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Workshop Towards the Neutrino Technologies

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Overview of neutrino masses and mixings

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Overview of ν masses and mixings (circa 2009)

Eligio Lisi
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Mainly based on the following papers (+ comments on TAUP'2009 updates):
G.L. Fogli et al., 0805.2517, 0806.2649, 0808.0807, 0810.5733, 0905.3549

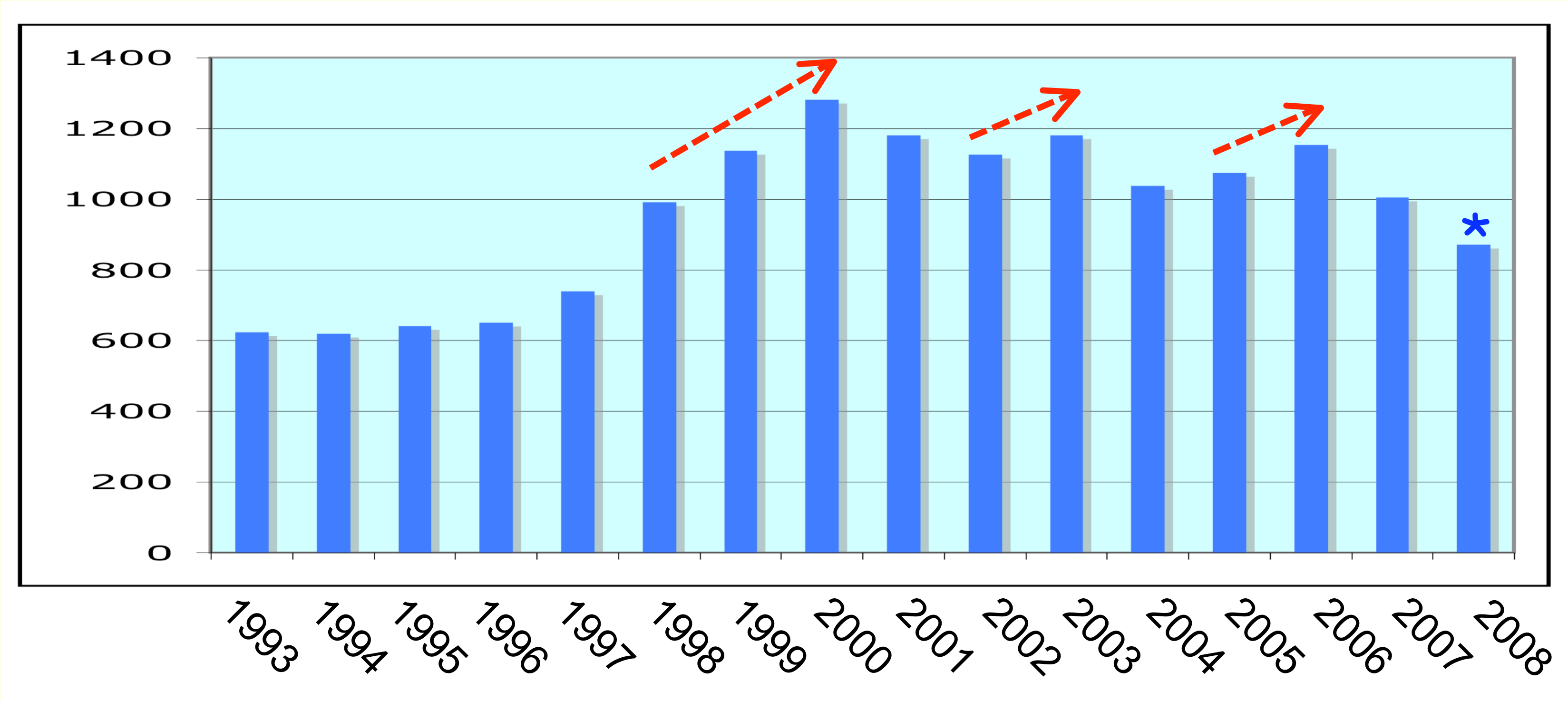
Interest in ν physics remains very high, with about 10^3 papers/year titled "…neutrino(s)…" on SPIRES

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).

Unsuspected "technological interest" even in PIRELLI

(the same of tires and calendars…)

I learned about a "PIRELLI ν telecommunication project" from a 2004 article in PANORAMA (a weekly Italian magazine). Two PIRELLI researchers were trying to reproduce the old J.Weber's claim of solar ν detection via coherent scattering on sapphire crystals, using his original equipment. I was asked to provide an opinion (negative!). No recent news about PIRELLI developments …

19-AGO-2004 Panorama da pag. 119

Settimanale Milano Direttore: Carlo Rossella Lettori Audipress 3294000

SCIENZE

TECNOLOGIE E FUTURO CONQUISTE (IM)POSSIBILI

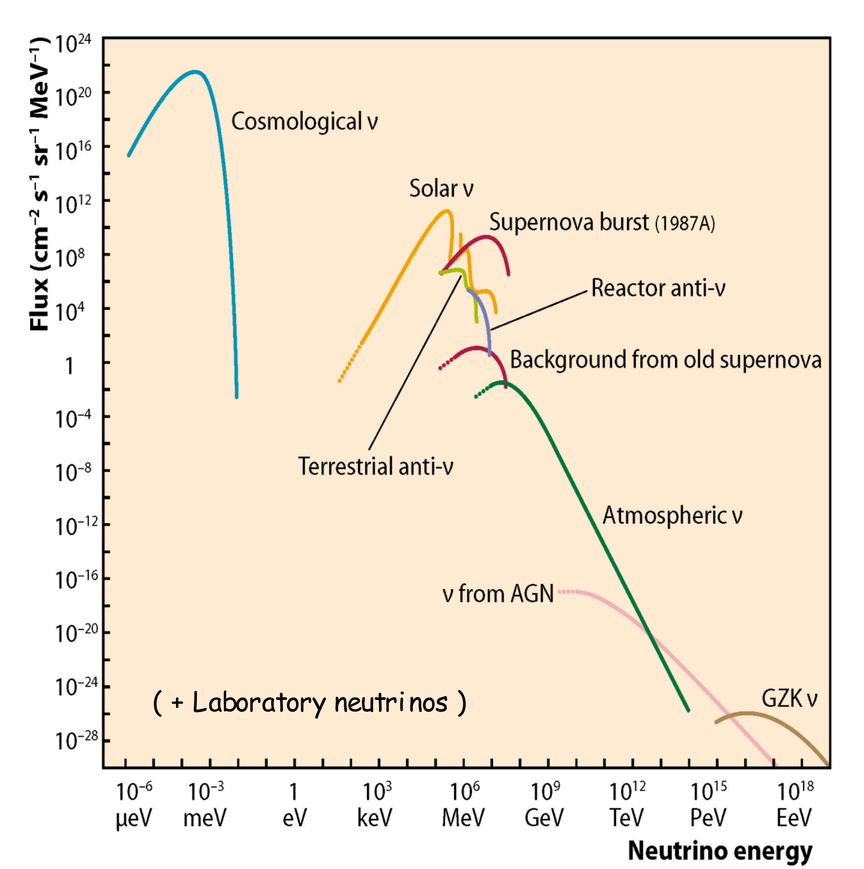
La ricetta: catturare e manipolare un fascio di sfuggenti particelle solari e usarlo per far viaggiare informazioni da un emisfero all'altro. Funzionerà? Due scienziati italiani ci stanno provando. Contro scetticismo e incredulità.

Ditelo con un neutrino

PANORAMA popular article, 2004

Neutrino researchers at PIRELLI-lab (Milan, Italy)

But, of course, we all expect many exciting developments in neutrino science, and possibly, in neutrino technology



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

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

- Flavor appearance ($\nu_\mu \rightarrow \nu_\tau$, $\nu_\mu \rightarrow \nu_e$)
- 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"
- **"Real" technological applications…**

Solid starting point: the 3ν mixing paradigm

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

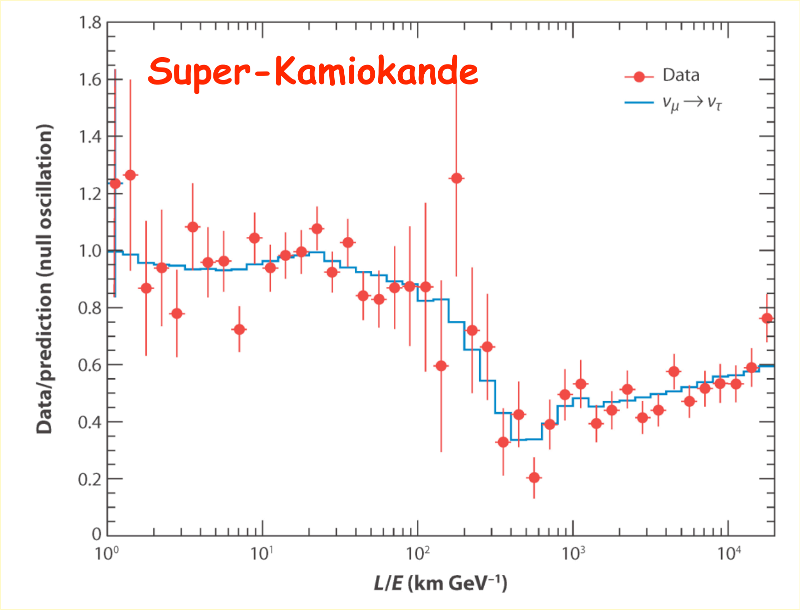
Conventionally (and usefully), same rotation ordering as in U_{CKM}:

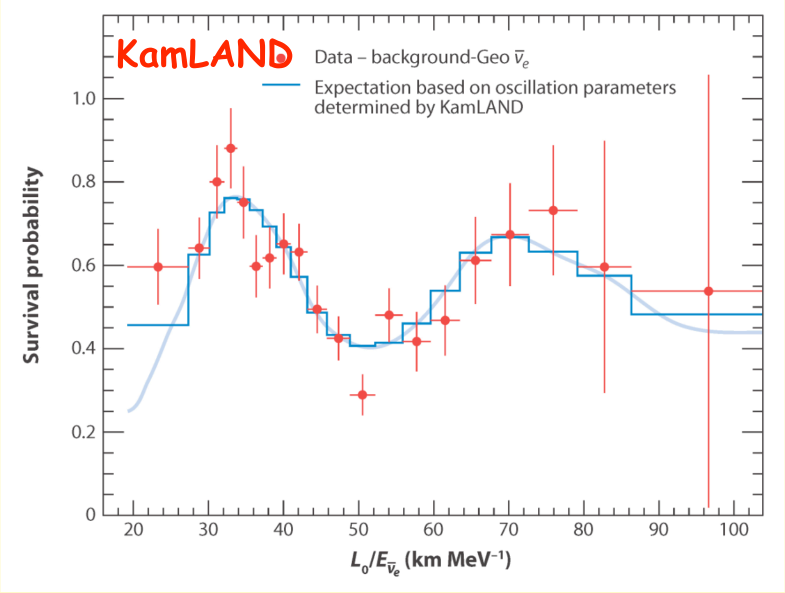
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$s_{23}^2 \sim 0.5$	$s_{13}^2 < \text{few}\ \%$	$s_{12}^2 \sim 0.3$
Measured by atmospheric and accelerator ν experiments	Mainly constrained by reactor experiments (CHOOZ, PaloVerde)	Measured by solar ν experiments & by KamLAND

Two vacuum oscillation frequencies:

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



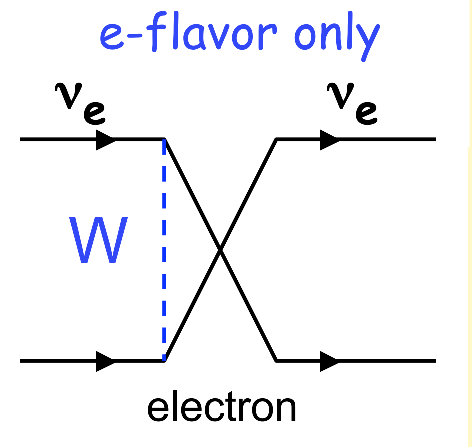


$\Delta m^2 = m_3^2 - m_{1,2}^2$ >> $\delta m^2 = m_2^2 - m_1^2$

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

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

Evidence for matter effects :

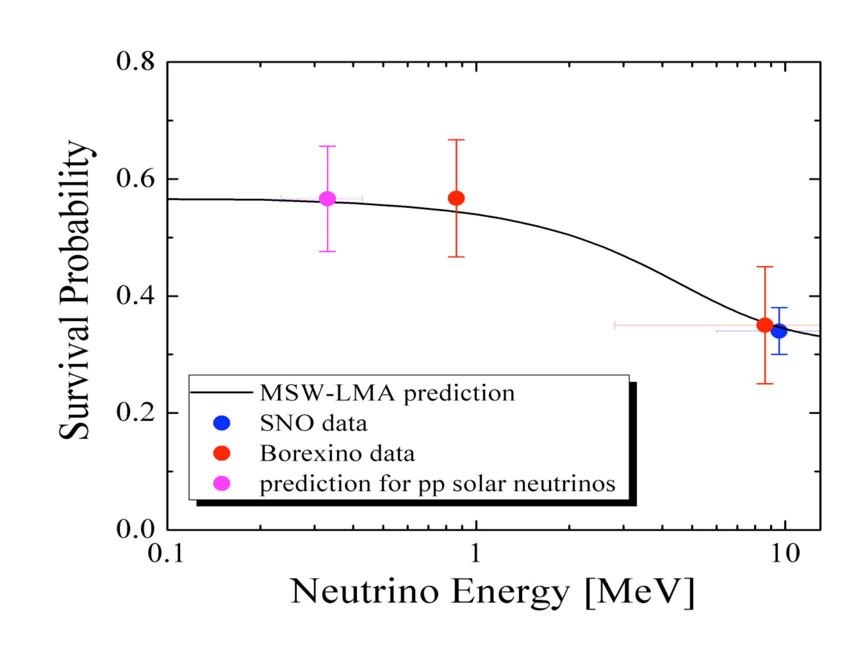


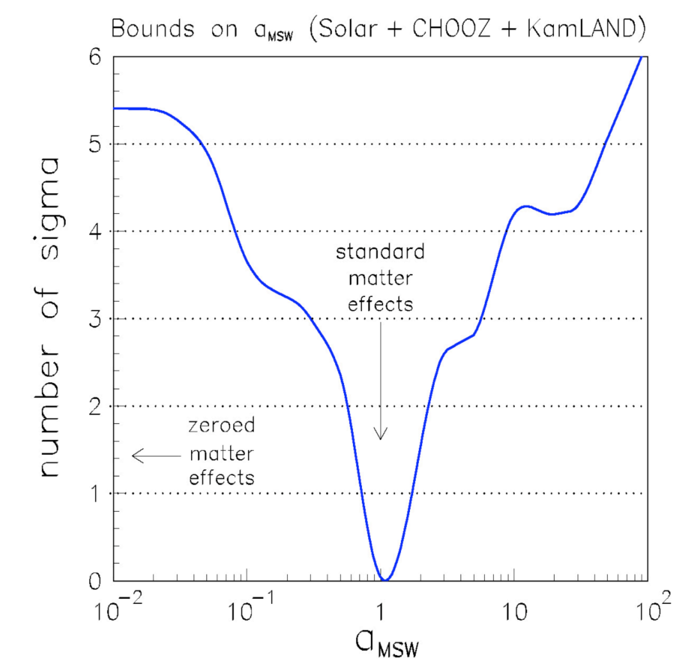
"Matter" contribution to phase (MSW effect):

~ G_F x Solar electron density

(but: averaged over many oscillation cycles)

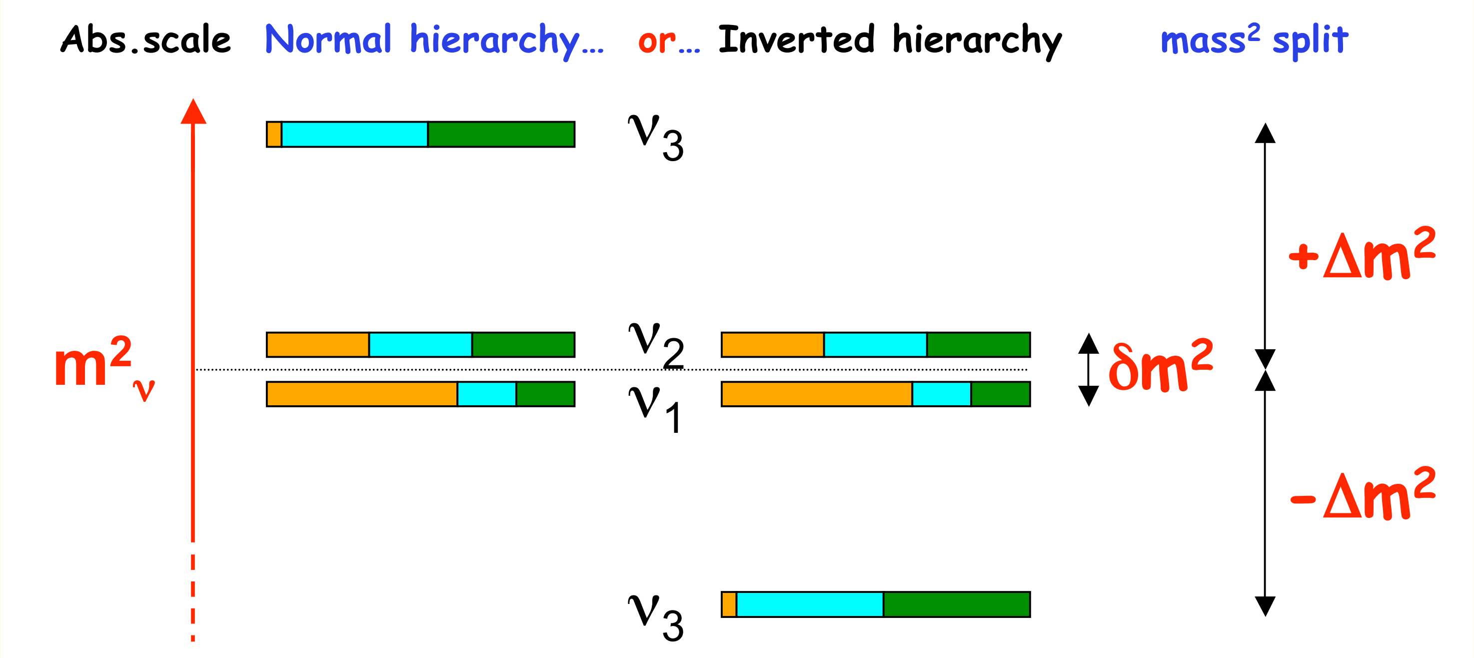
Effect observed in a single expt., **Borexino**… …in agreement with previous evidence





Current summary - if one needs just one significant digit…

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



$$\delta m^2 \sim 8 \times 10^{-5}\ \mathrm{eV}^2 \qquad \sin^2\theta_{12} \sim 0.3$$
$$\Delta m^2 \sim 3 \times 10^{-3}\ \mathrm{eV}^2 \qquad \sin^2\theta_{23} \sim 0.5$$

$$m_\nu < O(1)\ \mathrm{eV} \qquad \sin^2\theta_{13} < \mathrm{few}\%$$

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

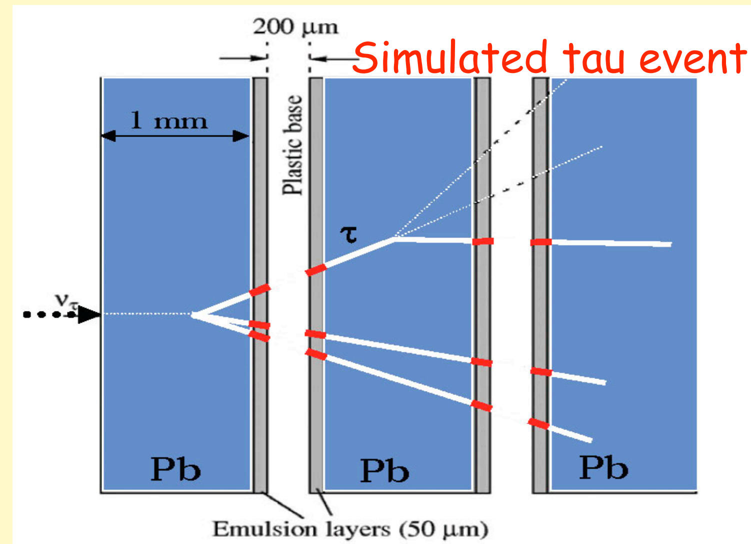
More significant digits ("precision physics"):

Always useful (fundamental parameters)

and needed for both experimental and theoretical reasons.

An experimental example: Δm^2 impact for CNGS physics

Two real tau events might already be hidden in the current statistics collected by **OPERA**…



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 "≈"

Oscillation parameters: state of the art (overview)

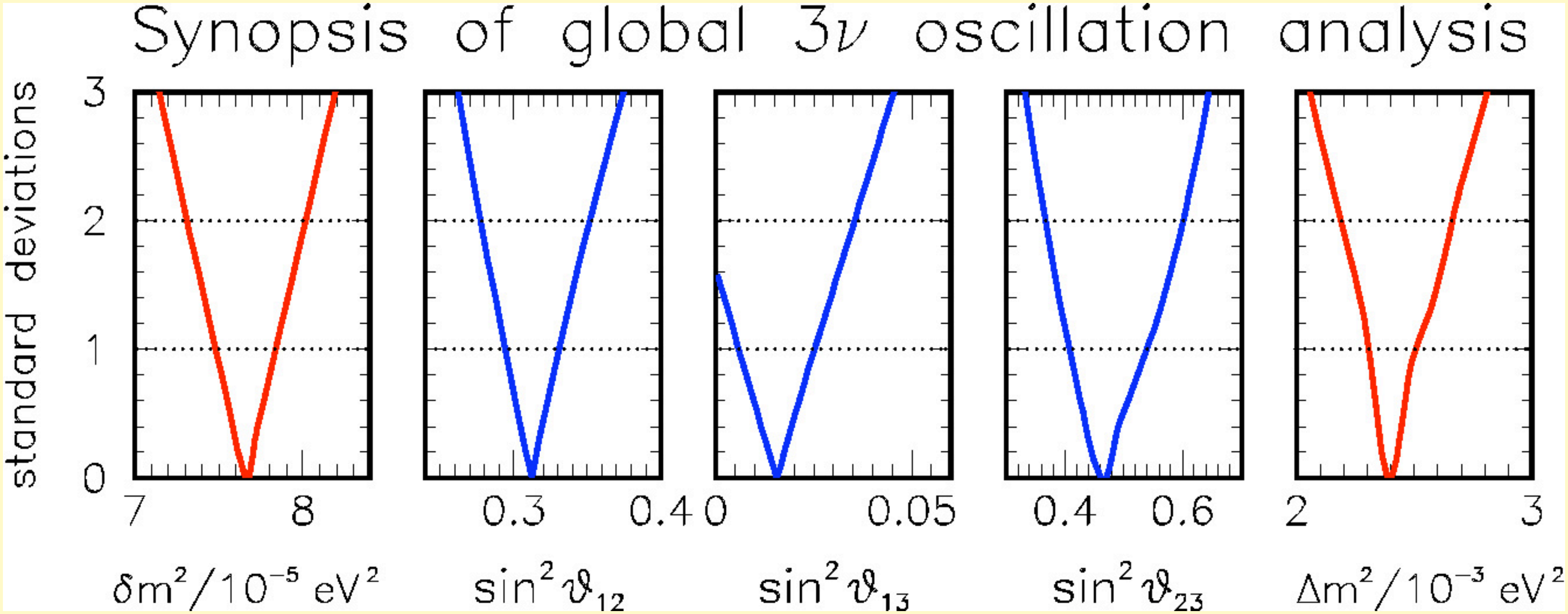
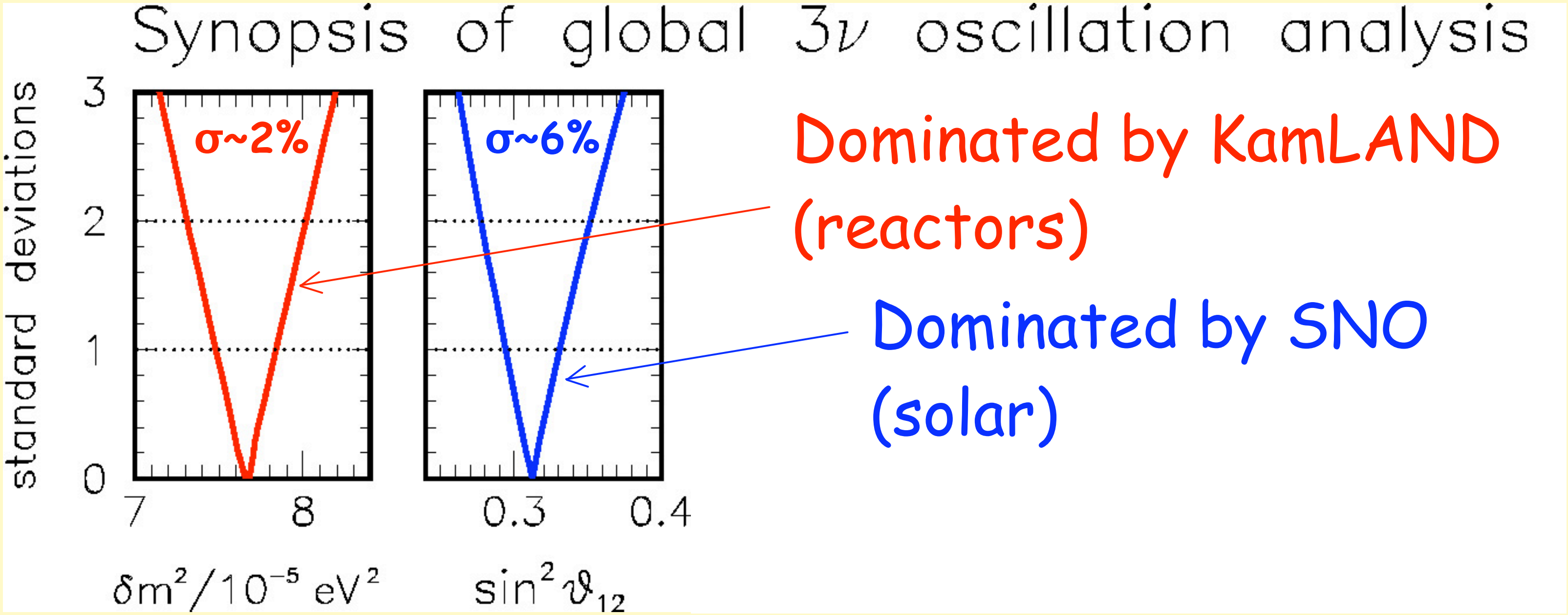


TABLE I: Global 3ν oscillation analysis (2008): best-fit values and allowed n_σ ranges for the mass-mixing parameters.

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)



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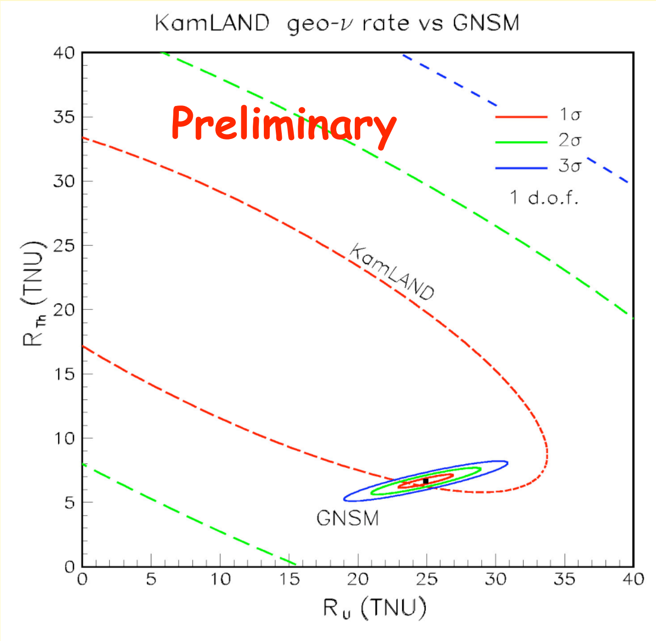
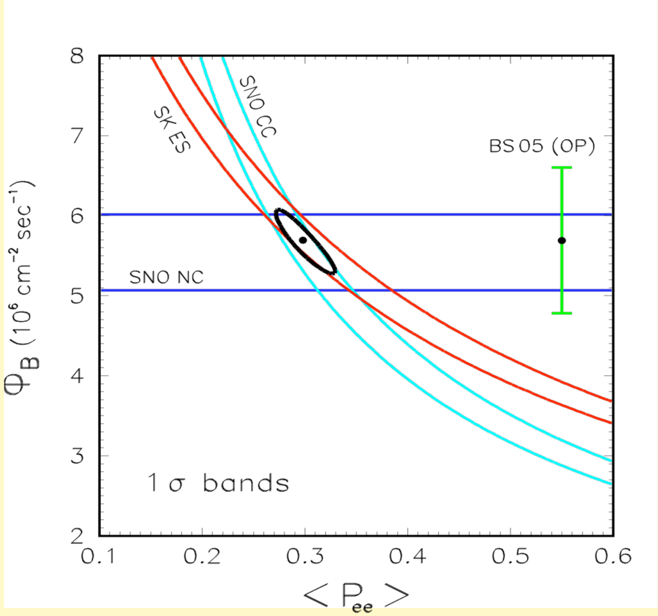
ADDITIONAL RESULTS:

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)…

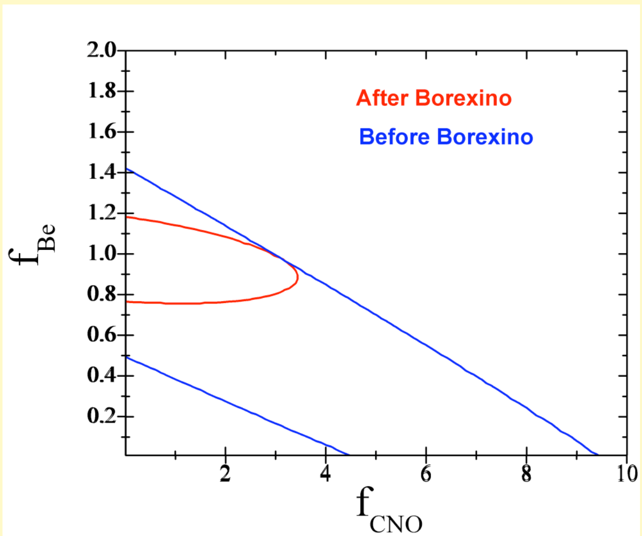


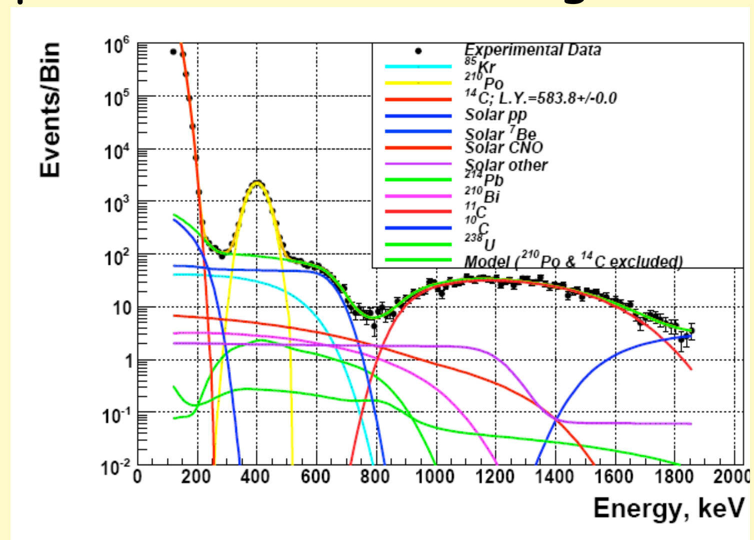
… and SNO+SK data agree with the
standard solar model expectations
for neutrino production in Boron-8
decays (within comparable errors)



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).

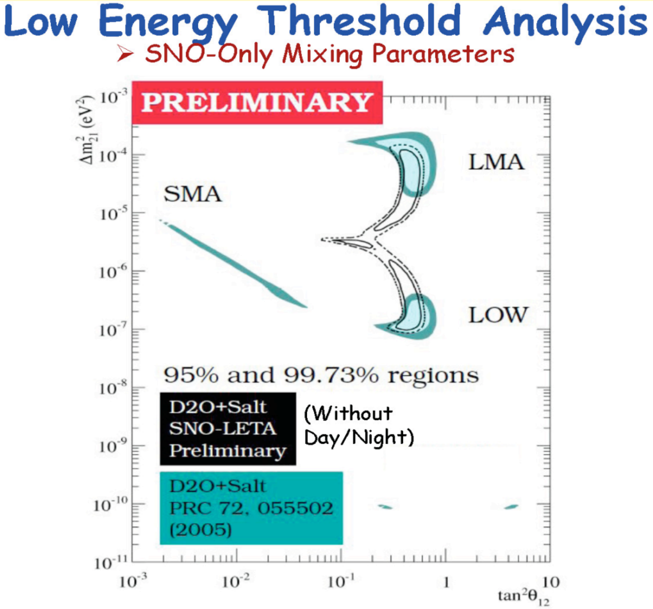




In general, CNO and low-energy fluxes are important goals for any future program of solar neutrino observations.

New confirmations (or surprises) might then emerge in the context of solar & Earth model (as well as of neutrino physics)

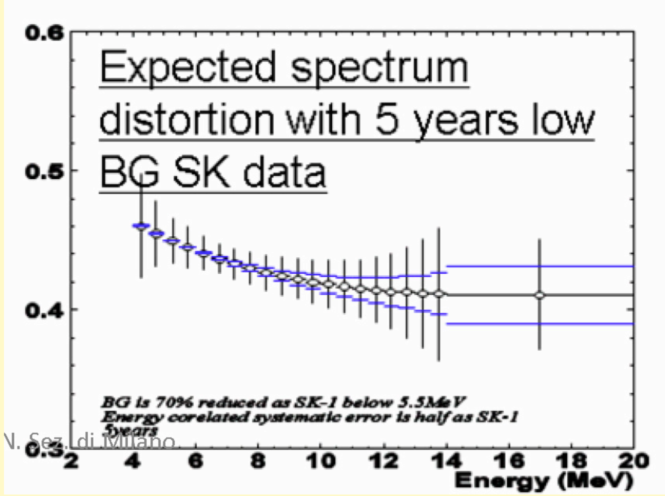
Near future: Expected improvements on θ_{12}



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

Preliminary results shown by J. Klein at TAUP 2009 seem to suggest a preference for relatively low values of θ_{12} in the SNO-LETA.

Also: Low-threshold analysis in progress in SK (see talks by Smy, Ranucci at TAUP 2009).
SK & SNO expected to shed light on expected LMA spectrum upturn at low energy.



N. Sez. di Milano

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

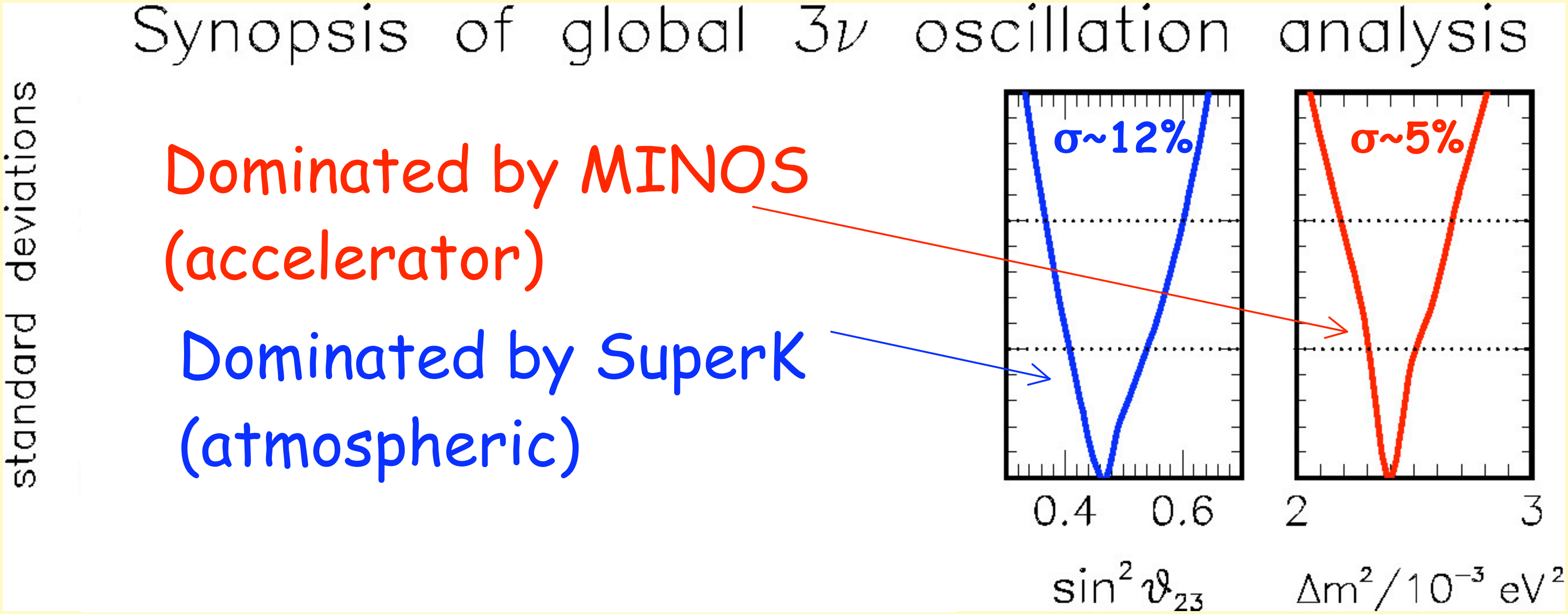
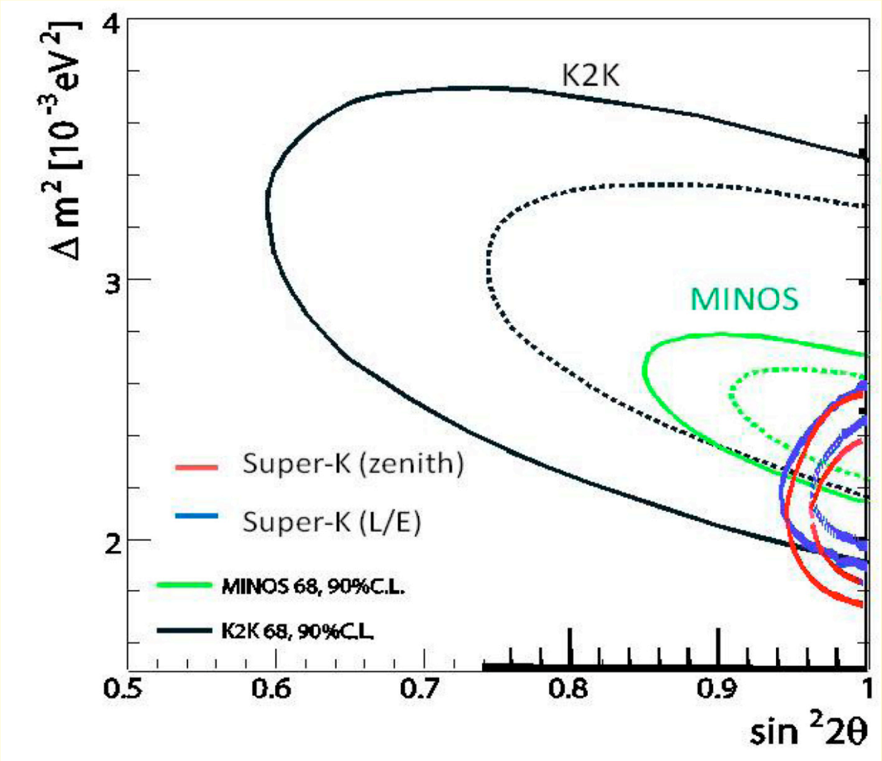


TABLE I: Global 3ν oscillation analysis (2008): best-fit values and allowed n_σ ranges for the mass-mixing parameters.

Parameter	$\sin^2\theta_{23}$	$\Delta m^2/10^{-3}$ 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% !

Latest MINOS and SK-I+II+III constraints in 2ν approximation (as reviewed by T. Kajita, TAUP'09):



For the sake of precision, it would be better to perform future official analyses in a 3ν framework, including "solar terms."

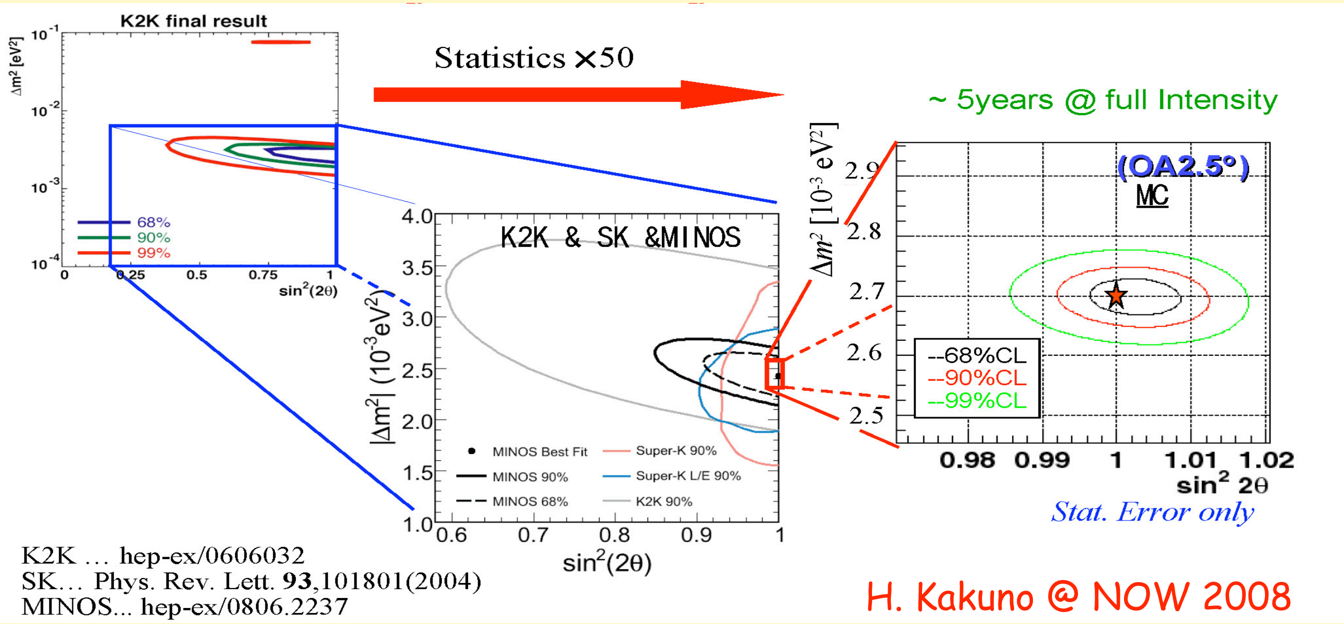
Unambiguous definition of "atmospheric" **Δm^2** is then mandatory.

Our convention:

$$\Delta m^2 = \left| \frac{\Delta m^2_{31} + \Delta m^2_{32}}{2} \right| = \left| m^2_3 - \frac{m^2_1 + m^2_2}{2} \right|$$

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

T2K (starting this year, but with low-intensity beam) expected to reach percent accuracy:



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, relevant to optimize R&D

- Detour on hierarchy -

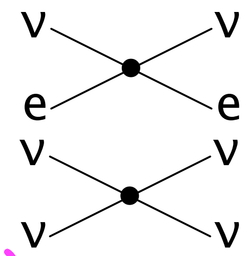
The ambiguity related to hierarchy, namely, sign($\pm\Delta m^2$), can be addressed (in principle), via interference of Δm^2-driven oscillations with oscillations driven by some quantity Q having a known sign.

Barring new 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; but the other two are also being investigated as long-term (or last resort!) options.

- Also: keep in mind high-precision cosmology… -

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

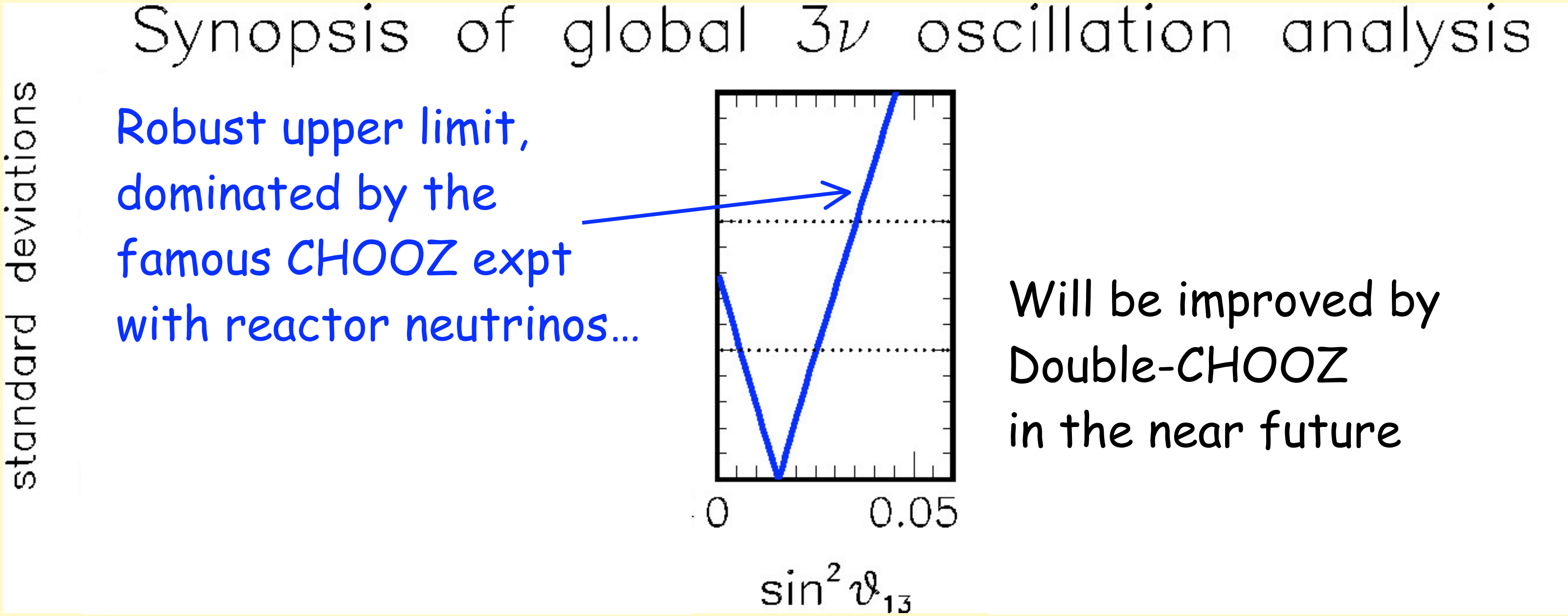
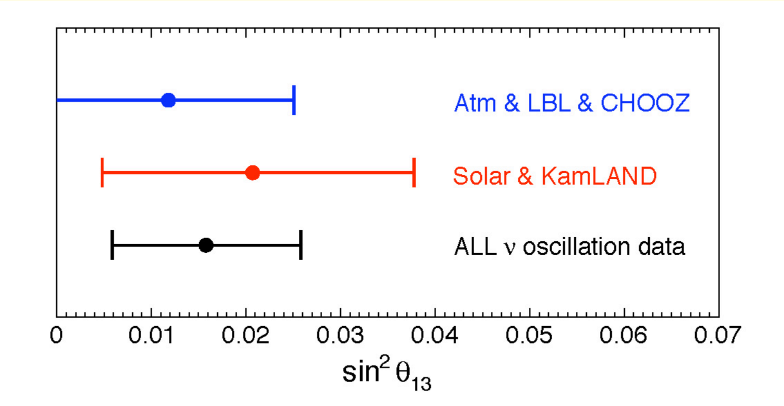


TABLE I: Global 3ν oscillation analysis (2008): best-fit values and allowed n_σ ranges for the mass-mixing parameters.

Parameter	$\sin^2\theta_{13}$
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…

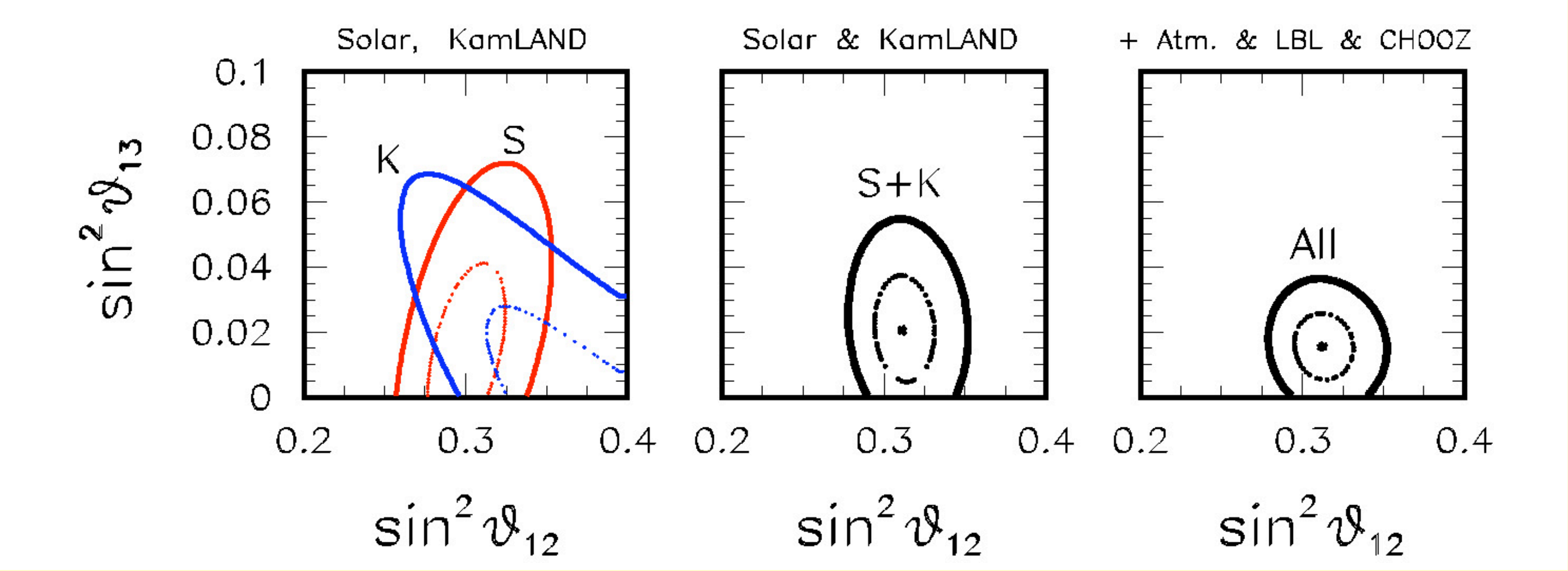


~1σ from sector (2,3)

~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):

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

– –

Solar, high energy (~MSW):

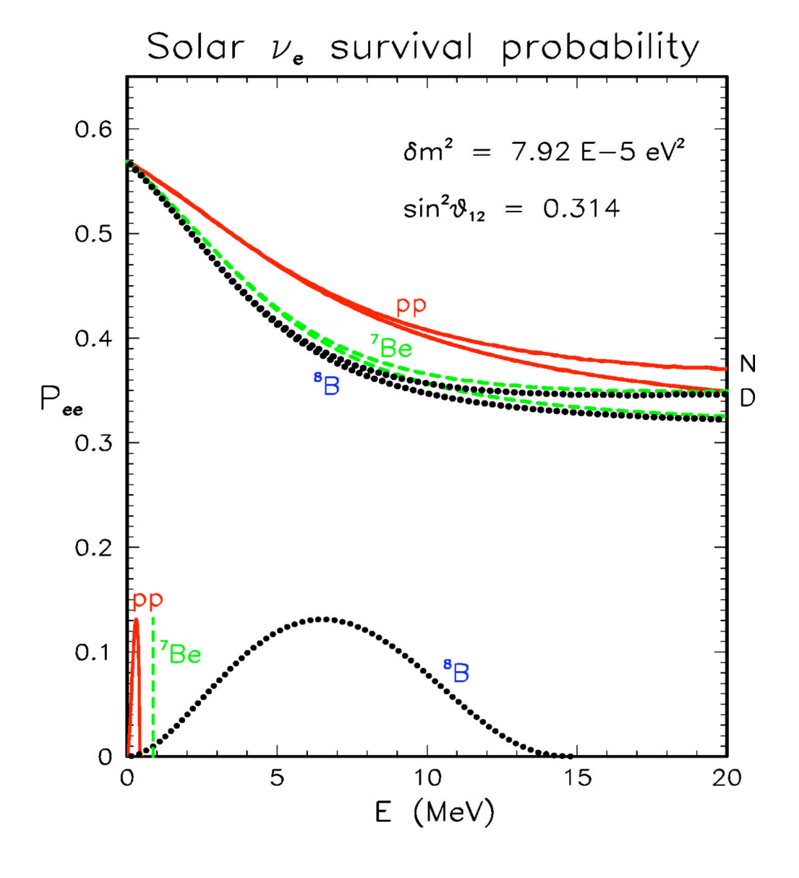
$$P_{ee} \simeq (1 - 2s^2_{13})(+s^2_{12})$$

– +

Reactor (~vacuum): KamLAND

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

– –



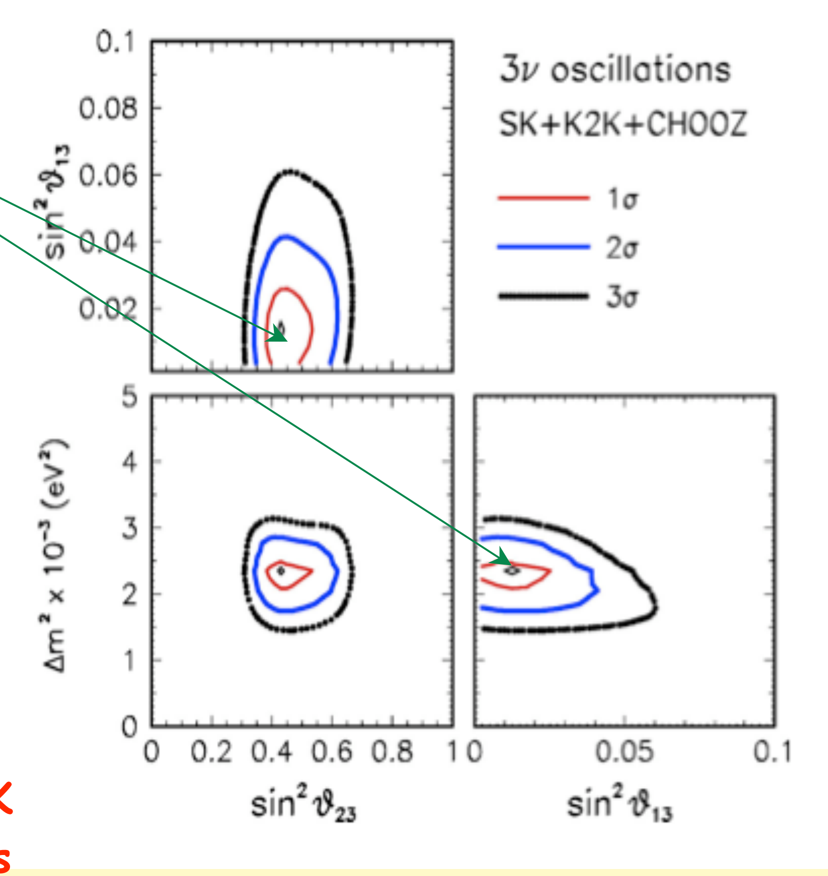
"Tension" on θ_{12} (solar vs KamLAND) can then be alleviated for θ_{13}>0

Atmospheric indication for θ_{13}>0 is less "direct" and more "fragile"

Some remarks on θ_{13} atmospheric hints

Weak hint for $\theta_{13} > 0$ in 3-neutrino analysis of atmospheric + LBL + Chooz data (Bari group, 2006), at the level of ~ 1 sigma.

best fit ~ 1 sigma away from zero



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

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

But, other analyses found weaker or no hint (Note: not all of them include solar terms).

The "last word" is expected from the SK collaboration, since their data analysis is becoming too difficult to be reproduced at the needed level of accuracy.

Status of official SK-I+II+III analysis: reported by T. Kajita at TAUP 2009. At present, SK analysis with solar terms is underway.

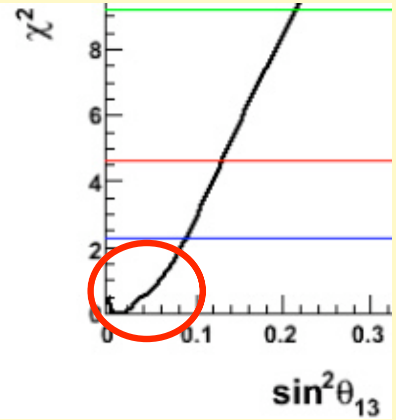
Without solar terms, preliminary SK results were summarized as:

No evidence for non-zero θ_{13} with an analysis that assumes $\Delta m_{12}^2=0$.

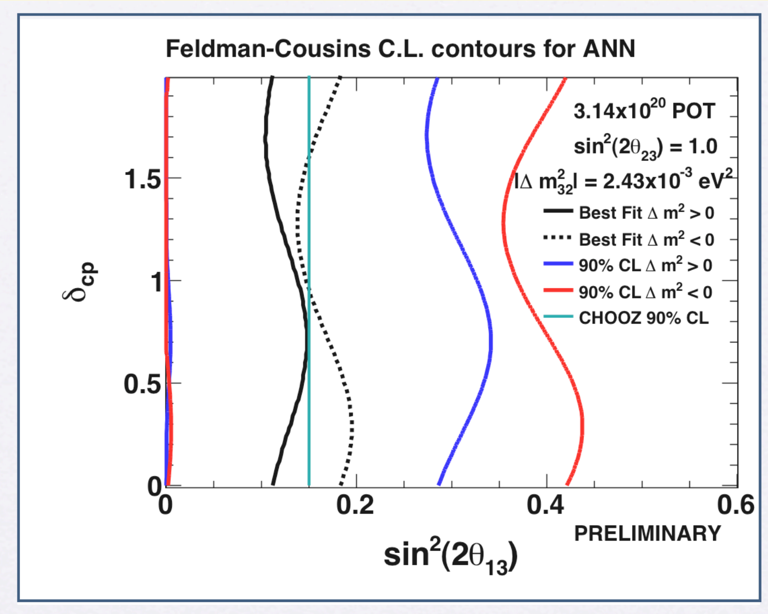
More details given by R. Wendell's at TAUP'09:

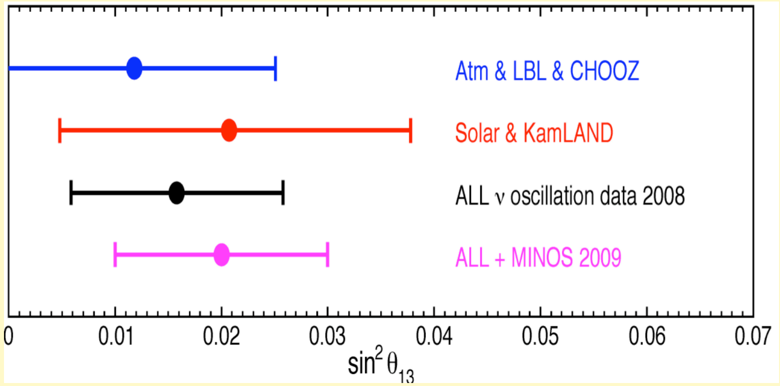
	χ^2 / dof	Δm^2	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$
Normal	469 / 417	2.1×10^{-3}	0.50	0
Inverted	468 / 417	2.1×10^{-3}	0.55	0.01

Let me note the weak preference for inverted hierarchy and nonzero θ_{13}... It remains to be seen how solar terms will affect these results in the final SK analysis.



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:

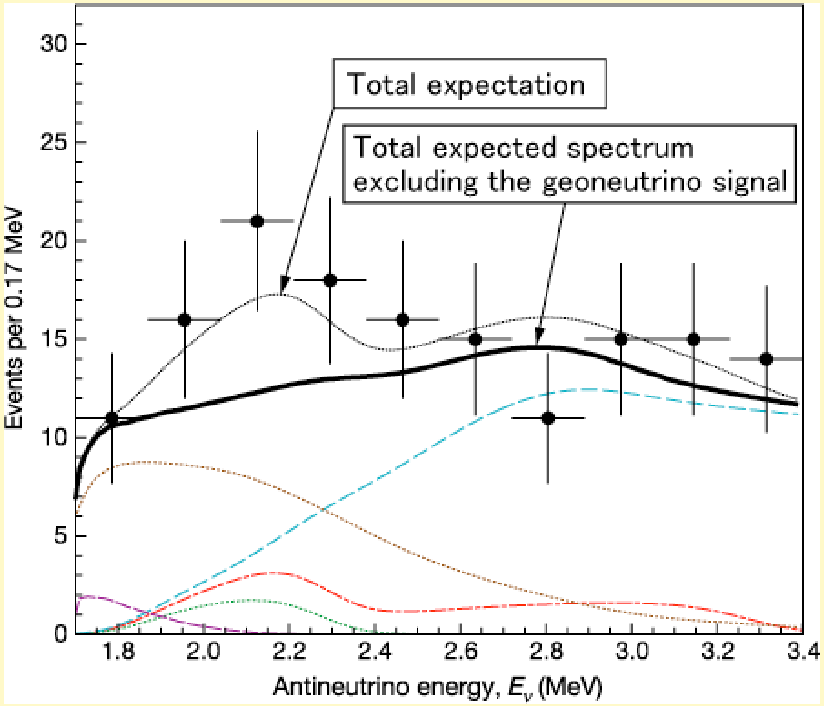
$$\sin^2\theta_{13} \approx 0.02 \pm 0.01 \quad \text{(all data, circa 2009)}$$

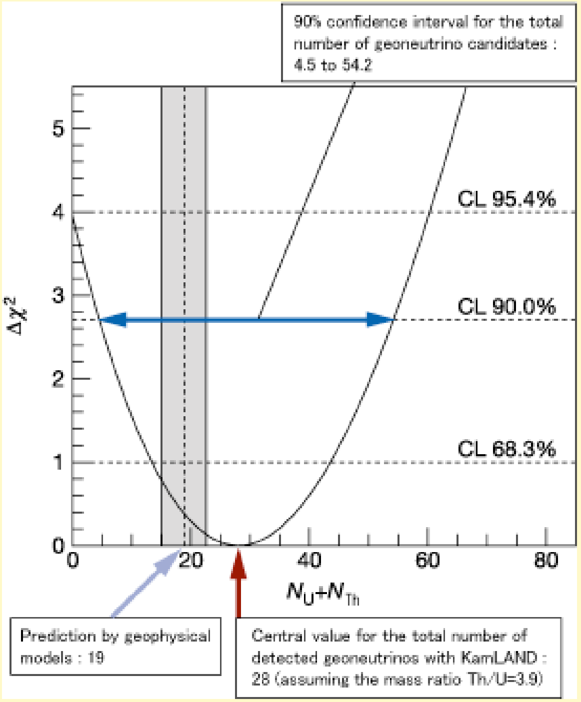
which is an encouraging 2σ hint, testable in the next few years.
(N.B.: MINOS, SK, SNO, KamLAND can still provide further improvements)

Is a "two-sigma hint" interesting or not? That's up to you…

[J. Bahcall's attitude: "Half of all three-sigma results are wrong"]

Note: the 2005 KamLAND geo-ν paper was based on a 2σ signal…





(latest published level of significance: ~ 2.7σ)

PDG quotes the θ_{13} hints in the 2009 update:

$\sin^2(2\theta_{13})$

At present time, limits of $\sin^2(2\,\theta_{13})$ are derived from the search for the reactor $\overline{\nu}_e$ disappearance at distances corresponding to the Δm^2_{23} value, i.e. L $\sim$ 1km. Alternatively, somewhat weaker limits can be obtained from the analysis of the solar neutrino data.

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<0.19	90	[148] APOLLONIO	99	CHOZ	Reactor Experiment
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.06 ± 0.04		[149] FOGLI	08	FIT	Global neutrino data
0.08 ± 0.07		[150] FOGLI	08	FIT	Solar + KamLAND data
0.05 ± 0.05		[151] FOGLI	08	FIT	Atmospheric + LBL + CHOOZ data
<0.48	90	[152] HOSAKA	06A	SKAM	3ν oscillation; normal mass hierarchy
<0.79	90	[153] HOSAKA	06A	SKAM	3ν oscillation; inverted mass hierarchy
<0.36		[154] YAMAMOTO	06	K2K	Accelerator experiment
<0.48	90	[155] AHN	04	K2K	Accelerator experiment
<0.36	90	[156] BOEHM	01		Palo Verde react.
<0.45	90	[157] BOEHM	00		Palo Verde react.

[148] The quoted limit is for $\Delta m^2_{32} = 1.9 \times 10^{-3}$ eV^2. That value of Δm^2_{32} is the 1-σ low value for ALIU 05. For the ALIU 05 best fit value of 2.8×10^{-3} eV^2, the $\sin^2 2\,\theta_{13}$ limit is < 0.13. See also APOLLONIO 03 for a detailed description of the experiment.

[149] FOGLI 08 obtained this result from a global analysis of all neutrino oscillation data, that is, solar + KamLAND + atmospheric + accelerator long baseline + CHOOZ.

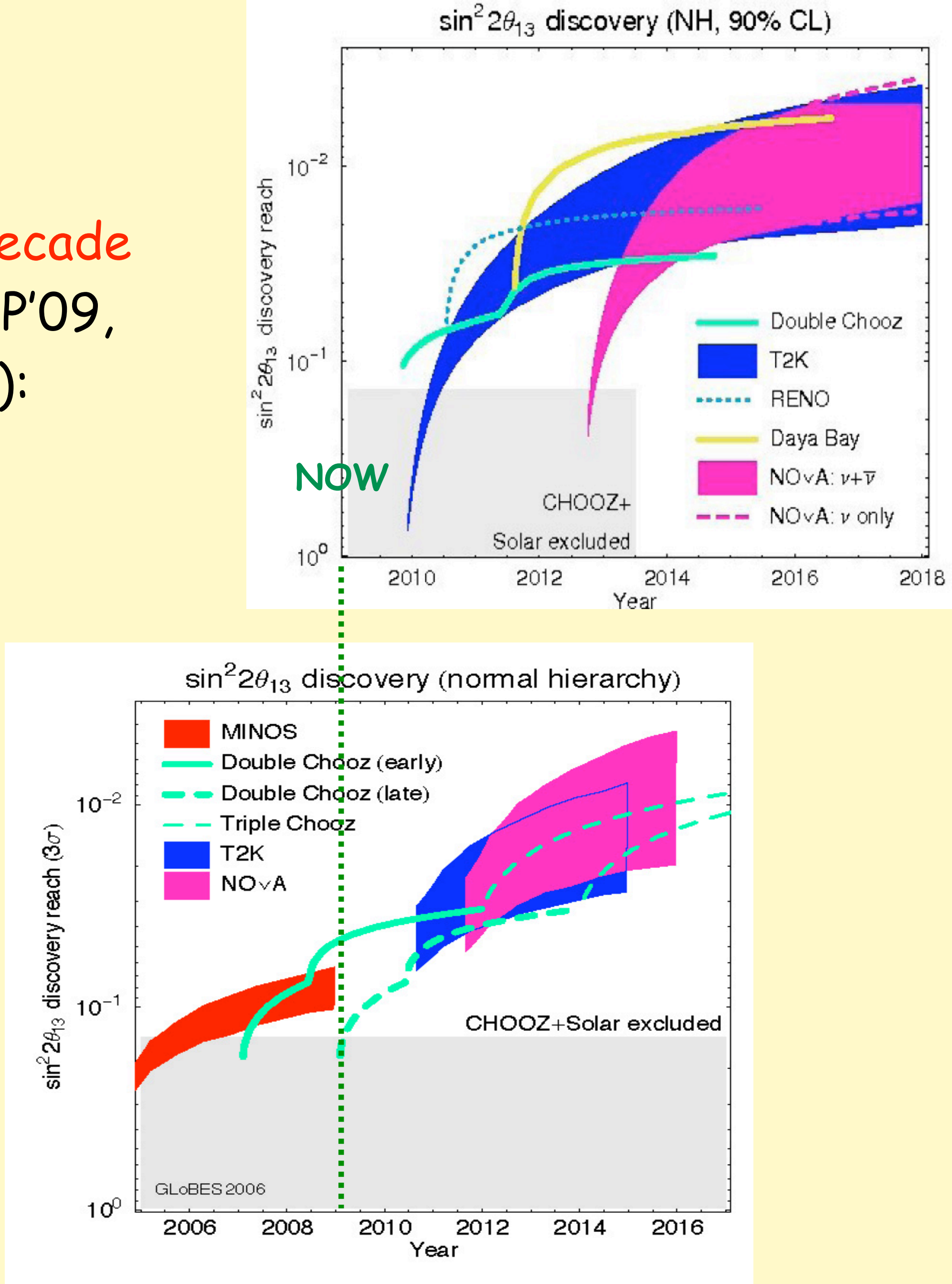
[150] FOGLI 08 obtained this result from an analysis using the solar and KamLAND neutrino oscillation data.

[151] FOGLI 08 obtained this result from an analysis using the atmospheric, accelerator long baseline, and CHOOZ neutrino oscillation data.

The future:

θ_{13} prospects for the next decade

(as shown by J. Valle at TAUP'09, courtesy of M. Lindner et al.):



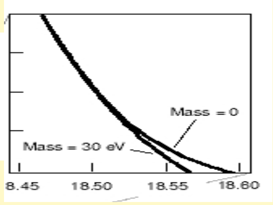
The same plot 3 years ago

(note time shift). Needless to say, neutrino physics is an exercise in patience…

Absolute neutrino masses. Threefold attack strategy: (m_β, $m_{\beta\beta}$, Σ)

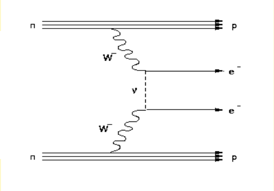
1) **Single β decay**: $m^2_i \neq 0$ alters the spectrum tail. Sensitive to the so-called "effective mass of electron neutrino":

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



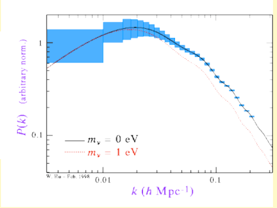
2) **Double 0νββ decay:** Iff $m^2_i \neq 0$ and ν=anti-ν (Majorana). Sensitive to the "effective Majorana mass" (and related phases):

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

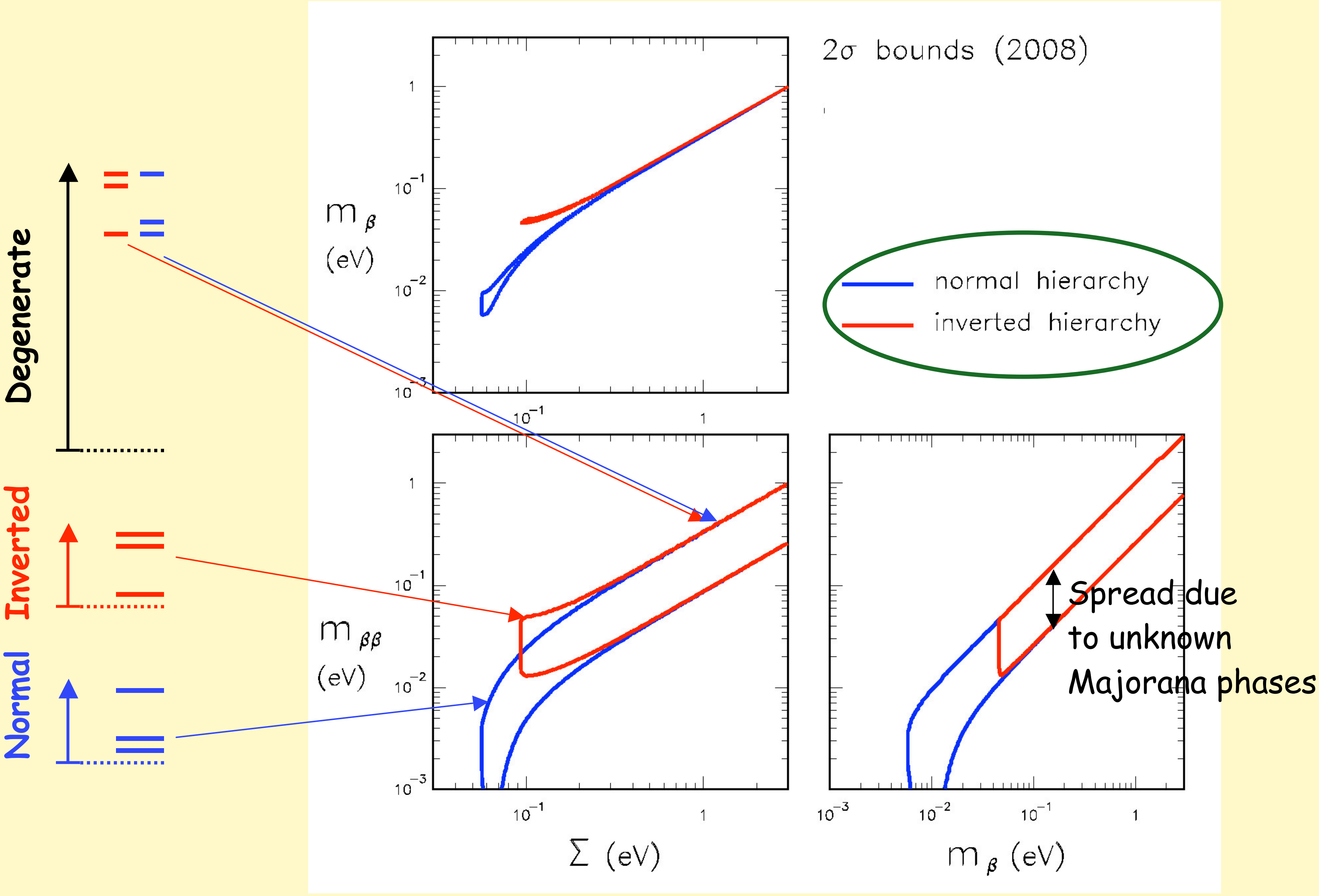


3) **Cosmology**: $m^2_i \neq 0$ alters large scale structure formation within standard cosmology constrained by CMB + other data. Measures:

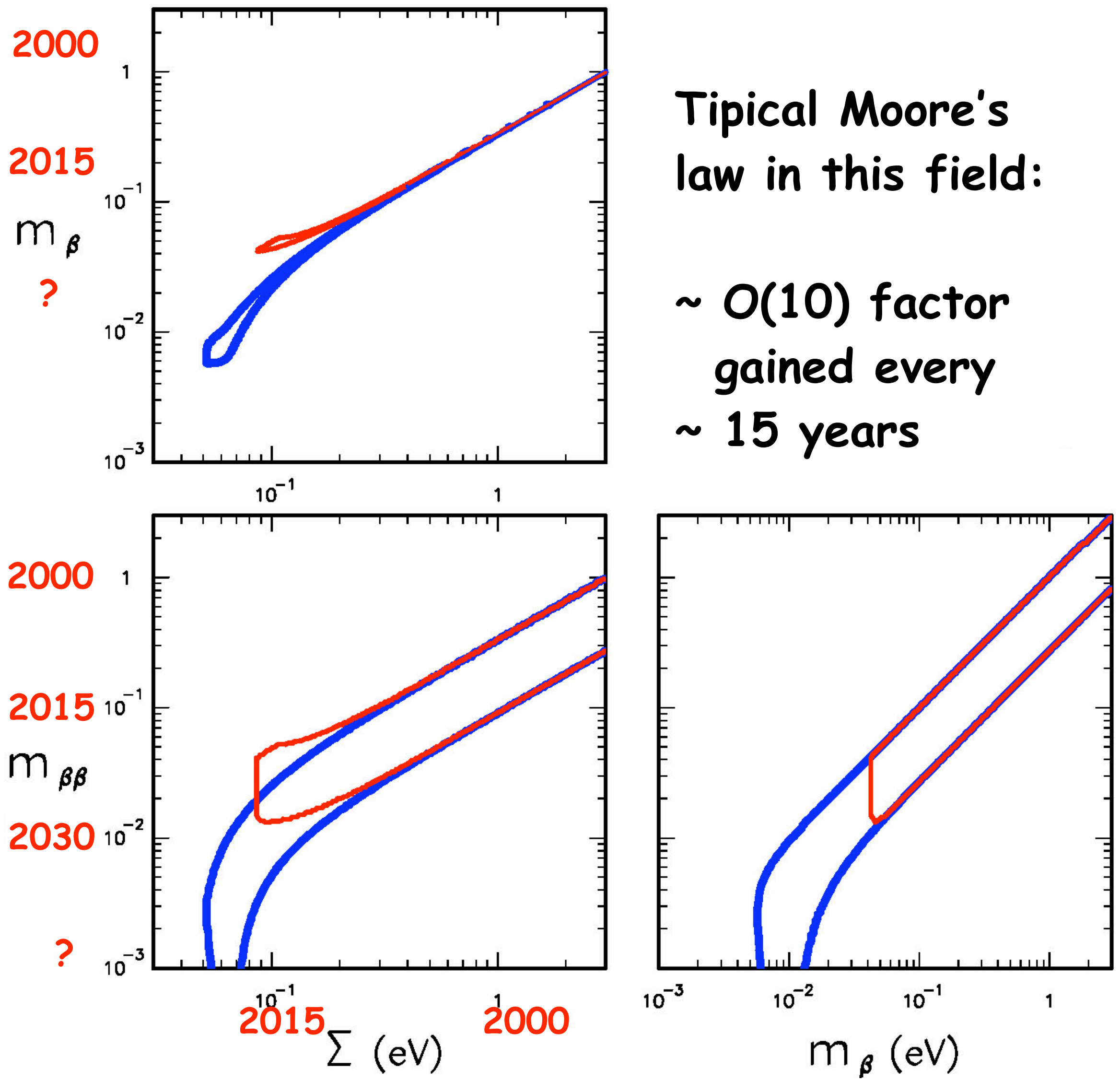
$$\Sigma = m_1 + m_2 + m_3$$



Oscillation data 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 on (m_β, $m_{\beta\beta}$, Σ) to make real progress: another exercise in patience…



Tipical Moore's law in this field:

~ O(10) factor gained every ~ 15 years

Single β decay

Tritium experiments:

Mainz + Troitsk: m_β < 2 eV

KATRIN: improvement of O(10)

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

m_β = 0.35±0.07 (5σ, discovery)

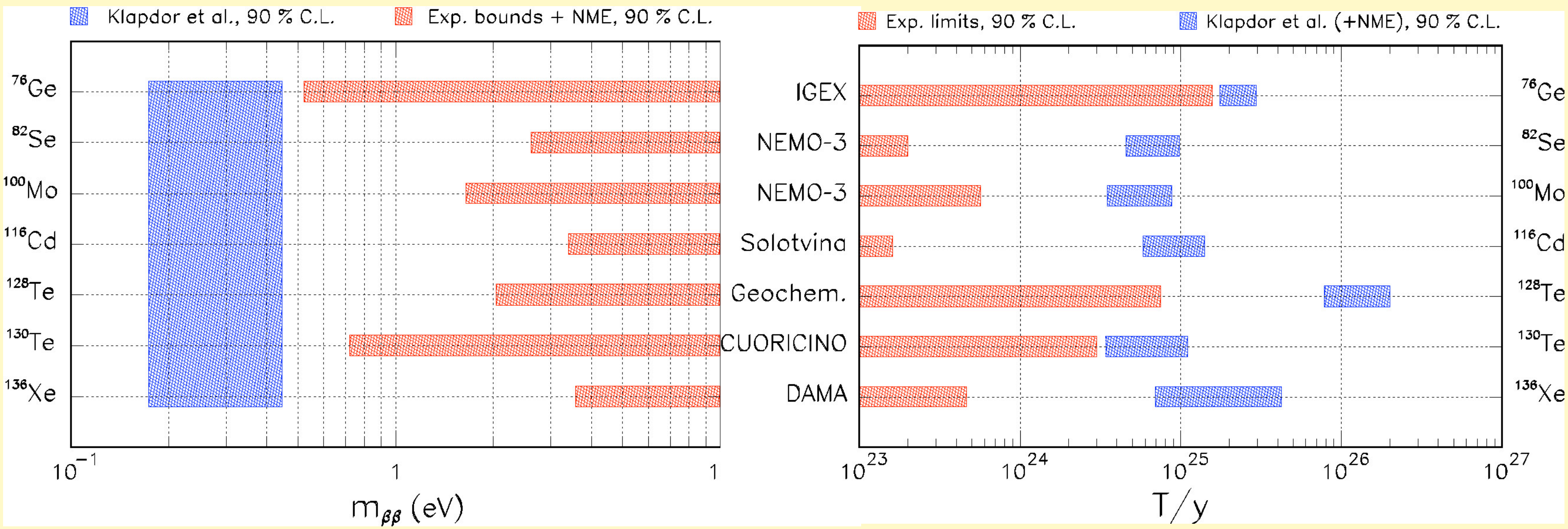
m_β = 0.30±0.10 (3σ, evidence)

m_β = 0 ±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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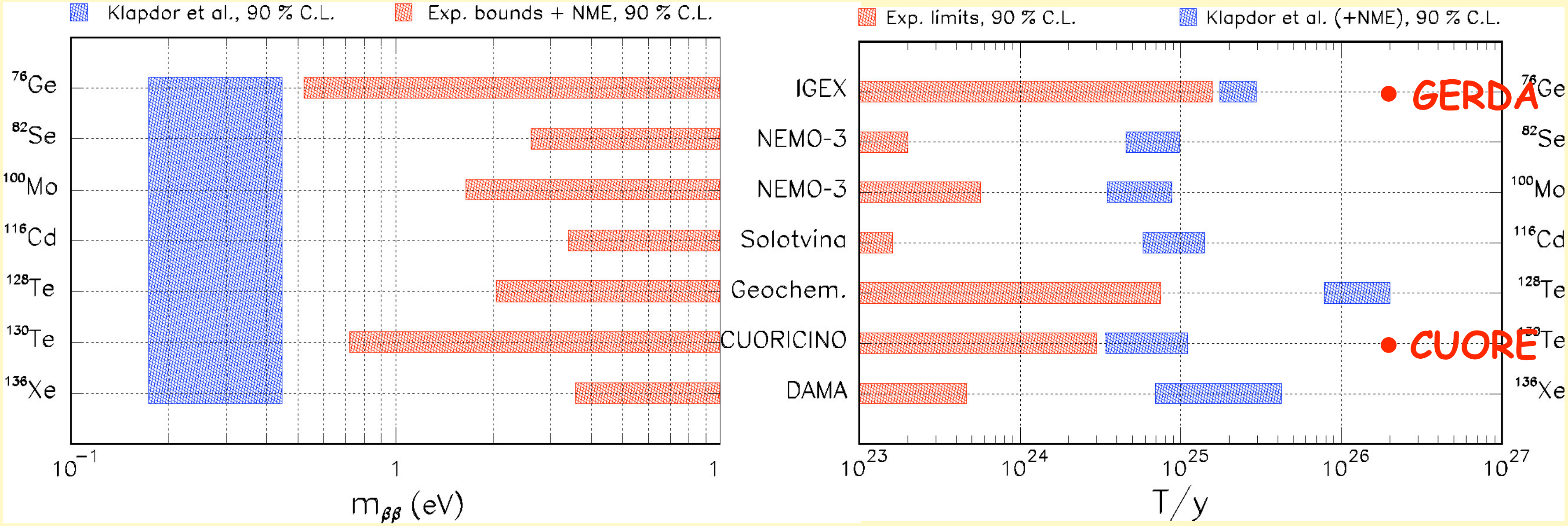


Expected sensitivities, e.g., for CUORE, GERDA @ LNGS

[and best wishes to all our colleagues & their families at GS & 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.

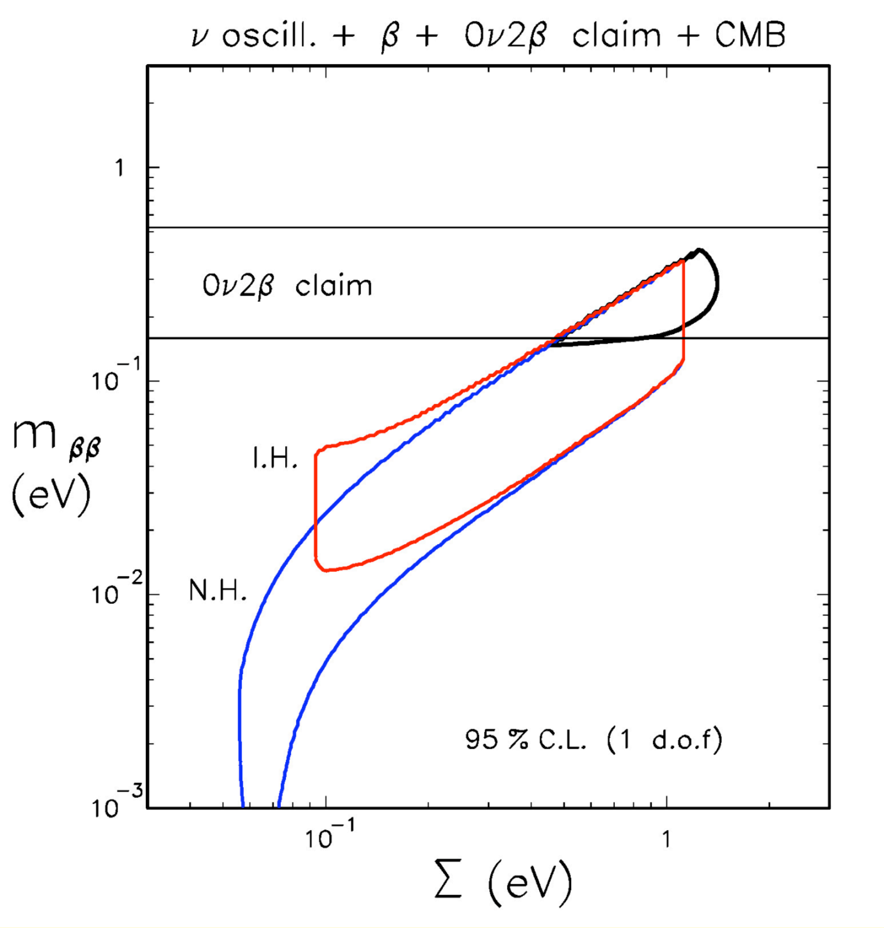
Case	Cosmological data set	Σ (at 2σ)
1	CMB	< 1.19 eV
2	CMB + LSS	< 0.71 eV
3	CMB + HST + SN-Ia	< 0.75 eV
4	CMB + HST + SN-Ia + BAO	< 0.60 eV
5	CMB + HST + SN-Ia + BAO + Lyα	< 0.19 eV

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

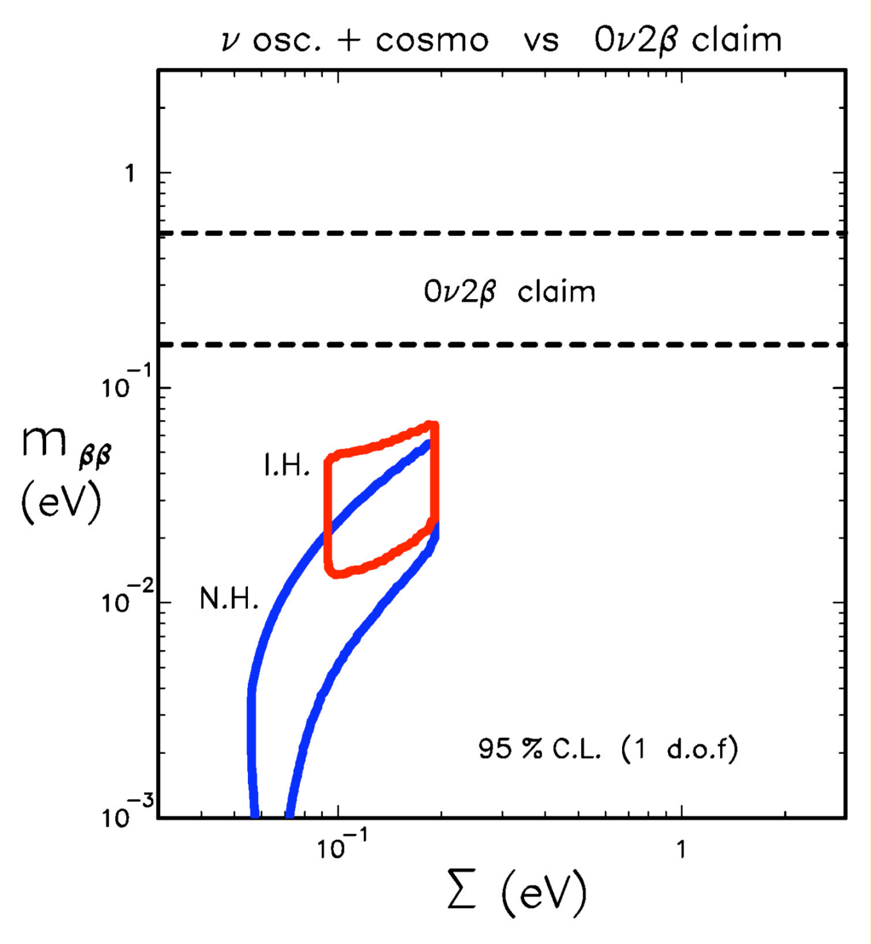
Upper limits in the range $\Sigma < 0.6$-1.2 eV have gained large consensus.

[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"



Status of absolute neutrino masses inconclusive…

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:

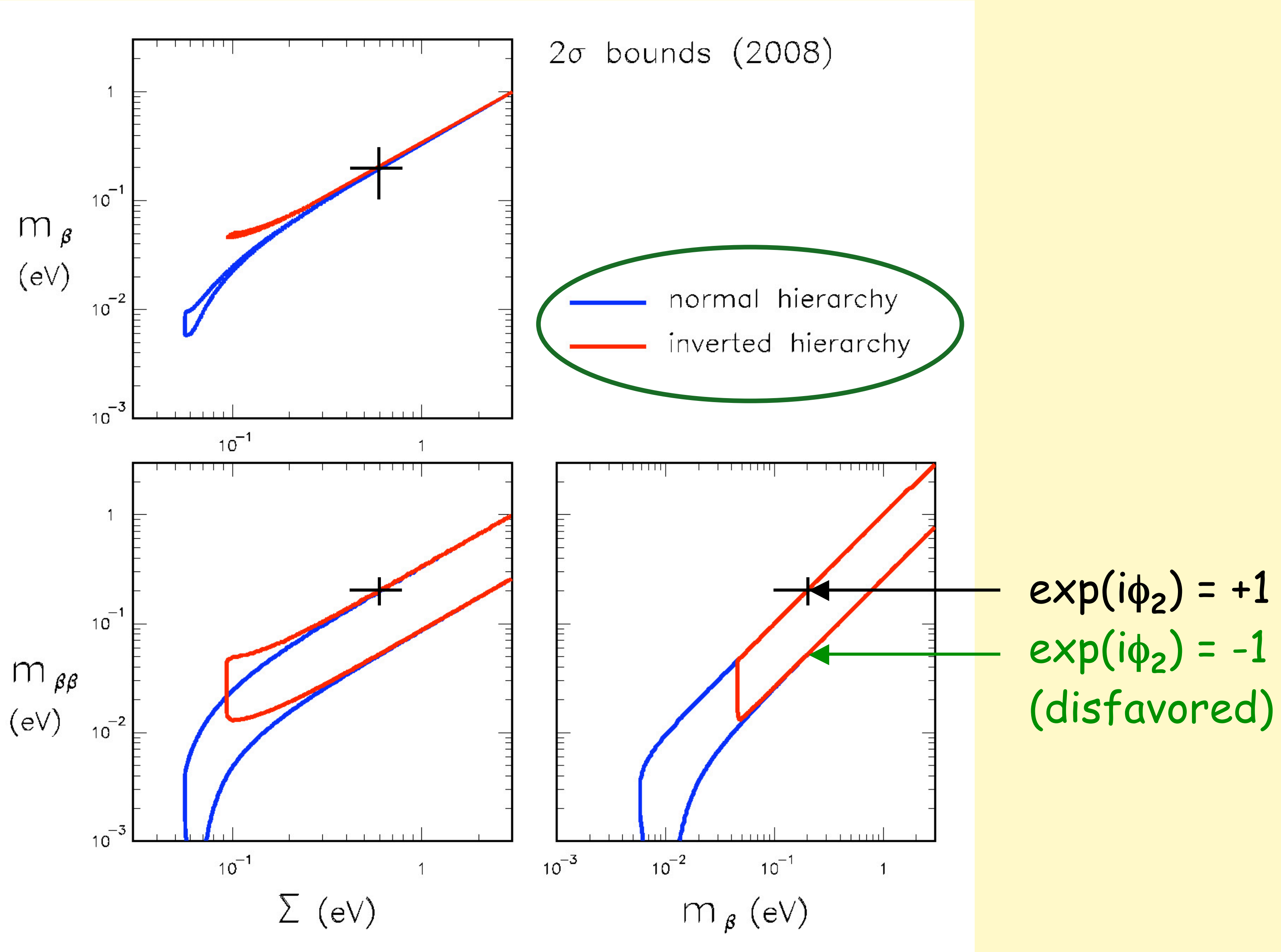
$$m_1 \sim m_2 \sim m_3 \sim 0.2\ \mathrm{eV}\ .$$

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

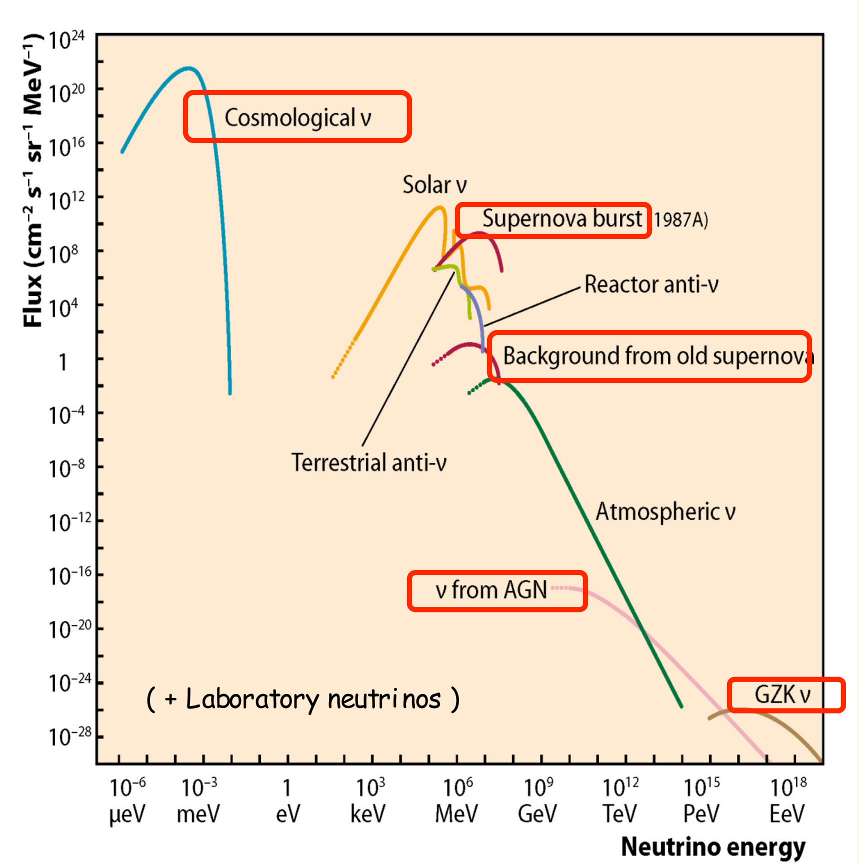
$$\begin{aligned} m_{\beta\beta} &\simeq 0.2(1 \pm 0.3)\ \mathrm{eV} \\ \Sigma &\simeq 0.6(1 \pm 0.3)\ \mathrm{eV} \\ m_\beta &\simeq 0.2(1 \pm 0.5)\ \mathrm{eV} \end{aligned}$$

In which case…

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



Just a dream? Maybe. However, “dreaming” is essential to face and overcome the many challenges of neutrino science (and technology!), including those related to cosmo/astro neutrino sources…



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

… whose discussion would require another seminar.

Thank you for your attention.