Int. School of Nuclear Physics, 39th Course:
Neutrinos in Cosmology, in Astro-, Particle- and Nuclear Physics
Erice, Sept. 16-24, 2017

Preparing the start of neutrino mass measurements with KATRIN

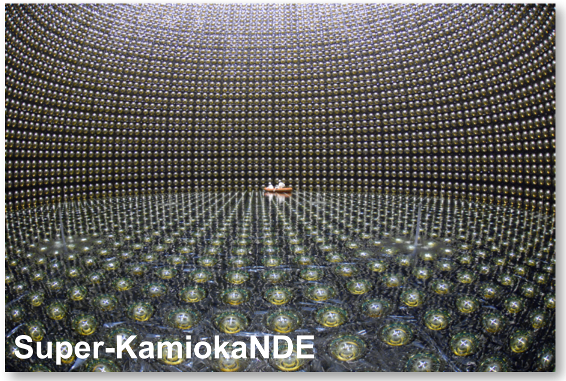
KATHRIN VALERIUS, KIT Center Elementary Particle and Astroparticle Physics (KCETA)

- Introduction:
  Absolute neutrino mass measurement in tritium β decay
- The KATRIN experiment
  - Status: Overview and commissioning results
  - Outlook: Final steps towards tritium data-taking

Massive neutrinos

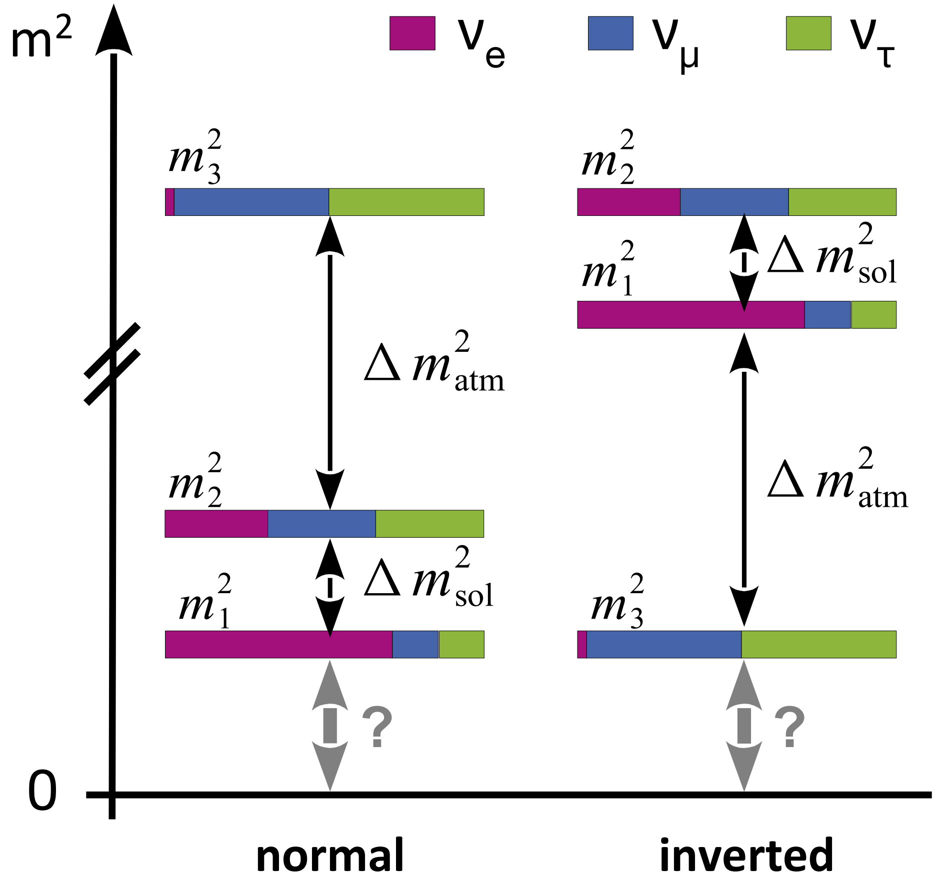
2015 Physics Nobel Prize

*"for the discovery of neutrino oscillations, which shows that **neutrinos have mass**"*



- Evidence for BSM physics
- Mass generation mechanism?
- Smallness of neutrino masses?

M.C. Gonzalez-Garcia, this session
+ many other contributions



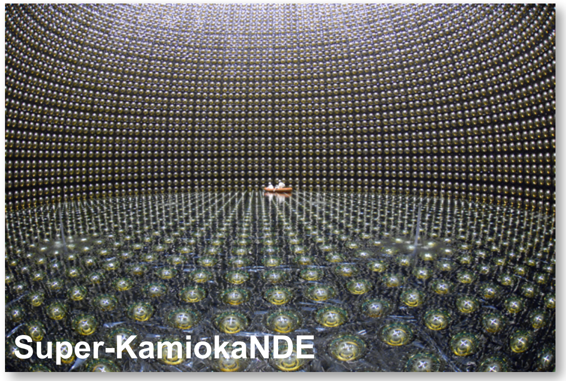
What is the absolute scale of neutrino masses?

Massive neutrinos

Karlsruhe Institute of Technology

2015 Physics Nobel Prize

"for the discovery of neutrino oscillations, which shows that ***neutrinos have mass****"*



- Evidence for BSM physics
- Mass generation mechanism?
- Smallness of neutrino masses?

Erice, anno 2001 …

PERGAMON

Progress in Particle and Nuclear Physics 48 (2002) 141–150

Progress in Particle and Nuclear Physics

http://www.elsevier.com/locate/npe

KATRIN, a Next Generation Tritium β Decay Experiment in Search for the Absolute Neutrino Mass Scale

Ch. WEINHEIMER for the KATRIN COLLABORATION*

Institut für Physik, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany

New address: Institut für Strahlen- und Kernphysik, Universität Bonn, 53115 Bonn, Germany

November 27, 2001

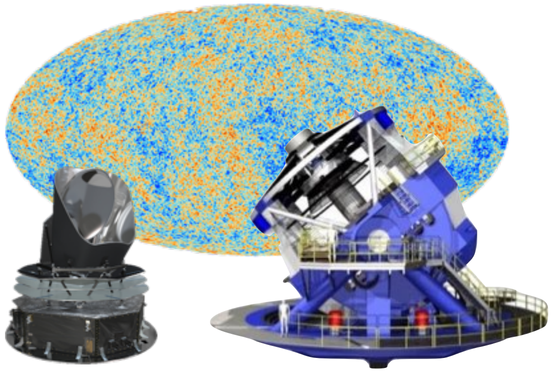
Abstract

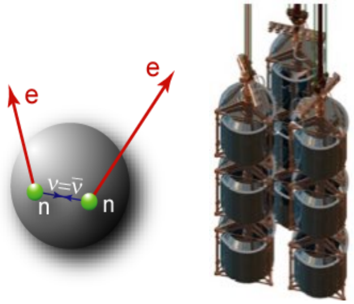
With the compelling evidence for massive neutrinos from recent ν-oscillation experiments, one of the most fundamental tasks of particle physics over the next years will be the determination of the absolute mass scale of neutrinos, which has crucial implications for cosmology, astrophysics and particle physics. A next generation tritium β decay experiment, the Karlsruhe Tritium Neutrino experiment (KATRIN), is proposed to reach a sub eV sensitivity on the absolute mass of the electron neutrino.

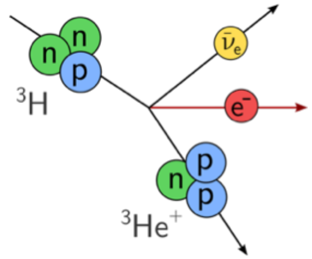
KATRIN Letter of Intent: ***arXiv:hep-ex/0109033***

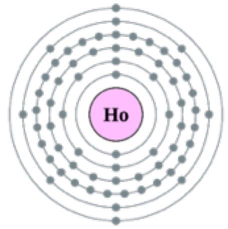
What is the absolute scale of neutrino masses?

Complementary paths to the ν mass scale









	Cosmology	Search for 0νββ	β-decay & EC
Observable	$M_\nu = \sum_i m_i$	$m^2_{\beta\beta} = \left\|\sum_i U^2_{ei}\, m_i\right\|^2$	$m^2_\beta = \sum_i \|U_{ei}\|^2\, m^2_i$
Present upper limit	~0.2 – 0.6 eV	~0.1 – 0.4 eV	2 eV
Potential: near-term (long-term)	60 meV (15 meV)	50 – 200 meV (20 – 40 meV)	200 meV (40 – 100 meV)
Model dependence	Multi-parameter cosmological model	- Majorana ν: LNV - BSM contributions other than m(ν)? - Nuclear matrix elements	**Direct,** only kinematics; no cancellations in incoherent sum

M. Archidiacono (today)

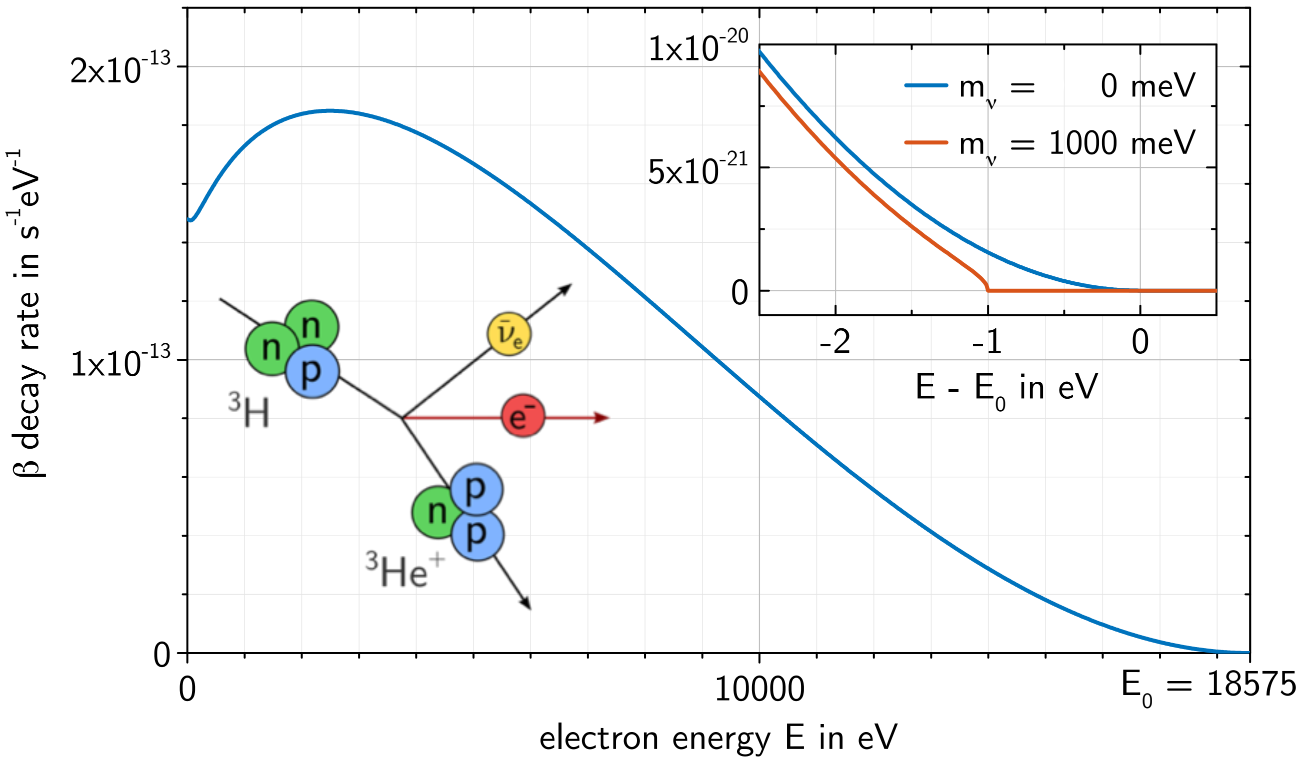
A. Piepke, **M. Agostini** (Mon), **A. Poon** (Tue) ***+ more***

G. Drexlin, **S. Mertens**, **S. Böser** (Thu); **M. Fertl**, **C. Tully** (Mon) ***+ more***

L. Gastaldo, **A. Faessler** (Tue), **F. Gatti** (Thu) ***+ more***

Direct kinematic determination of m(ν$_e$)

$$\frac{d\Gamma}{dE} = C\, F(Z,E)\, p\,(E+m_e)\,(E_0-E)\,\sum_i |U_{ei}|^2 \sqrt{(E_0-E)^2 - m^2(\nu_i)}$$



Key requirements:

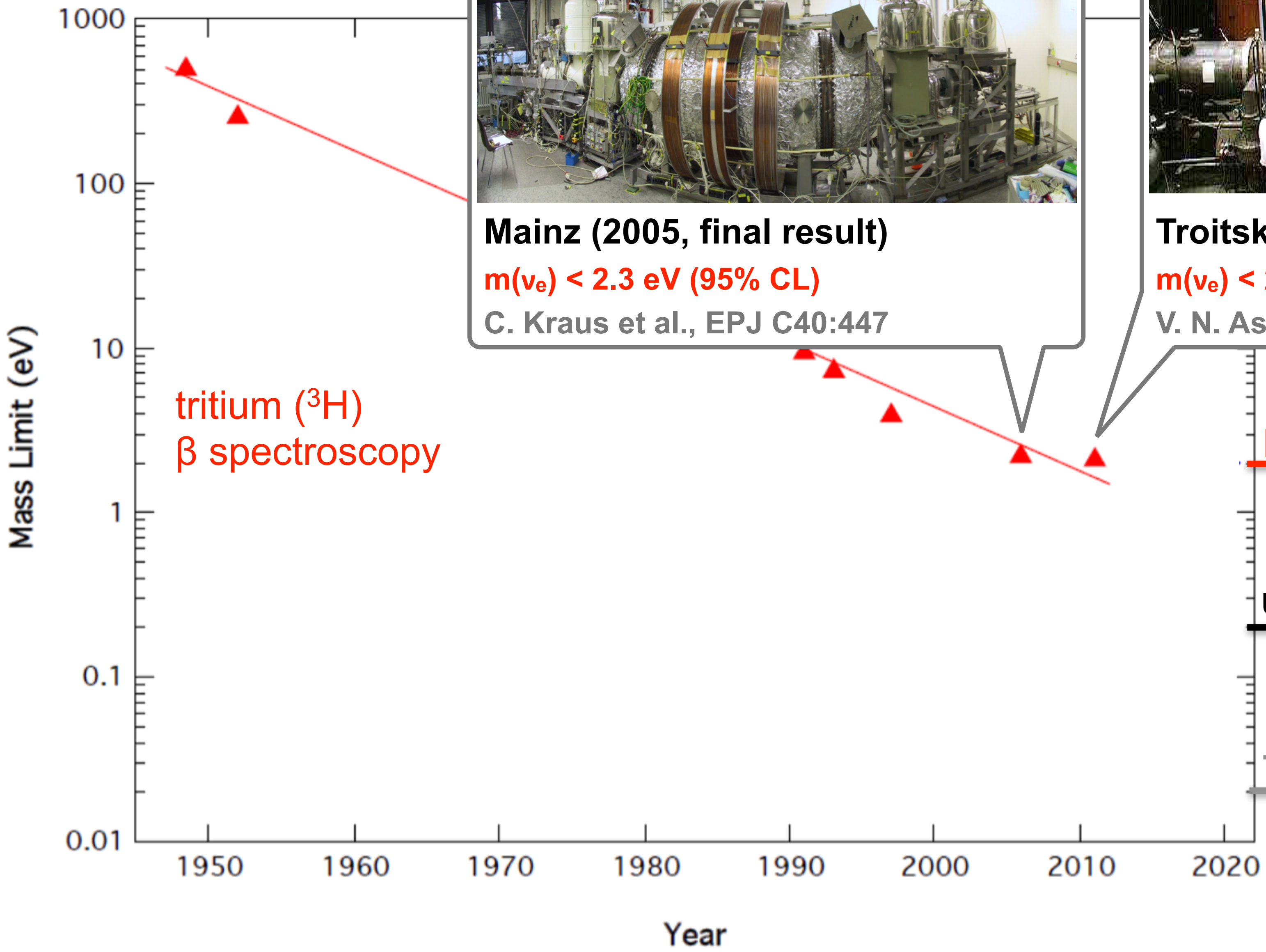
- Low-endpoint β/EC nuclide: E_0 = 18.6 keV for ^{3}**H**, 2.8 keV for ^{163}**Ho**
- High-activity source: $T_{1/2}$ = 12.3 yr for ^{3}**H,** 4.5 kyr for ^{163}**Ho**
- Excellent energy resolution (MAC-E filter or calorimeter)

Kinematic measurement can probe for **heavier neutrino states**
➜ eV-scale and keV-scale sterile ν

Spectral distortion measures **"effective" mass square:**

$$m^2(\nu_e) := \sum_i |U_{ei}|^2\, m_i^2$$

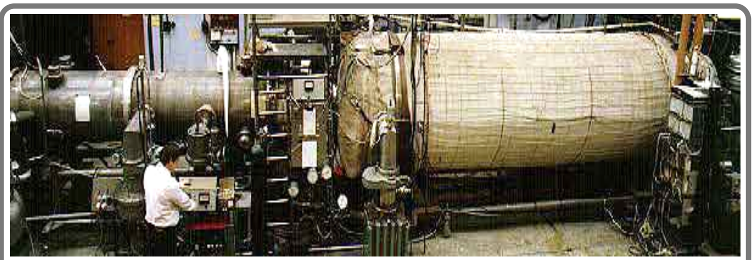
Moore's Law of direct neutrino mass searches



Mainz (2005, final result)

$m(\nu_e) < 2.3$ eV (95% CL)

C. Kraus et al., EPJ C40:447



Troitsk (2011, re-analysis)

$m(\nu_e) < 2.05$ eV (95% CL)

V. N. Aseev et al., PRD 84:112003

present limits (2 eV)

ν ruled out as DM

upcoming (KATRIN: 200 meV)

degeneracy scale

future approaches

hierarchy scale

Courtesy J.F. Wilkerson/R.G.H. Robertson

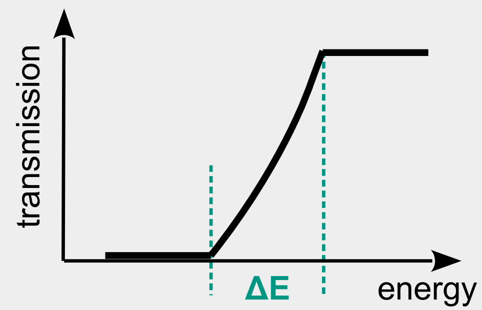
High-resolution β spectrometer

Magnetic Adiabatic Collimation & Electrostatic Filter

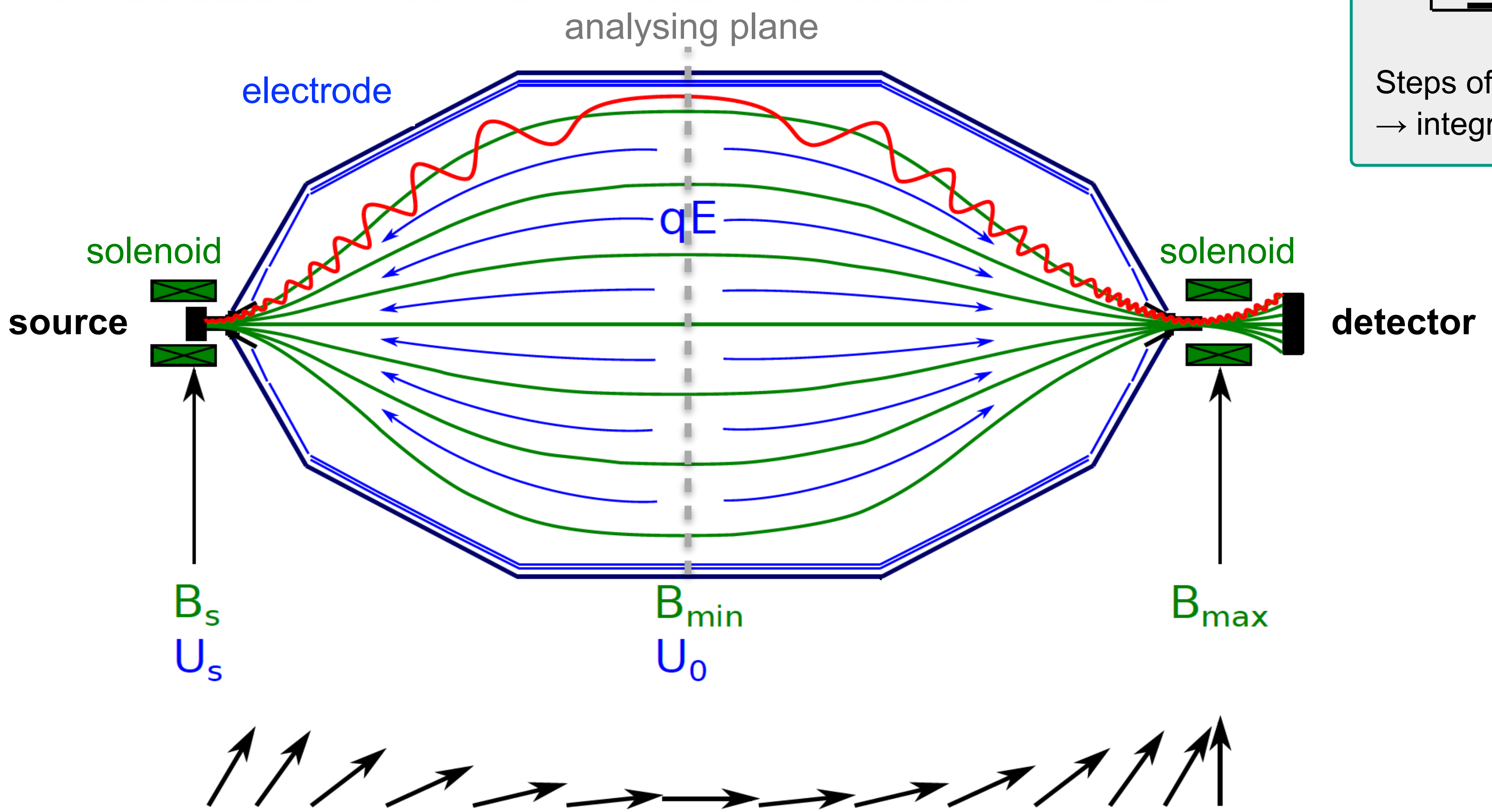
- integrating electrostatic filter ($E_{kin} > eU_0$)
- "clean" (analytic) response function
- $\Delta E < 1$ eV at 18.6 keV

$$\frac{\Delta E}{E} = \frac{B_{min}}{B_{max}}$$

Sharp high-pass filter:



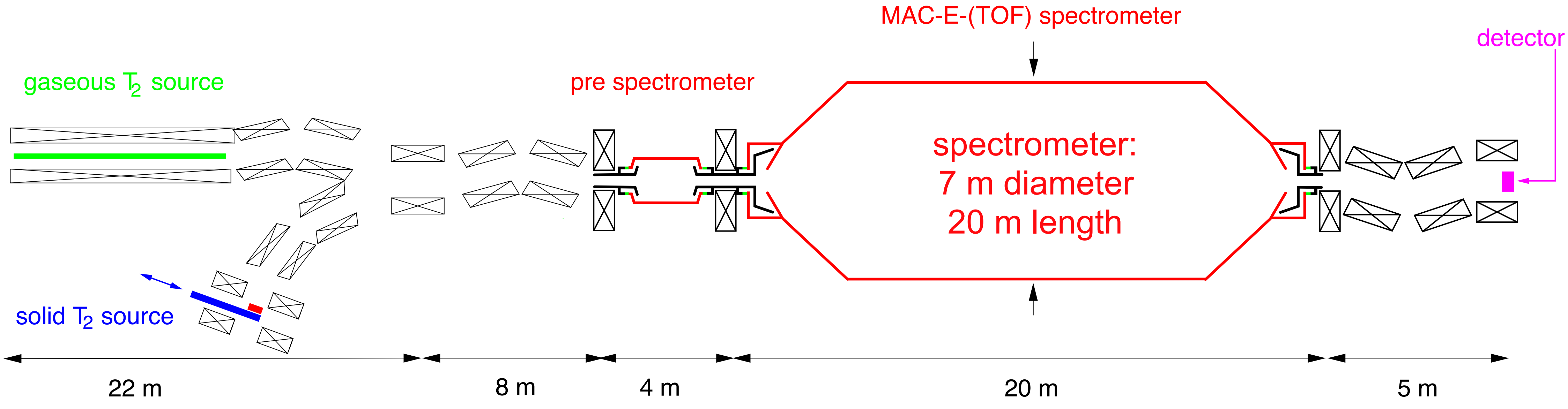
Steps of filter potential
→ integrated β spectrum



[Beamson et al. 1980; Kruit & Read 1983; **Lobashev 1985; Picard et al. 1992**]

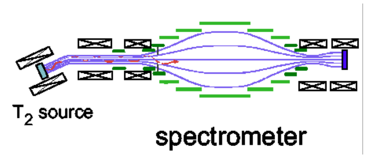
The Karlsruhe Tritium Neutrino Experiment

… back in 2001:



- Linear dim. of setup: **x10**
- Statistics increase: **x100**
- Systematics reduction: **÷100**

Mainz Setup :

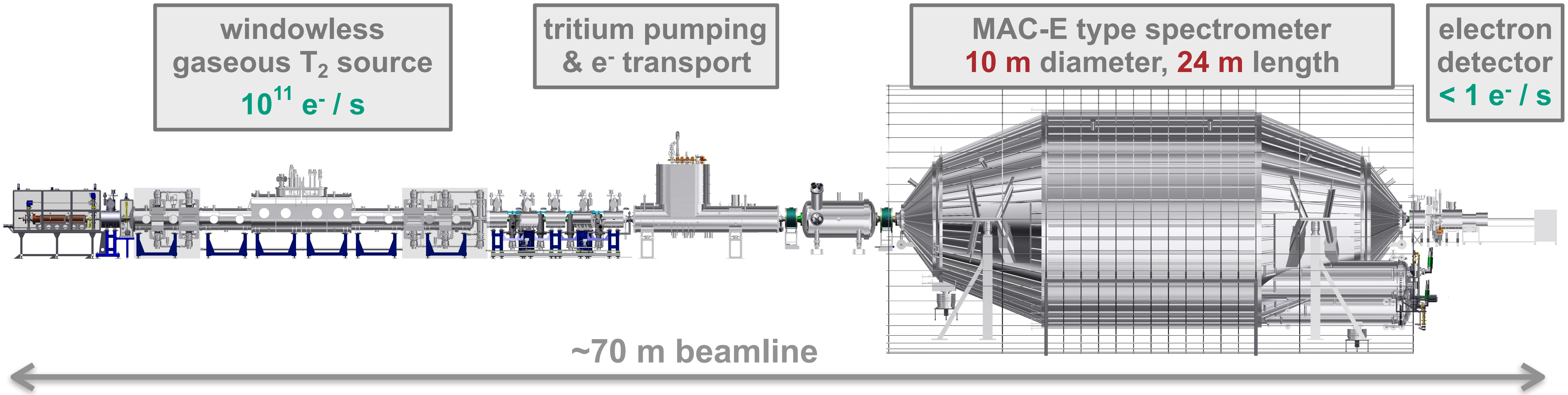


Ca. 50 authors on the Letter of Intent (*hep-ex/0109033*)
Initially: groups from Karlsruhe, Mainz, Troitsk, Seattle, Rez, Fulda

The Karlsruhe Tritium Neutrino Experiment

… as realized today:

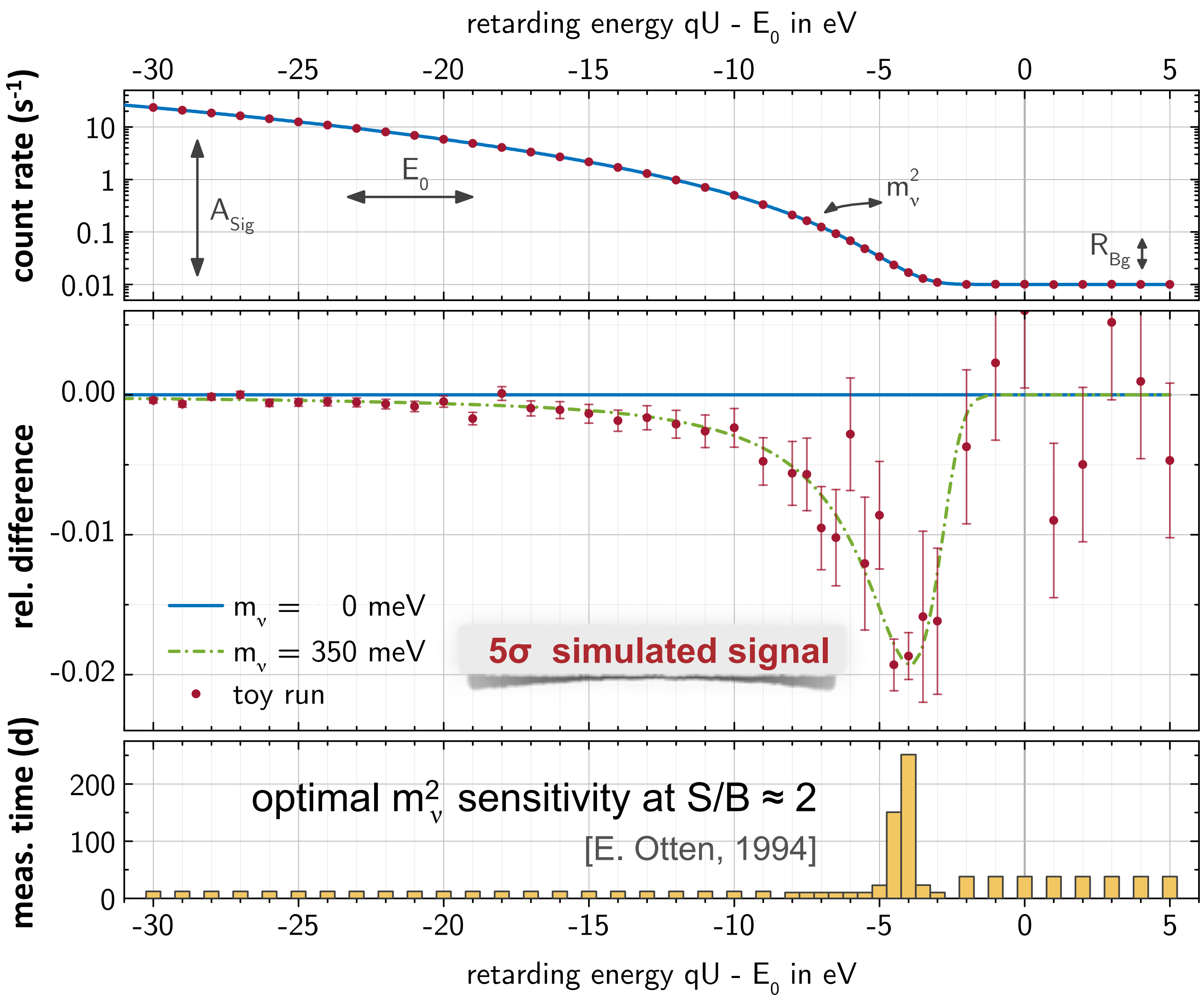
→ Lecture by G. Drexlin on Thursday



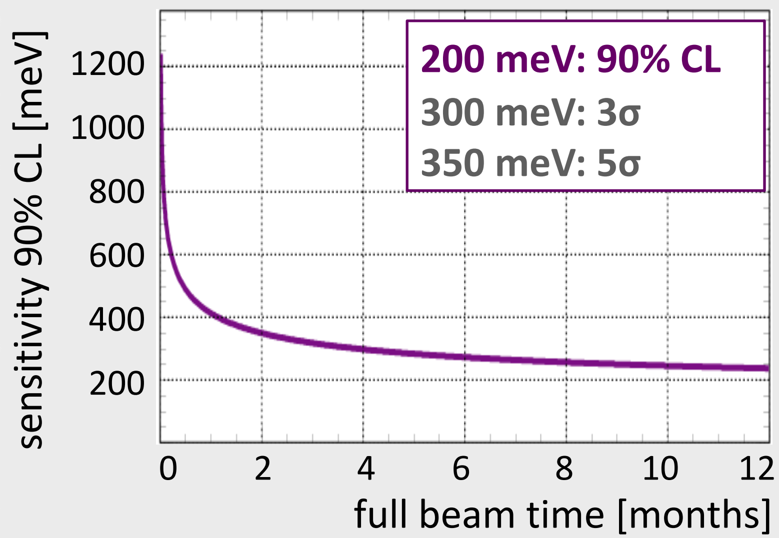
Sensitivity on $m(\nu_e)$: 2 eV → 200 meV

Ca. 140 collaboration members
from ~20 institutions in 6 countries

Neutrino mass analysis & sensitivity

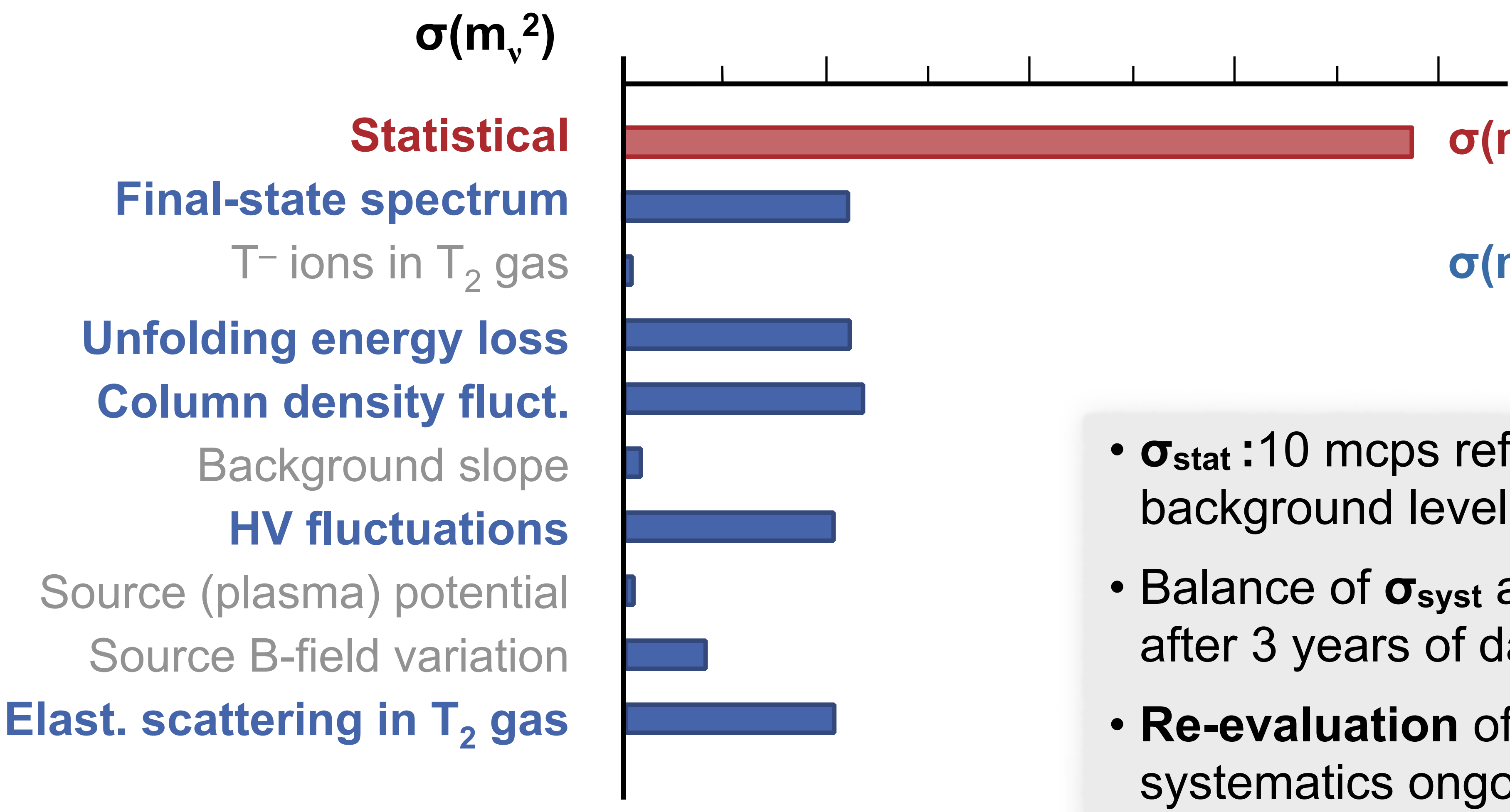


- Relative **shape** measurement of **integrated β spectrum**
- 4 fit parameters: m_ν^2, E_0, A_S, R_{Bg}



Statistical & systematic uncertainties

KATRIN's uncertainty budget (design sensitivity, ~2004):



$\sigma(m_\nu^2)_{stat} = 0.018\ eV^2$

$\sigma(m_\nu^2)_{syst} = 0.017\ eV^2$

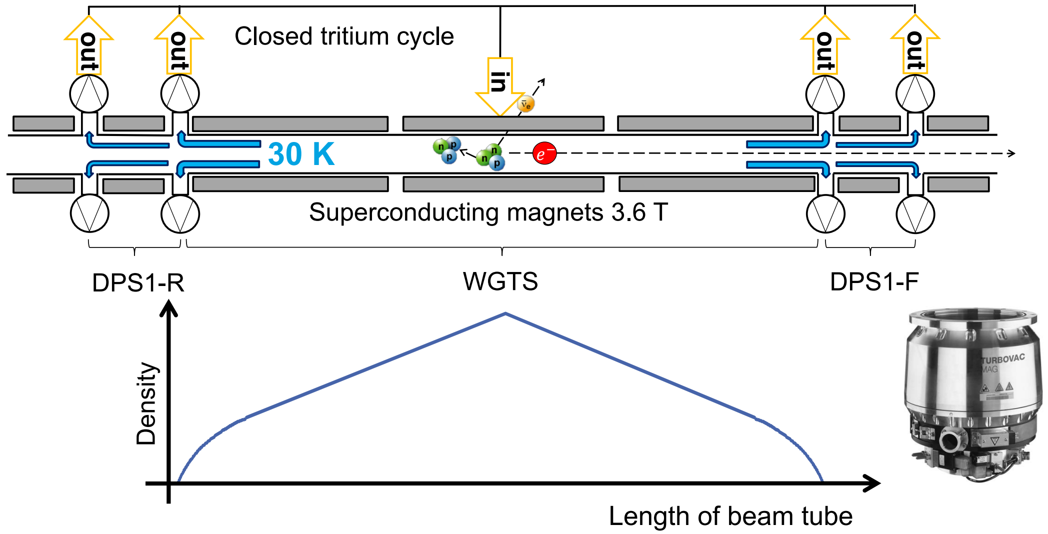
- $\boldsymbol{\sigma_{stat}}$: 10 mcps reference background level
- Balance of $\boldsymbol{\sigma_{syst}}$ and total $\boldsymbol{\sigma_{stat}}$ after 3 years of data
- **Re-evaluation** of individual systematics ongoing during system characterisation

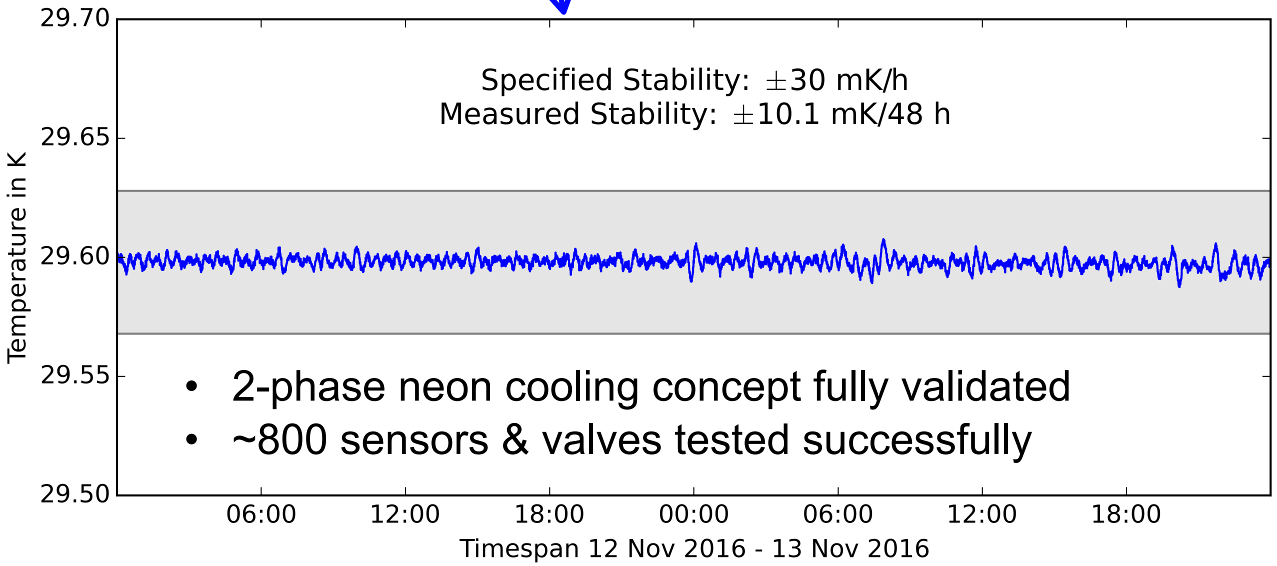
Windowless gaseous tritium source

Gaseous molecular tritium source of

- high activity (~170 GBq)
- high isotopic purity (ε_T > 95%)
- high gas column stability (0.1%)

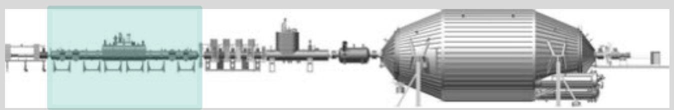
$n \sim \varepsilon_T \cdot p \cdot V / (R \cdot T)$





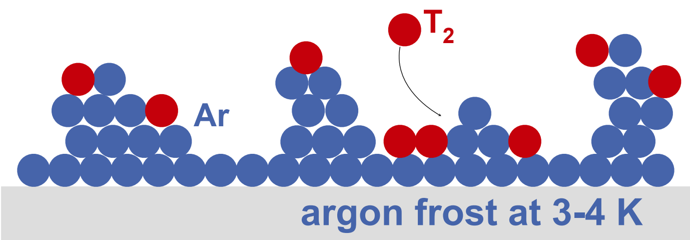
- 2-phase neon cooling concept fully validated
- ~800 sensors & valves tested successfully

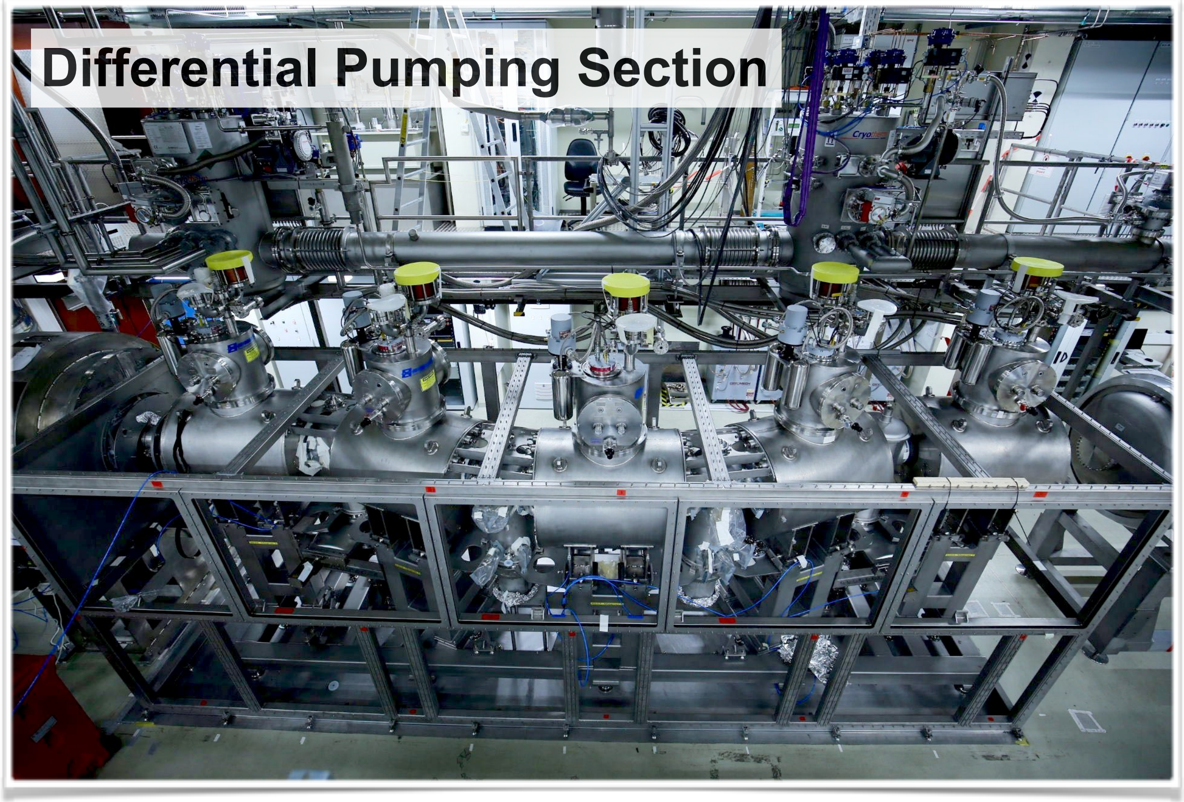
H. Seitz-Moskaliuk, S. Mirz (Sun)

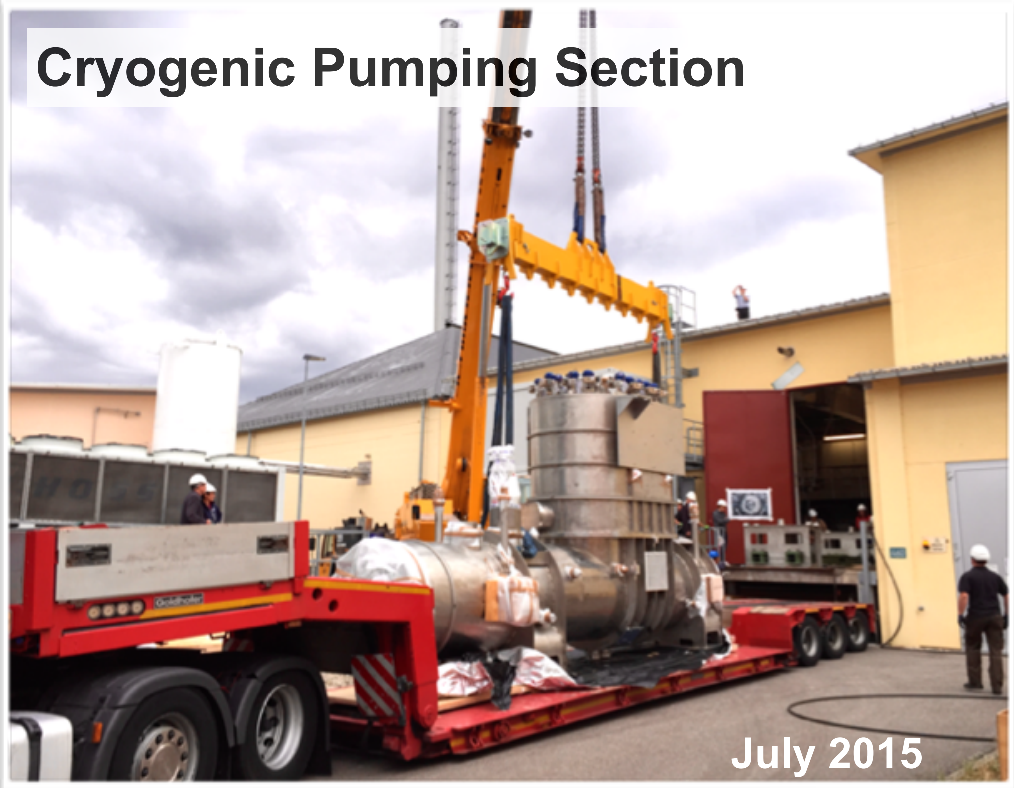


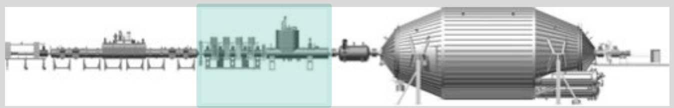
Transport & pumping sections

- Fully adiabatic, **lossless electron transport** in 5.6 T magnetic field
- **Reduction of T_2 flow rate** to spectrometers by factor **>10^{14}**: magnetic chicane with **differential** and **cryo-pumping**
- Ion diagnostics & **ion flux blocking** by electrostatic barrier



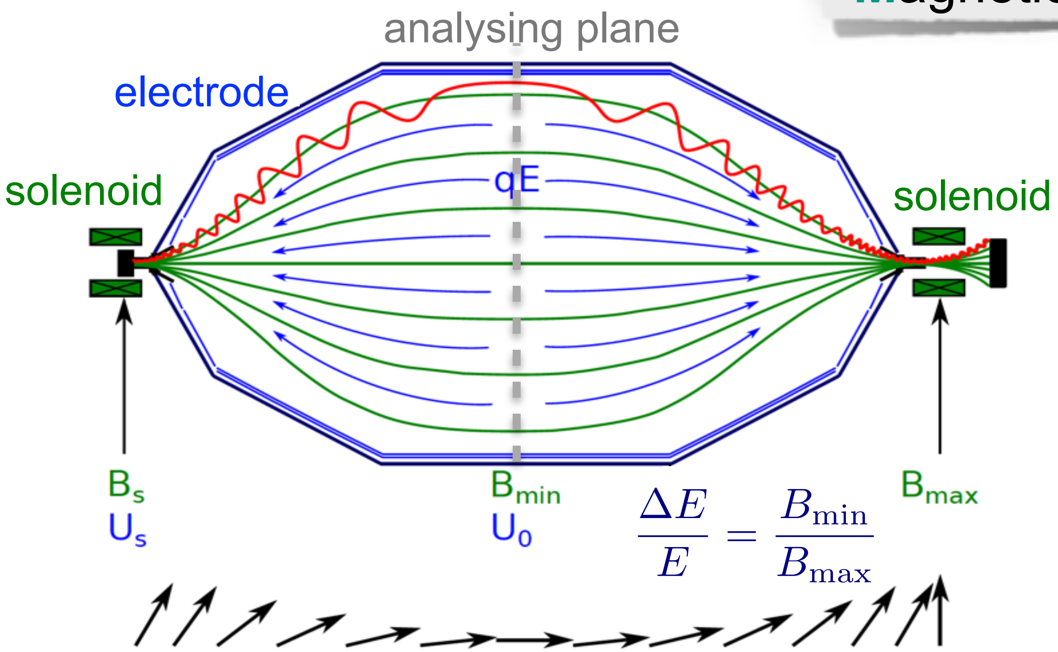




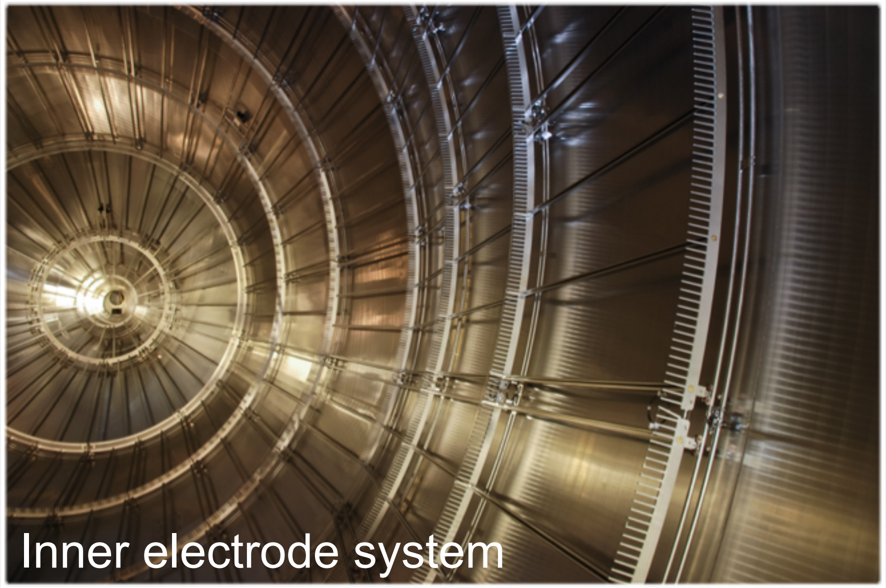


KATRIN main spectrometer

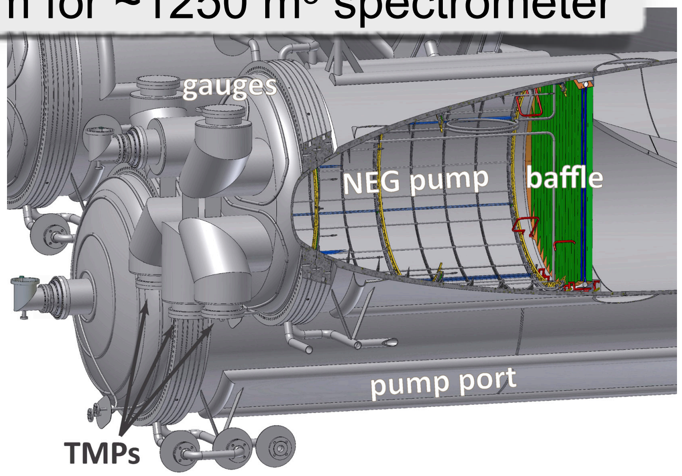
Magnetic Adiabatic Collimation and Electrostatic Filter

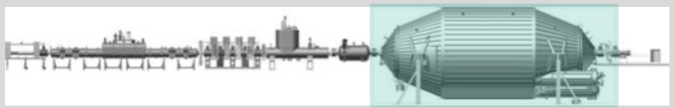


$$\frac{\Delta E}{E} = \frac{B_{\mathrm{min}}}{B_{\mathrm{max}}}$$

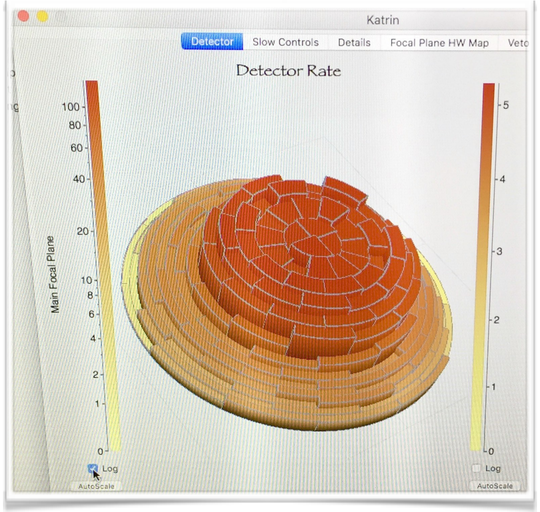


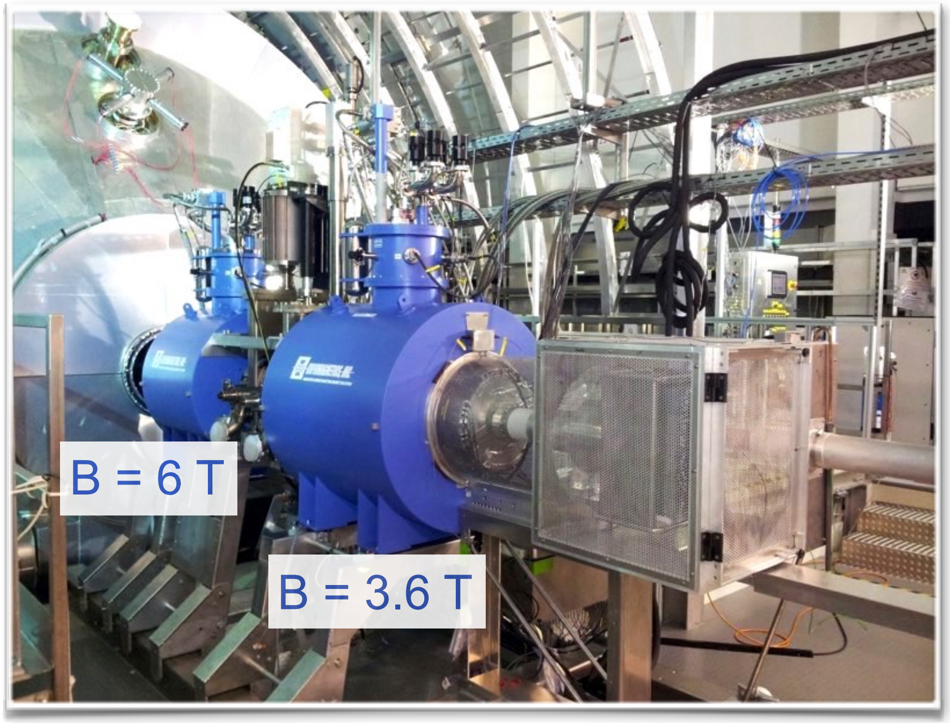
UHV system for ~1250 m^3 spectrometer





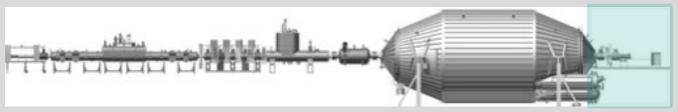
Detector system



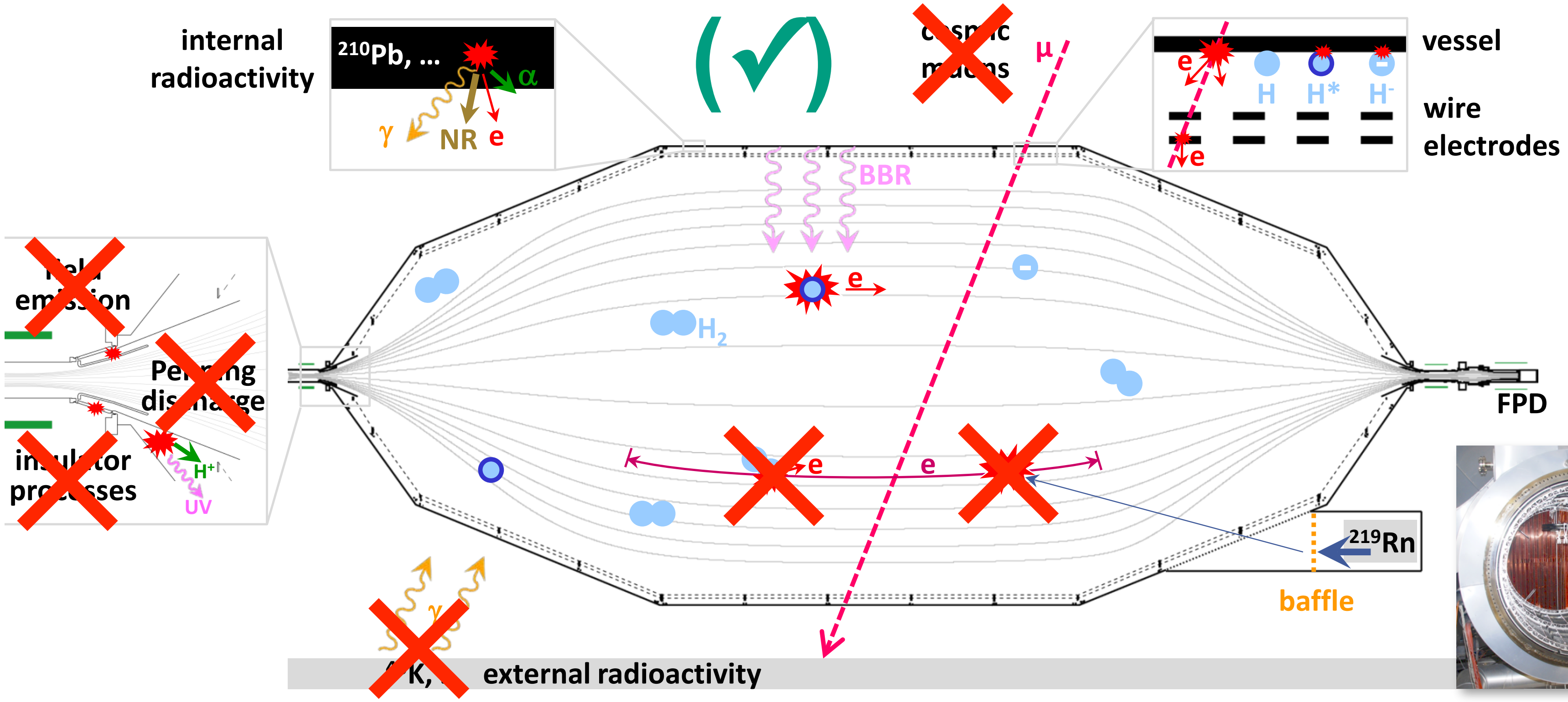


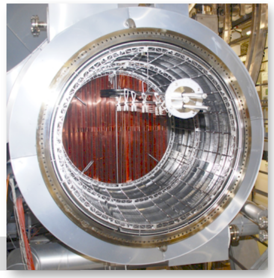
- Ø 90 mm Si-PIN diode
- 148 pixels (dartboard layout)
- ΔE_{FWHM} ~2 keV
- high detection efficiency

- low intrinsic background (passive & active shielding)
- post-acceleration up to 10 kV



Backgrounds in KATRIN

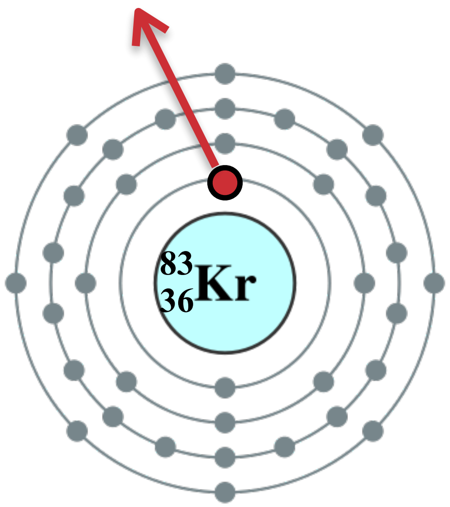


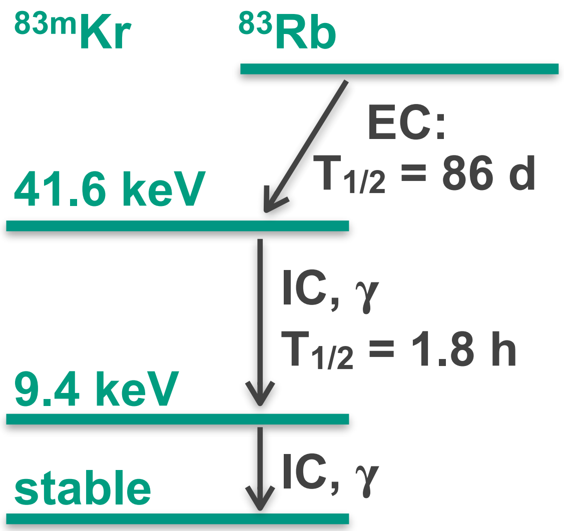


- **8 sources of background investigated and understood**
- **7 out of 8 avoided or actively eliminated by**
  - fine-shaping of special electrodes
  - inner electrode (wire grids on neg. potential)
  - symmetric magnetic fields
  - cold traps (LN_2-cooled baffles to remove ^{219}Rn)

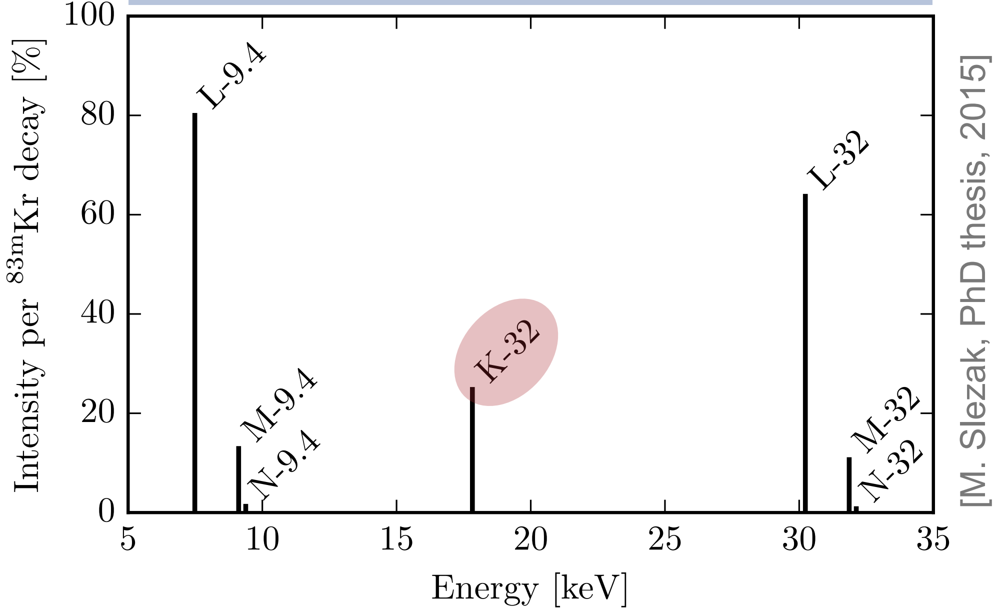
- **1 out of 8 remaining:**
  ^{210}Pb on spectrometer walls
  (thermal ionisation of neutral H* atoms)
- Countermeasures:
  - extensive bake-out (done)
  - irradiation by strong UV source (ongoing investigation)

KATRIN milestone: gearing up for tritium with ^{83m}Kr





narrow (< 2 eV) CE lines at 7 … 32 keV



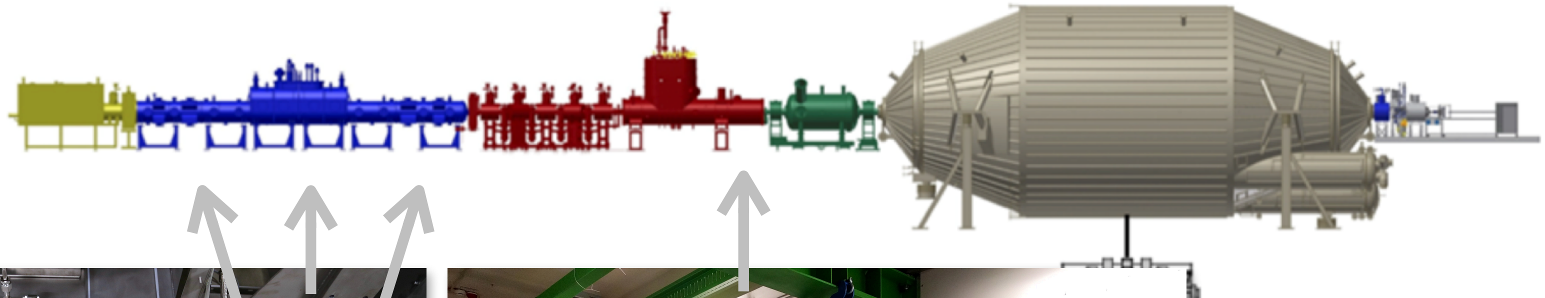
KATRIN krypton campaign: 3-19 July 2017

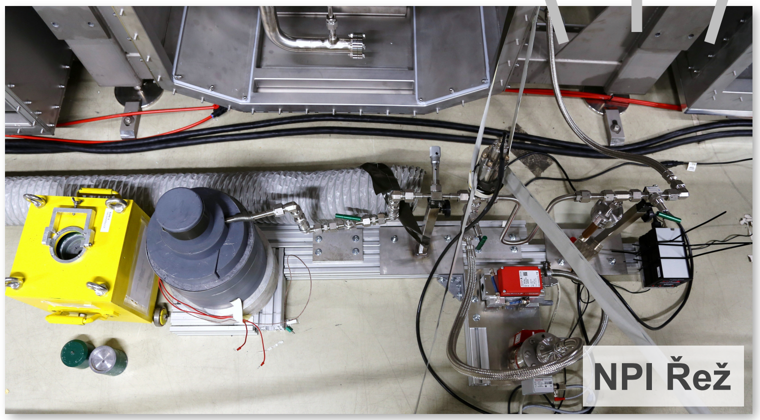
Hardware readiness from source to detector with ^{83m}Kr as short-lived "tracer"

Data chain from raw data & slow control parameters to high-level analysis tools

System characterization with mono-energetic & isotropic CE:
sharp transmission of MAC-E filter, detector properties, system alignment, absolute energy scale calibration, …

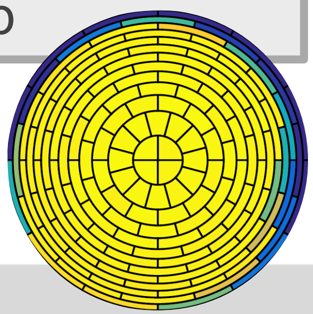
Krypton measurement programme at KATRIN





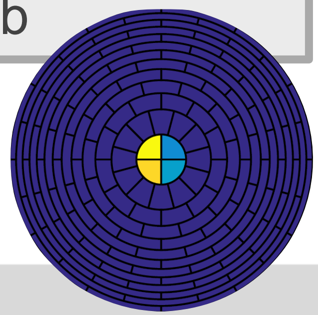
Gaseous ^{83m}Kr source

- Krypton decays inside WGTS beam tube (100 K)
- Homog. spatial distribution
- Ca. 1 GBq ^{83}Rb

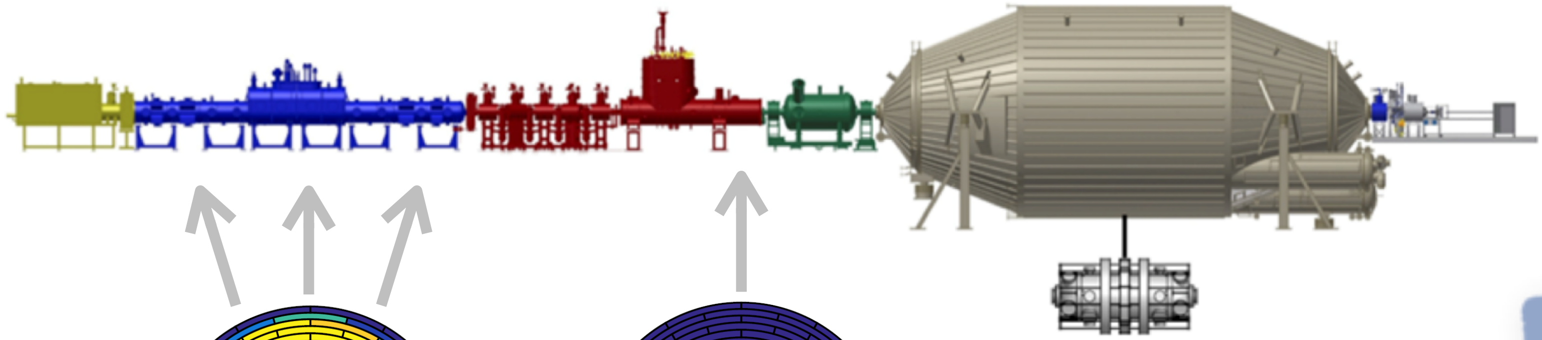


Condensed ^{83m}Kr source

- Thin film on cold substrate
- Spot-like source, can be moved across flux tube
- Ca. 1 MBq ^{83}Rb

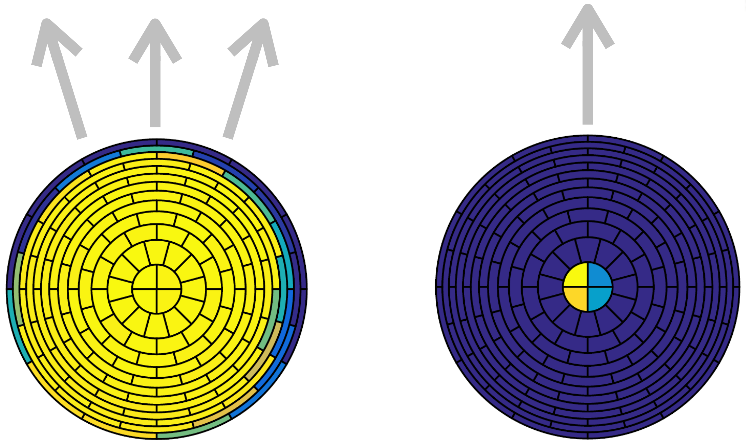


Krypton measurement programme at KATRIN



→ H. Seitz-Moskaliuk

July 2017



since 2012

Gaseous ^{83m}Kr source
- Krypton decays inside WGTS beam tube (100 K)
- Homog. spatial distribution
- Ca. 1 GBq ^{83}Rb

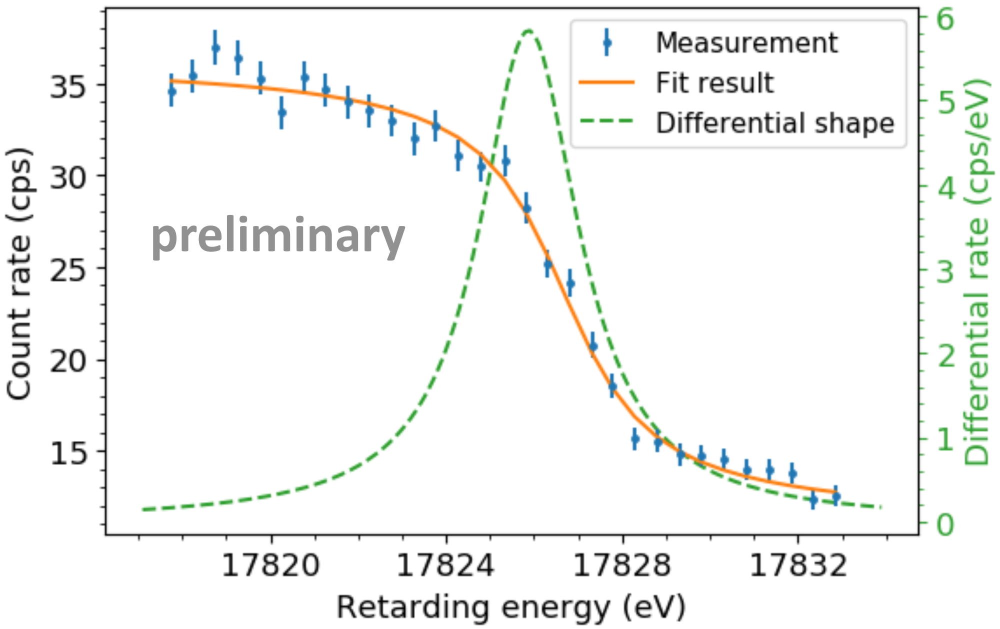
Condensed ^{83m}Kr source
- Thin film on cold substrate
- Spot-like source, can be moved across flux tube
- Ca. 1 MBq ^{83}Rb

Implanted ^{83m}Kr source
- Parallel measurement at Monitor Spectrometer
- Excellent stability proven since many years

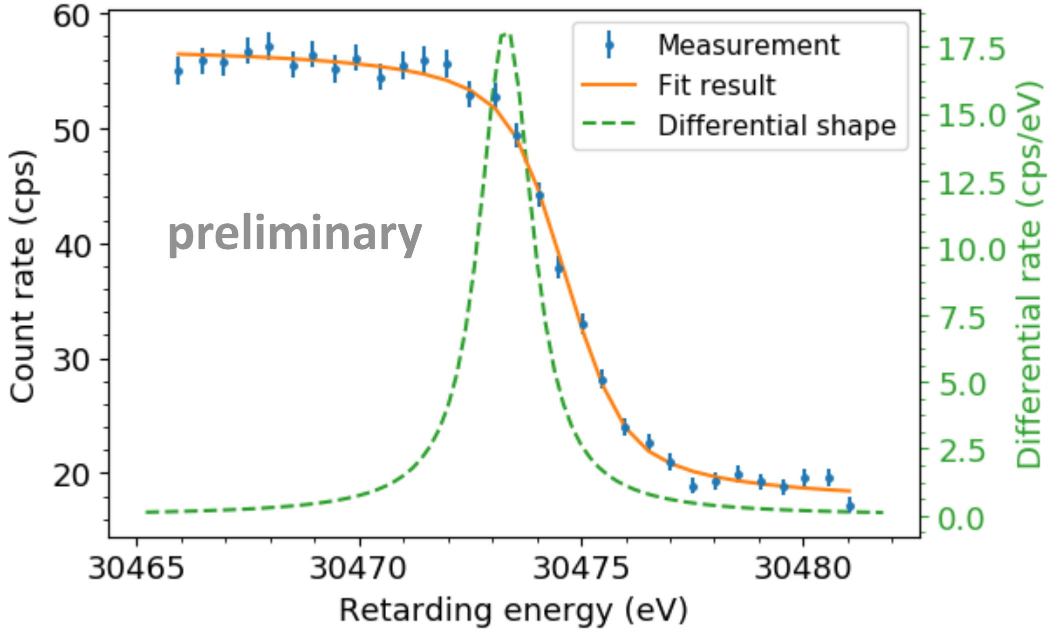
Three different krypton sources ➜ handle on systematics, extensive characterization

Line stability & absolute calibration (gaseous Kr source)

K-32 line (17.8 keV, Γ ~2.8 eV)



L_3-32 line (30.47 keV, Γ ~1.4 eV)

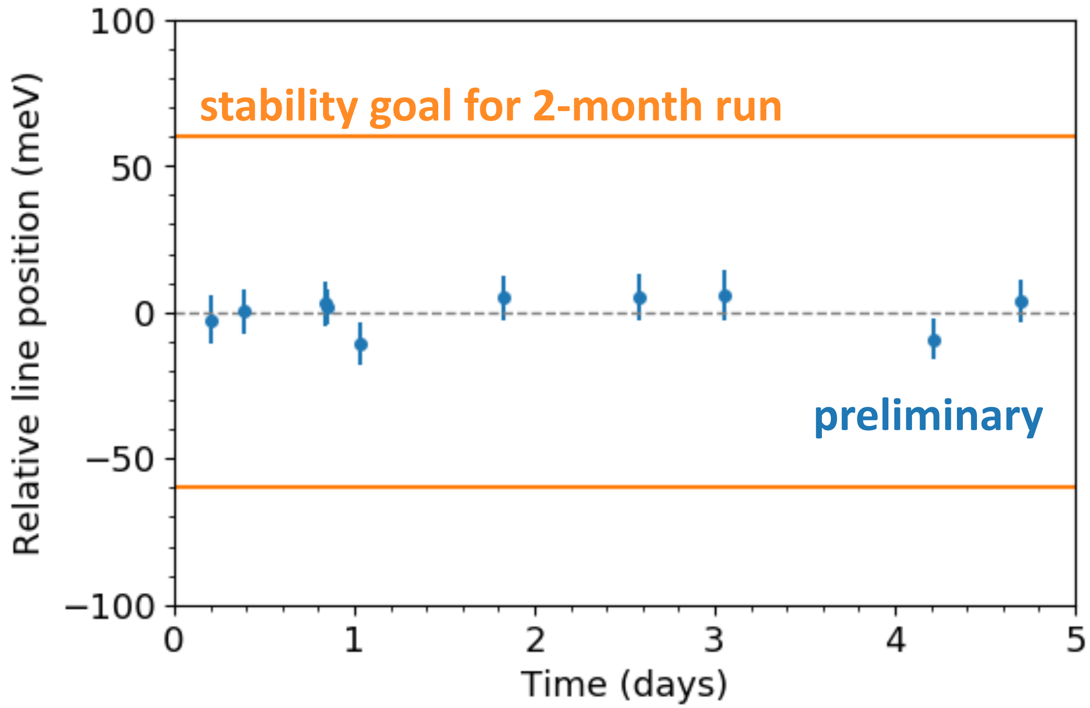


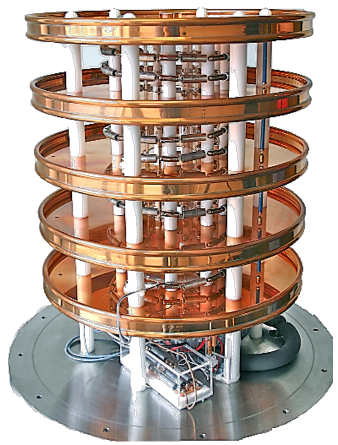
- Example runs (two out of many line scans)
- Only central detector ring shown (x30 more statistics available)
- High-resolution scans of narrow $N_{2,3}$-32 doublet (670 meV hyperfine splitting, sub-eV natural widths, background-free at 32 keV) currently being analyzed

Line stability & absolute calibration (gaseous Kr source)

- Repeated scans of L_3-32 line
- Line position stability well within KATRIN goal of ± 60 meV

➡ Excellent stability of Krypton source and HV system



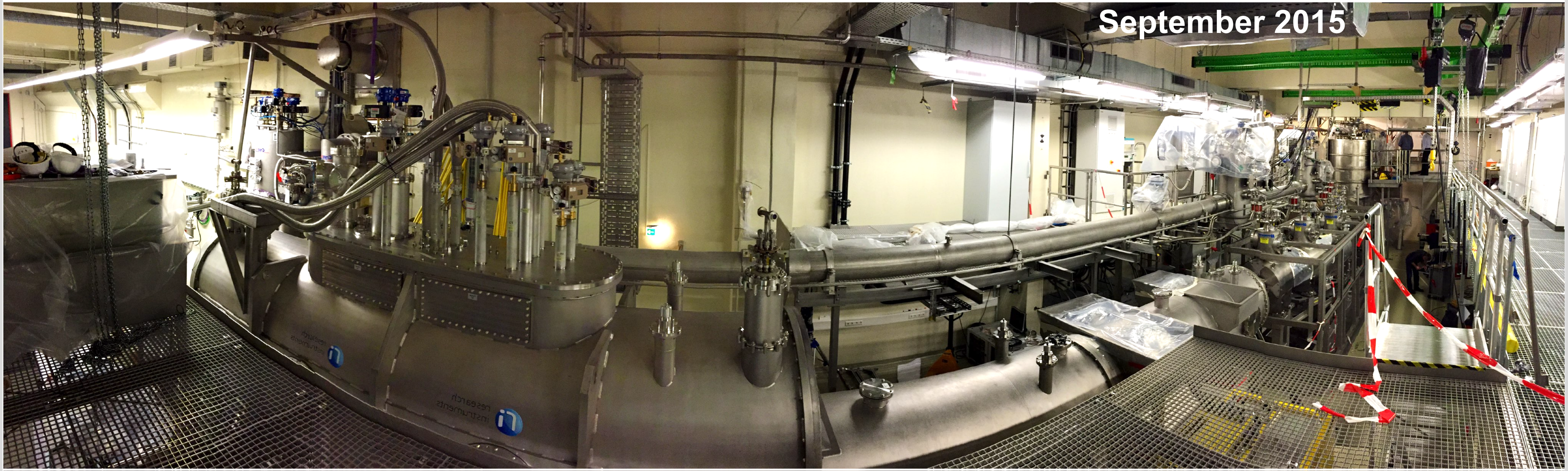


In cooperation with German national metrology institute PTB

- Absolute calibration of HV divider with nuclear standard
- Line position difference L3-32 — K-32
  → source-related systematics cancel
  → ~5 ppm preliminary uncertainty on energy scale
  (very good agreement with 2013 PTB calibration value!)

Status of tritium-bearing components

Karlsruhe Institute of Technology

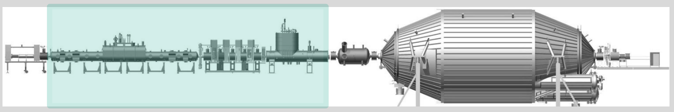


tritium source cryostat

differential pumping & cryo-pumping sections

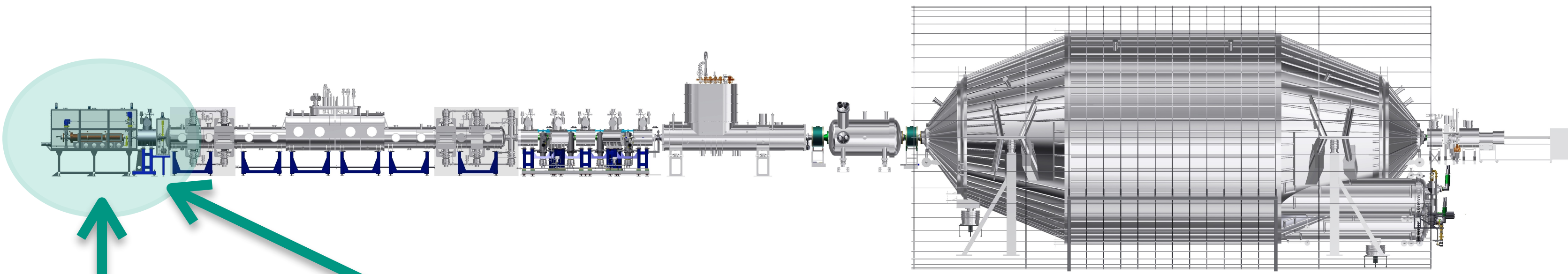
source instruments panel

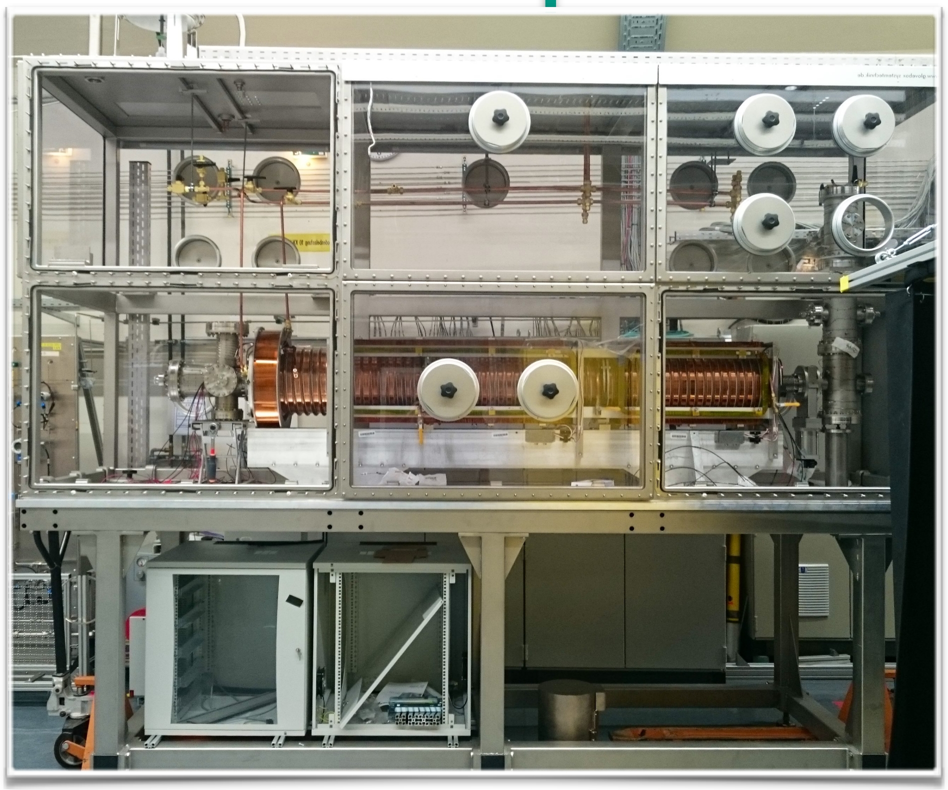
- Mechanical and cryo-infrastructure finished
- Superconducting solenoids operational
- Test of ~800 sensors completed
- Installation of tritium loops ongoing (~100 m of piping, valves)

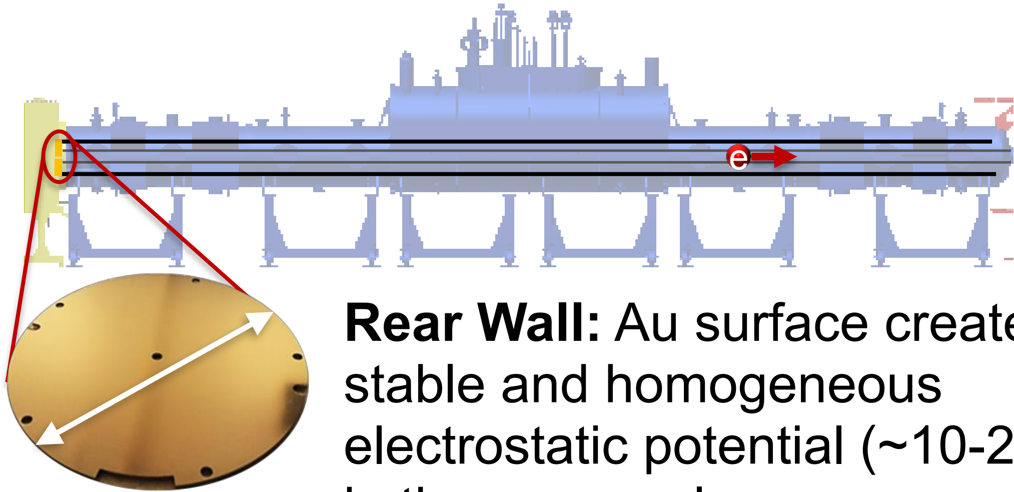


Integration of Calibration and Monitoring System

“Rear Section”: major importance for systematics control







⌀ 150 mm

Rear Wall: Au surface creates stable and homogeneous electrostatic potential (~10-20 mV) in the source plasma

under construction

Precision e^- source:
regular column density monitoring
+ determination of energy loss function (scattering)

Precision electron source for calibration & monitoring

Requirements:

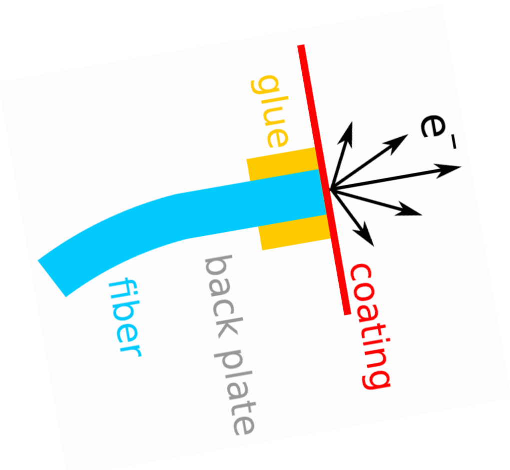
- sharp energies: < 200 meV at 18.6 keV
- short pulses (~ few 10 ns)
- defined pitch angles (spread 2-5°)
- rate stability

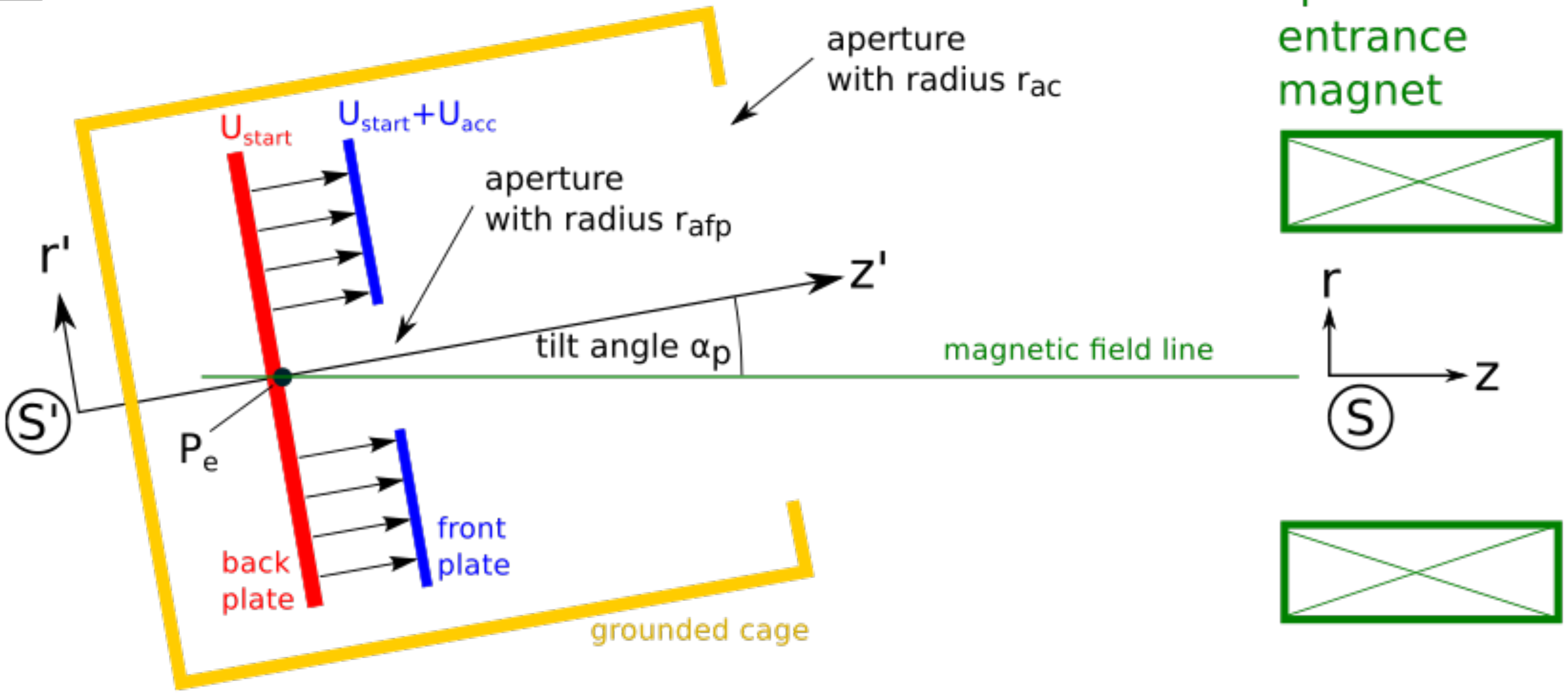
Realization:

1. photo emission
from Au cathode
UV light: 260–320 nm

2. acceleration in E-field

3. adiabatic guiding in B-field



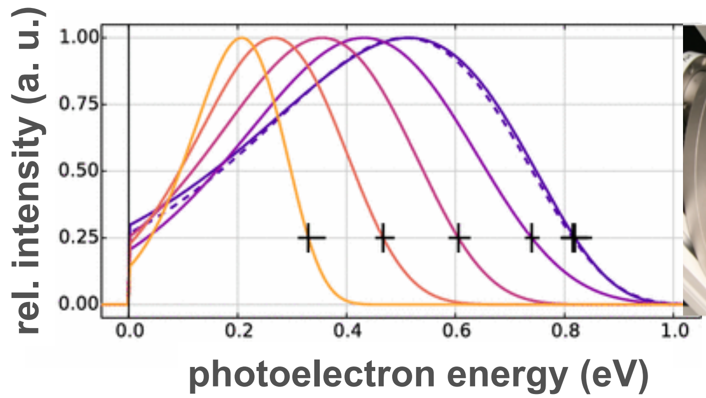


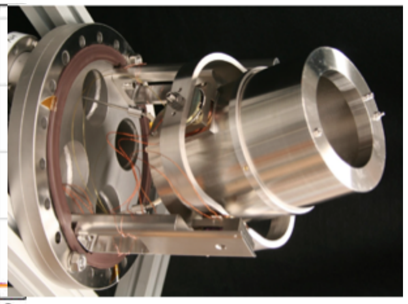
[Valerius *et al.*, JINST 6 (2011) 01002;
Beck *et al.*, JINST 9 (2014) 11020]

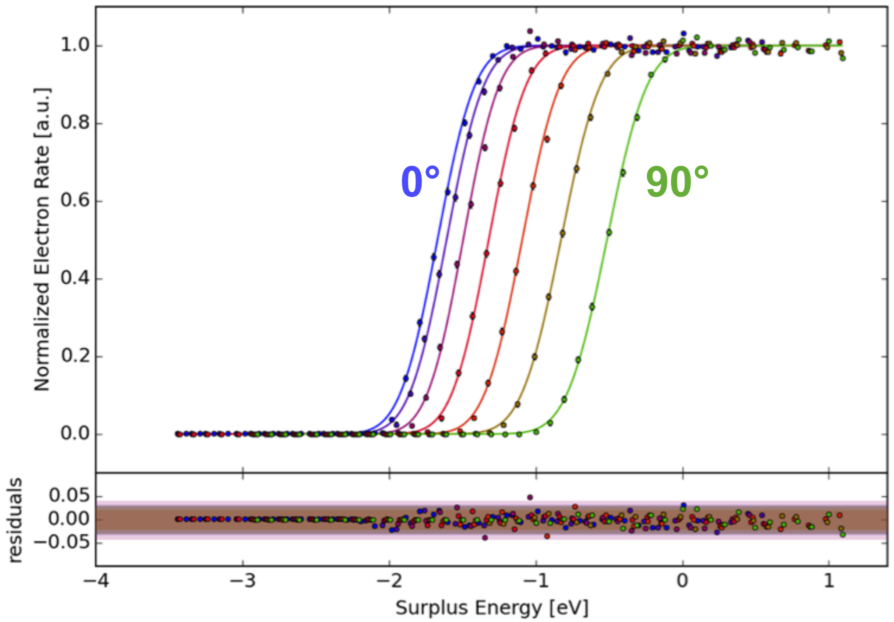
c. Jan Behrens

Precision electron source for calibration & monitoring

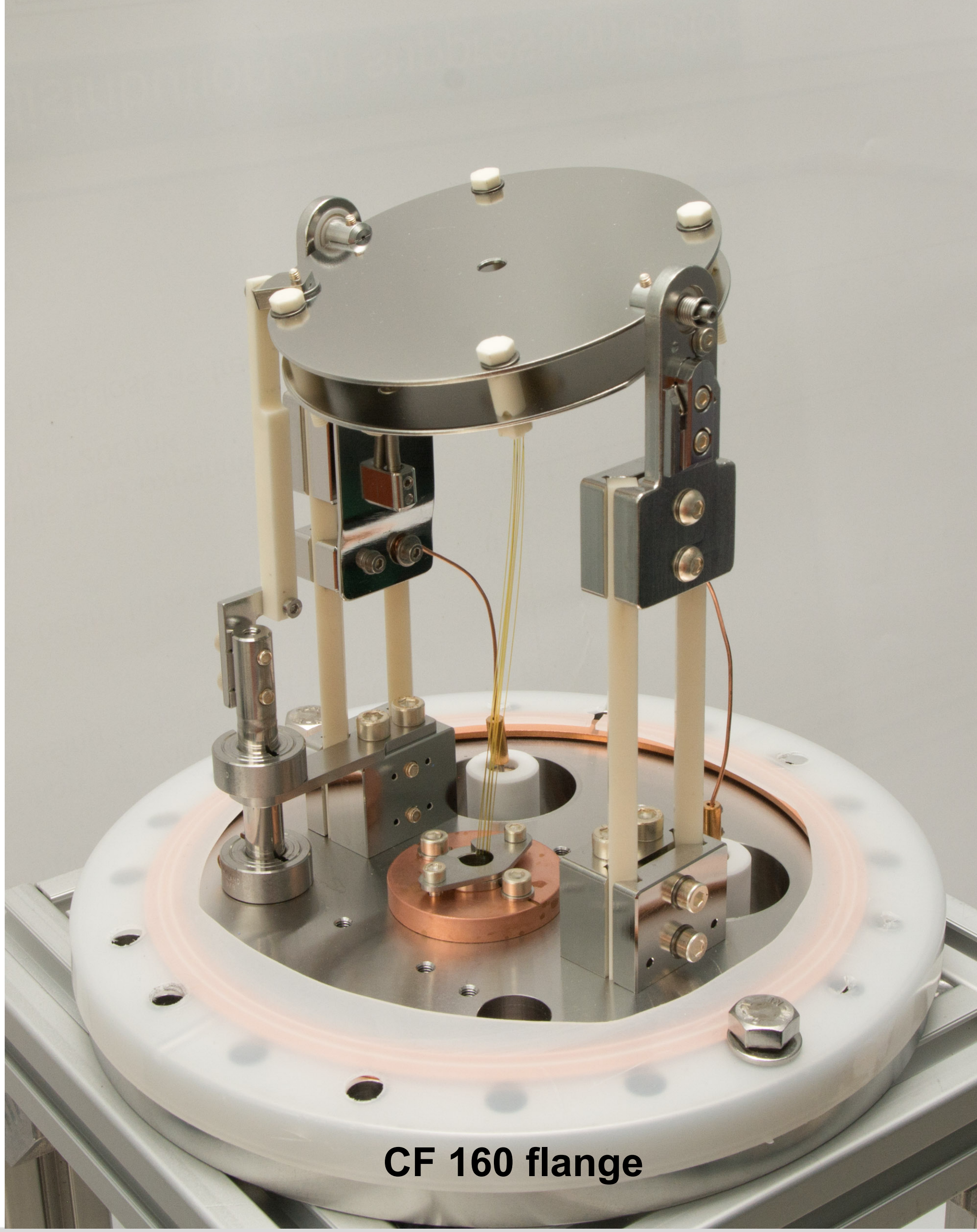
Concept successfully tested at Monitor and Main Spectrometers:







Rear Section electron source being prepared for commissioning



c. Philipp Ranitzsch

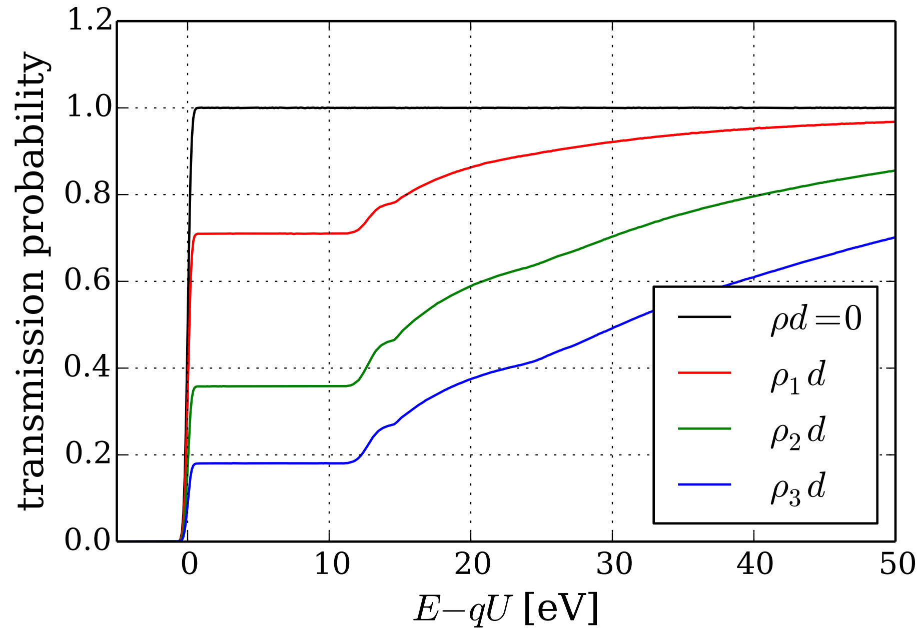
[Behrens *et al.*, EPJ **C**77 (2017) 410;
PhD theses Behrens, Erhardt, Barrett, Wierman, Kraus]

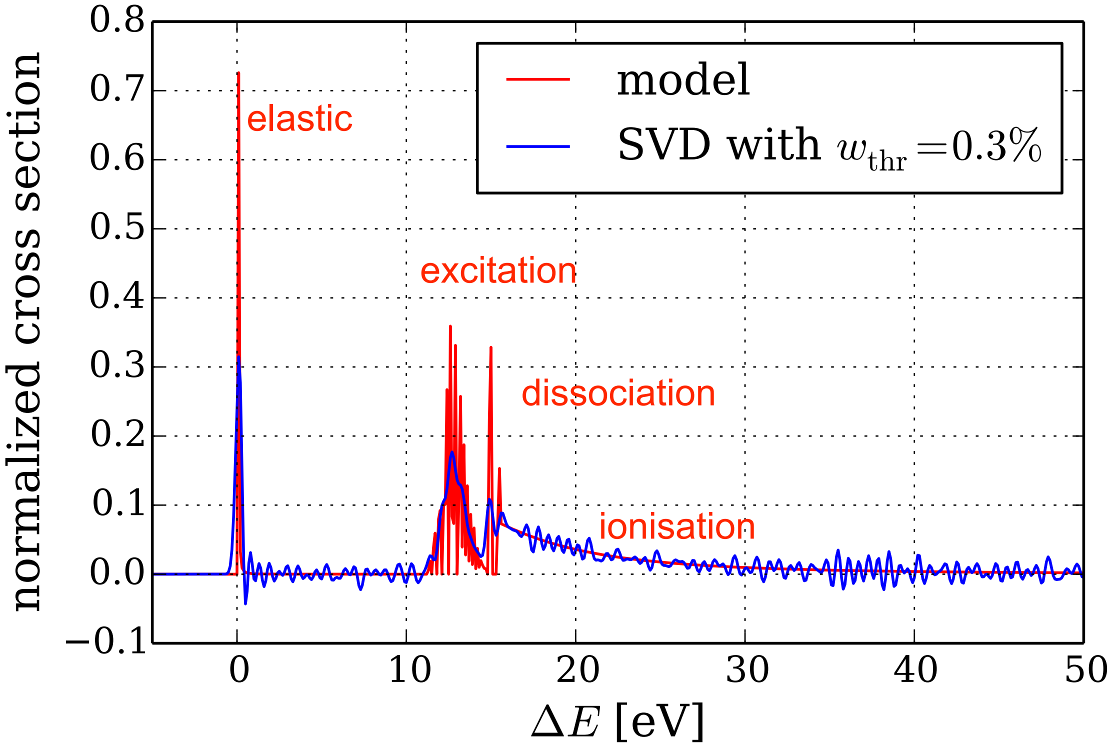
Determining the energy loss function

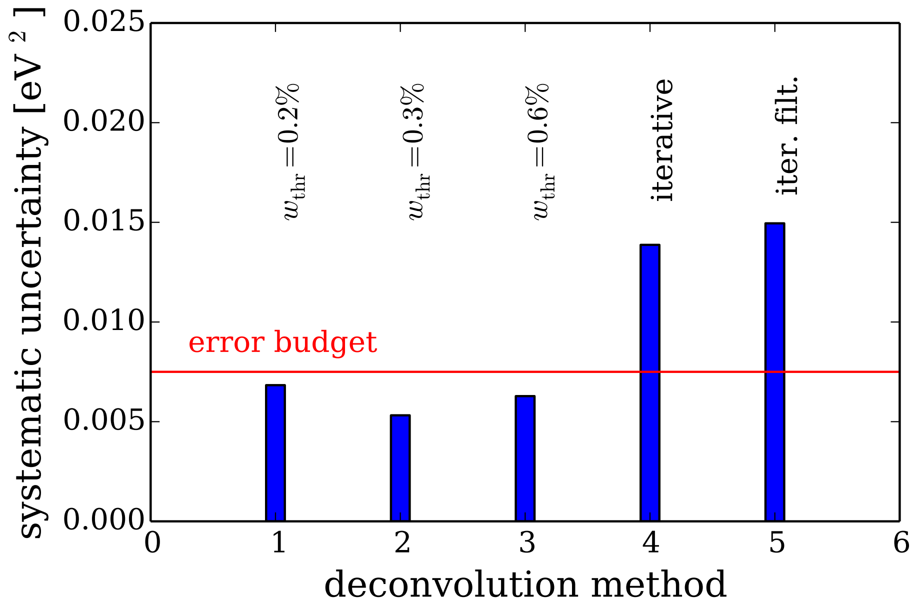
Measurement of electron transmission
at different gas column density

➜ determine energy loss function
through deconvolution

(here: singular value decomposition, SVD)





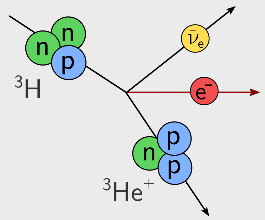


[V. Hannen, KV, *et al.*, Astropart. Phys. 89 (2017) 30]

Modelling of the β spectrum

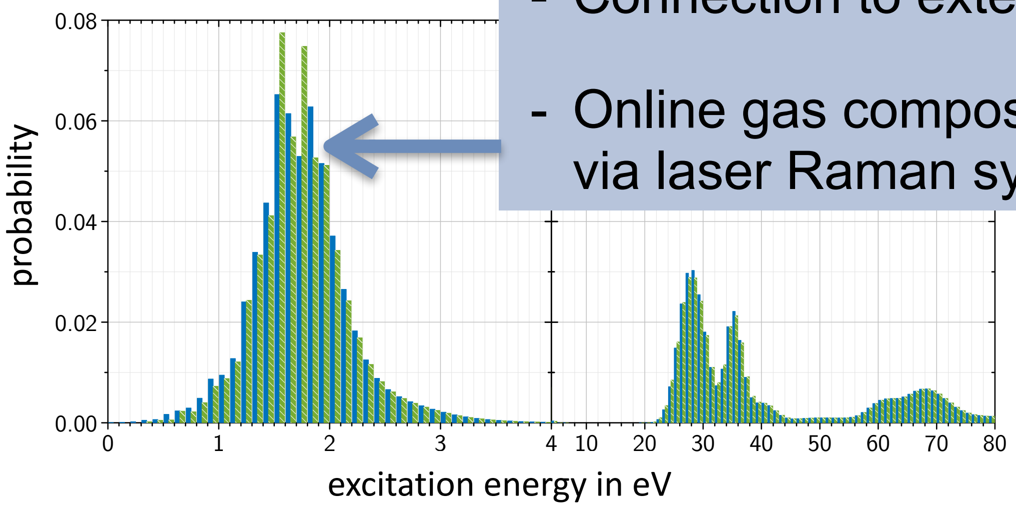
Karlsruhe Institute of Technology

Reference spectrum generator



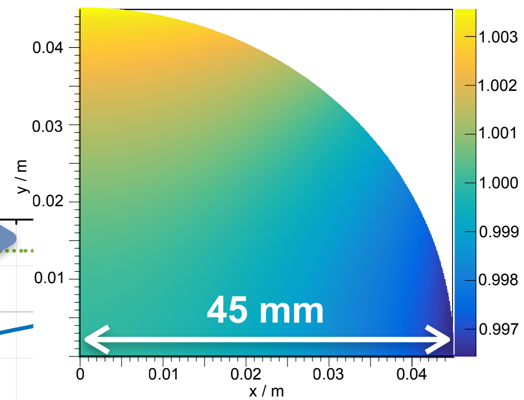
State-of-the-art nuclear & molecular theory

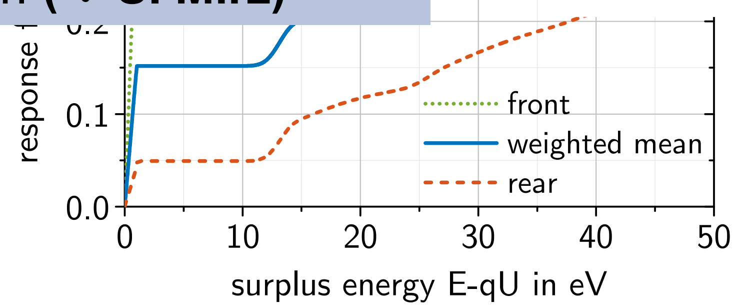
- electronic final states, radiative corrections, Doppler effect
- minor: relativistic Fermi function & recoil, screening, finite nuclear extension, …



3d gas-dynamics modelling

- longitudinal and radial pressure, density, temperature profiles
- plasma potential
- magnetic field model





- Connection to extensive sensor network
- Online gas composition monitoring via laser Raman system **(➜ S. Mirz)**

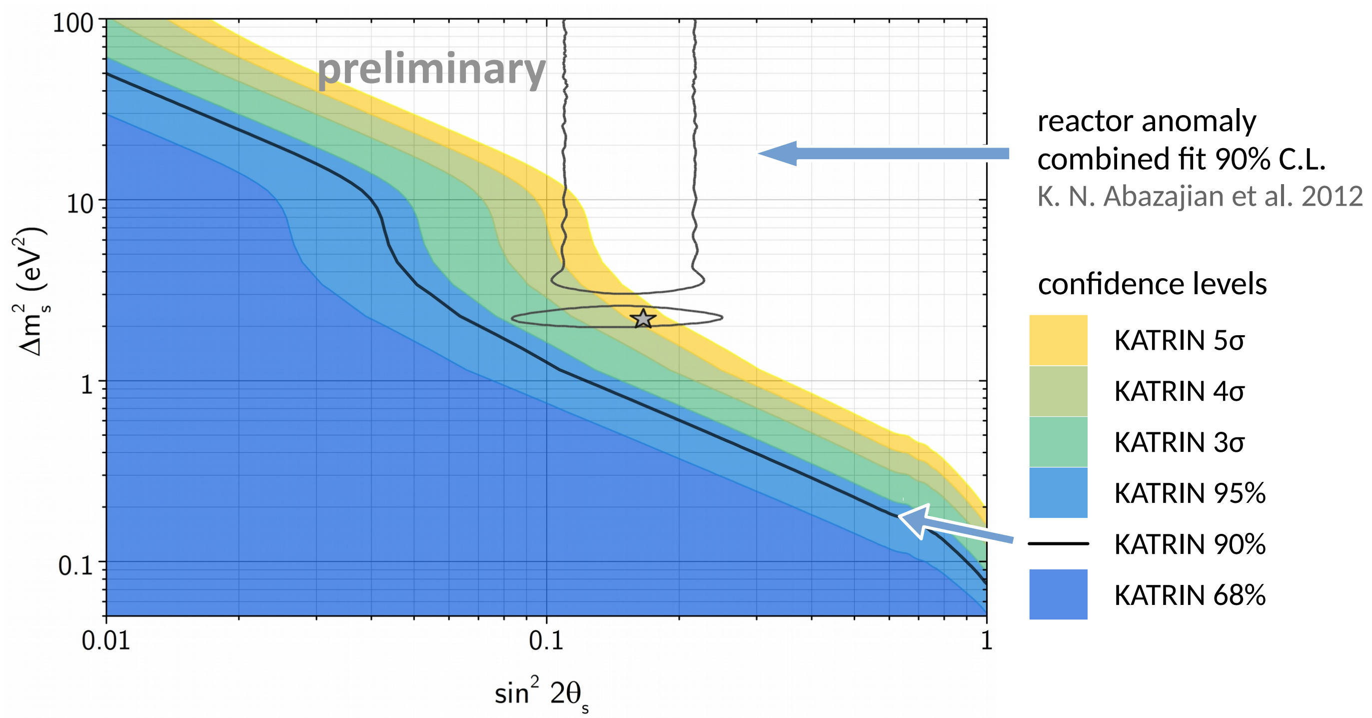
Exploring the physics potential

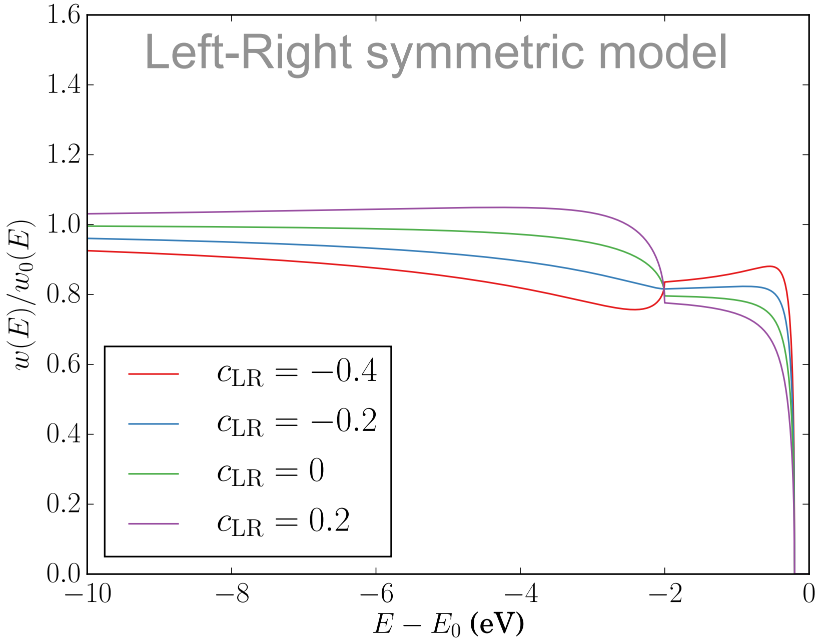
- … close to the **spectral endpoint E_0**:

standard operation mode for KATRIN

search for eV-scale sterile ν

… in the presence of non-SM currents





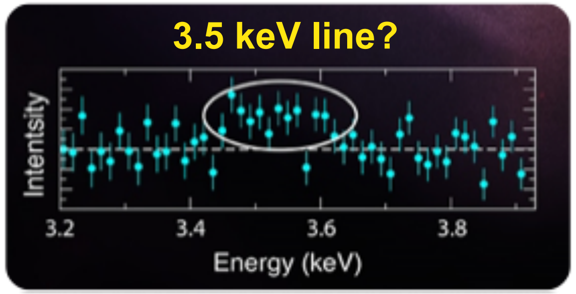
e.g. Formaggio & Barrett, PL B706 (2011) 68; Sejersen Riis & Hannestad, JCAP02 (2011) 011; Esmaili & Peres, PR D85 (2012) 117301

Steinbrink *et al.*, JCAP 06 (2017) 015

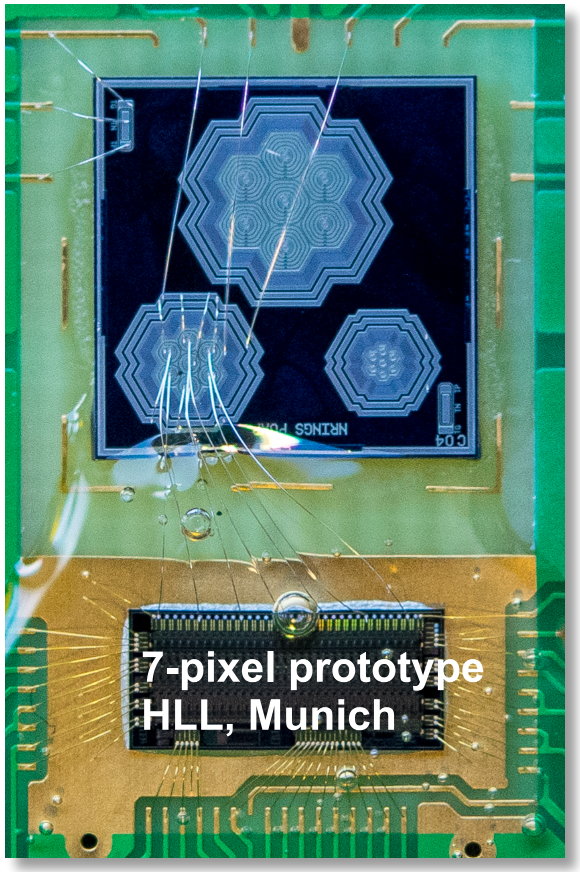
Exploring the physics potential

→ S. Mertens (Thu)

Karlsruhe Institute of Technology

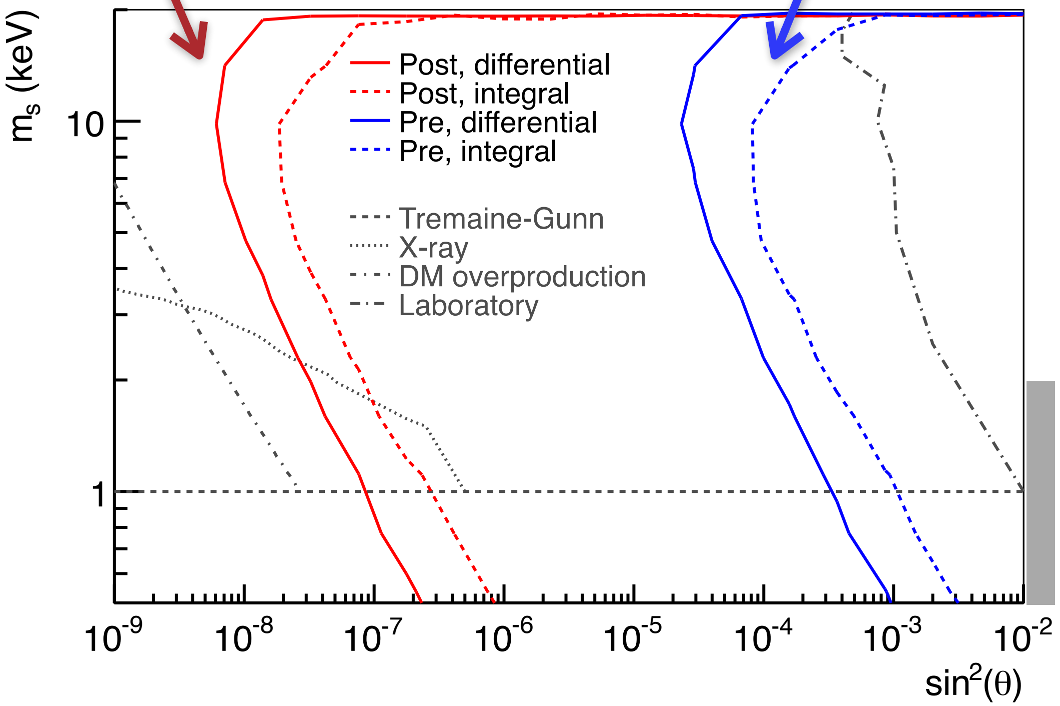


- … **further away from E_0:**
  search for keV-scale sterile ν as WDM candidates



novel concepts required

first tritium data at reduced source strength of KATRIN



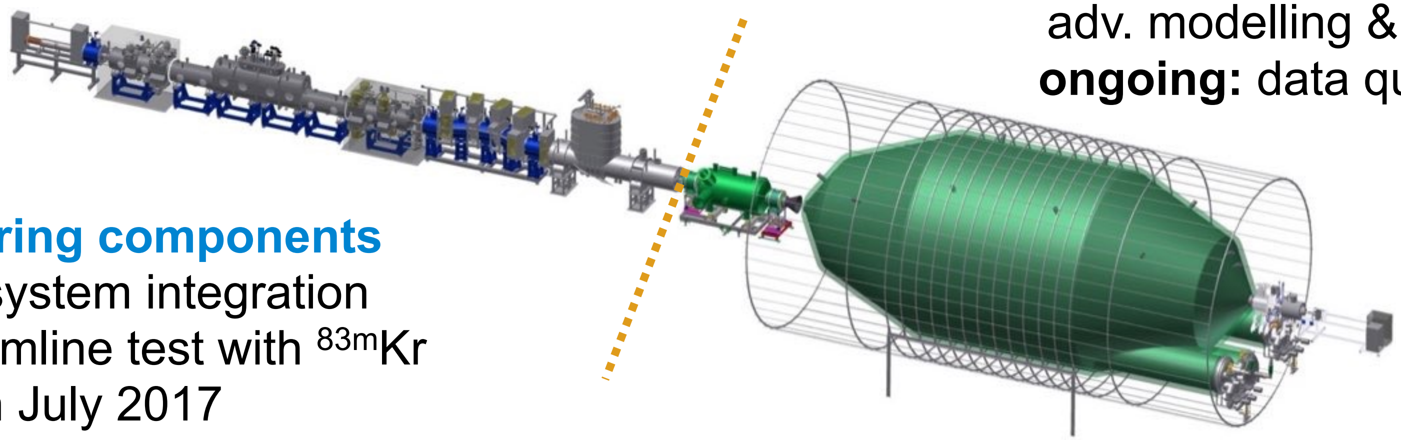
see: recent result of Troitsk nu-mass exp. [Abdurashitov *et al.*, JETP Lett. 105 (2017) 753]

KeV sterile neutrino white paper [Adhikari *et al.*, JCAP 01 (2017) 025]

Summary & outlook

- β decay allows model-independent, **direct** access to neutrino mass scale
- KATRIN will exhaust degenerate mass regime: **200 meV** (90% CL for 5 yrs of running); reaching sub-eV sensitivity with first few weeks of data
- Interesting physics potential beyond m_ν: eV and keV scale sterile ν, RH currents, LIV, …

Preparing KATRIN for neutrino-mass measurements:



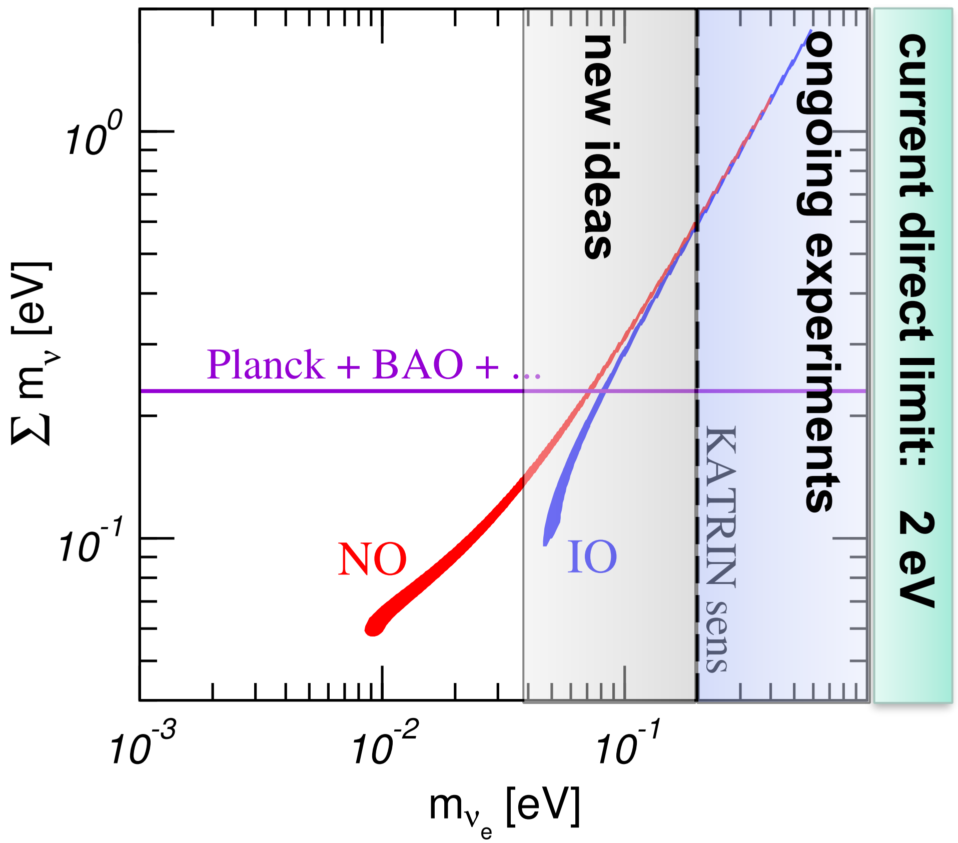
Analysis chain
adv. modelling & analysis framework
ongoing: data quality filters, blinding

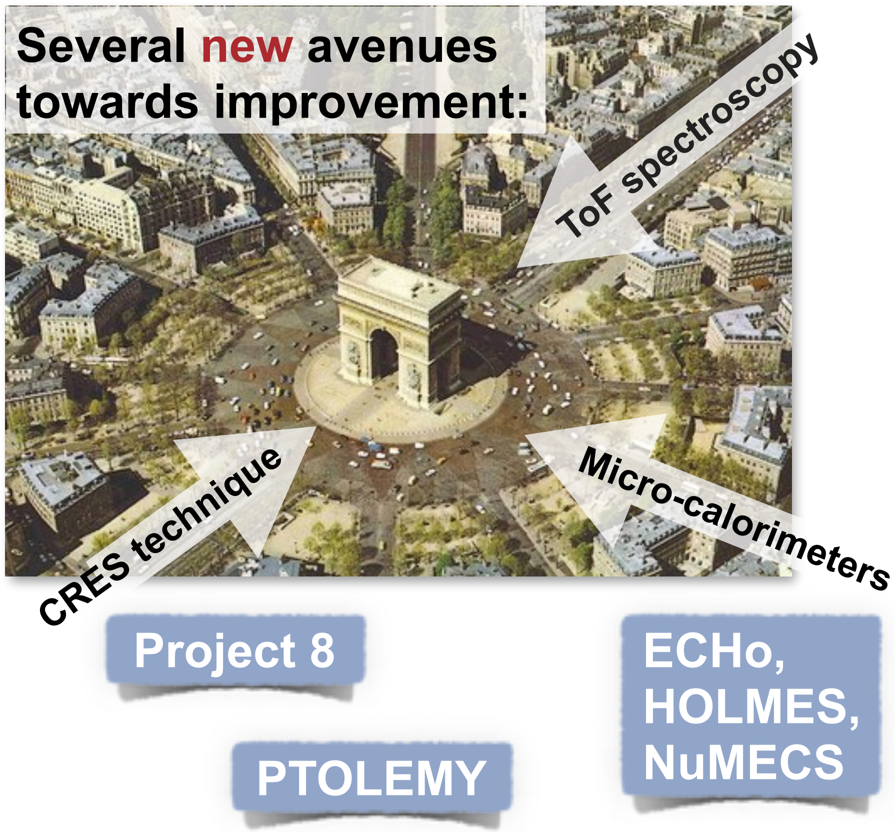
Tritium-bearing components
- now: final system integration
- overall beamline test with ^{83m}Kr achieved in July 2017
- **next:** inactive commissioning with D_2, then $D_2(T_2)$

Spectrometer & detector section
2 successful commissioning phases already done
ongoing: background investigations

➜ **First tritium runs starting in 2018, inauguration ceremony: 11 June 2018**

Looking ahead:
future prospects in direct neutrino mass search





Challenges for further improvement:

- Opacity of gaseous T_2 source (already optimised for KATRIN, ~40% no-loss e^-)
- MAC-E filter does not scale further, measures *integral* beta spectrum
- Molecular final state excitations (vib: ~100 meV) as ultimate limitation for T_2