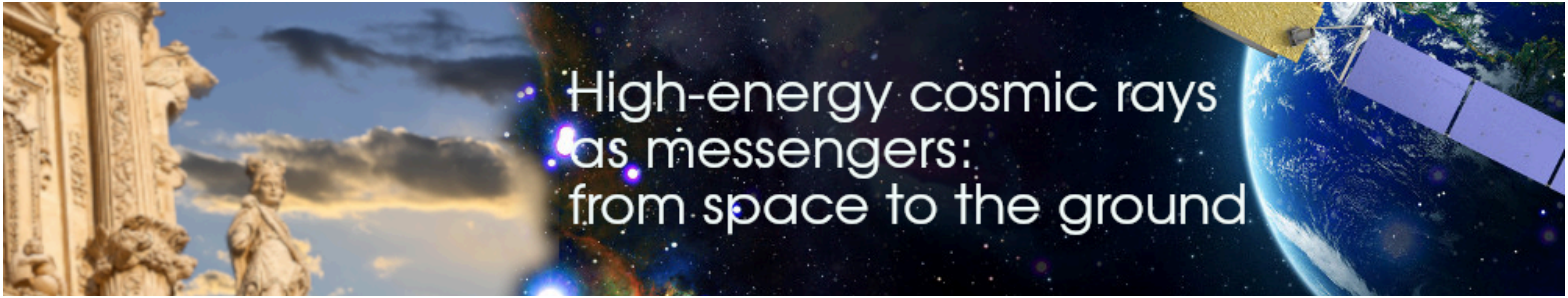
Neutrino Physics

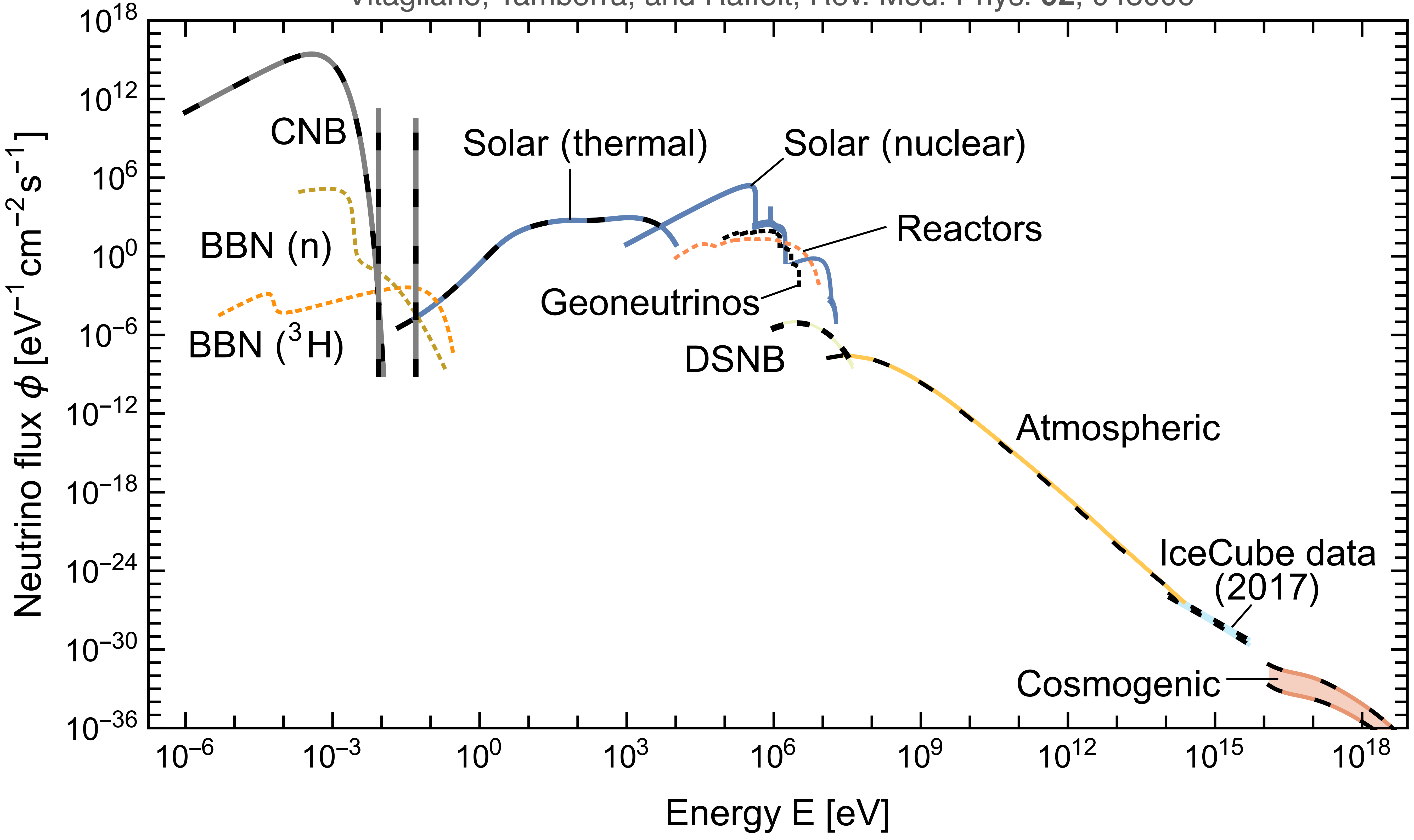
Antonio Marrone



The Neutrino World ...

Because of their weak interaction neutrinos tend to preserve the memory of the energy they have wen they are produced

Vitagliano, Tamborra, and Raffelt, Rev. Mod. Phys. **92**, 045006



Over ~24 orders of magnitude for their energy and ~50 for the flux

Probe many different fields of Physics and require many different experimental approaches

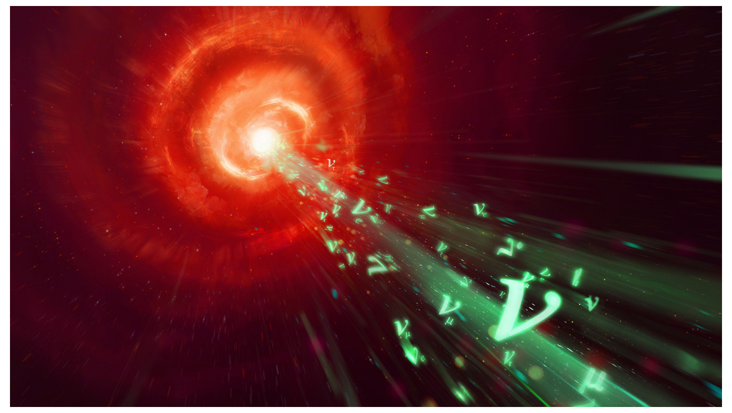
"Croce e Delizia" of Neutrino Physics

Thanks to this "ubiquity" of neutrinos they allow us to investigate extremely different environments from the Early Universe to the interior of the Sun or the Earth or to the structure of a Nucleus

The investigation of these environments is all the more precise the more the ν properties and interactions are known. Viceversa, the properties of neutrinos can be reconstructed if we know the properties of their source and their interactions in the detector

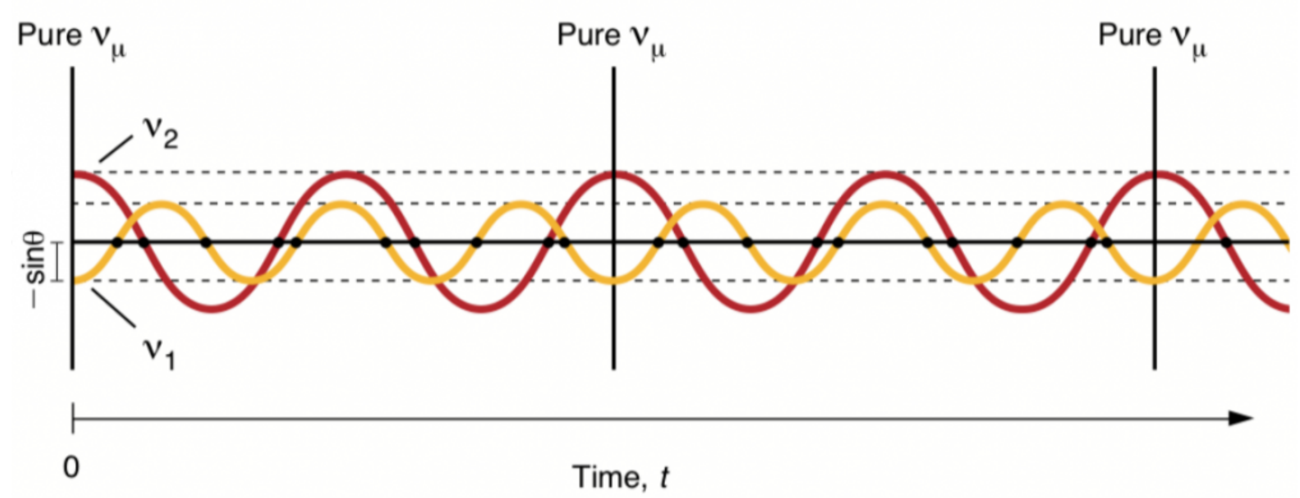
Therefore, the story of nearly every experiment on neutrinos is a story of a dualistic progress of knowledge

Source



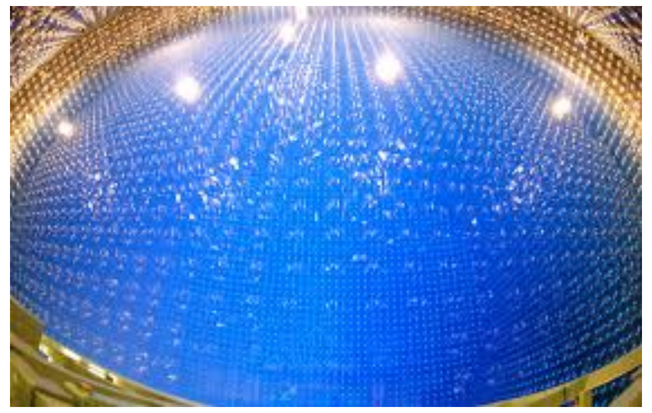
Informations on the source, on the production mechanism and on ν properties

Propagation



Informations on the propagation medium and on ν oscillations

Detection



Informations on the structure of the target and on ν properties

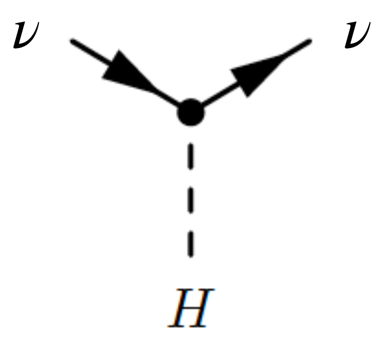
Oscillations → Neutrino masses → new mass terms for neutrinos must be added to $\mathscr{L}_{SM}$

Chiral fermions are the building blocks of the SM and for its extensions since they are smallest irreducible representations of the Lorentz group

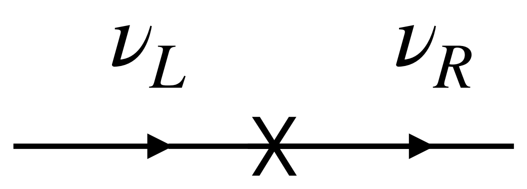
Dirac mass terms $\overline{\psi}\psi = \overline{\psi}_L\psi_R + \overline{\psi}_R\psi_L$ (via the Higgs mechanism) would require the existence of a Dirac field ν_R

$$g(\overline{\nu}_R\nu_L + h.c.)H$$

Lepton Number conserved because ν and $\overline{\nu}$ have opposite lepton number



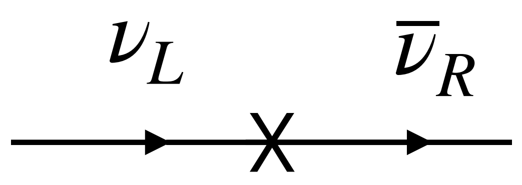
or



While ν_L has left chirality $(\nu_L)^c$ are right-handed

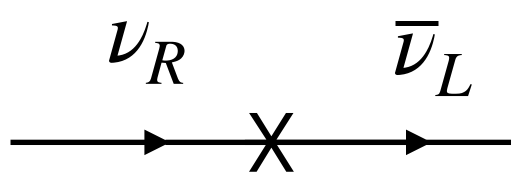
→ mass terms like $m_L\overline{(\nu_L)^c}\nu_L$ or $m_R\overline{(\nu_R)^c}\nu_R$

$m_L\overline{(\nu_L)^c}\nu_L$



Lepton Number violated by two units

$m_R\overline{(\nu_R)^c}\nu_R$



Lepton Number violated by two units

Majorana particles are their own antiparticles $\psi = \psi^c$

With $f = \nu_L + (\nu_L)^c$ (the SM neutrino) and $F = \nu_R + (\nu_R)^c$ (a new neutrino field) the two previous mass term (and their h.c.) can be written as $m_L\bar{f}f + m_R\overline{F}F$

After symmetry breaking the neutrino mass will be proportional to the Higgs VEV

First possibility (Minimally Extended Standard Model) —> Dirac mass term

A new field ν_R is introduced, one for each generation, as for charged fermions, but with a Yukawa coupling $\lesssim 10^{-6}$ smaller than the lepton in the same doublet

Flavor Lepton Numbers violated because it is not possible to find any transformation of the ν_R leaving invariant the Yukawa sector and the kinetic part of the Lagrangian —> Oscillations

Since fermions are intrinsically two-component objects, a massive Dirac neutrino could be related to some new symmetry. One could assume global lepton number conservation directly or could impose some new extended flavour symmetry that implies the conservation of lepton number

(see for instance Aranda, Bonilla, Morisi, Peinado, and Valle, Phys. Rev. D 89, 033001 (2014))

The number of sterile right-handed neutrino fields is not constrained by the theory nor it is their mass

Second possibility, ν as Majorana particles —> Majorana mass term

A Majorana mass term in the SM violates the gauge symmetry (it would require the existence of a triplet with weak isospin I= 1 and hypercharge Y=2)

Therefore, Majorana mass terms will be non-renormalizable
The lowest dimension mass term (the dimension-5 Weinberg operator) is of the kind $\frac{1}{\Lambda}\overline{(\nu)^c}\nu HH$, where Λ is some new, large, unknown scale.

There is also the possibility of both Majorana and Dirac mass terms

Dirac	Majorana Left	Majorana Right
$m_D\bar{\nu}_R\nu_L$	$m_L\overline{(\nu_L)^c}\nu_L$	$m_R\overline{(\nu_R)^c}\nu_R$

By introducing the doublet $N_L = \begin{pmatrix} \nu_L \\ (\nu_R)^c \end{pmatrix}$

the more general mass term in the Lagrangian will be $\overline{N_L}\begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix} N_L$

The most popular and simple mechanism to produce a small observable neutrino mass is the Seesaw mechanism —>

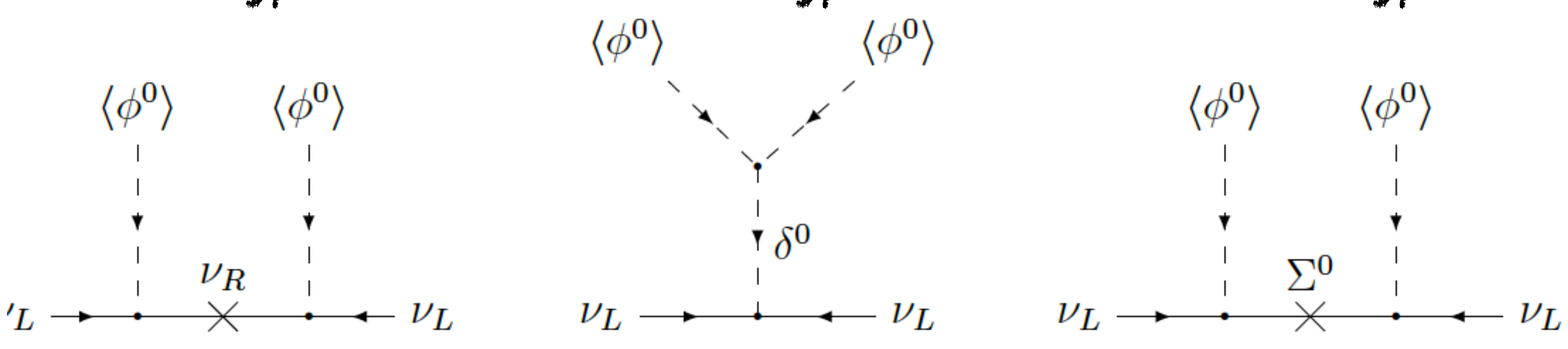
Seesaw Mechanism

With $m_L = 0$ and $m_R \gg m_D$, by diagonalising the mass matrix one gets two eigenvalues

$m \sim \frac{m_D^2}{m_R}$ Light Majorana neutrino

$M \sim m_R$ Heavy sterile Majorana neutrino

Seesaw Type-I | Seesaw Type-II | Seesaw Type-III



(a) seesaw type-I **(b)** seesaw type-II **(c)** seesaw type-III

Tree-level Feynman diagrams for the Weinberg operator

All seesaw models are connected to the effective dim.-5 Weinberg operator but realised through different intermediate heavy particles that are not experimentally observed

Type-I seesaw -> right-handed neutrino

Type-II seesaw -> scalar $SU(2)_L$ triplet $(\delta^0, \delta+, \delta^{++})$

Type-III seesaw -> fermionic $SU(2)_L$ triplet $(\Sigma^0, \Sigma+, \Sigma^-)$

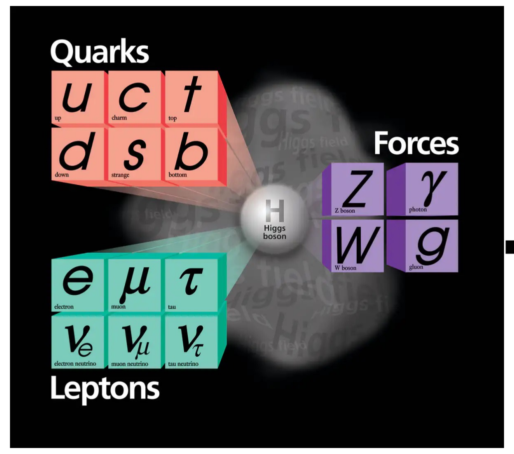
for a review see: Miranda and Valle, Nuclear Physics B 908 (2016) 436–455 and Agostini, arXiv:2202.01787

There is also a vaste class of theories where neutrino masses arise from loop realisations of the Weinberg operator -> heavy particles could be "less heavy" and therefore also at the TeV scale and detectable at present or future colliders

see for instance S. F. King, A. Merle, and L. Panizzi, JHEP, 11, p. 124, (2014)

Neutrino connection to Dark Matter

Standard Model



$SU(3)_c \times SU(2)_L \times U(1)_Y$

The Neutrino Portal

Dark Sector

G_{DM}

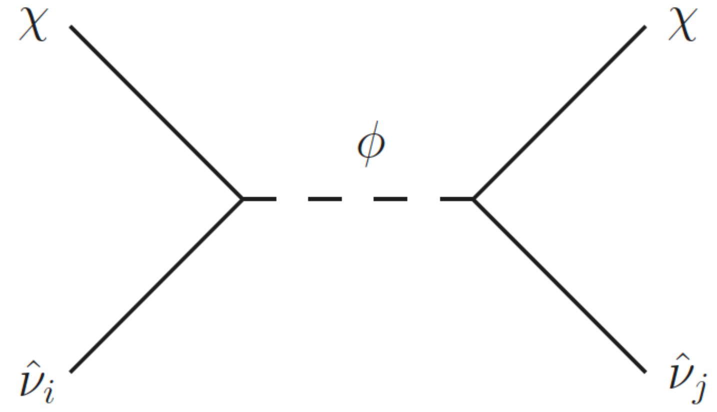
Assume all Standard Model particles are singlets under the (unknown) symmetry group of the Dark Sector G_{DM} and that all particles in the Dark Sector are singlets of the SM

ν and DM interactions can be safely generated through the "Neutrino Portal"

The couplings of the SM to DM occur through the operator HL (the Higgs doublet and a lepton doublet). An effective 4-Fermi interaction looks schematically like $(HL)^2(DM)^2$

$$-\mathcal{L} \supset m_\phi^2 \, |\phi|^2 + m_\chi \, \bar{\chi}\chi + m_N \, \bar{N} N$$
$$+ \left[\lambda_\ell \, \bar{L}_\ell \hat{H} N_R + \phi \, \bar{\chi} \, (y_L N_L + y_R N_R) + \text{h.c.} \right]$$

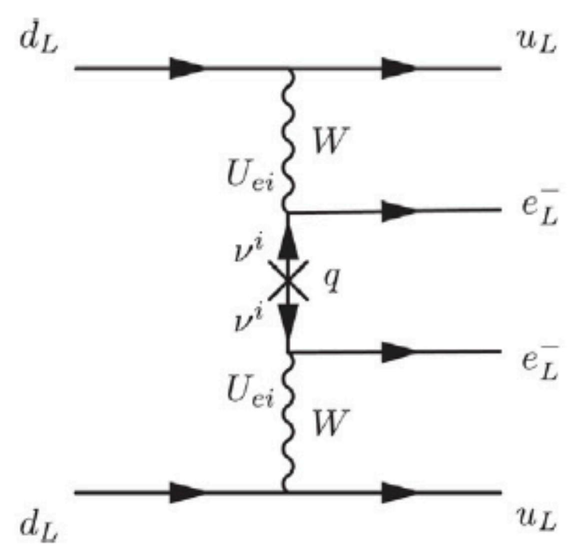
Scalar and fermion of the Dark Sector



B. Bertoni et al., *JHEP* 04 (2015) 170

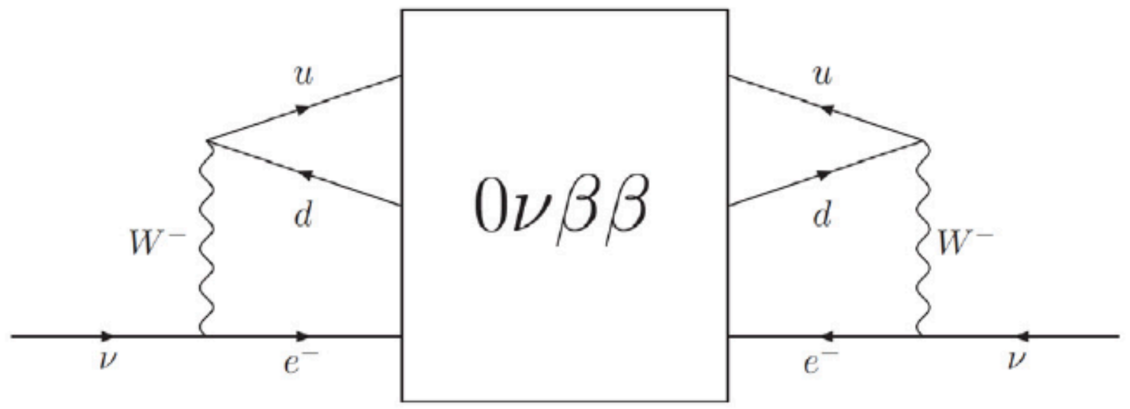
ν mass generation through the Seesaw mechanism (and most of the other models) implies neutrinos are Majorana particles

Majorana neutrinos $\Rightarrow$ $0\nu\beta\beta$ must exists



On the other hand
if $0\nu\beta\beta$ exists $\Rightarrow$

Black box theorem: ν masses radiatively generated (but too small to explain observed neutrino mass differences)



While other mechanism could contribute, we assume neutrino mass as the exclusive contributing process to $0\nu\beta\beta$. Nonetheless, $0\nu\beta\beta$ would be an exceptional discovery pointing to BSM Physics

Neutrino Mixing

$$\nu_\alpha = U_{\alpha i}\nu_i$$

$\alpha = e, \mu, \tau$

$i = 1,2,3$

Mixing Matrix (PNMS)

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

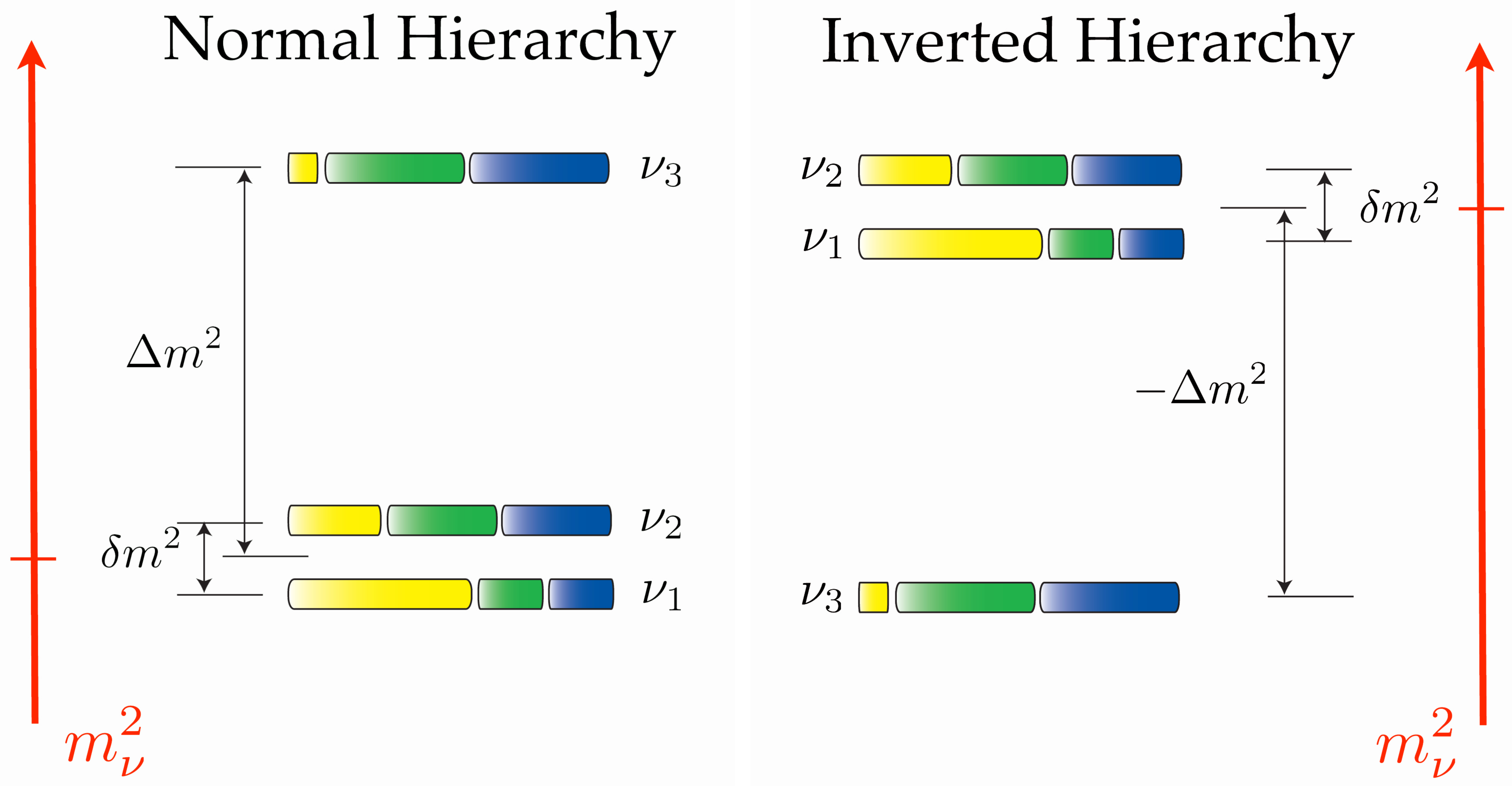
$c_{ij} = \cos\theta_{ij}$

$s_{ij} = \sin\theta_{ij}$

$(\theta_{12}, \theta_{23}, \theta_{13})$ 3 mixing angles

δ "CP" phase

Neutrino Mass Spectrum



Simplified case of 2 neutrino mixing

$$P_{\alpha\beta} = \sin^2(2\theta)\,\sin^2\!\left(\frac{\Delta m^2 L}{4E}\right) = \sin^2(2\theta)\,\sin^2\!\left(1.27\,\frac{\Delta m^2\,[\mathrm{eV}^2]\,L\,[\mathrm{km}]}{E\,[\mathrm{GeV}]}\right)$$

amplitude

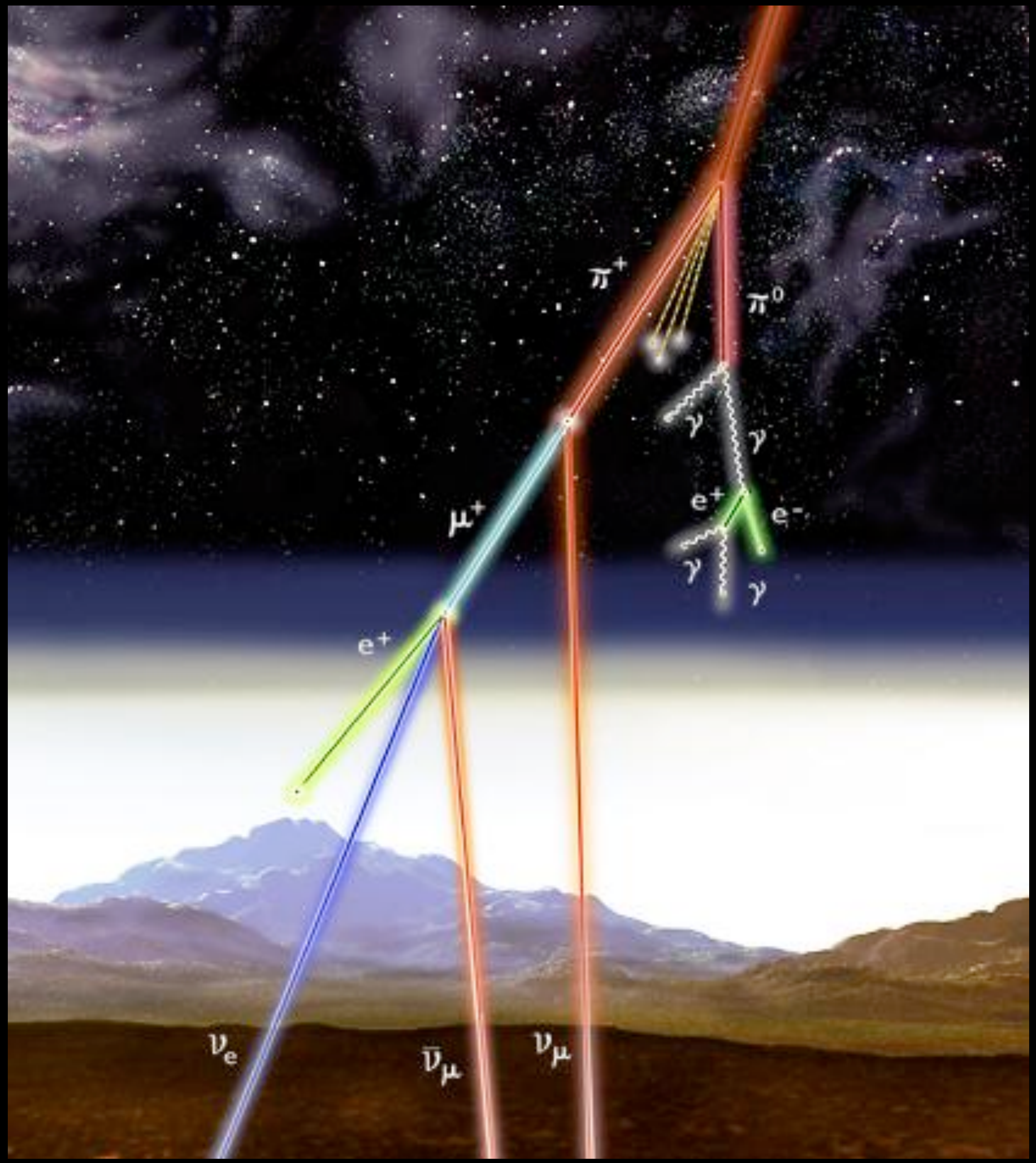
oscillating phase

Effect when phase is O(1)

$$\Delta m^2 \sim 3\times 10^{-3}\,\mathrm{eV}^2, \qquad E \sim 1\,\mathrm{GeV} \implies L_{\mathrm{osc}} \sim \frac{4\pi E}{\Delta m^2} \sim 700\ \mathrm{km}\,.$$

If $\left|\Delta m^2\right| \gg \delta m^2$ 2 neutrino mixing good approximation to explain solar and atm. oscillations

Atmospheric Neutrinos



$$p + \mathcal{N} \to \pi^\pm + \mathcal{X}$$

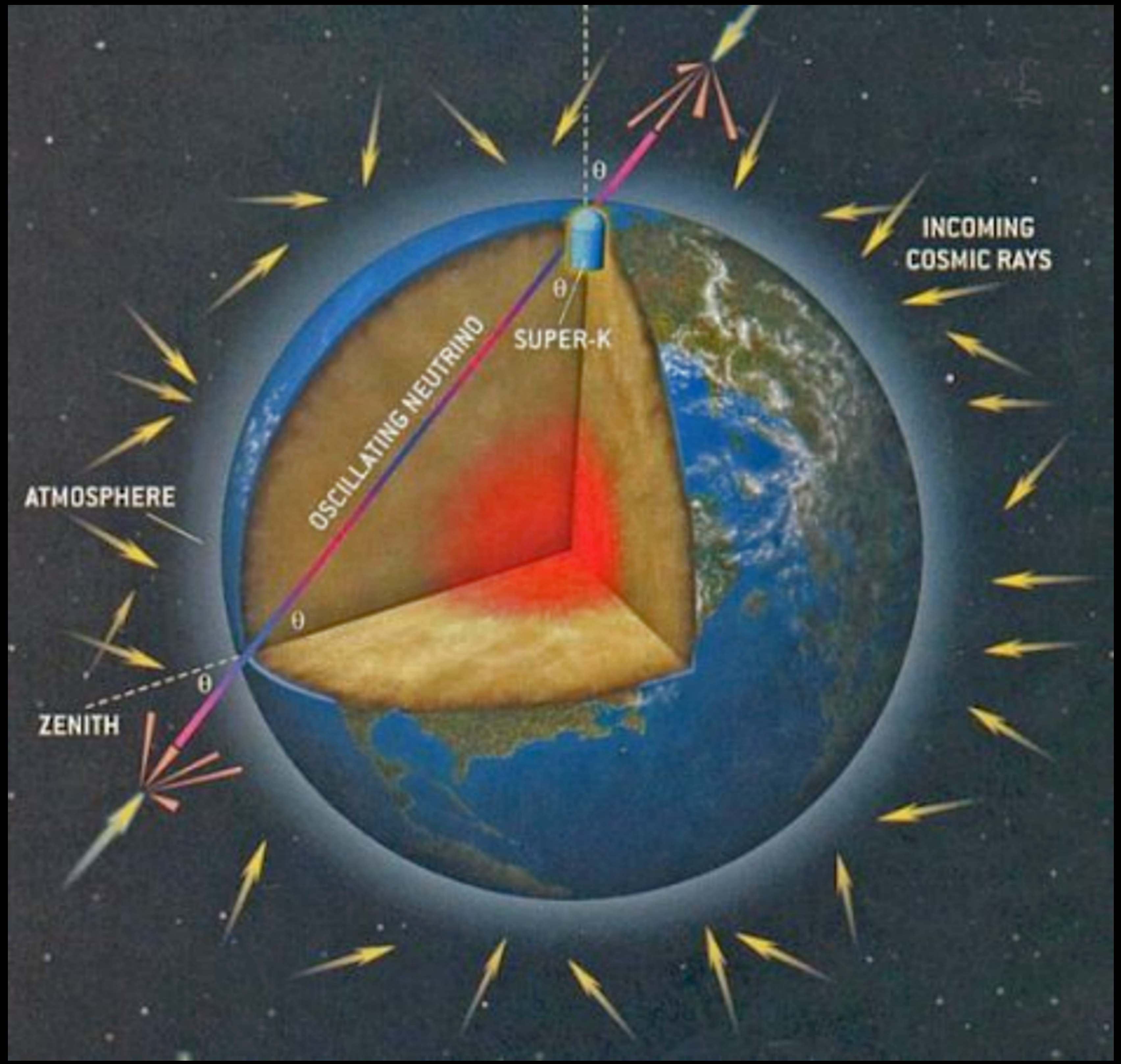
$$\pi^\pm \to \mu^\pm + \nu_\mu(\overline{\nu}_\mu)$$

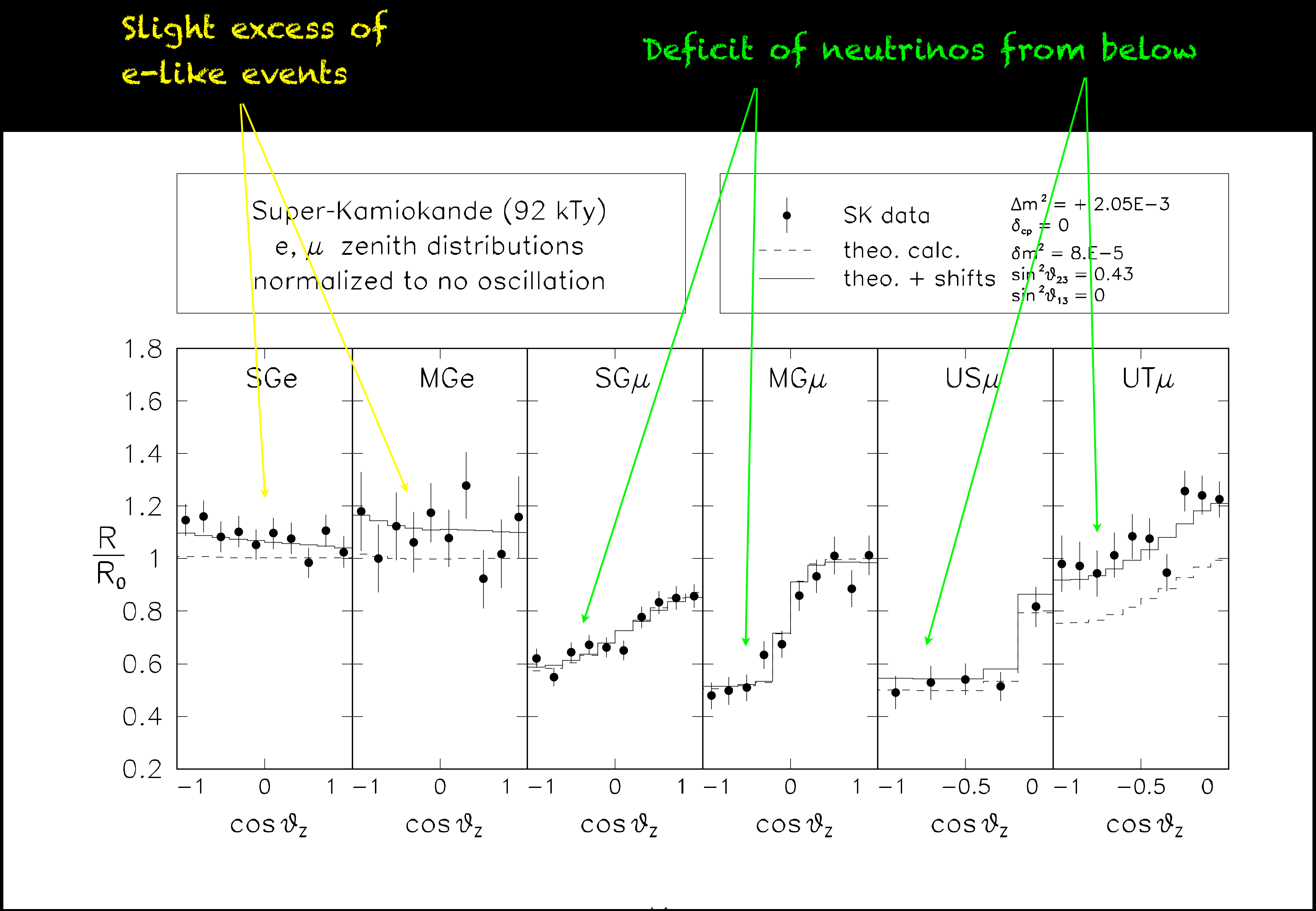
$$\mu^\pm \to e^\pm + \nu_e(\overline{\nu}_e) + \nu_\mu(\overline{\nu}_u)$$

$$\phi_{\nu_\mu}/\phi_{\nu_e} \sim 2$$

SuperKamiokande

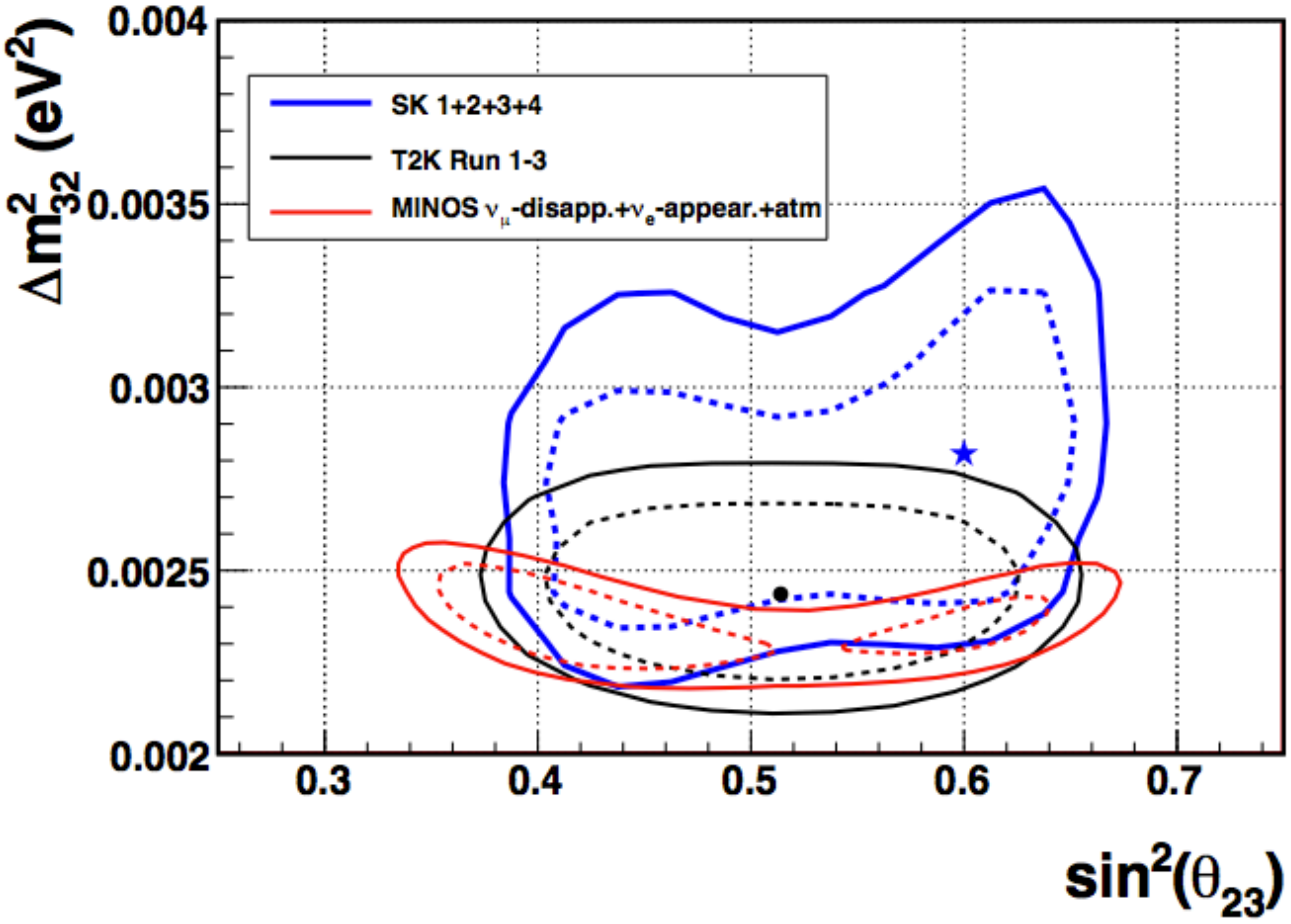
50 kTon water Cherenkov underground detector



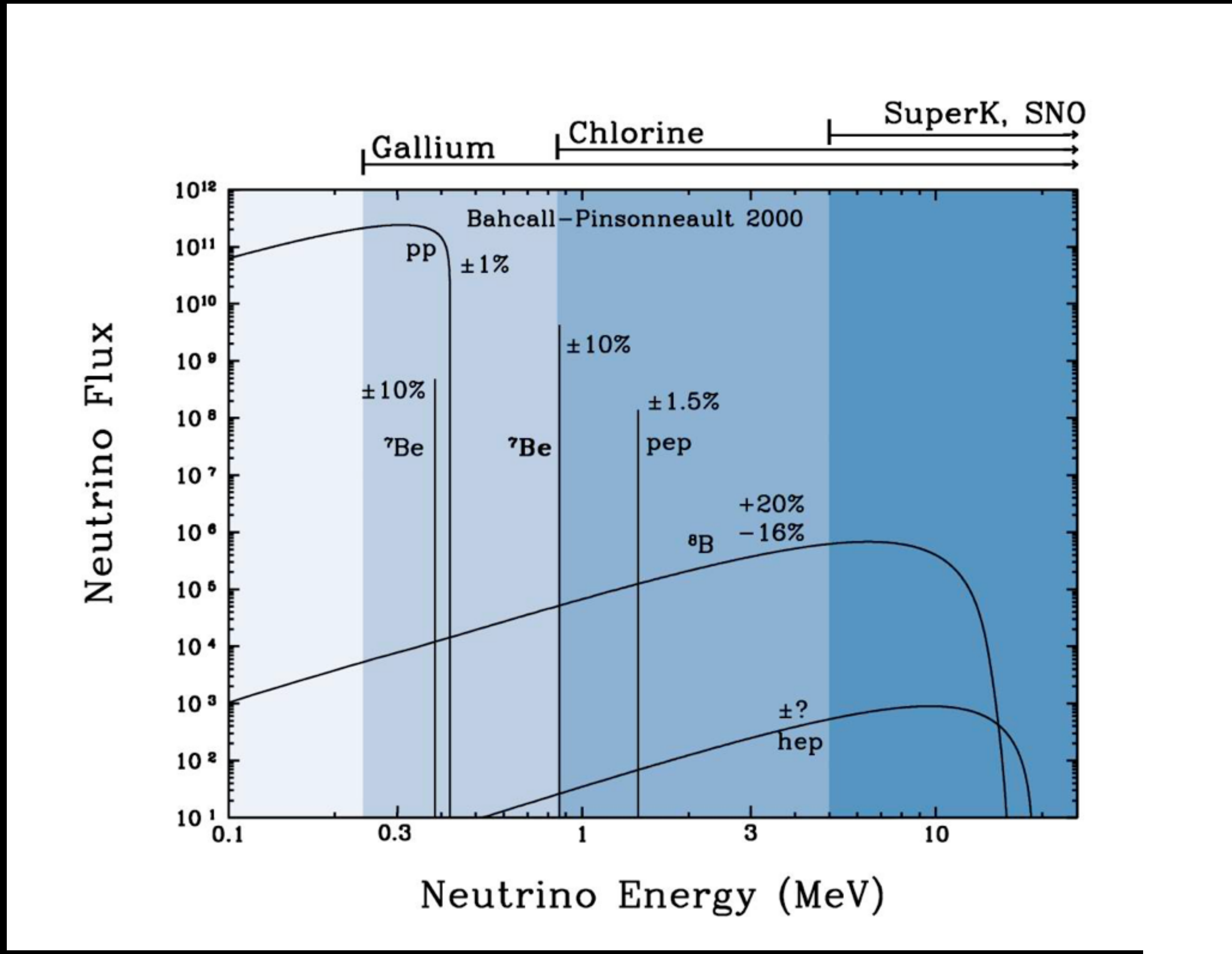


Slight excess of e-like events
Deficit of neutrinos from below
Super-Kamiokande (92 kTy)
e, μ zenith distributions
normalized to no oscillation
SK data
theo. calc.
theo. + shifts
Δm² = + 2.05E−3
δcp = 0
δm² = 8.E−5
sin²ϑ23 = 0.43
sin²ϑ13 = 0
SGe
MGe
SGμ
MGμ
USμ
UTμ
R/R0
cos ϑz

SK and LBL comparison



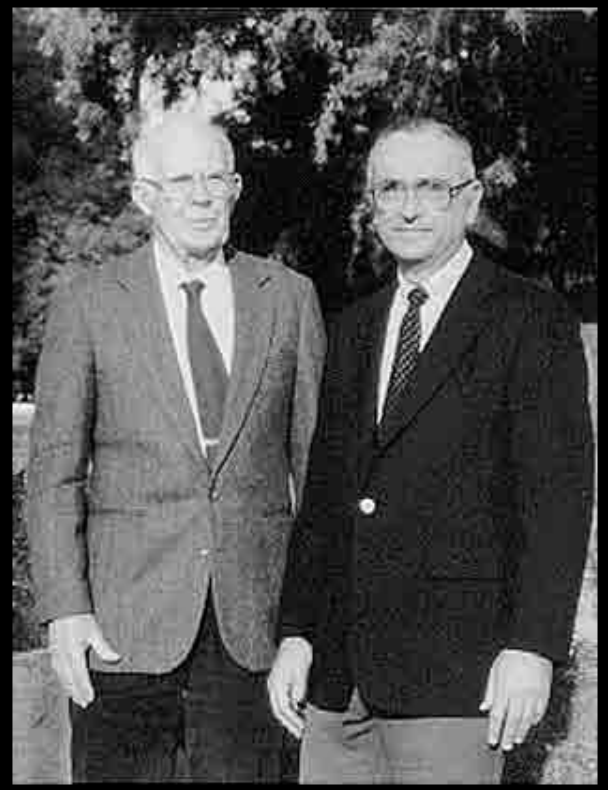
Solar Neutrinos

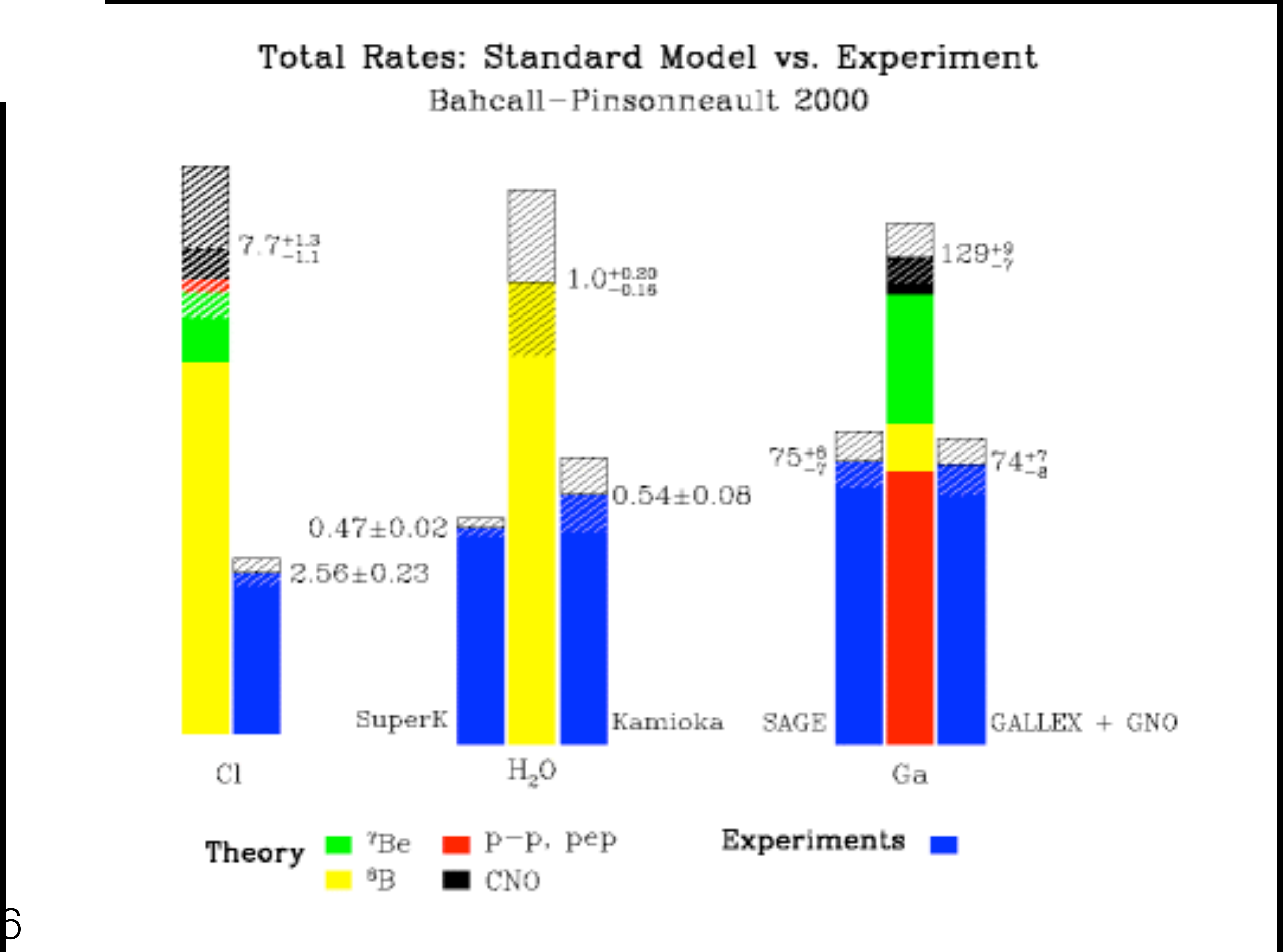


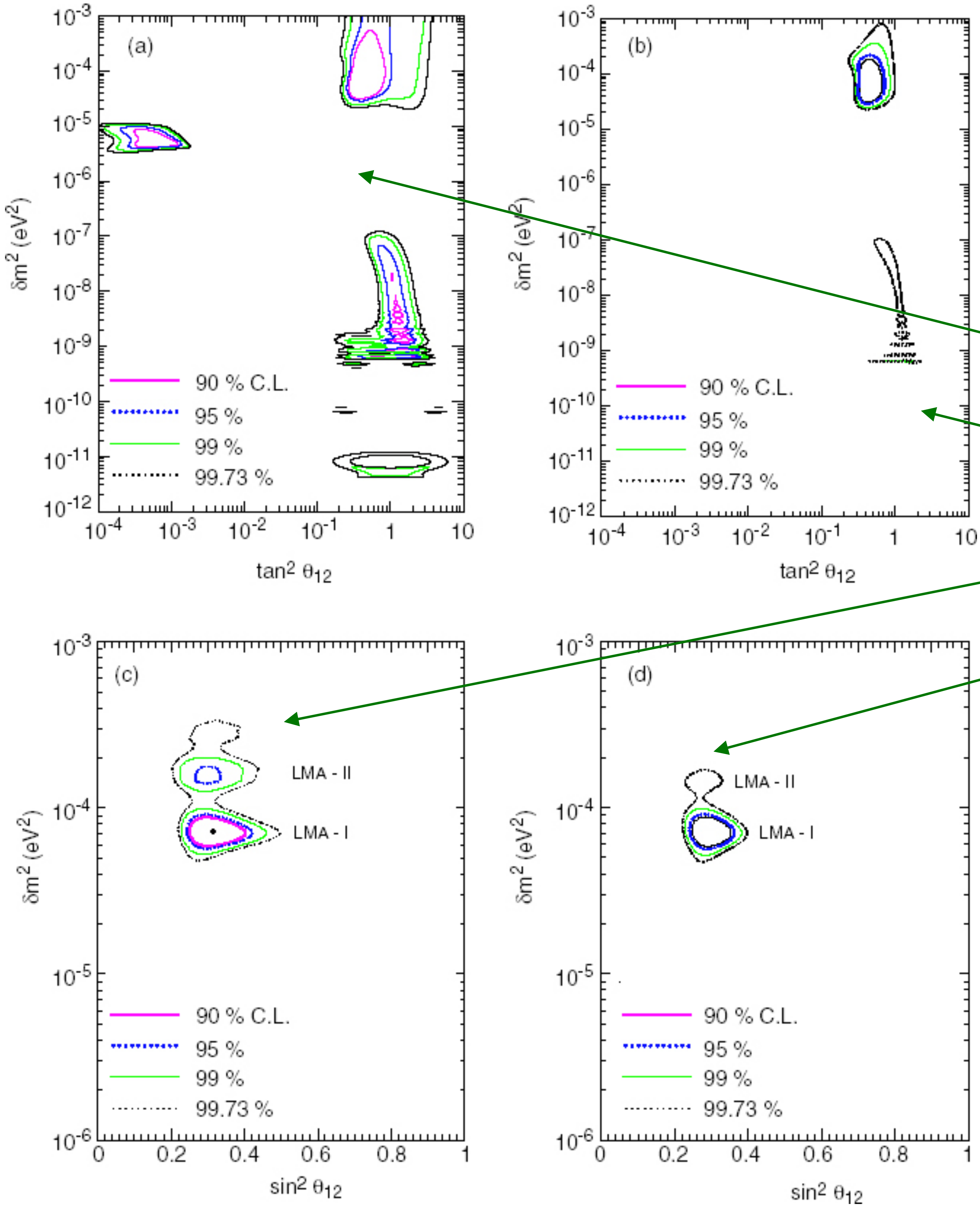
mostly

pp ^{8}B and ^{7}Be neutrinos

Davis and Bahcall







Impressive reduction of the parameter space ($\delta m^2, \theta_{12}$) in the years **2001-2003** (note the different scales !)

Cl+Ga+SK (2001)

+SNO-I (2001-2002)

+KamLAND-I (2002)

+SNO-II (2003)

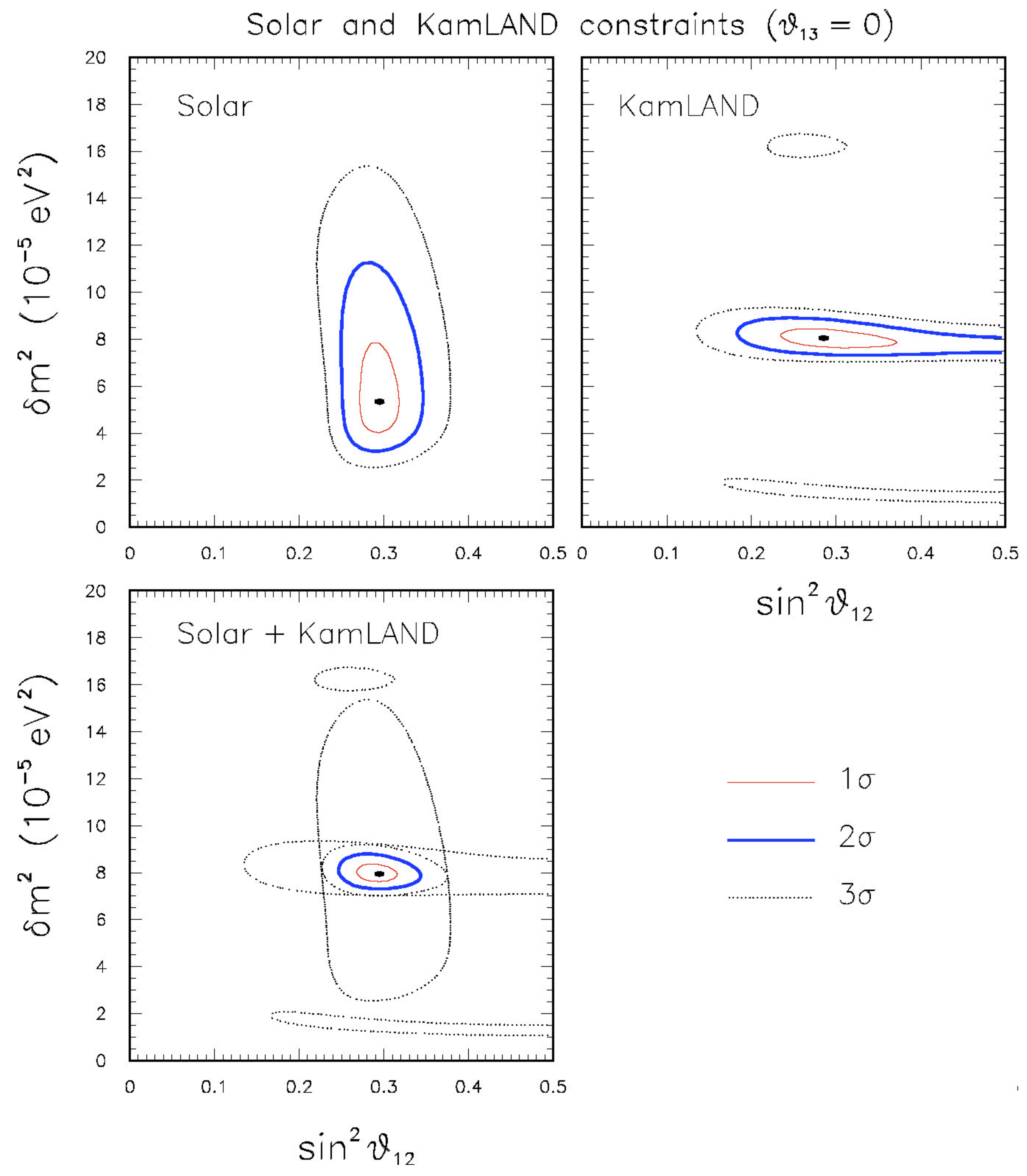
Standard Solar Model confirmed

Direct proof of $\nu_e \to \nu_{\mu,\tau}$ in SNO from the comparison of

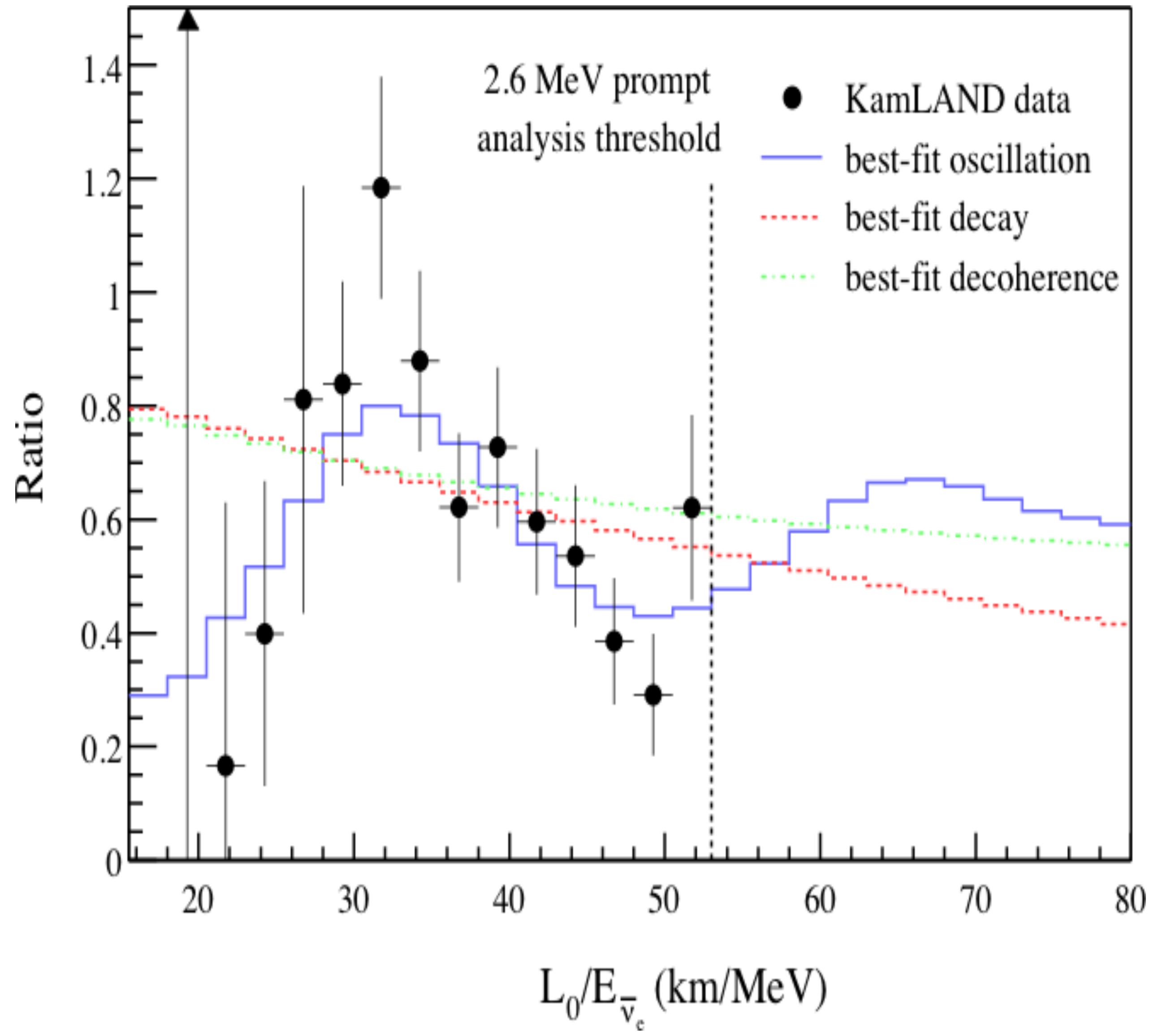
$$\begin{aligned} \text{CC}: &\quad \nu_e + d \to p + p + e \\ \text{NC}: &\quad \nu_{e,\mu,\tau} + d \to p + n + \nu_{e,\mu,\tau} \\ \text{ES}: &\quad \nu_{e,\mu,\tau} + e \to e + \nu_{e,\mu,\tau} \end{aligned}$$

Fogli, Bologna (2005)

... **2004**: a unique solution well identified (Large Mixing Angle)

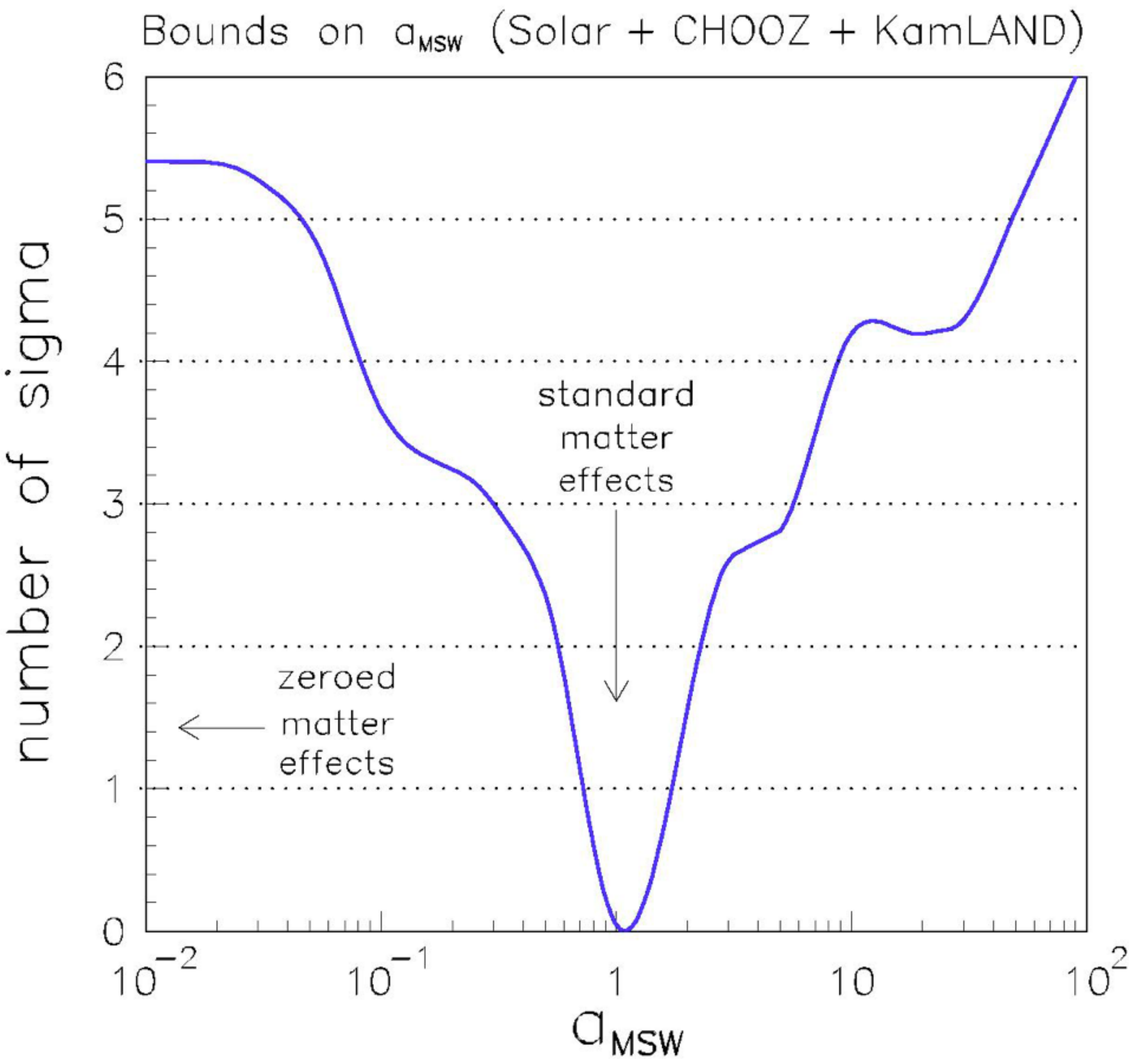


+ evidence for a half-cycle of oscillation in KamLAND



What can we say about the MSW effect ?

Fogli, Bologna (2005)



Prog.Part.Nucl.Phys. 57 (2006) 742-795

Precision era in neutrino oscillation phenomenology

Standard 3ν mass-mixing framework parameters

What we known

$\delta m^2 \sim 7.37 \times 10^{-5}\ \mathrm{eV}^2 \quad (2.2\%)$

$\Delta m^2 \sim 2.49 \times 10^{-3}\ \mathrm{eV}^2 \quad (1.3\%)$

$\sin^2\theta_{12} \sim 0.303 \quad (4.5\%)$

$\sin^2\theta_{13} \sim 2.23 \times 10^{-2} \quad (2.4\%)$

$\sin^2\theta_{23} \sim 0.473 \times 10^{-2} \quad (5.1\%)$

What we still do not know

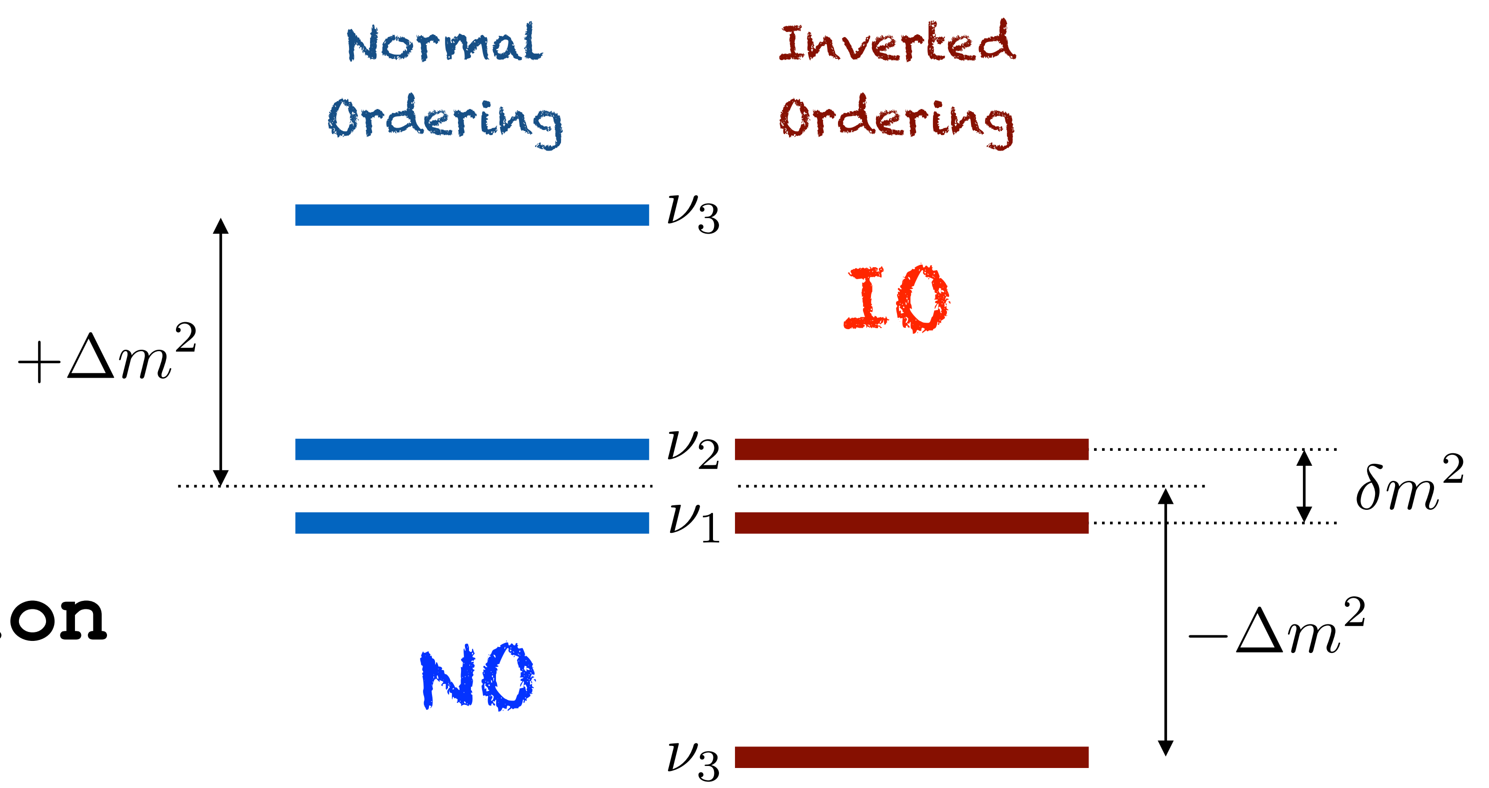
CP-violating phase δ

Octant of θ_{23}

Absolute mass scale

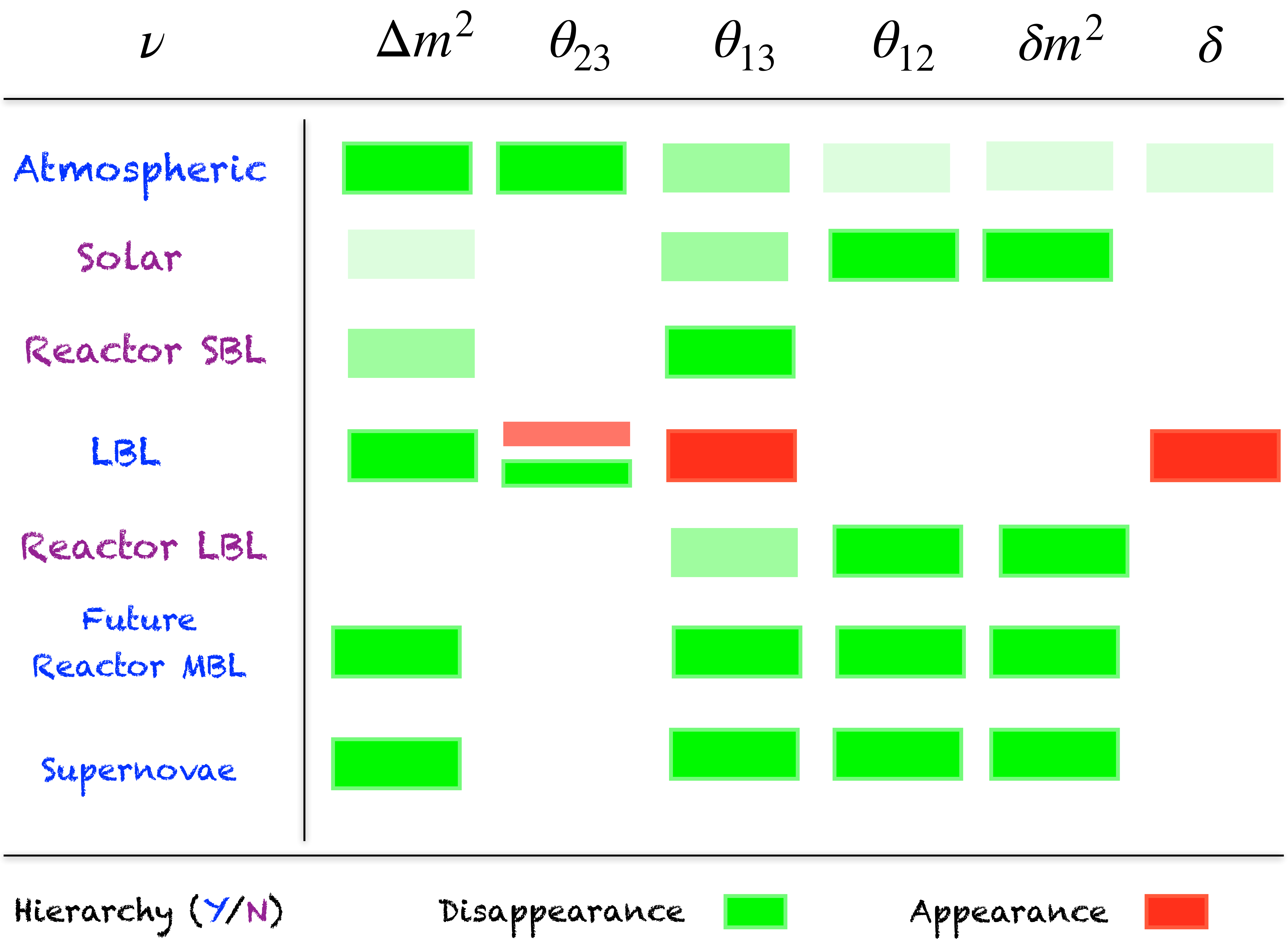
Nature of ν (Dirac/Majorana)

Mass Ordering --> $\mathrm{sign}(\Delta m^2)$



Note that in our notation

$$\Delta m^2 = \frac{\Delta m^2_{31} + \Delta m^2_{32}}{2}$$


ν
Δm^2
θ_{23}
θ_{13}
θ_{12}
δm^2
δ
Atmospheric
Solar
Reactor SBL
LBL
Reactor LBL
Future Reactor MBL
Supernovae
Hierarchy (Y/N)
Disappearance
Appearance

To understand how bounds on the oscillation parameter arise it is useful to look at their correlations and to consider the progressive contribution of different data sets

LBL accelerators (T2K and NOvA) are dominantly sensitive to $(\Delta m^2, \theta_{23}, \theta_{13})$ but also probe δ and NO vs IO, if $(\delta m^2, \theta_{12})$ are fixed by solar+KL,

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \simeq\ & \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta m^2}{A-\Delta m^2}\right)\sin^2\left(\frac{A-\Delta m^2}{4E}x\right) \\
+\ & \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\left(\frac{\Delta m^2}{A}\right)\left(\frac{\Delta m^2}{A-\Delta m^2}\right)\sin\left(\frac{A}{4E}x\right)\sin\left(\frac{A-\Delta m^2}{4E}x\right)\cos\left(\frac{\Delta m^2}{4E}x\right)\cos\delta \\
-\ & \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\left(\frac{\Delta m^2}{A}\right)\left(\frac{\Delta m^2}{A-\Delta m^2}\right)\sin\left(\frac{A}{4E}x\right)\sin\left(\frac{A-\Delta m^2}{4E}x\right)\sin\left(\frac{\Delta m^2}{4E}x\right)\sin\delta \\
+\ & \cos^2\theta_{13}\sin^2 2\theta_{12}\left(\frac{\Delta m^2}{A}\right)^2\sin^2\left(\frac{A}{4E}x\right)\ , \qquad (13)
\end{aligned}
$$

where $A = 2\sqrt{2}G_F N_e E$ governs matter effects, with $A \to -A$ and $\delta \to -\delta$ for $\nu \to \overline{\nu}$, and $\Delta m^2 \to -\Delta m^2$ for normal to inverted ordering. At typical NOvA energies ($E \sim 2$ GeV) it is $|A/\Delta m^2| \sim 0.2$,

Therefore we start combining

(1) LBL acc + Solar + KamLAND

Solar + KL data provide the necessary input for $(\delta m^2, \theta_{12})$, but also independent -although weak- constraints on θ_{13}. The data set (1) provides, by itself, a measurement of θ_{13}.

SBL reactors (Daya Bay, RENO, Double Chooz) are dominantly sensitive to (Δm^2, ϑ_{13}) and shrink the ϑ_{13} range dramatically, with correlated effects on the other parameters

(2) LBL acc + Solar + KamLAND + SBL Reactors

SBL reactors not only provide the most accurate determination of θ_{13} but also an independent determination of Δm^2

(3) LBL acc + Solar + KamLAND + SBL Reactors + Atmospheric

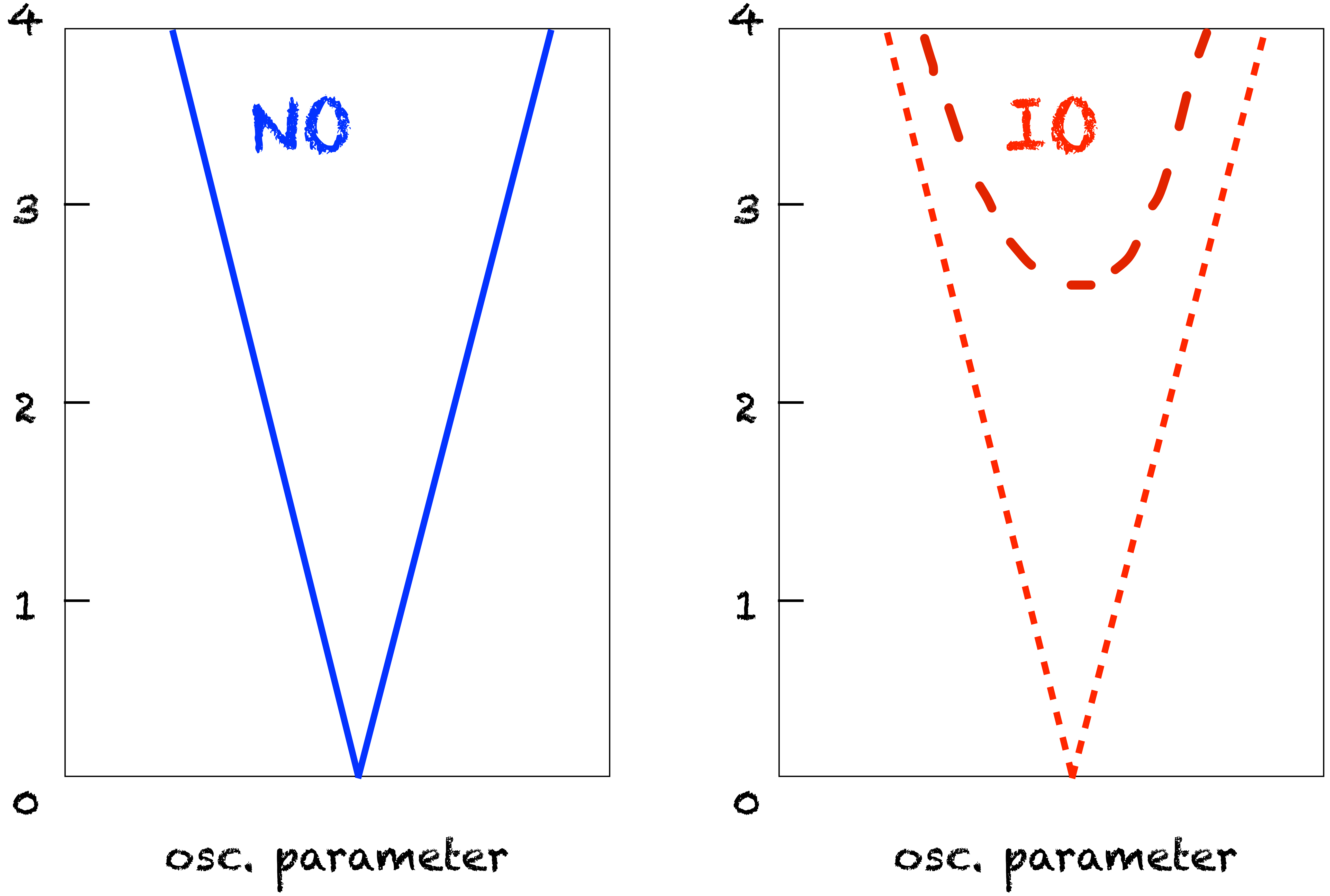
Atmospheric neutrino data (SK + DeepCore) sensitive in different ways to all the oscillation parameters via disappearance and appearance channels. Because of matter effects they depends on all parameters in the 3ν framework, but dominantly on (Δm^2, ϑ_{23}). Also important to test NO vs IO

Bounds on sigle parameters, obtained after marginalisation over all other parameter, shown in the following in terms of $N\sigma = \sqrt{\Delta\chi^2}$

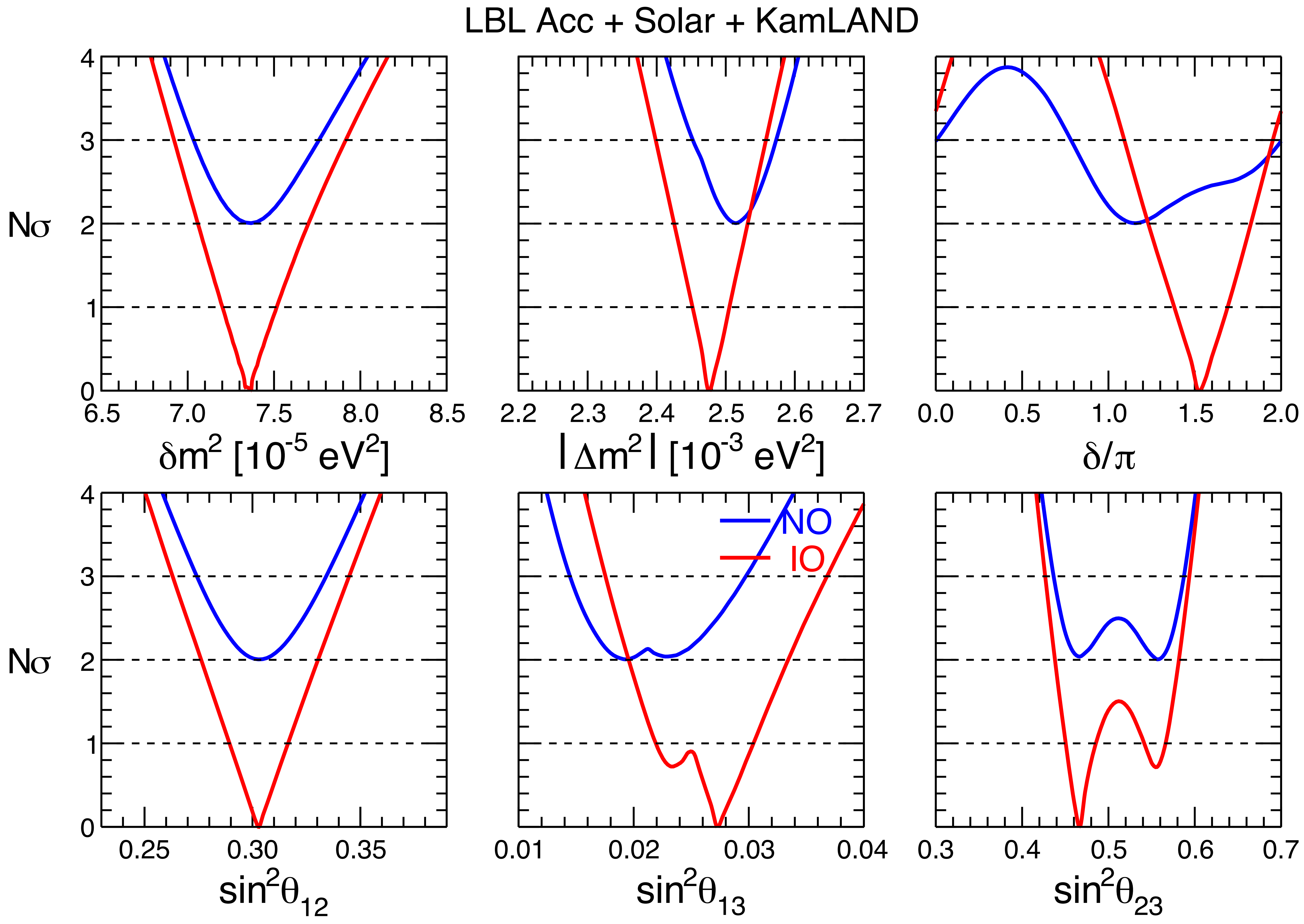
Separate best fits for both NO and IO

Typical bounds would be linear and symmetric for gaussian errors

Bounds for IO move upwards taking into account that currently NO gives the absolute best fit



Global fit results: **1804.09678 by F. Capozzi, E. Lisi, A. Marrone, A. Palazzo, PPNP 102, 48 (2018)**

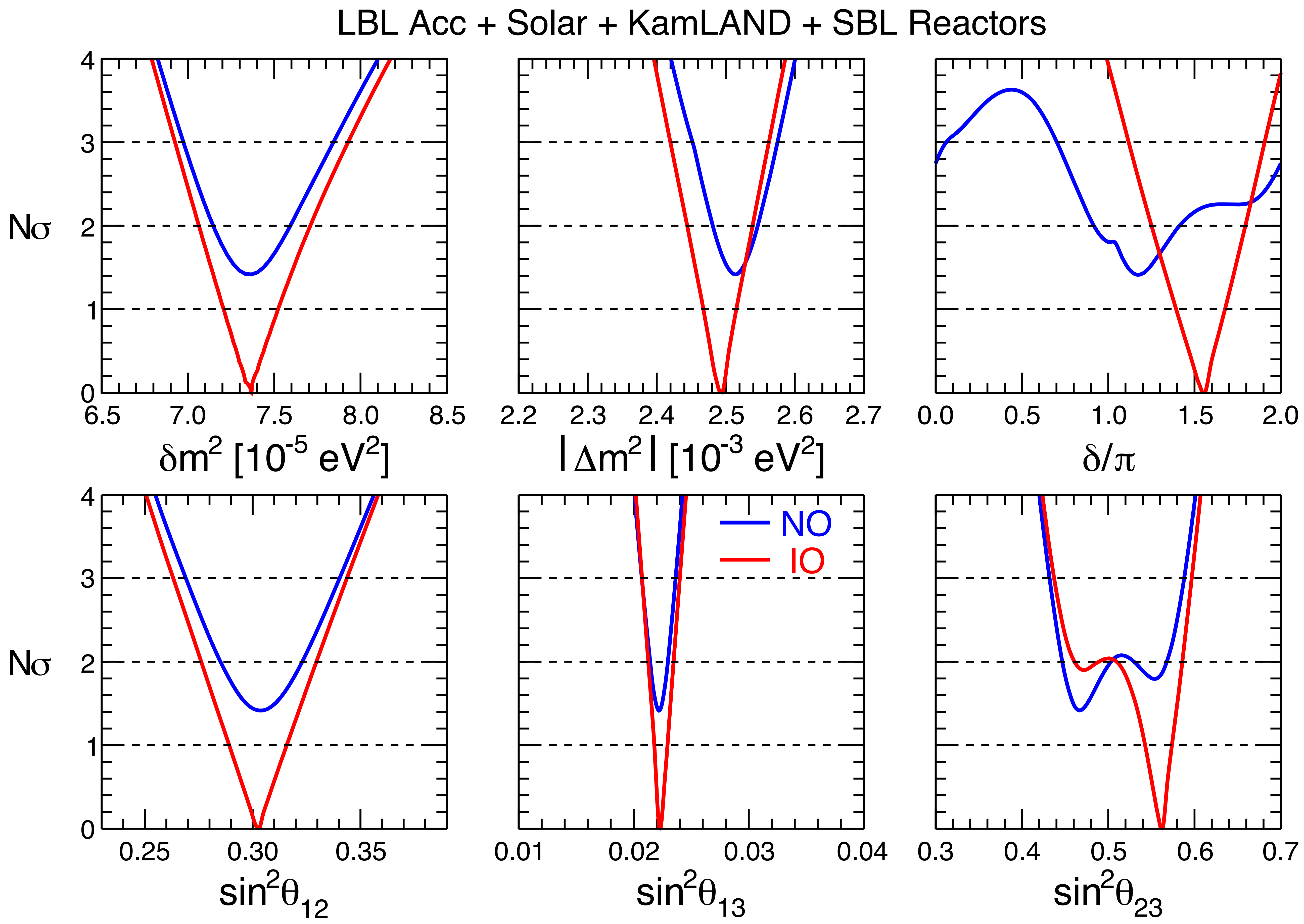


With the exception of δ and ϑ_{13}, all parameters bounded at more then 4σ level

ϑ_{23} nearly maximal but octant undetermined at 1σ

Maximal CP violation favoured in IO

IO favored with respect to NO at ~2σ level.

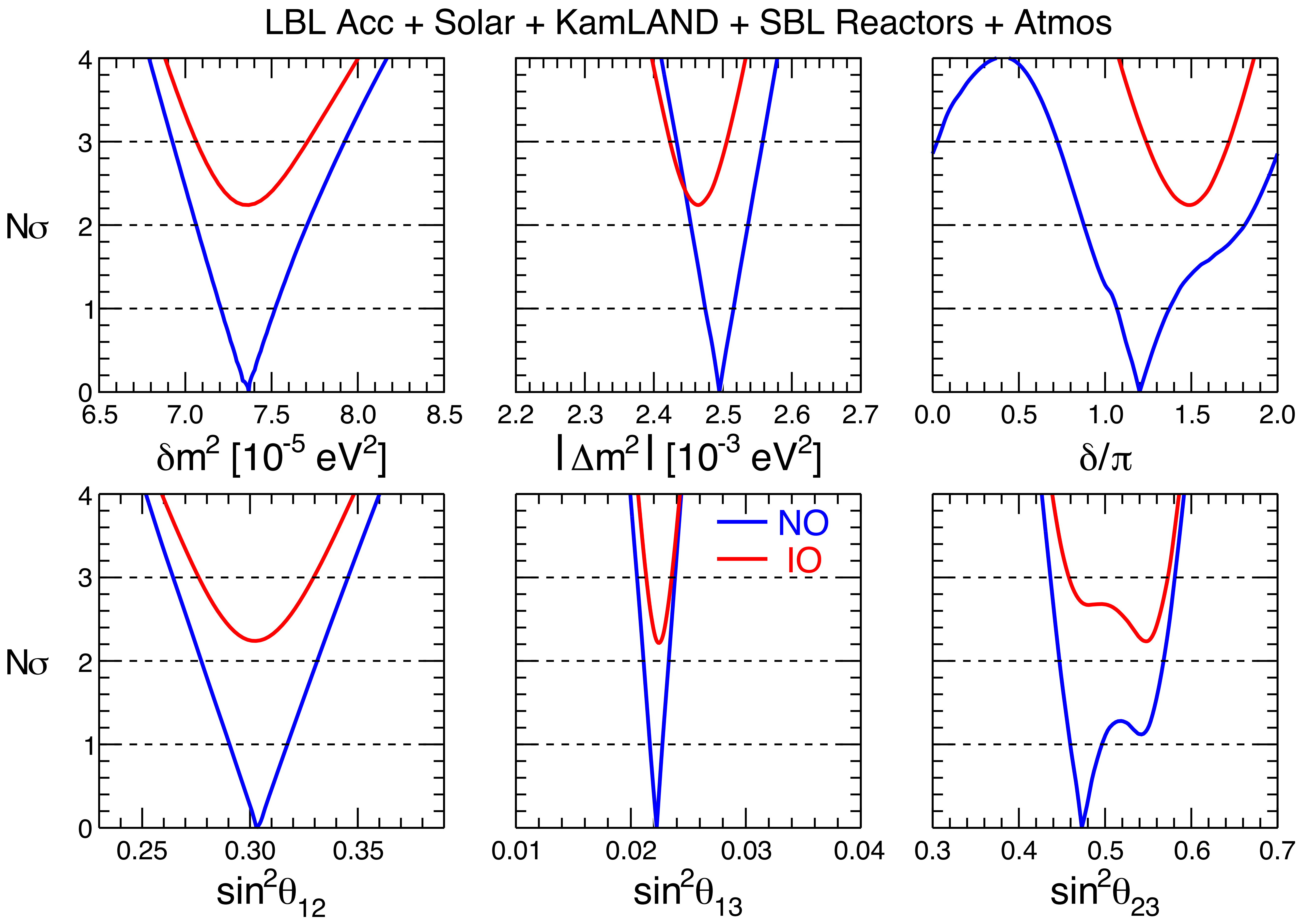


Range of smallest mixing angle ϑ_{13} dramatically reduced

Largest mixing angle ϑ_{23} unstable, but octant undetermined at 2σ in IO

Max CPV at $\sim 3\pi/2$ favored in IO , CP conservation allowed at $\sim 1\sigma$ in NO

IO favored with respect to NO at $\sim 1.4\sigma$ level.

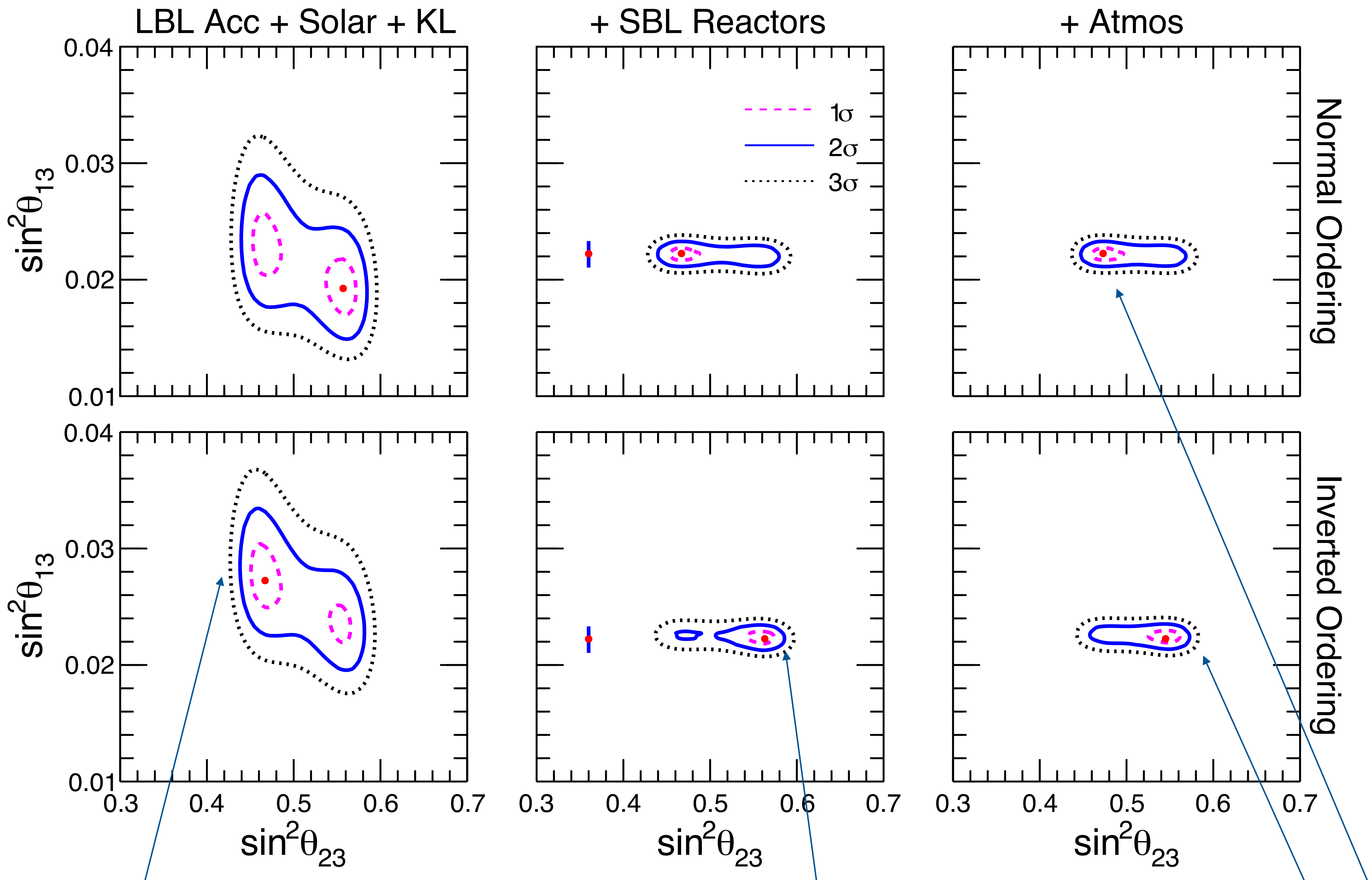


Further improvements for various parameters: 1σ bounds at few % level

Largest mixing angle ϑ_{23} close to $\pi/4$, but octant undetermined at ~1σ

Maximal CP Violation favored in IO, partial in NO

IO now disfavored with respect to NO, at ~2.3σ level



Anticorrelation between $(\vartheta_{23}, \vartheta_{13})$ due to leading term in the appearance channel probability at accelerators

lower ϑ_{13} value preferred by reactors data favours second octant for ϑ_{23}

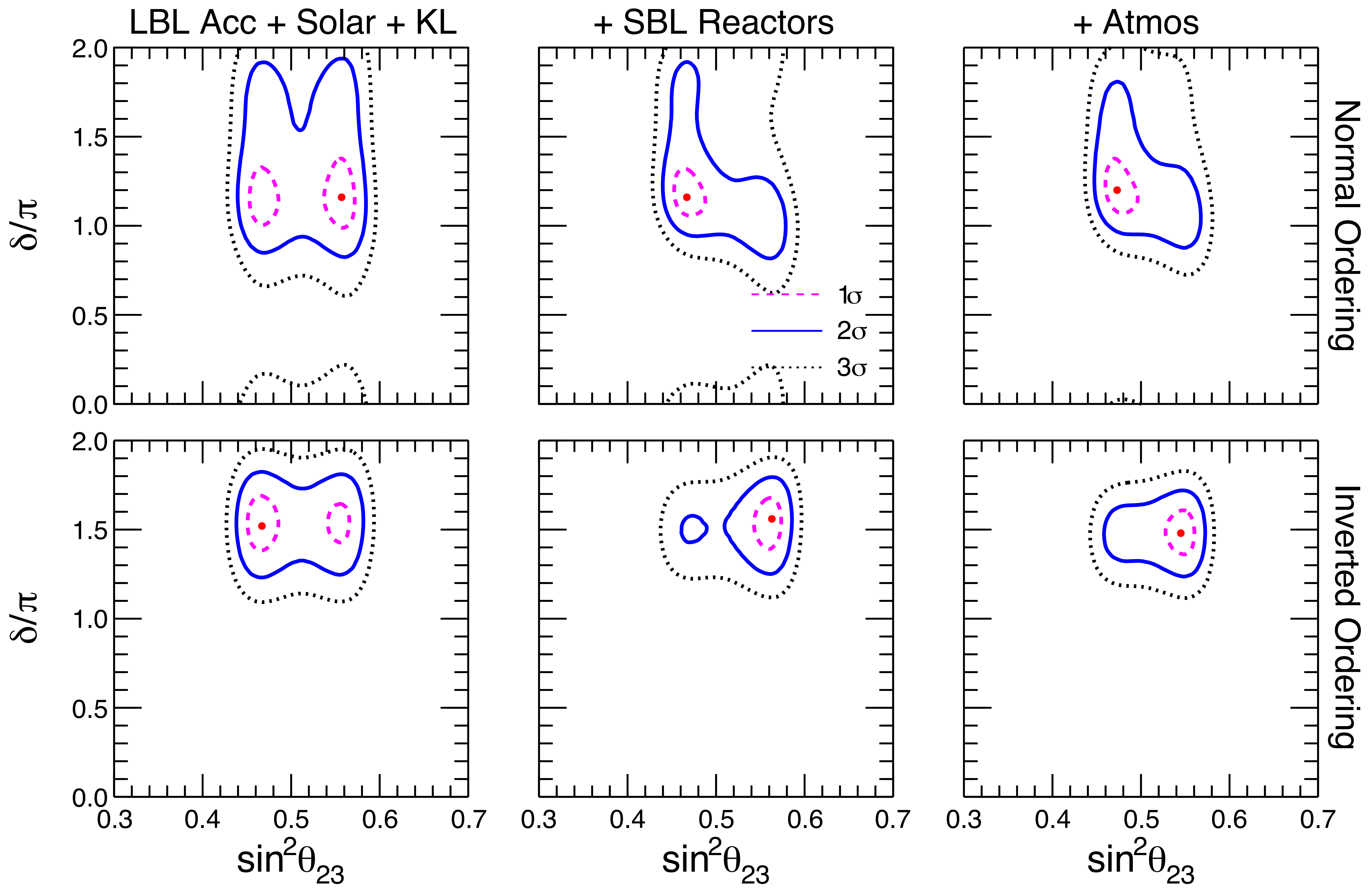
second octant favoured also by atmospheric data in IO, first octant in NO

The almost octant-symmetric contours in the left panels become rather asymmetric by adding reactor data (middle panels) and then atmospheric data (right panels)

The overall parameter correlation appears to be negative in NO and negligible in IO, when all data are included

If the octant best fits were hypothetically flipped, the current slight preference for CP violation would be weakened in NO, while it would remain stable in IO

This figure illustrates that a weak but interesting interplay already emerges among the three oscillation unknowns (the CP phase, θ23 octant, and mass ordering) and that future data



Global Fit - 2025

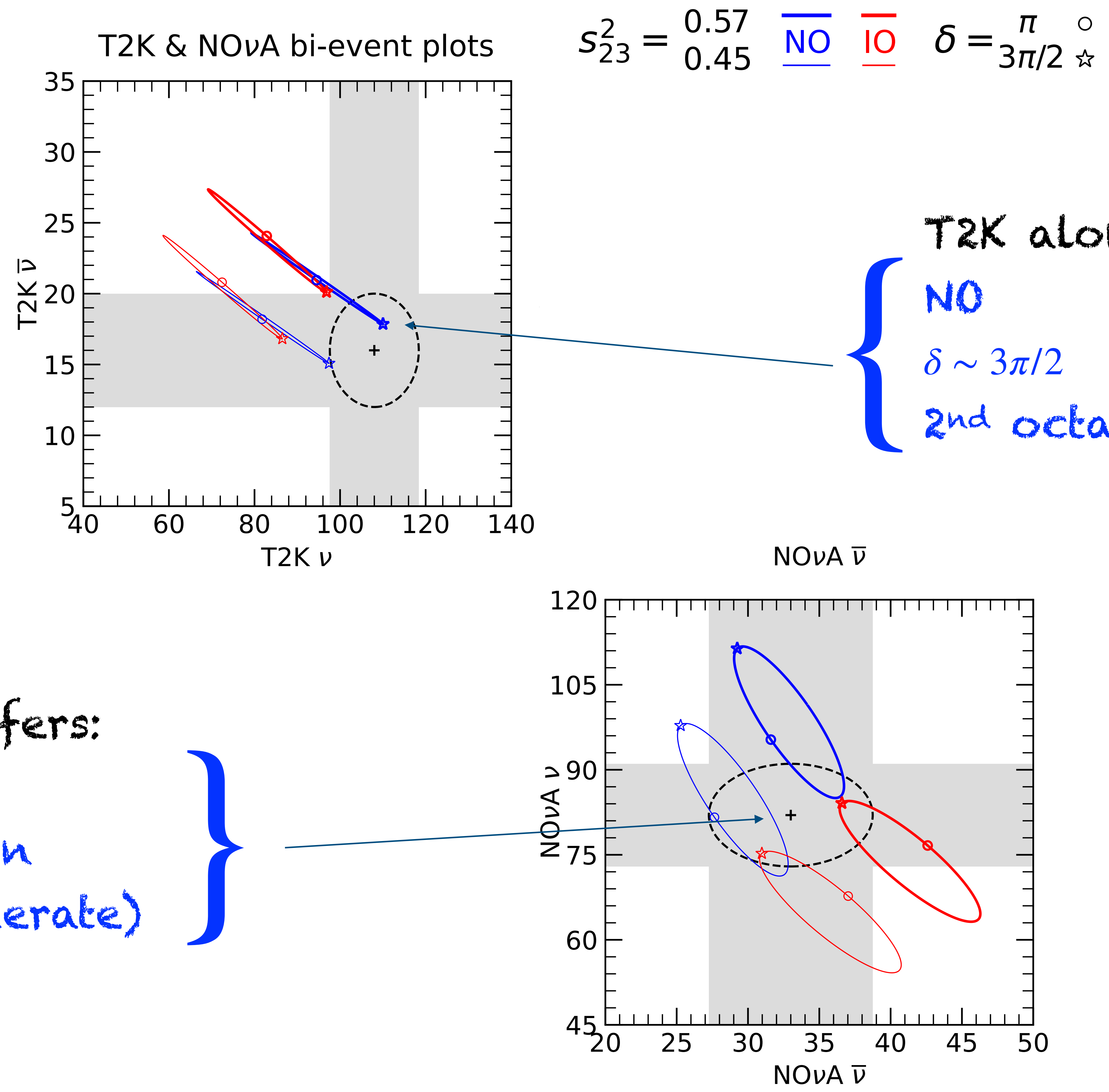
TABLE I. Global 3ν oscillation analysis: best-fit values and allowed ranges at $N_\sigma = 1, 2, 3$, for either NO or IO. The last column shows the formal "1σ parameter accuracy," defined as 1/6 of the 3σ range, divided by the best-fit value (in percent). We recall that $\Delta m^2 = m_3^2 - (m_1^2 + m_2^2)/2$ and that δ/π is cyclic (mod 2). Last row: $\Delta\chi^2$ offset between IO and NO.

Parameter	Ordering	Best fit	1σ range	2σ range	3σ range	"1σ" (%)
$\delta m^2/10^{-5}$ eV^2	NO, IO	7.37	7.21–7.52	7.06–7.71	6.93–7.93	2.3
$\sin^2\theta_{12}/10^{-1}$	NO, IO	3.03	2.91–3.17	2.77–3.31	2.64–3.45	4.5
$\lvert\Delta m^2\rvert/10^{-3}$ eV^2	NO	2.495	2.475–2.515	2.454–2.536	2.433–2.558	0.8
	IO	2.465	2.444–2.485	2.423–2.506	2.403–2.527	0.8
$\sin^2\theta_{13}/10^{-2}$	NO	2.23	2.17–2.27	2.11–2.33	2.06–2.38	2.4
	IO	2.23	2.19–2.30	2.14–2.35	2.08–2.41	2.4
$\sin^2\theta_{23}/10^{-1}$	NO	4.73	4.60–4.96	4.47–5.68	4.37–5.81	5.1
	IO	5.45	5.28–5.60	4.58–5.73	4.43–5.83	4.3
δ/π	NO	1.20	1.07–1.37	0.88–1.81	0.73–2.03	18
	IO	1.48	1.36–1.61	1.24–1.72	1.12–1.83	8
$\Delta\chi^2_{\text{IO-NO}}$	IO-NO	+5.0				

Known parameters constrained at few % level

The phase δ still "unknown"

Mass Ordering from T2K + NOνA



T2K alone prefers:
NO
$\delta \sim 3\pi/2$
2nd octant of θ_{23}

NOνA alone prefers:
NO
CP conservation
(octant ~degenerate)

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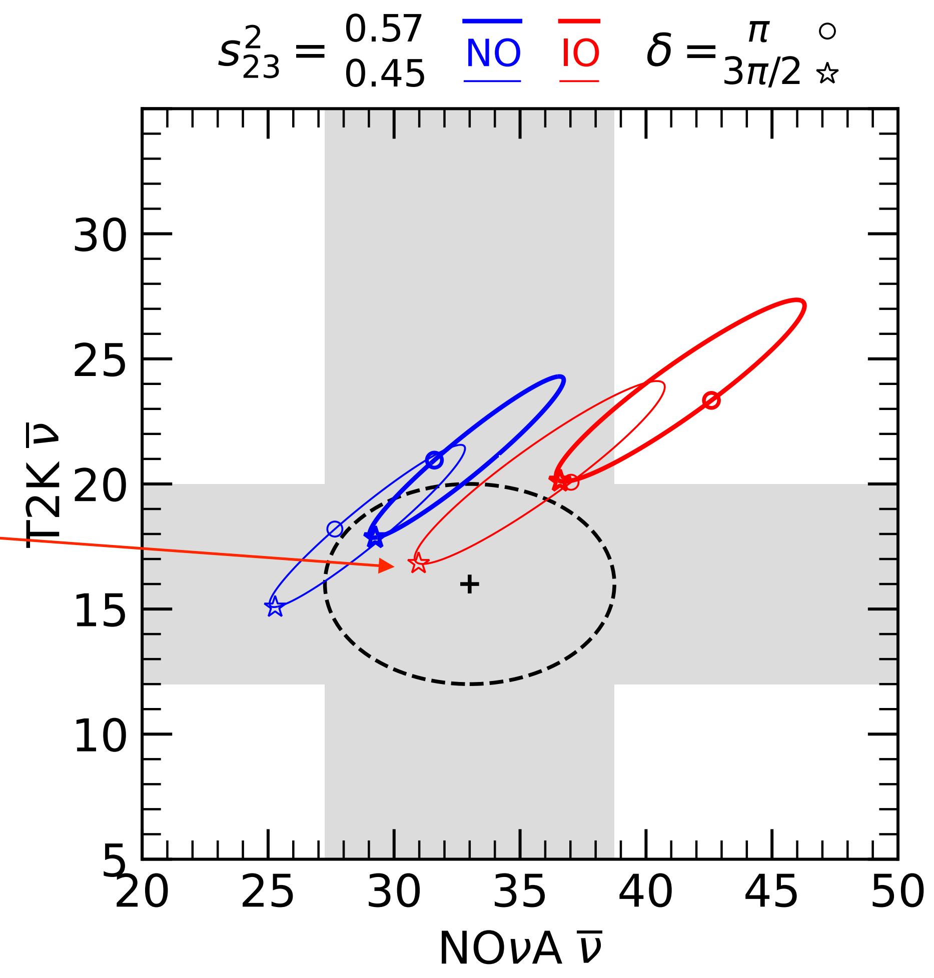
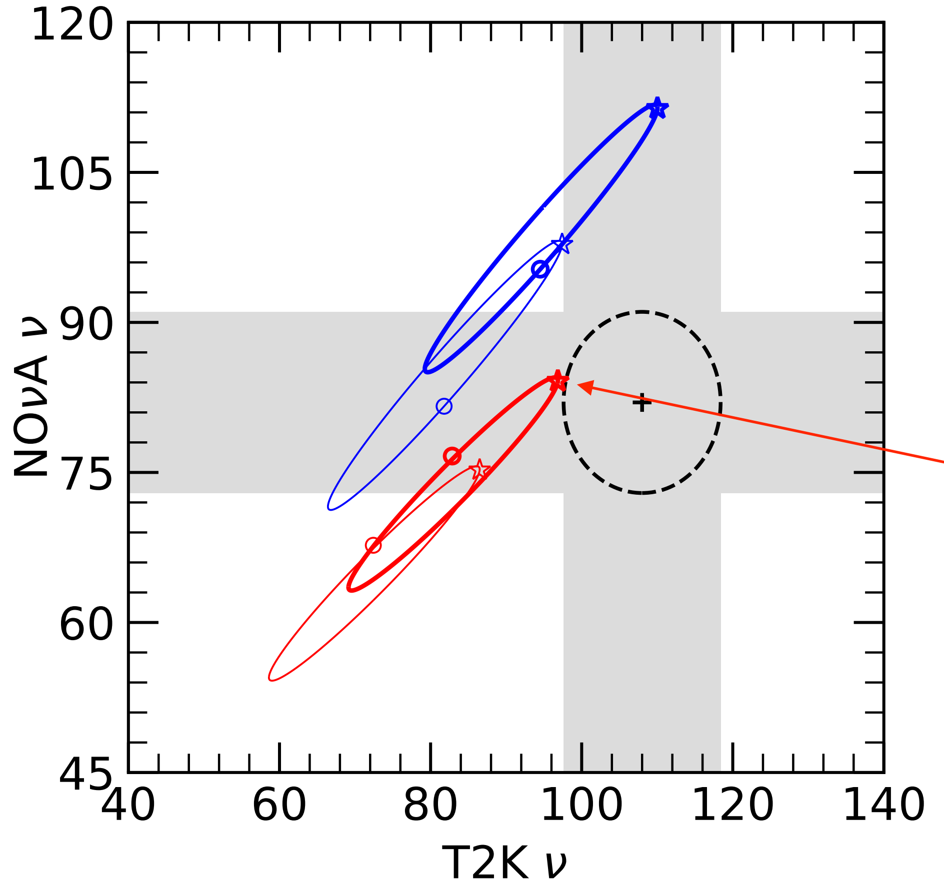
Both experiments prefer NO but give conflicting information on the CP phase

Integrated info on ν and $\bar{\nu}$, stat errors only
(but analysis uses spectral data)

T2K & NOνA bi-event plots



T2K + NOνA ($\bar{\nu}$) prefer:
IO
$\delta \sim 3\pi/2$
1st octant of θ_{23}



T2K + NOνA (ν) prefer:
IO
$\delta \sim 3\pi/2$
2nd octant of θ_{23}

T2K/NOνA alone:
NO preferred

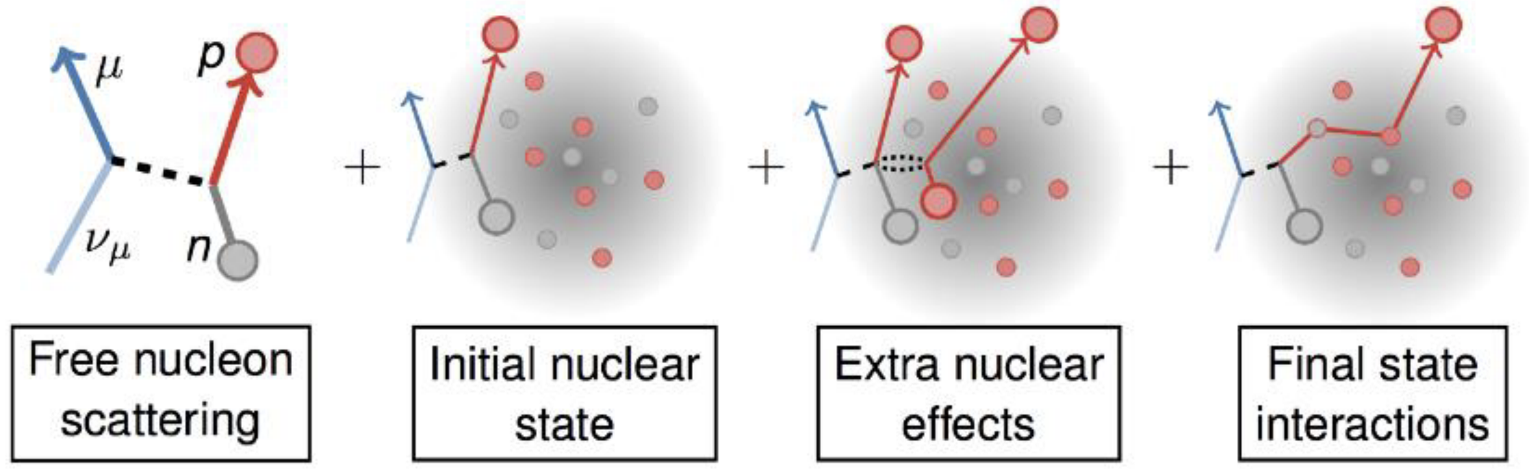
T2K/NOνA combined:
IO preferred

In IO:
CP violation preferred

Is there only statistics behind the T2K-NOνA: tension?

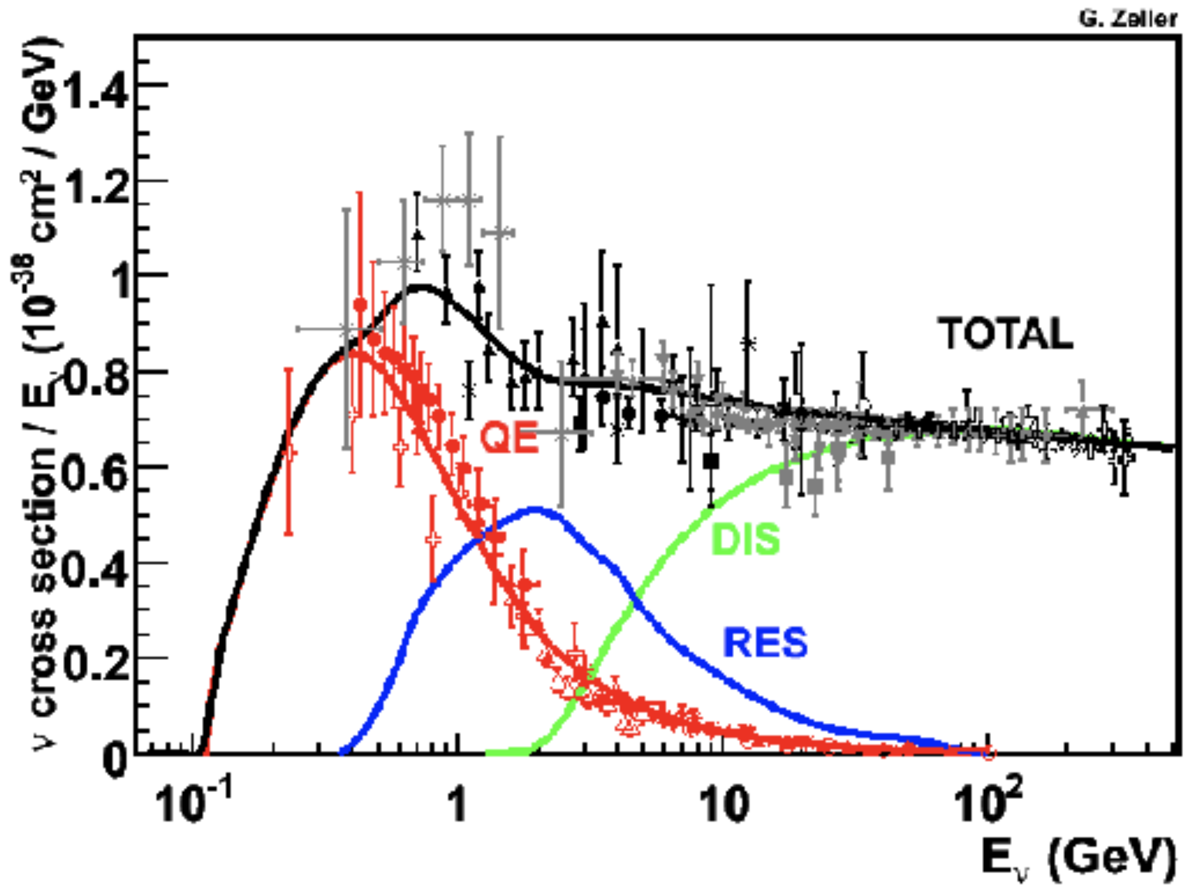
There is a general issue that affects all these (un)knowns:
neutrino interactions in nuclei are not known as precisely as desired

Theory: complex nuclear effects



Kajetan Niewczas @ NuFact2018

Experiment: relatively few data



ν cross sections in individual channels are known with a precision not better than 20-30%. A joint global fit with the existing generators to the existing data could reduce the uncertainties, as in QCD global fits of parton distribution functions

T. Katori, M. Martini, J. Phys. G45 (1) (2018) 013001

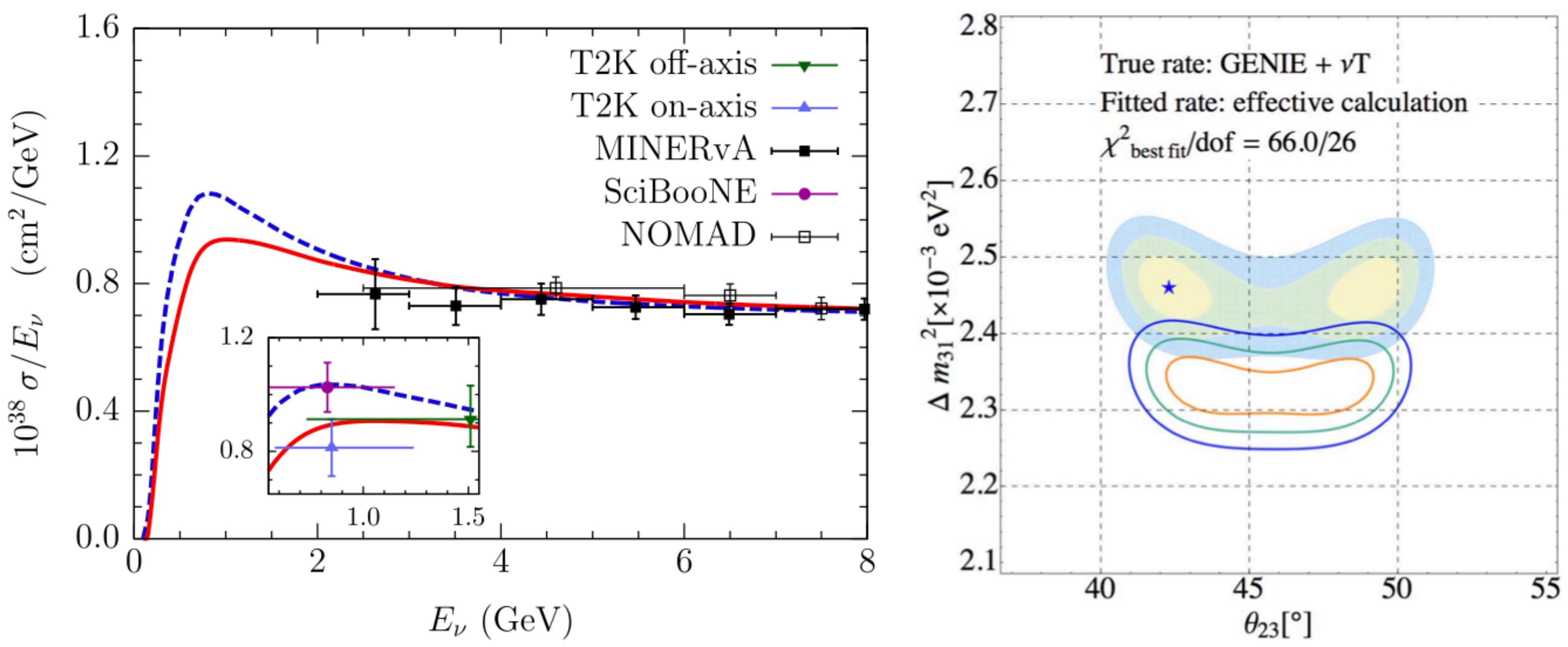


Figure 6. Impact of uncertainties of the 2*p*2*h* cross section for muon neutrinos on the oscillation analysis. Left: inclusive $^{12}_{6}\mathrm{C}(\nu_\mu, \mu^-)X$ cross sections obtained using the effective (solid line) and GENIE + νT (dashed line) calculations are compared with the NOMAD [16] and MINERvA [42] data. The inset presents the hydrocarbon results and

The impact of cross section uncertainties on the determination of oscillations parameter should not be underestimated

Very important is the precise knowledge of electron/muon neutrino cross section differences to check if there are any unexpected differences (Lesson learned from the reactor spectrum bump: errors may be larger than thought)

34

Correlations of common cross section model systematics in T2K and NOνA should be also estimated, since ignoring correlations artificially reduce systematic effects in the combination

Devi et al., arXiv:2201.08040v1

Future determination of CP violation and Mass Ordering in DUNE and HyperK-T2HK, a LArTPC and a water Cherenkov detector, relies on the knowledge of neutrino-argon and neutrino-water interactions at % level.

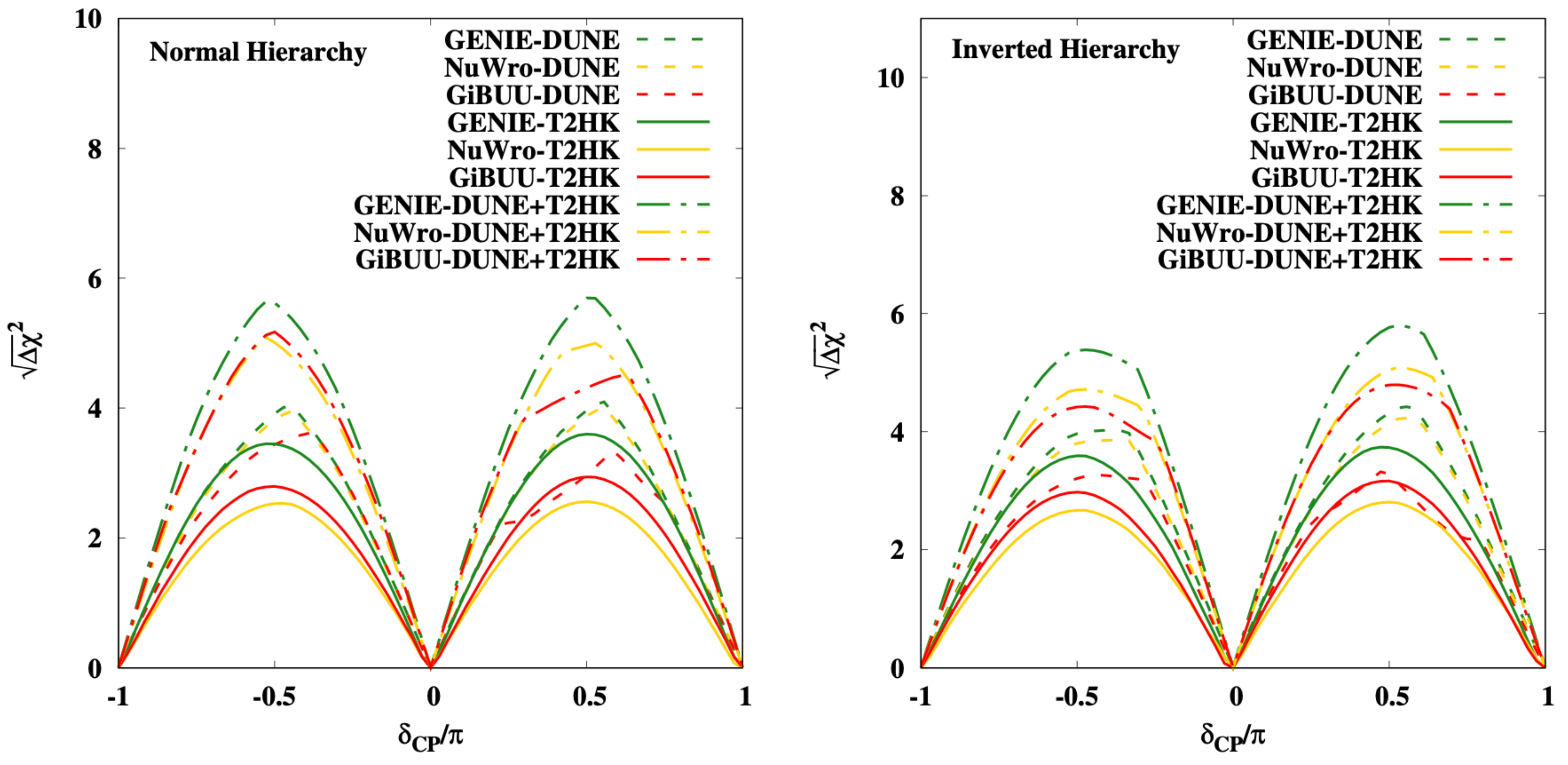


Figure 2: CP sensitivity measurement as a function of the true value of δ_{CP} for NH (left panel) and IH (right panel) by GENIE (green lines), NuWro(yellow lines), and GiBUU (red lines) for T2HK, DUNE, and T2HK+DUNE experiments.

Near future experiments will provide large amounts of data → Need to improve theoretical understanding and Monte Carlo implementation of all the reaction channels in the whole 1 to 10 GeV neutrino energy range

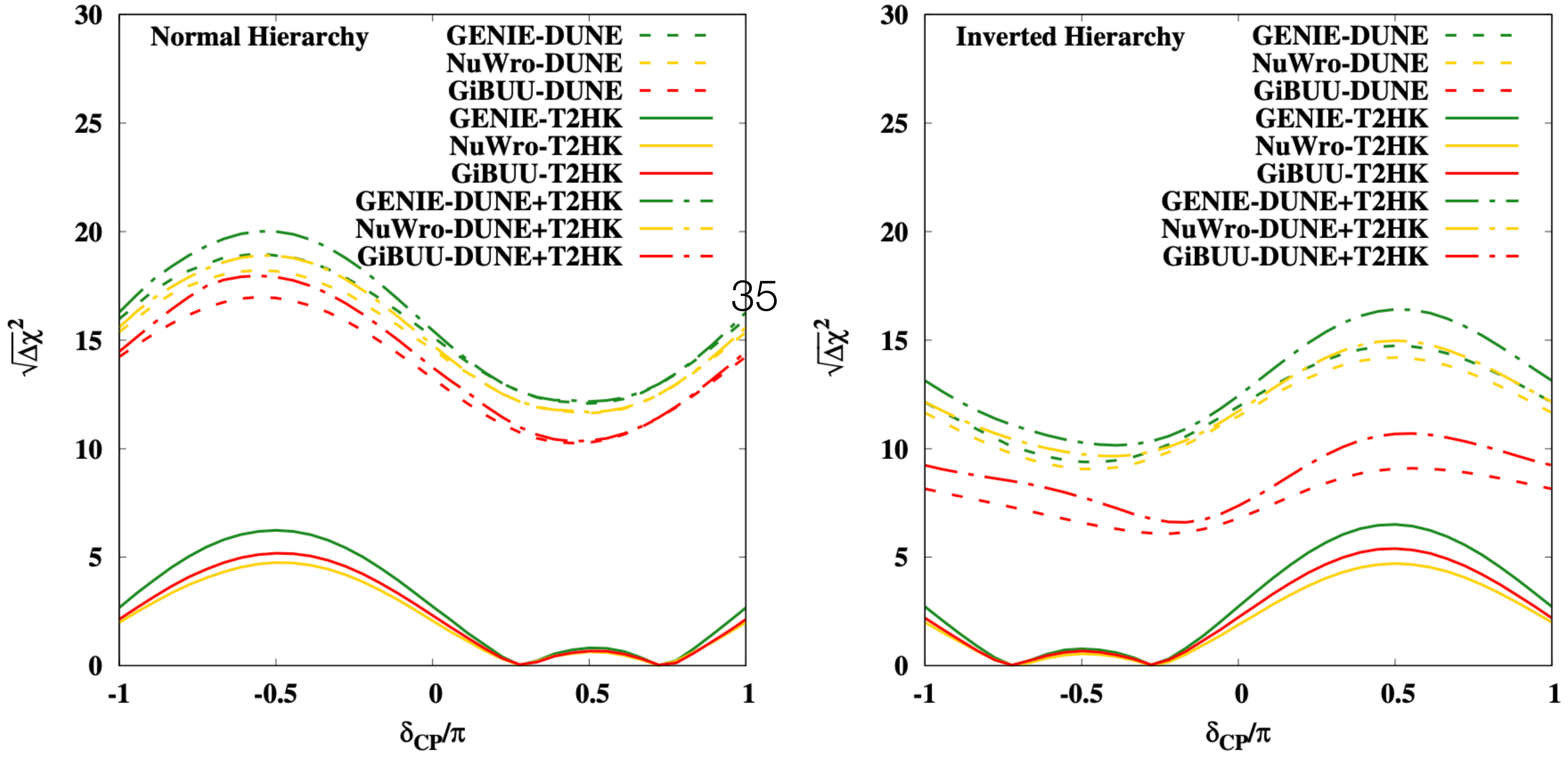


Figure 3: Mass hierarchy sensitivity measurement as a function of the true value of δ_{CP} for NH (left panel) and IH (right panel).

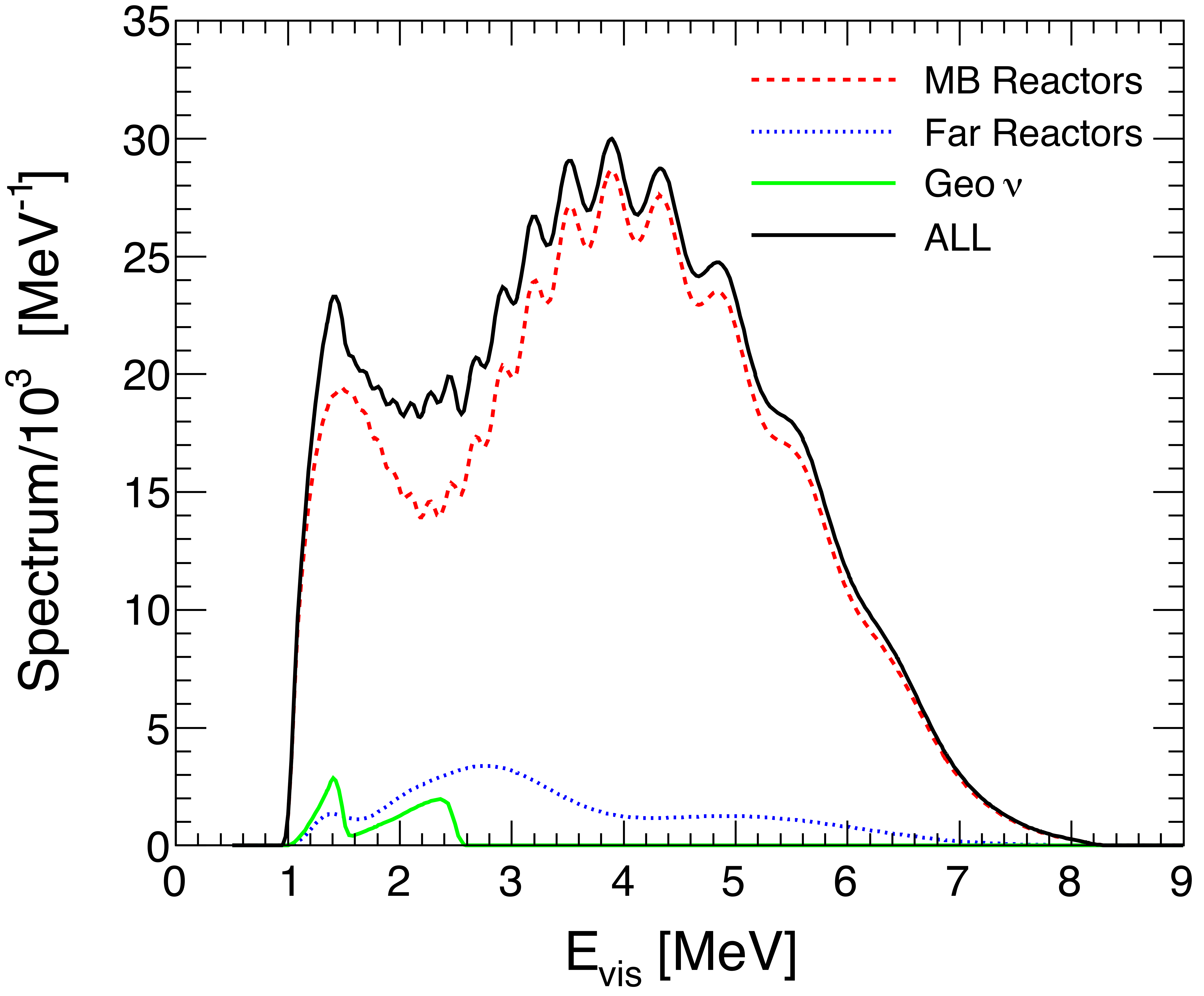
Medium-Baseline Reactor Neutrino Experiment

Possible discrimination of the hierarchy via high-statistics reactor neutrino experiments at medium baselines (few tens of km) was proposed more then 10 years ago

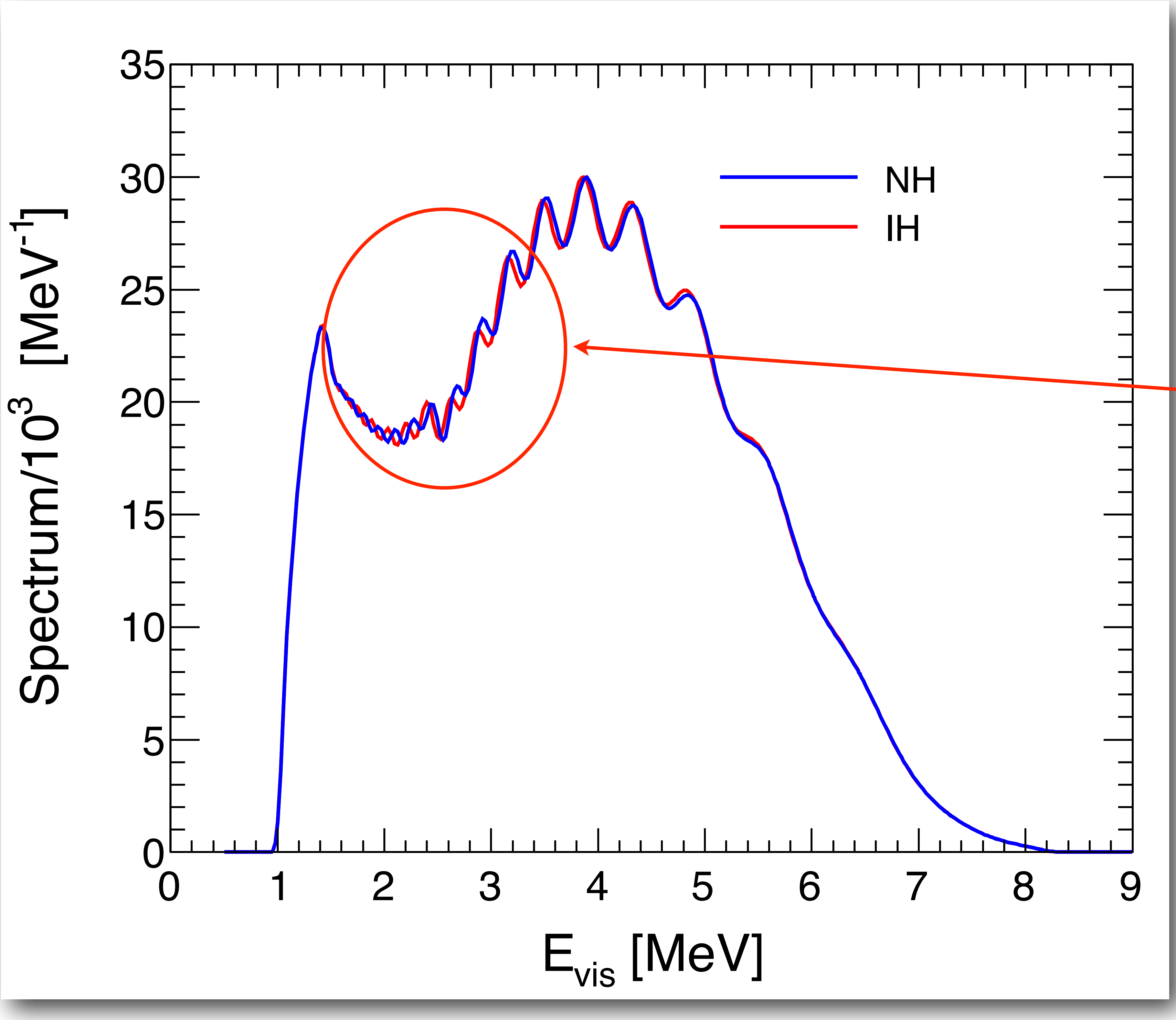
Probe mass-mixing parameters which govern oscillations at low frequency $(\delta m^2, \theta_{12})$ and at high frequency $(\Delta m^2, \theta_{13})$, and their tiny interference effects which depend on the mass hierarchy

Require unprecedented levels of detector performance and collected statistics, and the control of several systematics at (sub)percent level

Therefore, accurate theoretical calculations of reactor event spectra and refined statistical analyses are needed

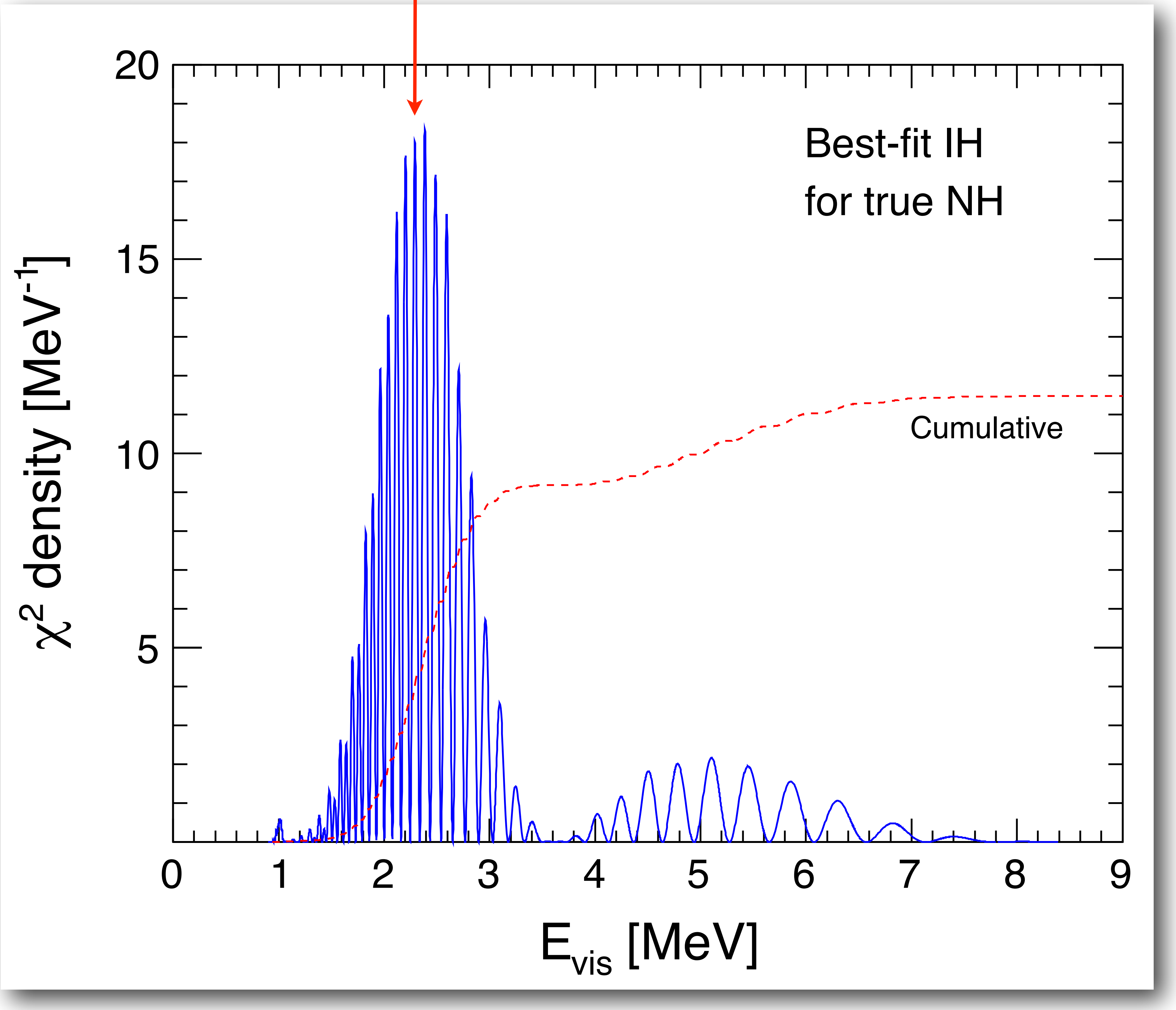


MB Reactors
Far Reactors
Geo ν
ALL
Spectrum/10^3 [MeV^-1]
E_vis [MeV]
0
5
10
15
20
25
30
35
0
1
2
3
4
5
6
7
8
9



Comparison between NH and IH, at central value oscillation parameters

Most of the discriminating power in the energy range $2-3$ MeV

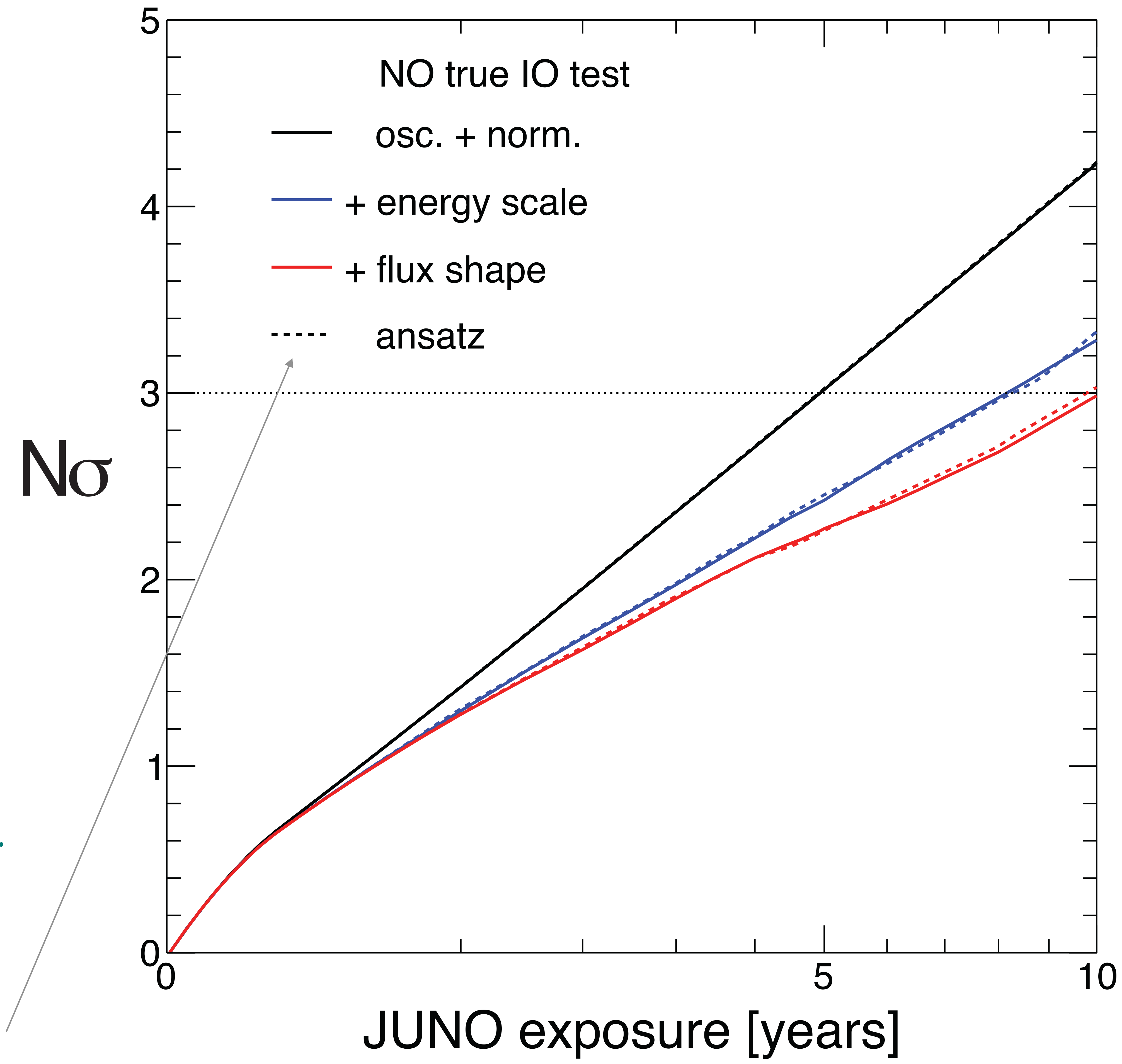


Comparison between NH reference data point and best fit for IH

Before DUNE and HyperK-T2HK, Sensitivity to mass ordering of JUNO

Main Physics goal:
Neutrino mass ordering determination at a $3 \div 4\sigma$ significance and the ν oscillation parameters $\sin^2\theta_{12}$, Δm^2, δm^2 measured at sub-percent level

The near detector TAO will provide a reference spectrum for the determination of neutrino mass ordering in JUNO and will be an essential tool to study the reactor antineutrino flux



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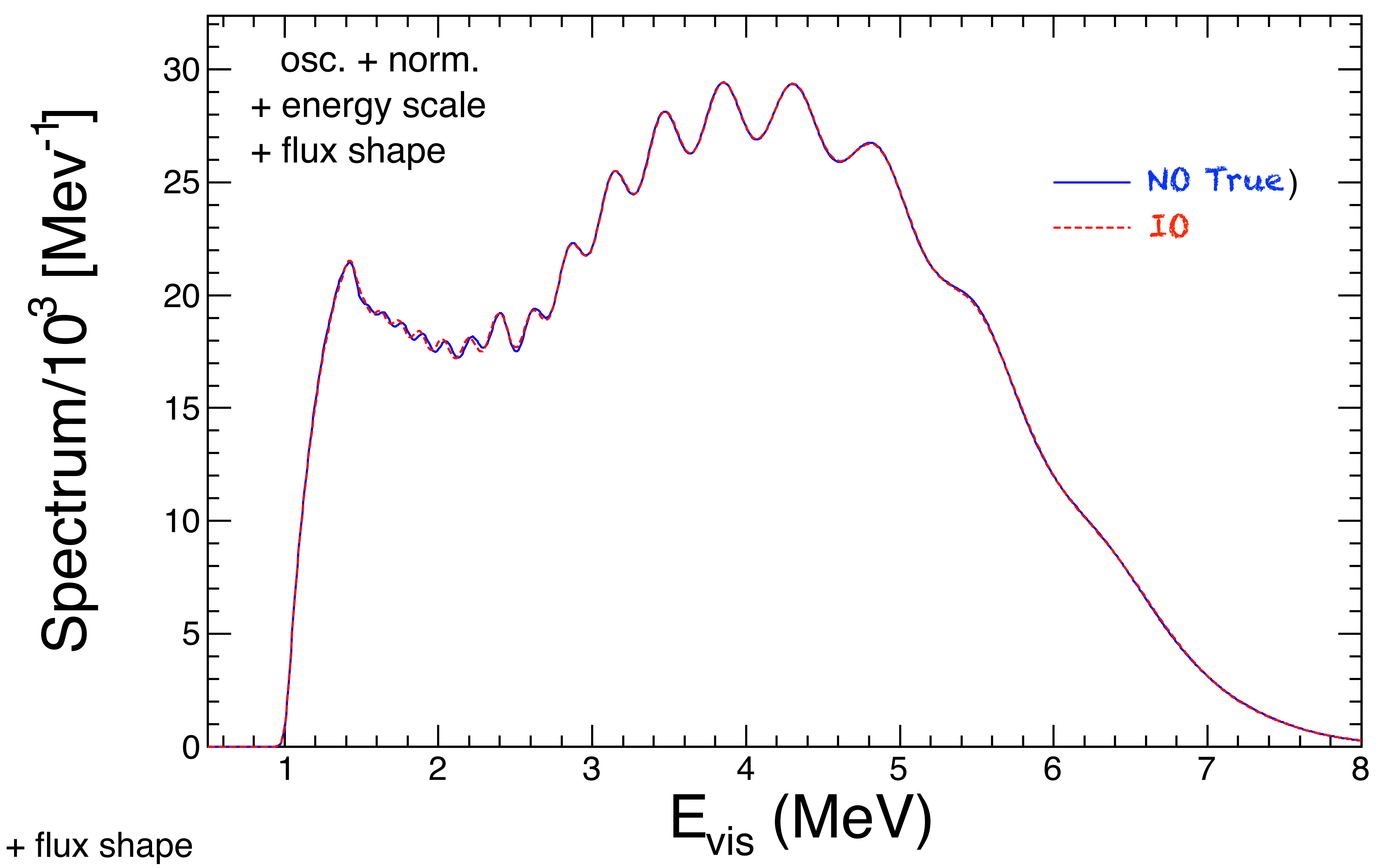
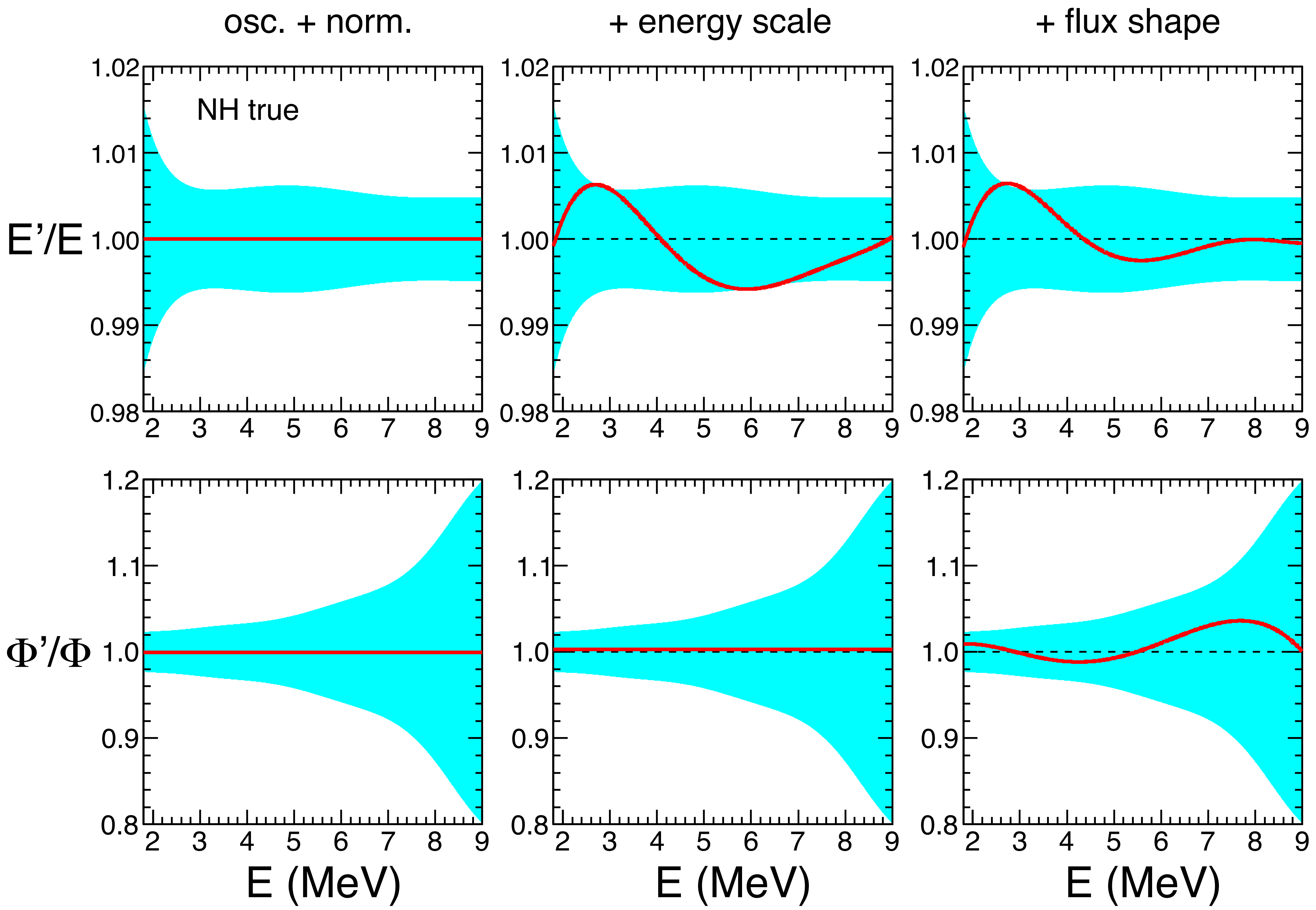
The experimentally measured TAO spectrum can be mapped into the oscillated JUNO spectrum without affecting the results of the analysis

After the inclusion of energy scale and flux shape uncertainties, NO (true) and IO (fit) spectra become less distinguishable -> some loss of sensitivity to mass ordering



Energy scale uncertainties
E->E'(E) stretch the "x-axis"

Flux shape uncertainties
Φ(E)->Φ'(E) stretch the "y-axis"



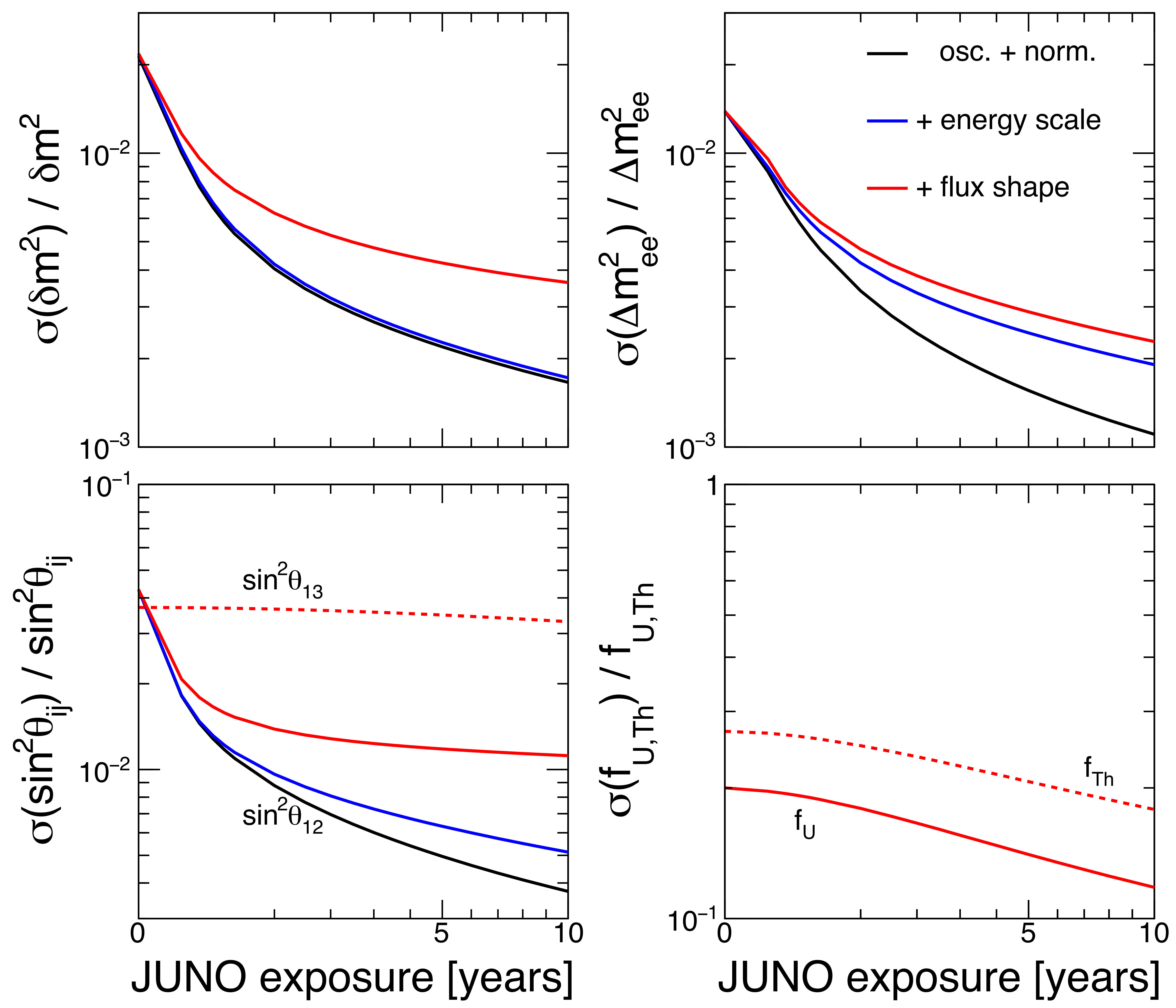
In the context of MBL experiments we introduce smooth deformations of the detector energy scale and the reactor anti-neutrino flux (up to 5th-order polynomials, i.e. +12 systematic pulls) constrained by current error bands (in blue at ±1σ)

Precision measurements of oscillation parameters

Sub-percent precision on $(\sin^2\theta_{12}, \Delta m^2, \delta m^2)$

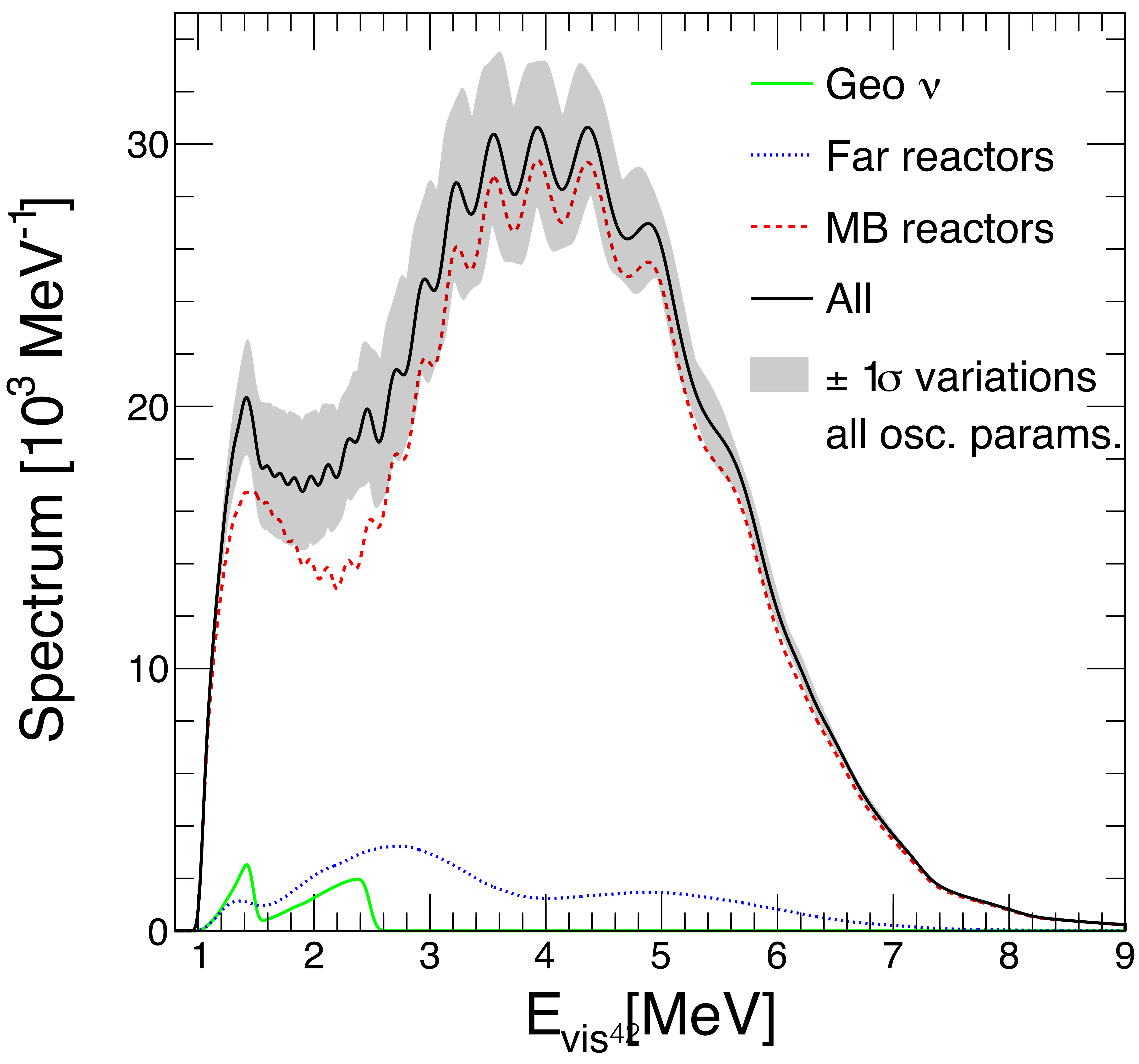
Such an incredible precision is paramount to break degeneracies in the oscillation parameters in the global analyses

Also essential to probe violations to the standard three-neutrino oscillation framework: unitarity of the mixing matrix, NSI, …

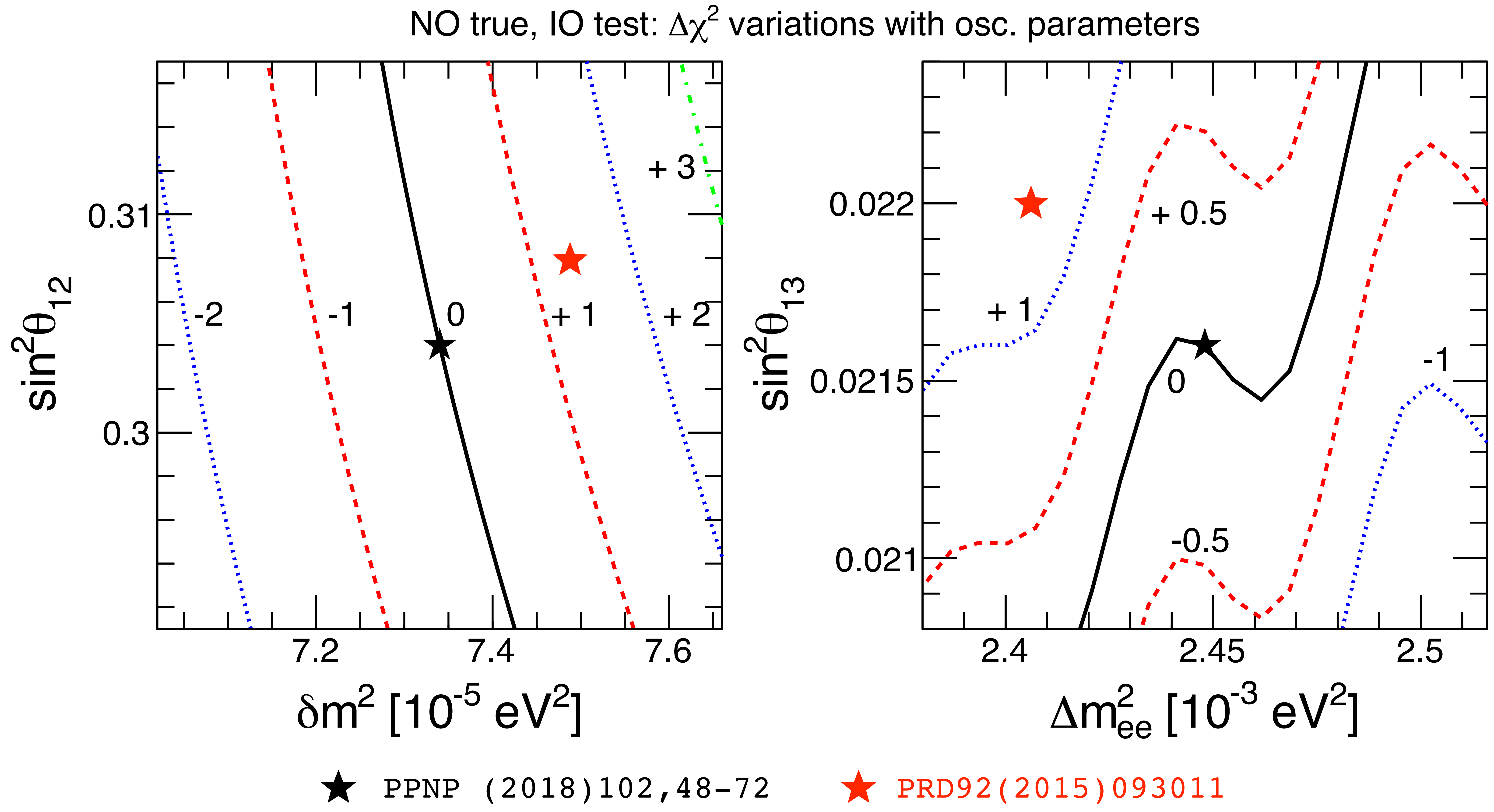


Phys.Rev.D 102 (2020) 5, 056001

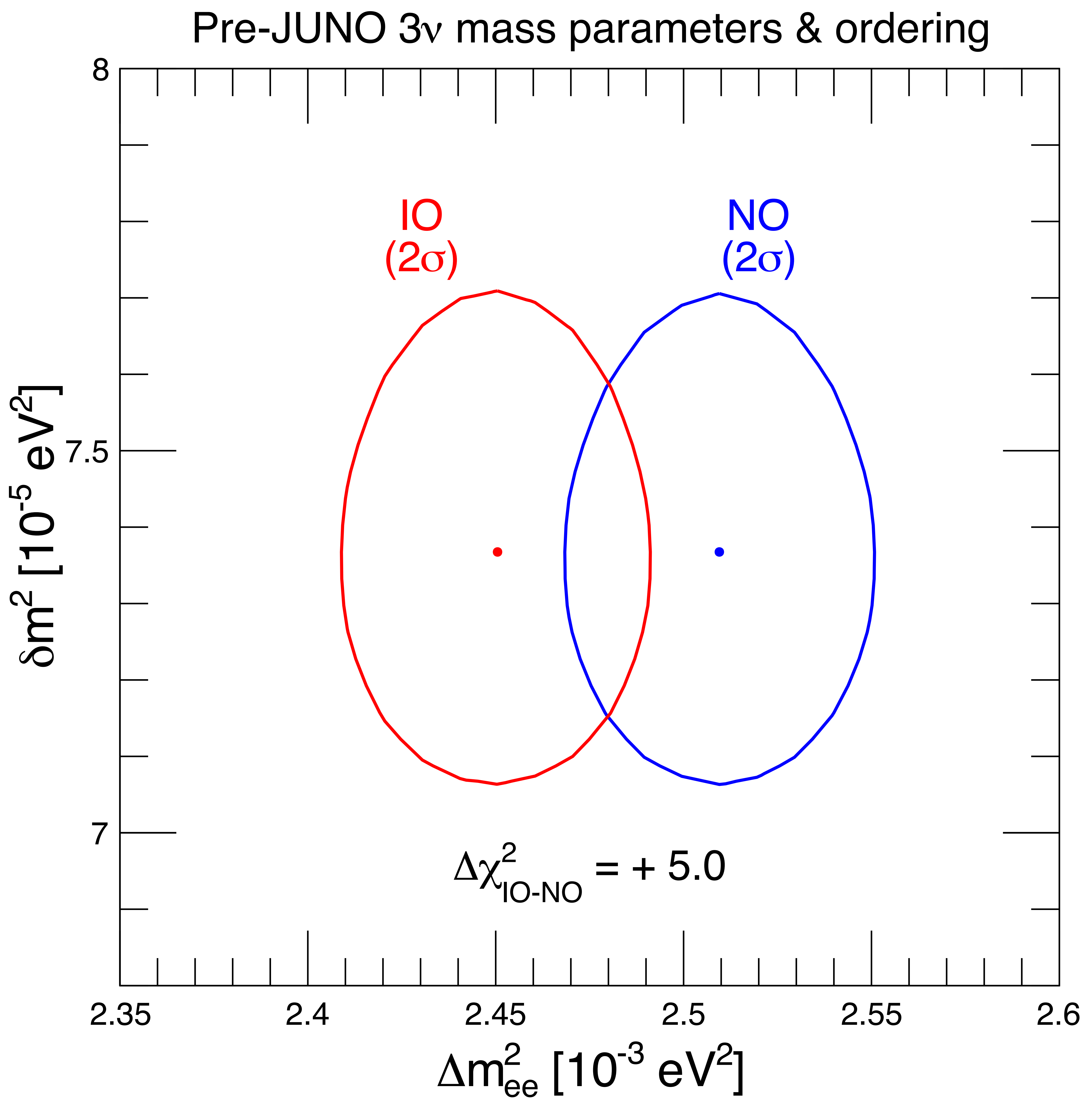
Varying the central values of oscillation parameters inside the current allowed 1σ region produces the gray shaded band for the predicted JUNO spectrum, after five years of data taking



JUNO sensitivity to mass ordering as a function of the oscillation parameter central values



The two most important parameters in this context are the two squared mass differences, but there is also a sensitivity to changes of the two mixing angles



Pre-JUNO 3ν mass parameters & ordering
IO
(2σ)
NO
(2σ)
$\Delta\chi^2_{IO-NO}$ = + 5.0
8
7.5
7
2.35
2.4
2.45
2.5
2.55
2.6
δm^2 [10^{-5} eV^2]
Δm^2_{ee} [10^{-3} eV^2]

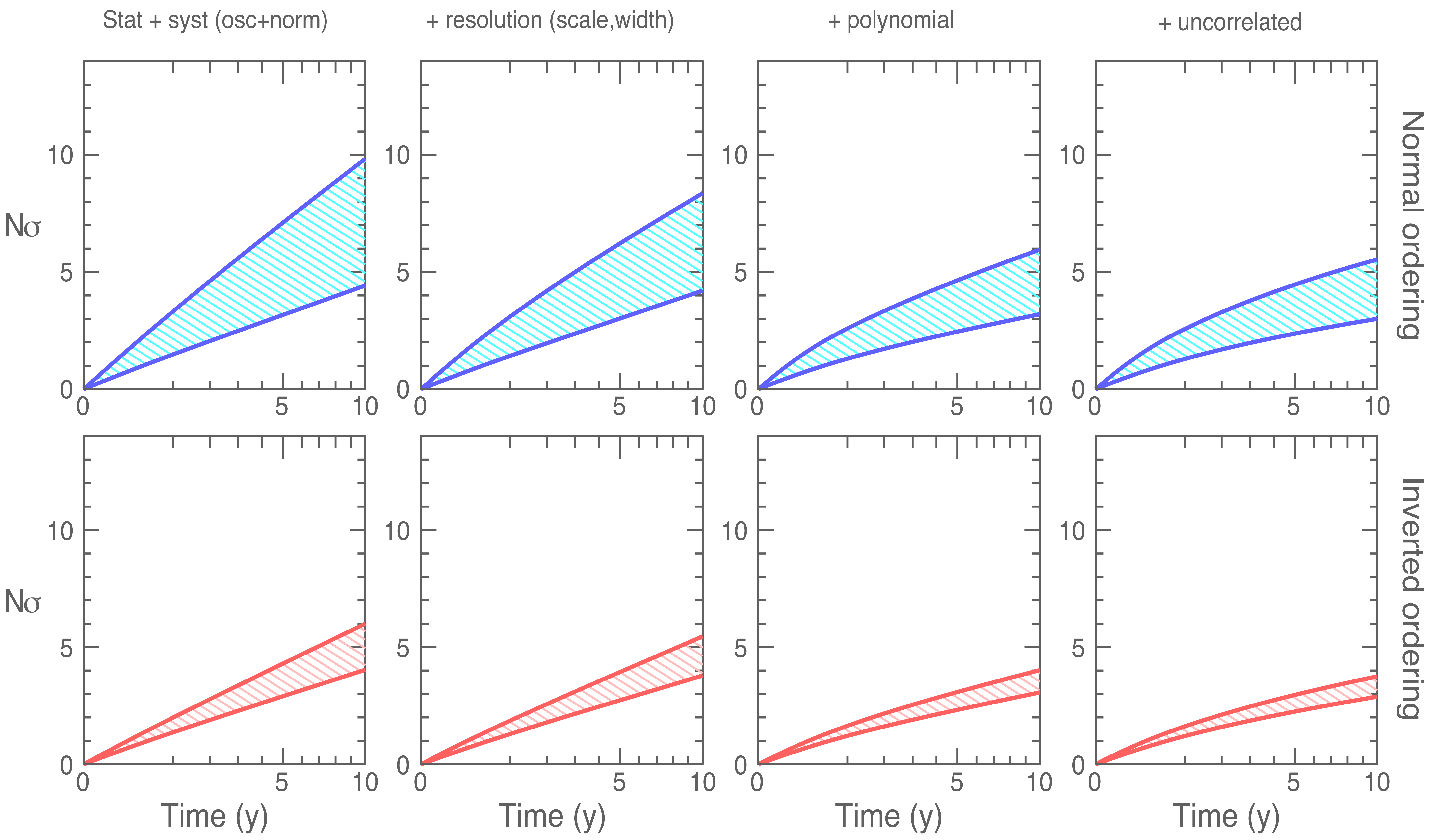
Conclusions for JUNO

The TAO spectrum will allow to calculate with very good accuracy the oscillated spectrum at JUNO, without any reference to a theoretical prediction

The fine structures of the ν spectrum do not constitute a problem for the MO sensitivity nor for the precision measurements of the oscillation parameters, even when all uncertainties in the summation calculation are taken into account (work in progress)

The projected JUNO sensitivity to MO depends more on the central values of the oscillation parameters than on the details of the ν spectrum

ORCA



Stat + syst (osc+norm)
+ resolution (scale,width)
+ polynomial
+ uncorrelated
Nσ
Nσ
Normal ordering
Inverted ordering
Time (y)
Time (y)
Time (y)
Time (y)

Three observables $(m_\beta, m_{\beta\beta}, \Sigma)$ sensitive to the absolute ν masses and broadly speaking three classes of experiments

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

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

$0\nu\beta\beta$ decay experiments sensitive to the "Effective Majorana mass":

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

Cosmology and Astrophysics observations, dominantly sensitive to the sum of neutrino masses:

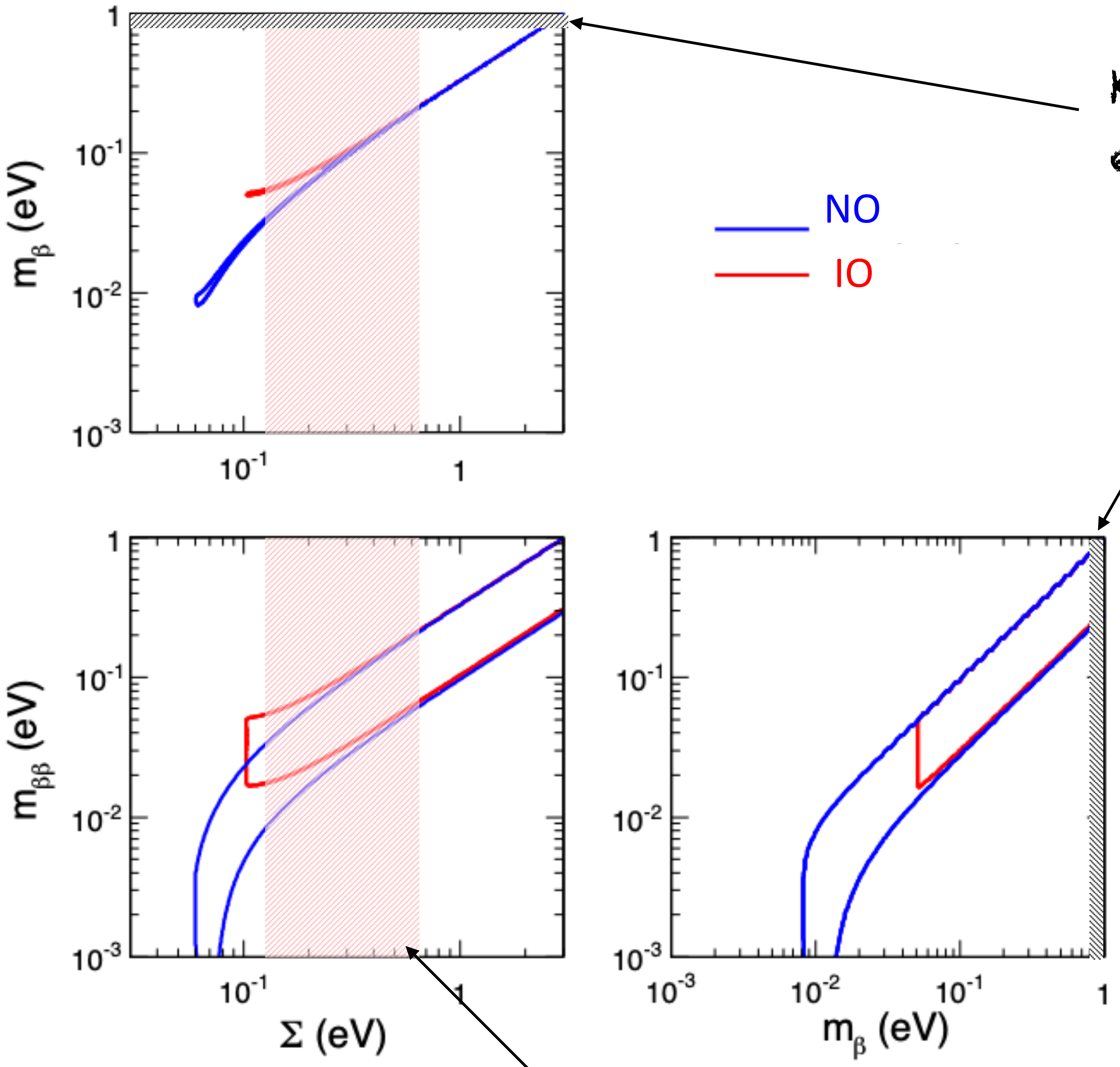
$$\Sigma = m_1 + m_2 + m_3$$

These observables may provide handles to distinguish NO/IO.

Majorana case gives a new source of CPV (unconstrained)

The three observables are correlated by oscillation data->

Impact of oscillations on nonoscillation parameter space



KATRIN result: $m_\beta < 0.8$ eV 90% C.L.

(Nature Physics 18, 160–166 (2022))

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

"Cosmology" results: $0.12 \lesssim m_\beta \lesssim 1$ eV 90% C.L.

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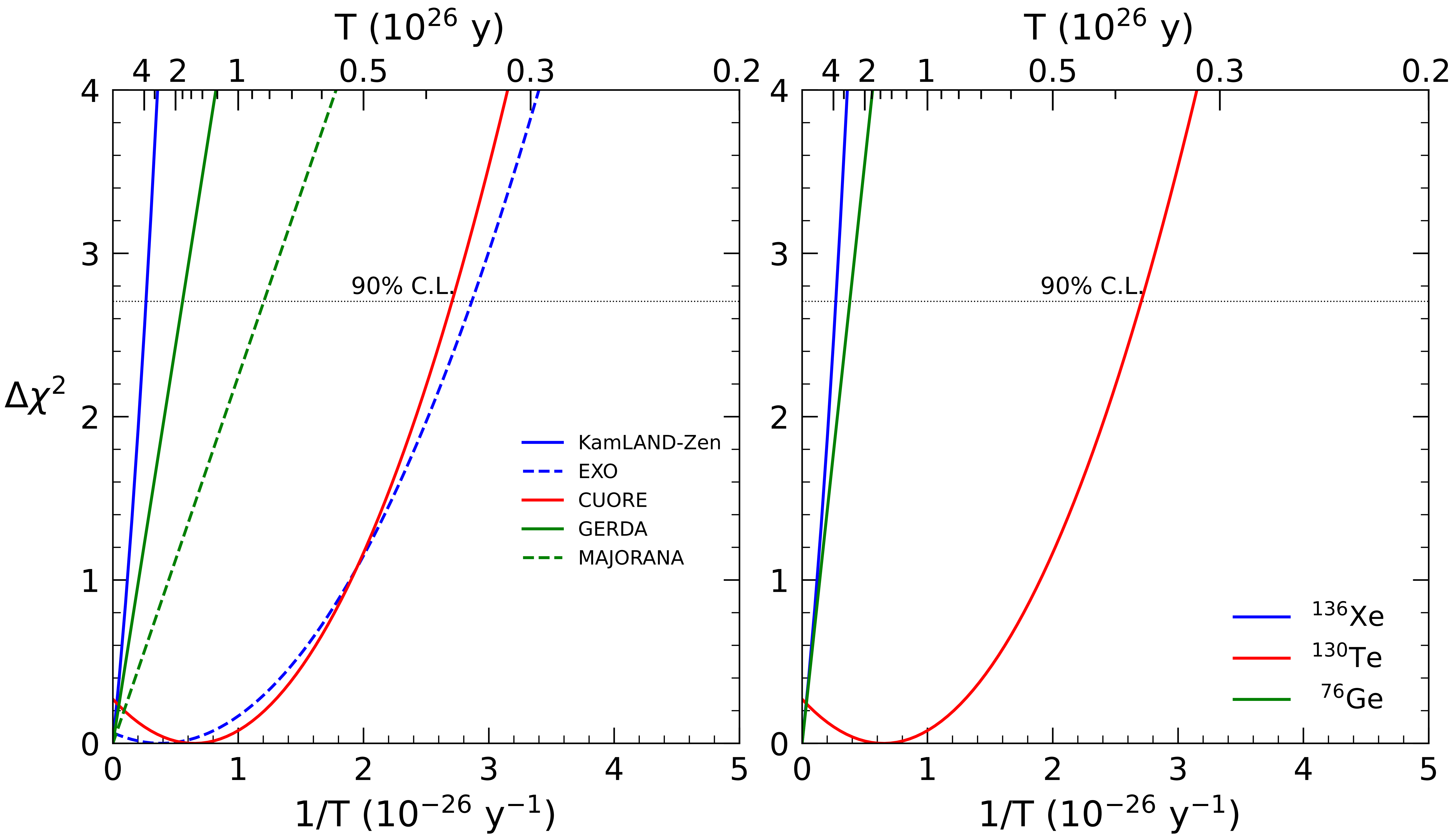
looking more closely at $0\nu\beta\beta$ results →

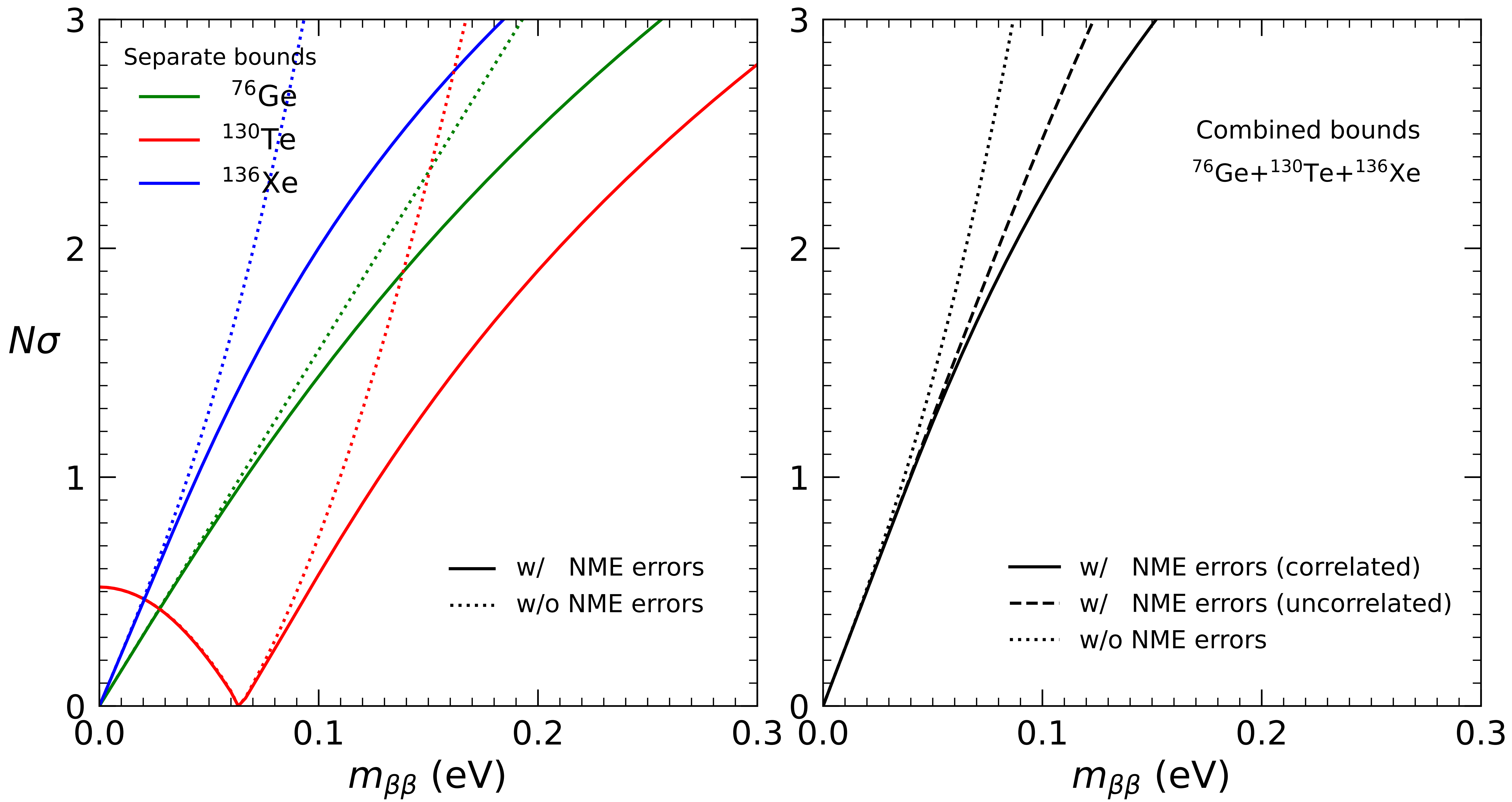
Neutrinoless Double Beta Decay results



$S = 1/T$ is proportional to $m^2_{\beta\beta}$

Translating bounds on the half-life T to bounds on $m_{\beta\beta}$ requires the knowledge of the nuclear matrix element M (NME) for the decay at issue since $\frac{1}{T} = \text{phase space} \times |M|^2 \times m^2_{\beta\beta}$

Neutrinoless Double Beta Decay results



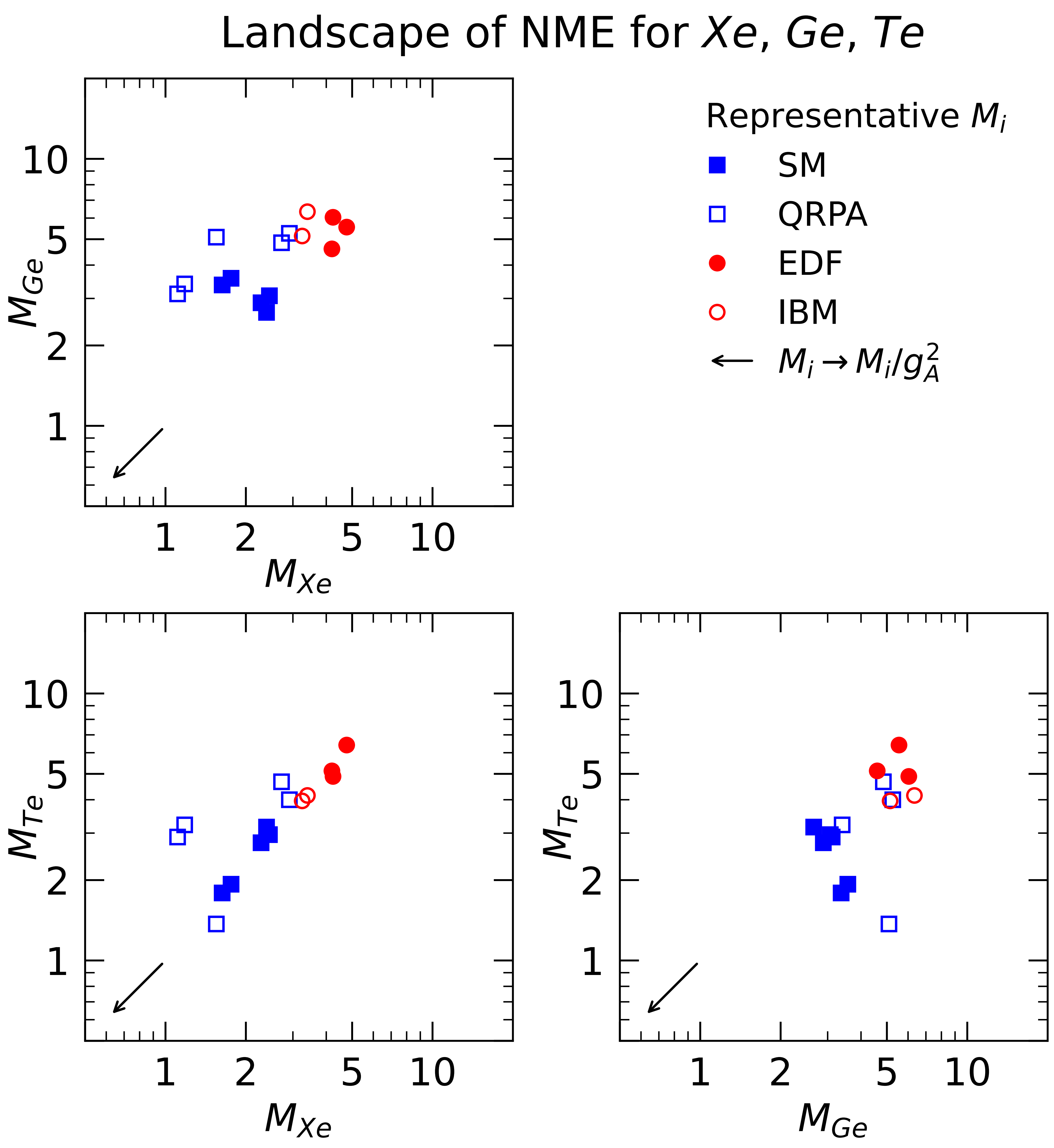
$S = 1/T$ is proportional to $m_{\beta\beta}^2$

Translating bounds on the half-life T to bounds on $m_{\beta\beta}$ requires the knowledge of the nuclear matrix element M (NME) for the decay at issue since $\frac{1}{T} = \text{phase space} \times |M|^2 \times m_{\beta\beta}^2$

The Spread between different calculations is still large, about a factor $2 \div 5$

Theoretical errors in a given model for different nuclei are correlated. This fact should be taken into account, if known, when combining different experiments

g_A quenching is another source of a potentially large error on Nuclear Matrix Elements



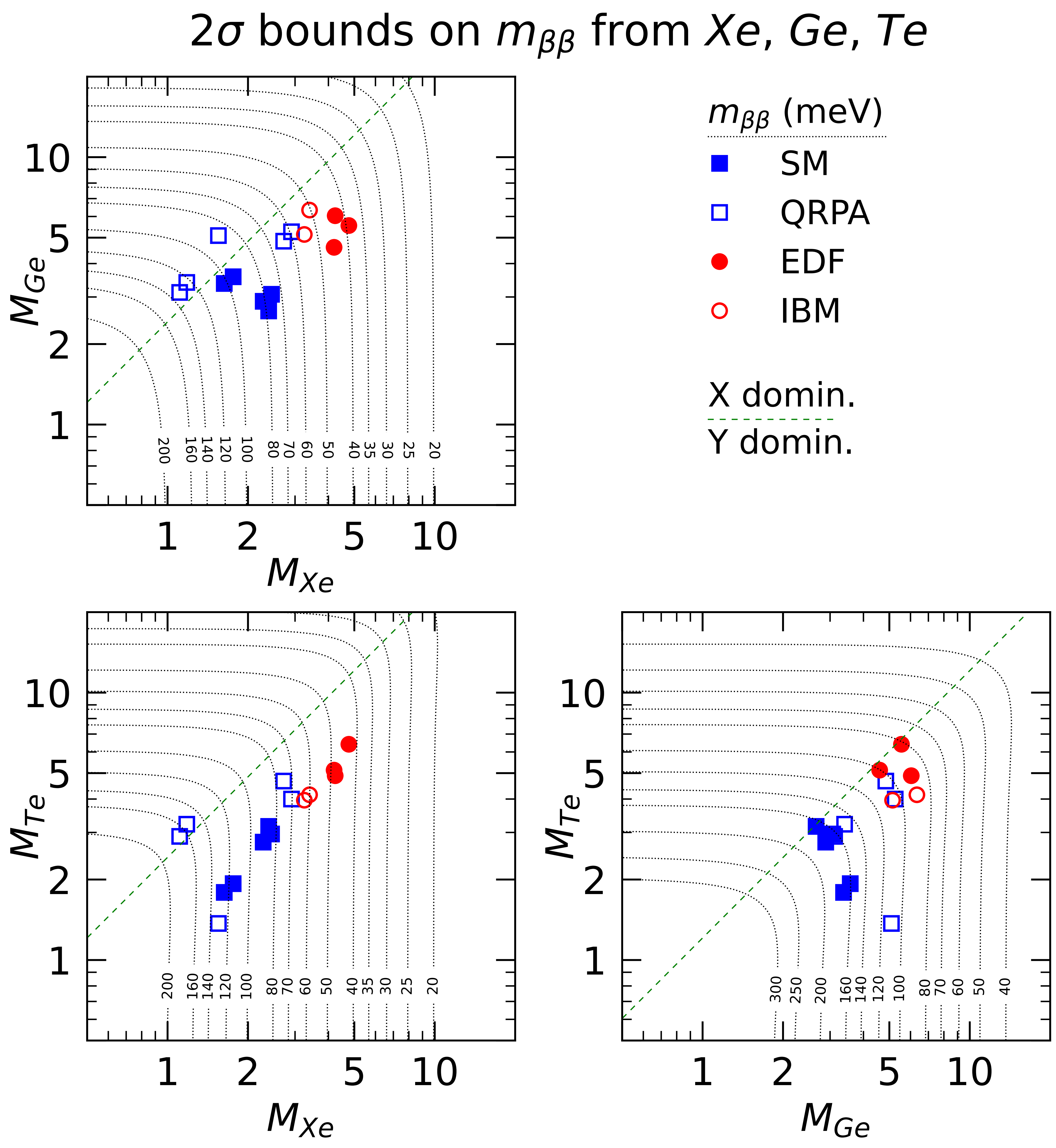
Compilation of NME from Agostini et al., arXiv:2202.01787

Planes of NME for the three nuclei Xe, Ge, Te and isolines of bounds on $m_{\beta\beta}$ at 2σ

Read bounds on $m_{\beta\beta}$ for each calculated model at once, both considering experiments separately and in the combination

Consistence of the bounds on $m_{\beta\beta}$ from different nuclei (the combination of data is not always trivial)

Given the present sensitivity, two-dimensional projections of the combination of all three nuclei results do not appreciably differ from the combinations shown here



Summary for $0\nu\beta\beta$ searches

Quintessential to probe the Majorana nature of neutrinos

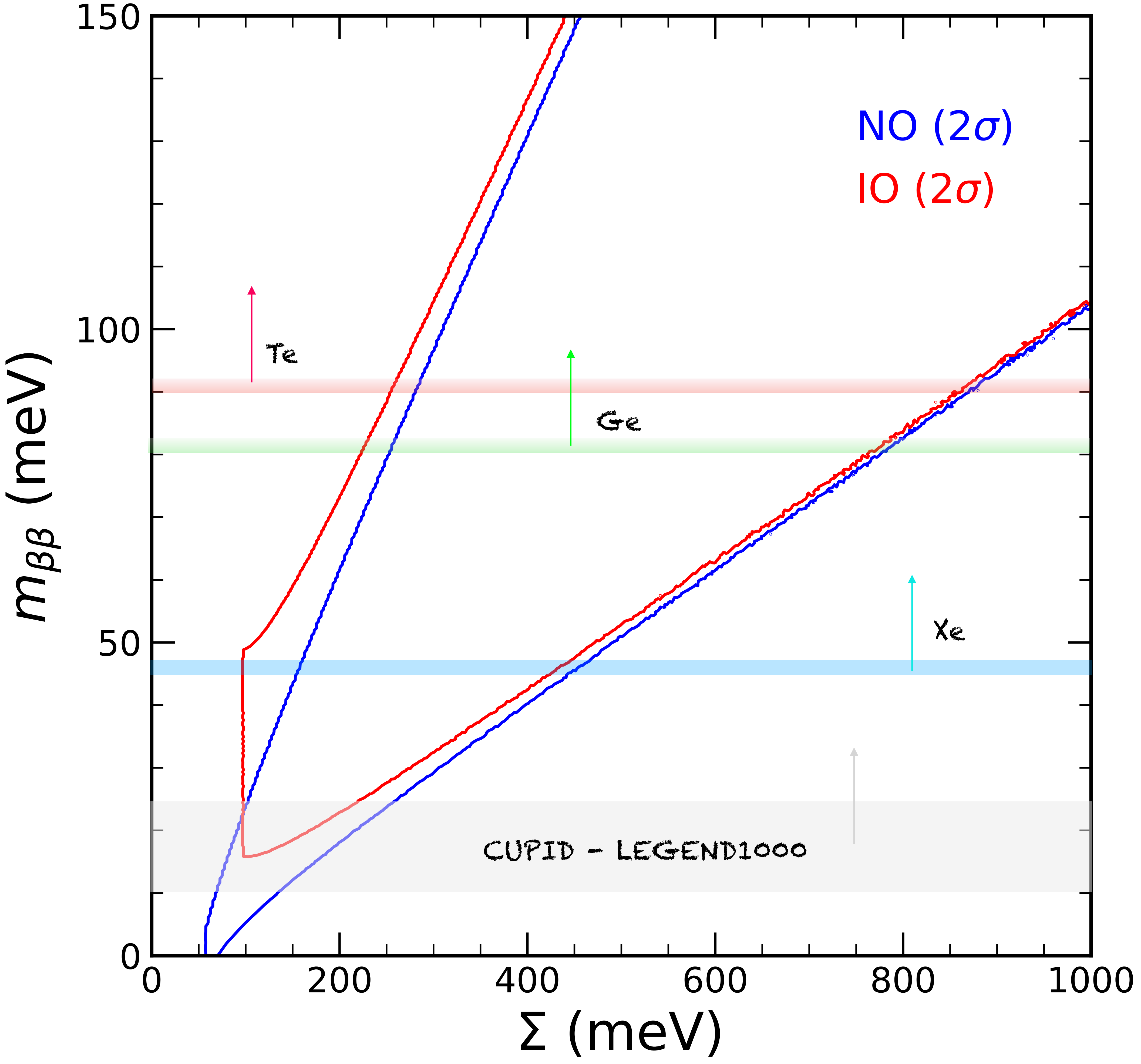
Experiments now probing the region of non-degenerate masses

Next-generation experiments will explore and possibly exclude all the region of Inverted Mass ordering (if neutrino masses are the exclusive mechanism for $0\nu\beta\beta$

Starting to be sensitive to Majorana phases, if Mass Ordering is known

Important to have experiments with different nuclei to check the consistency of the theoretical calculations (the combination can be tricky and also correlations, if known, should be taken into account)

Current bounds and future sensitivity



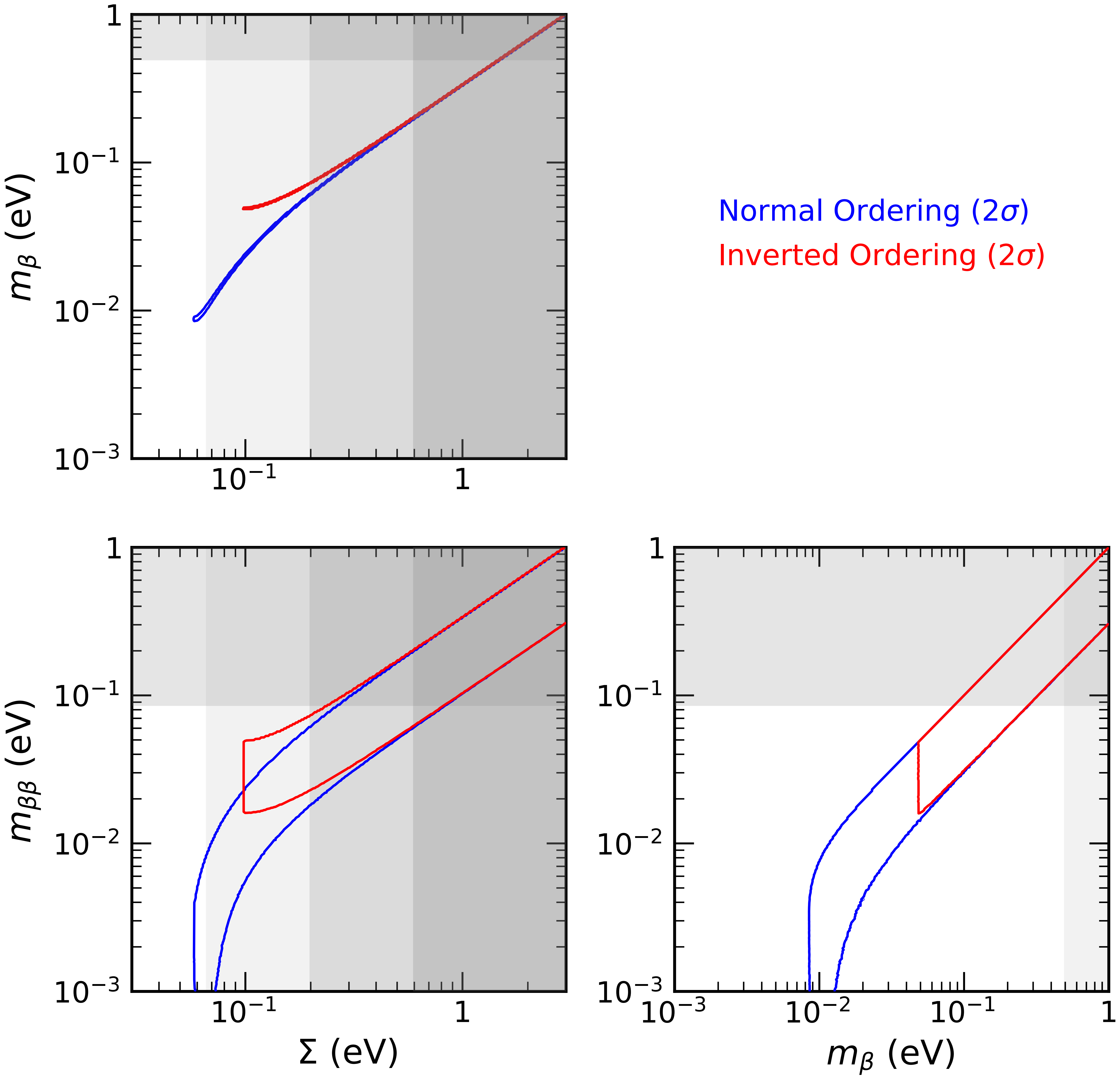
On the other side of the plot: bounds on Σ –>

TABLE IV. Results of the cosmological data analysis under three model assumptions: standard cosmology with neutrino masses (ΛCDM $+ \Sigma$), an extended model accounting for lensing systematics (ΛCDM $+ \Sigma + A_{\rm lens}$), and a nonstandard cosmology with dynamical dark energy and neutrino masses ($w_0 w_a$CDM $+ \Sigma$). The datasets used are listed in Sec. III C. For Planck, we consider both Plik and CamSpec likelihoods, which yield very similar results in all cases (shown explicitly only for ΛCDM $+ \Sigma$). Upper bounds on Σ are reported at the 2σ level.

No.	Model	Dataset	Σ (2σ) (eV)
1	ΛCDM $+ \Sigma$	Plik	< 0.175
2		Plik + DESI	< 0.065
3		Plik + DESI + PP	< 0.073
4		Plik + DESI + DESy5	< 0.091
5		CamSpec	< 0.193
6		CamSpec + DESI	< 0.064
7		CamSpec + DESI + PP	< 0.074
8		CamSpec + DESI + DESy5	< 0.088
9	ΛCDM $+ \Sigma + A_{\rm lens}$	Plik	< 0.616
10		Plik + DESI	< 0.204
11		Plik + DESI + PP	< 0.255
12		Plik + DESI + DESy5	< 0.287
13	$w_0 w_a$CDM $+ \Sigma$	Plik	< 0.279
14		Plik + DESI	< 0.211
15		Plik + DESI + PP	< 0.155
16		Plik + DESI + DESy5	< 0.183

Premature to quote a
"consensus" upper bound on Σ from cosmological data
at
present.

We prefer to quote a "range" of upper bounds,
noticing that the 2σ cosmological limits on Σ from
Table IV
cluster around a reasonable "geometric average" value
of
$\Sigma < 0.2$ eV, with variations up to a factor of 3 (up- or
downward), depending on the specific model and
dataset
employed.



Some general remarks

Cosmological + astrophysical analyses are based on a model, the Standard Cosmological Model (ΛCDM), not as solid as the SM of particle physics

Degeneracies exist between Σ and other cosmological parameters, as for instance the optical depth at reionization, the number of relativistic species and the parameter governing the dark energy evolution

Upcoming and future experiments on large scale structures could reduce the error on Σ to ~ 30 meV or ~ 15 meV in combination with CMB data, entirely probing the IO region and also with a possible signal in the NO region

(see for instance JCAP11(2019) 034,and JCAP06(2013) 020)

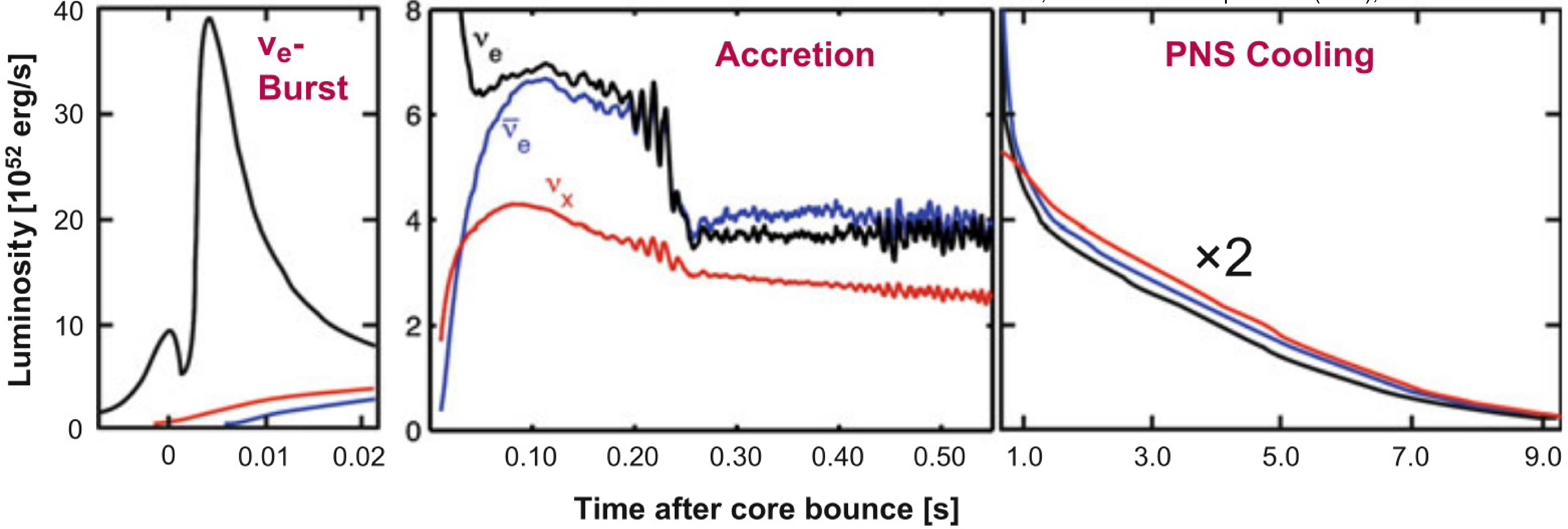
In the next decade Cosmological data + $0\nu\beta\beta$ searches have a good chance to measure neutrino masses and to give precious informations on the New Physics even through possible tensions between data

What Supernova Neutrinos can tell us?

While in the past SN neutrinos would have give us important information also on the oscillation parameters, today the most important piece of information we could have from a SN neutrino signal is on the mass ordering

SN neutrinos fluxes

Janka H.-T., in: Handbook of Supernovae (2016); arXiv:1702.08825



Emission on Time scale of 10 sec with different flux characteristics and hierarchies, matter and neutrino densities

Energy range ~1-100 MeV with different mean energy hierarchies in the three phases

Different kind of flavor conversions

General References

K. Scholberg, arXiv:1707.06384,J.Phys. G45 (2018) no.1, 014002

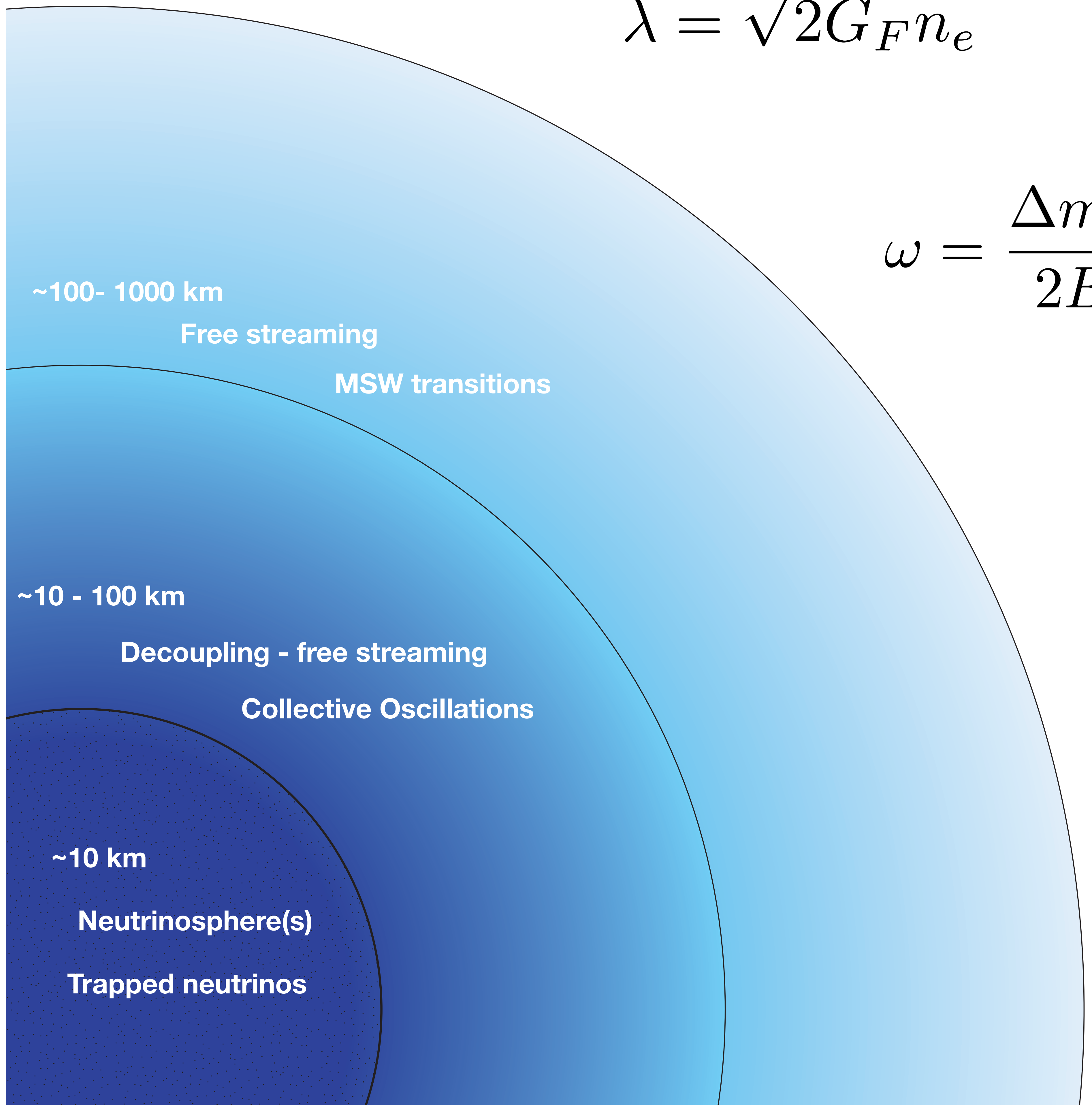
A. Mirizzi, I. Tamborra, H.T. Janka, N. Saviano, K. Scholberg, R. Bollig, L. Hudepohl, . Chakraborty. arXiv:1508.00785, Riv.Nuovo Cim. 39 (2016) no.1-2, 1-112.

Regimes of SN neutrino flavor transition governed by the relative size of

$$\mu = \sqrt{2} G_F (n_\nu + n_{\bar{\nu}})$$ neutrino self-interaction potential

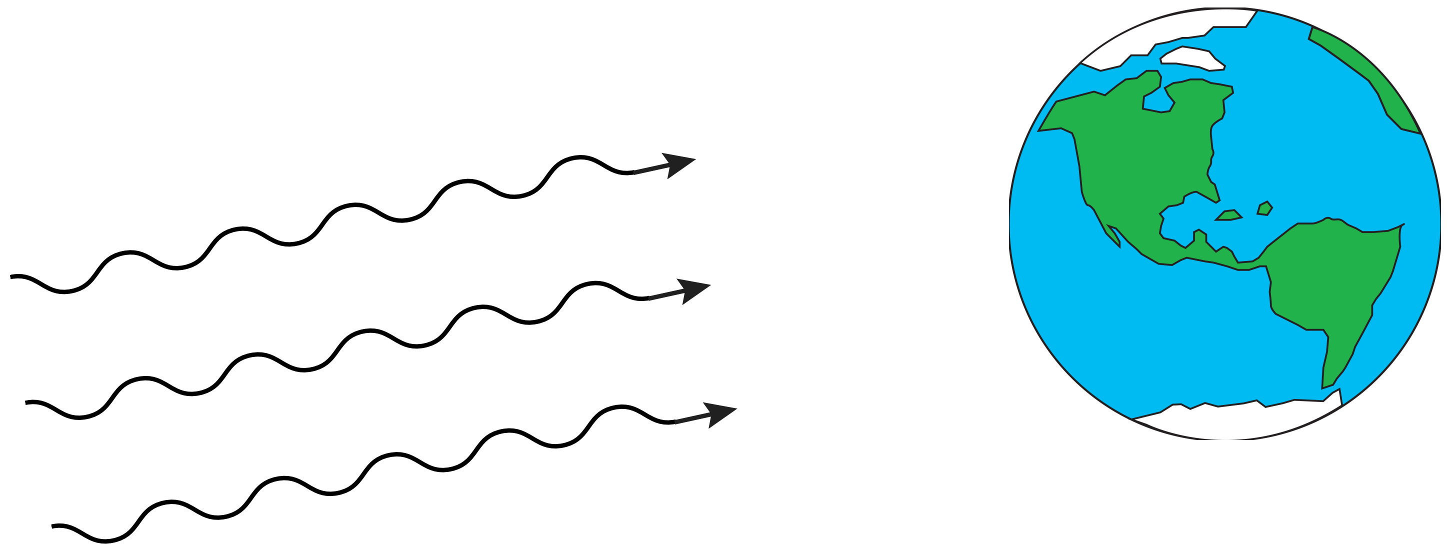
$$\lambda = \sqrt{2} G_F n_e$$ matter potential

$$\omega = \frac{\Delta m^2}{2E}$$ vacuum oscillation frequency



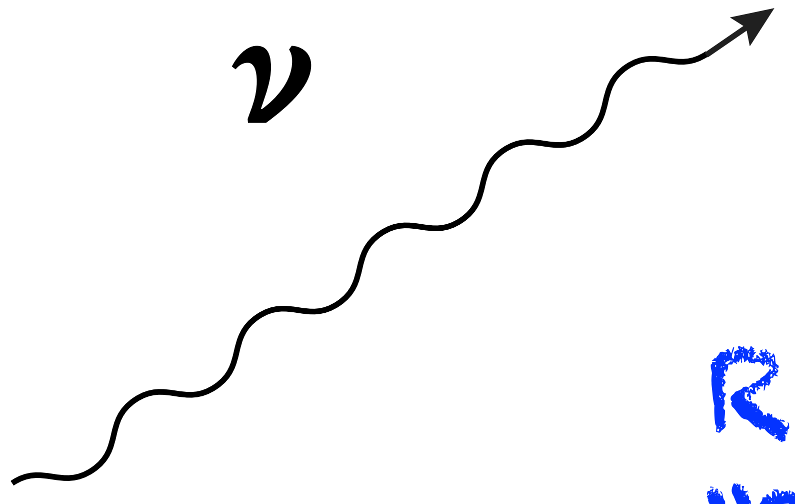
Neutrinos travel to earth

Kinematical decoherence



Possible MSW when passing through the Earth

From Outside to inside



R~1000 km
MSW conversion
Resonance at λ ~ ω

R~100km
"Slow" Collective conversion
Oscillation frequency $1/t \sim \sqrt{\omega\mu}$
Spectral swaps at μ ~ ω

R~10 km (at edge of the Neutrinosphere)
Decoupling
"Fast" Collective conversion
Oscillation frequency $1/t \sim \mu$

Single-angle approximation:
spectral swaps in IO

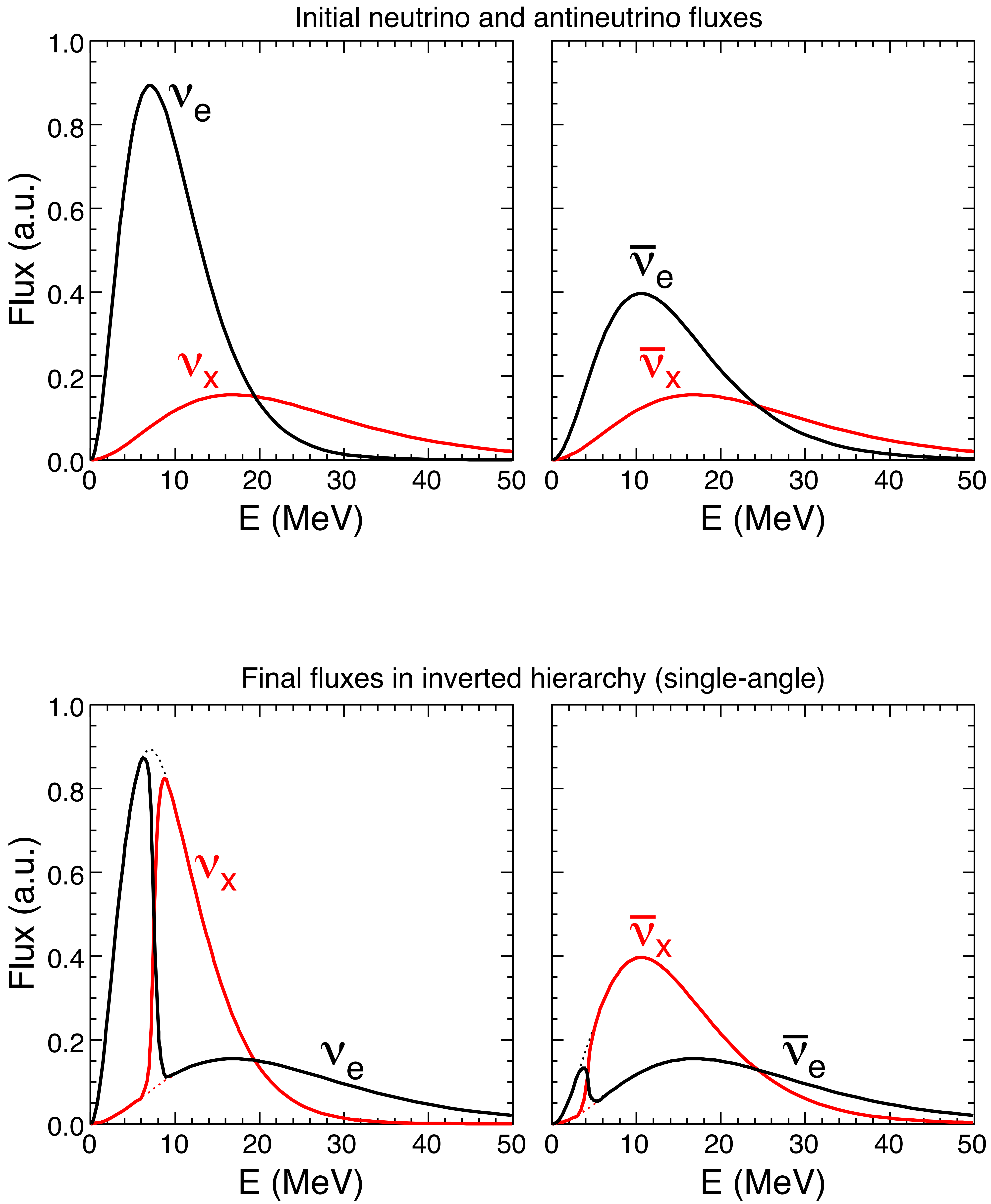
More realistic scenarios:

- multi-angle effects tend to smear spectral splittings

- matter multi-angle effects tend to block self-induced flavor conversions

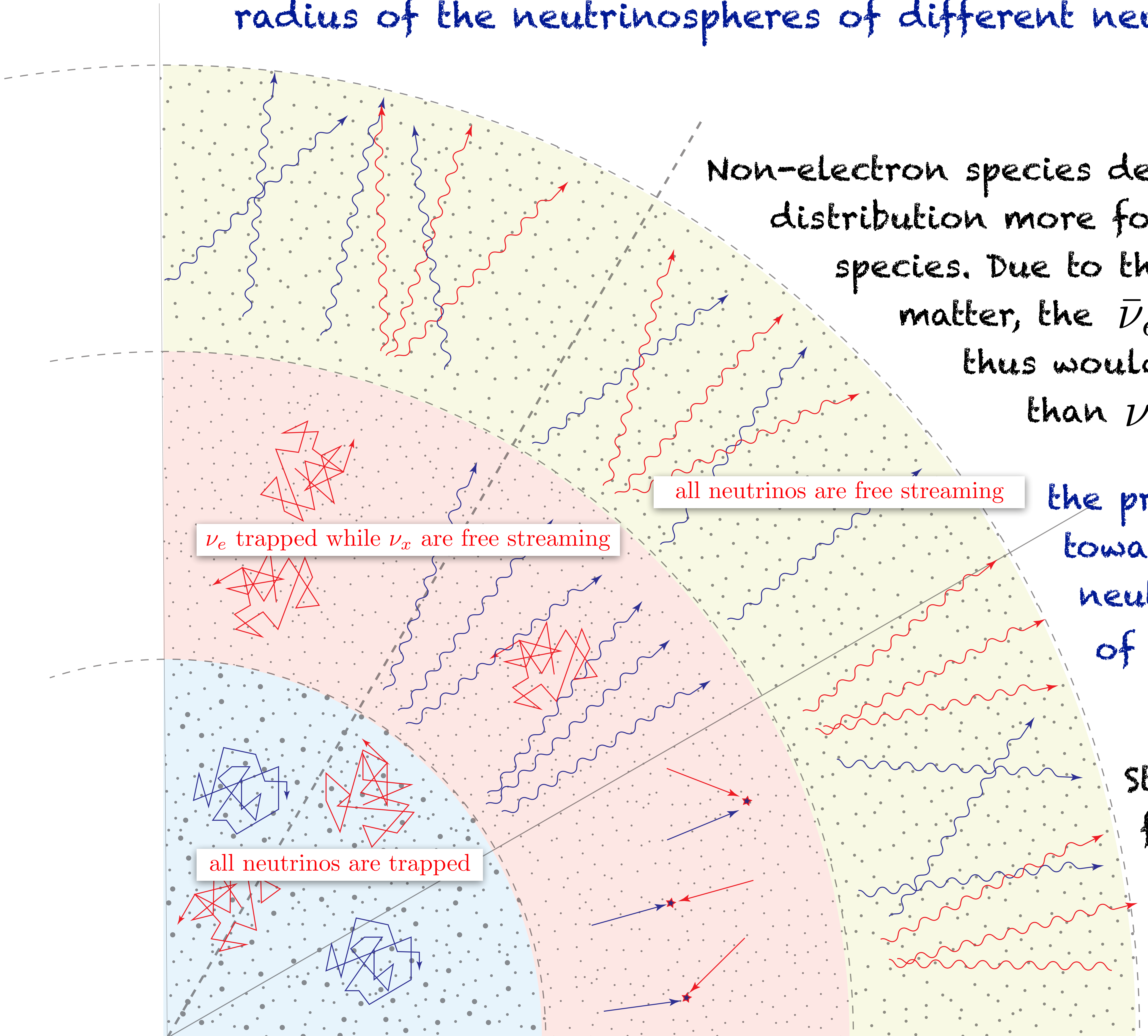
- breaking of space-time symmetries could favour flavor decoherence

- collective effects depend on ν flux hierarchy and less pronounced flavor hierarchies multiple splits can arise (and swaps can occur also in NO)



"Fast" collective neutrino conversions

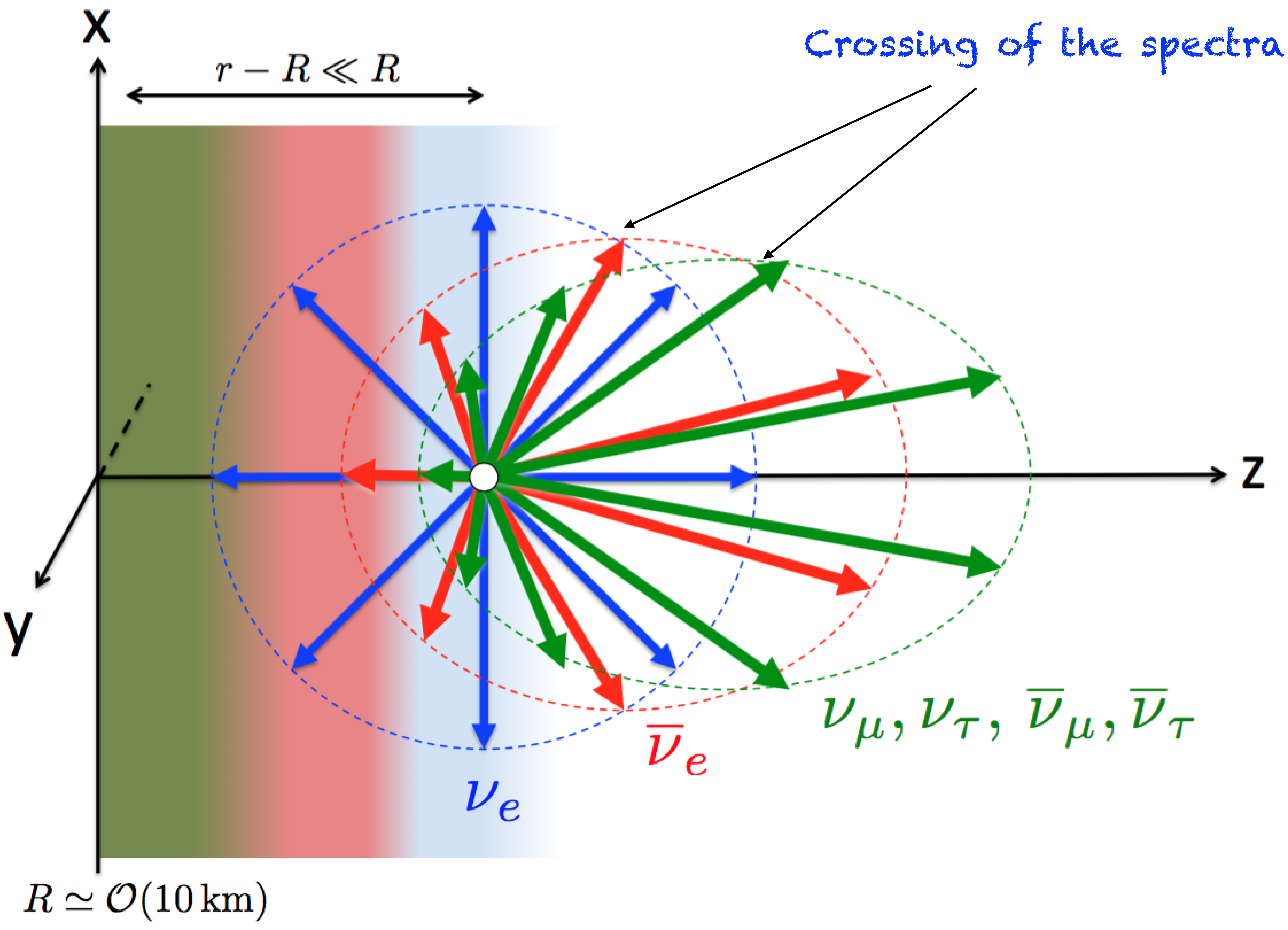
Refining the simple bulb model requires also taking into account that the radius of the neutrinospheres of different neutrino flavor are different



Non-electron species decouple earlier (angular distribution more forward peaked) than the electron species. Due to the neutron richness of stellar matter, the $\bar{\nu}_e$ would decouple earlier (and thus would be more forward peaked) than ν_e

the presence of neutrinos traveling towards the core can cause fast neutrino conversion on a time-scale of μ km^{-1} (i.e. occurring in few m)

Stability studies suggest that for fast conversion to happen the crossing in the zenith-angle spectra of different species is sufficient



From B. Dasgupta (Neutrino 2018)

Conclusions for SN neutrinos

- Knowledge of mass-mixing parameter will help to understand SN physics

- SN neutrino signal can help discriminate Mass Ordering through

Matter MSW propagation

"Slow" Collective conversion

"Fast" Collective conversion

Conclusions

We are in the transition period between the time of the discovery of neutrino oscillations and the time of new discoveries, as for instance LNV or CPV in the lepton sector, that will be within our reach in the next 10 to 15 years, thanks to an enormous effort for future experiments

In the meantime, there is a good chance that some of these discoveries are anticipated by upgrades of ongoing experiments or by experiments starting in a year or two, which have the potential to determine the ordering of the masses, to begin exploring the eventual Majorana nature of neutrinos and provide more robust indications on the phase δ

In this context, the sub-percent precision on the oscillation parameter measurements will allow to test subdominant effects of new physics

This experimental advance will take place not only in laboratory neutrino experiments but will be equally intense in cosmology and astrophysics

From this point of view, starting in the very near future, neutrinos will certainly constitute a portal for an advancement of our fundamental knowledge, as it has not been experienced for some time now

"Standard" MSW Neutrino Oscillations

Neutrino steaming through the outer SN layers undergo ordinary MSW transitions

Dighe, Smirnov, hep-ph/9907423. PRD.62.033007

After reaching the Earth surface, neutrinos may traverse Earth matter in their way to the detector depending on the location of the SN and on the arrival time

Calculation of osc. probability in the Earth analogous to solar neutrinos

Comparison of the SN signal in two detectors differently shadowed by Earth can reveal matter effect and hence be sensitive to mass ordering

Recent investigations on the subject by different groups worldwide find that conditions for fast conversions are fulfilled in realistic simulations near the SN core

Glas et al., Phys. Rev. D 101, 063001 (2020)

The phenomenology of self-induced flavor conversions in SNe could be much richer than previously expected

One might have that fast conversions could lead to a quick flavor equilibration among different neutrino species, if instabilities are general enough

If flavor equilibration were complete, further oscillation effects would be ineffective. Otherwise, one could have different regimes, e.g., fast conversions near SN core followed by spatial slow conversions at larger distances, and finally MSW evolution

"Standard" MSW Neutrino Oscillations

Neutrino steaming through the outer SN layers undergo ordinary MSW transitions

Matter effects important when $\lambda = \omega \Leftrightarrow \sqrt{2} G_F n_e(r) = \Delta m^2/2E$

Two squared mass differences

$$\delta m^2 \sim 7.34 \times 10^{-5}\ \mathrm{eV}^2$$
$$\Delta m^2 \sim 2.45 \times 10^{-3}\ \mathrm{eV}^2$$

Energy range

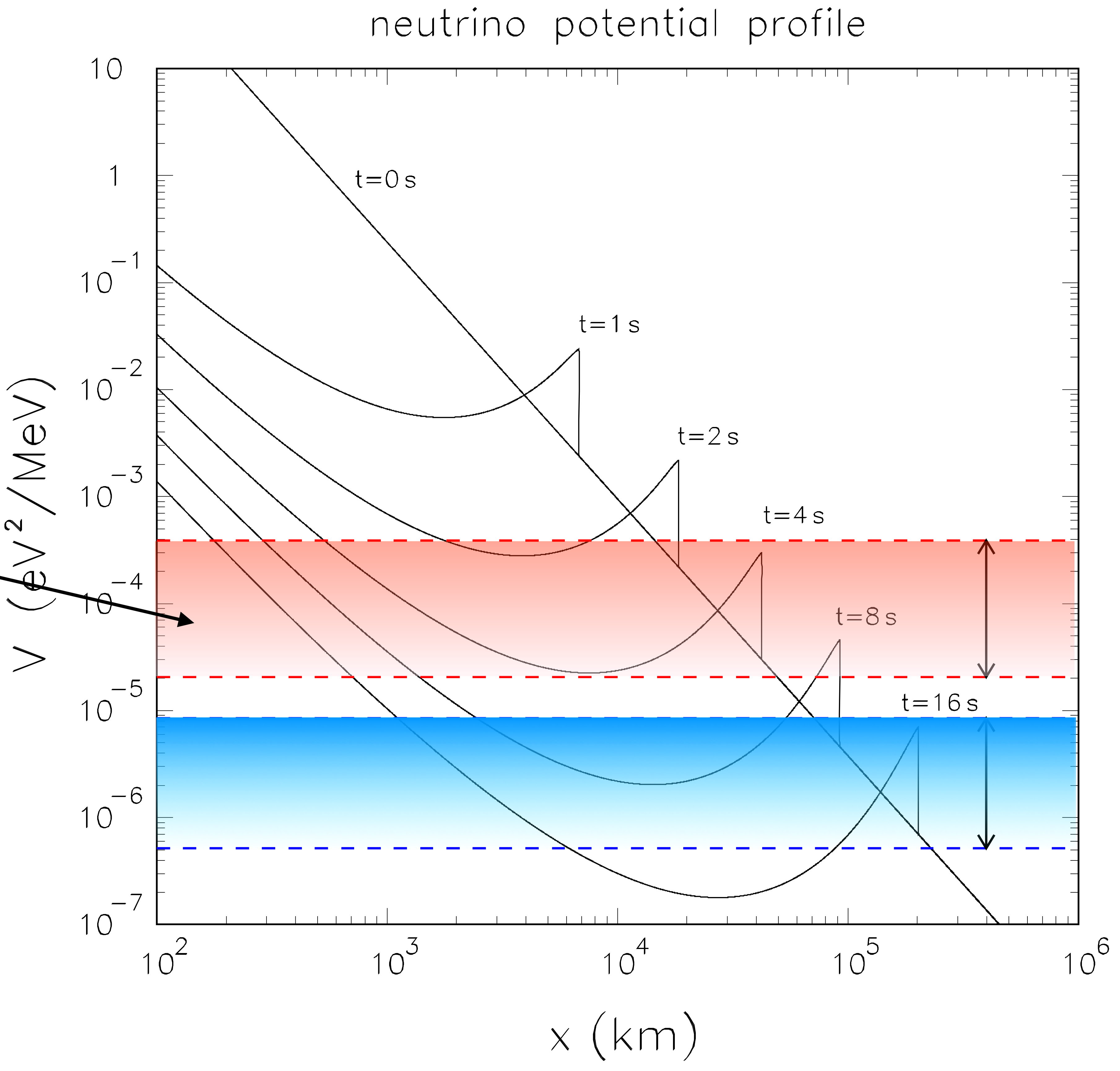
$$E \in [4, 70]\ \ \mathrm{MeV}$$

Two resonances ω_H (atm. mass difference) and ω_L (solar mass difference)

MSW transitions at R grater than ~1000 km (important for the following discussion on self-induced transitions)

Dynamics can be factorised: two neutrino oscillations with relevant parameters $(\delta m^2, \theta_{12})$ or $(\Delta m^2, \theta_{13})$

Dighe, Smirnov, hep-ph/9907423. PRD.62.033007



G. L. Fogli, E. Lisi, D. Montanino and A. Mirizzi, Phys. Rev. D 68, 033005 (2003) [hepph/0304056]

At production point $V/\omega_{L,H} \gg 1$

$$\cos 2\theta_m = \frac{\cos 2\theta - V/\omega}{\sqrt{(\cos 2\theta - V/\omega)^2 + \sin^2 2\theta}}$$

$$\sin 2\theta_m = \frac{\sin 2\theta}{\sqrt{(\cos 2\theta - V/\omega)^2 + \sin^2 2\theta}}$$

$$\cos 2\theta_m \to -\text{sign}(V)\text{sign}(\Delta m^2)$$

$$\sin 2\theta_m \to 0 \quad \Rightarrow \theta_m = 0, \pi/2$$

Since the solar squared mass difference δm^2 is positive, while the atmospheric Δm^2 is positive for NO and negative for IO, at the production point we have

	Normal Ordering	Inverted Ordering
ν	$(\theta_{13}^m = \pi/2, \theta_{12}^m = \pi/2) \quad \Rightarrow \quad \nu_e \equiv \nu_3^m$	$(\theta_{13}^m = 0, \theta_{12}^m = \pi/2) \quad \Rightarrow \quad \nu_e \equiv \nu_2^m$
$\bar{\nu}$	$(\theta_{13}^m = 0, \theta_{12}^m = 0) \quad \Rightarrow \quad \bar{\nu}_e \equiv \bar{\nu}_1^m$	$(\theta_{13}^m = \pi/2, \theta_{12}^m = \pi/0) \quad \Rightarrow \quad \bar{\nu}_e \equiv \bar{\nu}_3^m$

Normal ordering Crossing Diagram

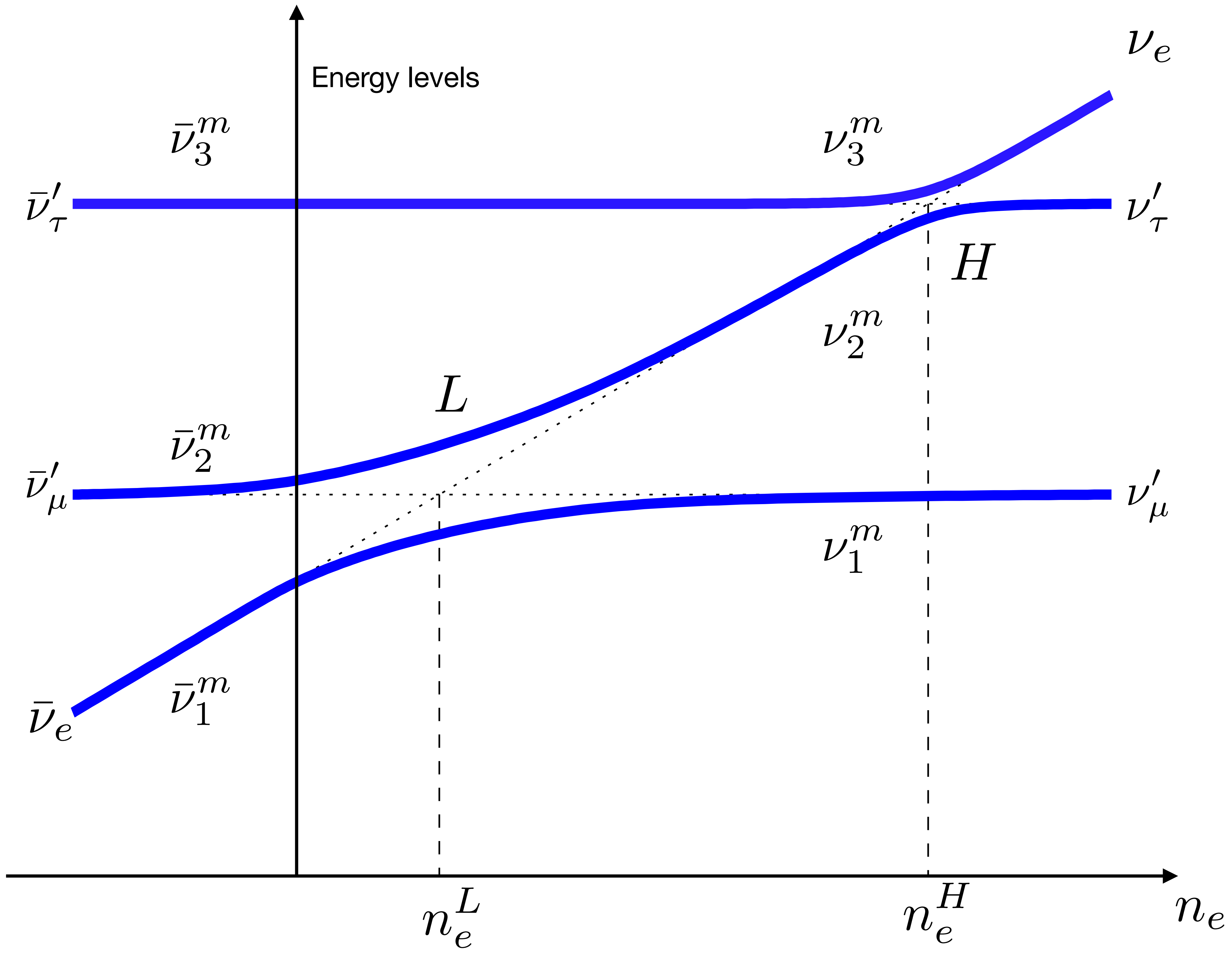
Neutrino evolution starts on the right

$$\nu_e \equiv \nu_3^m$$

ν'_μ and ν'_τ are linear combinations of ν_μ and ν_τ which diagonalise the 2-3 part of the Hamiltonian

Both the H and L resonances happen for neutrinos in NO, the transition probability being P_H and P_L, respectively

Fluxes for the mass eigenstates at the SN surface can be calculated as a function of the initial fluxes and the transition probabilities at the resonances (rescaled by a factor L^{-2})



Dighe, Smirnov, hep-ph/9907423. PRD.62.033007

For instance

$$F_{\nu_1} = P_H P_L F^0_{\nu_3^m} + (1 - P_L) F^0_{\nu_1^m} + P_L (1 - P_H) F^0_{\nu_2^m}$$

With $F^0_{\nu_3^m} = F^0_{\nu_e}$ and $F^0_{\nu_2^m} = F^0_{\nu_1^m} = F^0_{\nu_\mu} = F^0_{\nu_\tau} = F^0_{\bar{\nu}_\mu} = F^0_{\bar{\nu}_\tau} = F^0_{\nu_x} = F^0_{\bar{\nu}_x}$

But present value of θ_{13} implies adiabatic propagation

$$P_L = P_H = 0$$

$\Longrightarrow$

$$F_{\nu_3} = F_{\nu_3^m} = F^0_{\nu_e}$$
$$F_{\nu_1} = F_{\nu_2} = F^0_{\nu_1^m} = F^0_{\nu_x}$$

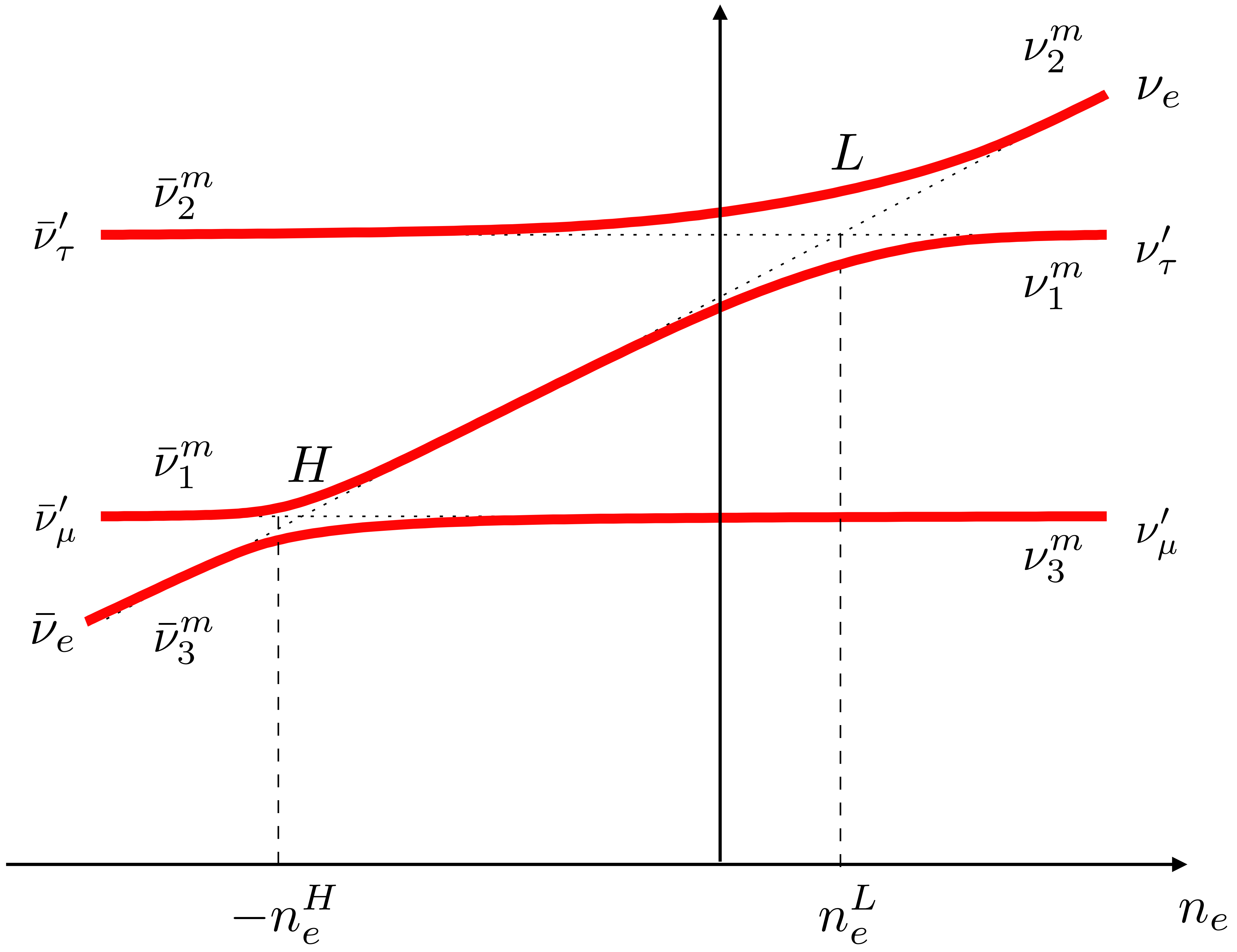
Analogously for antineutrinos (no resonances), but starting on the left of the diagram

Inverted ordering Crossing Diagram

Neutrino evolution starts on the right but this time

$$\nu_e \equiv \nu_2^m$$

For IO, L resonance happens for neutrinos and H resonance for antineutrinos (negative electron density)



The fluxes exiting the Supernova are

$$F_{\nu_2} = F^0_{\nu_2^m} = F^0_{\nu_e}$$

$$F_{\nu_1} = F_{\nu_3} = F^0_{\nu_1^m} = F^0_{\nu_3^m} = F^0_{\nu_x}$$

Analogously for antineutrinos, starting on the left of the diagram with the H resonance

After leaving the surface of the Supernova the neutrino mass eigenstates travel to Earth where they arrive (rescaled by a factor L^{-2}) so that for NO

$$F^E_{\nu_e} = \sum_i |U_{ei}|^2 F_{\nu_i} = pF^0_{\nu_e} + (1-p)F^0_{\nu_x}$$

$$p = |U_{e1}|^2 P_H P_L + |U_{e2}|^2 P_H (1 - P_L) + |U_{e3}|^2 (1 - P_H) = |U_{e3}|^2$$

$$|U_{e3}|^2 = \sin^2\theta_{13} \sim 0.02 \Rightarrow p \sim 0$$

so that $$F^E_{\nu_e} = F^0_{\nu_x}$$

Analogous simple formulas for antineutrinos and IO. Summarizing

	Normal Ordering	Inverted Ordering
ν	$F^E_{\nu_e} = F^0_{\nu_x}$	$F^E_{\nu_e} = \sin^2\theta_{12} F^0_{\nu_e} + \cos^2\theta_{12} F^0_{\nu_x}$
$\bar{\nu}$	$F^E_{\bar{\nu}_e} = \cos^2\theta_{12} F^0_{\bar{\nu}_e} + \sin^2\theta_{12} F^0_{\bar{\nu}_x}$	$F^E_{\bar{\nu}_e} = F^0_{\bar{\nu}_x}$

After reaching the Earth surface, neutrinos may traverse the Earth matter in their way to the detector depending on the location of the Supernova and on the arrival time

Calculation of the oscillation probability in the Earth matter is analogous to the case of solar neutrinos

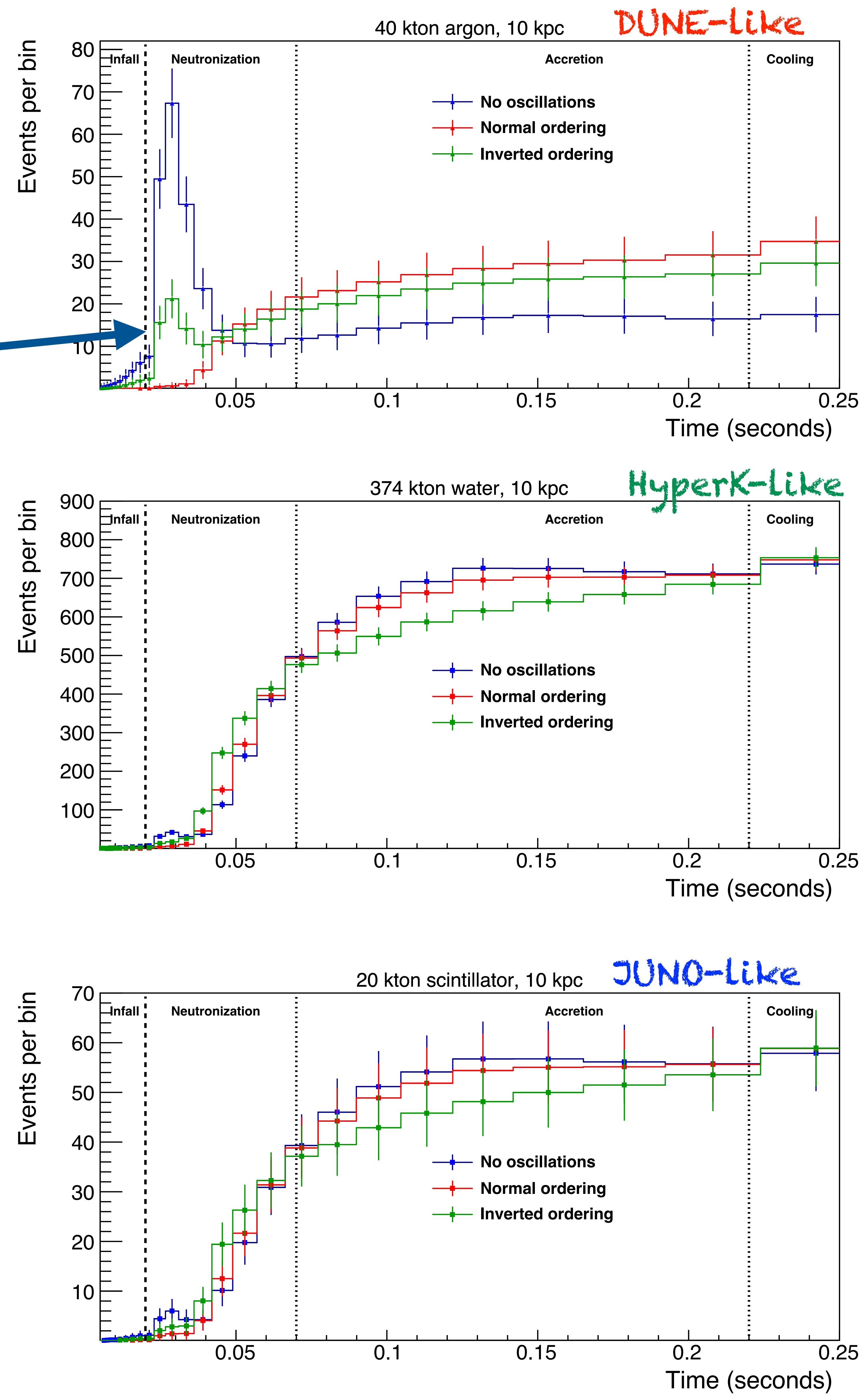
Comparison of the supernova signal in two detectors differently shadowed by Earth can reveal matter effect and hence be sensitive to mass ordering (matter effects vanish if initially $F^0_{\nu_e} = F^0_{\nu_x}$ exactly)

Mass Ordering signatures

Neutronization → Most robust signature

- burst is almost a standard candle
- luminosity time dependence almost model independent
- absent in NO
- partially suppressed in IO
- collective effects absent

Early time profile also important since dominated by MSW propagation, while collective effects matter suppressed



K. Scholberg, arXiv:1707.06384,J.Phys. G45 (2018) no.1, 014002

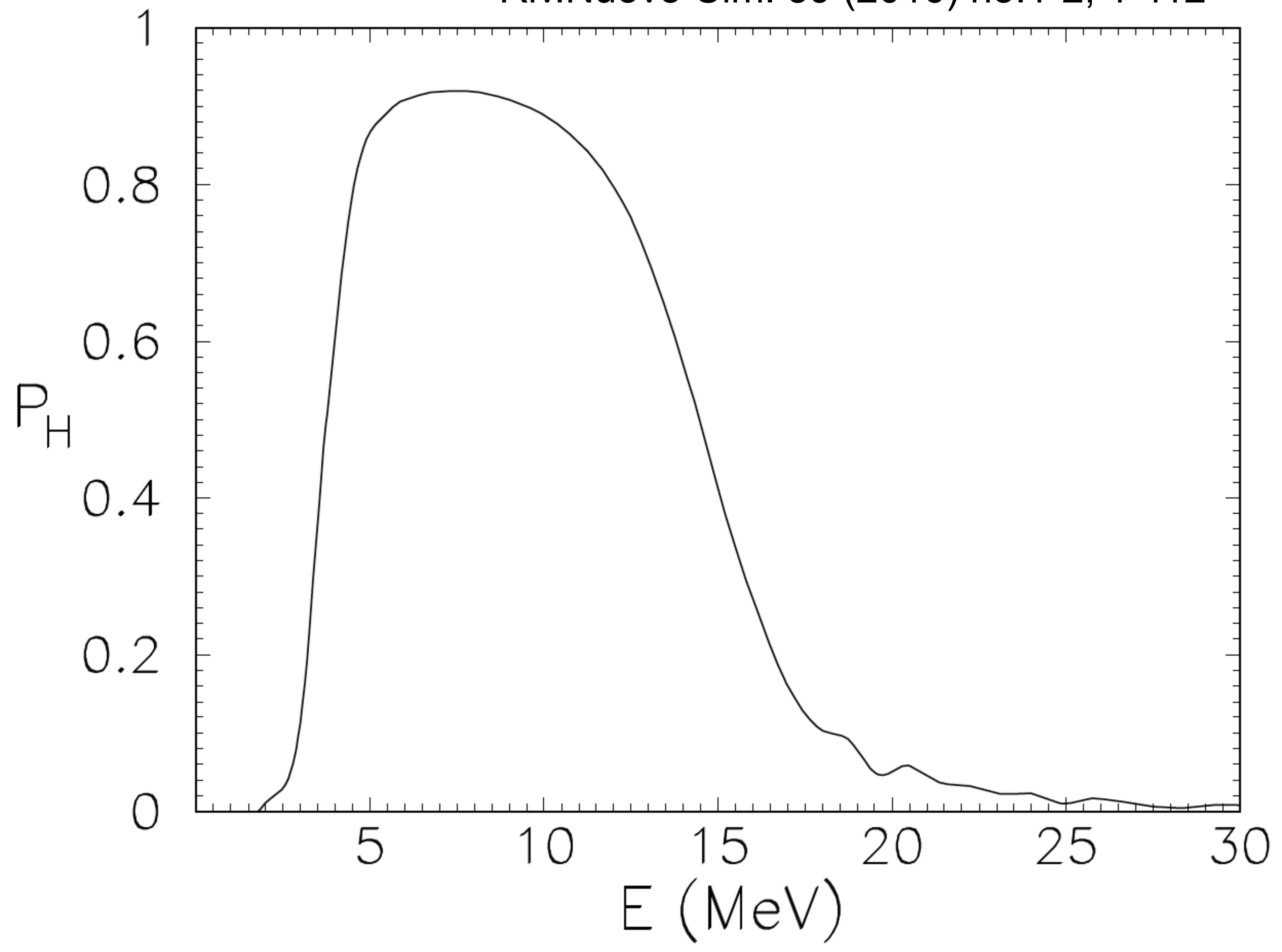
The real picture is complicated by the fact that

- real SN density profile is non monotonic decreasing at the shock front
- the SN density profile changes with time
- effect of density fluctuations should be taken into account

At the shock front the H resonance can be extremely non-adiabatic

Stochastic matter fluctuations of sufficiently large amplitude may suppress flavor conversions and lead to $P_H=1/2$ when the suppression is strong

Riv.Nuovo Cim. 39 (2016) no.1-2, 1-112



Spectral properties of the fluctuations very important for understanding the neutrino signal

At the moment there is no unanimous consensus about the impact of matter fluctuations on the SN neutrino flavor conversions

"Slow" collective neutrino conversions

The formalism of the neutrino density matrix is particularly useful in the context of SN neutrino flavor conversions

$$\partial_t \rho_{\mathbf{p},\mathbf{x},t} + \mathbf{v_p} \cdot \nabla_\mathbf{x} \rho_{\mathbf{p},\mathbf{x},t} = -i[\Omega_{\mathbf{p},\mathbf{x},t}, \rho_{\mathbf{p},\mathbf{x},t}]$$

The Hamiltonian is the sum of three terms depending on

$$\Omega_{\mathbf{p},\mathbf{x},t} = \Omega_{\text{vac}} + \Omega_{\text{MSW}} + \Omega_{\nu\nu}$$

$$\omega = \frac{\Delta m^2}{2E}$$

vacuum oscillation frequency

$$\lambda = \sqrt{2} G_F n_e$$

matter potential

$$\mu = \sqrt{2} G_F (n_\nu + n_{\bar{\nu}})$$

neutrino-neutrino interaction potential

$$\Omega_{\nu\nu} = \sqrt{2} G_F \int \frac{d^3\mathbf{q}}{(2\pi)^3} (\rho_\mathbf{q} - \bar{\rho}_\mathbf{q})(1 - \mathbf{v_p} \cdot \mathbf{v_q})$$

Multi-angle effect: the interaction depends on the relative angle of the colliding neutrinos θ_{pq}

Collective oscillations when μ dominates (typically $r \lesssim 100$ Km)

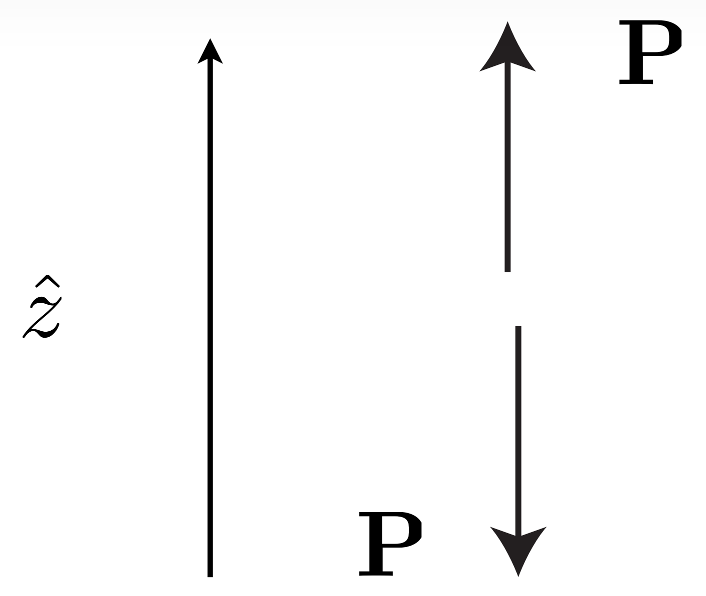
Tipically matter effects and collective effects induced by self interactions factorize and the range in which they are effective are well separated

ρ decomposed in term of polarization vectors

$$\rho = \frac{1}{2}(p_0 I + \mathbf{P} \cdot \sigma)$$

$\mathbf{P} = \mathbf{P}(E, \theta_0)$ neutrinos

$\bar{\mathbf{P}} = \bar{\mathbf{P}}(E, \theta_0)$ antineutrinos



Polarization vector in the upward direction $\quad P(\nu_e \to \nu_e) = 1$

Polarization vector in the downward direction $\quad P(\nu_e \to \nu_e) = 0$

Also important, the global vectors

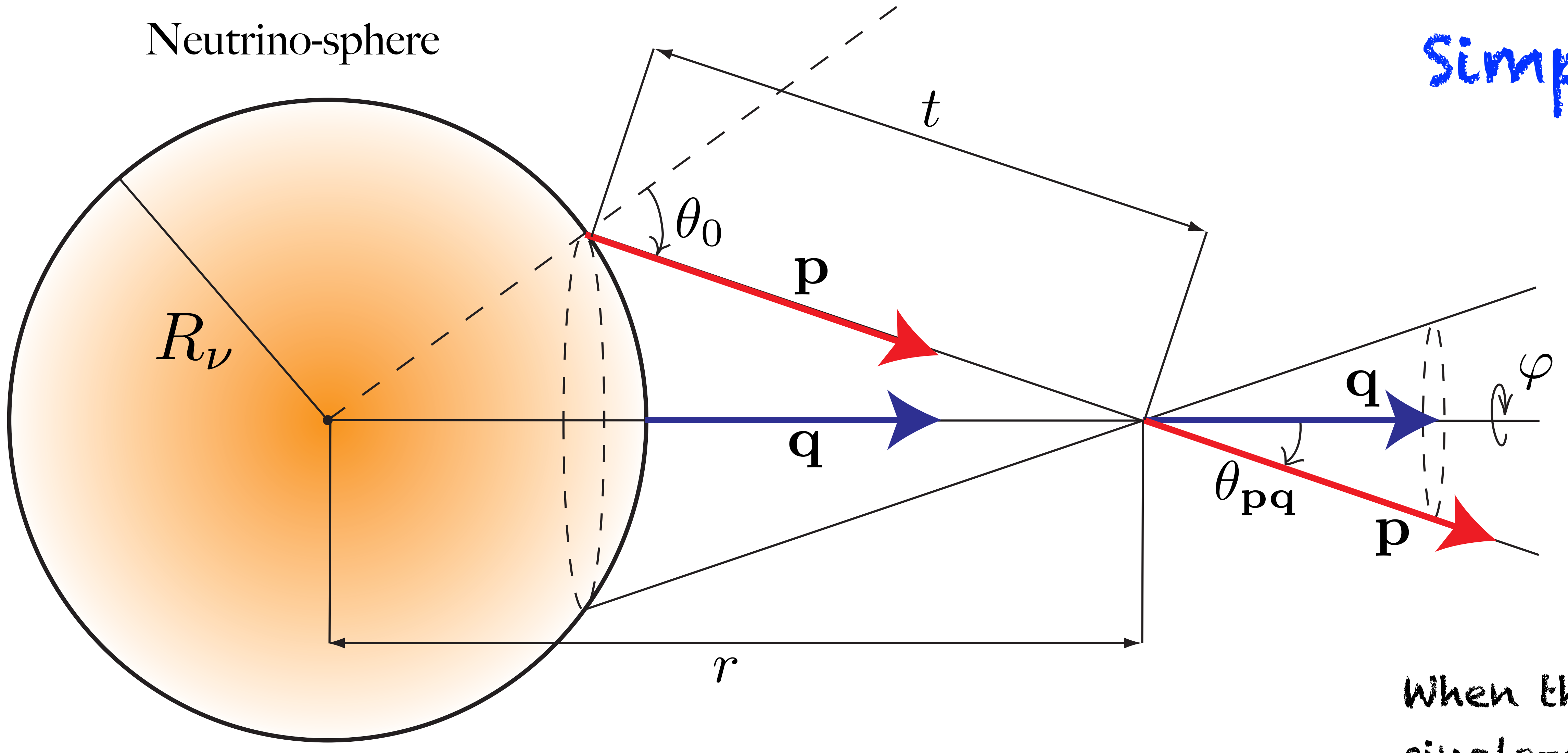
$$\mathbf{J} = \int dE \; d\theta_0 \; \mathbf{P}(E, \theta_0) \quad \bar{\mathbf{J}} = \int dE \; d\theta_0 \; \bar{\mathbf{P}}(E, \theta_0) \quad \mathbf{S} = \mathbf{J} + \bar{\mathbf{J}} \quad \mathbf{D} = \mathbf{J} - \bar{\mathbf{J}}$$

In particular from the EoM the lepton number conservation follows

$$D_z = \int dE d\theta_0 (n_{\nu_e}(E, \theta_0) - n_{\bar{\nu}_e}(E, \theta_0)) = \text{const}$$

implying transitions of the kind $\nu_e \bar{\nu}_e \to \nu_x \bar{\nu}_x$

Simple geometric model



Bulb model

Duan et al., PRD74,105014(2006)

When this angle is averaged out the single-angle approximation is obtained

$$H_{\nu\nu} = \sqrt{2} G_F \int \frac{d^3\vec{q}}{(2\pi)^3} (\mathbf{P}_{\vec{q}} - \overline{\mathbf{P}}_{\vec{q}})(1 - \cos\theta_{pq}) \longrightarrow H_{\nu\nu} = \mu \int dq (\mathbf{P}_{\vec{q}} - \overline{\mathbf{P}}_{\vec{q}}) = \mu(\mathbf{J} - \overline{\mathbf{J}}) = \mu\mathbf{D}$$

Equations of motion

$$\dot{\mathbf{P}} = (+\omega\mathbf{B} + \lambda\hat{\mathbf{z}} + \mu\mathbf{D}) \times \mathbf{P}$$
$$\dot{\overline{\mathbf{P}}} = (-\omega\mathbf{B} + \lambda\hat{\mathbf{z}} + \mu\mathbf{D}) \times \overline{\mathbf{P}}$$

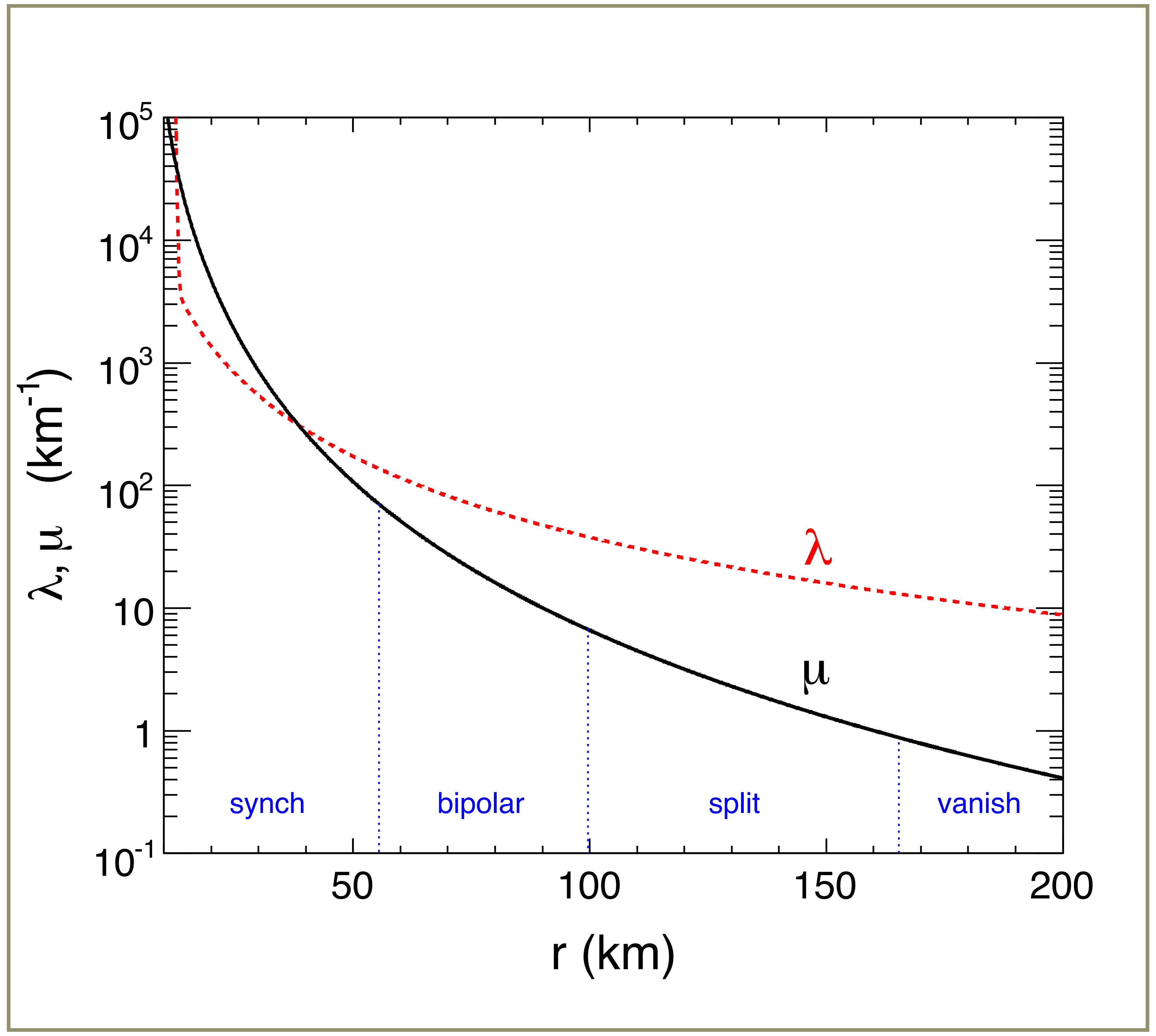
$\mathbf{B} \parallel \hat{\mathbf{z}}$ when $\theta_{13} = 0$ ($\lambda = 0$ in the following)

Regimes of Collective flavor Conversions

Near the neutrino-sphere (few tens of kilometers) all polarization vectors stay aligned with the z-axis: synchronized oscillations

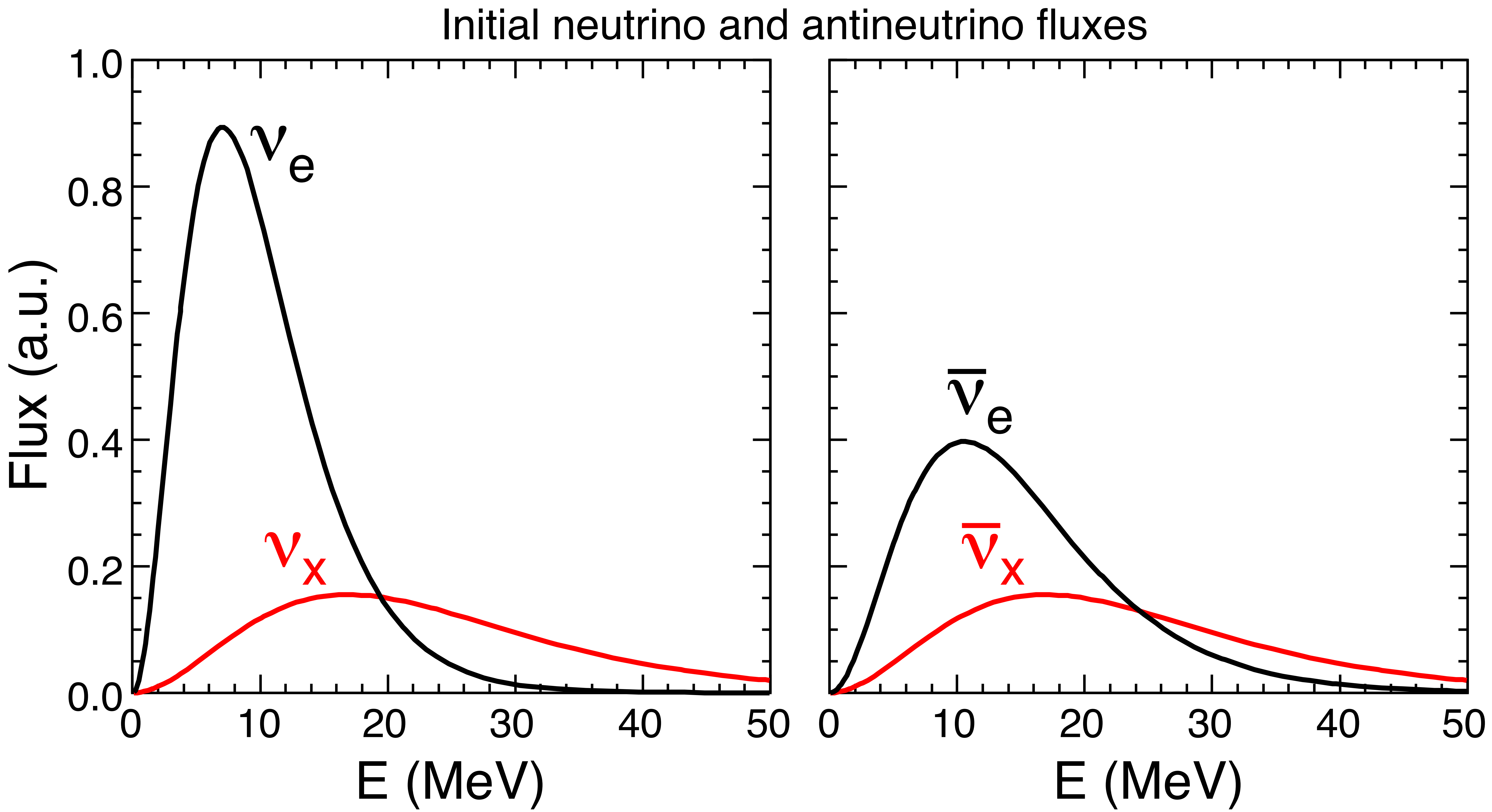
At a certain point, the polarization vectors start to move but the P's remain (approximately) parallel to their sum J (same for antineutrinos). This regime has a mechanical analogy with the motion of a spherical pendulum and corresponds to the so called bipolar oscillations

Hannestad, Raffelt, Sigl and Wong, PRD74,105010(2006)



IO corresponds to the pendulum starting close the unstable position while in NO it starts close the stable one

The bipolar regime ends when the vacuum frequencies of the P's are of the same order of the self-interaction potential. After that, the spectral split fully develops until the neutrino-neutrino potential is completely negligible



Two-neutrino scenario

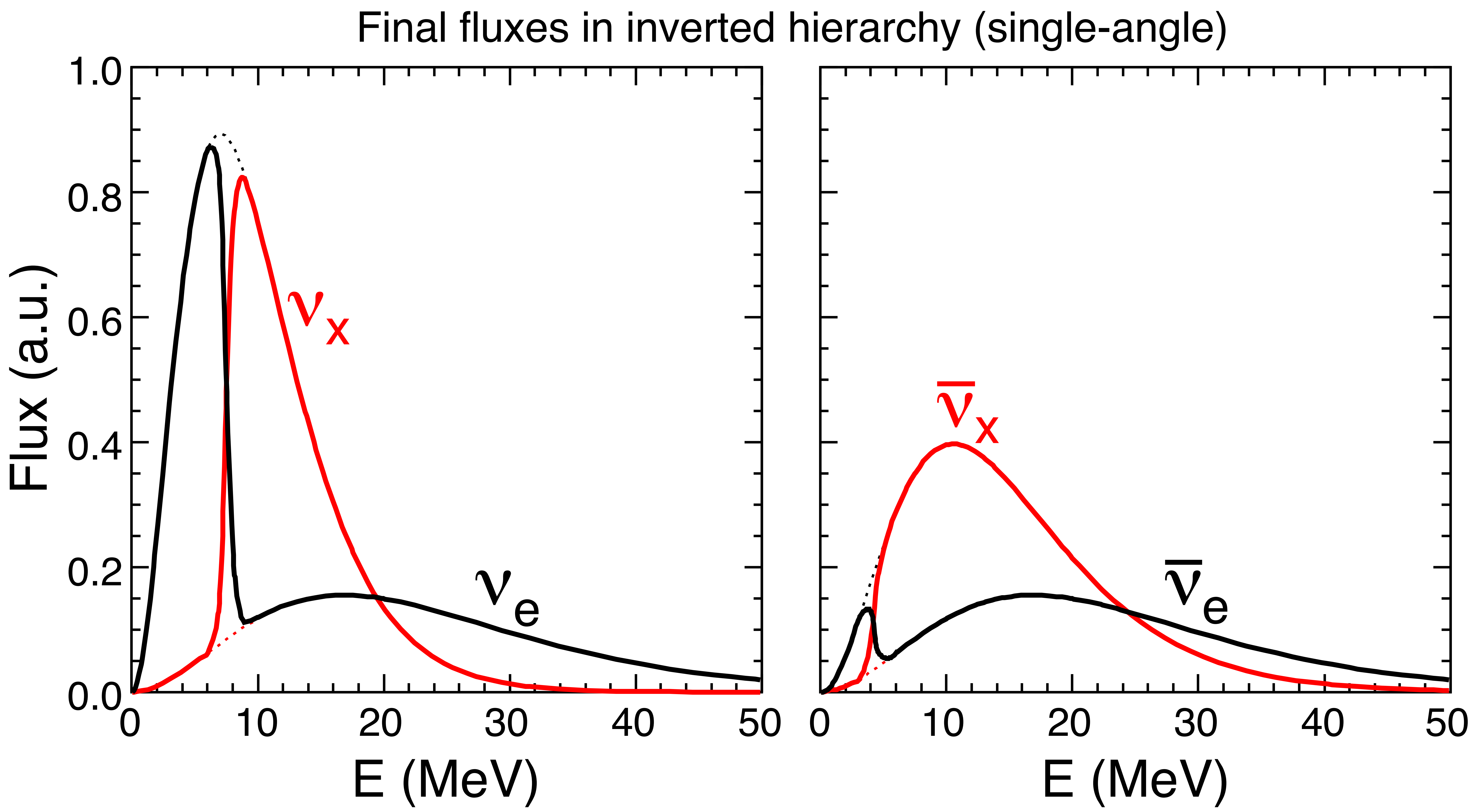
$$\Delta m^2 = \Delta m^2_{atm} = 2 \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2\theta_{13} = 10^{-2}$$

$$\langle E_{\nu_e}\rangle = 10\ \mathrm{MeV}$$

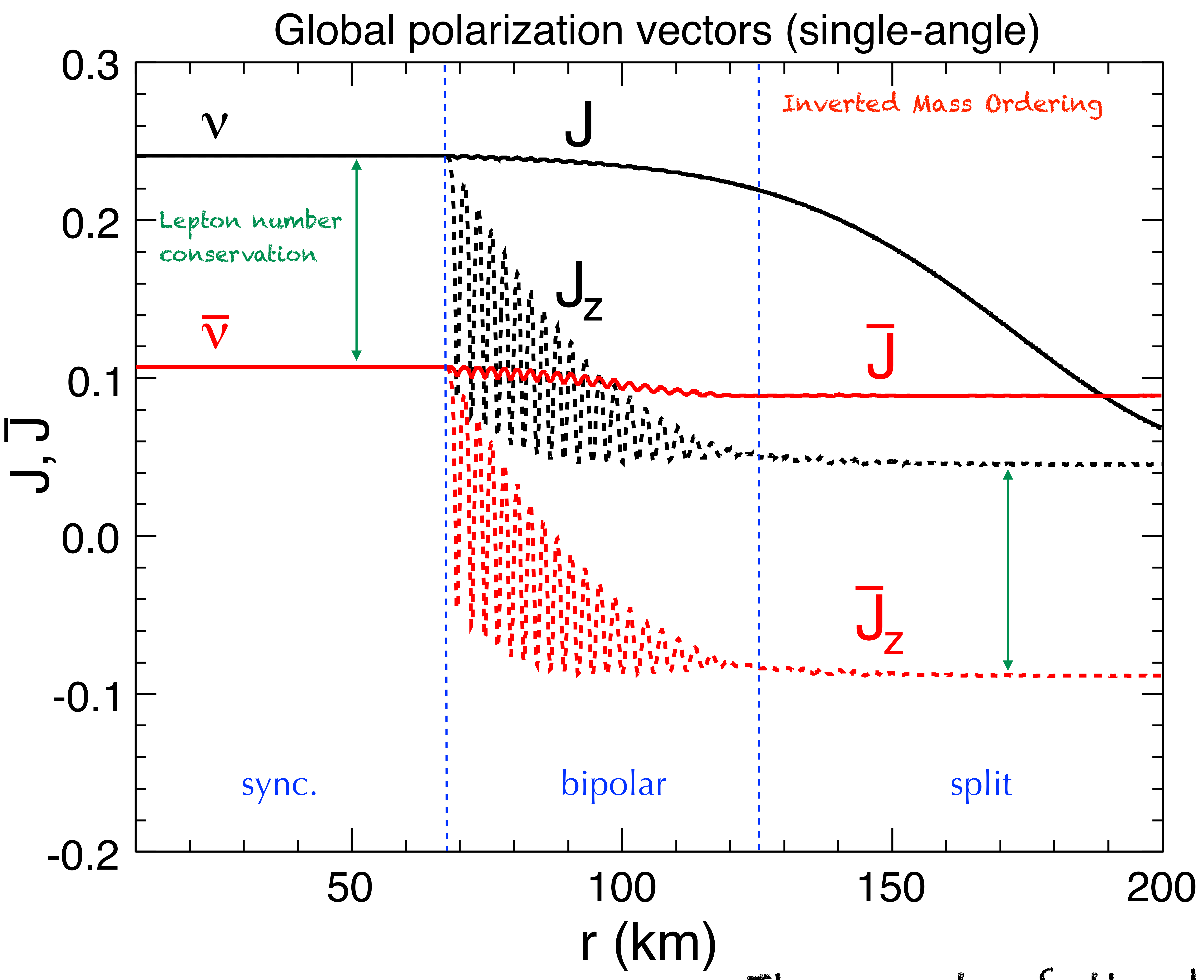
$$\langle E_{\bar{\nu}_e}\rangle = 15\ \mathrm{MeV}$$

$$\langle E_{\nu_x}\rangle = \langle E_{\bar{\nu}_x}\rangle = 24\ \mathrm{MeV}$$



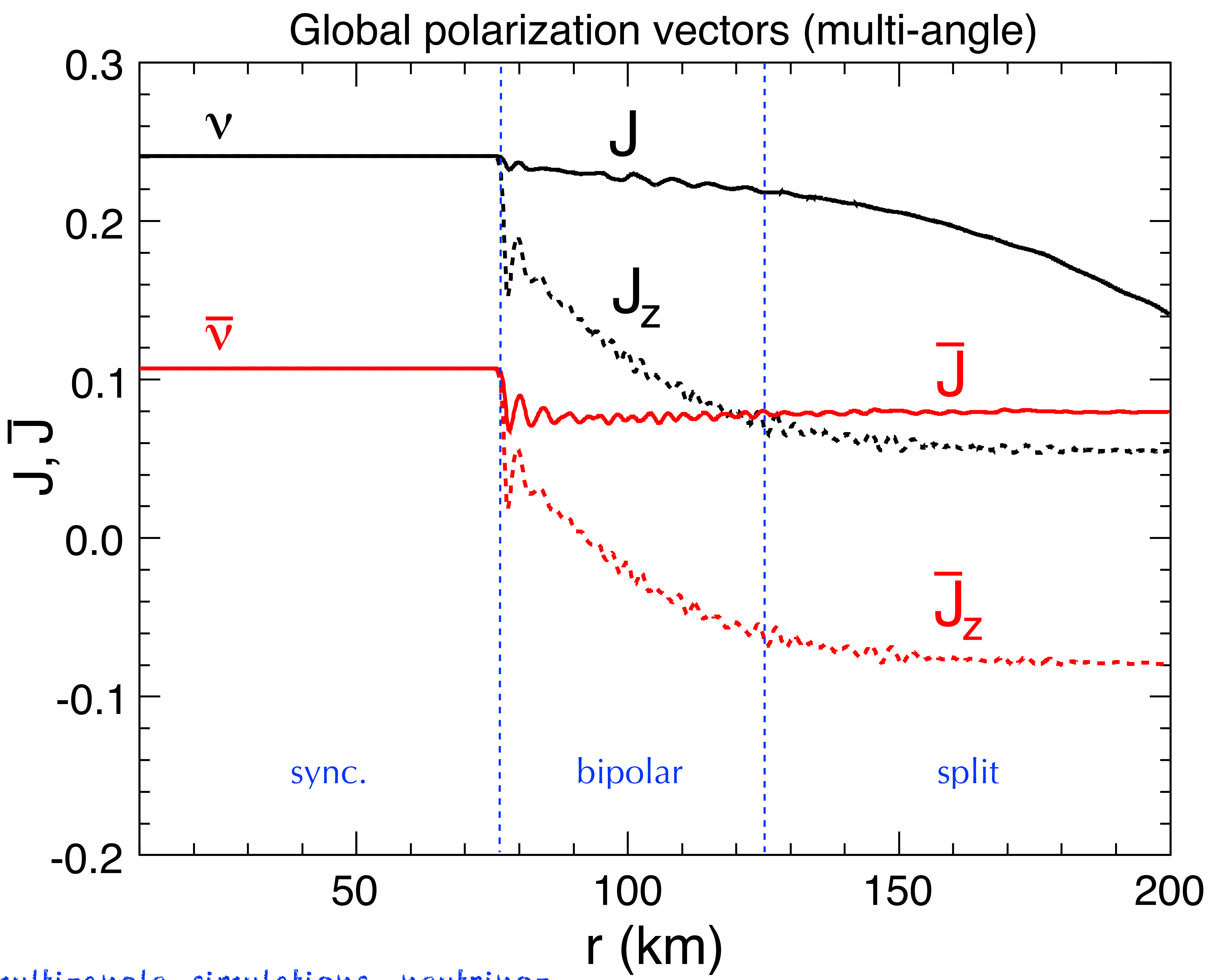
Spectral split for neutrinos above ~7 MeV as a consequence of lepton number conservation

Spectral split for antineutrinos at ~4 MeV



Note the inversion of $\bar{J}_z$ and the partial inversion of J_z

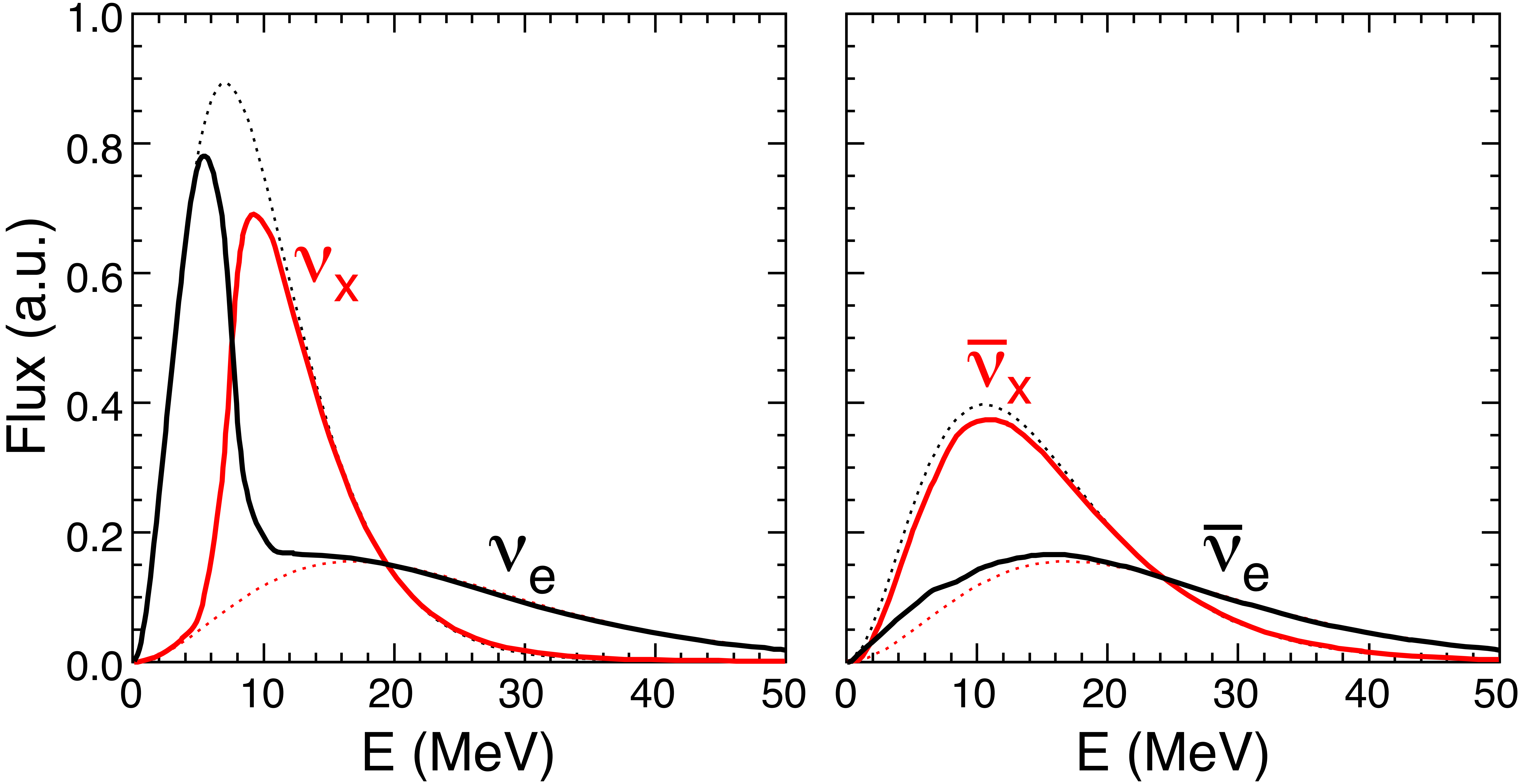
The onset of the bipolar regime depends on θ_{13} and on the matter potential



In multi-angle simulations, neutrino-neutrino angles can be larger than the (single-angle) average one, leading to somewhat stronger self-interaction effects

Bipolar regime starts later
More pronounced depolarization of J and prolonged coherence of $\bar{J}$

Final fluxes in inverted hierarchy (multi-angle)



The neutrino spectral split is evident, although less sharp than in the single-angle case

Antineutrino split largely washed out

Starting from the simplest single-angle approximation with the three phases of flavor conversions for IO, induced by self interactions (synchronization, bipolar oscillations, spectral swaps), the situation gets more complicated when moving towards more realistic scenarios:

- multi-angle effects tend to smear spectral splittings
- matter multi-angle effects tend to block self-induced flavor conversions
- breaking of the space-time symmetries could favour flavor decoherence
- collective effects depend on the neutrino flux hierarchy and less pronounced flavor hierarchies multiple splits can arise (and swaps can occur also in NO)

Multi-angle matter effects

$n_{e^-} - n_{e^+} \ll n_{\bar{\nu}_e} - n_{\bar{\nu}_x}$ subdominant

$n_{e^-} - n_{e^+} \gg n_{\bar{\nu}_e} - n_{\bar{\nu}_x}$ can inhibit self-induced flavor conventions

$n_{e^-} - n_{e^+} \sim n_{\bar{\nu}_e} - n_{\bar{\nu}_x}$ matter-induced multi-angle decoherence may occur

Multi-azimuthal-angle instability, depending on spectral crossings, may trigger new flavor conversions in NO, especially during the accretion phase, but are suppressed by by the dominant matter term

Time and/or space inhomogeneities may lead to flavor instabilities

Collective effects depend on the neutrino flux hierarchy

During the neutronization phase bipolar flavor conversions not possible
$\nu_e\bar{\nu}_e \rightarrow \nu_x\bar{\nu}_x$ transitions cannot occur because $F_{\nu_e} \gg F_{\nu_x} \gg F_{\bar{\nu}_e}$

During the accretion phase the deleptonization of the core implies $F_{\nu_e} \gg F_{\bar{\nu}_e}$
while for the absence of CC interactions for μ and τ neutrinos $F_{\bar{\nu}_e} \gg F_{\bar{\nu}_x}$
Bipolar oscillations and spectral swaps can occur. Multi-angle matter effects tend to inhibit self-induced flavor conversions

During the cooling phase, with less pronounced or vanishing neutrino flux hierarchy multiple spectral splits can appear both for neutrinos and antineutrinos. Three-flavor effects are observable in the single-angle scheme (suppressed in the multi-angle case). Spectral swaps and splits are less pronounced, due to some amount of multi-angle decoherence. For the flux ordering of the cooling phase spectral splits and swaps would occur also in NO.