Silicon drift detector prototypes for the keV-scale sterile neutrino search with TRISTAN

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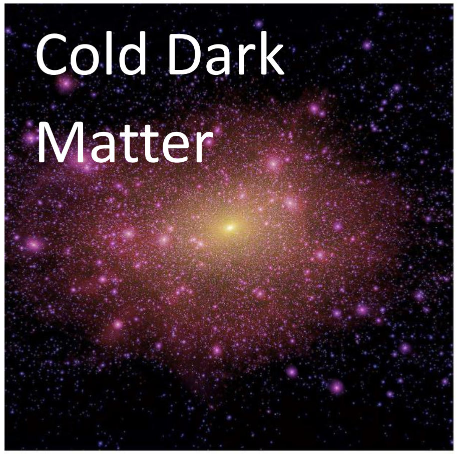
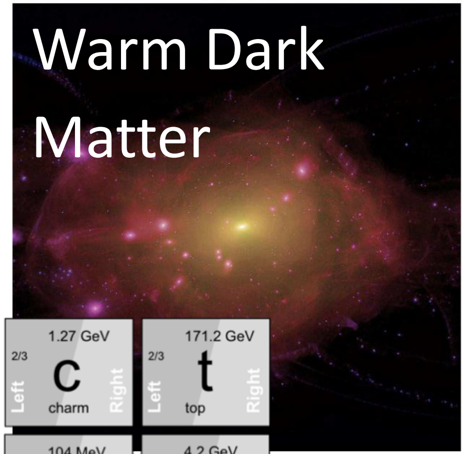
keV-scale sterile neutrinos

- Sterile neutrinos with keV-scale masses are dark matter candidates
- Sterile neutrinos could mitigate small scale problems
- X-ray telescopes put strong bounds on keV-scale sterile neutrinos (3.5 keV line?)
- Sterile neutrinos can be added as right-handed leptons to the standard model in a minimal extension





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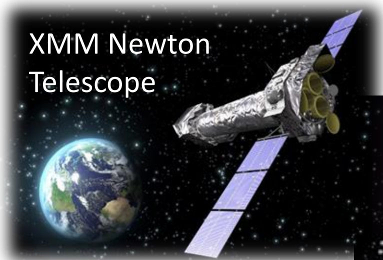
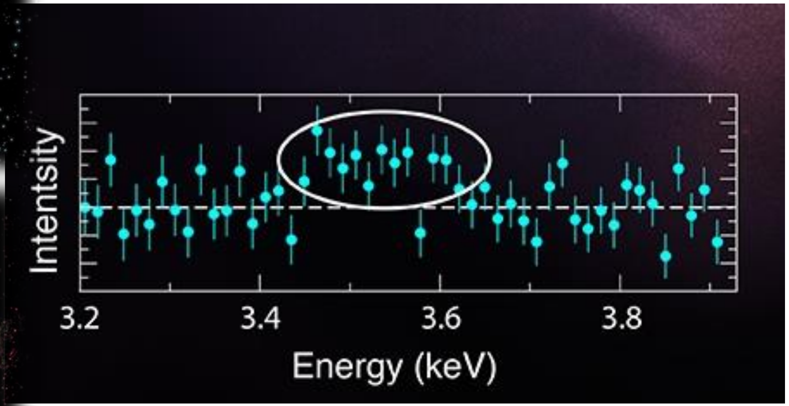
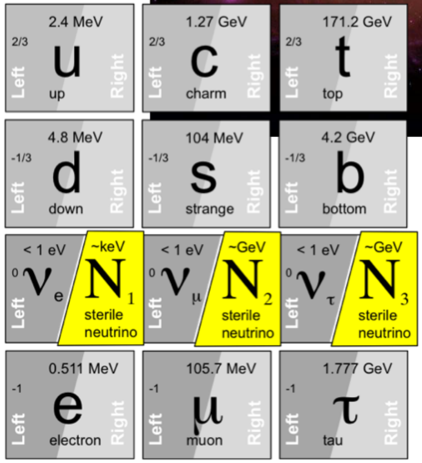






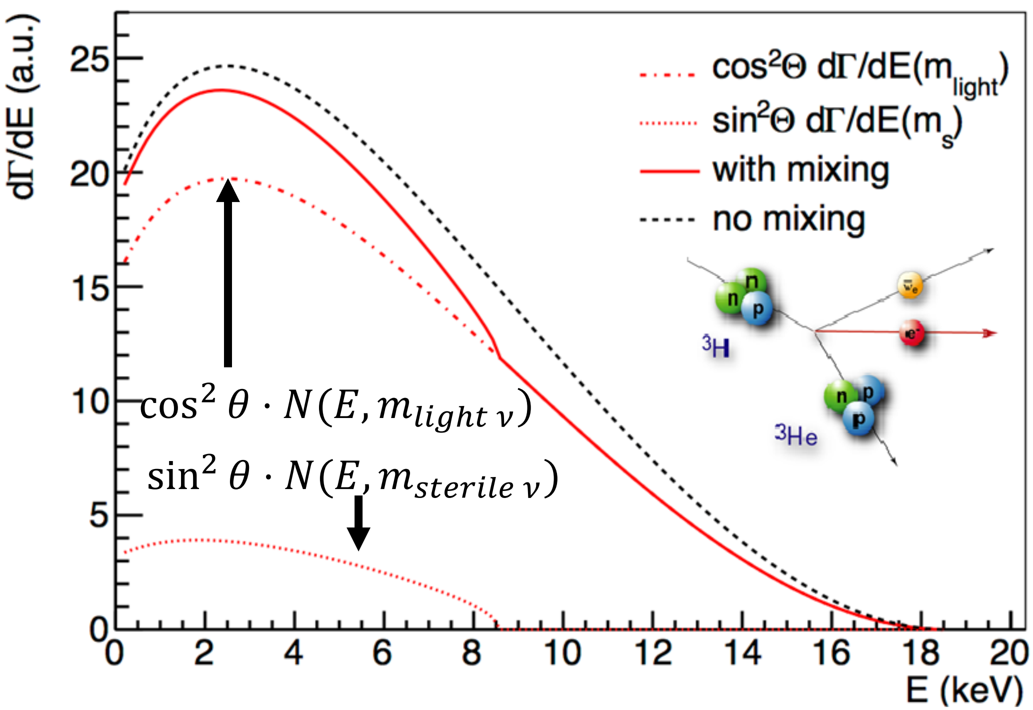
E. Bulbul *et al.* 2014 *ApJ* **789,** Boyarsky *et al.* 2014 *PRL* **113**

The KATRIN Experiment

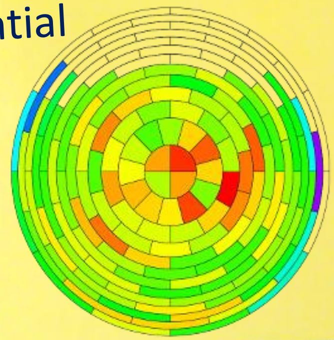
KATRIN measures the effective neutrino mass by its imprint on the tritium spectral shape at the endpoint:

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

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

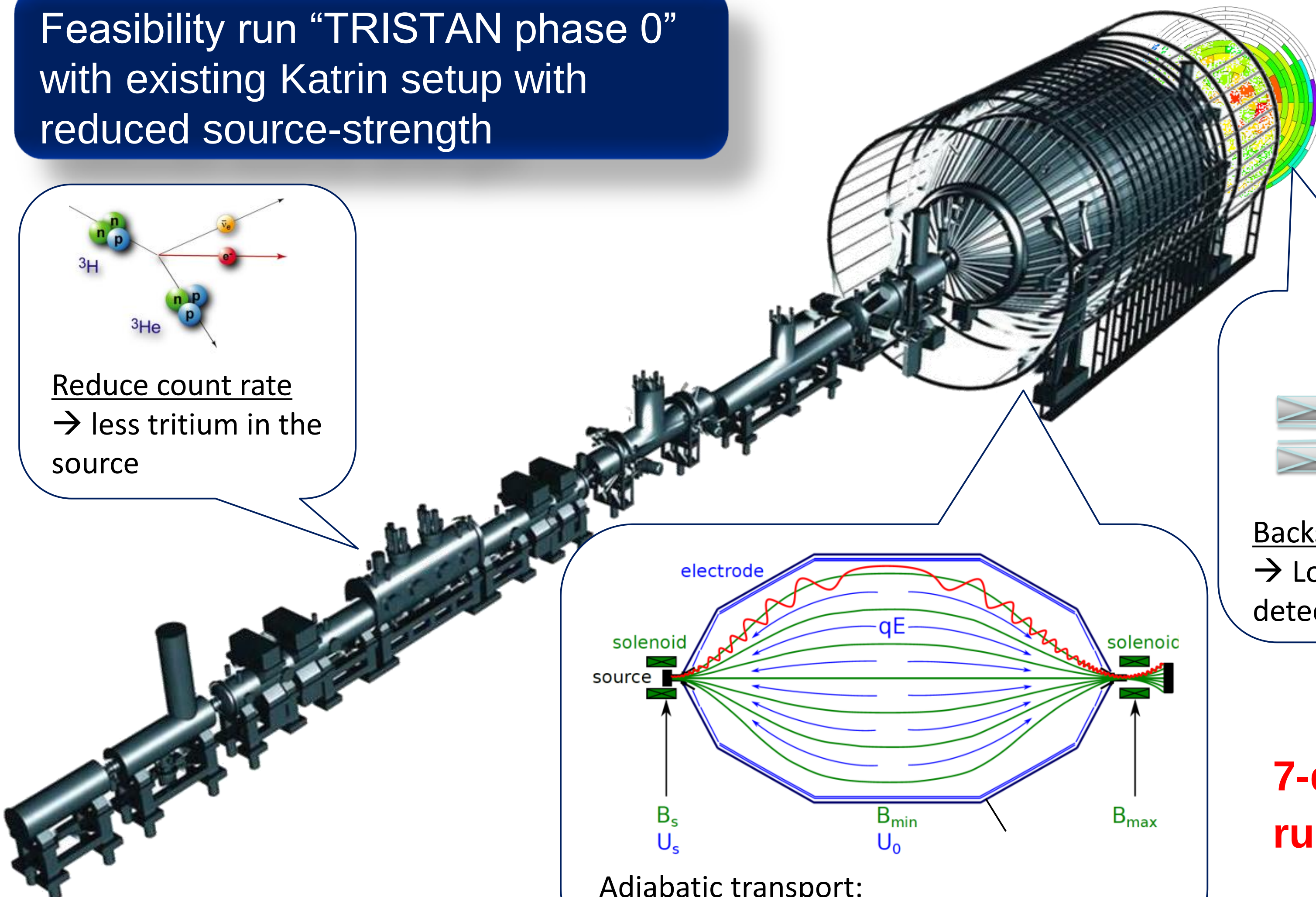


The KATRIN detector is not optimized for energy resolution and measures an intergral Spectrum by variing the retarding potential



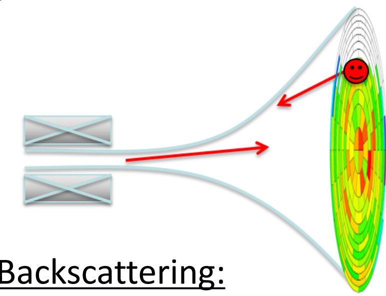
keV-scale sterile neutrinos in KATRIN

Feasibility run “TRISTAN phase 0” with existing Katrin setup with reduced source-strength



Reduce count rate
→ less tritium in the source

Adiabatic transport:
→ Increase magnetic field in spectrometer



Backscattering:
→ Low magnetic field at detector

7-day feasibility run next year!

The TRISTAN project

With a modified KATRIN setup, TRISTAN aims to scan the entire tritium spectrum – integral an differential – with unprecedented accuracy.

Following changes are necessary:

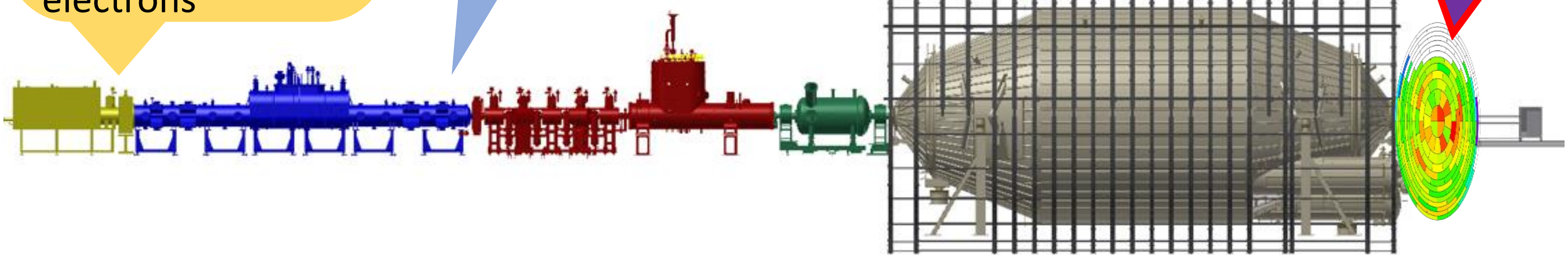
New rear wall, changed B-field parameters → mitigate back scattering of electrons and emission of auger electrons

Slightly less tritium→ lower rate, but new systematics like scattering, trapped electrons

Reduce down to low retarding potential → Electrons with all energies shall reach the detector

New detector → additionally to counting electrons their enegry has to be determined

THIS TALK

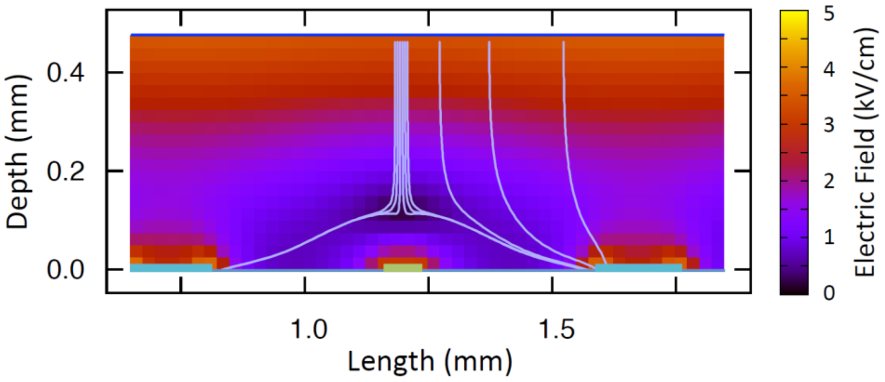


Detector requirement: handle high rates, good energy resolution → multi-pixel array of SDDs

Silicon Drift Detectors

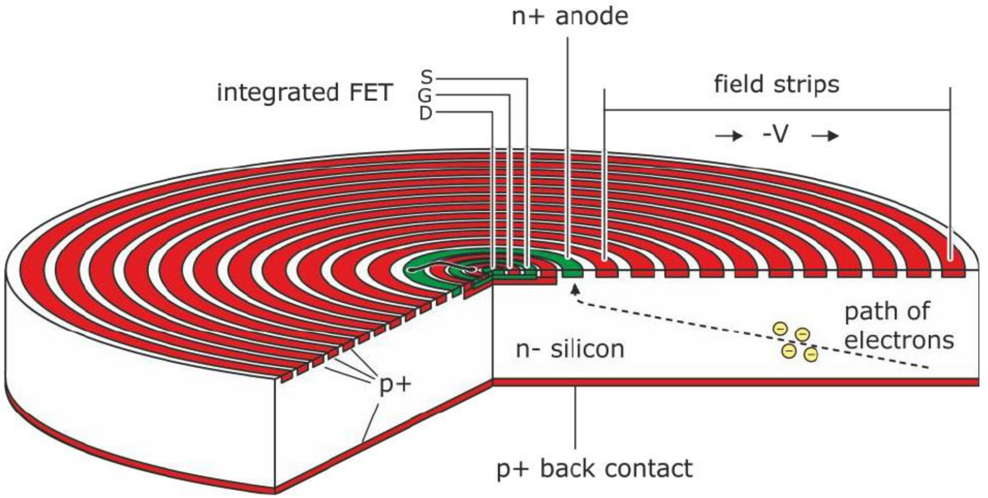
Principle: signal charge collection on small readout node by internal static electric field.

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
- Proven design, deep space experience, e.g. on board of ‘Opportunity‘



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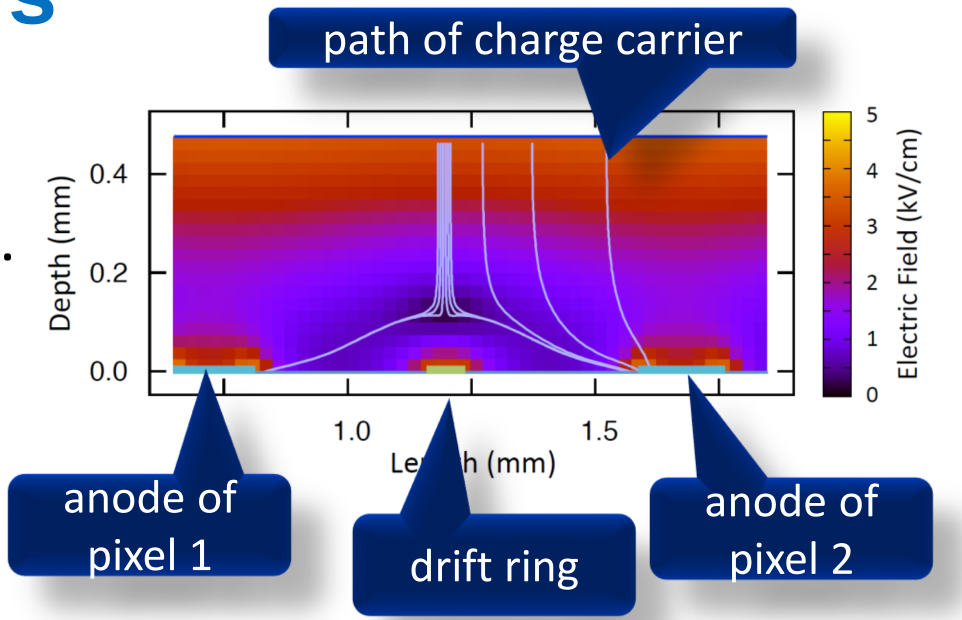

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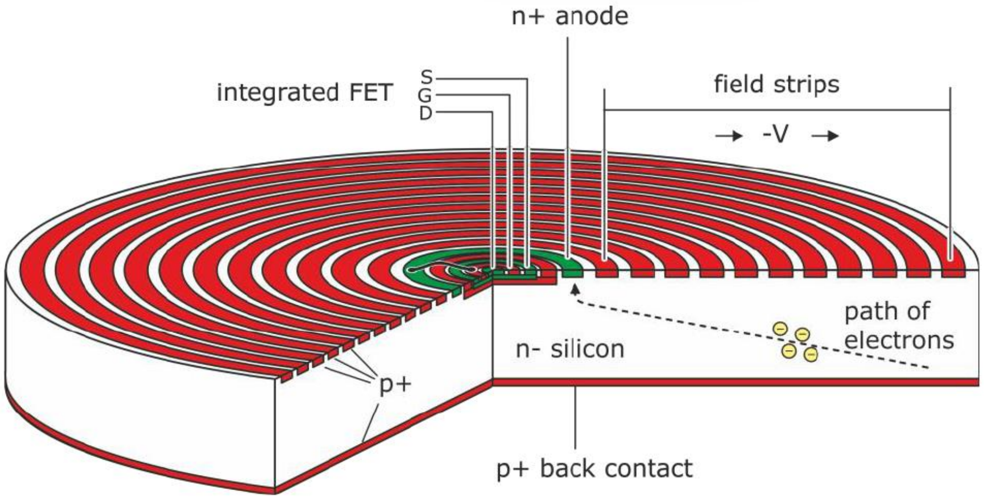
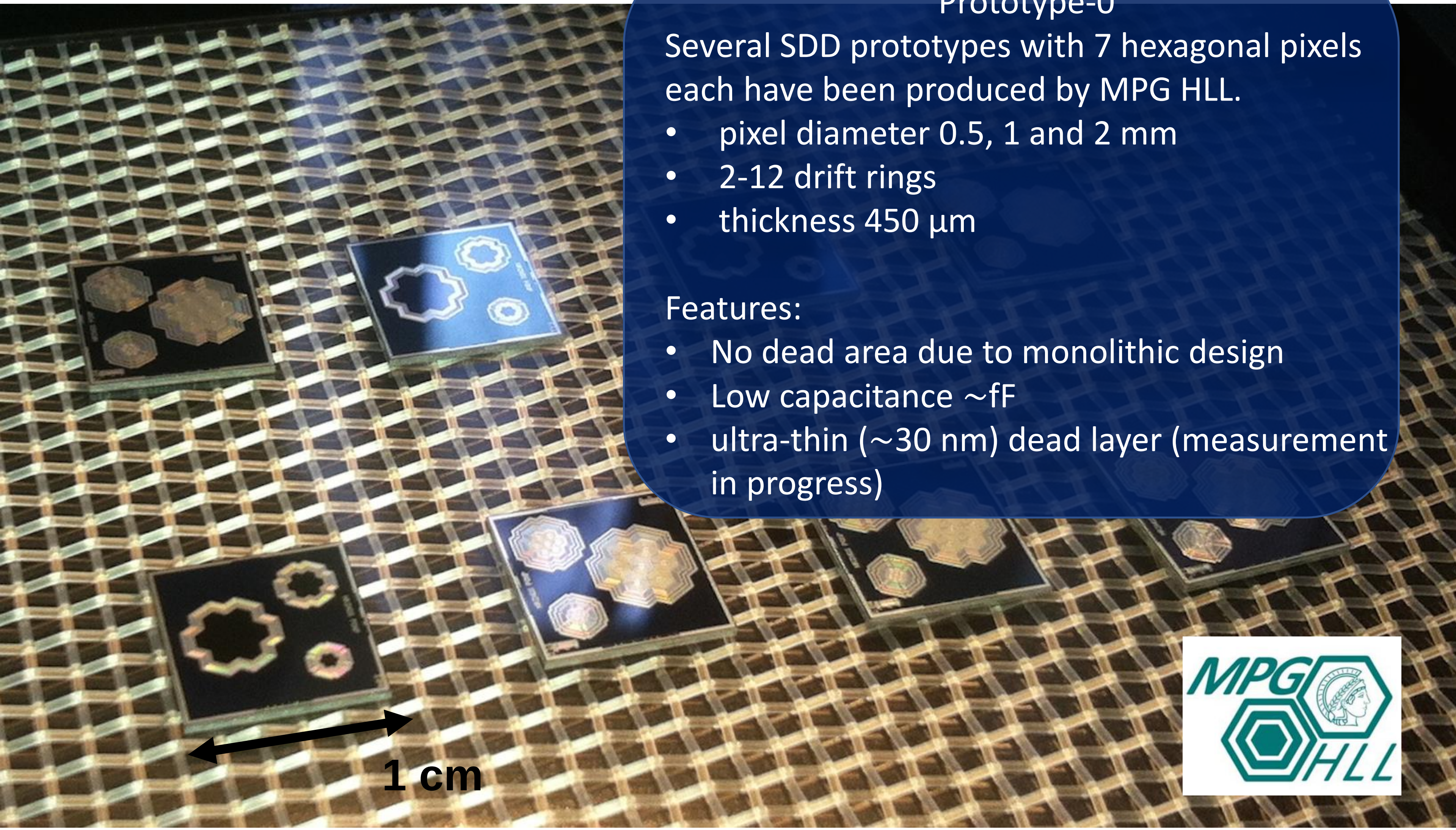


SDD prototypes



“Prototype-0”

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

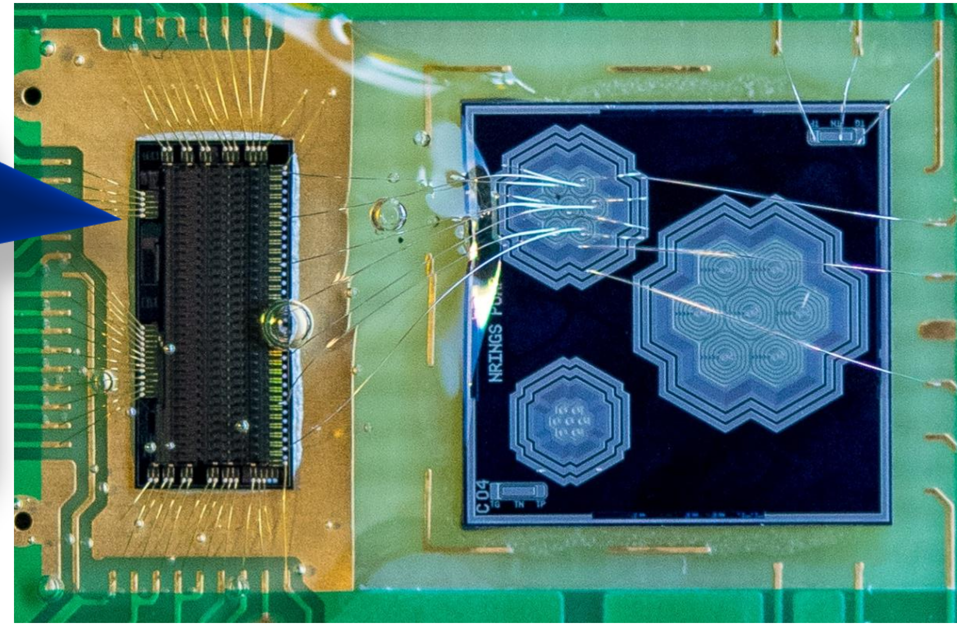
- pixel diameter 0.5, 1 and 2 mm
- 2-12 drift rings
- thickness 450 µm

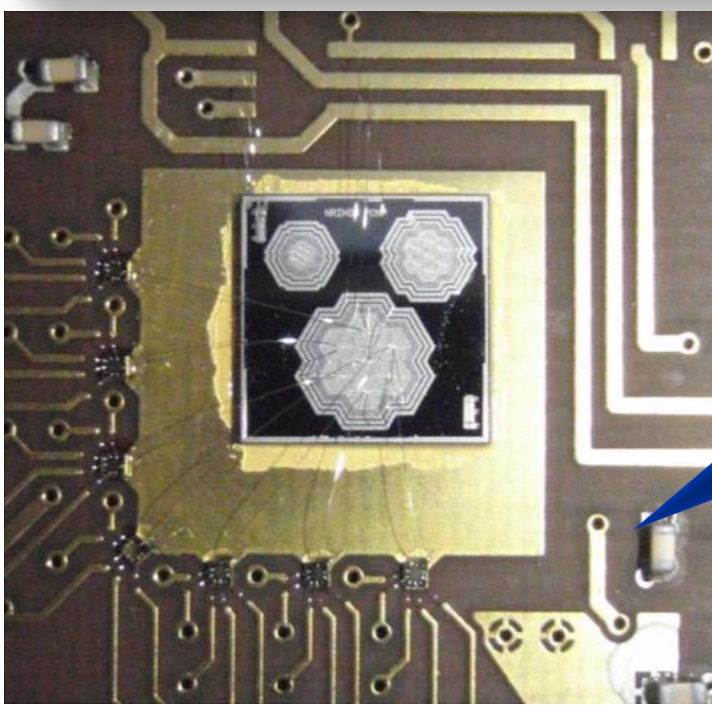
Features:

- No dead area due to monolithic design
- Low capacitance ~fF
- ultra-thin (~30 nm) dead layer (measurement in progress)

SDD prototypes

Idef-X BD ASIC by CEA Saclay
- 32 channel, proven system
- Originally developed for x-ray space telescopes
- Equivalent noise charge: 44 e^-



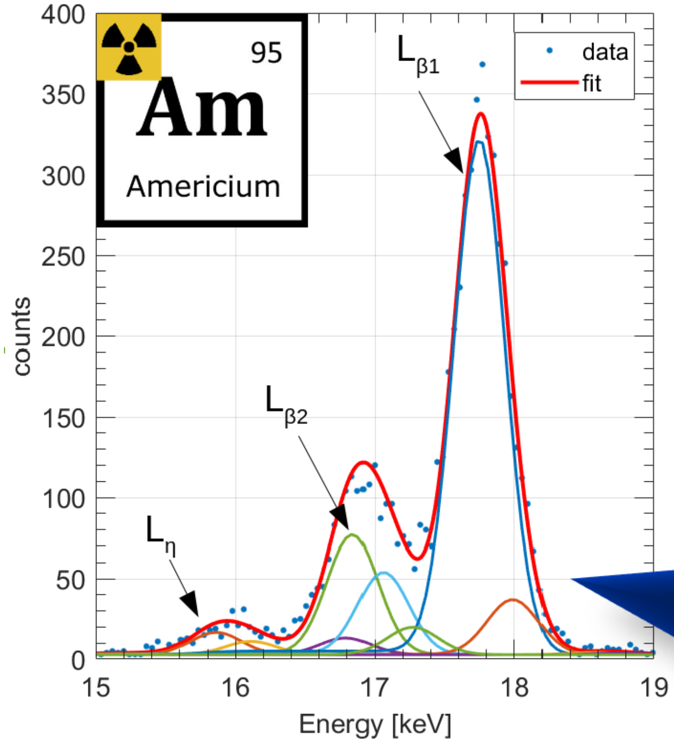


CUBE ASIC by XGLab
- Single channel
- Enc: 7 e^-
- pulsed reset

Another ASIC by KIT

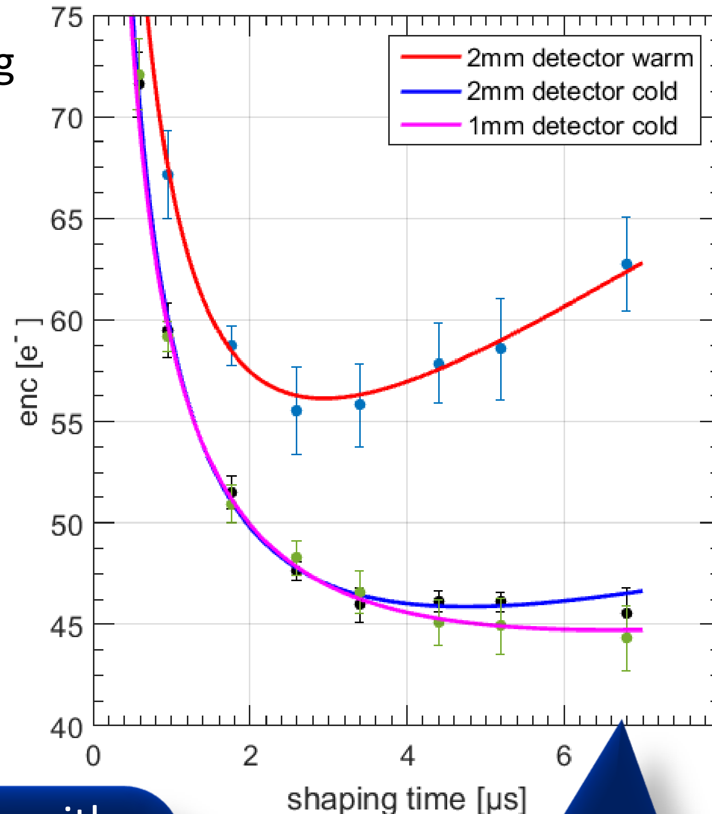
Characterization of CEA System

- Measuring the fwhm as a function of the peaking time allows to determine detector / read-out characteristics like capacity and leakage current
- The noise floor was reached with all “prototype-0” detectors → **the energy resolution is limited by the electronics, not the detector**



400 eV fwhm with CEA ASIC

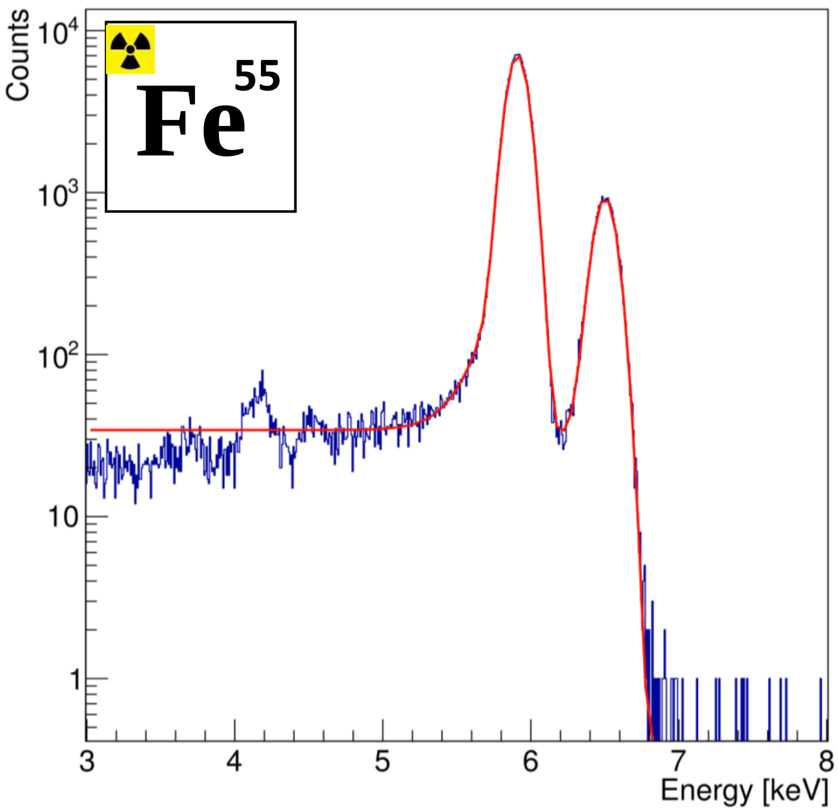
Symmetric peaks → efficient charge collection

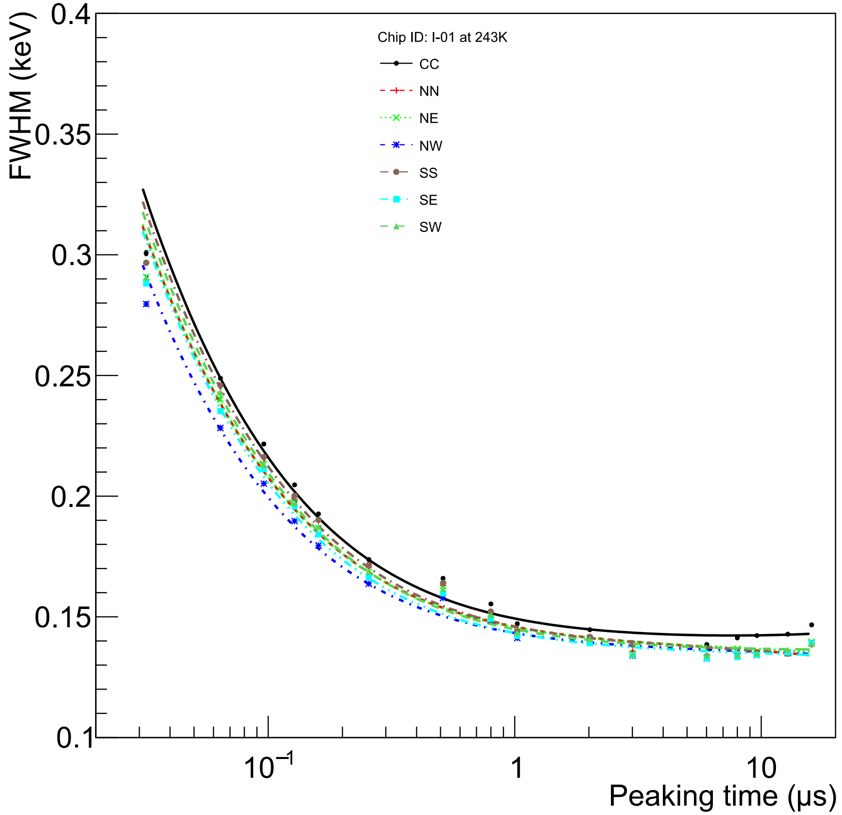


Cooling the detector to - 30 °C reduces thermal leakage current and the noise floor is reached

Characterization of XGLab system

fwhm < 150 eV at 5.9 keV → enc < 9





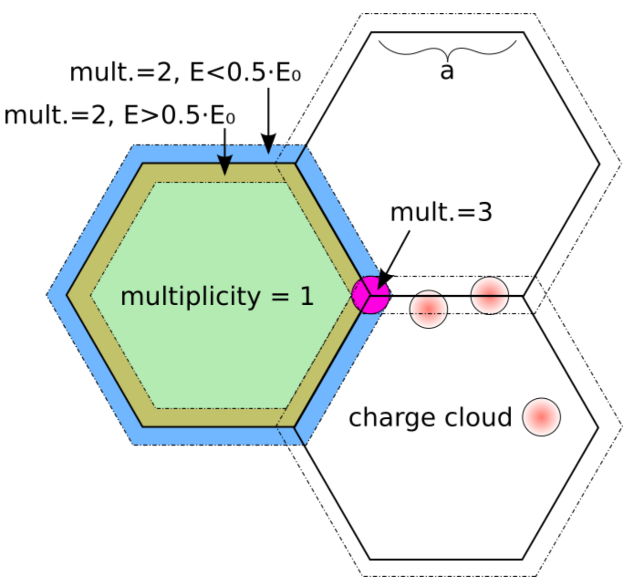
Excellent energy resolution!

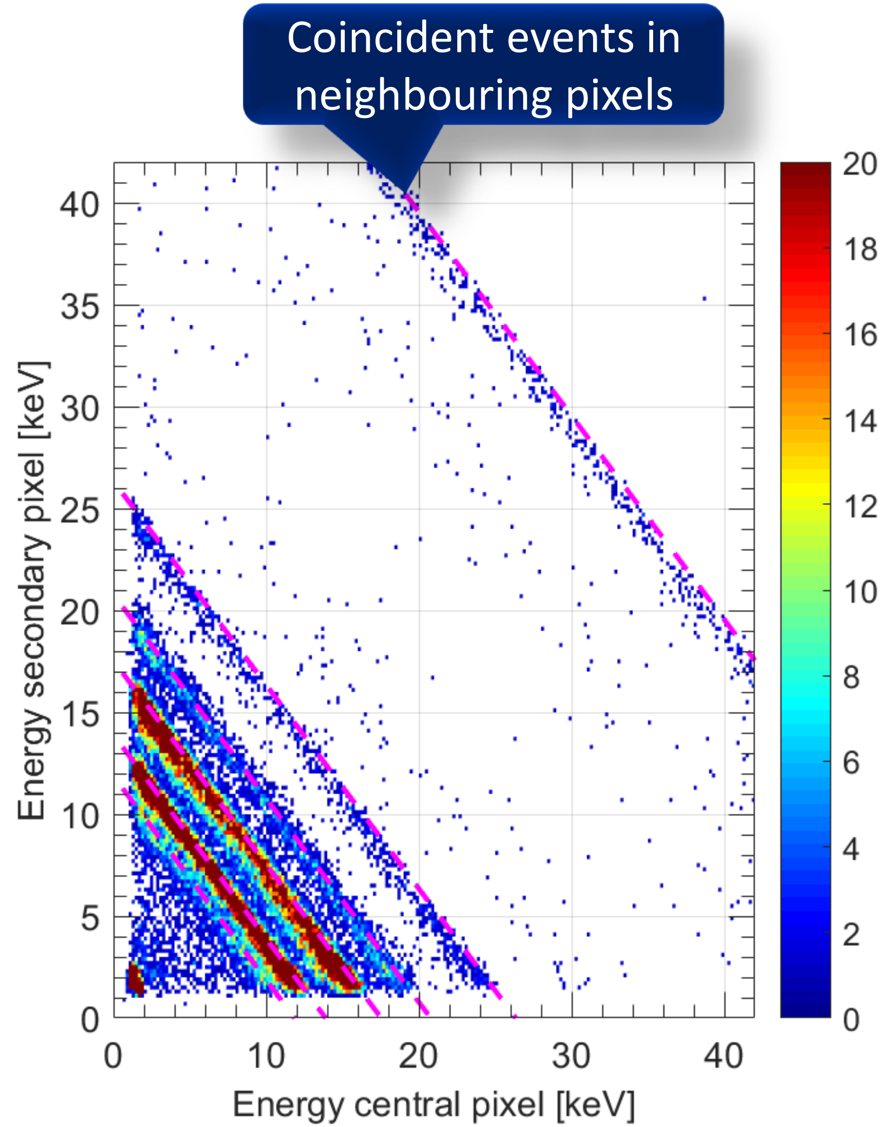
Charge sharing (CEA system)

Advantage of the CEA prototype system:
Multi-channel ASIC, all 7 pixels can be read-out simultaneously and are synchronized

Charge sharing can be studied by looking at coincident events in neighbouring pixels

- The charge of 3 % (10 %) of all events is shared between two or more pixels for 2 mm (1 mm) detector diameter

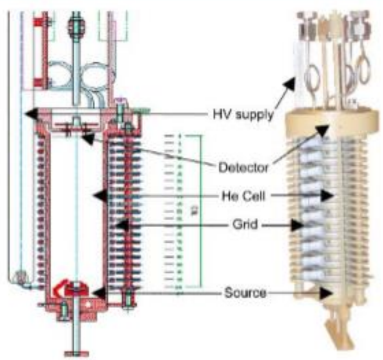




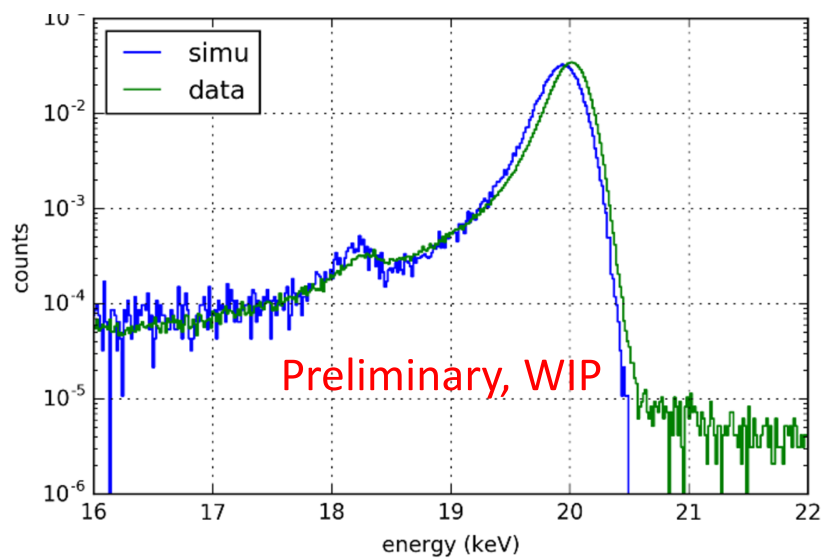
Dead layer (MPP system)

The excellent energy resolution allows to measure the dead layer thickness, which is depending on the production process and is not known with an acceptable accuracy

Particle sources and simulation software:

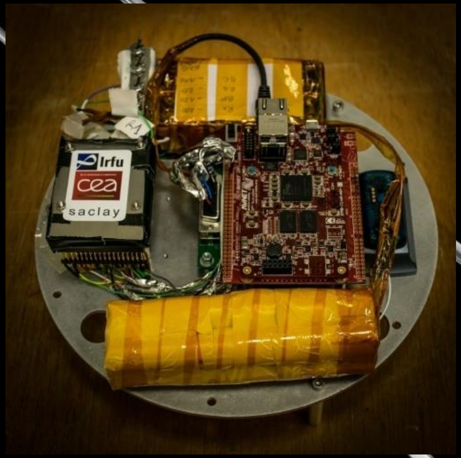
Electrons	Protons
Scanning electron microscope	Self-designed proton grid
	
KESS	SRIM

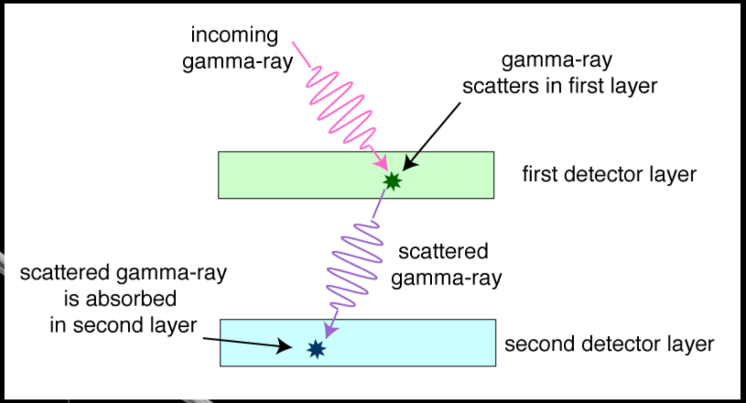
- The dead layer should be as thin as possible to achieve a low energy threshold
- The thickness is obtained by comparing measurements at different energies and incident angles with simulations



Other applications for TRISTAN SDDs

SDD detectors have many other applications:
- X-ray detectors in Axion search
- Compton telescope COCOTE: TRISTAN prototype-0 first science assignment as first detector layer in a compton telescope aboard a stratosphere balloon





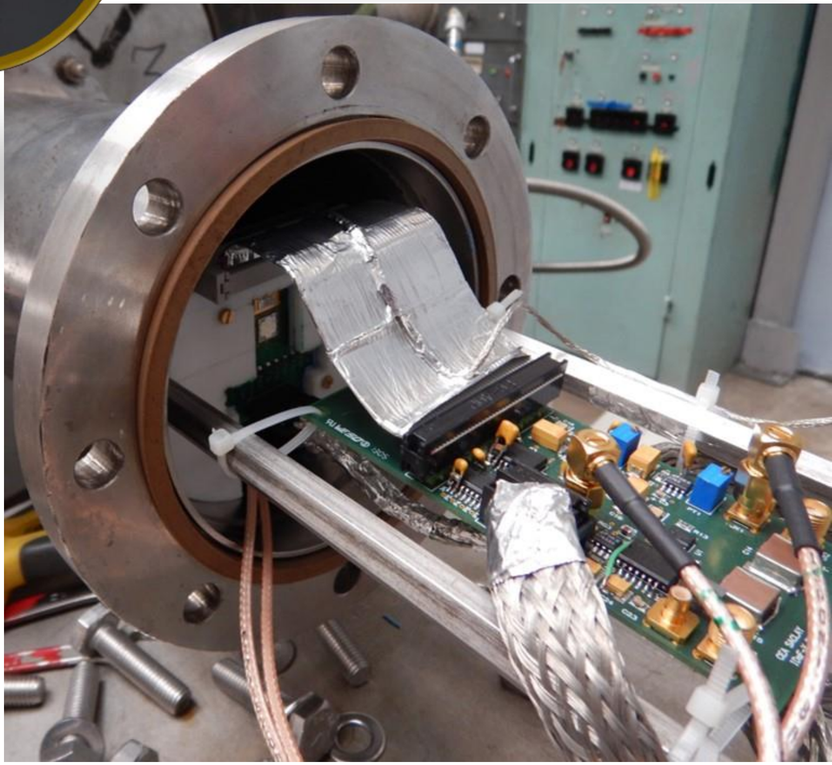
TRISTAN at Troitsk ν-mass

The Troitsk ν-mass experiment is a technological predecessor of KATRIN

- Gaseous tritium source
- lowest laboratory limit on effective neutrino mass (2 eV) together with Mainz
- Installation of 7-pixel TRISTAN detector with CEA ASIC in May/June 2017

Goals:

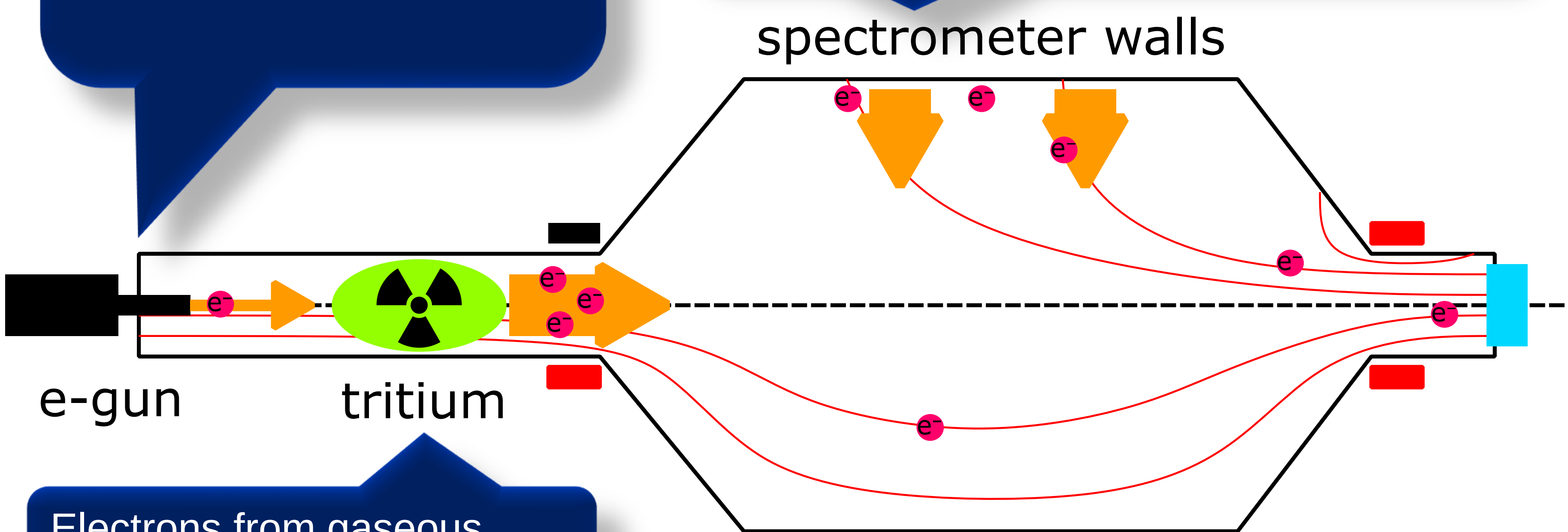
- **Detector characterization**
- **first tritium data, develop analysis tools**



Electron sources at Troitsk

E-gun: narrow (Ø < 1 mm) monoenergetic electron beam. The position of the beam can be controlled.

Spectrometer walls: monoenergetic electrons emitted from the electrodes. With a proper B-field configuration the electrons can be focused on the detector.



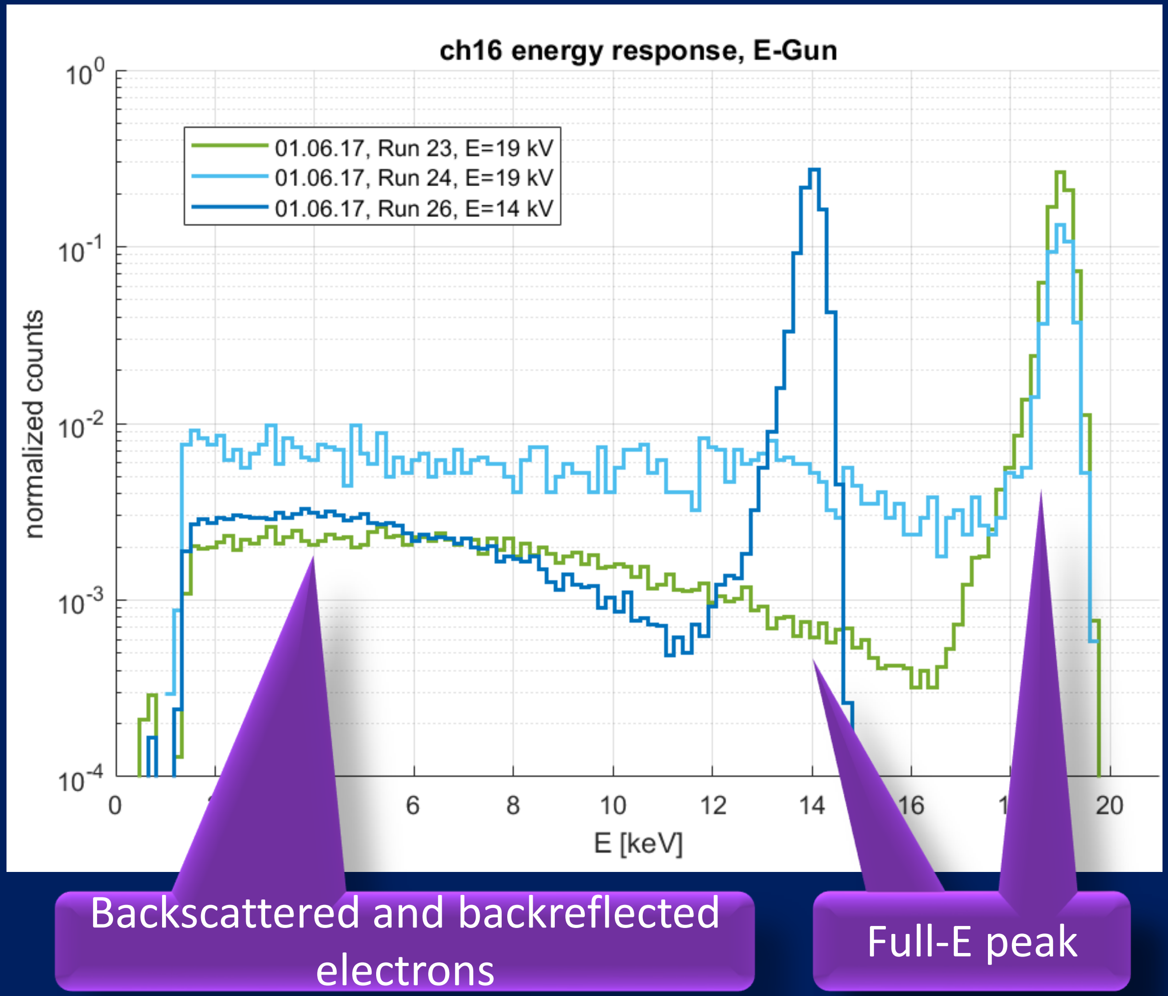
Electrons from gaseous tritium source

Determination of detector response with monoenergetic electrons

Calibration with E-Gun

Monoenergetic electrons from e-gun in source section

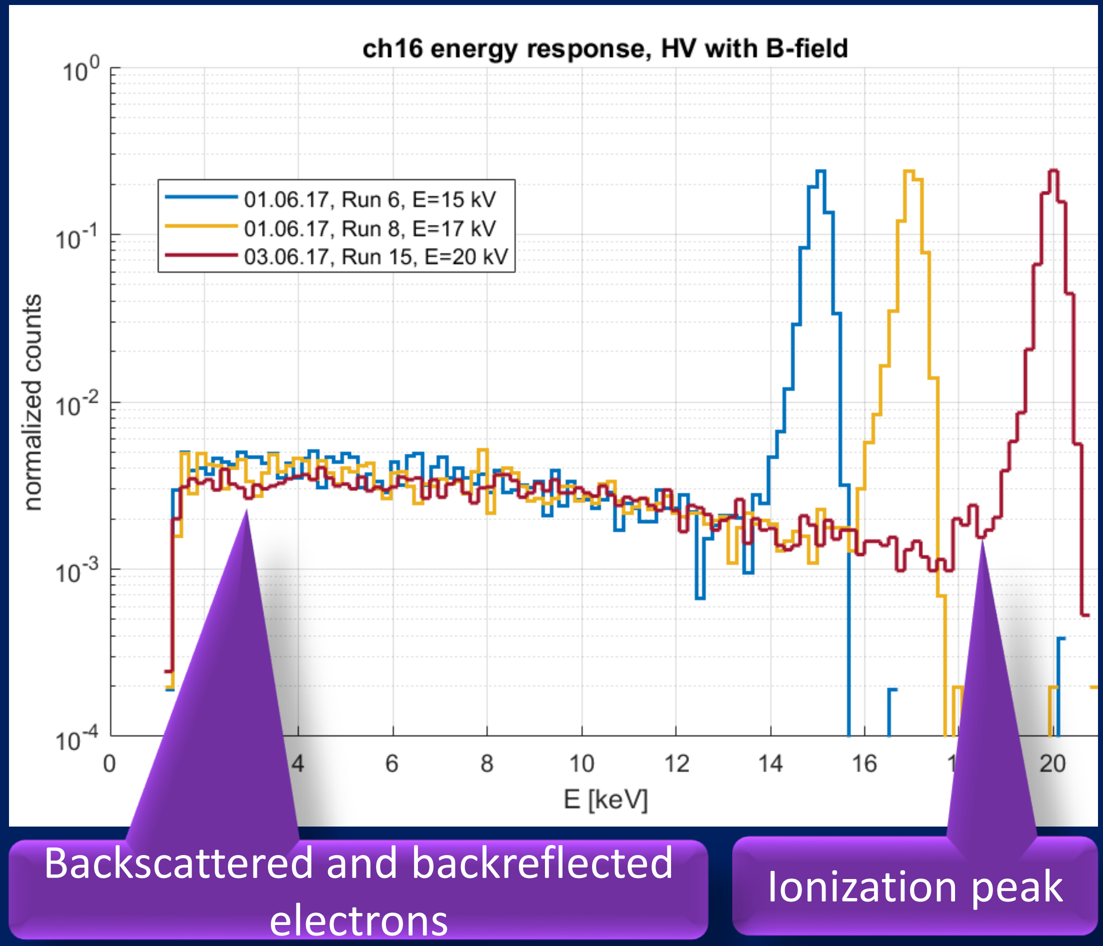
- Calibrate the detector
- Study energy response to determine backscattering, backreflection etc
- beam-spot is smaller then the pixel-diameter → number of event in peak / tail depends on position of beam.



Calibration with wall electrons

Monoenergetic electrons from spectrometer walls (retarding potential of MAC-E filter):

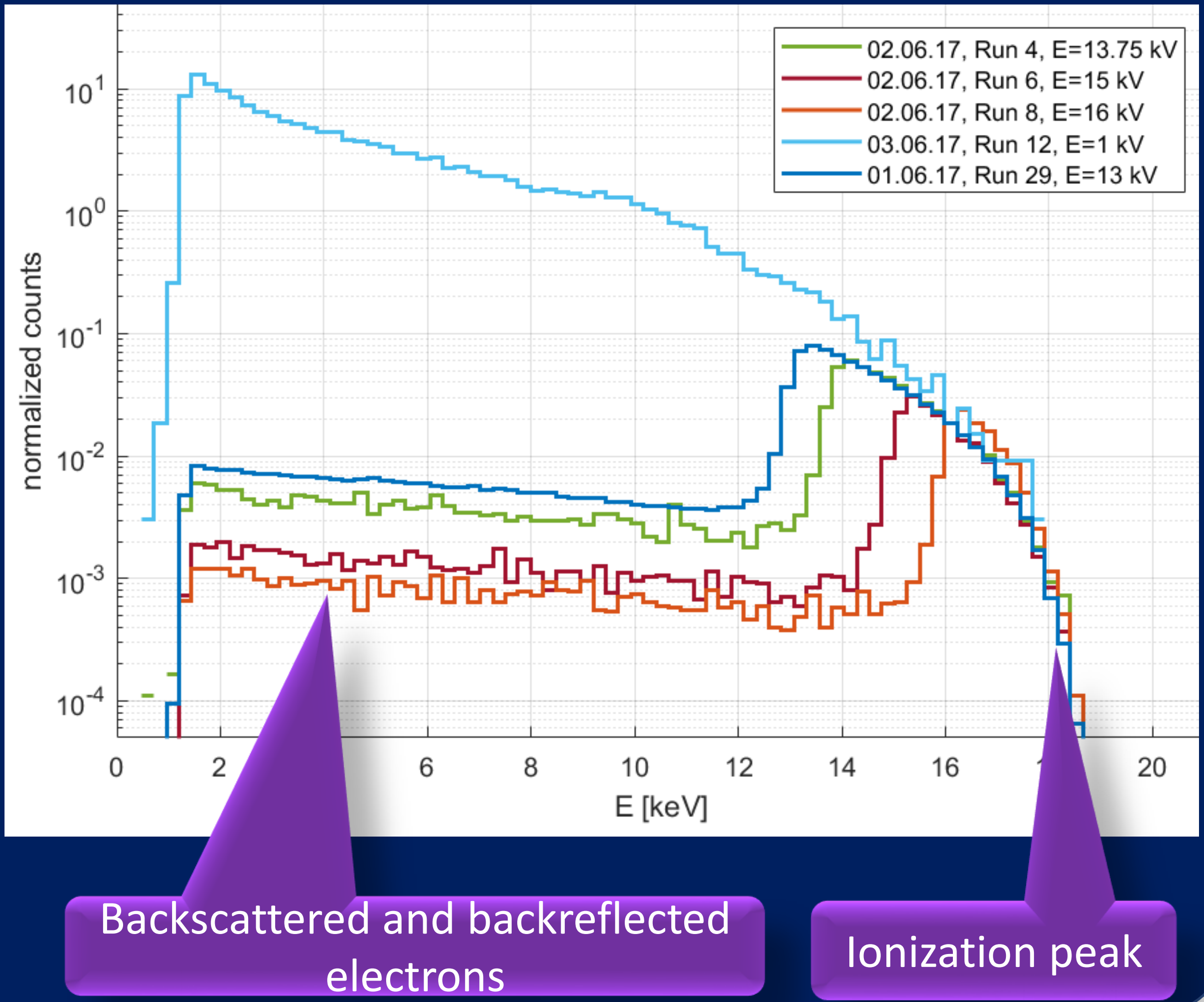
- Focus detector with the B-field onto the walls →
- Isotropic flux over detector radius, similar incident angles (constant backscattering probability)



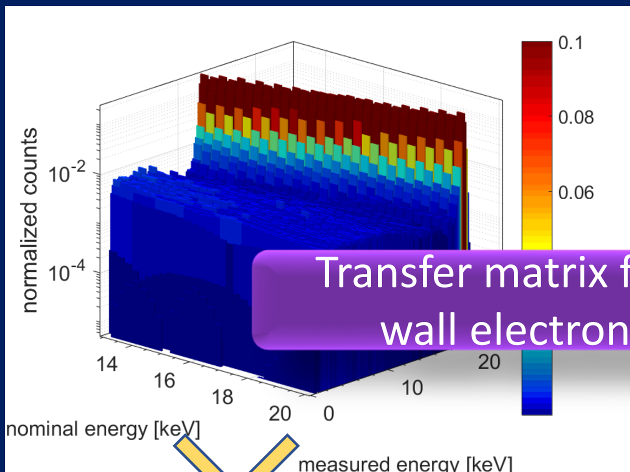
Calibration by subtracting tritium spectra

Tritium energy response

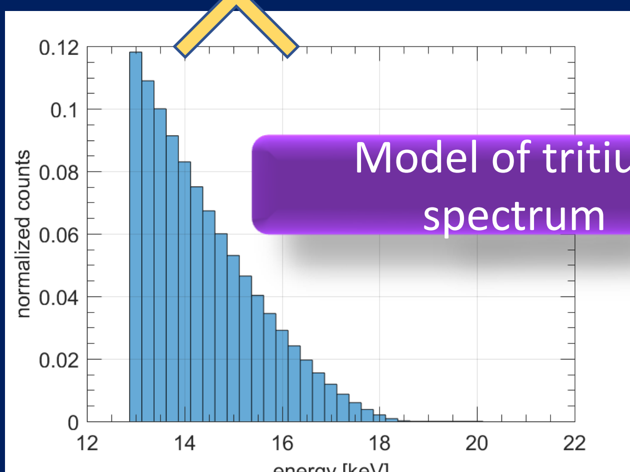
- A quasi-monoenergetic response can be obtained by subtracting tritium spectra with different retarding potentials
- Only a few spectra with high statistics so far



Measurements at Troitsk

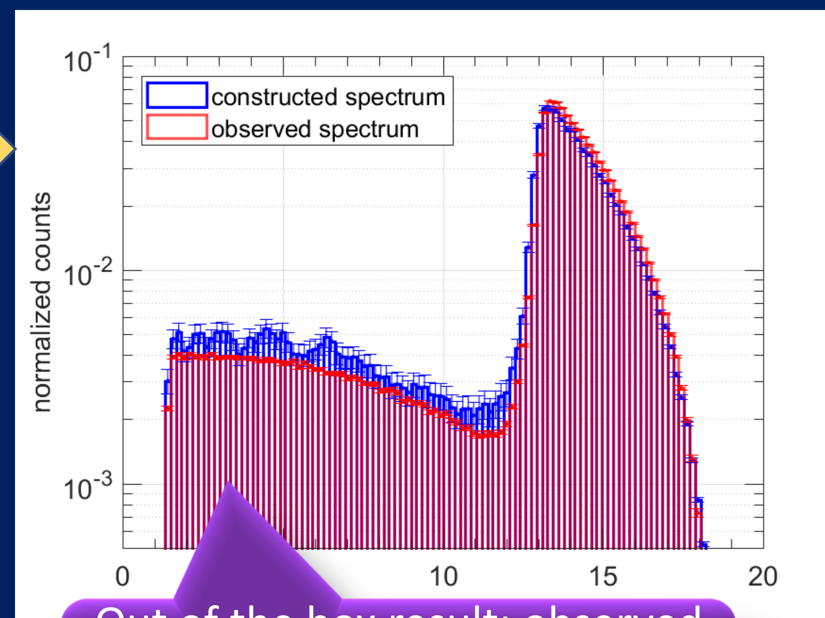


Transfer matrix from wall electrons



Model of tritium spectrum

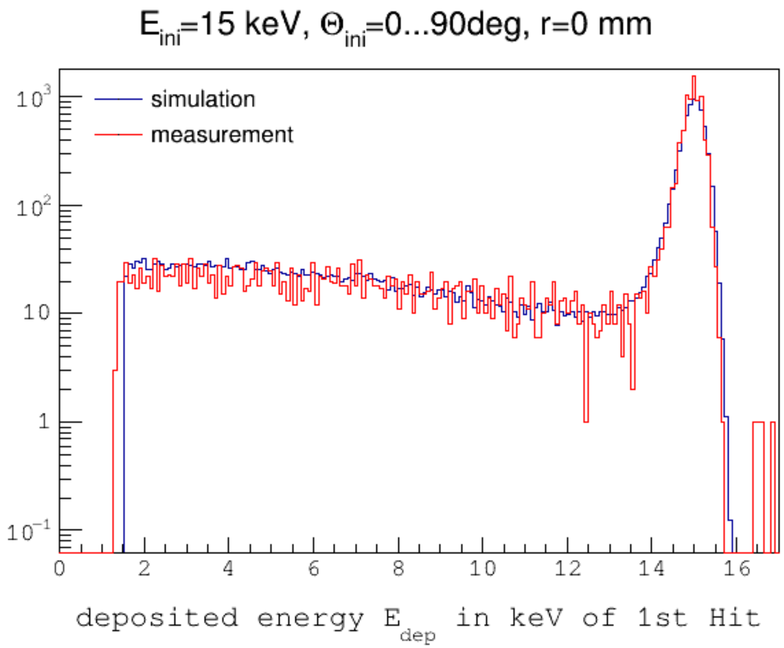
Response of wall electrons NOT equal to tritium electrons due to different magnetic field configurations: wall electrons that backscattered on the detector are always reflected back to the detector. This is not true for tritium electrons

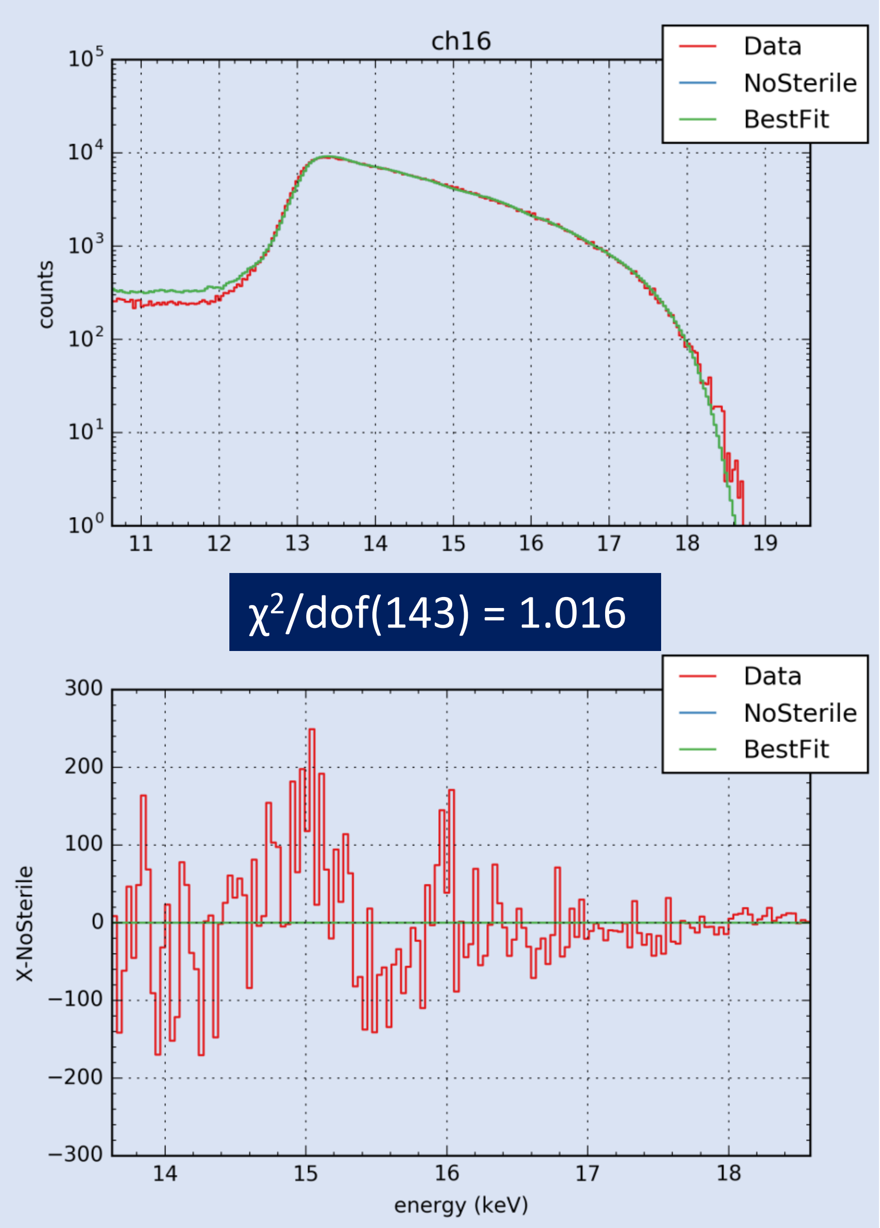


Out of the box result: observed spectrum has ~ 30 % less electrons that lost energy

Next steps

- Improve transfer matrix: use parametrized transfer function (Gaussian plus tail) or interpolated data to fit the spectrum above 13 keV
- Understand the response with the help of Monte Carlo simulations

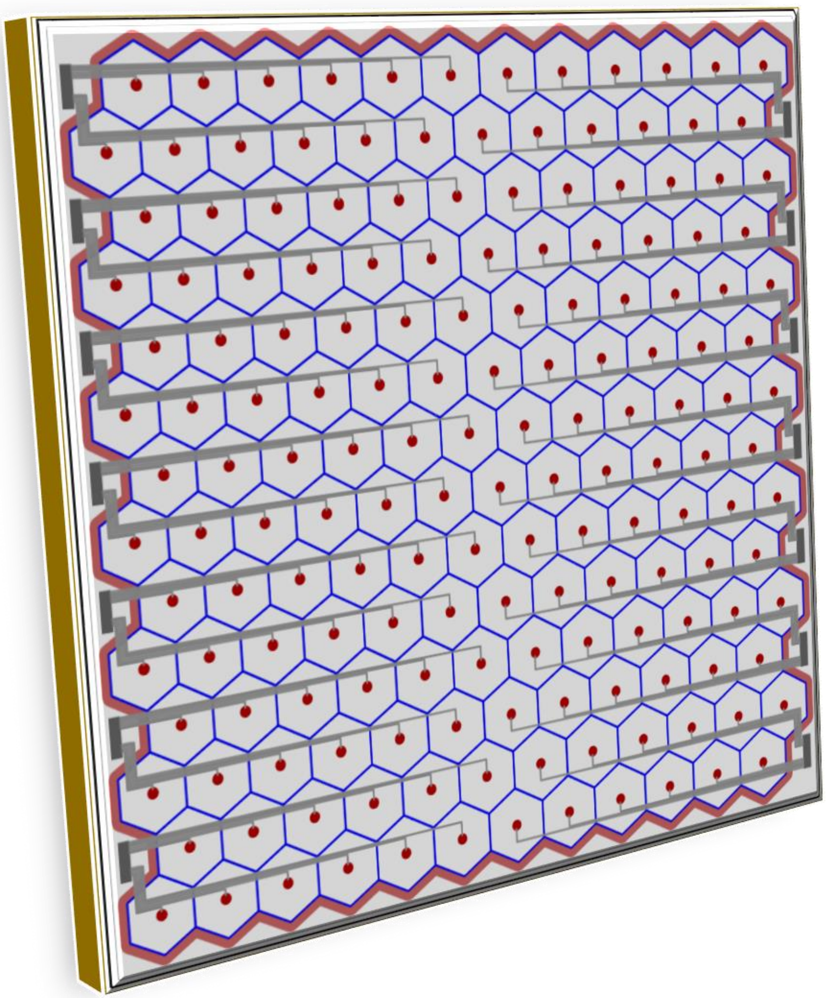




Next measurement campaign in November

The next prototypes

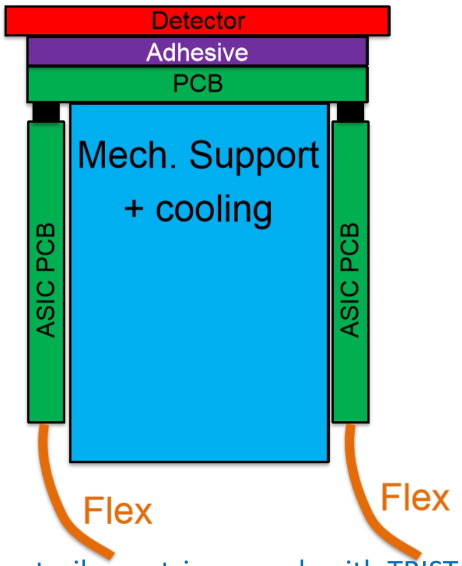
"Prototype-1"



Monolithic SDD array with
~100 3-mm-SDDs.

Characteristics:

- JFET (first amplification stage) integrated on detector surface
- Pulsed reset
- Common clock between pixels (identify multiplicity, pile-up tagging)
- Chip is glued on support-structure with integrated cooling



The final detector

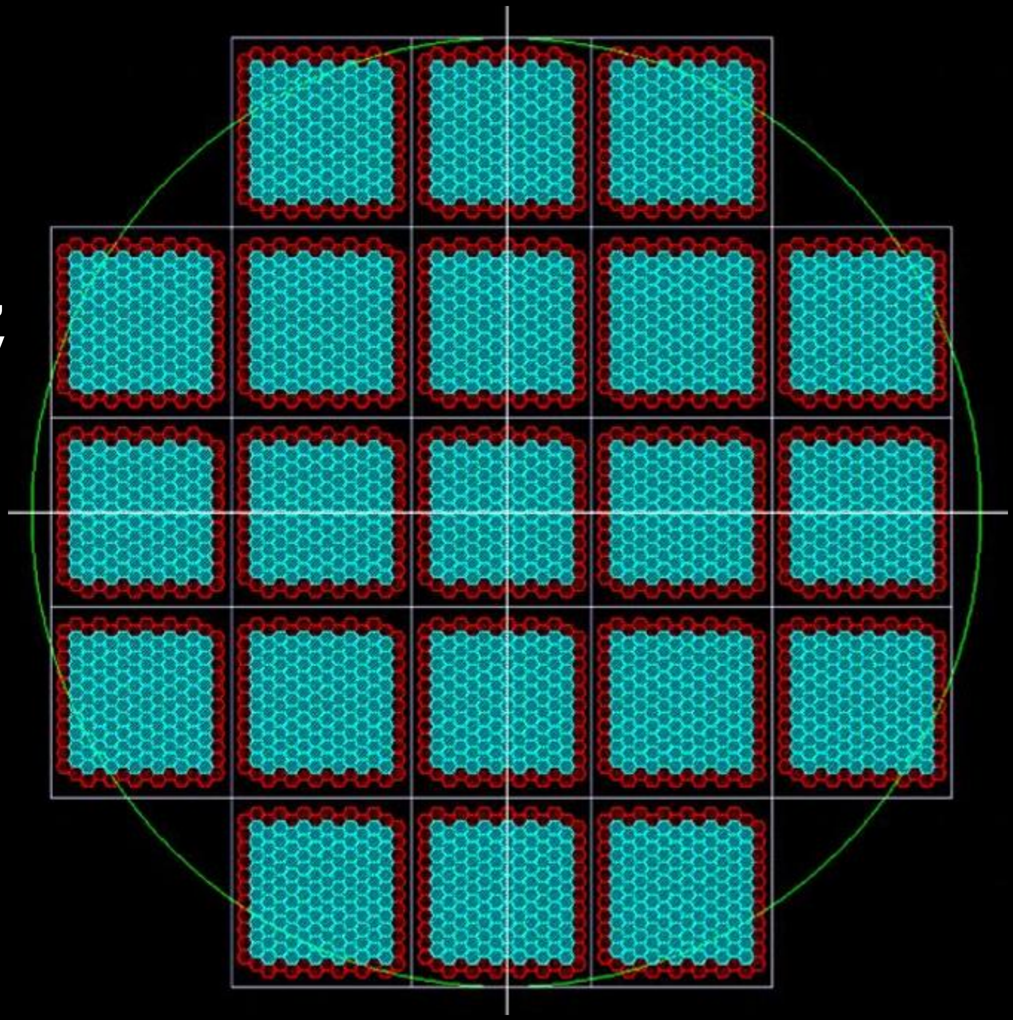
- 19 - 25 prototype-1 modules
- 3000 - 4000 pixels

  → 70 kcps /pixel
- maximize number of „golden“ pixels, which are completely surrounded by other pixels without a gap
- Minimize dead areas
- Minimize length of traces (wires) to reduce capacitance

→ Larger modules, approx. quadratic

- Efficient covering of fluxtube
- Yield in sensor chip production

→ Smaller modules



Conclusions

- Goal: measure the entire tritium spectrum at KATRIN to search for new physics, e.g. keV-scale sterile neutrinos

→ New detector system is needed = TRISTAN

- 7-pixel prototypes “prototype-0“ with different ASICS were characterized and showed promising results
- First tritum data was taken with a prototype detector at the Troitsk ν-mass spectrometer.
- Design and planning of final system is ongoing

- Next measurement campaign in Troitsk with improved detector and more statistics in November
- TRISTAN phase-0: feasibility run with KATRIN next year
- TRISTAN phase-1: installation of SDD array after data taking of KATRIN is finished in ~ 5 years