NNN05

Next Generation of **N**ucleon Decay and **N**eutrino Detectors

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Neutrino Parameters

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Mainly based on work done in collaboration with:
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Outline:

- 3ν mass-mixing parameters: notation, conventions, remarks
- Constraints on (Δm^2, $\sin^2\theta_{23}$, $\sin^2\theta_{13}$) from SK+K2K+CHOOZ
- Constraints on (δm^2, $\sin^2\theta_{12}$, $\sin^2\theta_{13}$) from solar+KamLAND
- “Grand total” from neutrino oscillation searches
- Constraints coming from observables probing absolute masses
- Galactic SN and Next generation of Nucleon decay and Neutrino detectors
- Conclusions

Disclaimer: references in proceedings, not in this ppt

3ν mass-mixing parameters: notation, conventions, remarks

3ν mixing: notation, conventions, remarks

"PDG" choice: $\nu_{\alpha L} = \sum_{i=1}^{3} U_{\alpha i}\, \nu_{iL}$ $(\alpha = e, \mu, \tau)$ $\leftarrow$ mixing of <u>fields</u>

so that: $|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}\, |\nu_i\rangle$ $(\alpha = e, \mu, \tau)$ $\leftarrow$ mixing of <u>states</u>

with: $U = O_{23}\, \Gamma_\delta\, O_{13}\, \Gamma^+_\delta O_{12}$

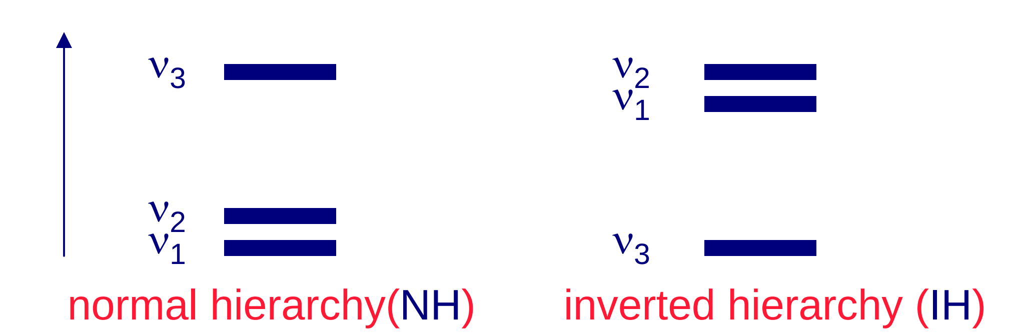
where:
- O_{ij} = real rotations by $\theta_{ij} \in [0, \pi/2]$ $\leftarrow$ mixing angles
- $\Gamma_\delta = \mathrm{diag}(1, 1, e^{i\delta})$ with $\delta \in [0, \pi/2]$ $\leftarrow$ CP phase

- No need to adopt a different convention, although many authors do it (e.g. by choosing $U \rightarrow U^*$, $\delta \rightarrow -\delta$, or both). Better to stick to PDG.

- In the following, numerical examples worked out only for the two <u>inequivalent</u> CP conserving cases $e^{i\delta} = \pm 1$ ($\delta = 0$ or $\delta = \pi$).

3ν masses: notation, conventions, remarks

- Most used ν_i labelling
  (including PDG & this talk)



i.e.:

$$\begin{cases} \Delta m^2_{21} = m^2_2 - m^2_1 > 0 \text{ , always} \\ \Delta m^2_{31} = m^2_3 - m^2_1 > 0 \text{ , normal} \\ \Delta m^2_{31} = m^2_3 - m^2_1 < 0 \text{ , inverted} \end{cases}$$

$\leftarrow$ conventional as far as $\theta_{12} \in [0, \pi/2]$

(normal, inverted) physically different

- Widely adopted notation:

$$(m^2_1 , m^2_2 , m^2_3) = m^2_1 + (0, \Delta m^2_{21}, \pm|\Delta m^2_{31}|)$$

$\begin{cases} + \text{ normal hierarchy} \\ - \text{ inverted hierarchy} \end{cases}$

But (NH) $\rightarrow$ (IH) mapping not exactly realized by just changing $\Delta m^2_{31} \rightarrow -\Delta m^2_{31}$, because

- in normal hierarchy, $|\Delta m^2_{31}|$ = largest squared mass difference
- in inverted hierarchy, $|\Delta m^2_{31}|$ = next-to-largest squared mass difference

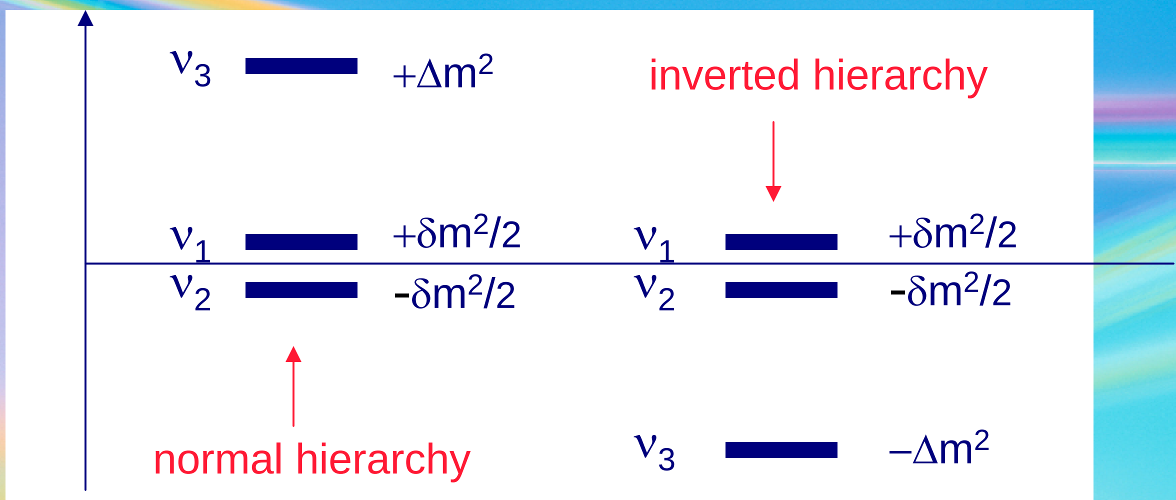
$\Rightarrow$ the above notation makes the comparison (NH) $\rightarrow$ (IH) tricky.

- For this reason, we prefer to adopt a more symmetrical convention,

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

with $\qquad \delta m^2=\Delta m^2_{21}$ $\qquad$ "solar splitting" as before

<u>but</u> $\qquad \Delta m^2=\dfrac{\Delta m^2_{31}+\Delta m^2_{32}}{2}$ $\qquad$ "atmospheric splitting" defined as the average of Δm^2_{31} and Δm^2_{32}



conventional "zero" of squared mass differences set at $\dfrac{m_1^2+m_2^2}{2}$

- With this convention, swapping hierarchy is exactly equivalent to swap $\pm\Delta m^2$:

$$(\mathrm{NH}\longleftrightarrow\mathrm{IH})\iff(+\Delta m^2\longleftrightarrow-\Delta m^2)$$

3ν Majorana phases: notation, conventions, remarks

- If $\nu = \bar{\nu}$ ➡ $U \to U \bullet U_M$ where U_M contains two independent Majorana phases

- PDG 2004 convention not unique:

$$\begin{cases} U_M = \mathrm{diag}(e^{\frac{i}{2}\alpha_1}, e^{\frac{i}{2}\alpha_2}, 1) & \to \quad \text{Kayser} \\ U_M = \mathrm{diag}(1, e^{\frac{i}{2}\alpha_1}, e^{\frac{i}{2}(\alpha_2+2\delta)}) & \to \quad \text{Vogel \& Piepke} \end{cases}$$

- We adopt the Vogel & Piepke convention (with a slight change of notation)

$$U_M = \mathrm{diag}(1, e^{\frac{i}{2}\phi_2}, e^{\frac{i}{2}(\phi_3+2\delta)})$$

so that the so-called "effective Majorana mass" in $0\nu2\beta$ decay reads

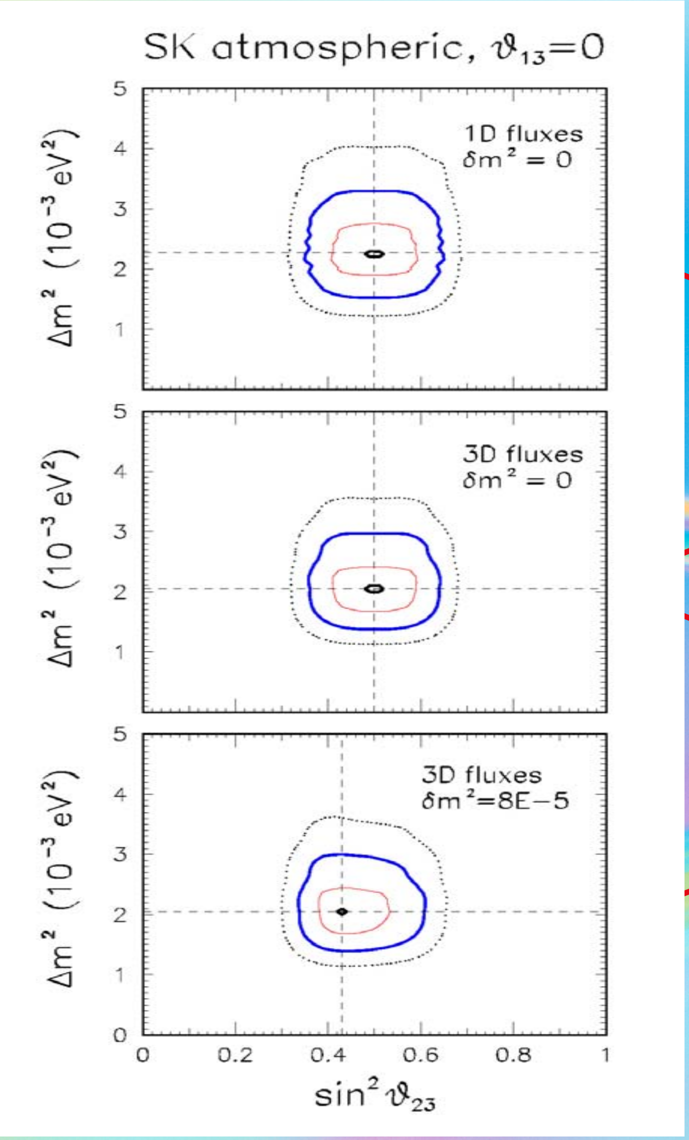
$$m_{\beta\beta} = \left|\sum U_{ei}^2 m_i\right| = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

not explicitly dependent on δ

- Convergence towards a unique convention on neutrino mixing angles, mass splittings and Majorana phases would be desirable.

Constraints on (Δm^2, $\sin^2\theta_{23}$, $\sin^2\theta_{13}$) from SK+K2K+CHOOZ

SK constraints on (Δm^2, $\sin^2\theta_{23}$) at $\sin^2\theta_{13} = 0$



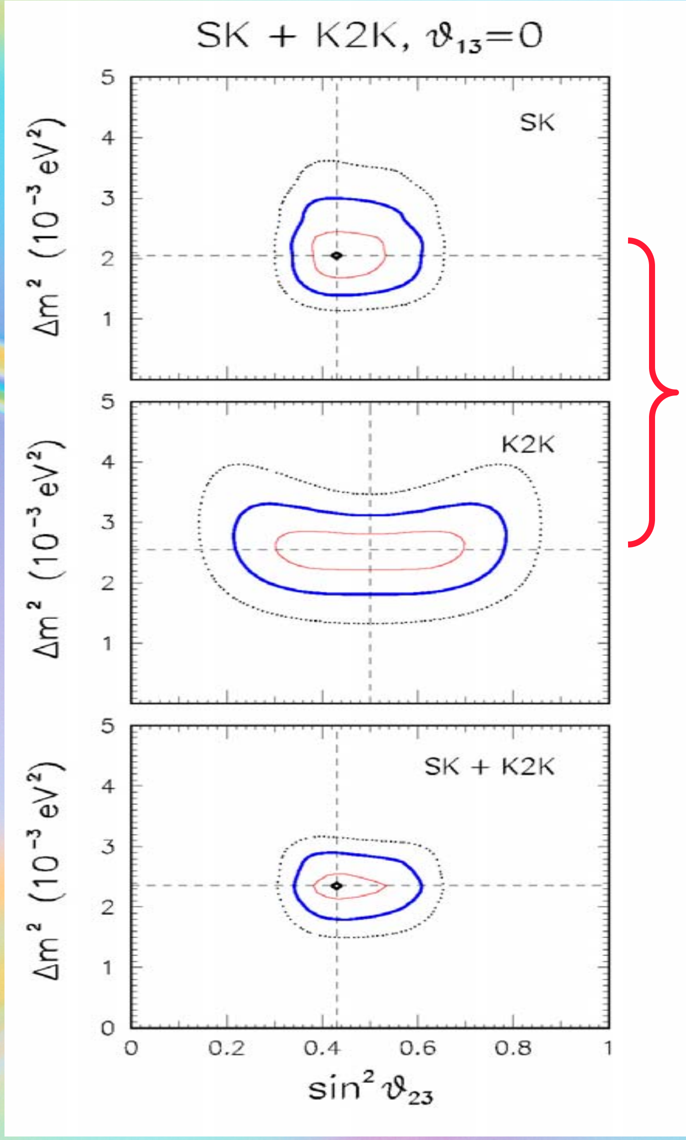
- 1σ, 2σ and 3σ contours ($\Delta\chi^2$ = 1, 4, 9) from SK atmospheric neutrinos (note linear scale).
- Some sensitivity to improved theoretical input:

about $-0.5\ \sigma$ shift of Δm^2
from 1D to 3D atmospheric ν fluxes

about $-0.5\ \sigma$ shift of $\sin^2\theta_{23}$
by including subleading effects due to LMA
($\delta m^2 \approx 8 \times 10^{-5}$ eV^2, $\sin^2\theta_{12} \approx 0.3$)

LMA-induced shift is small …

SK and K2K constraints on (Δm^2, $\sin^2\theta_{23}$) at $\sin^2\theta_{13} = 0$



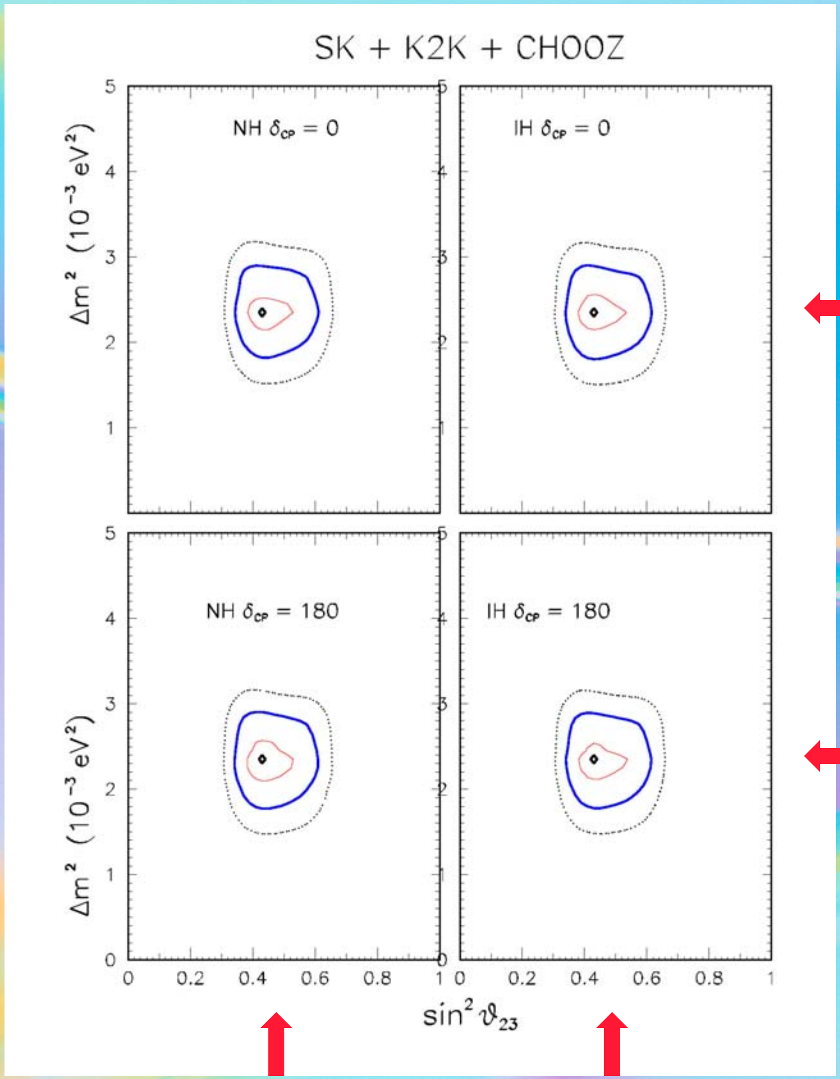
… but unaltered by K2K (~ poorly sensitive to s^2_{23})

Main effects of adding K2K:

- upward shift of the best-fit of Δm^2
- significant reduction of the upper uncertainty on Δm^2

A joint, official SK + K2K combination would be desirable (note that interaction and detection systematics are similar and correlated in SK and K2K).

Constraints on (Δm^2, $\sin^2\theta_{23}$) adding CHOOZ, with $\sin^2\theta_{13}$ unconstrained



$\delta = 0$

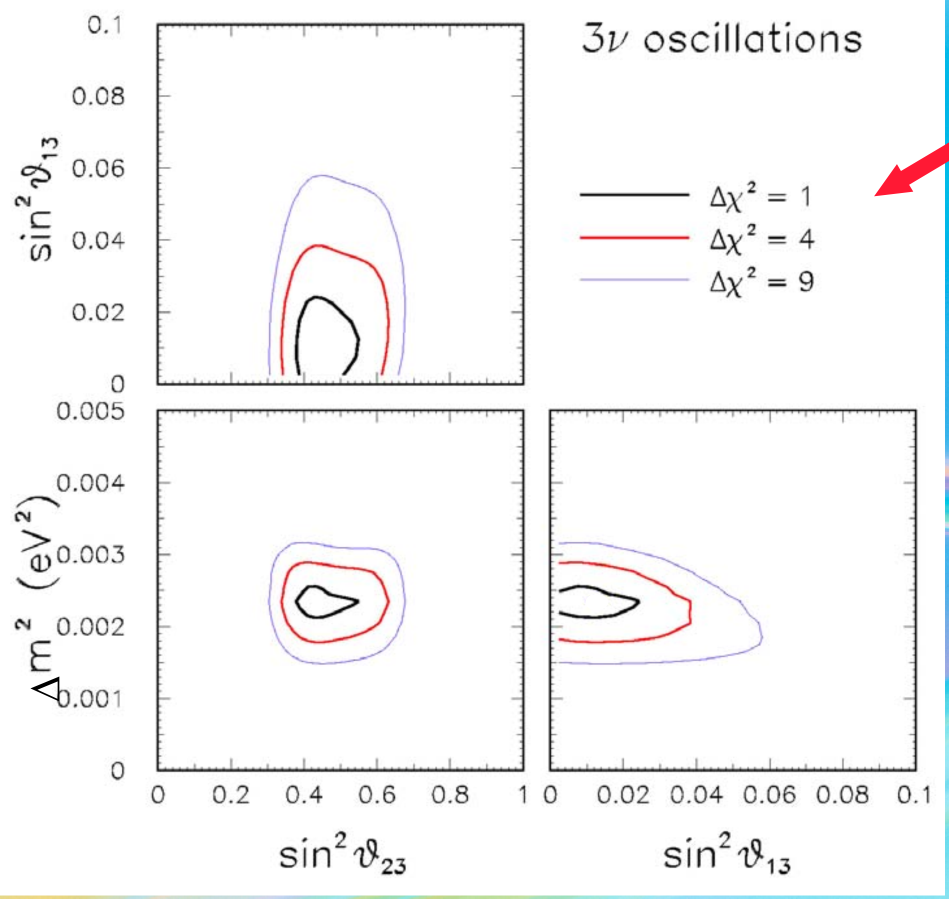
$\delta = \pi$

normal hierarchy

inverted hierarchy

- Current results basically unchanged by leaving s^2_{13} unconstrained (with CHOOZ data added) and by swapping hierarchy and/or CP-conserving cases
- Reason: $s^2_{13} \sim 0$ preferred by data, and for $s^2_{13} \to 0$ predictions converge in the four panels.
- Situation may change if, e.g., a future reactor experiment finds $s^2_{13} \neq 0$. In this case the current degeneracy among the four panels could be slightly lifted (not shown).

Constraints on (Δm^2, $\sin^2\theta_{23}$, $\sin^2\theta_{13}$) from SK + K2K +CHOOZ



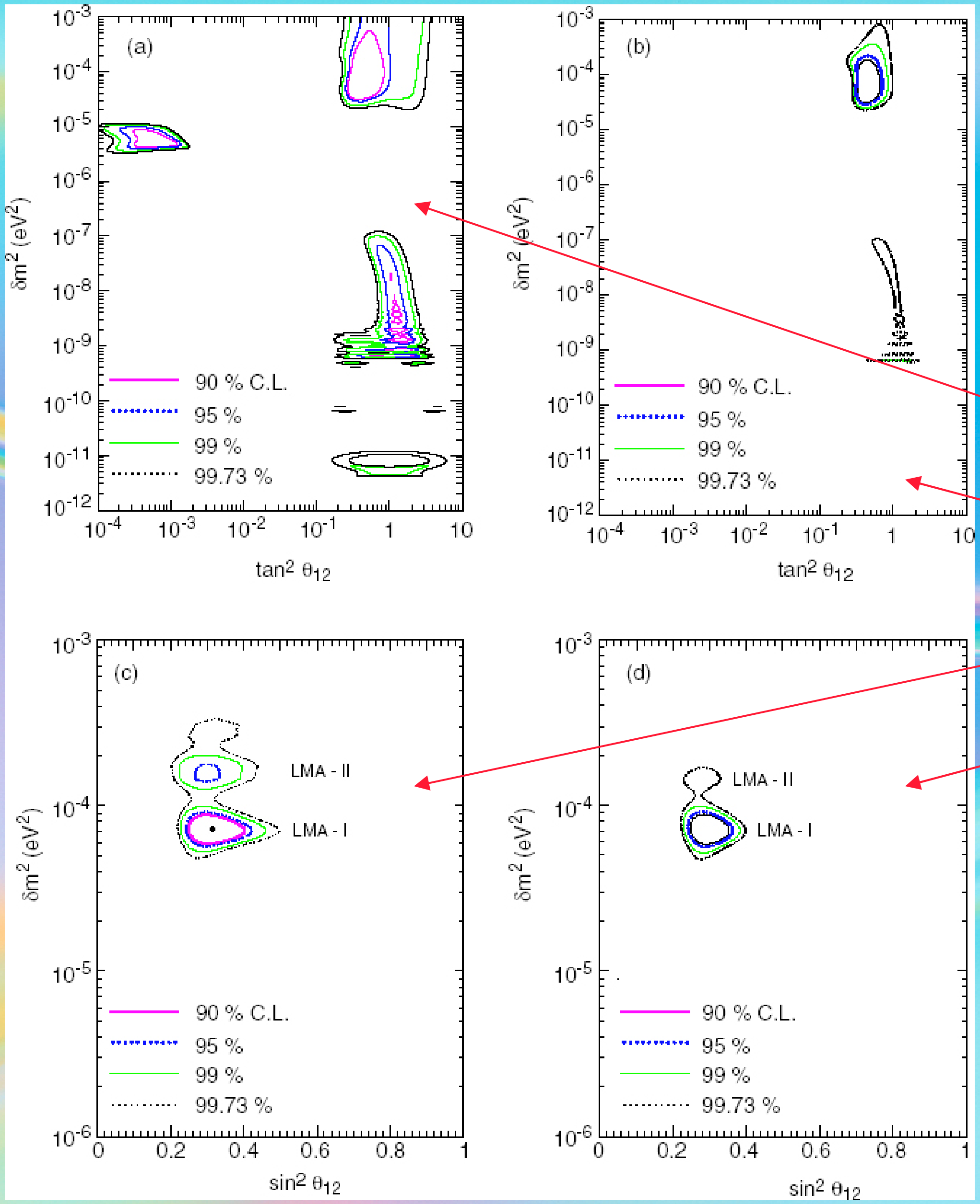
- Global SK+K2K+CHOOZ analysis if we marginalize over the 4 cases:

$$\left(\mathrm{sign}(\Delta m^2) = \pm 1\right) \otimes \left(e^{i\delta} = \pm 1\right)$$

- Note: very weak correlations among the leading parameters

$$\Delta m^2,\ \sin^2\theta_{23},\ \sin^2\theta_{13}$$

Constraints on (δm^2, $\sin^2\theta_{12}$, $\sin^2\theta_{13}$) from solar neutrinos + KamLAND



"Historical" notes

- **2001-2003**

  Dramatic reduction of the ($\delta m^2, \theta_{12}$) parameter space (note change of scales)

  Cl+Ga+SK (2001)

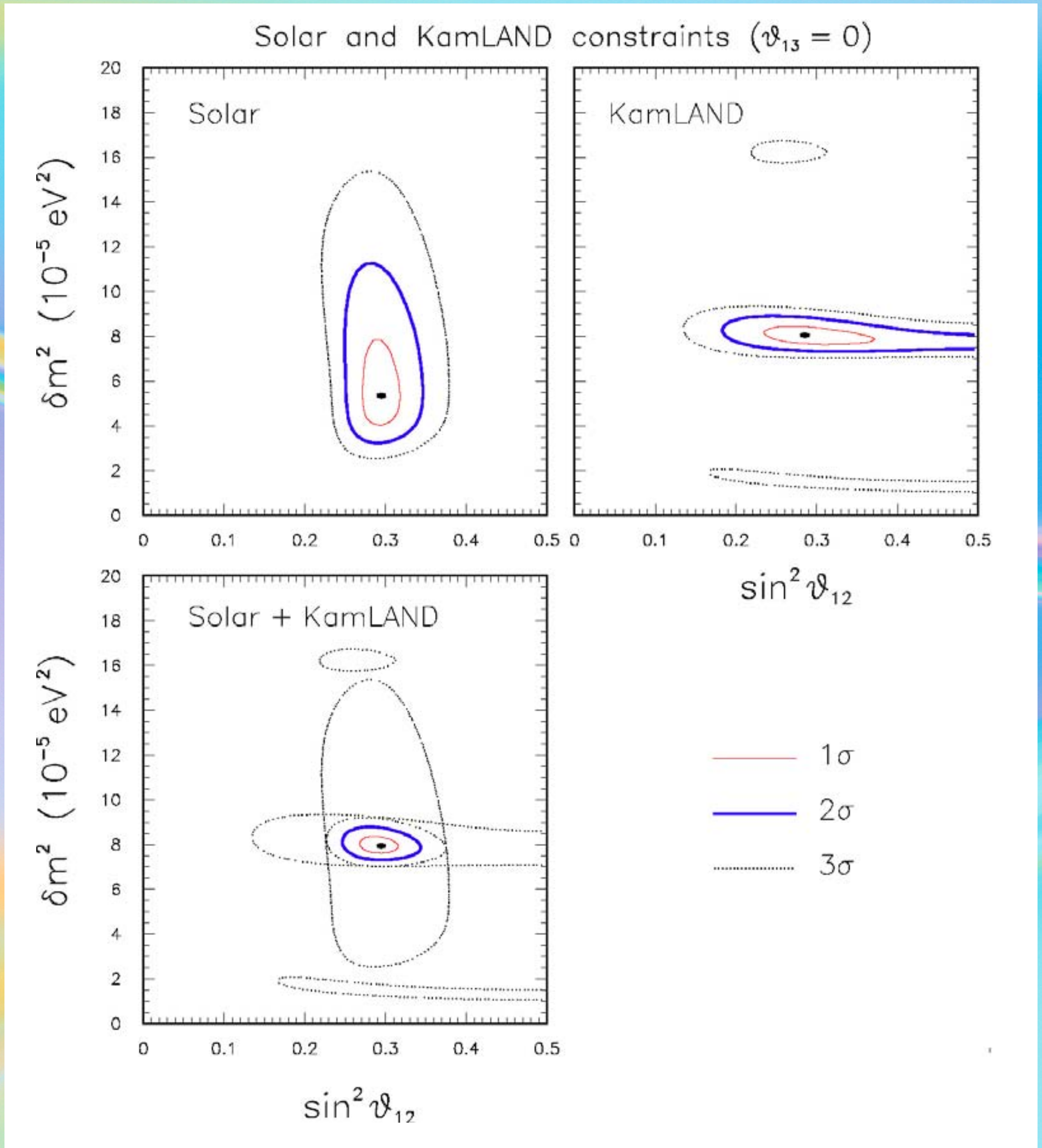
  +SNO-I (2001-2002)

  +KamLAND-I (2002)

  +SNO-II (2003)

- Direct proof of solar $\nu_e \rightarrow \nu_{\mu,\tau}$ in SNO through comparison of CC, NC (and ES)

… in 2004 at $\theta_{13} = 0$



Adding KamLAND-II
(with revised background):

unique Large Mixing Angle solution,
(and another change of scale…)

What about MSW effects in the Sun ?

Approach:

- Change MSW potential "by hand"

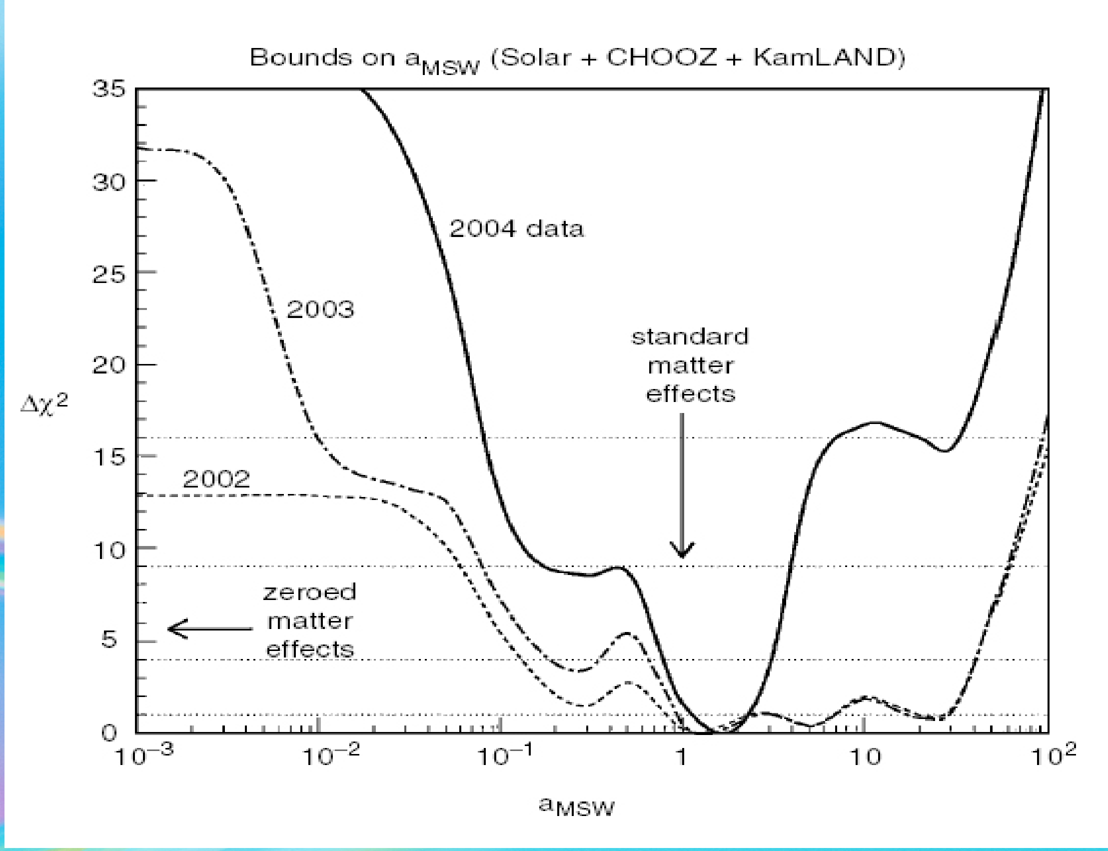
  $V \to a_{MSW} V$

- Reanalysis of all data in terms of

  $(\delta m^2, \theta_{12}, a_{MSW})$

- Project $(\delta m^2, \theta_{12})$ away and check if

  $a_{MSW} \sim 1$



Results:

with **2004** data,

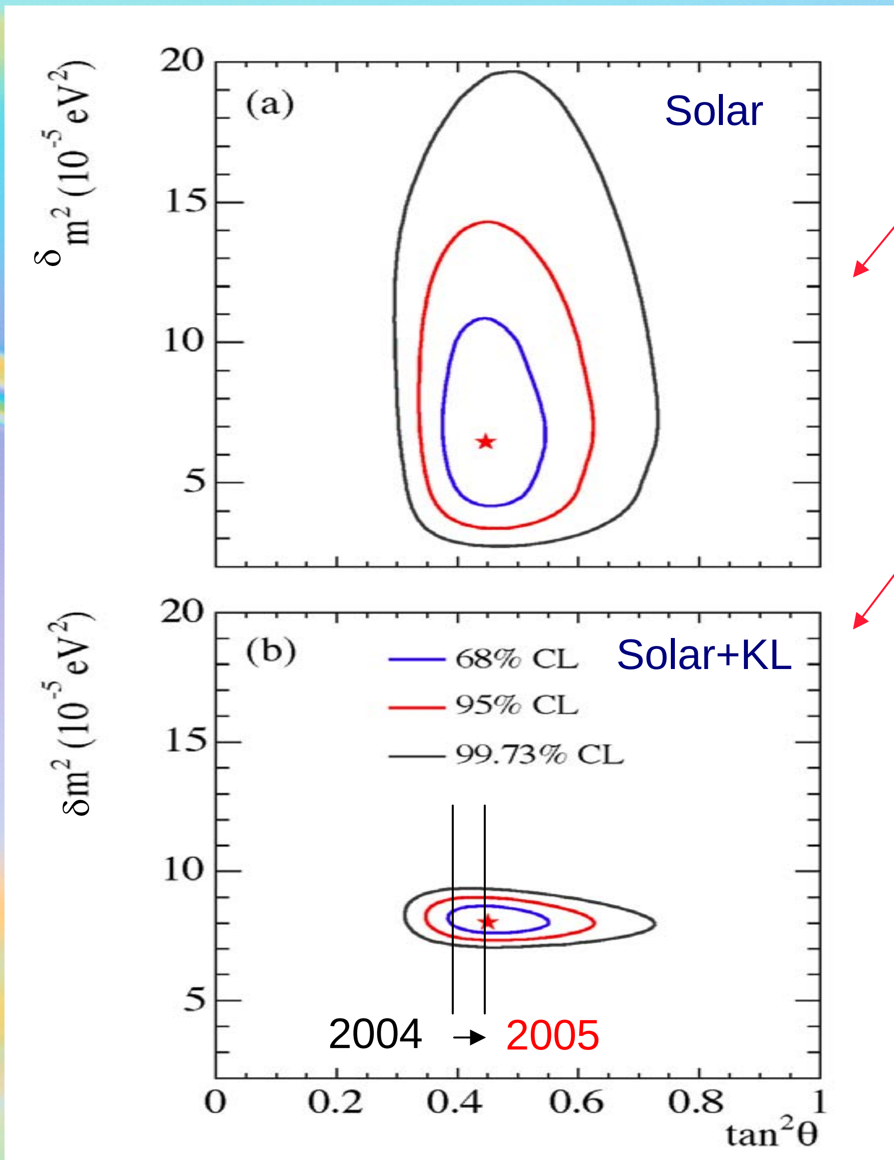
- $a_{MSW} \sim 1$ within a factor ~ 2
- $a_{MSW} \sim 0$ excluded

evidence for MSW effects in the Sun

But: expected subleading effect in the Earth (day-night difference) still below experimental uncertainties.

(… a way of "measuring" G_F through solar neutrino oscillations …)

2005 (last month)



New data + detailed analysis from SNO

- Previous results basically confirmed
- Slightly higher ratio

  CC/NC ~ P($\nu_e \rightarrow \nu_e$)
- Slight shift (<1σ upwards) of the allowed range for

  θ_{12}

3ν analysis of **2004** solar + KamLAND data (θ_{13} free)

- Solar and KamLAND data also prefer

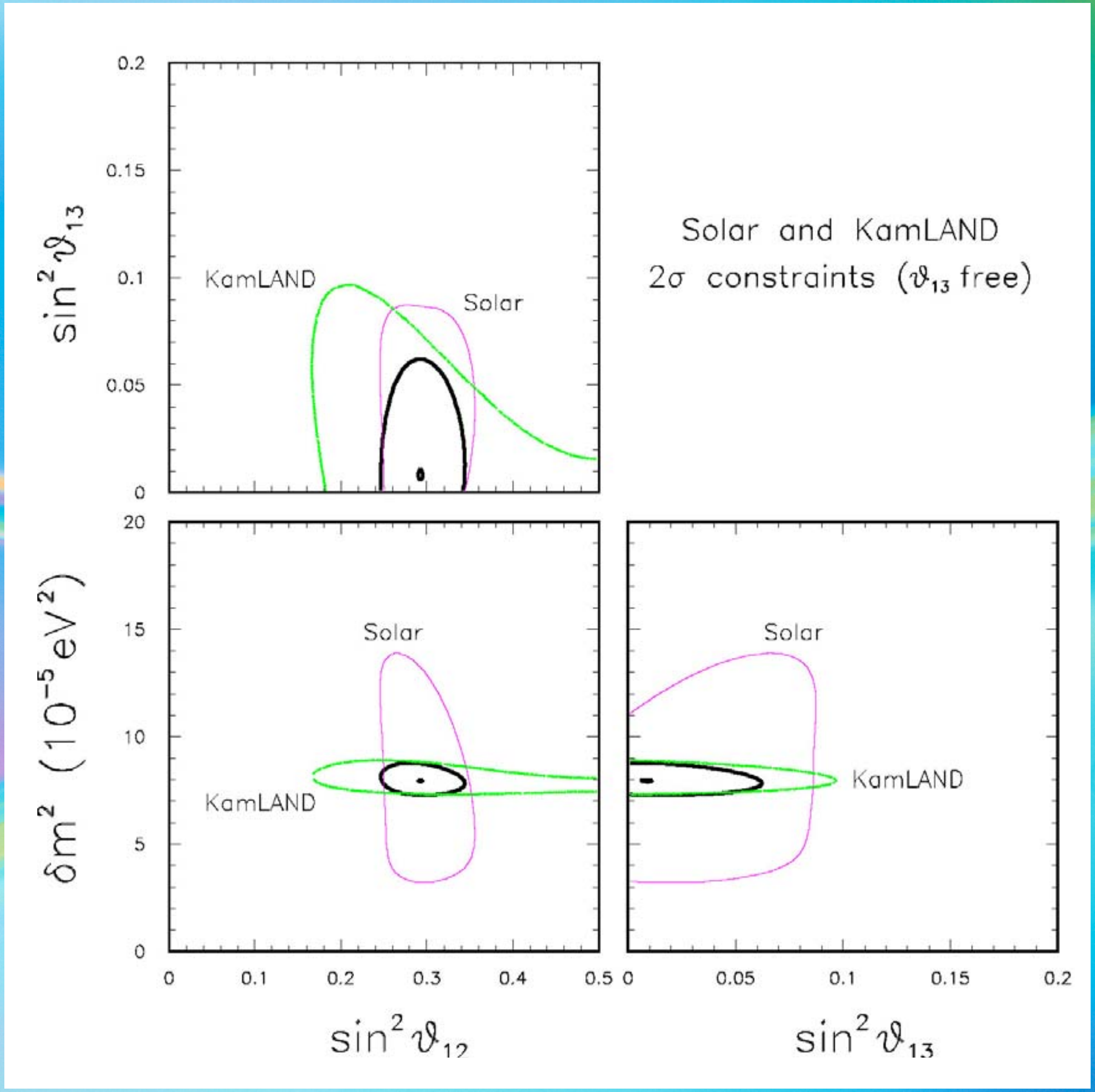
  $\theta_{13} \sim 0$

  ↓

  consistency with SK + CHOOZ (non trivial)

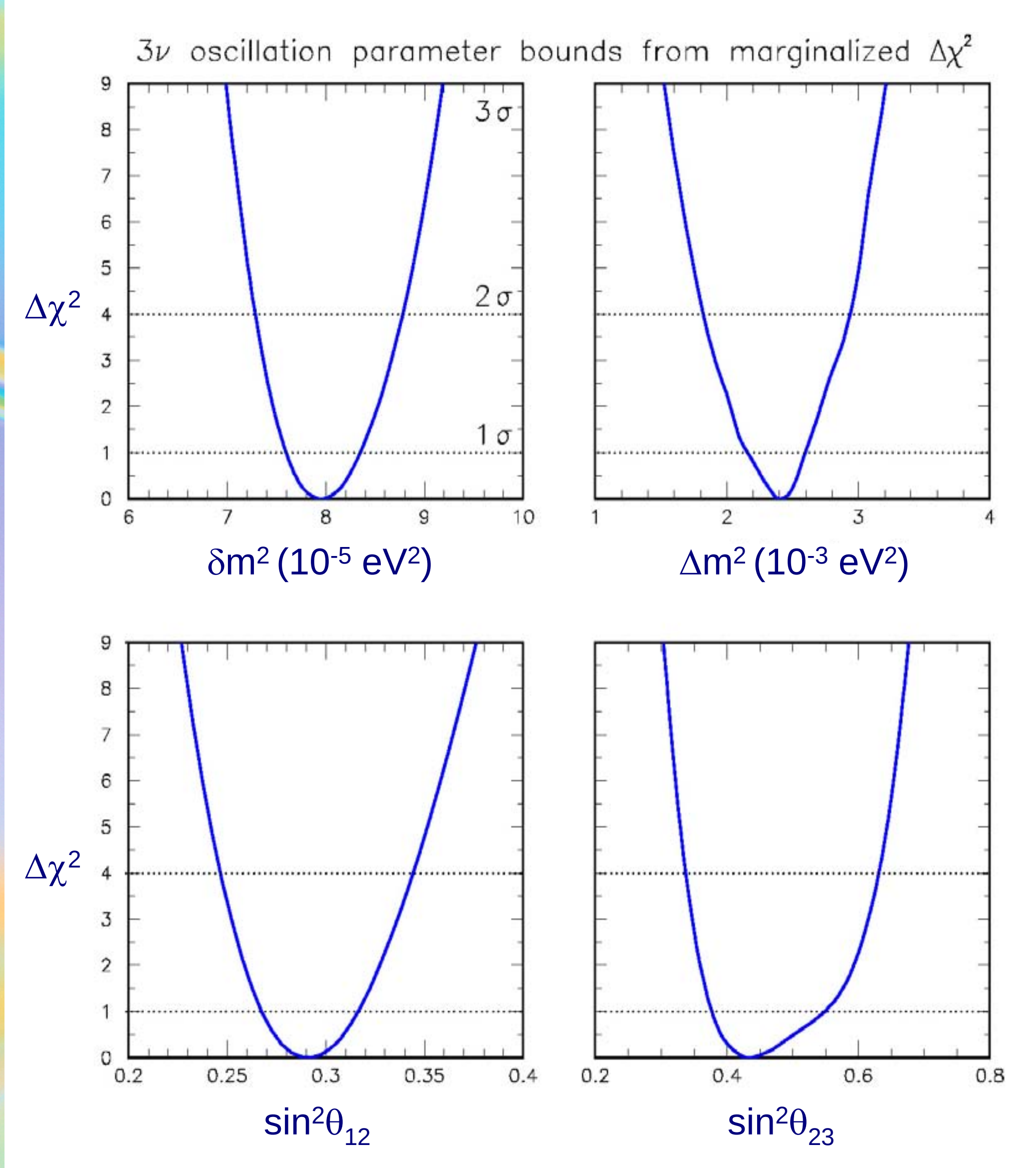
- Present bounds on (δm^2,θ_{12}) not significantly altered for unconstrained θ_{13}

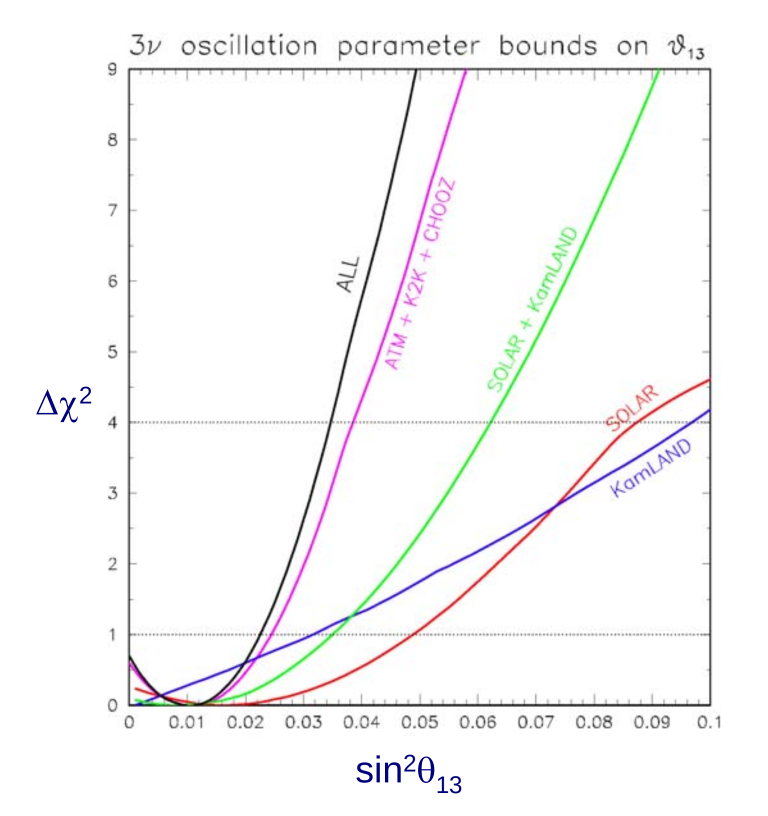
[SNO 2005 data not included]



“Grand Total” from global analysis of oscillation data

Marginalized $\Delta\chi^2$ curves for each parameter (2004)





Consistency of all data in preferring

$\sin^2\theta_{13} \sim 0$

(best fit ≠ 0, but not statistically significant)

Numerical ± 2σ ranges (95% CL for 1 dof), 2004 data

$$\delta m^2 = 8.0 \,^{+0.8}_{-0.7} \times 10^{-5}\ \mathrm{eV}^2$$

$$\Delta m^2 = 2.4 \,^{+0.5}_{-0.6} \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2\theta_{12} = 0.29 \,^{+0.05}_{-0.04}$$

SNO'05: $0.29 \rightarrow 0.31$

$$\sin^2\theta_{23} = 0.45 \,^{+0.18}_{-0.11}$$

$$\sin^2\theta_{13} \leq 0.035$$

sign($\pm\,\Delta m^2$): unknown

CP phase δ: unknown

Probing absolute ν masses through non-oscillation searches

Three main tools, identified with three observables sensitive to absolute ν masses

1) β **decay**: $m_i \neq 0$ can affect the spectrum endpoints. Sensitivity to the so-called "effective electron mass": *(most direct method)*

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

2) **0ν2β decay**: can occur if $m_i \neq 0$ and $\nu = \bar{\nu}$. Sensitivity to the so-called "effective Majorana mass" (and phases):

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

3) **Cosmology**: $m_i \neq 0$ can affect large scale structure in (standard) cosmology, constrained by CMB and other cosmological observations. They probe:

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

In the following we present a global phenomenological analysis of the constraints applicable in the parameter space

$$(m_\beta,\ m_{\beta\beta},\ \Sigma)$$

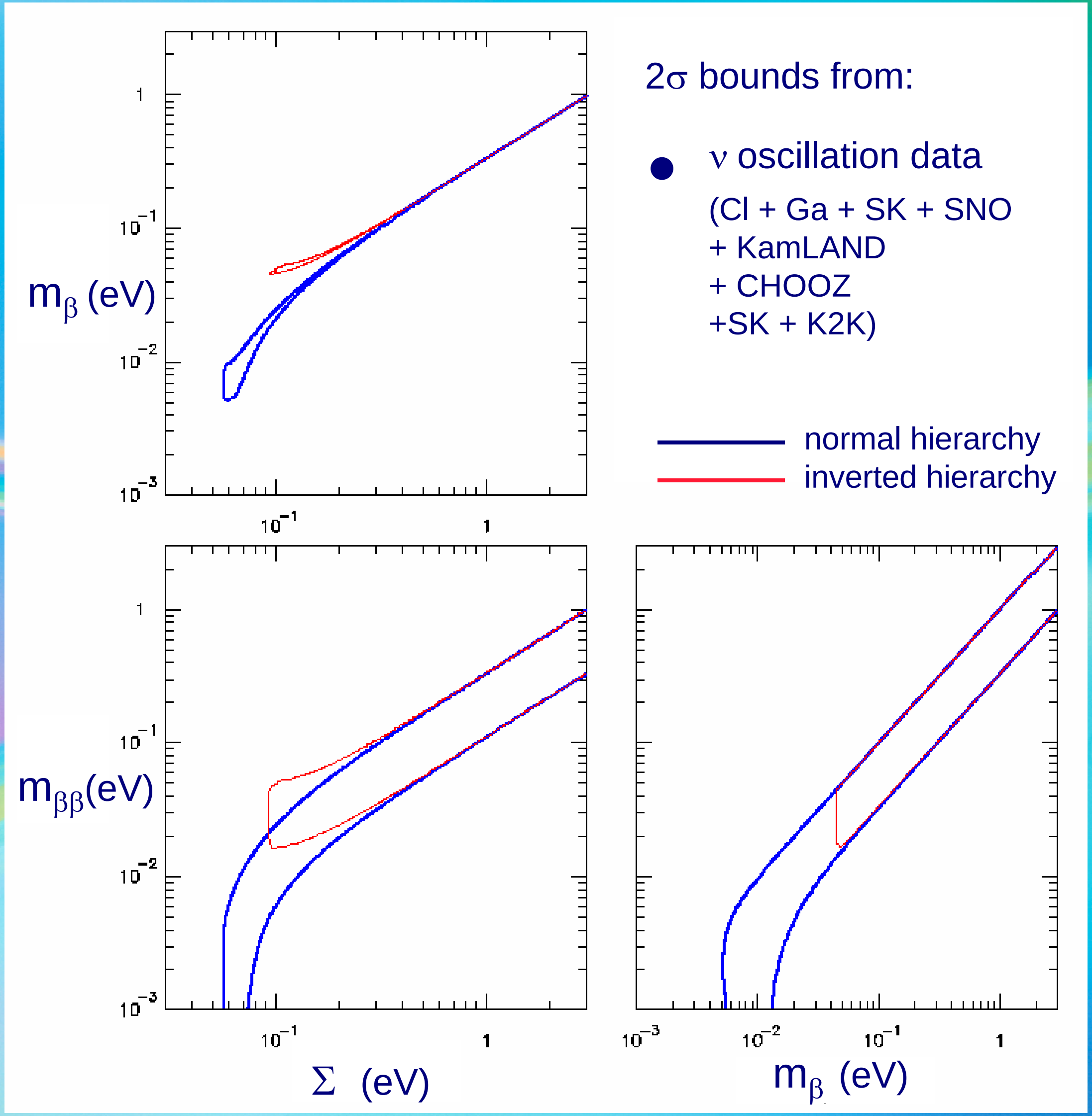
for both normal and inverted hierarchies.

Constraints from oscillation data only

Even without non-oscillation data the (m_β, $m_{\beta\beta}$, Σ) parameter space is constrained by the oscillation results.

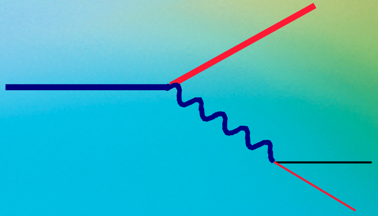
Note:

- Significant correlations
- Partial overlap between the two hierarchies
- Large $m_{\beta\beta}$ spread due to the unknown Majorana phases



Input from Tritium β-decay experiments

$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$



Updated determinations:

Mainz ⇨ $m_\beta^2 = -1.2 \pm 3.0 \text{ eV}^2$

Troitsk ⇨ $m_\beta^2 = -2.3 \pm 3.2 \text{ eV}^2$

→ by restricting the domain to the physical region

$m_\beta < 2.2$ eV 95% C.L.

$m_\beta < 2.1$ eV 95% C.L.

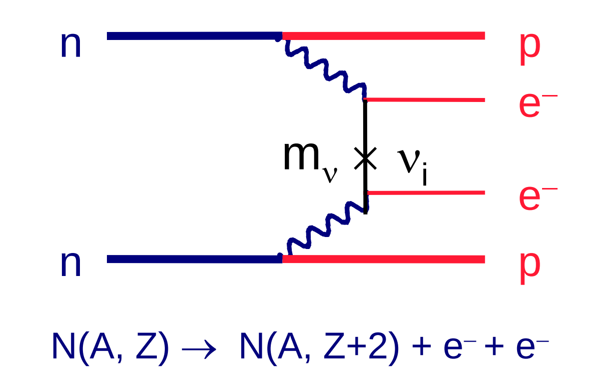
By combining the two determinations

$m_\beta < 1.8$ eV at 95% C.L. (Mainz + Troitsk)

- Limit less conservative than in other approaches
  [3 eV recommended in Review of Particle Physics, S. Eidelman et al., Phys. Lett. B592 (2004)1]
- In any case, present limits too weak to contribute significantly to restrict the parameter space

$$(m_\beta, m_{\beta\beta}, \Sigma)$$

Input from Germanium $0\nu2\beta$-decay experiments



Several experiments, using different isotopes, with negative results.

Recently, members of the Heidelberg-Moscow experiment have claimed the detection of a $0\nu2\beta$ signal from the ^{76}Ge isotope.

From the available estimates of the nuclear matrix elements with their uncertainties one can derive an estimate of the "effective Majorana mass". However, since the claim from Heidelberg-Moscow has been subject to criticism, in the following, we assume two possible $0\nu2\beta$ inputs for the global analysis (1σ error)

$$\begin{cases} \log_{10}(m_{\beta\beta}/\mathrm{eV}) = -0.23 \pm 0.18 & 0\nu2\beta \textbf{ claim assumed} \\ \log_{10}(m_{\beta\beta}/\mathrm{eV}) = -0.23^{+0.18}_{-\infty} & 0\nu2\beta \textbf{ claim rejected} \text{ (only upper limit)} \end{cases}$$

Finally, concerning the two unknown Majorana phases,

ϕ_2, ϕ_3 are assumed independent and uniformly distributed in the range $[0, \pi]$

Constraint on Σ from cosmological data

Likelihood distribution for Σ from joint analysis of several data sets. No evidence for a ν mass and upper bounds depending on several inputs and priors. In particular

- CMB + LSS (+ SN-Ia + HST)

  with LSS from SDSS - - - - - / 2dF ———

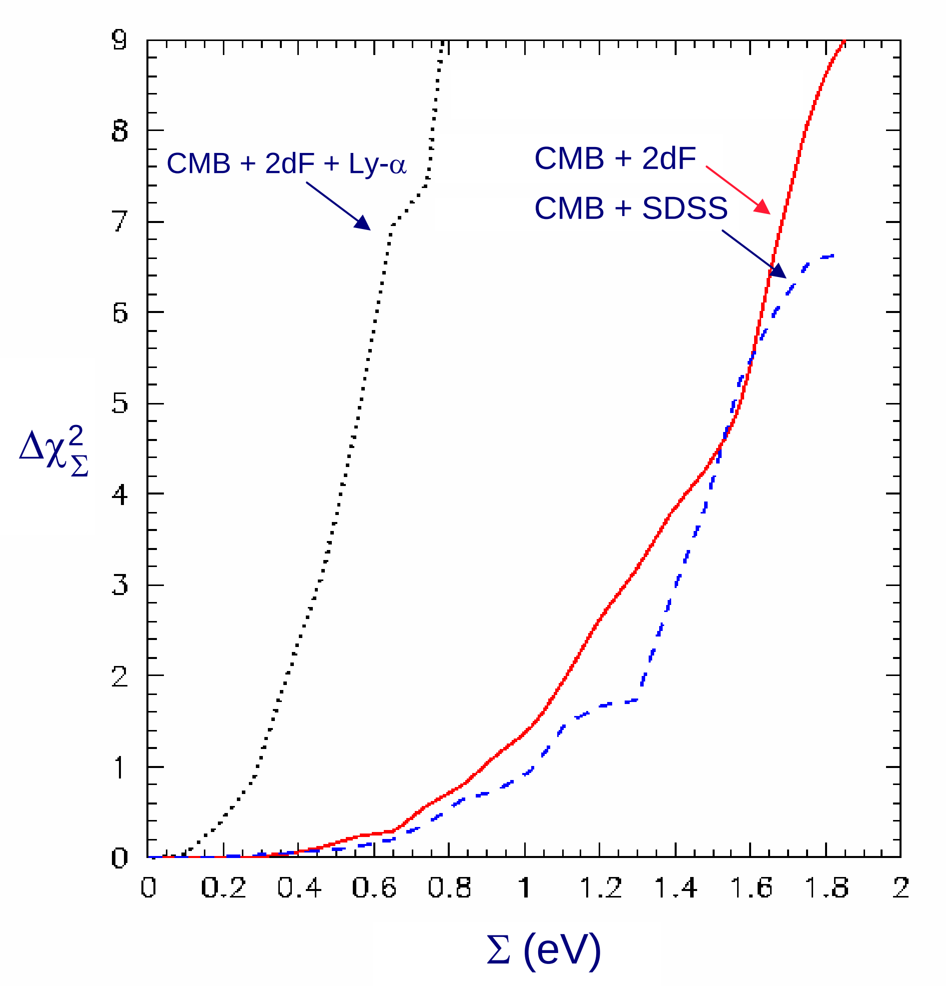
  ➡ $\Sigma < 1.4$ eV (2σ)

- the same + Lyman-α from SDSS

  (with LSS from SDSS)

  ➡ $\Sigma < 0.47$ eV (2σ)

  even though the effect of systematics needs here to be explored further.



Adding upper bounds from laboratory and cosmology

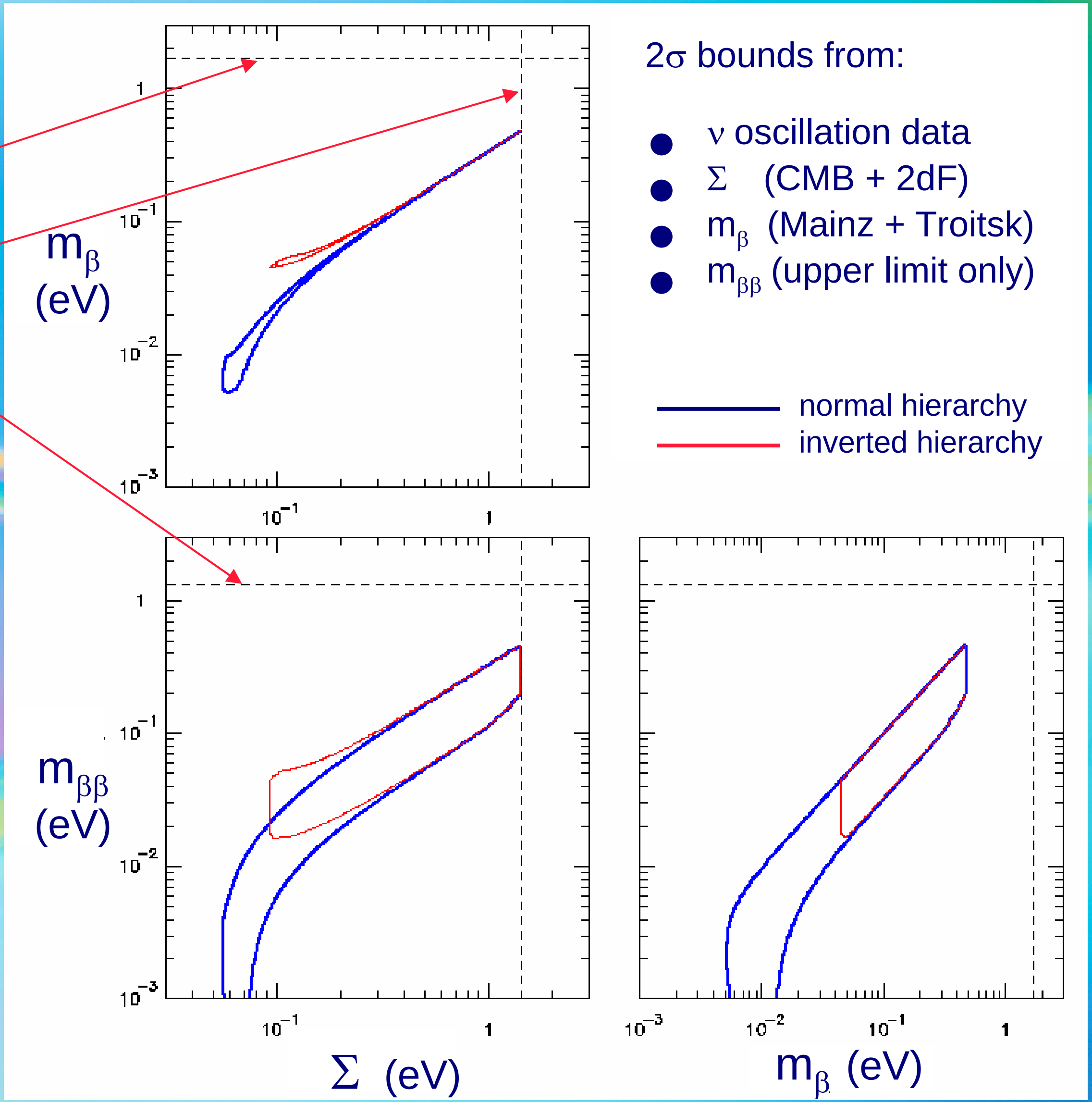
Added to the ν oscillation data the bounds (2σ level) on

- m_β (Mainz + Troitsk)
- Σ (CMB + 2dF)
- $m_{\beta\beta}$ (upper limit only)

The cosmological upper limit on Σ formally dominates over the lab upper limits on m_β and $m_{\beta\beta}$

⬇

This bound, via the correlations induced by oscillation data, provides upper limits also on m_β and $m_{\beta\beta}$, stronger than the present lab limits by a factor ~ 4.



Adding lower bounds on $m_{\beta\beta}$ from the claimed $0\nu2\beta$ signal

Added a lower bound on $m_{\beta\beta}$ at the 2σ level.

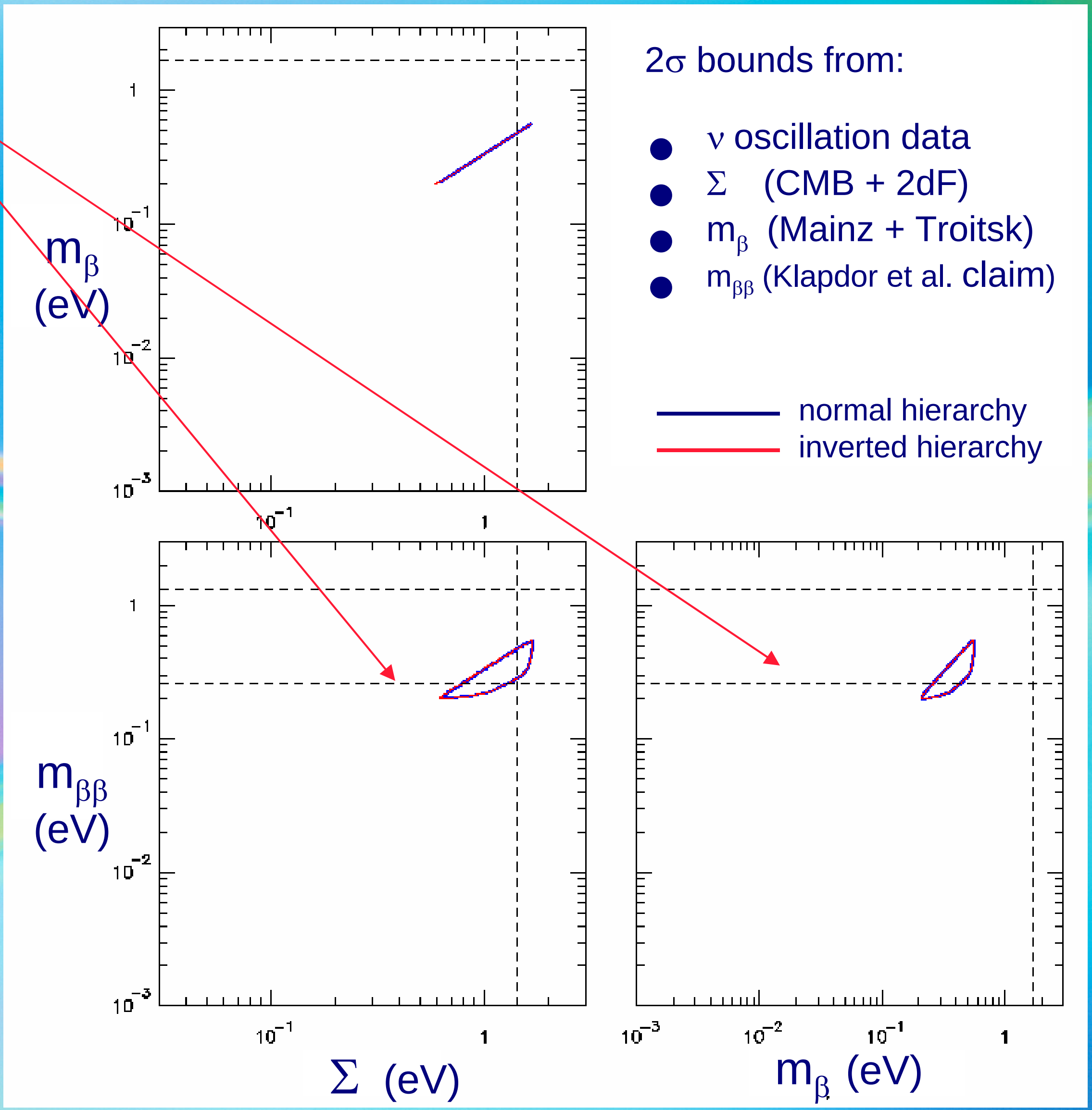
2σ bounds from:

- ν oscillation data
- Σ (CMB + 2dF)
- $m_{\beta\beta}$ (Klapdor et al. claim)
- m_{β} (Mainz + Troitsk)

still not relevant in the global fit

Combination of all data possible, with overlap of the two hierarchies (degenerate spectrum with "large" masses).

However, the global allowed region extends somewhat outside the 2σ limits from cosmology and $0\nu2\beta$ data separately: a clear indication of some tension between the two sets of data.



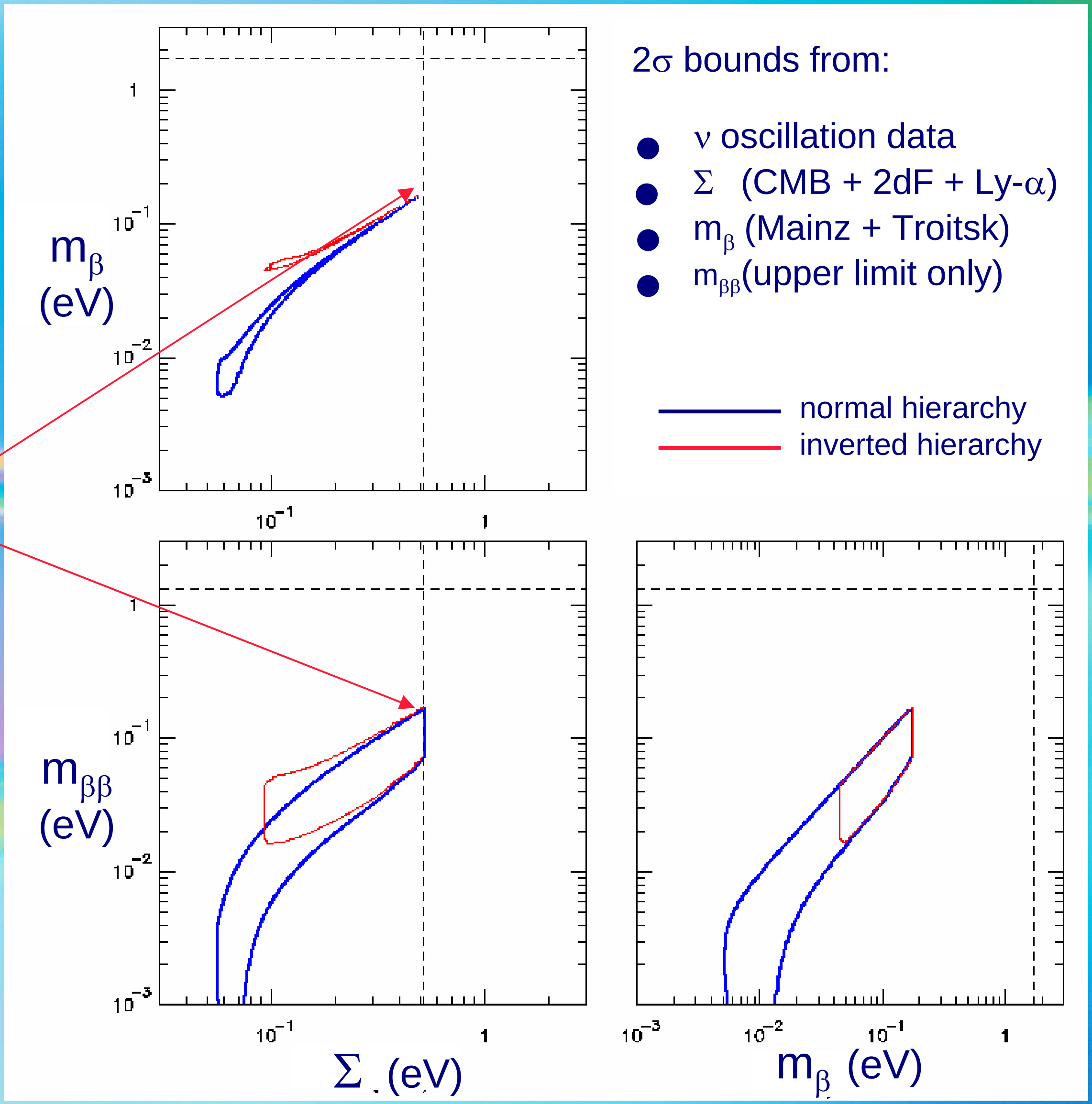
Adding Lyman-a forest to cosmological data

This modifies the upper limit on Σ, improved by a factor ~ 3.

A. <u>$0\nu2\beta$ claim rejected</u>

The upper limit on Σ, through the correlation effects, transforms into upper limits on m_β and $m_{\beta\beta}$, an order of magnitude stronger than the present upper limits.

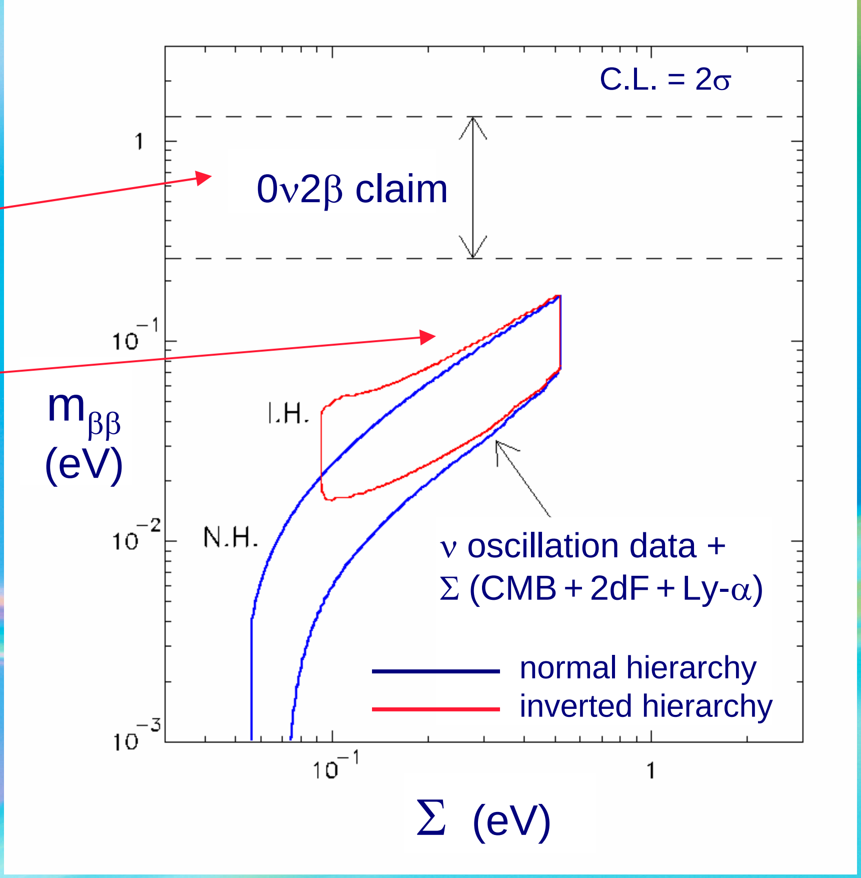
- Bounds strong enough to approach the regime of partially degenerate spectrum.
- Bounds set very stringent limits for future lab experiments (~ factor 10 of improvement).



B. $0\nu2\beta$ claim accepted

The strong upper bound on Σ increases the tension between cosmological data and $0\nu2\beta$ claim.

- $0\nu2\beta$ claim
- cosmological and oscillation data



The absence of overlap is a clear symptom of problems either in some data or in the theoretical interpretation, and prevents any global combination of data. However …

> It is premature to conclude that the $0\nu2\beta$ claim is "ruled out" by cosmological data

indeed
- cosmological data are rather indirect
- systematics of Lyman-α data are still to be scrutinized carefully

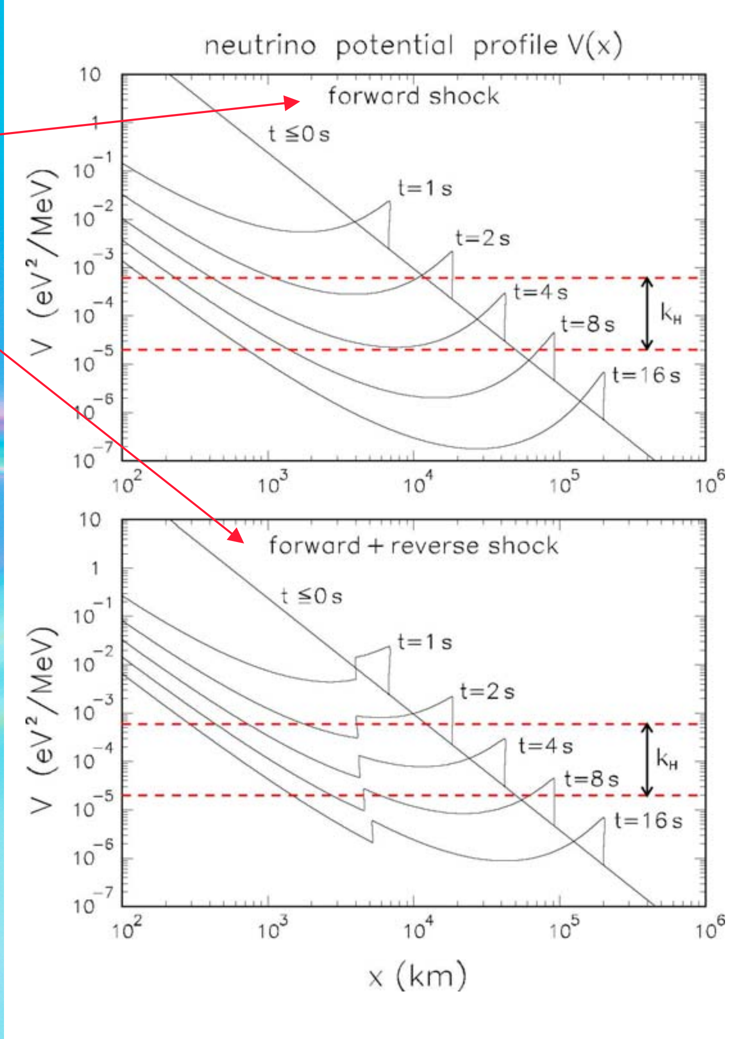
and more generally
- $0\nu2\beta$ decay might receive contribution from new physics effect beyond light Majorana ν
- some assumptions about standard three ν mixing and cosmological scenarios may be wrong

Galactic SN and Next generation of Nucleon decay and Neutrino detectors

NNN detectors and galactic SN

Two of the currently unknown parameters, sign(Δm^2) and θ_{13}, might be accessed in a large scale (e.g. 0.4 Mton) Cherenkov detector through their effect on supernova ν oscillations.

- Radial profiles of the ν potential **V(x)** at different times **t** for simplified SN shock-waves:
  - upper panel: forward shock only
  - lower panel: forward plus reverse shock



- Main feature is a sharp discontinuity at the shock front (which can induce a strongly non-adiabatic transition) leaving behind an extended rarefaction zone.

- In both panels, the band shown are spanned by the ν wavenumber $\mathbf{k_H} = \Delta m^2/2E$ for $E \in [2,60]$ MeV. The band marks the region where matter effects are potentially important ($V \sim k_H$).

- From the radial profiles one can derive the so-called crossing probability P_H

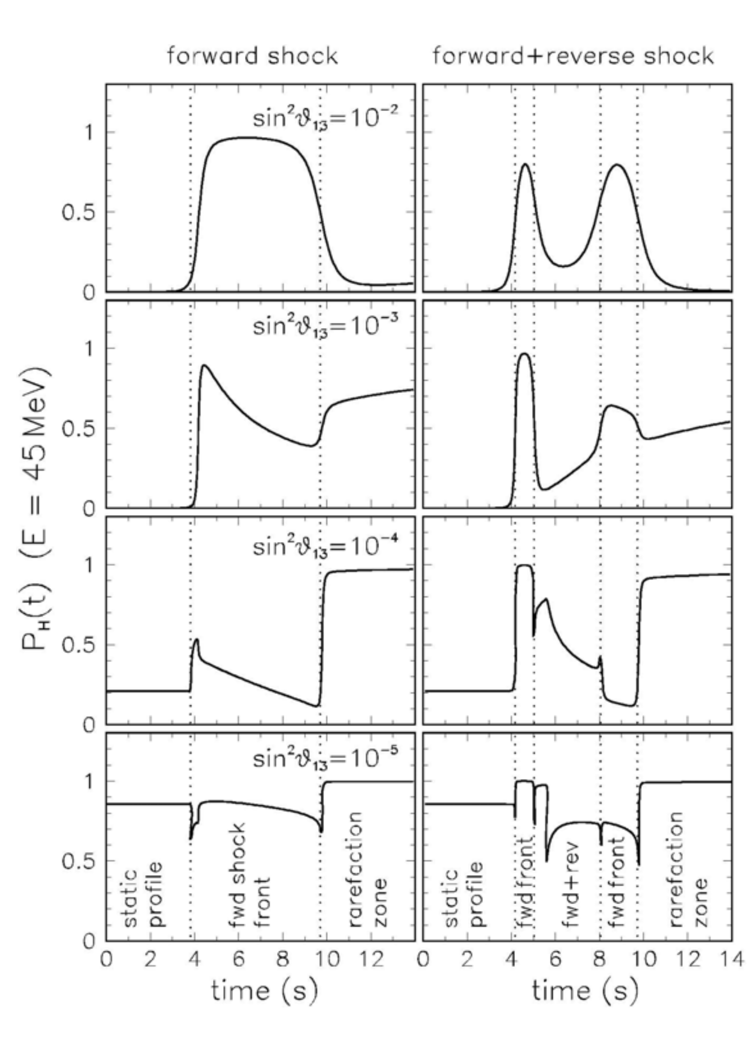
$$P_H = P_H[\Delta m^2/E, \sin^2\theta_{13}, V(x,t)]$$

Neutrino crossing probability

On the basis of the shock wave profiles, the ν crossing probability $P_H(t)$ can be estimated for representatives values of $\sin^2\theta_{13}$ and fixed E_ν.

- In the figure we report $P_H(t)$ for
  - relatively large ν energy (E_ν = 50 MeV);
  - $\sin^2\theta_{13} = 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}$;
  - both shock wave profiles.

- $P_H(t)$ changes rapidly at the times indicated by dotted vertical lines:
  - For forward shock waves, when the static profiles is first perturbed by the forward shock front and then by the rarefaction zone.
  - For forward+reverse shock waves, both forward and reverse shock fronts perturb the static profiles.



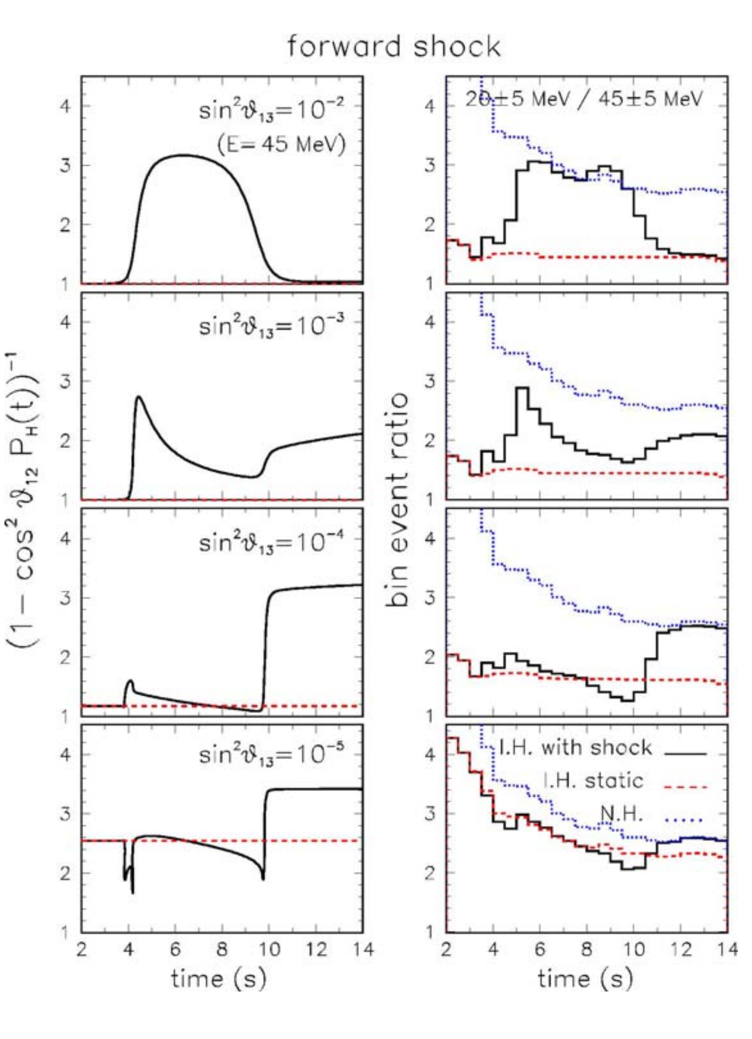
Signatures of shock wave effects

An analysis of the absolute time spectra shows that the signatures of shock wave effects can be enhanced by comparing time spectra at different energies.

- In particular, in the case of **inverted hierarchy,** with a proper choice of E_c and E_H we have

$$\frac{N(E_c, t)}{N(E_H, t)} \sim [1 - \cos^2\theta_{12} P_H(E_H,t)]^{-1}$$

- We can track the crossing probability (if the ν mass hierarchy is inverted), so obtaining a real-time movie of the shock wave effects, for both
  - forward shock waves …



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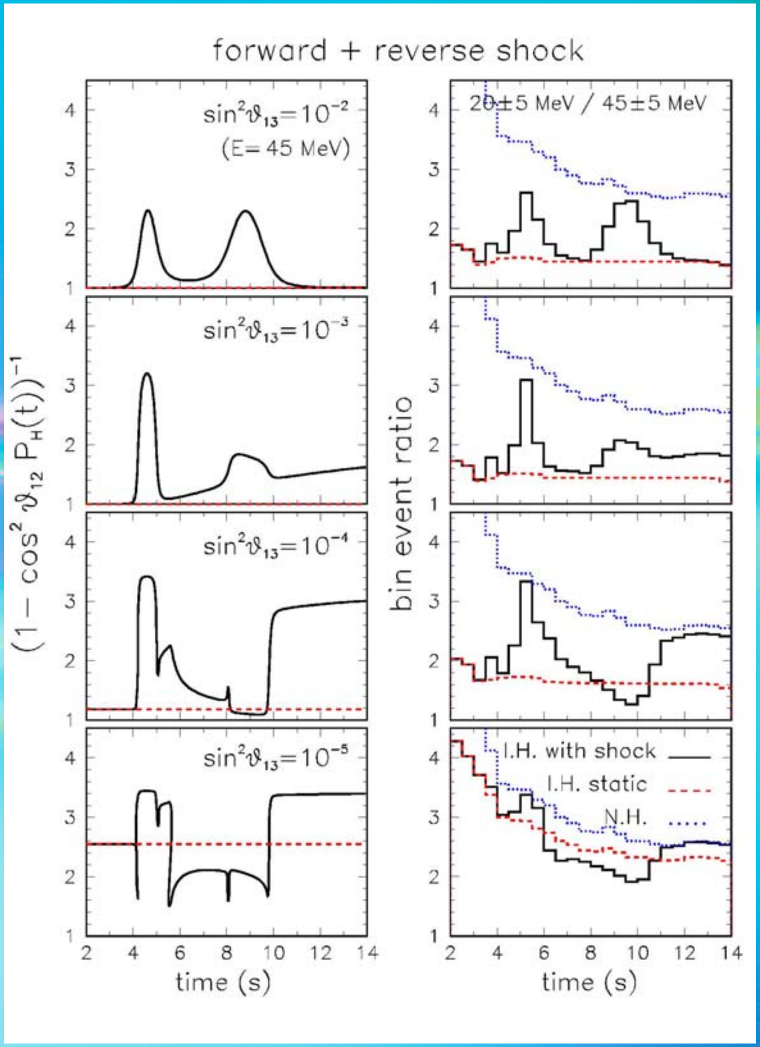
- We can track the crossing probability (if the ν mass hierarchy is inverted), so obtaining a real-time movie of the shock wave effects, for both
  - forward shock waves …
  - forward+reverse shock waves



Conclusions

- Recent years have been exciting …
  - neutrino mass and mixing are now an established fact
  - 3ν oscillation scenario basically OK (convergence on notation desirable)
  - two couples of parameters measured: (δm^2, θ_{12}) and (Δm^2, θ_{23})
  - non-trivial consistency of all data towards small θ_{13}
  - evidence of matter effects in solar neutrino flavor transitions
  - upper bounds on ν masses in sub(eV) range from β-decay, $0\nu2\beta$-decay and cosmology

- … but our knowledge is still poor:
  - kinematical unknowns: θ_{13}, CP violation, mass hierarchy, absolute mass
  - dynamical unknowns: new neutrino properties and/or interactions (LSND?)
  - theoretical unknowns: making sense of parameters, finding underlying symmetries and scales

… This workshop certainly help us to better understand how NNN detectors can

- shed light on these great puzzles through high-statistics measurements of
  - astrophysical neutrinos (solar, atmospheric, supernova)
  - man-made neutrinos (reactors, accelerators)
- as well as to provide a link between lower and higher energies through
  - nucleon decay

Input from cosmological data

Joint analysis of several data sets. In particular, the following data set have been considered:

- CMB (Cosmic Microwave Background) data from
  - Temperature and cross polarization from WMAP (with LAMBDA code)
  - BOOMERanG-98
  - DASI (Degree Angular Scale Interferometer)
  - MAXIMA-1
  - CBI (Cosmic Background Imager)
  - VSAE (Very Small Array Extended)
- LSS (Large Scale Structure) with power spectrum of galaxies from
  - either 2dF (2 degrees Fields) Galaxy Redshift Survey
  - or SDSS (Sloan Digital Sky Survey)
- Lyα (Lyman alpha) Forest in the SDSS
- SN- Ia luminosity measurements (GOLD data set)
- Hubble constant from the HST (Hubble Space Telescope) measurements