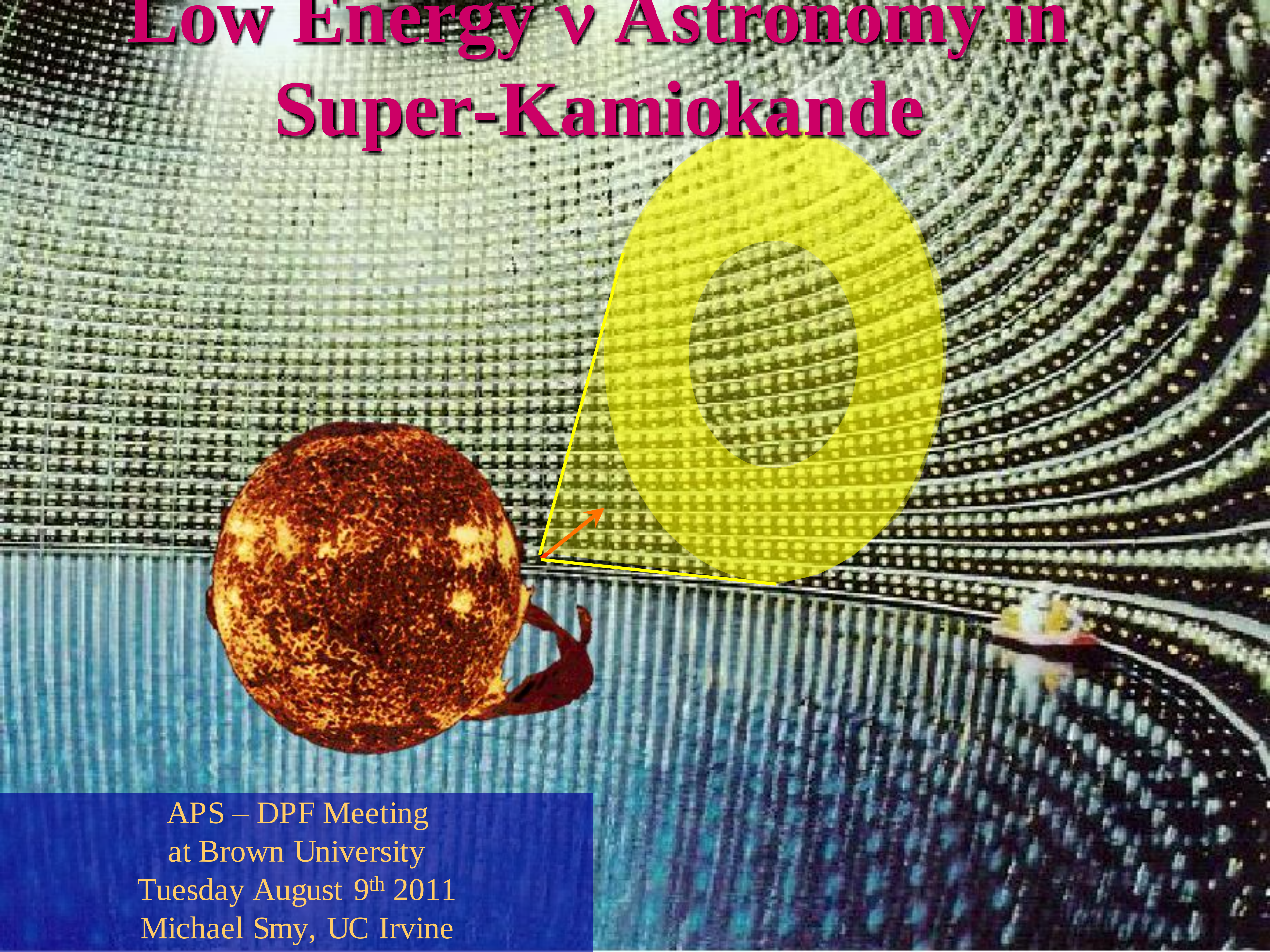
Low Energy ν Astronomy in Super-Kamiokande

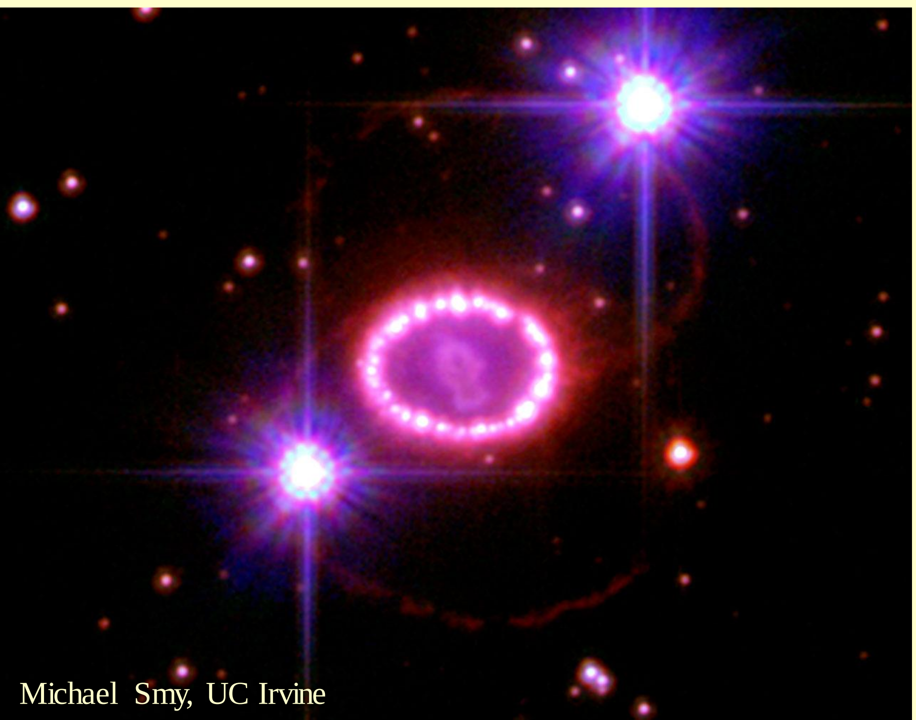


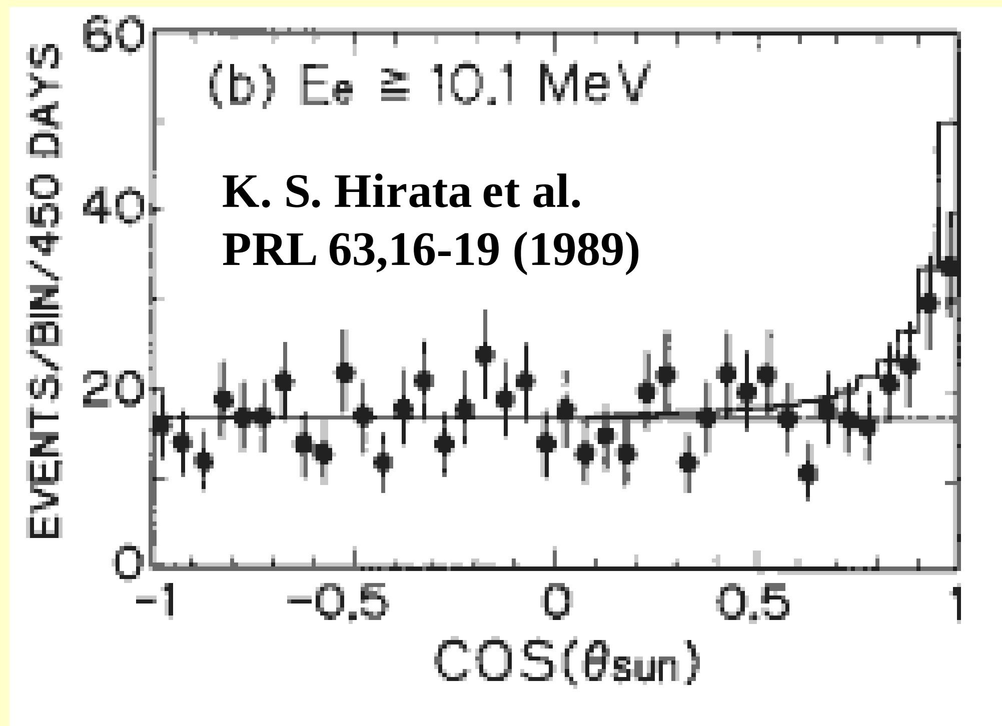
APS – DPF Meeting
at Brown University
Tuesday August 9th 2011

Michael Smy, UC Irvine

Birth of Neutrino Astronomy

- in 1987 the star Sanduleak -69^0 202a (distance: 50kpc) exploded and coincident within 13 sec
  - 11 neutrino interactions were seen by Kamiokande II
  - 8 neutrino interactions were seen by IMB
  - 5 neutrino interactions were seen by Baksan
- in the same year, Kamiokande observed an excess of events in the solar direction due to solar neutrino-electron elastic scattering
- since then, no extra-terrestrial neutrino sources have been observed



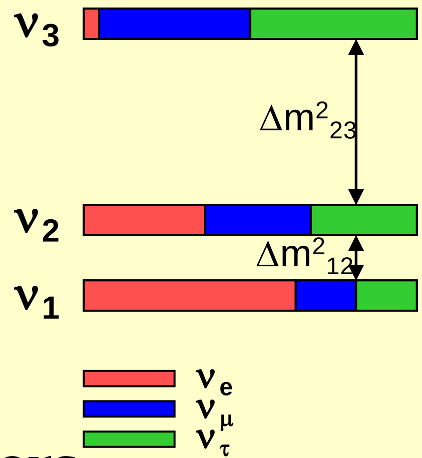


Search for Other ν Sources (just SK)

- no neutrinos from "Astrophysical Point Sources"
  E. Thrane et al., APJ 704: 503-512 (2009)
- no neutrinos from "GRB 080319B"
  E. Thrane et al., APJ 697: 730-734 (2009)
- no "Supernova Neutrino Bursts"
  M. Ikeda et al., APJ 669: 519-524 (2007)
- no "High Energy Neutrino Astronomy"
  K. Abe et al., APJ 652:198-205 (2006)
- no "Diffuse Astrophysical Neutrino Flux"
  M. Swanson et al., APJ 652: 206-215 (2006)
- no neutrinos from "Dark Matter WIMPs"
  S. Desai et al., PRD70: 083523 (2004)
- no "Supernova Relic Neutrinos"
  M. Malek, PRL 90: 061101 (2003)
- no neutrinos from "Gamma Ray Bursts"
  S. Fukuda et al., APJ 578: 317-324 (2002)

Neutrino Flavour Mixing: MNS Matrix

$$U = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & e^{-i\delta}s_{13} \\ -s_{12}c_{23} - e^{-i\delta}c_{12}s_{13}s_{23} & c_{12}c_{23} - e^{i\delta}s_{12}s_{13}s_{23} & c_{13}s_{23} \\ -e^{i\delta}c_{12}s_{13}c_{23} + s_{12}s_{23} & -e^{i\delta}s_{12}s_{13}c_{23} - c_{12}s_{23} & c_{13}c_{23} \end{pmatrix}$$



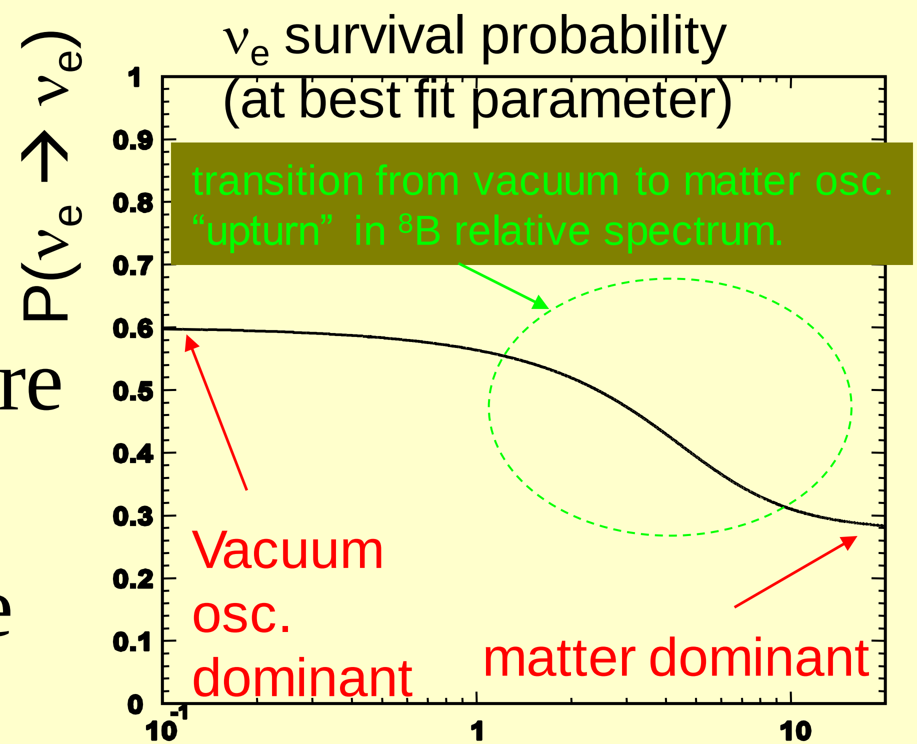
- Known Parameters
  - Two Mass² Diff. scales
    - atmospheric: Δm^2_{23}
    - solar /KamLAND: Δm^2_{12}
  - Two Mixing Angles
    - atmospheric : θ_{23}
    - solar/KamLAND: θ_{12}
  - Mass² ordering
    - solar: Δm^2_{12}

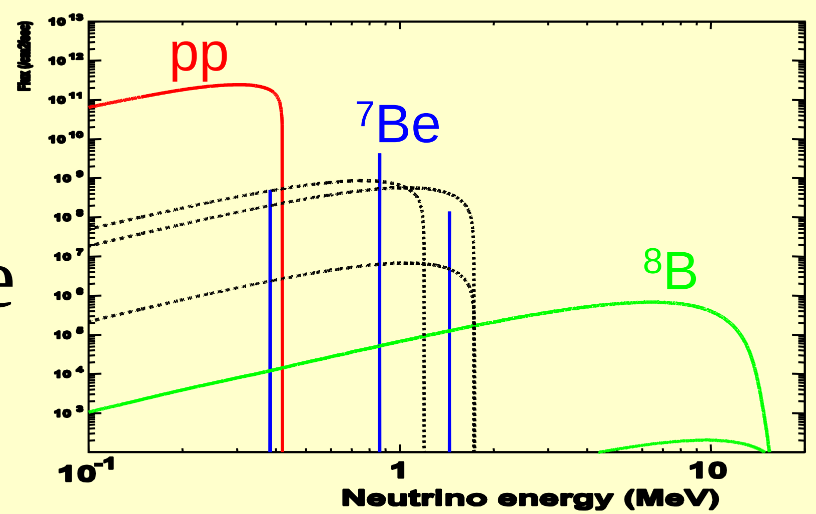
- Unknown Parameters
  - Third Mixing Angle θ_{13} (only limit)
  - CP-Violating Phases
    - accessible via ν oscillation: δ
    - accessible only via $0\nu\beta\beta$: α_1, α_2
  - Mass² ordering
    - atmospheric: Δm^2_{23}
  - Other
    - Mass?
    - Majorana or Dirac?

Courtesy T. Maruyama, KEK

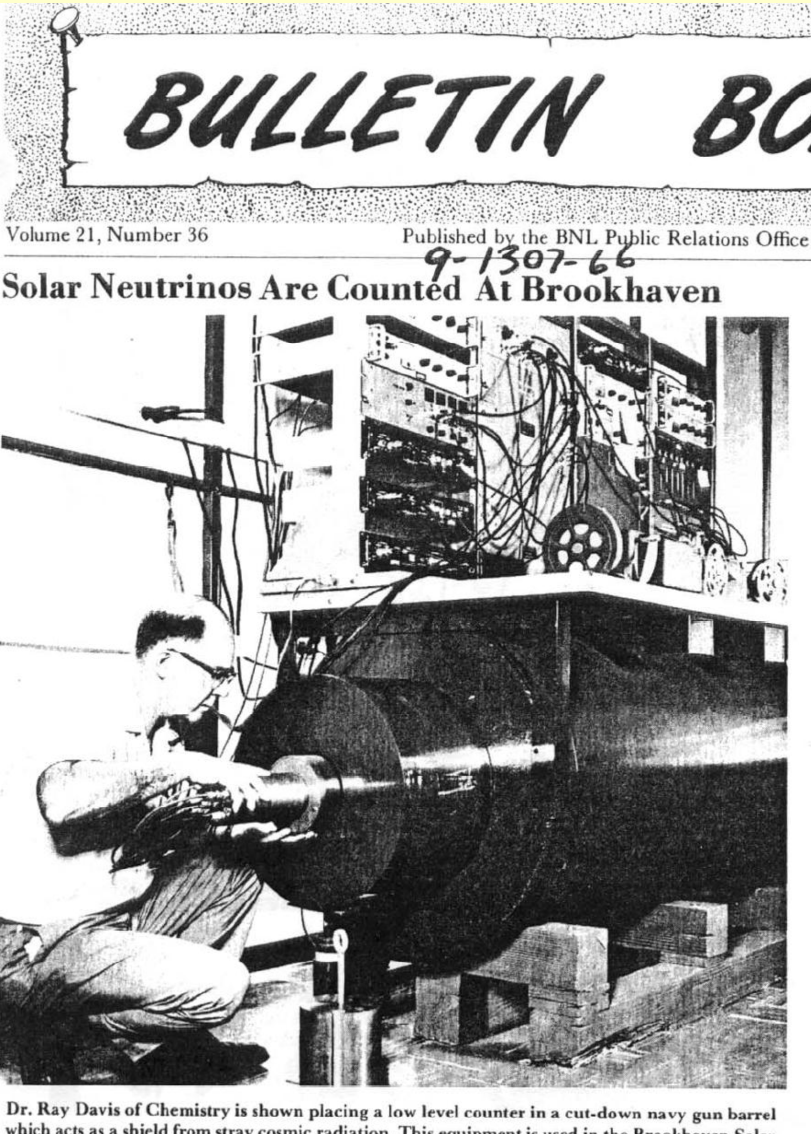
Solar Neutrinos

- conclusive proof that the sun shines because of nuclear reactions
- monitors directly solar core
- MSW-resonant flavor conversion happens in the sun for high energy solar neutrinos (>~3 MeV)
- flavor conversion modified if neutrinos pass through the earth





Solar ν Physics Began with Ray Davis…



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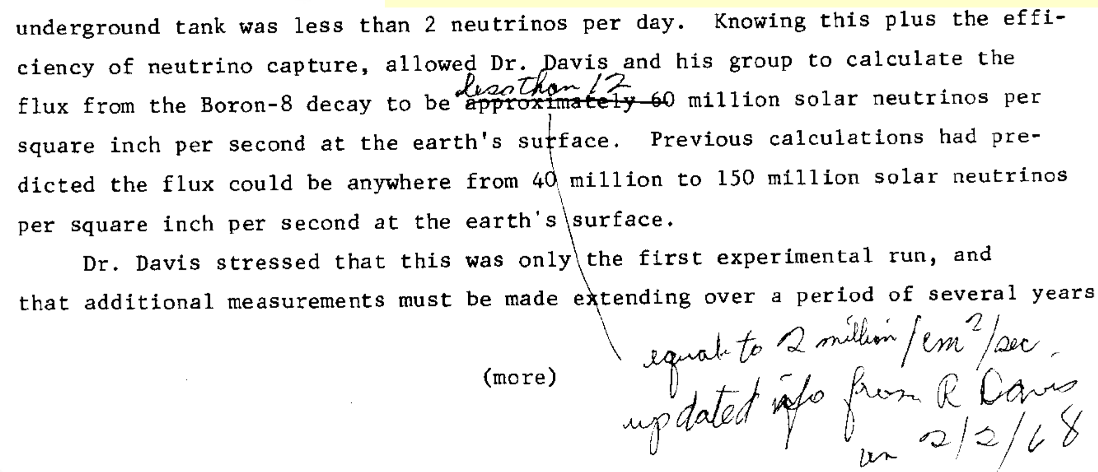
Volume 21, Number 36 — Published by the BNL Public Relations Office — September 14, 1967

9-1307-66

Solar Neutrinos Are Counted At Brookhaven

Dr. Ray Davis of Chemistry is shown placing a low level counter in a cut-down navy gun barrel which acts as a shield from stray cosmic radiation. This equipment is used in the Brookhaven Solar



underground tank was less than 2 neutrinos per day. Knowing this plus the efficiency of neutrino capture, allowed Dr. Davis and his group to calculate the flux from the Boron-8 decay to be ~~approximately 60~~ less than 12 million solar neutrinos per square inch per second at the earth's surface. Previous calculations had predicted the flux could be anywhere from 40 million to 150 million solar neutrinos per square inch per second at the earth's surface.

Dr. Davis stressed that this was only the first experimental run, and that additional measurements must be made extending over a period of several years.

(more)

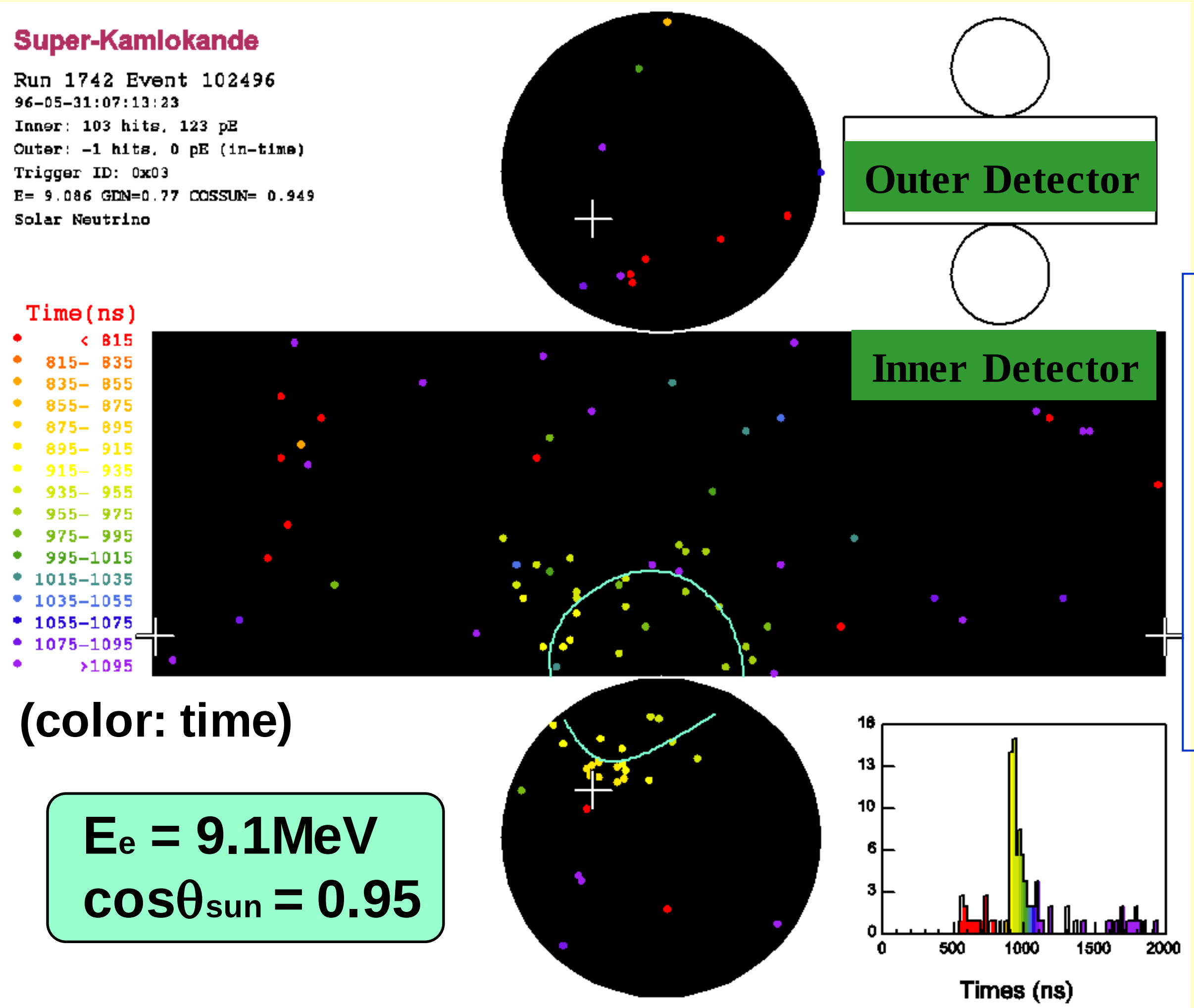
equal to 2 million/cm²/sec.
updated info from R Davis
on 2/2/68

SK-III result for ^{8}B Flux:

2.32+/-0.04(stat.)+/-0.05(syst.) (x10^6/cm^2/s)

(somewhat larger since oscillated solar neutrinos contribute)

Water Cherenkov Technique



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

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

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

~6hit / MeV
(SK-I, III, IV)

Resolutions (for 10MeV electrons) (software improvement)

Energy: 14%	Vertex: 87cm	Direction: 26°	SK-I
Energy: 14%	Vertex: 55cm	Direction: 23°	SK-III

Courtesy Y. Takeuchi, ICRR

Solar Neutrino Oscillation Data

- neutrino oscillations started from "solar problem"
- sensitive to Δm^2_{12} θ_{12} and θ_{13}

updates since our previous oscillation analysis (PRD78,032002(2008))

- SK Data
  - SK-I 1496 days, spectrum 5.0-20MeV + D/N ($E \geq 5.0$MeV)
  - SK-II 791 days, spectrum 7.0-20MeV + D/N ($E \geq 7.5$MeV)
  - SK-III 548 days, spectrum 5.0-20.0MeV + D/N ($E \geq 5.0$MeV)
- SNO Data
  - CC flux (Phase-I & II & III)
  - NC flux (Phase-III & LETA combined): $(5.14 \pm 0.21) \times 10^6/\mathrm{cm}^2\mathrm{s}$
  - Day/Night asymmetry (Phase-I, II & III)
- Radiochemical: Cl (Homestake), Ga (GALLEX/GNO/SAGE)
  - Ga rate: 66.1 ± 3.1 SNU (All Ga global): PRC80, 015807(2009)
  - Cl rate: 2.56 ± 0.23: Astrophys. J. 496 (1998) 505
- Borexino
  - ^{7}Be rate: 46 ± 2.2 cpd/100tons: arXiv: 1104.1816v1 (2011)
- KamLAND: Data 2008
- ^{8}B spectrum: Winter(2006)

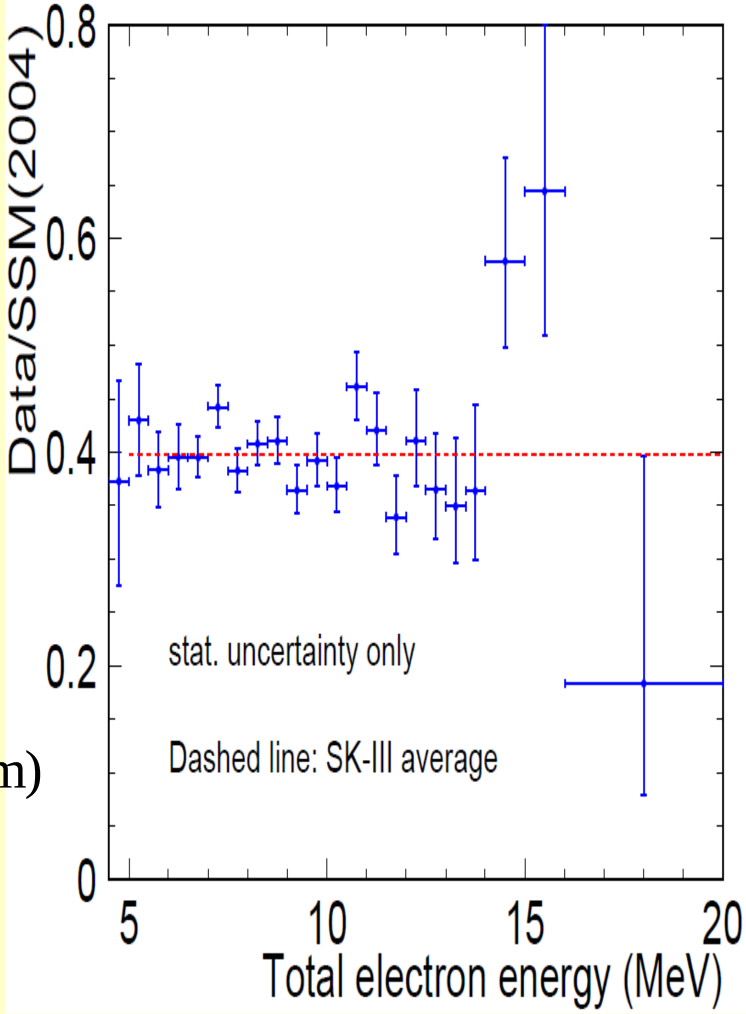
Courtesy Y. Takeuchi, ICRR

Solar ν Flavor Physics is done?

- Super-Kamiokande-I and SNO established solar neutrino flavor conversion, oscillation parameters are measured agree with reactor neutrino data…
- …but transition from solar resonance to averaged vacuum oscillation has not been probed; resulting distortion to the observed spectrum so far not confirmed
- … but modification of conversion by Earth matter effect is unobserved
- … but a better measurement of solar mass splitting Δm^2_{12} is needed for a more meaningful comparison to reactor neutrino measurements

SK-III solar neutrino results

- Total live time: 548 days, $E_{total} \geq 6.5$ MeV
  289 days, $E_{total} < 6.5$ MeV



- Energy region: E_{total}=4.5/5.0-20.0MeV

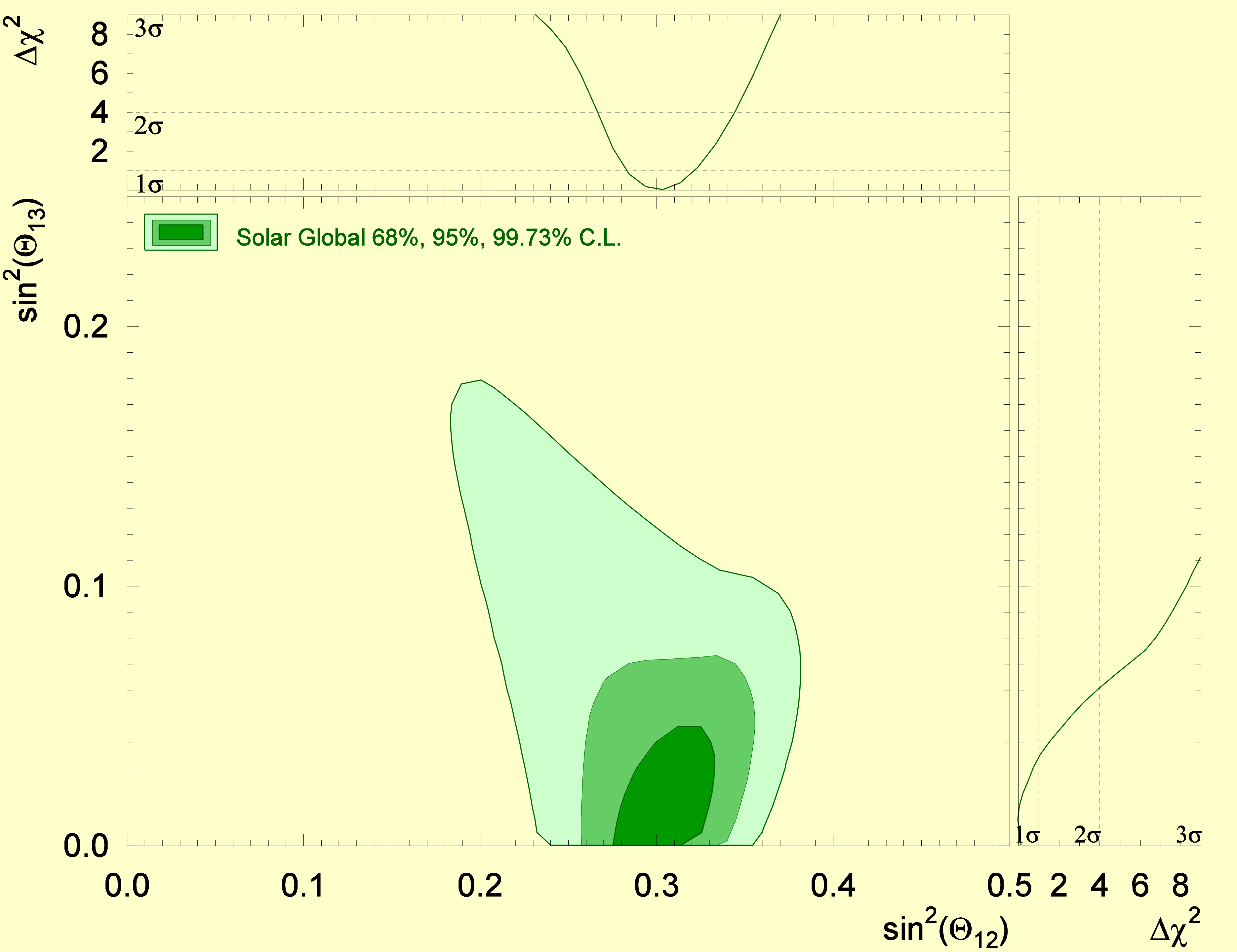
- ^{8}B Flux:
  2.32±0.04(stat.) ±0.05(syst.) (x10^6/cm^{2}s)
  - SK-I: 2.38±0.02(stat.) ±0.08(syst.)
  - SK-II: 2.41±0.05(stat.)+0.16/-0.15(syst.)
    (recalc. SK-I,II with the Winter06 ^{8}B spectrum)

- Day / Night ratio:

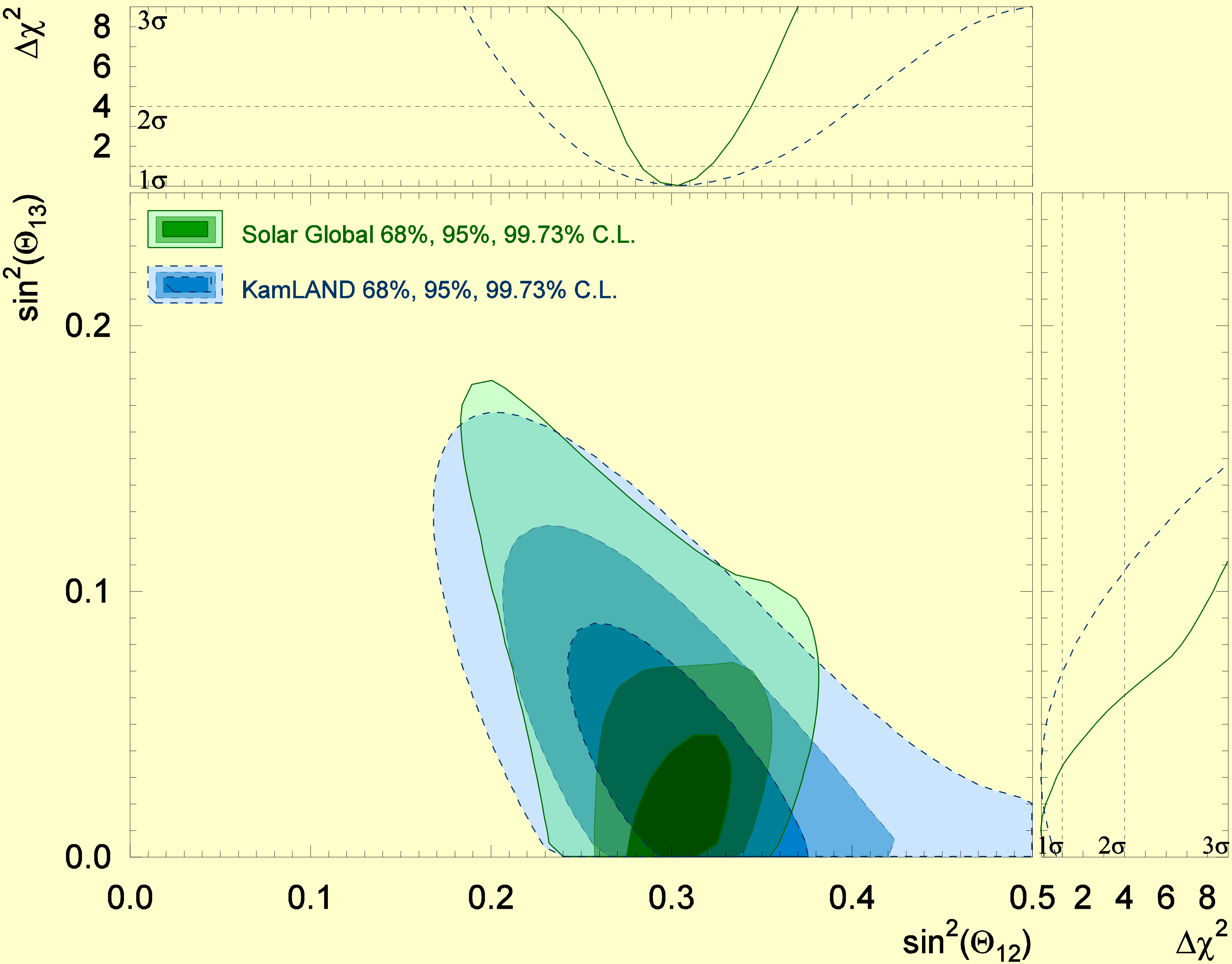
$$A_{DN} = \frac{(\Phi_{Day} - \Phi_{Night})}{(\Phi_{Day} + \Phi_{Night})/2} = -0.056 \pm 0.031(\text{stat.}) \pm 0.013(\text{syst.})$$

  - SK-I: -0.021±0.020(stat) ±0.013(syst.)
  - SK-II: -0.063±0.042(stat) ±0.037(syst.)

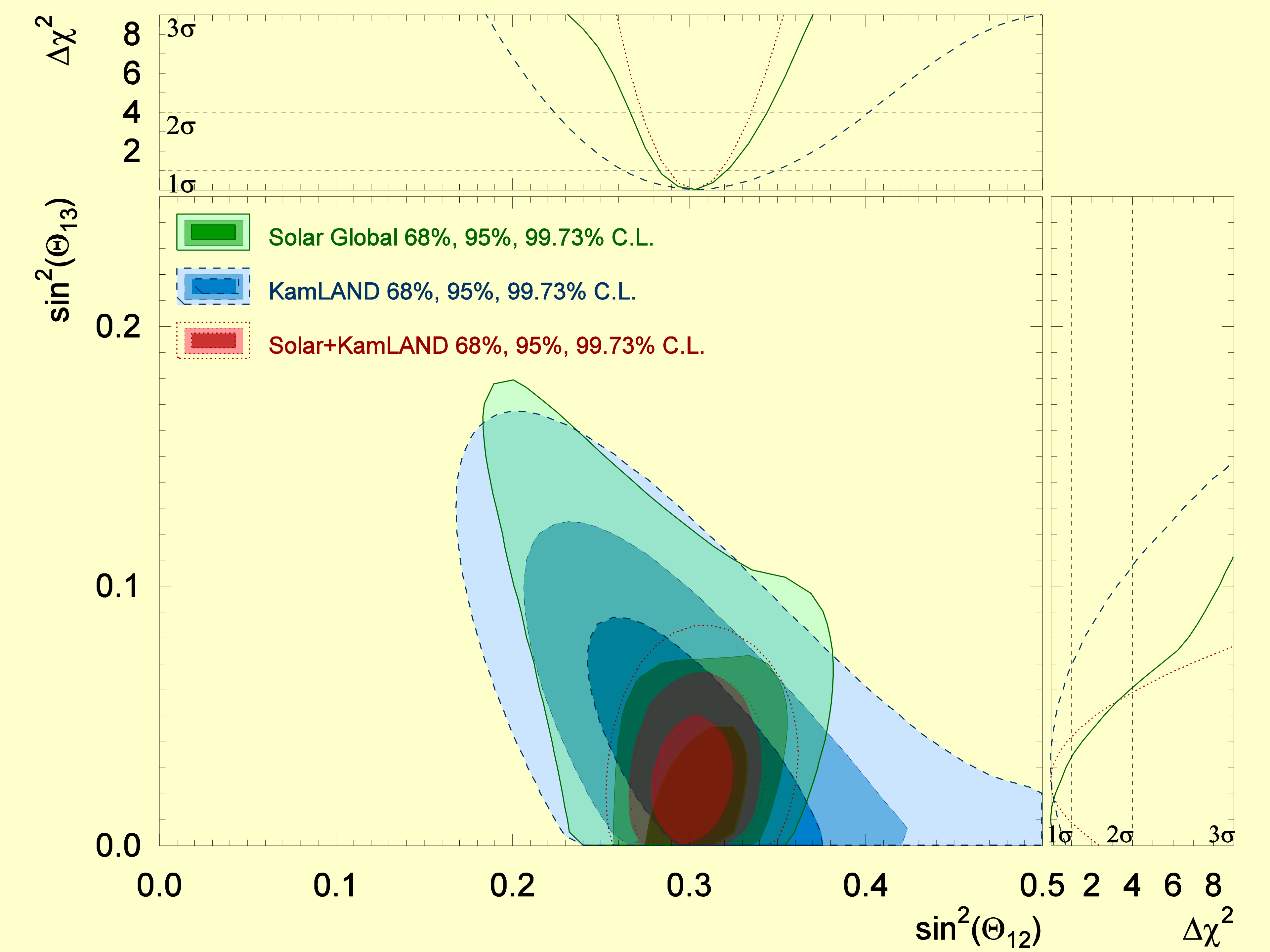
Courtesy Y. Takeuchi, ICRR



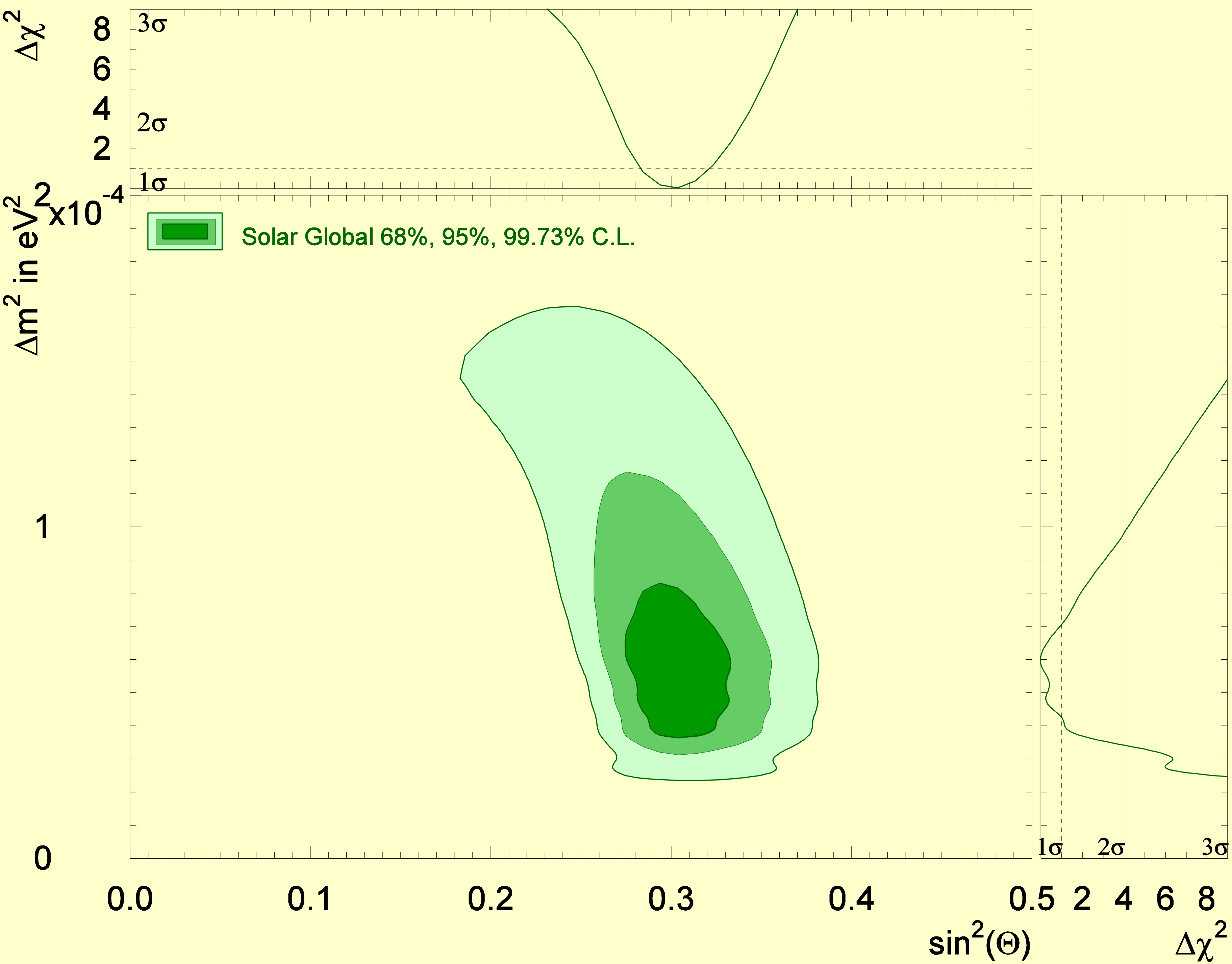
$\Delta\chi^2$
8
6
4
2
3σ
2σ
1σ
$\sin^2(\Theta_{13})$
0.2
0.1
0.0
Solar Global 68%, 95%, 99.73% C.L.
0.0
0.1
0.2
0.3
0.4
0.5
$\sin^2(\Theta_{12})$
2
4
6
8
$\Delta\chi^2$



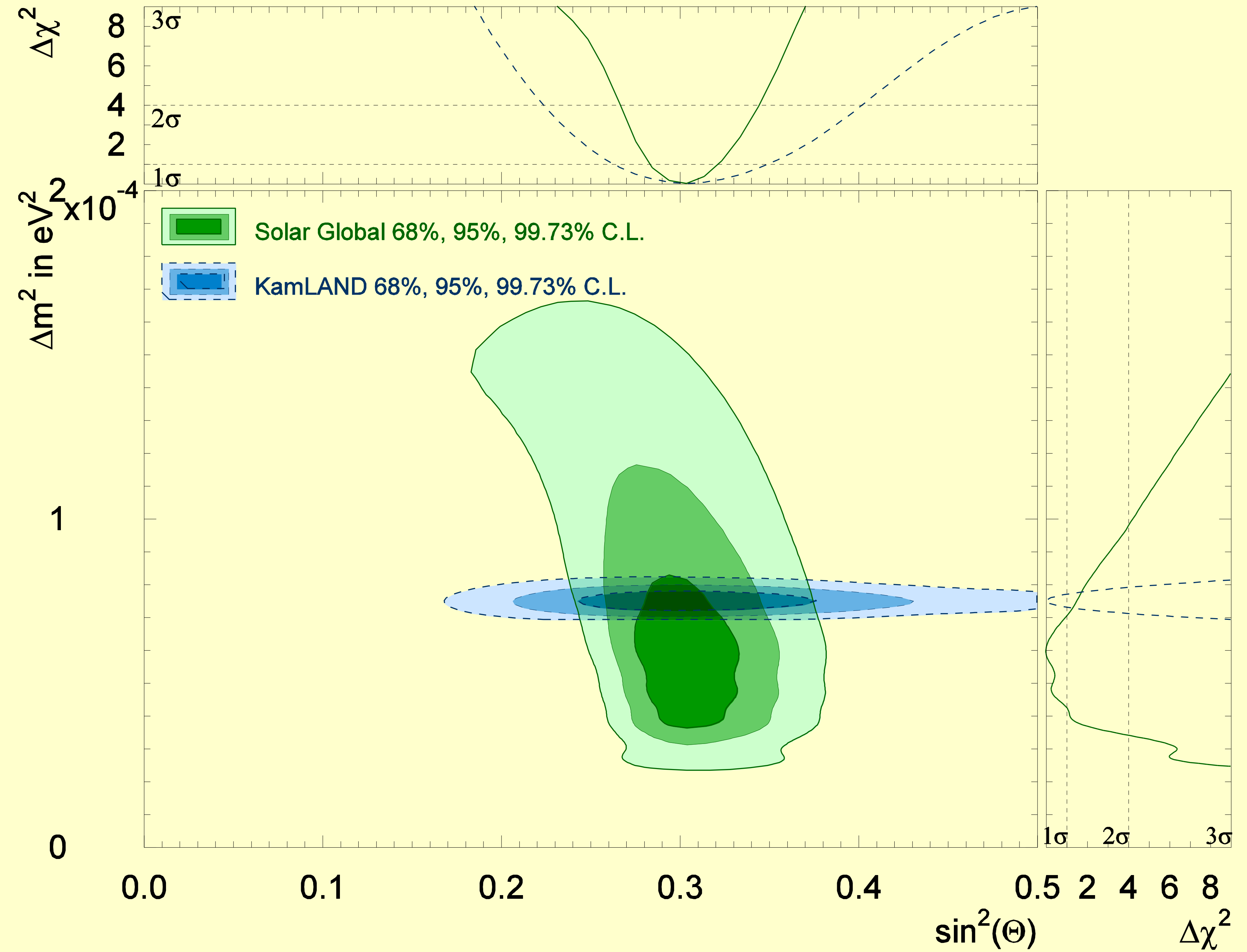
Solar Global 68%, 95%, 99.73% C.L.
KamLAND 68%, 95%, 99.73% C.L.
$\Delta\chi^2$
$\sin^2(\Theta_{13})$
$\sin^2(\Theta_{12})$
3σ
2σ
1σ
0.0
0.1
0.2
0.3
0.4
0.5
2
4
6
8



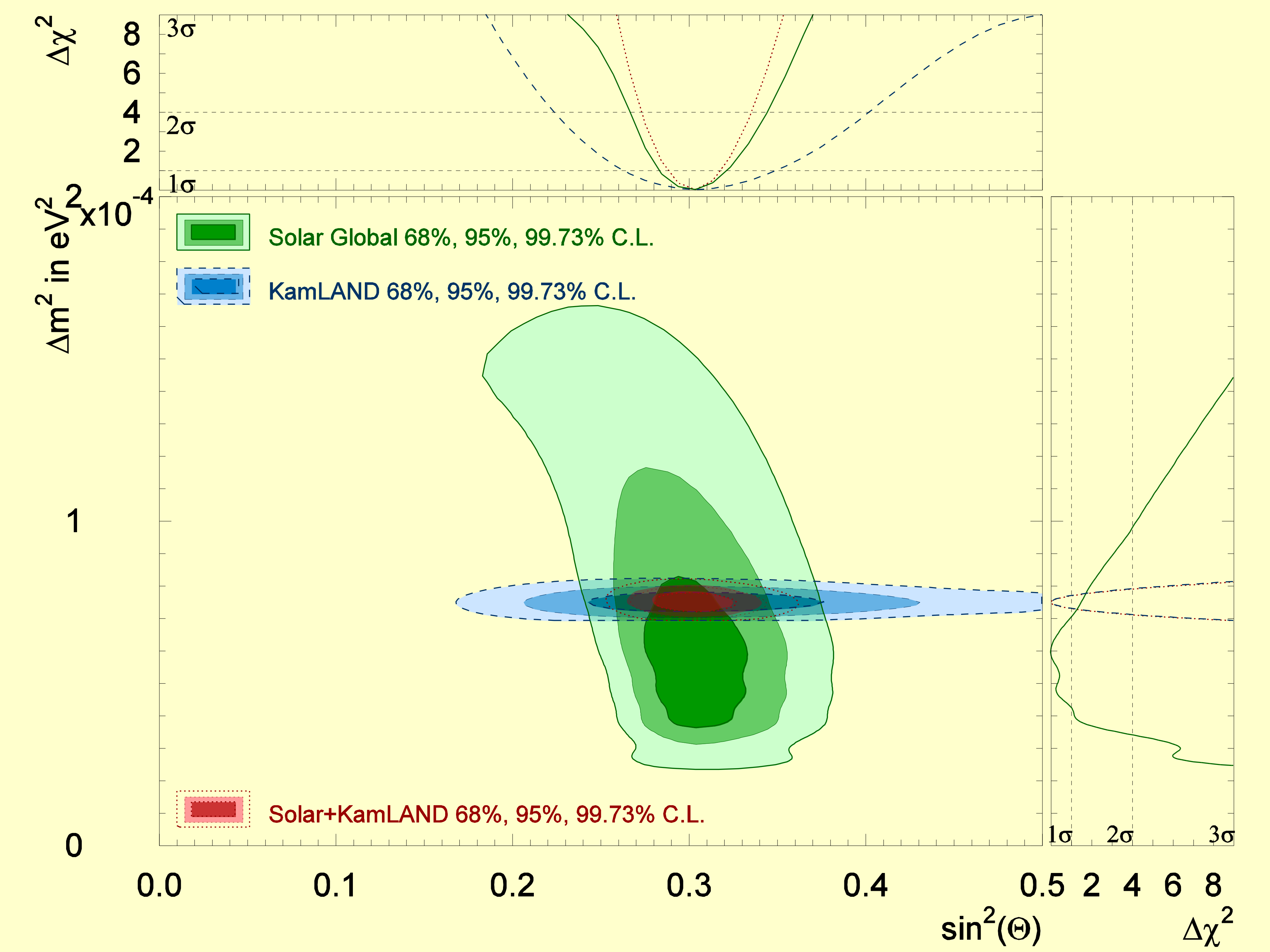
Solar Global 68%, 95%, 99.73% C.L.
KamLAND 68%, 95%, 99.73% C.L.
Solar+KamLAND 68%, 95%, 99.73% C.L.
$\Delta\chi^2$
$\sin^2(\Theta_{13})$
$\sin^2(\Theta_{12})$
1σ
2σ
3σ
0.0
0.1
0.2
0.3
0.4
0.5
2
4
6
8



Solar Global 68%, 95%, 99.73% C.L.
$\Delta\chi^2$
Δm^2 in eV^2 $\times 10^{-4}$
$\sin^2(\Theta)$
1σ
2σ
3σ
0.0
0.1
0.2
0.3
0.4
0.5
2
4
6
8
0
1
2



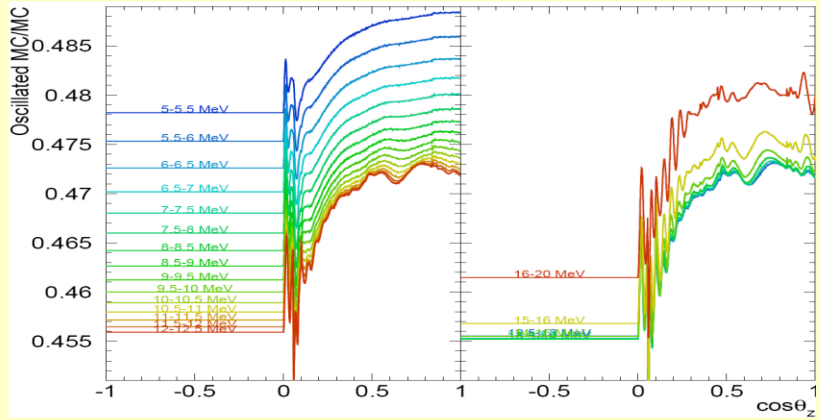
Solar Global 68%, 95%, 99.73% C.L.
KamLAND 68%, 95%, 99.73% C.L.
Δm^2 in eV^2 $\times 10^{-4}$
$\sin^2(\Theta)$
$\Delta\chi^2$
1σ
2σ
3σ
0.0
0.1
0.2
0.3
0.4
0.5
0
1
2
2
4
6
8

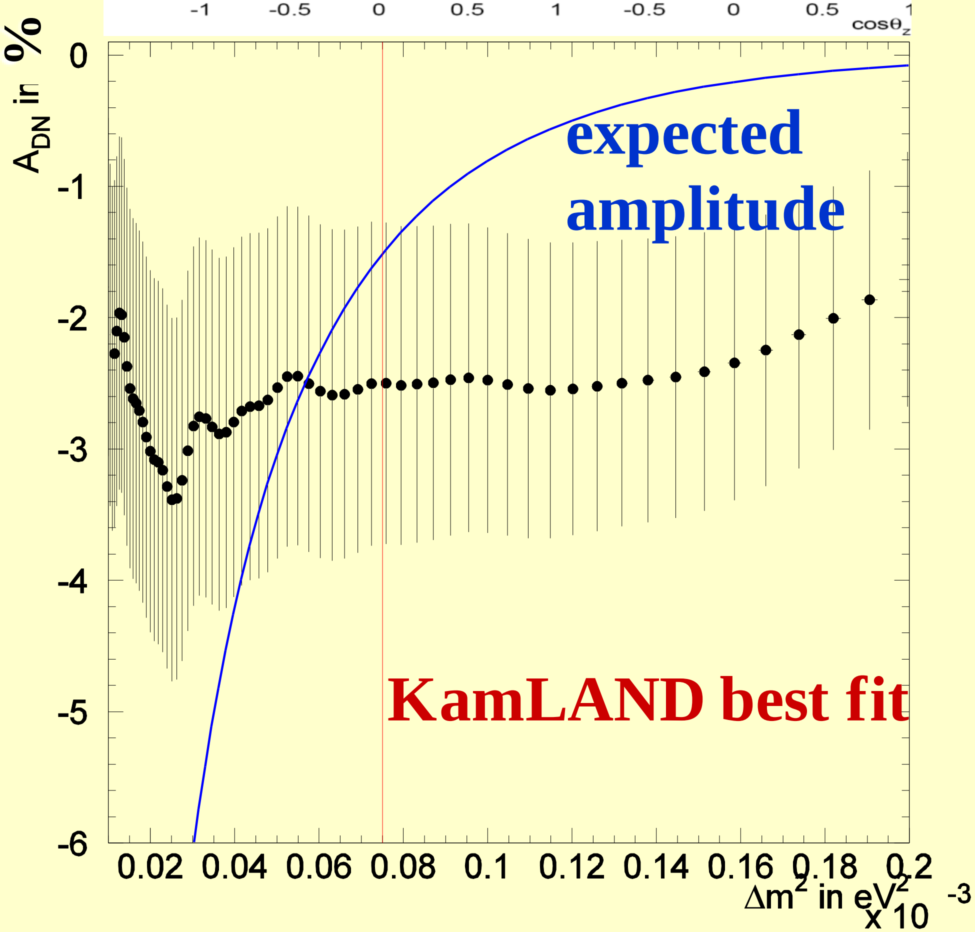


Solar Global 68%, 95%, 99.73% C.L.
KamLAND 68%, 95%, 99.73% C.L.
Solar+KamLAND 68%, 95%, 99.73% C.L.
Δm^2 in eV^2 x10^{-4}
$\sin^2(\Theta)$
$\Delta\chi^2$
1σ
2σ
3σ
0.0
0.1
0.2
0.3
0.4
0.5
0
1
2
2
4
6
8

Fit Day/Night Amplitude to SK Data

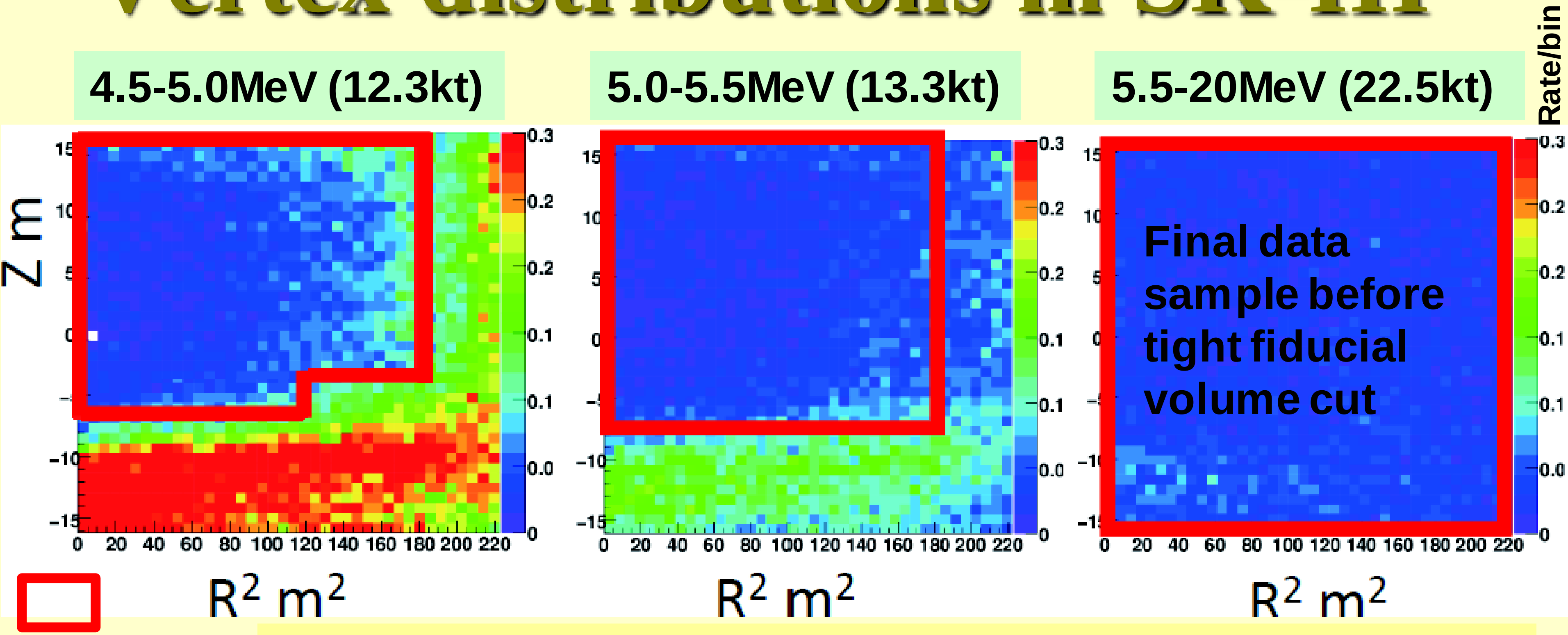
- used for SK-I: **A_{DN}(I)=** **-0.018±0.016(stat) ±0.013(syst)**
- **A_{DN}(II)=-0.036±0.035(stat),** **A_{DN}(III)=-0.040±0.025(stat)**
- depends on Δm^2
- Combine SK-I/II/III **-0.026±0.013(stat)** at KamLAND Δm^2
- consistent with expected amplitude
- consistent with zero within 2σ
- systematic uncertainty under study



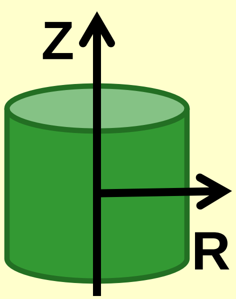


Michael Smy, UC Irvine

Vertex distributions in SK-III



SK-III fid. volume



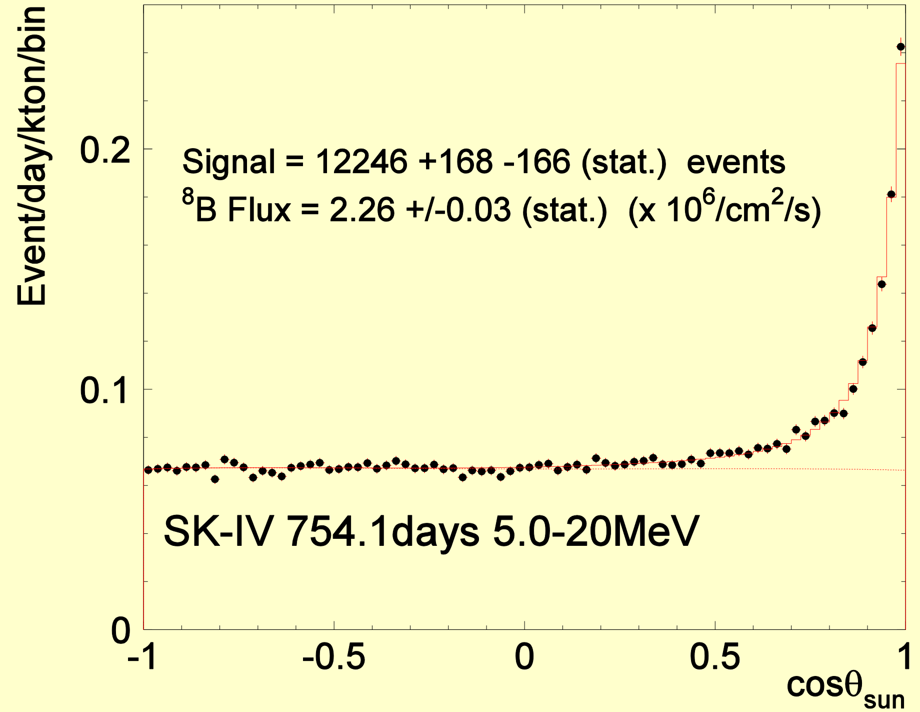
SK detector

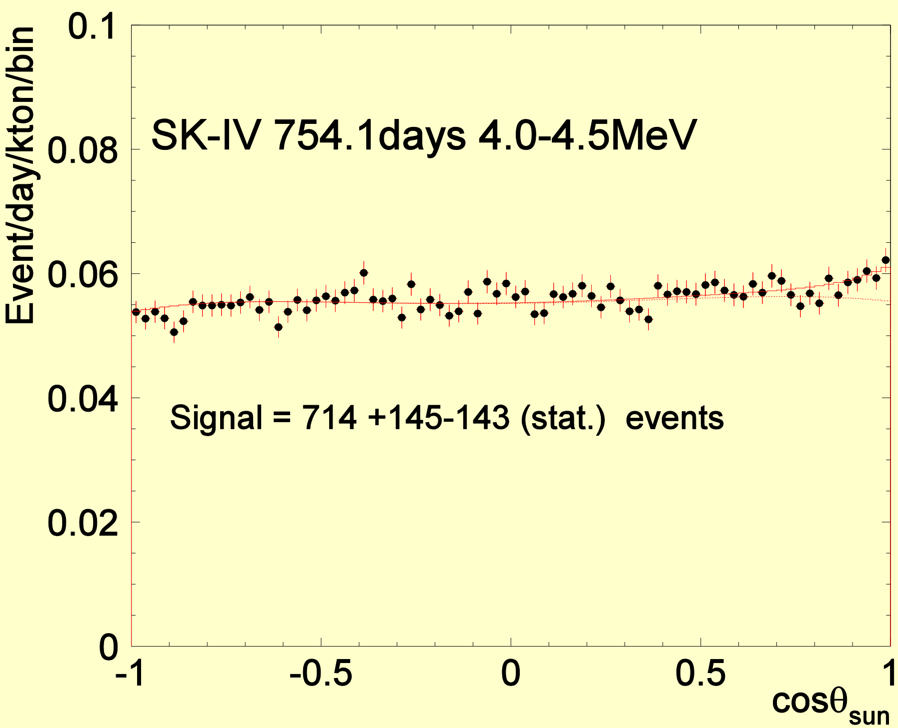
- reduce dissolved Radon gas bkg by water flow control detector (very precise injection water temp control)
- convection cell at the detector bottom transports Rn
- tight fiducial volume cut is applied in E_{total}<5.5MeV to remove the background events. (probably Rn, γ-rays from detector wall).

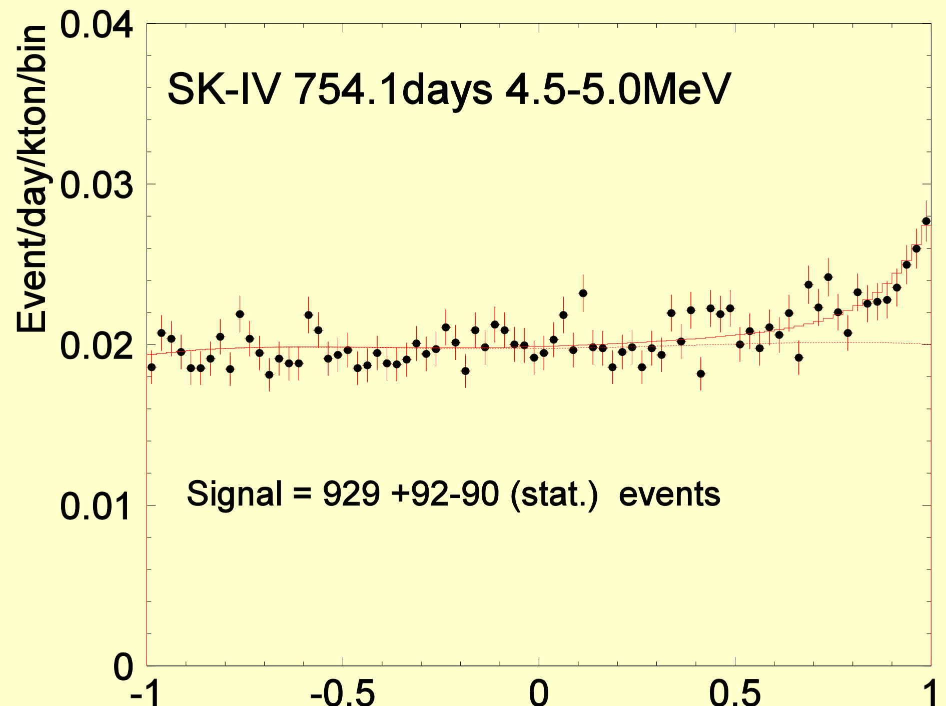
Courtesy Y. Takeuchi, ICRR

SK-IV

- no hardware trigger threshold; all triggers applied by software
- see solar ν elastic scattering peak >4 MeV



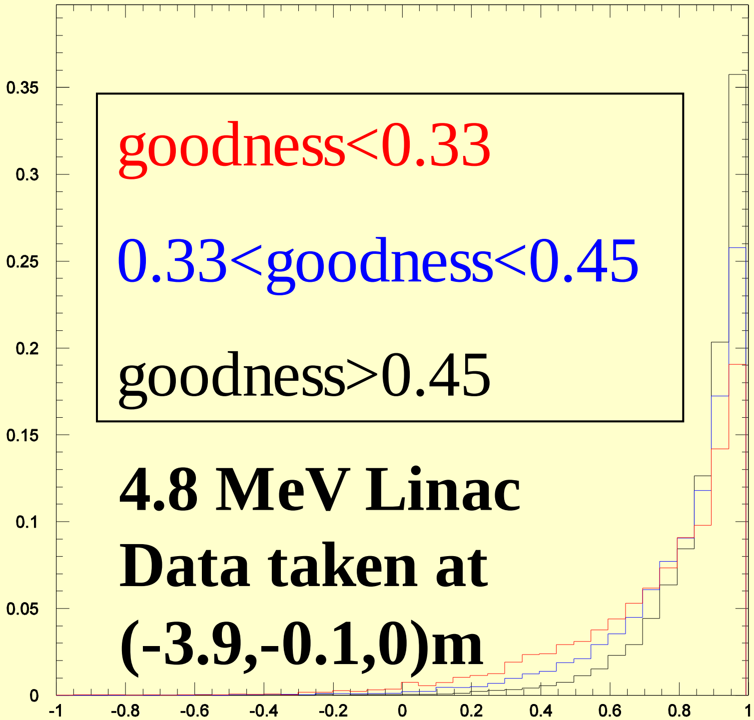




Probe Lower Energies: How to Reduce Radon Background?

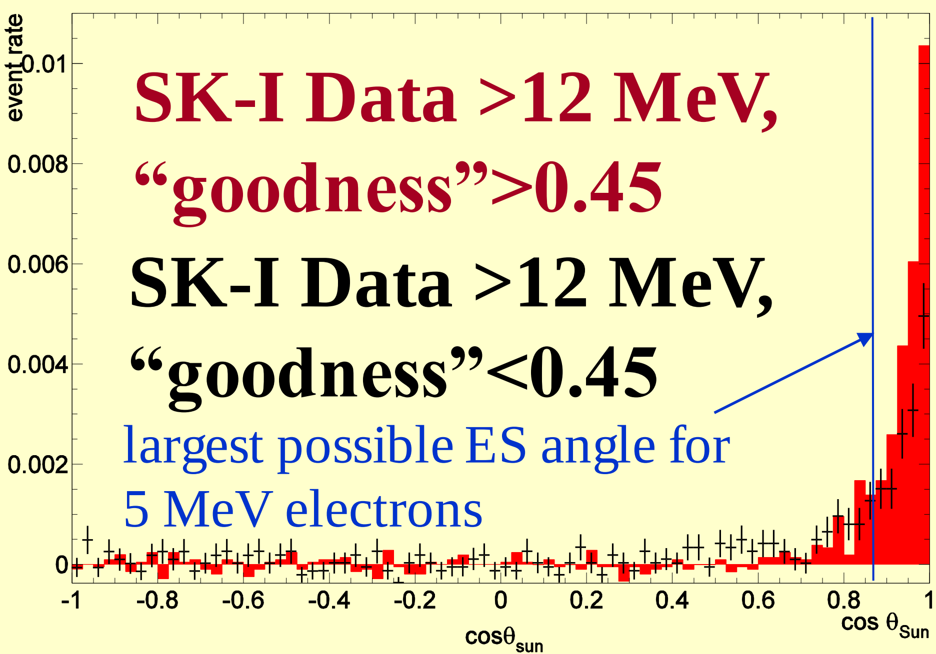
- work I did with my student Andrew Renshaw; not yet part of the official SK analysis
- Radon decays to ^{214}Bi which β decays: real electrons <3.1MeV fluctuating in light yield up to 6.5 MeV equivalent
- multiple Coulomb scattering (mCs) is still that of ~2 to 3 MeV electrons: events more isotropic than 4-5 MeV solar neutrinos
- reconstruct mCs from Cherenkov hit pattern: "goodness" of direction fit to simple cone
- select large "goodness": sharper angular resolution

$\cos\theta_{sun}$ Resolution

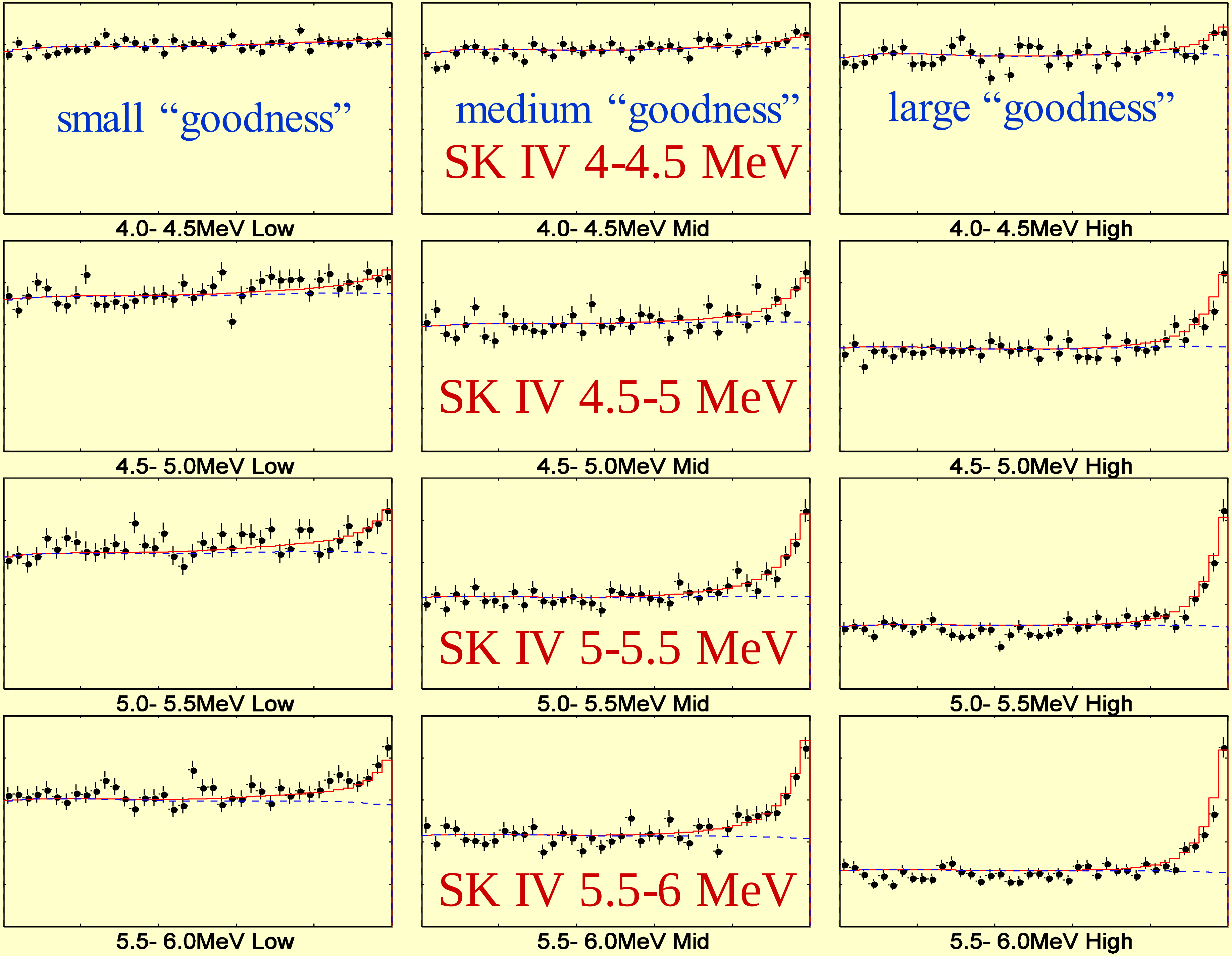


for LINAC θ_{sun} defined as the angle between –z (beam direction) and reconstructed direction

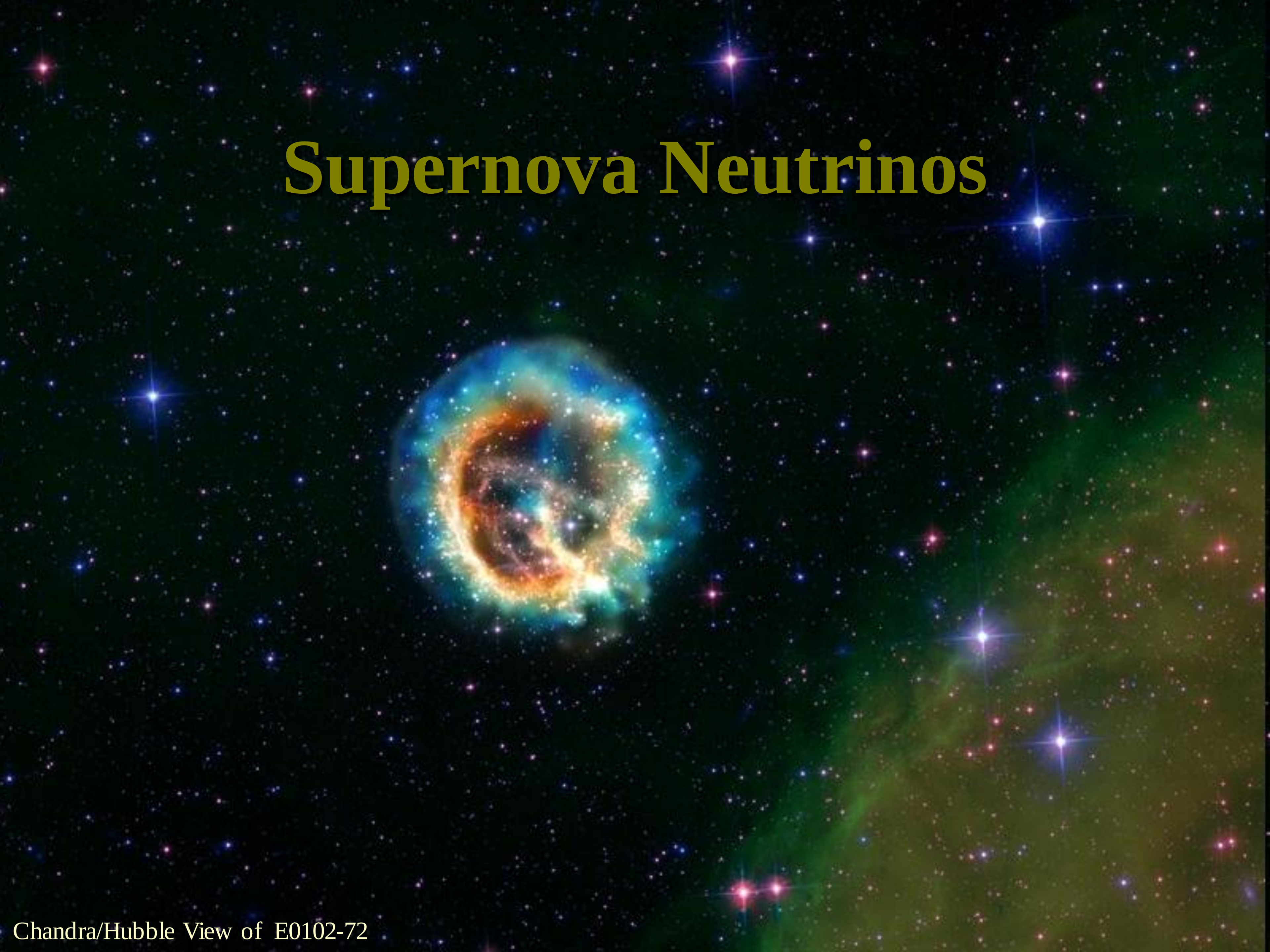
the "ES peak" sharpens in regions of higher goodness (true for all LINAC momenta at all positions)



size of sun: $\sim 0.5^0$, so $\cos\theta_{sun}^{max} \sim 0.99996$


small "goodness"
medium "goodness"
large "goodness"
SK IV 4-4.5 MeV
4.0- 4.5MeV Low
4.0- 4.5MeV Mid
4.0- 4.5MeV High
SK IV 4.5-5 MeV
4.5- 5.0MeV Low
4.5- 5.0MeV Mid
4.5- 5.0MeV High
SK IV 5-5.5 MeV
5.0- 5.5MeV Low
5.0- 5.5MeV Mid
5.0- 5.5MeV High
SK IV 5.5-6 MeV
5.5- 6.0MeV Low
5.5- 6.0MeV Mid
5.5- 6.0MeV High

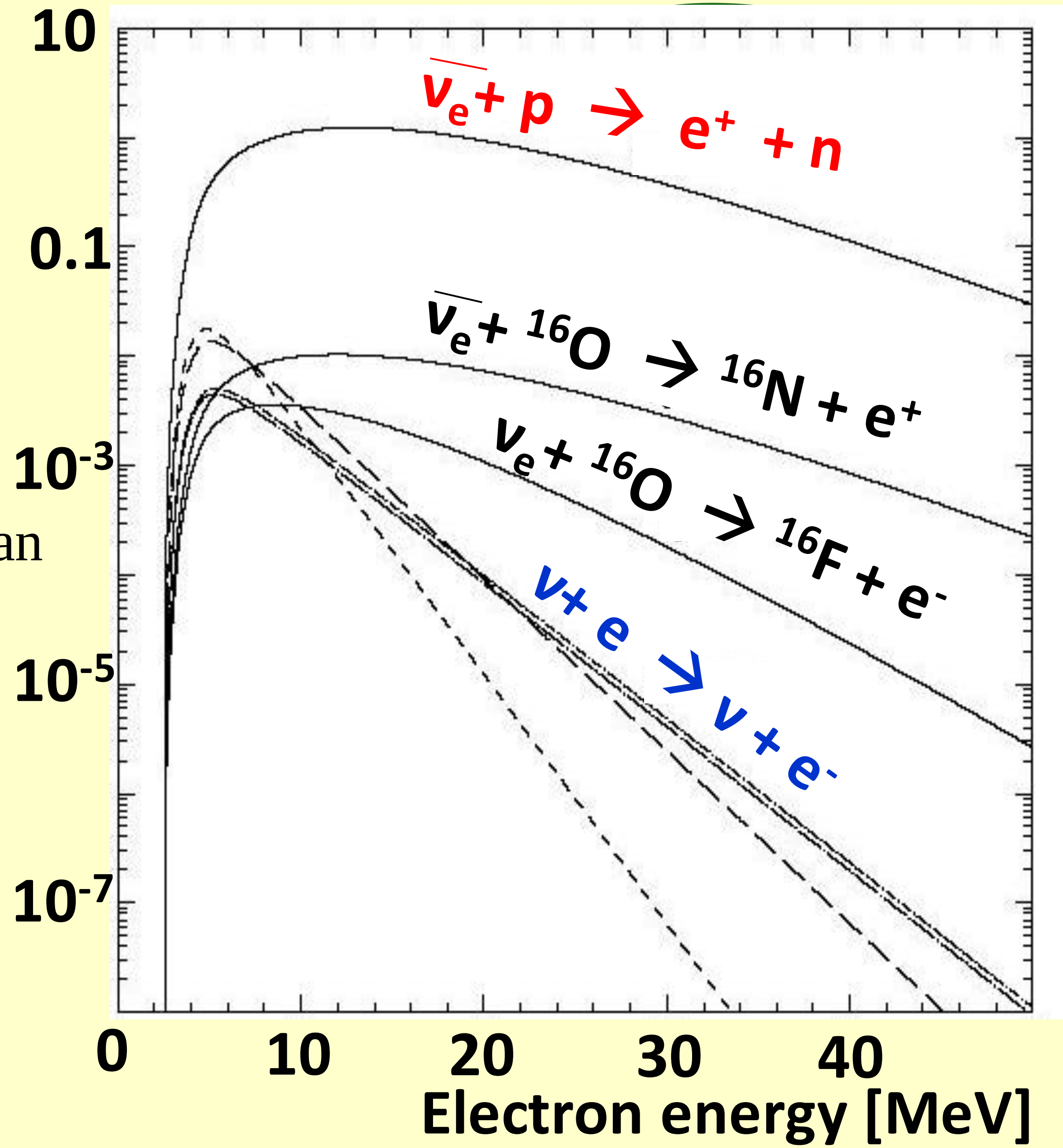
Supernova Neutrinos



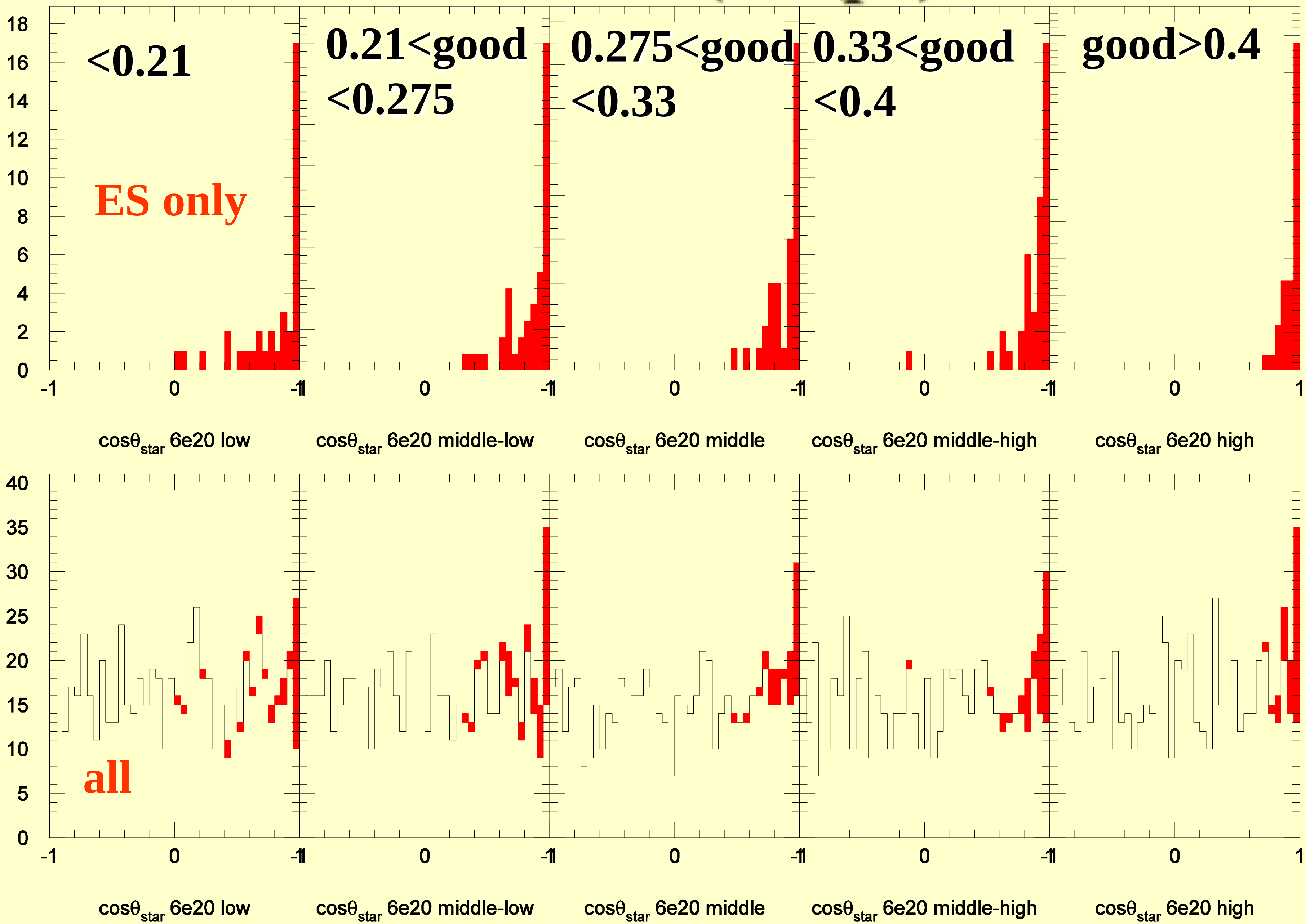
Chandra/Hubble View of E0102-72

Supernova Neutrinos in SK

- ~10k event burst at 10kpc distance
- or search for diffuse, distant supernova ν's (DSN)
- mostly inverse β's
- elastics will point
- mCs reconstruction can help determine SN direction quickly and accurately
- from MC simulations pointing accuracy is three to four degrees
- work in progress



Simulated SN ν Burst (10kpc): 6-20 MeV



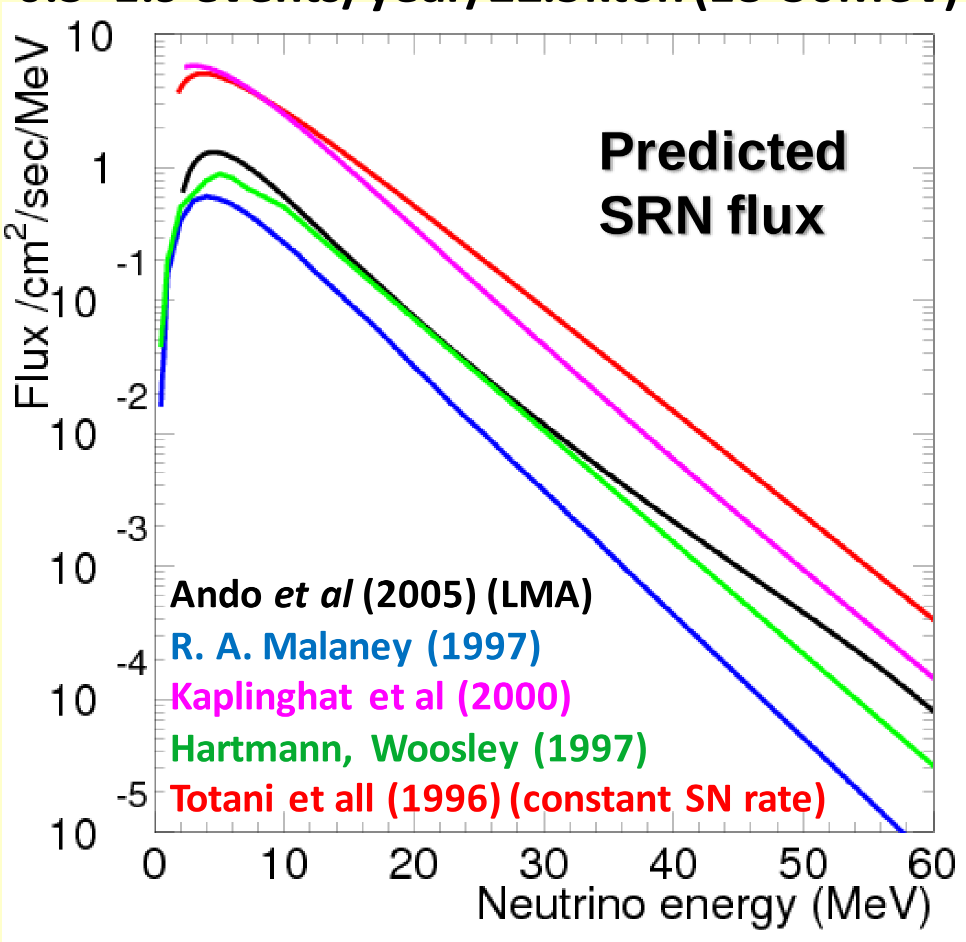
Diffuse Supernova Neutrinos (DSN)

=signal from all past supernovae

0.8 -5.0 events/year/22.5kton (10-30MeV)

0.5 -2.5 events/year/22.5kton (16-30MeV)

0.3 -1.9 events/year/22.5kton (18-30MeV)



Data	Live time	PMTs	%
SK-I	1497 days	11146	40
SK-II	793 days	5182	19
SK-III	562 days	11129	40
SK-IV	running	11129	40

Motivation

DSN studies ν emission of typical supernova folded with the supernova rate and thereby the cosmic star formation history

no signal has been detector thus far:

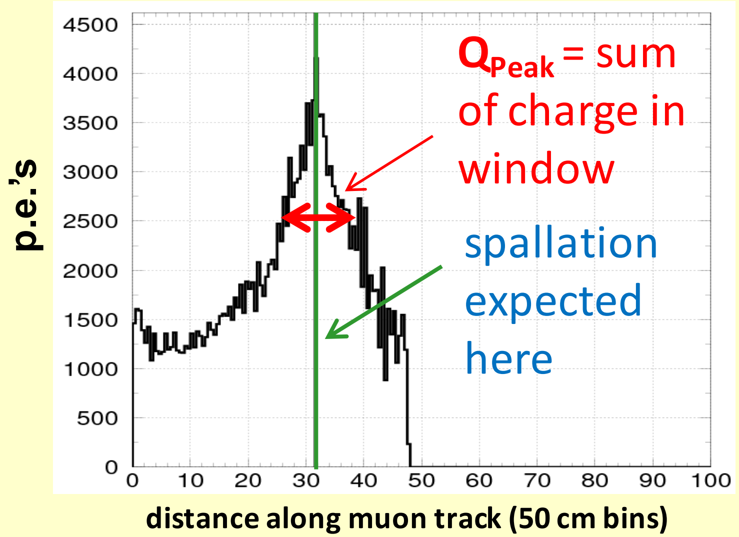
M. Malek, et al, Phys. Rev. Lett. 90, 061101 (2003) for SK

SNO, KamLAND and Borexino have searched as well

Spallation and Solar Cuts

- SPALLATION is cut using correlation to cosmic ray muons
- Original cut used 2-D spatial correlation, time and charge
- New method allows 3-D spatial correlation from μ dE/dx, and muon categorization
- Stricter cut < 18 MeV

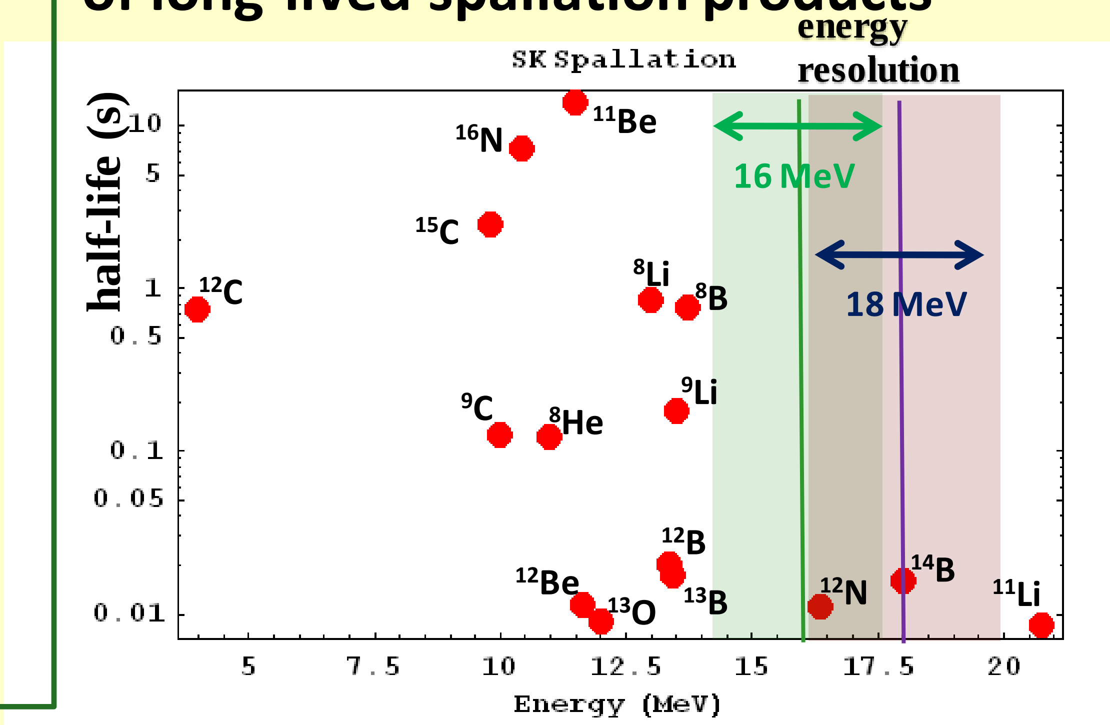
dE/dx Plot



- SOLAR events correlate with solar dir.
- use new multiple scattering recon.
- cut is tuned in 1 MeV bins using MC

New threshold 18 → 16 MeV!

search < 16 MeV difficult due to "wall" of long-lived spallation products



Total signal efficiency:

Cut	SK-I	SK-II	SK-III	2003 (SK-I)
Spall+ solar	88%	87%	89%	69%
Pion	98%	97%	98%	New
Incoming event	98%	95%	96%	93%
Total	79%	69%	77%	52%

Solar and Spallation cut inefficiency

	SOLAR CUT		SPALLATION CUT	
Energy range	2003 cut	new cut	2003 cut	new cut
16-18 MeV	N/A	23%	N/A	18%
18-20 MeV	7%	9%	36%	9%
20-24 MeV	7%	0%	36%	9%
24-34 MeV	7%	0%	36%	0%

Atmospheric ν Background

2003: two channels:

ν_μ CC spectrum modeled by decay electrons from cosmic ray μ's

ν_e CC spectrum from MC

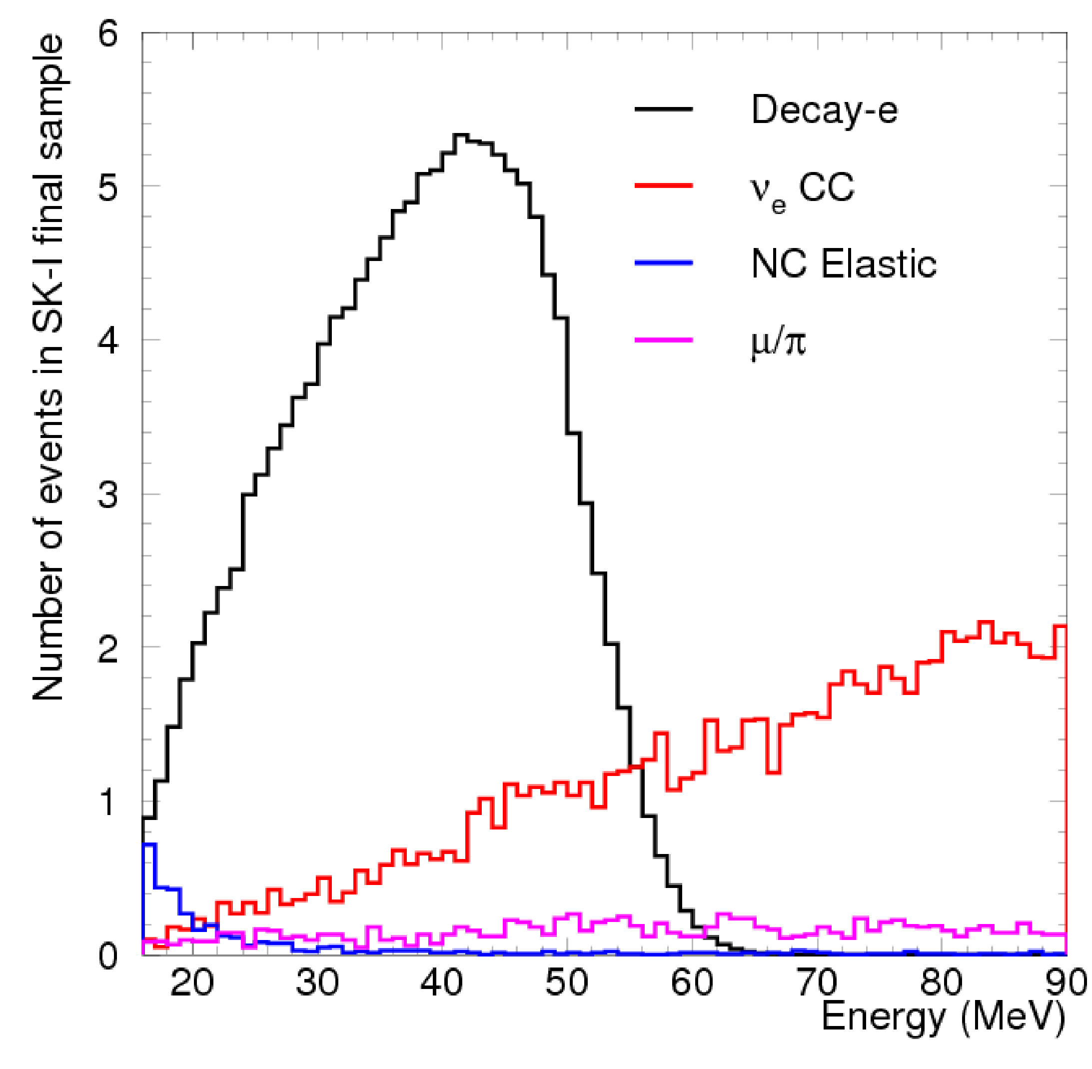
Now: four channels:

ν_μ CC

ν_e CC

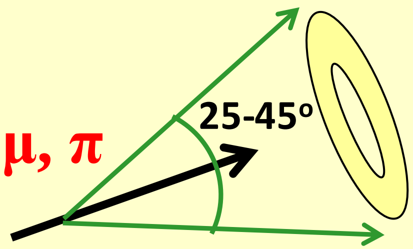
NC elastic required by lower E threshold; spectrum from MC

μ/π prod.: reduced by cuts; helps constrain NC in signal fit

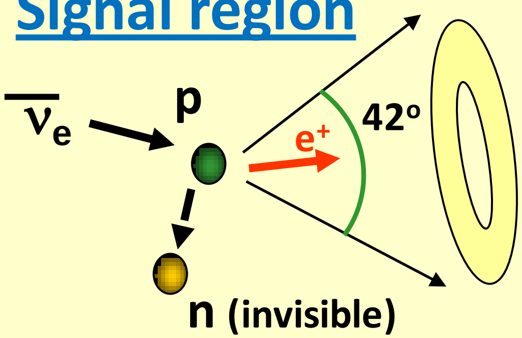


Fit to Signal & Background

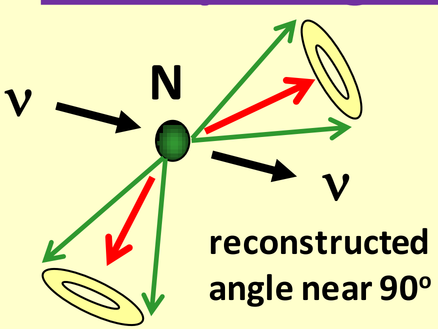
Low angle events

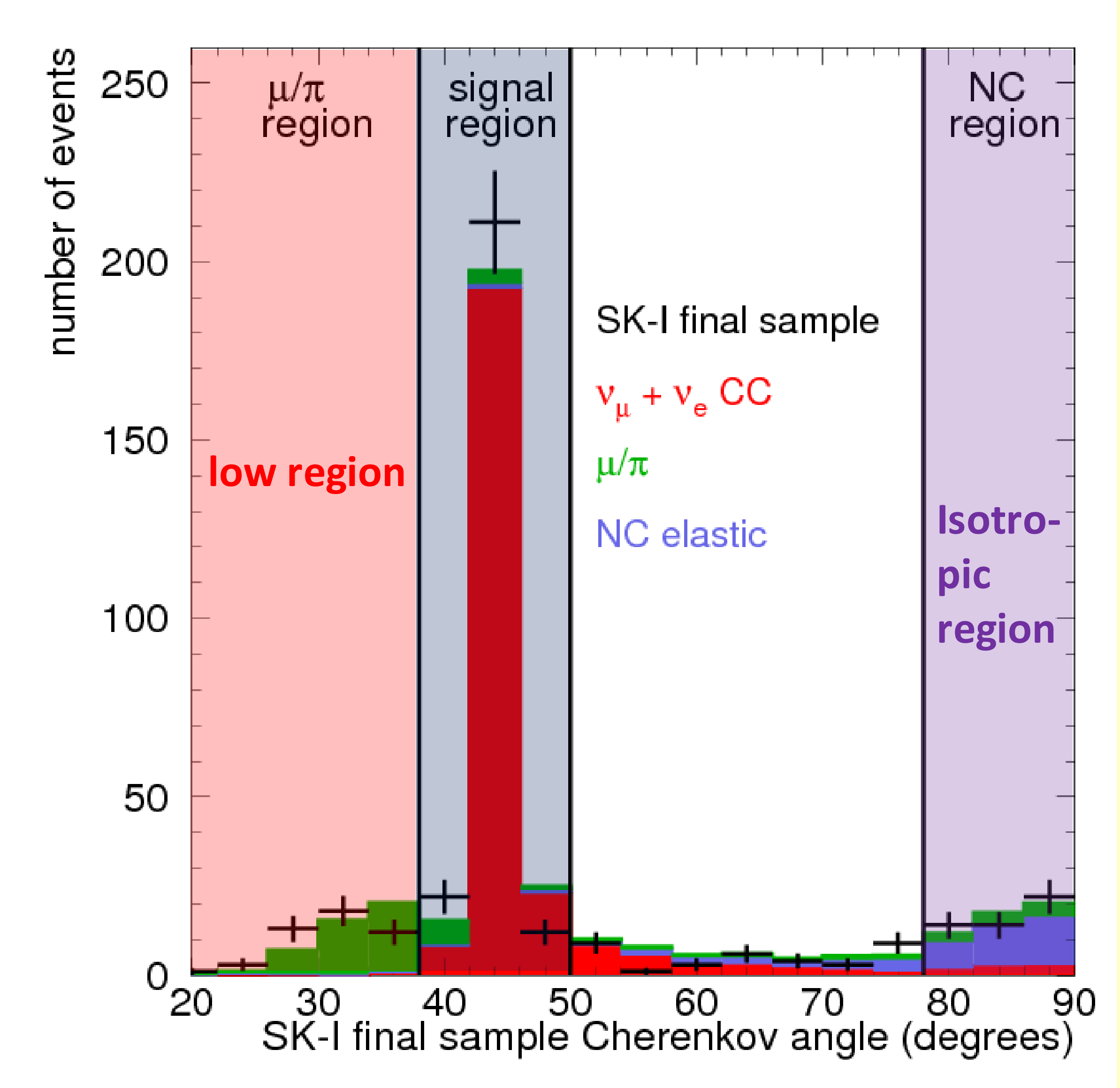


Signal region

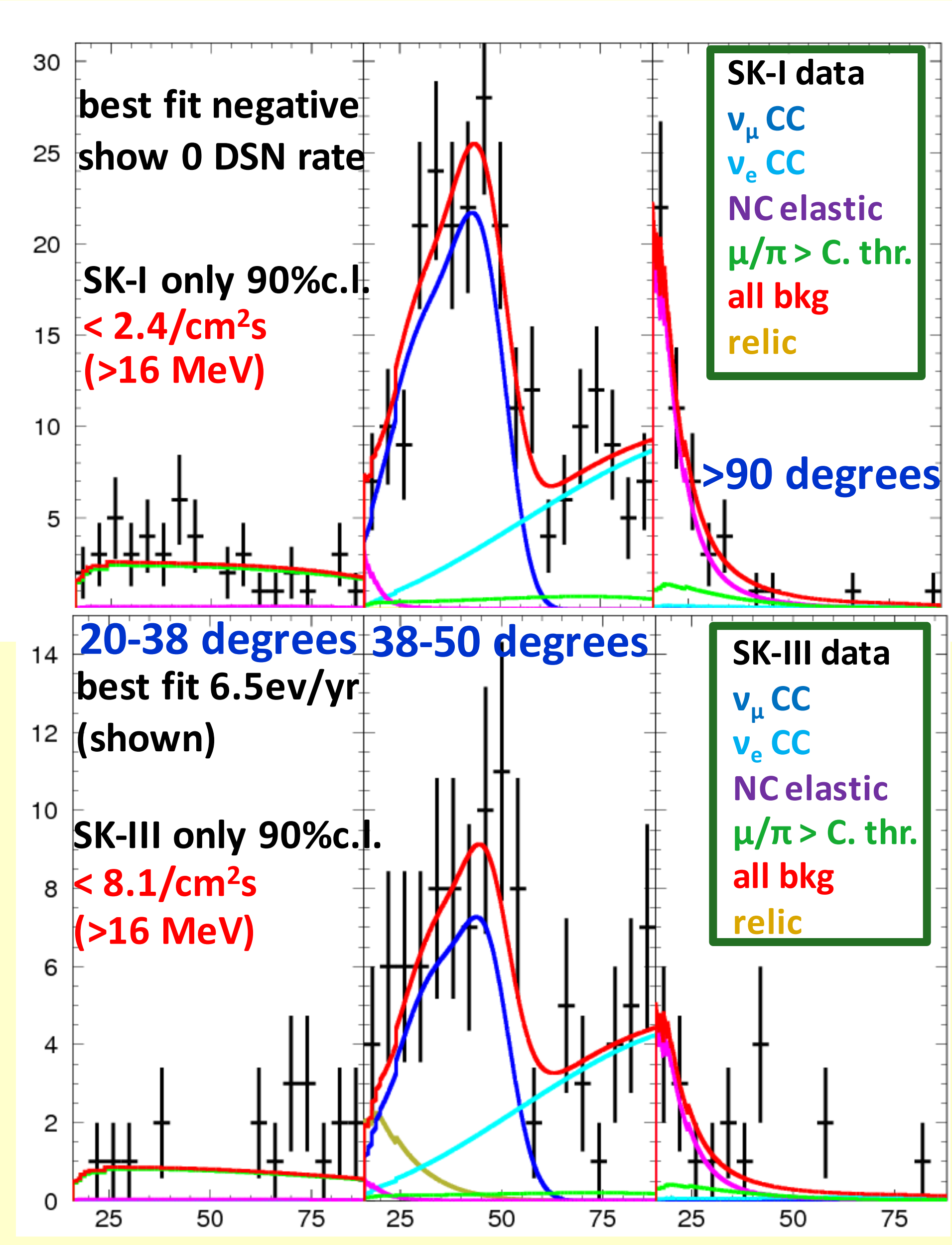


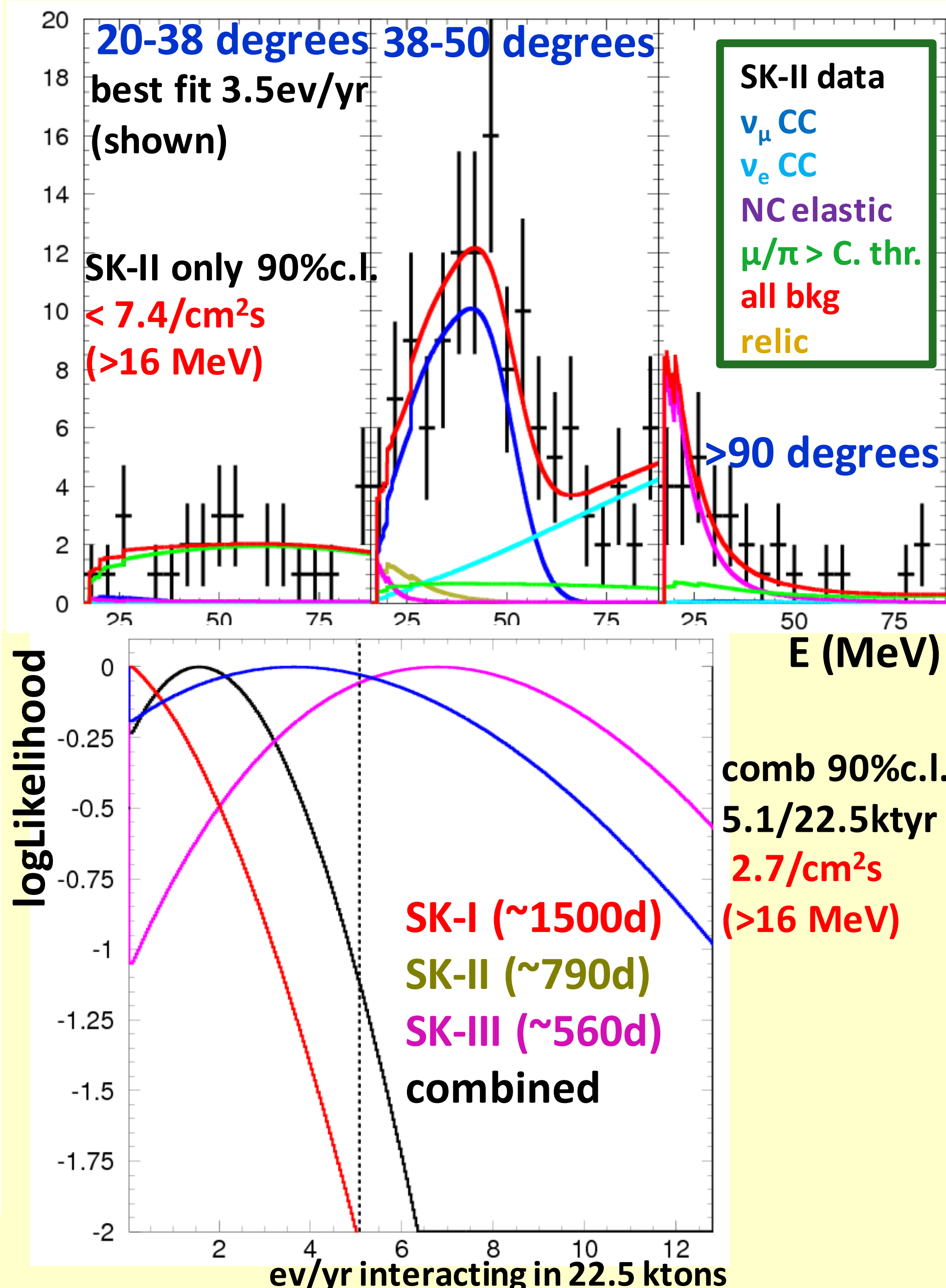
Isotropic region





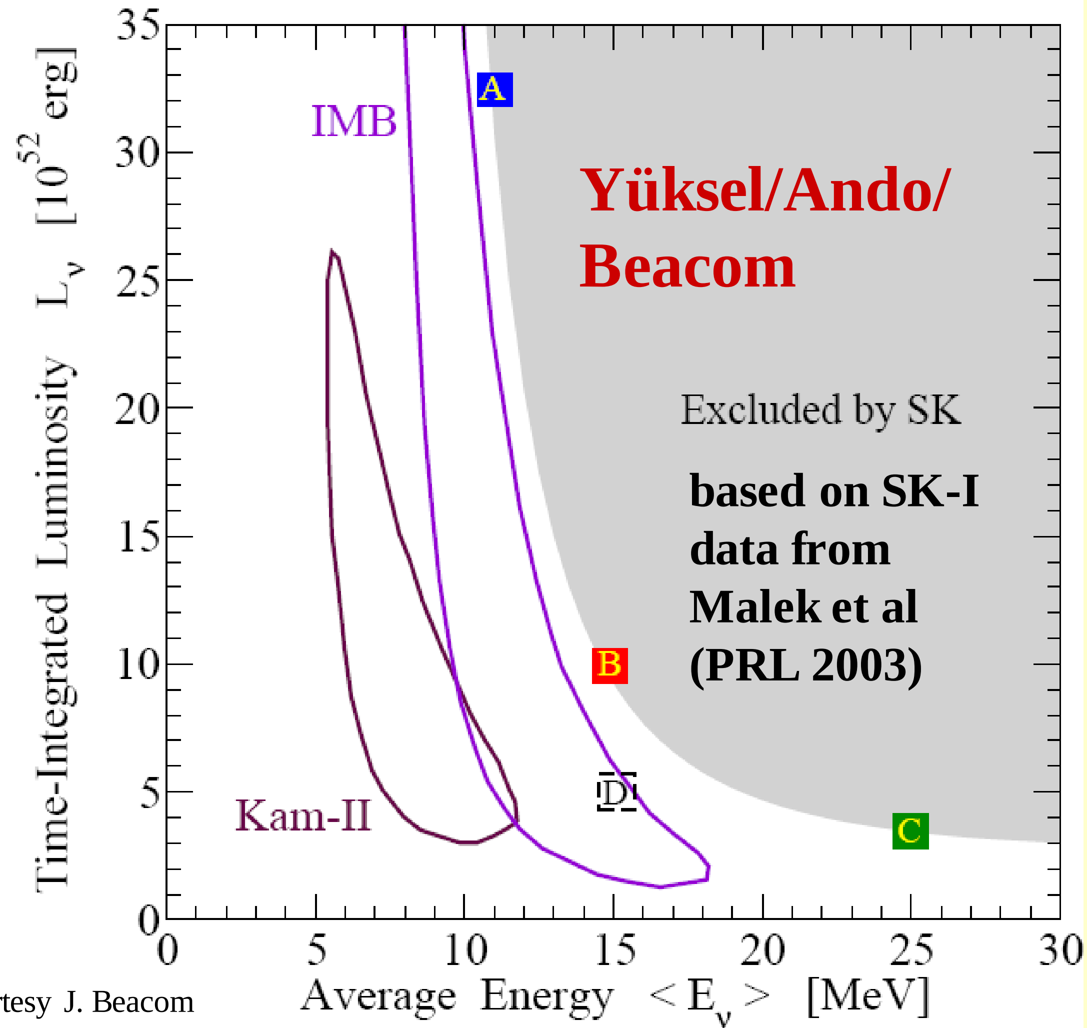
Fit DSN Rate for “LMA” Model





Limits on SN ν Emission Spectrum

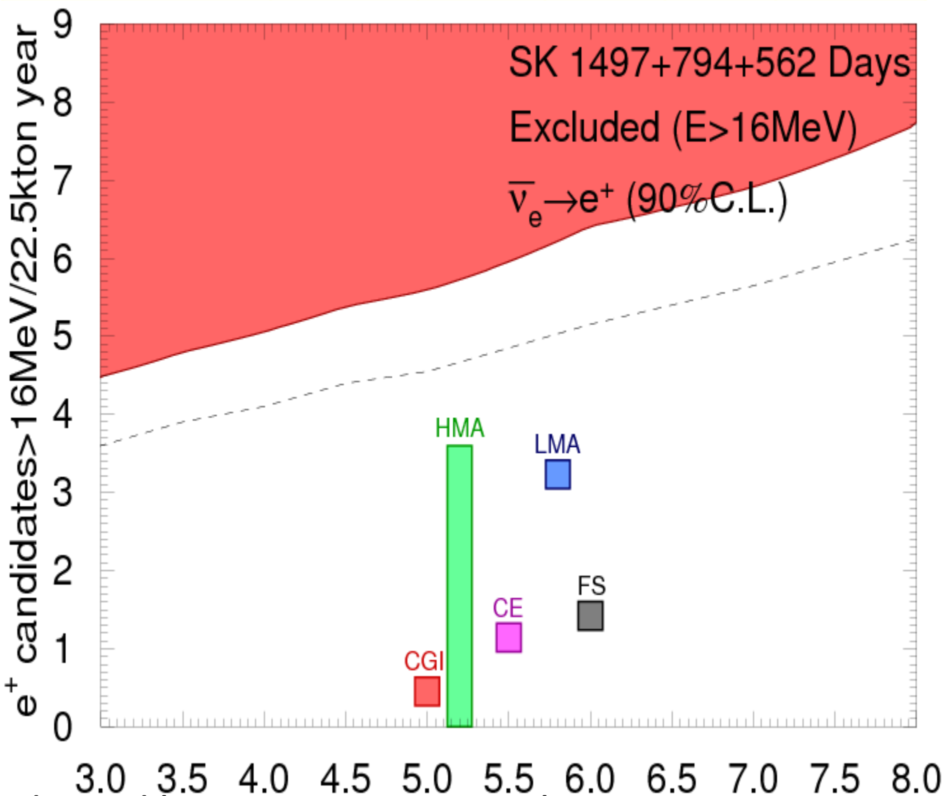
- effective emission spectrum with two parameters; anything more sophisticated couldn't be resolved with relic neutrinos: do a little astrophysics even in the absence of observation: limit typical SN luminosity and temperature
- assume FD spectrum & fix core-collapse SN rate as a function of red-shift: Astro-ph.HE 1004.3311v1, Astro-ph/0509297v2, New Journal of Physics 6 (2004) 170
- this example is based on the 2003 paper



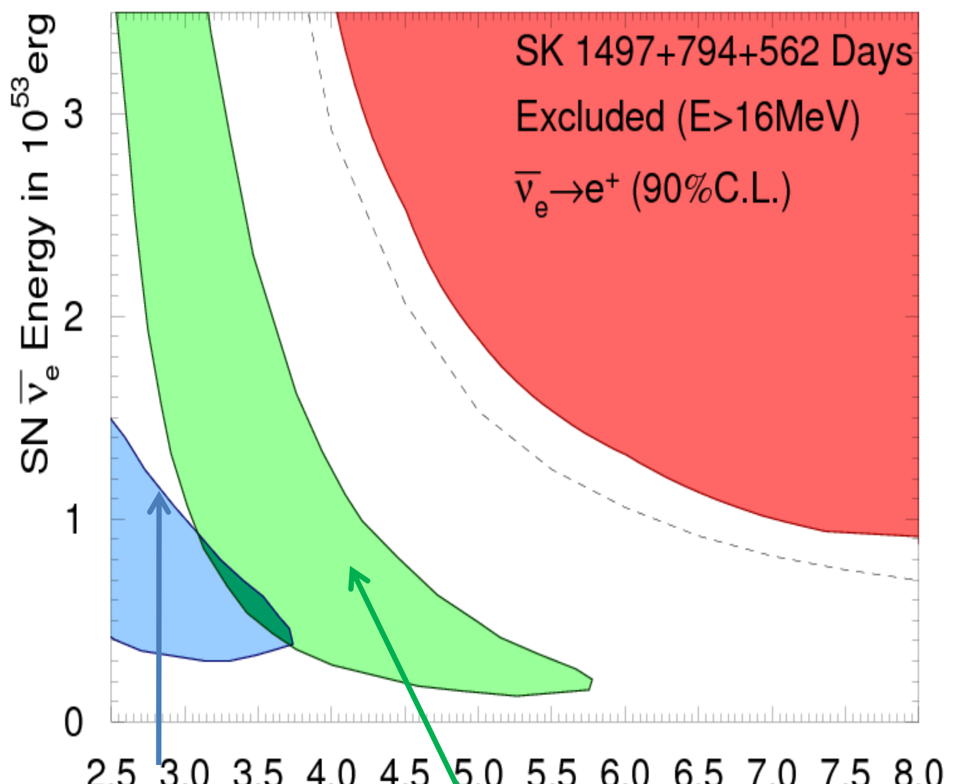
Limit of Diffuse Supernova Neutrinos

Model	SK-I	SK-II	SK-III	All	Predicted
Gas Infall	>2.1	>7.5	>7.8	>2.8	0.3
Chemical Ev	>2.2	>7.2	>7.8	>2.8	0.6
Heavy Metal	>2.2	>7.4	>7.8	>2.8	< 1.8
LMA	>2.5	>7.7	>8.0	>2.9	1.7
Failed SN	>2.4	>8.0	>8.4	>3.0	0.7

LMA = Ando et al (LMA model)
HMA = Kaplinghat, Steigman, Walker (heavy metal abundance)
CGI = Malaney (cosmic gas infall)
FS = Lunardini (failed SN model)
CE = Hartmann/Woosley (chemical evolution)



dotted line represents 1-D limit, red area 2-D limit

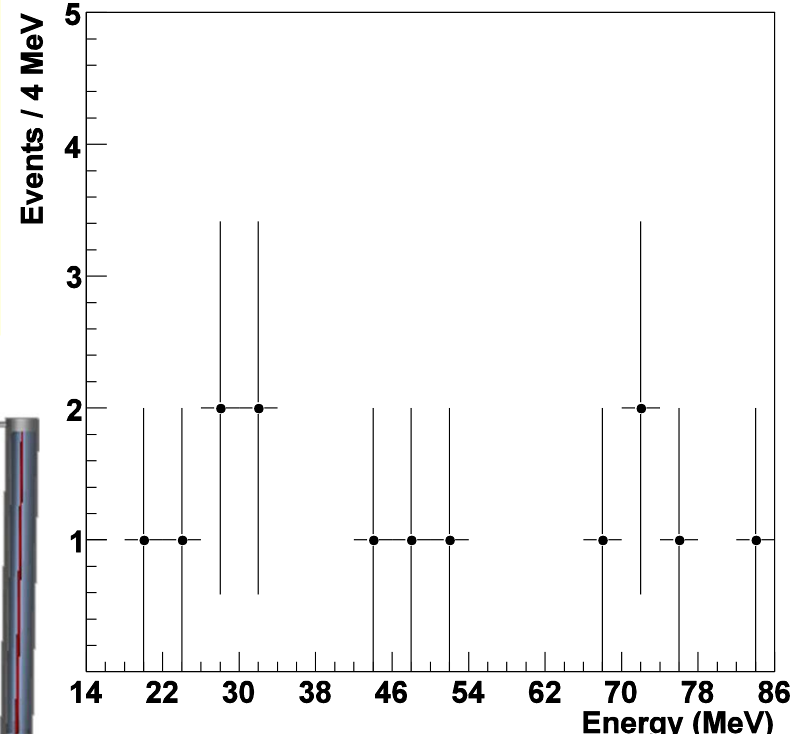


1987a Kamiokande allowed

1987a IMB allowed

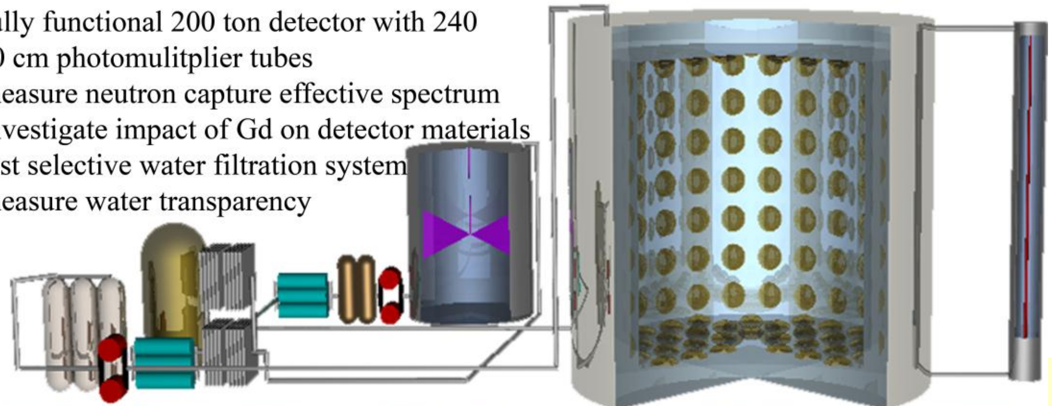
Future of DSN Search in SK-IV and beyond: Inverse β Neutron Tagging

- search for 2.2 MeV γ with ε=19%, ε_{fake}=1%: see 14 candidates between 14MeV amd 88 MeV
- limit is in preparation



Gadolinium Doping Test Facility

- fully functional 200 ton detector with 240 50 cm photomulitplier tubes
- measure neutron capture effective spectrum
- investigate impact of Gd on detector materials
- test selective water filtration system
- measure water transparency



Experimental Hall | Water Transparency Measurement | Inside 200 ton Detector

Beacom/Vagins:

Gadzooks! Dope SK with 0.1% Gd and see 8 MeV γ cascade from n captures

Conclusions

- SK-III data has already impacted solar ν global fits:
  - lower background
  - solar neutrino flux estimate below 5 MeV
  - three flavor analysis
- SK-IV can go lower in threshold: the goal is 4 MeV total recoil electron energy and it seems within reach
- SK solar analysis begins to see oscillation signatures
- SK diffuse supernova neutrino search sensitivity close to prediction
- even w/o a signal, SK's search already limits typical SN ν emission spectrum
- Neutron tagging techniques are likely to be required for further substantial progress