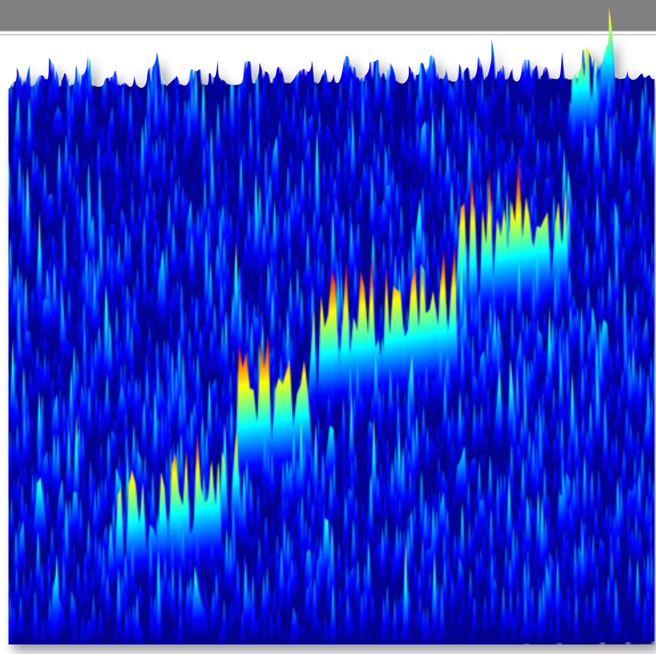
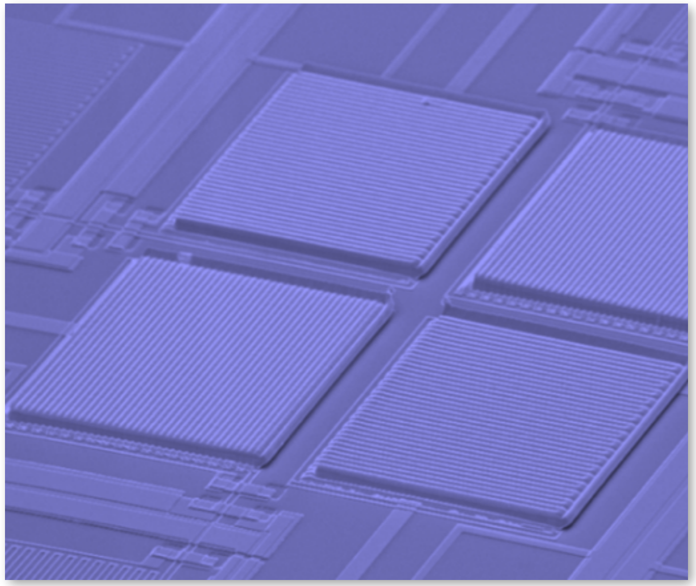
# A survey of direct neutrino mass measurements

Recent Developments in Neutrino Physics and Astrophysics // Borexino10th

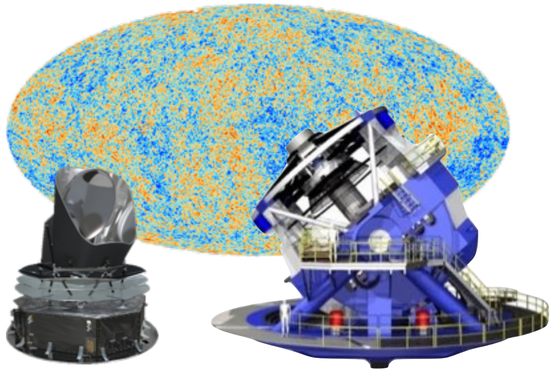
LNGS & GSSI, 4-7 September 2017

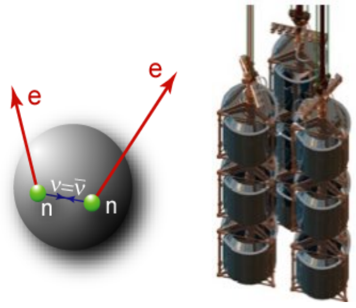
KATHRIN VALERIUS, Karlsruhe Institute of Technology

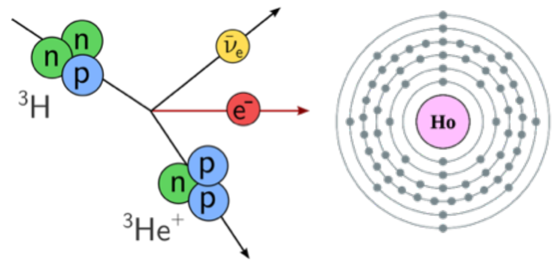




# Complementary paths to the ν mass scale






| | Cosmology | Search for 0νββ | β-decay & EC |
|---|---|---|---|
| **Observable** | $M_\nu = \sum_i m_i$ | $m_{\beta\beta}^2 = \left\|\sum_i U_{ei}^2 m_i\right\|^2$ | $m_\beta^2 = \sum_i \|U_{ei}\|^2 m_i^2$ |
| **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<br>- BSM contributions other than m(ν)?<br>- Nuclear matrix elements | **Direct,** only kinematics; no cancellations in incoherent sum |
| | ➜ R. Battye (Tue) | ➜ A.B. McDonald, J. Menendez (Wed) | ➜ this talk |

# Direct kinematic determination of $m(\nu_e)$

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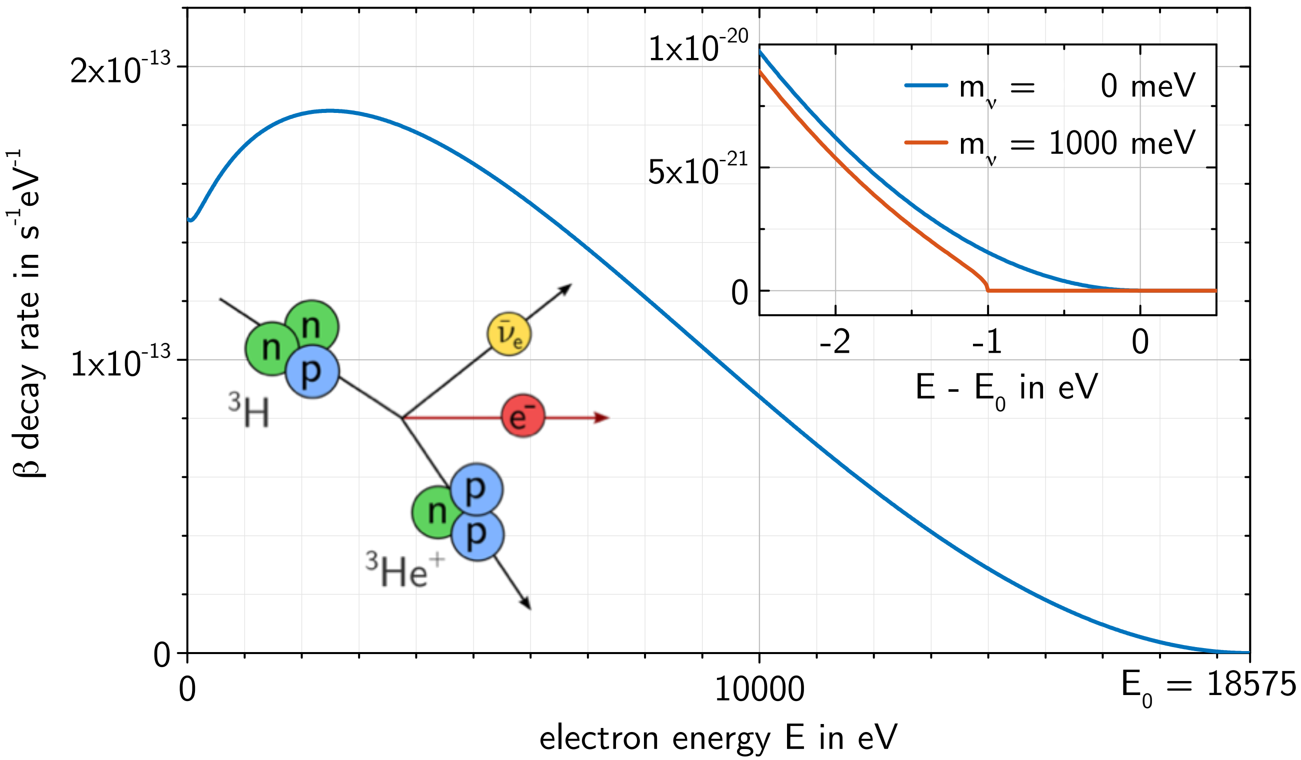
$$\frac{d\Gamma}{dE} = C\, F(Z,E)\, p\,(E+m_e)\,(E_0 - E)\, \sum_i |U_{ei}|^2 \sqrt{(E_0 - E)^2 - m^2(\nu_i)}$$




**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,**
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- Excellent energy resolution (MAC-E filter or calorimeter)

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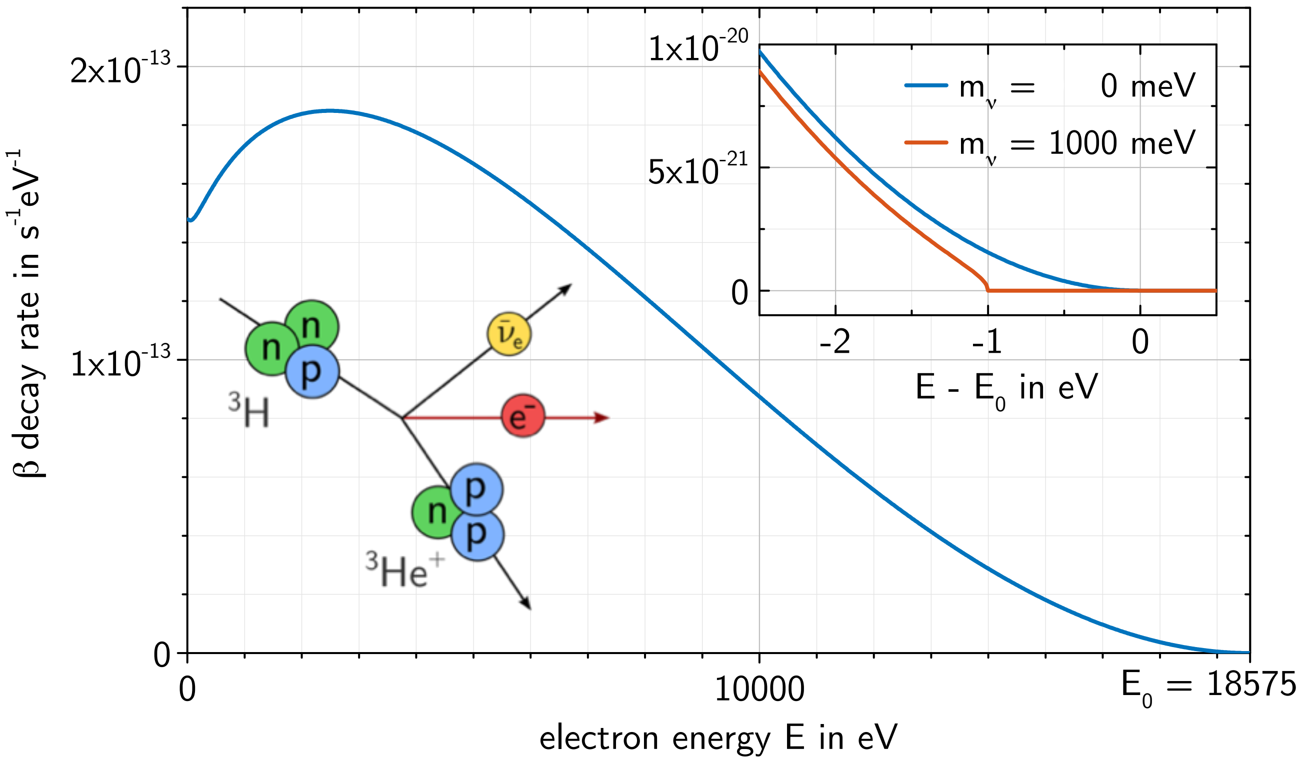


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Spectral distortion measures **"effective" mass square:**

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

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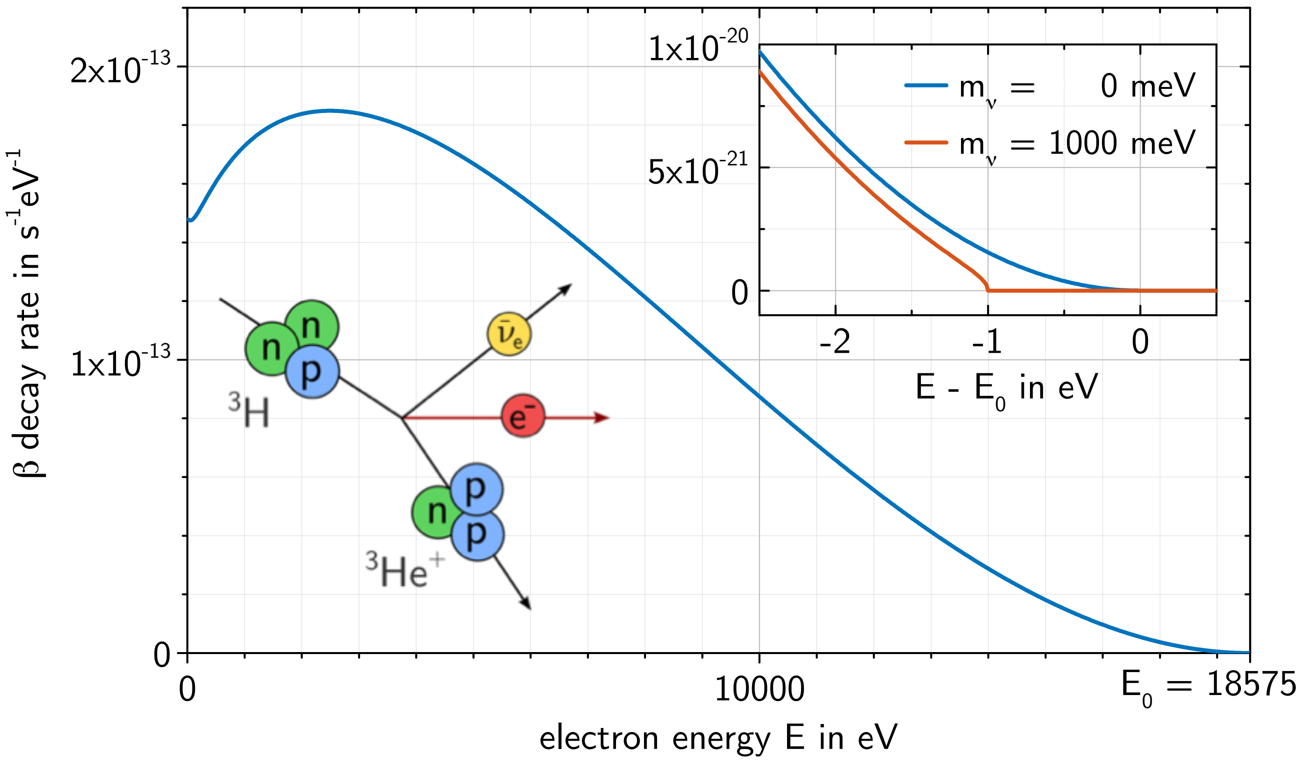


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Kinematic measurement can probe for **heavier neutrino states**
➜ eV-scale and keV-scale sterile ν

Spectral distortion measures **“effective” mass square:**

$$m^2(\nu_\mathrm{e}) := \sum_i |U_{\mathrm{e}i}|^2\, m_i^2$$

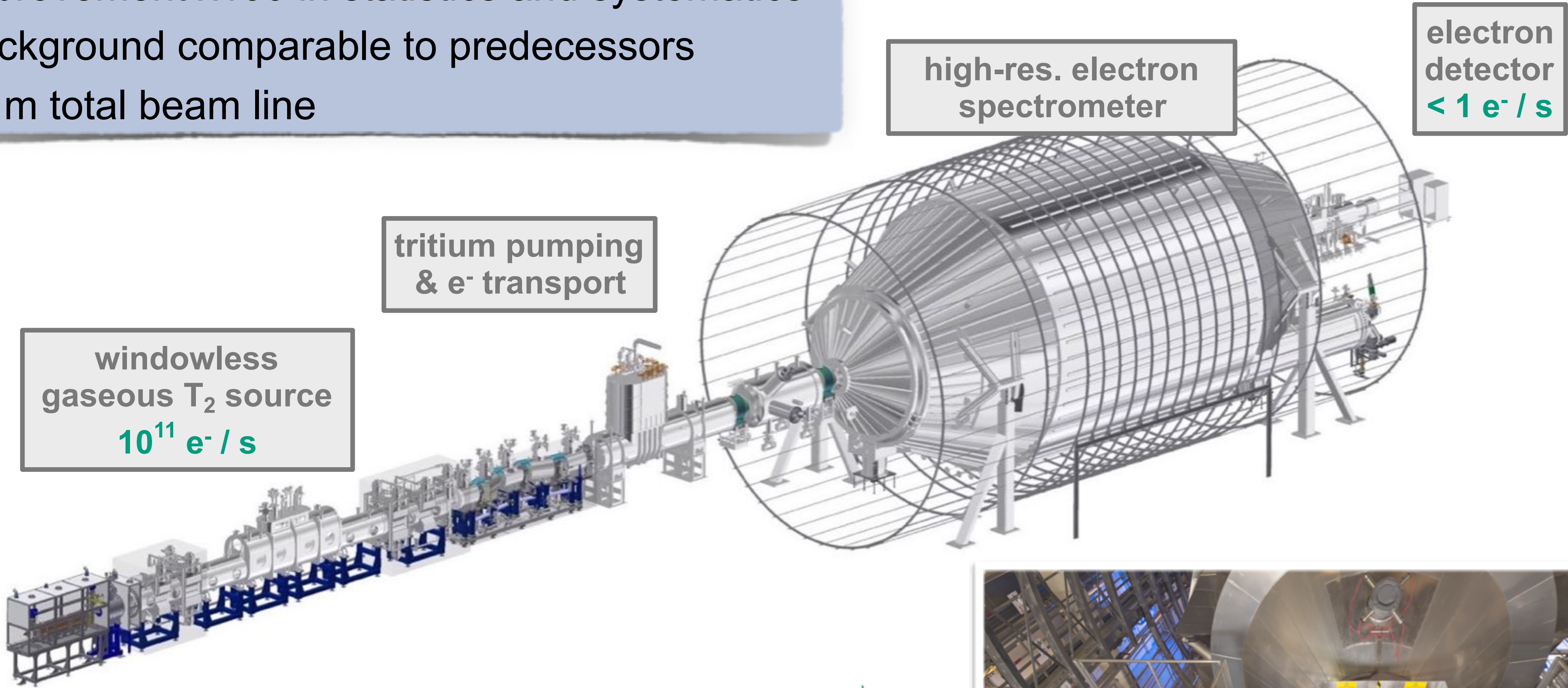
➜ **C. Giunti, S. Schönert, D. Iakubovskyi (Thu)**

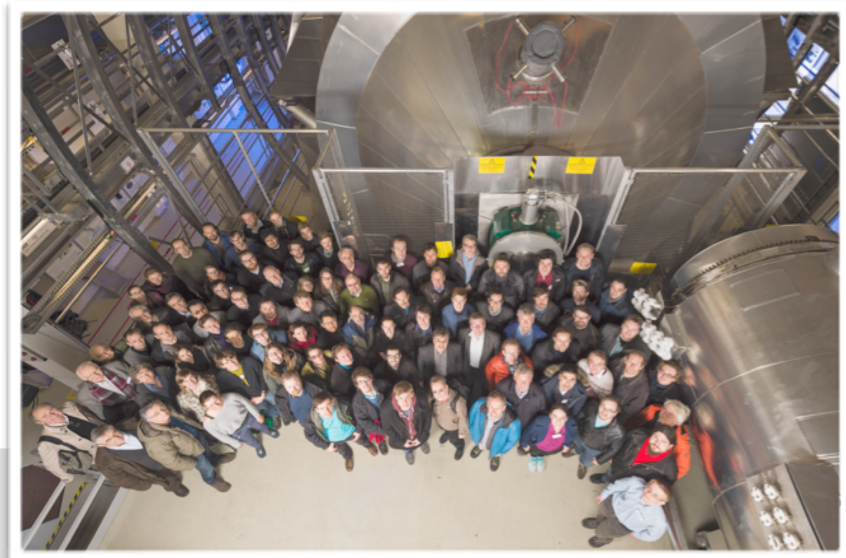
# Tritium beta spectroscopy

# The Karlsruhe Tritium Neutrino Experiment

**Sensitivity: 2 eV ➜ 0.2 eV**

- Improvement x100 in statistics and systematics
- Background comparable to predecessors
- 70 m total beam line

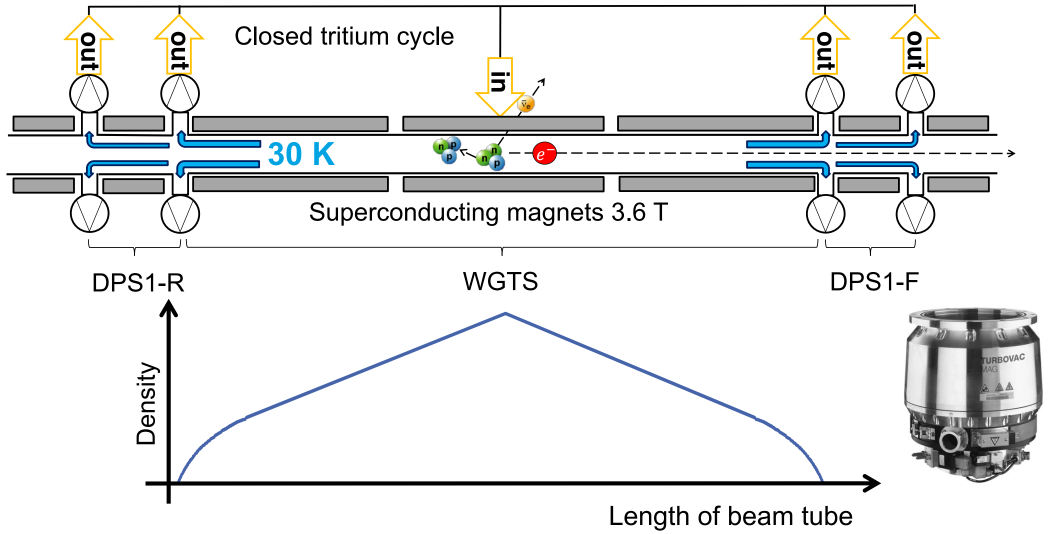


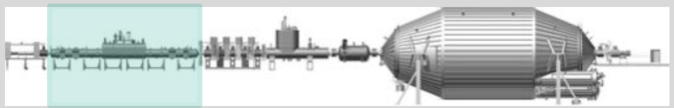



# Status of the KATRIN source

Gaseous molecular tritium source of

- high activity (~170 GBq)
- high isotopic purity ($\varepsilon_T$ > 95%)
- high stability (0.1%)



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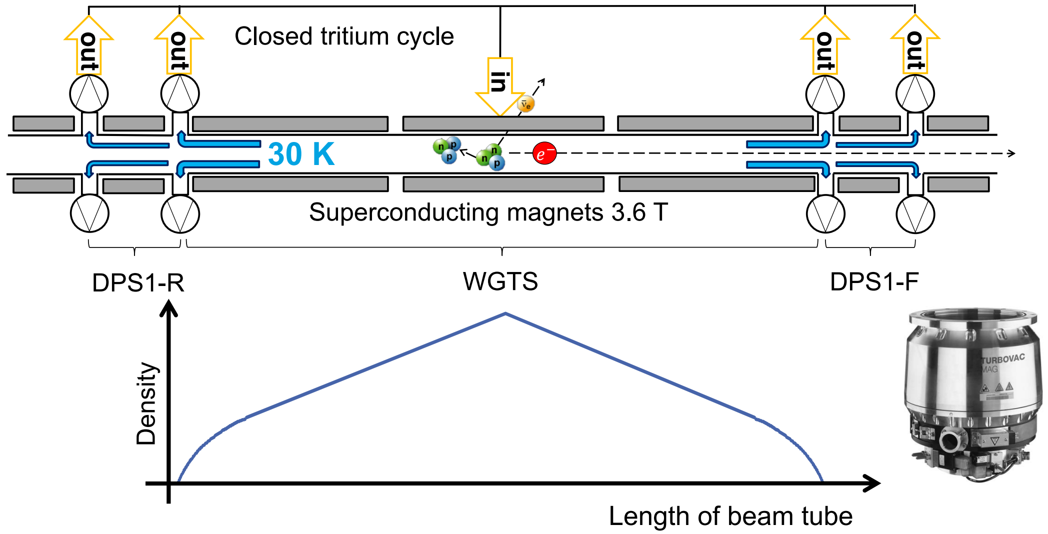


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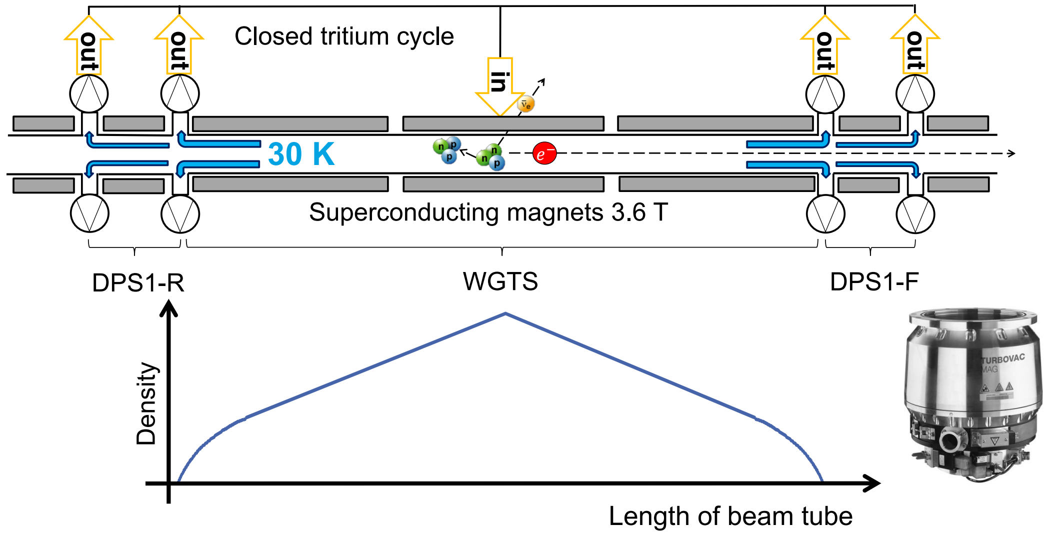
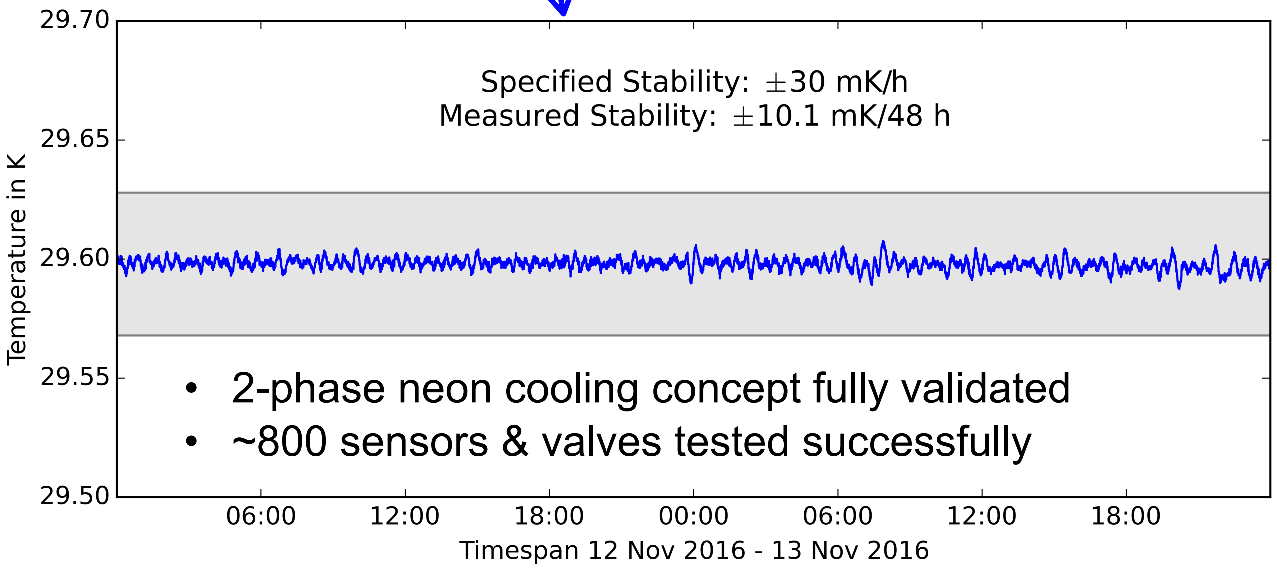
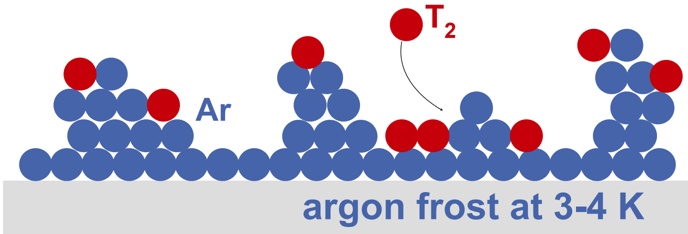


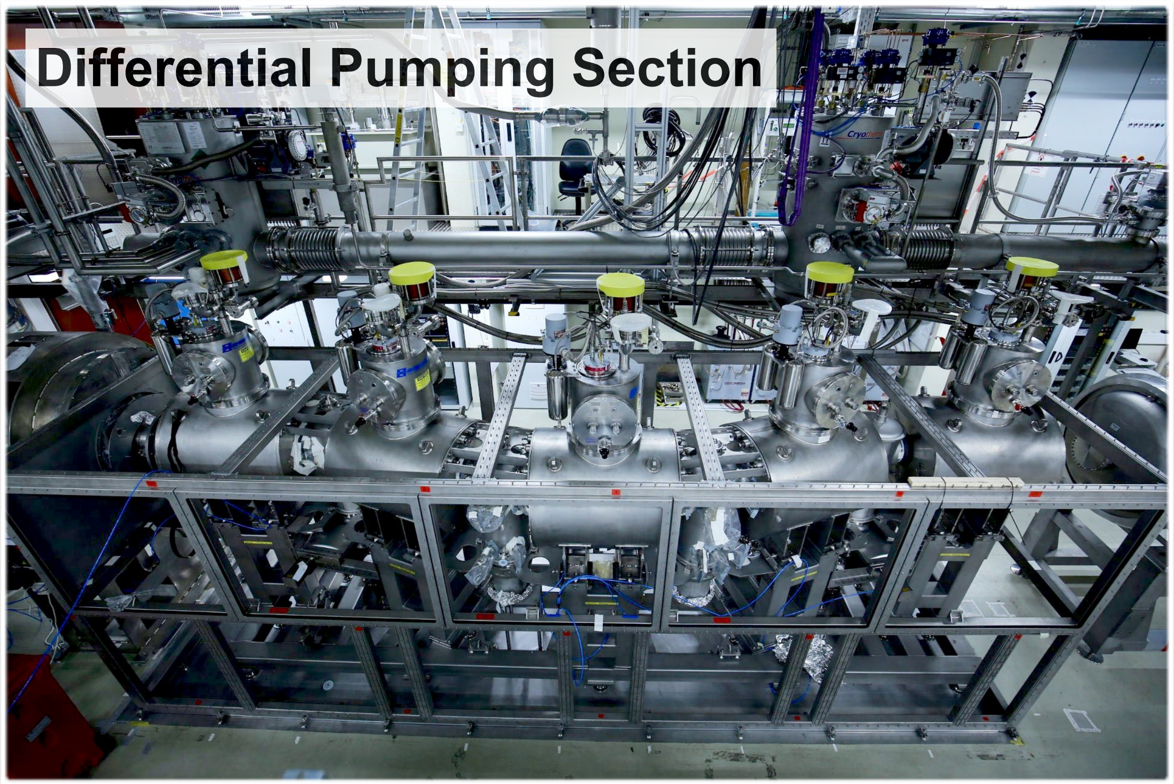



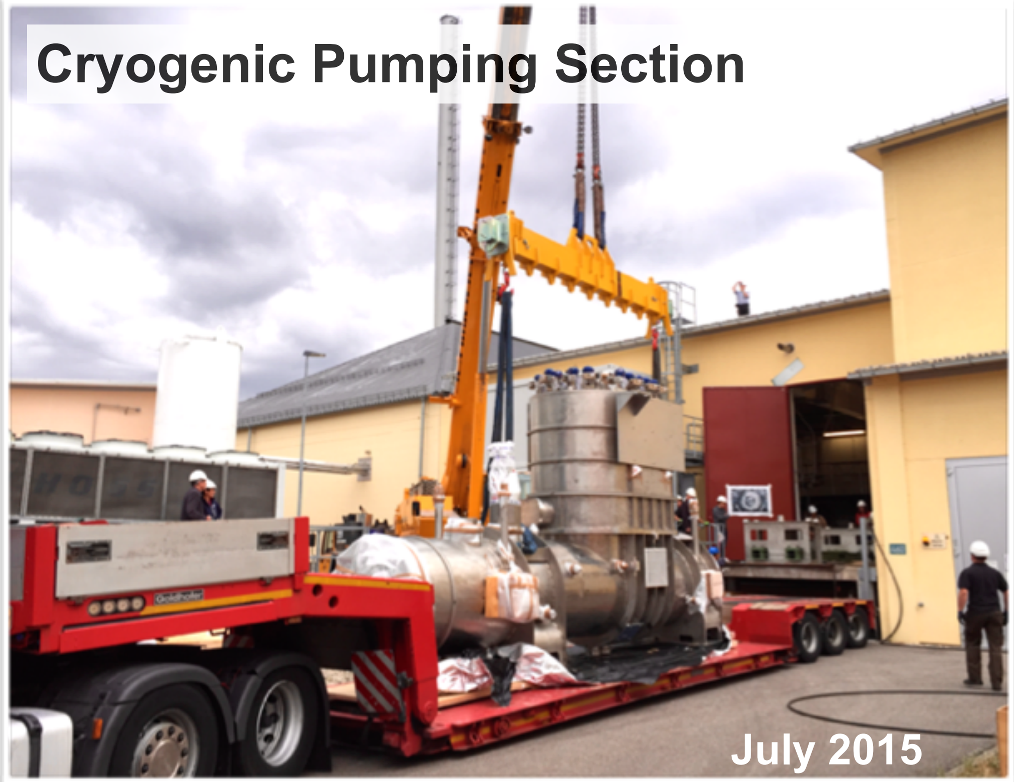

- 2-phase neon cooling concept fully validated
- ~800 sensors & valves tested successfully

# Transport & pumping sections

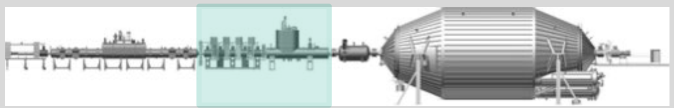
- Fully adiabatic, **lossless electron transport** in 5.6 T magnetic field
- **Reduction of $T_2$ flow rate** to spectrometers by factor **$>10^{14}$**: magnetic chicane with **differential** and **cryo-pumping**
- Ion diagnostics & **ion flux blocking** by electrostatic barrier



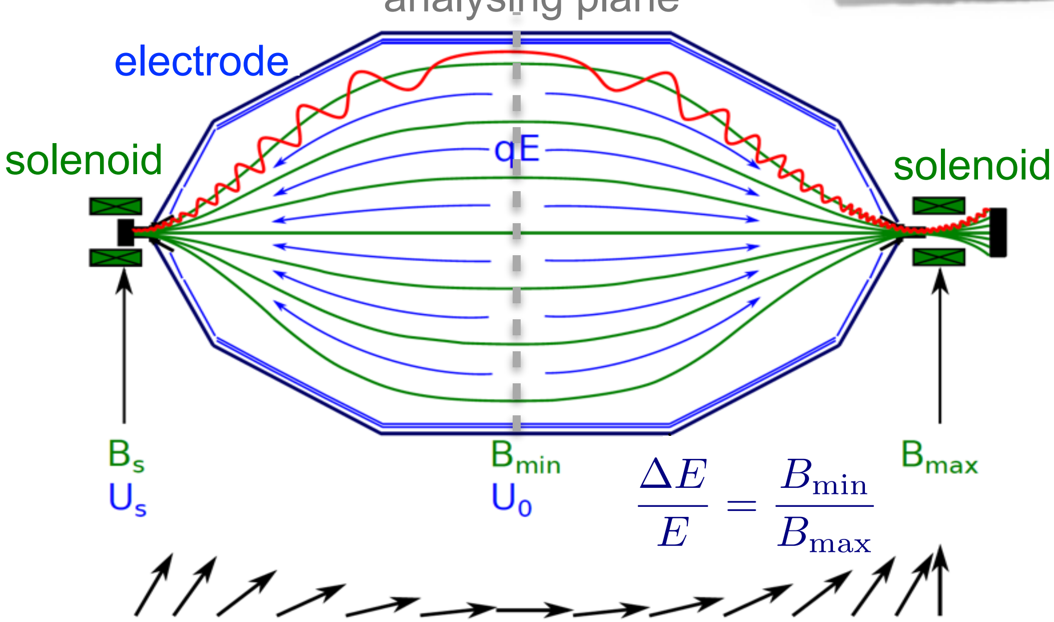



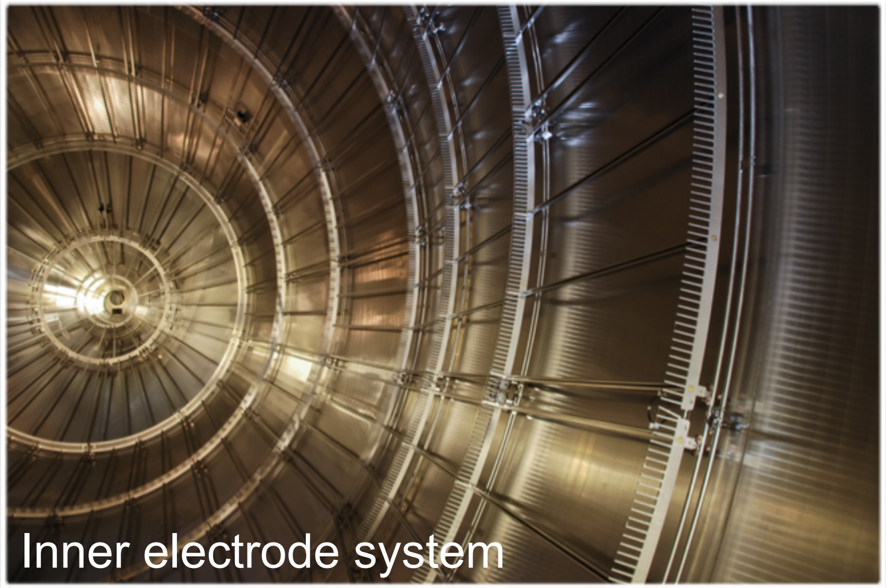


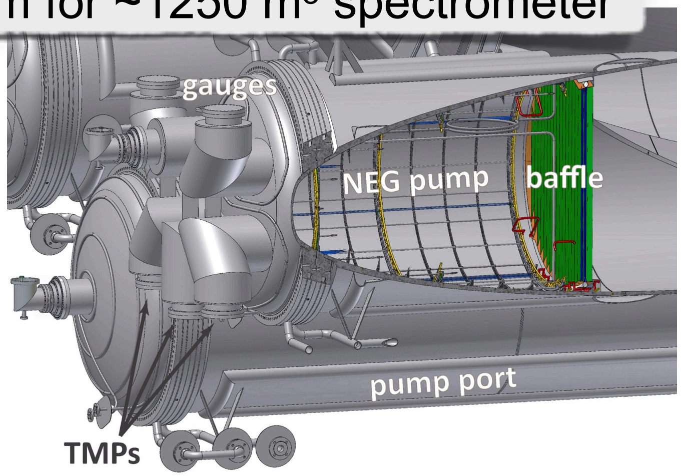
# KATRIN main spectrometer

**Magnetic Adiabatic Collimation and Electrostatic Filter**



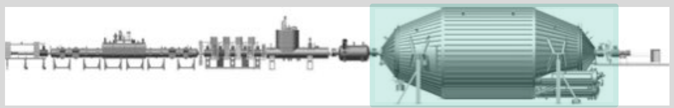




UHV system for ~1250 $m^3$ spectrometer

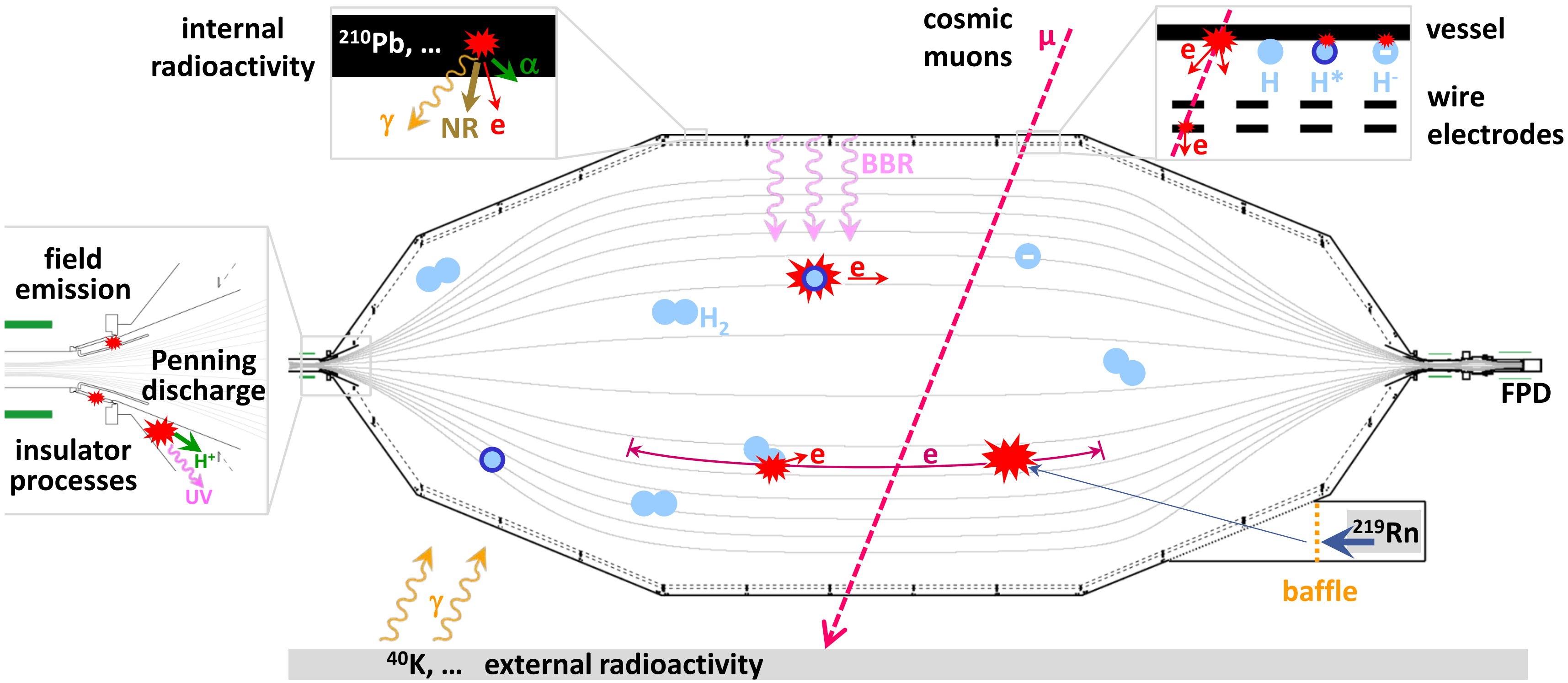









# Spectrometer-related backgrounds



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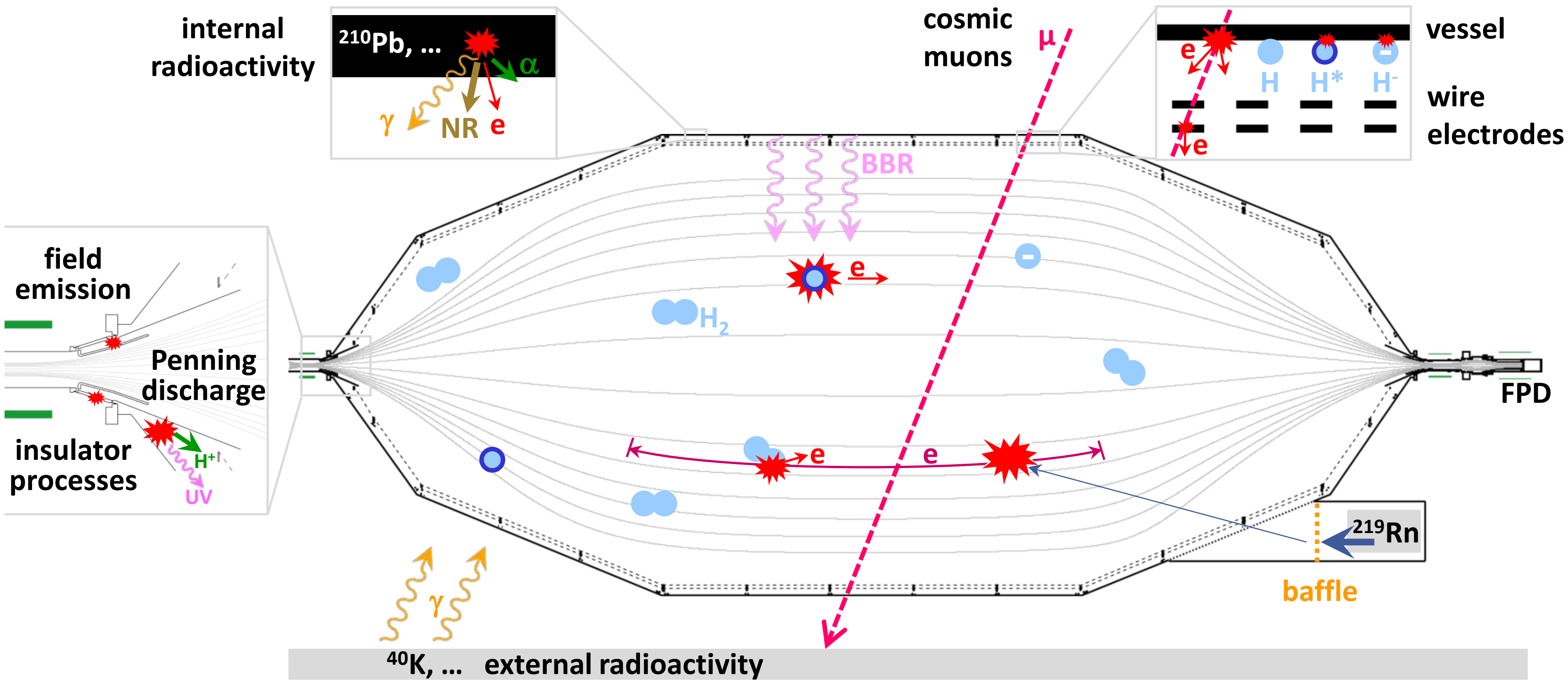
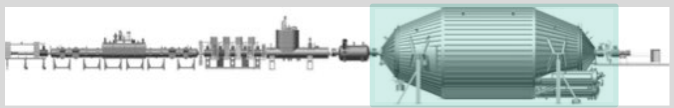



- **8 sources of background investigated and understood**
- **7 out of 8 avoided or actively eliminated by**
  - fine-shaping of special electrodes
  - inner electrode (wire grids on neg. potential)
  - symmetric magnetic fields
  - cold traps ($LN_2$-cooled baffles to remove $^{219}Rn$)



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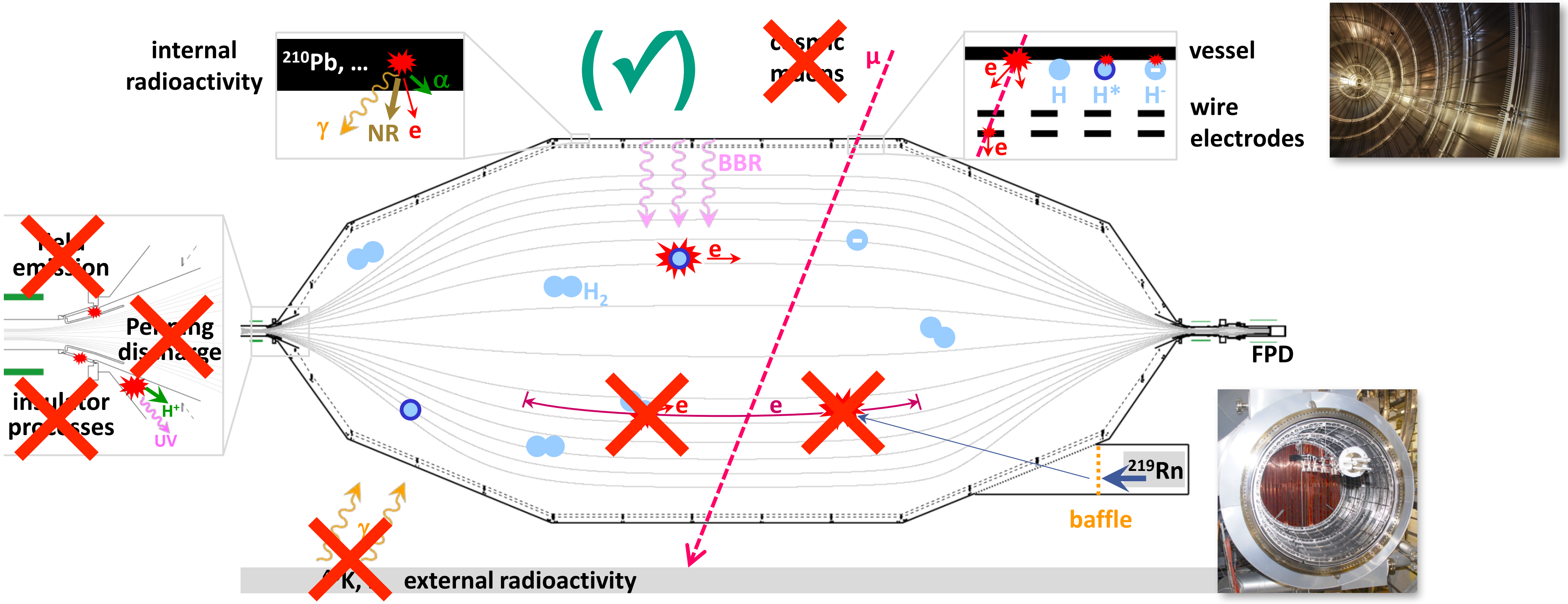


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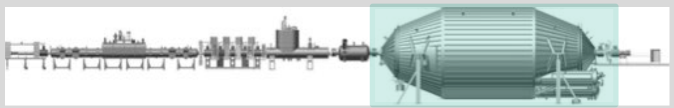

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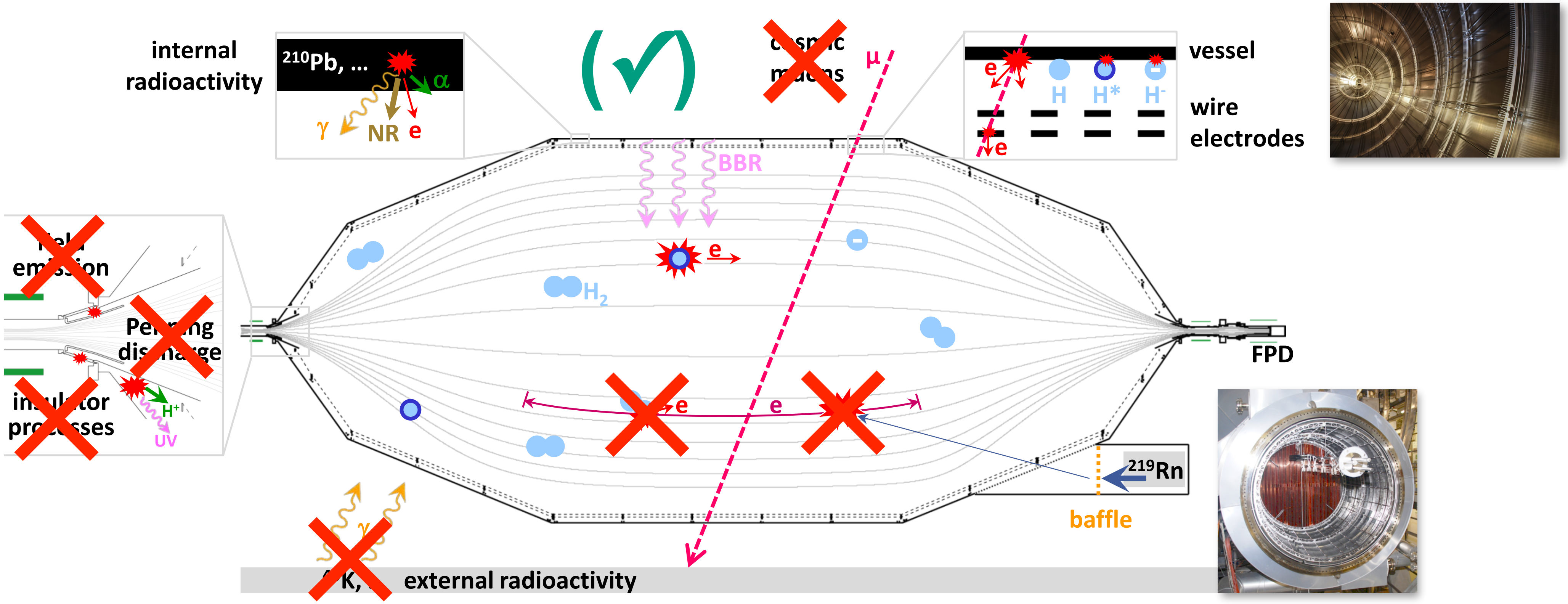


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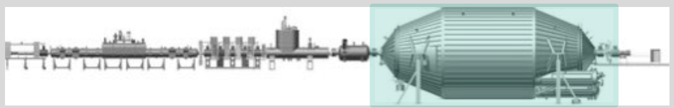
- **1 out of 8 remaining:**
  $^{210}Pb$ on spectrometer walls
  (thermal ionisation of neutral H* atoms)
- Countermeasures:
  - extensive bake-out (done)
  - irradiation by strong UV source (ongoing investigation)





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

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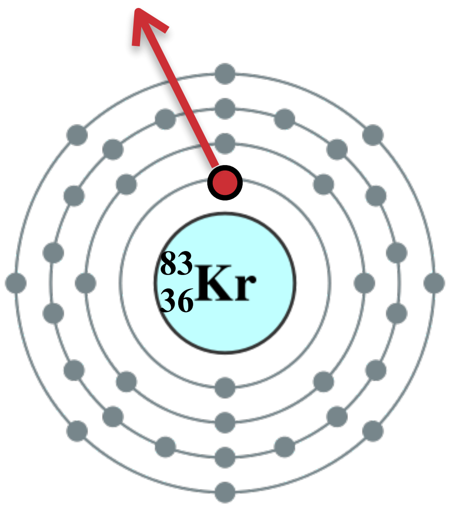
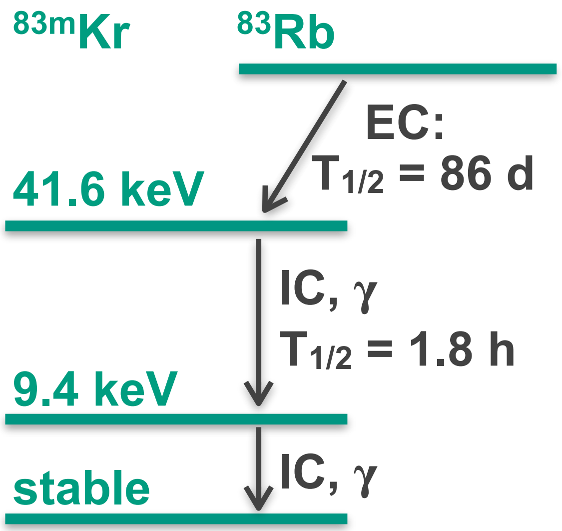
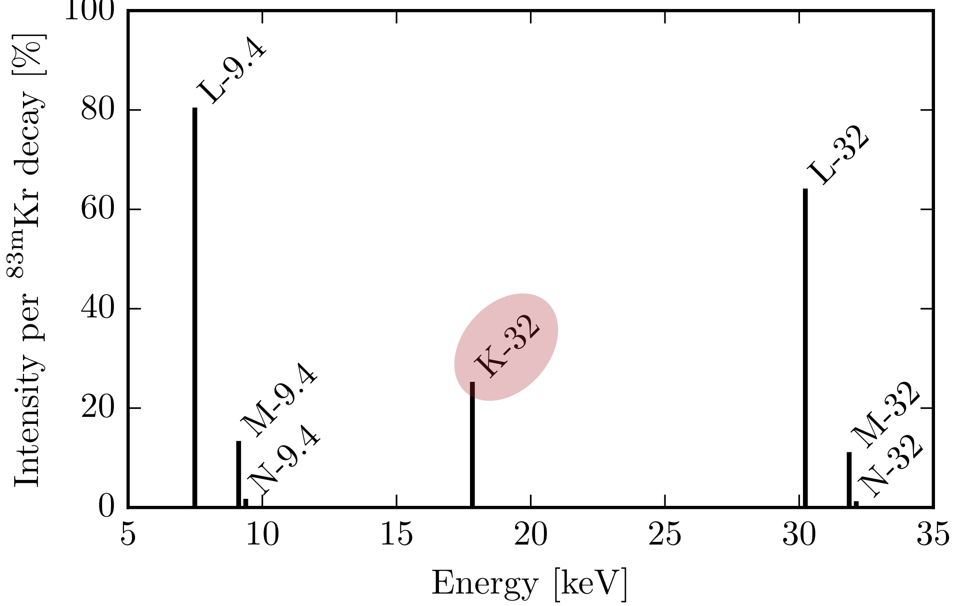



**narrow (< 2 eV) CE lines at 7 … 32 keV**




[M. Slezak, PhD thesis, 2015]

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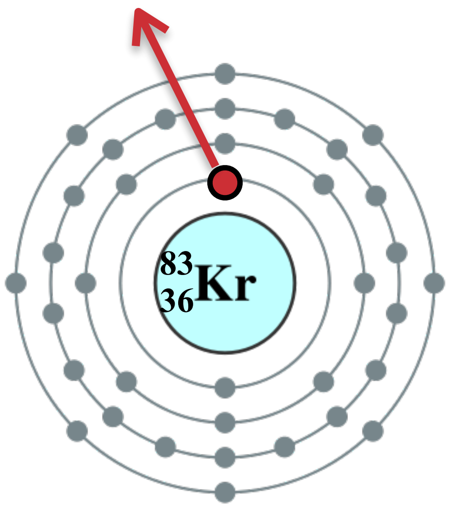


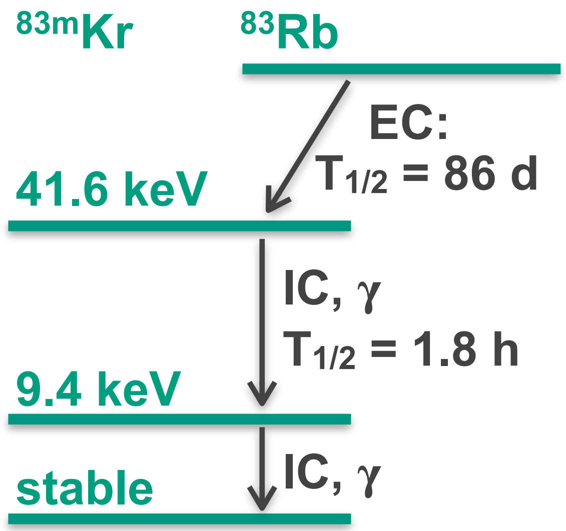


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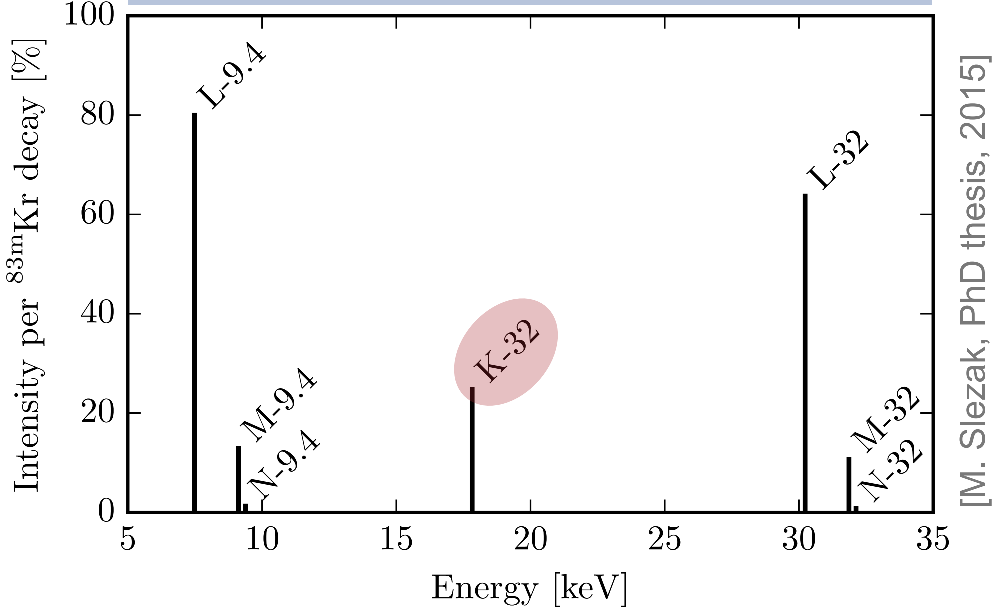


**KATRIN krypton campaign: 3-19 July 2017**

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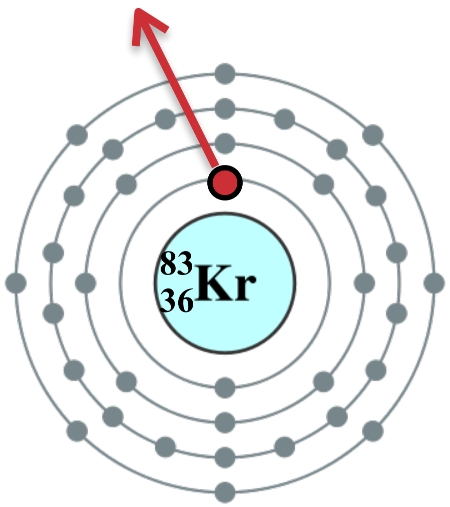


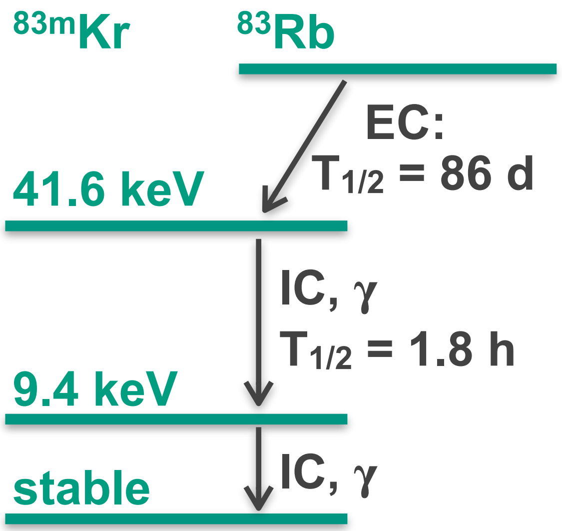


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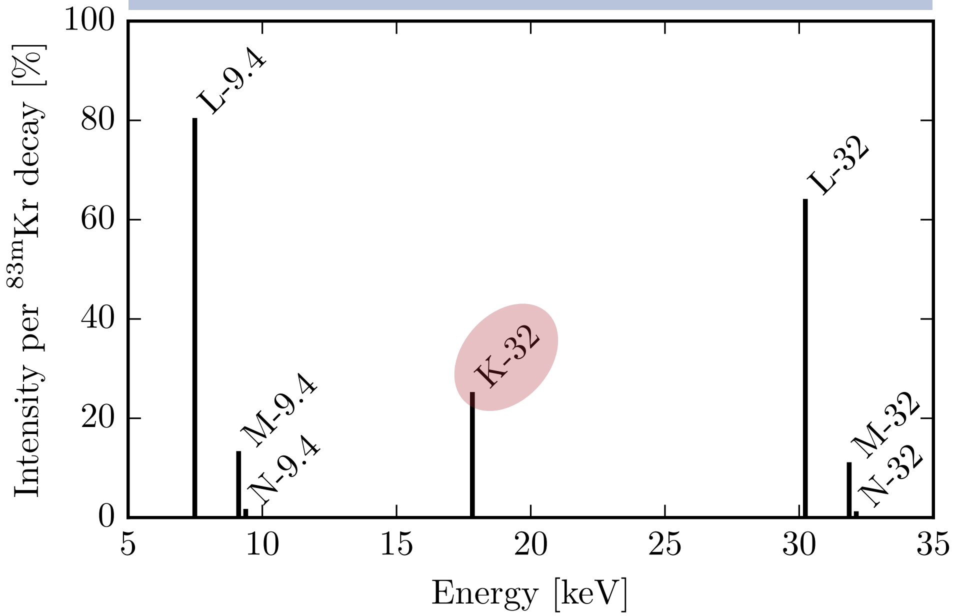


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**KATRIN krypton campaign: 3-19 July 2017**

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

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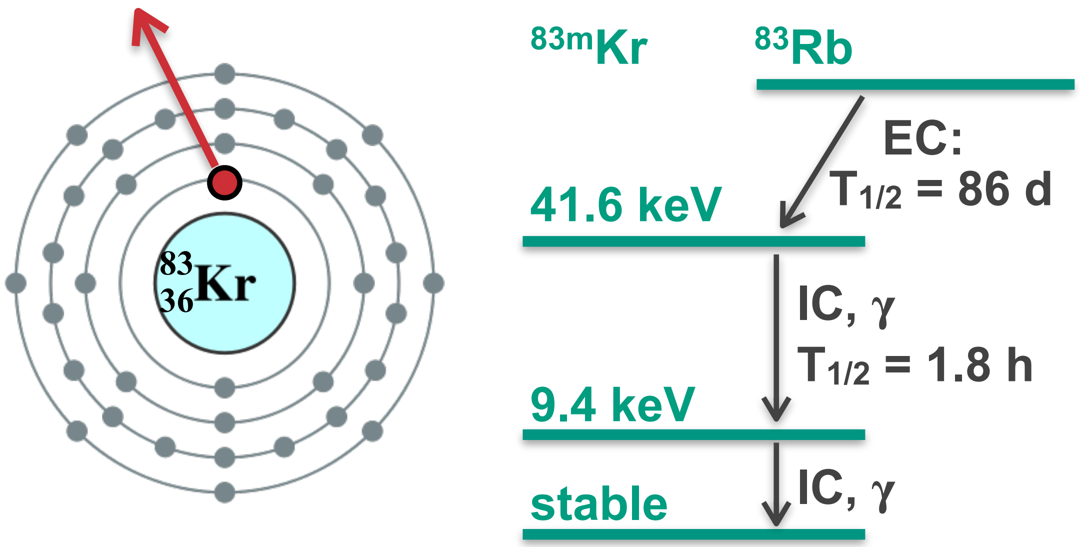


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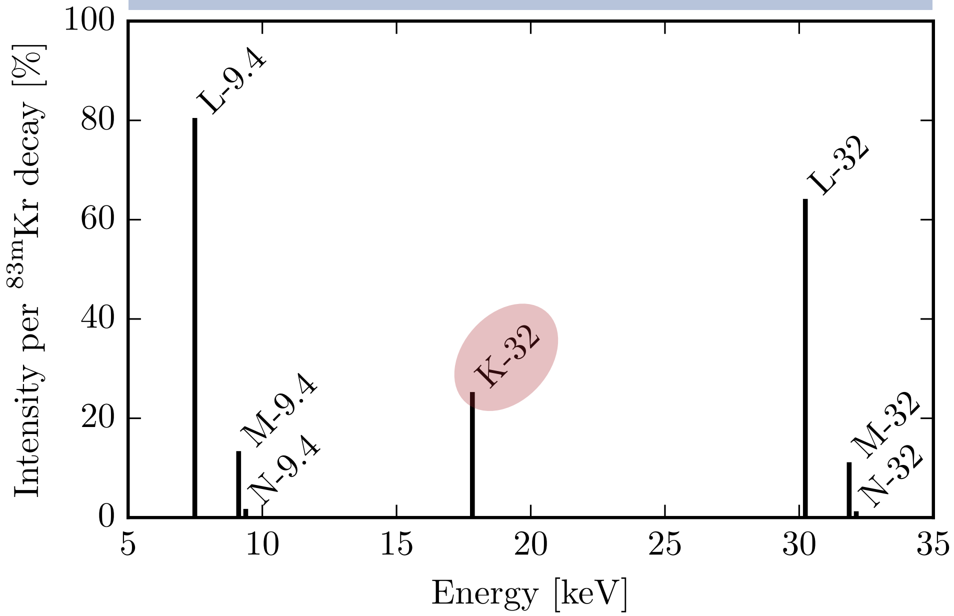


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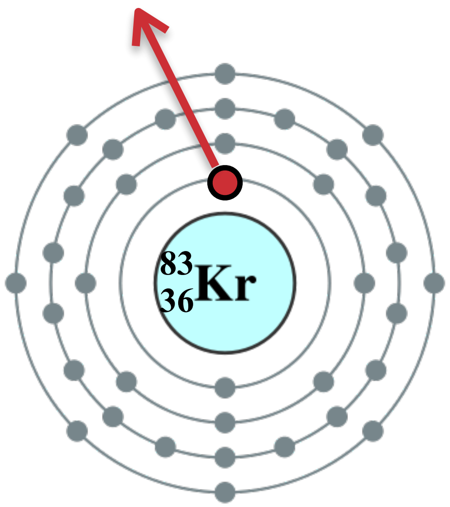


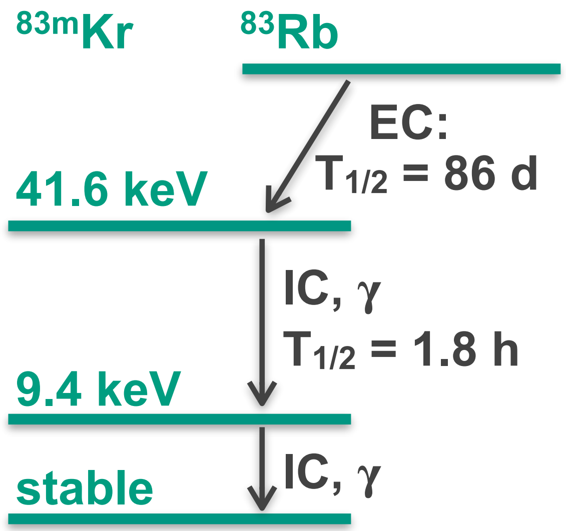


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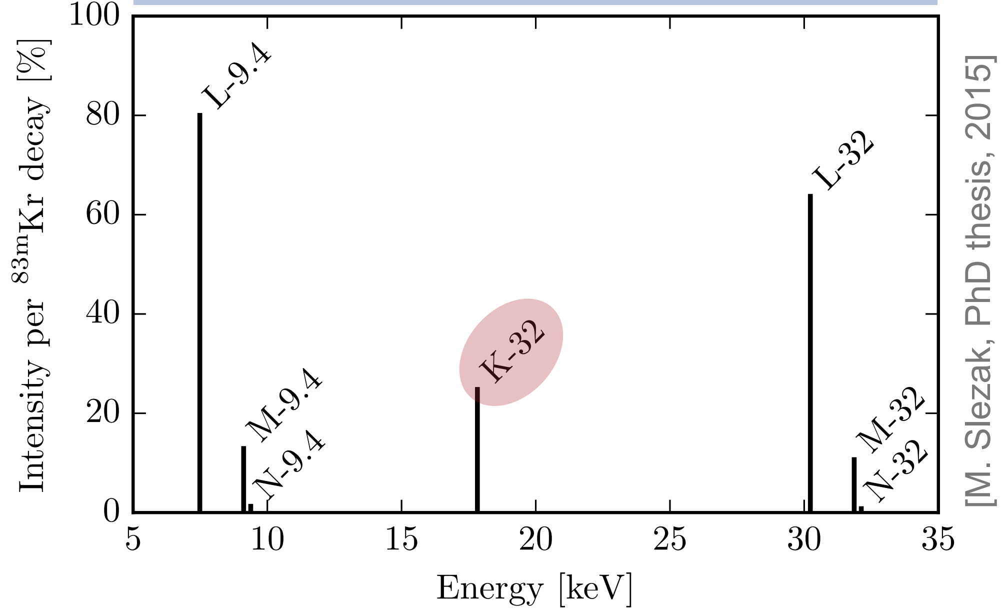


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**KATRIN krypton campaign: 3-19 July 2017**

**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, …

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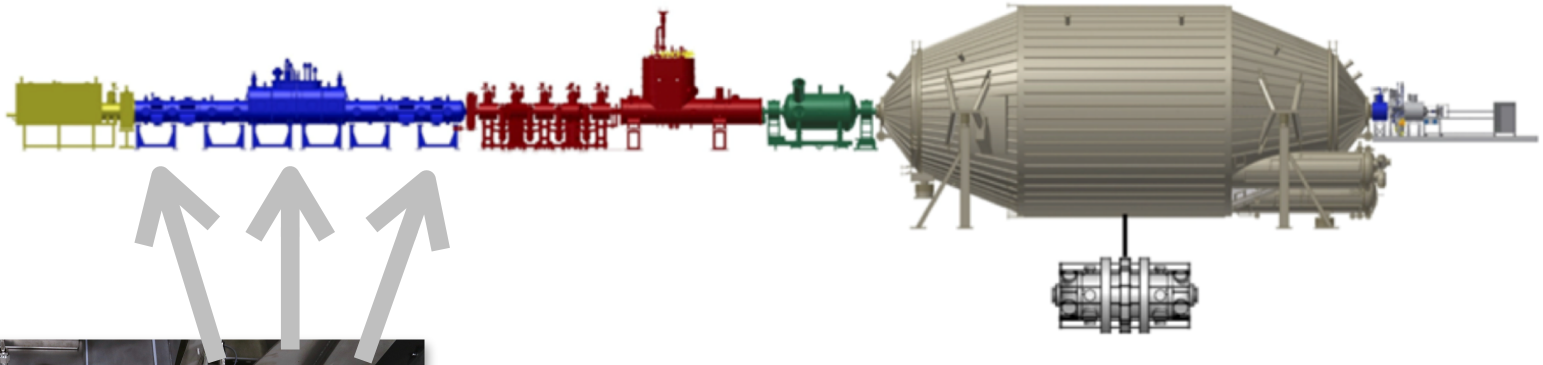
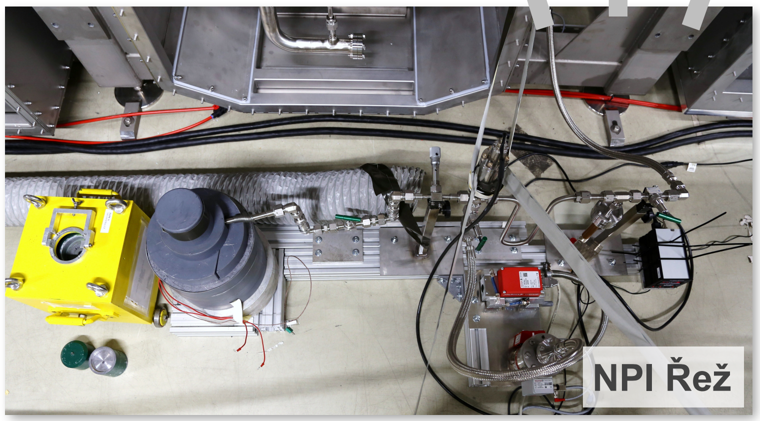
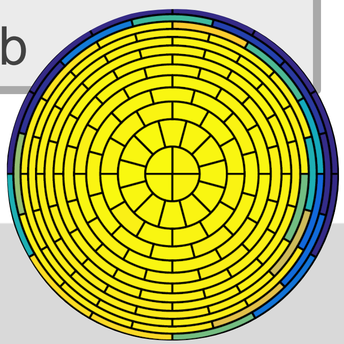


July 2017




**1. Gaseous $^{83m}$Kr source**

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



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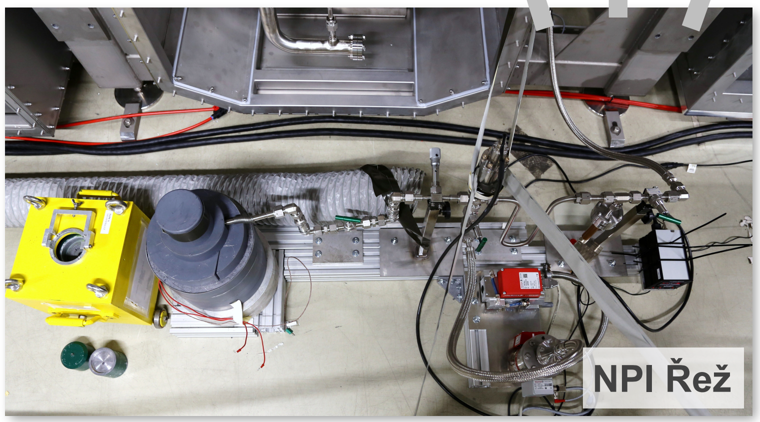
July 2017

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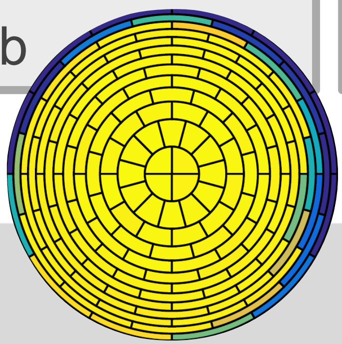
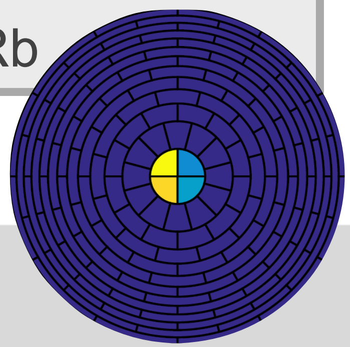


July 2017


### 2. Condensed $^{83m}$Kr source

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



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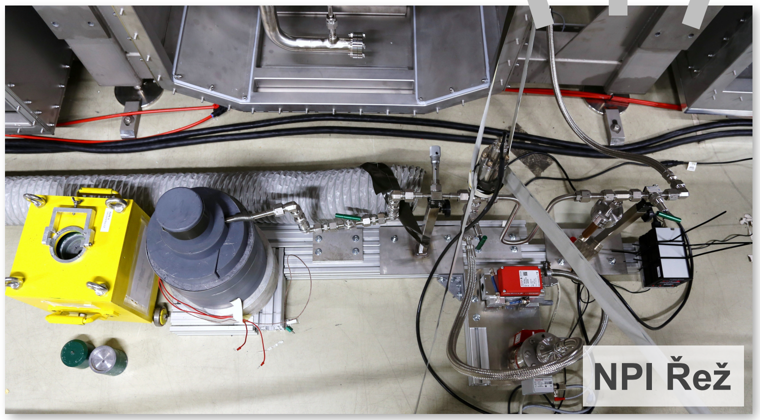
July 2017




July 2017


since 2012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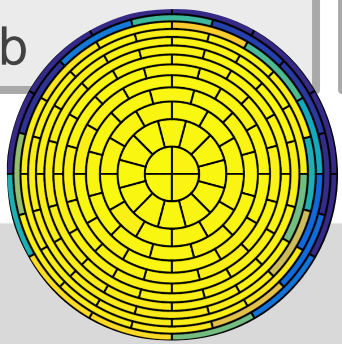

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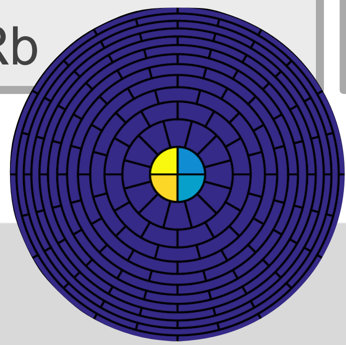
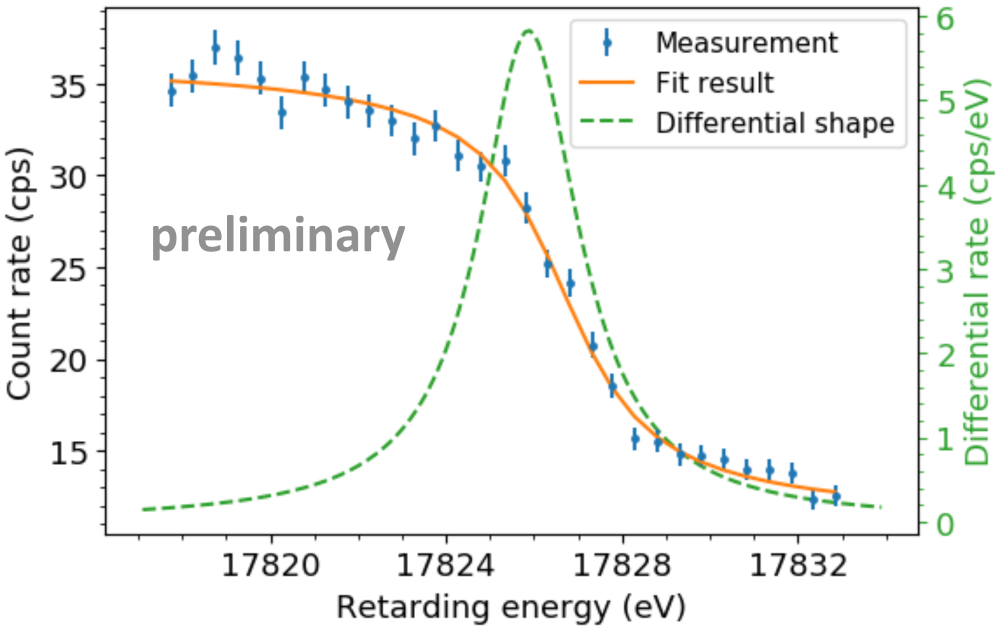


**3. Implanted $^{83m}$Kr source**

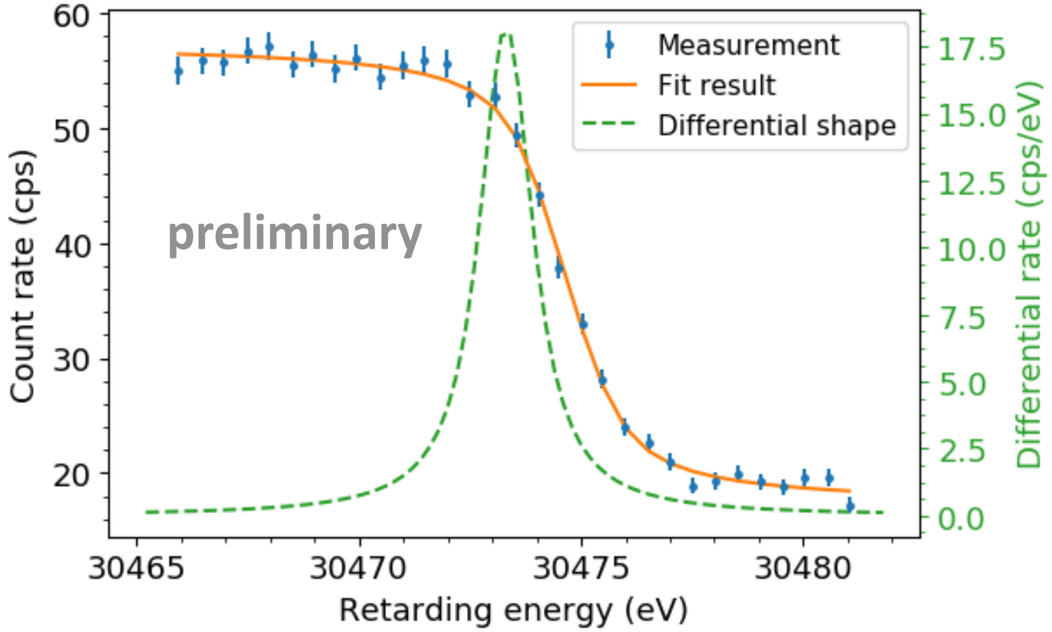
- Parallel measurement at Monitor Spectrometer
- Excellent stability proven over several years

# Integral conversion line spectra (gaseous Kr source)

**K-32** line (17.8 keV, $\Gamma$ ~2.8 eV)




**$L_3$-32** line (30.47 keV, $\Gamma$ ~1.4 eV)

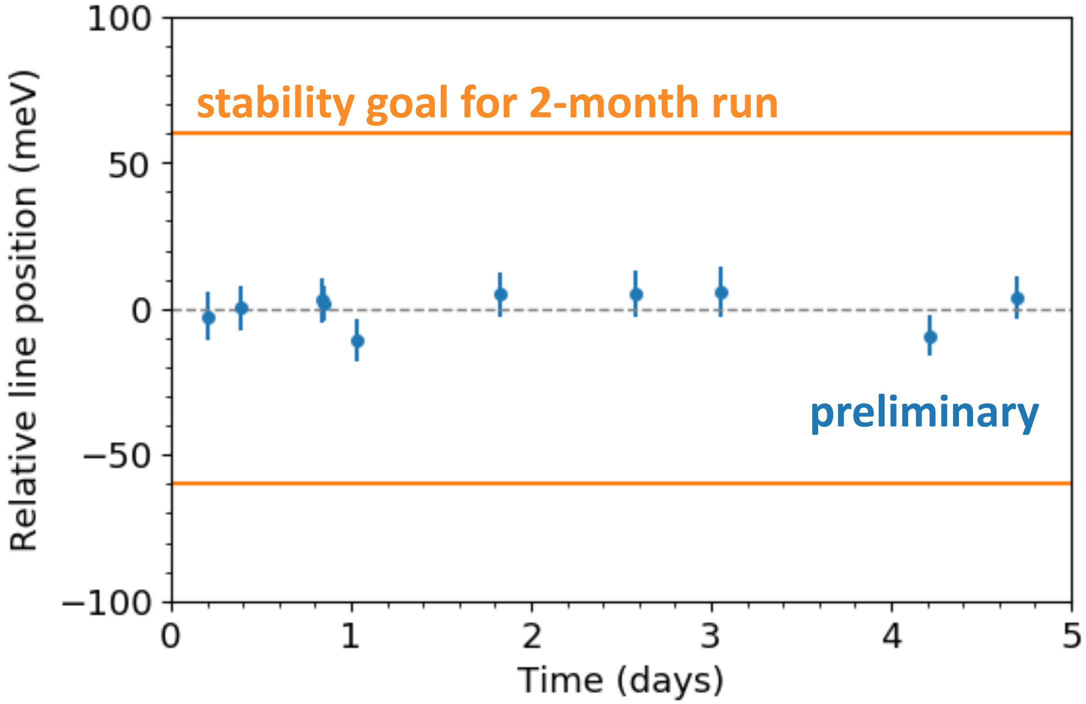



- Example runs (two out of many line scans)
- Only central detector ring shown (x30 more statistics available)
- High-resolution scans of narrow $N_{2,3}$-32 doublet (670 meV hyperfine splitting, sub-eV natural widths, background-free at 32 keV) currently being analyzed

# Line stability & absolute calibration (gaseous Kr source)

- Line position stability (L3-32) well within KATRIN goal of ± 60 meV

➡ Excellent stability of Krypton source and HV system



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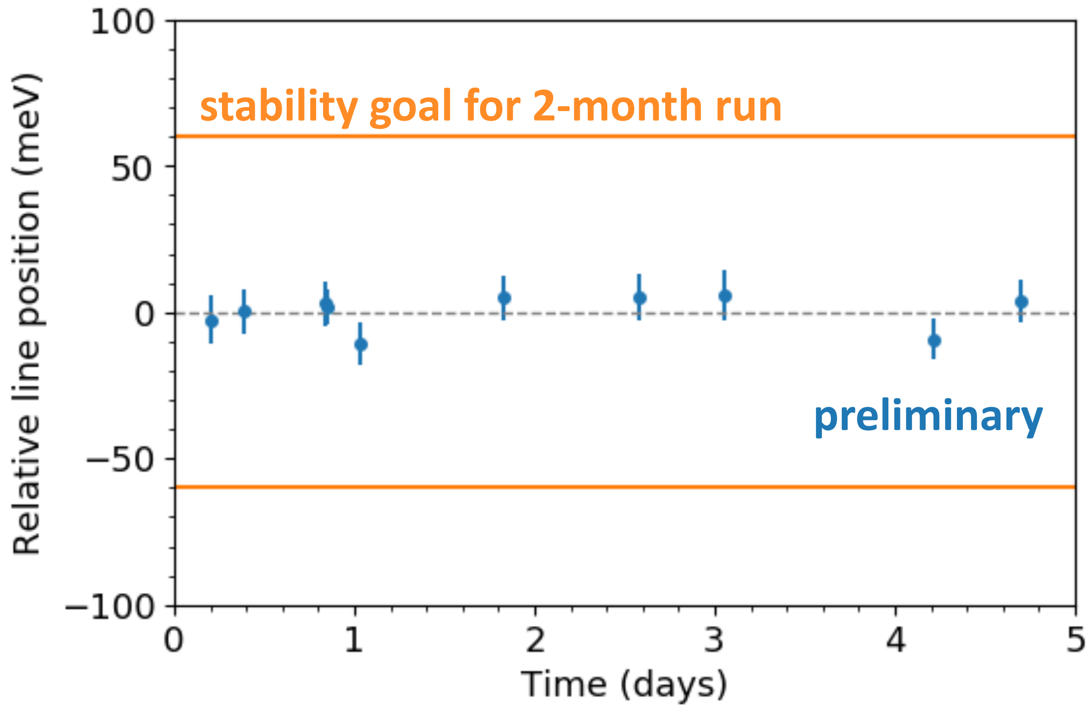
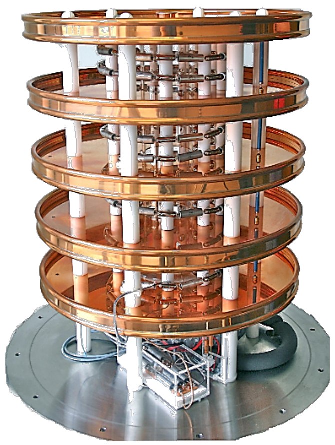


In cooperation with German national metrology institute PTB

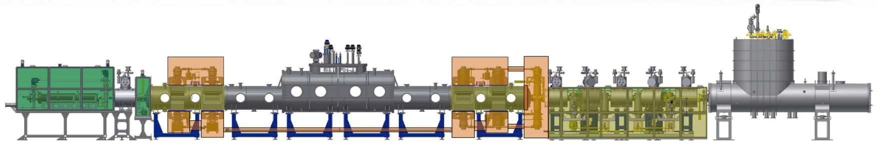
- Absolute calibration of HV divider with nuclear standard
- Line position difference L3-32 — K-32
  → source-related systematics cancel
  → ~5 ppm preliminary uncertainty on energy scale
  (very good agreement with 2013 PTB calibration value!)

# Outlook: next steps for KATRIN

[B. Bornschein *et al.*, Fusion Sci. Technol. (2017)]

**System complete**
**(except tritium loops, calibration system)**

**KATRIN beamline**



↕

**loops system** ↕

**TLK infra-structure**

**Central Tritium Retention System & isotope separation**

Tests with inactive $D_2$
➜ with traces of $T_2$

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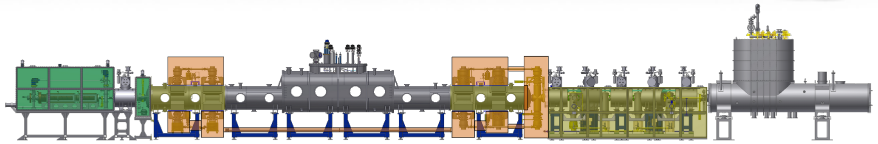

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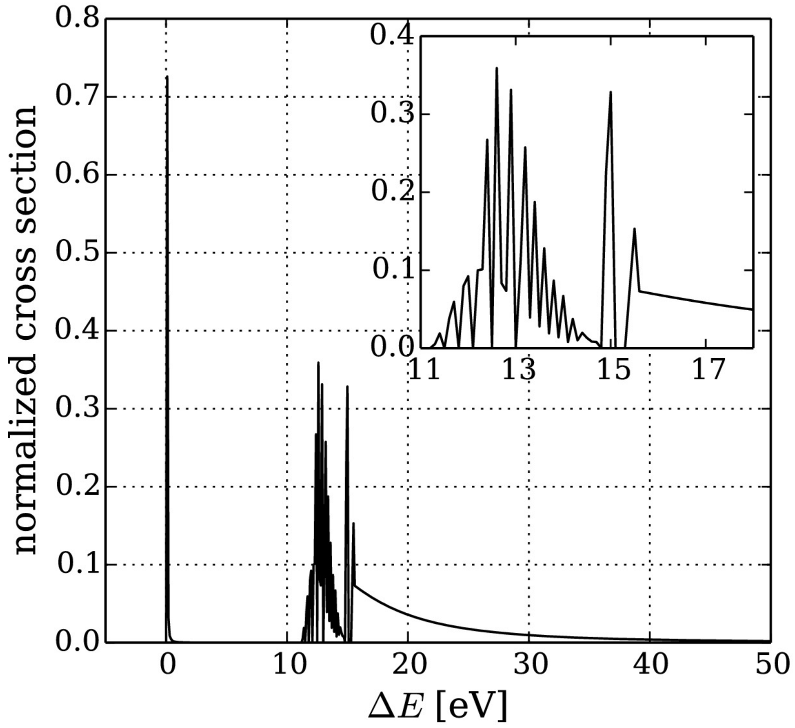
e.g. energy loss measurement




[V. Hannen *et al.*, Astropart. Ph. (2017)]

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Karlsruhe Institute of Technology

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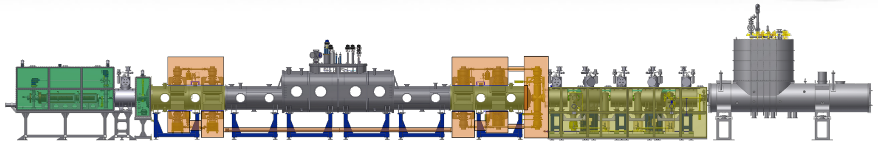

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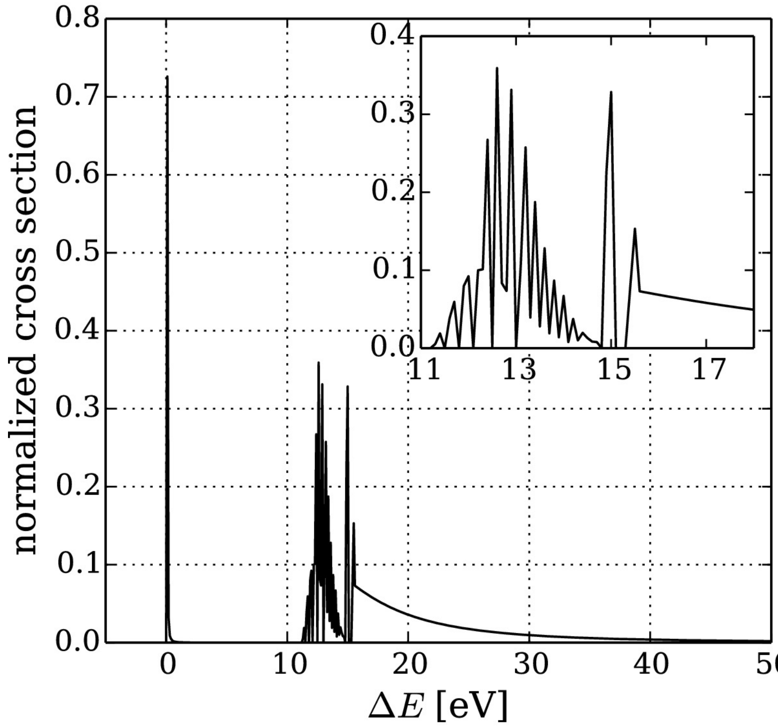
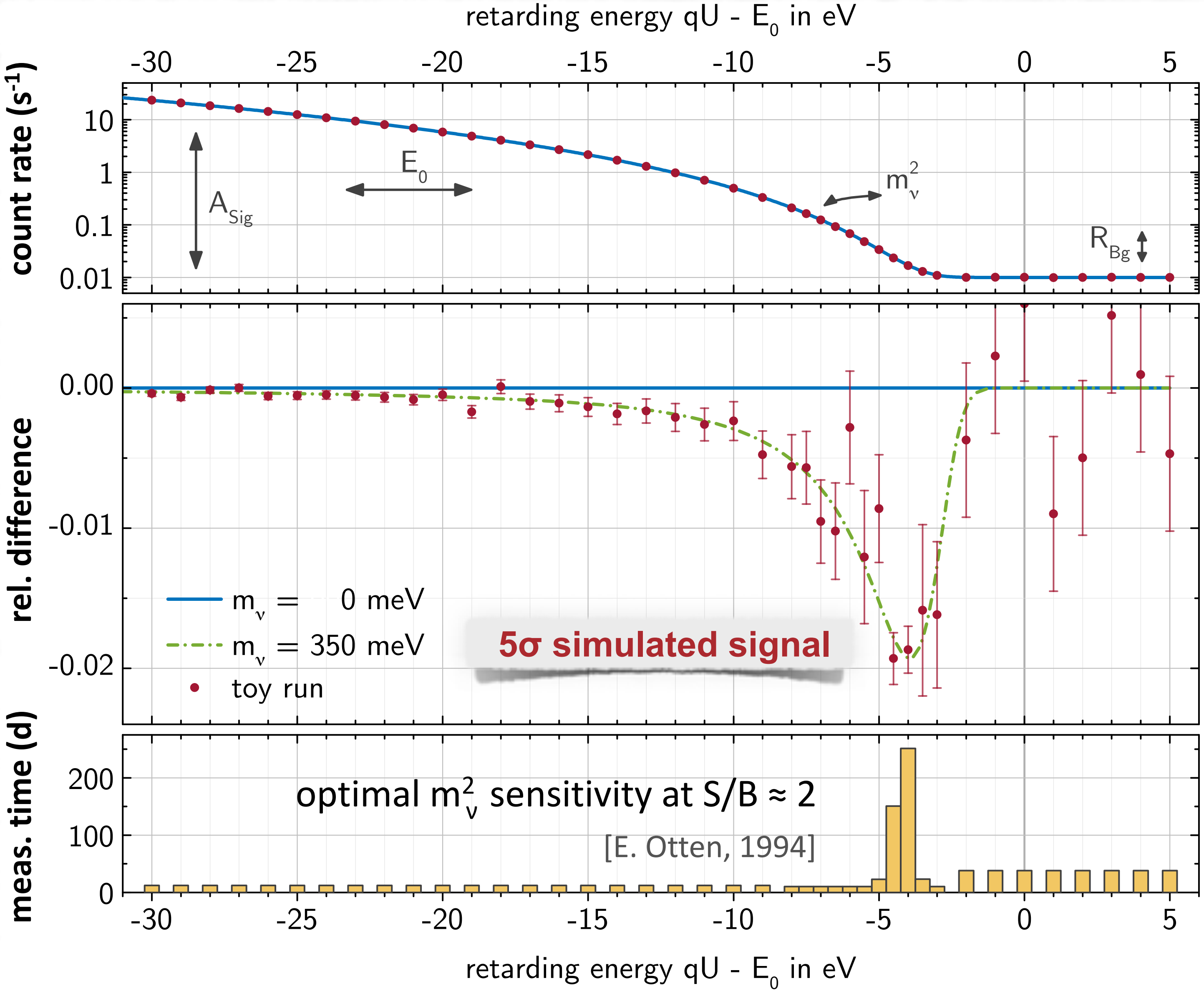



[V. Hannen *et al.*, Astropart. Ph. (2017)]

**Tritium data-taking: start in 2018**
**KATRIN inauguration ceremony: June 11, 2018** (after NEUTRINO'18 at Heidelberg)

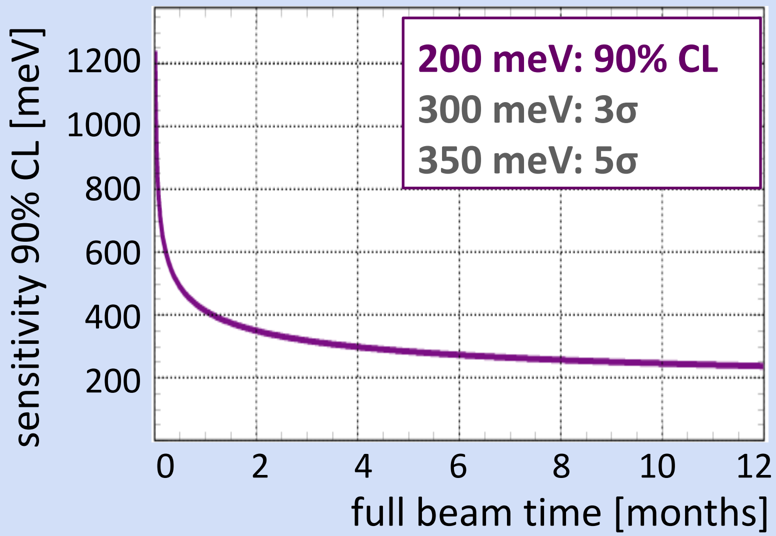
# KATRIN: neutrino mass analysis & sensitivity



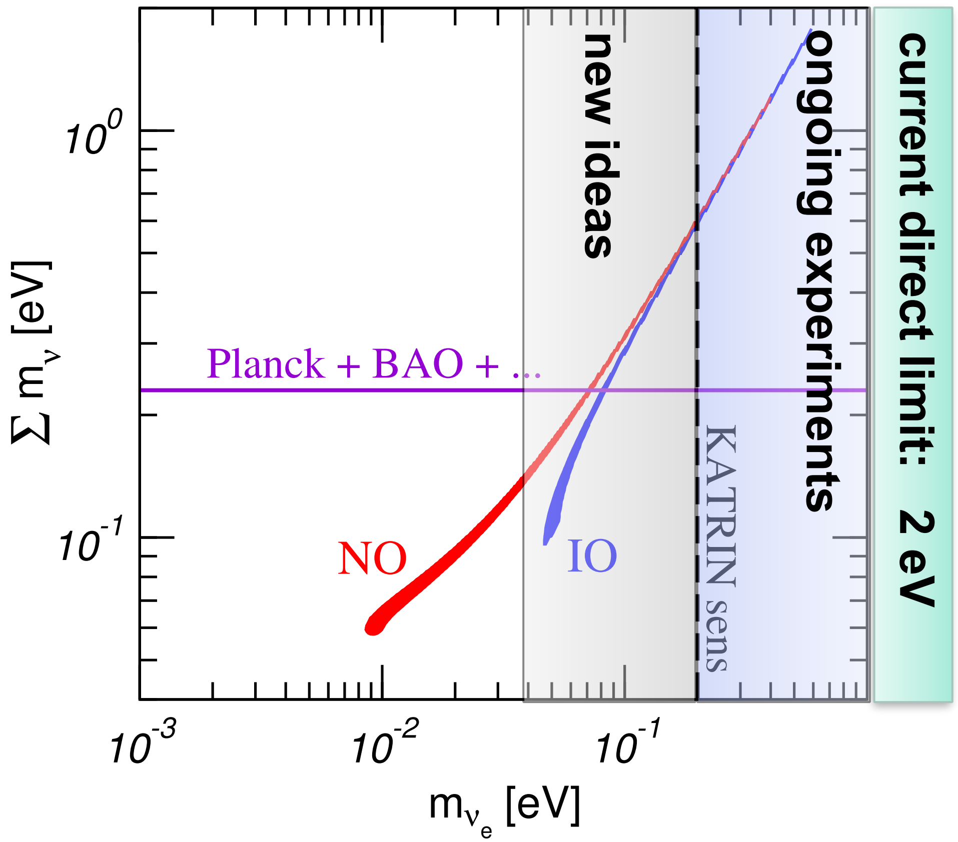

- Relative **shape** measurement of **integrated β spectrum**
- 4 fit parameters: $m^2_\nu$ , $E_0$ , $A_S$ , $R_{Bg}$

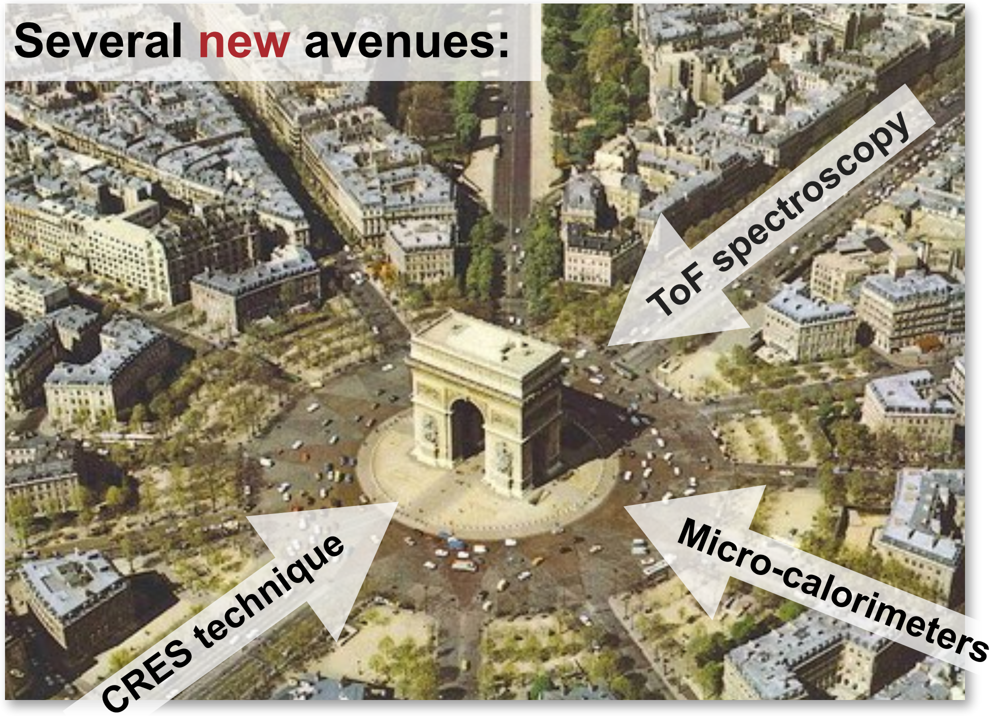
3 yrs (5 cal. yrs) to balance statistics and systematics

at design parameters:



# Future prospects in direct neutrino mass search

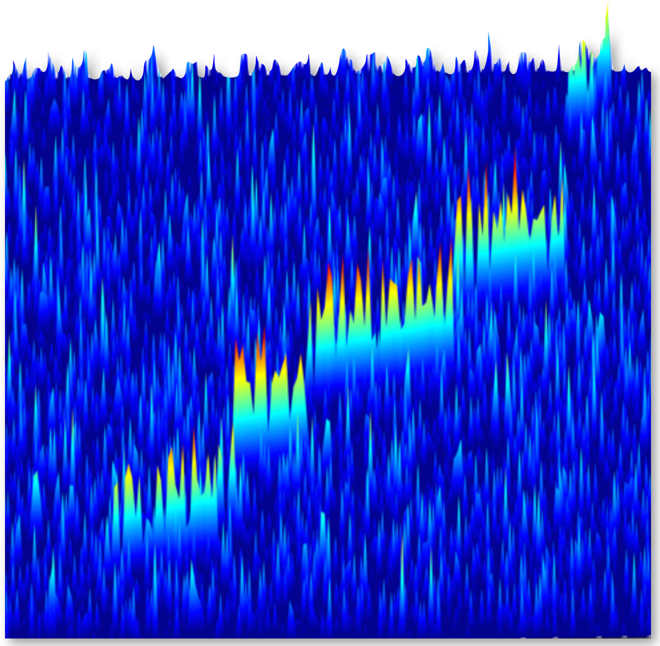



**Challenges for further improvement:**

- Opacity of gaseous $T_2$ source (already optimised for KATRIN, ~40% no-loss $e^-$)
- MAC-E filter measures *integral* beta spectrum
- Molecular final state excitations (vib: ~100 meV) as ultimate limitation for $T_2$

# Frequency-based approach



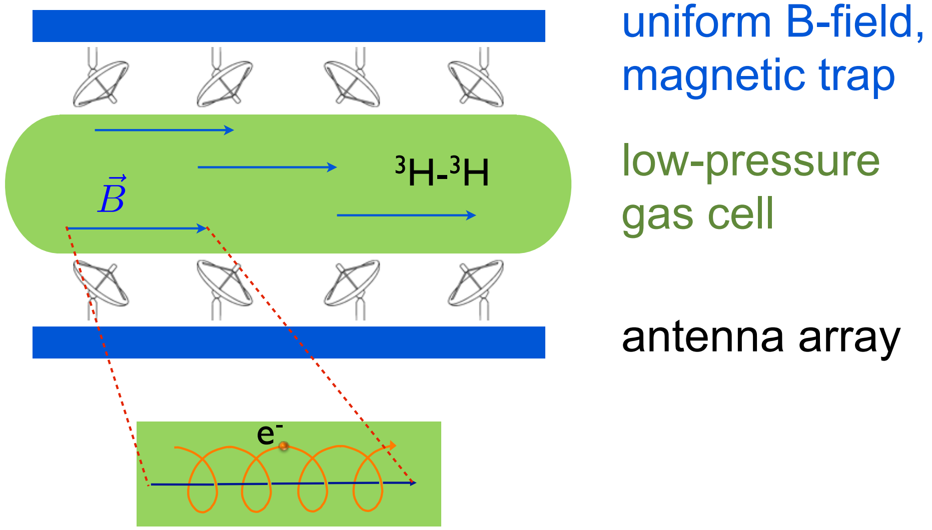
# Cyclotron Radiation Emission Spectroscopy (CRES)

PROJECT 8

UW Seattle, MIT, UCSB,
Pacific NW, CfA, Yale,
Livermore, KIT, U Mainz

Non-destructive measurement of electron **energy** via **cyclotron frequency:**

$$\omega(\gamma) = \frac{\omega_c}{\gamma} = \frac{eB}{E_{\mathrm{kin}} + m_e}$$




 [Monreal & Formaggio, PRD 80 (2009) 051301] 

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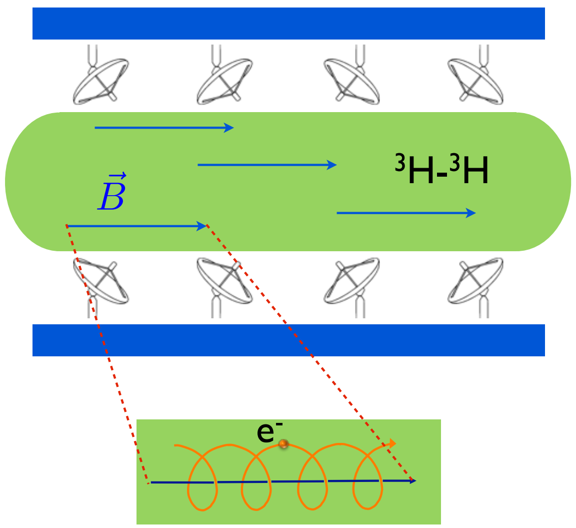
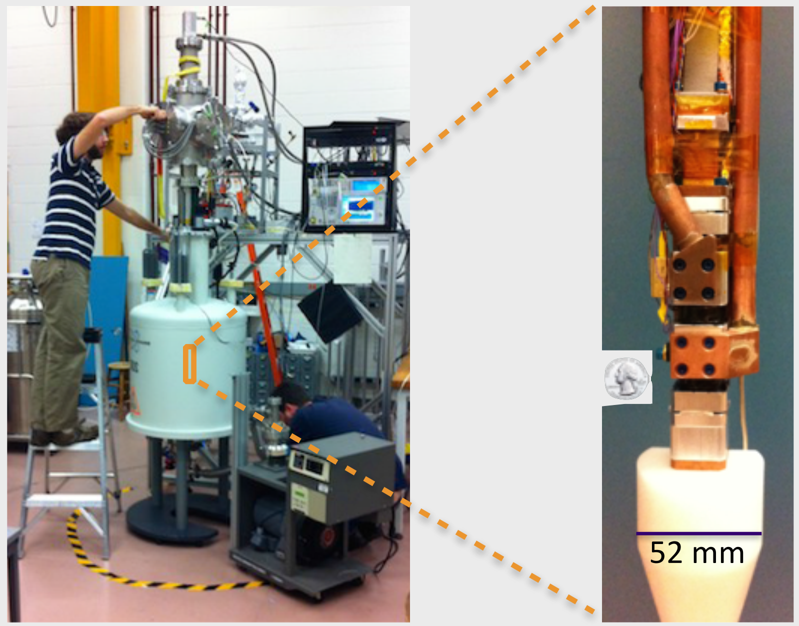



uniform B-field, magnetic trap

low-pressure gas cell

antenna array

## Phase I system



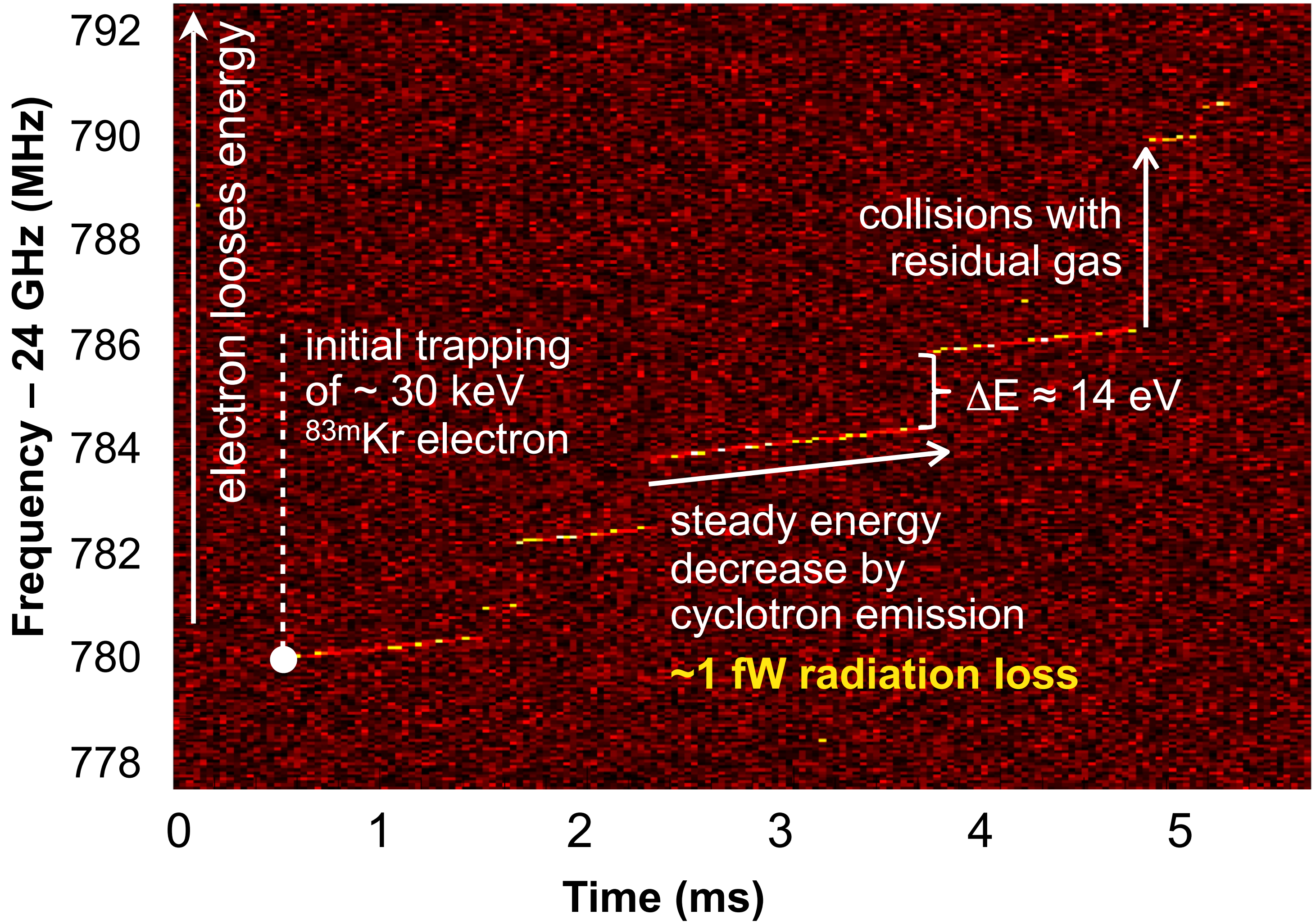

➜ Proof of principle of CRES technique

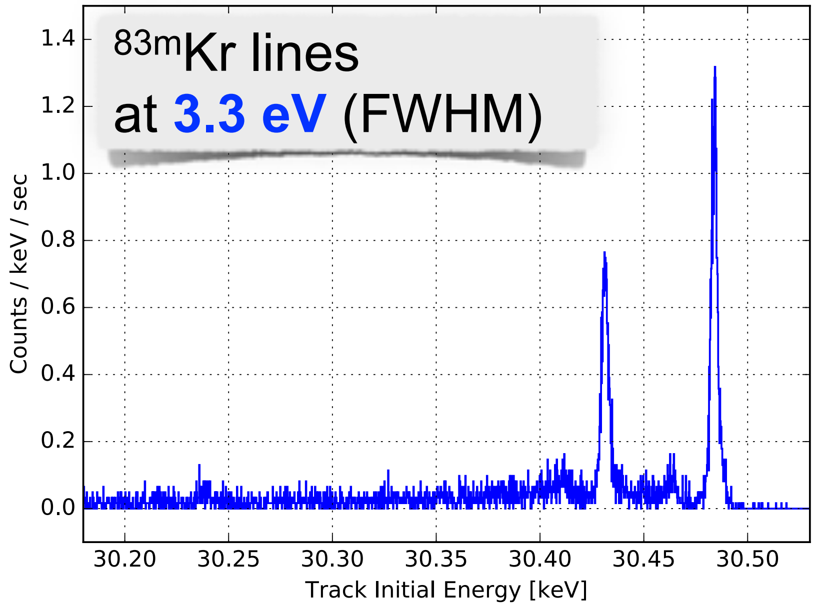


[Monreal & Formaggio, PRD 80 (2009) 051301]

# Project 8: phase I results

## First observation of cyclotron radiation from single keV electrons




[Asner *et al.*, PRL 114 (2015) 162501; La Roque et al., NEUTRINO 2016]

# Project 8: staged approach

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  Single-electron CRES demonstrated
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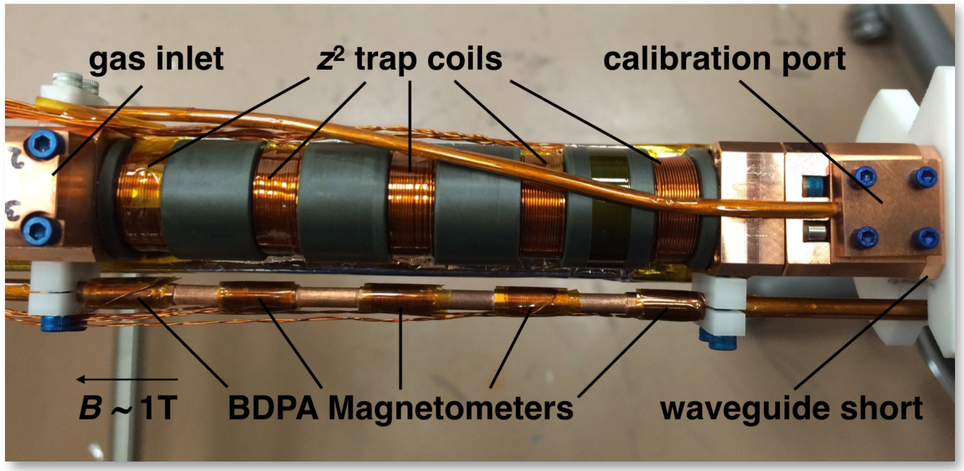

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  - Conceptual design for "open" receiver array, MRI magnet
  - $10^5$ Bq in 200 $cm^3$ volume (10 $cm^3$ effective)
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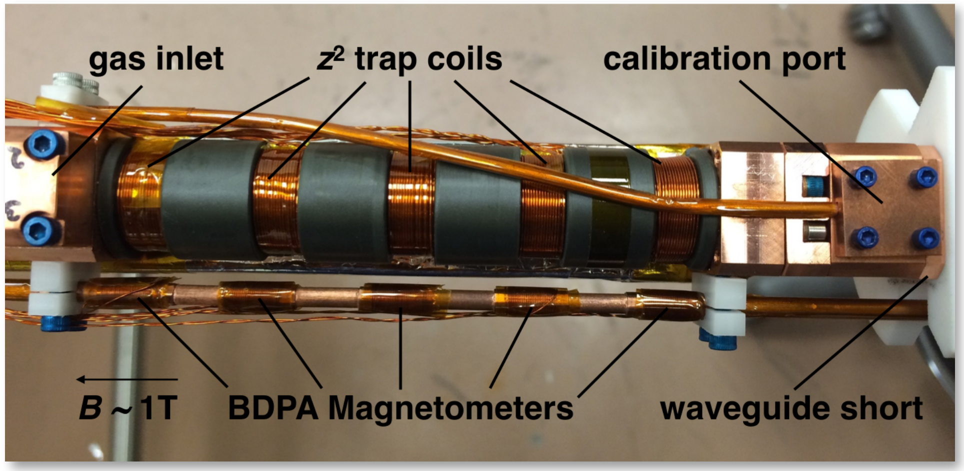


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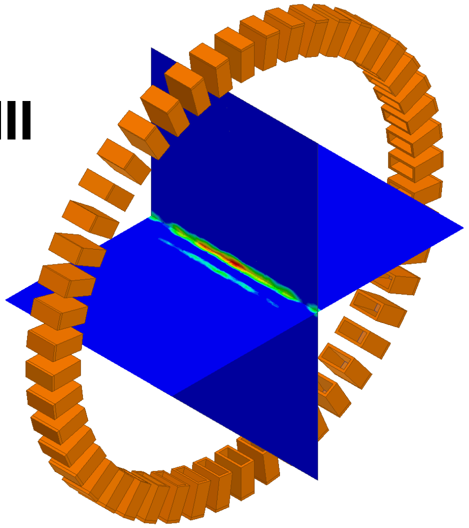

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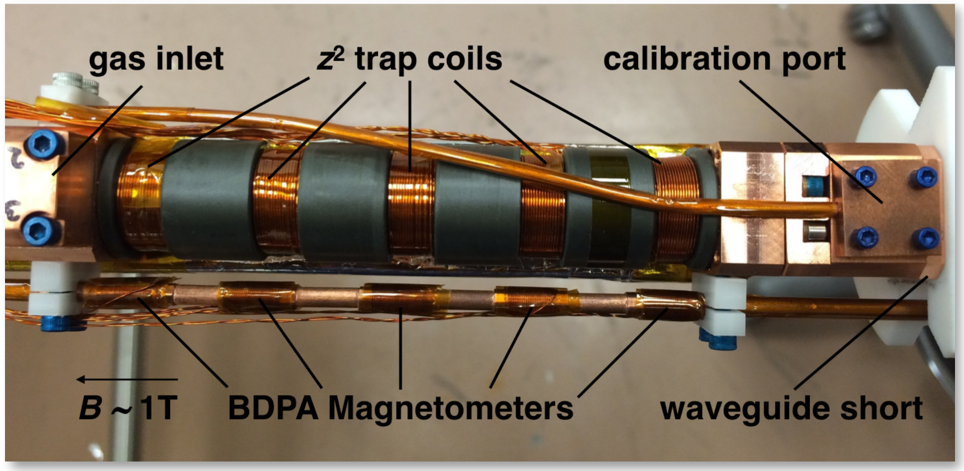
- **Phase IV (2017+): atomic tritium source**
  - R&D for large-volume (200 $m^3$) atomic tritium source (< 1 K), magnetic confinement
  - goal: sub-eV sensitivity at inverted hierarchy scale

Phase II

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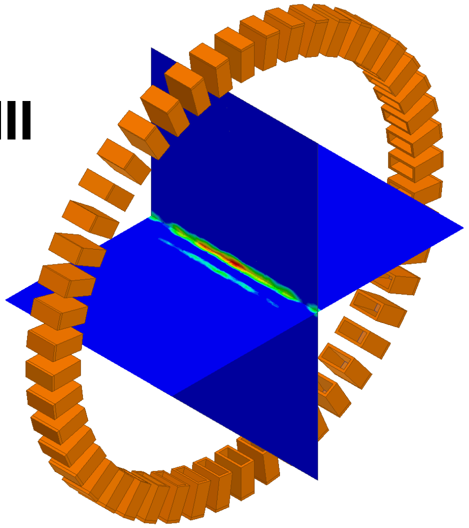
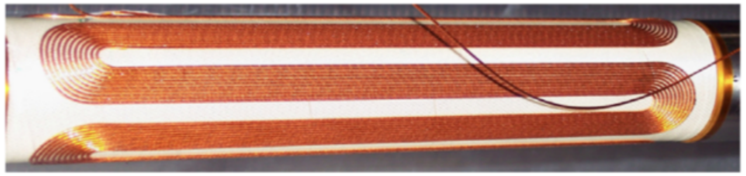
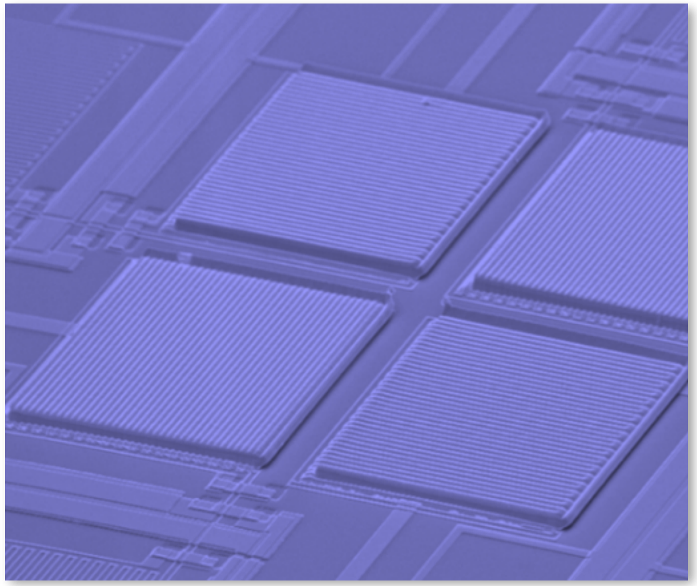


Phase IV



# Calorimetric approach using $^{163}$Ho

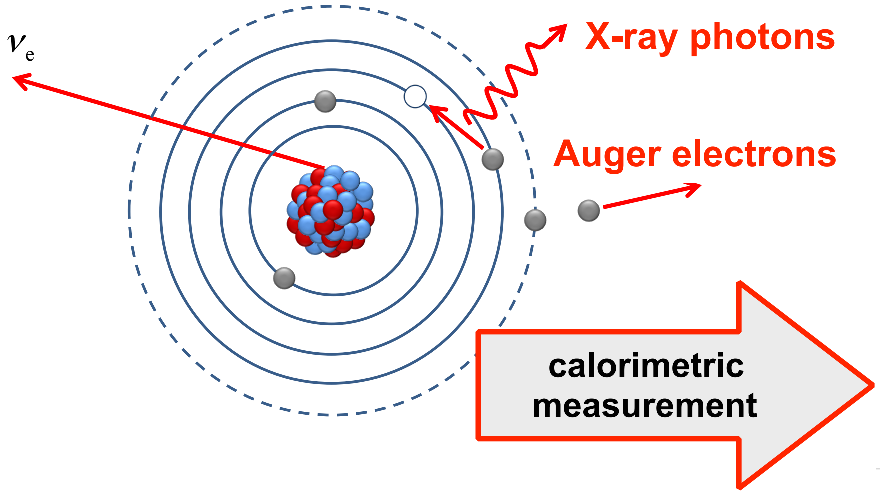


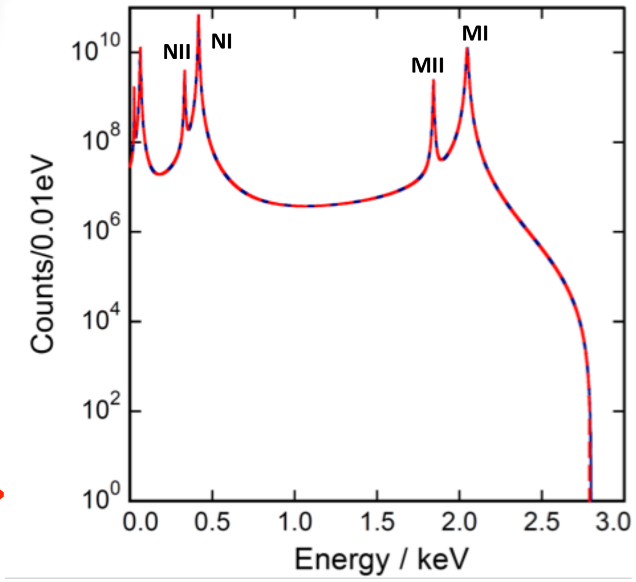
# ν-mass from $^{163}$Ho electron capture

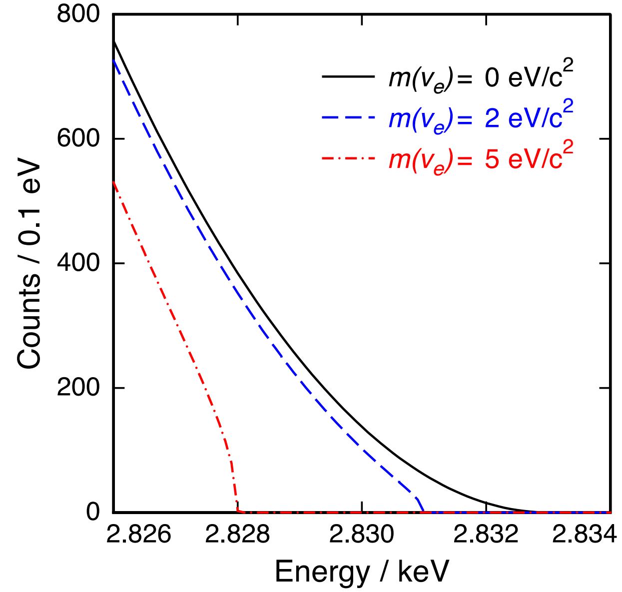
$^{163}Ho \rightarrow {}^{163}Dy^{*} + \nu_e$

Low $Q_{EC}$ ~2.8 keV and $T_{1/2}$ ~ 4570 years

[De Rujula & Lusignoli 1982]

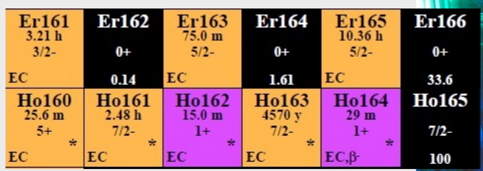



## Challenges:

- Production & purification of isotope $^{163}$Ho
- Incorporation of $^{163}$Ho into high-resolution detectors
- Operation & readout of large calorimeter arrays
- Understanding of calorimetric spectrum (nuclear & atomic physics + detector response)




[L. Gastaldo]

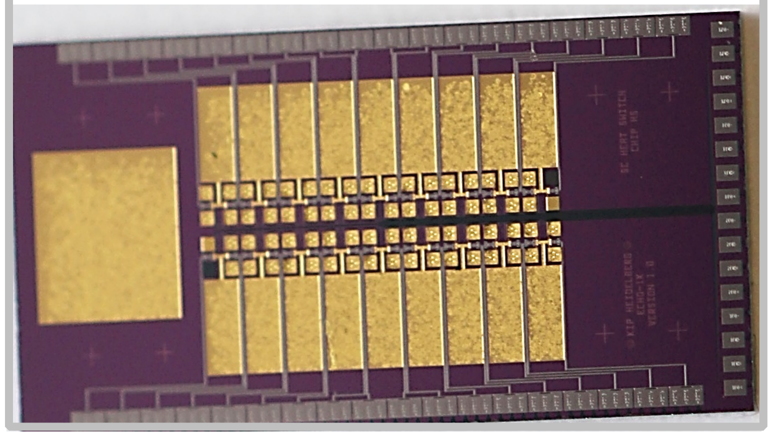
# World-wide efforts in $^{163}$Ho-based ν-mass search

Karlsruhe Institute of Technology

## ECHo

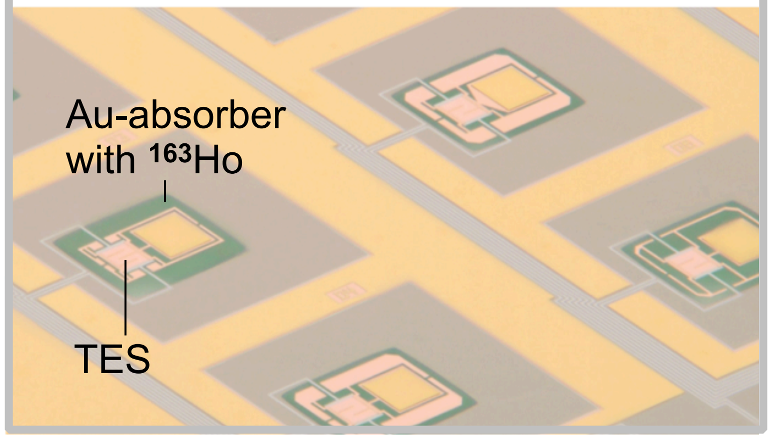
CERN
India Slovakia
Hungary Russia

- Metallic Magnetic Calorimeters
- ΔE < 5 eV achieved
- m(ν) sensitivity:
  10 eV with ECHo-1k (2015-18)
  sub-eV with ECHo-10M



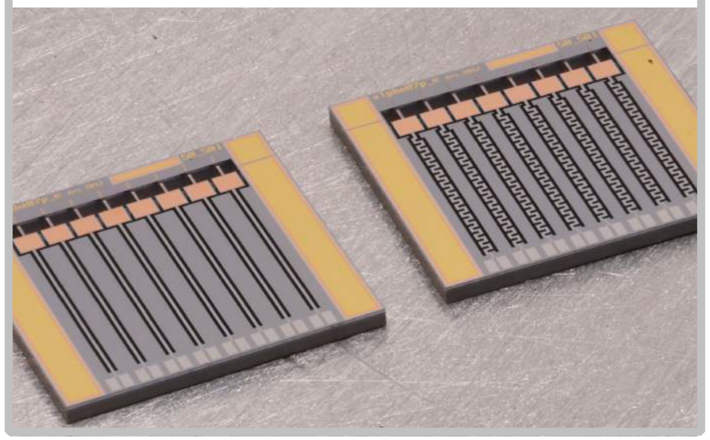
## HOLMES

- Transition Edge Sensors
→ detectors from NIST
→ implanting at Genoa
→ cryostat at Milano
- ΔE ~ 1 eV design
- sensitivity: m(ν) ~ 1 eV
  2018-20

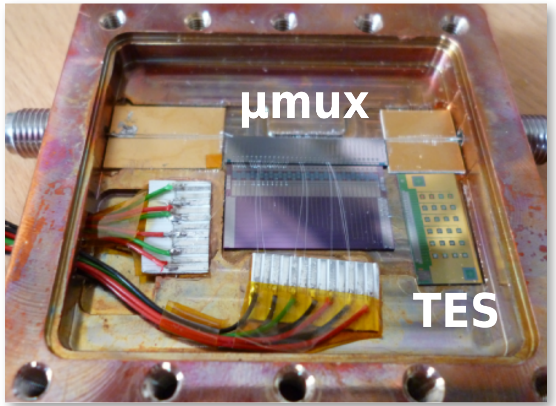



## NuMECS

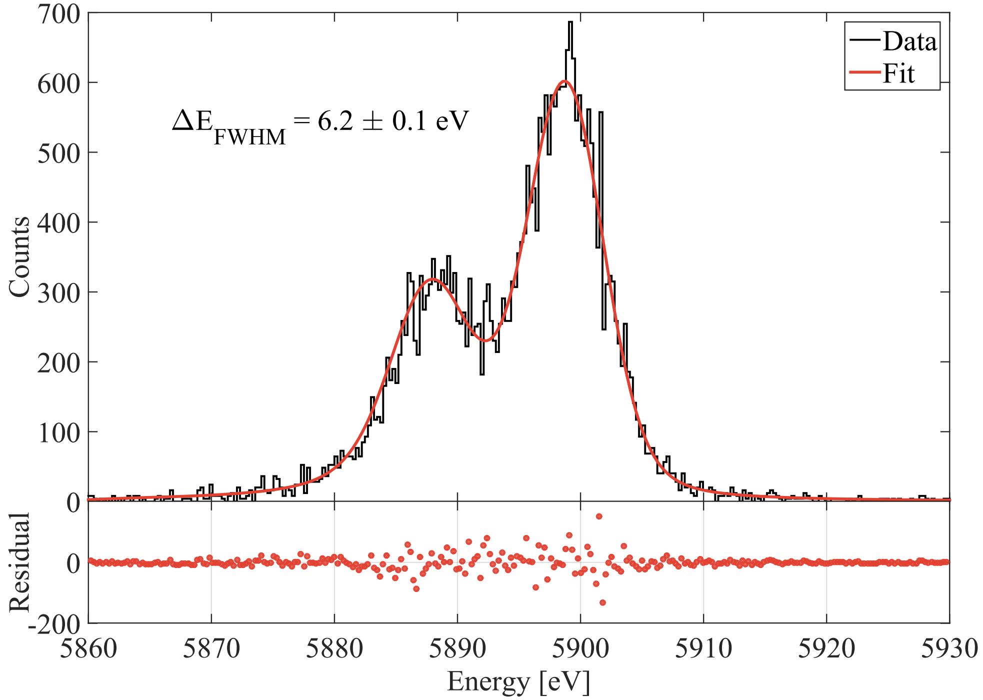
- Testing concepts of $^{163}$Ho-incorporation and TES read-out
- ΔE ~ 35 eV achieved
- sensitivity: mostly R&D up to now, maybe large array?



# TES technology: HOLMES


Mn K$\alpha_{1,2}$ lines at ~5 eV resolution, $\tau_{rise}$~ few µs




 [A. Giachero et al., JINST 12 (2017) C02046] [M. de Gerone, TAUP 2017] 

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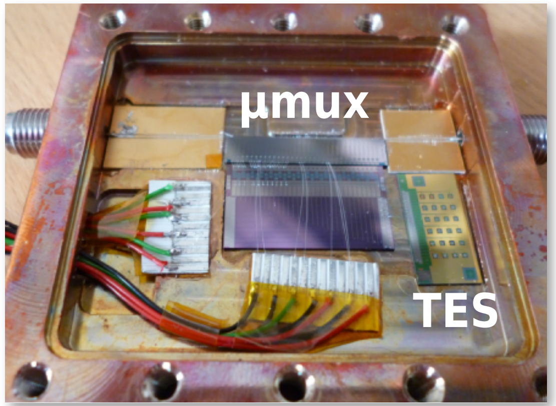


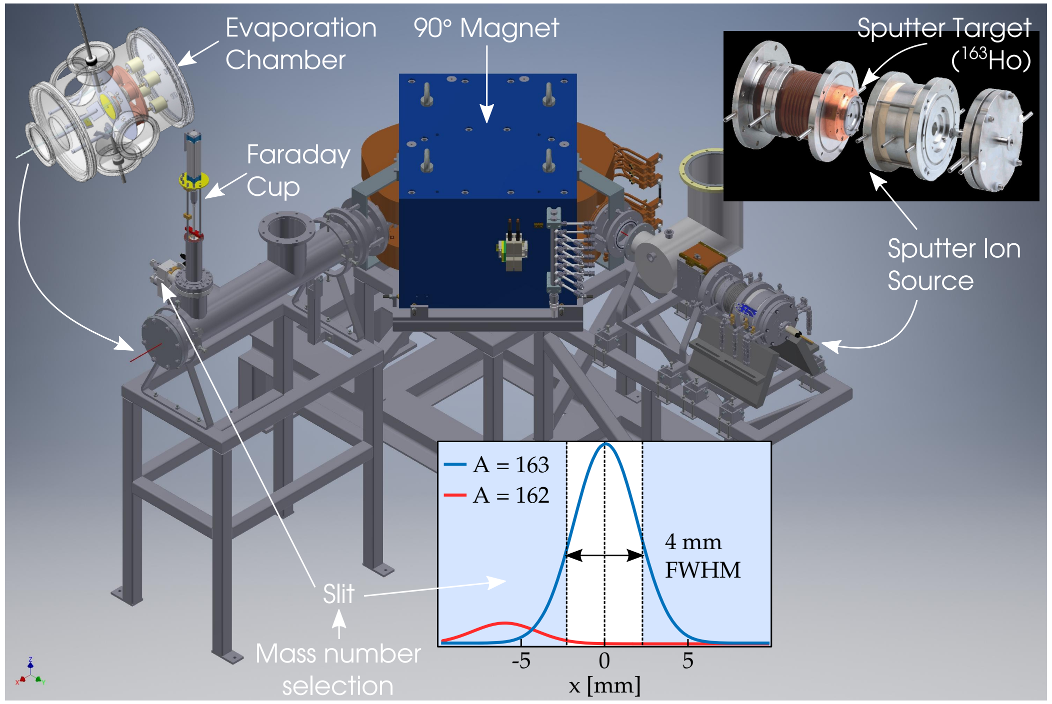


Custom mass-separator ion implanter at Genova

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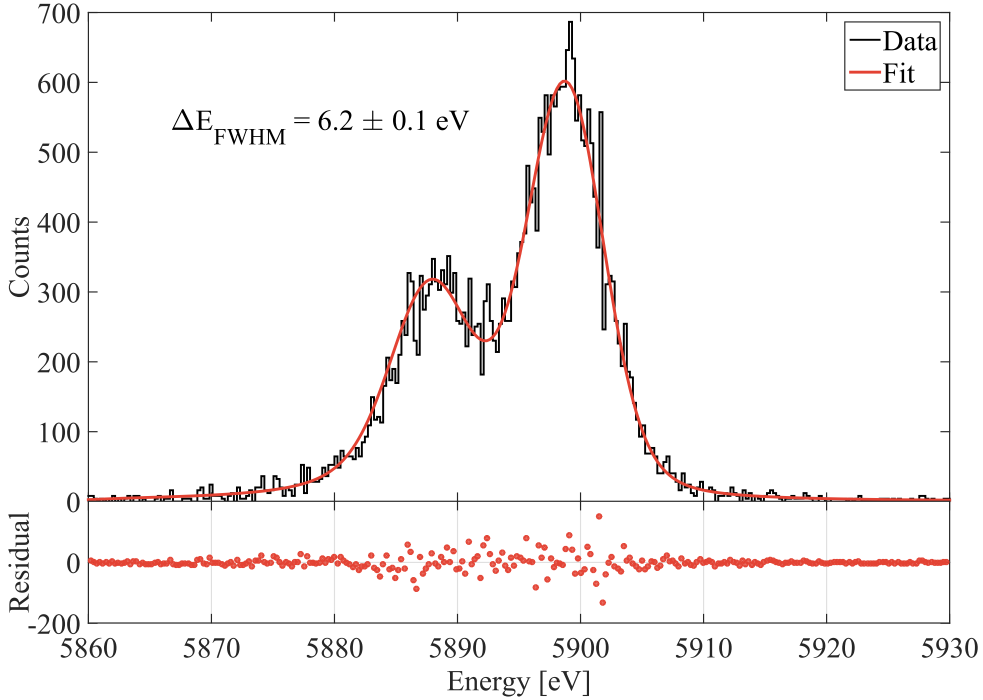

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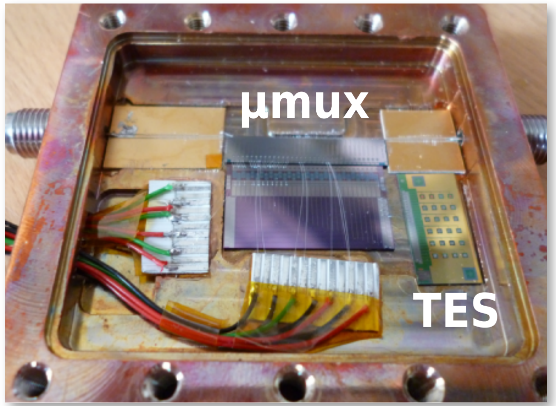


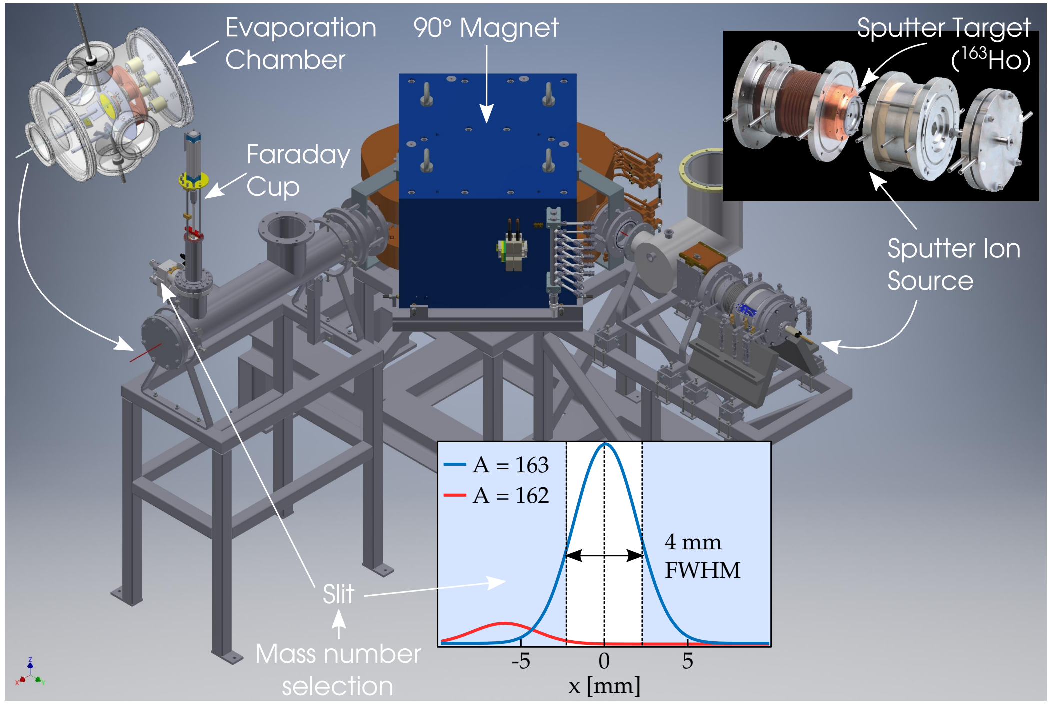


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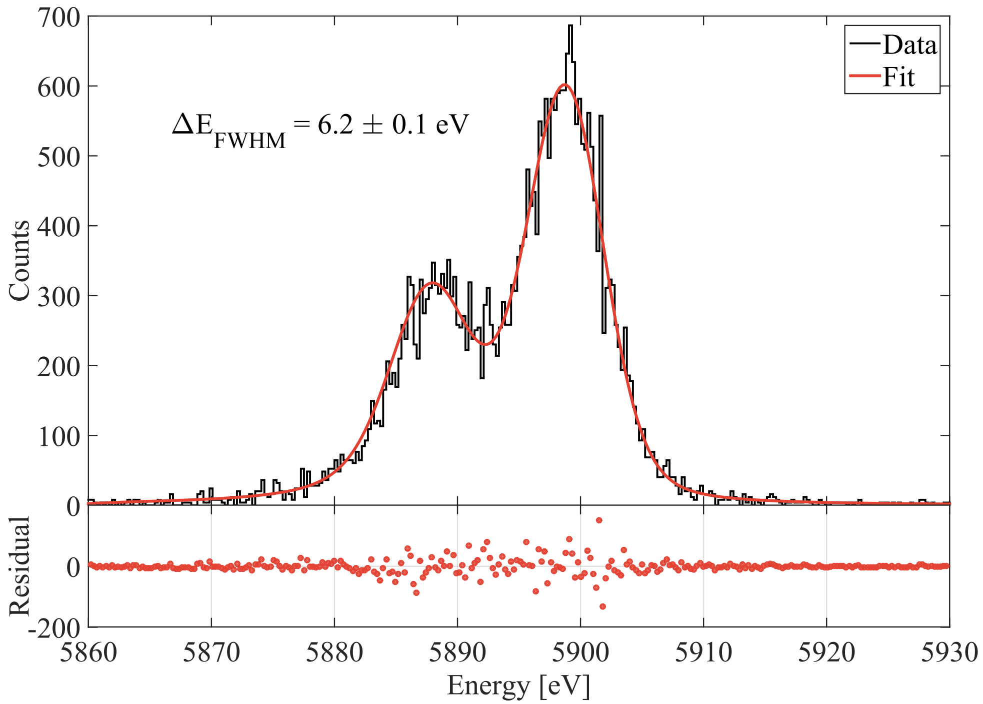



**Custom mass-separator ion implanter at Genova**

## HOLMES design & timeline:

- 6.5 x 10$^{13}$ nuclei $^{163}$Ho (~300 Bq) per pixel
- ΔE ~ 1 eV, $\tau_{rise}$~ 1 µs;
  1000-pix array operation expected for 2018
- TES array + DAQ ready, first implant. coming up
- Spectrum measurements to begin in late 2017
- **32 pixels for 1 month → $m_\nu$ sensitivity ~10 eV**

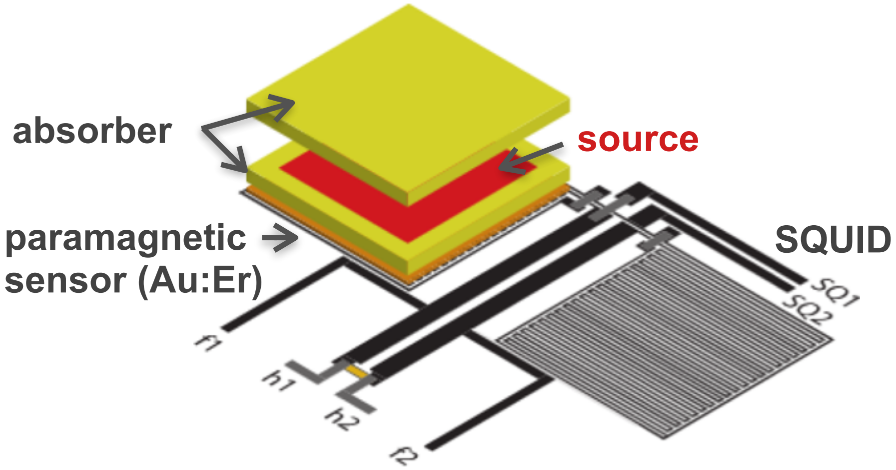


[A. Giachero et al., JINST 12 (2017) C02046] [M. de Gerone, TAUP 2017]

# MMC technology: ECHo

Heidelberg (Univ., MPIK), U Mainz, U Tübingen, TU Dresden, U Frankfurt, HU Berlin, ILL Grenoble, PNPI St Petersburg,U Bratislava, IIT Roorkee, Saha Inst. Kolkata

[Fleischmann *et al.* 2009; Gastaldo *et al.* 2013]




## Technology

- Fast rise time (~130 ns) and excellent linearity & resolution ($\Delta E_{FWHM}$ < 5 eV)
- Production: $^{162}Er(n,\gamma)^{163}Ho$ at ILL (Grenoble) implantation at ISOLDE-CERN & RISIKO
- Multiplexed readout of MMC arrays

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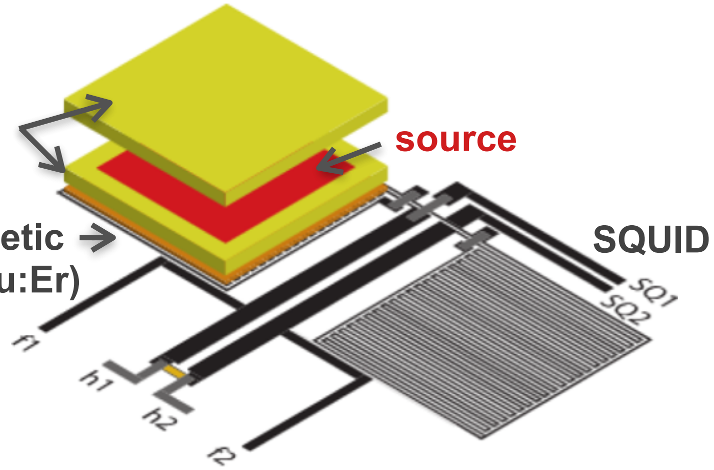
FOR 2202




[Fleischmann *et al.* 2009; Gastaldo *et al.* 2013]

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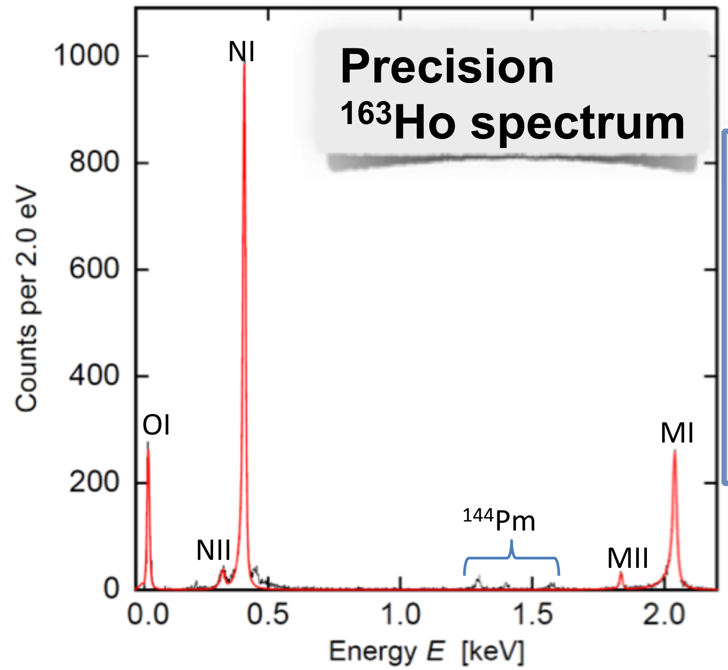
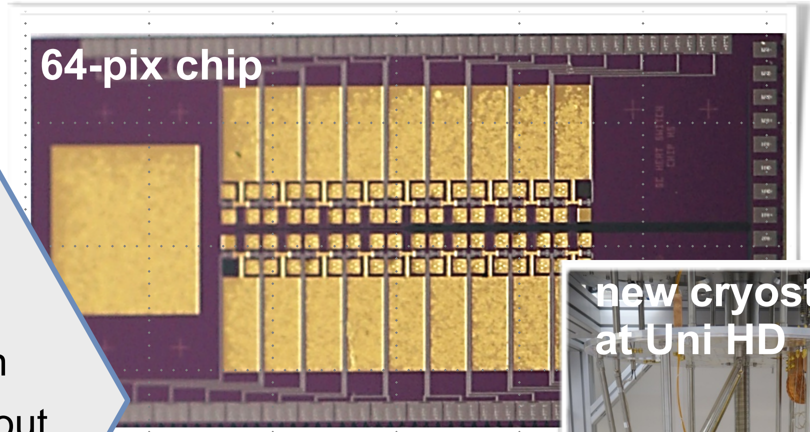
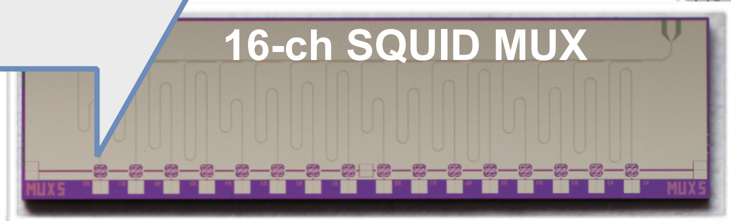
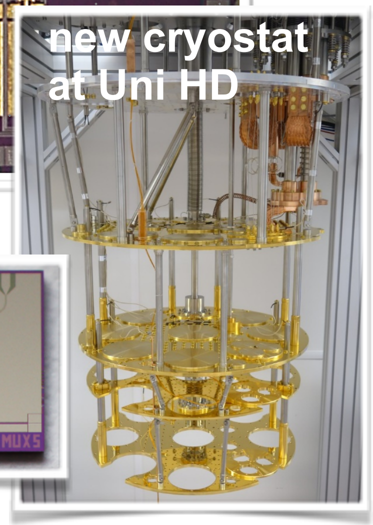



[Ranitzsch *et al.*, arXiv:1409:0071; Gastaldo *et al.* 2014]

- ☑ new 64-pix detectors optimised for implantation
- ☑ proof of multiplexed readout
- ☑ first underground meas.



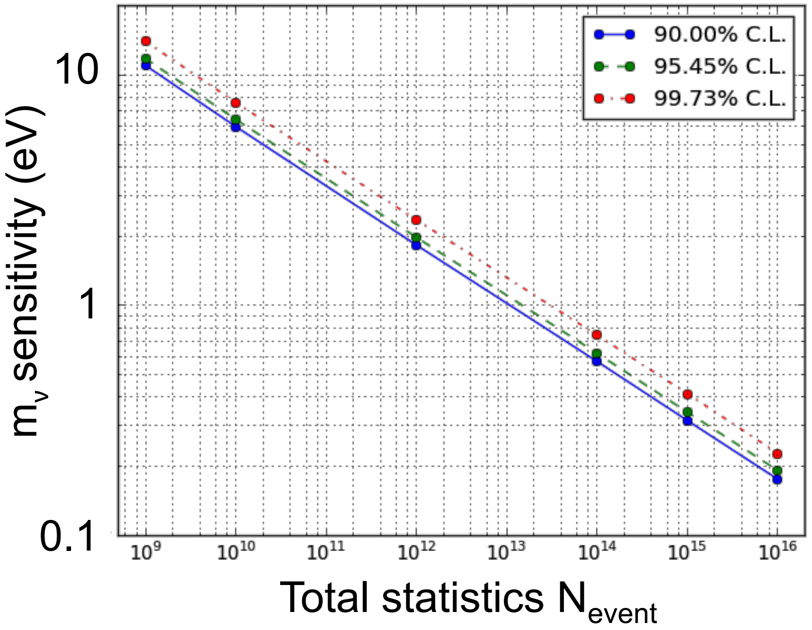



[Gastaldo *et al.*, J. Low Temp. Phys. 176 (2014) 876; Ranitzsch *et al.*, in prep.]

# ECHo : Timeline

- **ECHo-1k** (2015-2018)
  - prove scalability with medium-sized array
  - 1 yr meas. time for $N_{event} \sim 10^{10}$:
    ➜ $m(\nu_e) < 10$ eV

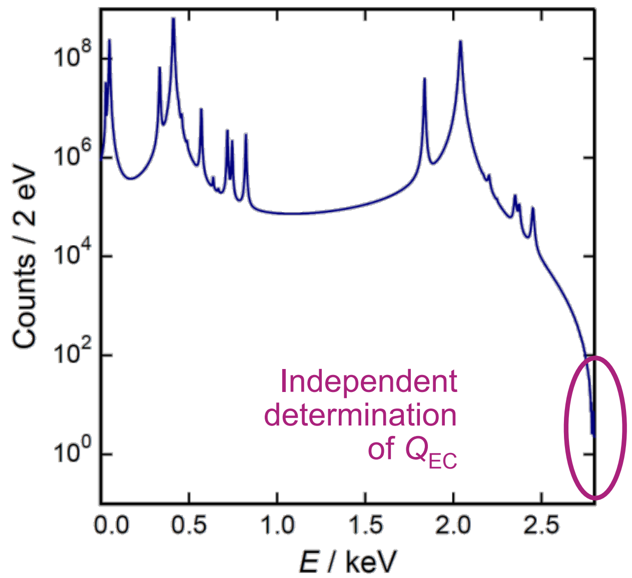
- Starts taking data now
- New limit on $m(\nu_e)$ is approaching




[courtesy L. Gastaldo]

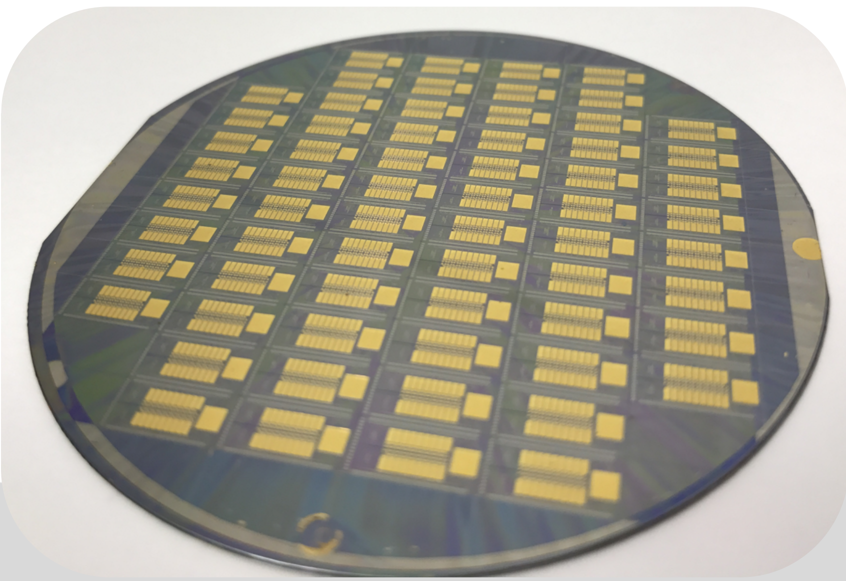
- Next step: **ECHo-10M**
  - large-scale detector array for sub-eV sensitivity
  - sterile neutrino search at eV and keV scale

Impact of higher-order excitations on $^{163}$Ho EC spectrum



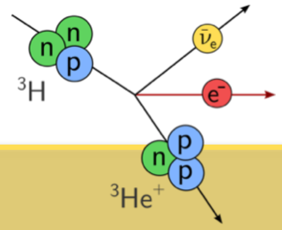

[A. Faessler et al., PRC 91 (2015) 045505, 064302]

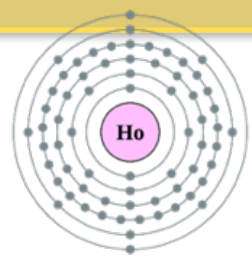
Chip fabrication for multiplexed MMC arrays



# Direct ν-mass determination: status and outlook

current achievements



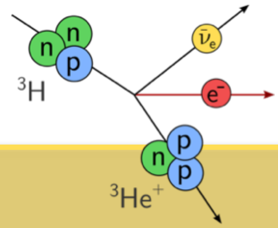

next goals

# Direct ν-mass determination: status and outlook

Full beamline commissioning with $^{83m}Kr$; start of $T_2$ data in 2018

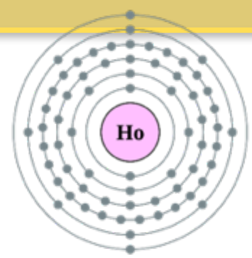
**KATRIN**

Long-term data-taking for full sensitivity **(0.2 eV)**




**current achievements**

**next goals**



# Direct ν-mass determination: status and outlook

Karlsruhe Institute of Technology

**KATRIN**

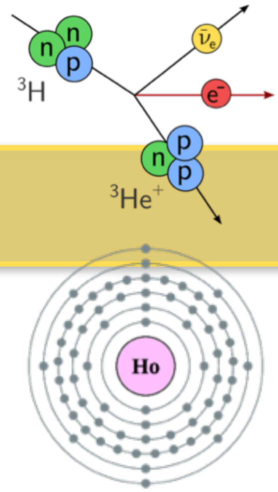
Full beamline commissioning with $^{83m}Kr$; start of $T_2$ data in 2018

Long-term data-taking for full sensitivity **(0.2 eV)**

**Project 8**

CRES proof of principle with $^{83m}Kr$, testing new cell for $T_2$

Develop CRES for **10 → 2 eV,** and towards IH (atomic source)




**current achievements** → **next goals**

# Direct ν-mass determination: status and outlook

| current achievements | | next goals |
| --- | --- | --- |
| Full beamline commissioning with $^{83m}$Kr; start of $T_2$ data in 2018 | **KATRIN** | Long-term data-taking for full sensitivity **(0.2 eV)** |
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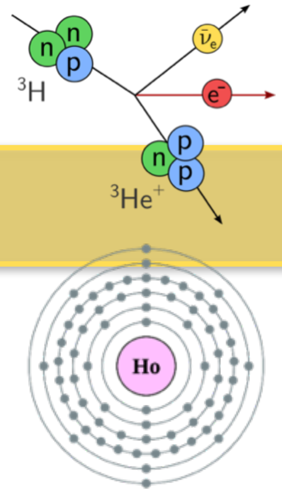
| R&D for atomic source concept, MAC-E + calorimeter | **PTOLEMY** | Devise large-scale experiment to tackle m(ν) and CνB |




**current achievements** → **next goals**

# Direct ν-mass determination: status and outlook

Karlsruhe Institute of Technology

## KATRIN

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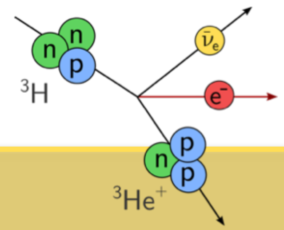
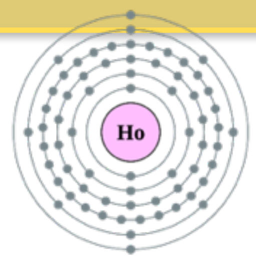



**current achievements** → **next goals**




## ECHo / HOLMES / NuMECS

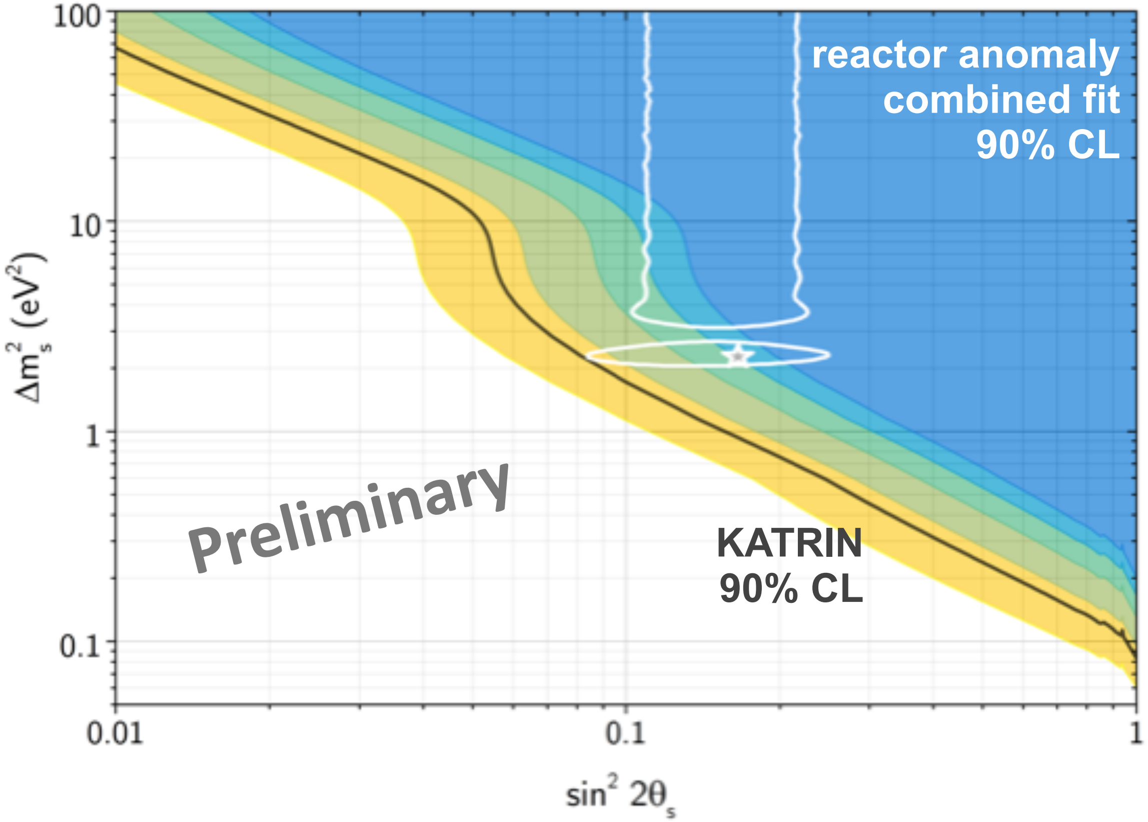
- Advanced detector development (MMC and TES technologies)
- Test of scalable arrays
- High-purity $^{163}Ho$ production and implantation

- Operate medium-size arrays ($\sim 10^{10}$ counts) for **10 eV** sens.
- Prepare large arrays ($\sim 10^{14}$ counts) for **sub-eV** sens.

# Supplementing slides

# Search for eV-scale sterile ν in $^{3}H$ and $^{163}Ho$ expts.

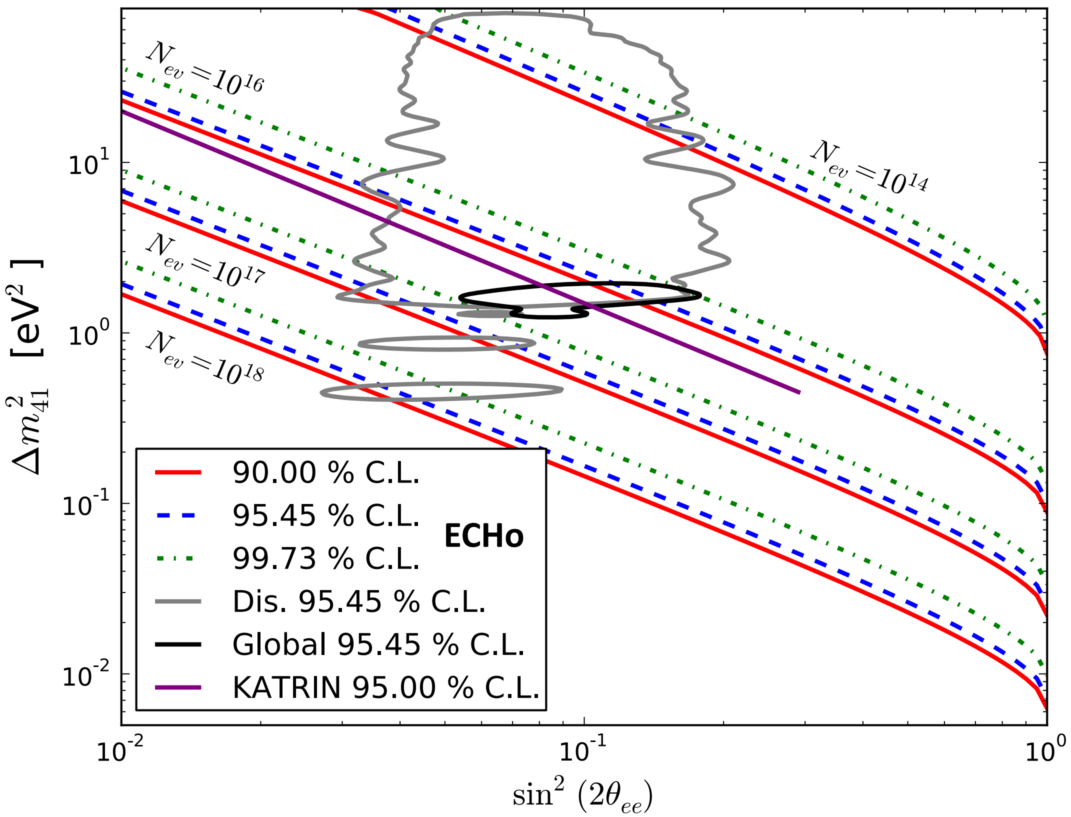
**Tritium: KATRIN**




[M. Kleesiek, PhD thesis (KIT, 2014)]

See also: Formaggio & Barrett, PL B706 (2011) 68;
Sejersen Riis & Hannestad, JCAP02 (2011) 011;
Esmaili & Peres, PR D85 (2012) 117301

**Holmium: ECHo**




[L. Gastaldo, C. Giunti, E. Zavanin, JHEP 06 (2016) 061]

**Sterile ν + non-standard weak interactions (e.g. RH currents):**
O. Ludl & W. Rodejohann, JHEP 06 (2016) 040;
N. Steinbrink, S. Hannestad *et al.*, JCAP 06 (2017) 015

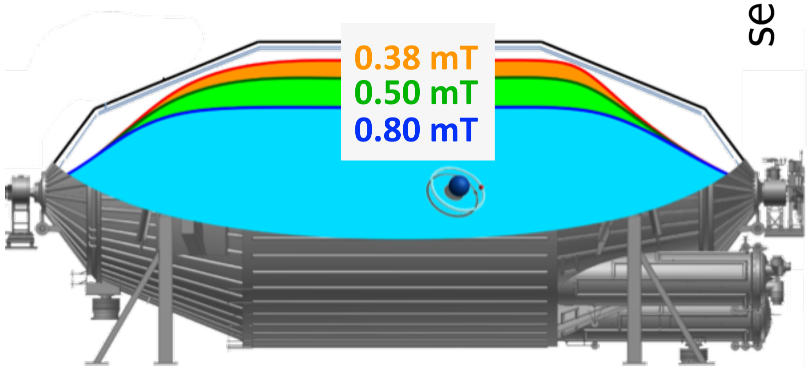
# Sensitivity and background

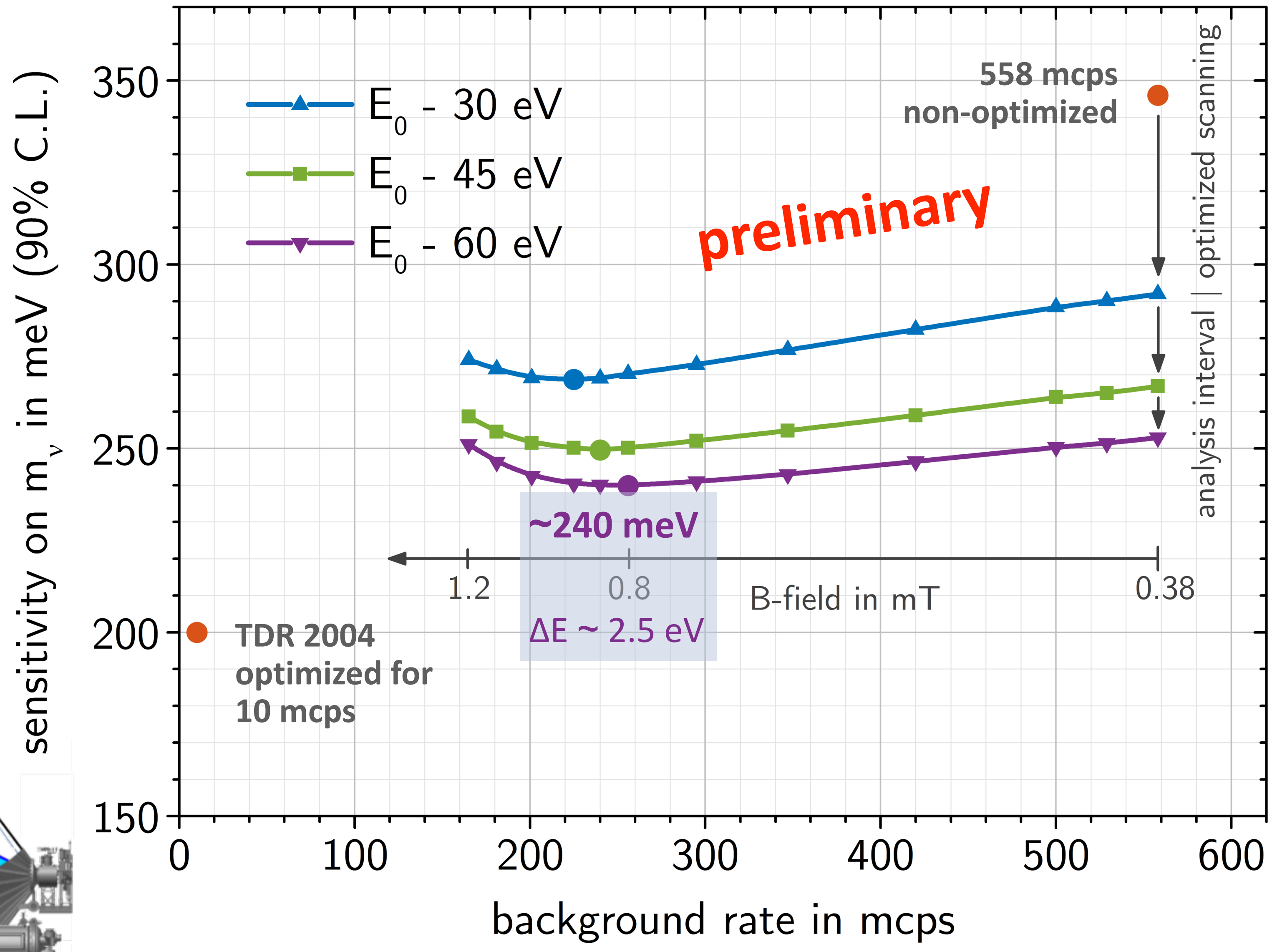
Karlsruhe Institute of Technology

- Further **background reduction measures** under investigation

- In addition: **several mitigation strategies**

- optimized scanning
- energy range of spectral analysis
- flux tube compression by increasing B



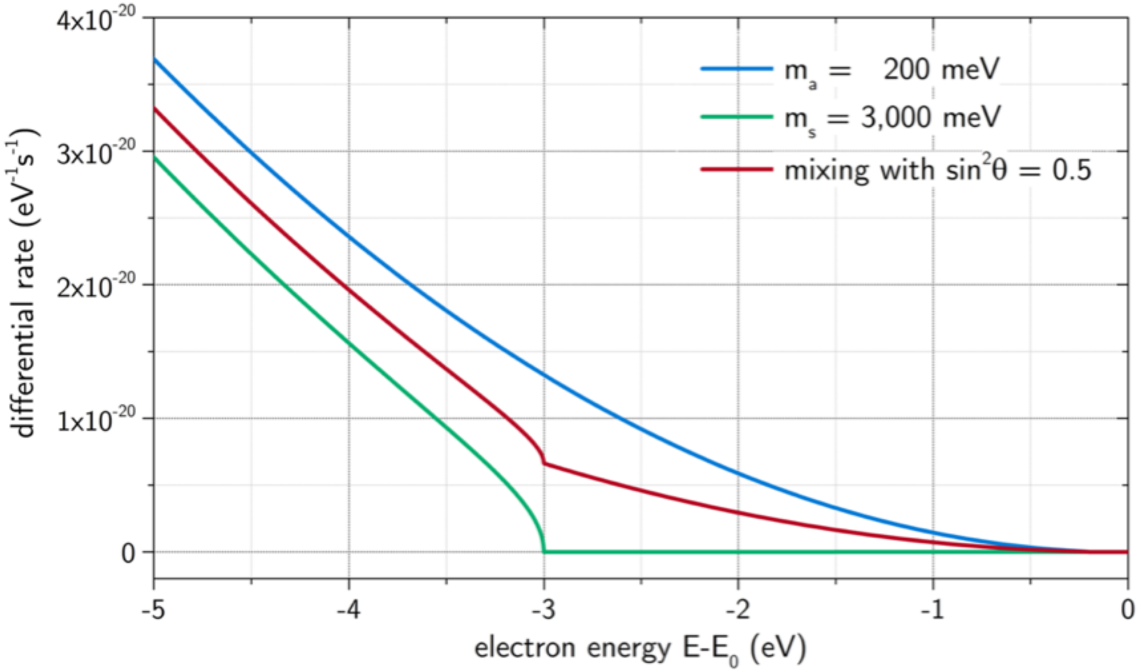
# Imprint of sterile neutrinos on β spectrum

Shape modification below $E_0$ by active $(m_a)^2$ and sterile $(m_s)^2$ neutrinos:

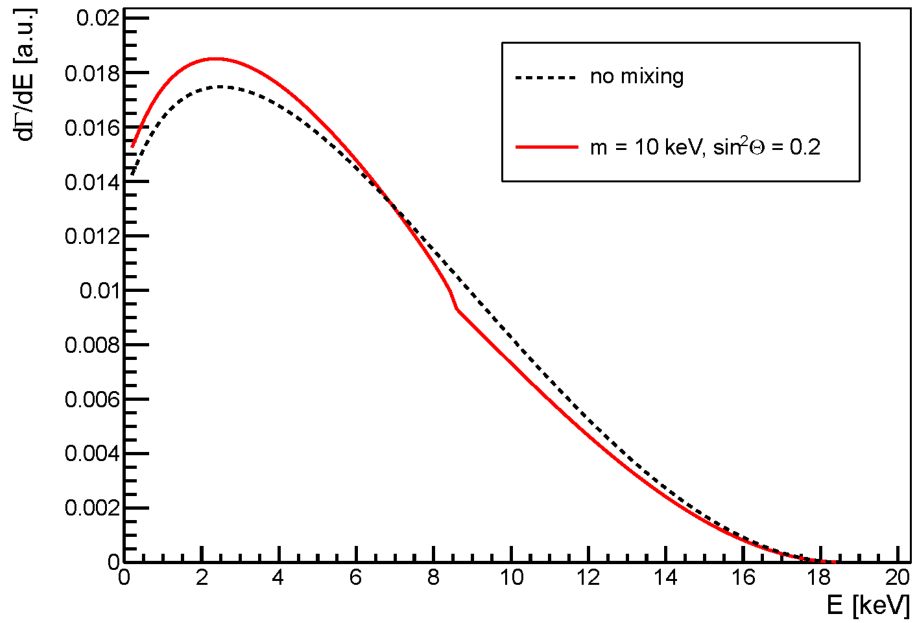
$$\frac{dN}{dE} = \cos^2\theta_s \, \frac{dN}{dE}(m_a^2) + \sin^2\theta_s \, \frac{dN}{dE}(m_s^2)$$

⇒ additional kink in β spectrum at $E = E_0 - m_s$

**light sterile ν, $m_s$ = 3 eV**

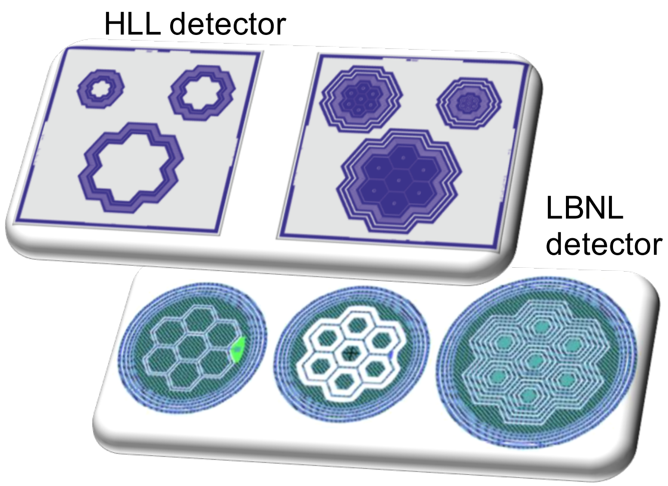



**keV sterile ν, $m_s$ = 10 keV**

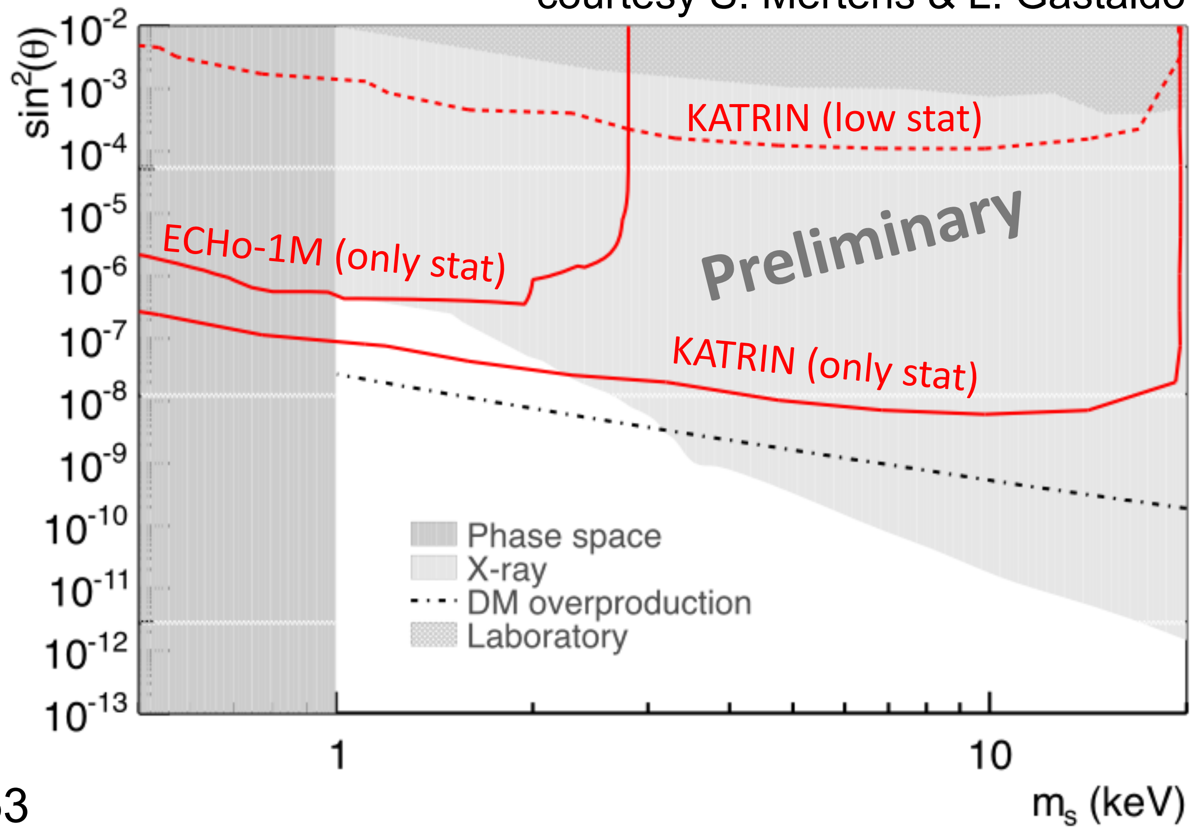


# Search for keV-scale sterile ν with direct mass experiments

- First measurements with KATRIN "baseline" set-up at reduced source strength
- Prototyping and sensitivity studies for upgraded detector system under way
- Sensitivity of holmium experiments restricted by low Q-value (2.8 keV)




courtesy S. Mertens & L. Gastaldo




See also recent results from Troitsk exp.
($m_s$ ~0.1 … 2 keV):
Abdurashitov *et al.*, JETP Lett. 105 (2017) 753

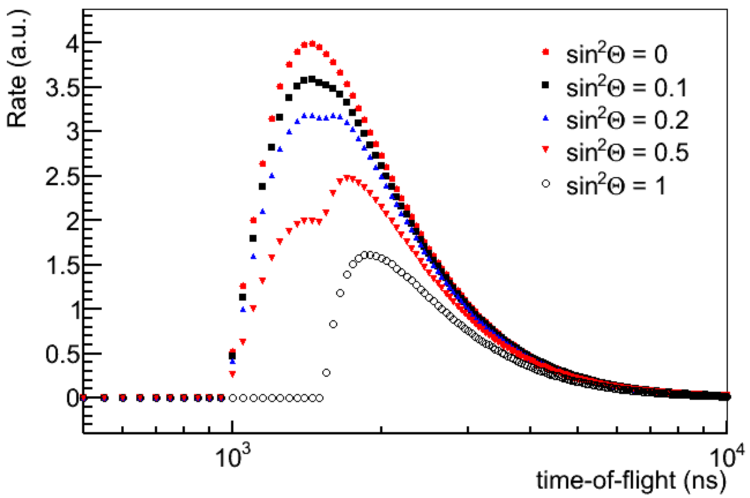
# Search for keV-scale sterile ν with KATRIN

## The challenge:

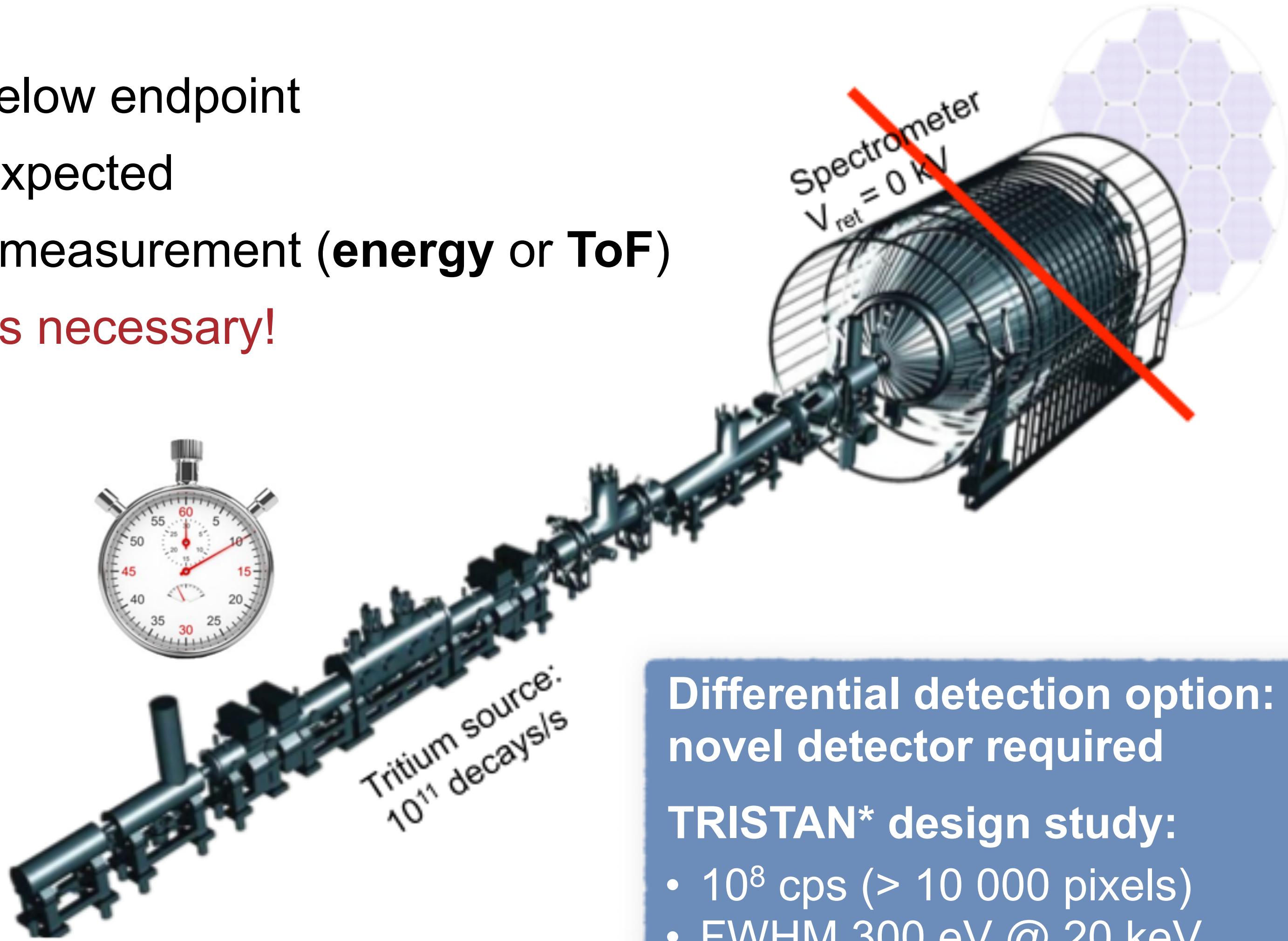
- High count rates at ~few keV below endpoint
- Tiny sterile admixture $\sin^2(\theta_s)$ expected
- Best sensitivity for **differential** measurement (**energy** or **ToF**)

➡ Development of new techniques necessary!

**ToF option:**
**electron tagger required**




[Steinbrink et al. (2013), Robertson et al. (in prep.)]




**Differential detection option:**
**novel detector required**

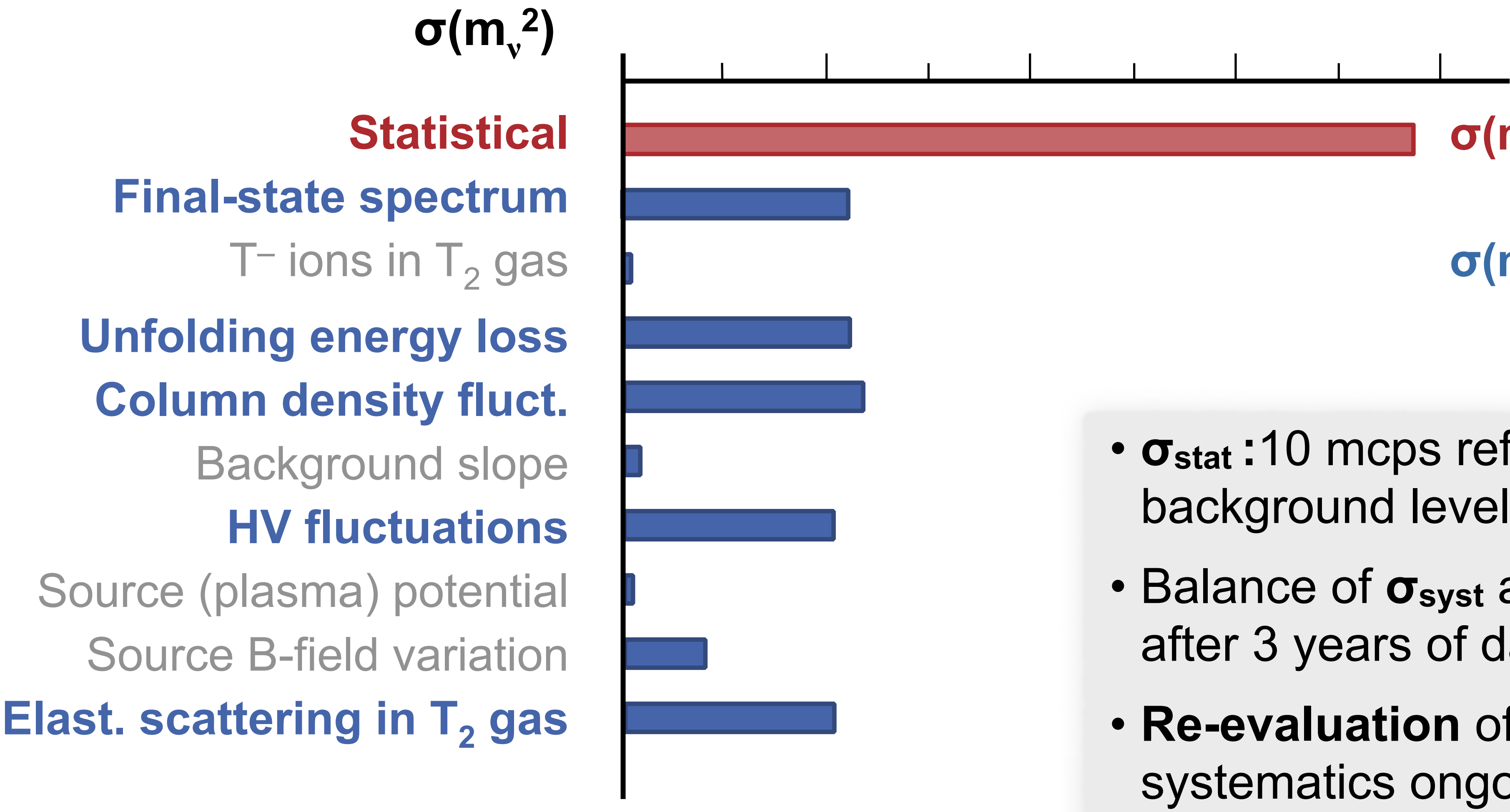
**TRISTAN* design study:**

- $10^8$ cps (> 10 000 pixels)
- FWHM 300 eV @ 20 keV
- > 20 cm diameter

[Mertens et al. (2015)]

*) **TR**itium beta decay **I**nvestigation on **S**terile **T**o **A**ctive **N**eutrino mixing

# KATRIN: Statistical & systematic uncertainties




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

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

- $\boldsymbol{\sigma_{stat}}$ :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 characterisation of components