Direct search of keV sterile neutrino in tritium beta decay by “Troitsk nu-mass” experiment

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Outline

- Historical remark
- Motivation
- Experimental setup
- Systematics
- Achievable limits
- Plans
- Conclusion

Troitsk ν-mass: experiment on electron neutrino mass is completed

Vladimir Lobashev

Citation: J. Beringer *et al.* (Particle Data Group), PR **D86**, 010001 (2012) and 2013 partial update for the 2014 edition (URL: http://pdg.lbl.gov)

Neutrino Properties

A REVIEW GOES HERE – Check our WWW List of Reviews

$\overline{\nu}$ MASS (electron based)

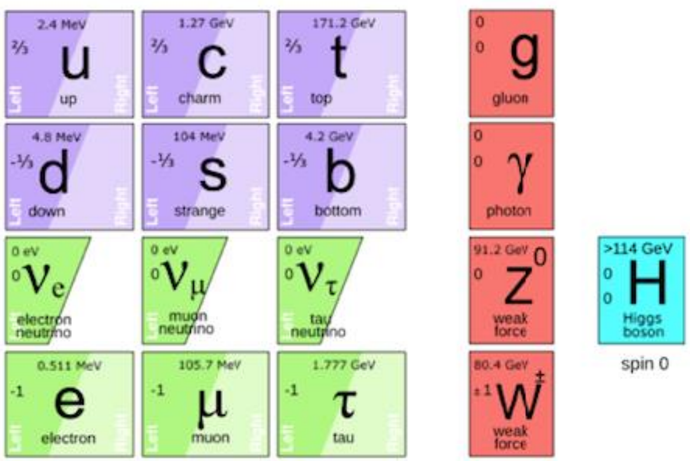
Those limits given below are for the square root of $m^{2(\text{eff})}_{\nu_e} \equiv \sum_i |U_{ei}|^2 m^2_{\nu_i}$. Limits that come from the kinematics of ^{3}H$\beta^- \overline{\nu}$ decay are the square roots of the limits for $m^{2(\text{eff})}_{\nu_e}$. Obtained from the measurements reported in the Listings for "$\overline{\nu}$ Mass Squared," below.

VALUE (eV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
< 2 **OUR EVALUATION**				
< 2.05	95	[1] ASEEV 11	SPEC	^{3}H β decay
< 2.3	95	[2] KRAUS 05	SPEC	^{3}H β decay

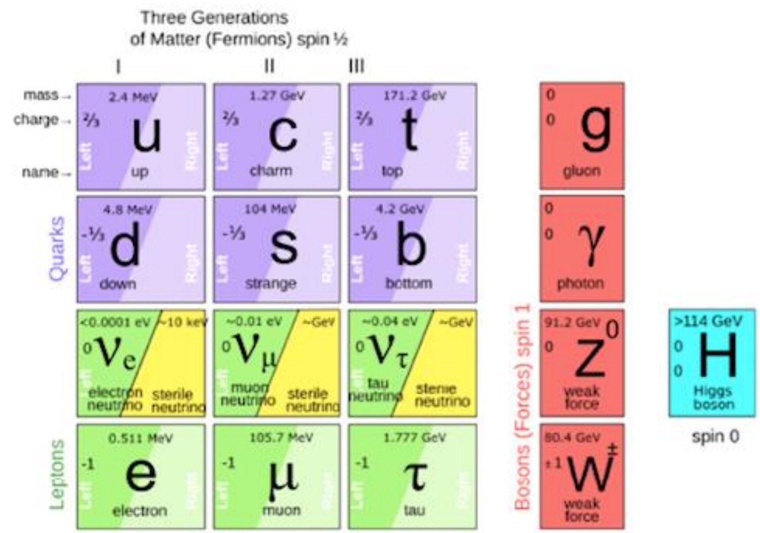
Particle Data Group

Why sterile neutrinos?
Motivation from Standard model

Standard Model



Extension with ν_R



Key question - mass of ν_R

Consider Standard Model with minimal extention to include right handed neutrinos N_j, $j = 1, 2, 3$

After that we can explain:

- Dark matter, if $M_1 \gtrsim$ keV

  Dodelson & Widrow (94)

- Dark matter and Baryon asymmetry, if $M_1 \gtrsim$ keV and $M_2, M_3 \sim$ GeV

  Akhmedov, Rubakov & Smirnov (98)

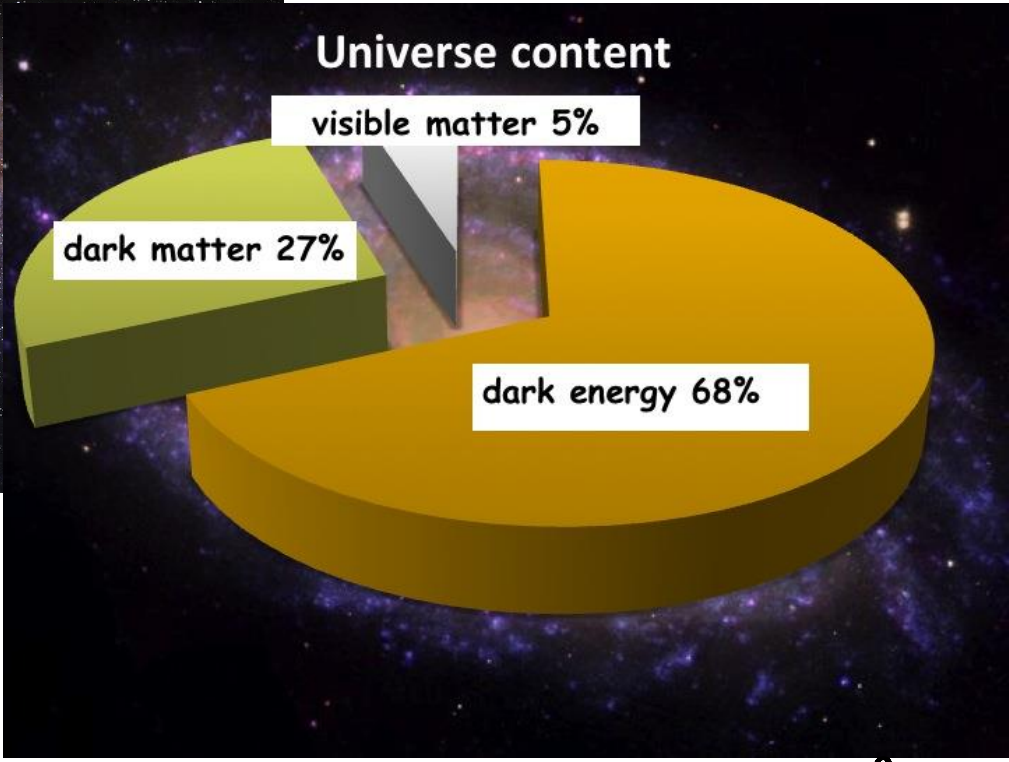
  Asaka & Shaposhnikov (05)

- Laboratory
  - $M_1 \lesssim 100$ eV: oscillation experiments
  - 10 eV $\lesssim M_1 \lesssim$ MeV: radioactive decay
  - MeV $\lesssim M_1 \lesssim$ GeV: leptonic decays of mesons
  - MeV $\lesssim M_1 \lesssim 100$ GeV: decays of sterile neutrino in "beam-dump"experiments.

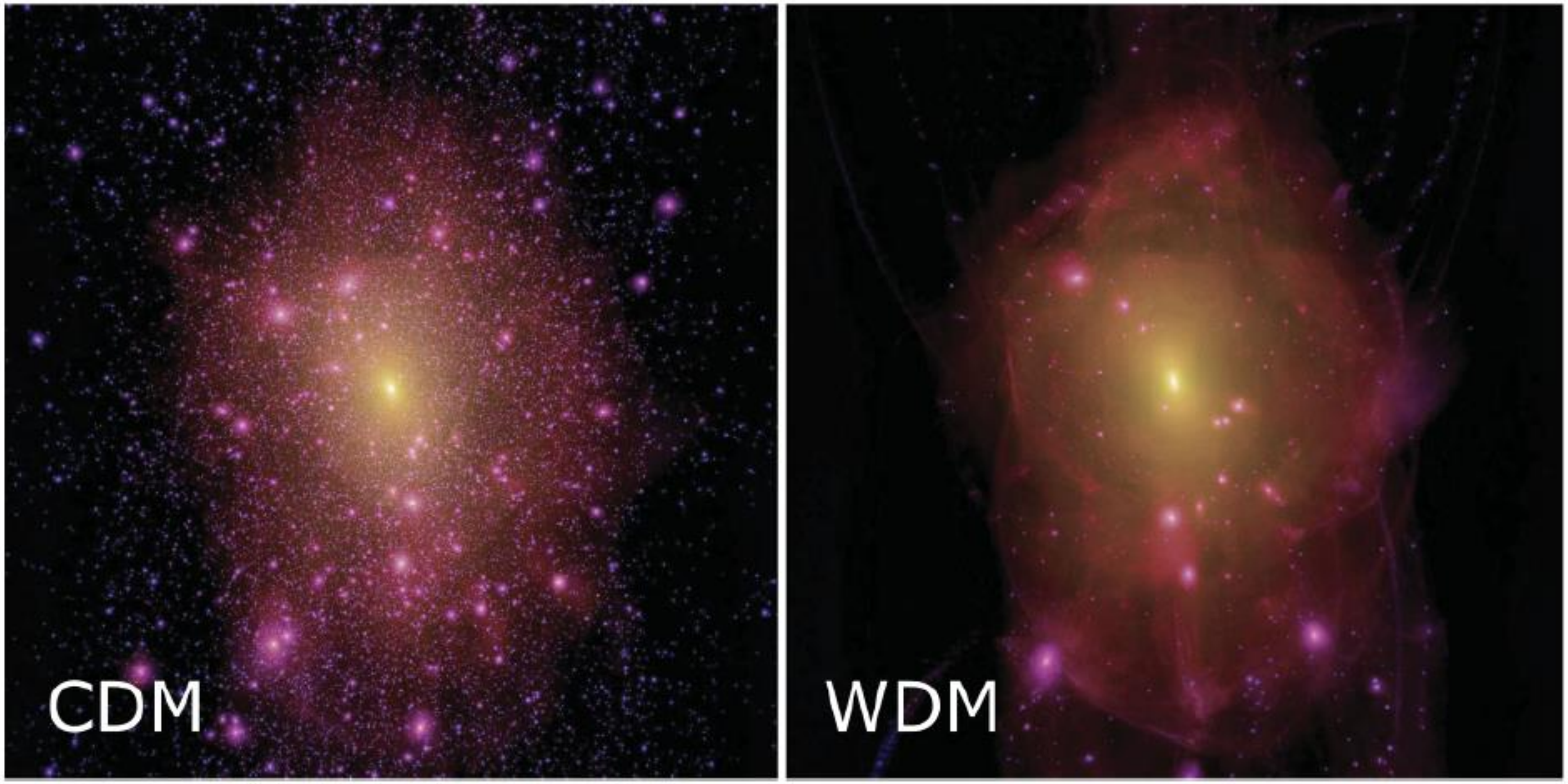
- Astrophysical and cosmological

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

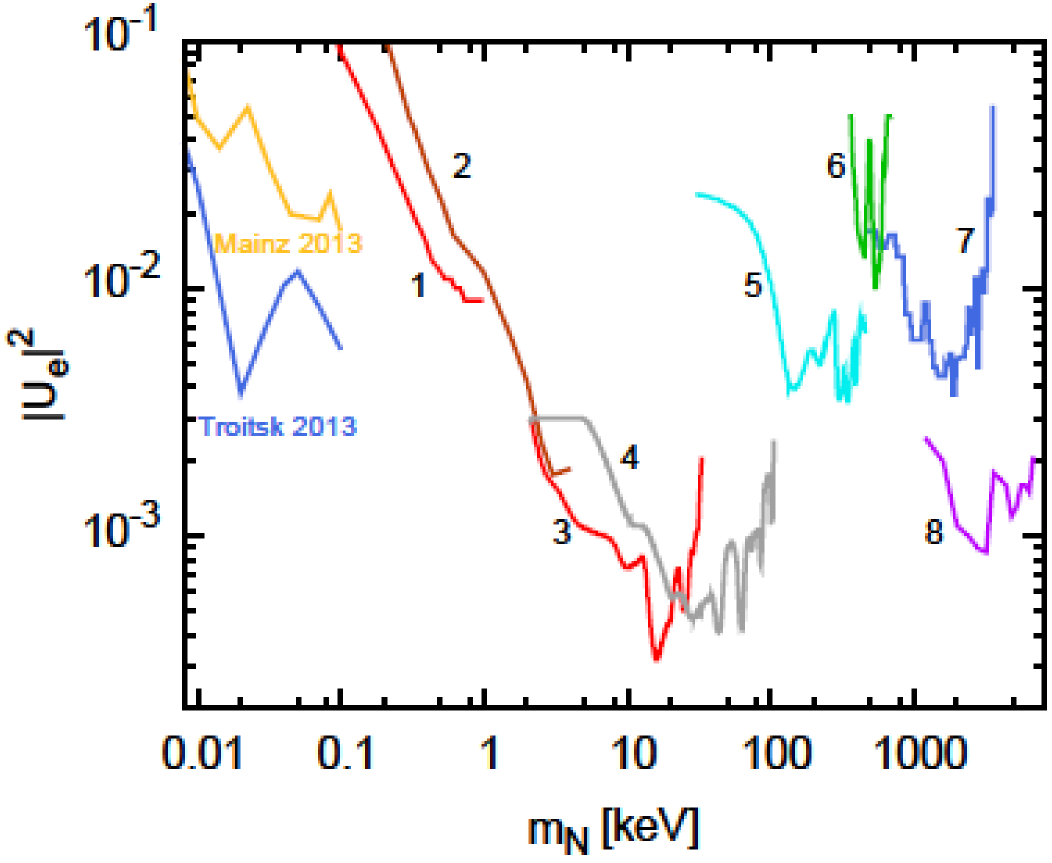
So, why keV- neutrino?
Candidate for Warm Dark Matter

- 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*

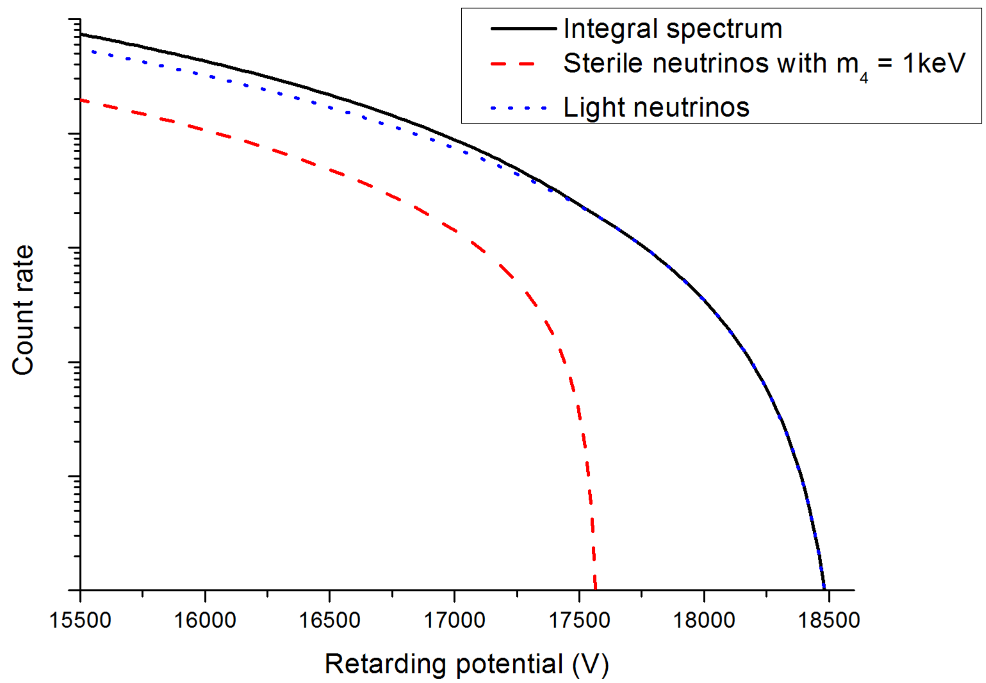
PS. keV mass range is not available in oscillation experiments

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



How can we find it?

Move away from the β-spectrum end point



Measure Tritium β-spectrum in wide energy range, at least in 13-19 keV

Search for distortion

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

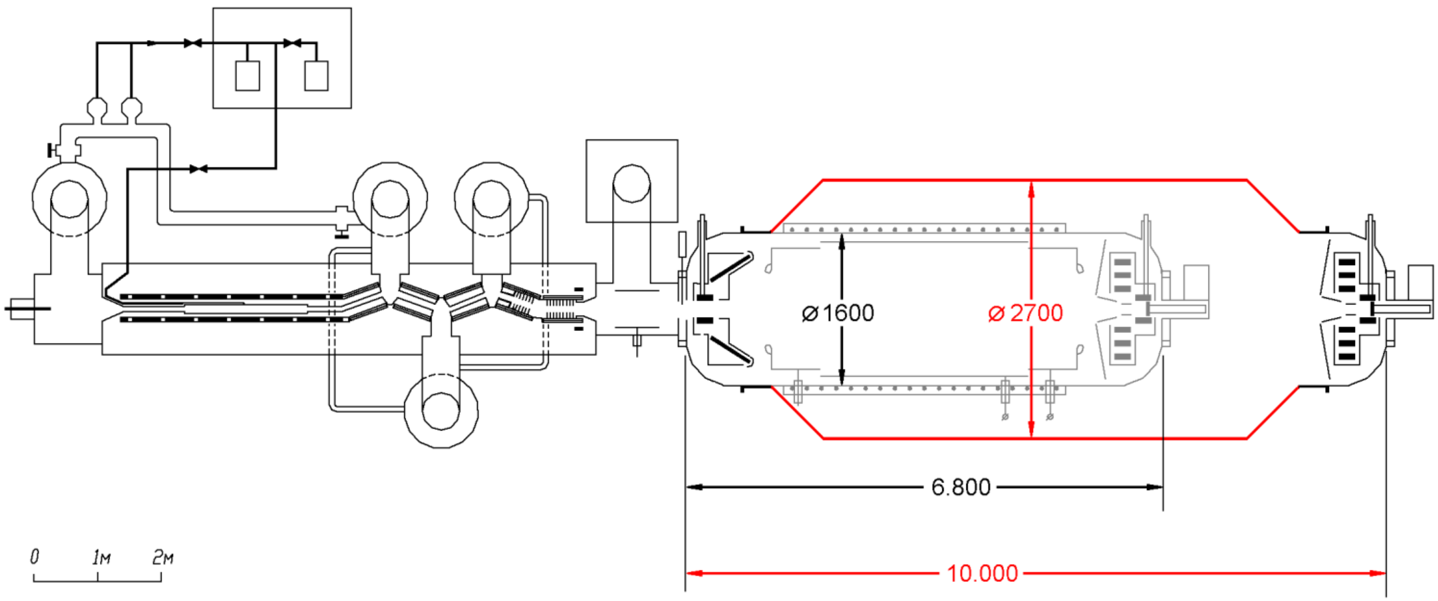
Then, we have to split spectrum into two parts

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

What is “Troitsk nu-mass” now?

The same Windowless Gaseous Tritium Source

New Spectrometer



+ a lot of upgrades

Energy range 13-19 keV
Energy resolution about 1.5 eV

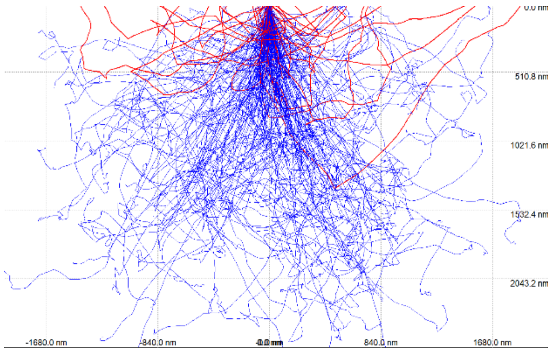
See also *Lett. Of Intent*, arxiv:1504.00544 JINST 10 (2015) no.10, T10005

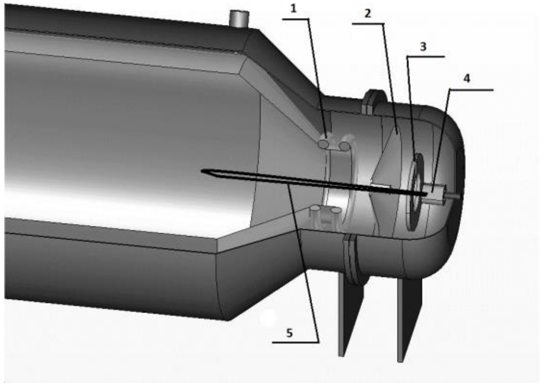
Devil is in details - systematics

- Insufficient accuracy of electron energy loss in gaseous source
- Electron trapping in "magnetic bottle" in the source
- Distortion of spectrometer transmission function
- Detector efficiency and electron scattering at different energy
- Electronics dead time and pile up
- Gas column density fluctuation
- High voltage stability

How to overcome? Calibrations, hardware upgrade, experimental measurements with electron gun, simulations

Problem with electron scattering from detector in MAC-E filter like our spectrometer

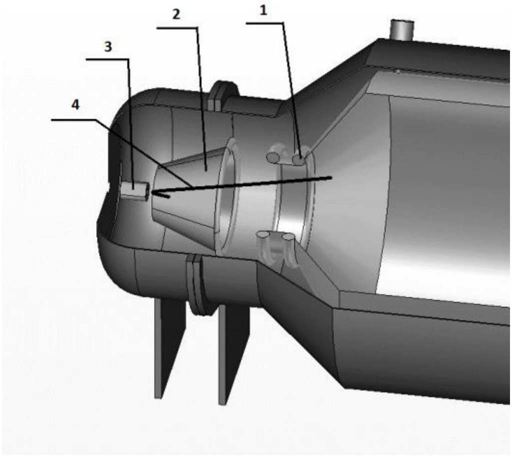




Electrostatic mirror

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

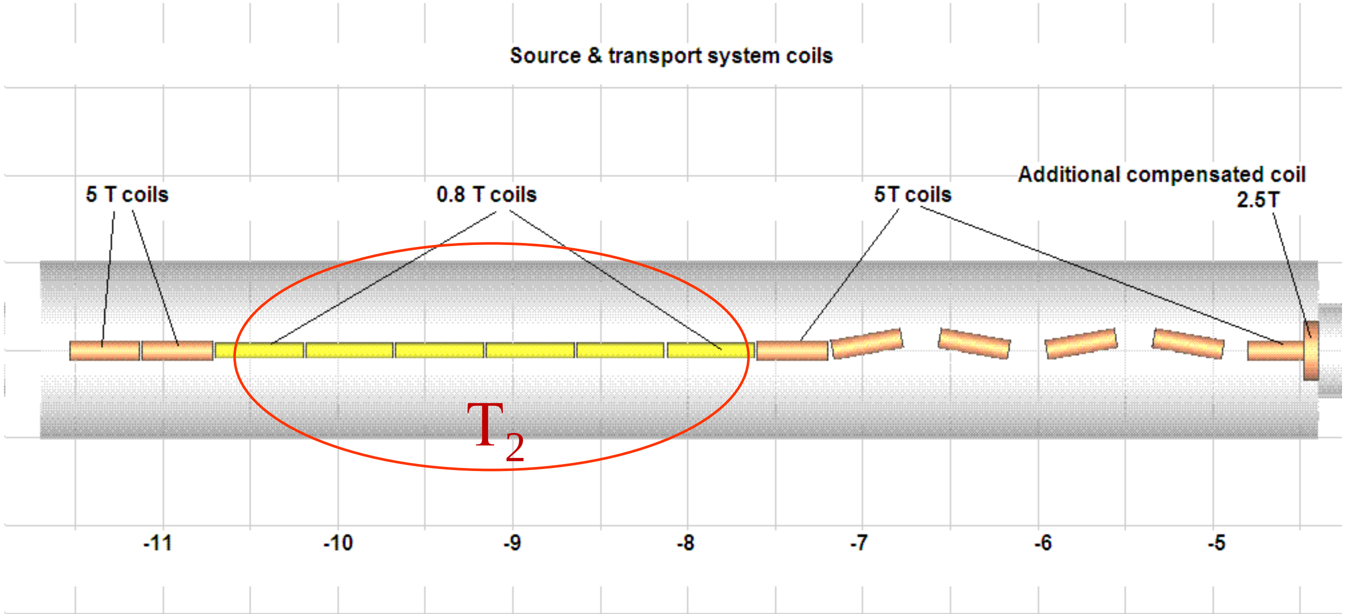
[NIM A832 (2016) 15](#)
[arXiv:1511.06129](#)



Magnetictic mirror

It changes transmission function and induces non-trivial time correlations

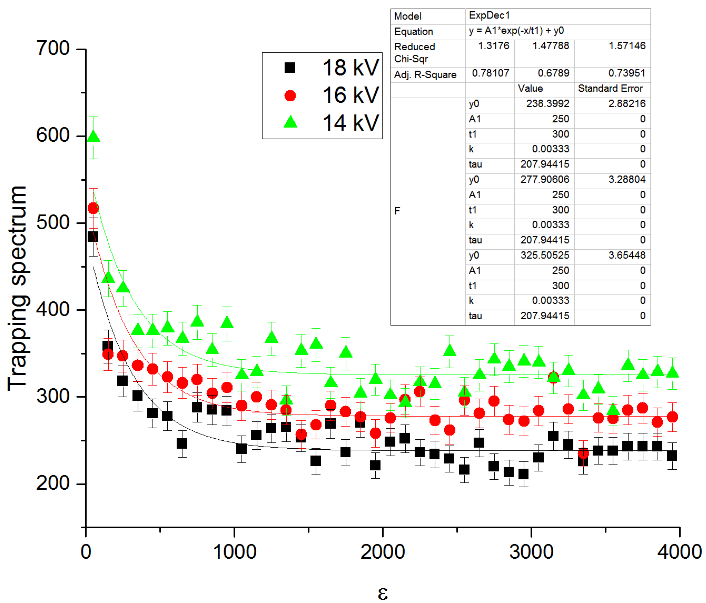
Field configuration in tritium source forms a bottle – magnetic Trap



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

Trapped electrons distort the actual β-spectrum

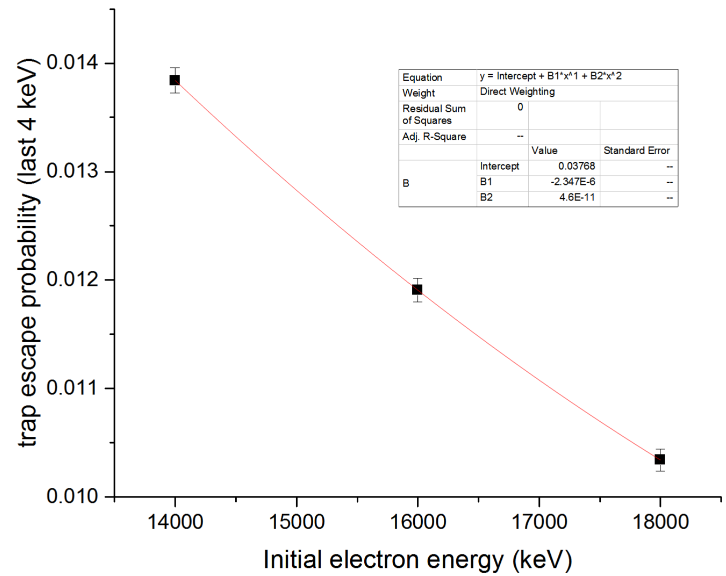
Simulation, for 6e+6 “normal” electrons



Model	ExpDec1		
Equation	y = A1*exp(-x/t1) + y0		
Reduced Chi-Sqr	1.3176	1.47788	1.57146
Adj. R-Square	0.78107	0.6789	0.73951
		Value	Standard Error
	y0	238.3992	2.88216
	A1	250	0
	t1	300	0
	k	0.00333	0
	tau	207.94415	0
	y0	277.90606	3.28804
	A1	250	0
F	t1	300	0
	k	0.00333	0
	tau	207.94415	0
	y0	325.50525	3.65448
	A1	250	0
	t1	300	0
	k	0.00333	0
	tau	207.94415	0

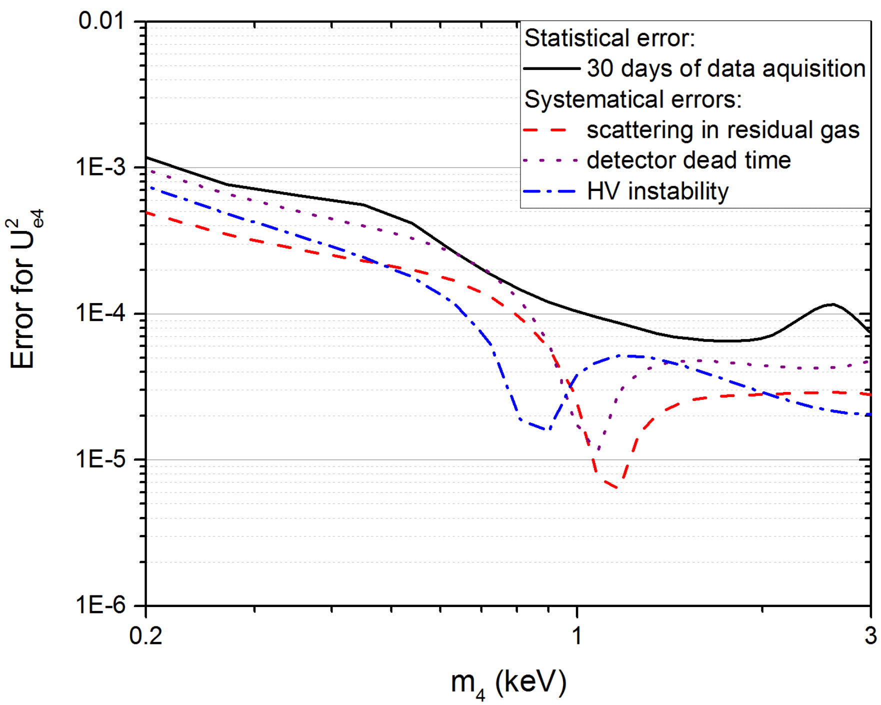
Delta of energy lost for trapped electrons before finally escaping to Spectrometer

Energy dependence



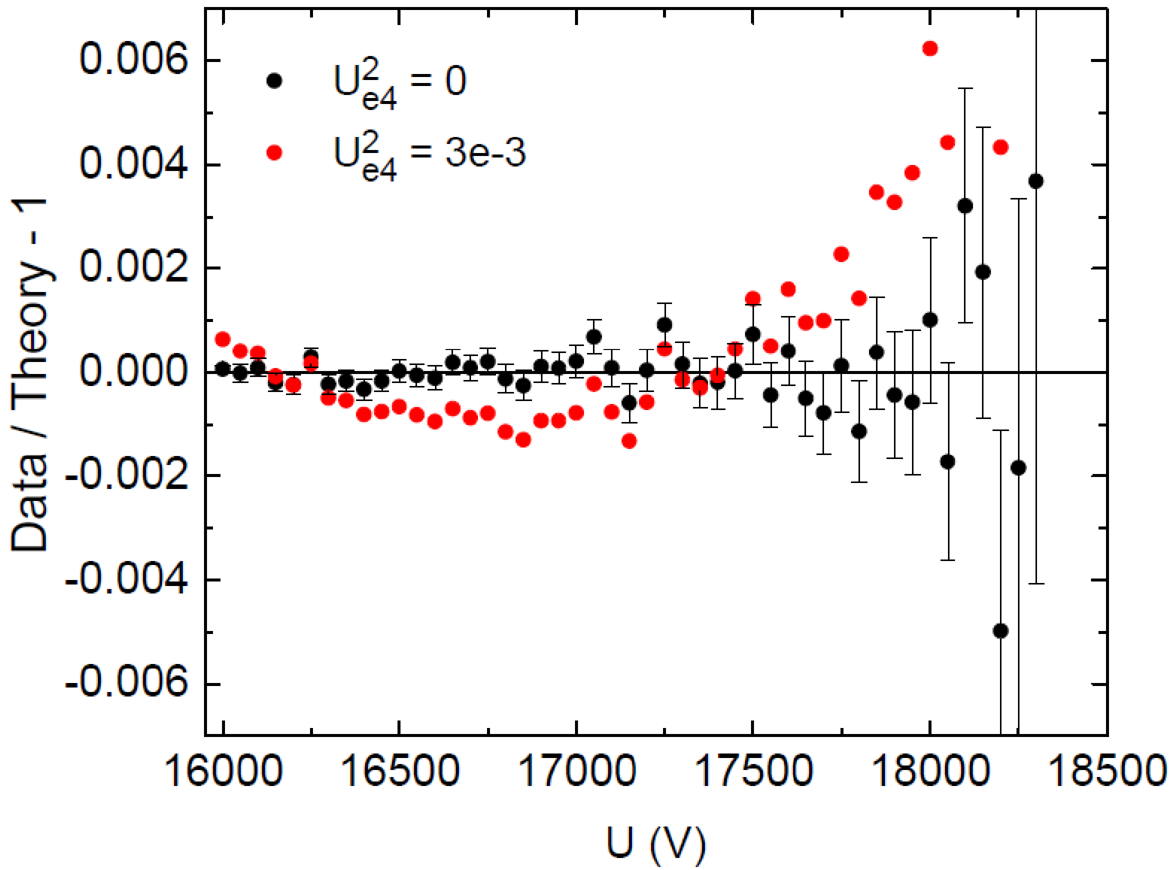
Equation	y = Intercept + B1*x^1 + B2*x^2		
Weight	Direct Weighting		
Residual Sum of Squares	0		
Adj. R-Square	--		
		Value	Standard Error
	Intercept	0.03768	--
B	B1	-2.347E-6	--
	B2	4.6E-11	--

Systematic limits on matrix element with the current setup



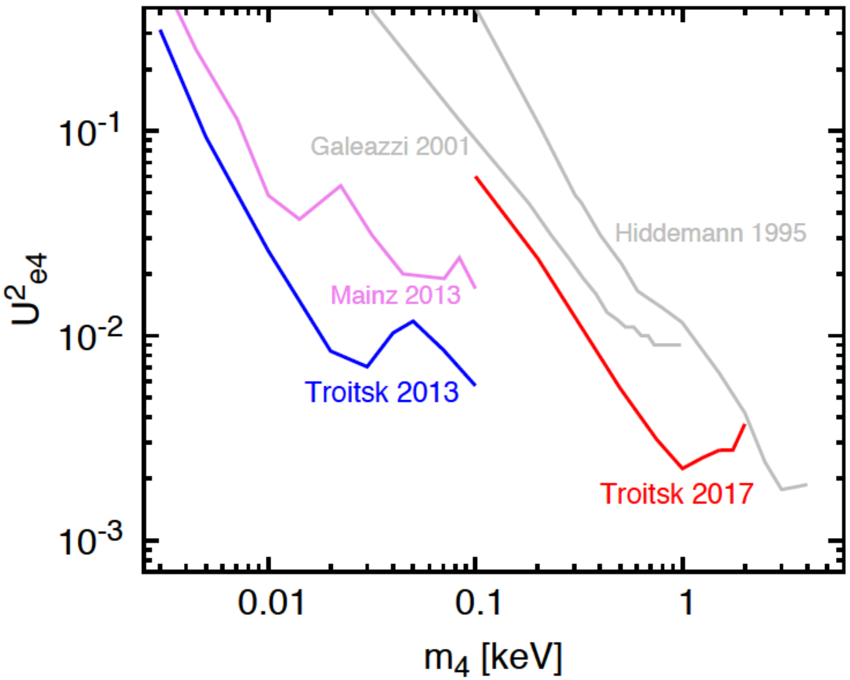
- Statistics for about 30 days of measurement including trapping error
- Energy loss in the source (current precision)
- Detector dead time and pile-up uncertainty (minor upgrade needed)
- HV instability (current precision)

Demonstration of sterile neutrino search: Oct 2016 measured spectrum versus U_{sp}



Recent precision measurements at Troitsk in a wider energy interval

We start data taking: Bounds on sterile neutrino based on October 2016 data

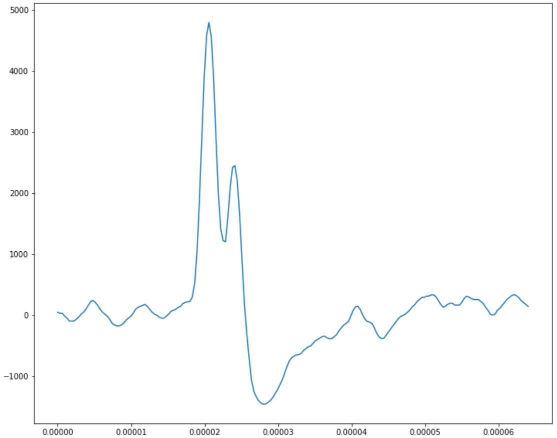


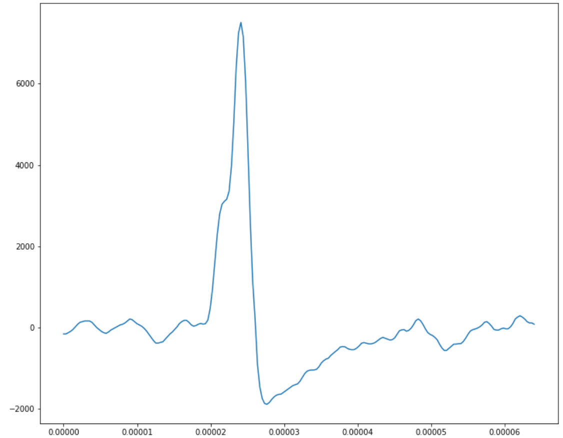
arXiv:1703.10779

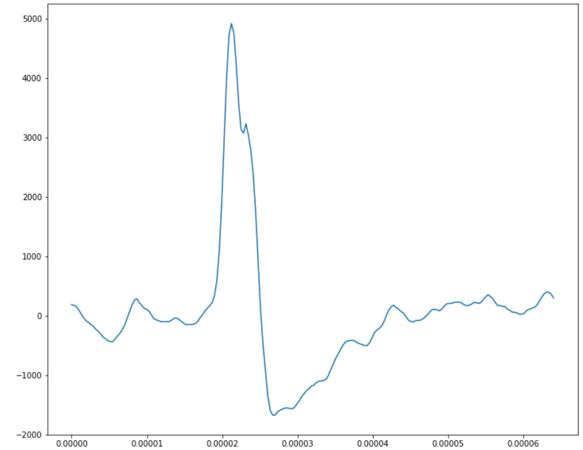
Plan for upcoming upgrades which will allow:

- Relative stability of electron gun intensity better than 0.1%
- Calibration of spectrometer transmission function with precisions 0.1%
- Absolute accuracy for gas column density less than 0.001 in units of mean free path
- Increase intensity of tritium source with multichannel detector
- Full signal digitization, pulse shape analysis and simulation

Signal shape plus noise simulation

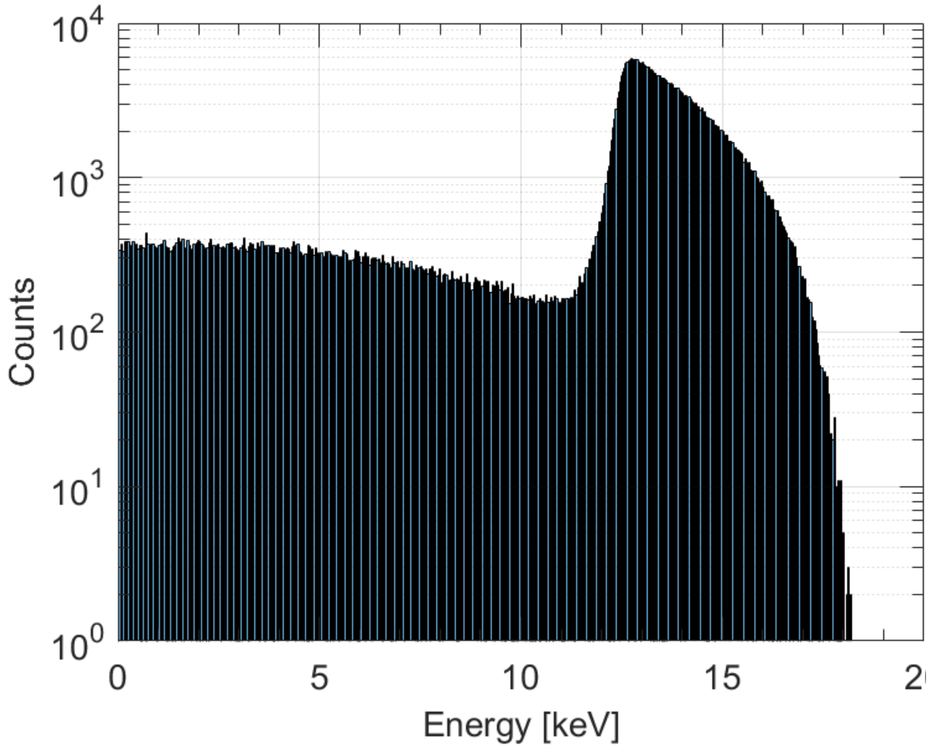




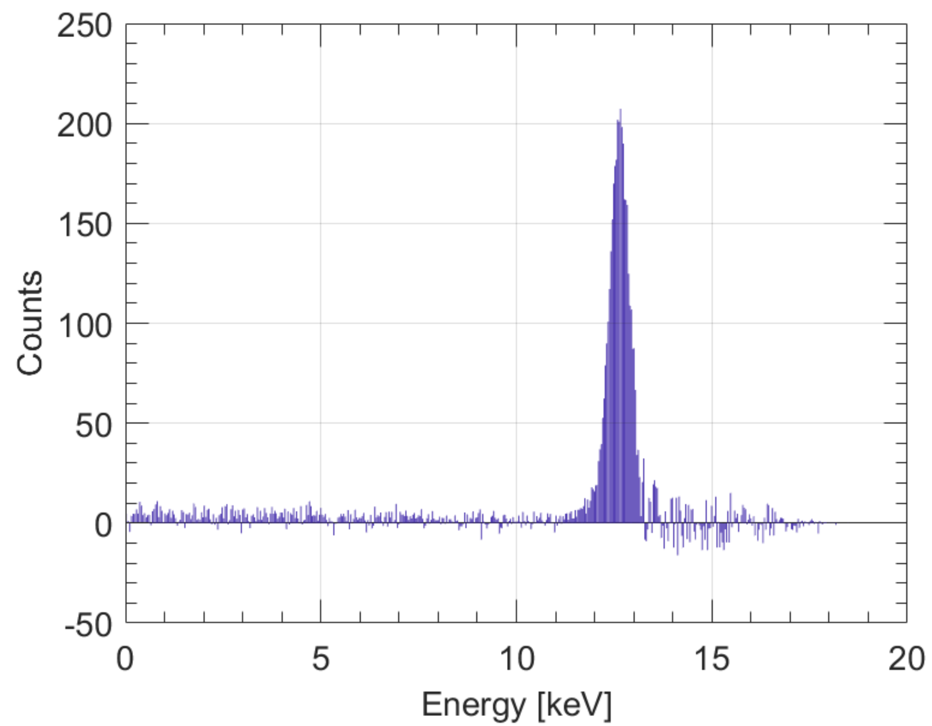


- With full signal digitization it allows to control pulse overlap
- To increase hit rate by 4-5 times

Test of 7-pixel prototype Si detector *(just from last Saturday measurements)*. German-French-Russian team in Troitsk



Integral Tritium spectrum at Usp=12.5 kV



Differential spectrum

Conclusions

- Measurements are underway
- We get official permission to work with tritium
- A lot of work is going on for calibration, simulation and upgrade
- Experiment is supported by RAS Program in Astroparticle Physics and RFBR grant
- New group within KATRIN collaboration is forming to work on new multichannel detector

Stay tuned!

Thank you for your attention

backup

What else?

- We understand that "inclusive" measurements have serious sensitivity limits, thus we have to find more sophisticated ways:
- To do exclusive measurements reconstructing the whole kinematics including recoil nucleus?
- Use other isotopes? Neutron decay?
- Electron capture? ^{7}Be ?
- To set Tritium on Graphane? (similar to PTOLEMY project)
- Do you get good idea?

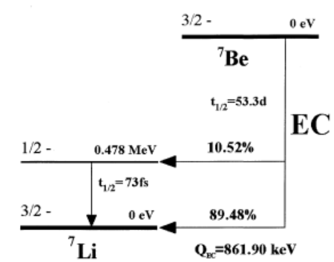
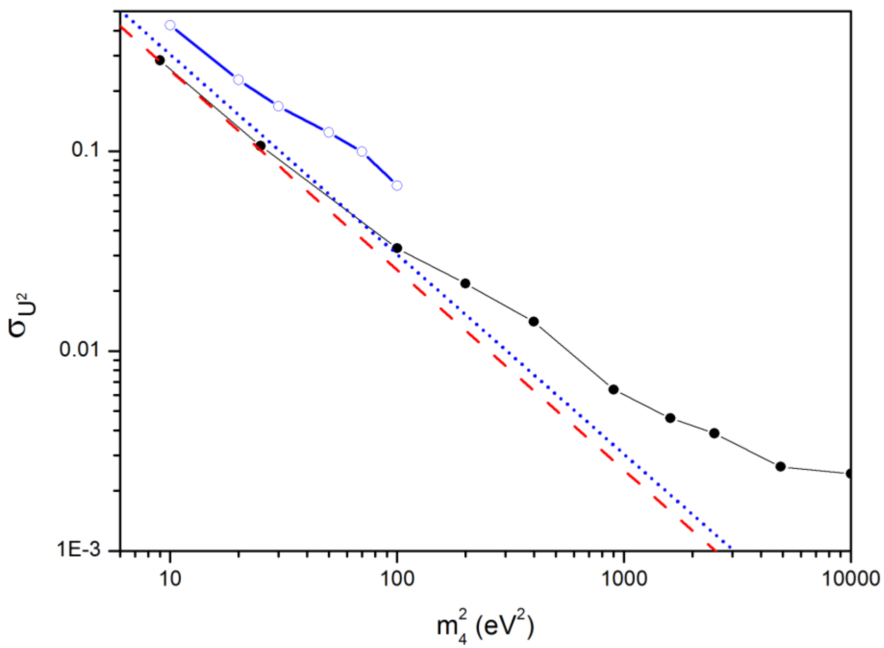


FIGURE 1. Decay scheme of ^{7}Be

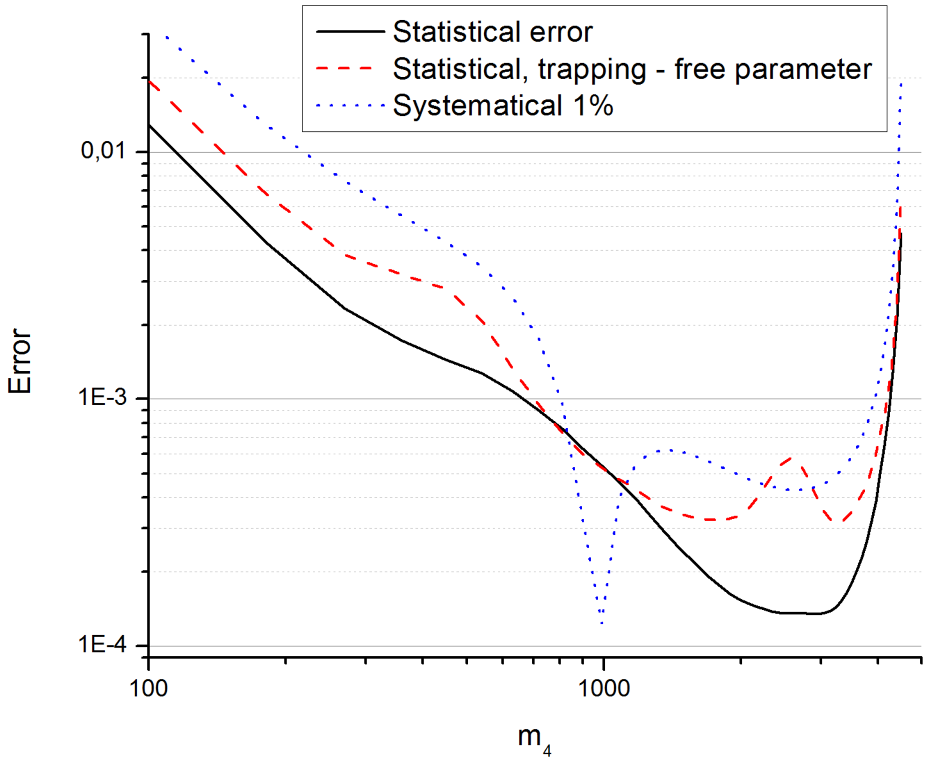
Comparison of errors for heavy neutrinos between Troitsk and Mainz experiments



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



Statistical error
Statistical, trapping - free parameter
Systematical 1%
0,01
1E-3
1E-4
Error
100
1000
m4

KATRIN. Everything is in place. Cryogenics tested. First shut by electron gun from the rear though the whole setup this month. Then test with Deuterium.