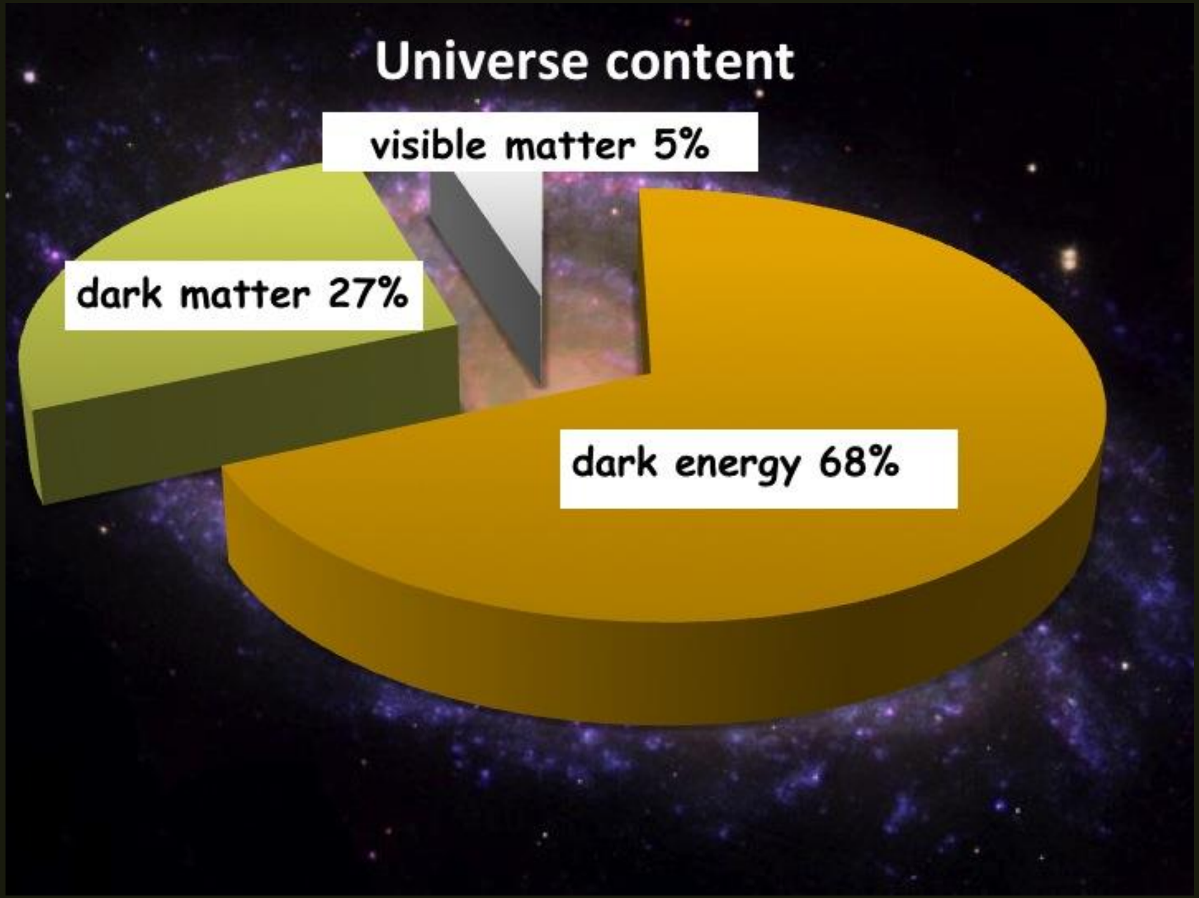
STATUS AND PERSPECTIVES OF TROITSK NU-MASS EXPERIMENT (2018)


Universe content
visible matter 5%
dark matter 27%
dark energy 68%

MOTIVATION

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

THE SETUP

The idea

Non-zero electron neutrino mass or additional neutrino mass eigenstates changes the shape of (tritium) electron beta-spectrum:

$$T_2 \rightarrow HeT^+ + e^- + \overline{\nu}$$

The dependency of electron spectrum shape on neutrino mass is the following:

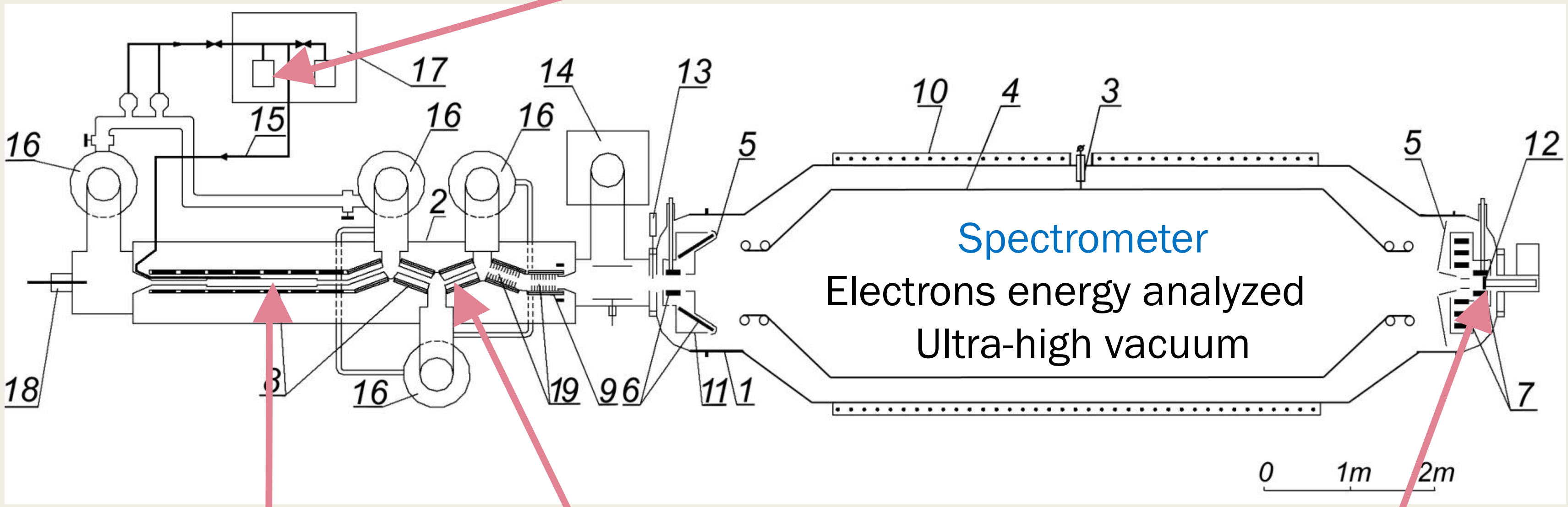
$$S \sim \sqrt{1 - \frac{m_\nu^2}{(E_0 - E)^2}}$$

Where E_0 is beta-spectrum endpoint (without neutrino mass).

The setup

Circulation system

Pumped tritium is injected back into the system



"Tritium tube"

Tritium decays here

Transport system

Electrons transported but tritium pumped out

Detector

Electrons are registered and counted

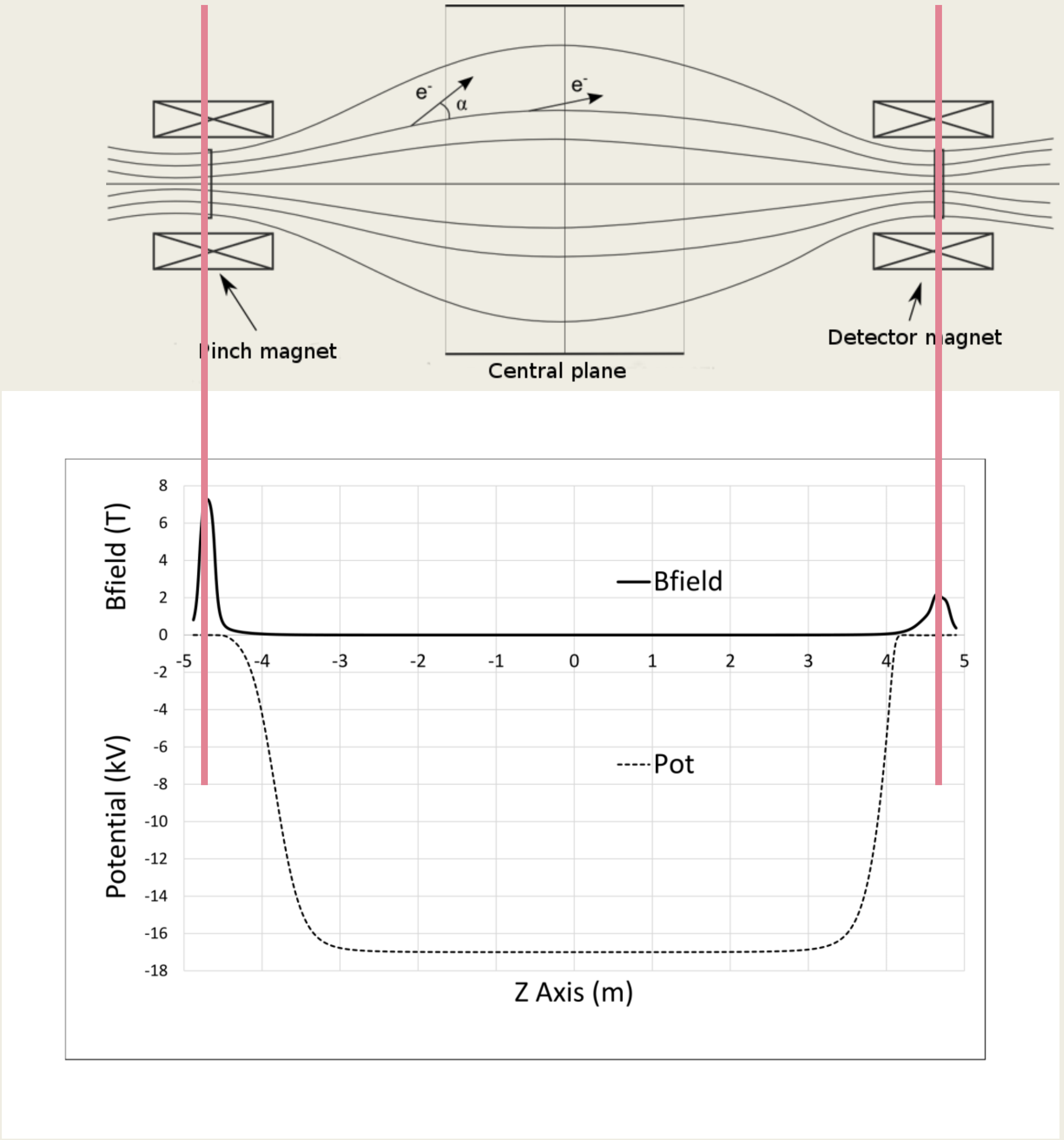
Adiabatic invariant

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

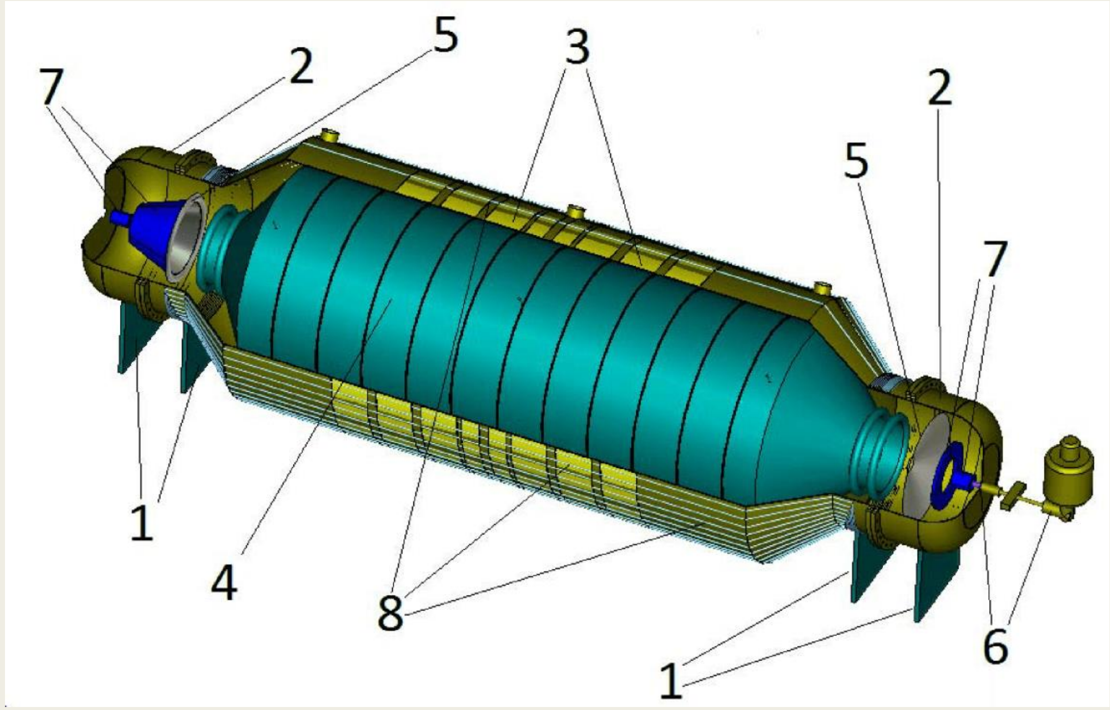
$$B_\parallel \cdot S = const$$

$$\frac{T_\perp}{T} = \frac{\Delta T}{T} = \frac{B}{B_P}$$

Electric field affects only $T_\parallel$



The spectrometer



1- supports,
2 – side cups,
3 – axial winding,
4 – main high voltage electrode,
5 – additional ground electrodes,
6 – detector with liquid N2 Dewar vessel,
7 - superconducting solenoids,
8 – correction coils

Timeline

1985 – start of the experiment

1994 – start of data acquisition

2002 – data acquisition complete

2003-2005 – Krypton measurements

2005-2010 – spectrometer upgrade

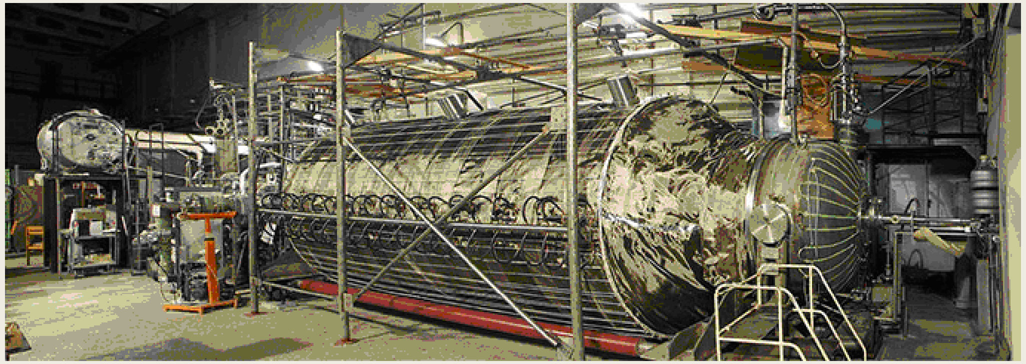
2011 – publication of final results for electron neutrino (arXiv:1108.5034)

2012 – start of sterile neutrino program

2015 – first measurements on sterile neutrino program (arXiv:1504.00544)

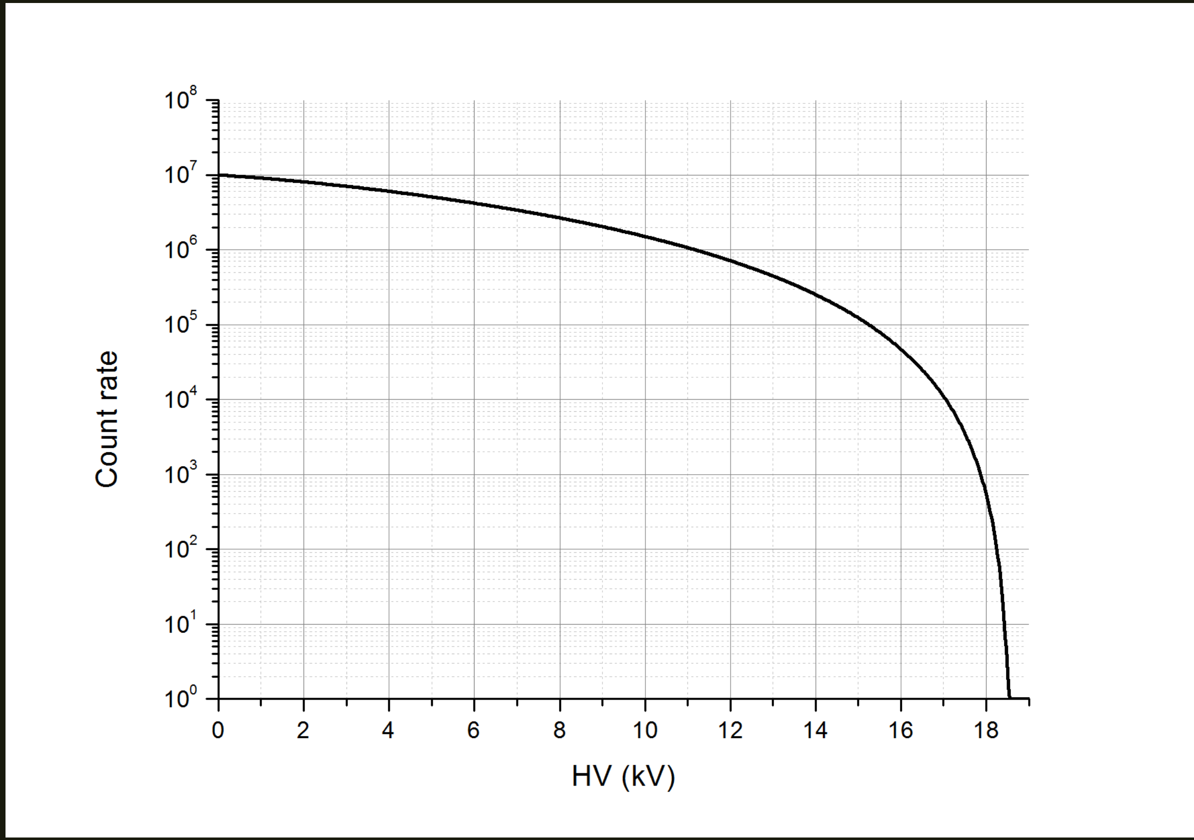
2018 – first full-scale measurement with TRISTAN detector prototype

Old spectrometer



New spectrometer

THE SPECTRUM



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:

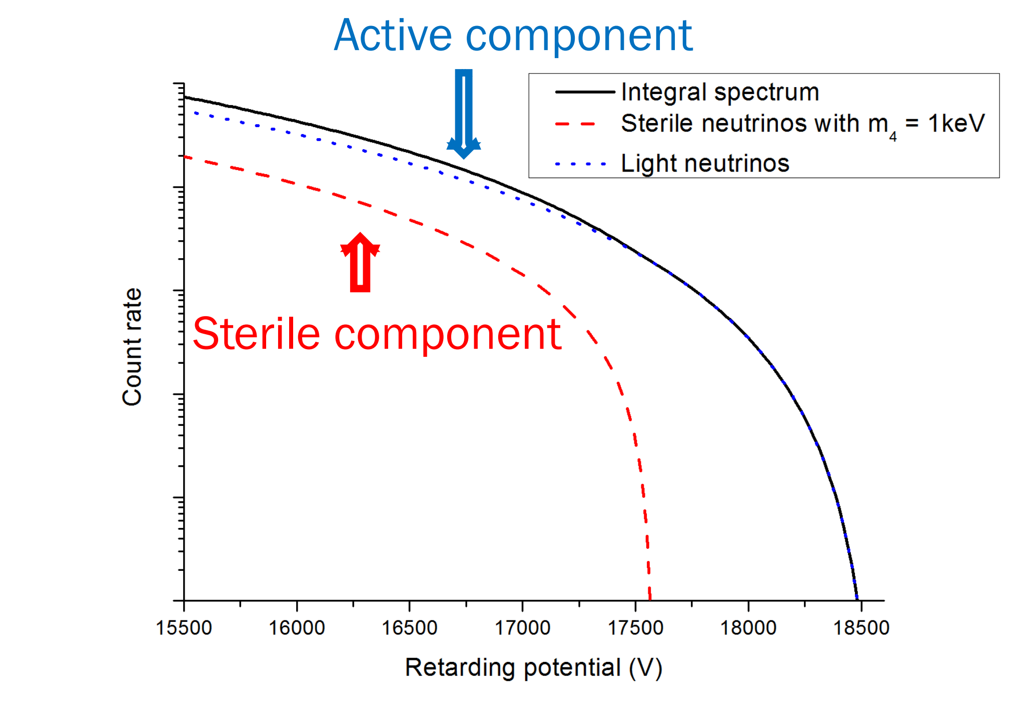
$$S(E, E_0, m_\nu) = \sum N(E, E_0 - E_i, m_\nu) \cdot P_i$$

A search for sterile neutrino

$$S(E) = U_{ex}^2 S(E, m_x) + (1 - U_{ex}^2) S(E, 0) \qquad |\nu_\alpha> = \sum U_{\alpha i} |\nu_i>$$

- One can add additional neutrino components in mixture.
- Tritium beta decay could provide information about mass region up to 10 keV
- (warm dark matter?).

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 or rear wall backscattering

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

Spectrum shape: resolution

The full resolution width:

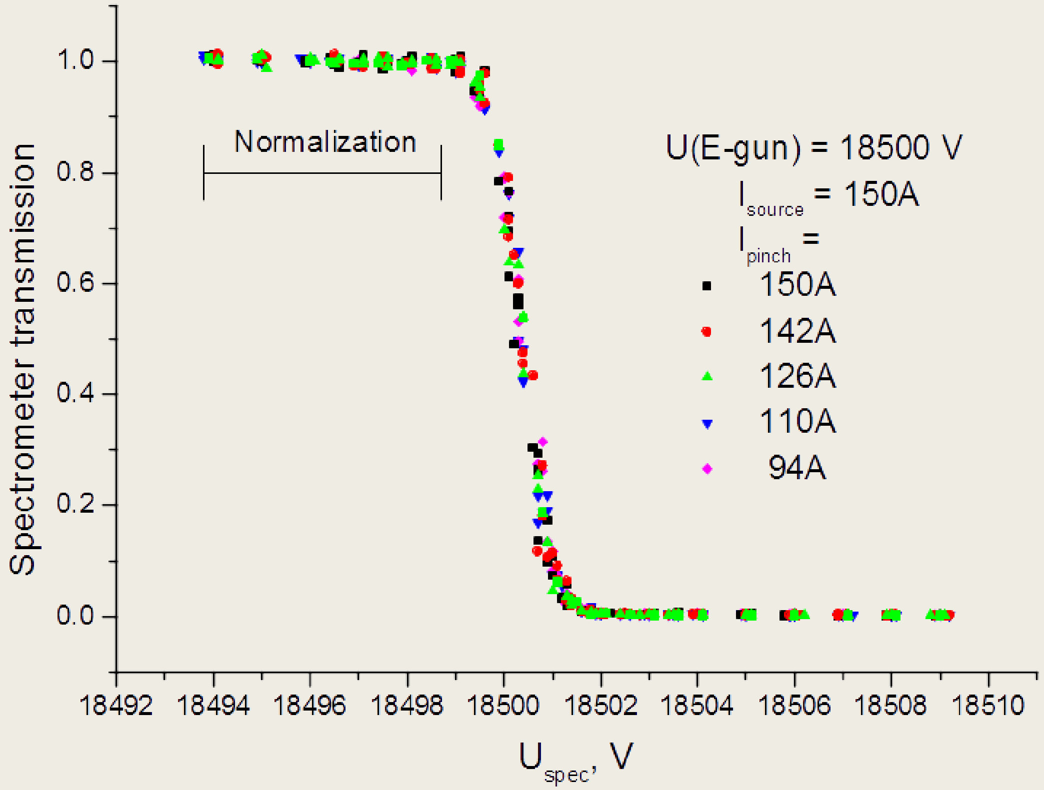
$$\frac{\Delta E}{E} = \frac{B_A}{B_P} = 8 \cdot 10^{-5}$$

The shape is nearly triangular, therefore

$$\frac{\sigma_E}{E} = 2.3 \cdot 10^{-5}$$

$$\sigma_E(E = 18500\ eV) = 0.43\ eV$$

Could be additionally improved with "super-resolution" mode.



SYSTEMATICS

Systematics

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

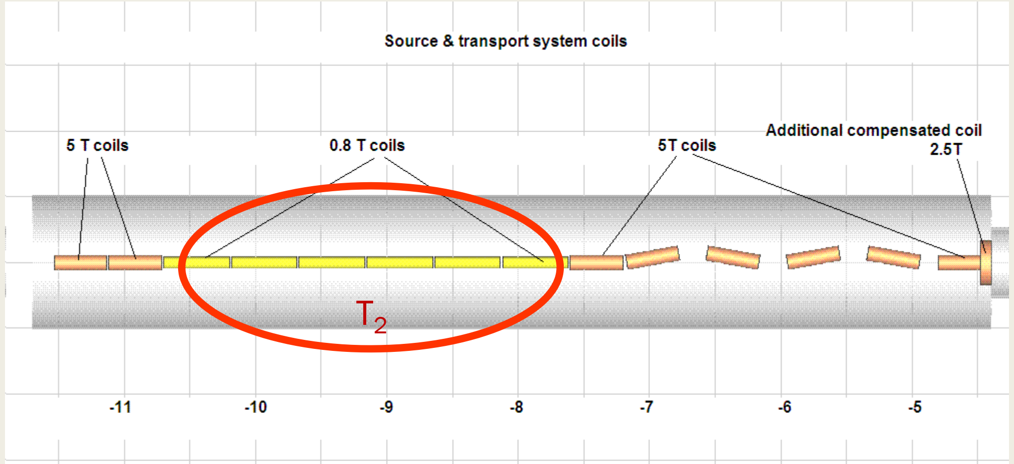
Very important!

Not very important at the moment for now

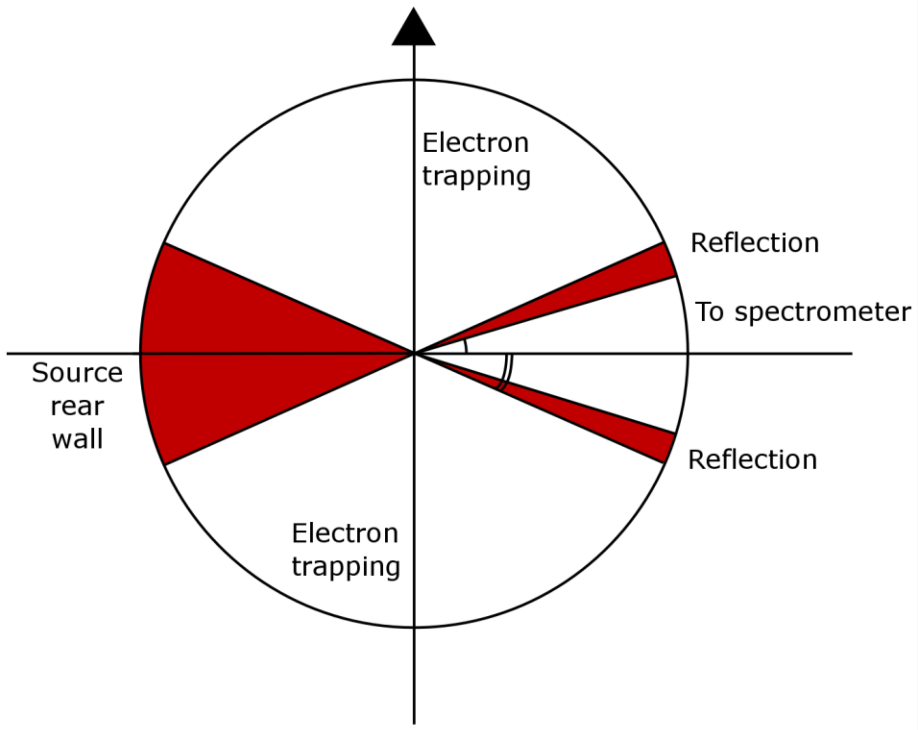
See details in https://arxiv.org/abs/1504.00544

Trapping: basics

Field configuration in tritium source forms
a bottle – magnetic Trap

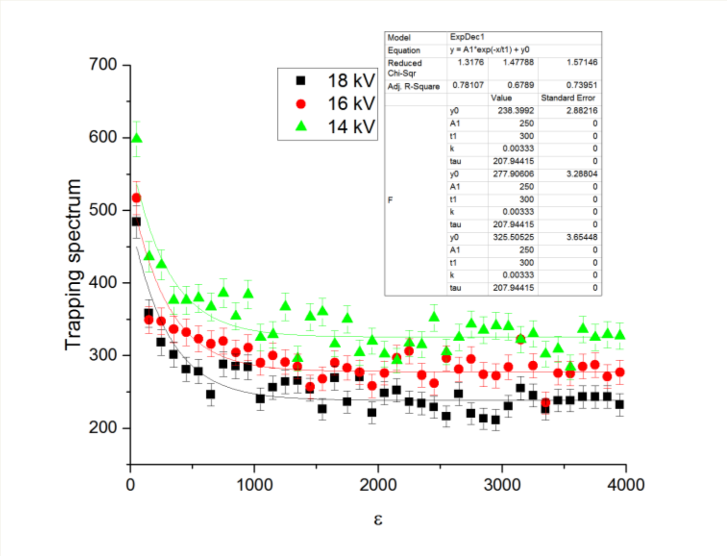


Trapped electrons can run back and forth up to thousand times passing few kilometers

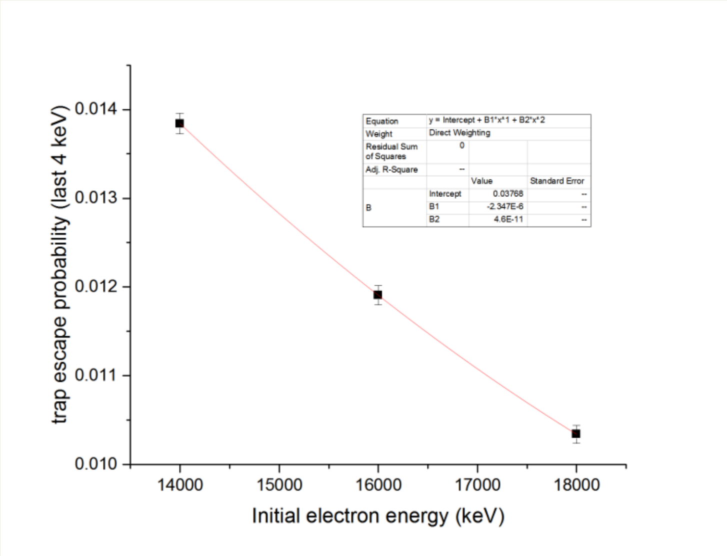


Trapped electrons distort the actual β-spectrum

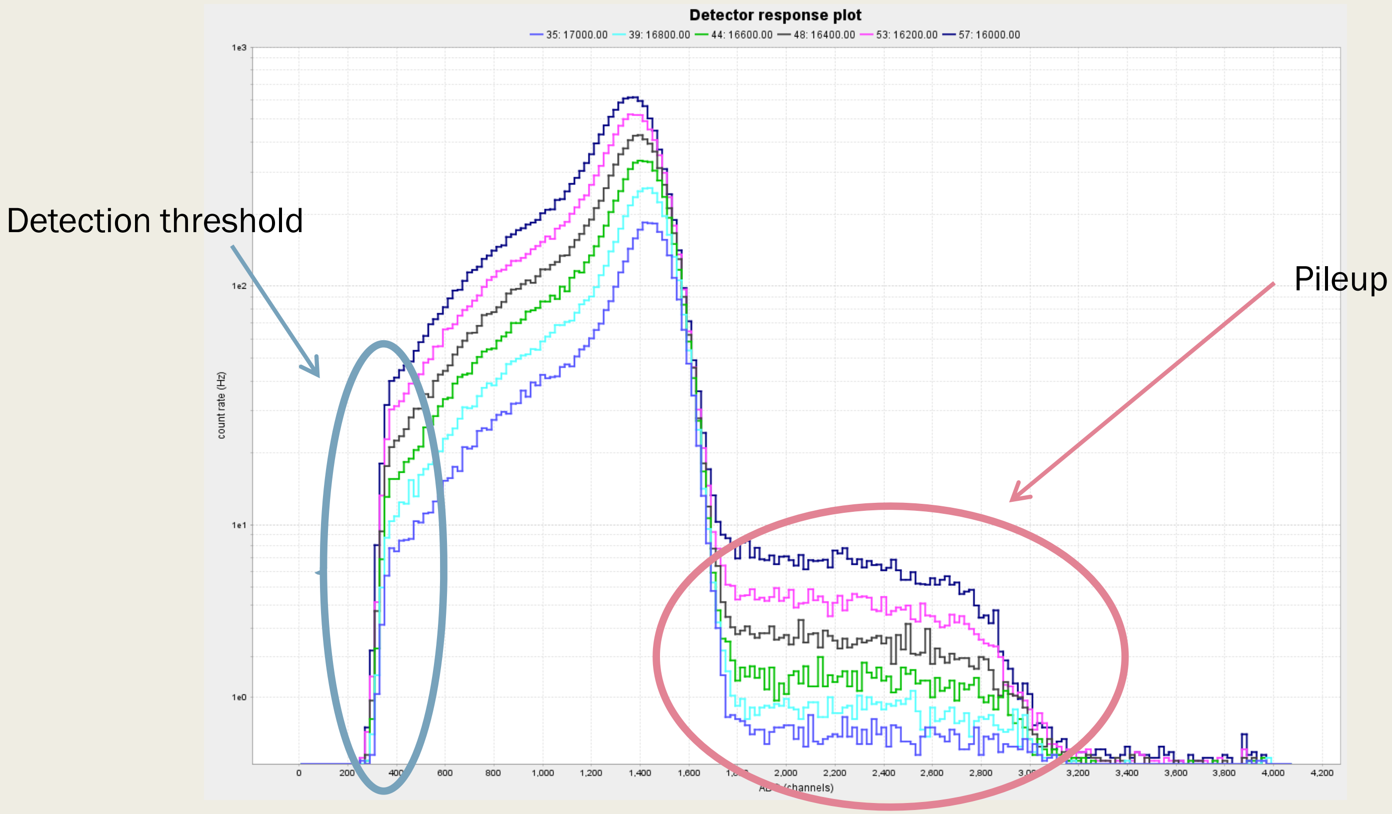
Simulation



Energy dependence



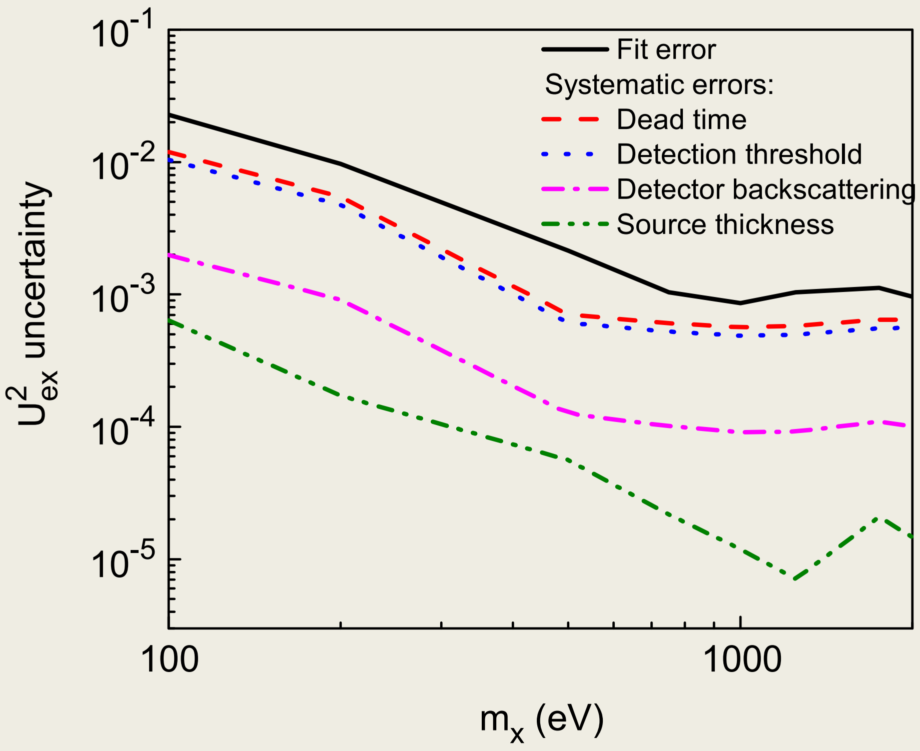
Amplitude spectrum



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

RESULTS AND PERSPECTIVES

Current results



One experiment ran with enhanced intensity

Systematic errors:

- DAQ dead time and pileup
- Events under detection threshold
- Backscattering from detector (arXiv:1603.04243)
- Interaction in the source.

JETP Lett. 105 (2017) no.12, 753-757
DOI: 10.1134/S0021364017120013

Current results

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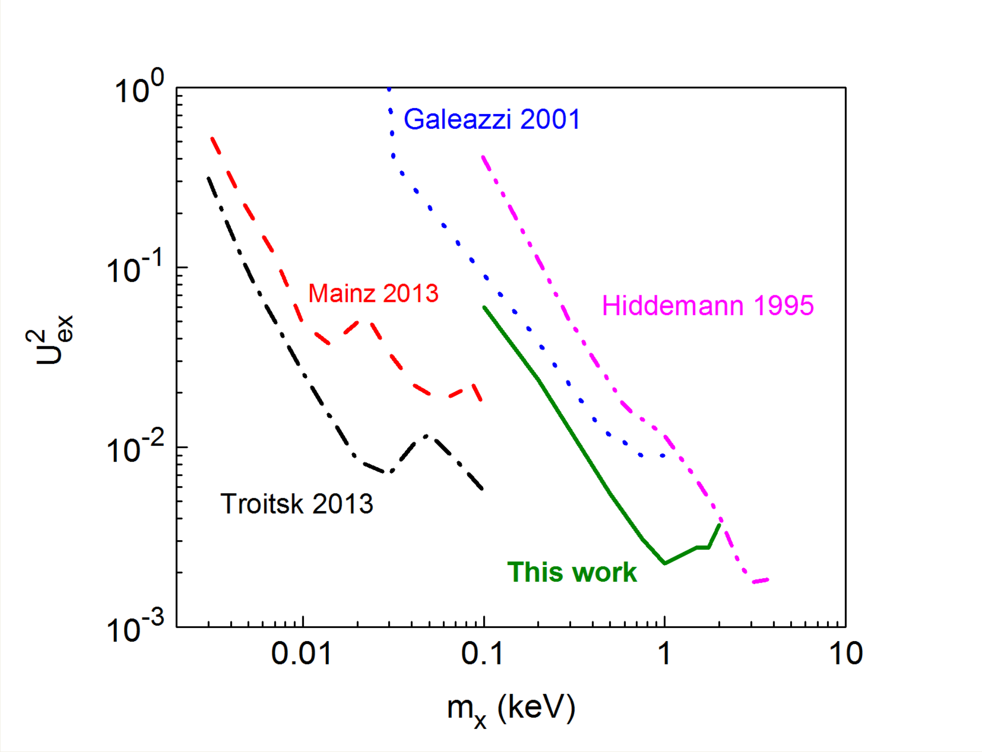
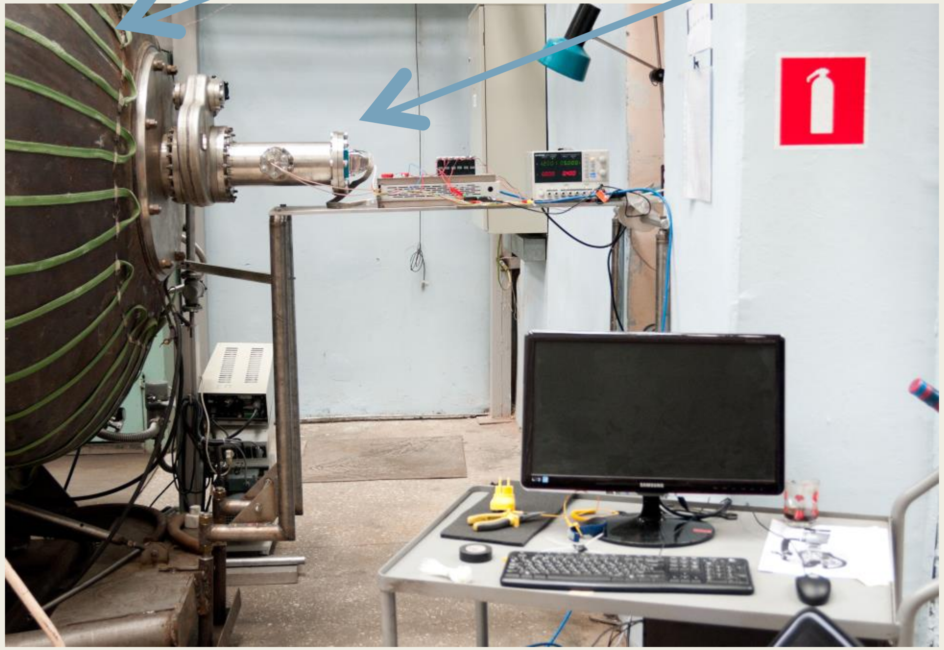


95 % Confidence Level (sensitivity limit) on mixing matrix element

Joint effort with TRISTAN project

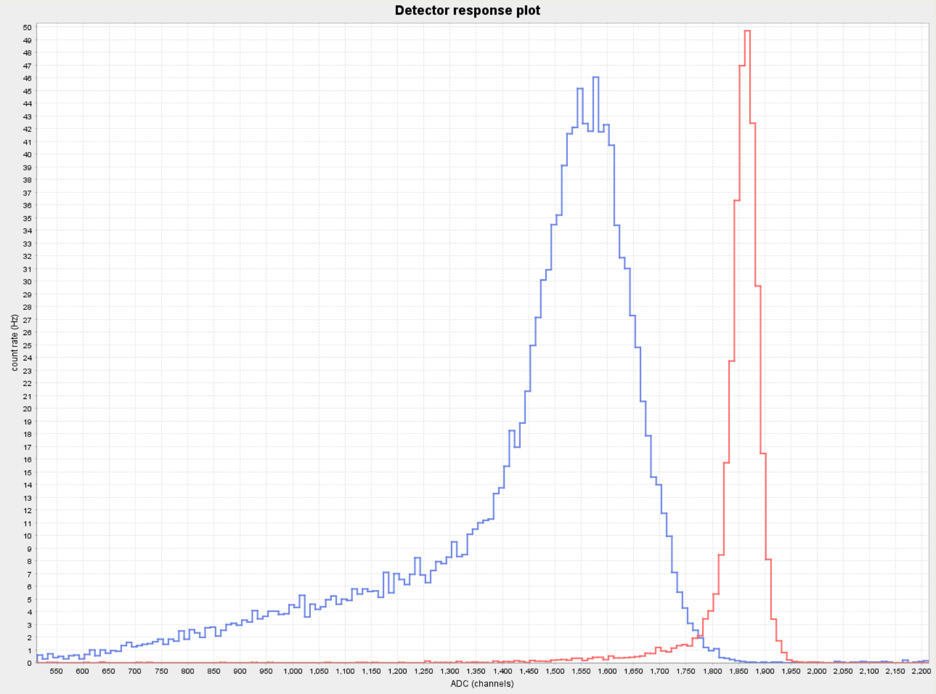
Troitsk nu-mass spectrometer

TRISTAN detector prototype



Since 2017 Troitsk nu-mass joined effort with TRISTAN project at MPI Munich.

Improvement with silicon drift detector



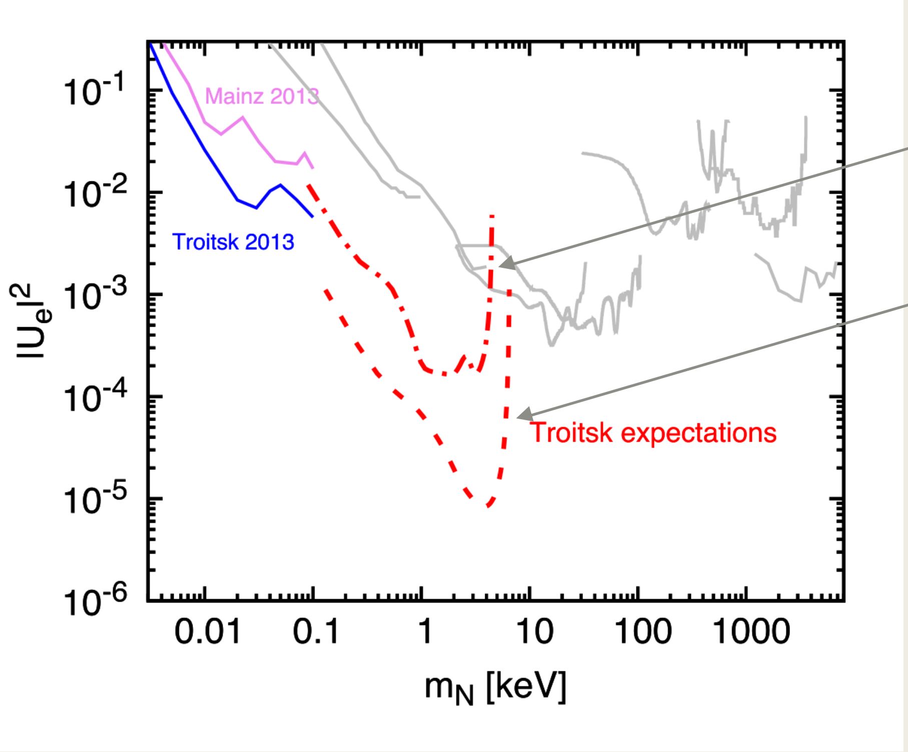
- Multi-pixel detector. Allows higher count rate.
- Better resolution and amplitude spectrum shape
- Controlled back-scattering conditions.
- Modern read-out and on-site preprocessing.

Thank you for your attention

Trotisk nu-mass → TRISTAN in Troitsk

THE FUTURE

Expected results



Currently possible

Best case scenario

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.*

Compact source

Sterile neutrino measurements do not require “large” source.

Old Troitsk nu-mass source is outdated and is very hard to maintain.

Solution: compact multi-purpose volume for different radioactive sources as well as e-gun measurements.

Problem: manpower.

Graphene infused source

Why make graphene infused radioactive source?

- Very high chemical bounding energy (no desorption).
- Very uniform surface.
- Conductor (no substrate charging).
- Mechanical durability (easy to cool down and heat up).
- Industrial availability (200$ per sample)

Electron capture instead of beta-decay

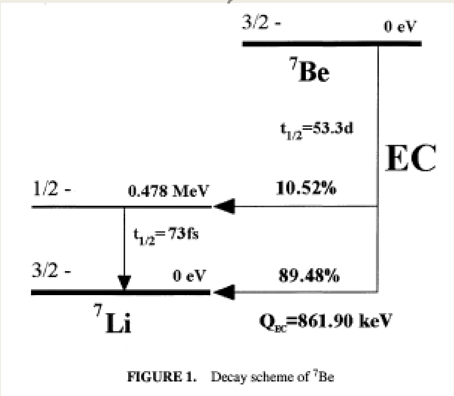
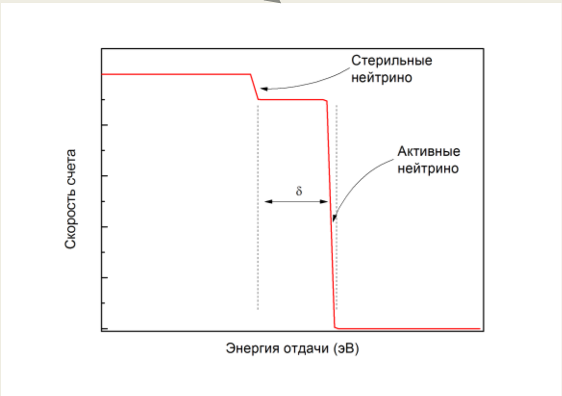
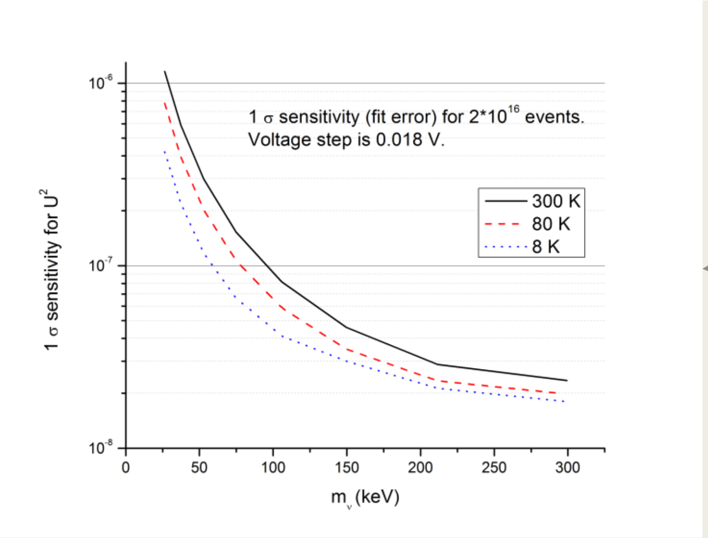


FIGURE 1. Decay scheme of ^{7}Be

$$Be \rightarrow Li + \nu$$

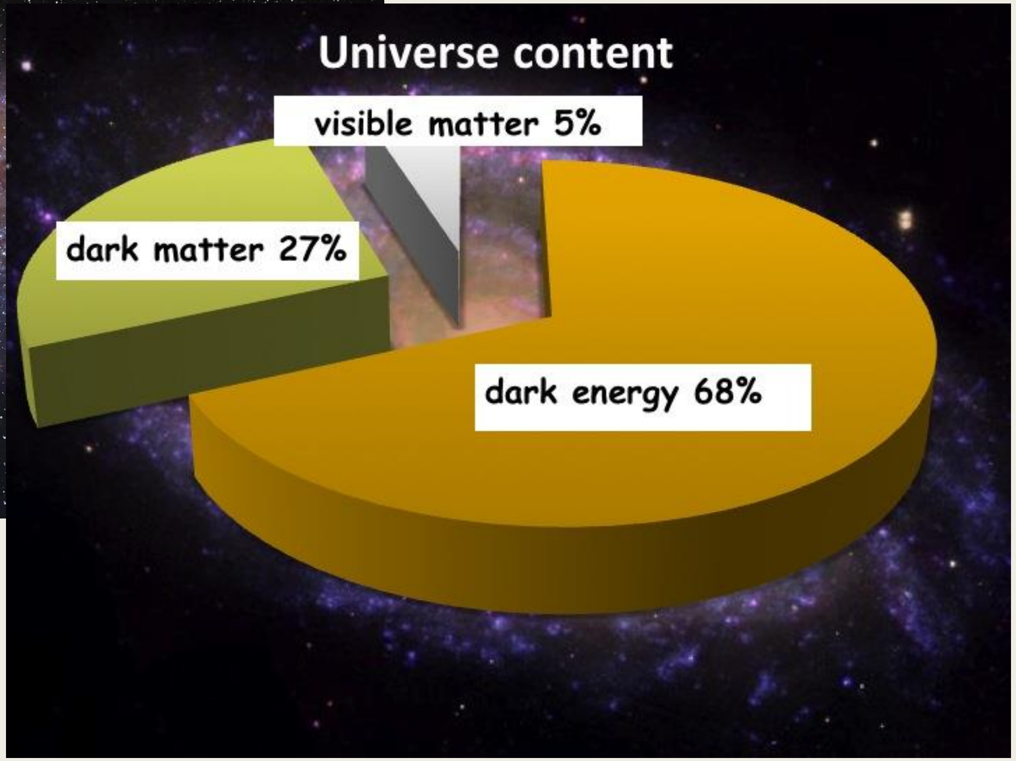




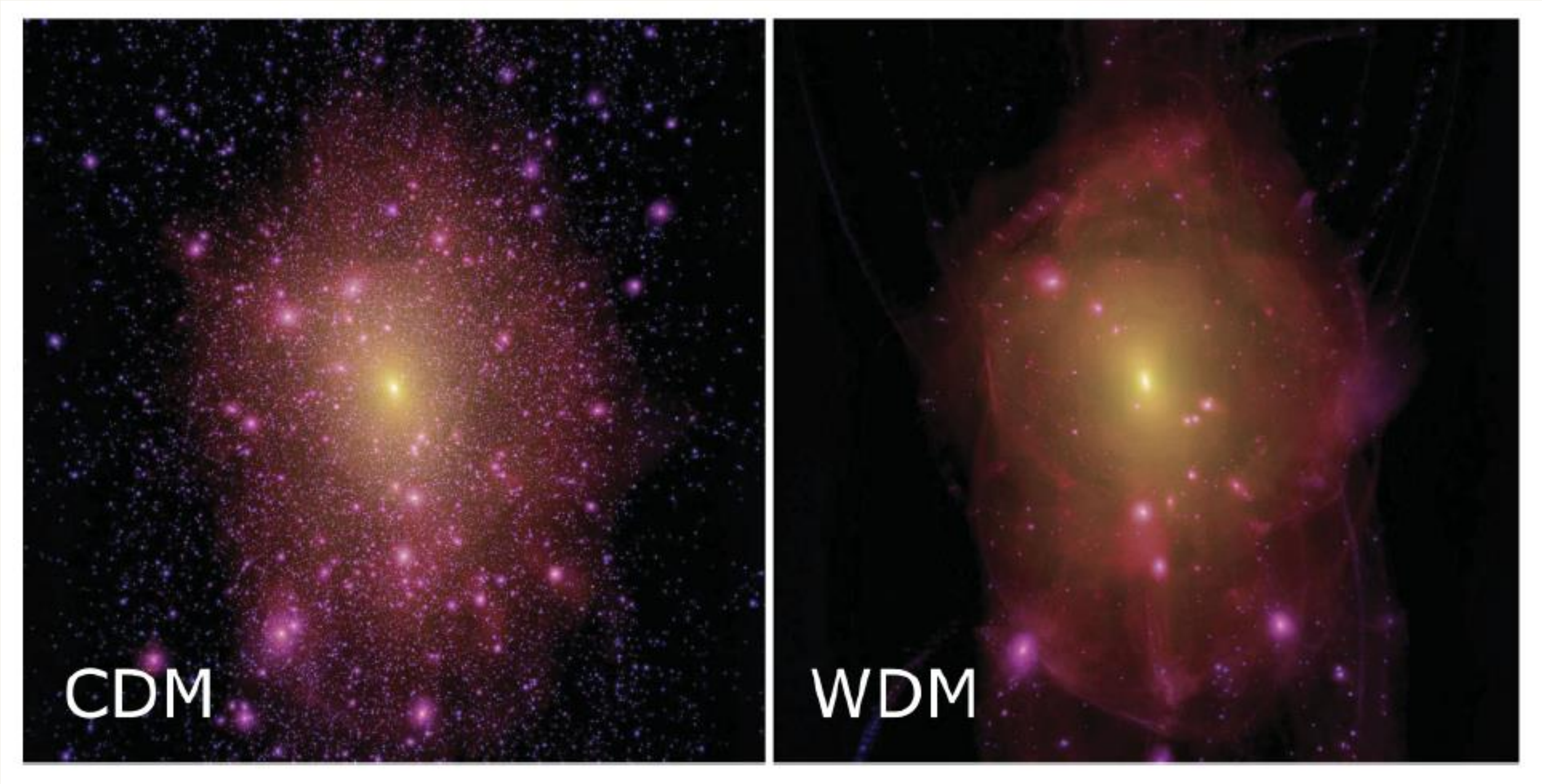
ADDITIONAL SLIDES

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**

Transmission: loss function

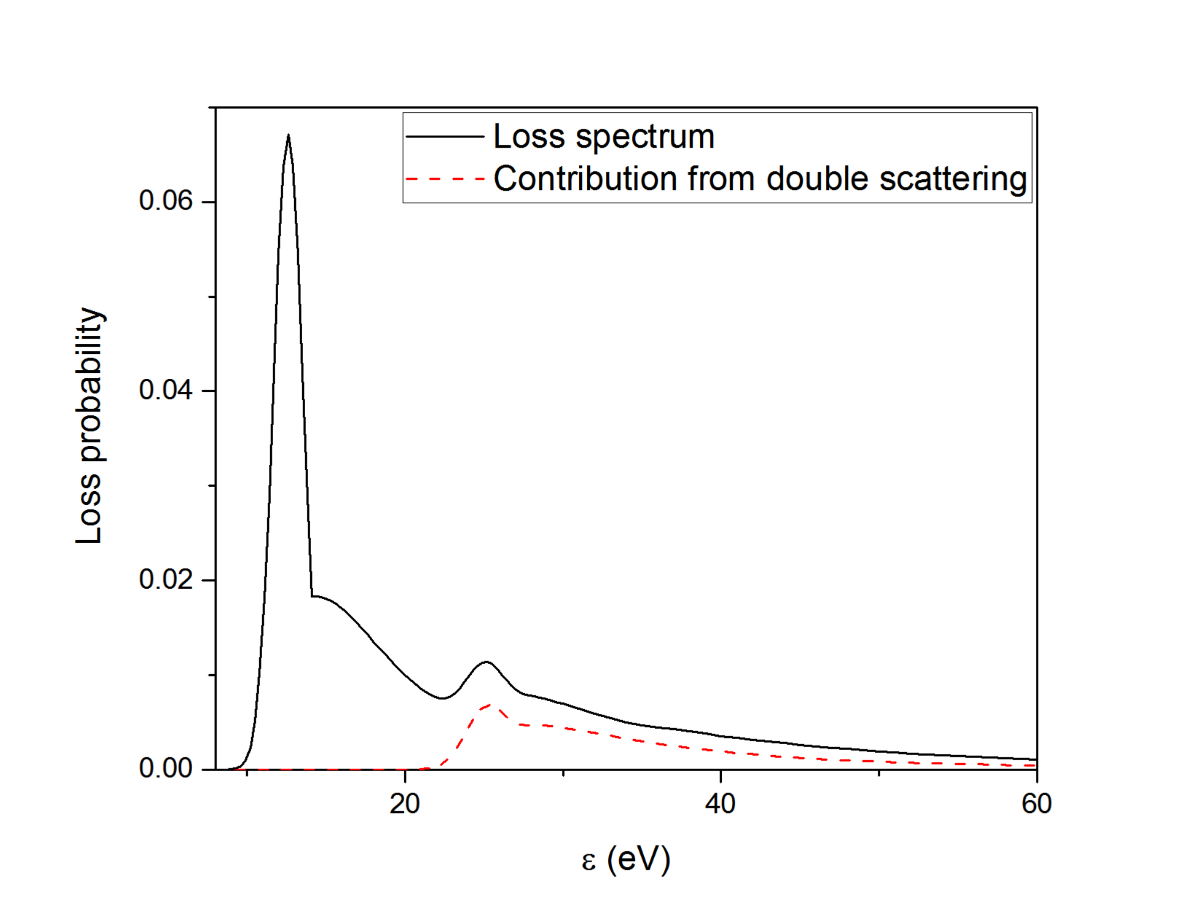
$$\varepsilon = E_{in} - E_{out}$$

X depends on E_{in}

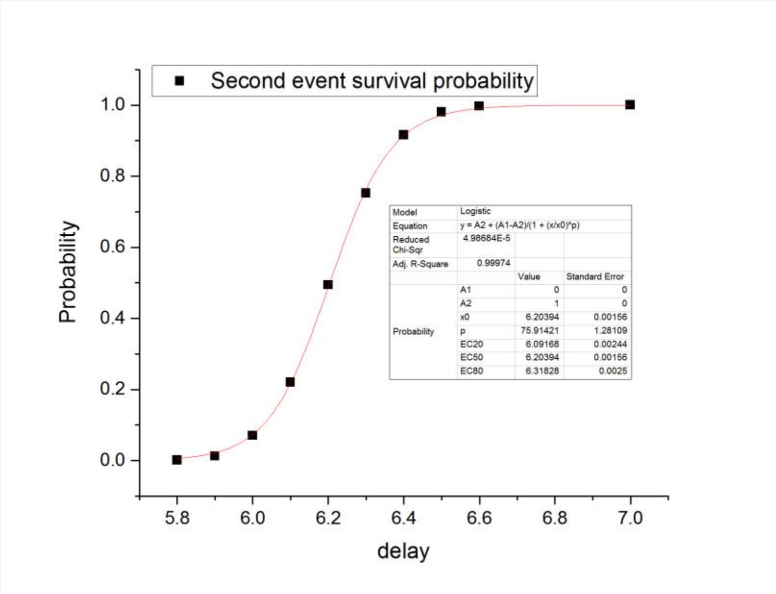
$$L_{i+1} = L_i \otimes L_1$$

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

Any effect with smoother ε dependency contributes to ???

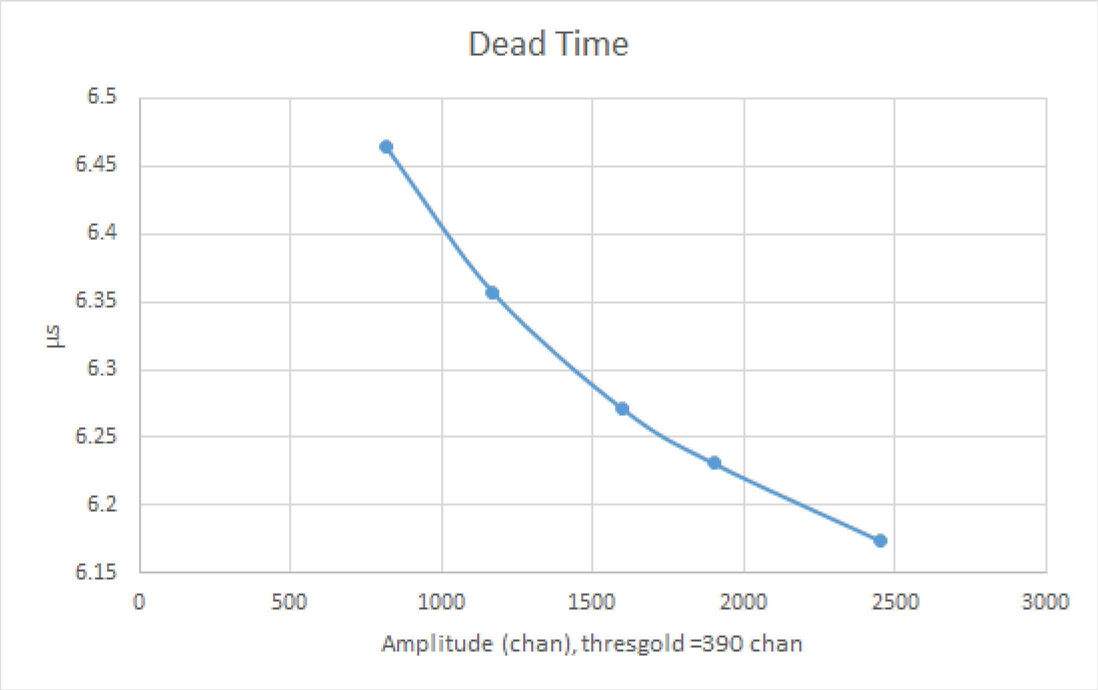


Dead time

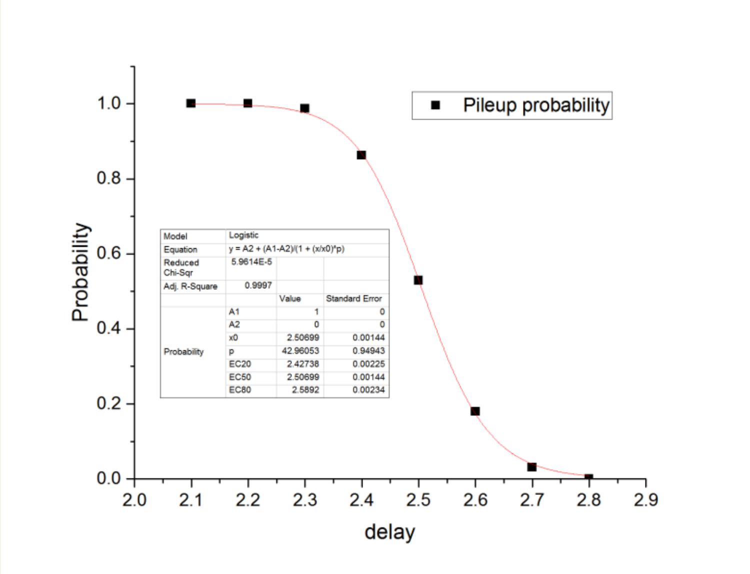


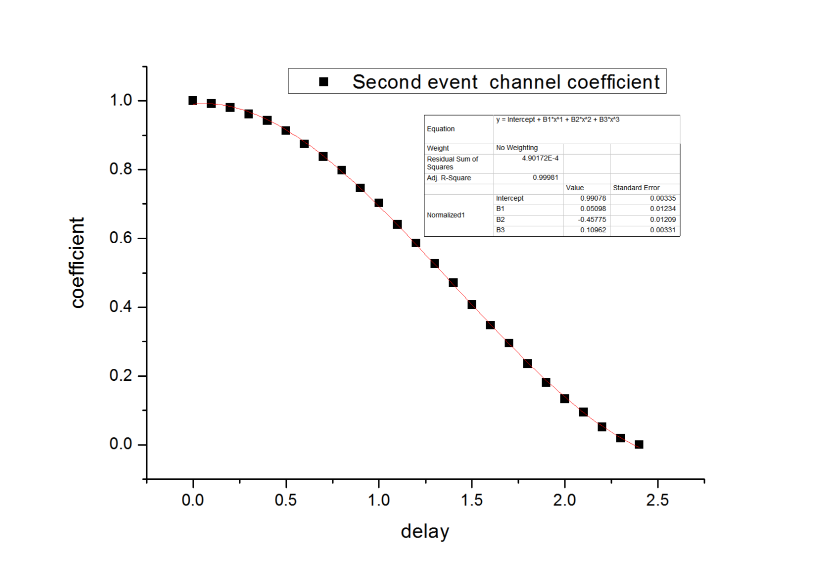
Dead time calibration by pulser and two delayed signals

Dead time amplitude dependence



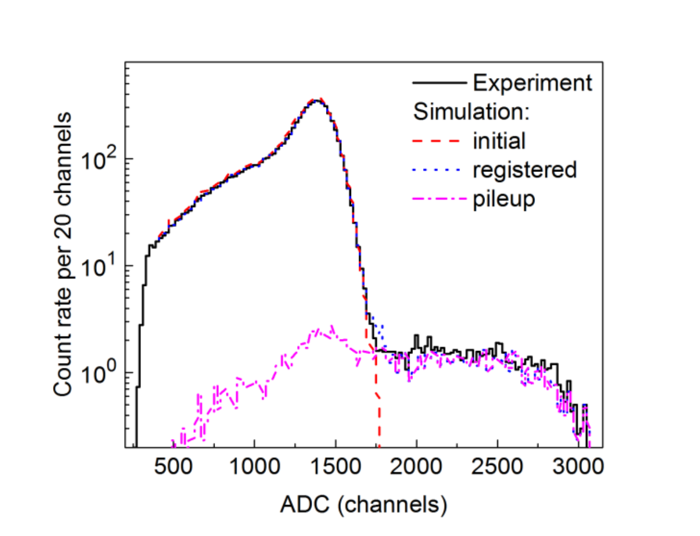
Pileup



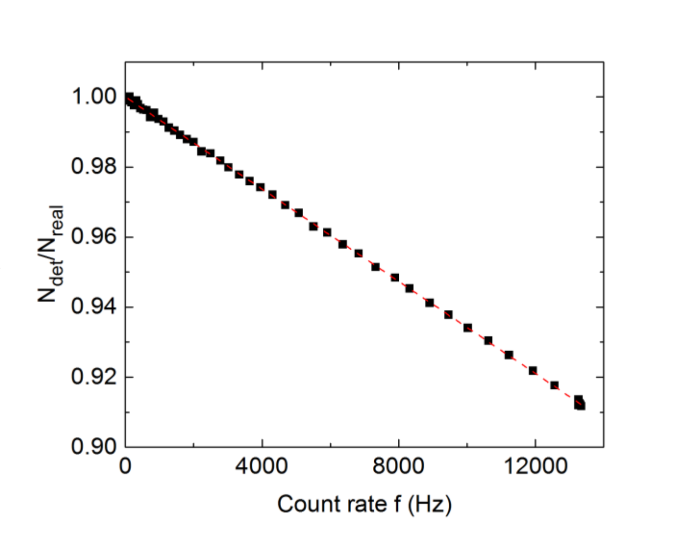


Pileup time calibration by pulser and two delayed signals

Pileup in real Tritium spectrum

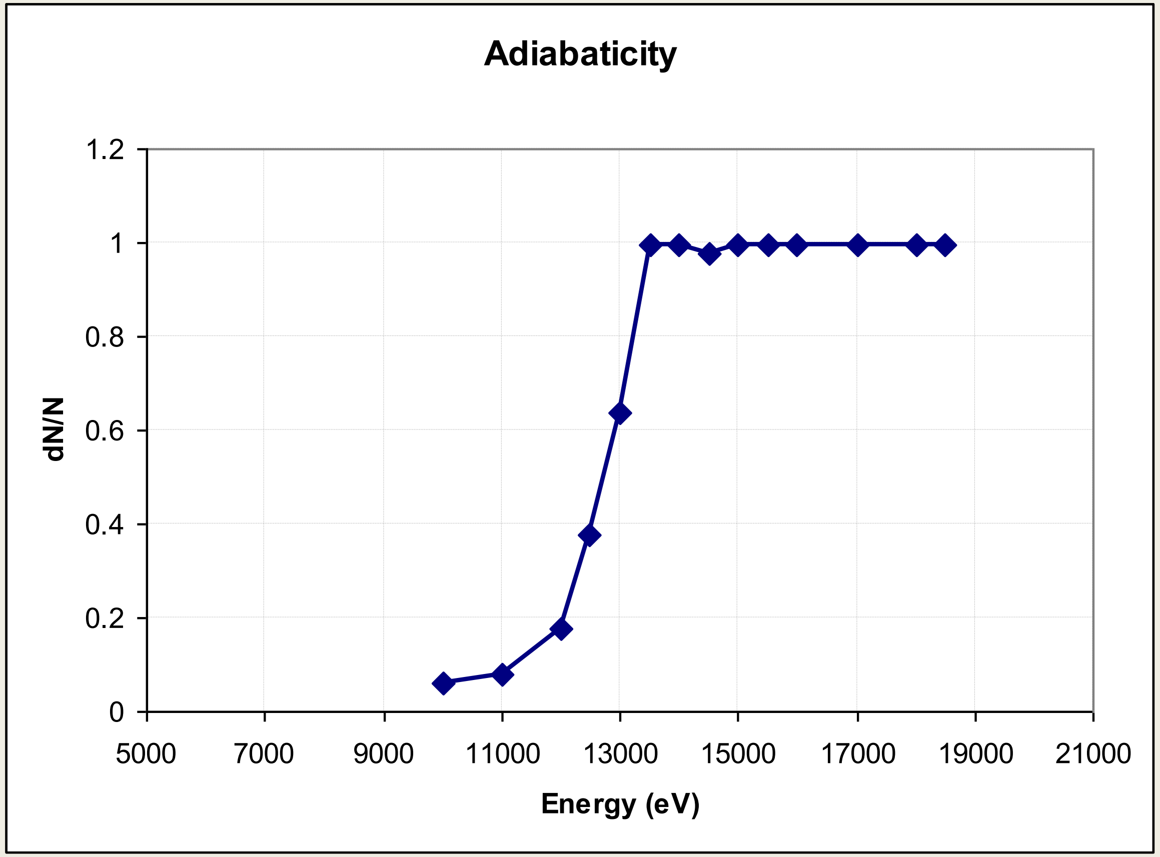


Monte-Carlo simulation using real spectrum and pulser calibration



Life time versus measured count rate

Adiabaticity violation



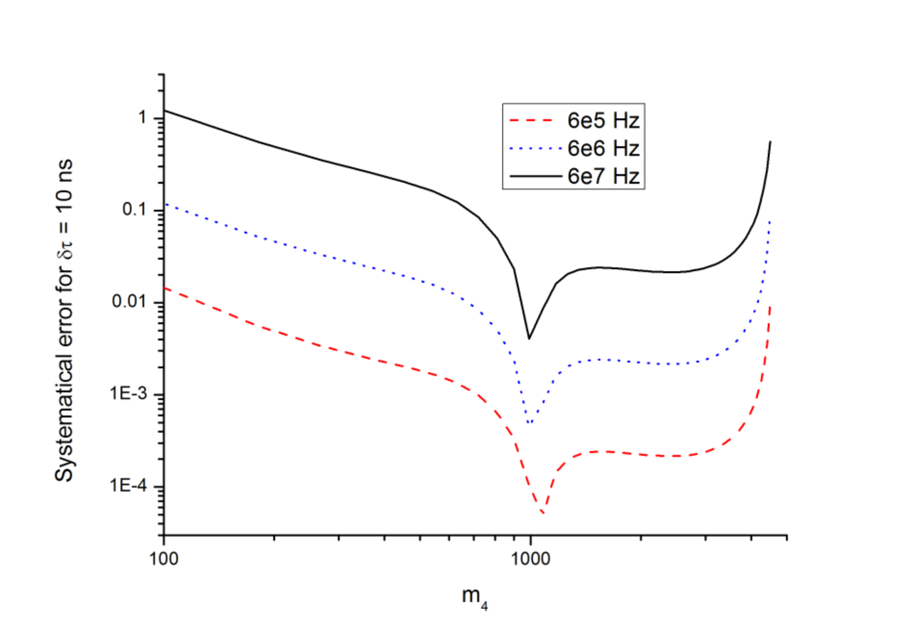
Simulation: Adiabaticity is not violated above 13.5 kV

Systematics: dead time

The correction factor:

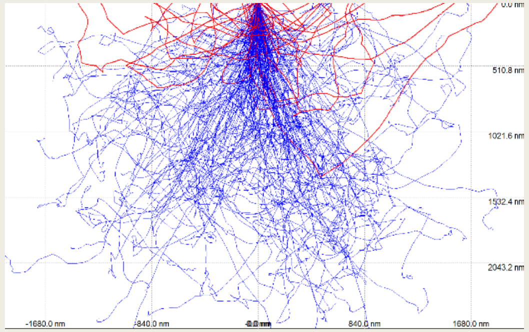
$$N = N_0\left(1 - N_0\frac{\tau}{T}\right)$$

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



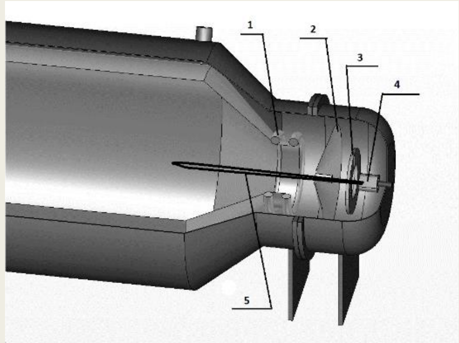
P.S. We wish to switch to completely new readout with continues signal digitization in upcoming run in May 2017

Detector backscattering

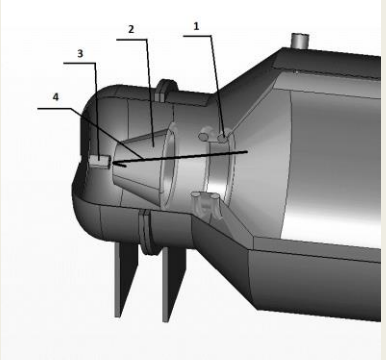


Up to 20% electrons scatter back from Si-detector.
CASINO simulation

NIM A832 (2016) 15
arXiv:1511.06129



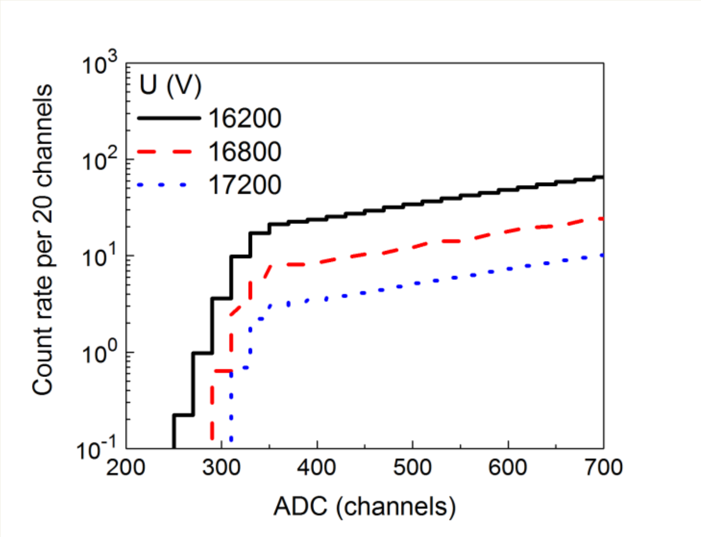
Electrostatic mirror



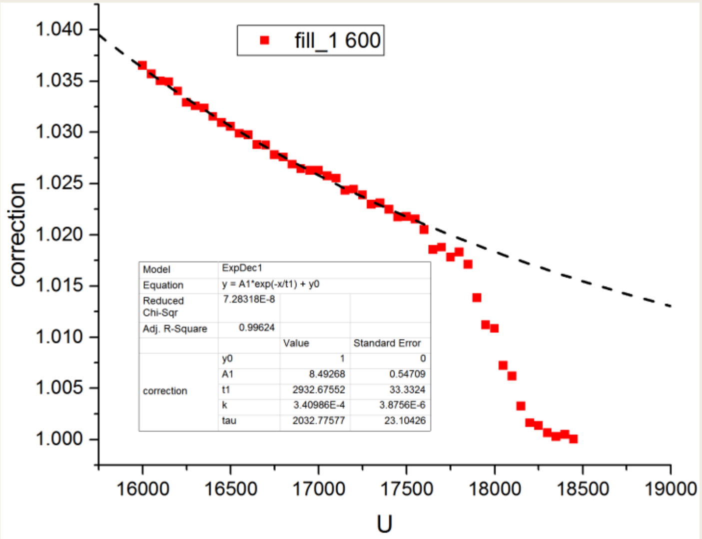
Magnetictic mirror

Detector threshold

Spectrum shape near cutoff point



The estimated correction factor vs. U_sp



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

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

Detector backscattering: experimental

Count rate for 25 keV electrons vs spectrometer retarding potential