Solar Neutrino Results from Super-Kamiokande

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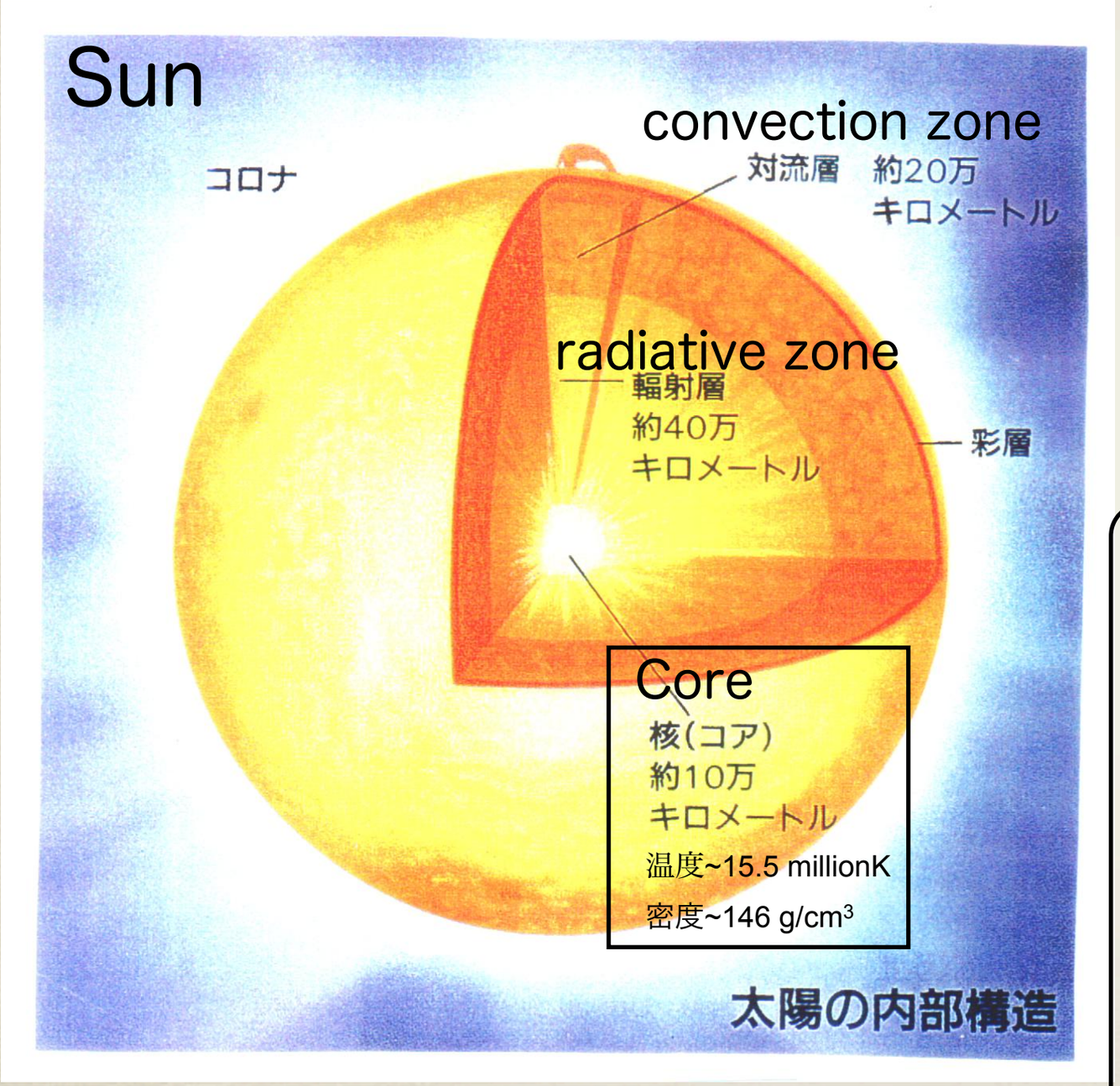
Solar neutrinos



Nuclear fusion reaction deep inside the Sun

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

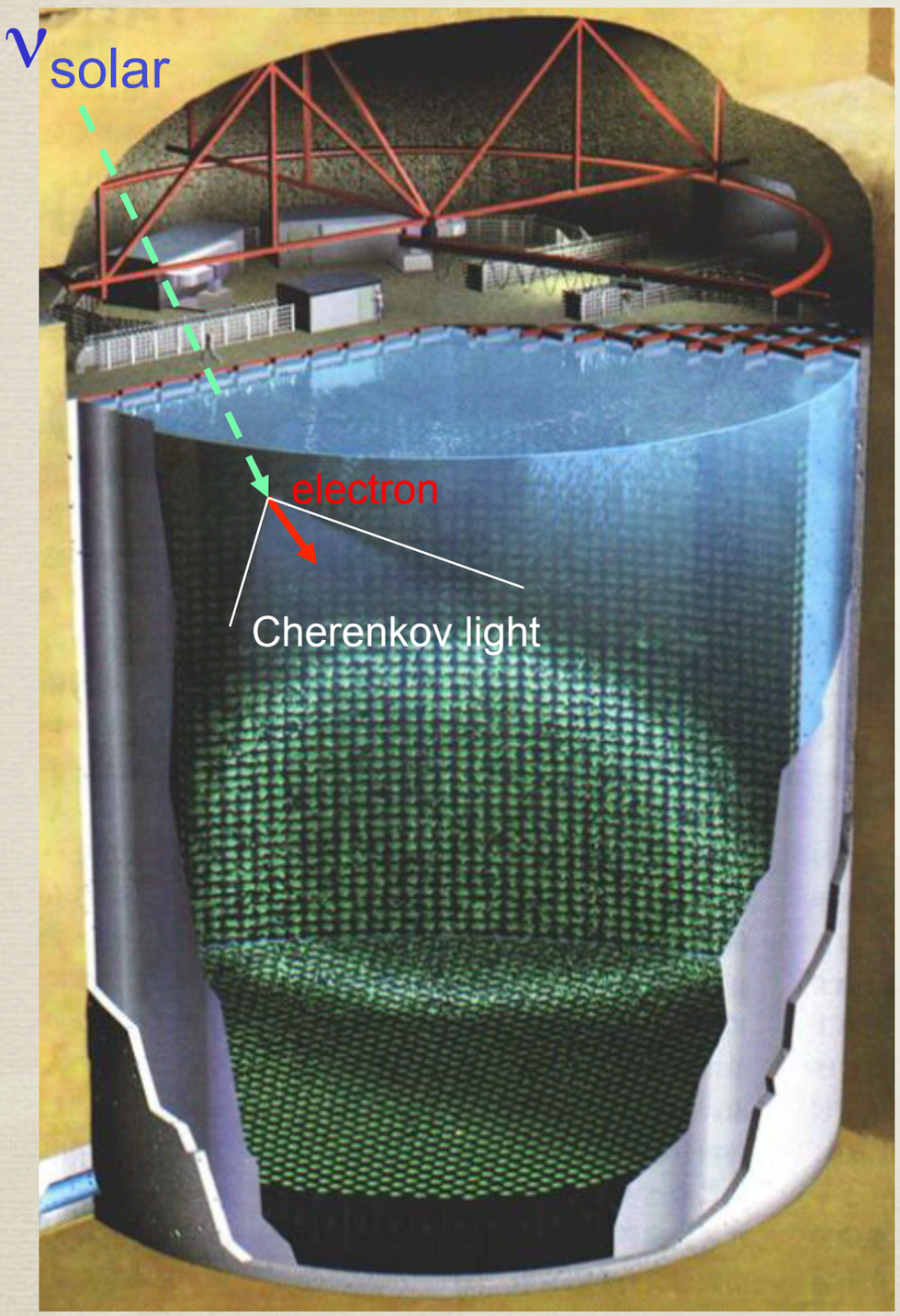
(~6.6×10^{10}neutrinos/sec/cm^2)

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

Feature/Purpose of measurement

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

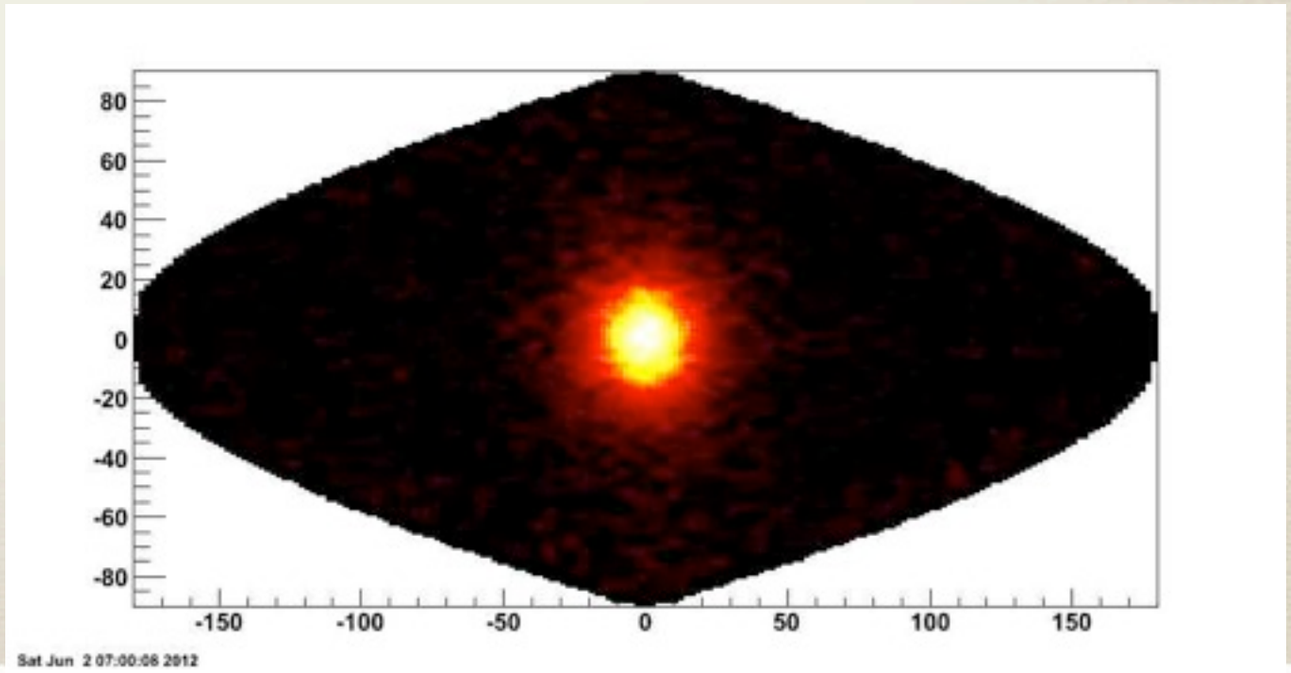
Observation in Super-K



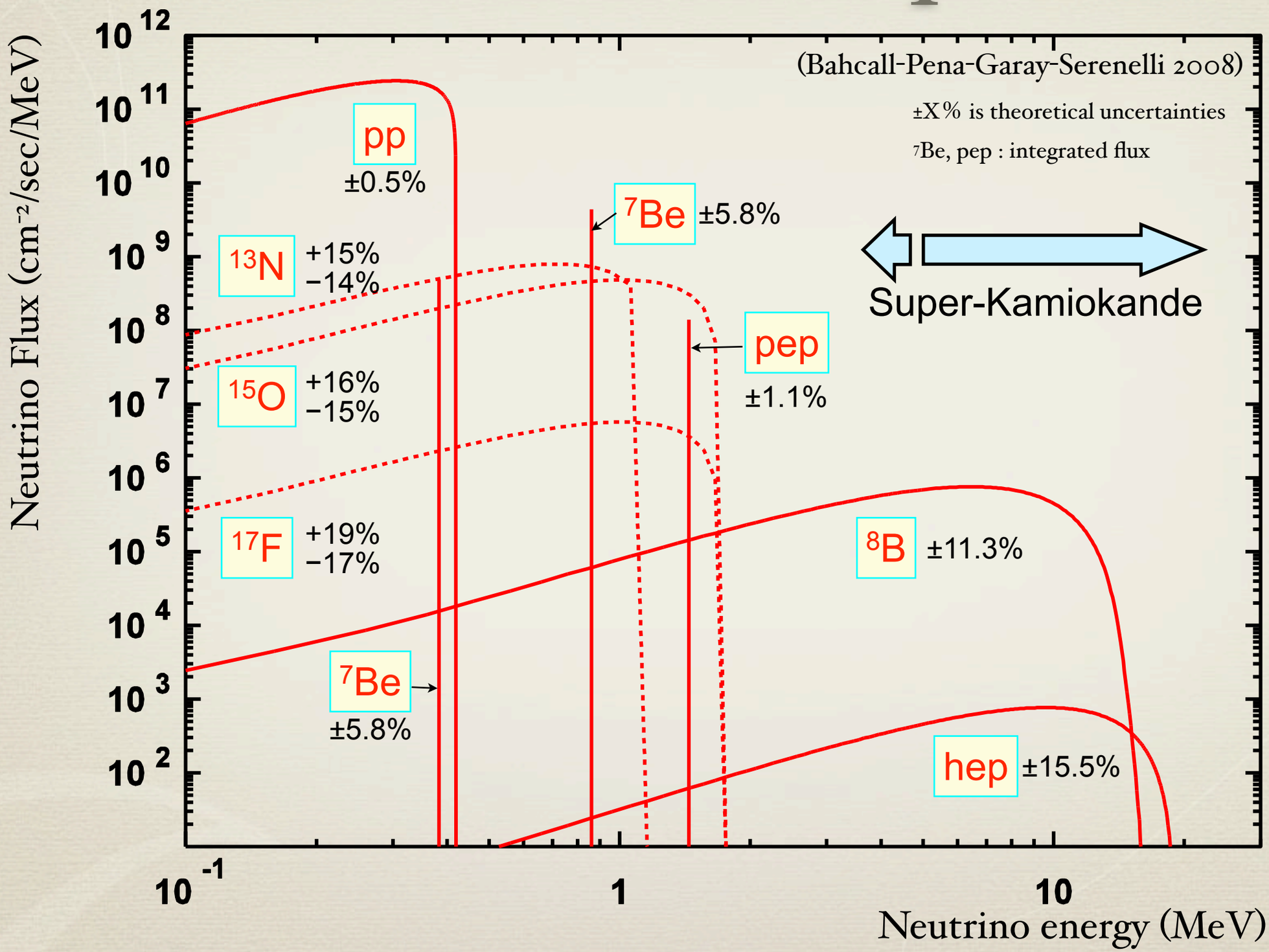
Neutrino-electron elastic scattering

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

- Find solar direction
- Realtime measurements
  - day/night flux differences
  - Seasonal variation
- Energy spectrum



Solar neutrino spectrum

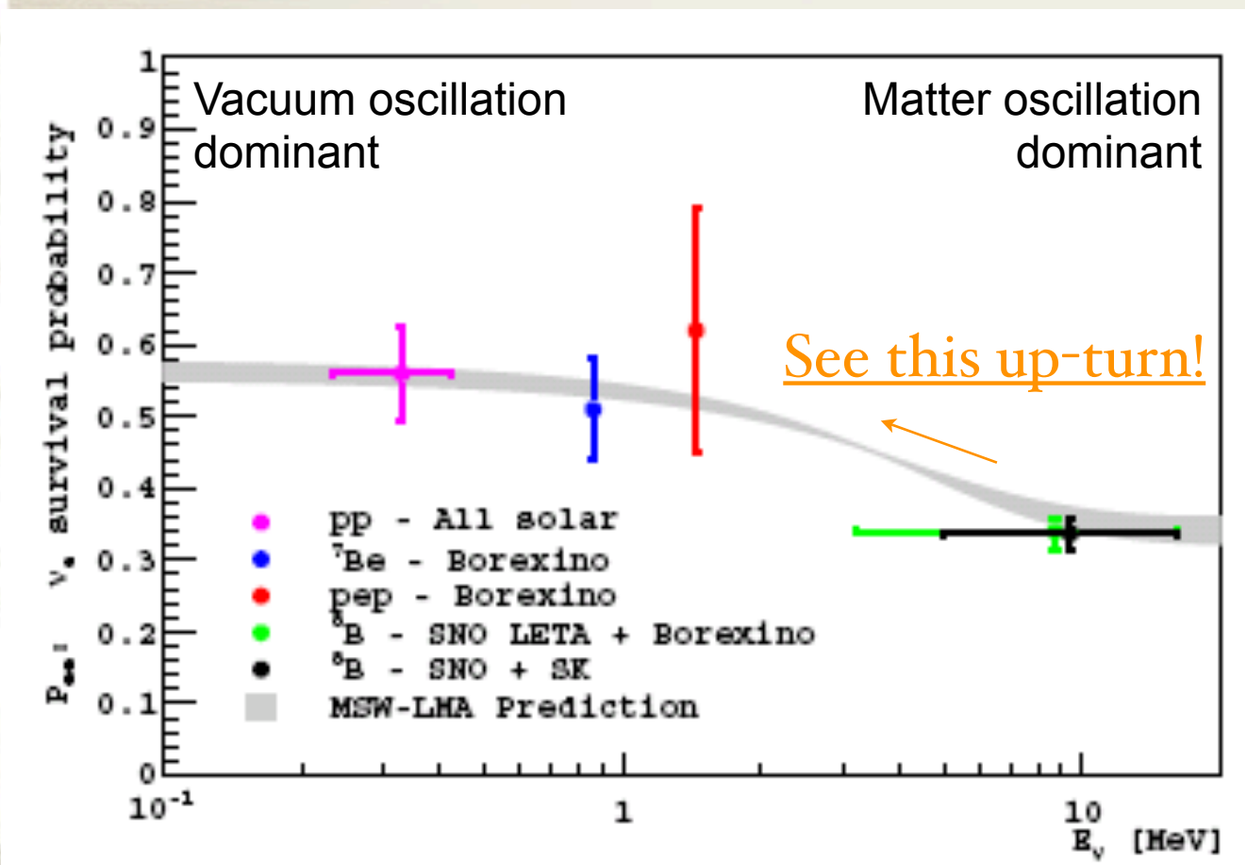


Motivation

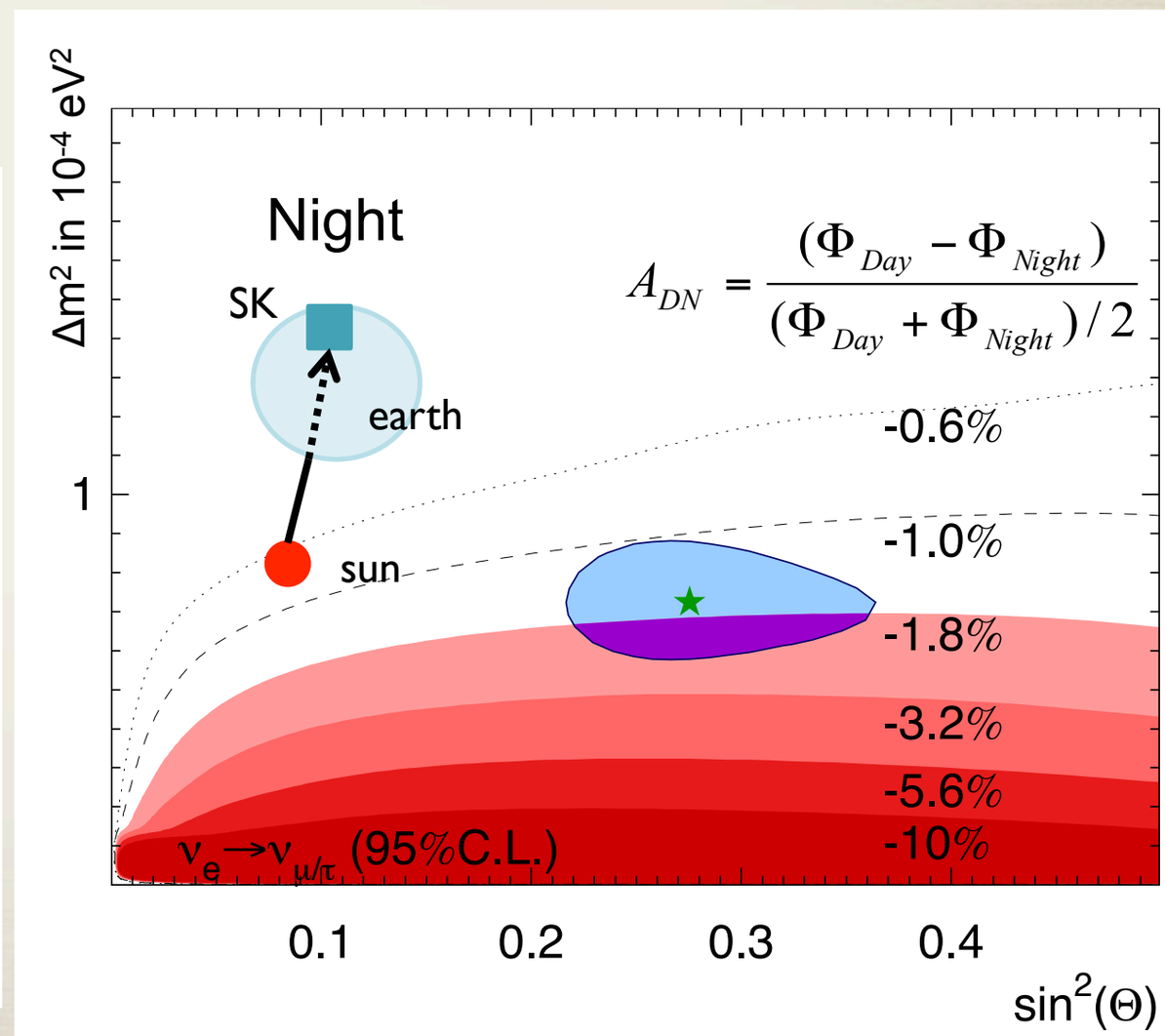
See the MSW effect directly

* Spectrum distortion

Neutrino survival probability measured by several experiments



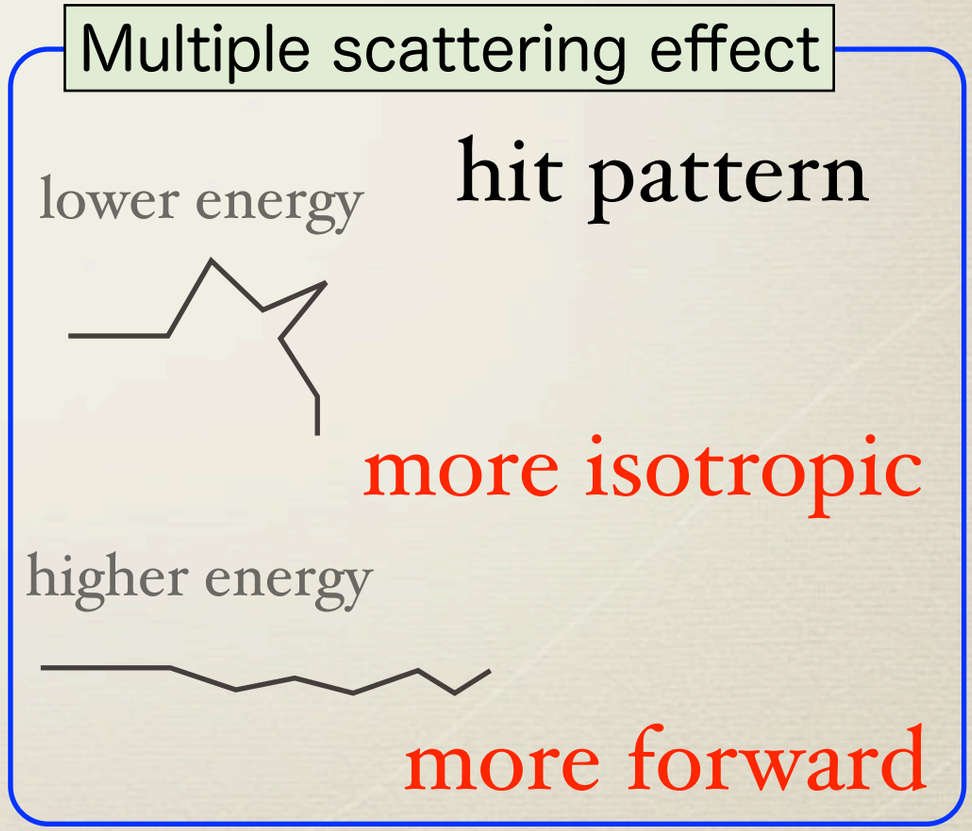
* Day/Night flux asymmetry



RESULTS

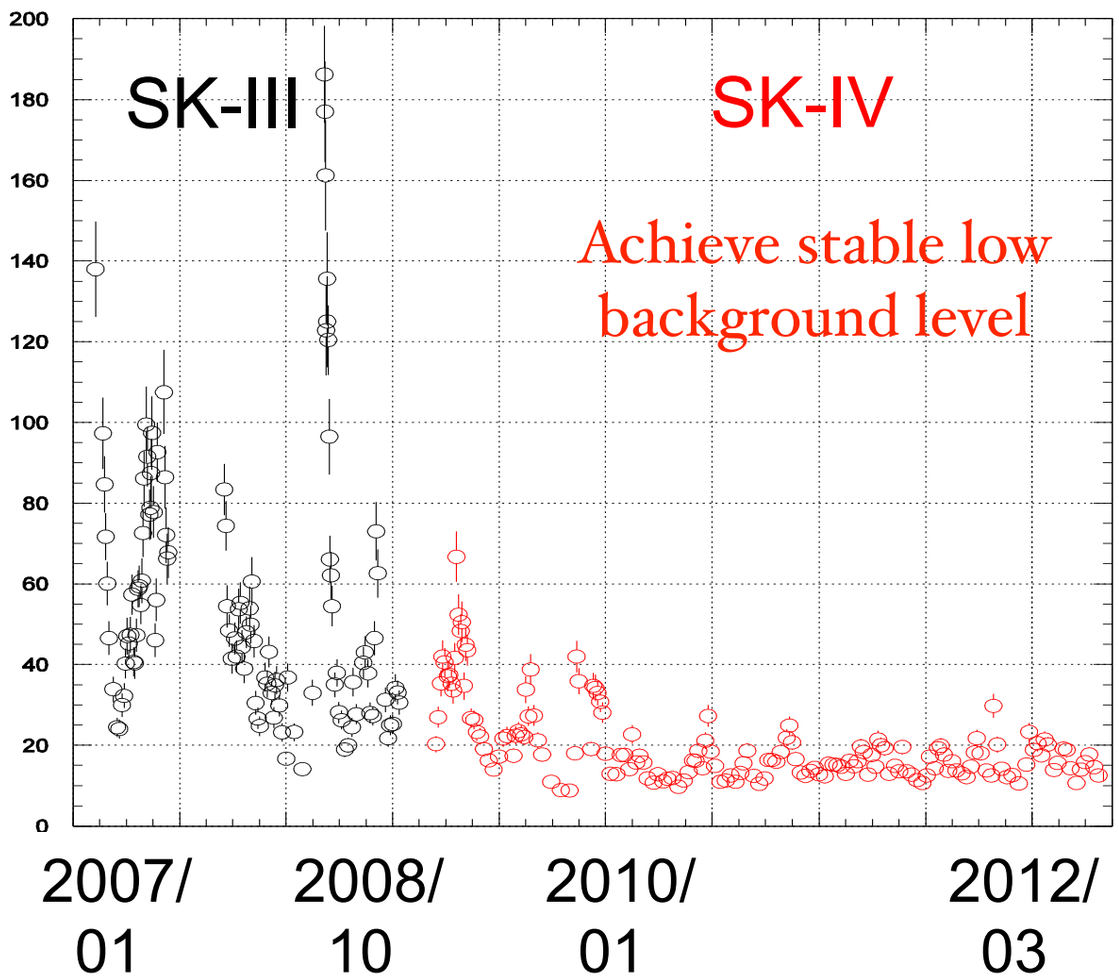
What's new

* mistake in SK-III calculation of expected solar neutrino event rate : best fit flux changes $2.32 \rightarrow 2.40 \times 10^6/(cm^2 \cdot sec)$
* 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

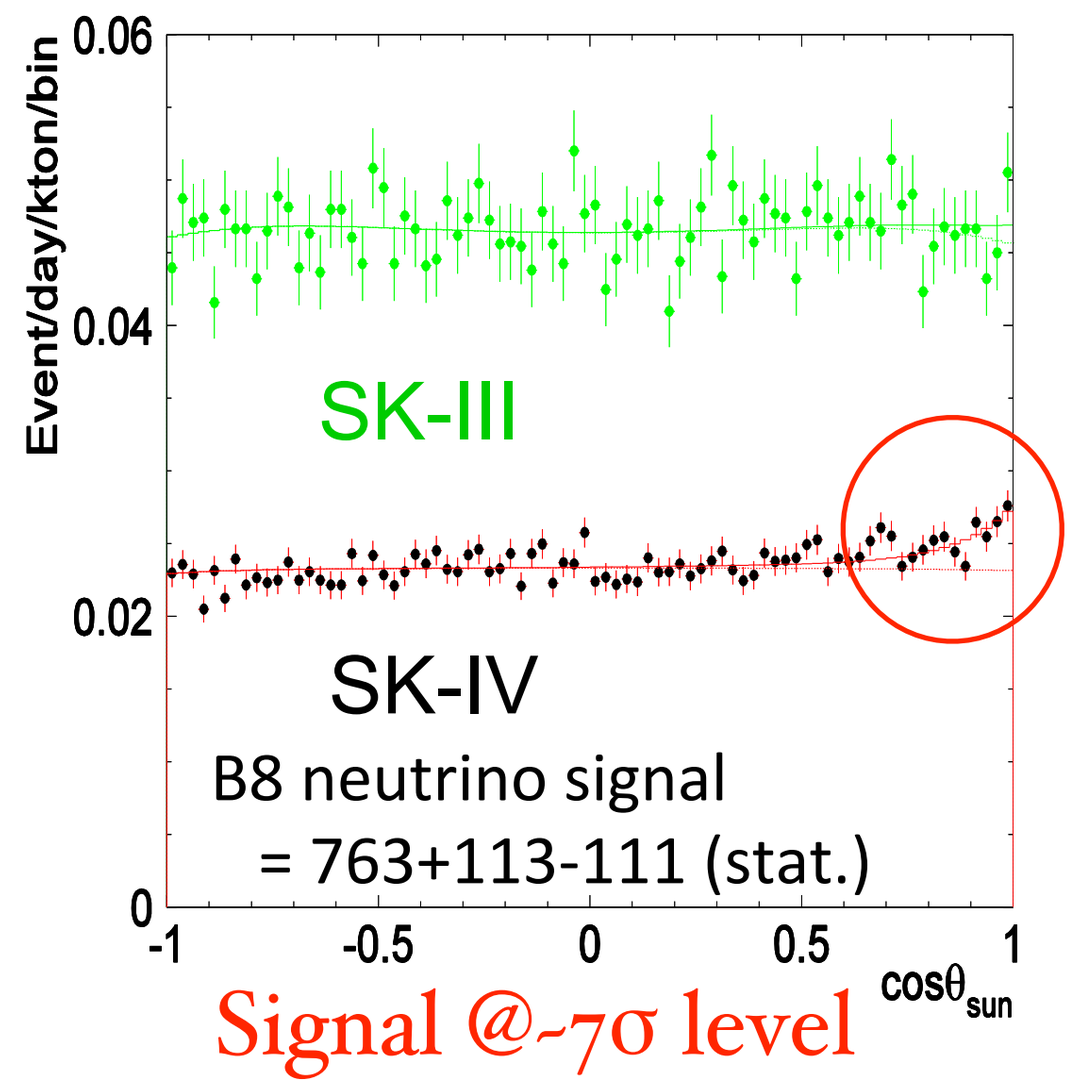


Lower background

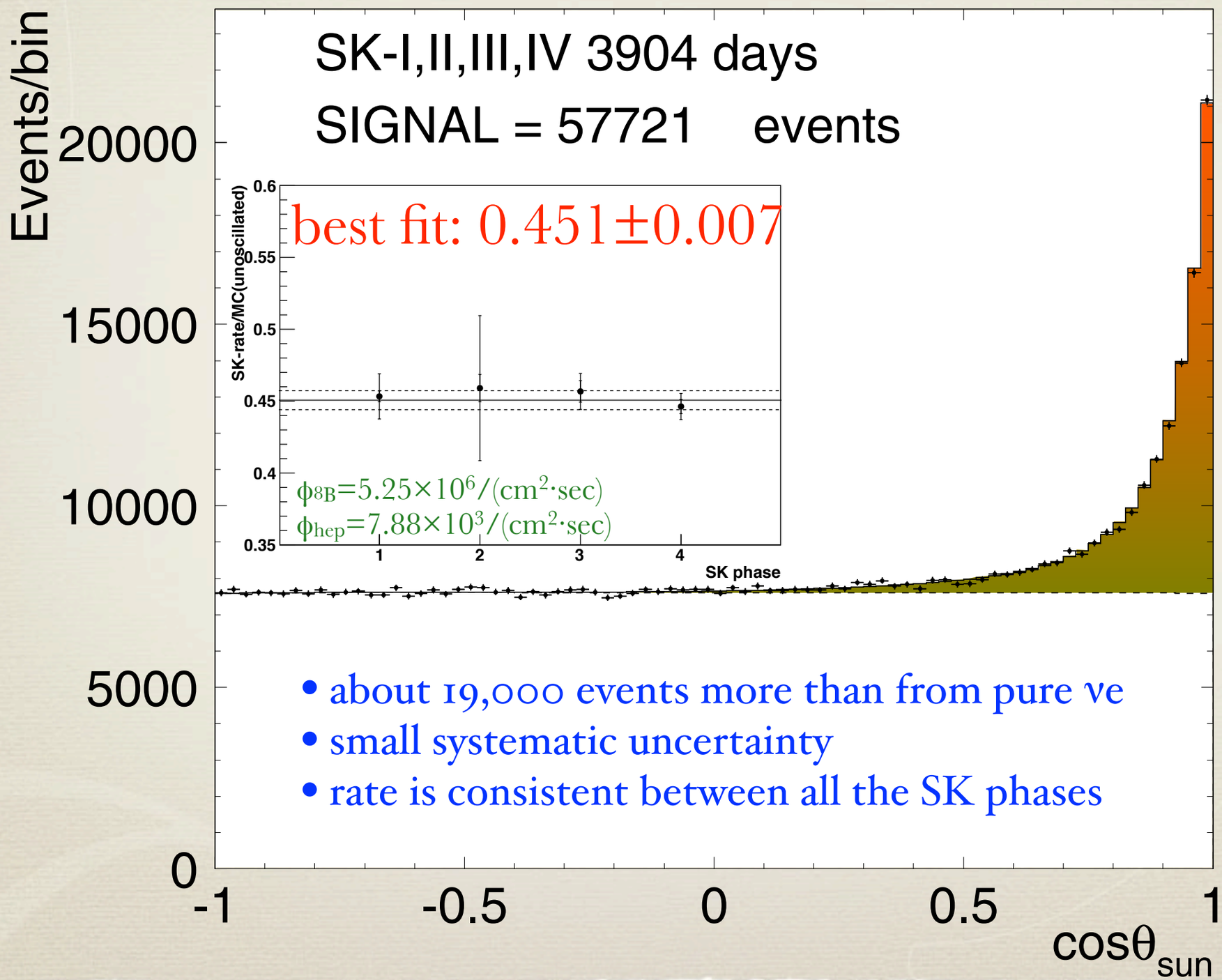
[event/day/kton @ 4.0-4.5MeV(kin.)]



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



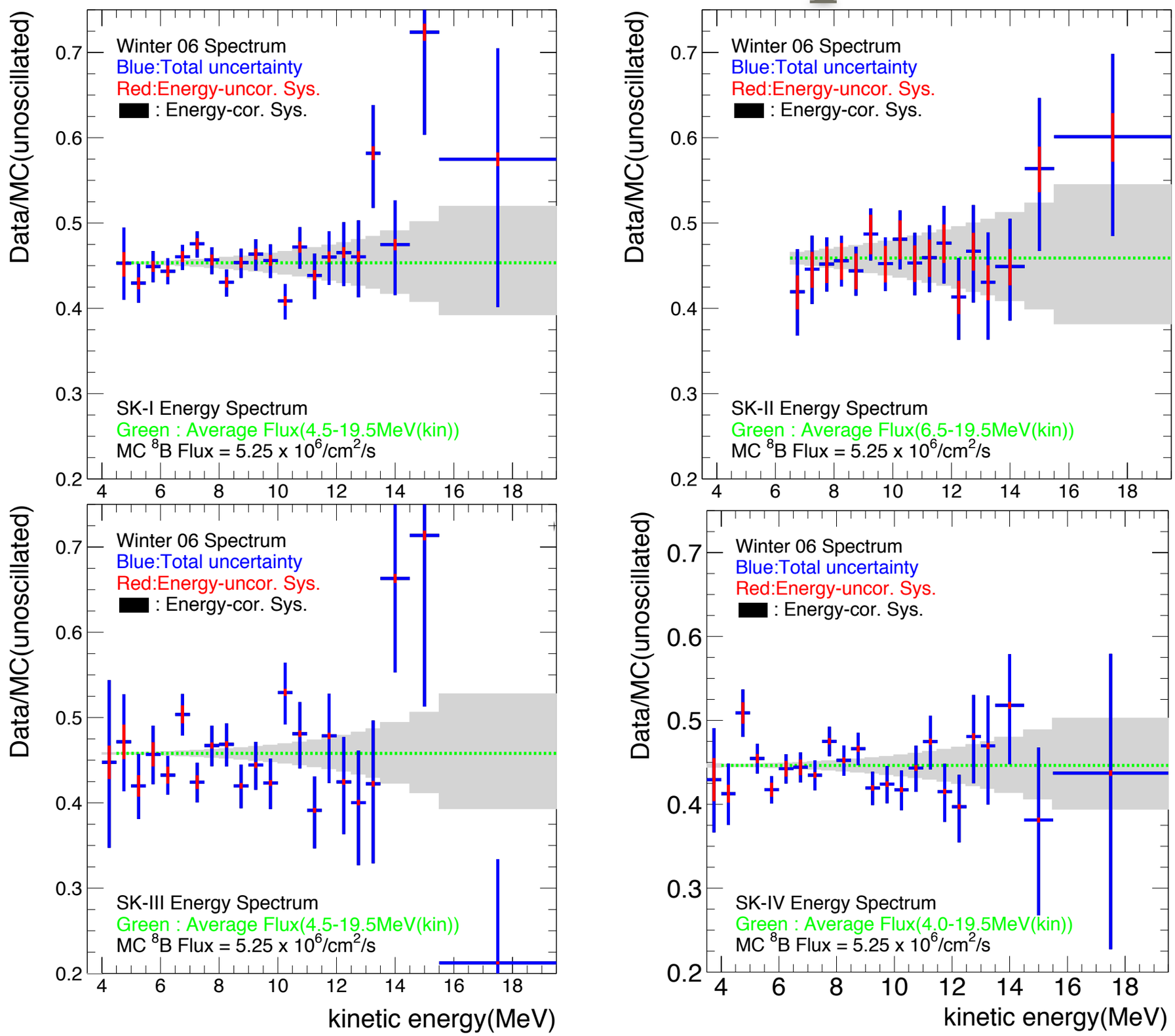
Total solar neutrino event



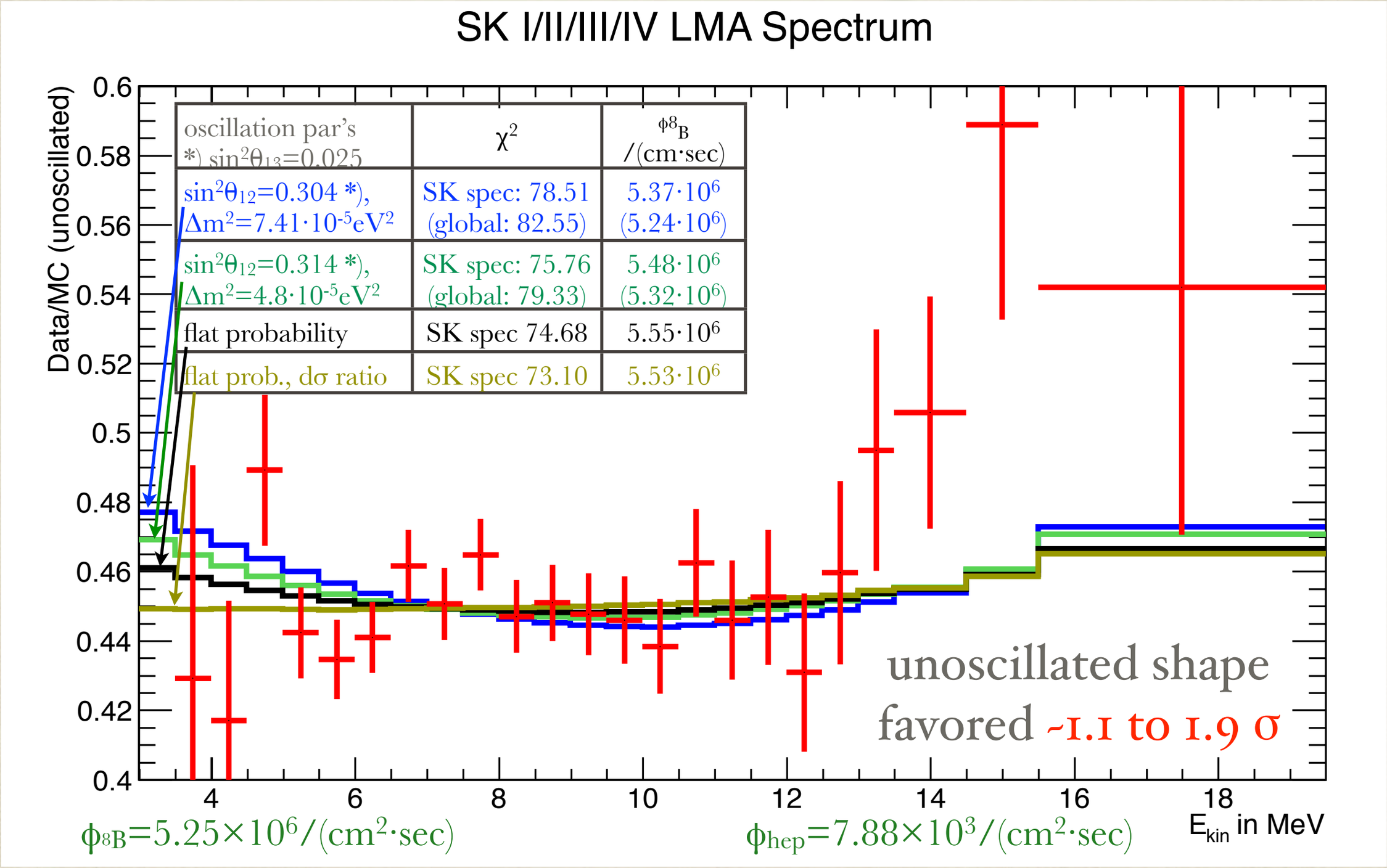
- about 19,000 events more than from pure νe
- small systematic uncertainty
- rate is consistent between all the SK phases

SPECTRUM

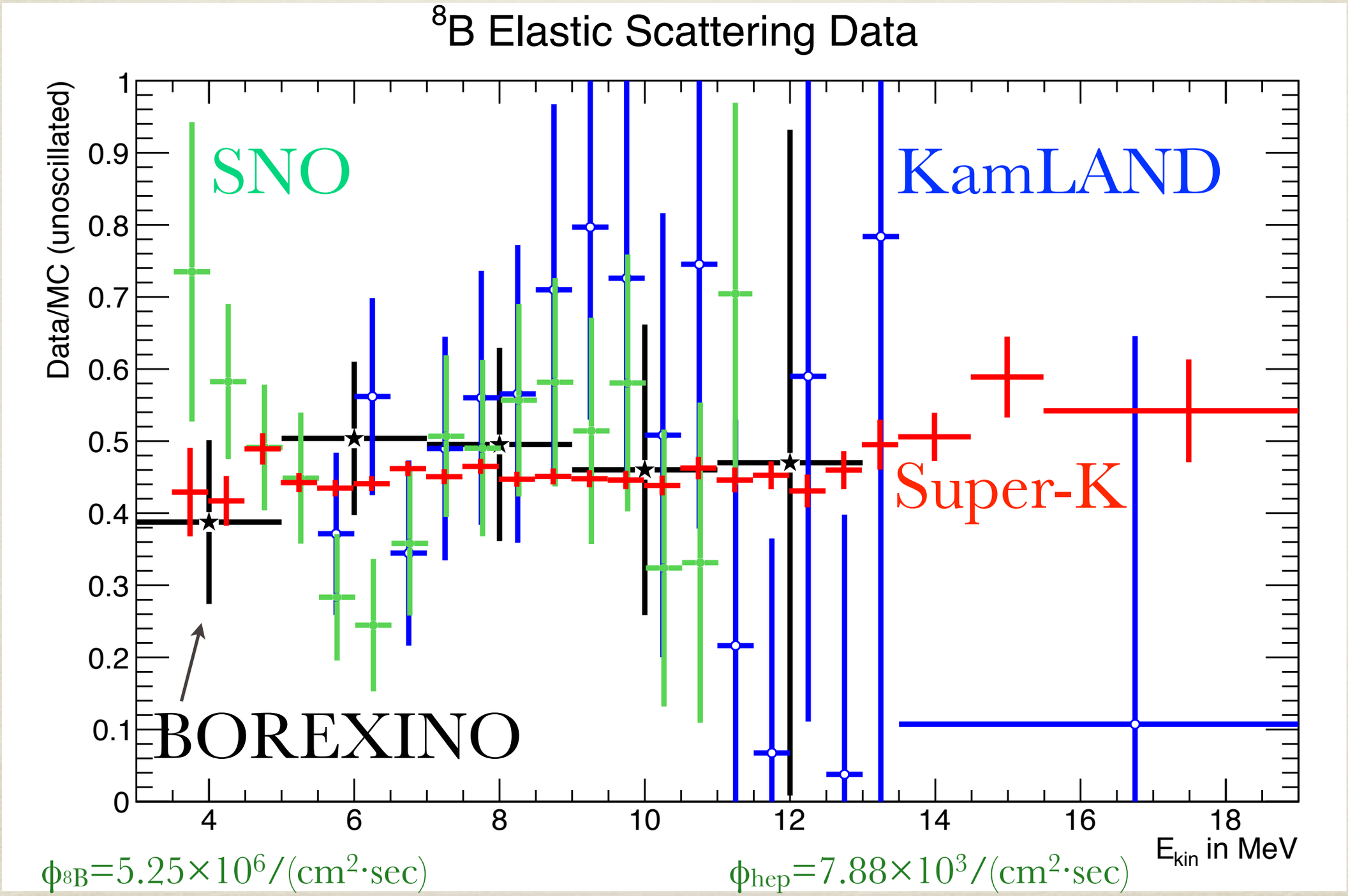
Recoil electron spectrum



Recoil electron spectrum

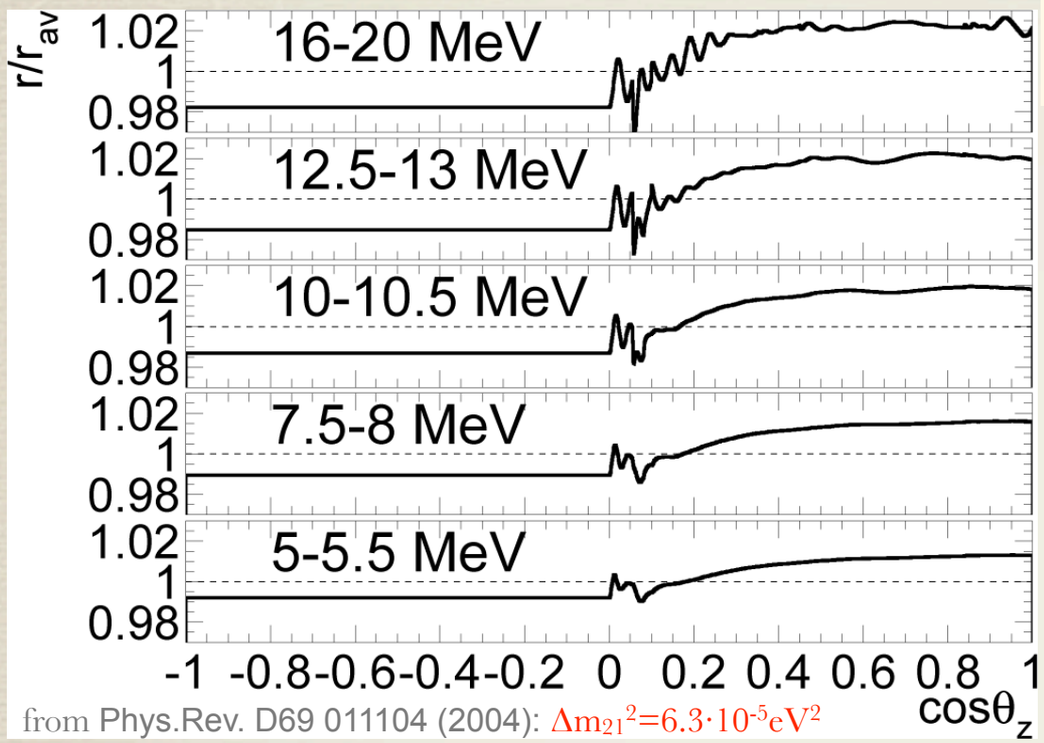


Comparison with other experiments



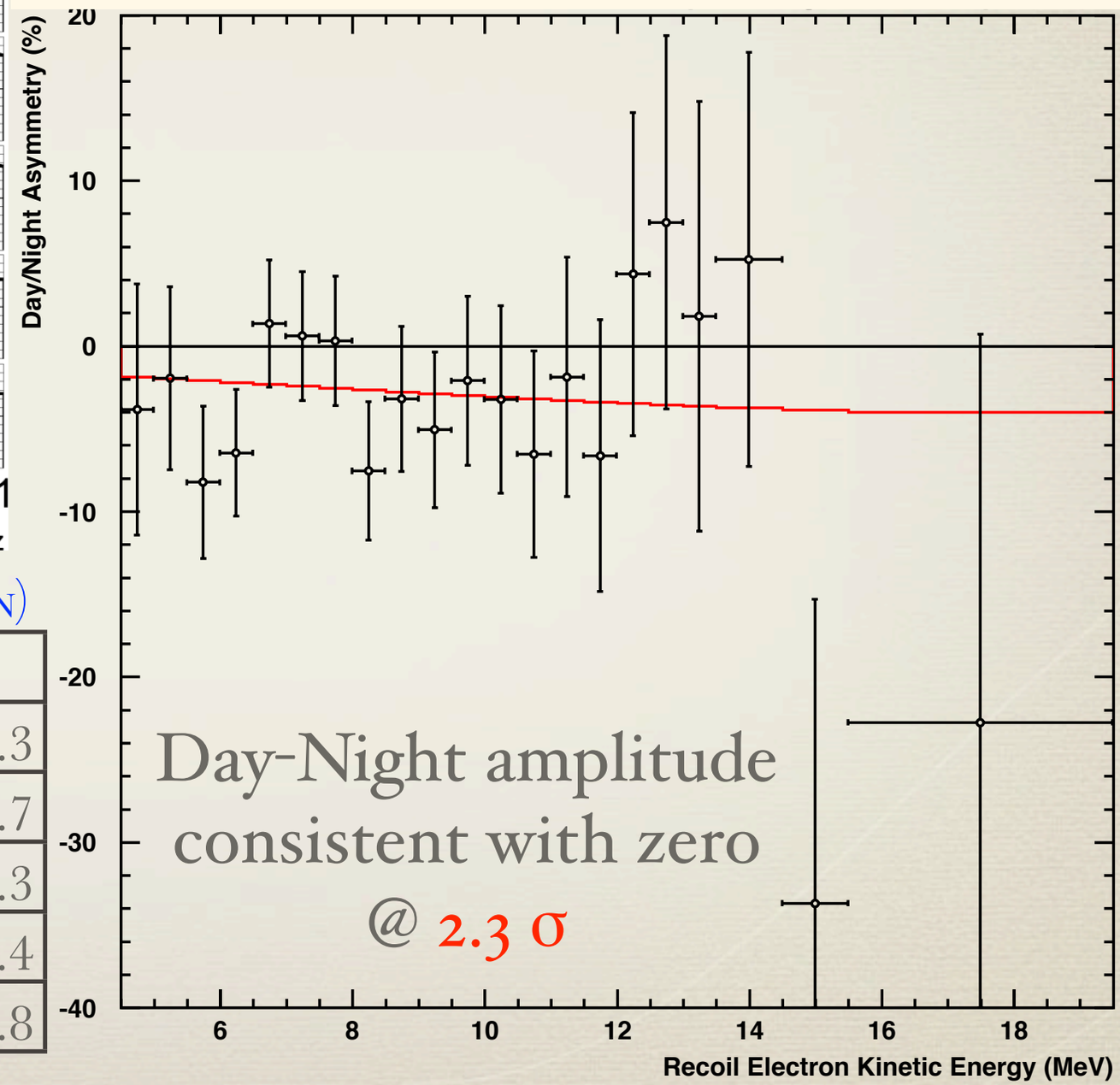
DAY/NIGHT FLUX DIFFERENCES

Day/Night variation



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

$\sin^2\theta_{12}=0.314$; $\Delta m_{21}^2=4.8\cdot10^{-5}eV^2$

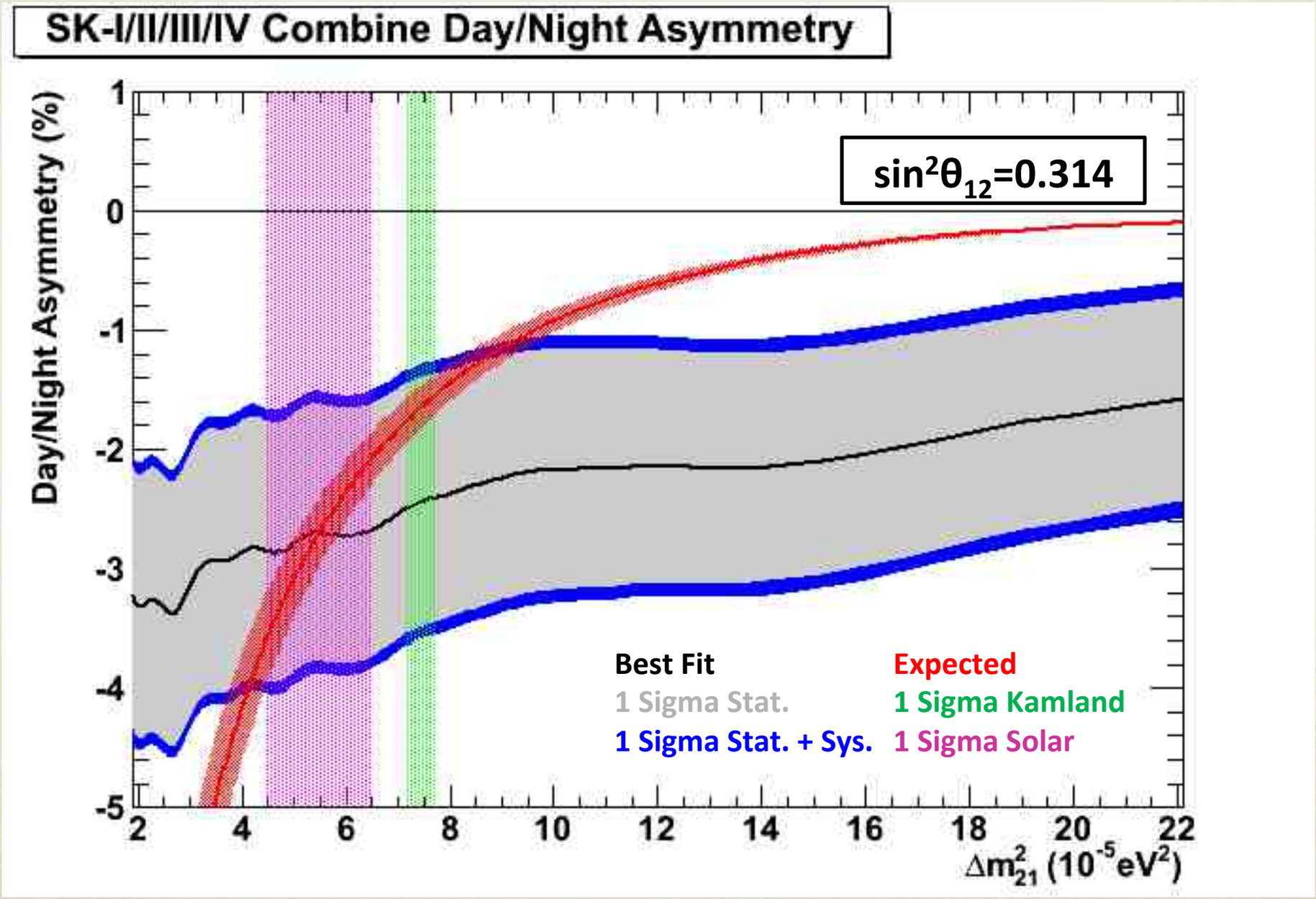


Day-Night amplitude consistent with zero @ 2.3 σ

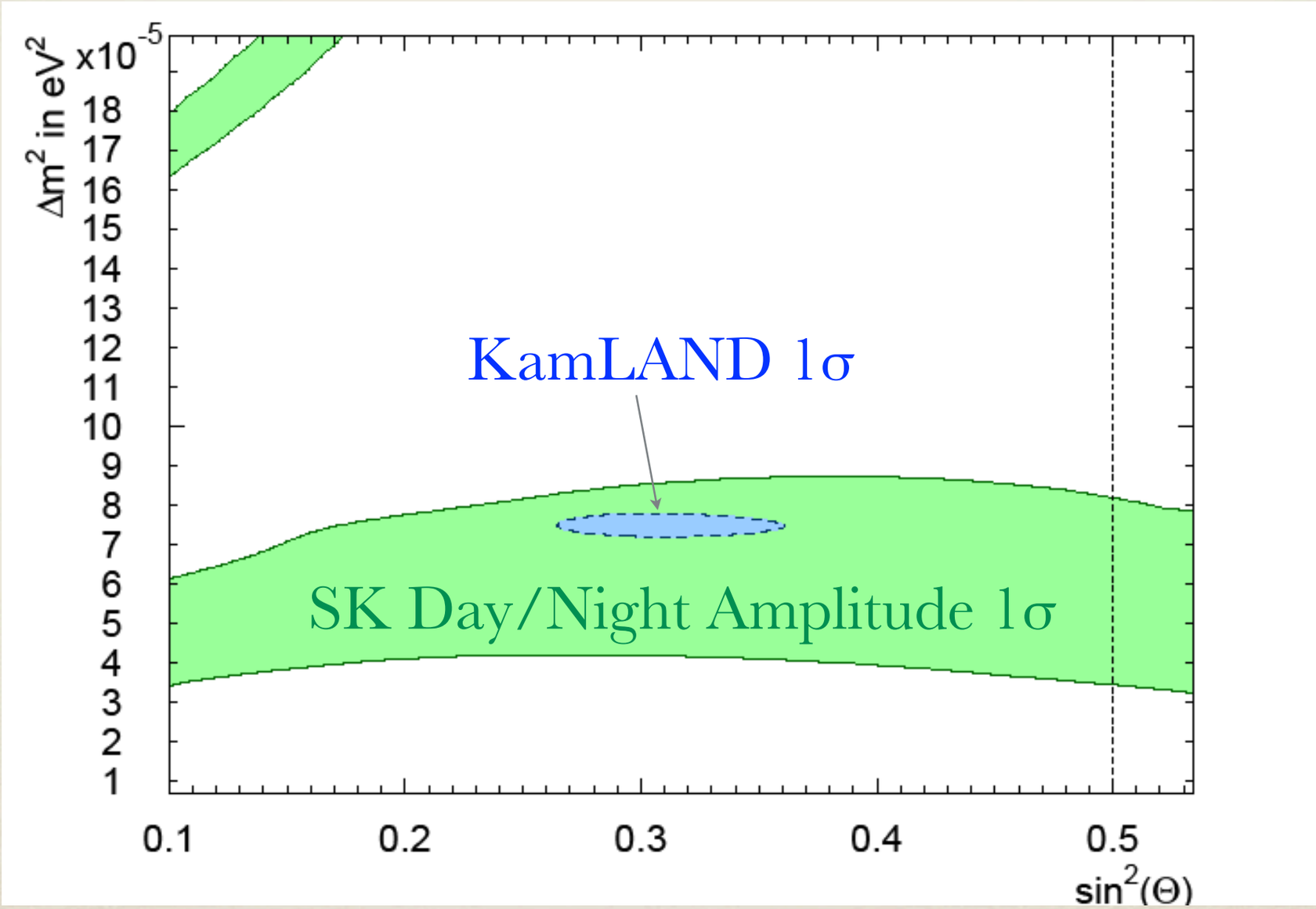
Day/Night Asym.: $A_{DN}=2(\phi_D-\phi_N)/(\phi_D+\phi_N)$

experiment	D/N amplitude	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 amplitude fits as a function of Δm^2

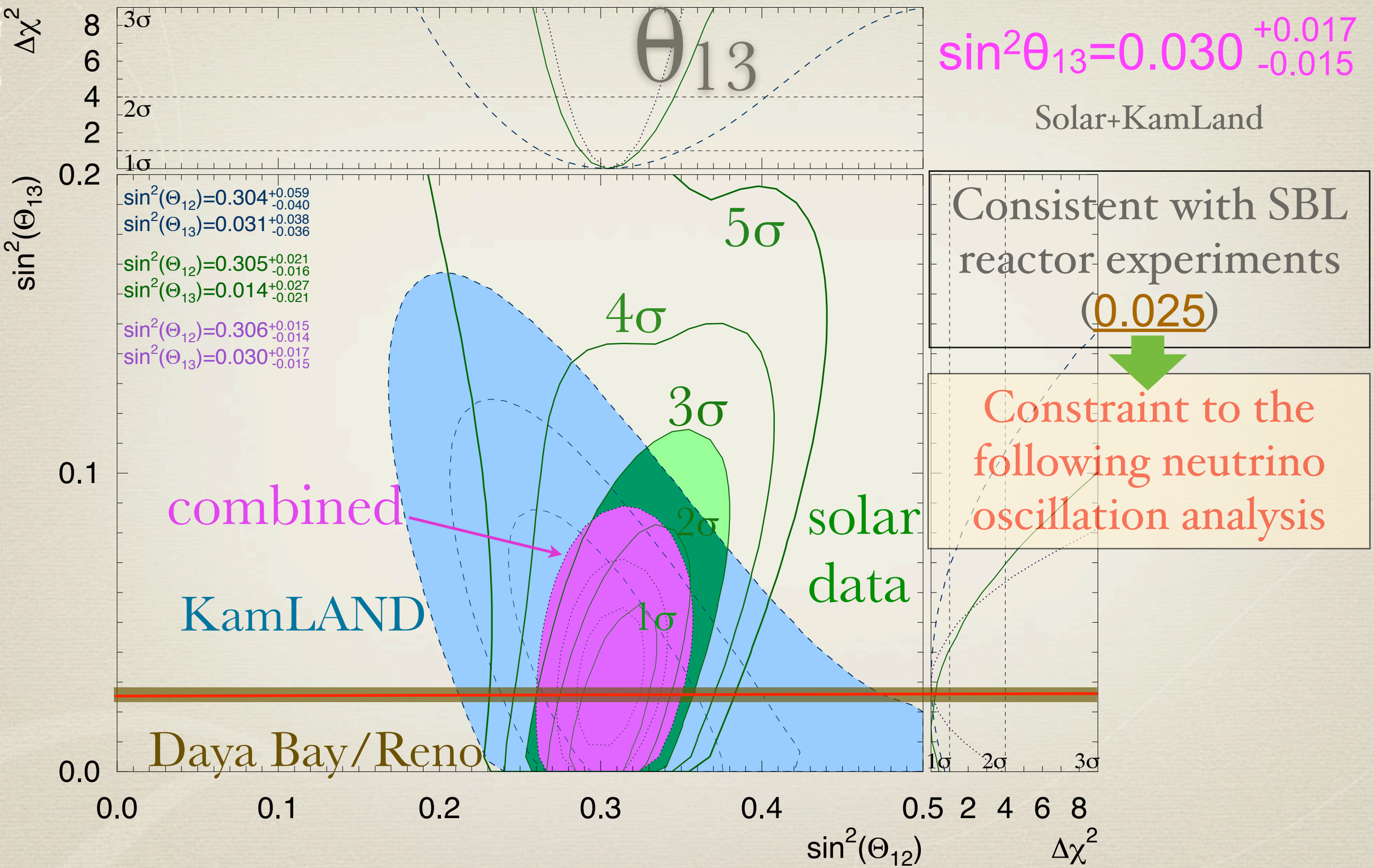


Allowed oscillation parameter region from Day/Night



NEUTRINO OSCILLATION ANALYSIS

Neutrino oscillation analysis



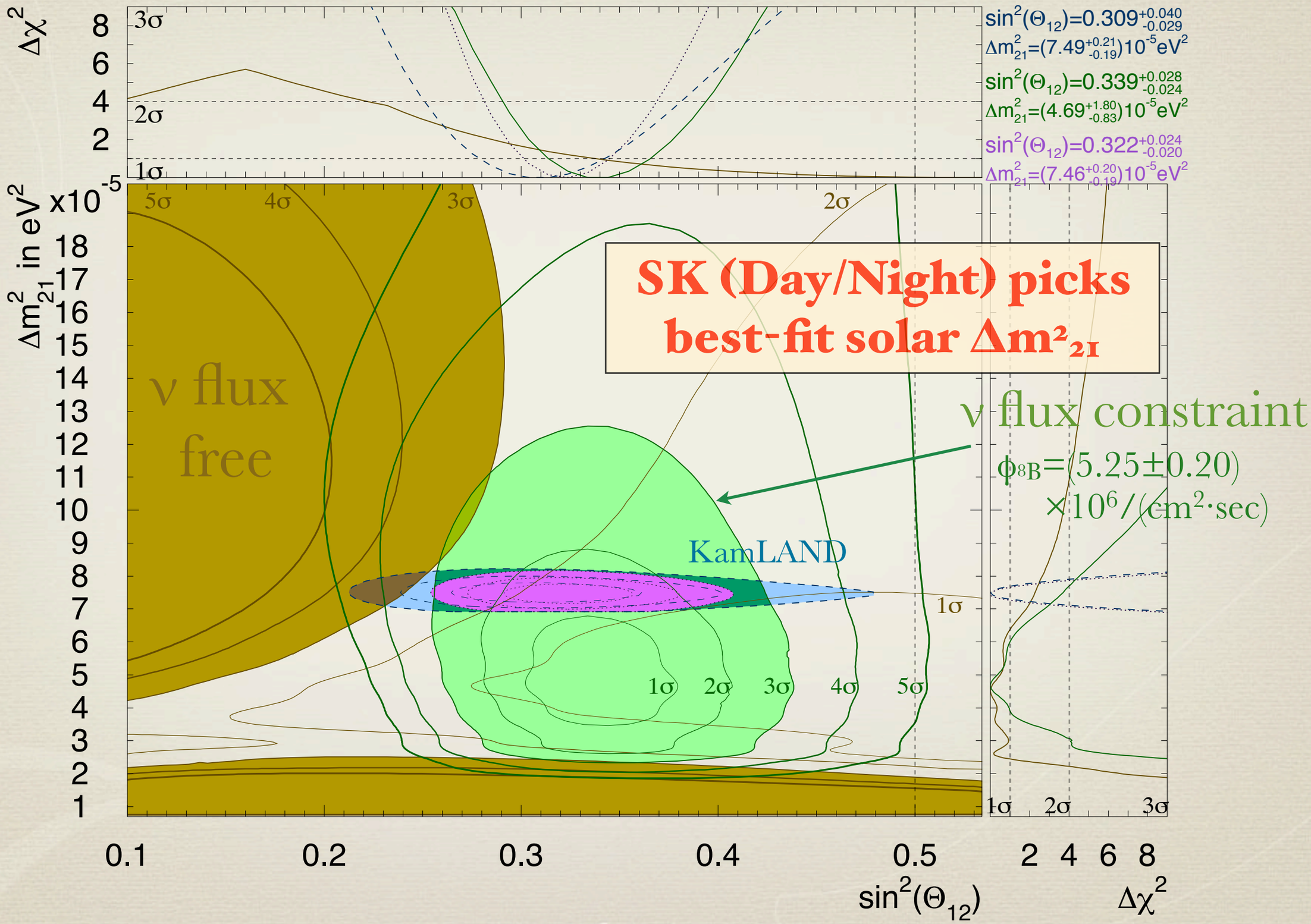
$\sin^2\theta_{13}=0.030^{+0.017}_{-0.015}$

Solar+KamLand

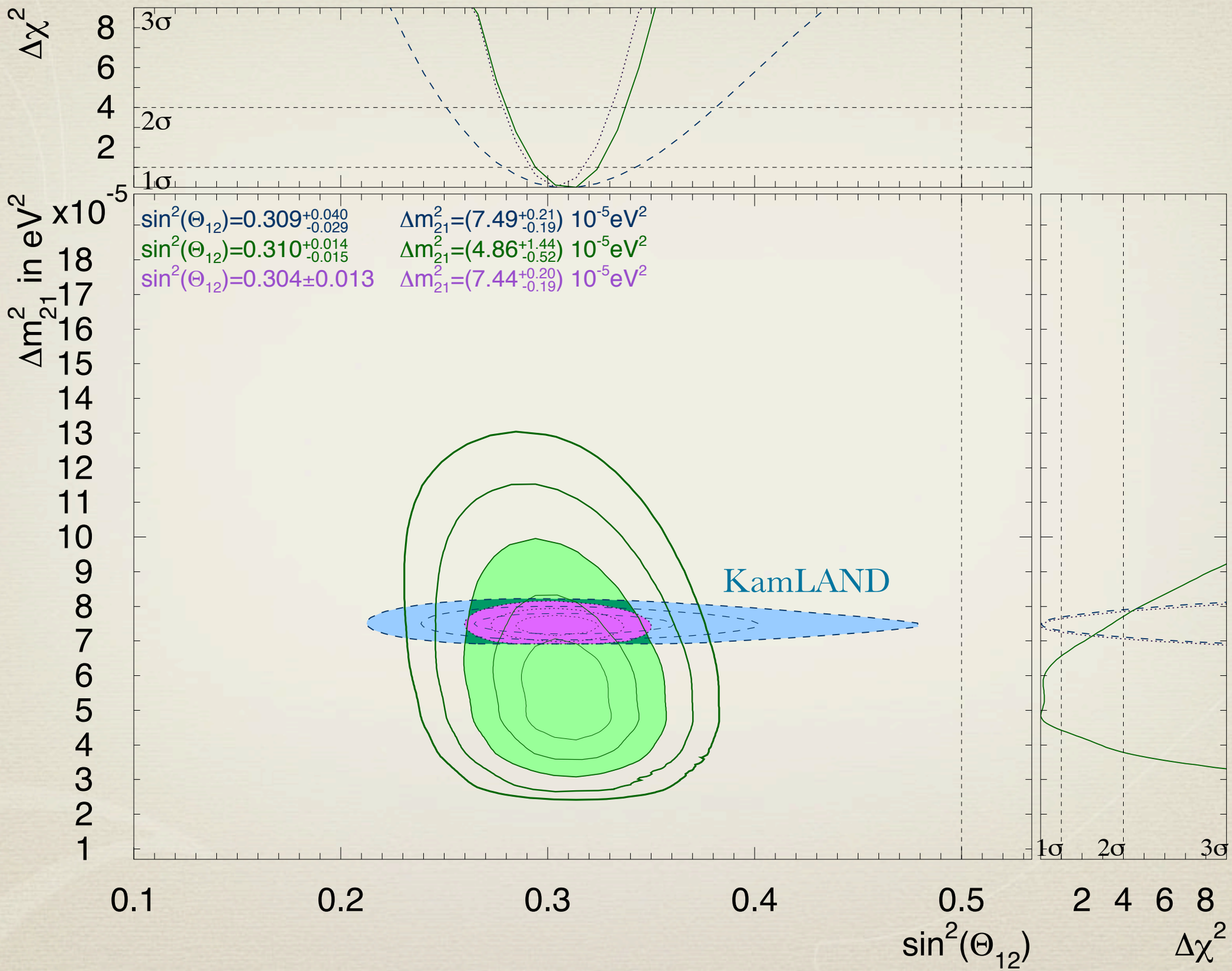
Consistent with SBL reactor experiments (0.025)

Constraint to the following neutrino oscillation analysis

Only Super-K solar



All solar neutrino data



Summary

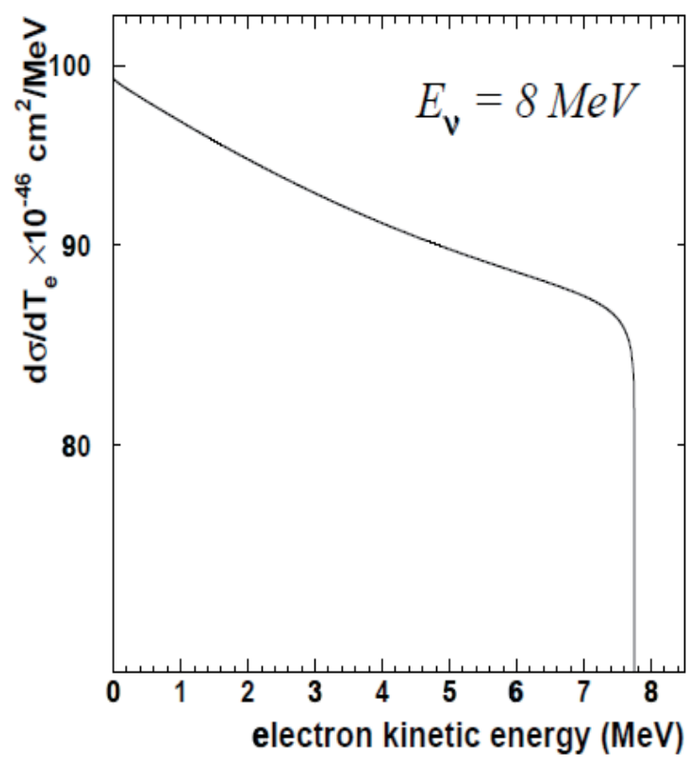
* Solar neutrino data taking in Super-K successfully keep going and improvement, e.g. lower threshold, lower background, small systematic uncertainties, large statistics, etc...
* No significant spectrum distortion can be seen.
* Some hint of non-zero day/night flux asymmetry. (2.3σ)
* Neutrino oscillation parameters are updated from Solar +KamLand global analysis; $\Delta m^2_{21}=7.44^{+0.20}_{-0.19}10^{-5}eV^2$, $\sin^2\theta_{12}=0.304\pm0.013$, $\sin^2\theta_{13}=0.030^{+0.017}_{-0.015}$

BACK UP

Problem in Solar ν MC vector generation in SK-III

Expected solar neutrino rate

$$F(T_e)dT_e = \left[\int_0^{E_{\nu,max}} \phi(E_\nu)\frac{d\sigma}{dT_e}dE_\nu\right] dT_e$$

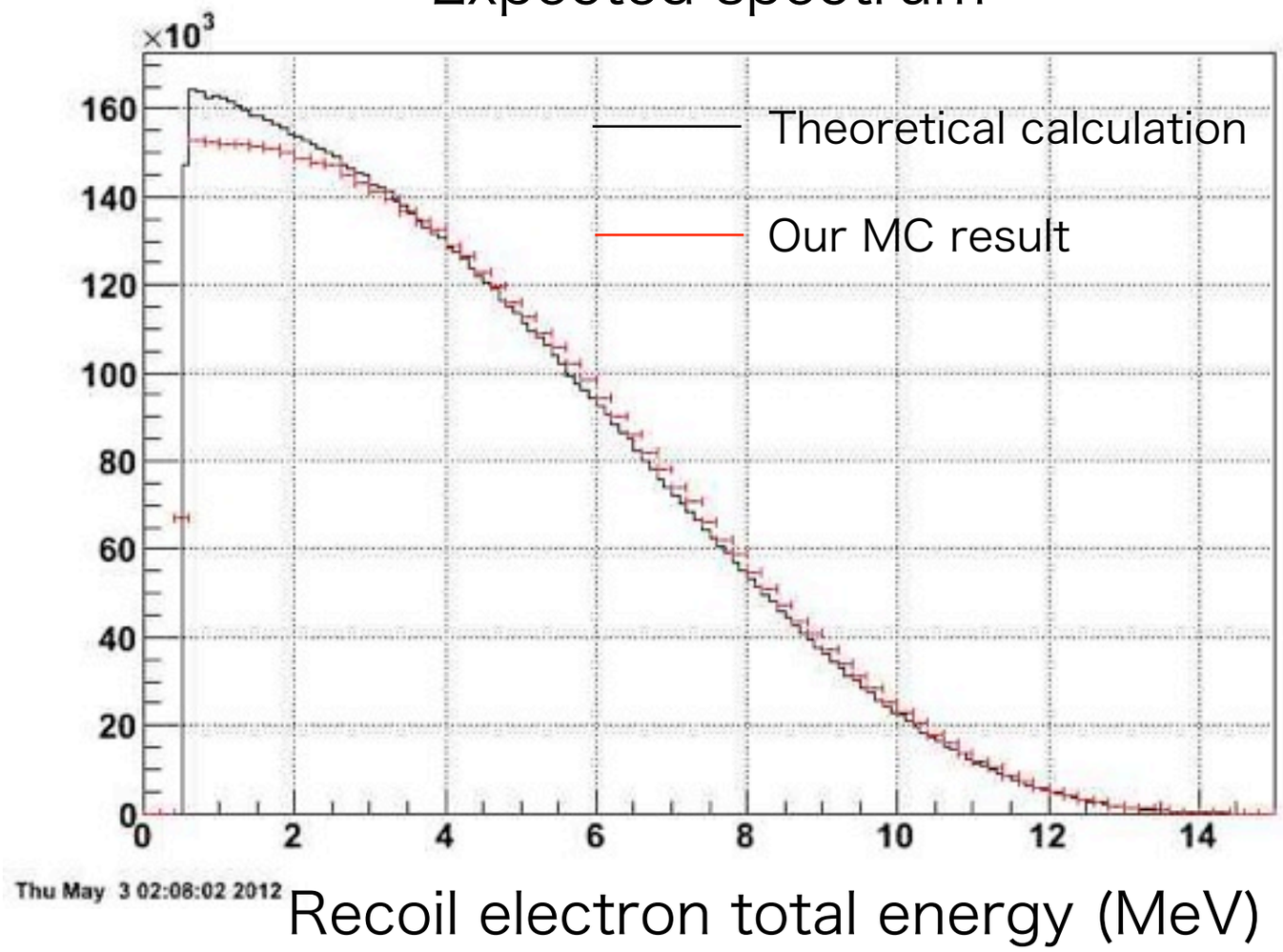


Not include this energy dependence...

How does it affect?

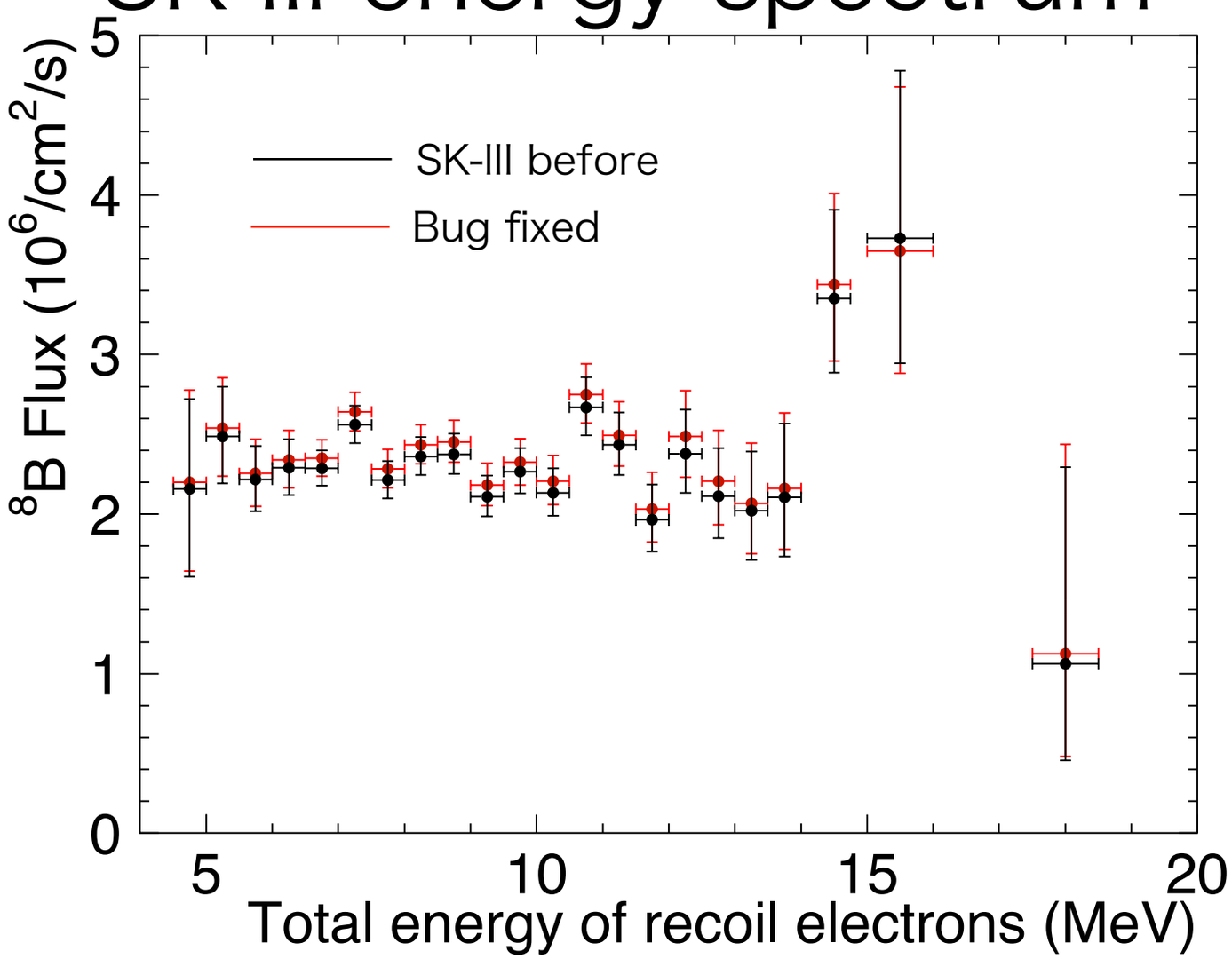
- No energy dependence in differential cross section.
  - The shape was shifted directed to higher region.
  - The Total flux was not changed.
- If you apply the energy cut, e.g. above 5MeV, though the spectrum was not changed, the expected flux became large.

Expected spectrum



How are the results changed?

SK-III energy spectrum



Flux results:

2.40 (fixed)

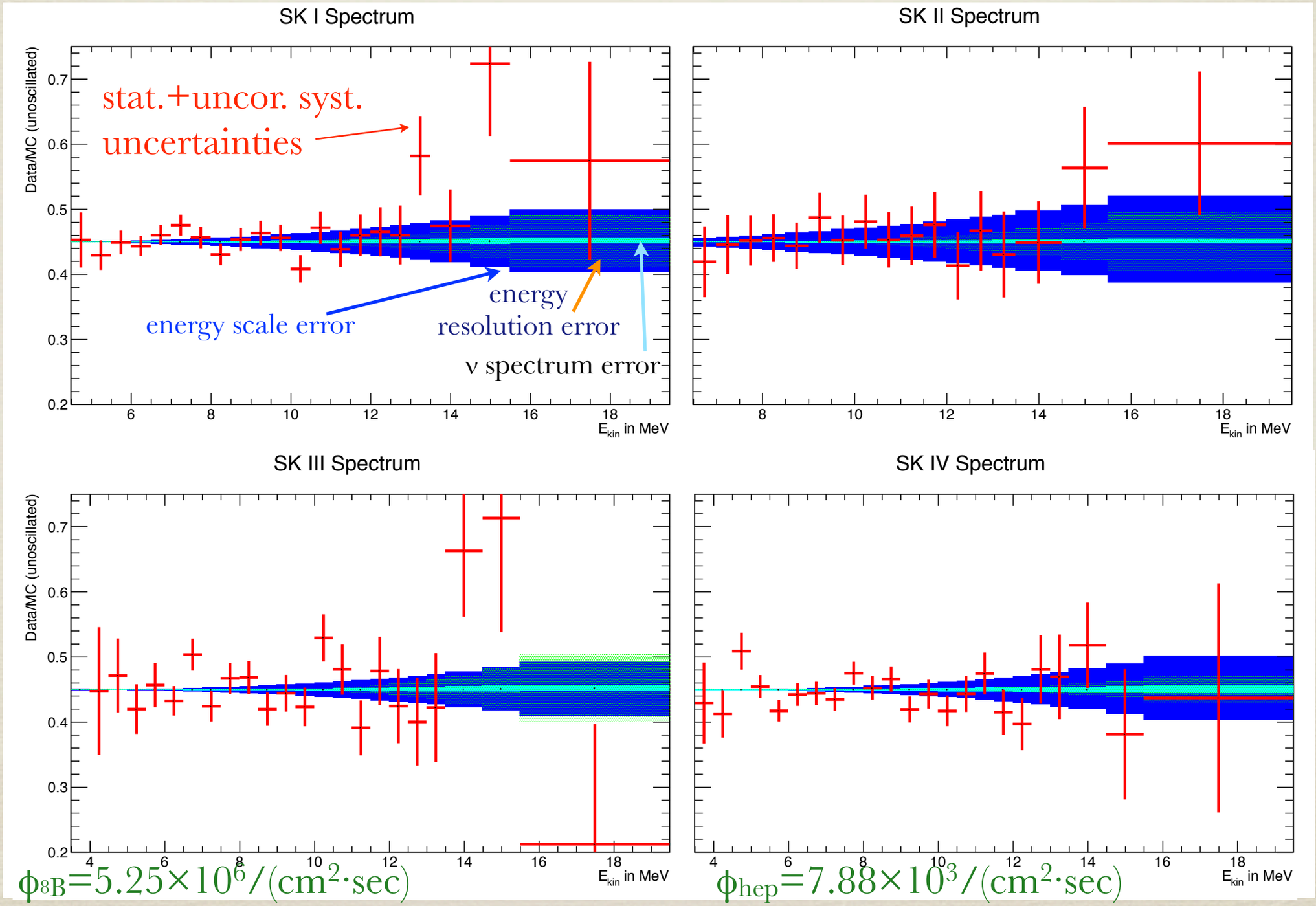
2.32 (before)

3% difference

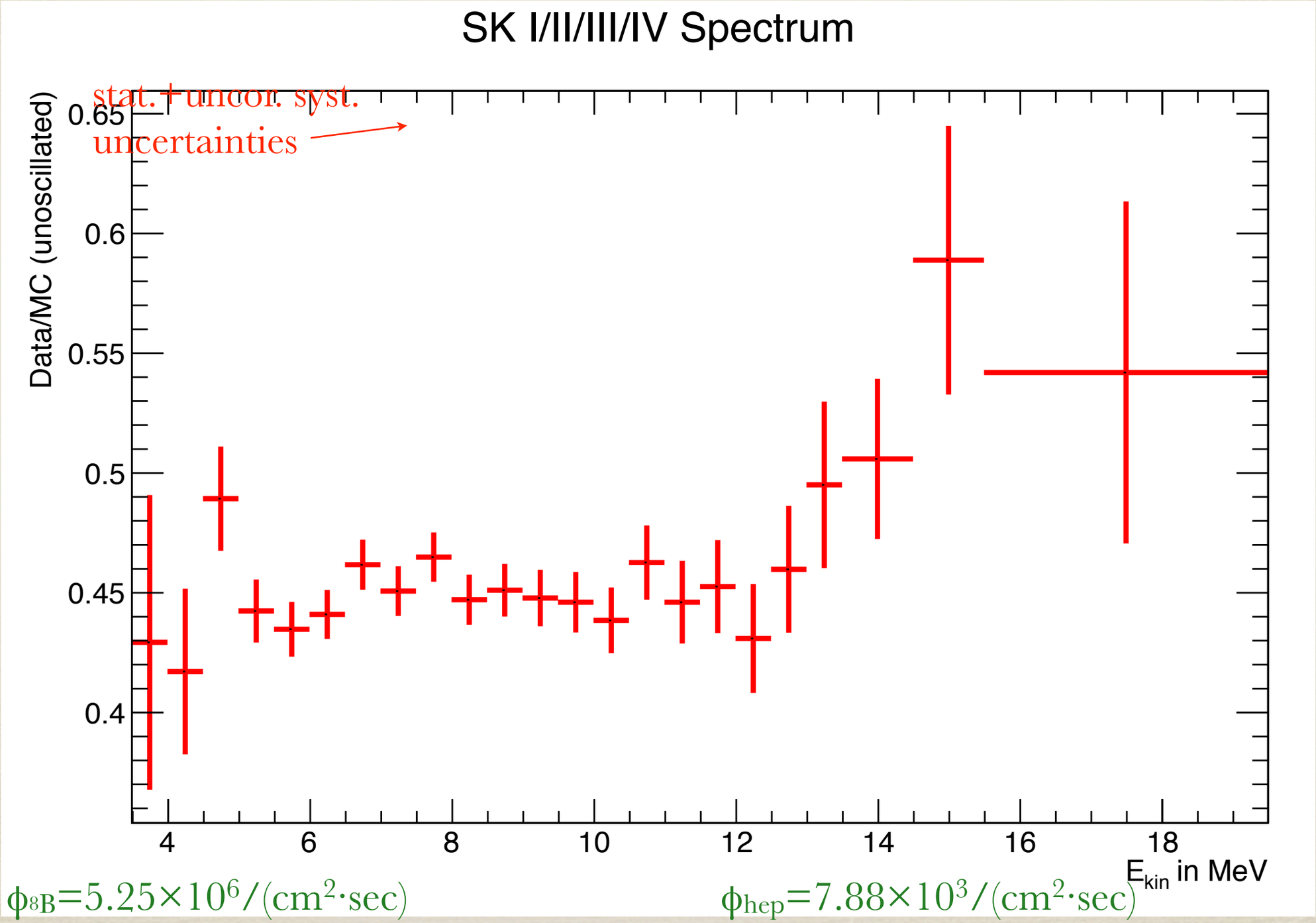
Multiple Scattering Goodness (MSG)

- Lower energy electrons will incur more multiple scattering and will have more unit vectors pointing along different directions, giving a lower goodness
- Higher energy electrons will scatter less and will have unit vectors in better agreement, resulting in higher goodness
- Although the Bi^{214} decay electrons (majority of low energy background) fluctuate up above 5.0 MeV in energy, they truly have energy <3.3 MeV and should have more multiple scattering than true 5.0 MeV electrons, and therefore a lower MSG

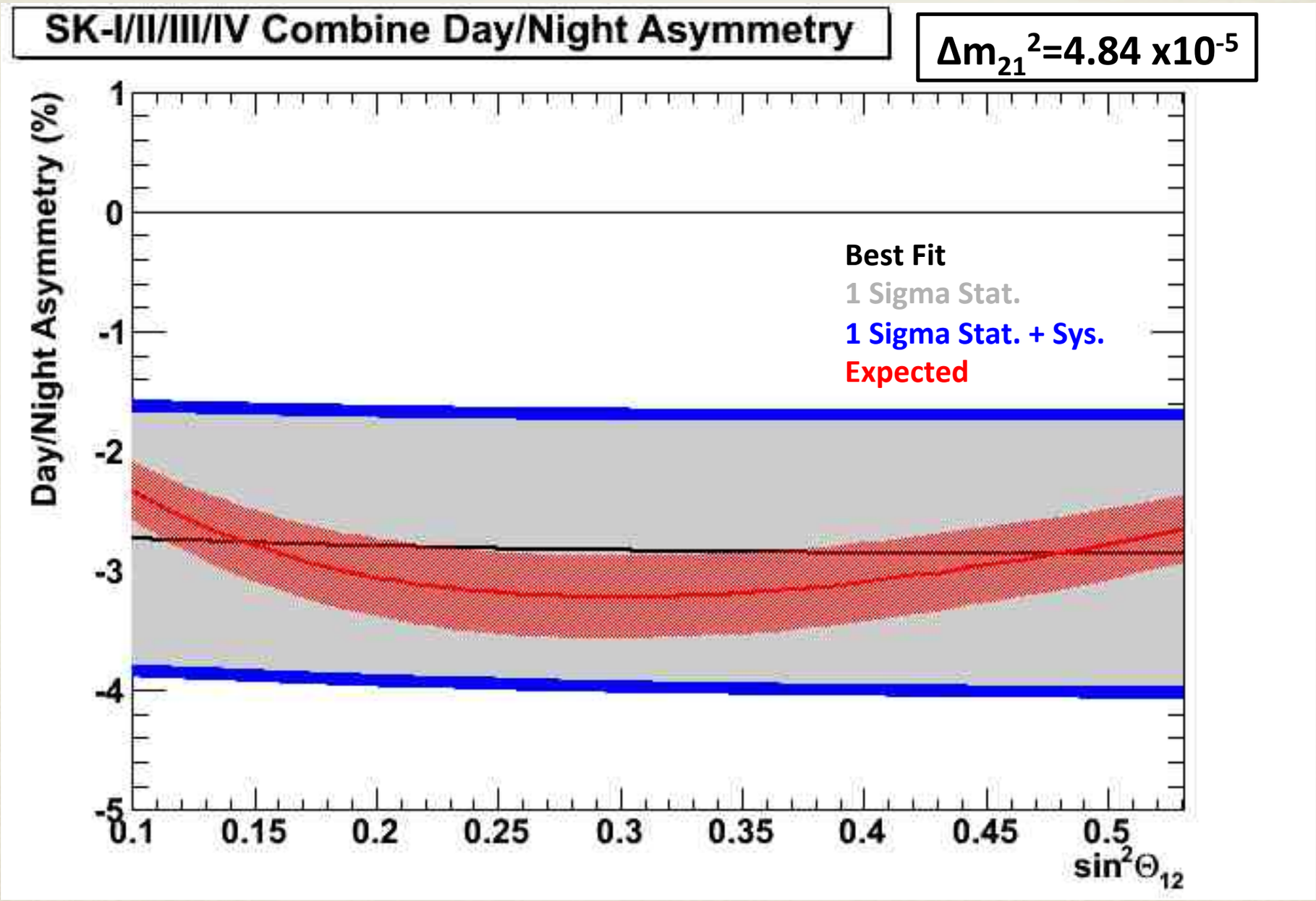
Recoil electron spectrum



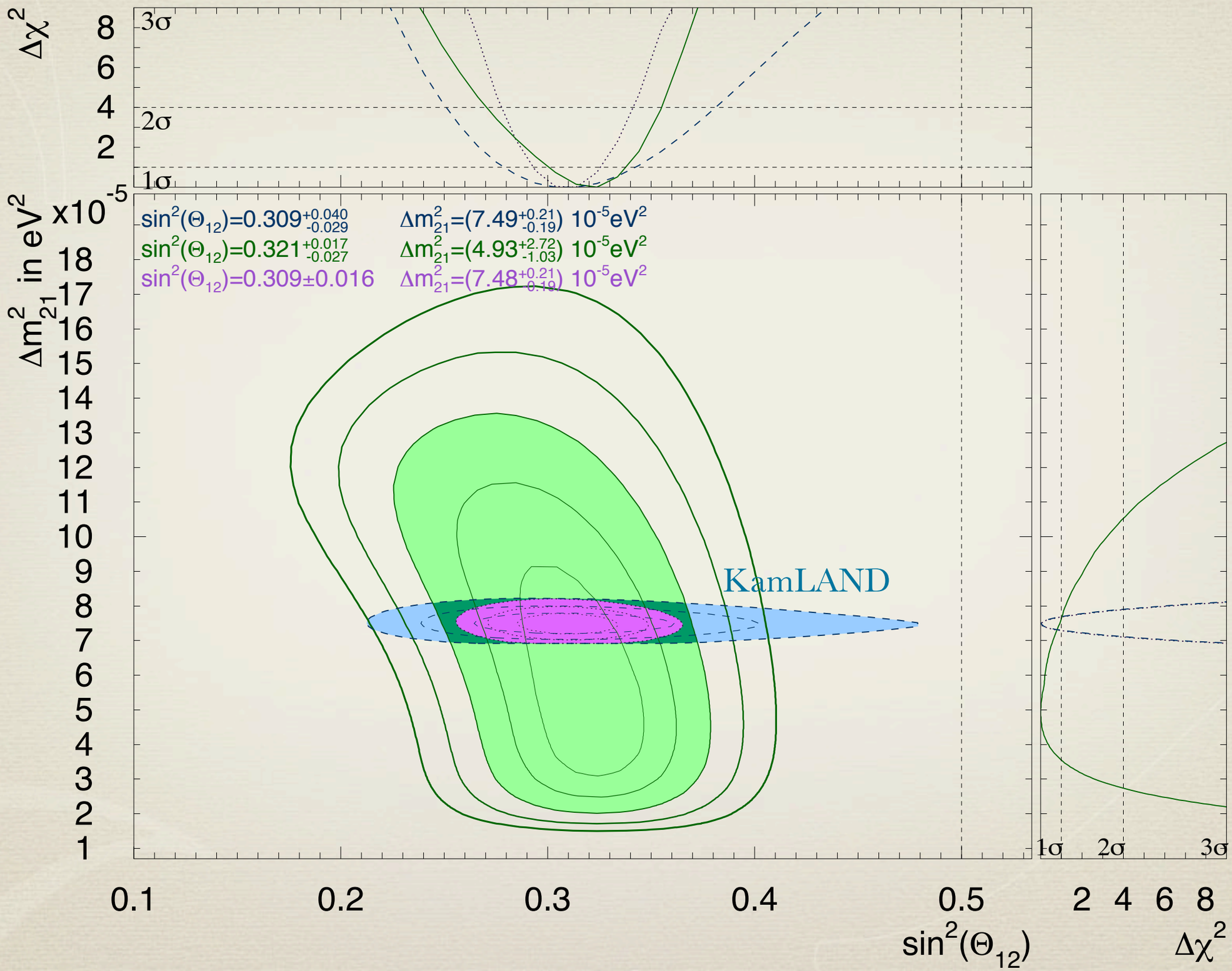
Recoil electron spectrum



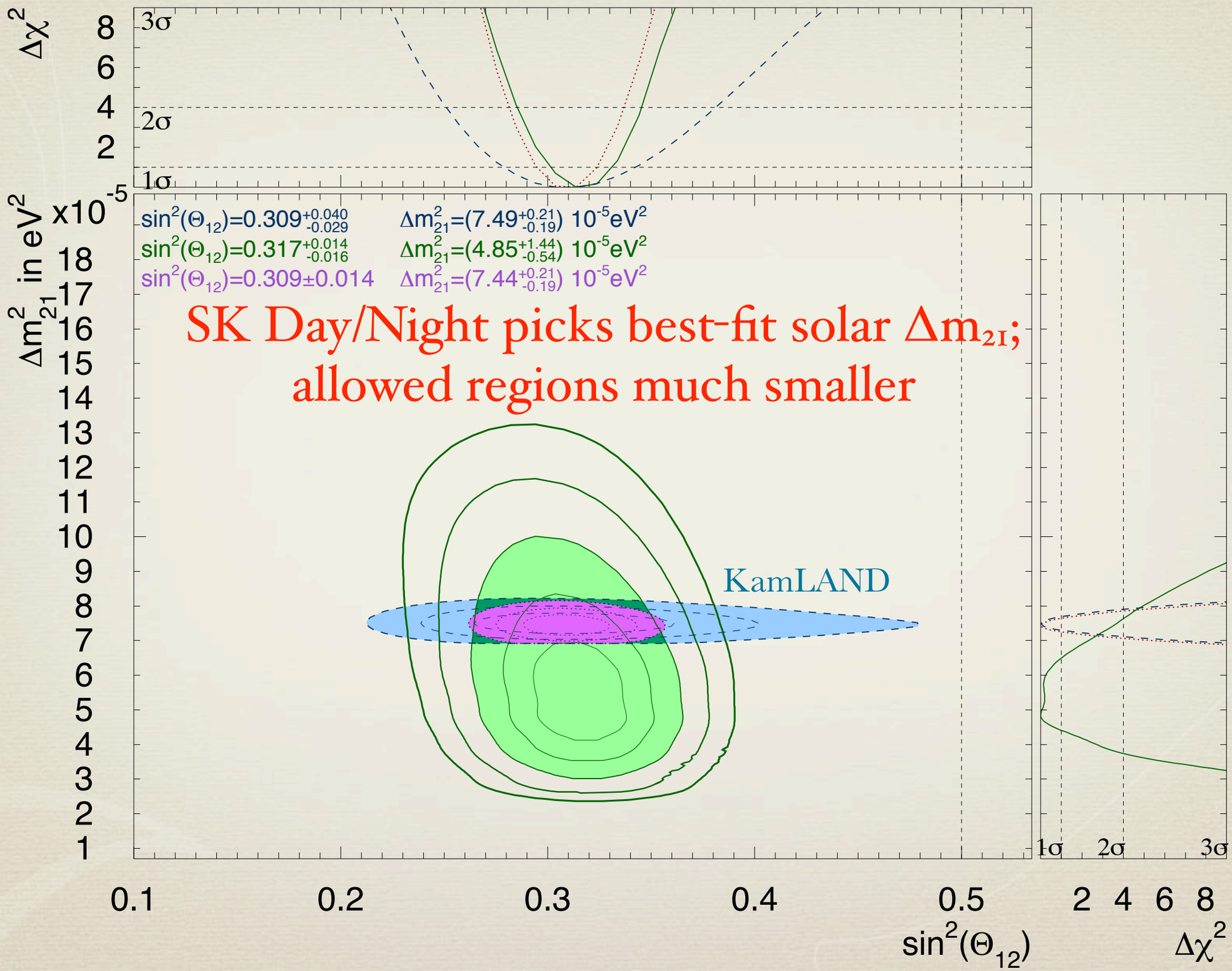
Day/Night amplitude fits as a function of $\sin^2\theta_{12}$



Only SNO


$\Delta\chi^2$
3σ
2σ
1σ
$\sin^2(\Theta_{12})=0.309^{+0.040}_{-0.029}$ $\Delta m^2_{21}=(7.49^{+0.21}_{-0.19})\ 10^{-5}eV^2$
$\sin^2(\Theta_{12})=0.321^{+0.017}_{-0.027}$ $\Delta m^2_{21}=(4.93^{+2.72}_{-1.03})\ 10^{-5}eV^2$
$\sin^2(\Theta_{12})=0.309\pm0.016$ $\Delta m^2_{21}=(7.48^{+0.21}_{-0.19})\ 10^{-5}eV^2$
Δm^2_{21} in eV^2 x10^{-5}
KamLAND
$\sin^2(\Theta_{12})$
$\Delta\chi^2$

Super-K + SNO


$\Delta\chi^2$
3σ
2σ
1σ
$\sin^2(\Theta_{12})=0.309^{+0.040}_{-0.029}$ $\Delta m^2_{21}=(7.49^{+0.21}_{-0.19})\ 10^{-5}eV^2$
$\sin^2(\Theta_{12})=0.317^{+0.014}_{-0.016}$ $\Delta m^2_{21}=(4.85^{+1.44}_{-0.54})\ 10^{-5}eV^2$
$\sin^2(\Theta_{12})=0.309\pm0.014$ $\Delta m^2_{21}=(7.44^{+0.21}_{-0.19})\ 10^{-5}eV^2$
SK Day/Night picks best-fit solar Δm_{21};
allowed regions much smaller
KamLAND
Δm^2_{21} in eV^2 x10^{-5}
$\sin^2(\Theta_{12})$
$\Delta\chi^2$