Super-Kamiokande: low-energy neutrinos

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(for Super-Kamiokande Collaboration)

Super-Kamiokande Collaboration

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~140 collaborators
34 institutions
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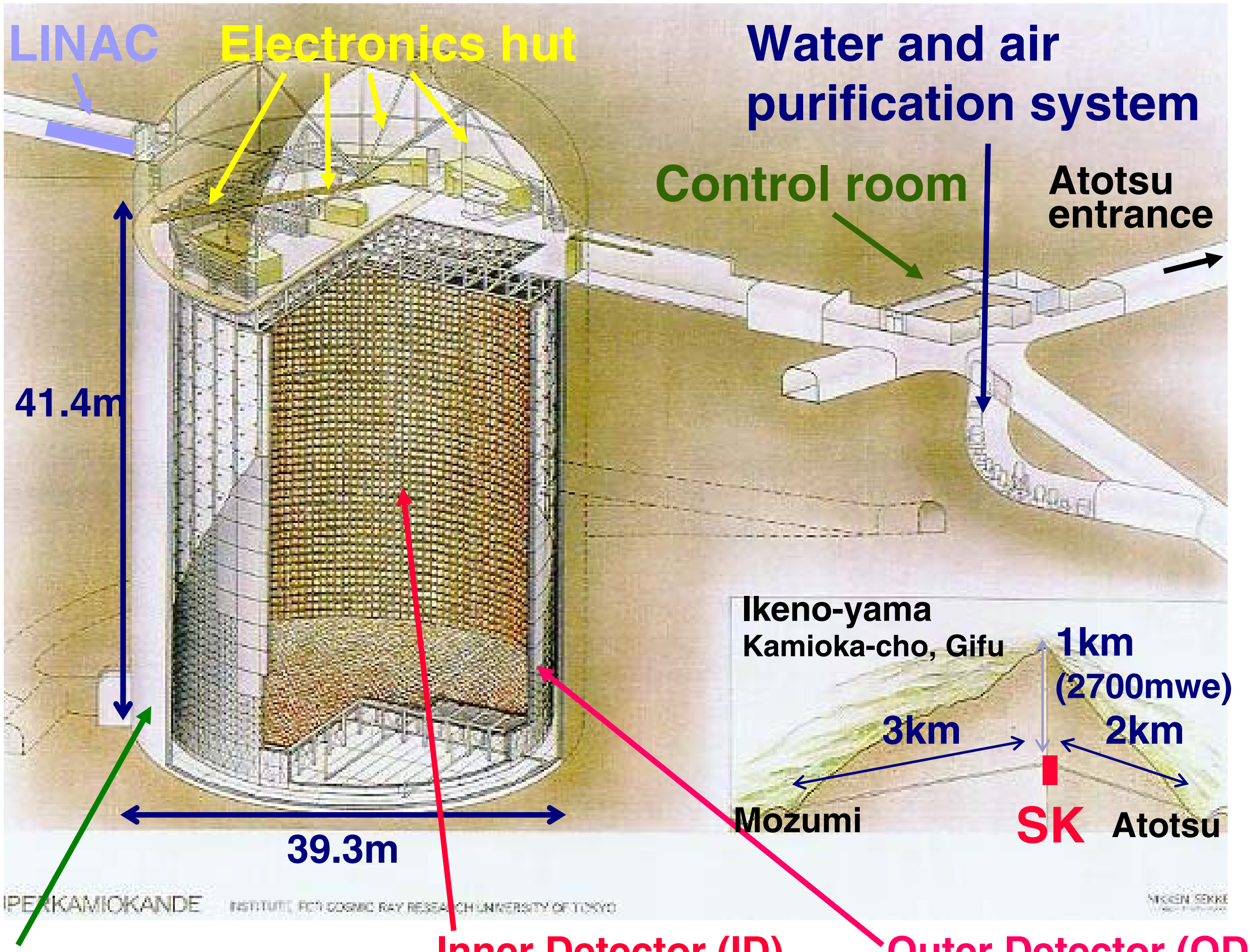
(as of Jan. 2005)

+Tsinghua Univ., China
(June, 2005~)

Outline

- Super-Kamiokande detector
- Solar neutrino results
  - ☐ SK-II latest results New
  - ☐ SK-I recent updates New
- Future plan
  - ☐ Solar neutrino measurements at SK-III
  - ☐ R&D on Gd doped SK (GADZOOKS! project)

Super-Kamiokande



50000 ton stainless steel tank

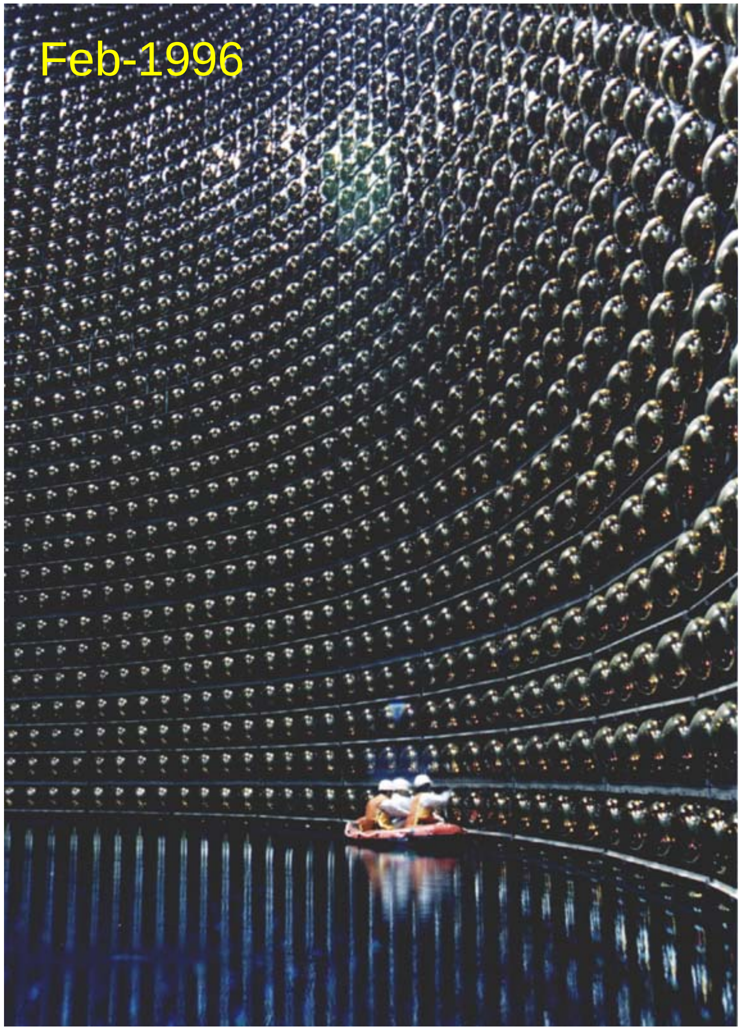
Inner Detector (ID)
11146 of 20 inch PMTs
(SK-I)

Outer Detector (OD)
1885 of 8 inch PMTs
(SK-I & SK-II)

- **SK-I (1996~2001)**
- **50000ton water**
- **~11200 of 20inch PMTs**
- **Fid. vol. 22.5kt**
- **Photo coverage 40%**
- **Stopped by the accident in Nov. 2001**

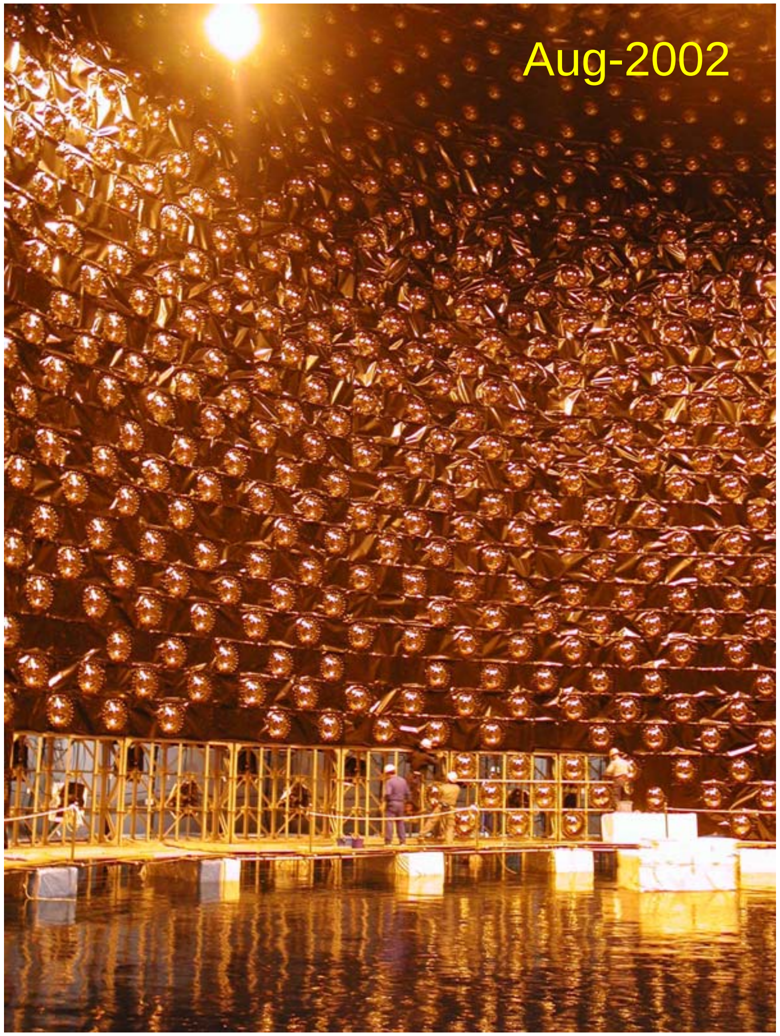
- **SK-II (Dec. 2002~)**
- **~5200 of 20inch PMTs**
- **Photo coverage 19%**

Inside of SK



Feb-1996

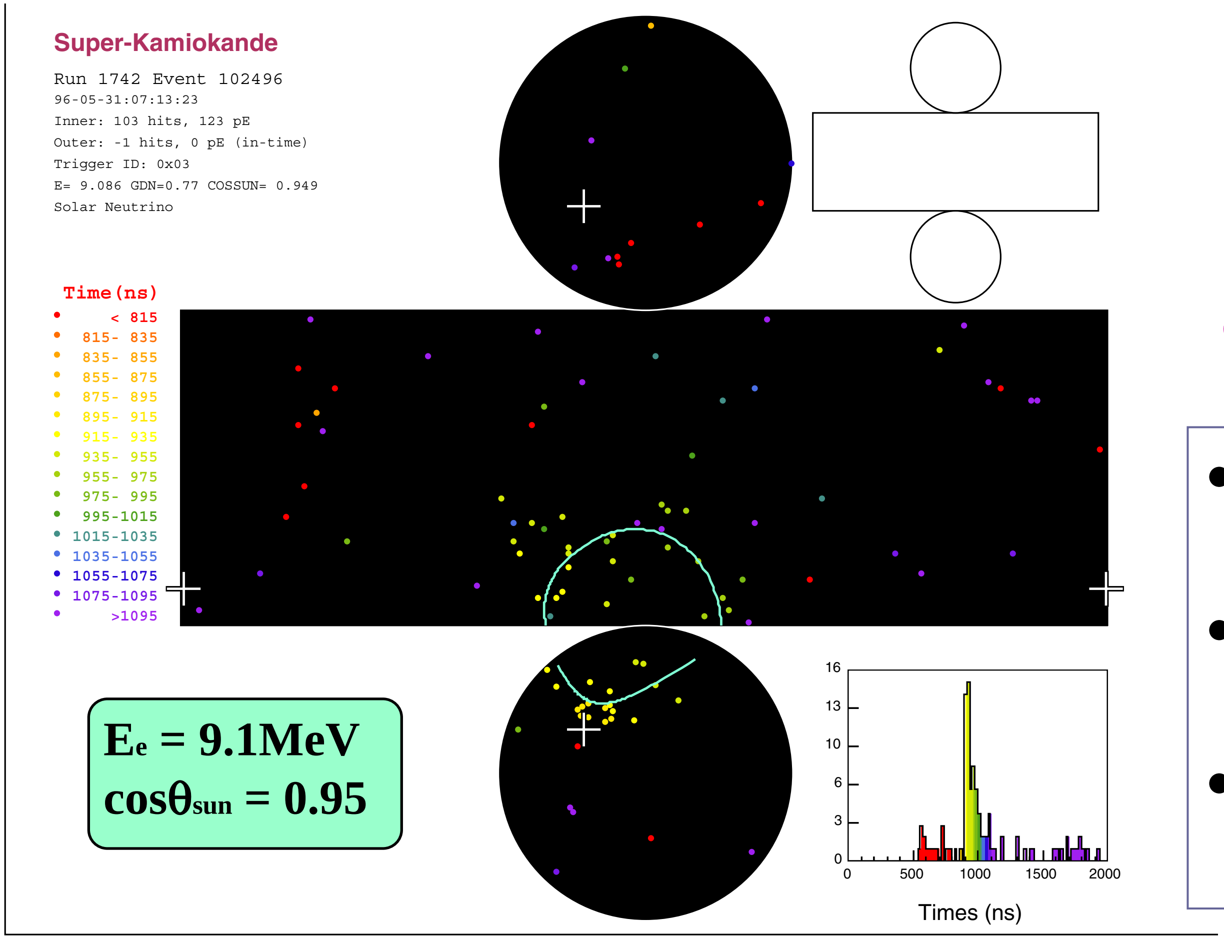
SK-I Photo coverage 40%



Aug-2002

SK-II Photo coverage 19%

Typical low-energy event at



Super-Kamiokande

Run 1742 Event 102496
96-05-31:07:13:23
Inner: 103 hits, 123 pE
Outer: -1 hits, 0 pE (in-time)
Trigger ID: 0x03
E= 9.086 GDN=0.77 COSSUN= 0.949
Solar Neutrino

$E_e = 9.1\text{MeV}$
$\cos\theta_{sun} = 0.95$

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

(for solar neutrinos)

Sensitive to ν_e, ν_μ, ν_τ

$\sigma(\nu_{\mu(\tau)}e^-) =\sim 0.15\times\sigma(\nu_e e^-)$

- **Timing information**
  ➡ **vertex position**
- **Ring pattern**
  ➡ **direction**
- **Number of hit PMTs**
  ➡ **energy**

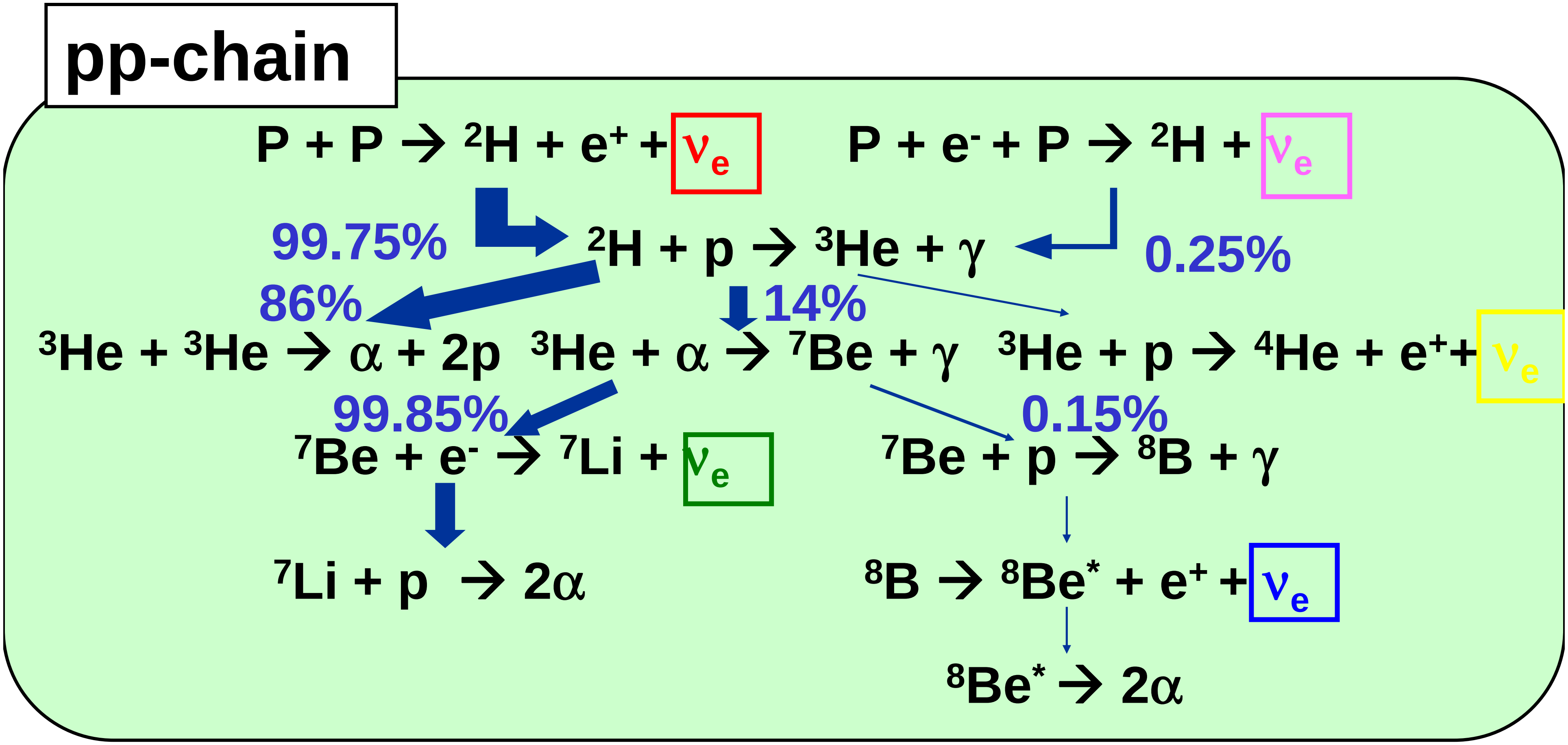
Resolutions (for 10MeV electron)

Energy: 14% **Vertex: 87cm** **Direction: 26°**

Solar neutrino

Standard Solar Model (SSM)

Sun burns through: $4p \rightarrow {}^{4}He + 2e^{+} + 2\nu_e + 25MeV$



pp-chain

$P + P \rightarrow {}^{2}H + e^{+} + \nu_e$

$P + e^{-} + P \rightarrow {}^{2}H + \nu_e$

99.75%

0.25%

${}^{2}H + p \rightarrow {}^{3}He + \gamma$

86%

14%

${}^{3}He + {}^{3}He \rightarrow \alpha + 2p$

${}^{3}He + \alpha \rightarrow {}^{7}Be + \gamma$

${}^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu_e$

99.85%

0.15%

${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_e$

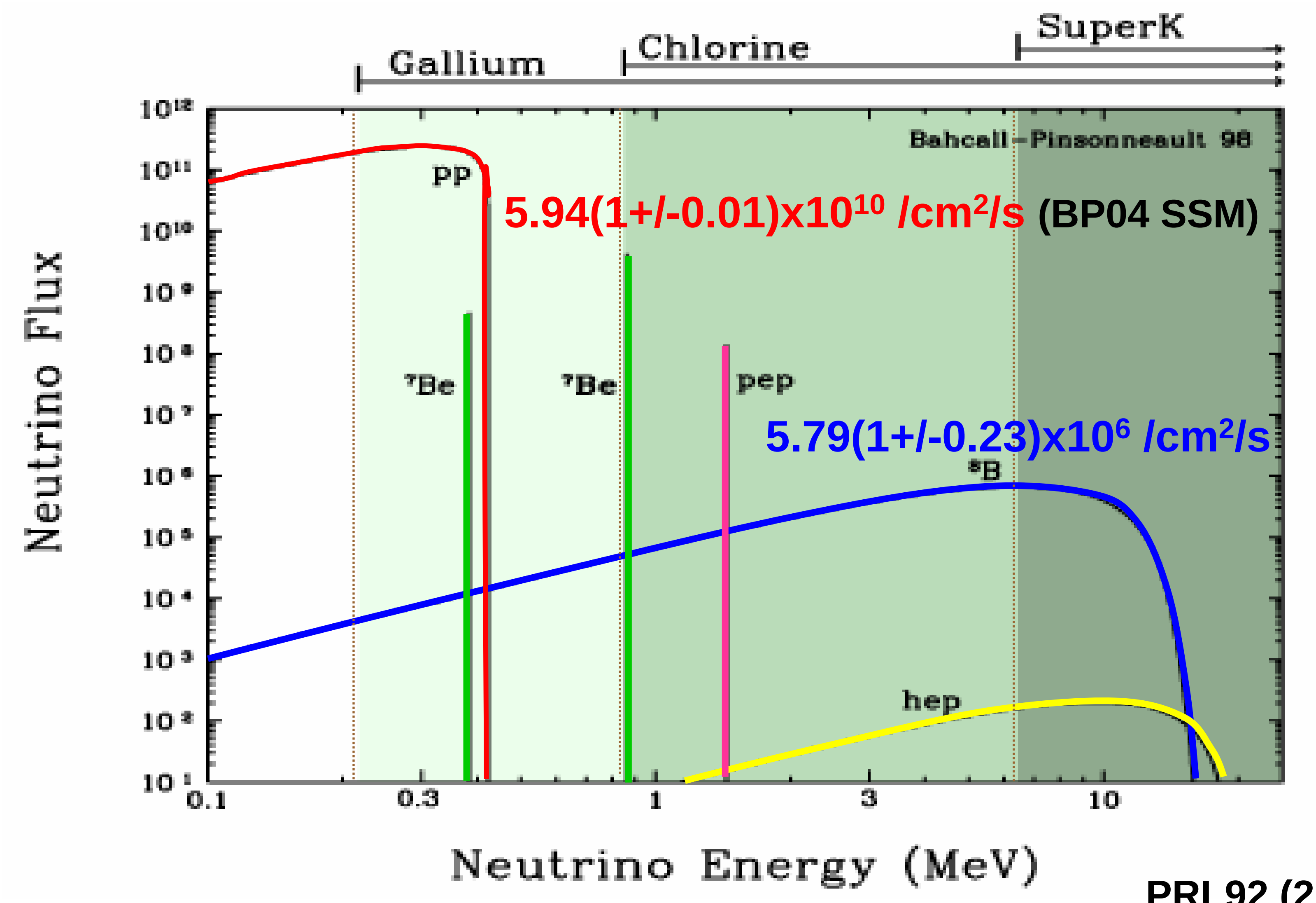
${}^{7}Be + p \rightarrow {}^{8}B + \gamma$

${}^{7}Li + p \rightarrow 2\alpha$

${}^{8}B \rightarrow {}^{8}Be^{*} + e^{+} + \nu_e$

${}^{8}Be^{*} \rightarrow 2\alpha$

Solar neutrino fluxes



5.94(1+/-0.01)x10^{10} /cm^2/s (BP04 SSM)

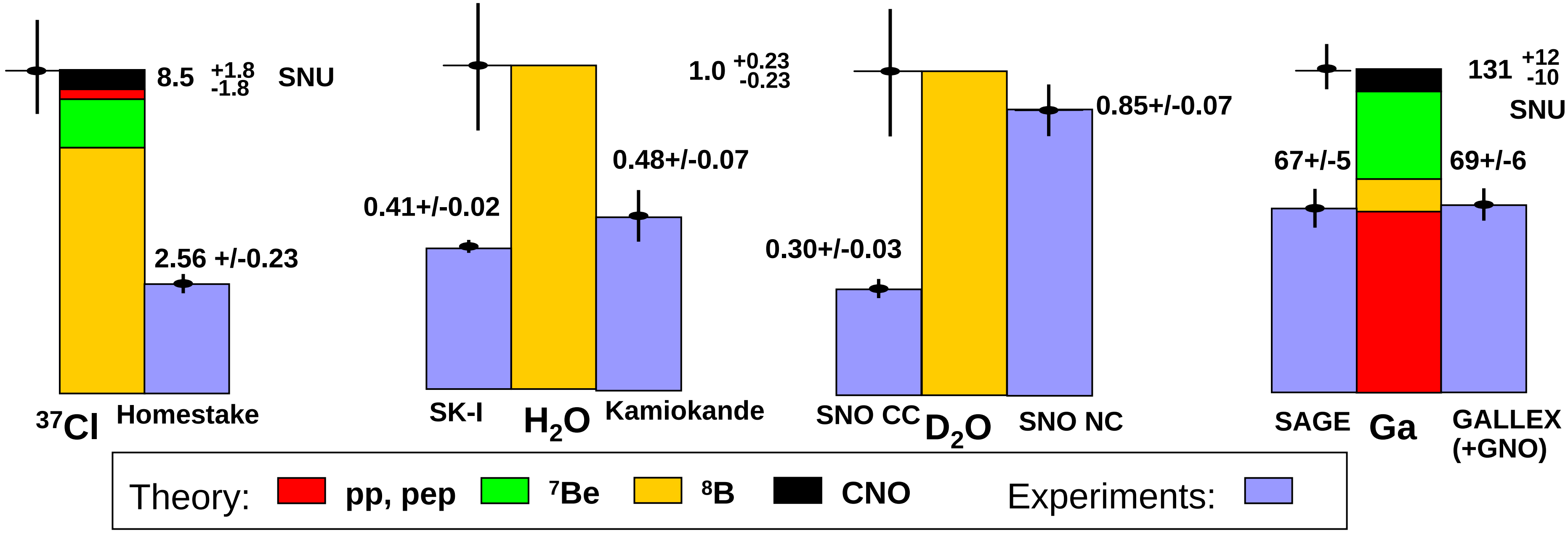
5.79(1+/-0.23)x10^{6} /cm^2/s

PRL92 (2004) 121301
http://www.sns.ias.edu/~jnb/

Flux measurements

		target	Data/SSM$_{BP04}$
ν_e (mainly)	▪ Homestake	^{37}Cl	0.30+/-0.03
	▪ SAGE	^{71}Ga	0.51+/-0.04
	▪ GALLEX+GNO	^{71}Ga	0.53+/-0.04
	▪ SK	e^- (water)	0.41+/-0.02
	▪ SNO pure D_2O CC	d (D_2O)	0.30+/-0.03
All ν	▪ SNO salt NC	d (D_2O)	0.85+/-0.07

Neutrino oscillation can explain these results (+KamLAND)

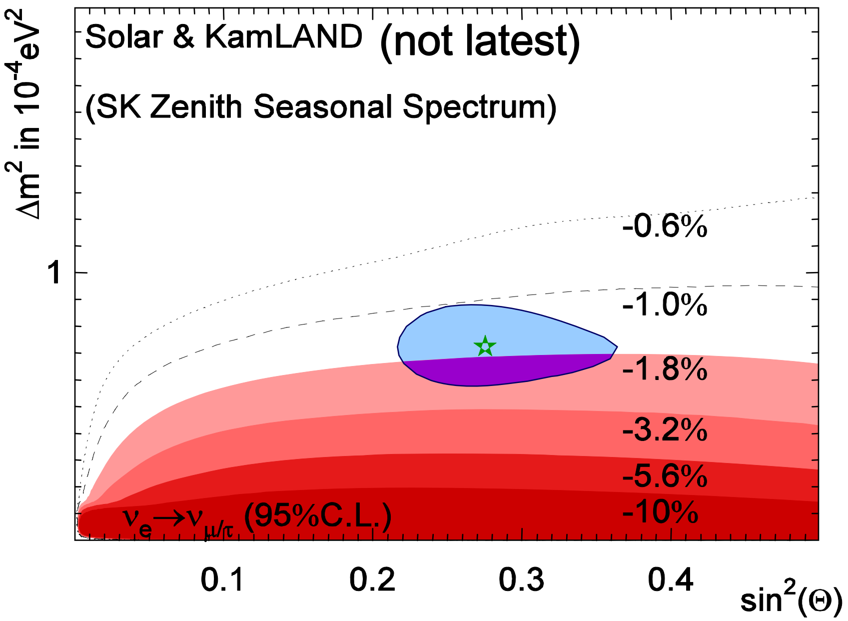


Precision phase (Need evidence of oscillation)

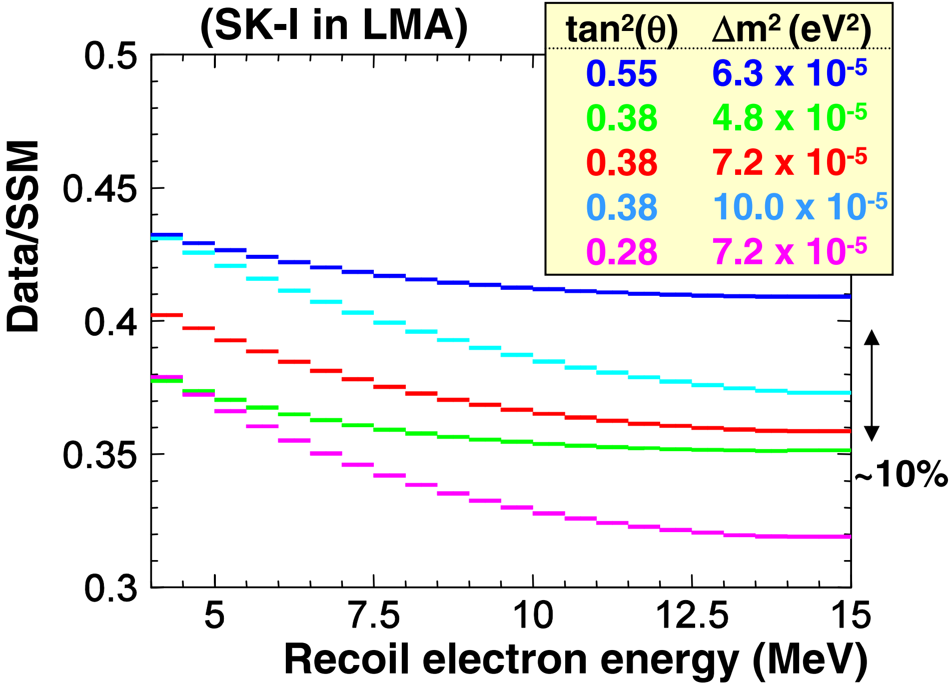
Solar neutrino measurements in SK

- **High statistics** ~15events/day with E_e > 5MeV, ^{8}B(+hep)
- **Time variations** (Day/Night, Seasonal, 5days each, etc.)
- **Energy spectrum** (Sensitive to ν oscillation parameters)
- **Precise energy calibration** by electron LINAC and ^{16}N
- **Flux independent analysis** (Time variation, Energy spectrum)

Expected Day/Night asymmetry



Expected spectrum distortion

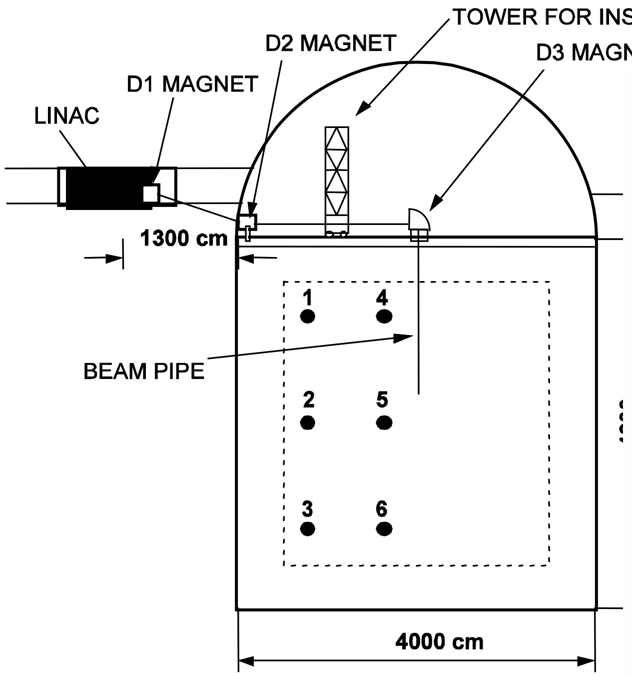


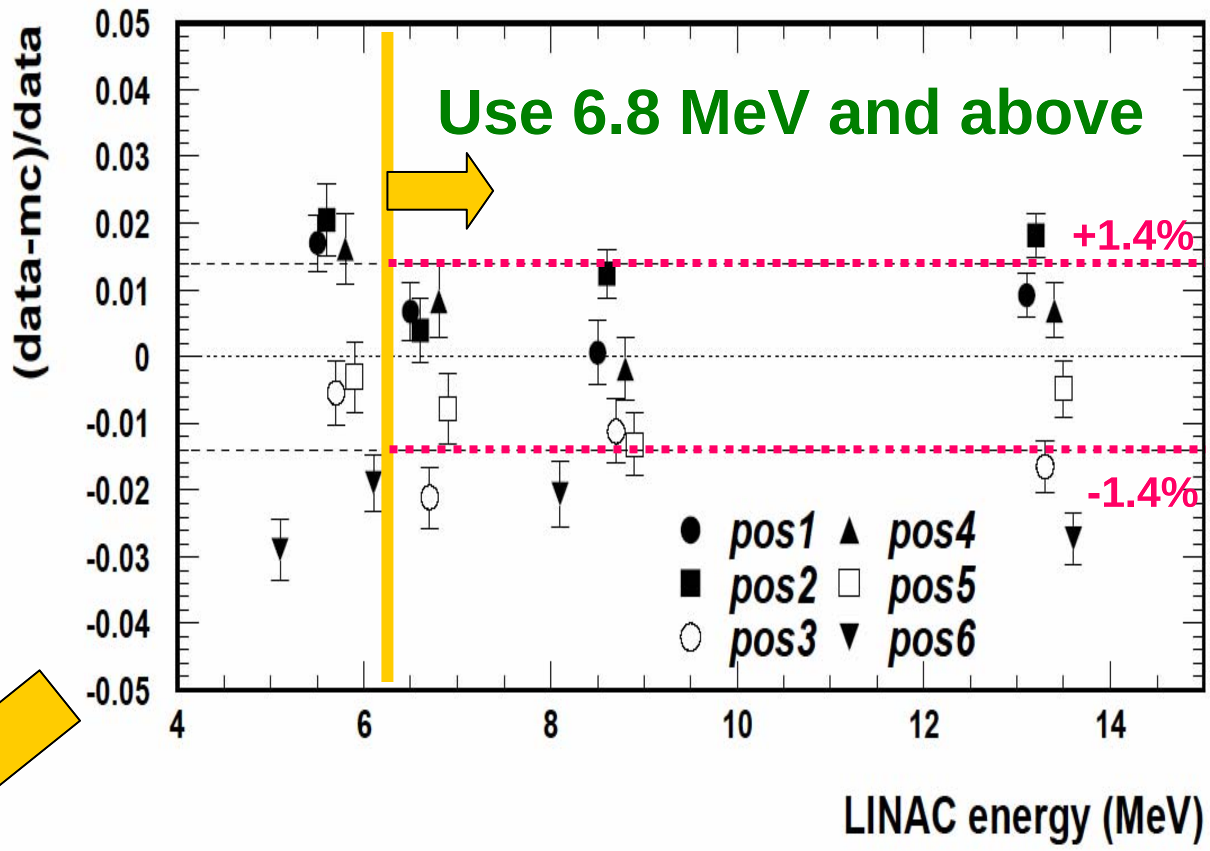
SK-II recent progresses

New

- Retuned the MC simulation, then obtained preliminary systematic errors on flux
  - Previous: only stat. errors
- Applied an improved low-energy noise reduction, then lower energy threshold to 7.0MeV
  - Previous: 8.0MeV
- Obtained SK-II 622day preliminary results
  - Previous: 478day

LINAC Calibration





Energy Scale Uncertainty (absolute)

$\sigma = 1.4\%$

(Preliminary)

(SK-I: 0.64%)

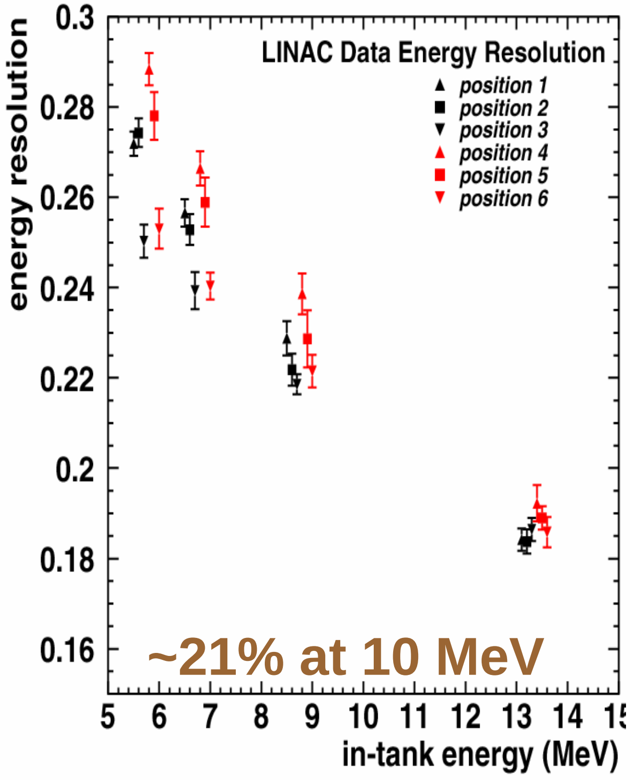
- **There still exist a minor problem.**
- **More tuning will be done in near future.**

SK-II detector performance

(SK-II LINAC data, 622day analysis, Preliminary)

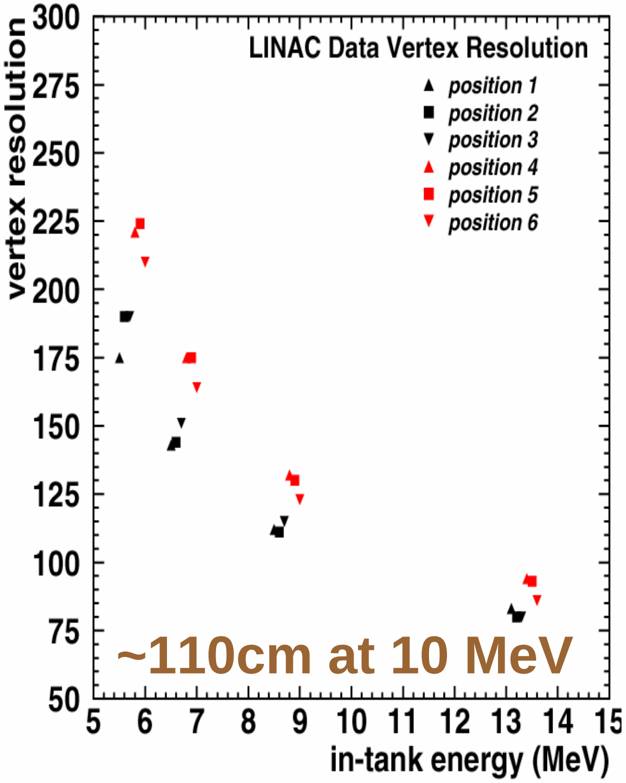
Energy resolution

(SK-I: 14%)



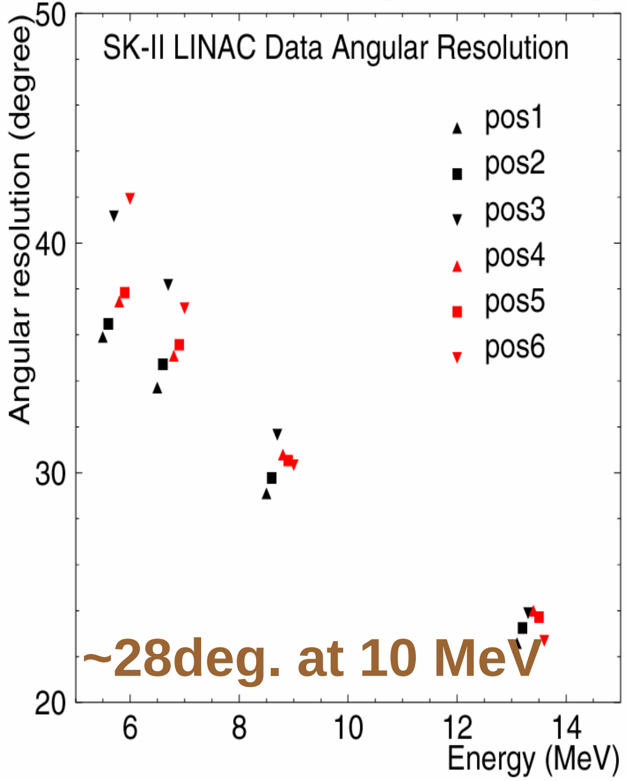
Vertex resolution

(SK-I: 87cm)



Angular resolution

(SK-I: 26^o)

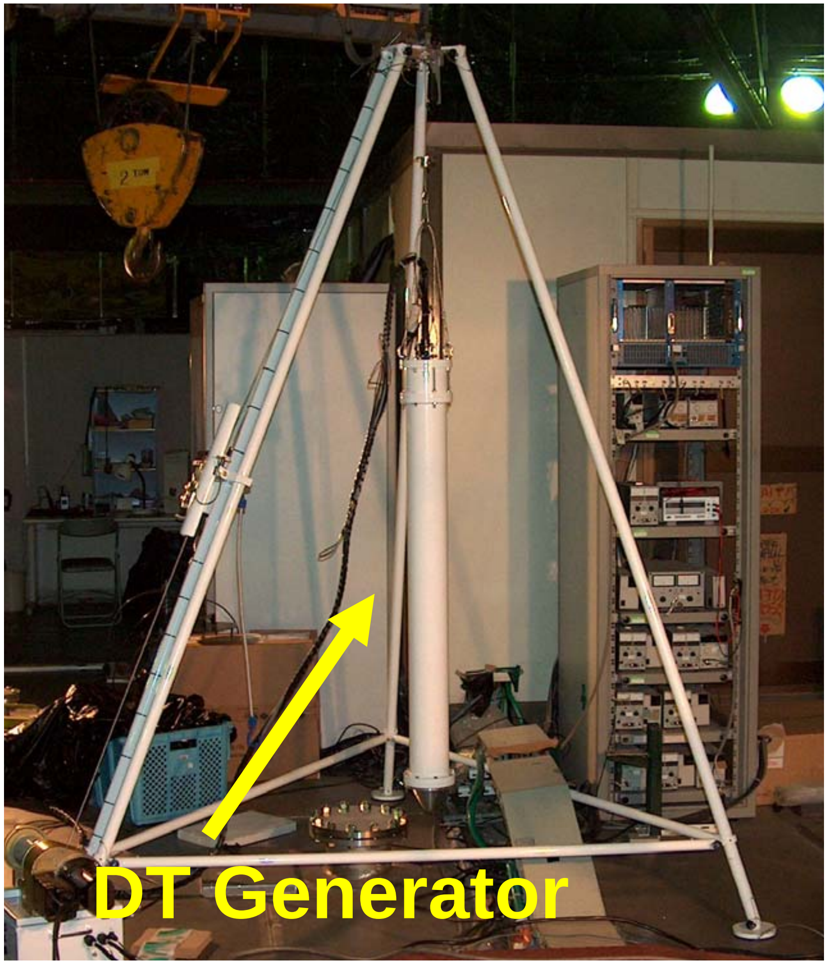


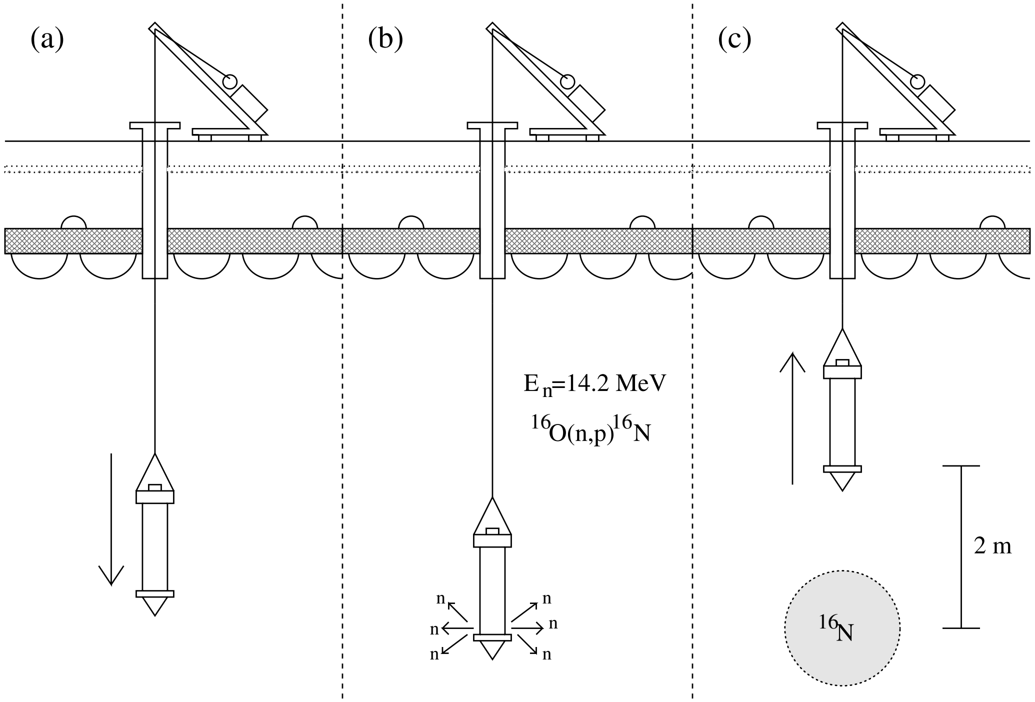
- There still exist a minor problem.
- More tuning will be done in near future.

^{16}N calibration

$D + T \rightarrow {}^{4}He + n$

$n + {}^{16}O \rightarrow p + {}^{16}N$





~10^6 neutrons / pulse

~1% of neutrons create ^{16}N

^{16}N decay is precisely known.

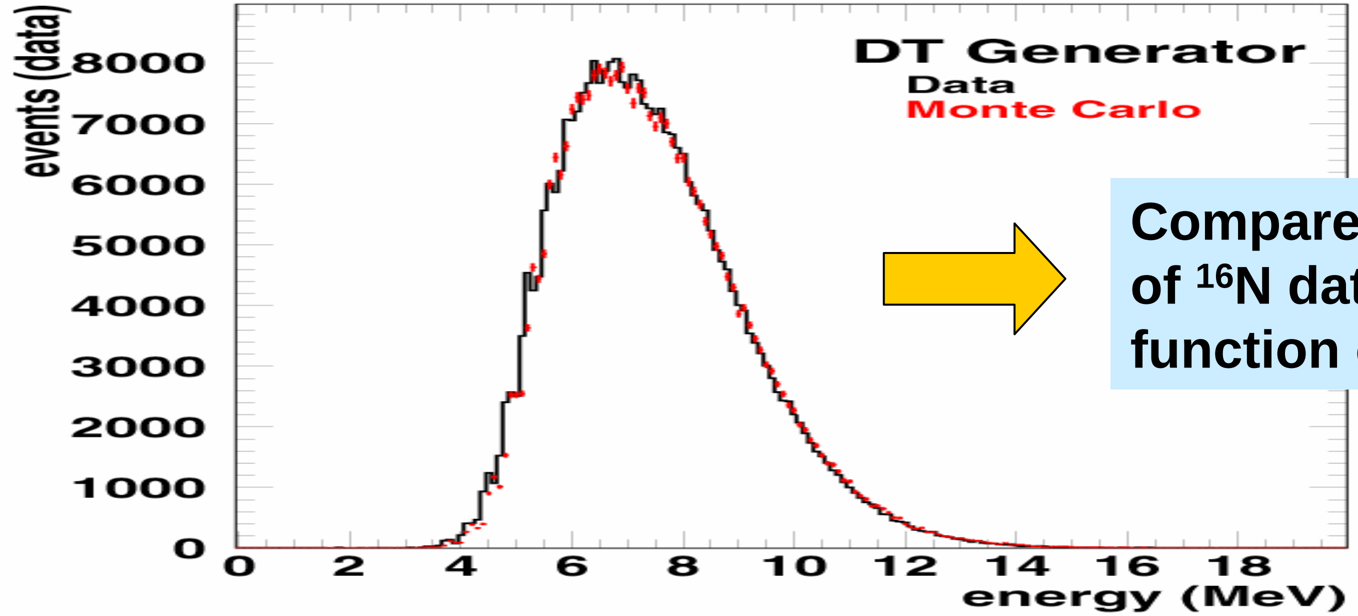
66.2% 6.129MeV γ + 4.29MeV β,

28.0% 10.419 MeV β, etc.

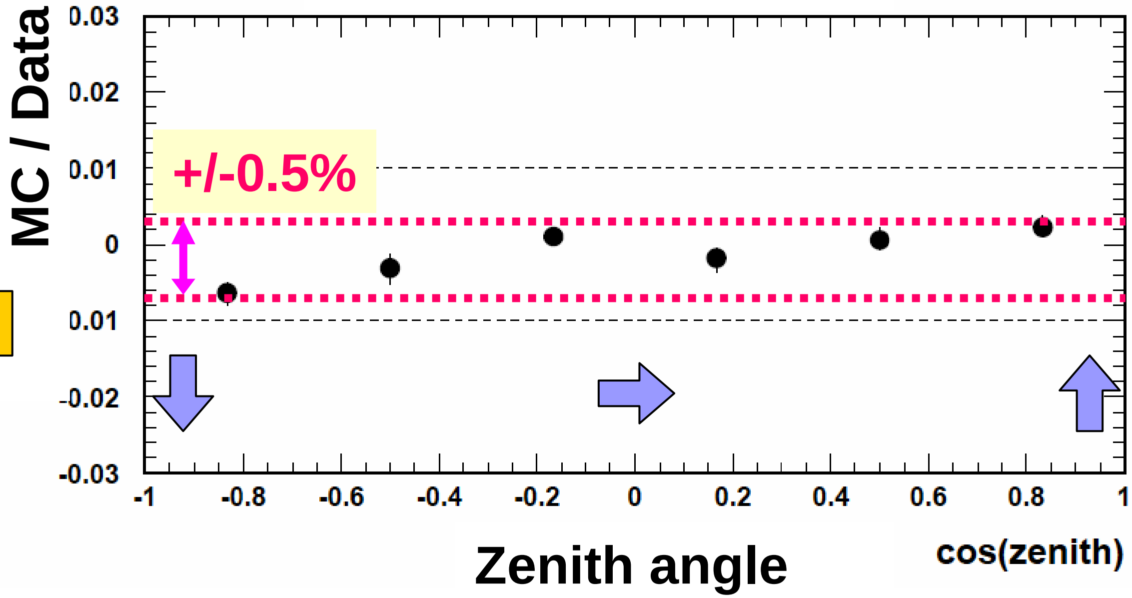
Data taken at various positions.

Uniform direction complementary to LINAC calibration.

^{16}N Calibration



Compare energy distribution of ^{16}N data and MC as a function of zenith angle



Energy Scale Uncertainty (relative)

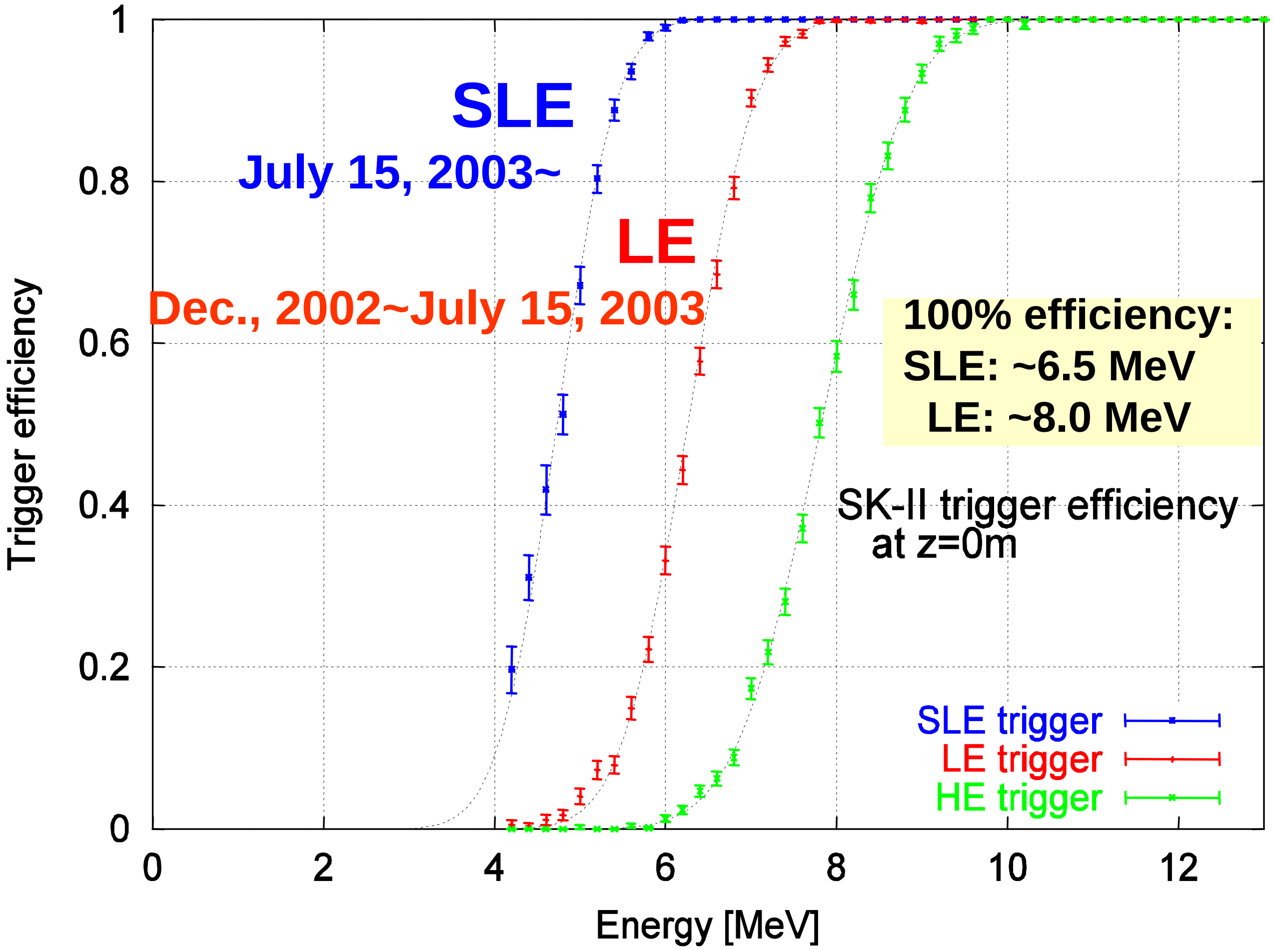
+/-0.5%

(Preliminary)

(SK-I: 0.5%)

SK-II: Trigger efficiency

Low Energy (LE) trigger: Number of hit PMTs within 200nsec: $N_{200ns} > 14$
Super Low Energy (SLE) trigger: $N_{200ns} > 10$ (added after July 15, 2003)



- **Obtained by DTG**
- **Online vertex reconstruction and fiducial volume cut (Intelligent Trigger) are applied to SLE events.**

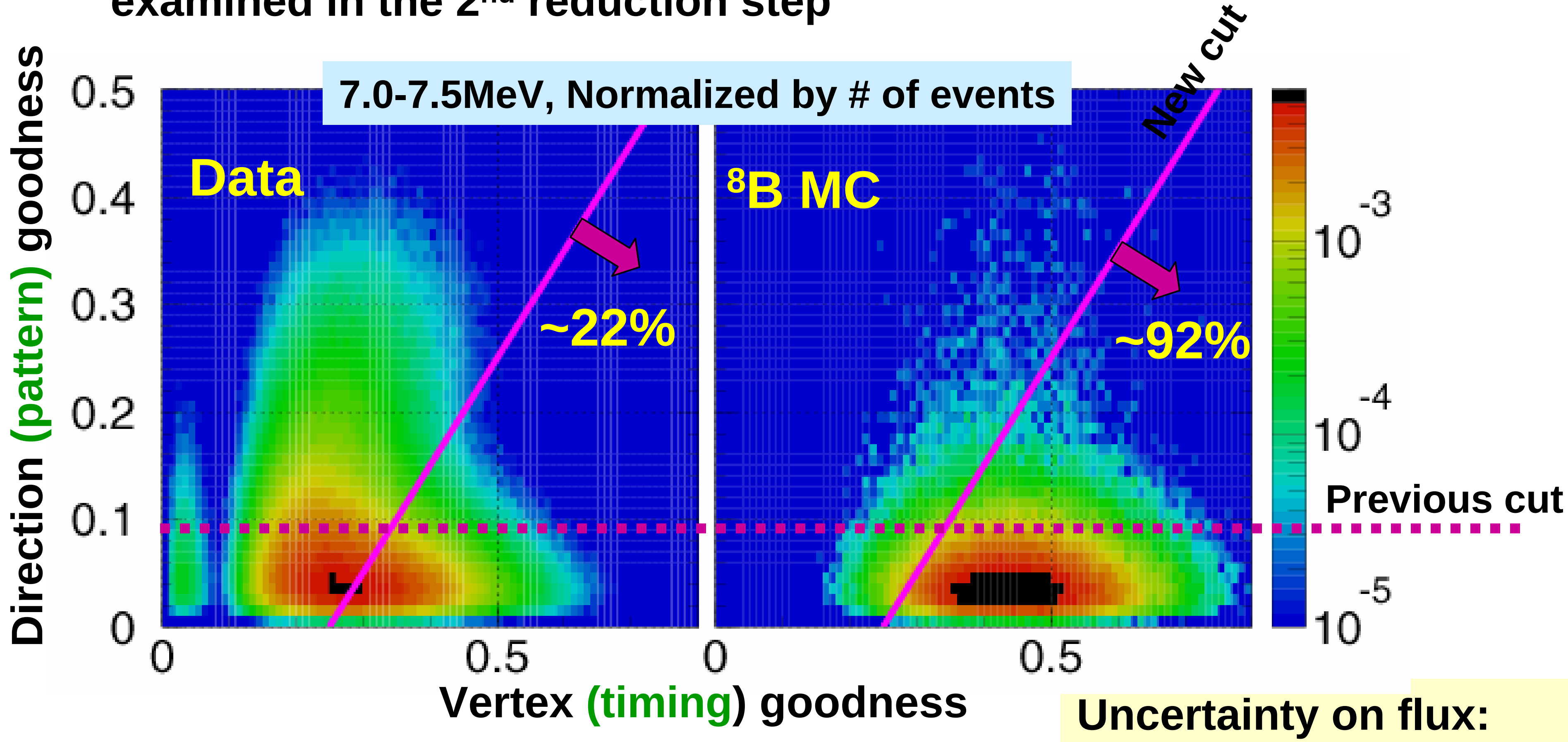
Analysis threshold:

During LE only: 8.0 MeV

After SLE: 7.0 MeV

Low-energy BG reduction

- Major BG in low-energy region comes from vertex resolution tail of the events outside fiducial volume.
- Goodness of vertex and direction reconstructions are precisely examined in the 2nd reduction step

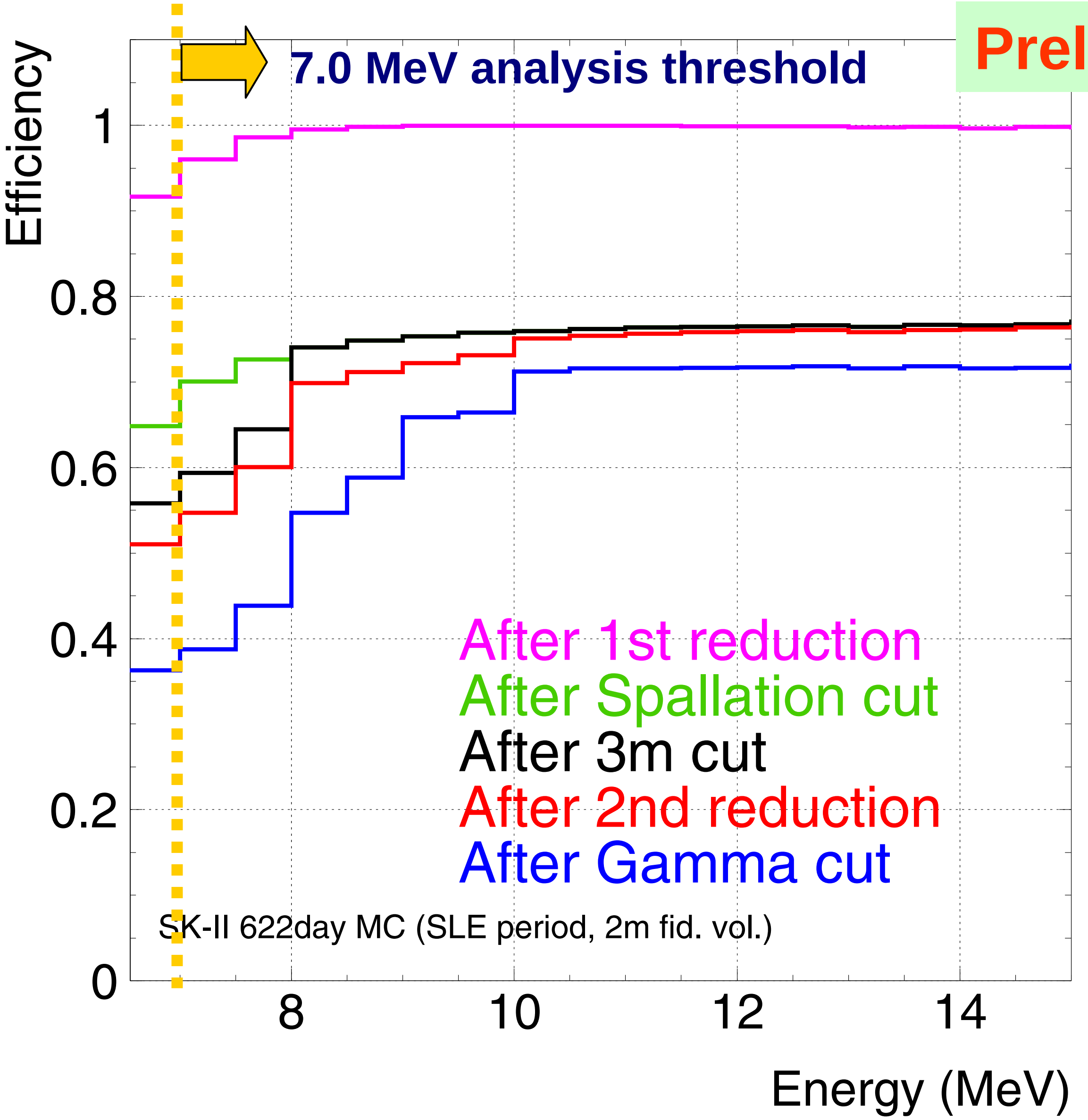


Apply the same cut on LINAC data & MC

Uncertainty on flux:

+/-3.0% for 7.0-20MeV

Reduction efficiencies



Preliminary

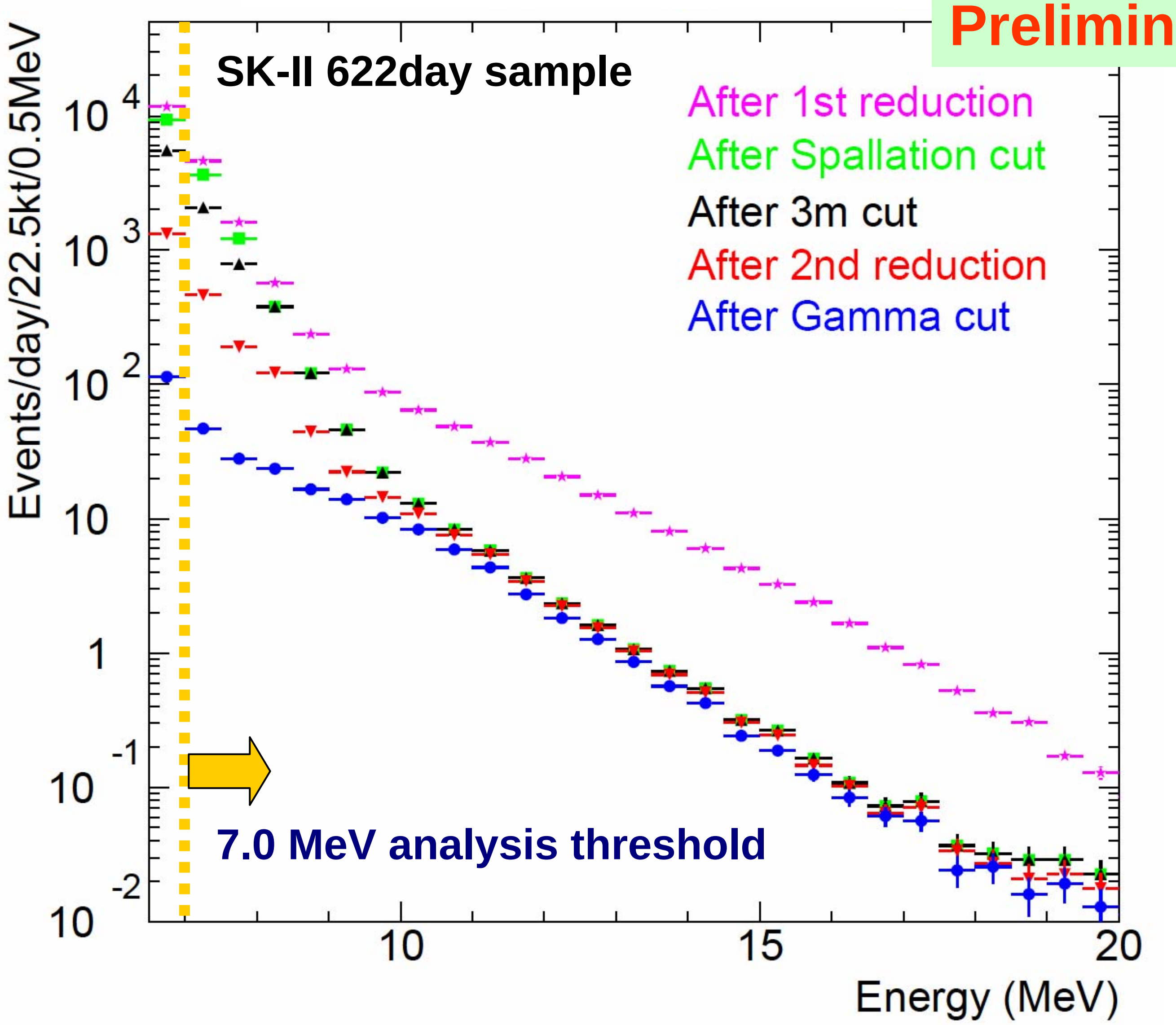
- Keep 40~70% signals
- **Inefficiency in the low-energy region in the 1st reduction is due to the online fiducial volume cut by a different fitter in the Intelligent Trigger (IT).**

Uncertainty of IT on flux:

+/-0.5% for 7.0-20MeV

Reduction steps

Preliminary



- **Spallation cut reduces BGs in higher energy region**
- **Other cuts reduce BGs in lower energy region**

Summary of systematic errors

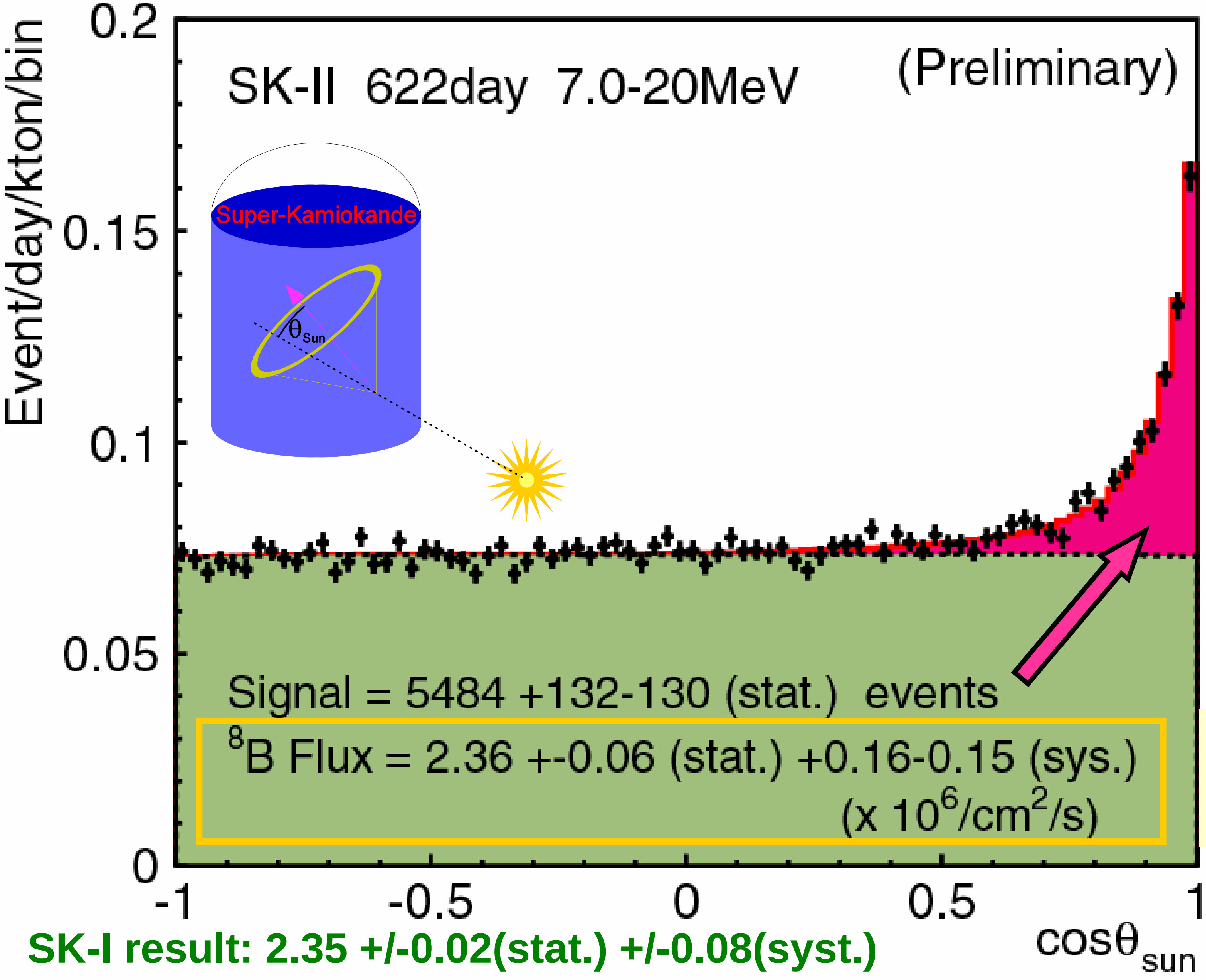
For 622day results, Preliminary	Flux (%) 7.0-20 MeV	Day/Night 7.5-20 MeV
Energy scale (absolute +/-1.4%)	+4.3 -3.9	-
Energy scale (relative +/-0.5%)	-	+1.4 -1.5
Energy resolution (2.5%)	+/-0.3	-
^{8}B spectrum	+/-1.9	-
Trigger efficiency	+/-0.5	-
1st reduction	+/-1.0	-
2nd reduction	+/-3.0	-
Spallation dead time	+/-0.4	-
Gamma cut	+/-1.0	-
Vertex shift	+/-1.1	-
Non-flat background	+/-0.4	+/-2.0
Angular resolution	+/-3.0	-
Cross section	+/-0.5	-
Live time	+/-0.1	+/-0.1
Total	**+6.7 -6.4**	**+2.4 -2.5**

Could be reduced by further MC simulation tuning

SK-II 622day Data set

- Analysis periods & energy thresholds:
  - Dec. 24, 2002 – July 15, 2003, 159 days, 8.0-20MeV
  - July 15, 2003 – March 19, 2005, 463 days, 7.0-20MeV
  - Total live time: 622 days

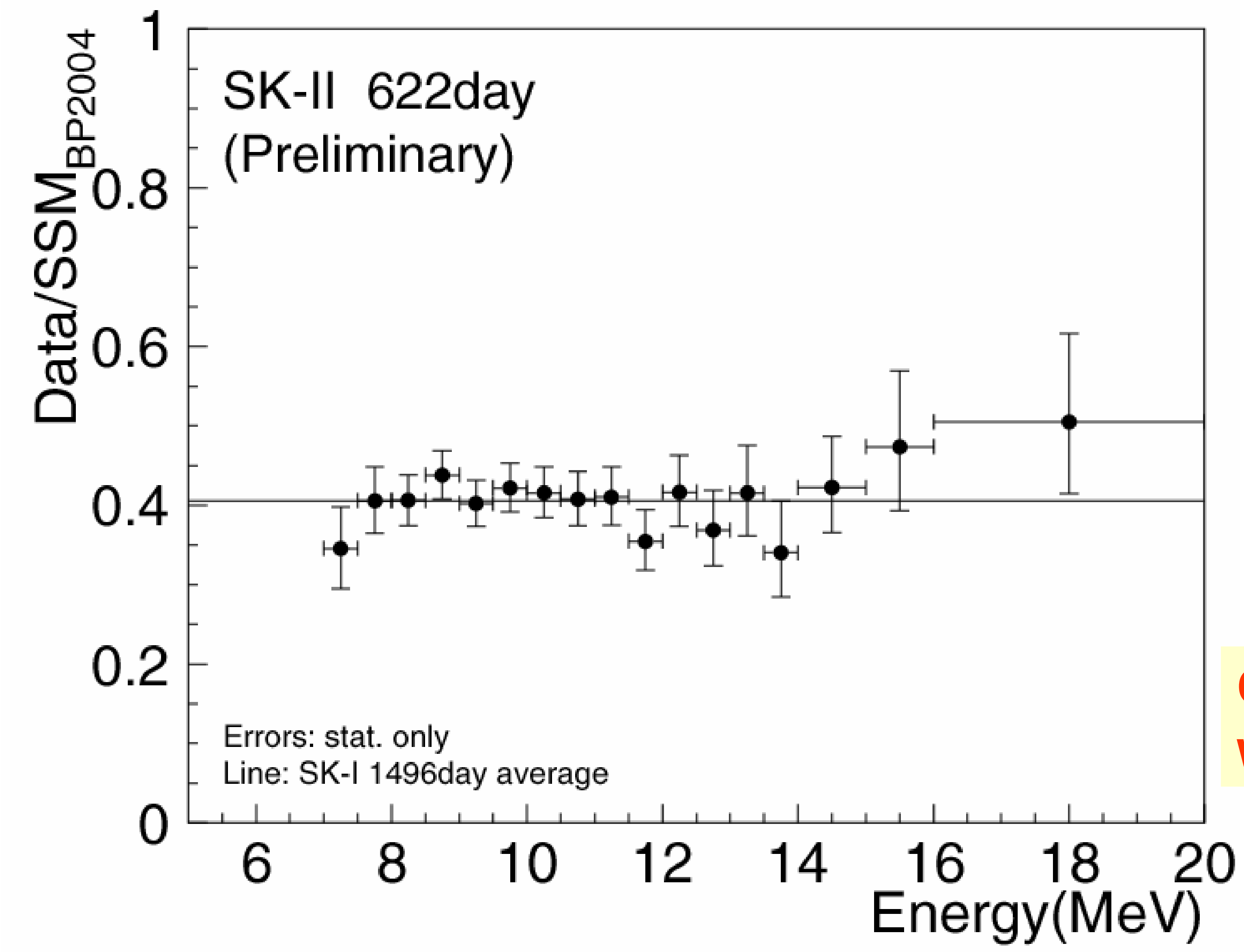
^{8}B Flux



Consistent with SK-I

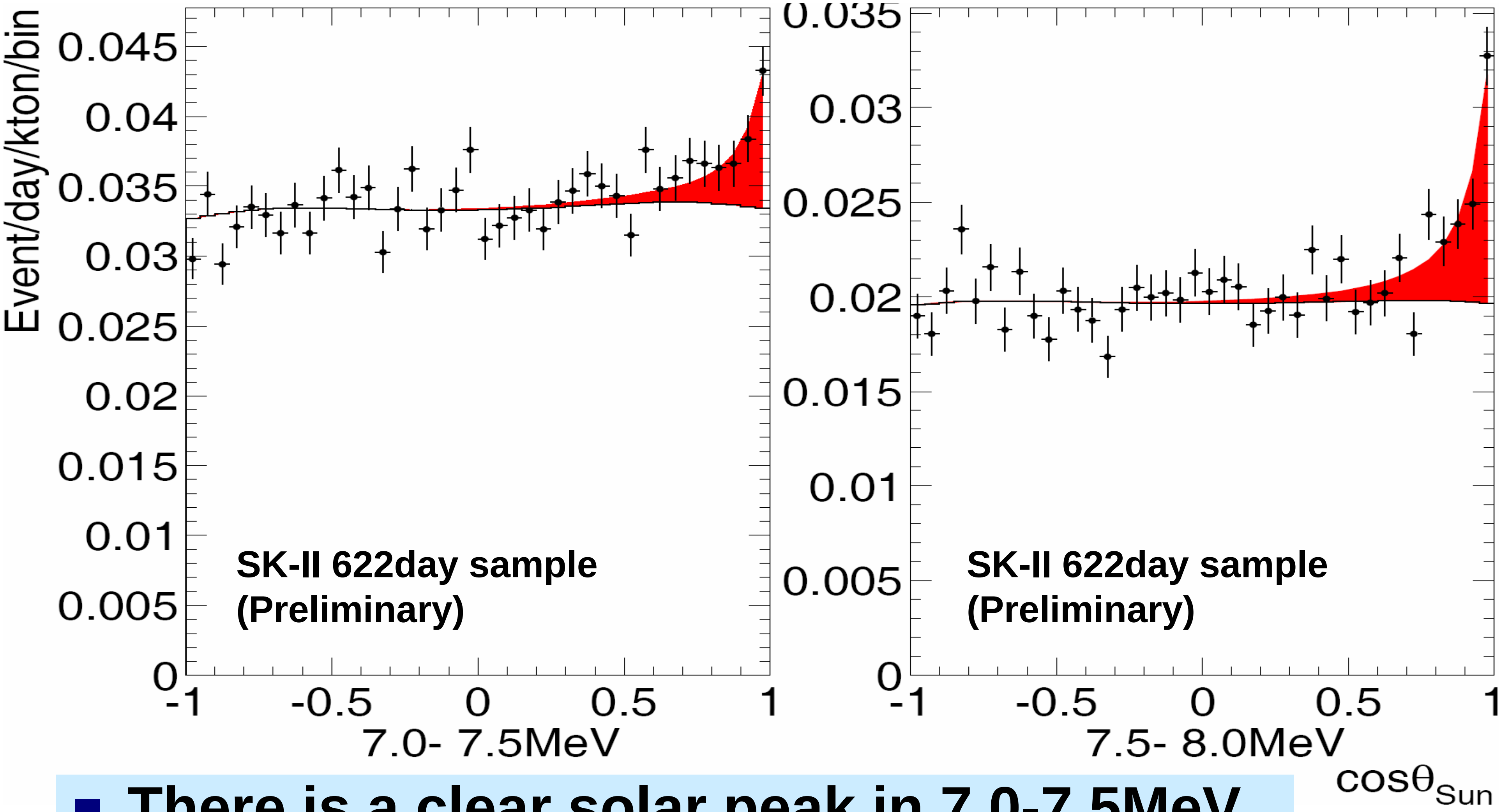
SK-I result: 2.35 +/-0.02(stat.) +/-0.08(syst.)

Energy spectrum



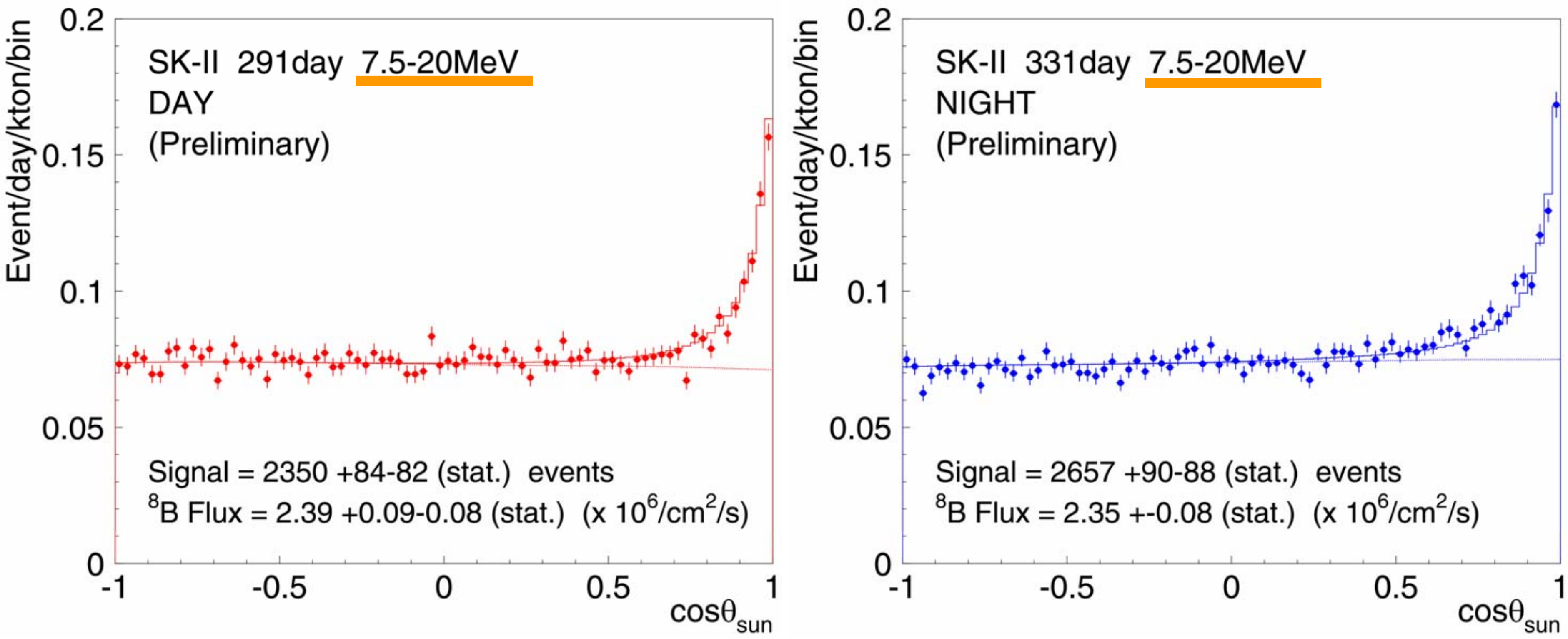
Consistent with SK-I

Solar peak in 7.0-8.0MeV



- **There is a clear solar peak in 7.0-7.5MeV**
- **Study SK-II 6.5-7.0MeV region soon**

Day / Night asymmetry

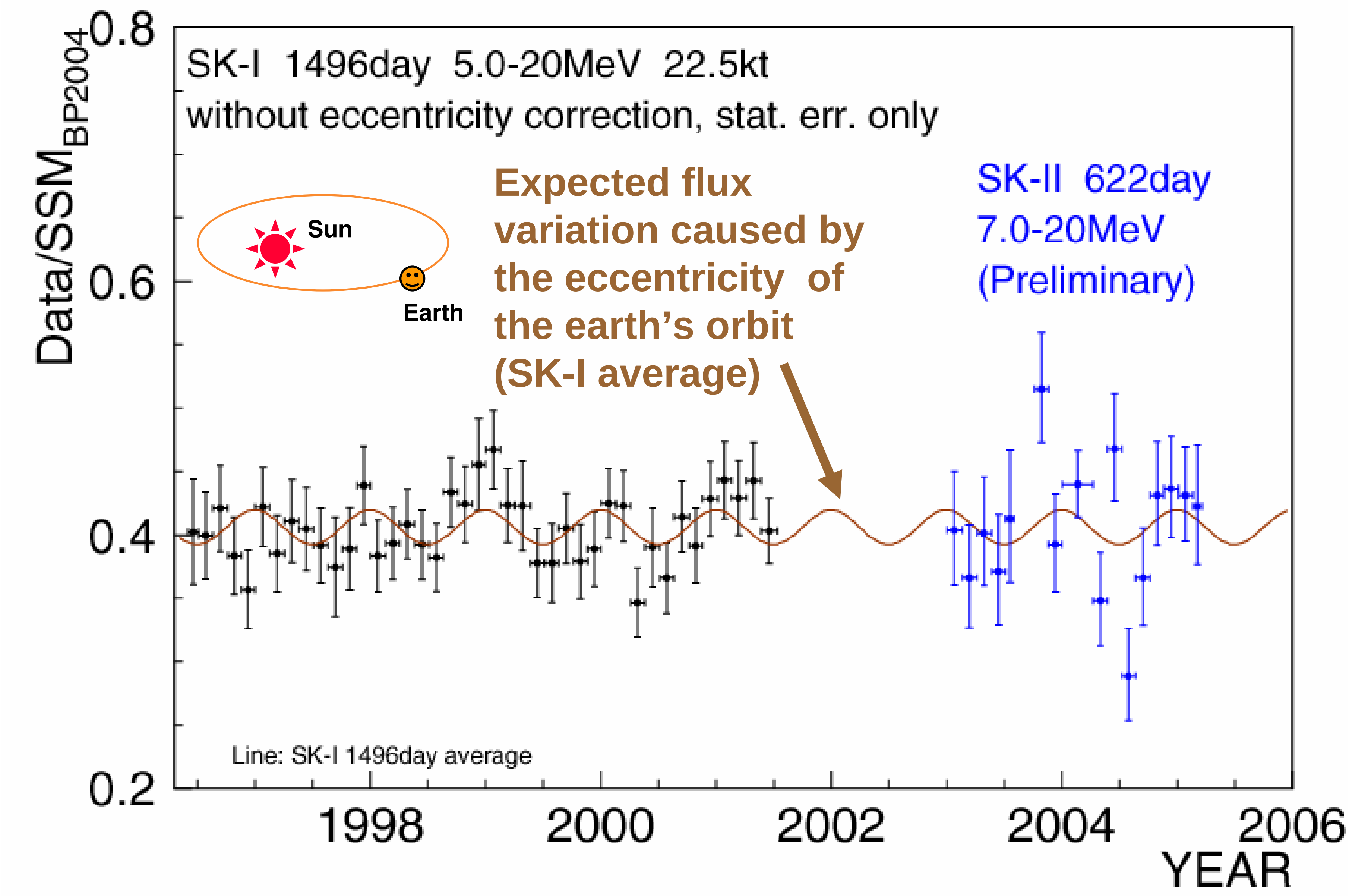


$$A_{DN} = \frac{(\text{Day-Night})}{(\text{Day+Night})/2} = 0.014 +/- 0.049(\text{stat.})\,^{+0.024}_{-0.025}\,(\text{sys.})$$

Preliminary

SK-I D/N Asymmetry: $-0.021 +/- 0.020\,^{+0.013}_{-0.012}$

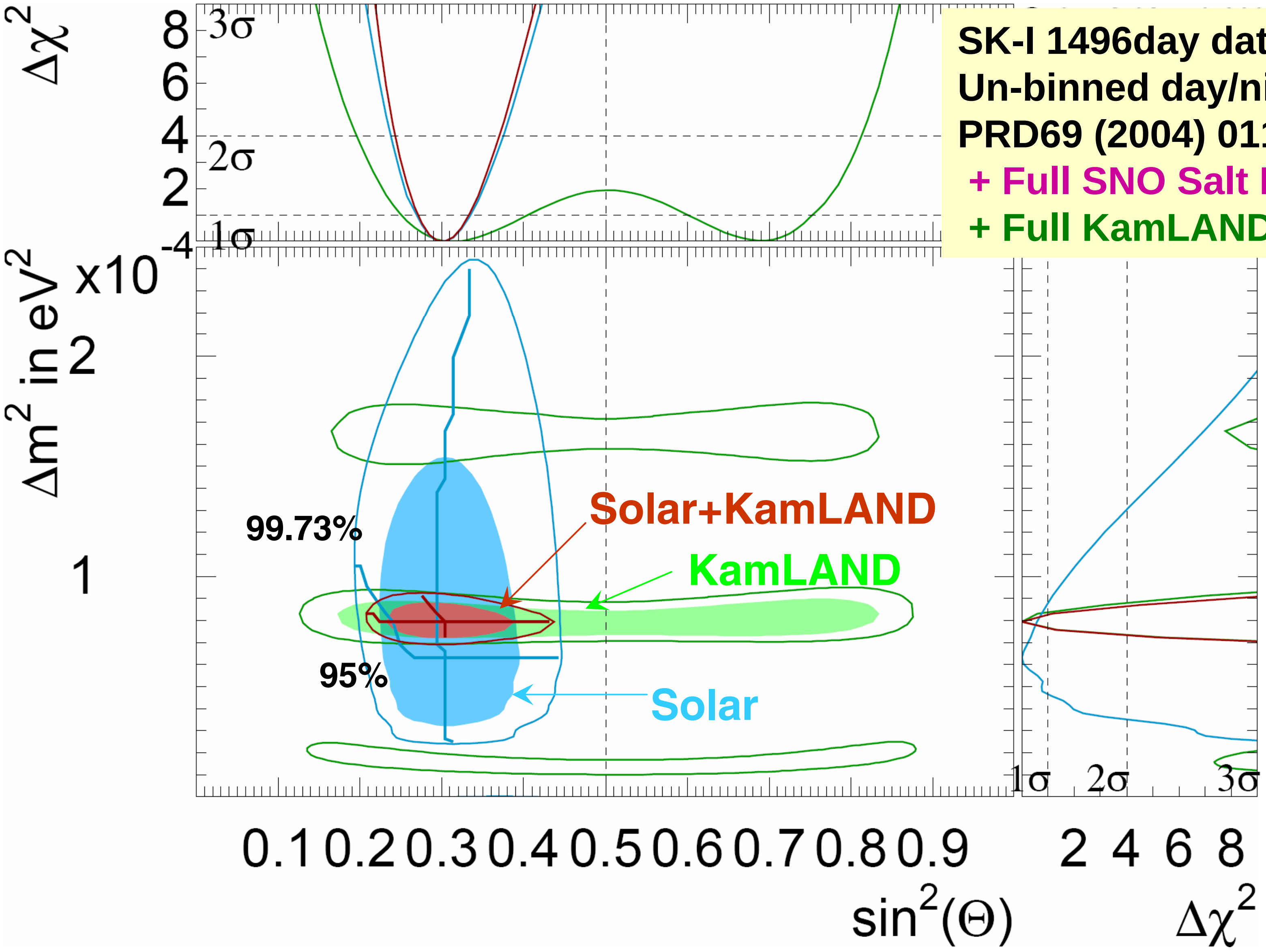
Time variation



Expected flux variation caused by the eccentricity of the earth's orbit (SK-I average)

SK-I 2-flavor oscillation analysis update

SK-I 1496day data
Un-binned day/night analysis
PRD69 (2004) 011104
+ Full SNO Salt NC & CC fluxes
+ Full KamLAND likelihood



SK-I 3-flavor solar neutrino oscillation analysis

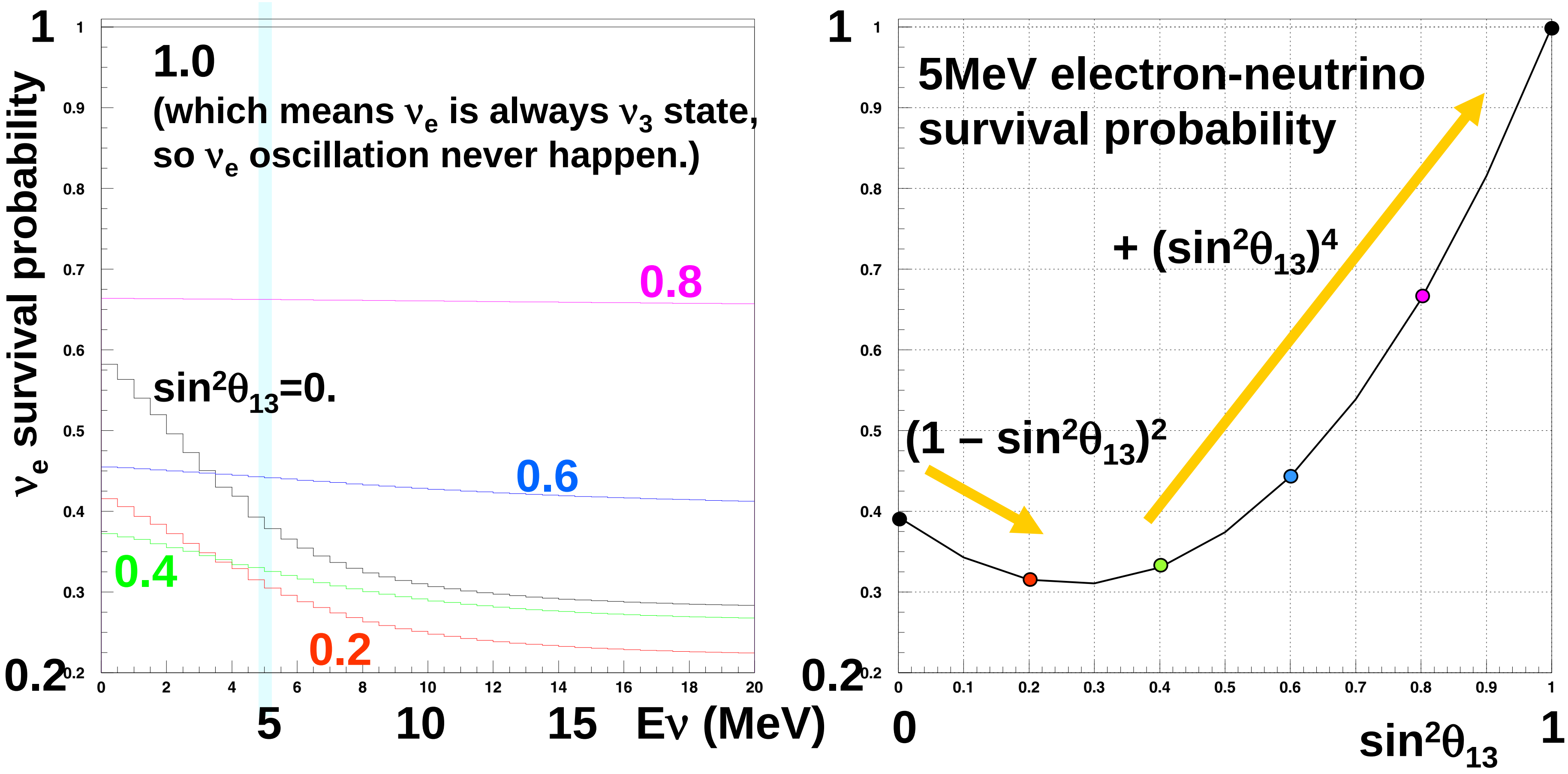
- Started to develop 3-flavor solar neutrino oscillation analysis tools
- Use the following formula. (C.S.Lim et al)

$$P^{(3)}(\nu_e \rightarrow \nu_e; A(x)) = (1-|\underset{\sin^2\theta_{13}}{\boxed{U_{e3}|^2}})^2 P^{(2)}(\nu_e \rightarrow \nu_e; (1-|U_{e3}|^2)\underset{\text{Matter effect}}{\boxed{A(x)}}) + |U_{e3}|^4$$

- Input data (for now)
  - SK-I zenith spectra (44bins)
  - SNO Salt NC and CC fluxes
  - Results from Ga and Cl experiments

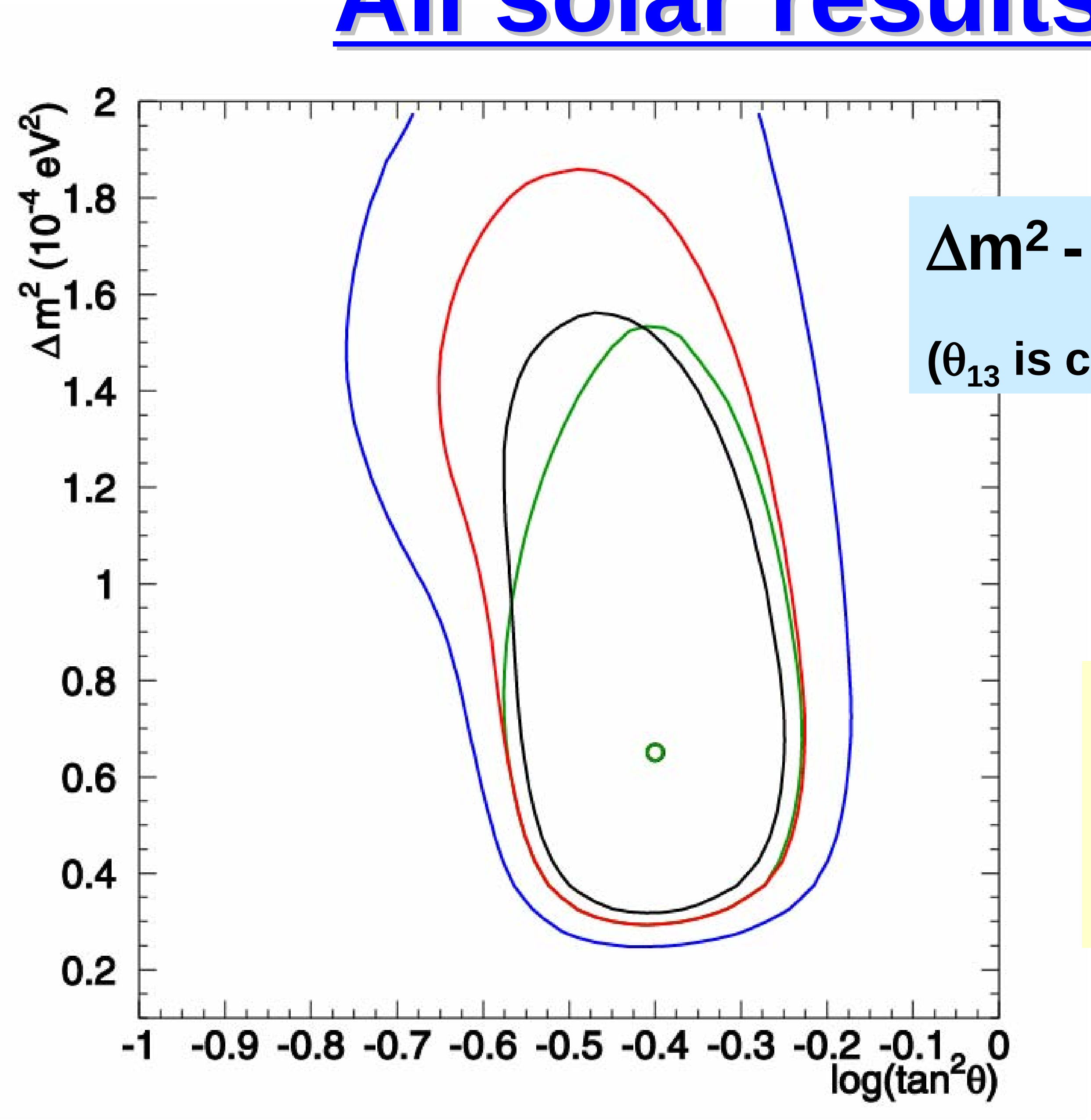
Expected effect by θ_{13}

($\tan^2\theta_{12}$=0.38, Δm_{12}^2=8.3x10^{-5})



Absolute ν_e flux change and spectrum distortion are expected.

All solar results



Δm^2 - θ_{12} plot.

(θ_{13} is chosen to minimize χ^2.)

90%C.L. θ_{13}=0

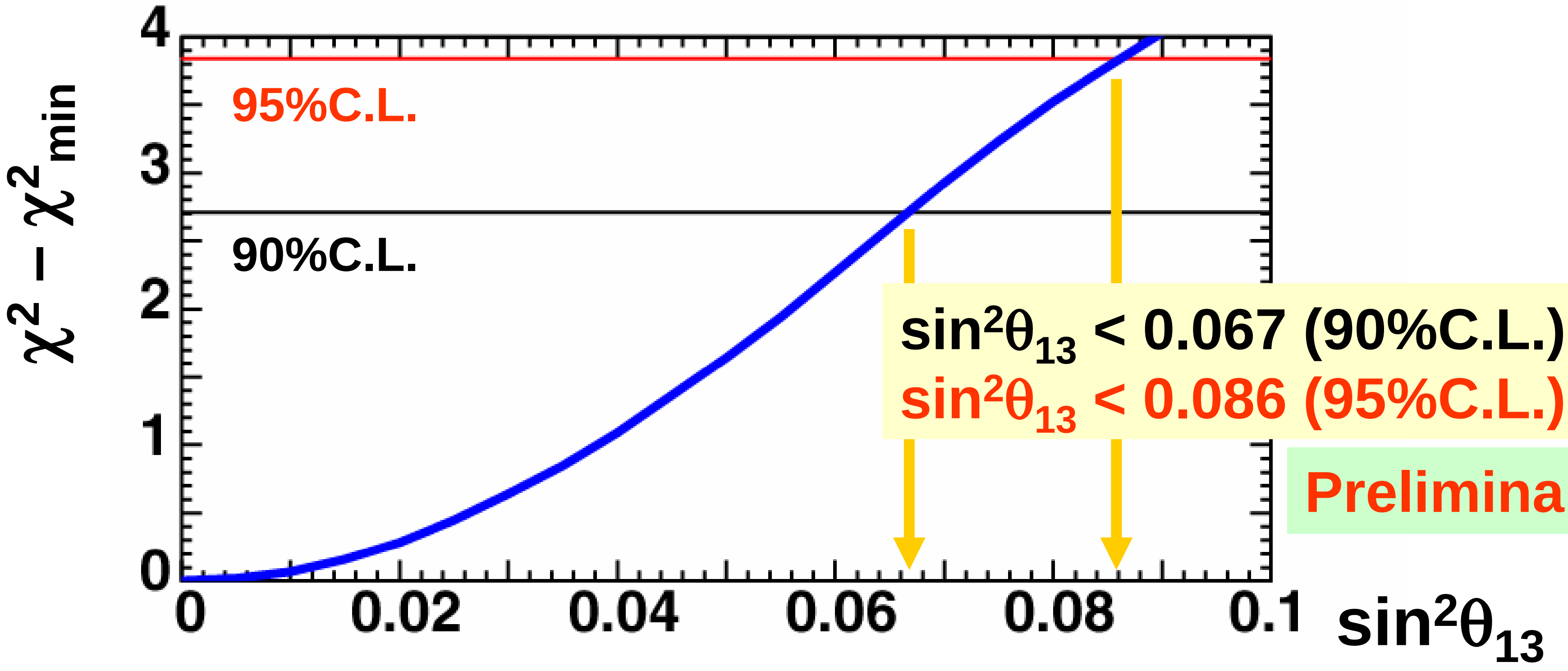
90%C.L.

95%C.L.

99%C.L.

1-dimention plot (θ_{13})

$\chi^2 - \chi^2_{min}$ distribution as a function of $\sin^2\theta_{13}$.
(here, the other oscillation parameters are chosen to minimize χ^2.)

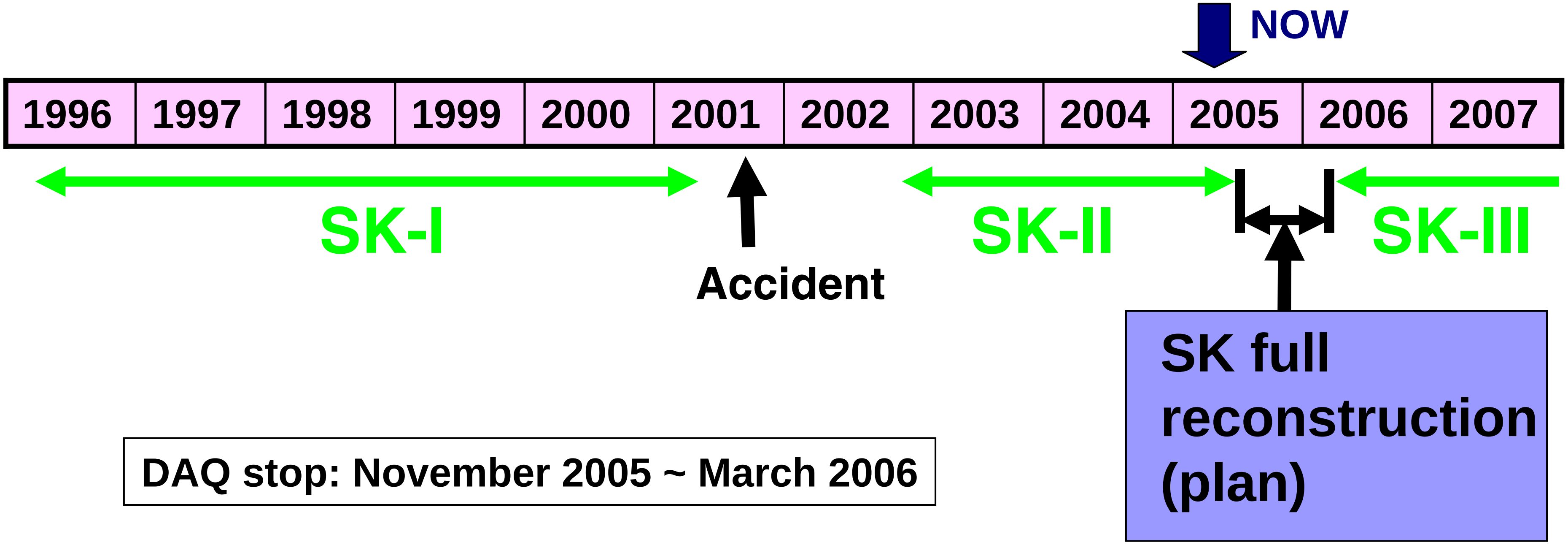


$\sin^2\theta_{13} < 0.067$ (90%C.L.)
$\sin^2\theta_{13} < 0.086$ (95%C.L.)

Preliminary

- To do:
  - ☐ Include KamLAND, move to un-binned D/N
  - ☐ Integration with atmospheric neutrino data

Future plan



NOW

1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007

SK-I

Accident

SK-II

SK-III

SK full reconstruction (plan)

DAQ stop: November 2005 ~ March 2006

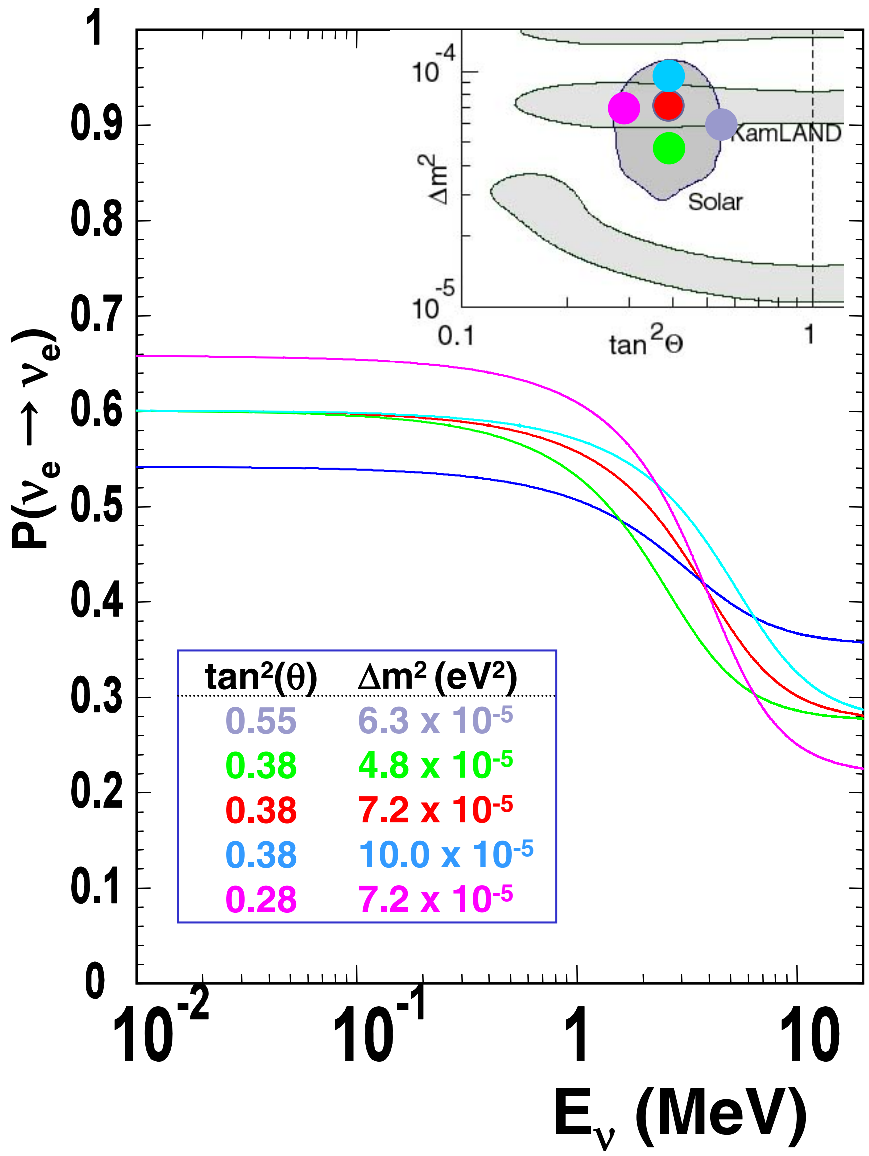
ID PMT: SK-II = ~5200 ⇨ SK-III = 11146 (same as SK-I)
Original energy & vertex resolutions for low-energy events

⇨ **Solar neutrinos below 5.0MeV with improved analysis tools and lower Rn backgrounds**

⇨ **Precise study on spectrum distortion in SK-III**

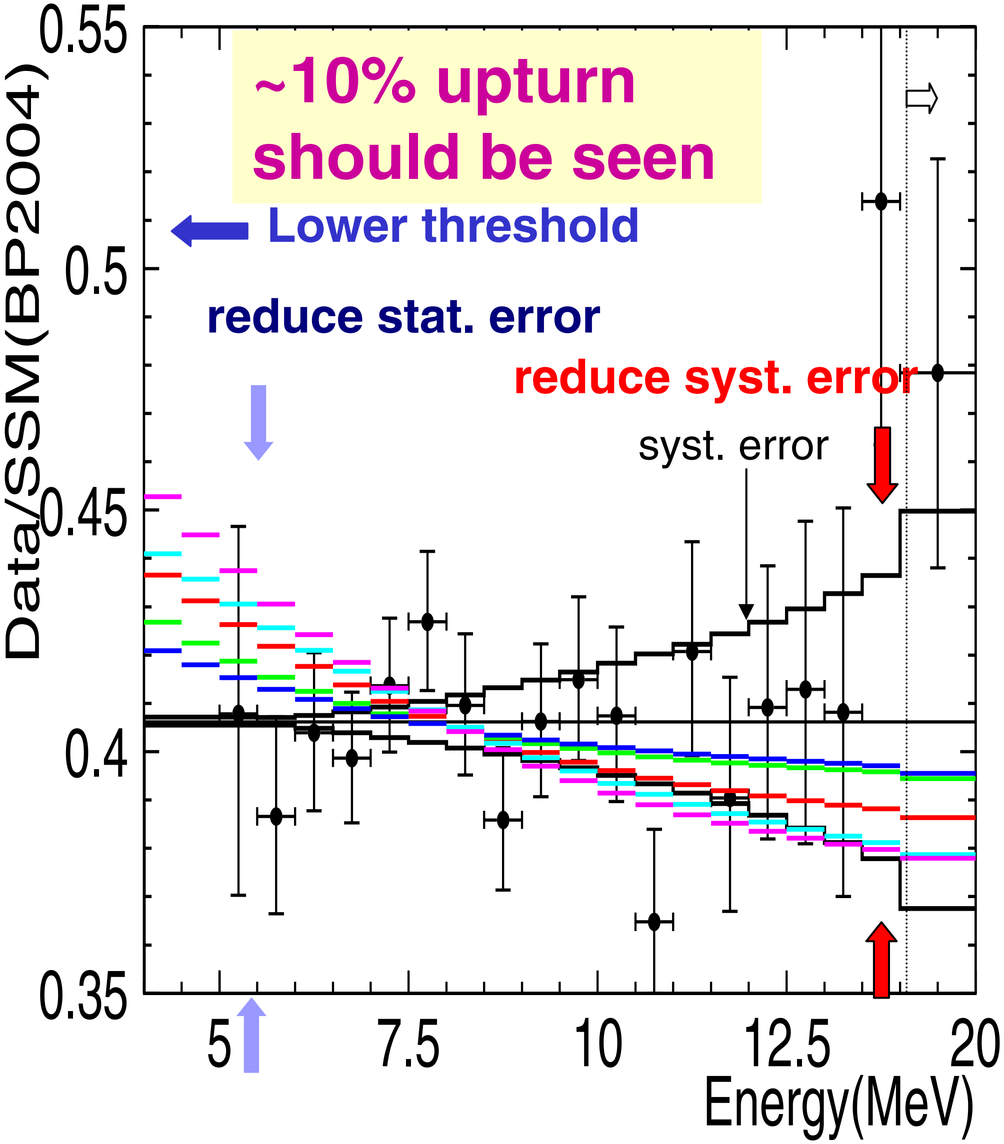
Possibility of detecting spectrum distortion

ν_e survival probability



$\tan^2(\theta)$	Δm^2 (eV²)
0.55	6.3×10^{-5}
0.38	4.8×10^{-5}
0.38	7.2×10^{-5}
0.38	10.0×10^{-5}
0.28	7.2×10^{-5}

Recoil electron spectrum



~10% upturn should be seen

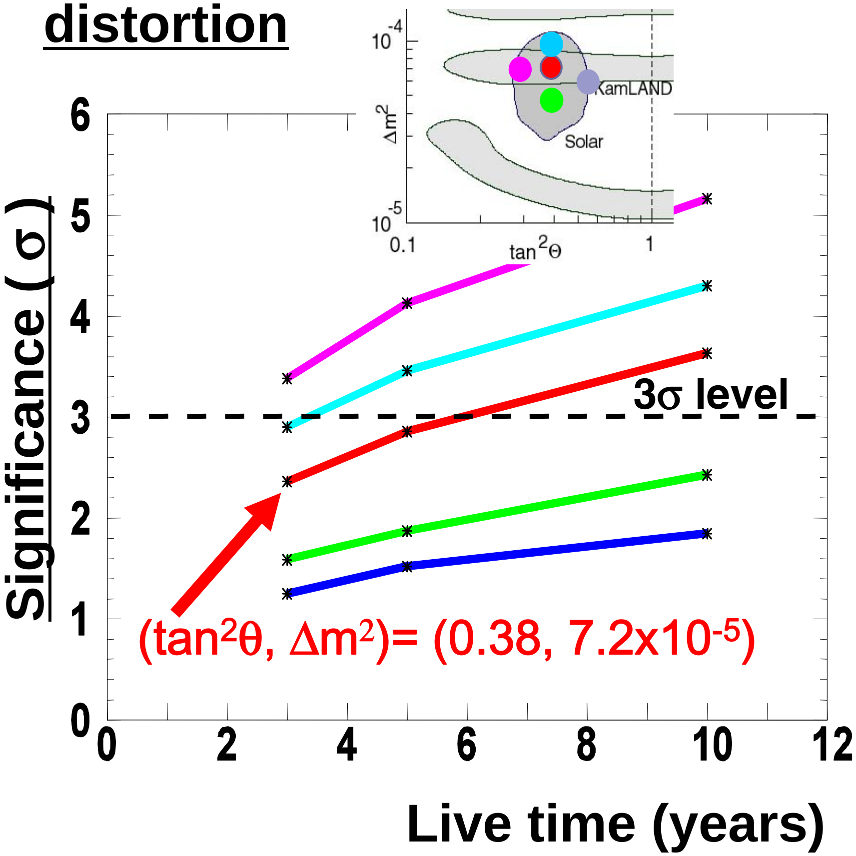
Lower threshold

reduce stat. error

reduce syst. error

Future prospects towards SK-III

Significance of spectrum distortion



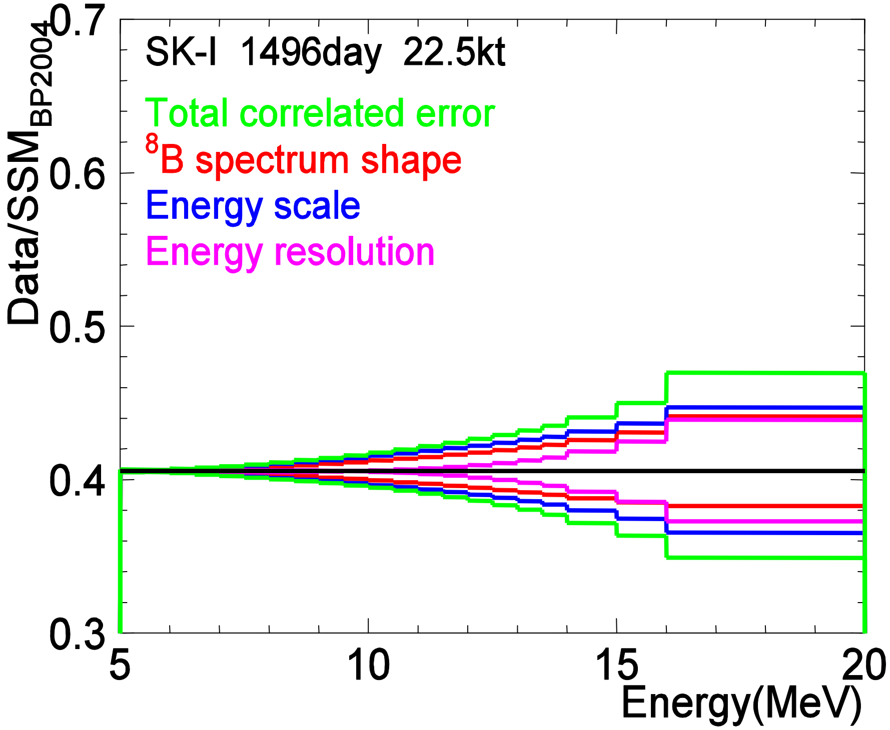
Assumptions:

Correlated systematic error: x 0.5

4.0-5.5MeV background: x 0.3

(same BG as SK-I above 5.5MeV)

Current breakdown of correlated systematic errors



- **Better energy scale calibration (~+/-0.4%) is needed.**
- **Better ^{8}B spectrum shape from nuclear physics is needed.**

A future option - Gd doped SK (GADZOOKS!)

Beacom & Vagins,

PRL93 (2004)171101

- "Gd doped SK" is seriously studied as a future option of SK, lead by UCI group.

$\overline{\nu}_e + p \rightarrow e^+ + n$ ← (tag this neutron)

0.2% $GdCl_3$ ⇒

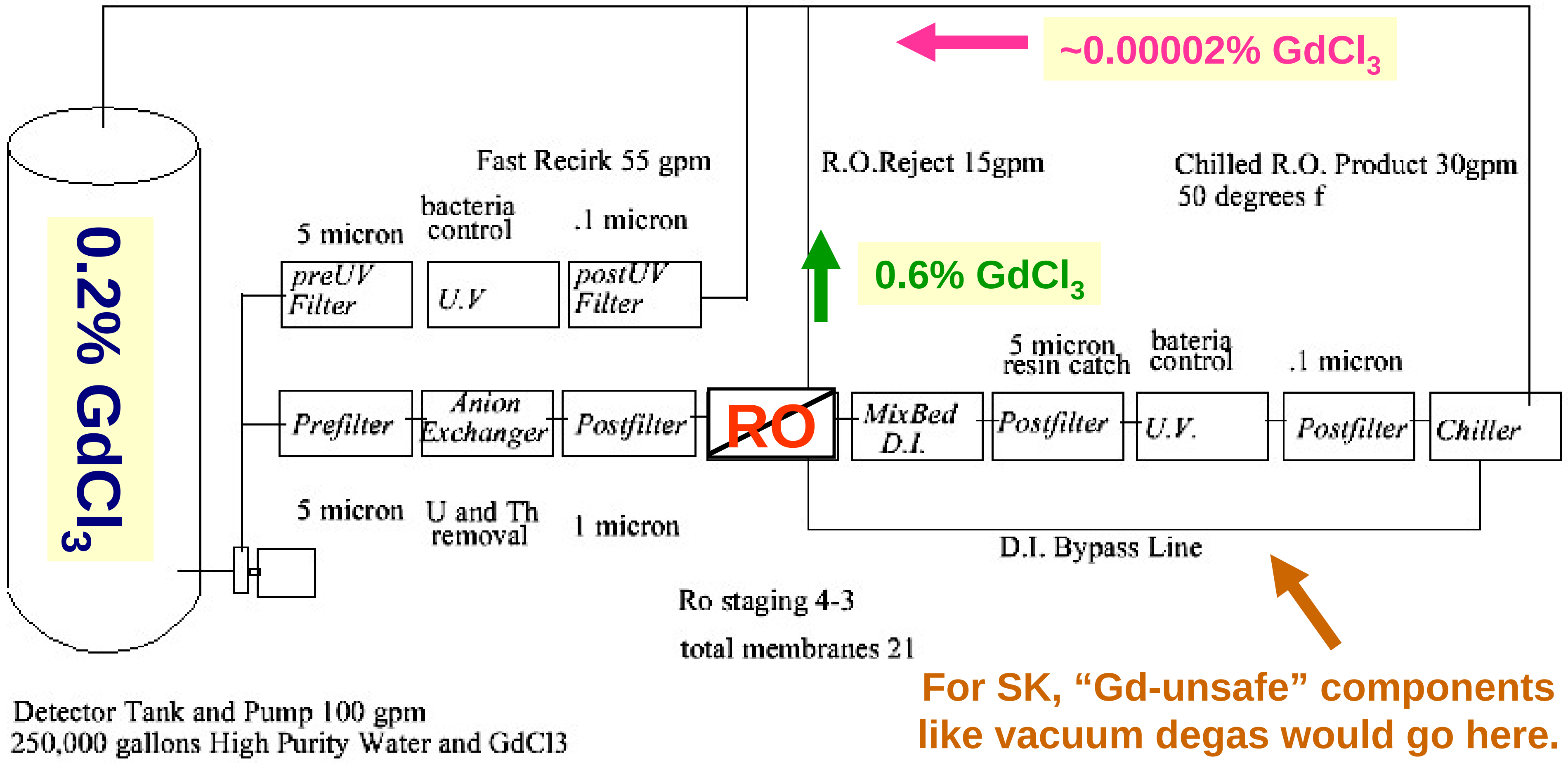
90% captured on Gd, γs, total Eγ = 8MeV
0.2% on Cl, γs, total Eγ = 8.6MeV
Others on p, 2.2MeV γ

- Physics targets: SN relic neutrinos, reactor anti-neutrinos, galactic SN neutrinos, long-baseline neutrinos, proton decay BG reduction, …

GADZOOKS!: R&D status 1

- Water purification test bench @UCI
  - Done RO test for removing Gd (~99.99% removal)
  - Under testing various anion resins for ^{238}U removal
- Material test @LSU
  - Under acceleration test of materials in SK detector
- Purification measurements by ICP-MS @Kamioka
  - 0.2% $GdCl_3$ + purified water
    - ^{238}U: 9.1×10^{-12} g/g and ^{232}Th: 6.5×10^{-13} g/g
- 1kt scale test @KEK (starting in this summer)
  - Reuse K2K 1kt water cherenkov detector after K2K run end
  - Gd Water Filtering – UCI built and maintains this water system
  - Gd Light Attenuation – using real 20” PMTs
  - Gd Materials Effects – many similar detector elements as in SK

GADZOOKS!: water system design for K2K 1kt detector



~0.00002% $GdCl_3$

0.6% $GdCl_3$

0.2% $GdCl_3$

For SK, “Gd-unsafe” components like vacuum degas would go here.

The entire one kiloton volume is recirculated every two days.

Summary

- High statistics solar neutrino data has been taken at Super-Kamiokade.
- Energy threshold was lowered to 7.0MeV in SK-II
- Preliminary results from SK-II 622 days data are obtained. They are consistent with SK-I.
    - ^{8}B flux: 2.36 +/-0.06(stat.) +0.16/-0.15(syst.)
- Full reconstruction of the SK detector is planned in November 2005 ~ March 2006.
- Hope to see definite energy spectrum distortion in SK-III, if it should be there.