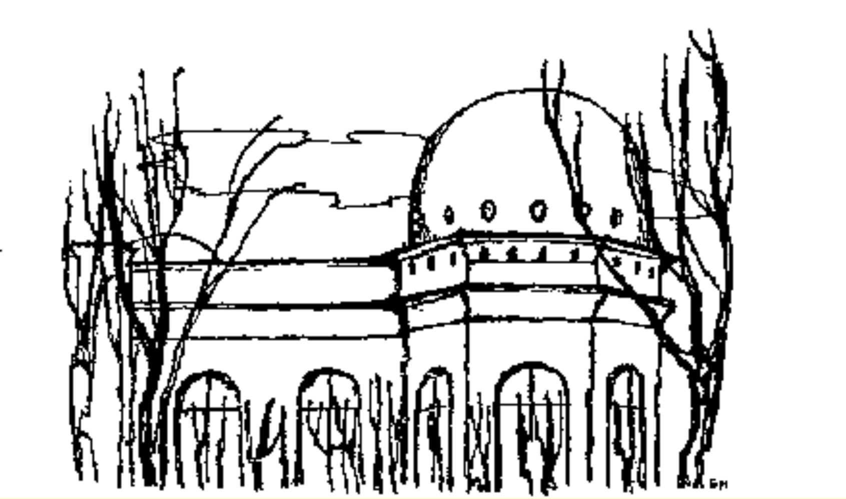

Ecole Internationale Daniel Chalonge

18th Paris Cosmology Colloquium 2014

"Latest news from the Universe: Lambda Warm Dark Matter (LWDM), CMB, Dark Matter, Dark Energy, Neutrinos and Sterile Neutrinos"

Neutrino Masses, Phases and Mixings: Theory vs. Experiments. A Status Report

Gianluigi Fogli

Dipartimento di Fisica & INFN - Bari

Outline

1. The 3ν Mass-Mixing Framework
   - 1.1 Notation for neutrino masses
   - 1.2 Notation for neutrino mixing
   - 1.3 The role of the mixing angles
2. Status of Neutrino Oscillations in the three active neutrinos framework
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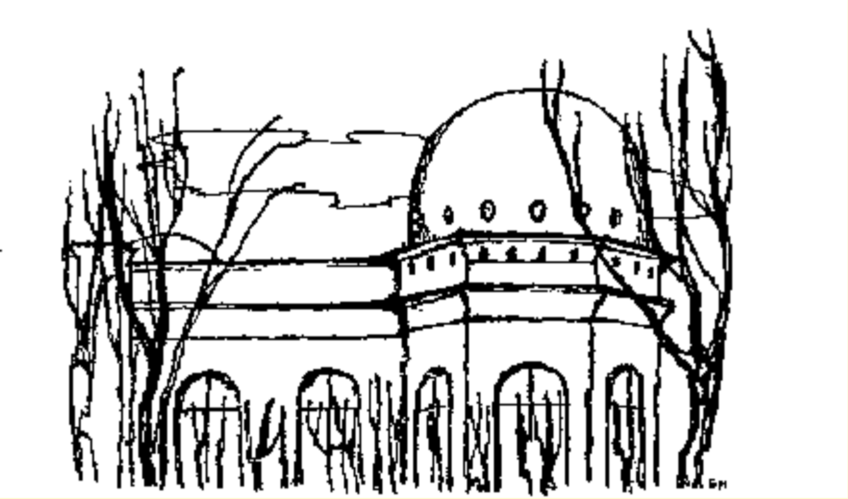
3. Neutrino Oscillations with Sterile Neutrinos
   - 3.1 Why a sterile neutrino?
   - 3.2 Sterile neutrinos in SBL experiments
   - 3.3 ~~Sterile neutrinos as Warm Dark Matter candidates~~



1. The 3ν Mass-Mixing Framework

1.1 Notation for neutrino masses

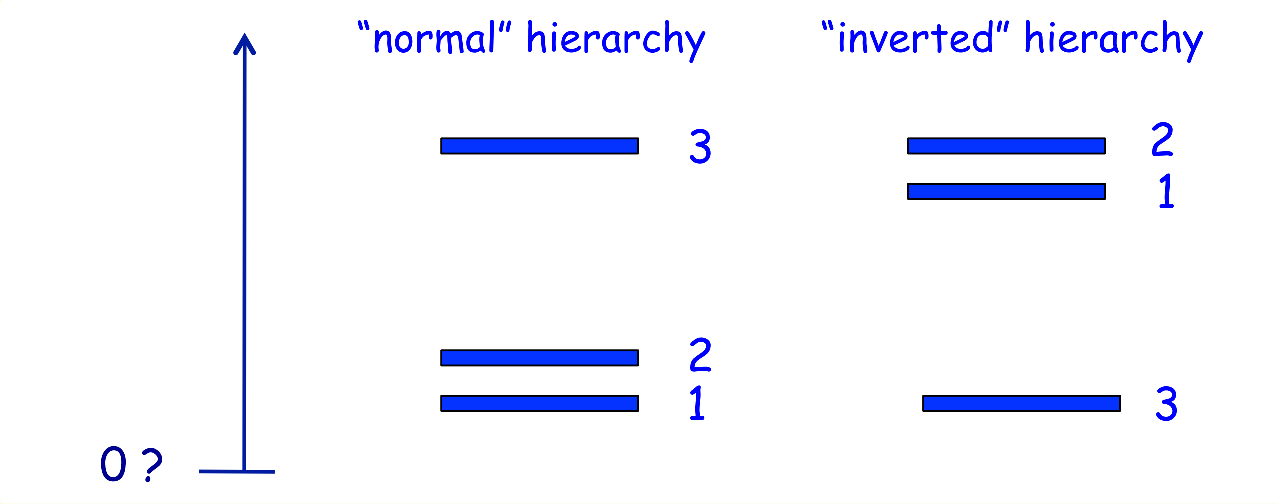
- Three mass eigenstates $\nu_1\ \nu_2\ \nu_3$ with masses $m_1\ m_2\ m_3$
- Neutrino oscillations probe $\Delta E \approx \Delta m^2_{ij}$
- 3 neutrinos → 2 independent mass differences, say, δm^2 and Δm^2
- Experimentally very different values: $\delta m^2/\Delta m^2 \sim 1/30$

$\delta m^2 = 7.5 \times 10^{-5}\ eV^2$ small or "**solar**" splitting

$\Delta m^2 = 2.5 \times 10^{-3}\ eV^2$ large or "**atmospheric**" splitting

- Very difficult to probe both splittings in the same experiment!
- Absolute ν mass scale unknown: lightest m_i could be zero
- However, upper limits exist: $m_i \lesssim \mathcal{O}(eV)$

- Two possible arrangements, called "**hierarchies**", for the splittings



- In both hierarchies, there is "doublet" of close mass states and a "lone" mass state. Universal convention: ν_3 is the lone state, (ν_1, ν_2) is the doublet, with ν_1 being the lightest state: $m_1 < m_2$.

- Splittings: $\delta m^2 = m_2^2 - m_1^2 > 0$ (> 0 by definition)

  $\Delta m^2 = m_3^2 - m_{1,2}^2 > \text{or} < 0$ (± an important physical sign)

- We use

  $$\Delta m^2 = \frac{1}{2}\left[m_{3,1}^2 - m_{3,2}^2\right]$$ (our convention)

2.2 Notation for neutrino mixing

- Three flavor states $\nu_e\, \nu_\mu\, \nu_\tau$ coming from mixing of the mass eigenstates $\nu_1\, \nu_2\, \nu_3$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

- If these are the only ν states in nature, then the matrix U is unitary

$$UU^\dagger = I$$

- For antineutrinos $U \to U^*$

- As for quarks, the unitary mixing matrix U can be expressed in terms of four independent physical parameters:

3 mixing angles + 1 ~~CP~~ phase

- The Particle Data Group notation is universally adopted:

$$U = O_{23}\,\Gamma_\delta\,O_{13}\,\Gamma_\delta^\dagger\,O_{12} =$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} =$$

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

where

$$\Gamma_\delta = \begin{pmatrix} 1 & & \\ & 1 & \\ & & e^{i\delta} \end{pmatrix} \quad \text{and} \quad \begin{cases} c_{ij} = \cos\theta_{ij} \\ s_{ij} = \sin\theta_{ij} \end{cases}$$

- The matrix U is often called "Pontecorvo-Maki-Nakagawa-Sakata" (PMNS) matrix.

1.3 Role of the mixing angles

- We can write U in the form of matrix product

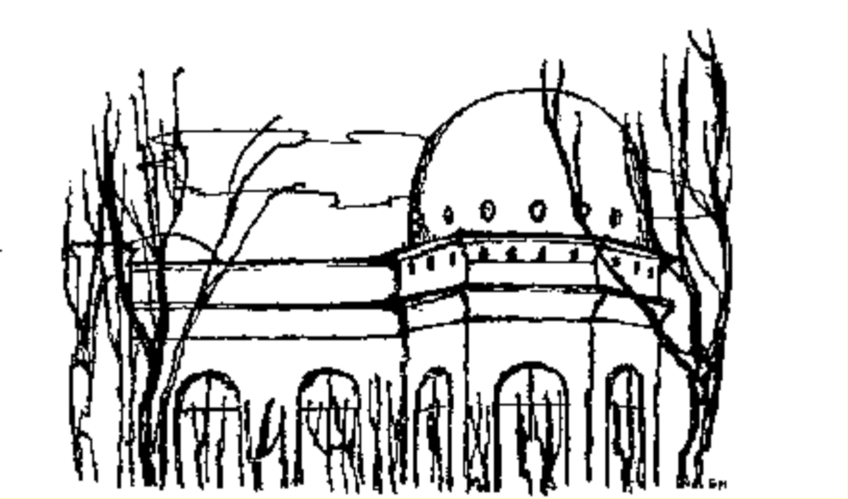
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Experimentally it is

$\sin^2\theta_{23} \sim 0.5$	$\sin^2\theta_{13} \sim 0.02$	$\sin^2\theta_{12} \sim 0.3$
~ maximal	small	large
($\theta_{23} \sim \pi/4$)	(δ = ?)	

- The presence of two small parameters, $\sin^2\theta_{13} \sim 0.02$ and $\delta m^2/\Delta m^2 \sim 1/30$, makes 3ν mixing approximatively reducible to an "effective 2ν mixing" in several cases of phenomenological interest.

- Goal of many currents and future experiments is to find evidence of "genuine 3ν effects" beyond the 2ν approximation.



2. Status of Neutrino Oscillations (in the three active neutrinos framework)*

* Mainly based on arXiv:1312.2878v2 + work done in collaboration with:
F. Capozzi, E. Lisi, A. Marrone, D. Montanino, A. Palazzo, A.M. Rotunno.

2.1 The experiments

- Oscillation parameters are extracted with their correlations from solar, atmospheric, accelerator and reactor neutrino data, as of summer 2014 (Neutrino Conference in Boston).

- Data set:

LBL Accelerators	→	K2K + T2K + MINOS
Solar	→	Homestake, Gallex/GNO, SAGE, SK, SNO, Borexino
KamLAND	→	KamLAND reactor data
SBL Reactors	→	Double Chooz + RENO + Daya Bay
SK Atm	→	Super-Kamiokande Atmospheric data

- Full 3ν probabilities included, no approximation.

- Reference paper

F. Capozzi, G.L.F., E. Lisi, A. Marrone, D. Montanino, A. Palazzo, "Status of three-neutrino oscillation parameters, circa 2013" Phys. Rev. D 89, 093018 (2014) , [arXiv:1312.2878]

A note about Methodology

- **LBL Accelerator** data are dominantly sensitive to (Δm^2, θ_{23}, θ_{13}). But accurate constraints on these parameters do need (δm^2, θ_{12}) coming from **Solar + KL** in order to include and compute sub-dominant effects.

- Then, we combine first **LBL accelerator** data with **solar+KamLAND** data, since the latter provide the "solar parameters" needed to calculate the full 3ν LBL probabilities in matter. So, analysis includes increasingly rich data sets:

LBL Acc + Solar + KL

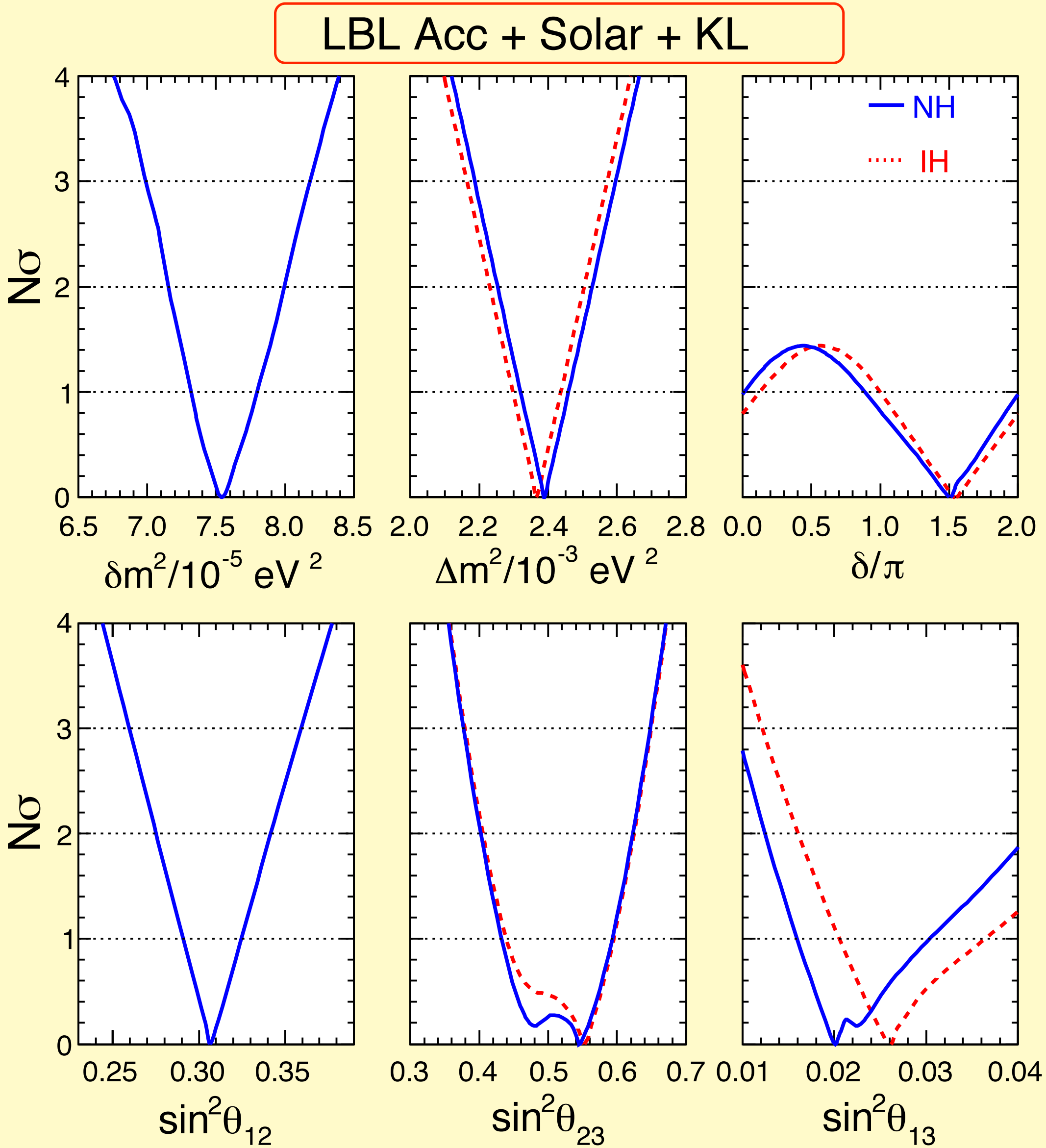
LBL Acc + Solar + KL + SBL Reactor

LBL Acc + Solar + KL + SBL Reactor + SK Atm.

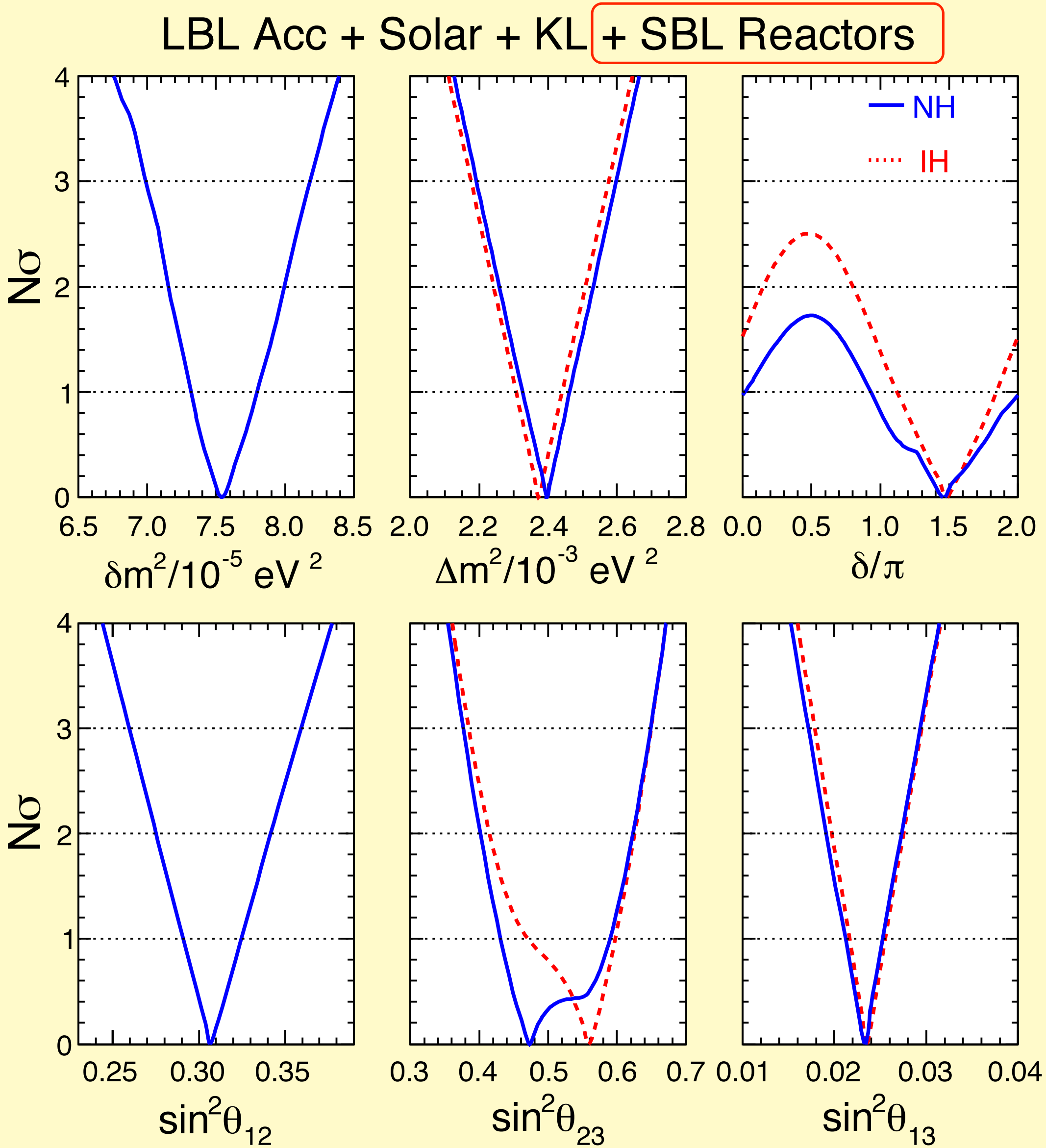
- Note. As it can be seen, **Solar + KL** data carry a clear preference ("hint") for

$$\sin^2\theta_{13} \sim 0.02$$

2.1 The global analysis

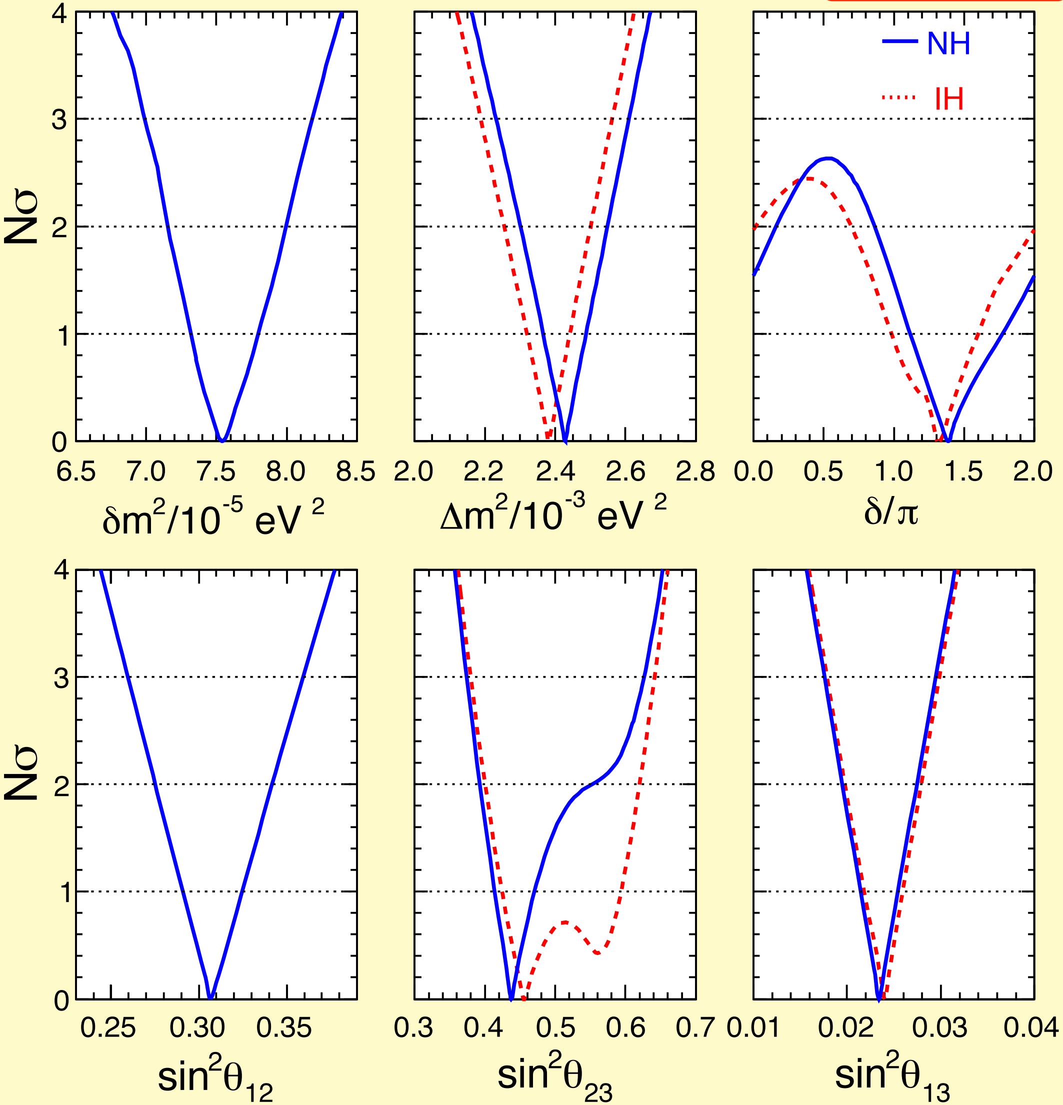


- Upper and lower bounds on all oscillations parameters but δ
- Slight preference for $\delta \sim 1.5\,\pi$
- Slight preference for θ_{23} non-maximal in the 2nd octant



- Strong θ_{13} bounds
- Still a preference for $\delta \sim 1.4\text{-}1.5\ \pi$
- Still a preference for non-maximal θ_{23} but octant flips with hierarchy

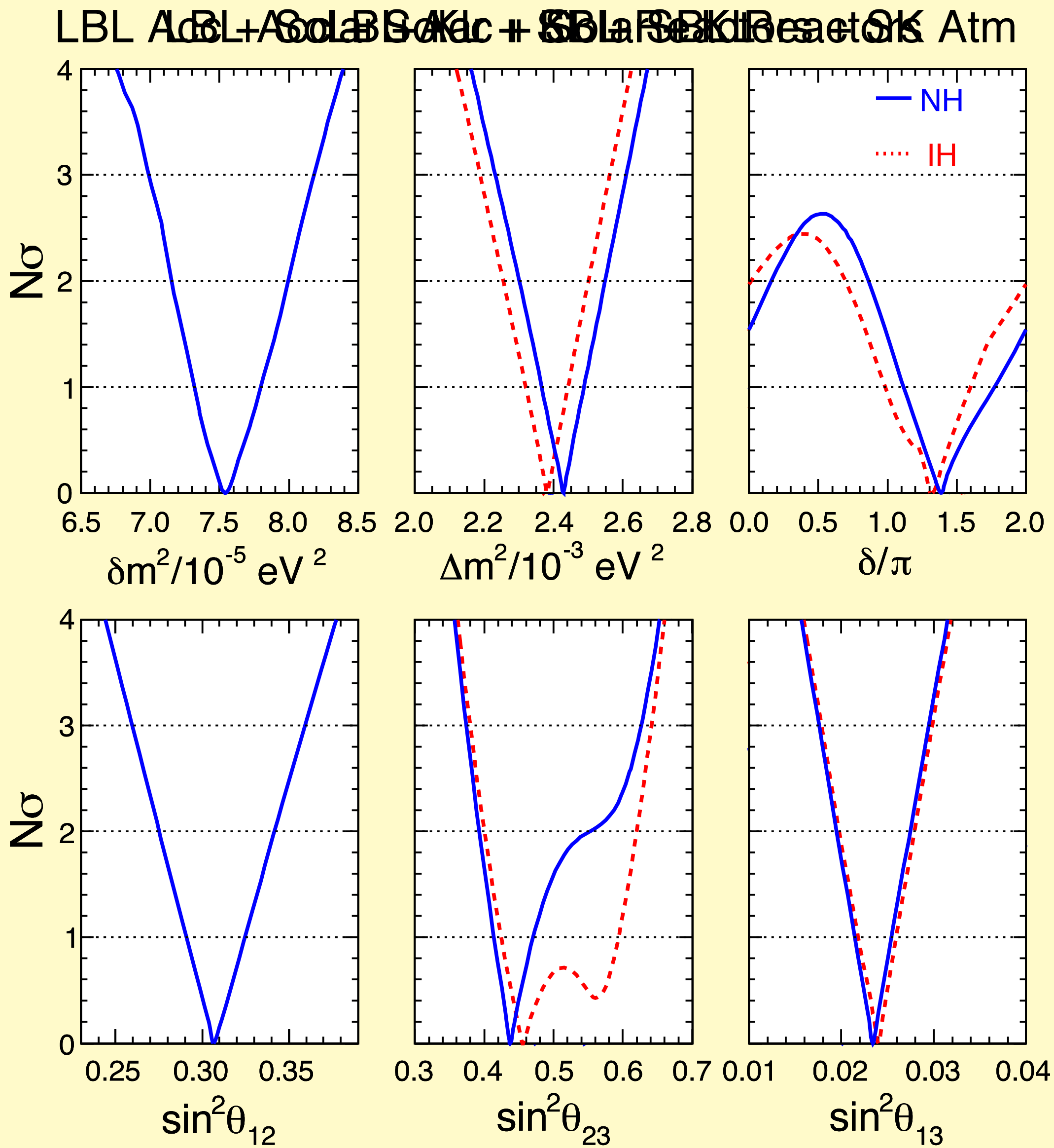
LBL Acc + Solar + KL + SBL Reactors + SK Atm



- Some effects on the $\nu_\mu \rightarrow \nu_\tau$ dominant parameters (Δm^2, θ_{23})
- Preference for $\delta \sim 1.4\,\pi$
- Preference for non-maximal θ_{23} and 1[st] octant in NH, much weaker in IH:

  somewhat fragile

Let us appreciate the improvement obtained by adding the new sets of data!



LBL Acc. + Solar + KamLAND

+

SBL reactors

+

SK atmospheric

Nσ ranges for single parameters (pre-Neutrino'14)

TABLE I: Results of the global 3ν oscillation analysis, in terms of best-fit values and allowed 1, 2 and 3σ ranges for the 3ν mass-mixing parameters. See also Fig. 3 for a graphical representation of the results. We remind that Δm^2 is defined herein as $m_3^2 - (m_1^2 + m_2^2)/2$, with $+\Delta m^2$ for NH and $-\Delta m^2$ for IH. The CP violating phase is taken in the (cyclic) interval $\delta/\pi \in [0, 2]$. The overall χ^2 difference between IH and NH is insignificant ($\Delta\chi^2_{\mathrm{I-N}} = -0.3$).

Parameter	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54	7.32 – 7.80	7.15 – 8.00	6.99 – 8.18
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.08	2.91 – 3.25	2.75 – 3.42	2.59 – 3.59
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.43	2.37 – 2.49	2.30 – 2.55	2.23 – 2.61
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.38	2.32 – 2.44	2.25 – 2.50	2.19 – 2.56
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.34	2.15 – 2.54	1.95 – 2.74	1.76 – 2.95
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.40	2.18 – 2.59	1.98 – 2.79	1.78 – 2.98
$\sin^2\theta_{23}/10^{-1}$ (NH)	4.37	4.14 – 4.70	3.93 – 5.52	3.74 – 6.26
$\sin^2\theta_{23}/10^{-1}$ (IH)	4.55	4.24 – 5.94	4.00 – 6.20	3.80 – 6.41
δ/π (NH)	1.39	1.12 – 1.77	0.00 – 0.16 ⊕ 0.86 – 2.00	—
δ/π (IH)	1.31	0.98 – 1.60	0.00 – 0.02 ⊕ 0.70 – 2.00	—

Fractional 1σ accuracy [defined as 1/6 of ±3σ range]

δm^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	Δm^2
2.6%	5.4%	8.5%	~10%	2.6%

Note: in 2014 1σ error on $\Delta m^2 \approx 6 \times 10^{-5}$ eV^2 < δm^2 !

Moreover …

- No significant **hierarchy** preference from the global fit [$\Delta\chi^2$(I-N) = -0.3]
- Weak preference for the **1st octant** (more fragile after T2K 2014 data).
- Intriguing hint of nonzero **CP violation**, with **sinδ < 0** …

  [Similar CP hint: Gonzalez-Garcia, Maltoni, Schwetz, Salvado 2013/14; SK, T2K official data analyses 2013/14.

About ~~CP~~ …

CP violation requires genuine 3ν oscillations, in particular …

- 3 mixing angles should be nonvanishing ✔
- 2 mass gaps should be nonvanishing ✔
- 1 Dirac phase should be nonvanishing …

Nature has already provided us with **5 favorable** conditions satisfied …

Let us hope that the 6th is also realized !

Concerning CP violation, let me remind you the fundamental paper by **Nicola Cabibbo** …

Volume 72B, number 3 PHYSICS LETTERS 2 January 1978

TIME REVERSAL VIOLATION IN NEUTRINO OSCILLATION

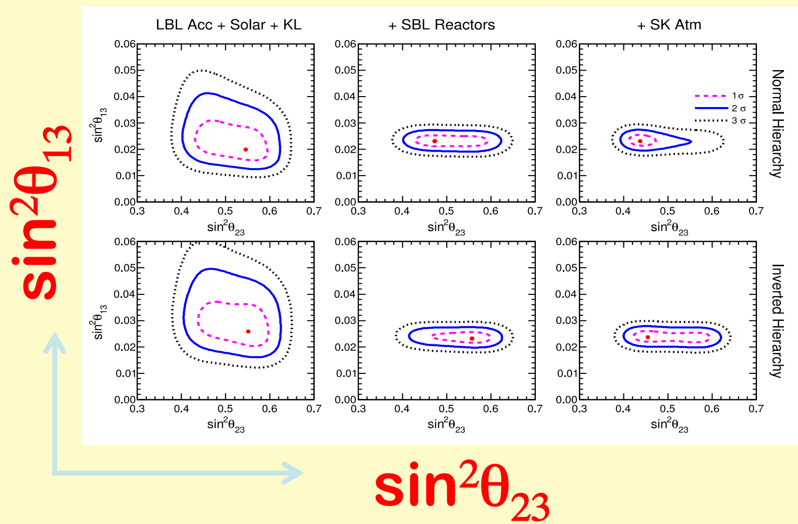
Nicola CABIBBO*

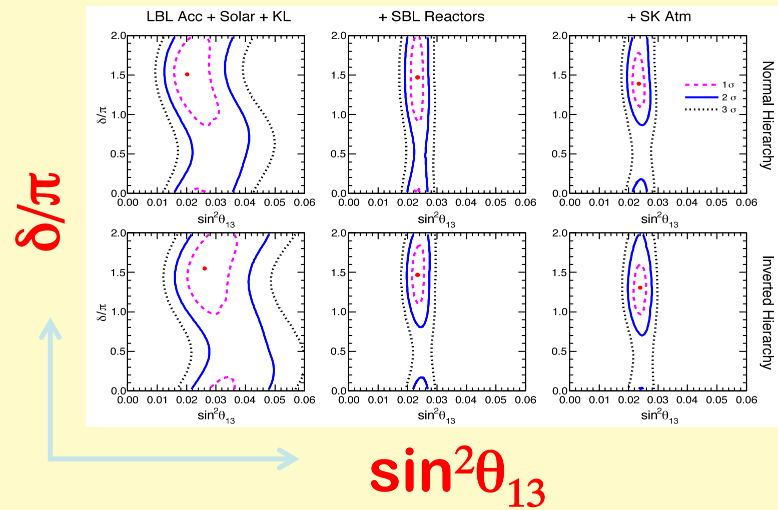
*Laboratoire de Physique Théorique et Hautes Energies, Paris, France***

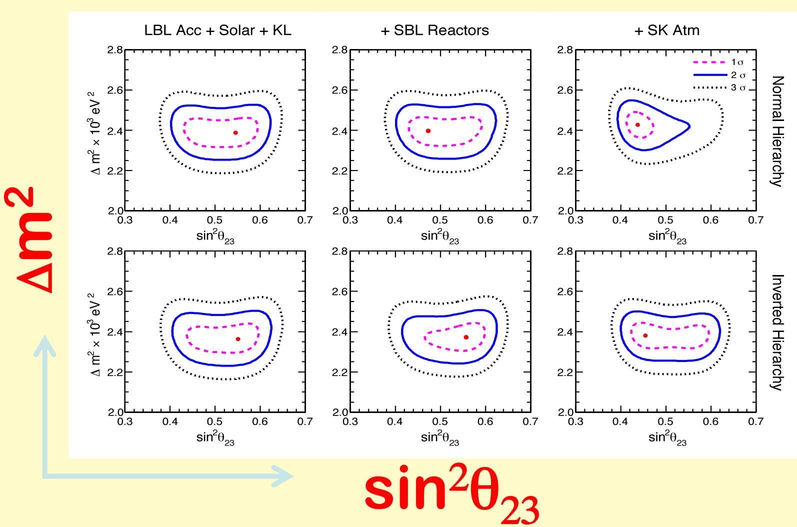
Received 11 October 1977

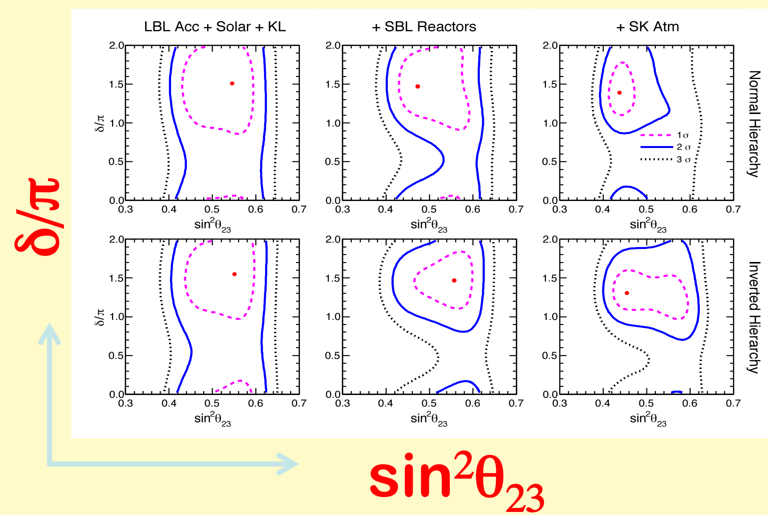
We discuss the possibility of CP or T violation in neutrino oscillation CP requires $\nu_\mu \longleftrightarrow \nu_e$ and $\bar{\nu}_\mu \longleftrightarrow \bar{\nu}_e$ oscillations to be equal Time reversal invariance requires the oscillation probability to be an even function of time Both conditions can be violated, even drastically, if more than two neutrinos exist

From variances to covariances: analysis of 2D plots







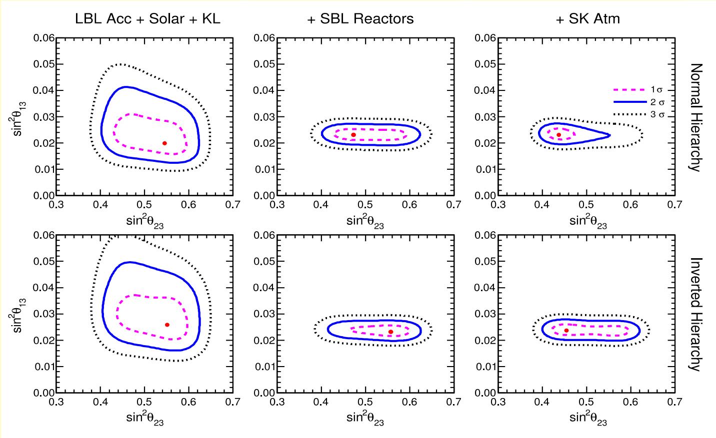


2.3 $(\theta_{13}, \theta_{23})$ correlation

NH →

IH →

$\sin^2\theta_{13}$



$\sin^2\theta_{23}$

Main aspects:

- Leading appearance amplitude at LBL Acc. ~ $\sin^2\theta_{23}\sin^2(2\theta_{13})$

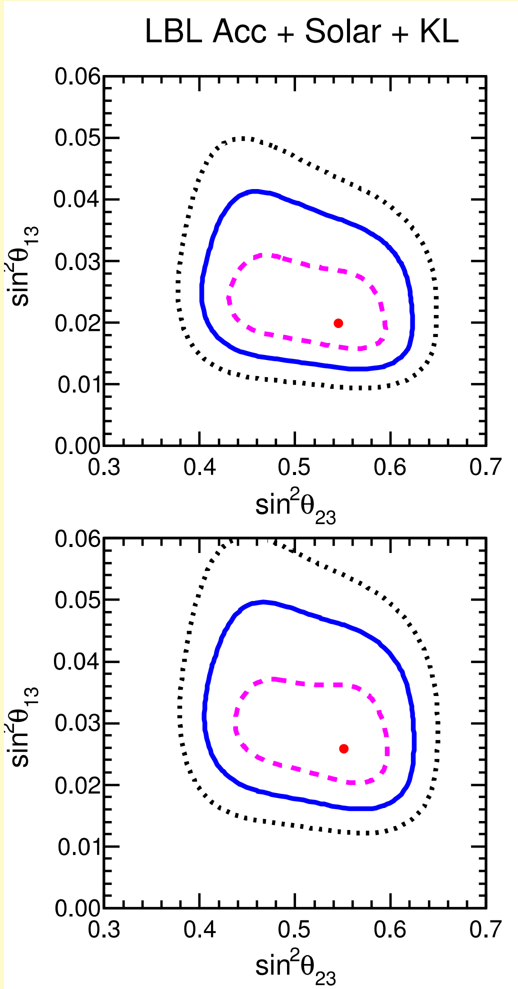
  ↳ anticorrelates θ_{23} and θ_{13}

- Leading disappearence amplitude at SBL Reac. ~ $\sin^2(2\theta_{13})$
- Subleading disappearence effects in Solar + KL ~ $\sin^2\theta_{13}$

  ↳ both indirectly help in selecting high/low θ_{23}

NH

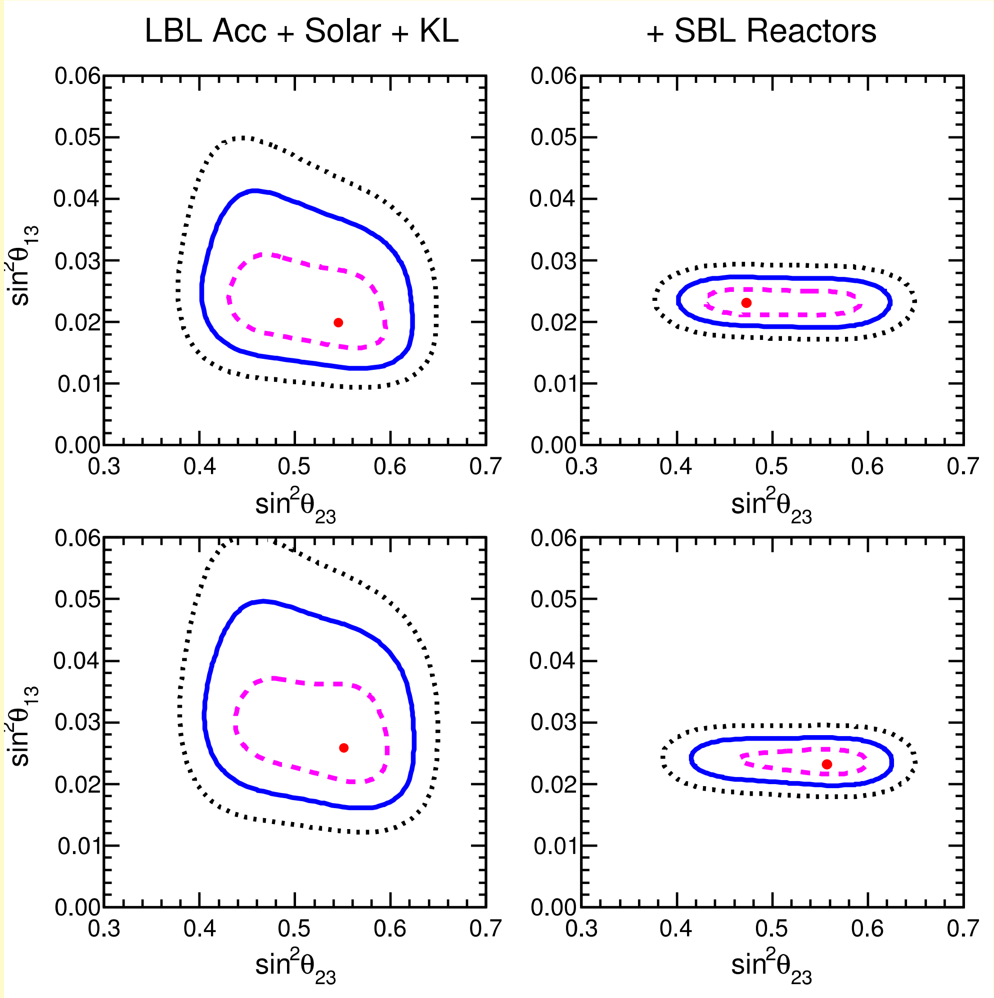
IH



- MINOS disappearance prefers non-maximal mixing (still wins over T2K preference for ~ maximal)
  - ⮡ two degenerate minima for θ_{23}
- T2K + MINOS appearance anticorrelate the two minima with θ_{13}
  - ⮡ the higher θ_{23}, the lower θ_{13}
- Contours extend to relatively high $\sin^2\theta_{13}$ to accommodate the relatively "strong" T2K appearance signal, especially in IH
- In the combination, Solar + KL data lift the degeneracy and prefer the second octant solution, associated with "low" $\sin^2\theta_{13} \sim 0.02$

NH

IH



SBL Reactor data prefer

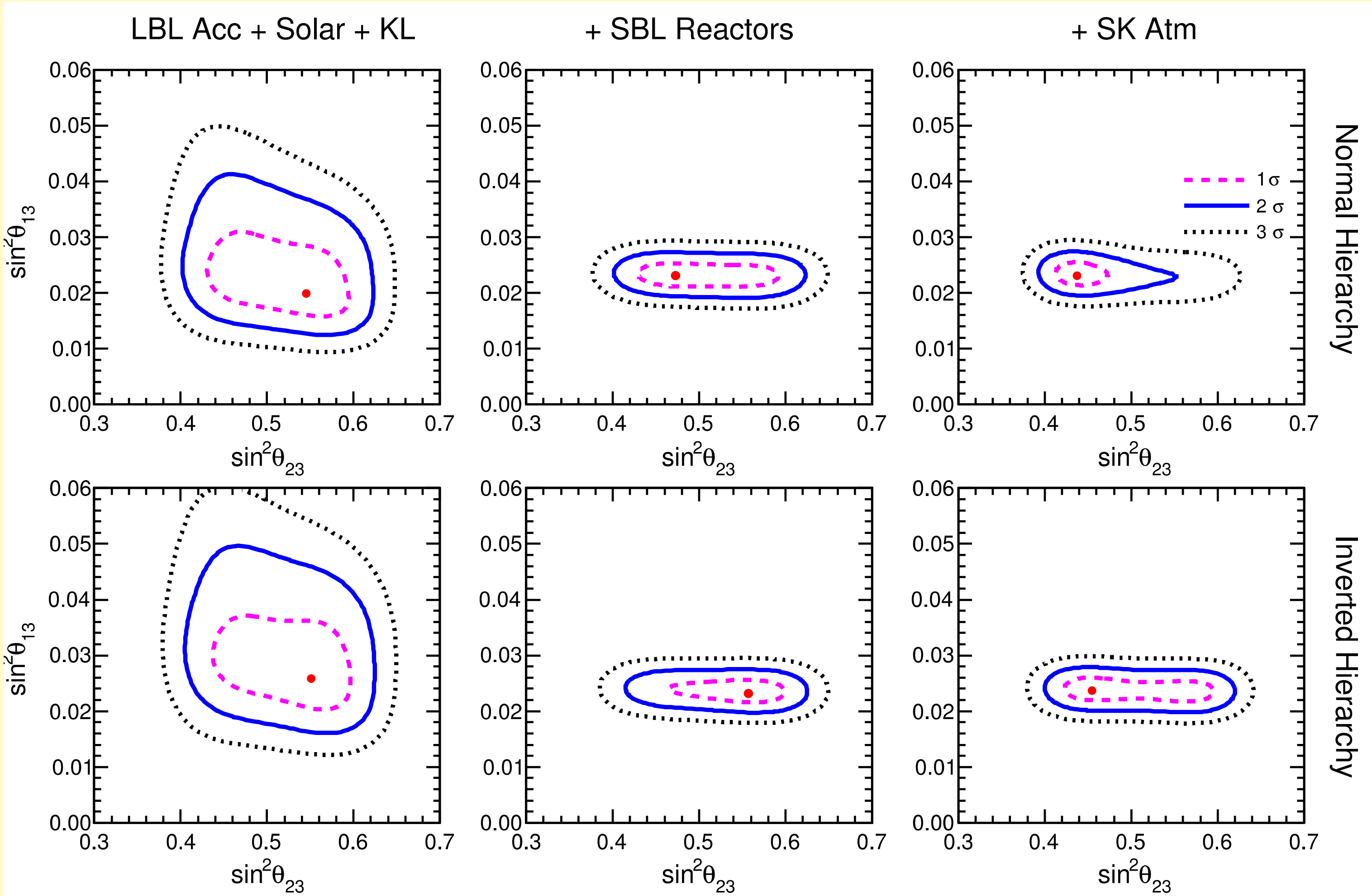
$\sin^2\theta_{13} \sim 0.023$

slightly higher than Solar + KL

enough to flip the octant in NH, but not enough to do so in IH.

NH

IH



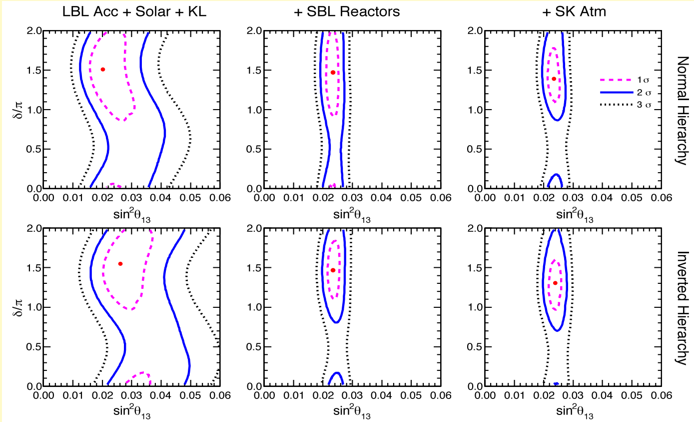
SK atm: In our analysis we still find an overall preference of these data for 1st octant. But, global balance for $\theta_{23} < \pi/4$ somewhat fragile.

2.3 $(\theta_{13}, \delta_{CP})$ correlation

NH →

IH →

δ/π



$\sin^2\theta_{13}$

Main aspects:

- Leading appearance amplitude at LBL Acc. ~ $\sin^2\theta_{23} \sin^2(2\theta_{13})$

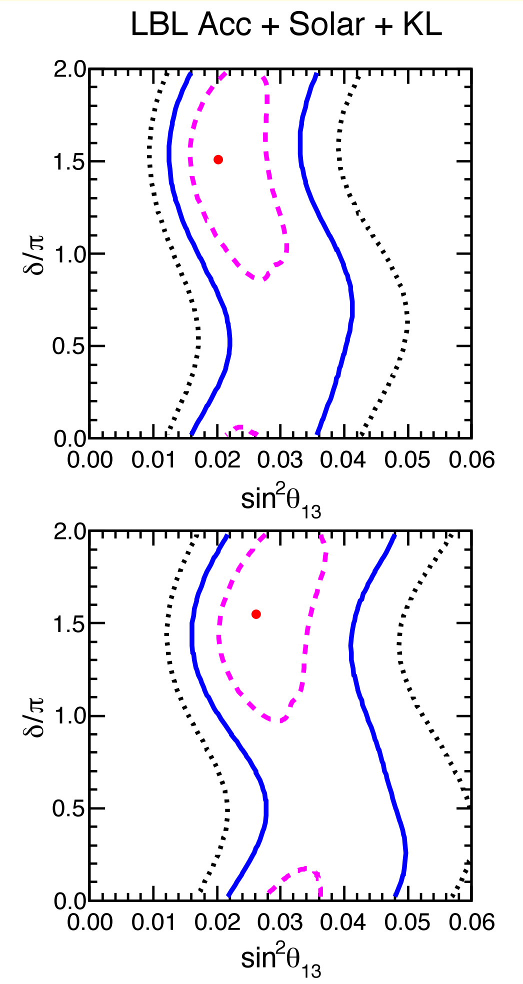
  ⮡ uncertainty on θ_{23} somewhat affects subleading terms

- Subleading CPV appearance amplitude at LBL ~ $\sin\delta$

  ⮡ T2K signal maximized for $\sin\delta \sim -1$ ($\delta \sim 1.5\pi$)

NH

IH



- Each wavy band is in part determined by superposition of "two bands" for the two θ_{23} octants [more evident in previous fits].

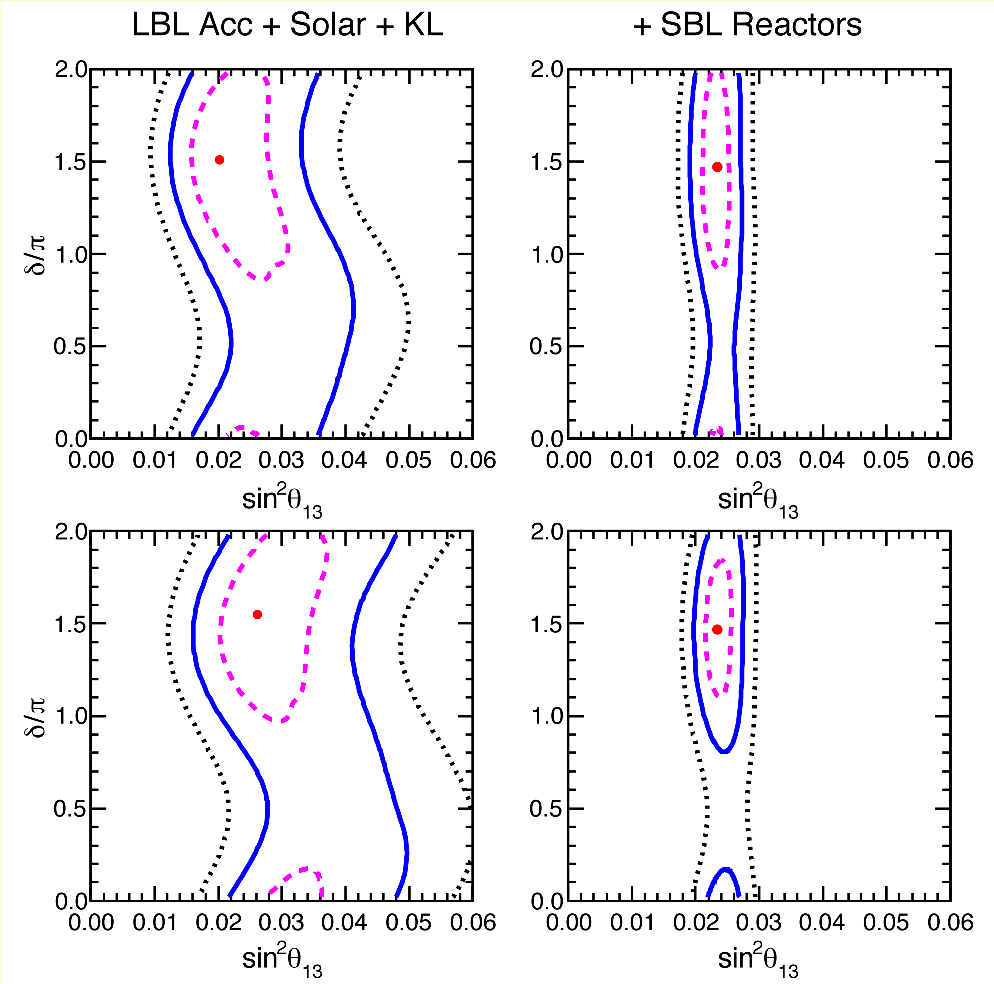
- For the relatively "low" value $\sin^2\theta_{13} \sim 0.02$ preferred by Solar + KL data, appearance signal in T2K maximized by subleading CP-odd term for $\sin\delta < 0$ [i.e., $1 < \delta/\pi < 2$]

- Best agreement with relatively "strong" T2K appearance signal is for $\delta/\pi \sim 1.5$, irrespective of the hierarchy.

- This trend wins over weaker MINOS appearence signal, which tend to prefer $\sin\delta > 0$.

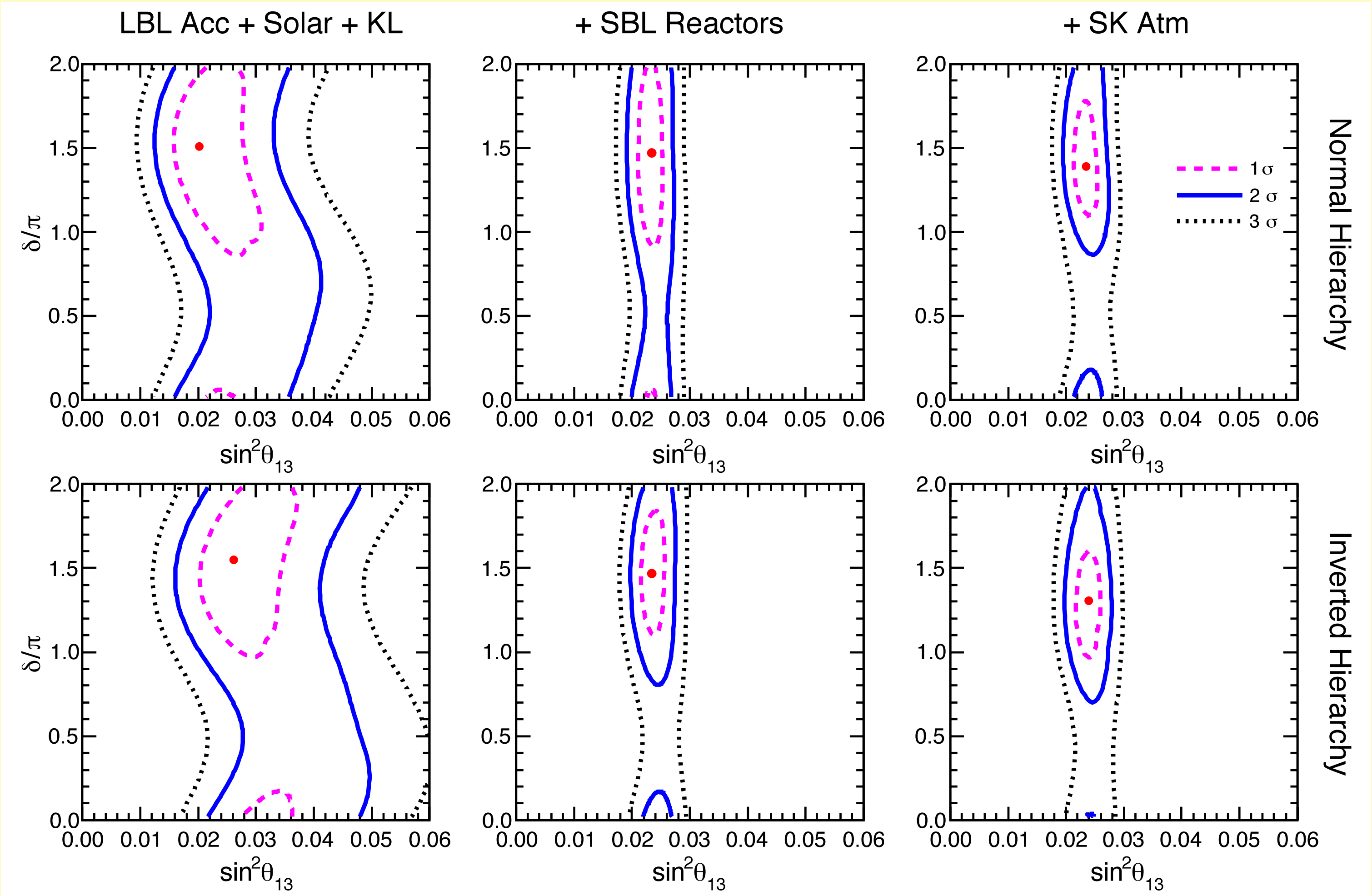
NH

IH



SBL Reactors data shrink the band around $\sin^2\theta_{13}$ ~ 0.023, a bit higher than Solar + SK but still on the leftmost side of the band: a preference persists for

$\delta/\pi \sim 1.5$



SK atm: In combination, these data further shrink the allowed regions, and slight lower the preferred value to **$\delta/\pi \sim 1.3\text{-}1.4$.**

Impact of (some) "Neutrino 2014" data: SBL reactors

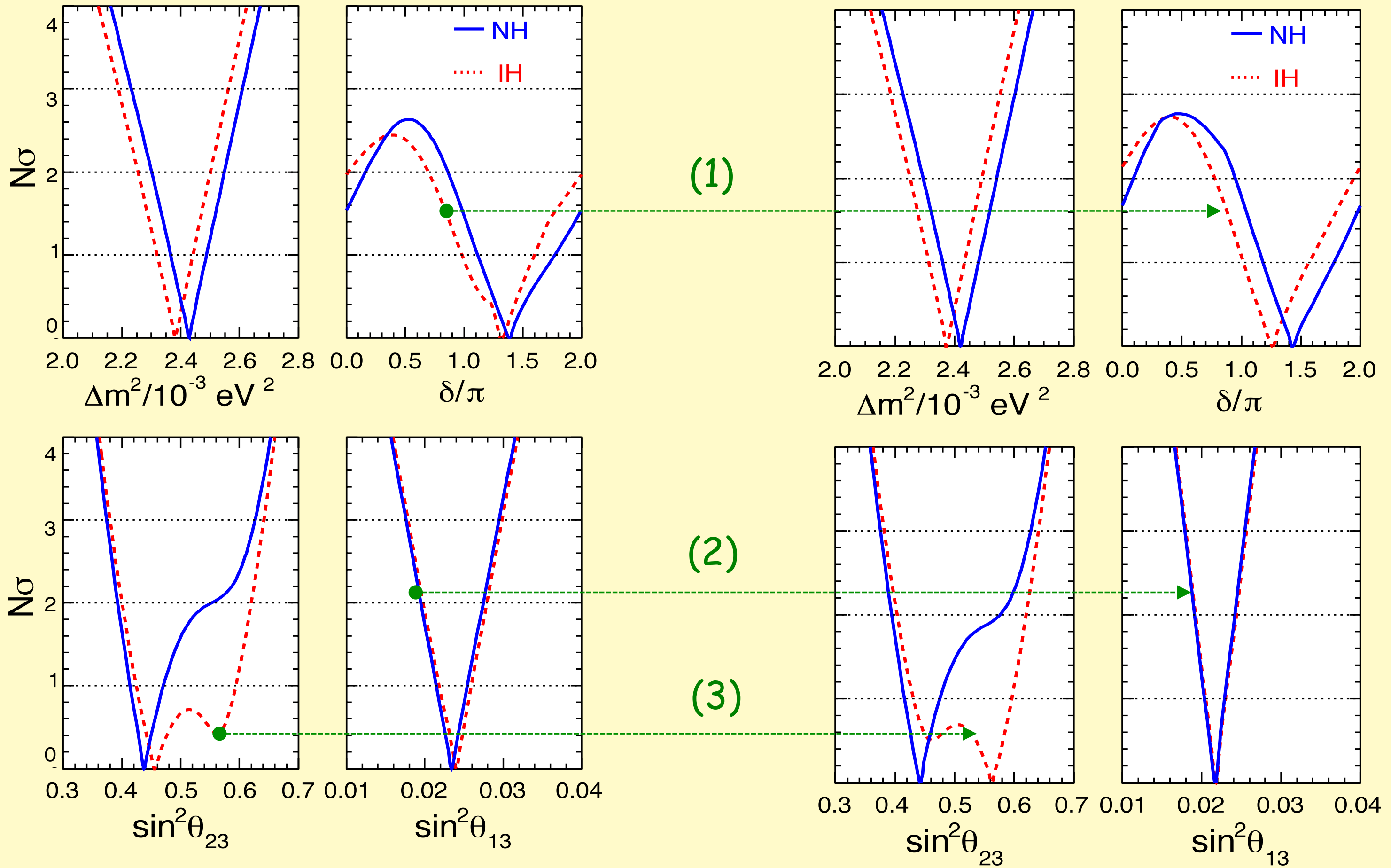
- **Daya Bay** - Gives more stringent bounds on (Δm^2, $\sin^2\theta_{13}$).
  In particular: $\sin^2\theta_{13} = (2.15 \pm 0.13) \times 10^{-2}$
  (a bit lower than previously).
- **RENO** - Claims observation of new reactor component at ~ 4-6 MeV.
- **Double Chooz** - Sees ~ 5 MeV bump but with lower significance
  [Rumors: Presumably seen also by Daya Bay ? ...]

In any case the estimate of (Δm^2, $\sin^2\theta_{13}$) from near-far comparison seems robust under this possible new reactor component.

Let us assume a pragmatic attitude:

While waiting for a clarification of the ~ 5 MeV "bump" origin, let us take the dominant Daya Bay 2014 bounds at face value

pre- Neutrino 2014 + Daya Bay 2014 (prelim.)



(1) Slightly sharper bounds on δ, via interplay of SBL reac. with LBL accel. data.

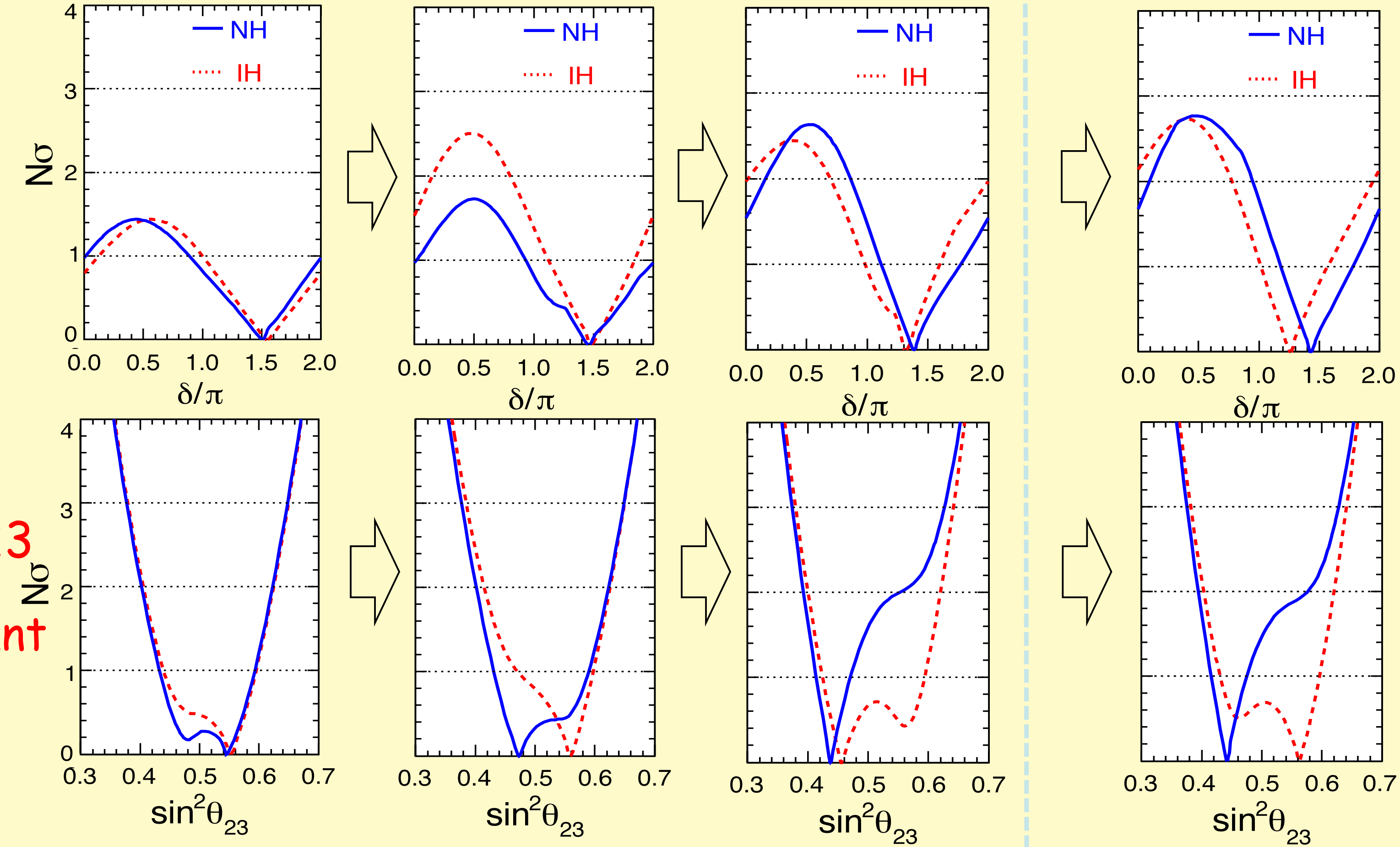
(2) Significantly more precise (and slightly lower) $\sin^2\theta_{13}$.

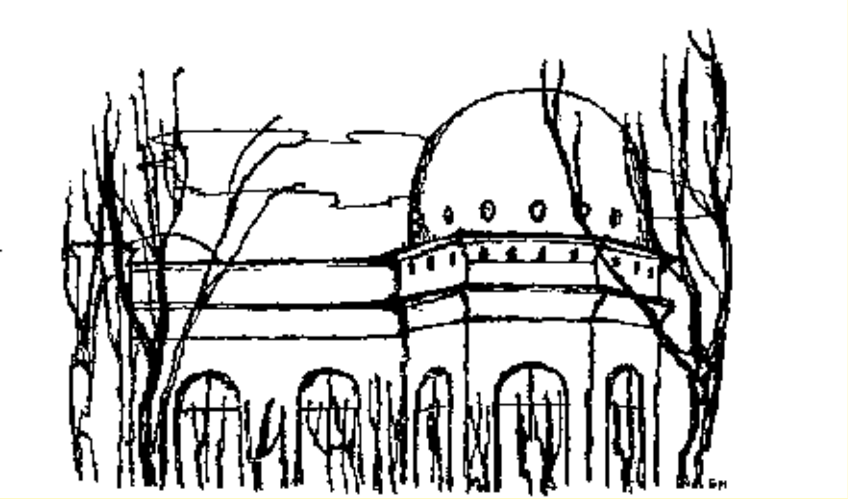
(3) 2nd octant of θ_{23} : more favored in IH, via anticorr. with θ_{13}

(4) NH/IH: no hint, $\Delta\chi^2(I-N) = +0.1$

Recap on δ, θ_{23}, $\Delta\chi^2$(IH-NH)

	LBL+Sol+KL	+SBL Reac	+SK atm	+Daya Bay'14 (prelimin.)	
			pre-ν2014	post-ν2014	
δ					intriguing, $\sin\delta < 0$ favored
θ_{23} octant					unstable, fragile
$\Delta\chi^2$ (IH-NH)	-1.4	-1.1	-0.3	-0.1	irrelevant





3. Neutrino Oscillations with Sterile Neutrinos*

* K.N. Abazajan et al., "Light Sterile Neutrino: a White Paper", arXiv: 1204.5379 [hep-ph].

J. Kopp, P.A.N. Machado, M. Maltoni, T. Schwetz, "Sterile neutrino oscillations: the global picture", JHEP 1305 (2013) 050.

3.1 Why a sterile neutrino ?

The hypothesis of sterile neutrinos has been formulated to explain several **anomalies** observed in neutrino experiments.

Note that at present it is **by no means certain** that sterile neutrinos are responsible for the set of anomalies which have triggered the current interest.

However, the extraordinary consequences related to such a possibility justifies a detailed assessment of the status of this theoretical hypothesis.

Decades of experimentation have produced a vast number of results in neutrino physics and astrophysics, a large part of which are in perfect agreement with only **three active neutrinos**, while a **small subset** calls for new physics beyond the Standard Model.

The first, and individually still most significant, argument pointing towards new physics is the

→

LSND anomaly

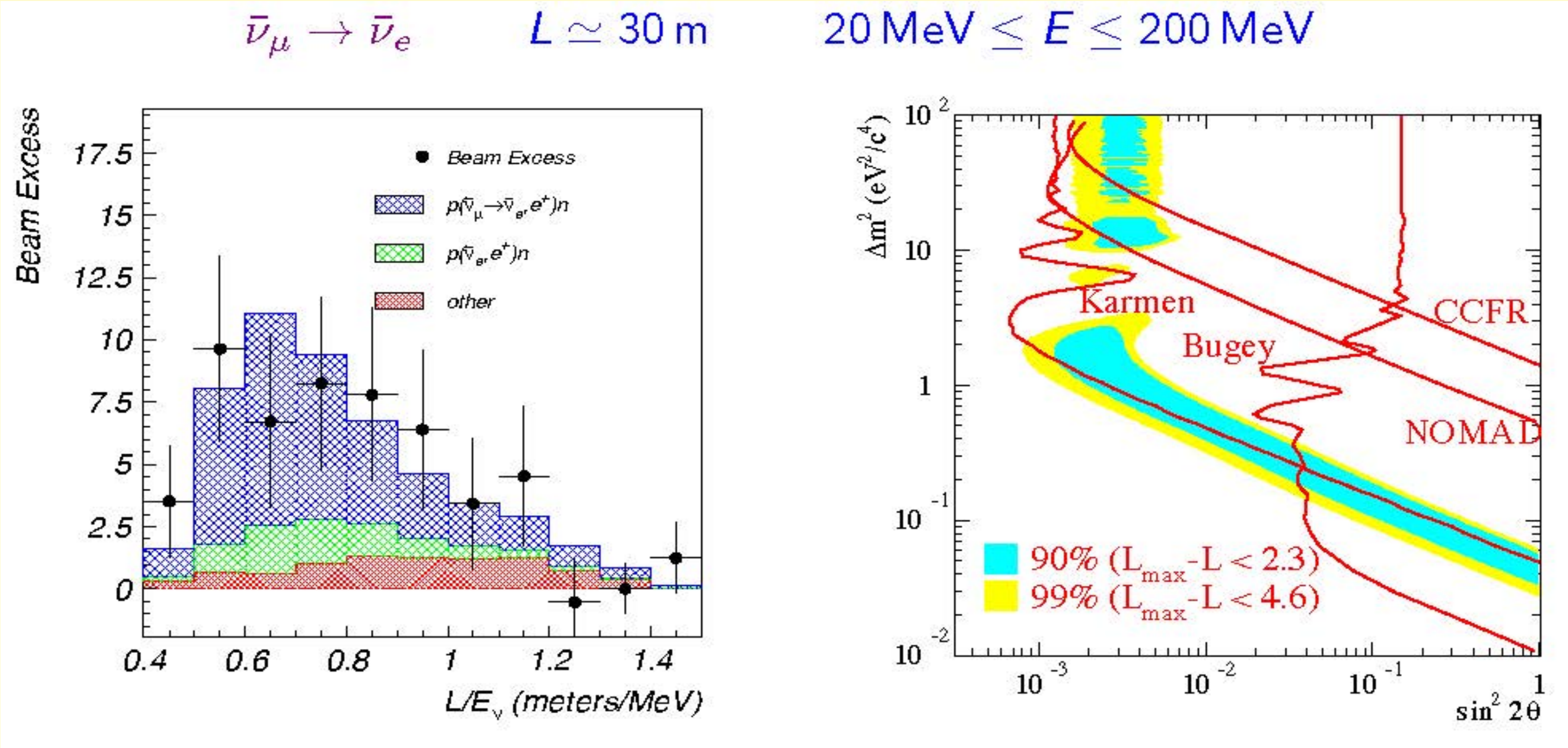
In the 90's **LSND**, a short-baseline accelerator experiment, observed **electron antineutrinos excess** in a pure muon antineutrino beam. The most straightforward interpretation of this result is **antineutrino oscillation** with a mass squared difference, $\Delta M^2 \sim 1$ eV^2.

A mass difference quite larger than the two mass differences Δm^2 and δm^2 discussed until now. This means that we need a **fourth neutrino**.

However, the results from LEP at CERN on the **invisible decay width** of the Z boson show that there are **only** three neutrinos which couple to the Z boson with a mass below one half of the mass of the Z boson.

Therefore the fourth neutrino, if it indeed exists, cannot couple to the Z boson and hence is a **sterile neutrino**, i.e. a Standard Model gauge singlet.

LSND signal

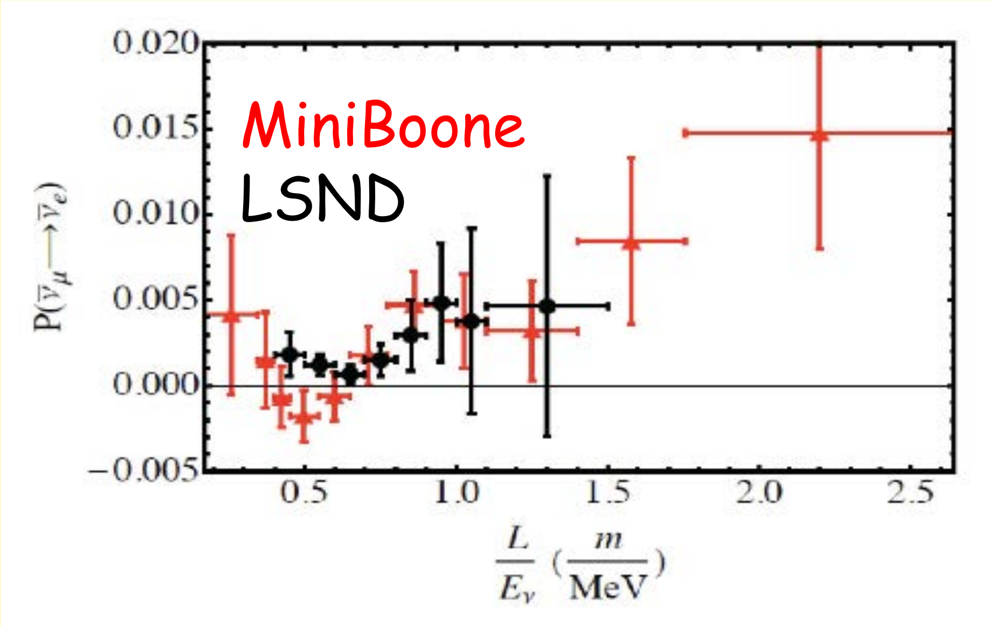


On the left the signal (beam excess) seen in LSND …

… and on the right the allowed region, reported together with the limit coming from the experiments Karmen and Bugey.

Unfortunately, after more than 20 years, this result has not been either confirmed or ruled out conclusively, even by dedicated appearance experiments (e.g., MiniBoone).

Indeed, you may or may not see an oscillation pattern here ...



... especially if you exclude the two rightmost data points at lowest energy and highest background.

The reactor neutrino anomaly

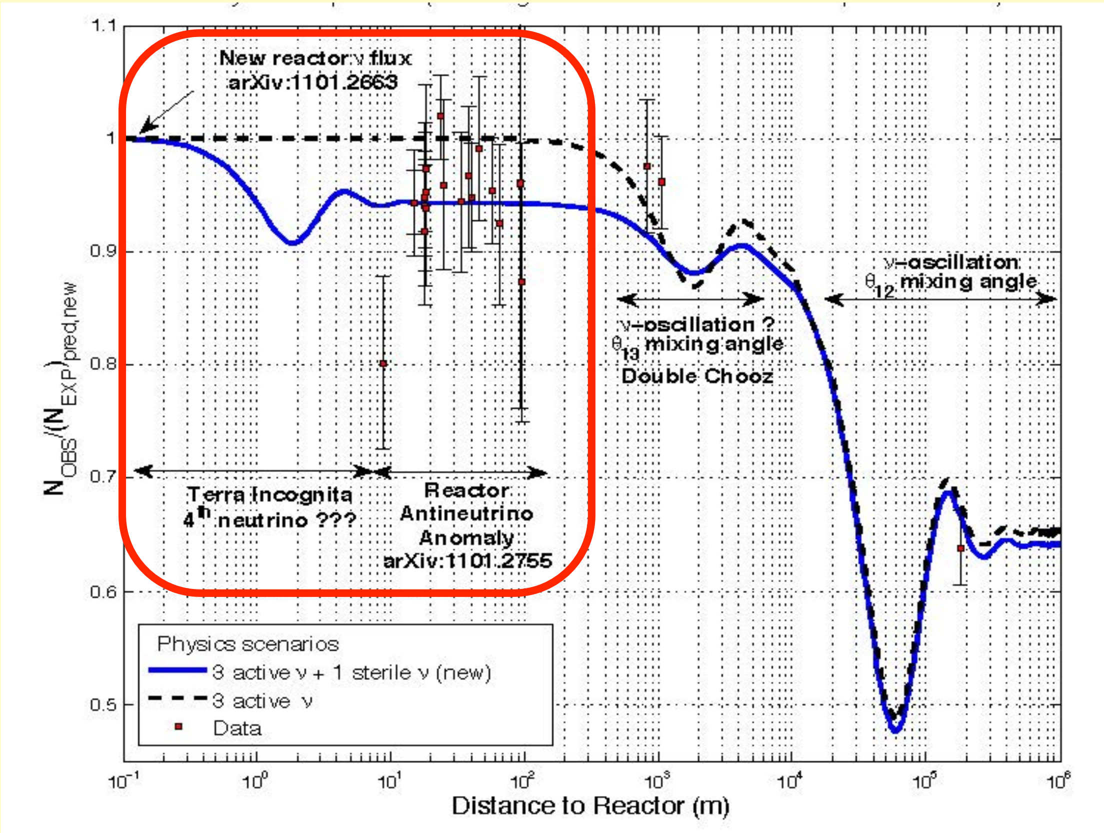
On the other hand, a new anomaly supporting the sterile neutrino hypothesis emerges from the recent **re-evaluations of reactor antineutrino fluxes**, which find a 3% increased flux of antineutrinos relative to the previous calculations.

At the same time, the experimental value for the neutron lifetime became significantly smaller, which in turn implies a larger inverse β-decay cross section.

As a consequence, the **overall expectation value for antineutrino events** from nuclear reactors increased by roughly 6%.

We have to conclude that more than 30 years of data from reactor neutrino experiments, formerly in good agreement with the flux prediction, have become the **observation of an apparent 6% deficit of electron antineutrinos** …

… a deficit compatible with sterile neutrinos having a $\Delta m^2_{sterile} > 1\ eV^2$.



Mueller et al.

In addition to the known disappearance due to 3ν oscillations at L > O(100 m), there seems to be **an extra deficit at small L.**

The Gallium anomaly

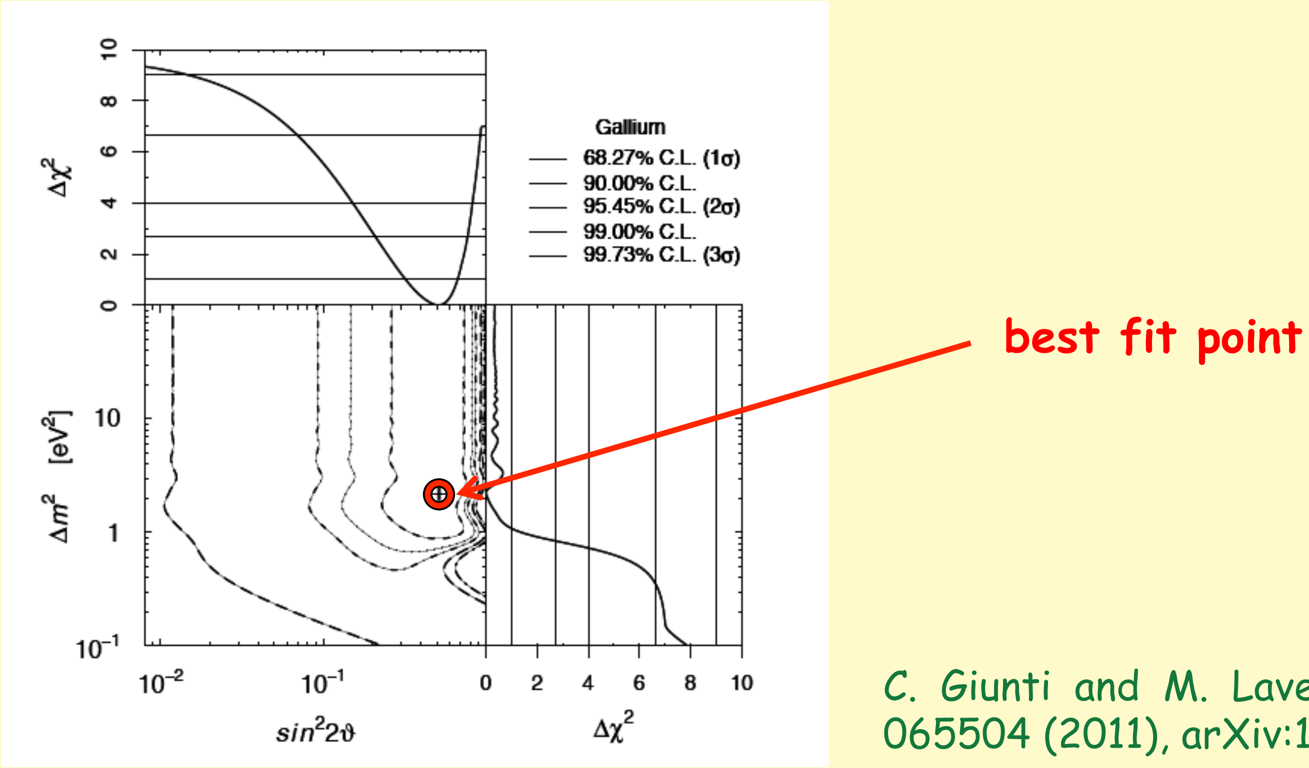
Another hint consistent with sterile neutrinos comes from the **source calibrations** performed for radio-chemical solar neutrino experiments based on **gallium** (Gallex and Sage).

In these calibrations **very intense artificial sources** ^{51}Cr and ^{37}Ar, which decay via electron capture and emit mono-energetic electron neutrinos, were placed in proximity to the detector and the resulting event rate were measured.

Both the source strength and reaction cross section are known with some precision and a **5-20% deficit** of the measured to expected count rate was observed.

Again, this result would find a natural explanation by a **sterile neutrino** with $\Delta m^2_{sterile} > 1\ eV^2$, which would allow some of the electron neutrinos from the source to **"disappear"** before they can interact.

In the figure **allowed regions in the $(\sin^2 2\theta, \Delta m^2)$ plane** and **marginal χ^2's** obtained from the combined fit of the different source experiments are reported.



C. Giunti and M. Laveder, Phys.Rev. C83, 065504 (2011), arXiv:1006.3244 [hep-ph].

The previous results suggesting a sterile neutrino with mass around **1 eV** have to be contrasted with a number of results which clearly **disfavor** this interpretation.

The strongest constraints derive from the **non-observation of muon neutrino disappearance by accelerator experiments** like CDHSW or MINOS.

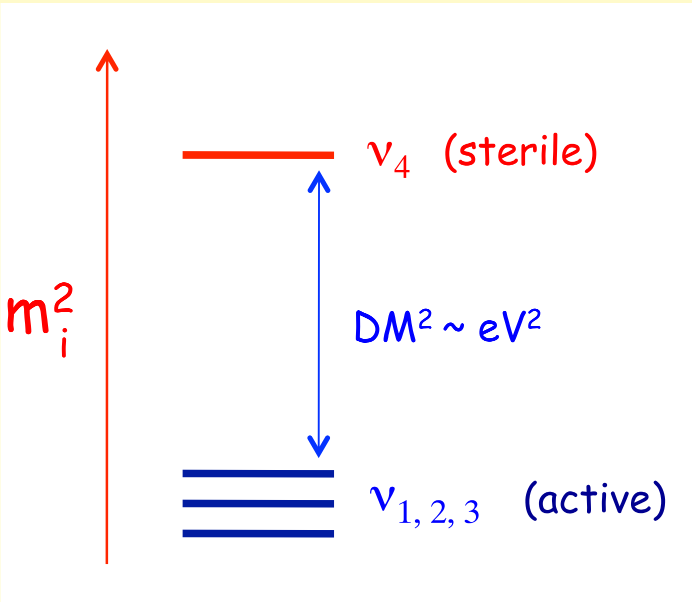
Bounds on the **disappearance of electron neutrinos** are obtained from **KARMEN** and **LSND**, as well.

The **MiniBooNE** neutrino result, a **non-observation of electron neutrino appearance** in a muon neutrino beam, is incompatible with the LSND appearance result, if CP is conserved. On the other hand, the **antineutrino** result from the same experiment is fully compatible with the LSND result.

A further difficulty in interpreting experimental evidence in support of a light sterile neutrino is that the effects are purely in **count rates**. The dependence on energy and distance characteristic of the oscillation phenomena associated with sterile neutrinos remains to be observed.

3.2 Sterile neutrinos in SBL experiments

Let us discuss the point by assuming a **(3 + 1)** scheme, i.e. the usual **three active neutrinos** and **1 sterile neutrino**.



We can apply the "one dominant mass scale approximation":

The mixing matrix takes now the form,

$$\begin{pmatrix} \begin{bmatrix} & & \\ & U_{PMNS} & \\ & & \end{bmatrix} & \begin{matrix} U_{e4} \\ U_{\mu 4} \\ U_{\tau 4} \end{matrix} \\ U_{s1} \quad U_{s2} \quad U_{s3} & U_{s4} \end{pmatrix}$$

with the PMNS 3x3 matrix no more **unitary**, being part of a larger 4x4 mixing matrix.

In order not to alter too much the established 3ν phenomenology we assume

$$|U_{s4}|^2 \sim 1 - \text{epsilon} \qquad\qquad |U_{\alpha 4}|^2_{\alpha = e,\mu,\tau} << 1$$

For experiments sensitive mainly to $\Delta M^2 \sim eV^2$, one can take the limits $\delta m^2 \to 0$ and $\Delta m^2 \to 0$, and apply the same logic as for the dominant mass scale in $3\nu \to (2\nu) \oplus (1\nu)$ i.e.

$$4\nu \to (3\nu) \oplus (1\nu)$$

Accordingly, one gets

"singly" suppressed by $|U_{\alpha 4}|^2 << 1$

Disappearance ($\alpha = \beta$) $$1 - P_{aa} \cong 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2) \sin^2\left(\frac{\Delta M^2 x}{4E}\right)$$

Appearance ($\alpha \neq \beta$) $$P_{aa} \cong 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2 \sin^2\left(\frac{\Delta M^2 x}{4E}\right)$$

"doubly" suppressed by $\begin{cases} |U_{\alpha 4}|^2 << 1 \\ |U_{\beta 4}|^2 << 1 \end{cases}$

It follows that, if there is a

$\nu_\mu \to \nu_e$ **appearance** signal

there must be larger

$\nu_\mu \to \nu_\mu$ and $\nu_e \to \nu_e$ **disappearance** signals

at the same scale, $\Delta M^2 \sim O(eV^2)$, since, as we have seen, appearance in "doubly" suppressed, wheras disappearance is only "singly" suppressed.

However, no unambiguous disappearance signal has been seen, especially in $\nu_\mu \to \nu_\mu$ mode.

In particular, it is easy to verify that there exists a relation between appearance and disappearance in the limit of **large enough baseline**.

If we assume $L \gg 4\pi E/\Delta m^2_{41}$, but $L \ll 4\pi E/\Delta m^2_{31}$ (quite reasonnable), then

$$P_{ee} \cong 1 - 2|U_{e4}|^2 (1 - |U_{e4}|^2)$$

$$P_{\mu\mu} \cong 1 - 2|U_{\mu 4}|^2 (1 - |U_{\mu 4}|^2)$$

$$P_{e\mu} \cong 2|U_{e4}|^2 \, |U_{\mu 4}|^2$$

It follows

$$2 P_{e\mu} \cong (1 - P_{ee})(1 - P_{\mu\mu})$$

i.e. a one-to-one relation between the appearance and disappearance probabilities.

Appearance/disappearance tension in 3+1 (and 3+2) scenario

The previous relation can be re-written in terms of the three **mixing angles**

$$\sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$$

which is the main source of tension in the global fit of the SBL experiments.

The strong tension between disappearance and appearance experiments is not reflected in the global $\Delta\chi^2$, since there is a large number of data points not sensitive to the tension.

It can be quantified by using the so-called parameter goodness of the fit (PG) test, designed to test the consistency of different parts of the global data. Without entering the details, it is estimated

$$\chi^2_{PG} = \chi^2_{min,glob} - \chi^2_{min,app} - \chi^2_{min,dis} = \Delta\chi^2_{app} + \Delta\chi^2_{dis}$$

which indicates that appearance and disappearance data are consistent with each other only with a p-value of about 10^{-4}.

The global oscillation fit (3+1)

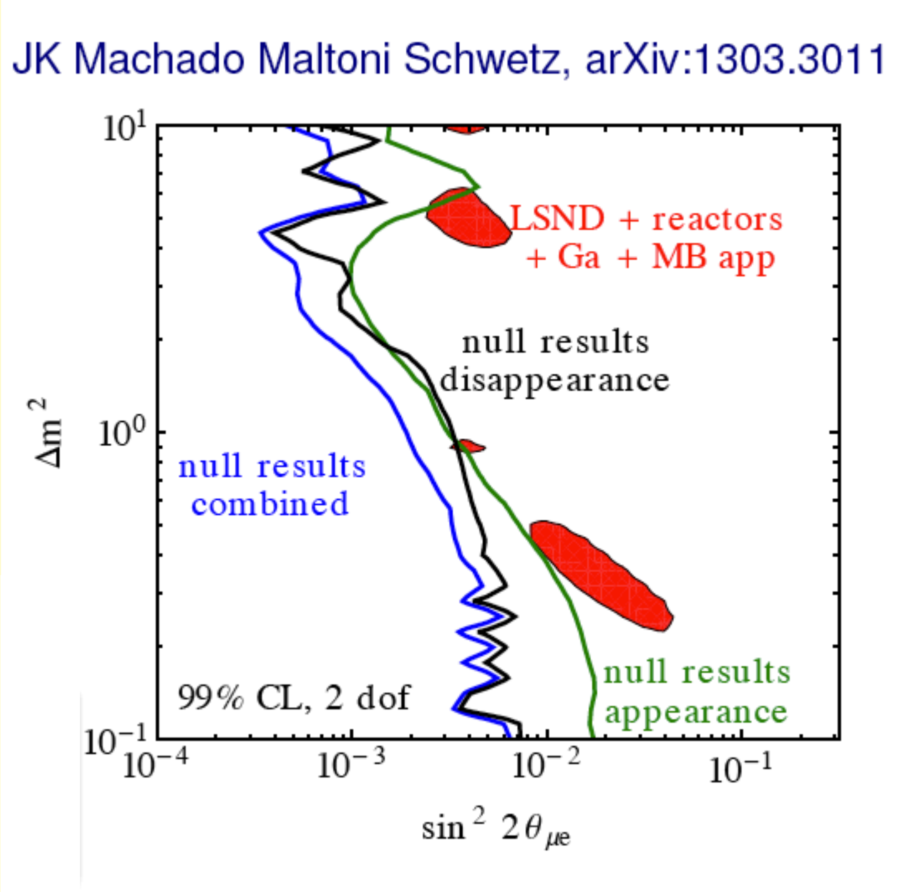
There are several global fits. The most recent one has been performed by Kopp, Machado, Maltoni Schwetz (arXiv 1303.3011). It includes also the data coming from reactor anomaly and Gallium calibration.

In red the **parameter regions** indicated by the combined hints for oscillations including SBL reactor, Gallium, LSND, and MiniBooNE appearance data.

Those regions are compared to the constraint emerging from all other data. There is **no overlap region at 99% CL**.

Hence, explanation of anomalies within the **(3+1) scheme** is in **strong tension** with constraints from null-result experiments.

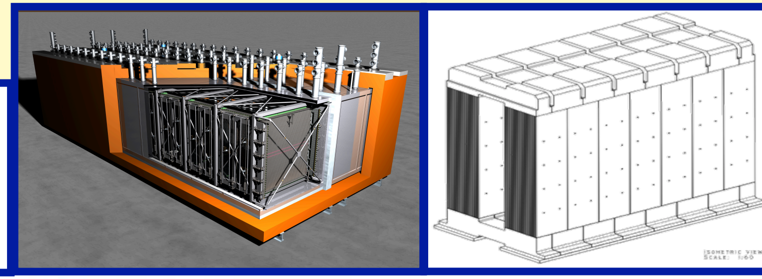
Finally, no appreciable improvement going to **two sterile neutrinos** schemes.

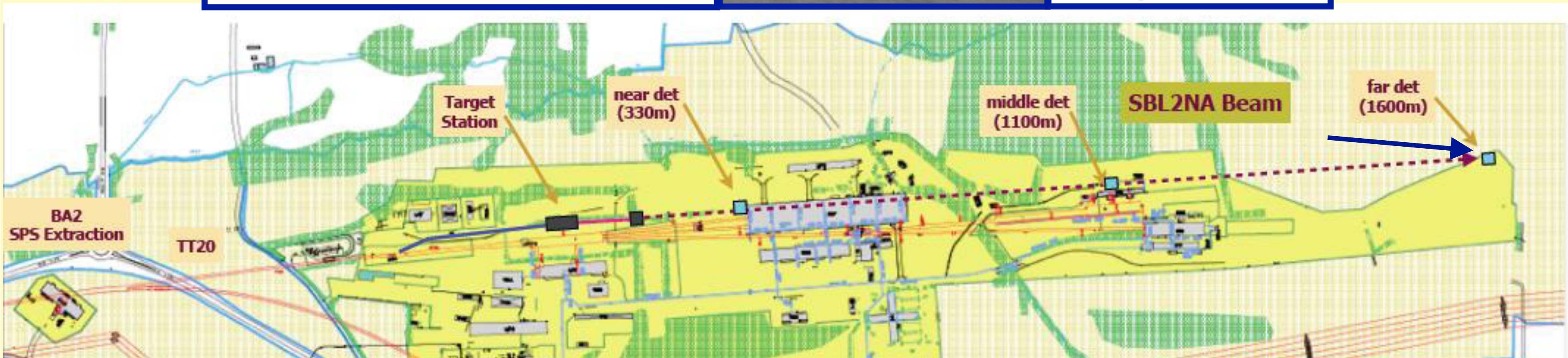


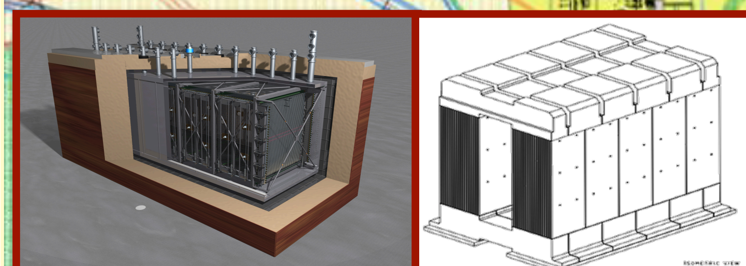
An experiment for the future ?

Try to test both disappearance and appearance in one and the same experiment, using near/far and good flavor identification. One idea out of many: ICARUS/ NESSiE at CERN or FNAL.

Far position (1600 m)
ICARUS-T600 detector +
magnetic spectrometer



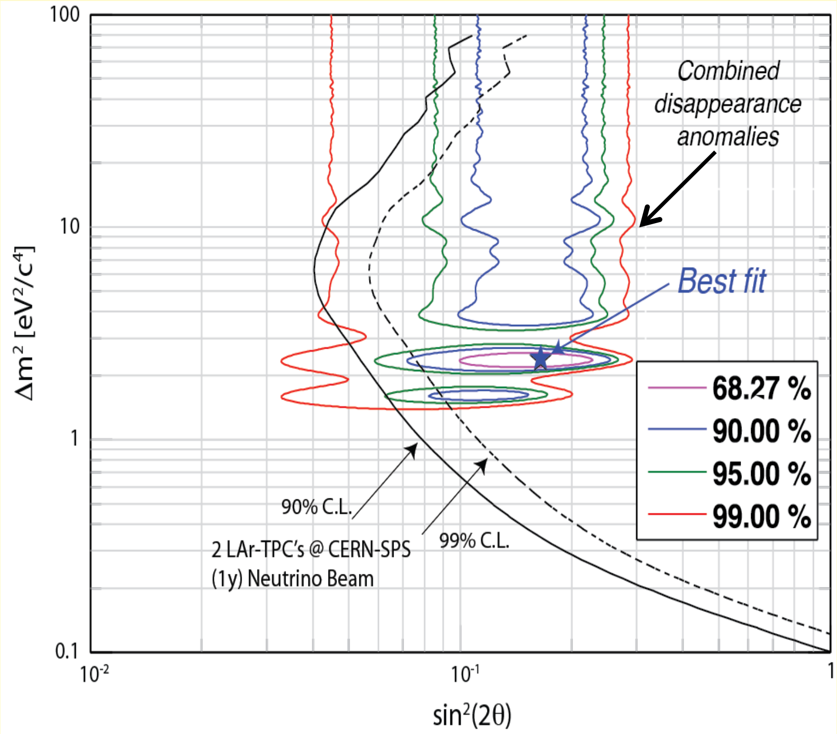




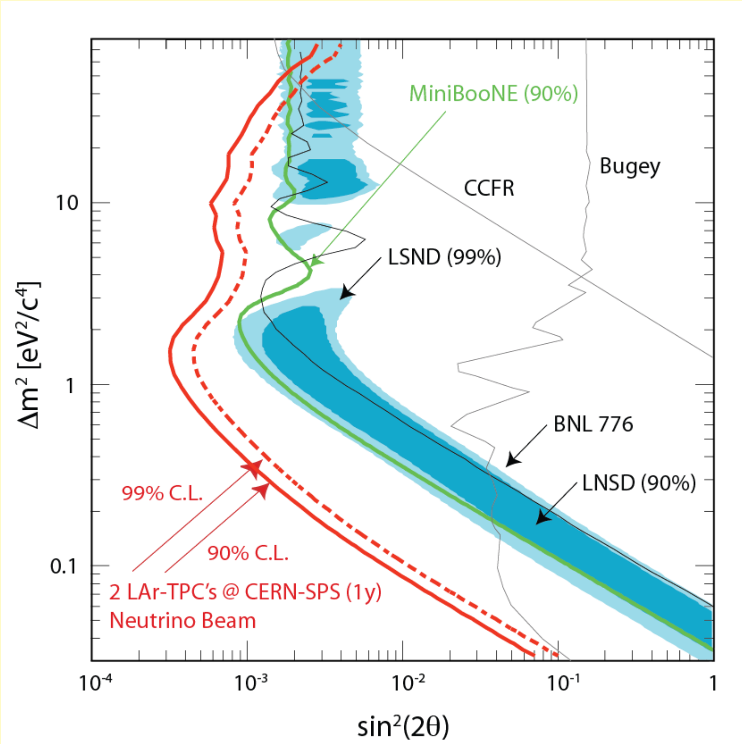
Near position (330m)
150t LAr-TPC detector
To be build anew + magnetic
spectrometer

Estimated potential (with hypothetical CERN-like beam)

Sensitivity in disappearance:



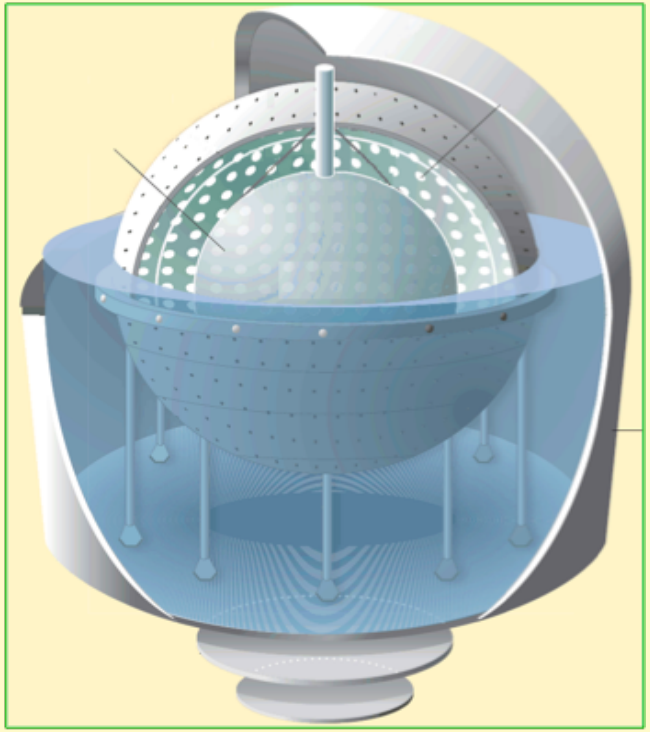
Sensitivity in appearance:

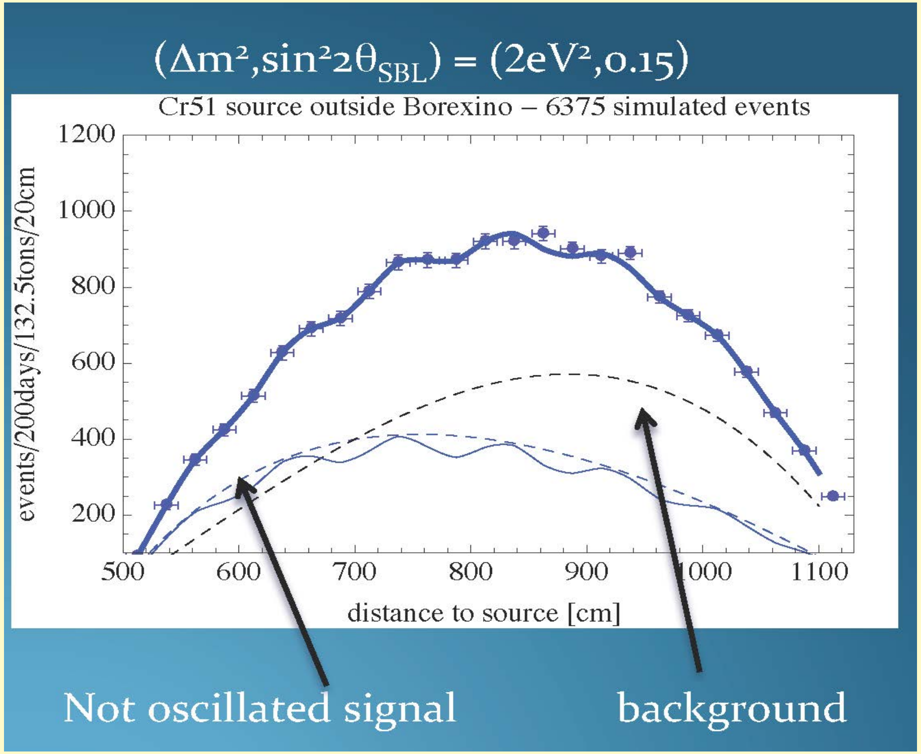


The experiment seems able of giving a conclusive answer.

Another (funded) project

Test sterile neutrino oscillations with a strong radioactive source (inside or) just outside **Borexino**: one might observe the oscillation pattern at scale of meters.





Many other ideas/projects being discussed. Time will tell !

Conclusions and Open Problems

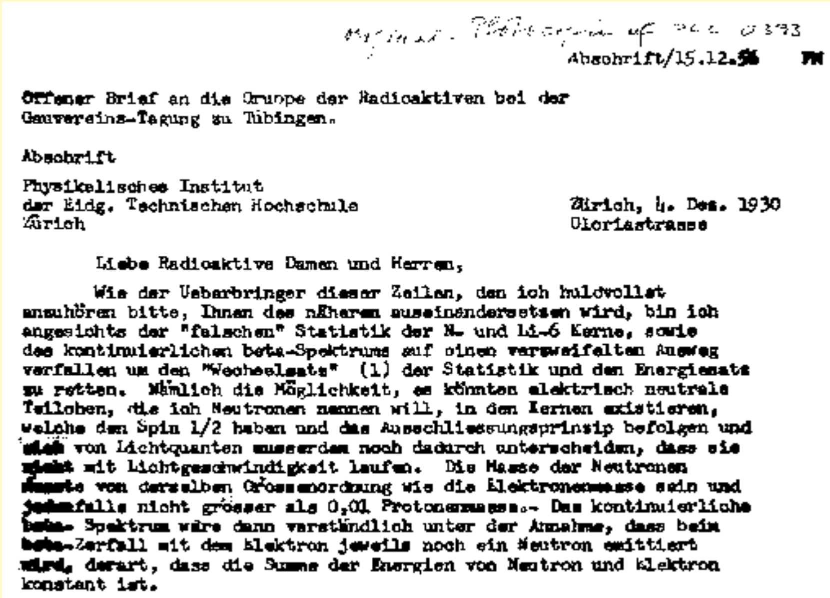
Great progress in recent years …

Neutrino mass & mixing: established fact
Determination of $(\delta m^2, \theta_{12})$ and $(\Delta m^2, \theta_{23})$
Determination of θ_{13} at reactors (+ accel.)
Observation of (half)-period of oscillations
Direct evidence for solar ν flavor change
Evidence for matter effects in the Sun
Upper bounds on ν masses in (sub)eV range
…………

Further ν_e, ν_τ appearance data at accelerators
Leptonic CP violation
Absolute m_ν from β-decay and cosmology
Test of $0\nu2\beta$ claim and of Dirac/Majorana ν
Matter effects in the Earth, Supernovae…
Normal vs inverted hierarchy
Octant of θ_{23}
Sterile neutrinos in oscillations and cosmology
New neutrino interactions
Deeper theoretical understanding
See-saw and leptogenesis scenarios
…………

… and great challenges for the future!

After 84 years... (W. Pauli, Letter from Zurich, 1930)



Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

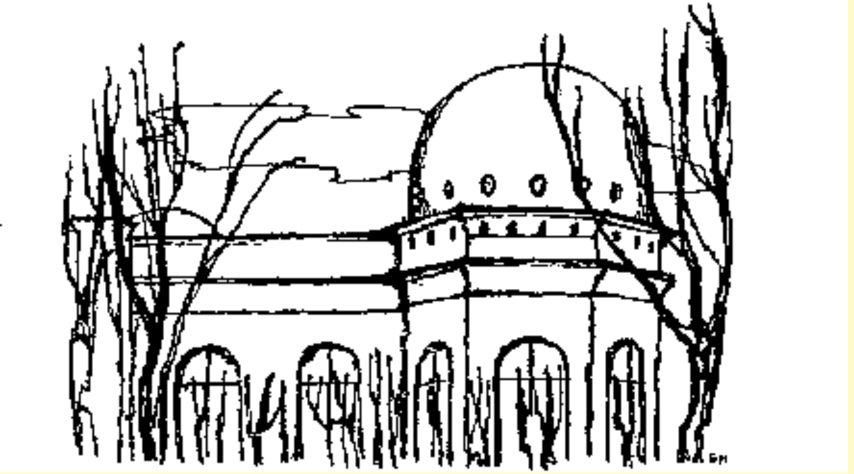
Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

… the neutrino continues to be a source of surprise !



Ecole Internationale Daniel Chalonge
18th Paris Cosmology Colloquium 2014

"Latest news from the Universe: Lambda Warm Dark Matter (LWDM), CMB, Dark Matter, Dark Energy, Neutrinos and Sterile Neutrinos"

Thanks for your attention!