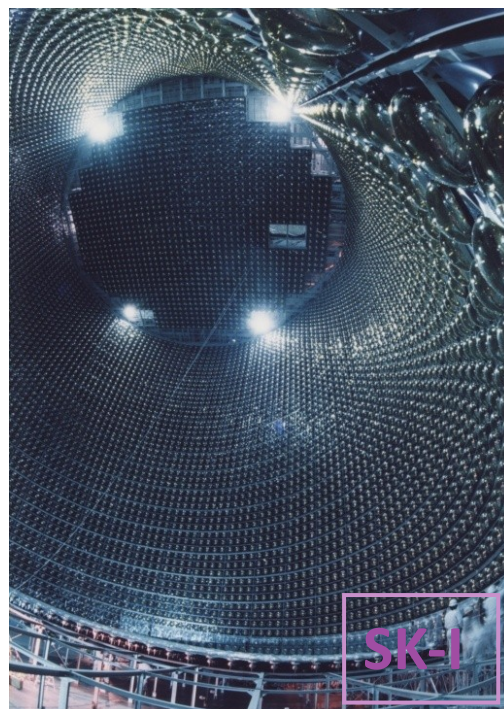


# SuperKamioKANDE

**Introduction**  
**Solar neutrinos**  
**Supernova Relic Neutrinos**  
**Gadzooks!**

Lluís Martí Magro, UA Madrid.  
Neutrino Champagne, 19<sup>th</sup> of October 2009.

# SuperKamiokande History



SK-I

11146 ID PMTs  
(40% coverage)

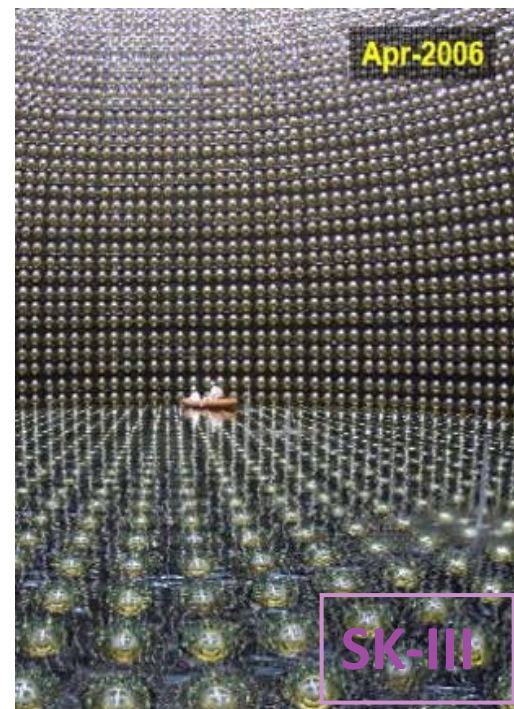
Energy Threshold **5.0 MeV**  
(Total energy) **~4.5MeV**  
(Kinetic energy)



SK-II

5182 ID PMTs  
(19% coverage)

**7.0 MeV**  
**~6.5MeV**



SK-III

11129 ID PMTs  
(40% coverage)

**4.5 MeV**  
**~4.0MeV**

Work in progress



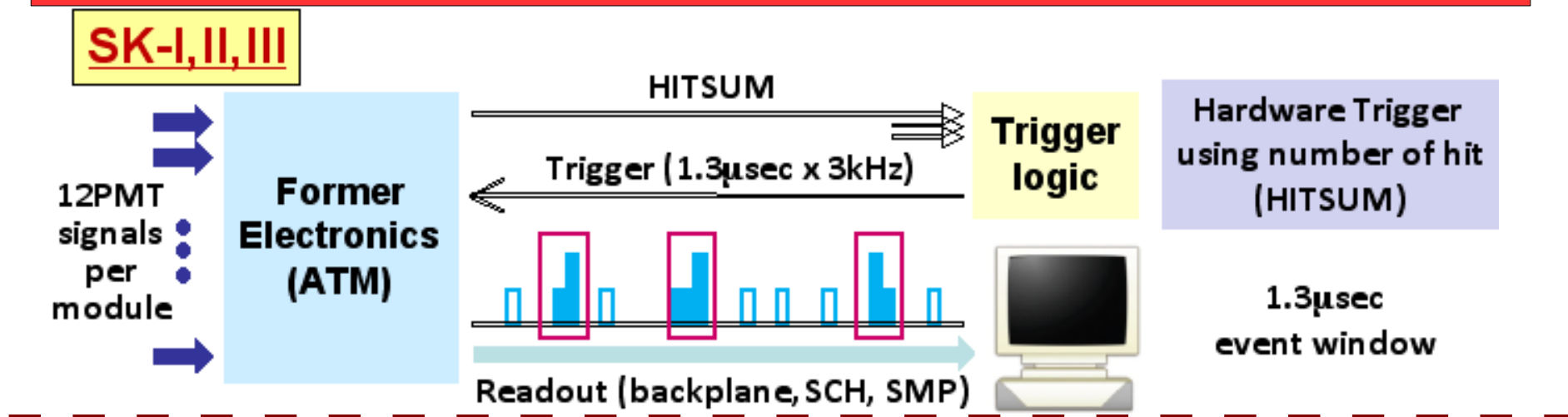
SK-IV

Electronics Upgrade

**< 4.0 MeV**  
**<~3.5MeV**

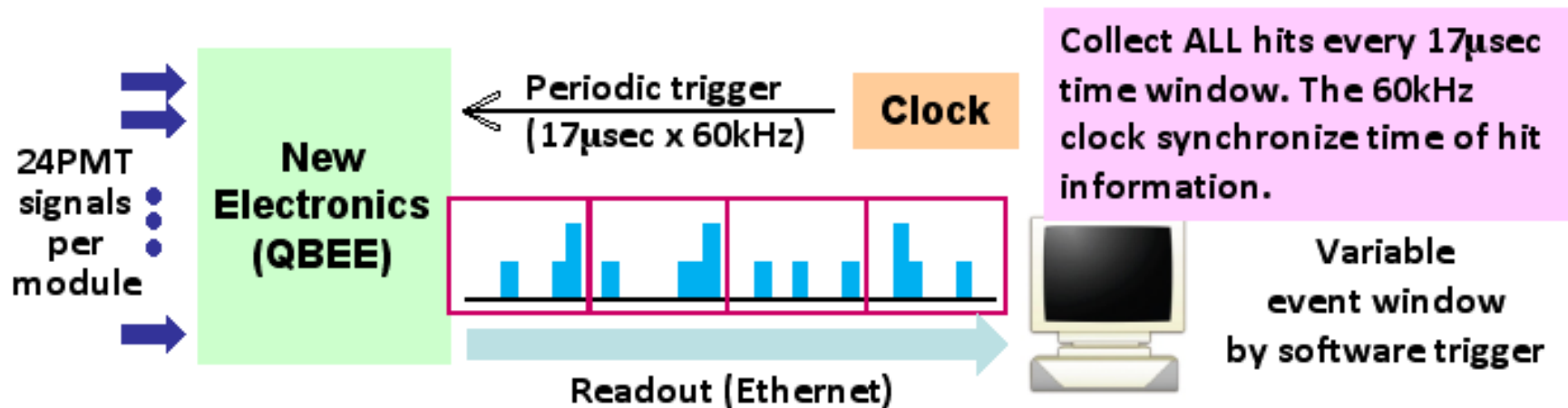
Target

# SK-IV Software Trigger



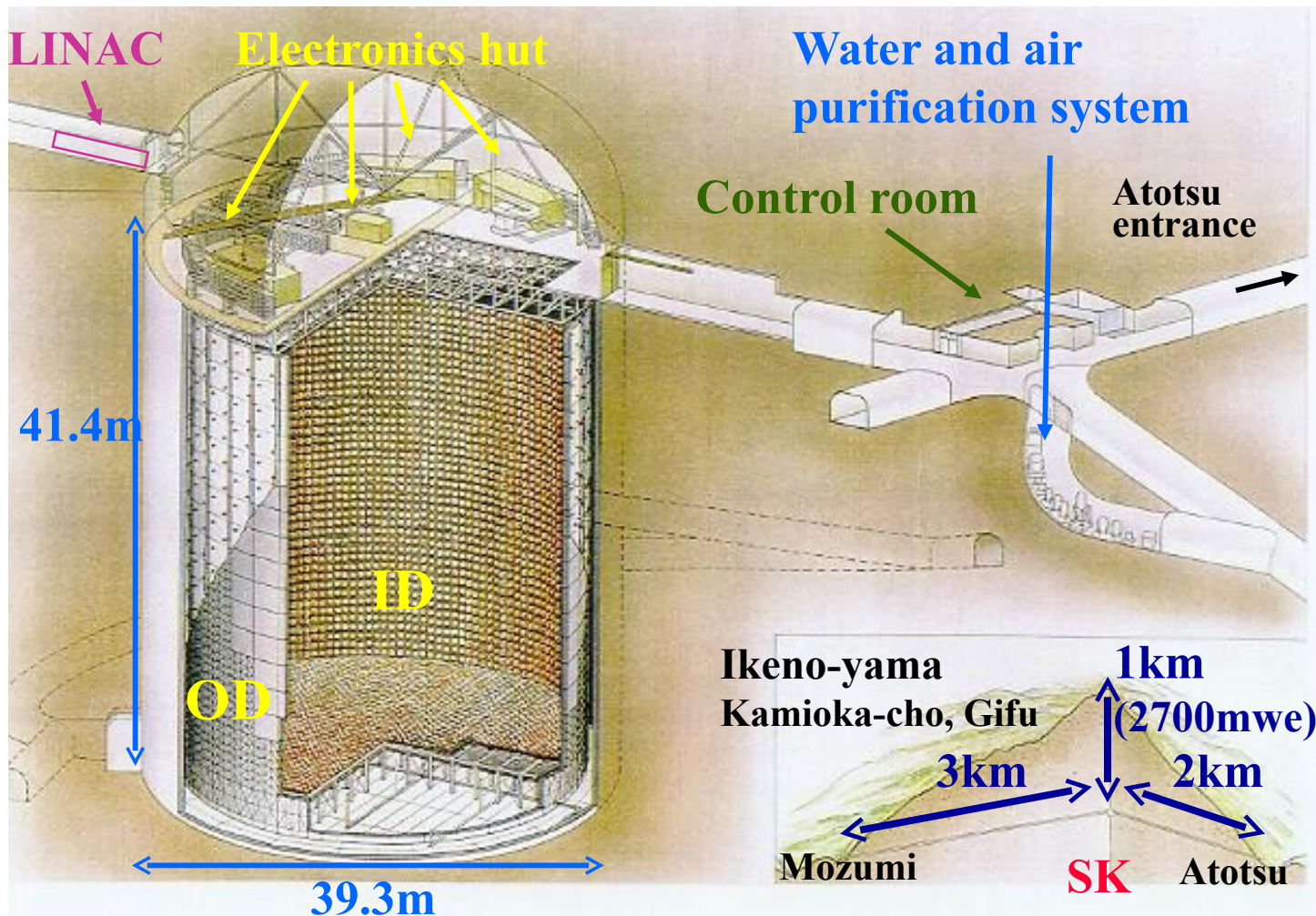
**SK-IV**

**No hardware trigger. All hits are readout. Apply software trigger.**



More sophisticated/flexible triggering can be implemented. For example a neutron trigger: Open a time gate of  $500\ \mu\text{s}$  after a  $E_{\text{total}} > 10\text{MeV}$  event to search for neutron capture

# SuperKamiokande Detector



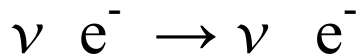
- 50kton water
- ~2m OD viewed by 8-inch PMTs
- 32kt ID viewed by 20-inch PMTs
- **22.5kt fid. vol.** (2m from wall)
- ~5MeV energy threshold
- April 1996~

**Inner Detector (ID) PMT: ~11100 (SK-I,III,IV), ~5200 (SK-II)**

**Outer Detector (OD) PMT: 1885**

# Event reconstruction in a Nutshell

Solar neutrino



✓ Reconstruction method:

- Interaction vertex:

⇒ Timing information

- Electron direction:

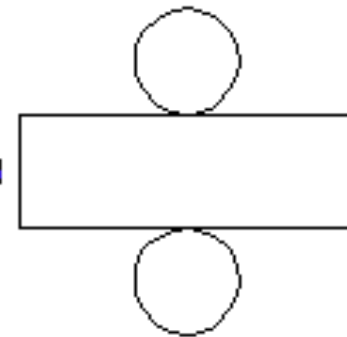
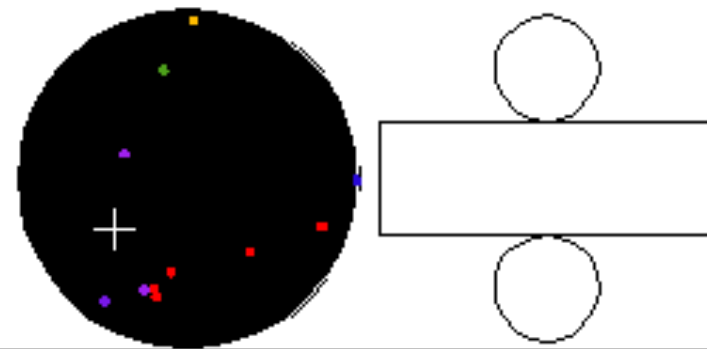
⇒ Cherenkov Ring pattern

- Electron energy:

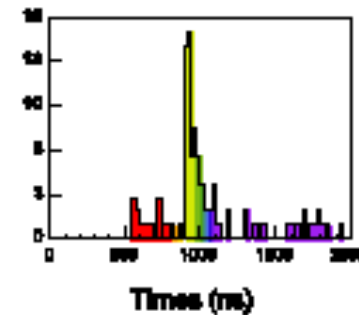
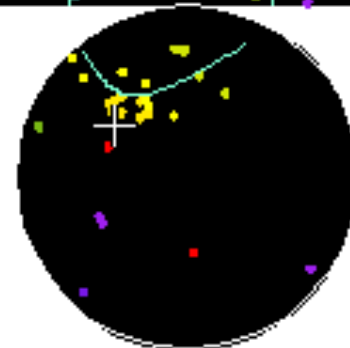
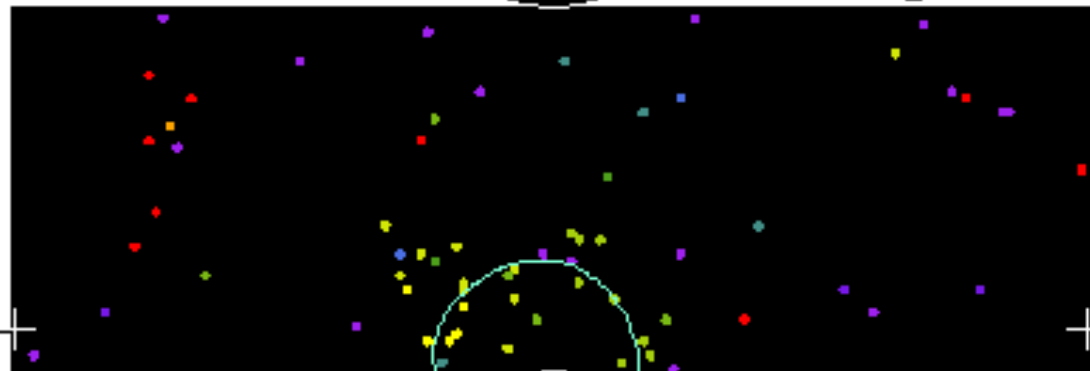
⇒ Number of hit PMTs,  $N_{\text{eff}}$ , ( $\sim 6$  hit/MeV @ SK-I, III and IV)

Super-Kamiokande

```
Run 1742 Event 102496
94-08-31:07:13:23
Input: 109 hits, 131 pE
Output: -1 hits, 0 pE (In-time)
Trigger ID: 0x03
E= 9.084 MeV-0.57 GeV@SK-I 0.348
Solar Neutrino
```



```
Time [ns]
* < 015
* 015-035
* 035-055
* 055-075
* 075-095
* 095-115
* 115-135
* 135-155
* 155-175
* 175-195
* 195-215
* 215-235
* 235-255
* 255-275
* 275-295
* 295-315
* 315-335
* 335-355
* 355-375
* 375-395
* 395-415
* 415-435
* 435-455
* 455-475
* 475-495
* 495-515
* 515-535
* 535-555
* 555-575
* 575-595
* 595-615
* 615-635
* 635-655
* 655-675
* 675-695
* 695-715
* 715-735
* 735-755
* 755-775
* 775-795
* 795-815
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* 835-855
* 855-875
* 875-895
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* 935-955
* 955-975
* 975-995
* 995-1015
* 1015-1035
* 1035-1055
* 1055-1075
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* 1115-1135
* 1135-1155
* 1155-1175
* 1175-1195
* 1195-1215
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* 9935-9955
* 9955-9975
* 9975-9995
* >1000
```



Resolution (10 MeV electron@SK-I)

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

# Solar Neutrino Analysis

## Analysis current status

---

Goal: reduce background and systematic uncertainties to further reduce the energy thresholds and improve limits.

Systematic Uncertainty Sources under improvement:

- Water quality:
  - Fine water temperature control in the tank → Lower radon concentration in fiducial volume
  - MC position water quality parametrization: 1% position dependence in energy scale included in the MC simulation
- Fiducial volume uncertainty reduction:
  - Some non-linearity in the electronics caused a vertex shift of  $\sim 15$  cm at the edge of the fiducial volume. It was taken into account and became  $< 10$  cm → larger fiducial volume: correction also applicable in SK-I/II data!
- Optical properties of the detector material:
  - Precise measurement of the ID black sheet cover reflectivity included in MC
- Improved direction fitter: → 10% angular resolution

The estimation of the systematic uncertainties are currently under way

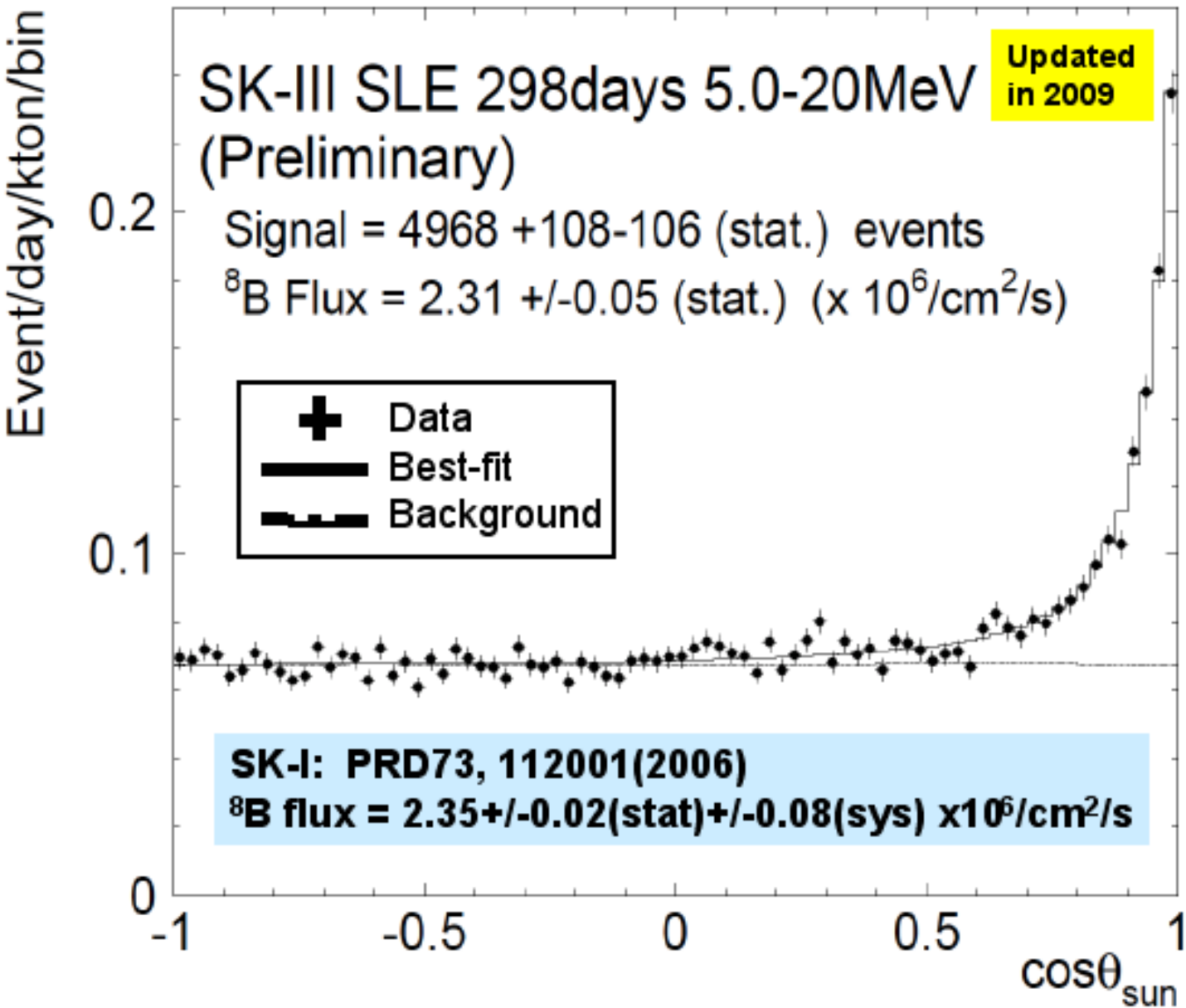
Goal: reduce background and systematic uncertainties to further reduce the energy thresholds and improve limits.

For **SK-IV** data:

- 100% efficiency at  $E_{\text{total}} = 4.5 \text{ MeV}$  ( $E_{\text{kin}} = 4.0 \text{ MeV}$ )
- This threshold will be lowered in the future. Current target is  $E_{\text{total}} \leq 4.0 \text{ MeV}$  ( $E_{\text{kin}} = 3.5 \text{ MeV}$ )

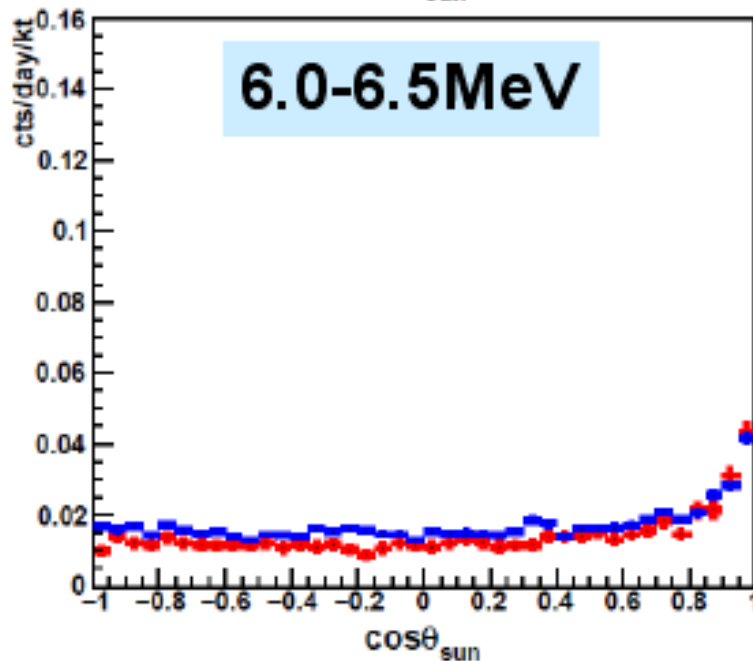
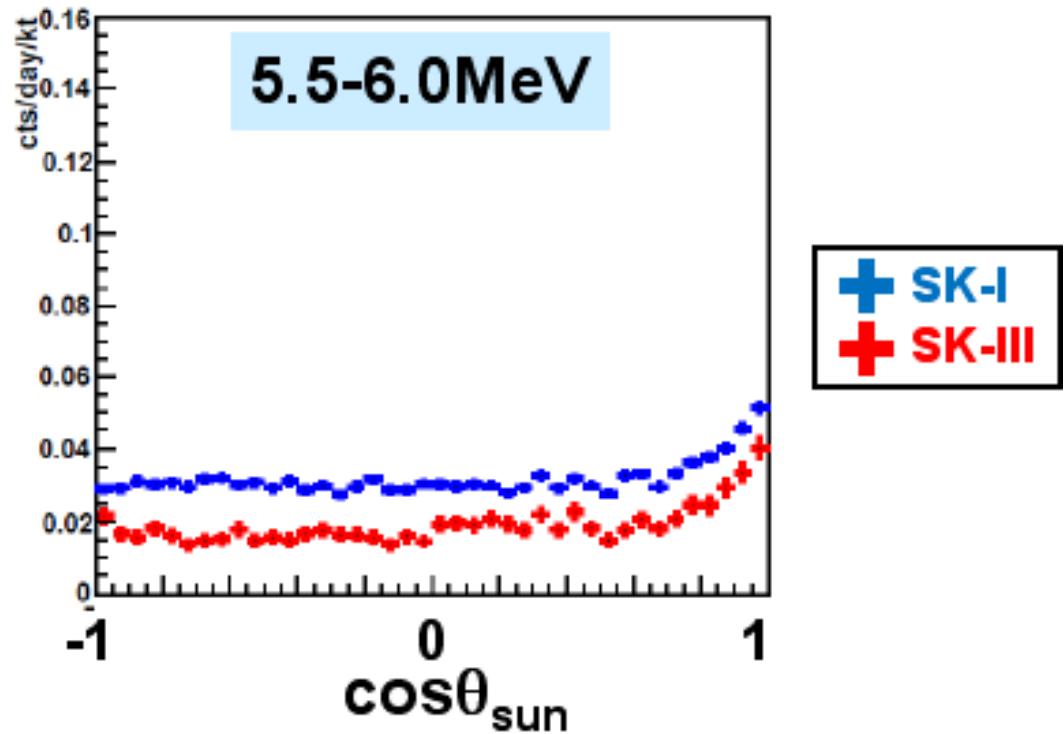
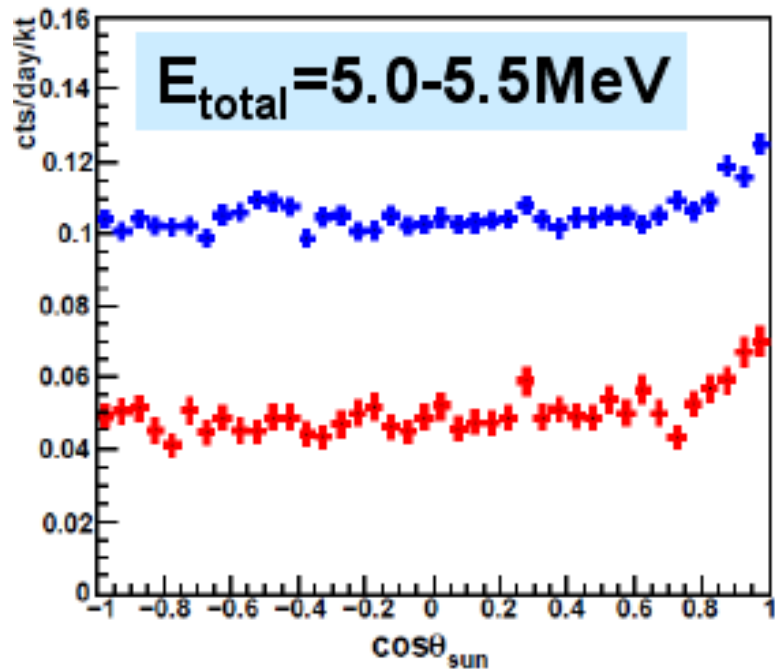


# $^8\text{B}$ Flux @ SK-III



- ✓ Flux consistent with SK-I
- ✓ Better angular resolution compared to SK-I
- ◆ Systematic uncertainties are currently being estimated (trying to reduce them)

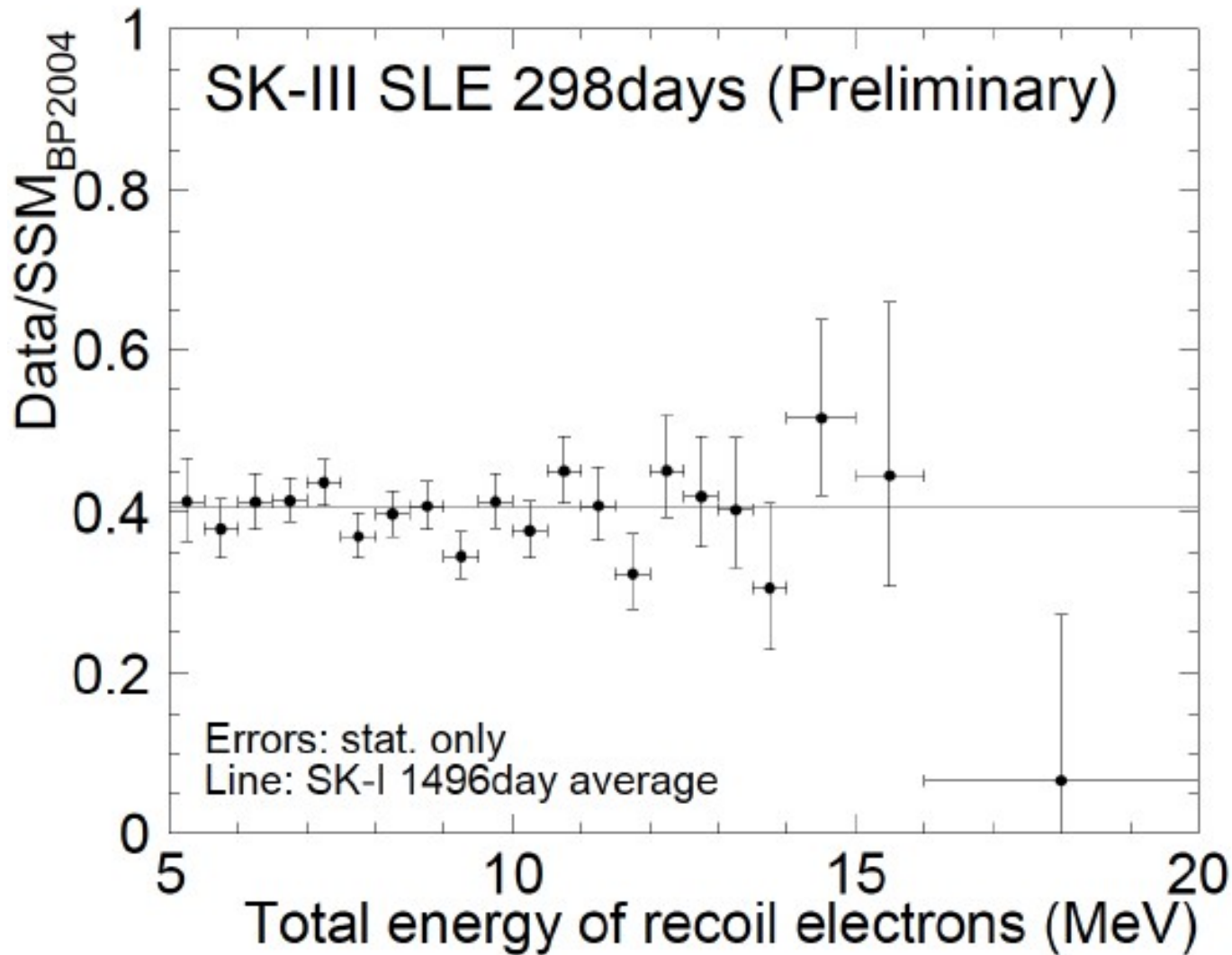
# Angular distributions 1/2



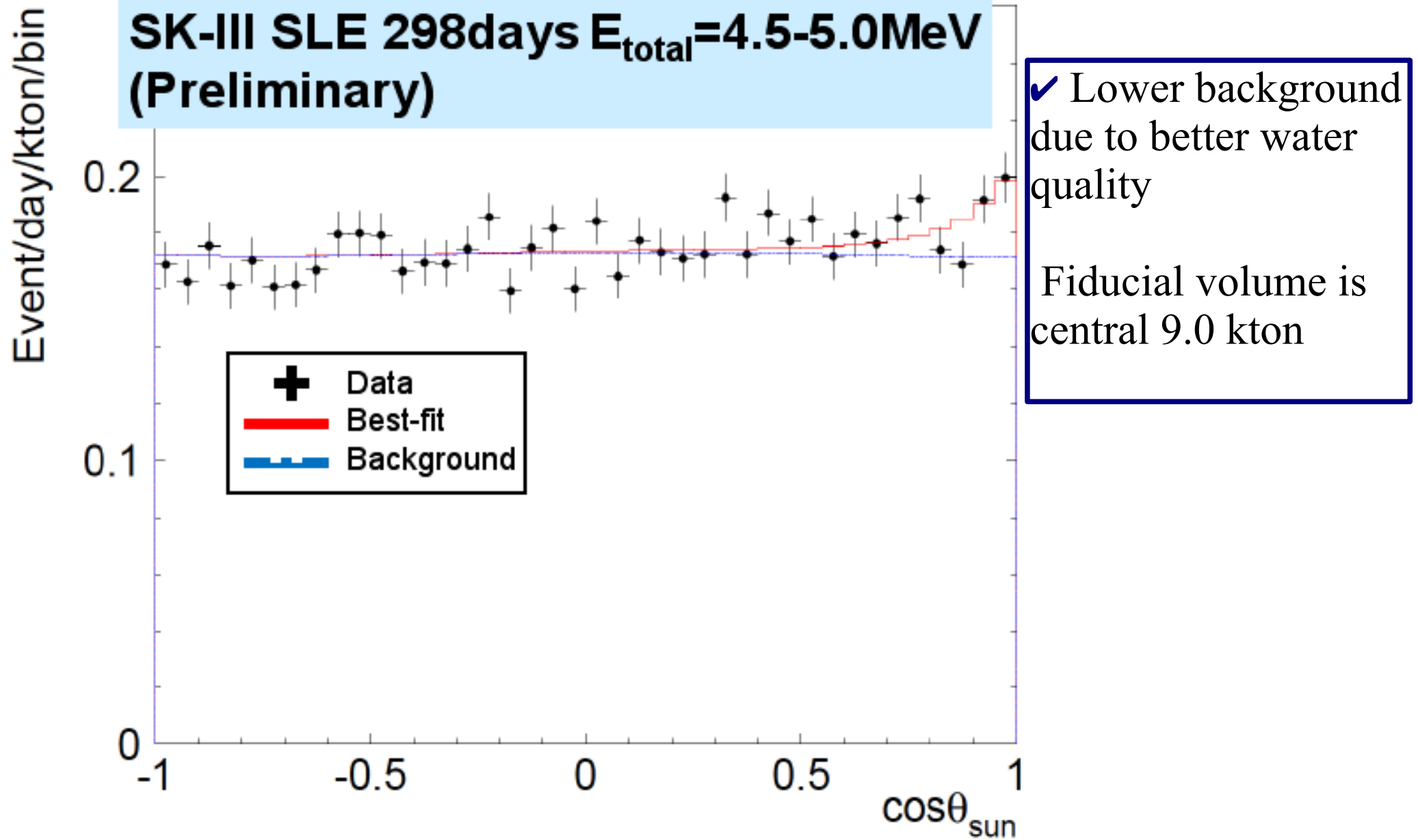
✓ Lower background level due to better water quality

Fiducial volume is central 13.3 kton

# $^8\text{B}$ energy spectrum

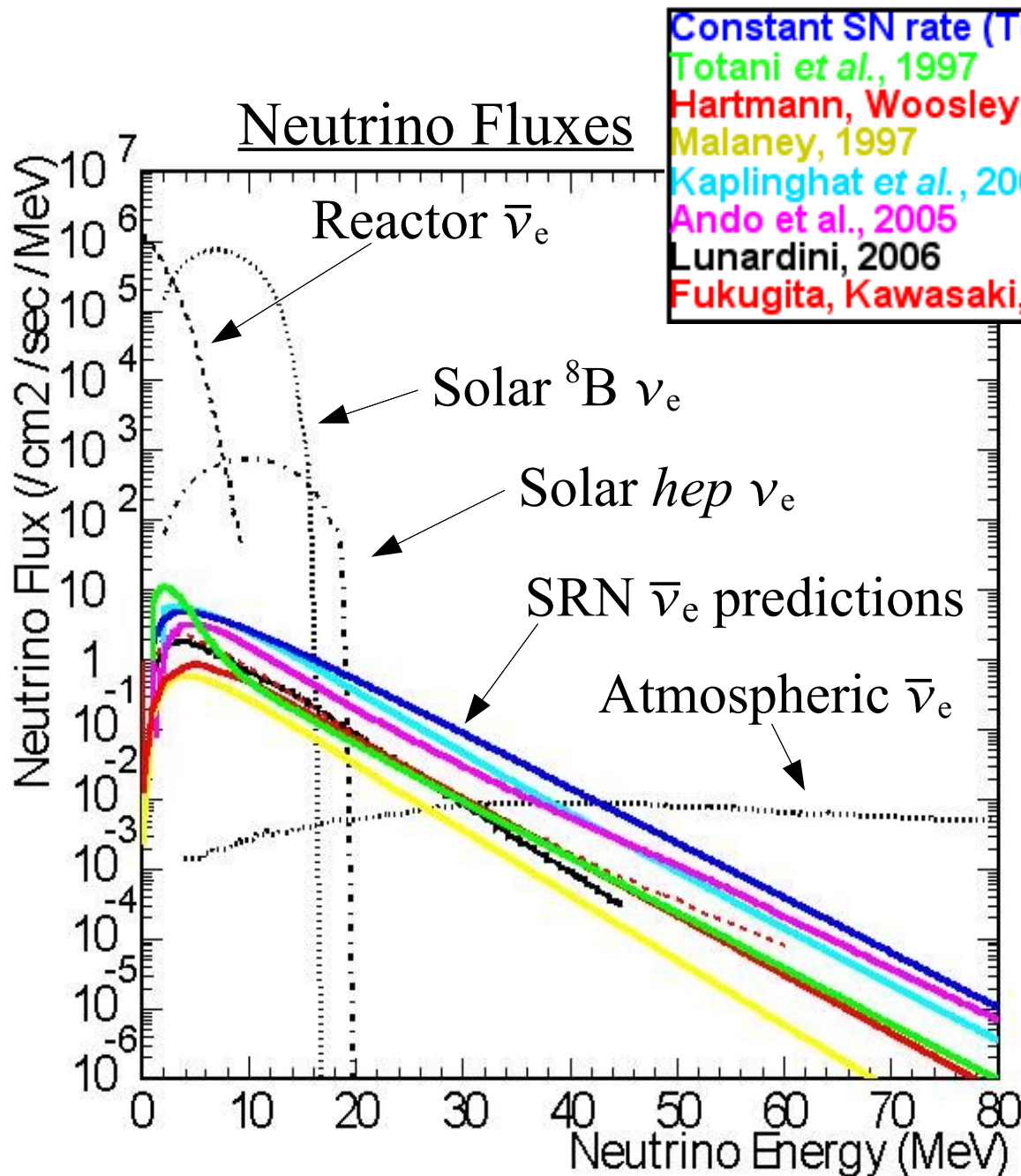


# Angular distributions 2/2

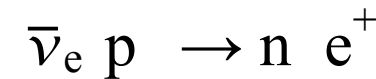


# Supernova Relic Neutrinos

# Supernova Relic Neutrinos (SRN)



Dominant interaction@SK:



Motivation: obtain supernova and star formation rate for  $M > 8 M_{\odot}$  and metal enrichment rate.

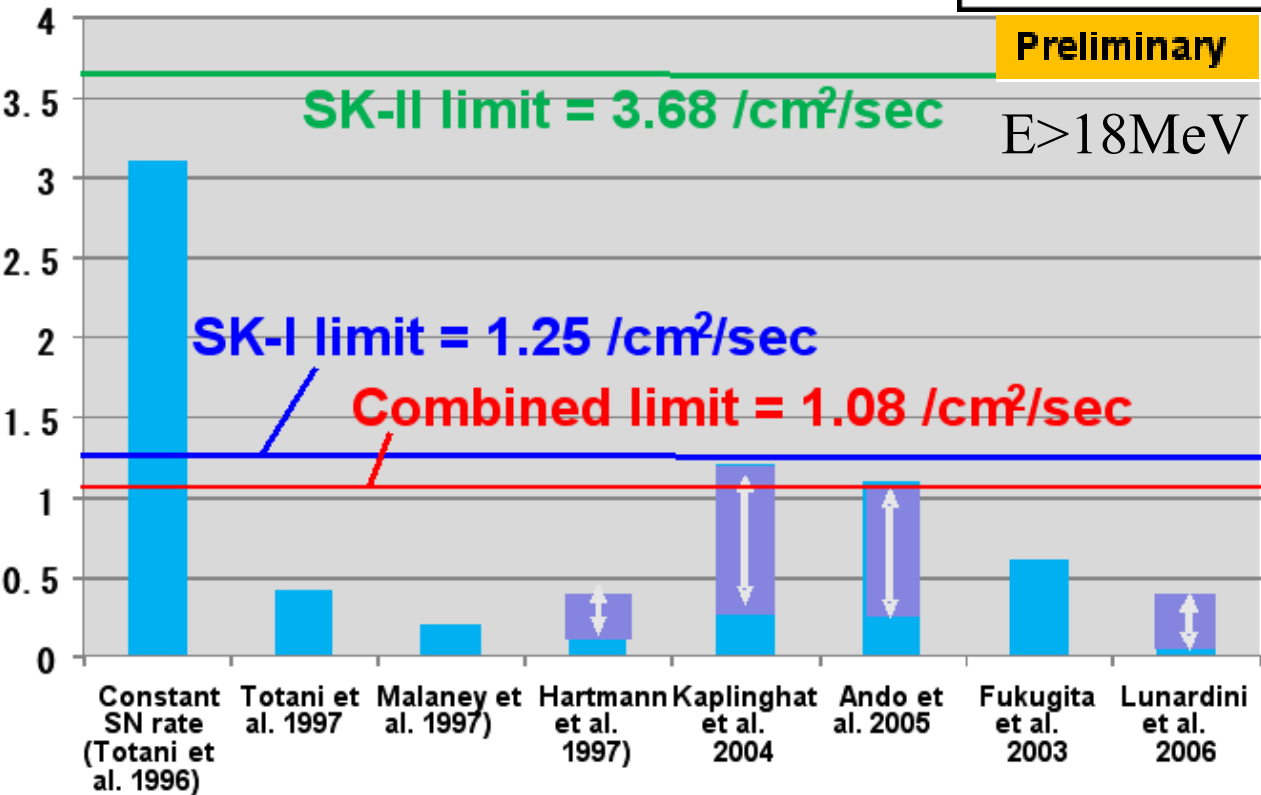
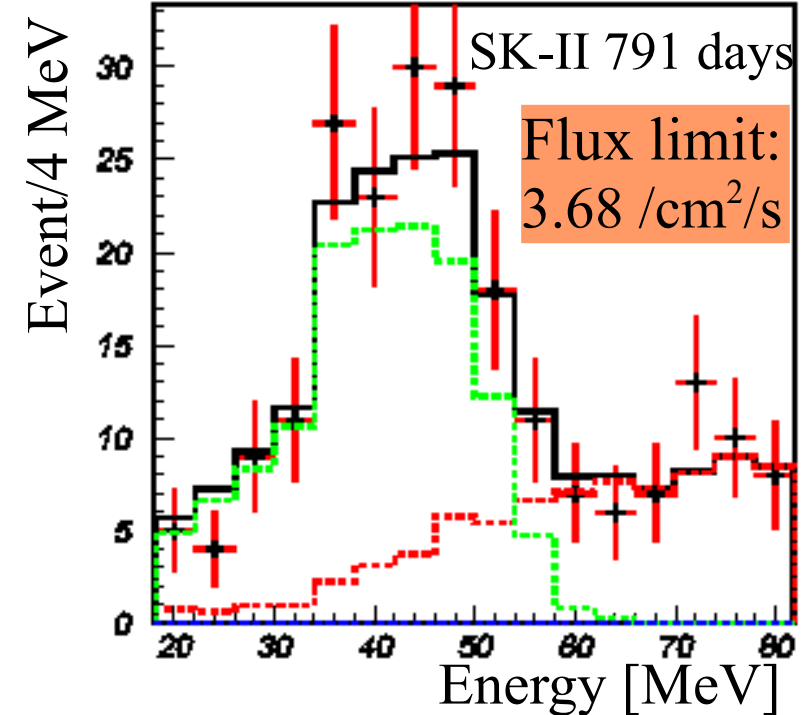
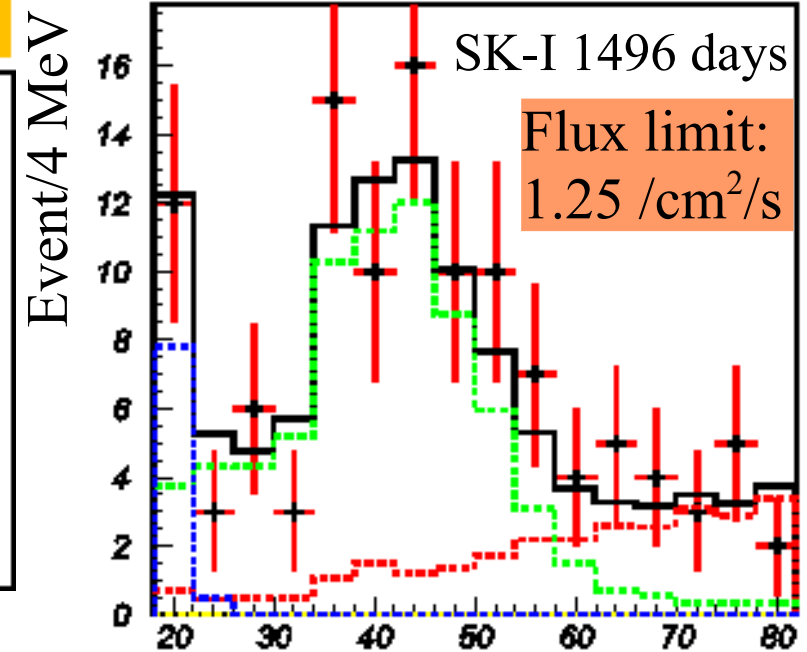
Since: 
$$\frac{E_{\text{detect}}}{E_{\text{emit}}} = \frac{1}{1+z}$$

a smaller energy threshold would allow us to probe lower  $z$  values

# Current results: SRN Flux Limits vs Model Predictions

Combined SRN flux limit:  $< 1.08 \text{ cm}^2/\text{s}$

Our model exclusion and constrain power is increasing !!



# Currently applied event selection

Solar neutrino cut: Reject **solar neutrinos** using direction information  $\longrightarrow$  **improving!!**  
7% inefficiency

Gamma ray cut: Reject **gamma-rays** originated from outside the fiducial volume  $\longrightarrow$  **improving!!**  
7% inefficiency

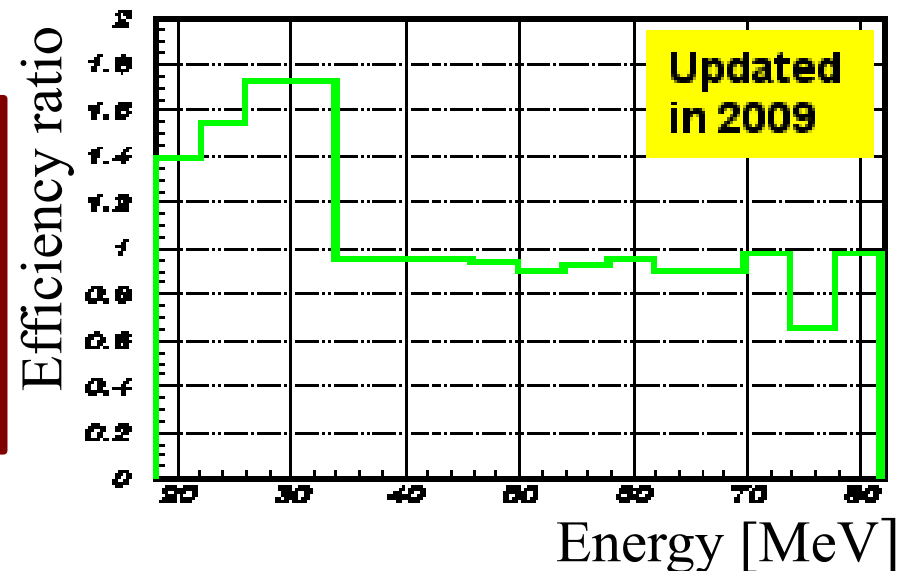
Standard spallation cut: Reject **spallation** events using  $\Delta t$  and  $\Delta l$  information from previous muons

Tight spallation cut: Reject **spallation** events using a tight  $\Delta t$  selection  $\longrightarrow$  **improving!!**  
Spallation cuts total: 36% inefficiency

Subevent cut: Reject **decay-e** by checking time correlating events  
0.5% inefficiency

Cherenkov angle cut: Reject **low energy muons** using Cherenkov opening angle

- ✓ Improved reconstruction tools & flux calculation
  - ✓ Reduction criteria are currently being improved
- $\rightarrow$  The SRN signal efficiency will be improved





# Currently applied event selection

---

## In the short term:

- Finish the new event selection
- Combine the SK-I (1496 days), SK-II (791 days) and SK-III (425 days) data
- Try to enlarge the fiducial volume by  $\sim 0.5$ -1m
- New results will be summarized this year

## Long term...

The long term future means Gadzooks!:

- The background could be reduced by neutron tagging
- The R&D program is on going

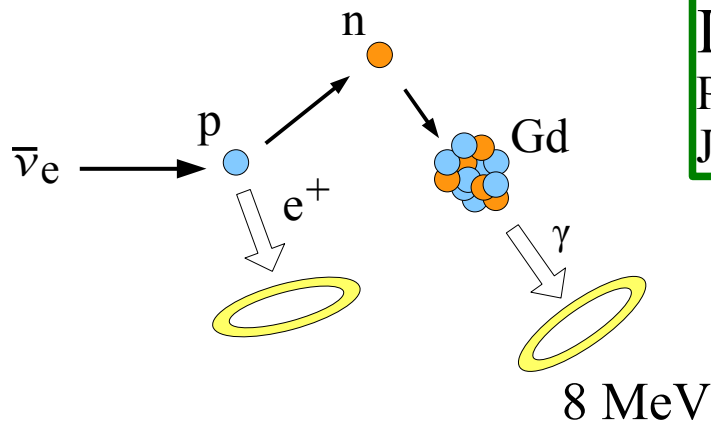
The budget for a 200-ton tank has been (EGADS) approved

Updated  
in 2009

See next slides!! 

Gadzooks!

# Gadzooks!

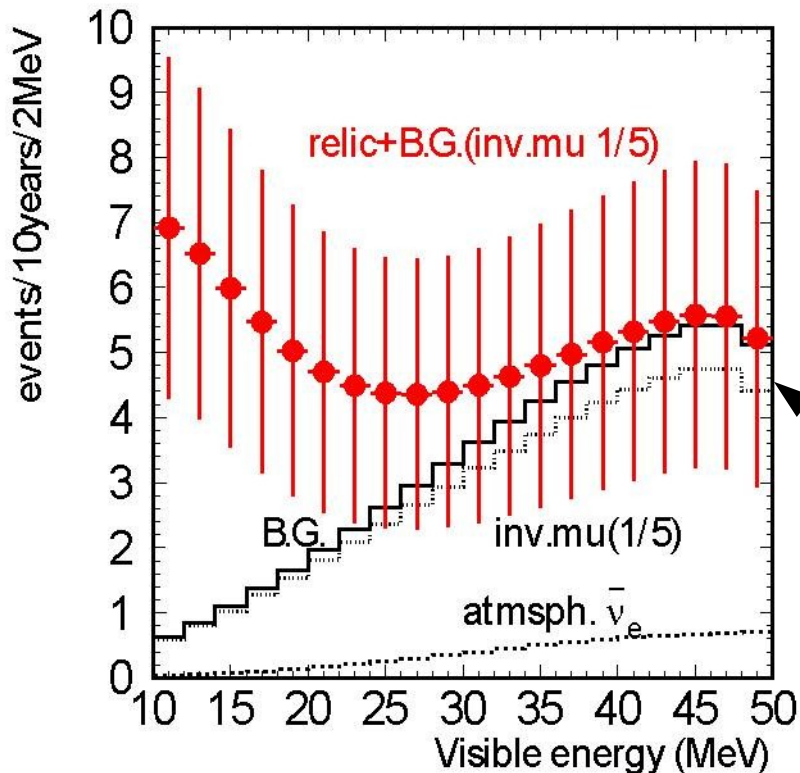


Idea: add 0.2% of Gd in the SK water  
 Phys. Rev. Lett. 93, 171101 (2004)  
 J.Beacom and M.Vagins

$\bar{\nu}_e$  signal could be separated from BG by  
 neutron tagging, i.e. coincidence  
 detection of positron and neutron  
 Vertex correlation  $\sim 50\text{cm}$

After 10 years of SK data taking:  
**Signal: 33 events**; Background: 27 events  
 $E_{\text{vis}} = 10\text{-}30\text{ MeV}$

Assumption:  
 - 67% detection efficiency  
 - Invisible  $\mu$  background can be reduced by  
 a factor of 5

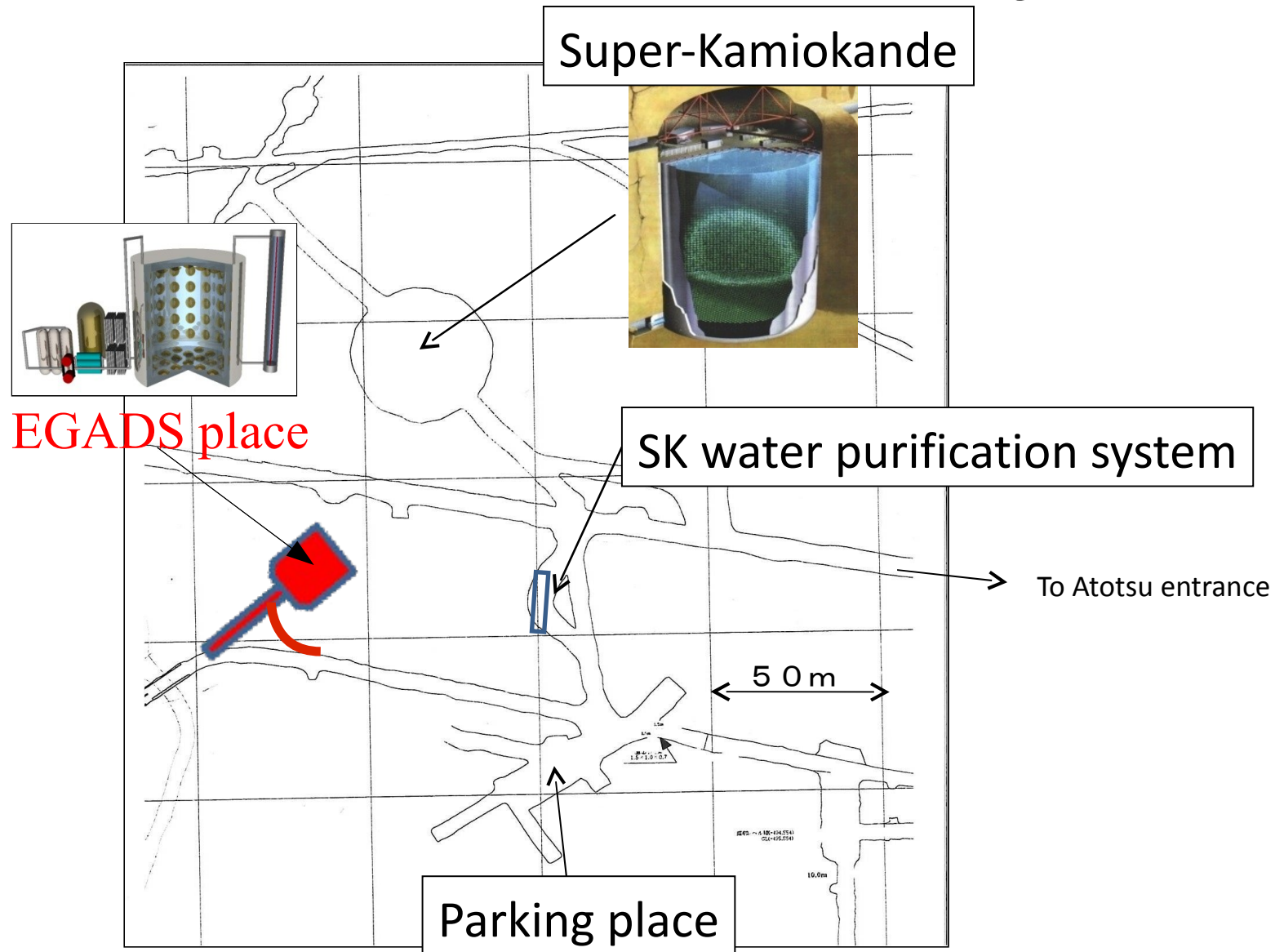


Relic model: *Astropart.Phys.*18,  
 307(2003) with flux revise in NNN05.

# EGADS

## Evaluating Gadolinium's Action on Detector Systems

Study the effect of Gd on all the materials and the neutron background

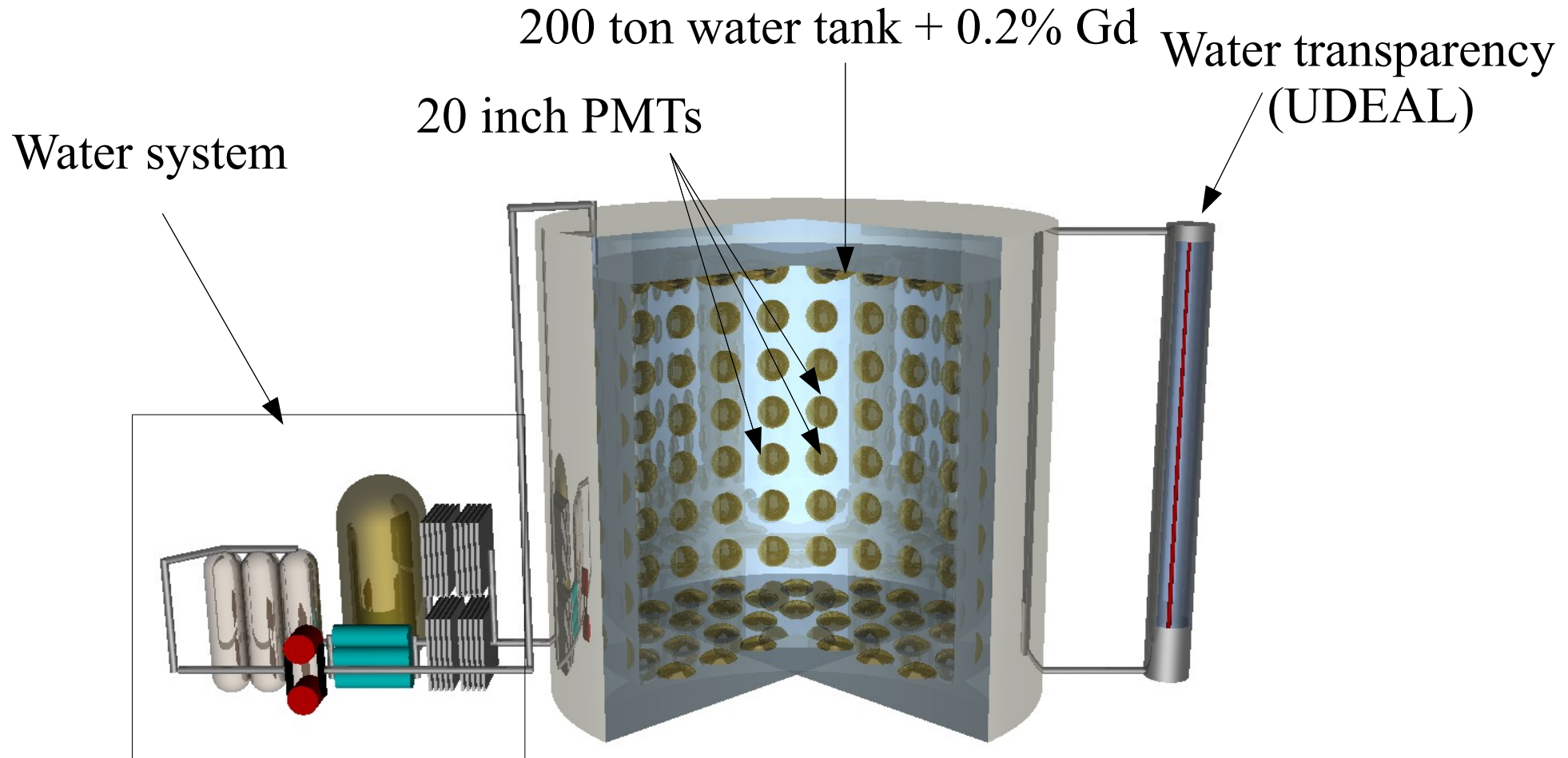


# EGADS



## Evaluating Gadolinium's Action on Detector Systems

Study the effect of Gd on all the materials and the neutron background



**Water Transparency:** as a water Čerenkov detector the water transparency must be large and with no time degradation.

**Water Purification system:** the new purification system should remove all ions except Gd

**How to Add/Remove Gd:** how uniform can be dissolve Gd? How efficient/economical can we remove Gd?

**Material Effects:** the addition of the Gd solution could corrode SK materials

**Neutron Background:** since neutron background is going to be seen, how does this will affect the trigger rates and the current analysis?

➔ No Gd should leak to the environment and therefore the SK tank has to be repaired

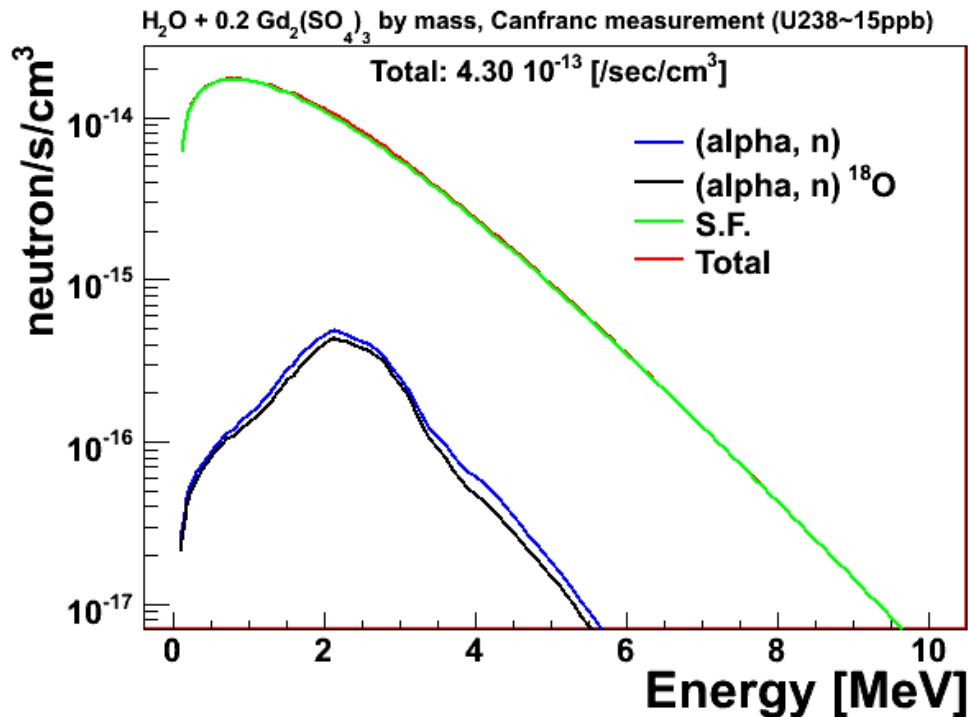
- EGADS will be in operation in summer 2010
- Main results will arrive in 2011

# EGADS: neutron background estimation

Mass considered: 32.5kton (SK ID)

Source	neutron/s·cm <sup>3</sup>	neutron/s
U <sup>238</sup>	$4.284 \cdot 10^{-13}$	0.0139
U <sup>235</sup>	$1.734 \cdot 10^{-13}$	0.0056
Th <sup>232</sup>	$0.213 \cdot 10^{-13}$	0.0007
Total:	$6.231 \cdot 10^{-13}$	0.0202

neutrons/s in the ID



This is ~1750neutrons/day

Largest neutron background is expected to come from the U<sup>238</sup> chain



# Summary

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Analyses with SK-III data are ongoing:

- Solar neutrino results will be summarized by the fall of this year. The goal is to reduce the systematic uncertainties.
- SRN search results will be finalized using SK-I, SK-II and SK-III data this year. The goal is to reduce the event selection inefficiency and therefore increase the sensitivity.

SK-IV runs with the lowest energy threshold in its history.

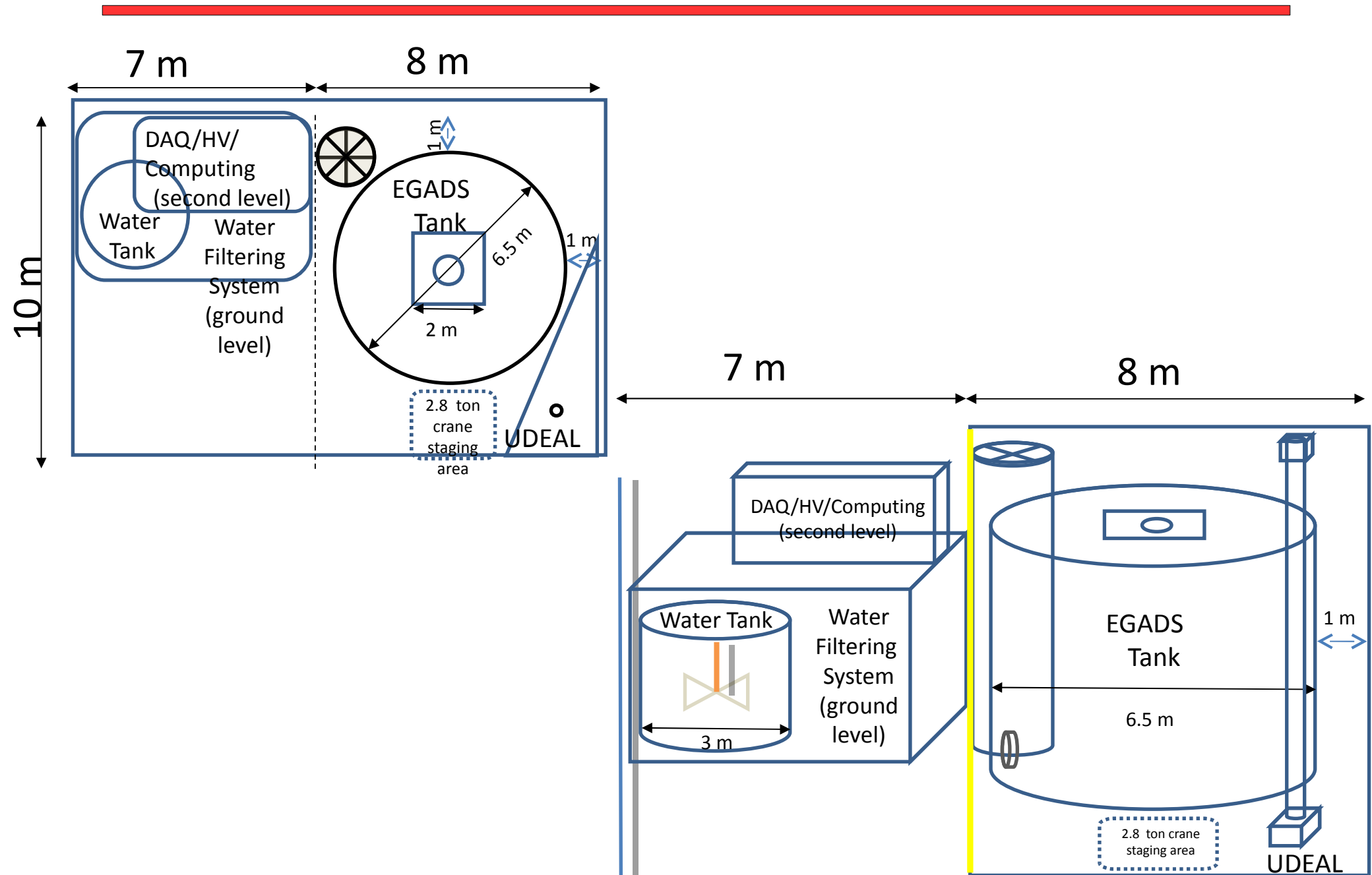
- Now, with 100% efficiency @  $E_{\text{total}} \leq 4.5$  MeV
- Current target is  $E_{\text{total}} \leq 4.0$  MeV

The **Gadzooks!** R&D project is entering into a crucial phase!

- A 200 ton test tank is going to be the test field: [its budget was approved!](#)

Thank you for your attention!!

# EGADS

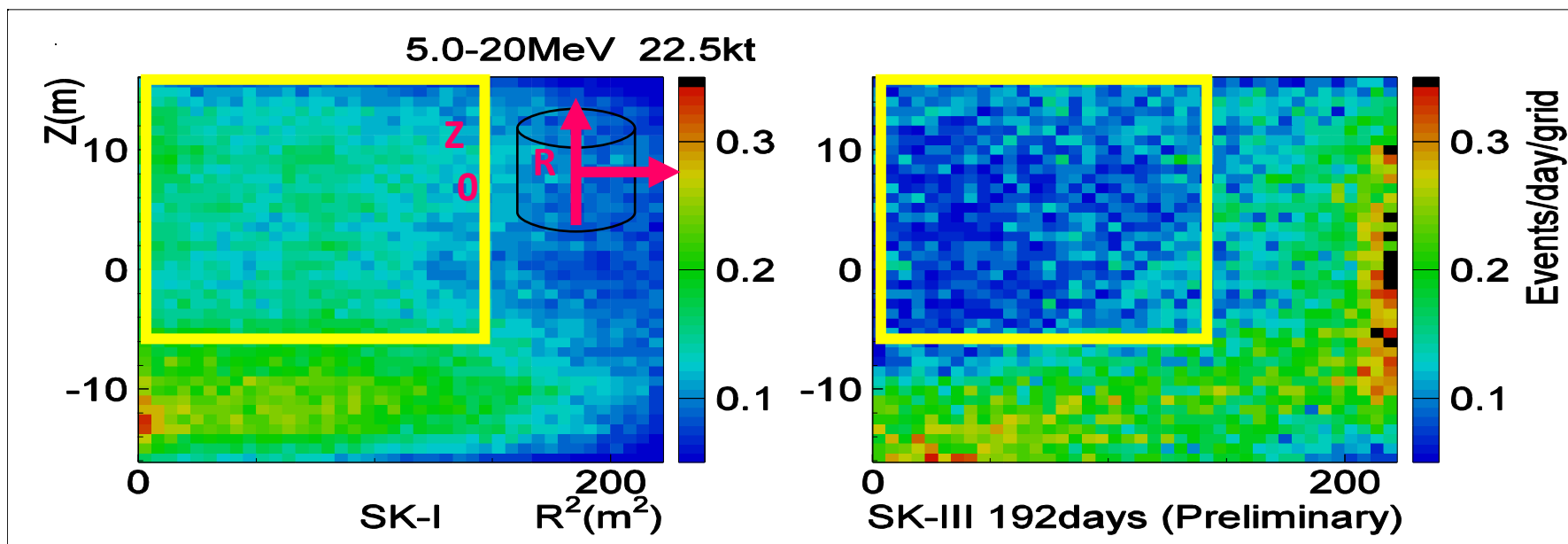
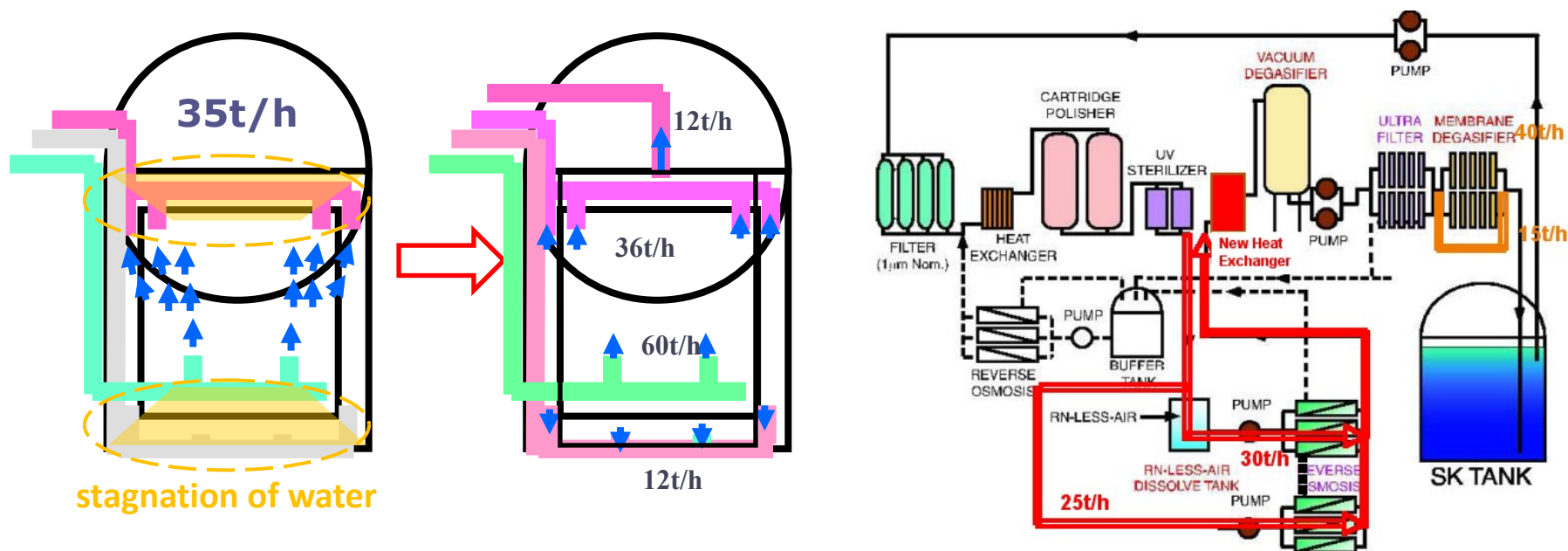


# Current systematic uncertainty estimation

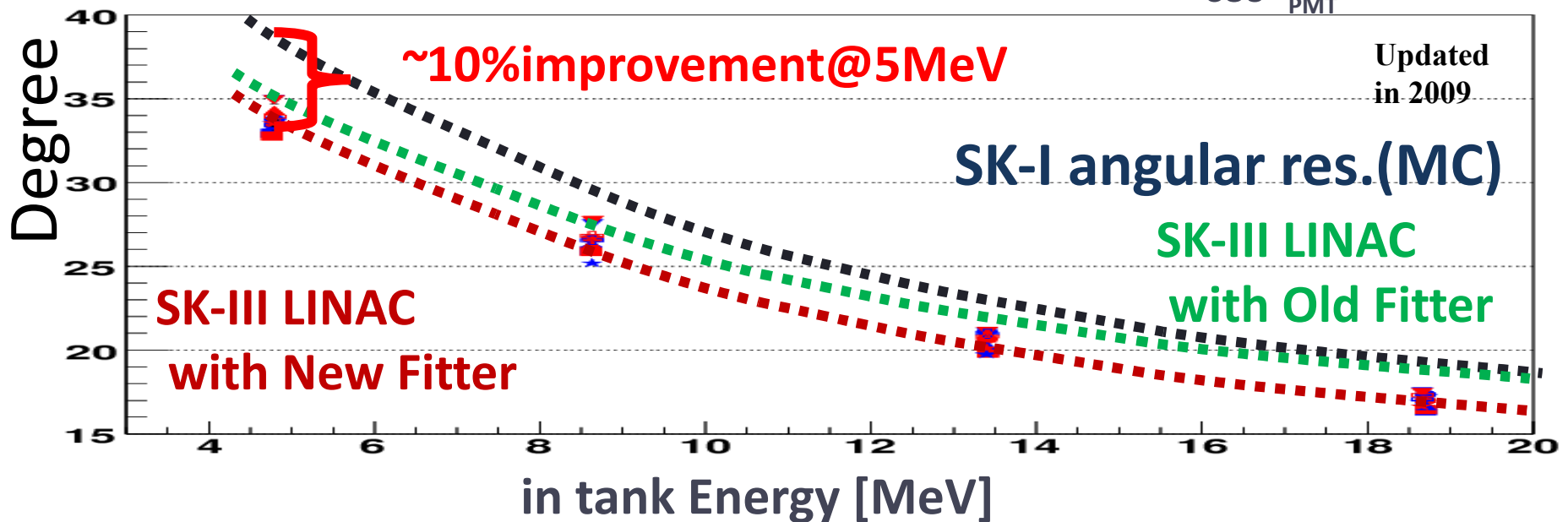
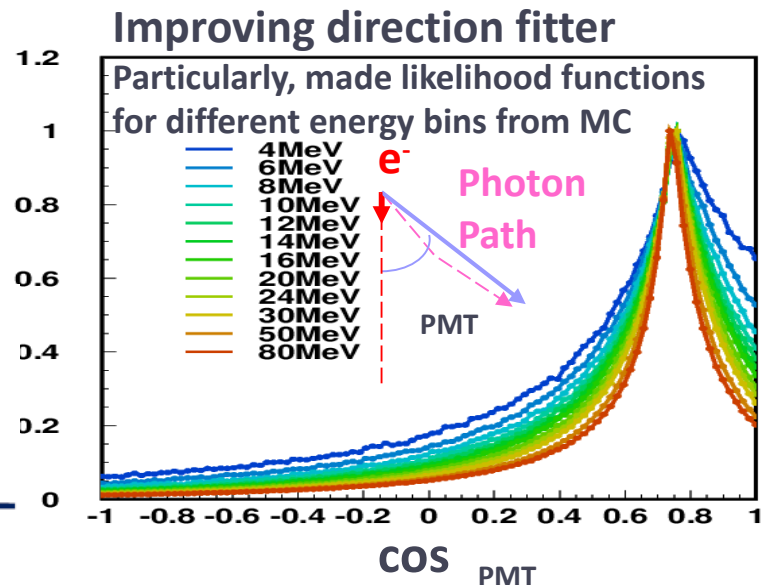
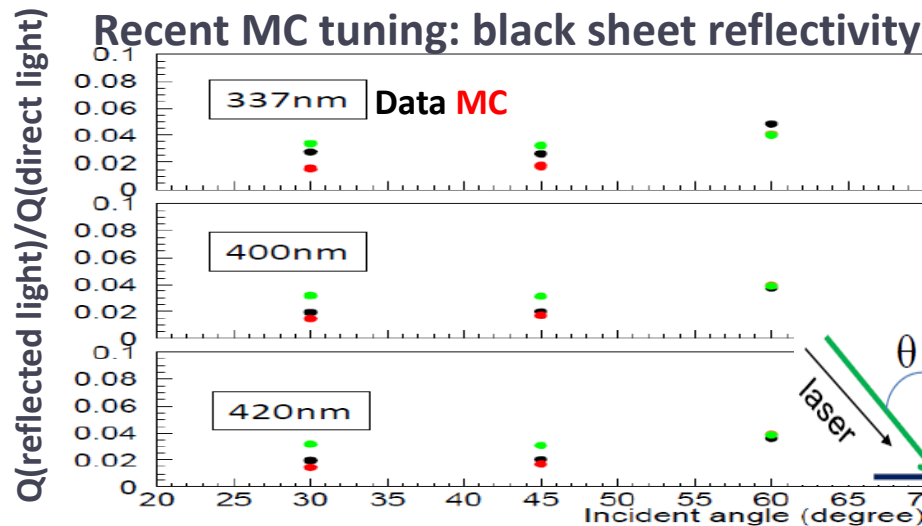
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	SK-I Flux(%)	SK-III Flux(%) (underway)
Energy Scale	$\pm 1.6$	Can be smaller (?)
Trigger efficiency	+0.4 -0.3	
Spallation cut	$\pm 0.2$	
Reduction	+2.0 -1.6	Trying to reduce
Gamma cut	$\pm 0.5$	Trying to reduce
Vertex shift	$\pm 1.3$	Can be smaller
Angular resol.	$\pm 1.2$	Can be smaller
BG shape	$\pm 0.1$	
Livetime calculation	$\pm 0.1$	
<b>Total</b>	<b>+3.5 -3.2</b>	

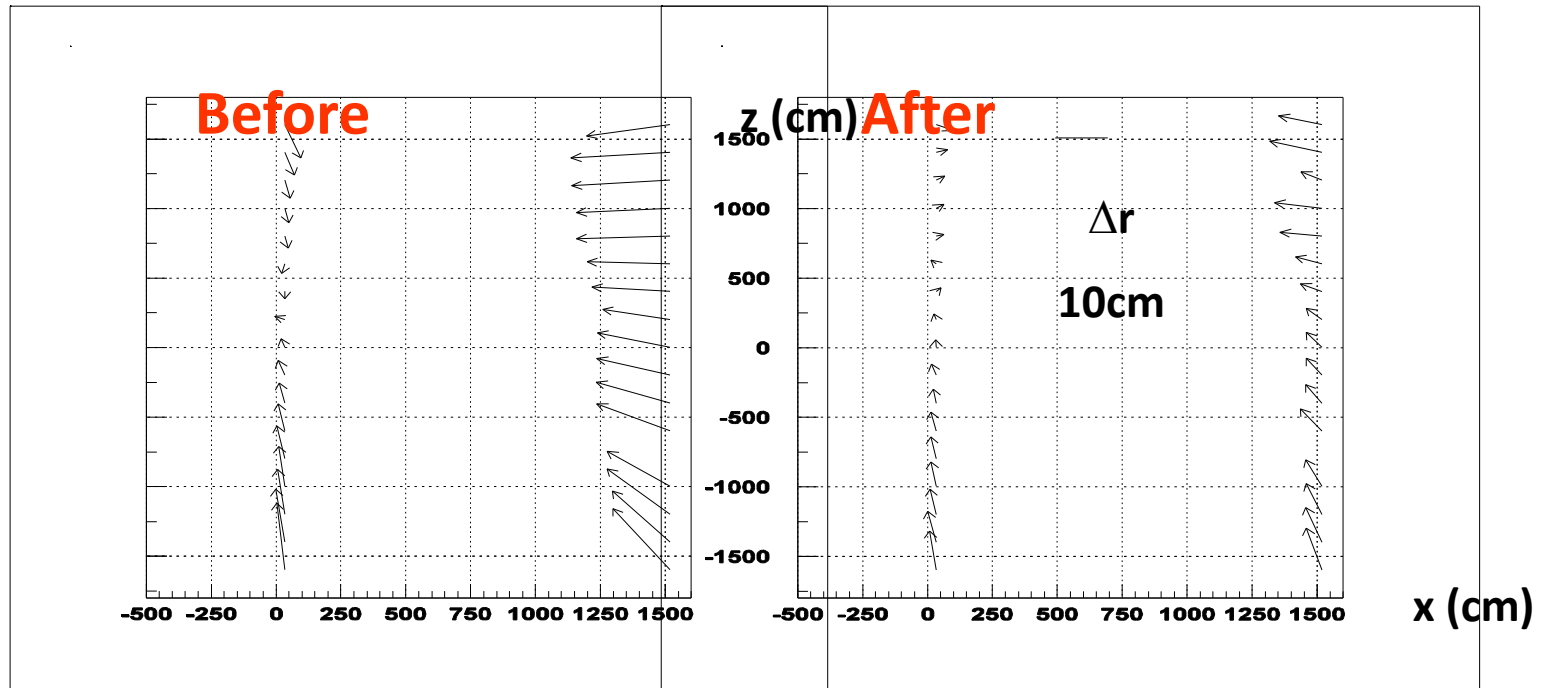
# Water system



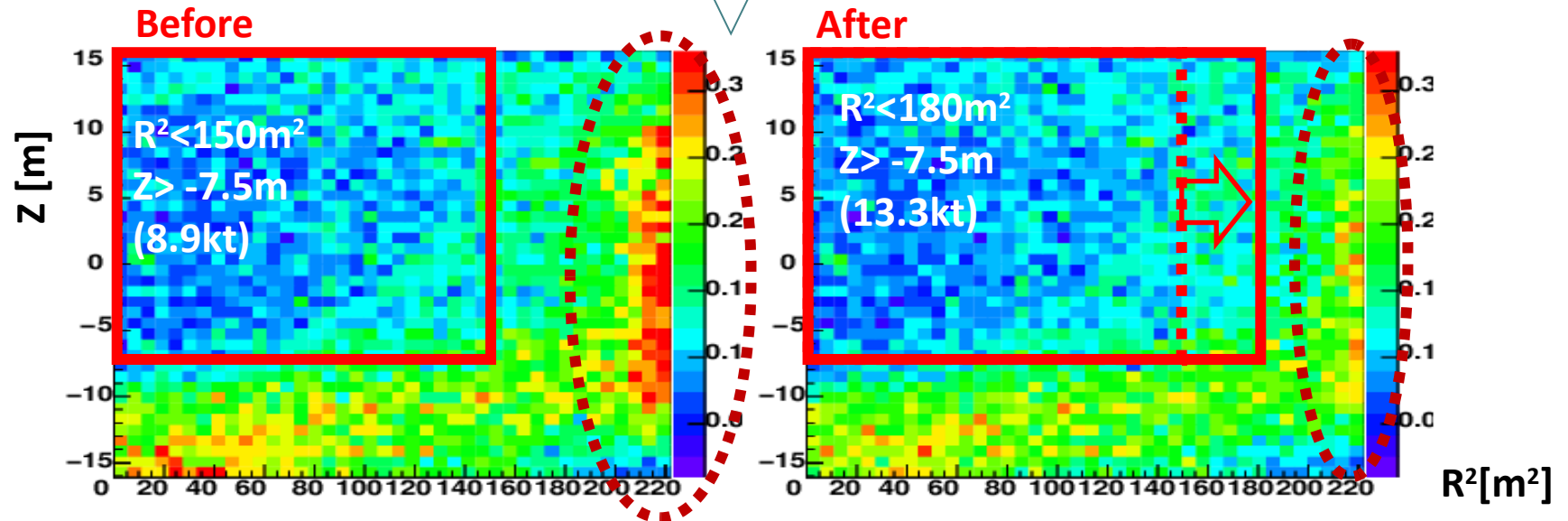
# Better angular resolution



# Shift Vertex Correction



R31851-33899(192days) 5-20 MeV



# Old Spallation selection

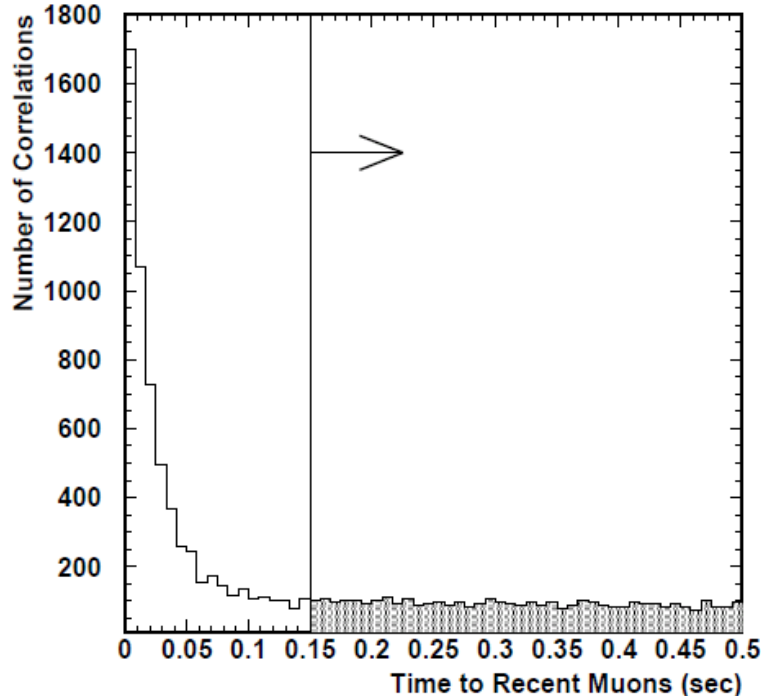
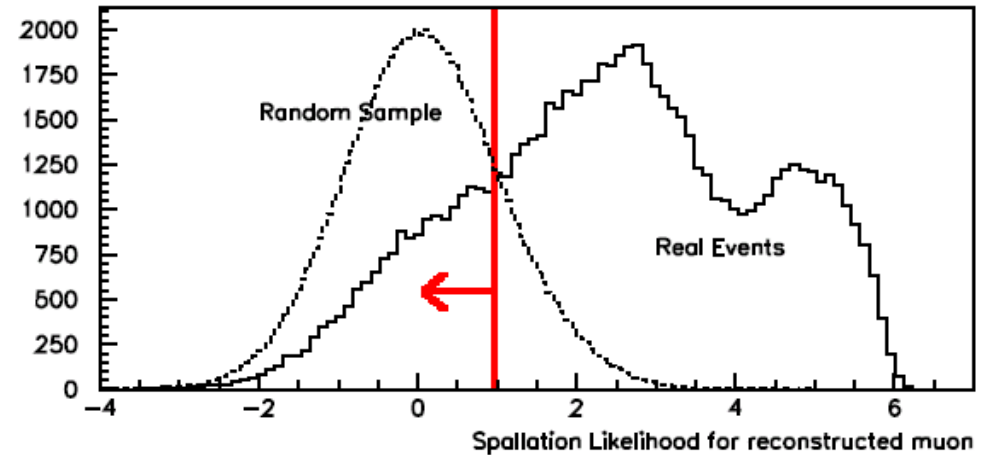
## Spallation likelihood (spalike)

$$L = L(dt) L(dl) L(\text{res}Q)$$

dt: time difference from preceding muons.

dl: distance from preceding muon track.

resQ: muon measured pulse height minus pulse height expected from track length.



$dt > 0.15 \text{ sec}$  cut is also applied.  
Basically all the spallation BG is removed.

**Total inefficiency 36%**



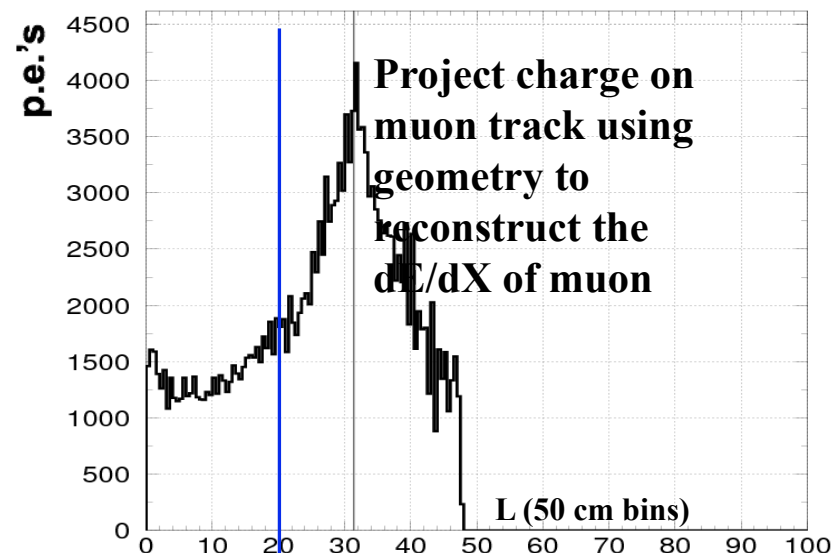
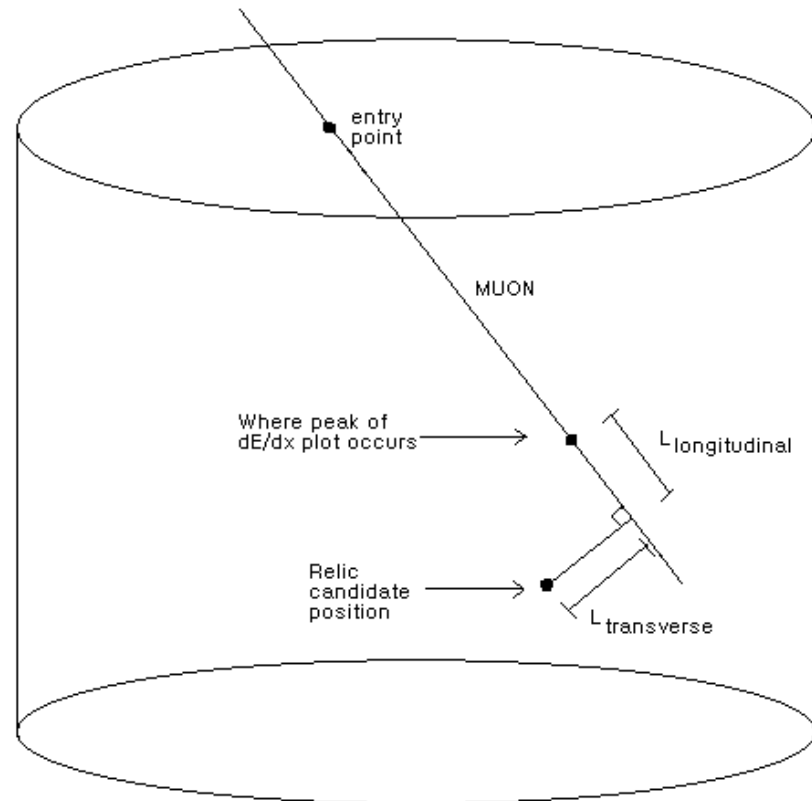
## New Spallation Cut

- ▶ 4 variable likelihood cut
- ▶ 4 variables:
  - ▶  $dt$
  - ▶  $dl_{\text{transverse}}$
  - ▶  $dl_{\text{longitudinal}}$
  - ▶  $Q_{\text{peak}}$
- ▶ We apply cut up to 24 MeV
- ▶ Improvements allow lowering the energy threshold

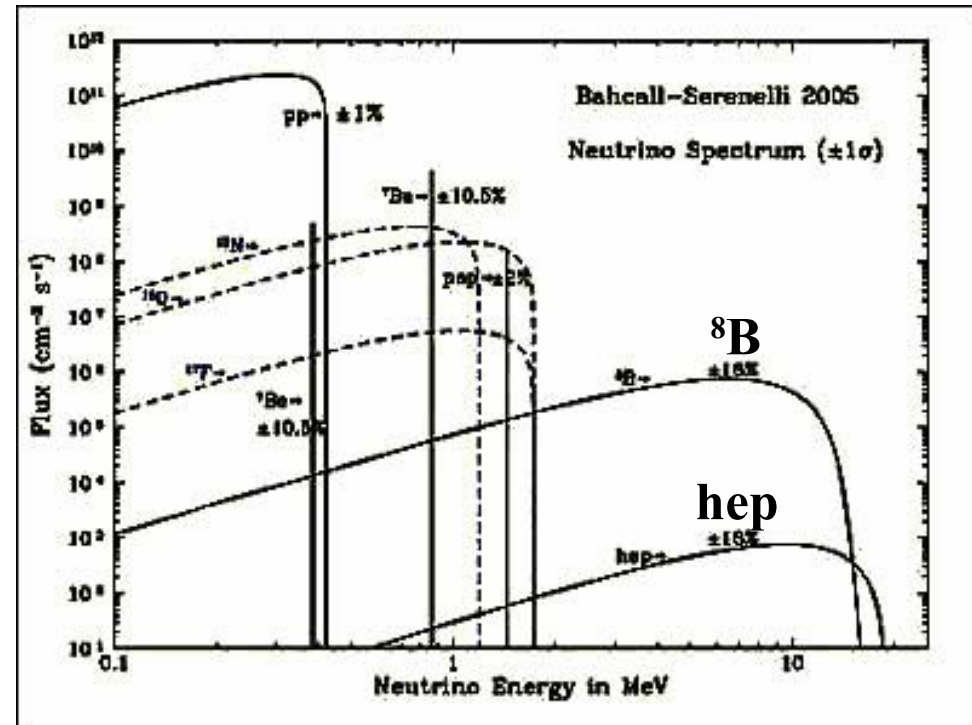
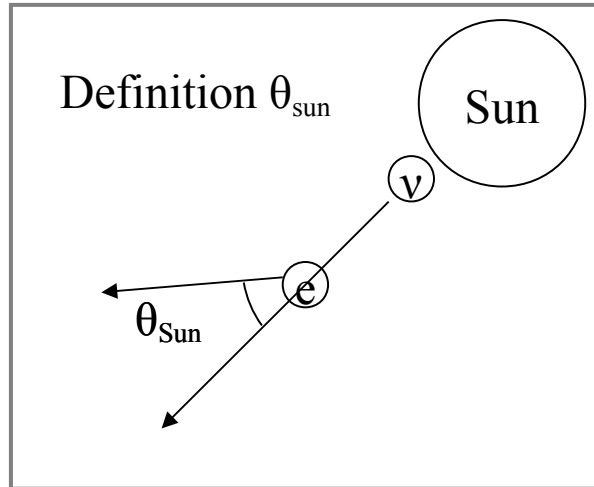
### Inefficiency

**22.5% for 16-18MeV**  
**18.5% for 18-24MeV**  
**(36% for 18-34MeV in OLD)**

*Improved!!*

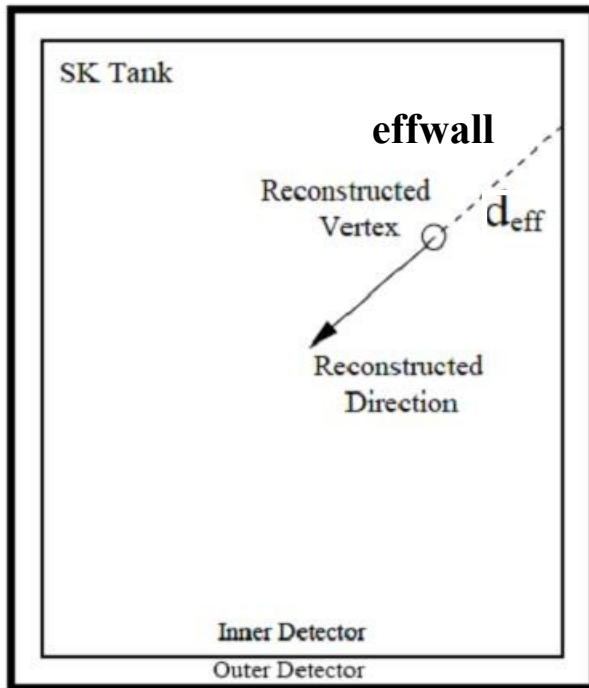


# New Solar neutrino cut



- Solar B8 and hep neutrino can be BG of SRN search due to energy resolution.
- Angle between solar direction and reconstructed direction ( $\theta_{\text{sun}}$ ) is used to separate SRN and Solar  $\nu$
- Cut criteria is optimized using B8/hep MC

# Effective wall selection



Some **ray events** originating from outside of fiducial volume have possibility of **being reconstructed within fiducial volume of SK**.

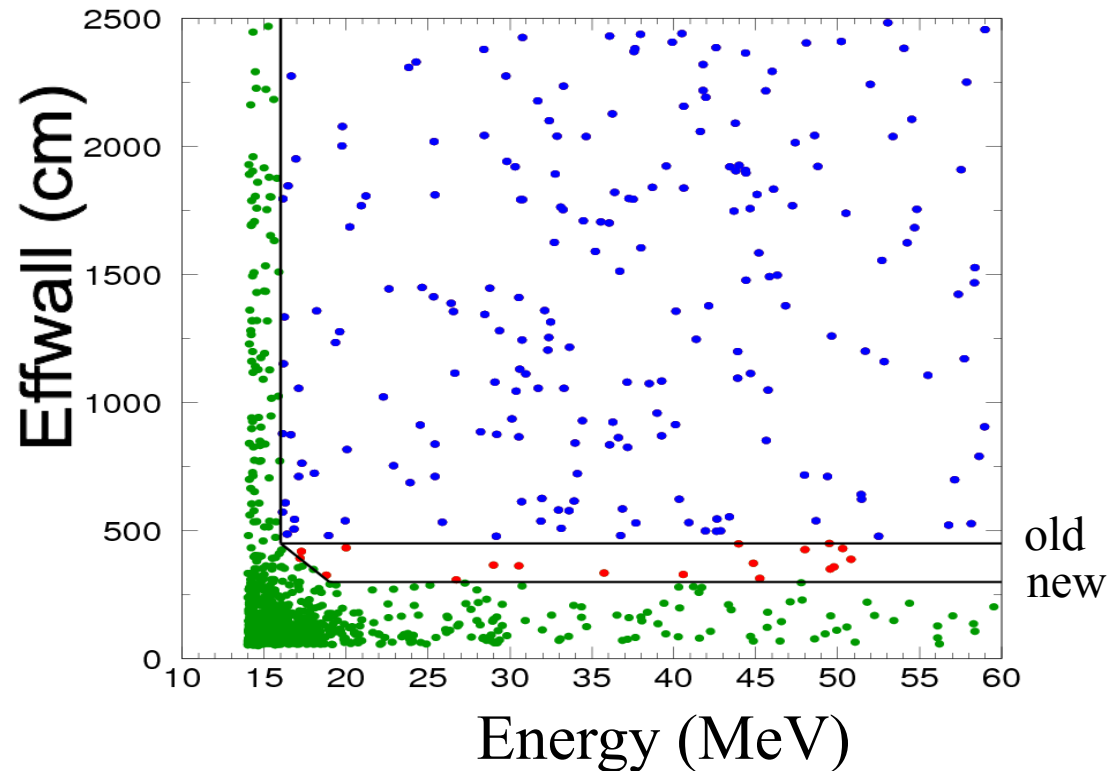
In order to remove these events, an effwall cut is applied which uses the travel distance from tank wall.

The new criteria depends on the energy

## Inefficiency for signal

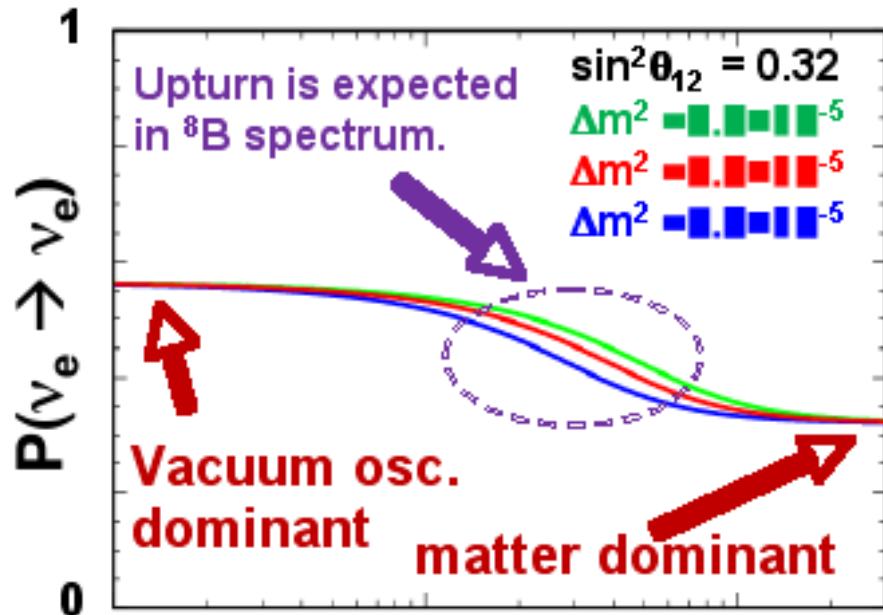
Old: 7%      18-34MeV

New: 2.5%      *Improved!!*

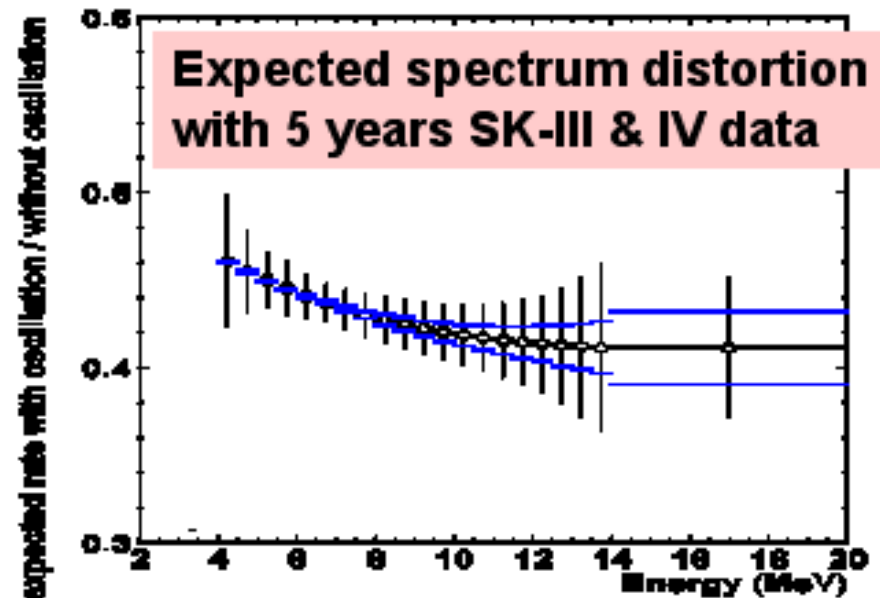
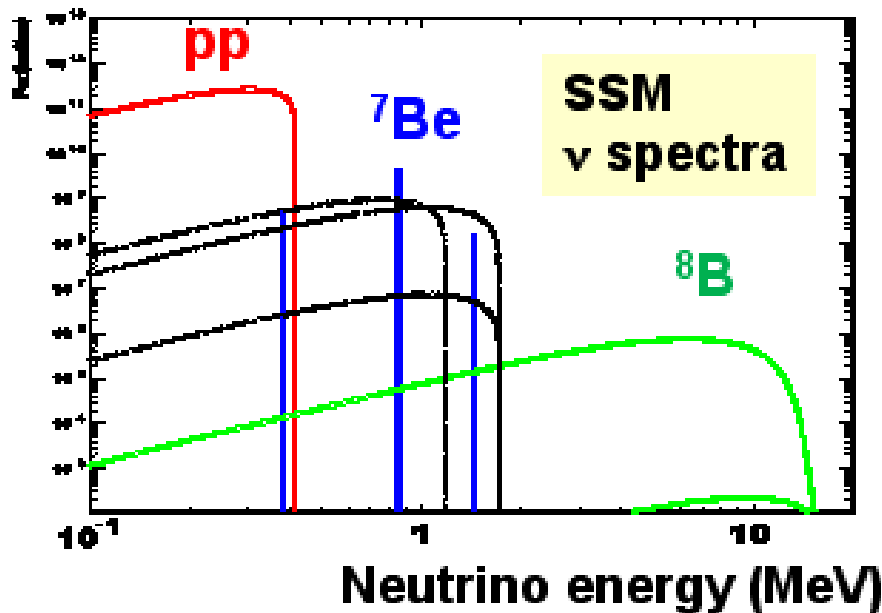
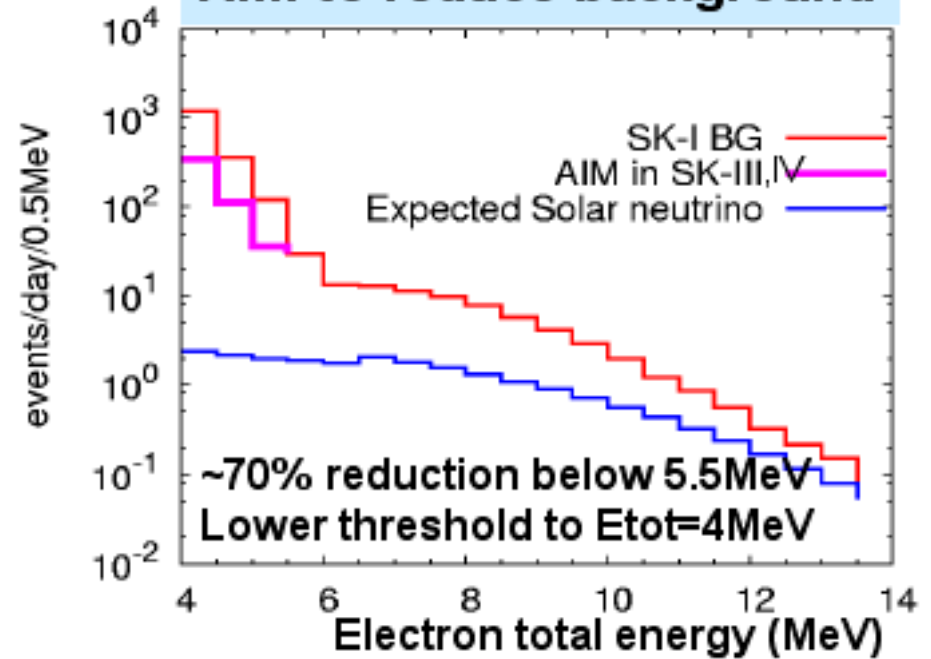


# Solar Neutrino Prospects

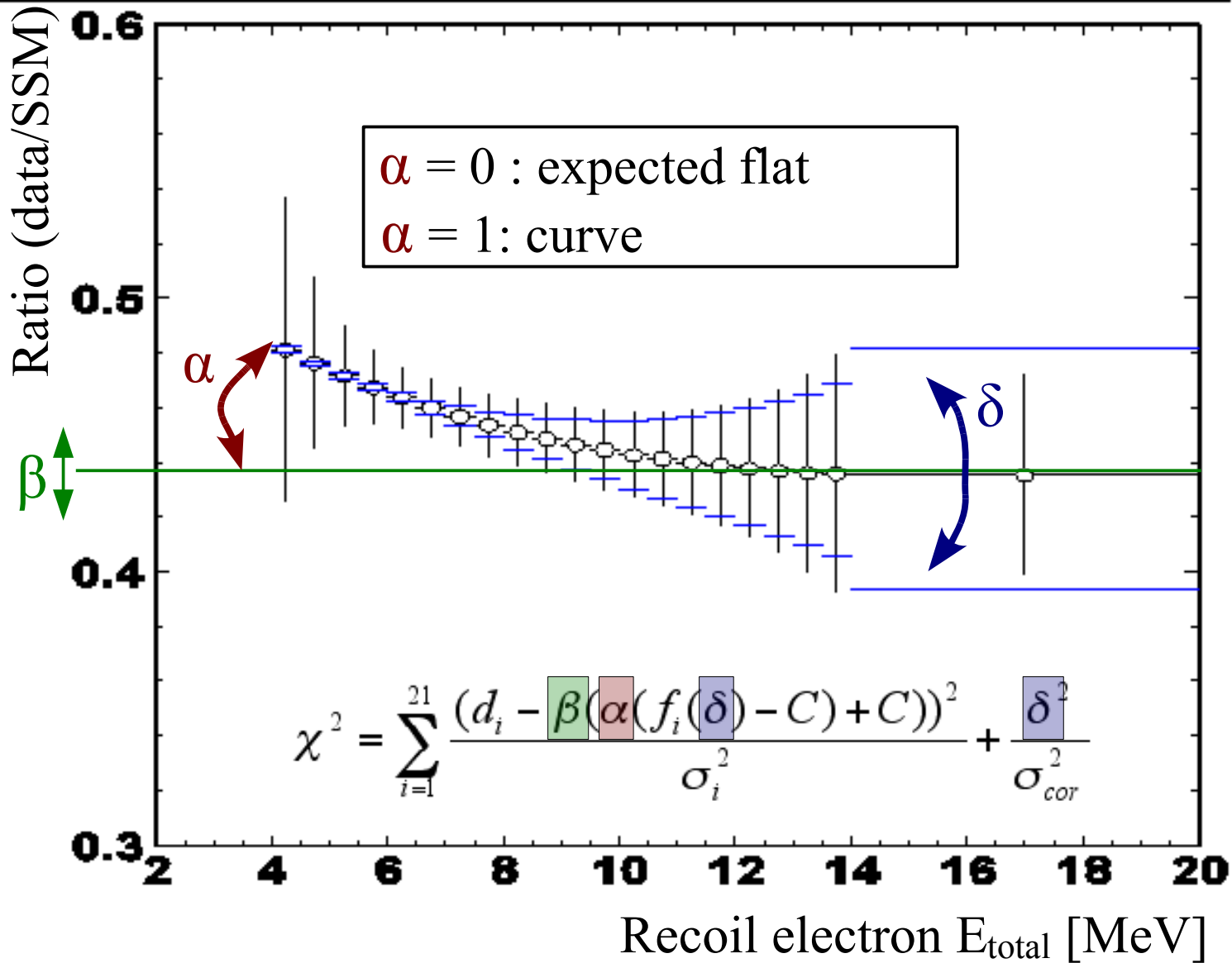
## $\nu_e$ survival probability



## Aim to reduce background

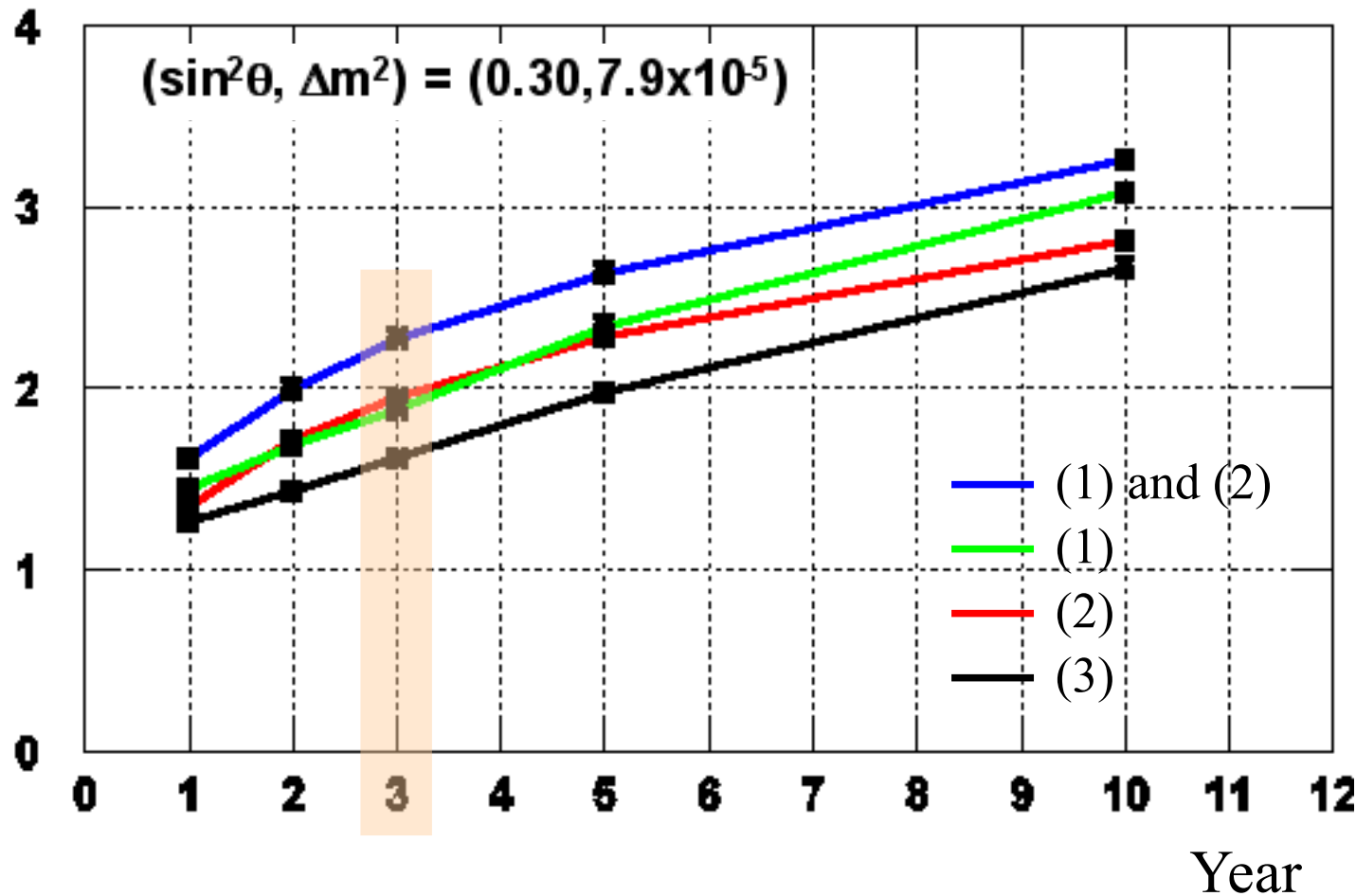


# Upturn Sensitivity Estimation



# Upturn Sensitivity

Sigma level for up-turn



■ First target: 2 sigma level up-term discovery after 3 years observation (or its exclusion)

■ Enlarge fiducial volume and while keeping control of BG

■ Reduction of the energy correlated systematic uncertainty

(1) Enlarge fiducial volume to 22.5kton (low BG)

(2) Half energy correlated systematics as SK-I

(3) 13.3 kton  $E < 5.5$  MeV and 22.5 kton  $E > 5.5$  MeV and same energy correlated uncertainty as SK-I