New Results from the DANSS Collaboartion

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For the DANSS Collaboration

International Workshop on Applied Antineutrino Physics

RWTH Aachen University

28-30 October 2024

There are several indications in favor of existence of the 4th neutrino flavor - "sterile" neutrino seen in short distance oscillations

LSND + MiniBooNE – **accelartor anomaly**: appearance of ν_e ($\overline{\nu}_e$)
6.1σ combined result
MiniBooNE, PRL **121**, 221801 (2018)

MicroBooNE – doesn't confirm MiniBooNE, but doesn't exclude
MicroBooNE, PRL **128**, 241802 (2022)

GALEX (Gran Sasso) and SAGE (Baksan) – **gallium anomaly**: deficit of ν_e from neutrino source in gallium detectors calibration. Phys. Rev. C **80**, 015807 (2009)

Recent results from BEST demonstrate event larger deficit of neutrinos.
The combined significance >5σ
Phys. Rev. D **105**, L051703 (2022)

Reactor anomaly – deficit of ν_e (5.7%) in combined analysis of reactor experiments.
G. Mention et al. Phys. Rev. D **83**, 073006 (2011)

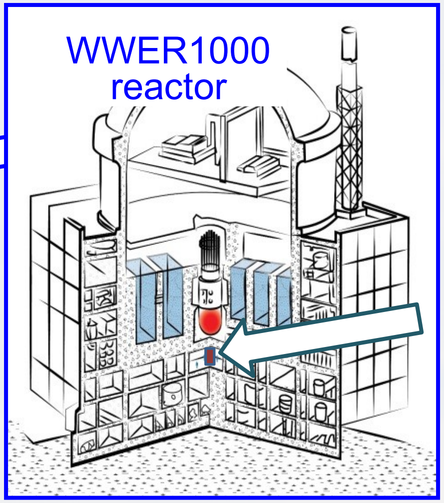
Much smaller (3.7%): M. Estienne et al. PRL **123**, 022502 (2019)
No anomaly (0.6%): V. Kopeikin et al. Phys. Rev. D **104**, L071301 (2021)
^{235}U rate measurements by Daya Bay and RENO

Neutrino-4: 2.7σ @ $\Delta m^2 \sim 7 eV^2$ $\sin^2 2\theta \sim 0.35$ Phys. Rev. D **104**, 032003 (2021)

Criticism of the Neutrino-4 analysis: M. Danilov et al. JETP Lett. **112** no. 7, 452 (2020)
C. Giunti et al. *Phys. Lett. B* 816, 136214 (2021)

These are one of the statistically strongest indications of the New Physics

Kalininskaya Nuclear Power Plant, Russia, ~300 km NW from Moscow

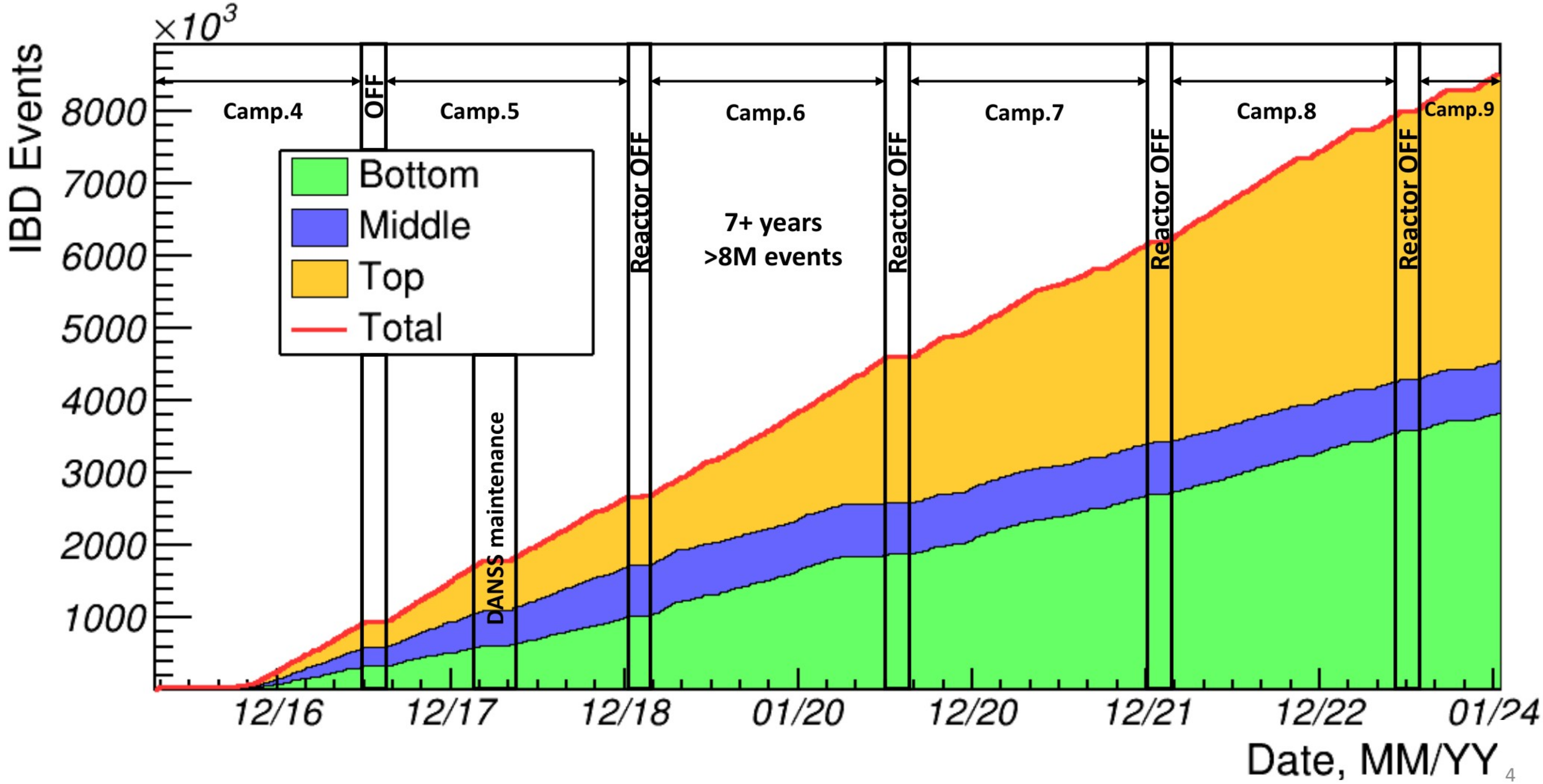


Below 3.1 GW_{th} commercial reactor $\sim 5\cdot 10^{13}\ \nu\cdot cm^{-2}c^{-1}$@11m

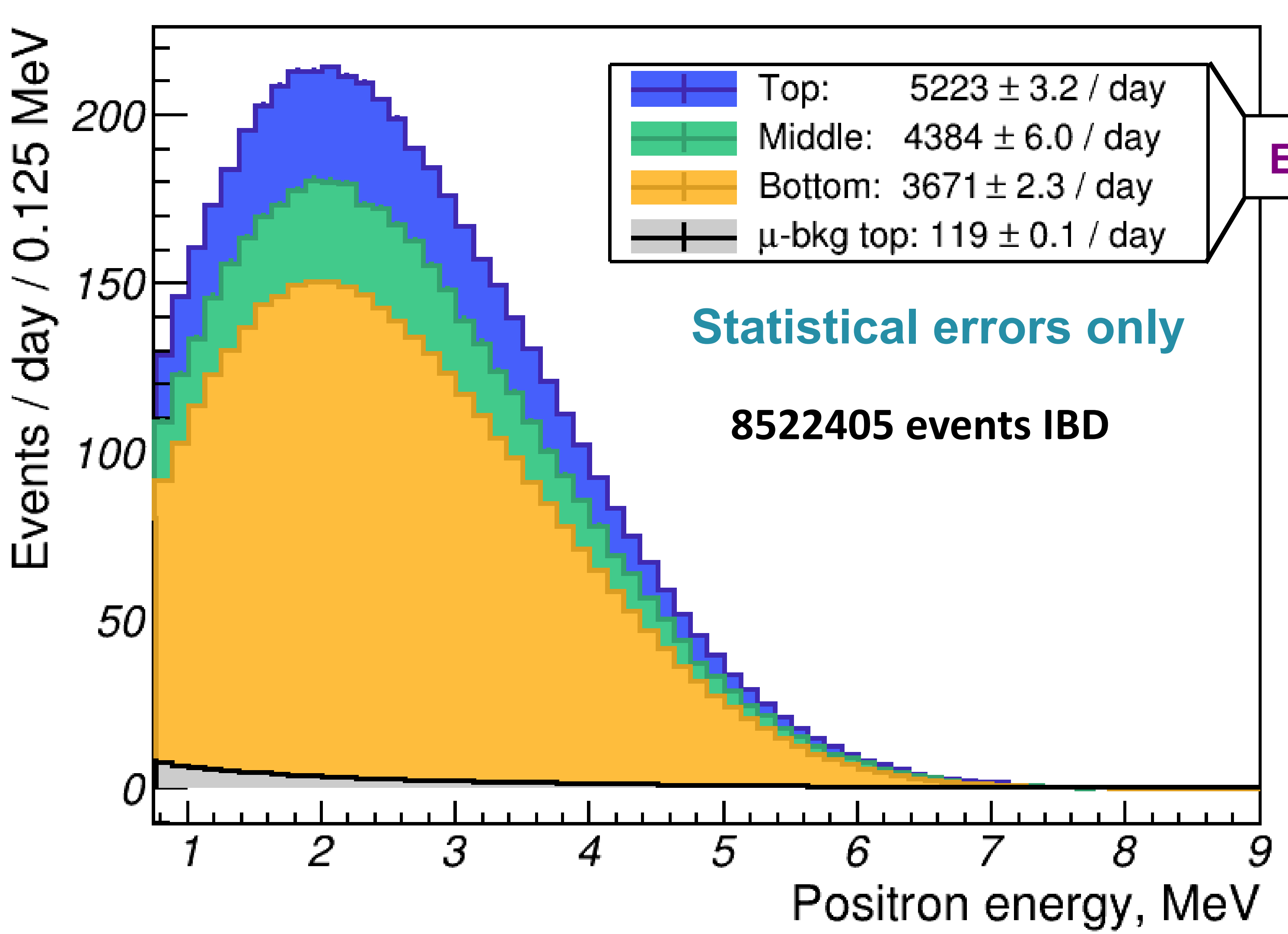
DANSS on a lifting platform
A week cycle of up/middle/down position

- Detector of the reactor AntiNeutrino based on Solid-state Scintillator - no flammable or dangerous materials – can be put just after reactor shielding
- Inverse Beta-Decay (IBD) to measure antineutrinos: $\bar{\nu}_e + p \rightarrow e^+ + n$
- Reactor fuel and body with cooling pond and other reservoirs provide overburden ~50 m w.e. for cosmic background suppression
- Lifting system allows to change the distance between the centers of the detector and of the reactor core from 10.9 to 12.9 m on-line
- The setup details: JINST 11 (2016) no.11, P11011
- The first results: Phys.Lett. B787(2018)56 – one year of running

DANSS statistics accumulation



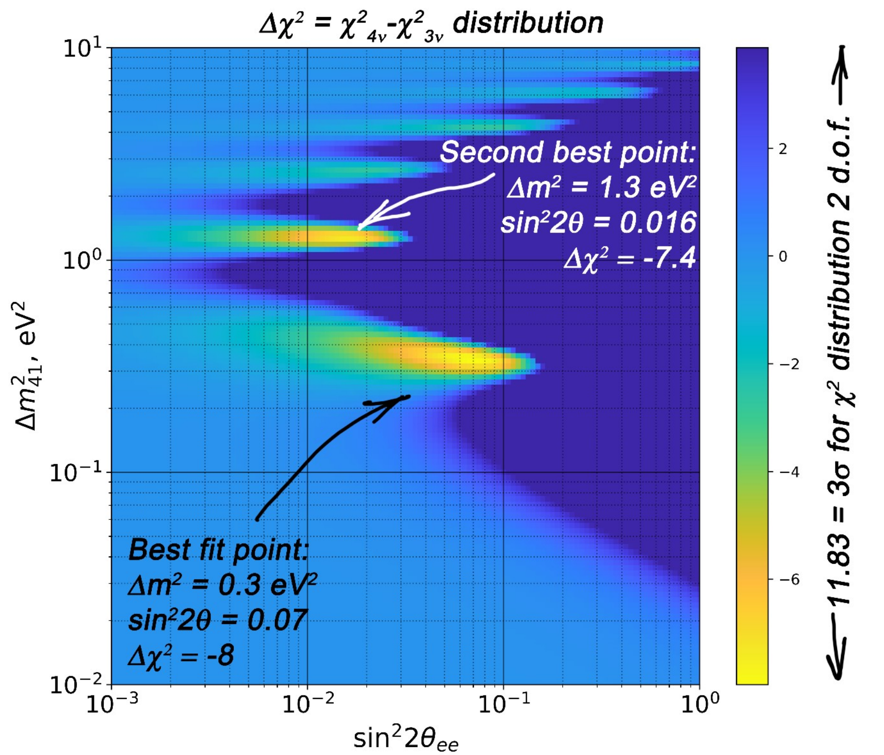
- ✓ **4 full reactor cycles !**
- ✓ **Data January-August 24 is under processing – to be released soon.**
- ✓ **Previous analysis (2023): I.G. Alekseev. Bull. Lebedev Phys. Inst. 51, 8 (2024)**



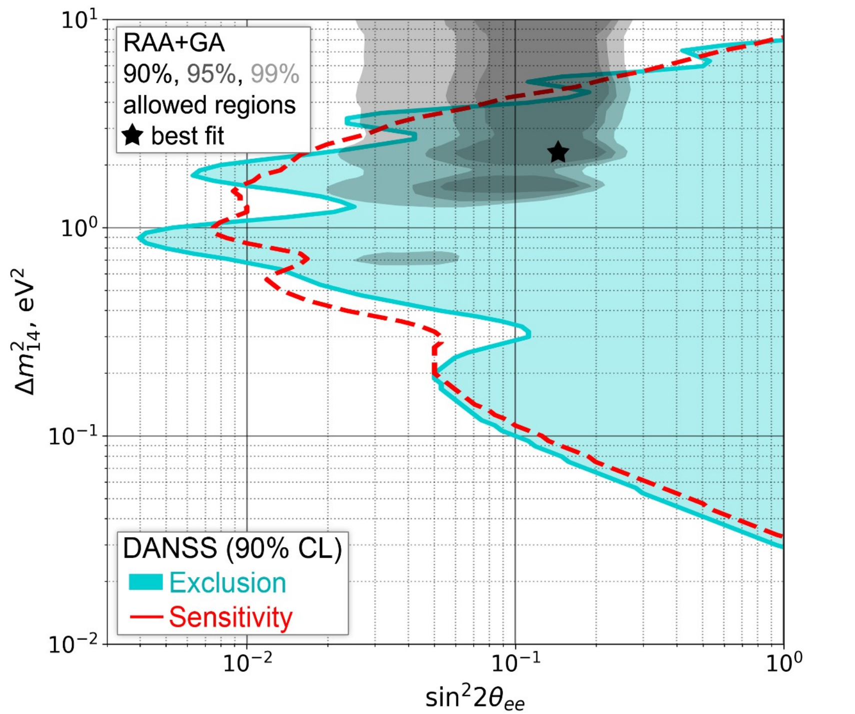
E_{e+}=[0.75-8] МэВ

- ✓ **All backgrounds subtracted**
- ✓ **Neighbor reactors at 160 m, 334 m, and 478 m, 0.6% of neutrino signal at top position, subtracted**
- ✓ **For E_{e+}=[1.5-6] MeV background = 1.75% in top position: S/B > 50 !**

Sterile neutrino search



CLs method: X. Qian et al. Nucl.Inst. Meth. A 827 (2016) 63



- ✓ 6 M IBD events 1.5 MeV < E < 7 MeV (conservative approach)
- ✓ $\Delta\chi^2$=-8.0 (2.0σ) – No statistically significant hint of 4ν oscillations
- ✓ The RAA best point is deep inside the exclusion region (5σ level reached in 2018 [PLB **787** (2018) 56])

Using absolute counting rates

$$\chi^2_{abs} = \chi^2_{rel} + ((N_{top} + N_{mid} + N_{bottom})^{obs} - (N_{top} + k_2 \cdot \sqrt{k_1} \cdot N_{mid} + k_1 \cdot N_{bottom})^{pre})^2/\sigma^2_{abs}$$

χ^2_{rel} — χ^2 using counts ratios only, $N_{top/mid/botom}$ — total counts in the corresponding detector positions

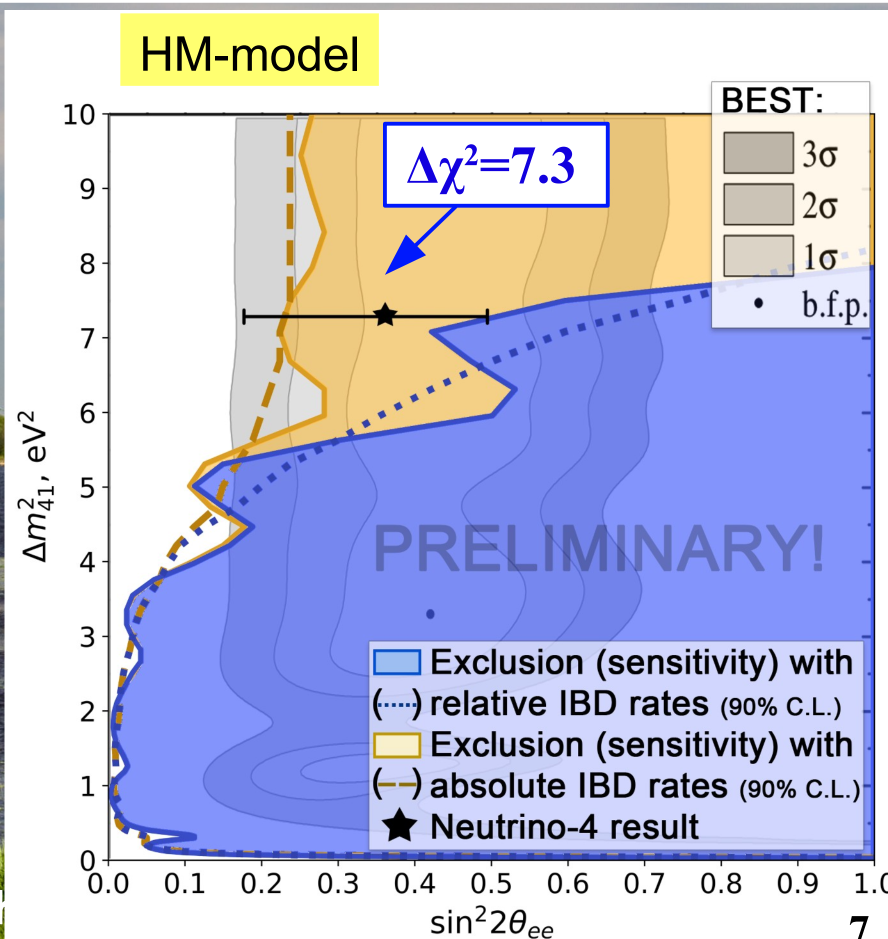
σ_{abs} — systematic uncertainty taken as **7%** (very conservative)

Exclusions for large Δm^2_{41} are consistent with previous results (Daya Bay, Bugey-3, …)

Our preliminary results exclude the dominant fraction of BEST expectations [Phys.Rev.Lett.128,232501] as well as best fit point of Neutrino-4 experiment [Phys. Rev. D 104, 032003].

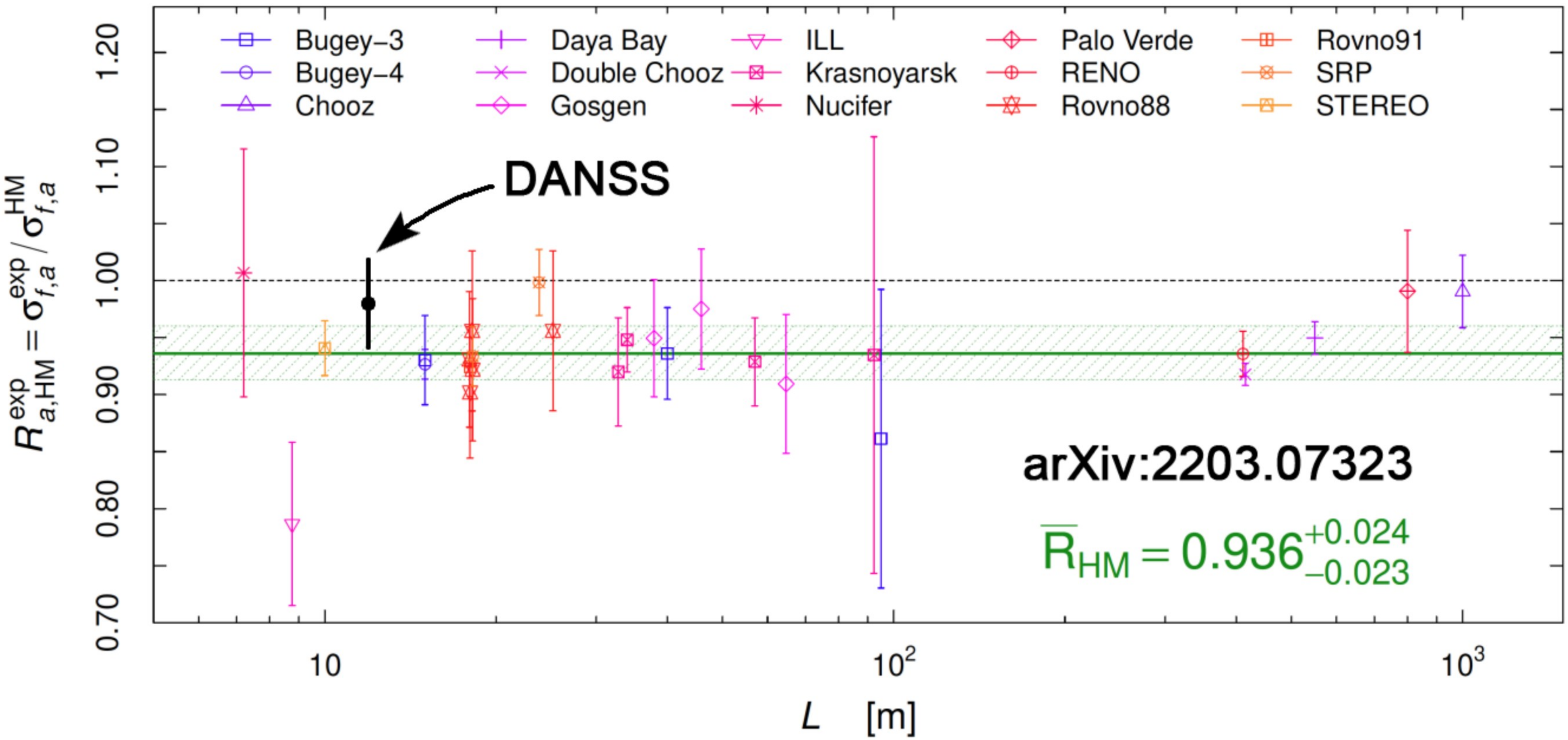
Systematic uncertainties

Source	Uncertainty
Number of protons	2%
Selection criteria	2%
Geometry (distance and fission points distribution)	1%
Fission fractions (from KNPP)	2%
Average energy per fission (Phys. Rev. C **88**, 014605)	0.3%
Reactor power (from KNPP)	1.5%
Backgrounds	0.5%
Total without flux predictions	**4%**
Flux predictions	2-**5%**
Total	5-**7%**



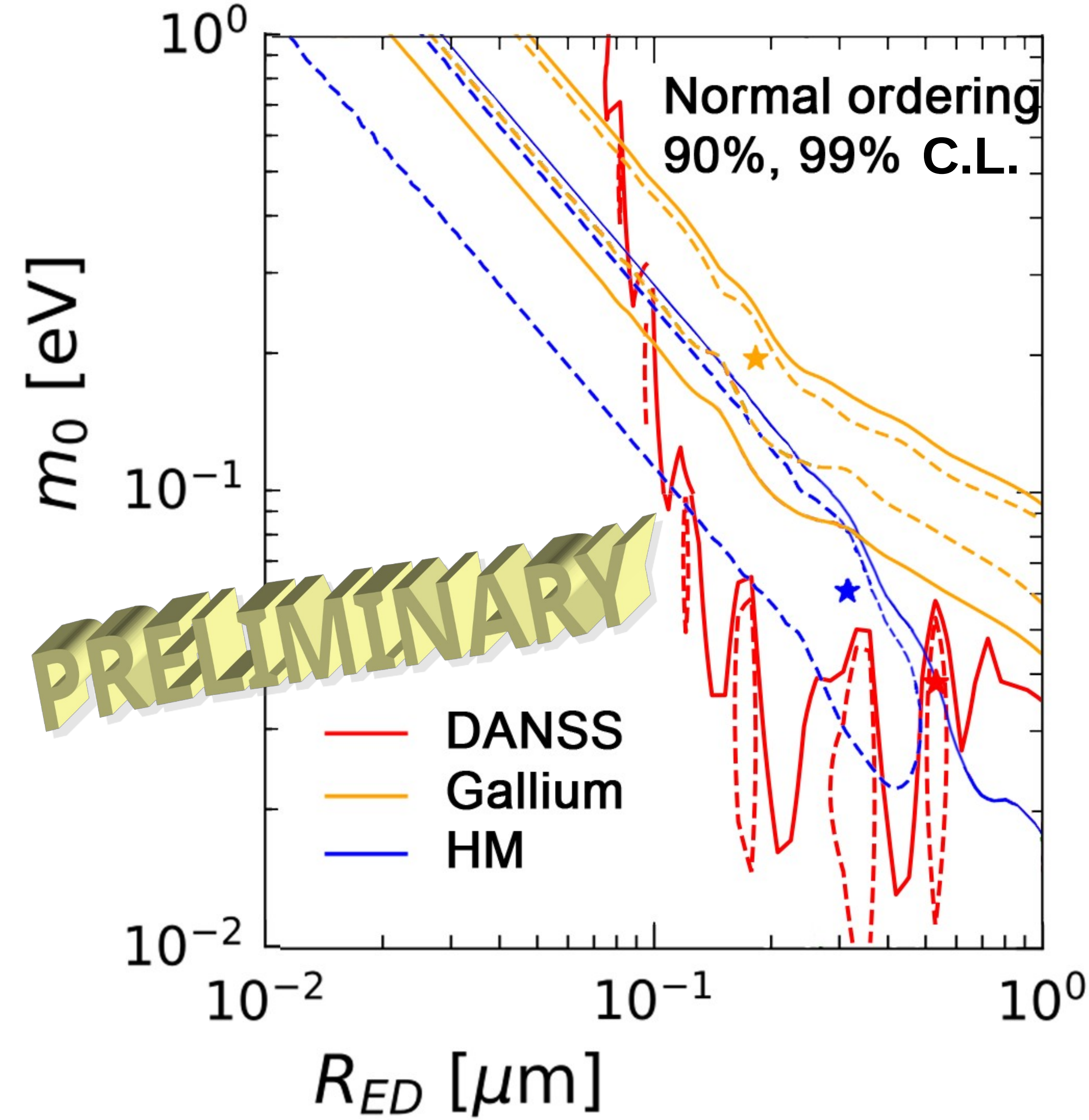
KI model exclusions are slightly stronger

Direct comparison with RAA



Observed to predicted ratio with absolute ν_e counting rates is 0.98±0.04 for HM model, and is 1.02±0.04 for KI model

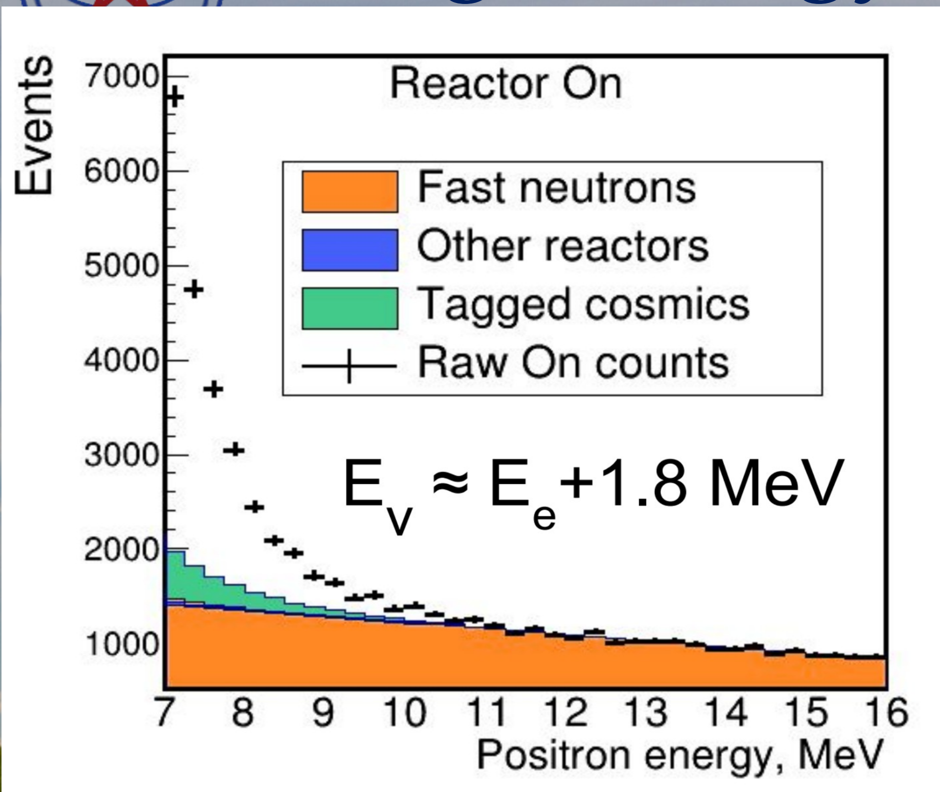
Large extra dimensions

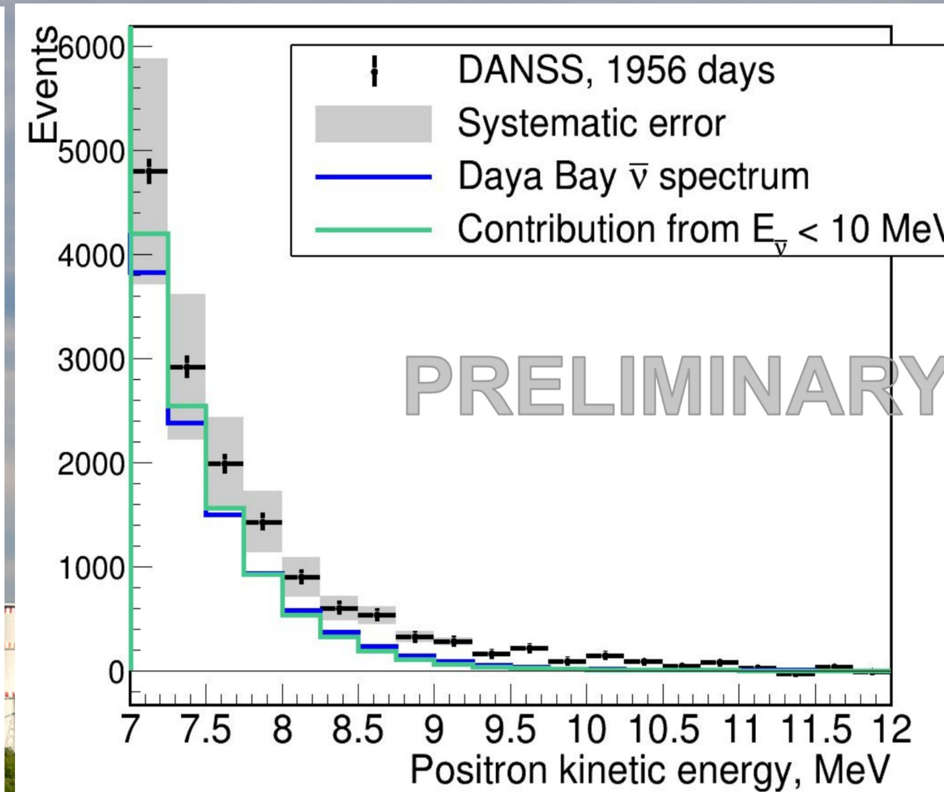


- Another way to solve reactor and gallium anomalies — oscillation to large extra dimensions.
- The analysis is similar to sterile neutrino search, but different L/E pattern.
- Only normal neutrino mass ordering studied so far.
- No statistically significant evidence for LED. The best point significance is 2σ only.
- We exclude large and interesting region preferred by GA and RAA.
- GA best point is excluded at > 3σ level.

- P.A.N. Machado et al., PRD 85, 073012 (2012)
- D.V. Forero et al., PRD 106, 035027 (2022)

High energy antineutrinos





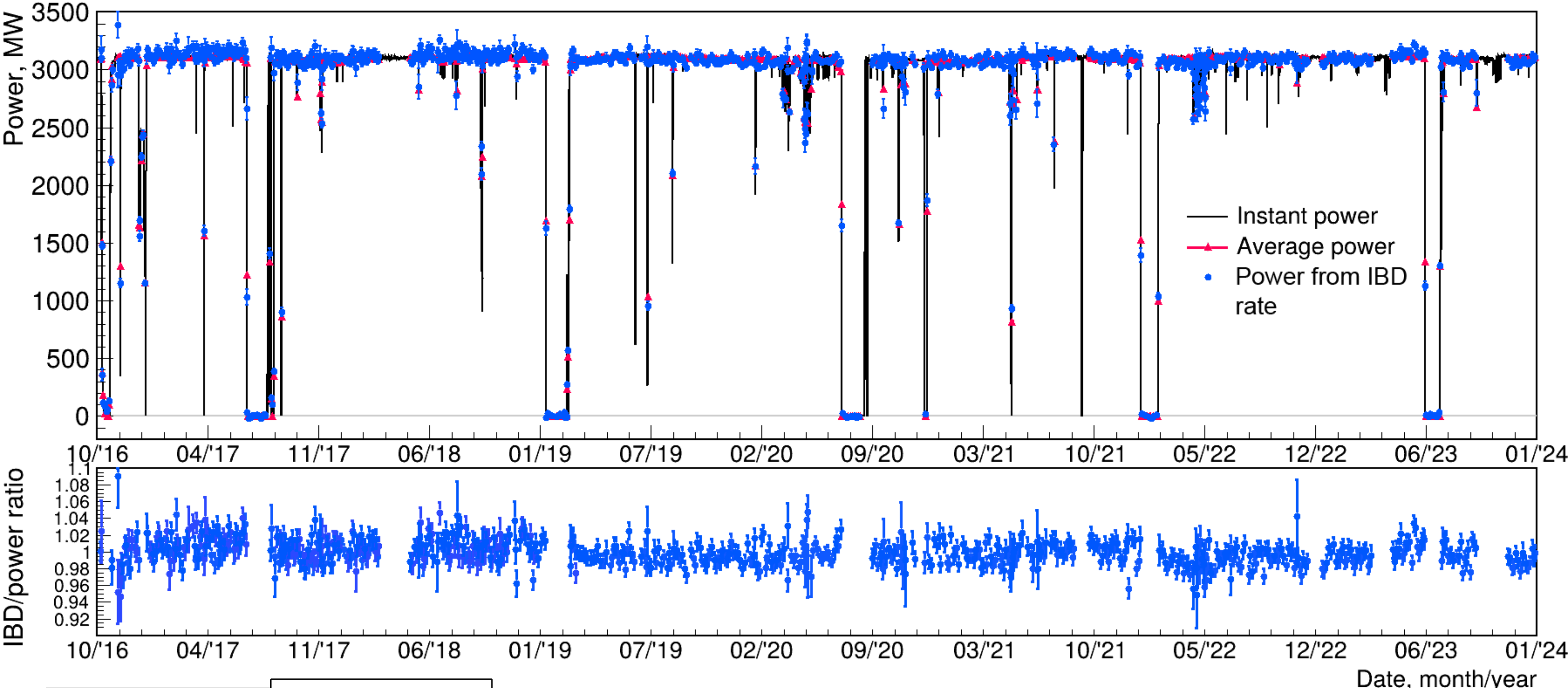
Background subtraction is based on 5 “reactor off” periods

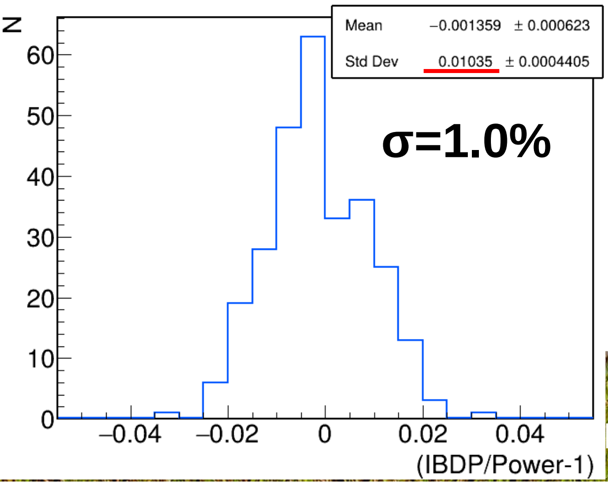
DANSS observes antineutrino with energy > 10 MeV: **$1561 \pm 157_{stat} \pm 168_{sys}$ ev. (6.8σ)**

Scale uncertainty makes the largest contribution to the systematic error

Fraction of high energy events is somewhat larger than at Daya Bay **[PhysRevLett.129.04180]**

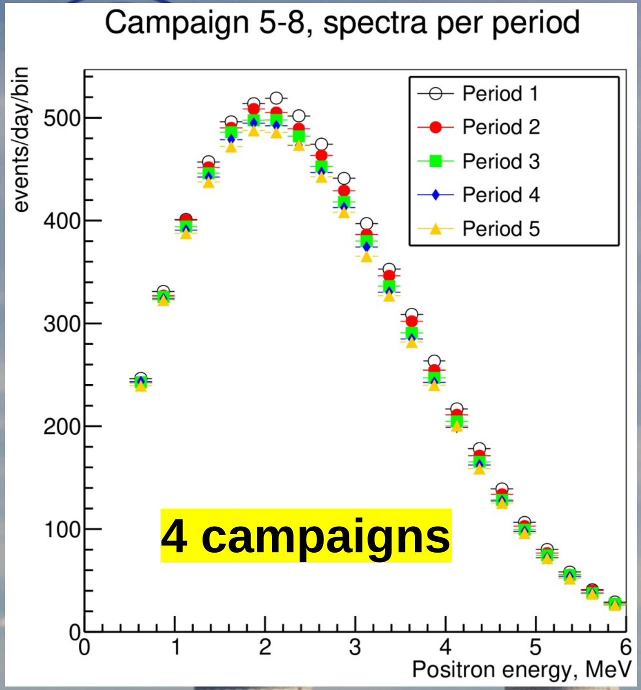
Reactor power measurements during 7+ years





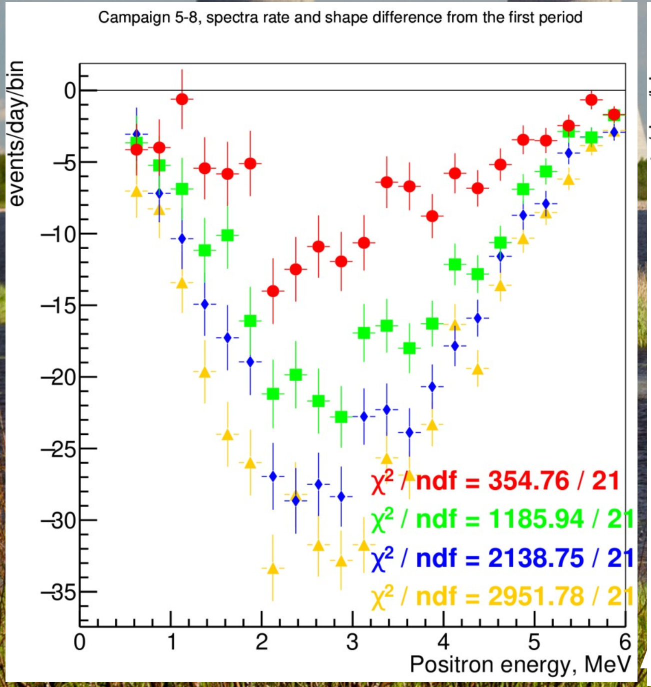
Weekly IBD rate measurements corrected for different detector position, efficiency variation, dead time and fuel evolution. Average statistical error **0.67%**. Residual uncertainty **0.79%** is due to systematic error in both methods and statistical error in conventional method is compatible with **0.8%** error in conventional method reported by KNPP personnel.

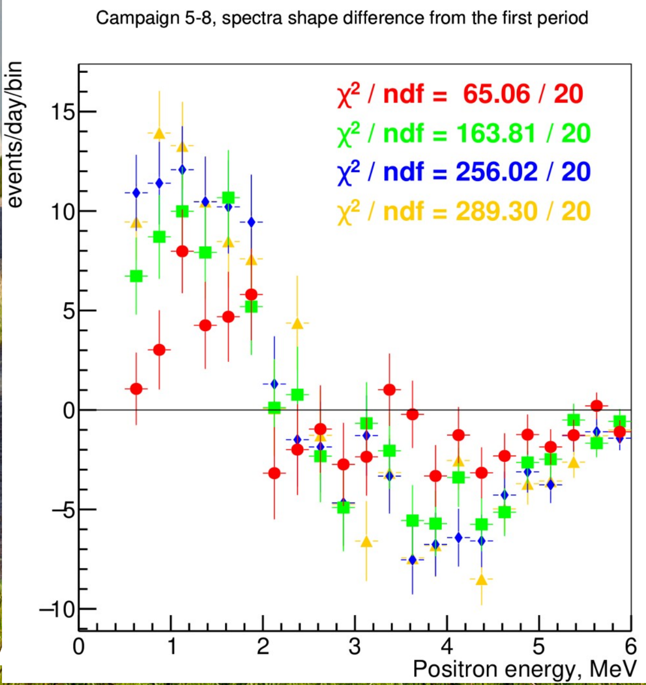
Neutrino spectrum evolution

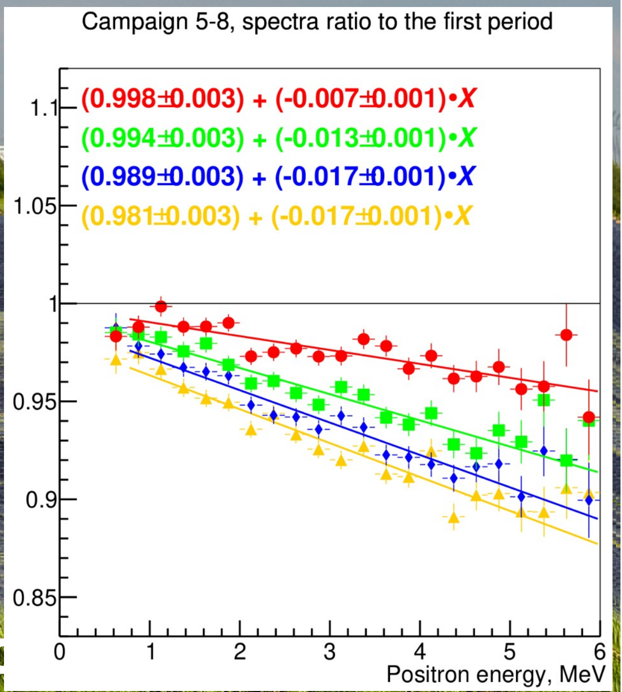


Inspired by E. Christensen, P. Huber, P. Jaffke, and T.E. Shea PRL 113, 042503 (2014)

- The effect is clearly demonstrated at power reactor.
- Campaigns are divided into five 100-days periods.
- Combined statistics for campaigns 5-8 shown.
- 1st to 2nd period ~+60 kg ^{239}Pu => We seen in the ratio at 3.5σ level.
- Both spectrum and rate dependence connected to the fuel burn up are clearly seen

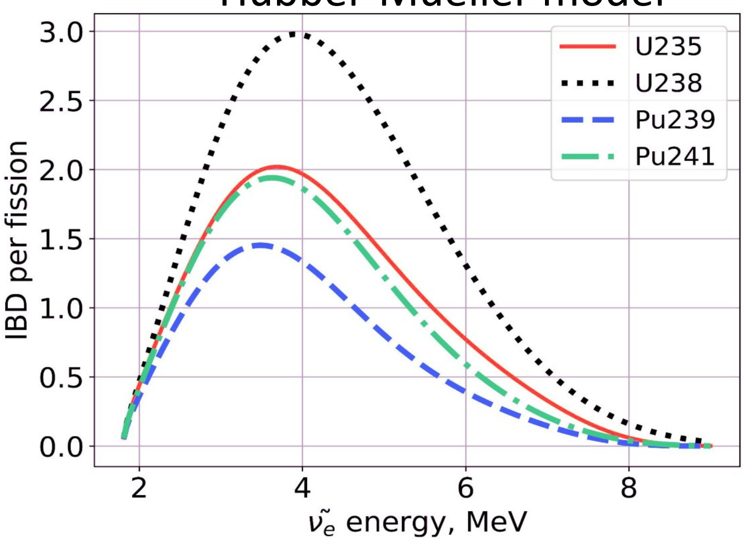




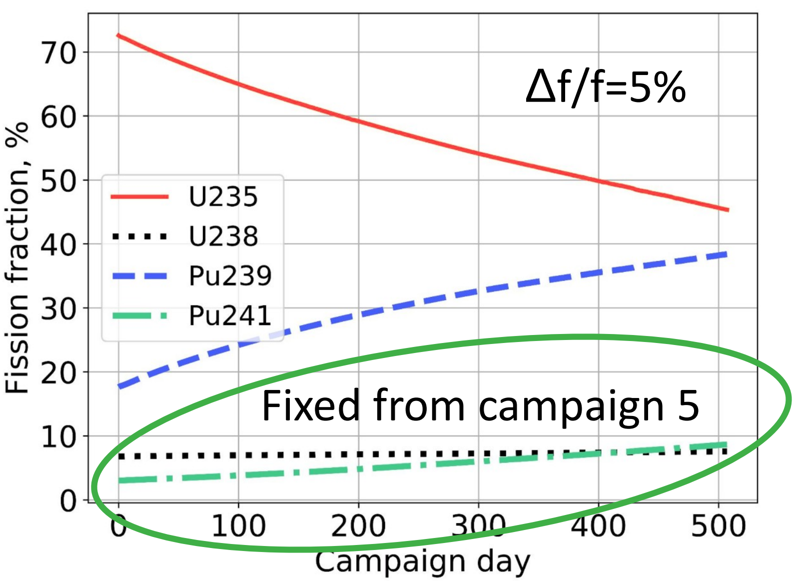


Measurements of fission fractions

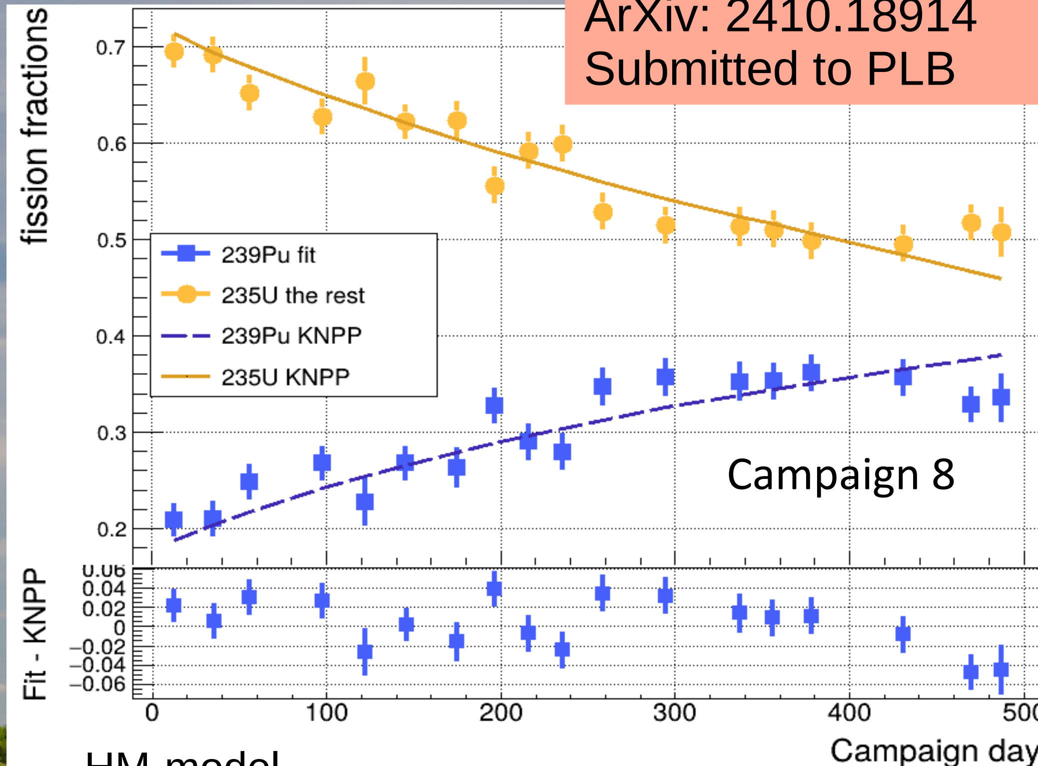
Hubber-Mueller model



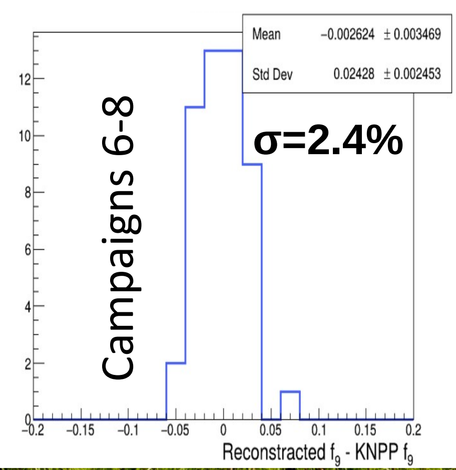
Typical campaign



ArXiv: 2410.18914
Submitted to PLB



HM-model



Fit of the observed spectrum with a sum of model spectra ("bump" region excluded). The resulting fractions of ^{235}U and ^{239}Pu are in agreement with the KNPP calculations within **3%,** which is compatible with KNPP calculations precision.

Determination of the ^{235}U to ^{239}Pu IBD yield ratio

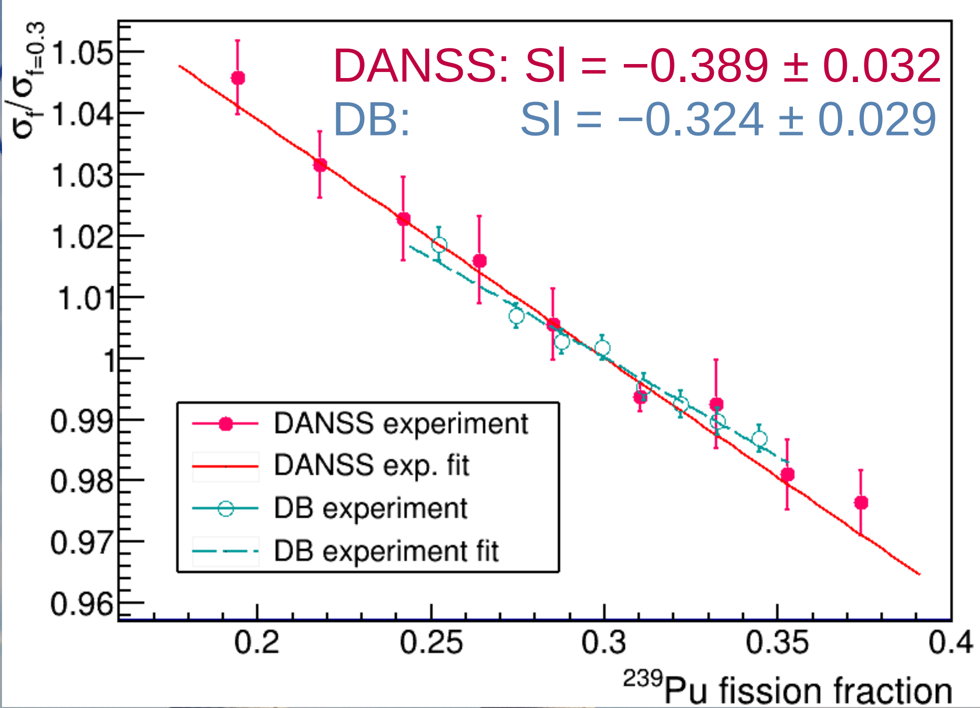
Counts per fission $N = \alpha \cdot (\sigma_8 f_8 + \sigma_1 f_1 + \sigma_5 f_5 + \sigma_9 f_9)$

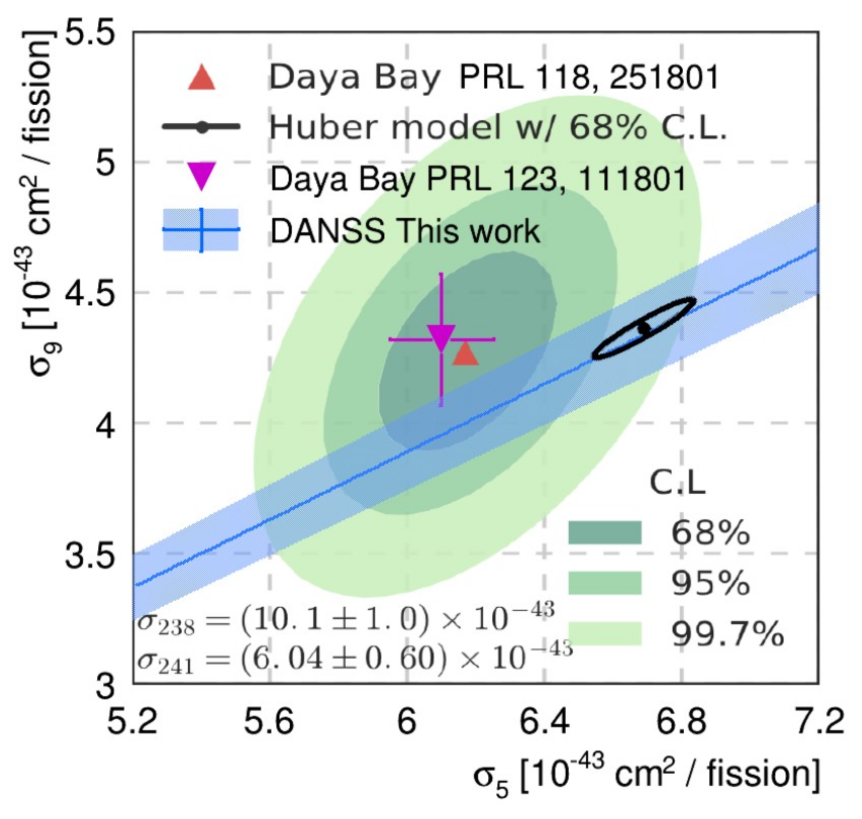
$$\frac{dN}{df_9} = \alpha \cdot \left(\sigma_8 \frac{df_8}{df_9} + \sigma_1 \frac{df_1}{df_9} + \sigma_5 \frac{df_5}{df_9} + \sigma_9 \right)$$

Slope $Sl = \left(\frac{dN}{df_9} \right) / N = \frac{\frac{\sigma_8}{\sigma_9} \frac{df_8}{df_9} + \frac{\sigma_1}{\sigma_9} \frac{df_1}{df_9} + \frac{\sigma_5}{\sigma_9} \frac{df_5}{df_9} + 1}{\frac{\sigma_8}{\sigma_9} f_8 + \frac{\sigma_1}{\sigma_9} f_1 + \frac{\sigma_5}{\sigma_9} f_5 + f_9}$

$$\frac{\sigma_5}{\sigma_9} = -\frac{\frac{\sigma_8}{\sigma_9}(Sl \cdot f_8 - \frac{df_8}{df_9}) + \frac{\sigma_1}{\sigma_9}(Sl \cdot f_1 - \frac{df_1}{df_9}) + (Sl \cdot f_9 - 1)}{Sl \cdot f_5 - \frac{df_5}{df_9}}$$

(σ_8/σ_9 and σ_1/σ_9 are taken from HM)





	σ_5/σ_9
DANSS data	1.541±0.058
Huber-Mueller model	1.53±0.05
Daya Bay data (F. P. An *et al.* PRL **130** (2023), 211801)	1.430±0.048
Our calculations using Daya Bay slope	1.459±0.052

It could be a bit too early to consider RAA solved with new σ_5/σ_9 ratio

ArXiv: 2410.19182
Submitted to PRL

- DANSS recorded the first data in April 2016 and is running now. More than 8.5 million IBD events collected. The experiment is still running.
- We record more than 5 thousand antineutrino events per day in the closest position. Signal to background ratio is > 50.
- A search for sterile neutrinos done using relative counts only (model-independent approach). Two best points observed:

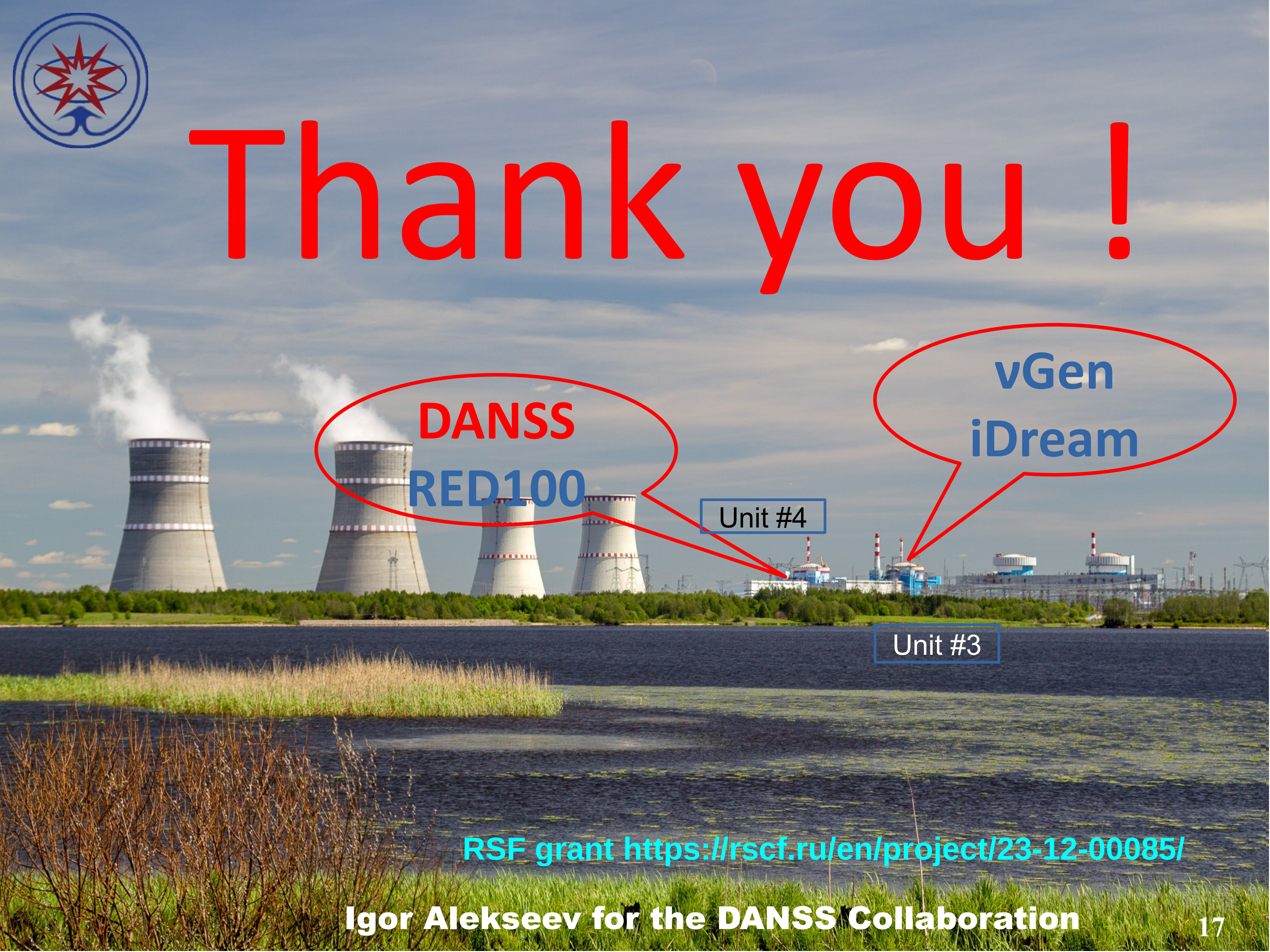
$$\Delta m^2=0.3\ eV^2,\ \sin^2_{ee}2\theta=0.07:\ \Delta\chi^2=-8.0\ (2.0\sigma)$$

$$\Delta m^2=1.3\ eV^2,\ \sin^2_{ee}2\theta=0.016:\ \Delta\chi^2=-7.4$$

This is not statistically significant (2.0σ) to claim an indication of sterile neutrino.

- Analysis using absolute rates allows further (though model dependent) advance into larger Δm^2. It practically excludes all sterile neutrino parameter space preferred by BEST. Observed to predicted ratio with absolute ν_e counting rates is 0.98±0.04 for HM model, and is 1.02±0.04 for KI model.
- We use relative counts at top and bottom positions to search for large extra dimensions (LED) [Normal ordering only so far]. A large exclusion region set covering a very interesting part of LED parameters space, preferred by gallium and reactor anomalies. The significance of DANSS best point $a = 0.536\ \mu m$, $m_0 = 0.038\ eV$ is 2σ only => no evidence of LED oscillations. GA best point is excluded with significance more than 3σ.
- DANSS observes antineutrino with energy > 10 MeV: $1561 \pm 157_{stat} \pm 168_{sys}$ (6.8σ).
- We present 7+ years of power reactor monitoring. 4 full fuel cycles observed.
- A weekly reactor power measurement has precision 1.0% and a possible systematic error <0.8%, which also includes errors in the conventional measurements.
- We measure ^{235}U and ^{239}Pu fission fractions and agree within 3% with KNPP calculations.
- In both cases the agreement of the two independent methods based on very different physics principles provides confidence in both of them.
- The IBD yield ratio $\sigma_5/\sigma_9 = 1.541\pm0.058$ is directly determined based on the analysis of the relative changes in the detector counting rate throughout the reactor campaign. The value obtained is in a good agreement with HM model and slightly larger then measured by Daya Bay.
- Our analysis plans are to finalize the energy calibration and to include larger E_{e+} range in the analysis. We are also working on detector upgrade aimed to reach 12% resolution @ 1 MeV.

Thank you !



RSF grant https://rscf.ru/en/project/23-12-00085/

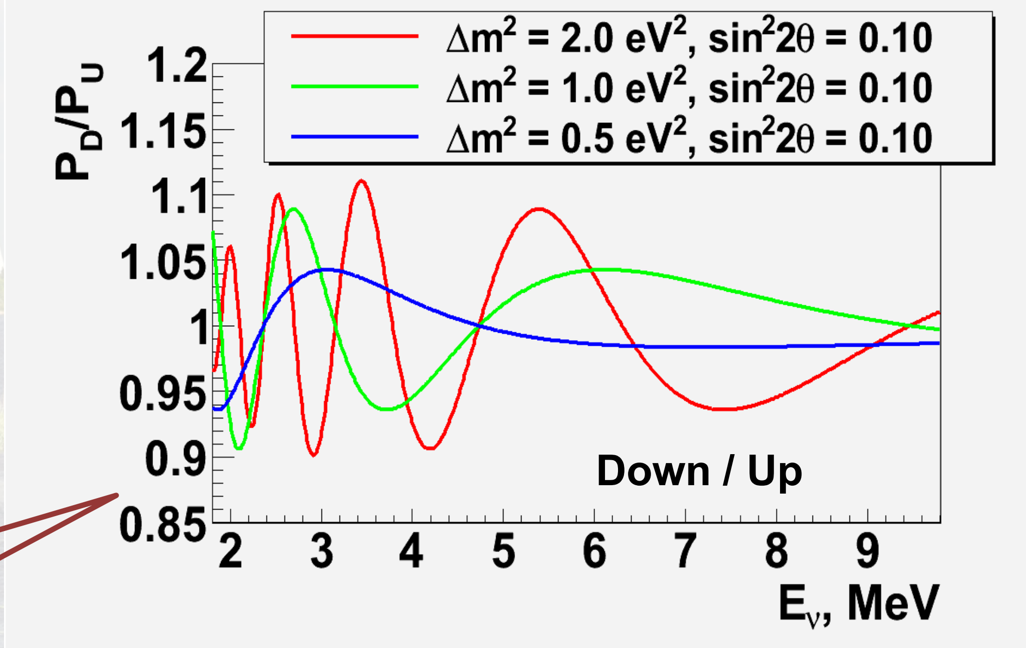
Igor Alekseev for the DANSS Collaboration

In a simple model with the 4th neutrino survival probability of electron antineutrino from the reactor is given by the formula:

$$P_{ee}^{2\nu}(L) = 1 - \sin^2(2\theta_i)\sin^2\left(1.27\frac{\Delta m_i^2[\mathrm{eV}^2]L[\mathrm{m}]}{E_{\bar{\nu}_e}[\mathrm{MeV}]}\right)$$

DANSS: Measure ratio of neutrino spectra at different distance from the reactor core – both spectra are measured in the same experiment with the same detector. No dependence on the theory, absolute detector efficiency or other experiments.

Naïve ratio without smearing by reactor and detector sizes and the resolution

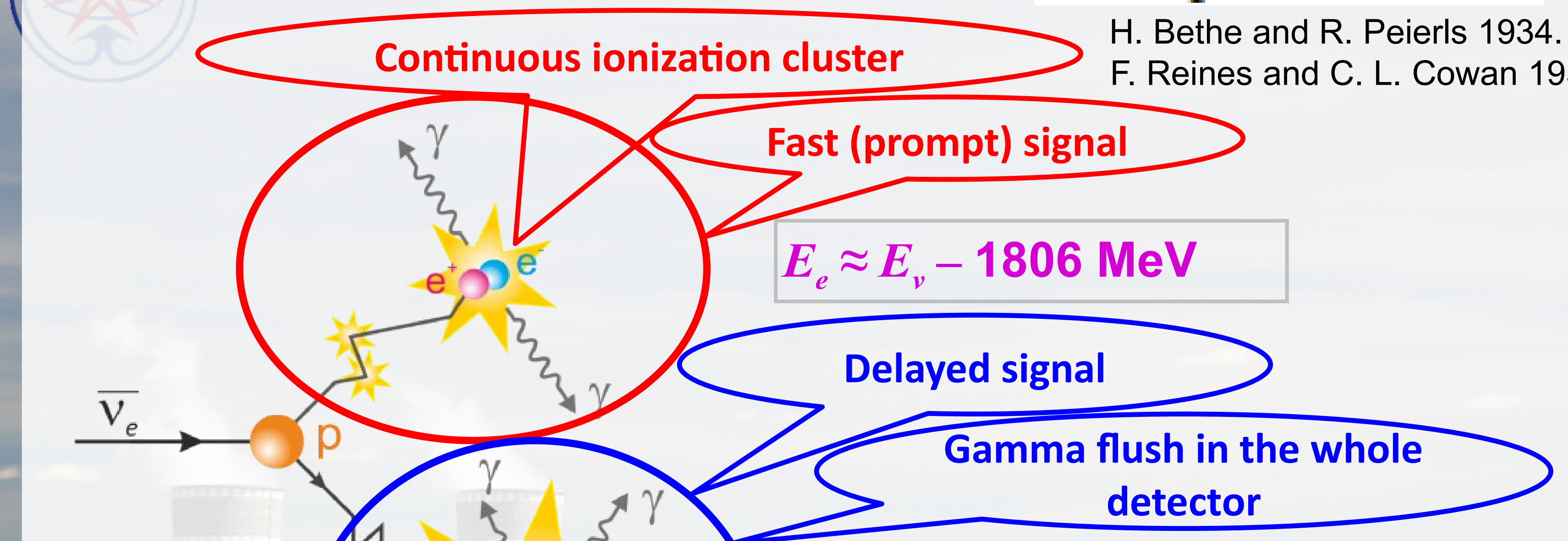


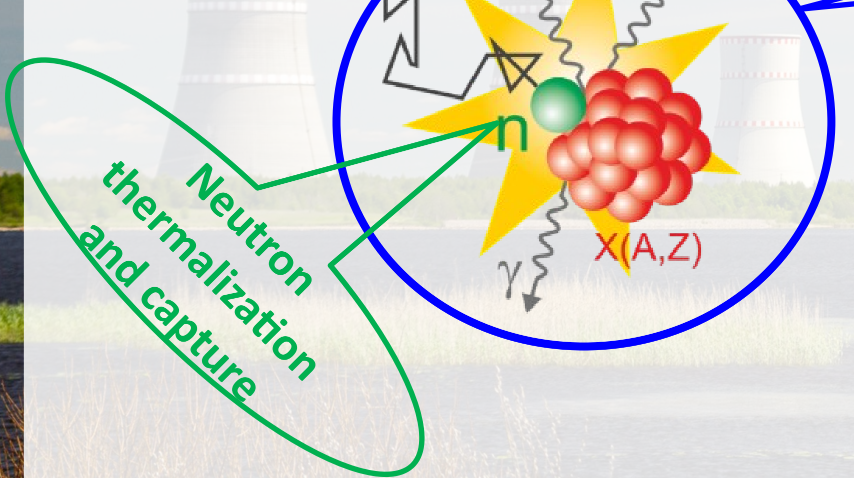
Inverse Beta-Decay (IBD)

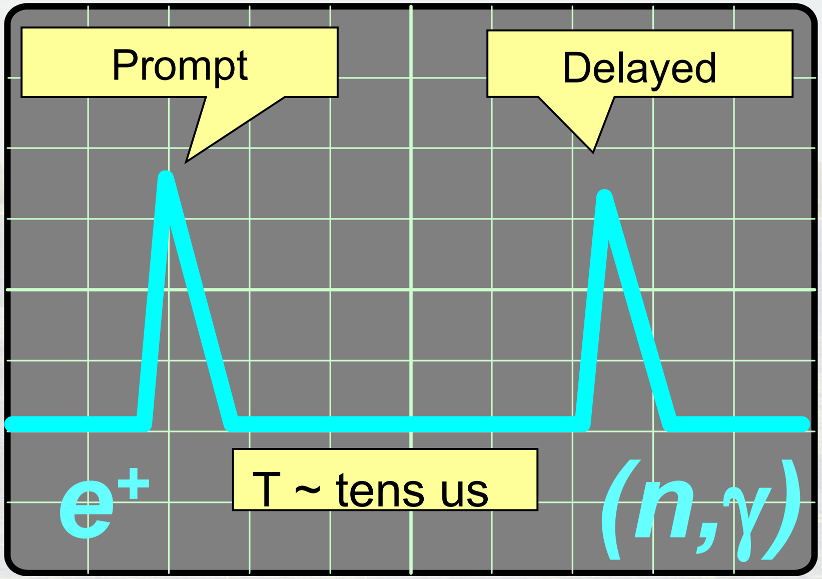
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

H. Bethe and R. Peierls 1934.
F. Reines and C. L. Cowan 1953-56

$E_e \approx E_\nu$ – 1806 MeV

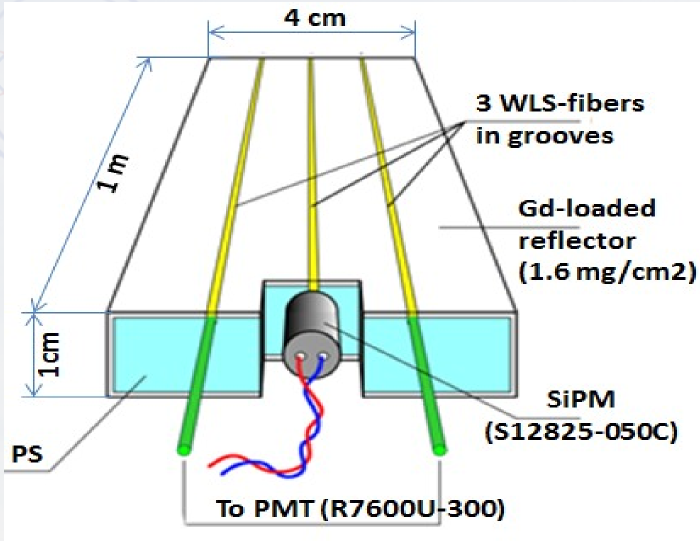


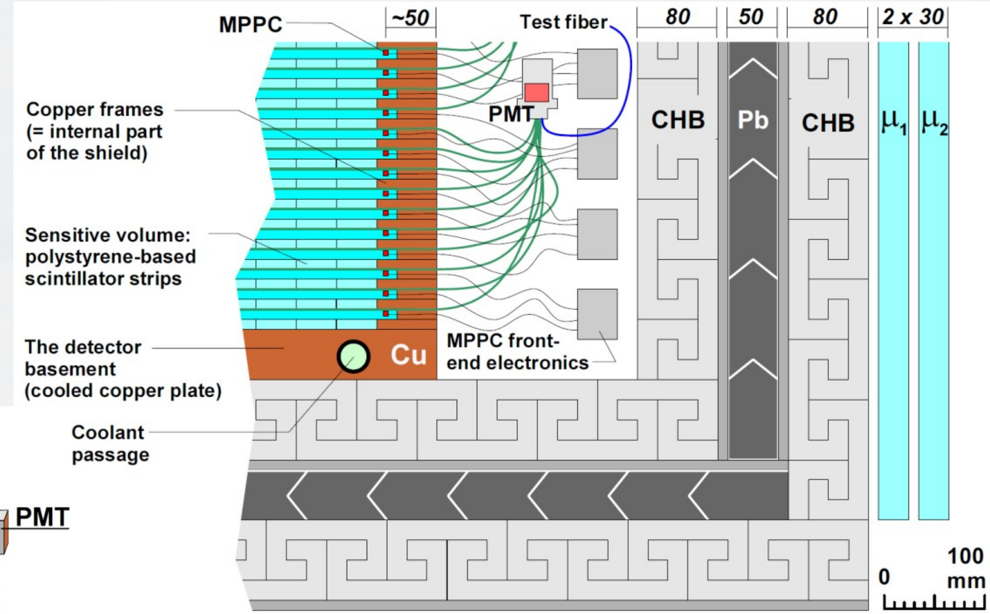




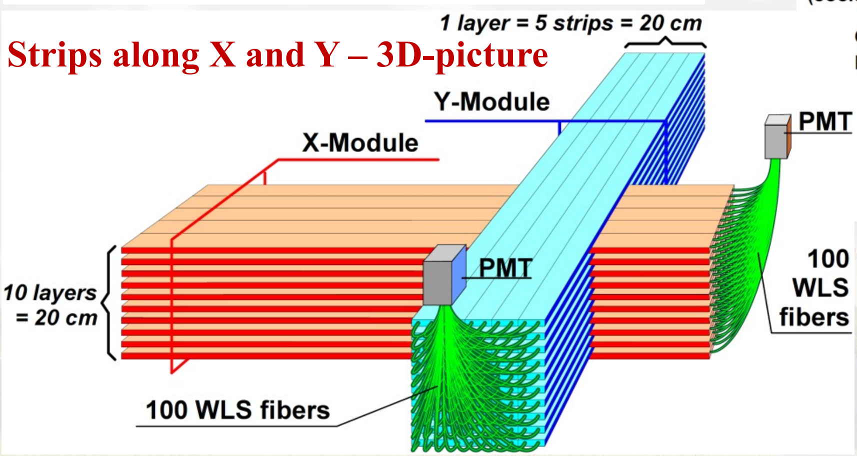
Detector of the reactor AntiNeutrino based on Solid-state Scintillator

(ITEP and JINR Collaboration)





Strips along X and Y – 3D-picture

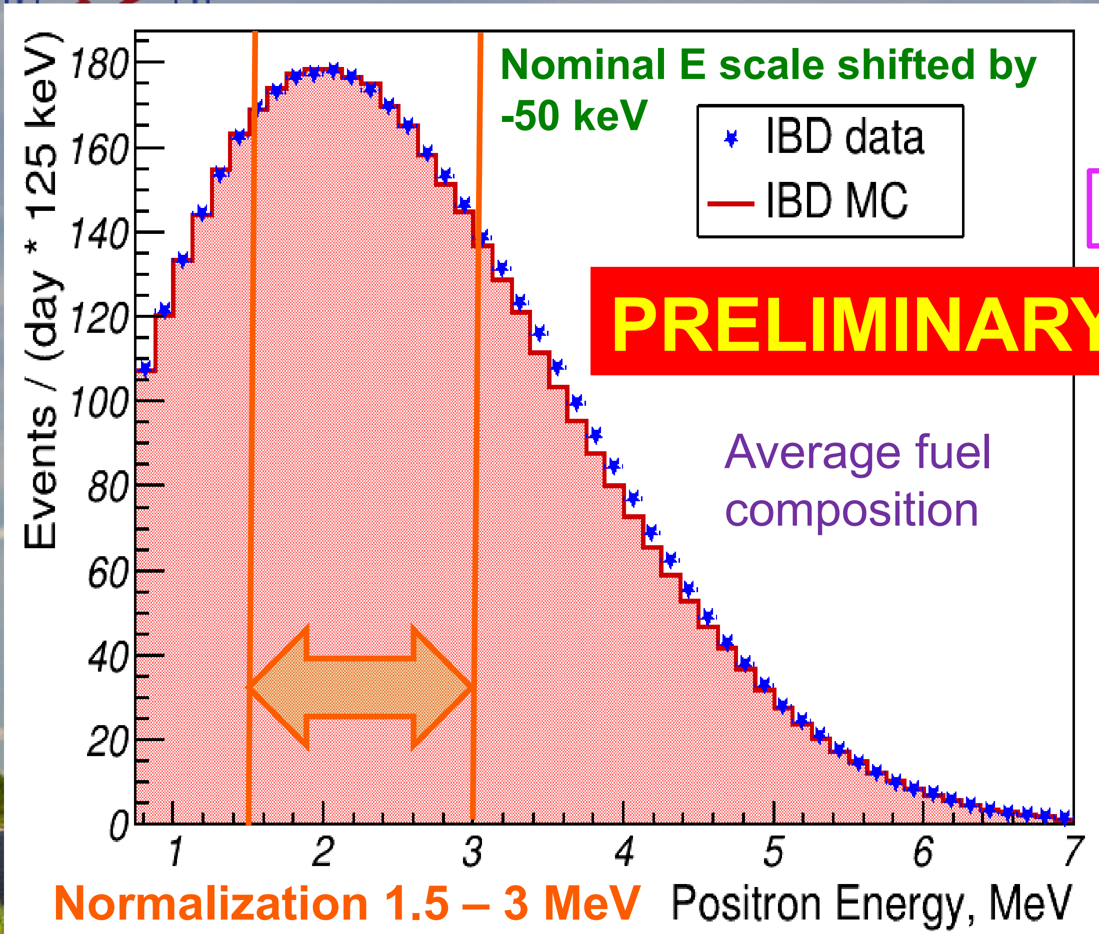


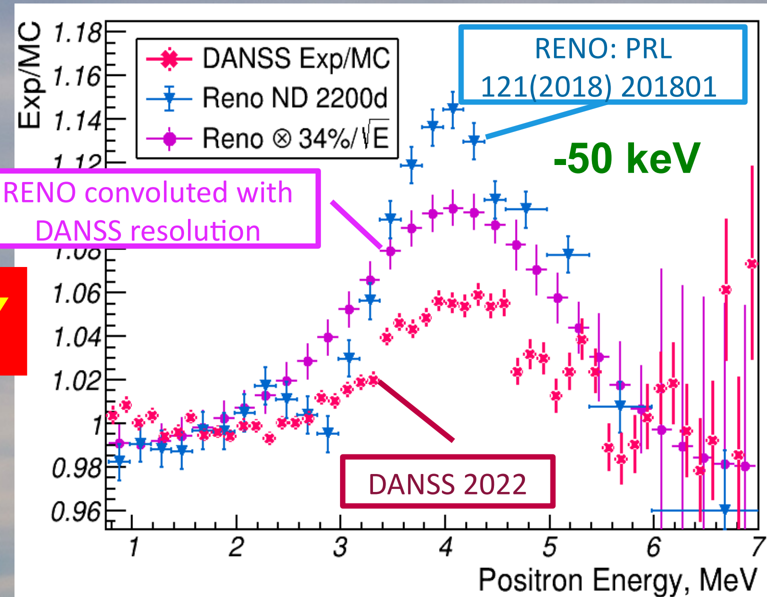
- Scintillation strips 10x40x100 mm³ with Gd-dopped coating (0.35%wt)
- Double PMT (groups of 50) and SiPM (individual) readout
- SiPM: 18.9 p.e./MeV & 0.37 X-talk
- PMT: 15.3 p.e./MeV
- 2500 strips = 1 m³ of sensitive volume

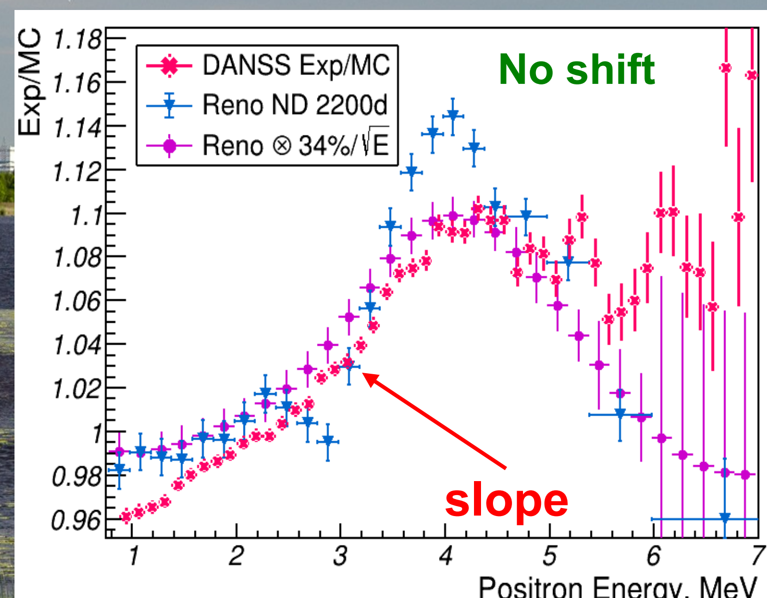
- Multilayer closed passive shielding: electrolytic copper frame ~5 cm, borated polyethylene 8 cm, lead 5 cm, borated polyethylene 8 cm
- 2-layer active μ-veto on 5 sides
- Dedicated WFD-based DAQ system
- Total 46 64-channel 125 MHz 12 bit Waveform Digitisers (WFD)
- System trigger on certain energy deposit in the whole detector (PMT based) or μ-veto signal
- Individual channel selftrigger on SiPM noise (with decimation)

JINST 11 (2016) no.11, P11011

Positron spectrum comparison to H-M model

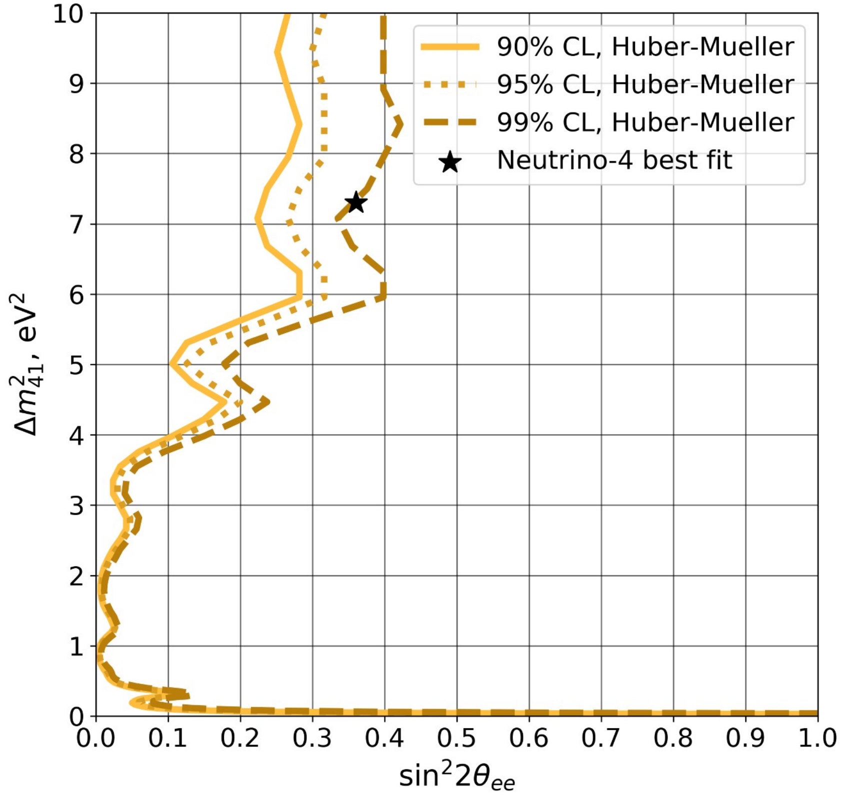


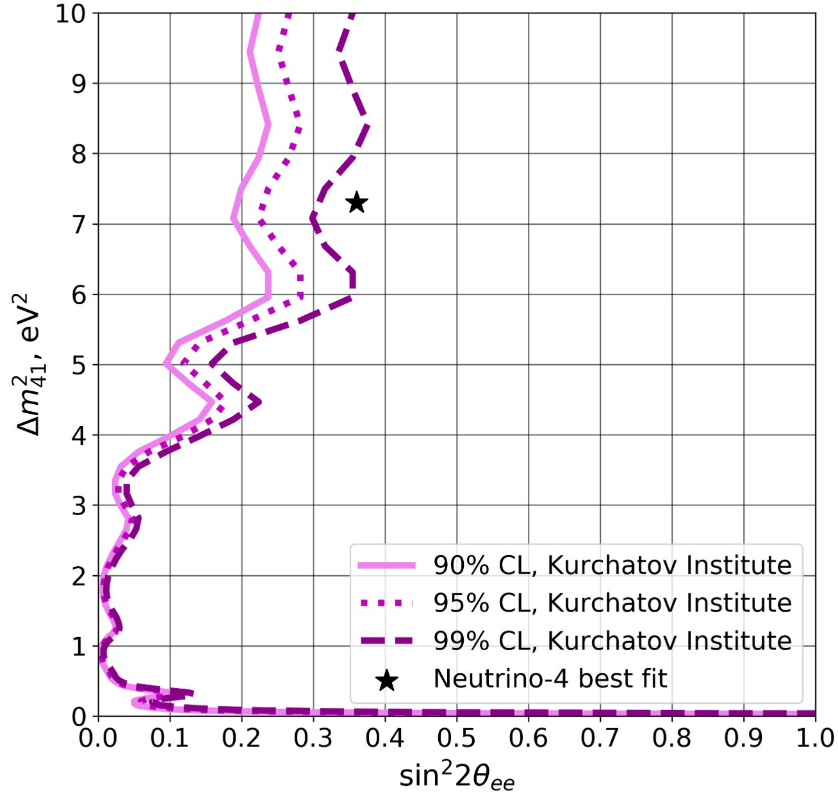




- New energy calibration
- Strong dependence on energy shift and scale
- Effect (if does exist) looks twice smaller than expected from other measurements

Using absolute counting rates





Large extra dimensions

- Neutrino oscillations (case of n=1, other are much smaller if exist)
  - Right neutrinos ν_R (and $\bar{\nu}_L$) being $SU(2)$ singlets can oscillate to LED.
  - An amplitude for survival probability for $\bar{\nu}_{ee}$ is given by

$$A_i \approx \left(1 - \frac{\pi^2}{6} m_i^2 a^2\right) \exp\left(i \frac{m_i^2 L}{2E}\right) + 2 m_i^2 a^2 \exp\left(i \frac{m_i^2 L}{E}\right) \sum_{n=0}^{\infty} \frac{\exp\left(i \frac{n^2 L}{2 e a^2}\right)}{n^2}, a m_i \ll 1$$

where m_i is a mass of i-th neutrino state and $\frac{n}{a} = m_n^{KK}$ - mass of n-th Kaluza-Klein state [1]

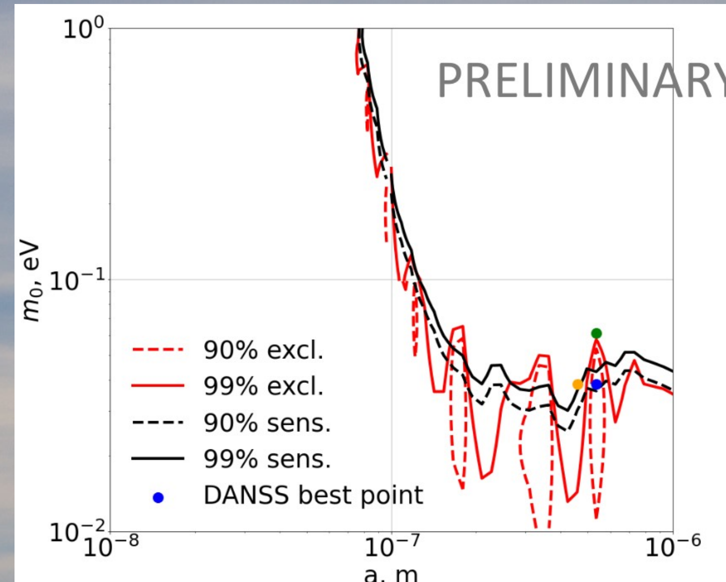
$$\bar{\boldsymbol{S}}_{MC} = \sum_{L\,(r_d, r_r)} \left(\left| Amplitude\left(\frac{\boldsymbol{E}_{\bar{\nu}}}{L}, a, m_0\right) \right|^2 \cdot profile(r_r) \cdot spectra(\boldsymbol{E}_{\bar{\nu}}) \cdot \frac{1}{L^2} \right) @M_{response}$$

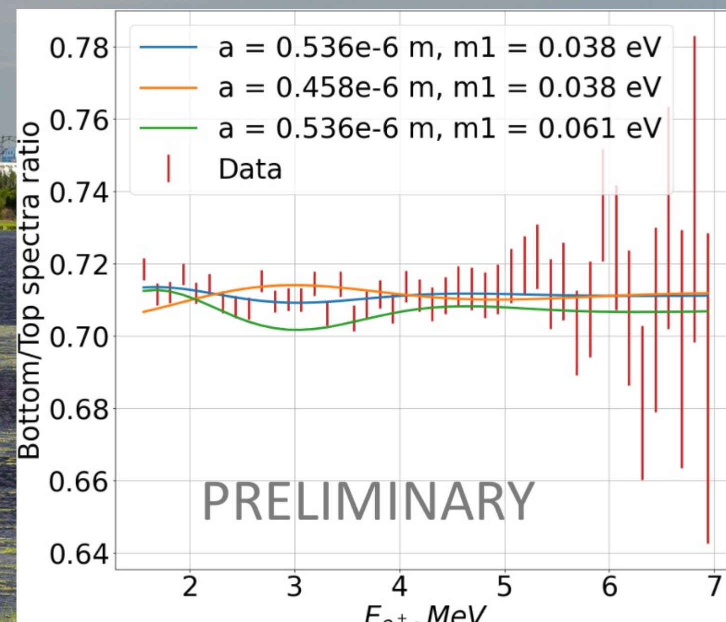
Oscillations to LED | Distribution of fission points | $\bar{\nu}$ energy spectrum | Geometric flux attenuation | Modelled matrix of detector's response

Test statistics

$$\chi^2 = \sum_{bins} \frac{(R_i^{MC}(\eta) - R_i^{Data})^2}{\sigma_i^2} + \sum_{syst} \frac{(\eta - \eta_0)^2}{\sigma_\eta^2}$$

- R – ratio of spectra in Bottom and Top position
- σ – experimental error
- η – systematic parameter:
  - Relative efficiency k: $k_0 = 1, \sigma_k = 0.3\%$
  - Background b: $b_0 = 0, \sigma_b = 35\%$ of subtracted correlated background [3]





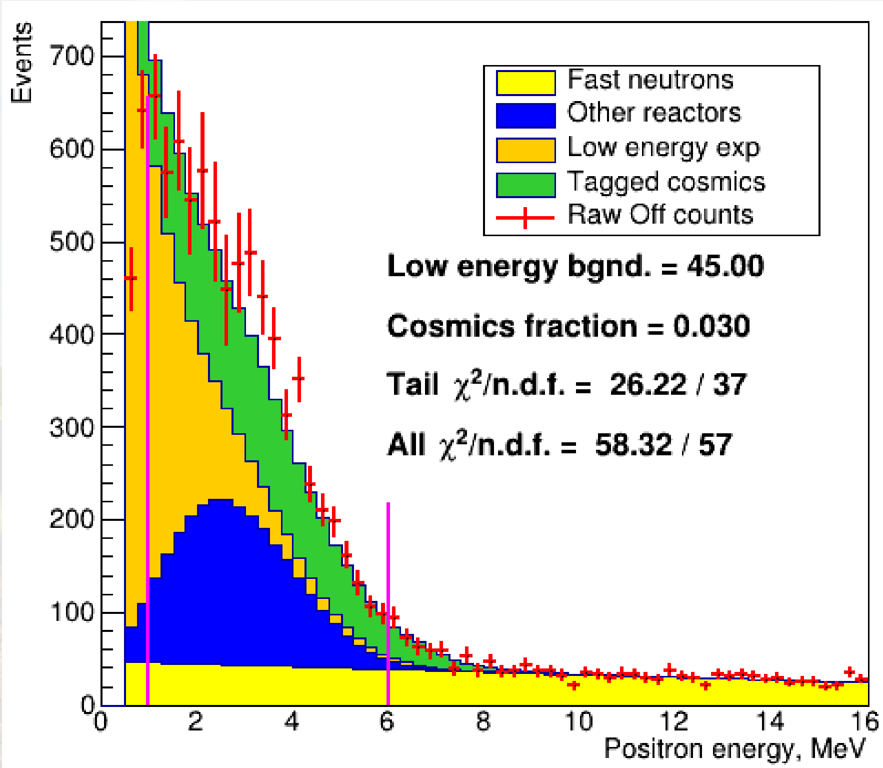
Reactor off background subtraction

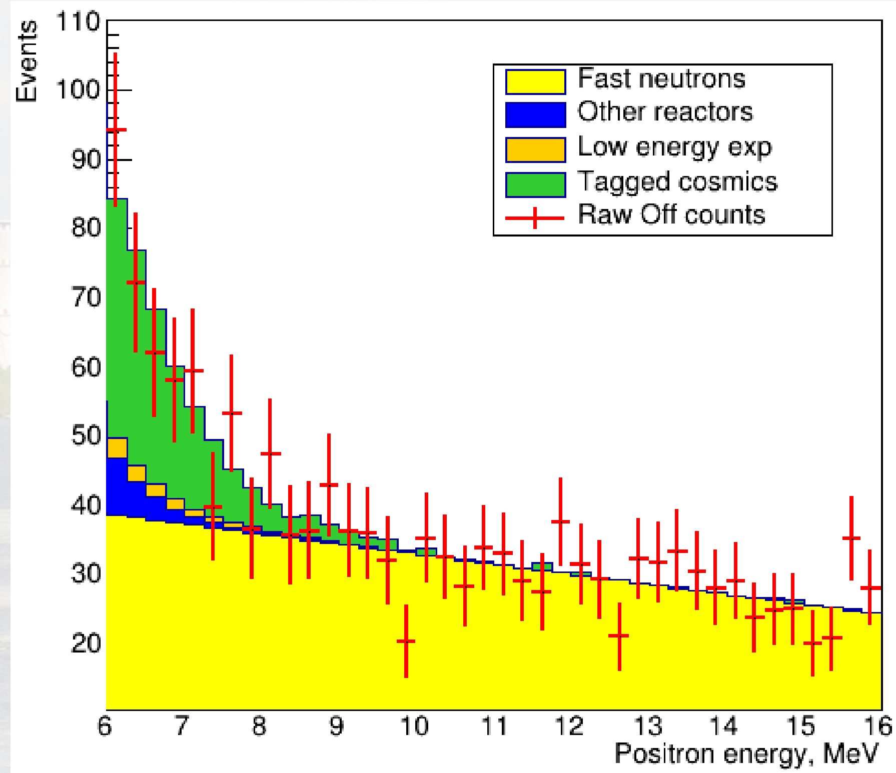
Fast neutron background is a line extrapolation from 11-16 MeV.

Neutrinos from the adjacent reactors — 0.6 % of the top position counts at reactor on.

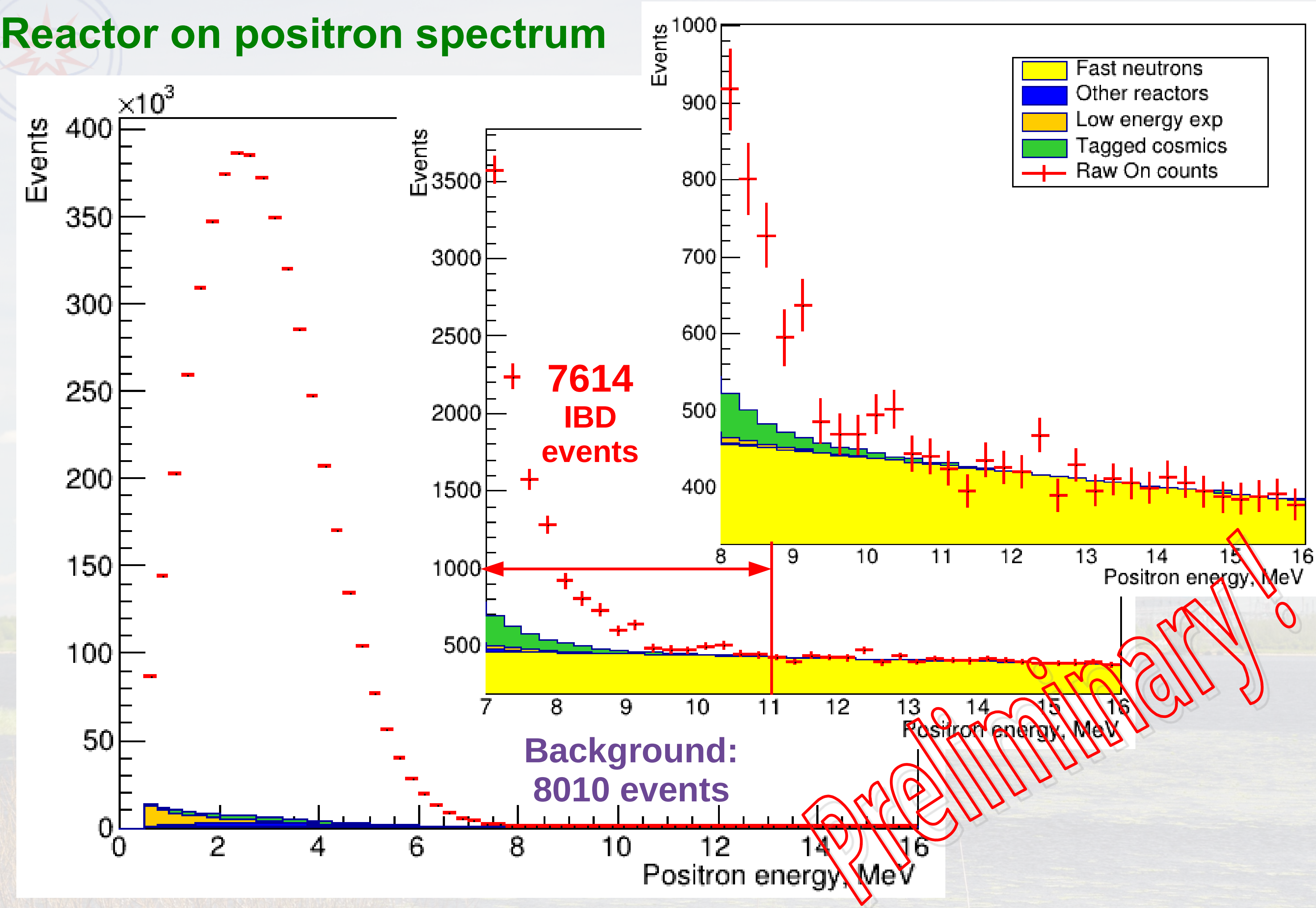
Background from VETO inefficiency (missed muons) is from and approximation of reactor off spectrum above 6 MeV by scaling spectrum from tagged muon background events.

The residual background at low energies is appriximized by the function $e^{-(E/1.0\ МэВ)}$. The contribution is optimized using reactor off data. It is small at high energies.

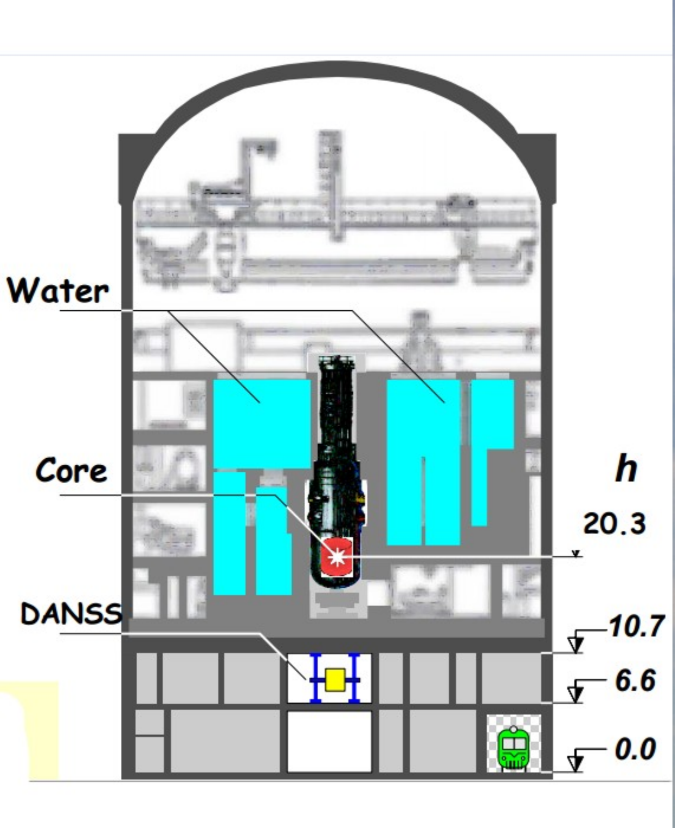




Reactor on positron spectrum

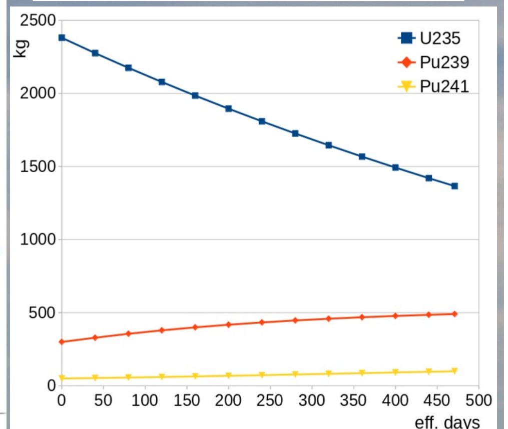


Reactor WWER-1000: 3.1GW$_{th}$



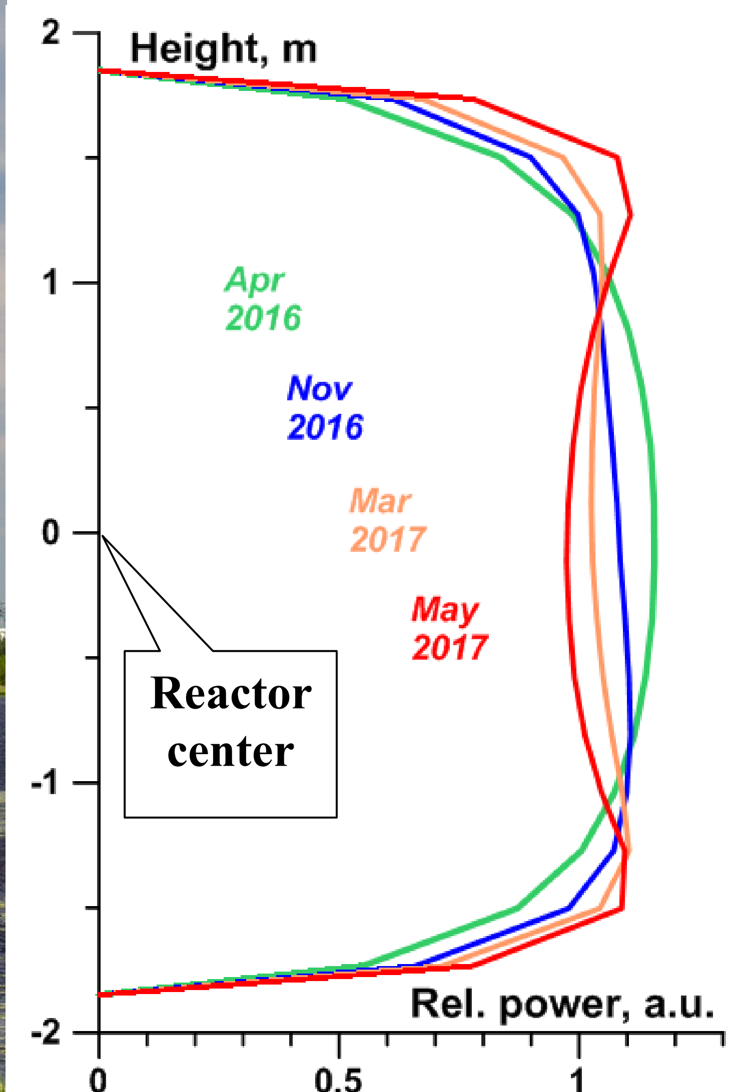
LEU 4.4-4.7% ^{235}U

Main fuel nuclei



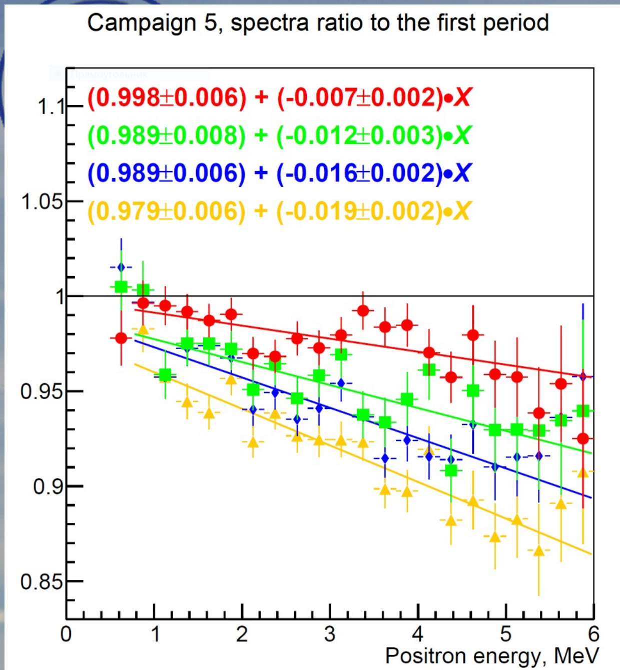
+70 t ^{238}U

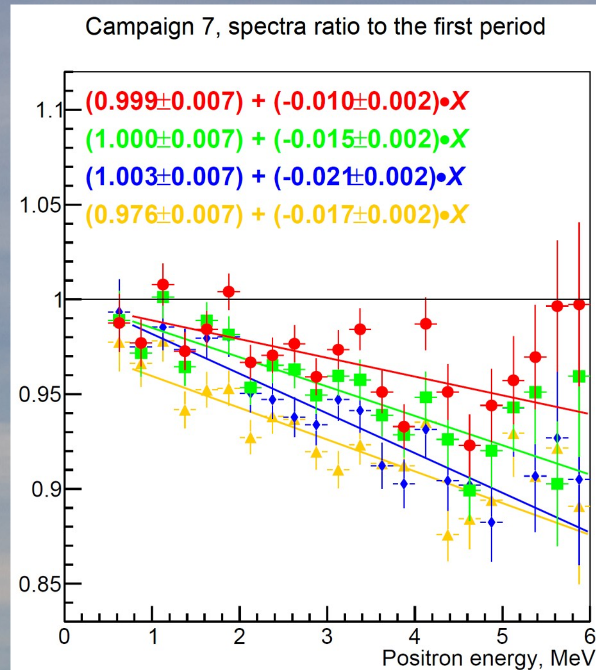
Reactor vertical burning profile for 100% power during the campaign



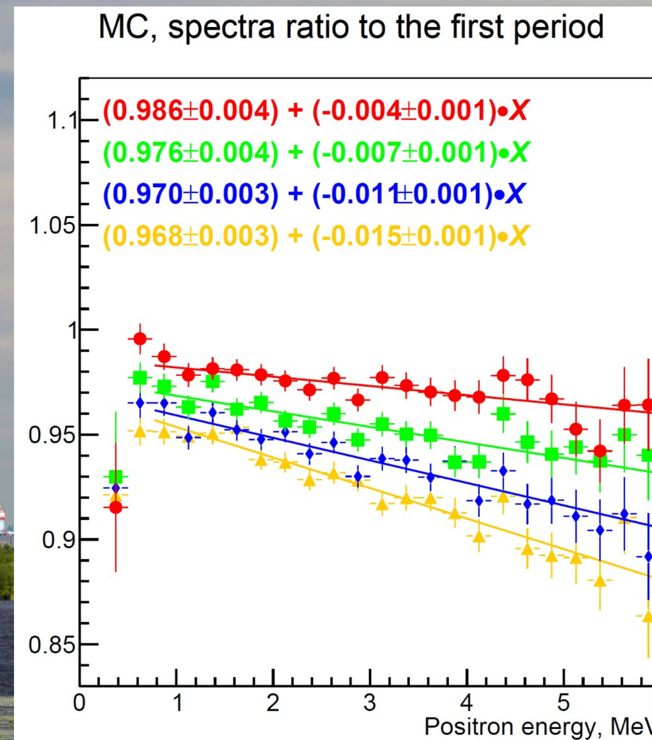
Fission fractions

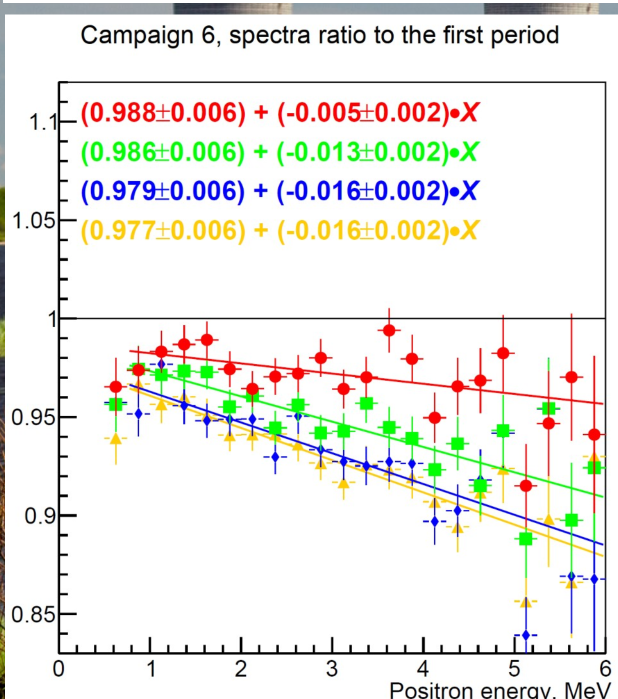
	Begin 4	End 4	Begin 5	End 5	Begin 6	End 6	Begin 7
^{235}U	63.5%	44.1%	65.8%	43.9%	66.3%	45.6%	68.7%
^{238}U	6.7%	7.8%	6.9%	7.8%	6.5%	7.3%	6.7%
^{239}Pu	26.7%	39.3%	24.9%	39.4%	24.8%	38.6%	22.8
^{241}Pu	2.7%	8.6%	2.2%	8.6%	2.3%	8.6%	1.7%

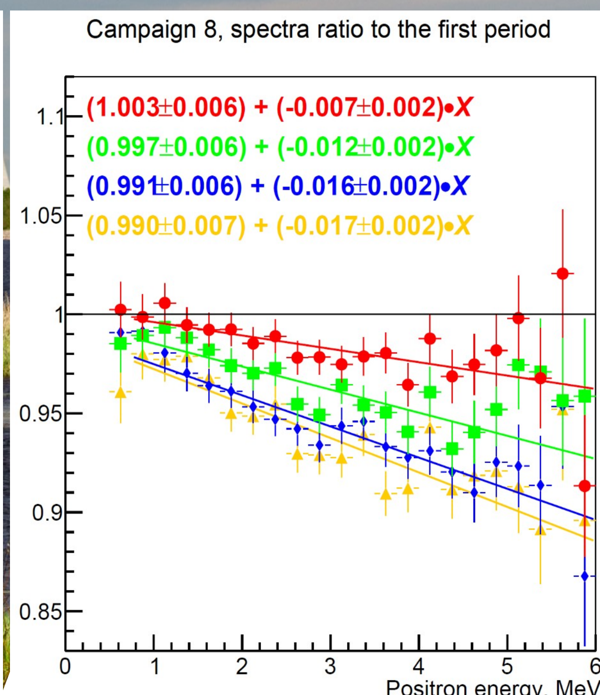




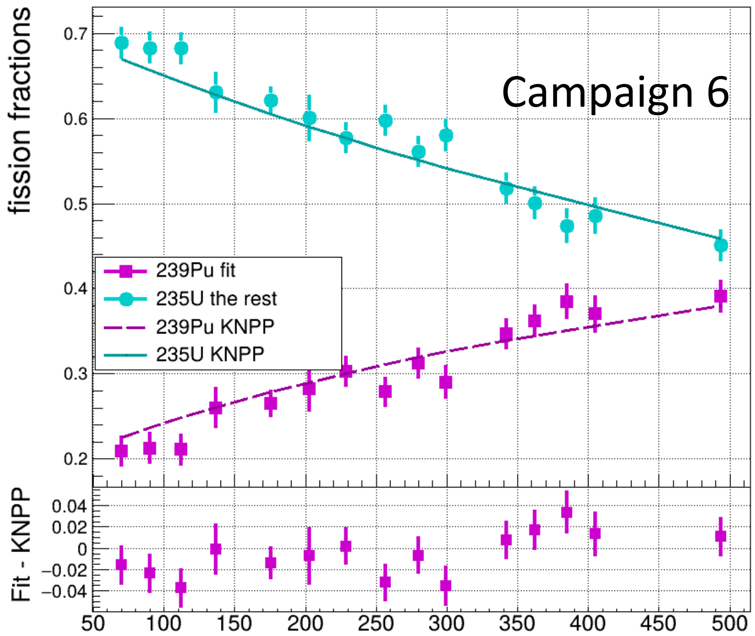
HM model, ~ 2.5 campaigns statistics

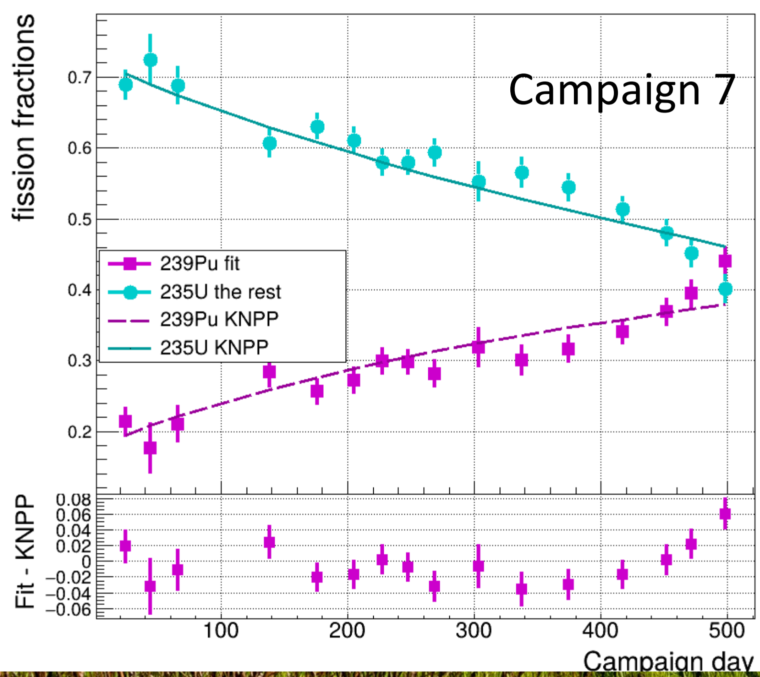


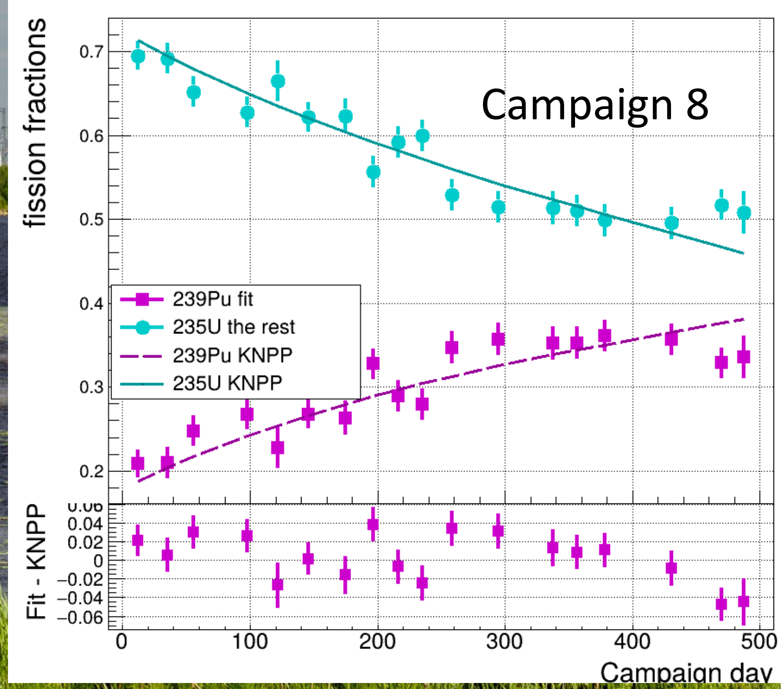




Fission fractions reconstruction for campaigns 6-8

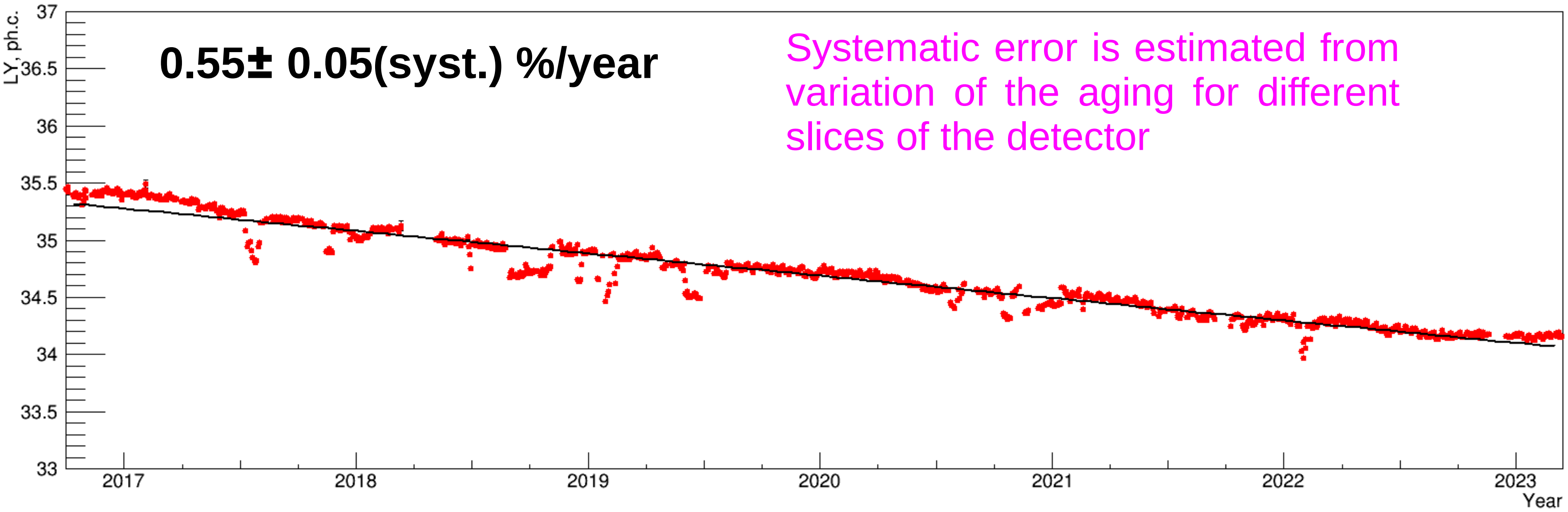






Aging of DANSS scintillator

JINST 19 (2024) P04031

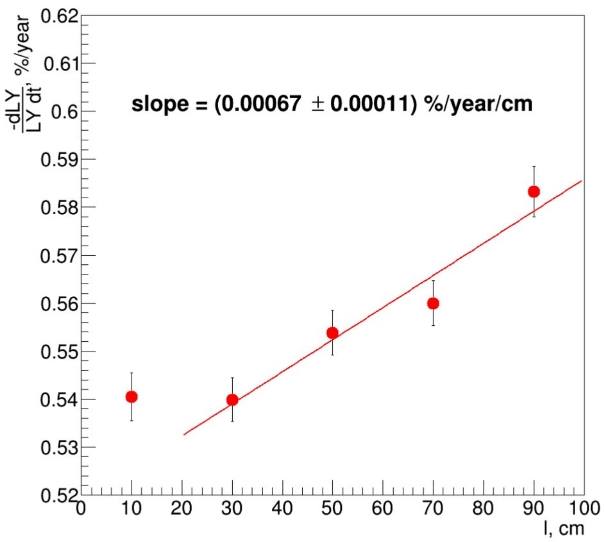


0.55± 0.05(syst.) %/year

Systematic error is estimated from variation of the aging for different slices of the detector

$$\frac{1}{L_{\rm att}}\frac{\partial L_{\rm att}}{\partial t} = L_{\rm att}\frac{\partial}{\partial l}\left(\frac{1}{LY}\frac{\partial LY}{\partial t}\right)$$

L_{att} = 394 cm



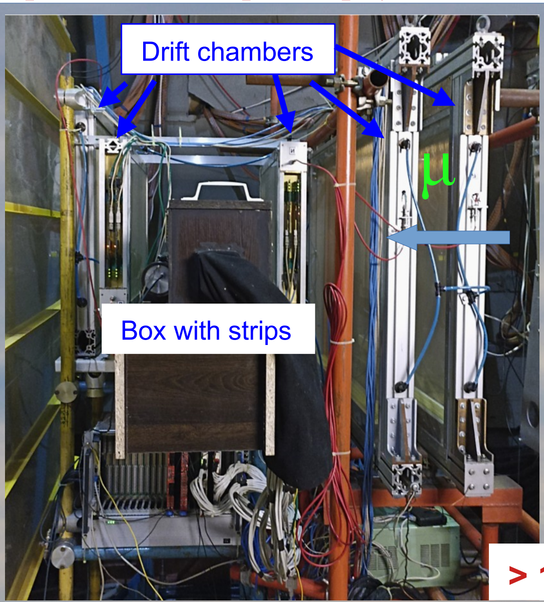
We can not separate aging of the scintillator and of the conversion efficiency of the WLS fiber. But we observe a hint of some decrease in its attenuation length. The increase of aging effect with the distance from SiPM gives an estimation of WLS attenuation length shortening $-dL_{att}/dt$ = **0.26 ± 0.07**(stat.) %/year

The DANSS upgrade

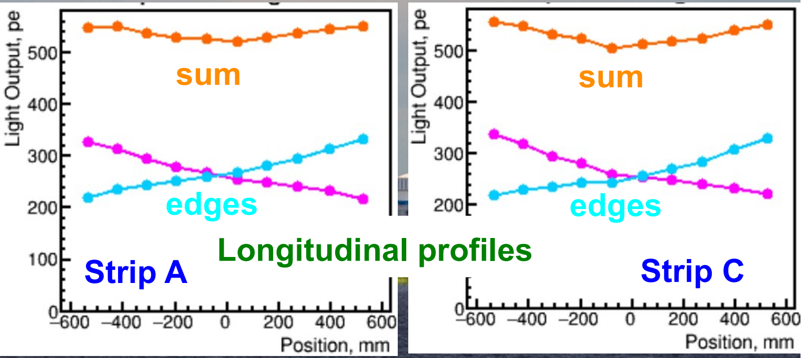
Main goal of the upgrade is to improve energy resolution:
34%/√E --> 12%/√E

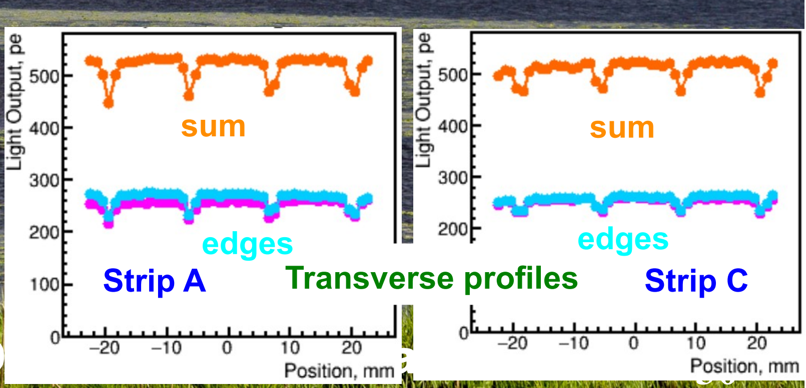
- ✓ New scintillation strips: 20x50x1200 mm³; **JINST 17 (2022) P04009**
- ✓ 60 layers x 24 strips — cube (120 cm)³ → 1.7 times larger fiducial volume;
- ✓ **No PMT** – SiPM readout from both sides of each WLS;
- ✓ 8 grooves with WLS, **16 SiPM** per strip to get high light yield and uniformity;
- ✓ TOF to get longitudinal coordinate in each strip. Faster (4.0 ns decay time) WLS fiber KURARAY **YS-2**; **JINST 17 (2022) P01031**
- ✓ Chemical whitening of strips – no large dead layer with titanium and gadolinium;
- ✓ Gadolinium in polyethylene film between layers;
- ✓ New front end electronics – low power inside passive shielding. Cool SiPMs to 10°C.
- ✓ Keep platform, passive shielding and digitization.

New strip test (16 SiPM per strip) μ-beam at U-70 (Protvino)

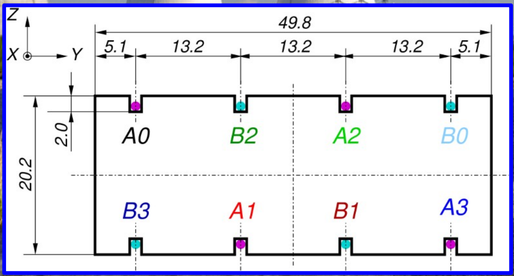


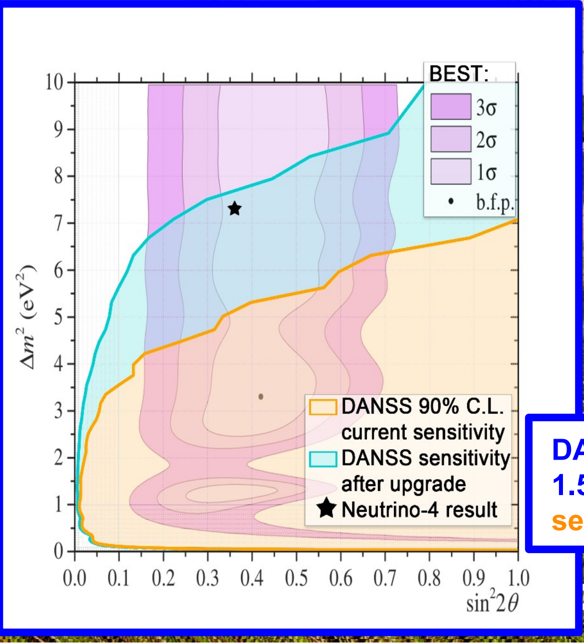
> 140 p.e./MeV





Strip cross section





DANSS sensitivity after upgrade – 1.5 years of running and current setup – 4.5 years of running