TRISTAN: a laboratory search for keV-scale sterile neutrinos

Konrad Altenmüller,
Technical University of Munich & CEA Saclay

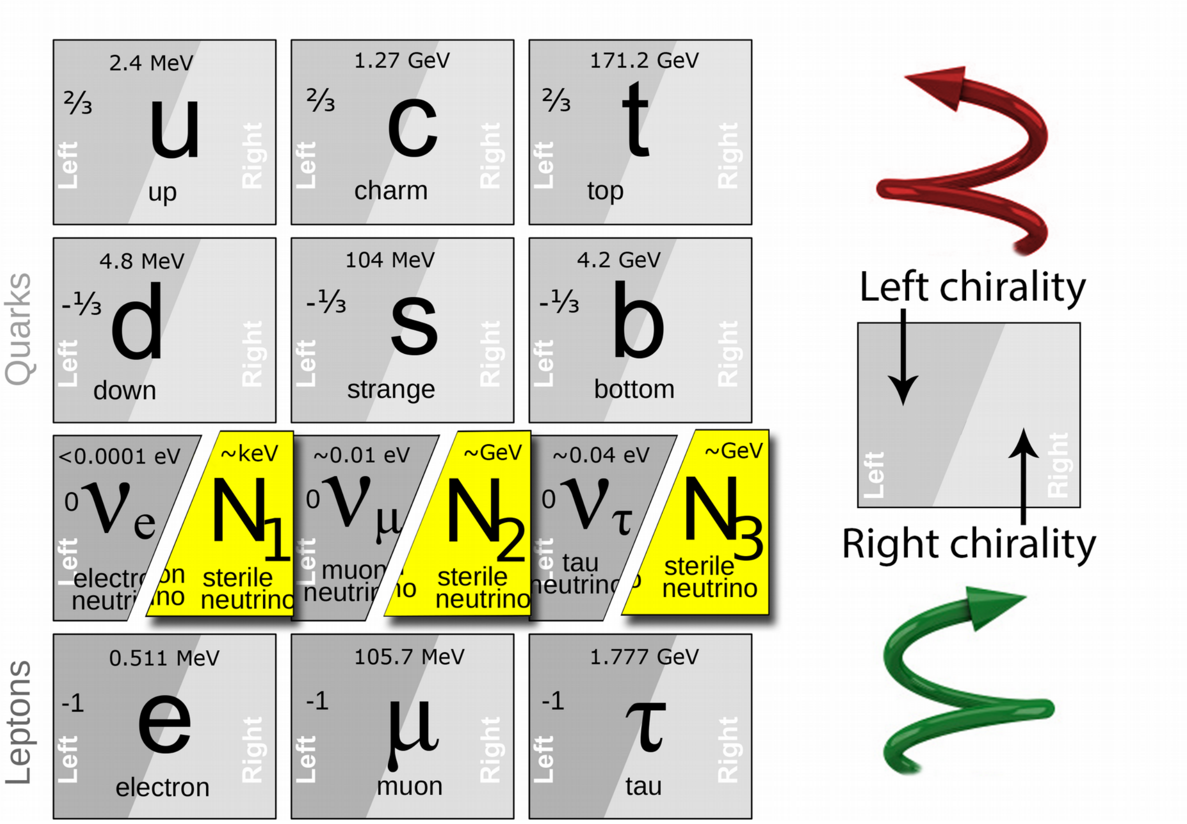
16th Baksan School on Astroparticle Physics
12.04.2019

Outline

- Sterile neutrinos as dark matter candidates
- The TRISTAN project
- Analysis of a tritium spectrum

Sterile neutrinos in the standard model

- The standard model is incomplete, as it fails to explain neutrino mass
- The **seesaw mechanism**: adds right-handed (sterile) neutrinos that generate the neutrino mass
- **νMSM** – a specific variant of the seesaw mechanism that adds **3 sterile neutrinos** to explain cosmological and astrophysical observations



N_1
m ~ keV

(warm) dark matter

N_1, N_2
m ~ GeV

Generate neutrino masses and matter-antimatter asymmetry via leptogenesis

keV-scale sterile neutrino dark matter

Warm dark matter (WDM) can explain discrepancies between ΛCDM N-body simulations and observations

- Dwarf galaxy problem (too few DM subhaloes)
- Cusp-core problem (density profiles of dwarf galaxies)
- Too-big-too-fail issue (why are massive subhaloes dark?)

These Problems can be resolved by WDM.

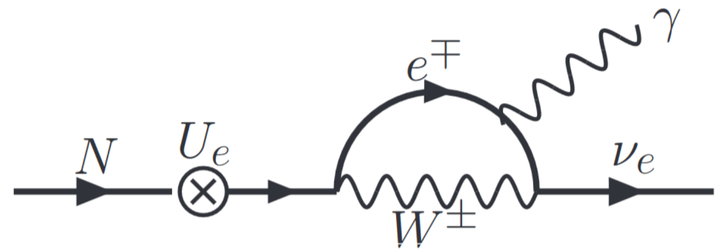
But:

- Are these problems existent?
- If yes, they could also be explained by baryonic feedback or self-interacting dark matter (e.g. resonantly scattering SIMPS)

Mon. Not. Roy. Astr. Soc., 420 (2012) 2318-2324

Sterile neutrino dark matter: X-ray bounds

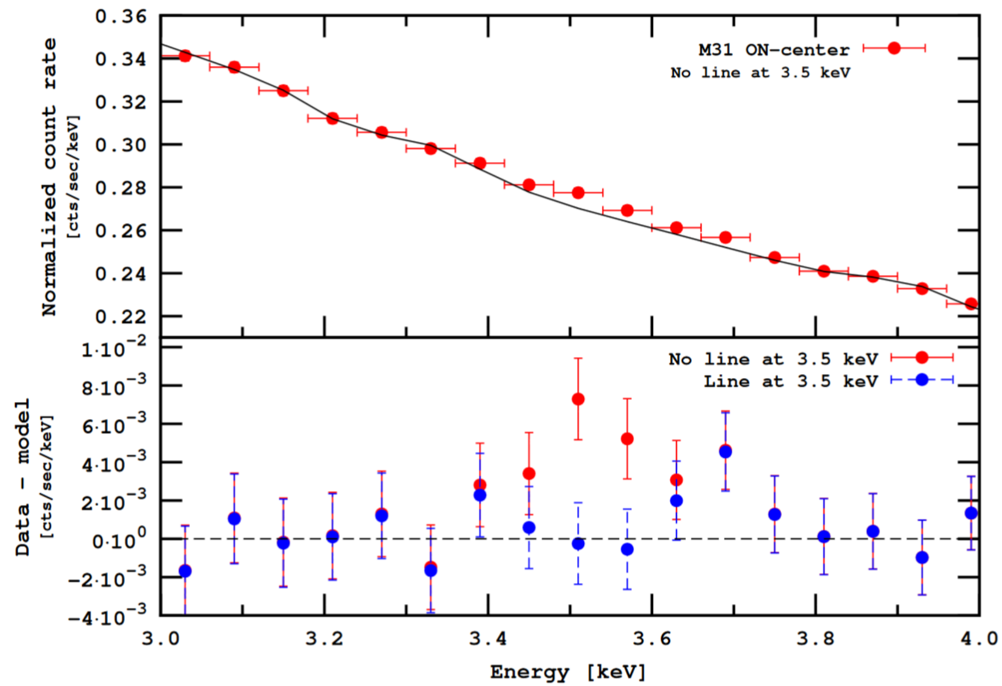
Radiative 2-body decay of sterile neutrinos produces photons with $E = 0.5 \cdot m_N$ → X-ray for m ~ keV



An unidentified line at 3.5 keV was observed at > 3σ by Chandra, XMM Newton, Suzaku and NuSTAR

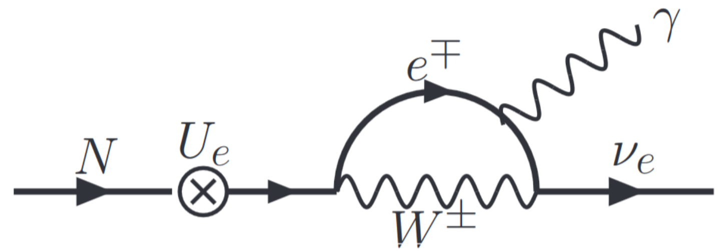
This line could be caused by

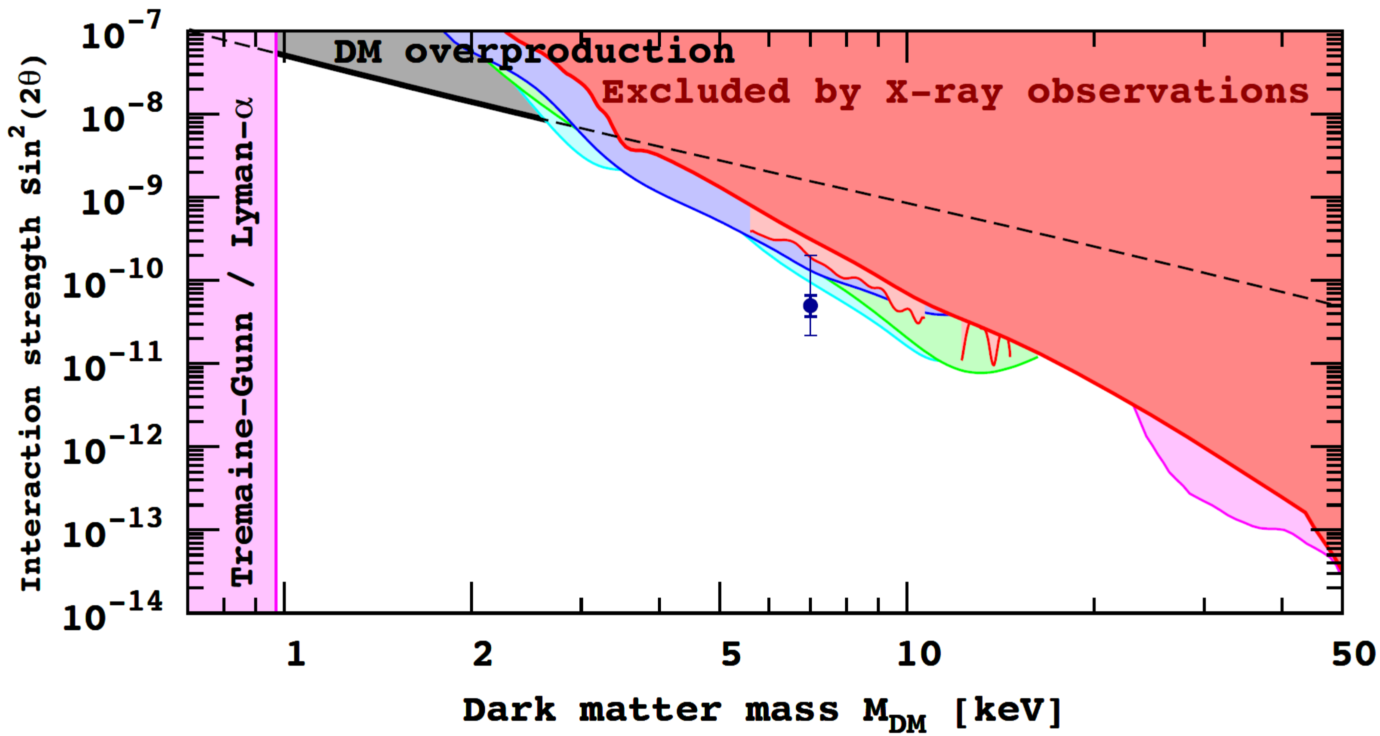
- statistical fluctuations
- a plasma emission line
- the decay of a 7 keV sterile neutrino
- fluorescent dark matter (Axions)



Sterile neutrino dark matter: X-ray bounds

Radiative 2-body decay of sterile neutrinos produces photons with $E = 0.5 \cdot m_N$ → X-ray for m ~ keV



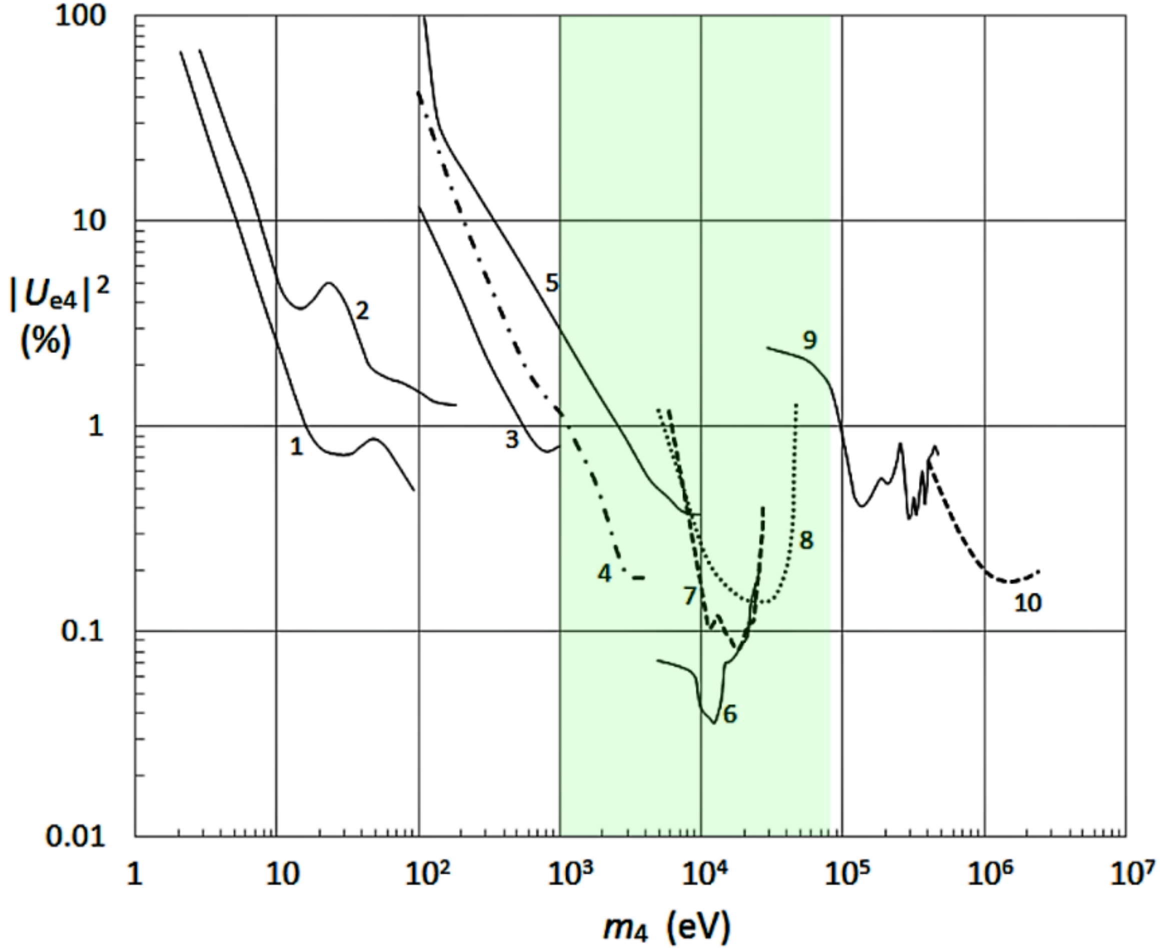


Sterile neutrinos: laboratory searches

Many laboratory searches, mainly in response to the 17 keV claim

Much weaker bounds than from the X-ray observations

 TRISTAN

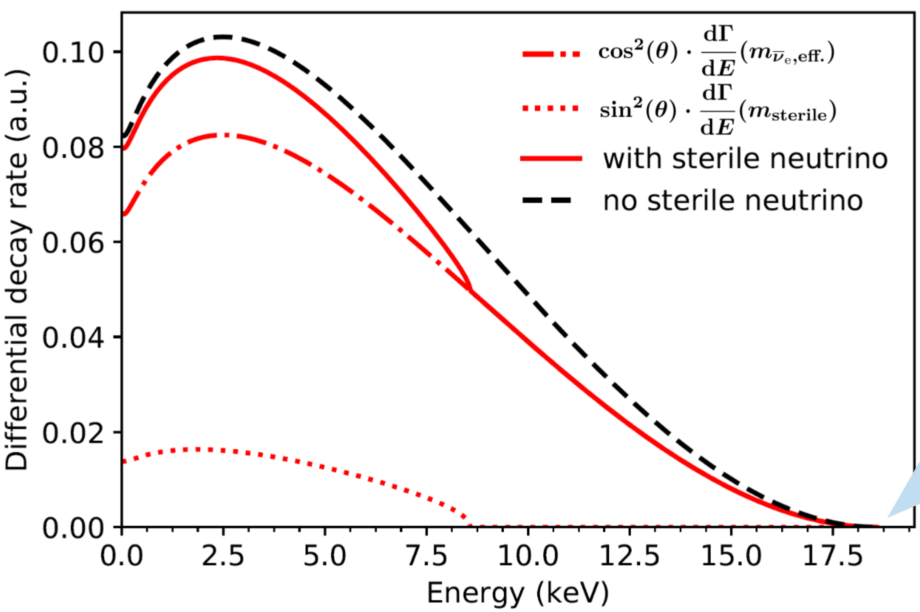


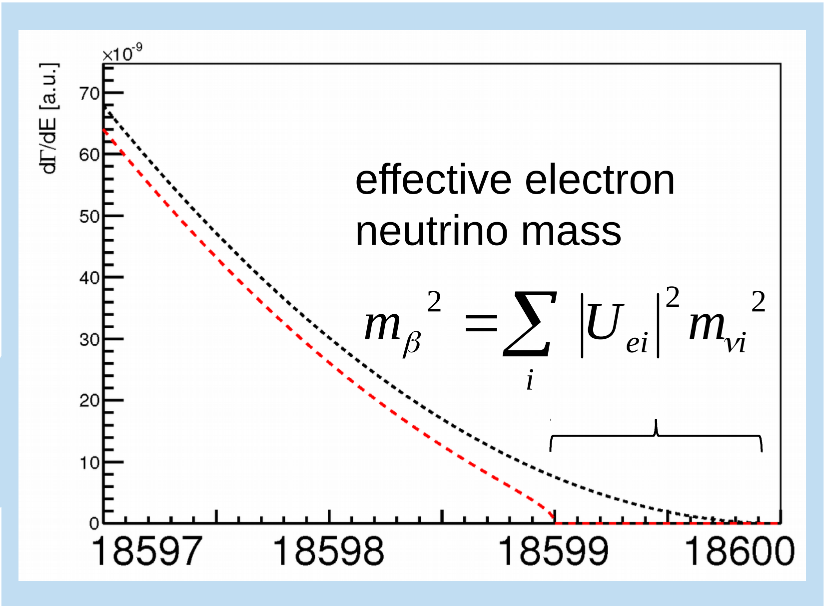
The KATRIN experiment

KATRIN measures the effective neutrino mass by its imprint on the tritium spectral shape at the endpoint:

$$N(E) = C(E) \cdot F(Z,E) \cdot p \cdot (E + m_e) \cdot (E - E_0) \cdot \sqrt{(E - E_0)^2 - m_\beta^2}$$

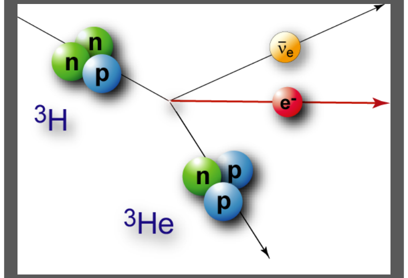
Also sterile neutrinos distort the spectrum by their admixture to active neutrinos:



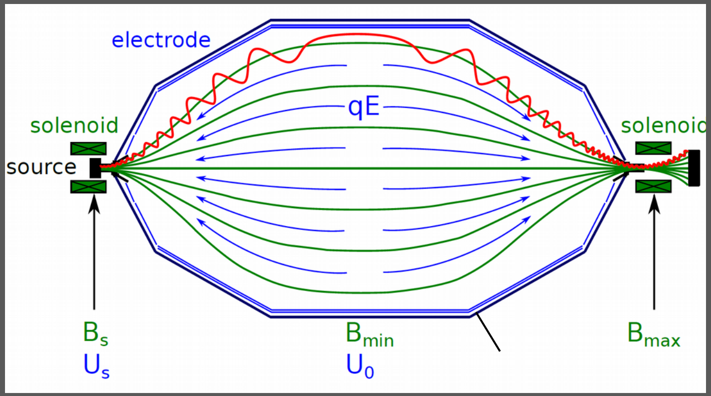


The KATRIN setup

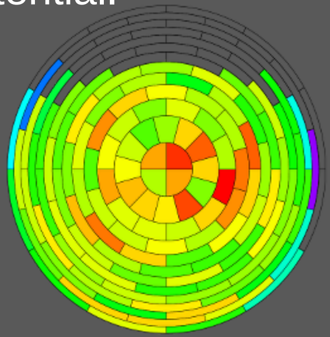
Tritium source:
10^{11} decays / s

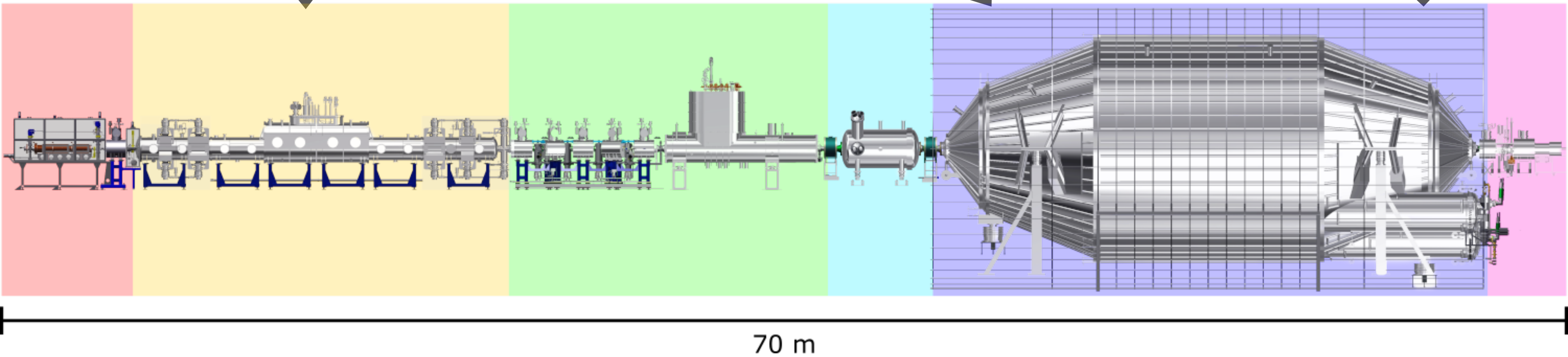


MAC-E filter: transfer vertical (cyclotron) motion of electrons into parallel motion, select energy threshold through electrostatic retarding potential



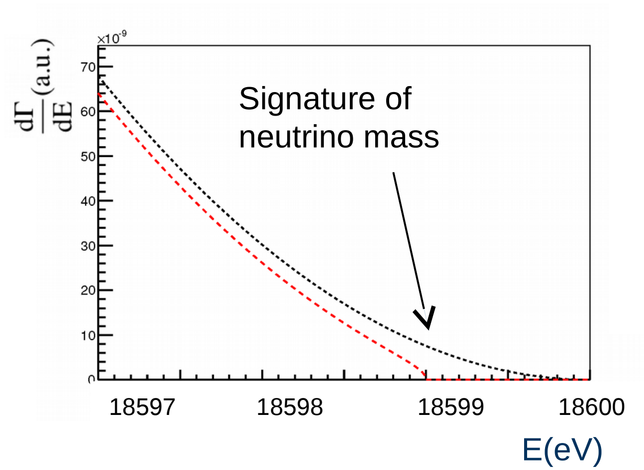
The detector is not optimized for energy resolution. An integral spectrum is measured by variing the retarding potential.

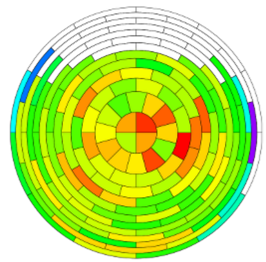




The TRISTAN project

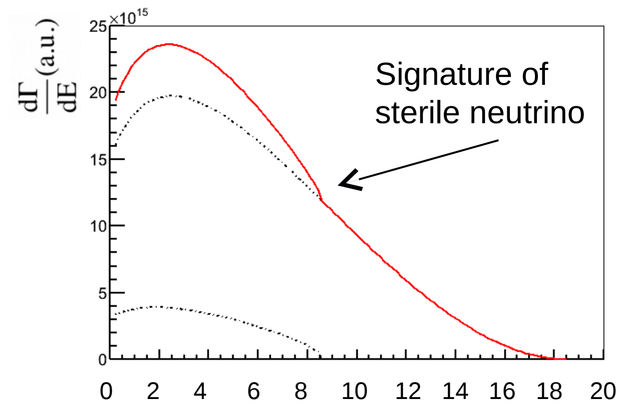
Neutrino mass measurement

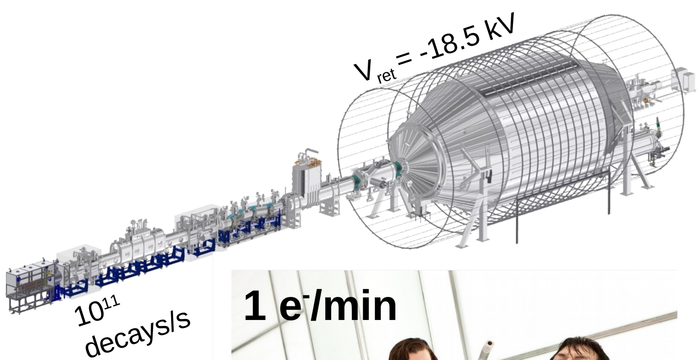


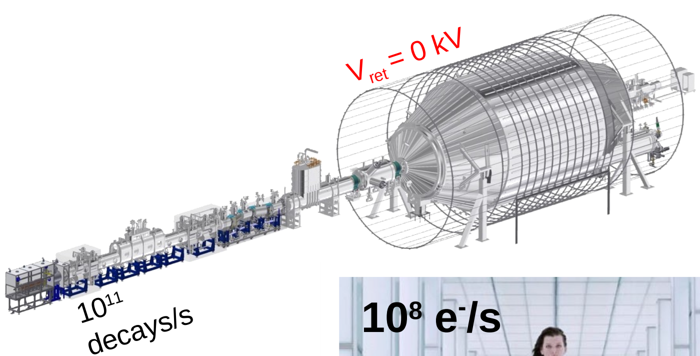


150 pixel detector

Sterile neutrino search

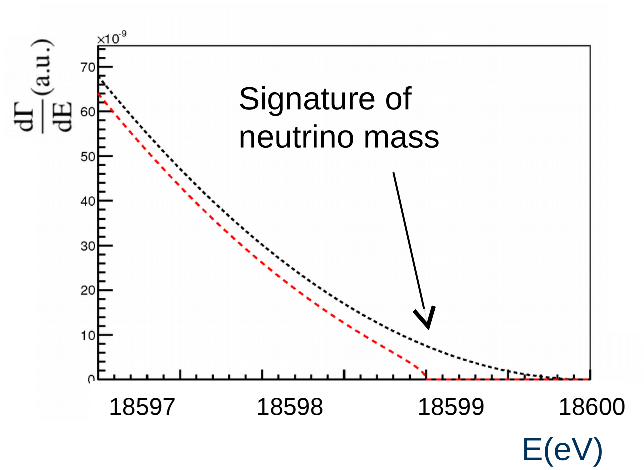


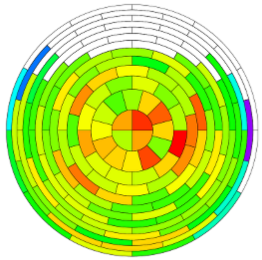




The TRISTAN project

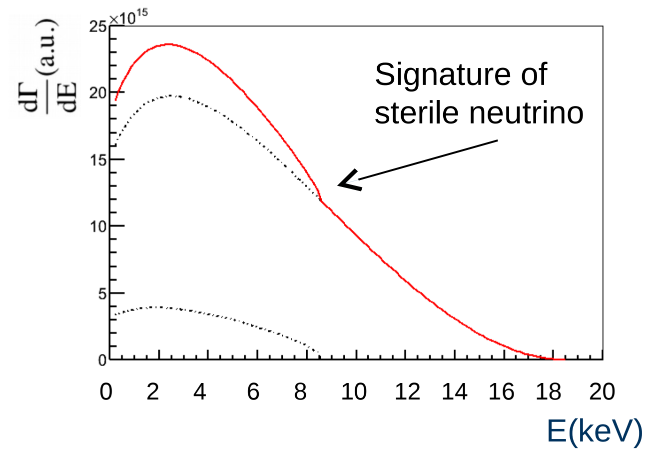
Neutrino mass measurement

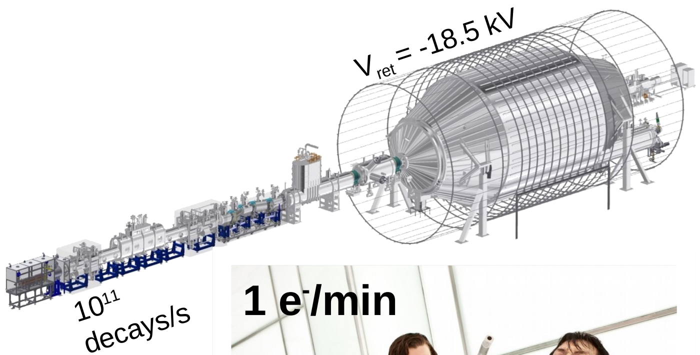


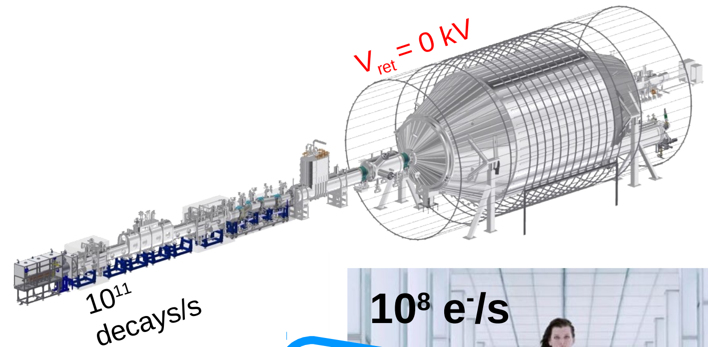


150 pixel detector

Sterile neutrino search







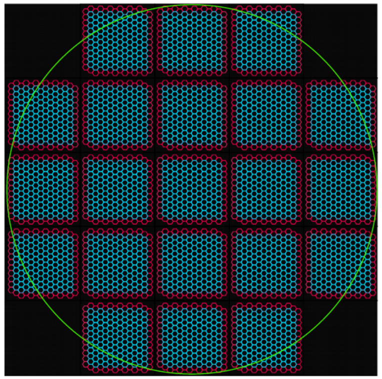
KATRIN detector cannot deal with too high rates!

The TRISTAN detector

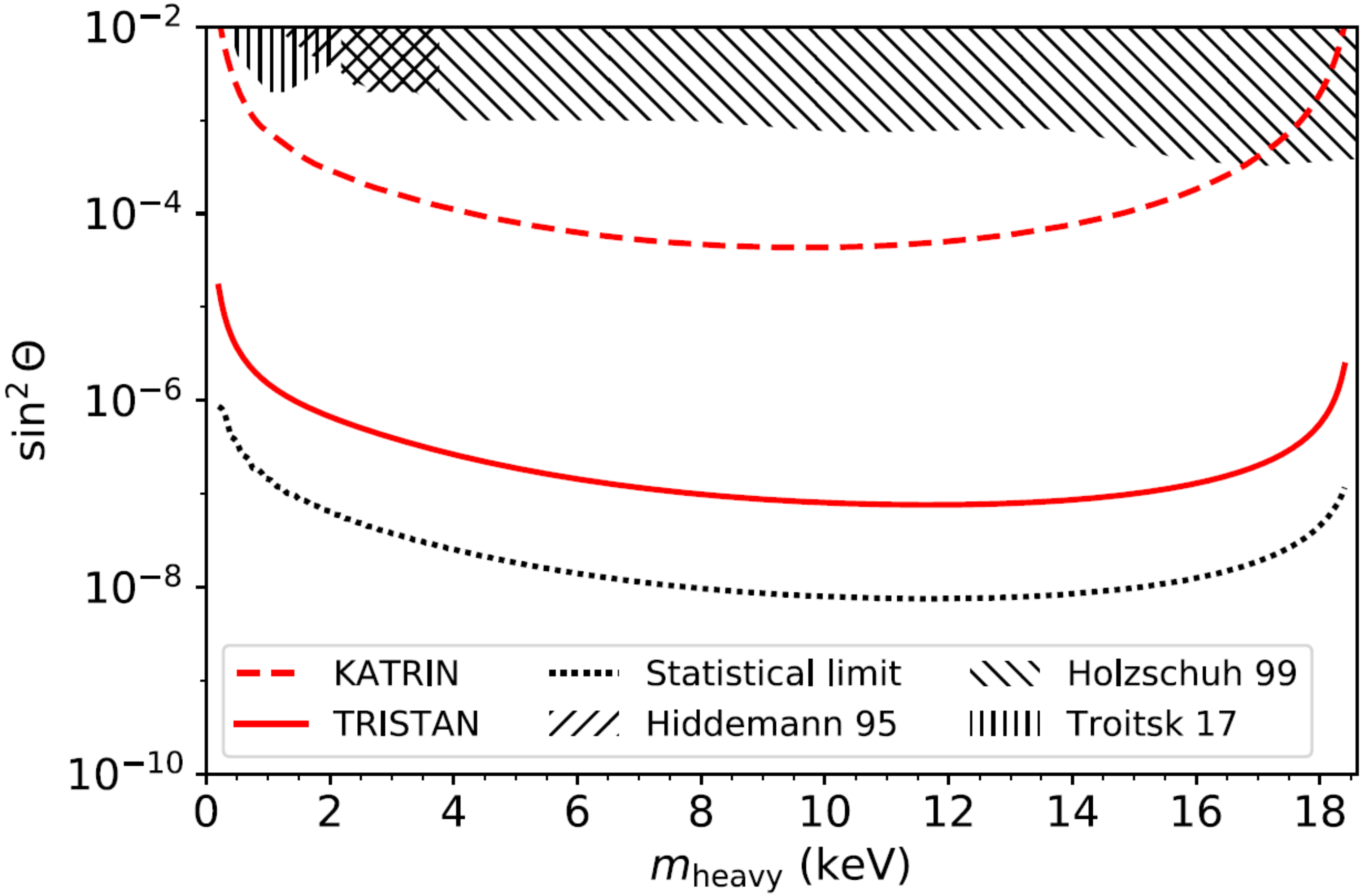
Novel detector system

- 3500 pixel silicon drift detector (SDD) array,
  3 mm pixel diameter
- very low noise
  (enc < 20,
  ~ 200 eV fwhm @ 18 keV)
- Very fast read-out

7-pixel prototypes are ready for measurements!



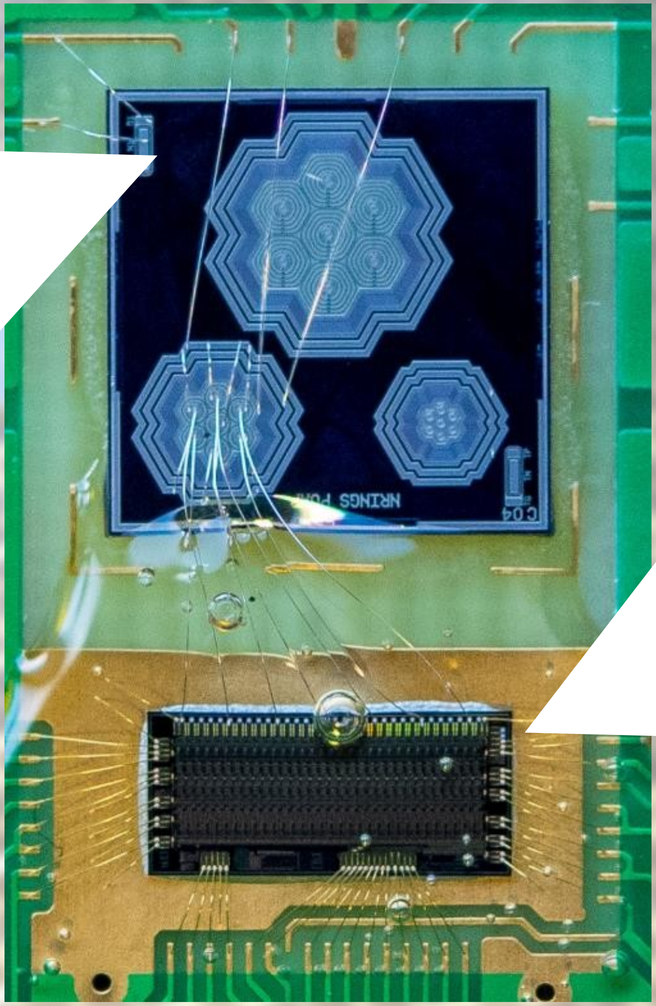
TRISTAN sensitivity



SDD prototypes with CEA readout

7-pixel SDD prototype by HLL MPG

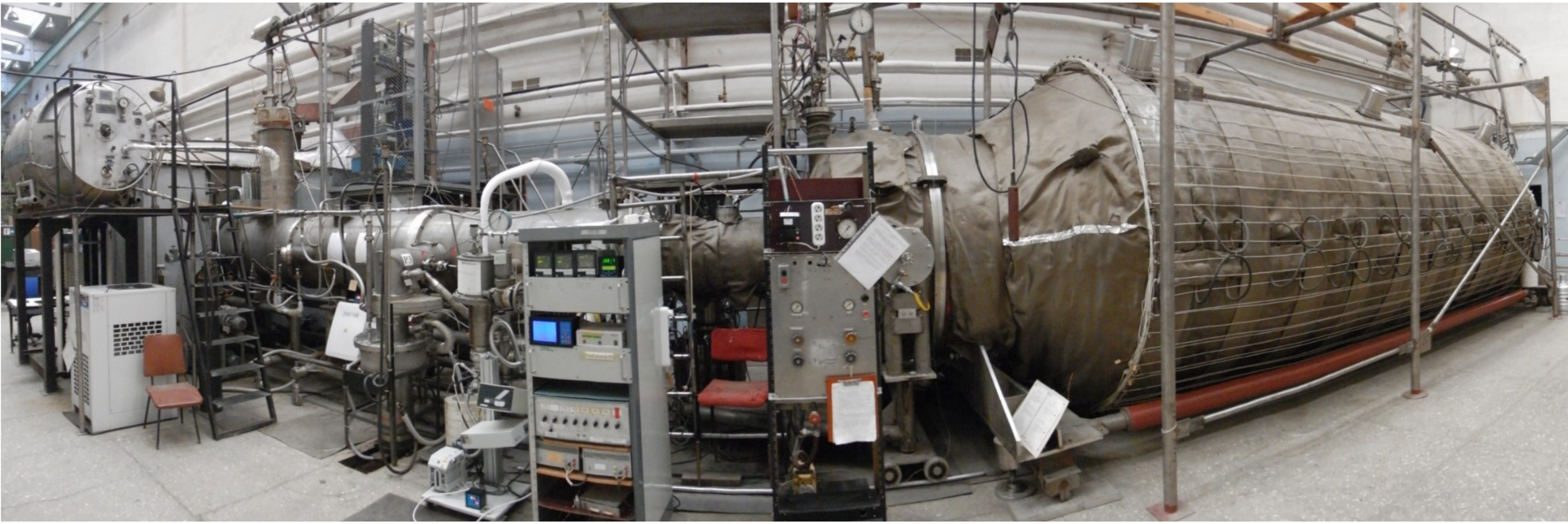
- 1 mm pixel diameter
- 450 µm thickness
- 6 drift rings
- very thin dead layer
  < 100 nm
- monolithic
   no dead area
- ultra-low capacitance



Idef-X BD ASIC by CEA Saclay

- Multi-channel read-out (32 channels), synchronized time
- Equilvalent noise charge: 44 e^-
   400 eV fwhm
  @ 18 keV

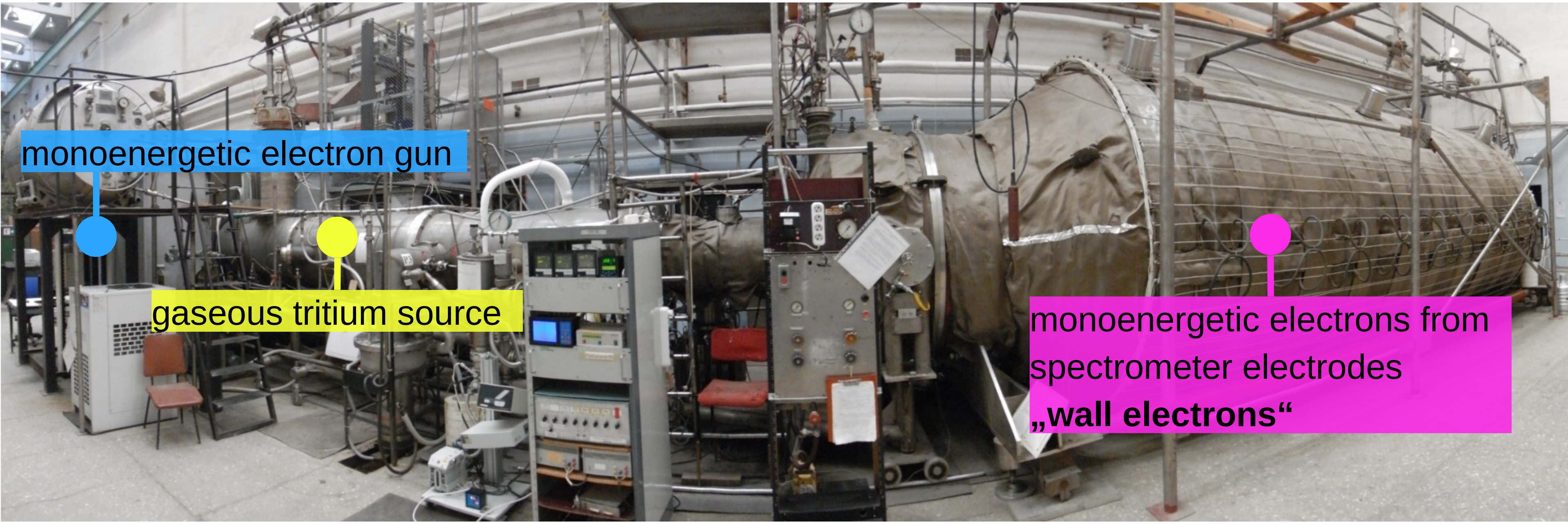
Measurements at Troitsk ν-mass



Troitsk ν-mass is a predecessor of KATRIN: set the current limit of $m_\nu < 2$ eV neutrino mass (together with the Mainz experiment)

- Neutrino mass program: late 80s to 2011
- Still active, doing sterile neutrino runs
- 3 runs with TRISTAN prototype detectors so far

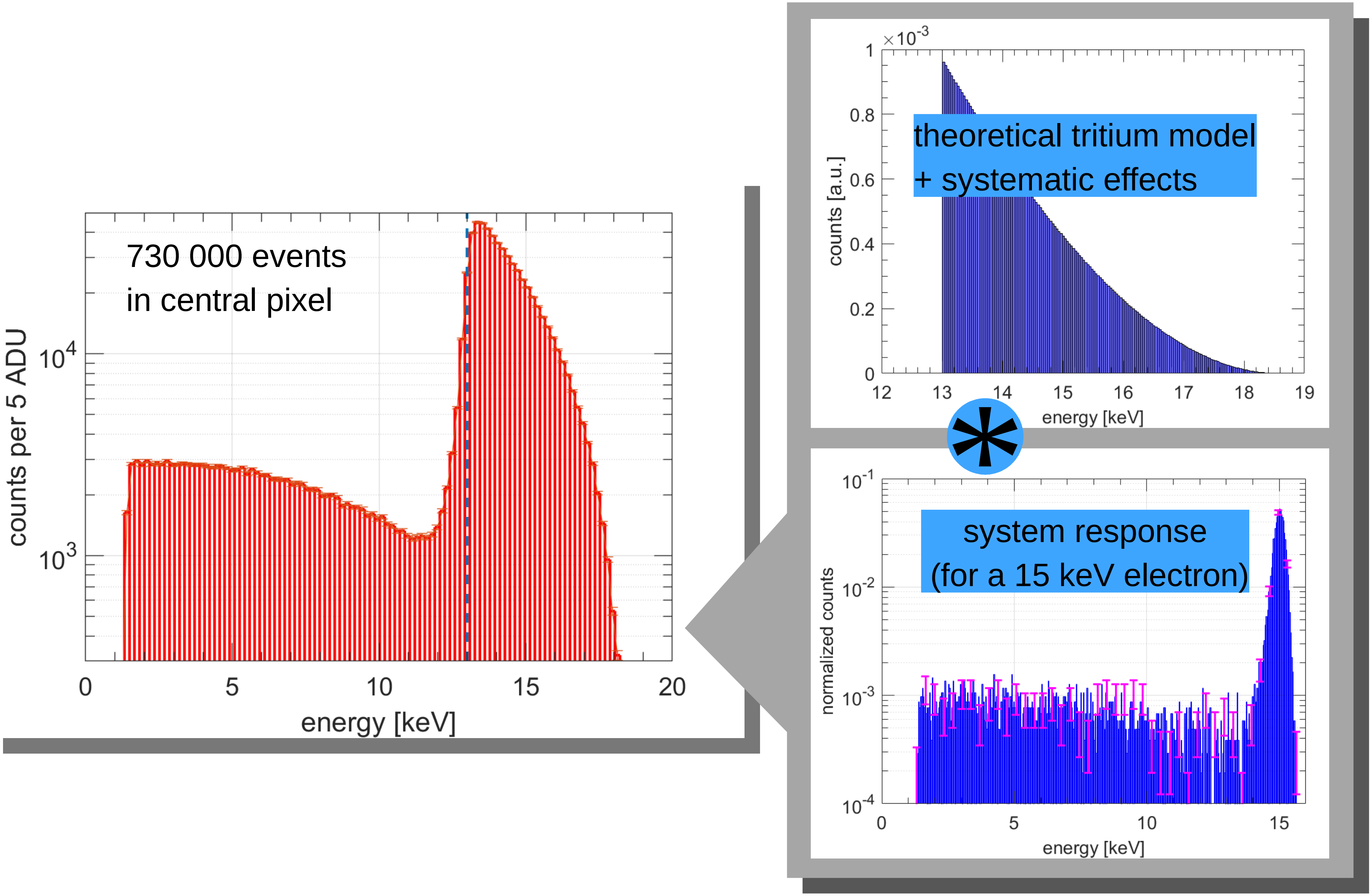
Measurements at Troitsk ν-mass



Troitsk ν-mass is a predecessor of KATRIN: set the current limit of $m_\nu < 2$ eV neutrino mass (together with the Mainz experiment)

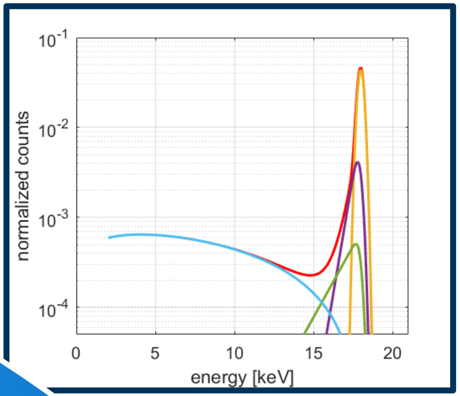
- Neutrino mass program: late 80s to 2011
- Still active, doing sterile neutrino runs
- 3 runs with TRISTAN prototype detectors so far

Measurements at Troitsk ν-mass



Analysis approach

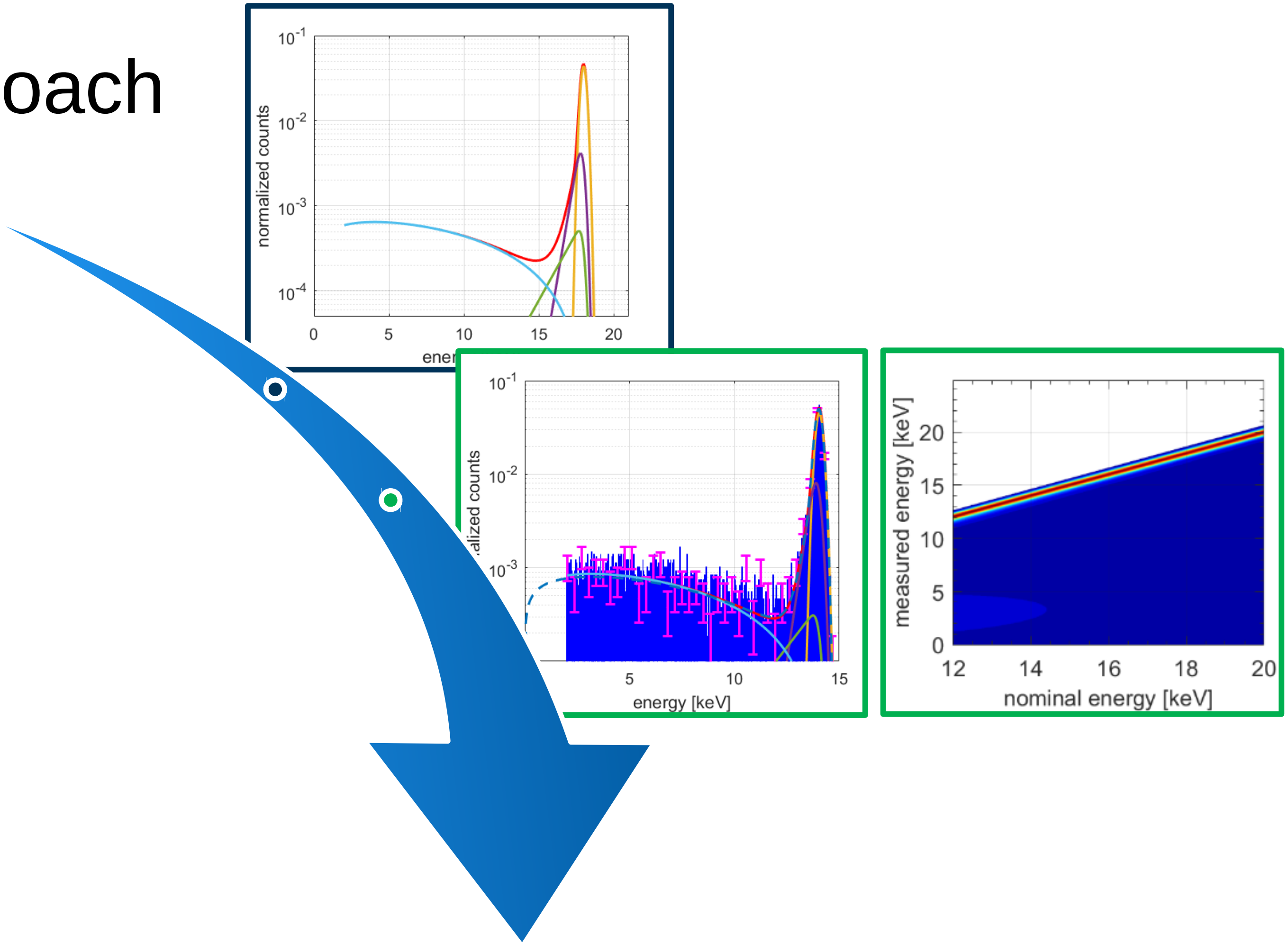
Step 1: find empirical response model



Analysis approach

Step 1: find empirical response model

Step 2: fit model to all datasets at once to obtain transfer matrix

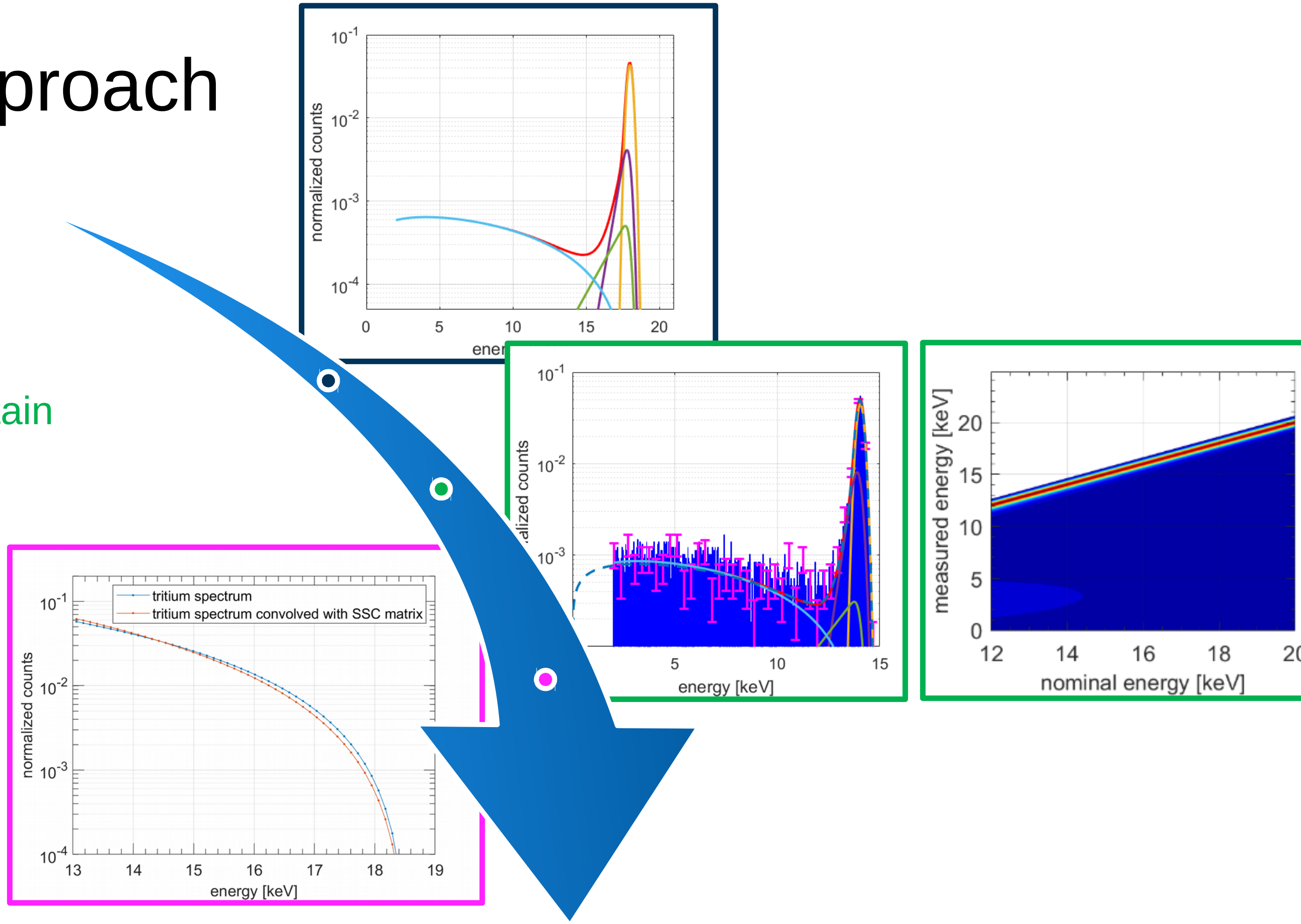


Analysis approach

Step 1: find empirical response model

Step 2: fit model to all datasets at once to obtain transfer matrix

Step 3: add effects that are not included in the response to the tritium model



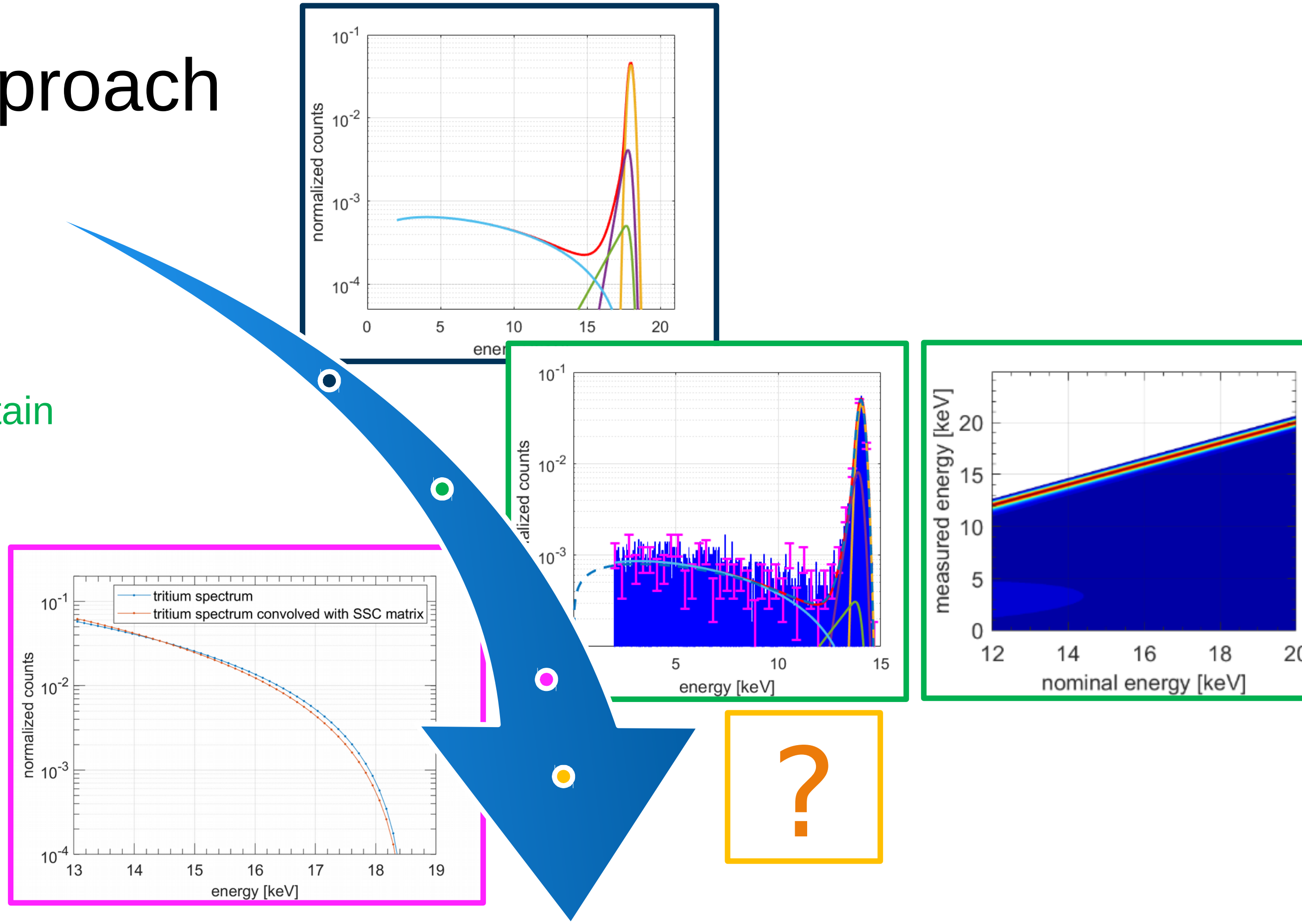
Analysis approach

Step 1: find empirical response model

Step 2: fit model to all datasets at once to obtain transfer matrix

Step 3: add effects that are not included in the response to the tritium model

Step 4: subtract background



Analysis approach

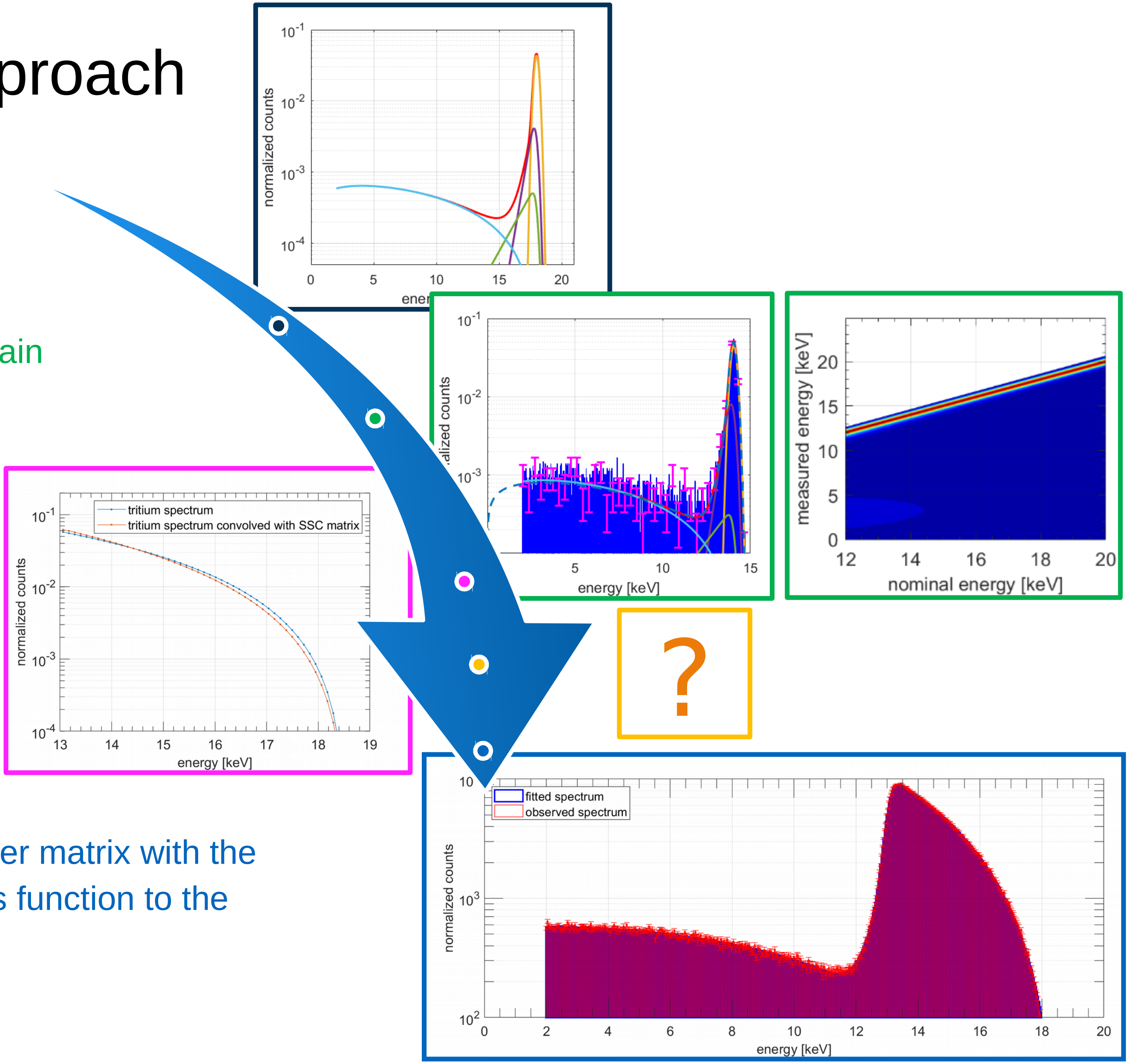
Step 1: find empirical response model

Step 2: fit model to all datasets at once to obtain transfer matrix

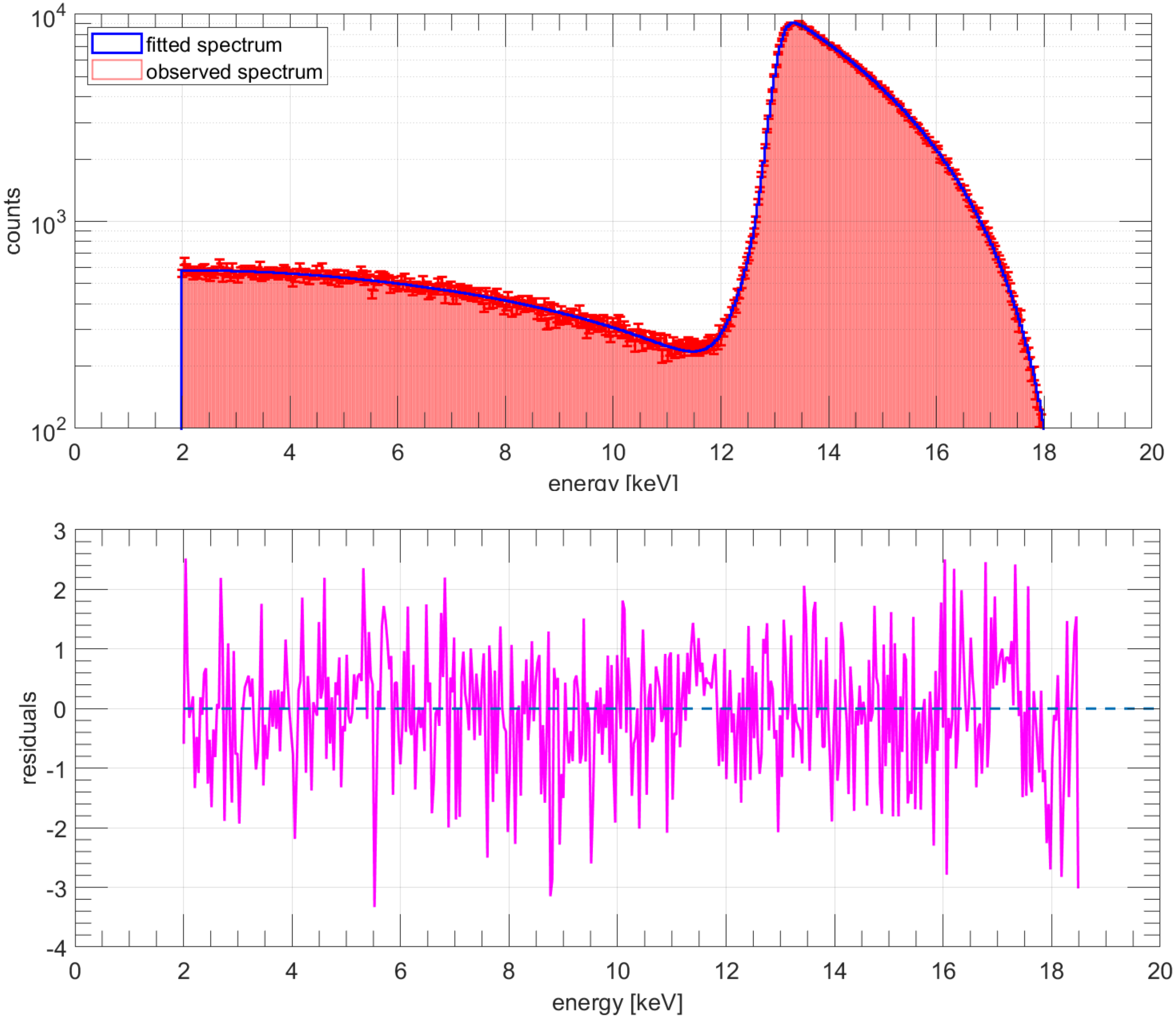
Step 3: add effects that are not included in the response to the tritium model

Step 4: subtract background

Step 5: convolve transfer matrix with the tritium model and fit this function to the observed spectrum



The tritium spectrum fit



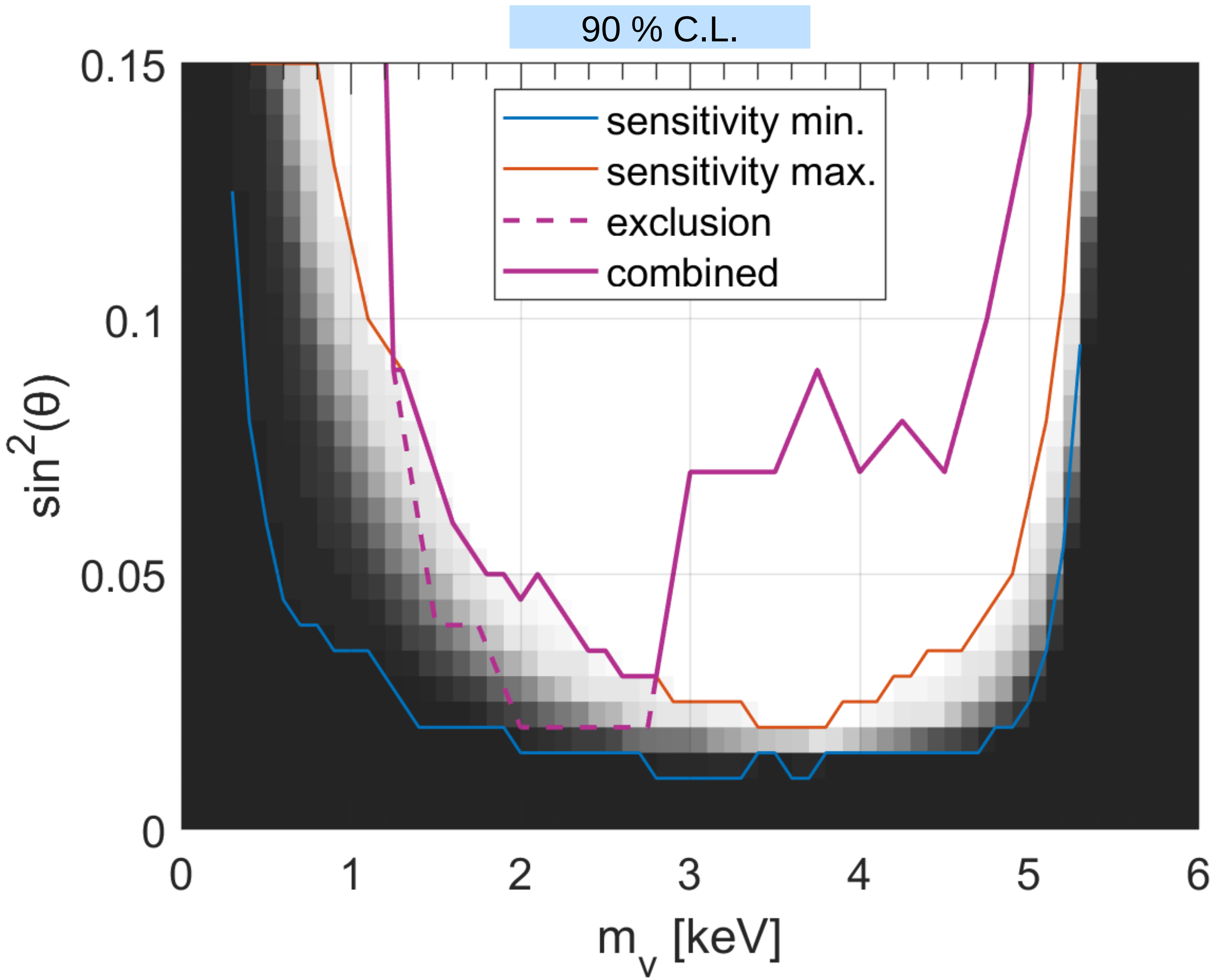
Minimization algorithm: Simplex

$$\frac{\chi^2}{\text{ndof}} = 1.085$$

$$(\text{ndof} = 469)$$

Returned parameters are reasonable and were validated with simulations the spectrum is understood

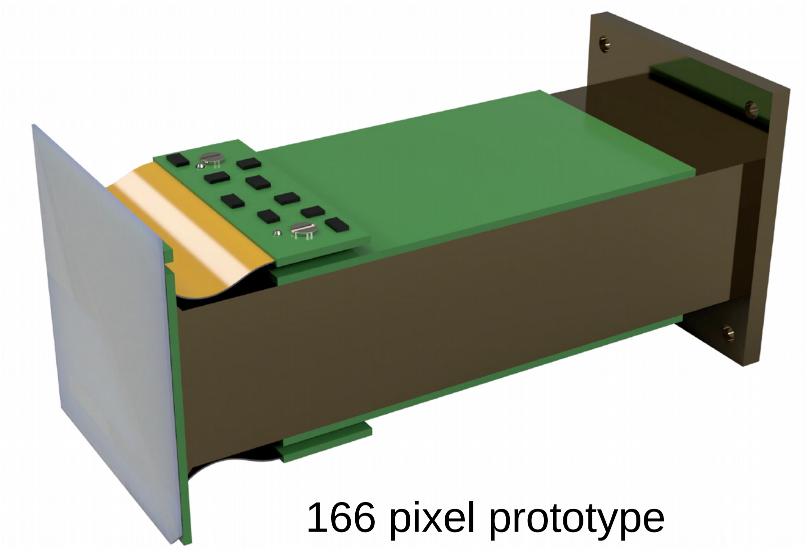
Statistical sensitivity and exclusion



Conclusions and Outlook

- TRISTAN is searching for keV-scale sterile neutrinos in the tritium spectrum
- A novel detector system is developed for KATRIN to measure the entire spectrum at very high rates of 10^8 cps with an energy resolution of a few hundred eV
- Prototype detectors very characterized and showed promising results
- Pilot study of (first) differential spectrum analysis for a MAC-E type tritium spectrometer. It was shown that the spectrum can be fitted with reasonable parameters
- Production of a larger prototype (166 pixels) has started (a module of the final array)
- Continuation of measurements at Troitsk with larger prototype

Start of final TRISTAN project after KATRIN's neutrino mass program is finished in 2024



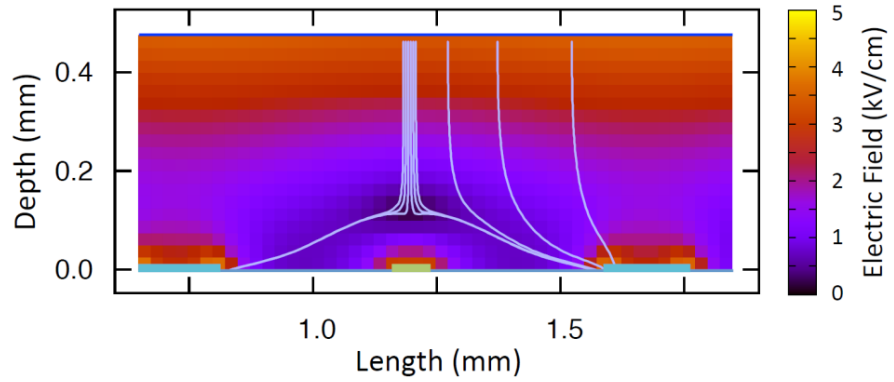
166 pixel prototype

Backup

Silicon drift detectors

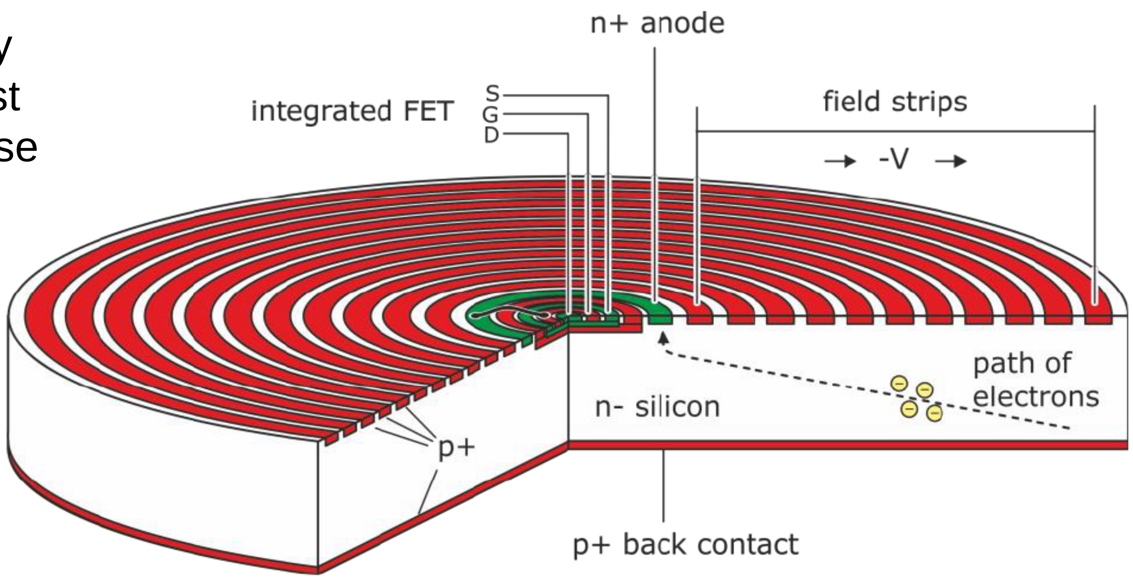
Principle: signal charge collection on small readout node by internal static electric field.

Drift rings shape the electrical field for the charge collection.



Some advantages of SDDs:

- Small capacitance due to point-like anode:
  - Low noise high energy resolution
  - High count rates
- Flexible size, flexible geometry
- possible to integrate JFET (first amplification stage) less noise
- Proven design, deep space experience, e.g. on board of ‘Opportunity‘



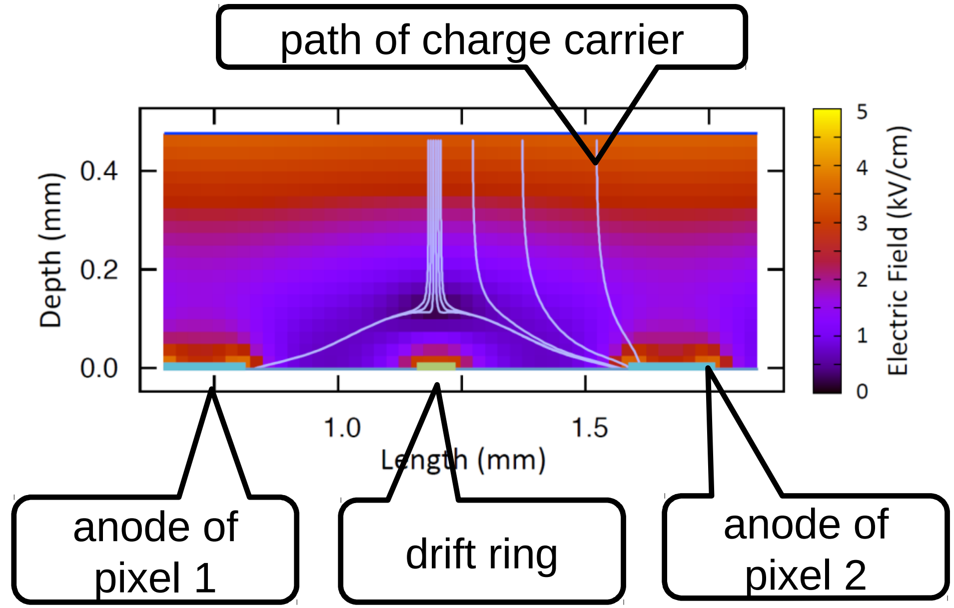
Silicon drift detectors

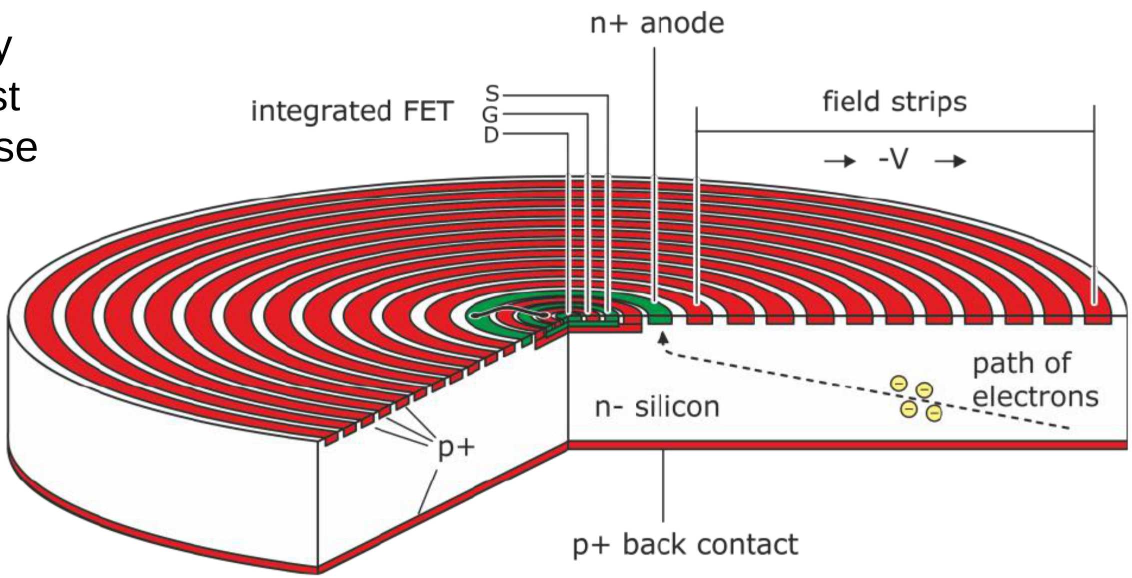
Principle: signal charge collection on small readout node by internal static electric field.

Drift rings shape the electrical field for the charge collection.

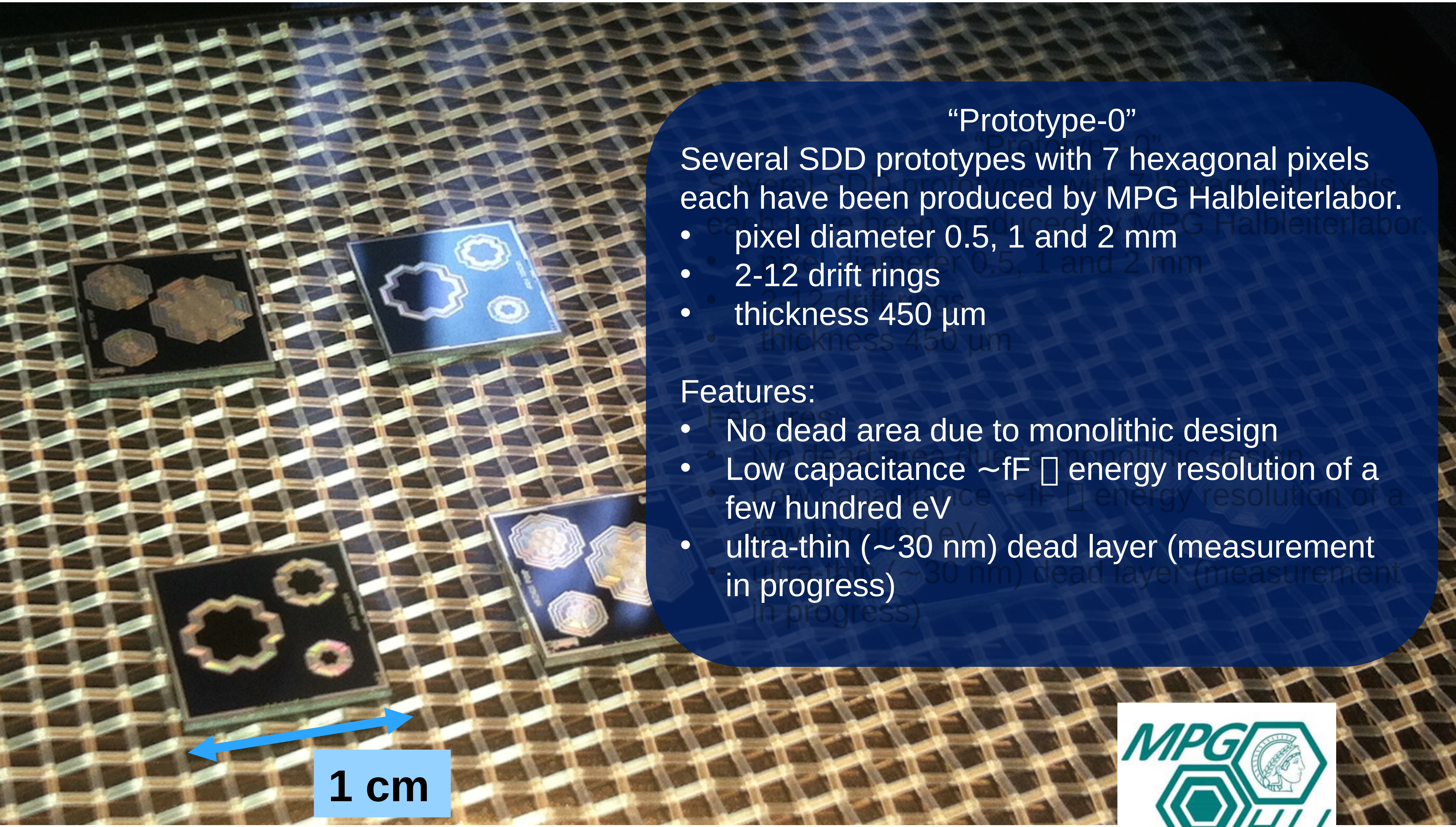
Some advantages of SDDs:

- Small capacitance due to point-like anode:
  - Low noise high energy resolution
  - High count rates
- Flexible size, flexible geometry
- possible to integrate JFET (first amplification stage) less noise
- Proven design, deep space experience, e.g. on board of ‘Opportunity‘





SDD prototypes



“Prototype-0”

Several SDD prototypes with 7 hexagonal pixels each have been produced by MPG Halbleiterlabor.

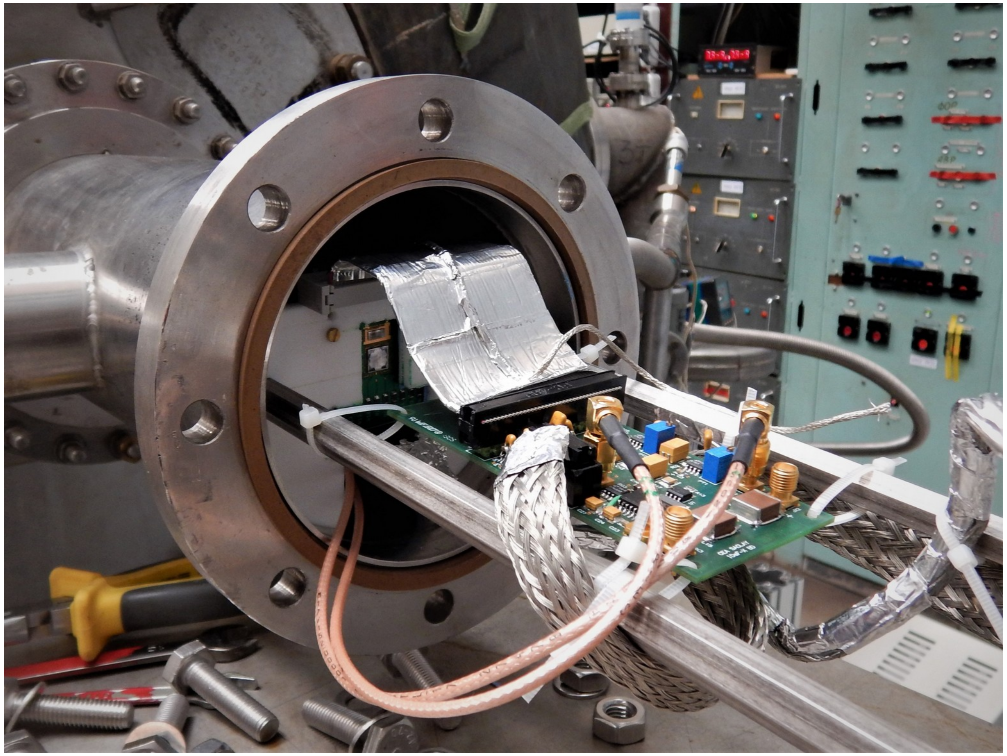
- pixel diameter 0.5, 1 and 2 mm
- 2-12 drift rings
- thickness 450 µm

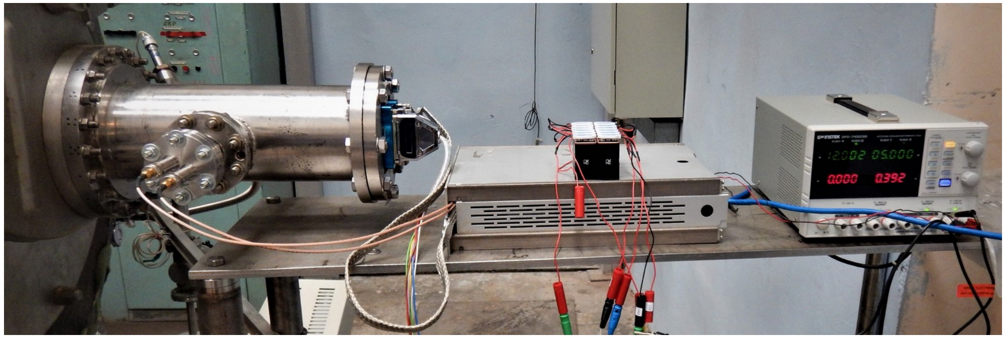
Features:

- No dead area due to monolithic design
- Low capacitance ~fF energy resolution of a few hundred eV
- ultra-thin (~30 nm) dead layer (measurement in progress)

Measurements at Troitsk ν-mass

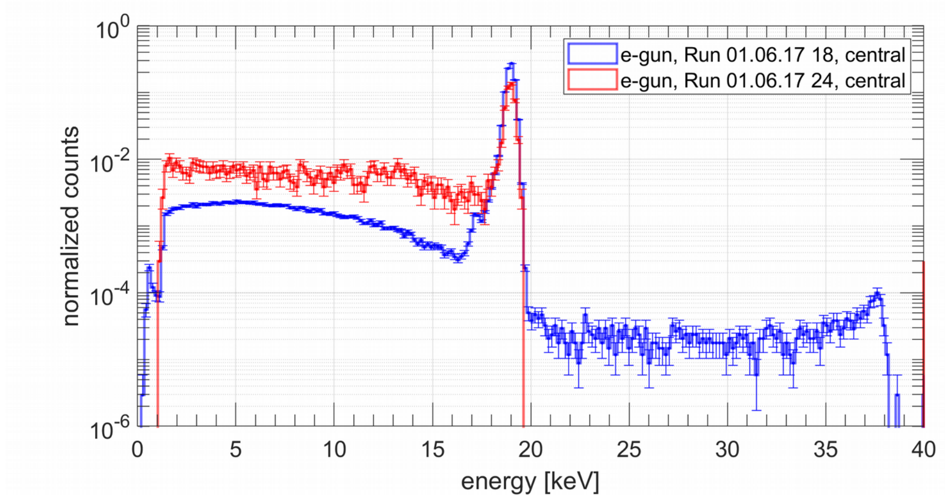
Measurements at Troitsk ν-mass

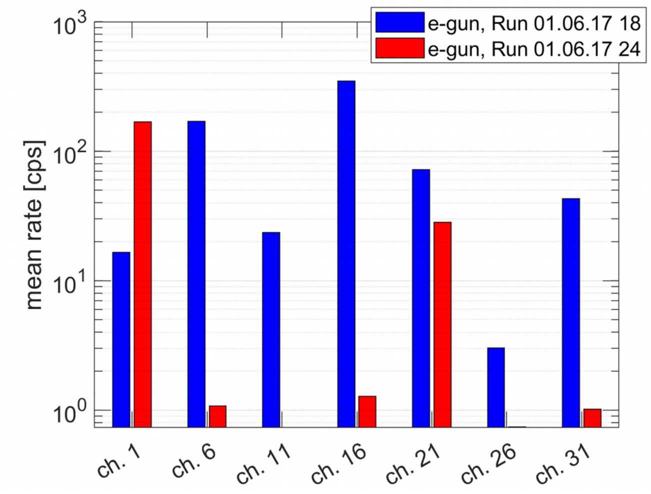




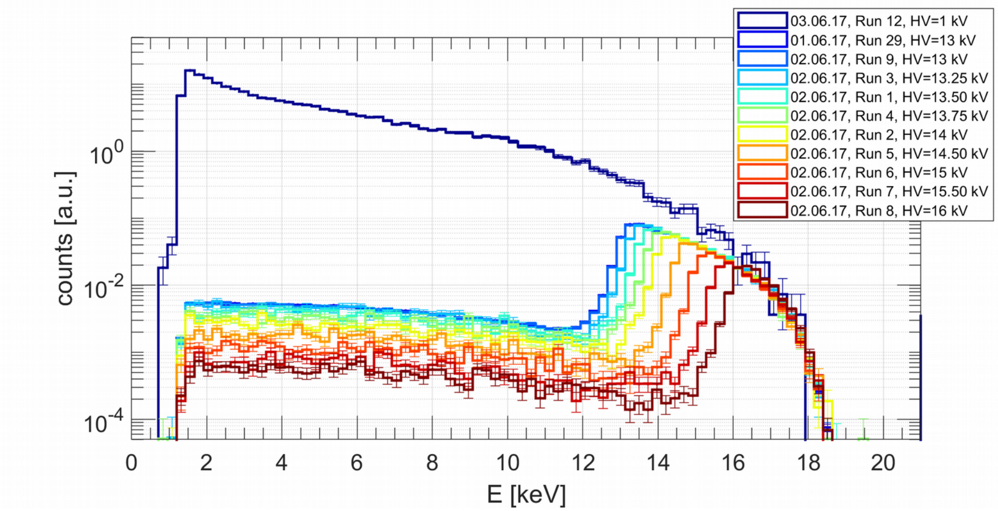
Why are we using the wall electron data?

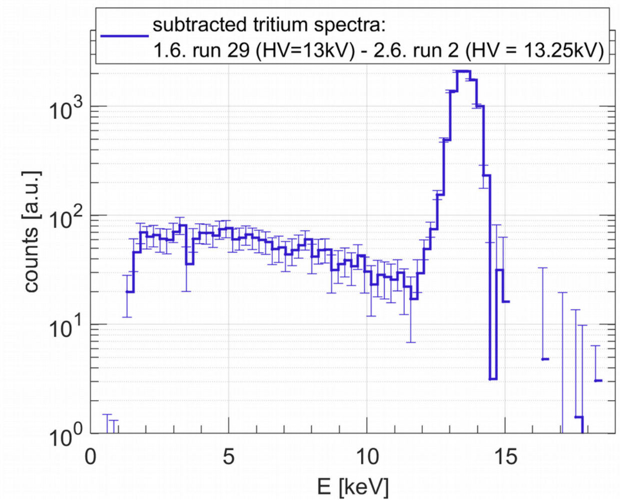
E-gun response depends on the position of the beam spot.





Subtraction of tritium spectra fails due to low statistics and poor normalization.





Parametrization of the response data

All 7 sets of **wall electron data** are fitted at once:

$$N = n \cdot exp\left(-0.5 \cdot \left(\frac{x-\mu}{\sigma}\right)^2\right)$$ Gaussian

$$+ n \cdot n_2 \cdot exp\left(\frac{x-\mu}{\beta}\right) \cdot \mathrm{erfc}\left(\frac{x-\mu}{\sqrt{2}\cdot\sigma} + \frac{\sigma}{\sqrt{2}\cdot\beta}\right)$$ exponential tail

$$+ n \cdot n_4 \cdot \left(\frac{x}{\mu}\right)^b \cdot \left(1 - \left(\frac{x}{\mu}\right)\right)^c$$ back-scatter tail

Each red parameter is itself a linear function of the inital electron energy, μ, e.g.: $n_2 = p(1) + p(2) \cdot \mu$

→ **10 parameters**

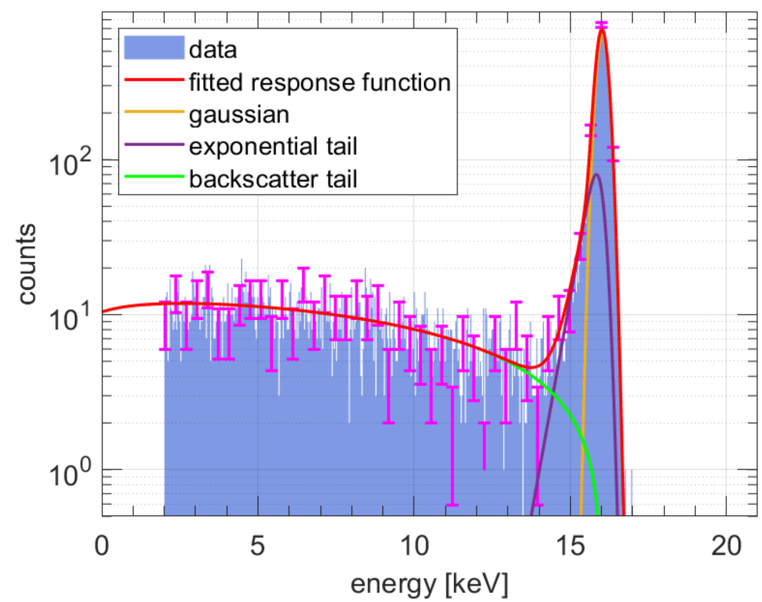
+ normalization n for each data set: **7 parameters**

+ resolution σ for each data set: **7 parameters**

+ calibration: **7 parameters** (only offset, gain was fixed)

In total: 31 parameters

→ iterative fitting with MINUIT



Parametrization of the response data

All 7 sets of wall electron data are fitted at once:

$$N = n \cdot exp\left(-0.5 \cdot \left(\frac{x-\mu}{\sigma}\right)^2\right)$$ Gaussian

$$+\, n \cdot n_2 \cdot exp\left(\frac{x-\mu}{\beta}\right) \cdot \mathrm{erfc}\left(\frac{x-\mu}{\sqrt{2}\cdot\sigma} + \frac{\sigma}{\sqrt{2}\cdot\beta}\right)$$ exponential tail

$$+\, n \cdot n_4 \cdot \left(\frac{x}{\mu}\right)^b \cdot \left(1 - \left(\frac{x}{\mu}\right)\right)^c$$ back-scatter tail

Each red parameter is itself a linear function of the inital electron energy, μ, e.g.: $n_2 = p(1) + p(2) \cdot \mu$

→ **10 parameters**

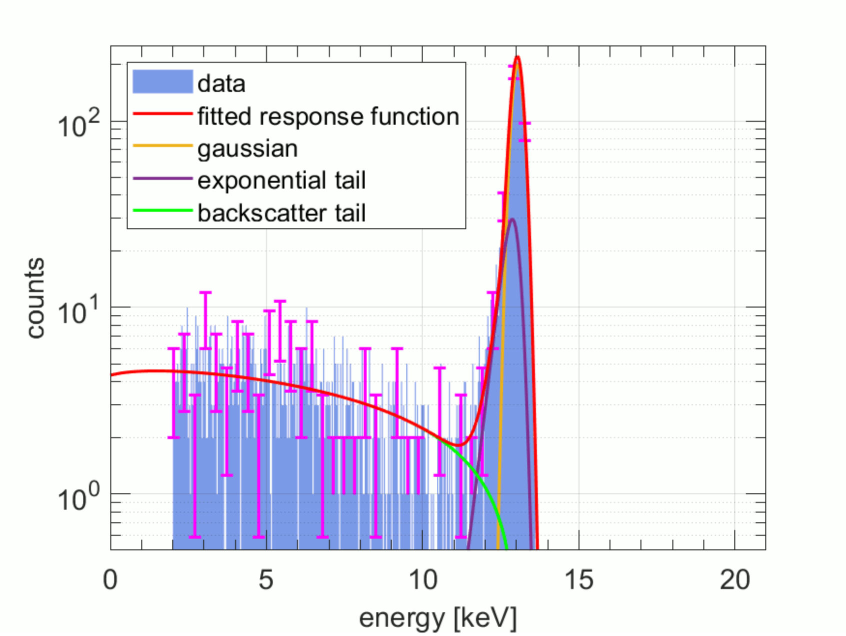
+ normalization n for each data set: **7 parameters**

+ resolution σ for each data set: **7 parameters**

+ calibration: **7 parameters** (only offset, gain was fixed)

In total: 31 parameters

→ iterative fitting with MINUIT



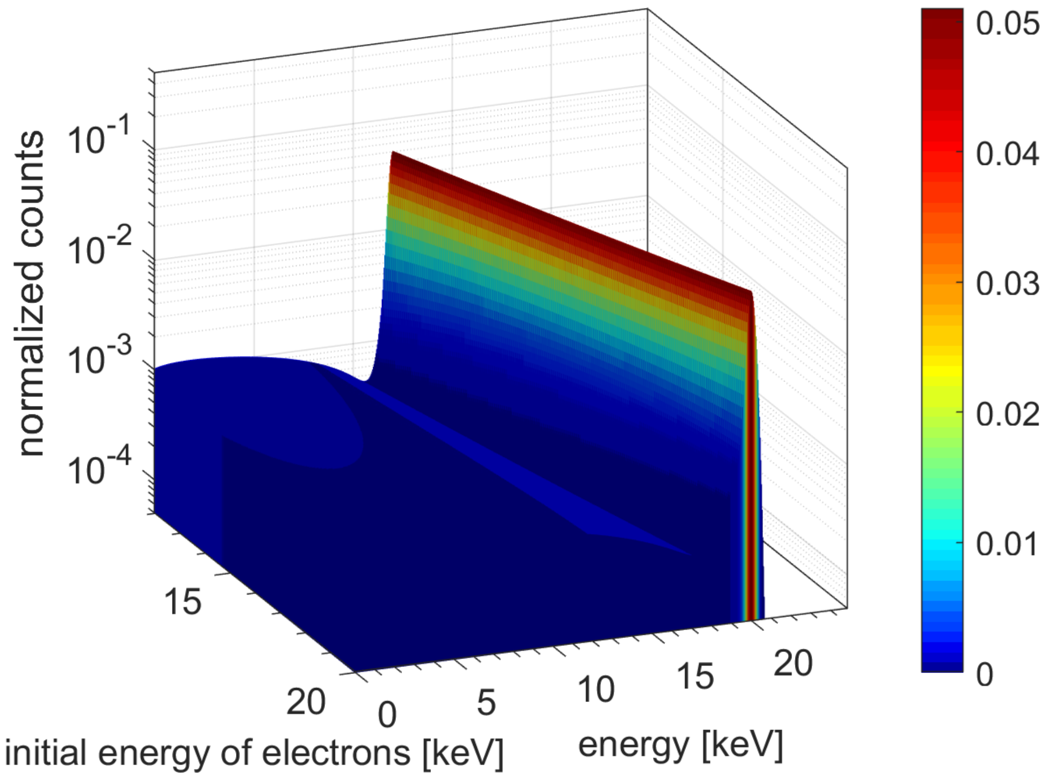
Parametrization of response data

Some bins contain only a few events: minimization of Poissonian chi squared:
Some bins contain only a few events: minimization of Poissonian chi squared:

Result:

$$\chi_P^2 = -2 \cdot \sum_i \left(n_i - \nu_i + n_i \cdot \log\left(\frac{\nu_i}{n_i}\right)\right)$$

Result: $\frac{\chi_P^2}{\mathrm{ndof}} = 1.089 \; (\mathrm{ndof} = 2969)$



The tritium spectrum fit

<u>Fitting function:</u>

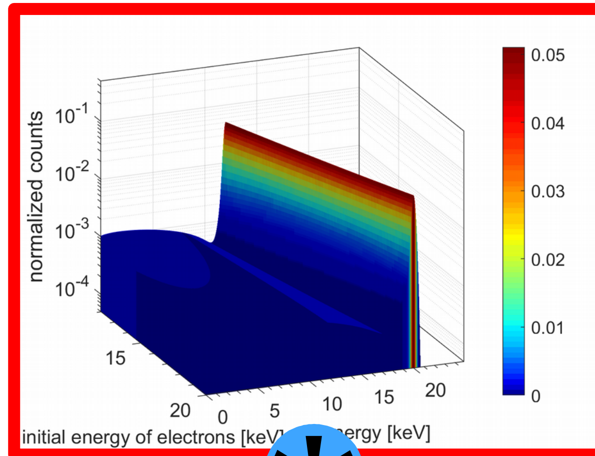
- n: 1 parameter for normalization
- p: measured response of electrons from the spectrometer electrodes is not similar to the response of tritium electrons
  → parametrization is included with 10 parameters
  + 1 parameter for noise (fwhm)
- p_{calib}: 2 parameters for calibration
- p_{SSC}: 3 parameters to account for scattering in the source

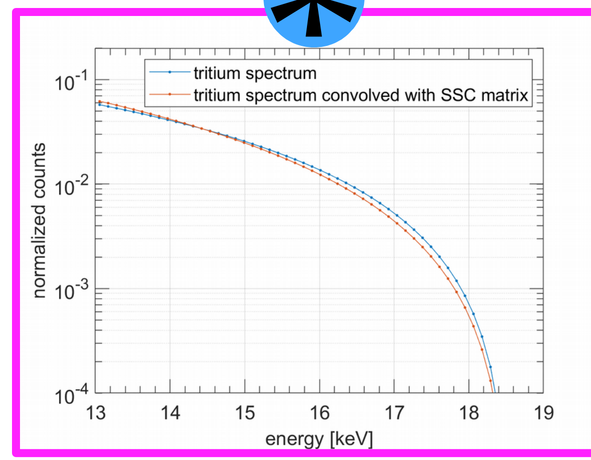
→ **in total 17 parameters**

Fitting function:
- : 1 parameter for normalization
- : measured response of electrons from the spectrometer electrodes is not similar to the response of tritium electrons
  □ parametrization is included with 10 parameters
  + 1 parameter for noise (fwhm)
- : 2 parameters for calibration
- : 3 parameters to account for scattering in the source

□ **in total 17 parameters**

$$f_{\text{spectrum}}(n, p, p_{\text{calib}}, p_{\text{SSC}}, E) = n \cdot \sum_{j}^{N} f_{\text{response}}\left(p, E_{\text{in},j}, E \cdot p_{\text{calib}}(1) + p_{\text{calib}}(2)\right) \times \left(f_{\text{SSC}}(p_{\text{SSC}}, E_{\text{in},j}) \cdot f_{\text{tritium model}}(\Delta m_S, \sin^2\theta_S, E_{\text{in},j})\right)$$





Simulations: how do the responses differ?

<u>Wall electrons:</u>

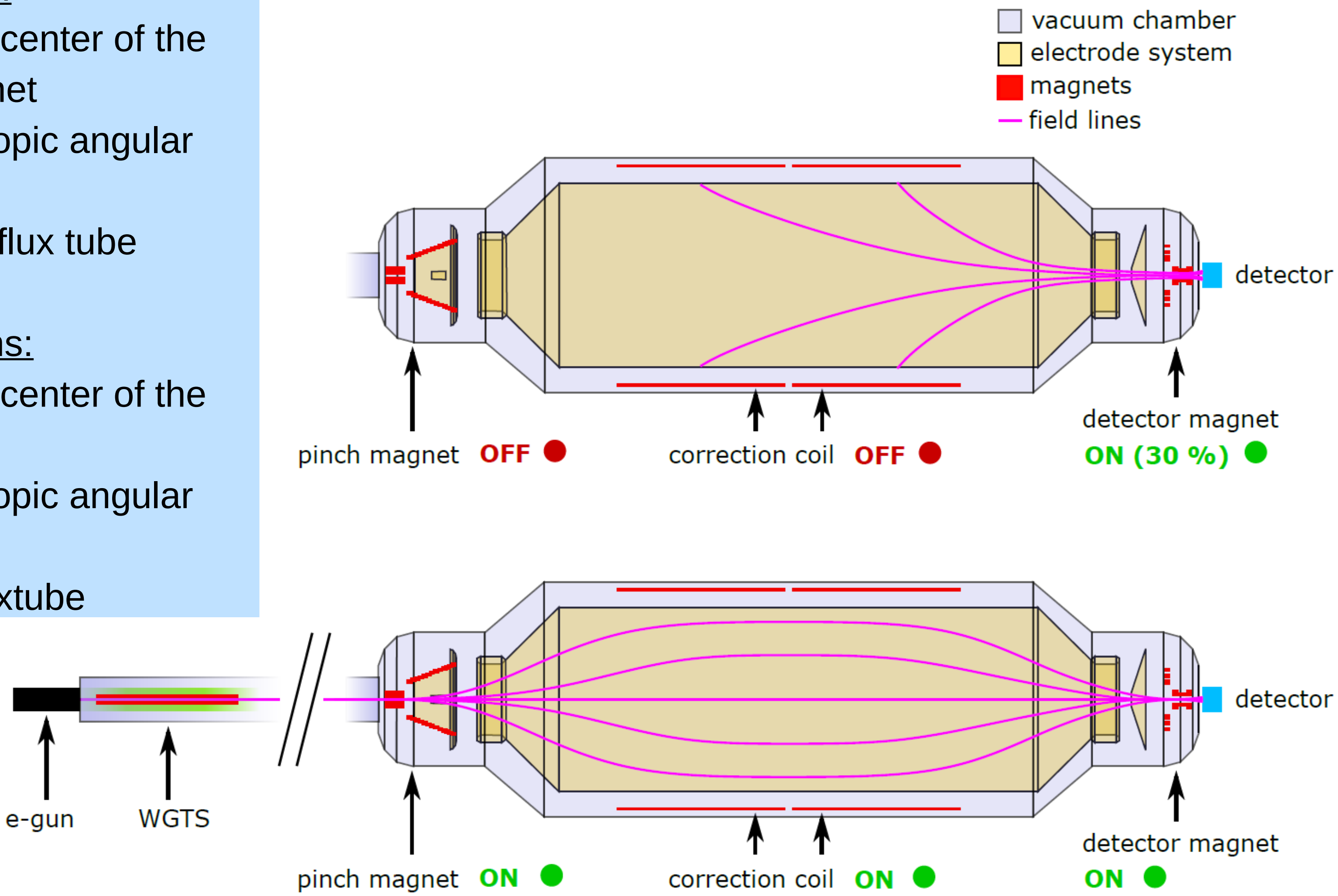
Started in the center of the detector magnet

- 0-90° isotropic angular distribution
- 1.581 mm flux tube

<u>Pinch electrons:</u>

Started in the center of the pinch magnet

- 0-52° isotropic angular distribution
- 1.4 mm fluxtube



Statistical sensitivity and exclusion