Status of Neutrino Oscillations

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based on work done in collaboration with:
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Outline

LMA Oscillations

Solar neutrinos -> LMA solution

KamLAND -> LMA confirmed by $\bar{\nu}_e$ disappearance and spectral distortion

"Atmospheric" oscillations (SK + K2K + MINOS)

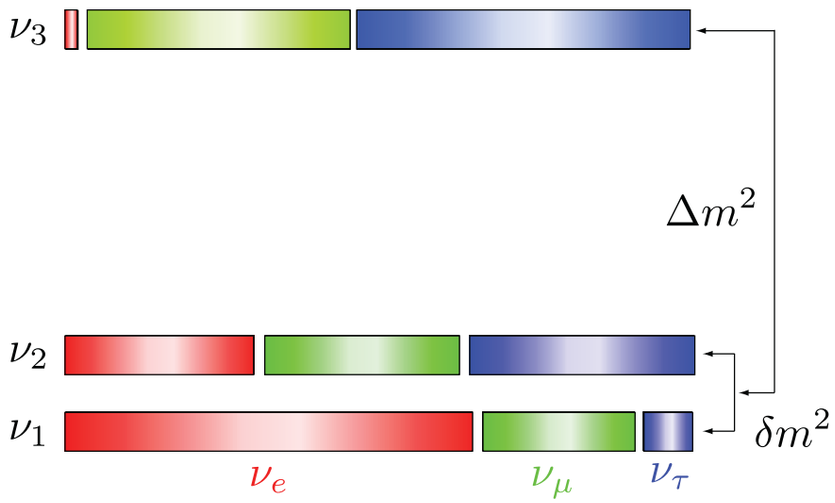
MiniBooNE

Cosmology + Astrophysics limits
Direct ν mass measurements

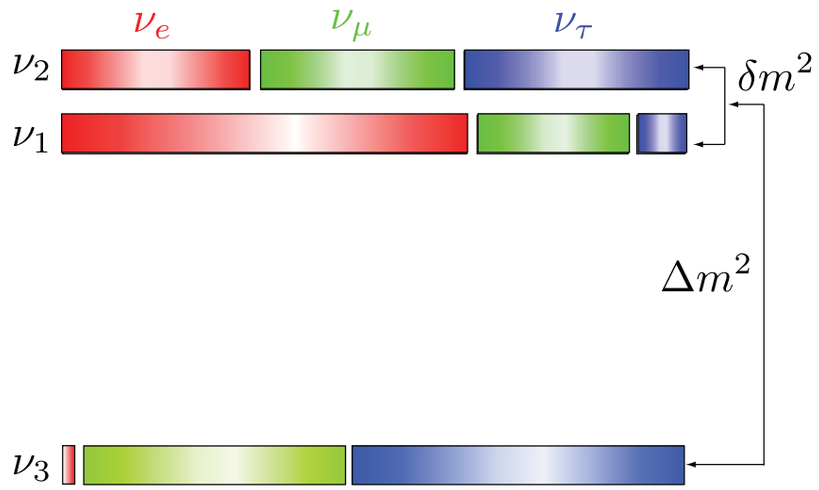
Conclusions

Mass Spectrum

Absolute mass scale unknown



Normal Hierachy



Inverted Hierachy

Mixing Angles

Solar $\left[\delta m^2\ ,\ \theta_{12}\ ,\ \theta_{13}\ ,\ \theta_{23}\ ,\ \Delta m^2\right]$ Atmosph.

δ CP viol. phase

(ϕ_2, ϕ_3) Majorana phases

Solar parameters

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

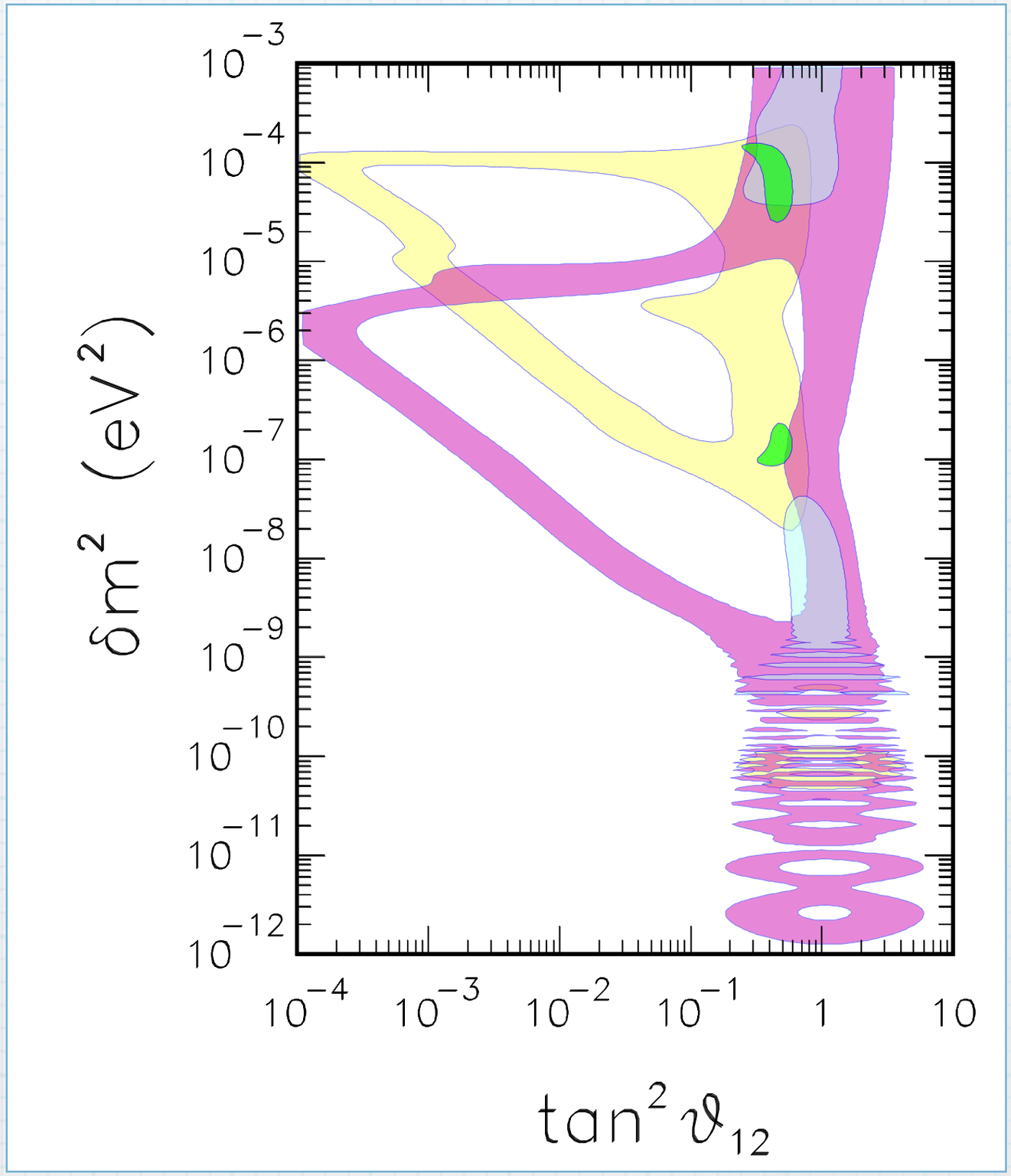
Solar neutrino data

Chlorine (completed)

Gallium (completed)

Super-Kamiokande (completed)

SNO I/II



Solar neutrino data identify LMA solution

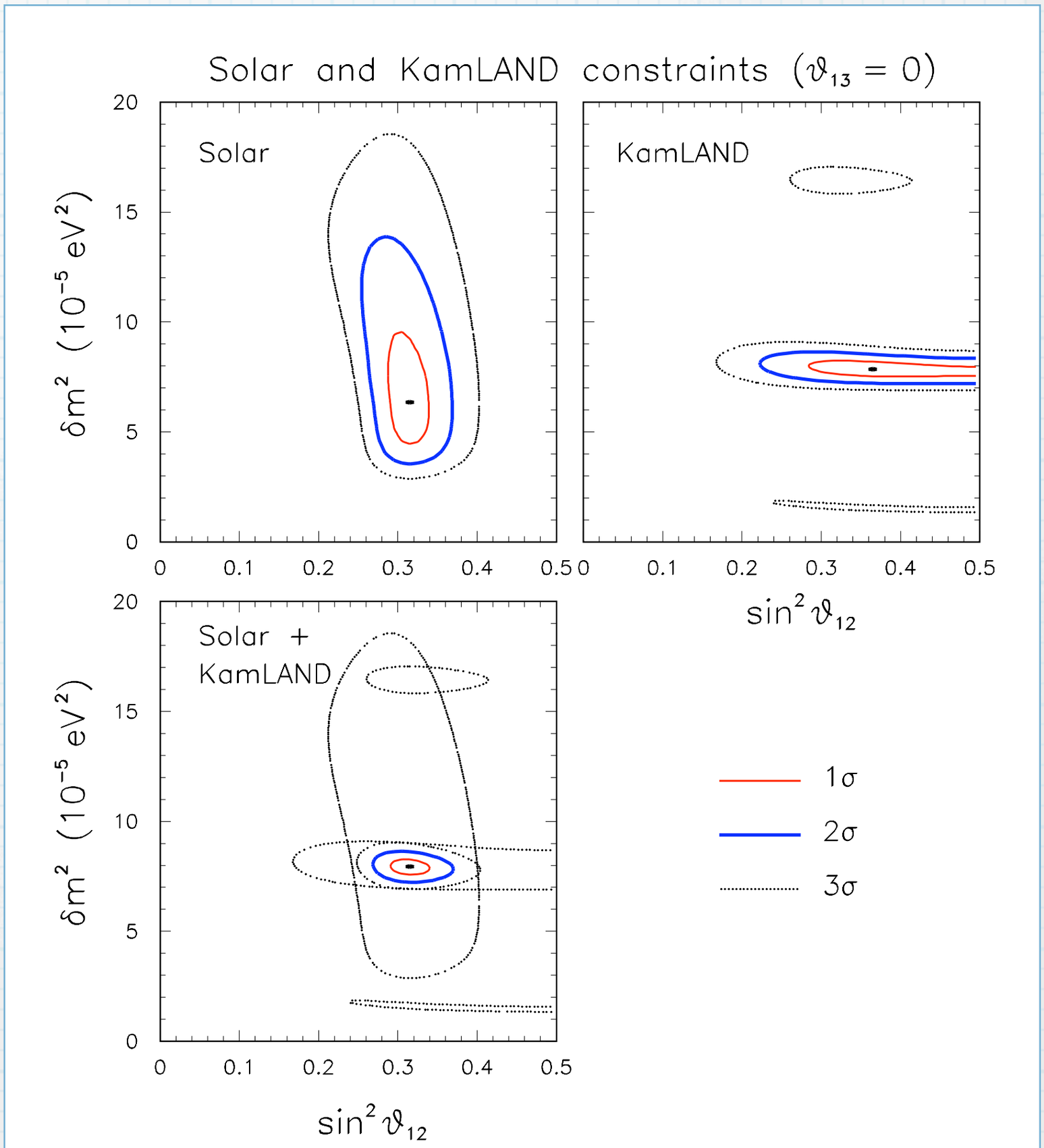
SNO CC/NC disfavors maximal mixing by more then five sigmas

Mass hierarchy in the solar sector fixed by MSW effect

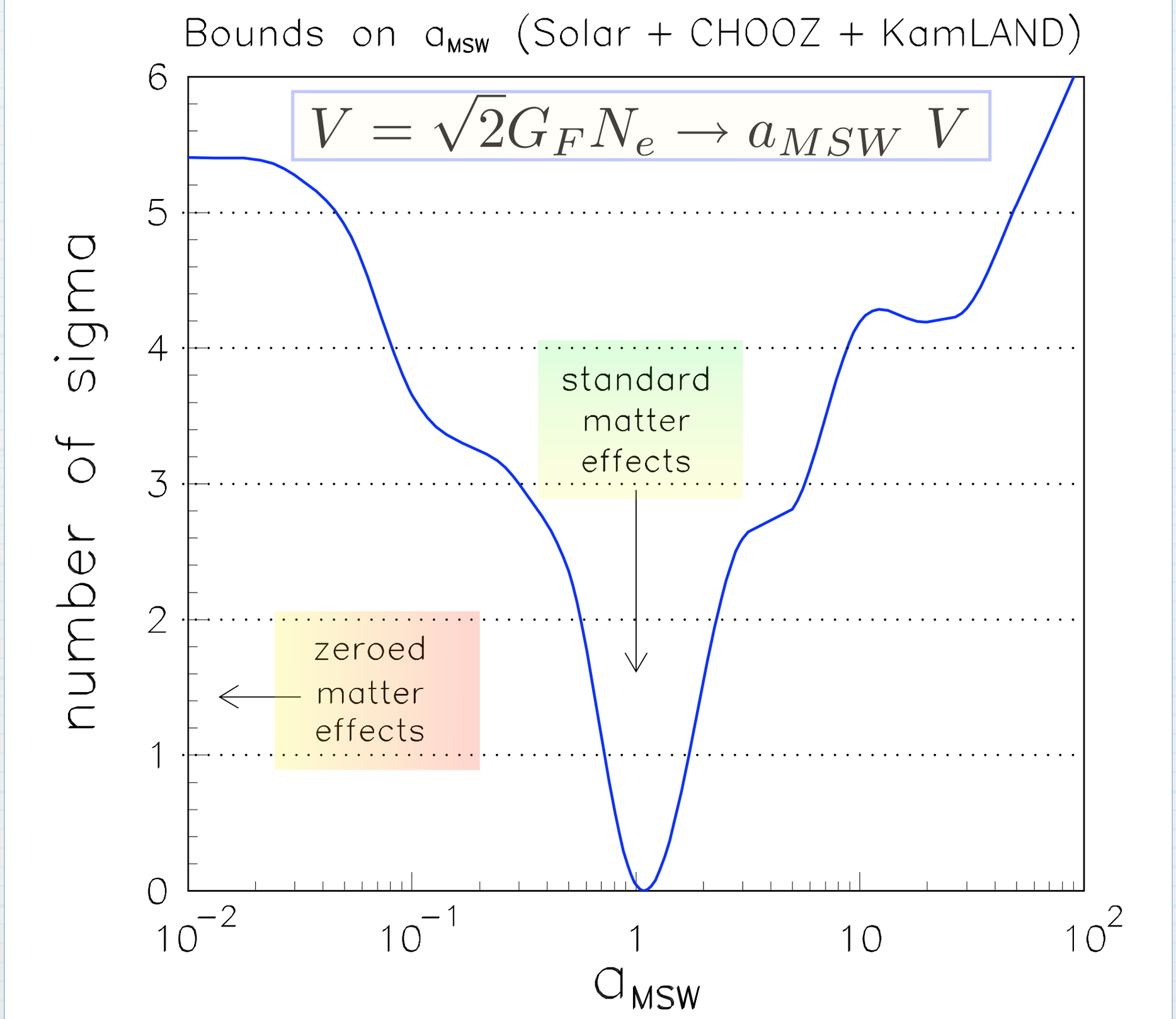
KamLAND -> δm^2

Seasonal variation in agreement with $1/R^2$

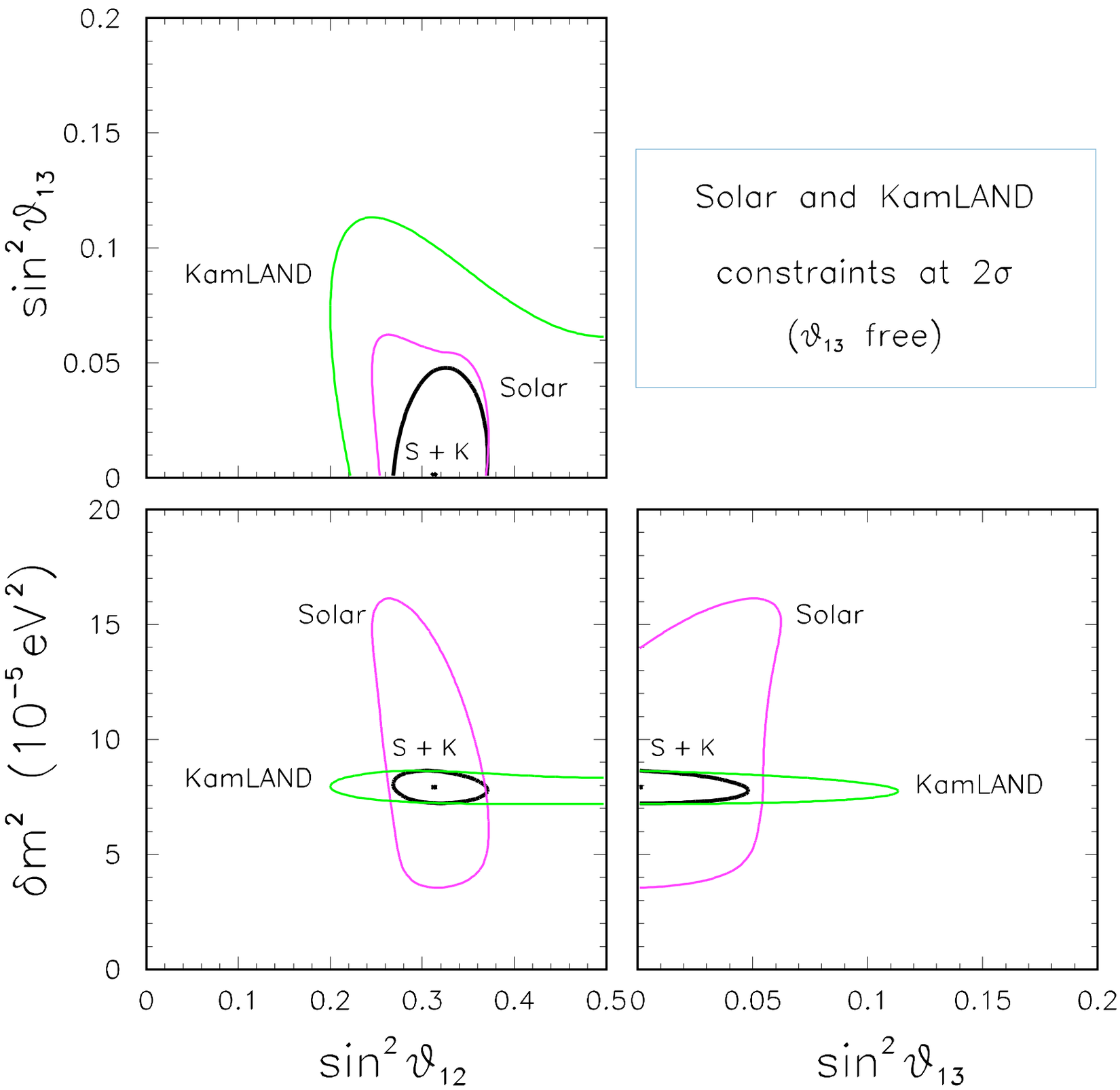
No evidence of day/night variation (--> earth MSW)



Mikheyev-Smirnov-Wolfenstein effect confirmed



3ν Analysis: Solar + KamLAND



Solar and KamLAND constraints at 2σ (ϑ_{13} free)

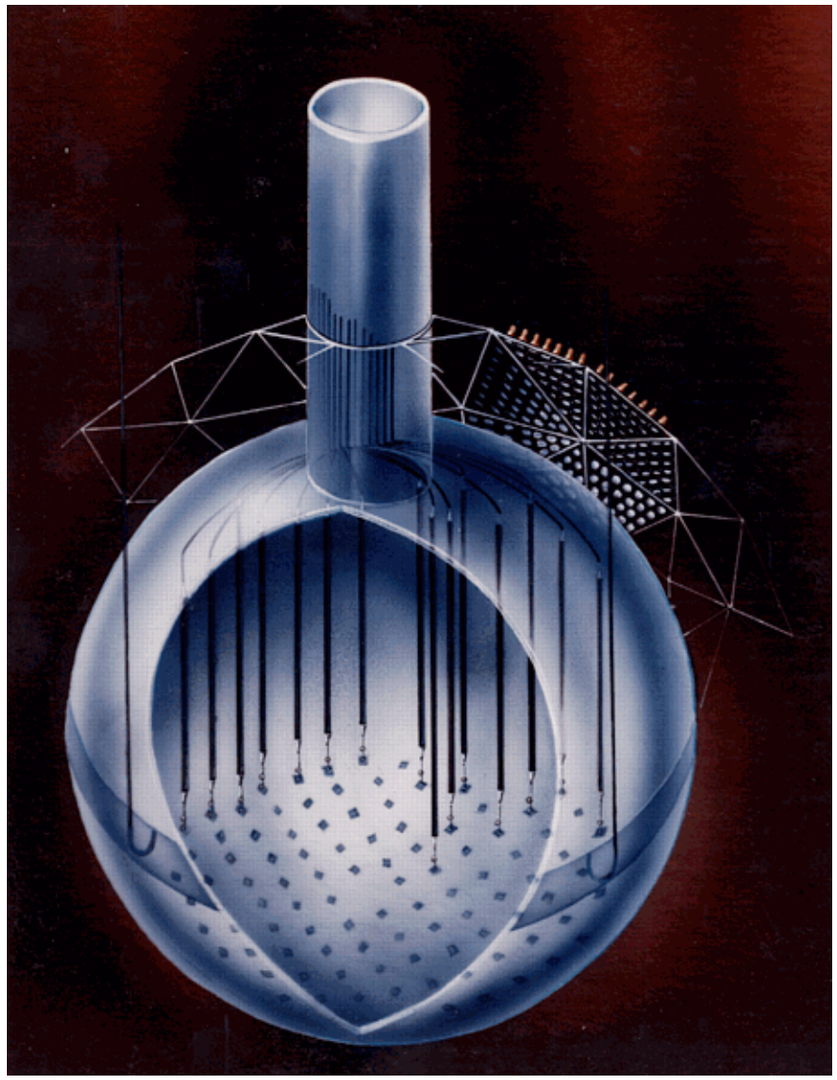
SNO phase III (completed)

Better NC determination through 40 strings of proportional counters

Reduction of systematic uncertainties

Lower analysis energy threshold

Better solar neutrino flux determination by breaking CC-NC correlation



Correlations	D_2O unconstrained	D_2O constrained	Salt unconstrained	NCD
NC,CC	-0.950	-0.520	-0.521	~0
CC,ES	-0.208	-0.162	-0.156	~-0.2
ES,NC	-0.297	-0.105	-0.064	~0

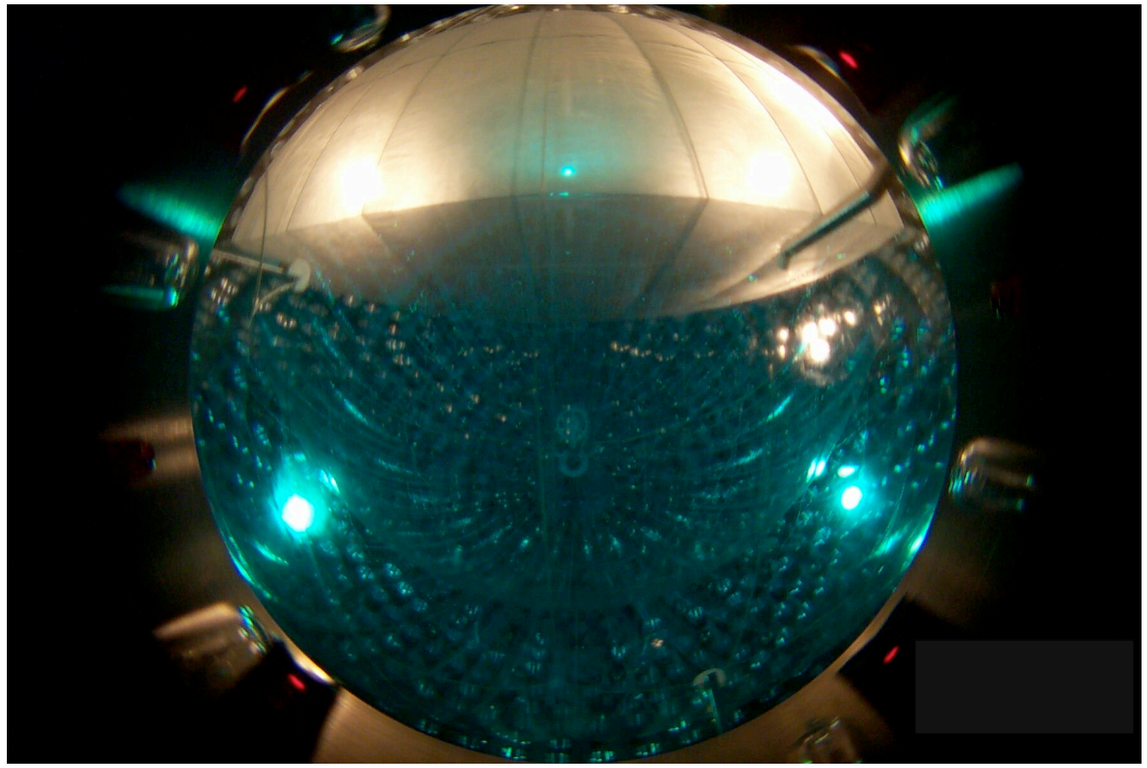
Borexino

Real-time measurement of the solar $^{7}\mathrm{Be}$ neutrino flux

Day-night, seasonal, periodic variations

Detector filling complete in May 2007

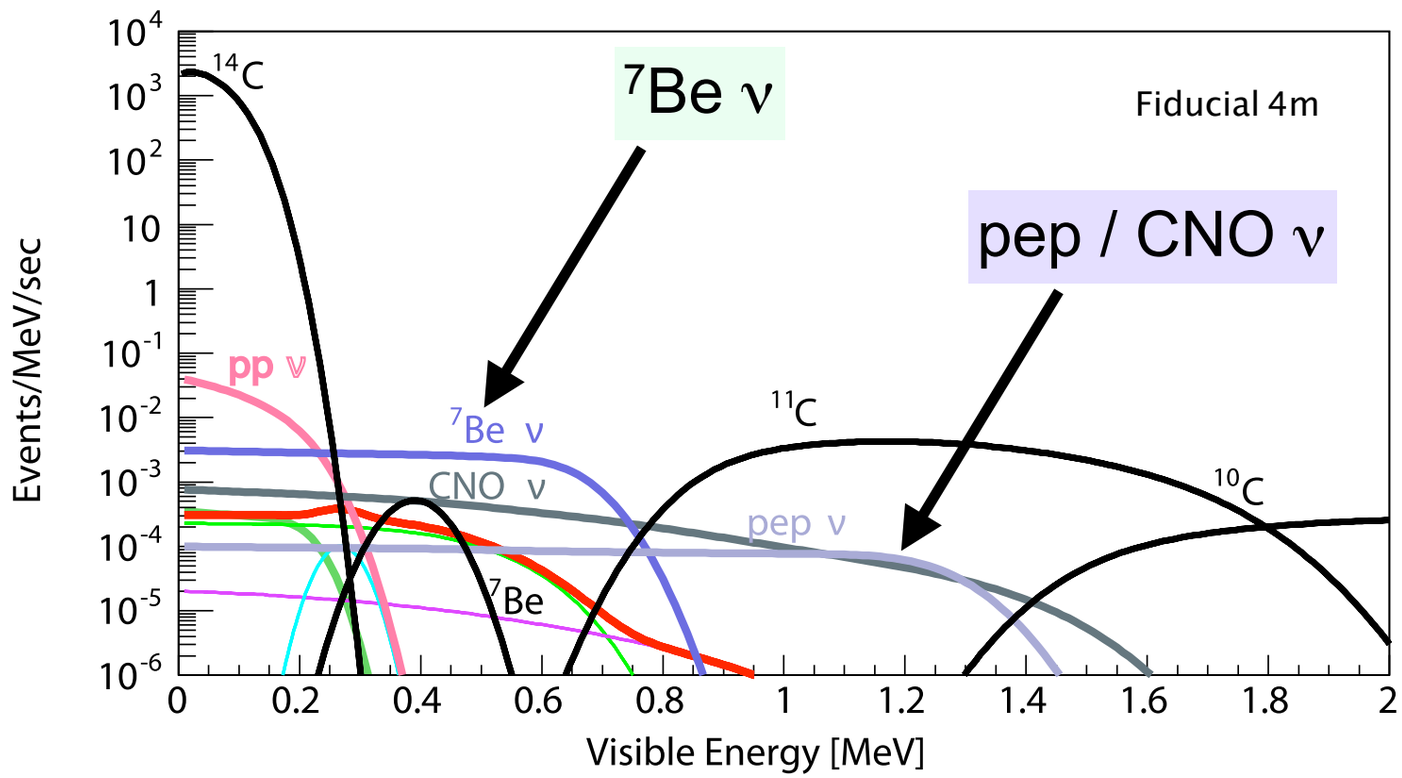
Borexino (Oct. 2006)



KamLAND

$^{7}\mathrm{Be}$	79.9 ev/day
CNO	3.8 ev/day
pep	16.3 ev/day

KamLAND II
starting this year



Atmospheric parameters

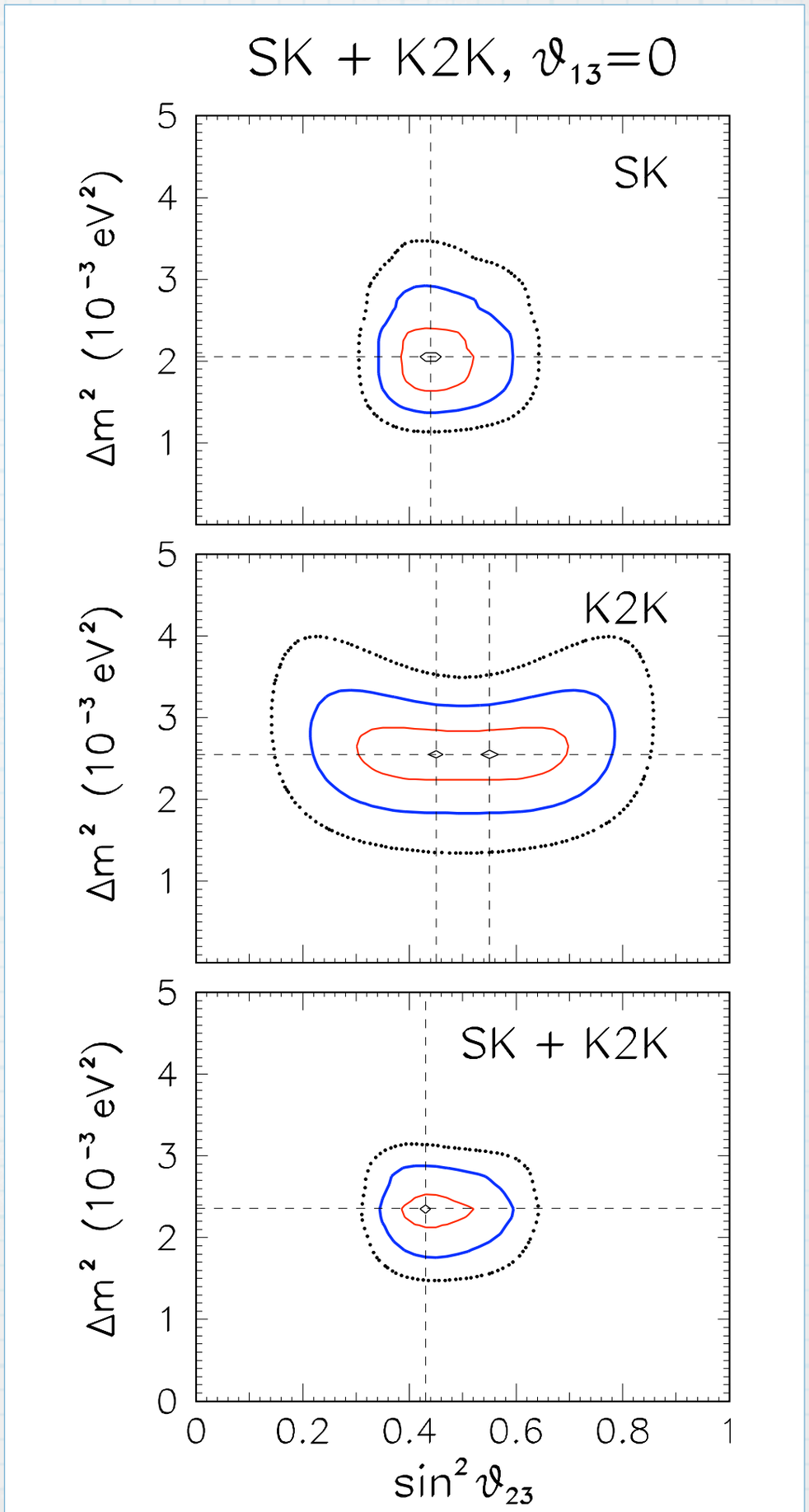
$$(\Delta m^2, \theta_{23}, \theta_{13})$$

2ν Analysis of SK + K2K

Solar (+ KamLAND) parameters fixed at their best-fit point

The dependence of the K2K analysis on the solar parameters is almost negligible

LMA induced effects break the octant symmetry of the mixing angle θ_{23}



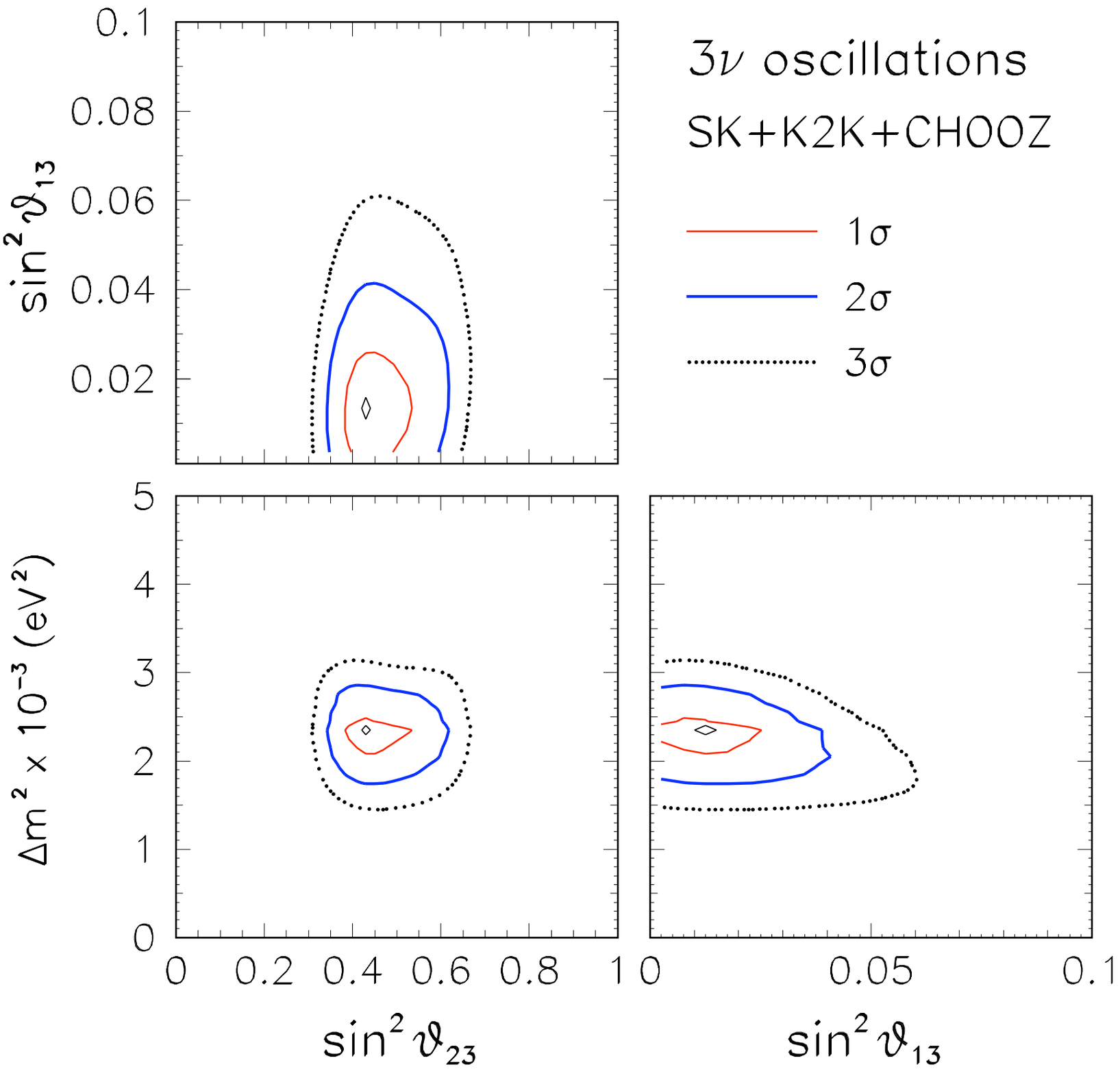
3ν Analysis of SK + K2K + CHOOZ

The more stringent limit on θ_{13} comes from the negative results of the CHOOZ experiment

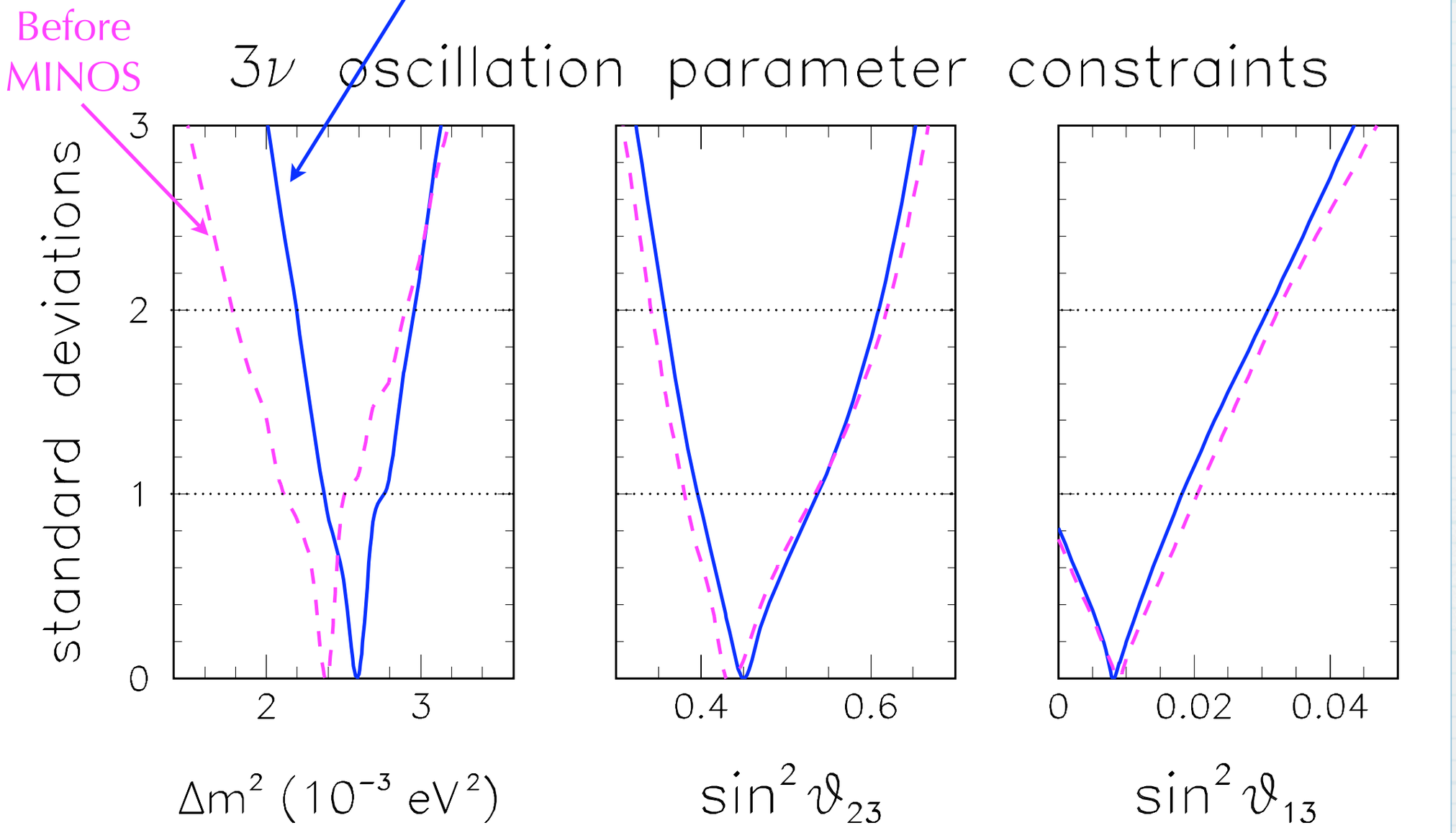
The analysis includes subleading LMA effects and marginalization with respect to the four cases

$$[\cos\delta = \pm 1] \otimes [\mathrm{sign}(\pm\Delta m^2)]$$

A slightly non zero value of θ_{13} is preferred, although without statistical significance



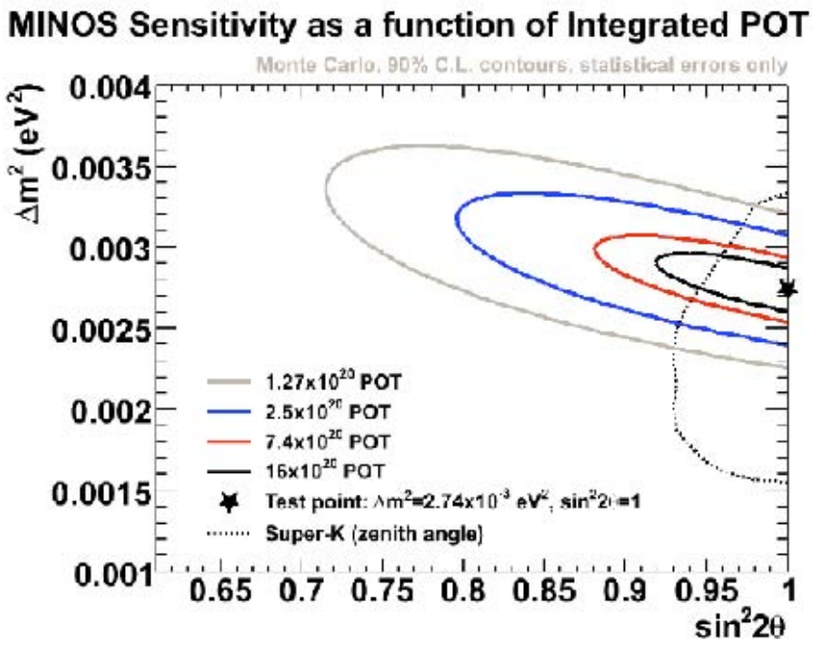
Impact of MINOS



2σ error on Δm^2 reduced from 24% to 15%

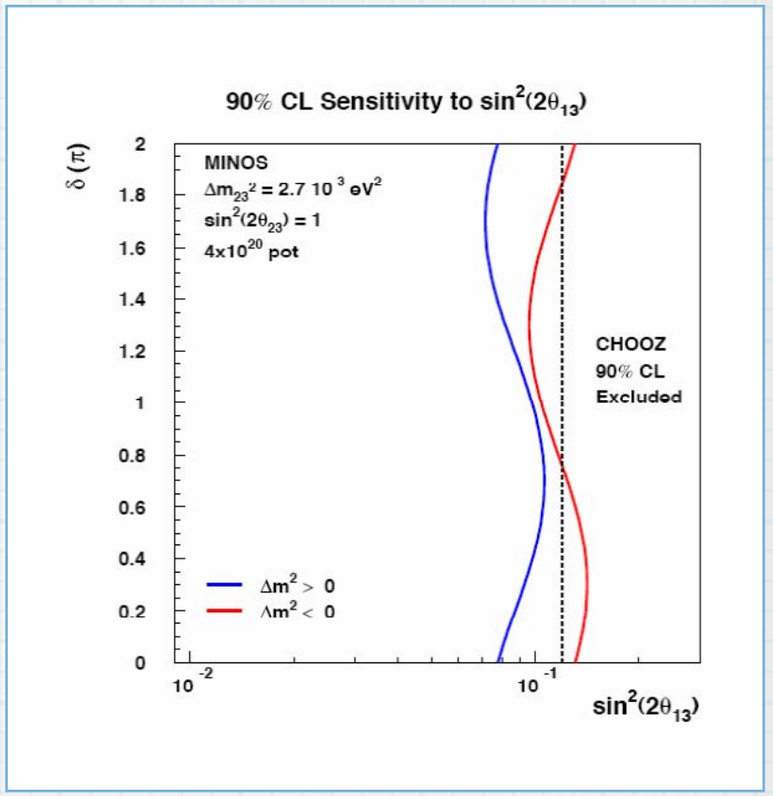
MINOS currently insensitive to $(\delta m^2, \theta_{12})$

MINOS & OPERA



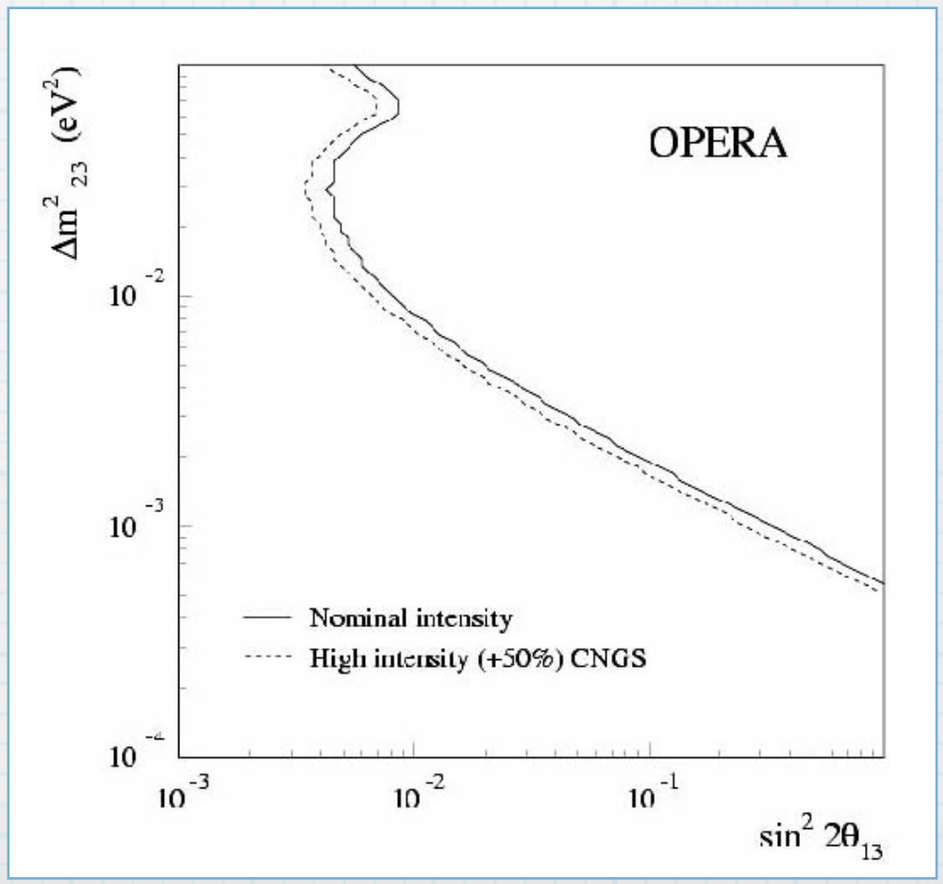
MINOS ν_μ CC $(4 \times 10^{20}$ POT)
Can improve limit of CHOOZ

5-10 % error on Δm^2



Harris@win07

5 years of nominal CNGS beam



Sirignano@neutrino2006

Oscillation Parameters

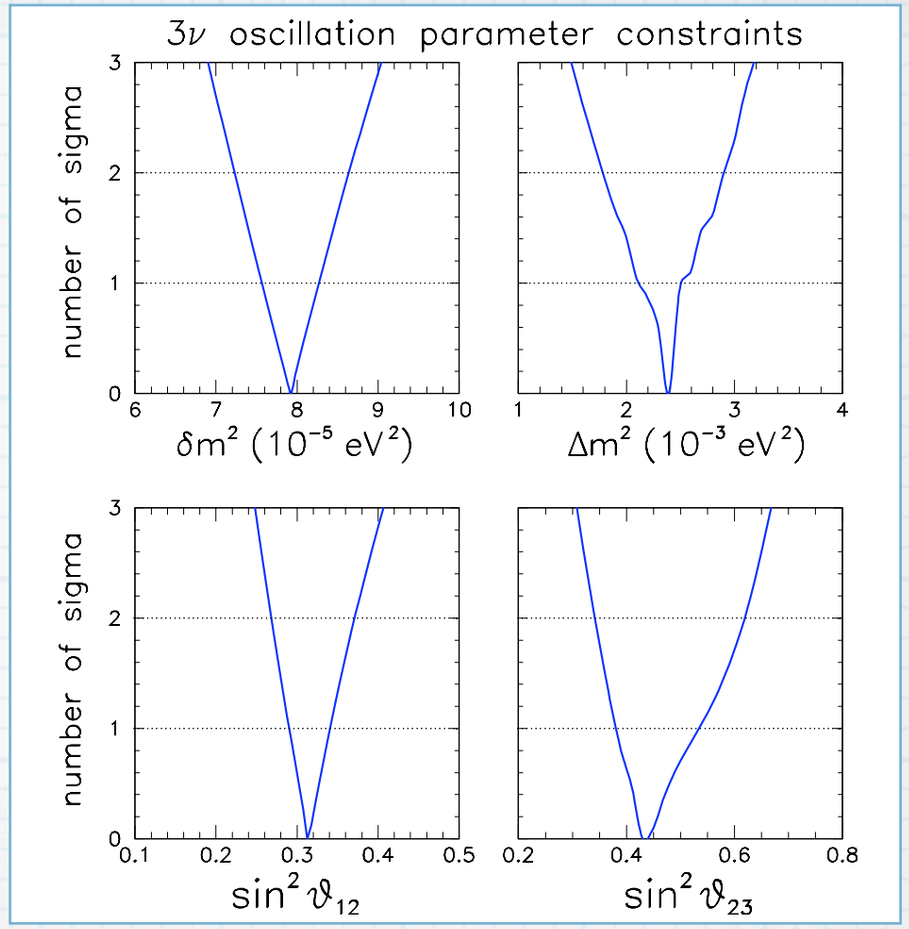
$$\delta m^2 = 7.92(1 \pm 0.09) \times 10^{-5}\ \mathrm{eV}^2$$

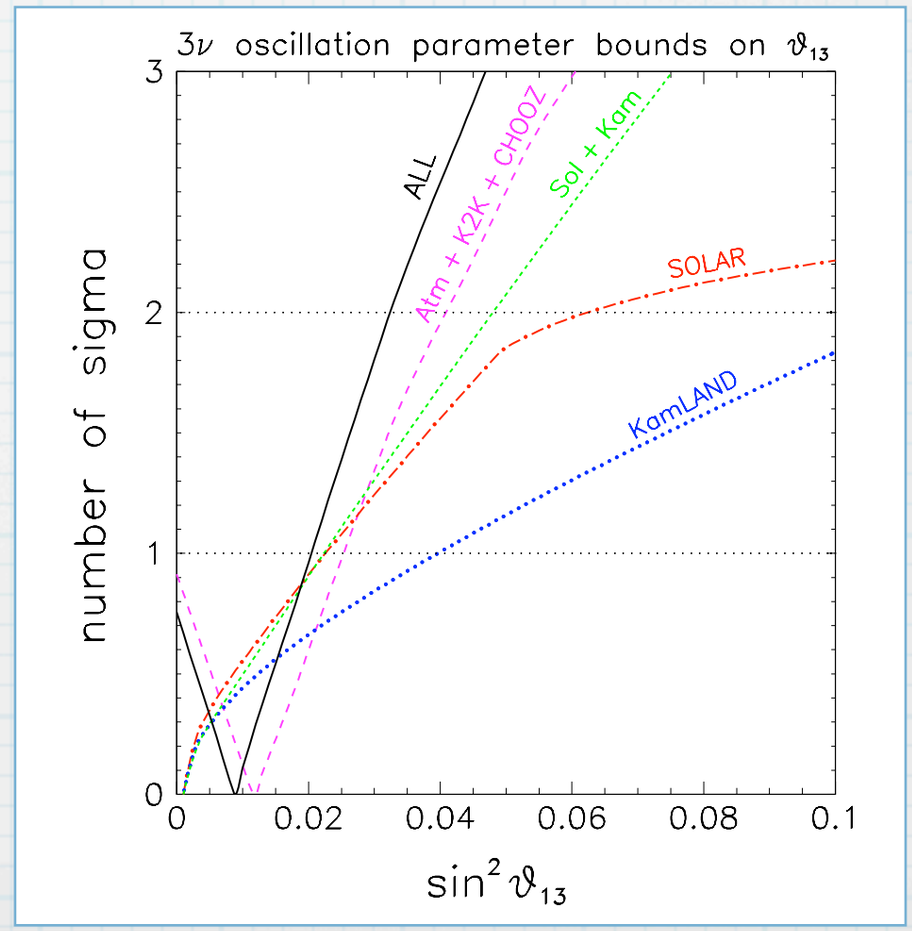
$$\sin^2\theta_{12} = 0.314(1^{+0.18}_{-0.15})$$

$$\Delta m^2 = 2.6(1^{+0.14}_{-0.15}) \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.45(1^{+0.35}_{-0.20})$$

$$\sin^2\theta_{13} = 0.8(1^{+2.3}_{-0.8}) \times 10^{-2}$$





The path behind ...

Discovery of neutrino masses

Leading structure of the mixing matrix

Vacuum oscillations (Atm) + Adiabatic MSW (Sol)

Three active neutrino oscillation scenario satisfactory

the way still to go ...

Majorana vs Dirac nature of neutrinos

Mass spectrum: degenerate/ non-degenerate & hierarchy

θ_{23} exactly maximal (if not, which octant)

θ_{13} is zero or not

δ_{CP} , Majorana phases

Non-oscillation observables

Beta decay

No signal so far

$m_\beta < 1.8$ eV (Mainz+Troitsk)

$$m_\beta = \sqrt{c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2}$$

effective neutrino mass, as far as the single mass eigenstates are not experimentally resolvable

$0\nu2\beta$

No signal, excepted the debated claim by part of the (Heidelberg-Moscow coll.)

claim accepted	$\log_{10}(m_{\beta\beta}/\mathrm{eV}) = -0.23 \pm 0.14$
claim rejected	$\log_{10}(m_{\beta\beta}/\mathrm{eV}) = -0.23^{+0.14}_{\infty}$

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

only V-A charged weak current with the exchange of Majorana neutrinos

Cosmology

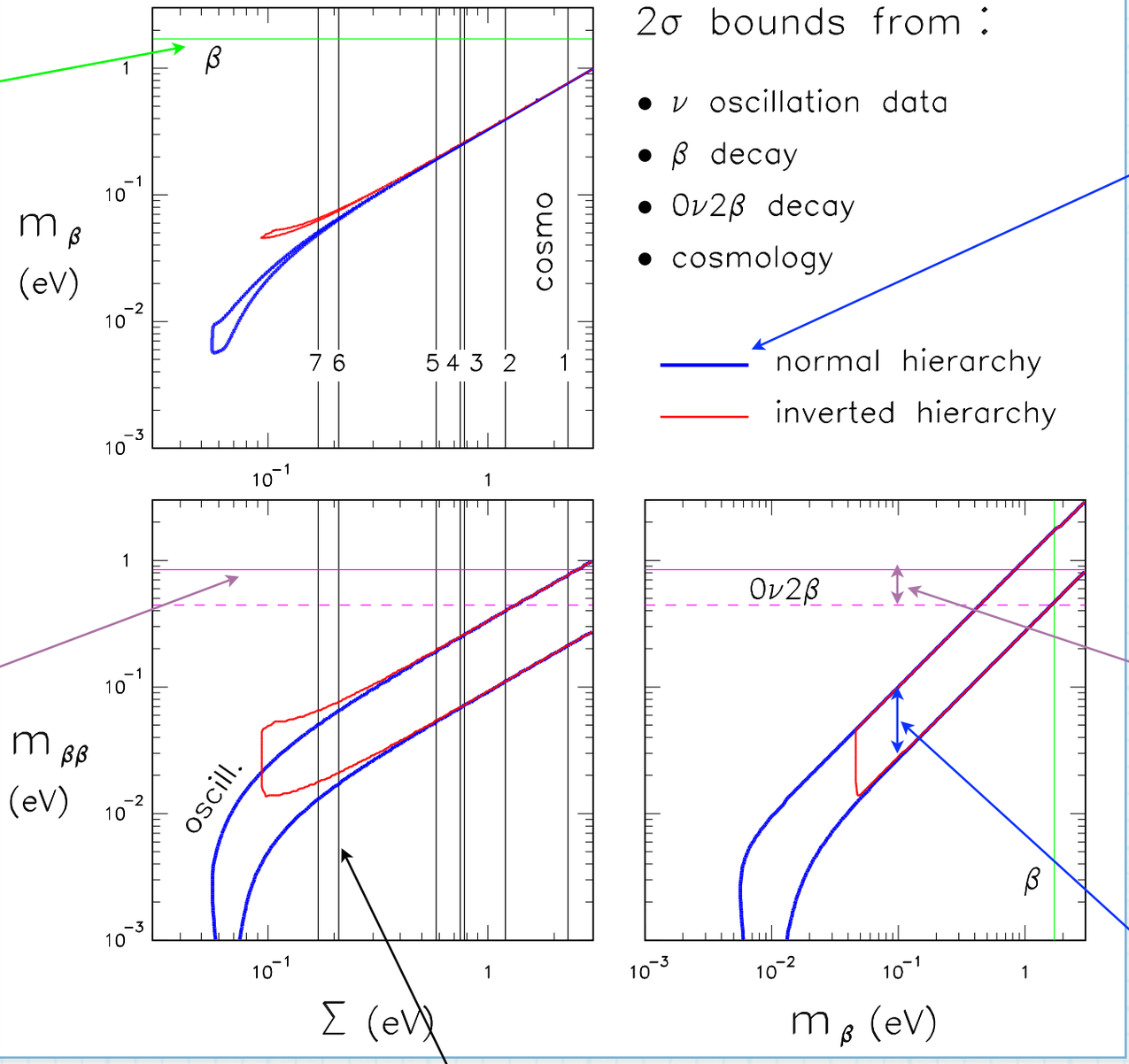
Upper bound of the order of 0.1-1 eV depending on the adopted inputs and priors

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

very weak sensitivity to the details of the spectrum

Superposition of all the constraints

decay (Mainz & Troitsk)



Bands from oscillation data (normal and inverted hierarchy bands overlap for degenerate spectrum)

Heidelberg-Moscow

Klapdor et al. claim

intrinsic uncertainty due to Majorana phases

Cosmology constraints for different inputs

CMB (WMAP3 + others)

Type Ia Supernovae (SN)

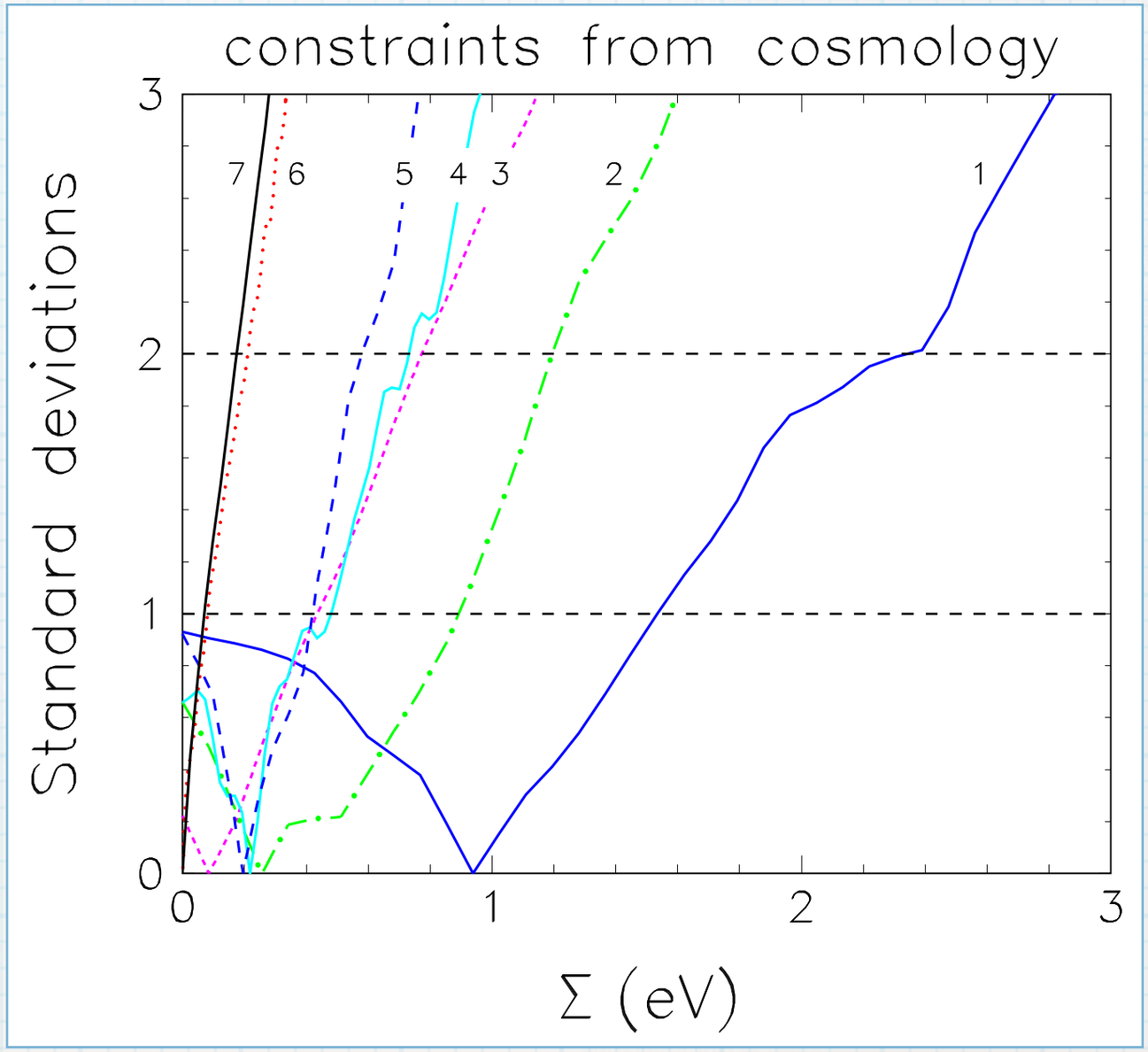
Large Scale Structure (SDSS)

Hubble Space Telescope (HST)

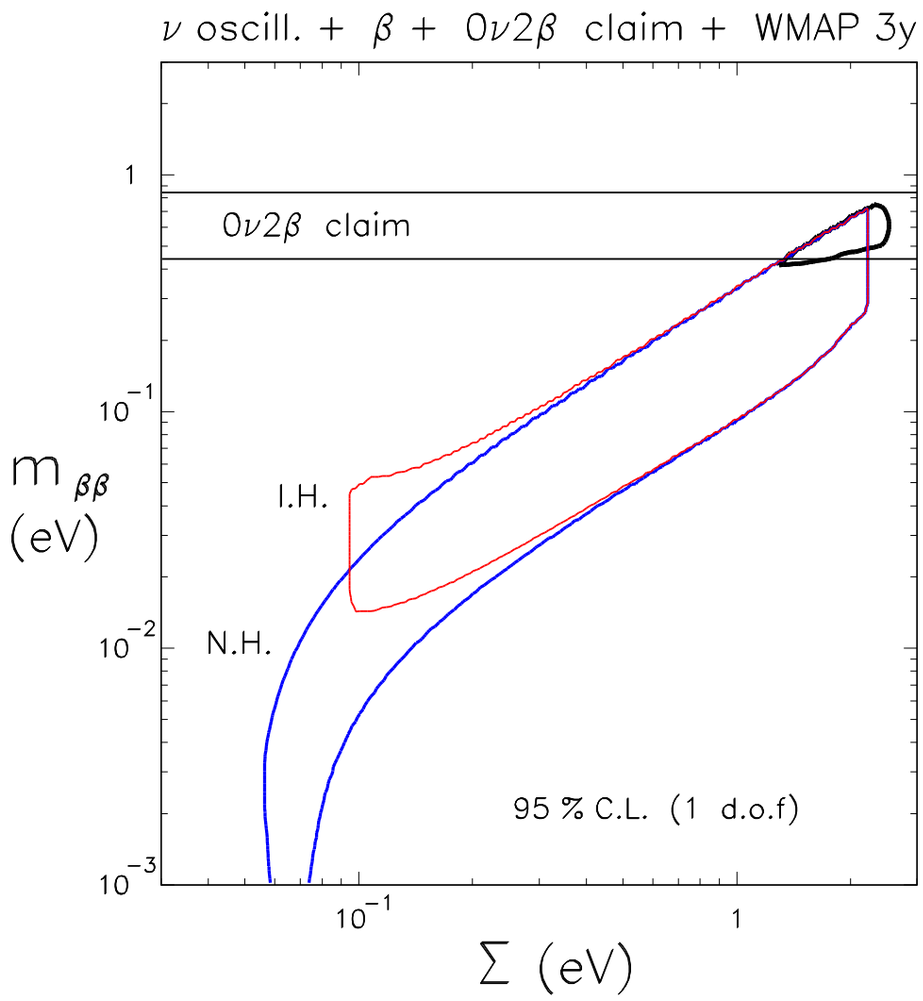
Baryon Acoustic Oscillations (BAO)

Lyman-α (Ly-α)

Big Bang Nucleosyinthesis (BBN)



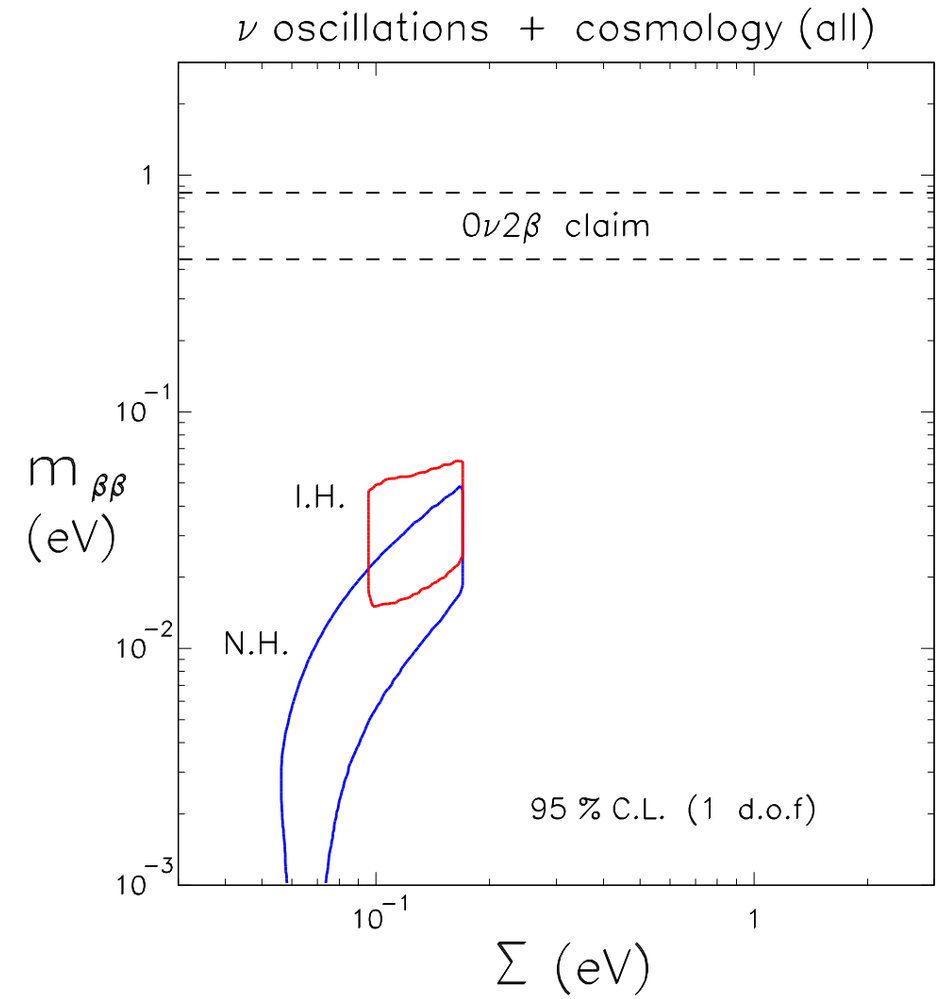
Case	Cosmological data set	Σ bound (2σ)
1	WMAP	< 2.3 eV
2	WMAP + SDSS	< 1.2 eV
3	WMAP + SDSS + $\mathrm{SN_{Riess}}$ + HST + BBN	< 0.78 eV
4	CMB + LSS + $\mathrm{SN_{Astier}}$	< 0.75 eV
5	CMB + LSS + $\mathrm{SN_{Astier}}$ + BAO	< 0.58 eV
6	CMB + LSS + $\mathrm{SN_{Astier}}$ + Ly-α	< 0.21 eV
7	CMB + LSS + $\mathrm{SN_{Astier}}$ + BAO + Ly-α	< 0.17 eV



Global combination allowed

Degenerate spectrum

$$m_\nu \sim 0.6 \ (\mathrm{eV})$$



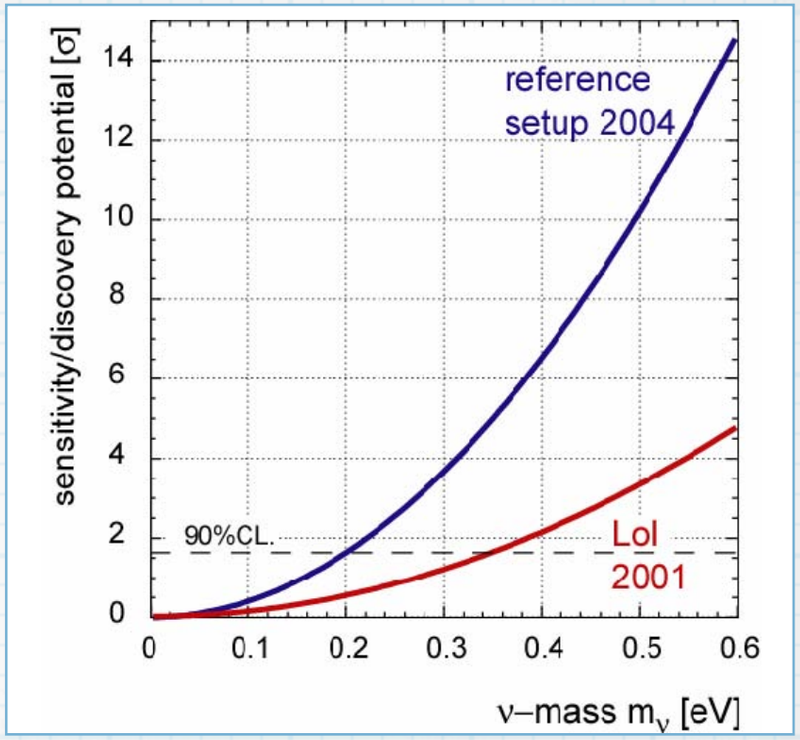
Global combination not possible

$$\Sigma < 0.17 \ (\mathrm{eV})$$
$$m_\beta < 0.06 \ (\mathrm{eV})$$
$$m_{\beta\beta} < 0.06 \ (\mathrm{eV})$$

KATRIN

Starting data taking 2009
full sensitivity 2015

Limits down by an order of magnitude $m_\beta \lesssim 0.2$ (eV)



Next generation
$0\nu 2\beta$ experiments

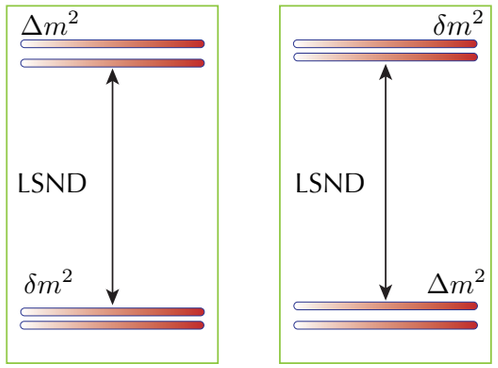
$m_{\beta\beta} \lesssim 0.01 \div 0.1$ (eV)

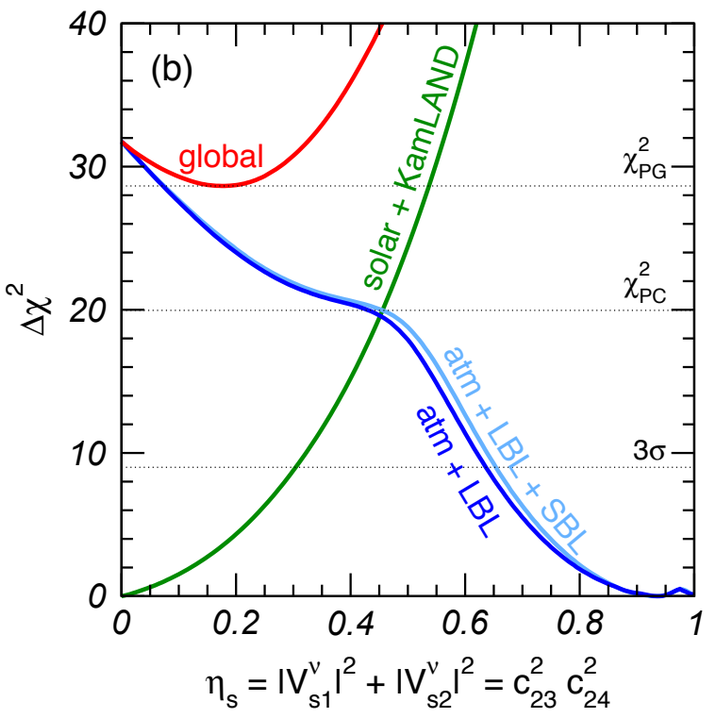
Name		%	$Q_{\beta\beta}$	% E	B c/y	T (year)	Tech	<m>
CUORE	^{130}Te	34	2533	90	3.5	1.8×10^{27}	Bolometric	9-57
GERDA	^{76}Ge	7.8	2039	90	3.85	2×10^{27}	Ionization	29-94
Majorana	^{76}Ge	7.8	2039	90	.6	4×10^{27}	Ionization	21-67
GENIUS	^{76}Ge	7.8	2039	90	.4	1×10^{28}	Ionization	13-42
Supernemo	^{82}Se	8.7	2995	90	1	210^{26}	Tracking	54-167
EXO	^{136}Xe	8.9	2476	65	.55	1.3×10^{28}	Tracking	12-31
Moon-3	^{100}Mo	9.6	3034	85	3.8	1.7×10^{27}	Tracking	13-48
DCBA-2	^{150}Nd	5.6	3367	80		1×10^{26}	Tracking	16-22
Candles	^{48}Ca	.19	4271	-	.35	3×10^{27}	Scintillation	29-54
CARVEL	^{48}Ca	.19	4271	-		3×10^{27}	Scintillation	50-94
GSO	^{160}Gd	22	1730	-	200	1×10^{26}	Scintillation	65-?
COBRA	^{115}Cd	7.5	2805				Ionization	
SNOLAB+	^{150}Nd	5.6	3367				Scintillation	

4 Neutrino Mixing

2+2 Scenario

Disfavored at more then four sigmas





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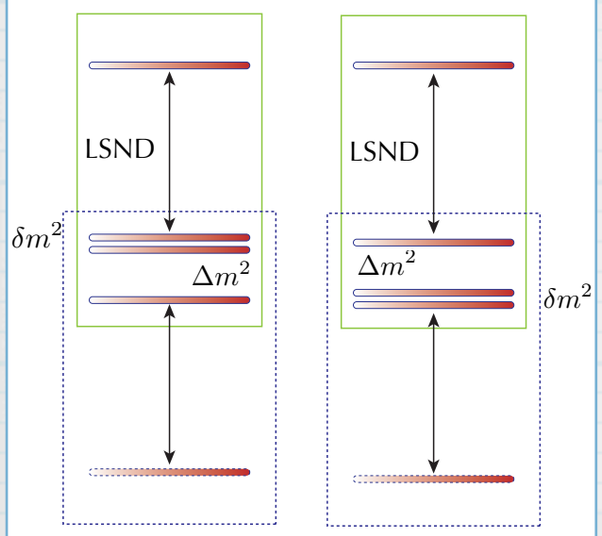
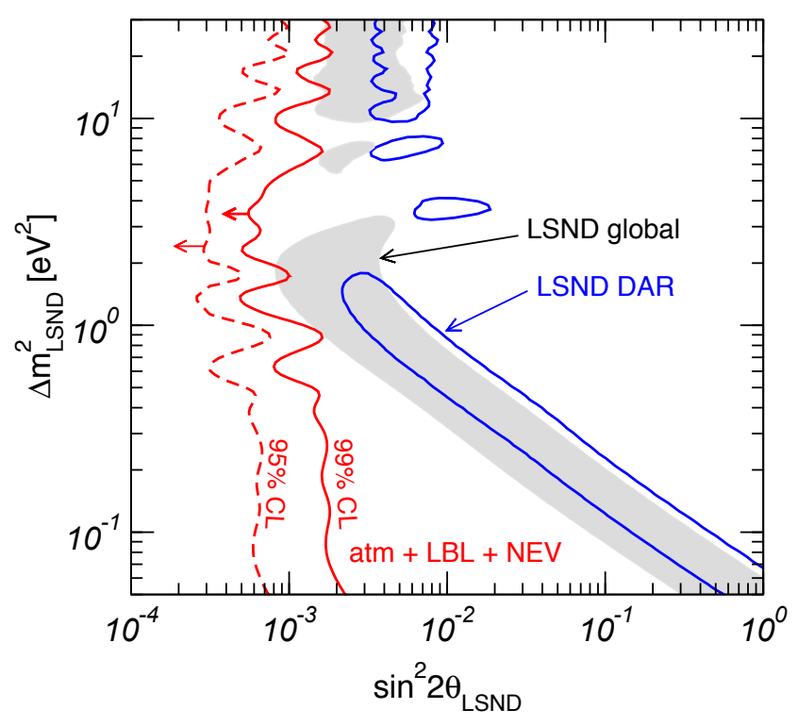
3+1 Scenario

Only small regions at 99% C.L.





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Also

CPT disfavored at more than four sigmas

Could work

4 neutrinos + "something"

- 3 + 2 light sterile neutrinos
- 3 + 1 light sterile + CPT viol.
- 3 + 1 light sterile + decay
- 3 + 1 light sterile with extra dimensions
- 3 + quantum decoherence and CPT violation

Conclusions

Robust evidence in favour of oscillations
in a three neutrino flavor scenario:
vacuum oscill, + adiabatic MSW conversion

to survive ...the MiniBooNE results!!

Improvement on the oscillation parameters

MINOS, OPERA, SNO, KamLAND, Borexino

and on absolute masses

KATRIN, GERDA, CUORE, SuperNemo, ...

Near future (T2K, Double CHOOZ, Daya Bay, ...)

Severely constrain θ_{13} or discover non-zero value

few % precision on the relevant parameters + CP, hierarchy, ..