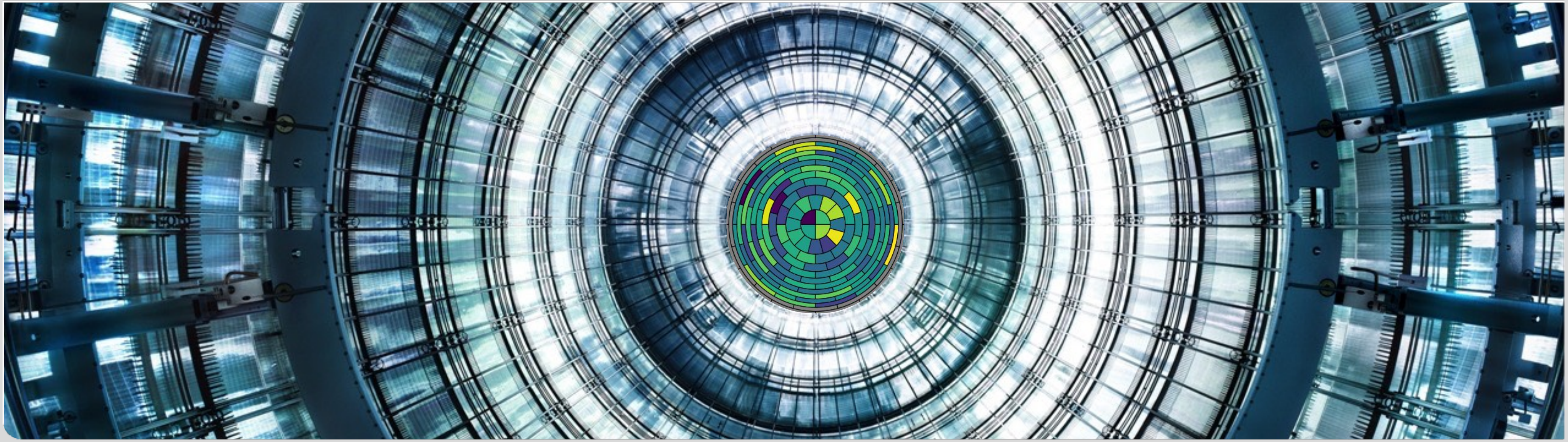
KATRIN:
Electron spectroscopy at the precision frontier

KIT, September 16, 2019

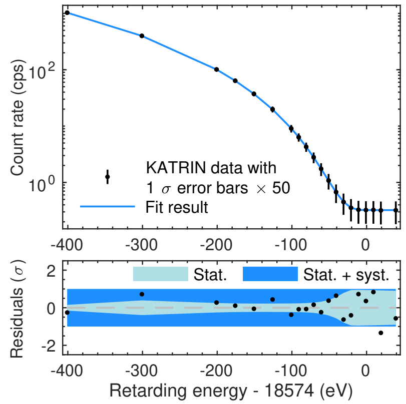
KATHRIN VALERIUS (KIT, Institute for Nuclear Physics) for the KATRIN Collaboration



From commissioning to ν-mass data-taking

Karlsruhe Institute of Technology

[JINST 13 (2018) P04020]



[arXiv:1909.06069]

Completion of beamline
"First Light" demonstrates transmission of electrons

"First Tritium" campaign
first β-spectra and verification of system stability

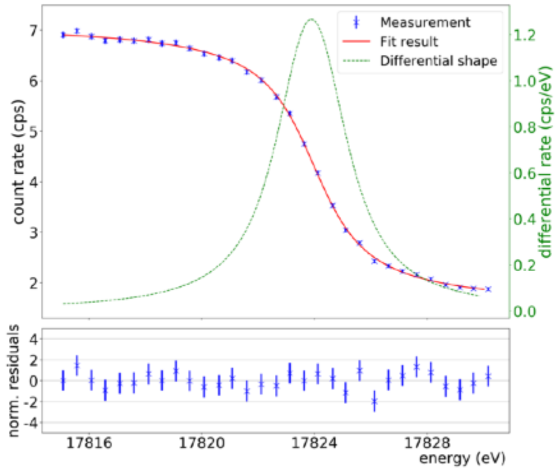
First ν-mass campaign
start of scientific harvest of KATRIN

Fall 2016 | **Summer 2017** | **Spring 2018** | **Fall 2018** | **Spring 2019**

Krypton campaign
precision spectroscopy of monoenergetic electrons

Systematics campaign
response function with precision electron gun

[EPJ C 78 (2018) 368, JINST 13 (2018) P04018, arXiv:1903.066452]

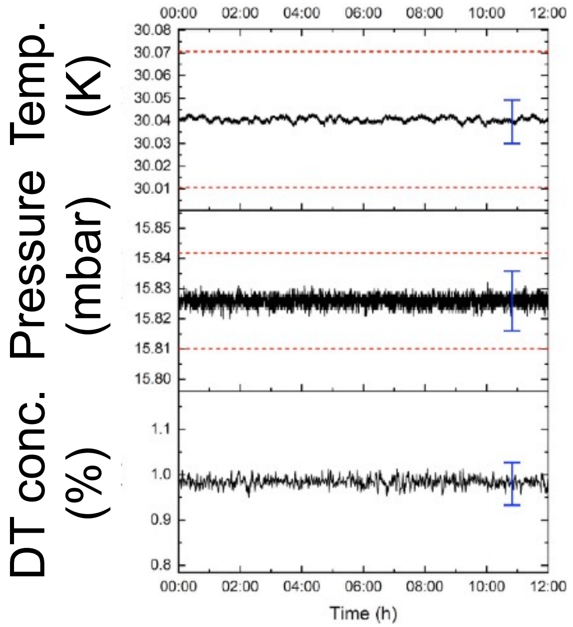


Sept. 2019: Release of first ν-mass result!

[arXiv:1909.06048]

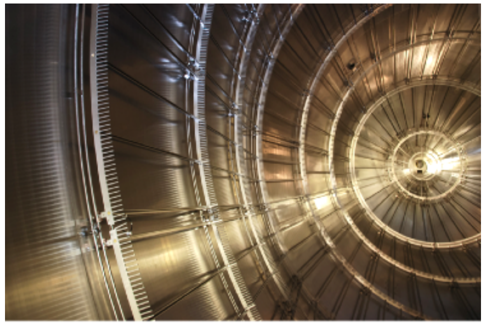
Precision β-electron spectroscopy: ingredients

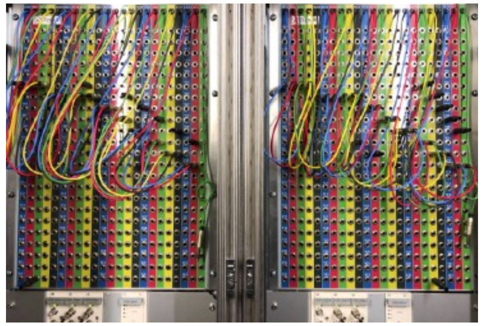
β-decay source stabilized and monitored at 0.1% level



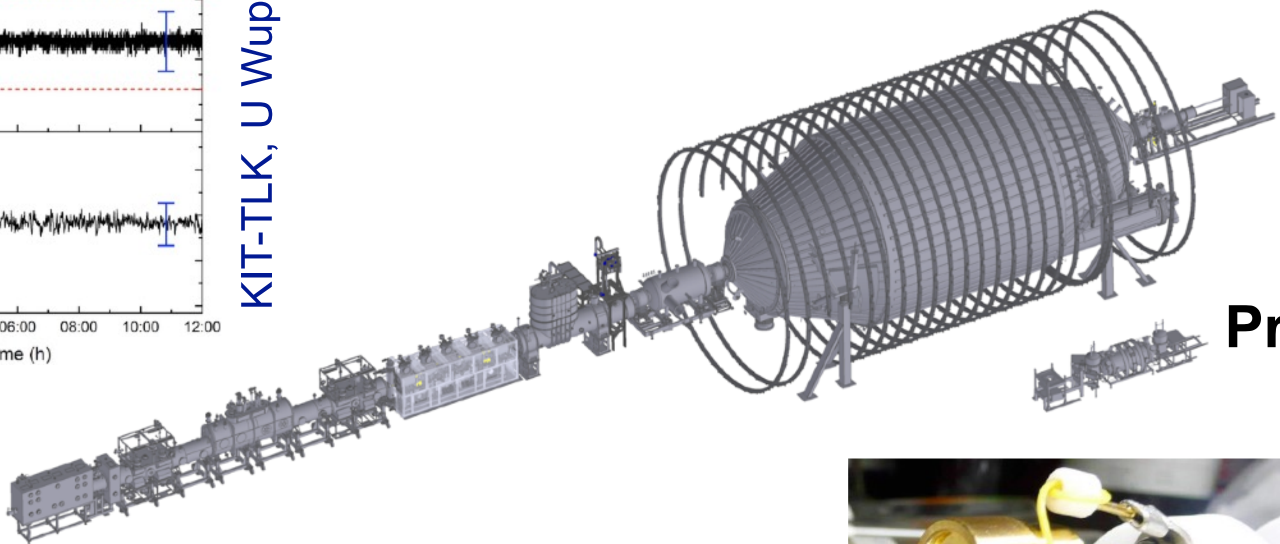
KIT-TLK, U Wuppertal, MPIK

Retardation voltage at ppm stability

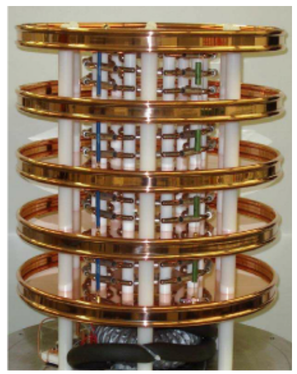




U Münster, KIT

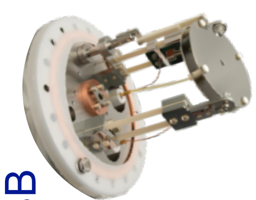


Precision monitoring of energy scale



U Münster, Řež, U Bonn, U Mainz, MPP Munich, KIT

U Münster, KIT UCSB



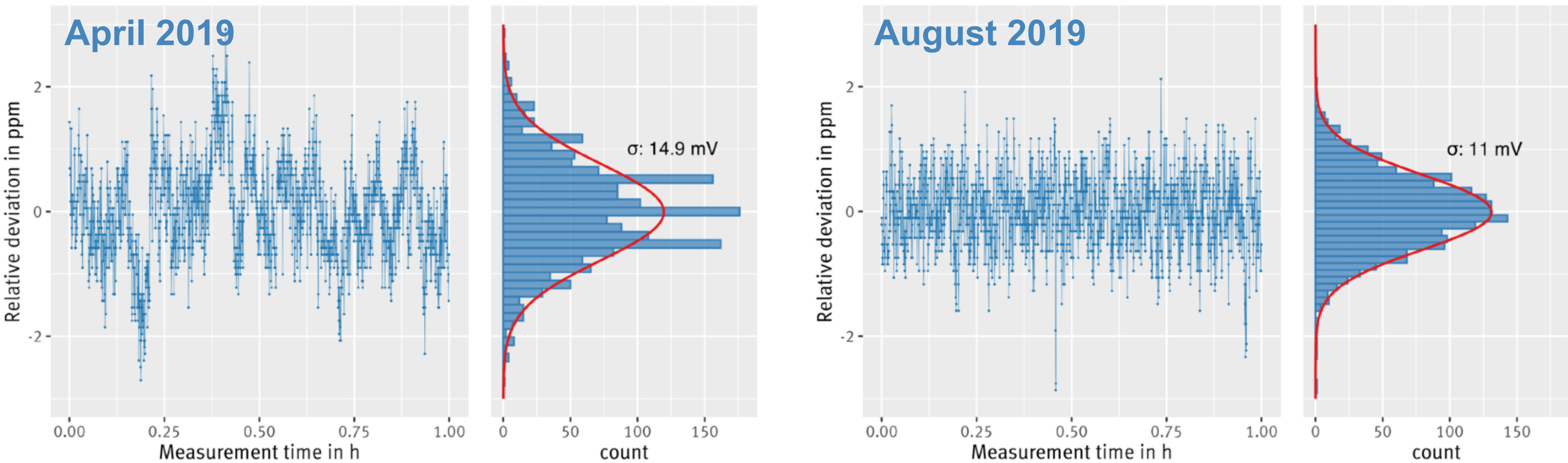
Precision electron sources for calibration

Precision high voltage supply & monitoring

Karlsruhe Institute of Technology

Relative stability was instrumental for the 2019 first science run and keeps improving:

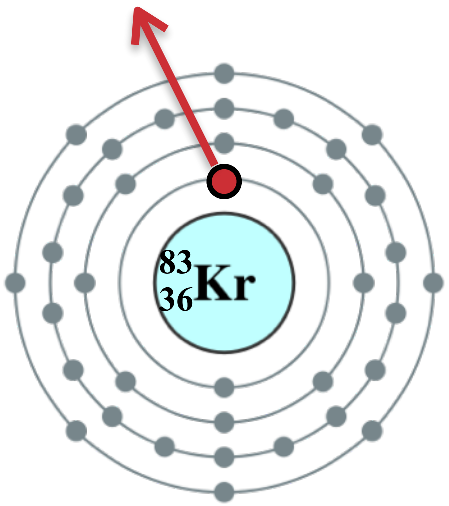
Active post-regulation of retarding potential at the main spectrometer

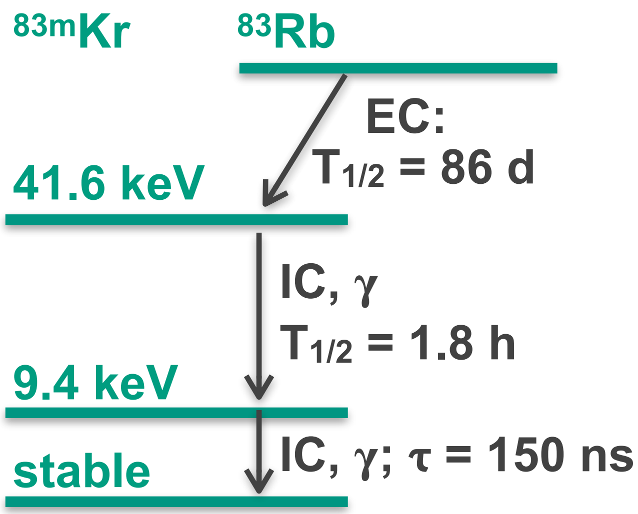


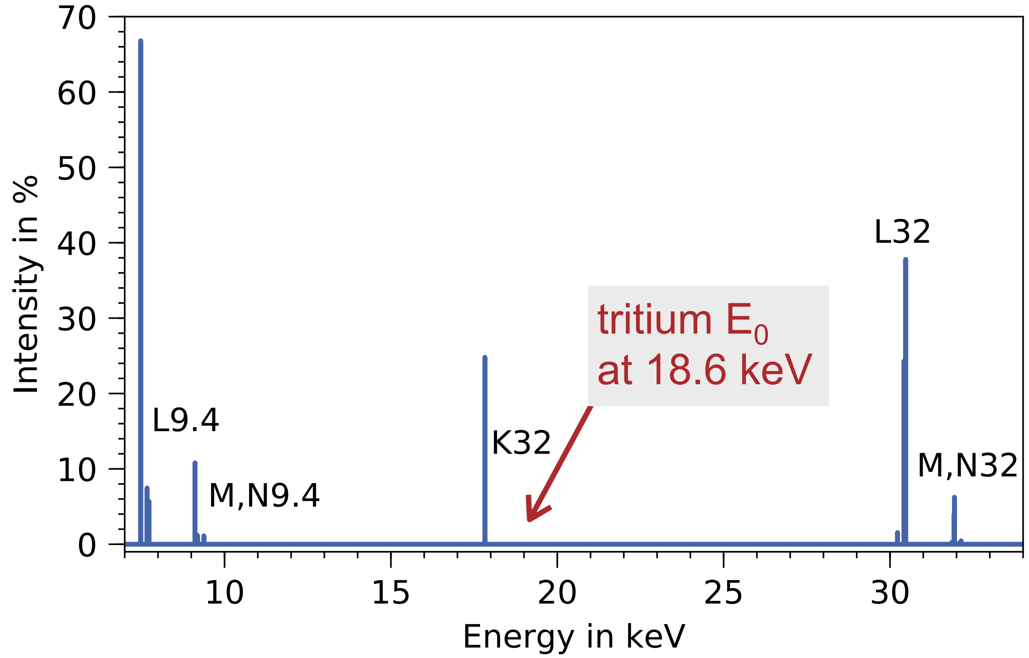
Absolute calibration (needed for syst. checks with ^{3}He-^{3}H mass difference) also reaches ppm level through new method [Rest *et al.*, Metrologia 56 (2019) 045007]

Precision calibration sources (1): Krypton

- Nuclear/atomic standard widely used in neutrino and dark matter experiments
- Short half-life eliminates risk of contamination
- Mono-energetic (< 3 eV) conversion electrons, isotropic angular distribution
- Convenient range of line energies







- System characterization: transmission of MAC-E filter, detector properties, system alignment, absolute energy scale calibration, …

[JINST 13 (2018) T02012 & P04018, and further works]

Three ^{83m}Kr calibration sources for KATRIN

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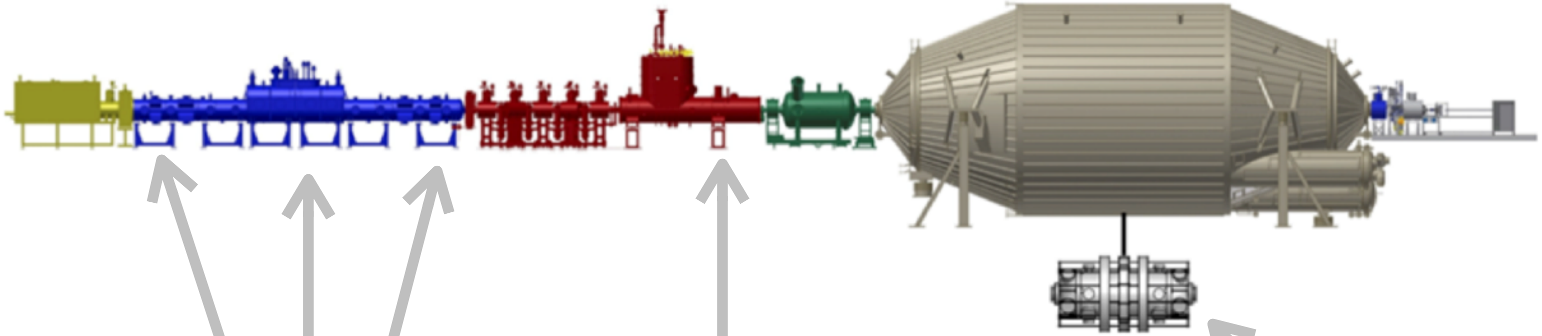
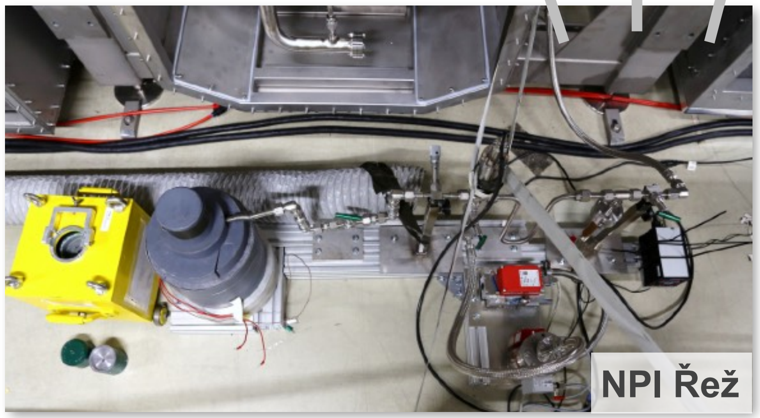
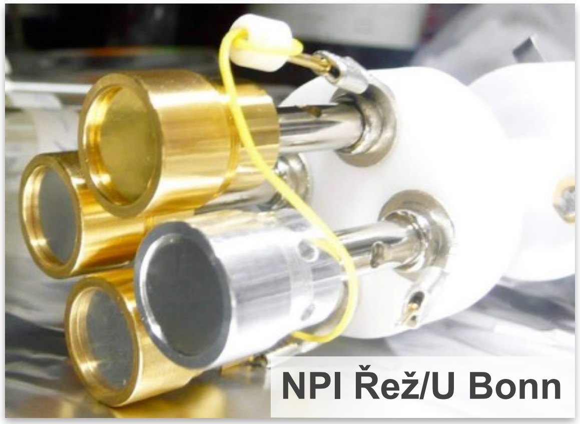






Gaseous ^{83m}Kr source

- Krypton decays filling WGTS beam tube
- Can be mixed with tritium to probe plasma

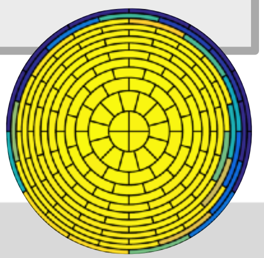
Condensed ^{83m}Kr source

- Thin film on cold substrate ➜ no scattering
- Spot-like source, moving across flux tube

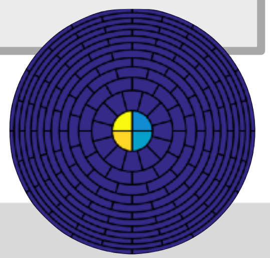
Implanted ^{83m}Kr source

- Parallel measurement at Monitor Spectrometer
- Excellent stability proven over many years

[JINST 9 (2014) P12010, JINST 13 (2018) P04018]



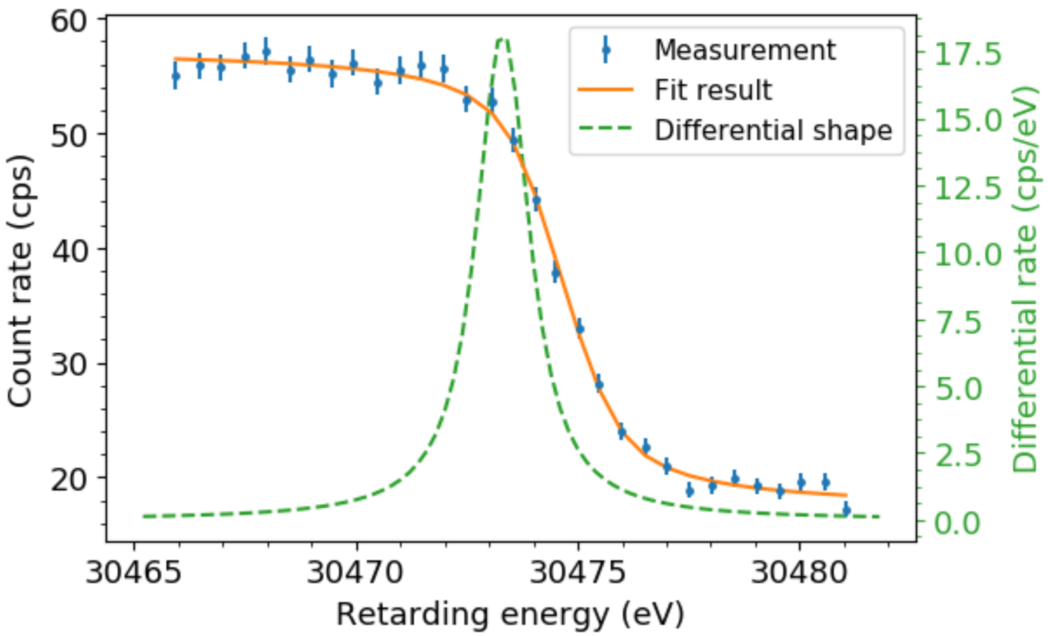
[RSI 84 (2013) 123103]

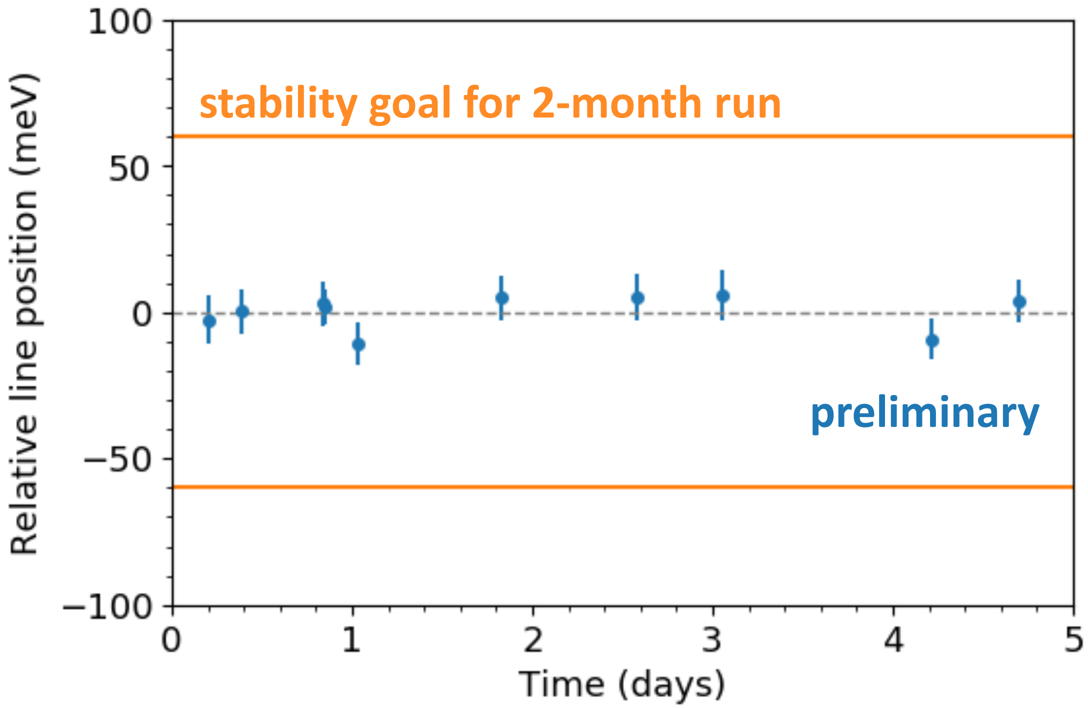


[JINST 8 (2013) P03009 & T12002, JINST 9 (2014) P06022]

Precision and stability traced with ^{83m}Kr

Example: **L_3-32** line (30.5 keV, Γ ~1.4 eV)





- ✓ Sharp resolution (~2 eV at 30 keV) and excellent linearity of energy scale
- ✓ ^{83m}Kr in empty beam tube, in D_2 and in T_2 to characterize gaseous source
- ✓ Highly stable overall system from source to detector
- ✓ New calibration method of HV meas. (< 5 ppm) based on relative line positions

[EPJ C 78 (2018) 368; JINST 13 (2018) P04018; arXiv:1903.066452]

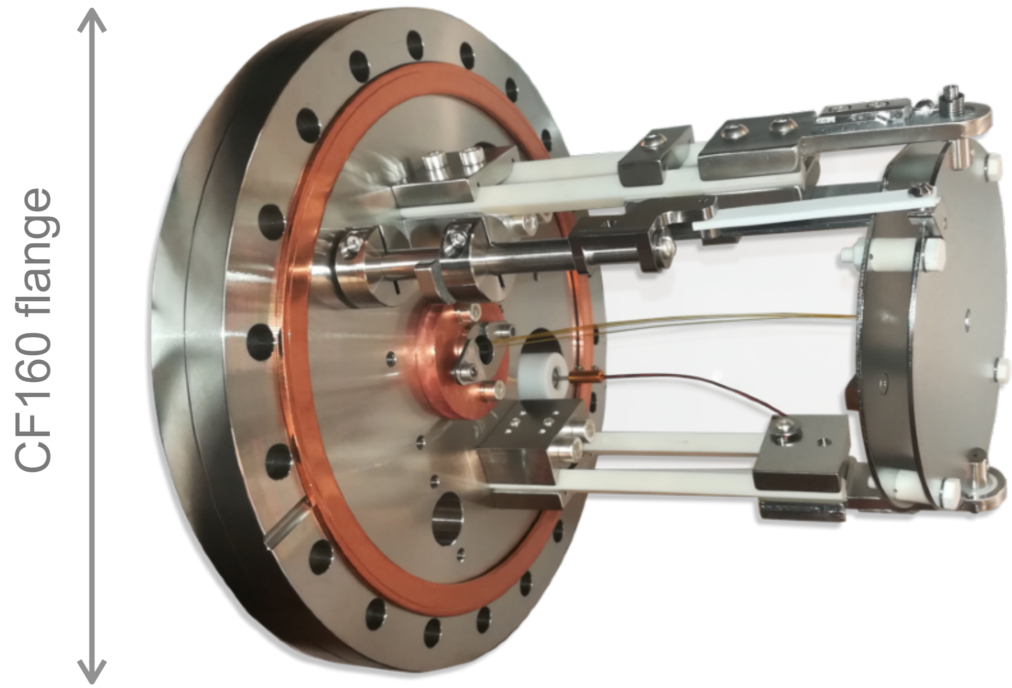
Precision calibration sources (2): e-gun

Requirements

- Tunable beam energy and narrow energy spread (σ_E < 150 meV)
- Tunable ratio of E_{long}, $E_{cyclotron}$ (emission angle) to characterize spectrometer transmission
- Beam intensity up to ~10 kcps
- Individual pixels; beam steering in x/y direction across full flux tube
- Pulsed emission for time-of-flight measurements

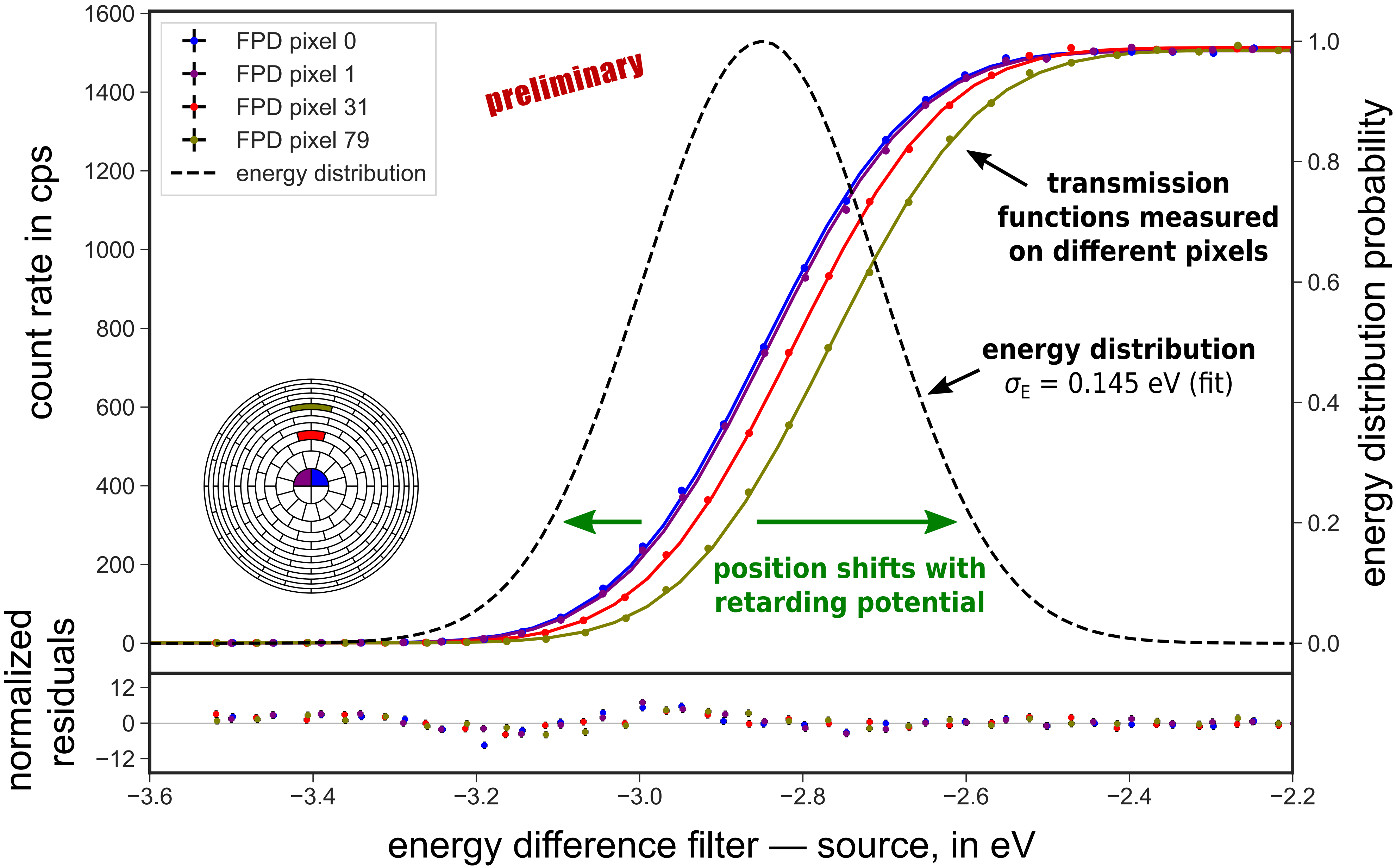
Custom-made solution

- UV optics for photoelectron creation
- Timing by pulsed UV laser
- Beam forming in staged E & B fields



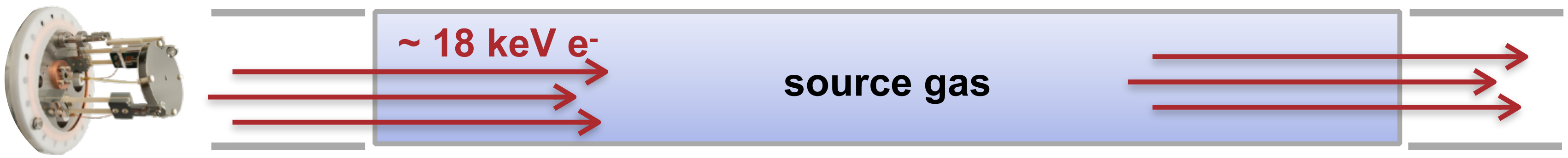
[NJP 11 (2009) 063018; PPNP 64 (2010) 288; JINST 6 (2011) P01002; EPJ C77 (2017) 410]

Precision calibration sources (2): e-gun

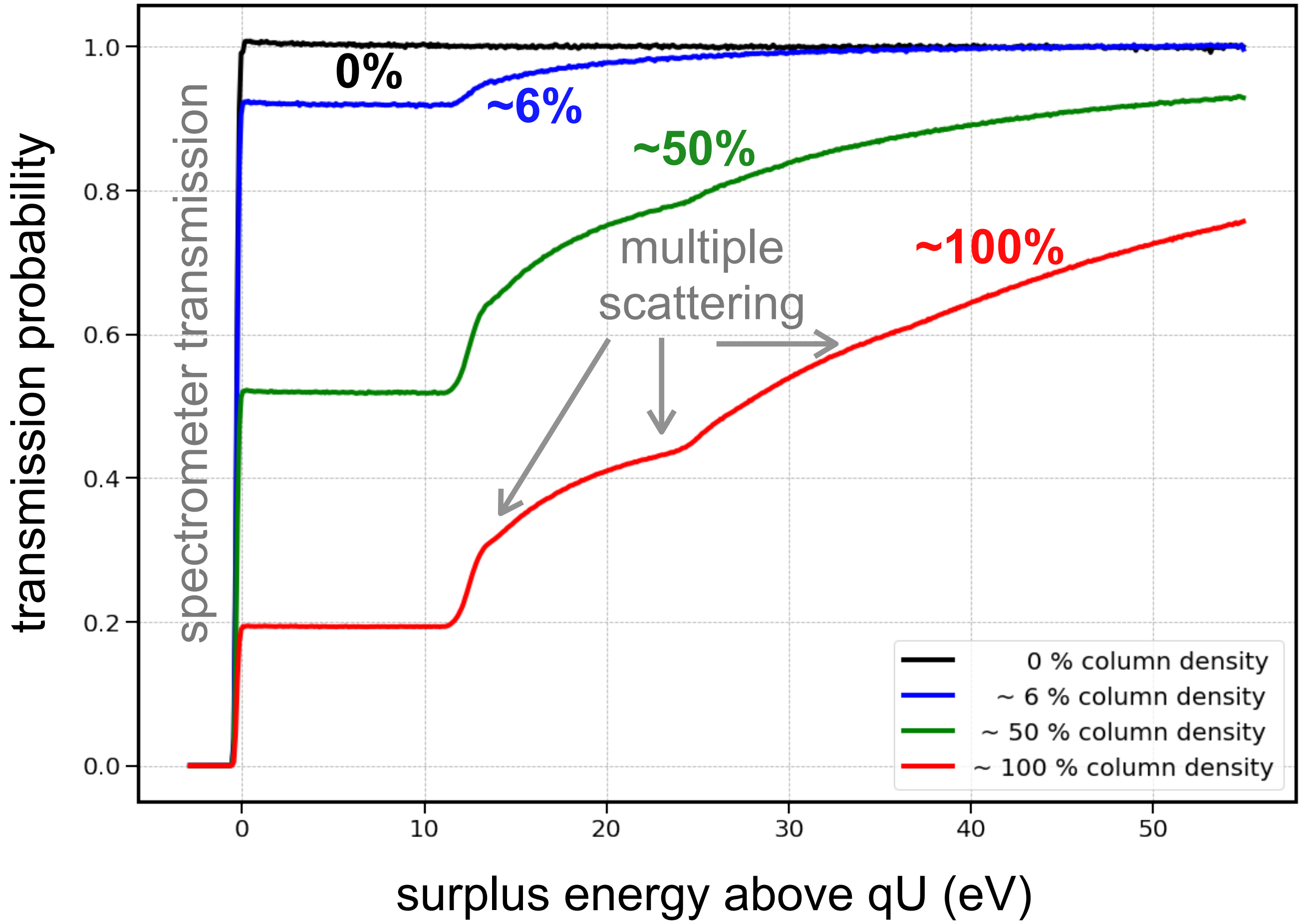


[EPJ C77 (2017) 410, and further works]

Systematics campaign

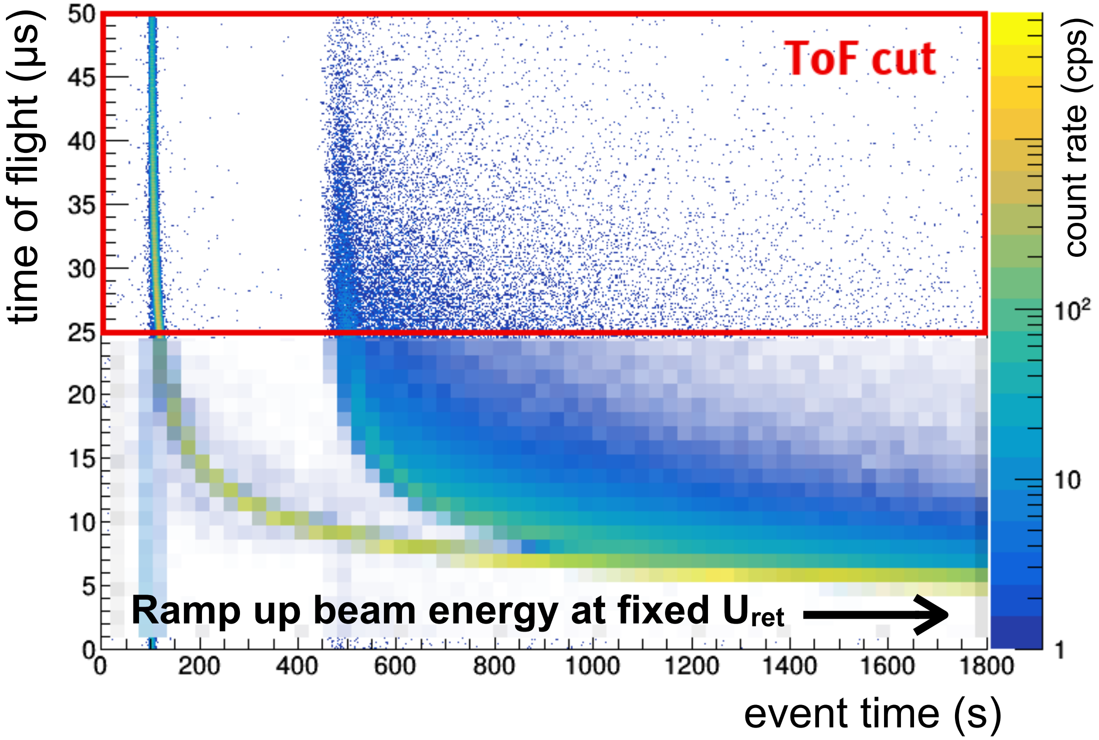


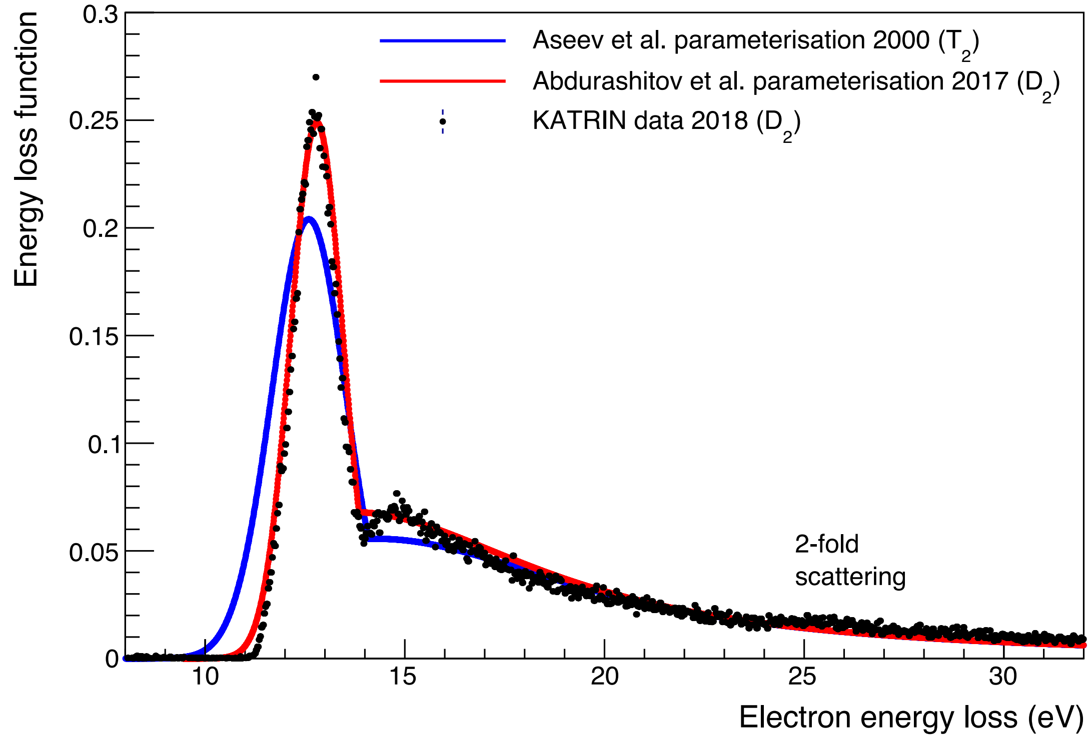
- Column density and energy loss by inelastic scattering are key systematics in ν-mass measurement
- Precision e-gun allows measurement of “response function”
- Measurements agree well with model over full range of gas densities (here: D_2)



Energy loss function from time-of-flight

- ToF signal from pulsed e-gun (70 ns at 20 kHz):
  High-pass filter turned into narrow band-pass ➜ recover "differential" spectrum.

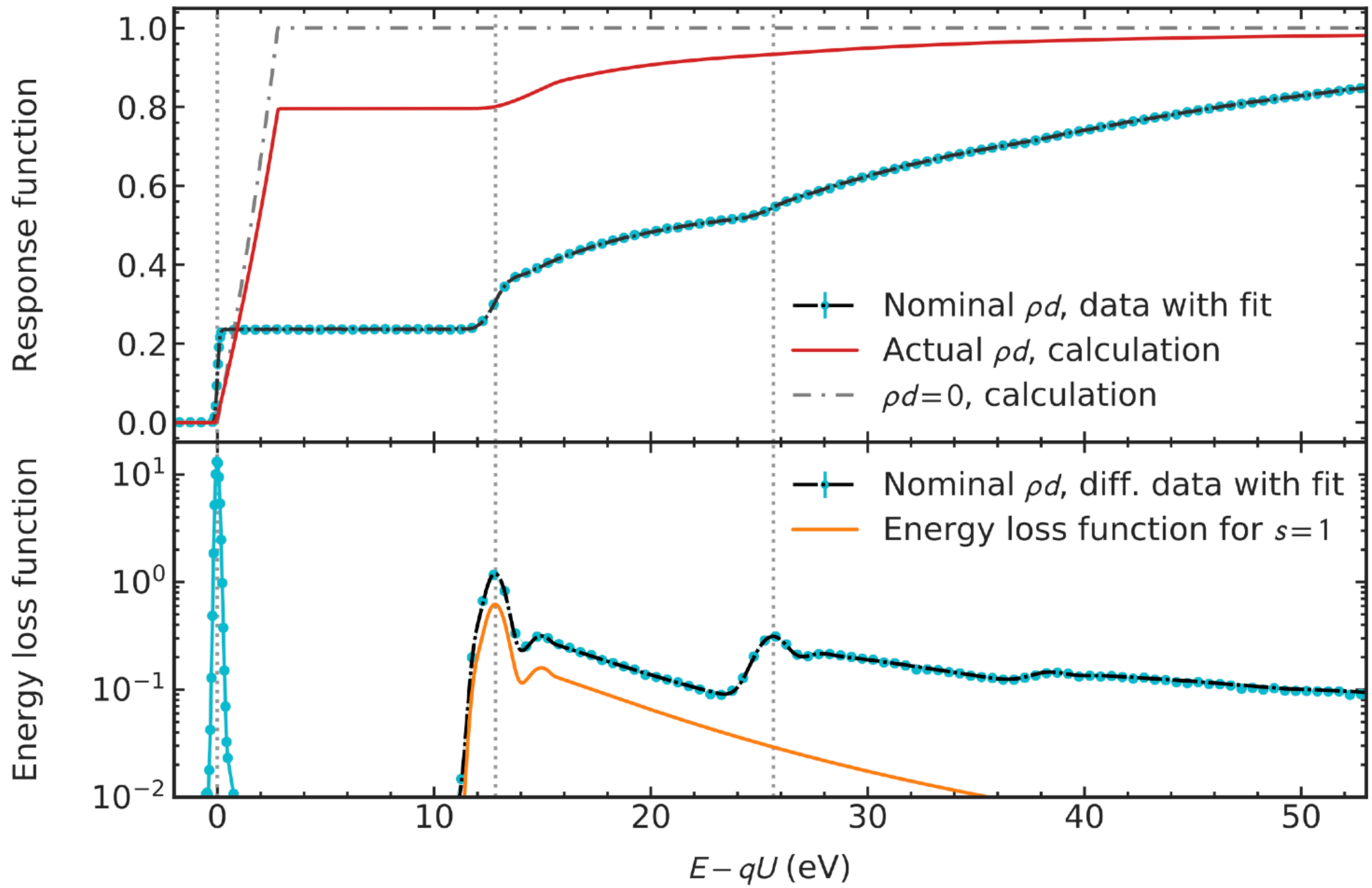




- New parameterisation developed for e-D_2 scattering (2018) and for e-T_2 (2019).
- Response function model ready for ν-mass measurements.

["MAC-E-ToF" idea by J. Bonn *et al.*, NIM A421 (1999) 256; see also Steinbrink *et al.* NJP 15 (2013) 113020]

Response function for ν-mass measurements



from arXiv:1909.06048, reporting first ν-mass result

Summary

KATRIN is made for precision electron spectroscopy.

Successive measurement campaigns (2017-2019) have verified

- energy resolution,
- energy-scale linearity,
- energy-scale stability (short- and long-term),

electron energy filter

- efficiency of measures to retain and eliminate ions,
- constraints on source charging,
- detailed understanding of energy loss through scattering.

tritium source

➜ **Requirements for neutrino-mass measurement are fulfilled!**