I.S.N.P., 31st Course   Erice, Sep. 19, 2009

Analysis of ν mass, mixing and flavor change

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Mainly based on the following papers:
0805.2517, 0806.2649, 0808.0807, 0810.5733, 0905.1832, 0905.3549

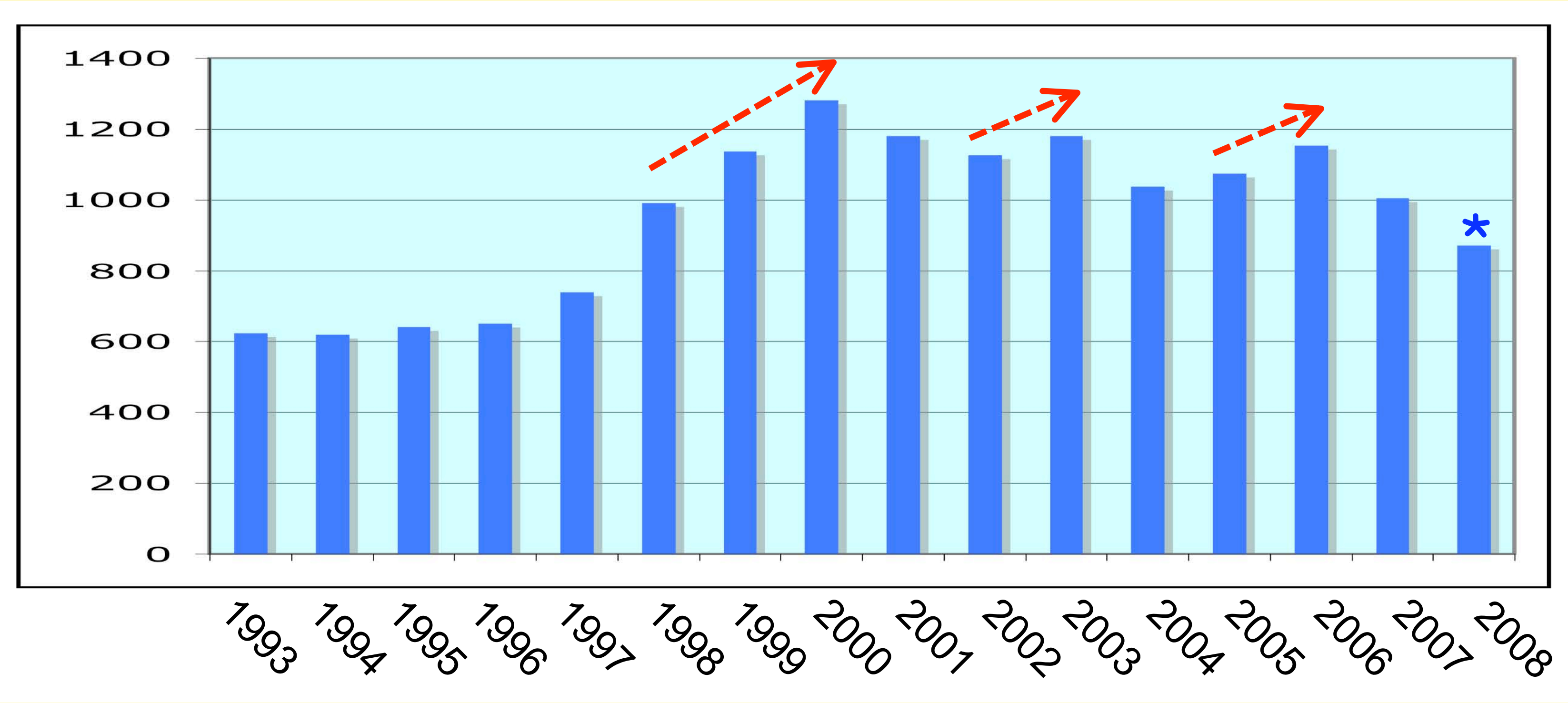
Interest in ν physics remains very high, with about 10^3 "neutrino(s)" papers/year (on SPIRES database)

Peaks of interest:

Atmospheric ν oscillations,
Limit from CHOOZ

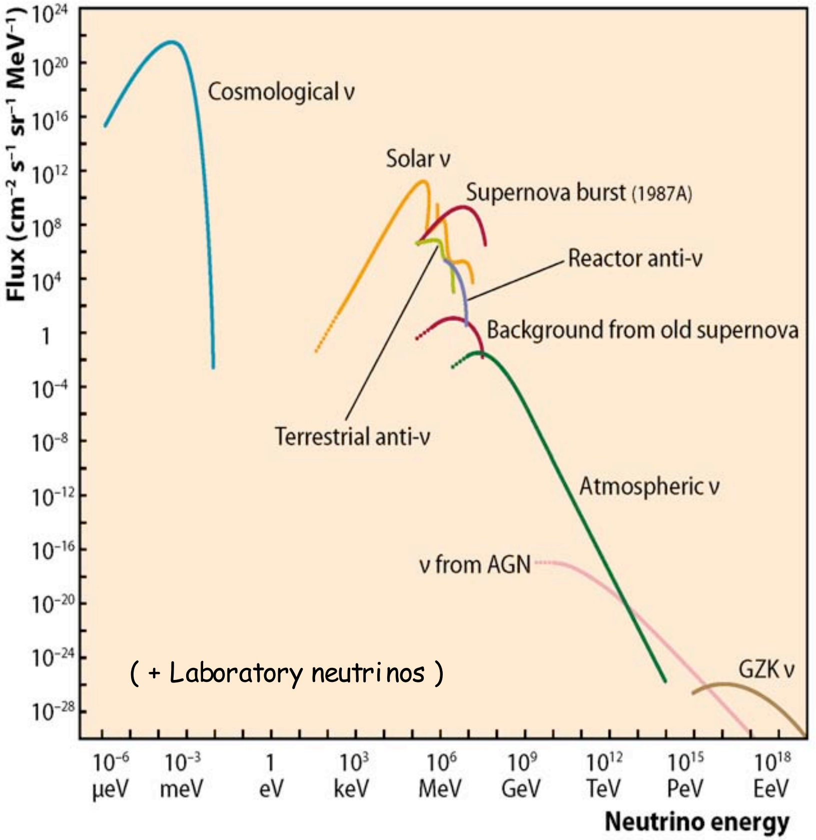
Solar and reactor ν oscillations,
Nobel 2002 to Davis & Koshiba

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).

But, of course, we all expect many exciting developments in the physics of neutrino mass, mixing, and flavor change:



(+ Laboratory neutrinos)

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

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

- Flavor appearance (ν_μ->ν_τ, ν_μ->ν_e)
- Mixing between 1st-3rd family
- Mass spectrum hierarchy
- Absolute masses
- Spinorial nature (Majorana/Dirac)
- Leptonic CP violation
- Earth/Astro/Cosmo sources
- Possible new states/interactions
- Links with other LFV processes
- Theoretical "illumination"
- …

In this talk I shall review the current

status of ν mass-mixing parameters

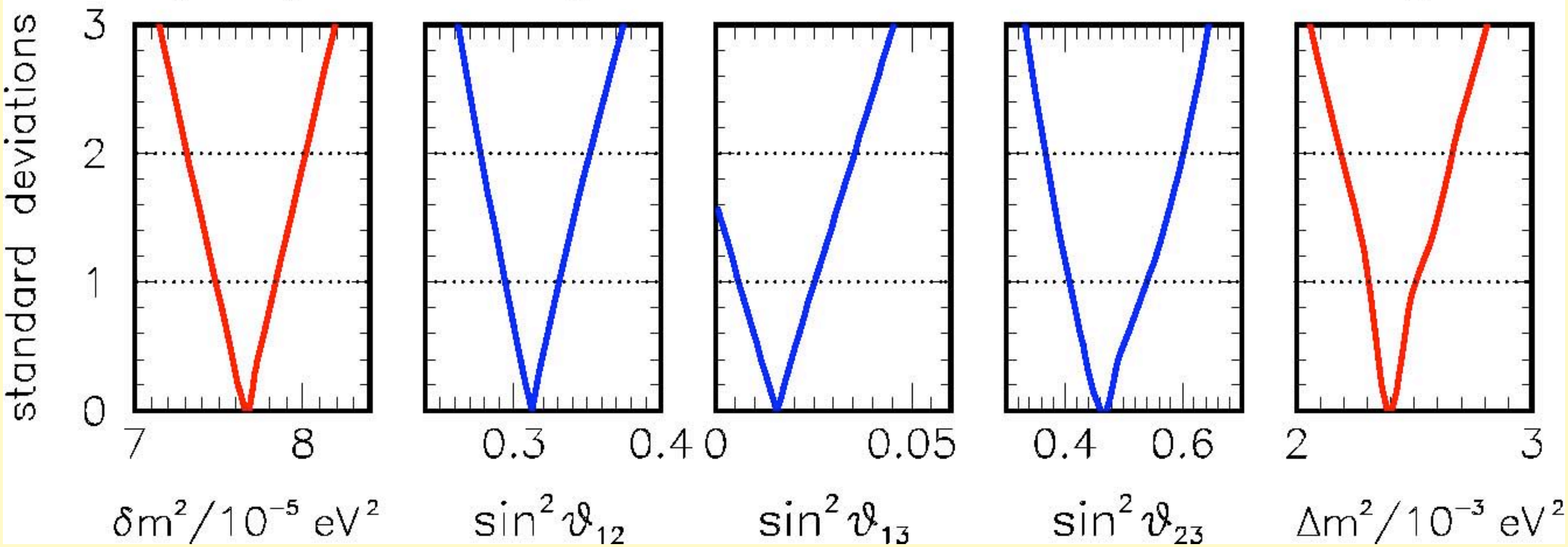
and comment on some issues related to

θ_{13}, $0\nu\beta\beta$, sign(Δm^2)

which may be of near-future interest

Synopsis of neutrino mass^2 and mixing parameters:

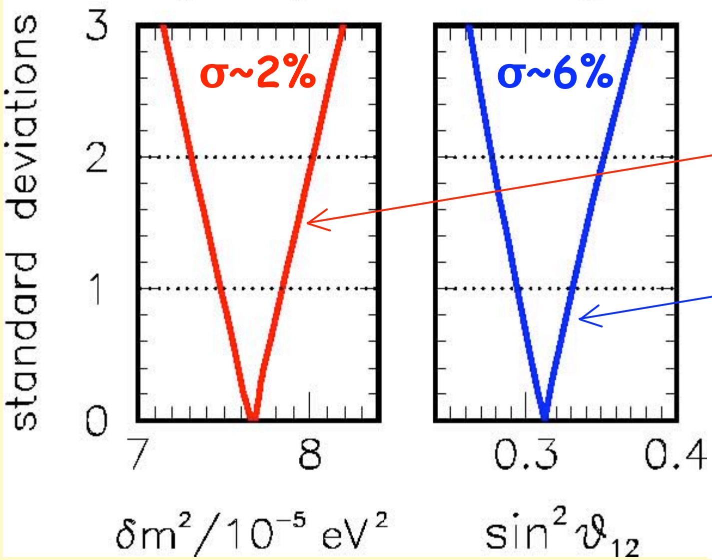
central values and n-σ ranges from global 3ν analysis



(1,2) sector   (1,3)   (2,3) sector

Increasingly precise data: ~linear & symmetric (gaussian) errors

Oscillation parameters in (1,2) sector:



Dominated by KamLAND (reactors)

Dominated by solar (especially by SNO)

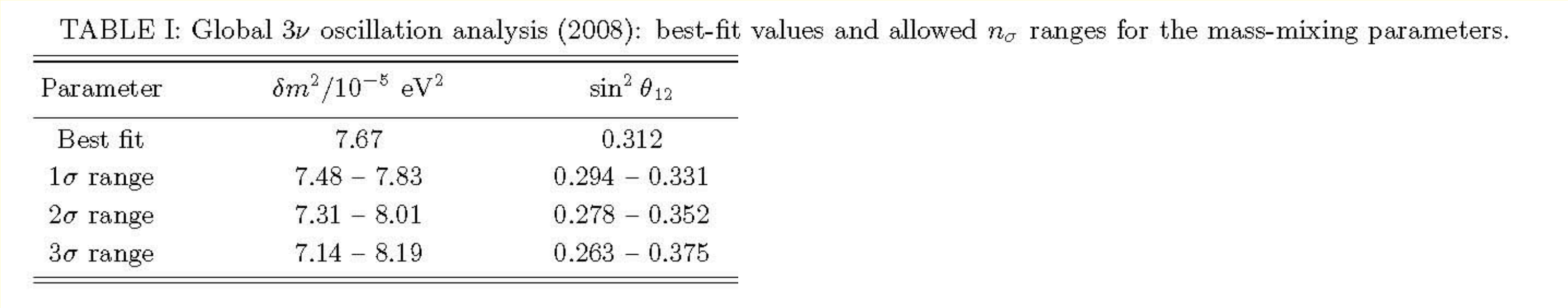
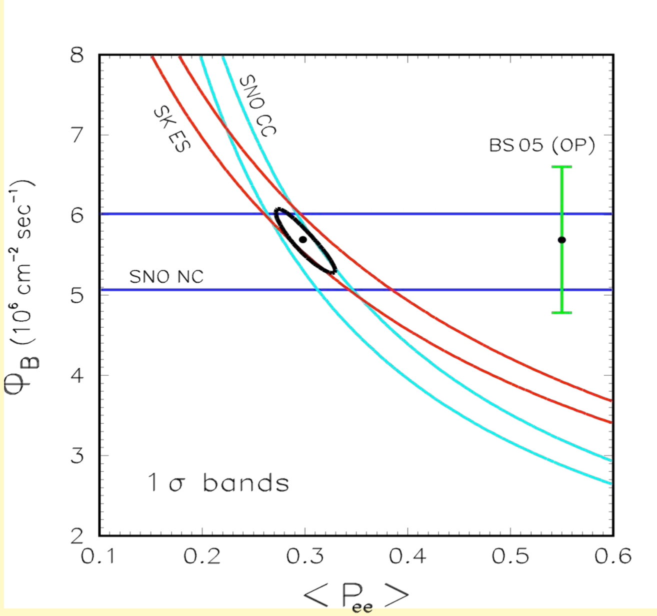


TABLE I: Global 3ν oscillation analysis (2008): best-fit values and allowed n_σ ranges for the mass-mixing parameters.

Parameter	$\delta m^2/10^{-5}$ eV^2	$\sin^2\theta_{12}$
Best fit	7.67	0.312
1σ range	7.48 – 7.83	0.294 – 0.331
2σ range	7.31 – 8.01	0.278 – 0.352
3σ range	7.14 – 8.19	0.263 – 0.375

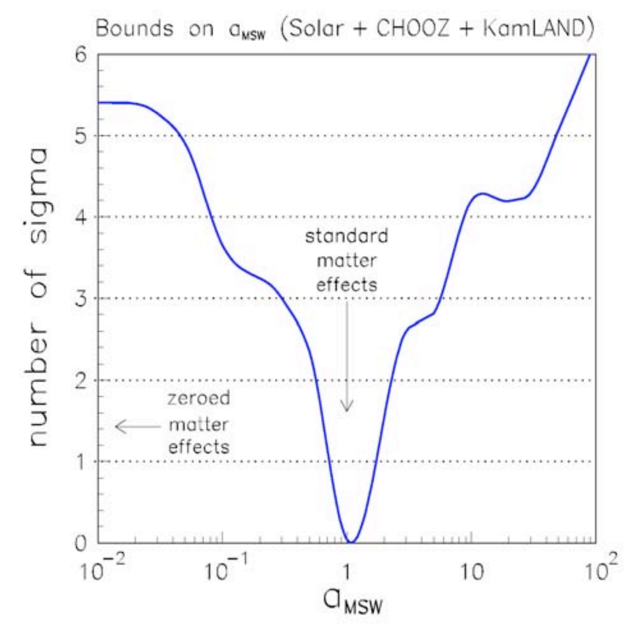
Further results from (1,2) sector (just a few among many others):

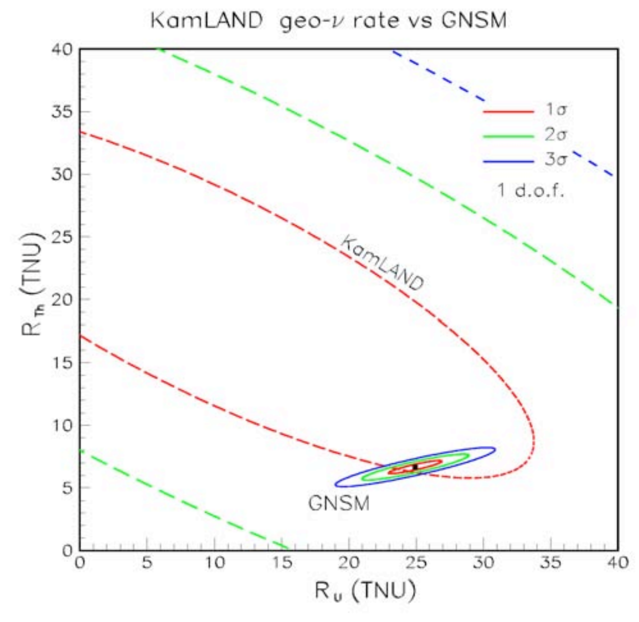
SK-SNO model-ind. analysis



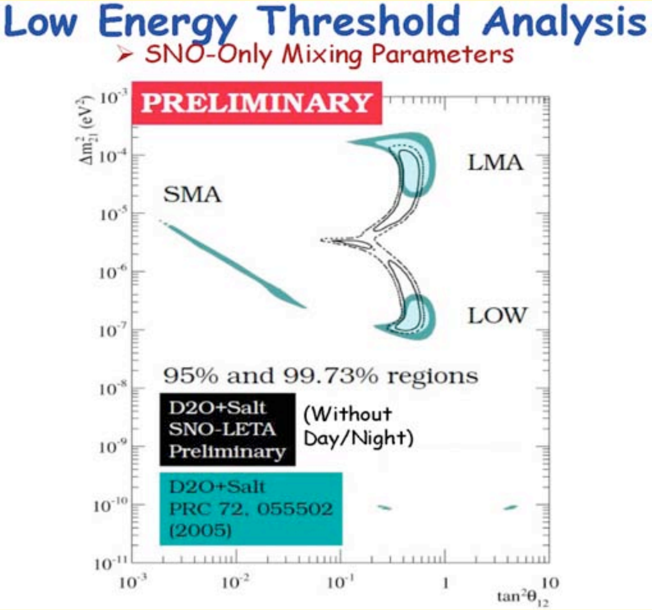
Evidence for geoneutrinos

Evidence for MSW effects





Near-future improvements on θ_{12} (from TAUP'09)

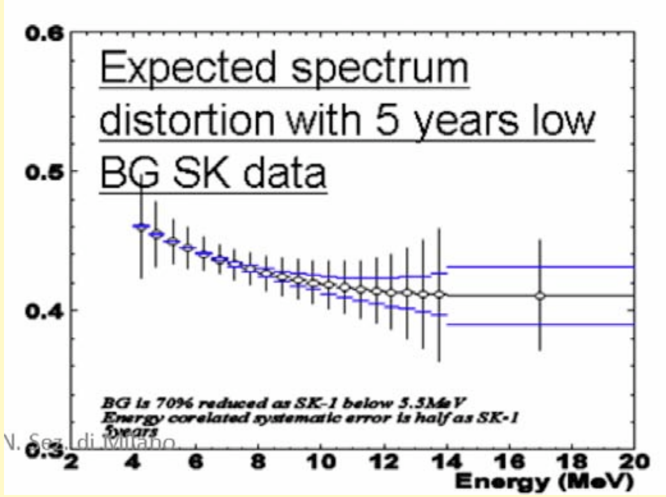


Final results from SNO low-energy threshold analysis (LETA) imminent.

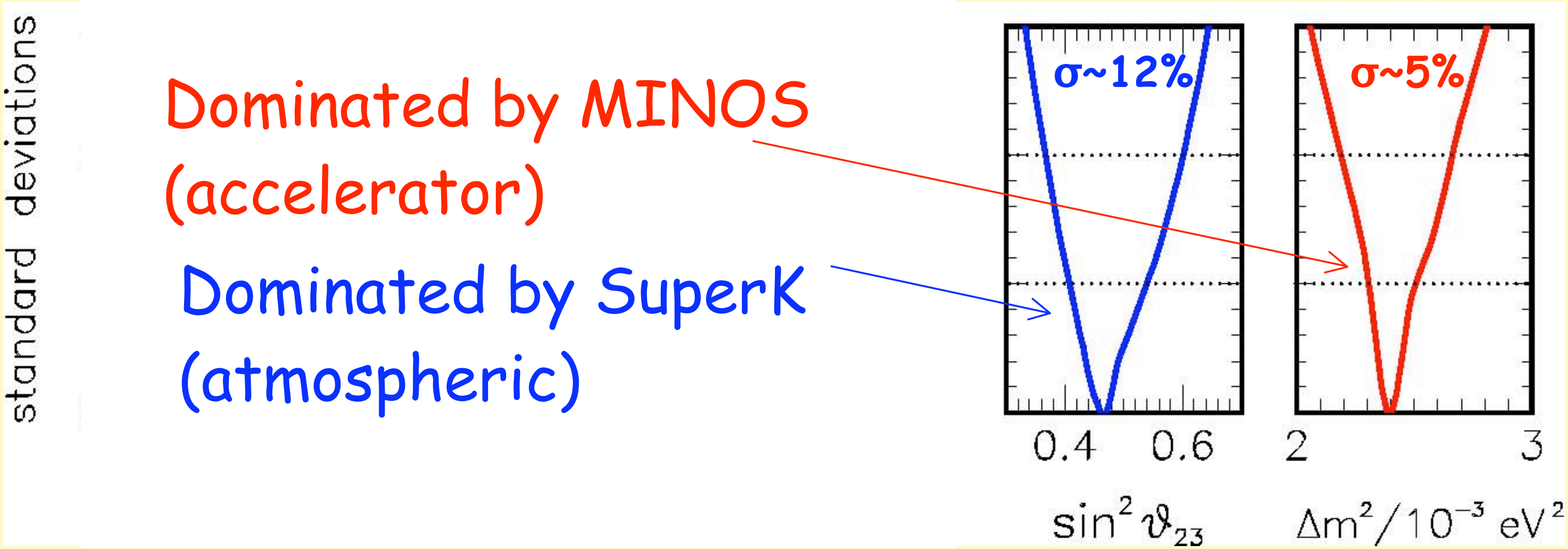
Preliminary results seem to suggest a preference for relatively low values of θ_{12} in the SNO-LETA → Possible implications for θ_{13}

Low-E analysis also in progress in SK →

SK & SNO expected to probe the expected LMA spectrum upturn at low energy.



Oscillation parameters in (2,3) sector:



Dominated by MINOS (accelerator)

Dominated by SuperK (atmospheric)

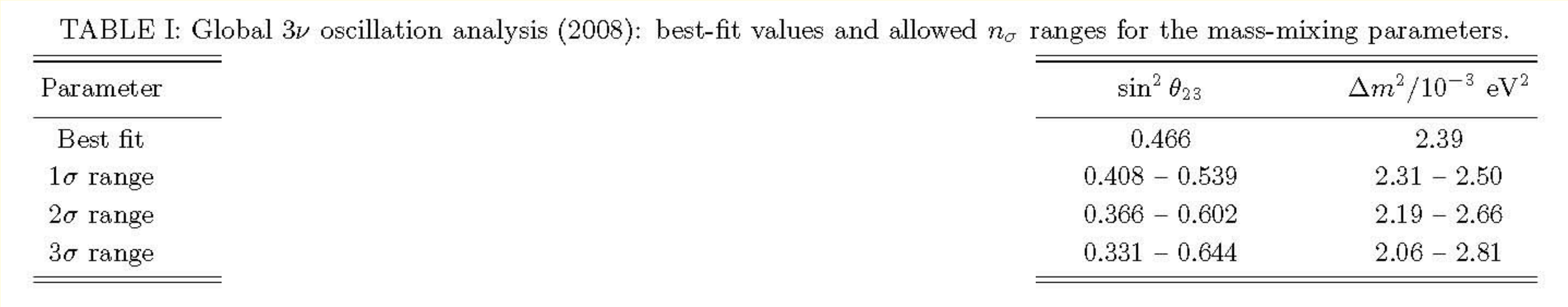


TABLE I: Global 3ν oscillation analysis (2008): best-fit values and allowed n_σ ranges for the mass-mixing parameters.

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%**, comparable to **$\sigma(\Delta m^2)$ ~5%**

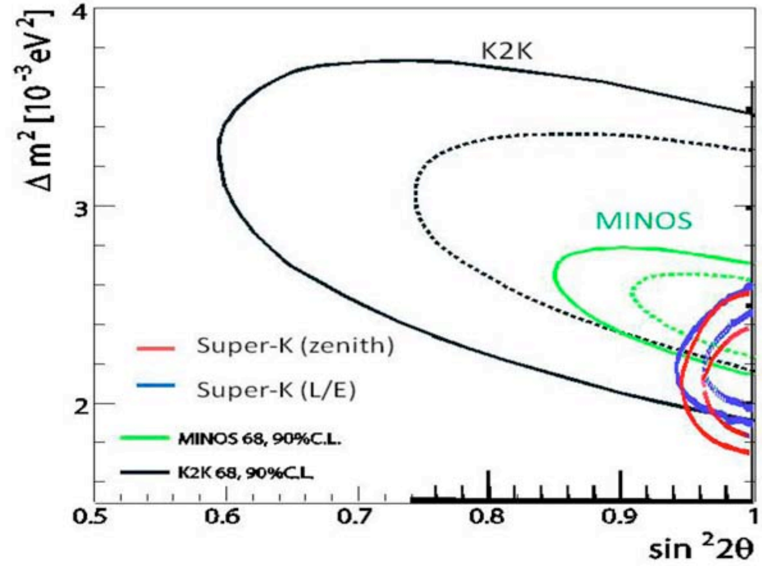
Desiderata: For the sake of precision, future official analyses should adopt a full 3ν framework, rather than 2ν approximations.

Unambiguous definition of "atmospheric" **Δm^2** is then required.

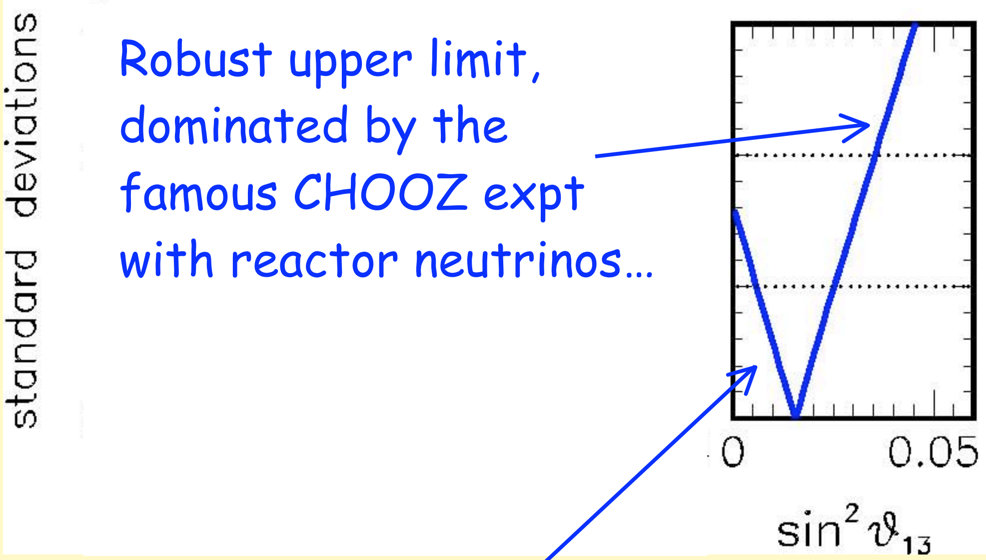
Our convention: $\Delta m^2 = \left|\frac{\Delta m^2_{31} + \Delta m^2_{32}}{2}\right| = \left|m_3^2 - \frac{m_1^2 + m_2^2}{2}\right|$

so that: $\begin{cases} \Delta m^2_{13} = \pm\Delta m^2 + \frac{\delta m^2}{2} \\ \Delta m^2_{23} = \pm\Delta m^2 - \frac{\delta m^2}{2} \end{cases}$ (NH/IH sign flip)

Latest accelerator and SK-I+II+III constraints within 2ν approximation (Kajita @ TAUP'09):



(1,3) sector: the smallest mixing angle



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

Will be improved by Double-CHOOZ + … in the near future

However, some datasets may suggest two hints of lower limits…

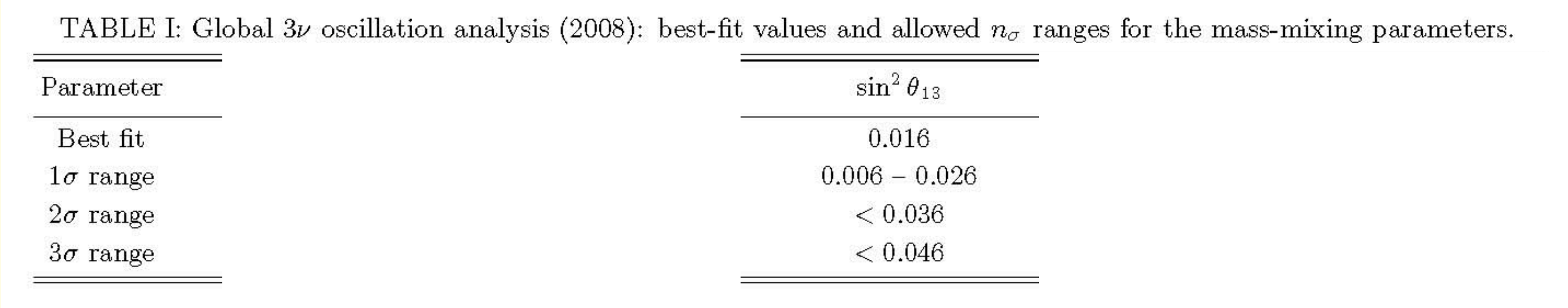
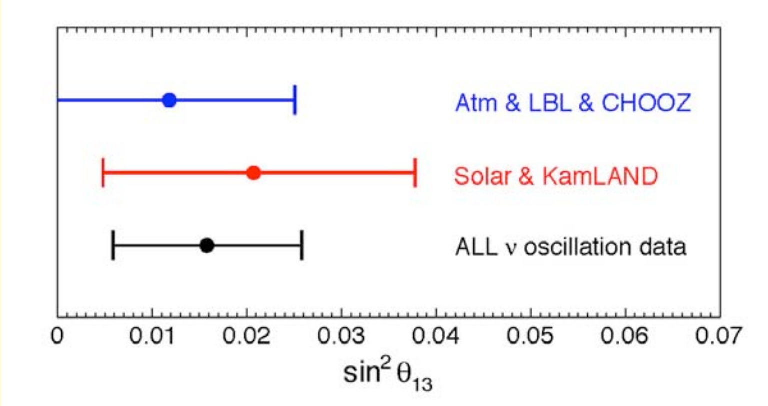


TABLE I: Global 3ν oscillation analysis (2008): best-fit values and allowed n_σ ranges for the mass-mixing parameters.

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

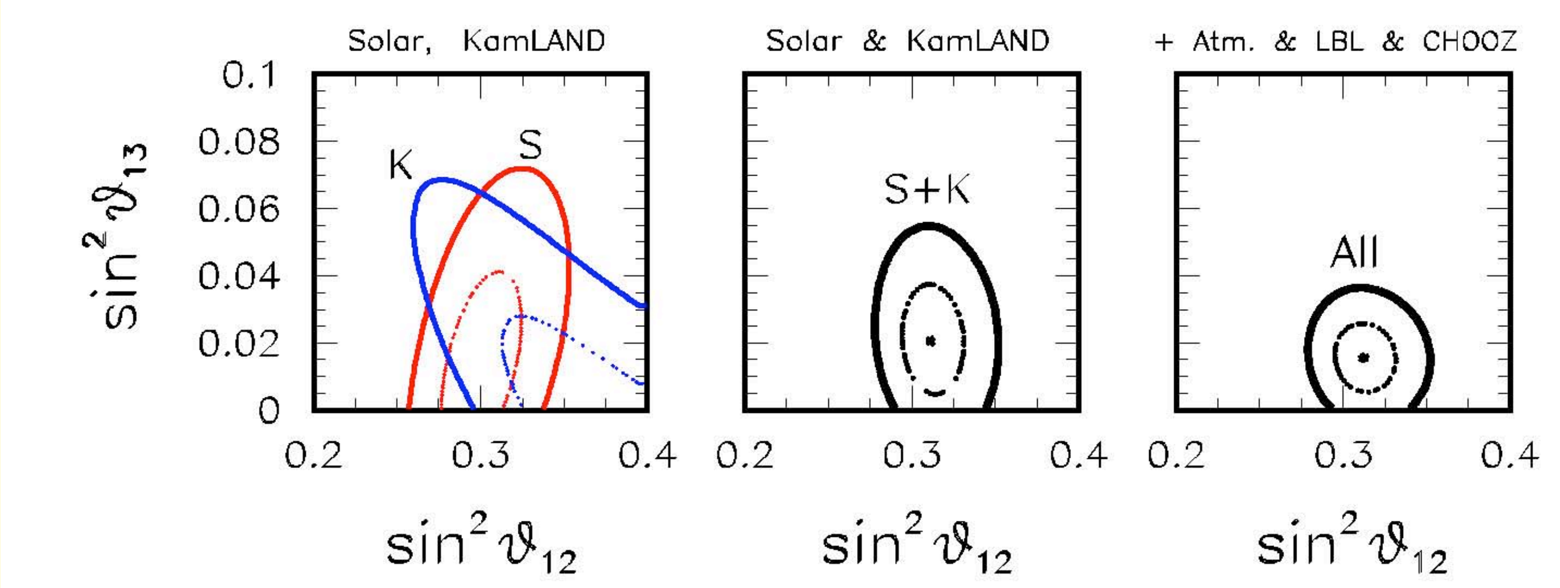


~1σ from sector (2,3) - “old”

~1σ from sector (1,2) - “new”

~90% CL total:

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



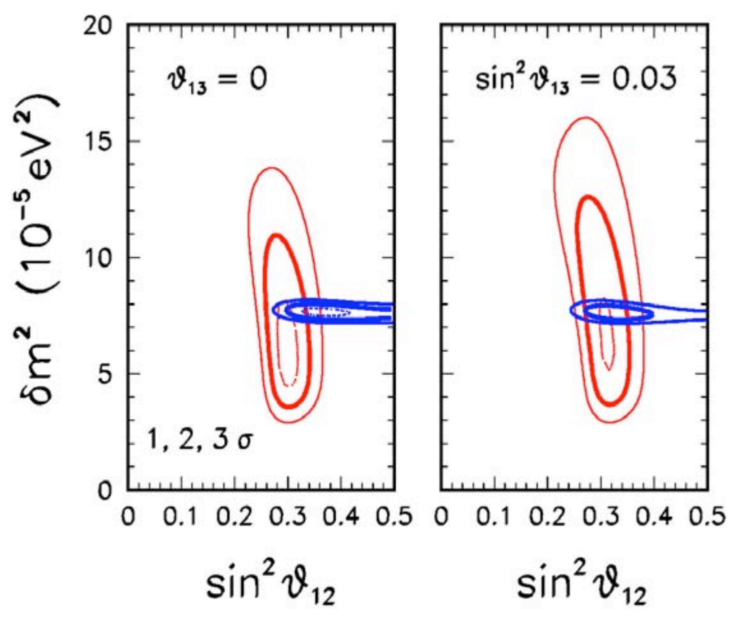
"New" hint arises from slight tension on θ_{12} (solar vs KamLAND) and from different correlation bewteen mixing angles, related to different relative signs in P_{ee} (survival probability) of solar vs KamLAND:

Solar, high energy (~MSW):

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

Reactor (~vacuum): KamLAND

$$P_{ee} \simeq (1 - \underset{-}{2s^2_{13}})(1 - \underset{-}{4s^2_{12}c^2_{12}} \sin^2(\delta m^2 L/4E))$$

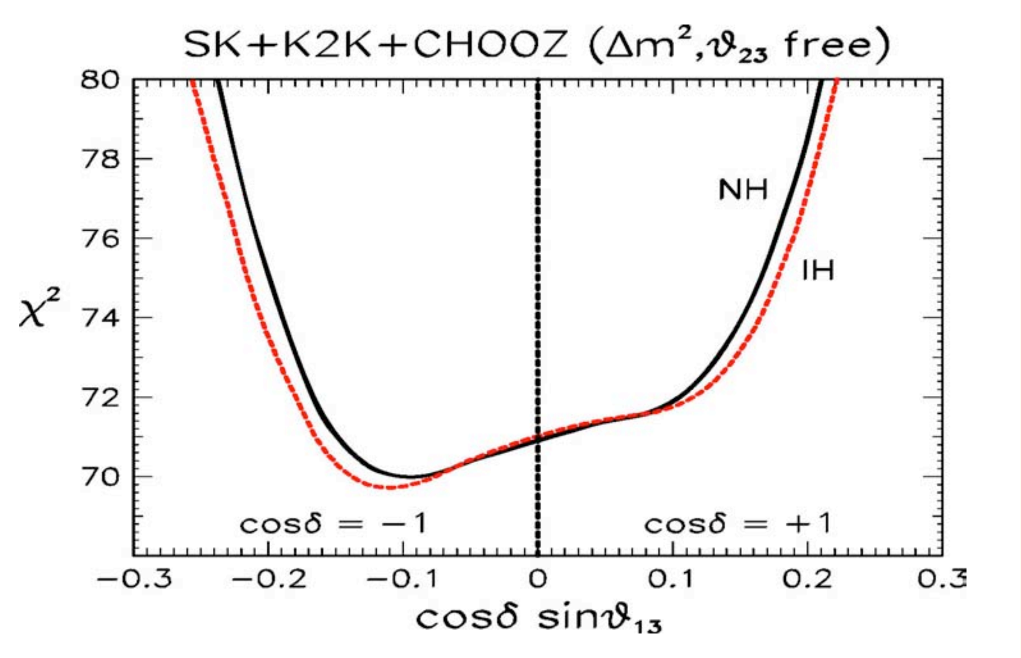


Slight "tension" on θ_{12} can be reduced for $\theta_{13}>0$

"Old" θ_{13} hint from atmospheric data - remarks

Weak hint for $\theta_{13} > 0$ from atmospheric + LBL + Chooz data (Bari group, 2006), at the level of ~1 sigma. **Results as presented by E.L. at Erice ISNP'05:**

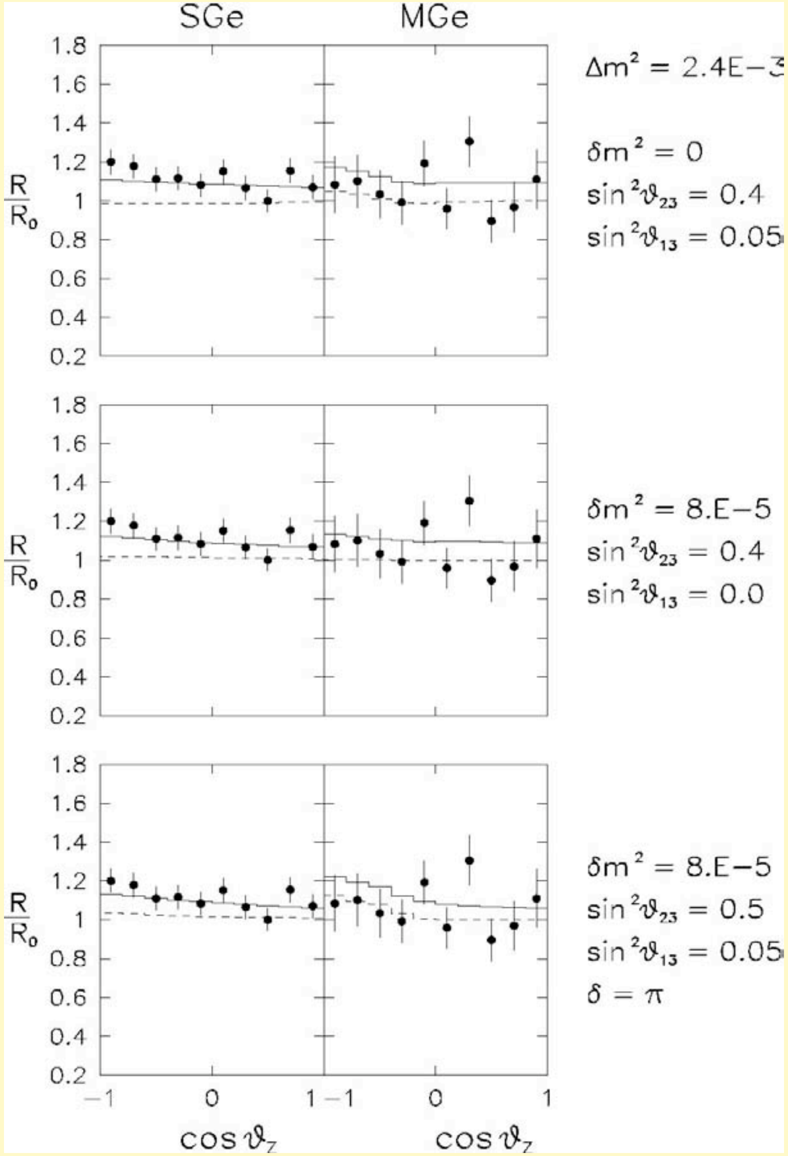
"



Slight preference (<1σ) for $s_{13} \neq 0$ and $\delta = \pi$ (over $\delta = 0$) driven by atmospheric electron neutrino data

Very tiny difference at $s_{13} = 0$ (entirely due to $\delta m^2 > 0$) "

Three selected examples in sub- and multi-GeV SK electron samples



δm^2 off, θ_{13} on

δm^2 on, θ_{13} off

δm^2 on, θ_{13} on

(*Dashed: central values*
Solid: +system. shifts)

Effects often smaller than stat+syst errors in each bin; need global fits to large datasets

We attributed the preference for $\theta_{13}>0$ to “solar term” interference effects (δm^2 on & θ_{13} on), which seem to help the fit of sub-GeV e-like data in SK-I.

[Hint is NOT killed by adding K2K and MINOS disappearance data.]

But, other analyses found weaker or no atmospheric hint (Note: not all of them include solar terms). Such “old” hint seems to be still fragile.

The “last word” can only be expected from the Super-K collaboration, since their atm. data analysis is becoming too difficult to be reproduced at the needed level of accuracy (hundreds of bins, dozens of systematics).

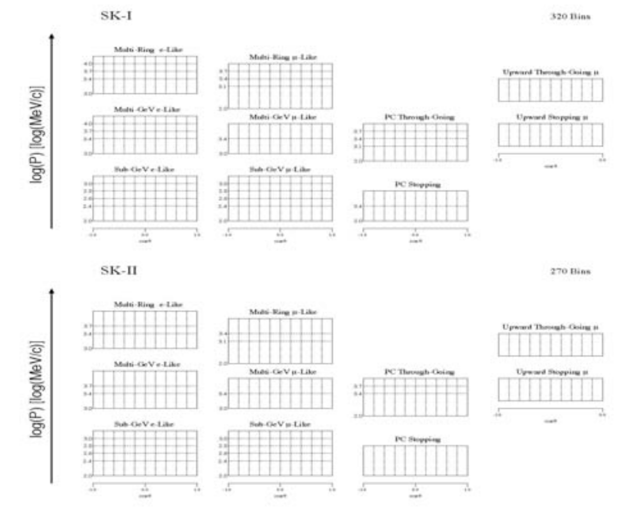
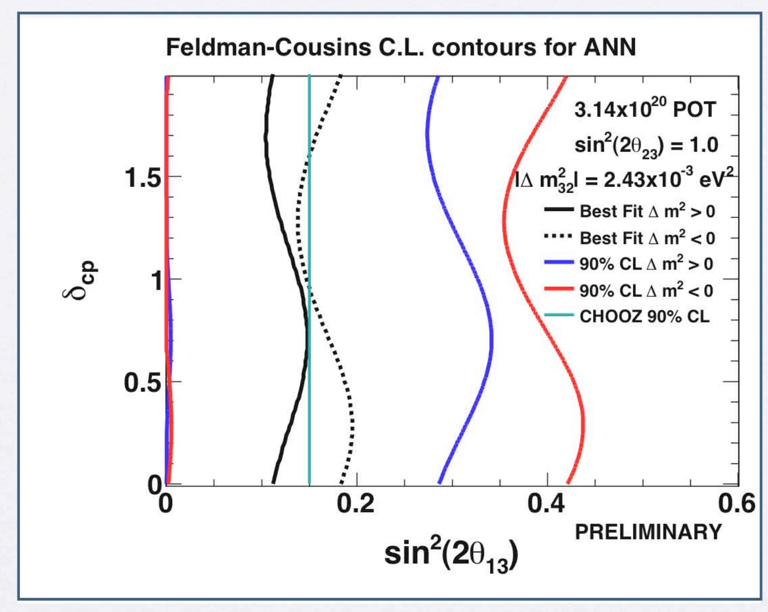
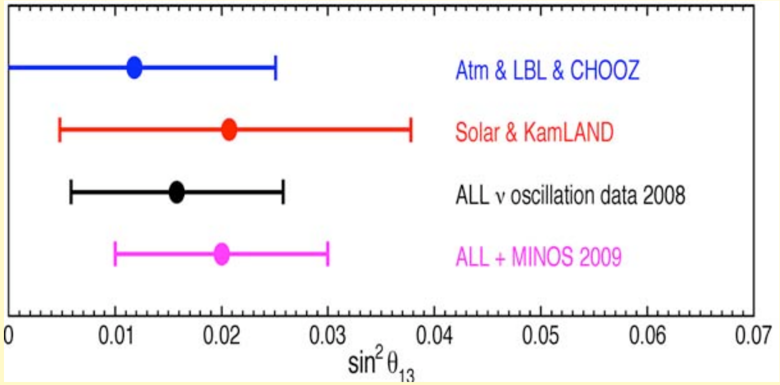


Figure 8.5: Binning for SK-I (top) and SK-II (bottom) for each of the ten samples used in the analysis. SK-I has a total of 320 bins and SK-II has 270.

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.

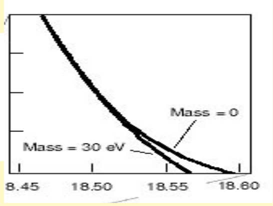
(N.B.: MINOS, SK, SNO, KamLAND can still provide further improvements)

Absolute neutrino mass issues.

Three probes: (m_β, $m_{\beta\beta}$, Σ). In first approximation:

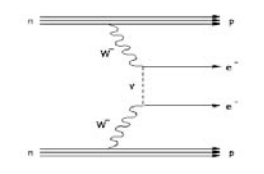
1) **Single β decay**: $m^2_i \neq 0$ alters the spectrum tail. Sensitive to the so-called "effective mass of electron neutrino":

$$m_\beta = \left[c^2_{13}c^2_{12}m^2_1 + c^2_{13}s^2_{12}m^2_2 + s^2_{13}m^2_3\right]^{\frac{1}{2}}$$



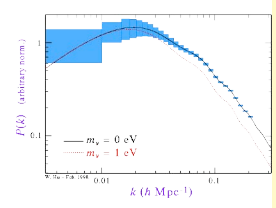
2) **Double 0νββ decay:** Iff $m^2_i \neq 0$ and ν=anti-ν (Majorana). Sensitive to the "effective Majorana mass" (and related phases):

$$m_{\beta\beta} = \left|c^2_{13}c^2_{12}m_1 + c^2_{13}s^2_{12}m_2e^{i\phi_2} + s^2_{13}m_3e^{i\phi_3}\right|$$

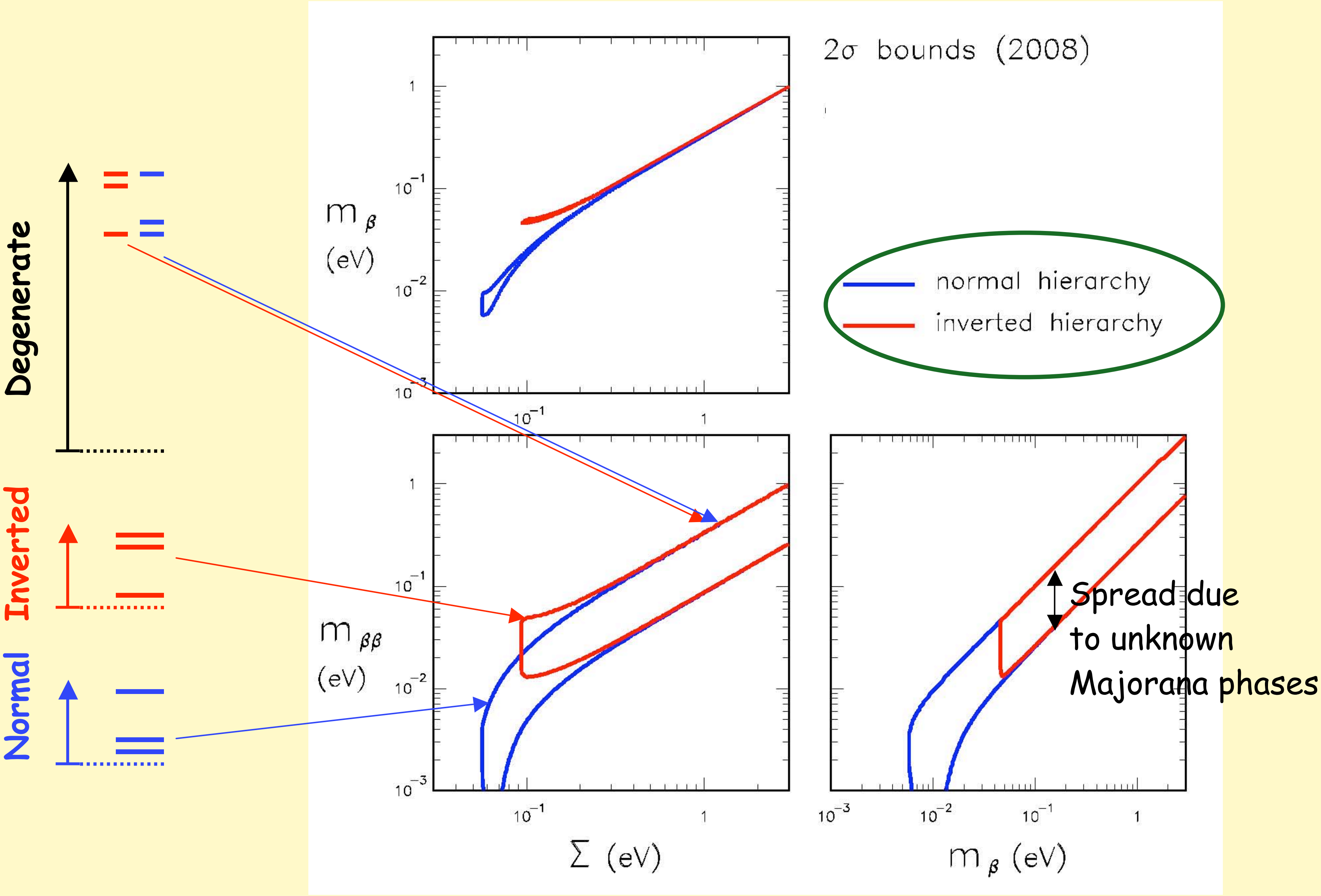


3) **Cosmology**: $m^2_i \neq 0$ alters large scale structure formation within standard cosmology constrained by CMB + other data. Measures:

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



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



Spread due to unknown Majorana phases

Current nonoscillation data mainly provide upper bounds in these planes. How would positive signals look like?

Let's entertain the possibility that the "true" masses are just around the corner… For instance, that neutrinos are Majorana, with nearly degenerate mass values as high as:

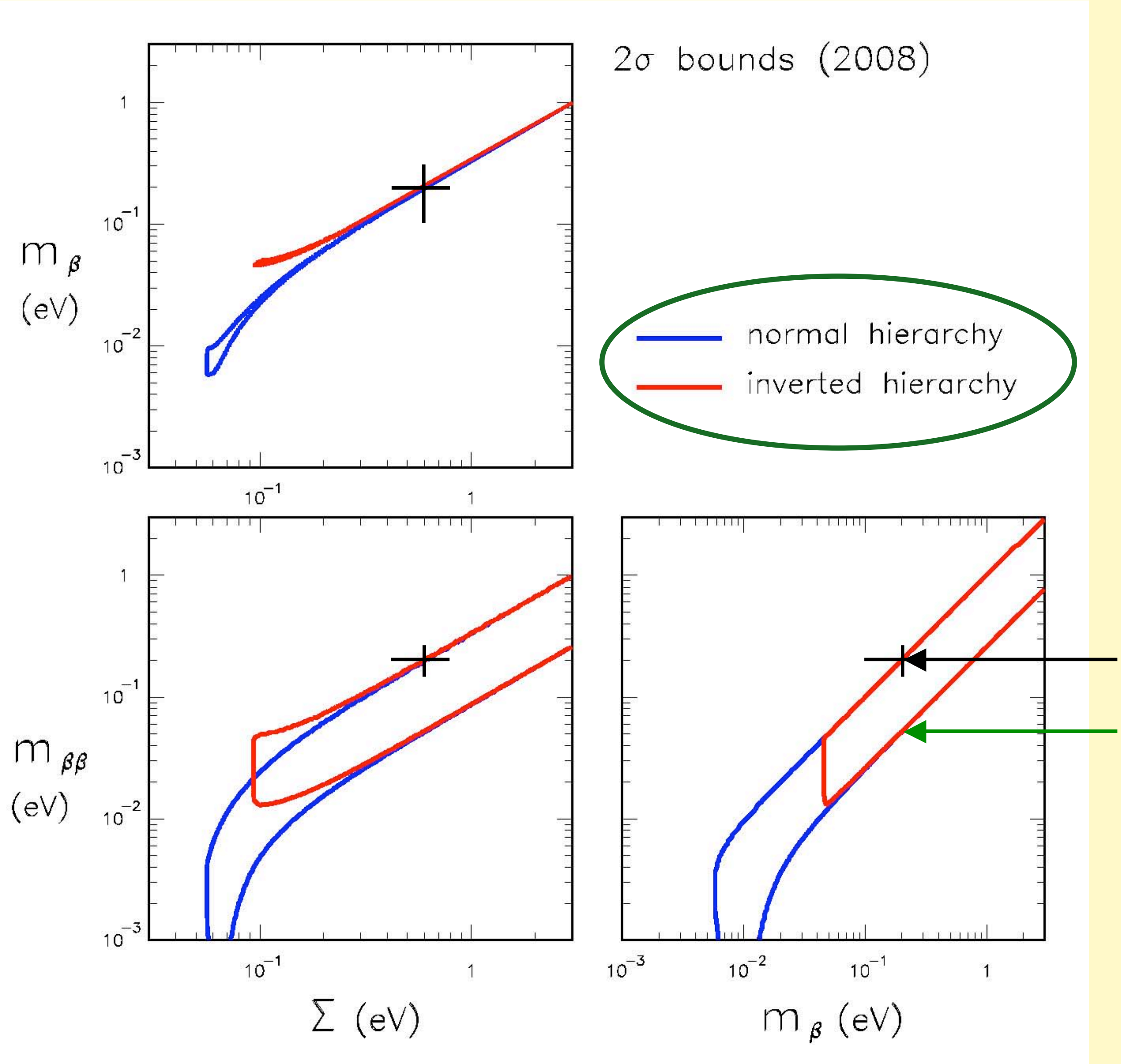
$$\mathbf{m_1 \sim m_2 \sim m_3 \sim 0.2\ eV\ \ .}$$

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

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

In which case…

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



$\exp(i\phi_2) = +1$

$\exp(i\phi_2) = -1$
(disfavored)

Q.: Can the crucial (theoretical NME) error on $\mathbf{m}_{\beta\beta}$ be reduced by exploiting half-life data in different nuclei?

A.: NO, because typical NME uncertainties are highly correlated !

E.g., if the NME "scale up" in each i-th nucleus,

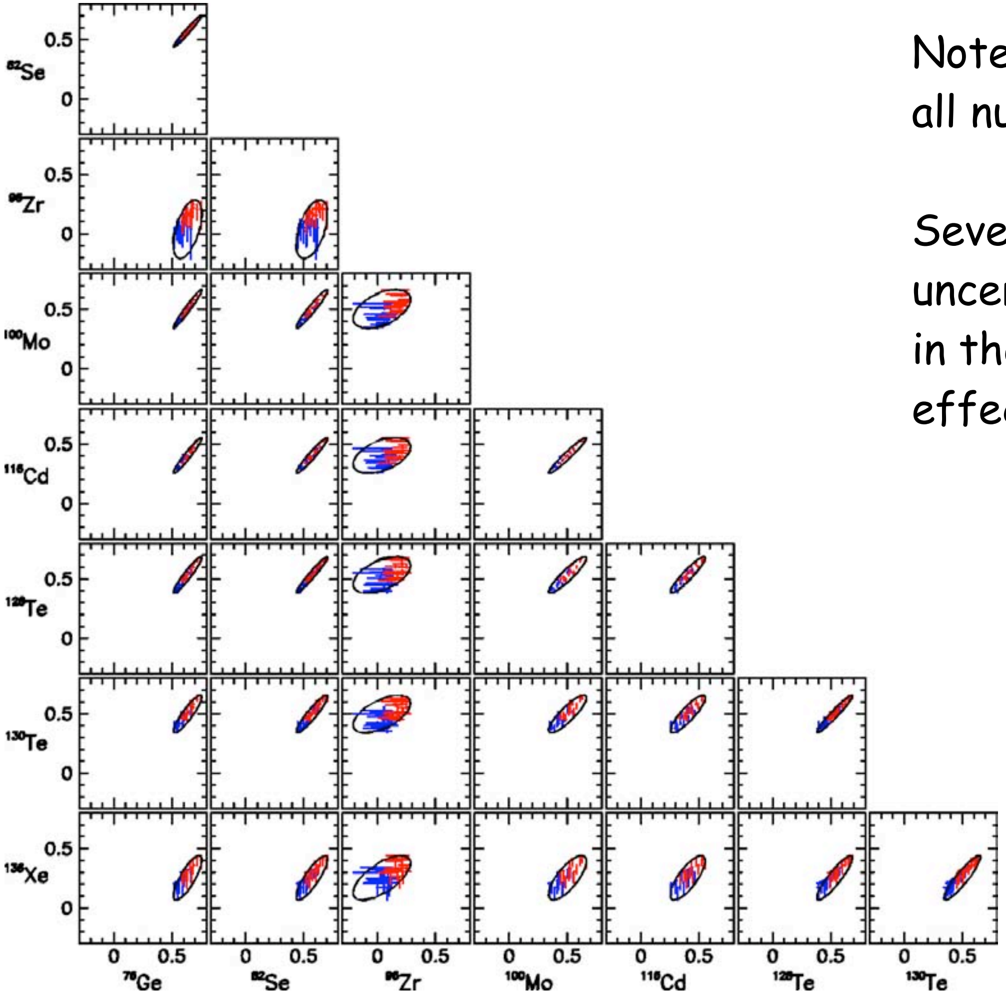
$$T_i^{-1} = G_i\,|M'_i|^2{\uparrow}\,m^2_{\beta\beta}$$

an opposite rescaling of $m_{\beta\beta}$ leaves all half-lives T_i unchanged,

$$T_i^{-1} = G_i\,|M'_i|^2{\uparrow}\,m^2_{\beta\beta}{\downarrow}$$

Thus, smallest $m_{\beta\beta}$ error is set by the smallest NME error (currently ~30%), no matter how many half-life data are used.

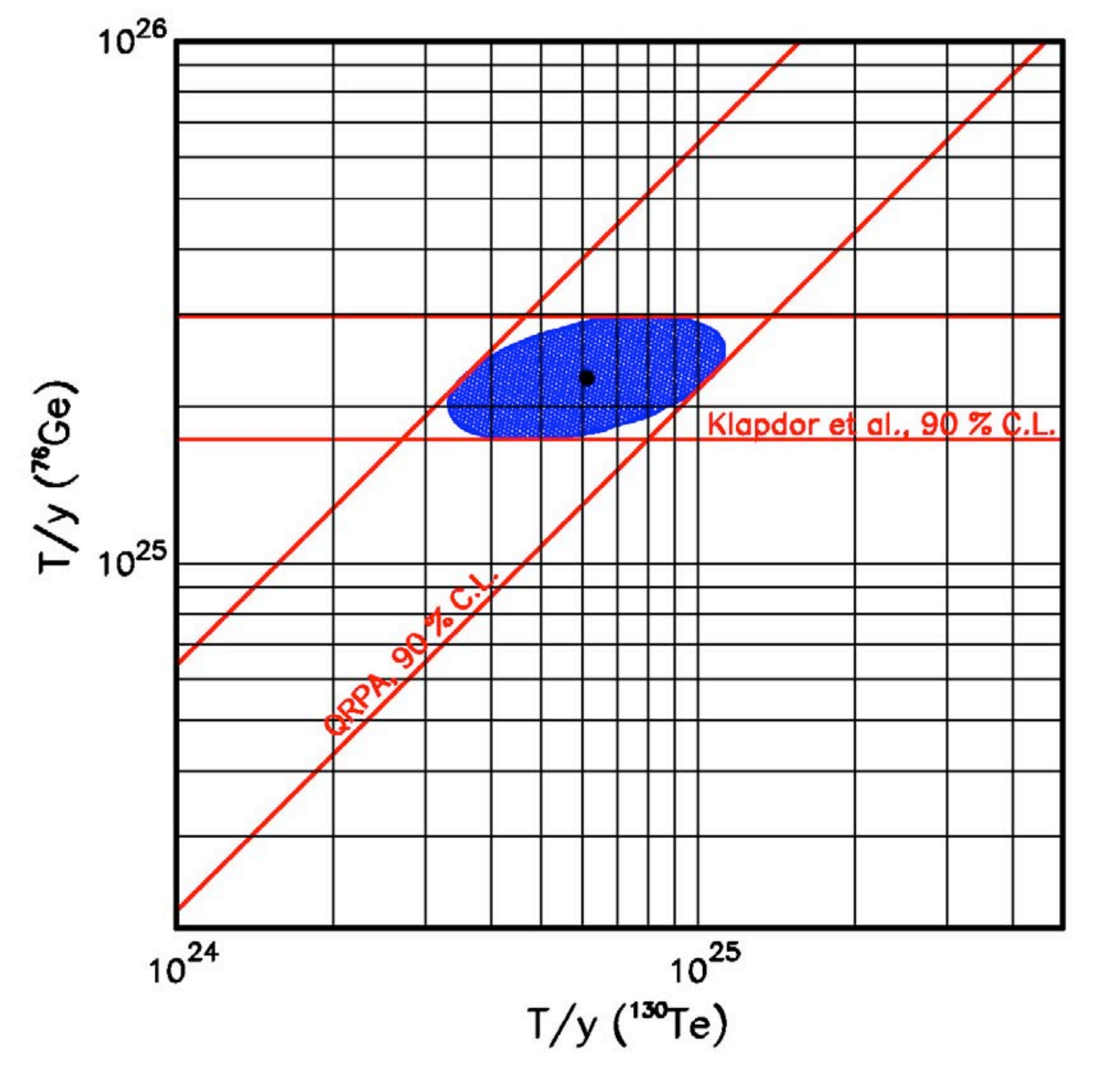
QRPA (Tuebingen): Errors and correlations for $\eta=\log|M'|$



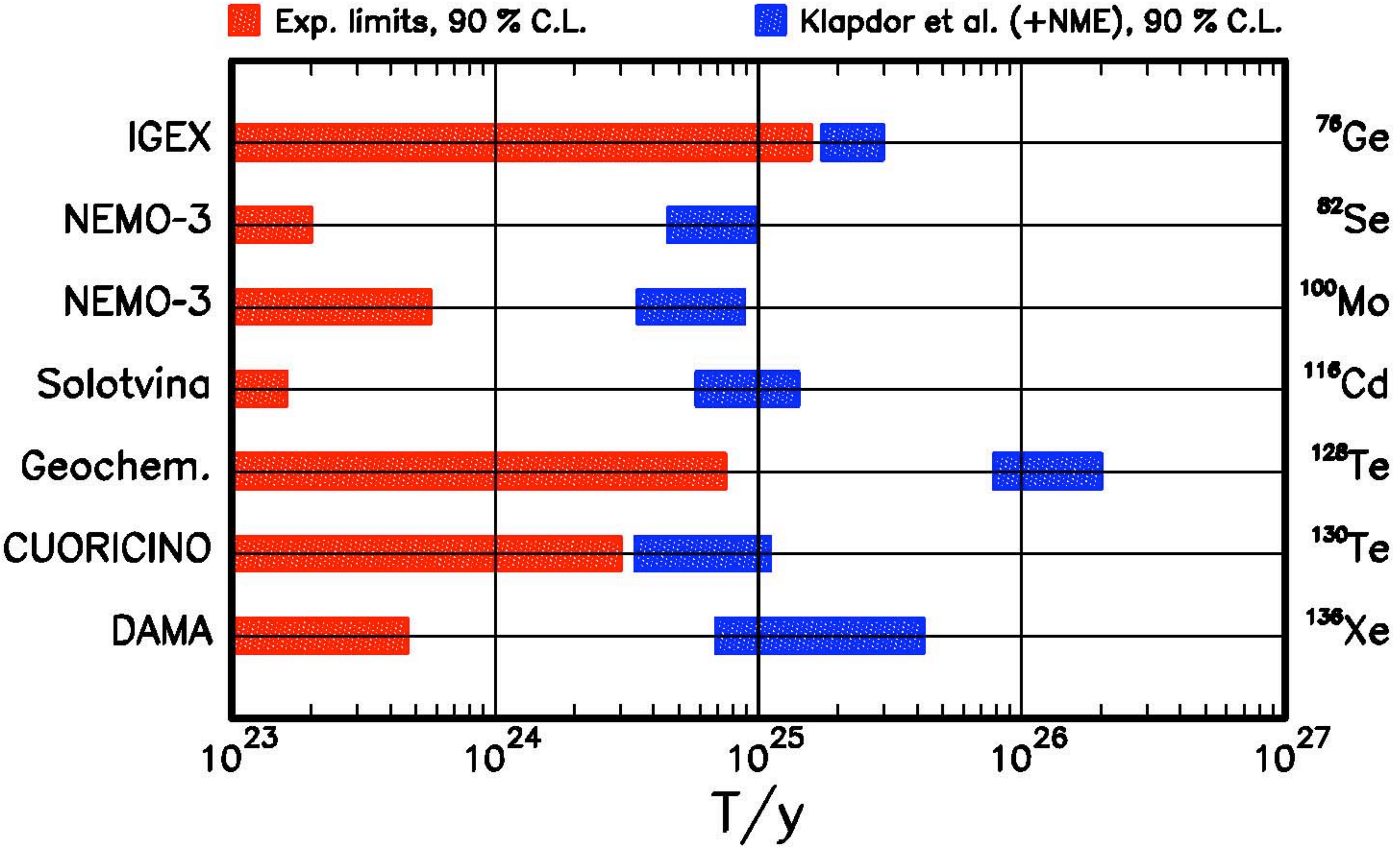
Note strong covariances among all nuclear matrix elements.

Several sources of theoretical uncertainties affect all nuclei in the same direction (e.g., the effective value of g_A)

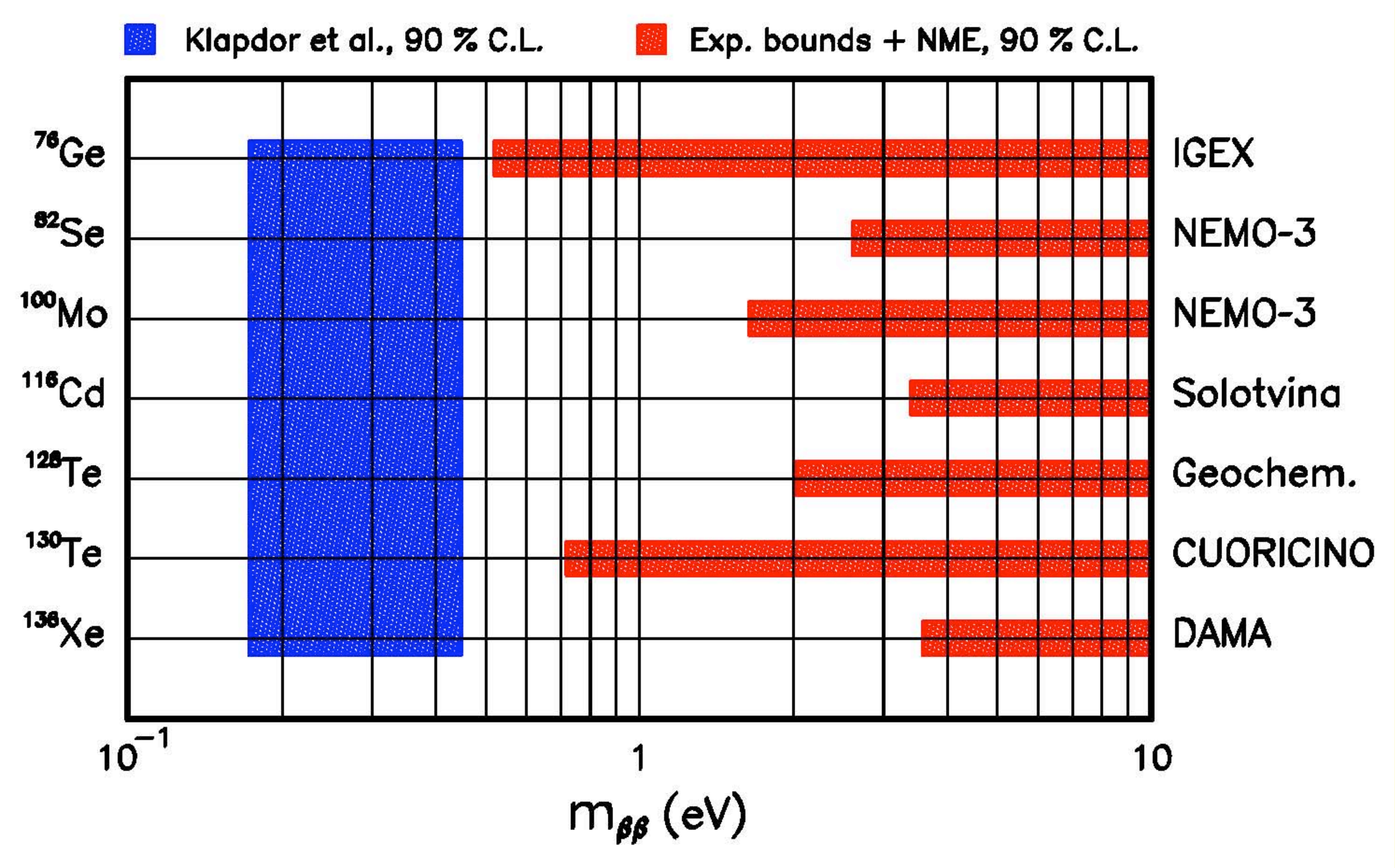
Application 1: ^{130}Te predictions from ^{76}Ge claim



Application 2: Repeat for more nuclei, compare with expt. limits



Previous comparison in terms of observable half-lives is preferable to the more popular comparison in terms of unobservable Majorana mass, where covariance info is lost (although patterns are similar).



Application 3: Testing nonstandard mechanisms for $0\nu\beta\beta$ decay

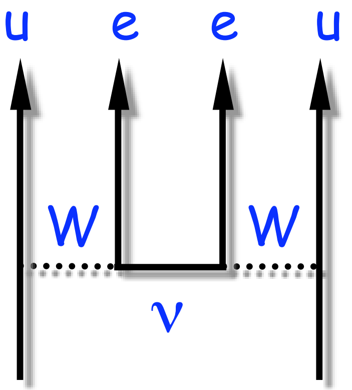
Here, correlations among different NME actually help!

Statis. approach: Compare a **null hypothesis** with **mock data.**
Set 95% C.L. as threshold for discrimination.
Use 4 nuclei for simplicity: ^{76}Ge, ^{82}Se, ^{130}Te, ^{136}Xe.

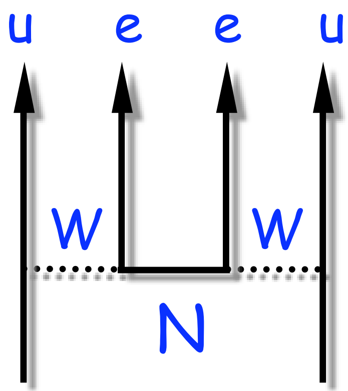
Null hypothesis: Standard case with light Majorana neutrino exchange, assuming ^{76}Ge half-life of 10^{26} y (just to set a scale). Attach previously estimated theoretical covariances.

Mock data: Assume data centered at theoretical predictions for nonstandard mechanisms, rescaled to match benchmark value of T(^{76}Ge)= 10^{26} y. Attach 25% expt. error.

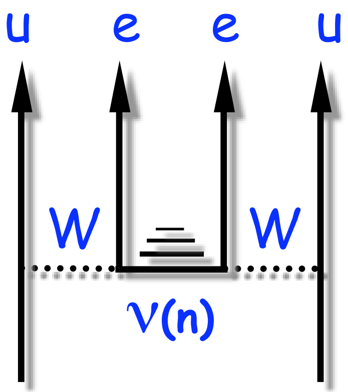
Each (non)standard case is assumed to be dominant (no interference)



Standard

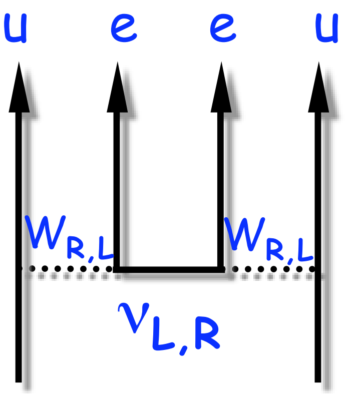


Heavy ν



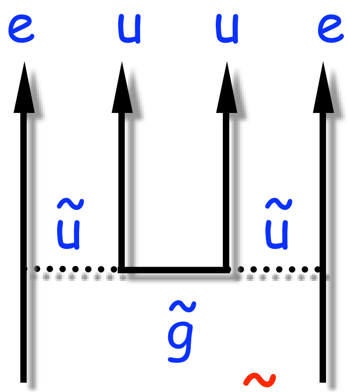
Kaluza-Klein

(KK±1 Brane:a=$10^{\pm1}$/GeV)

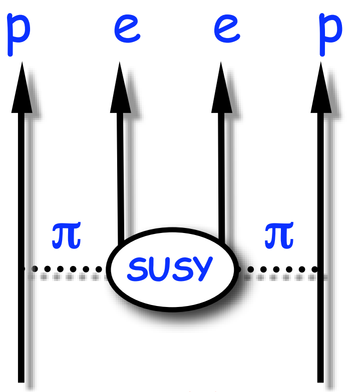


RHC λ,η

λ=RH had, η=LH had

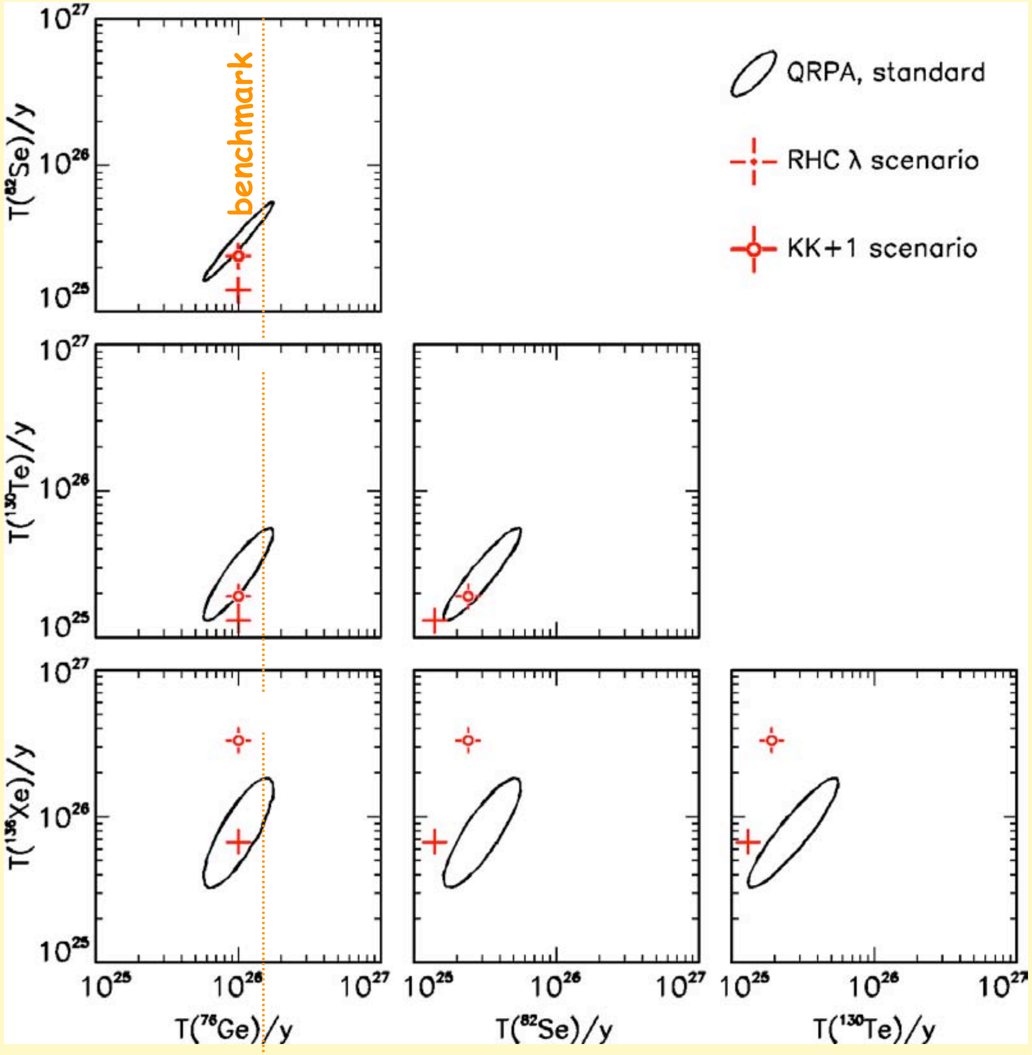


SUSY $\tilde{g}$



SUSY π

Results: two of the previous mechanisms can be distinguished at >95 % CL

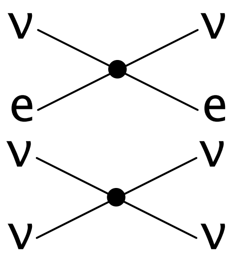


Discrimination would be insignificant if correlations were ignored.

MASS HIERARCHY: NORMAL vs INVERTED

The ambiguity related to hierarchy, namely, sign($\pm\Delta m^2$), can be addressed (in principle), via interference 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)

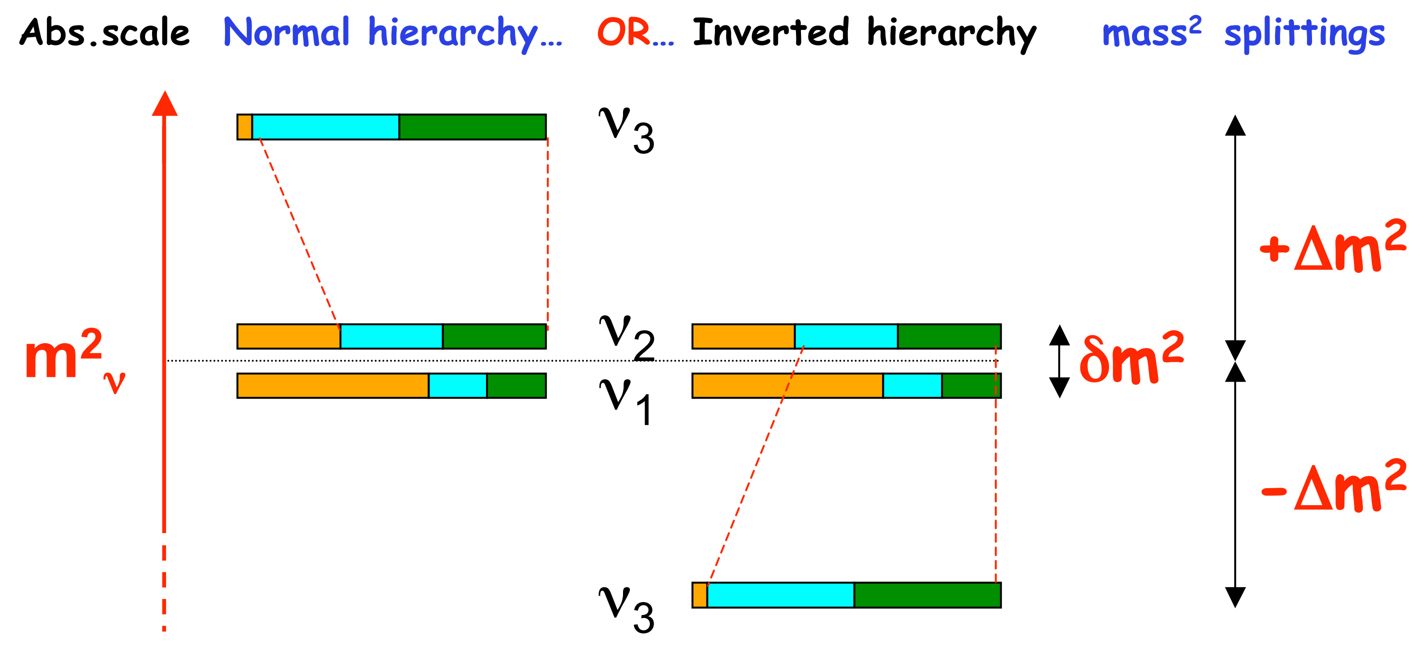
Q = δm^2 (High-resolution oscill. patterns)

In addition, nonoscillation data provide another handle.

In any case, the name of the game is: high accuracy!

Oscillation probes. 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 $\theta_{13}>0$:

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

"slow osc."
(KamLAND, LBL)

"fast osc."
(CHOOZ, SBL)

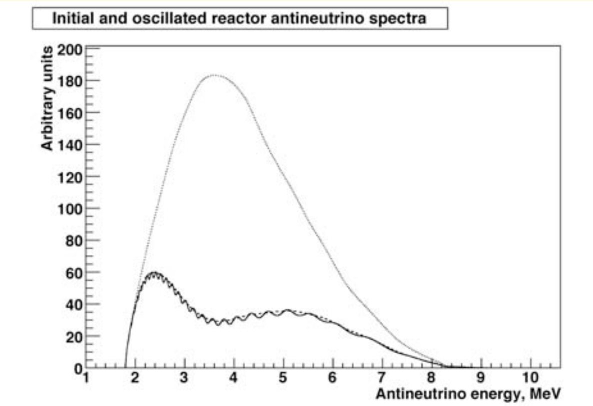
Fast oscillations not invariant under hierarchy swap, iff $U_{e1} \neq U_{e2}$
(Fogli, EL & Palazzo hep-ph/0105080)

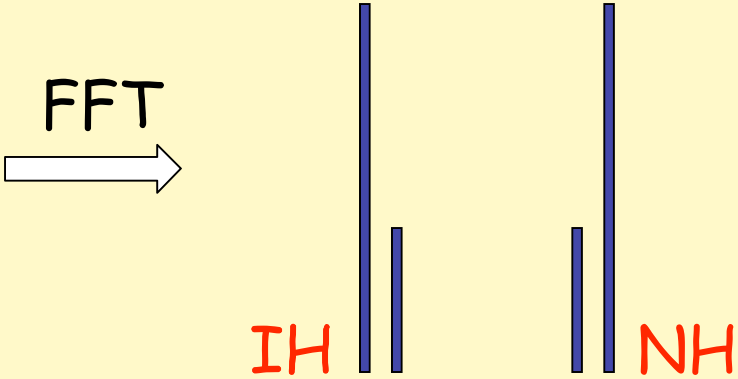
A reactor experiment at intermediate baseline (few tens of km), sensitive in principle to both slow and fast terms, might then distinguish the hierarchy (Petcov & Piai hep-ph/0112074; Choubey, Petcov and Piai, hep-ph/0306017)

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

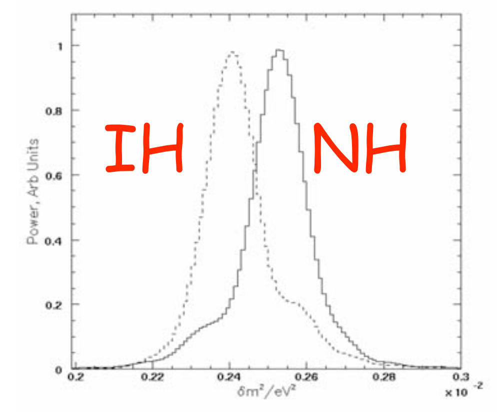
(Learned et al., hep-ex/0612022). For perfect resolution, should find two high frequencies $\Delta m^2 \pm \delta m^2/2$ with different amplitudes:





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.

Q.: can the peak shape be measured accurately enough?



Recent studies seem to 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)

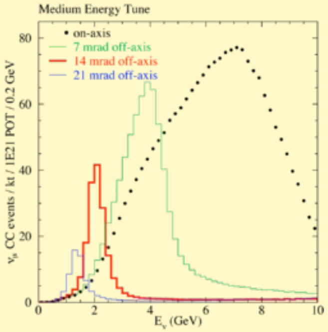
In principle, one could think about a similar effect with ν_μ: not dependent on $\theta_{13}=0$ or >0, since all mass states mix with μ flavor. (De Gouvea, Jenkins, Kayser hep-ph/0503079; Nunokawa, Parke, Funchal, hep-ph/0503283). But, how to reach % accuracy with muons?

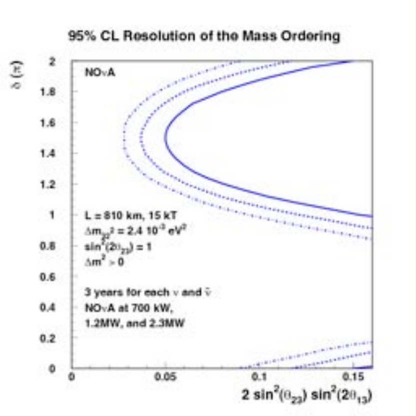
Difficult to probe the hierarchy by beating $\pm\Delta m^2$ with δm^2 !

But we have two more bullets: the two possible interaction terms (with matter or neutrinos) affecting the $\pm\Delta m^2$-induced phase.

The first bullet is provided by the usual MSW effect (neutrino-matter forward 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 ± 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., NOνA:



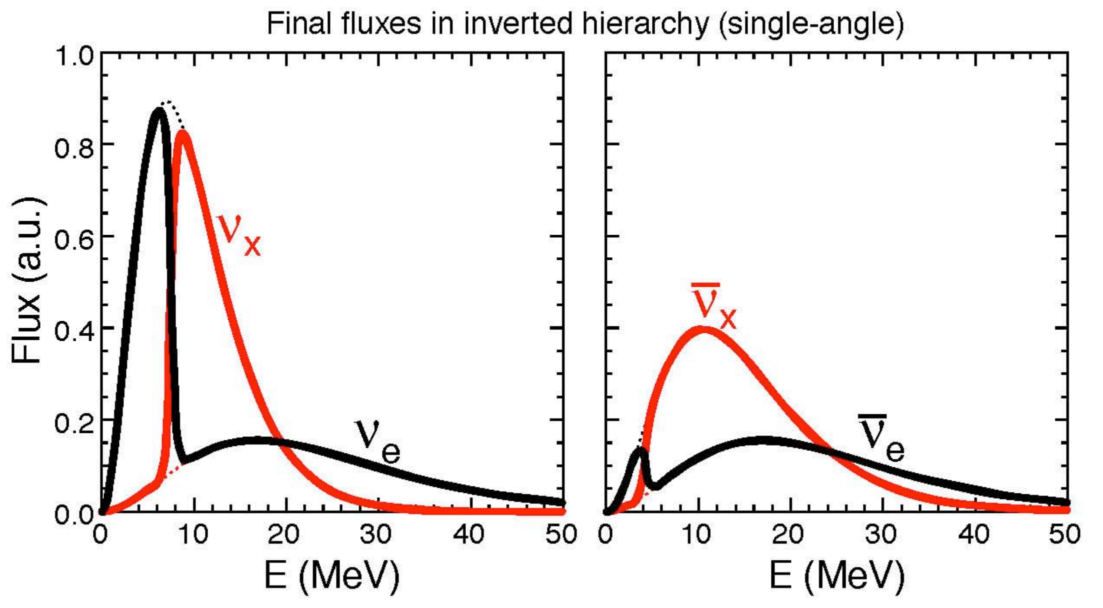


But: absolute amplitude of ν_μ->ν_e scales as $\sin^2\theta_{13}$, with strong δ dependence. Must be lucky with both parameters!

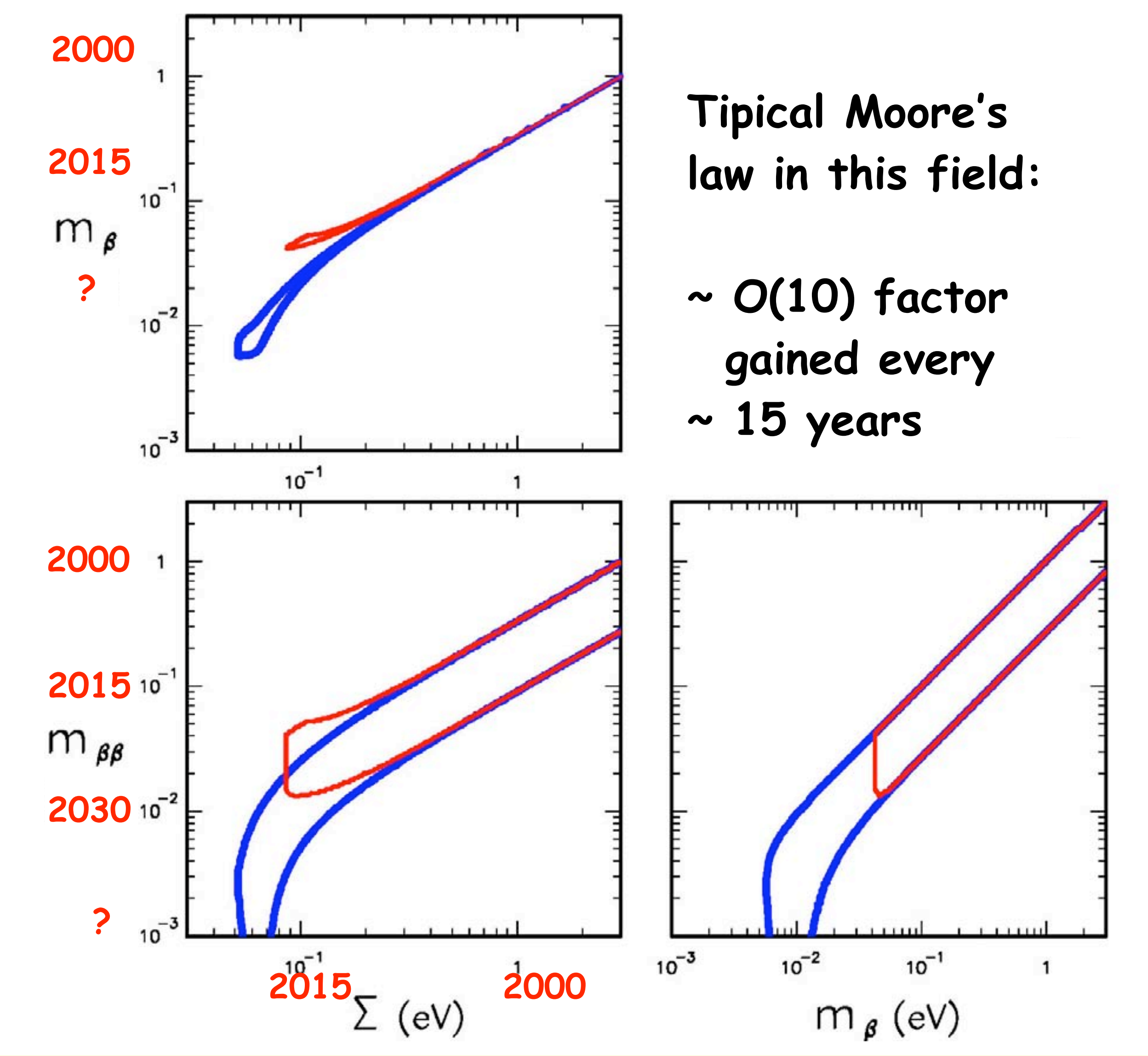
The second bullet is provided by neutrino-neutrino forward scattering in core-collapse SN. In this case, $\pm\Delta m^2$ compares with $\pm 2\sqrt{2} G_F\, E$ * density (nu + antinu).

Recently revived after seminal work by UCSD group (Fuller et al.) Interesting and peculiar nonlinear phenomena arise, such as spectral split/swap effects (Fuller et al., Raffelt & Smirnov, ...)

Observation of such effects, if any, may be difficult if entangled with possible matter effects (MSW and/or turbulence), and with unknowns in SN astrophysics.



Finally, there are non-oscillation probes of the hierarchy. E.g. lowest values of **(m_β, $m_{\beta\beta}$, Σ)** can only be reached in NH (but it will take time to get there…)

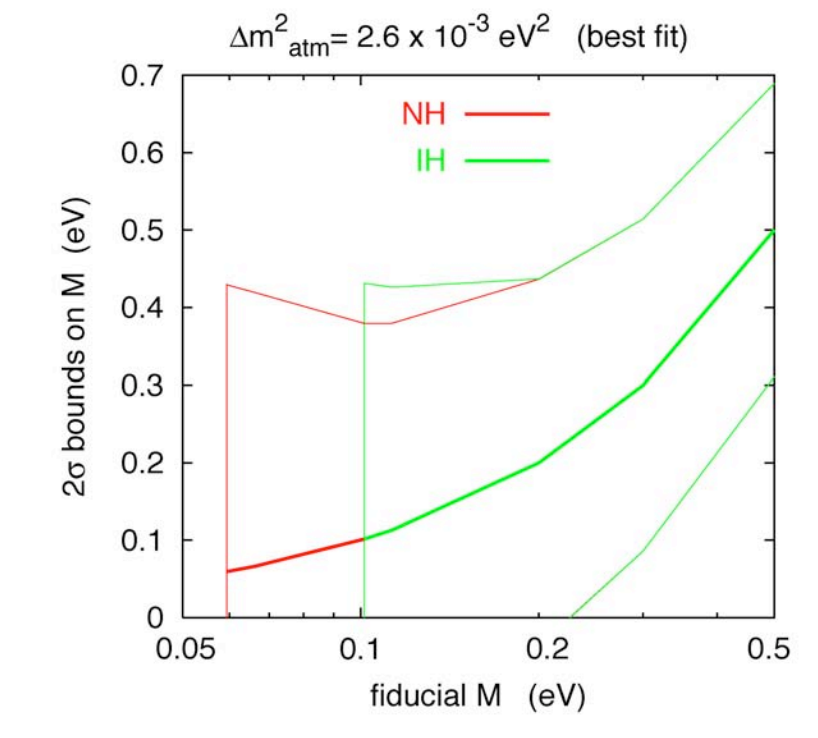


Tipical Moore's law in this field:

~ O(10) factor gained every ~ 15 years

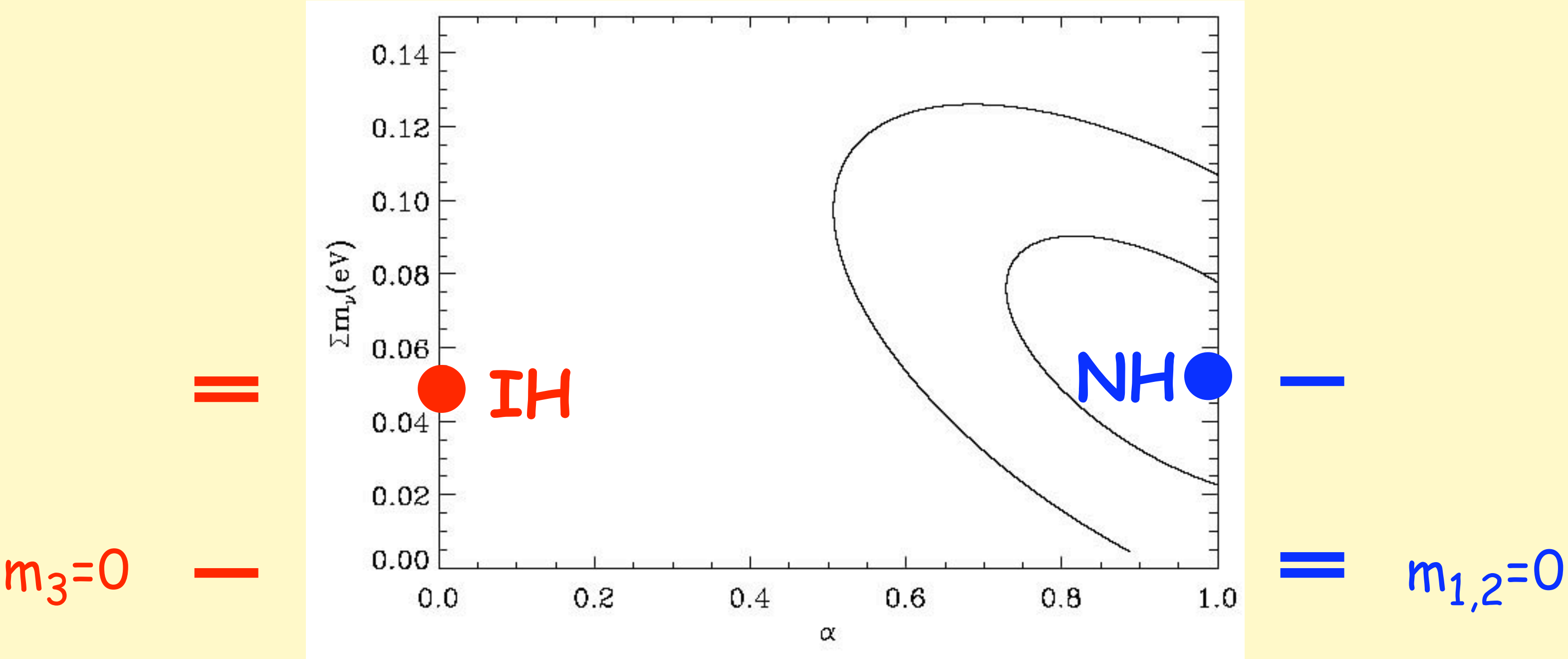
Far future: may we get hierarchy hints from high-precision cosmology? After all, relic neutrinos with different masses become nonrelativistic at slightly different times…

First prospective studies (Lesgourgues, Pastor, Perotto '04) were not particularly promising (i.e., the hierarchy ambiguity just added another error to the reconstructed value of Σ)…



… but a recent study (F. De Bernardis et al., 0907.1917) is more optimistic.

Assuming $m_1=m_2$, and defining $\alpha=m_3/(m_1+m_2+m_3)=m_3/\Sigma$, they find that future galaxy survey + CMB data could constrain both Σ and α accurately enough to distinguish the hierarchy:



This possibility deserves further scrutiny.

Thank you for your attention.