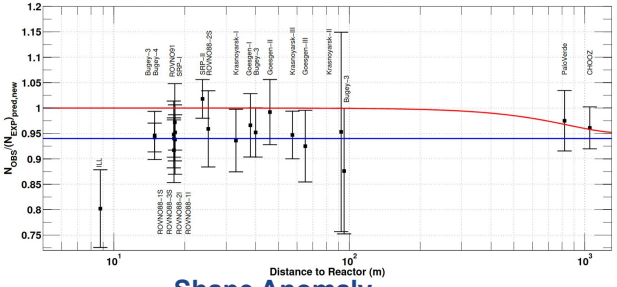
Recent results from the DANSS experiment

Nikita Mashin
on behalf of DANSS collaboration

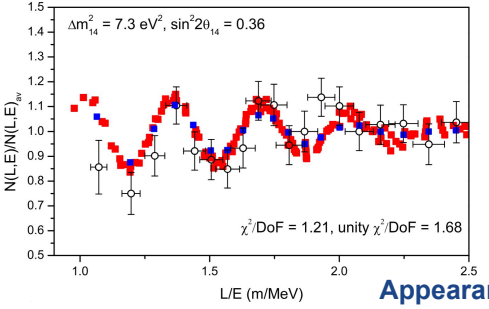
Motivation

The Reactor Antineutrino Anomaly
[Phys.Rev.D83:073006 (2011)]



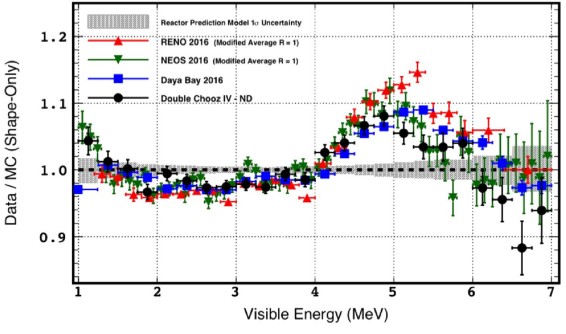
Deficit in reactor ν fluxes 3σ (Phys.Rev.C 83 054615). Probably explained by Kurchatov Institute (KI) (arXiv:2103.01684v1), Daya Bay, RENO results.

Neutrino-4 results
[Phys. Rev. D 104, 032003 (2021)]



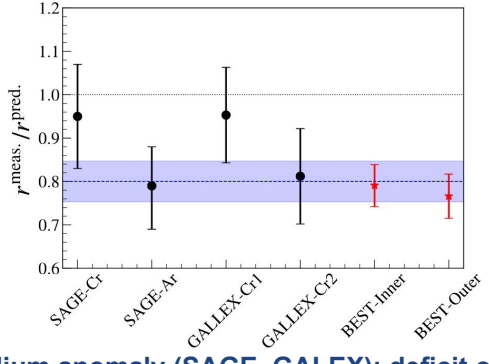
Disappearance of ν from reactor. Significance 2.7σ (Jetp Lett. 109, 213-221 (2019), Phys. Rev. D 104, 032003 (2021))

Shape Anomaly
[doi.org/10.3390/universe7100360]



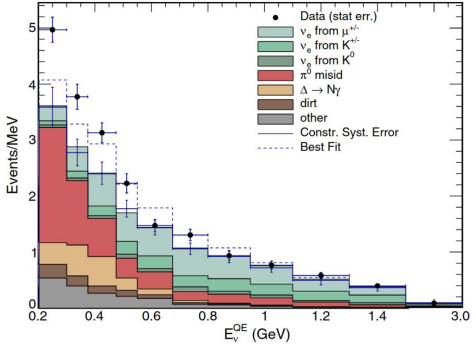
An excess of events around 6 MeV in antineutrino energy, observed by reactor experiments (Daya Bay, RENO, Double Chooz). The spectral unfolding is of particular interest.

Gallium Anomaly
[Phys. Rev. C 105, 065502 (2022)]



Galium anomaly (SAGE, GALEX): deficit of ν in calibration runs with radioactive sources (Phys.Rev.C 83 065504).
Results from BEST (PhysRevLett.128.232501) confirm GA. Significance > 5σ

Appearance anomaly
[PRL 128, 221801 (2018)]



LSND and MiniBoone: appearance of ν̃e in ν̃μ beam at short distances. Significance 6σ for combined results. (Phys.Rev.Lett. 121, 221801 (2018)). Not confirmed by MicroBoone (arXiv:2110.14054v2) but not excluded.

These anomalies can be described by 3+1ν model at short baseline:

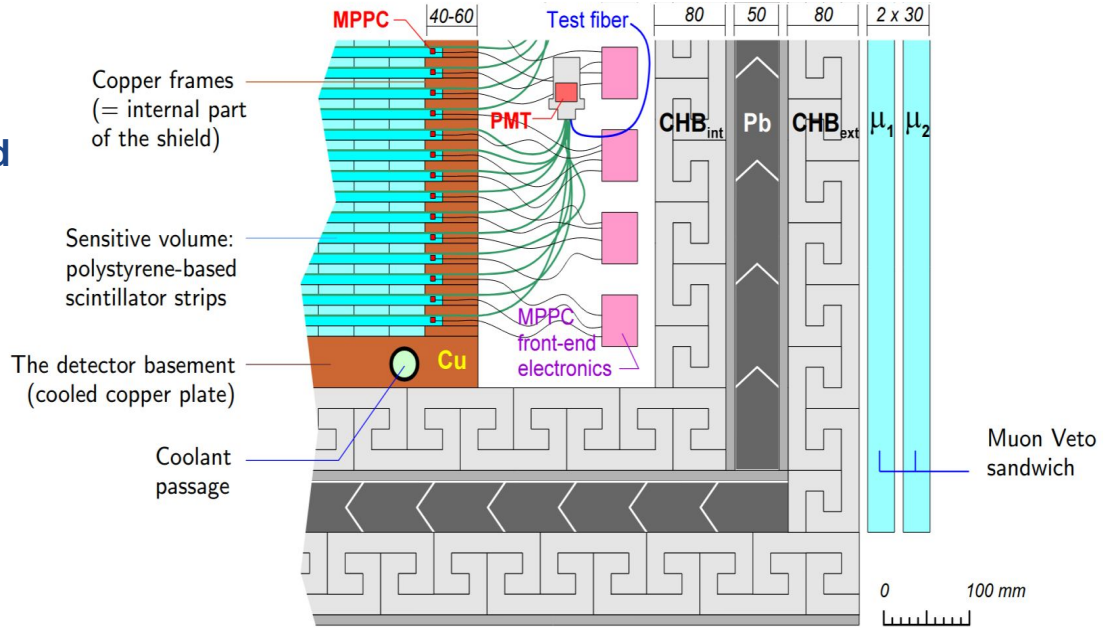
$$P_{ee} \approx 1 - \sin^2(2\theta_{14}) \sin^2\left(1.27 \frac{\Delta m^2_{41}[\mathrm{eV}^2] L[m]}{E_\nu[MeV]}\right)$$

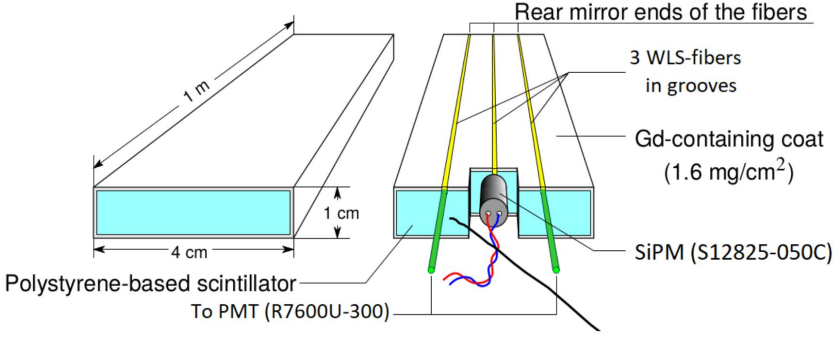
Practical motivation:

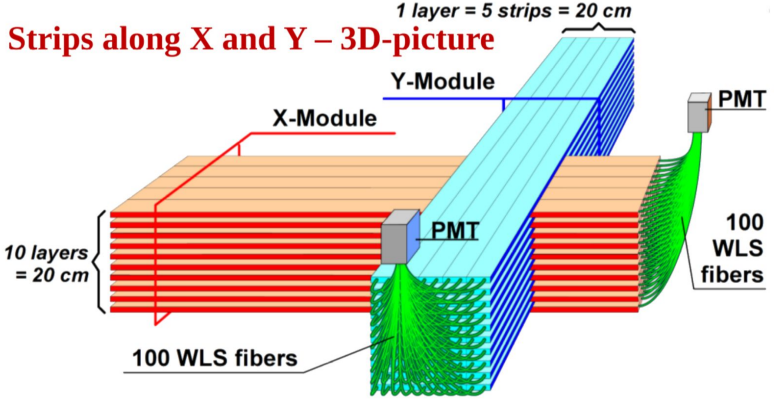
- Independent reactor power monitoring
- Determination of fuel burnout

DANSS design

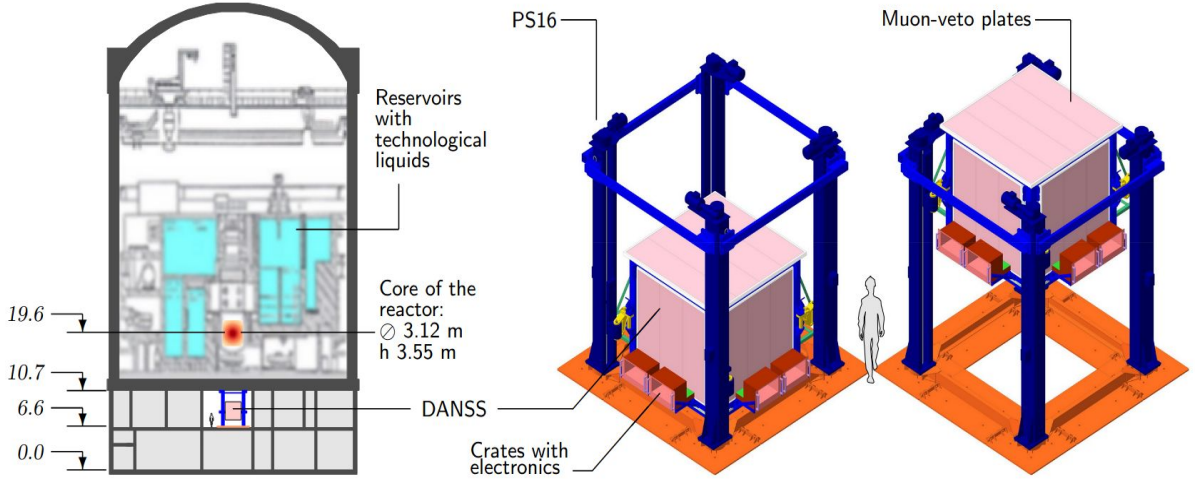
- Multilayer passive shielding: electrolytic copper frame 5 cm, borated polyethylene 8 cm, lead 5 cm, borated polyethylene 8 cm
- 2-layer active μ-veto on 5 sides
- 2500 scintillator strips with Gd containing coating for neutron capture
- Light collection with 3 WLS fibers
- Central fiber read out with individual SiPM
- Side fibers from 50 strips make a bunch of 100 on a PMT cathode = Module

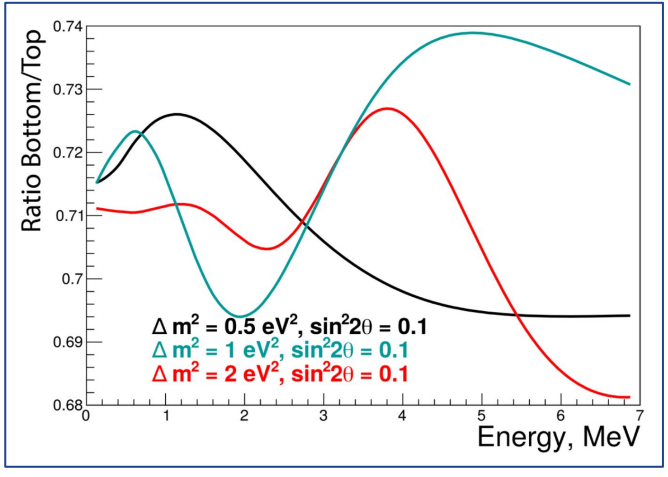




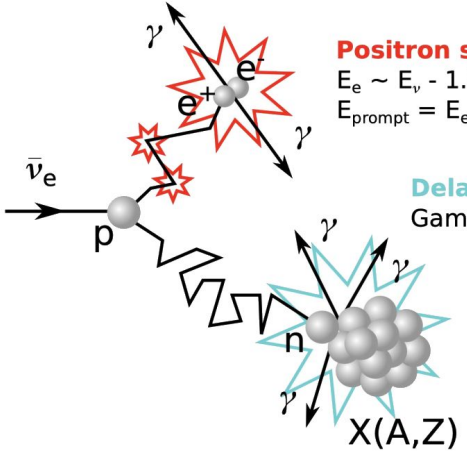


Detector site and data taking strategy





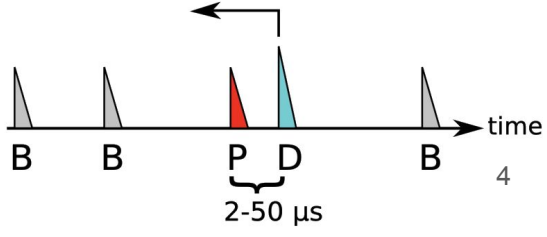
- Located at Kalinin NPP
- 10.9–12.9 m from reactor core
- Measures the positron kinetic energy from the IBD reaction
- Spectra at different distance are measured in the same experiment with the same detector ➡ The ratio of spectra does not depend on the theory, absolute detector efficiency or other experiments.



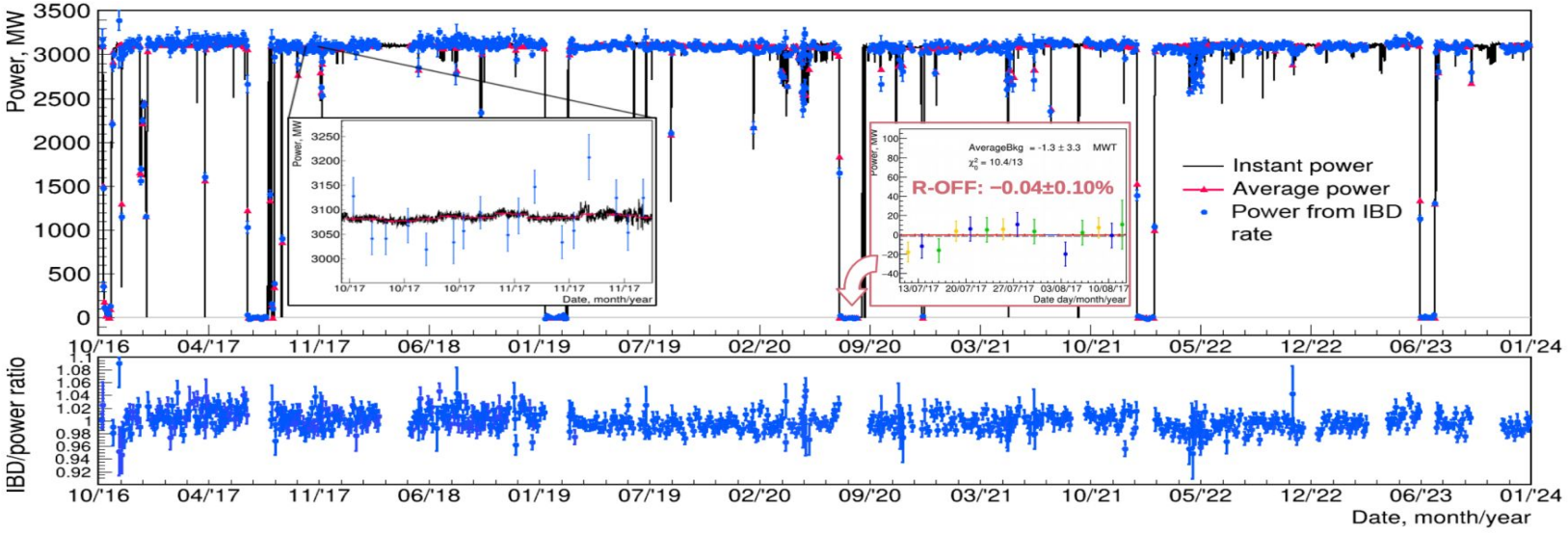
Positron signal
$E_e \sim E_\nu - 1.806$ MeV
$E_{prompt} = E_e + E_{2\gamma}$

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

Delayed signal
Gamma flush in the whole detector

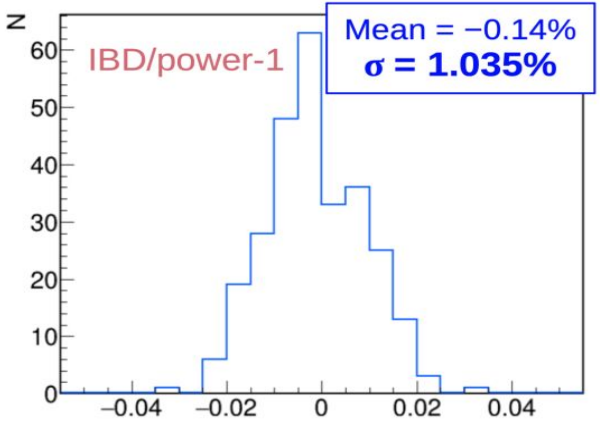


Reactor power monitoring (Phys.Lett.B 866 (2025) 139575)



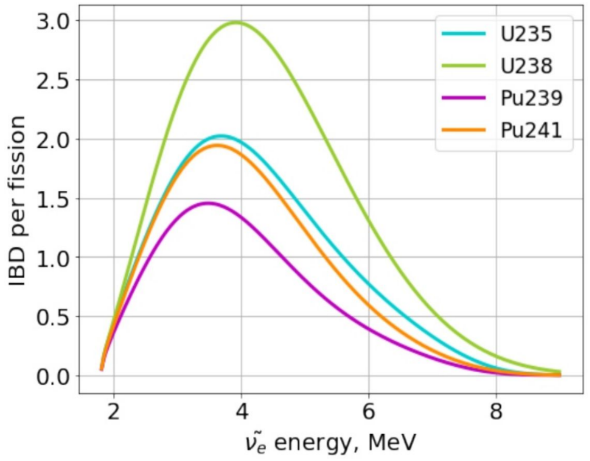
IBD Count Rate Corrections:

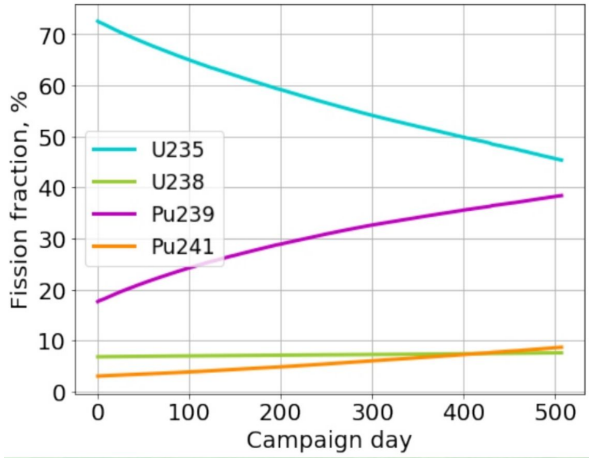
- Fuel composition evolution (H-M model)
- Detection efficiency (channel mapping)
- Dead time (isolating cuts)
- Neighboring reactors (~0.6% contribution)

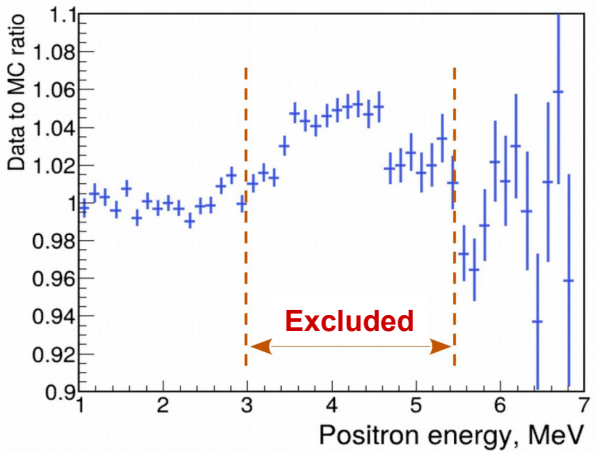


Unified normalization baseline (October 2016)
Negligible drift: 0.14% over 8 years
Statistical accuracy of weekly measurements: 0.66%
Actual observed spread: 1.04%
DANSS systematics+reactor measurements 0.8%
KNPP estimates: no better than 1%

Fission fractions determination (Phys.Lett.B 866 (2025) 139575)

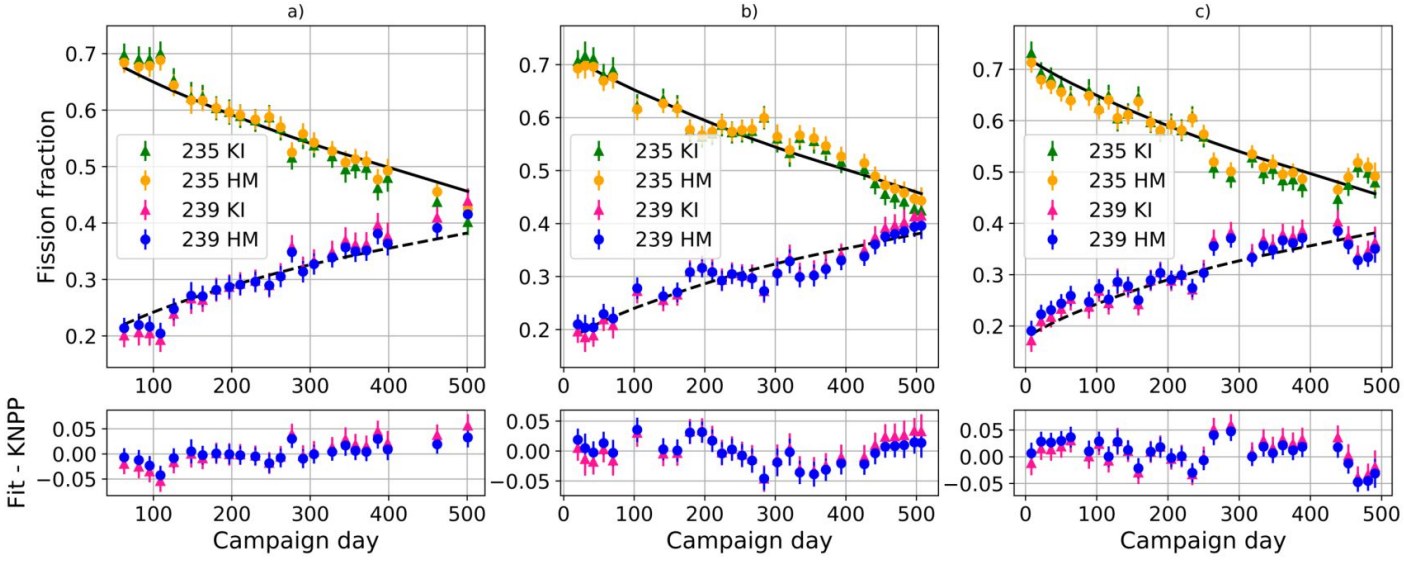






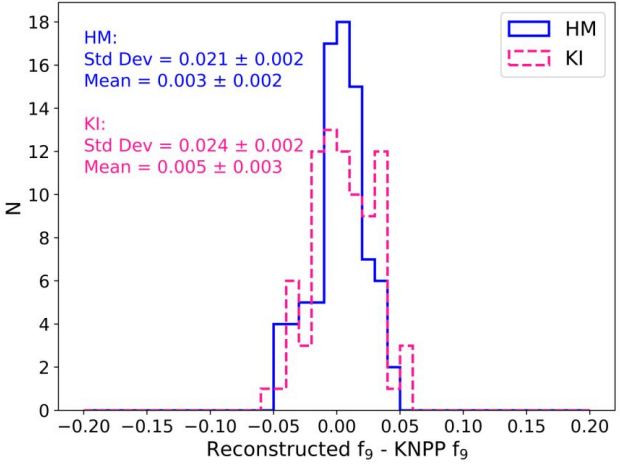
- Neutrino spectra from different isotopes are distinct
- Total spectrum and count rate vary with fuel composition
- Single measurement period: 12-15 days
- Observed positron spectra are fitted as a sum of contributions from 4 main isotopes using H-M model for each measurement
- Spectral regions in the "bump" range (3-5.5 MeV e^+) are excluded from fitting
- Fission fractions from ^{238}U and ^{241}Pu are fixed according to a typical campaign (Campaign 5), total sum normalized to unity
- Effectively one fit parameter
- Normalization based on campaign averages
- Counts at different positions are matched using toy MC simulations of reactor and detector points
- Corrections applied for dead time, detection efficiency, background from neighboring reactors
- Reactor power exact value and burnup center position are not accounted for

Fission fractions determination (Phys.Lett.B 866 (2025) 139575)



HM - Huber-Mueller
KI - Kurchatov Institute

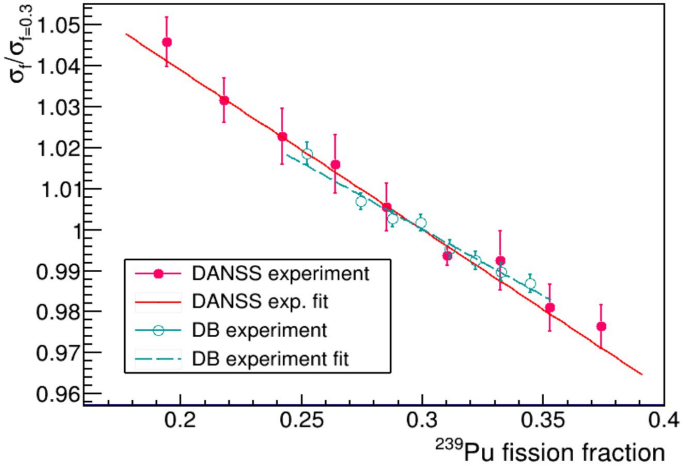
- The results are consistent with KNPP data based on neutron transportation simulations
- Mean difference is almost zero
- Scatter of differences 2.1% – NPP estimate 5%
- The good agreement between the two very different methods adds confidence in both results
- It is demonstrated that it is possible to determine the isotopic composition without interfering with the reactor operation and information on its parameters.



The ratio of σ_5/σ_9 (arXiv:2410.19182v1)

Inverse problem: knowing everything about the reactor: power, fission fractions, position of the burning centre, let's study the count rate (and spectra)

Normalised slope SI is the relative rate of change of the IBD count rate when the fraction of ^{239}Pu changes DANSS measurements: 1.3σ higher slope than DB



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

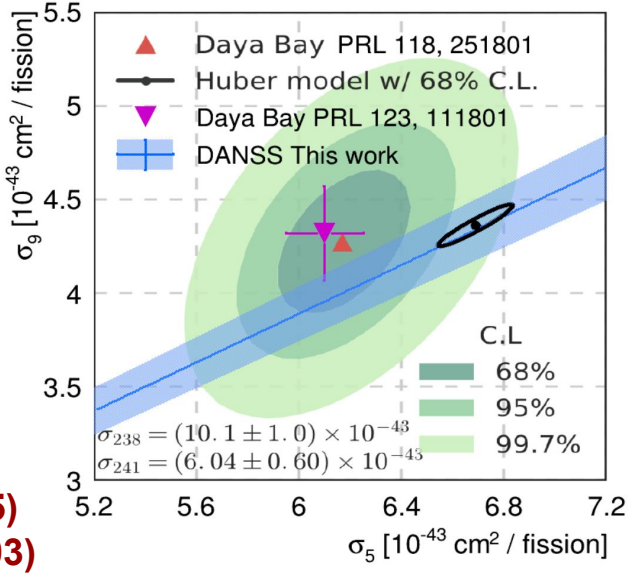
$$\frac{dN}{df_9} = \alpha \cdot \left(\sigma_8 \frac{df_8}{df_9} + \sigma_1 \frac{df_1}{df_9} + \sigma_5 \frac{df_5}{df_9} + \sigma_9\right)$$

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

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

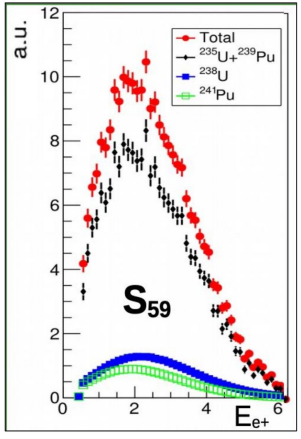
$$\frac{\sigma_5}{\sigma_9} = -\frac{\frac{\sigma_8}{\sigma_9}(SI \cdot f_8 - \frac{df_8}{df_9}) + \frac{\sigma_1}{\sigma_9}(SI \cdot f_1 - \frac{df_1}{df_9}) + (SI \cdot f_9 - 1)}{SI \cdot f_5 - \frac{df_5}{df_9}}$$

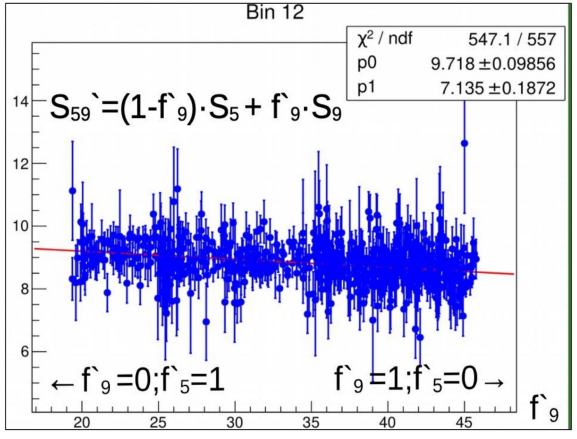
(σ8/σ9 and σ1/σ9 are taken from HM model)

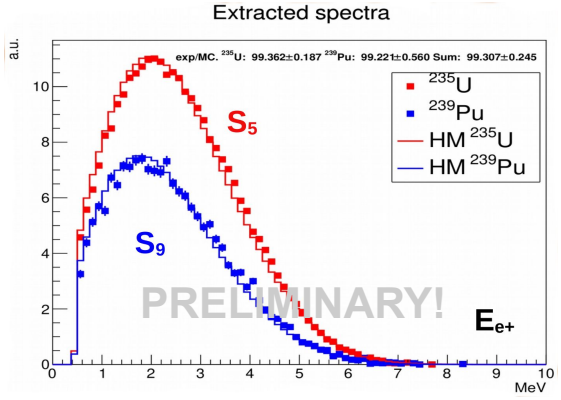


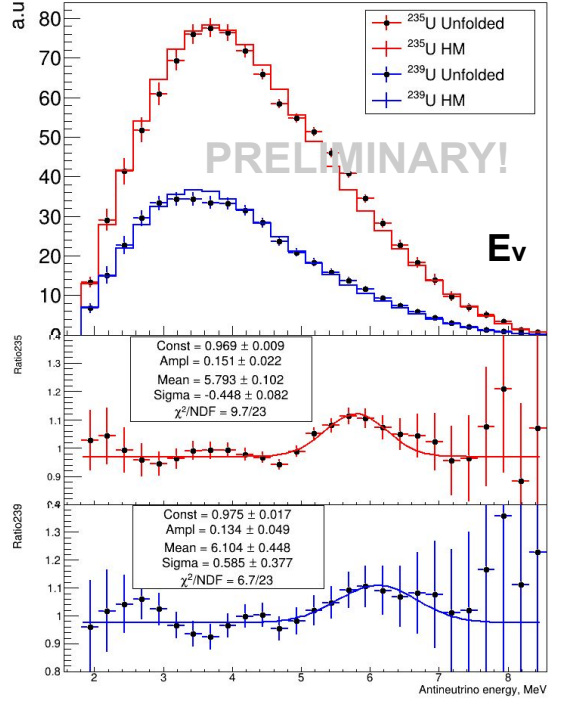
DANSS result σ5/σ9 = 1.528±0.058 almost matches H-M (1.53±0.05) and is larger than Day Bay (1.445±0.097) (Phys.Rev.Lett.120,022503)

Extraction of ^{235}U and ^{239}Pu Spectra



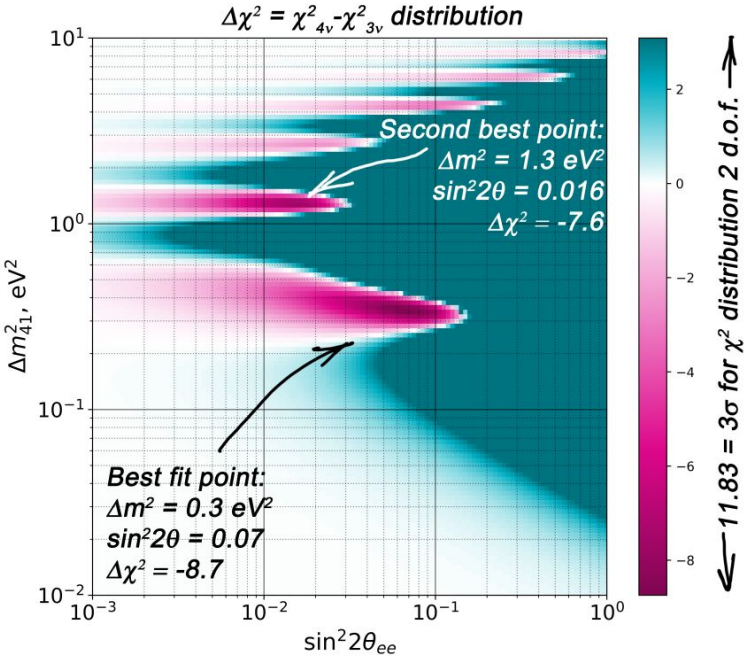


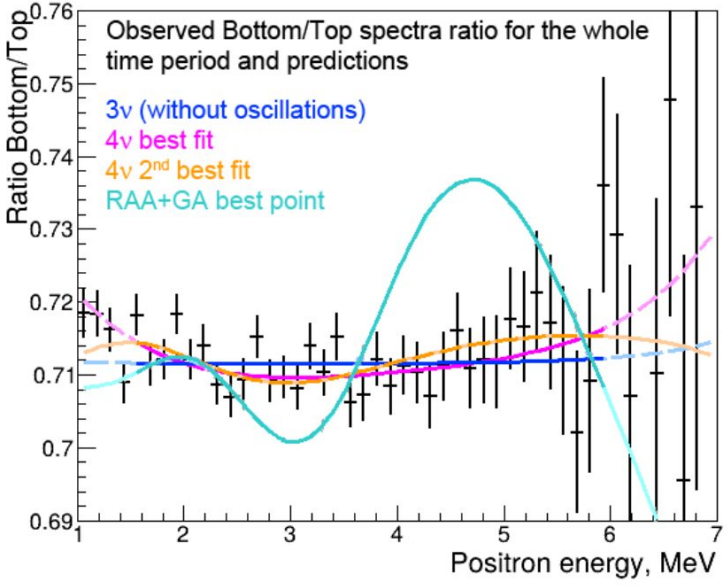




- Individual 'weekly' points at full power. Total 559 points, range E_{e+} (0.5–10 MeV)
- At each point we renormalise the positron spectrum (on fission) on MC by H-M with known FF
- We subtract the MC spectra of ^{238}U and ^{241}Pu with their FF
- We make the substitution: $f'_5=f_5/(f_5+f_9)$, $f'_9=f_9/(f_5+f_9)$, $S'_{59}=S_{59}/(f_5+f_9)$ so $f'_5+f'_9=1$
- For each energy bin, $S'_{59}=(1-f'_9)S_5 + f'_9S_9$
- In each energy bin, perform a linear fit with free parameters S_5 and S_9
- Relative normalisation, but the correct ratio
- Using the SVD method we convert the spectrum of positrons to the antineutrino spectrum (regularisation 8)

Sterile neutrino searches





Difference in χ^2 between 4v and 3v hypotheses.

Magenta:

$$\chi^2_{4\nu} < \chi^2_{3\nu}$$

Cyan:

$$\chi^2_{4\nu} > \chi^2_{3\nu}$$

Using current statistics 2016-2024 we see no statistically significant evidence of 4v signal. Best points:

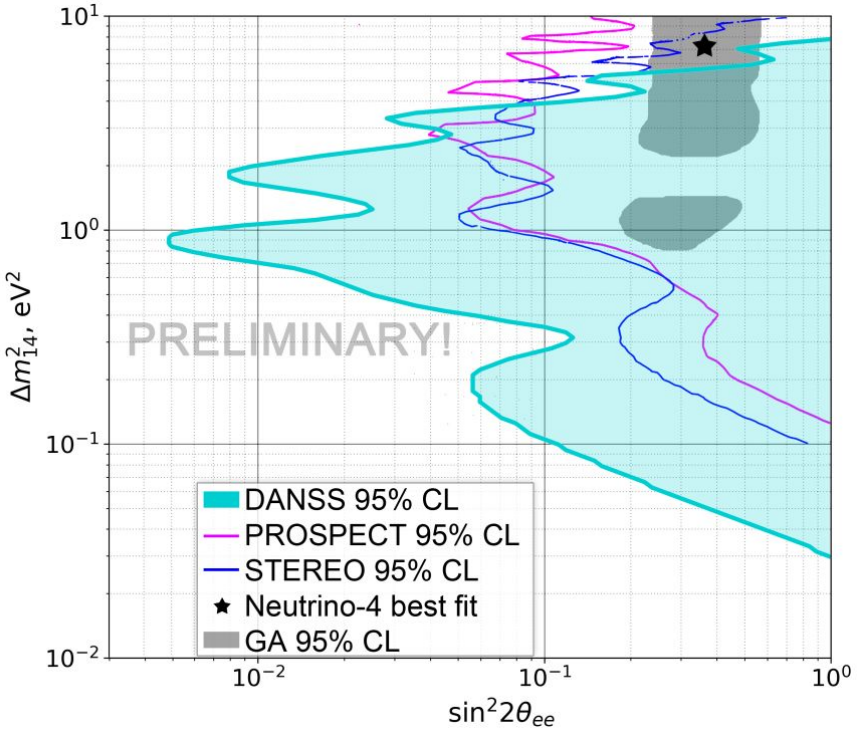
$$\Delta m^2_{41} = 0.33\,\mathrm{eV}^2, \sin^2 2\theta_{ee} = 0.07, \chi^2_{4\nu} - \chi^2_{3\nu} = -8.7 (\sim 2.5\sigma)$$

$$\Delta m^2_{41} = 1.3\,\mathrm{eV}^2, \sin^2 2\theta_{ee} = 0.016, \chi^2_{4\nu} - \chi^2_{3\nu} = -7.6$$

RAA and GA best point has been excluded with much more than 5σ.

Sterile neutrino searches

95% C.L. exclusion calculated using Gaussian CLs method.



1σ values used in the penalty terms (changes with respect to nominal values):

- relative detector efficiencies at different distances (0.4%)
- distance to the fuel burning prole center (5 cm)
- correlated backgrounds (35%)
- additional smearing in energy resolution (6%/√E ⊕ 2%)
- energy scale (2%)
- energy shift (50 keV)

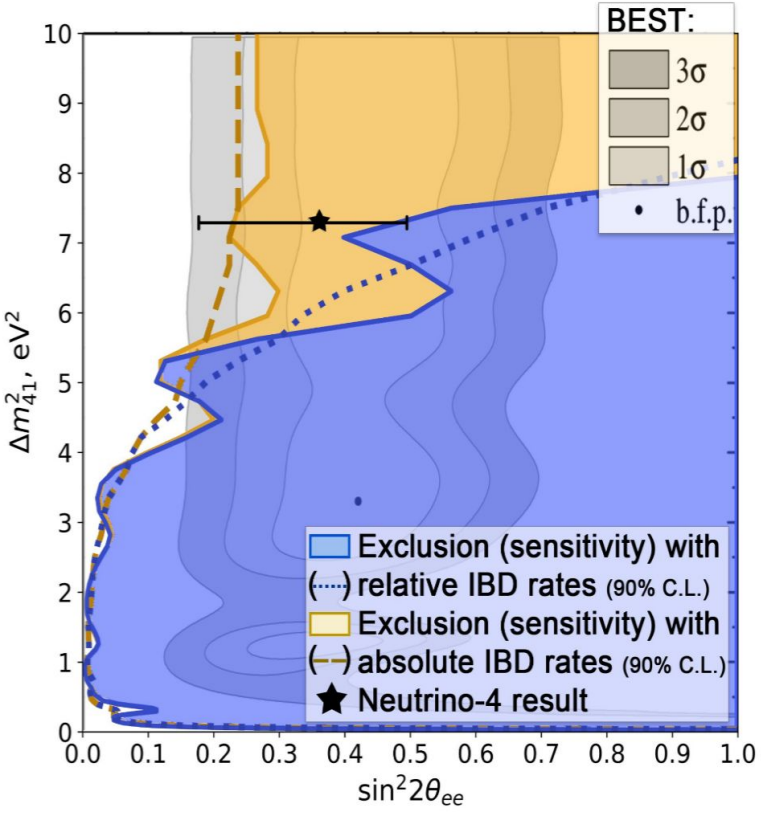
DANSS analysis without absolute counting rates excludes a large and the most interesting fraction of sterile neutrino parameter space preferred by BEST using only ratio of e+ spectra at 3 distances (6.8 mln IBD events).

Search for sterile neutrinos using absolute counting rates

Test statistics with absolute counting rates:

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

σ_{abs} – total systematic uncertainty (7% in absolute rates). HM model used for predictions.



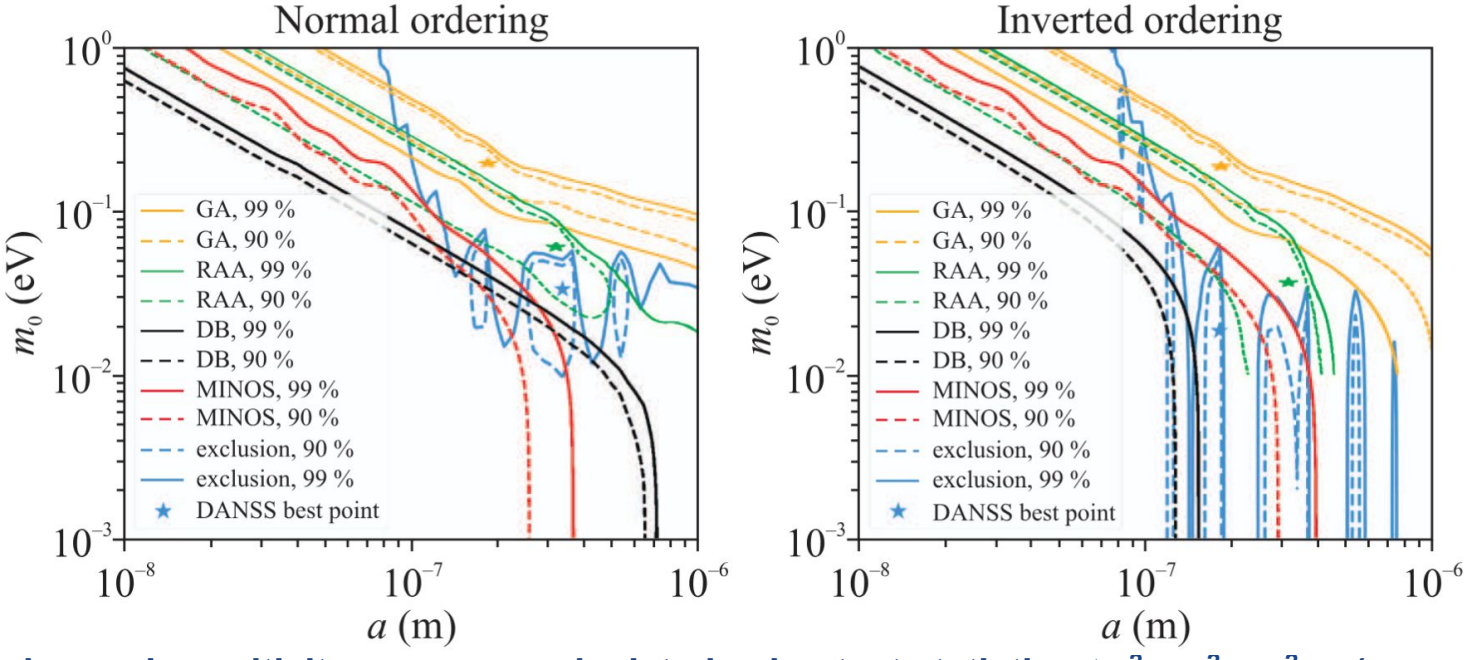
A large of available parameter space for sterile neutrino was excluded with model-independent analysis.

Exclusions based on absolute counting rates for large Δm^2_{41} support previous results (Daya Bay, Bugey-3, ...)

Our preliminary results exclude the dominant fraction of BEST expectations as well as best fit point of Neutrino-4 experiment. In KI model exclusions are even more more strict.

These results depend on the predictions of the antineutrino flux from reactors, for which we assumed a conservative uncertainty of 5%.

Large Extra Dimensions searches (jetpletters.ru/ps/2505/article_36718.shtml)



- Exclusion and sensitivity areas are calculated using test statistics $\Delta\chi^2 = \chi^2 - \chi^2_{min}$ (assuming Wilks' theorem), $\Delta\chi^2 = 4.61(9.21)$ corresponds to 90% (99%) C.L.
- Data collected at Top and Bottom detector positions are included into analysis (6.3 mln IBD ev.)
- DANSS best-fit point significance is 2.1 (1.8)σ for NO (IO)
- DANSS data exclude RAA at 4.2σ C.L. for NO (IO), GA is excluded at > 5σ C.L.
- For NO DANSS exclusions are the most stringent for some a values and based only on spectra ratio information while Daya Bay exclusions are based on absolute counting rates as well.
- For IO DANSS exclusions are consistent with other experiments

Conclusions

- The DANSS detector has been taking up data since 2016 at a rate of ~ 5000 events per day, which is a world record. Currently, over 9 million IBD events have been accumulated
- The reactor power is measured to an accuracy of 1% per week, including 0.8% of the total systematic uncertainties of DANSS and KNPP operational measurements
- For the first time in the world, a reconstruction of fission fractions from measured spectra has been performed, the agreement with the KNPP data based on neutron transportation simulations is within 2.1%, this adds confidence in both approaches
- The output ratio $\sigma5/\sigma9 = 1.528\pm0.058$ almost matches H-M (1.53±0.05) and is larger than Day Bay (Phys.Rev.Lett.120,022503) (1.445±0.097)
- Searches for sterile neutrinos were updated using additional 1 million of neutrino events. We do not see any significant hint for the sterile neutrino hypothesis.

  DANSS excludes a large and the most interesting fraction of sterile neutrino parameter space preferred by BEST using only ratio of e+ spectra

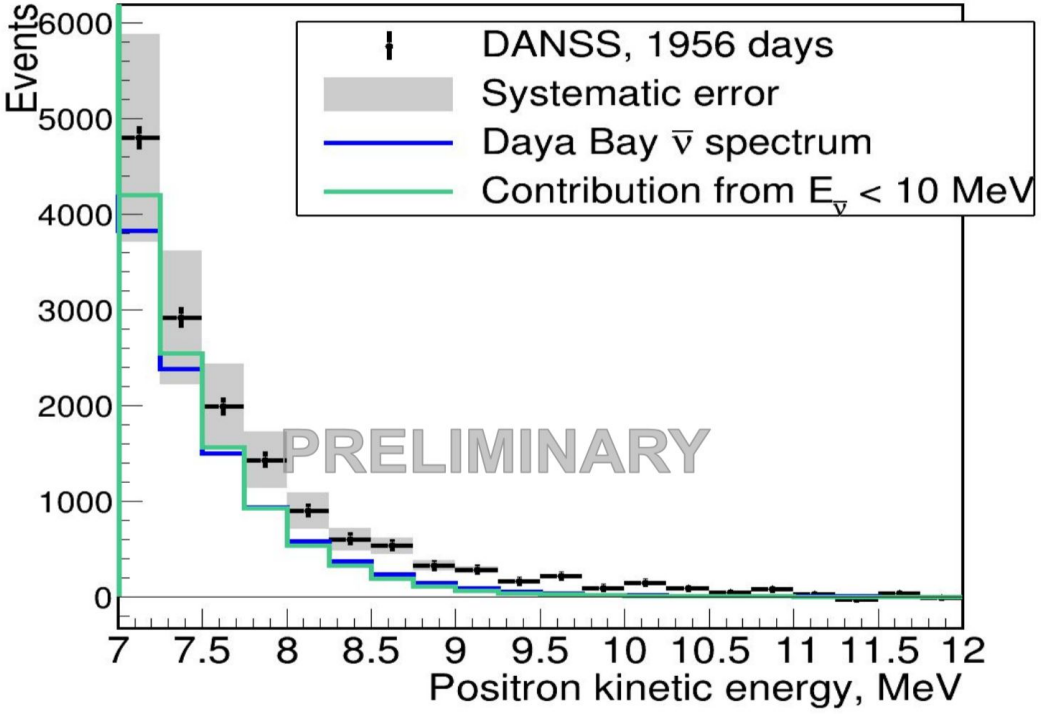
- In a search for Large Extra Dimensions the best fit point in a model with one dominant LED has a statistical significance of 2σ

Thank You!

Outline

- Motivation
- The DANSS setup
- Reactor power monitoring
- Fission fractions determination
- The ratio of σ_5/σ_9
- Extraction of ^{235}U and ^{239}Pu isotope spectra
- Unfolding of positron spectra
- Searches for sterile neutrinos
- Searches for Large Extra Dimensions (LED)

High Energy Neutrinos



- Background subtraction is based on 5 “reactor off” periods
- DANSS observes ve events with ve energy > 10 MeV: **1561 ± 157(stat) ± 168(sys) events (6.8σ)**
- Fraction of high energy ve (**~1.5x10^{-4}**) is somewhat larger than at Daya Bay (**PhysRevLett.129.041801**)

Absolute IBD counting rates

$$\frac{dN(t)}{dt} = N_p \cdot \int_{E_{min}}^{E_{max}} \varepsilon \frac{1}{4\pi L^2} \sigma(E_\nu) \frac{d^2\phi(E_\nu, t)}{dEdt} \cdot P(L, E_\nu) dE$$

$$\frac{d^2\phi(E,t)}{dEdt} = \frac{W_{th}}{< E_{fis} >} \sum f_i \cdot s_i(E)$$

$$< E_{fis} >= \sum E_i \cdot f_i$$

N_p – the number of target protons,
ε – detector efficiency,
L – the distance between the centers of the detector and the reactor core (distribution of fission points, reactor and detector sizes are taken into account)
$\sigma(E_\nu)$ – the IBD reaction cross section,
W_{th} – reactor thermal power (data from KNPP),
E_{fis} – energy released per fission (Phys. Rev. C 88, 014605),
f_i – fission fraction
s_i – $\tilde{\nu_e}$ energy spectrum per fission (Huber + Mueller and Kurchatov Institute models are considered),
$P(L, E_\nu)$ is the survival probability due to neutrino oscillations

Oscillation analysis: test statistics

Test statistics is defined as follows:

$$\chi^2_{rel} = \min_{\eta,k} \sum_{i=1}^{N_{bins}} \begin{pmatrix} Z_{1i} & Z_{2i} \end{pmatrix} \cdot W^{-1} \cdot \begin{pmatrix} Z_{1i} \\ Z_{2i} \end{pmatrix} + \sum_{i=1}^{N_{bins}} \frac{Z_{1i}^2}{\sigma_{1i}^2} + \sum_{j=1,2} \frac{(k_j - k_j^0)^2}{\sigma_{kj}^2} + \sum_{l} \frac{(\eta_l - \eta_l^0)^2}{\sigma_{\eta l}^2}$$

phase I: Top, Middle, Bottom — phase II: Top, Bottom — penalty terms

i – energy bin (36 total) in range 1.5–6 MeV,
$Z_j = R_j^{\mathrm{obs}} - k_j \times R_j^{\mathrm{pre}}(\Delta m^2,\ \sin^2 2\theta,\ \eta)$ for each energy bin, (obs for observed, pre for predicted),
$R_1 = Bottom/Top$, $R_2 = Middle/\sqrt{Bottom \cdot Top}$, where
Top, $Middle$, $Bottom$ – absolute count rates per day for each detector position,
k – relative efficiency (nominal values $k_1^0 = k_2^0 = 1$),
$\eta(\eta^0)$ – other nuisance parameters (and their nominal values),
W – covariance matrix to take into account correlations in spectra ratios at different positions (Z_1 and Z_2),
N – total absolute rates.

Systematic uncertainties are treated as nuisance parameters

During the fit each absolute (Top, $Middle$, $Bottom$) spectrum $S(E, \eta)$ was approximated using first-order Taylor expansion:

$$S(E, \eta) = S(E, \eta^0) + \sum_l \frac{\partial S}{\partial \eta_l} d\eta_l$$

Oscillation analysis: test statistics with absolute IBD rates

Test statistics is defined as follows:

$$\chi^2_{rel} = \min_{\eta,k} \sum_{i=1}^{N_{bins}} \begin{pmatrix} Z_{1i} & Z_{2i} \end{pmatrix} \cdot W^{-1} \cdot \begin{pmatrix} Z_{1i} \\ Z_{2i} \end{pmatrix} + \sum_{i=1}^{N_{bins}} \frac{Z^2_{1i}}{\sigma^2_{1i}} + \sum_{j=1,2} \frac{(k_j - k_j^0)^2}{\sigma^2_{kj}} + \sum_{l} \frac{(\eta_l - \eta_l^0)^2}{\sigma^2_{\eta l}}$$

phase I: Top, Middle, Bottom — phase II: Top, Bottom — penalty terms

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W – covariance matrix to take into account correlations in spectra ratios at different positions (Z_1 and Z_2),
N – total absolute rates.

With absolute counting rates:

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

σ_{abs} – systematic uncertainty (7% in absolute rates)

Large Extra Dimensions searches (jetpletters.ru/ps/2505/article_36718.shtml)