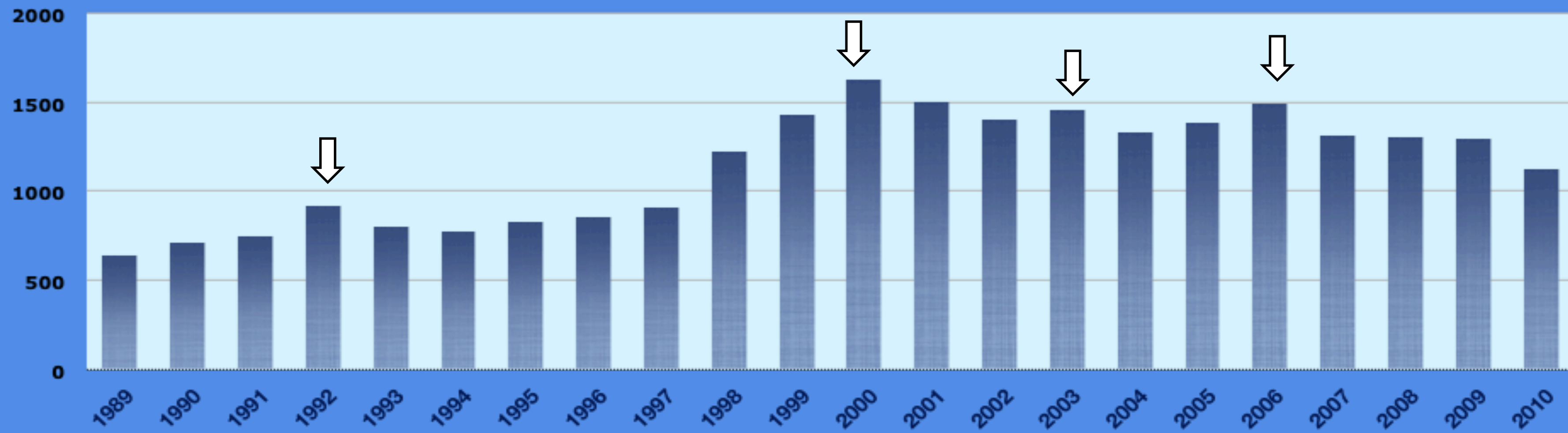
TAUP 2011
Munich, Germany

Neutrinos: Phenomenology and Interpretation

Eligio Lisi
INFN, Bari, Italy

N. of neutrino preprints since first TAUP (1989) - from INSPIRE



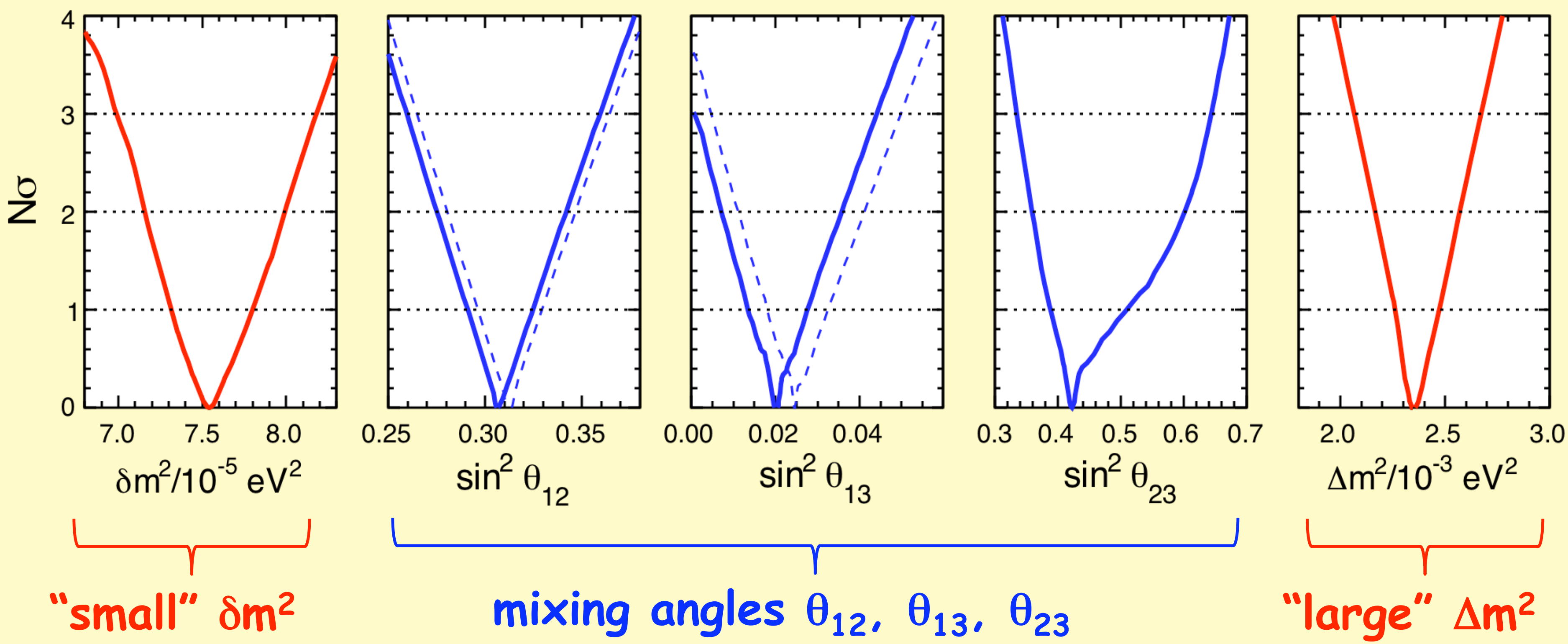
2011 likely to become another "peak year:" θ_{13}, sterile ν hints, ...

→ topics of this talk: 3ν & $3\nu+\nu_s$

Status of 3ν oscillation parameters, circa 2011

Results of recent global data analysis in terms of $N\sigma = \sqrt{\Delta\chi^2}$

(the more linear and symmetric, the more gaussian errors)



G.L.Fogli, E.L., A.Marrone, A.Rotunno (Univ. & INFN, Bari), **A. Palazzo** (TUM, Munich)

"Evidence of $\theta_{13}>0$ from global neutrino data analysis", arXiv:1106.6028v2

Numerical 1σ, 2σ, 3σ ranges:

Parameter	$\delta m^2/10^{-5}$ eV^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	$\Delta m^2/10^{-3}$ eV^2
Best fit	7.58	0.306	0.021	0.42	2.35
		(0.312)	(0.025)		
1σ range	7.32 – 7.80	0.291 – 0.324	0.013 – 0.028	0.39 – 0.50	2.26 – 2.47
		(0.296 – 0.329)	(0.018 – 0.032)		
2σ range	7.16 – 7.99	0.275 – 0.342	0.008 – 0.036	0.36 – 0.60	2.17 – 2.57
		(0.280 – 0.347)	(0.012 – 0.041)		
3σ range	6.99 – 8.18	0.259 – 0.359	0.001 – 0.044	0.34 – 0.64	2.06 – 2.67
		(0.265 – 0.364)	(0.005 – 0.050)		

Typical 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%	0.7×10^{-2} (abs.err.)	12%	4.3%

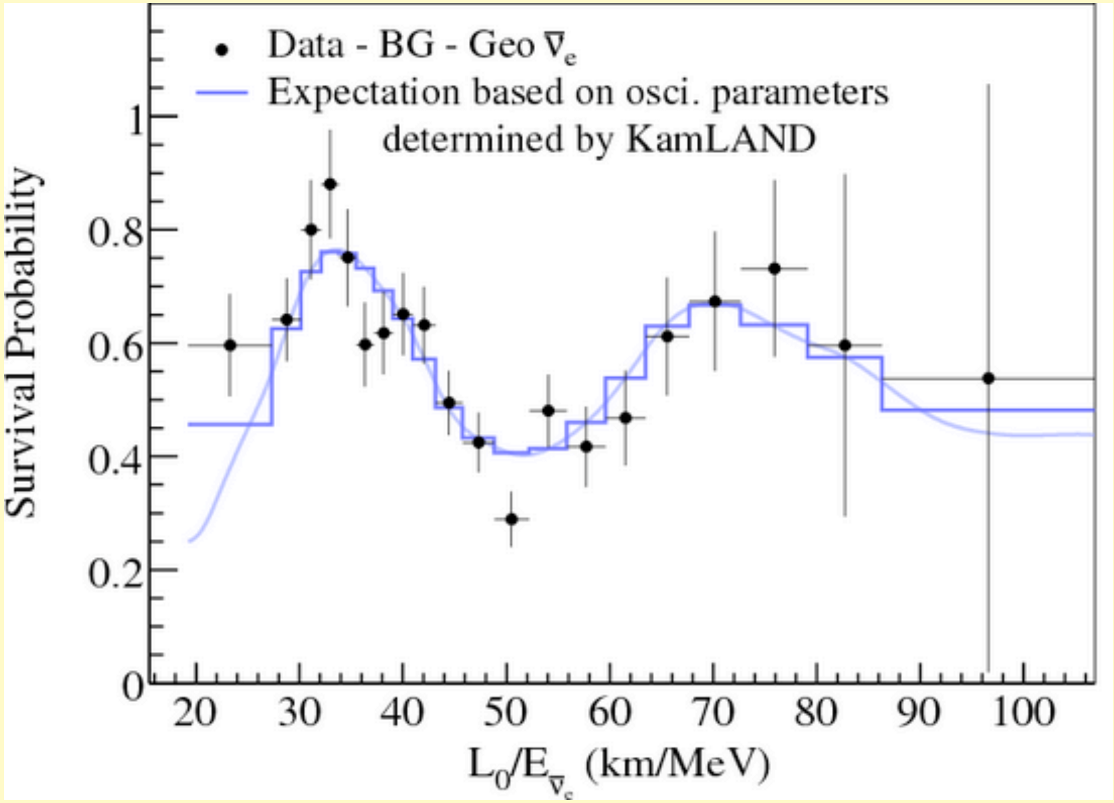
We are already in the precision era for ν physics!

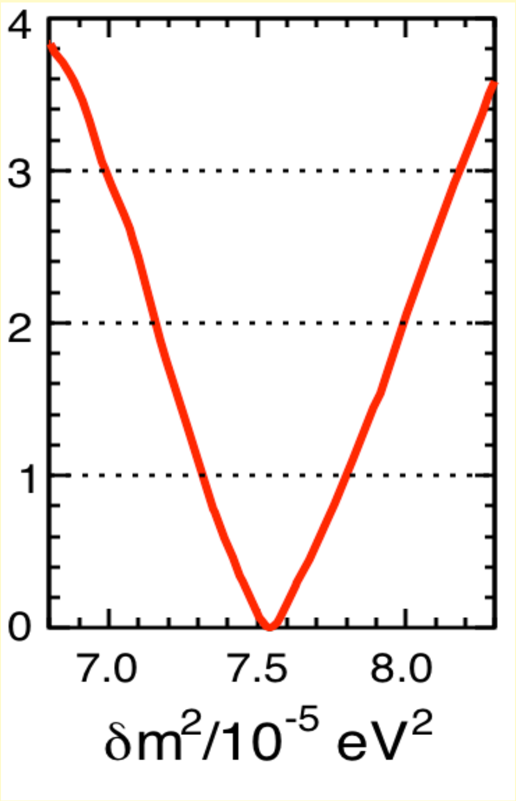
More details on 3ν parameters →

Zooming in on $\delta m^2 = \Delta m^2_{12}$

Vacuum oscillation frequency
$\delta m^2/2E$: dominated by KamLAND
(interesting by-product: geoneutrinos!)

Accuracy:
near ultimate limit
(~2% energy scale)



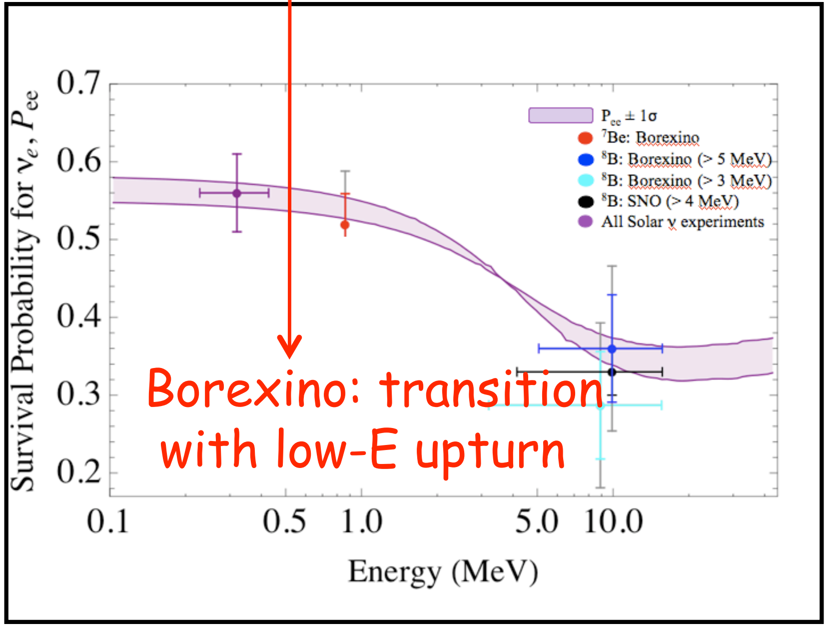


Vacuum frequency $\delta m^2/2E$ (unknown sign) interferes with
ν_e interaction energy $\sqrt{2}G_F N_e$ (known sign) in solar matter: MSW

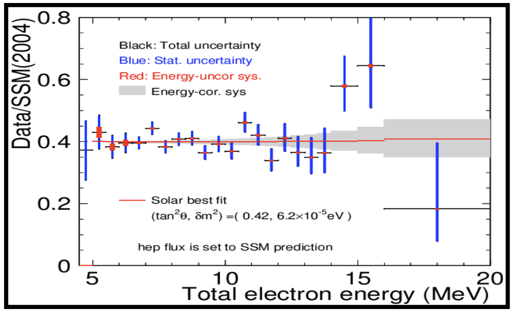
→ Get (ν_1, ν_2) hierarchy: state with largest ν_e component
is the lightest of the two – conventionally, ν_1

Main features of matter effects: established

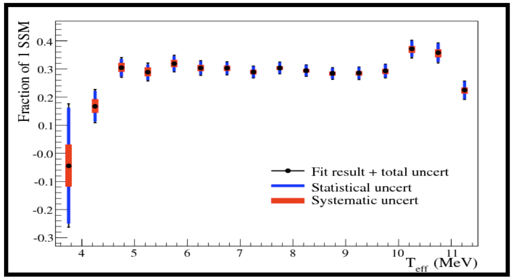
Spectral details: need higher stat, lower E



Borexino: transition
with low-E upturn



SK:
~flat

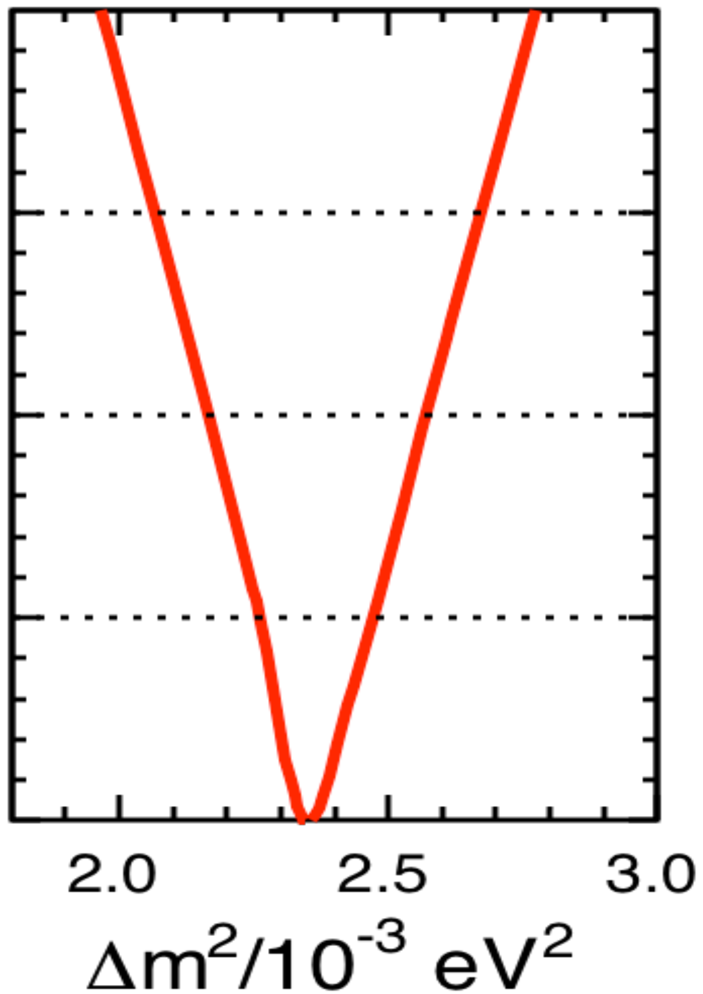


SNO:
~downturn

Here at TAUP 2011: Final SNO data analysis and first Borexino pep flux data!

Zooming in on $\Delta m^2 \approx |m^2_3 - m^2_{1,2}|$

Δm^2 (ATM+K2K+MINOS)



$\sigma(\Delta m^2) \sim 1.3 \cdot \delta m^2$!

Setting $\delta m^2=0$ is no longer a reasonable approximation in fitting Δm^2.

For $\delta m^2>0$ need to declare Δm^2 convention. We use:

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

in both normal and inv. hierarchy.

[Changing hierarchy just flips sign of $\pm\Delta m^2$ with no significant difference in current fit; results marginalized over sign(Δm^2).]

Can the "δm^2 success story" be repeated for sign($\pm\Delta m^2$) ?
Is the state with smallest ν_e component (ν_3) lightest or heaviest?

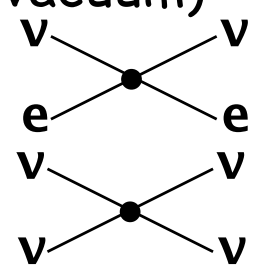
The hierarchy, namely, sign($\pm\Delta m^2$), can be probed (in principle), via interference of Δm^2-driven oscillations with some other Q-driven oscillations, where Q is a quantity with known sign.

At present, the only known possibilities (barring new physics) are:

Q = δm^2 (e.g., high-precision oscillometry in vacuum)

Q = Electron density (e.g., matter effects in Earth)

Q = Neutrino density (SN ν–ν interaction effects)



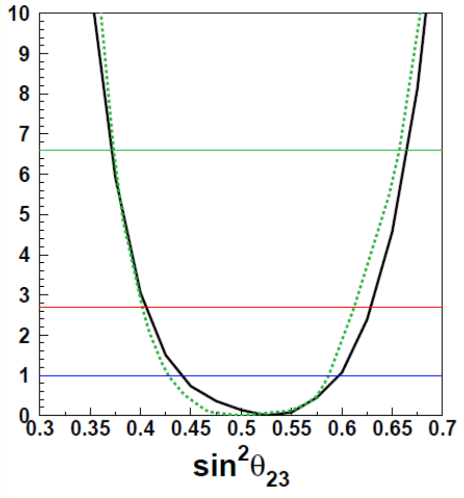
Each of them is very challenging, for rather different reasons.

The latter possibility has recently raised increasing interest, being associated with **highly nonlinear flavor evolution effects**.
All of them worth revisiting in the light of possible "large" θ_{13} !

Zooming in on $\sin^2\theta_{23}$: maximal ν_μ-ν_τ mixing, or not ?

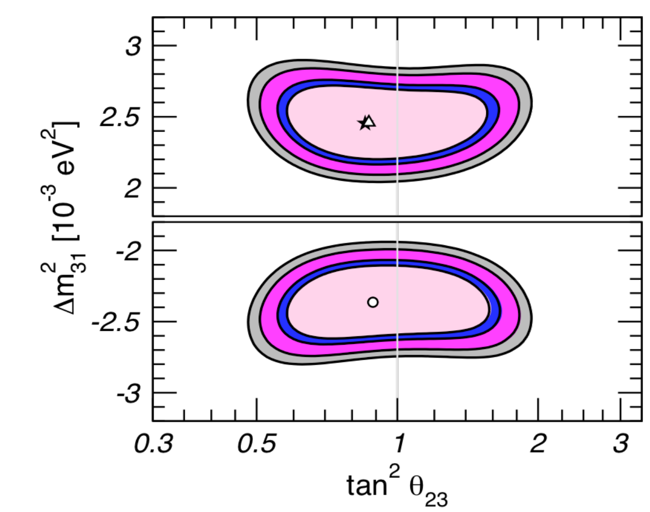
3ν analyses including SK-I+II+III data with both $\theta_{13}\neq0$ and $\delta m^2\neq0$:

SK@Neutrino2010



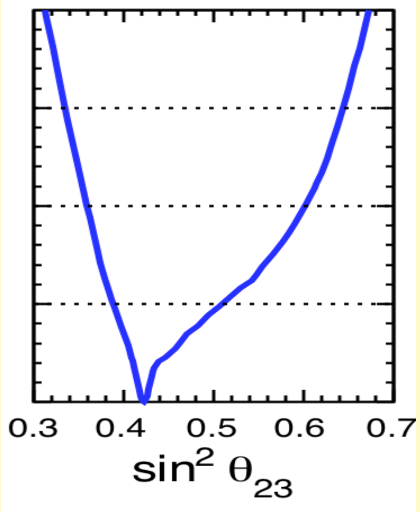
Nearly maximal…

Gonzalez-Garcia et al. 2010



Slightly nonmaximal…

Our analysis, 2011



Slightly more nonmaximal…

In general, two "signs" appear to be "fragile" in current best fits:

sign($\pm\Delta m^2$) → hierarchy, **sign($\sin^2\theta_{23}-1/2$) → octant**,

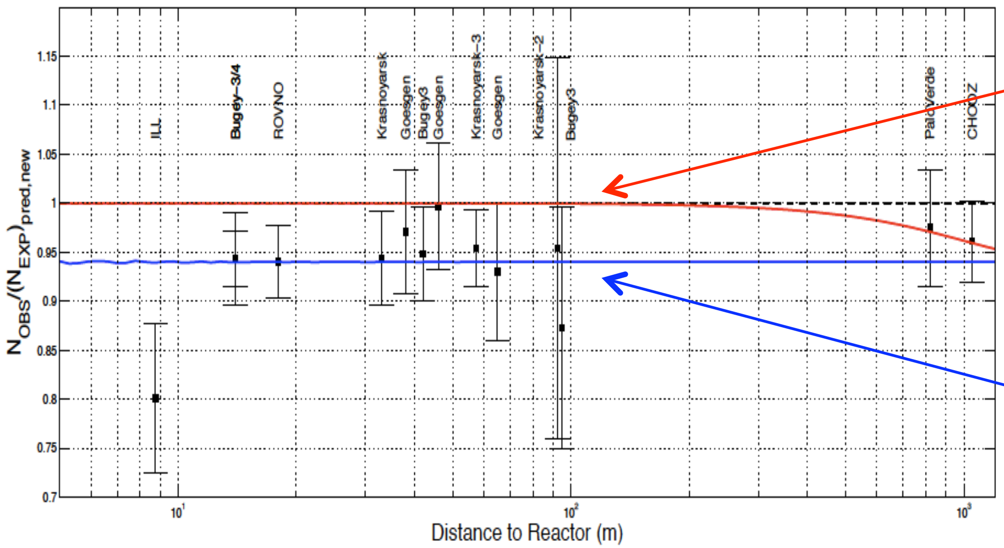
their effects being comparable to stat/syst errors (approximations ?)

Zooming in on $\sin^2\theta_{12}$ and $\sin^2\theta_{13}$: ν_e mixing

Here, short and long baseline reactor data play an important role.

Reactor neutrino flux normalization revision in 2011*: about +3.5%.

Systematic problem in comparing old ν-rate and β-decay data:



"New" or "high" normalization agrees with ILL β spectra but not with very-SBL reactor rates

"Old" or "low" normalization agrees with VSBL reactors but not with ILL β spectra

Tension at 2-3σ level. ν_s ?

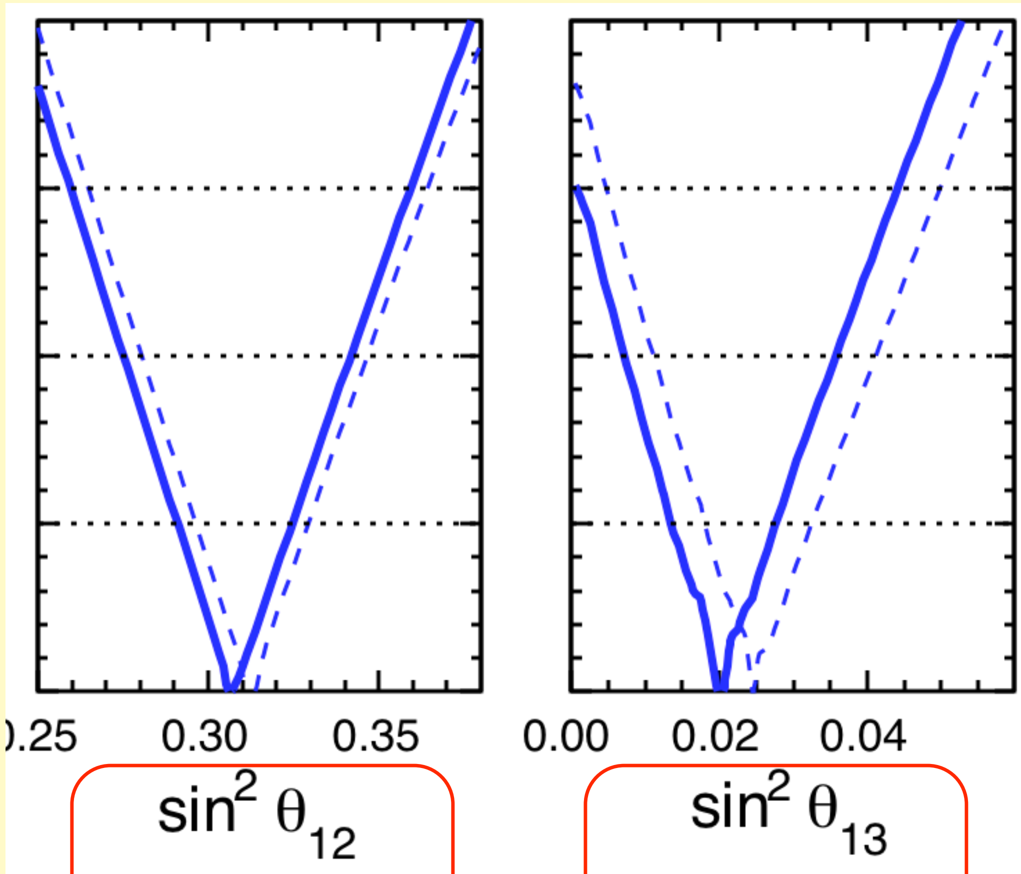
Within 3ν (no new physics) → unundersttood theo/exp systematics ?

May gauge the impact by comparing effects of old/new fluxes

Expect: higher flux → more disappear. → larger θ_{12}, θ_{13} angles

*Mention et al., arXiv:1101.2633; Huber, arXiv:1106.0687

Passing from "old" to "new" fluxes:



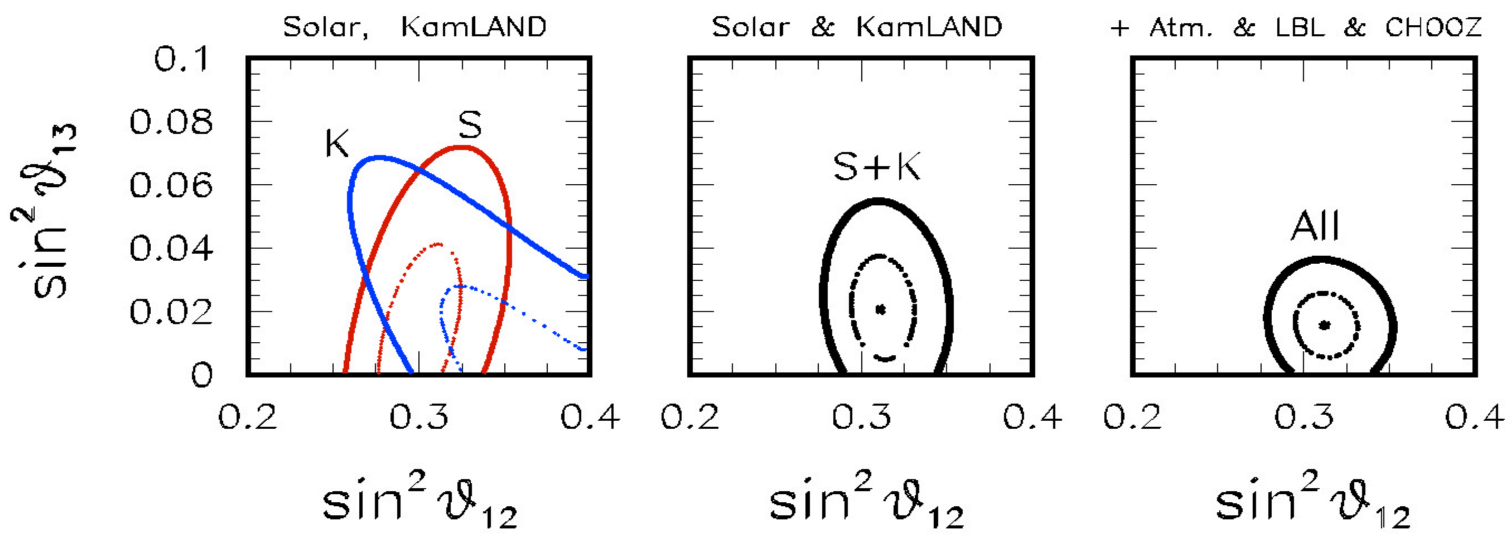
+0.006 shift

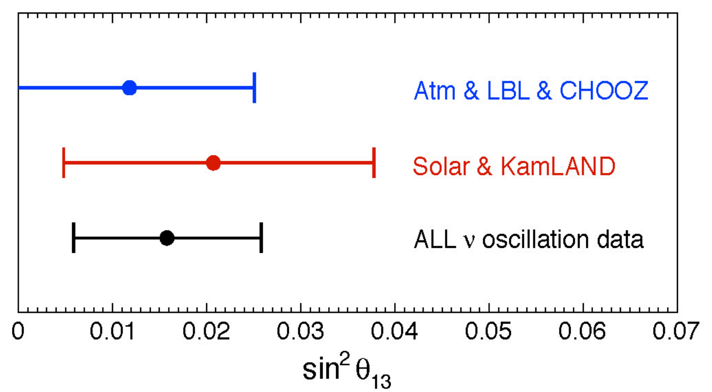
+0.004 shift

Note: Analyses that privilege "old" or "low" normalization by fitting VSBL reactor data [Schwetz et al., arXiv:1108.1376] tend to prefer lower θ_{13}

The increasing convergence of hints for $\theta_{13}>0$

2008: "Hints of $\theta_{13}>0$ from global neutrino data analysis"
[Fogli, EL, Marrone, Palazzo, Rotunno, arXiv:0806.2649]





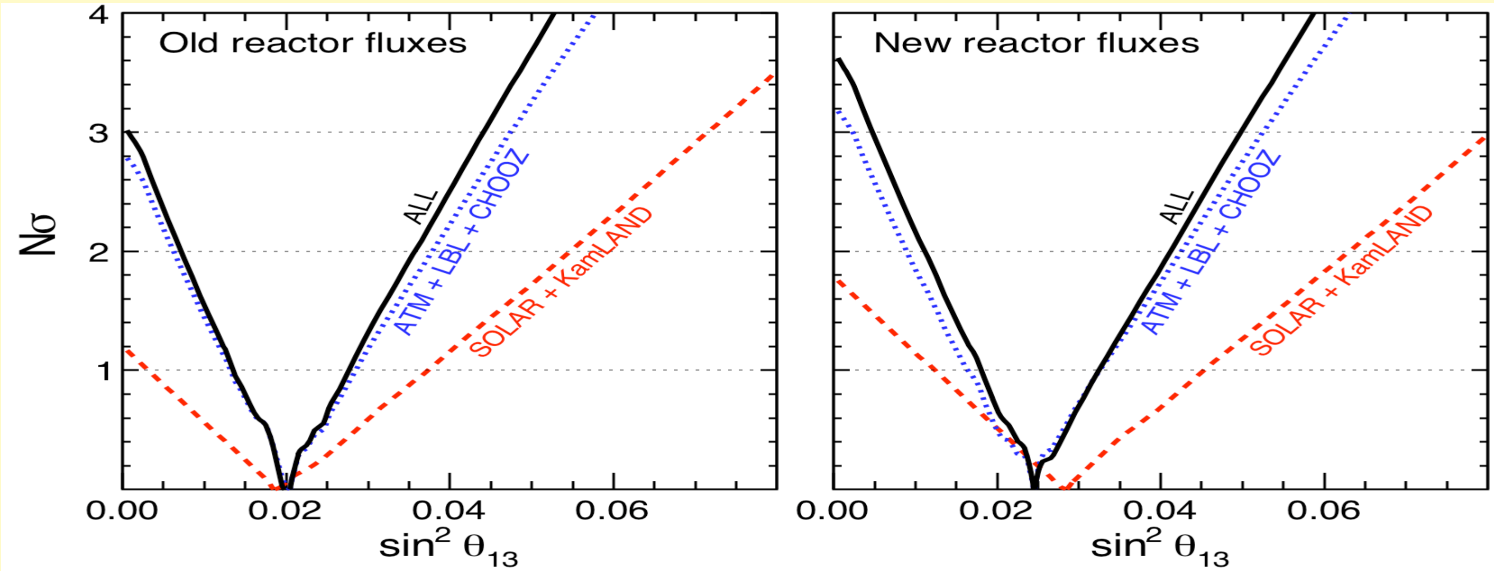
Hint significance: 90% CL.

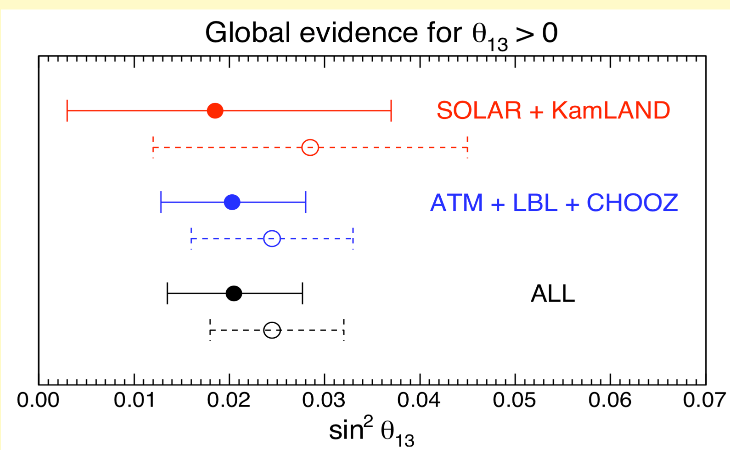
$\sin^2\theta_{13}=0.016\pm0.010$

[Large literature and debate 2008-2011]

June 2011 breakthrough: new T2K and MINOS appearance results!

→ "Evidence of $\theta_{13}>0$ from global neutrino data analysis"
[Fogli, EL, Marrone, Palazzo, Rotunno, arXiv:1106.6028]





Statist. significance >3σ

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

0.021±0.007 (old fluxes)
0.025±0.007 (new fluxes)

Words of caution, from someone we all miss:

"Half of all 3σ results are wrong."

J.N. Bahcall

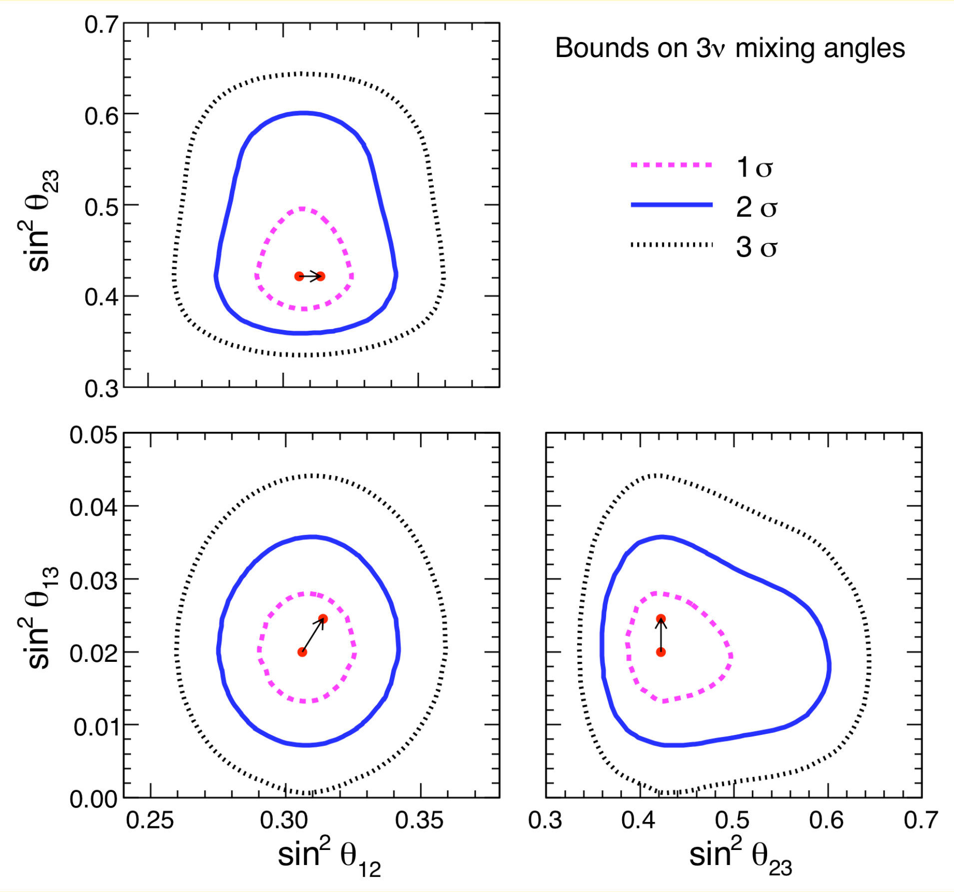
No doubt: we need further experimental tests of $\theta_{13}>0$
and, in particular, at least a single result at $>3\sigma$ level !

But, it would be very surprising if the current evidence were just due to a conspiracy of fluctuations in rather different categories of neutrino oscillation experiments.

In planning future ν beams/detectors, useful to consider the likely possibility that $\sin^2\theta_{13}\sim0.02$

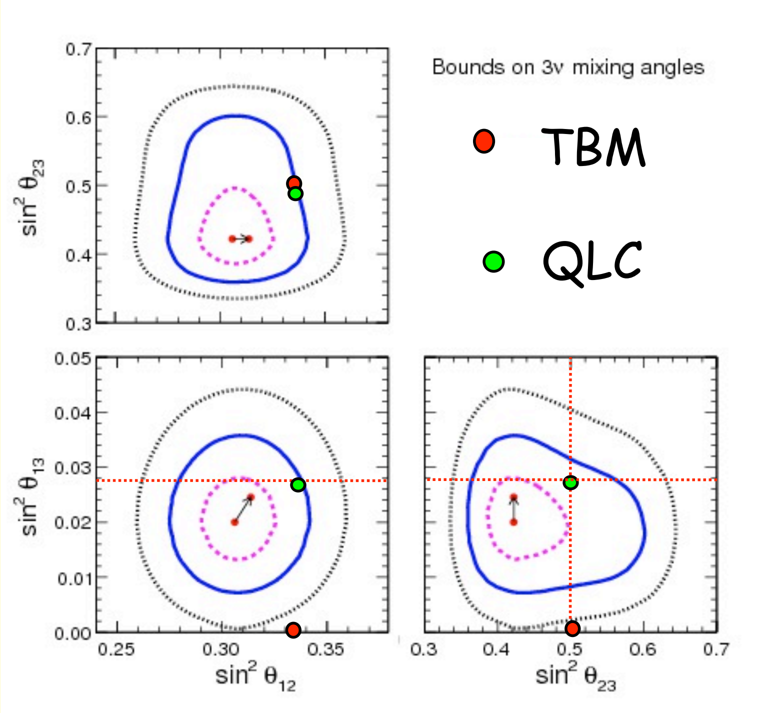
Overview of 3ν mixing: joint bounds on $\sin^2\theta_{ij}$

(arrows: shifts from "old" to "new" fluxes)

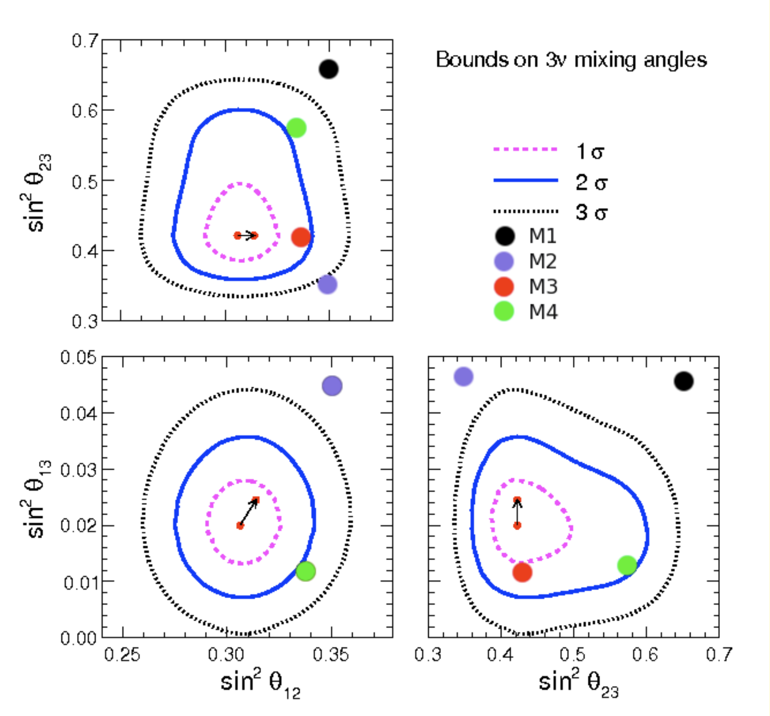


Note slight **anticorrelation** between $\sin^2\theta_{23}$ and $\sin^2\theta_{13}$, induced by T2K+MINOS appearance data which constrain their product.

Several theoretical models undergoing more sever tests, e.g.,



A. Smirnov @ Nufact 2011

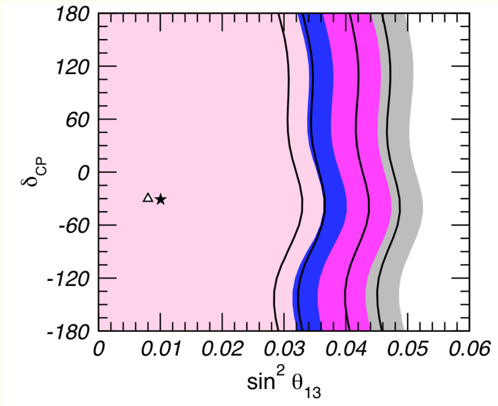


Feruglio et al., arXiv:1107.3486

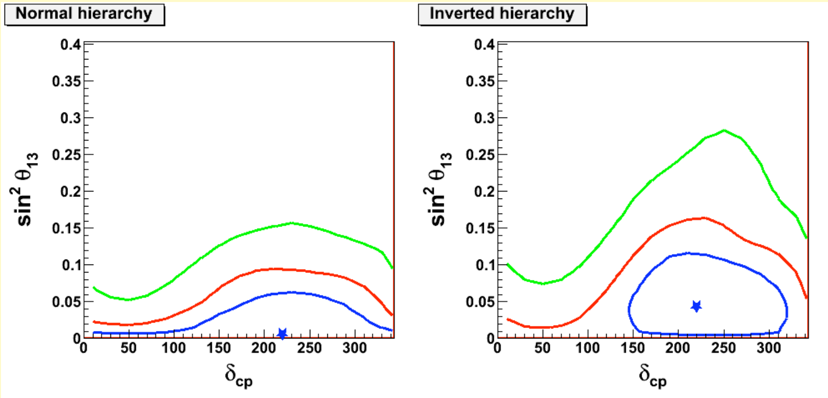
Many ideas being proposed to make sense (if any) of "large" θ_{13}.
Can it be linked to some other small parameters, such as $\theta_{Cabibbo}$?

θ_{13}>0 opens the door to leptonic CP violation (δ).

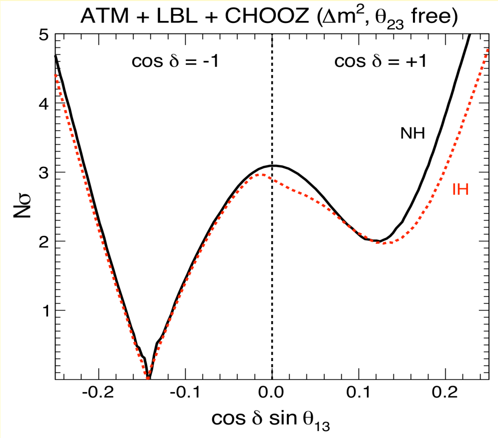
Wild dream: peeking through the door… now?



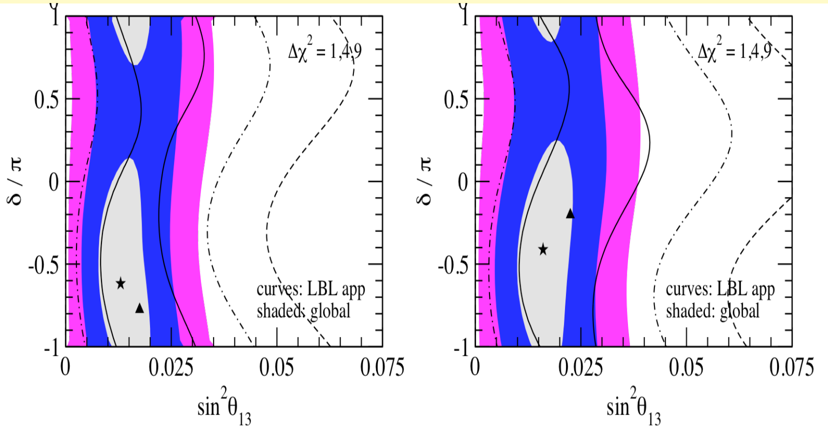
Gonzalez-Garcia et al. 2010



Takeuchi [SK atmospheric] @ Neutrino 2010



Fogli et al., 2011



Schwetz et al., 2011

Emerging sensitivity to δ_{CP} ? Time will tell…

More dreams…: 3ν convergence of (osc, m_β, $m_{\beta\beta}$, Σ) data

Beta decay

Double beta decay

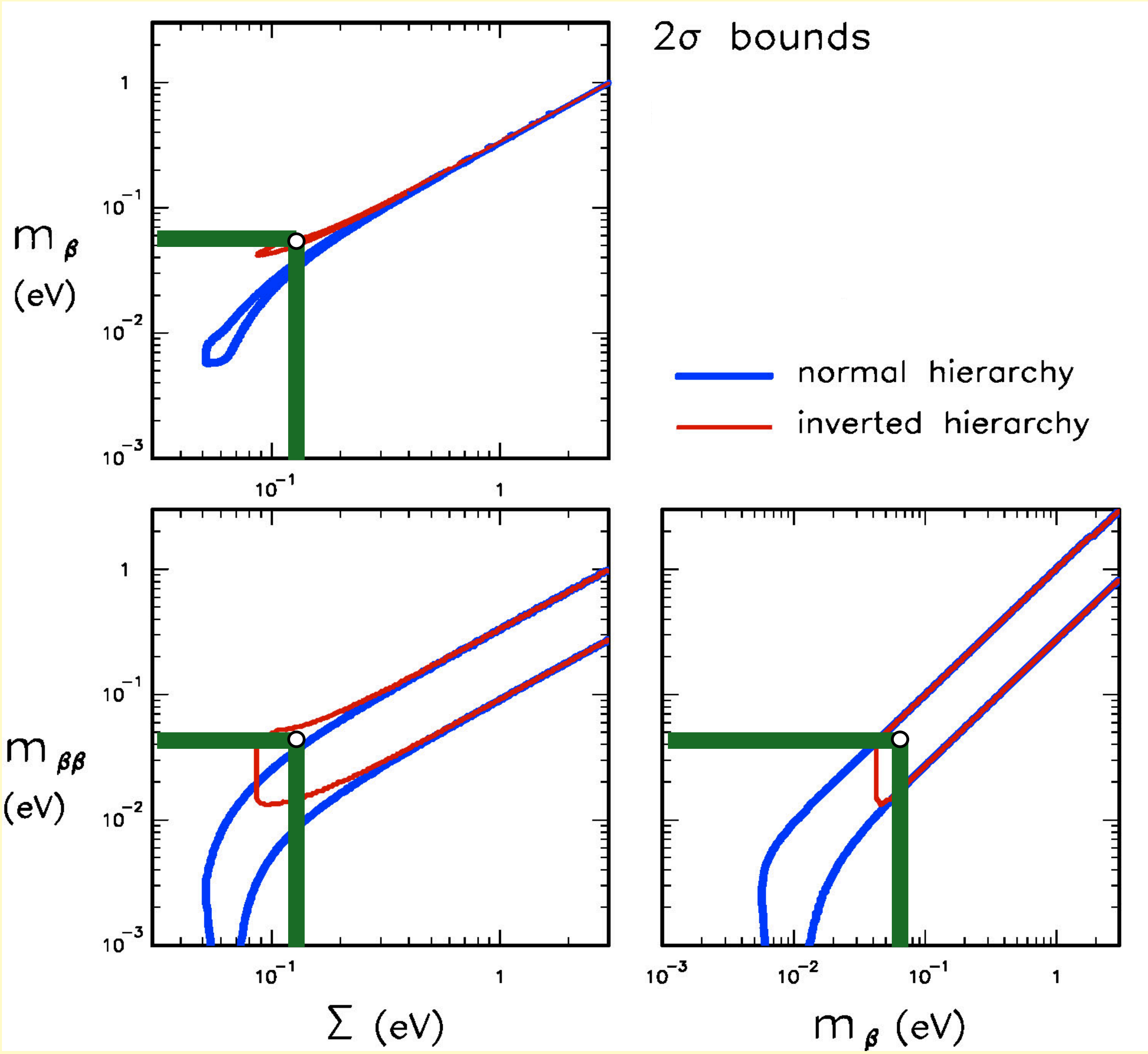
Cosmology

If realized, one might…

Determine the mass scale…

Identify the hierarchy …

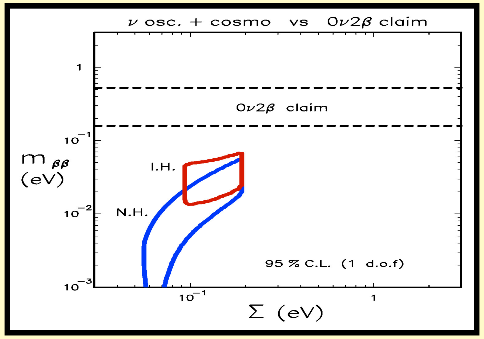
Probe the Majorana nature and phase(s)…



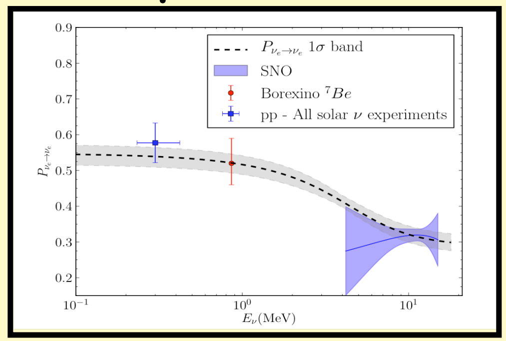
Of course, also “**divergences**” of results are intringuing, as they might indicate **new particles or interactions**.

Some more-or-less “anomalous” results still under scrutiny:

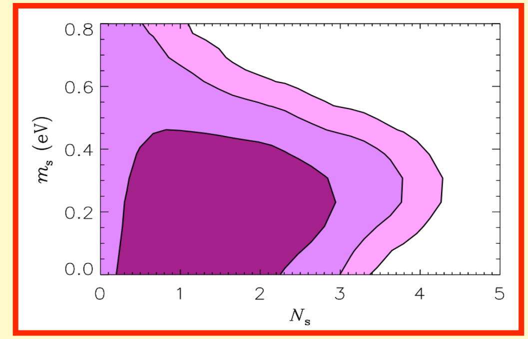
Klapdor claim vs Cosmo?



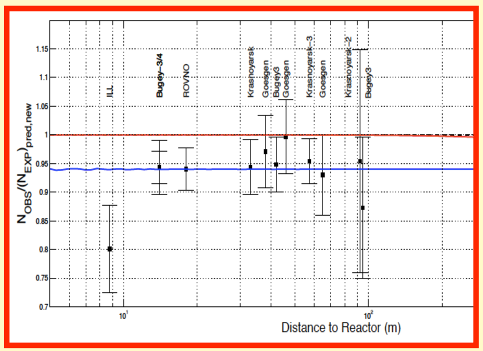
MSW upturn, solar ^{8}B?



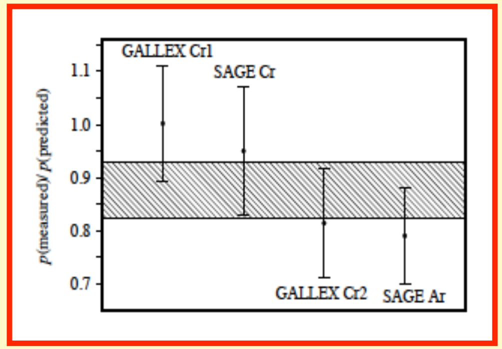
Extra cosmic radiation?



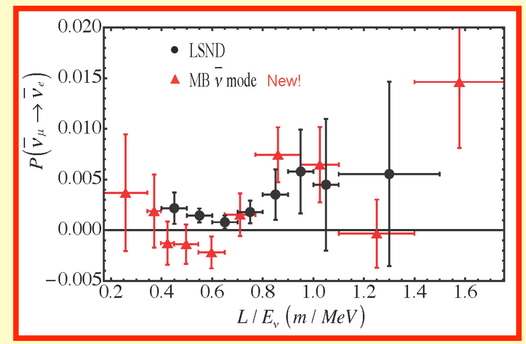
Reactor anomaly?



Gallium anomaly?



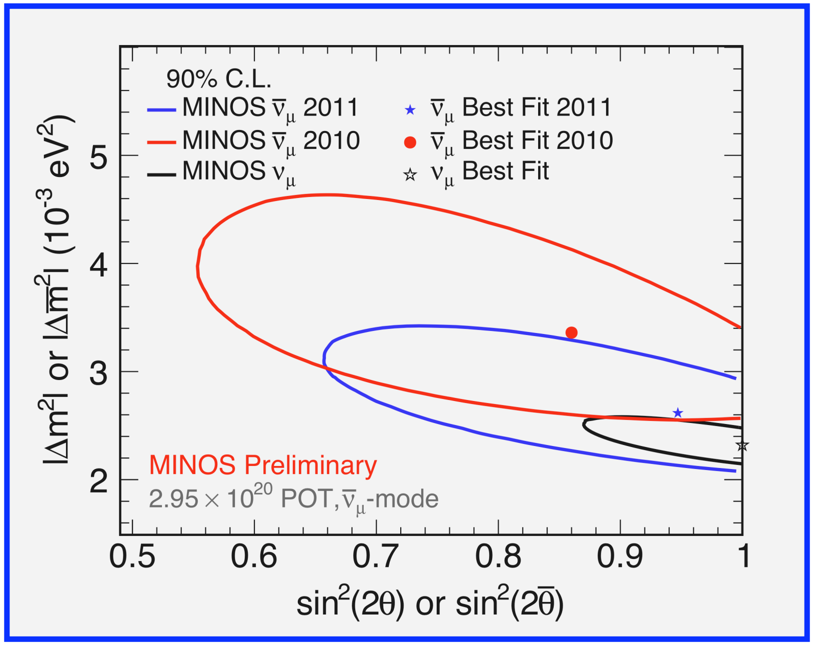
LSND/MiniBooNE (SBL)?



Attempts to interpret the latter four in terms of O(eV) sterile neutrino(s)

Footnote:

MINOS neutrino/antineutrino anomaly…

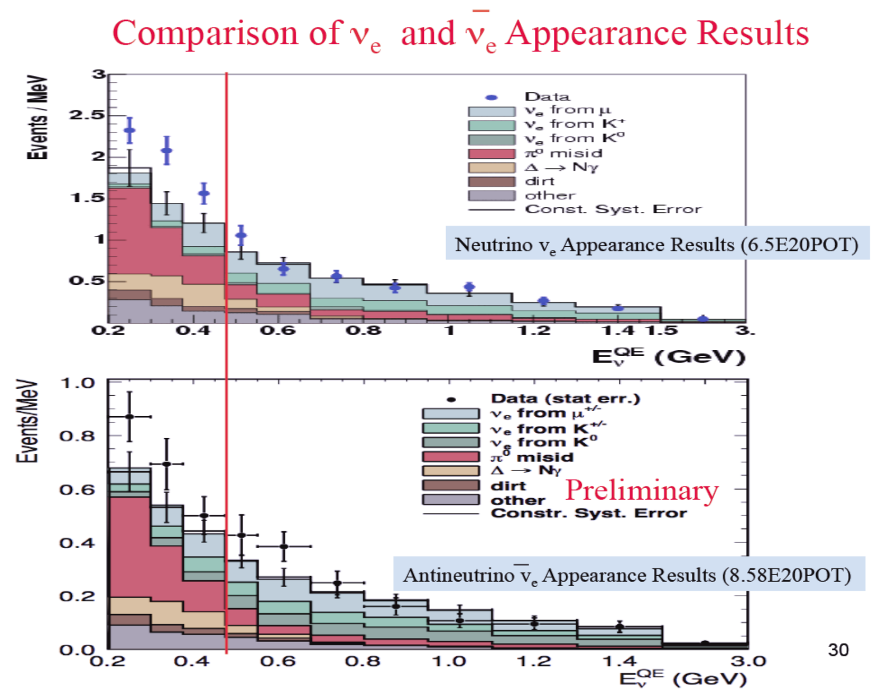


…does not show up in 2011 data!

QUO VADIS, MiniBooNE?

Reminder: conventional threshold (E > 475 MeV) initially set to look for LSND-like oscillations in ~background-safe range.
(below: higher background and $\nu \rightarrow$ anti-ν contamination)

2011 data: Similar ν & anti-ν excess, smoothly decreasing with E.
Both spectra show no statistically significant signal >475 MeV.



Neutrino excess significance:
Full E range: ~3σ
E >475 MeV: **0.6**σ

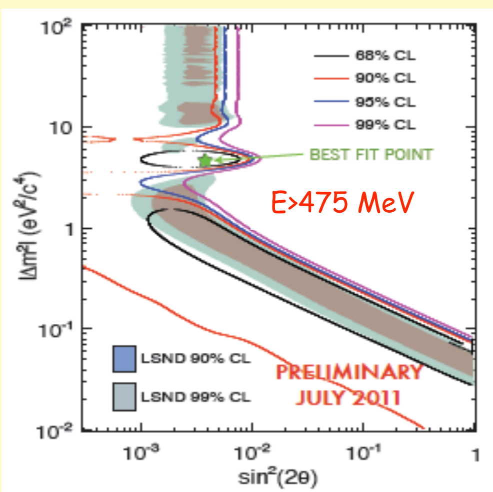
Antineutrino exc. significance:
Full E range: ~2σ
E >475 MeV: **0.84**σ

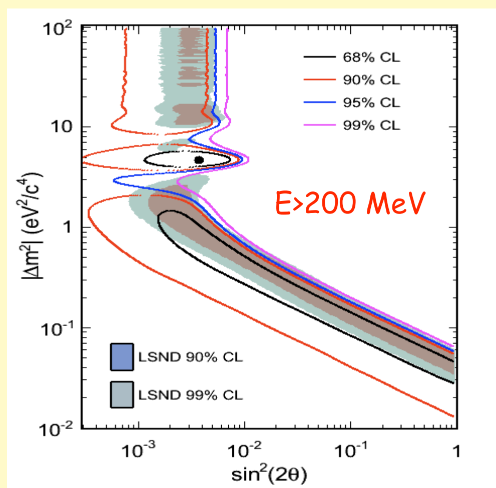
No real indication for LSND-like L/E oscillations…

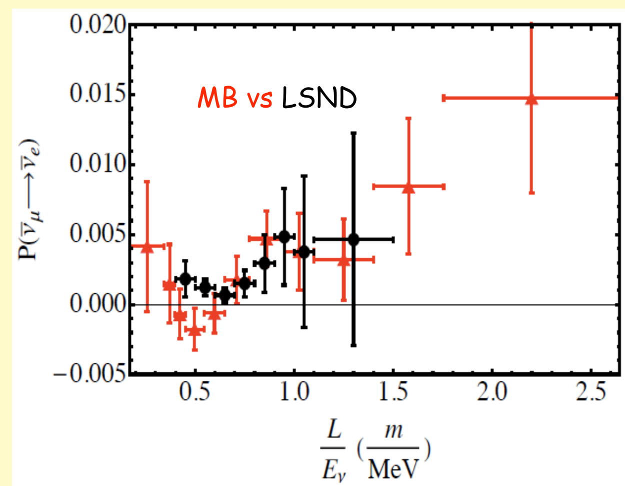
If the slight MB anti-ν excess is fitted in terms of 2ν:

- best fit falls in LSND-excluded region (“out-of-phase”);
- at ~2σ, both LSND-like and no oscillations are allowed;
- similarly for E>200 MeV, if ν contamination accounted for.

→ **“compatibility,” rather than “convergence.”**

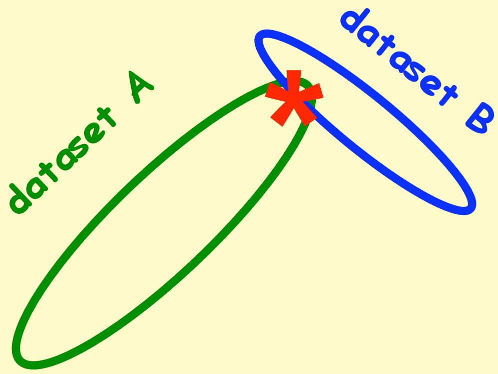




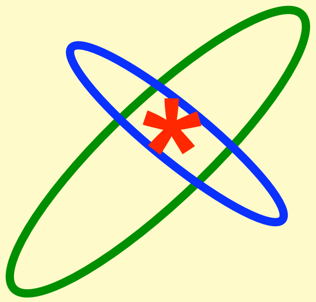


[Preliminary antineutrino plots taken from LSND presentation at PIC 2011]

Similarly, global interpretations of these and other data in terms of active-sterile oscillations only show rough compatibility among partial data sets, but not convergence in details:



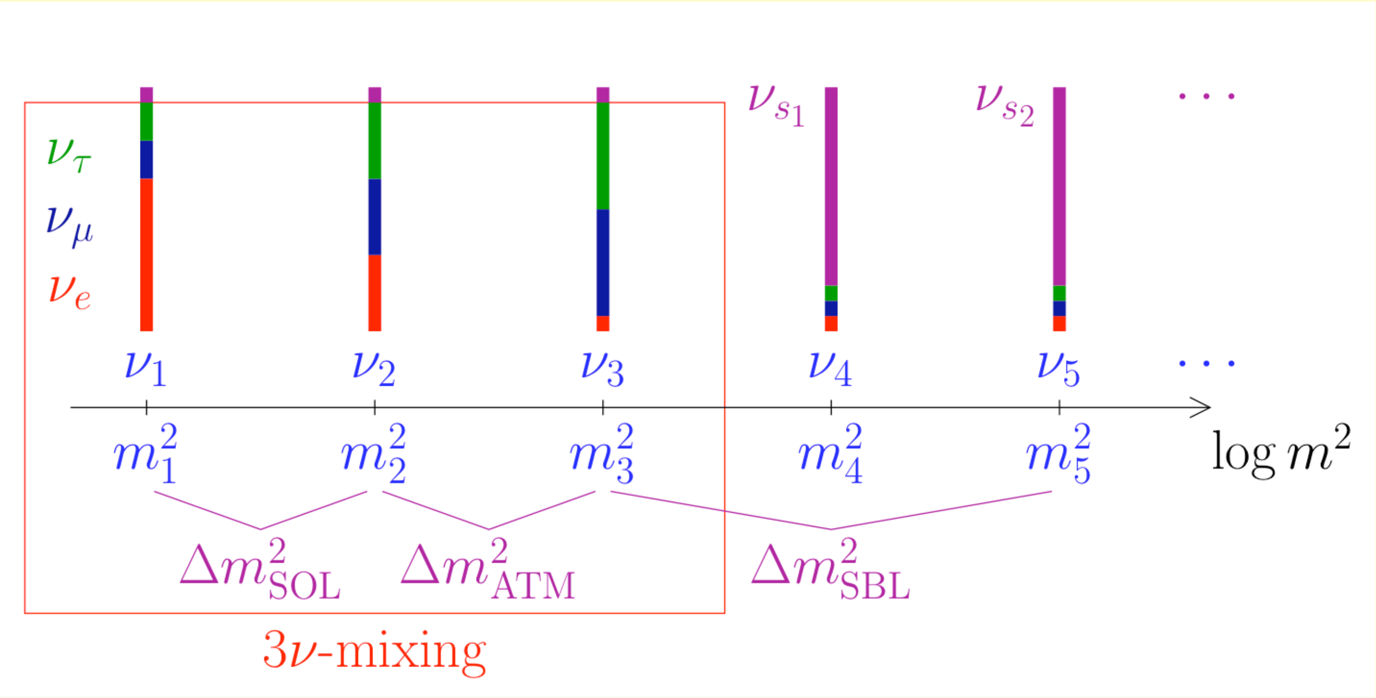
...rather than...



with corresponding instabilities/poor quality of fits, living in the "tails" of pdf's or in unstable "corners" of parameter space.

Most disturbing and persistent tension is between LSND (+MB) **appearance** data and world **disappearance** data.

If one or more sterile neutrinos mediate muon-to-electron appearance at the LSND L/E scale, then they must induce both muon and electron disappearance at the same SBL scale.

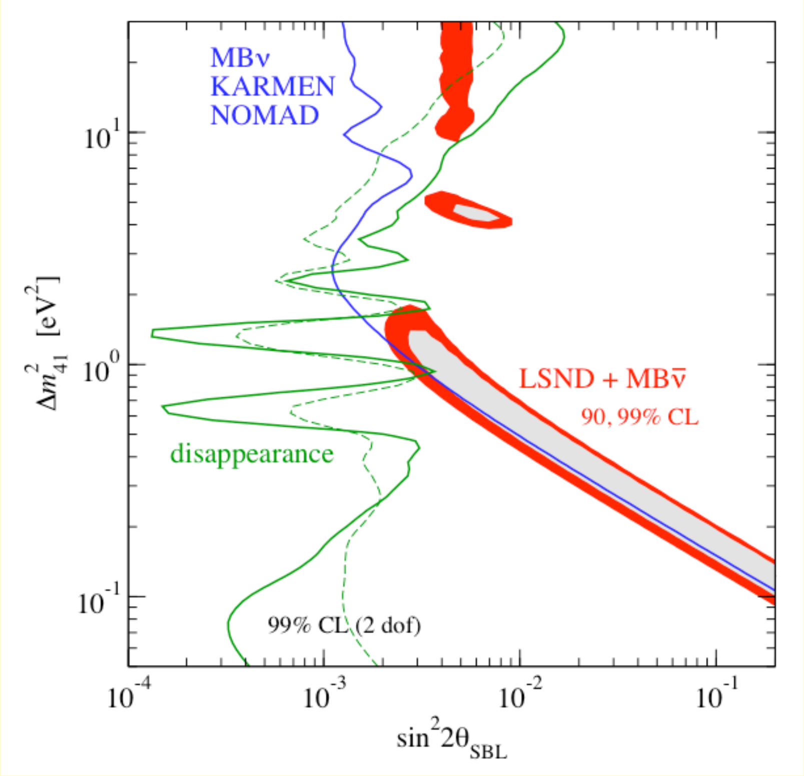


While some electron flavor disappearance is supported by the **reactor and gallium anomalies**, for muon flavor disapp. only upper bounds exist. Constraints do not match →

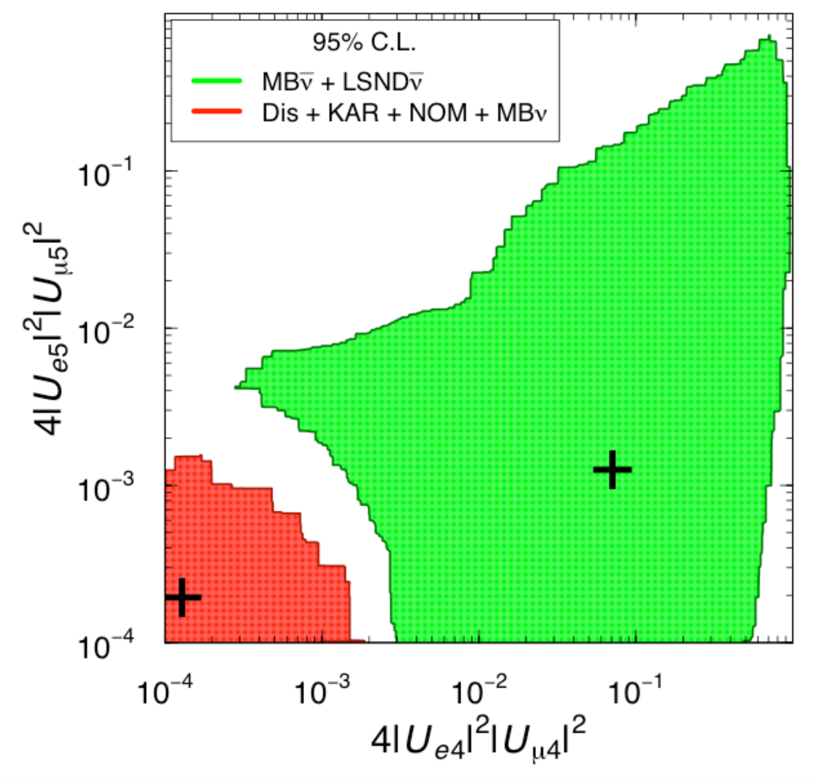
[Figure taken by C. Giunti]

Appearance/disappearance tension in 3+1 and 3+2

recent fits:

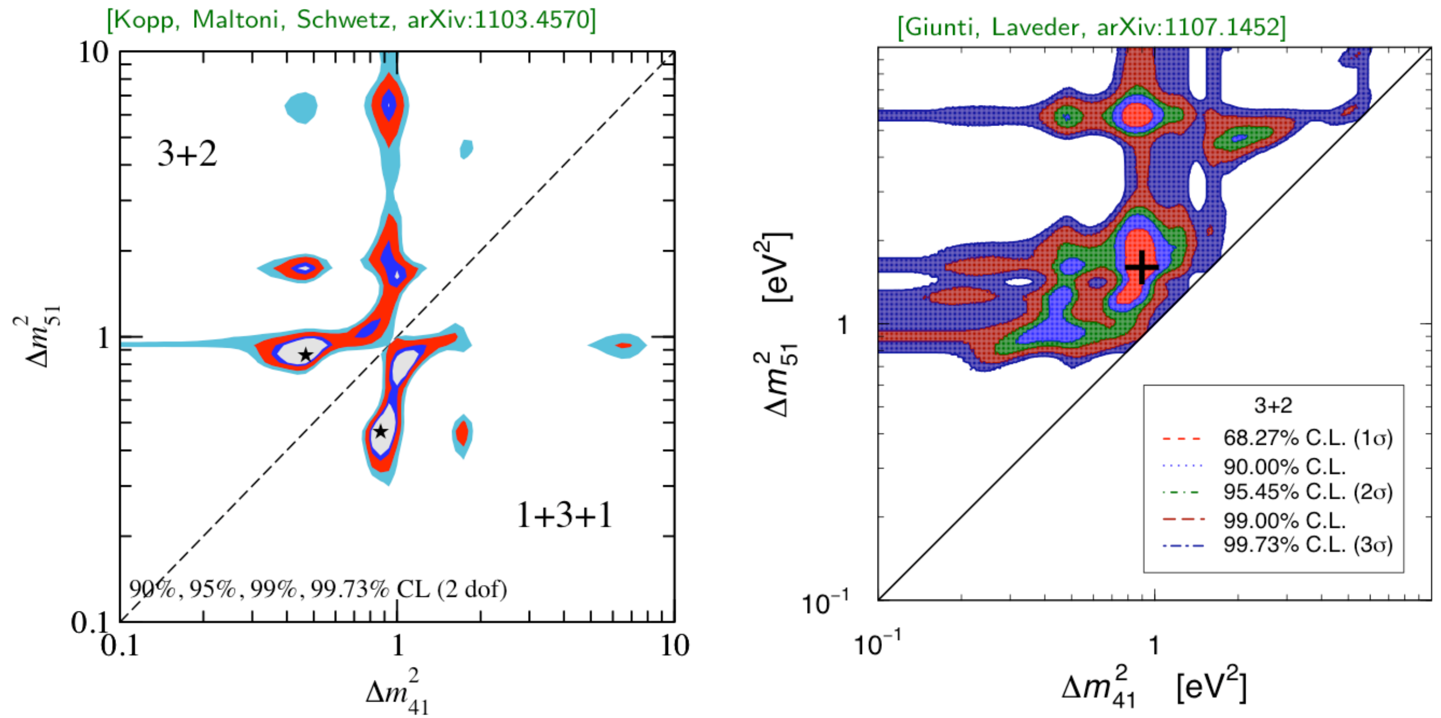


Kopp, Maltoni, Schwetz 2011



Giunti and Laveder 2011

3+2 less strongly disfavored than 3+1, if sterile CP phase tuned…



Best Fit: $\eta = 1.64\pi$

$\Delta m^2_{41} = 0.47\,\mathrm{eV}^2$ $\Delta m^2_{51} = 0.87\,\mathrm{eV}^2$

$|U_{e4}|^2 = 0.016$ $|U_{e5}|^2 = 0.019$

$|U_{\mu 4}|^2 = 0.027$ $|U_{\mu 5}|^2 = 0.022$

Best Fit: $\eta = 1.52\pi$

$\Delta m^2_{41} = 0.90\,\mathrm{eV}^2$ $\Delta m^2_{51} = 1.60\,\mathrm{eV}^2$

$|U_{e4}|^2 = 0.017$ $|U_{e5}|^2 = 0.017$

$|U_{\mu 4}|^2 = 0.018$ $|U_{\mu 5}|^2 = 0.0064$

But then… tension also with standard cosmology: too high ν total mass and radiation density [Hamann et al. 2011 + refs. therein]

Cosmological issues will be largely clarified before next TAUP (relevant Planck release expected early 2013).

Oscillation issues are more delicate and call for new accurate expts. Using 3+2 best fit as guidance, required sensitivity is challenging:

$$U^2_{e4} \sim U^2_{\mu4} \sim U^2_{e5} \sim U^2_{\mu5} \sim 0.02$$

→ not easy to test effects of such small mixings

$$\Delta m^2_{51} \sim O(1)\ \mathrm{eV}^2 \sim 2 \times \Delta m^2_{41}$$

→ not easy to disentangle two new frequencies

Moreover, the noted "tensions" suggest that some (or all) of the data may have nothing to do with ν_s. More complicated scenarios (ν_s + new interactions) can be built, but with "ad hoc" hypotheses.

Need new, possibly "redundant" expt. tests !

Imperative: do not add confusion, aim at >3σ signals !

CONCLUSIONS

2011 likely to be another "peak year" in neutrino physics.
I focused on just two recent topics:

- progress on theta(13) and standard 3ν parameters,
- renewed interest on SBL data and sterile ν's issues

The standard 3ν framework remain solid, with converging evidence for $\theta_{13}>0$ at $>3\sigma$. Precision physics, but still many unknowns: hierarchy, CP, absolute mass, Dirac/Majorana...

There are sparse indications in favor of oscillations mediated by sterile ν's, but a coherent picture has not emerged yet. Even more unknowns in this context...

Exciting times are guaranteed also for next TAUPs!