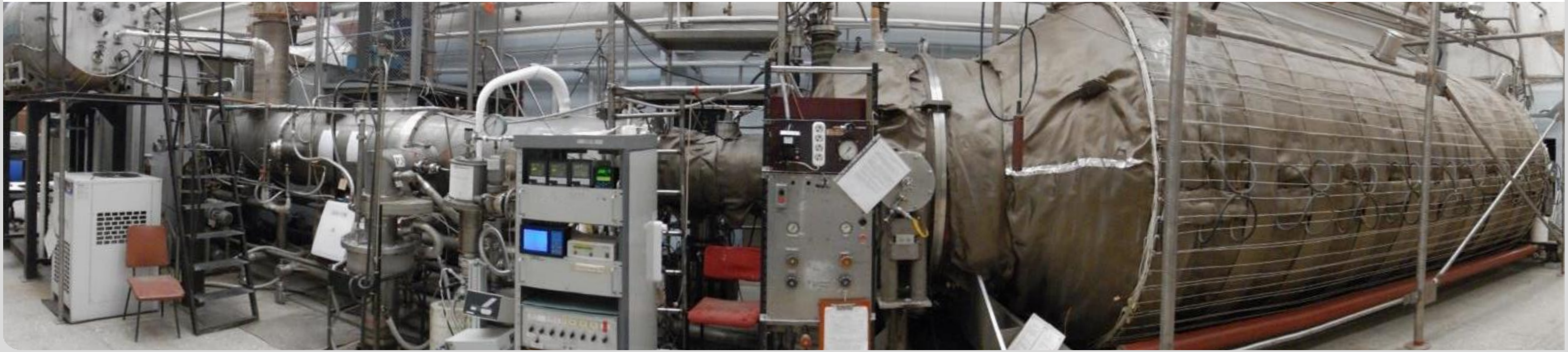
# TRISTAN measurements
# at the Troitsk nu-mass experiment

**Tim Brunst**, IMPRS Young Scientist Workshop at Ringberg Castle, September 8th 2018



# Troitsk impressions

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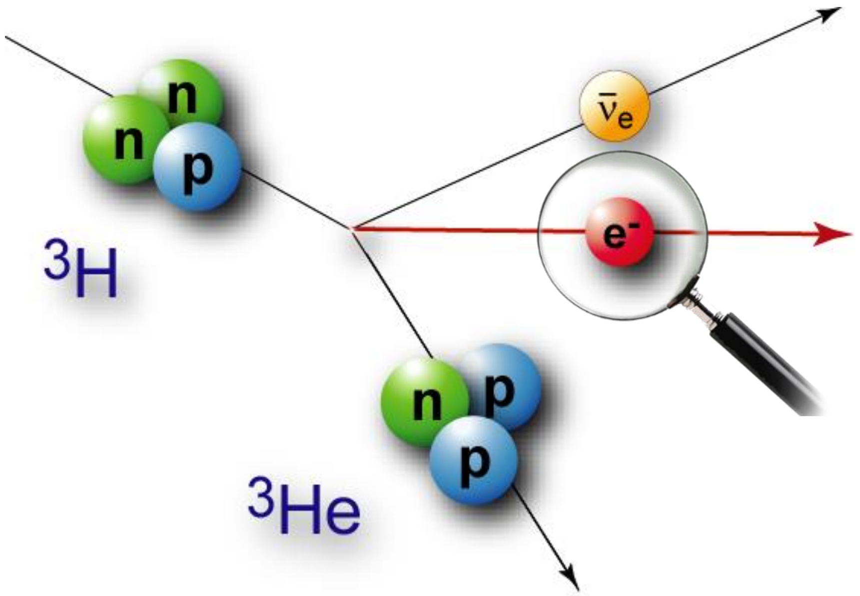
Troitsk 1: May 2017 | Troitsk 2: November 2017 | Troitsk 3: April 2018

# Outline

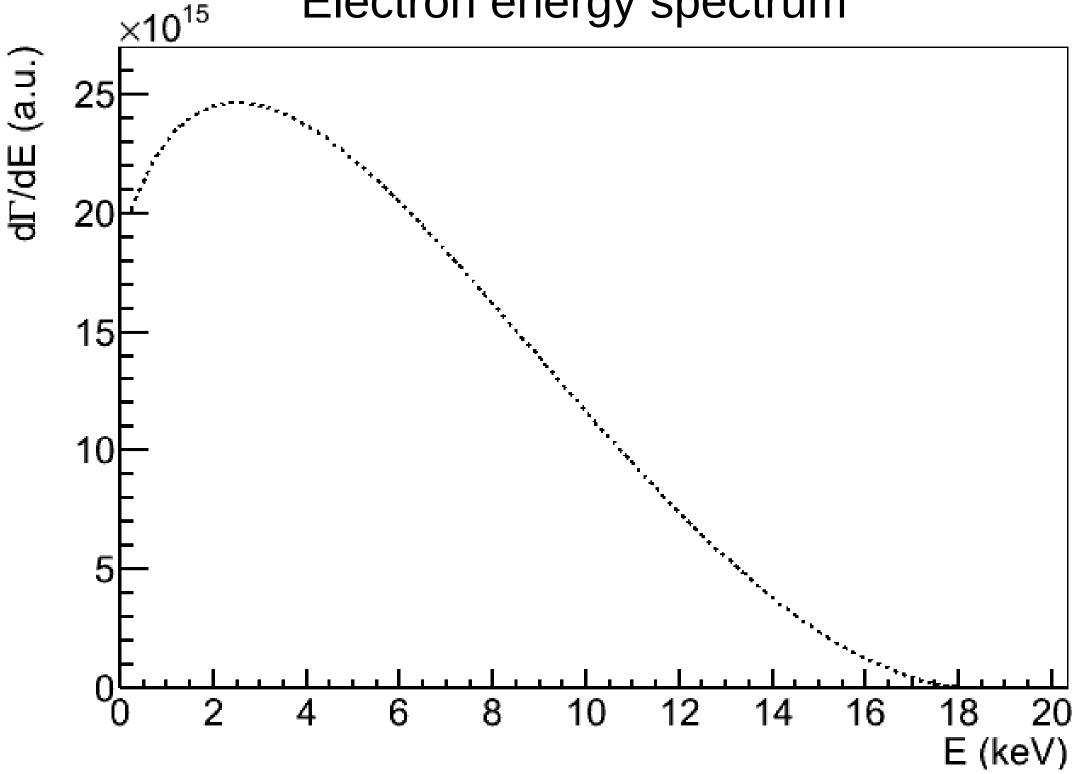
- $\nu$'s in the tritium ß-spectrum
- Troitsk measurements
- Integral analysis
- Summary & Outlook

# Imprint of ν's on tritium ß-spectrum

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} \propto C\, F(Z,E)\, p(E+m_\mathrm{e})(E_0-E)\sqrt{(E_0-E)^2 - m_\beta^2(\nu_\mathrm{e})}$$




Electron energy spectrum



# Imprint of ν's on tritium ß-spectrum

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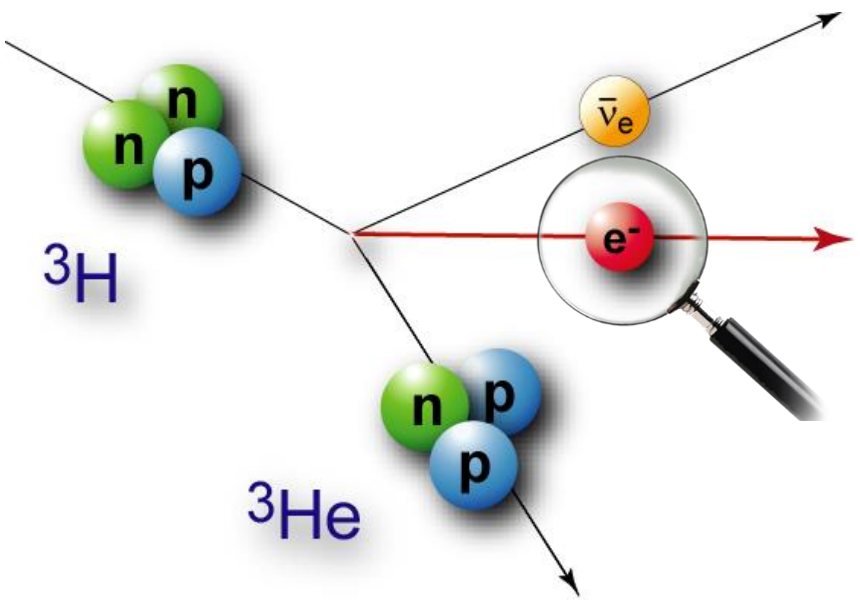
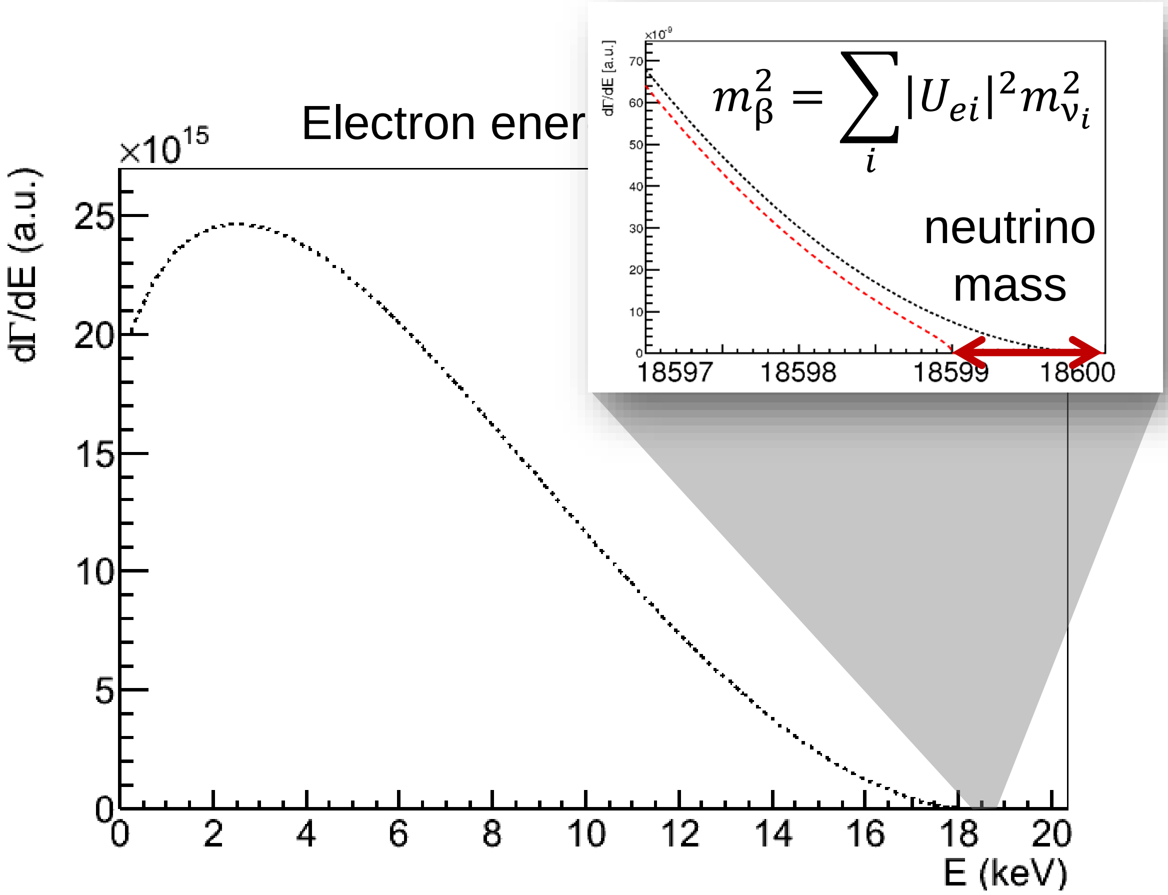


# KATRIN and TRISTAN

- The KATRIN experiment measures the neutrino mass
  - in a model-independent way
  - via ultrahigh precision measurements of the kinematics of electrons from tritium beta-decay

- What else can it be used for?

# Sterile ν's

- A sterile neutrino is a lepton with no ordinary electroweak interaction except those induced by mixing
  (JCAP 2017, 10.1088/1475-7516/2017/01/025)

- keV-scale sterile neutrinos (~ 1 - 50 keV)
  - Suitable dark matter candidate

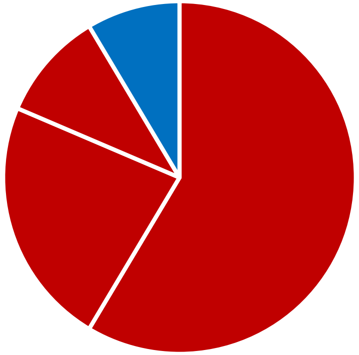

**3+1 scenario**

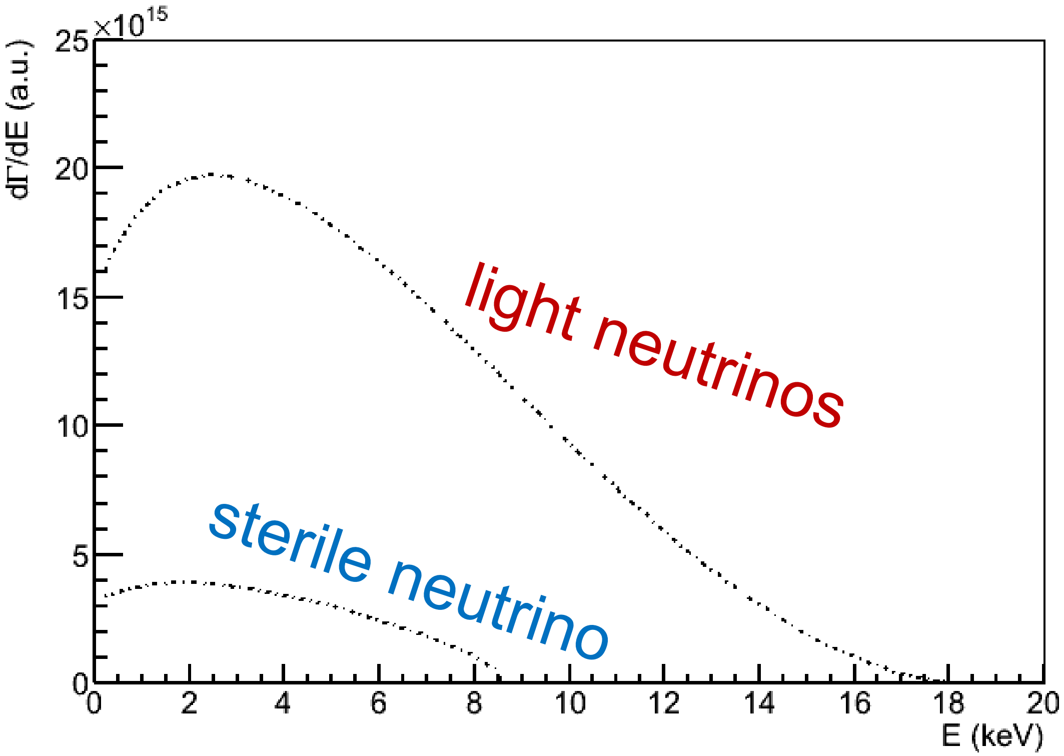
$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix}$$

# Imprint of sterile ν‘s on ß-spectrum

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} = \cos^2(\theta)\frac{\mathrm{d}\Gamma}{\mathrm{d}E}(m_\beta) + \sin^2(\theta)\frac{\mathrm{d}\Gamma}{\mathrm{d}E}(m_s)$$

$\nu_e$





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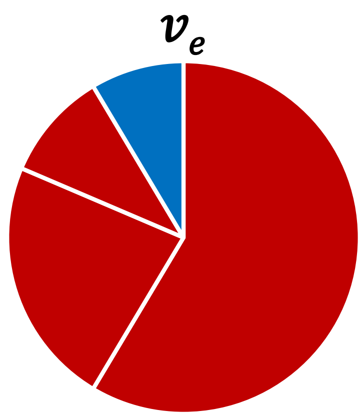


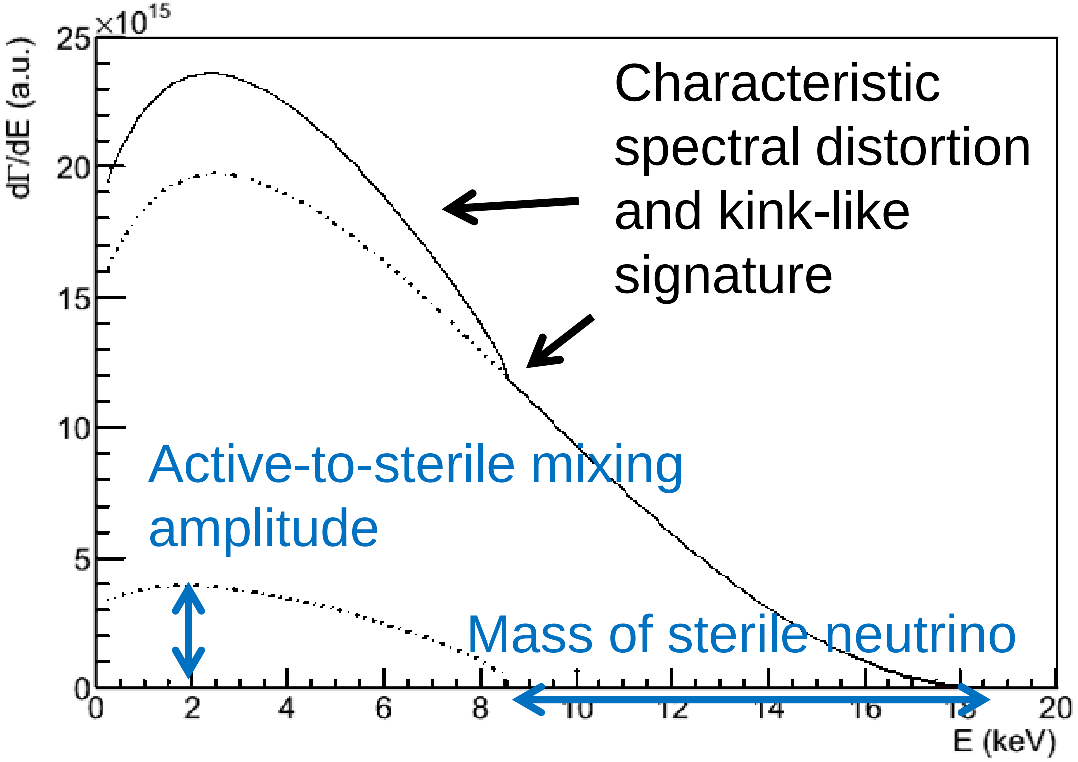

# Imprint of sterile ν's on ß-spectrum

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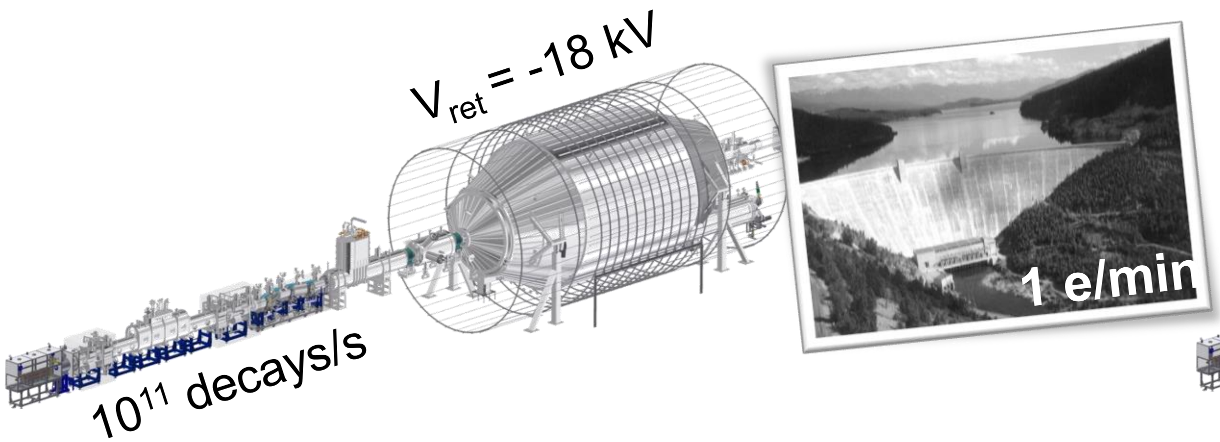
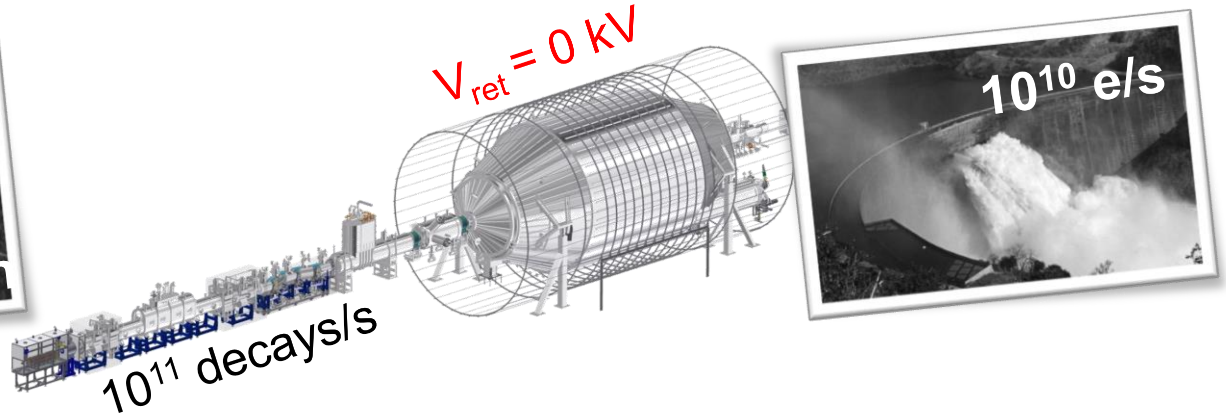
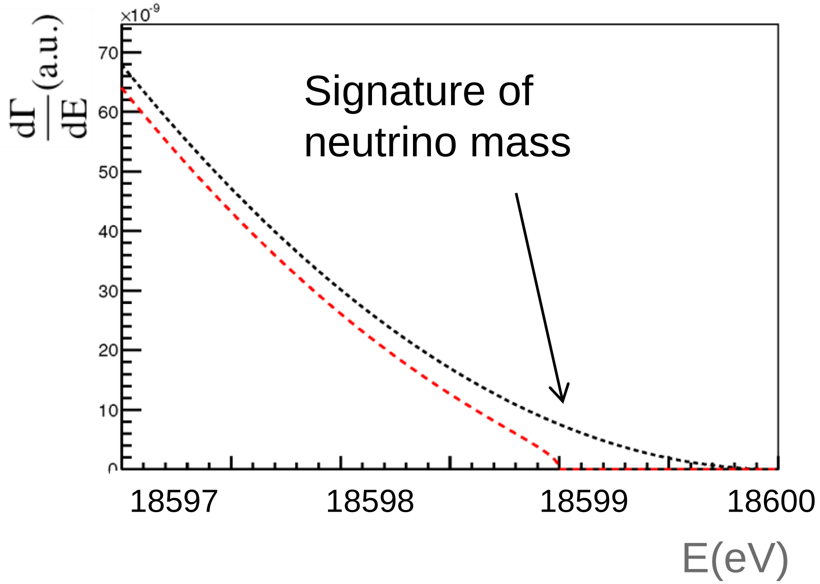
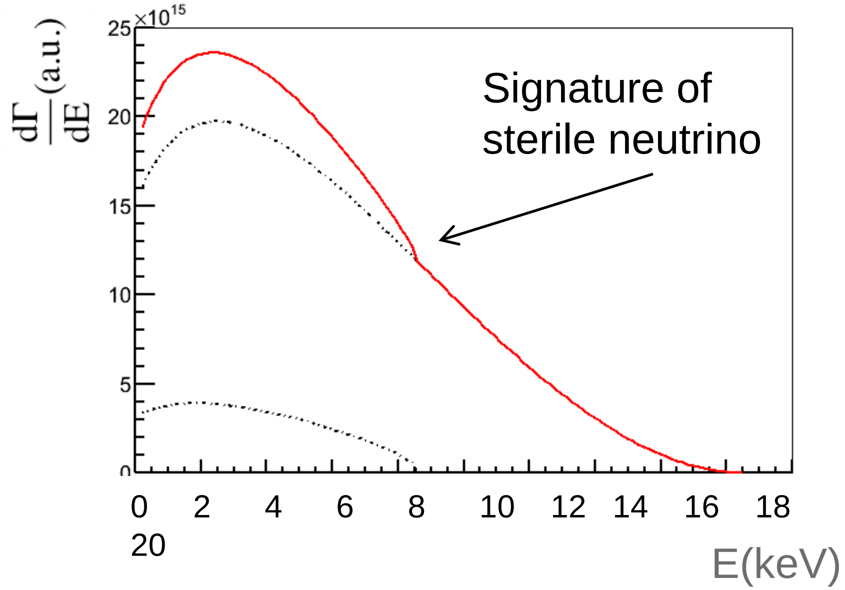
(Werner-Heisenberg-Institut)



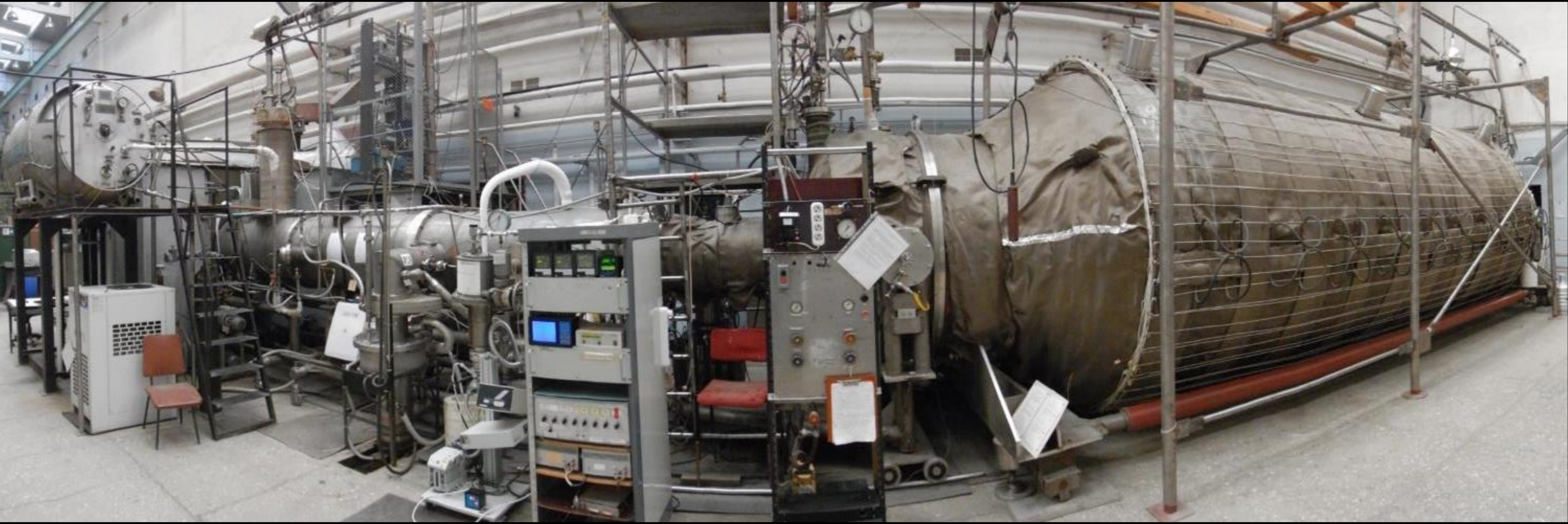



# KATRIN and TRISTAN

- The KATRIN experiment measures the neutrino mass
  - in a model-independent way
  - via ultrahigh precision measurements of the kinematics of electrons from tritium beta-decay

- The TRISTAN project builds a new detector for KATRIN
  - in order to be able to handle the high rates from the tritium source
  - and thus search for a sterile neutrino

# Troitsk impressions



**Troitsk re-analysis (2011)**
**selected data from 1994-2004:**
$m(\nu_e) < 2.05 eV\ (95\%\ C.L.)$

# Troitsk impressions

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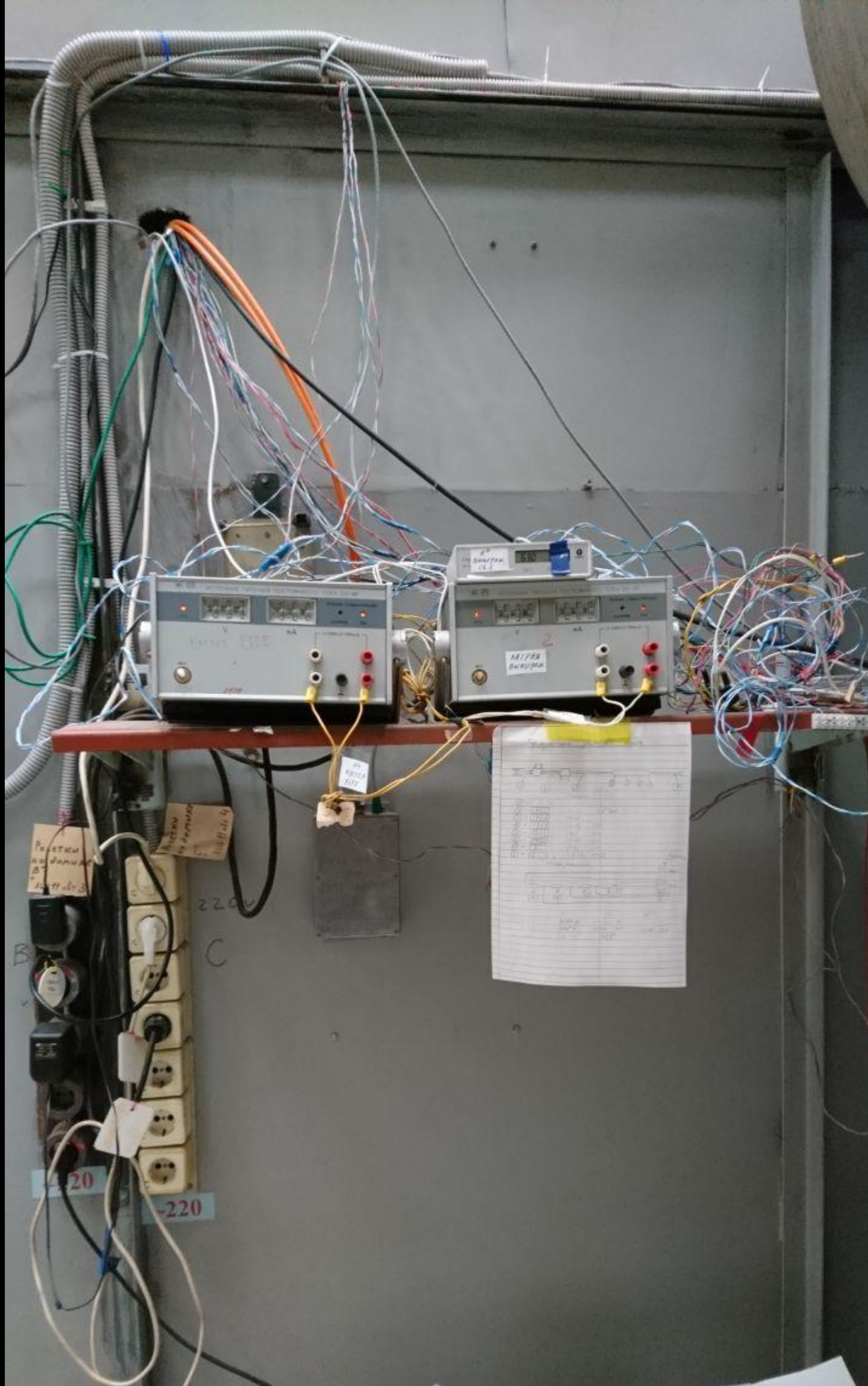

# Troitsk nu-mass experiment

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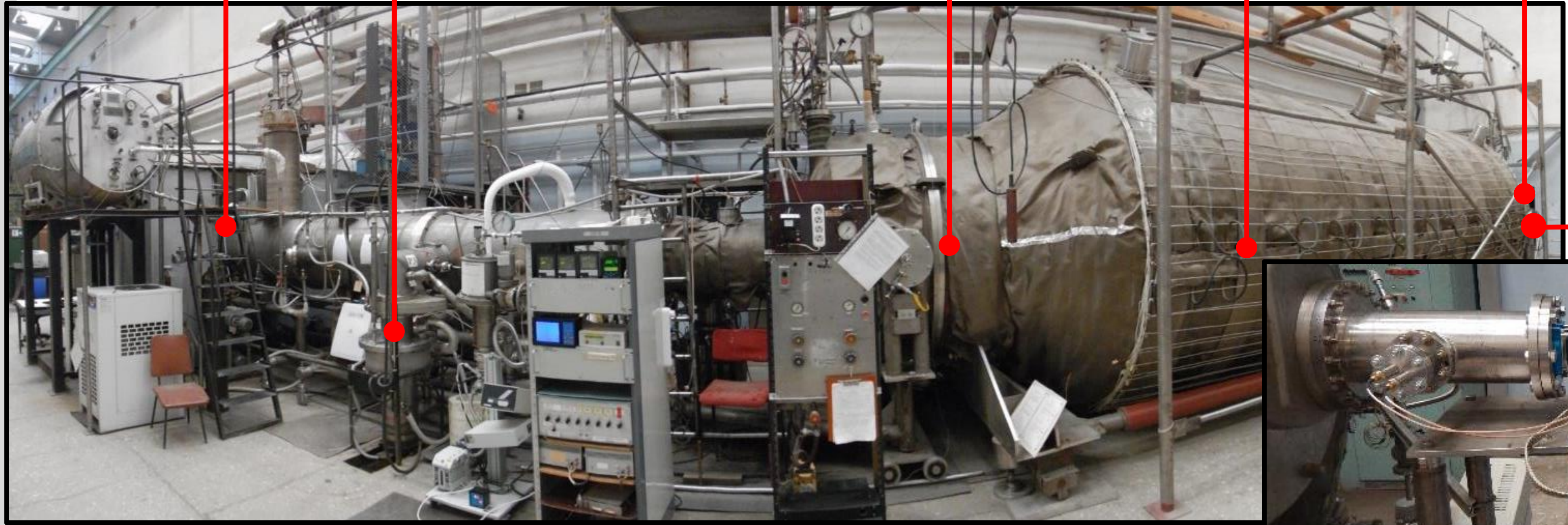
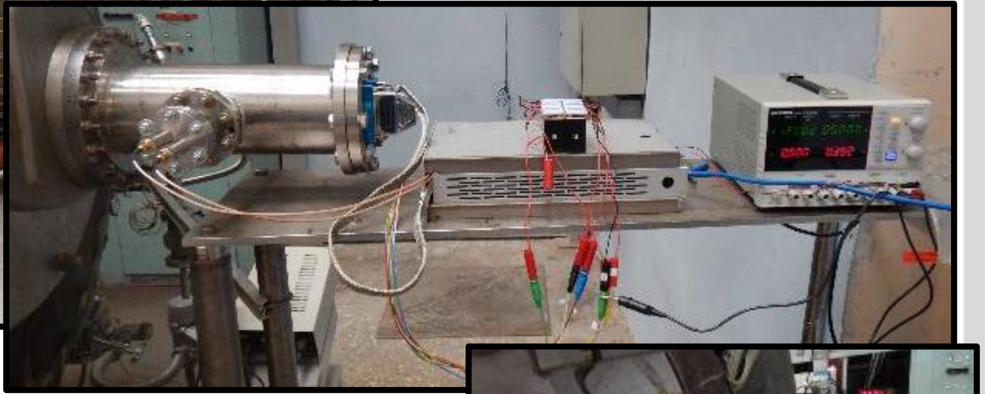
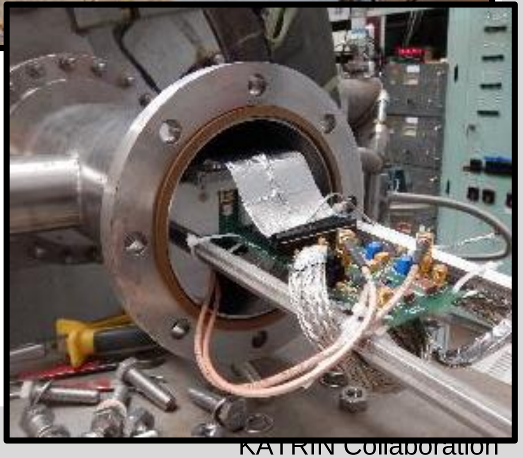
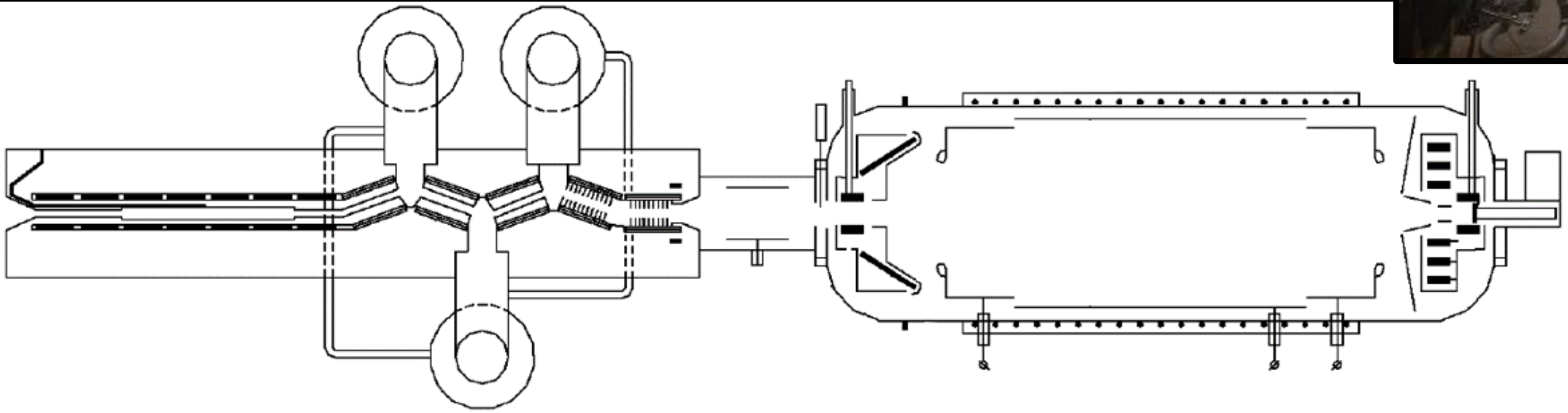
tritium pumps magnet spectrometer magnet



TRISTAN
prototype detector



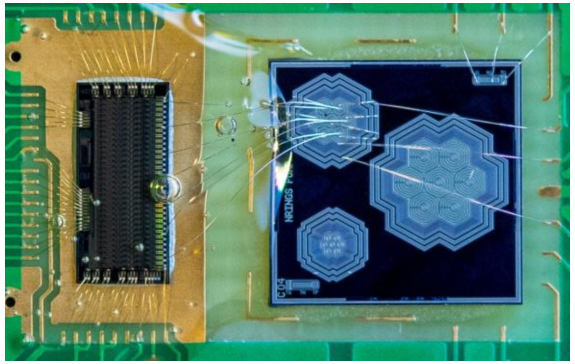




# Troitsk measurements

**Troitsk-1** (May-June 2017)

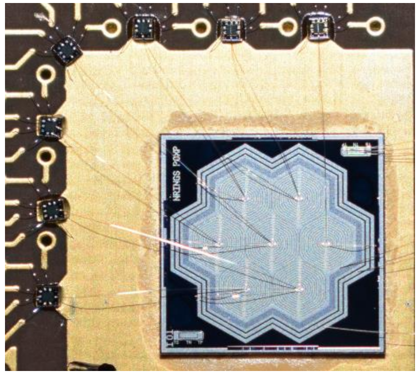
CEA-System with 1 mm pixels
44 e- (400 eV fwhm @ 18 keV)



**Main goals**
- Take first tritium data and proof detector functionality
- Detector characterization with electrons in KATRIN-like environment
- Develop differential analysis strategy and tools

**Troitsk-2** (Nov-Dec 2017)

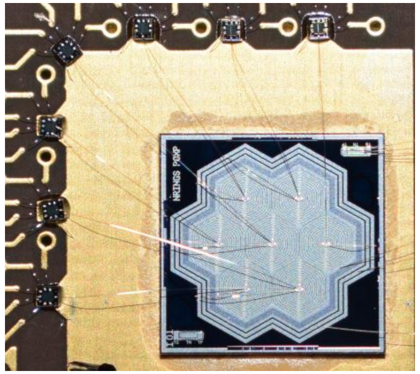
XGLab-System with 2 mm pixels
26 $e^-$ (300 eV fwhm @ 18 keV)



**Main goals**
- Gather more statistics in relevant measurements
- Test of XGLab system
- Cross-check of analysis strategy with Troitsk-1 and do further steps

**Troitsk-3** (April 2018)

XGLab-System with 2 mm pixels
26 $e^-$ (300 eV fwhm @ 18 keV)



**Main goals**
- Integrate DAQ into Troitsk system
- Develop integral analysis strategy and tools and compare to differential measurement

# Troitsk measurements

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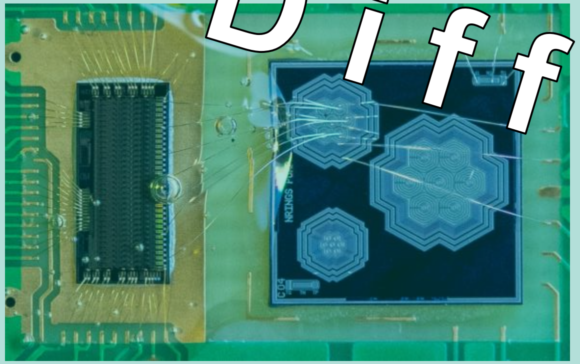

Differential

**Main goals**

- Take first tritium data and proof detector functionality
- Detector characterization with electrons in KATRIN-like environment
- Develop differential analysis strategy and tools

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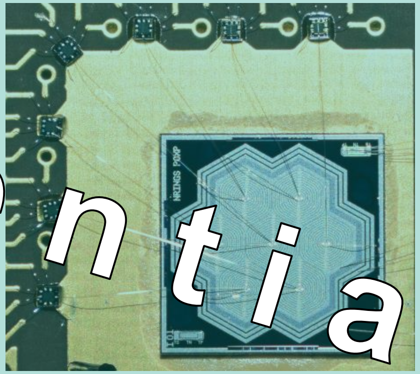

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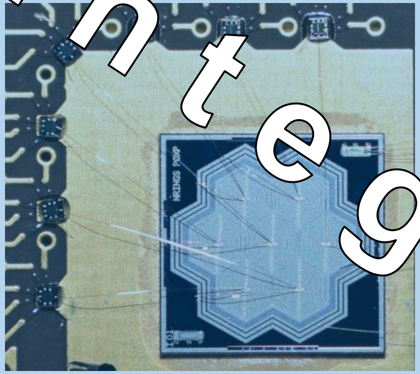


Integral

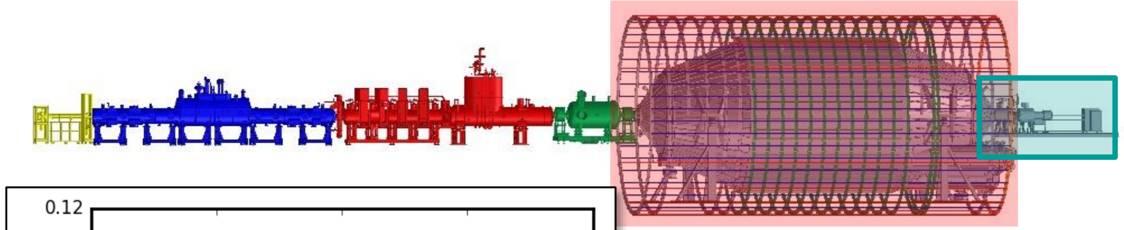
**Main goals**

- Integrate DAQ into Troitsk system
- Develop integral analysis strategy and tools and compare to differential measurement

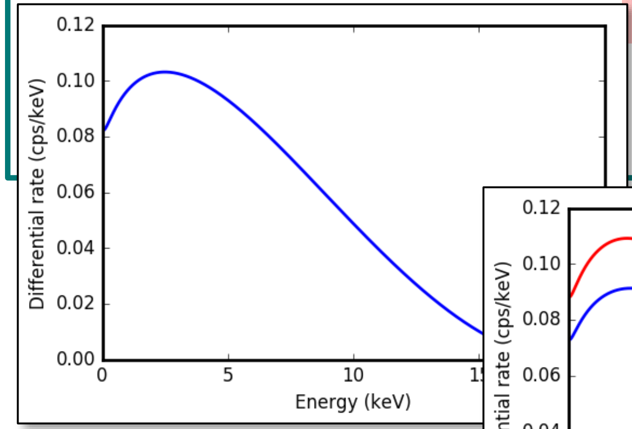
# Measurement methods

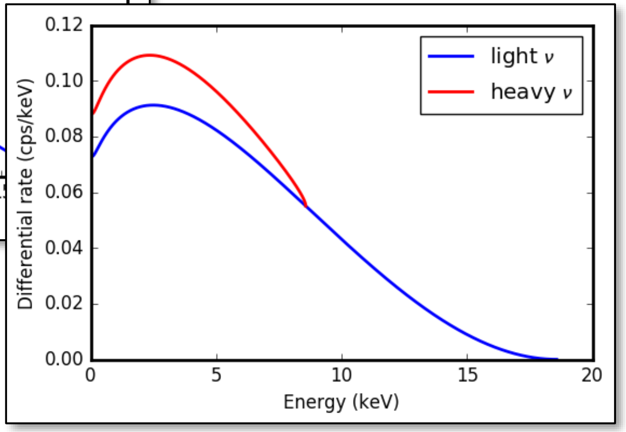
differential measurement

set main spectrometer to 0 kV or small non-zero potential



use detector to measure β-spectrum






KATRIN Collaboration
TRISTAN Group

# Measurement methods

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(Werner-Heisenberg-Institut)

**differential measurement**

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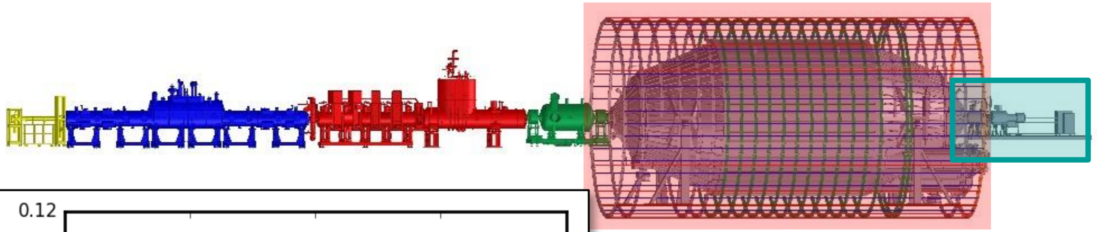

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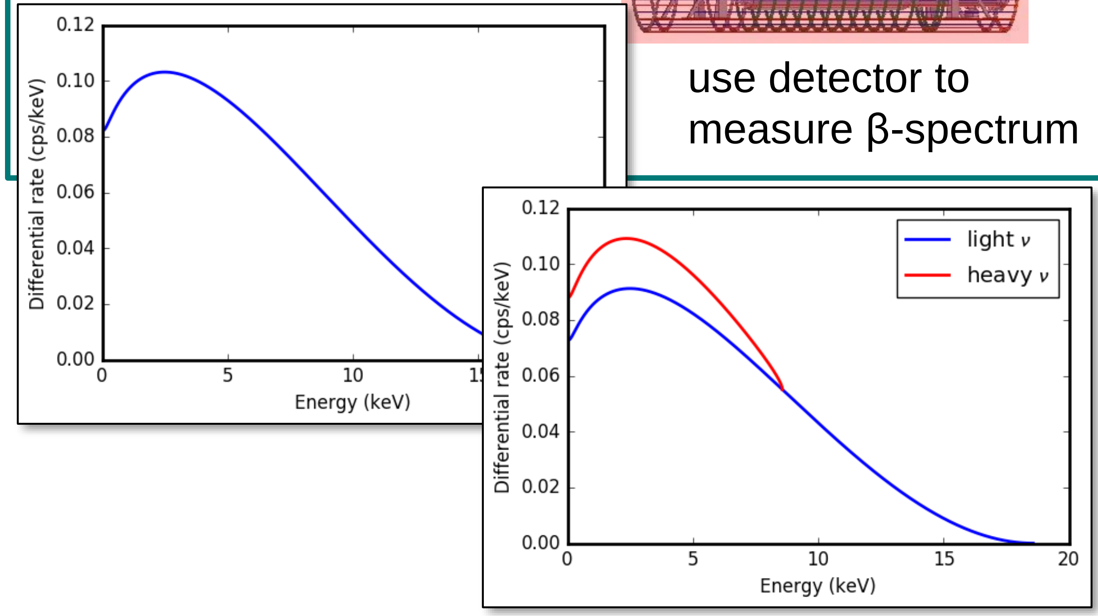
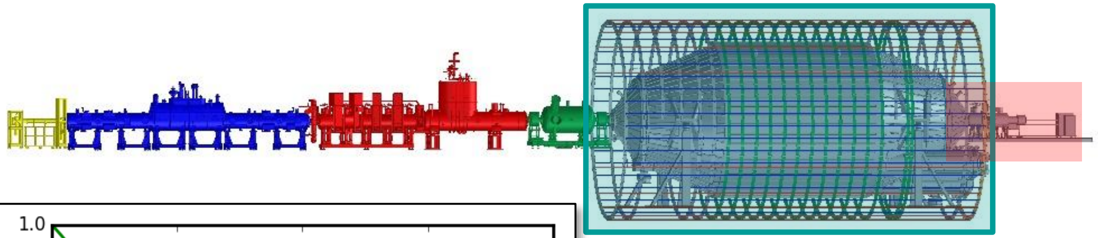
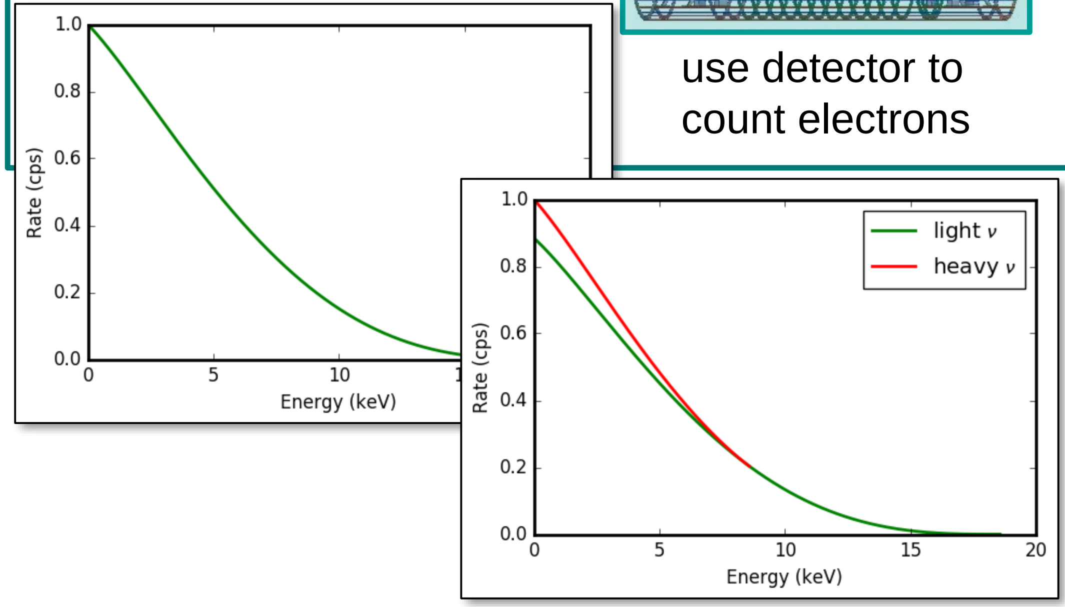



**integral measurement**

change retarding potential in steps to cut lower part of the spectrum



use detector to count electrons



# Measurement methods

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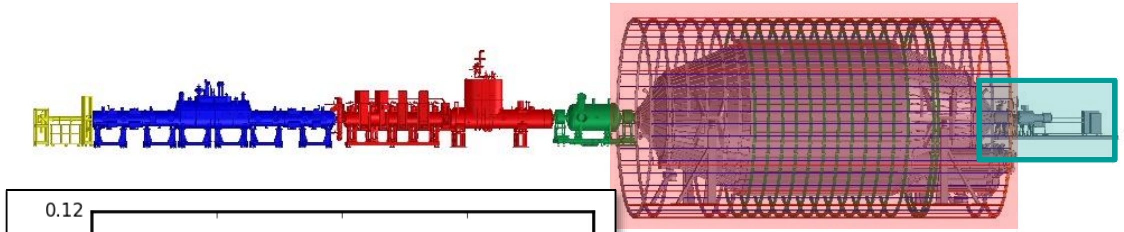
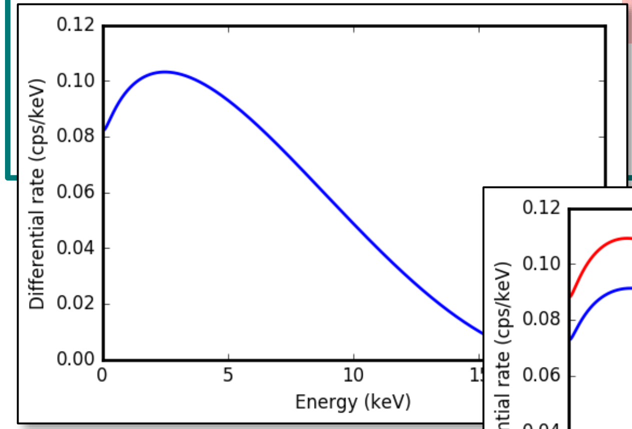
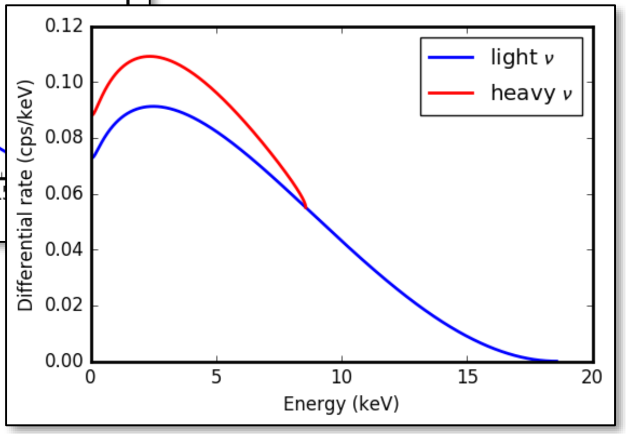
**differential measurement**

set main spectrometer to 0 kV or small non-zero potential





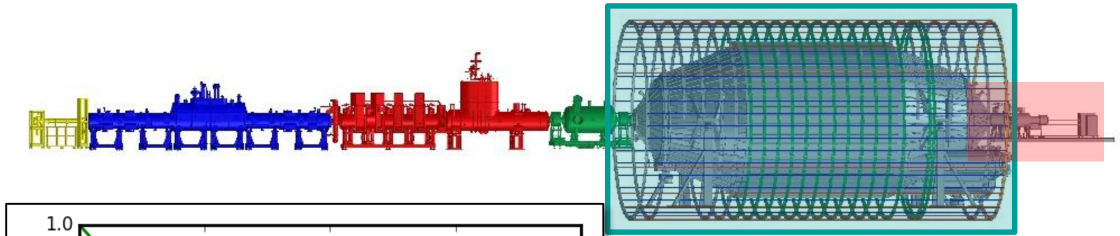

use detector to measure β-spectrum

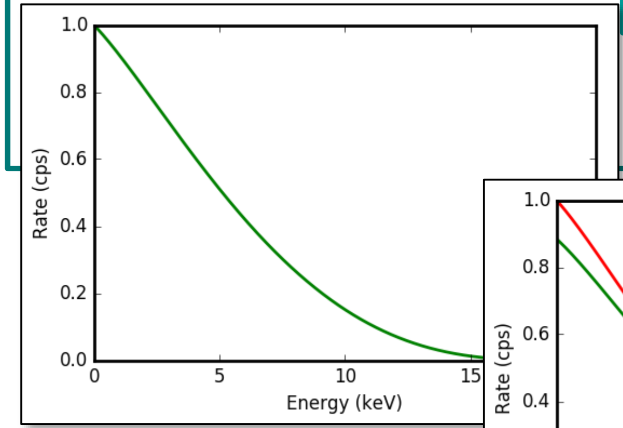



main systematic effect: detector energy response (resolution, dead layer, backscattering, ...)

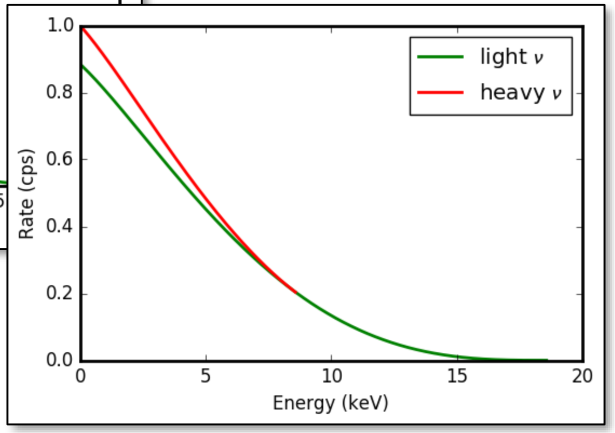
**integral measurement**

change retarding potential in steps to cut lower part of the spectrum






use detector to count electrons




main systematic effect: electron rate stability (tritium decay, adiabaticity, source scattering, ...)

# Integral analysis

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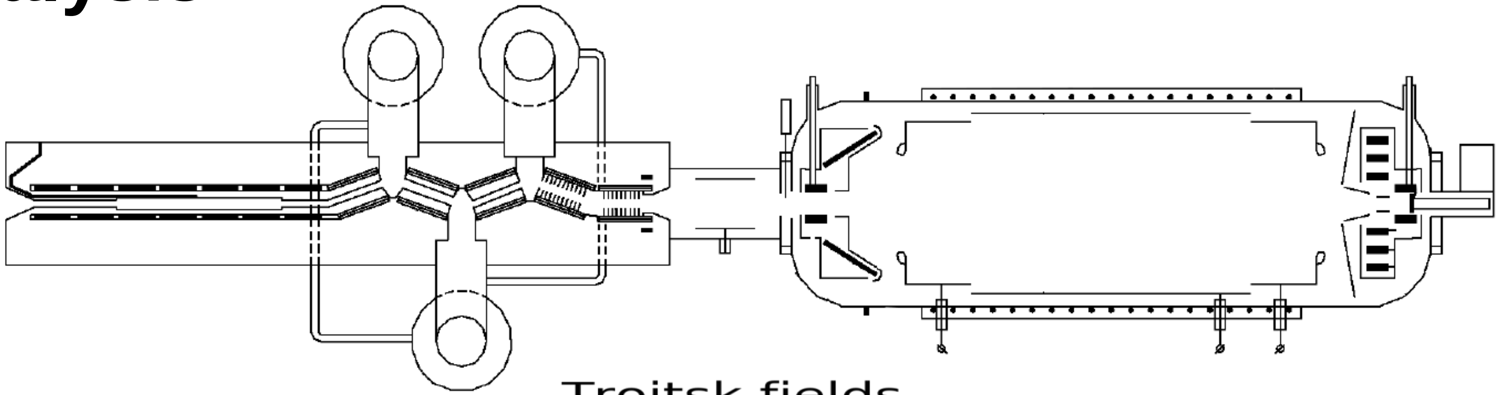
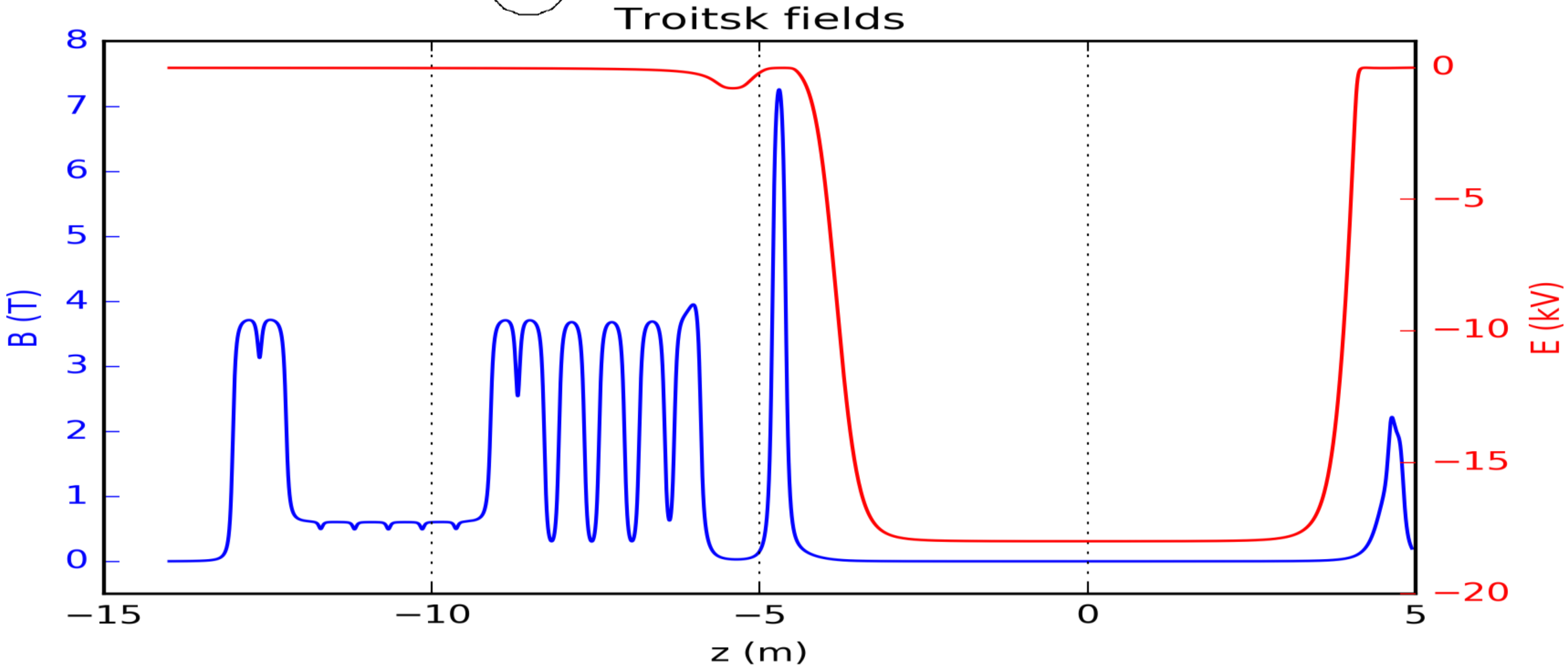
| Effect | Correction |
|---|---|
| FSD | Find model for energy dependent ground states (Corny)<br>Integrate into tritium model |
| Multiplicity cut | Find multiplicity events and remove from px0<br>Use only px0 for analysis |
| Calibration | Detemine turning point in tritium spectra and connect to HV<br>Fit linearly and determine calibration parameters |
| Bump subtraction | Use empty_2 spectra<br>Fit position and amplitude<br>Subtract bump |
| Events below threshold | Fit region slightly above detection threshold<br>Extrapolate as constant offset |
| Dead time | Use exp( „DT-window“ * „rate“ )<br>Multiply integral spectrum before 15kV-monitor-correction |
| Adiabaticity | Simulate adiabaticity in spectrometer and fit linear function<br>Multiply with integral spectrum before 15kV-monitor-correction |
| Rate decrease and fluctuation | Fit 15 kV monitor points linearly in every set<br>Calculate correction values for every HV in every set<br>Multiply with intergal spectrum |
| Stacking | Add the rates of various sets and divide by the amount<br>Fit resulting spectrum |
| Source Scattering (trapping effect) | Simulate efficiency<br>Fit linearly and determine HV dependent correction function<br>Multiply with intergal spectrum as a parameters in the fit |
| Background | Put constant background as free parameter in final fit |

# Integral analysis





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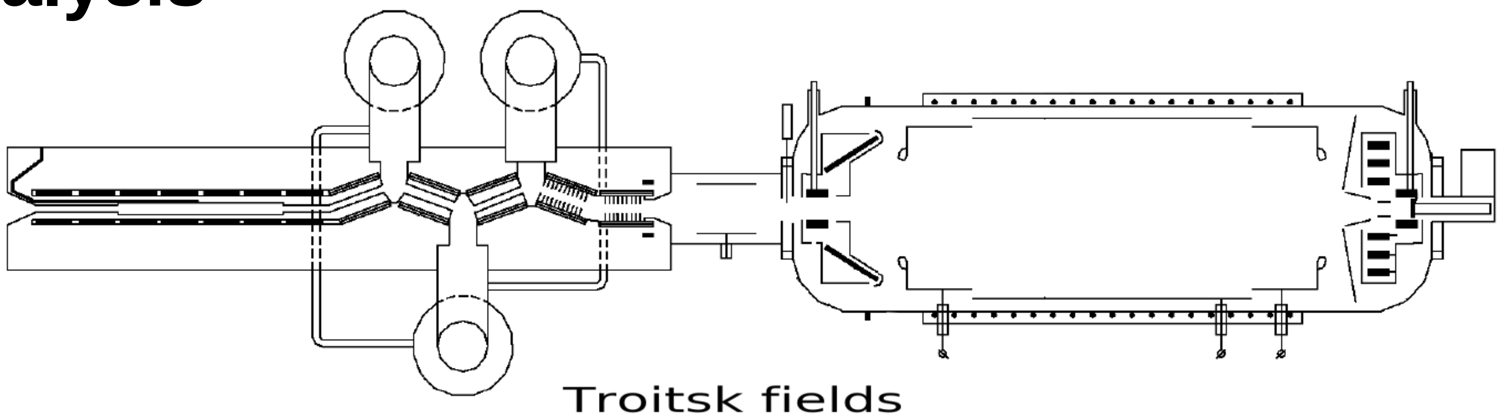
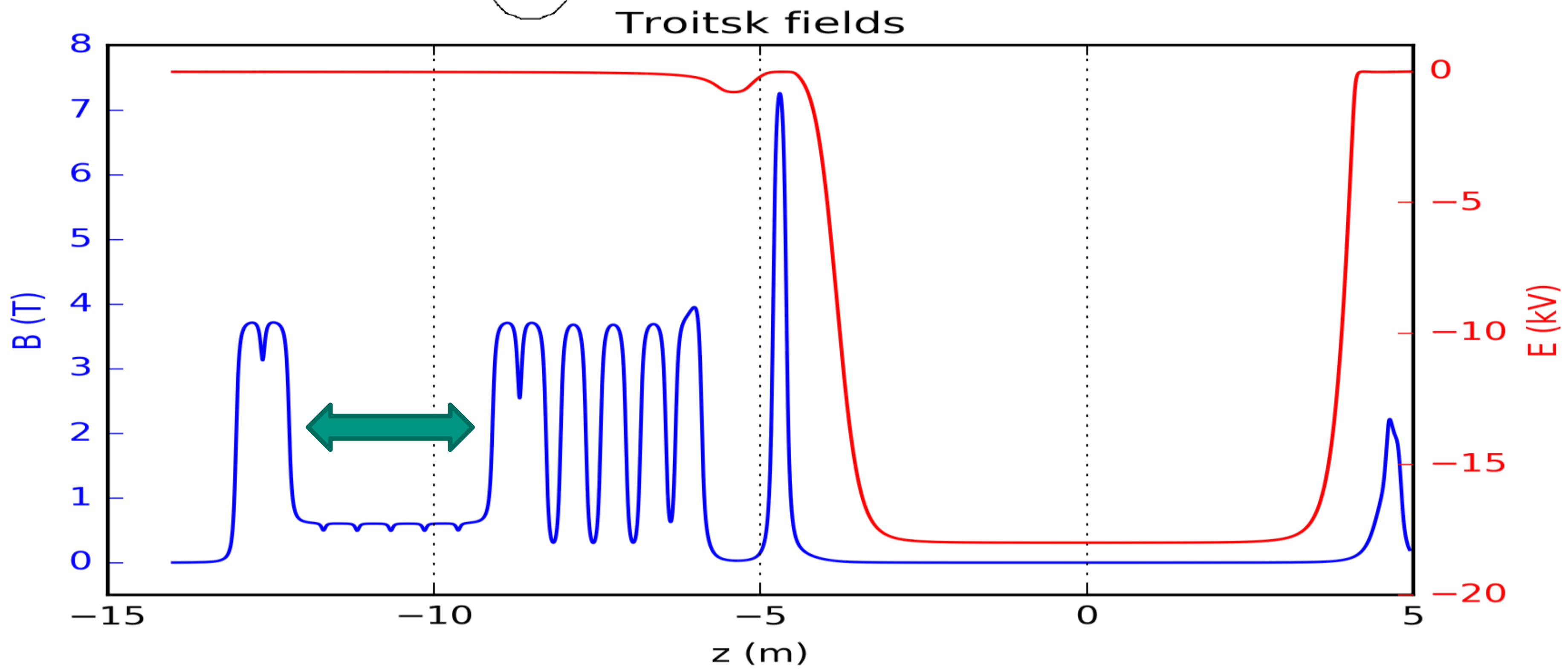
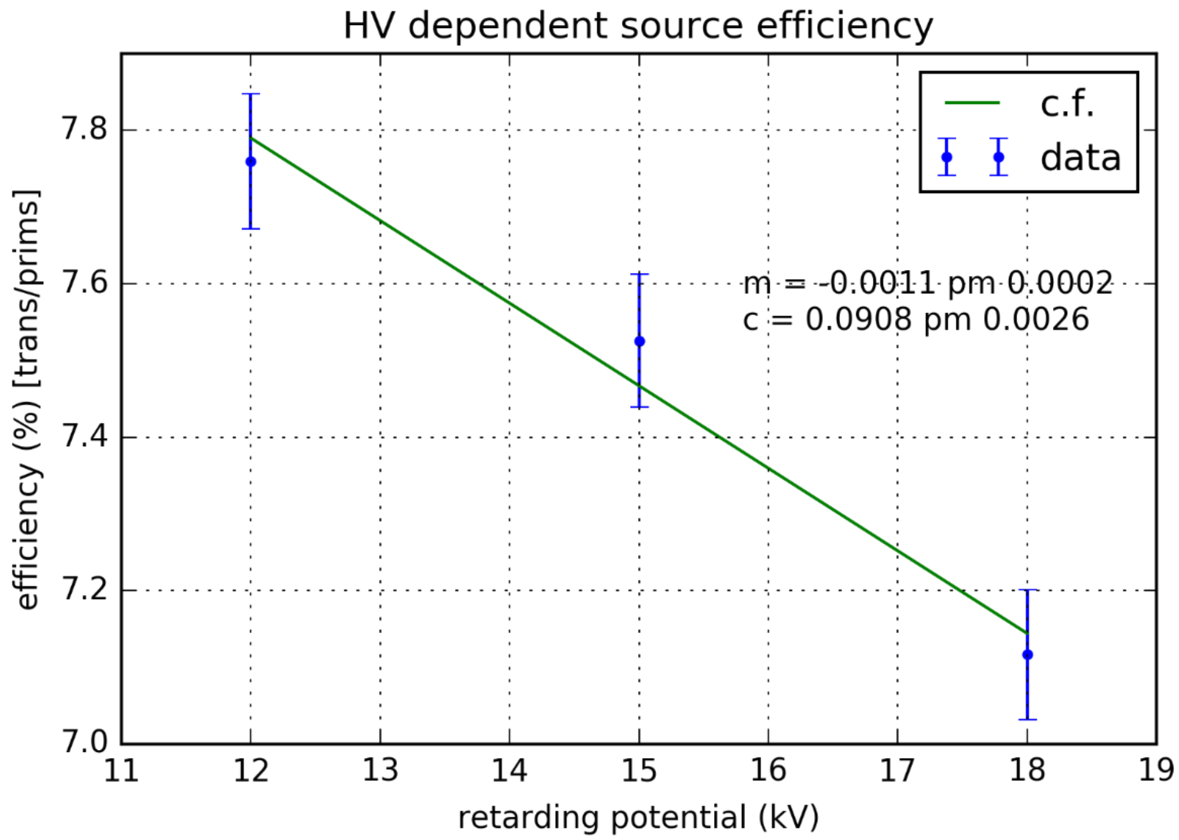




# Integral analysis

- Simulate tritium electrons in the source
- Calculate HV dependent source efficiency
- Use obtained parameters with pull terms in final fit



# Integral analysis

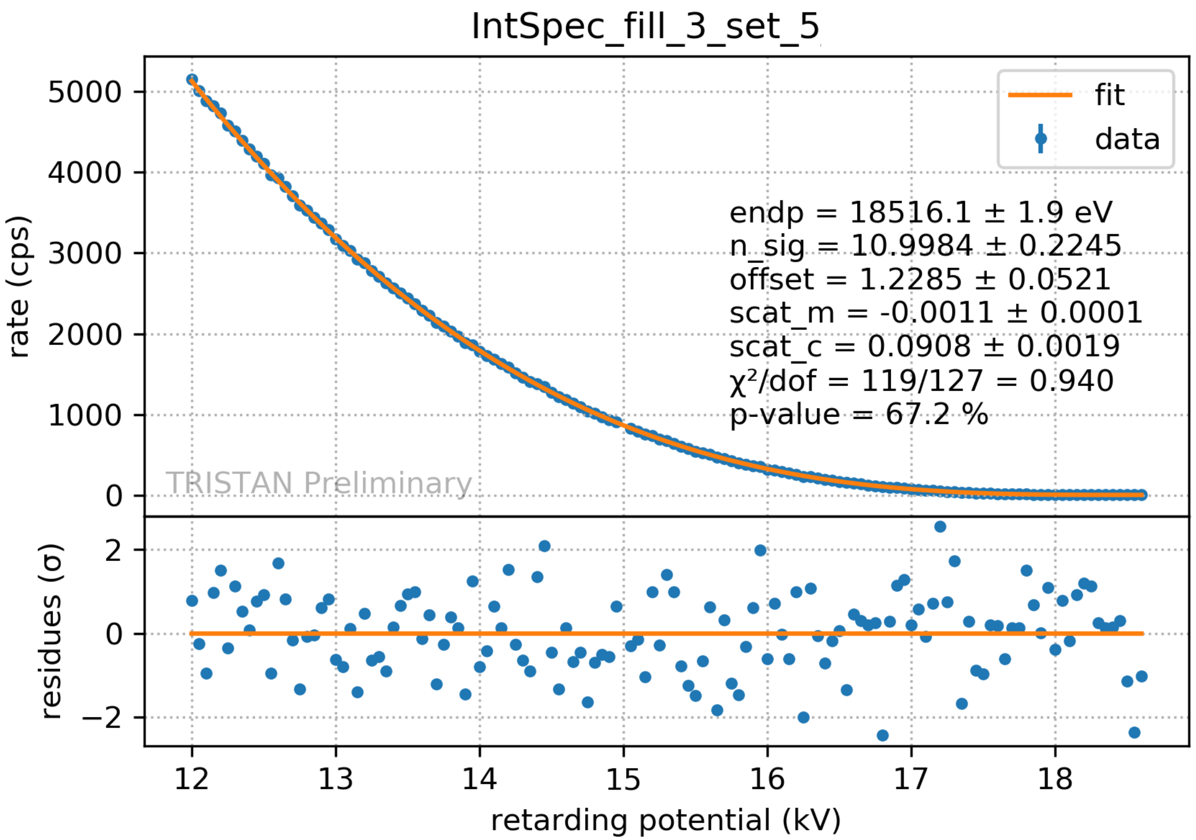
- Fit function

$$\chi^2 = \sum \frac{(x - y(HV; A, E_0) * (m * HV + c) - B)^2}{\sigma^2}$$

$$+ \ (scat - scat_0)\, M^{-1}\, (scat - scat_0)^T$$

- 5 parameters
  - Normalization $(A)$
  - Endpoint $(E_0)$
  - Background $(B)$
  - Scattering slope $(m)$
  - Scattering offset $(c)$

- scat = $\binom{m}{c}$

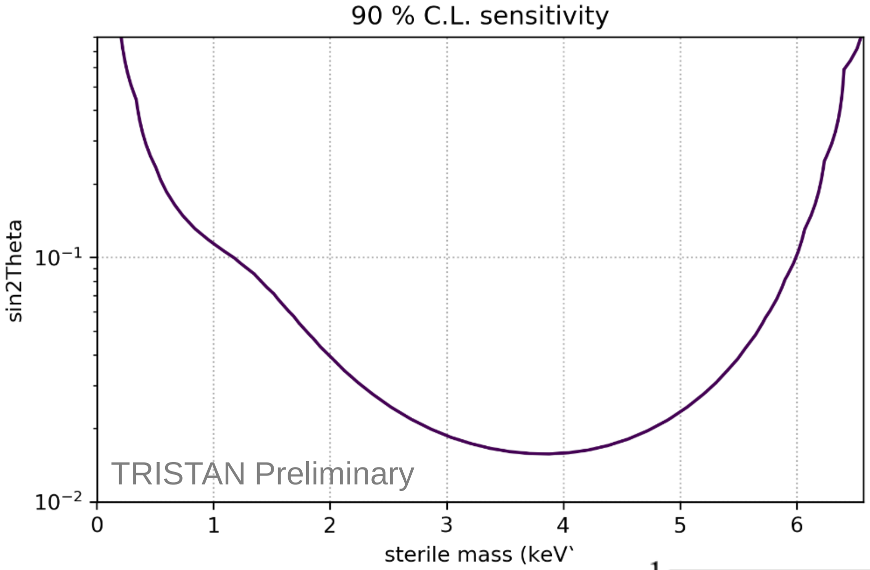


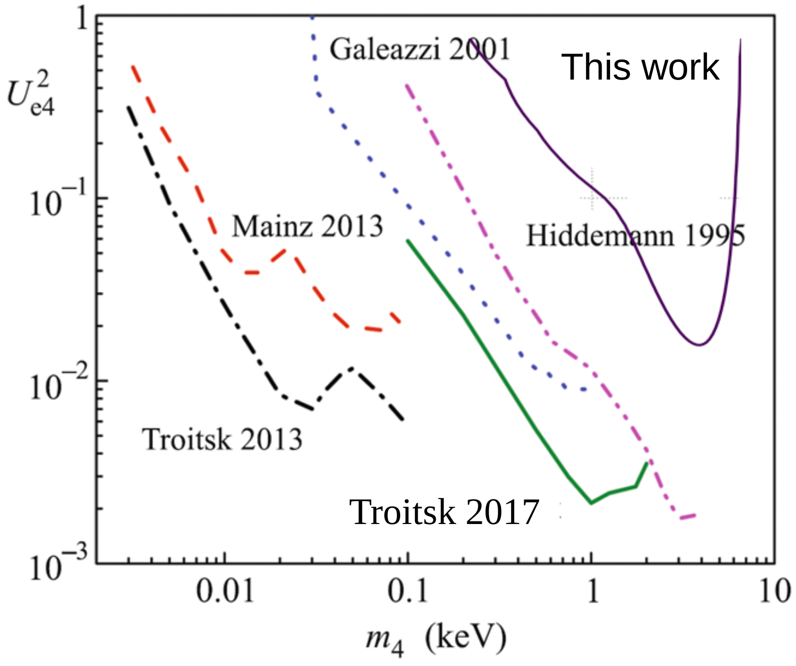
# Integral analysis

- Include a sterile neutrino in the model
- Scan through sterile neutrino parameter space

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} = \cos^2(\theta)\frac{\mathrm{d}\Gamma}{\mathrm{d}E}(m_\beta) + \sin^2(\theta)\frac{\mathrm{d}\Gamma}{\mathrm{d}E}(m_s)$$

- Draw line at $\chi^2$(NoSterile) + 9.24
  (10% quantile for $\chi^2$-distr. with 5 dof)
- Exclusion curve for 90% C.L.



# Summary

- **Successful operation**
  - of two TRISTAN prototype detector systems
  - In two different measurement modes

  at Troitsk nu-mass experiment

- Good progress in analysis strategy development

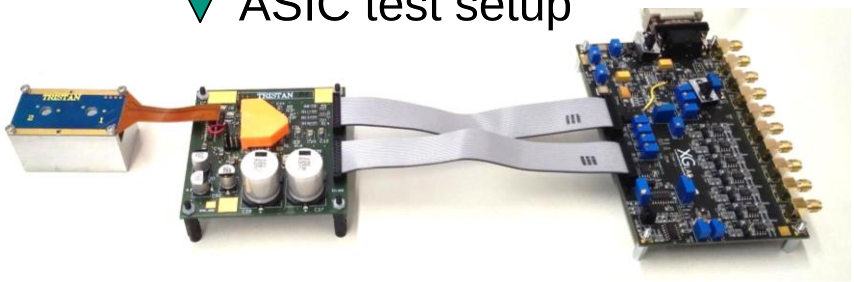
- Results will be presented at KATRIN Collaboration Meeting in November 2018

- No sterile neutrino yet

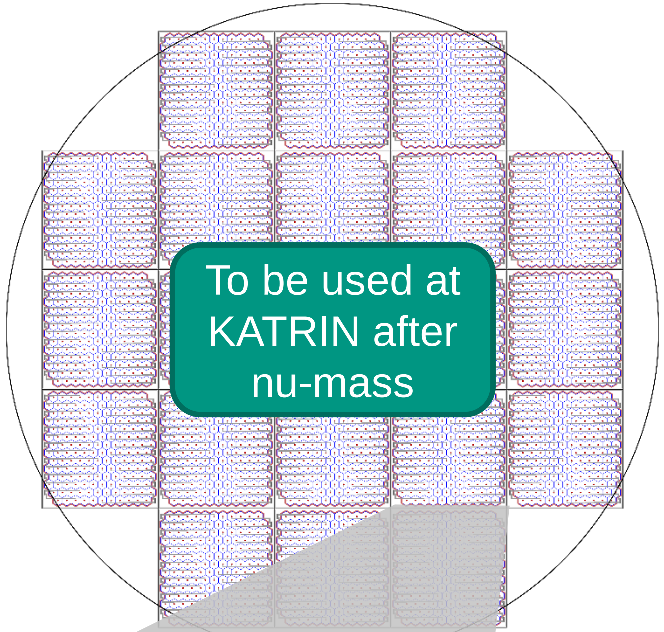
# Outlook

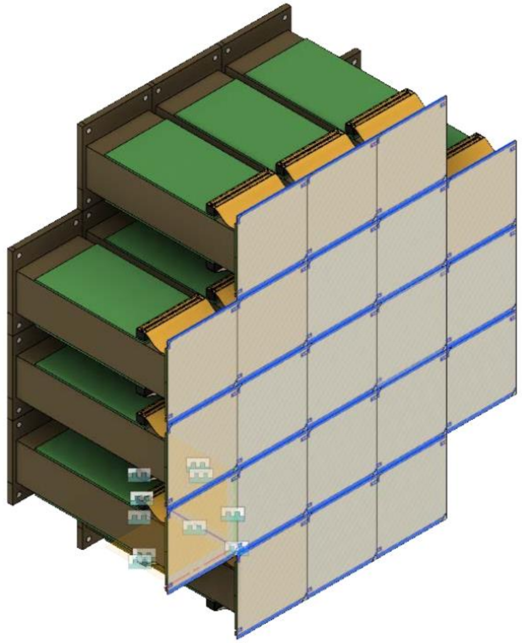
- Pixel design:
  - SDD with integrated nJFET
  - Pixel size: ~ 3 mm diameter
- Module design:
  - 166 pixels
  - Module size: ~ 4x4 cm$^2$
  - Completion: Feb 2019
- Final detector design:
  - 21 modules → 3500 pixels
  - Detector size: ~ 20 cm diameter
  - Completion: 2023

▼ ASIC test setup

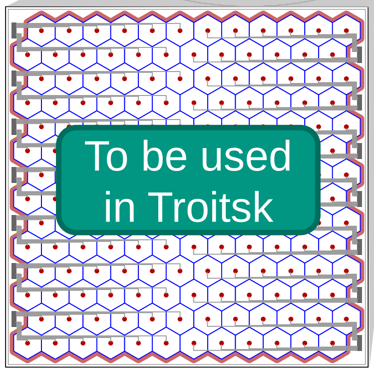


Full detector ▼



▲ Detector with holding structure




▲ Detector module

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# Thank you ...

... and

- Vlad Pantuev
- Sascha Nozik
- Igor Tkachev
- Nikita Titov
- John Abdurashitov
- Alexey Lokhov
- Aino Skasyrskaya

and the whole Troitsk nu-mass team,

- Susanne Mertens
- Thierry Lasserre
- Konrad Altenmüller
- Anton Huber
- Thibaut Houdy
- Daniel Siegmann
- Tobias Bode

and many more...

# Backup

# Troitsk impressions

# Troitsk impressions

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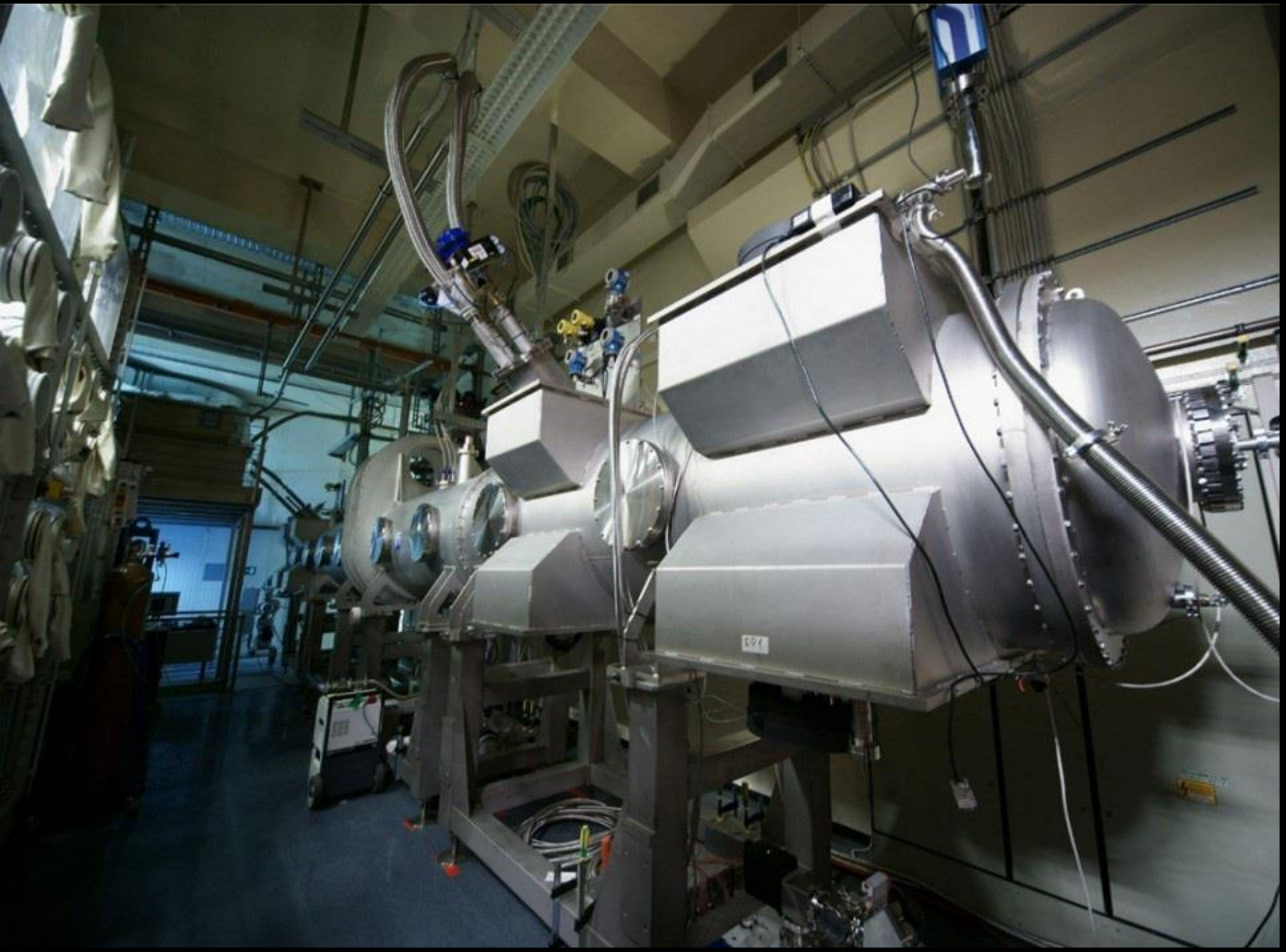
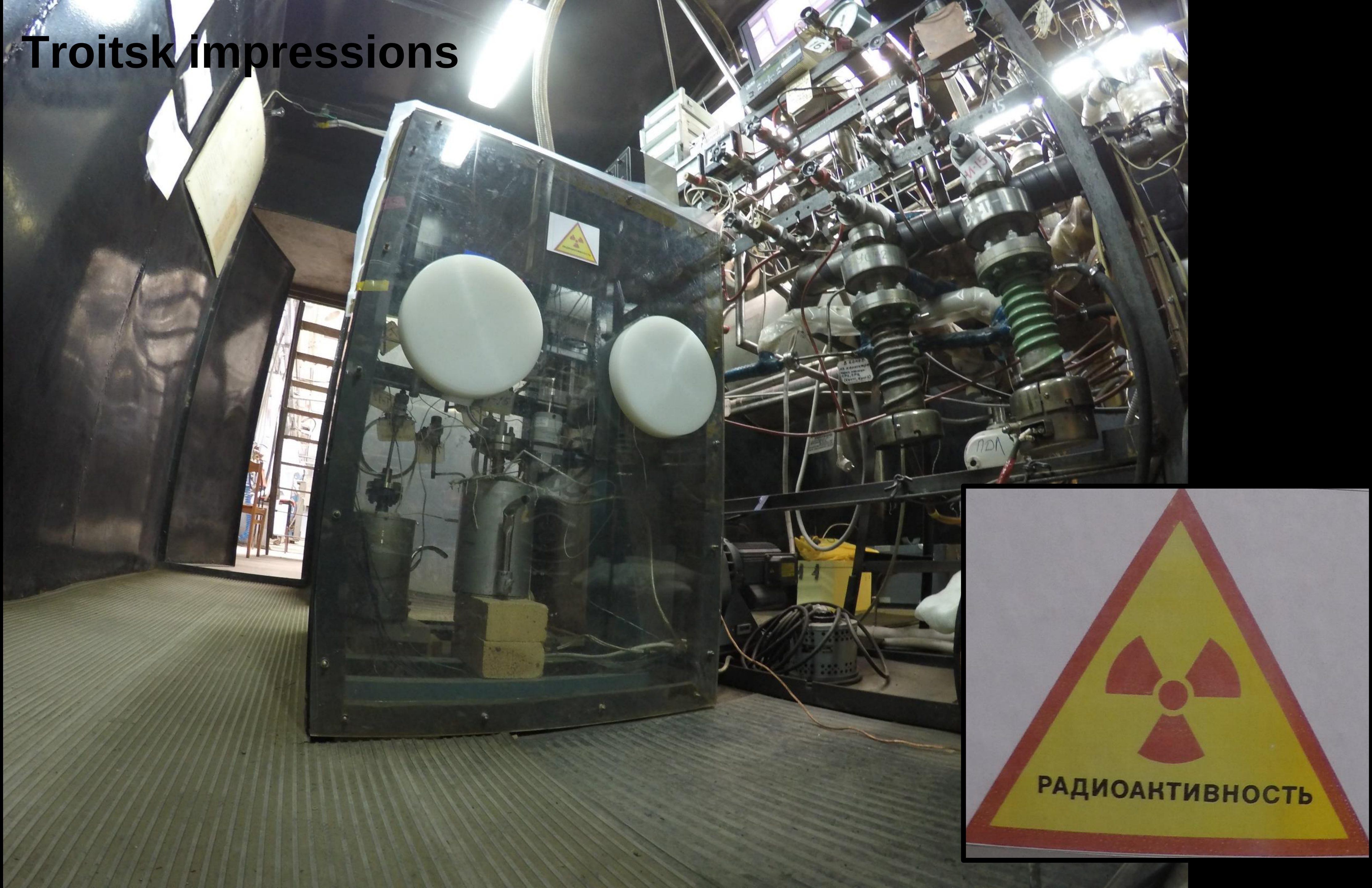


# Troitsk impressions

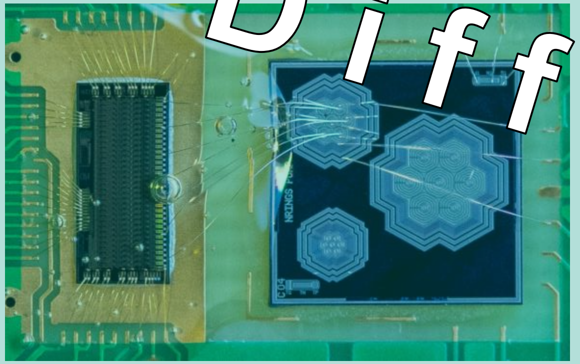


# Troitsk measurements

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

**Troitsk-1** (May-June 2017)

CEA-System with 1 mm pixels
44 e- (400 eV fwhm @ 18 keV)

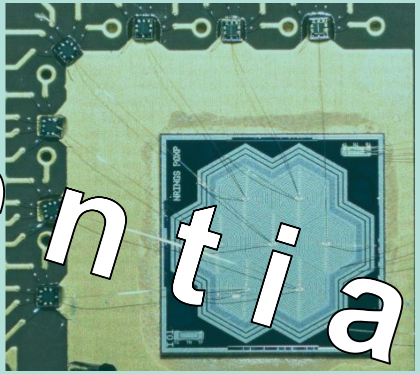


Main goals

- Take first tritium data and proof detector functionality
- Detector characterization with electrons in KATRIN-like environment
- Develop differential analysis strategy and tools

**Troitsk-2** (Nov-Dec 2017)

XGLab-System with 2 mm pixels
26 $e^-$ (300 eV fwhm @ 18 keV)



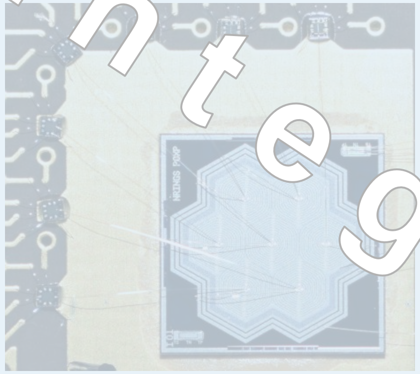
Main goals

- Gather more statistics in relevant measurements
- Test of XGLab system
- Cross-check of analysis strategy with Troitsk-1 and do further steps

Differential

**Troitsk-3** (April 2018)

XGLab-System with 2 mm pixels
26 $e^-$ (300 eV fwhm @ 18 keV)



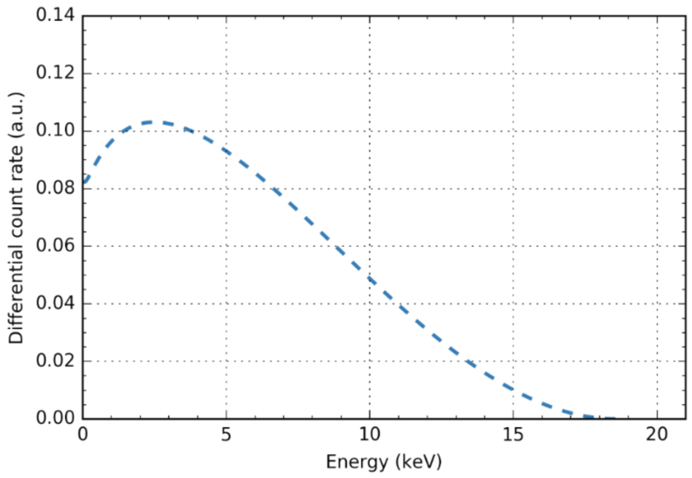
Main goals

- Integrate DAQ into Troitsk system
- Develop integral analysis strategy and tools and compare to differential measurement

Integral

# Differential analysis

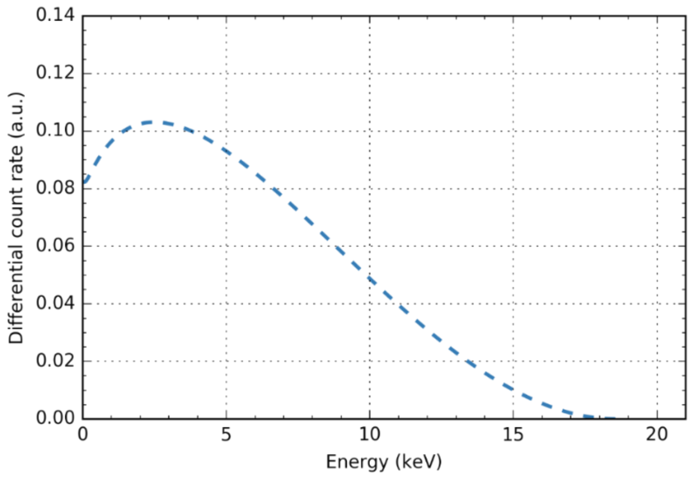
**Source**

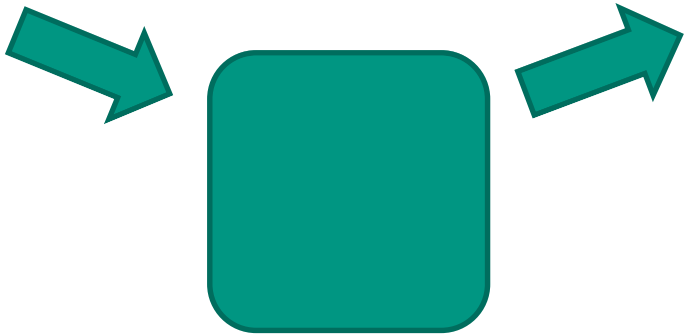


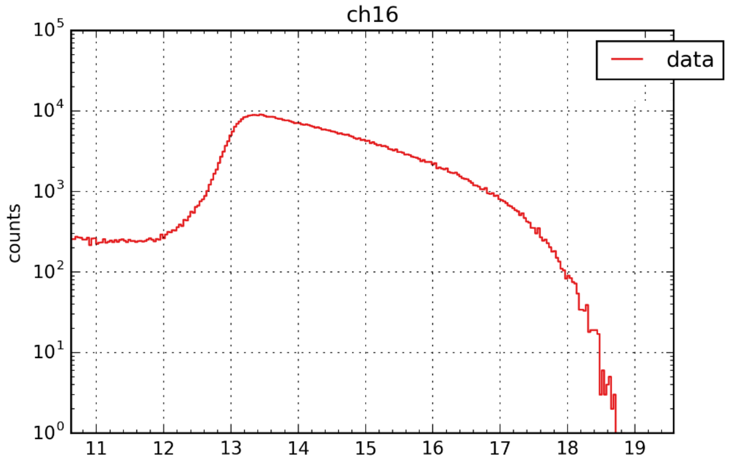

**Experiment**

# Differential analysis

**Source** | **Experiment** | **Observation**





# Differential analysis

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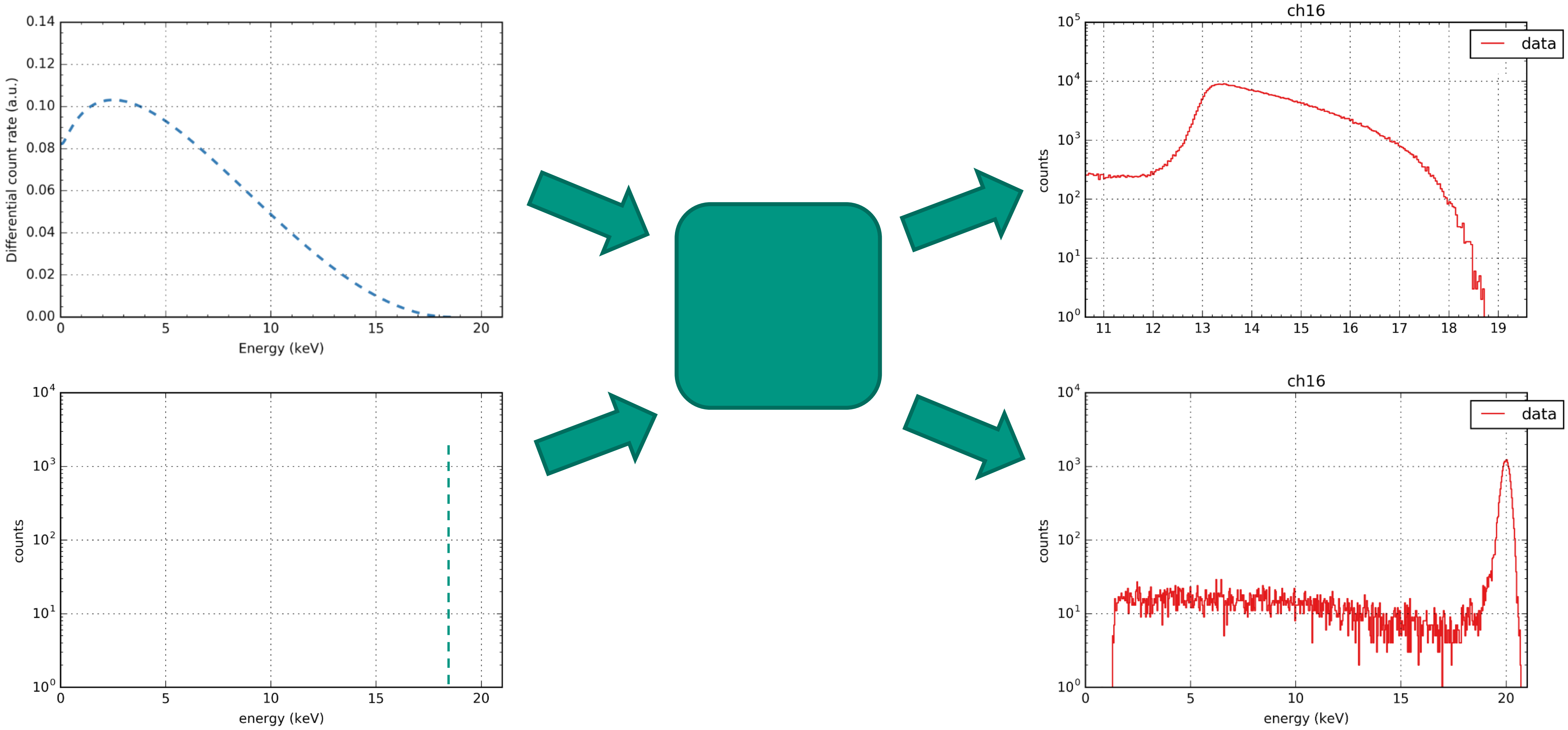
(Werner-Heisenberg-Institut)

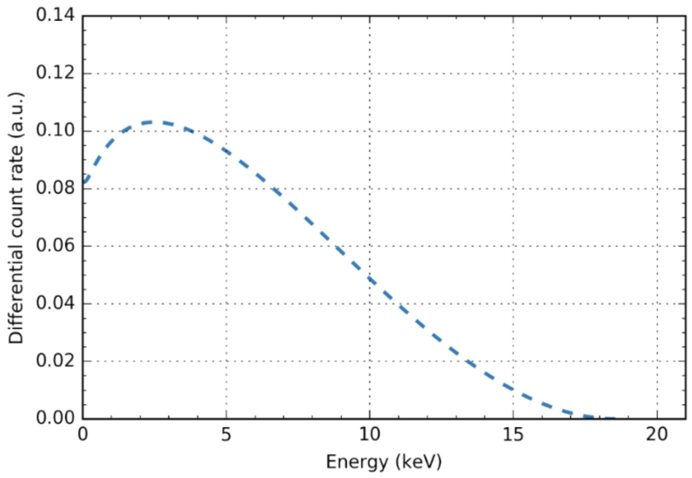
**Source** **Experiment** **Observation**

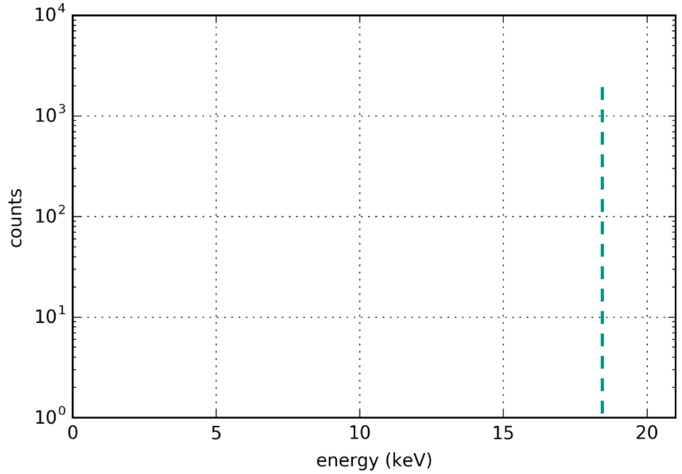


Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

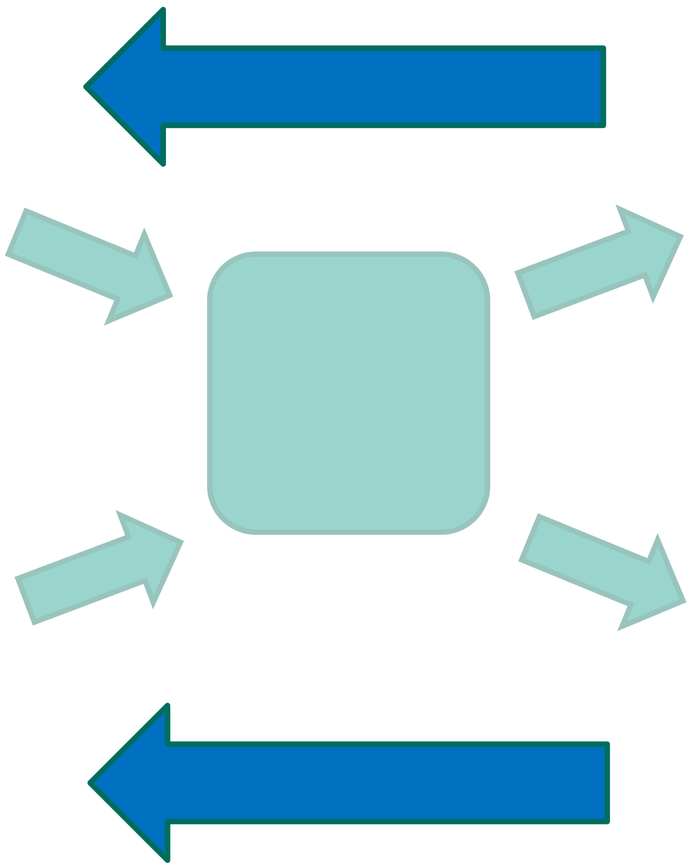
# Differential analysis

## Source

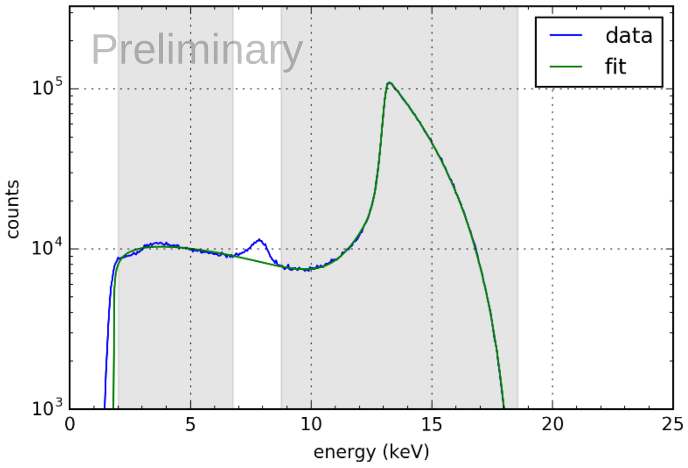


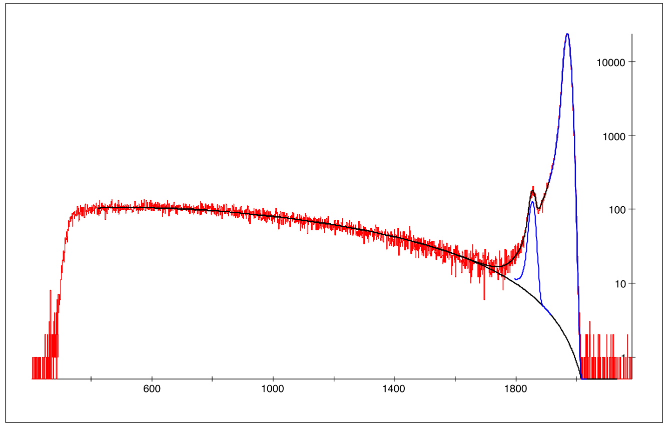




## Experiment



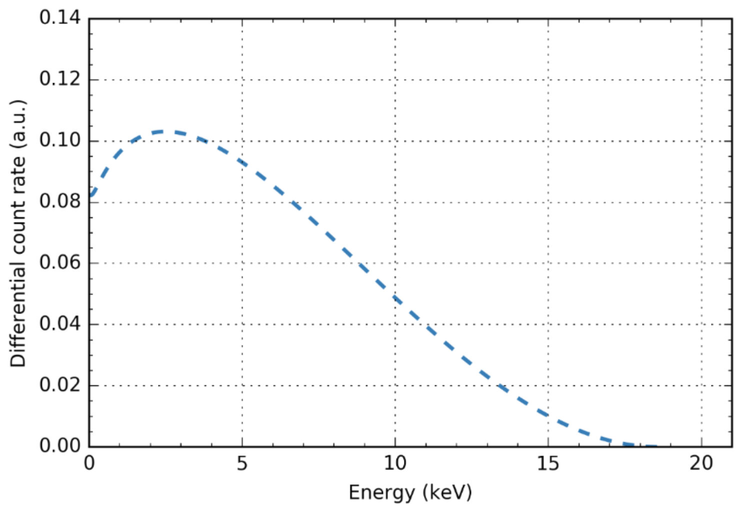
## Observation



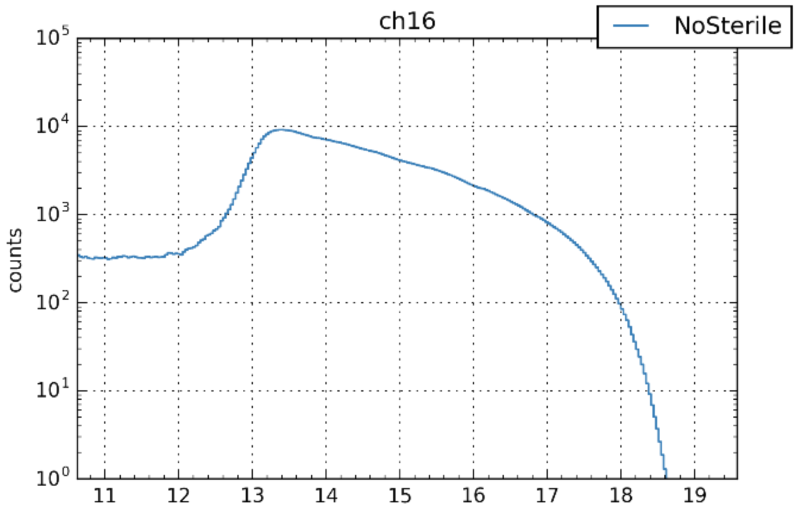



# Differential analysis

**Theoretical** beta spectrum




**Model** of beta spectrum

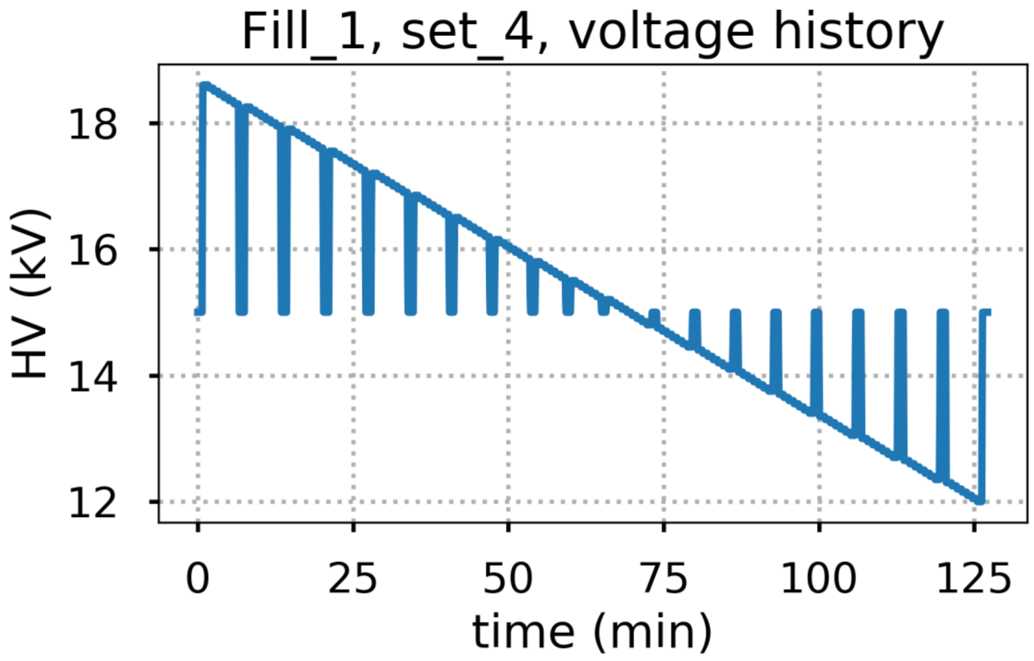


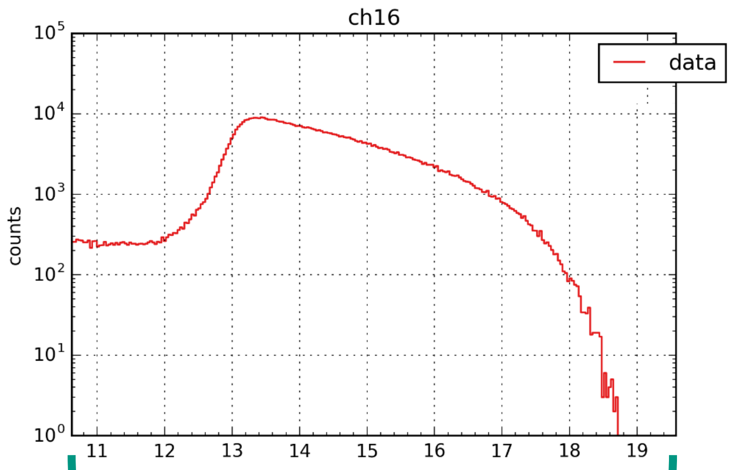

× ( Response matrix ) =

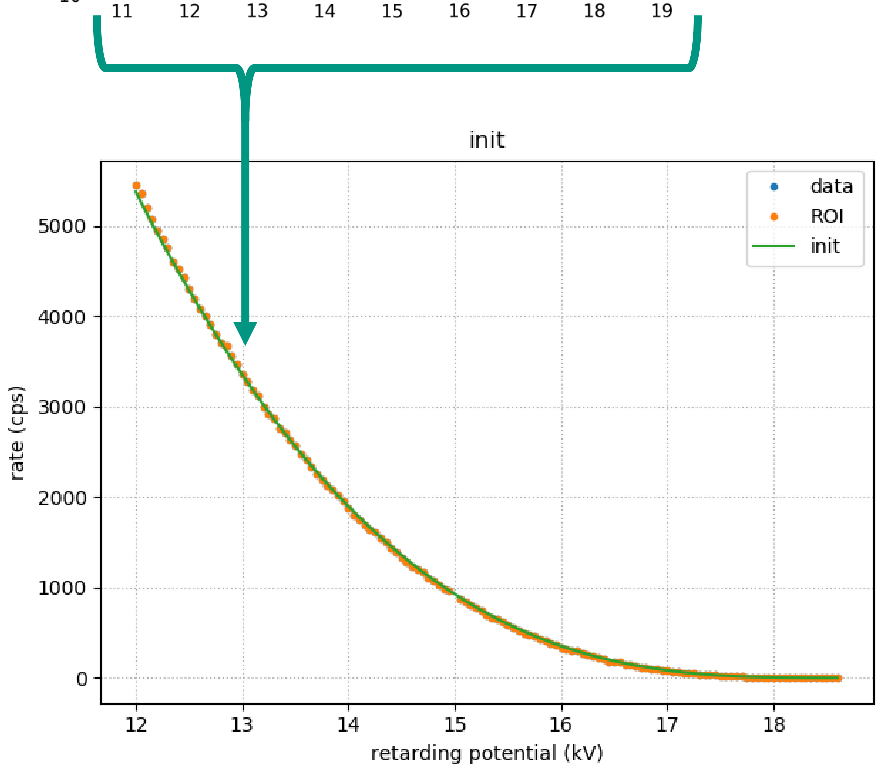
**The response matrix**

1. describes the response of the setup to electrons with a certain energy for all energies
2. includes all relevant systematic effects

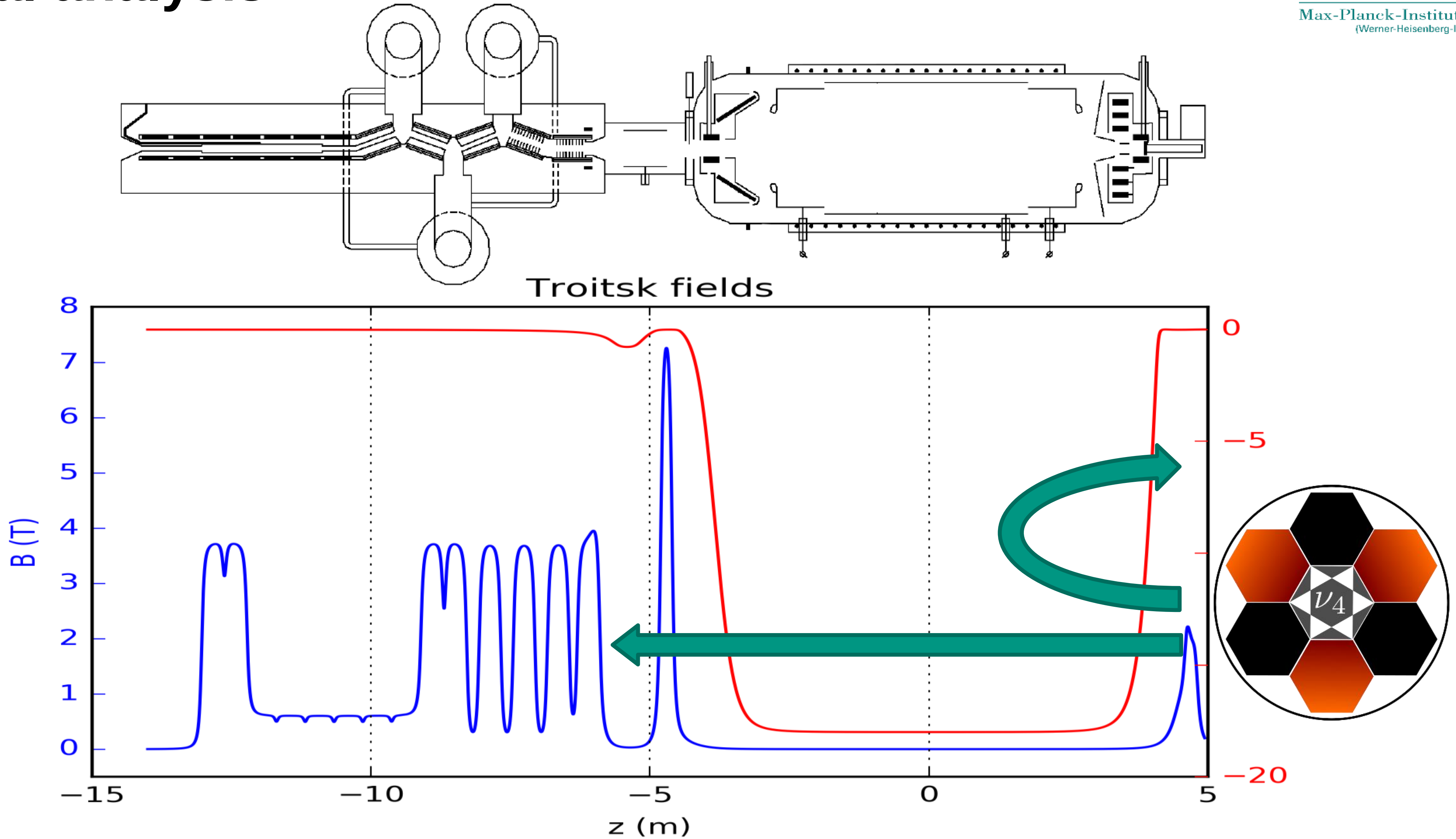
# Integral analysis



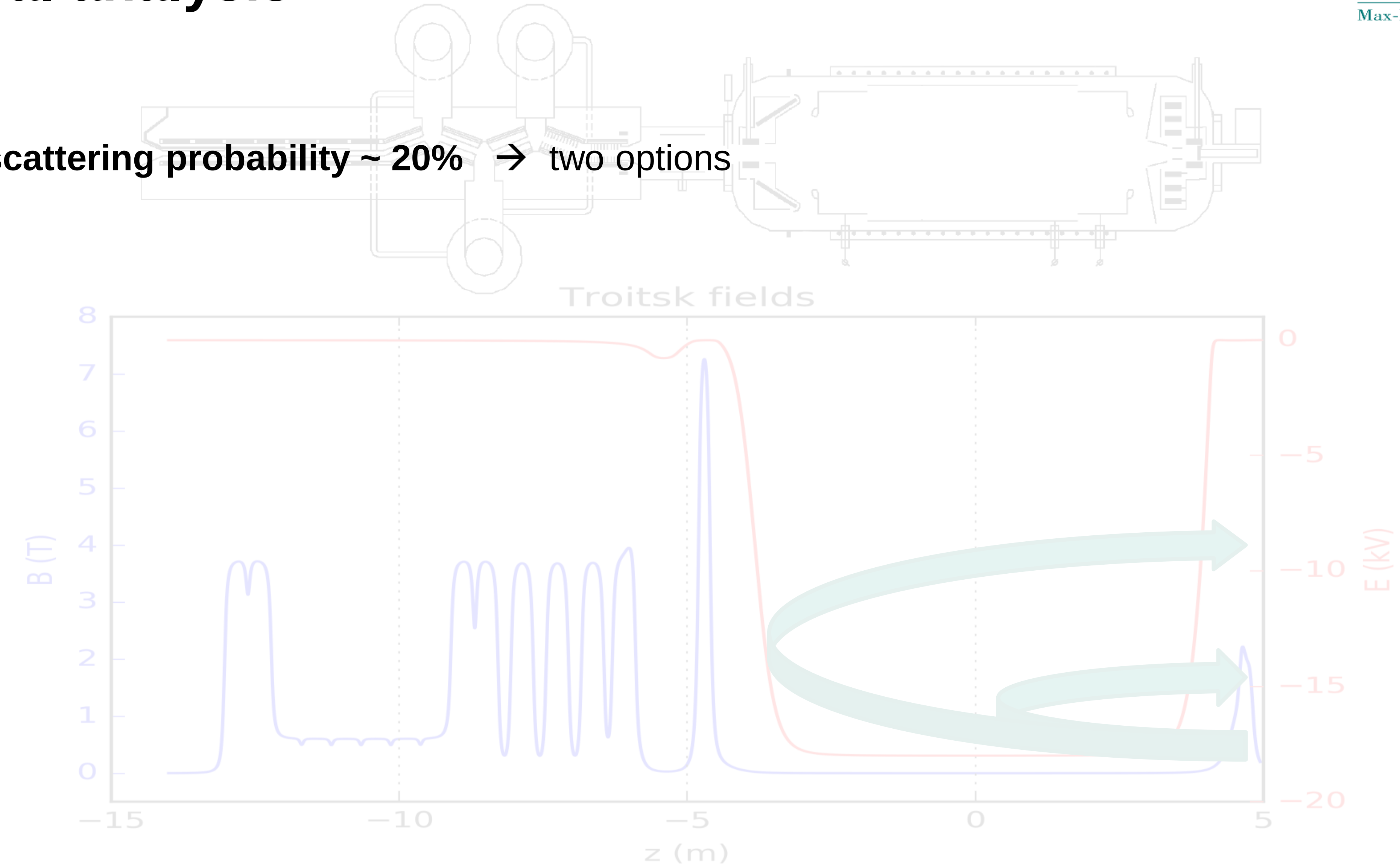



# Integral analysis



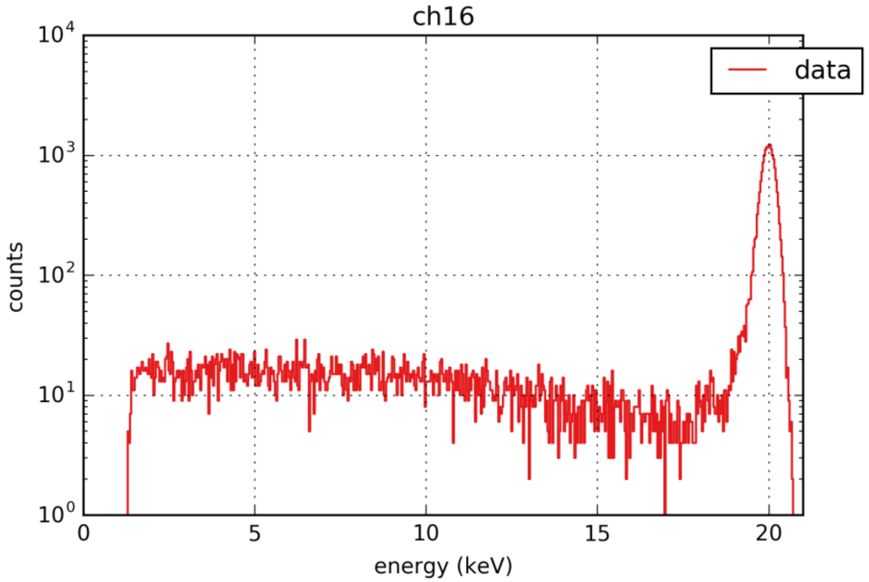
# Integral analysis

- **Backscattering probability ~ 20%** → two options



# Integral analysis

- **Backscattering probability ~ 20%** → two options
  - **Electron is lost** → two options
    - Event above detection threshold → Event detected ✓
    - Event below detection threshold → Simulate spectral shape and estimate systematic error



# Integral analysis

- **Backscattering probability ~ 20%** → two options
  - **Electron is lost** → two options
    - Event above detection threshold → Event detected ✓
    - Event below detection threshold → Simulate spectral shape and estimate systematic error
  - **Electron comes back onto the detector** → two options
    - Electron hits the same pixel → Event falls into filter integration time ✓
    - Electron hits another pixel → Cut multiplicity event within certain time window