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
- 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 $m^{2(\mathrm{eff})}_{\nu_e} \equiv \sum_i |U_{ei}|^2 m^2_{\nu_i}$. Limits that come from the kinematics of ^{3}H$\beta^- \overline{\nu}$ decay are the square roots of the limits for $m^{2(\mathrm{eff})}_{\nu_e}$. 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

Question raised: what next with our setup, with new spectrometer and our experience? – STERILE ν

Discussions about possible existence of additional heavy neutrino is now in textbooks

Particle Data Group : $$|\nu_l\rangle = \sum_j U^*_{lj}\,|\nu_j;\tilde{p}_j\rangle, \quad l = e, \mu, \tau\,,$$

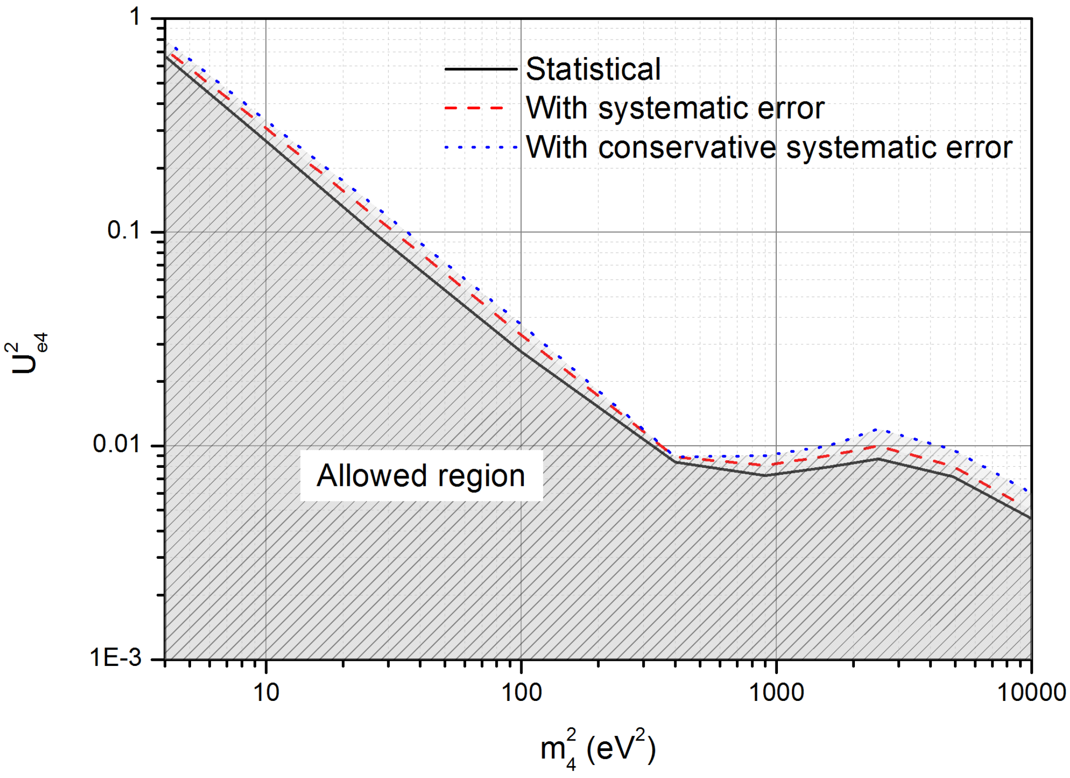
If the number n of massive neutrinos ν_j is bigger than 3 due to a mixing between the active flavour and sterile neutrinos, one will have additional relations similar to that in Eq. (13.5) for the state vectors of the (predominantly LH) sterile antineutrinos. In the case of just one RH sterile neutrino field $\nu_{sR}(x)$, for instance, we will have in addition to Eq. (13.5):

$$|\bar{\nu}_{sL}\rangle = \sum_{j=1}^{4} U^*_{sj}\,|\nu_j;\tilde{p}_j\rangle \cong \sum_{j=1}^{4} U^*_{sj}\,|\nu_j, L;\tilde{p}_j\rangle\,, \qquad (13.6)$$

where the neutrino mixing matrix U is now a 4×4 unitary matrix.

We re-analyzed our Tritium date from 1994-2004 it search for signal of sterile neutrino and get some new limits …

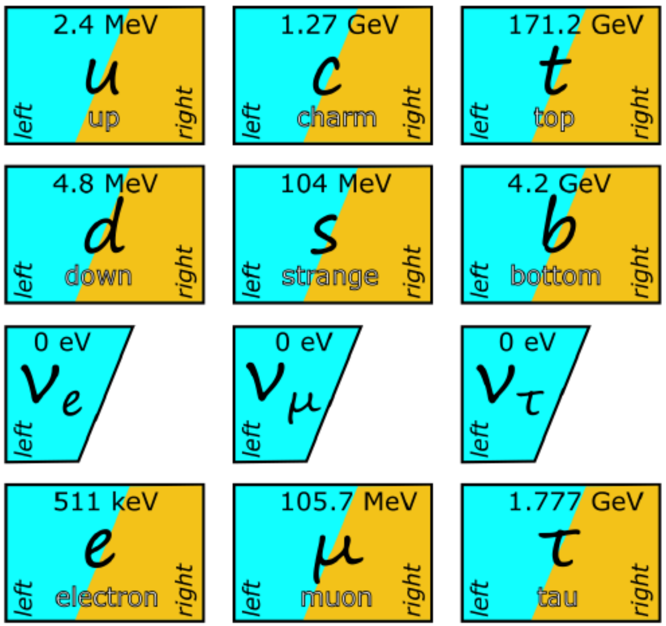
95% CL limits on sterile neutrino matrix element based on previous statistics 1994-2005



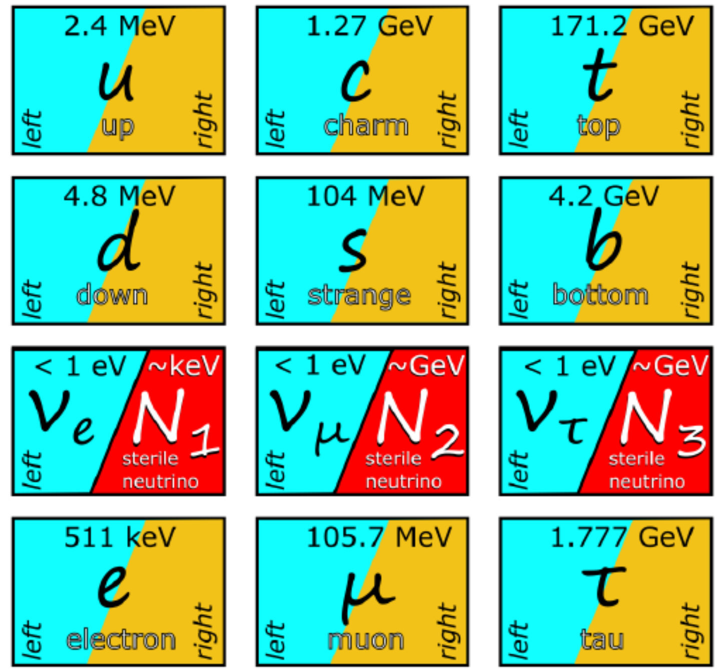
A.I. Belesev et al., J.Phys. G41 (2014) 015001, arXiv:1307.56387

Why sterile neutrinos?

Motivation from Standard model



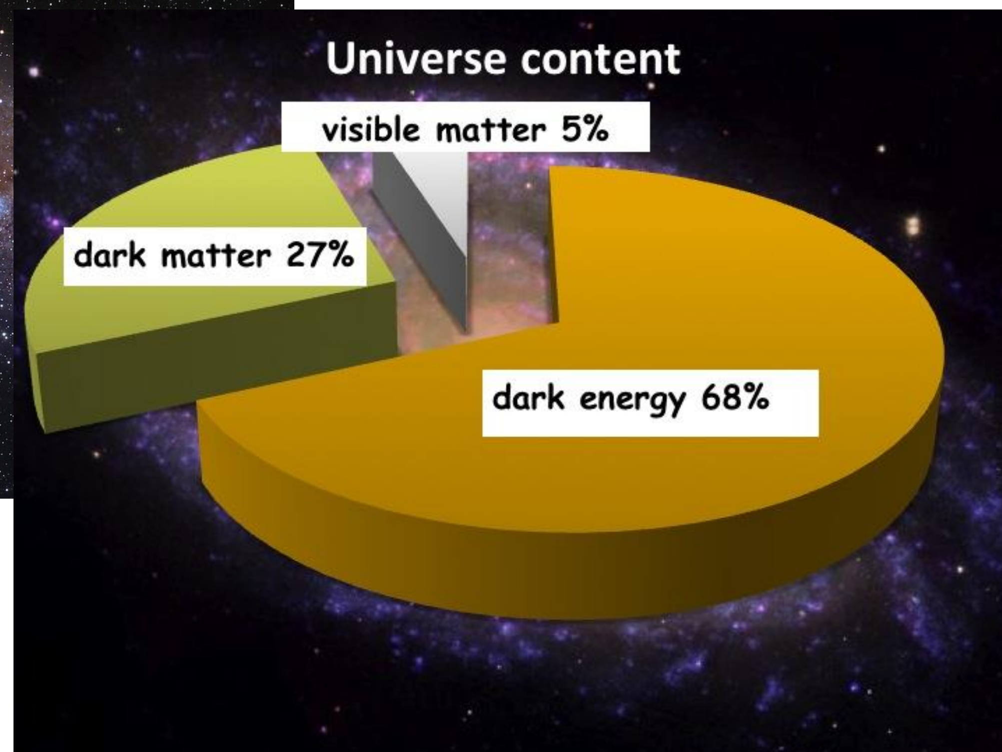
Right-handed neutrinos are missing



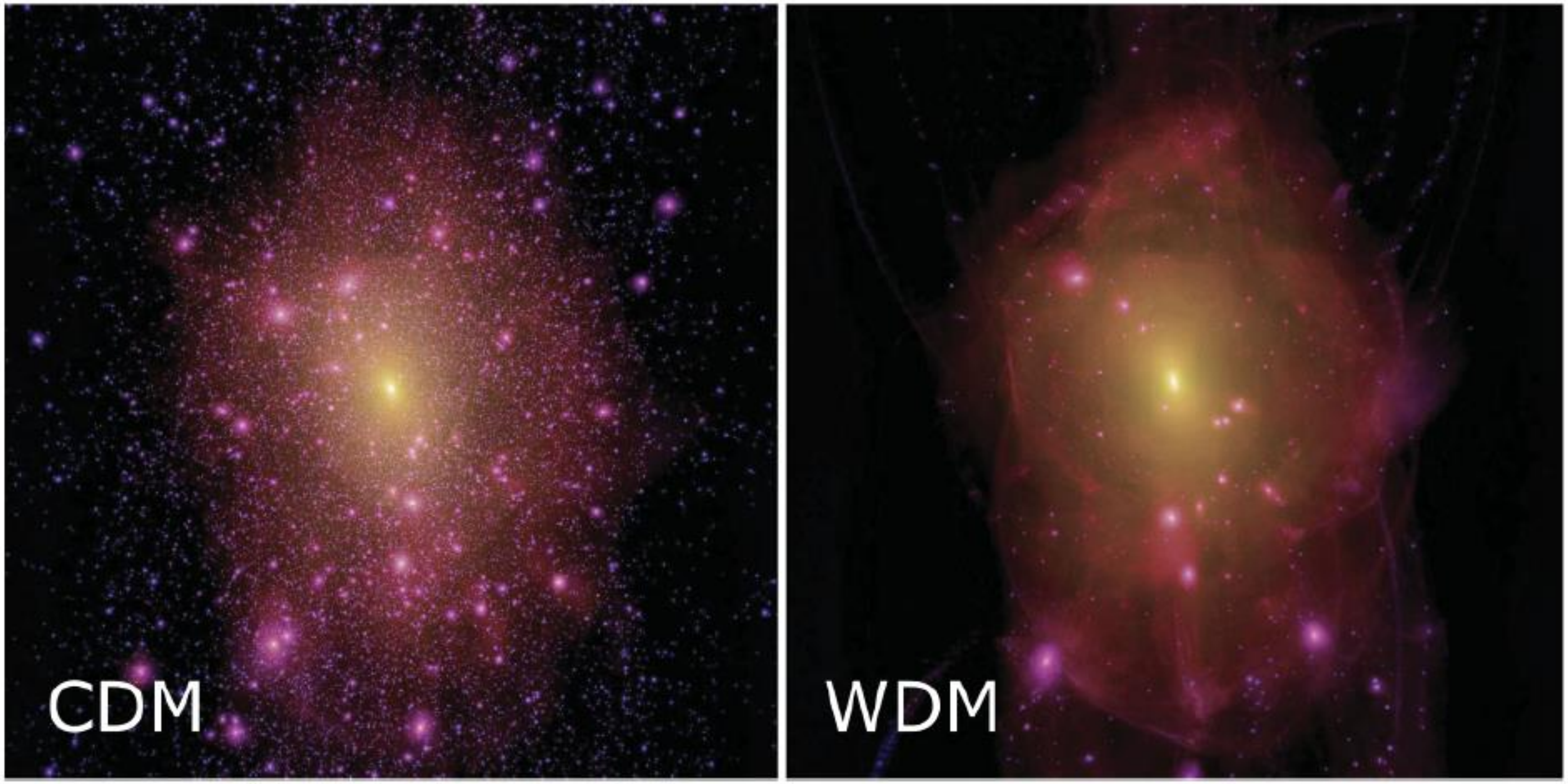
Steriles can fill these gaps

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

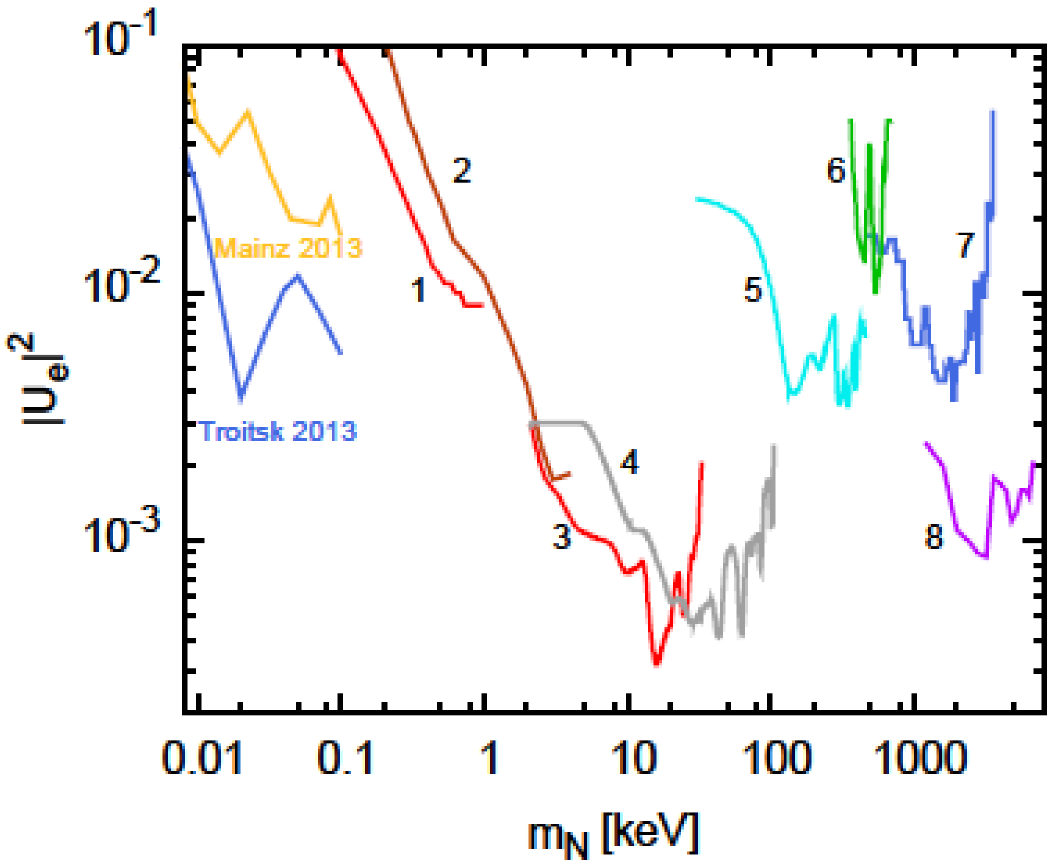
So, why keV- neutrino?
Candidate for Warm Dark Matter

- 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*

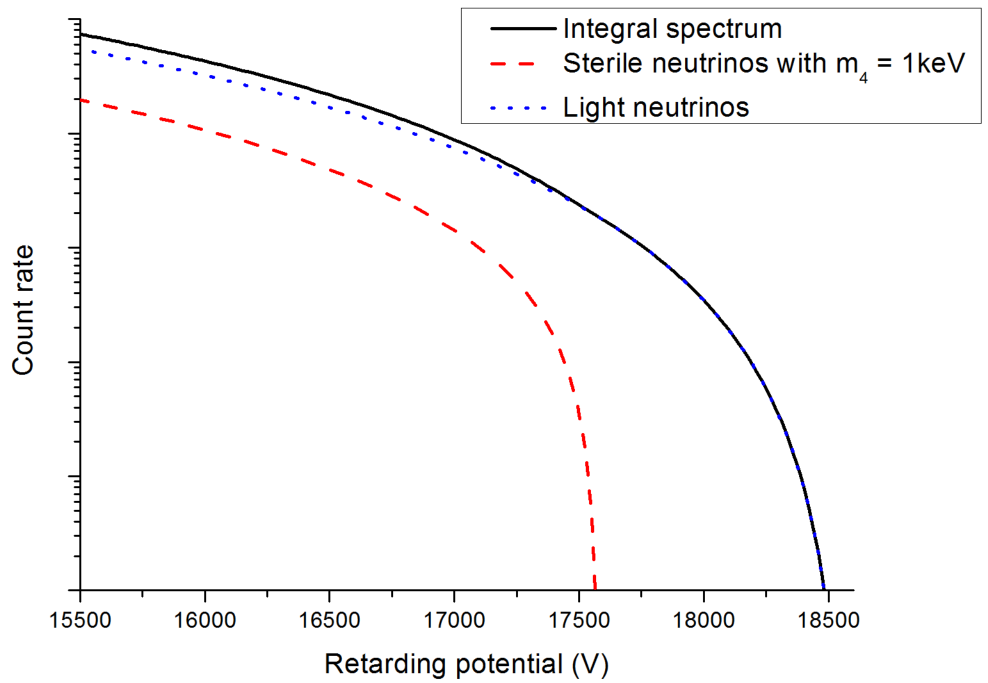
PS. keV mass range is not available in oscillation experiments

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

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

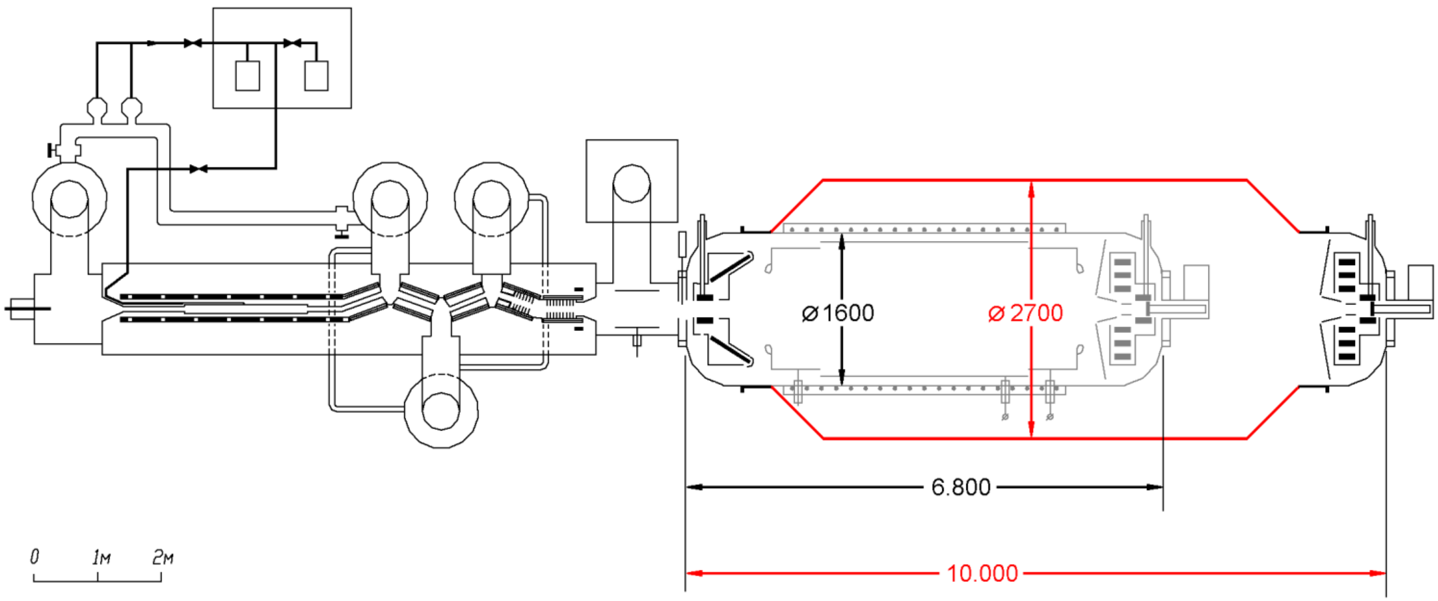
Then, we have to split spectrum into two parts

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

What is “Troitsk nu-mass” now?

The same Windowless Gaseous Tritium Source

New Spectrometer

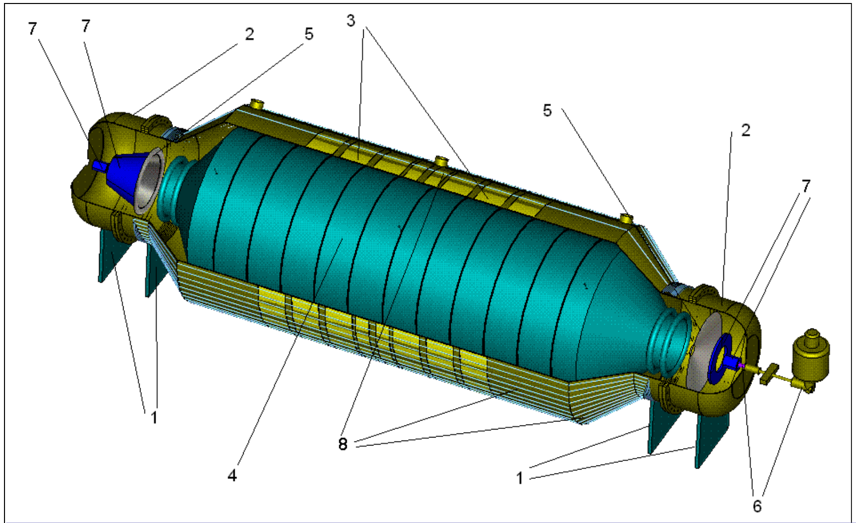


+ a lot of upgrades

Energy range 13-19 keV
Energy resolution about 1.5 eV

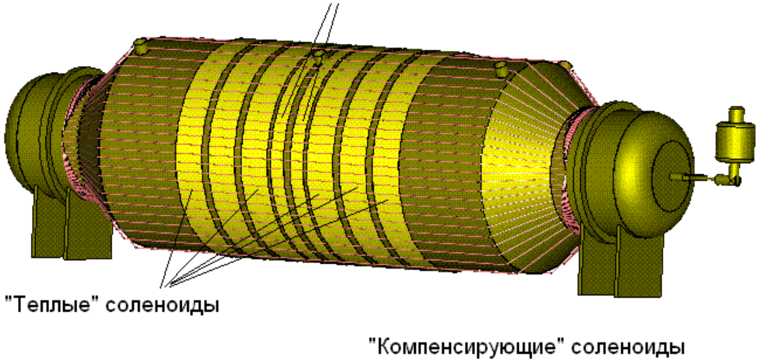
See also *Lett. Of Intent*, arxiv:1504.00544 JINST 10 (2015) no.10, T10005

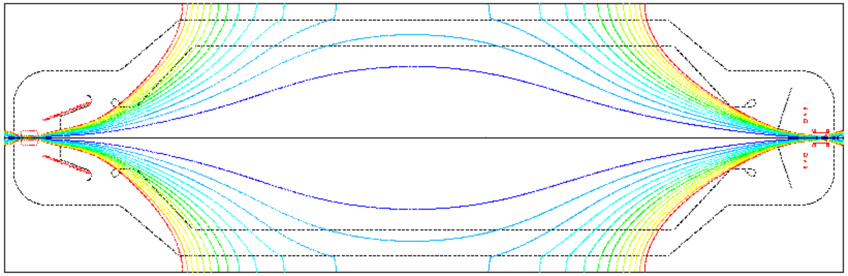
Electrostatic and magnetic field configuration



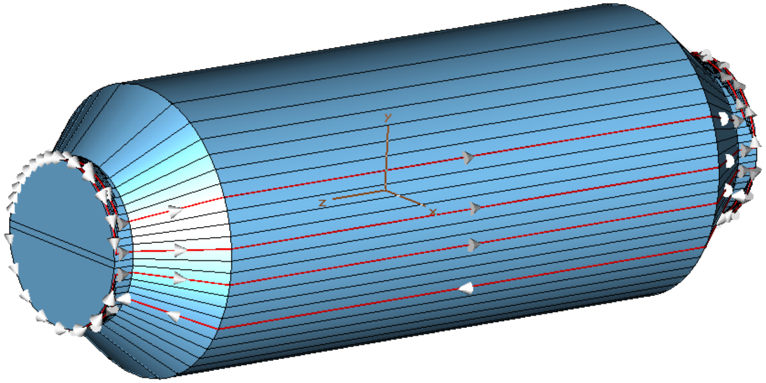
Main vessel, about 10 m long

Warm correction coils





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



Inner electrostatic electrode,
13-19 kV

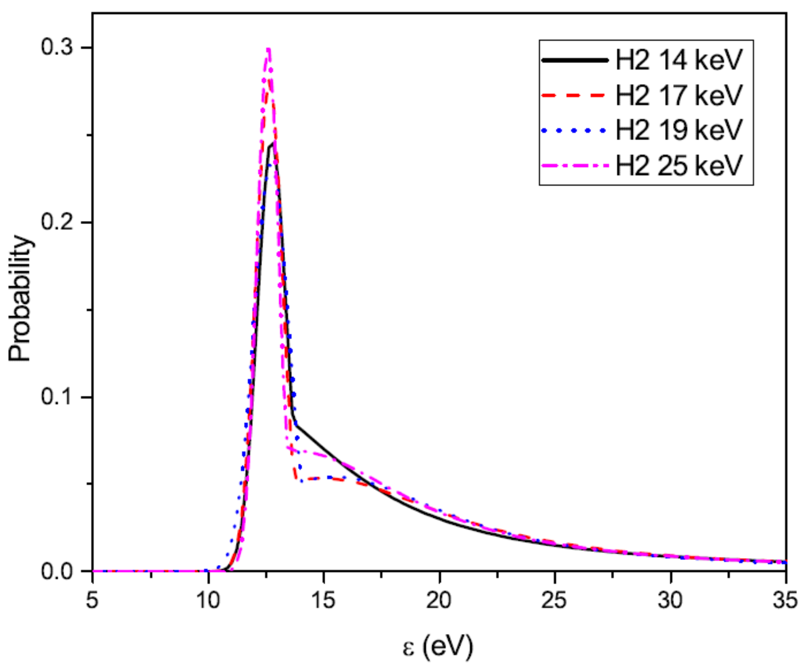
Devil is in details - systematics

- 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

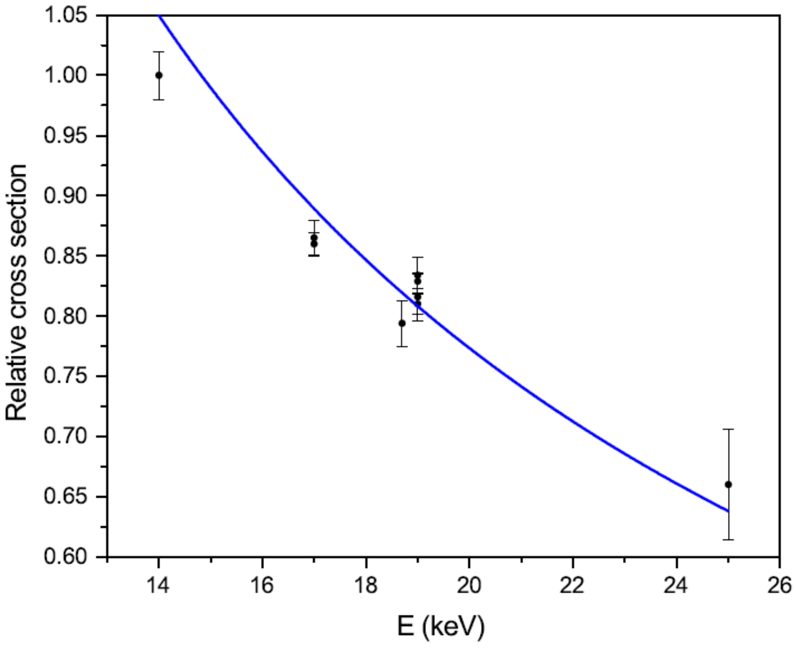
How to overcome? Calibrations, hardware upgrade, experimental measurements with electron gun, simulations

Some recent calibration measurements: electron scattering on H2 and D2 from 14 keV to 25 keV

Excitation and ionization

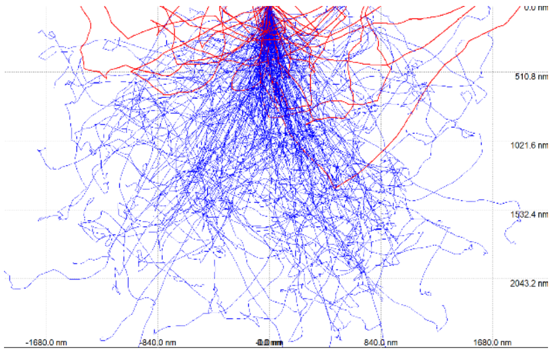


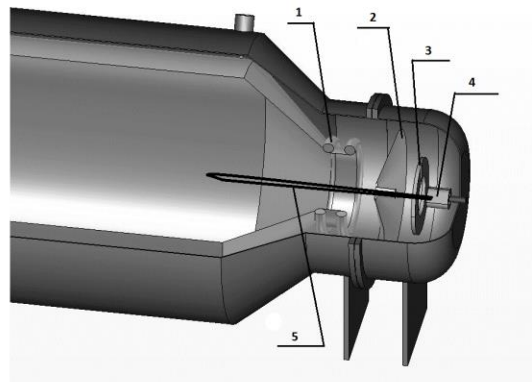
Energy dependence



“Electron scattering on hydrogen and deuterium molecules at 14-25 keV by the "Troitsk nu-mass" experiment” arXiv:1603.04243

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





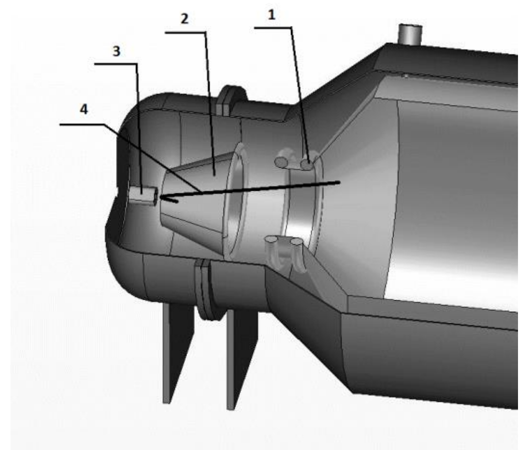
Electrostatic mirror

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

CASINO simulation

[NIM A832 (2016) 15](#)

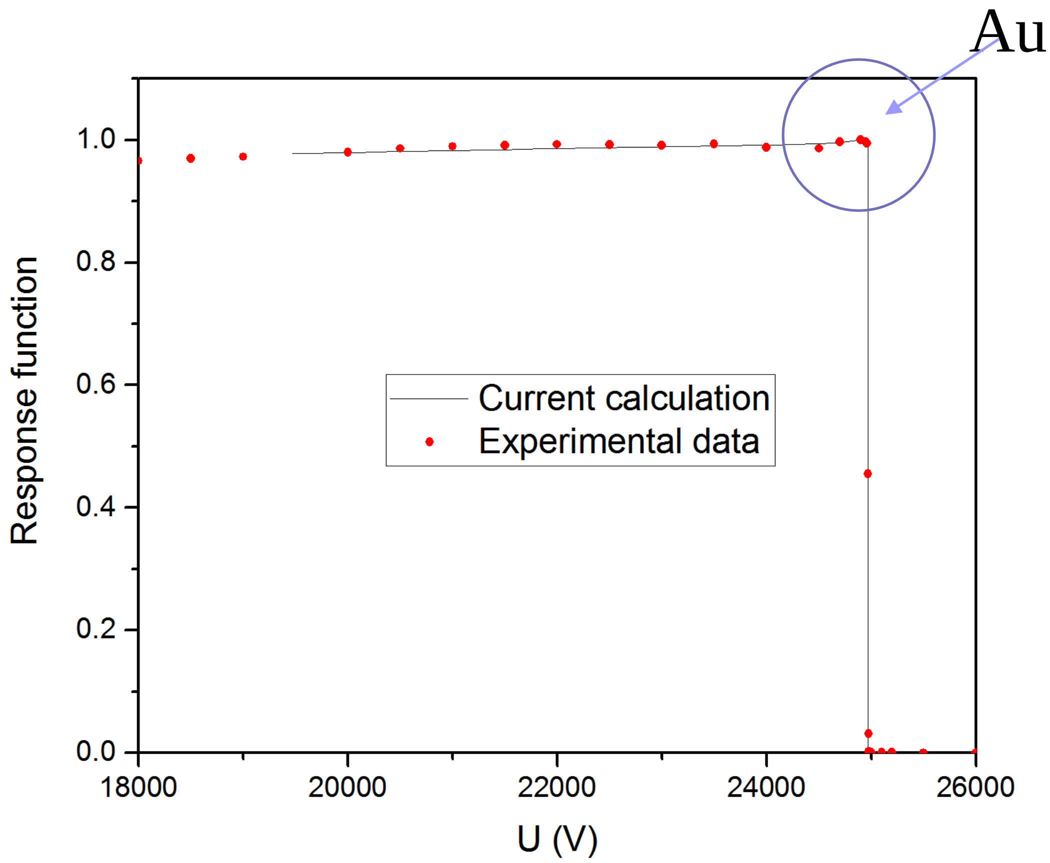
[arXiv:1511.06129](#)



Magnetictic mirror

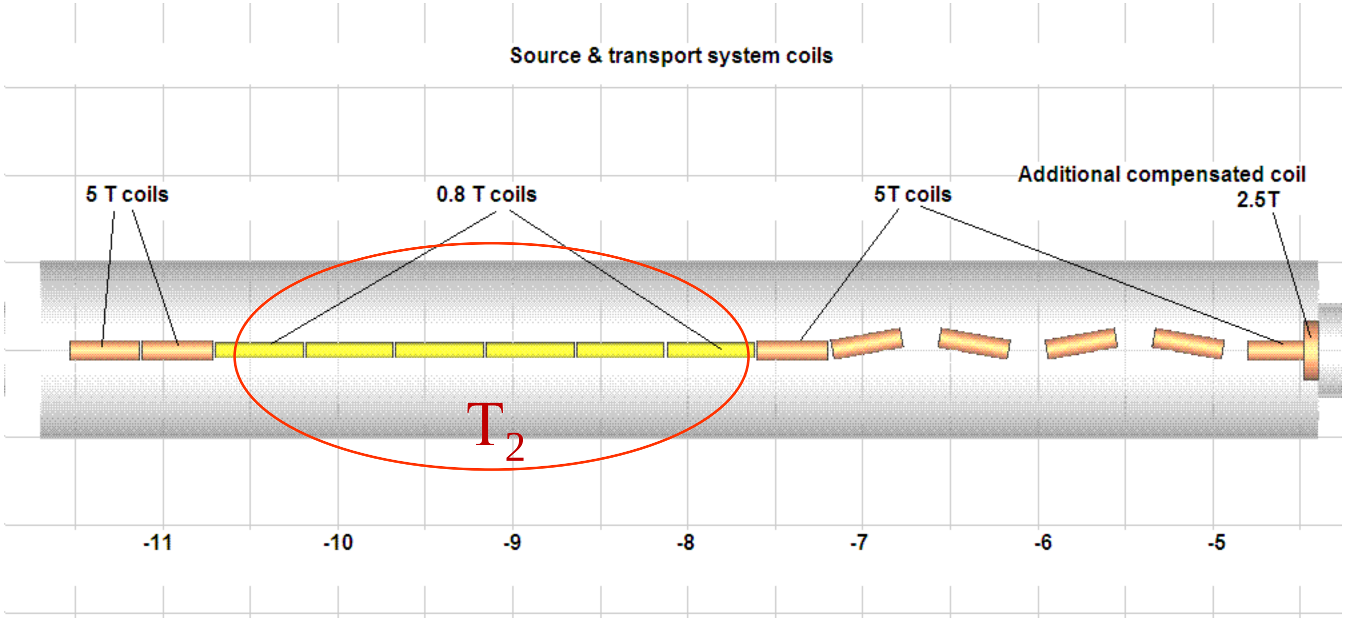
It changes transmission function and induces non-trivial time correlations

Scattering on Si detector with Au window explains the long standing problem why integral spectrum **rises** with increasing spectrometer retarding potential



Count rate for 25 keV electrons vs spectrometer retarding potential

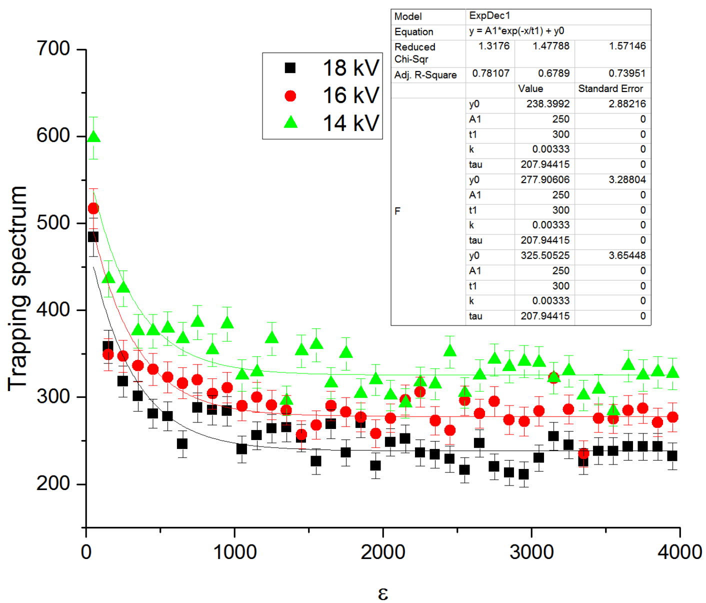
Field configuration in tritium source forms a bottle – magnetic Trap



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

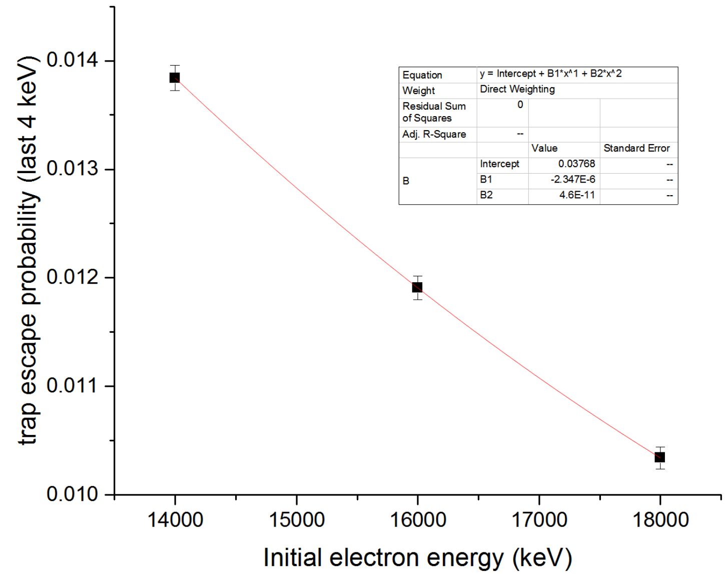
Trapped electrons distort the actual β-spectrum

Simulation, for 6e+6 “normal” electrons

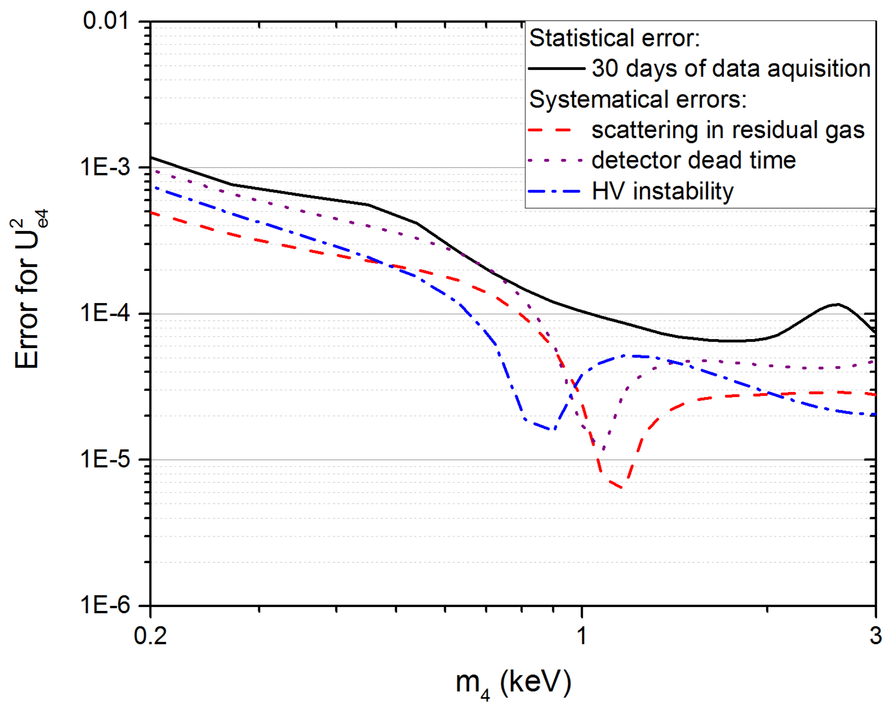


Delta of energy lost for trapped electrons before finally escaping to Spectrometer

Energy dependence



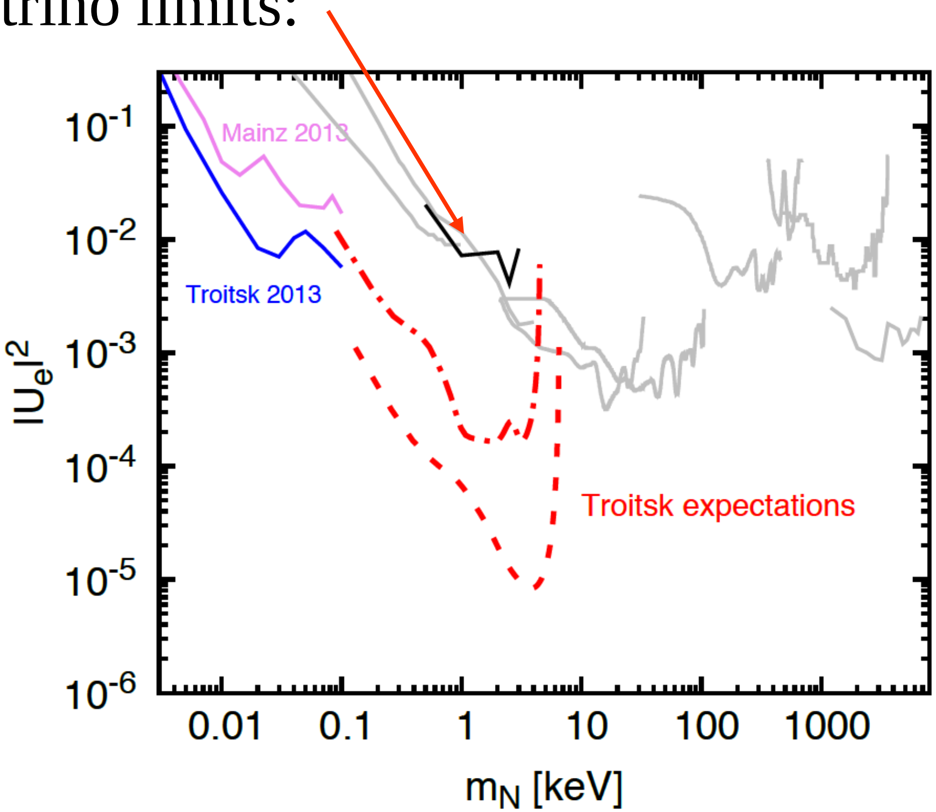
Systematic limits on matrix element with the current setup



- 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)

Measurements started this year. First calibration run with just two days of data taking.

Already get current neutrino limits:



The goal of 2016-2017 – Statistics, statistics, statistics!

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%
- Improve knowledge of electronics dead time to the order of 1 nsec
- Absolute accuracy for gas column density less than 0.001 in units of mean free path
- Increase intensity of tritium source with faster electronics

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?

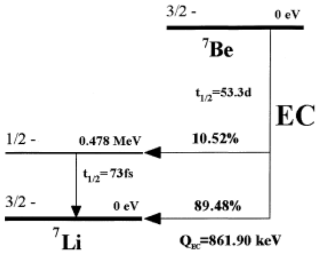


FIGURE 1. Decay scheme of ^{7}Be

Conclusions

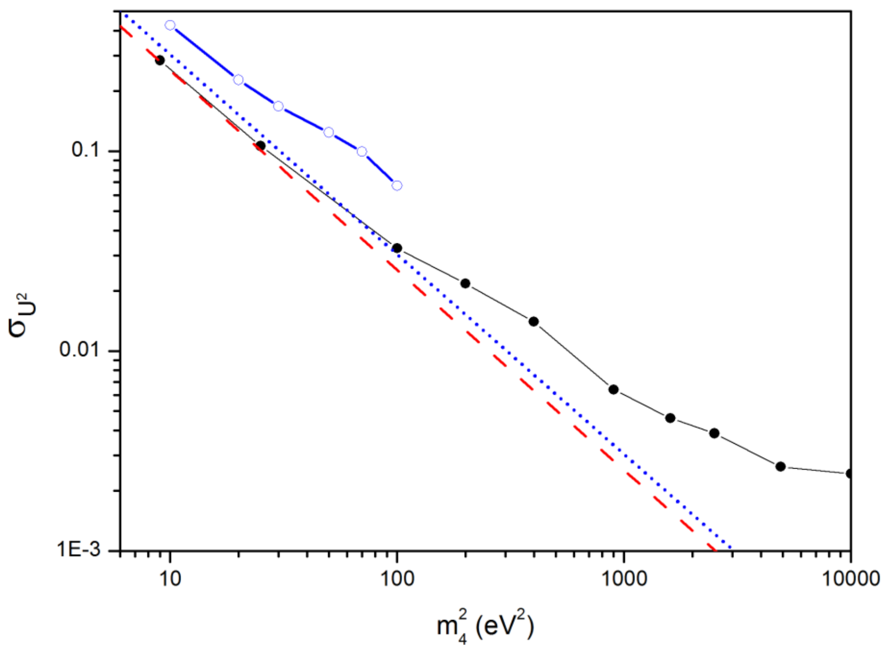
- Measurements are underway
- We get official permission to work with tritium
- A lot of work is going on for calibration, simulation and upgrade
- Experiment is supported by RAS Program in Astroparticle Physics and two RFBR grants
- We invite for collaboration

Stay tuned!

Thank you for your attention

backup

Comparison of errors for heavy neutrinos between Troitsk and Mainz experiments

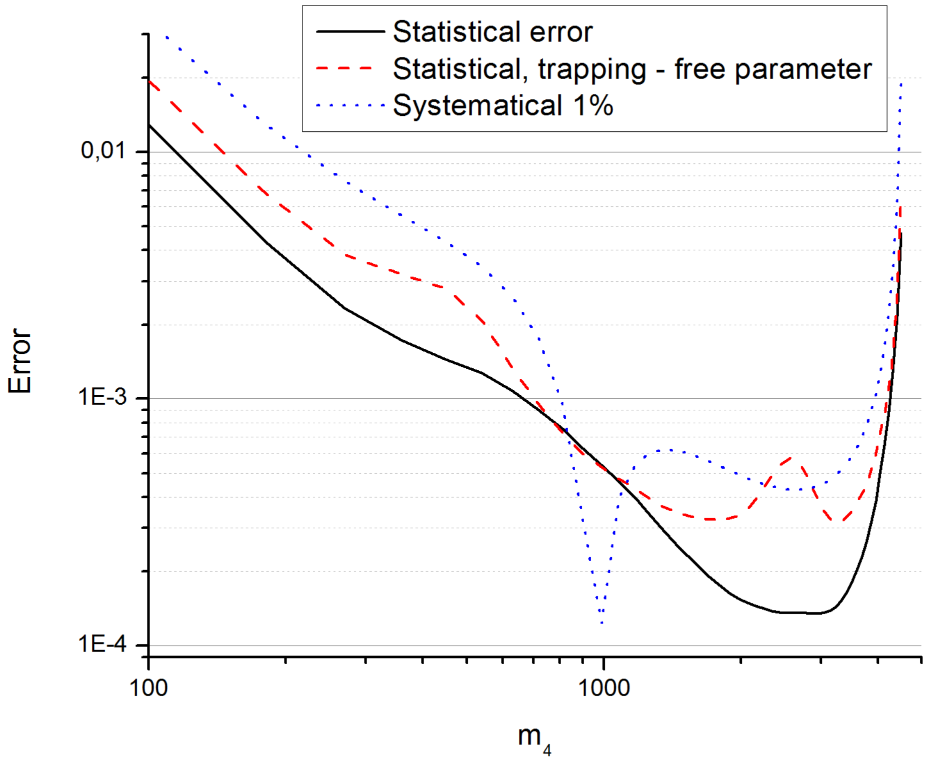


Comparison of errors for heavy neutrino mass obtained by the analysis, black symbols connected by solid lines, and approximate estimation $\sigma(U_{e4}^2) = 2.53/m_\nu^2$ based on the result for the electron antineutrino mass *V. N. Aseev et. al., Phys. Rev. D84, 112003 (2011)*, red dashed line.

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
m_4

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.