The 52nd Rencontres de Moriond
ELECTROWEAK INTERACTIONS
AND UNIFIED THEORIES
La Thuile, March 24, 2017

Searches for Sterile neutrinos at very short baselines reactor experiments

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(NRNU MEPhI and LPI, Moscow)

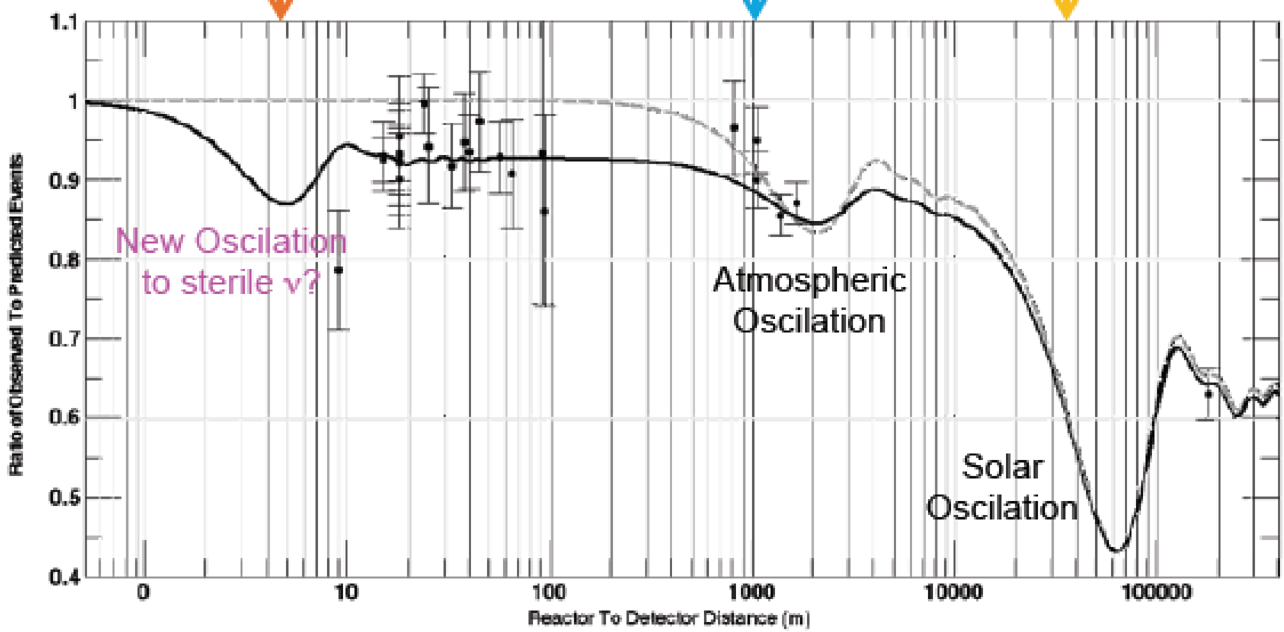
There are several ~3σ indications of 4^{th} neutrino

LSND, MiniBoone: $\bar{\nu}_e$ appearance
SAGE and GALEX ν_e deficit
Reactor $\bar{\nu}_e$ deficit

→

Indication of a sterile neutrino
$\Delta m^2 \sim 1\ eV^2$
$Sin^2 2\theta_{14} \sim 0.1$ (wait for C.Giunti talk)
=> Short range neutrino oscillations

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\Theta_{14} \sin^2(1.27\Delta m^2_{41} \frac{L}{E}) - c^4_{14} \sin^2 2\Theta_{13} \sin^2(1.27\Delta m^2_{31} \frac{L}{E}) - c^4_{14} c^4_{13} \sin^2 2\Theta_{12} \sin^2(1.27\Delta m^2_{21} \frac{L}{E})$$



G. Mention et al. Phys Rev D 83 073006 (2011)

Reactor models do not describe well neutrino spectrum

Measurements at one distance are not sufficient!

Many reactor experiments plan to search for sterile neutrino
(only 2 in this talk. Aurelie Bonhomme will present Stereo at YSF4)

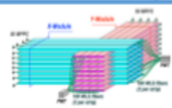
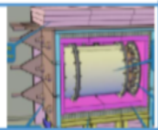
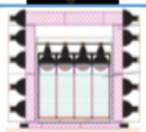
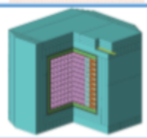
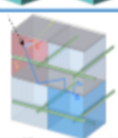
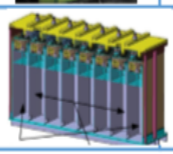
Experiment	Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia) 	3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea) 	2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA) 	40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia) 	100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA) 	85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France) 	57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD

Table from N.Bowden at Neutrino 2016

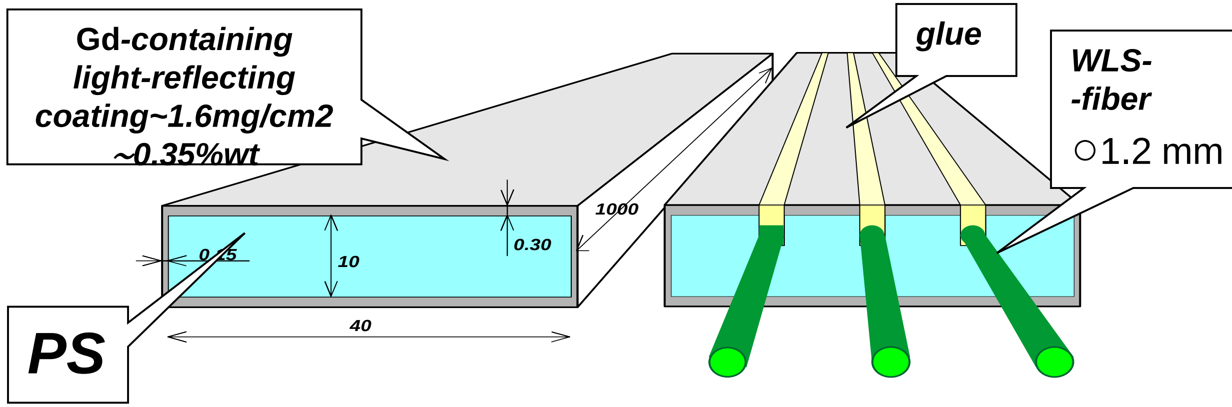
DANSS (JINR, Dubna & ITEP, Moscow)

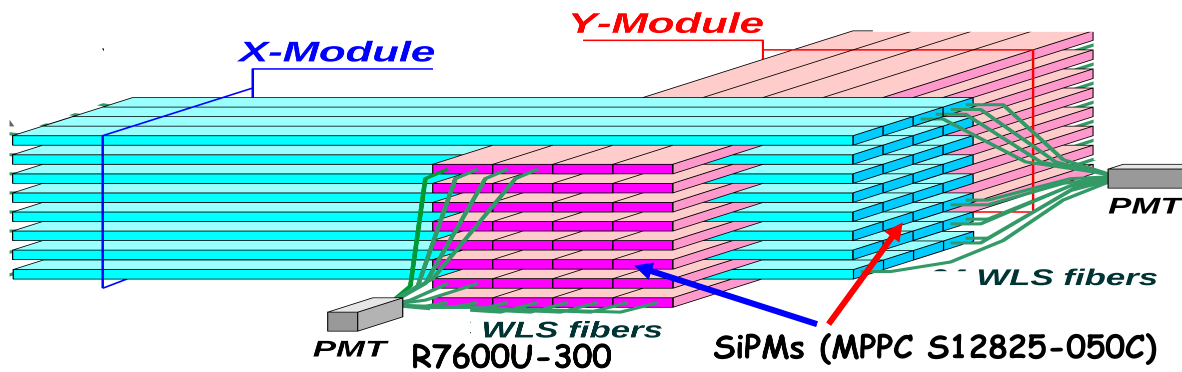
Design

Each scintillator strip is read out individually by a Silicon Photo Multiplier (SiPM) via a WLS fiber.

Sensitivity is ~18 p.e./MeV

Light attenuation ~20%/m (corrected in analysis!)

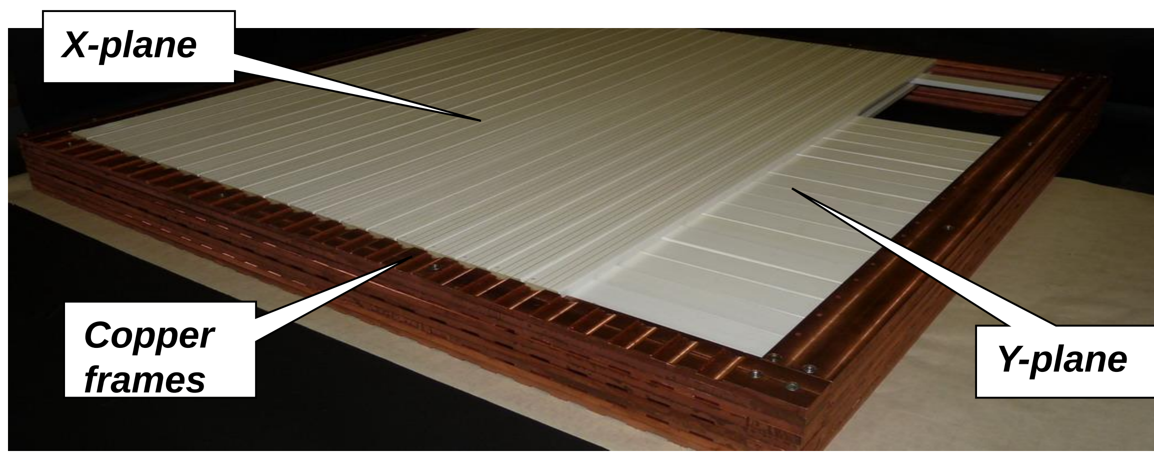




- 50 strips are combined into a Module which is also read out by a small PMT (via 2 additional WLS fibers per strip).

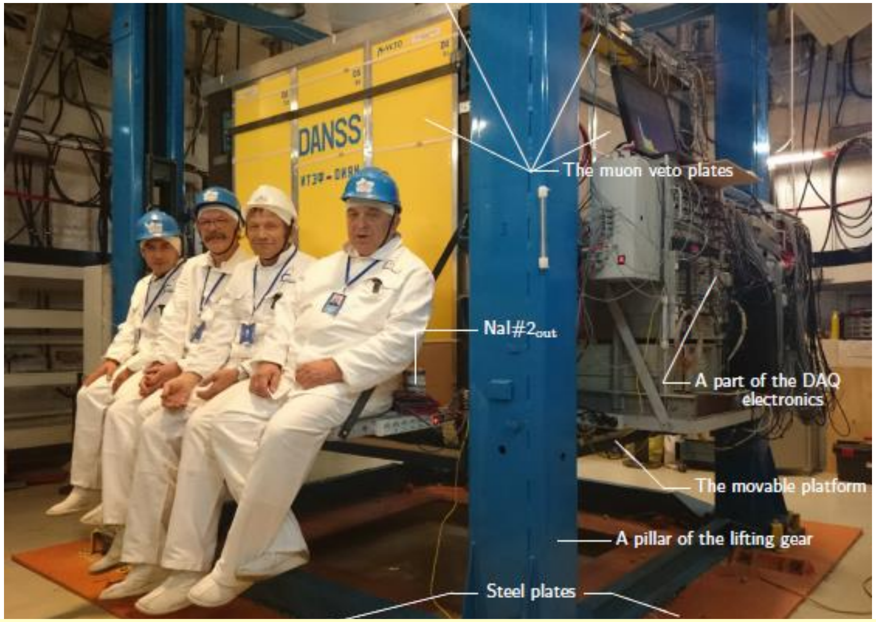
Sensitivity is ~20 p.e./MeV

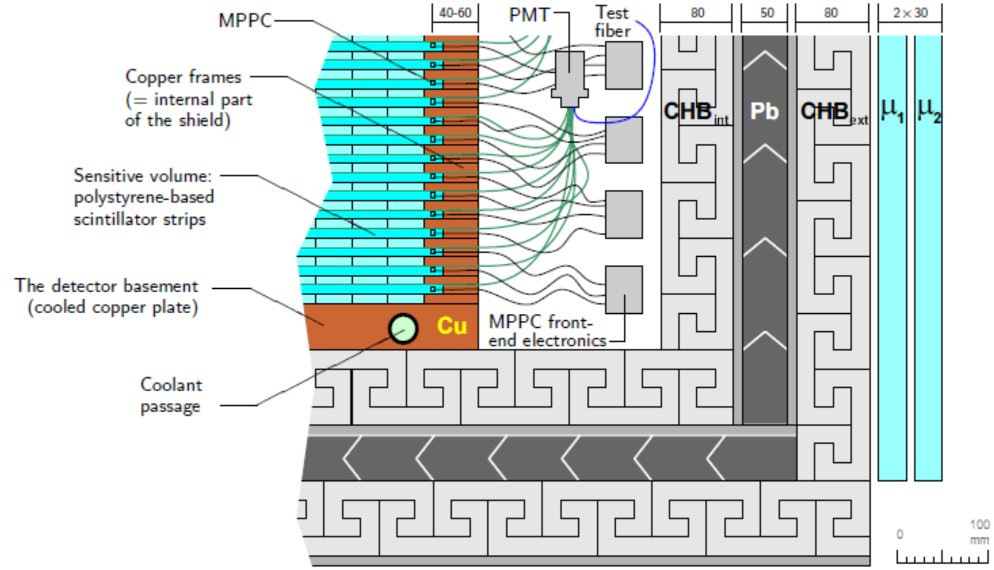
- **The frame of a Module** is made of radio-pure electrolytic copper and thus **shields the sensitive part** against insufficiently pure components of front-end electronics placed outside the frame.



View of a Module (under construction).

DANSS at Kalinin Nuclear Power Plant





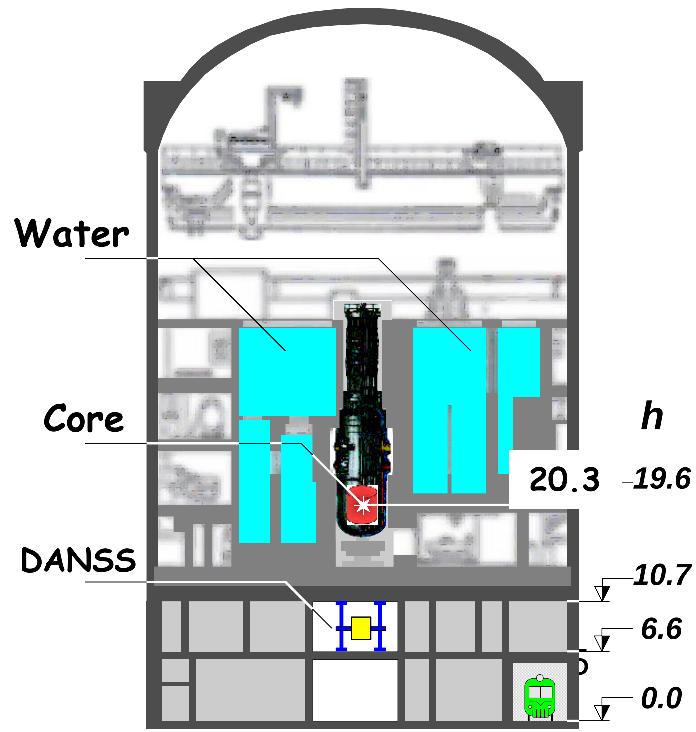
DANSS is installed on a movable platform under 3GW WWER-1000 reactor (Core:h=3.5m, ∅=3.1m) at Kalinin NPP. ~50 mwe shielding => μ flux reduction ~6! No cosmic neutrons!

Detector distance from reactor core 10.7-12.7m (center to center)

Fuel contribution at beginning and middle of campaign

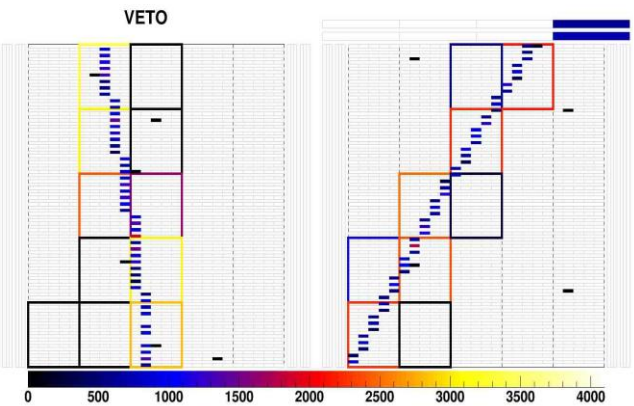
	beginning	middle
235U	69%	58%
239Pu	21%	30%
238U	7%	7%
241Pu	3%	5%

Trigger: ΣEpmt>0.7MeV => Read 2600 wave forms (125MHz), look for correlated pairs offline.

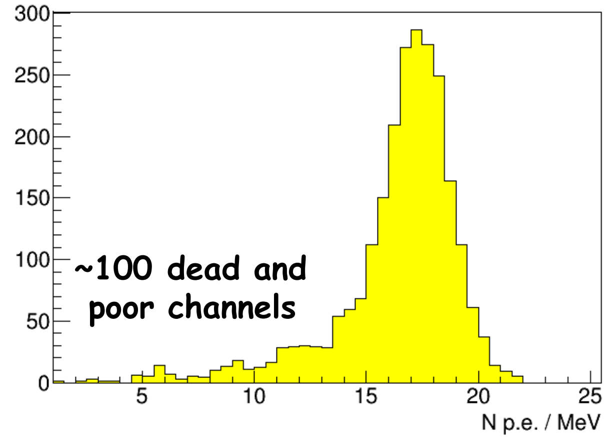


Calibration

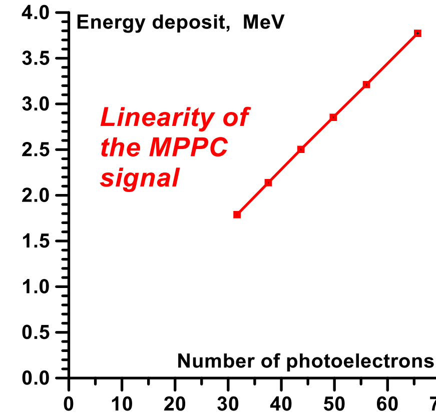
With cosmic muons



Uniformity of SiPM response before calibration

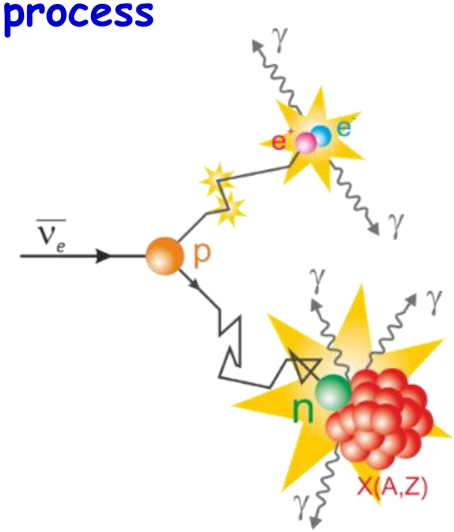


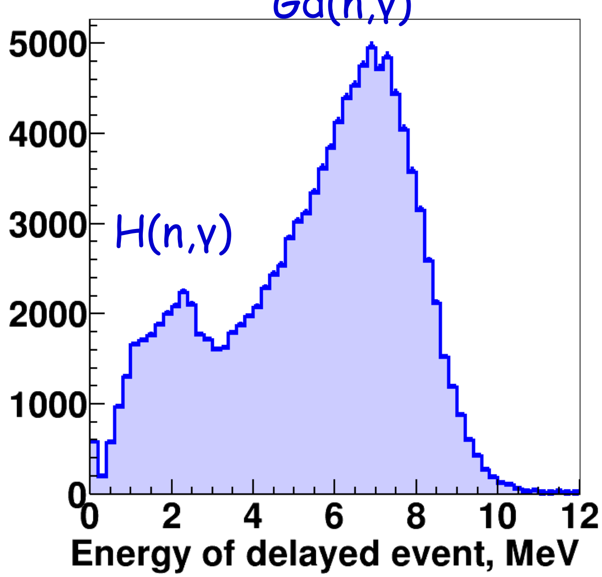
Response is linear with energy



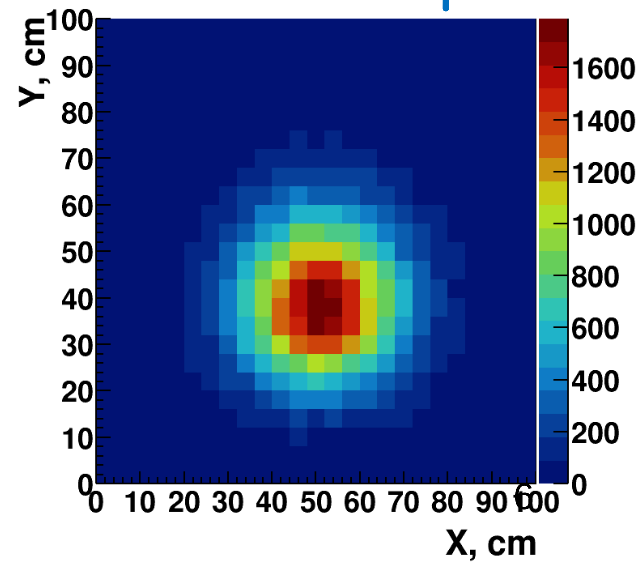
With radioactive sources. 248Cm n source is similar to IBD process

Inverse Beta Decay (IBD) process

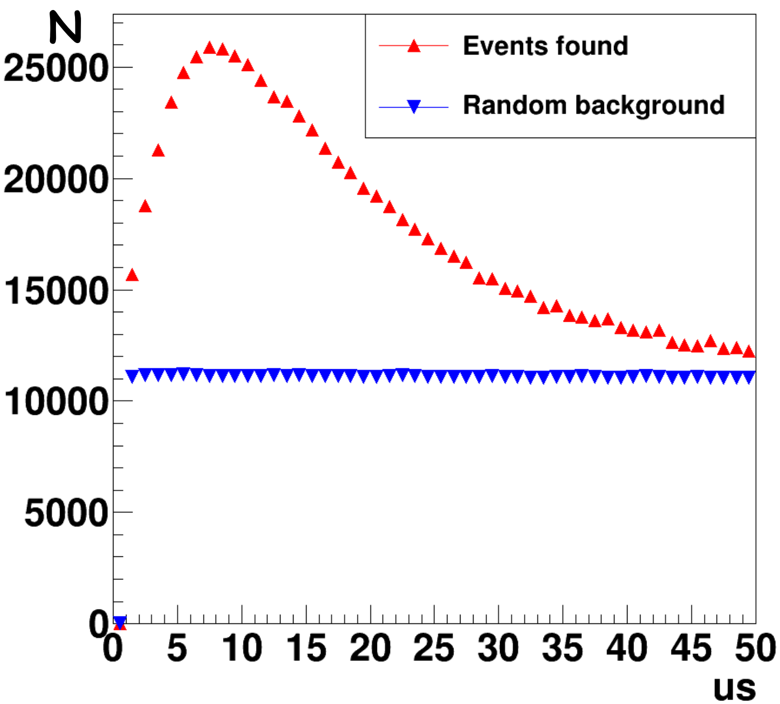




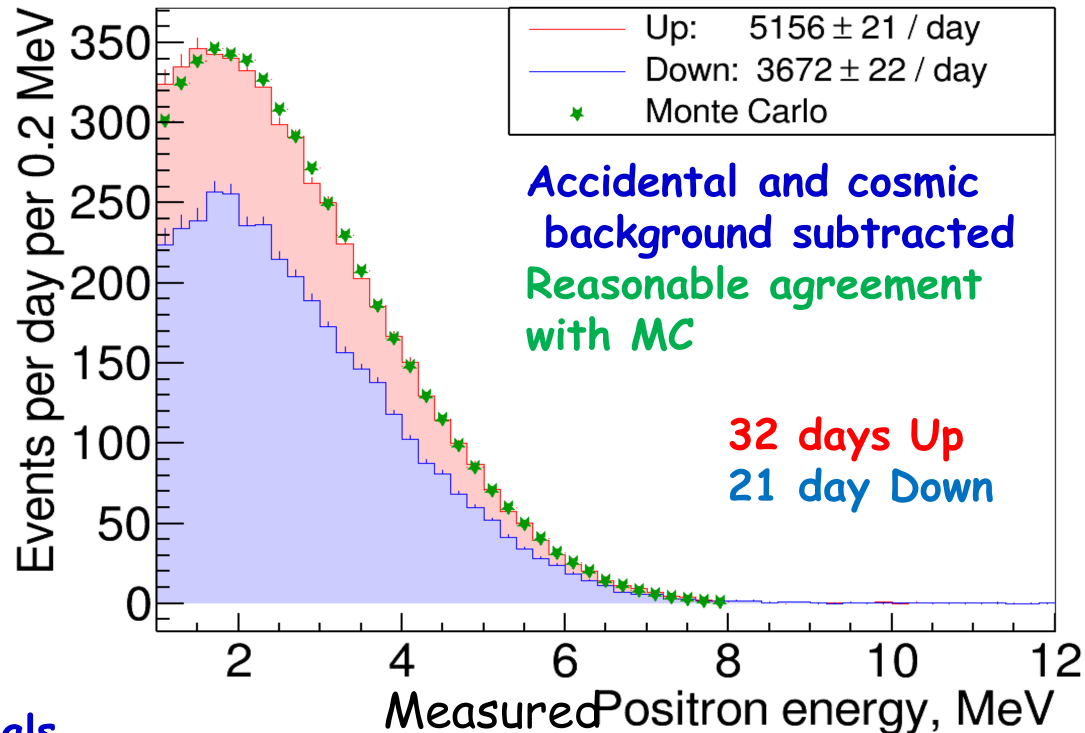
Reconstructed n position



Selection: Ee+>1MeV, En>3MeV, 2μs<ΔT<50μs, no cosmic Veto, e+ not in outer 4cm, no additional signals, periods with 100% reactor power, middle detector position not yet used. **Cuts not yet optimized**

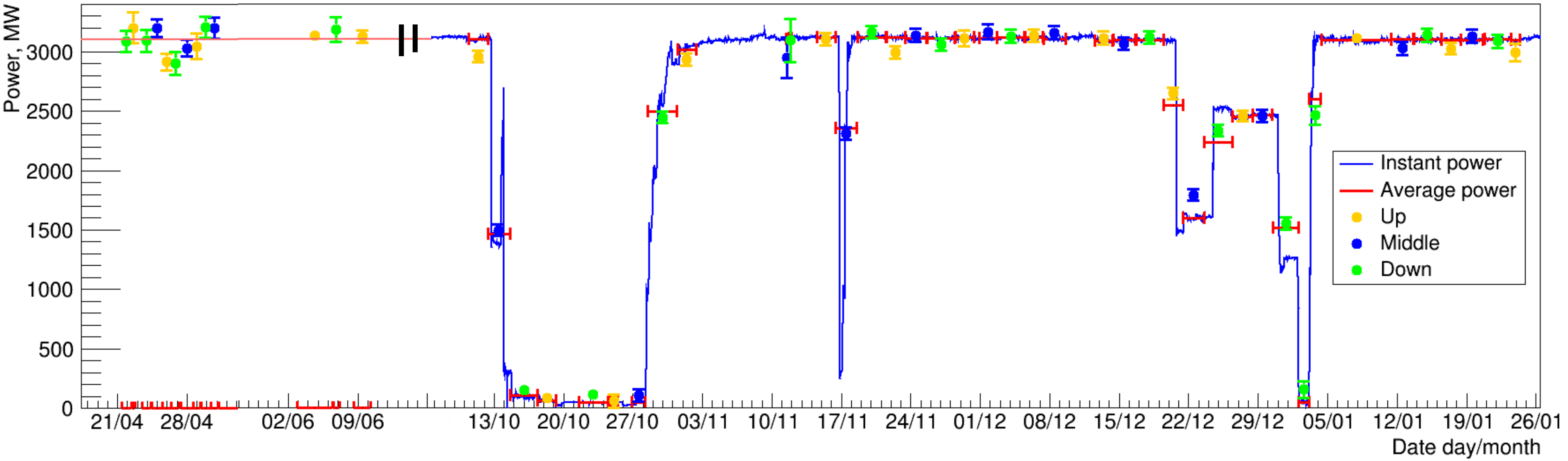


Time between prompt and delayed signals

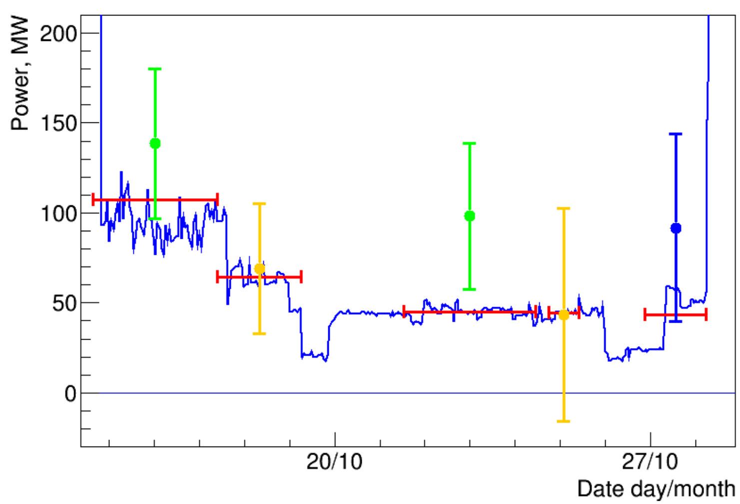


- Accidental background is comparable to signal but subtracted **exactly**
- Only ~25% of accidental background is caused by reactor
- Half of accidental background is below Ee+<2MeV
- Cosmic background is estimated from events with μ in detector and no VETO signal and from reactor off data. **It is only 2.5% in Up position.**
- About 5000 neutrino events/day is detected in fiducial volume of 78%

$\bar{\nu}$ rate ~ reactor power and stable during 9 months
(points at different detector positions are scaled as $1/R^2$)

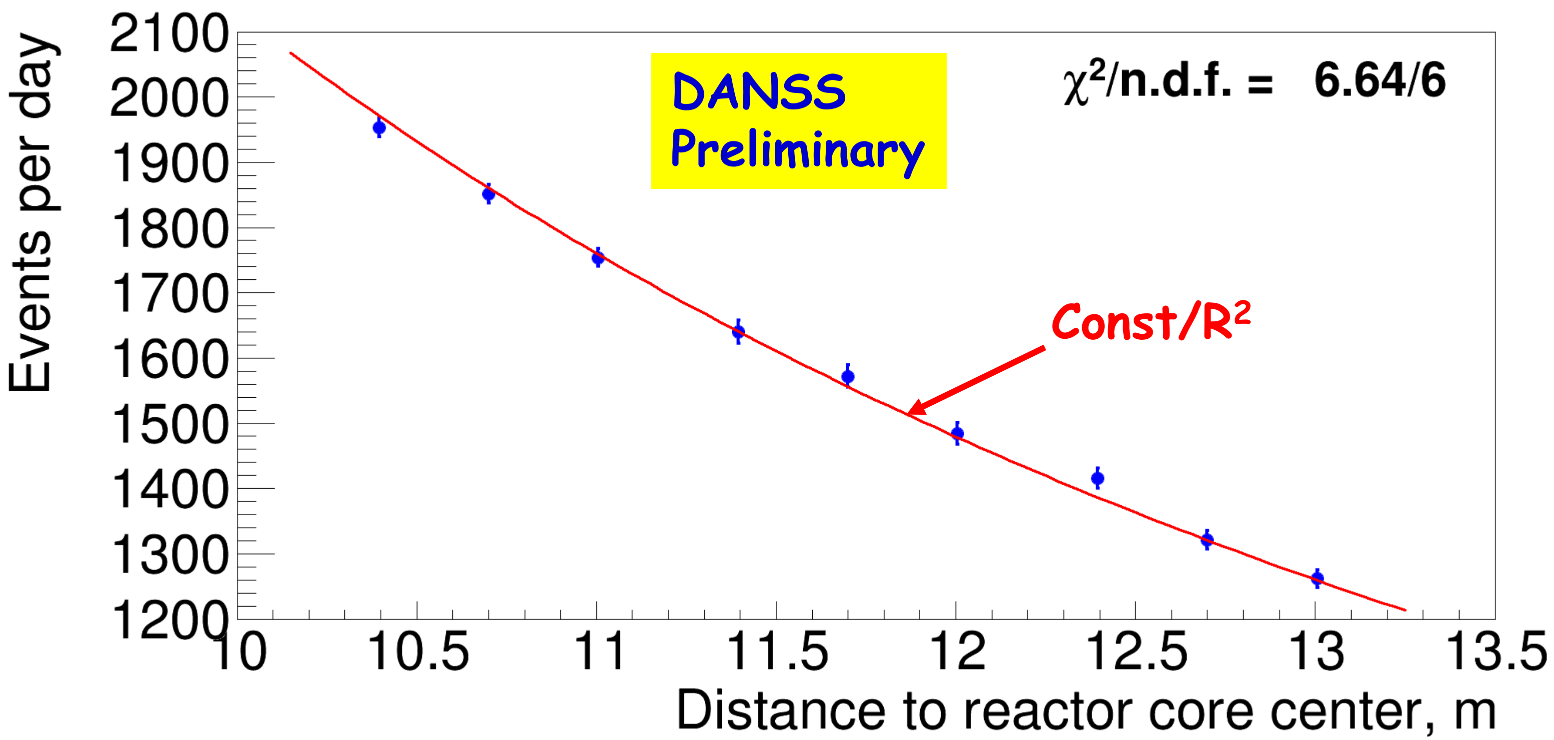


Small excess (0.88+-0.63)% at small power is consistent with overestimation of cosmic veto efficiency and was used to correct it



$\bar{\nu}$ counting rate dependence on distance from reactor core

Detector was split into 3 sections along z (~30cm each)
Each section has 3 positions – up, middle, down
Normalization (efficiency) for central section is a fit parameter
Differences in efficiency of central and 2 other sections are also fit parameters



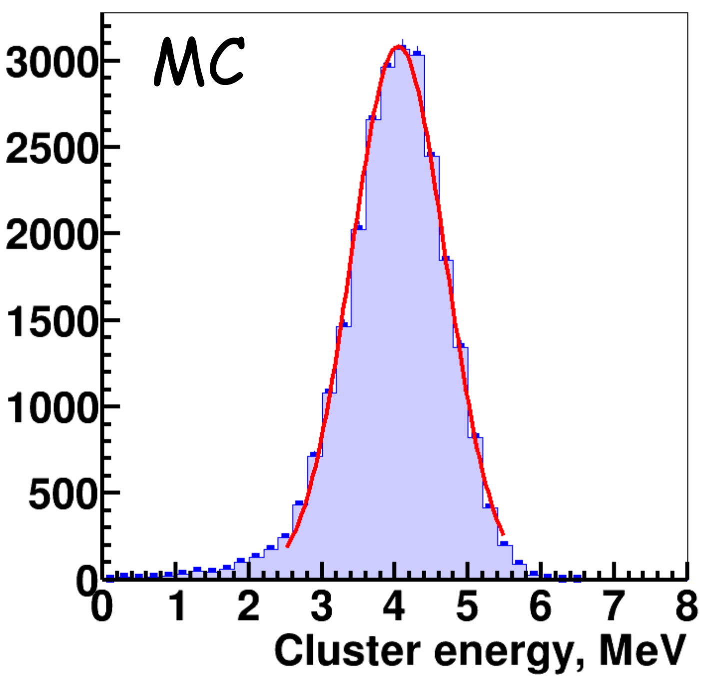
Perfect agreement with 1/R² dependence

Data Analysis

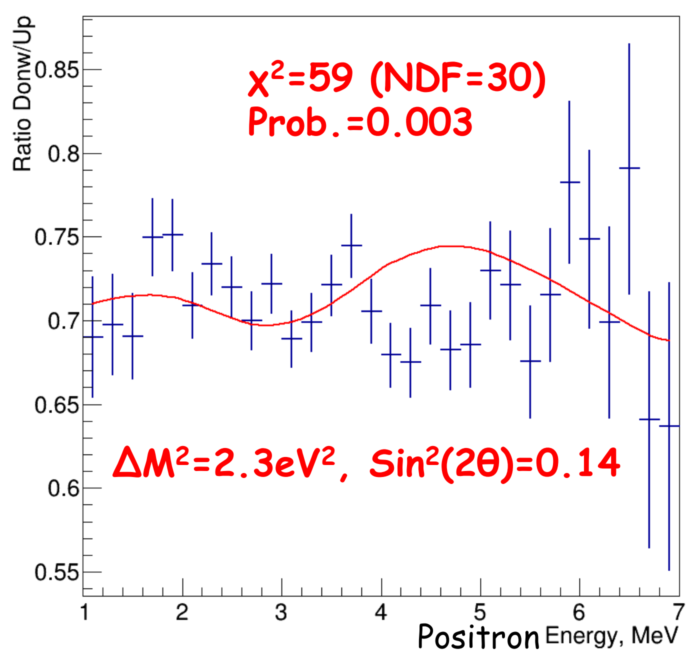
For every ΔM^2 and $Sin^2(2\theta)$ e^+ spectrum was calculated for Up and Down detector positions taking into account reactor core size and detector energy response including tails (obtained from cosmics calibration and GEANT-4 MC simulation identical to data analysis)

Reactor burning profile was provided by NPP
Theoretical neutrino spectrum was taken from Huber and Mueller
Ratio of Down/Up spectra was calculated and compared with experiment
(independent on ν spectrum, detector efficiency, and many other problems!)

Response to 4 MeV e+



Ratio Down/Up



Fit with constant:
$\chi^2=32$
Prob.=0.39

Most plausible parameter set is excluded

Preliminary results

Exclusion region was calculated using Gaussian $CLs=CL^{4\nu}/CL^{3\nu}$ method

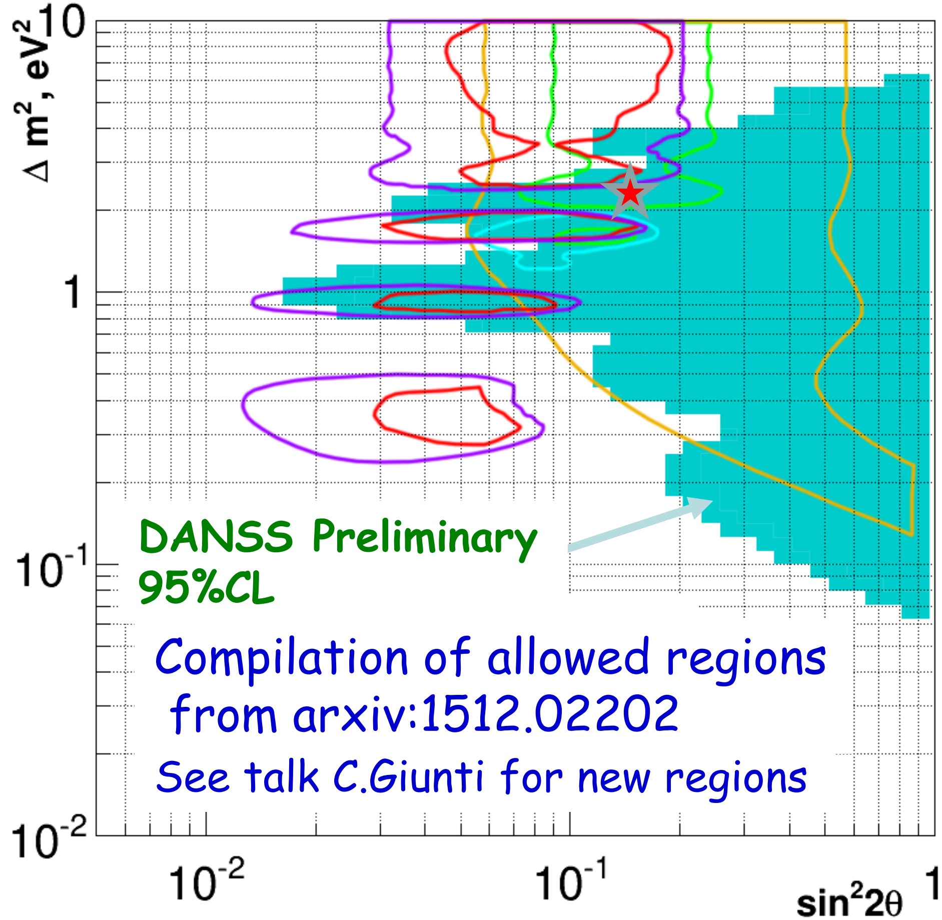
$CLs < 1-\alpha$ forms a CLs region (X.Qian et al. arXiv:1407.5052/v2 [hep-ex])

CLs method is more conservative than usual Confidence Interval method

Systematics studies include variations in:

- -Burning profile in reactor core
- -Energy resolution
- -Level of cosmics background
- -Energy intervals used in fit

Systematics is small



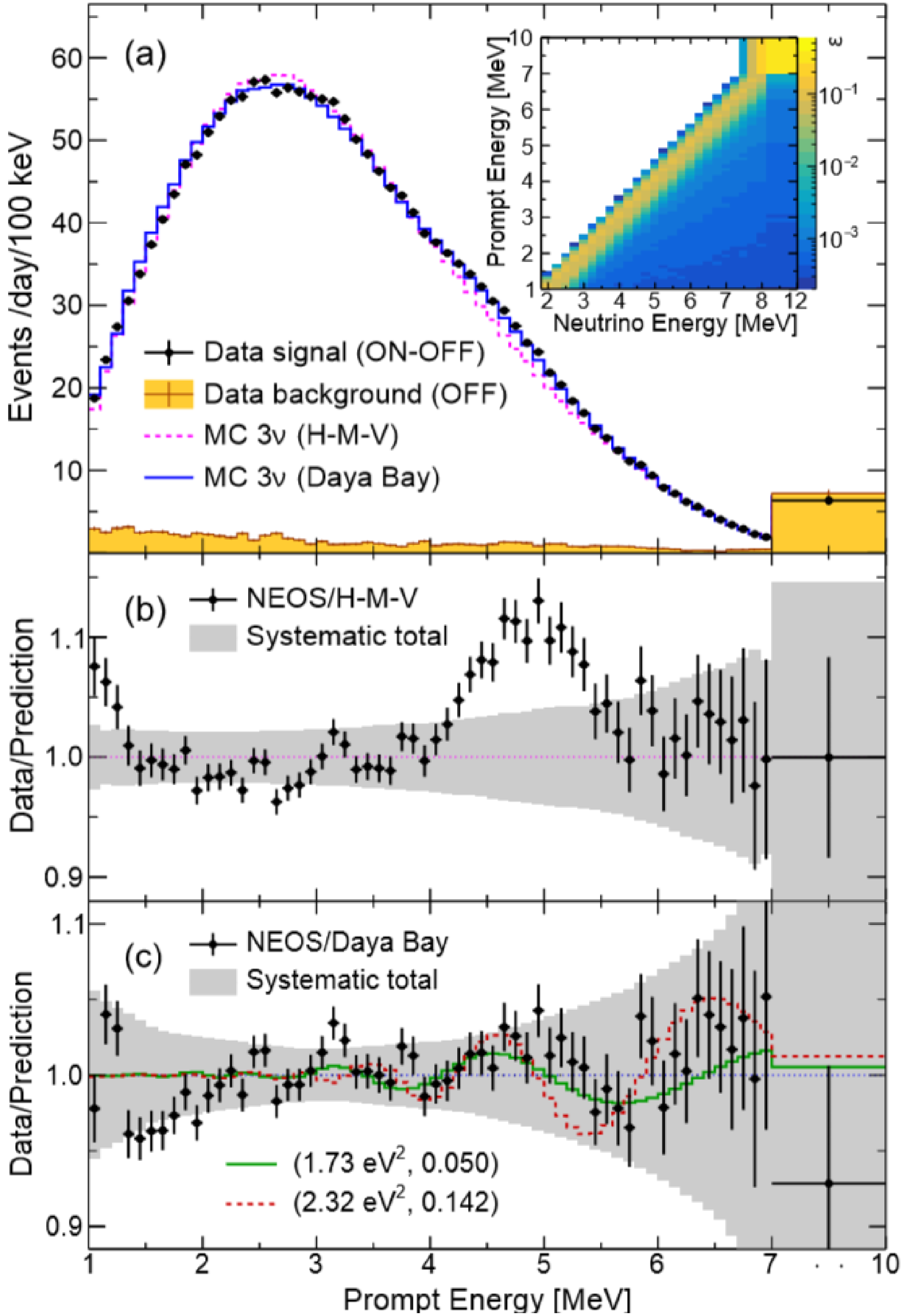
A large fraction of allowed parameter region is excluded by preliminary DANSS results using only ratio of e+ spectrum at different L

-DANSS plans to collect 3 times more data by Summer and to include into analysis all available now data

-Detector calibration and systematics studies will be continued

-More elaborated analysis methods will be used

=> much better sensitivity



NEOS experiment has recently published similar upper limits on sterile neutrino parameters using comparison of ν spectrum at 24m with Daya Bay spectrum

C.Giunti will discuss this

However comparison of different experiments could suffer from systematic errors.
There is a difference in the ratio below 2 MeV and not explained oscillation pattern at larger E

My personal conclusion:
Be very careful comparing different experiment

Experiment Neutrino-4 at SM-3 reactor (42×42×35 cm3, 90MW)

arXiv: 1702.00941

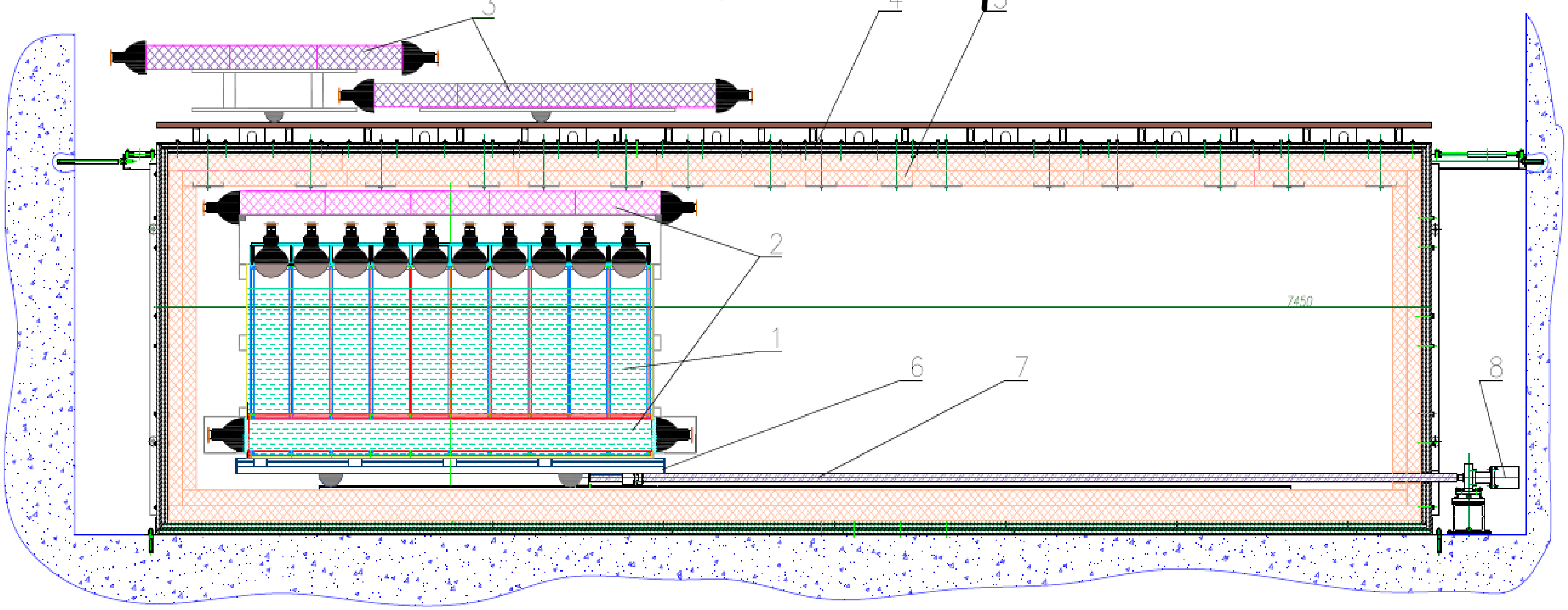
Neutrino channel outside and inside

Passive shielding of 60 tons

Range of measurements of the reactor antineutrino flux is 6 – 12 meters from reactor core

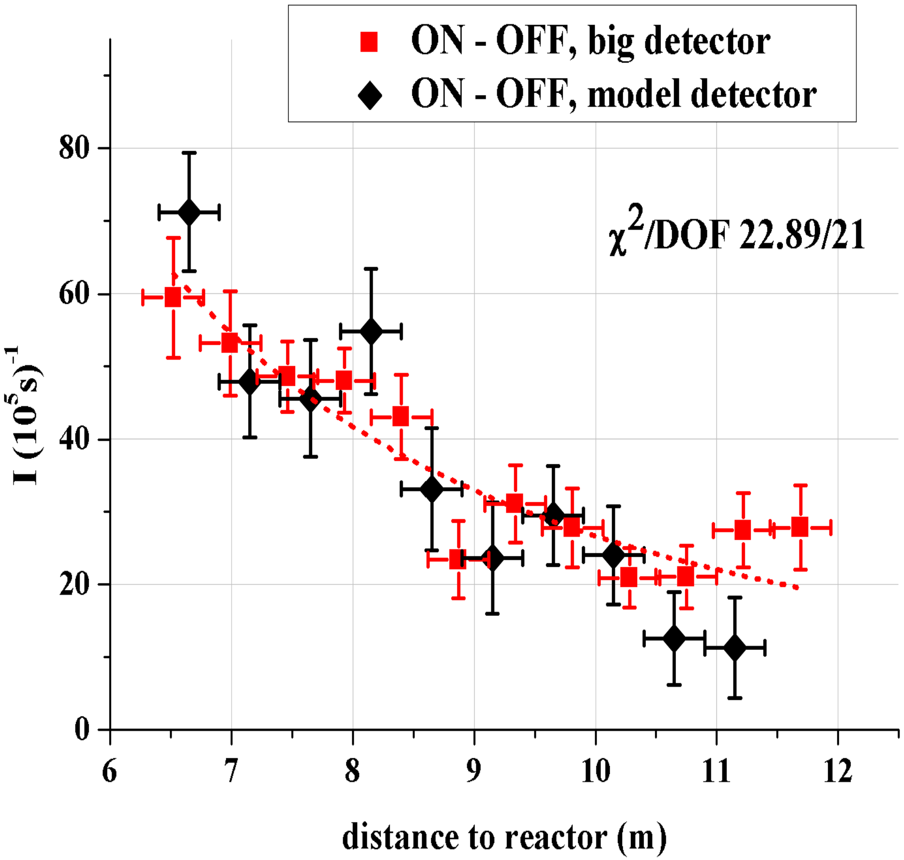
General scheme of experimental setup

3m^3 (5x10 sections) Liquid scintillator detector (1g Gd/l)
Section size is 22.5x22.5x70 cm^3 . One PMT per section
Overburden ~ 5-10 meters of water equivalent



. 1 – detector of reactor antineutrino, 2 – internal active shielding, 3 – external active shielding (umbrella), 4 – steel and lead passive shielding, 5 – borated polyethylene passive shielding, 6 – moveable platform, 7 – feed screw, 8 – step motor.

Measurements of antineutrino flux from reactor at small distances of 6-12m with a moveable detector were carried out for the first time.

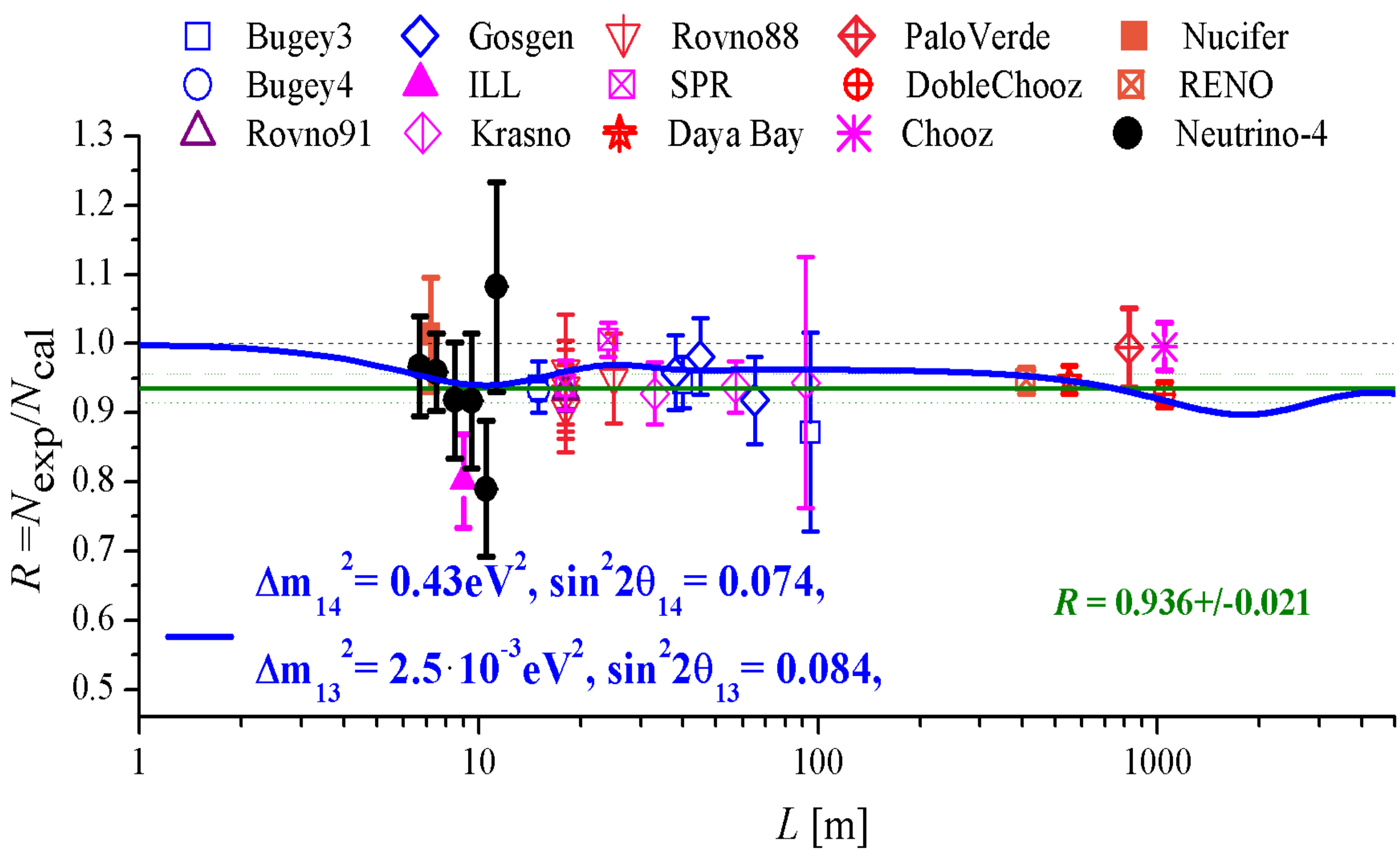


With available statistical accuracy no reliable deviations of antineutrino flux from the $1/L^2$ law was revealed (L – distance from reactor core center)

Measurements with in reactor ON regime was carried out for 111 days and in reactor OFF regime for 74 days. In total there were 15 reactor turning on and off.

Some experiments at long distances show deficit of reactor antineutrino flux in comparison with calculated flux. This can be explained by additional sterile neutrino. We add Neutrino-4 data and perform a fit to determine sterile neutrino parameters.

$\bar{\nu}$ flux dependence on distance



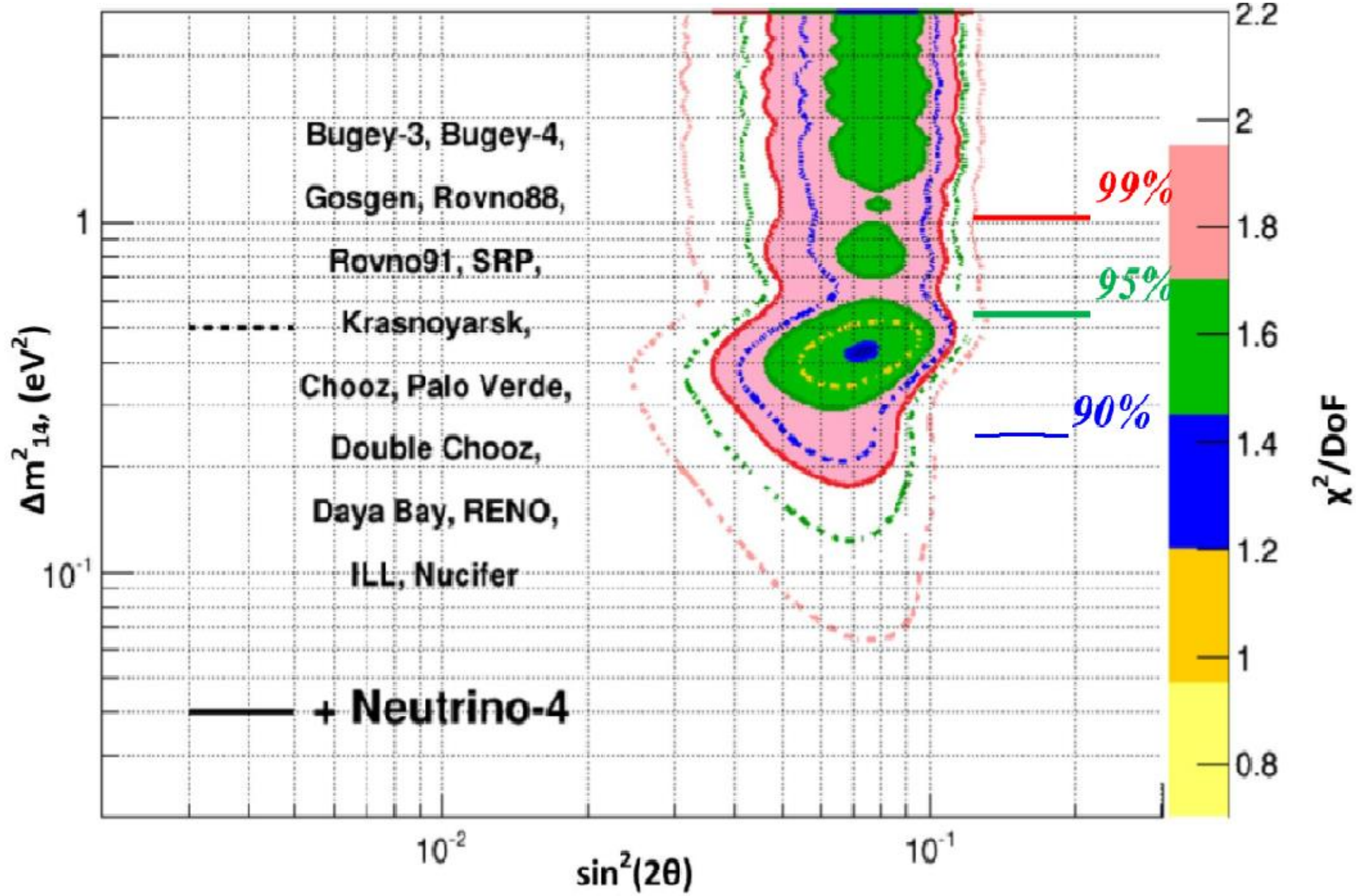
Neutrino-4 does not measure absolute $\bar{\nu}$ flux with sufficient accuracy

Therefore they take normalization from other experiments at different distances and fix their average R at 0.936

Validity of such an assumption is questionable

Then they fit ν flux data from all experiments at short distances

Analysis of the parameters for one sterile neutrino model



Solid line - the analysis of one sterile neutrino model parameters using data obtained by Neutrino-4, data obtained if ILL and Nucifer at short distances and all known data obtained at long distances.

Dash line – the same analysis without data of Neutrino-4.

Due to adding new data and increasing of degrees of freedom the reduced χ^2 is used with taking into consideration unequal accuracy of measurements.

CONCLUSION (Neutrino-4)

Current statistical accuracy of our measurements is not sufficient to observe the assumed processes with high precision. In order to further improve precision of the experiment we need to continue measurements to obtain better statistical accuracy and also use additional methods of background suppression.

Best regards from Russia



A Serebrov[1], V Ivochkin[1], R Samoilov[1], A Fomin[1], A Polyushkin[1], V Zinoviev[1], P Neustroev[1], VGolovtsov[1], A Chernyj[1], O Zherebtsov[1], V Martemyanov[2], V Tarasenkov[2], V Aleshin[2], A Petelin[3], A Izhutov[3], A Tuzov[3], S Sazontov[3], D Ryazanov[4], M Gromov[3], V Afanasiev[3], M Zaytsev[1,4], MChaikovskii[1]

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[3] JSC “SSC RIAR”, Dimitrovgrad, 433510 Russia

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Summary

Searches for sterile neutrinos is a very active field
Combination of different experiments is problematic (systematics)
Measurements at different L with the same detector are crucial
DANSS and Neutrino-4 presented such data.

- DANSS detects ~5000 ν events/day with ~2.5% cosmic background.
- Neutrino-4 detects ~200 ν ev./day with ~200% cosmic background, but it has smaller distance to a point-like reactor, larger L range and better resolution.

Preliminary DANSS analysis excludes a large and most interesting fraction of available parameter space for sterile neutrino using only ratio of e+ spectra at two distances.
Use of ν spectrum and rate information can further increase sensitivity

Neutrino-4 obtained 99%CL preferable region for sterile ν parameters from the fit of ratio of $\bar{\nu}$ flux to theoretical predictions from all short base line experiments using questionable normalization of their data to world average

DANSS and Neutrino-4 will collect more data and will increase their sensitivity to sterile neutrinos

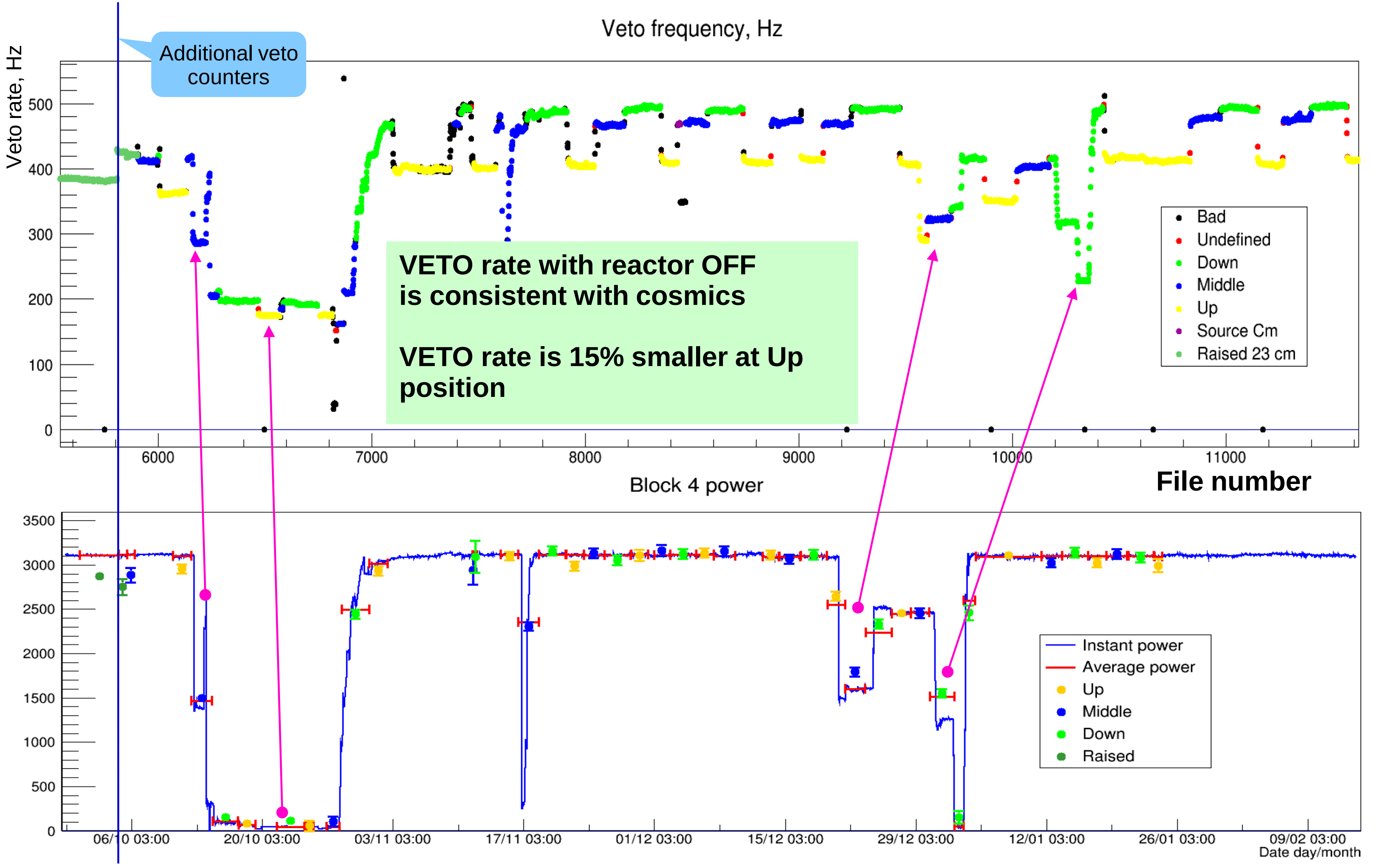
Backup slides

Physics cuts

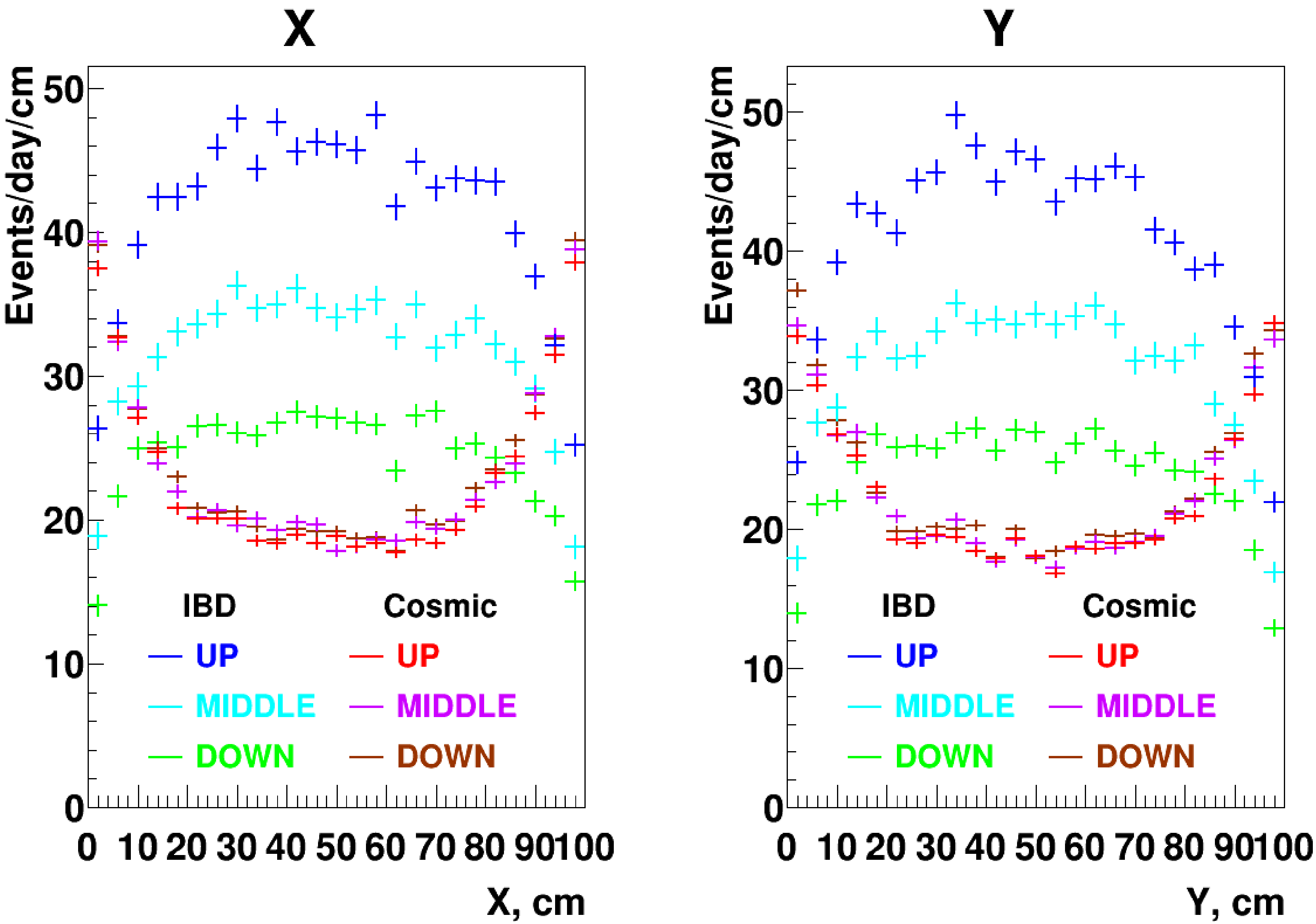
- Neutron energy > 3 MeV and < 10 MeV
- Positron energy > 1 MeV and < 12 MeV
- Minimum 3 SiPM hits in neutron trigger
- Time difference between positron and neutron < 50 us

- Time after VETO > 60 us
- Time after ANY trigger > 45 us
- Time to ANY trigger excluding neutron > 80 us
- No triggers between positron and neutron
- Positron cluster >4 cm from detector edge
- Distance between positron and neutron < 60 cm
- Distance along Z between positron and neutron < 40 cm
- Time difference between positron and neutron > 2 us
- Energy in positron trigger out of cluster < 1.5 MeV
- Number of hits in positron trigger out of cluster < 9

Veto

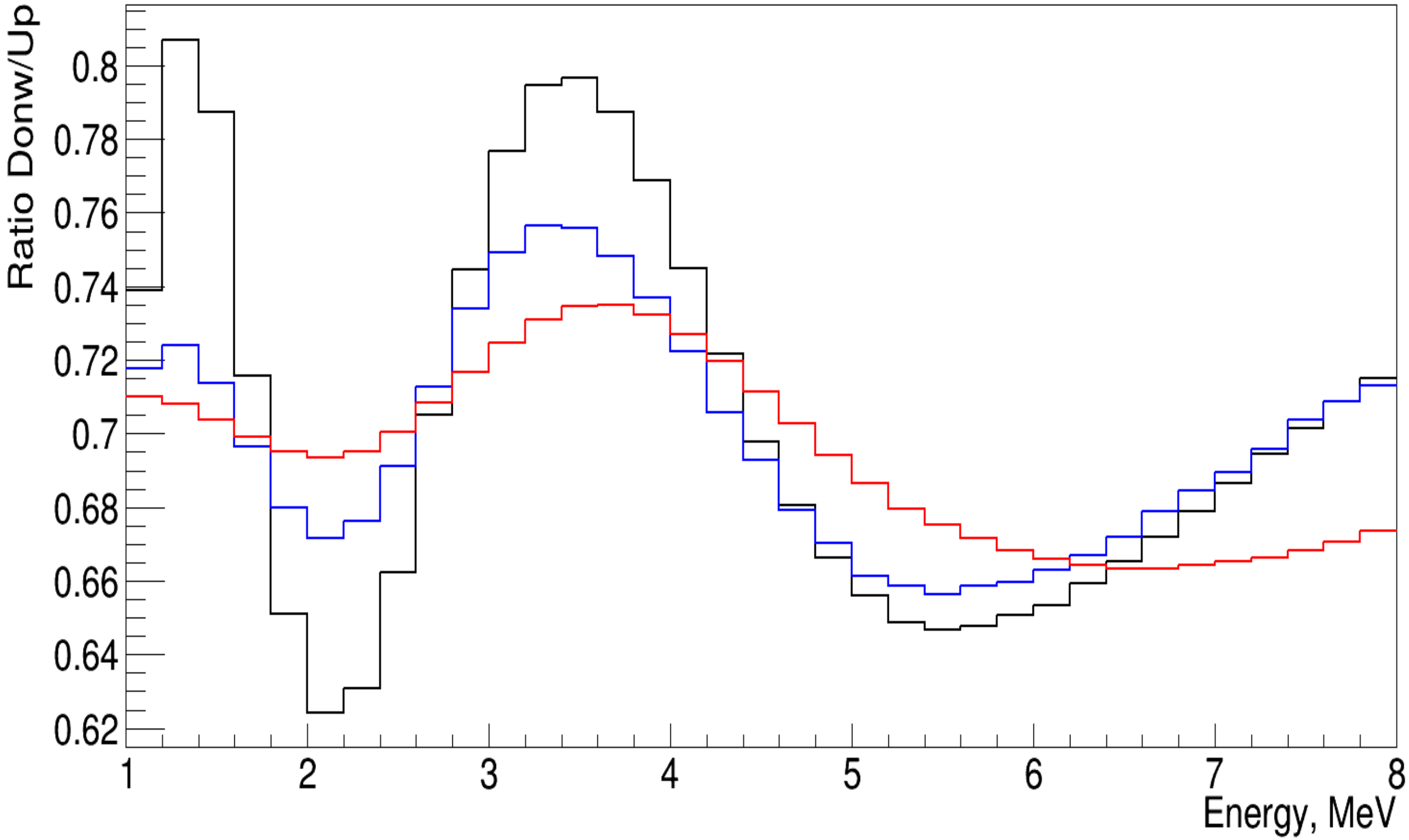

Veto frequency, Hz
Additional veto counters
Veto rate, Hz
500
400
300
200
100
0
6000
7000
8000
9000
10000
11000
File number
Bad
Undefined
Down
Middle
Up
Source Cm
Raised 23 cm
VETO rate with reactor OFF is consistent with cosmics
VETO rate is 15% smaller at Up position
Block 4 power
3500
3000
2500
2000
1500
1000
500
0
06/10 03:00
20/10 03:00
03/11 03:00
17/11 03:00
01/12 03:00
15/12 03:00
29/12 03:00
12/01 03:00
26/01 03:00
09/02 03:00
Date day/month
Instant power
Average power
Up
Middle
Down
Raised

Spatial distribution of ν and cosmic events
No sign of fast n background in ν events

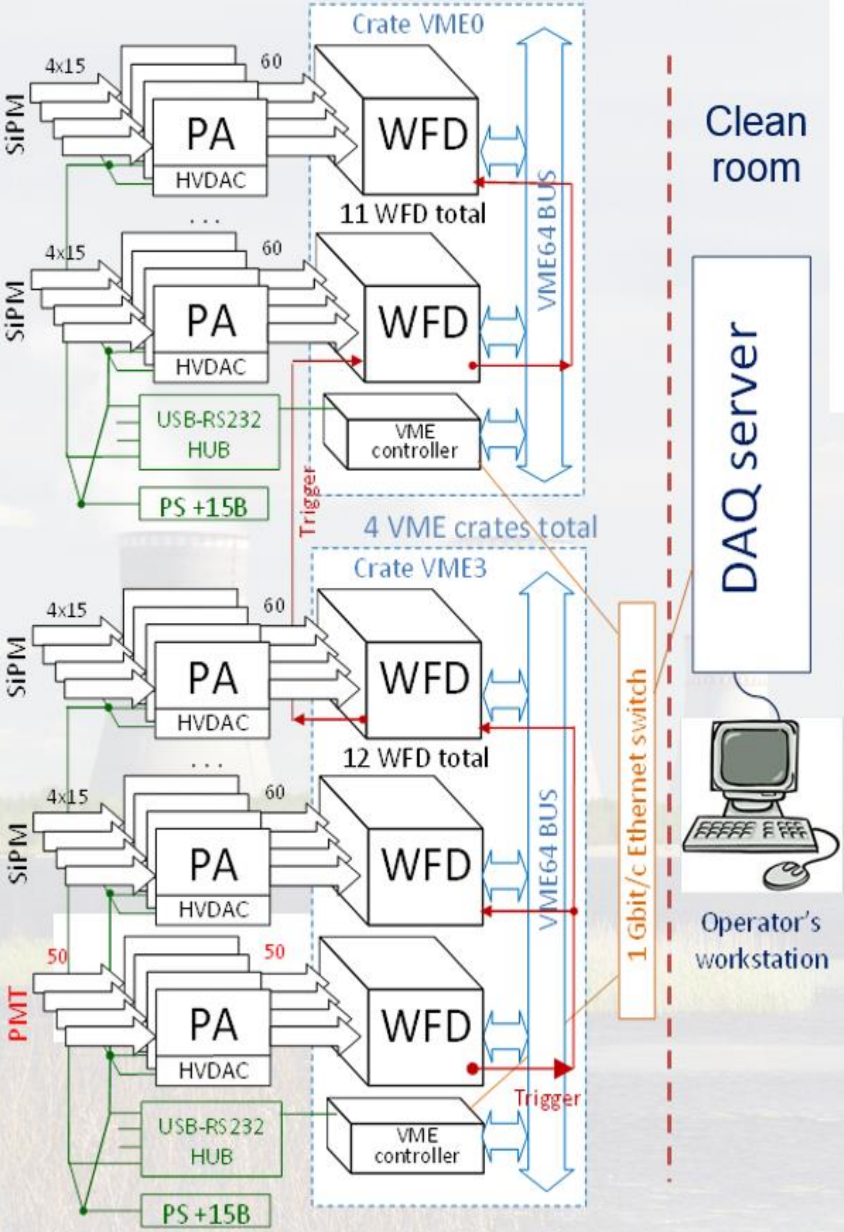


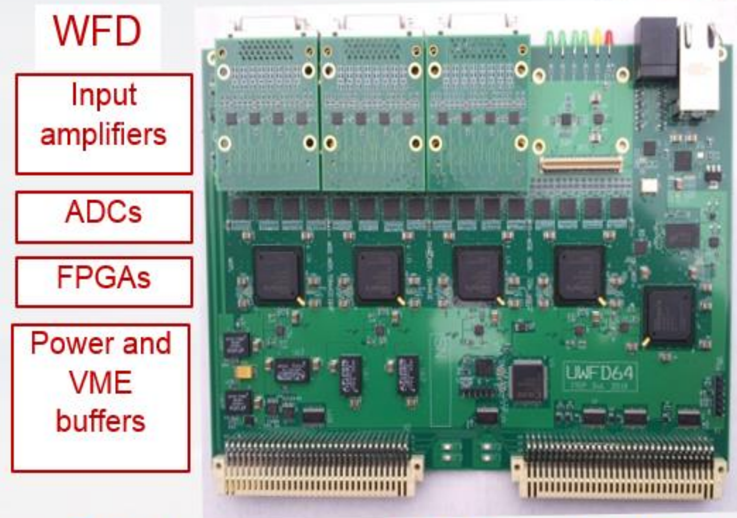
Smearing due to reactor core size and energy resolution

$\sin^2 2\theta = 0.14$, $\Delta m^2 = 2\ eV^2$
Ideal case
Reactor size
Reactor size+Energy resolution

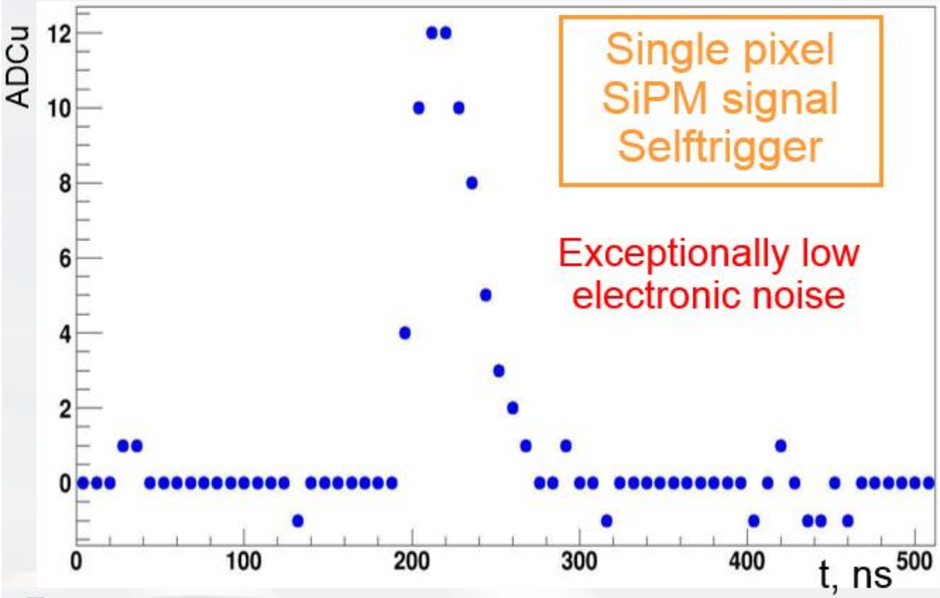


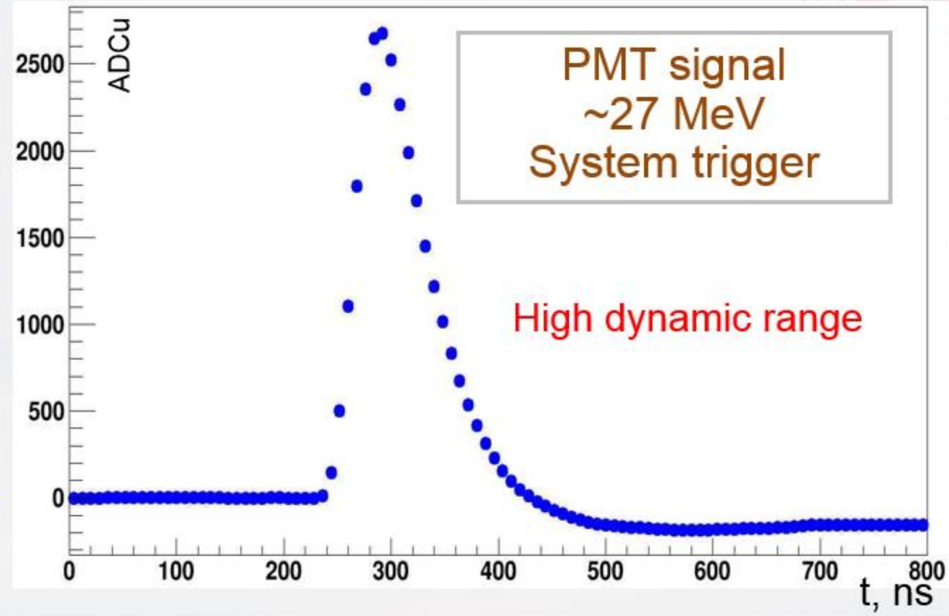
Specially designed DAQ system

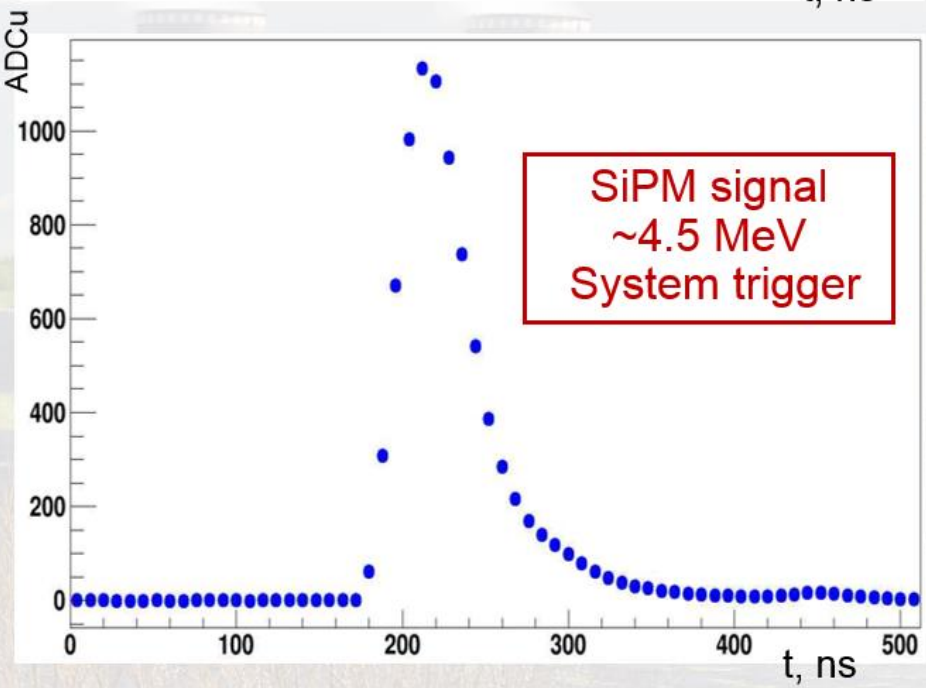


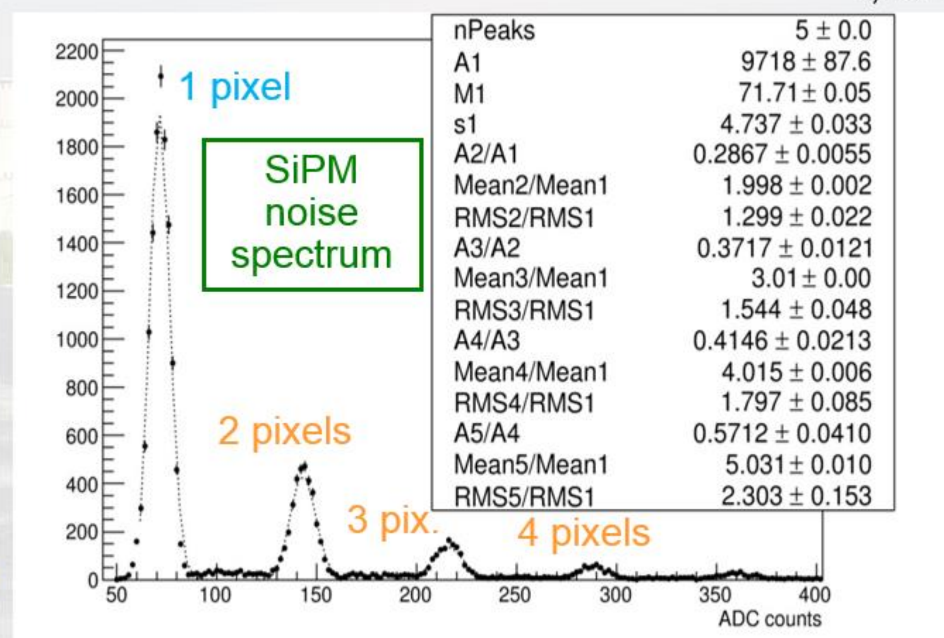


- Preamplifiers PA in groups of 15 and SiPM power supplies HVDAC for each group inside shielding, current and temperature sensing
- STP cables to get through the shielding
- Total 46 Waveform Digitisers WFD in 4 VME crates on the platform
- WFD: 64 channels, 125 MHz, 12 bit dynamic range, signal sum, trigger generation and distribution (no additional hardware)
- 2 dedicated WFDs for PMTs and μ-veto
- System trigger on certain energy deposit in the whole detector (PMT based) or μ-veto signal
- Each channel selftrigger on SiPM noise (with decimation)


ADCu
Single pixel
SiPM signal
Selftrigger
Exceptionally low
electronic noise
t, ns


ADCu
PMT signal
~27 MeV
System trigger
High dynamic range
t, ns


ADCu
SiPM signal
~4.5 MeV
System trigger
t, ns


1 pixel
SiPM
noise
spectrum
2 pixels
3 pix.
4 pixels
ADC counts
nPeaks 5 ± 0.0
A1 9718 ± 87.6
M1 71.71 ± 0.05
s1 4.737 ± 0.033
A2/A1 0.2867 ± 0.0055
Mean2/Mean1 1.998 ± 0.002
RMS2/RMS1 1.299 ± 0.022
A3/A2 0.3717 ± 0.0121
Mean3/Mean1 3.01 ± 0.00
RMS3/RMS1 1.544 ± 0.048
A4/A3 0.4146 ± 0.0213
Mean4/Mean1 4.015 ± 0.006
RMS4/RMS1 1.797 ± 0.085
A5/A4 0.5712 ± 0.0410
Mean5/Mean1 5.031 ± 0.010
RMS5/RMS1 2.303 ± 0.153

Data analysis

Raw data:
wafeforms
~500 Gb/day

Extract hit parameters

"digi"-files:
hit parameters
~50 Gb/day

Calculate trigger parameters

root-files:
trigger parameters
~5 Gb/day

Make events and random events

root-files:
event parameters
~30 Mb/day

Make physics distributions

Monte Carlo and Data analyses are identical

Calibration

Calibration is extremely important for stable energy scale
Shifts in energy scale can imitate oscillations and reduce sensitivity

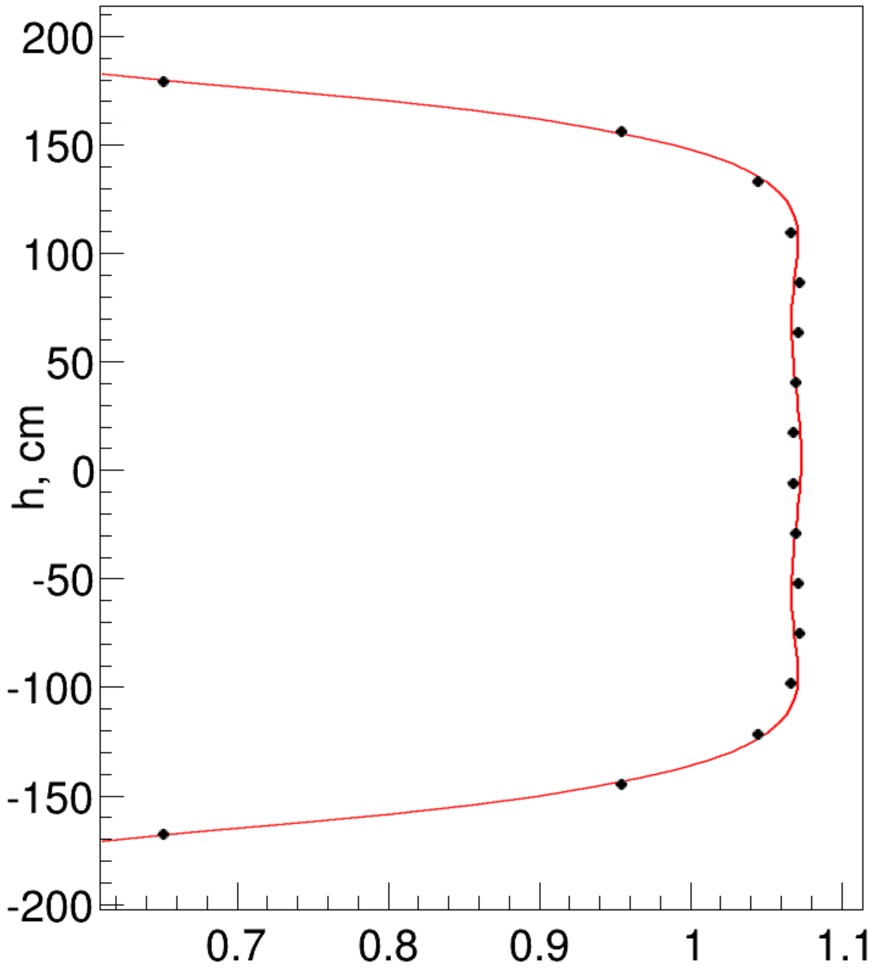
Elaborated system of calibration is foreseen in DANSS

1. Several radioactive sources can be put into 2 special tubes
   ^{248}Cm neutron source provides signals similar to IBD
   Gamma sources will be used to check the energy scale and resolution

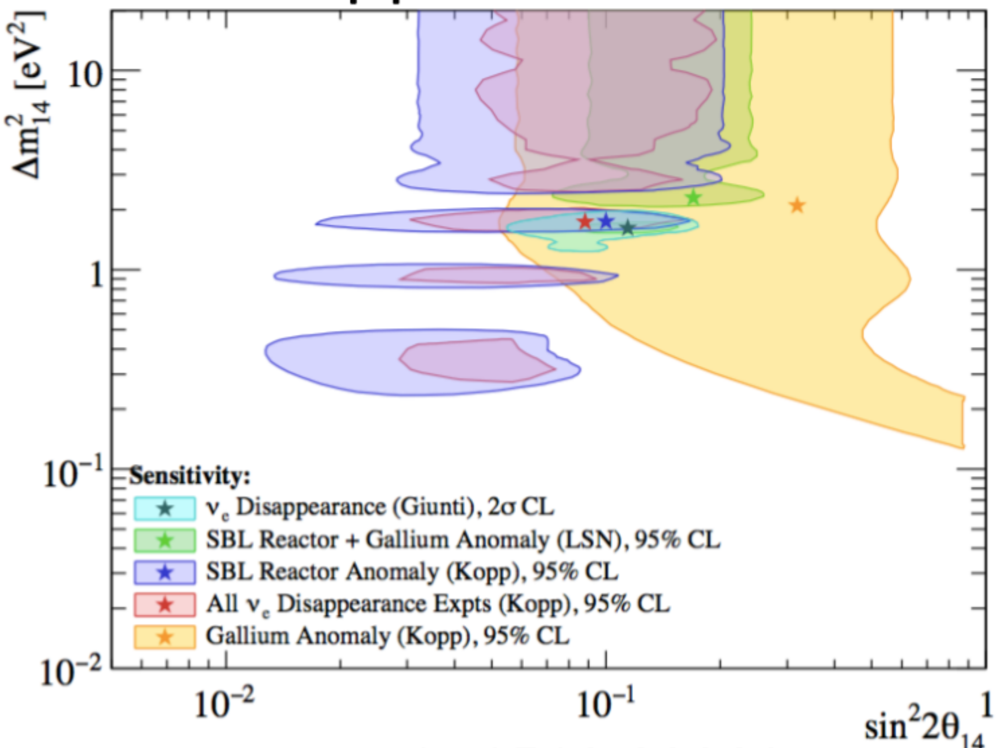
2. High granularity of DANSS allows cosmic calibration with ~20000 events/strip/day.
   Cosmics spans E range 2-5MeV for each strip with SiPM readout and 10-40MeV for modules of 50 strips read out by one PMT
   Cross-calibration between SiPM and PMT is possible

3. SiPM amplification is calibrated continuously

Reactor core burning profile averaged over campaign

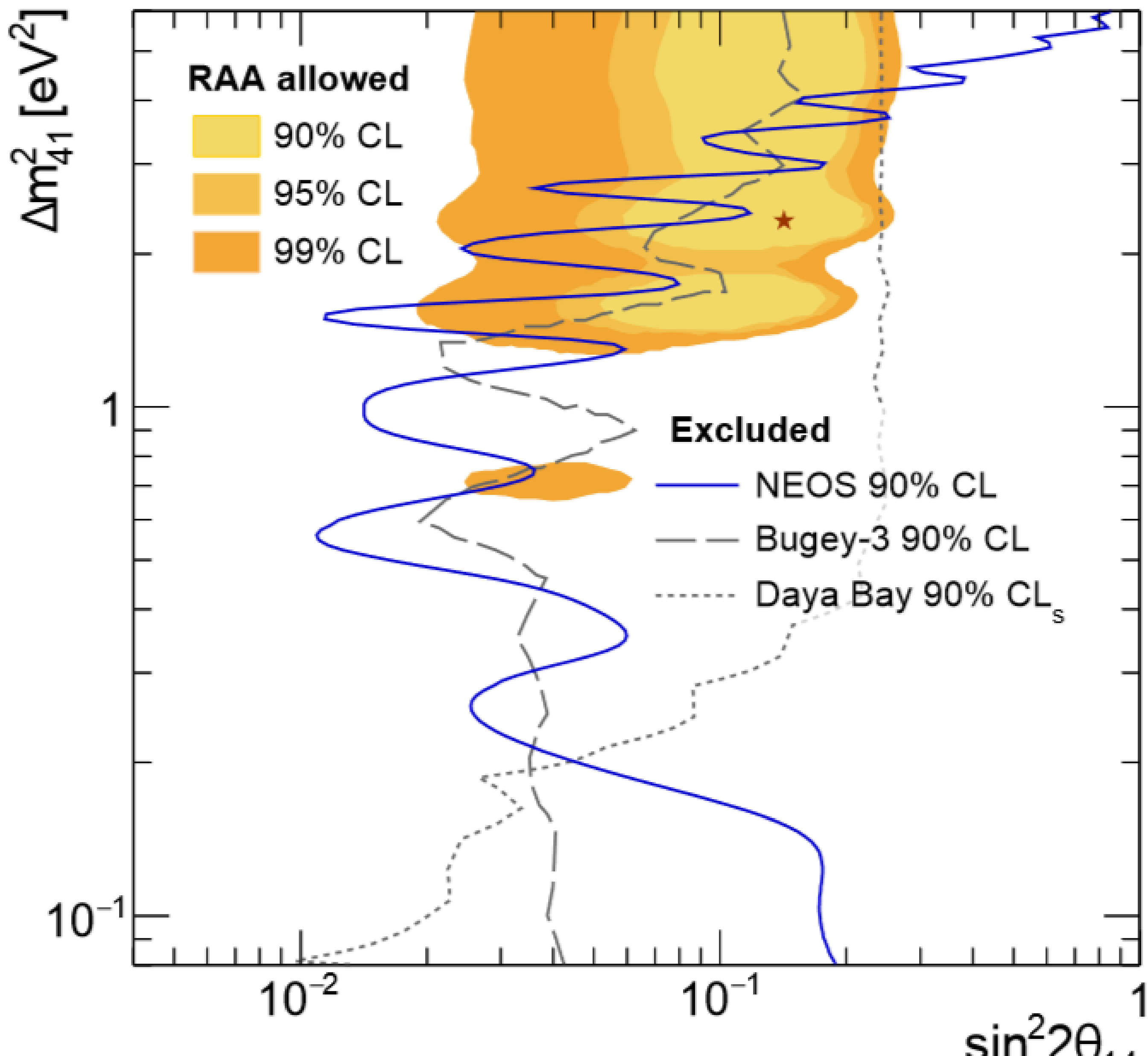


Allowed regions in 3+1 framework for ν_e disappearance data

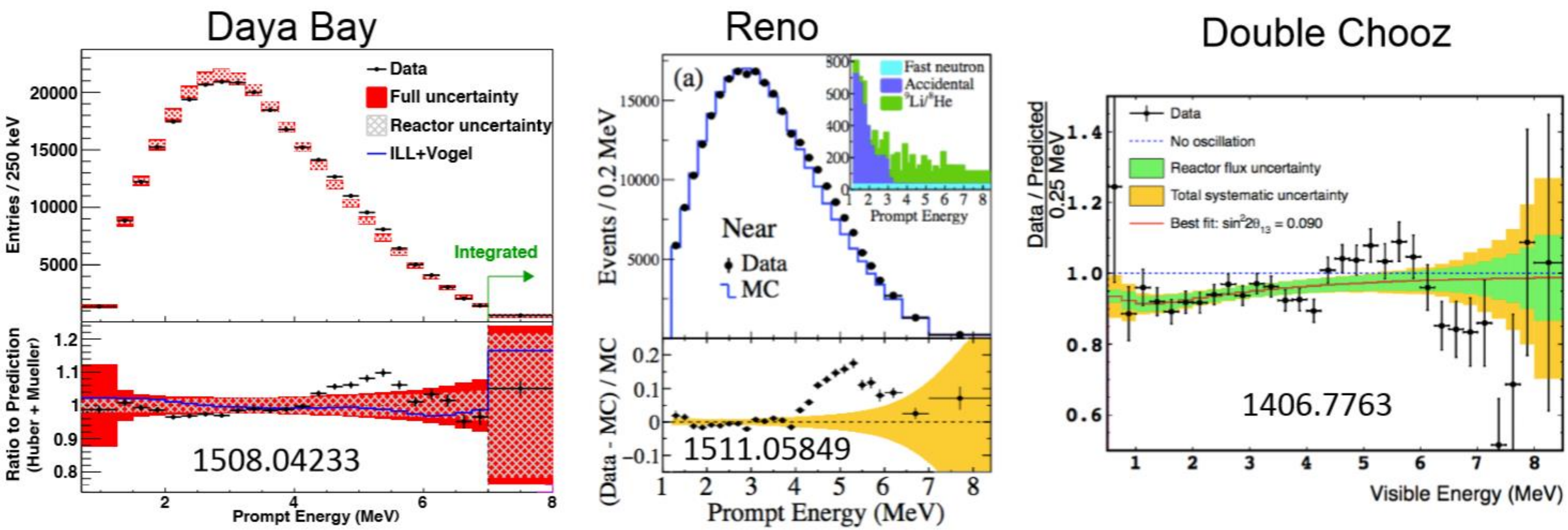


arxiv:1512.02202
allowed regions from 1101.2755, 1303.3011, 1308.5288

Allowed regions differ a bit in different analyses
Carlo Guinti will present the most resent analysis


RAA allowed
90% CL
95% CL
99% CL
Excluded
NEOS 90% CL
Bugey-3 90% CL
Daya Bay 90% CL_s
Δm^2_{41} [eV^2]
$\sin^2 2\theta_{14}$
10^{-2}
10^{-1}
1
10^{-1}
1

Reactor models do not describe well neutrino spectrum

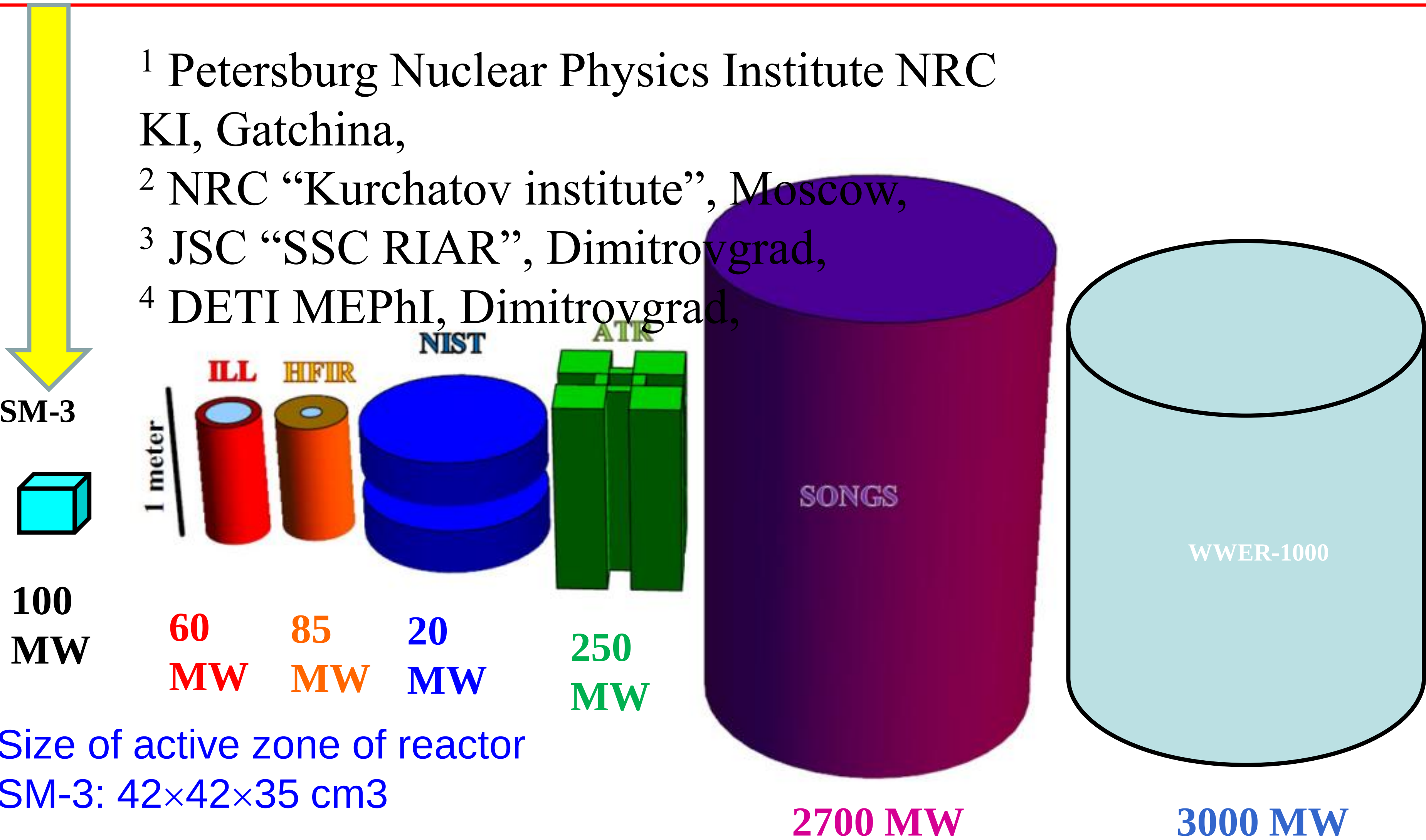


Measurements at one distance are not sufficient!

Best strategy – measurements with the same detector at different distances since many systematic effects are cancelled out

Experiment Neutrino-4 at SM-3 reactor (42×42×35 cm, 90MW)

[1] Petersburg Nuclear Physics Institute NRC KI, Gatchina,
[2] NRC “Kurchatov institute”, Moscow,
[3] JSC “SSC RIAR”, Dimitrovgrad,
[4] DETI MEPhI, Dimitrovgrad,



Size of active zone of reactor
SM-3: 42×42×35 cm3

Core size and power of different reactors

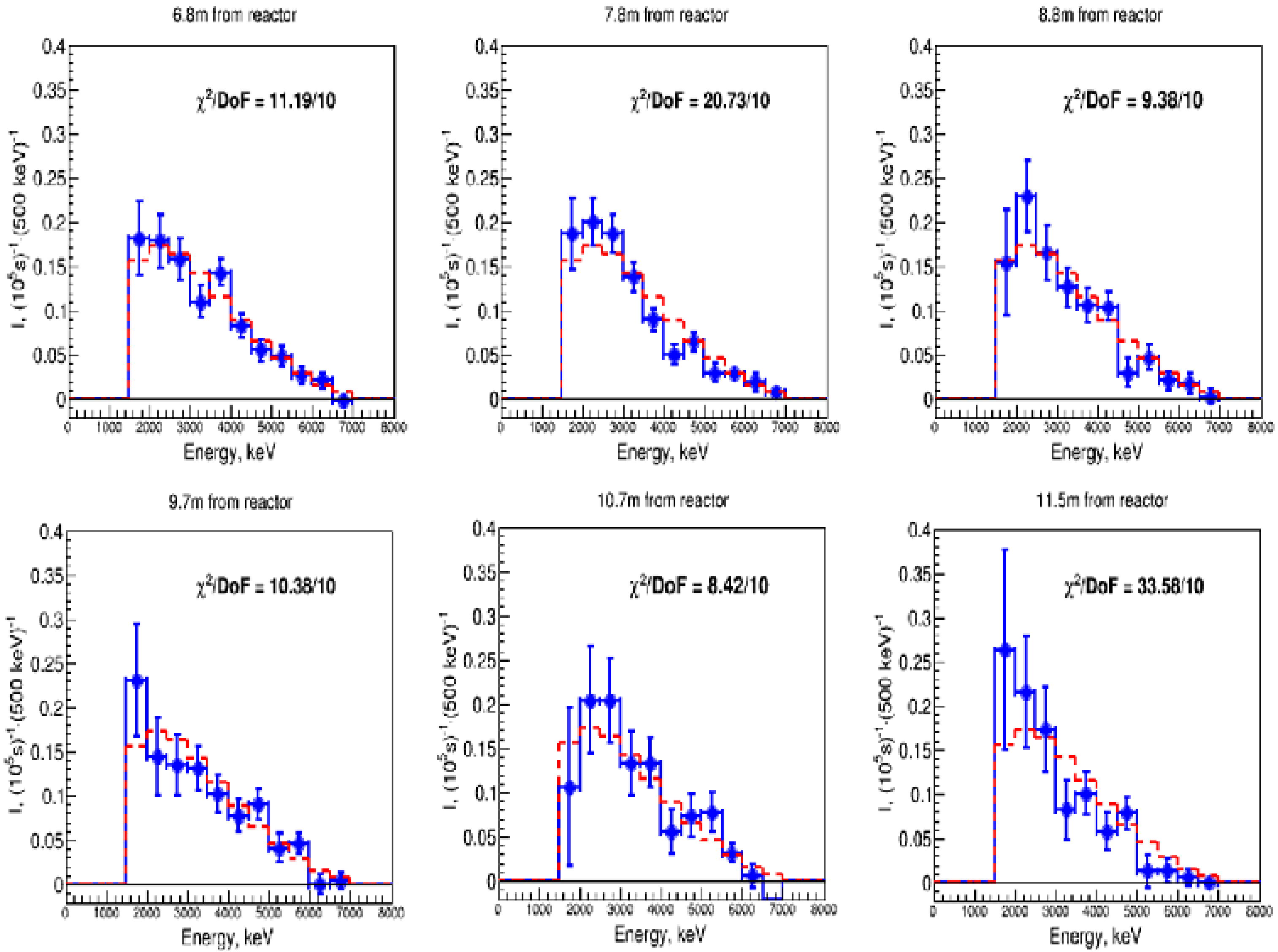
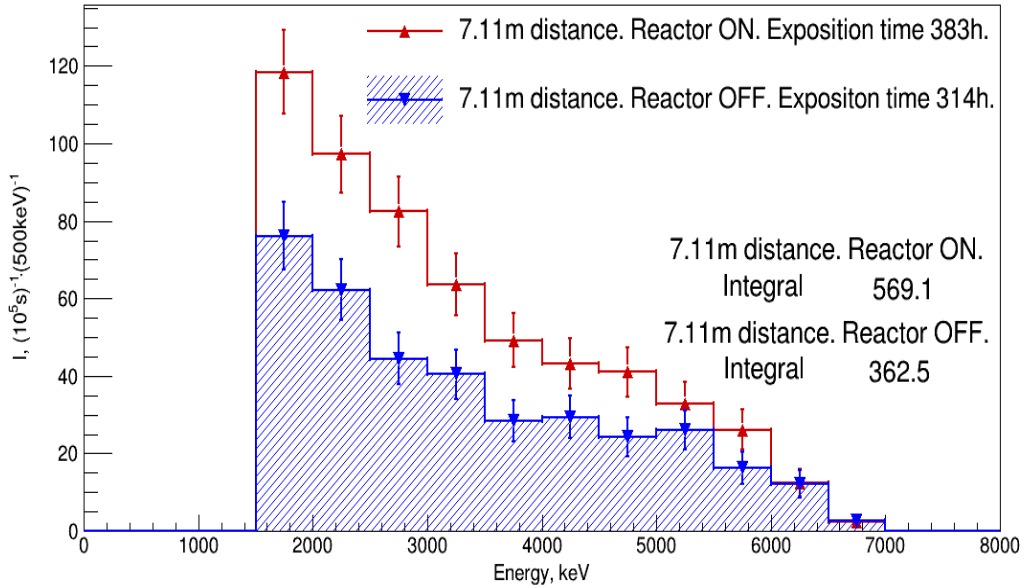
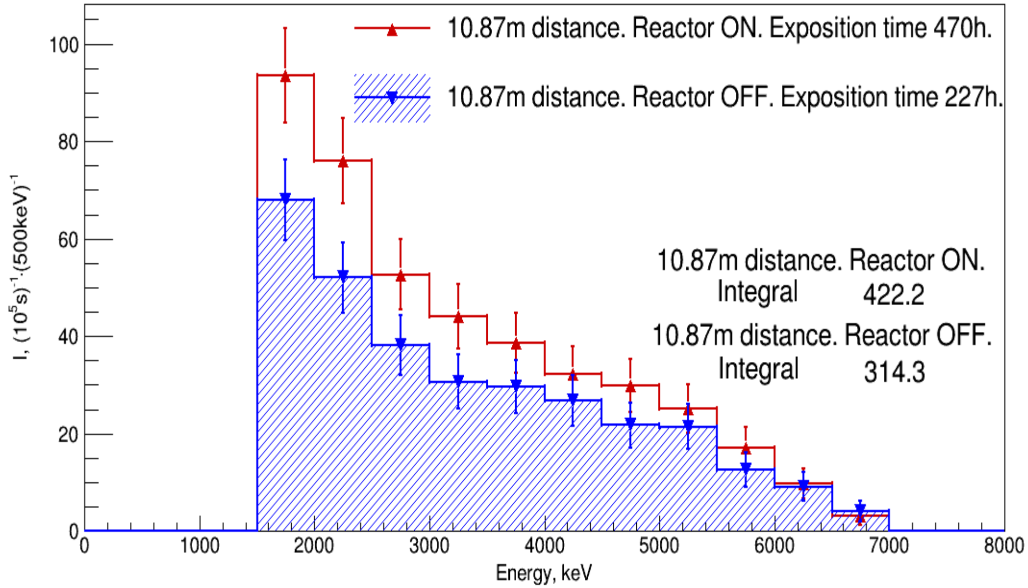


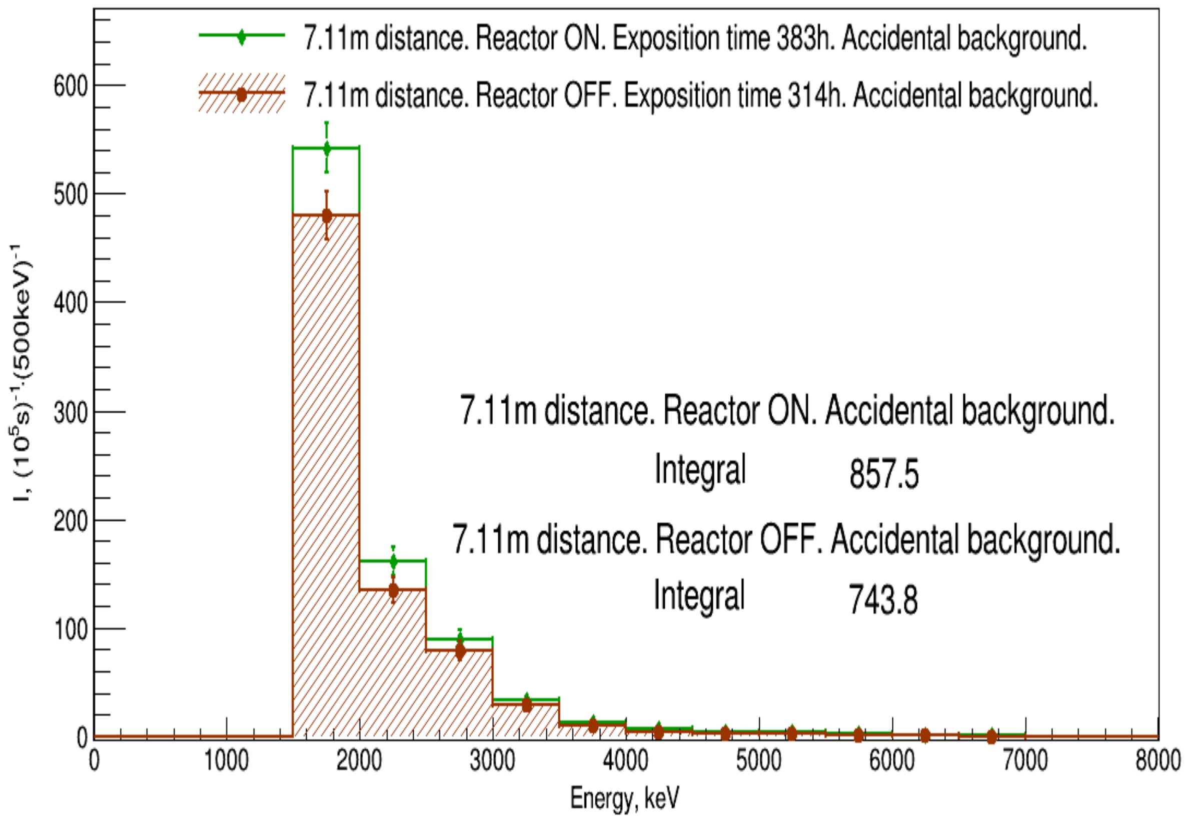
Figure 3. Results of spectrum measuring at various distances (solid line) and result of Monte-Carlo simulation for prompt signals spectrum (dashed line). Spectra normalized to 1.

Neutrino-4 reactor On and OFF rates (S/B~0.5)





Neutrino-4 reactor On and OFF accidental background (S/B ~0.25)



Calibration of Neutrino-4 experiment

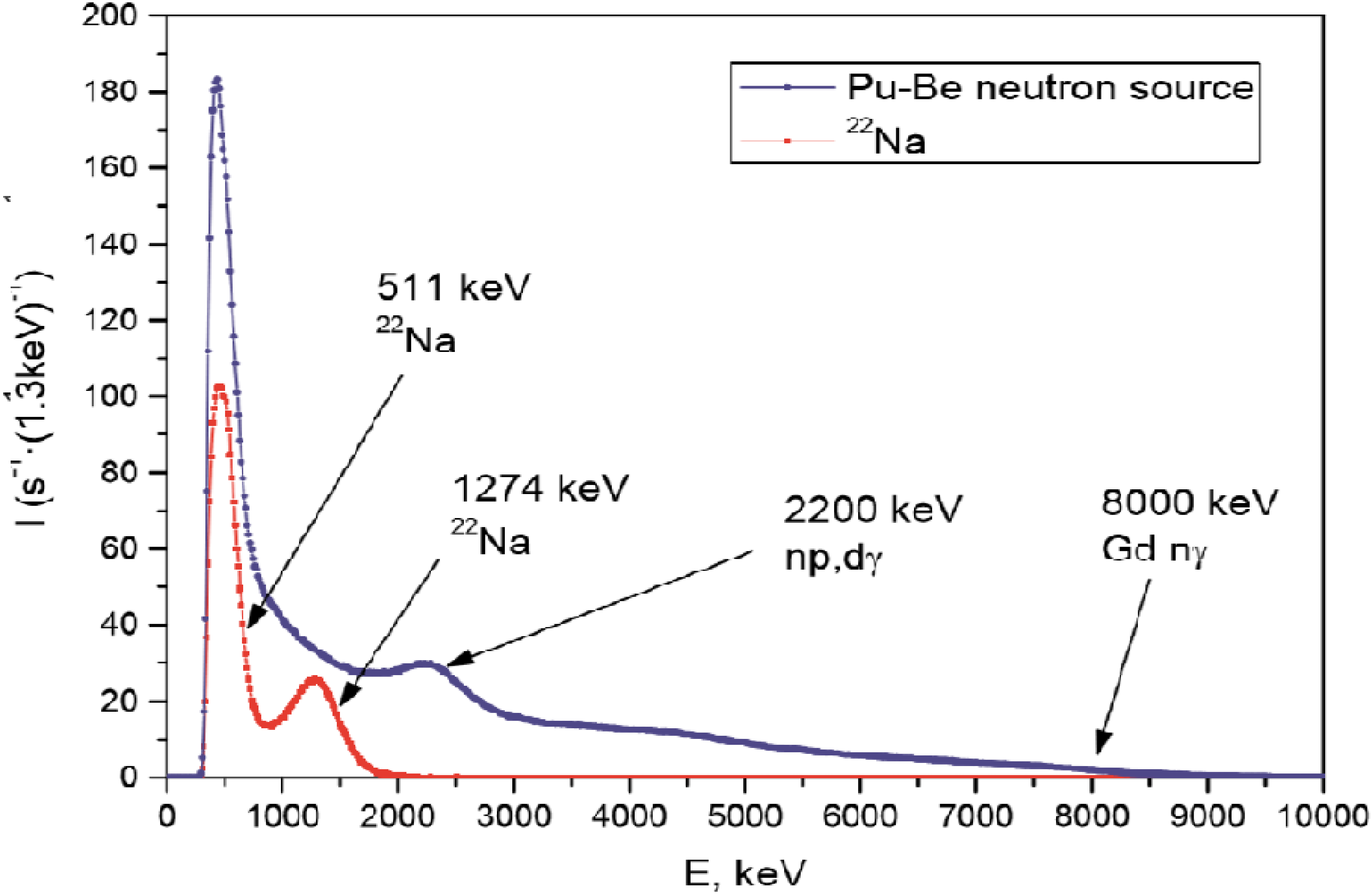


Fig. 5. Results of energy calibration.

Neutrino-4 Prompt Energy Spectrum