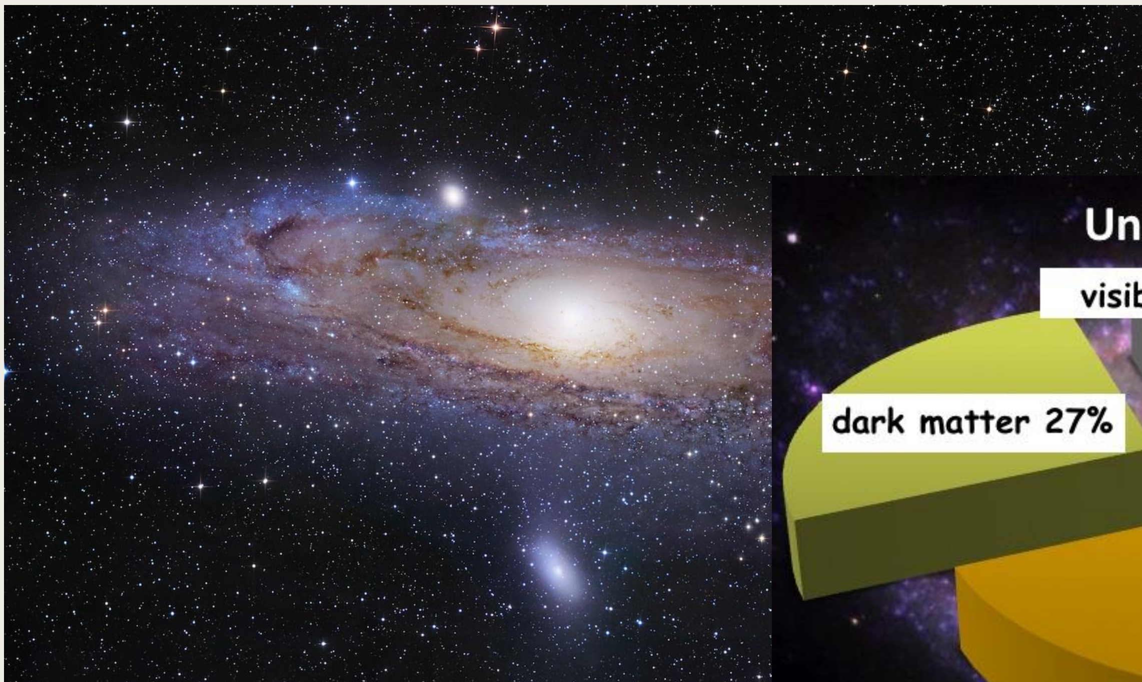
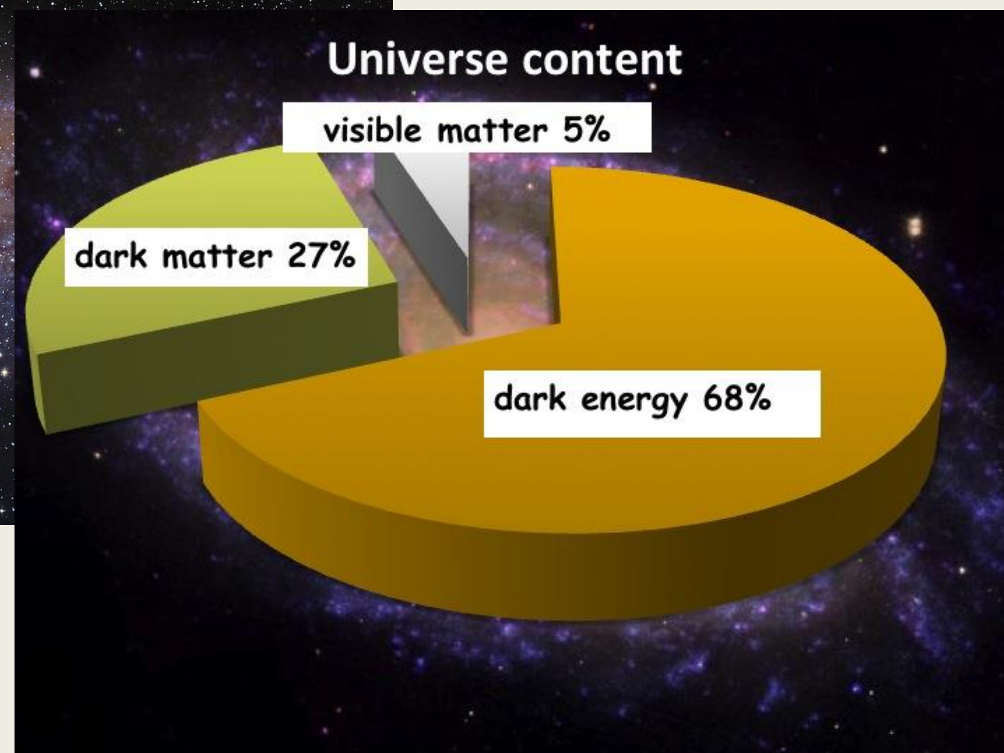
FIRST RESULTS OF “TROITSK NU-MASS” EXPERIMENT ON SEARCH FOR STERILE NEUTRINO BELOW 2 KEV

Troitsk nu-mass group

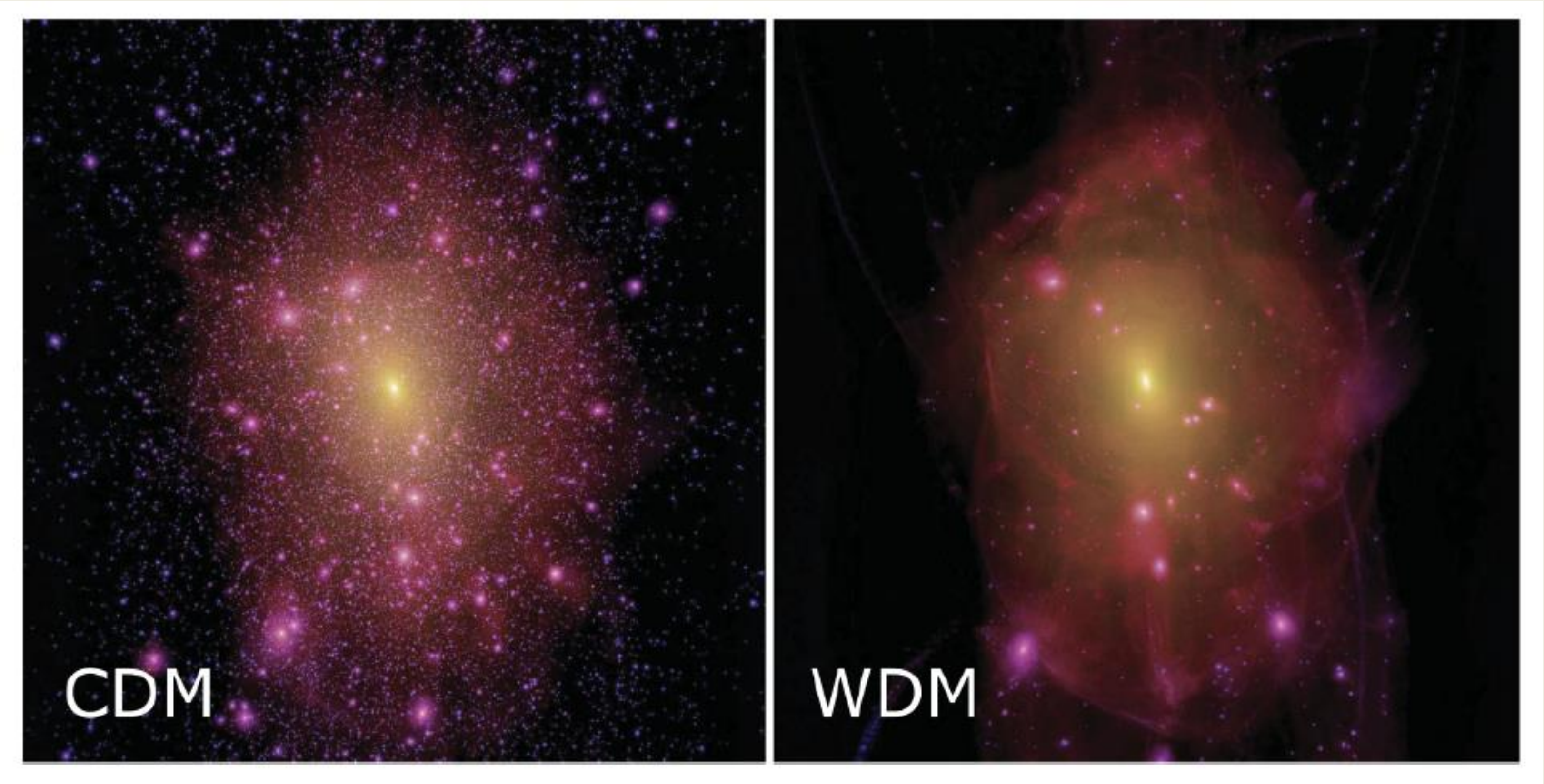
Motivation from cosmology:

Visible matter only 5%. What is the rest ?





Cold or warm Dark Matter?



Heavy particles?

1-10 keV particles?

Simulations favor **Warm Dark Matter**

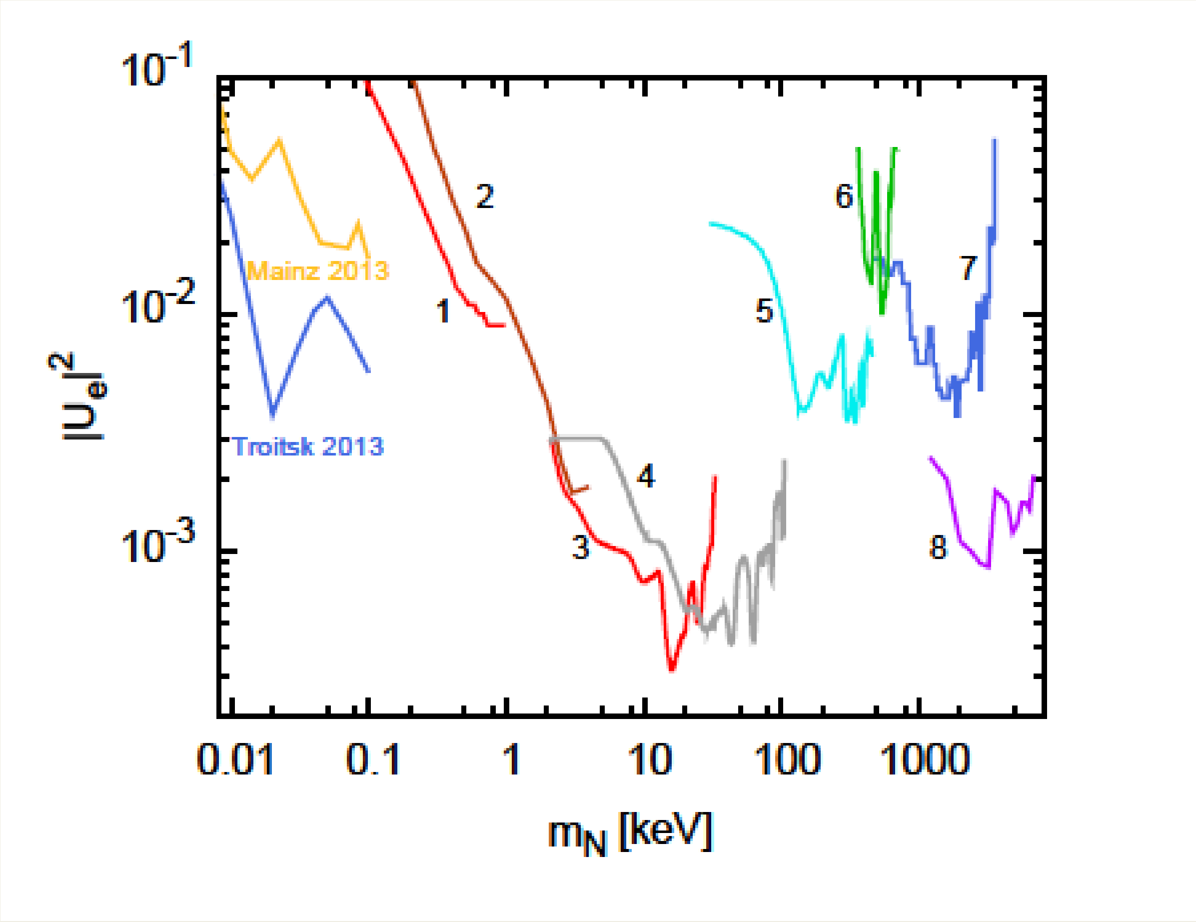
So, why keV- neutrino?
Candidate for Warm Dark Matter

- LHC results confirm expectations from Standard Model, but
- Neutrino mass, Dark Energy and Dark Matter are well beyond SM
- There is a set of candidates for DM, like WIMPs, they should be heavy and cold – but it contradicts cosmological structures at small scales
- Sterile neutrino with keV-scale mass is a good candidate for Warm Dark Matter.

See - *White Paper on keV Sterile Neutrino Dark Matter,* *arXiv:1602.048*

PS. keV mass range is not available in oscillation experiments

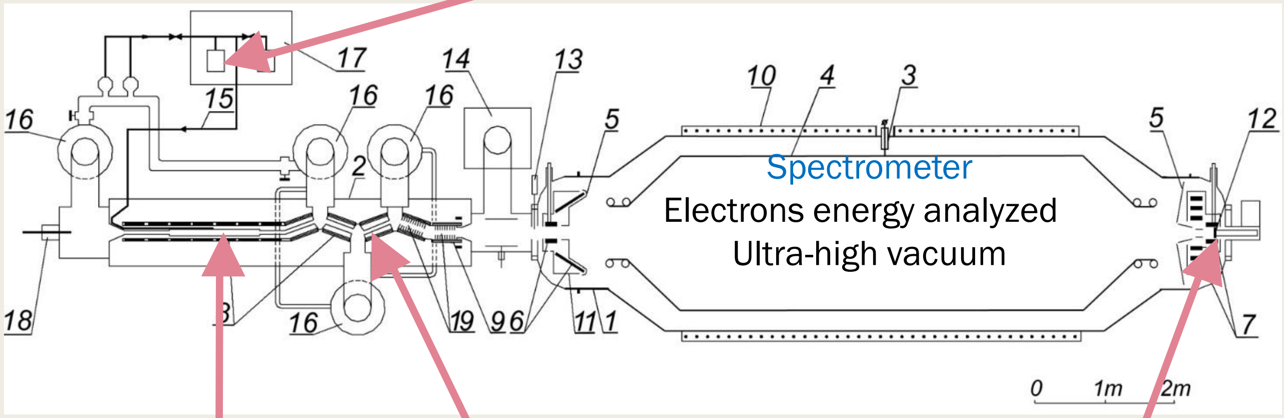
What is the situation now?
Current limits for keV-sterile neutrino



TDR, https://arxiv.org/abs/1504.00544 JINST 10 (2015) T10005

Troitsk nu-mass
The setup

Circulation system
Pumped tritium is injected back into the system



Spectrometer
Electrons energy analyzed
Ultra-high vacuum

Tritium pipe
Tritium decays here

Transport system
Electrons transported but tritium pumped out

Detector
Electrons are registered and counted

Integral spectrometer
Spectrum shape

Tritium source transmission

Spectrometer resolution

Beta spectrum

$$F(U) = \int S(E_{in}) \cdot Tr(E_{in}, E_{out}) \cdot R(E_{out}, U) dE_{in} dE_{out}$$

E_{in} - energy at decay,

E_{out} - energy entering spectrometer,

U – spectrometer potential.

Spectrum shape: beta spectrum

$$N(E, E_0, m_\nu) = CF(Z, E)(E + m_e)p_e(E_0 - E)^2 \sqrt{1 - \frac{m_\nu^2}{(E_0 - E)^2}}$$

$F(Z, E) - Fermi\ correction\ for\ electrostatic\ interraction$

Correction for final states spectrum:

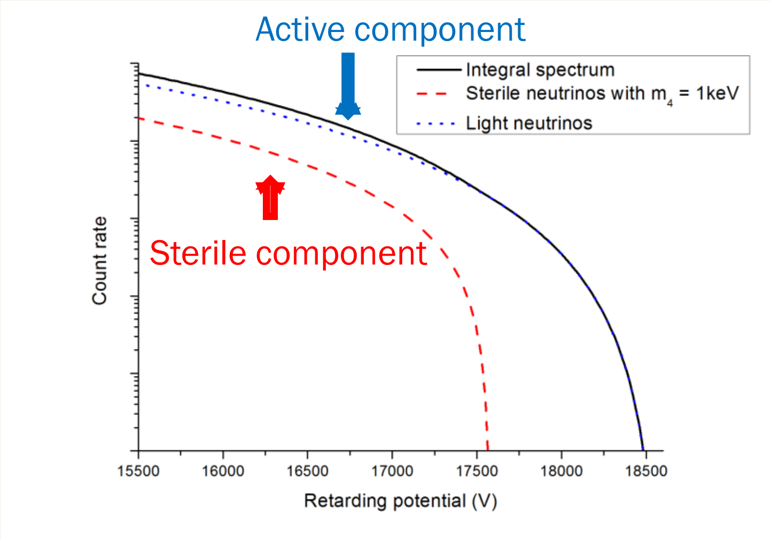
$$S(E, E_0, m_\nu) = \sum N(E, E_0 - E_i, m_\nu) \cdot P_i$$

Spectrum shape: sterile neutrinos

$$|\nu_\alpha> = \sum U_{\alpha i} \, |\nu_i>$$

$$\boldsymbol{S(E) = U_{ex}^2 S(E, m_x) + \left(1 - U_{ex}^2\right) S(E, 0)}$$

Spectrum changes like:



Spectrum shape: transmission

$$Tr(E_{in}, E_{out}) = P_0 \cdot \delta(E_{in} - E_{out}) + \sum P_i L_i(E_{in}, E_{out}) + trap(E_{in}, E_{out})$$

Passage without losses (includes quasi-elastic)

Inelastic losses (i – number of collisions)

Trapping effect

$$P_0 = \frac{1}{X}(1 - e^{-X}), \quad P_1 = \frac{1}{X}(1 - e^{-X}) - e^{-X}, \quad P_2 = \frac{1}{2X}\left(2 - e^{-X}(X^2 + 2X + 2)\right), \quad P_3 = \cdots$$

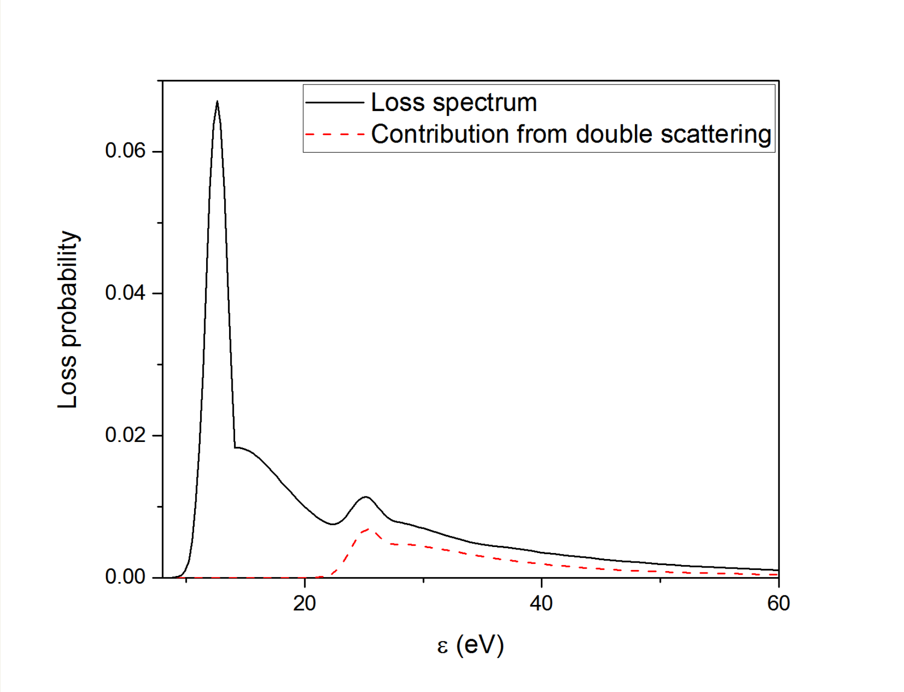
Transmission: energy loss function

$$\varepsilon = E_{in} - E_{out}$$

X depends on E_{in}

$$L_{i+1} = L_i \otimes L_1$$

$$L(\varepsilon) \xrightarrow[\varepsilon \to \infty]{} \frac{1}{\varepsilon^2}$$



arXiv:1603.04243, to be published in 2017

Systematics

- Trapping effect / Rear wall backscattering
- Dead time / pileup
- Detector efficiency / threshold underflow
- Adiabaticity violation / detector backscattering
- Source thickness
- Spectrometer voltage instability
- Final states distribution

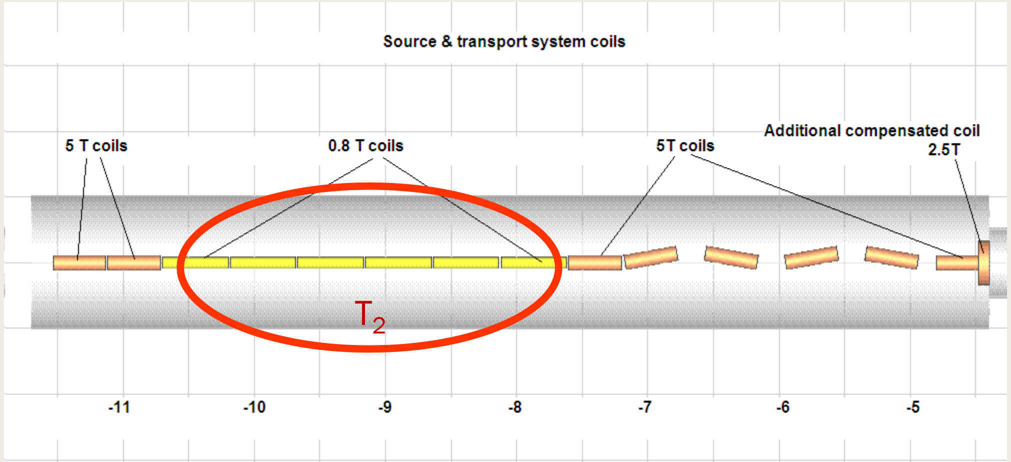
Very important!

Not very important

See details in https://arxiv.org/abs/1504.00544

Trapping: basics

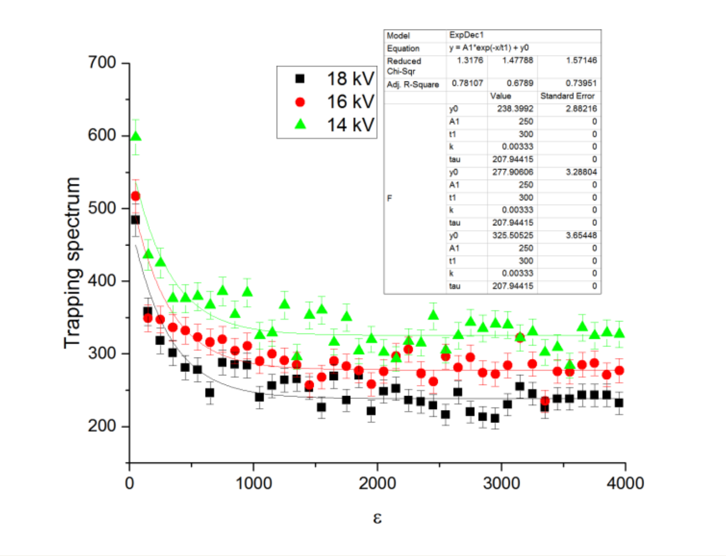
Field configuration in tritium source forms a bottle – magnetic Trap



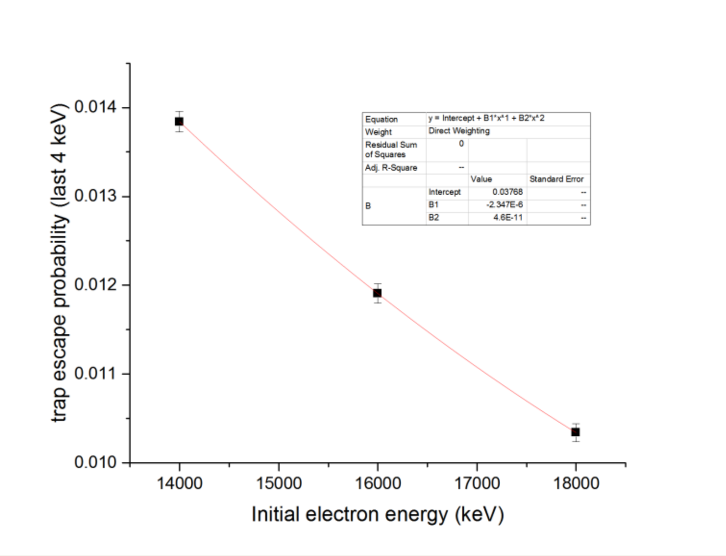
Trapped electrons can run back and forth up to thousand times passing few kilometers

Trapped electrons distort the actual β-spectrum

Simulation



Energy dependence

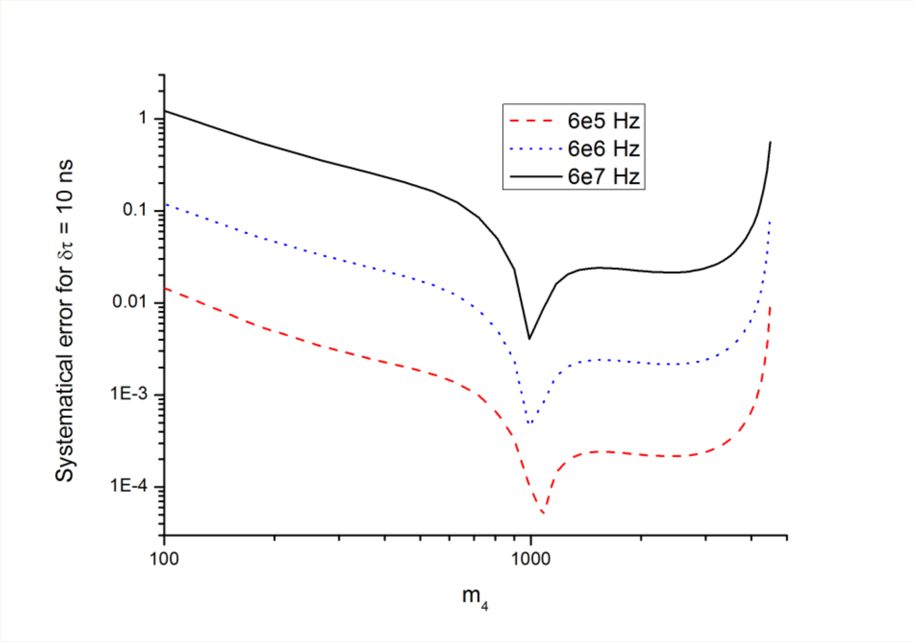


Systematics: dead time

The correction factor:

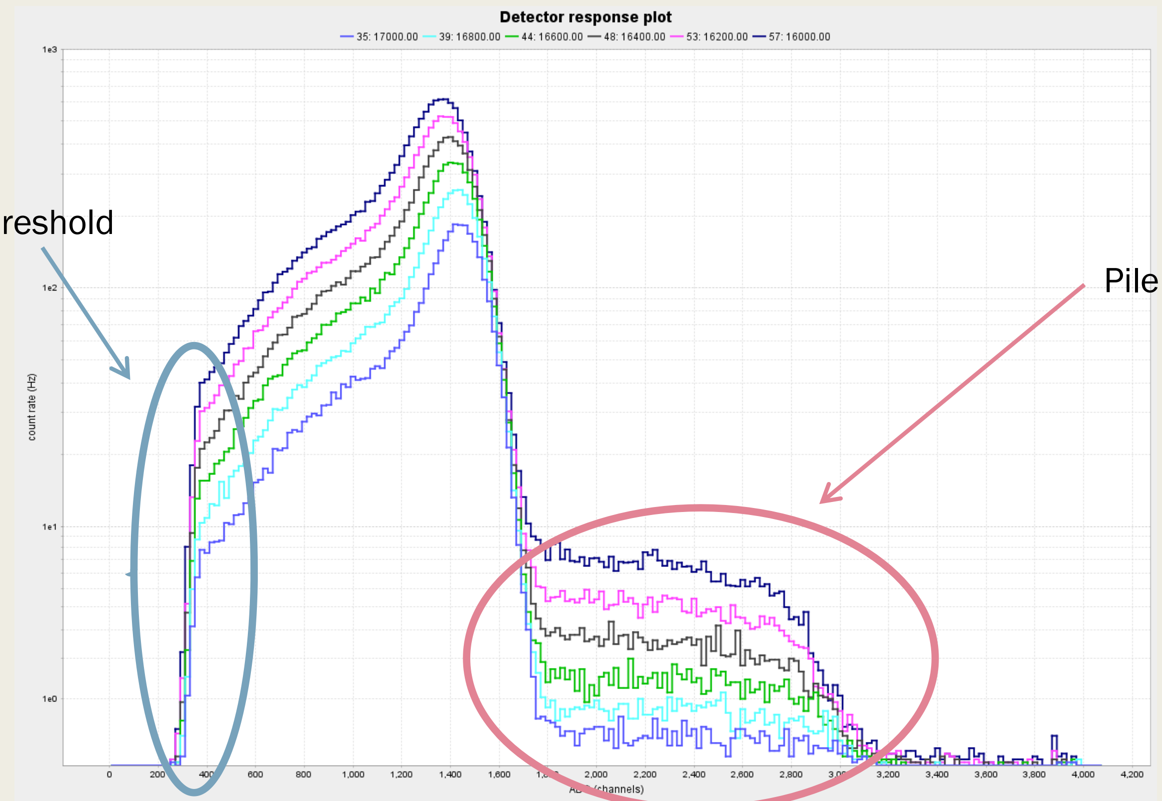
$$N = N_0\left(1 - N_0\frac{\tau}{T}\right)$$

The dead time uncertainty is the main current limit on experiment sensitivity.



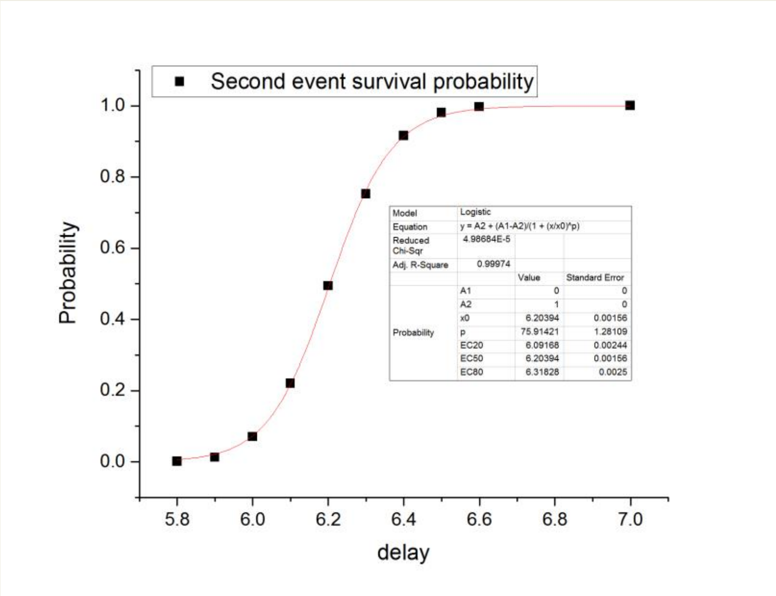
P.S. We wish to switch to completely new readout with continues signal digitization in upcoming run in May 2017

Detector spectrum



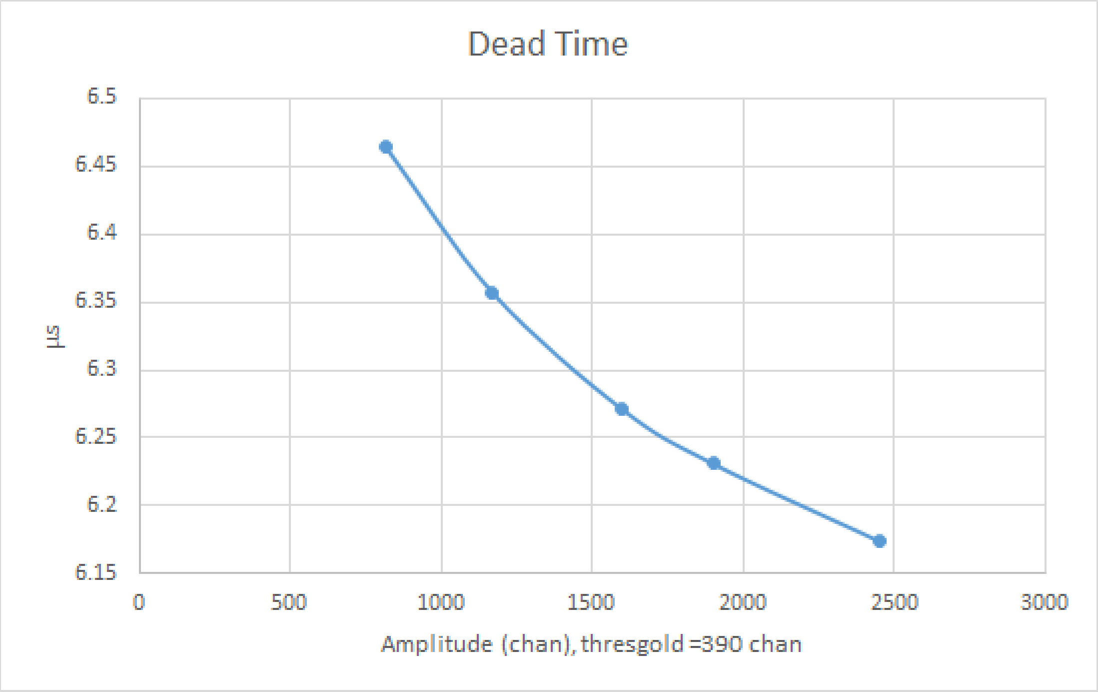
Signal amplitudes in Si(Li) detector at different spectrometer potentials – different intensity

Dead time

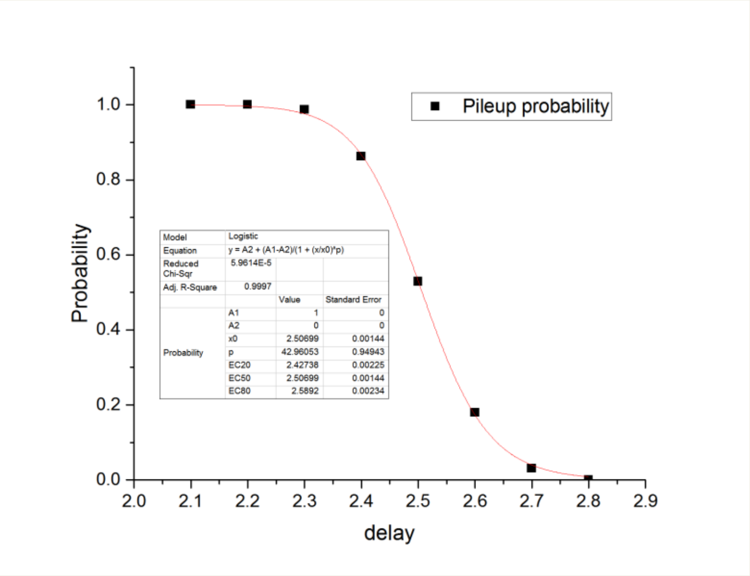


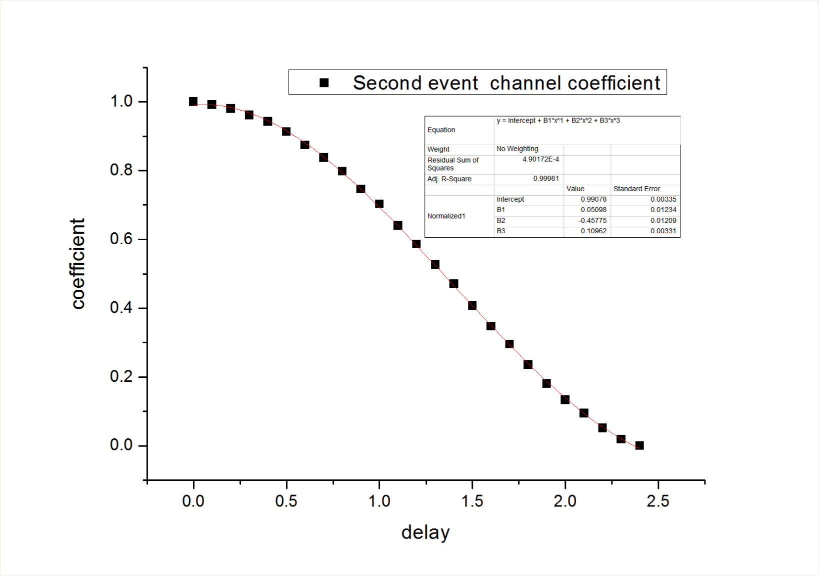
Dead time calibration by pulser and two delayed signals

Dead time amplitude dependence



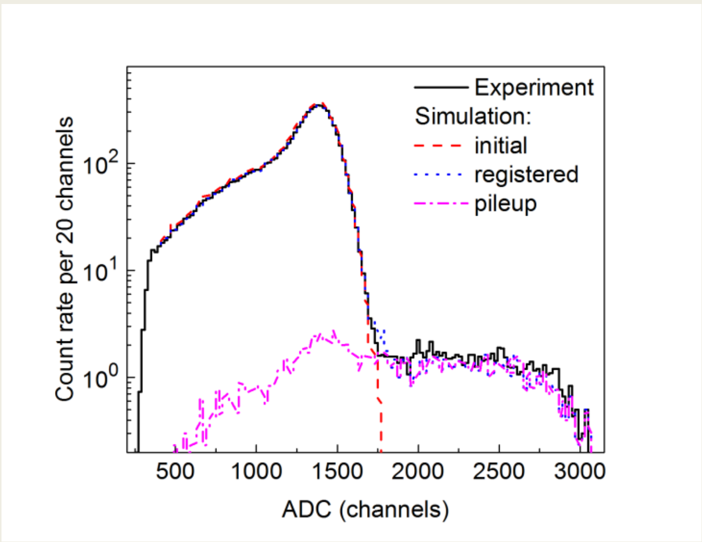
Pileup



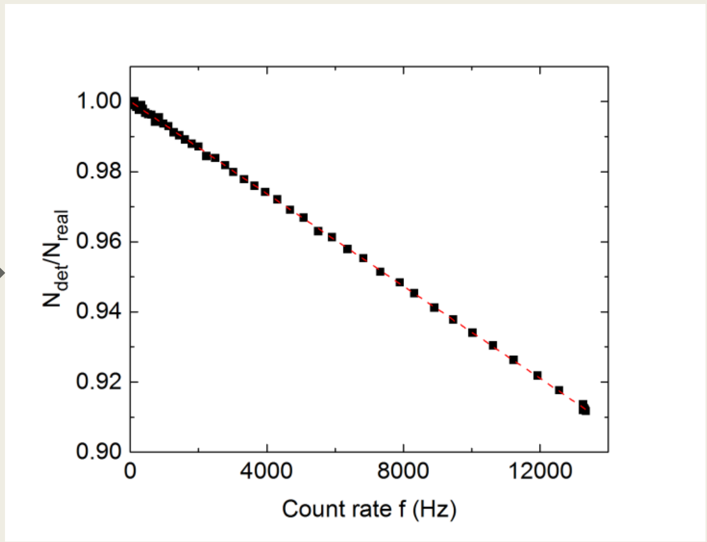


Pileup time calibration by pulser and two delayed signals

Pileup in real Tritium spectrum



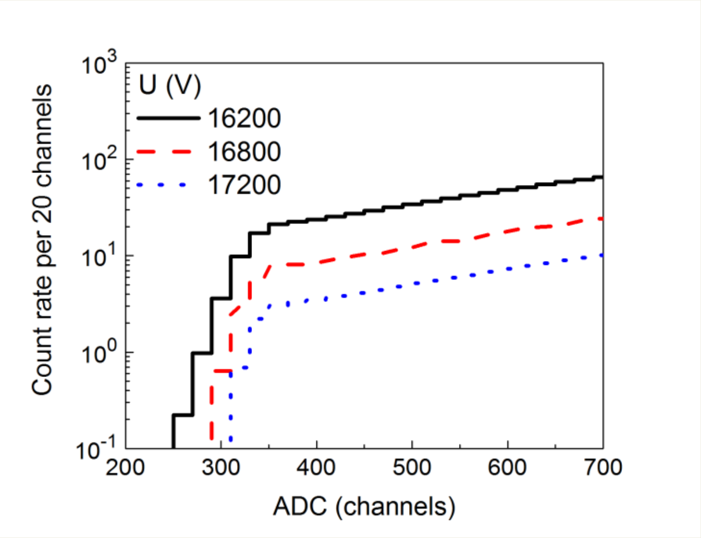
Monte-Carlo simulation using real spectrum and pulser calibration



Life time versus measured count rate

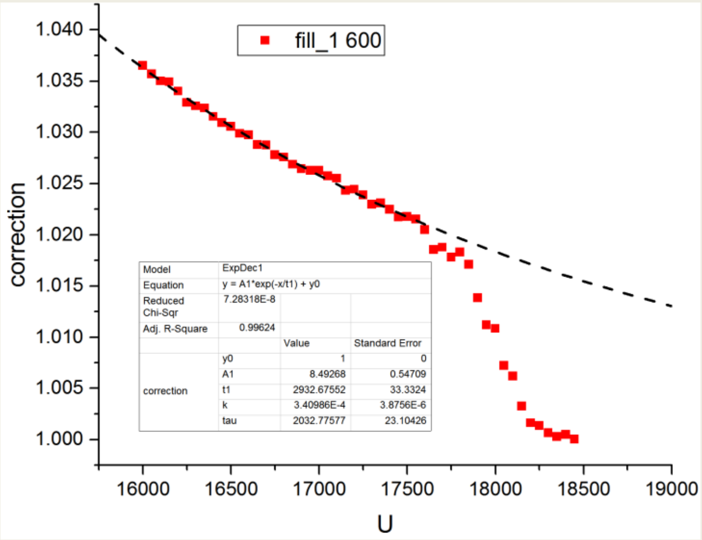
Detector threshold

Spectrum shape near cutoff point



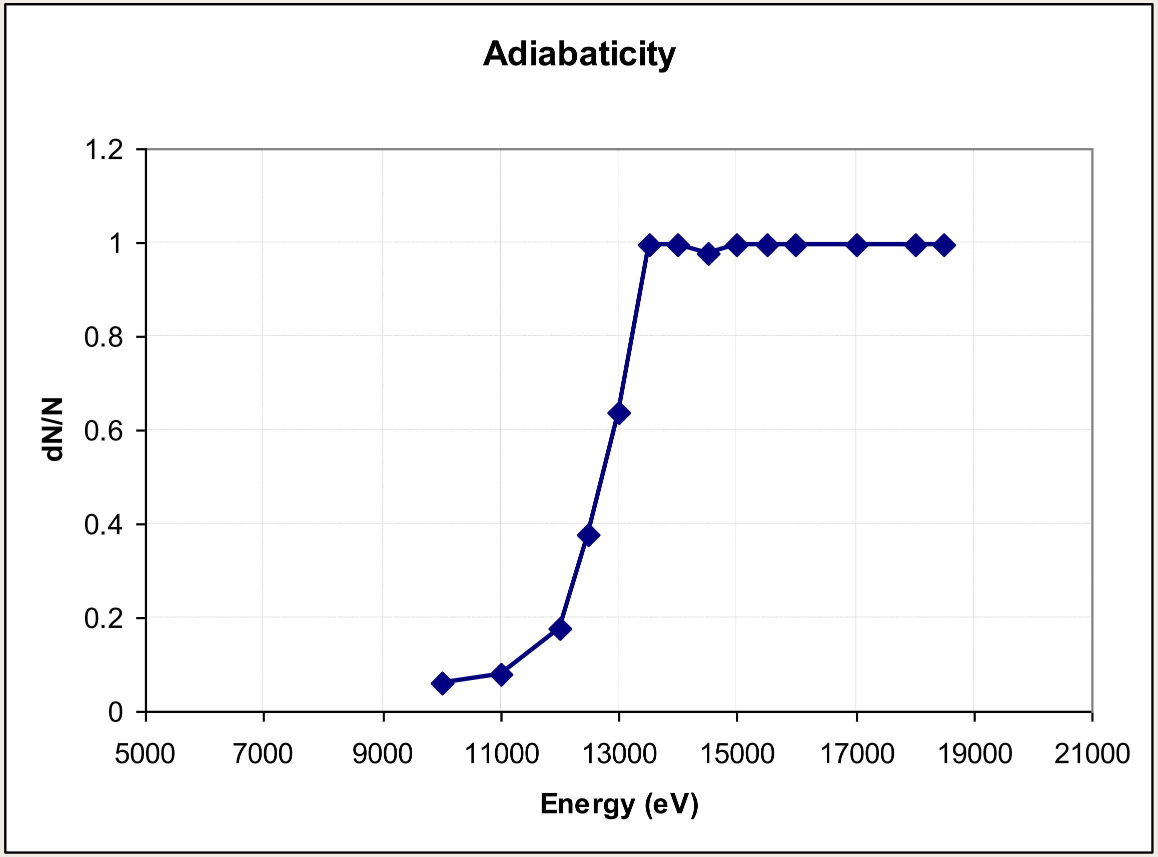
$$D = A * e^{\frac{c}{\sigma}}$$

The estimated correction factor vs. U_sp



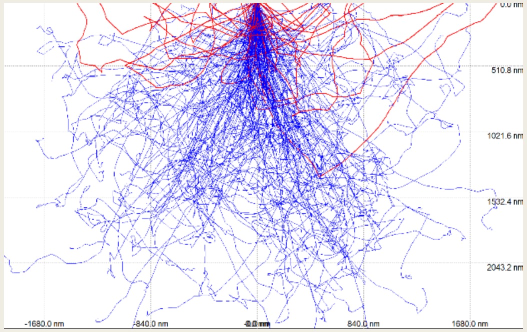
$$corr = 1 + A1 * e^{-\frac{U}{t1}}$$

Adiabaticity violation



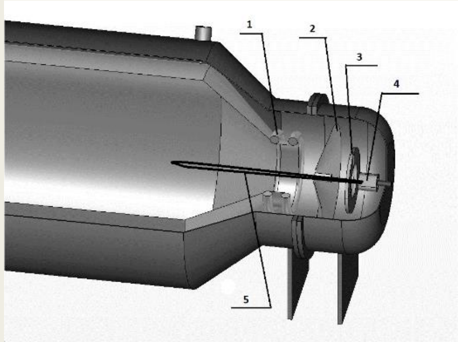
Simulation: Adiabaticity is not violated above 13.5 kV

Detector backscattering

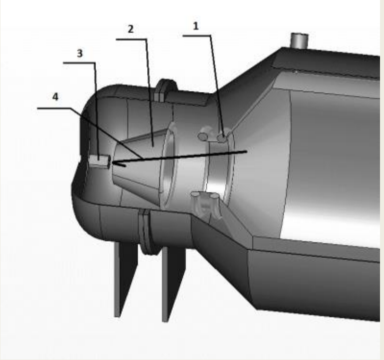


Up to 20% electrons scatter back from Si-detector.
CASINO simulation

NIM A832 (2016) 15
arXiv:1511.06129



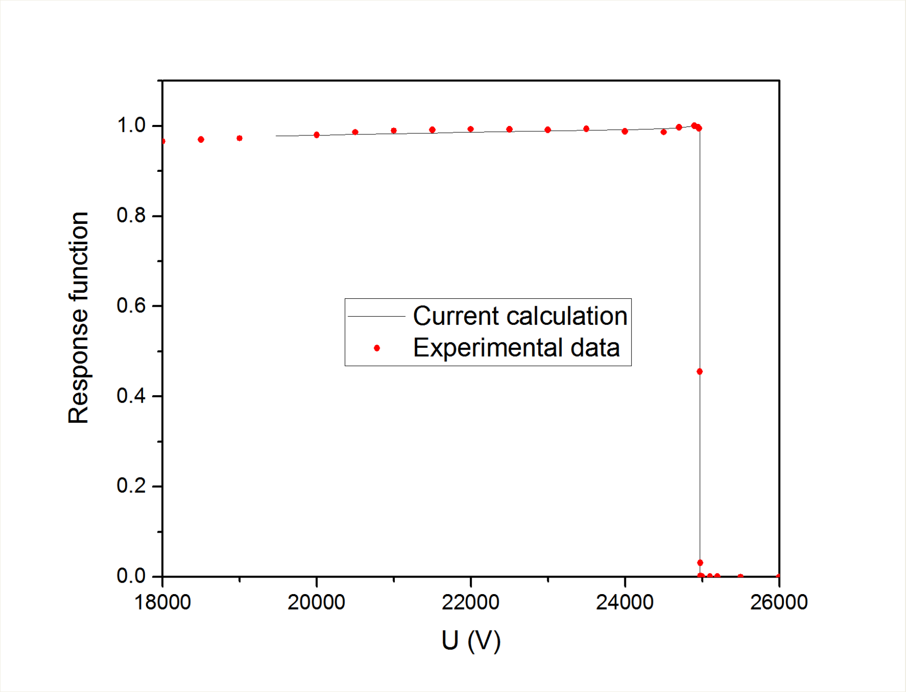
Electrostatic mirror



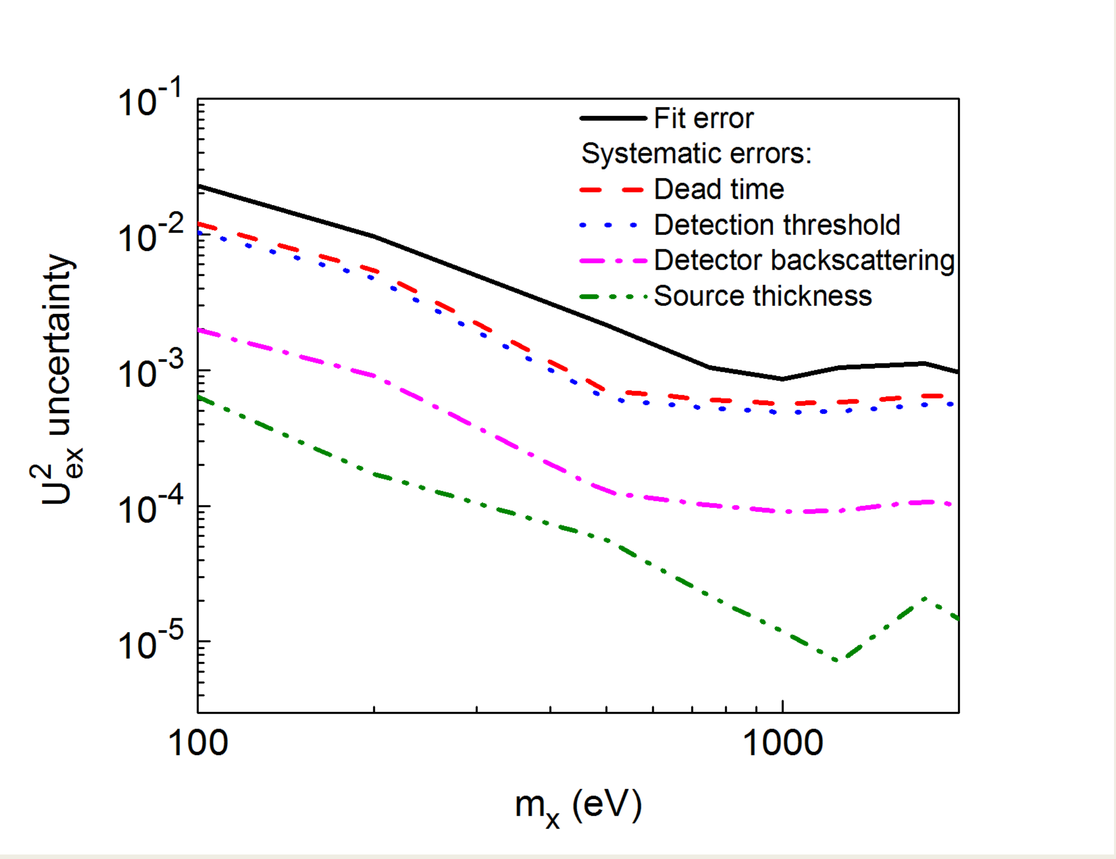
Magnetictic mirror

Detector backscattering: experimental

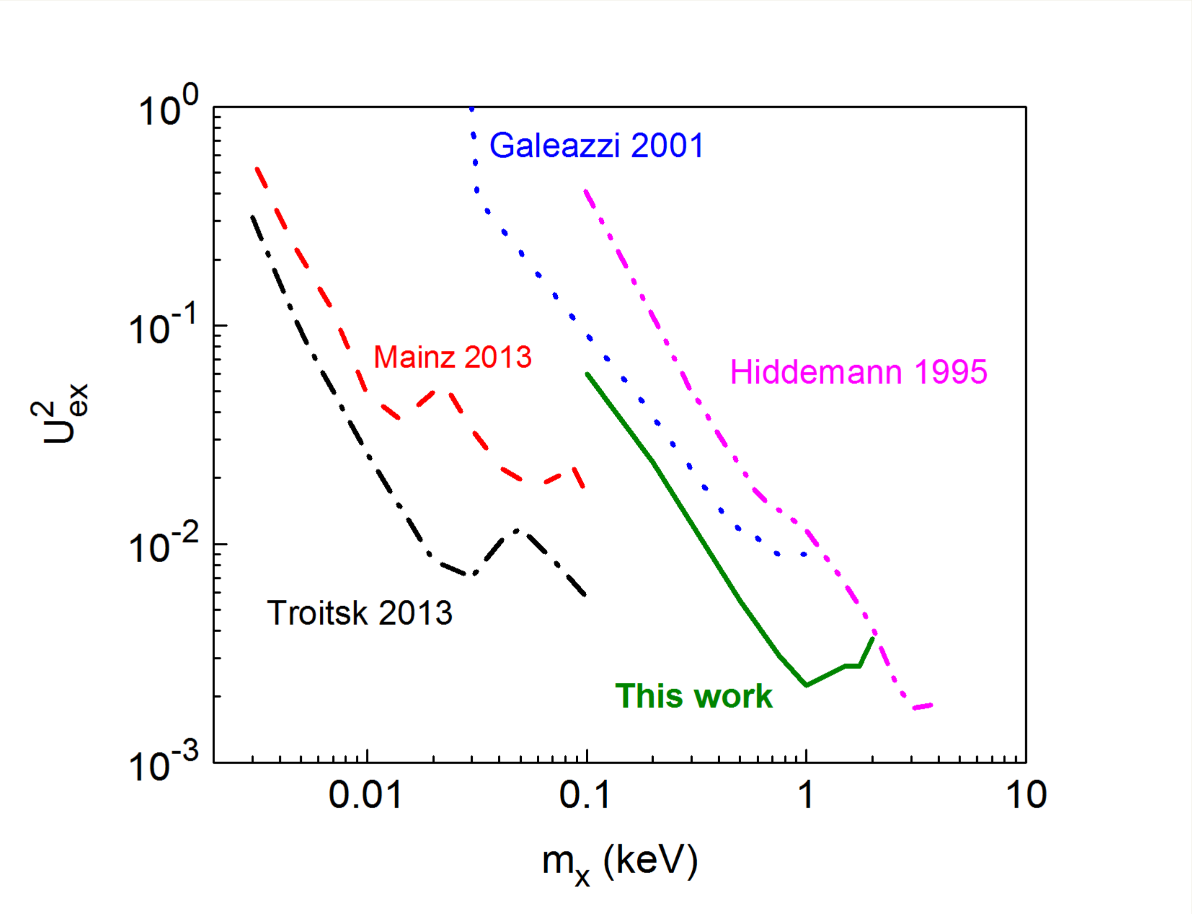
Count rate for 25 keV electrons vs spectrometer retarding potential



Uncertainties summary



Result



95 % Confidence Level (sensitivity limit) on mixing matrix element

Summary

- Two successful experiment runs with tritium in October 2016 and January 2017. One data set with $U_{low} = 16\ kV$ and two with $U_{low} = 14\ kV$.
- All the systematic effects on current level of precision were accounted for.
- The resulting limit is 2-5 times better then existing ones.

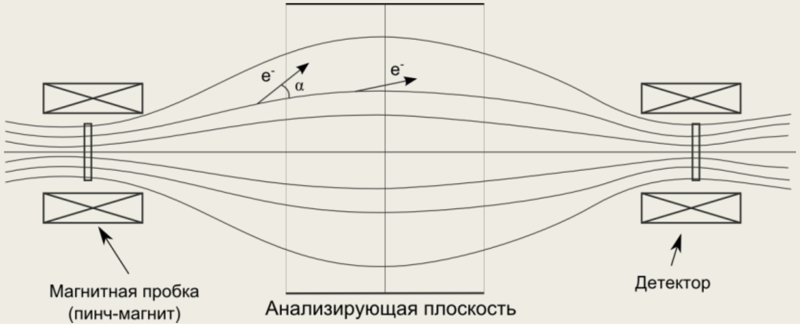
- Agreement and Proposal for collaboration with KATRIN-TRISTAN group on new detector development and electronics.

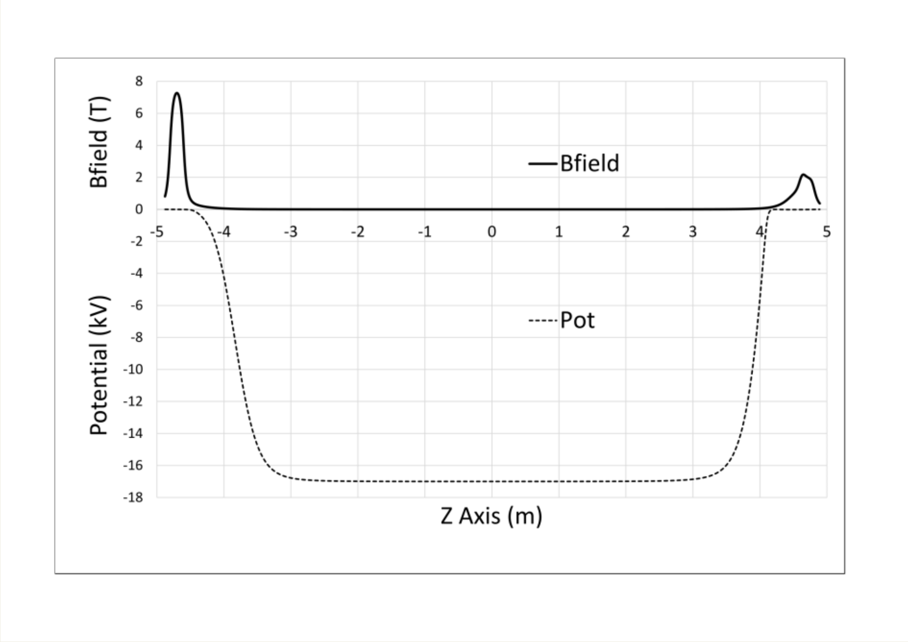
Thank you for your attention

ADDITIONAL SLIDES

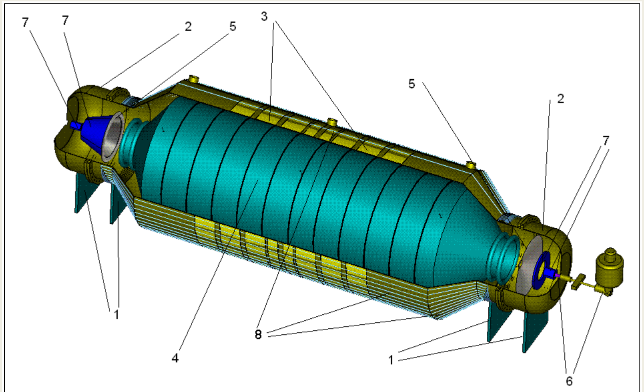
$$\frac{V_\perp^2}{B_\parallel} = const$$

$$B_\parallel \cdot S = const$$



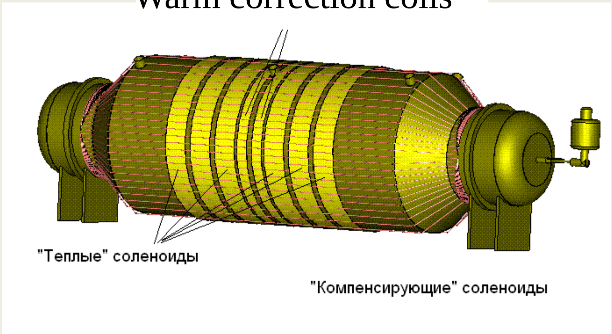


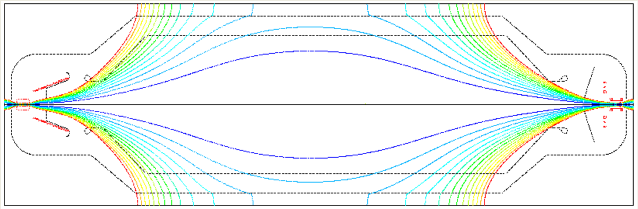
Electrostatic and magnetic field configuration



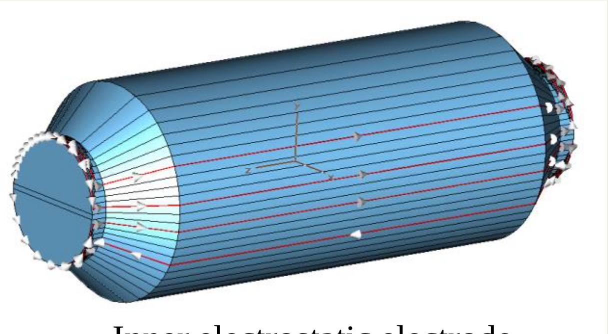
Main vessel, about 10 m long

Warm correction coils



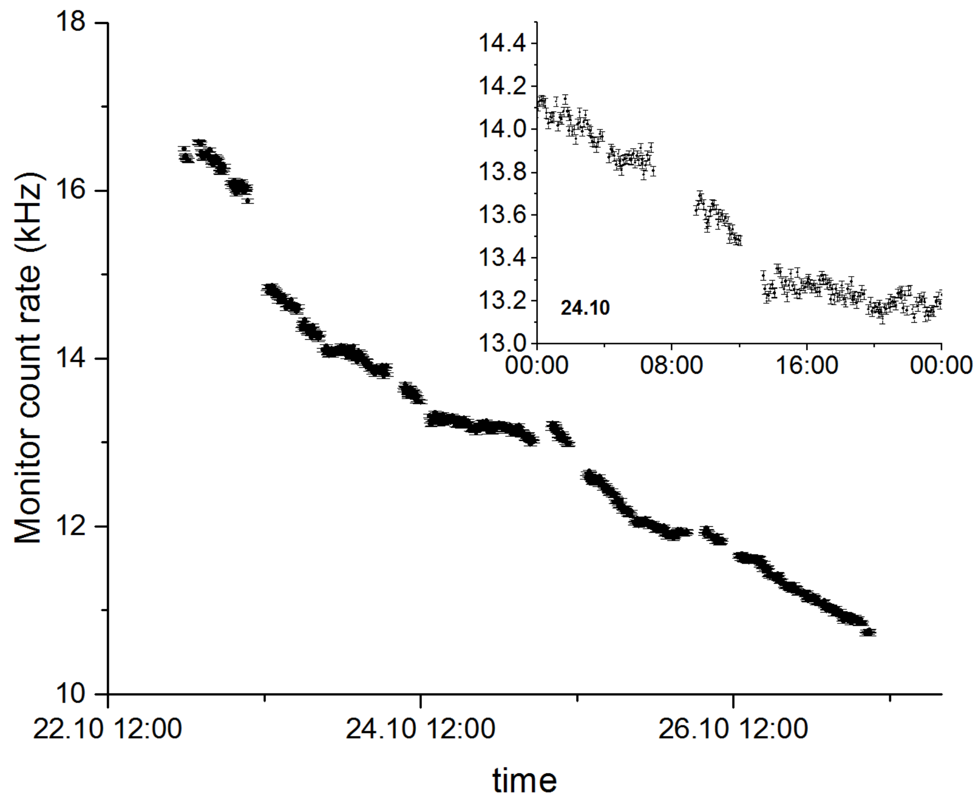


Magnetic field 7.2 T at the entrance,
1.2 mT in the center



Inner electrostatic electrode,
13-19 kV

Run 2016_10

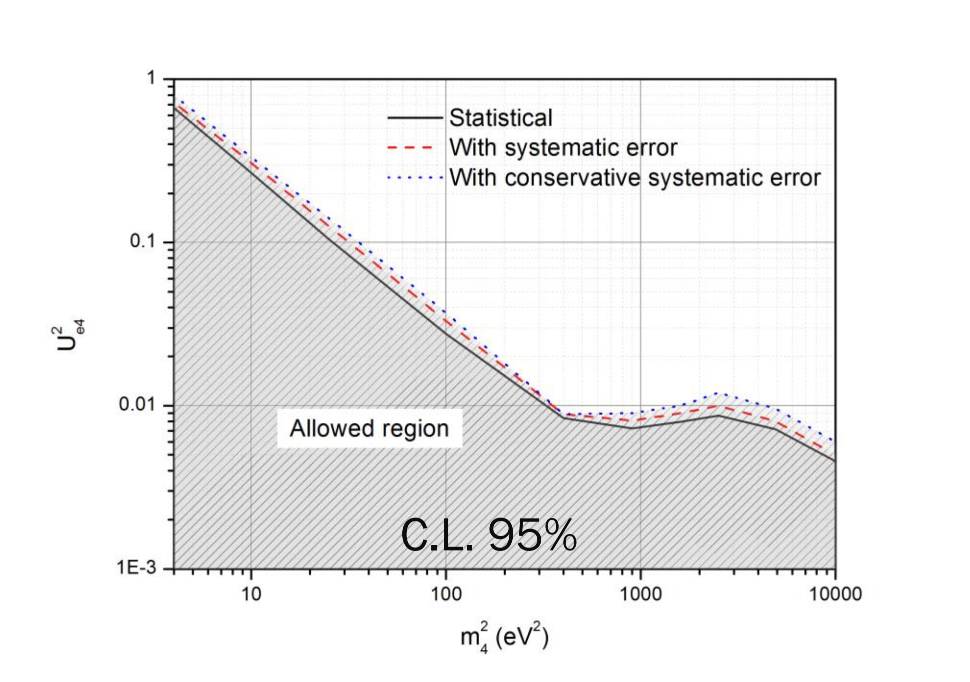


Count rate in monitor point at 16.0 kV

The DataForge

- *The DataForge is a scientific framework based on modern trends and solutions in programming.*
- *It introduces a few new concepts into scientific (hep-physics) software:*
  - The analysis as a metadata process
  - Declarative description of analysis process (the analysis as a build system)
  - Convention over configuration on a large scale
- *It is completely and “true” cross-platform (not “compile wherever you want on your on risk”).*
- *It is modular!*
- *It has a few very important ideological effects that could be expanded further and can open a whole new world of possibilities for scientific data processing.*

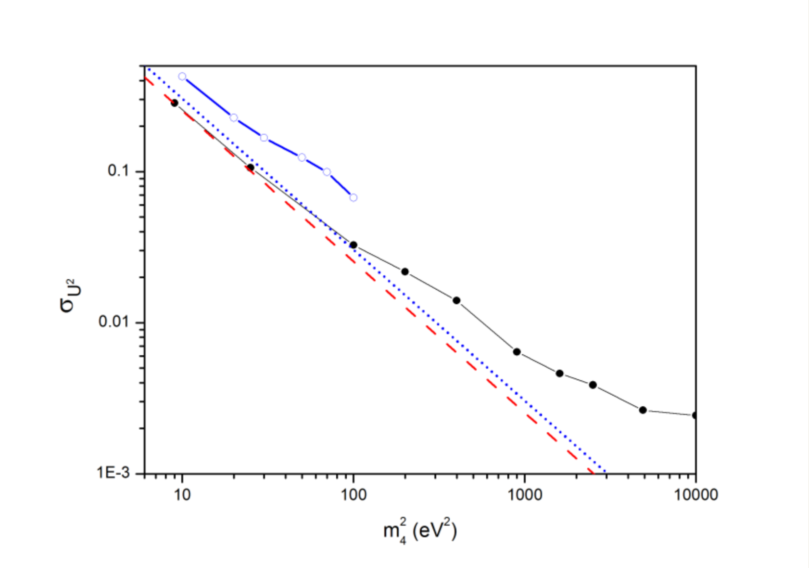
Data from 1994-2005.
Sterile neutrino search in 300 eV below the spectrum endpoint



Some results on sterile neutrino could be obtained from **data acquired in search for electron neutrino mass**!

A.I. Belesev et al., J.Phys. G41 (2014) 015001, arXiv:1307.56387

Comparison of errors for heavy neutrinos between Troitsk and Mainz experiments

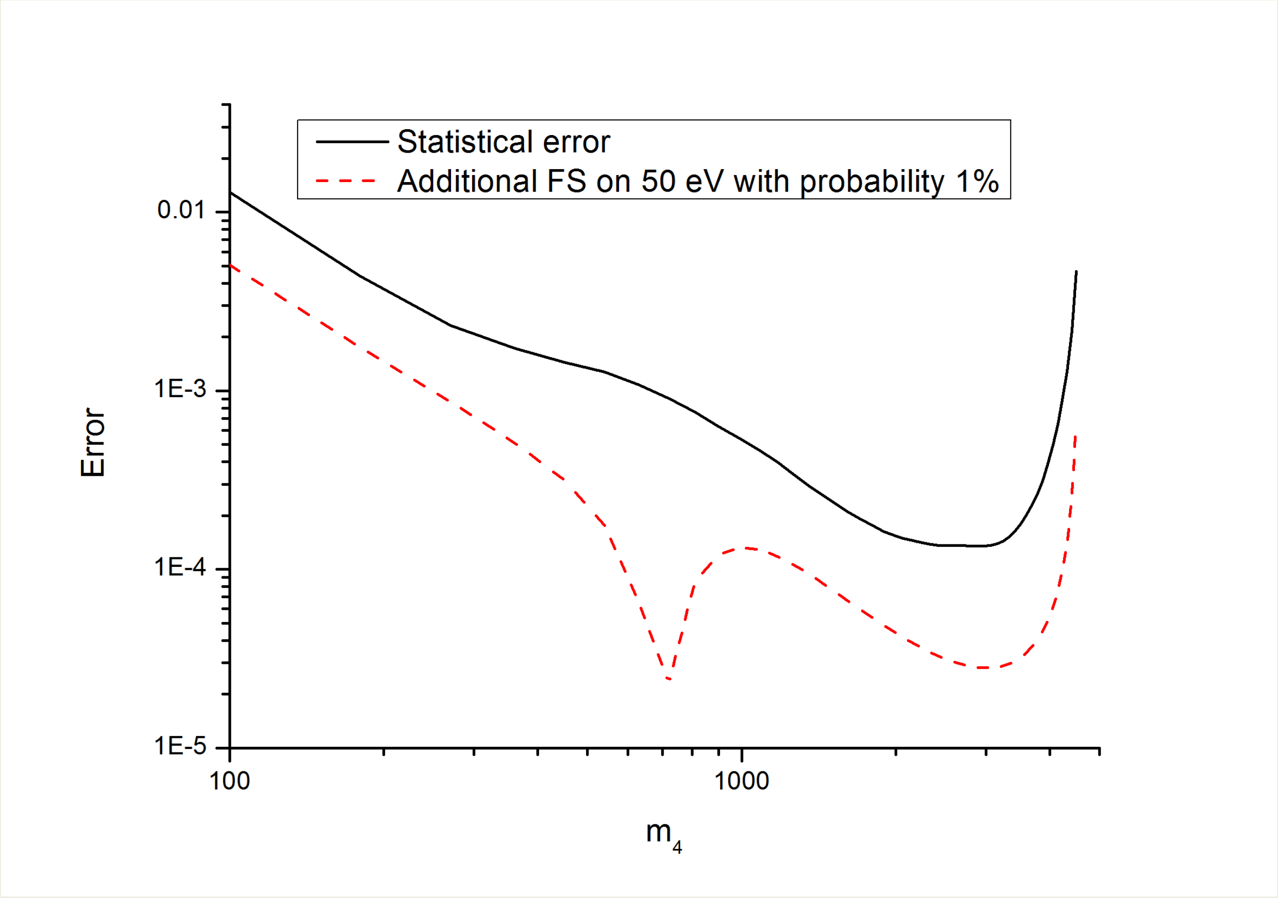


Comparison of errors for heavy neutrino mass obtained by the analysis, black symbols connected by solid lines, and approximate estimation $\sigma(U_{e4}^2) = 2.53/m_\nu^2$ based on the result for the electron antineutrino mass *V. N. Aseev et. al., Phys. Rev. D84, 112003 (2011)*, red dashed line.

The blue dotted line corresponds to the estimation $\sigma(U_{e4}^2) = 3.04/m_\nu^2$ for the total error from *C. Kraus, et al., Eur. Phys. J. C 40, 447 (2005)*

Solid black -Troitsk 2013: A.Belesev et al., J. Phys. G41 (2014)015001
Solid blue - *Mainz 2013*: C. Kraus et al., Eur. Phys. J C73 (2013) 2323

Final states spectrum



Gun measurements