Other neutrino oscillation measurements

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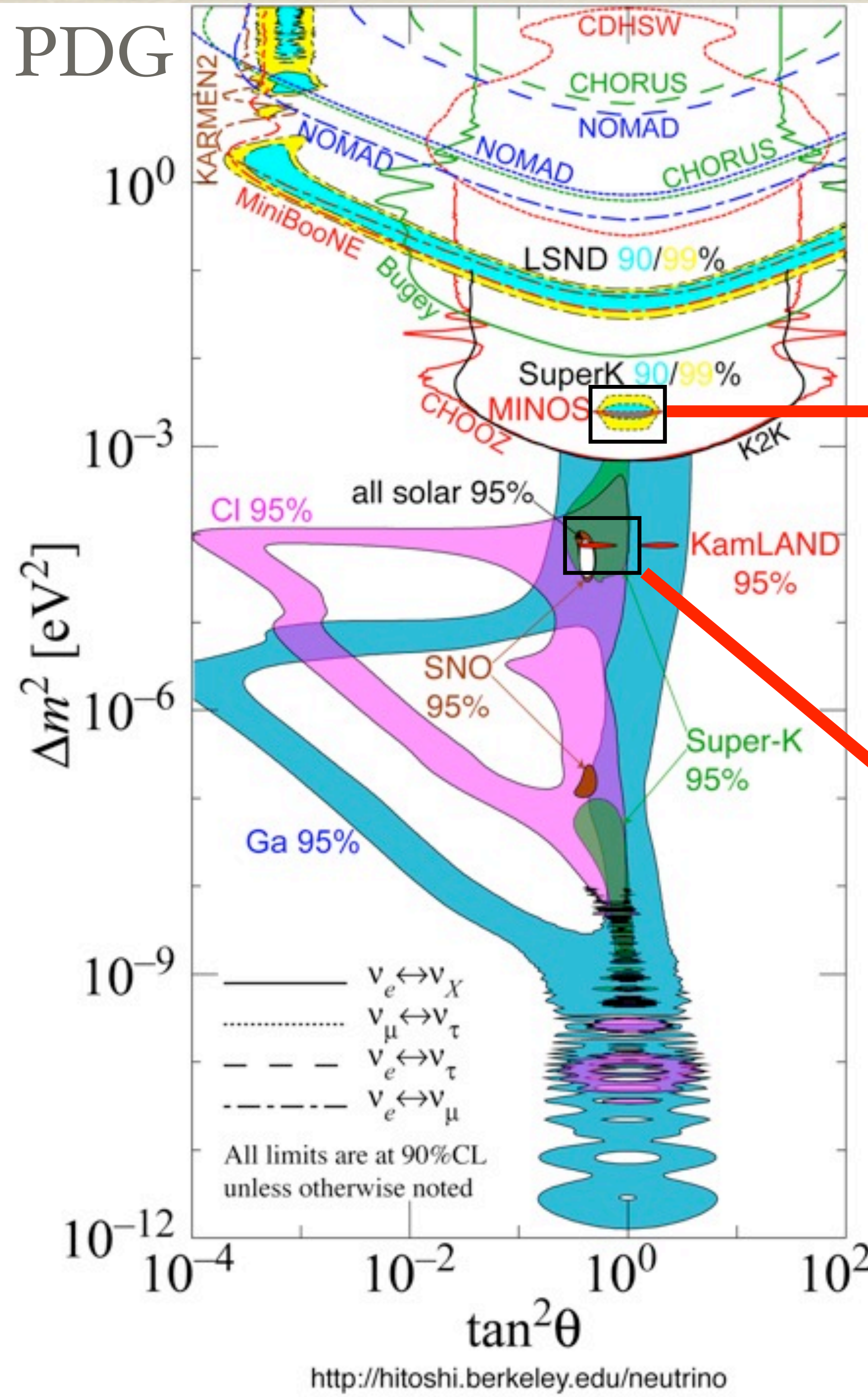
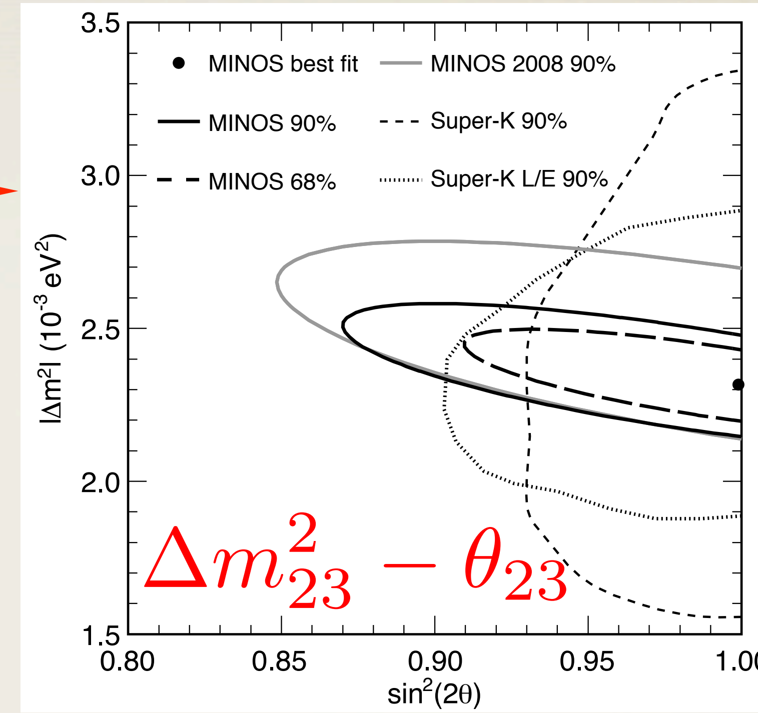
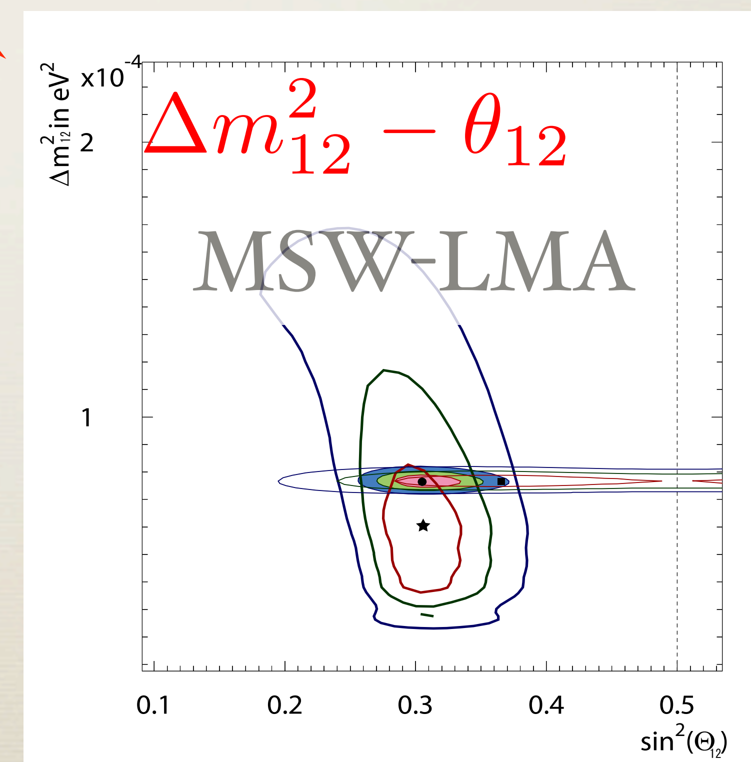
Neutrino oscillation results before 2011





atm.-nu
acc.-nu



sol.-nu
kamL.

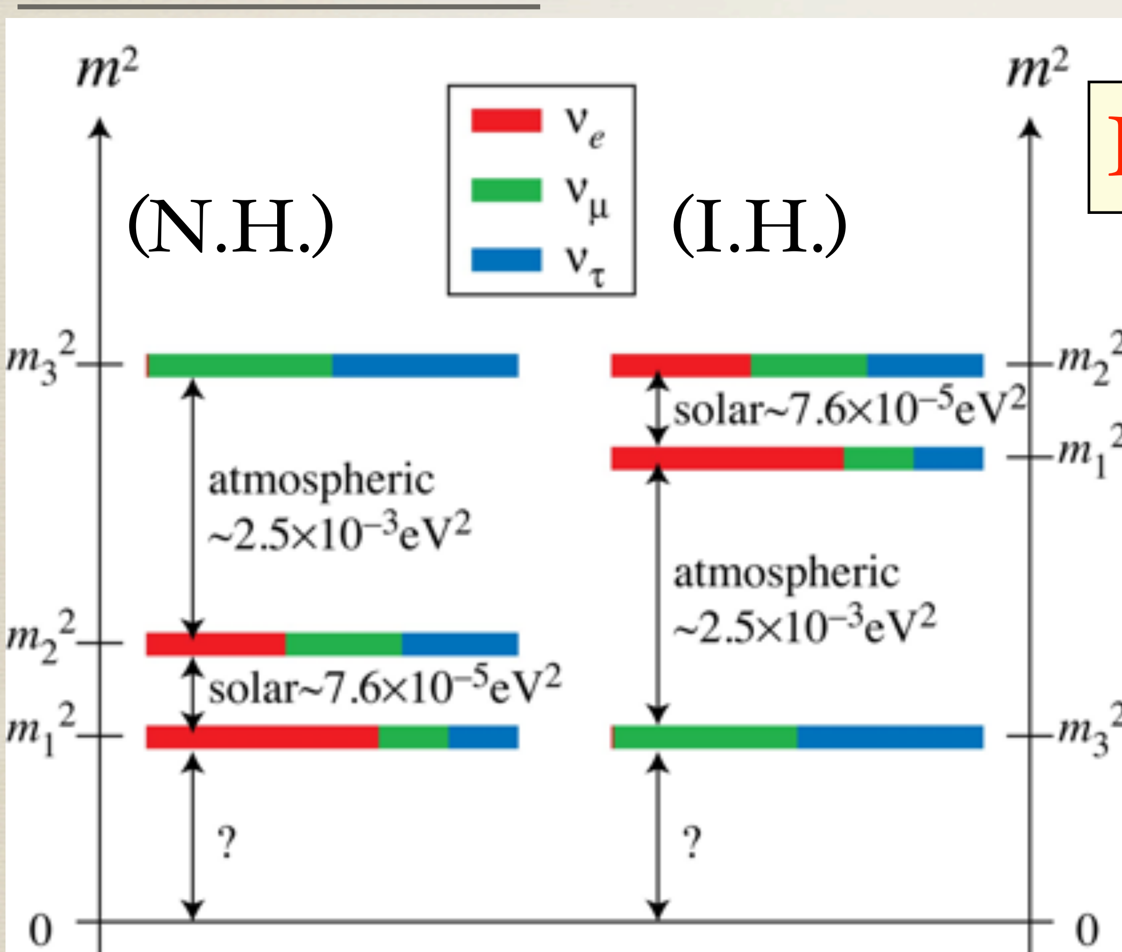
Neutrino Oscillation

Mixing angle

atm.-nu, acc.-nu | acc.-nu, reactor (SBL) | solar-nu, reactor (KamL.)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass differences



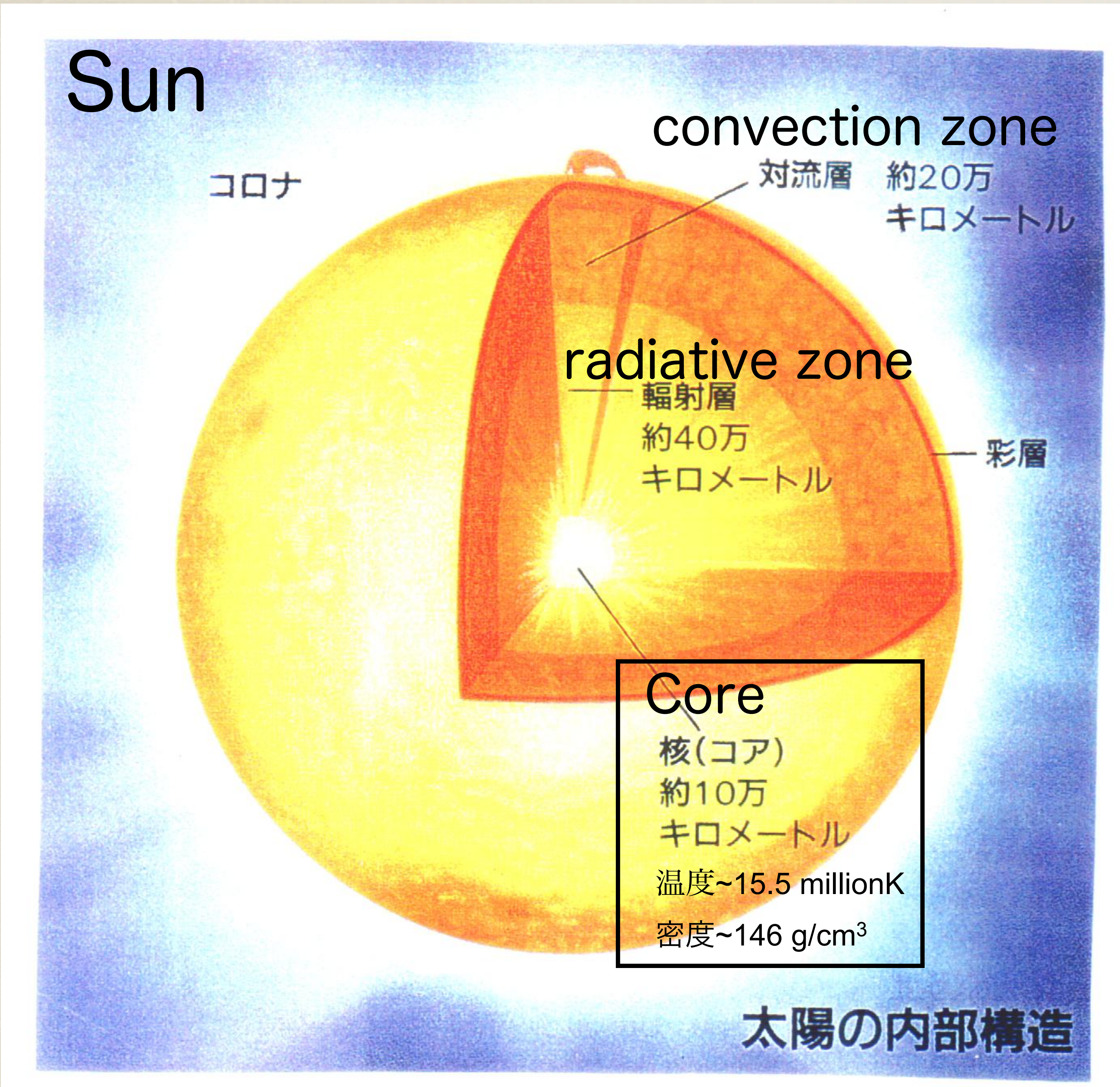
In 2012, discovery of surprisingly large θ13

$$\sin^2 2\theta_{13} = 0.099 \pm 0.014$$

What does non-zero θ13 affect other parameters?

SOLAR NEUTRINOS

Solar neutrinos



Nuclear fusion reaction
deep inside the Sun

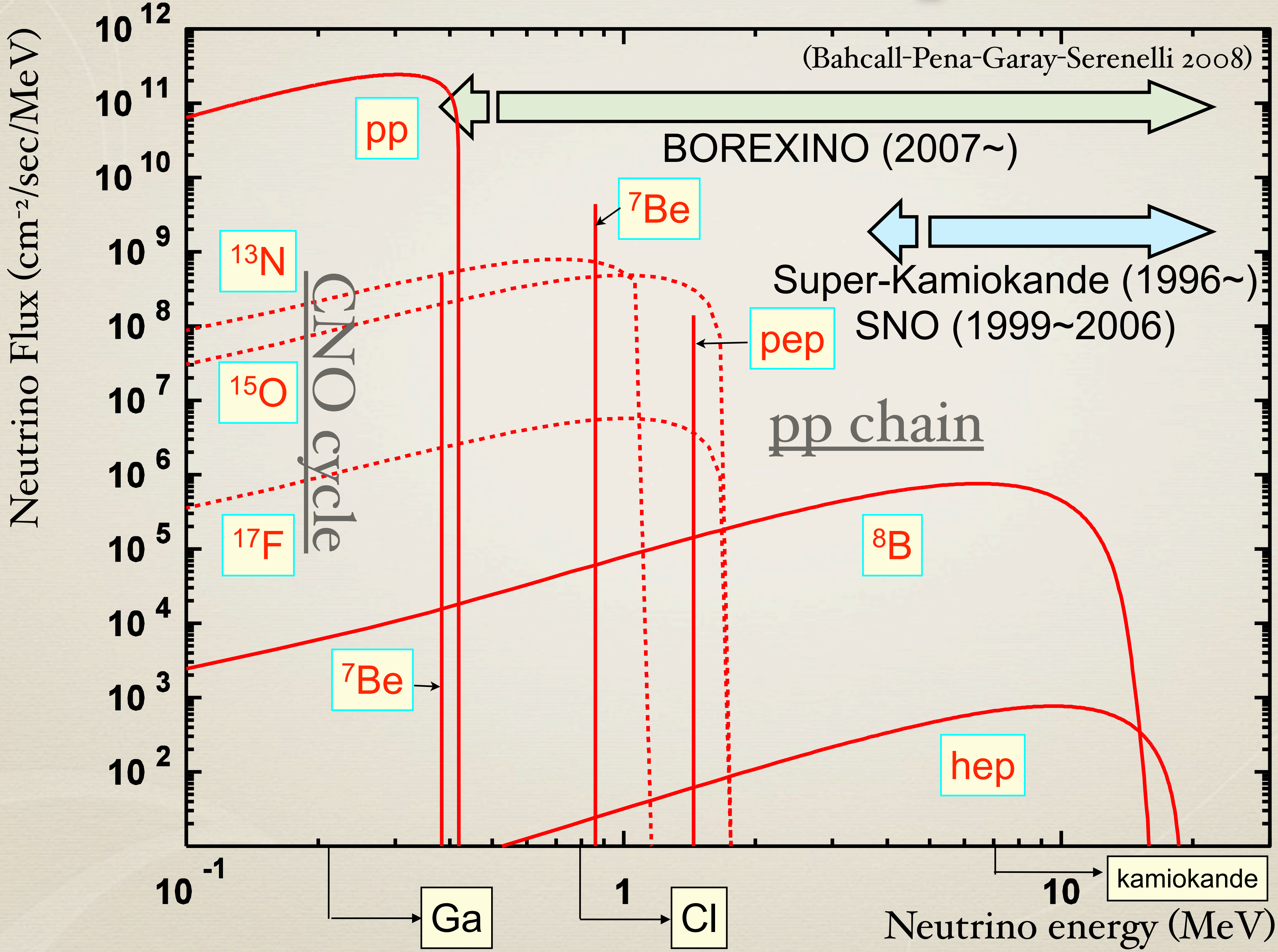
$$4p \rightarrow {}^{2}He + 2e^{+} + 2\nu_{e}$$

(~6.6×10^{10}neutrinos/sec/cm^2)

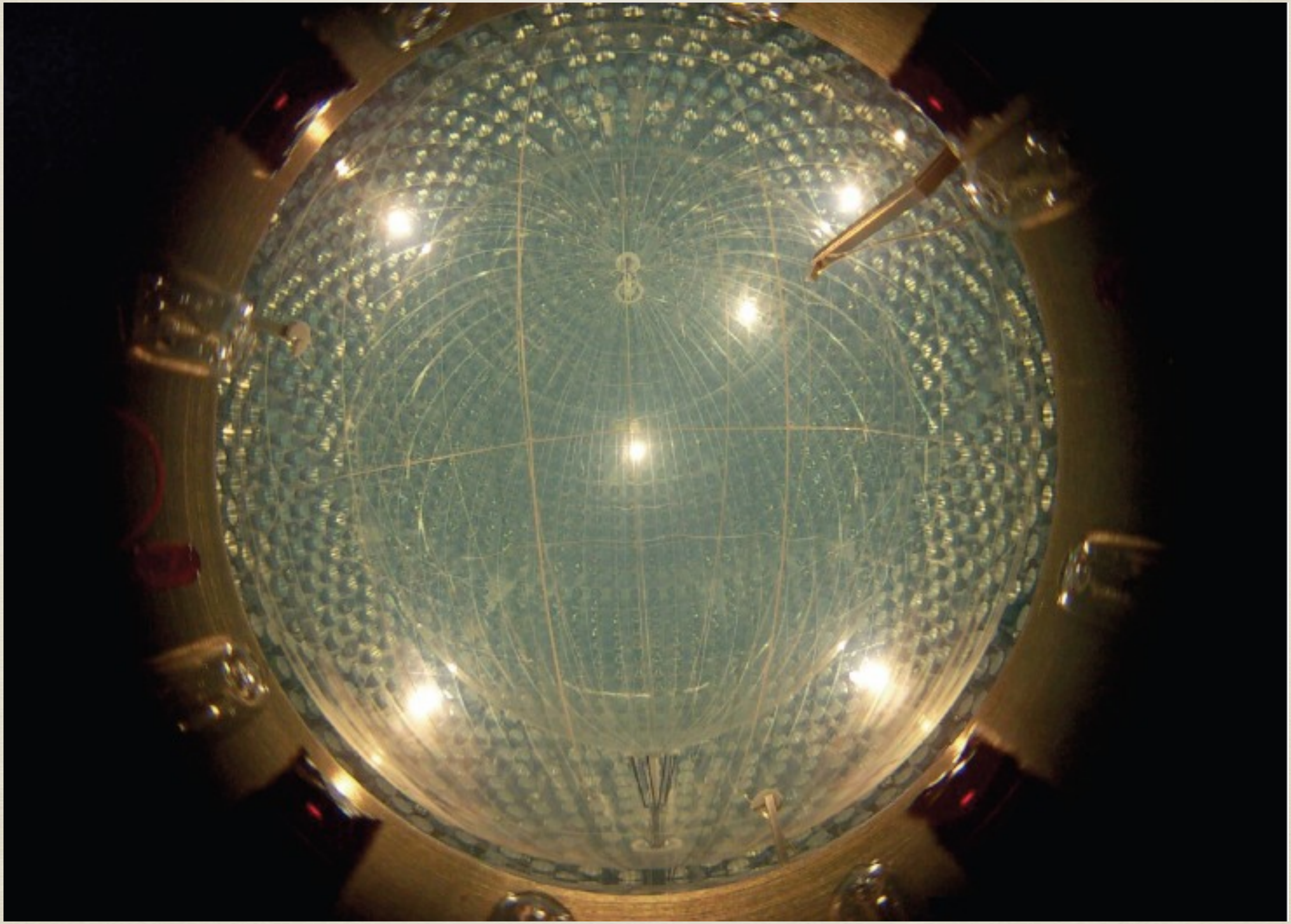
This reaction is actually realized through pp-chain / CNO cycle.

- Measurement of the current status in the center of the Sun
- Study of
  - a mechanism of the energy generation in the Sun
  - a property of neutrinos

Solar neutrino spectrum

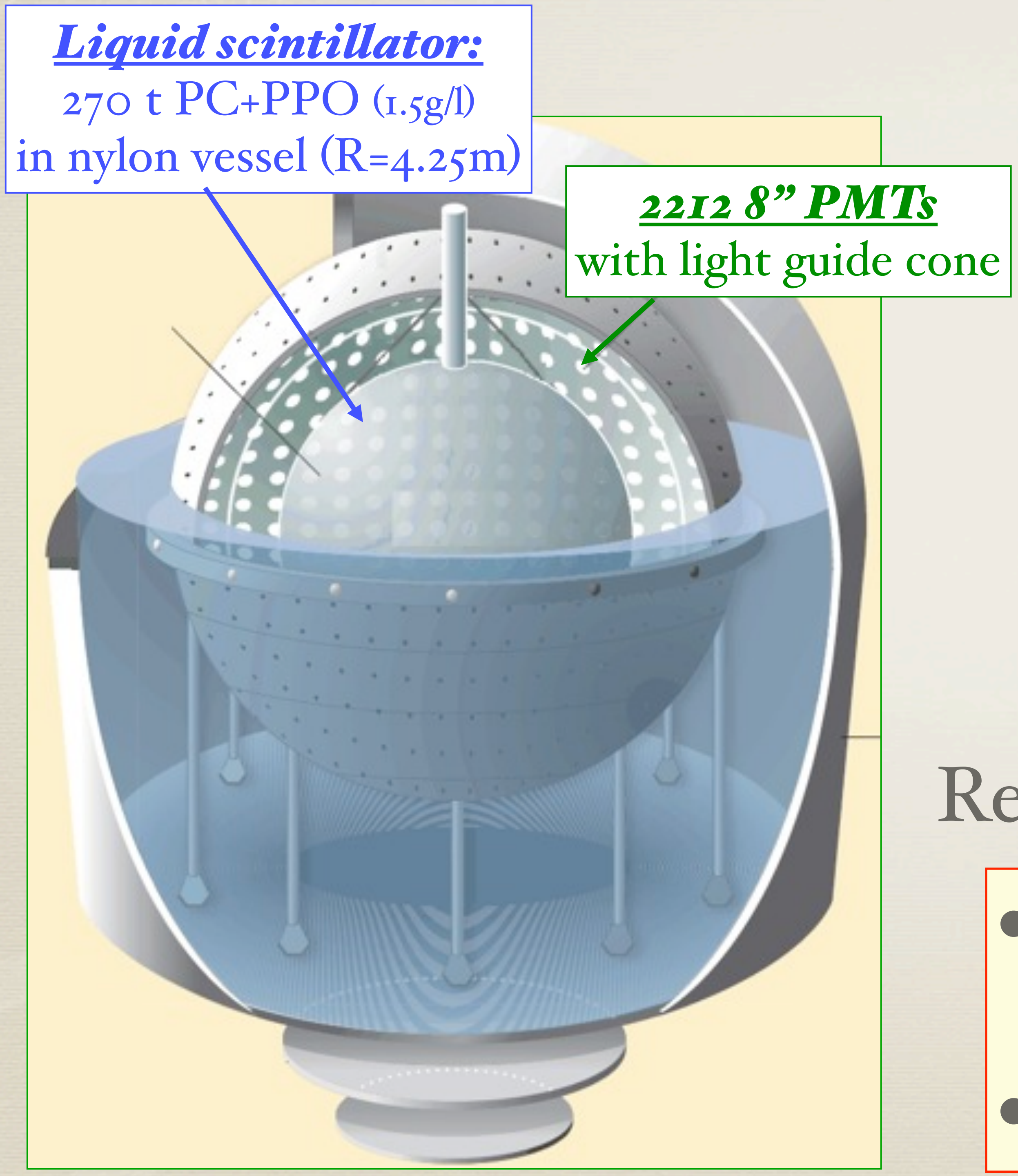


Borexino



Observation in Borexino

Gran Sasso, Italy



Neutrino-electron elastic scattering

$$\nu + e^- \rightarrow \nu + e^-$$

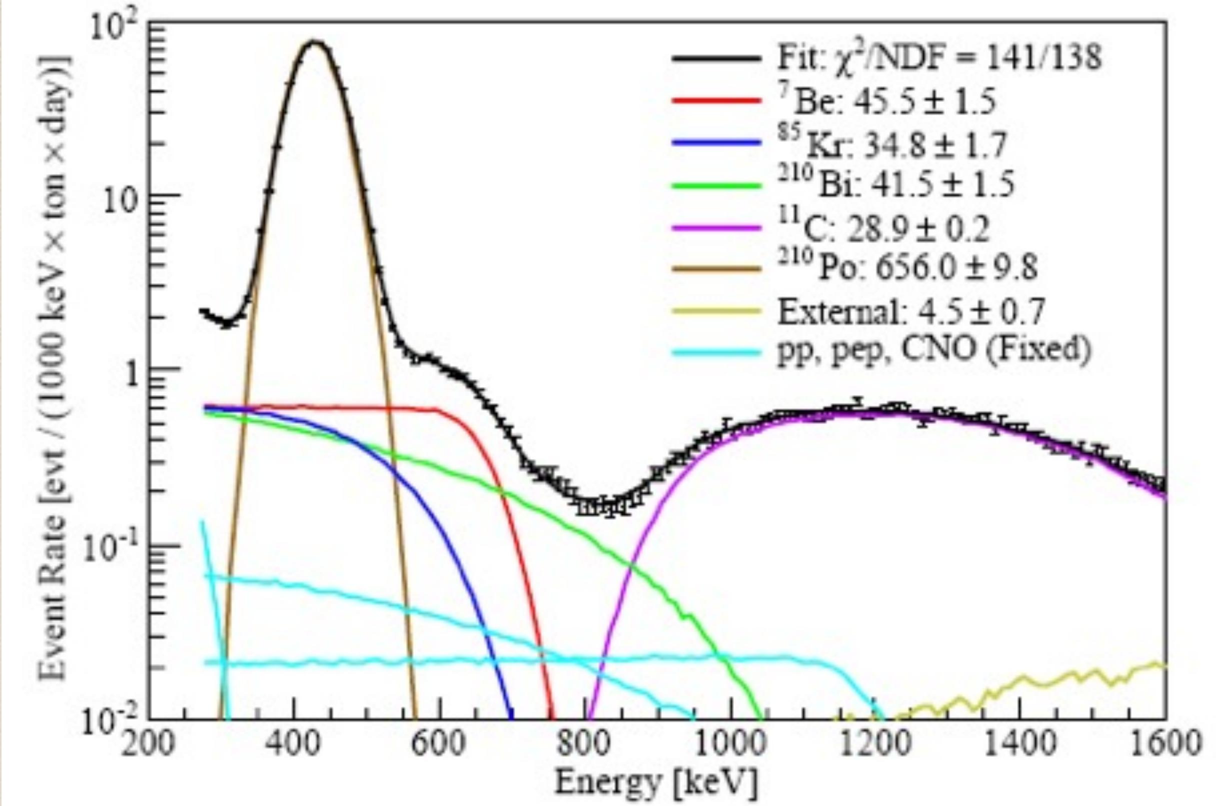
- High light yield
  - lowering threshold
  - good energy resolution
- No neutrino direction inf.
  - hard to distinguish signal and background...

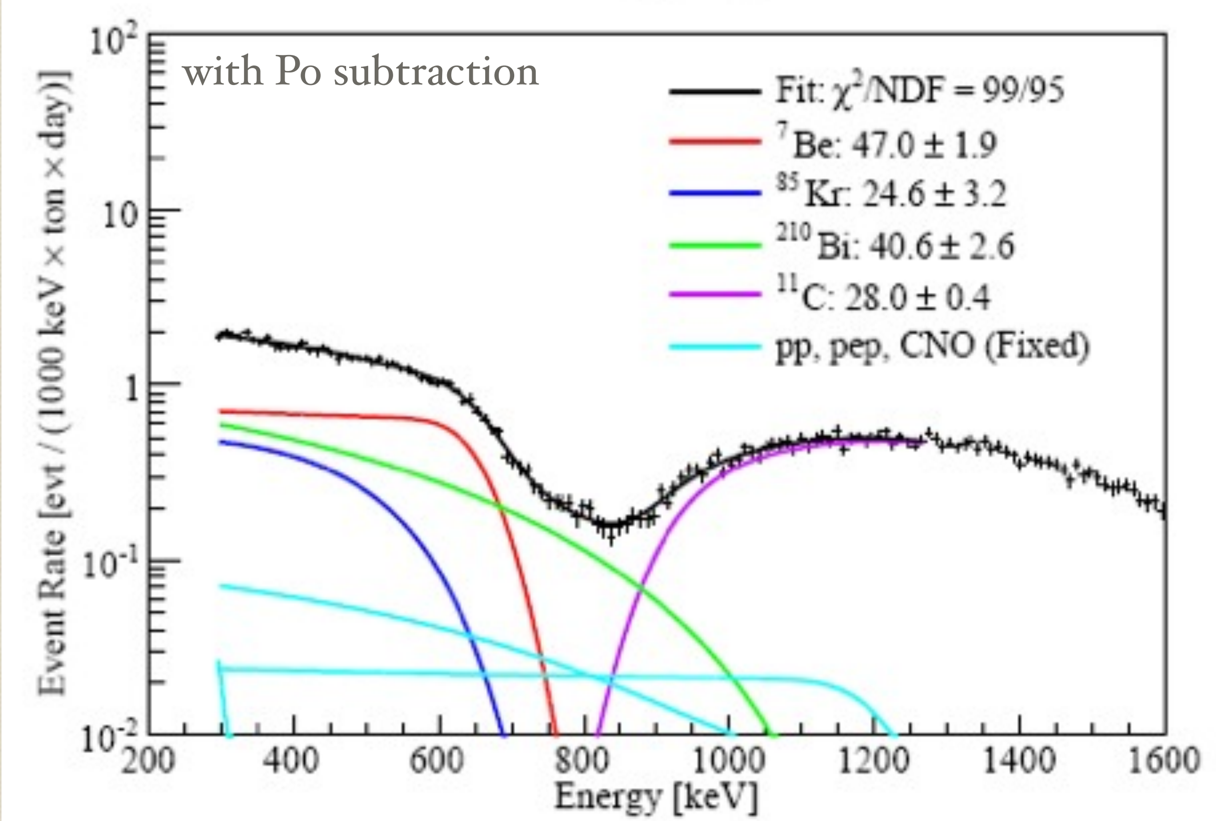
Recent progress:

- Precise detector calibration
  - reduce systematic error
- First results in pep and CNO

Result of ^{7}Be solar neutrino

w/o Po subtraction



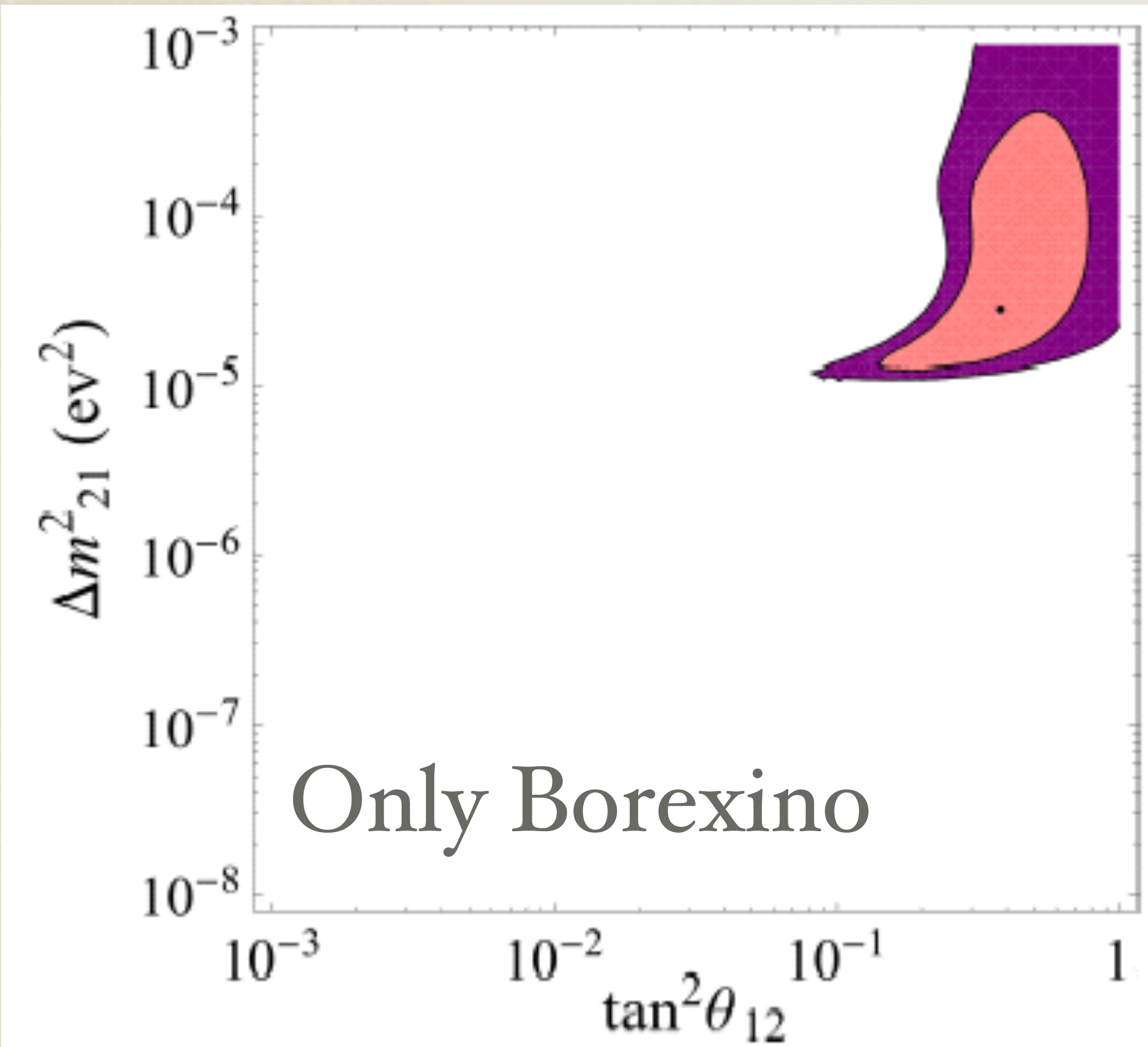


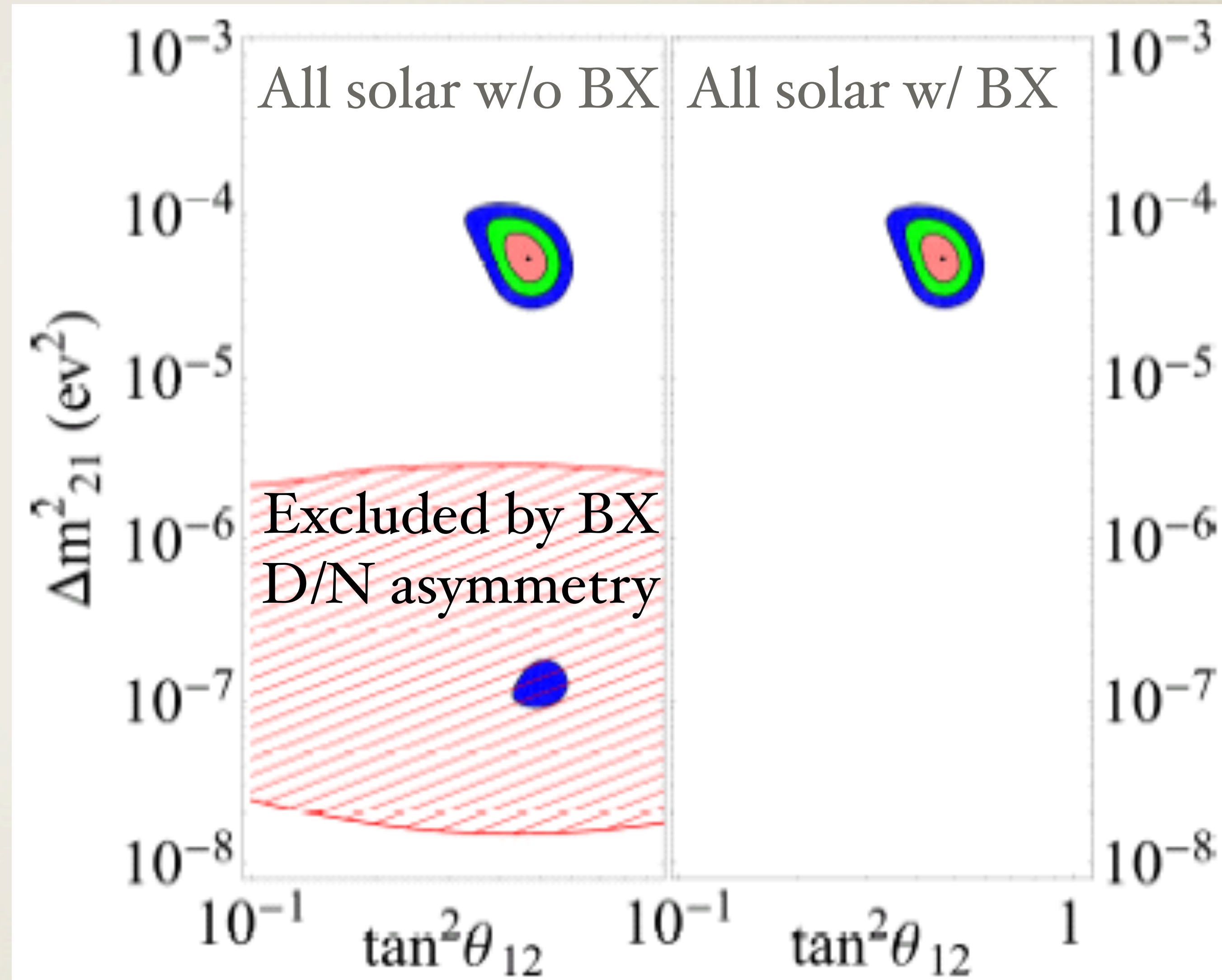
^{7}Be rate (E=862 keV line)
in 750 days of data
46.0 ± 1.5 (stat) $^{+1.5}_{-1.6}$ (sys)
counts/(day x 100t)
(total uncertainty is 4.7%)

Source of systematic error		previous
Trigger eff. And stability	<0.1 %	
Live time	0.04%	
Scintillator density	0.05 %	
Sacrifice of cuts	0.10 %	
Fiducial volume	+0.5 −1.3%	← 6%
Fit methods	2.0 %	
Energy response	2.7%	← 6%
Total	**+3.4 −3.6%**	← 8.5%

No significant Day-Night flux differences found.

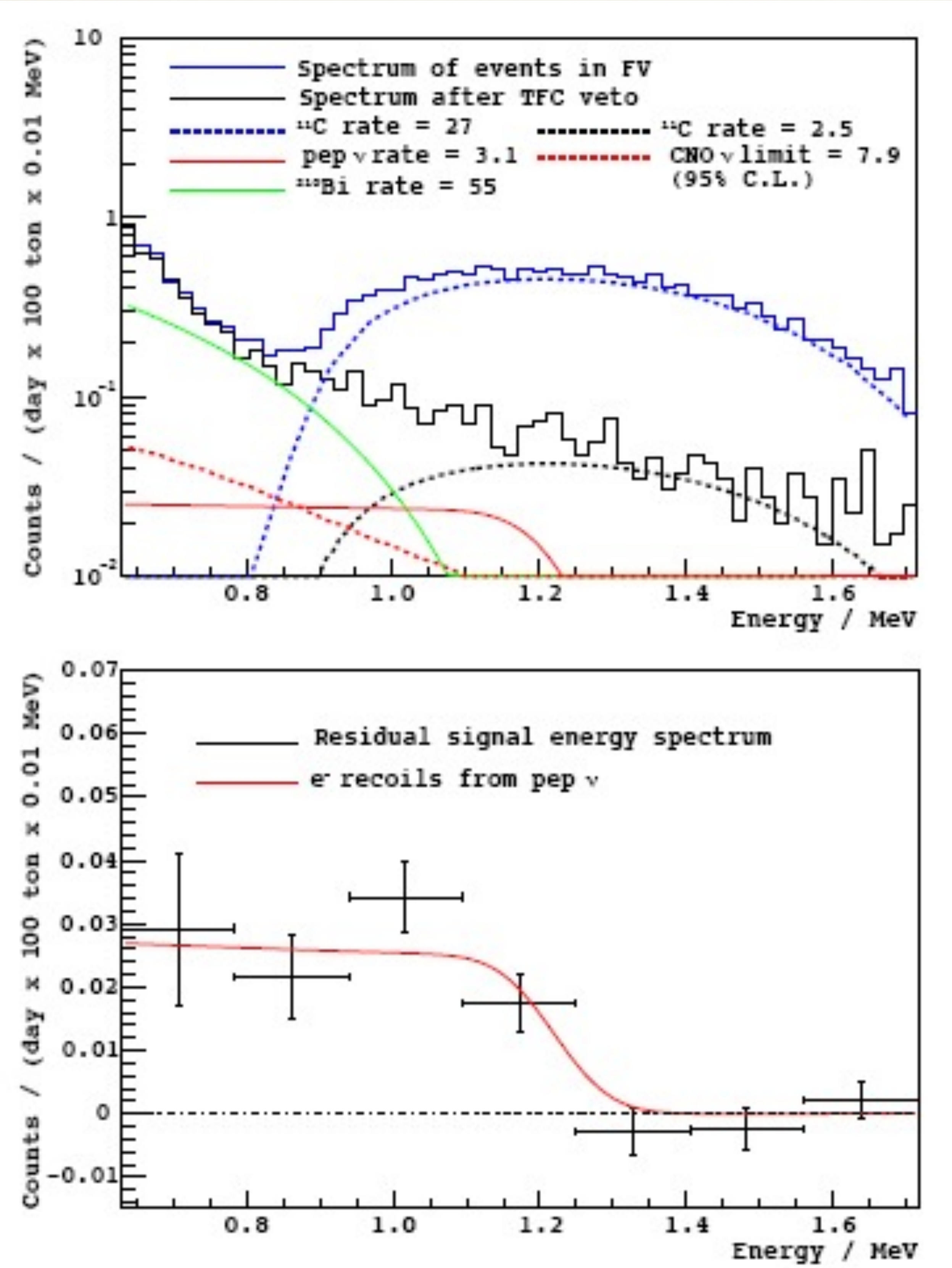
Neutrino oscillation analysis





Confirm the current neutrino oscillation scenario
(MSW-LMA)

Result of pep and CNO neutrino



pep rate:

3.1±0.6(stat.)±0.3(sys.)

count/day/100ton

→ $(1.6\pm0.3) \times 10^{8}$ cm^{-2} s^{-1}

First direct observation. (98%C.L.)

CNO rate:

< 7.9 count/day/100ton

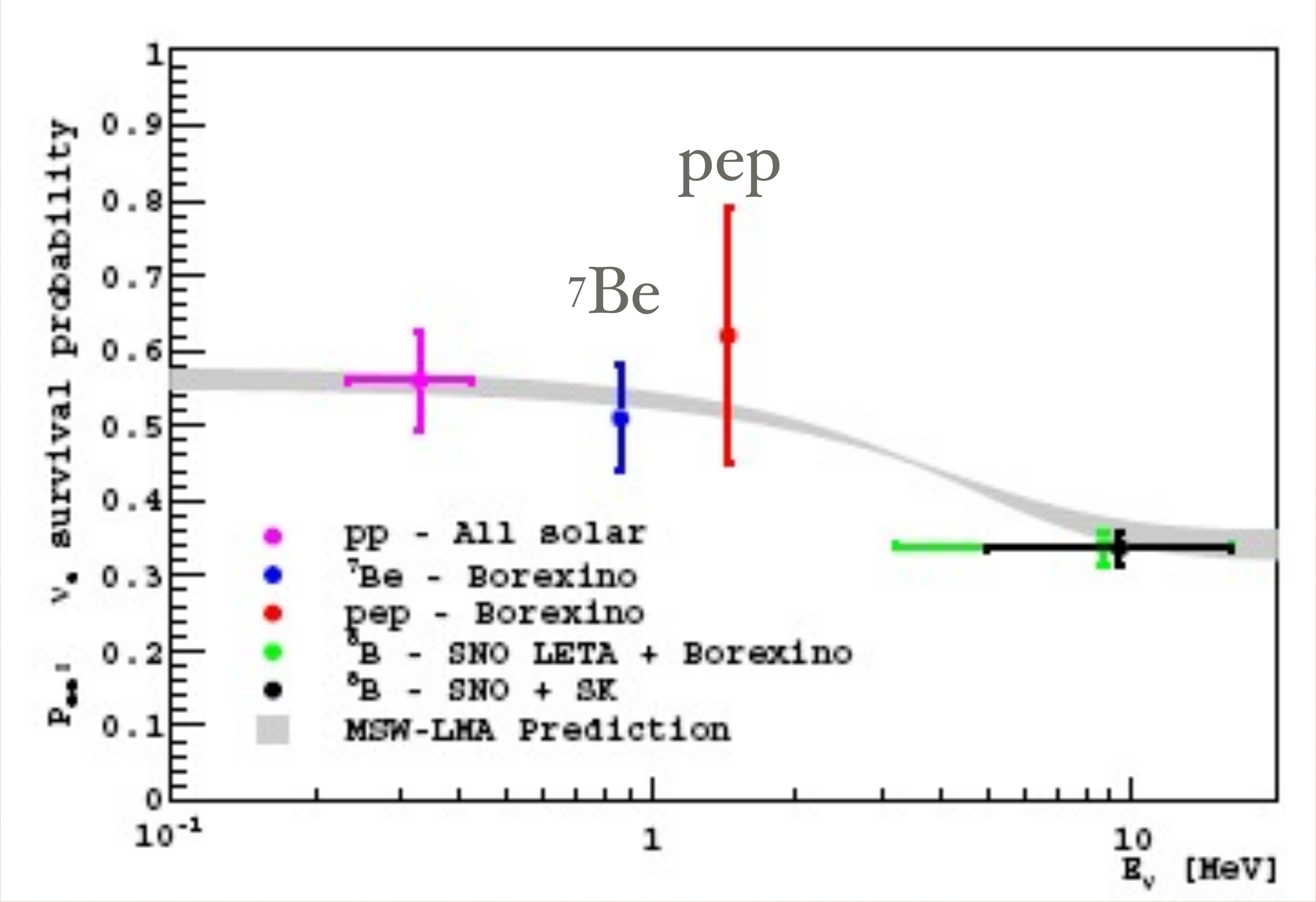
→ $< 7.7 \times 10^{8}$ cm^{-2} s^{-1}

(95%C.L. upper limit)

Strongest constraint

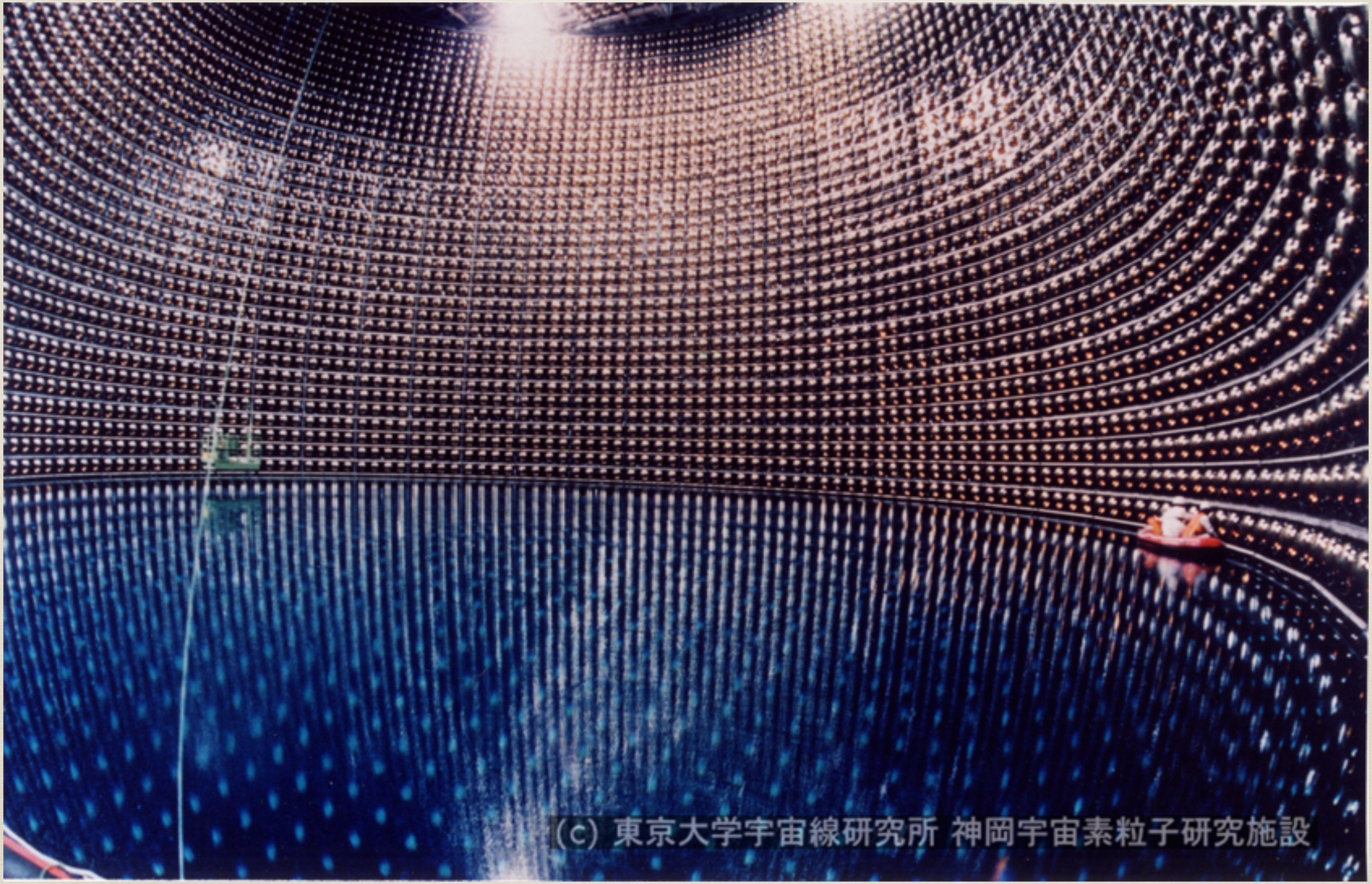
($f_{CNO} < 1.4$)

ν_e survival Probability (Pee)



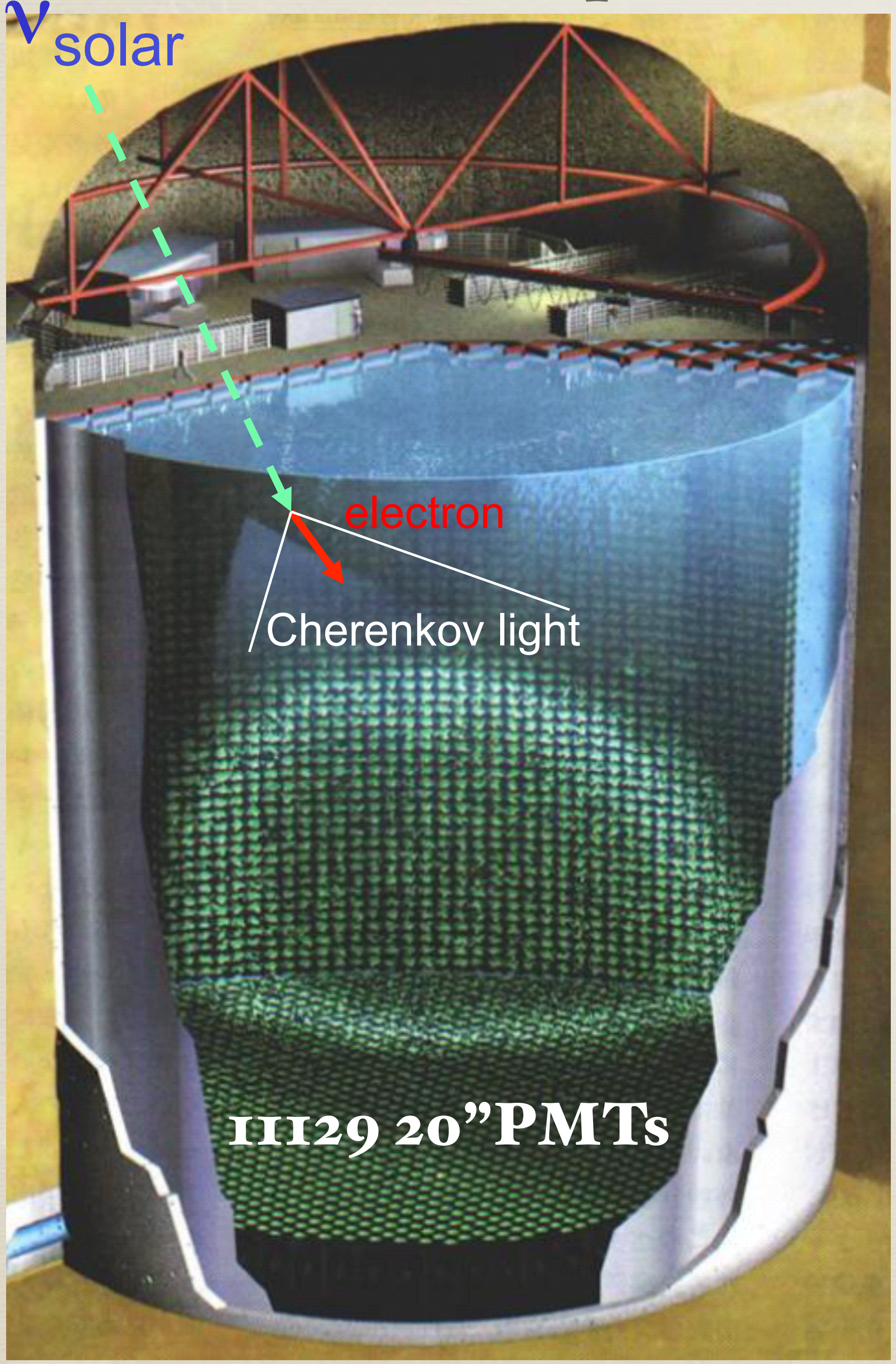
Consistent with the current neutrino oscillation scenario

Super-Kamiokande



Observation in Super-K

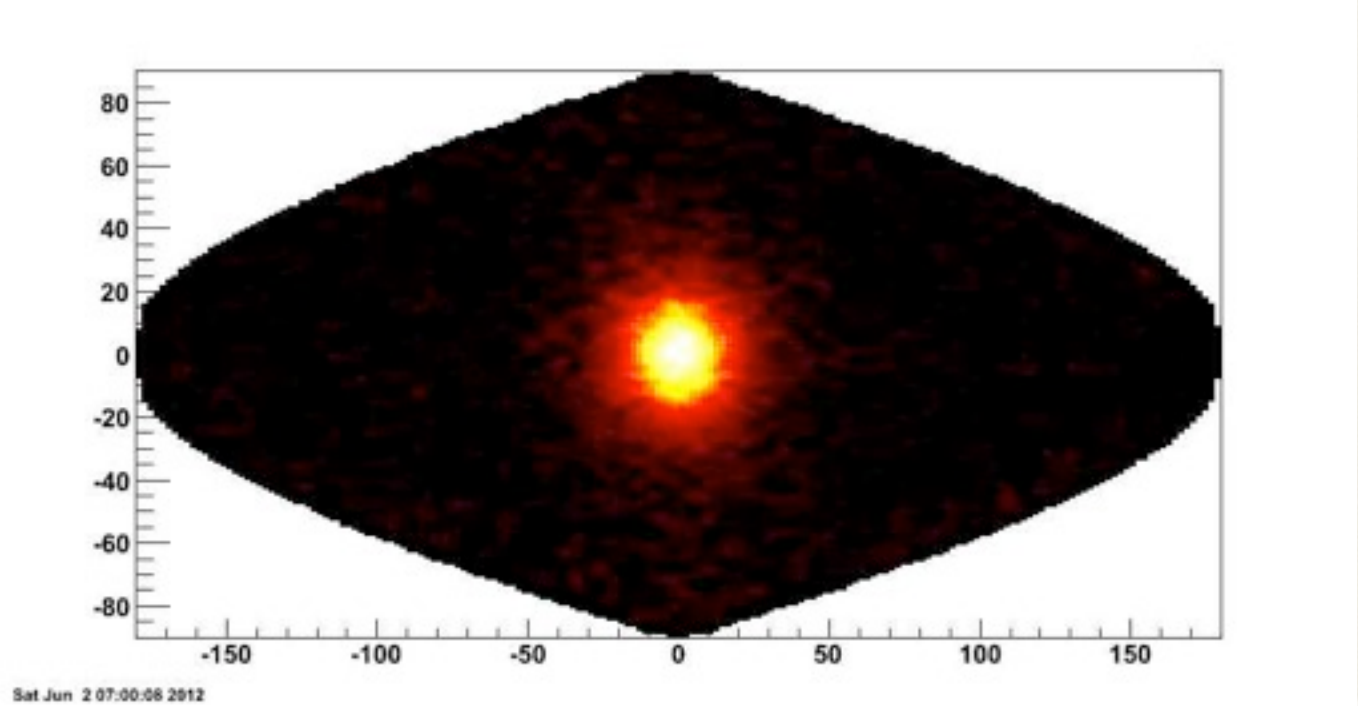
Kamioka, Japan



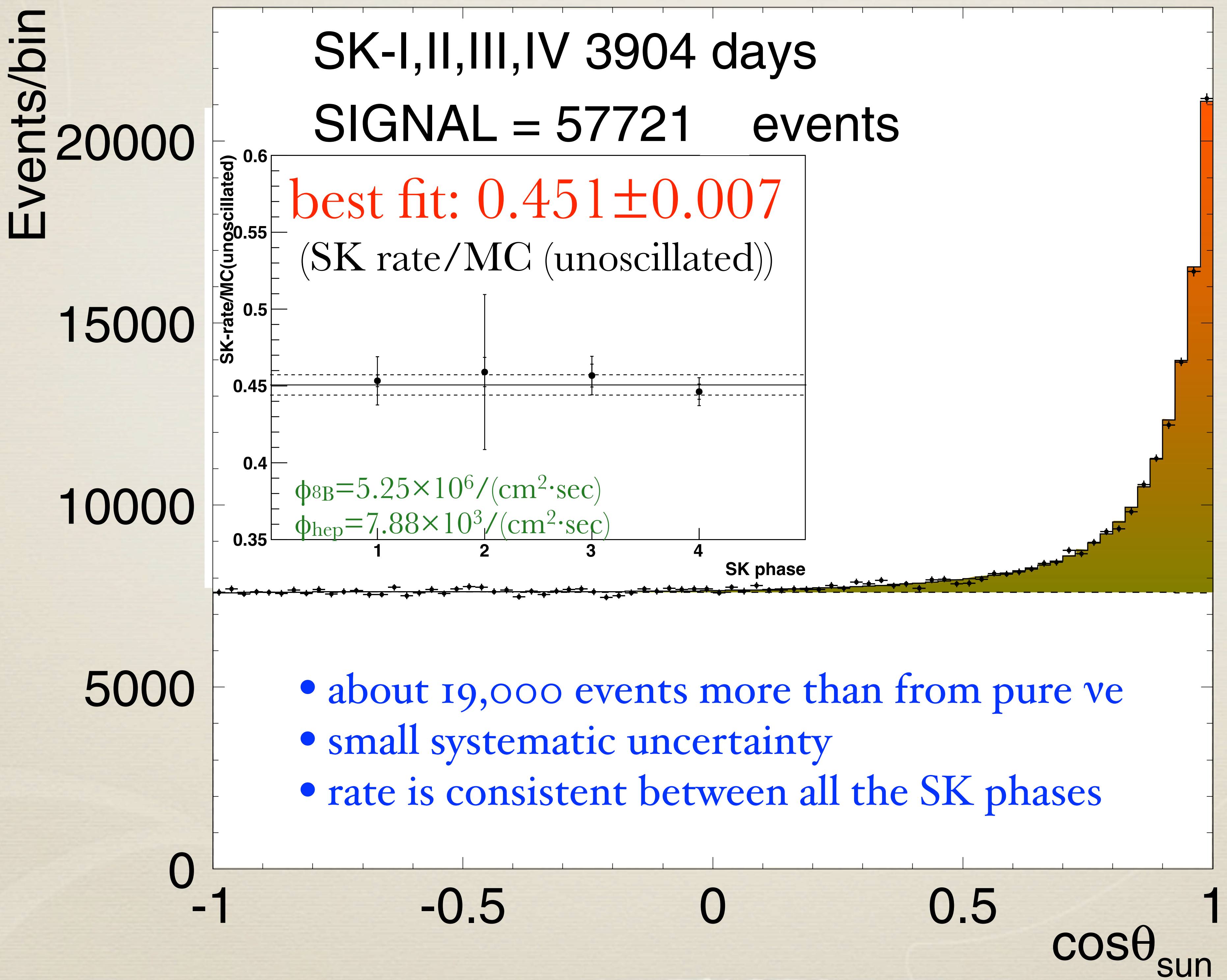
Neutrino-electron elastic scattering

$$\nu + e^- \rightarrow \nu + e^-$$

- Find solar direction
- Realtime measurements
  - day/night flux differences
  - Seasonal variation
- Energy spectrum (~MeV)

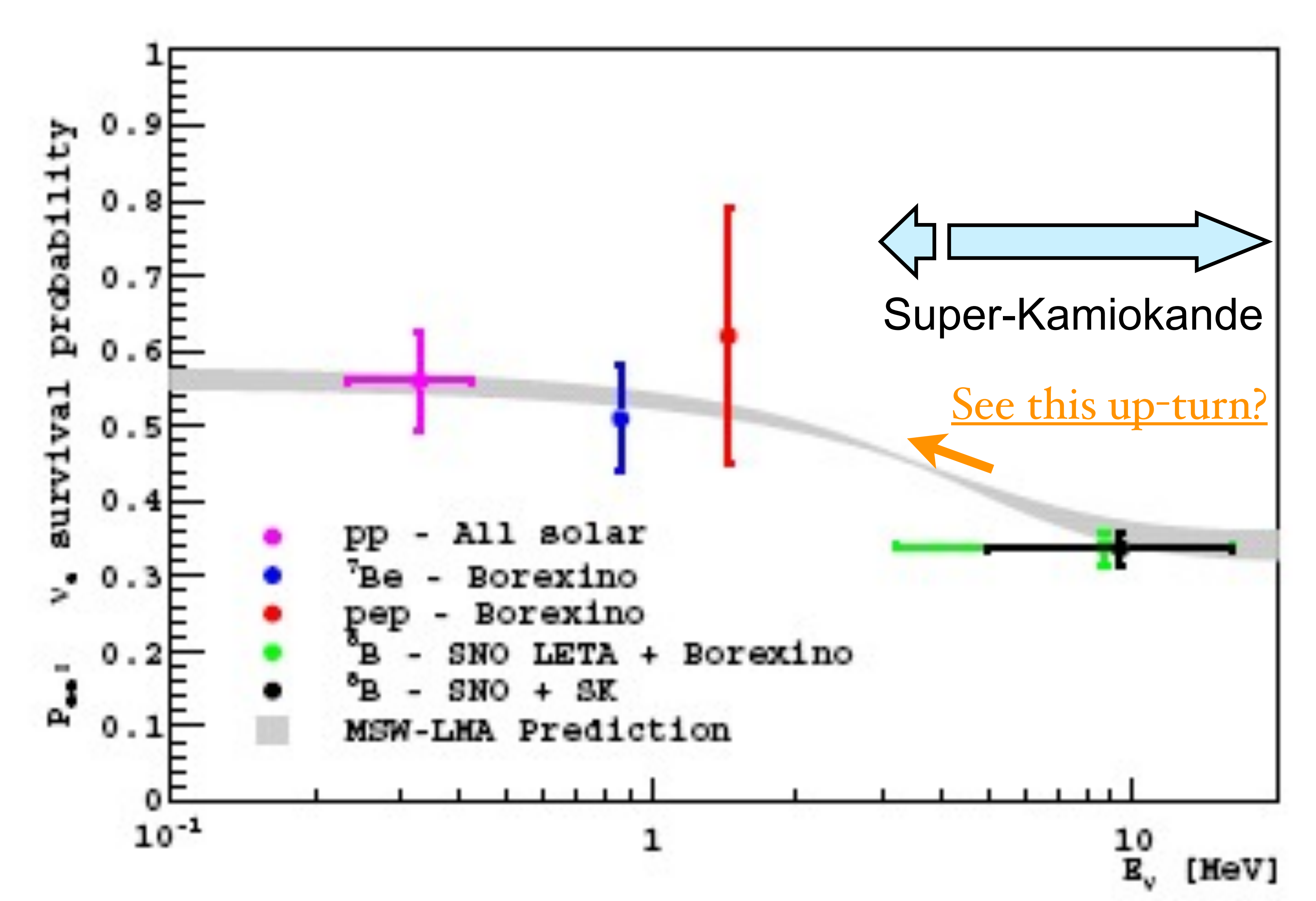


Total solar neutrino event



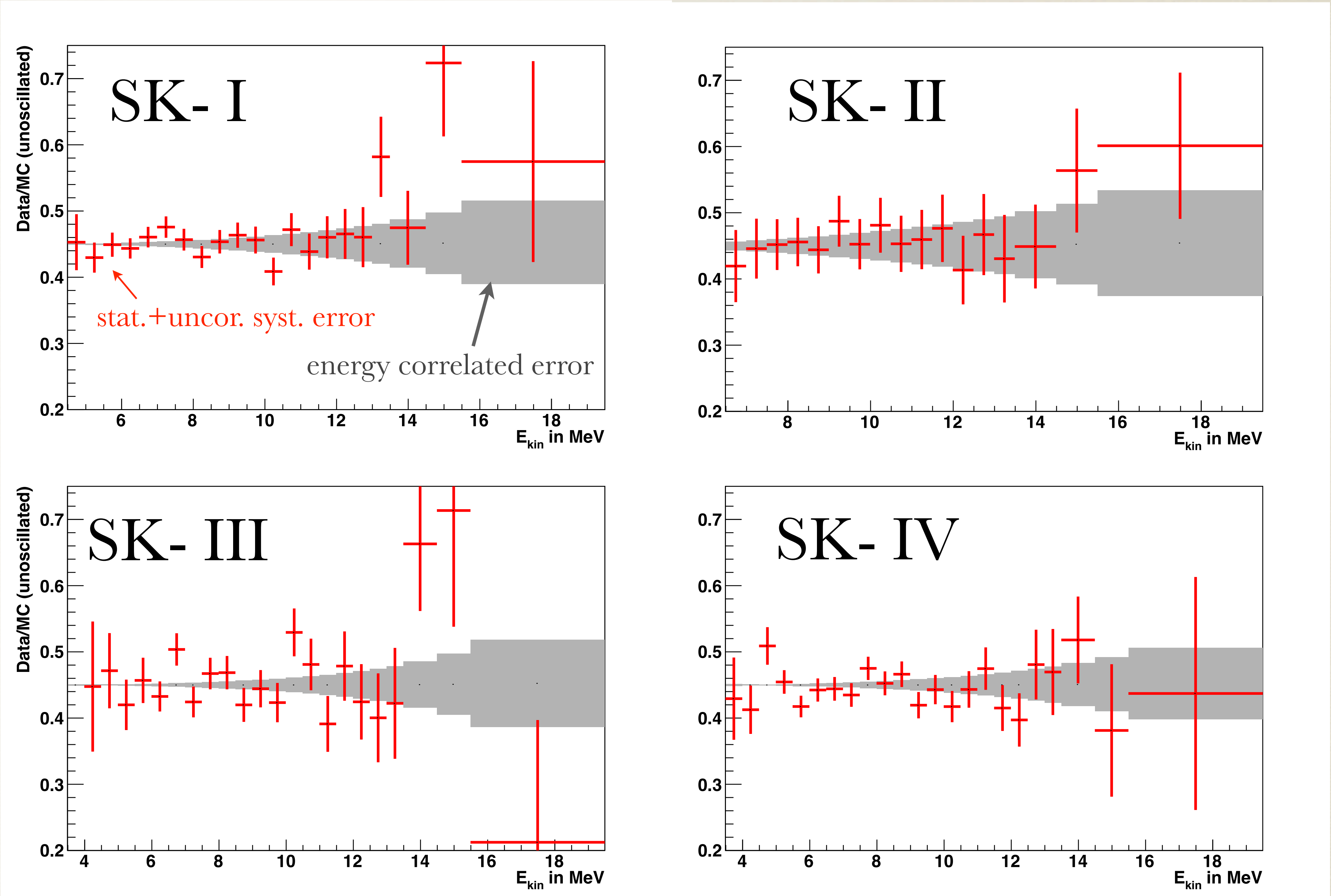
- about 19,000 events more than from pure νe
- small systematic uncertainty
- rate is consistent between all the SK phases

ν_e survival Probability (Pee)



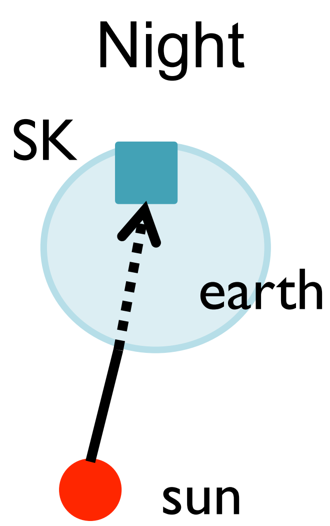
Consistent with the current neutrino oscillation scenario

Recoil electron spectrum



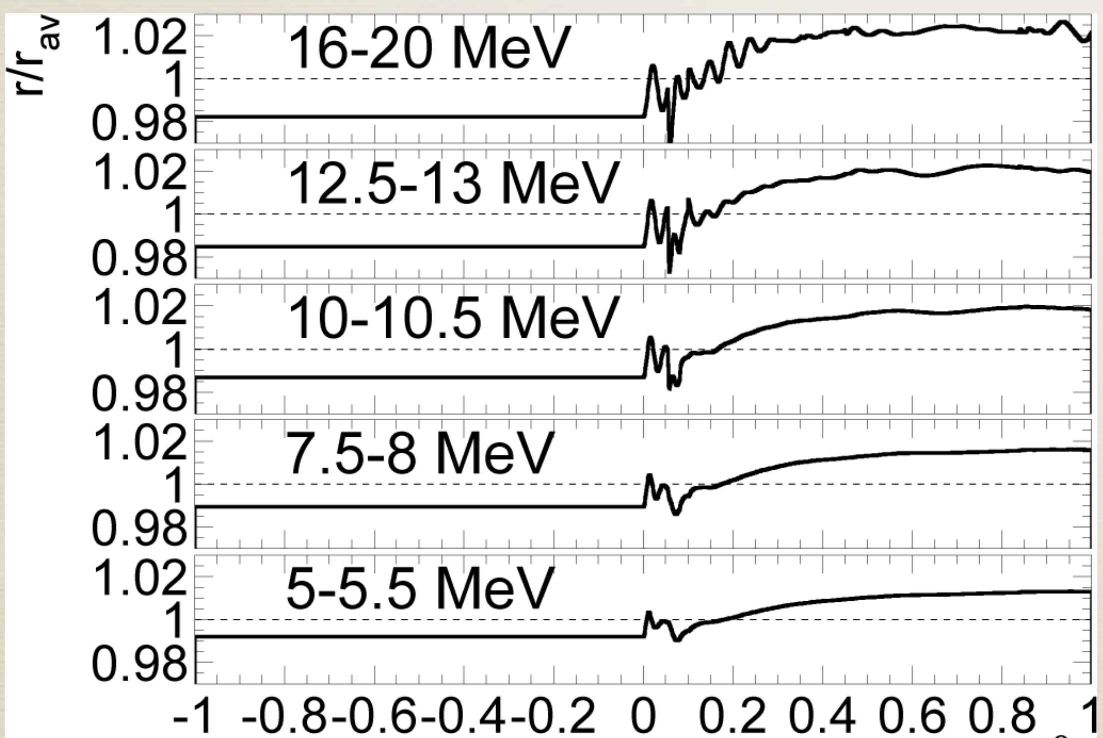
Unoscillated shape favored ~1.1 to 1.9 σ

Day/Night variation



Day/Night Asymmetry
$A_{DN}=2(\phi_D-\phi_N)/(\phi_D+\phi_N)$

2~4% effect in the current neutrino oscillation scenario



from Phys.Rev. D69 011104 (2004): $\Delta m_{21}^2=6.3\cdot10^{-5}eV^2$

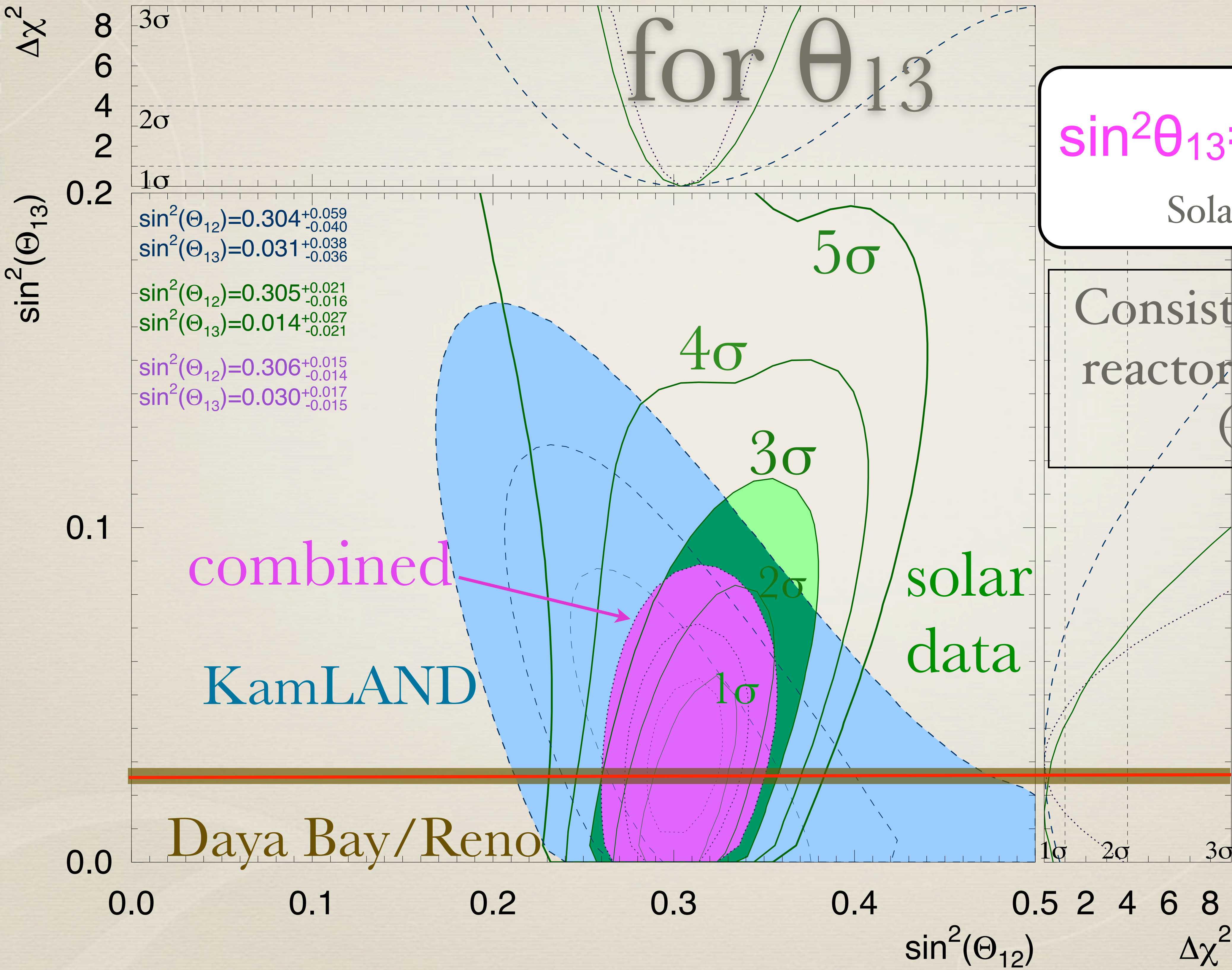
Results

experiment	D/N amplitude method	A_{DN}
SK-I	-2.0±1.7±1.0%	-2.1±2.0±1.3%
SK-II	-4.3±3.8±1.0%	-6.3±4.2±3.7%
SK-III	-4.3±2.7±0.7%	-5.9±3.4±1.3%
SK-IV	-2.8±1.9±0.7%	-5.2±2.3±1.4%
SK comb.	**-2.8±1.1±0.5%**	-4.0±1.3±0.8%

Day-Night asymmetry consistent with zero at 2.3 σ

Some hint to see a direct MSW effect?

Neutrino oscillation analysis for θ_{13}

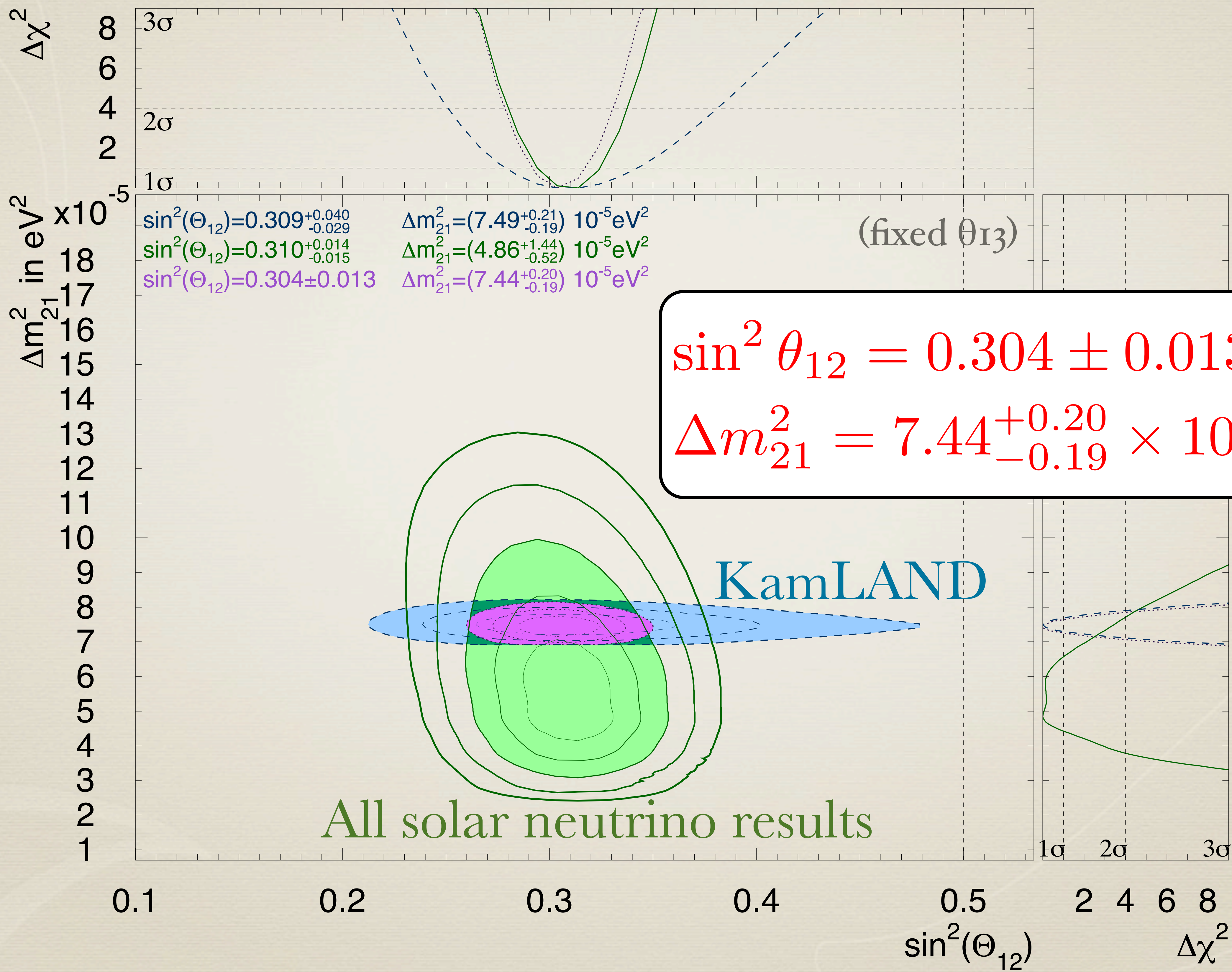


$\sin^2\theta_{13}=0.030\,^{+0.017}_{-0.015}$

Solar+KamLand

Consistent with SBL reactor experiments (0.025)

Neutrino oscillation analysis



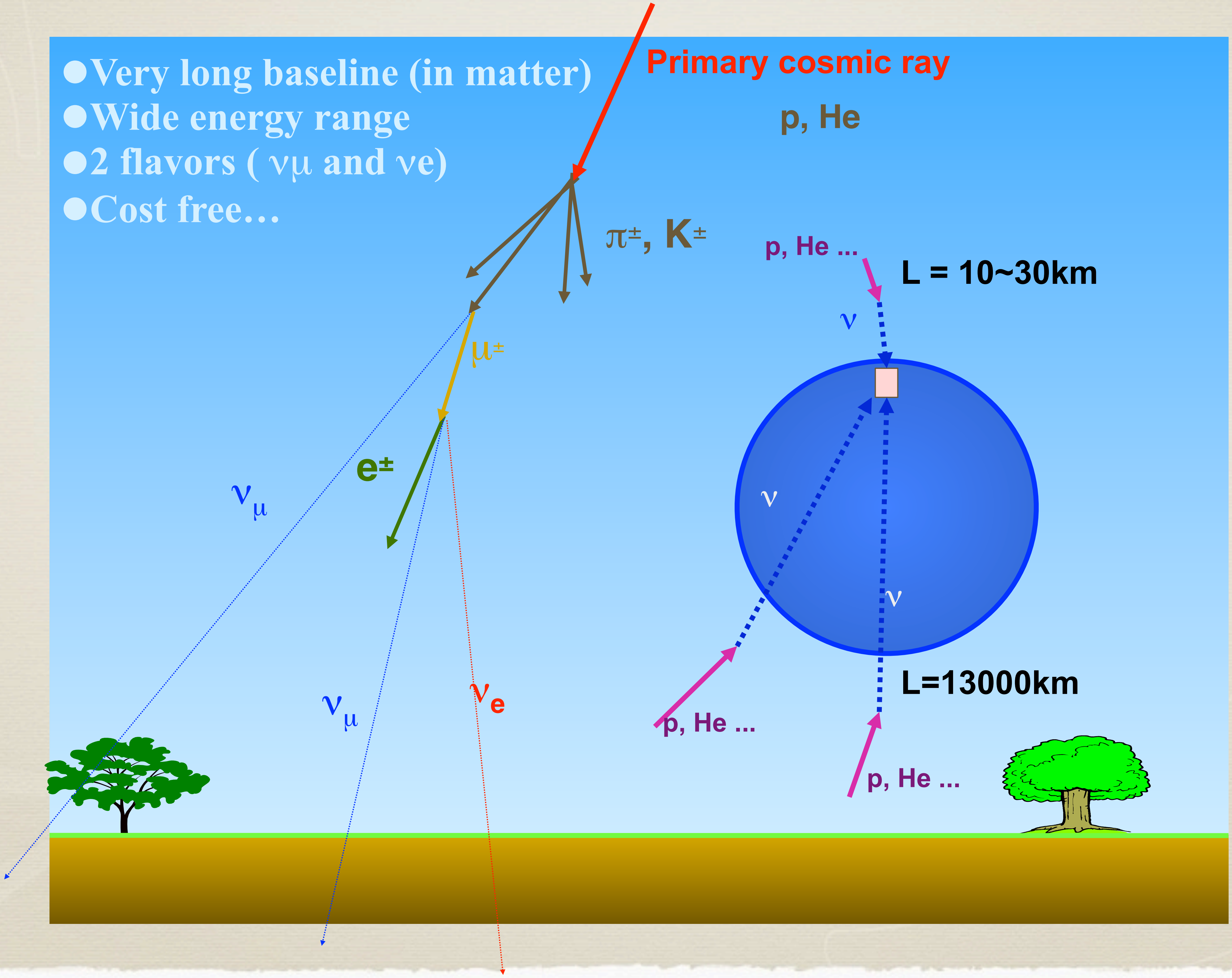
$$\sin^2\theta_{12} = 0.304 \pm 0.013$$

$$\Delta m^2_{21} = 7.44^{+0.20}_{-0.19} \times 10^{-5} eV^2$$

ATMOSPHERIC NEUTRINOS

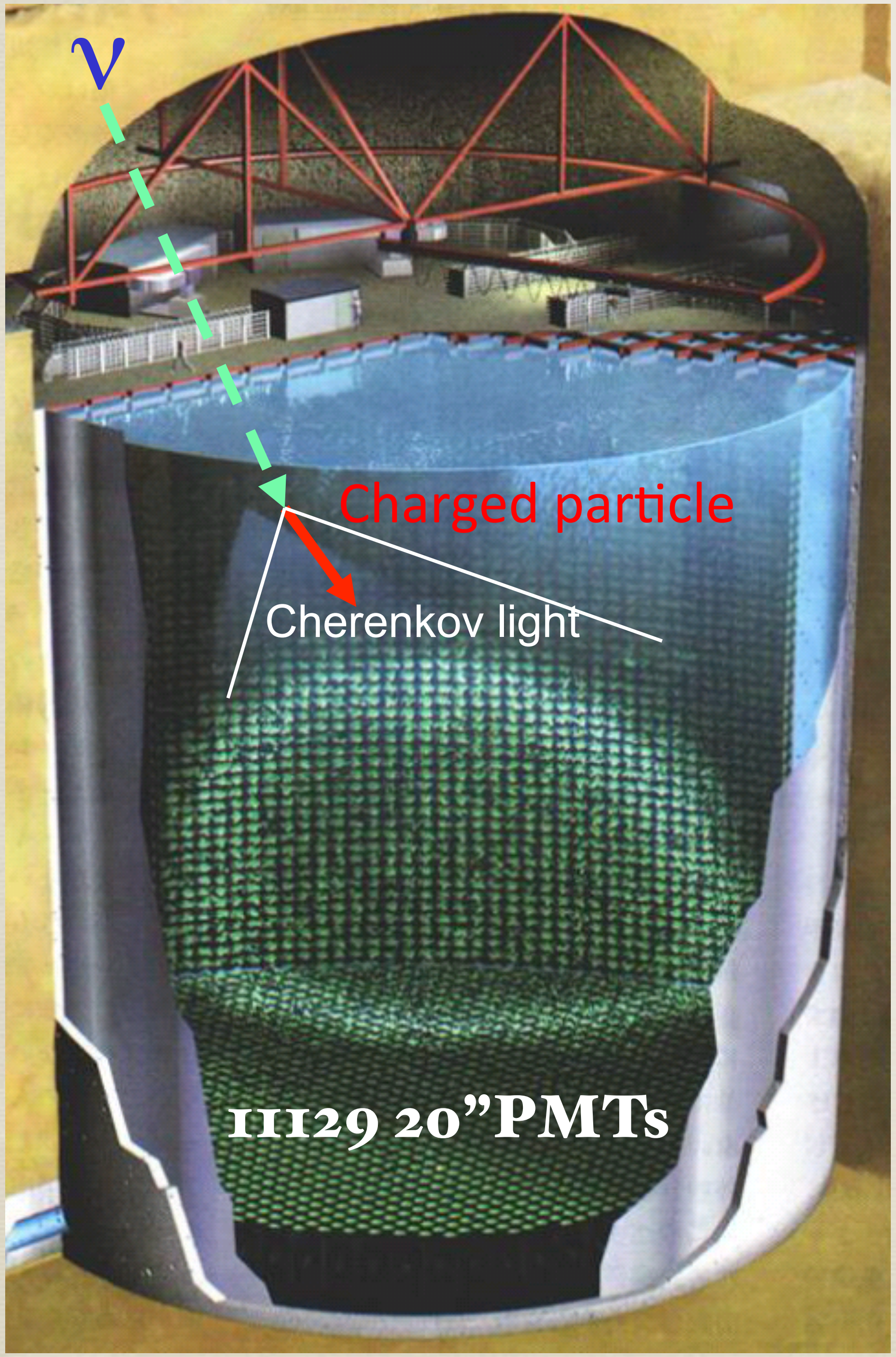
Atmospheric neutrinos

- Very long baseline (in matter)
- Wide energy range
- 2 flavors (νμ and νe)
- Cost free…



Observation in Super-K

Kamioka, Japan

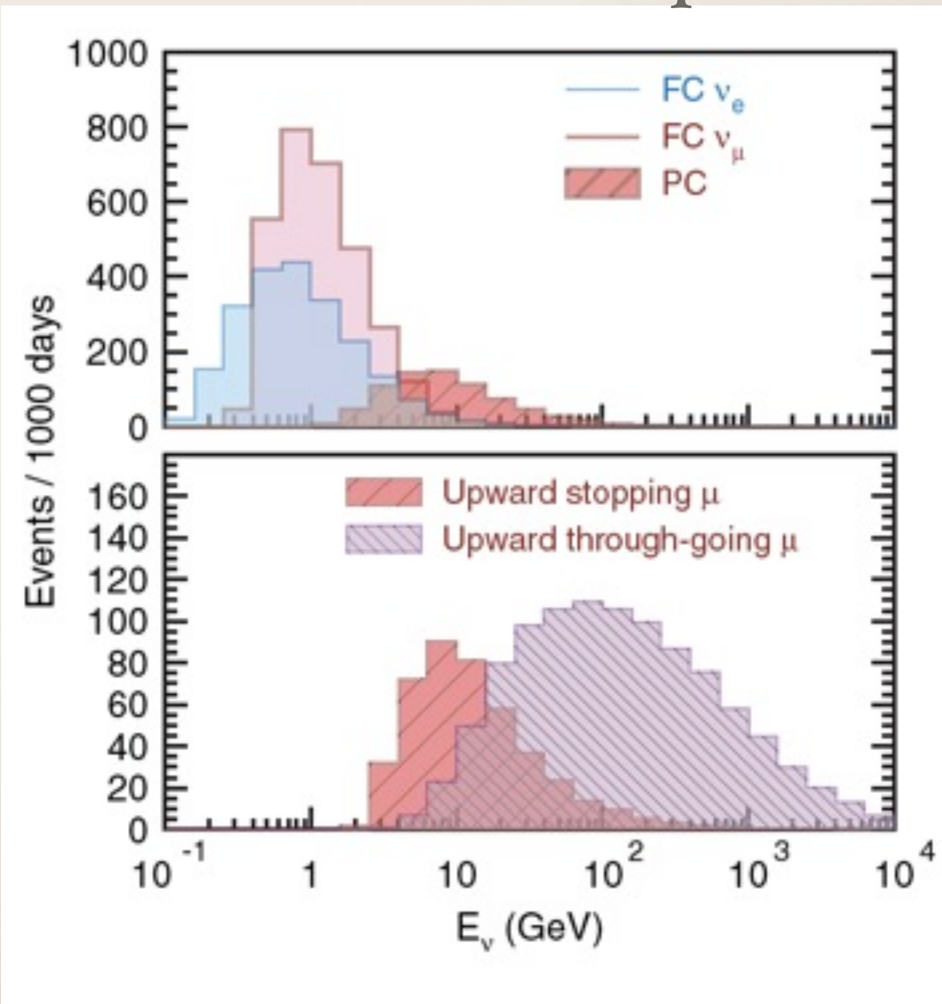


Charged Current Quasi Elastic scattering

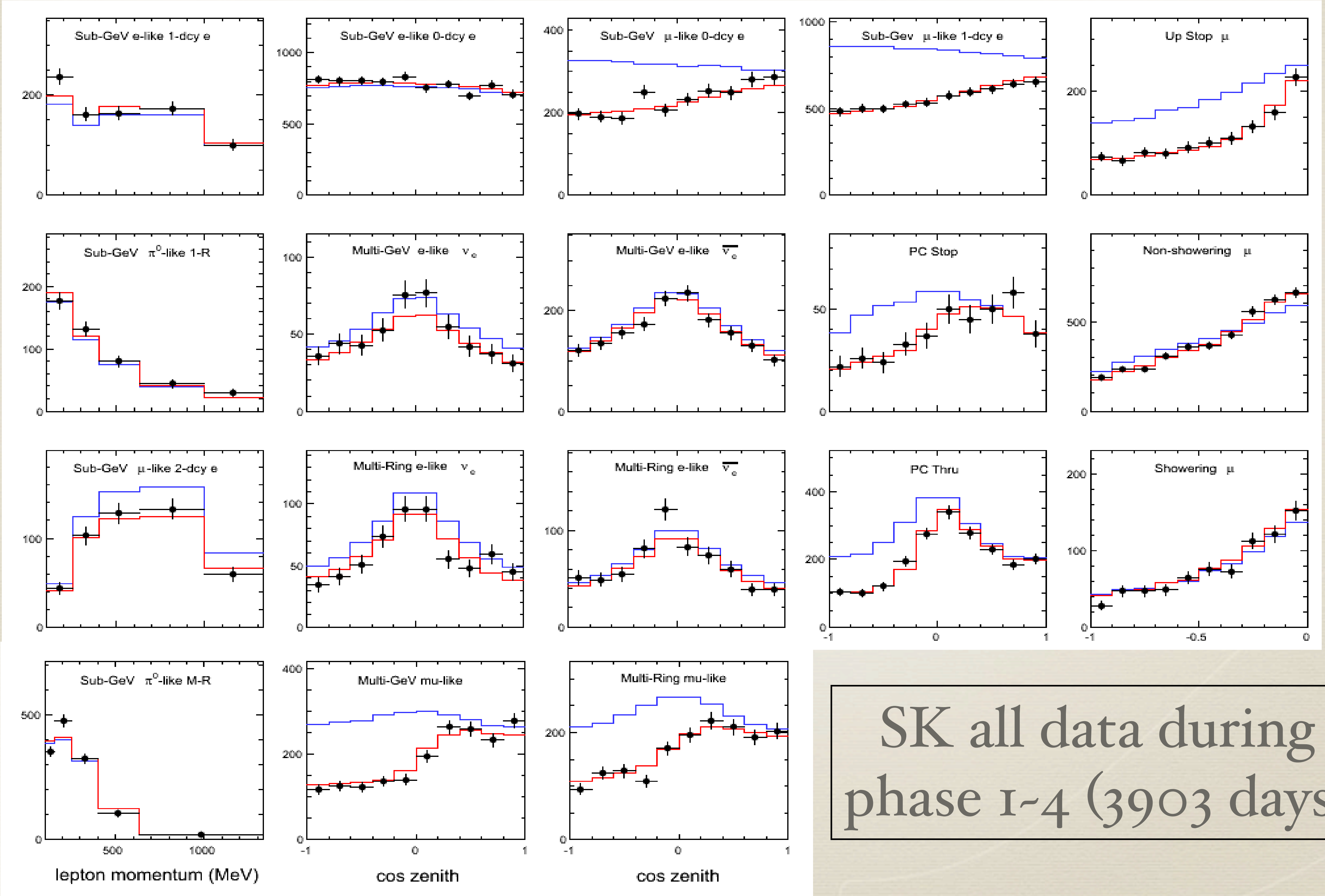
- $\nu + N \rightarrow l + N'$ etc..

electron/muon

Parent neutrino spectra

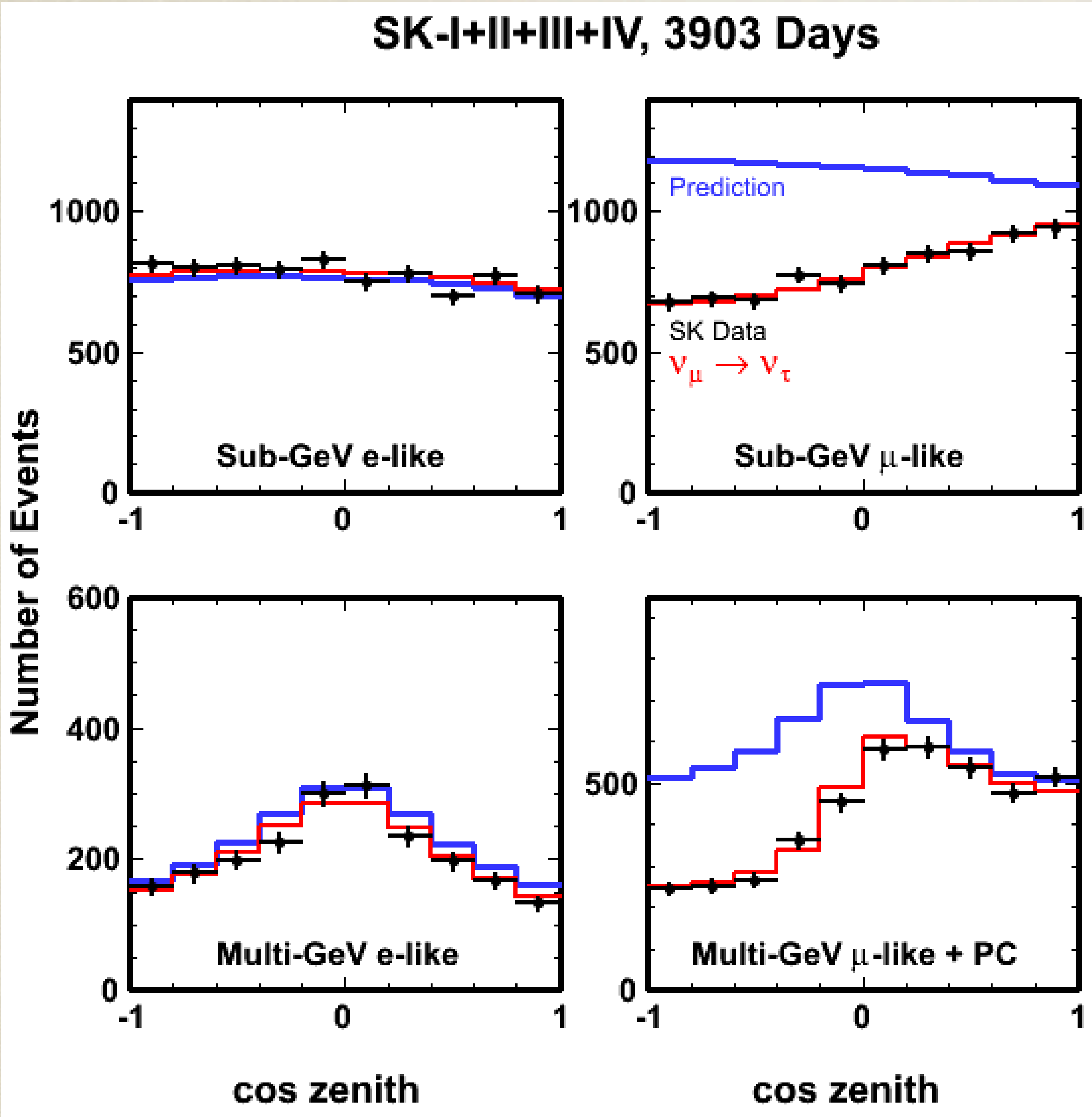


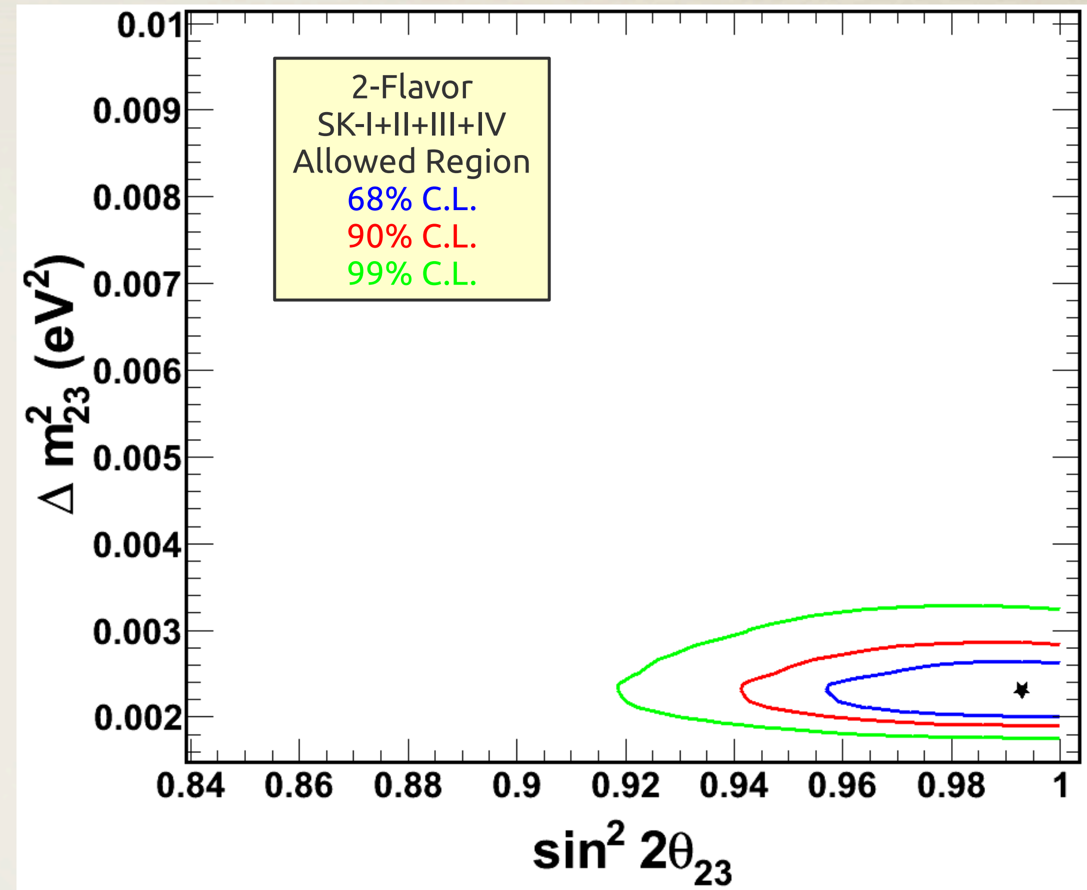
2-flavor analysis update



SK all data during phase 1-4 (3903 days)

2-flavor analysis update





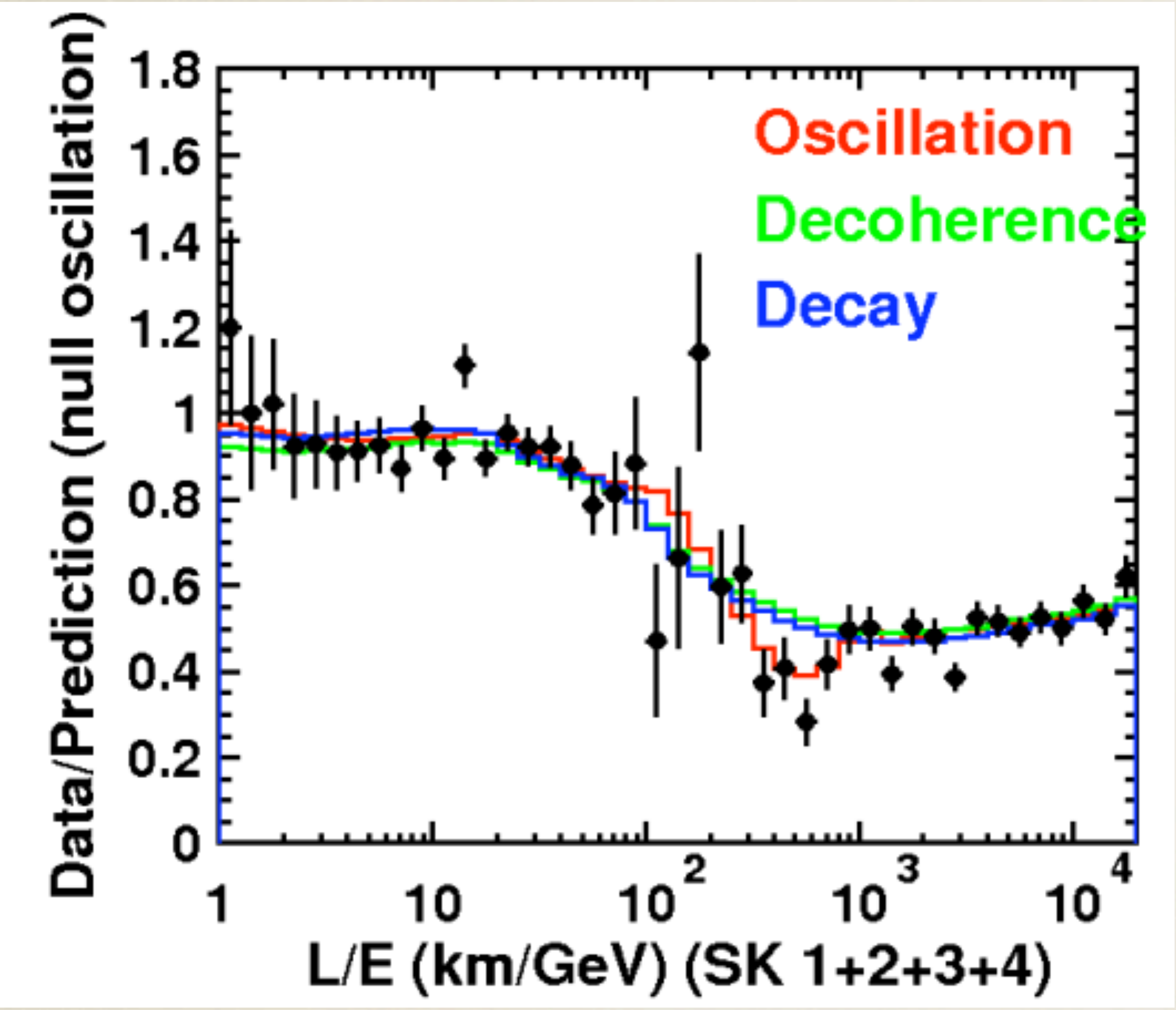
Red: SK-I+II+III+IV Best Fit Oscillations

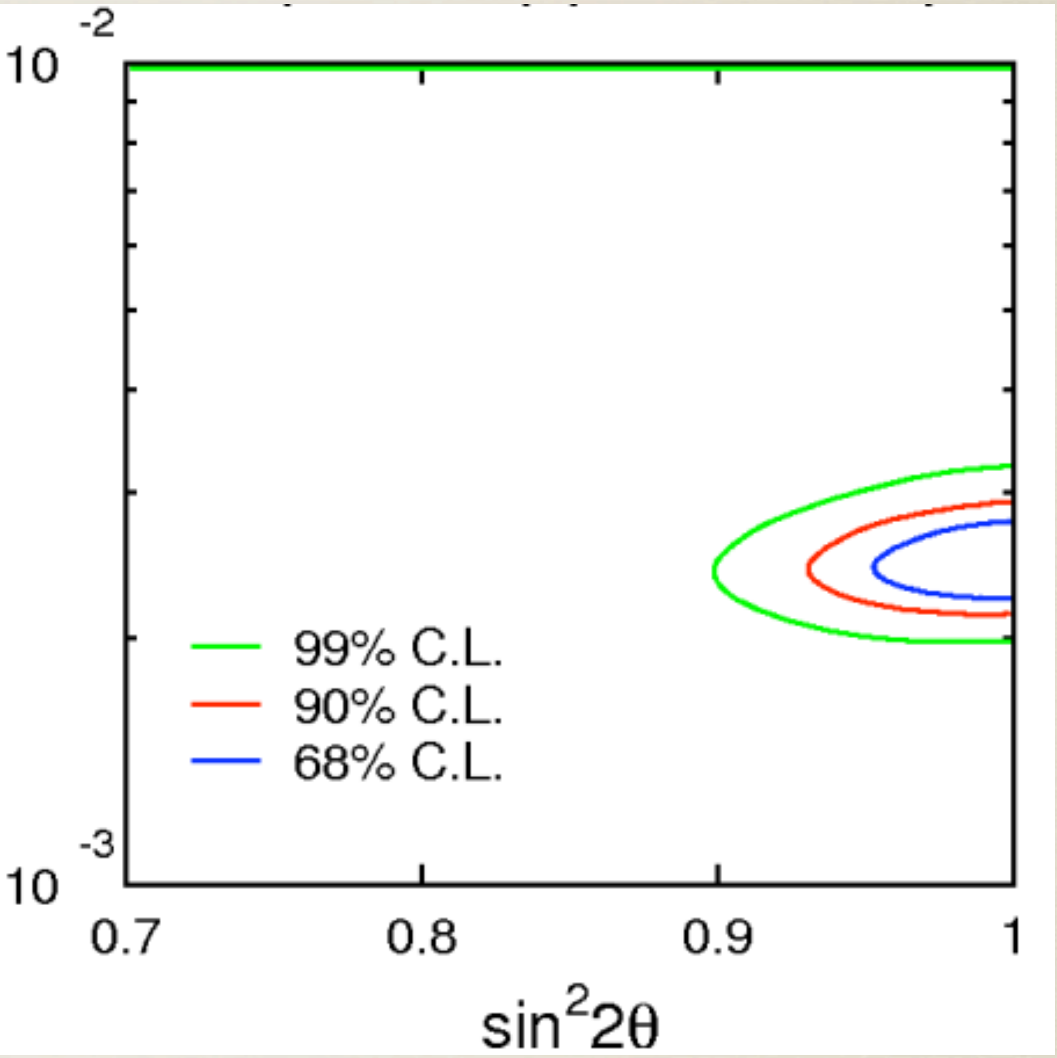
$$\Delta m^2_{23} = 2.30 \times 10^{-3}\ eV^2$$

$$\sin^2 2\theta_{23} = 0.99$$

Blue: No Oscillations Prediction

2-flavor L/E analysis update





Neutrino decay

$$\chi^2_{\min} = 187.8/169 (4.0\sigma)$$

Neutrino decoherence

$$\chi^2_{\min} = 194.8/169 (4.8\sigma)$$

⇔

2 ν oscillation result

$$\sin^2 2\theta = 1.00 (\geq 0.93 (90\% CL))$$

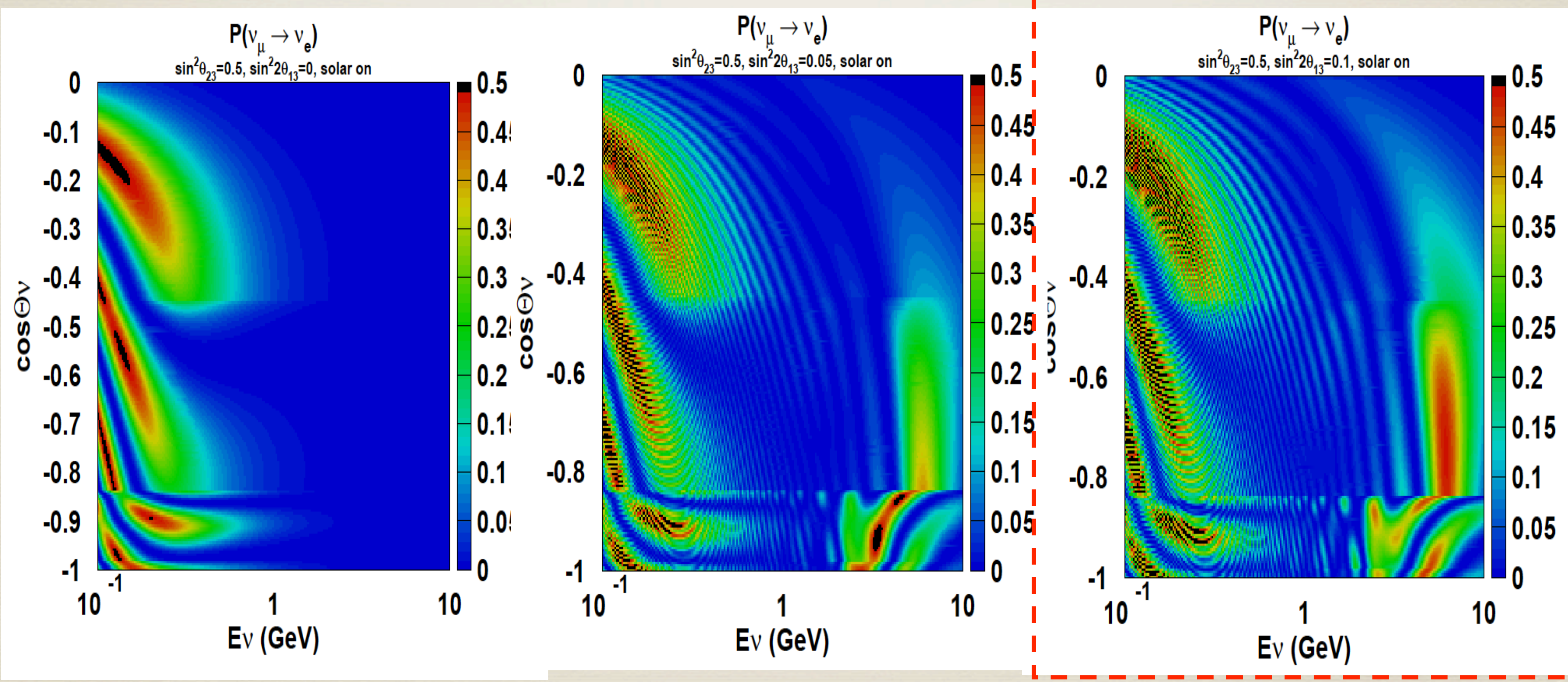
$$\Delta m^2 = (2.5^{+0.27}_{-0.27}) \times 10^{-3} eV^2$$

$$\chi^2_{\min} = 171.7/169$$

3-flavor analysis

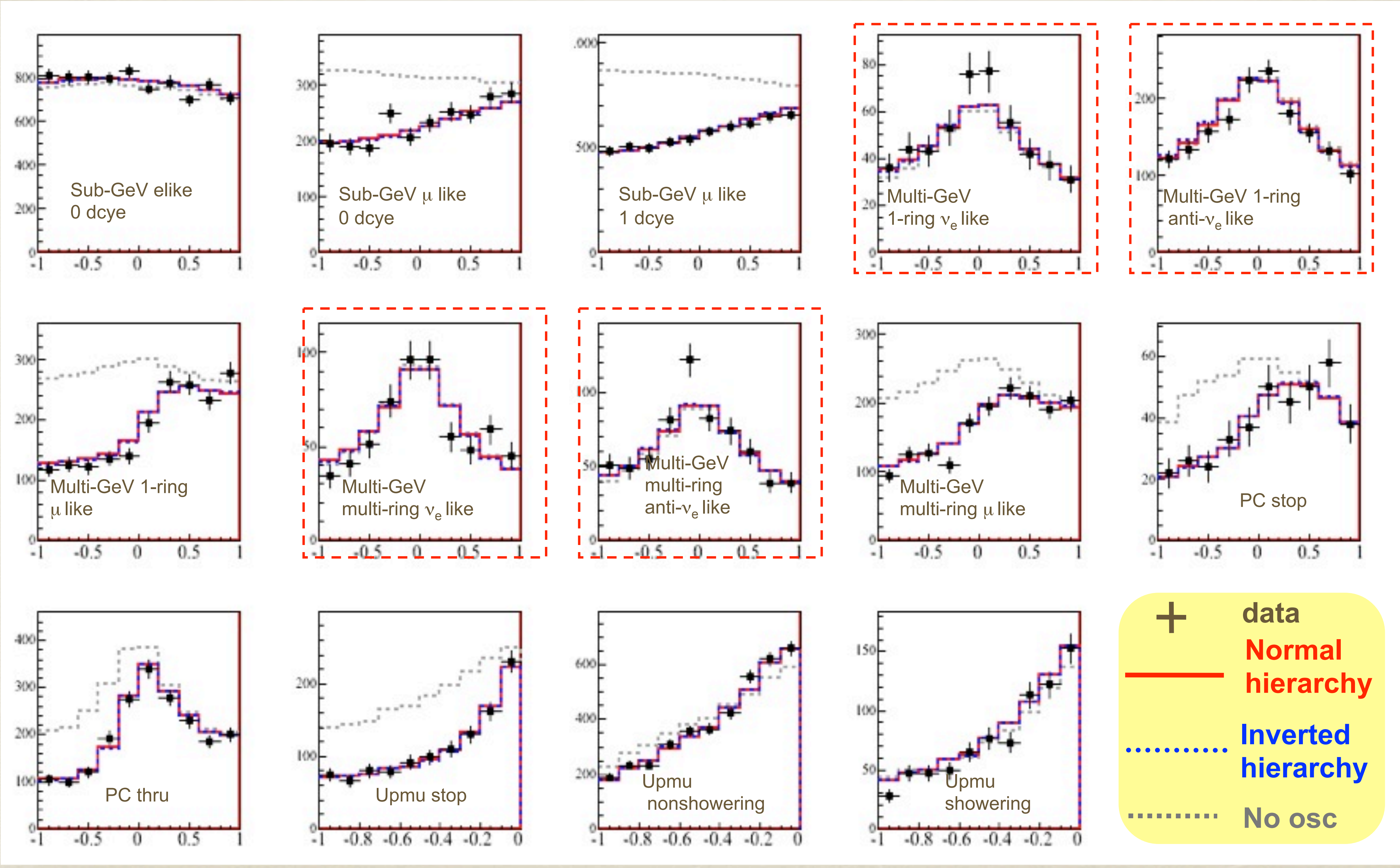
Non-zero θ13 makes sub-leading effect appear

$\sin^2 2\theta_{13} = 0$ $\sin^2 2\theta_{13} = 0.05$ $\sin^2 2\theta_{13} = 0.1$

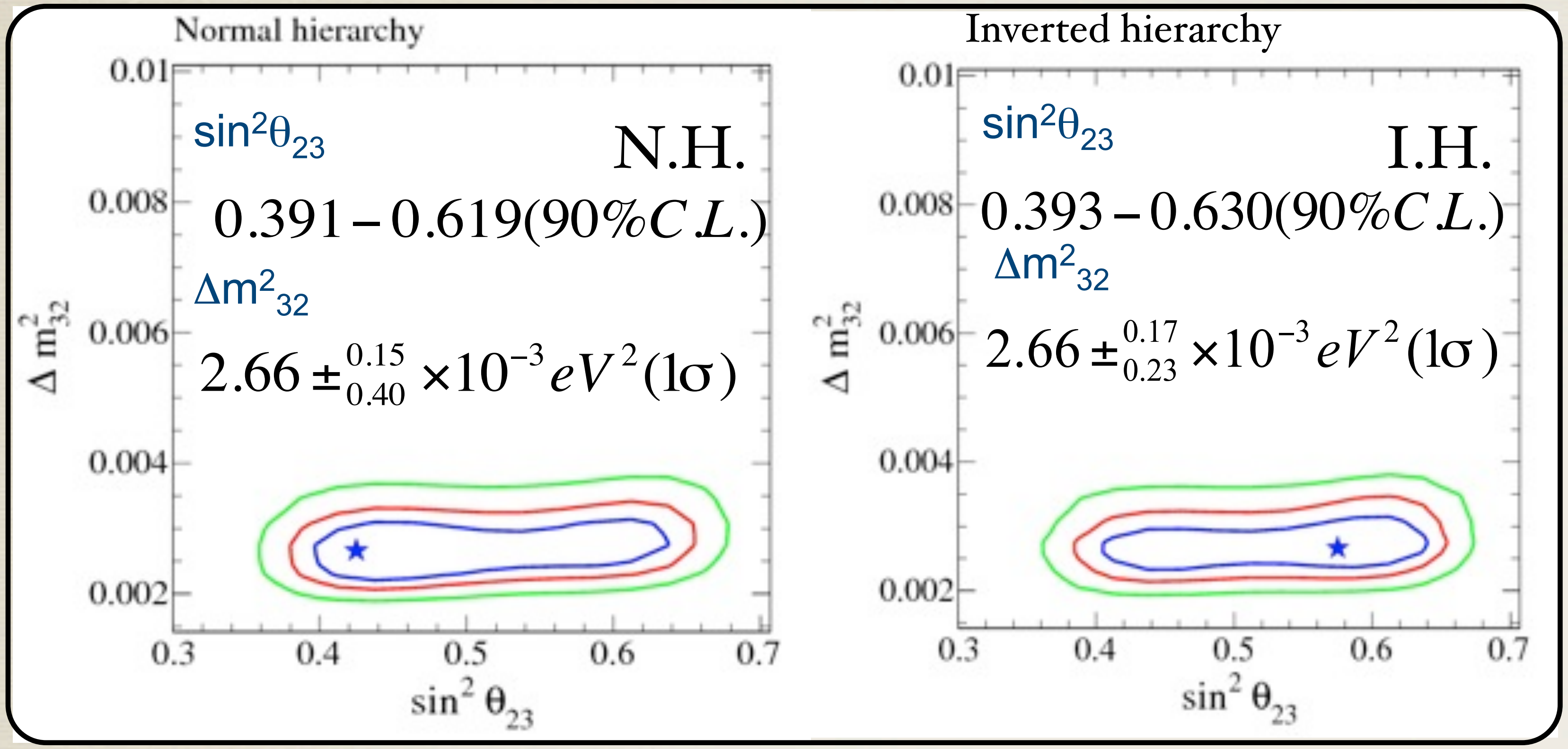


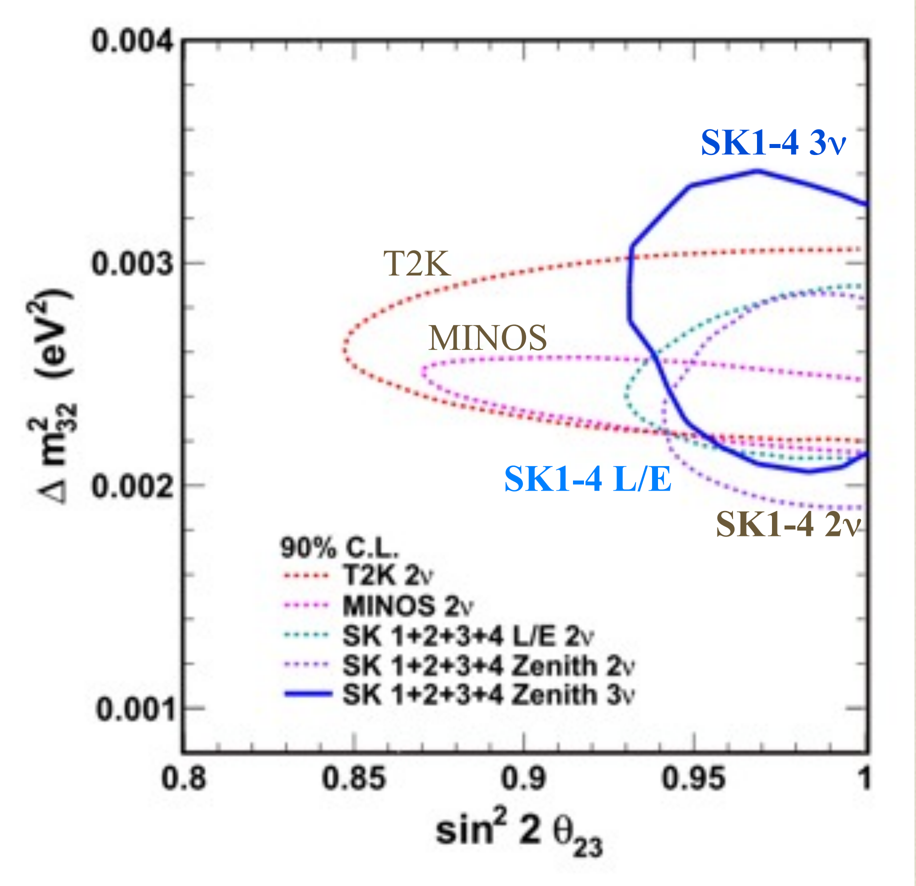
Region of interest : up-going (cosΘ<-0.4) , multi-GeV(2-12GeV)

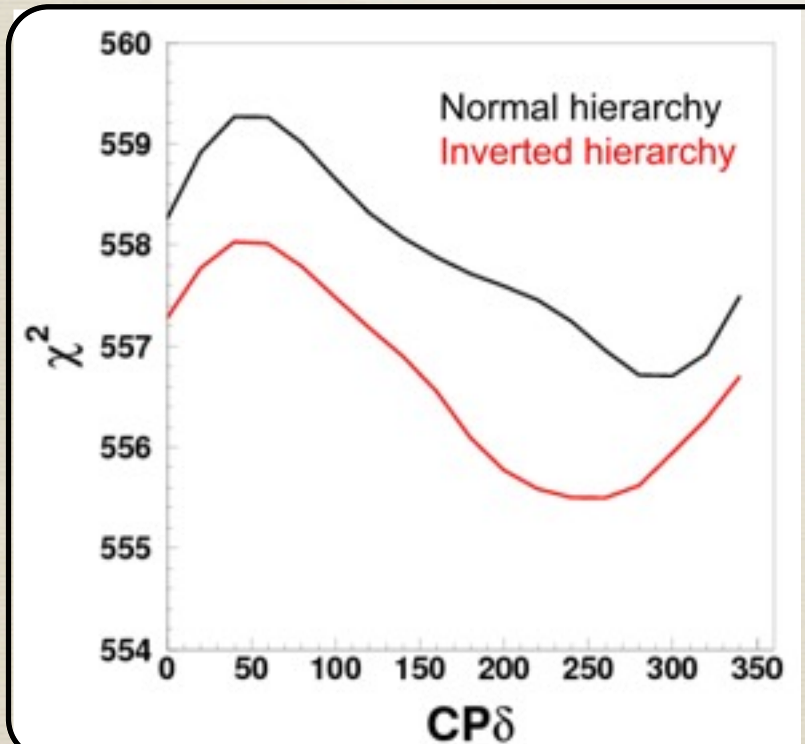
3-flavor analysis with reactor constraint ($\sin^2\theta_{13}=0.25$)



Oscillation results

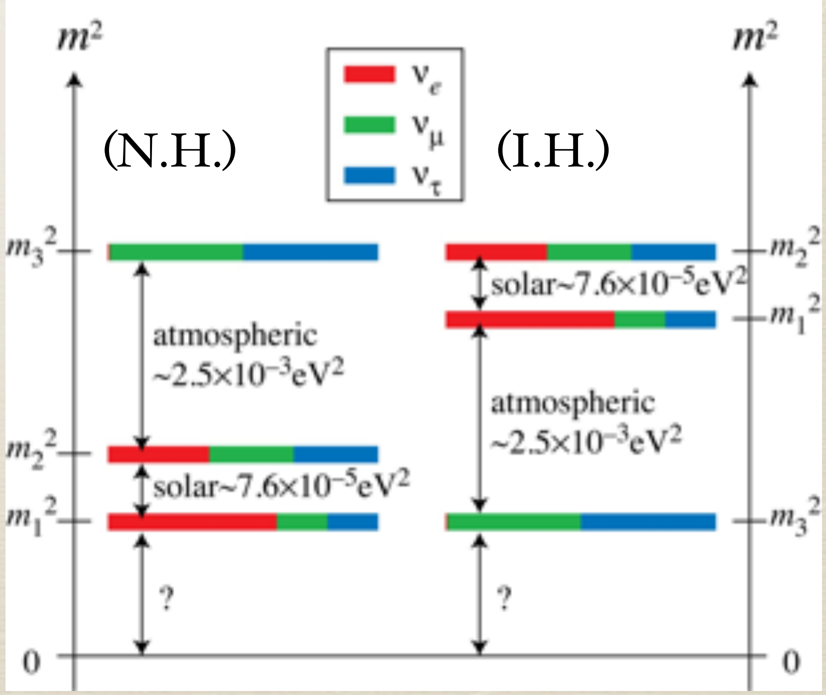




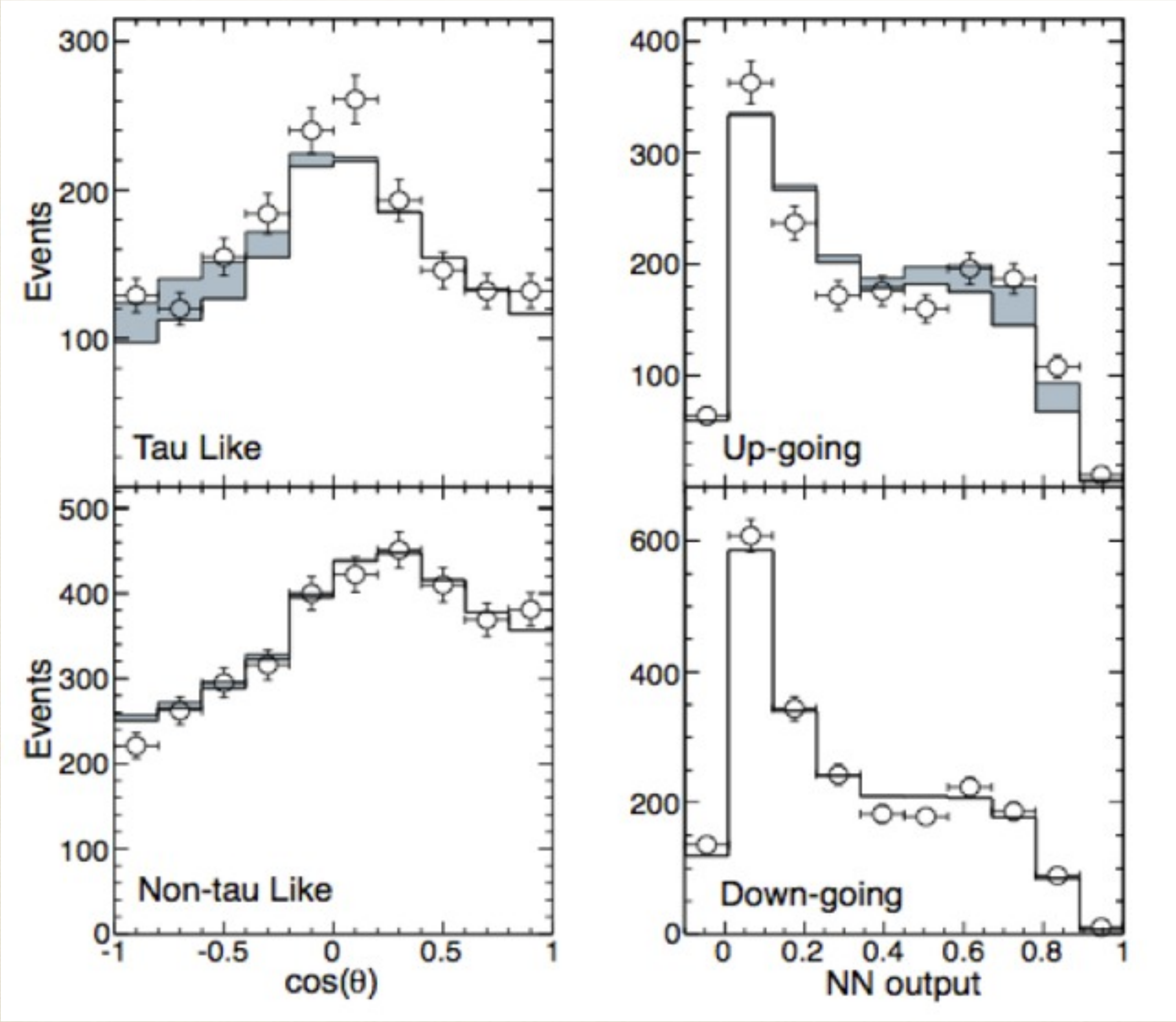


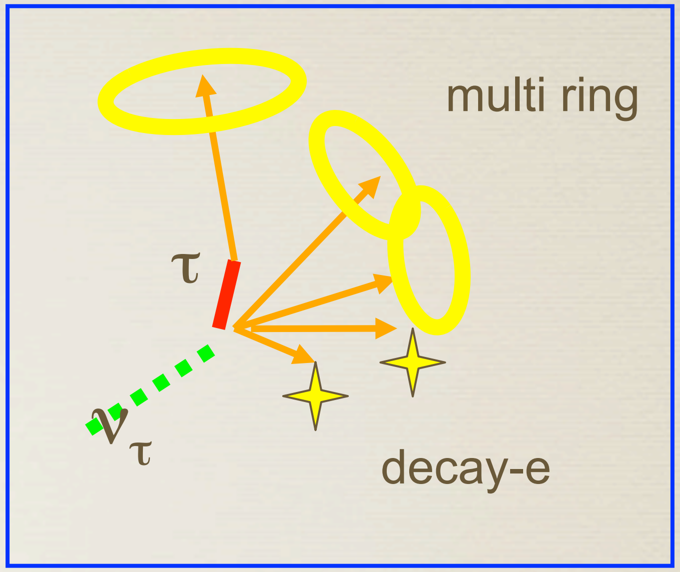
- δCP : all region allowed @90%C.L.
- χ^2(NH)-χ^2(IH)=1.2

<u>Need more statistics</u>



ν_τ appearance?





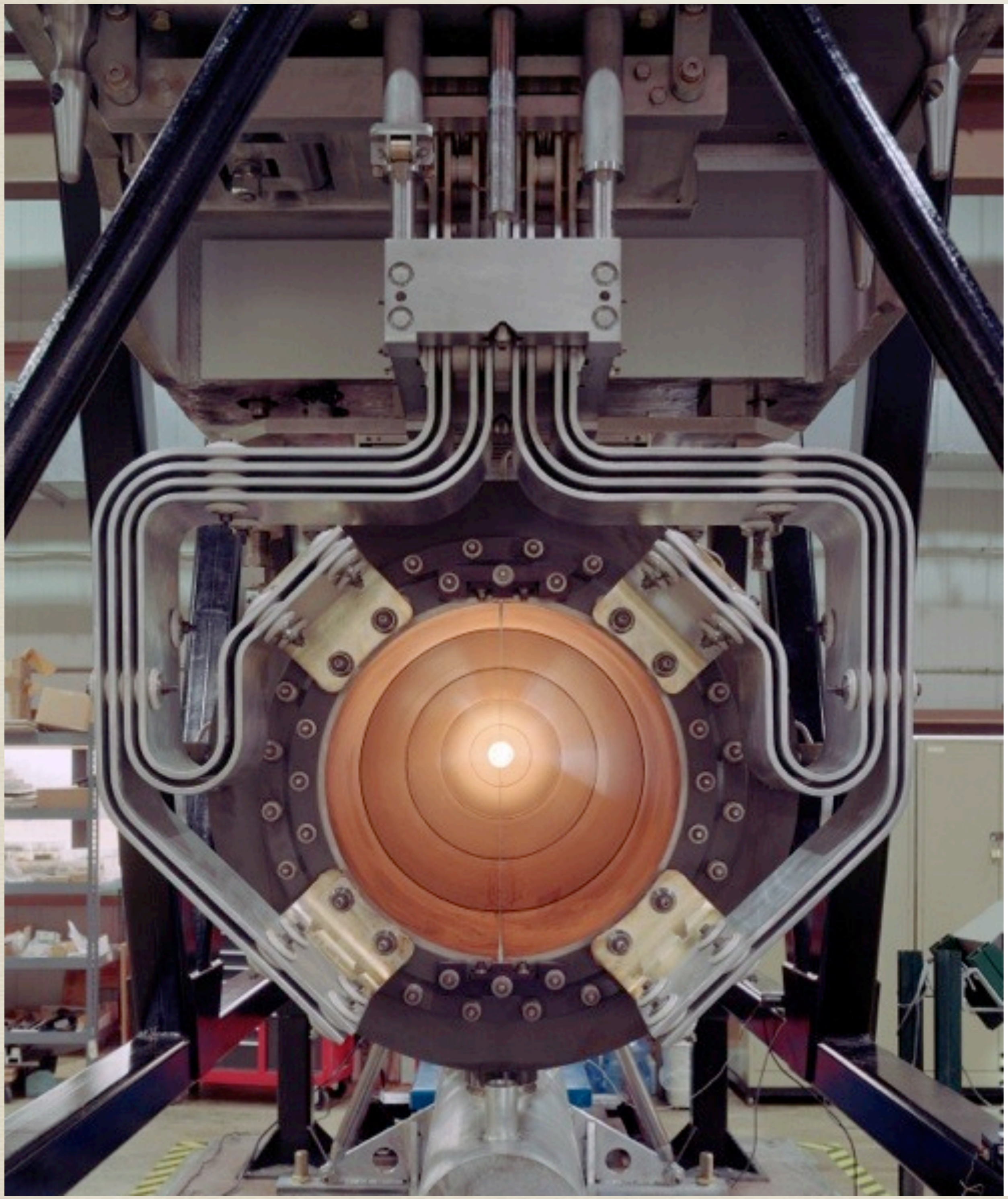
Corresponding τ events of

$$180.1 \pm 44.3(stat)^{+17.8}_{-15.2}(sys)$$

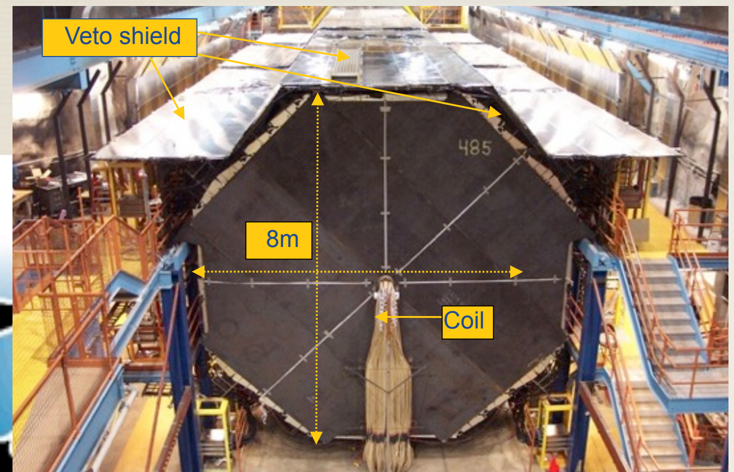
3.8σ deviation from "no ν_τ appearance"

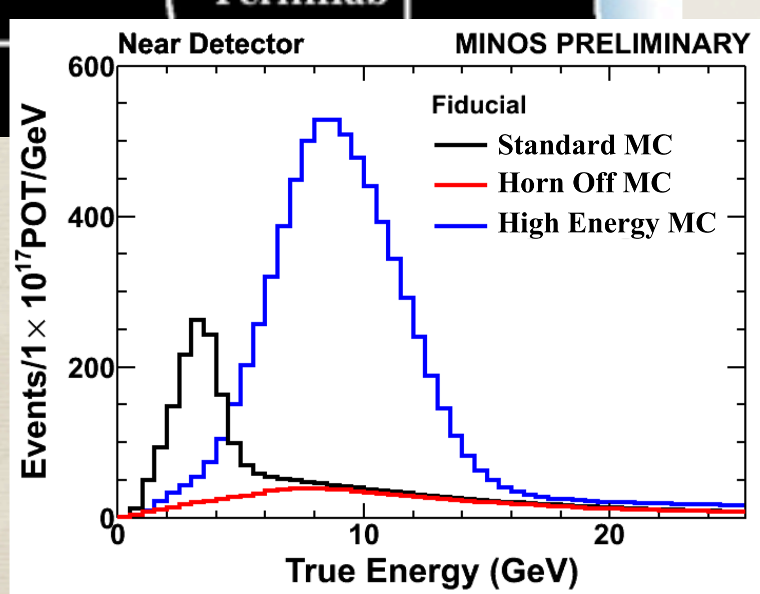
OTHER ACCELERATOR NEUTRINO EXPERIMENTS

MINOS



MINOS (2005~2012)



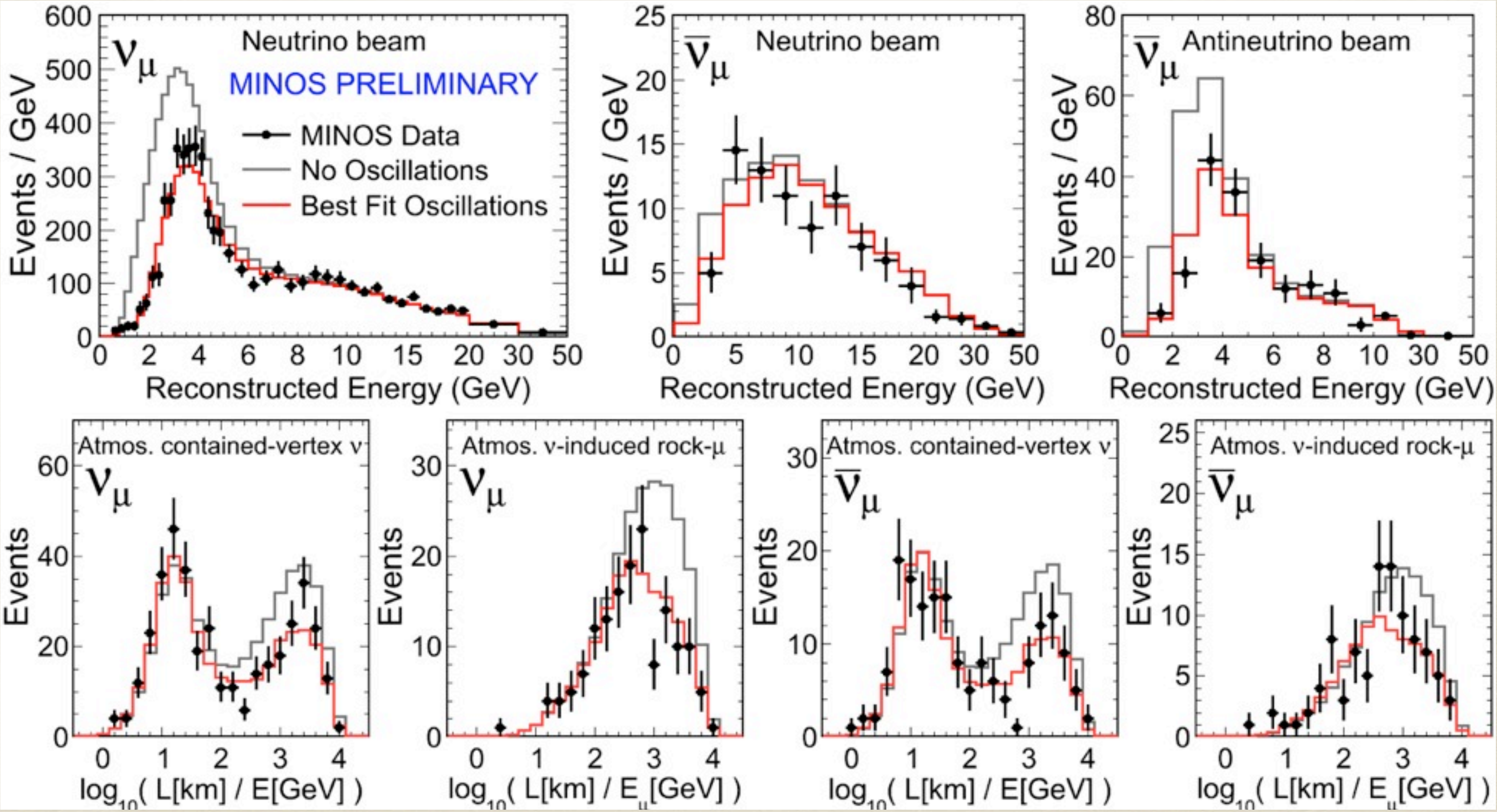


- ~3GeV ν_μ beam from FNAL 120GeV MI
  - 10.7 x 10^{20} POT for ν_μ
  - 3.4 x 10^{20} POT for anti-ν_μ
- magnetized iron-scintillator tracker at 5.4kt (far) / 980t (near)
- event-by-event charge discrimination

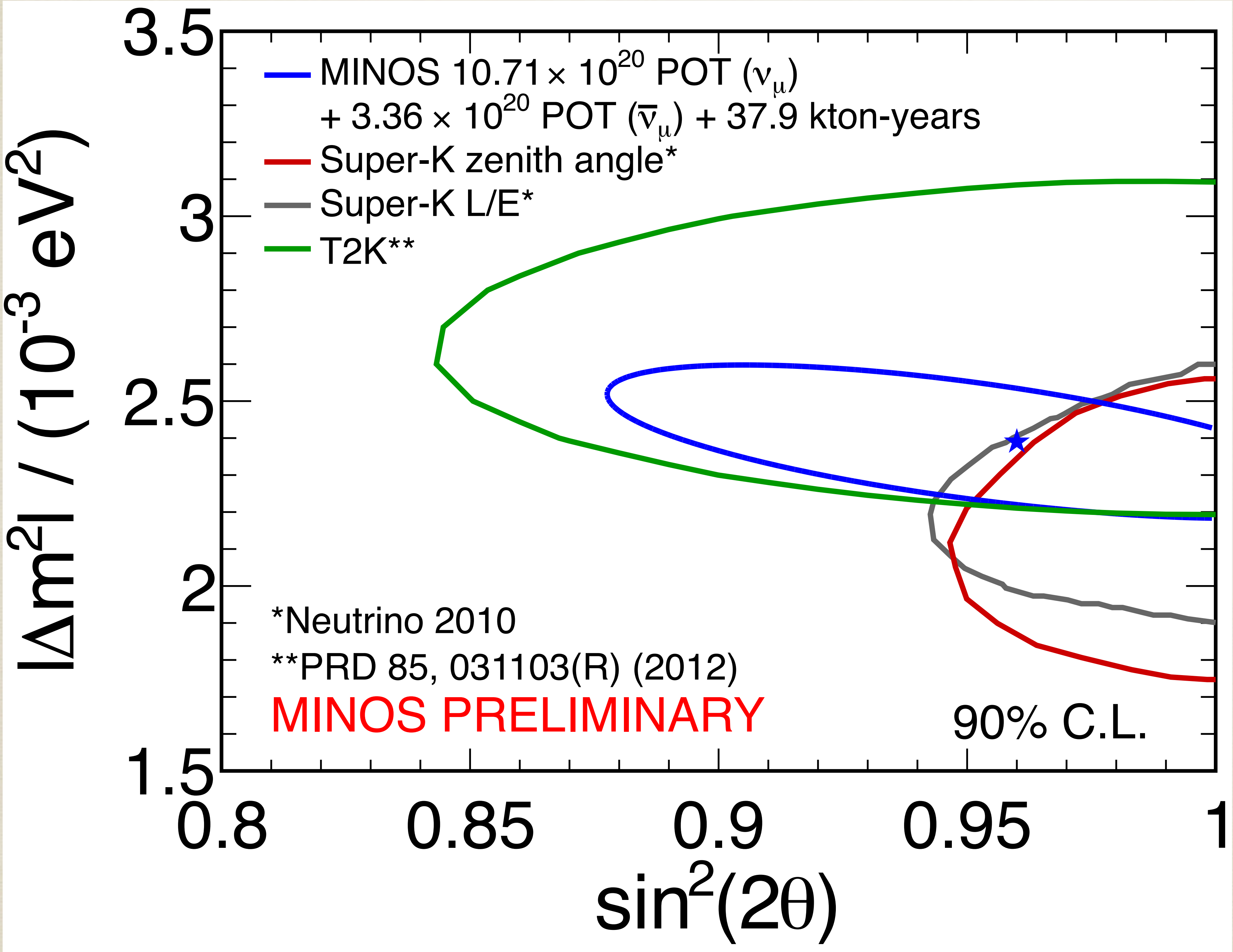
Recent progress:

- Both neutrino and anti-neutrino beam data
- Atmospheric neutrino data

Results in beam and atmospheric neutrinos



Oscillation contour for ν



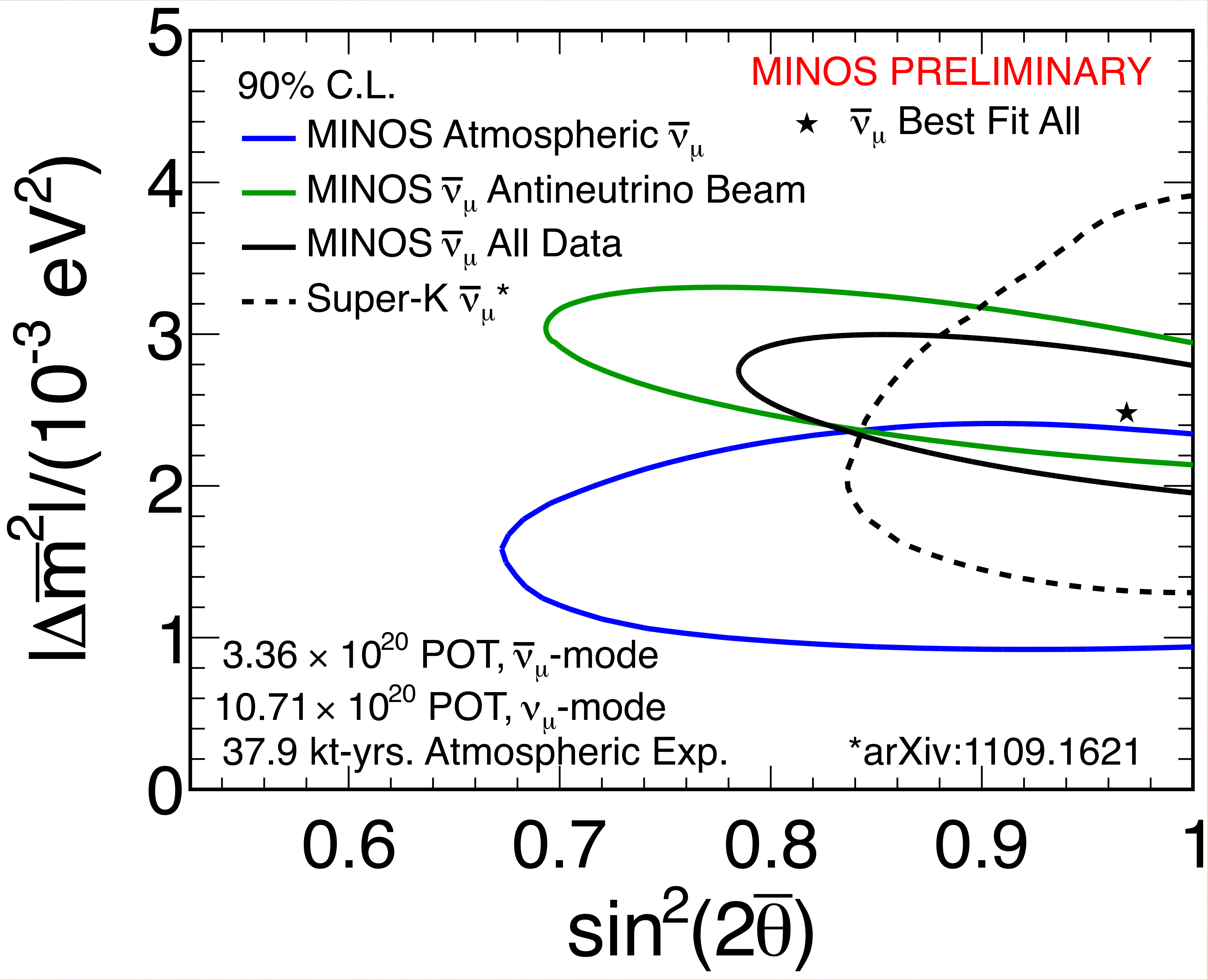
best fit parameters

$$\Delta m^2 = 2.39^{+0.09}_{-0.10} \times 10^{-3} eV^2$$

$$\sin^2(2\theta) = 0.96^{+0.04}_{-0.04}$$

$$\sin^2(2\theta) > 0.90 \text{ at } 90\% \text{ C.L.}$$

Oscillation contour for anti-ν



best fit parameters

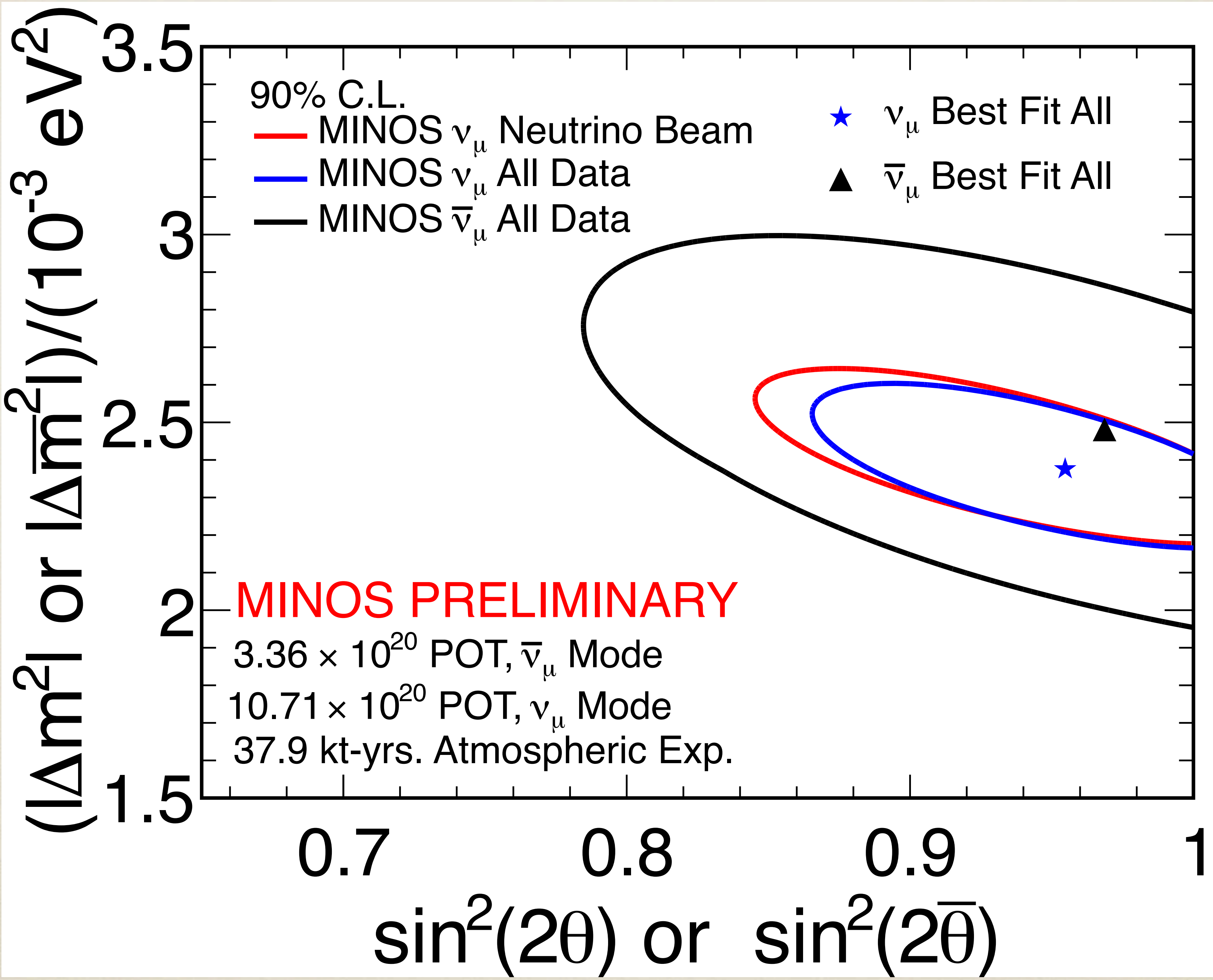
$$\left|\Delta\overline{m}^2\right| = 2.48^{+0.22}_{-0.27} \times 10^{-3} eV^2$$

$$\sin^2\left(2\overline{\theta}\right) = 0.97^{+0.03}_{-0.08}$$

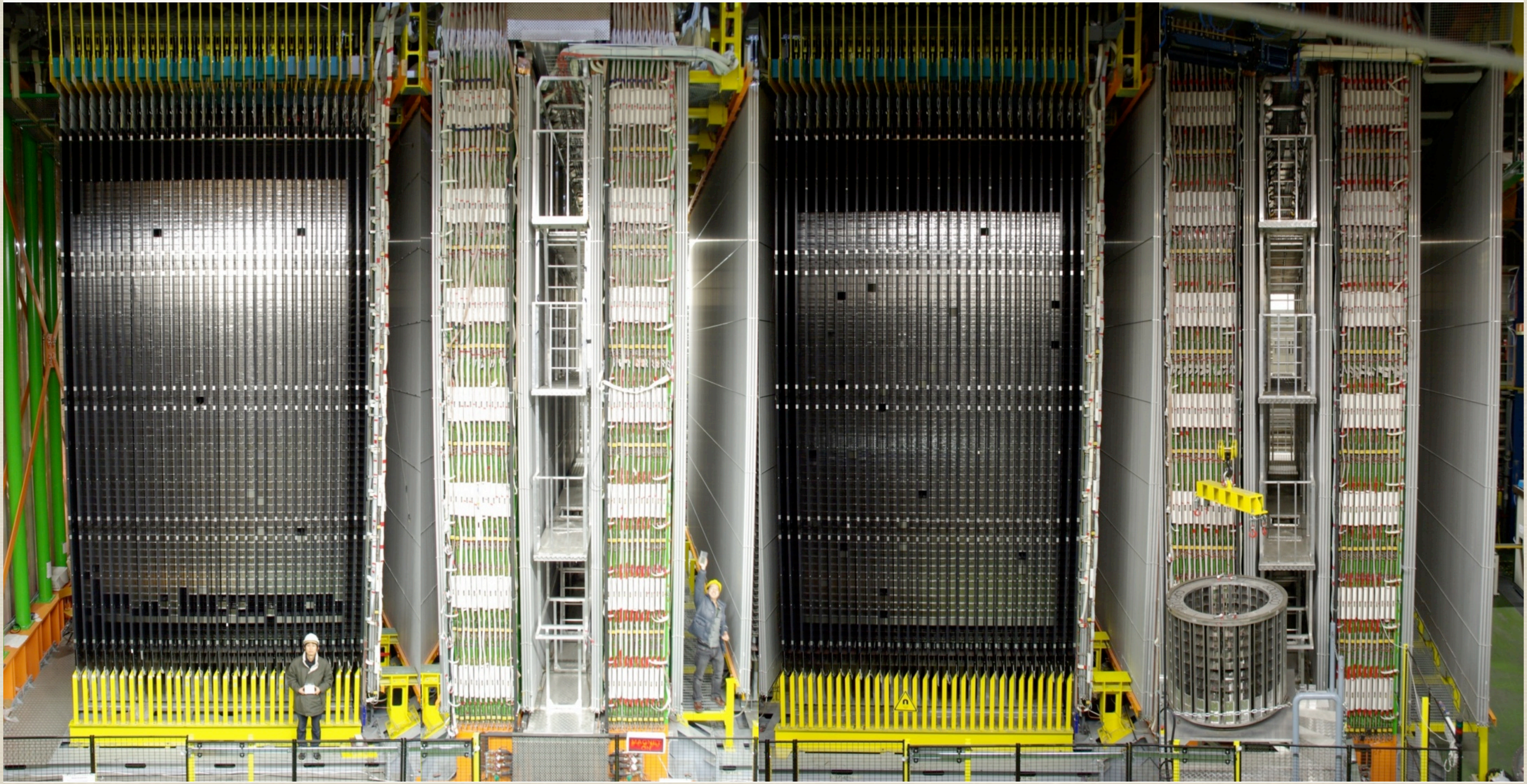
$$\sin^2\left(2\overline{\theta}\right) > 0.83 \text{ at } 90\% \text{ C.L.}$$

Oscillation contour

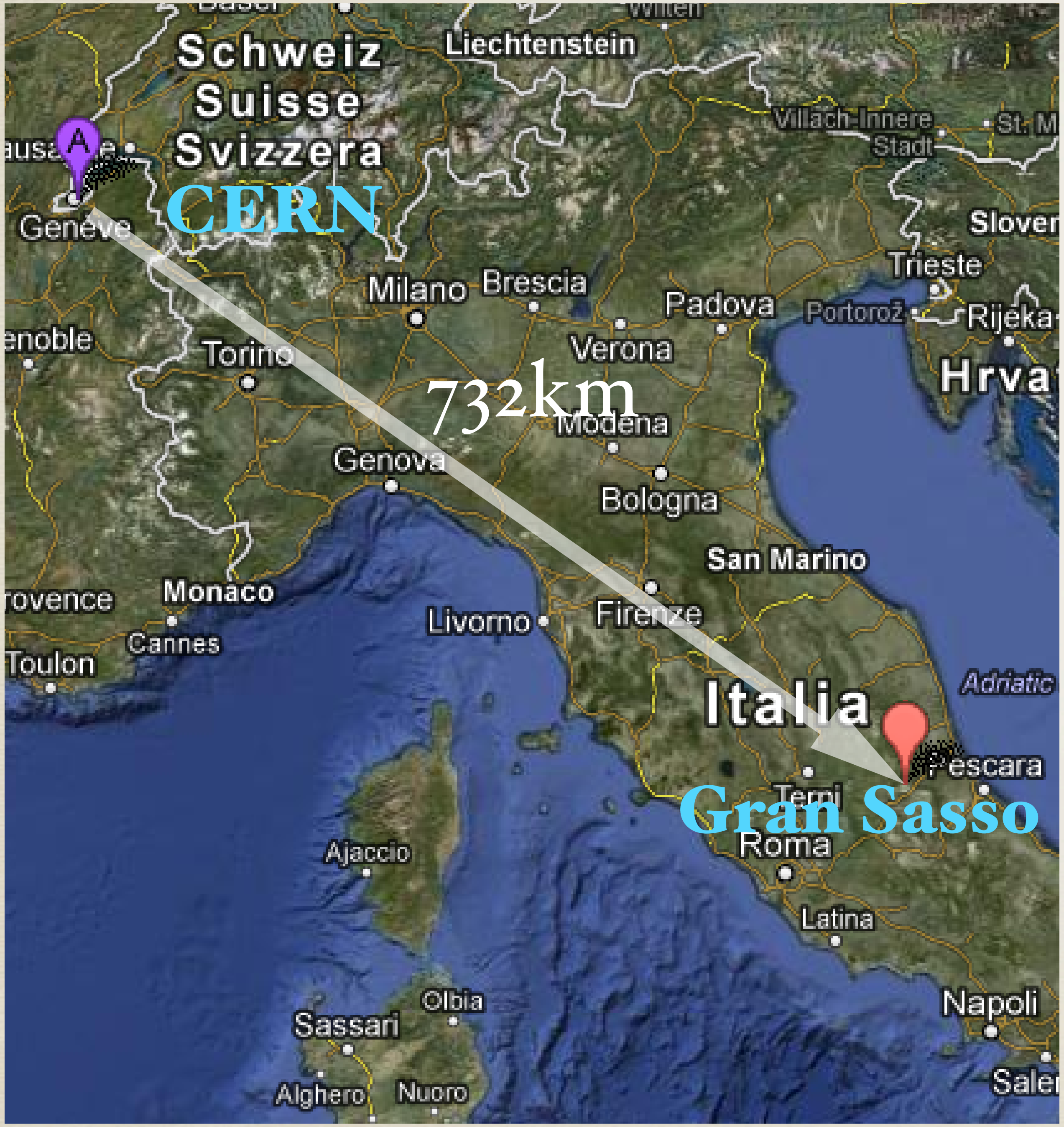
Neutrino vs Anti-Neutrino



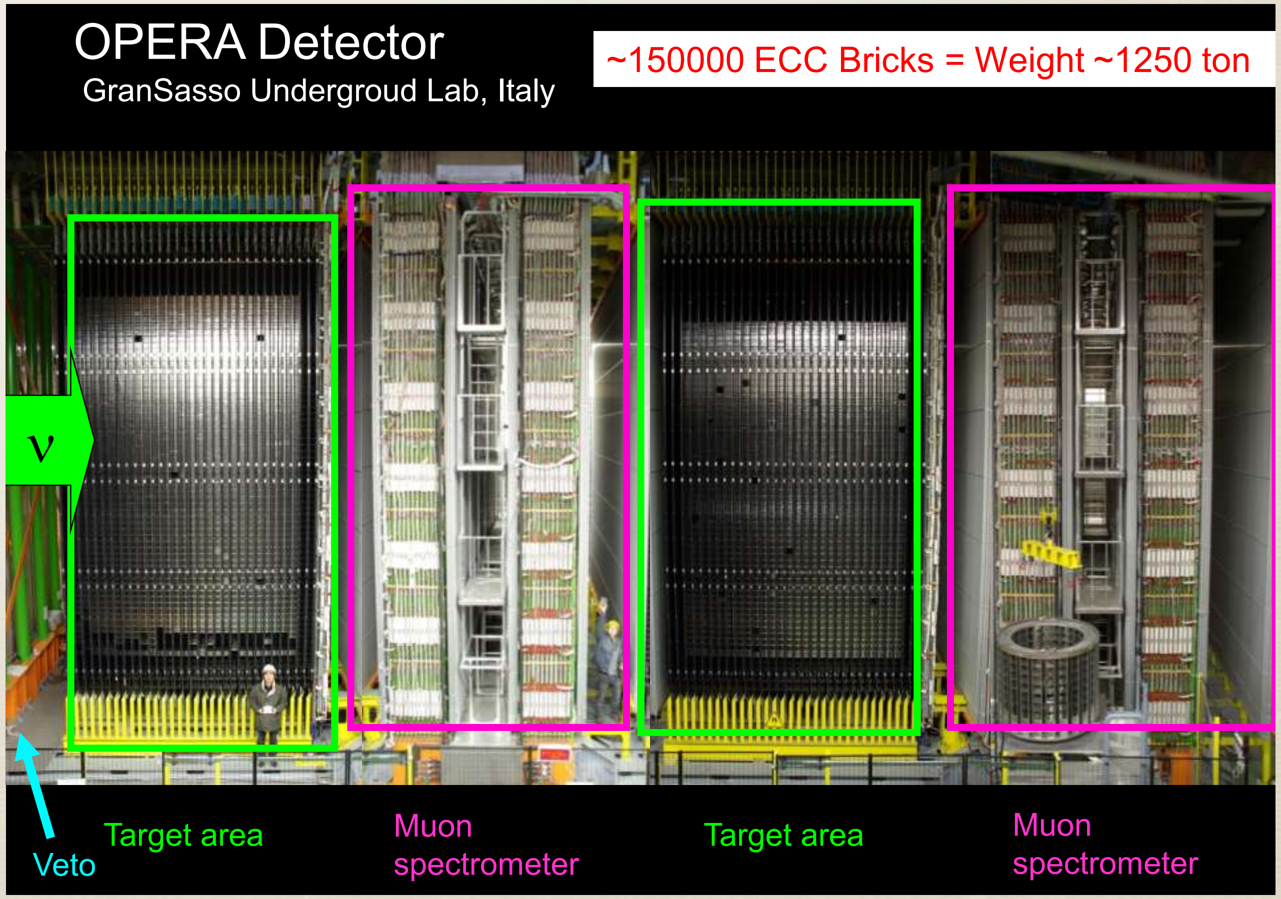
OPERA



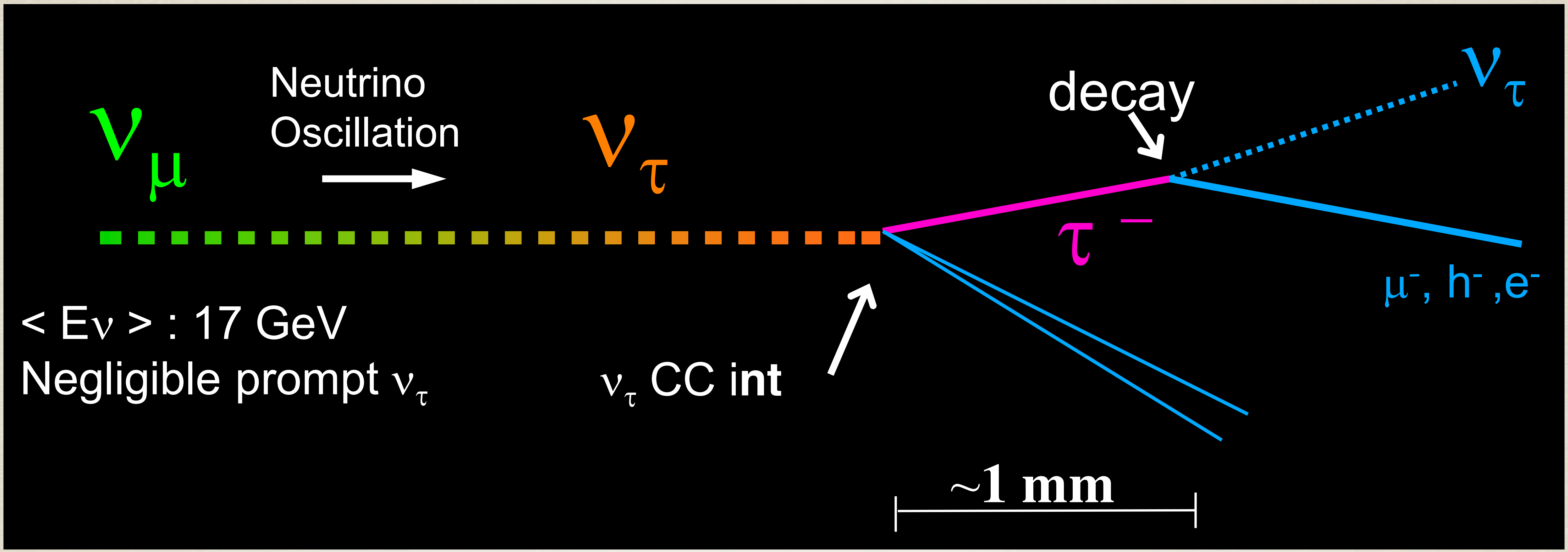
OPERA (2008~)



- Wide band ν_μ beam (10-30GeV) from CERN 400GeV SPS
  - $\langle E \rangle$=17GeV
  - 14.2 x 10^{19} POT up to 2011
- Emulsion-Counter Hybrid



ν_τ appearance search



Years	Status	# of events for decay search	Observed	Expected signal	Expected BG
2008-2009	Finished	2783	1		
2010-2011	In analysis	1343	1		
2012	Started				
Total		4126	2	2.1	0.2

progress in estimating detection efficiency and B.G.

SUMMARY

* Neutrino oscillation parameters are updated

Mass differences	Mixing angle	
$\Delta m^2_{21} = 7.44^{+0.20}_{-0.19} \times 10^{-5} eV^2$	$32.7 \leq \theta_{12} \leq 34.3\,\mathrm{deg}$	(sol.+kaml.)
$\Delta m^2_{32} = 2.66^{+0.15}_{-0.40} \times 10^{-3} eV^2$	$38.7 \leq \theta_{23} \leq 51.9\,\mathrm{deg}$	(SK-atm.)
$= 2.39^{+0.09}_{-0.10} \times 10^{-3} eV^2$	$36.8 \leq \theta_{23} \leq 53.2\,\mathrm{deg}$	(MINOS)

* Notes:
  - ✓ New solar neutrino results, pep and CNO, appeared. (Borexino)
  - ✓ Hints of direct MSW effects? (SK-sol. D/N)
  - ✓ Analysis for δCP and NH/IH, need more statistics. (SK-atm.)
  - ✓ Hints of ν_τ appearance? (SK-atm., OPERA)
  - ✓ Neutrino and anti-neutrino oscillation is consistent (MINOS)
  - ✓ etc..

BACK UP

Speed of neutrinos

To summarize S.Bertolucci @ Nu2012

- All experiments consistent with no measurable deviation from the speed of light for neutrinos:
  - **Borexino**: $\delta t = 2.7 \pm 1.2$ (stat) ± 3(sys) ns
  - **ICARUS:** $\delta t = 5.1 \pm 1.1$(stat) ± 5.5(sys) ns
  - **LVD:** $\delta t = 2.9 \pm 0.6$(stat) ± 3(sys) ns
  - **OPERA:** $\delta t = 1.6 \pm 1.1$(stat) [+ 6.1, -3.7](sys) ns
- Very preliminary analyses, more refinements to be expected soon
- A paradigmatic example of collaboration and competition!

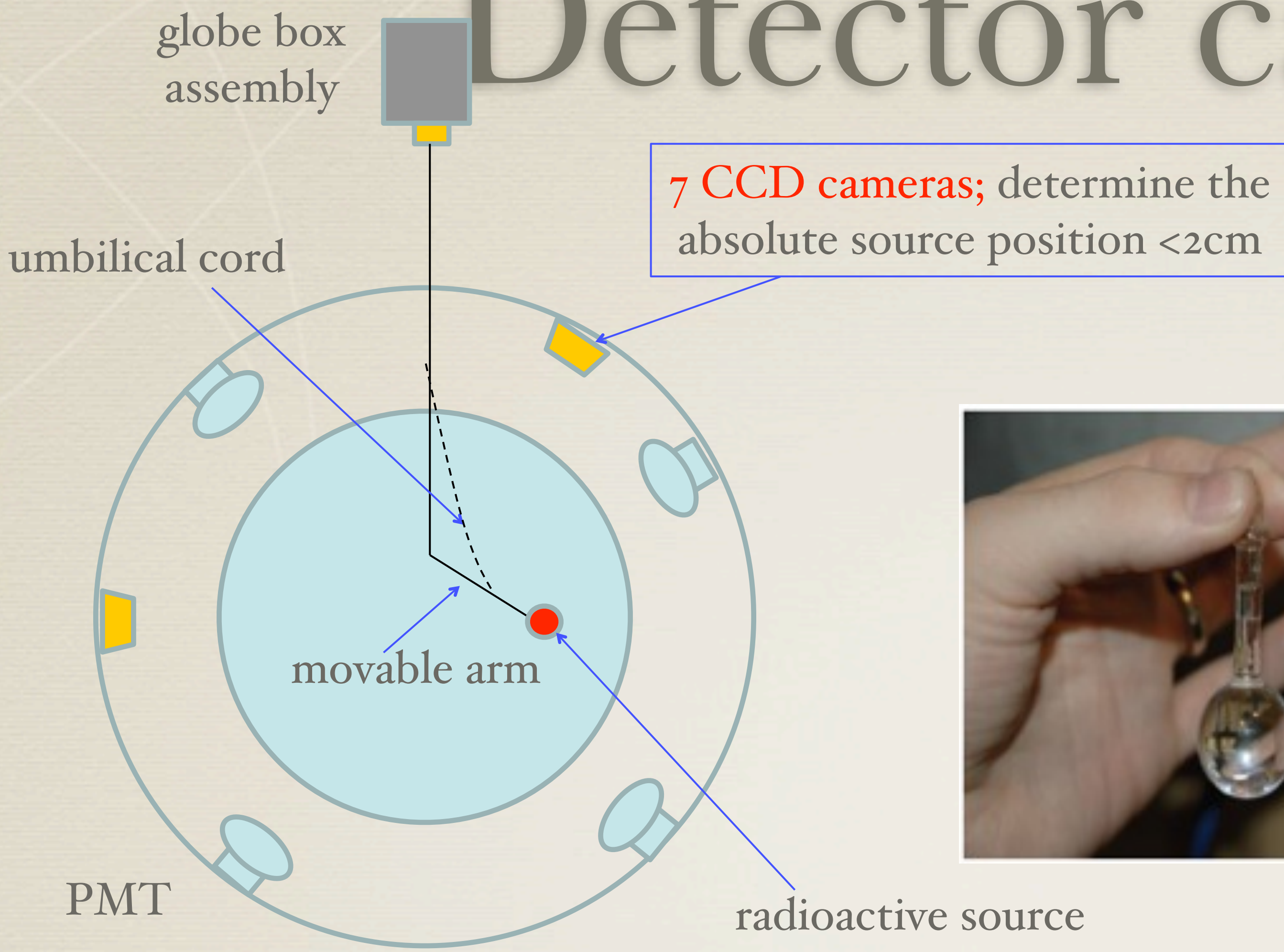
MINOS measurement (Giles Barr)

15 ± 11 (stat.) ± 29 (syst.) ns

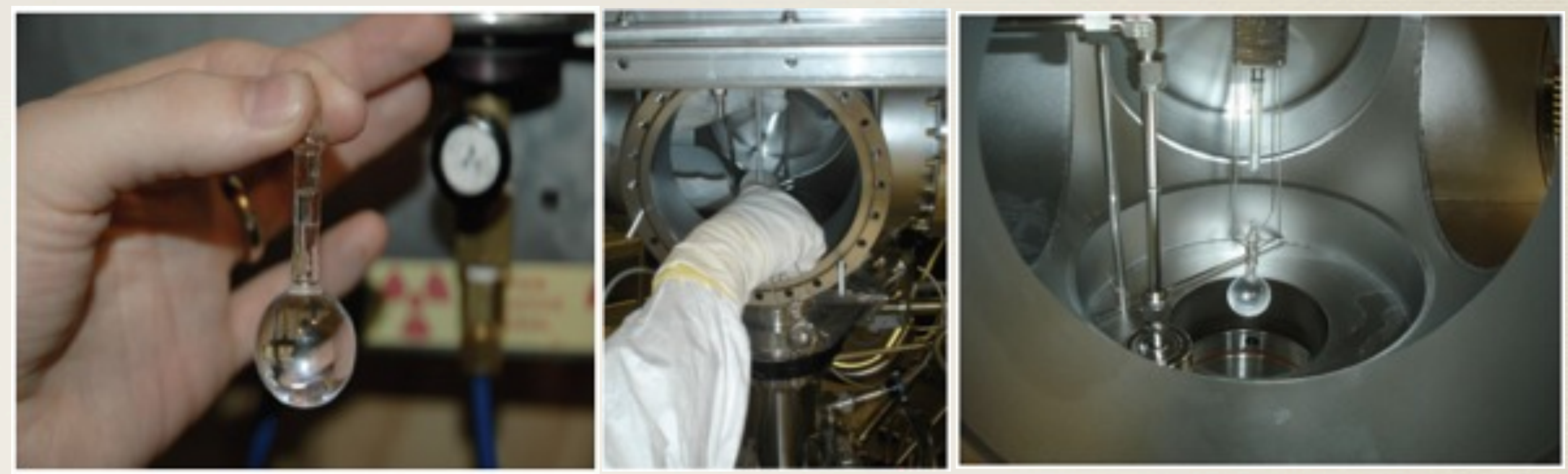
which is consistent with v=c

All are consistent with light speed

Detector calibration



Source insertion



	γ								β		α	n		
	dopant dissolved in small water vial								^{222}Rn loaded liq. scint. vial			Am-Be		
	^{57}Co	^{139}Ce	^{203}Hg	^{85}Sr	^{54}Mn	^{65}Zn	^{60}Co	^{40}K	^{14}C	^{214}Bi	^{214}Po	n-p	n +^{12}C	n+Fe
Energy (MeV)	0.122	0.165	0.279	0.514	0,834	1.1	1.1 1.3	1.4	0.15	3.2	(7.6)	2.2	4.94	~7.5

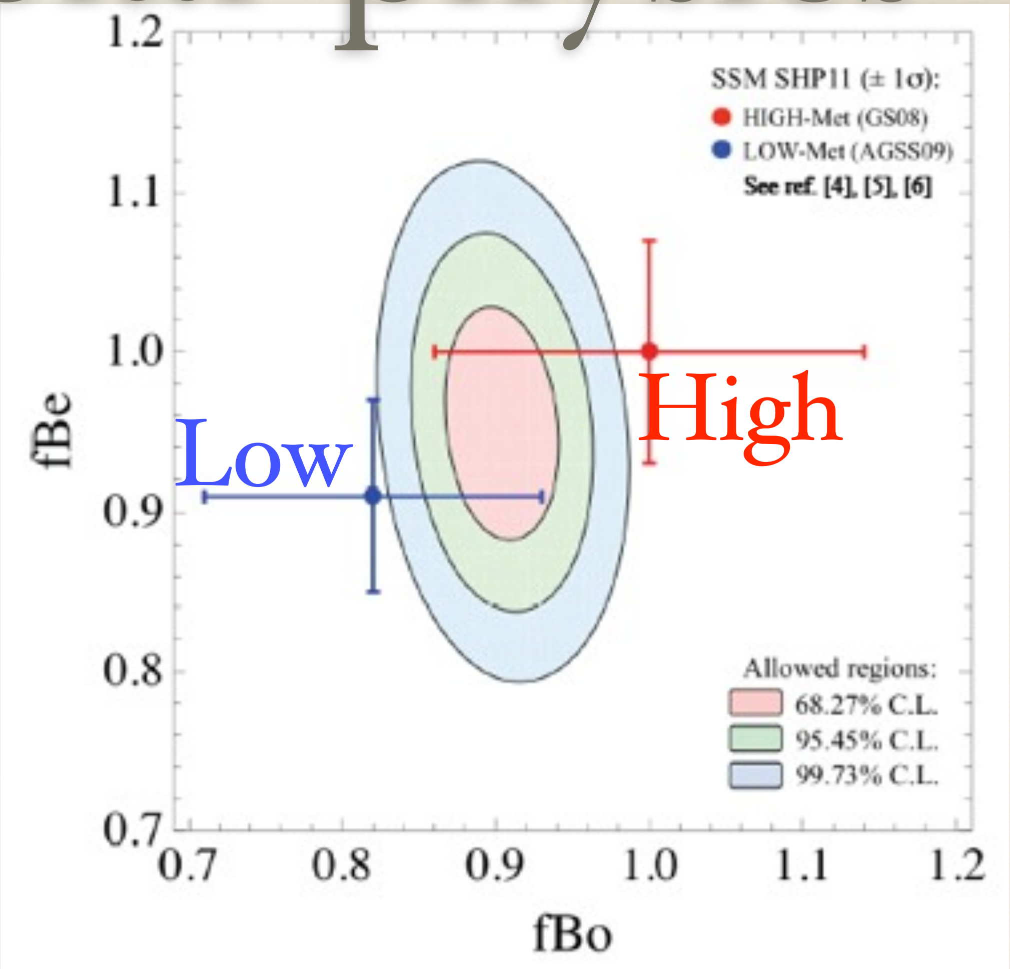
clear tag from Bi-Po
fast coincidence

Implication on solar physics

- Metallicity controversy

  Fit to the available all solar neutrino data leaving free f_{Be} and f_{BO} ($f = \Phi/\Phi(SSM)$)

  Hard to discriminate



- Other solar neutrino sources

  Each solar neutrino flux can be calculated with solar luminosity constraint.

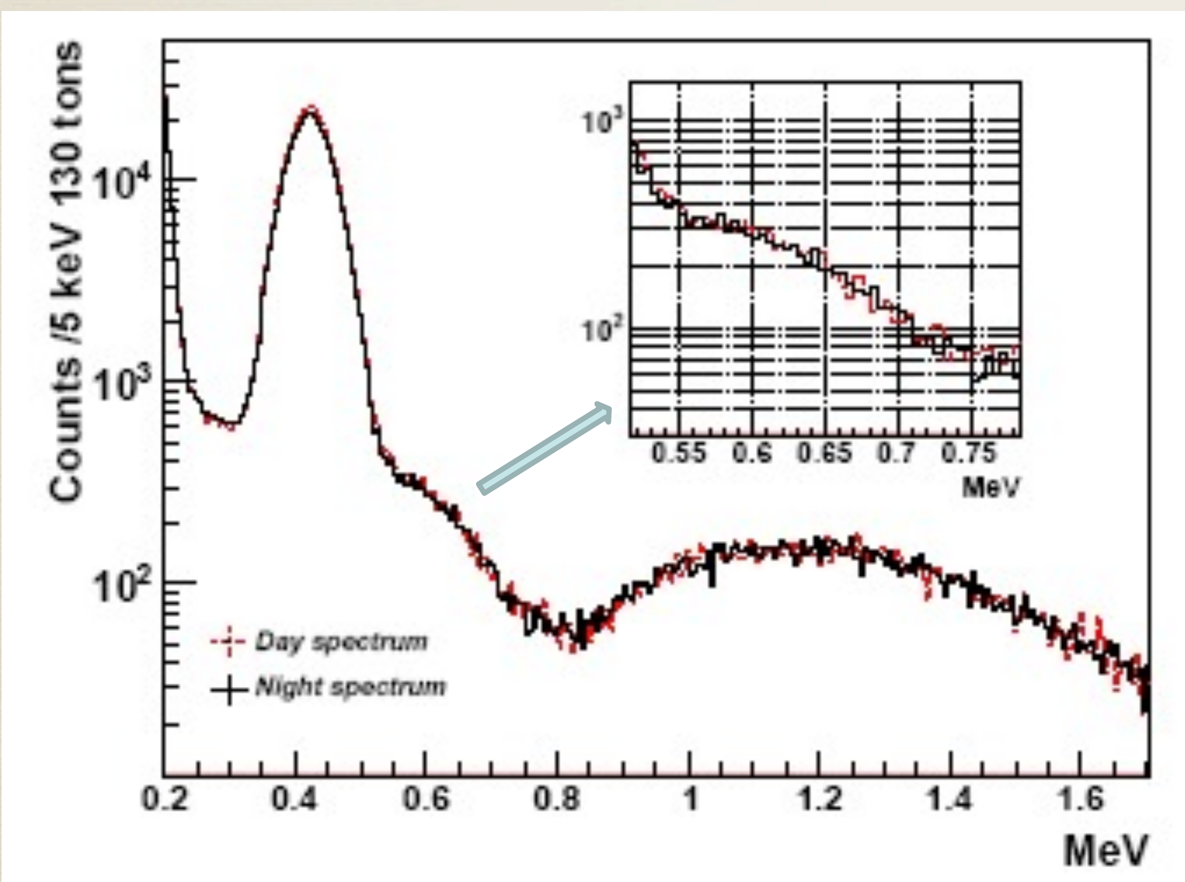
M.C.Gonzalez-Garcia, M.Martoni, J.Salvado
JHEP 05(2010)072 / 0910.4584

$\Phi_{pp} = (6.06^{+0.02}_{-0.06})\times 10^{10} cm^{-2}s^{-1}$ ($f_{pp} = 1.013$)

$\Phi_{CNO} < 1.3\times 10^{9} cm^{-2}s^{-1}$ ($f_{CNO} < 2.5$) at 95%C.L.

Day/Night asymmetry in ^{7}Be rate

- In the MSW scenario, the flux rate in Night should be higher than Day because of the regeneration effect.
- In the ^{7}Be energy region, no effect expected in MSW-LMA region, but large in MSW-LOW region (~20%).



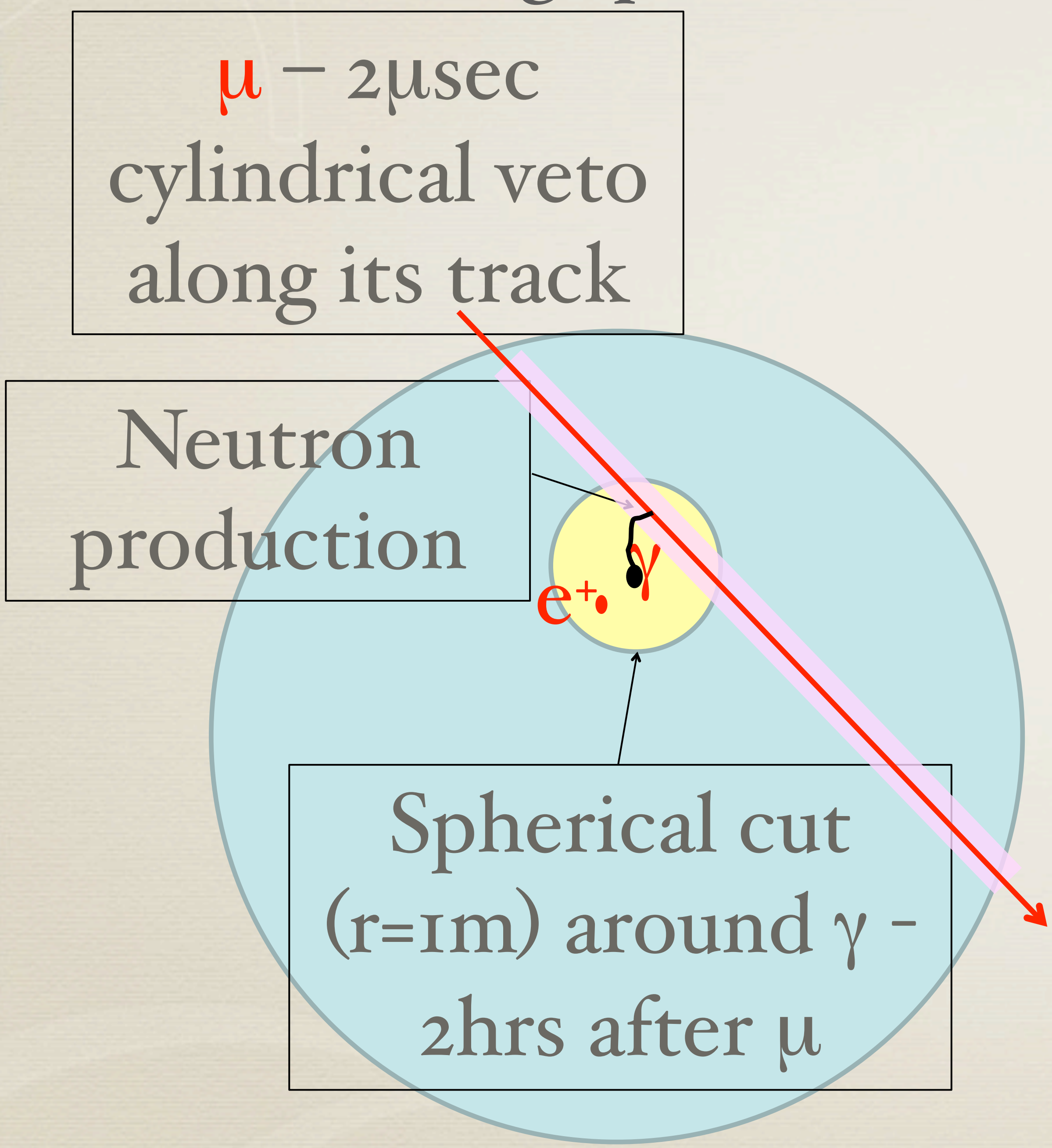
Day (positive Sun altitude)
360.25 days
Night (negative Sun altitude)
380.63 days

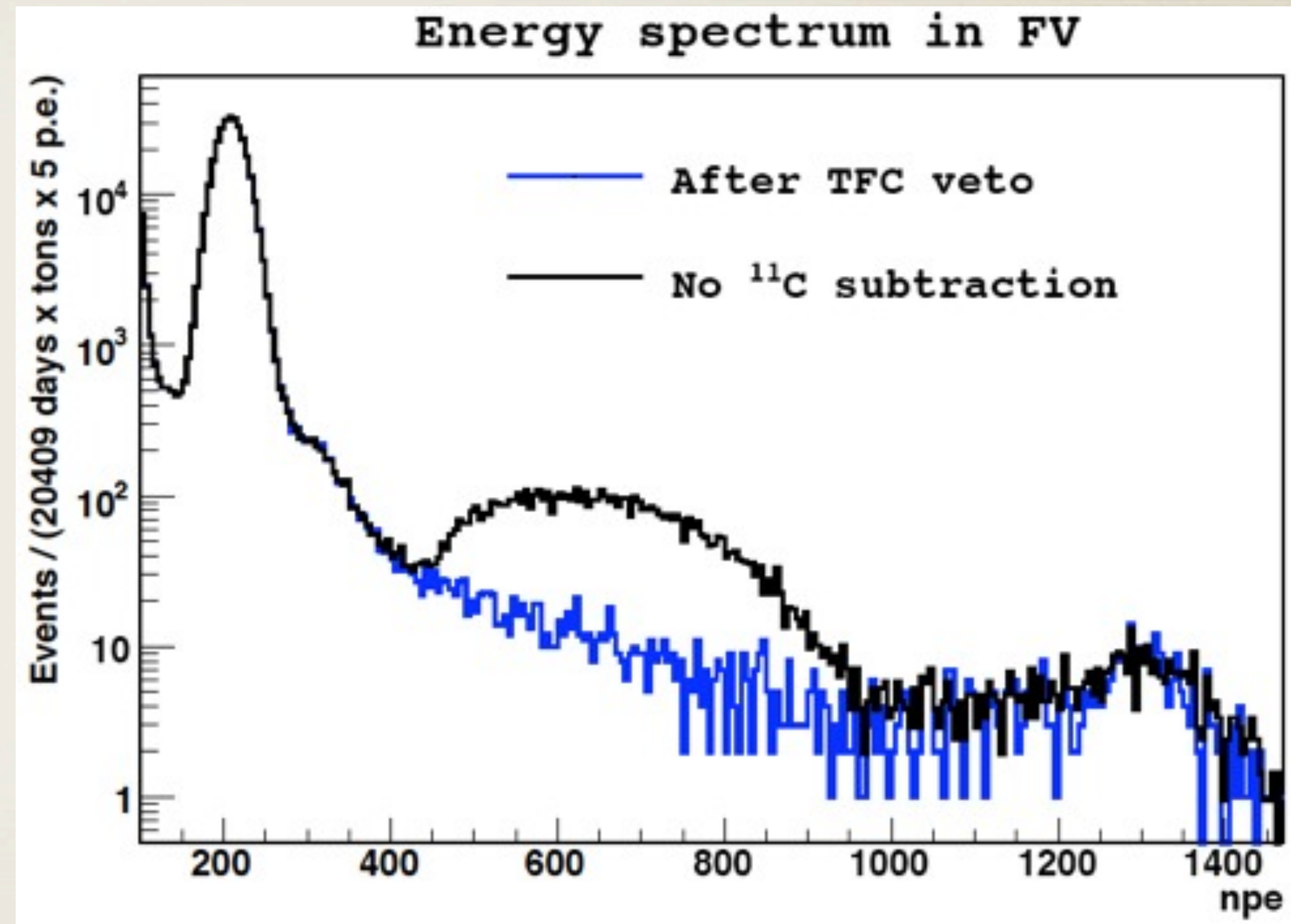
No significant effect was found

$$Adn = \frac{N - D}{(N + D)/2}$$
$$= 0.001 \pm 0.012\,(stat.) \pm 0.007(sys.)$$

Three Fold Coincidence

- Veto using space-time correlation

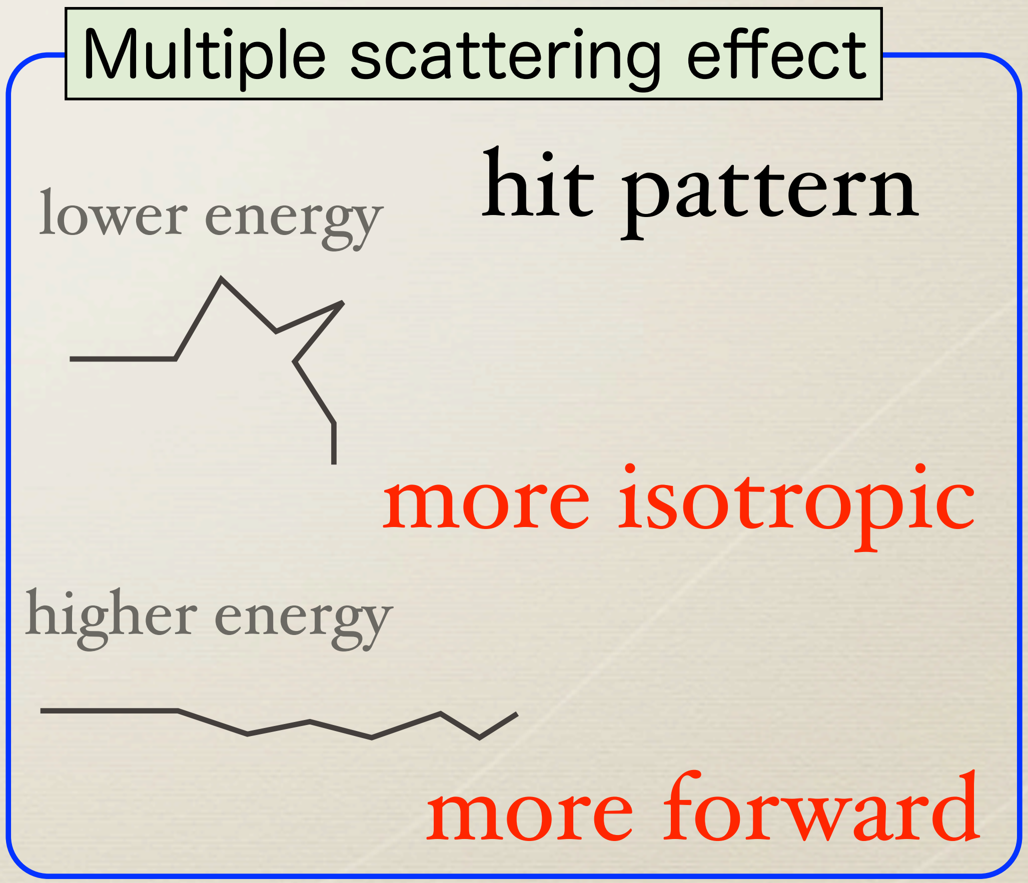




Optimal compromise: 91% rejection of ^{11}C keeping 48.5% residual exposure

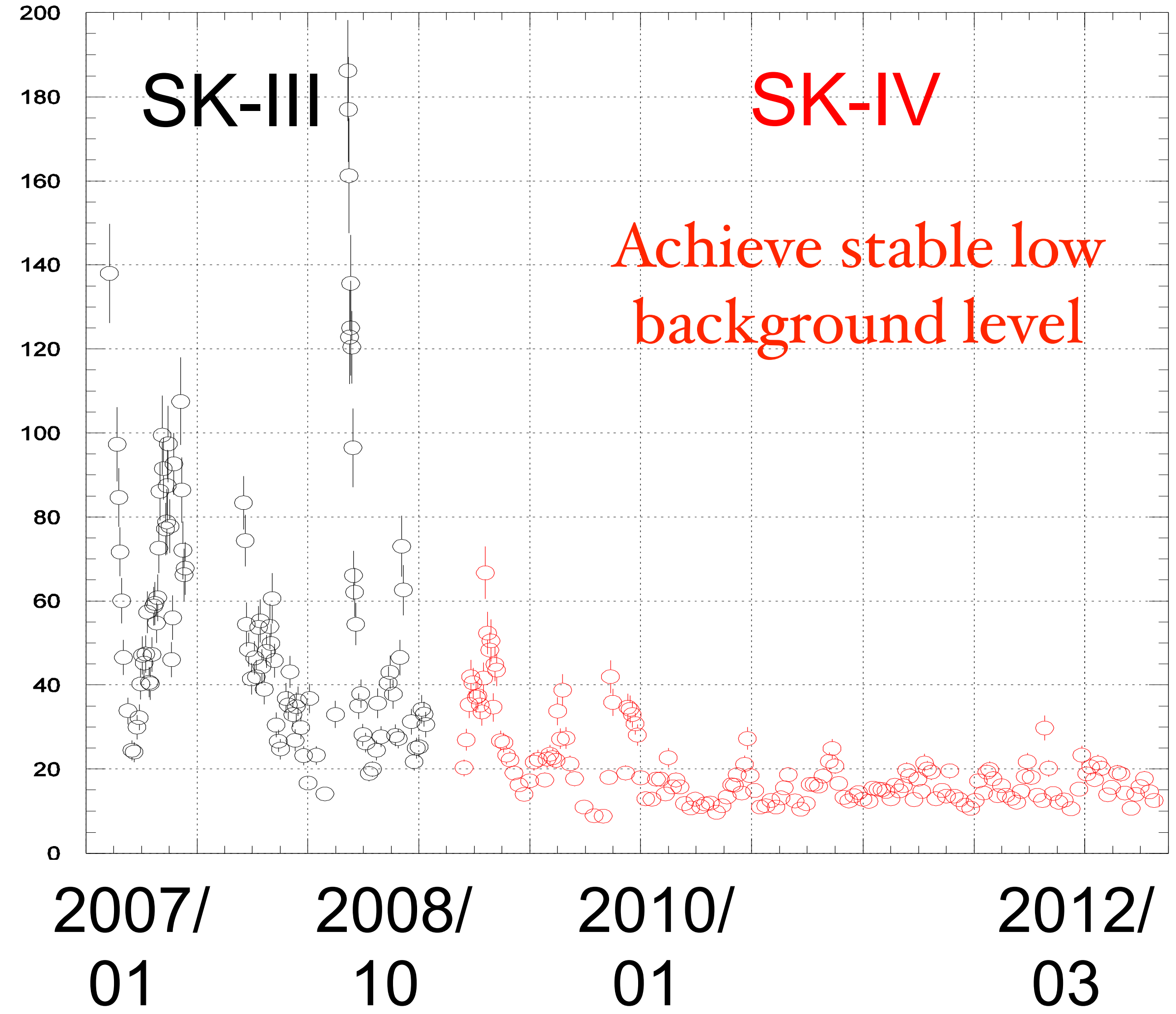
What's new

* mistake in SK-III calculation of expected solar neutrino event rate : best fit flux changes $2.32 \to 2.40 \times 10^6/(cm^2 \cdot sec)$
* First results from SK-IV (1069.3 days of data)
    - Large statistics with lower backgrounds.
    - Reduce systematic error (1.7% for flux)
        - new electronics : 2.1% (SK-III), 3.4% (SK-I)
            - better timing determination
            - better MC model of trigger eff.
    - Lower threshold (~3.5MeV (kin.))
* Introduce multiple scattering goodness

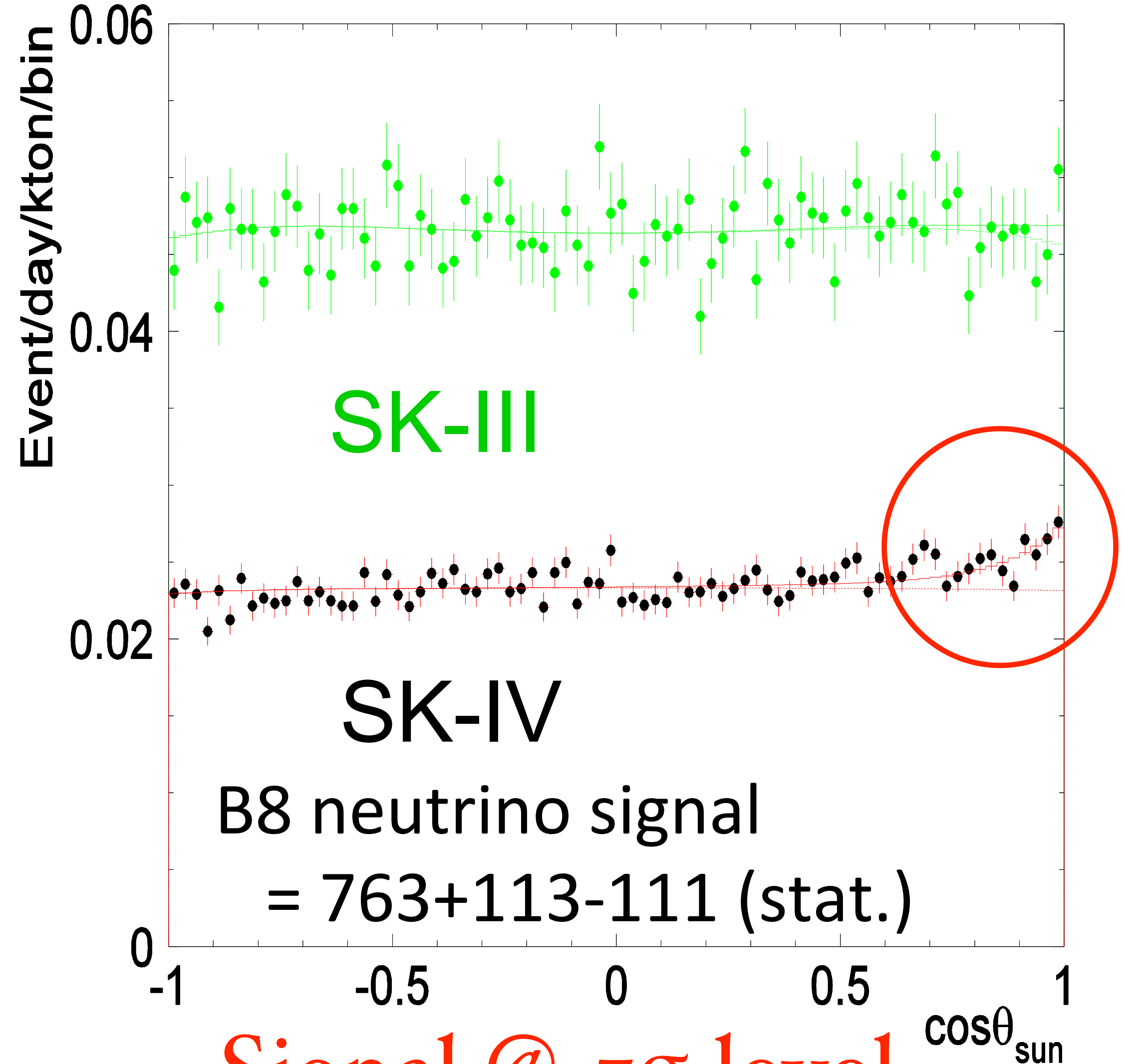


Lower background

[event/day/kton @ 4.0-4.5MeV(kin.)]

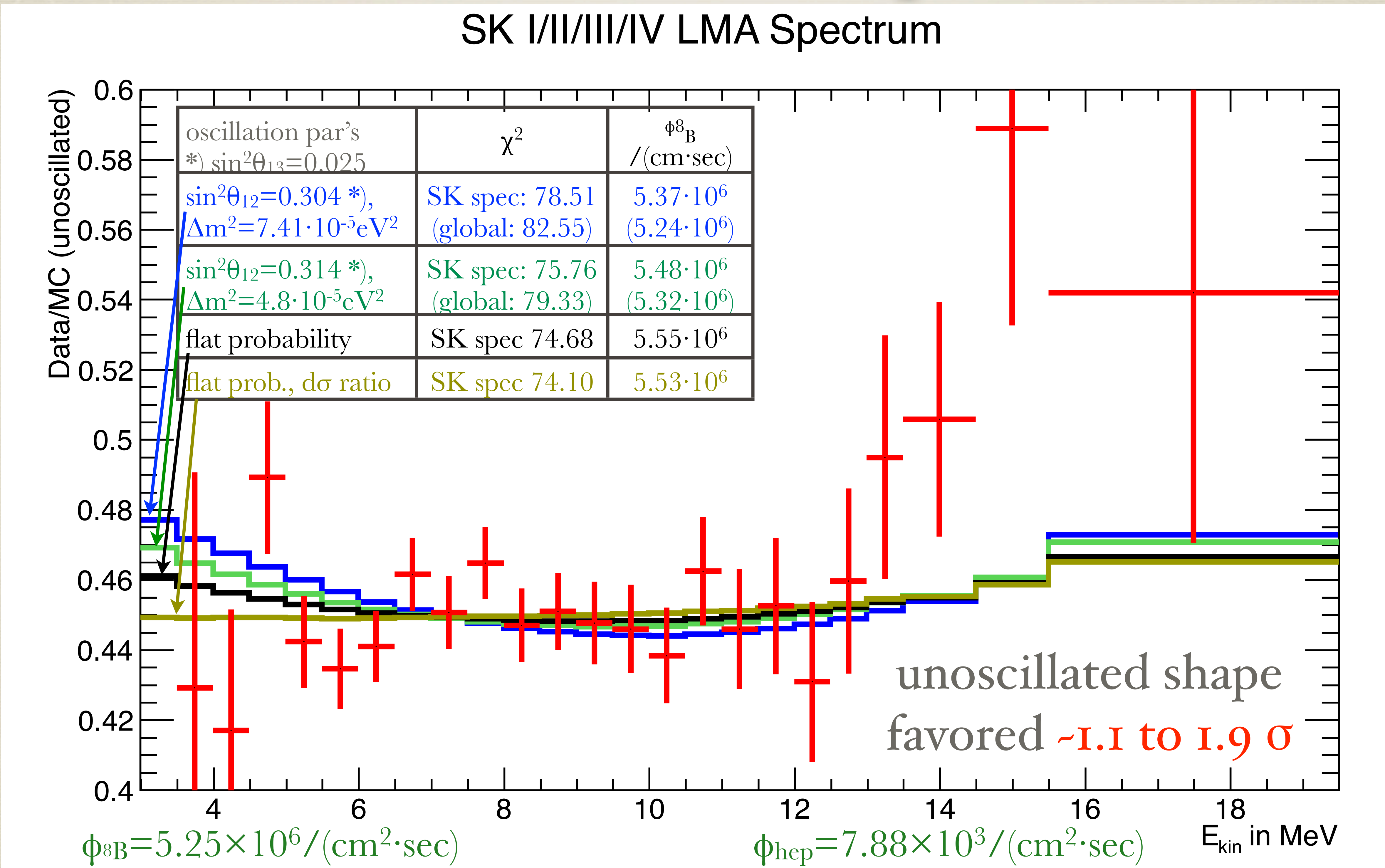


Solar angular distribution (3.5~4.0MeV(kin.))

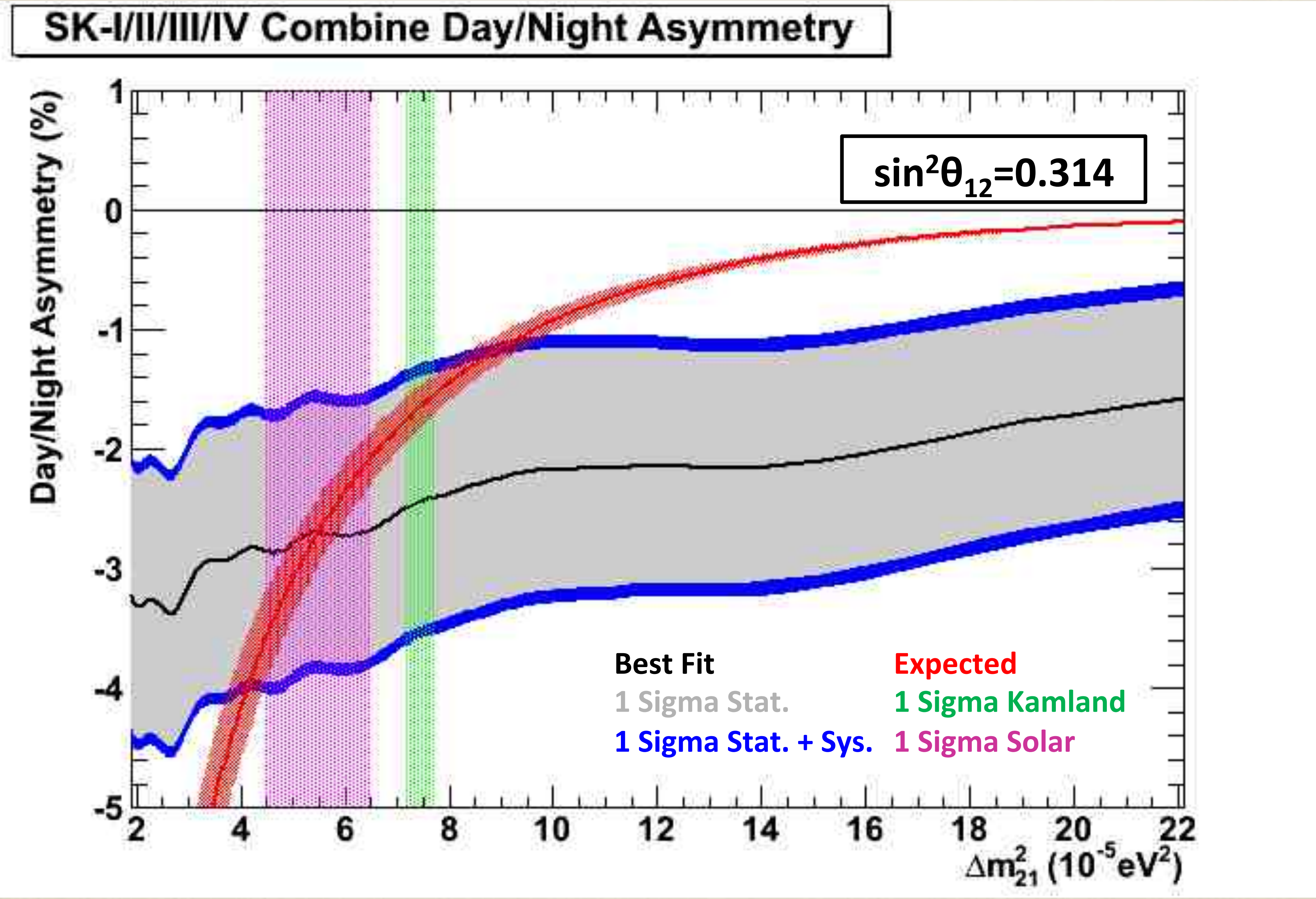


Signal @~7σ level

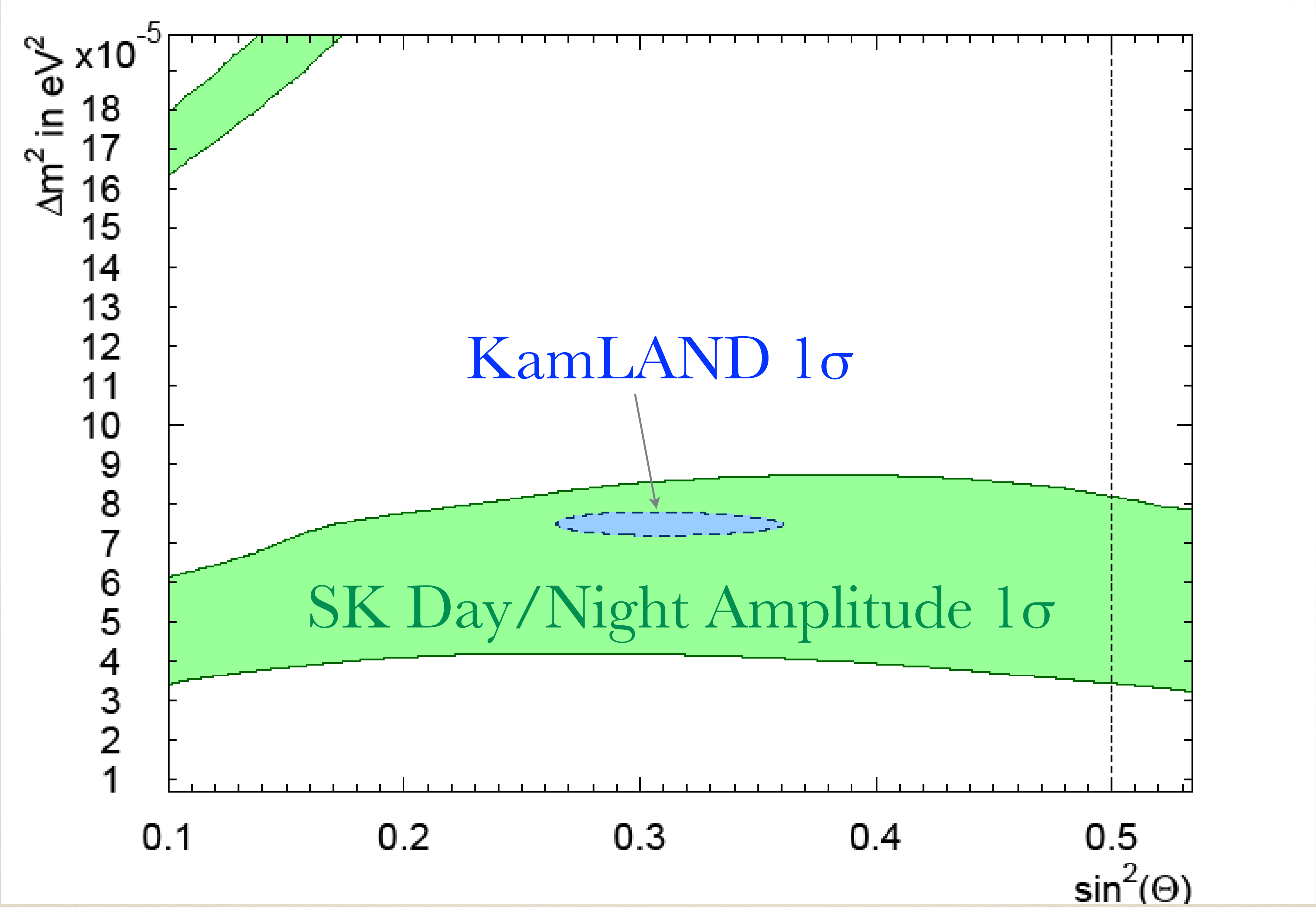
Recoil electron spectrum



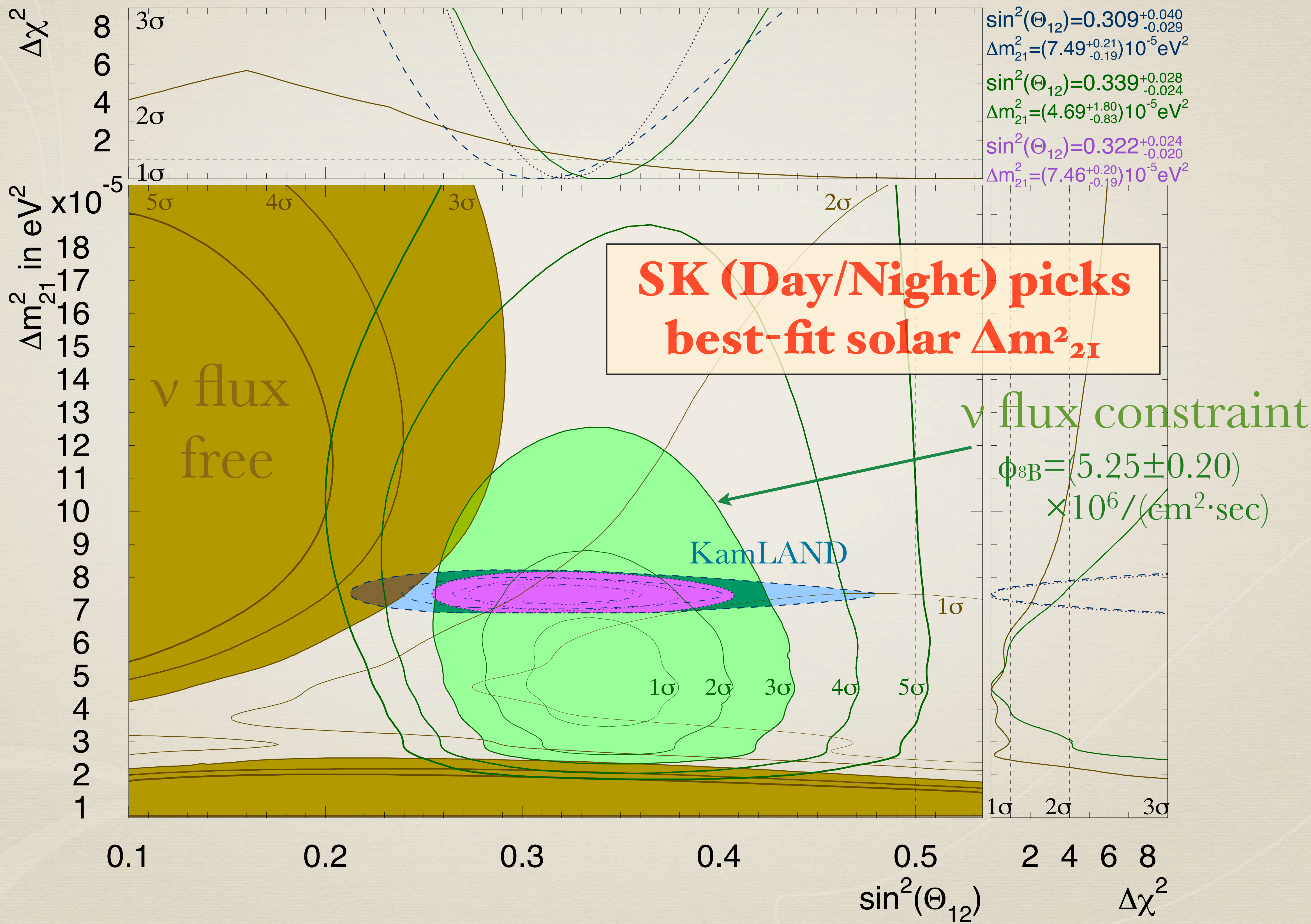
Day/Night amplitude fits as a function of Δm^2



Allowed oscillation parameter region from Day/Night



Only Super-K solar

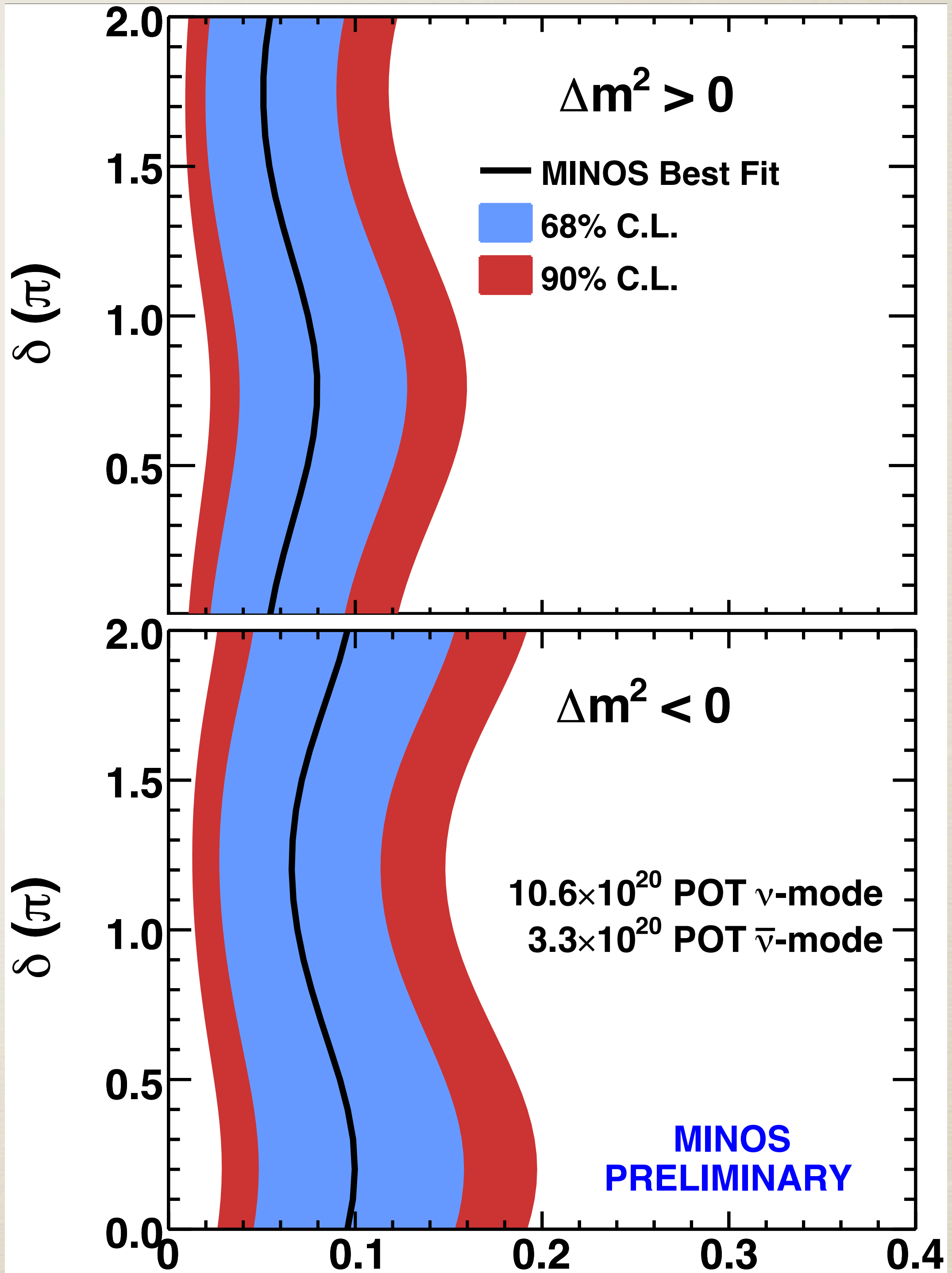


Electron appearance (θ_{13}) in MINOS

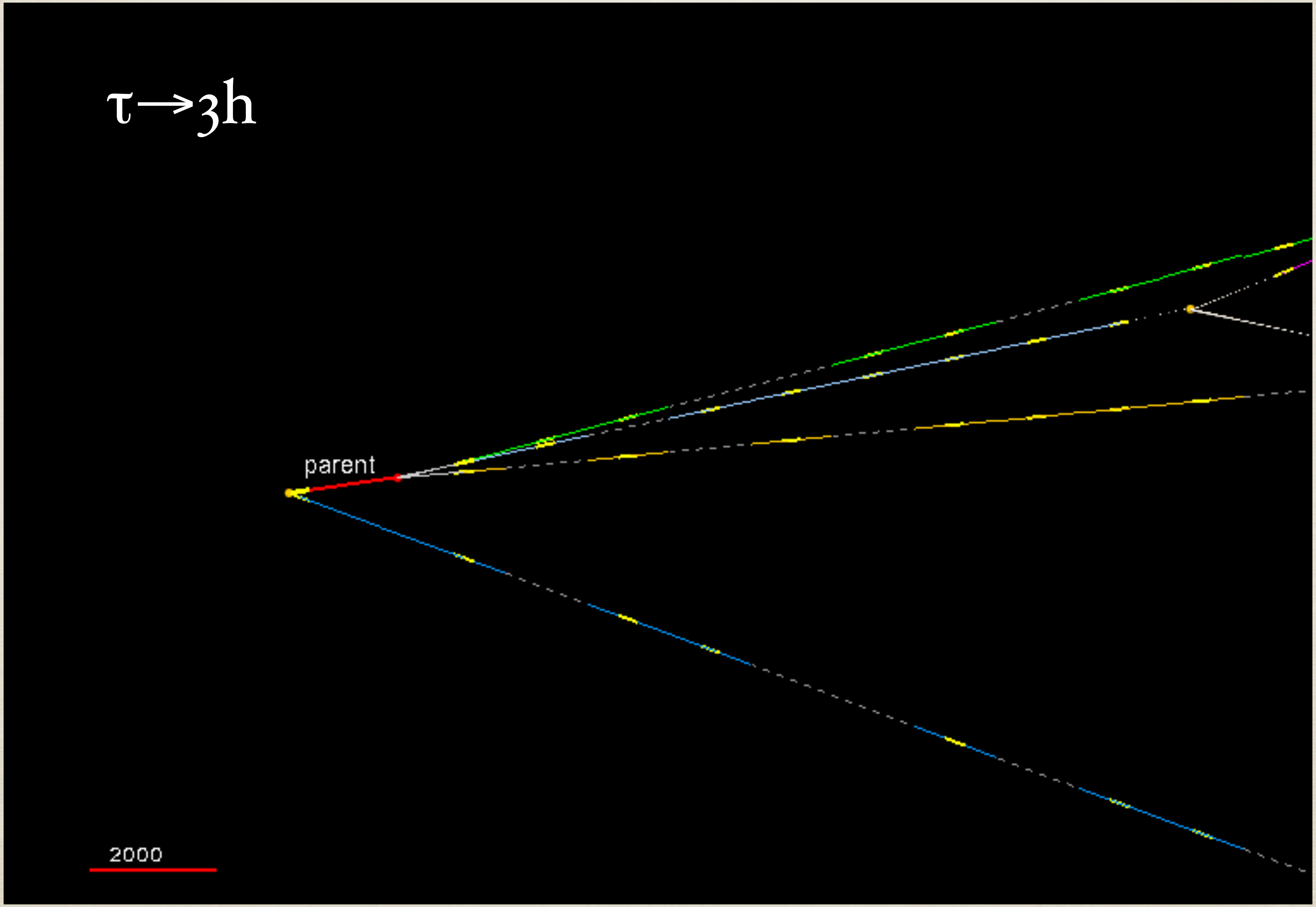
	ν beam	anti-ν beam
Expect	128.6 (+32.5)	17.5 (+3.7)
Observe	152	20

Signal prediction for N.H.
$\sin^2(2\theta_{13})=0.1$, $\delta cp=0$

disfavor $\theta_{13}=0$ @96%C.L.



2nd candidate reported in June 2012 in OPERA



ν_e appearance search in OPERA