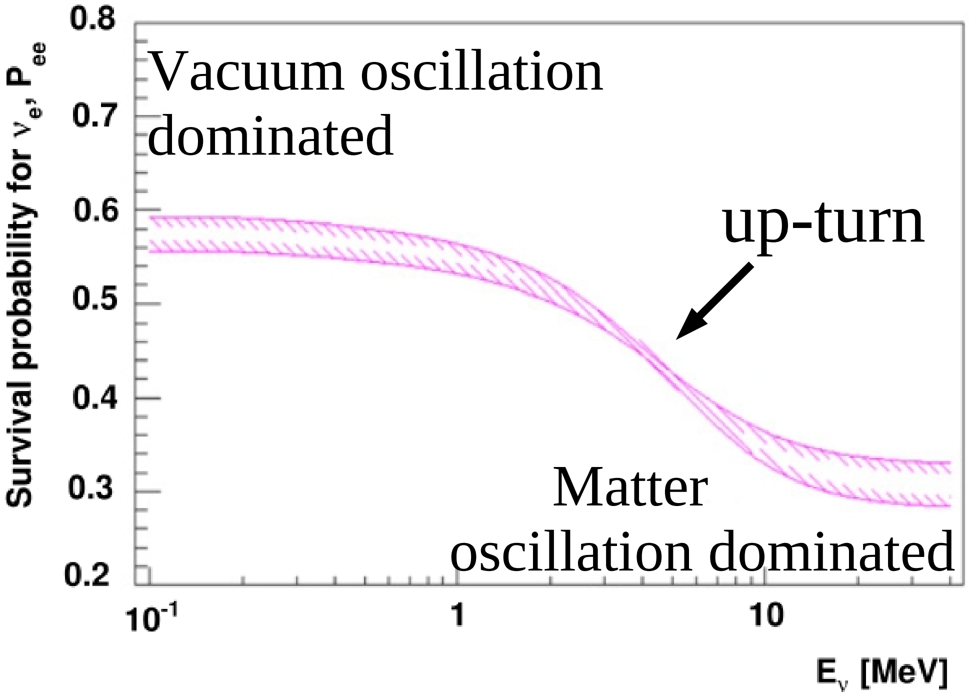
Recent results from SK on solar and SN neutrinos and the SK-Gd project

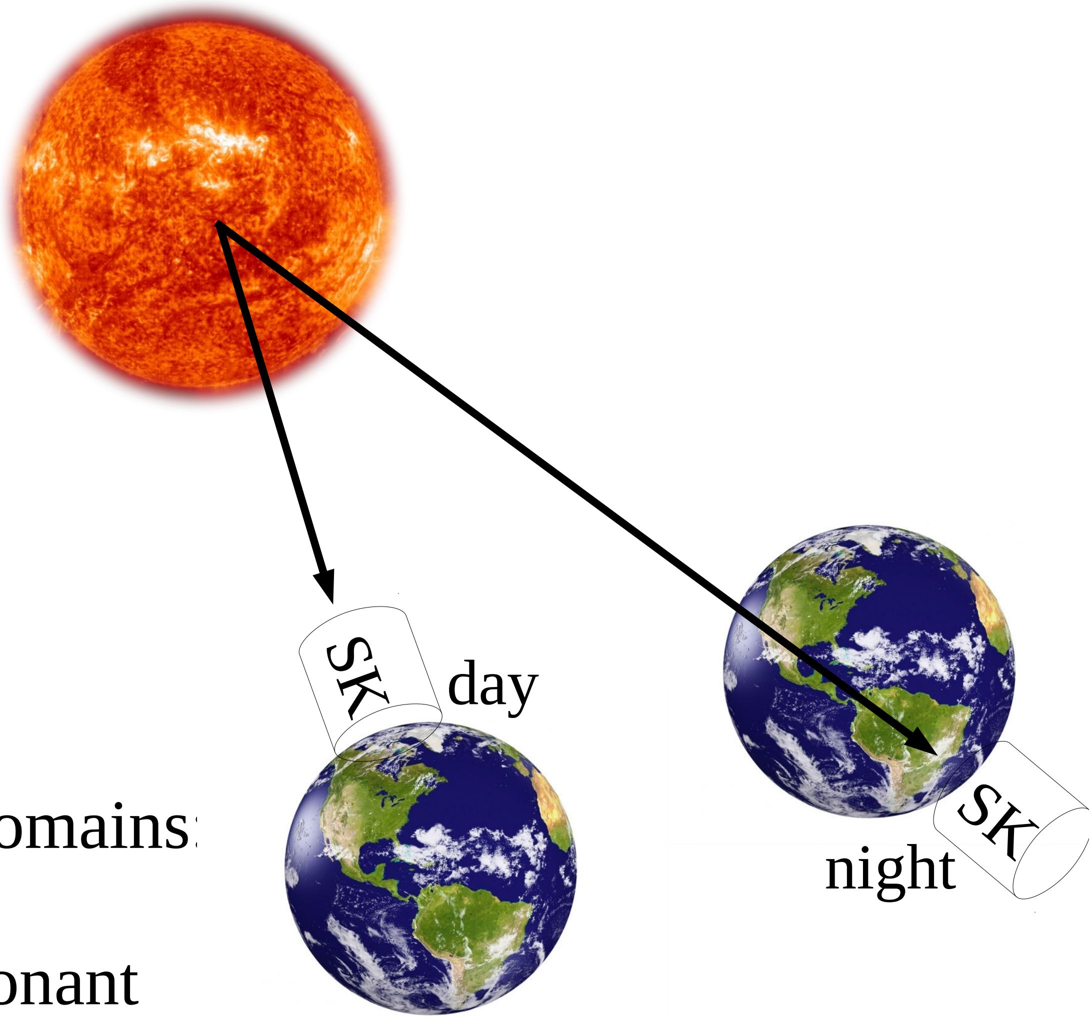
Lluís Martí Magro, Kavli IPMU

ICRR workshop, December 19th, 2015.

Kashiwa

Why are solar neutrinos interesting?

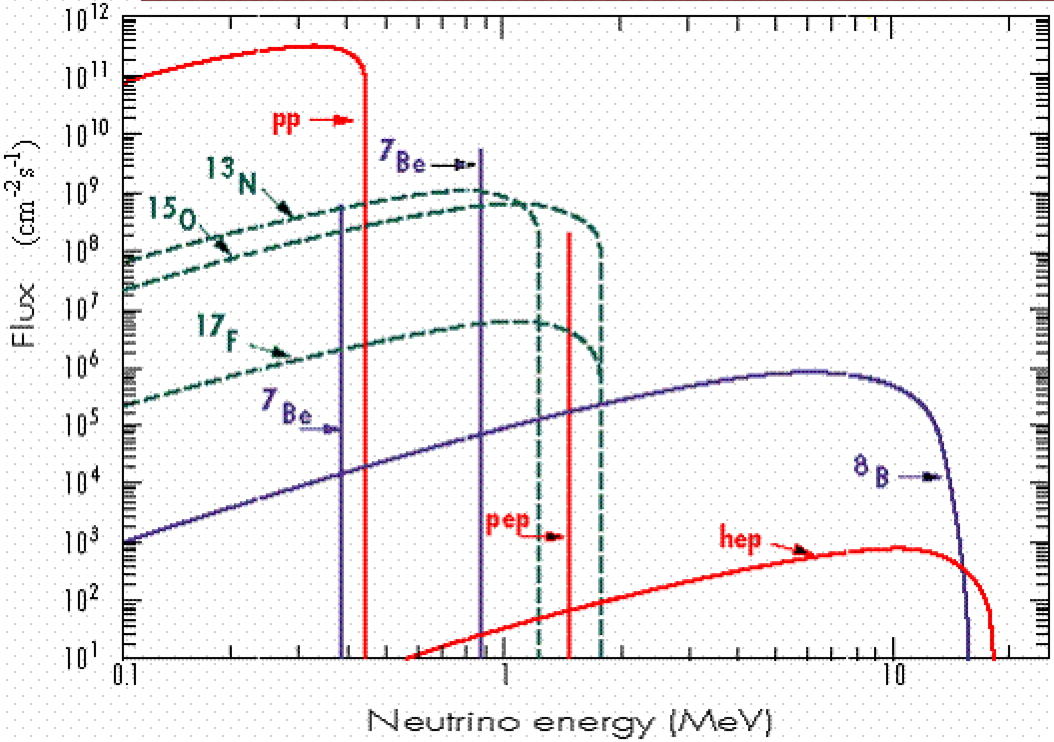




Two energy dependent oscillation domains: at low energies vacuum oscillation dominates while above ~3 MeV resonant conversion inside the Sun occurs.

Because of the earth matter effect, ν_e regenerate. Thus, ^8B flux is expected to be larger at night.

Solar neutrinos



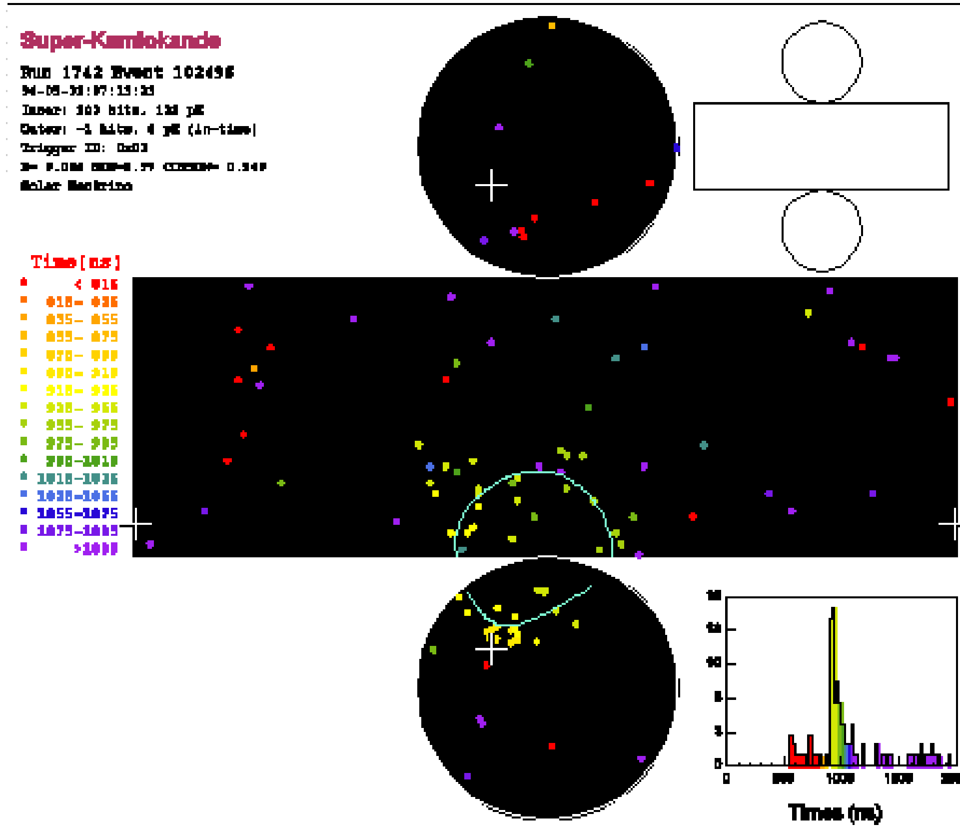
Detection: $\nu\, e^- \rightarrow \nu\, e^-$

Threshold: E_{kin} < 3.5 MeV

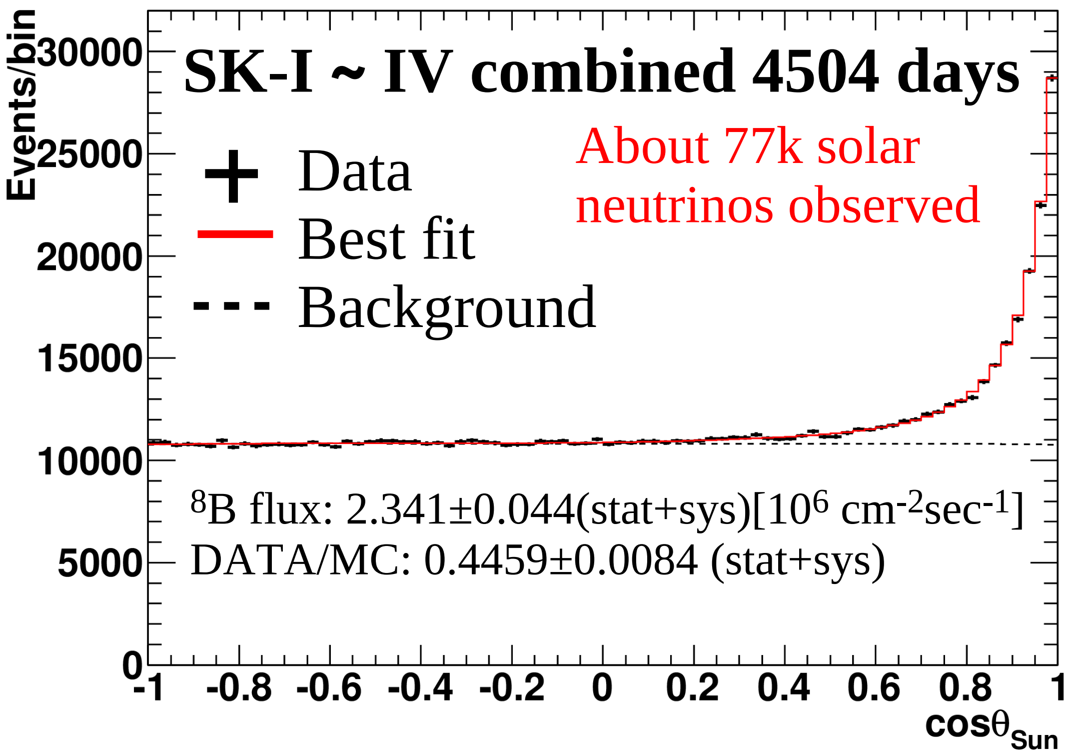
Recently: hit-threshold 34 → 31
Eff. 91.8% → 99.6% @3.5-4.0 E_{kin}
Eff. 99.8% → 100% @4.0-4.5 E_{kin}

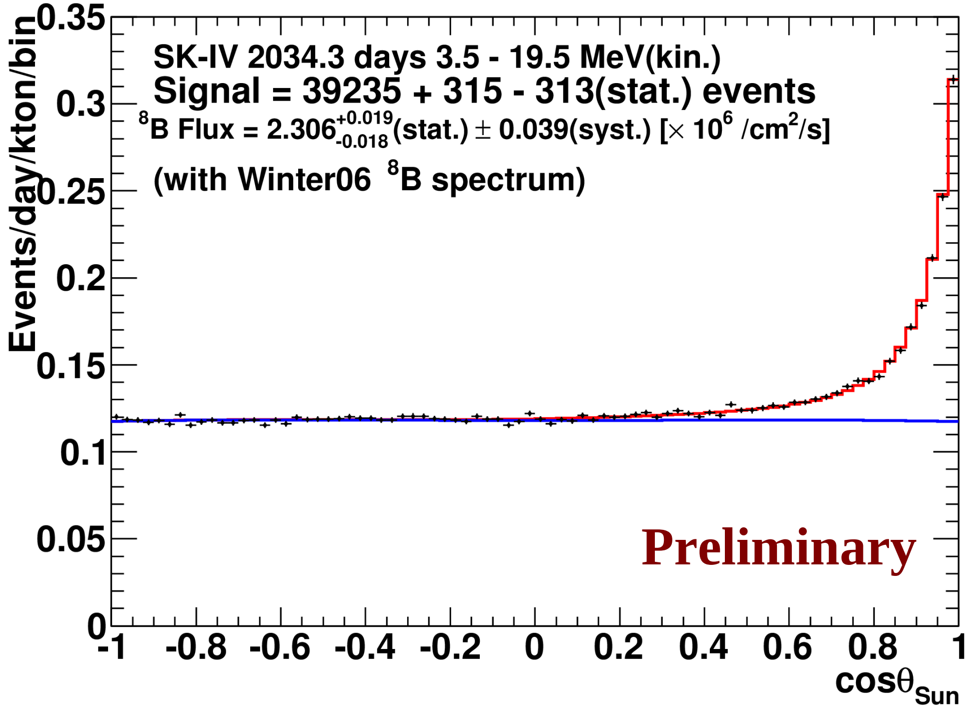
Large statistics: ~20 events/day

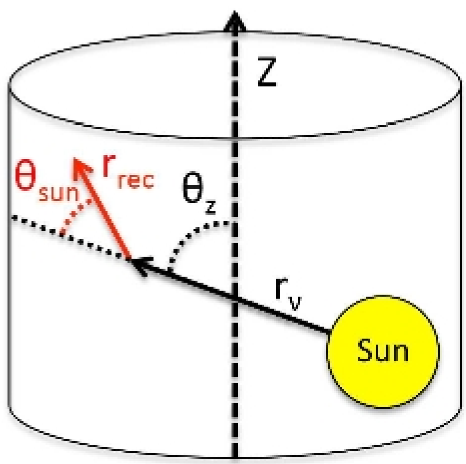
- Interaction vertex:
  - ⇨ Timing information:
  Resolution: 52cm @10 MeV
- Electron direction:
  - ⇨ Cherenkov Ring pattern
  Resolution: 23° @10MeV
- Electron energy:
  - ⇨ Number of hit PMTs (N_{eff})
  Resolution: 14% @10MeV

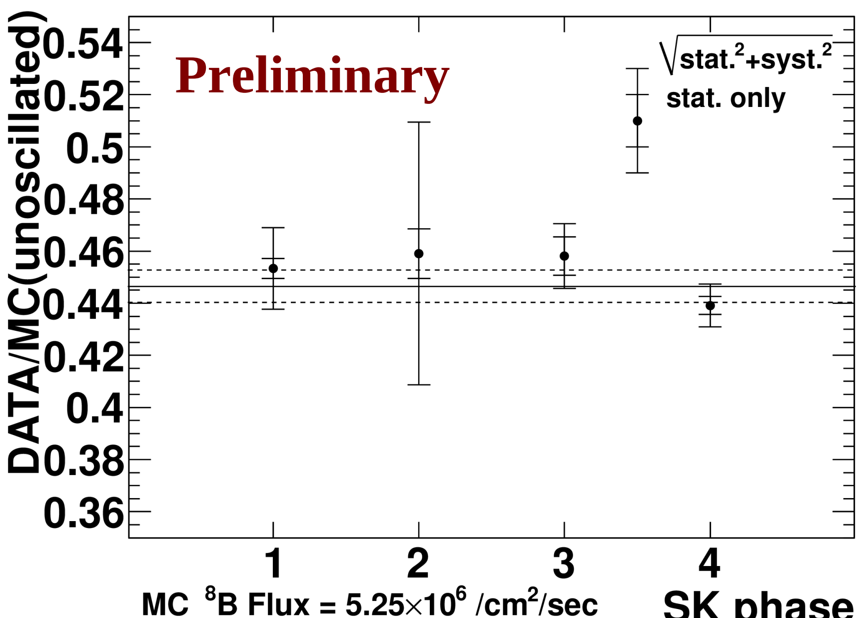


Solar ^8B Neutrinos: angular distribution and flux









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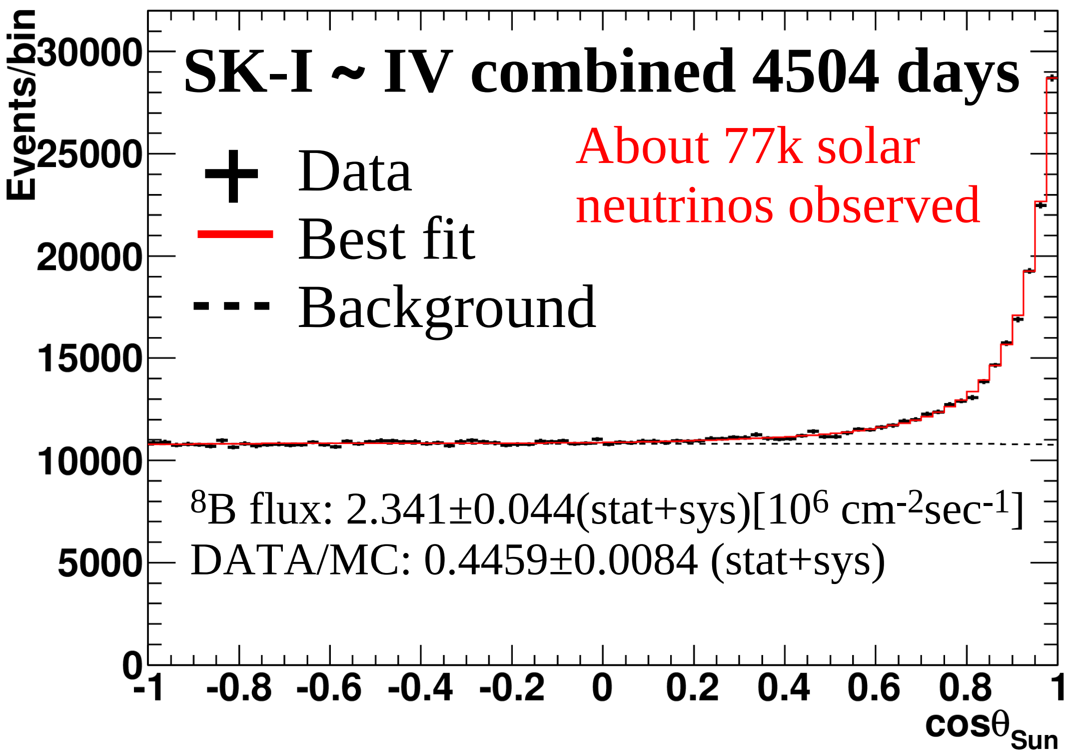
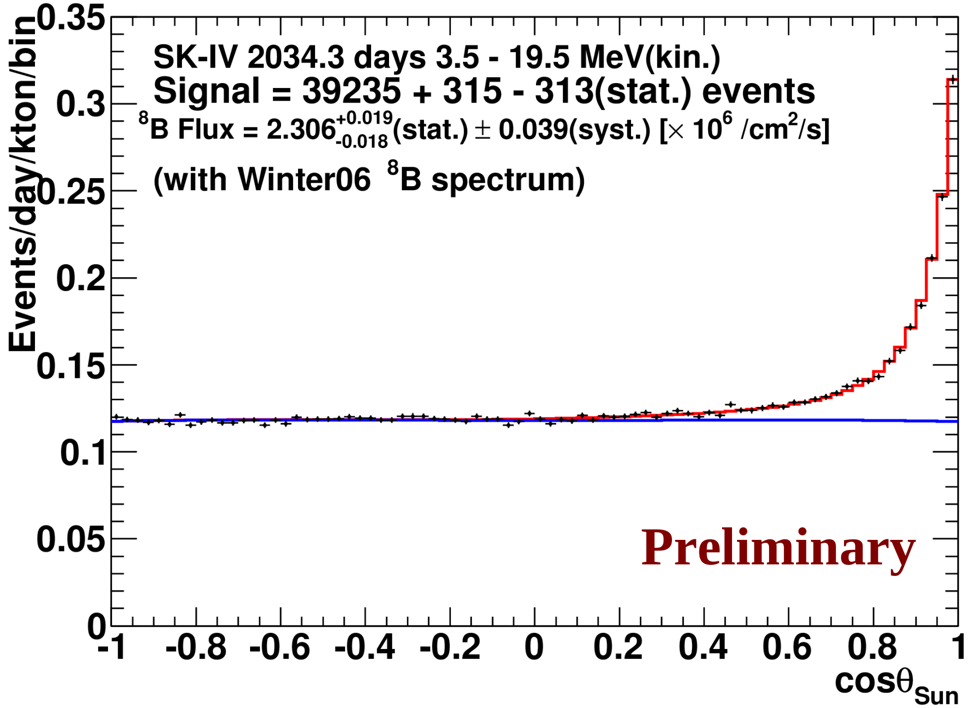
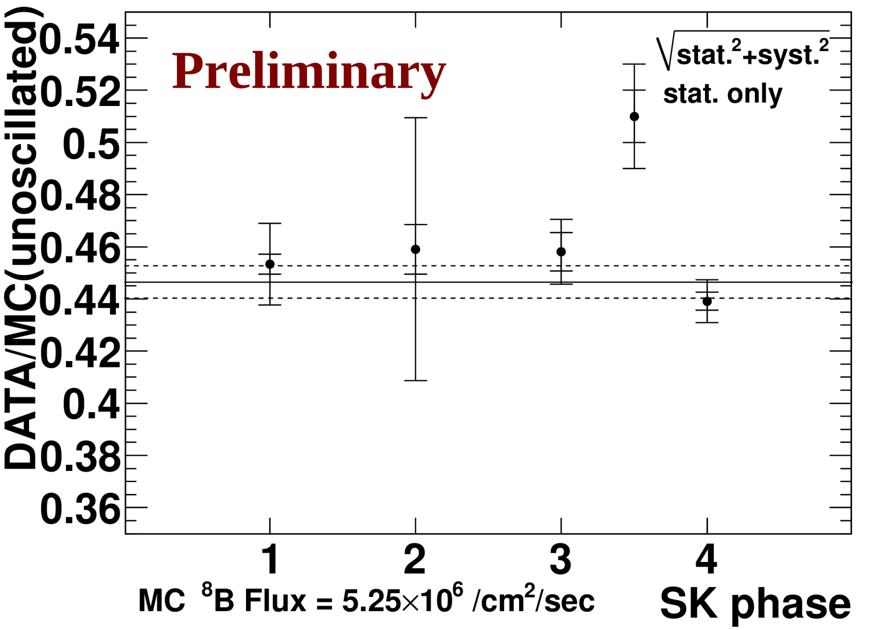


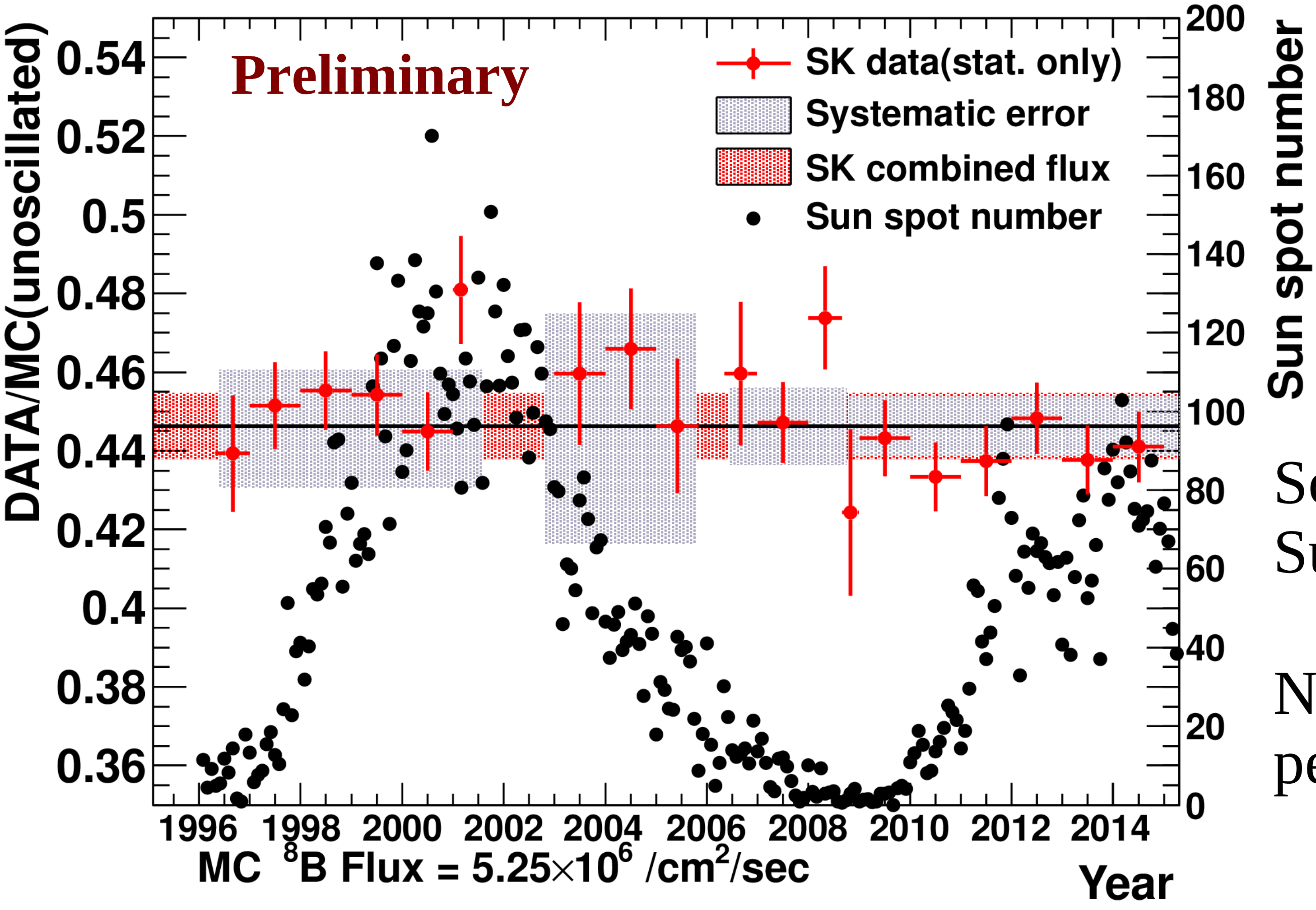


SK phase	E_{kin} threshold [MeV]	Live time [day]	^{8}B flux [10^6 cm^{-2}sec^{-1}]
I	4.5 – 19.5	1496	2.38±0.02±0.08
II	6.5 – 19.5	791	$2.41\pm0.05^{+0.16}_{-0.15}$
III	4.0 – 19.5	548	2.40±0.04± 0.05
IV	3.5 – 19.5	2034	2.31±0.02± 0.04



Solar Neutrinos vs #Sunspots

Sunspot Data: **http://solarscience.msfc.nasa.gov/greenwch/spot_num.txt**



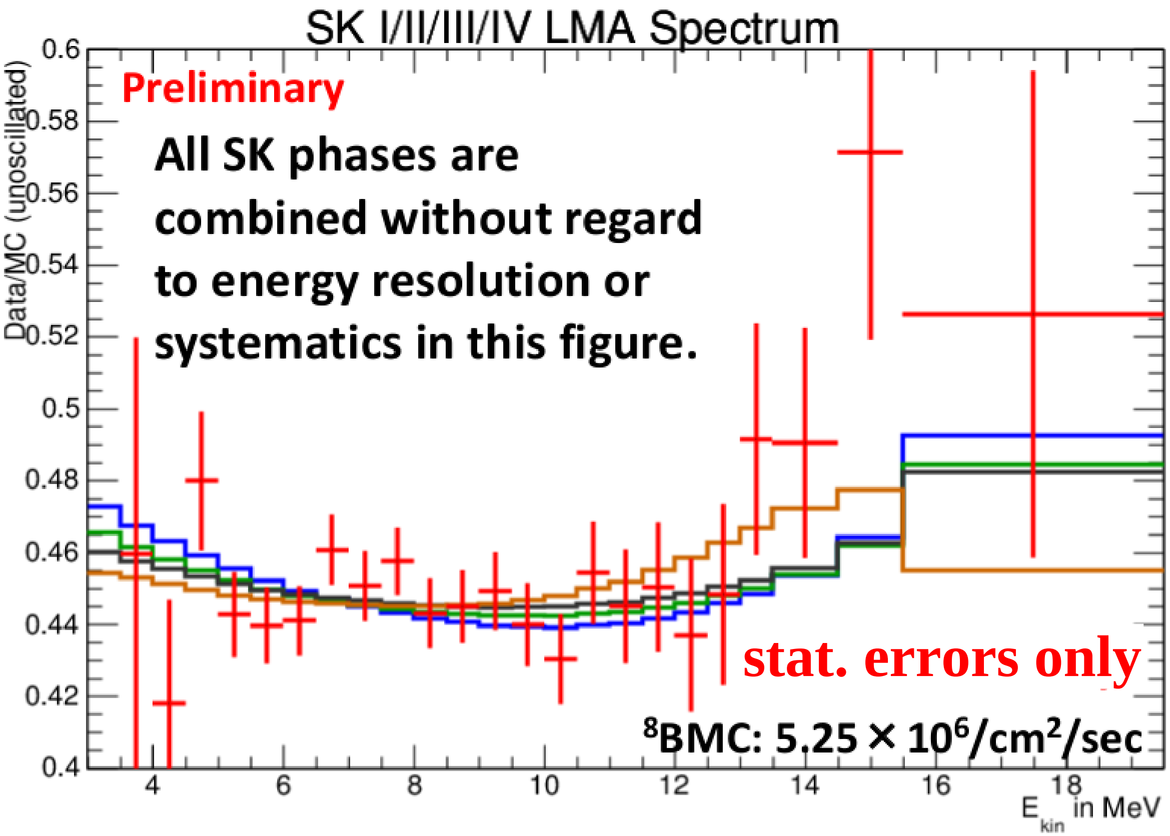
Solar neutrino data from SuperK since 96'

Now ~1.5 sunspot solar period

χ^2 =13.10/(DOF)18 → prob.=78.6%

No clear Solar neutrino vs sunspot number correlation is seen.

Search for the up-turn with the recoil electron spectrum



Total # of bins for SK I-IV is 83

Fit	χ^2
solar+KamLAND	70.13
Solar global	68.14
Quadratic	67.67
Exponential	67.54

$$P_{ee}(E_\nu) = c_0 + c_1\left(\frac{E_\nu}{MeV} - 10\right) + c_2\left(\frac{E_\nu}{MeV} - 10\right)^2 \text{(quadratic)}$$

$$P_{ee}(E_\nu) = e_0 + \frac{e_1}{e_2}\left(\exp\left(e_2\left(\frac{E_\nu}{MeV} - 10\right)\right) - 1\right) \text{(exponential)}$$

MSW is slightly disfavoured:

→ ~1.7σ with the solar+KamLAND best fit parameters

→ ~1σ with the global solar best fit parameters

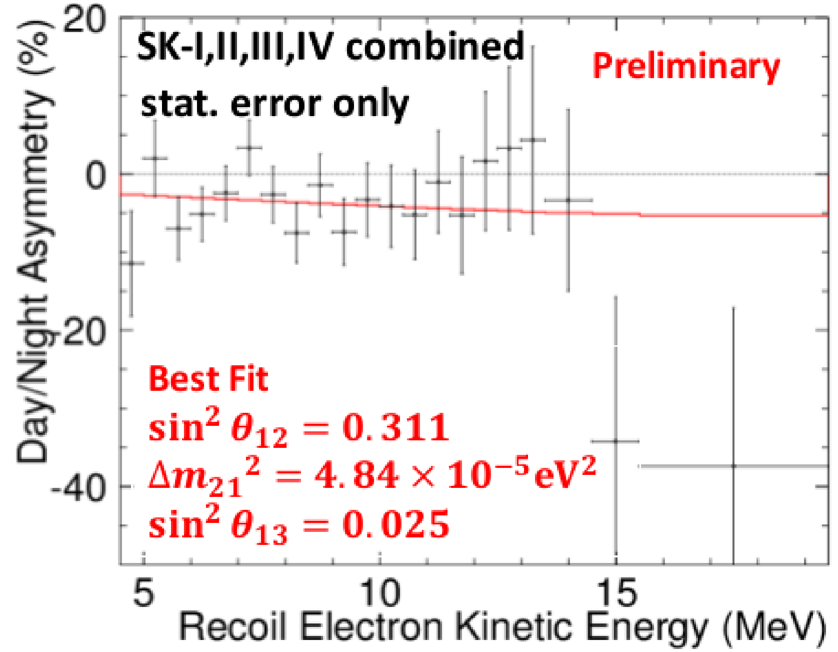
Day-Night Asymmetry

Straight-forward method: Separately measure the day and night solar neutrino flux. Then calculate the asymmetry:

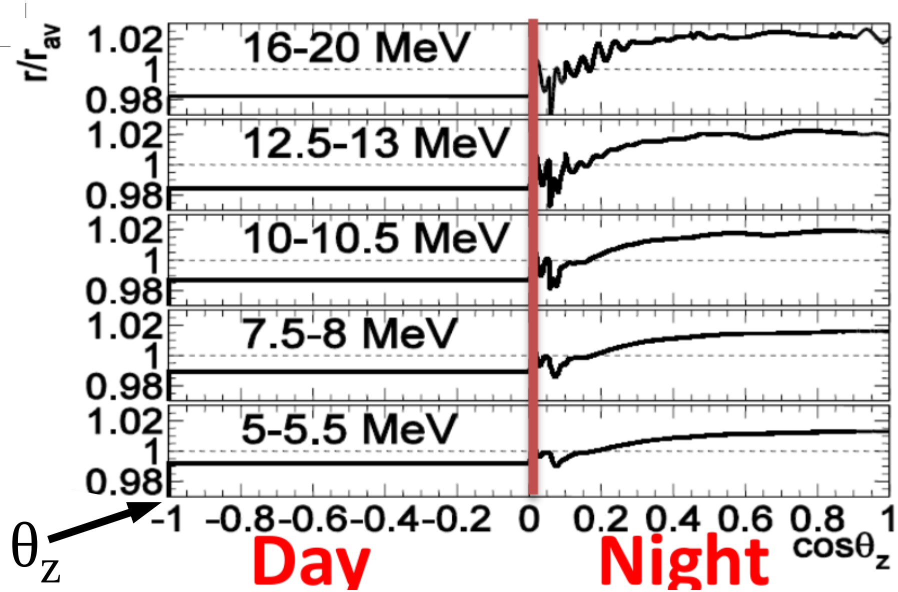
$$A_{DN} = \frac{\Psi_D - \Psi_N}{(\Psi_D + \Psi_N)/2}$$

SK phase	Amplitude fit [%]	Straight method [%]
I	-2.0±1.8±1.0	-2.1±2.0±1.3
II	-4.3±3.8±1.0	-5.5±4.2±3.7
III	-4.2±2.7±0.7	-5.9±3.2±1.3
IV	-3.6±1.6±0.6	-4.9±1.8±1.4
Combined:	-3.3±1.0±0.5	-4.1±1.2±0.8

3.0σ from zero   2.8σ from zero



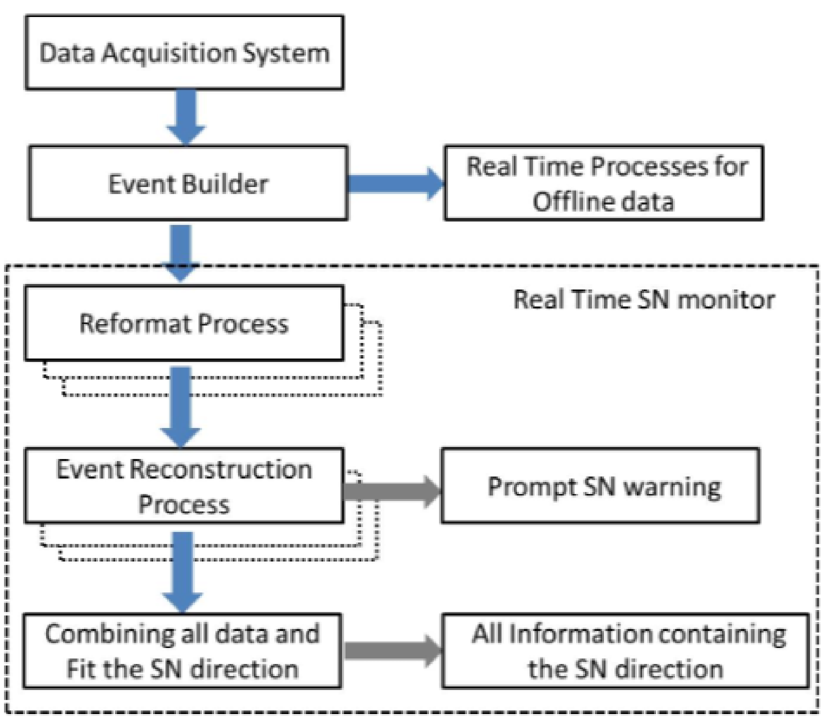
Solar neutrino flux is larger at night than during the day. This directly indicates a matter enhanced neutrino oscillation.



Iteration rate as a function of $\cos\theta_z$

Supernova Detection

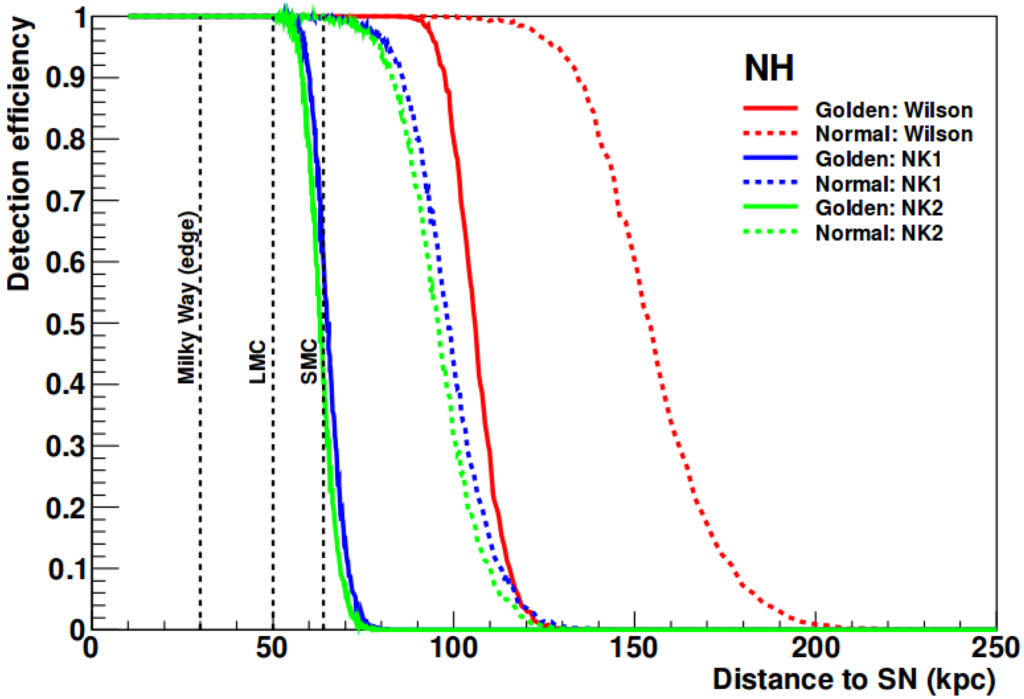
- One of the major goals at Super-K is to detect a ccSN.
- In our galaxy these are expected to happen 1-2 a century.
  - Astronomers are interested in recording such event from the beginning of the electromagnetic signal onset.
  - Therefore, it is very important to be prepared!
    - Keep SN live time as high as possible
    - Be prepared to deliver a warning to the community as soon as possible

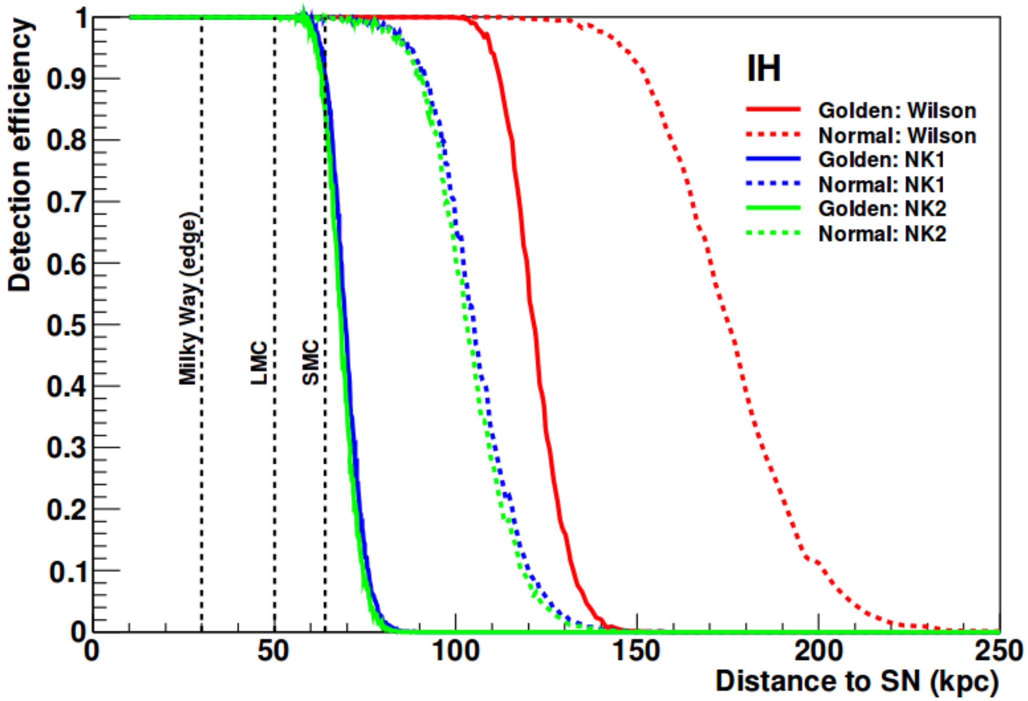


- Three warning types:
  - Golden: 100% eff. @ LMC (50 kpc)
  - Normal: 100% eff. @ SMC (64 kpc)
  - Silent: lower thresholds. ~few/day

The goal is to announce the burst time, # of events and estimated SN direction within 1 hour world-wide

Supernova Detection: efficiencies





Efficiencies mostly depend on:
- the number of inverse beta decay events
- the spectrum of the ν_e (different for NH and IH)

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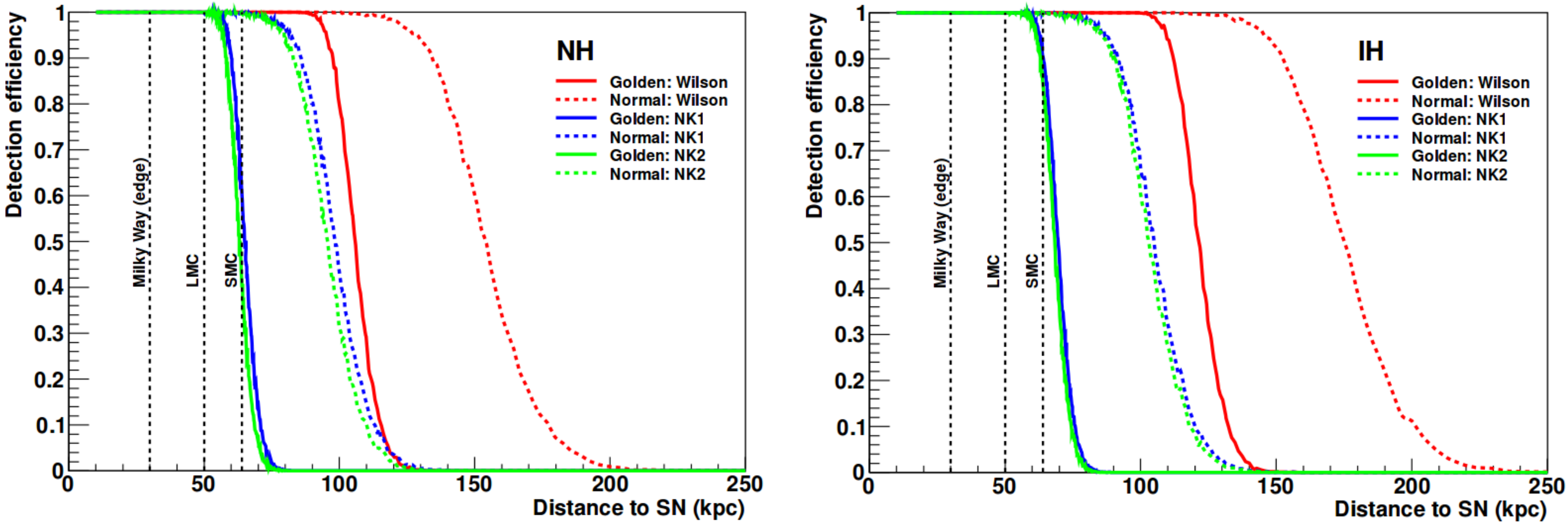

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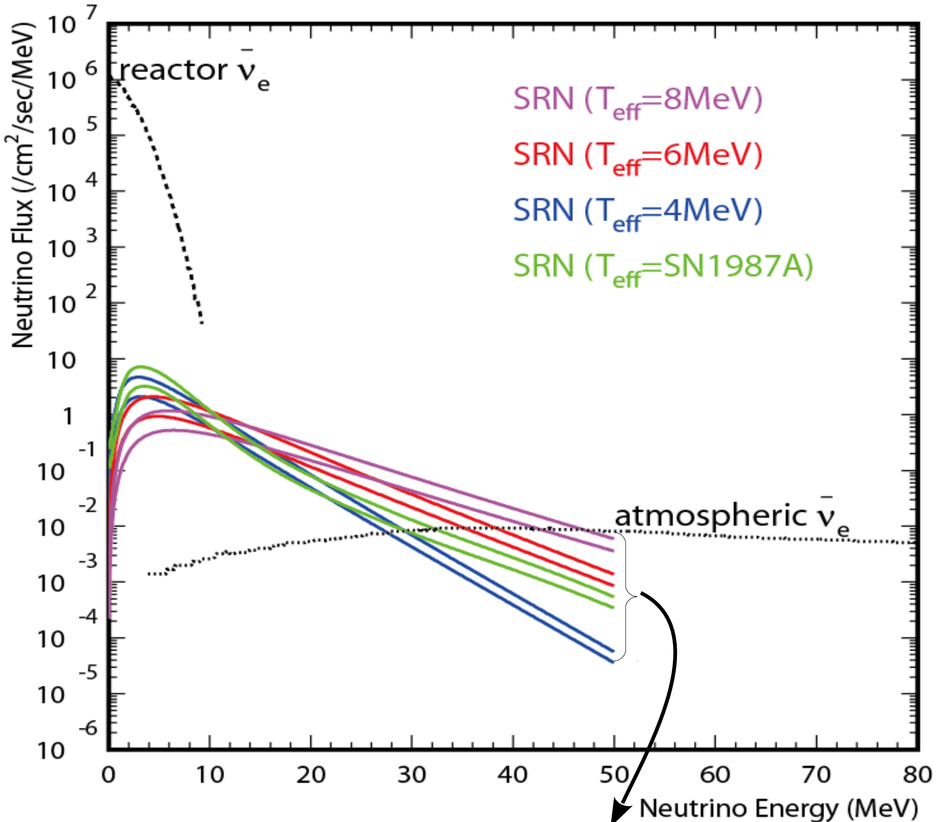
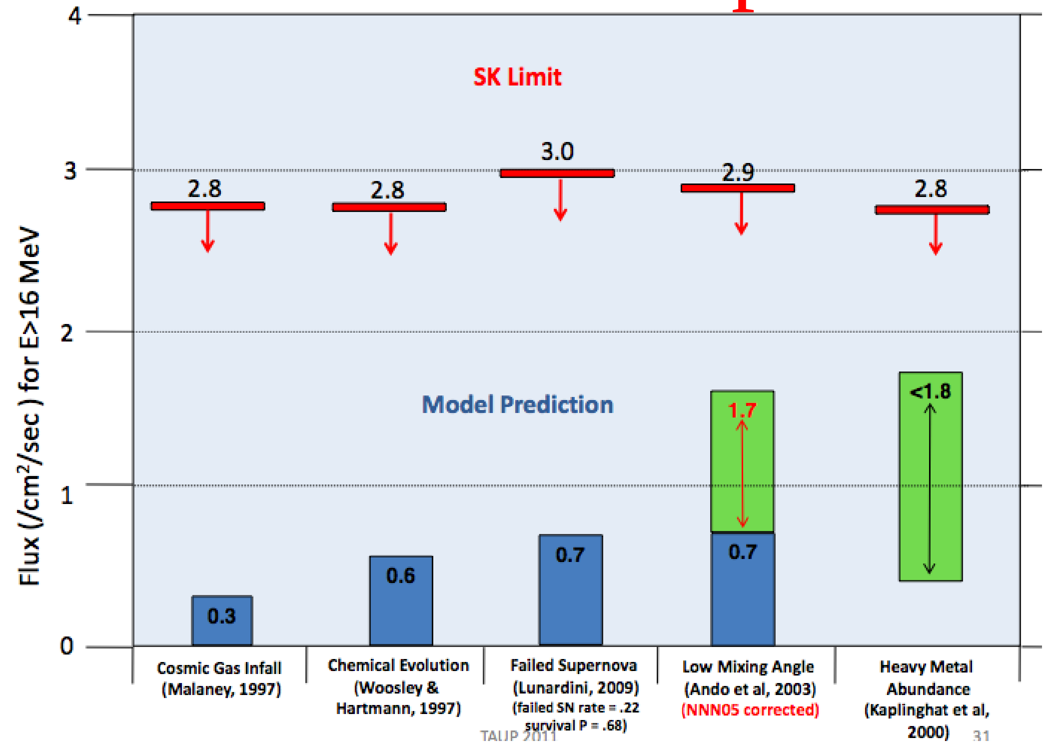
Supernova Relic Neutrino

Supernova relic neutrinos (SRN) are those neutrinos from all the past core collapse supernovae in the history of the universe.



Phys.Rev. D 79, 08013 (2009)

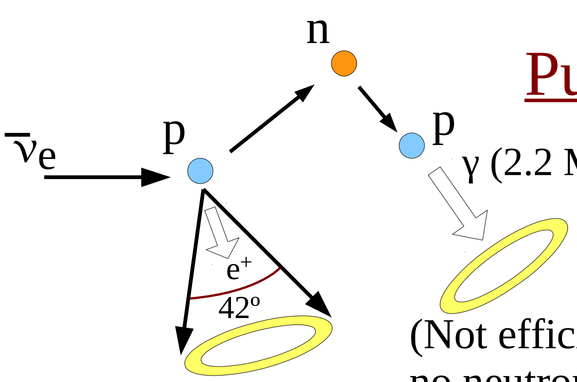
Flux limit at Super-K



Phys. Rev. D 85, 052007 (2012)

→ Large backgrounds dominate this analysis.
→ Measurement limits are getting closer to predictions.
→ Expand the energy range starting from 10 MeV.

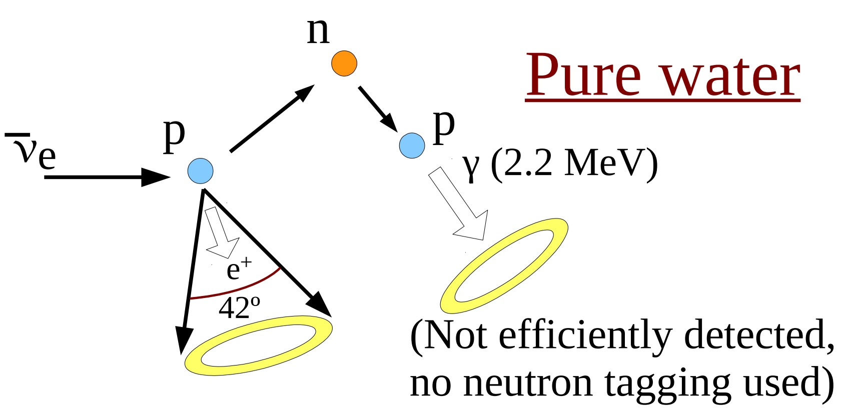
Supernova Relic Neutrino: How to

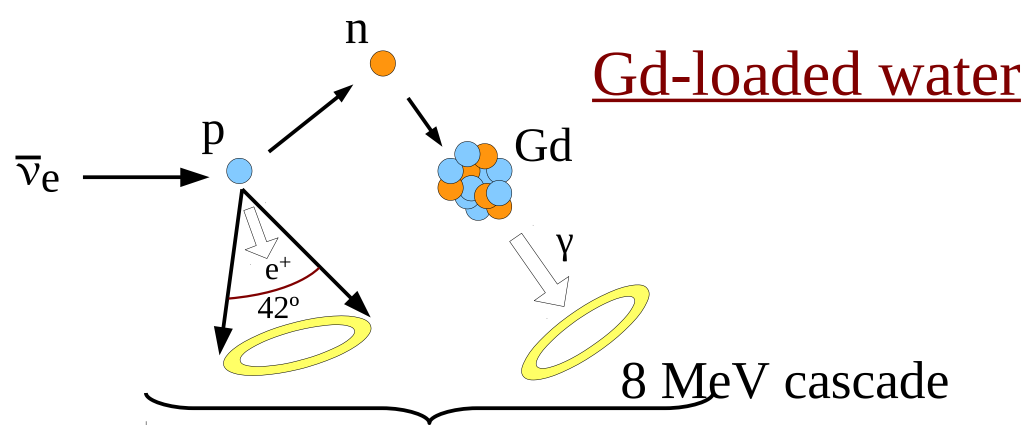


Pure water

(Not efficiently detected, no neutron tagging used)

Supernova Relic Neutrino: How to





With Tight time (delayed) and position coincidence between positron and neutron capture (90% neutron capture on Gd with 0.2% $Gd_2(SO_4)_3$ concentration) we will be able to reduce backgrounds and <u>detect SRN for the first time</u>!

Idea proposed as GADZOOKS!
by Beacom & Vagins PRL.93, (2004) 171101

@ EGADS we will show that:

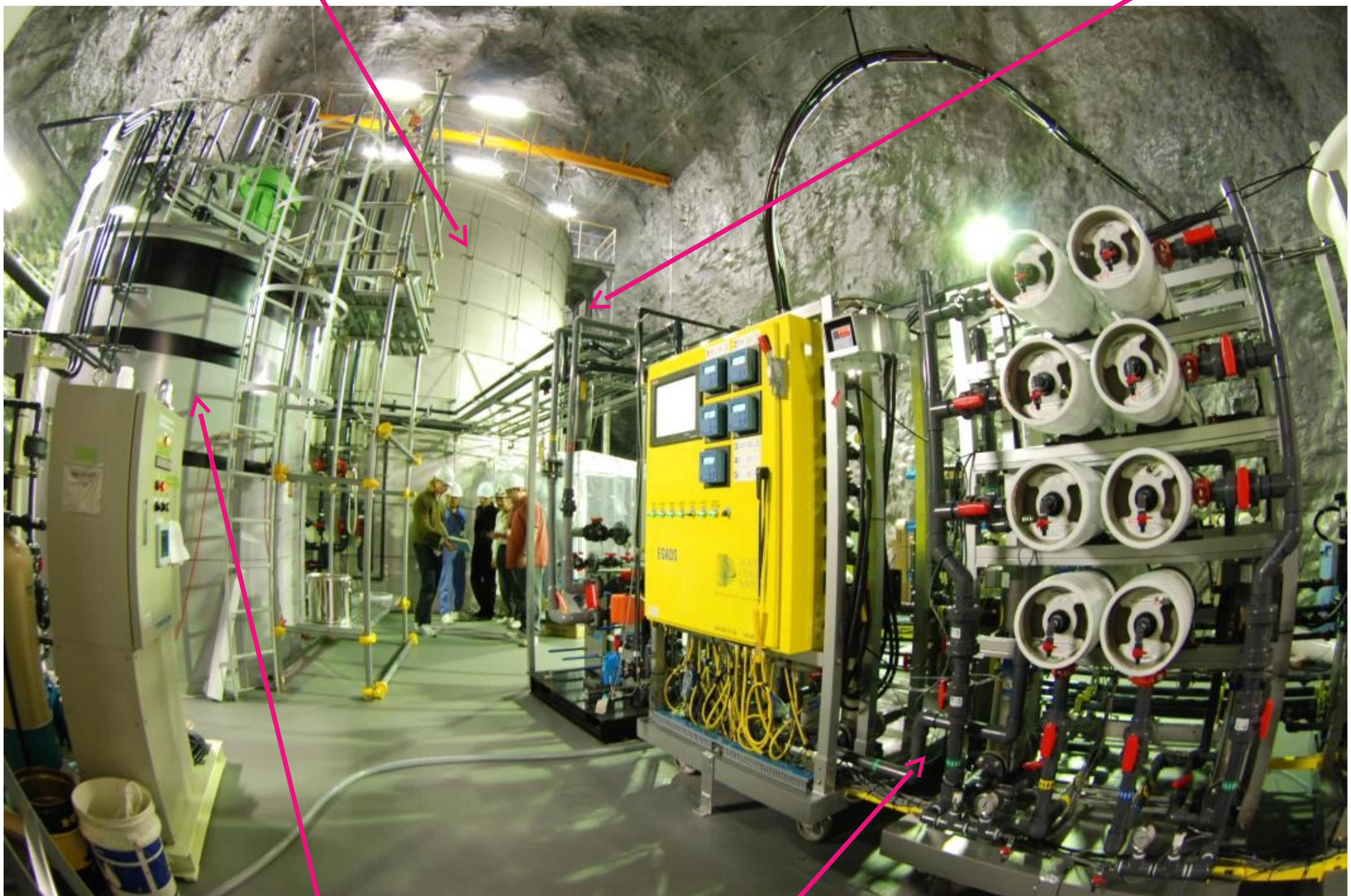
- Easy to dissolve
- Good optical properties
- Compatible with detector components

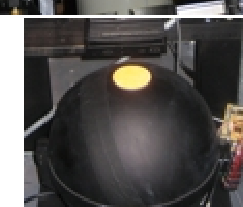
EGADS

Evaluating Gadolinium's Action on Detector Systems

200 m^3 detector tank

Transparency measurement (UDEAL)





15 m^3 tank

Water circulation system
(band pass-filtration system)

Antineutrino Spectroscopy with Large Water Čerenkov Detectors

John F. Beacom[1] and Mark R. Vagins[2]

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(Received 25 September 2003; published 20 October 2004)

We propose modifying large water Čerenkov detectors by the addition of 0.2% gadolinium trichloride, which is highly soluble, newly inexpensive, and transparent in solution. Since Gd has an enormous cross section for radiative neutron capture, with $\sum E_\gamma = 8$ MeV, this would make neutrons visible for the first time in such detectors, allowing antineutrino tagging by the coincidence detection reaction $\bar{\nu}_e + p \rightarrow e^+ + n$ (similarly for $\bar{\nu}_\mu$). Taking Super-Kamiokande as a working example, dramatic consequences for reactor neutrino measurements, first observation of the diffuse supernova neutrino background, galactic supernova detection, and other topics are discussed.

DOI: 10.1103/PhysRevLett.93.171101 PACS numbers: 95.55.Vj, 29.40.Ka

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GADZOOKS! Proposal

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(Dated: June 16, 2015)

Our Goals

Water Transparency: the water transparency is being constantly monitored to ensure a high quality and no time degradation

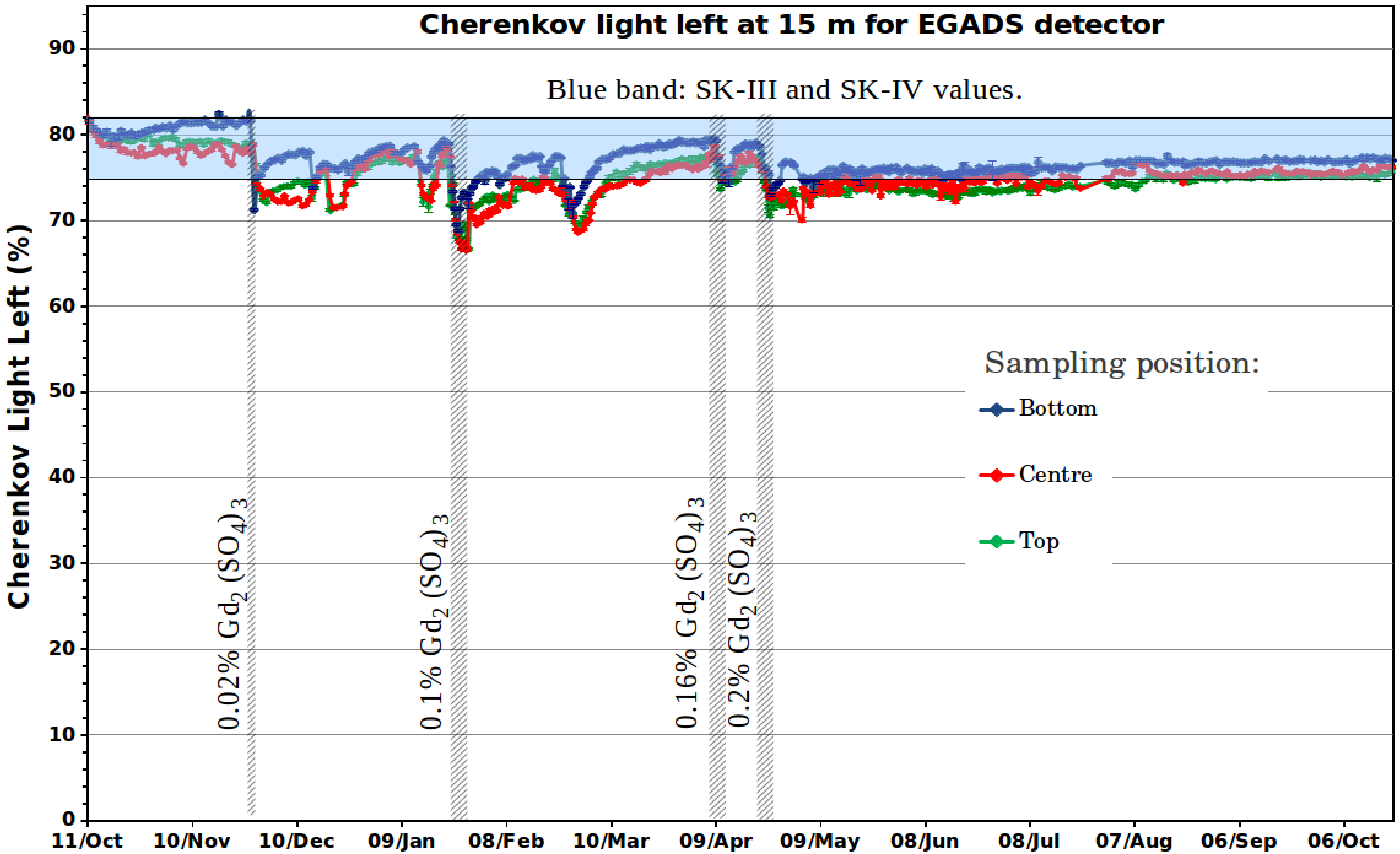
Water Purification system: the purification system should remove all impurities for a high water transparency (including ions except Gd)

How to Add/Remove Gd: how uniformly can Gd be dissolved? How quickly/economically/completely can Gd be removed?

Material Effects: are there any effects on the detector components? examination of the tank components and water quality monitoring

Neutron Background: since ambient neutrons are going to be seen, how will this affect the trigger rates and the current analyses?

Water Quality



Water transparency in the typical SK rangeeven after full Gd loading

Official statement

On June 27, 2015, the Super-Kamiokande collaboration approved the SuperK-Gd project which will enhance anti-neutrino detectability by dissolving gadolinium to the Super-K water.

The actual schedule of the project including refurbishment of the tank and Gd-loading time will be determined soon taking into account the T2K schedule.

SuperK-Gd is moving forward!!

Summary

SuperK has an overwhelming solar neutrino data sample

- Solar neutrino flux constant along al SK phases and no correlation with sunspots is seen.
- Solar neutrino spectrum: data shows a small preference for no distortions
- Solar neutrino day/night asymmetry: data shows a first indication of earth matter effects on ^{8}B solar neutrinos (2.8-3.0σ).

SuperK is the only detector with SN pointing capabilities:

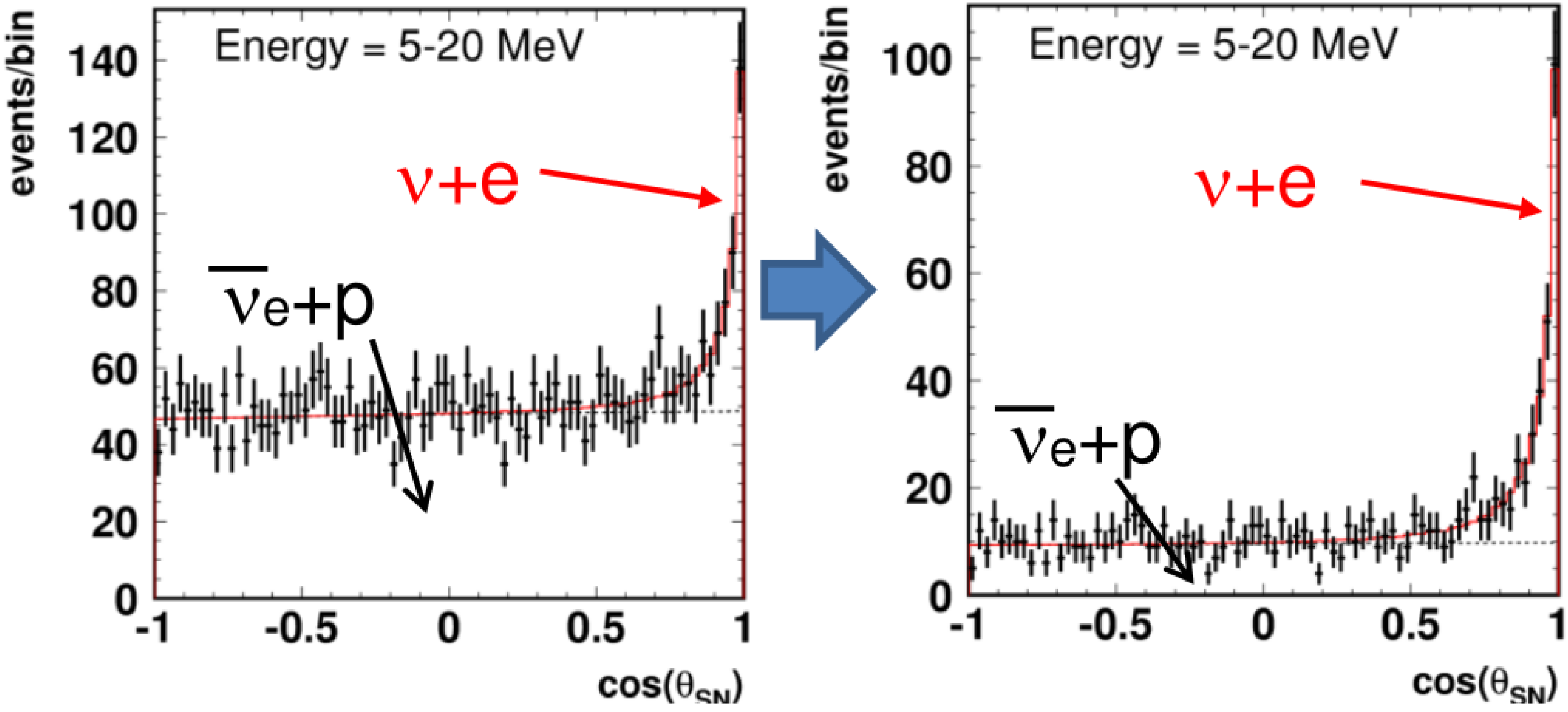
- It is our task to provide astronomers with an early warning
- SK has a dedicated real time burst monitor
- The goal is to provide an early warning within 1 hour

SuperK looks into the future with the SuperK-Gd project:

- After an extensive R&D program with EGADS no showstopper for the SuperK-Gd project was seen and the collaboration approved to move forward.
- Time schedule to be determined together with T2K

BACKUP

Other Physics Possibilities

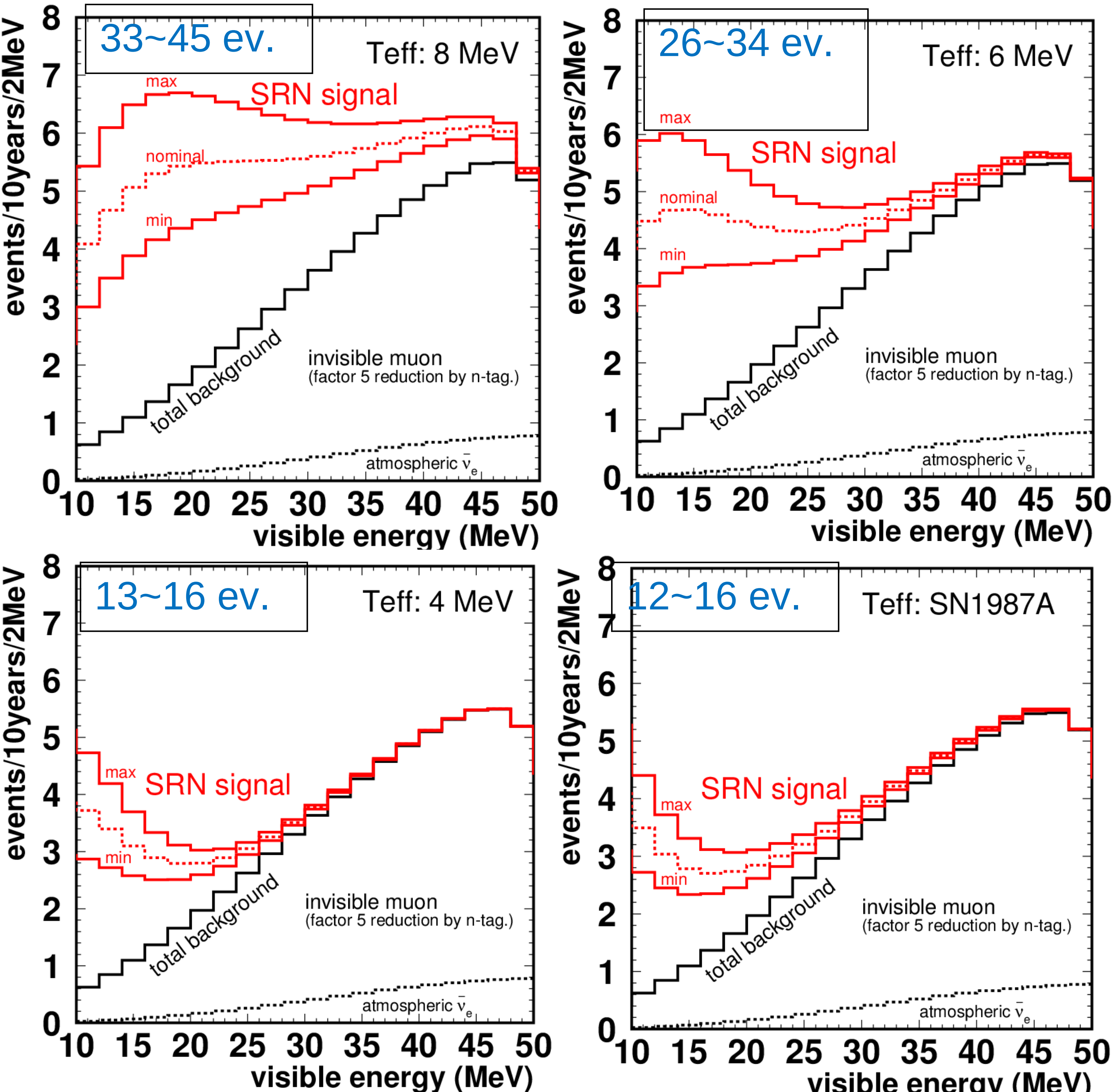


In case of core collapse Supernova burst the pointing accuracy would improve from ~4-5º → 3º (90% C.L.) @ 10 kpc

<u>Others:</u>

Nearby SN burst early warning
Reduce backgrounds for proton decay searches
Neutrino/anti-neutrino identification
Etc......

Expected signal and background



Expect number of events in 10 years in E_{total} =10-30 MeV

Assuming

Capture efficiency of 90% and Gd gamma detection efficiency of 74%.

Invisible muon B.G. is 35% of the SK-IV invisible muon BG.

Min/nominal/Max are due to uncertainties in astronomy.

Background: ~18 ev.

Galactic Core-collapse SN & more

Core-collapse burst: gadolinium will allow us neutrino tagging, i.e. identify the dominant IBD events:

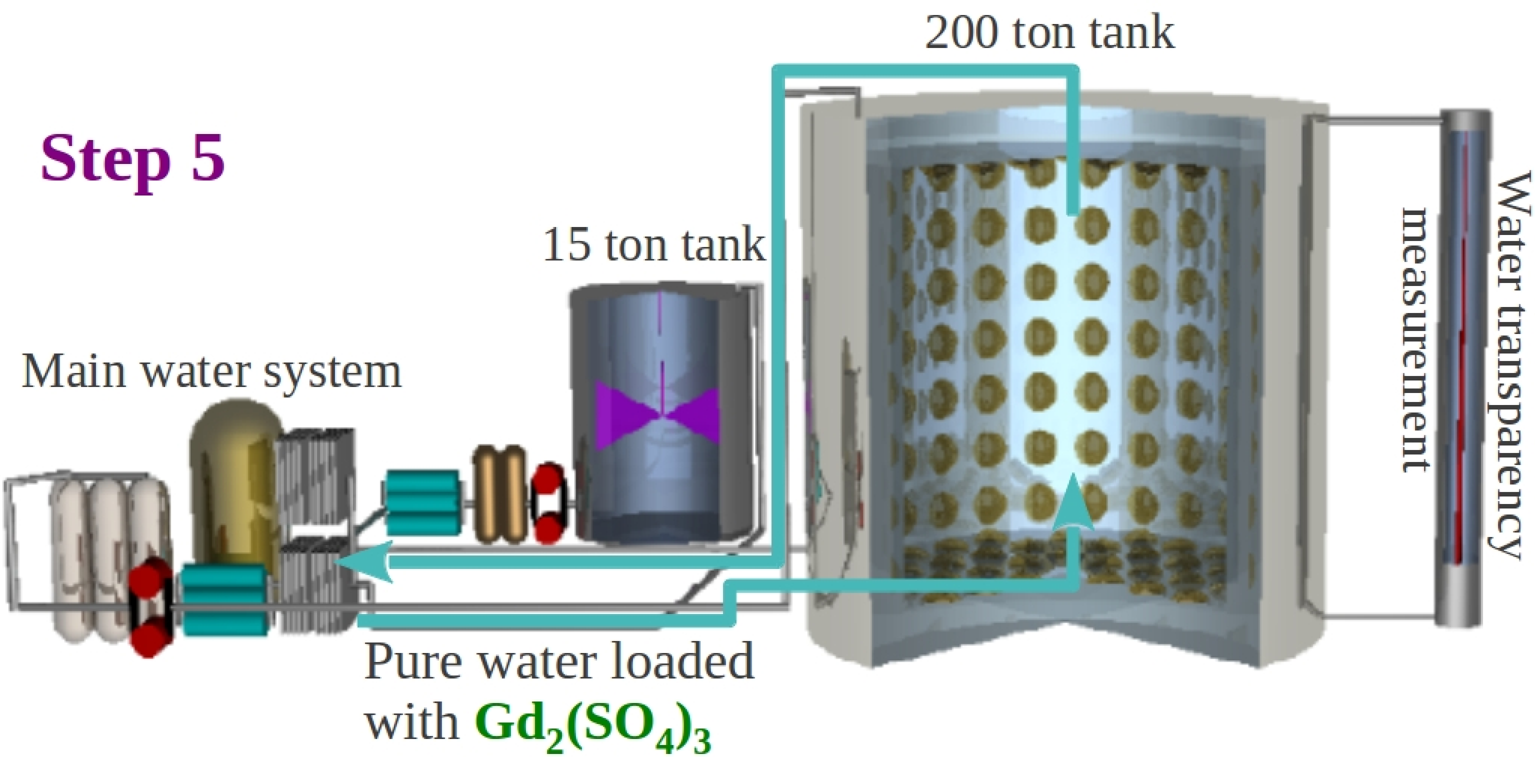
- Prompt recognition of a SN
- This would outline the ν_x elastic scattering: $\nu_x + e^+ \rightarrow \nu_x + e^+$ and hence greatly improve the pointing accuracy to the SN
- Measure $\bar{\nu}_e$ and ν_e spectra

Pre-burst signal: for $M > 8\ M_\odot$ during Si burning (last hours or days at most) pair annihilation νs are generated and if close enough (a few kp) could be detectable:

Detector	Target mass	Min $\bar{\nu}_e$ energy	48-24 hours before collapse	24-0 hours before collapse	3-0 hours before collapse
Super-K	32 kton	5 MeV	0.6	173	158
GADZOOKS!	22.5 kton	3.8 (1.8) MeV	9 (204)	442 (1883)	345 (1130)

A.Odrzywolek et al. AIP Conf.Proc.944,109 (2007)

EGADS & plan schedule



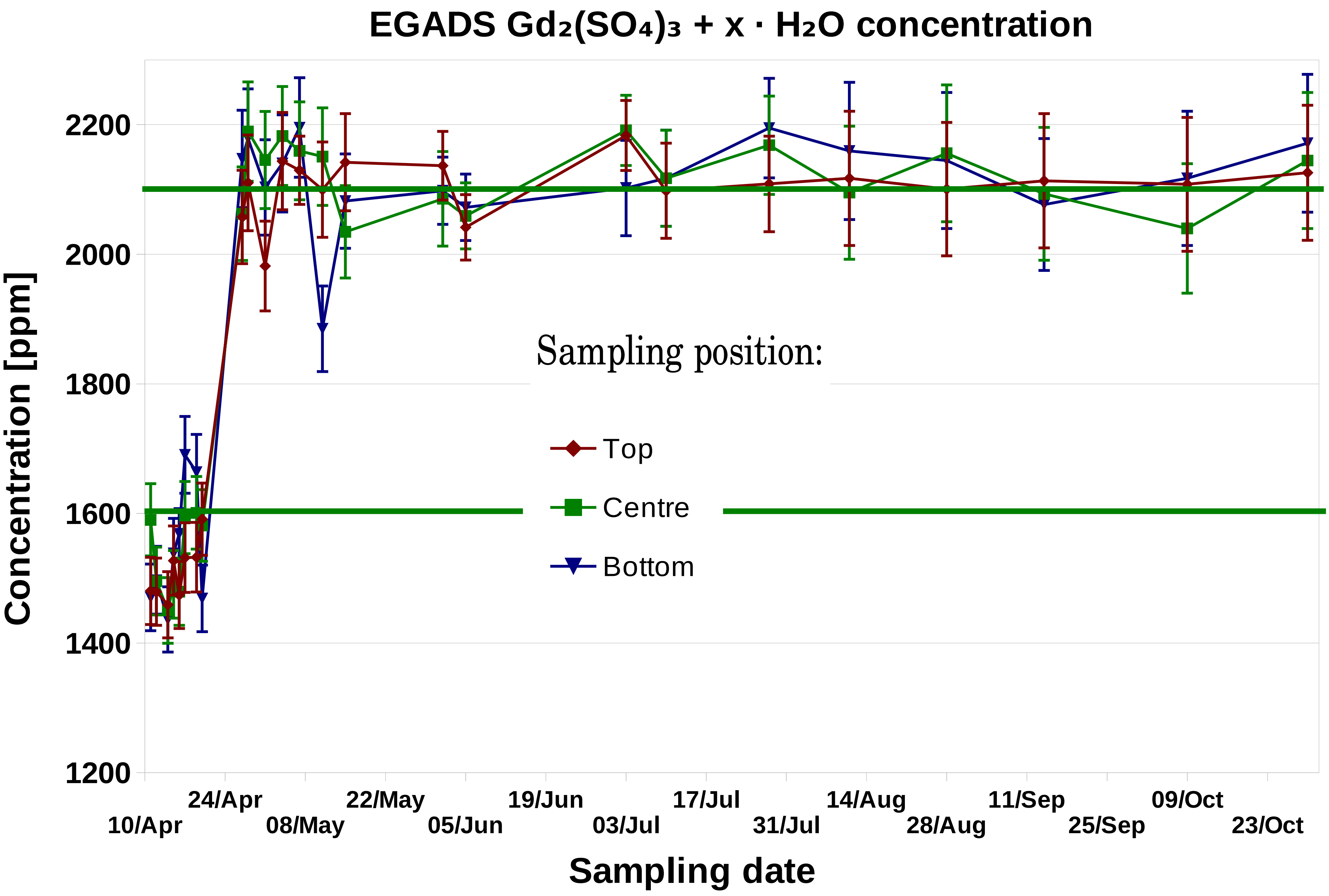
- **Step 1:** Circulation through the 200 ton tank with pure water (no PMTs) **Done!**
- **Step 2:** Circulation through the 15 ton tank with $Gd_2(SO_4)_3$ **Done!**
- **Step 3:** Circulation though the 200 ton tank with $Gd_2(SO_4)_3$ loaded water **Done!**
- **Step 4:** PMT mounting (240 in total) **Done!**

- **Step 5:** Full realization of the EGADS project **In Progress!**

Summary of systematic error table

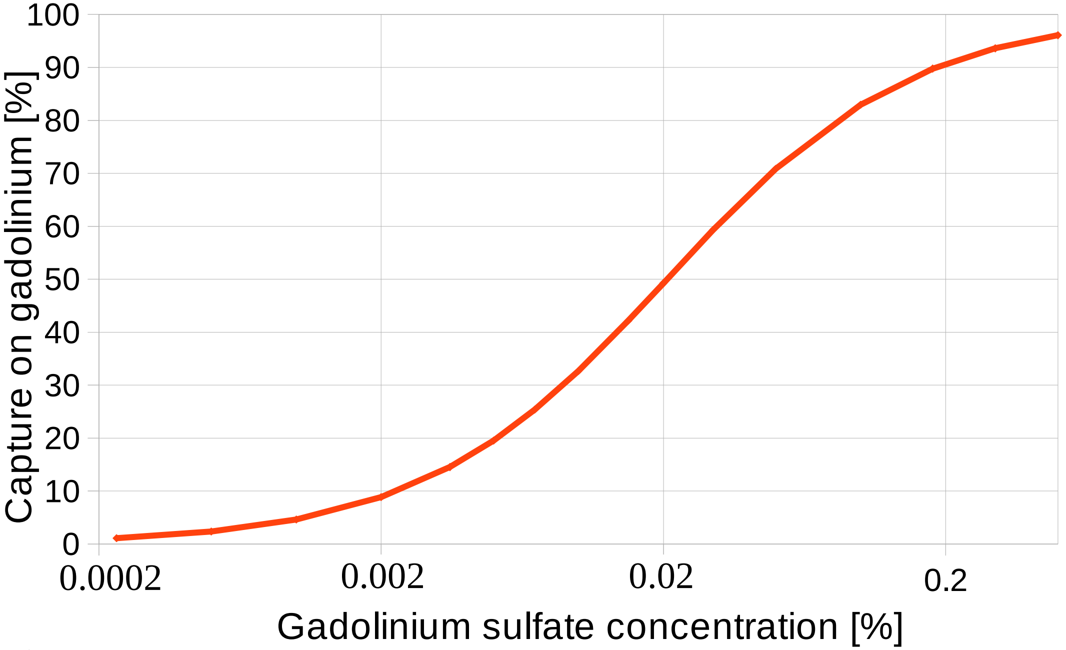
Systematic error	2034.3 days(+shift)	2034.3 days(-shift)	1668.8 days
Energy scale	-1.14	+1.16	-1.15/+1.16
Energy resl.	-0.09	+0.14	-0.03/+0.06
B8 spectrum	-0.33	+0.38	-0.34/+0.37
Trigger	-0.02	+0.03	-0.03/+0.02
Vertex shift	+/- 0.22		+/- 0.22
Ovaq	-0.12	+0.11	-0.11/+0.34
Patlik	+0.48	-0.47	-0.45/+0.45
Spallation	+/- 0.2		+/- 0.2
Gamma ray	+/- 0.25		+/- 0.25
Click	-0.44	+0.45	-0.45/+0.45
Angular resolution	+0.01	-0.09	-0.01/-0.27
Bckgrd shape	Not done yet(assuming +/-0.01)		+/- 0.01
Signal extract	+/- 0.7		+/- 0.7
Cross section	+/- 0.5		+/- 0.5
Total	1.7(1.6573)	1.7(1.6867)	1.7(1.69/1.72)
Energy 3.5-19.5 MeV(kin)	Uncorr 1.2(1.1532)	Uncorr 1.2(1.1556)	Uncorr 1.2 (1.19/1.22)

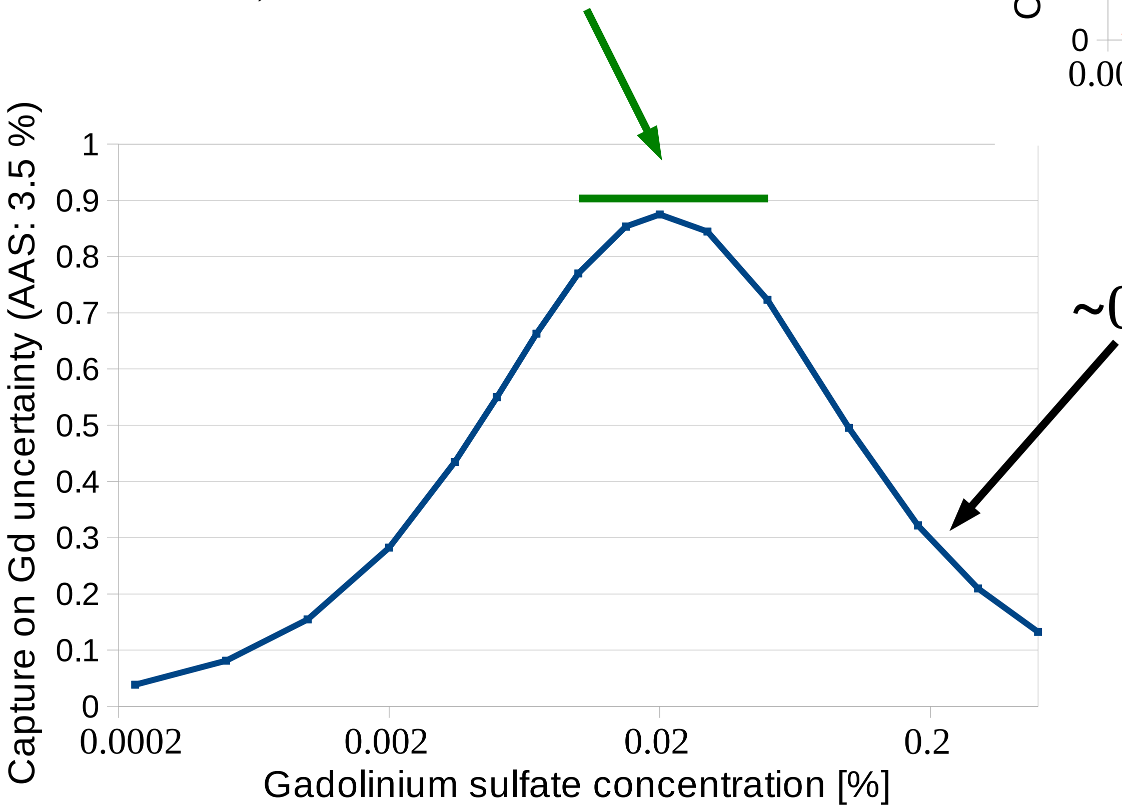
Gd Sulfate Concentration



Concentration Uncertainties

The uncertainty on the % of Gd capture is less than 0.9% (max. at 0.02% of gadolinium sulfate considering 3.5% uncertainty from the AAS)





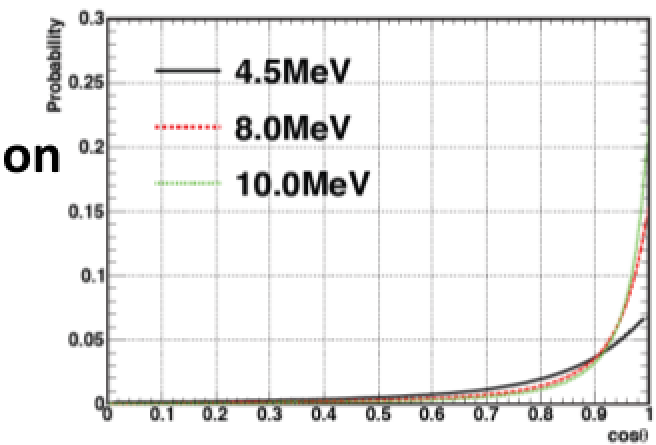
~0.3% uncertainty at 0.2% $Gd_2(SO_4)_3$

Searching for the Day/Night effect

$$\mathcal{L} = e^{-(\sum_i B_i + S)} \prod_{i=1}^{N_{\rm bins}} \prod_{\nu=1}^{n_i} \left(\beta_i(c_\nu) B_i + \sigma_i(c_\nu) m_i S\right)$$

- $N_{\rm bin} = 23$: **20 bins (0.5MeV from 3.5MeV), 2 bins (1MeV) and 1bin (4MeV)**
- B_i : **# of background events, energy bins i**
- S : **# of signal events**
- $c_\nu = \cos\theta_{\nu,{\rm Sun}}$: **angle from solar direction**
- $\beta_i(c_\nu)$: **background shapes**
- $\sigma_i(c_\nu)$: **signal shapes (solar peak)**
- $m_i = \dfrac{{\rm MC}_i}{\sum_k {\rm MC}_k}$: **MC ratio of energy bin i**

$\sigma_i(c_\nu)$



$$\mathcal{L} = e^{-(\sum_i B_i + S)} \prod_{i=1}^{N_{\rm bins}} \prod_{\nu=1}^{n_i} \left(\beta_i(c_\nu) B_i + \sigma_i(c_\nu) z_i(t_\nu) m_i S\right)$$

$z_i(t_\nu)$: **New signal factor can include any time variable, such as zenith angle (day/night effect),distance(eccentricity, seasonal), etc.**

Searching for the Day/Night effect(2)

$$\mathcal{L} = e^{-(\sum_i B_i + S)} \prod_{i=1}^{N_{\text{bins}}} \prod_{\nu=1}^{n_i} (\beta_i(c_\nu) B_i + \sigma_i(c_\nu) z_i(t_\nu) m_i S)$$

$$z_i(t_\nu) \rightarrow z_i(\alpha, t) = \frac{1 + \alpha((1 + a_i) r_i(t)/r_i^{\text{ave}} - 1)}{1 + \alpha a_i} \times z_{\text{exp}}(t)$$

α : Day/Night scaling parameter

a_i : Effective Day/Night asymmetry

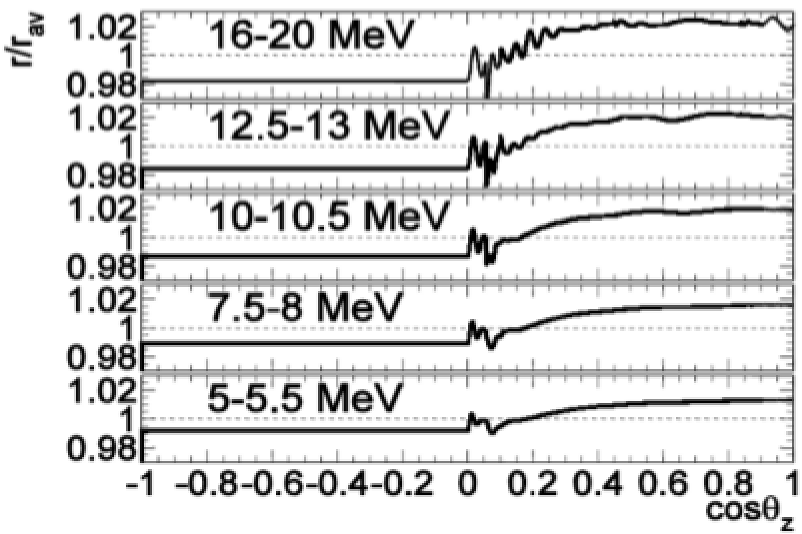
$r_i(t)$: rate in zenith bin of event(MC)

r_i^{ave} : livetime averaged rate

$$A_{\text{DN}} = \frac{r_i^{\text{day}} - r_i^{\text{night}}}{(r_i^{\text{day}} - r_i^{\text{night}})/2} = \alpha \times A_{\text{DN},i}$$

$z_{\text{exp}}(t)$

: take into account eccentricity corrections and the Day/Night MC efficiency difference, does not depends on α



Day/Night Asymmetry

◆Day/Night Asymmetry

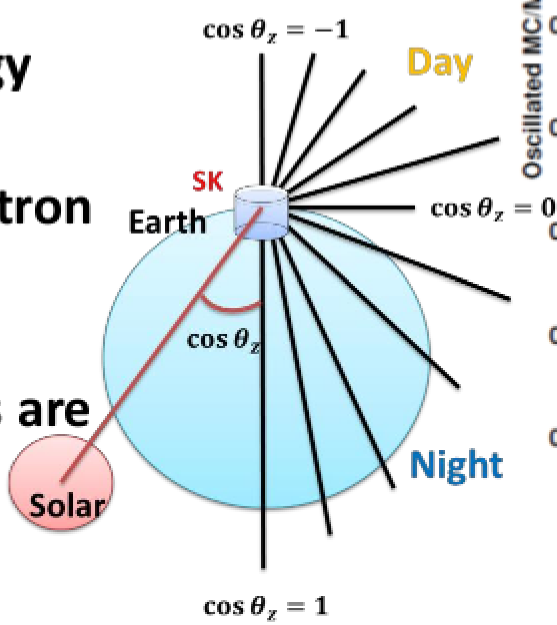
Compare ^8B solar neutrino flux(Ψ) during day/night time.

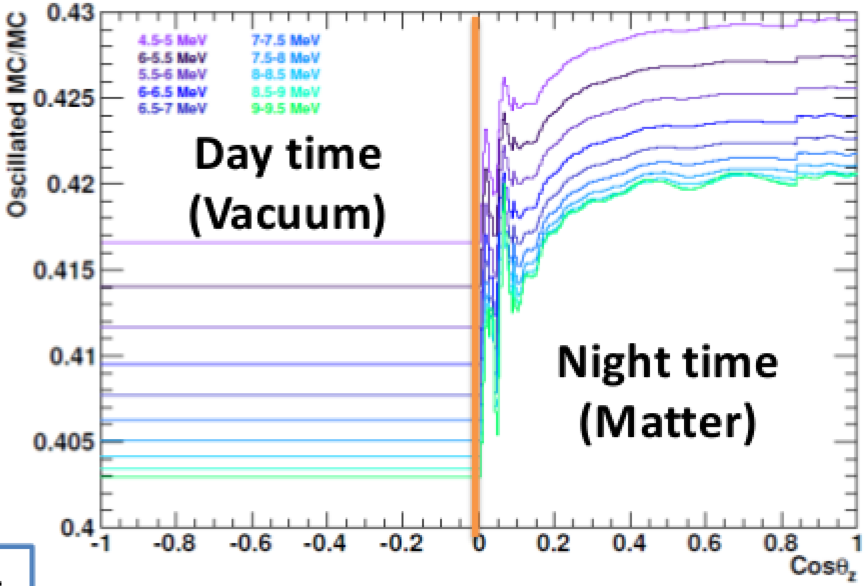
$$A_{DN} = \frac{\Psi^{day} - \Psi^{night}}{(\Psi^{day} + \Psi^{night})/2}$$

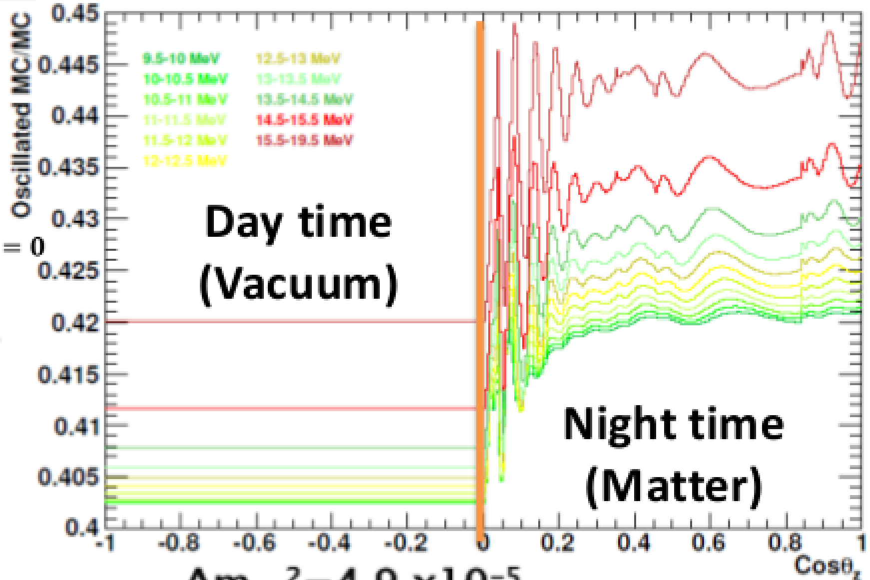
◆Neutrino oscillation due to matter effect

A_{DN} depends on
(1)Neutrino energy
(2)Mass $\Delta m_{21}{}^2$
(3)Density of electron in the Earth

These parameters are considered in our analysis.







$\Delta m_{21}{}^2 = 4.9 \times 10^{-5}$
$\sin^2\theta_{12} = 0.314$

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ADN systematics

- Large reduction in energy scale error from SK-I to SK-III comes from introduction of z-dependence water transparency parameter into MC.

- External event cut had a negligible affect in SK-I and SK-II because no tight fiducial volume cut was applied.

- Total errors among SK phases are considered uncorrelated

	SK-I	SK-II	SK-III	SK-IV
Energy scale	0.8%	0.8%	0.2%	0.05%
Energy resolution	0.05%	0.05%	0.05%	0.05%
Background shape	0.6%	0.6%	0.6%	0.6%
External event cut	-	-	0.2%	0.1%
Earth model	0.01%	0.01%	0.01%	0.01%
Total	1.0%	1.0%	0.7%	0.6%