Conca Specchiulla (LE) September 7, 2008

Neutrino mass & mixing: 2008 status

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based on work done in collaboration with:
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A. Melchiorri, P. Serra, J. Silk , A. Slosar

Outline

Sharpening the known parameters:

- Oscillation frequencies (δm^2, Δm^2)
- Leading oscillation amplitudes (θ_{12}, θ_{23})

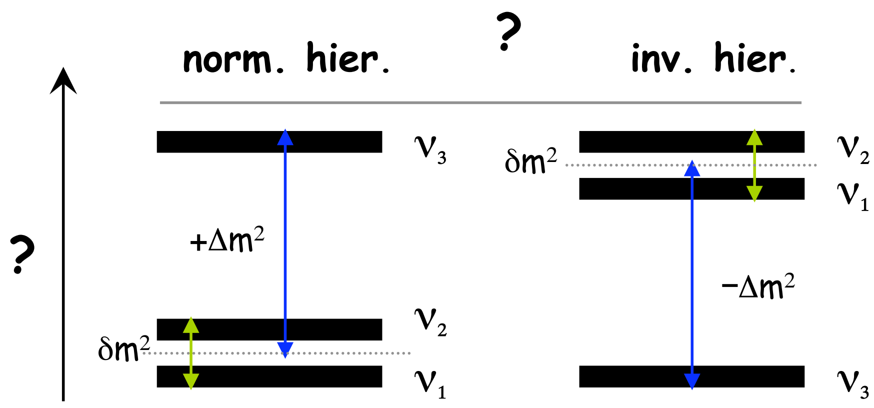
Probing the unknown ones:

- Subleading oscillation amplitude θ_{13}
- Absolute neutrino mass scale

The standard 3ν framework

mass

absolute scale
not probed by
oscillations



mixing

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}|\nu_i\rangle$$

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

δ , Dirac phase unknown

sensitivities

leading

Atmospheric, LBL — $(\Delta m^2,\ \theta_{23},\ \theta_{13})$

Solar, KamLAND — $(\delta m^2,\ \theta_{12},\ \theta_{13})$

CHOOZ — $(\Delta m^2,\ \theta_{13})$

sub-leading

main link between
two distinct 2ν sectors

Updated constraints on

$(\Delta m^2, \theta_{23})$

from

Atm. & LBL

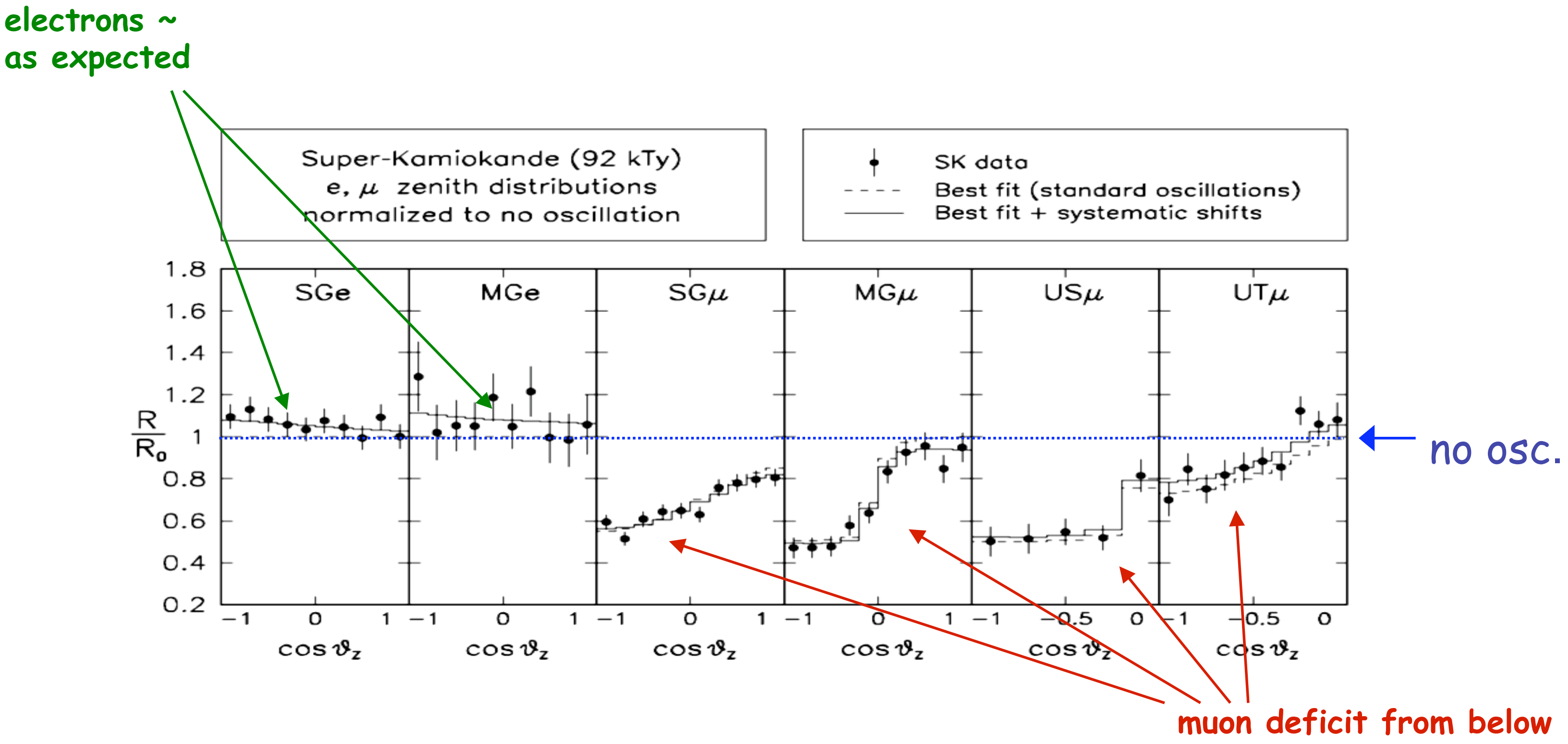
Super-Kamiokande: zenith angle dependence

SGe	Sub-GeV electrons
MGe	Multi-GeV electrons
SGμ	Sub-GeV muons
MGμ	Multi-GeV muons
USμ	Upward Stopping muons
UTμ	Upward Through-going muons

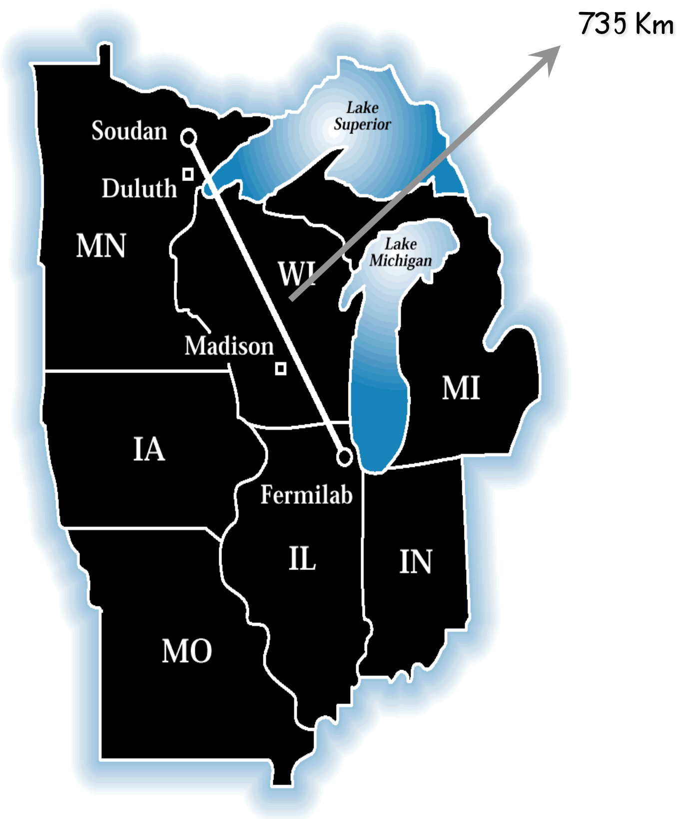
Channel

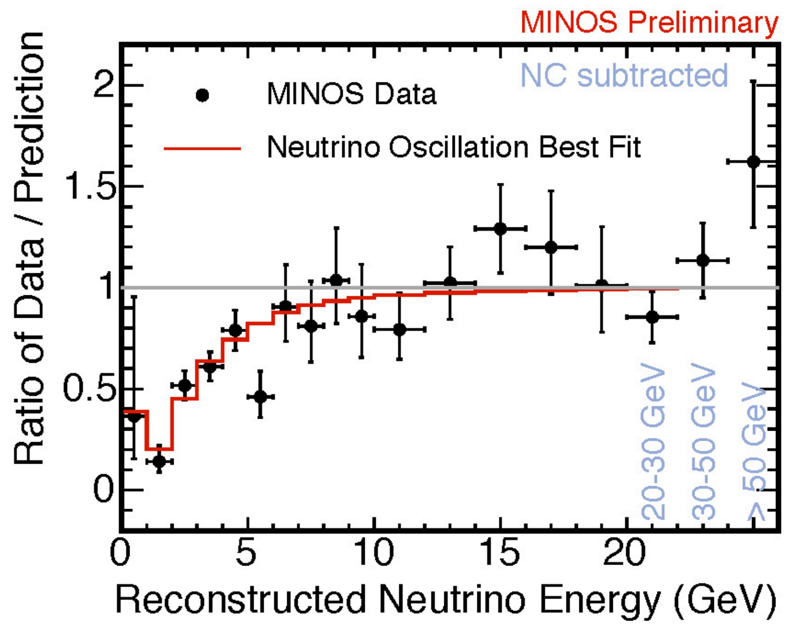
$\nu_\mu \longrightarrow \nu_\tau$ **dominant**

$\nu_\mu \longrightarrow \nu_e$ **sub-dominant ?**



MINOS: long-baseline accelerator experiment

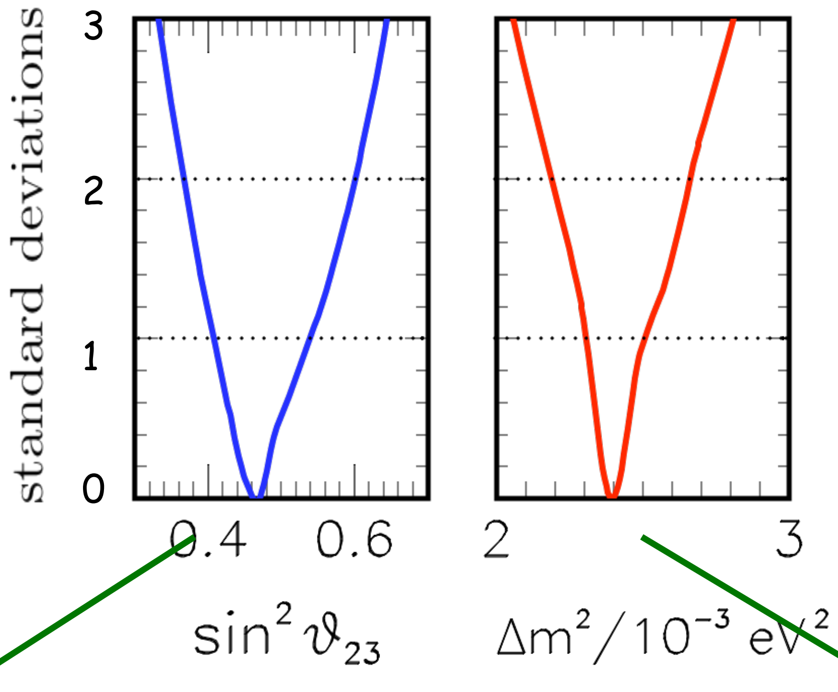




L fixed

Controlled ν flux → **allow precision studies**

Constraints on the leading "atmospheric" parameters



Stable:
(still) dominated by atmospheric data.
Improvement expected from MINOS

Precision quickly increasing
after each new MINOS data release

Fogli et al., Phys. ReV. D 78, 033010 (2008) [arXiv:0805.2517v3]

Updated constraints on

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

from

Solar & KamLAND

Solar neutrinos

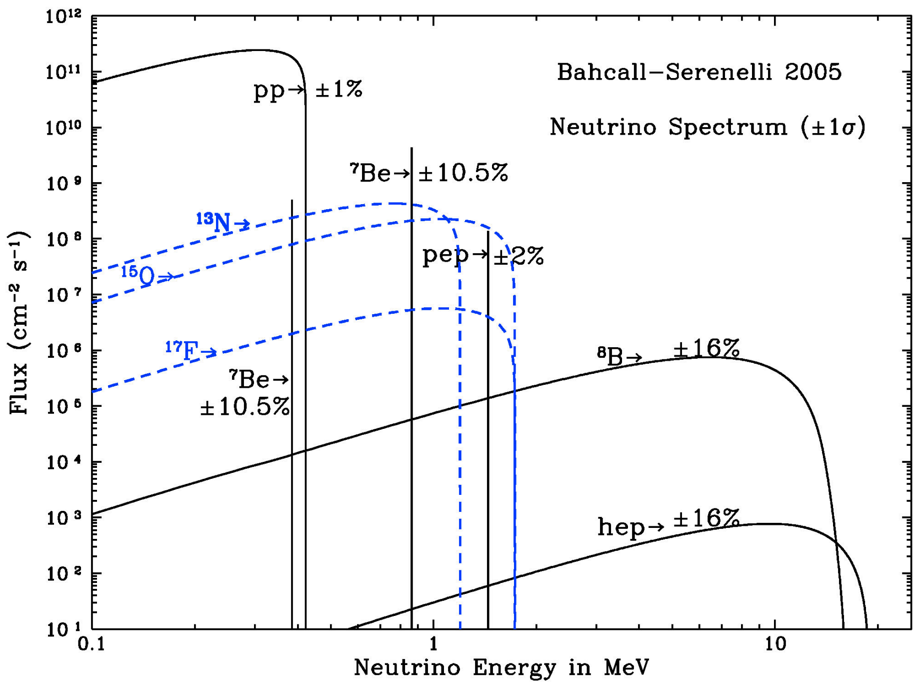
BS(05) OP

neutrino fluxes …

pp

CNO

Source	Reaction	Energy (MeV)	Flux ($cm^{-2}s^{-1}$)
pp	$p+p \rightarrow {}^2H+e^++\nu_e$	≤ 0.42	5.99×10^{10}
pep	$p+p+e^- \rightarrow {}^2H+\nu_e$	1.44	1.42×10^8
B	${}^8B \rightarrow {}^8Be+e^++\nu_e$	≤ 15	5.69×10^6
hep	${}^3He+p \rightarrow {}^4He+e^++\nu_e$	≤ 18.77	7.93×10^3
Be^1	${}^7Be+e^- \rightarrow {}^7Li+\nu_e$	0.38 (10.3%)	0.68×10^9
Be^2	(2nd branch)	0.86 (89.7%)	4.16×10^9
N	${}^{13}N \rightarrow {}^{13}C+e^++\nu_e$	≤ 1.20	3.07×10^8
O	${}^{15}O \rightarrow {}^{15}N+e^++\nu_e$	≤ 1.73	2.33×10^8
F	${}^{17}F \rightarrow {}^{17}O+e^++\nu_e$	≤ 1.74	5.84×10^6



… and their

energy

spectra

Now detected by five experiments

Homestake $(E_\nu > 0.818\ \text{MeV})$

$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

SK (High E)

ES: $\nu_x + e^- \rightarrow \nu_x + e^-$

SAGE & GALLEX-GNO $(E_\nu > 0.232\ \text{MeV})$

can see pp

$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$

Borexino (Low & High E)

ES: $\nu_x + e^- \rightarrow \nu_x + e^-$

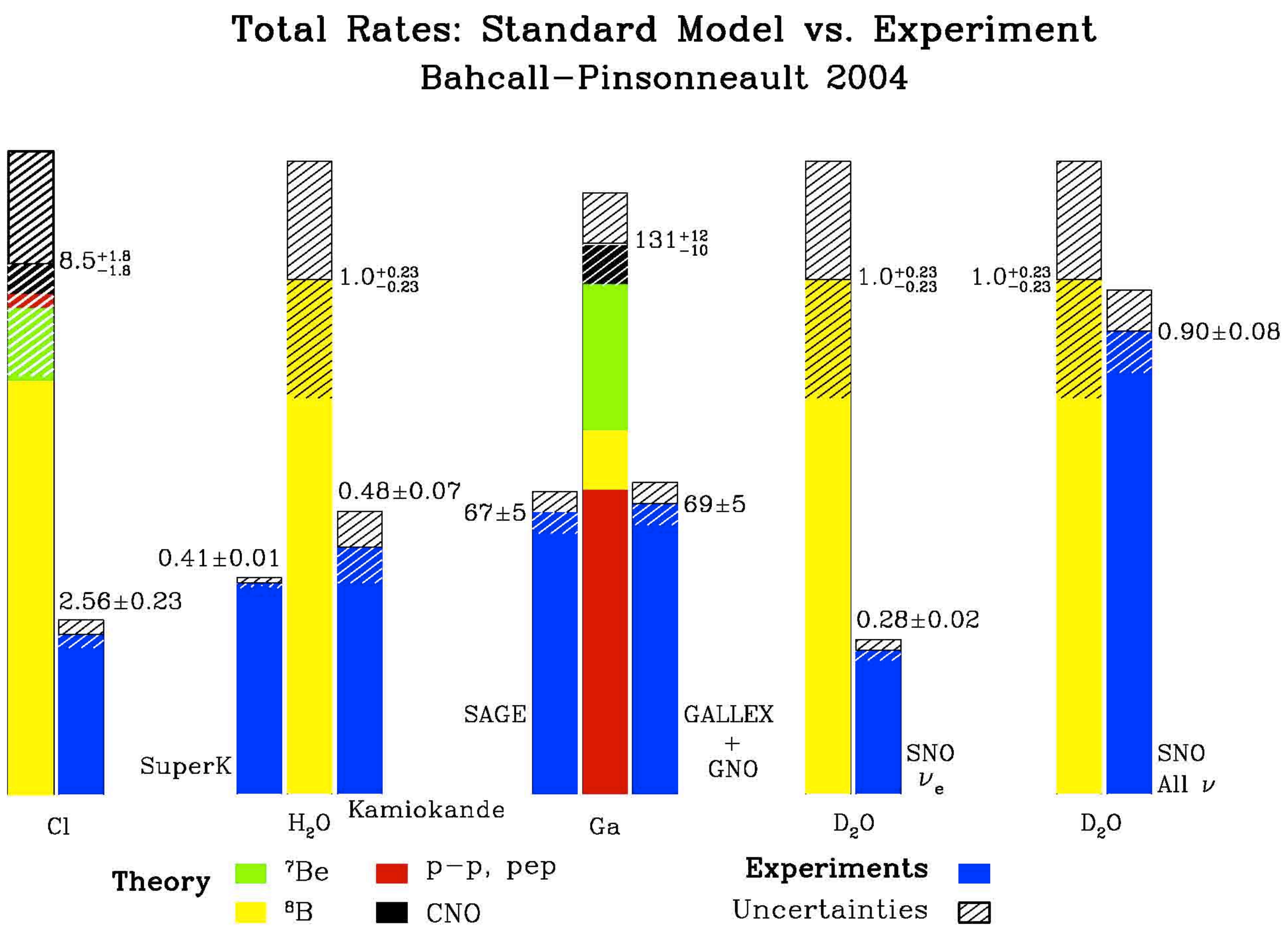
SNO $(E > 5\ \text{MeV})$

CC: $\nu_e + d \rightarrow p + p + e^-$

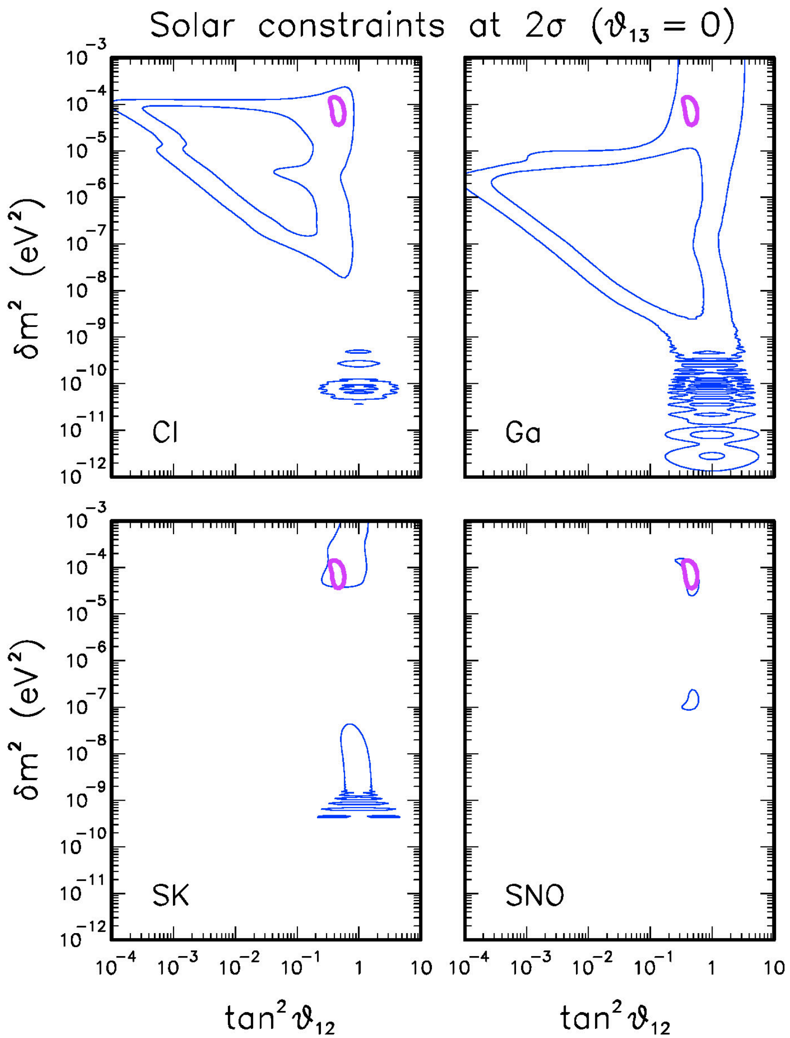
flavor blind → **NC:** $\nu_x + d \rightarrow p + n + \nu_x$

ES: $\nu_x + e^- \rightarrow \nu_x + e^-$

The solar neutrino problem



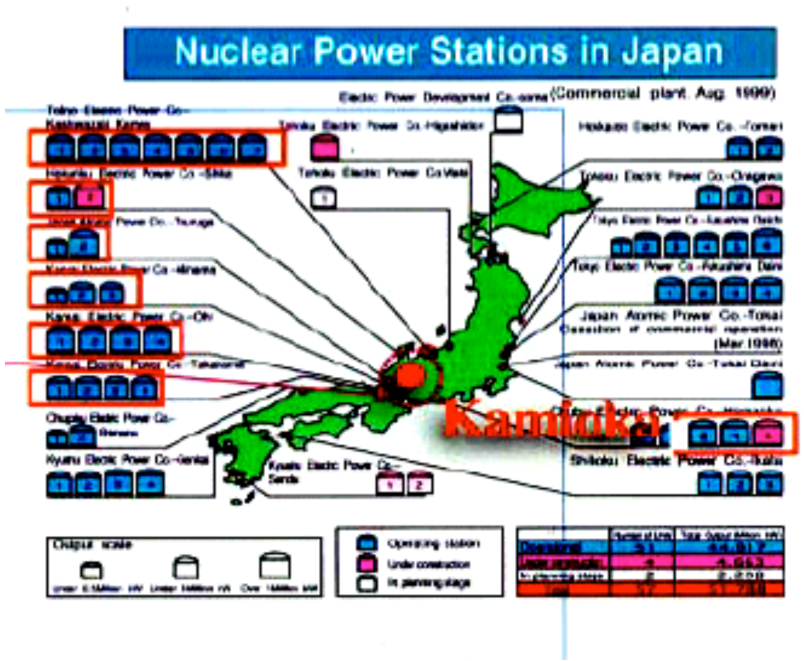
Beautifully explained in term of flavor oscillations

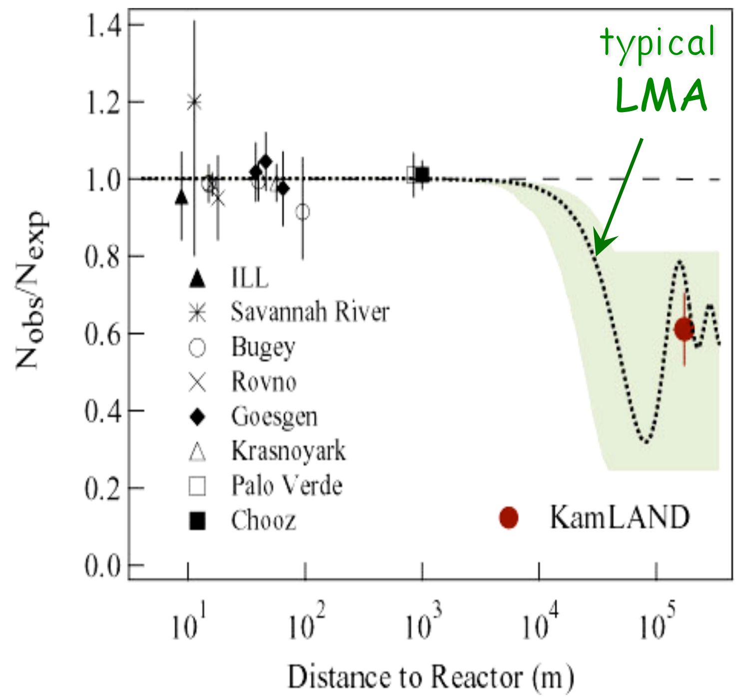


Non trivial consistency among different exp.

LMA solution essentially determined by SNO + SK sensitive to high energy ^8B ν's

KamLAND: long-baseline multi-reactor experiment





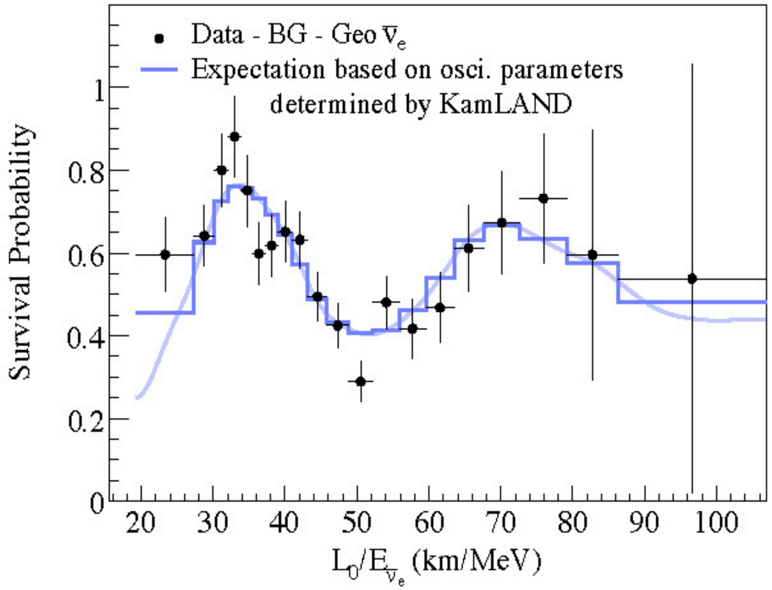
Average distance: ~180 km

Typical ν energy: few MeV

Sensitivity to δm^2 ~ few x 10^{-5} eV^2

KamLAND: the latest measurements

2008

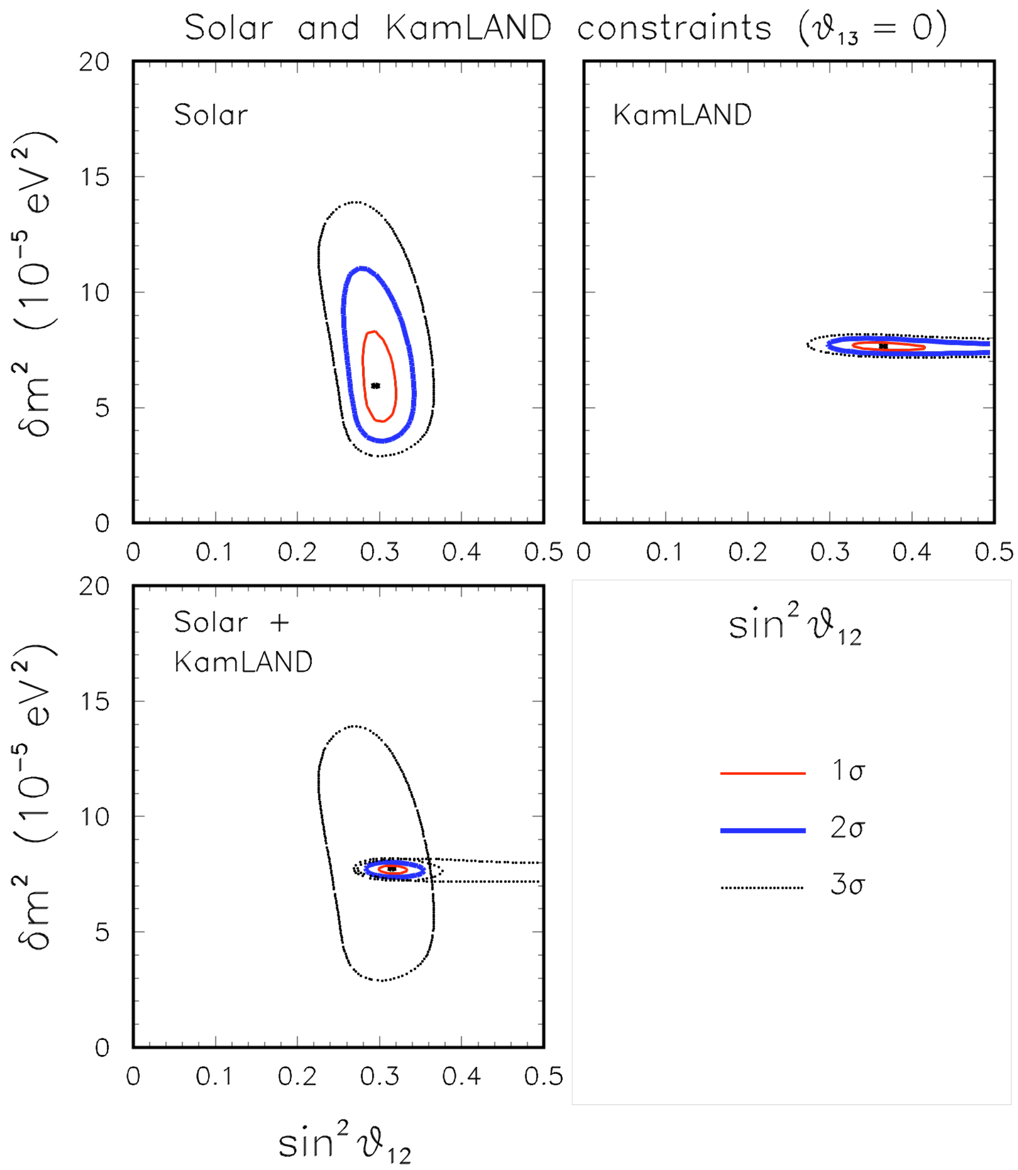


Precision measurement of spectral distortions

Oscillations observed over one entire period

Determination of δm^2 with high precision

2ν Solar + KamLAND contraints (2008)

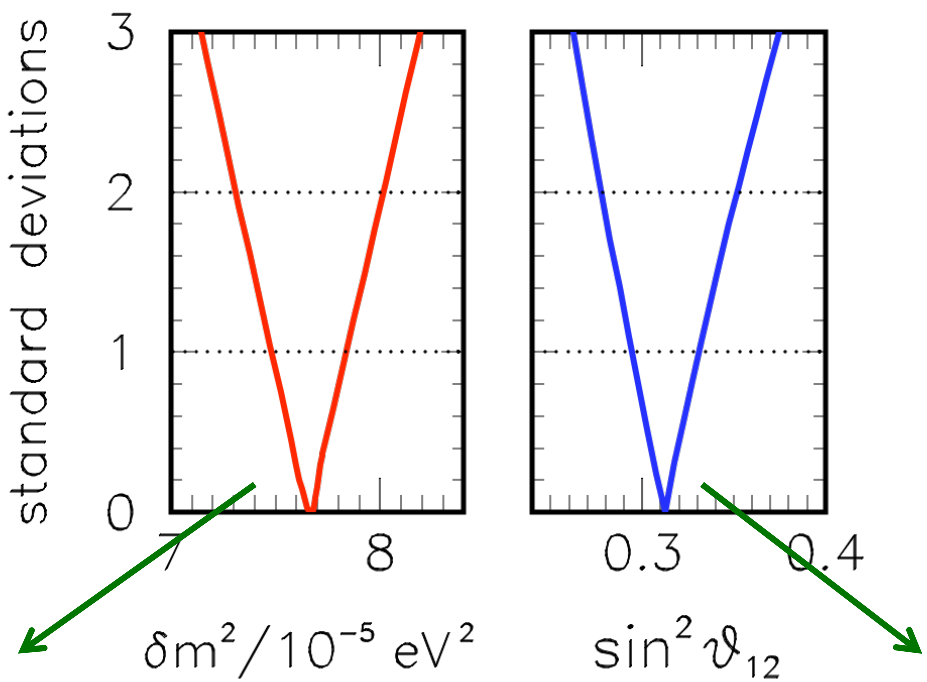


KamLAND dominates δm^2 constraints

Interplay of solar and KamLAND in determining θ_{12}

but small tension among them is present

Constraints on the leading "solar" parameters

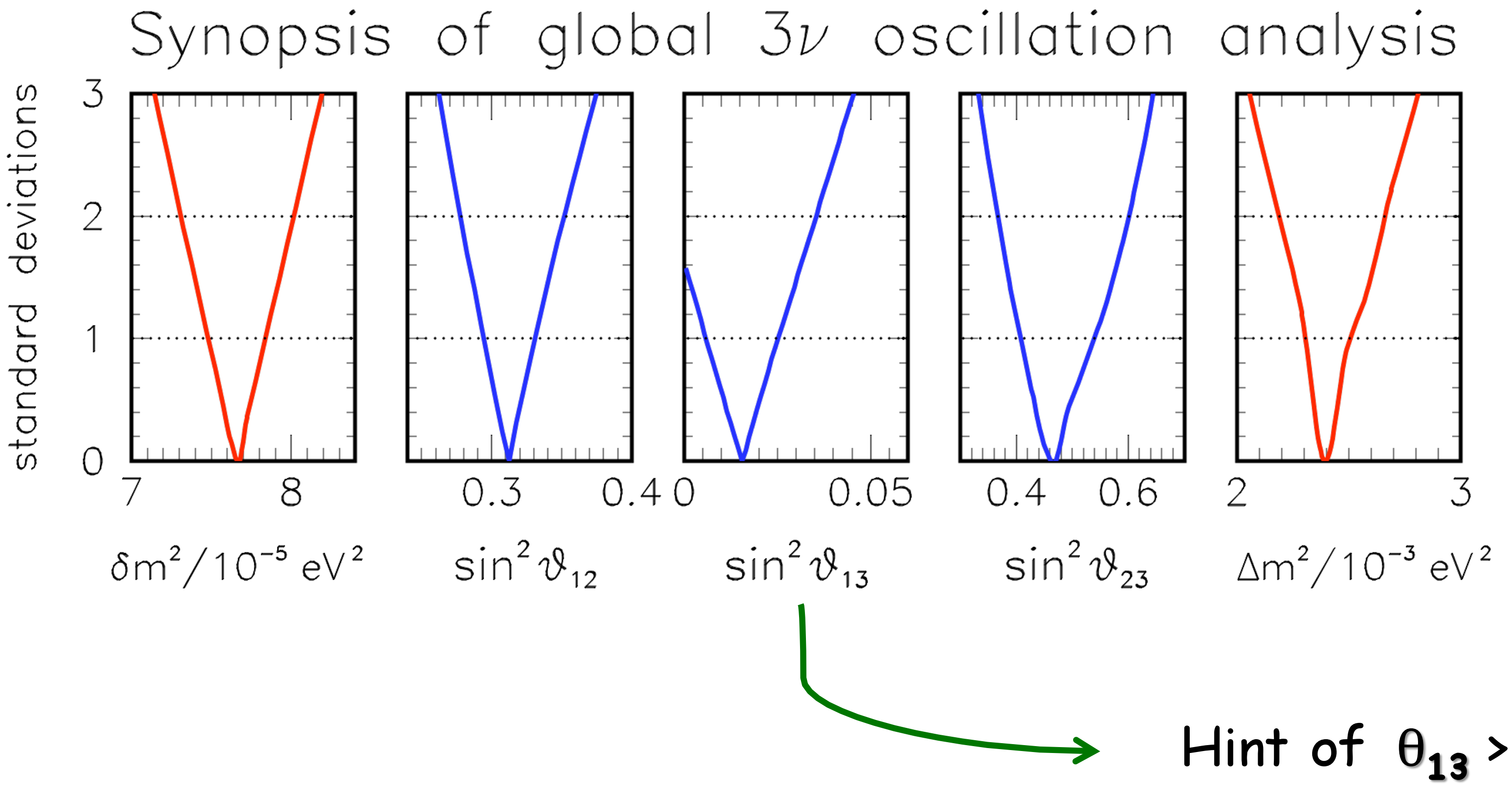


High precision determined by KamLAND

Interplay of solar and KamLAND

Fogli et al., Phys. ReV. D 78, 033010 (2008) [arXiv:0805.2517v3]

Status of θ_{13}

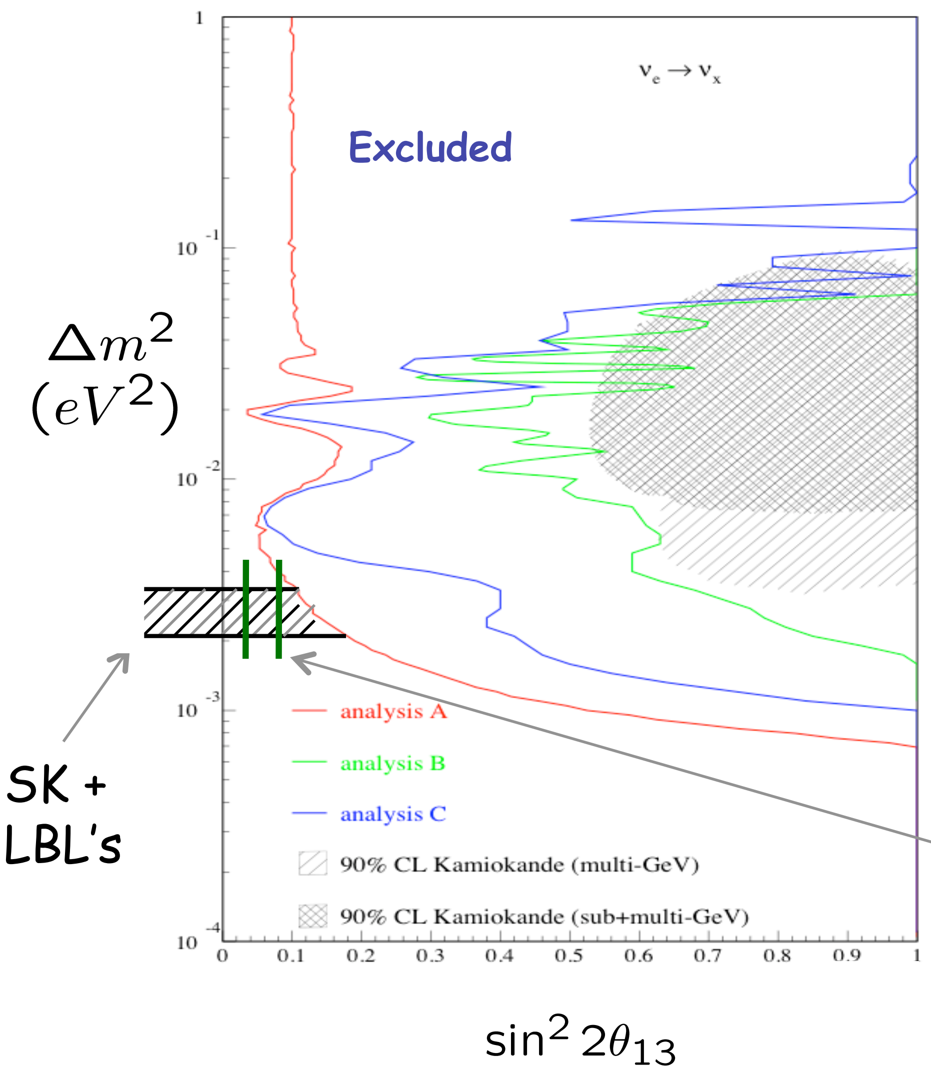


Hint of $\theta_{13} > 0$

Fogli et al. [arXiv:0806.2649]

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

CHOOZ and global analyses: Interplay in pinning down θ_{13}



In the past

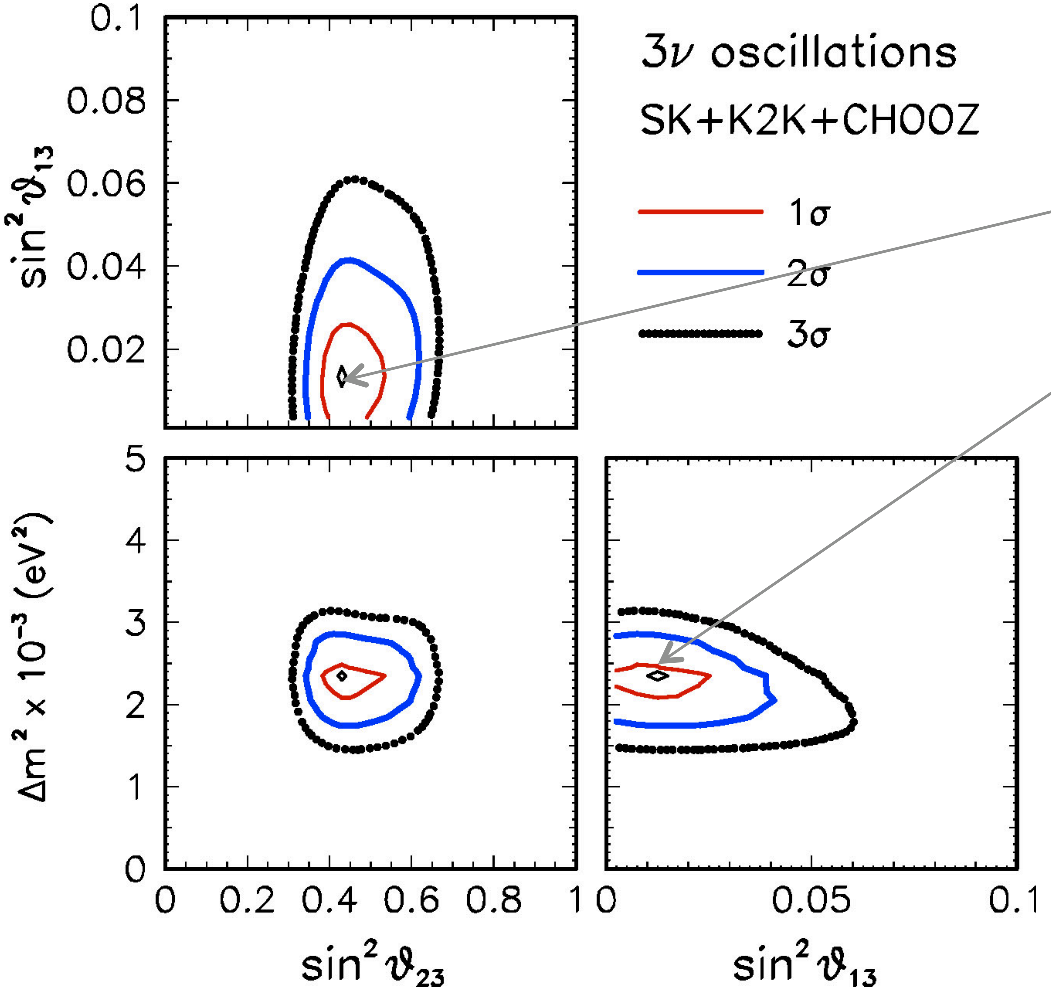
3ν global analyses have **corroborated** & **strengthened** the CHOOZ upper bound

Now

They seem capable to **go beyond** the CHOOZ sensitivity, giving us two intriguing hints of $\theta_{13}>0$

The "old" hint from atmospheric data

Fogli et al., Prog. Part. Nucl. Phys. 57, 742 (2006)

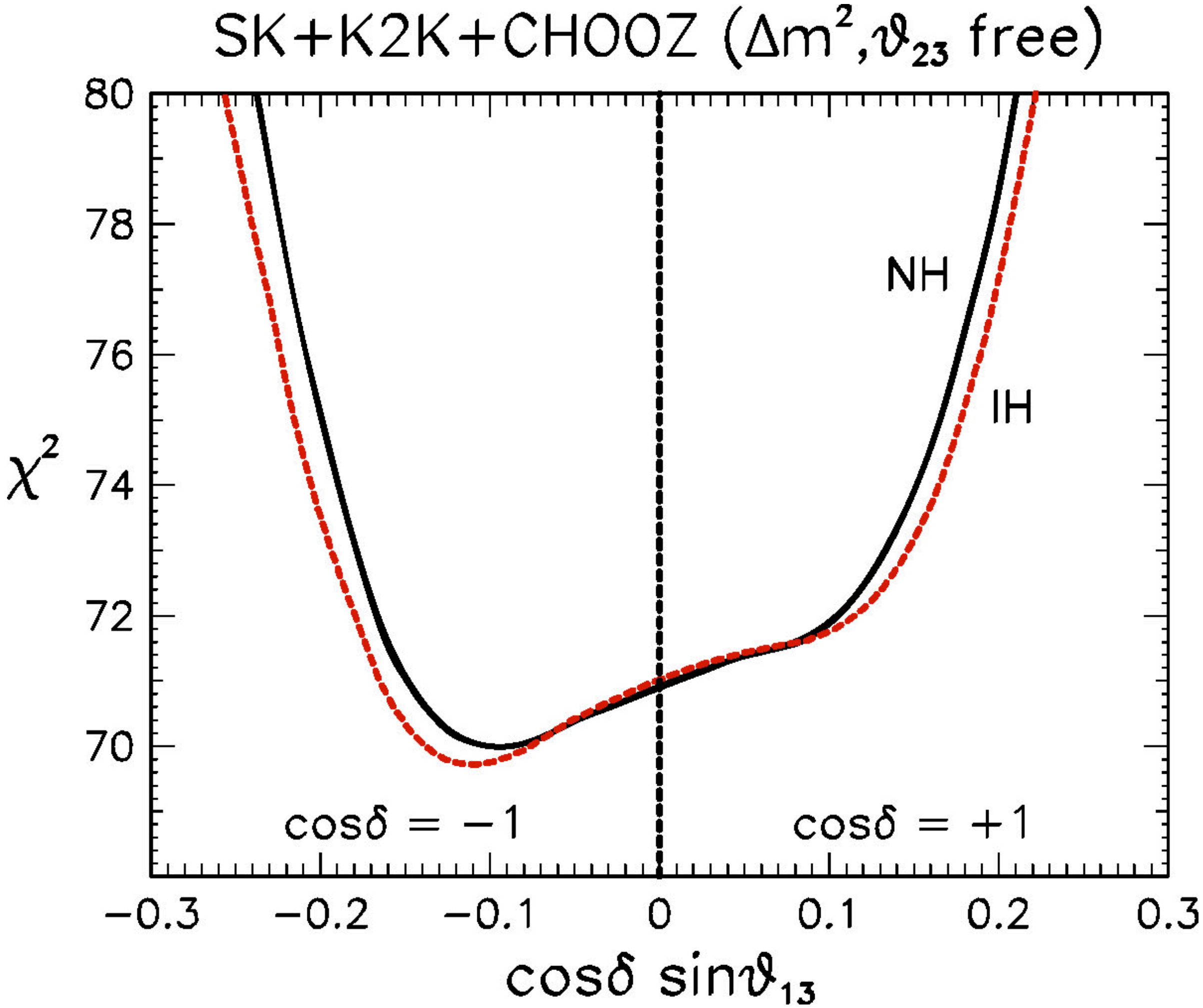


Weak (~0.9σ) preference for $\theta_{13}>0$

Origin: Excess of sub-GeV electron-like events partially explained by 3ν subleading effects* driven by the "solar" splitting δm^2

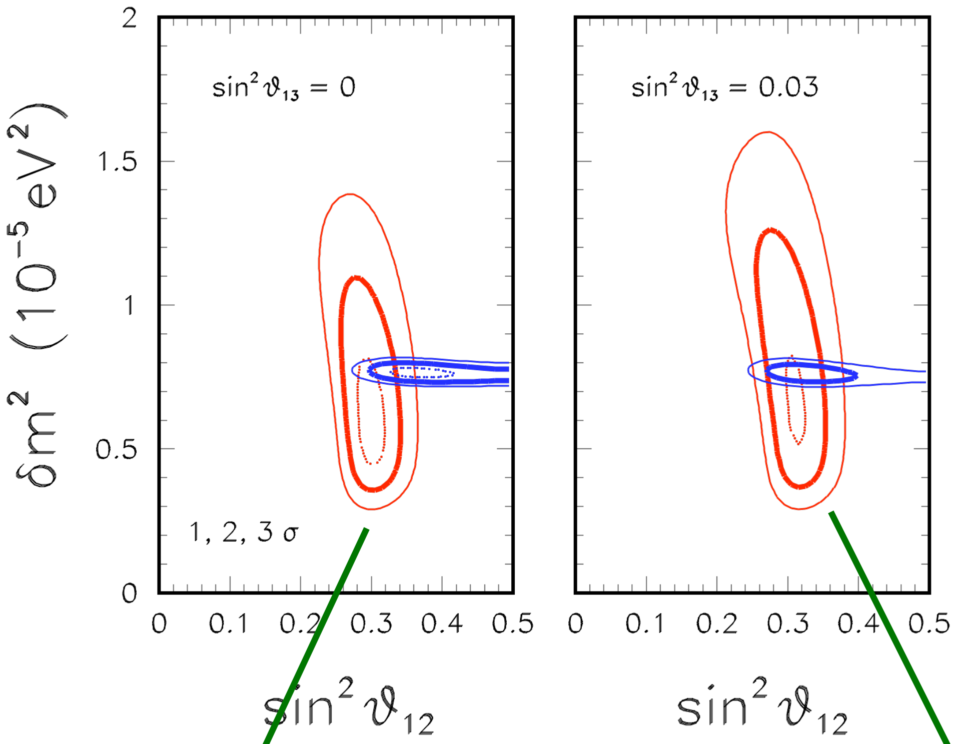
*O.L.G Peres and A.Yu. Smirnov , Nucl. Phys. B 456, 204 (1999); ibidem 680, 479 (2004)

3ν analysis including subleading LMA effects



Fogli et al., Prog. Part. Nucl. Phys. 57, 742 (2006)

The new hint from Solar & KamLAND



	SNO-II	SNO-III
$\frac{CC}{NC}$	$= 0.34 \pm 0.38$	0.301 ± 0.33

- **Central value lower than before:**

  best fit of θ_{12} at a slightly lower value

- **Error reduced when combined:**

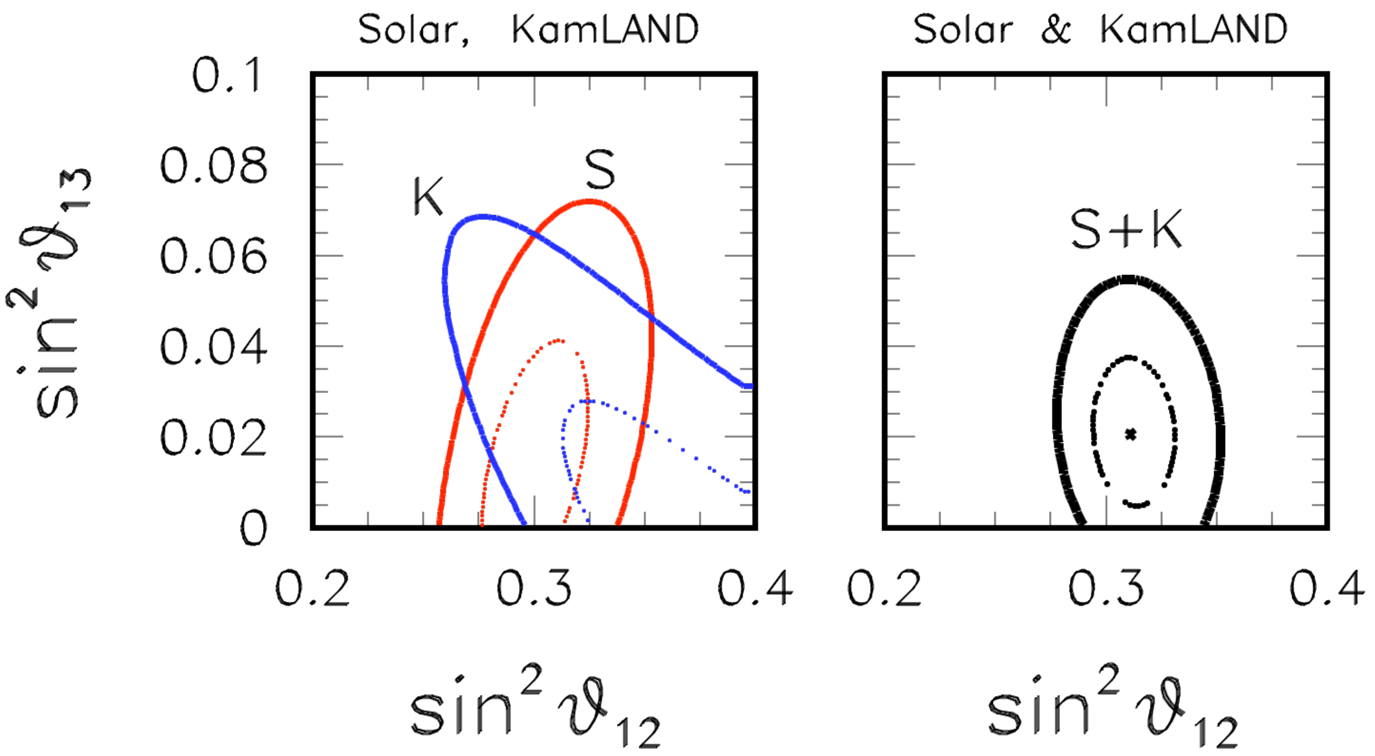
  range allowed for θ_{12} appreciably narrowed

for $\theta_{13} = 0$
Solar and KamLAND
prefer different values of θ_{12}
(no overlap at 1σ level)

for $\theta_{13} > 0$
Solar prefer higher θ_{12}
KamLAND prefer lower θ_{12}
(disagreement reduced*)

*See also Balantekin and Yilmaz, J. Phys. G. 35, 075007 (2008)

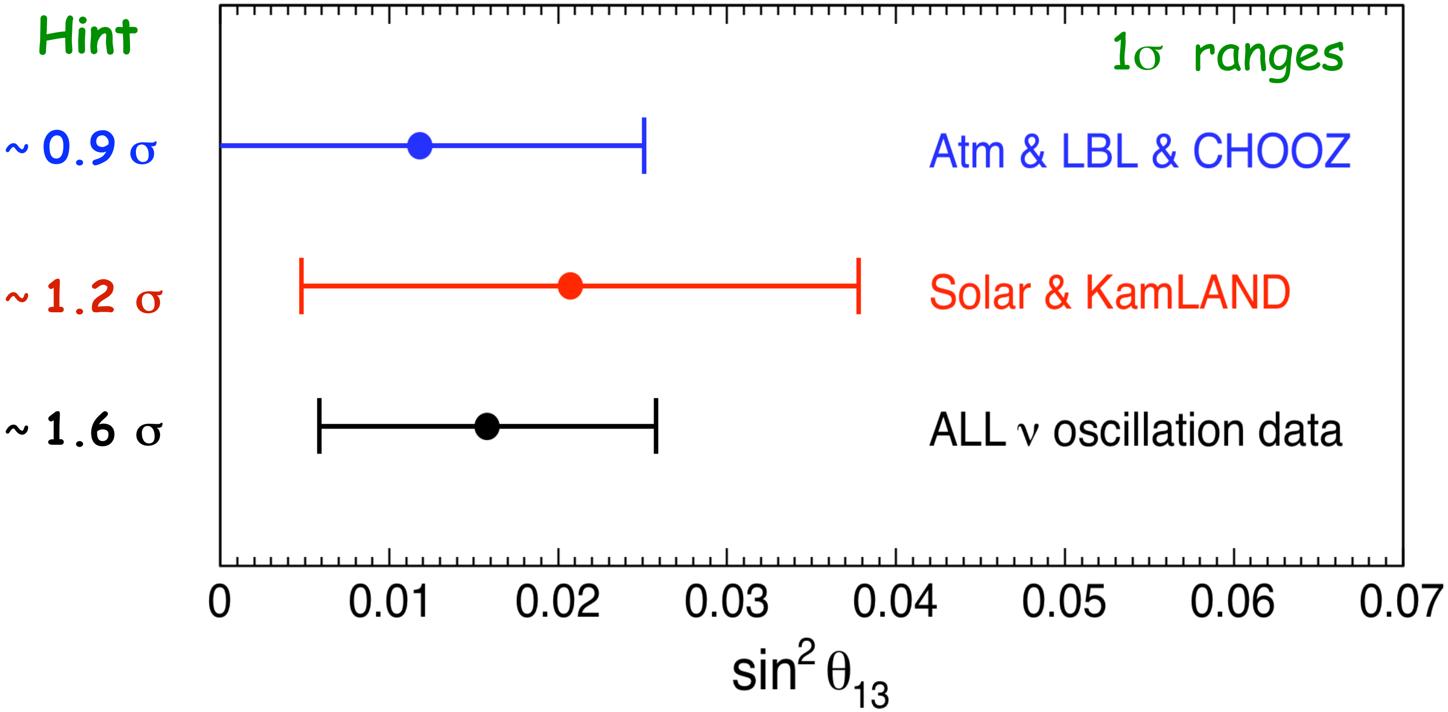
Interplay of Solar and KamLAND



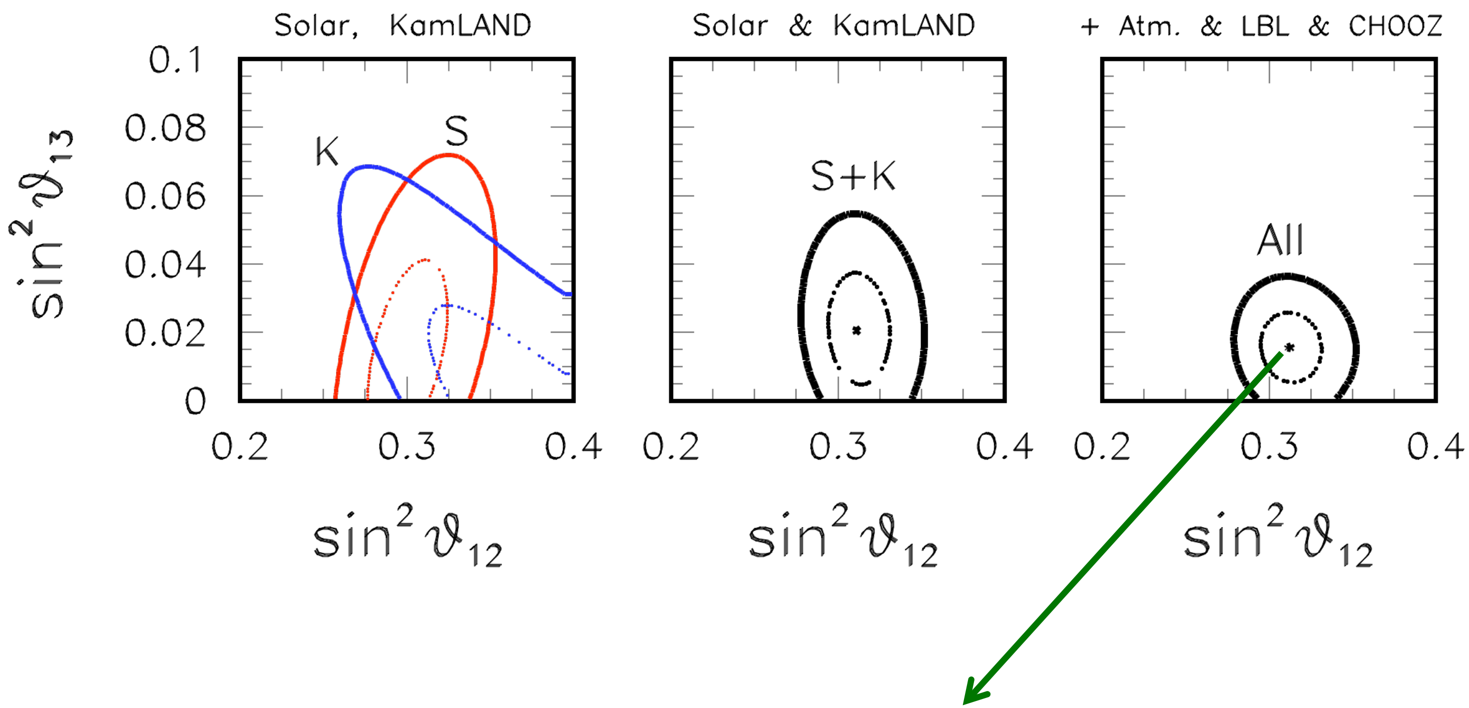
~1.2σ preference for $\theta_{13} > 0$

Similar hint found in Schwetz et al., arXiv:0808.2016 [hep-ph]

Status of θ_{13}



Status of the electron neutrino mixing

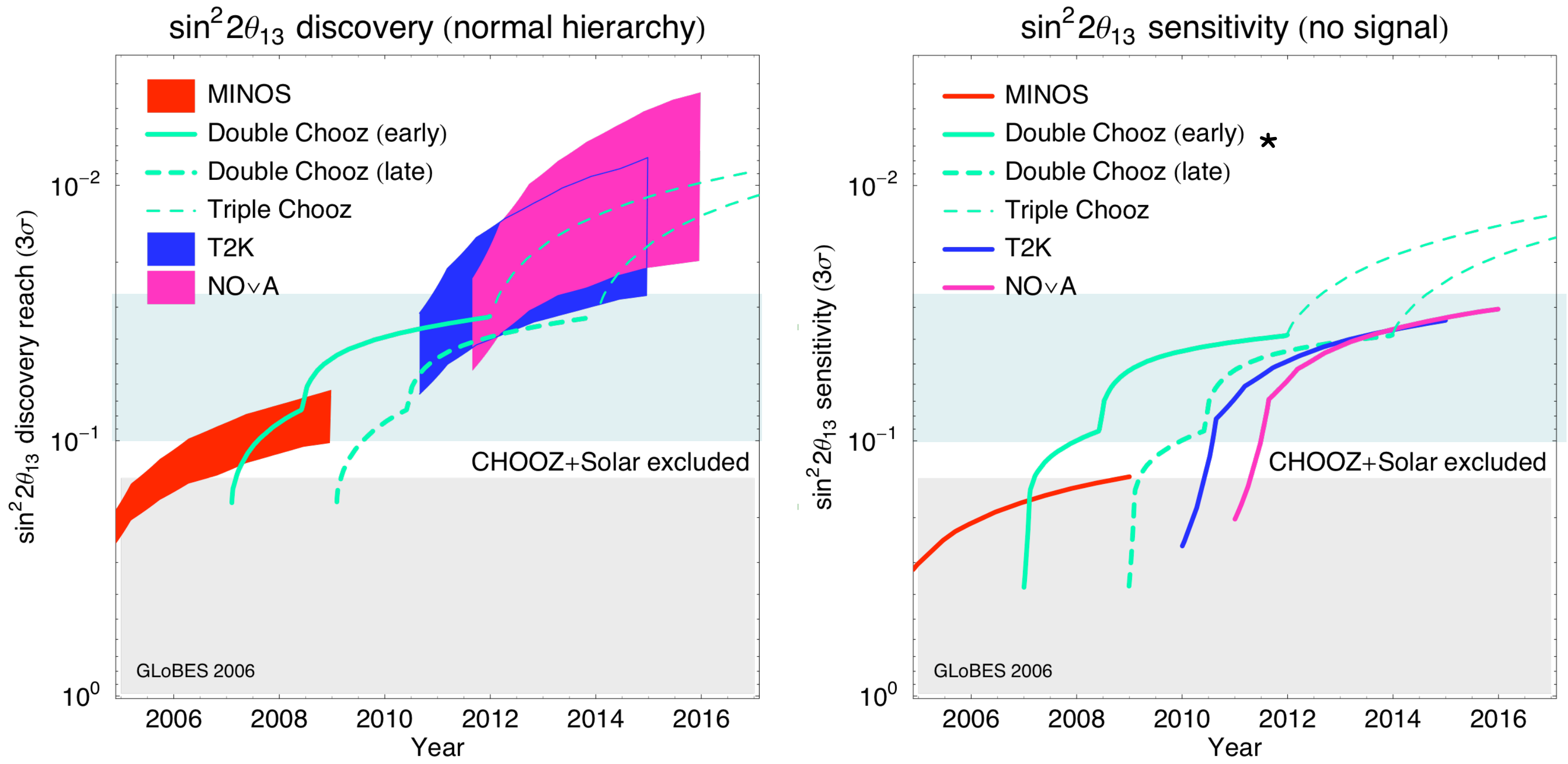


$$|U_{e1}|^2 = \cos^2\theta_{13}\cos^2\theta_{12} \sim 0.667$$

$$|U_{e2}|^2 = \cos^2\theta_{13}\sin^2\theta_{12} \sim 0.307$$

$$|U_{e3}|^2 = \sin^2\theta_{13} \sim 0.016$$

Comparison with experimental sensitivity



Plot from Huber et. al JHEP 0605, 072 (2006)

superimposed to
the 1σ range (green band)
found in the global analysis

range within the reach of sensitivity & discovery potential in 3-5 years

* Comparable sensitivity (and time scale) expected in Daya Bay

Current ν data show two **independent** hints of $\theta_{13}>0$

They call for:

Attention

They may constitute the first signs of an emergent signal

If the trend is confirmed the hints may be promoted to indications

Prudence

The statistical significance, albeit not negligible, is not high (90% CL)

Indirect indications need to be confirmed by direct measurements

Precision

Refined global analyses will play a crucial role in deciphering the precious information concealed in the difficult neutrino data

Patience

The present hints will be testable at reactor and accelerator experiments but we need to be patient and wait some years

Probing absolute ν masses through non-oscillation searches

Observables sensitive to absolute ν masses

1) Tritium β decay: ν masses can affect spectrum endpoint.
Sensitive to the "effective electron neutrino mass":

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

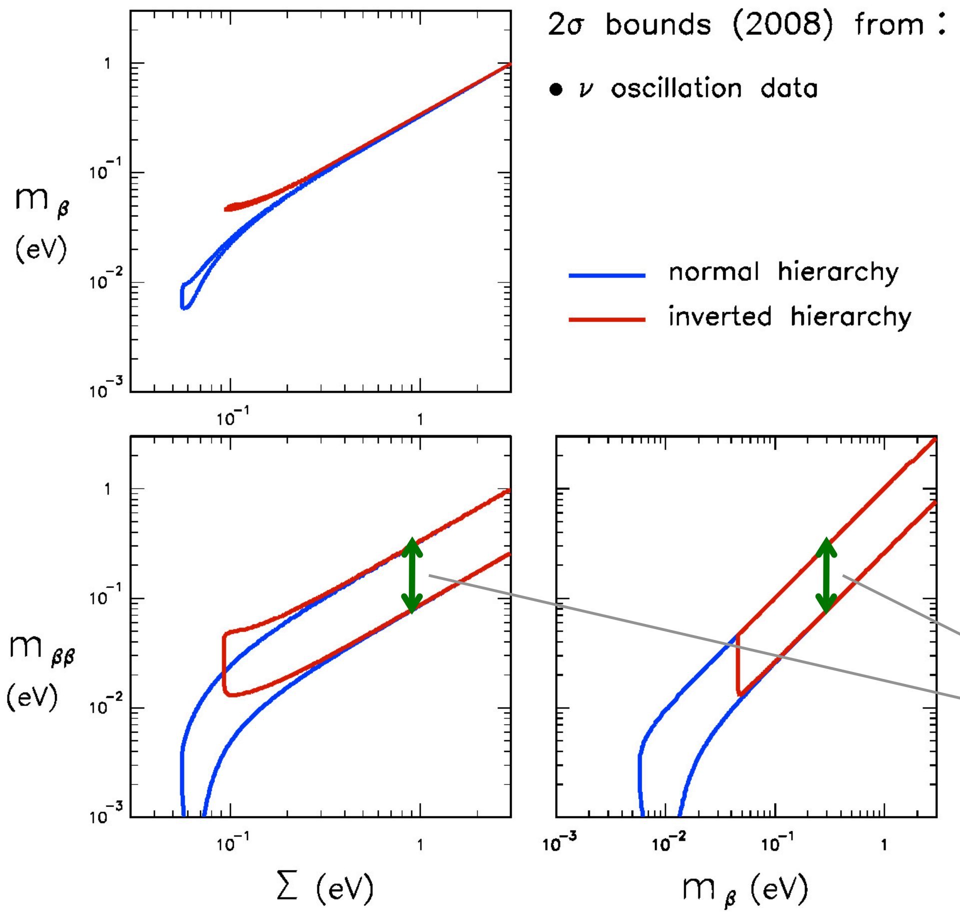
2) 0ν2β decay: can occur only if massive ν are Majorana particles.
Sensitive to the "effective Majorana mass":

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

3) Cosmology: ν masses can affect CMB and structure formation
Sensitive to:

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

Oscillation results provide important constraints on (m_β, $m_{\beta\beta}$, Σ)



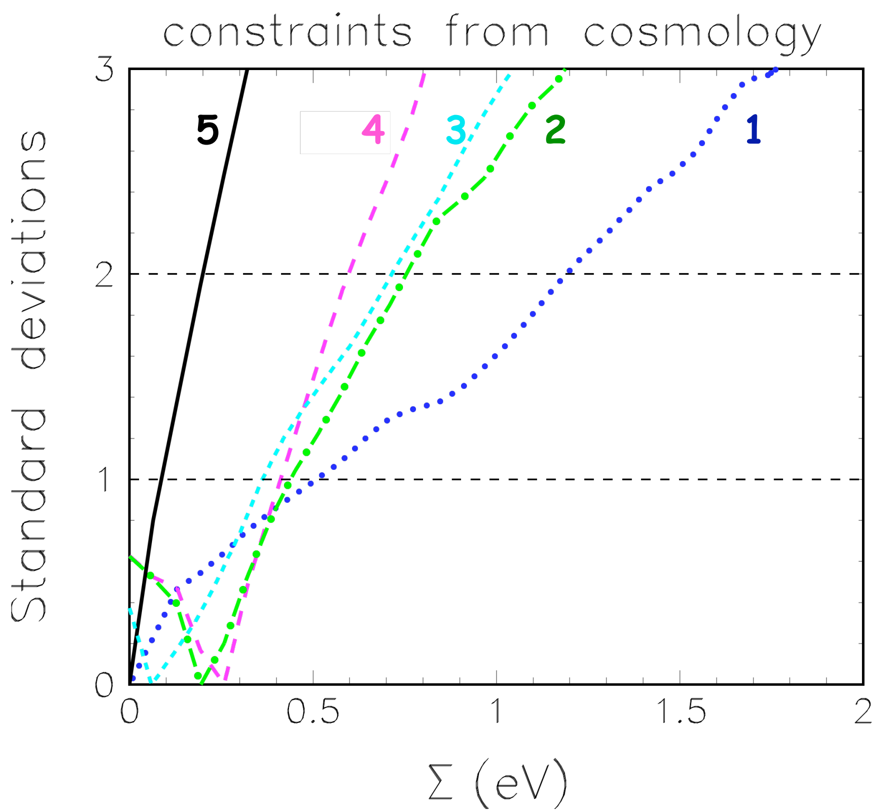
Significant correlations

Partial overlap between the two hierarchies

Large $m_{\beta\beta}$ spread due to uknown Majorana phases

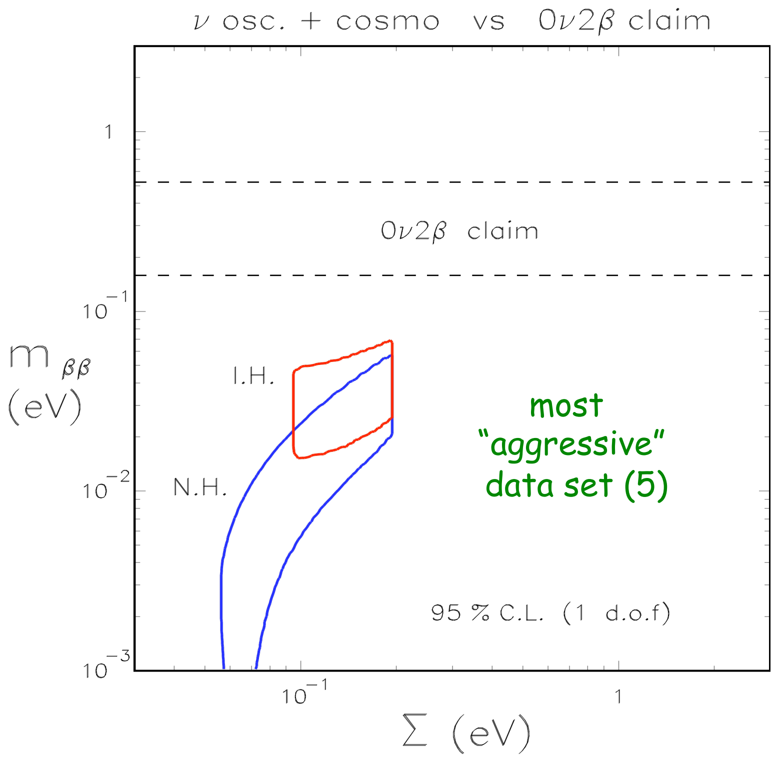
Results from the analysis of cosmological data

data set	*2σ limit*
1- CMB	1.19 eV
2- CMB + HST + SN-Ia	0.75 eV
3- CMB + LSS	0.72 eV
4- CMB +HST + SN + BAO	0.60 eV
5- CMB+ HST + SN + BAO + Ly-α	0.19 eV

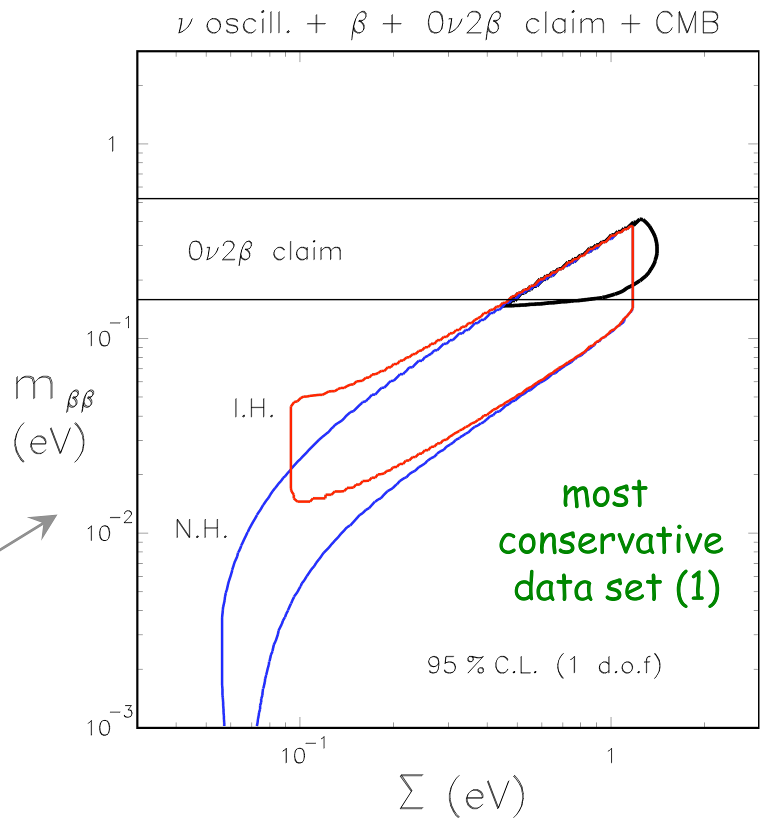


Fogli et al., Phys. ReV. D 78, 033010 (2008) [arXiv:0805.2517v3]

(In)compatibility with the 0ν2β claim



combination of 0ν2β claim with cosmological bounds
not feasible



… unless we disregard most of the cosmological data and consider only the CMB results

However,

we should not be hasty in concluding that :
"cosmological data rule out the claim of Klapdor et al.,"

since:

- The $0\nu 2\beta$ signal might be due to new physics beyond light Majorana ν's

- Astrophysical data may be affected by unknown systematics

- Bounds on Σ unavoidably depend on assumptions on the Cosmological Model

Only another $0\nu 2\beta$ experiment
with higher sensitivity
can (dis)prove such claim

Summary

- All the existing data fit perfectly within the standard 3ν framework

- Basic parameters determined with a [5-30]% accuracy

- Two independent hints of $\theta_{13}>0$ deserving of attention

- Cosmology is the most sensitive probe of absolute ν mass

- Tension with $0\nu2\beta$ claim requires further scrutiny

In conclusion:

The 2008 status of neutrino mass & mixing

is good and promising!

Thank you for your attention!

[redacted]

Back-up slides

Excess of electron events induced by 3ν subleading effects

$$\frac{N_e}{N_e^0} - 1 = (P_{ee} - 1) + r\, P_{e\mu}$$

→ zero when both $\theta_{13}=0$ & $\delta m^2 = 0$

r: ν_μ/ν_e flux ratio

sub-GeV $r \sim 2$

multi-GeV $r \sim 3.5$

Constant density approximation $$\frac{N_e}{N_e^0} - 1 \simeq \Delta_1 + \Delta_2 + \Delta_3$$

"θ_{13} term"

$$\Delta_1 \simeq \sin^2 2\tilde{\theta}_{13} \sin^2\left(\Delta m^2 \frac{\sin 2\theta_{13}}{\sin 2\tilde{\theta}_{13}} \frac{L}{4E}\right) \cdot (r s_{23}^2 - 1)$$

"δm^2 term"

$$\Delta_2 \simeq \sin^2 2\tilde{\theta}_{12} \sin^2\left(\delta m^2 \frac{\sin 2\theta_{12}}{\sin 2\tilde{\theta}_{12}} \frac{L}{4E}\right) \cdot (r c_{23}^2 - 1)$$

"Interference term" *

$$\Delta_3 \simeq \sin^2 2\tilde{\theta}_{12} \sin^2\left(\delta m^2 \frac{\sin 2\theta_{12}}{\sin 2\tilde{\theta}_{12}} \frac{L}{4E}\right) \cdot r s_{13} c_{13}^2 \sin 2\theta_{23} (\tan 2\tilde{\theta}_{12})^{-1}$$

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*O.L.G Peres and A.Yu. Smirnov , Nucl. Phys. B 456, 204 (1999); ibidem 680, 479 (2004)

Expressions valid for $[\nu, \quad \text{N.H.}, \quad \delta = 0]$:

Mixing angles in matter

$$\frac{\sin 2\theta_{13}}{\sin 2\tilde{\theta}_{13}} \simeq \sqrt{\left(\frac{A}{\Delta m^2 + \frac{\delta m^2}{2}\cos 2\theta_{12}} - \cos 2\theta_{13}\right)^2 + \sin^2 2\theta_{13}}$$

$$\frac{\sin 2\theta_{12}}{\sin 2\tilde{\theta}_{12}} \simeq \sqrt{\left(\frac{Ac_{13}^2}{\delta m^2} - \cos 2\theta_{12}\right)^2 + \sin^2 2\theta_{12}}$$

Order of magnitude of the potential

$$\frac{A}{\Delta m^2} \simeq 1.3 \left(\frac{2.4 \times 10^{-3}\ \text{eV}^2}{\Delta m^2}\right)\left(\frac{E}{10\ \text{GeV}}\right)\left(\frac{N_e}{2\ \text{mol/cm}^3}\right)$$

$$\frac{A}{\delta m^2} \simeq 3.8 \left(\frac{8 \times 10^{-5}\ \text{eV}^2}{\delta m^2}\right)\left(\frac{E}{1\ \text{GeV}}\right)\left(\frac{N_e}{2\ \text{mol/cm}^3}\right)$$

"Swapping" relations

$$+A \to -A \qquad (\nu \to \bar{\nu})$$

$$+\Delta m^2 \to -\Delta m^2 \qquad (\text{N.H.} \to \text{I.H.})$$

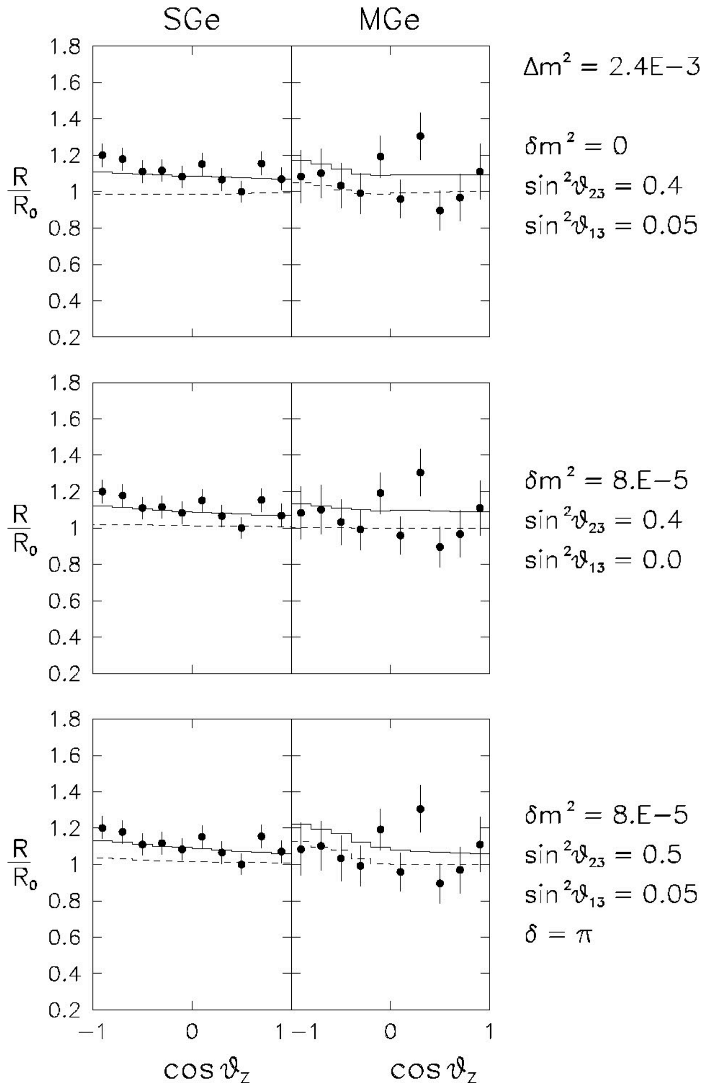
$$+s_{13} \to -s_{13} \qquad (\delta = 0 \to \delta = \pi)$$

Exact numerical examples

“θ_{13} term” dominant

“δm^2 term” dominant

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



Fogli et al., Prog. Part. Nucl. Phys. 57, 742 (2006)

Model-independent consistency checks

1) "internal" consistency among SNO (CC,NC) and SK (ES)
2) consistency among NC measurement and Solar Model

both already good in SNO-II and even better in SNO-III