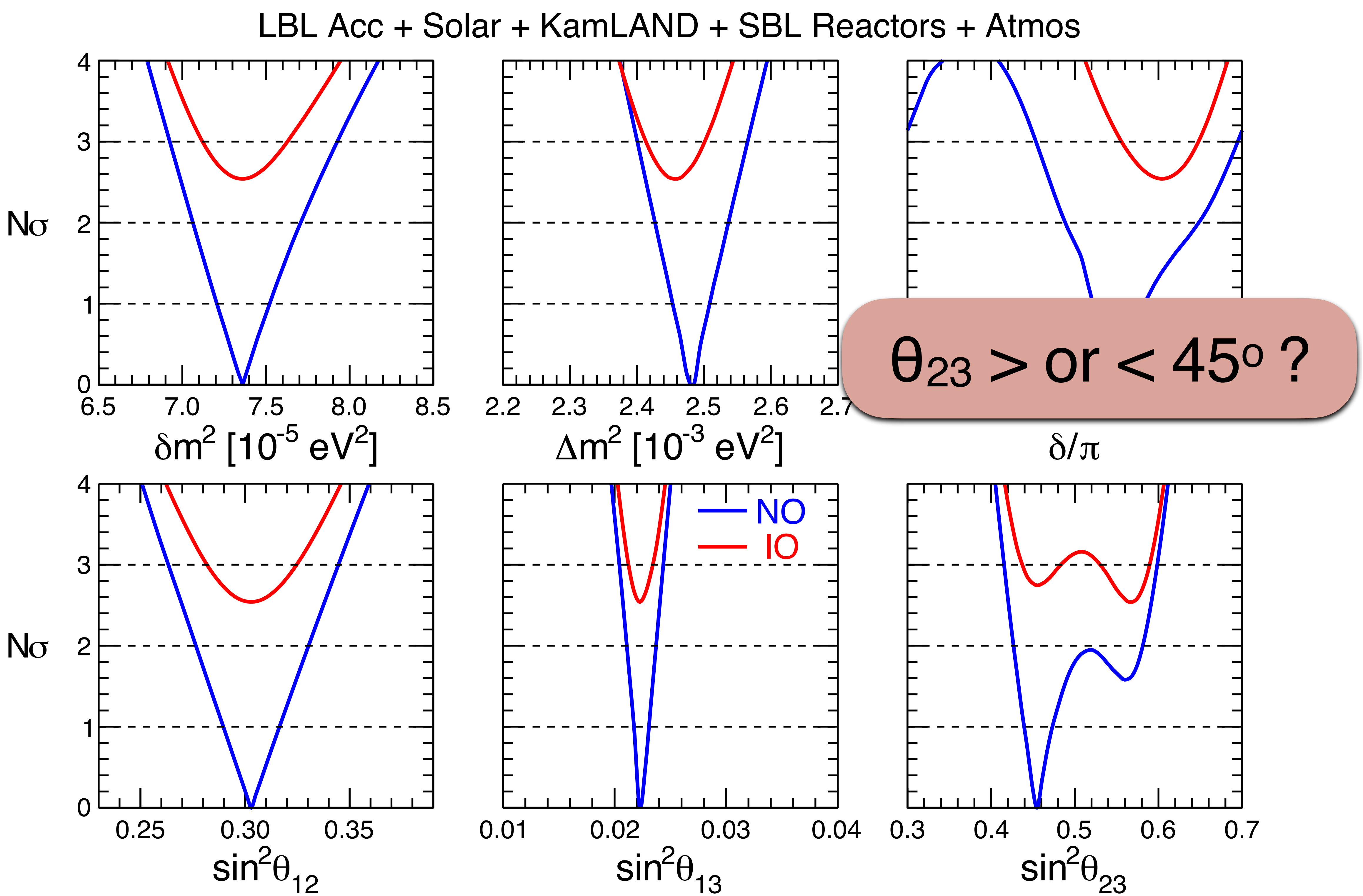

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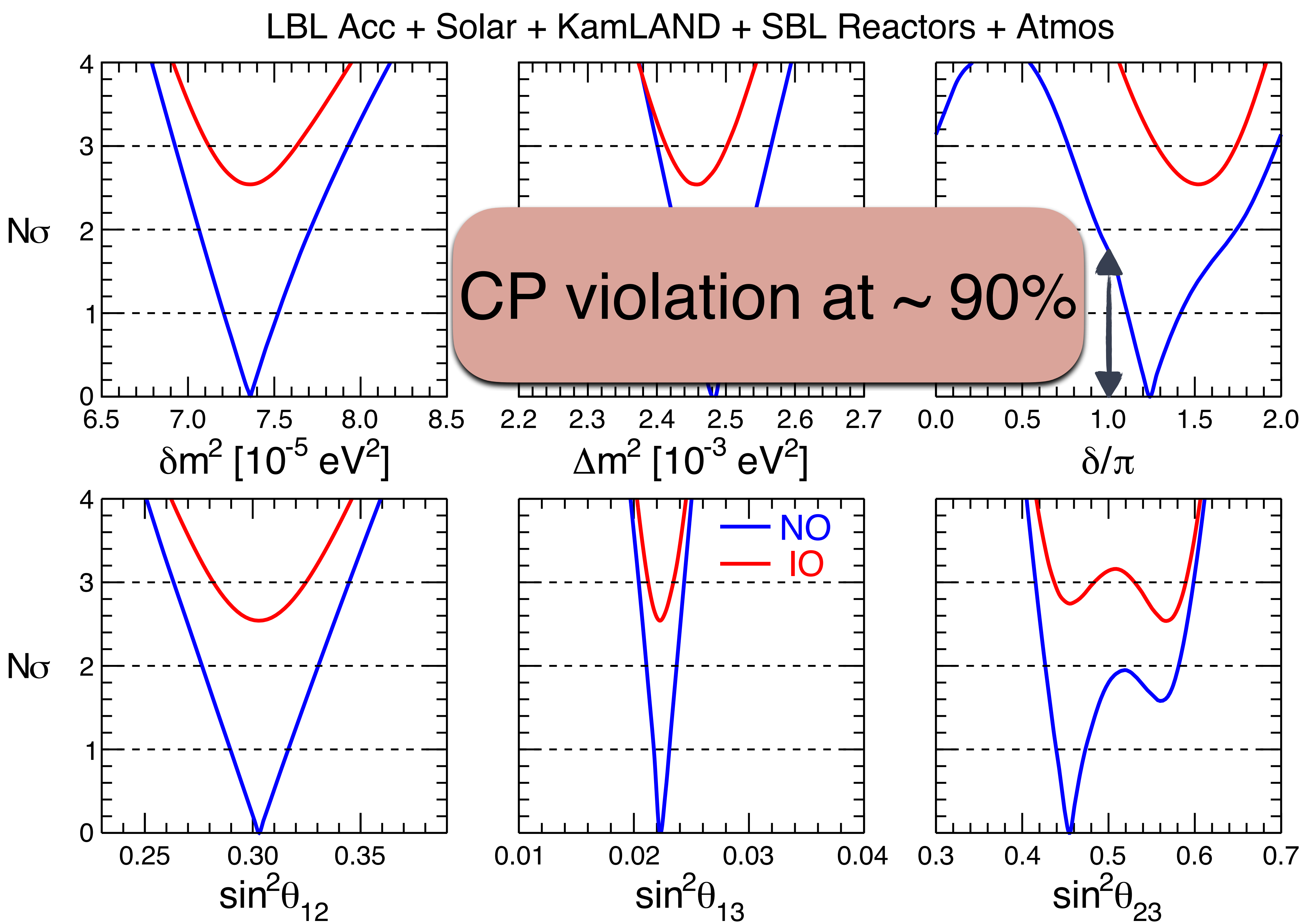

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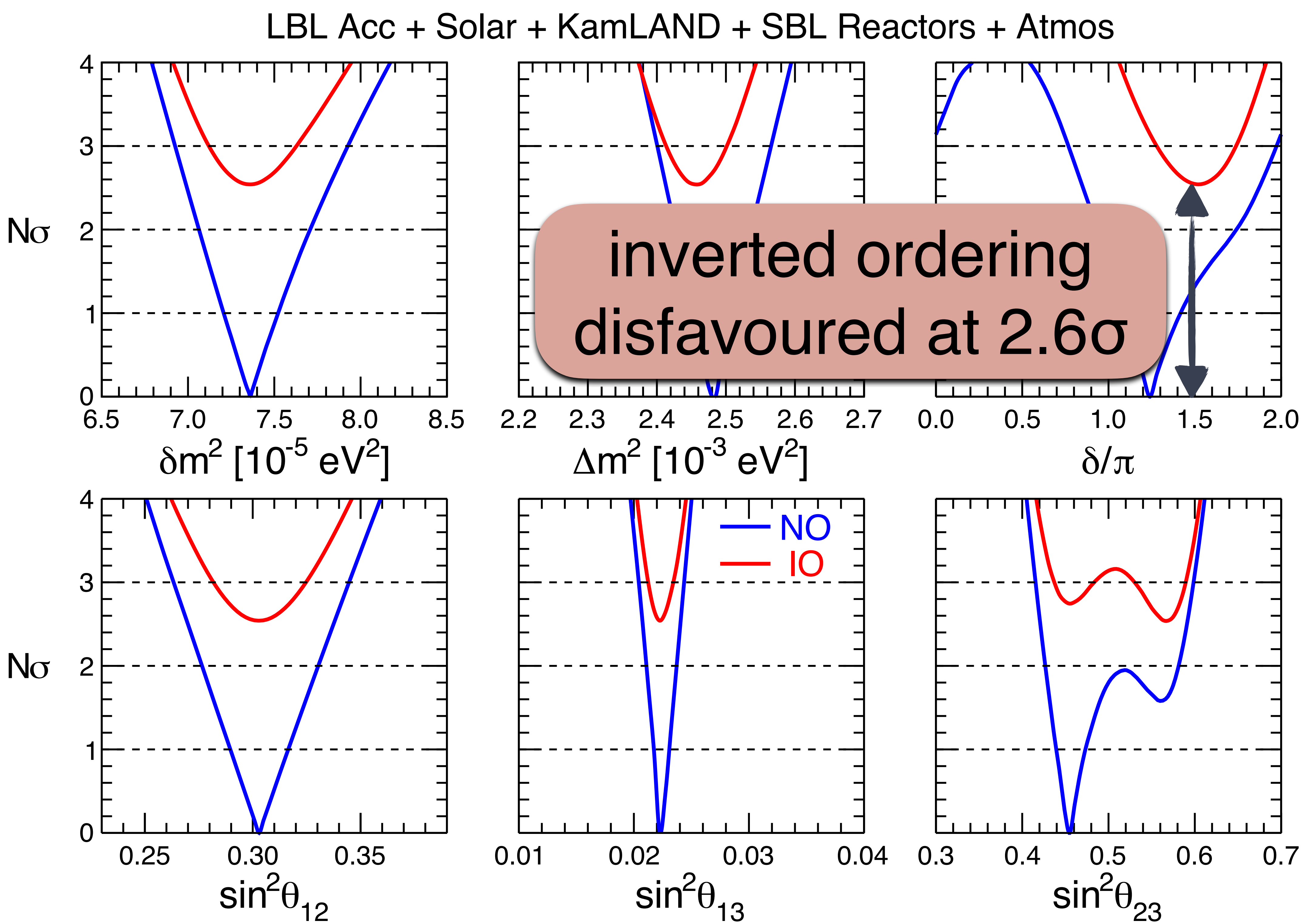


Future challenges and directions

Current and future level of precision creates unprecedented challenges:

Theoretical understanding of all ingredients must be refined

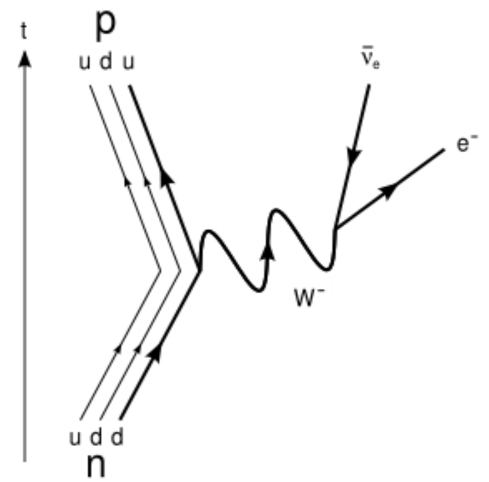
analysis details are becoming too complicated for external pheno groups

common ingredients must be treated in the context of a global analysis (models for cross sections, fluxes, …)

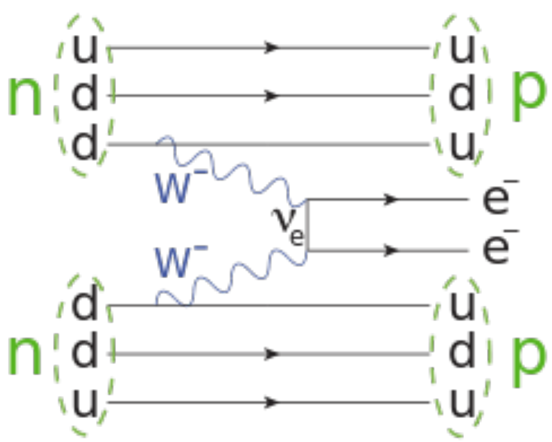
Global analyses will require joint experimental/pheno effort

Non oscillation data

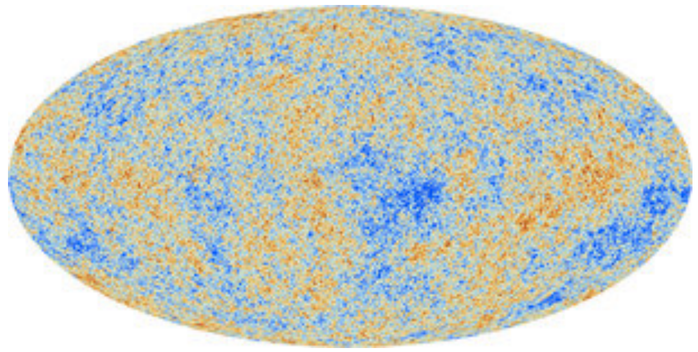
Cosmology, β and 0νββ decays can probe ABSOLUTE neutrino masses:



$$m_\beta^2 = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2$$

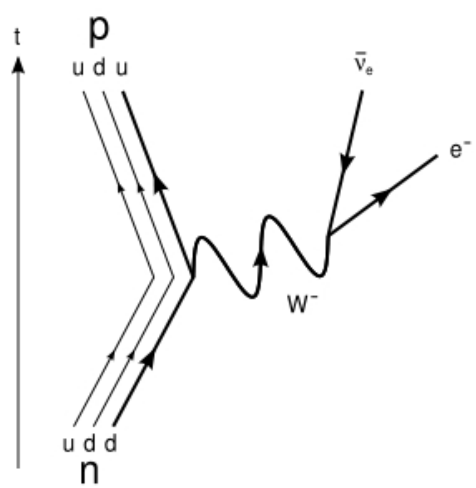


$$m_{\beta\beta} = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$



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

Non oscillation data



$$m_\beta^2 = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2$$

Beta decay with Katrin

M. Aker *et al.* [KATRIN Collaboration], arXiv:2105.08533

$$m_\beta^2 = 0.1 \pm 0.3 \text{ eV}^2$$

Non oscillation data

Neutrinoless double beta decay measures the decay time T of a nucleus

$$\frac{1}{T_i} = G_i\,|M_i|^2\, m_{\beta\beta}^2$$

Nuclide	Experiment(s)
^{76}Ge	GERDA
^{76}Ge	MAJORANA
^{130}Te	CUORE
^{136}Xe	KamLAND-Zen 400
^{136}Xe	KamLAND-Zen 800 prelim.
^{136}Xe	EXO-200

Non oscillation data

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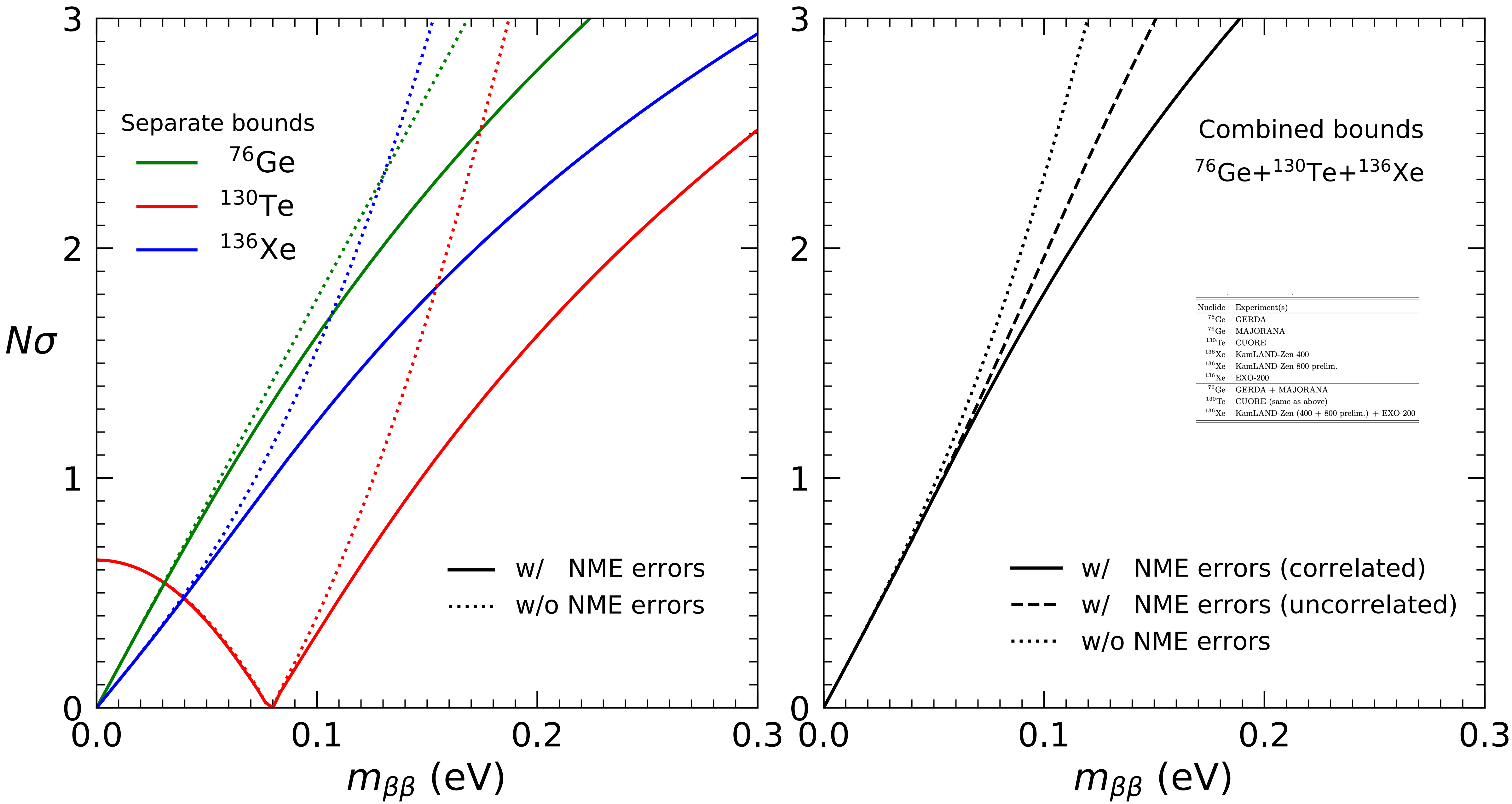

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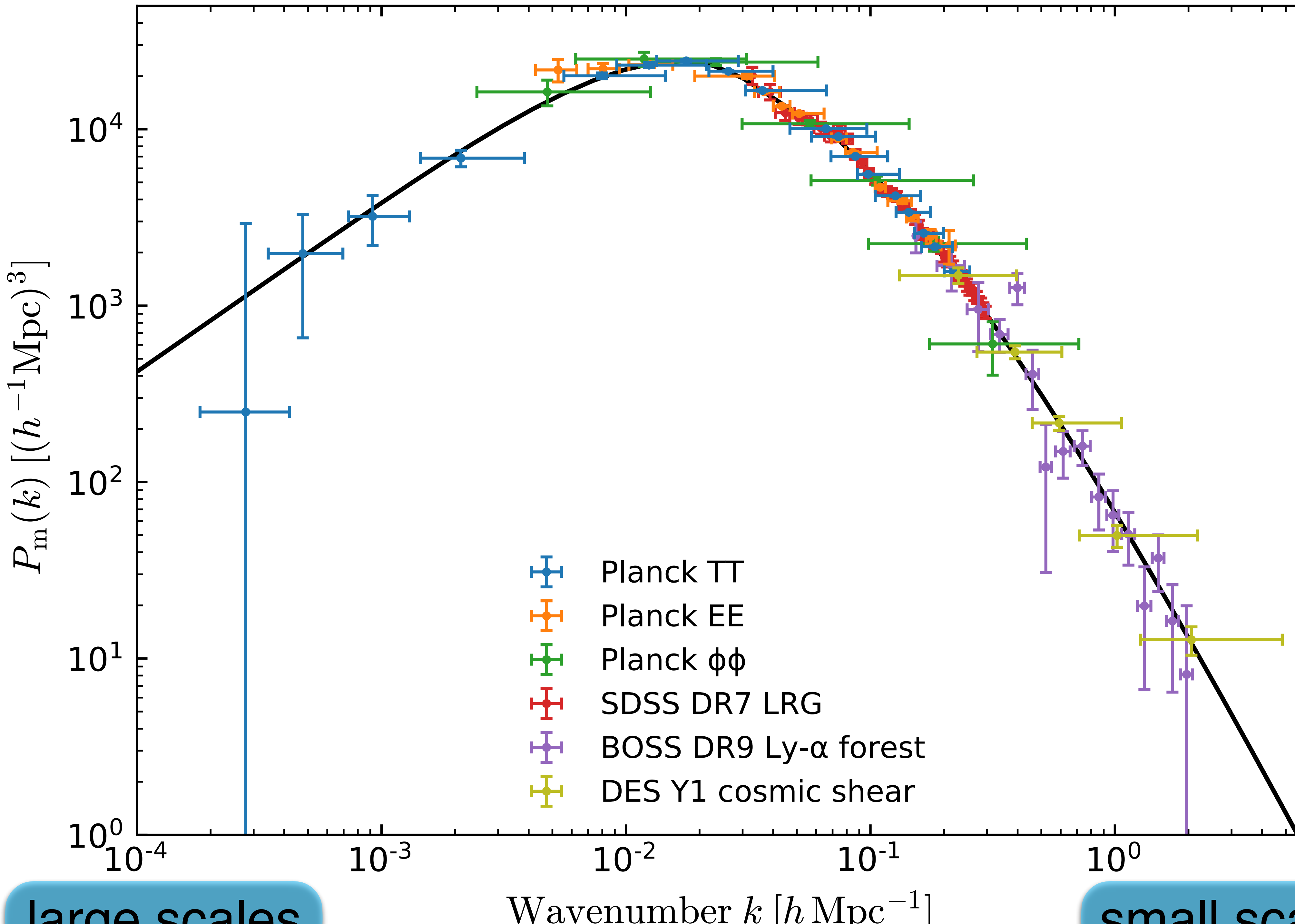
^{76}Ge	MAJORANA
^{130}Te	CUORE
^{136}Xe	KamLAND-Zen 400
^{136}Xe	KamLAND-Zen 800 prelim.
^{136}Xe	EXO-200
^{76}Ge	GERDA + MAJORANA
^{130}Te	CUORE (same as above)
^{136}Xe	KamLAND-Zen (400 + 800 prelim.) + EXO-200

Nuclear matrix elements correlations are important

Non oscillation data

Cosmology probe sum of neutrino masses Σ: e.g. matter power spectrum

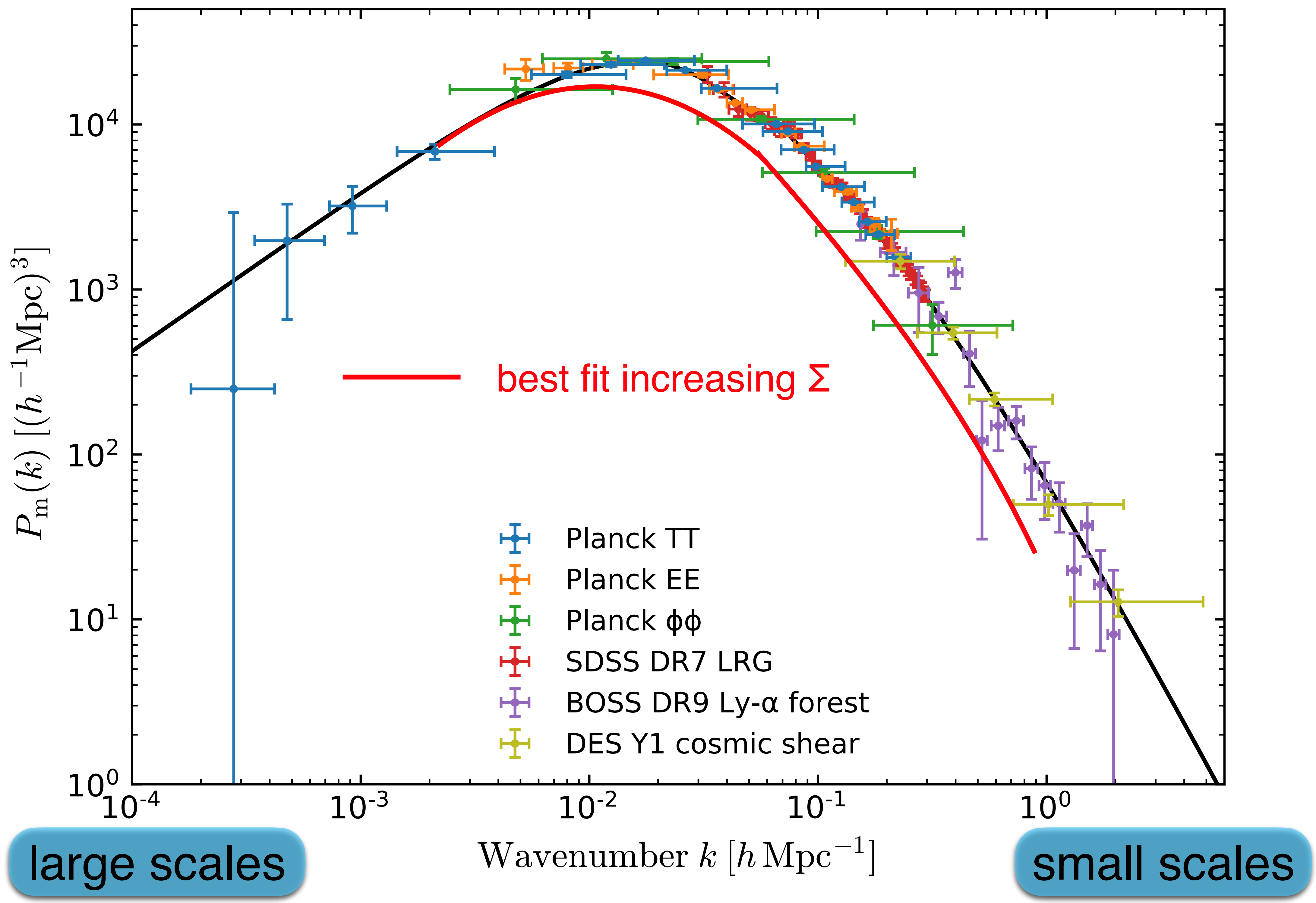


large scales

small scales

Non oscillation data

Cosmology probe neutrino masses



Non oscillation data

Cosmological inputs for nonoscillation data analysis			Results: Cosmo only		Cosmo + m_β + $m_{\beta\beta}$	
#	Model	Data set	Σ (2σ)	$\Delta\chi^2_{\mathrm{IO-NO}}$	Σ (2σ)	$\Delta\chi^2_{\mathrm{IO-NO}}$
0	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT, TE, EE	< 0.34 eV	0.9	< 0.32 eV	1.0
1	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT, TE, EE + lensing	< 0.30 eV	0.8	< 0.28 eV	0.9
2	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT, TE, EE + BAO	< 0.17 eV	1.6	< 0.17 eV	1.8
3	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT, TE, EE + BAO + lensing	< 0.15 eV	2.0	< 0.15 eV	2.2
4	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT, TE, EE + lensing + H_0(R19)	< 0.13 eV	3.9	< 0.13 eV	4.0
5	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT, TE, EE + BAO + H_0(R19)	< 0.13 eV	3.1	< 0.13 eV	3.2
6	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT, TE, EE + BAO + lensing + H_0(R19)	< 0.12 eV	3.7	< 0.12 eV	3.8
7	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT, TE, EE + lensing	< 0.77 eV	0.1	< 0.66 eV	0.1
8	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT, TE, EE + BAO	< 0.31 eV	0.2	< 0.30 eV	0.3
9	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT, TE, EE + BAO + lensing	< 0.31 eV	0.1	< 0.30 eV	0.2

CHALLENGE: tensions between different datasets (Hubble, lensing)

Non oscillation data

Cosmological inputs for nonoscillation data analysis			Results: Cosmo only		Cosmo + m_β + $m_{\beta\beta}$	
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9	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT, TE, EE + BAO + lensing	< 0.31 eV	0.1	< 0.30 eV	0.2

A possibility is considering less constraining but consistent datasets

10	$\Lambda\mathrm{CDM}+\Sigma$	ACT + WMAP + τ_{prior}	< 1.21 eV	−0.1	< 1.00 eV	0.1
11	$\Lambda\mathrm{CDM}+\Sigma$	ACT + WMAP + Planck lowE	< 1.12 eV	−0.1	< 0.87 eV	0.1
12	$\Lambda\mathrm{CDM}+\Sigma$	ACT + WMAP + Planck lowE + lensing	< 0.96 eV	0.0	< 0.85 eV	0.1

Non oscillation data

Cosmological inputs for nonoscillation data analysis			Results: Cosmo only		Cosmo + m_β + $m_{\beta\beta}$	
#	Model	Data set	Σ (2σ)	$\Delta\chi^2_{\rm IO-NO}$	Σ (2σ)	$\Delta\chi^2_{\rm IO-NO}$
0	ΛCDM + Σ	Planck TT, TE, EE	< 0.34 eV	0.9	< 0.32 eV	1.0
1	ΛCDM + Σ	Planck TT, TE, EE + lensing	< 0.30 eV	0.8	< 0.28 eV	0.9
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7	ΛCDM + Σ + $A_{\rm lens}$	Planck TT, TE, EE + lensing	< 0.77 eV	0.1	< 0.66 eV	0.1
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9	ΛCDM + Σ + $A_{\rm lens}$	Planck TT, TE, EE + BAO + lensing	< 0.31 eV	0.1	< 0.30 eV	0.2
10	ΛCDM + Σ	ACT + WMAP + $\tau_{\rm prior}$	< 1.21 eV	−0.1	< 1.00 eV	0.1
11	ΛCDM + Σ	ACT + WMAP + Planck lowE	< 1.12 eV	−0.1	< 0.87 eV	0.1
12	ΛCDM + Σ	ACT + WMAP + Planck lowE + lensing	< 0.96 eV	0.0	< 0.85 eV	0.1

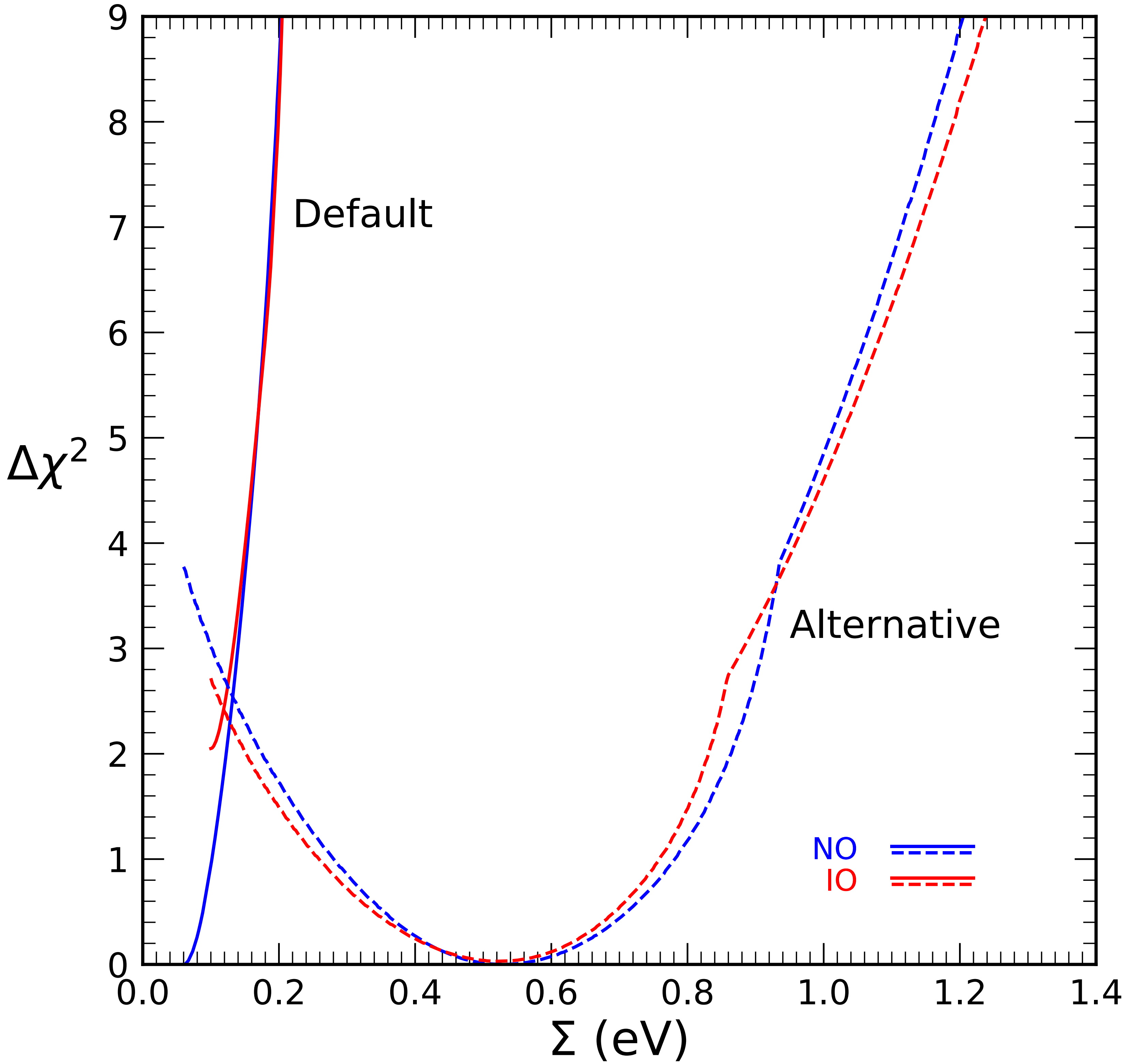
DEFAULT (row 3)

A possibility is considering less constraining but consistent datasets

ALTERNATIVE (row 12)

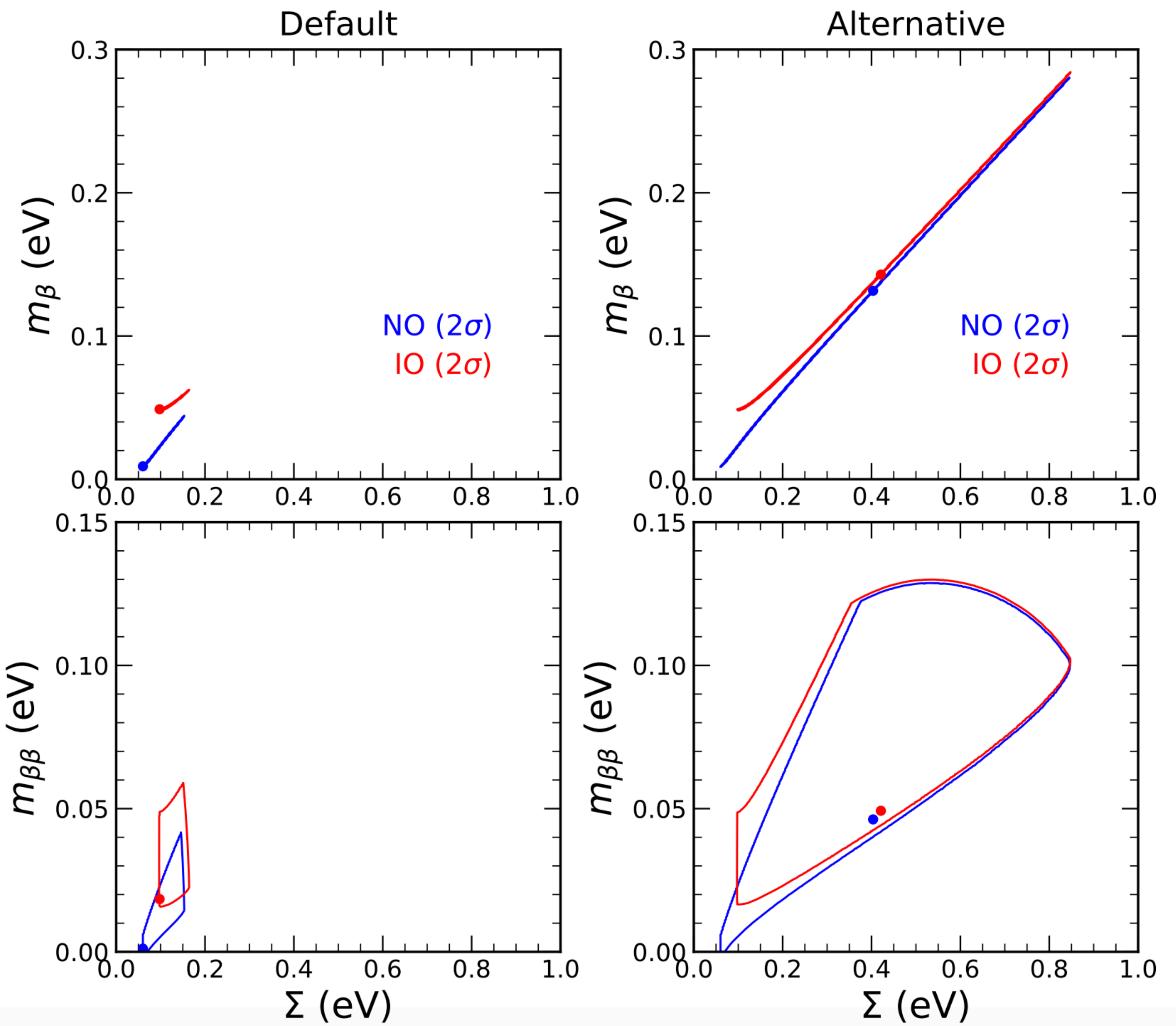
Non oscillation data

F. Capozzi, E. Di Valentino, E. Lisi, A. Marrone, A. Melchiorri and A. Palazzo, arXiv:2107.00532



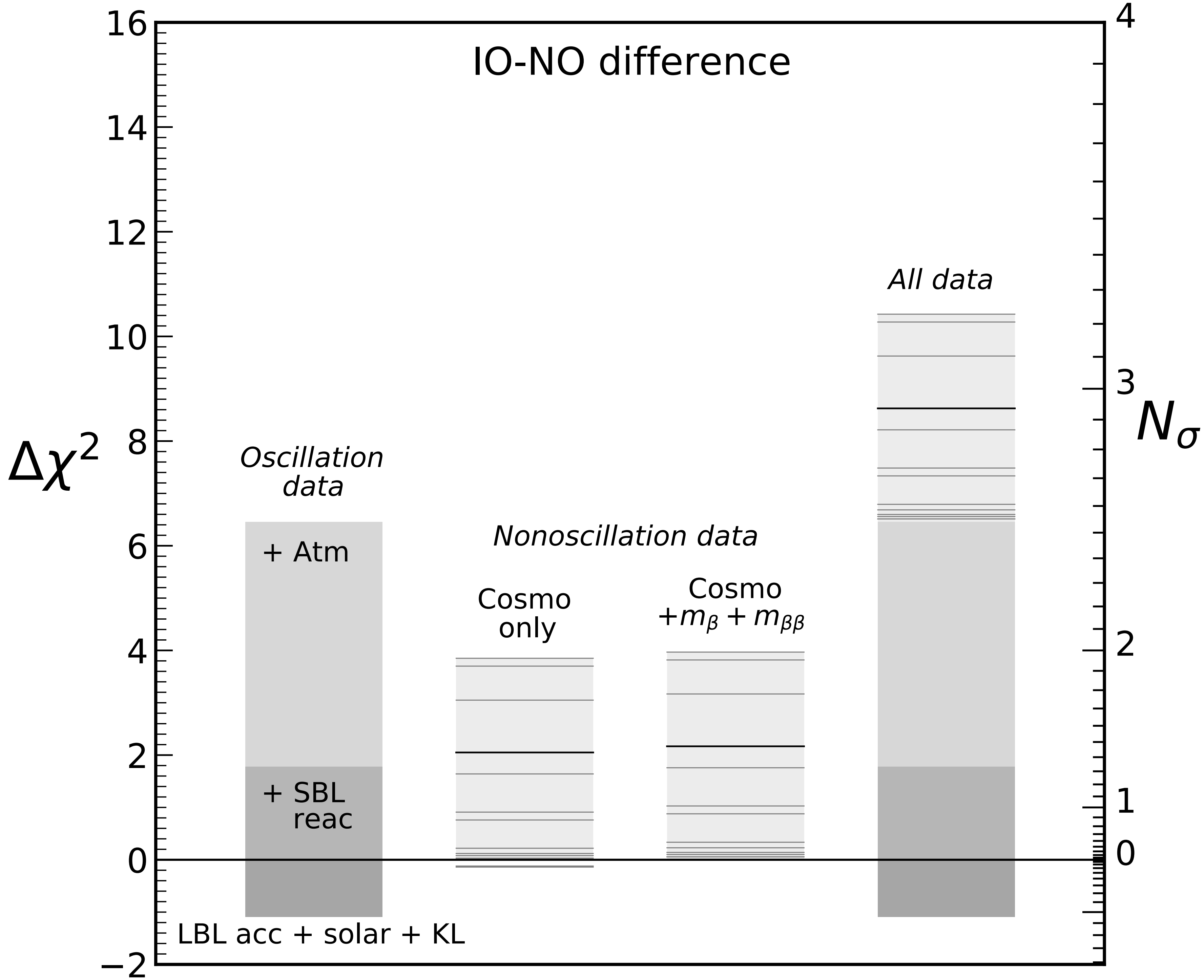
Global analysis

Let us combine oscillation and non-oscillation data



Σ can be constrained down to < 0.15 eV, $m_{\beta\beta}$ < 0.05 eV

Global analysis



Preference for NO can go up to 3.4σ with “aggressive” cosmological data

Conclusions

- Neutrino mass differences and mixing angles known at few % precision

- Parameters not completely known: δ, mass ordering, θ_{23}, absolute mass

- 90% hint for CP violation

- 2/3σ hint in favor of normal ordering, depending on cosmological dataset

- Entering precision era for both oscillation and absolute neutrino masses. Analysis are becoming extremely complicated (correlated uncertainties, tensions among data sets, ecc…)