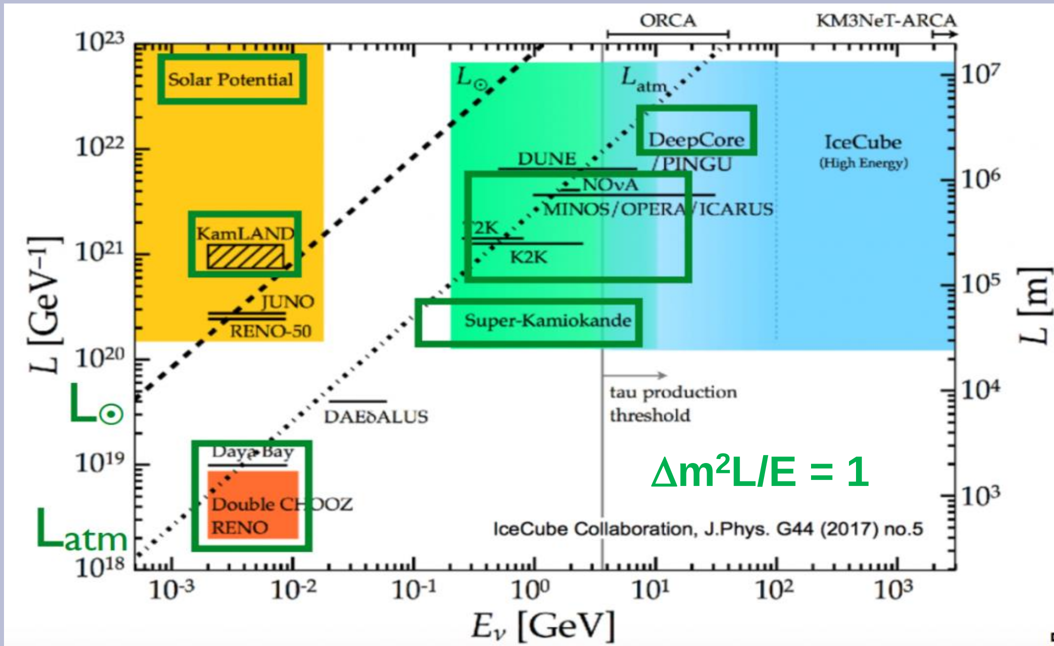
New results from the DANSS experiment

Yury Shitov, JINR

On behalf of the DANSS collaboration

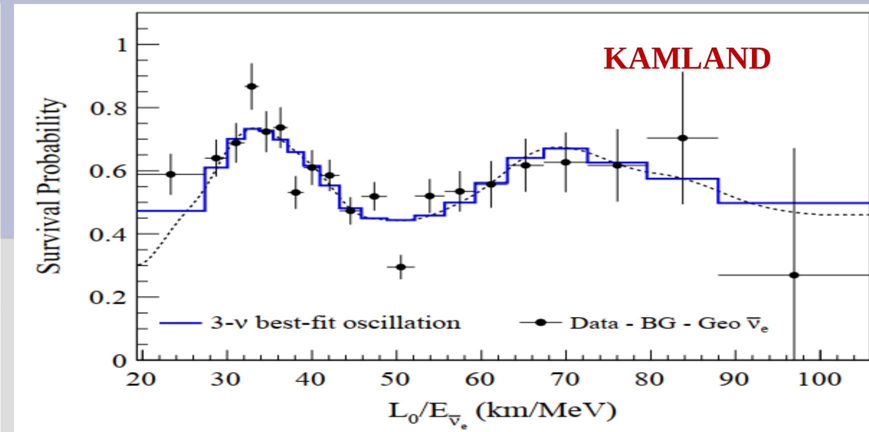
ν19 @ Prague

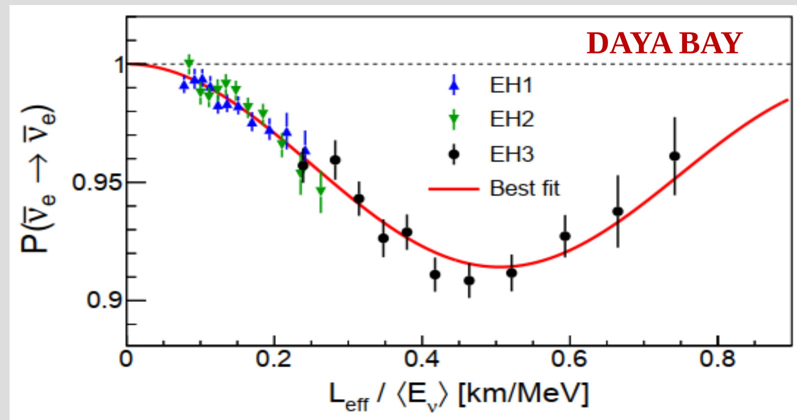
Neutrino landscape in L/E scale

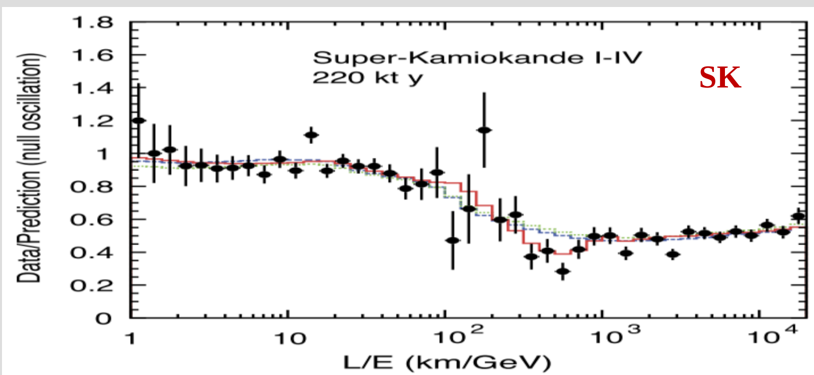


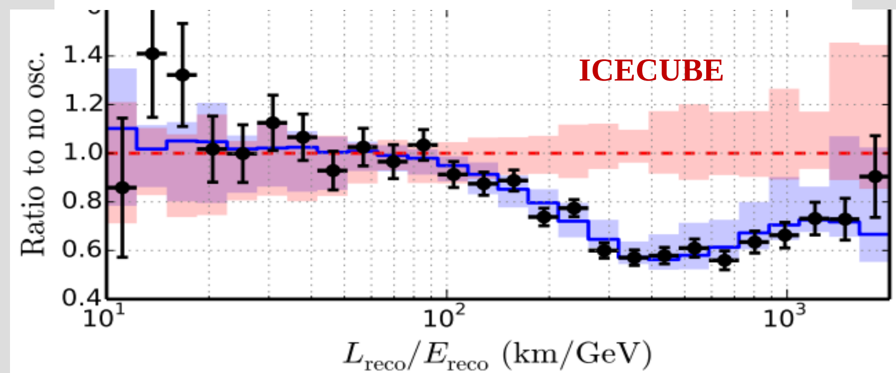
$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(1.27\Delta m^2\ [\mathrm{eV}^2]\frac{L\ [\mathrm{km}]}{E\ [\mathrm{GeV}]}\right)$$

$\Delta^2 m_{SOL} << \Delta^2 m_{ATM}$



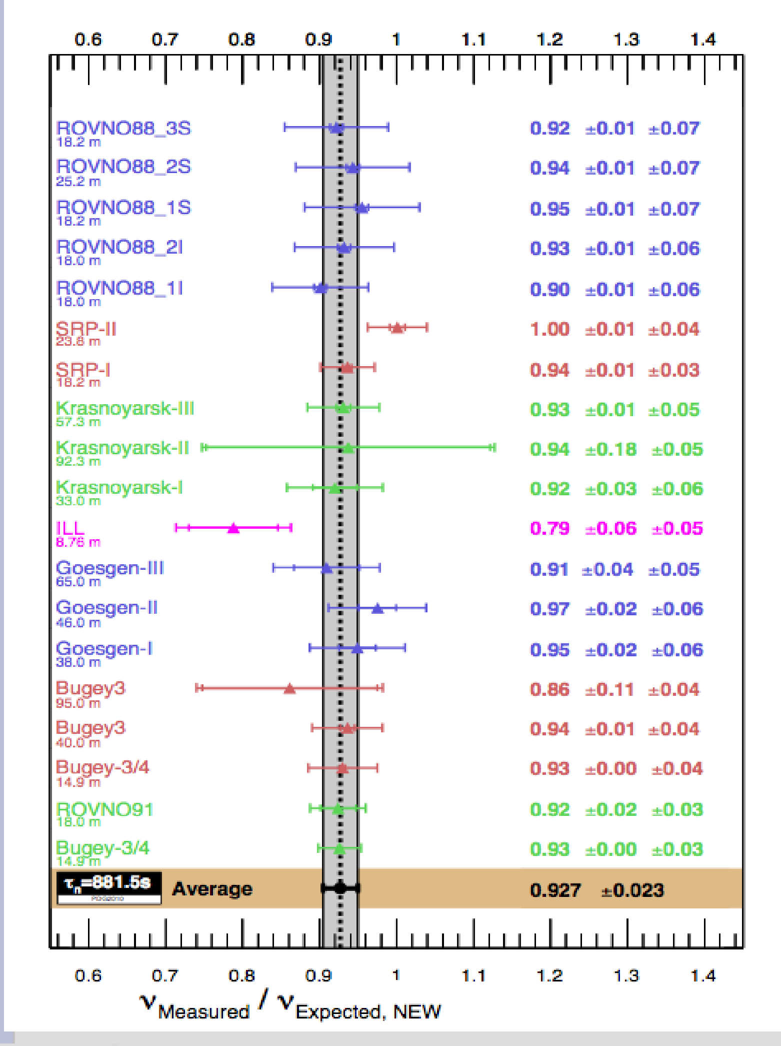






New puzzles: sterile ν?

Reactor Neutrino Anomaly - 1

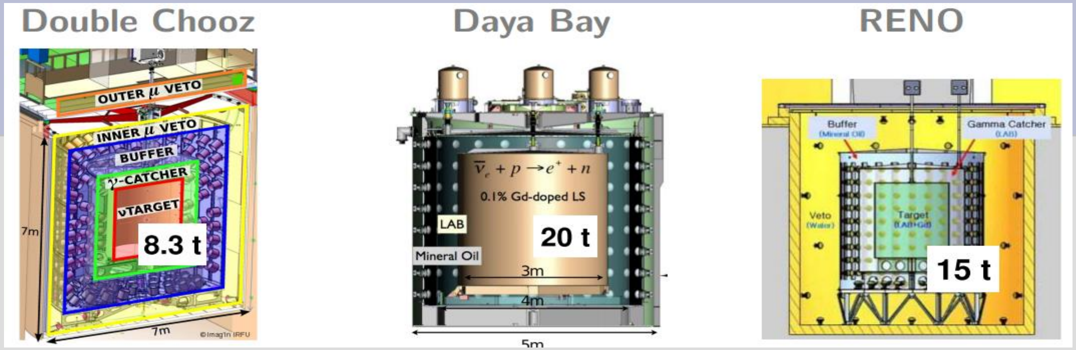


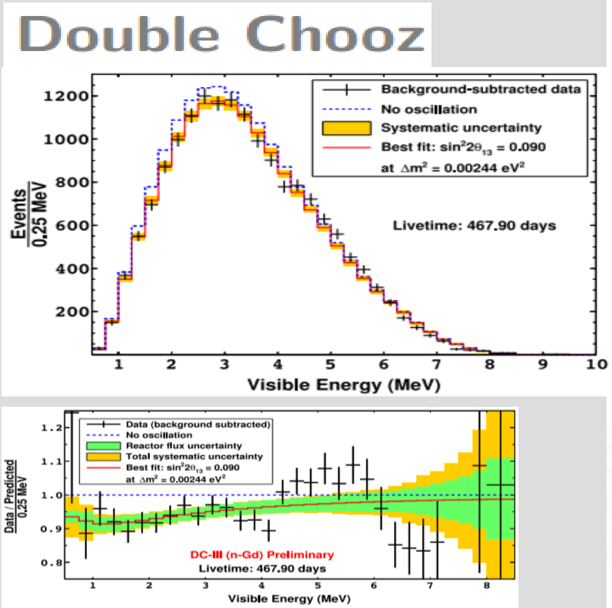
Best fit: 0.927 ± 0.023 (3 σ)

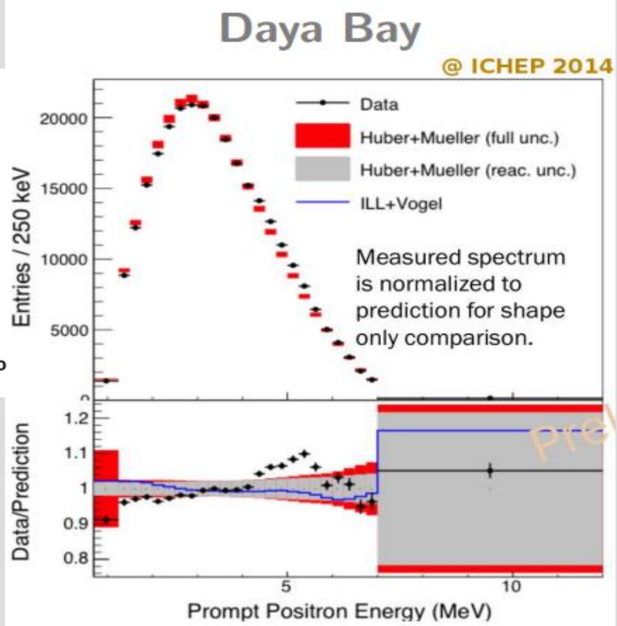
arXiv:1204.5379

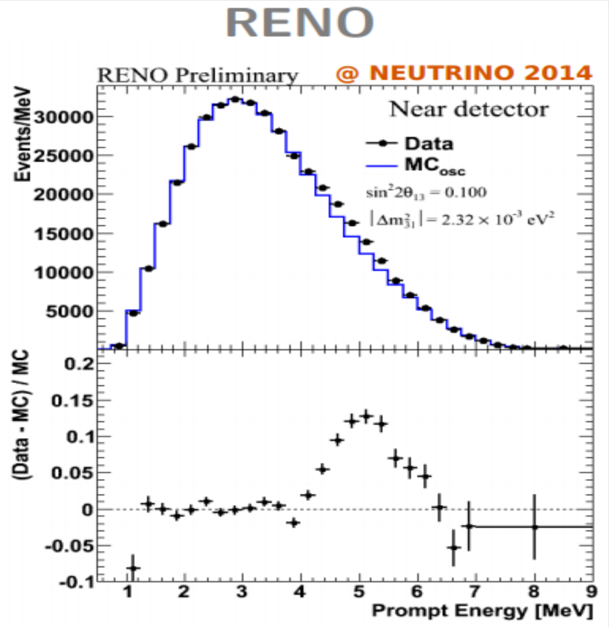
- **Flux reevaluation (Th. Mueller et al. Phys. Rev C 83, 054615 (2011) gives a antineutrino deficit @ 3%/5-7% level for flux/rate exp vs. theor comparison**
- **new reactor antineutrino spectra re-analysis of 19 reactor experiments < 100m baseline including all known corrections & uncertainties**
- **What is the reason?**
  - **unknown bias,**
  - **wrong assumptions**
  - **new physics?**
- **Experimentalists definitely vote for the last options!**

Reactor spectrum anomaly - 2







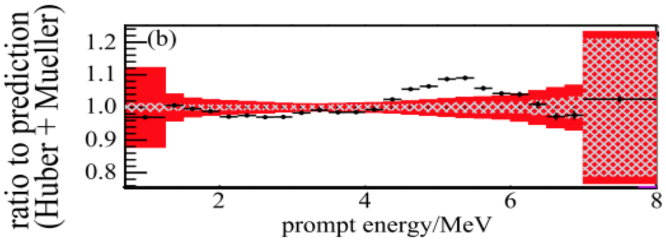


The event excess (4-6 MeV bump) has been observed in all reactor experiments, the effect is under intensive studies today.

Motivation: Reactor Antineutrino Spectrum Deviations

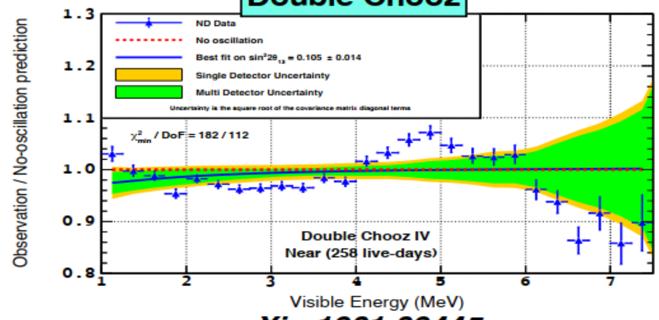
Experiments precisely measured spectrum from Low Enriched Uranium (LEU) reactors ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

Daya Bay



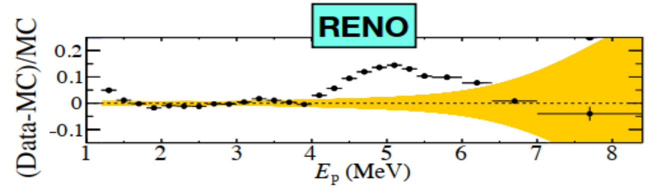
CPC Vol. 41 (1) (2017)

Double Chooz



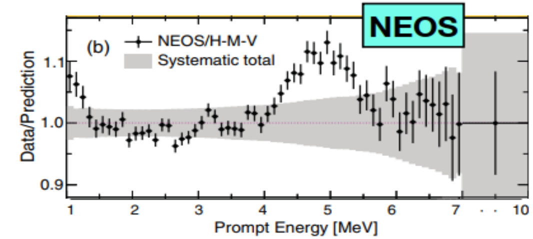
arXiv:1901.09445

RENO



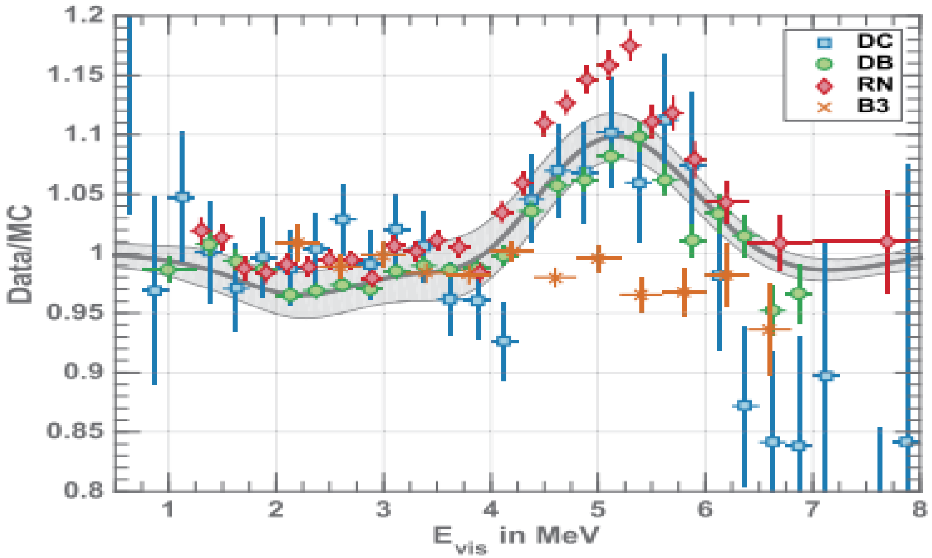
PRD 98, 012002 (2018)

NEOS



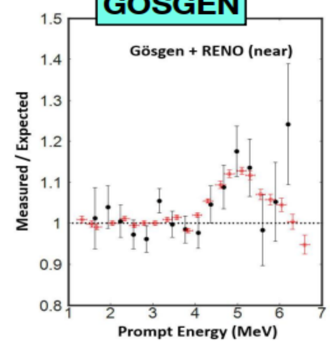
PRL 118, 121802 (2017)

Distortion in 4-6 MeV prompt energy, not only on theta13 experiments.



Physics Letters B 773 (2017)

GOSGEN



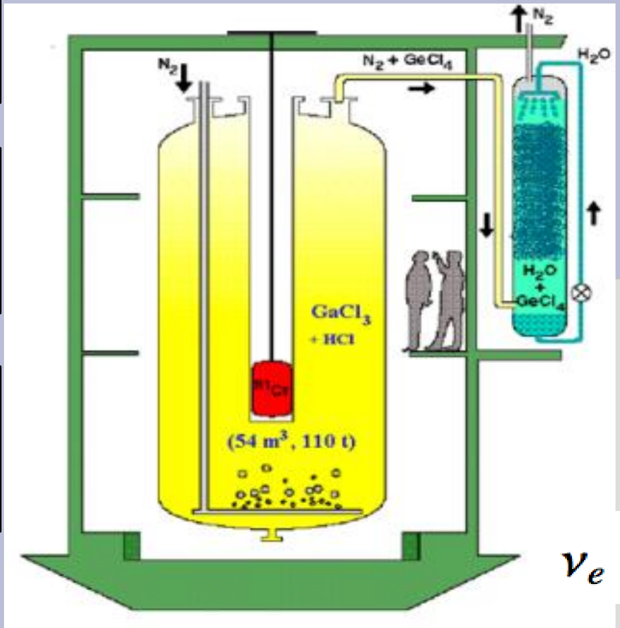
Re-evaluation (2018) of Gosgen(1980's) experiment also showed a deviation in 4-6 MeV region.

arXiv:1807.01810

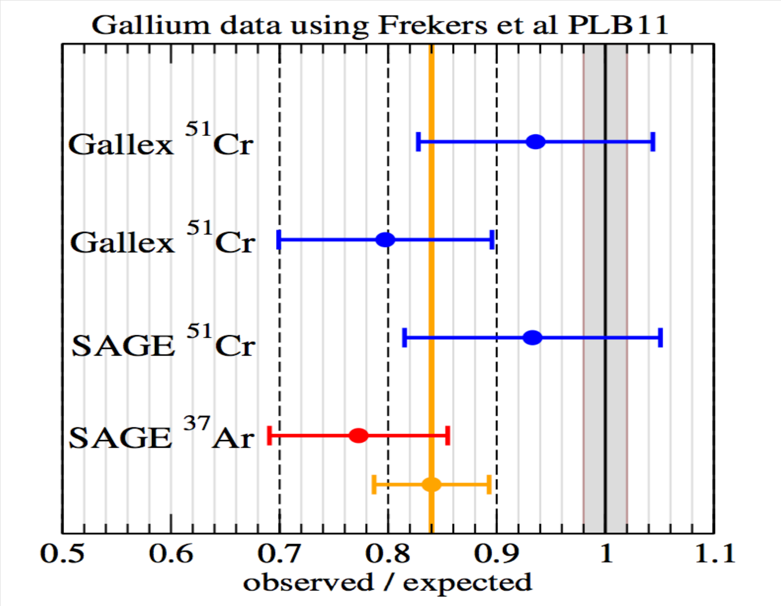
Where this deviation is coming from?

- Cannot be explained by the sterile neutrino introduced for flux deficit.
- Could be an issue with reactor models? Experiments used conventional reactors (LEU).

Gallium Anomaly

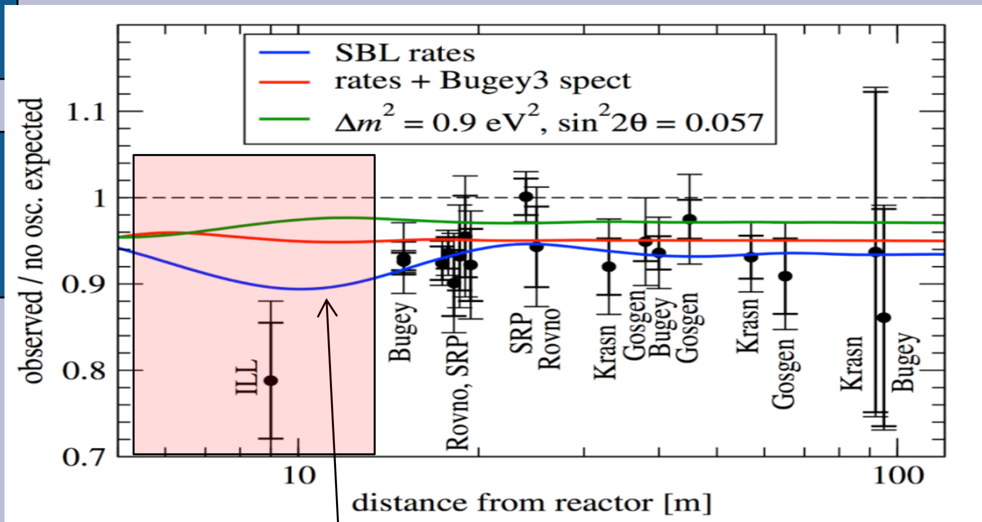


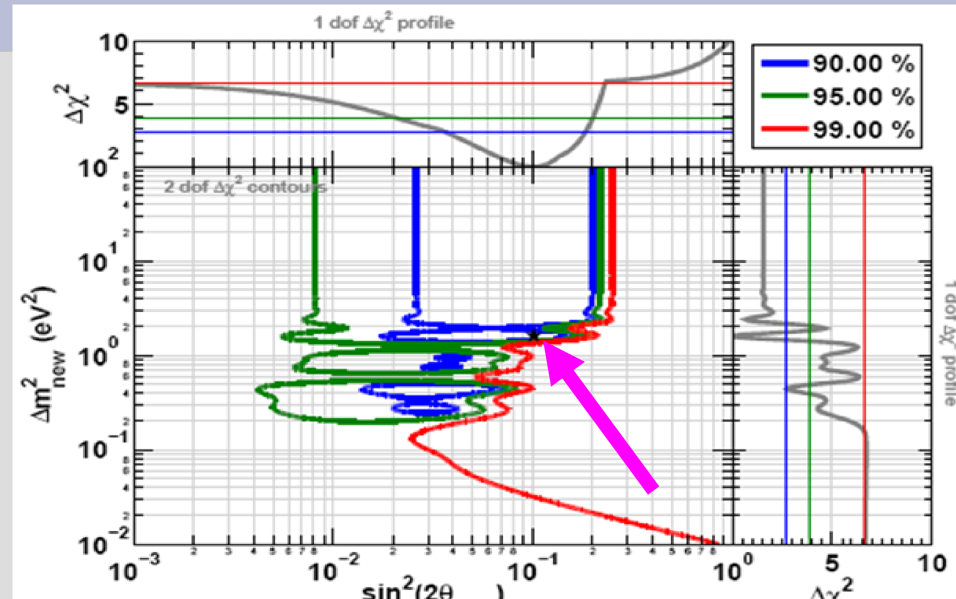
$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$$



- Re-evaluation by C. Giunti & M. Laveder
  Phys. Rev C 83, 065504 (2011)
- Calibration of solar neutrino experiments
  - Distance <≈ 1 m
- GALLEX
  - 2 ^{51}Cr ν_e sources
- SAGE
  - 1 ^{51}Cr ν_e source
  - 1 ^{37}Ar ν_e source
- Overall deficit of detected vs. expected neutrino is : 14 ± 6 %

The sterile neutrino hypothesis





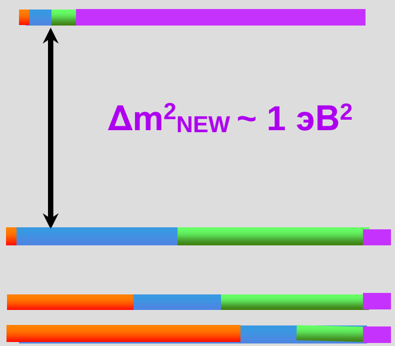
arXiv:1204.5379

Lack of data here!

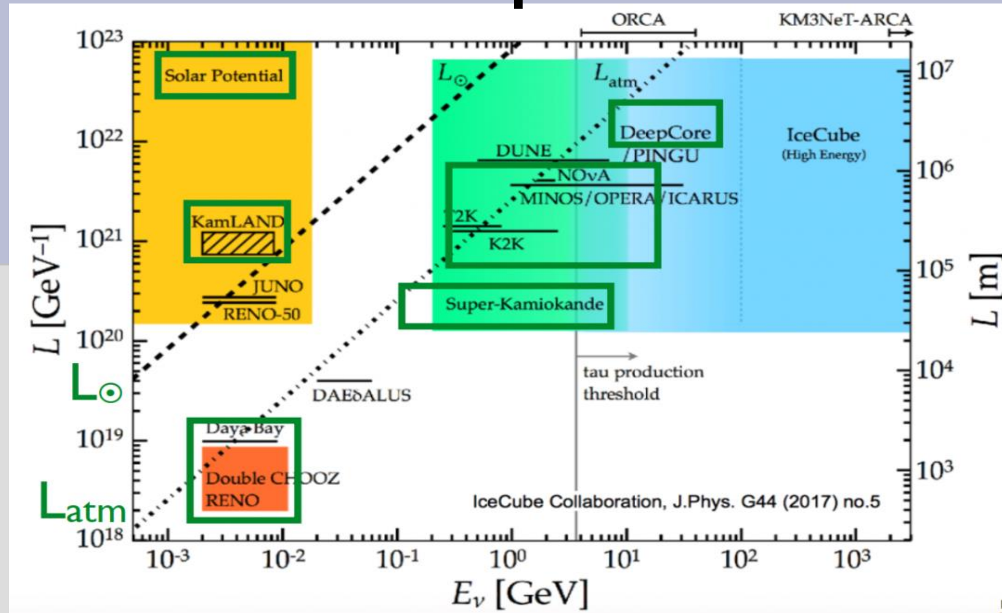
Best fit RAA-1:
$\sin^2(2\theta_{NEW})$~0.1,
Δm^2_{NEW}~ 2 eV^2

Neutrino landscape in L/E scale

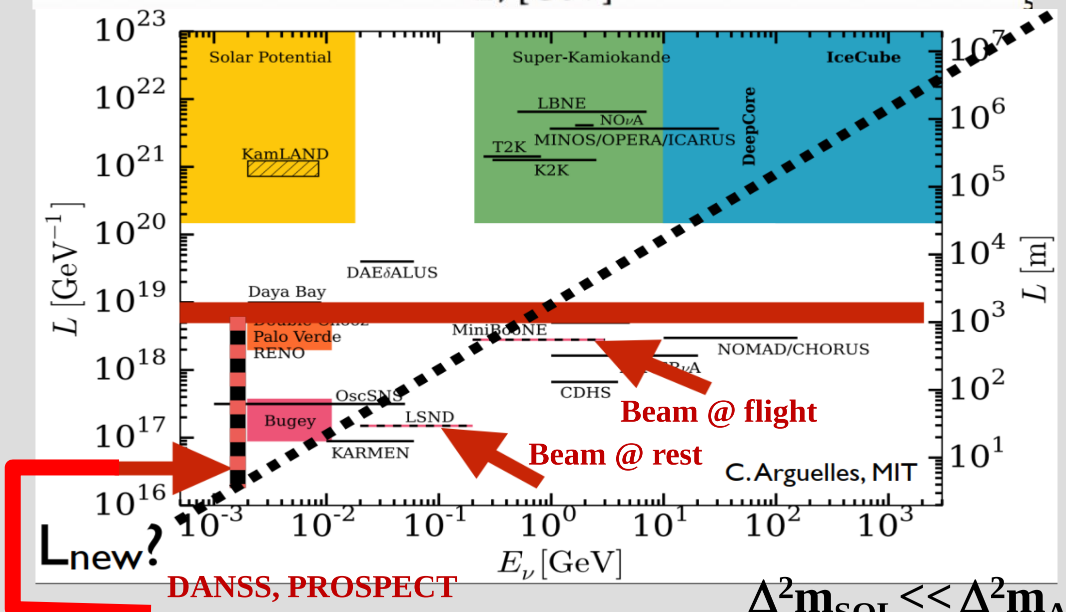
New neutrino stage
(3+1) ?



$\Delta m^2_{NEW} \sim 1$ эВ^2



~ 1 eV



DANSS, PROSPECT
STEREO, SOLID, N4
Reactor ν

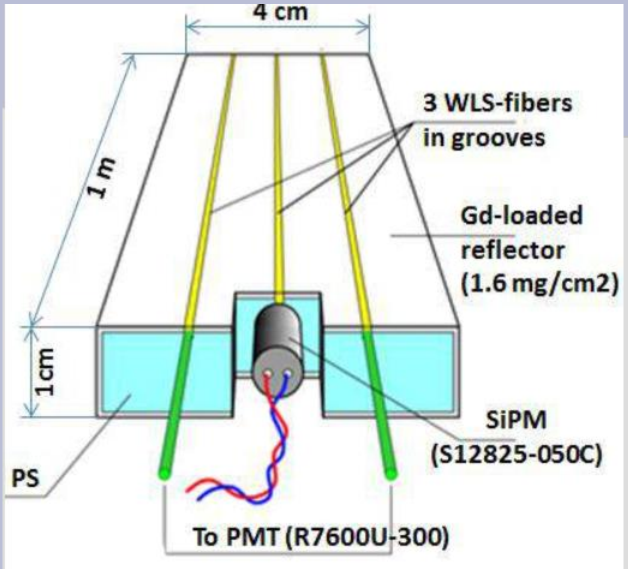
$\Delta^2 m_{SOL} << \Delta^2 m_{ATM} << \Delta^2 m_{newx`x`}$

Motivation for new reactor experiments

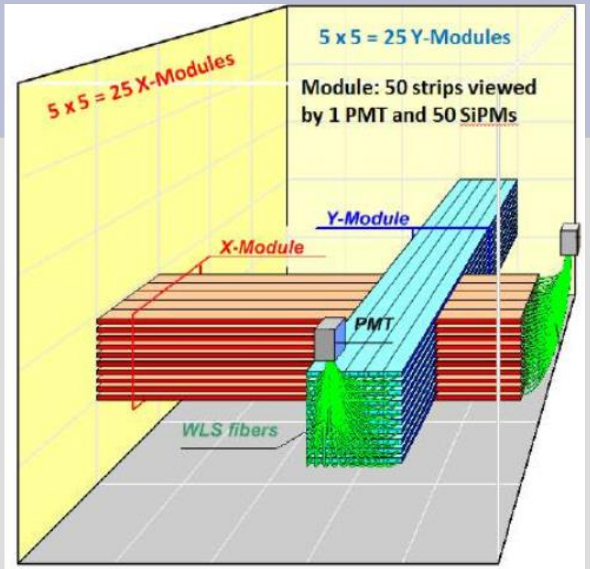
- One need more good quality data in the range of very short base line (SBL) (5-20 m between an detector and reactor) in order to check definitely the sterile neutrino hypothesis.
- The discovery of the sterile neutrino would be the fundamental result.
- Precision measurement of the energy spectrum of reactor antineutrinos will be important contribution for the neutrino oscillation physics. It will help to improve reactor , and, thus, to reduce uncertainties of the results obtained by reactor neutrino experiments.
- Developed technologies can be used in a set of applications: reactor monitoring, nuclear safeguarding, tomography of reactor zone.

The DANSS design

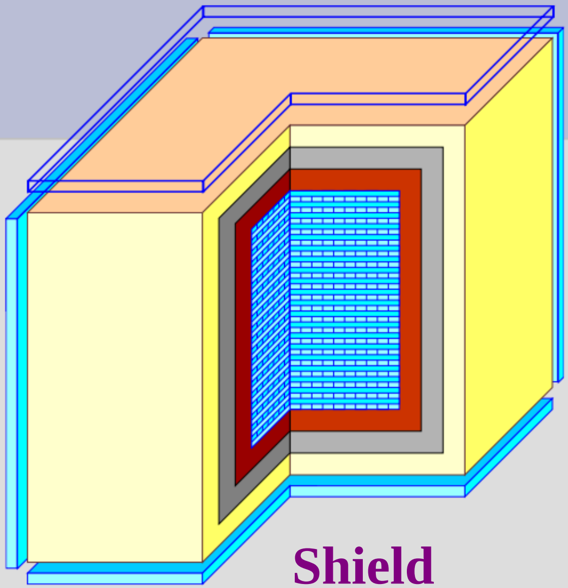
Strip



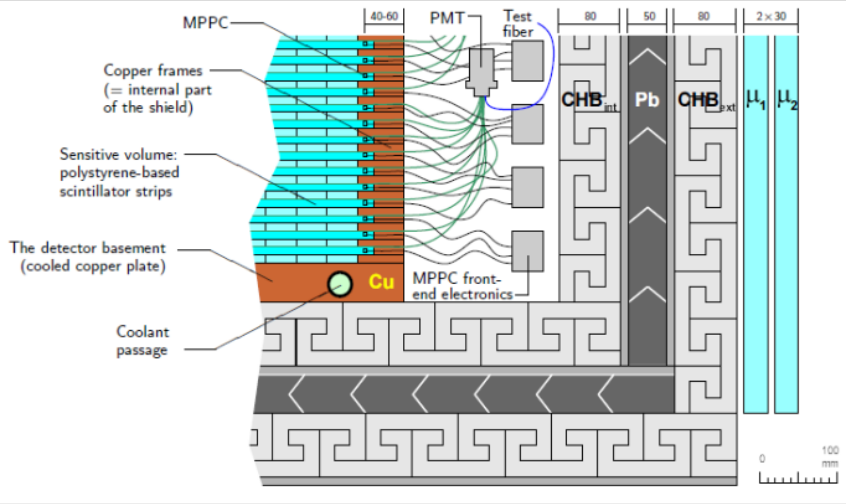
Module



Detector

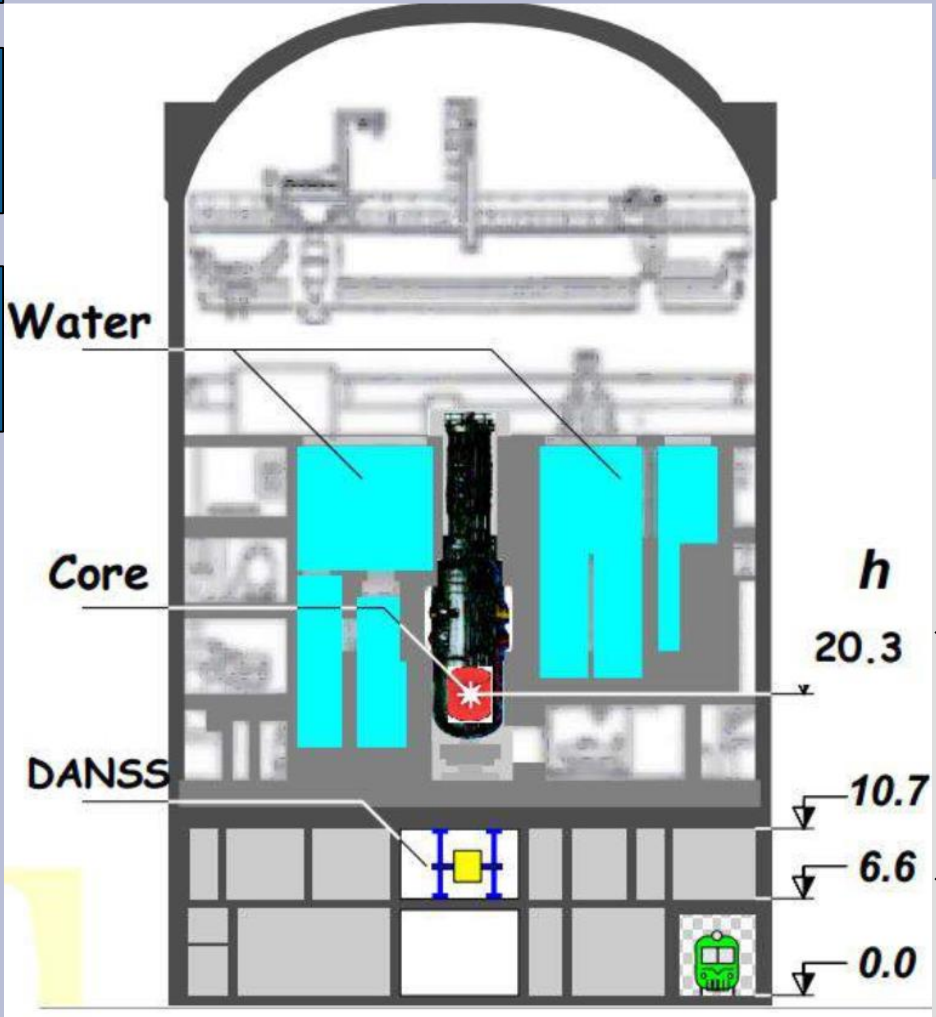


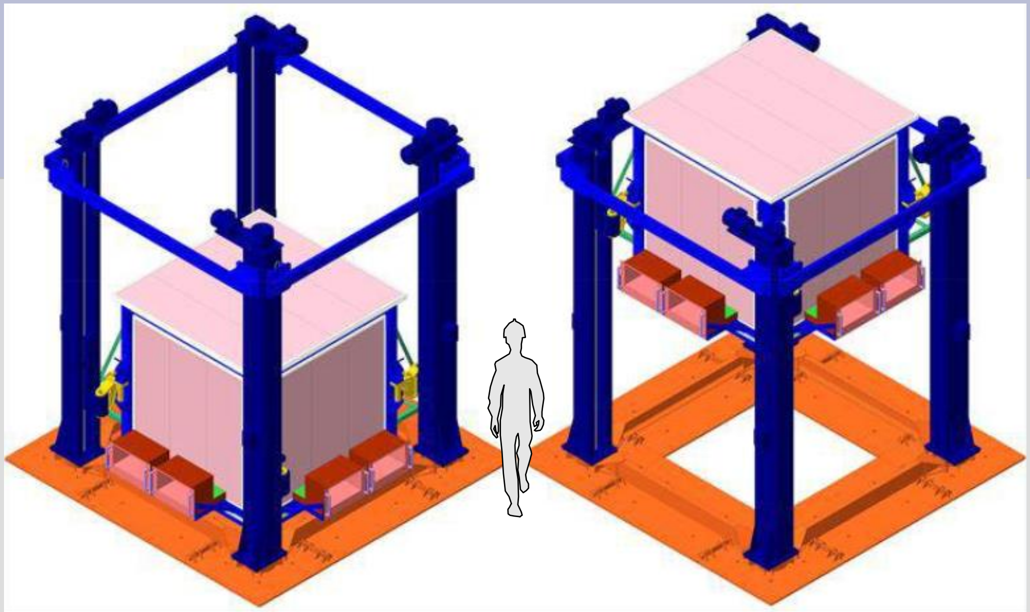
Shield



- **Cubic meter highly segmented neutrino spectrometer made of 2500 PS strips viewed by 2500 SiPMs & 50 PMTs.**
- **Multilayer passive shielding: Cu/CHB/Pb/CHB=5/8/5/8 cm**
- **Active muon veto made of 2 x 3 cm PS plates from all sides except bottom.**

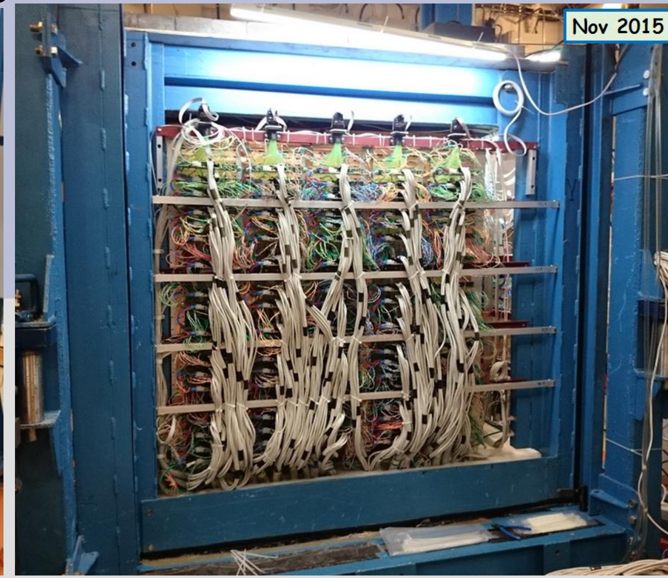
The location and movable platform



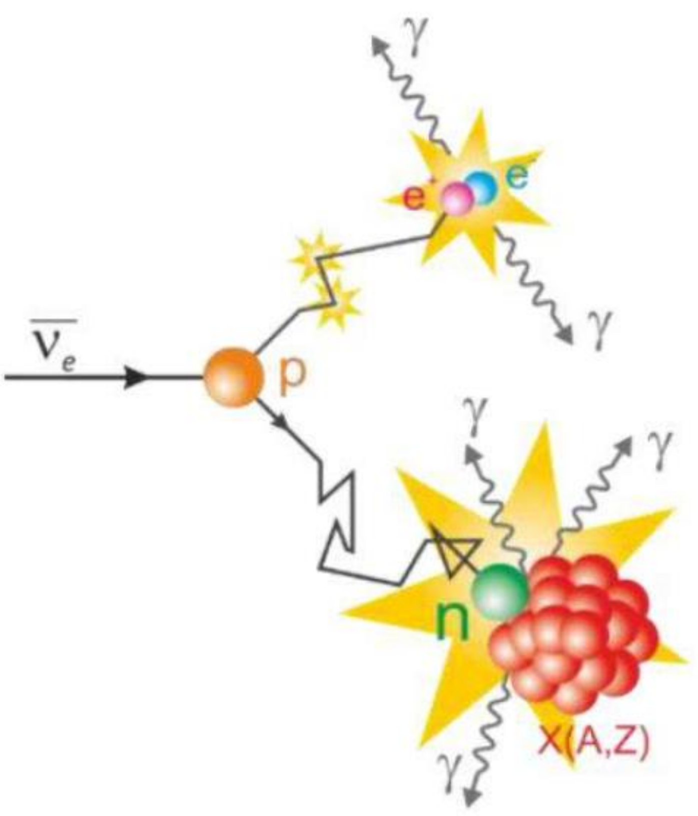


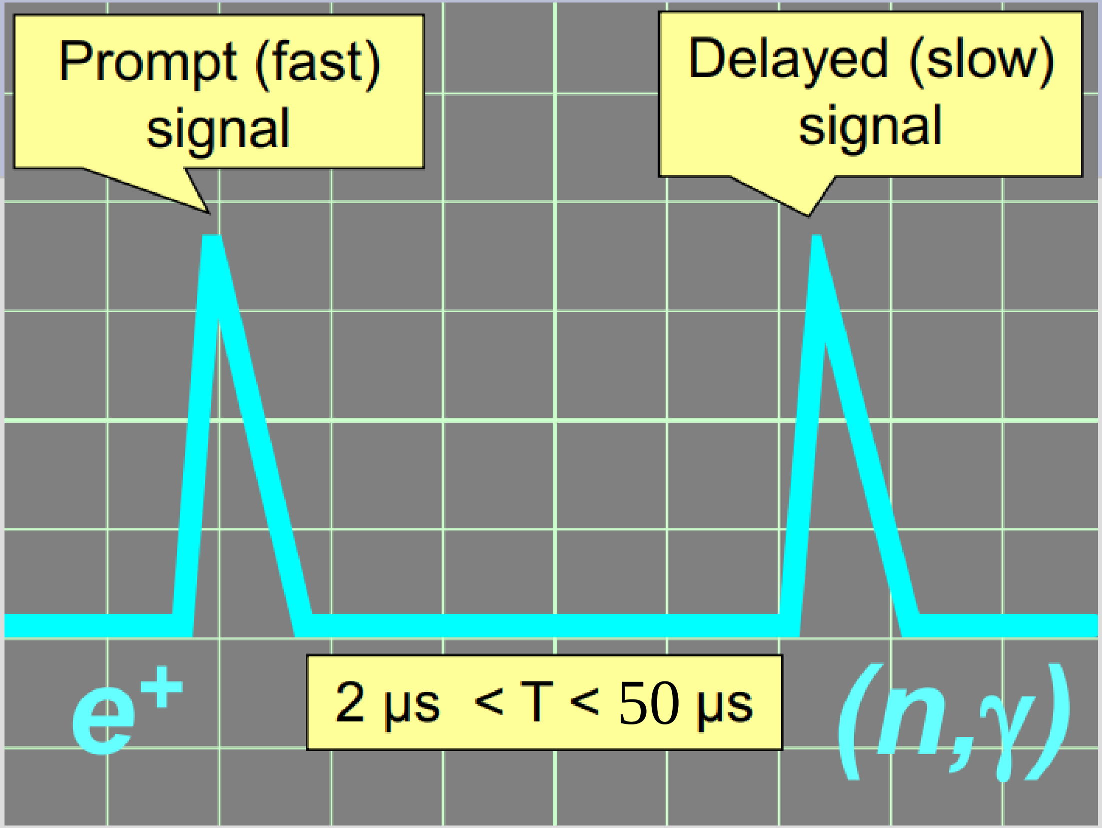
- The DANSS is located at Kalininskaya NPP (KNPP) under 3 GW WWER-1000 reactor (H=3.6 m, ∅ =3.1 m), which provides ~ 50 m.w.e. (6-fold μ reduction and no cosmic n).
- The detector is built on a movable platform. Data are taken at 3 distances 10.7 m (Up), 11.7 m (Middle), and 12.7 m (Down) from the reactor (center to center), changed sequentially 3 times per week.

Detector Assembly



IBD signal pattern & basic cuts

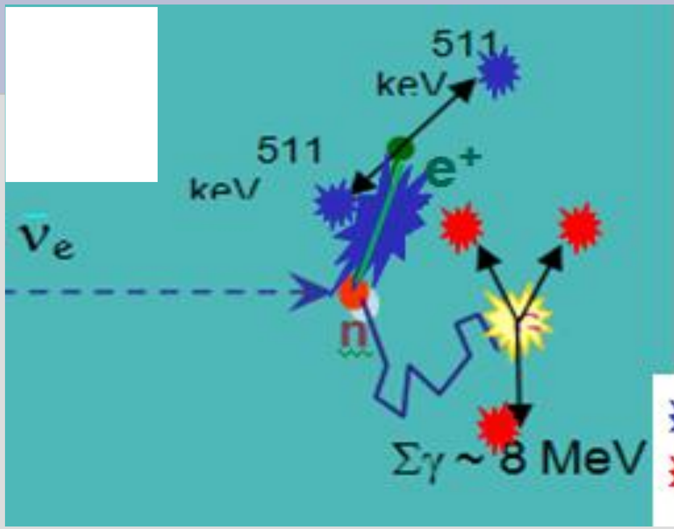


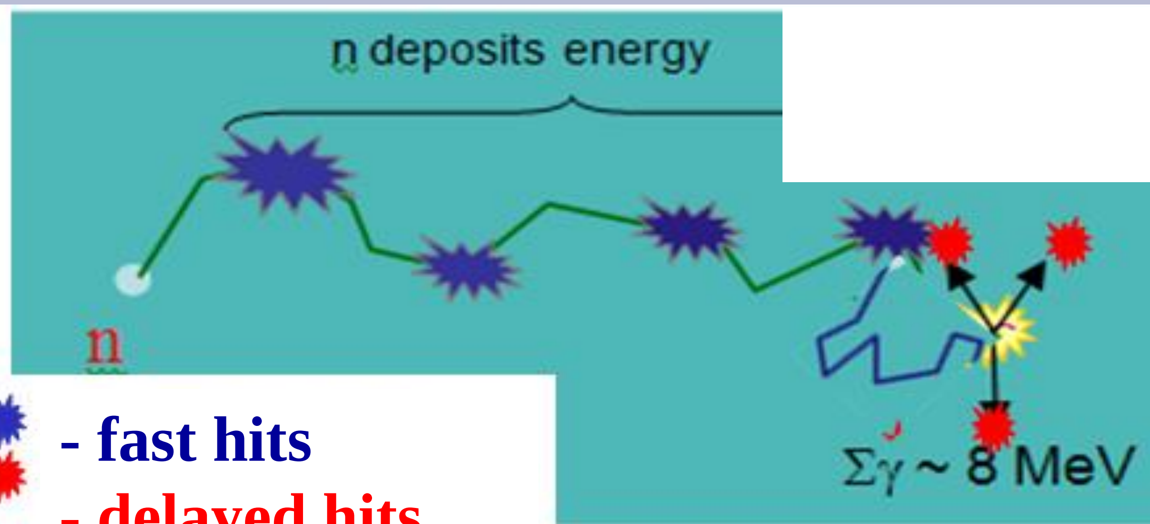


Main cuts (maximally relaxed):
- Prompt signal (E > 0.7 MeV)
- Delayed signal (E>3 MeV)
- Time between signals is in [2, 50] μs
- No muons before prompt signal in 60 μs

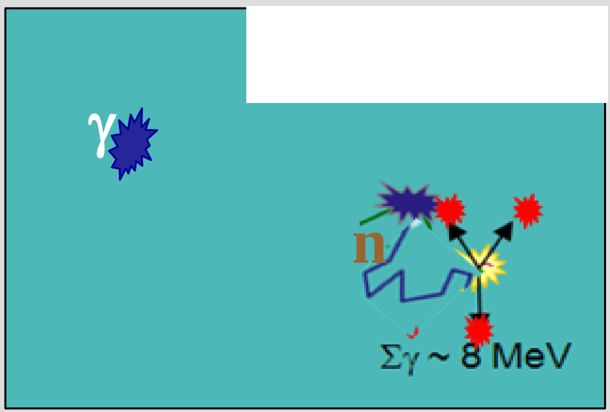
Additional cuts:
- Hit multiplicities for both signals
- Positron clustering pattern cuts
- Spatial cut on distance between fast and slow signal vertexes

IBD & Background signatures





- fast hits
- delayed hits



Main background are fast neutrons and accidentals.

Methods to fight:

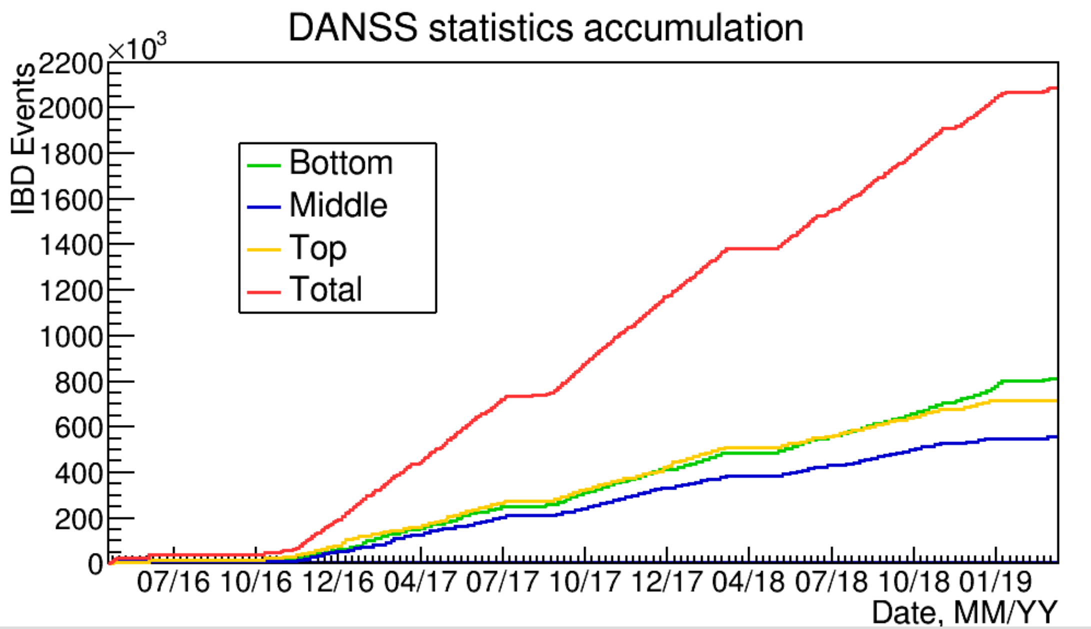
A) Active & passive shielding
Б) n/γ discrimination
B) Detector segmentation & event rejection by geometrical cuts.

Improvements in analysis*

- **Improvement in signal processing (use of SiPM and PMT signal shapes for T_0 and charge determination) and MC simulations (signal WF simulations, taking into account Birks effect & Cherenkov radiation).**
- **Cut modification (requirement for PMT-SiPM coincidences to suppress noise, requirement of annihilation photons for 1strip positron clusters to reduce accidental/neutron background for low energy positrons).**
- **More frequent energy calibrations (gain – each 15min, MIP – each 2 days).**
- **Usage of ^{12}B spectrum for energy scale calibration.**
- **Two lowest detector layers added to the VETO system**
- **Four times finer grid of points on the (Δm^2, $\sin^2(2\theta)$) phase space**

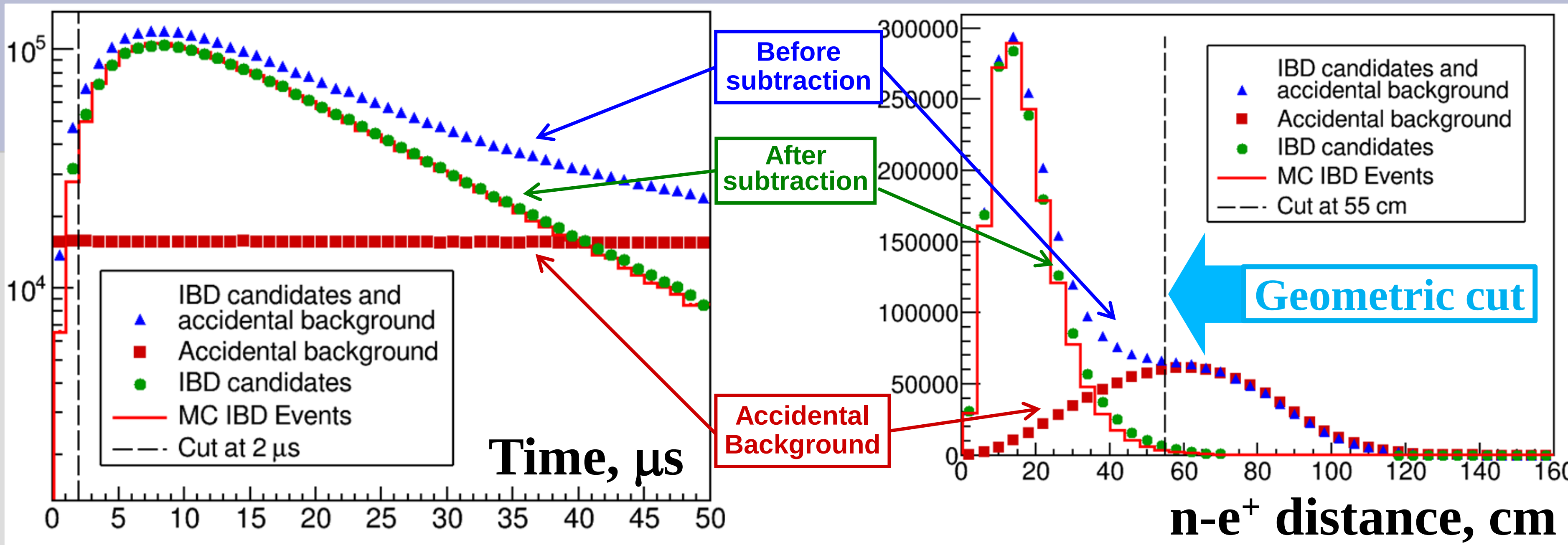
***) in comparison with our last published result Phys.Lett. B787 (2018) 56**

Results of improvements



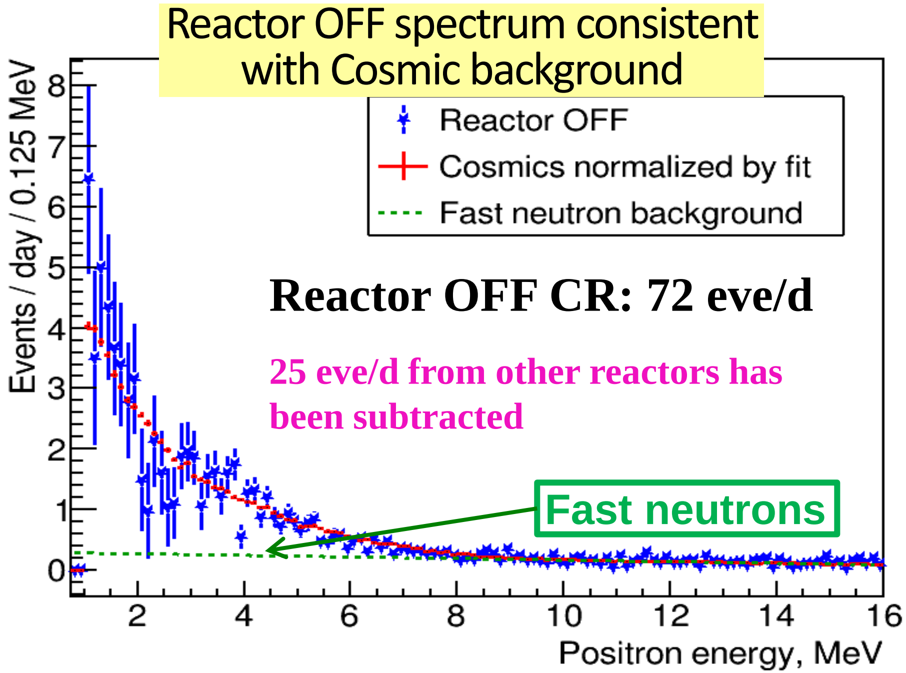
- **Accidental energy in event has been reduced from 100 keV to 5 keV**
- **Accidental background was suppressed from 71% to 29% (up position)**
- **Cosmic background is reduced from 2.8% to 1.9%**
- **Statistics has been increased from 0.97 to 2.1 million IBD events: old data (10/2016-07/2017) + new data (09/2017-01/2019)**
- **Sensitivity of experiment has been improved by a factor of ~1.4**
- **Energy resolution for calibration sources is still worse than in MC and additional smearing of 17%/√E has been added to MC (as in published results)**

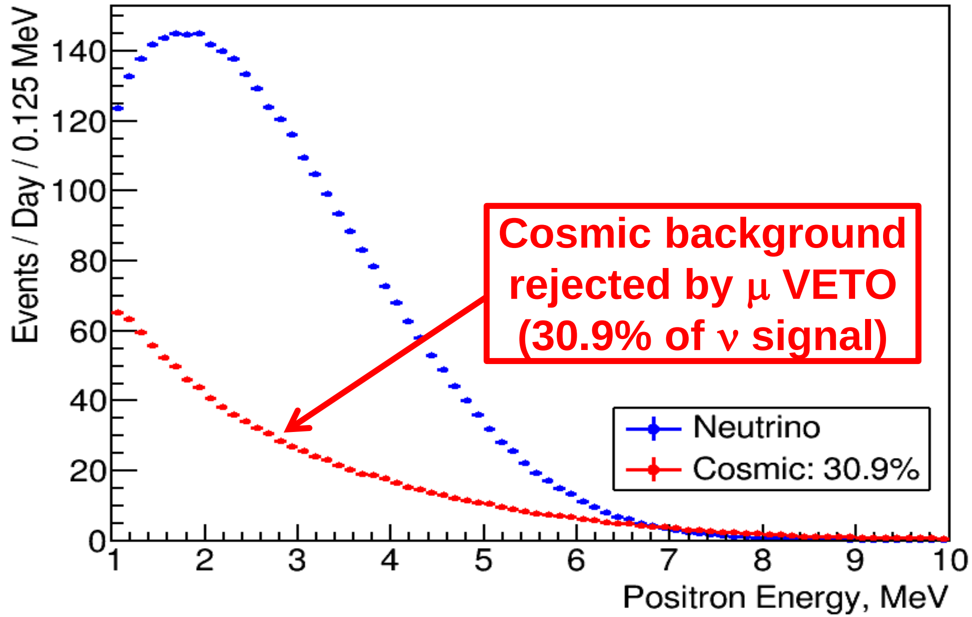
Accidental coincidence background



- **Accidental coincidence of 2 uncorrelated signals (e+-like and neutron-like) in a IBD window [2-50] μs → accidental coincidence background (ACB)**
- **ACB spectrum is constructed directly from data applying the same physics cuts as for IBD signal except coincidence time taken outside IBD time window [2-50] μs in numerous non-overlapping intervals (large statistics is essential to decrease statistical errors of subtraction).**
- **ACB rate is ~29% of IBD rate (up detector position)**
- **Selection of cuts (e.g. geometric) to reduce ACB ⇒ smaller statistical errors**

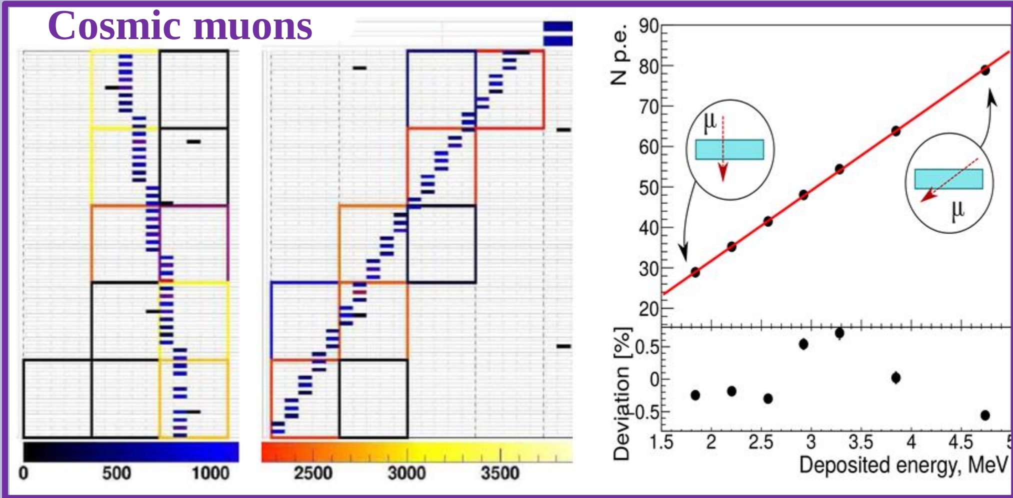
Subtraction of residual backgrounds

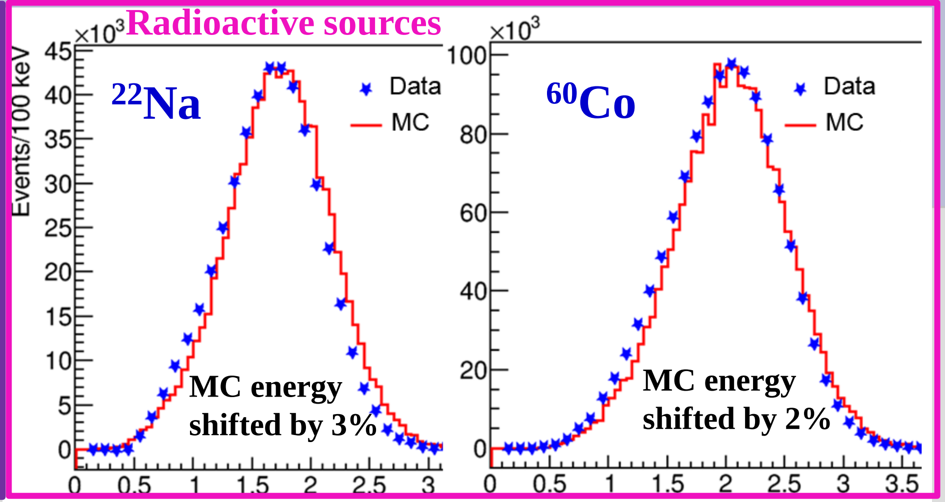


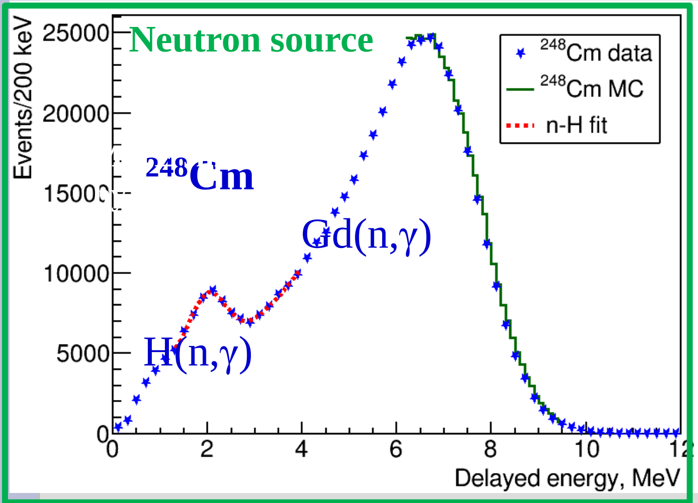


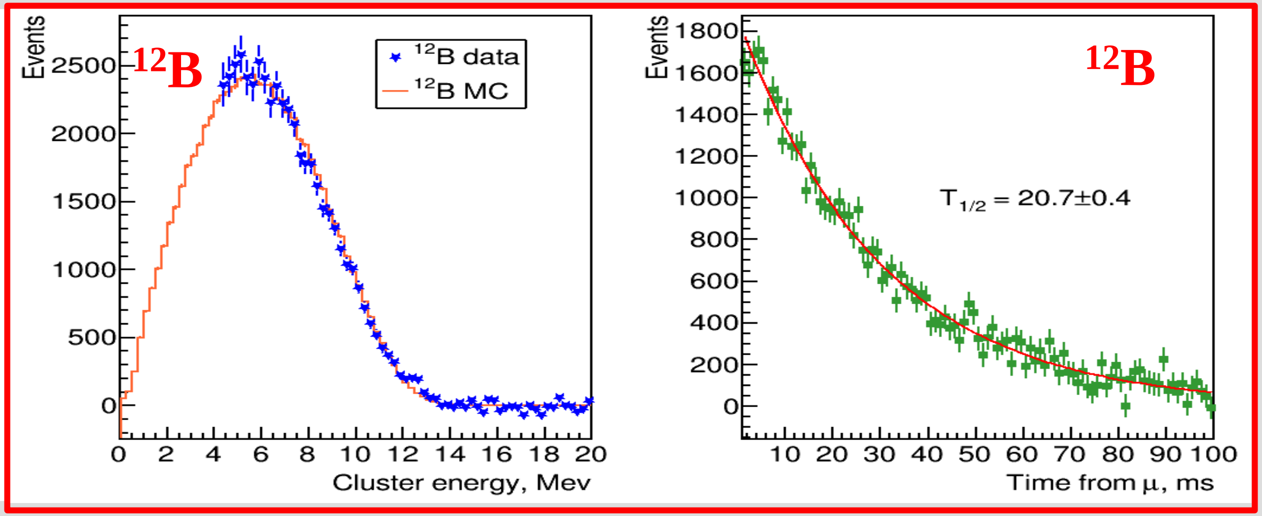
- **Fast neutrons**: linearly extrapolate from high energy region and subtract separately from positron and visible cosmic spectra
- **Visible cosmic background (CB)** has been directly rejected by VETO, it is 30.9% of neutrino signal (for up position)
- Additional CB presents in the IBD-signal due to VETO inefficiency, which was found to be 6.2% from reactor OFF spectra.
- **Not vetoed CB fraction** (due to VETO inefficiency) at level of ~1.9% (=6.2%*30.9%) of IBD-signal has been subtracted from IBD signal (positron spectrum).
- **Final anti-neutrino spectrum (Ee^+ + 1.8 MeV) has no background!**

Calibrations



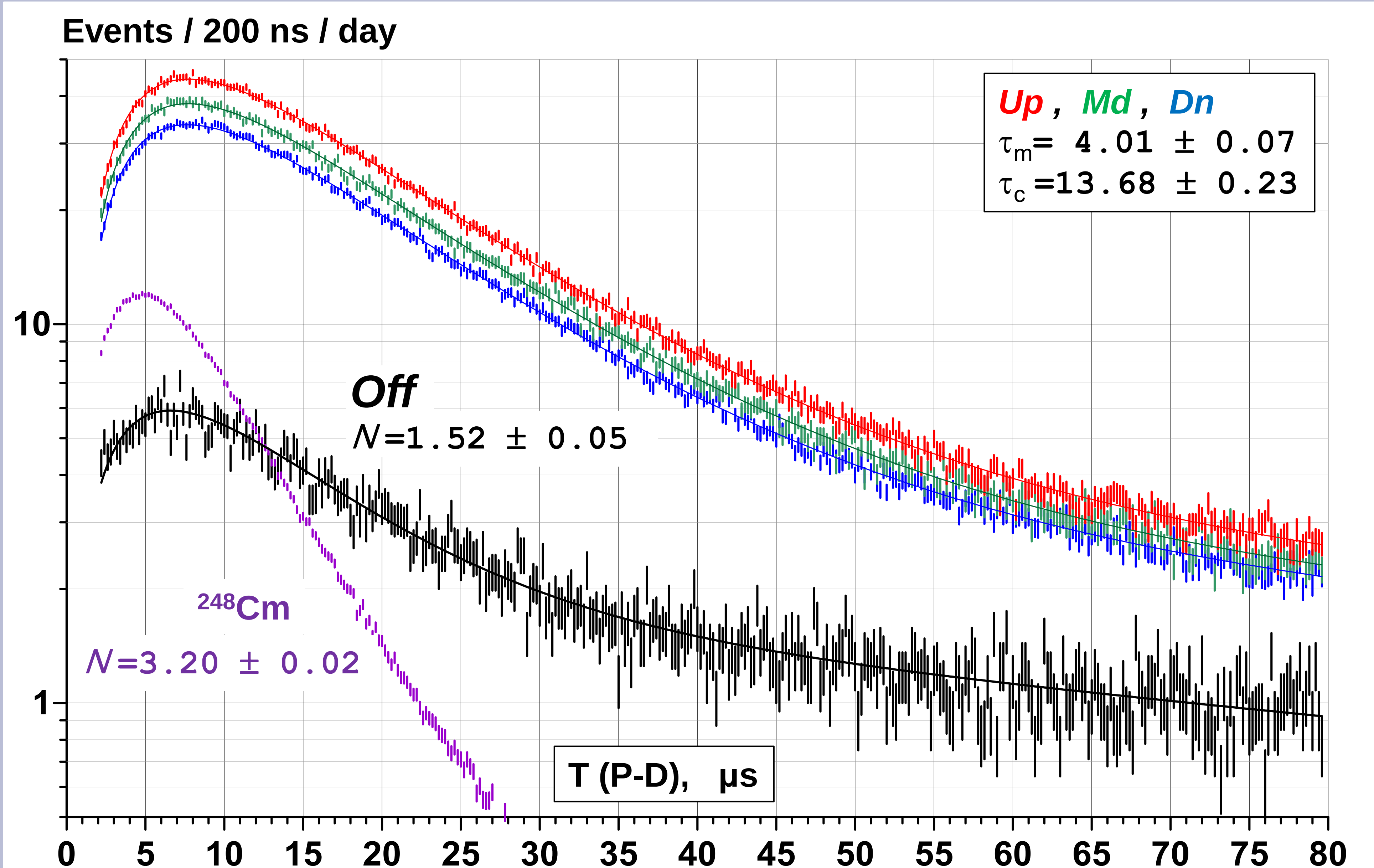




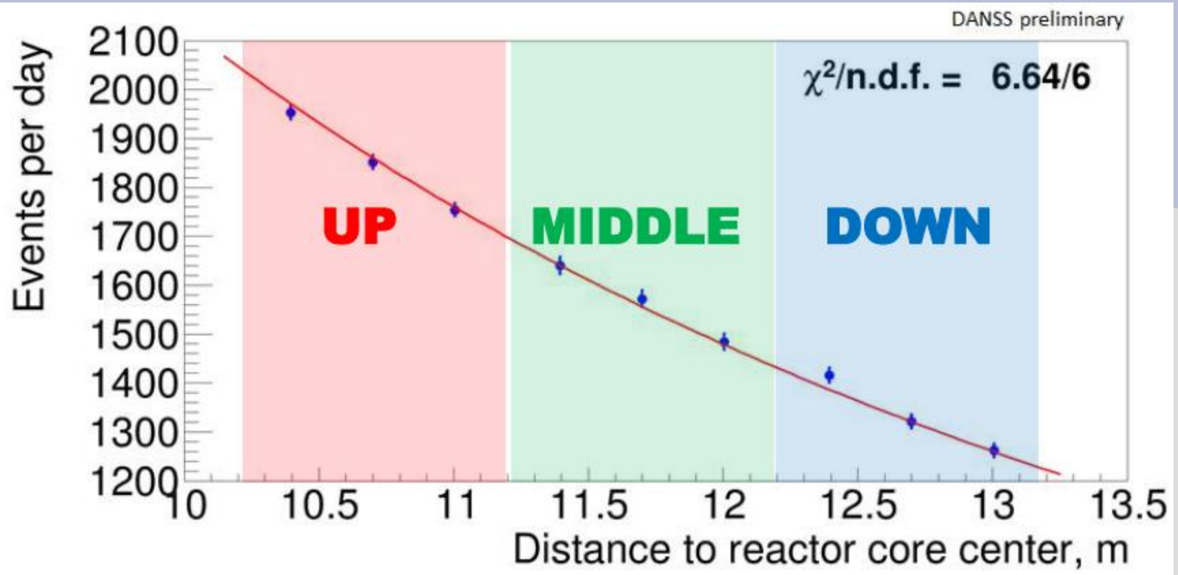


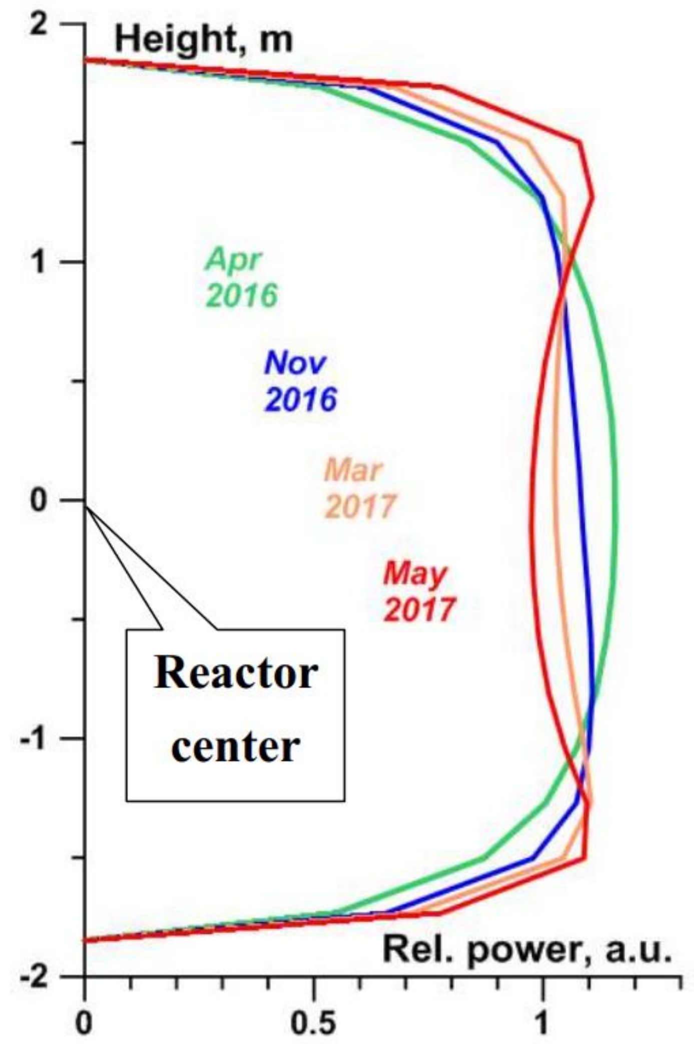
- **Energy scale has been fixed using β-spectrum of ^{12}B, which is similar to positron signal**
- **Systematic error on E scale of +/-2% has added due to source response uncertainties**

Time distribution spectra



IBD total rate vs. effective distance

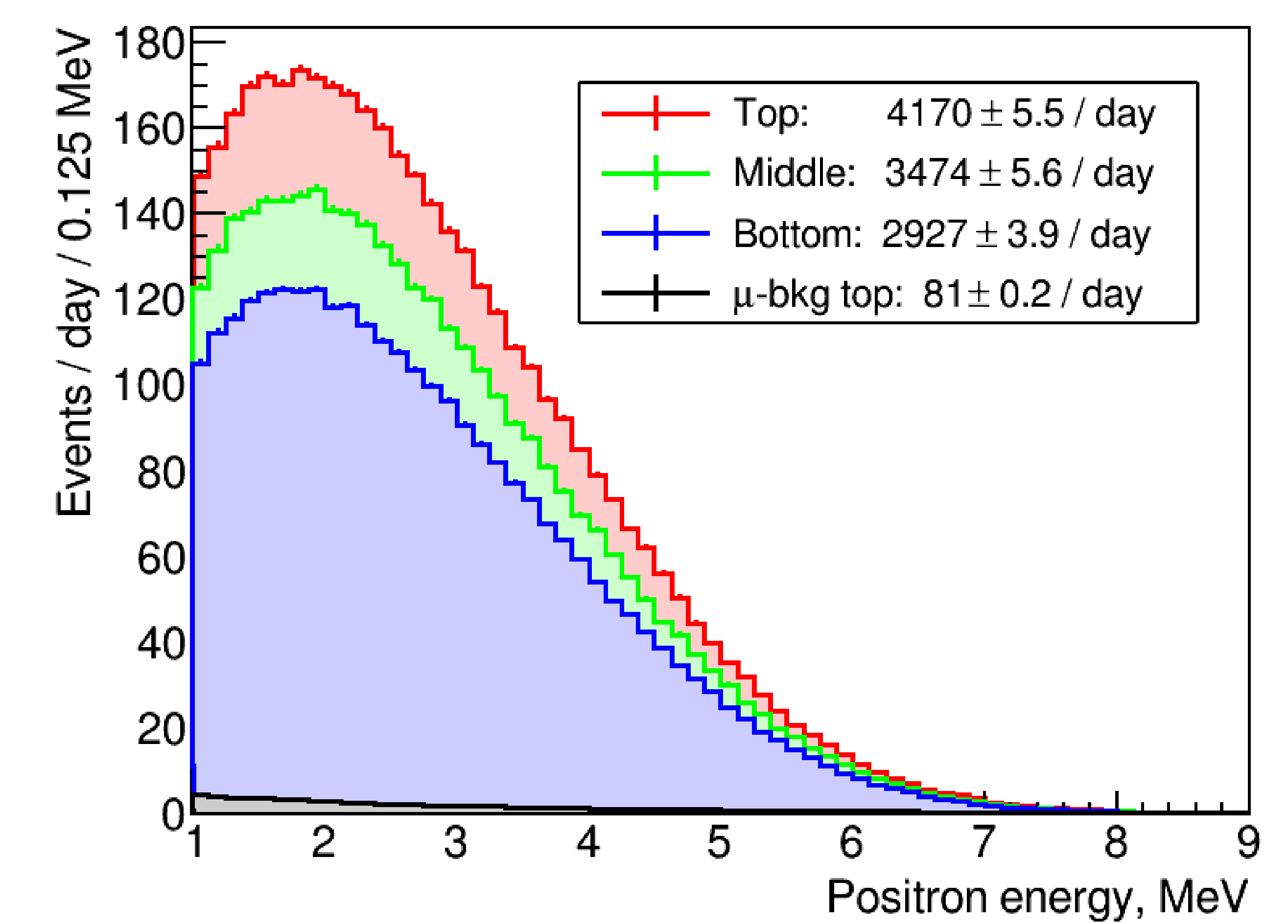




Time evolution of the core burning profile

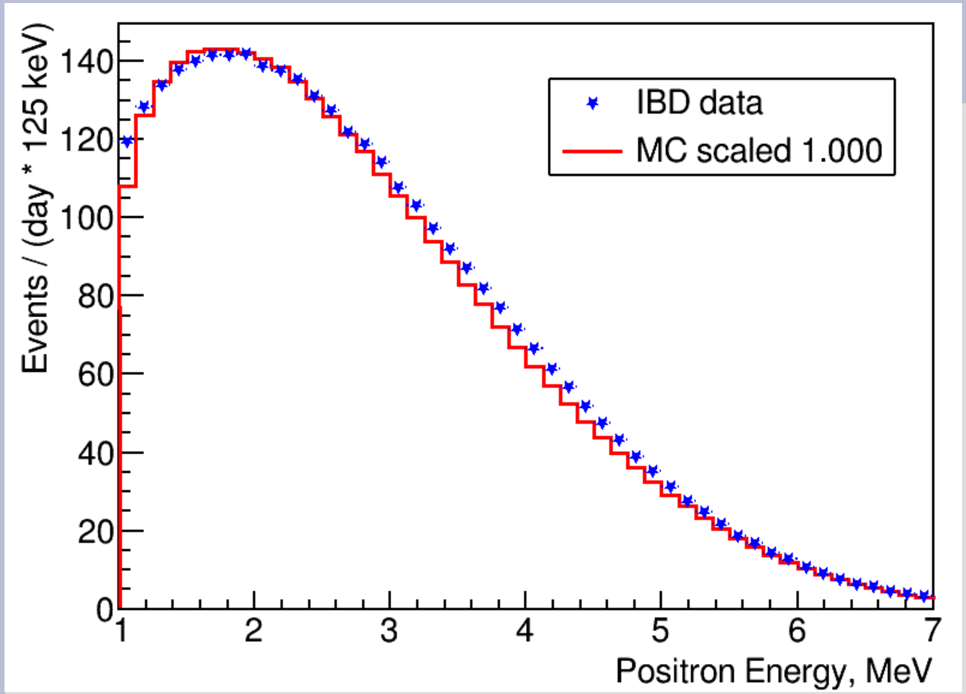
- IBD intensity **follows reasonably the 1 / L^2 dependence**.
- Effective distance L takes into account real spatial distribution of the detection efficiency and the reactor core burning profile (**monitored permanently by the KNPP staff**) .
- The time variation of reactor core burning profile is available **with a precision of 30 min and ~10 cm**.
- Average core burning profile has been used in analysis, and it has negligible effect for the results.

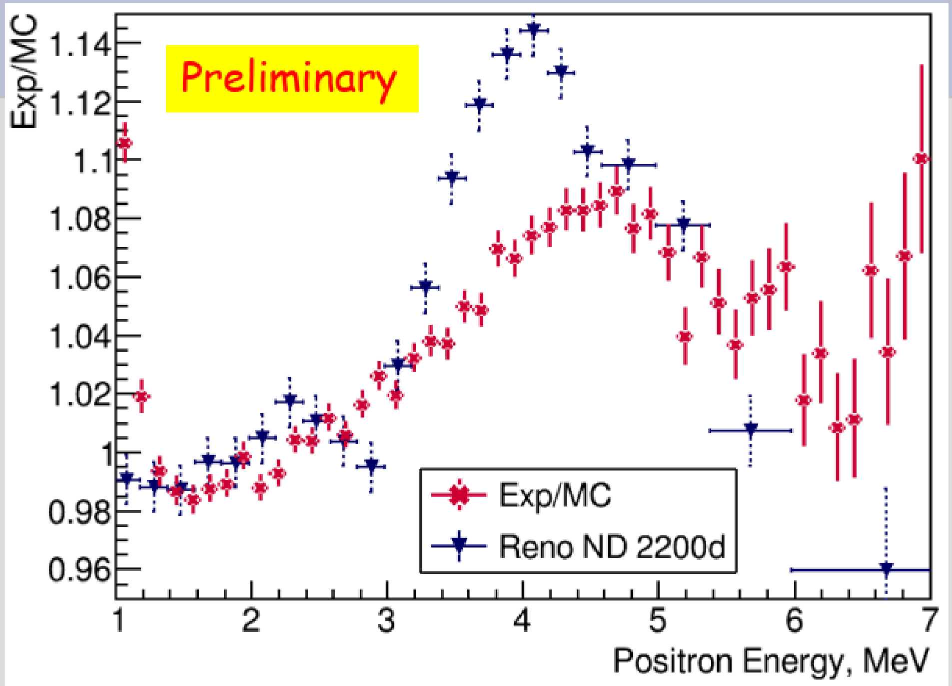
Positron spectrum of IBD-signal



- **Pure positron spectra @ 3 positions (no annihilation photons)**
- **> 4000 eve/d in detector fiducial volume (78% of full volume) @ 'Up' position (closest to the reactor).**

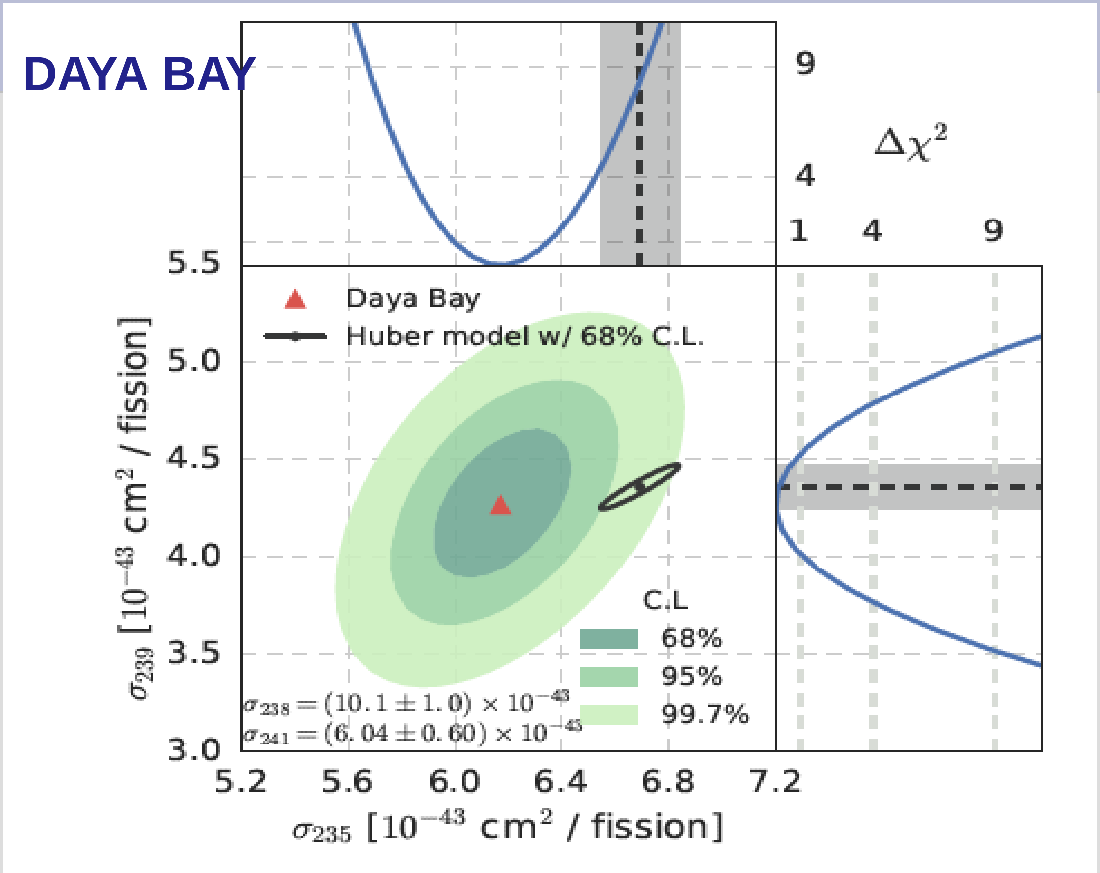
Positron spectrum: experiment vs. theory

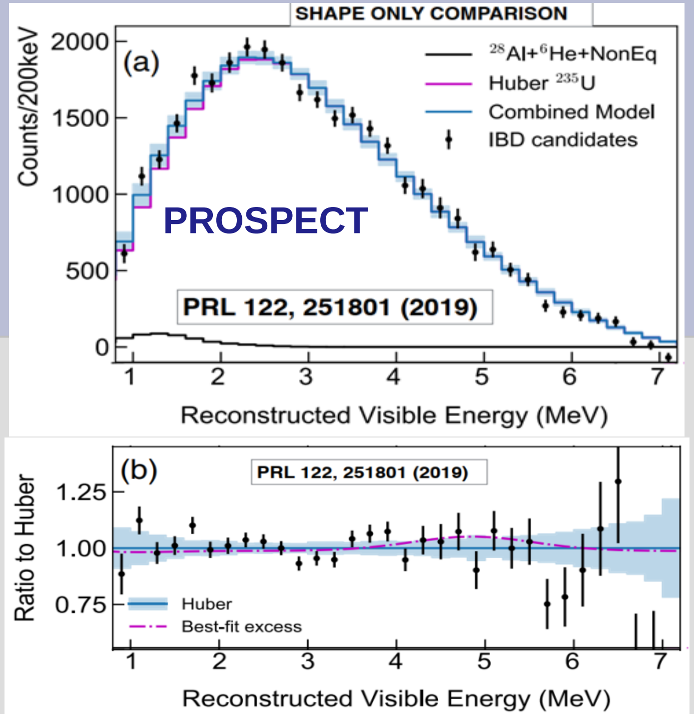


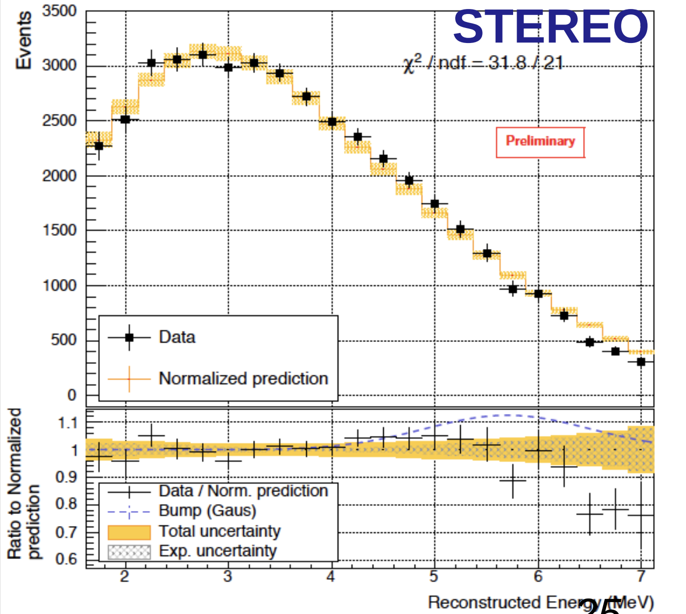


- Experimental spectrum is in rough agreement with MC using Huber-Muller theoretical neutrino spectrum.
- Indication of a bump (normalization in 1.5-3 MeV), but no conclusion on the bump existence now due to strong sensitivity to energy scale.
- More work on calibration is required before precision comparison.

ν-spectra from ^{235}U



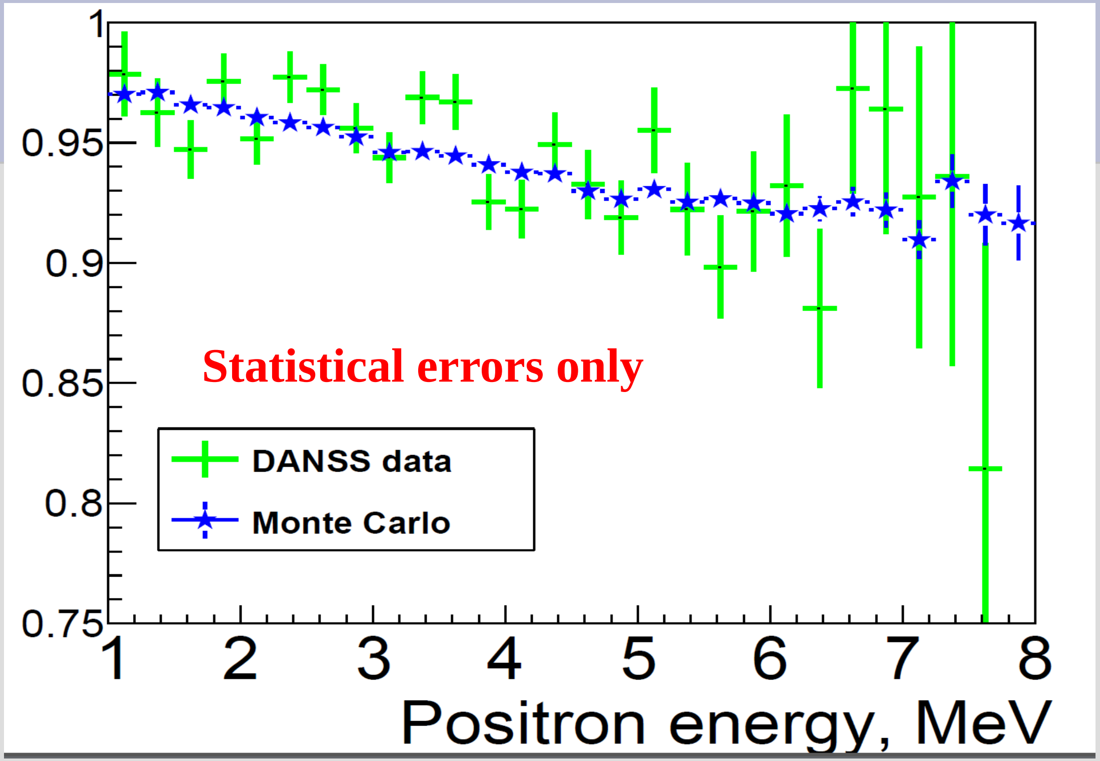




Preliminary results from PROSPECT&STEREO - no bump, contrary to DYB result

Sensitivity to fuel composition

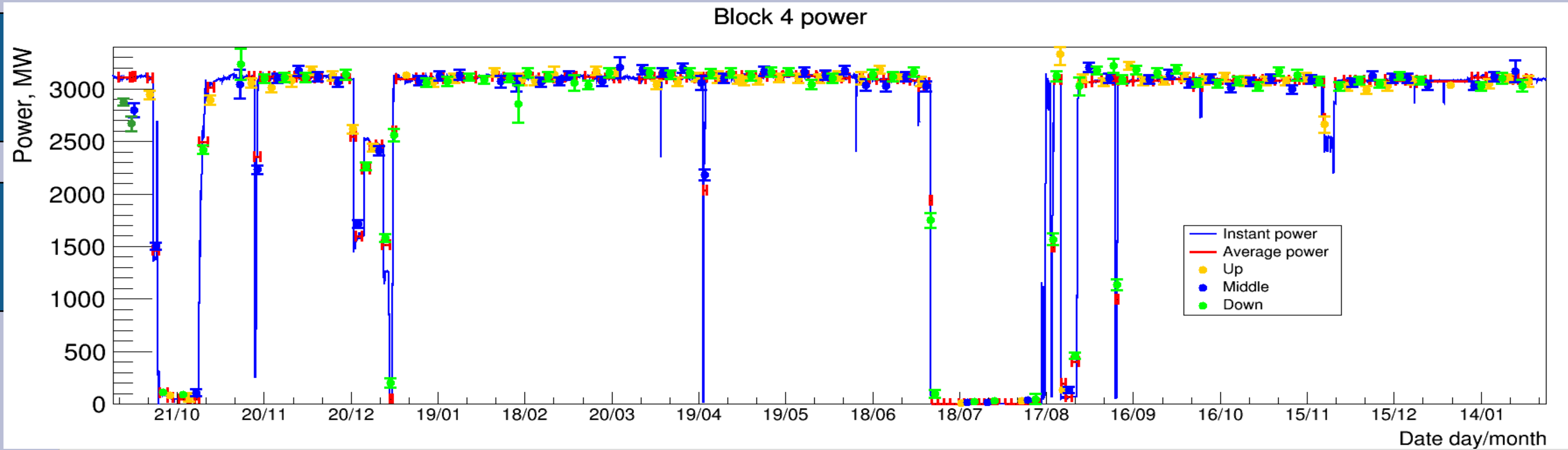
- The figure shows the ratio (bin per bin) of the e^+ energy spectrum collected in the last 4 months of the campaign to the one collected in the 2-5 months of the next campaign.
- Clear evidence for spectrum evolution, which is consistent with MC.
- Result is for old + fraction of new data. For full data set more work is needed for absolute efficiency calibration of the new data (not important in oscillation analysis).



Fission fractions [%]

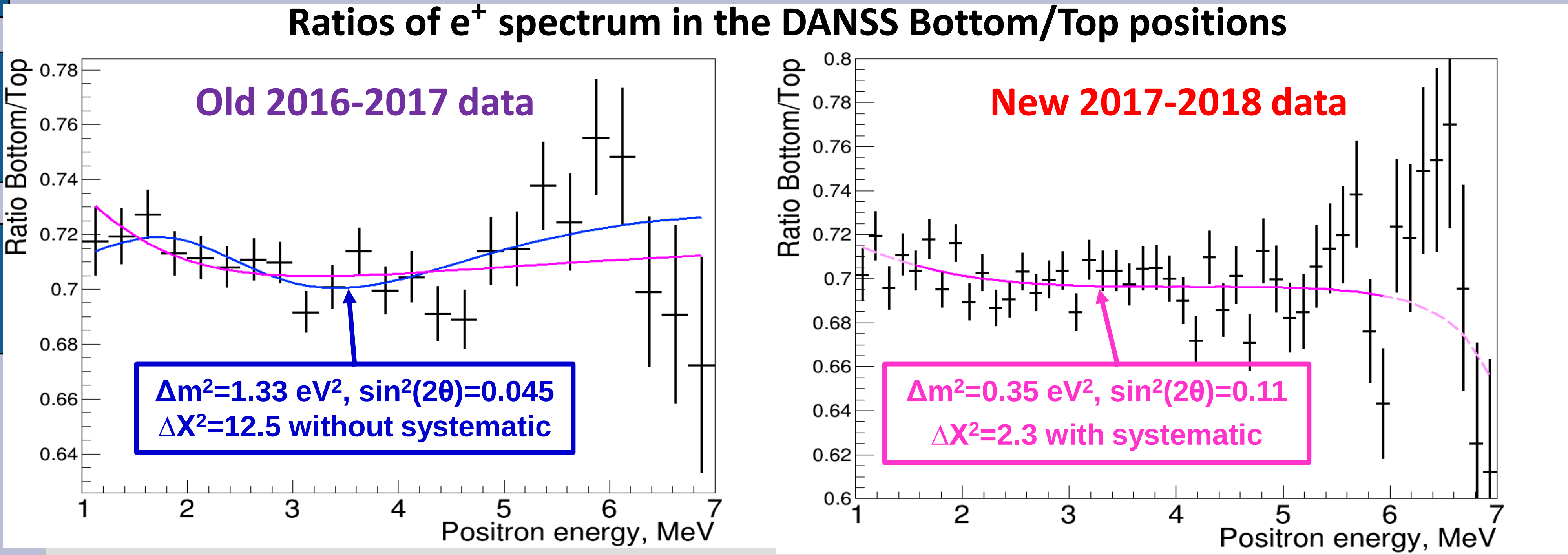
	^{235}U	^{238}U	^{239}Pu	^{241}Pu
End	45.8	7.7	38.3	7.9
Start	61.7	7.1	28.0	3.1

Reactor power monitoring



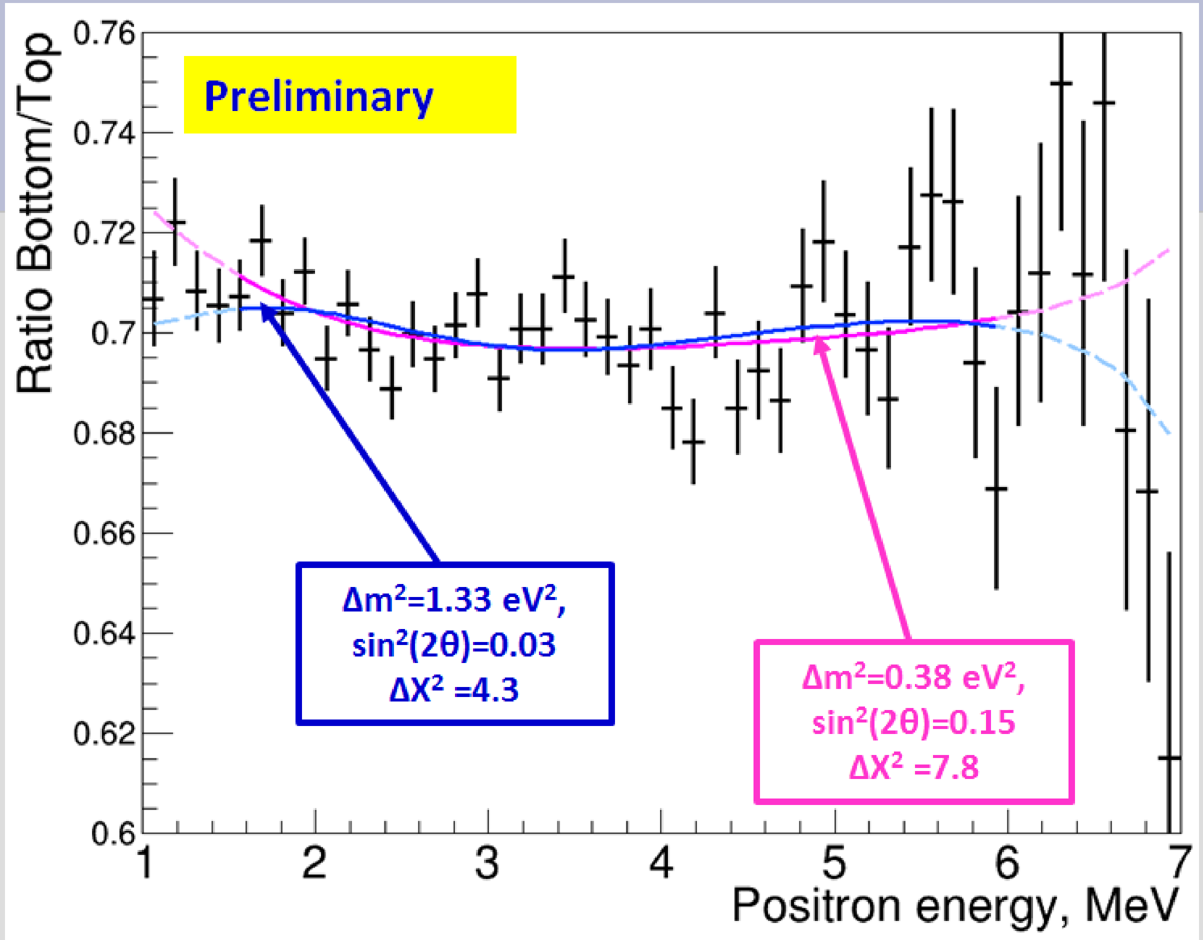
- ❖ **Points at different positions equalized by $1/r^2$; normalization by 12 points in November-December 2016**
- ❖ **Cosmics and adjacent reactor fluxes (0.6%) has been subtracted; spectrum dependence on fuel composition has been included**
- ❖ **Reactor power is measured by the DANSS with neutrino flux with 1.5% accuracy in 2 days**
- ❖ **Result is for old + fraction of new data. For full data set more work is needed for absolute efficiency calibration of the new data (not important in oscillation analysis).**

The DANSS: new vs. old results



- In the first data (2016-2017) 4ν hypothesis had smaller X^2 than 3ν one ($\Delta X^2=12.5$).
- This triggered a lot of excitement in the field although we clearly stated that significance of this difference would be studied taking into account systematics after collection of more data.
- On the new statistics 2017-2018 (1 million events) we see no indication of 4ν signal ($\Delta X^2=2.3$ for 4ν hypothesis).

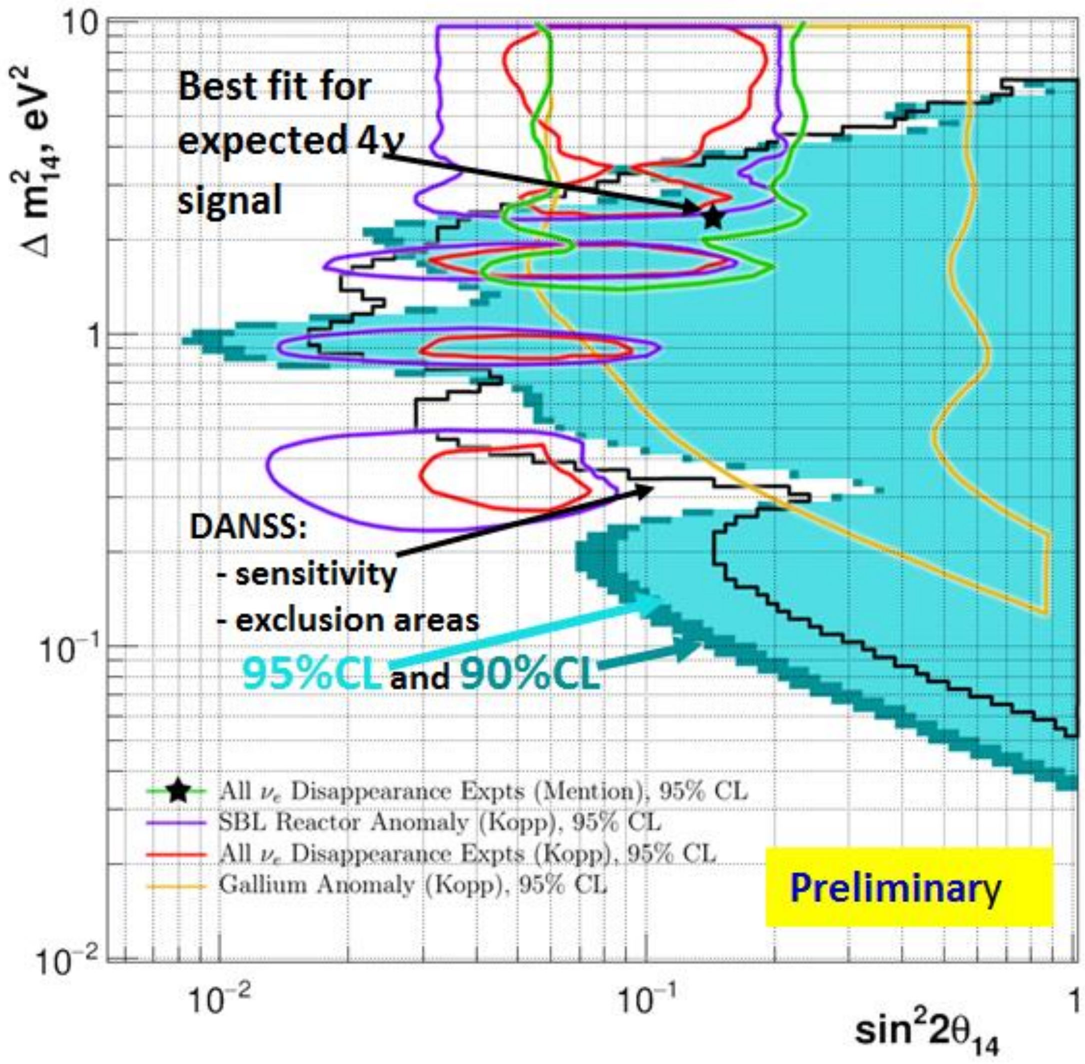
The DANSS: result with full dataset



- **The best 4ν point (Δm^2=0.38 eV^2, $\sin^2(2\theta)$=0.15, ΔX^2 =7.8) has CL of 1.8σ: no statistically significant sign of the sterile neutrino effect.**
- **Best point in old data (Δm^2=1.33 eV^2) is also shown.**

The DANSS: sensitivity plot

- Exclusion region was calculated using Gaussian CLs method (for e^+ in 1.5-6 MeV to be conservative), which is also more conservative than usual CI method.
- Systematics included:
  - Energy resolution +/-10%
  - Energy scale +/-2%
  - Cosmic background +/-25%
  - Flat background +/-30%
- Systematics influence is small, results of our method are independent from shape of ν-spectrum and detector efficiency.
- New data allowed to extend excluded area of 4ν phase space in comparison with old results published in 2018.



Summary

- **DANSS is in operation since April 2016 with regular (physics) data taking since October 2016 at a rate of ~4000 events per day with cosmic background ~ 1.7%.**
- **Antineutrino spectrum and counting rate dependence on fuel composition is clearly demonstrated.**
- **Reactor power was measured using anti-ν rate with statistical error of ~1.5% in two days during > 1 year of operation.**
- **With doubled data set we have no sign of sterile ν oscillations.**
- **Preliminary DANSS analysis (based on 2 million statistics) excludes a large fraction of available parameter space for sterile neutrino using only ratio of e^+ spectra at two distances. This method is independent from shape of ν-spectrum and detector efficiency (+ small systematics influence).**
- **Future plans: further improvements of MC & calibrations; detector upgrade; precision comparison of ν spectra with theory (bump problem).**

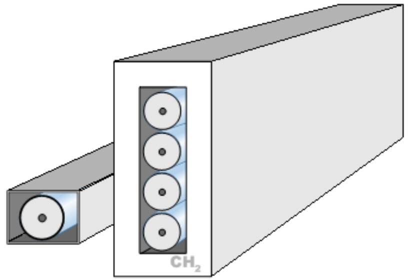
Backup slides

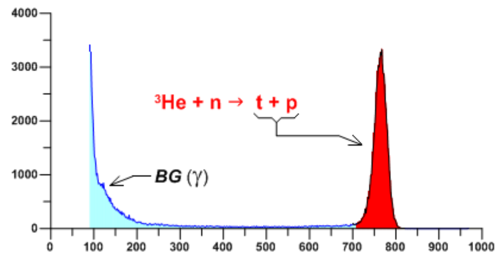
Background monitoring

- **Permanent monitoring of gamma-BG with four NaI (3'x3'): 1 inside + 3 outside the DANSS shield**

  no (ON – OFF) visible difference

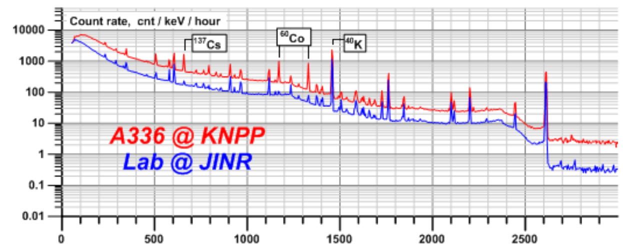
- **Permanent monitoring of neutron flux with three ^{3}He neutron counters: 1 inside + 2 outside the shield**

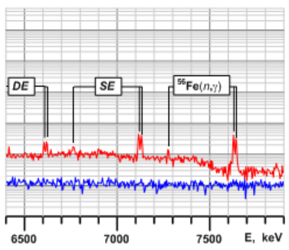


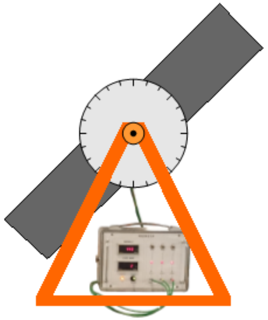


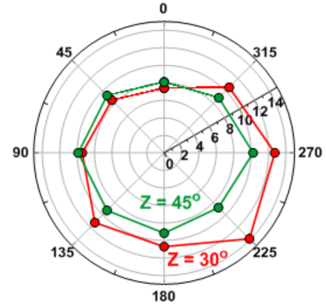
Φn =	0.57	outside (OFF)
Φn =	300.4	outside (ON)
Φn =	0.03	inside (OFF)
Φn =	0.04	inside (ON)
Φn =	6.0	en plein air

- **Episodic measurements with HPGe and "MuMeter"**

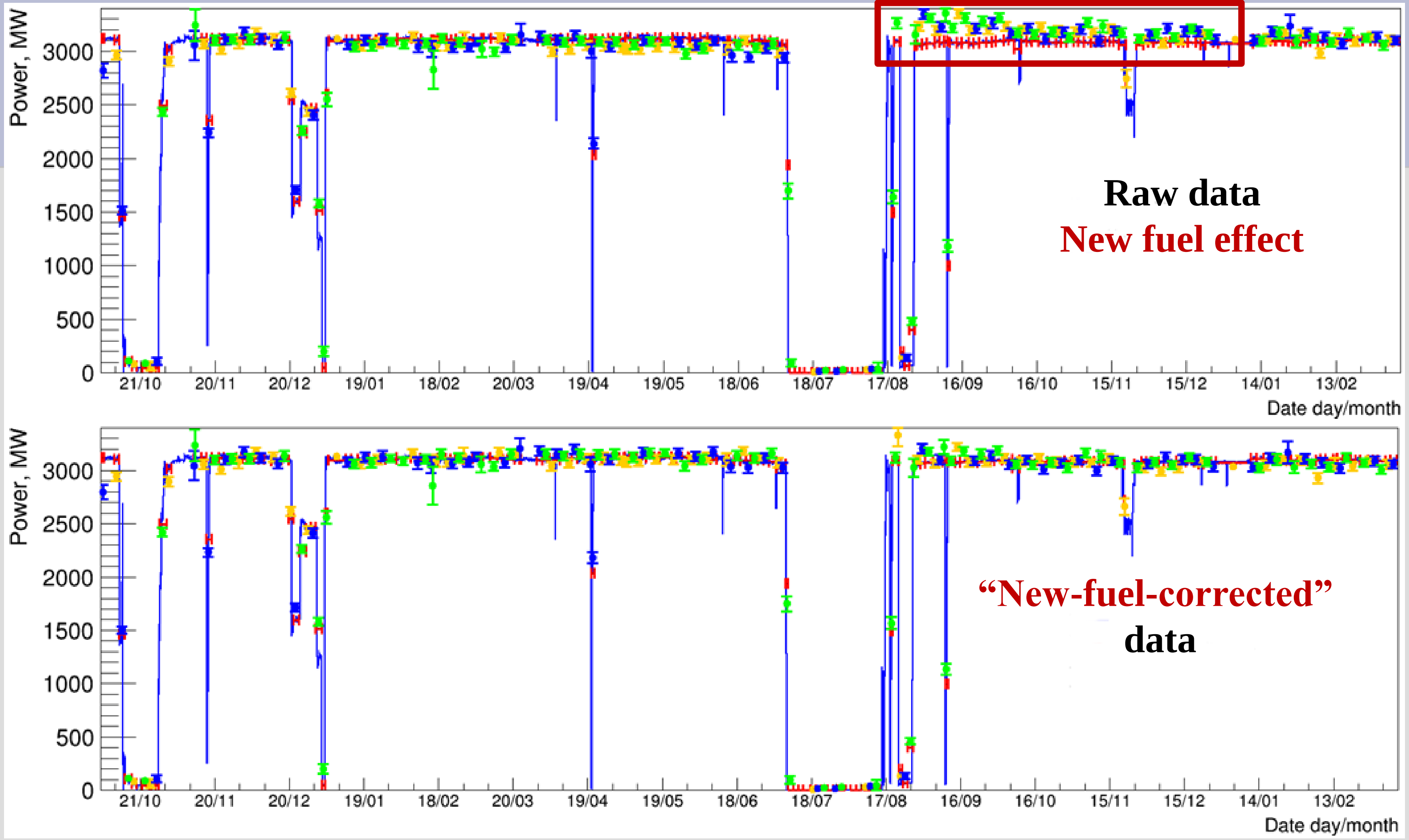








Reactor monitoring: Up – Middle – Down data



- ❖ **The DANSS is constantly monitoring reactor since October 2016.**
- ❖ **We are sensitive to the fuel composition (U-Pu content in fuel)**