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Neutrino masses and mixings, circa 2009

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1st part: General overview (30′)
2nd part: More on sign Δm^2 and θ_{13} (10′+10′)

Please feel free to ask questions at any time

Neutrino physics is an exercise in patience.
The three most basic questions were formulated in the past century…

1. How small is the neutrino mass?
(Pauli, **Fermi**, '30s)

2. Can a neutrino turn into its own antiparticle?
(**Majorana**, '30s)

3. Do different neutrino flavors change ("oscillate") into one another?
(**Pontecorvo**, Maki-Nakagawa-Sakata, '60s)

The last question has been positively answered only in recent years,
while hard work is still going on to get an answer to the others
(with a qualified and significant Italian contribution)

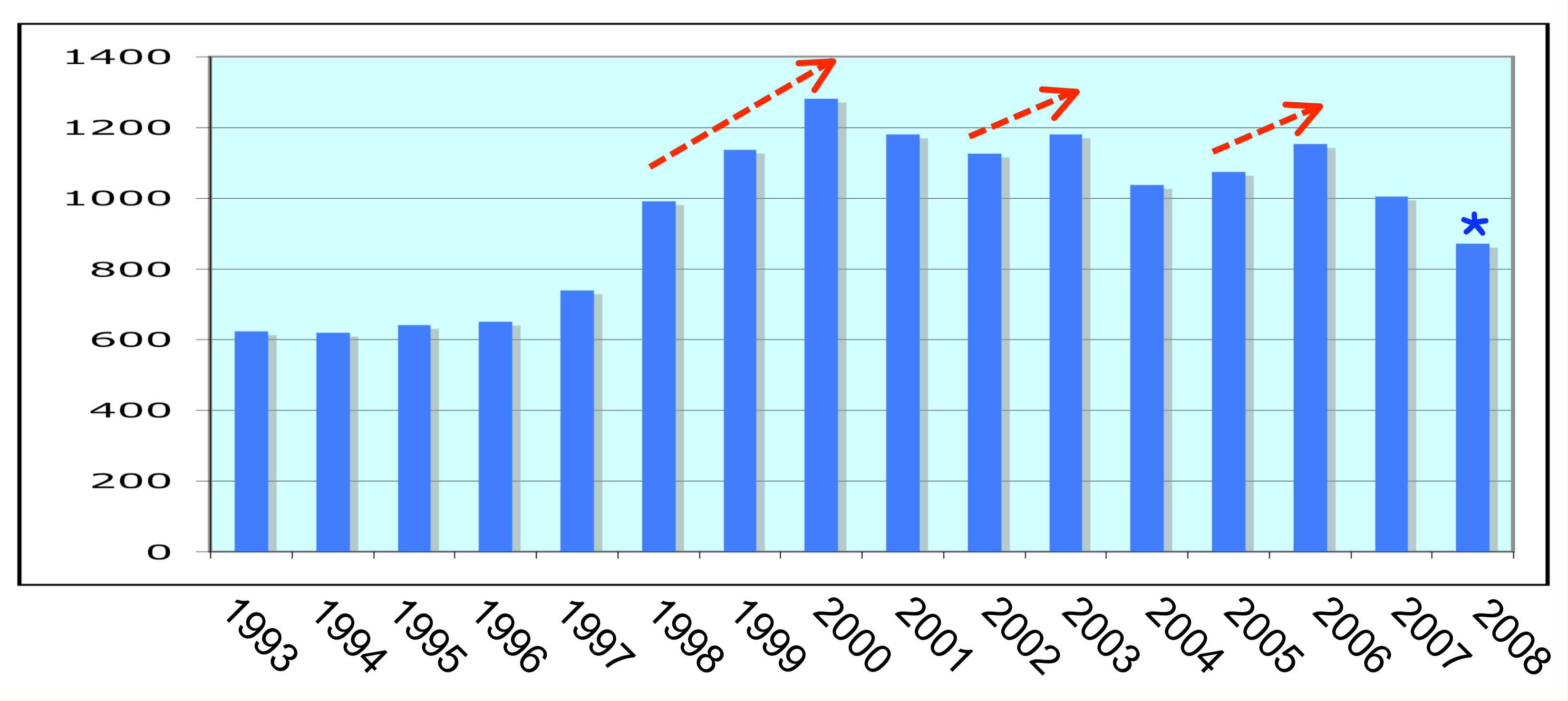
The oscillation discovery has raised the level of interest, with ~10³ papers/year titled "…neutrino(s)…" on SPIRES

Peaks of interest:

Atmospheric ν oscillations, Limit from CHOOZ

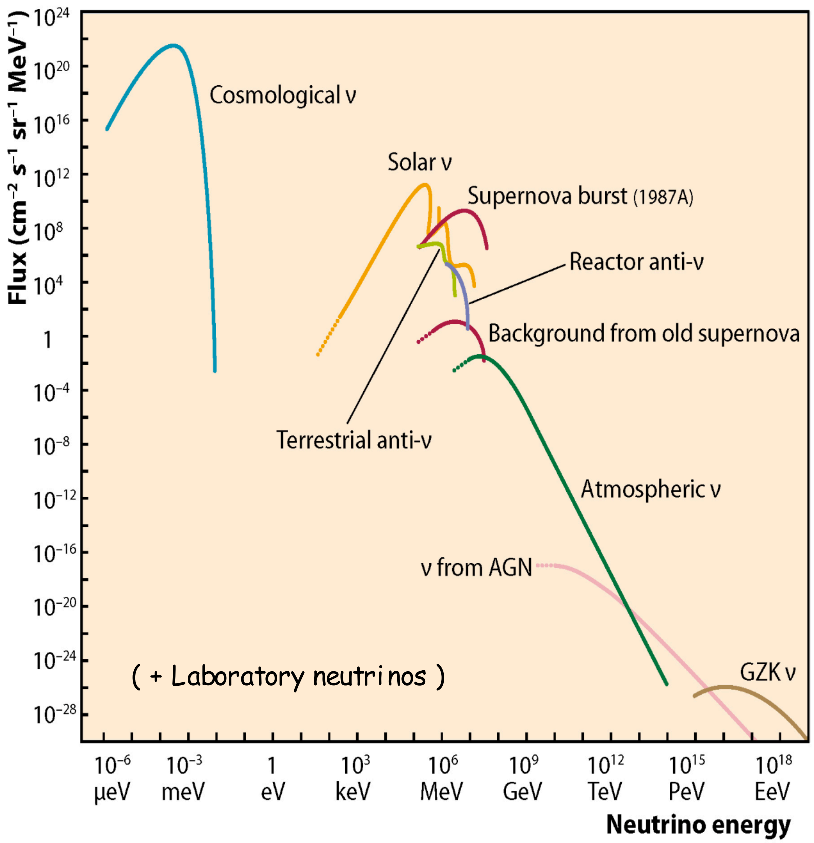
Solar and reactor ν oscillations, Nobel 2002 to Davis & Koshiba

Accelerator ν oscillations, Cosmological limits on absolute masses



*Apparent drop in 2008 is not really a sign of decline (SPIRES counts saturate only after >1 year).

Important goals have been reached, but the neutrino spectrum is wide, and with many unexplored aspects.



A synoptic view of neutrino fluxes. (from ASPERA roadmap)

Likely/possible "peaks of interest" in future years:

- Flavor appearance ($\nu_\mu \to \nu_\tau$, $\nu_\mu \to \nu_e$)
- Mixing between 1st-3rd family
- Mass spectrum hierarchy
- Absolute masses
- Spinorial nature (Majorana/Dirac)
- Leptonic CP violation
- Astro/Cosmo sources
- Possible new states/interactions
- Links with other LFV processes
- Theoretical "illumination"
- …

Fundamental achievement: 3ν mixing

3 eigenstates of mass, flavor: $(\nu_e, \nu_\mu, \nu_\tau)^T = U\,(\nu_1, \nu_2, \nu_3)^T$

Unitary matrix U_{PMNS} : 3 Euler rotation angles + 1 CP phase

Conventionally (and usefully), same rotation ordering as in U_{CKM}:

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

$s^2_{23} \sim 0.5$

Measured by atmospheric and accelerator ν experiments

$s^2_{13} < \text{few}\,\%$

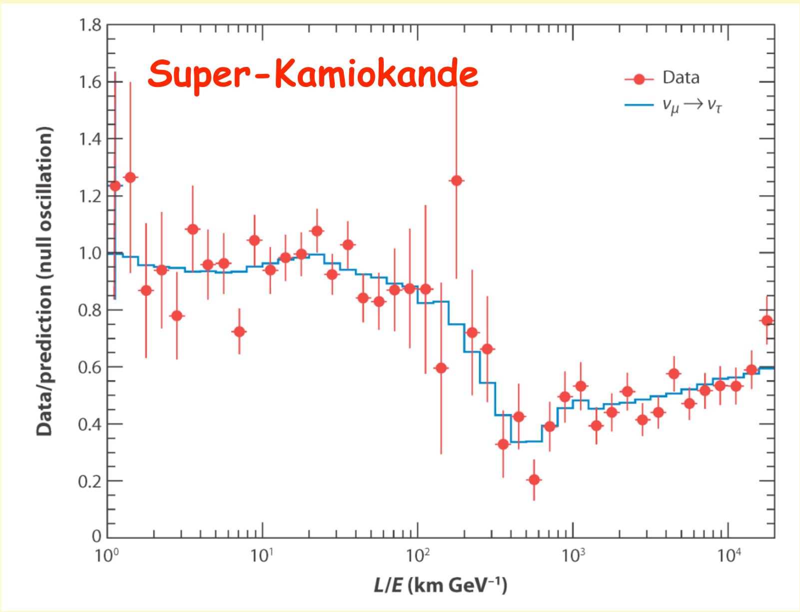
Mainly constrained by reactor experiments (CHOOZ, PaloVerde)

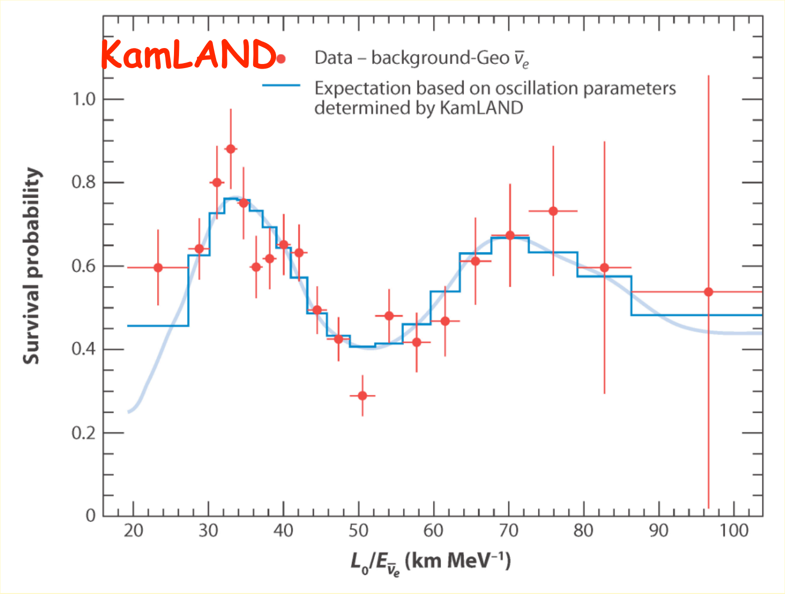
$s^2_{12} \sim 0.3$

Measured by solar ν experiments & by KamLAND

Two independent oscillation frequencies:

"Vacuum" phase ~ $(m_i^2 - m_j^2)$Length/Energy



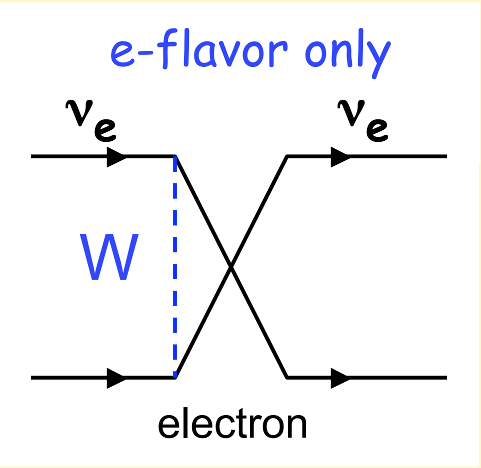


$\Delta m^2 = m_3^2 - m_1^2$ $\gg$ $\delta m^2 = m_2^2 - m_1^2$

(ν from atmosphere, long-baseline accelerator, short-baseline reactors)

(ν from long-baseline reactors, solar ν with corrections)

Solar (electronic) neutrinos:

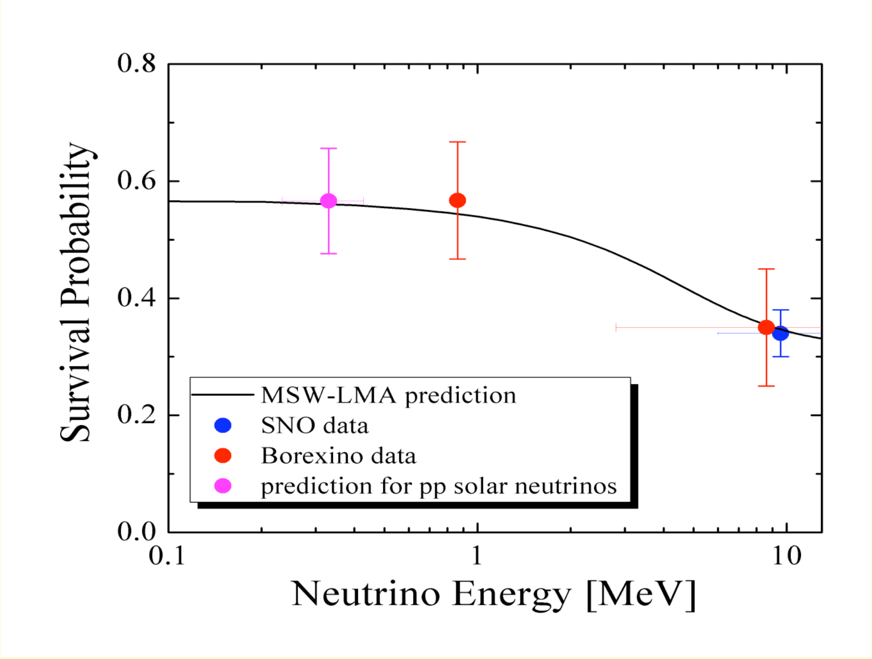


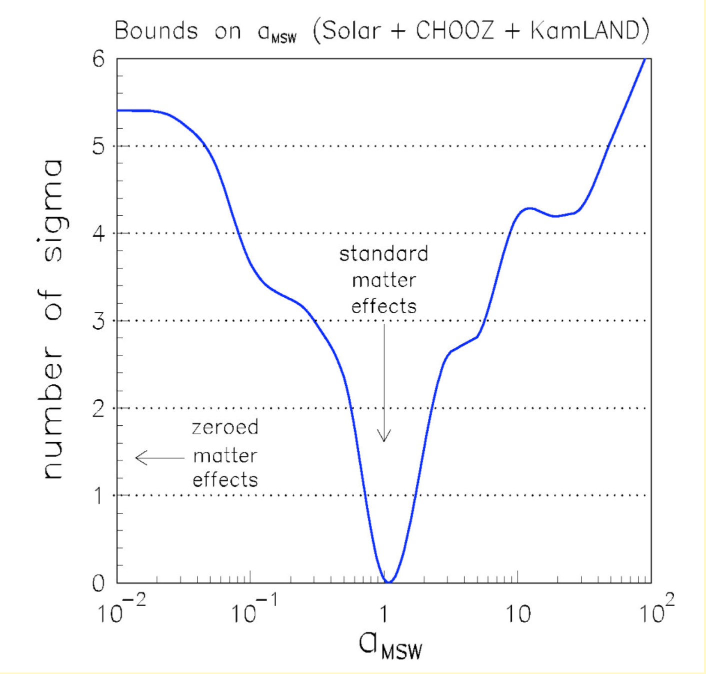
Extra contribution to phase (MSW effect):

~ G_F x Solar electron density

(but: averaged over many oscillation cycles)

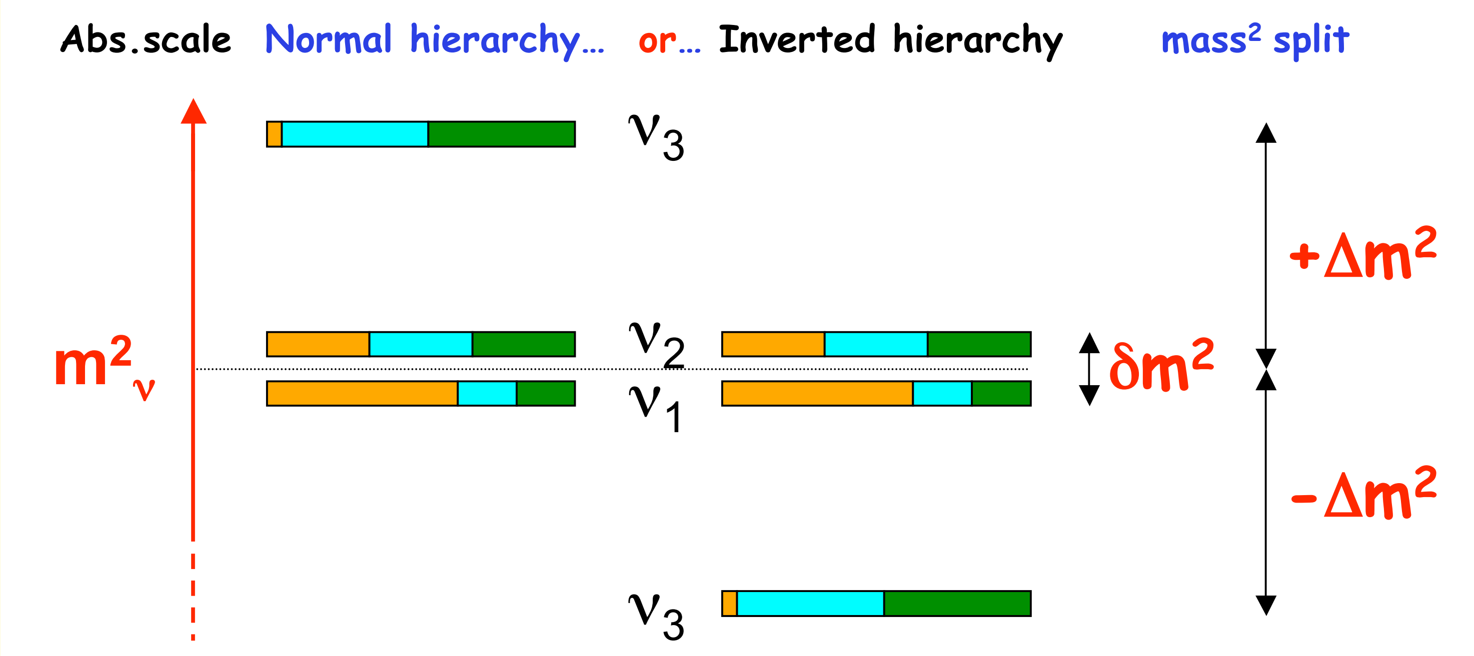
Effect observed in a single expt., **Borexino**… …in agreement with previous evidence





Answering Pontecorvo's question with one significant digit… if any:

(Useful for a global overview. **Flavors** = e μ τ)



$\delta m^2 \sim 8 \times 10^{-5}\ \mathrm{eV}^2$

$\Delta m^2 \sim 3 \times 10^{-3}\ \mathrm{eV}^2$

$\sin^2 \theta_{12} \sim 0.3$

$\sin^2 \theta_{23} \sim 0.5$

$m_\nu < O(1)\ \mathrm{eV}$

$\sin^2 \theta_{13} <$ few%

$\mathrm{sign}(\pm \Delta m^2)$ unknown

δ (CP) unknown

More significant digits ("precision physics"):

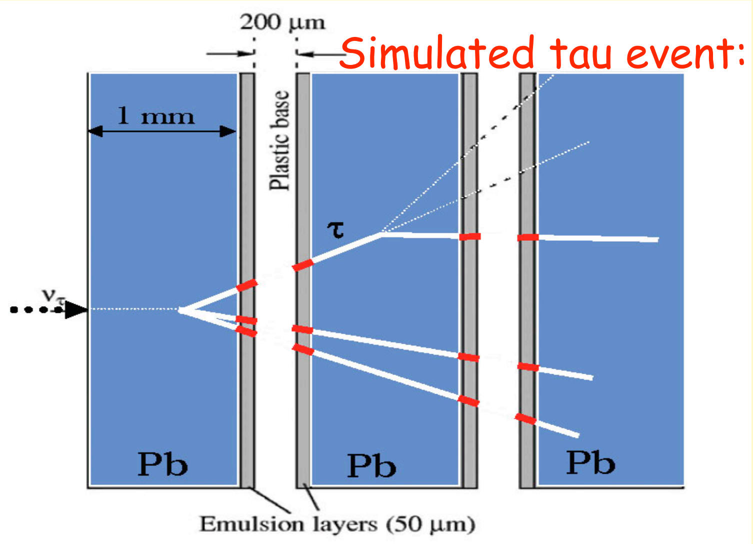
Always useful (fundamental parameters)

and needed for both experimental and theoretical reasons.

An experimental example: Δm^2 impact for CNGS physics

On beam:
OPERA (running)
ICARUS (2009?)

One real tau event might already be hidden in the current statistics collected by **OPERA**...



CNGS beam of relatively high energy; compromise due to the need of producing tau leptons (at high E), without suppressing too much oscill. $\nu_\mu \to \nu_\tau$ (L/E phase) -> Expected tau production rate proport. to $(\Delta m^2)^2$.

Currently: Δm^2 uncertainty lower than 5-year statistical error

A theoretical example: accuracy of θ_{ij} for model building

Mixing angles seem to have some "special" values:

$\sin^2\theta_{23} \approx 1/2$
$\sin^2\theta_{12} \approx 1/3$ "tri-bimaximal mixing"
$\sin^2\theta_{13} \approx 0$
A signal of discrete symmetries in the neutrino sector?

$\theta_{12}+\theta_C \approx \pi/4$ "quark-lepton complementarity"
$[\theta_{23}+\theta_{23,q} \approx \pi/4]$
A possible link between neutrino and quark mixing?

Model diagnostic: dependent on the above "$\approx$"

Oscillation parameters: state of the art

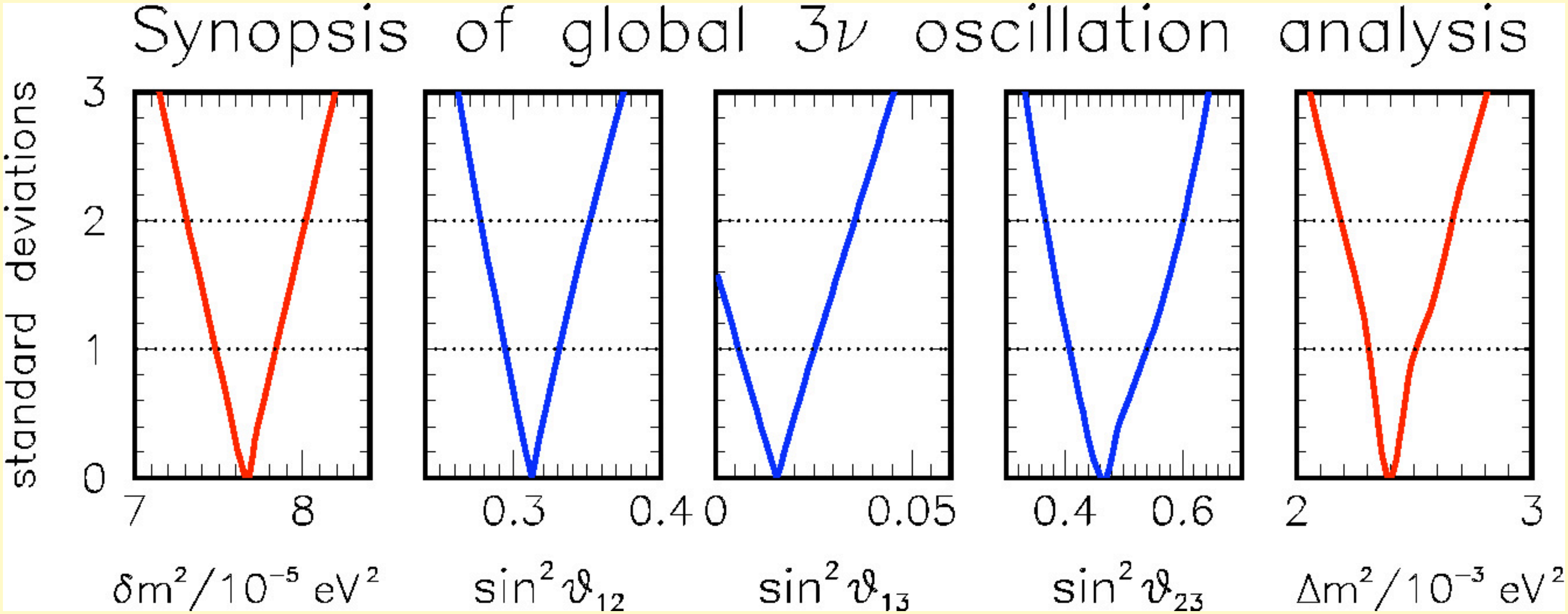
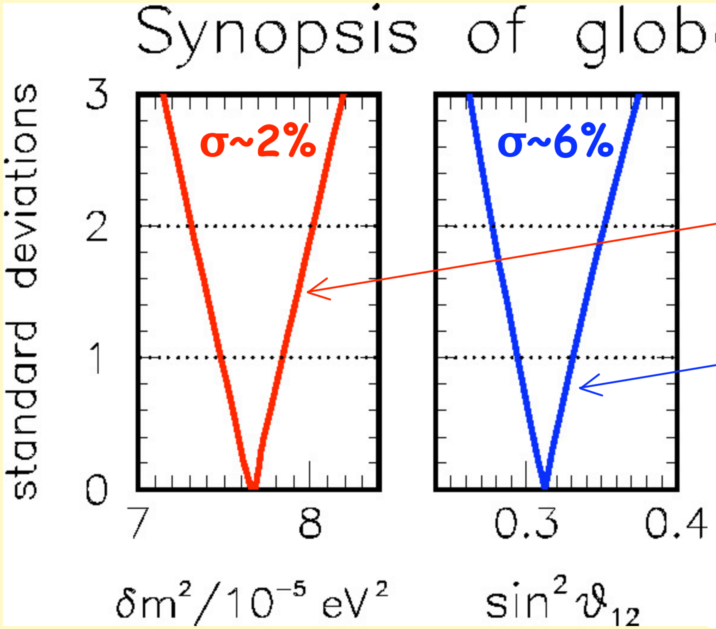


TABLE I: Global 3ν oscillation analysis (2008): best-fit values and allowed n_σ ranges for the mass-mixing parameters.

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	7.67	0.312	0.016	0.466	2.39
1σ range	7.48 – 7.83	0.294 – 0.331	0.006 – 0.026	0.408 – 0.539	2.31 – 2.50
2σ range	7.31 – 8.01	0.278 – 0.352	< 0.036	0.366 – 0.602	2.19 – 2.66
3σ range	7.14 – 8.19	0.263 – 0.375	< 0.046	0.331 – 0.644	2.06 – 2.81

Oscillation parameters: state of the art, sector (1,2)



Dominated by KamLAND (reactors)

Dominatated by SNO (solar)

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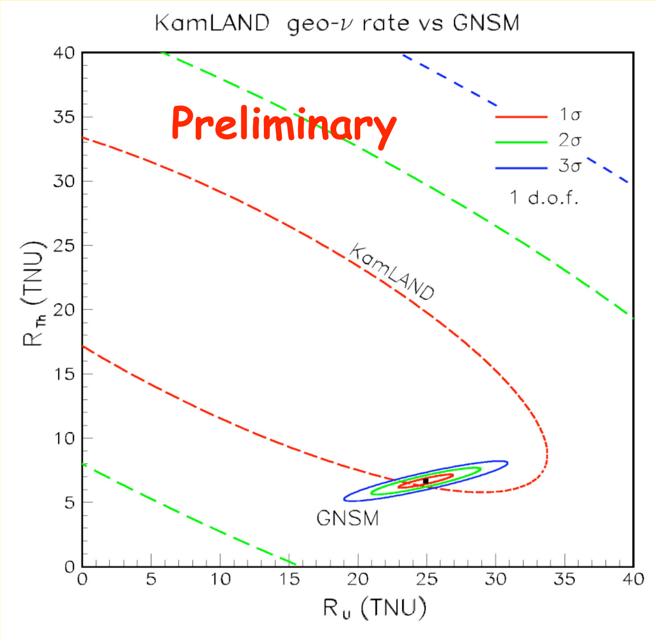
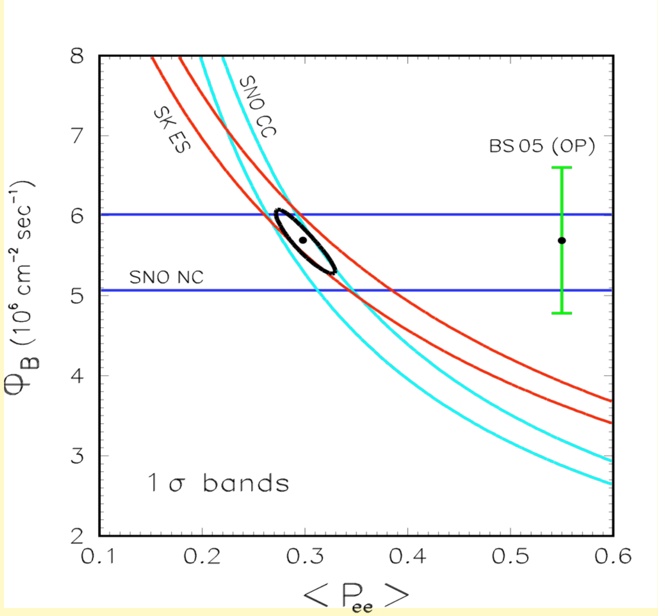
SIDE RESULTS:

Moreover, KamLAND results on geo-nu's agree with geo-chemical/physical models for radiogenic heat production from U, Th decays inside the Earth (within large errors)…

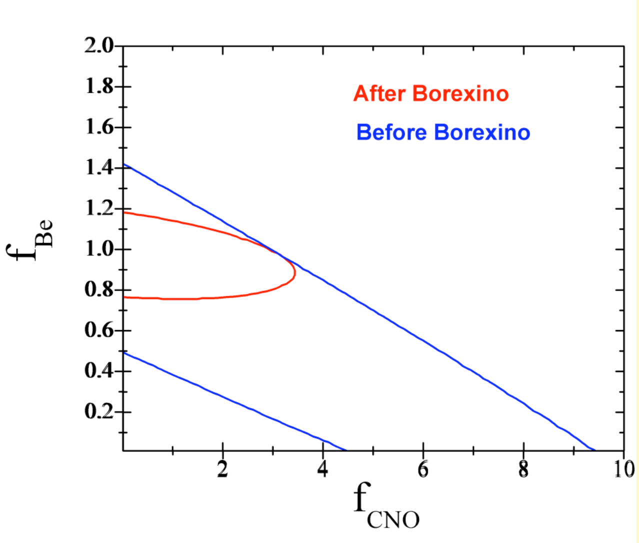
… and the SNO data agree with the standard solar model expectations for neutrino production in Boron-8 decays (within comparable errors)

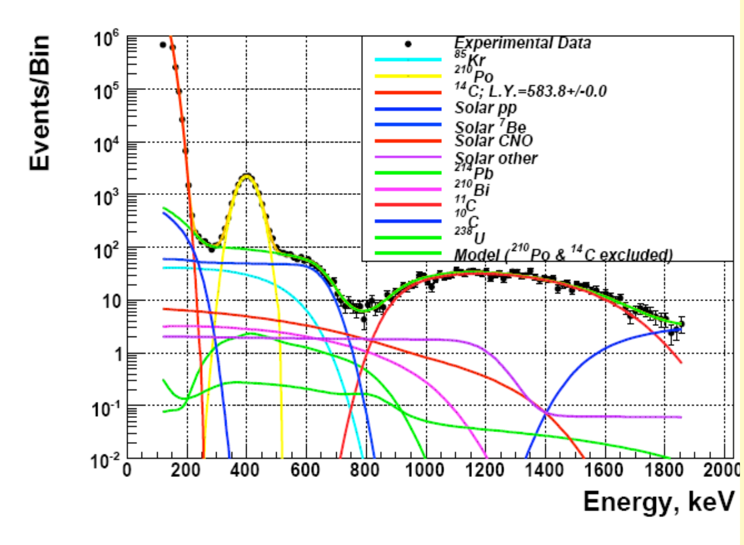
Future precision measurements in the (1,2) neutrino sector might lead to more significant tests of current models of the Earth and Sun interior.





Borexino can perform an independent measurement of the geoneutrino flux in a few years. A more challenging goal is to measure solar neutrino fluxes from the CNO cycle, which are relevant in the connection to the solar metallicity problem (discrepancy between photospheric & helioseismological data).





At the same time, LUNA could further reduce the uncertainties related to nuclear reactions of solar astrophysics interest. New confirmations (or surprises) might then emerge in the context of solar & Earth model (as well as of neutrino physics)

Oscillation parameters: state of the art, sectors (2,3)

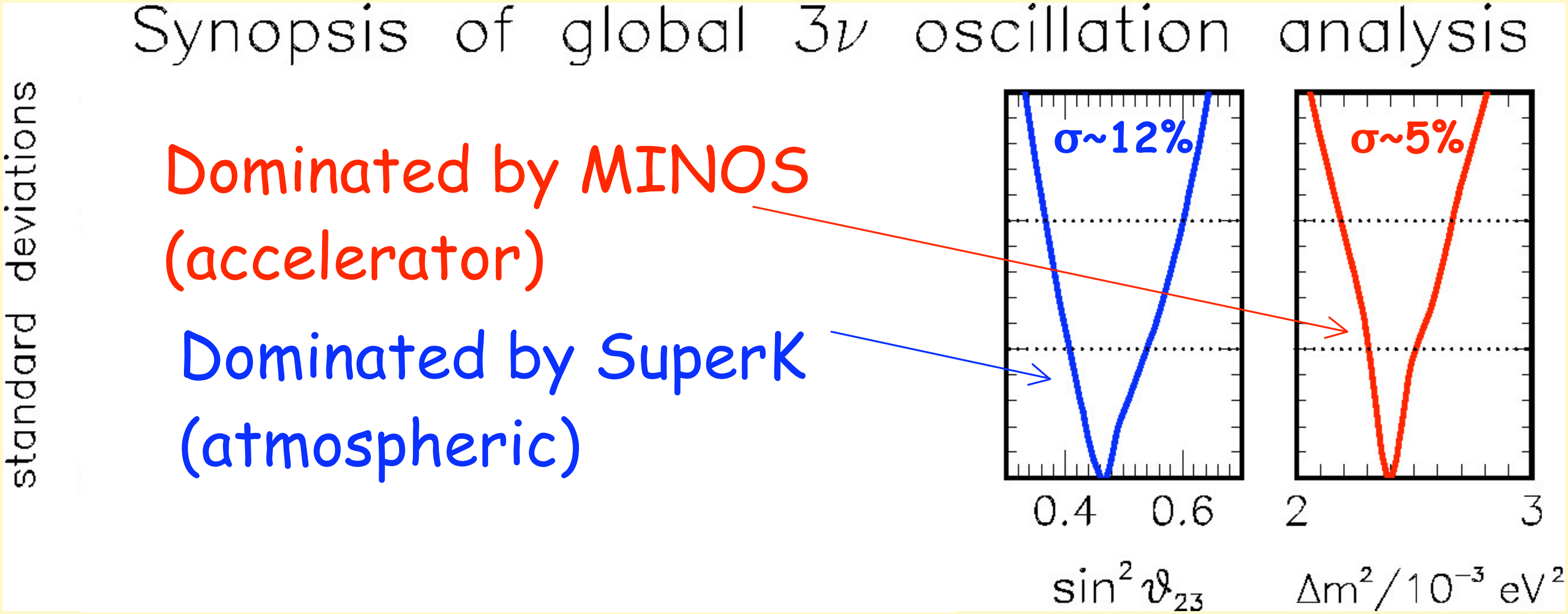


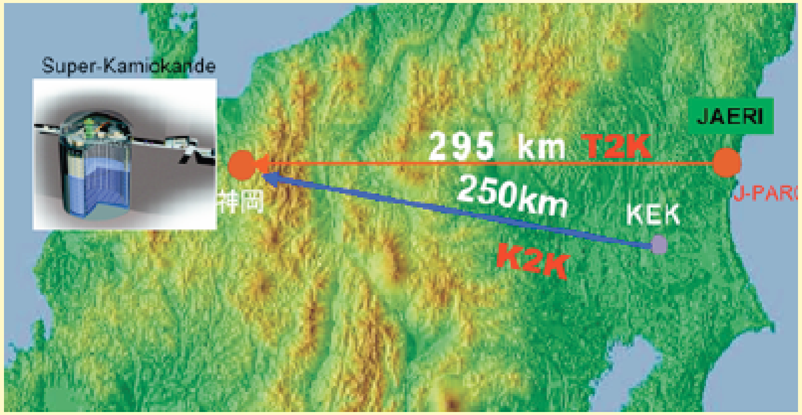
TABLE I: Global 3ν oscillation analysis (2008): best-fit values and allowed n_σ ranges for the mass-mixing parameters.

Parameter	$\sin^2\theta_{23}$	$\Delta m^2/10^{-3}\ \mathrm{eV}^2$
Best fit	0.466	2.39
1σ range	0.408 – 0.539	2.31 – 2.50
2σ range	0.366 – 0.602	2.19 – 2.66
3σ range	0.331 – 0.644	2.06 – 2.81

note:
$\delta m^2/\Delta m^2$ ~3% !

MINOS & SK may provide further fractional improvements in the disappearance channel $\nu_\mu \to \nu_\mu$.

In order to get percent (or smaller) errors: T2K (starting this year). Italian participation to the near detector.



From T2K onward: Multiple solutions may appear in the parameter space (θ_{23}, θ_{13}, sign(Δm^2), δ) or in some subspaces

-> "degeneracy" or "clone" problem, of great importance to optimize specific R&D directions (BENE)

Solution: many accurate data, at various E - L, in different channels

- Detour -

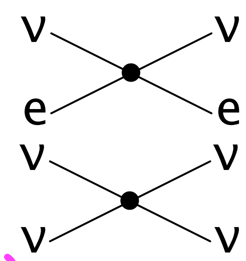
The ambiguity related to hierarchy, namely, sign($\pm\Delta m^2$), can be addressed (in principle), via <u>interference</u> of Δm^2-driven oscillations with oscillations driven by some quantity Q having a known sign.

Barring states/interactions, the only known options are:

Q = Electron density **(MSW effect in Earth or SNe)**

Q = Neutrino density **(Collective effects in SNe)**

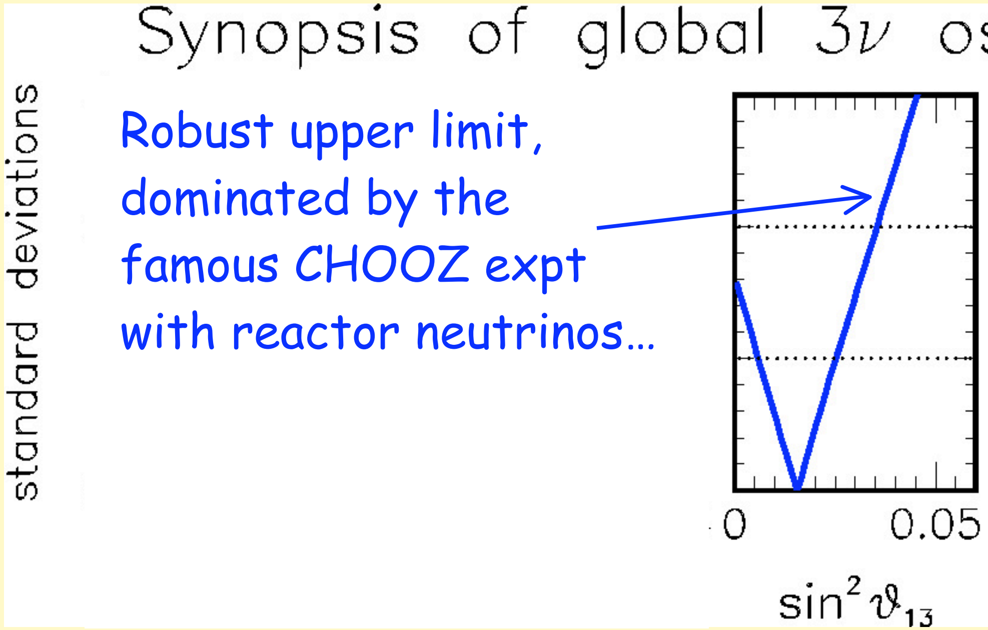
Q = δm^2 **(High-resolution oscill. patterns)**



The first option seems more realistic (e.g., in NOνA or T2KK), provided that θ_{13} is not too small; ma the other two are also being investigated as long-term (or last resort!) options.

More later.

Oscillation parameters: state of the art, angle (1,3)



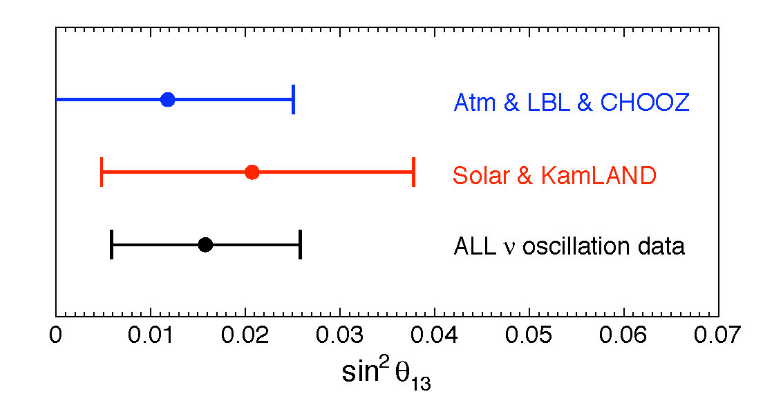
Robust upper limit, dominated by the famous CHOOZ expt with reactor neutrinos…

(unfortunately, not followed by an Italian participation to the upcoming DoubleCHOOZ)

TABLE I: Global 3ν oscillation analysis (2008): best-fit values and allowed n_σ ranges for the mass-mixing parameters.

Parameter	$\sin^2\theta_{13}$
Best fit	0.016
1σ range	0.006 – 0.026
2σ range	< 0.036
3σ range	< 0.046

However, some datasets seem to suggest also a weak lower limit…

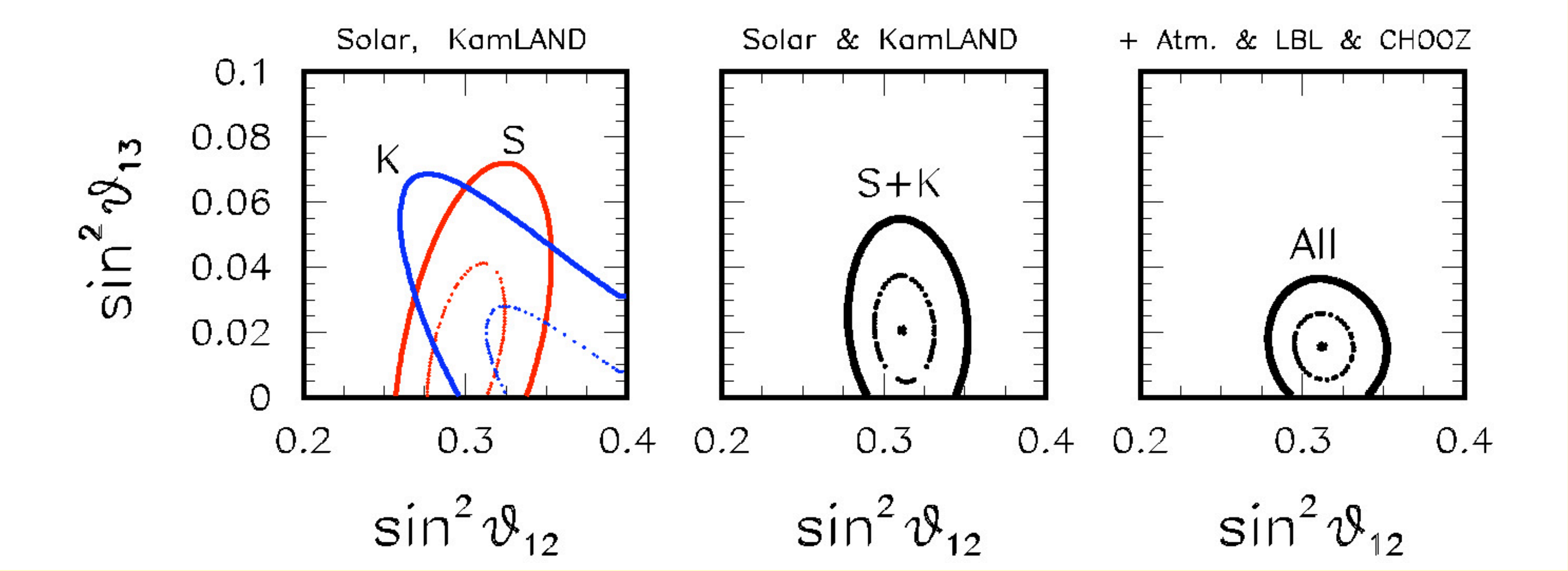


~1σ from sector (2,3)

~1σ from sector (1,2)

~90% CL total:

$\sin^2\theta_{13} = 0.016 \pm 0.010$



Well understood aspect: different correlation bewteen mix. angles in KamLAND vs Solar, arising from different relative signs in P_{ee} (survival probability)

Solar, low energy (~vacuum): GNO

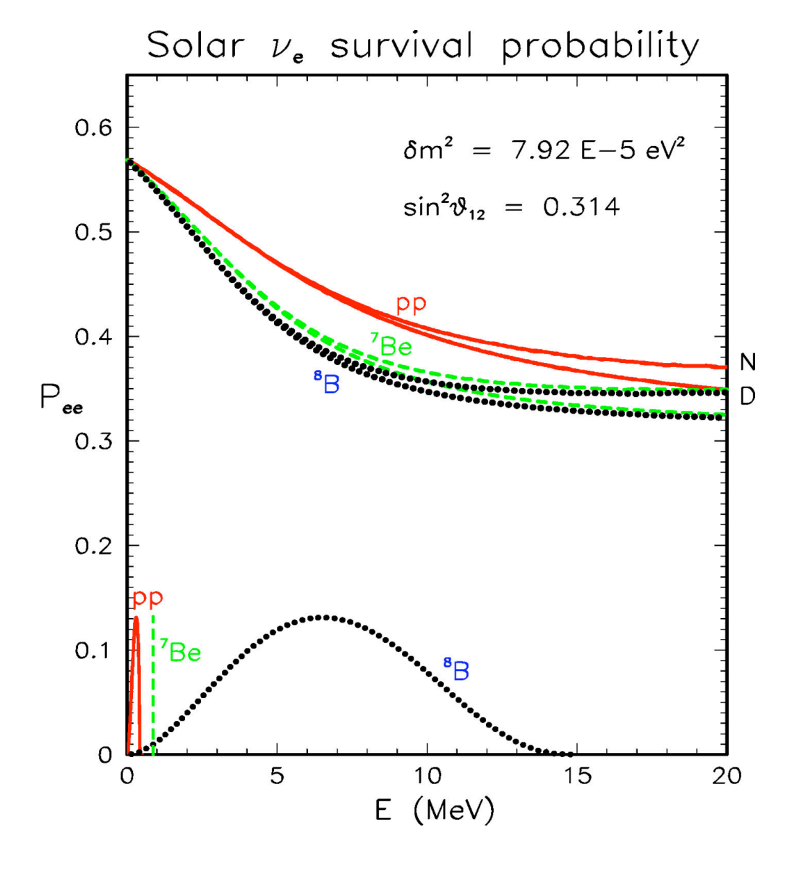
$$P_{ee} \simeq (1 - 2s_{13}^2)(1 - 2s_{12}^2 c_{12}^2)$$

Solari, high energy (~MSW): SNO

$$P_{ee} \simeq (1 - 2s_{13}^2)(+s_{12}^2)$$

Reactor (~vacuum): KamLAND

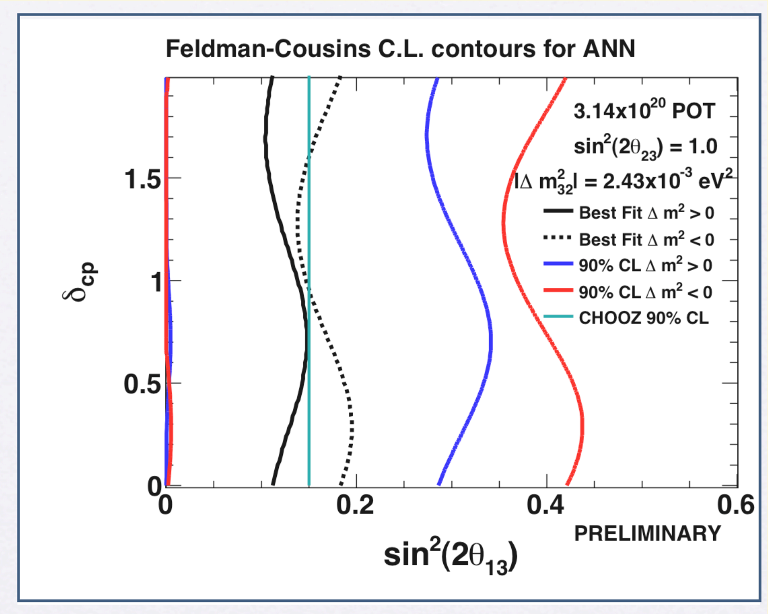
$$P_{ee} \simeq (1 - 2s_{13}^2)(1 - 4s_{12}^2 c_{12}^2 \sin^2(\delta m^2 L/4E))$$

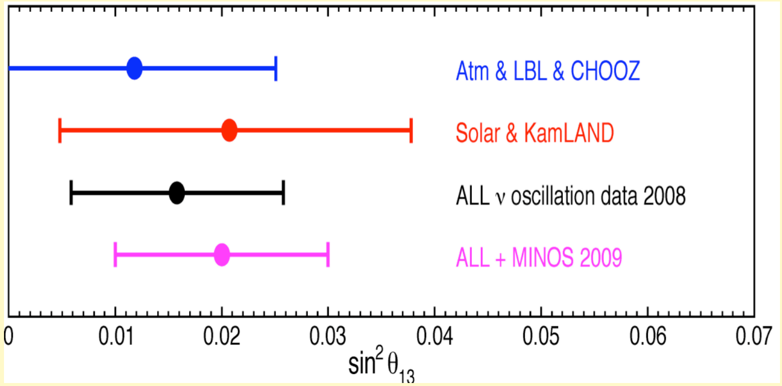


"Tension" on θ_{12} (solar vs KamLAND) can then be alleviated for θ_{13}>0

(Atmospheric indication for θ_{13}>0 is less "direct;" more later)

A possible independent hint of $\theta_{13}>0$ (at 90% C.L.) seems to come from the recent, preliminary MINOS results in appearance channel $\nu_\mu \to \nu_e$





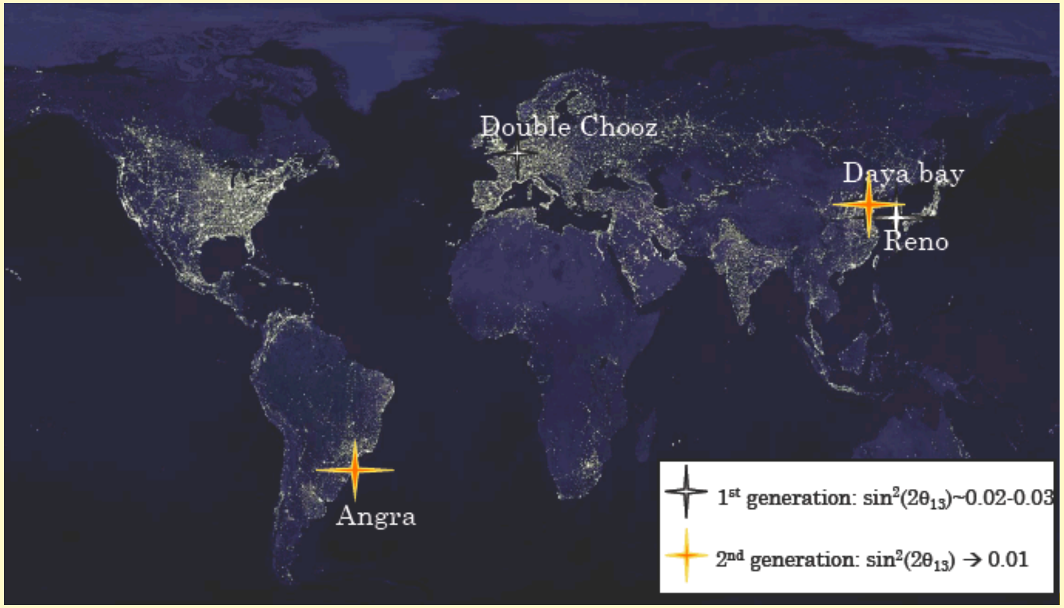
Combining all data (with some optimism), the grand total is:

$$\sin^2\theta_{13} \approx 0.02 \pm 0.01 \quad \text{(all data, circa 2009)}$$

which is an encouraging 2σ hint, testable in the next few years.

(N.B.: MINOS, SK, SNO, KamLAND can still provide further improvements)

In particular, such θ_{13} range is not only accessible to T2K in the appearance channel $\nu_\mu \to \nu_e$, but also to next-generation reactor neutrino experiments in the disappearance channel $\nu_e \to \nu_e$



In any case, measuring $\theta_{13}>0$ (no matter how small) …

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

… would open the door to **leptonic CPV** searches

(and would re-direct many theoretical models and expt. projects)

For instance:

Evidence for **$\sin^2\theta_{13}$>few x 10^{-3}** would allow CPV searches with "conventional" (though more intense) beams. Otherwise, one should consider radically new options, currently subject to R&D (Nufact, beta-beams)

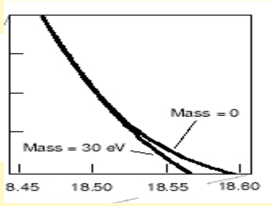
Evidence for **CP violation + Majorana neutrino** would render more palusible (via see-saw) the existence of heavy neutrinos at ~GUT scale, with asymmetric decays into leptons/antileptons (Leptogenesis)

What about the 7-decades-old questions by Fermi e Majorana?

Threefold attack strategy: (m_β, $m_{\beta\beta}$, Σ)

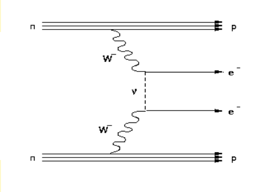
1) **Single β decay**: $m^2_i \neq 0$ alters the spectrum tail. Sensitive to the so-called "effective mass of electron neutrino":

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



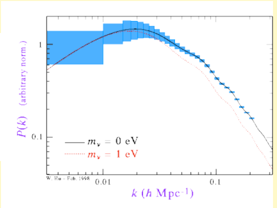
2) **Double 0νββ decay:** Iff $m^2_i \neq 0$ and ν=anti-ν (Majorana). Sensitive to the "effective Majorana mass" (and related phases):

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

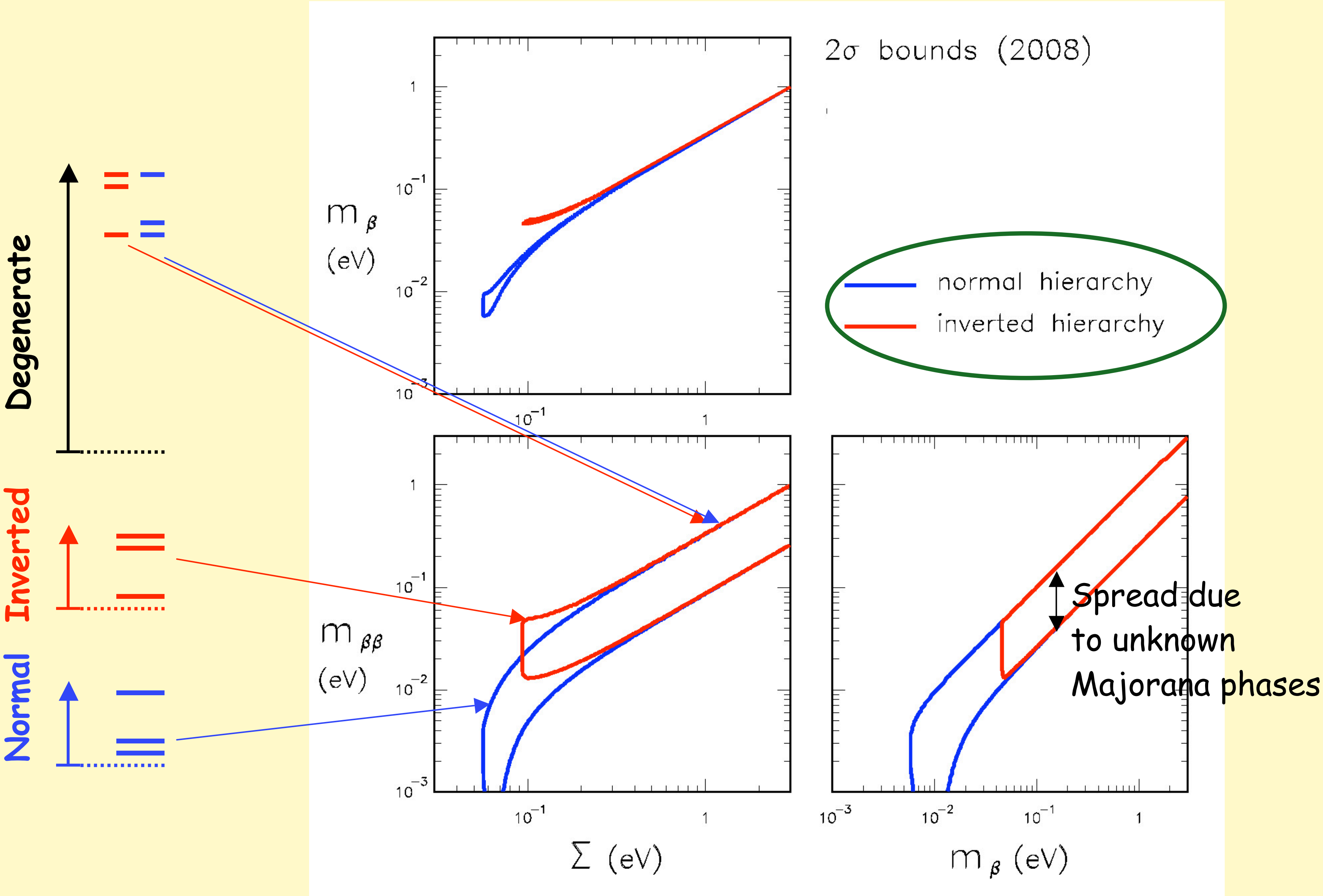


3) **Cosmology**: $m^2_i \neq 0$ alters large scale structure formation within standard cosmology constrained by CMB + other data. Measures:

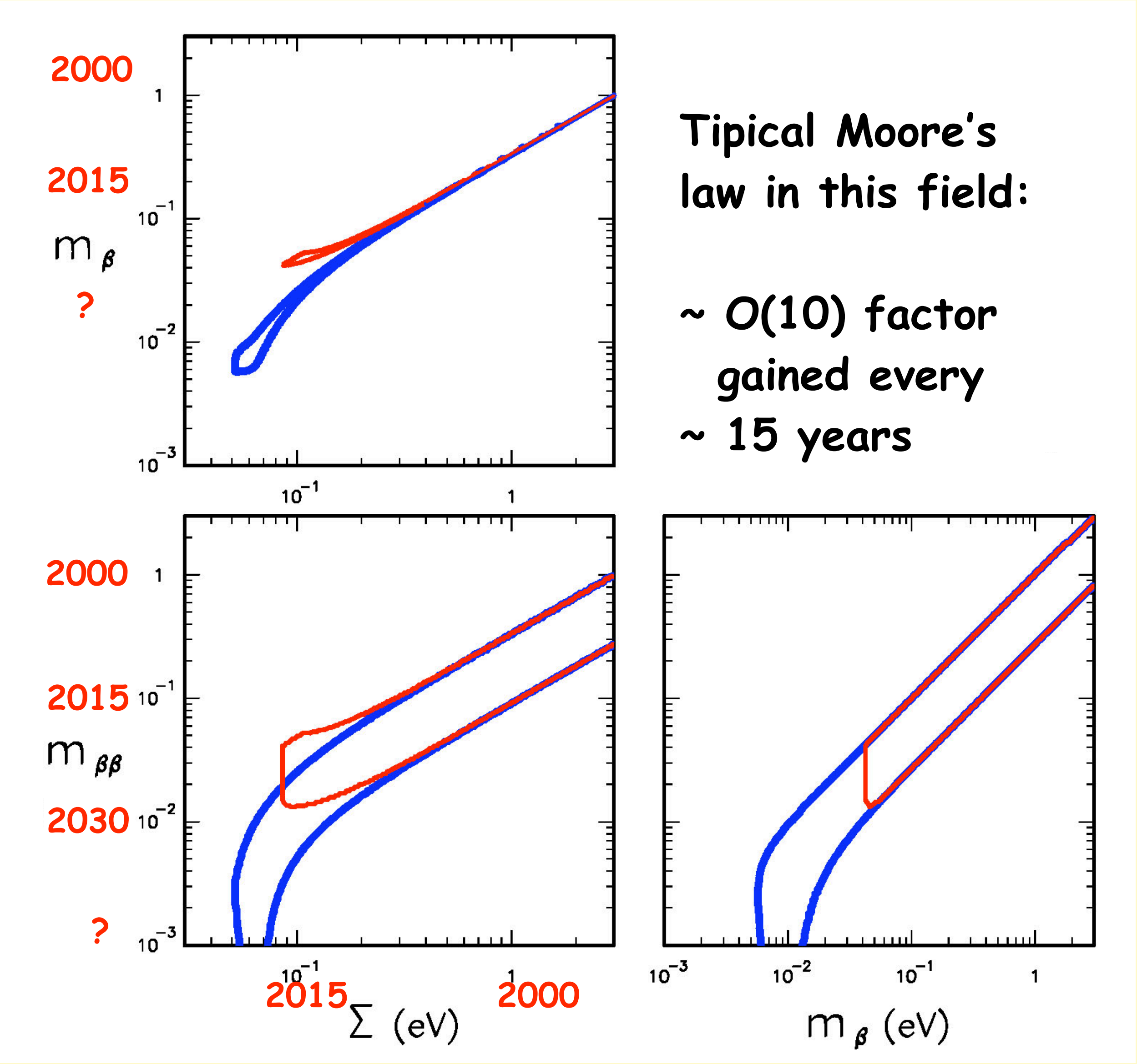
$$\Sigma = m_1 + m_2 + m_3$$



Oscillation data do constrain regions of the non-oscillation parameter space **(m_β, $m_{\beta\beta}$, Σ)** for both hierarchies (degenerate in the "large" mass limit)



… But, of course, we do need proper non-oscillation data **(m_β, $m_{\beta\beta}$, Σ)** to make real progress: another exercise in patience…



Single β decay

Tritium experiments:

Mainz + Troitsk: $m_\beta < 2$ eV

KATRIN: improvement of O(10)

Some possible outcomes from KATRIN (±1σ, [eV]):

$m_\beta = 0.35 \pm 0.07$ (5σ, discovery)

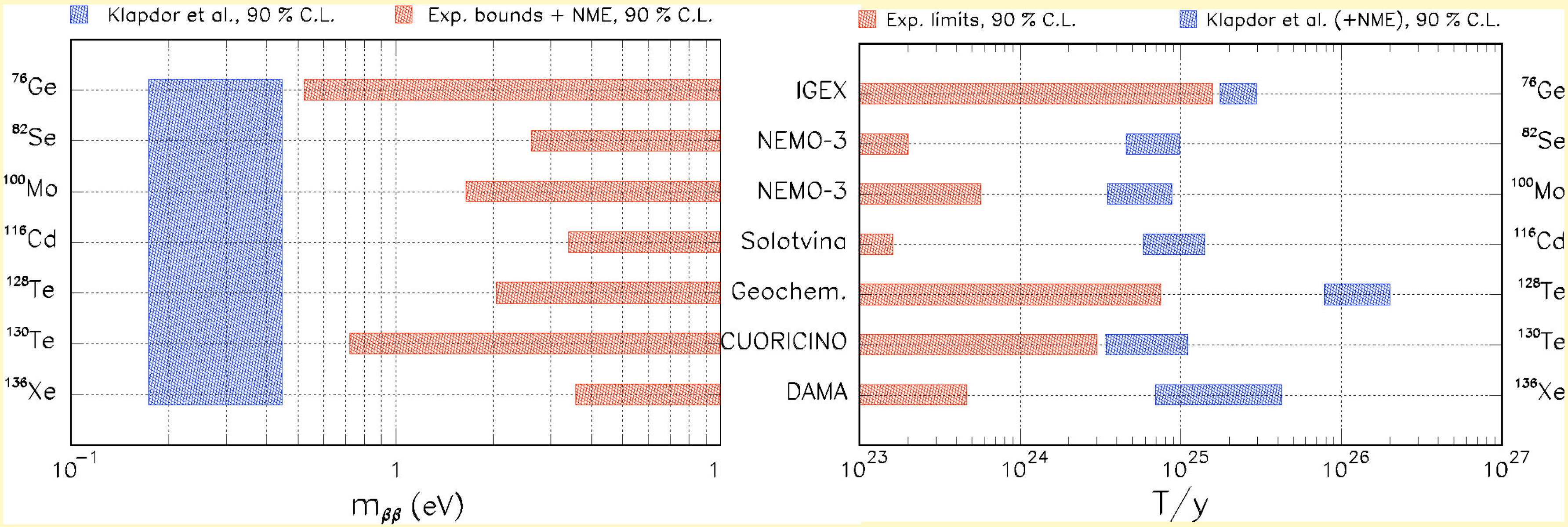
$m_\beta = 0.30 \pm 0.10$ (3σ, evidence)

$m_\beta = 0 \pm 0.12$ (<0.2 at 90% CL)

Clearly, new ideas are needed to go below ~0.2 eV. **MARE** ?

Neutrinoless double β decay

Only upper limits, except for a controversial signal in the most sensitive Experiment to date (Klapdor et al.). By using recent estimates of nuclear matrix elements and their covariances:



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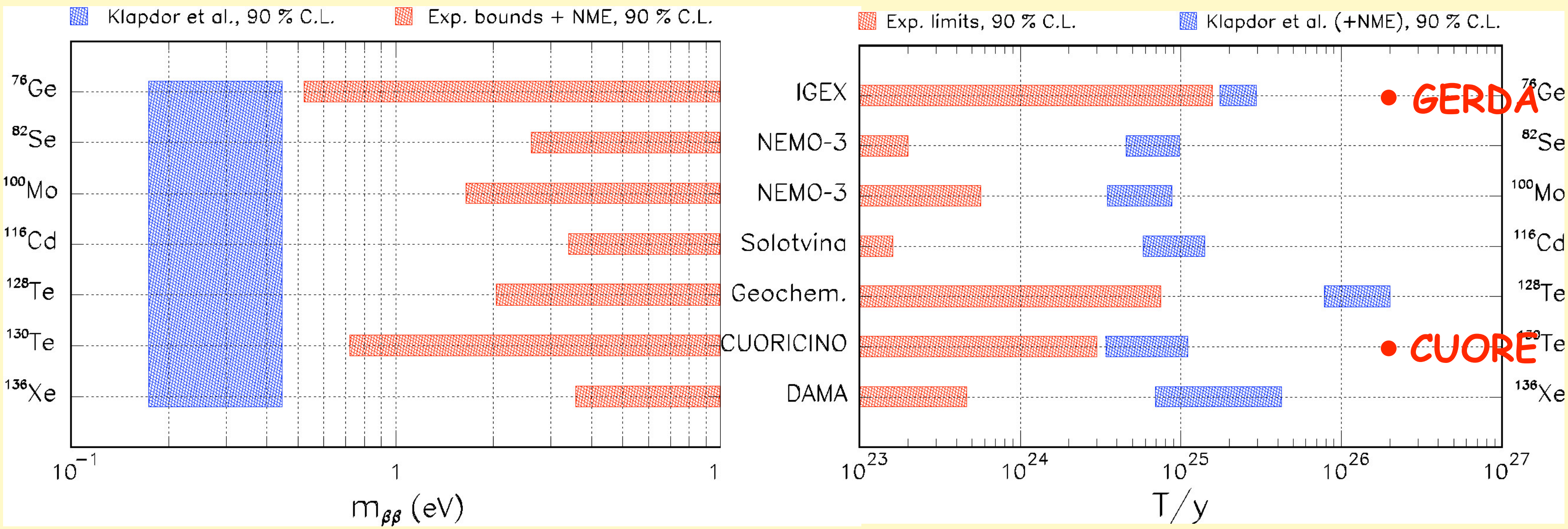


Excellent perspectives for CUORE, GERDA @ LNGS

[and best wishes to all our colleagues & their families at GS e L'Aquila]

Cosmology: Updated limits (2008) on the sum of ν masses from various data sets (assuming the "flat ΛCDM model"):

TABLE II: Representative cosmological data sets and corresponding 2σ (95% C.L.) constraints on the sum of ν masses Σ.

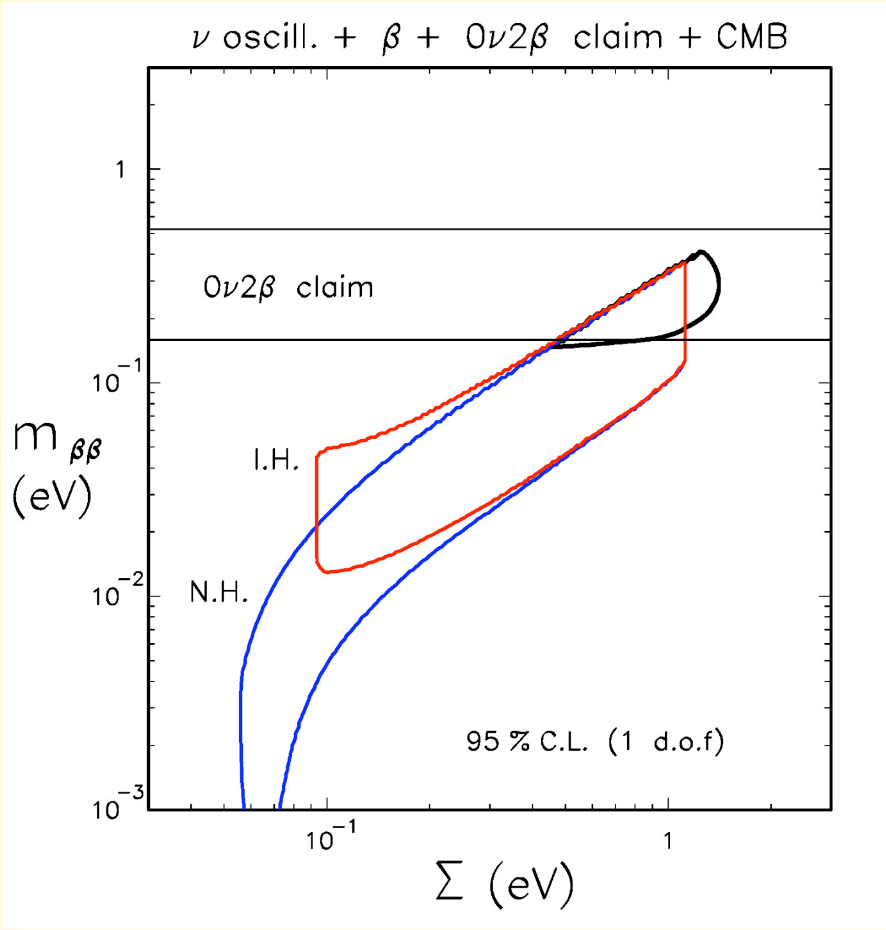
Case	Cosmological data set	Σ (at 2σ)
1	CMB	< 1.19 eV
2	CMB + LSS	< 0.71 eV
3	CMB + HST + SN-Ia	< 0.75 eV
4	CMB + HST + SN-Ia + BAO	< 0.60 eV
5	CMB + HST + SN-Ia + BAO + Lyα	< 0.19 eV

Case 1: "conservative" (only CMB data, dominated by WMAP 5y)
Case 5: "aggressive" (all relevant cosmological data)

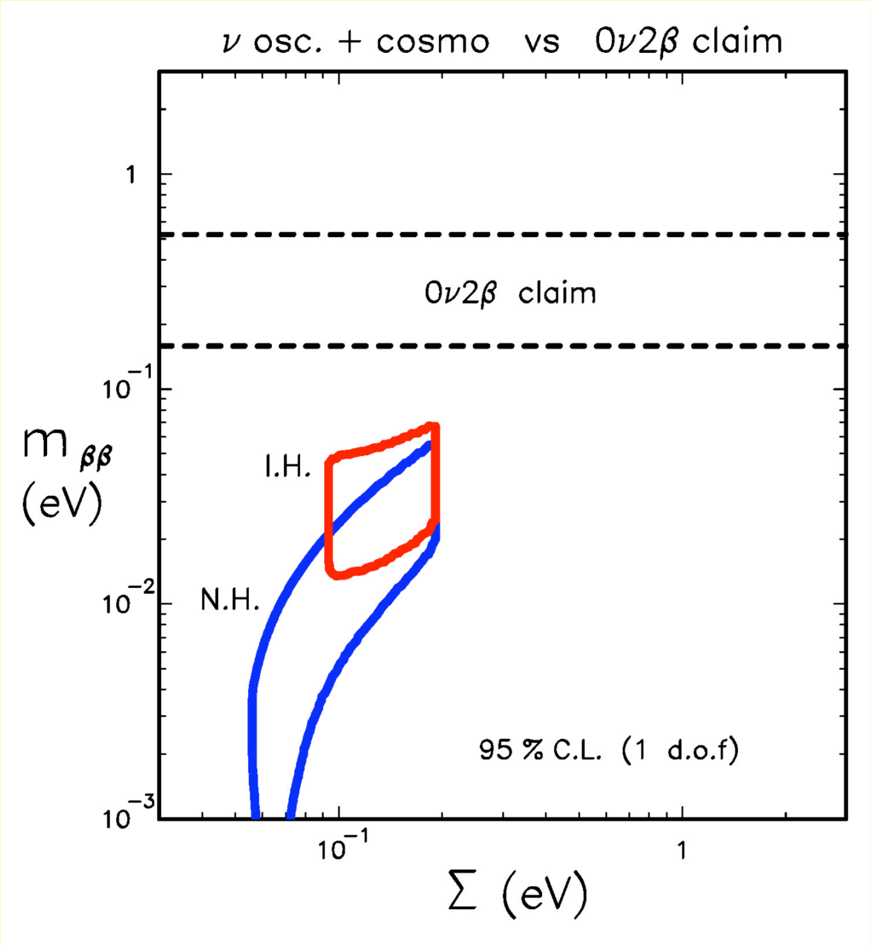
Upper limits in the range Σ < 0.6-1.2 eV have gained large consensus.

[Cosmologists envisage a brighter future, with sensitivities at the level of ~0.1 eV and, perhaps, to the hierarchy. But, will particle physicists be ready to accept a cosmological claim for $\Sigma > 0$?]

Cosmo-"conservative"



Cosmo-"aggressive"



Two very different answers to Fermi's e Majorana's questions…

Let's entertain the possibility that the "true" answer is just around the corner... For instance, that neutrinos are Majorana, with nearly degenerate and relatively large masses:

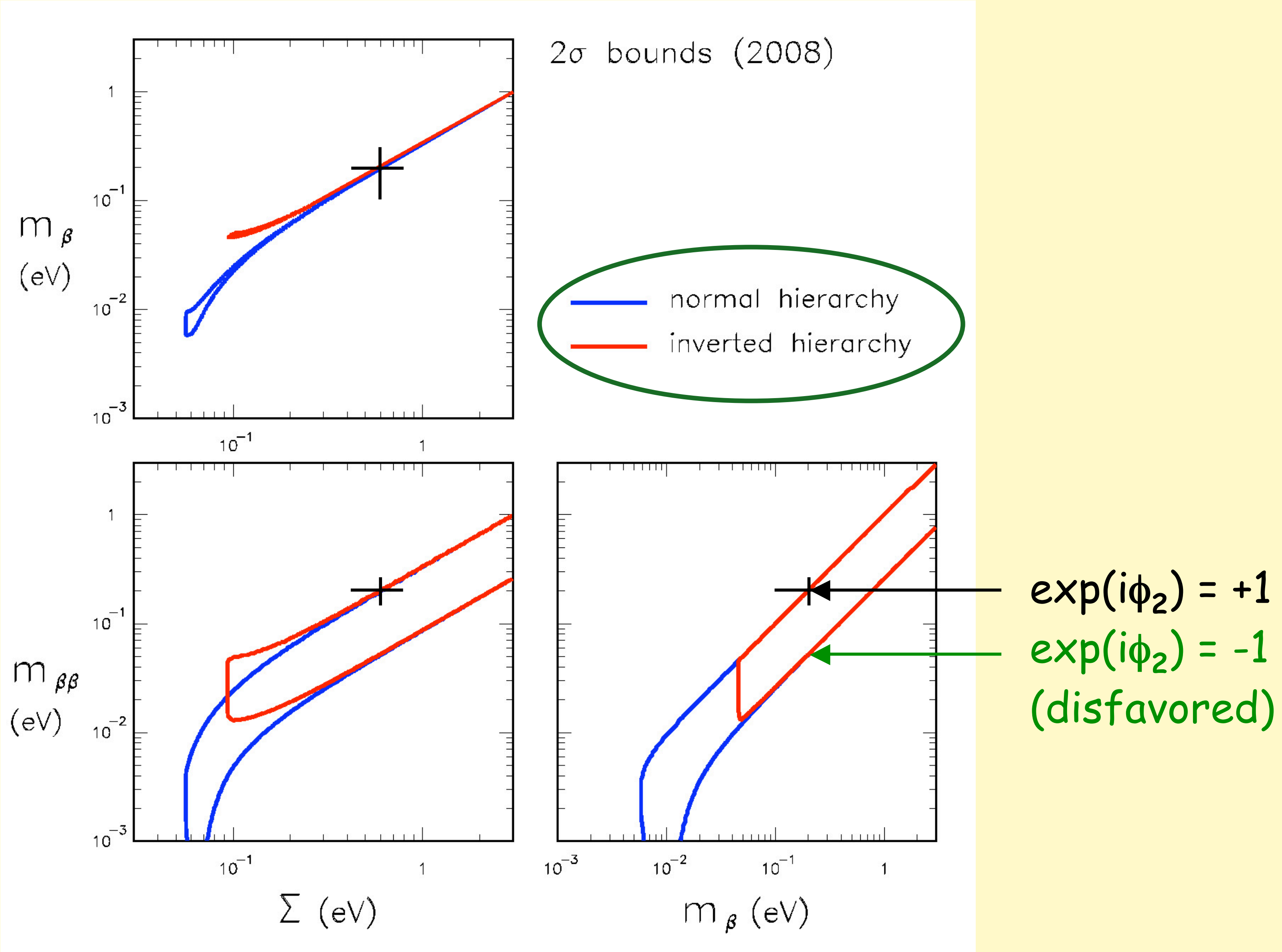
$$m_1 \sim m_2 \sim m_3 \sim 0.2 \text{ eV} .$$

Then we might reasonably hope to observe all three nonoscillation signals, e.g.,

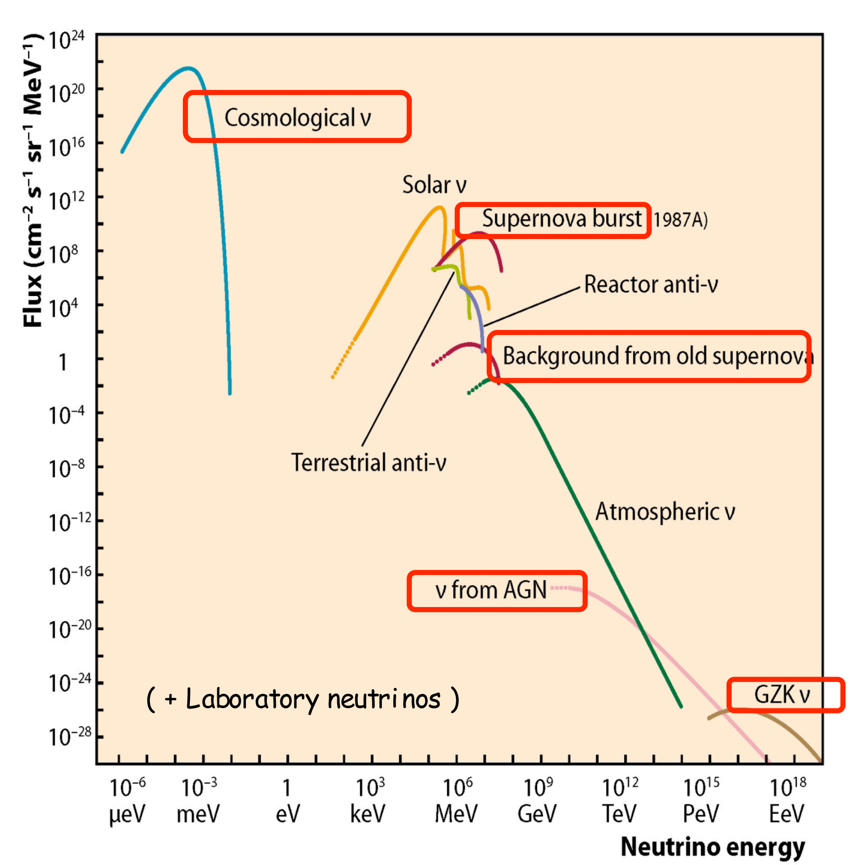
$$\begin{aligned} m_{\beta\beta} &\simeq 0.2(1 \pm 0.3) \text{ eV} \\ \Sigma &\simeq 0.6(1 \pm 0.3) \text{ eV} \\ m_\beta &\simeq 0.2(1 \pm 0.5) \text{ eV} \end{aligned}$$

In which case...

…The absolute neutrino mass would be reconstructed within ~25% uncertainty, and one Majorana phase (ϕ_2) would be constrained…



Just a dream? Maybe. However, "dreaming" is essential to face and overcome the many challenges of neutrino physics, including those related to the detection of cosmo/astro neutrino sources…



A synoptic view of neutrino fluxes. (from ASPERA roadmap)

…where the Italian (theo+expt) contribution is relevant, but whose discussion would require another seminar.

END OF FIRST PART

For further details on previous mass-mixing parameter estimates:
G.L. Fogli et al., 0805.2517, 0806.2649, 0808.0807, 0810.5733, 0905.3549

To navigate in the nu literature, start from: www.nu.to.infn.it)

SECOND PART: More on sign Δm^2 and θ_{13}

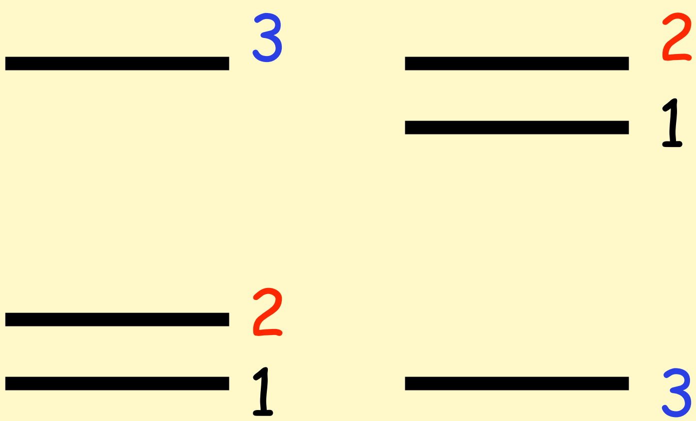
(two known unknowns)

We'll be talking about small effects, and need first to clarify "innocent" definitions, such as:
What does Δm^2 mean, exactly?

Reminder: $\delta m^2/\Delta m^2 \sim 3\%$ and $\sigma(\Delta m^2)/\Delta m^2 \sim 5\%$

Masses: labels and splittings

Consensus labels: doublet=(ν_1, ν_2), with ν_2 heaviest in both hierarchies



$$\delta m^2 = m_2^2 - m_1^2 > 0$$

Sign of smallest splitting: conventional. The relative ν_e content of ν_1 and ν_2 is instead physical (given by MSW effect): ν_e is more mixed with ν_2 then ν_1 in both hierachies

$$\text{Note}: \ |m_3^2 - m_1^2| = \begin{cases} \text{largest splitting (N.H.)} \\ \text{next−to−largest splitting (I.H.)} \end{cases}$$

$$\Rightarrow \Delta m_{31}^2 \ (\text{or } \Delta m_{32}^2) \text{ change physical meaning from NH to IH}$$

We prefer to define the 2nd independent splitting as:

$$\Delta m^2 = \left| \frac{\Delta m^2_{31} + \Delta m^2_{32}}{2} \right| = \left| m_3^2 - \frac{m_1^2 + m_2^2}{2} \right|$$

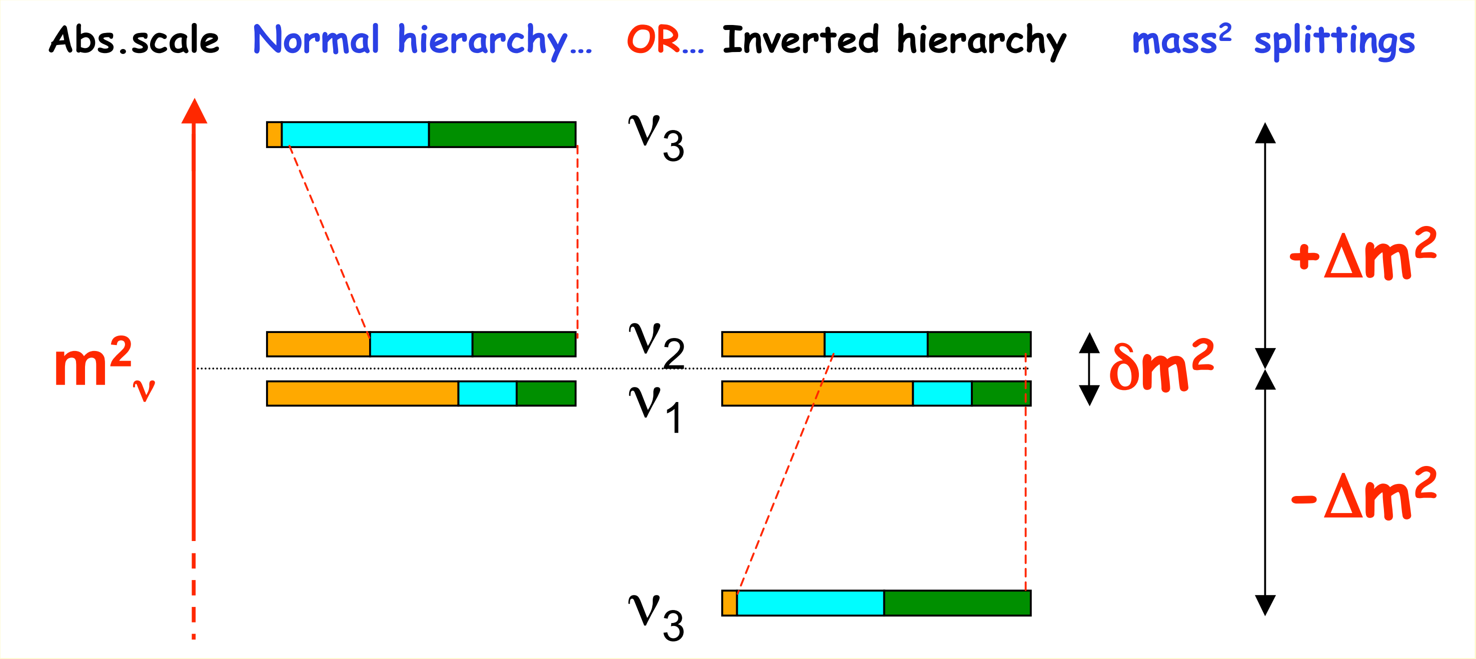
so that the largest and next-to-largest splittings, in both NH & IH, are given by: $\Delta m^2 \pm \frac{\delta m^2}{2}$

and only one physical sign distinguishes NH (+) from IH (-), as it should be:

$$(m_1^2, m_2^2, m_3^2) = \frac{m_2^2 + m_1^2}{2} + \left(-\frac{\delta m^2}{2}, +\frac{\delta m^2}{2}, \pm\Delta m^2 \right)$$

In vacuum, $\nu_\alpha \rightarrow \nu_\beta$ oscillation amplitudes between ν_i and ν_j are proportional to $|U_{\alpha i} U_{\alpha j} U_{\beta i} U_{\beta j}|$, while their phases are proportional to $m^2_i - m^2_j$.

E.g., for $\alpha\beta=\mu\tau$ and $ij=23$:



Same amplitude, but role of largest and next-to largest phases interchanged in different hierarchies (distinguishable in principle)

E.g., consider the full 3ν survival probability for reactor neutrinos (upper/lower Δm^2 sign for normal/inverted hierarchy), assuming $\theta_{13}>0$:

$$\begin{aligned} 1-P_{ee} &= 4|U_{e1}|^2|U_{e2}|^2\sin^2\left(\frac{\delta m^2 L}{4E}\right) \\ &+ 4|U_{e1}|^2|U_{e3}|^2\sin^2\left(\frac{\pm\Delta m^2+\delta m^2/2}{4E}L\right) \\ &+ 4|U_{e2}|^2|U_{e3}|^2\sin^2\left(\frac{\pm\Delta m^2-\delta m^2/2}{4E}L\right) \end{aligned}$$

"slow osc."
(KamLAND, LBL)

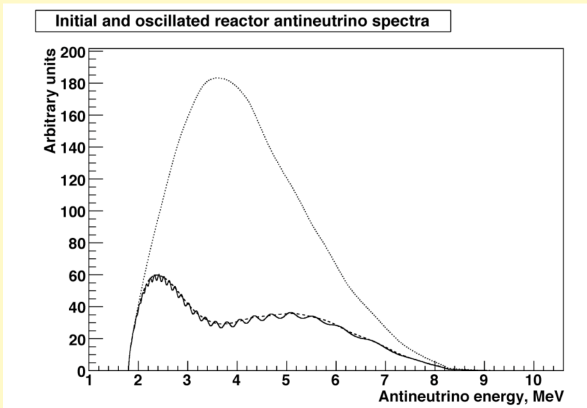
"fast osc."
(CHOOZ, SBL)

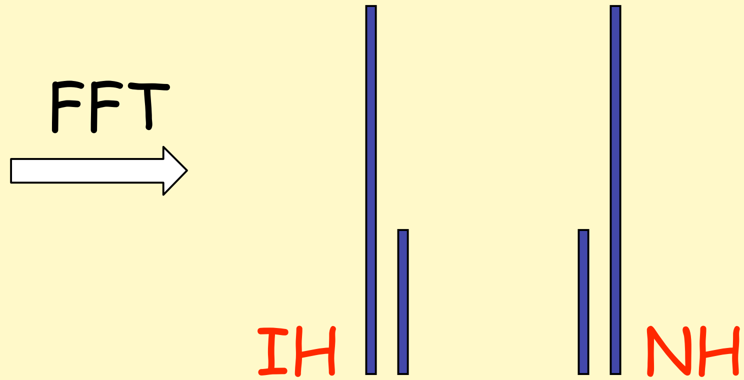
Fast oscillations not invariant under hierarchy swap, iff $U_{e1} \neq U_{e2}$
(Fogli, EL & Palazzo hep-ph/0105080)

A reactor experiment at intermediate baseline (few tens of km), sensitive in principle to both slow and fast terms, might then distinguish the hierarchy (Petcov & Piai hep-ph/0112074; Choubey, Petcov and Piai, hep-ph/0306017)

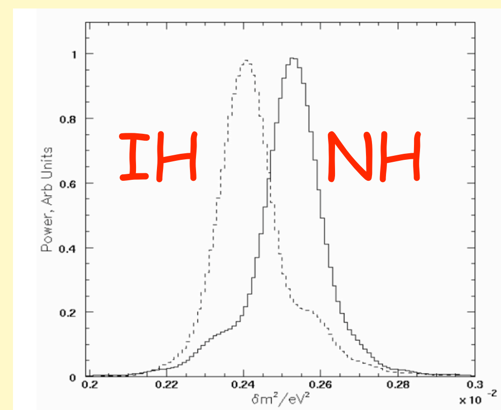
Lucky facts about reactor expts.: inverse beta decay reaction does not smear energy spectrum signatures; liquid scintillators provide high energy resolution.

Intuitive strategy: Fourier analysis of the fast oscillations (Learned et al., hep-ex/0612022). For perfect resolution, should find two high frequencies $\Delta m^2 \pm \delta m^2/2$ with different amplitudes:





For finite resolution, the two peaks would merge, but the lowest one should still survive as a "shoulder" on the left (NH) or on the right (IH) of the dominant peak:



Obvious question: can the peak shape be measured accurately enough?

Unfortunately, recent studies show that the expt. requirements are too demanding for current or near-future antineutrino detector technology, even if θ_{13} is close to its upper limits (Batygov, Dye, Learned 0810.0580; Zahn et al., 0901.2976)

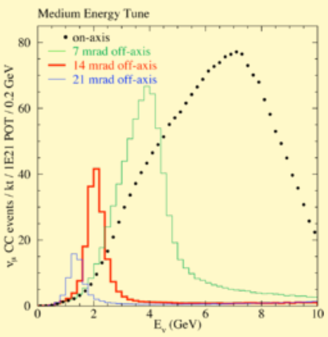
In principle, one could think about similar effects in the muon (rather than electron) neutrino disappearance channel. This would not depend on θ_{13}=0 or >0, since all mass states mix with muon flavor. (De Gouvea, Jenkins, Kayser hep-ph/0503079; Nunokawa, Parke, Funchal hep-ph/0503283). But, of course, nobody knows how to reconstruct fast oscillations with percent accuracy using muons…

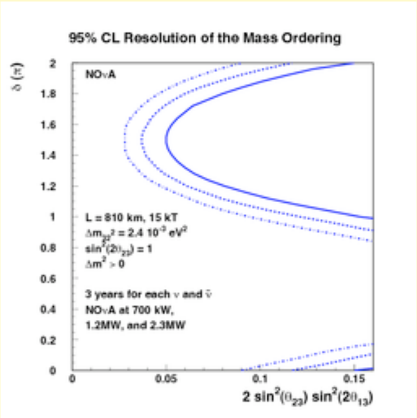
So, beating $\pm\Delta m^2$ with δm^2 does not seem to be the most promising way to access the hierarchy with oscillations.

However, we still have two bullets: two possible interaction terms affecting the $\pm\Delta m^2$-induced phase.

The first bullet is provided by the usual MSW effect (forward neutrino-matter scattering). Fractional variation of amplitude or phase is roughly $\pm 2\sqrt{2} G_F N_e E/(\pm \Delta m^2)$, where the first $\pm$ refers to nu/antinu and the second to NH/IH.

Variations can be up to ~30% in accelerator beams with relatively sharp E-spectra (off-axis) and relatively long L inside the Earth crust (optimal choice: ~oscillation maximum). E.g., NOvA:



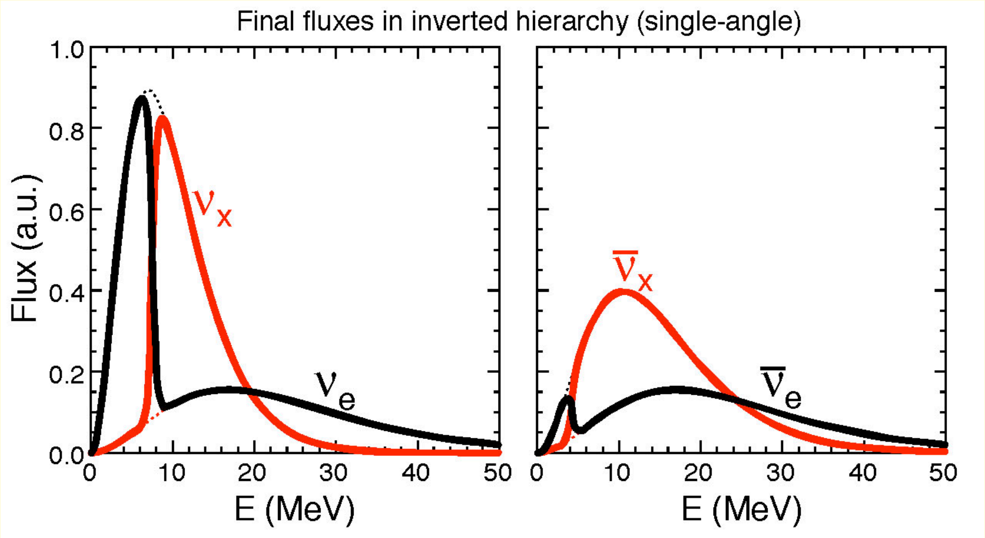


But: absolute amplitude of $\nu_\mu \to \nu_e$ scales as $\sin^2\theta_{13}$, with strong δ dependence. Must be lucky with both parameters.
Anyway, most promising (or "less unpromising") option so far.

The second bullet is provided by a rather peculiar phenomenon: forward neutrino-neutrino scattering in core-collapse SN. In this case, $\pm\Delta m^2$ compares with $\pm 2\sqrt{2}G_F\, E$ * density (nu + antinu). Recently revived after seminal work by UCSD group (Fuller et al.)

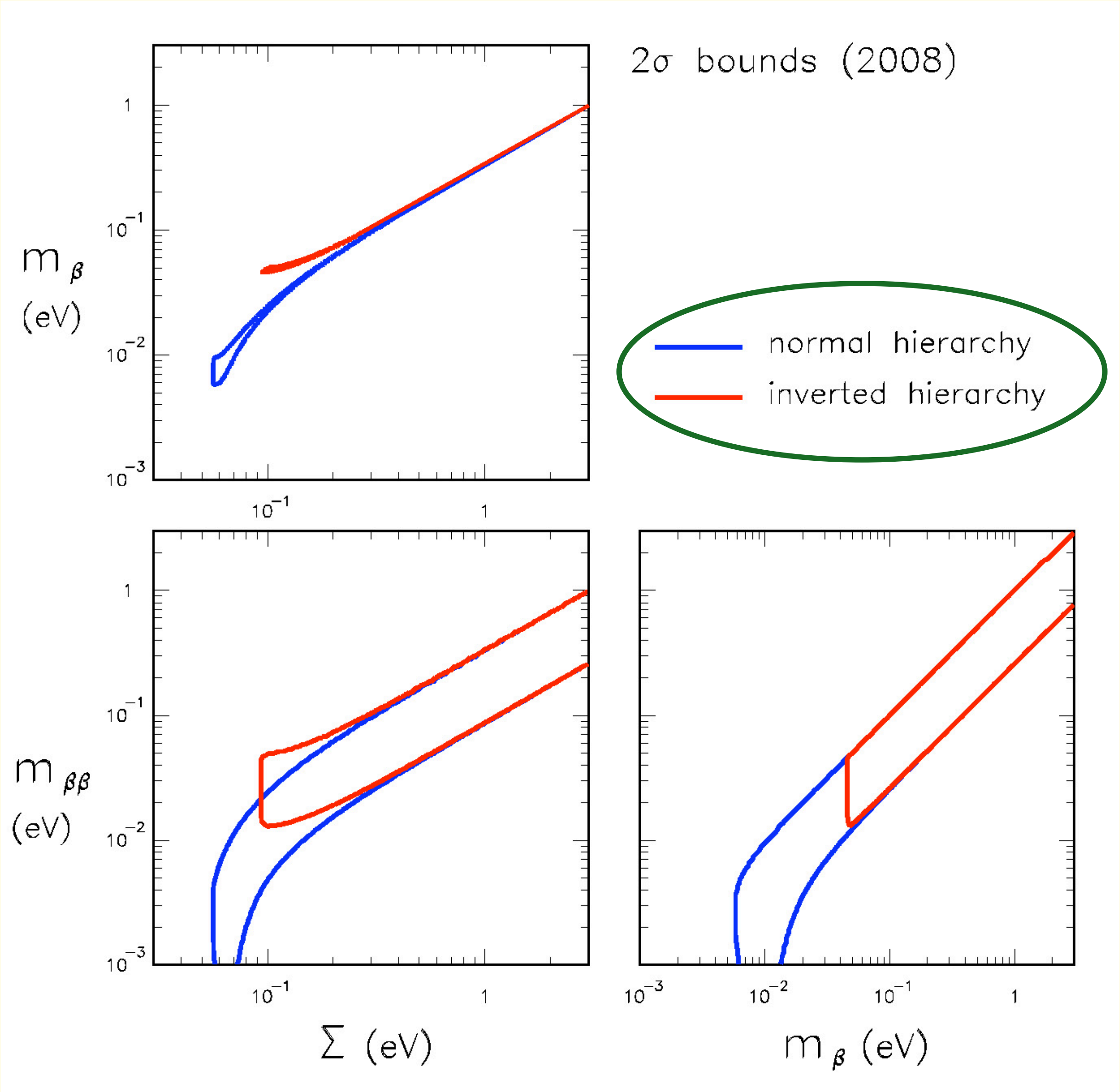
In this case, "order of magnitude" estimates or "rule-of-thumb" approaches fail: flavour evolution is highly nonlinear, and several collective transformations emerge

However, in inverted hierarchy, and for any $\theta_{13}>0$, unique spectral split/swap effects seem to be "generic" (Fuller et al., Raffelt & Smirnov, ...):



Observation of such effects, if any, is admittedly difficult, episodic (!), and entangled with possible MSW effects and with unknowns in SN astrophysics. However, it might provide an independent probe of the mass hierarchy and of nonzero theta(13).

Finally, there are non-oscillation probes of the hierarchy.
E.g., very low values of **(m_β, $m_{\beta\beta}$, Σ)** can only be reached in NH

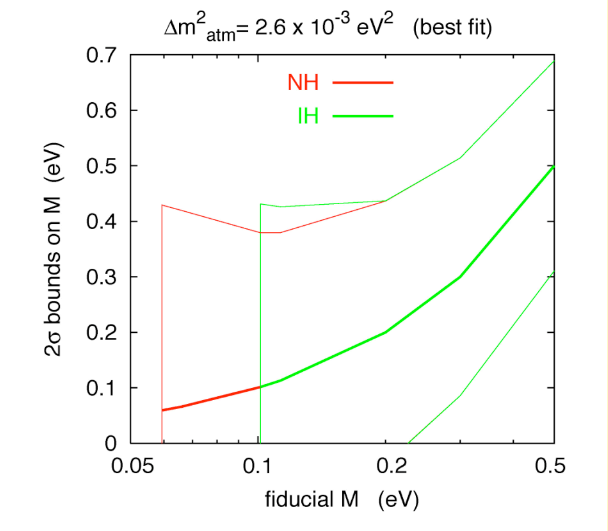


As values increase, however, some overlap with IH develops.

Overlap is complete for degenerate masses, Where IH and NH are not distingushable.

Far future: can we get hierarchy hints from high-precision cosmology? After all, relic neutrinos with different masses do not become nonrelativistic at exactly the same time...

Prospective studies (Lesgourgues, Pastor, Perotto 2004) not particularly promising...

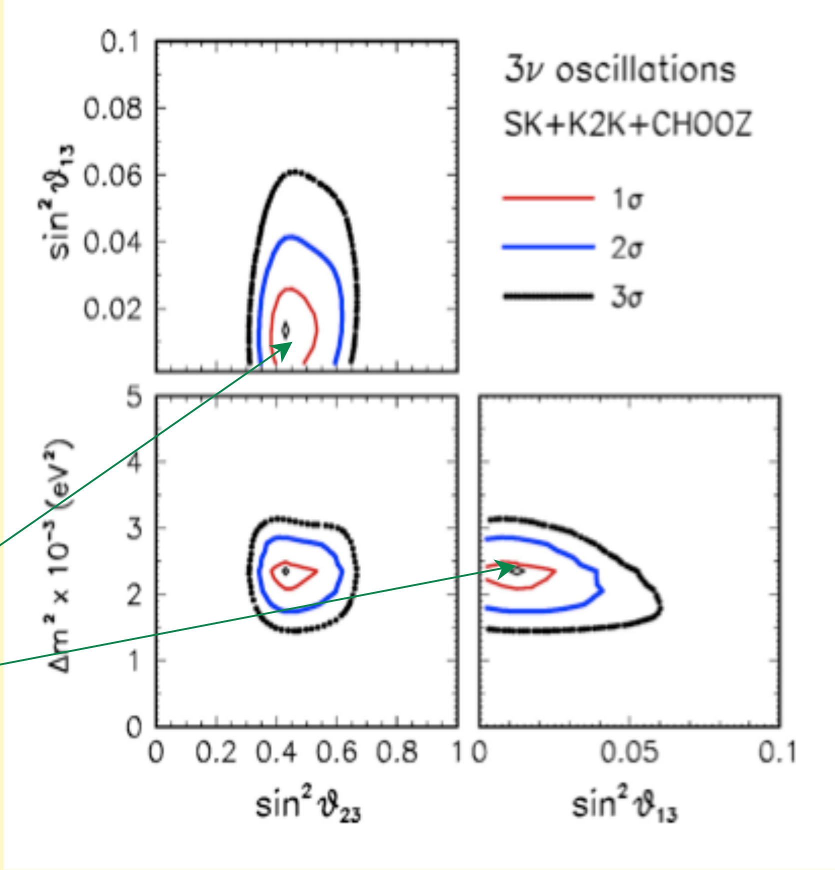


... but the last word has not been said yet.

FINALLY, some remarks on θ_{13} atmospheric hints

We obtained a weak hint for $\theta_{13} > 0$ in our 3-neutrino analysis of atmospheric + LBL + Chooz data in 2006

Fogli, EL, Marrone, Palazzo
Progr. Part. Nucl. Phys. 57, 742 (2006)
See also Escamilla et al., arXiv:0805.2924



... which we attributed to subleading "solar term" effects, which help to fit the atmospheric electron-like event data (especially sub-GeV) in Super-K phase I.

best fit ~ 1 sigma away from zero

We find that the hint is NOT killed by adding K2K and MINOS disappearance data.

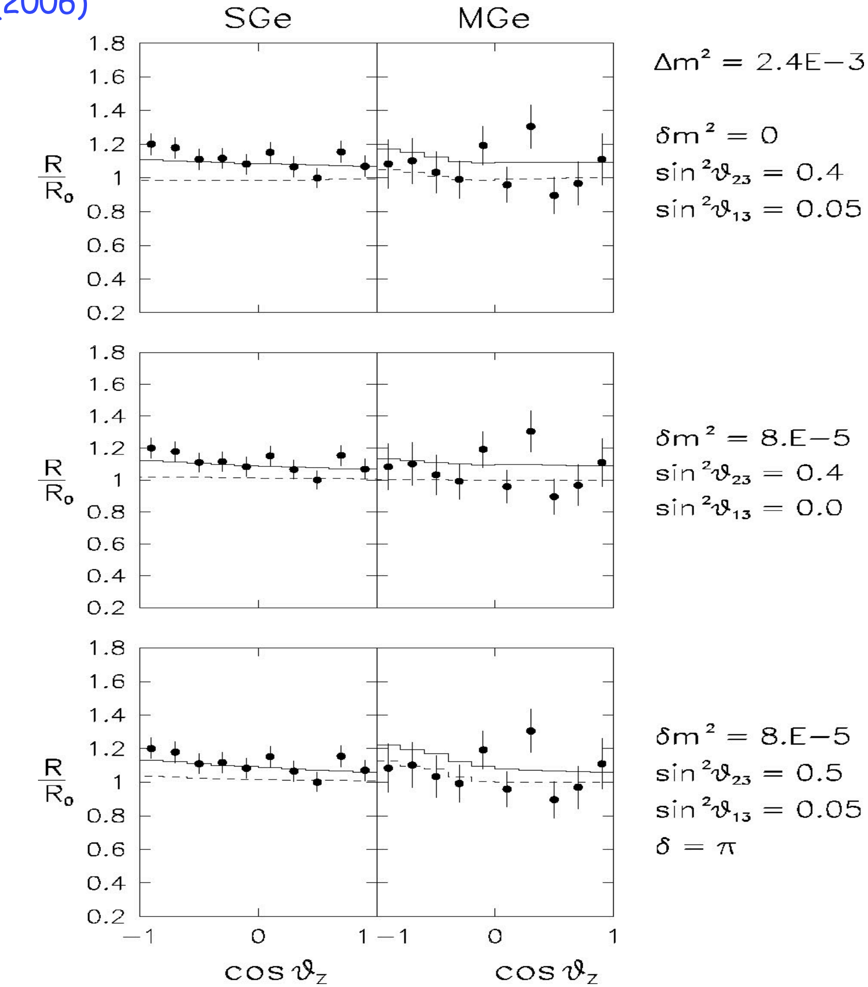
Subleading terms can be roughly split as

“ q_{13} term”

“ dm^2 term”

“ Interference term”
(~ only in sub-GeV)

GLF, Lisi, Marrone, Palazzo, Progr. Part. Nucl. Phys. 57, 742 (2006)



the last one being crucial to the hint, according to our analysis.

The atmospheric three-neutrino analyses in

- SK Collaboration, hep-ex/0604011
- Schwetz, Tortola, Valle, arXiv:0808.2016

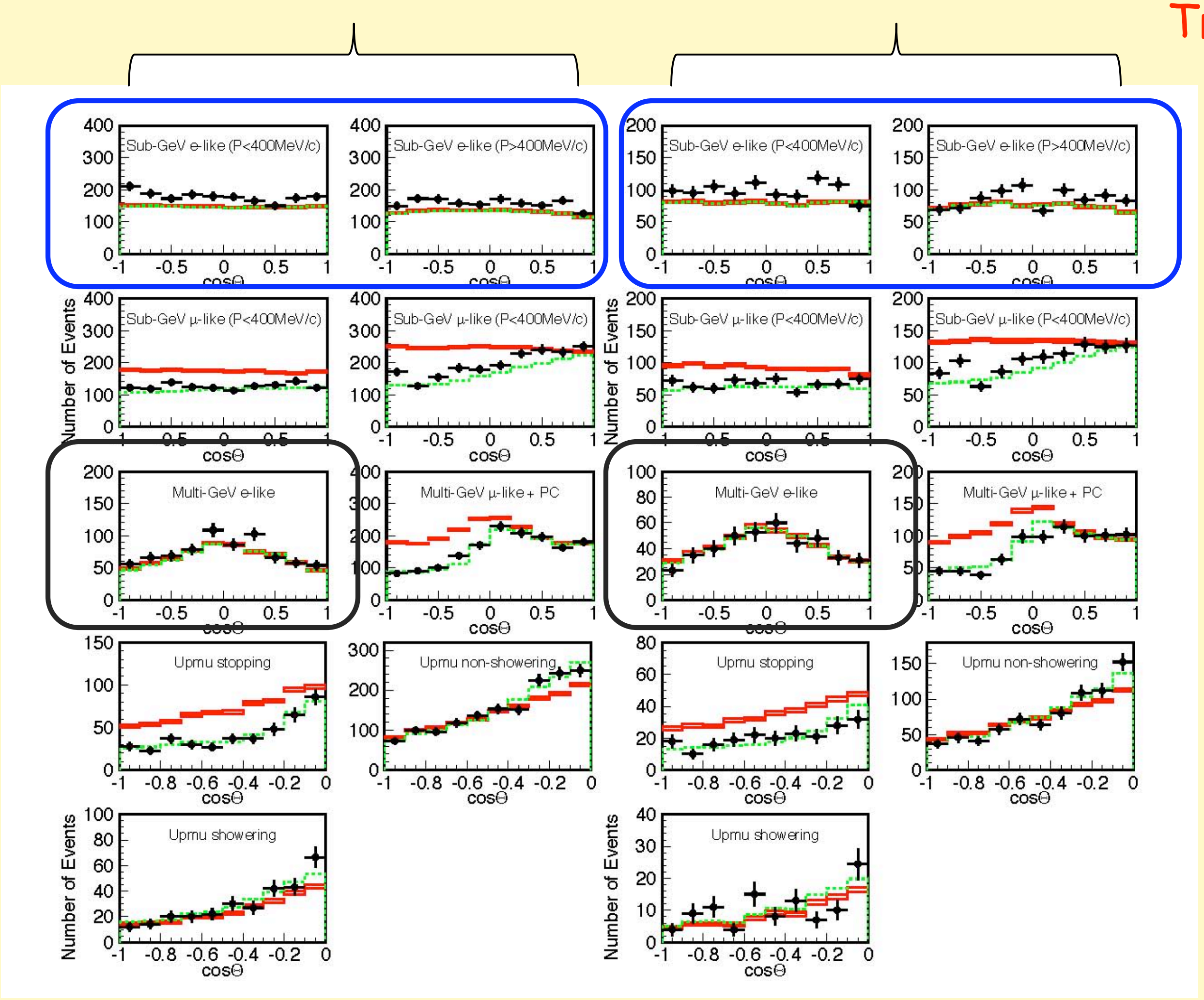
(which are also based on SK-I data), do not find any atmospheric hint. However, they set $dm^2 = 0$ a priori for simplification. Thus, they miss two of the three subleading terms, and their results cannot be directly compared with ours.

The atmospheric three-neutrino analyses in

- Roa. Latimer, Ernst 0904.3930
- Gonzalez-Garcia & Maltoni, arXiv 0704.1800
- Maltoni & Schwetz (arXiv:0808.2016)

do include all terms. However: the first finds a hint, the second not, the third maybe – or maybe not, depending on details and on the dataset.
-> The atmospheric hint is "fragile" and can only be tested in detail by the SK collaboration, using all their data and a full three-flavor analysis.

SK-I data   SK-II data



(zenith distributions from Takenaga PhD thesis, 2008)

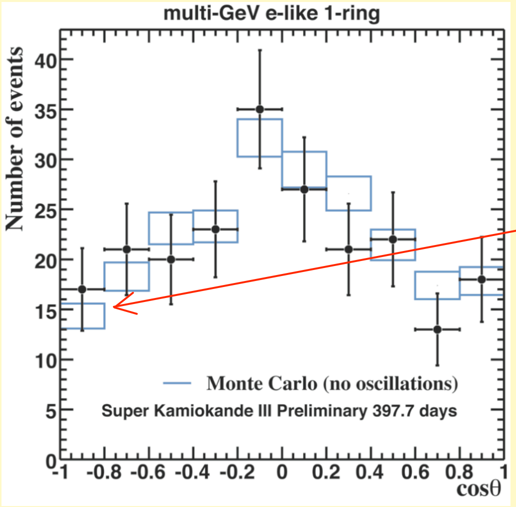
Trend from SK-I to SK-II:

Sub-GeV electron excess persists in both phases I and II

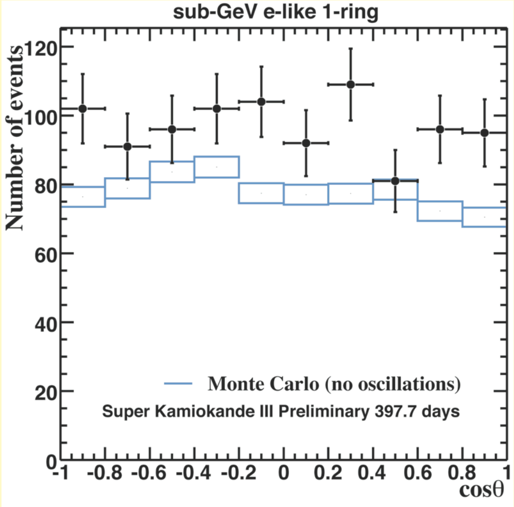
Slight excess of upgoing Multi-GeV electrons in SK-I but <u>not</u> in SK-II

This downward MGe fluctuation may disfavor $\theta_{13}>0$ (as noted by Maltoni and Schwetz)

… However …



...in **SK-III** data, a slight excess of upgoing MGe seems to be back...



...together with a persisting excess of SGe data!

(SK-III data, from
J. Raaf at Neutrino 2008)

Can all this be explained away by statistical fluctuations + systematic uncertainties?

The answer requires a refined statistical analysis

SK-I+II Collaboration analysis currently includes:

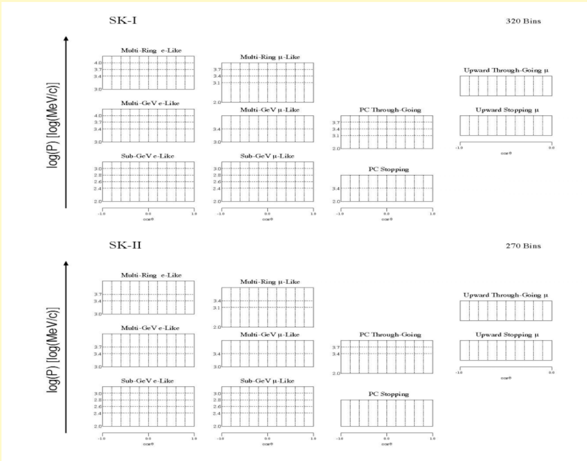


Figure 8.5: Binning for SK-I (top) and SK-II (bottom) for each of the ten samples used in the analysis. SK-I has a total of 320 bins and SK-II has 270.

R. Wendell thesis, 2008

- 320+270 energy-angle bins for SK-I + SK-II
- 20+26+20 sources of systematics for SK-I +II
  (26 being **common** to both phases)

handled within the so-called "pull method"
(that we advocated in hep-ph/0206162 and hep-ph/0303064)

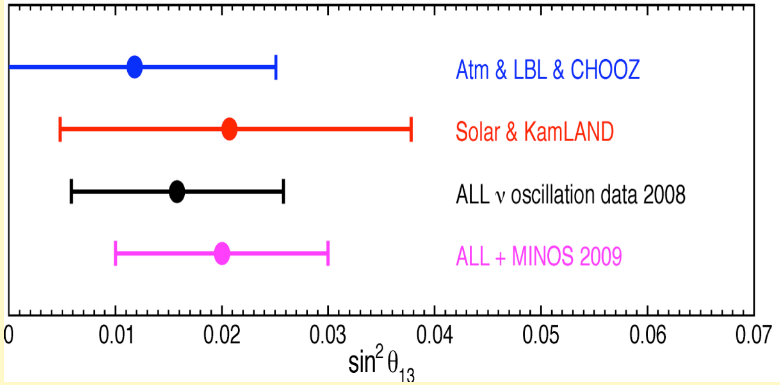
Such a level of refinement, with ~600 bins and ~70 systematics, partly shared in SK-I+II, is difficult to be reproduced in detail outside the SK collaboration.

Independent analyses of atmospheric data searching for small effects (or hints) at the level of ~1 sigma, like ours, are thus getting harder and harder to perform.

Therefore, it will be very important to see the next official SK data release and especially the official SK oscillation analysis, hopefully including a complete treatment of 3flavor oscillations with both $dm^2 > 0$ and $\theta_{13} > 0$, and possibly including SK-III (+…?) data besides SK-I+II.

In the meantime, we do not have yet compelling reasons to revise our 0.9 sigma hint of $\theta_{13}>0$ obtained from published SK-I data, although it may have, admittedly, a more fragile status than the ~ 1.2 sigma hint from the analysis of solar + KamLAND data.

Anyway, the situation is not static. New data/analyses with impact on $q_{13}>0$ hints might be presented in less than one month at TAUP'09 (Rome) if blessed by the collaborations:



New 3ν SK analysis?
New 3ν SNO analysis?

Conclusions

In the last decade, beautiful neutrino territories have been discovered and charted with increasing accuracy…

… We are now sailing towards unknown lands, to find the key to very old questions – or surprising new challenges!

Extra slide
Hierarchy effects in SK data analysis