Study of solar neutrino energy spectrum above 4.5 MeV in Super-Kamiokande-I

16, Feb. 2004 in ICEPP symposium
Niigata Univ. C.Mitsuda
for Super-Kamiokande collaboration

1, Solar Neutrino Oscillation

2, Super-Kamiokande detector

3, Data set for 4.5 MeV analysis

4, Results and Energy spectrum above 4.5MeV

5, Conclusions and Future prospect

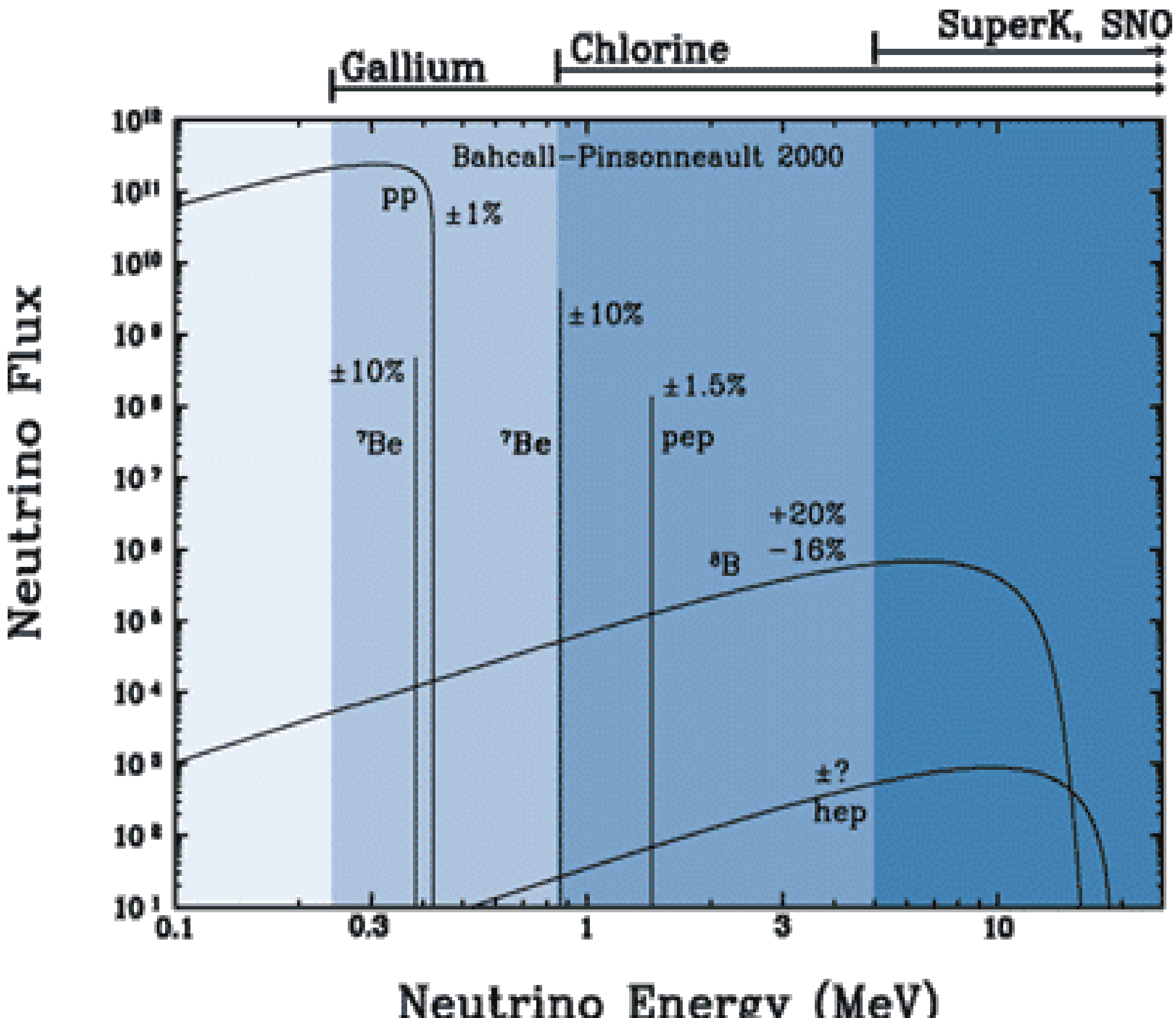
6, Most current SK result

1, Solar Neutrino Oscillation

Solar Neutrino

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

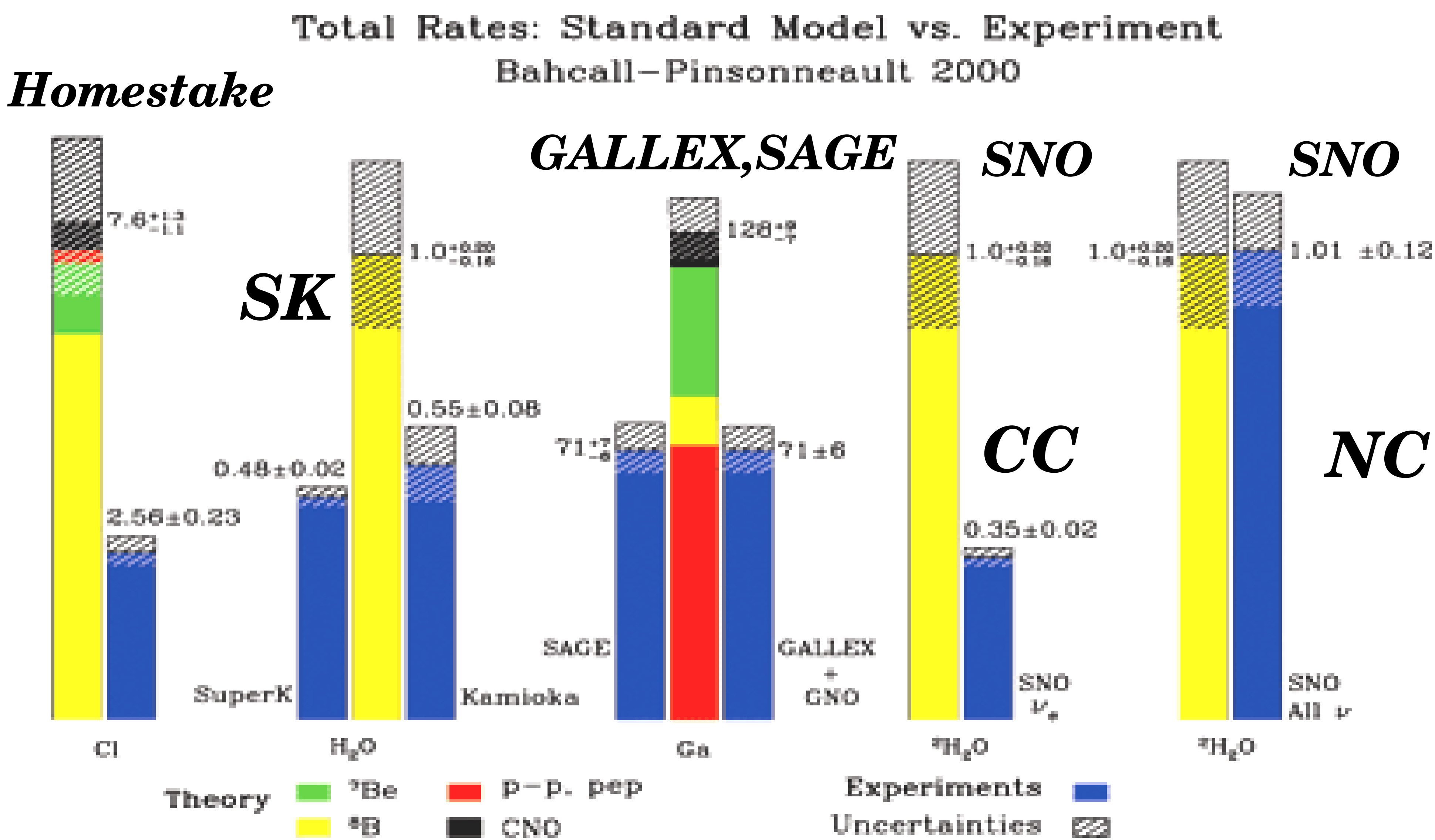
Standard Solar Model(SSM)



Solar Neutrino Expriments	Target
Homestake (1968, USA)	Cl
Kamiokande (1987, Japan)	Water
GALLEX,GNO (1991, Italy,Germany)	Ga
SAGE (1990, Russia)	Ga
Super-K (1996, Japan)	Water
SNO (1999, Canada)	D2O

Solar Neutrino Problem : Data/SSM

Observed solar neutrino flux/Expected flux from solar < 1.0

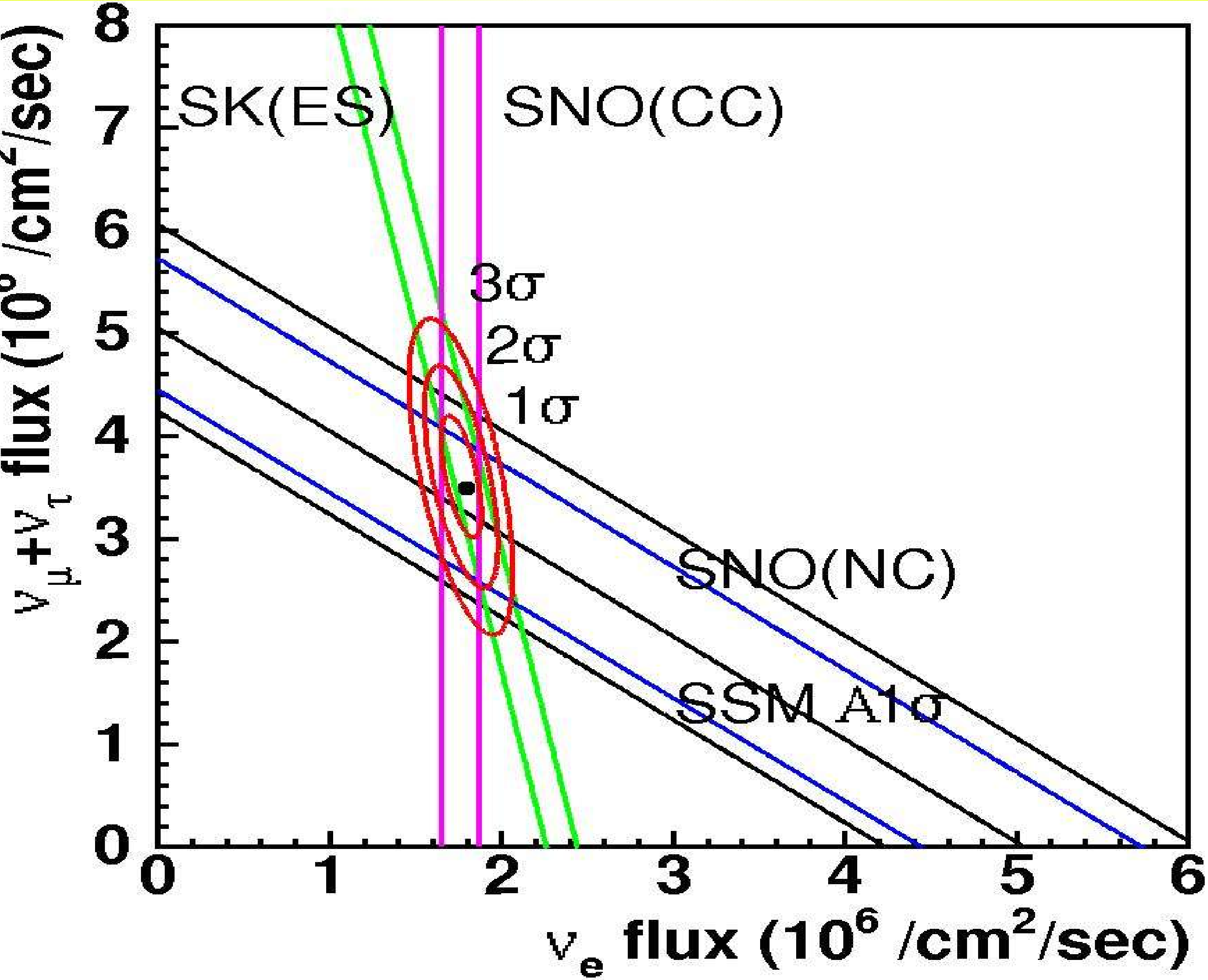


http://www.sns.ias.edu/~jnb

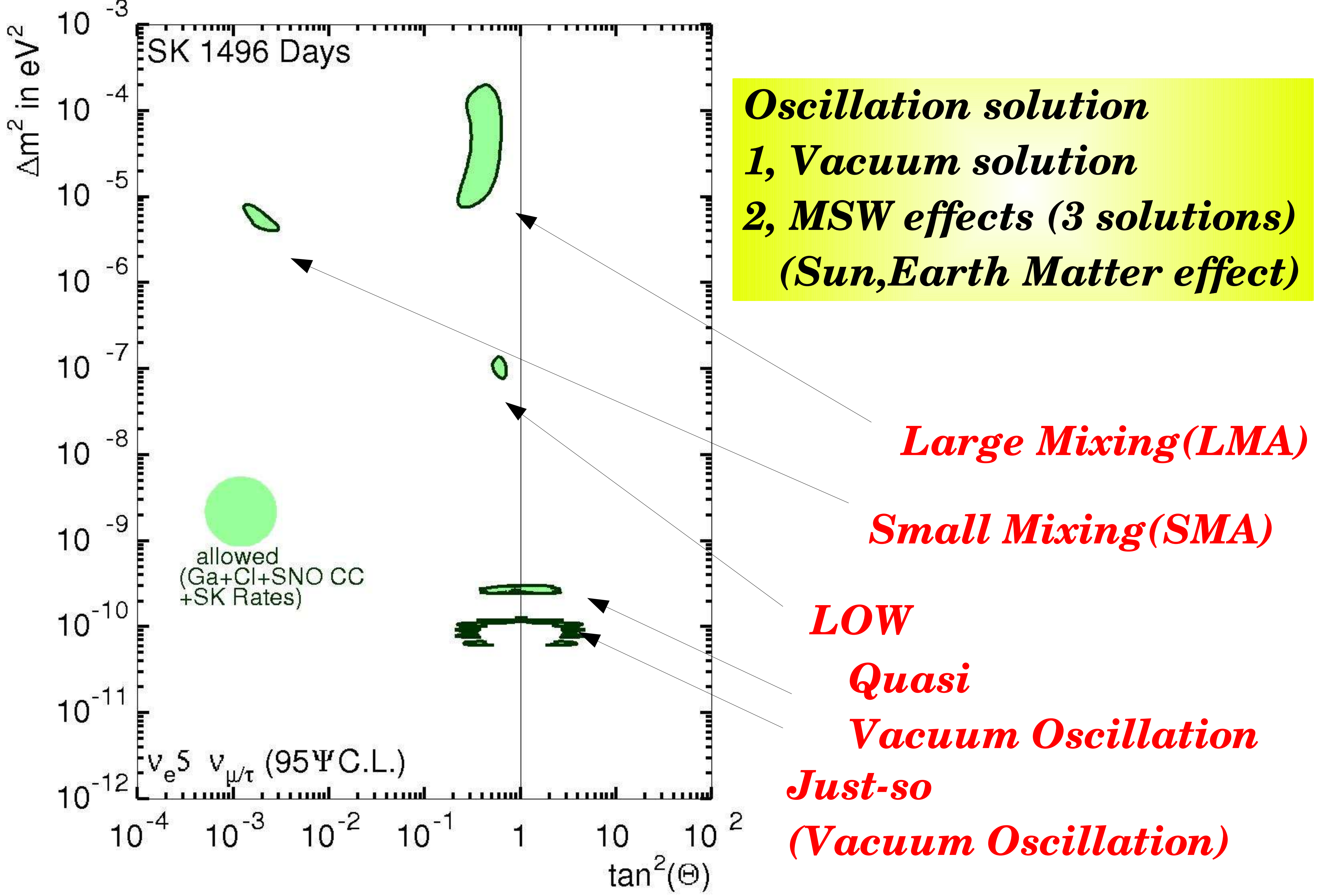
The evidence of solar neutrino oscillation

Flux(neutrino another flavor) = Flux(SK,ES) -Flux(SNO,CC)

= 0.73±0.17 $10^6\,cm^{-2}\,s^{-1}$



Oscillation parameters based on flux from Ga,Cl,SK,SNO(CC)



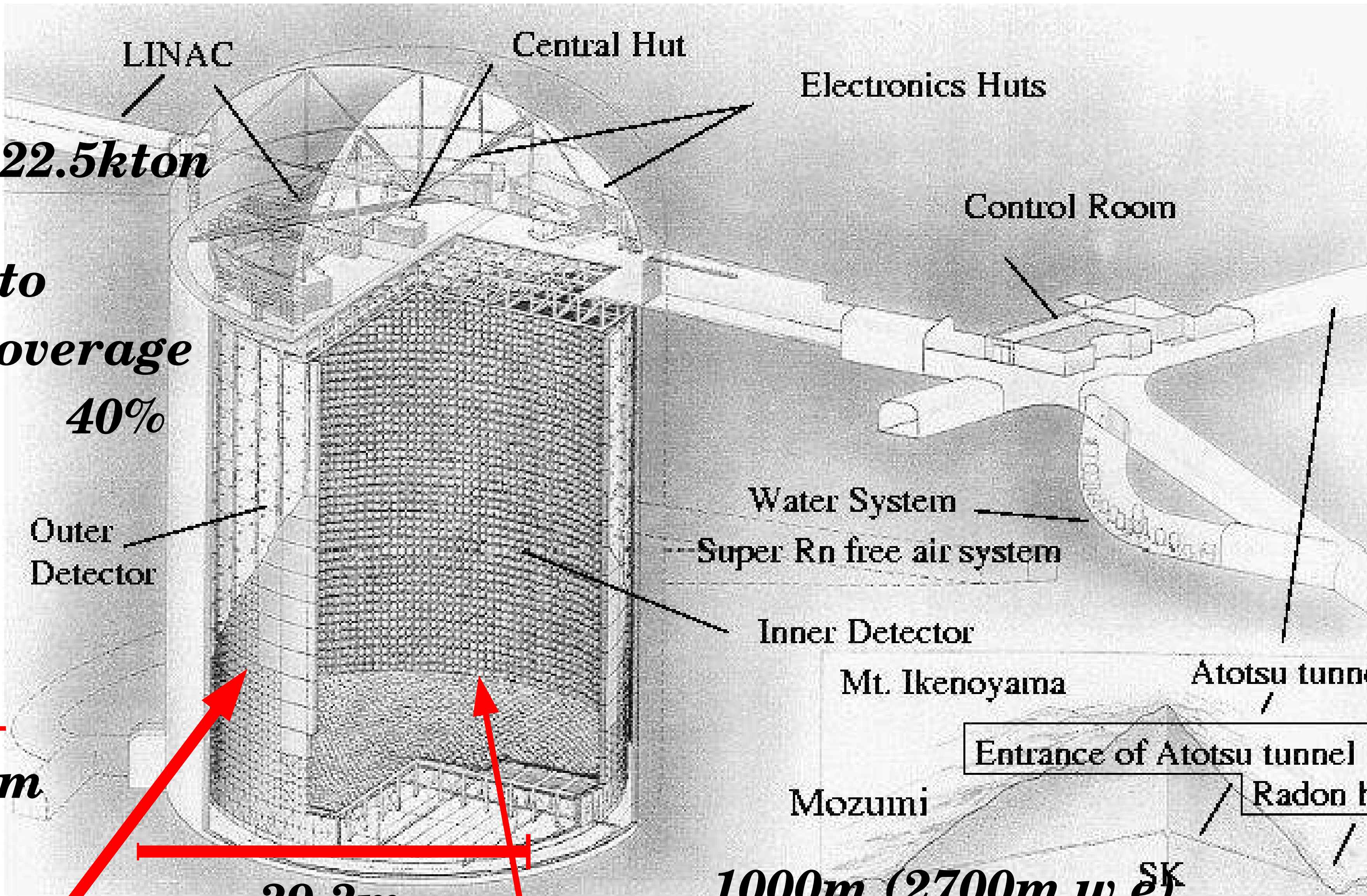
Oscillation solution

1, Vacuum solution

2, MSW effects (3 solutions)

(Sun,Earth Matter effect)

2,Super-Kamiokande detector



F.V 22.5kton

Photo coverage 40%

41.4m

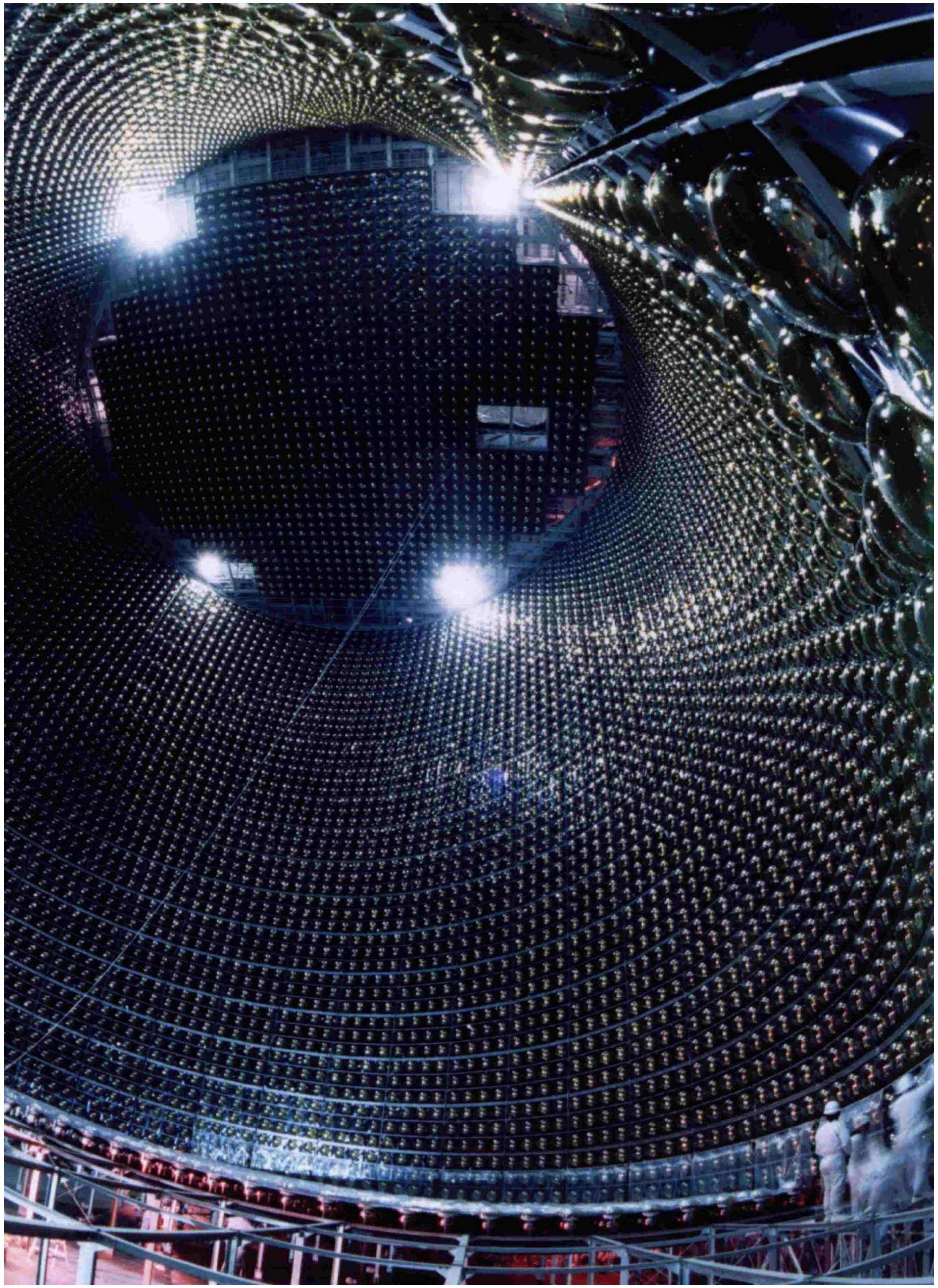
39.3m

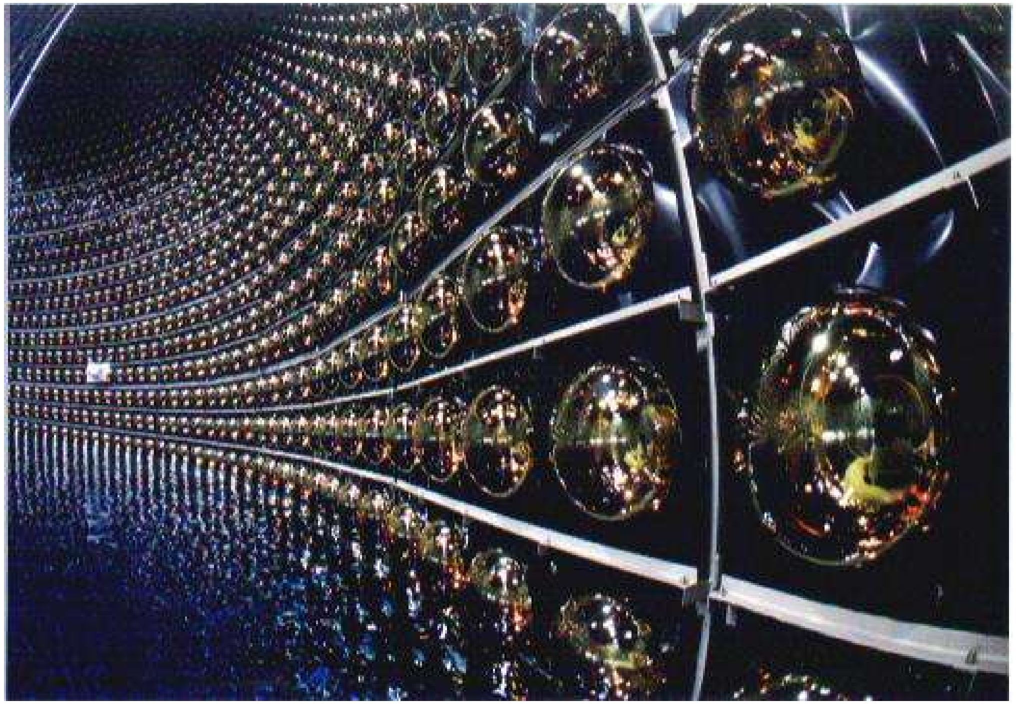
1000m (2700m w.e)

Outer Detector 1867 of 8 inch PMTs

Inner Detector 11146 of 20 inch PMTs

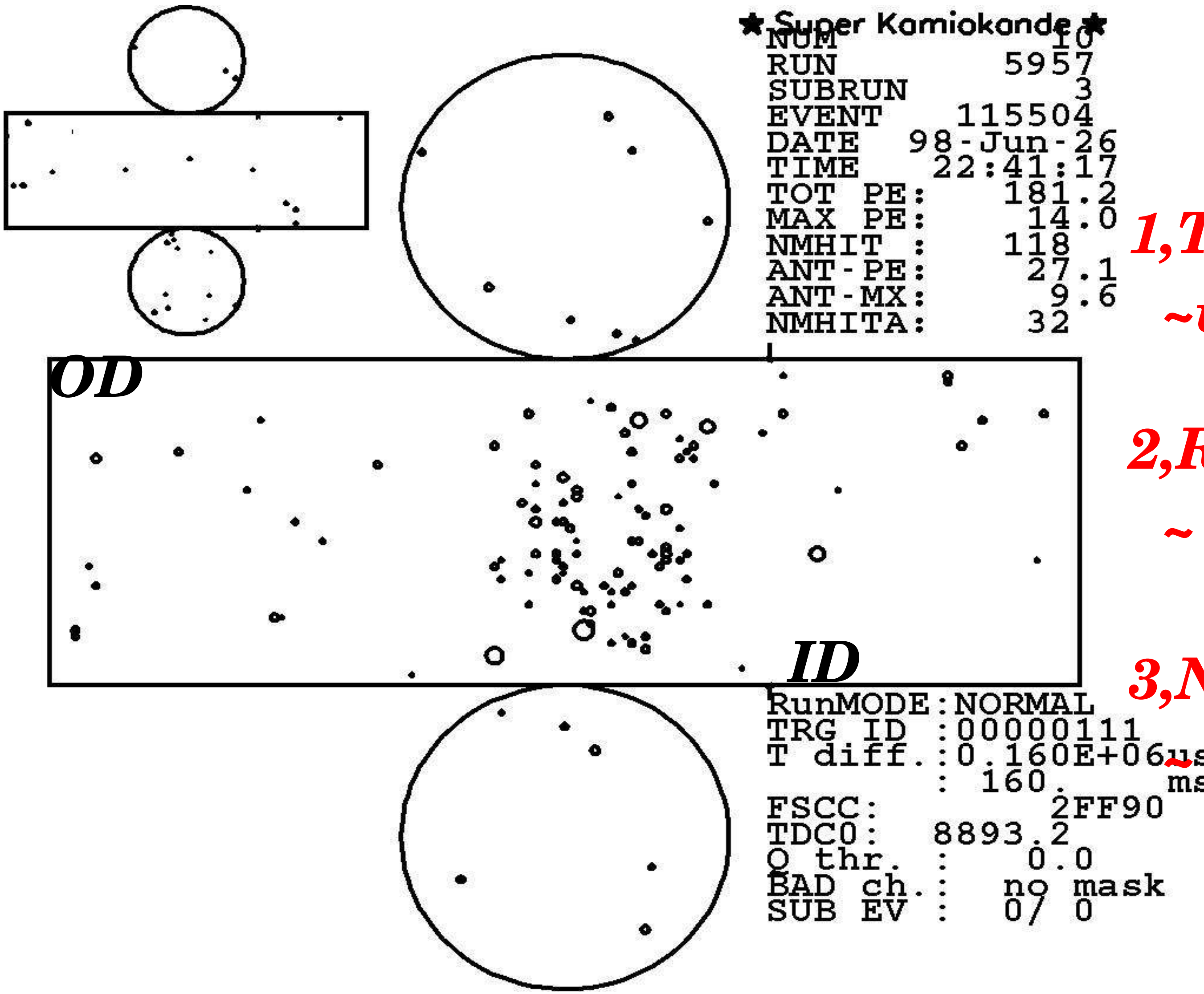
The overview of SK detector





Typical low energy event

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



10 MeV

~ about 60 hits

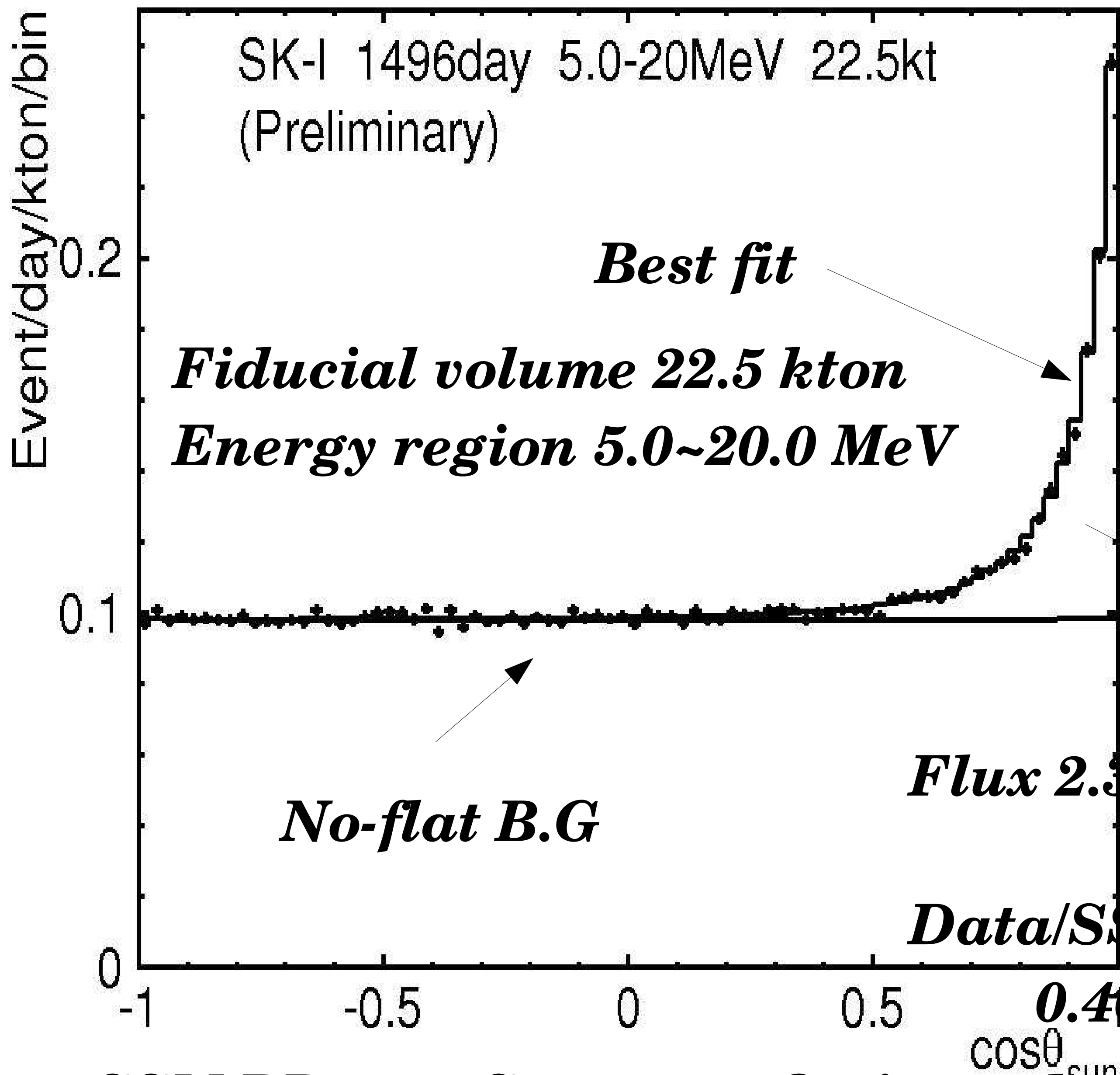
1,Timing information
~vertex position

2,Ring pattern
~ direction information

3,Number of hit PMTs
~energy information

Results from Super-Kamiokande-I

1996/5/31 ~2001/7/15 1496 days (D: 733,N:763 days)

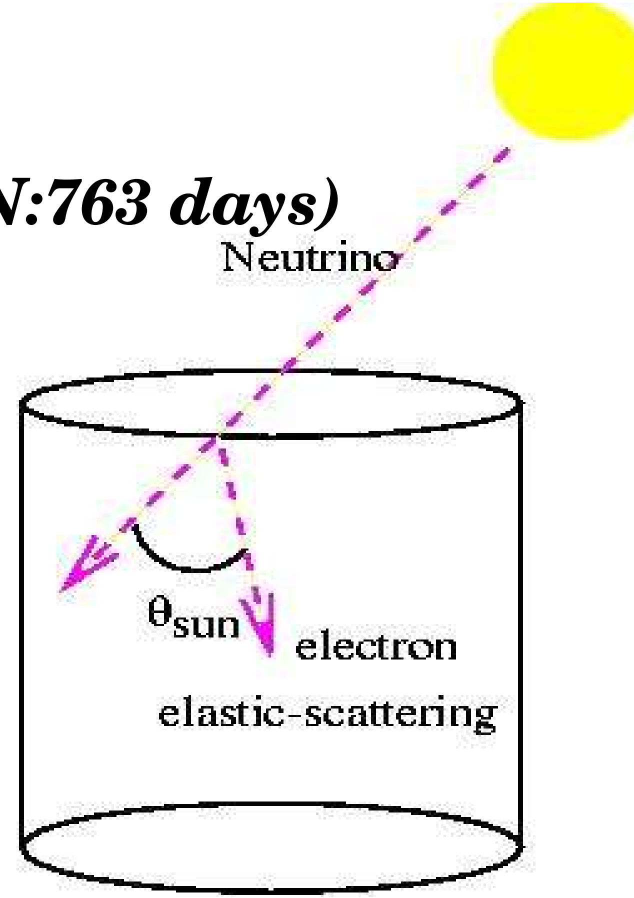


Best fit

Fiducial volume 22.5 kton

Energy region 5.0~20.0 MeV

No-flat B.G



22385±226 events

Exp. 48173 events

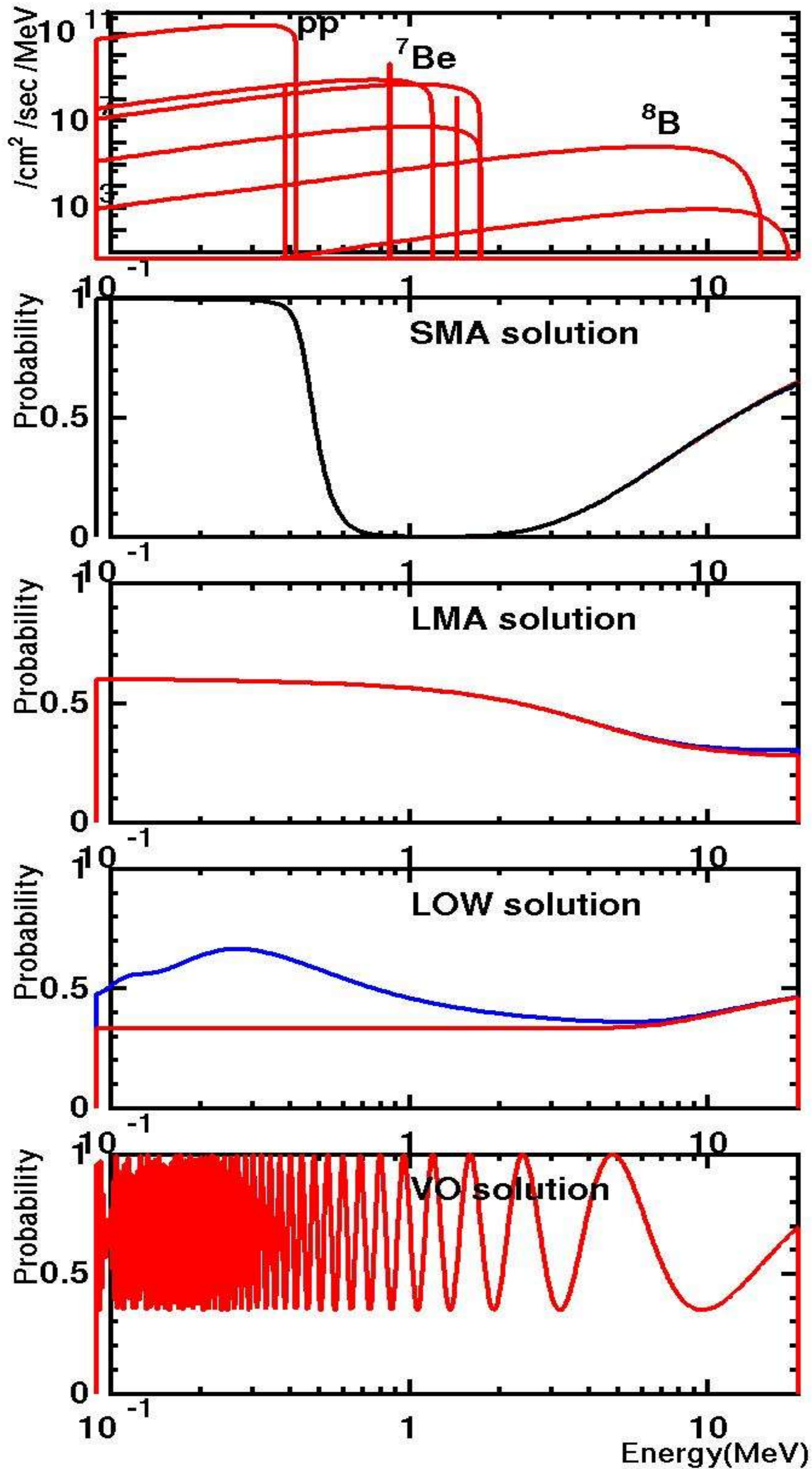
Flux 2.35±0.02(sta.)±0.08(sys.) $(1.0\times10^{6}\,cm^{-2}s^{-1})$

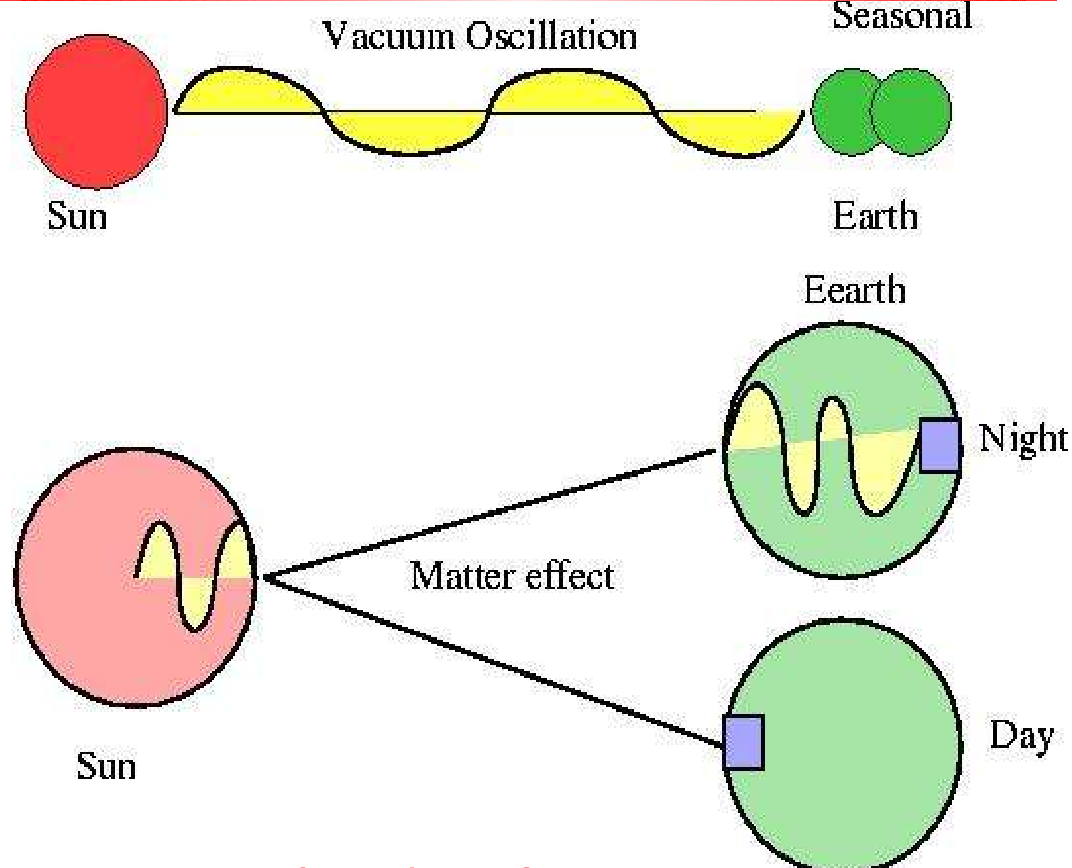
Data/SSM

0.465±0.005(sta.)±0.016(sys.)

SSM:BP2000 Spectrum Ortiz et al. $5.05\times10^{6}\,cm^{-2}s^{-1}$

Flux(SSM) independent analysis





1,For SMA,LOW,Vacuum

Energy Spectrum distortion

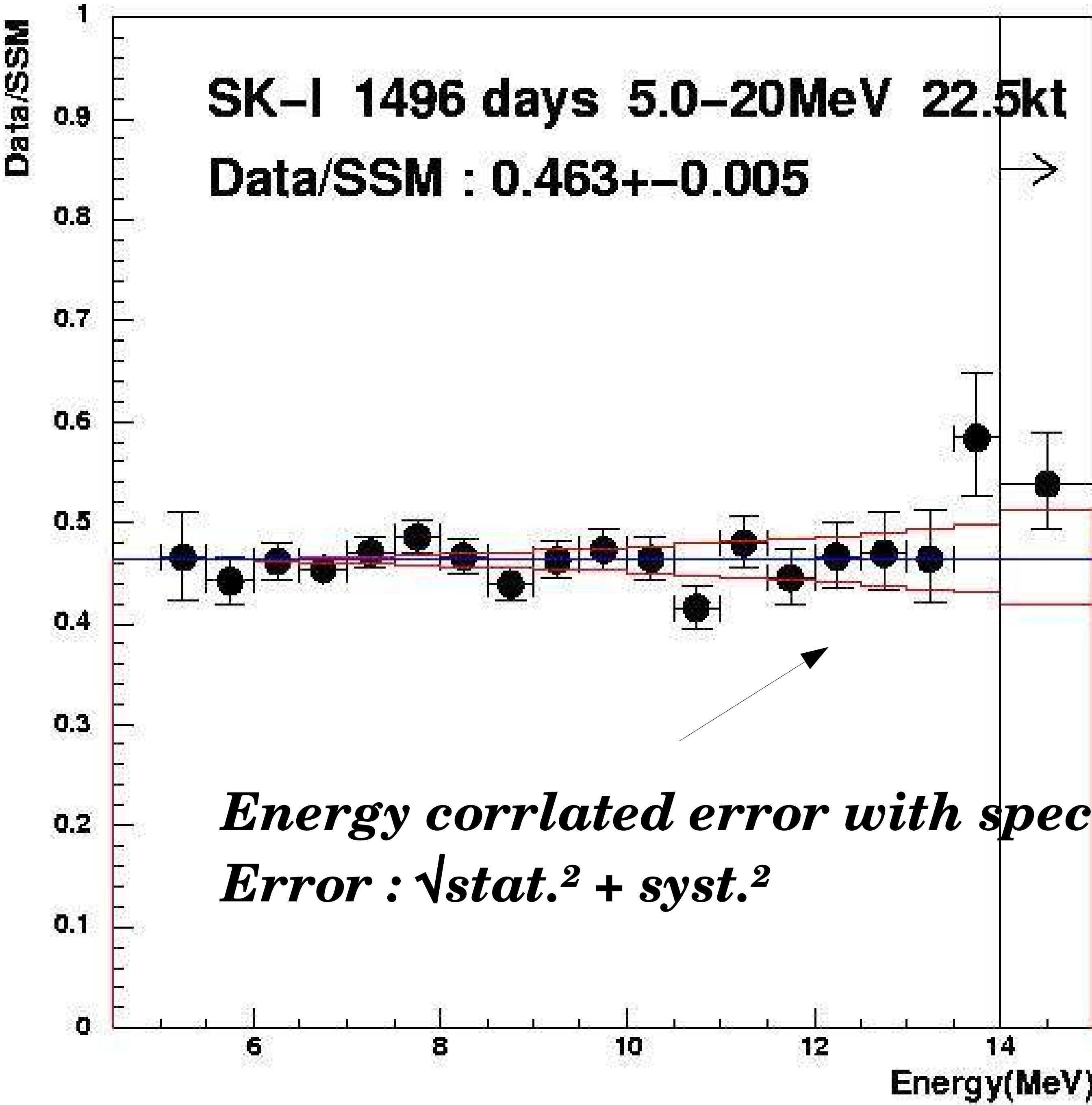
2,For LMA

Day/Night flux difference

3,For Vacuum

Seasonal variation

Energy spectrum analysis



Is there distortion ?

χ^2 for flat

17.4/19-1 d.o.f 50% C.L

Energy corrlated error with spectrum

Error : $\sqrt{stat.^2 + syst.^2}$

Physical Motivation for 4.5 MeV

Analysis threshold of low energy is 5.0 MeV in SK-I.

This energy threshold is limited by Rn background
,external gamma rays and mis-fitting events.

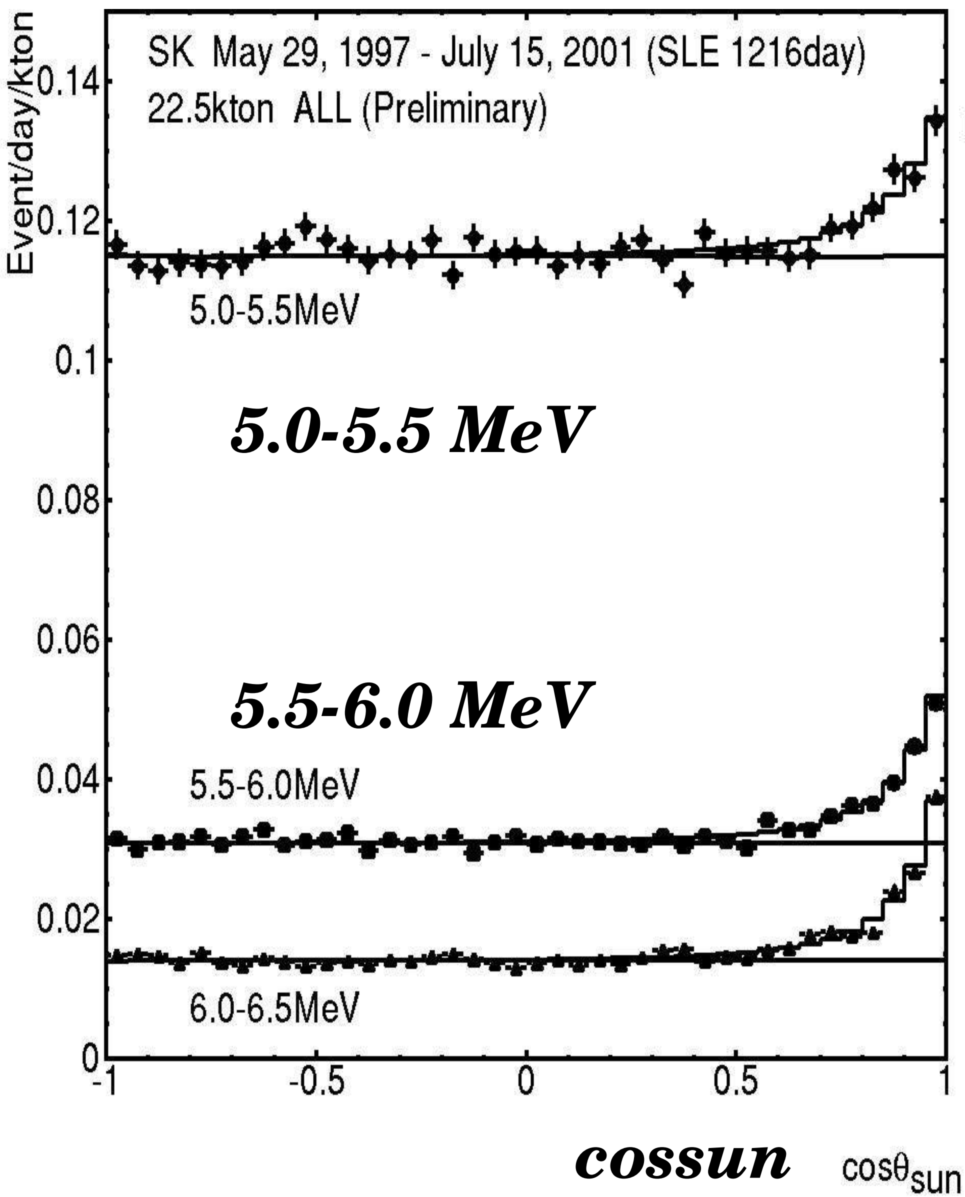
We want to look energy spectrum of lower energy bin
to inspect the energy distortion widely.

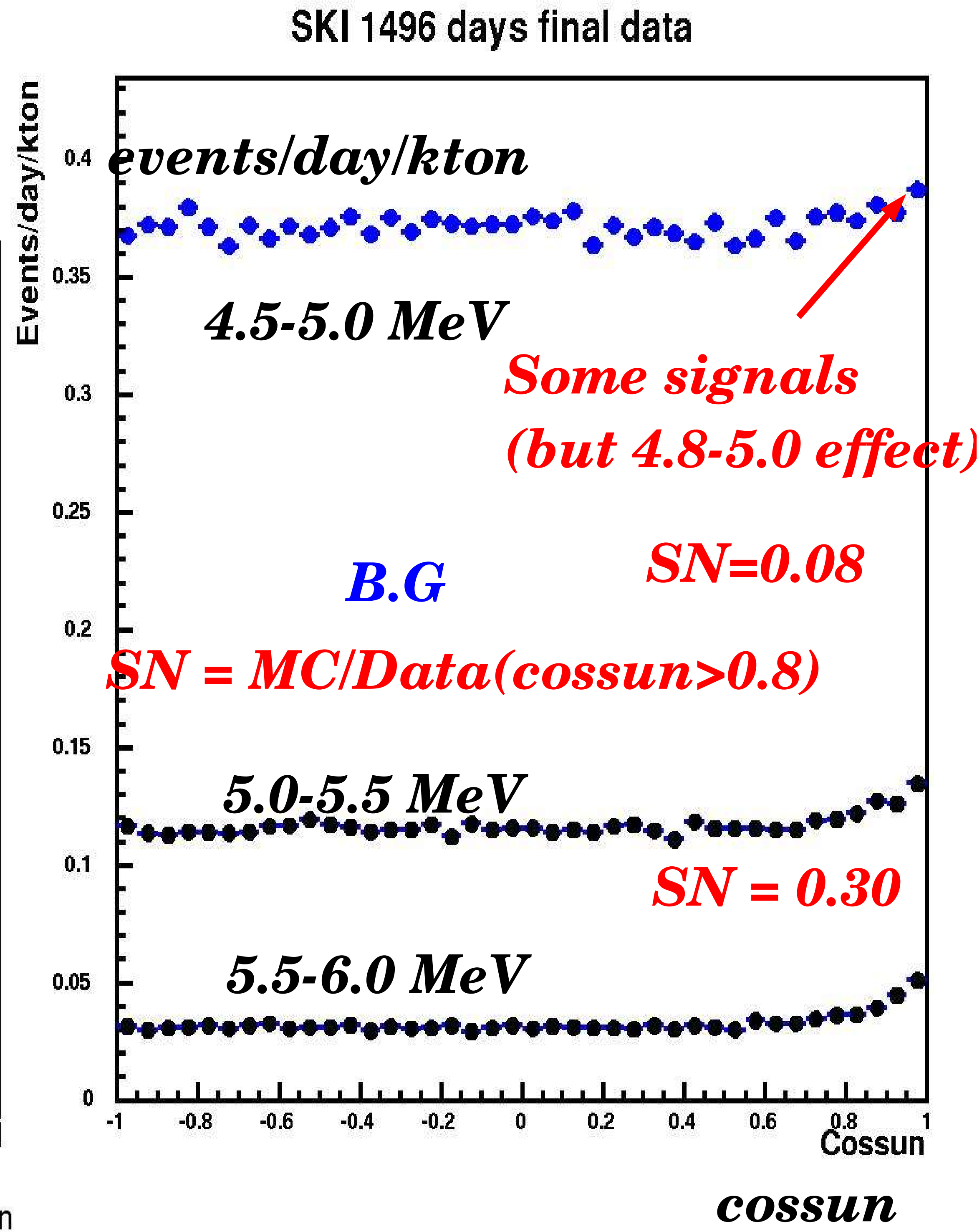
1, Can we see energy spectrum distortion by matter effect
in low energy region?
2, How much does 4.5 MeV energy bin have constrain
for solar neutrino oscillation analysis?
3, How much power does SK detector have
for energy spectrum analysis?

SK-I data overview

Solar direction distribution

events/day/kton





The main source of the Background in low energy

The main source of the background is Radon……

In the mine, there is no another candidate.

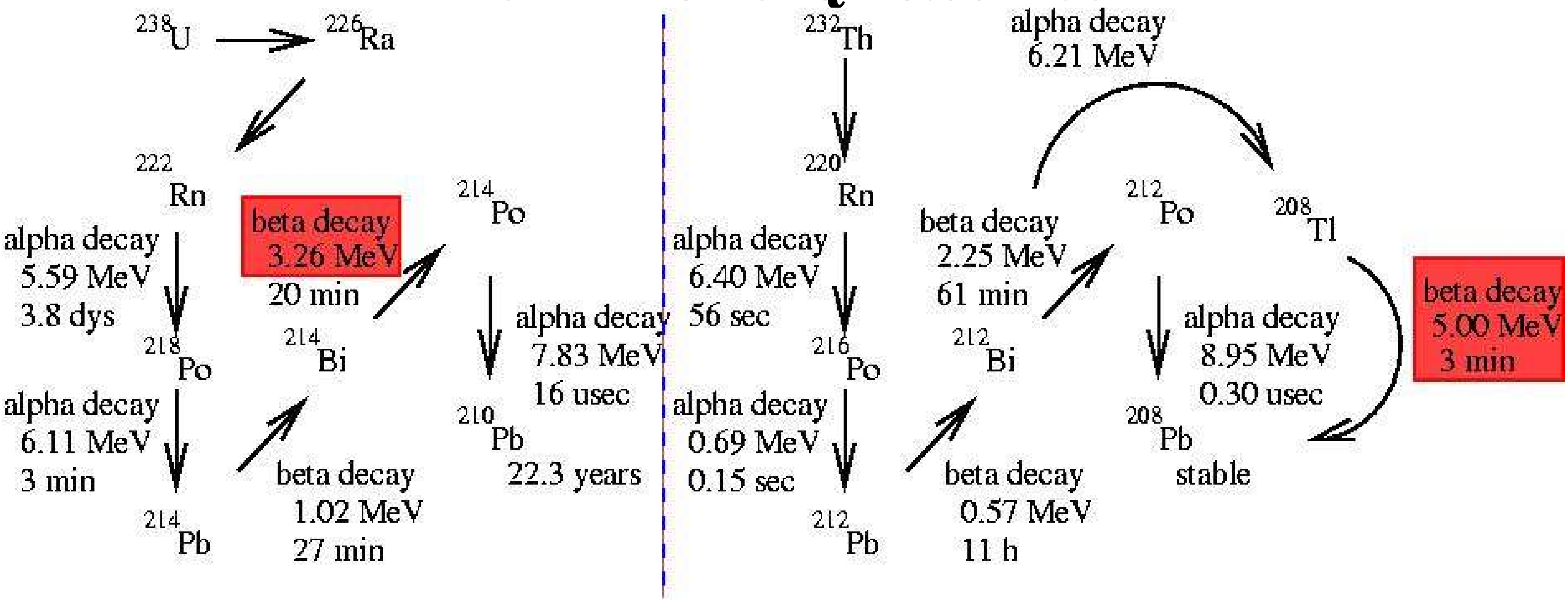
1, Rn from the mine air dissolves into water

2, Rn from Ra in the mine water

3, Rn emanated from material used in SK tank

$$^{214}Bi \rightarrow {}^{214}Po + e^- \quad Q = 3.26\ MeV$$

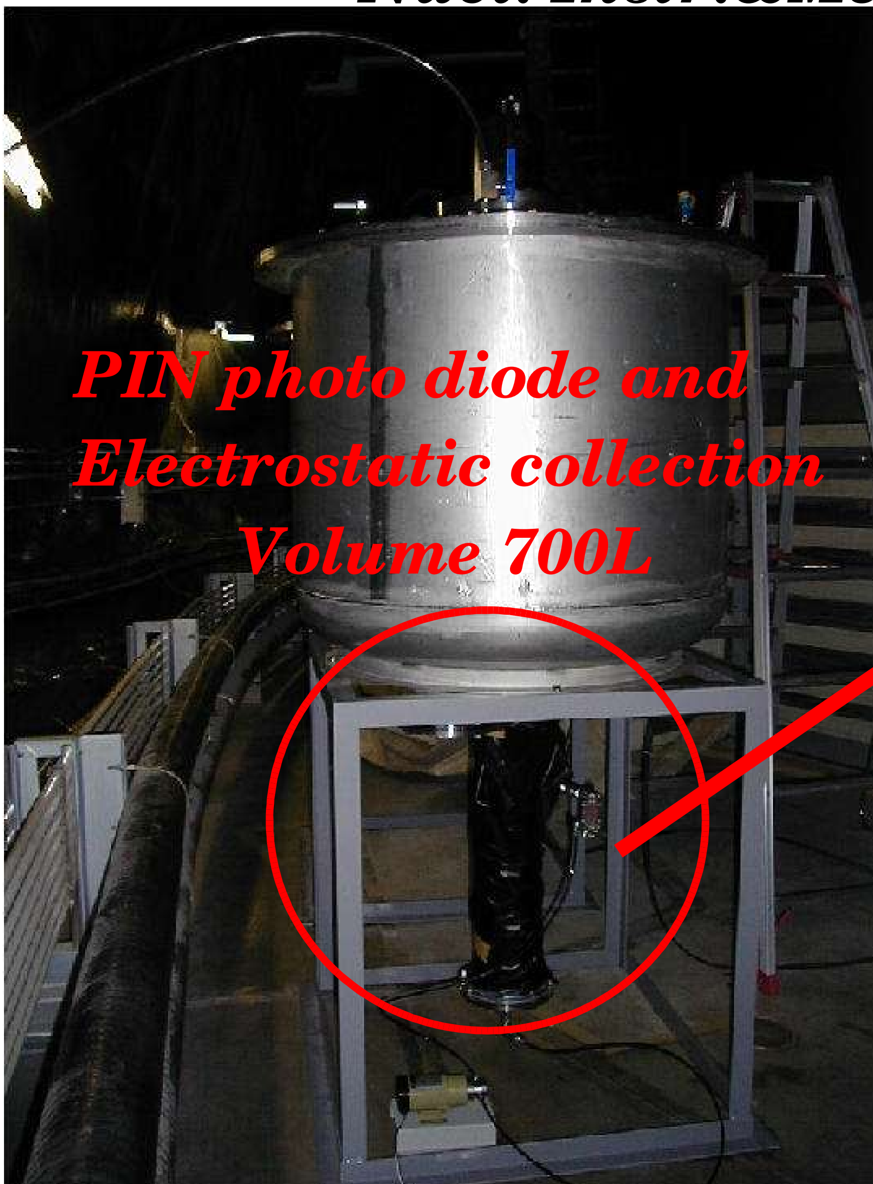
$$^{208}Tl \rightarrow {}^{208}Pb + e^- \quad Q = 5.00\ MeV$$

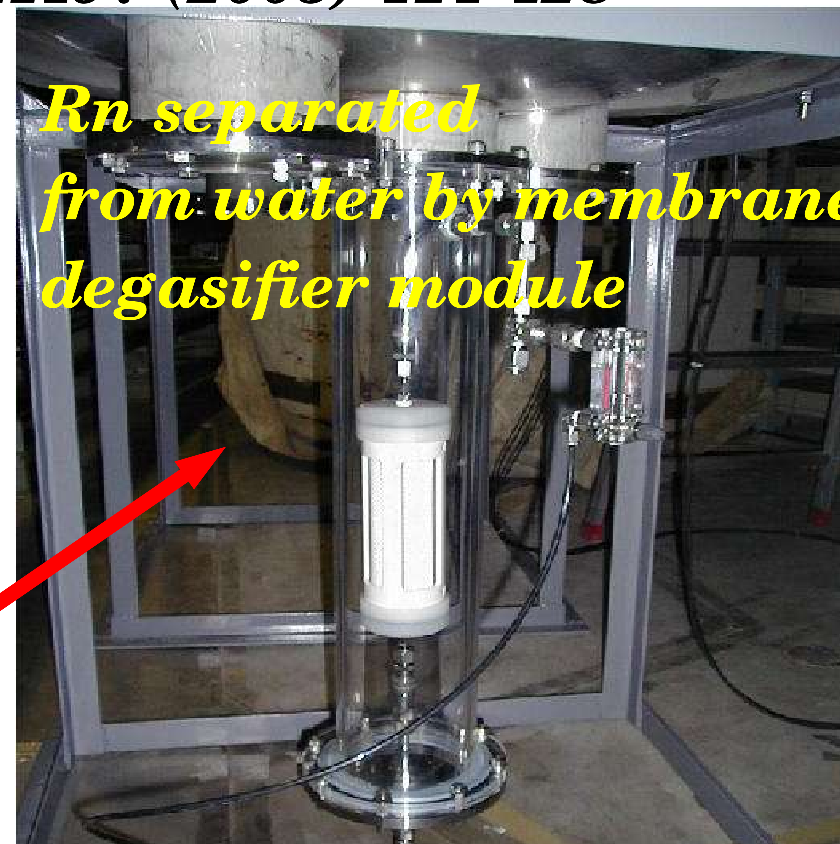


Radon reduction approach I

We need to obtain the absolute value of radon in water.
The super-high sensitivity radon detector was developed.

Nucl. Instr.&Meth A497 (2003) 414-428





Detection limit
0.7 mBq/m³/day in real-time
SK supply water
~6.5 mBq/m³ in 1999

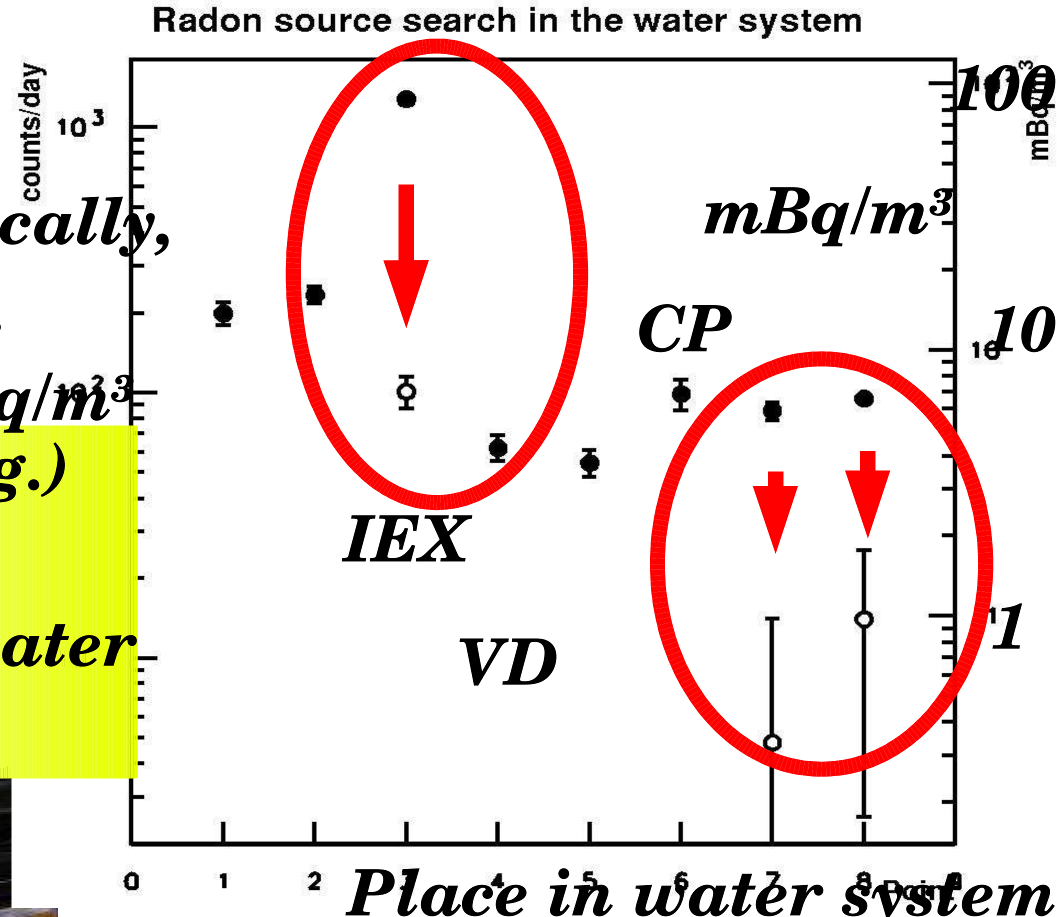
Radon reduction approach II

To reduce radon in water physically, the water system was improved.

In 1999, supply water : 6.5 mBq/m³

1.Radon source search (right fig.)

Radon source point was found then, improved, The radon in water reduced down to 1.0mBq/m³



2.New radon reduction system

Membrane degasifier module can reduce radon which already dgasified by -90%.

Thus, radon in supply water

＜ 0.7 mBq/m³

expected e.r = 1.2×10^-4 e/d

Approach to the lower energy threshold of 4.5 MeV

With the approach of physically radon reduction,
We tried to analysis 4.5 MeV from the aspect of soft-ware
in SK－I data(1996.5.31-2001.7.15)

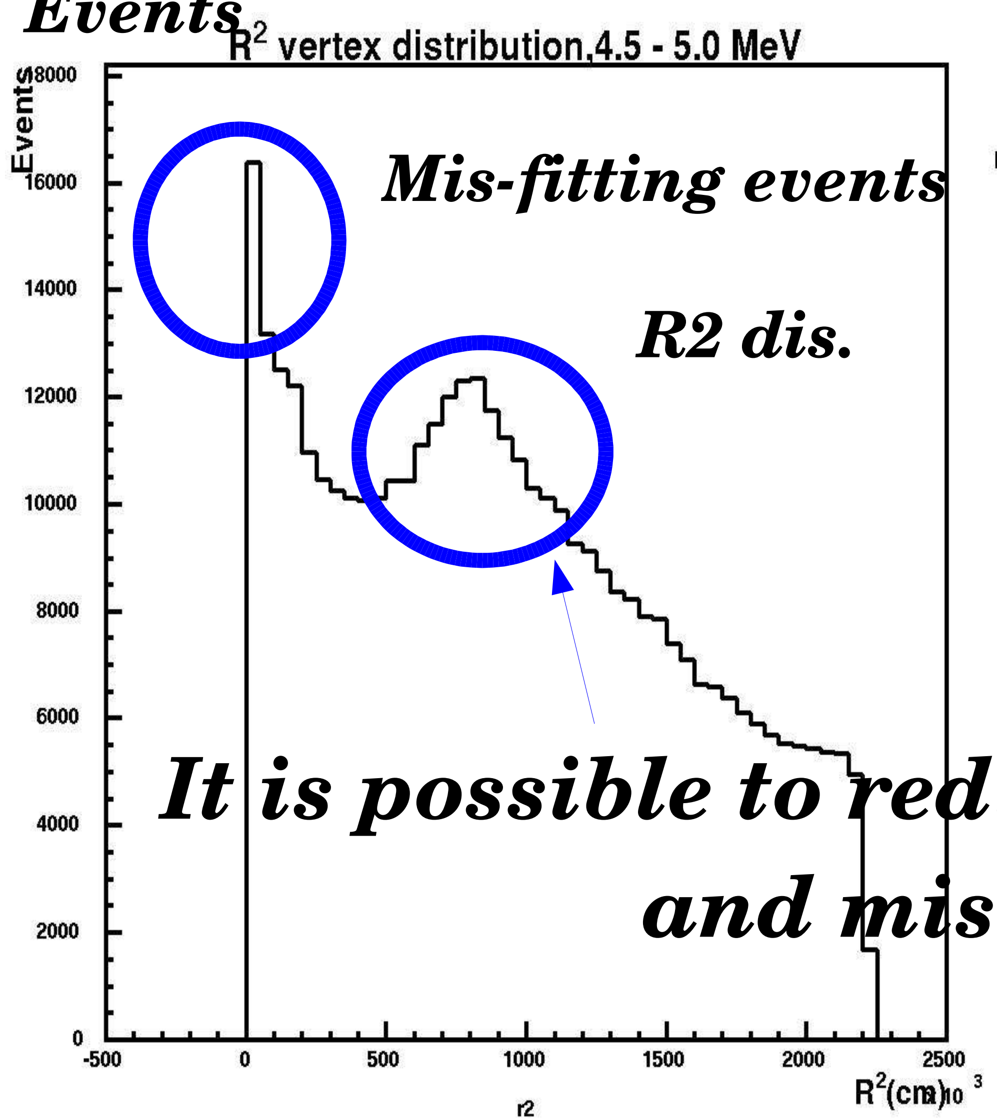
To observe the 4.5 MeV bin,
Remove Radon high rate run
Improve the reduction method
Develop the new event-reconstruction tool
We applied various reduction optimized to 4.5 MeV data
by blind analysis.

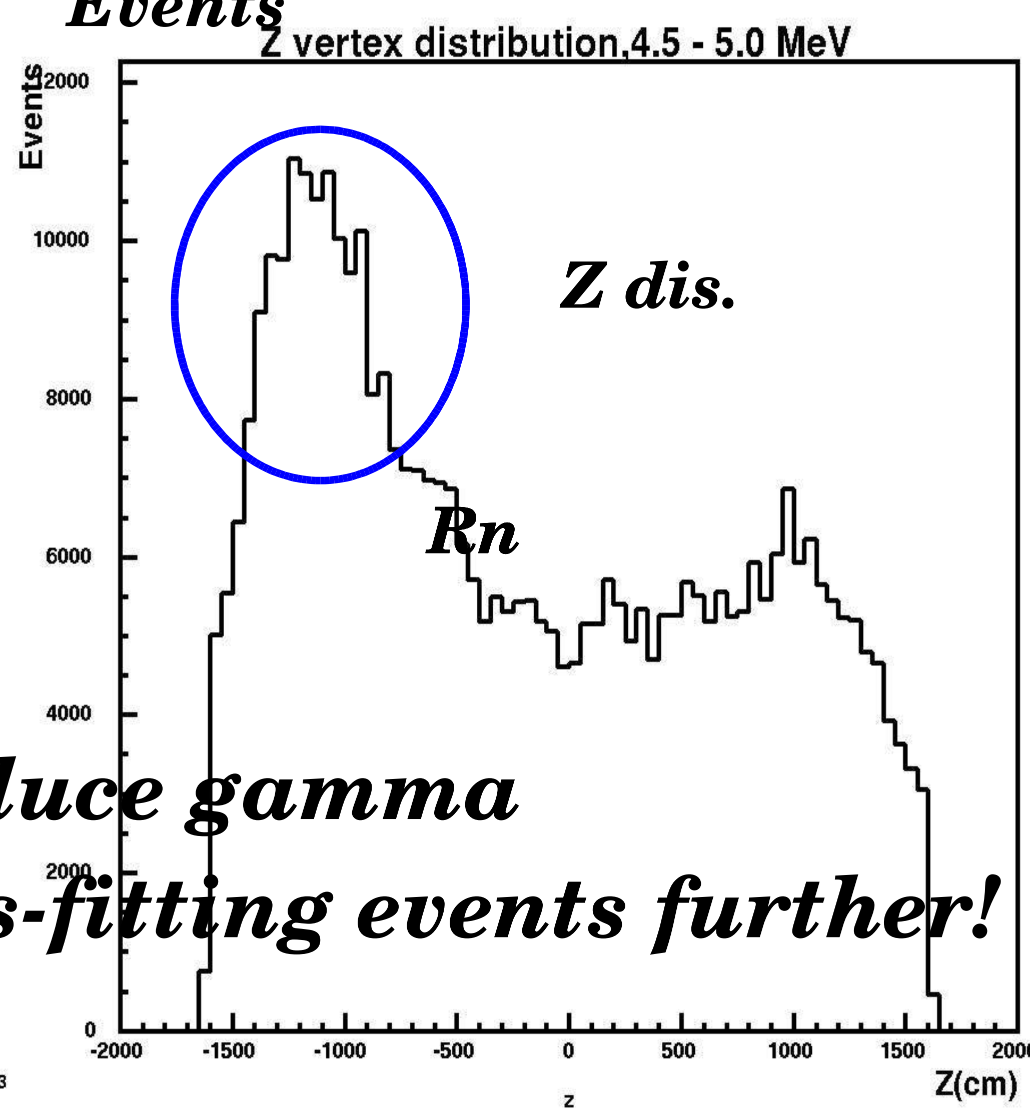
Data set : Trigger efficiency in 4.5 MeV > 95% 566 days
Sep. 17 1999 ~ Jul. 15 2001
Radon high rate run rejection 511 days
* SK-I full data is 1496 days

As a results, we succeeded in observing the neutrino flux
from 4.5 to 5.0 MeV in this time.

3, The data set for 4.5 MeV analysis

R2 Z distribution for 4.5-5.0 MeV (SK-I final sample)

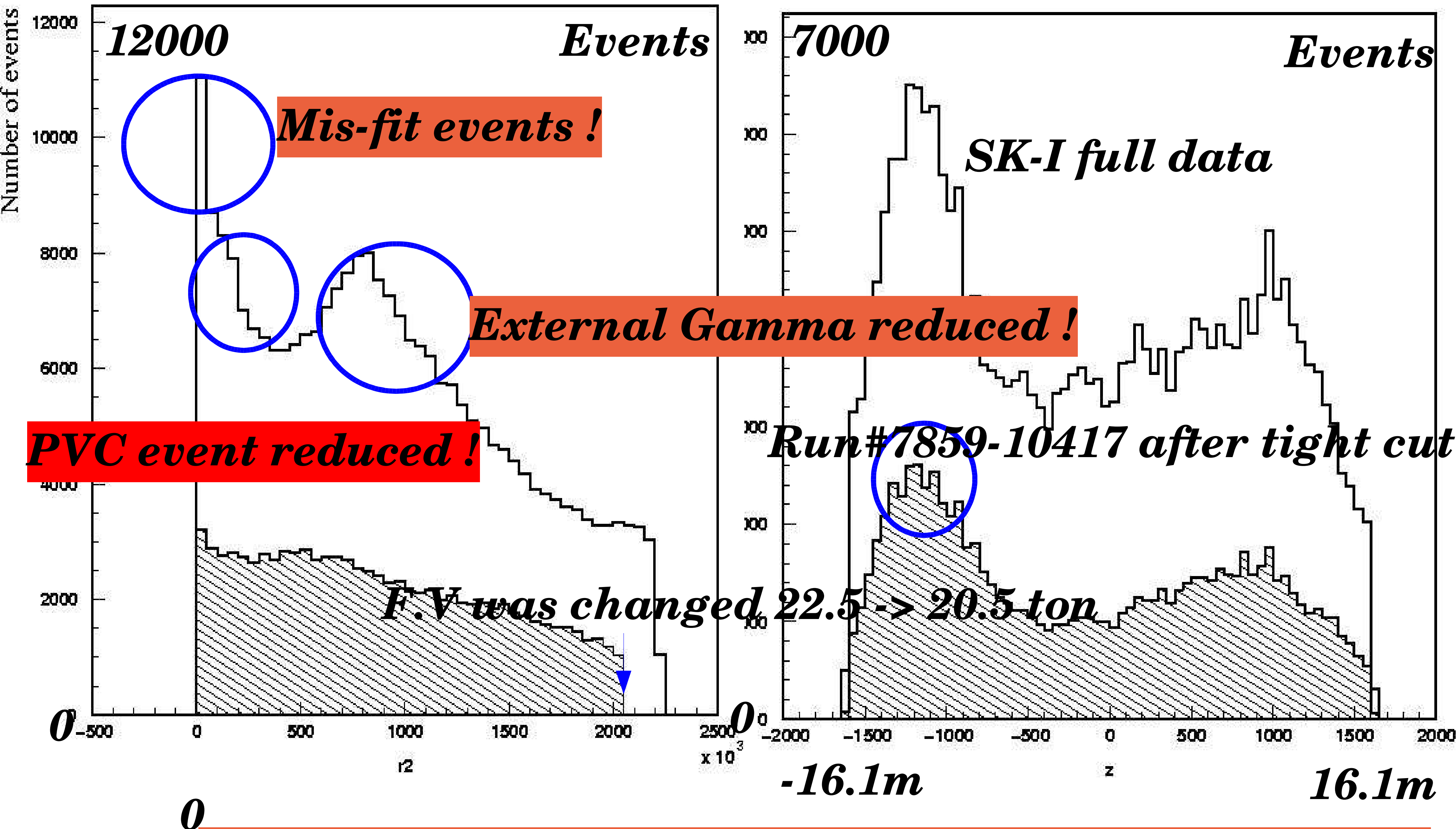




It is possible to reduce gamma and mis-fitting events further!

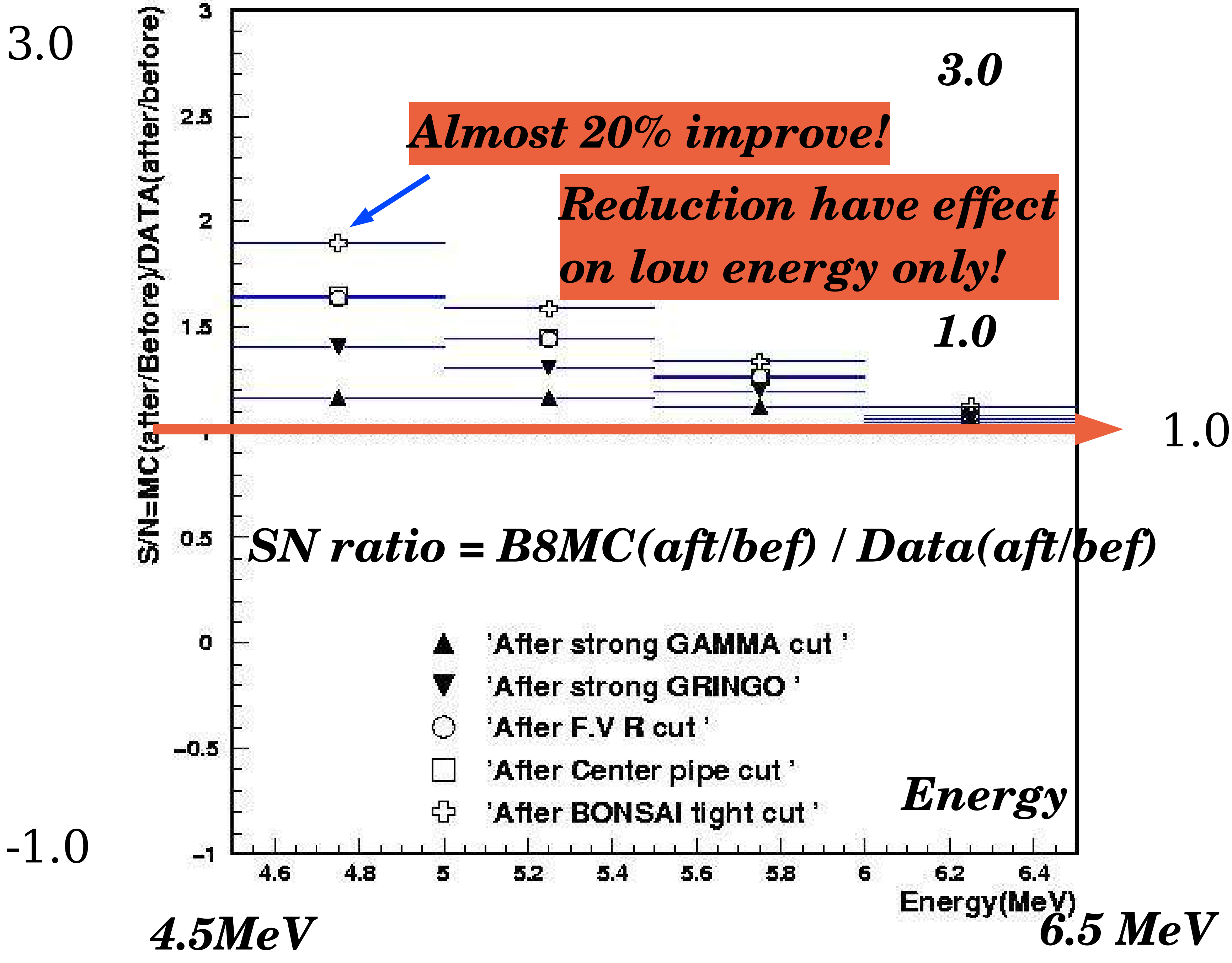
R2 and Z Vertex distribution after new reduction

4.5-5.0MeV F.V 20.5 kton



If we assume mirror B.G of top, remaining Rn is little !

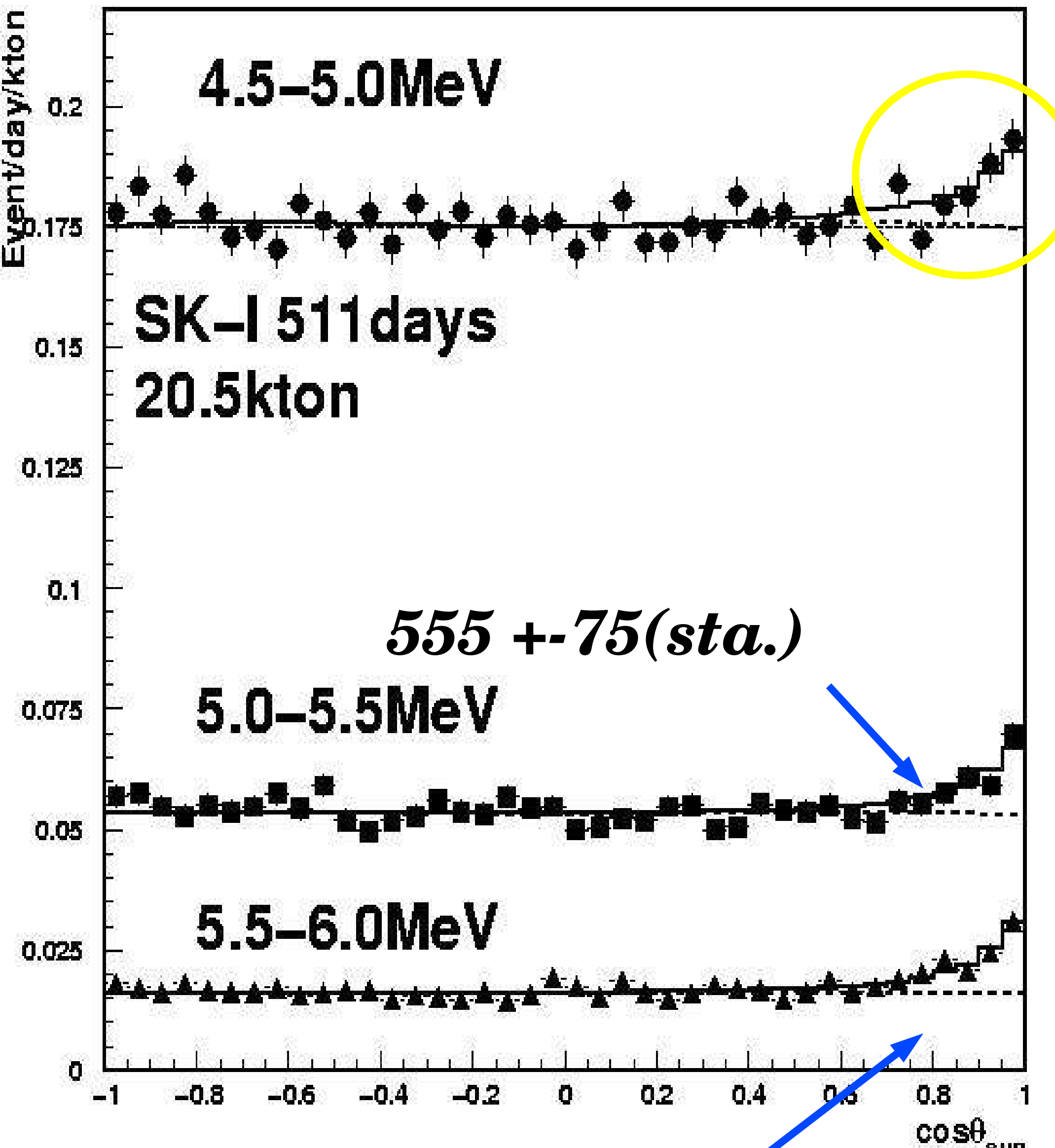
Energy spectrum of SN ration in each reduction step



Angular distribution

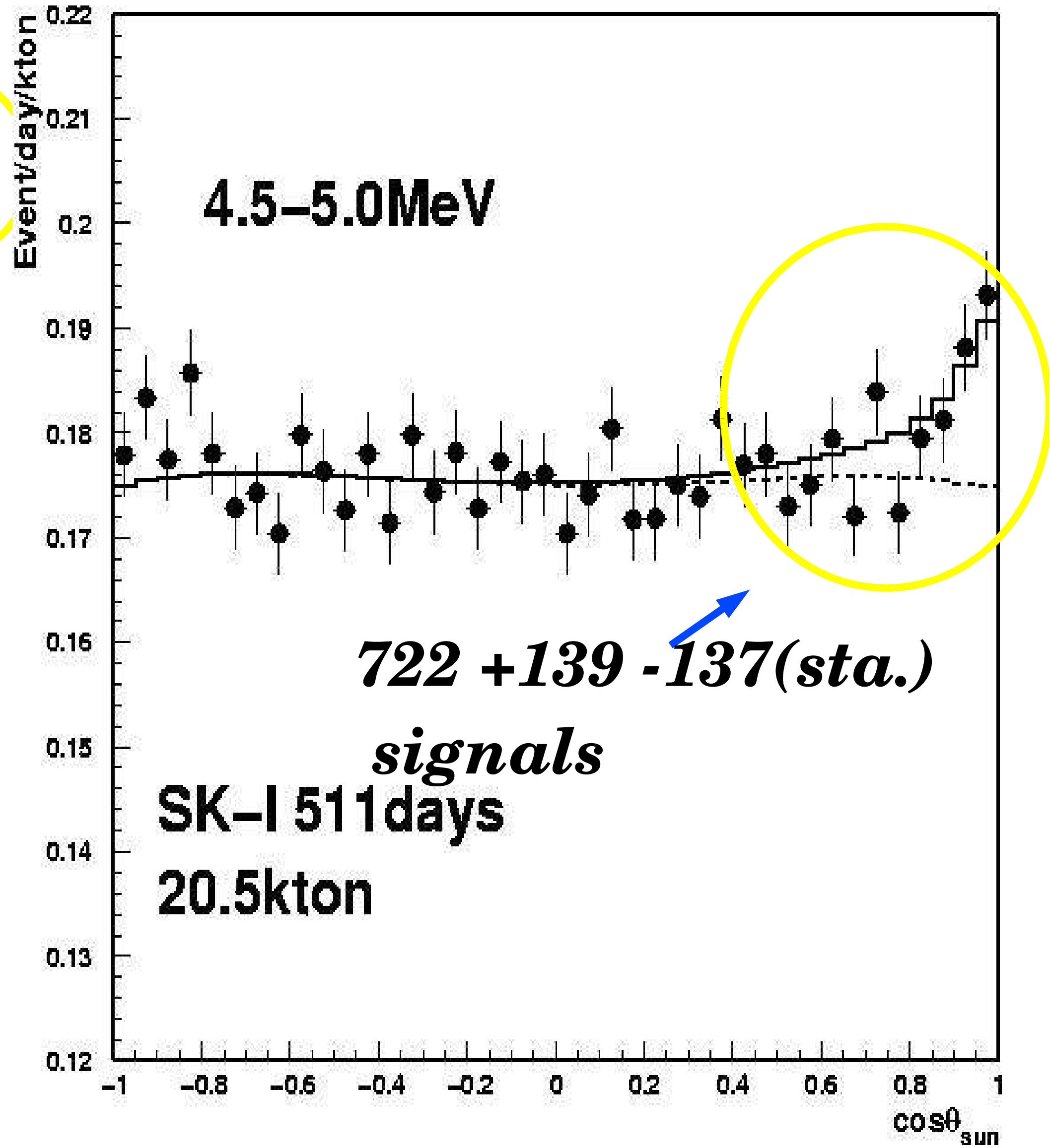
events/day/kton

4.5 MeV Clear Peak!



554 +-46(sta.)

$\cos\theta_{sun}$



$\cos\theta_{sun}$

Flux results

4.5 MeV bin

5.9% syst. error

B8 flux(4.5) = 3.28+0.63-0.62 $1.0\times10^{6}/cm^{2}/$

Data/SSM(4.5) = 0.649 + 0.125-0.124

1,511 days 20.5 kton F.V energy 4.5-20.0 MeV

Signal = 5823 +120-119(stat.) events

B8 flux (all) = 2.41 +0.05-0.05(stat.) $1.0\times10^{6}/cm^{2}/$

Data/SSM(all) = 0.477 + 0.01-0.01(stat.)

New data

+5.8-5.3% syst. error

2,566 days 22.5 kton F.V w/o tight cut energy 5.0-20.0 MeV

Signal = 8920 +146-145(stat.)

B8 flux (all) = 2.33 +0.04-0.04(stat.)

Data/SSM(all) = 0.462 + 0.008-0.008(stat.)

Same period but w/o tight cut !

3,1496 days 22.5 kton F.V 5.0-20.0 MeV

Signal = 22297+226-225(stat.)

B8 flux (all) = 2.34 +0.02-0.02(stat.)

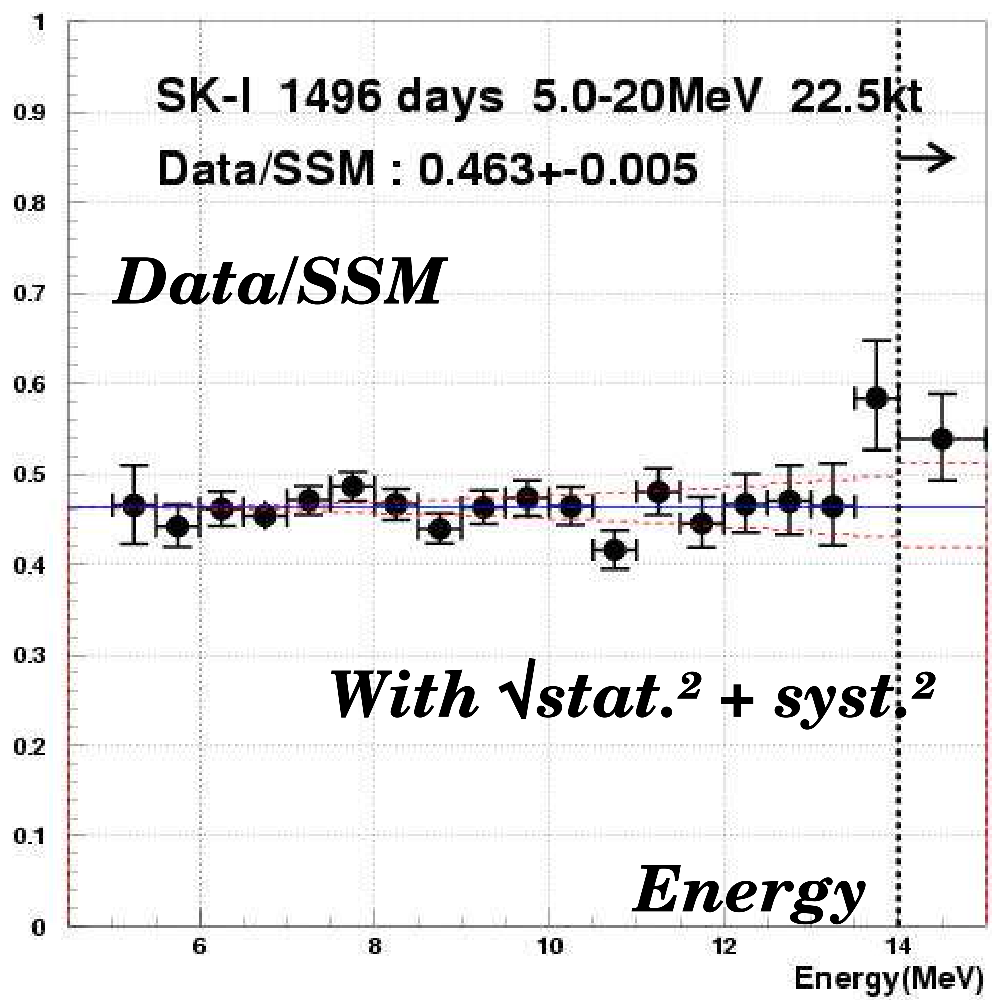
Data/SSM(all) = 0.463 + 0.005-0.005(stat.)

Full data

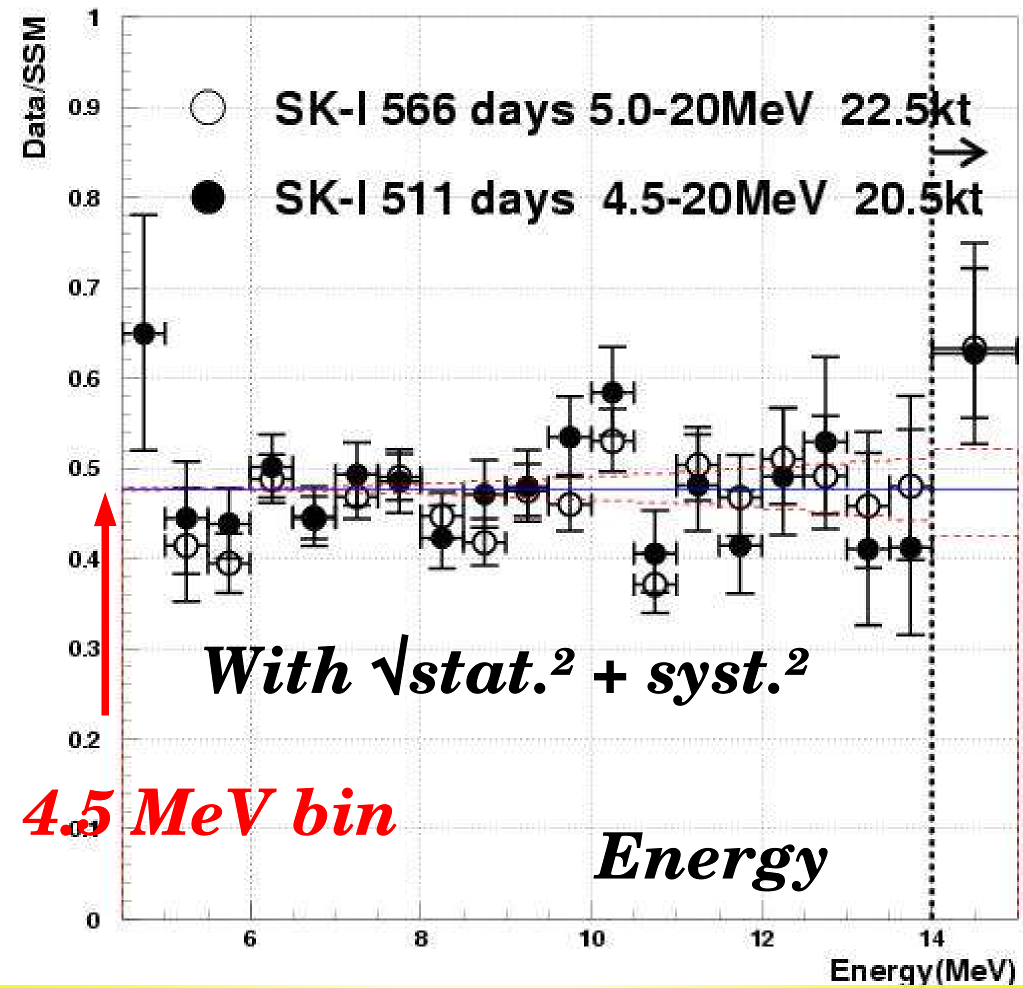
+3.5-3.2% syst. error

Energy spectrum

SK-I full data w/o 4.5 MeV



New data w/ 4.5 MeV



Diff for full data < 1.3 sigma

Diff for 566d data < 1.2 sigma

566 d Chi² for flat : 27.2 C.L 0.07%

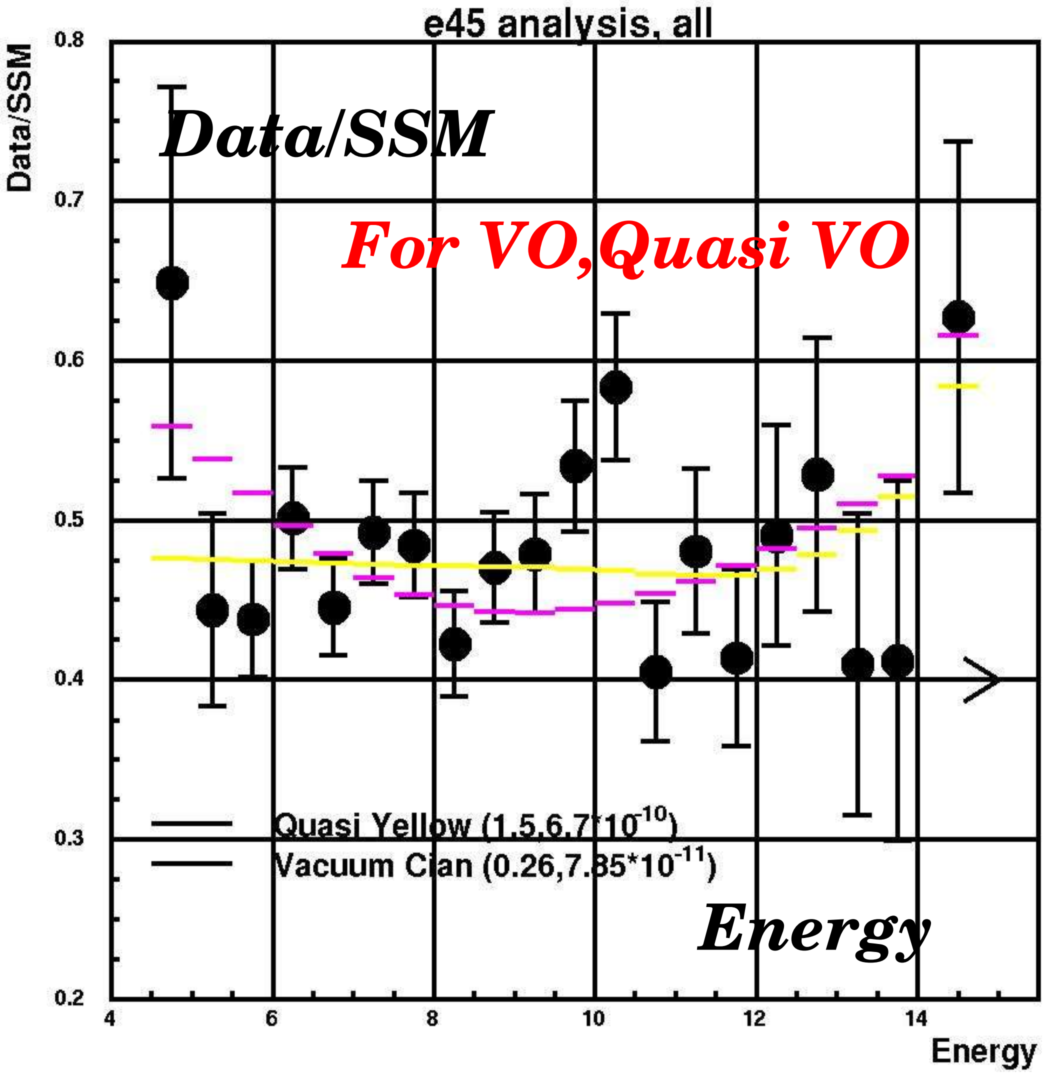
New chi² for flat : 20.1 C.L 38.8%

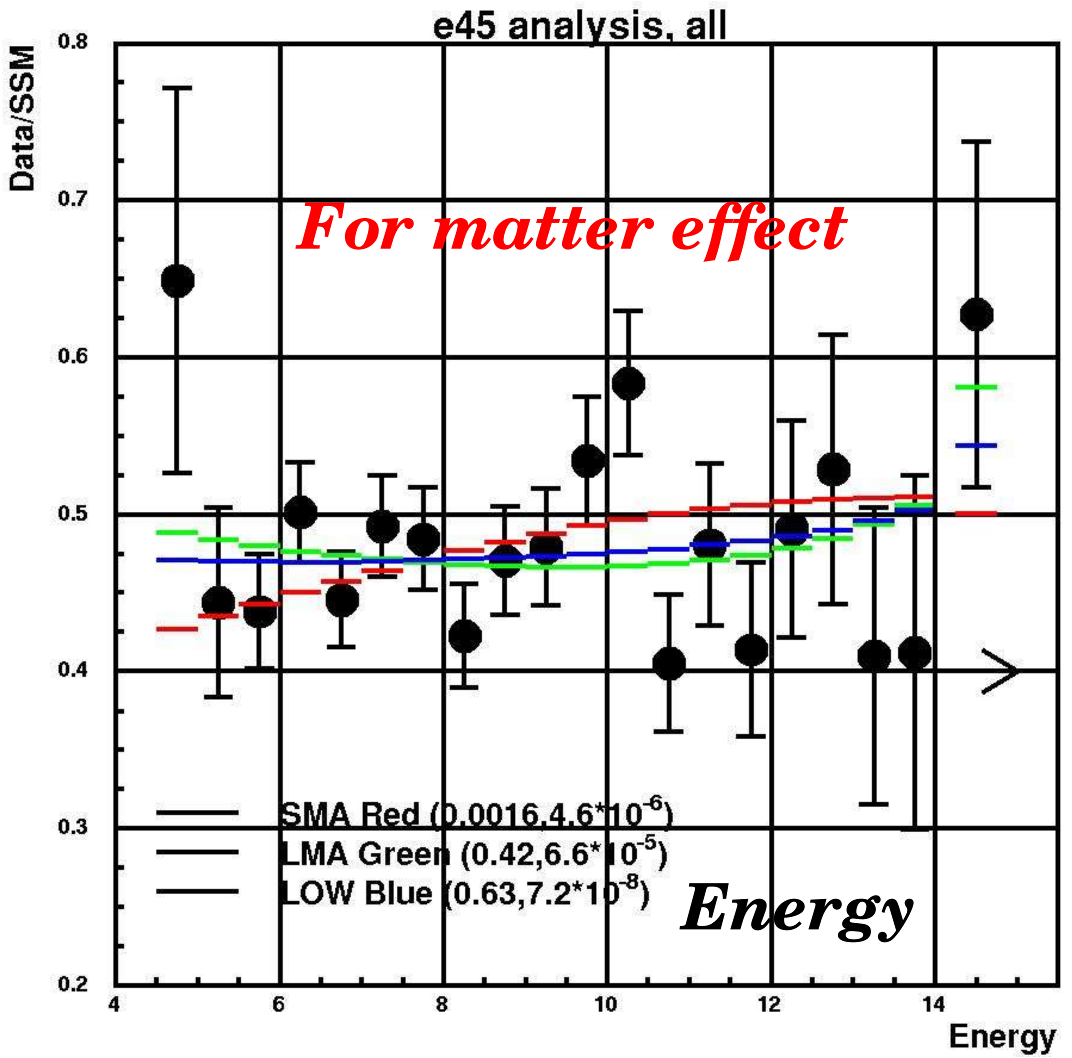
Energy spectrum distortion-I

Active two-neutrino oscillation

New data w/ 4.5 MeV

With $\sqrt{stat.^2 + syst.^2}$





VO: chi^2 = 28.2(C.L. 8.1%) Quasi VO = 19.4(C.L. 43.3%)

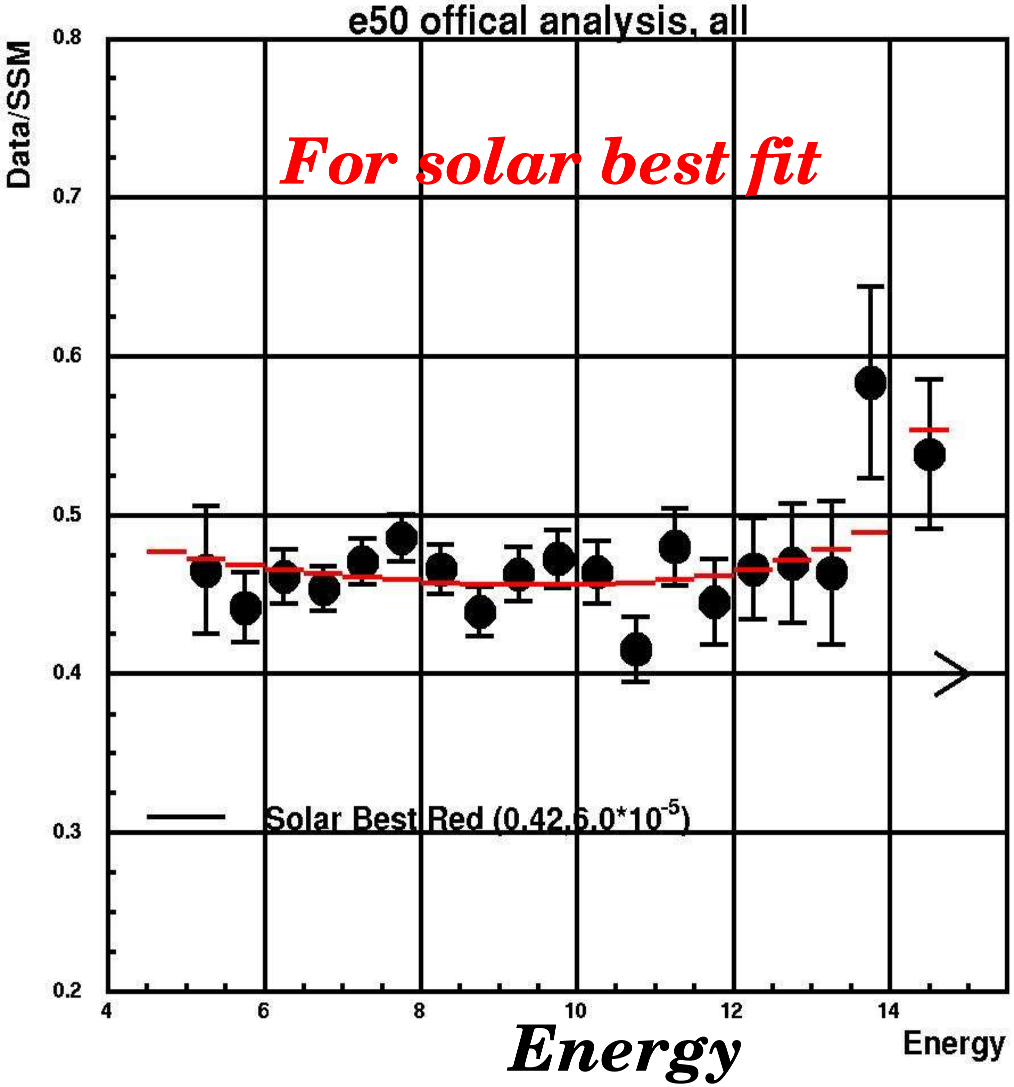
SMA = 24.4(C.L. 18.1%)

LMA = 19.8(C.L. 40.8%) Low = 19.6(C.L. 41.8%)

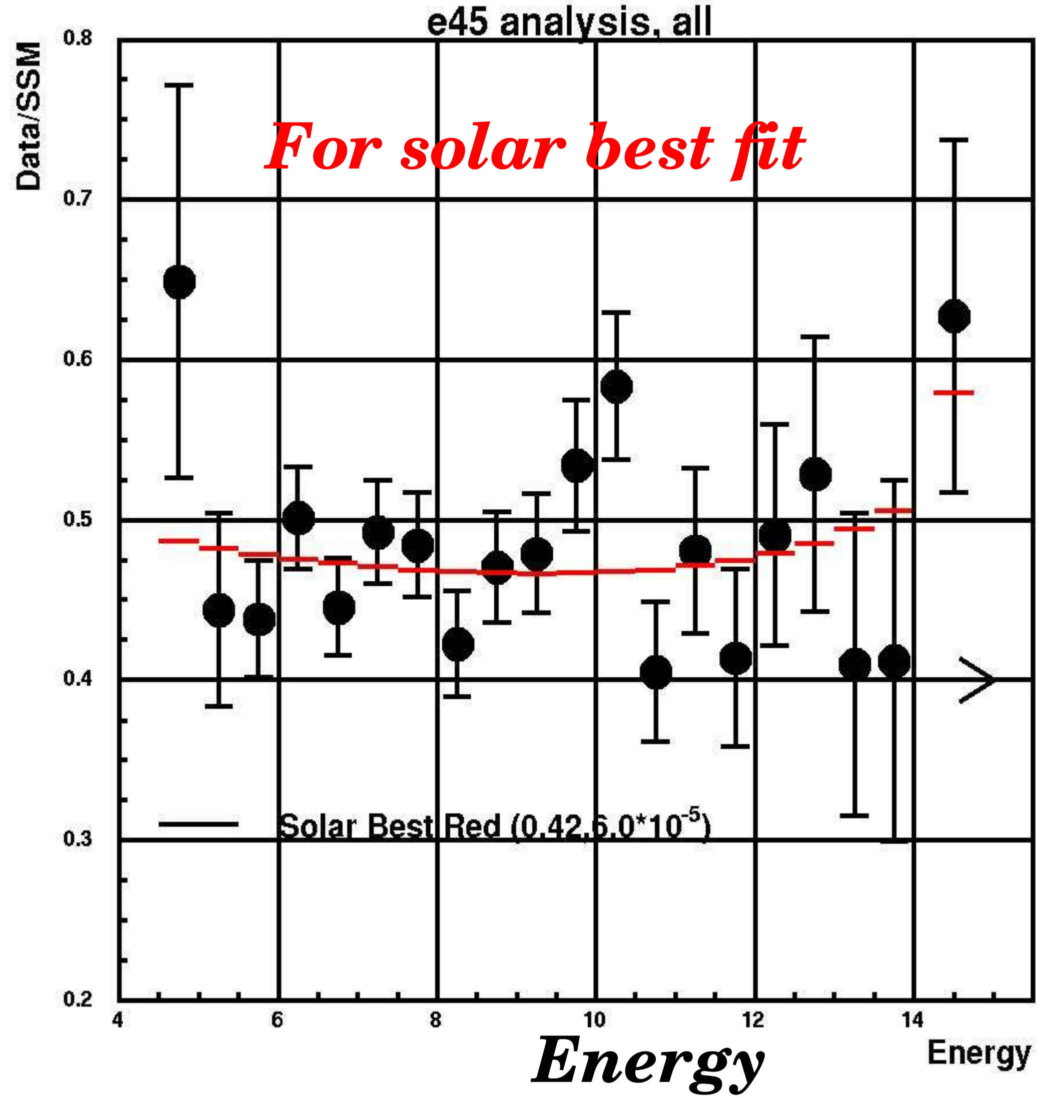
Energy spectrum distortion-II

With $\sqrt{stat.^2 + syst.^2}$

SK-I full data w/o 4.5 MeV



New data w/ 4.5 MeV



SKI full data: chi^2 = 14.7 (C.L 68.3%) d.o.f 19-1

New data : = 19.7 (C.L 41.1%) d.o.f 20-1

5, Summary and Future Plan

1. We installed various reduction which is optimized to 4.5-5.0 MeV analysis in this time, and S/N ration of 4.5 MeV bin was improved by about 20%!

2. We can see clear solar peak in 4.5-5.0 MeV!

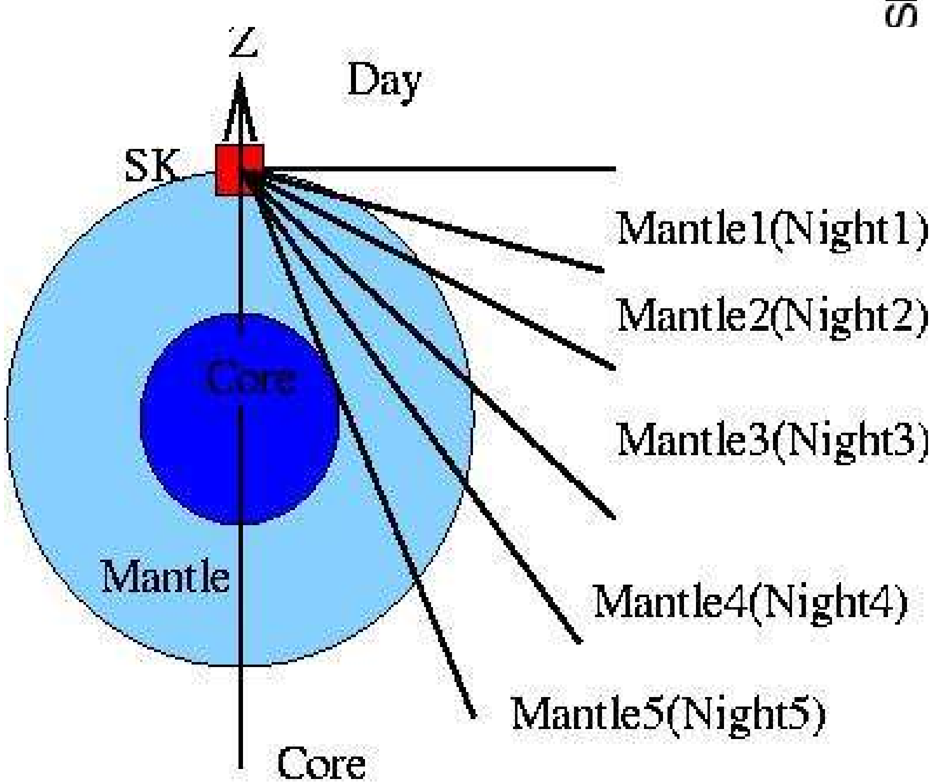
3. After solar fitting, we obtained 722 +139 -137(sta.) solar signals in 4.5-5.0 MeV by 5 sigma level . Then, we observed the Solar Flux of 3.28 +0.63-0.62(sta.) $1.0\times10^{6}\ cm^{3}/sec$

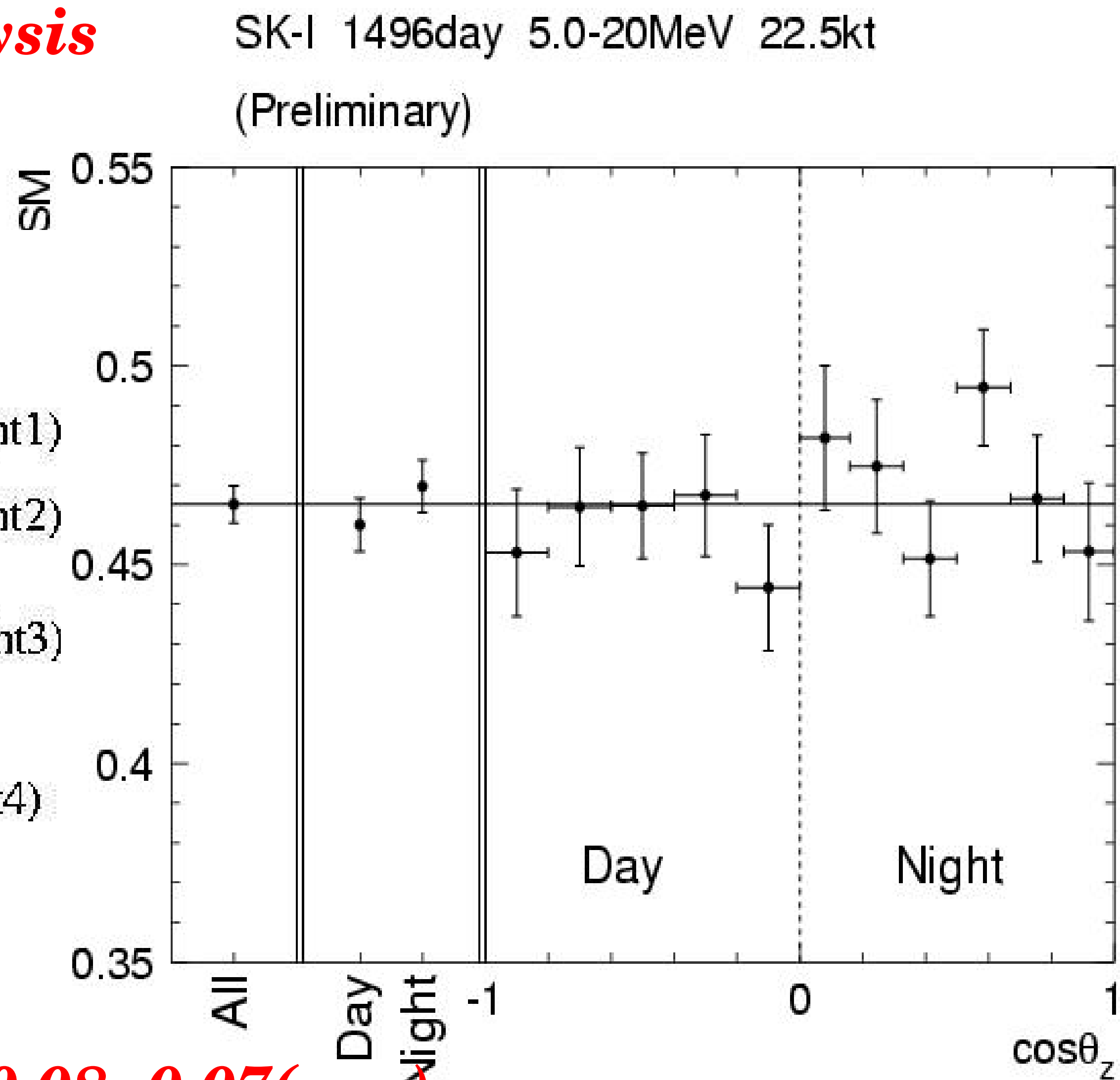
4. The Data/SSM of new results is consistent with full data results within 1.3 sigma. Therefore, new data gives a strong credit to oscillation phenomenon and SK-I full data results.

5. In the oscillation analysis, the 4.5 MeV bin have a some power for energy spectrum distortion in spite of low statistics.

6. When the statistics will be integrated, the constraint will be more powerful.

Day/ Night spectrum analysis





Day flux 2.32 ± 0.03 (sta.)+0.08 -0.07(sys.)

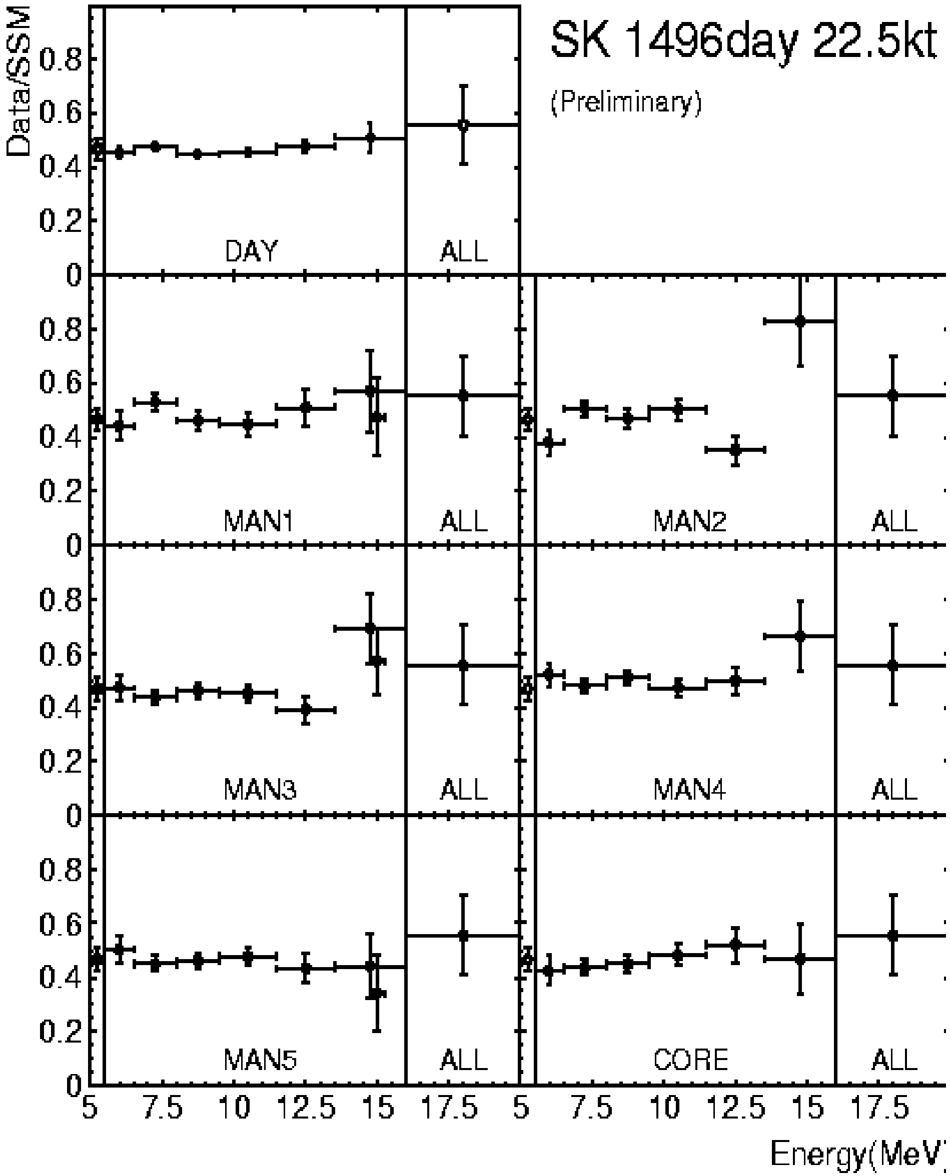
Night flux 2.37 ±0.03(sta.) ±0.08(sya.) $(1.0\times10^{6}\,cm^{-2}\,s^{-1})$

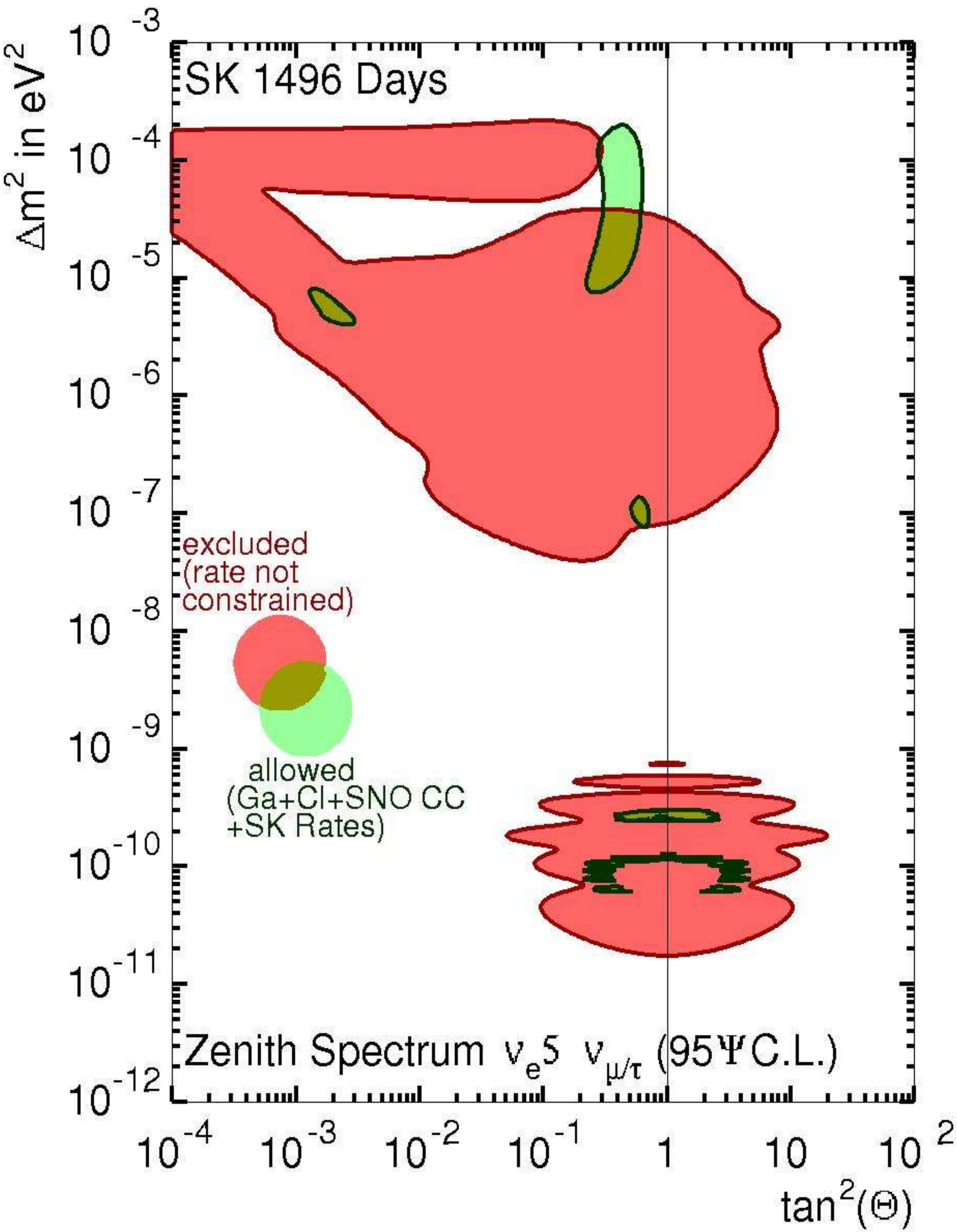
$$\frac{Day - Night}{(Day + Night)/2} = -0.021 \pm 0.020\ (sta.) + 0.013 - 0.012 (sys.)$$

no significant day/night asymmetry

Zenith spectrum analysis

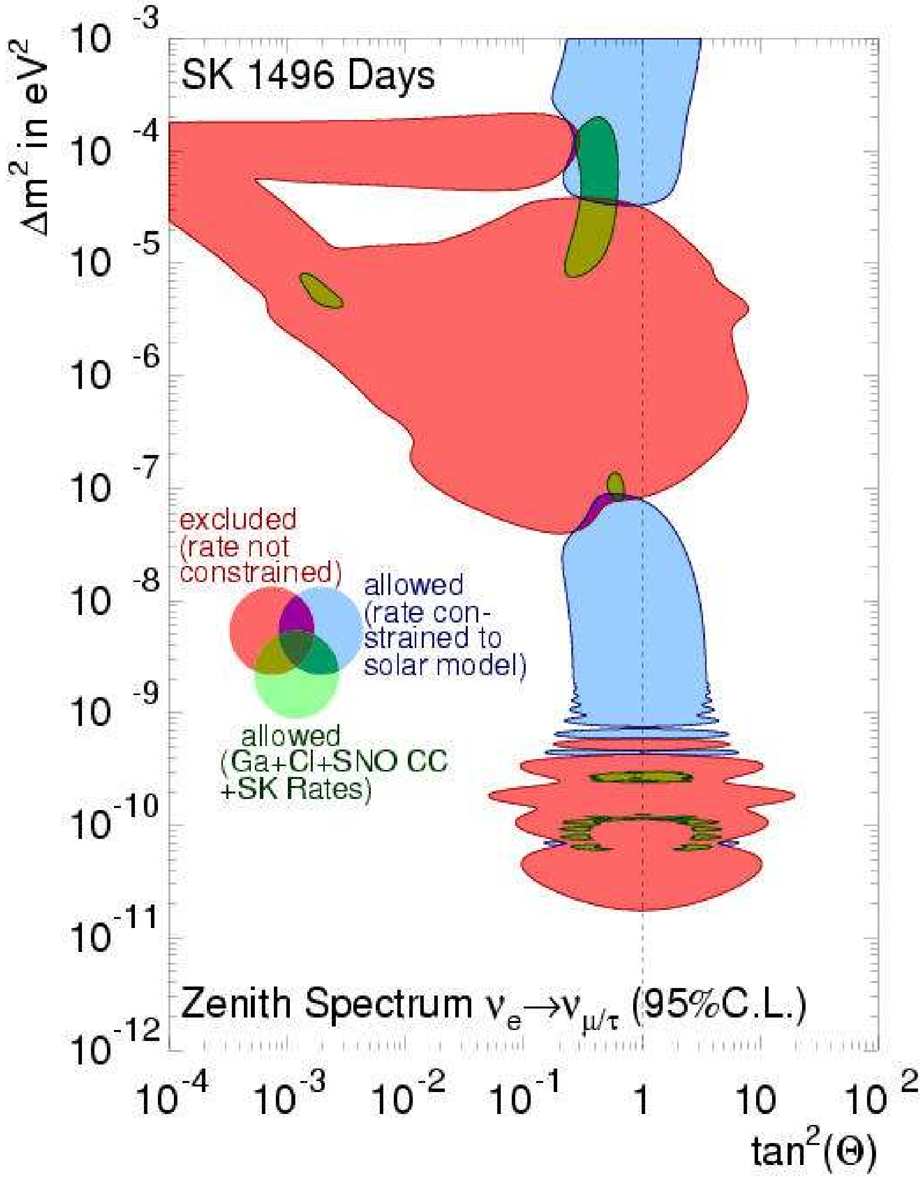
It is most powerful analysis, excludes large area.

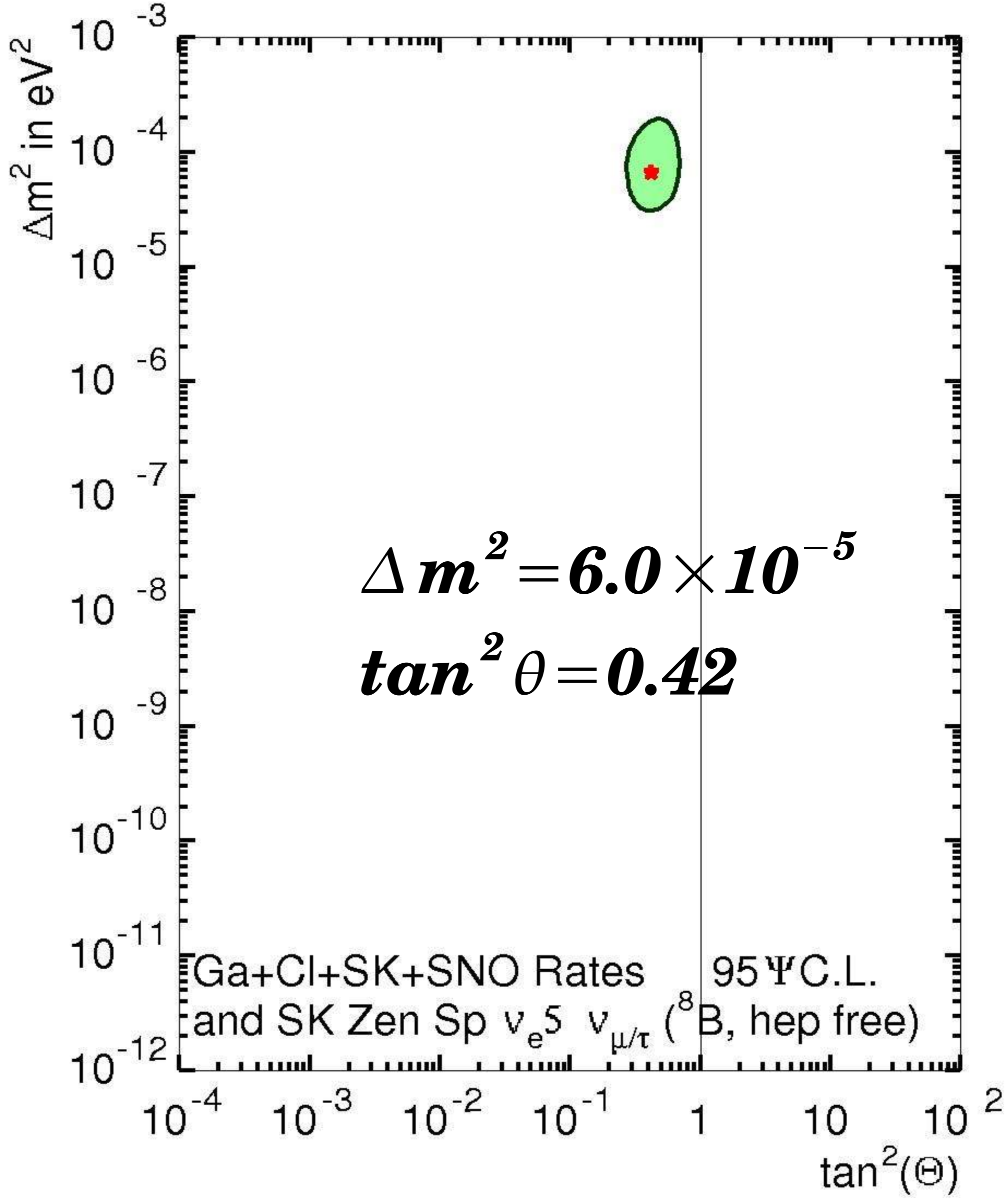




Solution is defined by the SK zenith spectrum results and SNO CC/NC results!

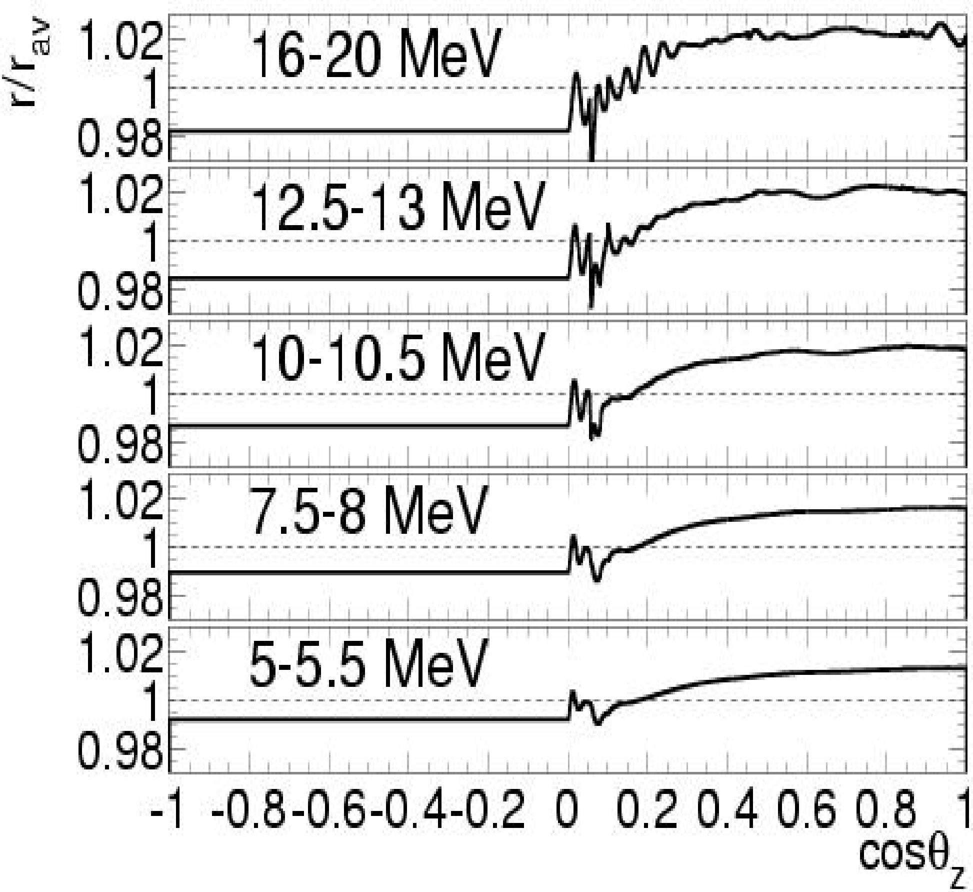
Next step is the precise determination of the oscillation parameter!

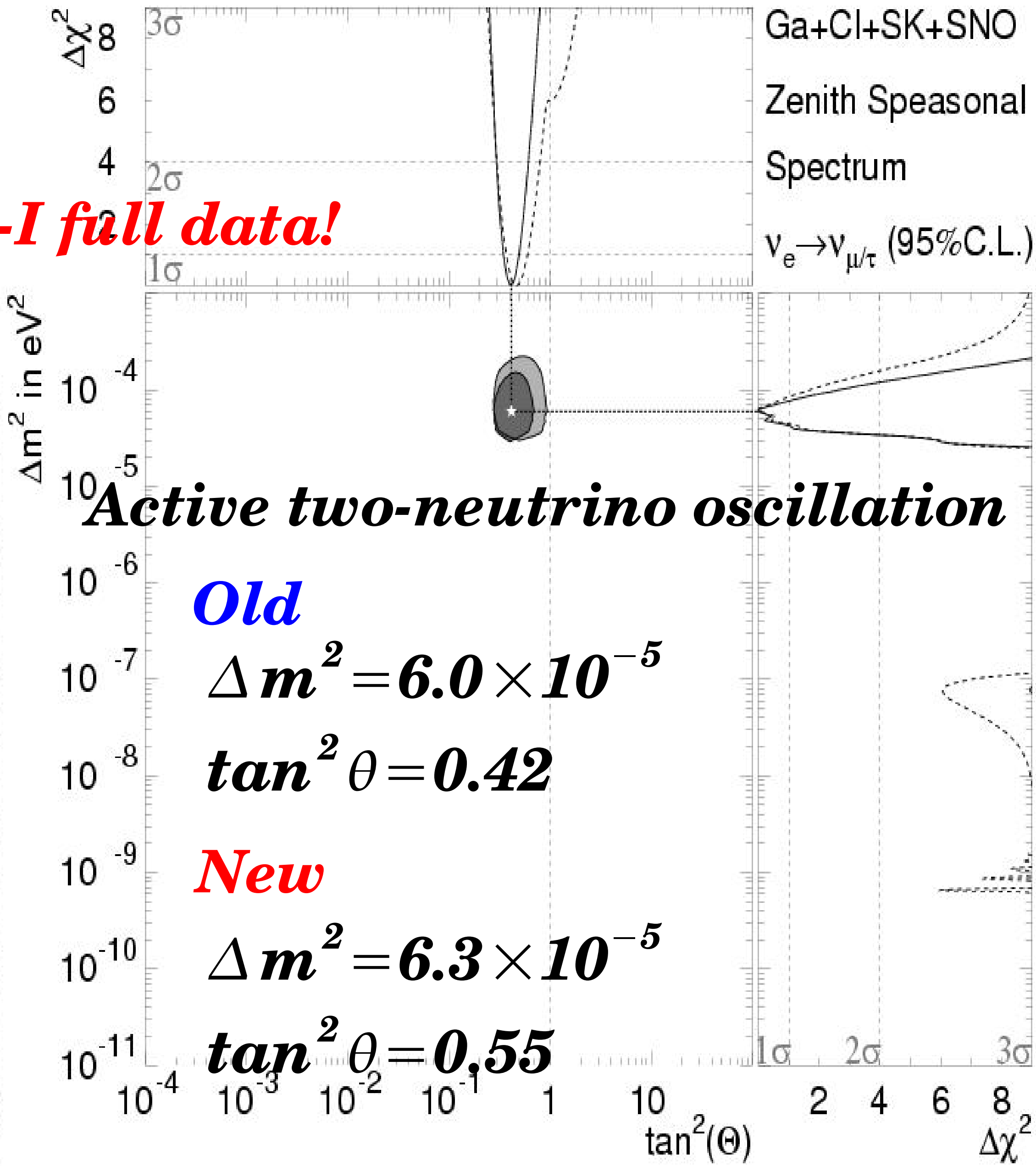




6,Most current result!

New analysis method shrink the allowed region using SK-I full data! (w/o 4.5 MeV data)





Active two-neutrino oscillation

Old

$\Delta m^2 = 6.0 \times 10^{-5}$

$\tan^2\theta = 0.42$

New

$\Delta m^2 = 6.3 \times 10^{-5}$

$\tan^2\theta = 0.55$

$$\frac{Day - Night}{(Day + Night)/2}$$

= -0.021 ± 0.020(stat.) +0.013-0.012(syst.)

= -0.018± 0.016(stat.)+0.013-0.012(syst.)

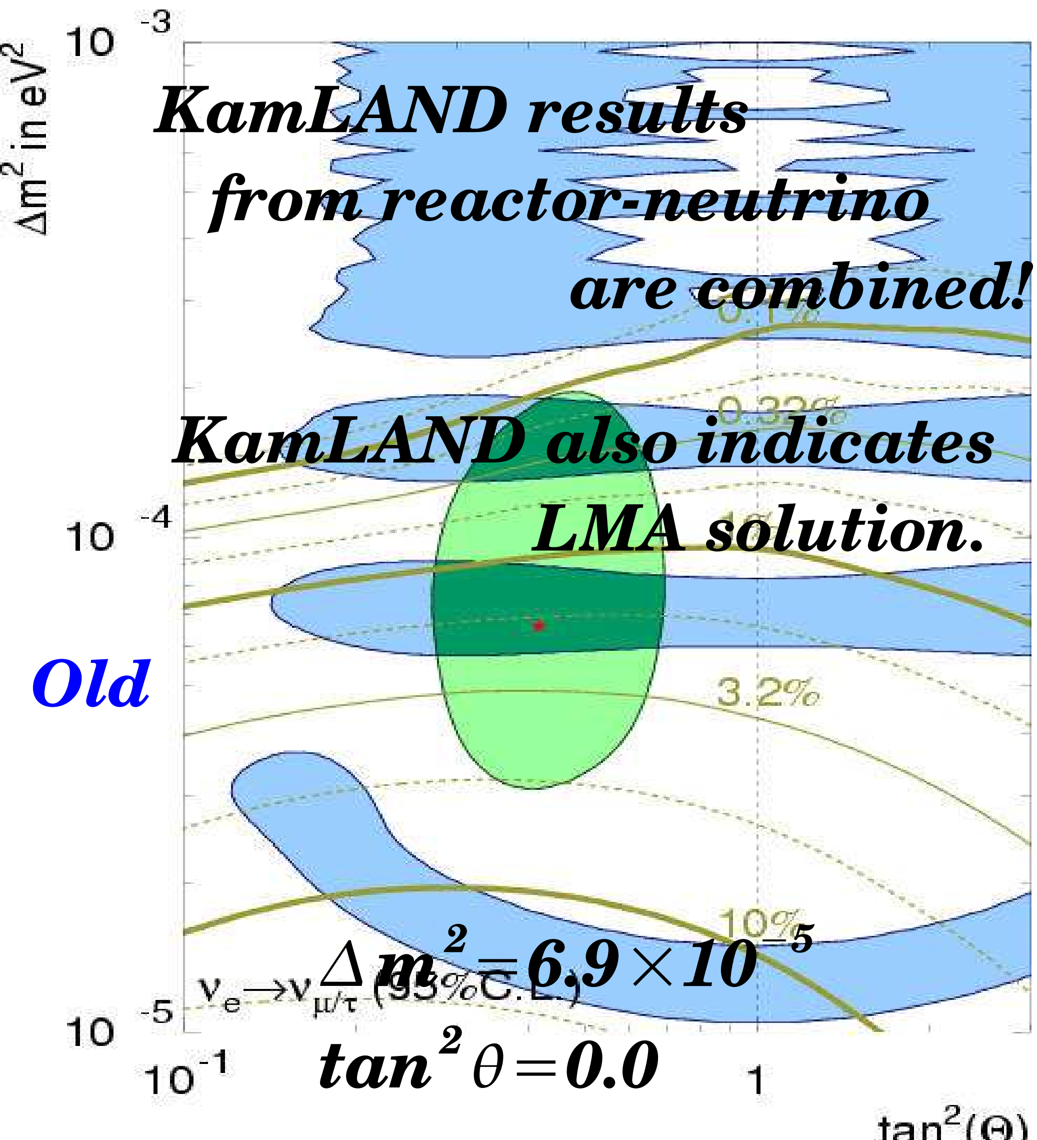
statical error is improved by 25%!

Solar neutrino observation is going to new phase !

Old *Is solar neutrino oscillated?*

Which oscillation solution is correct?

Now, the determination of oscillation paramater



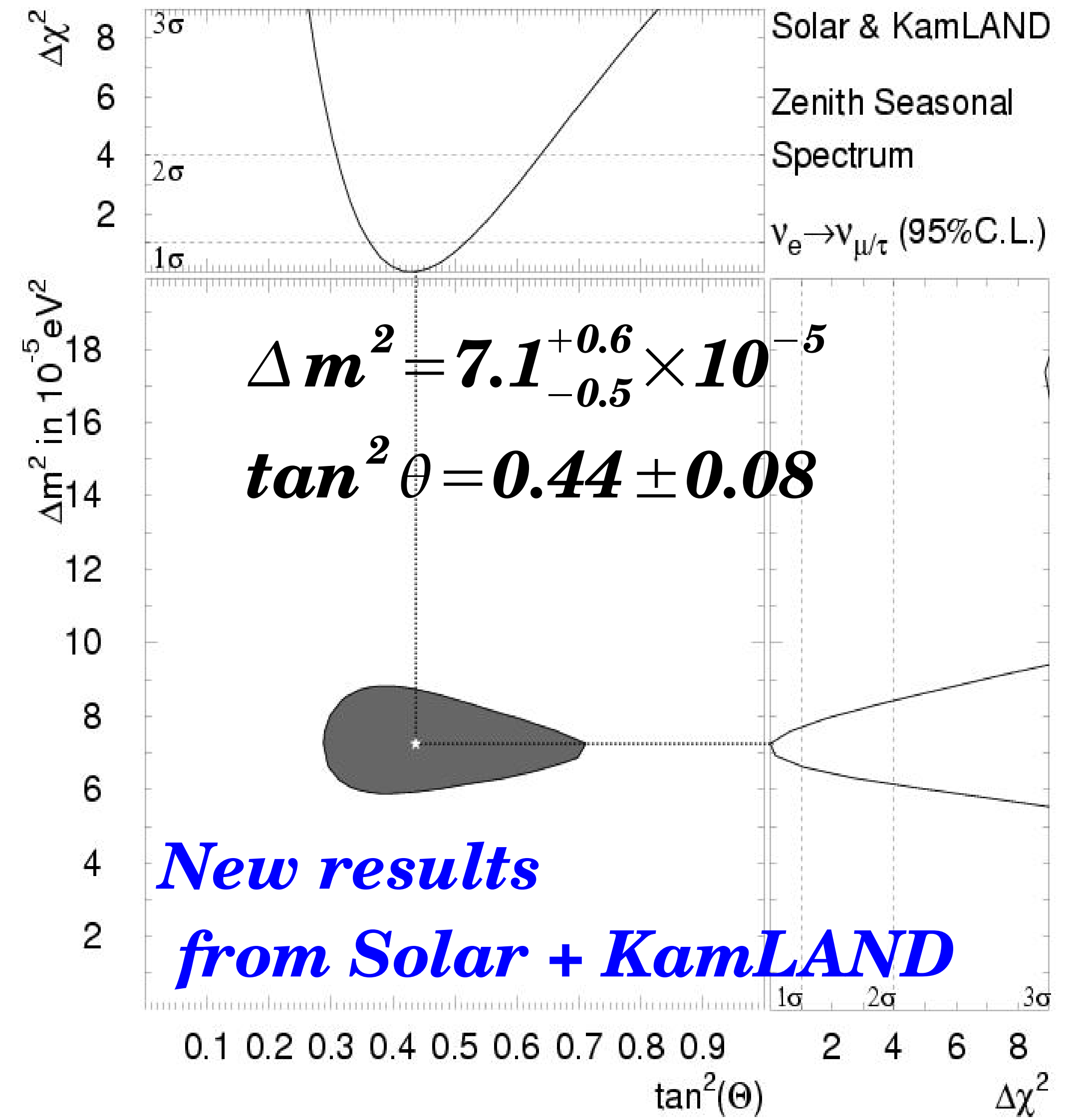
KamLAND results from reactor-neutrino are combined!

KamLAND also indicates LMA solution.

Old

$\Delta m^2 = 6.9 \times 10^{-5}$

$\tan^2 \theta = 0.0$



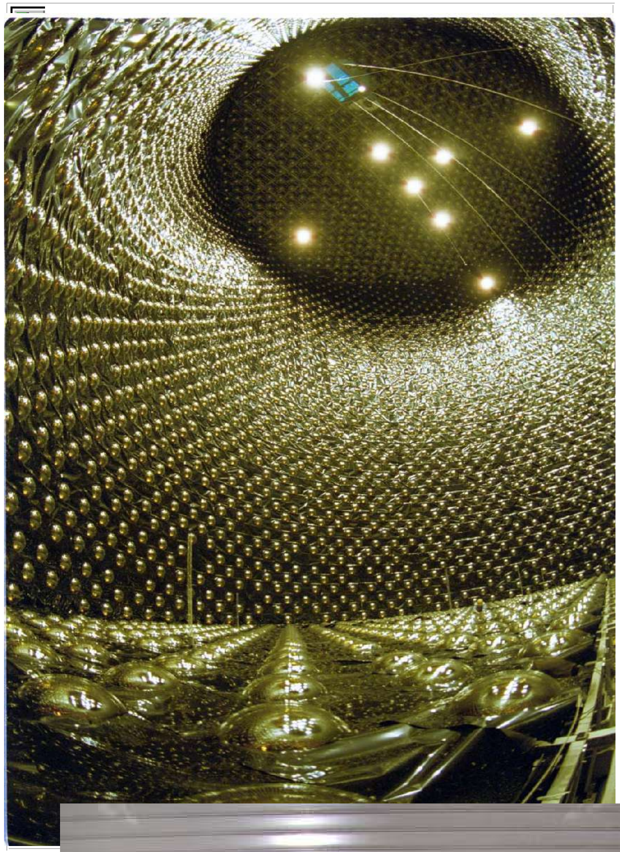
$\Delta m^2 = 7.1^{+0.6}_{-0.5} \times 10^{-5}$

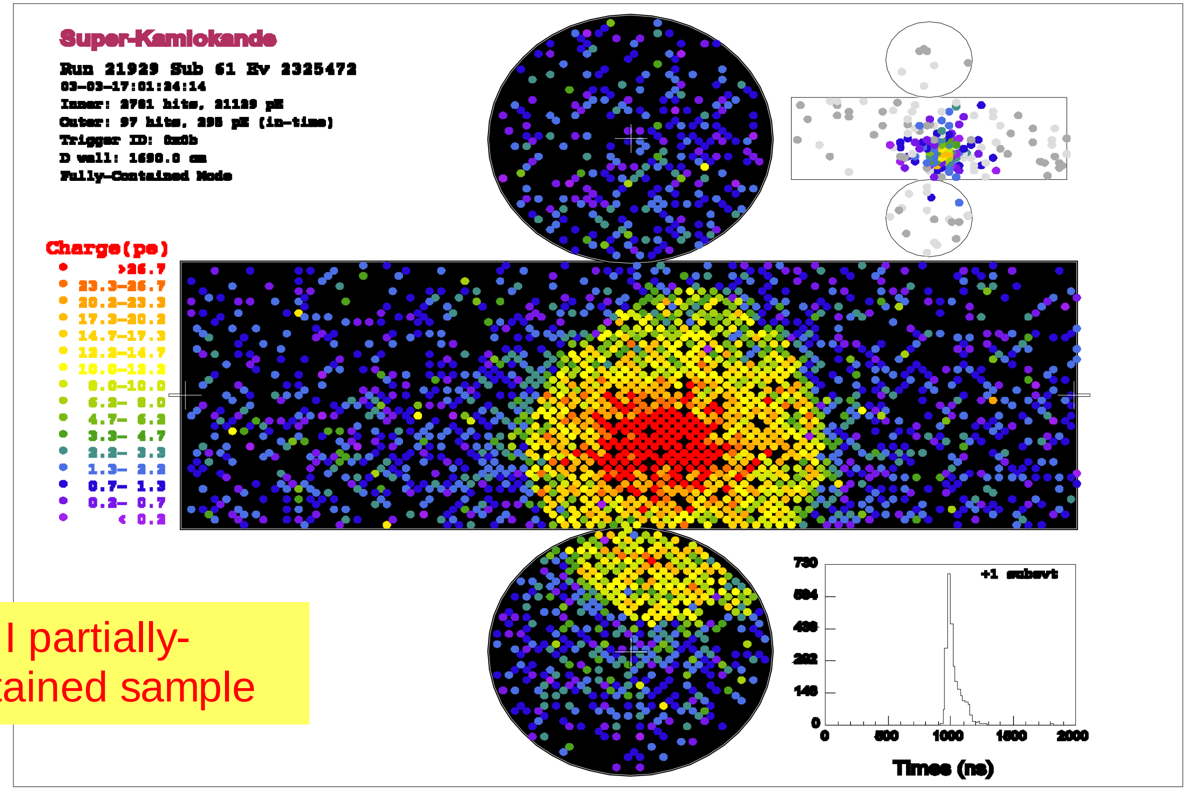
$\tan^2 \theta = 0.44 \pm 0.08$

New results from Solar + KamLAND

Snow Town Kamioka

SK-II is taking data



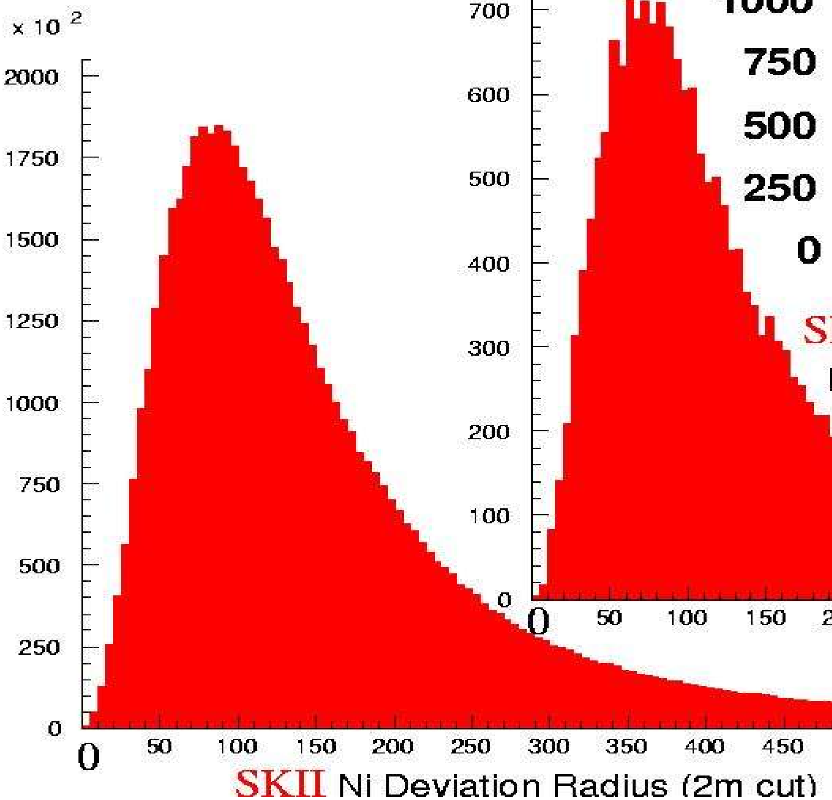


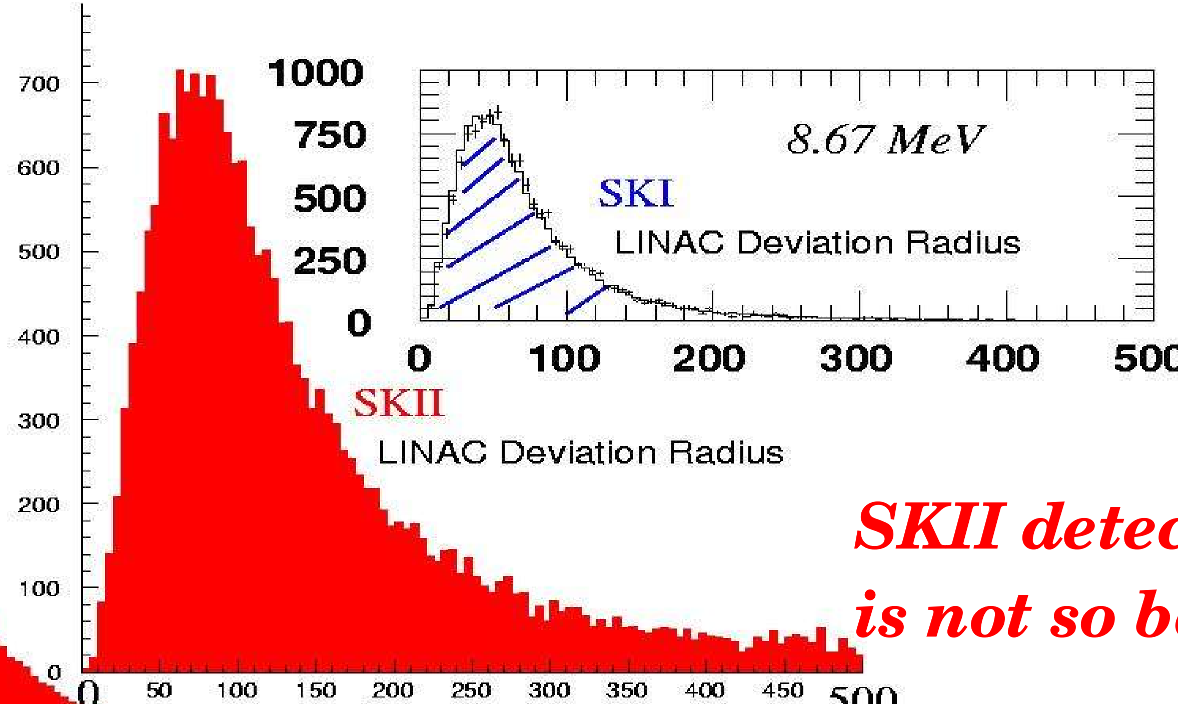
SK-II partially-contained sample

- **Rebuilt in summer 2002**
  - Has 47% of original ID 20inch PMTs (~5200)
  - 20inch PMTs in acrylic shells to prevent future chain implosions
  - Has full OD 8inch PMTs (1885)
- **Started data taking at Dec. 2002**

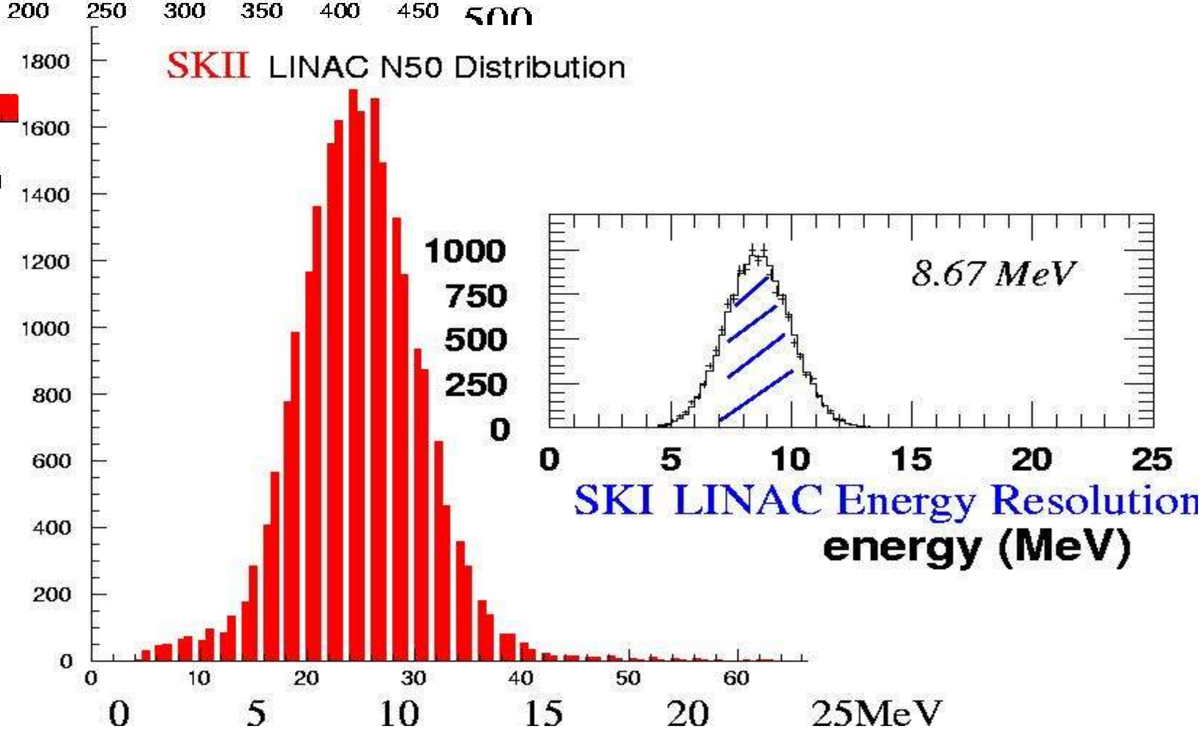
20inch PMT with Acrylic + FRP vessel

SKII resolution in low energy region





SKII detector resolution is not so bad !



Vertex res.

85 cm -> ~160 cm

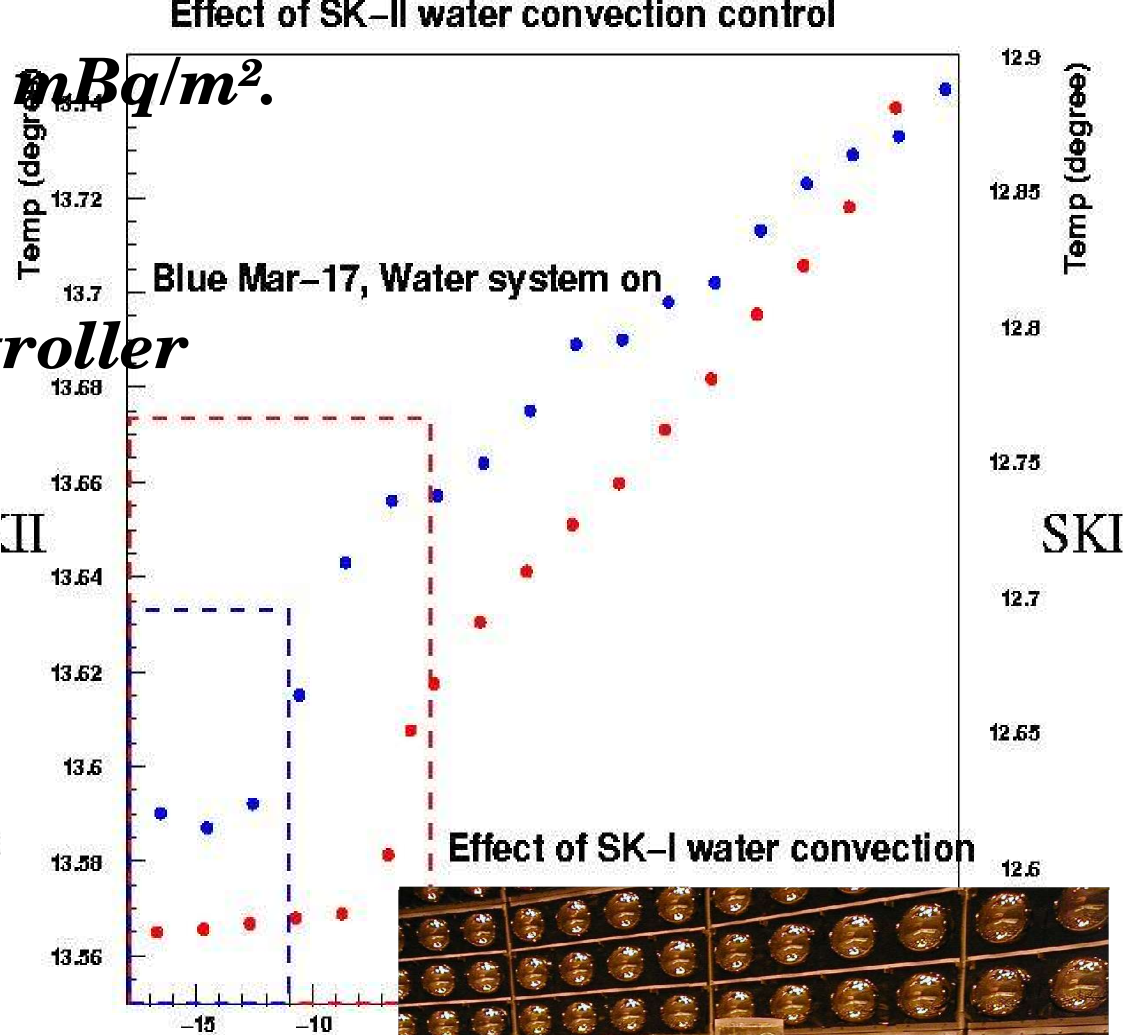
Energy res.

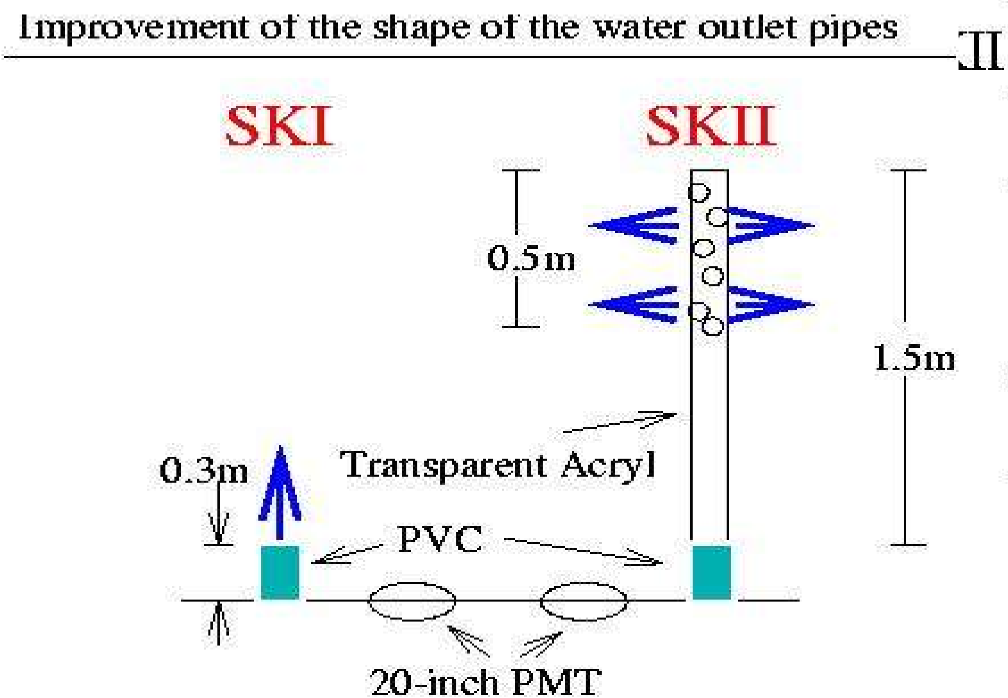
16% -> ~26%

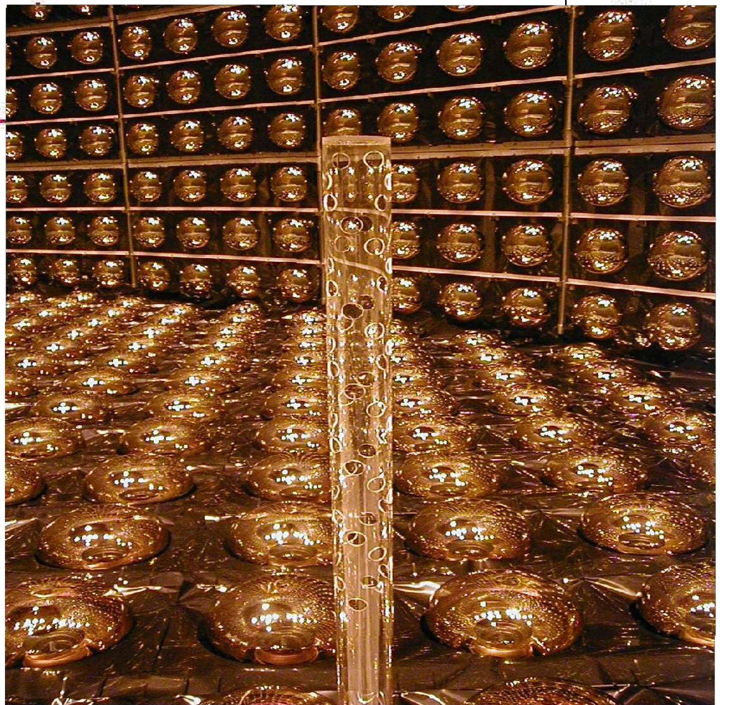
0, SK water is less than 0.75 mBq/m^2.

1, The all PMT are covered with the acrylic case.

2, Installed convection controller is going well in SK-II







We can expect the lower energy analysis in SK-III after full recovered detector (now, SK-II half-recover)