Power Reactor Monitoring with Antineutrinos by the DANSS Detector

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DANSS — Detector of reactor Anti-Neutrino based on Solid-state Scintillator

Unique location

- 10.9 – 12.9 m from the core center
- Cosmic background shielding 50 m.w.e.
- Weekly distance alternation

Safety and segmentation

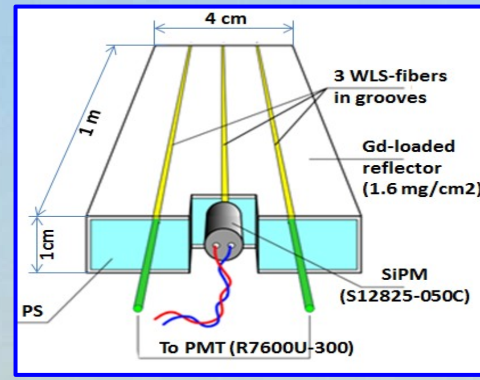
- 1 m^3 of polysterene based scintillation strips 10x40x1000 mm^3 with Gd-coating and light collection by 3 WLS fibers
- 100 layers with alternating direction, 25 strips in a layer
- Middle fibers – SiPM, 2500 channels
- Two side fibers from each of 50 strips of certain direction – PMT, 50 channels

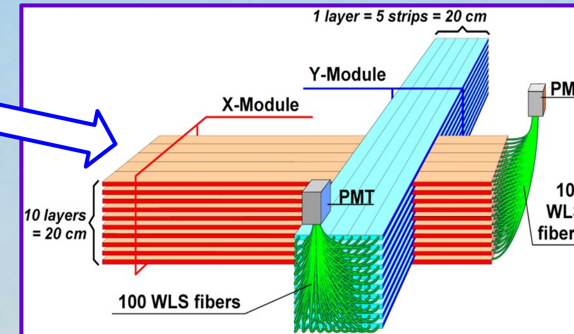
Multilayer hermetic shielding

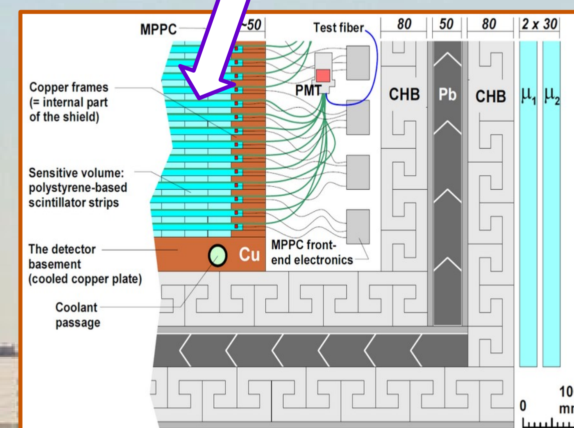
- Cu (5 cm) + CHB (8 cm) + Pb (5 cm) + CHB (8 cm) passive shielding
- 2-layer μ-veto at 5 sides

Versatile DAQ system

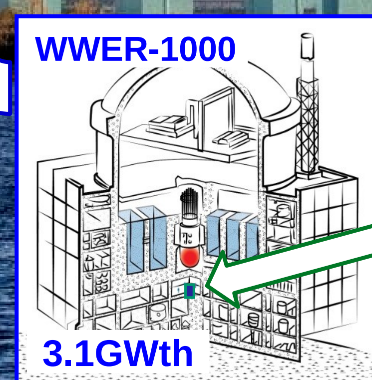
- Waveform digitizers 125 MHz, 64 chan.

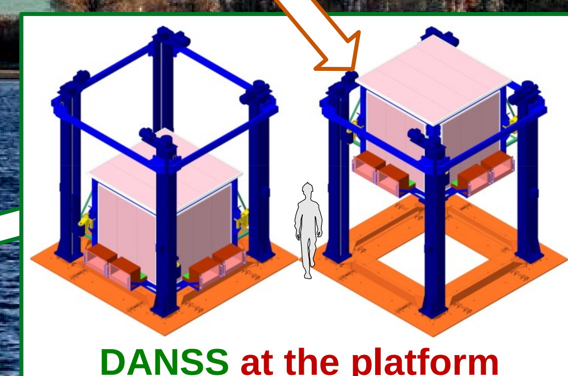






Kalinin NPP unit 4





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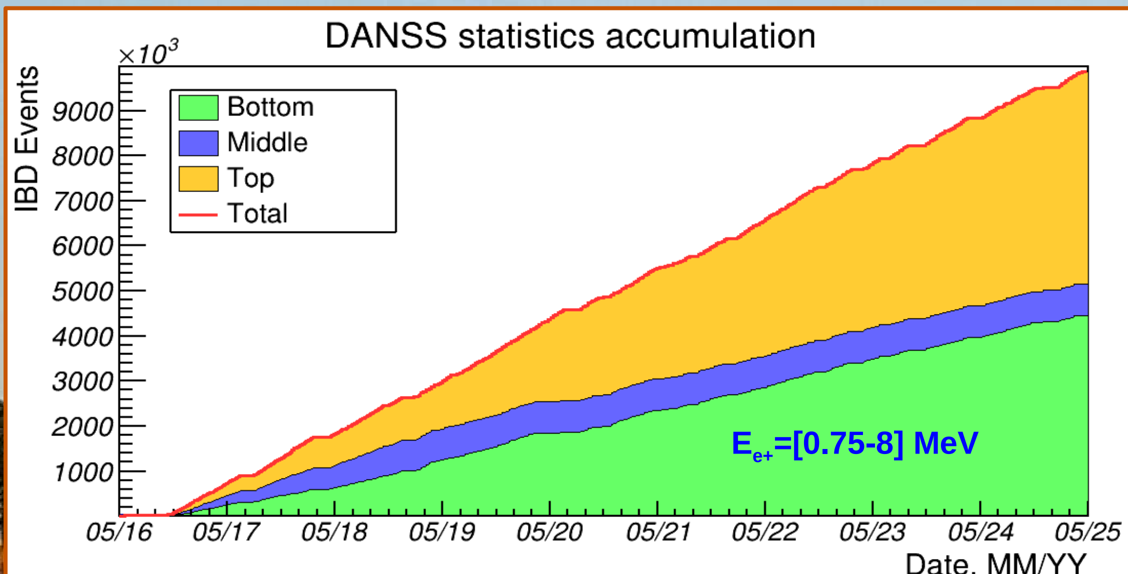
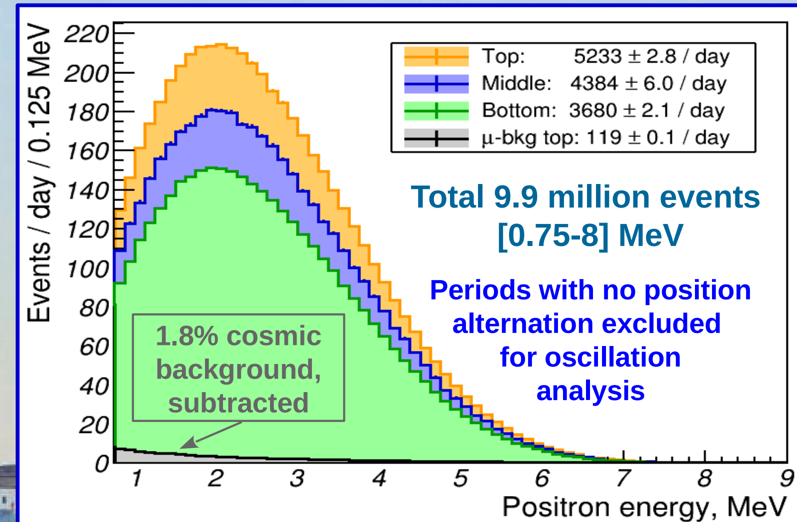
JINST 11 (2016) P11011

Making Good Progress

- 9 years of very stable and almost continuous running
- ~10 million neutrino events selected
- > 5000 events/day in the top position, > 50:1 sinal to background ratio
- Scintillator aging 0.55% per year **JINST 19 (2024) P04031**
- Absolute efficiency changes proofed to be below 1% in more than 8 years
- 5 full fuel campaigns, 6 reactor-OFF periods





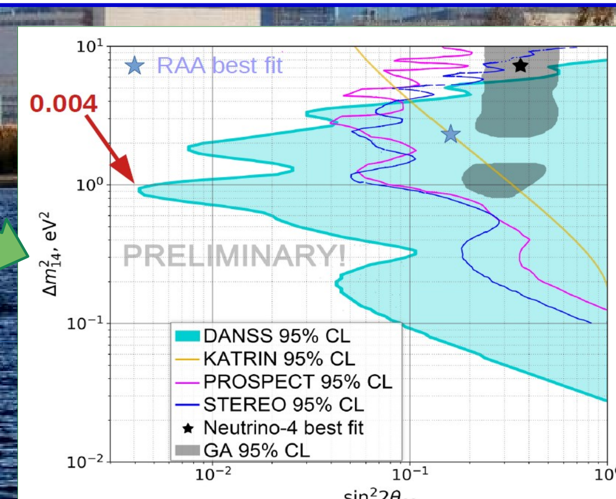
Important fundamental results

– searches for Sterile neutrino and other New Physics

Igor Alekseev @ TAUP-2025

August 28 17:40

(Neutrino Physics and Astrophysics #8B)



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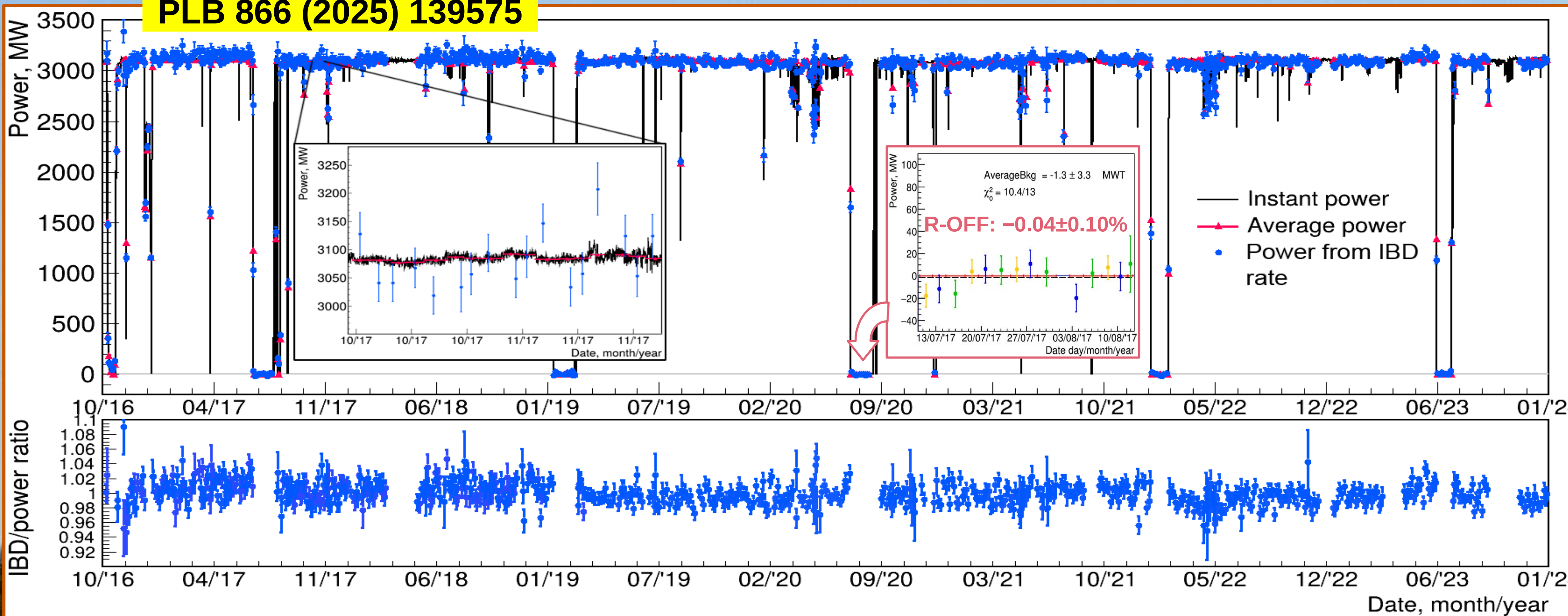
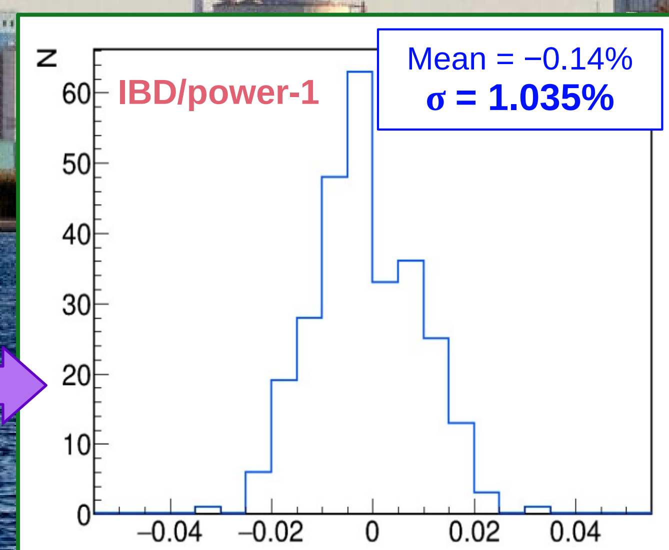
Reactor Power Monitoring

PLB 866 (2025) 139575



- **IBD rate corrections:**
  - **Fuel composition with burnout – H-M**
  - **Detection efficiency – dead channel map**
  - **Dead time (isolating cuts in the analysis)**
  - **Adjacent reactors ~0.6%**
- **Single normalization on 1 month (10.2016)**
- **Negligible shift 0.14% in 8 years**
- **Statistical error per week 0.66%**
- **Actual spread 1.04%**
- **Combined systematics of DANSS+Reactor power measurements 0.8%**
- **NPP estimates: not better than 1%**



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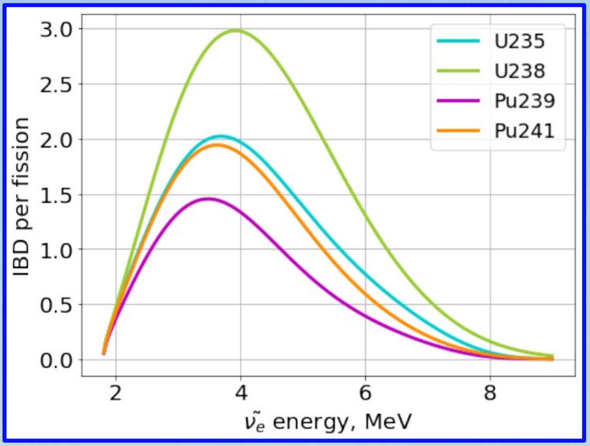
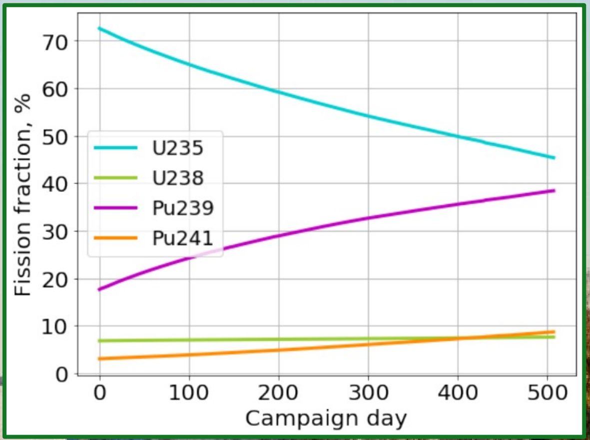
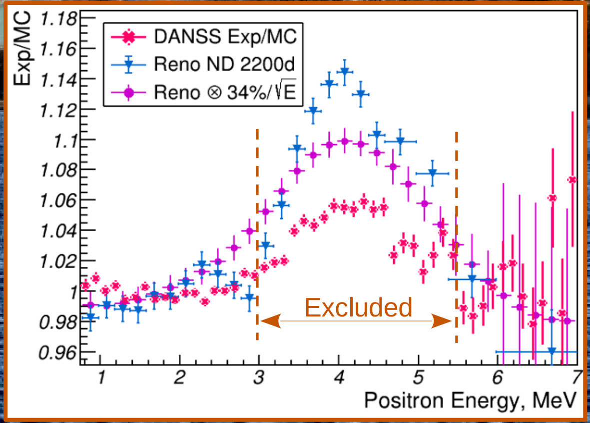
Fission Fraction Determination

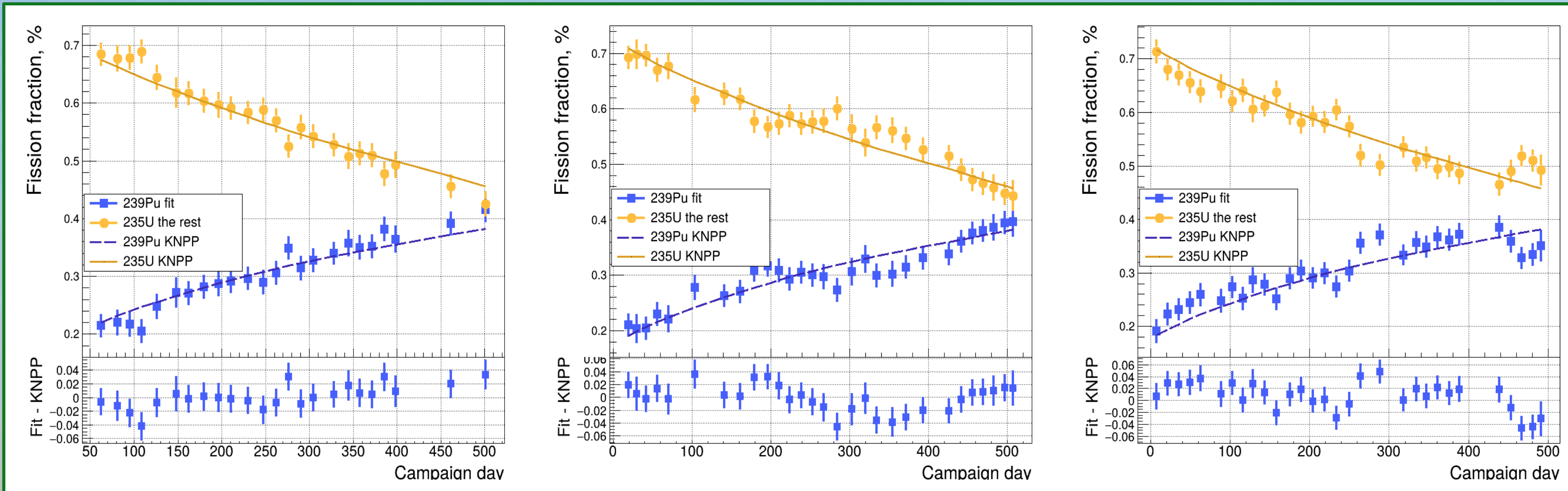
- Antineutrino spectra from fission isotopes are different
- The total antineutrino spectrum and the IBD counting rate changes with burnout
- One measurement − 12-15 days continuously
- The positron spectrum obtained for each measurement is fit with a sum of 4 main isotopes using the H-M model
- The “BUMP” area of the spectrum (3-5.5 MeV e^+) is excluded from fitting
- The small FF contributions of ^{238}U and ^{241}Pu are taken from a typical campaign (campaign 5), the total sum normalized to 1
- Actually only one fit parameter
- IBD rate normalization based on campaign averages
- Rates at different detector positions are matched using «toy MC» of production and detection points
- Corrections for the adjacent reactors, detector dead time and efficiency
- The actual reactor power and burning center position is not accounted (“blind” measurement)



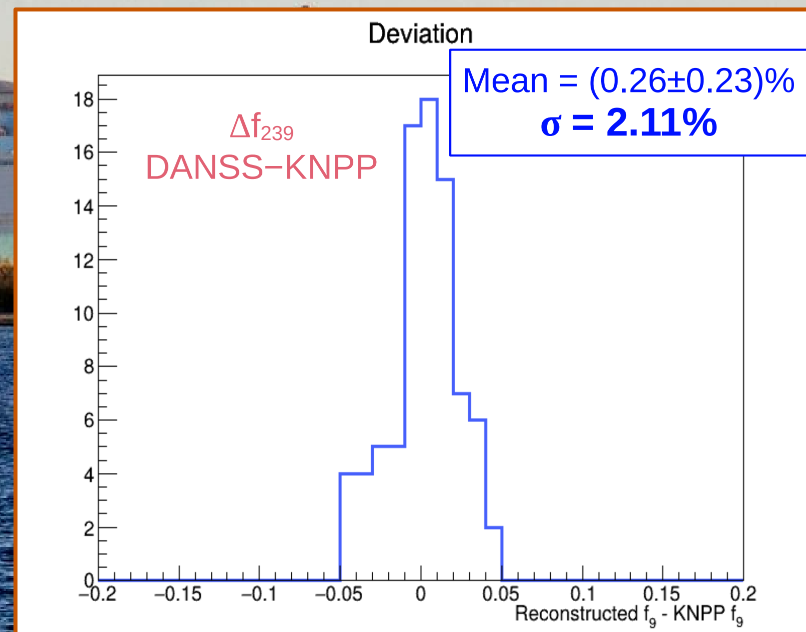




Fission Fraction Determination



- **The results are in good agreement with the NPP data**
- **Average difference is almost zero**
- **Spread of the difference 2.1% – NPP estimate 5%**
- **Excellent agreement between the two totally different approaches only proofs the confidence of both results**
- **For the first time the practical determination of the isotopic composition in the core is demonstrated without actual information on the reactor parameters**



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Yield Ratio σ_5/σ_9

- **Reverse problem: know everything about the reactor – power, fission fractions, burning profile – study IBD counting rate (and spectra)**
- **Normalized slope *SI* – relative speed of IBD rate change per unit of ^{239}Pu fission fraction**
- **DANSS *SI* measurement: 1.3σ greater than DB**

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

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

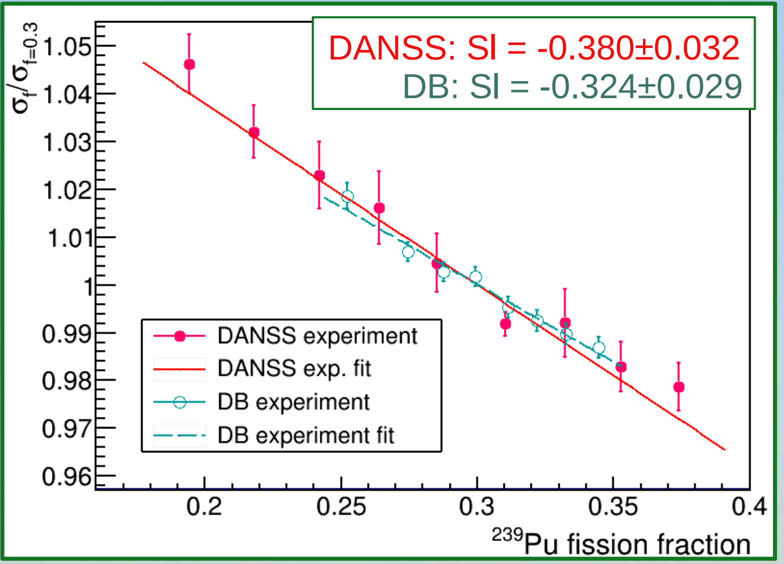
N – IBD rate per fission
σ_i – IBD yields
f_i – fission fractions

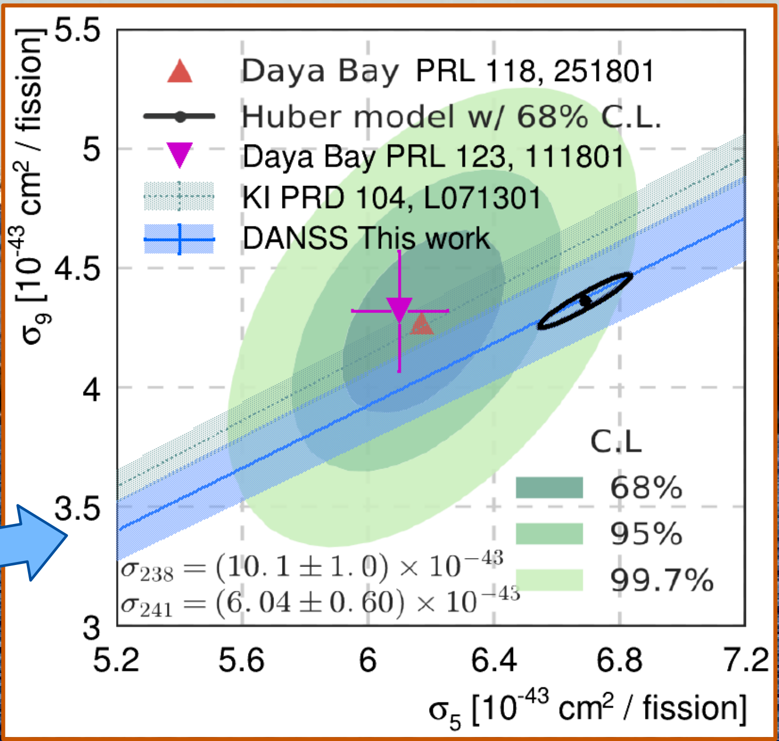
$$SI = \left(\frac{dN}{df_9}\right) / N = \frac{\frac{\sigma_8}{\sigma_9}\frac{df_8}{df_9} + \frac{\sigma_1}{\sigma_9}\frac{df_1}{df_9} + \frac{\sigma_5}{\sigma_9}\frac{df_5}{df_9} + 1}{\frac{\sigma_8}{\sigma_9} f_8 + \frac{\sigma_1}{\sigma_9} f_1 + \frac{\sigma_5}{\sigma_9} f_5 + f_9}$$

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

- **Simple, but extremely stable formula for σ_5/σ_9**
- **DANSS result σ_5/σ_9 = 1.529±0.057 almost coincide with H-M (1.53±0.06), but differ from DB (1.412±0.089, 1.1σ) and KI (1.45±0.03, 1.2σ)**

Our formula with DB slope results in 1.46±0.052 => difference due to the slope





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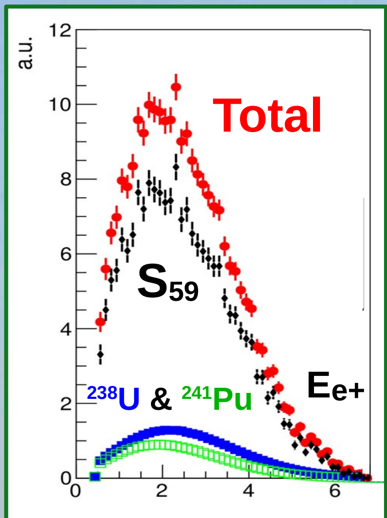
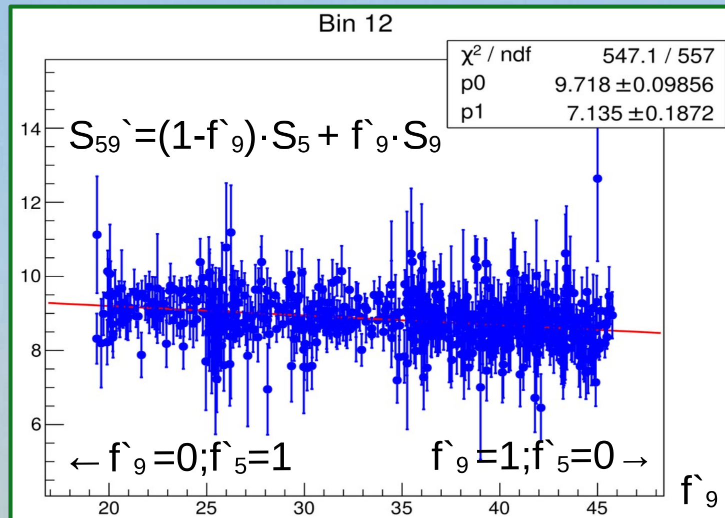
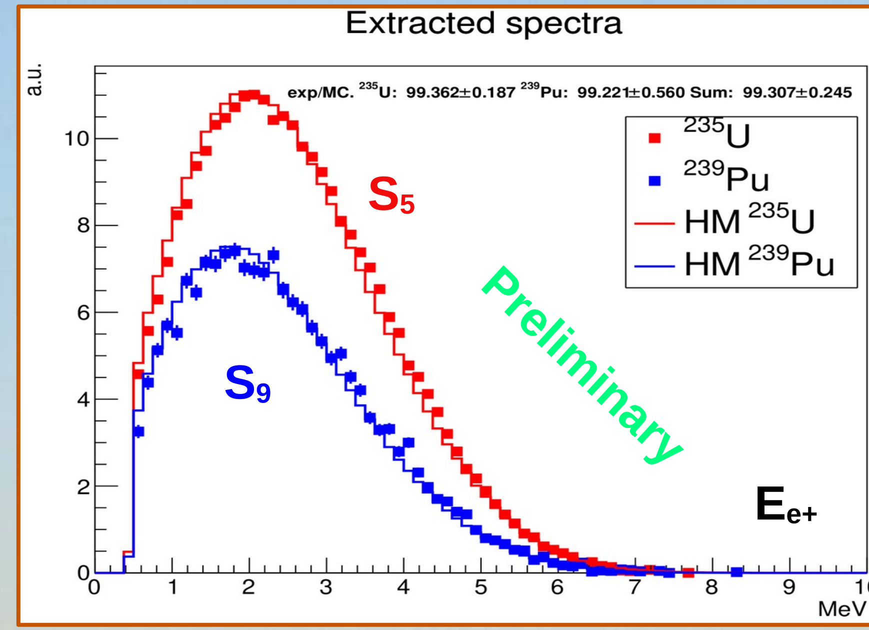
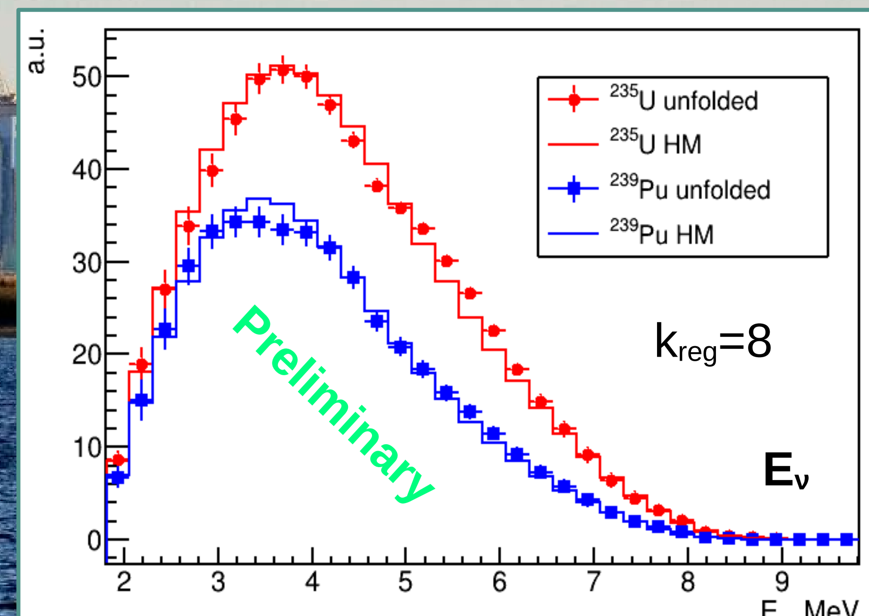
^{235}U and ^{239}Pu Spectrum Decomposition









- Weekly measurements at full power. Totally 559 points, energy range E_{e+}(0.5-10 МэВ)
- In each point the positron specrum (per fission) is renormalized upon MC based on H-M with known FF
- Subtract MC spectra ^{238}U and ^{241}Pu with their FF
- Substitution: $f`_5=f_5/(f_5+f_9)$, $f`_9=f_9/(f_5+f_9)$, $S`_{59}=S_{59}/(f_5+f_9)$ so that $f`_5+f`_9=1$
- For each bin in positron energy $S_{59}`=(1-f`_9)\cdot S_5 + f`_9\cdot S_9$
- In each energy bin a fit is made with S_5 and S_9 as free parameters
- Arbitrary normalization, but correct ratio – nontrivial !
- SVD method with regularization 8 is used to convert positron spectrum into antineutrino spectrum
- Not bad at all for the first try !

Conclusions

- Extreme stability of the DANSS detector allow precision measurements already during 9 years
- The reactor power is measured with antineutrino to the accuracy of 1% in a week, including 0.8% of the combined systematic uncertainty from both DANSS and operational measurements by KNPP
- The reconstruction of the fission fractions is in 2.1% agreement with the KNPP calculations; this only proofs the reliability of both independent approaches
- The normalized slope *Sl* of the IBD rate during the fuel campaign is in agreement with the H-M model and slightly greater than the DB result
- Yield ratio σ_5/σ_9 = 1.529±0.057 almost coincide with H-M (1.53±0.05), but differs from DB (1.412±0.089, 1.1σ) and KI (1.45±0.03, 1.2σ)
- First results on the spectrum decomposition of ^{235}U and ^{239}Pu describe the ratio of positron spectra from the H-M model fairly well, and allow the reconstruction of the antineutrino spectra by the SVD method

Thank you for you attention !

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

Backup

The 'BUMP' – ^{235}U and ^{239}Pu Decomposition

- Pronounced for both isotopes with similar strength
- Amplitude comparable to that of the total spectrum ratio
- Significance analysis is under way