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MÜNSTER

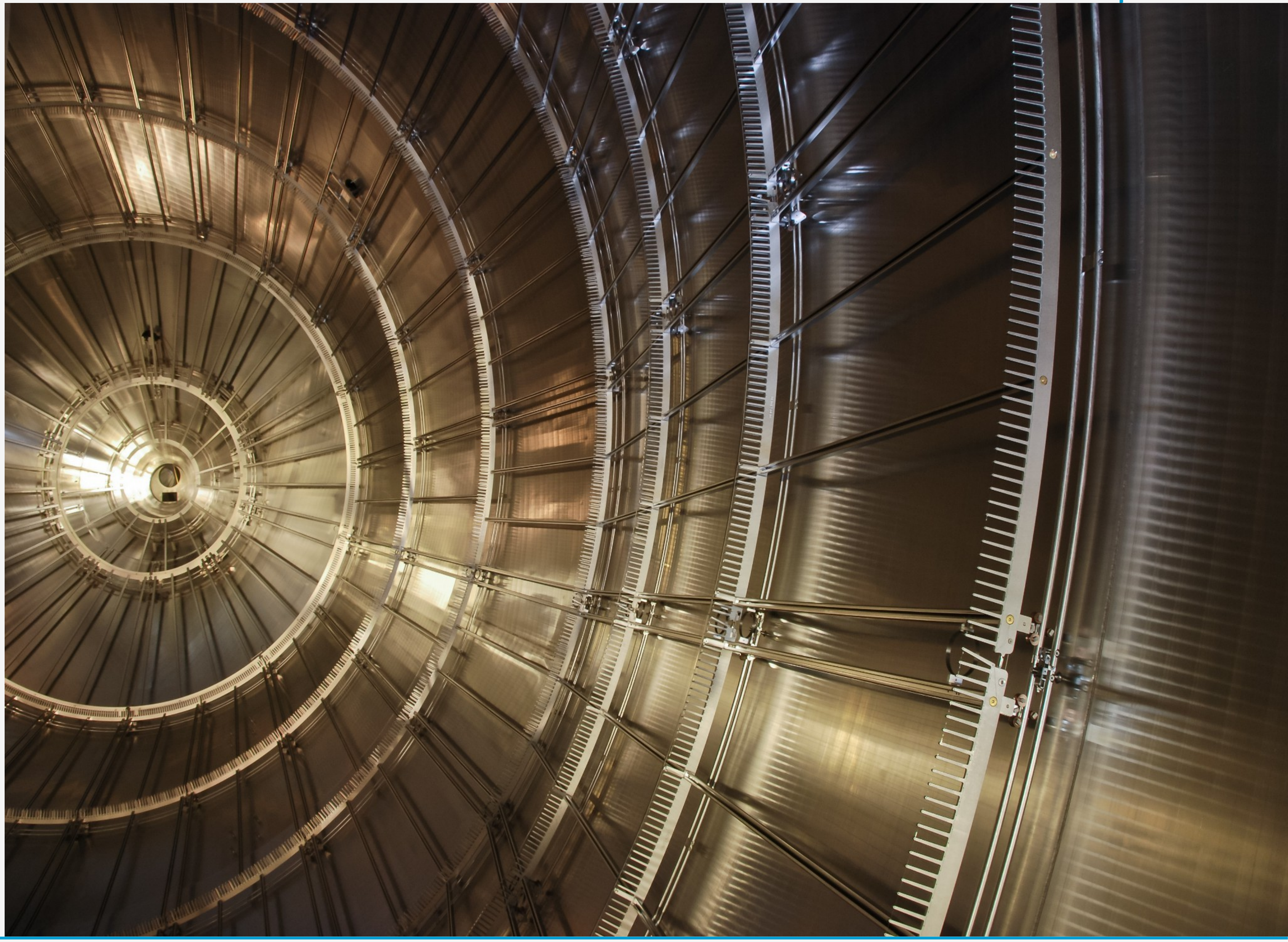
Towards a Direct Measurement of the Neutrino Mass
The KATRIN experiment

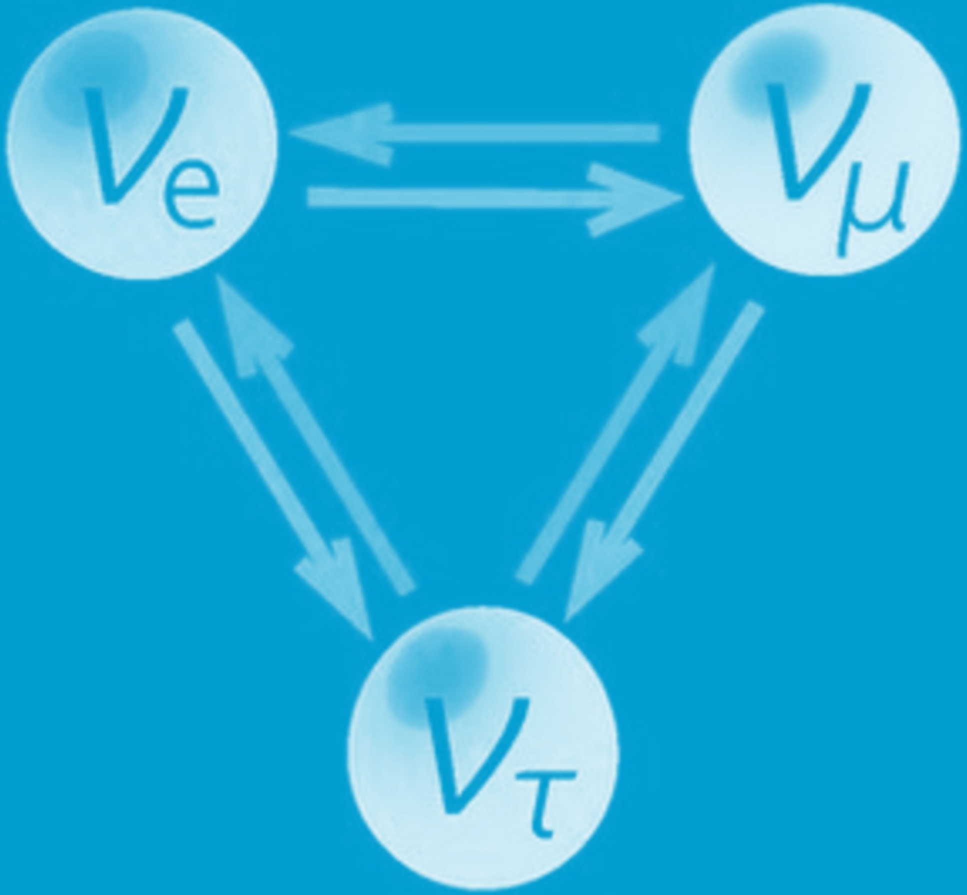
Neutrino Telescopes / Venice / 20.03.2019
Stephan Dyba for the KATRIN collaboration

Institut für Kernphysik
AG Weinheimer

Outline

- Neutrino and mass measurements
- KATRIN experiment
  - Tritium source and Transport
  - Spectrometer and Detector
- Spectrometer Background
- Milestones
- System stability and next steps





Neutrinos and mass measurements

Neutrinos and the Standard Model of Particle Physics

Standard Model of particle physics describes:

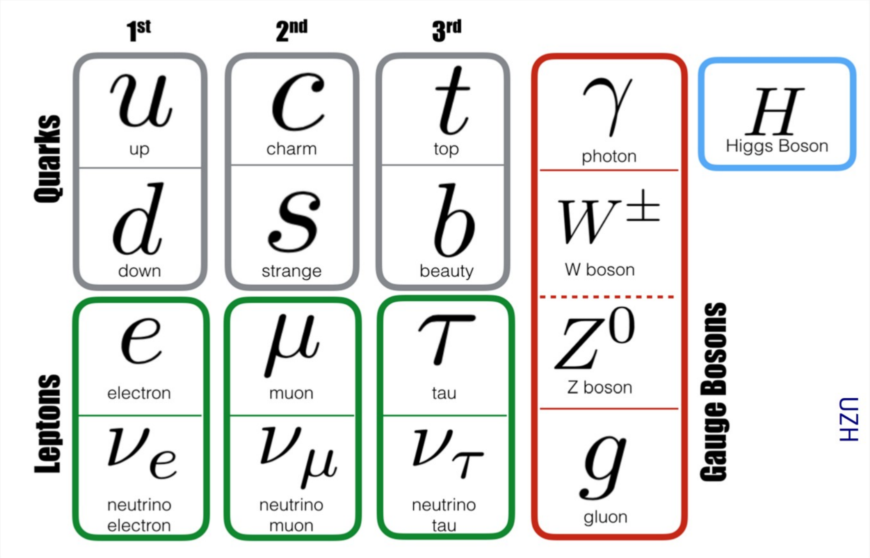
- 12 fermions and 12 bosons as mediators of the interactions
- Includes 3 neutrinos $(\nu_\mathrm{e}, \nu_\mu, \nu_\tau)$
- Neutral particle, spin ½
- Weak interacting

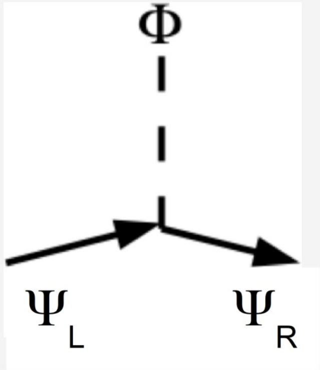
Standard Model mass terms:

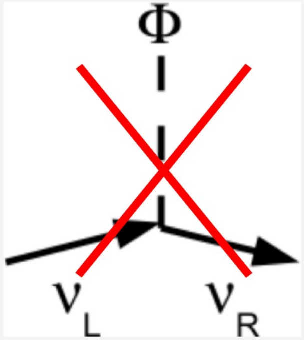
Left and right handed particles couple to Higgs

↯ neutrino only left handed

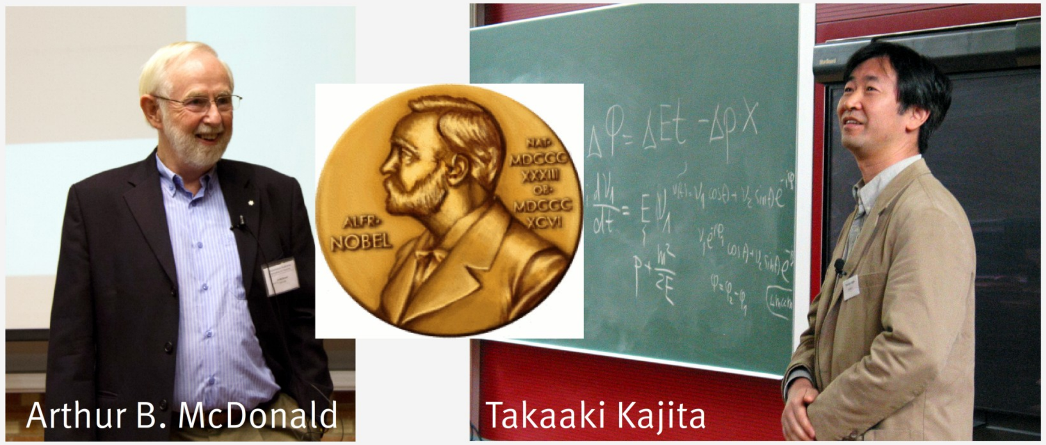
↯ Yukawa coupling to Higgs not existing in SM







Discovery of neutrino oscillation

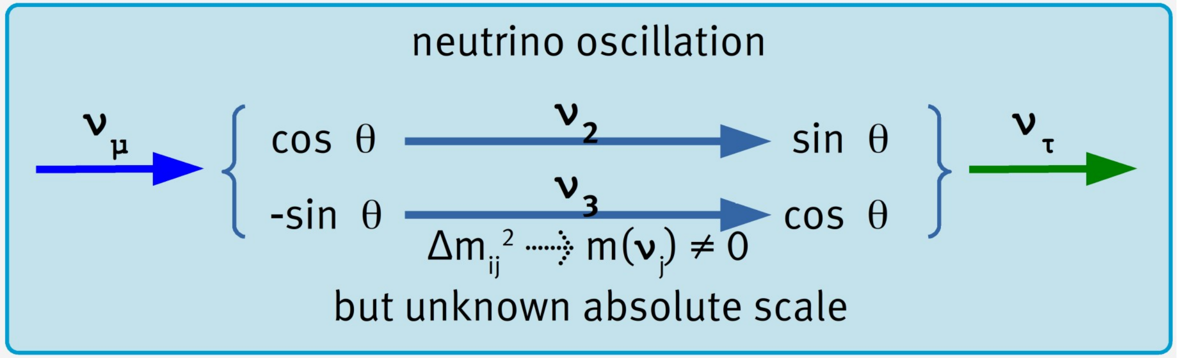


Neutrino oscillation observed:

- Nobel price 2015: T. Kajita and A. B. McDonald
- Neutrinos are massive $\dashrightarrow m(\nu) \neq 0$
- Flavor eigenstates ≠ mass eigenstates
- Connected by unitary mixing matrix $\dashrightarrow \begin{pmatrix} \nu_\mathrm{e} \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_\mathrm{PNMS} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$

Evidence for oscillations found in experiments

- **Atmospheric**
(Kamiokande, Super-Kamiokande, IceCube, ANTARES)
- **Accelerator**
(K2K, T2K, MINOS, OPERA, MiniBoone)
- **Solar**
(Homestake, Gallex, Sage, Super-Kamiokande, SNO, Borexino)
- **Reactor**
(KamLAND, CHOOZ, Daya Bay, Double CHOOZ, RENO)



neutrino oscillation

ν_μ

cos θ $\xrightarrow{\nu_2}$ sin θ

-sin θ $\xrightarrow{\nu_3}$ cos θ

ν_τ

$\Delta m_{ij}^2 \dashrightarrow m(\nu_j) \neq 0$

but unknown absolute scale

Determine mass property of neutrino

From oscillation experiments:

- Three mixing angles: θ_{23}, θ_{12}, θ_{13}
- Two mass differences: $|\Delta m^2_{13}|$, Δm^2_{12}

↯ cannot measurement absolute value

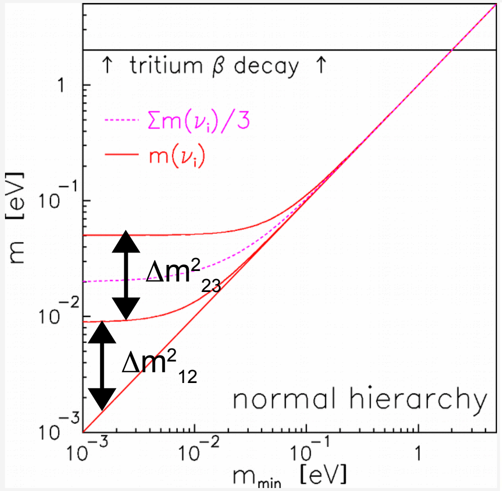
Need dedicated experiments:

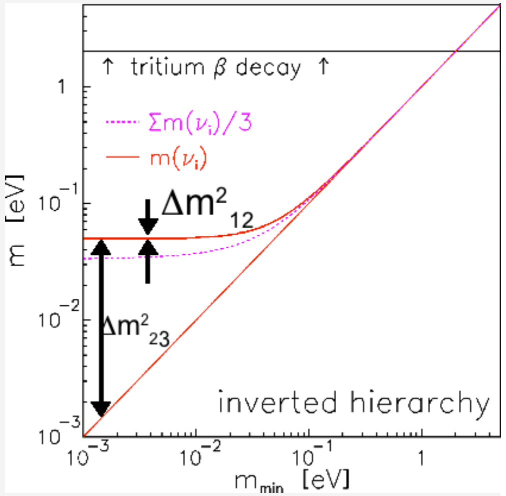
- Measure mass scale
- Neutrino mass degenerated?

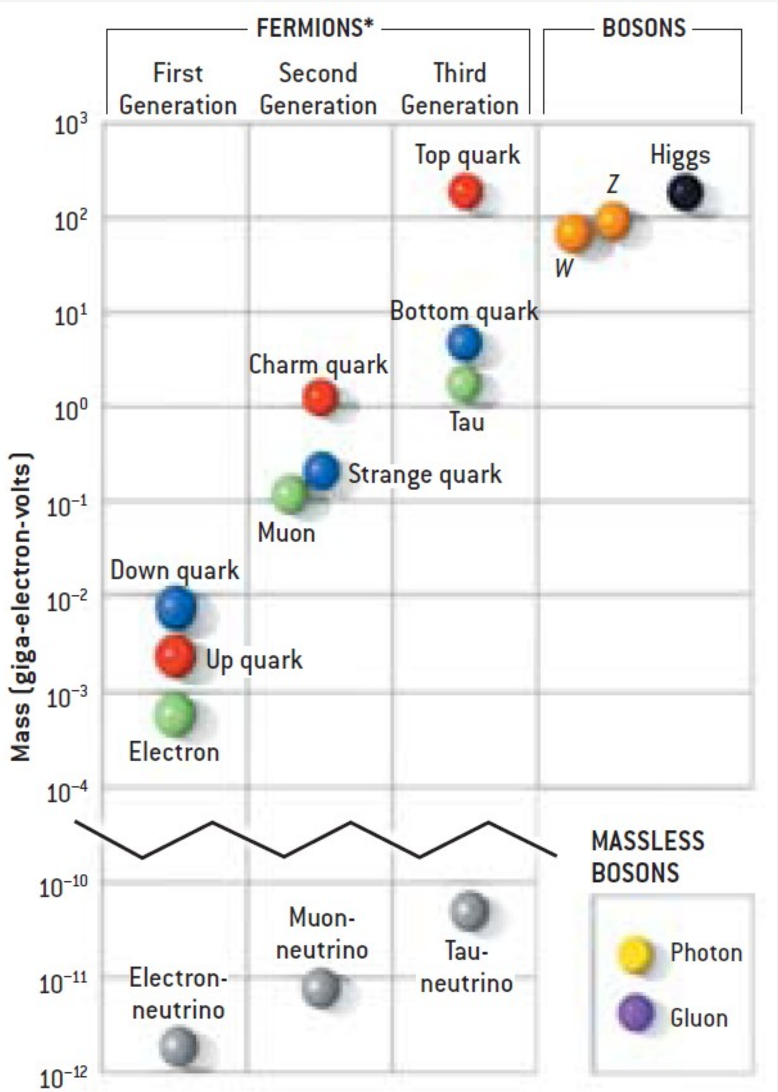
⇢ structure formation / e.g. seesaw type II

- Hierarchical ordered masses?

⇢ smallness of masses / e.g. seesaw type I



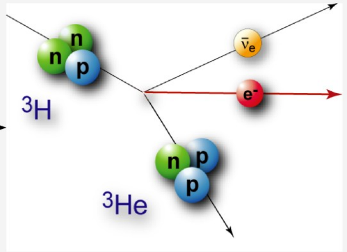




Approaches to measure the neutrino mass

Neutrino Mass Measurements

model independent, kinematics



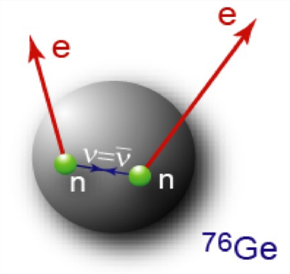
β-decay: absolute ν-mass

status: $m_\nu < 2.3$ eV

potential: $m_\nu \approx 0.2$ eV

e.g.: KATRIN, Project-8, ECHO HOLMES, NuMECS

model-dependent (CP-phases)



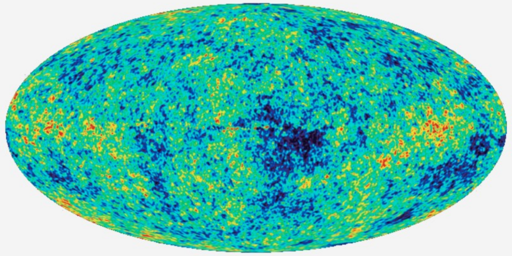
0νββ-decay: eff. Majorana mass

status: $m_{\beta\beta} < 0.31$ eV

potential: $m_{\beta\beta} \approx 20\text{-}50$ meV

e.g.: GERDA, CUORE, EXO, SNO+, Majorana, Nemo 3, COBRA, KamLAND-Zen

model dependent, analysis of CMB and structure formation data



cosmology: ν hot dark matter Ω_ν

status: $\Sigma m_\nu < 0.23$ eV

(*Planck Collaboration, A&A 594 (2016) A13*)

possible signal: $\Sigma m_\nu = 0.11 \pm 0.03$eV

(*Emami et al., arXiv:1711.05210*)

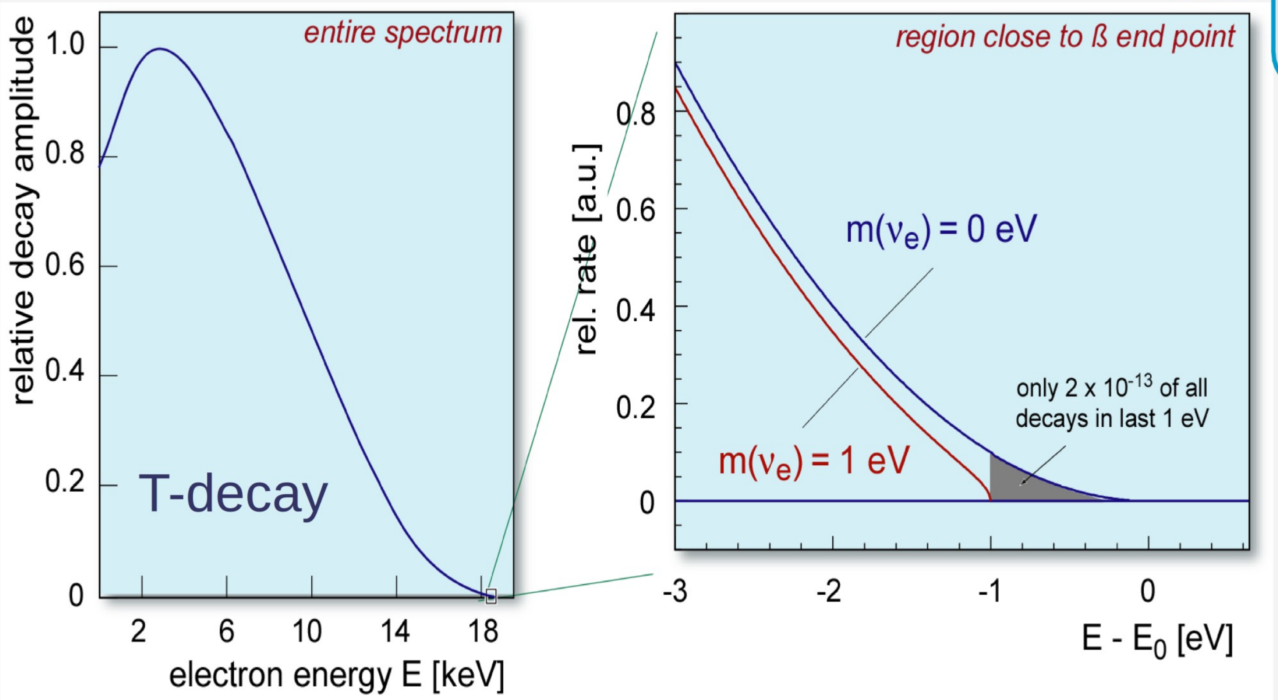
Direct determination of neutrino mass

$$\frac{d\Gamma}{dE}=C\,p(E+m_e)(E_0-E)\sqrt{(E_o-E)^2-m_{\nu_e}^2}\,F(Z+1,E)\,\Theta(E_0-E-m_{\nu_e})\,S(E)$$

$$C=\frac{G_F^2}{2\pi^3}\cos^2\theta_C|M|^2$$

$$m_{\nu_e}=\sqrt{\sum_{i=1}^{3}|U_{ei}|^2 m_i^2}$$

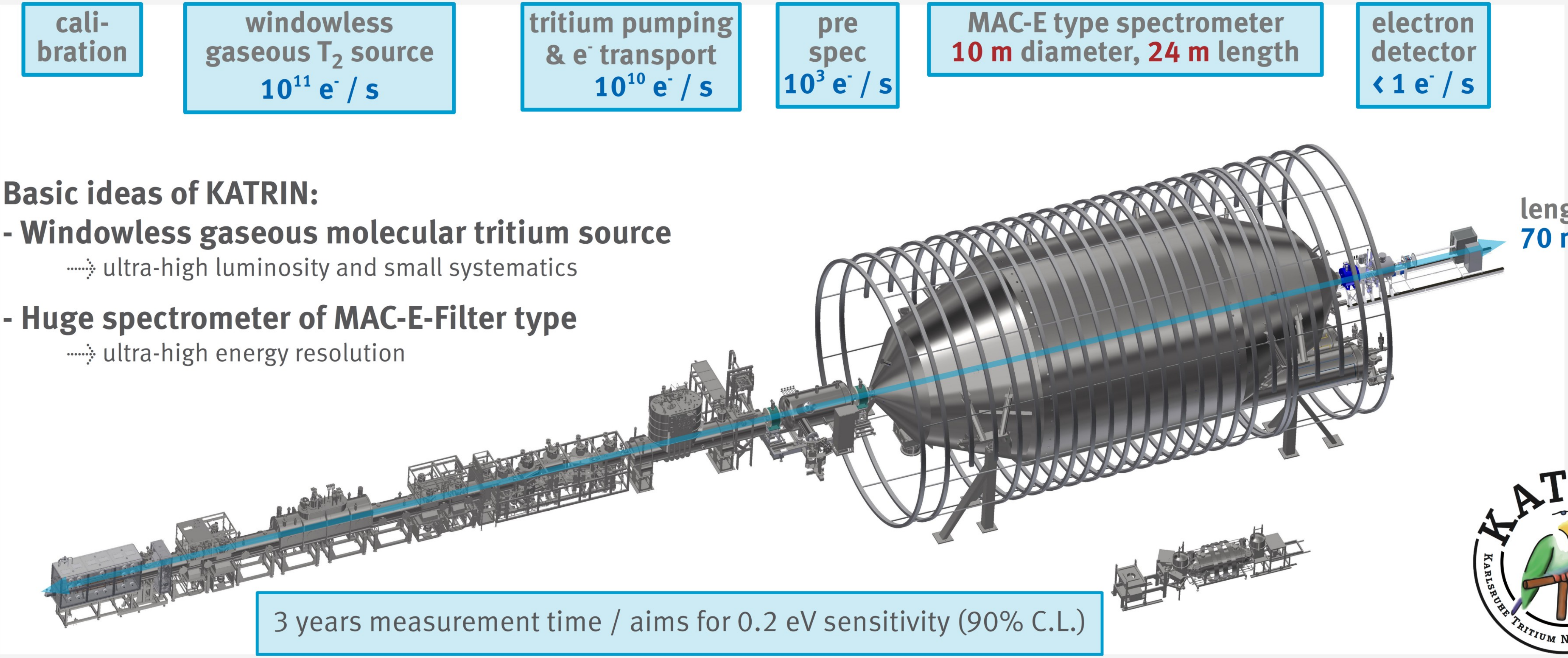
(modified by final state distribution, recoil corrections, radiative corrections, ...)



Need:
low endpoint energy ⇢ Tritium ^{3}H
very high energy resolution &
very high luminosity & ⇢ MAC-E-Filter
very low background


KATRIN
Karlsruhe Tritium Neutrino Experiment
T_2

The Karlsruhe Tritium Neutrino experiment (KATRIN)



cali-
bration

windowless
gaseous T_2 source
10^{11} e⁻ / s

tritium pumping
& e⁻ transport
10^{10} e⁻ / s

pre
spec
10^3 e⁻ / s

MAC-E type spectrometer
10 m diameter, 24 m length

electron
detector
< 1 e⁻ / s

Basic ideas of KATRIN:

- Windowless gaseous molecular tritium source

⇢ ultra-high luminosity and small systematics

- Huge spectrometer of MAC-E-Filter type

⇢ ultra-high energy resolution

length
70 m

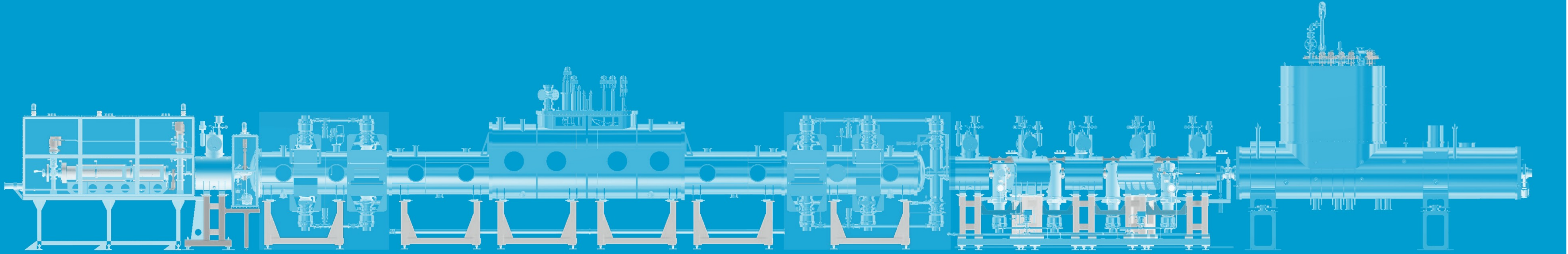
3 years measurement time / aims for 0.2 eV sensitivity (90% C.L.)

The KATRIN Collaboration

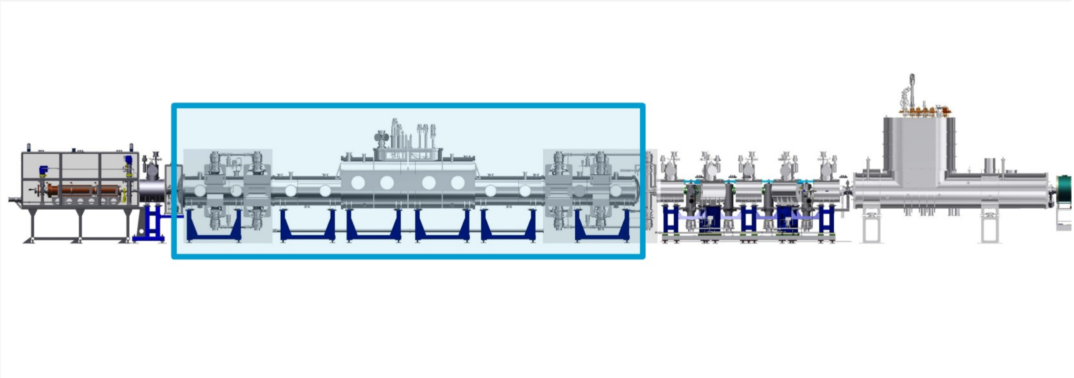
KATRIN
Karlsruhe Tritium Neutrino Experiment

The international KATRIN Collaboration

Karlsruhe Institute of Technology
WWU MÜNSTER
CENPA
cea
TUM
univer sität mainz
THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL
BERKELEY LAB
Max-Planck-Institut für Kernphysik
Max-Planck-Institut für Physik
BERGISCHE UNIVERSITÄT WUPPERTAL
universitätbonn
CASE WESTERN RESERVE UNIVERSITY EST. 1826
CARNEGIE MELLON UNIVERSITY
HUMBOLDT-UNIVERSITÄT ZU BERLIN

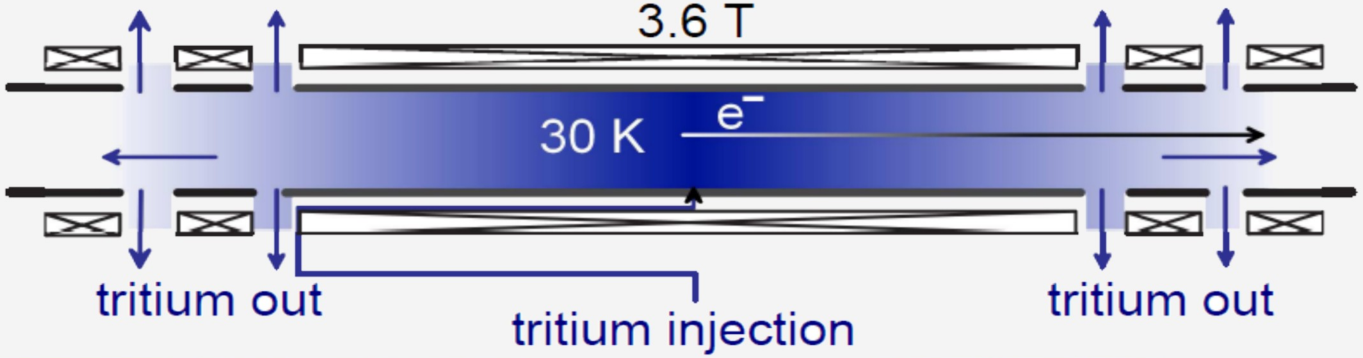


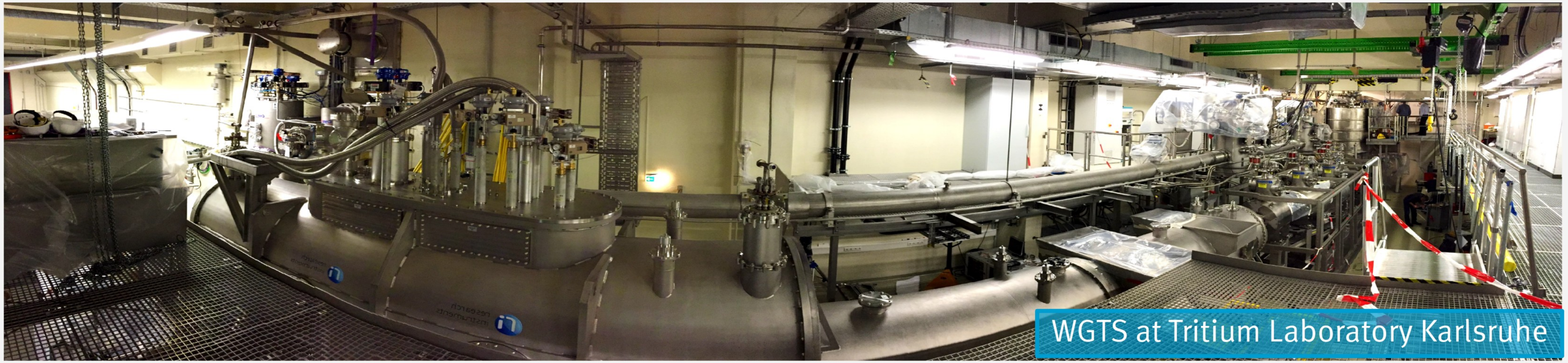
Beamline: Tritium source and Transport section



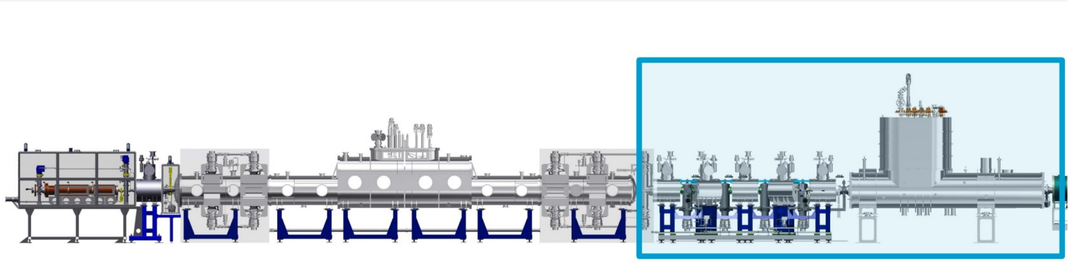
Windowless gaseous tritium source

beam tube	Ø = 9 cm , L = 10 m
guiding field	3.6 T
temperature	T = 30 K ± 30 mK
T_2 flow rate	$5{\cdot}10^{19}$ molecules/s (40 g of T_2 / day)
T_2 purity	95% ± 0.1 %
T_2 inlet pressure	10^{-3} mbar ± 0.1 %
column density	$5{\cdot}10^{17}$ T_2/cm^2
luminosity	$1.7{\cdot}10^{11}$ Bq

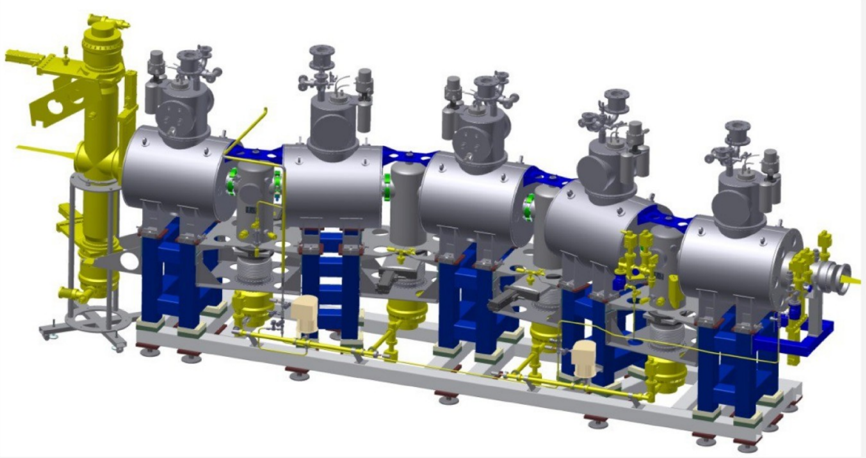


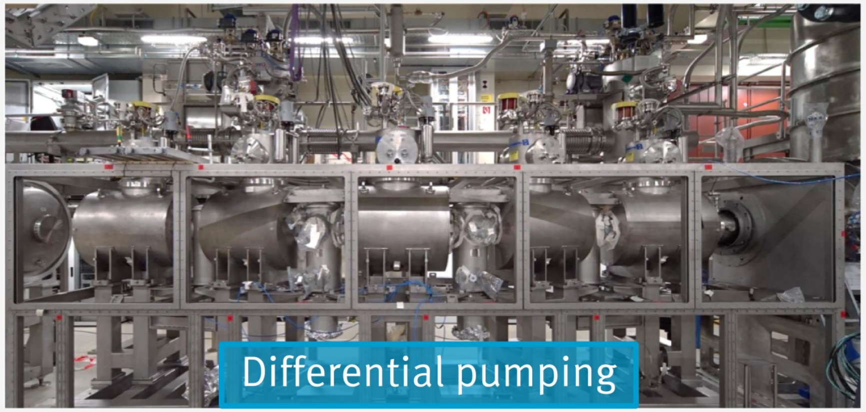


WGTS at Tritium Laboratory Karlsruhe



Tritium suppression by differential and cryo pumping




Differential pumping

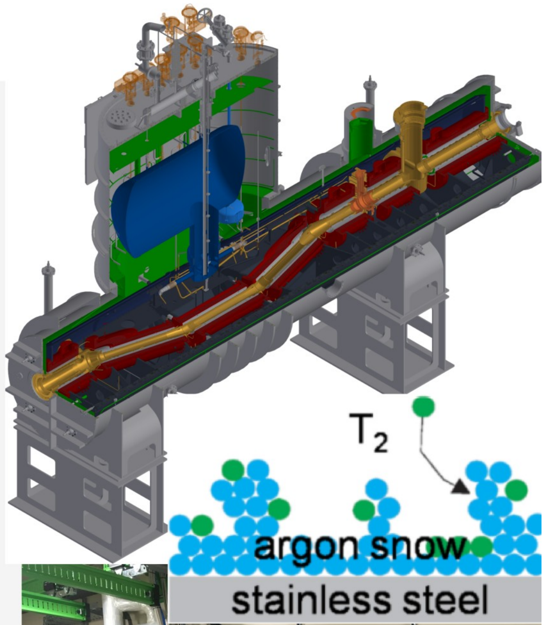
Differential pumping section

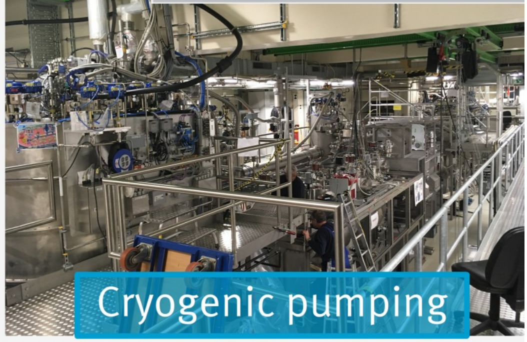
- active pumping: 4 TMPs
- Tritium retention: 10^5
- magnetic field: 5.6 T
- Ion monitoring and ion manipulation by dipole and monopole electrodes inside

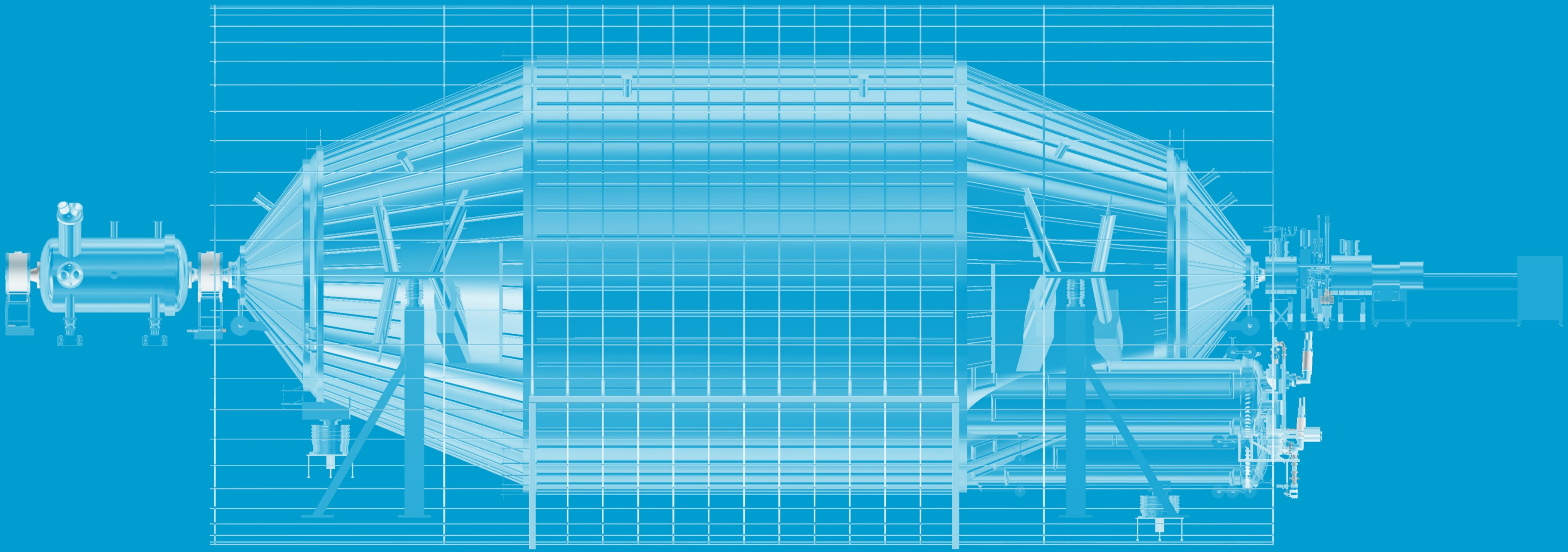
Cryogenic pumping section

- based on by cryo-sorption at Ar snow at 3-4 K
- Tritium retention: $>10^7$
- magnetic field: 5.6 T

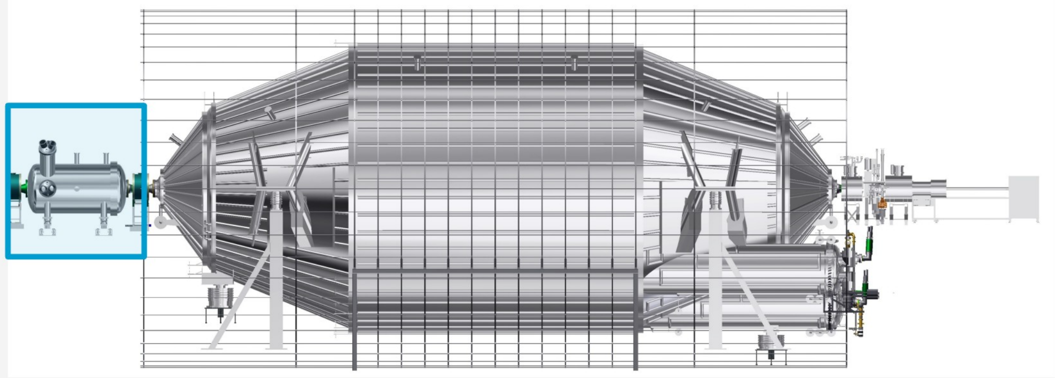
Retention by 14 orders of magnitude



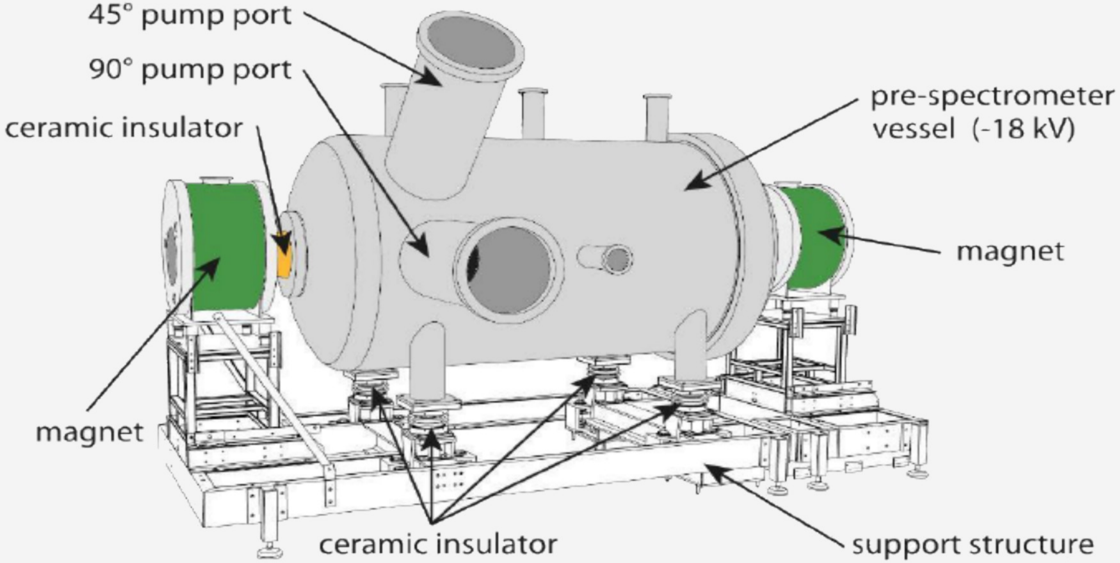

Cryogenic pumping



Beamline: Spectrometer and Detector section



Pre spectrometer



Pre-filter with a fixed potential: E = 18.3 keV

Transmission of high energy electrons only

⇢ reduction from 10^{10} to 10^{3} e^{-}/s
⇢ reduction of background due to scattering in the main spectrometer

Testing ground for many systematical effects and background sources, e.g.:

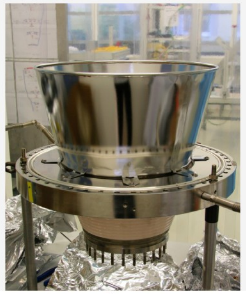
Removal of Penning traps
(special electrode shapes)

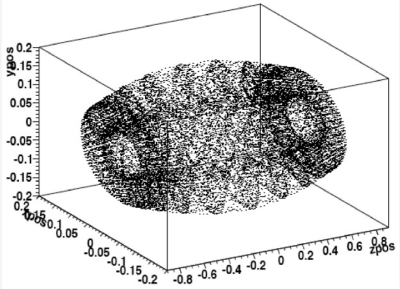
Compensation of high frequency HV noise
(triode shunt circuit)

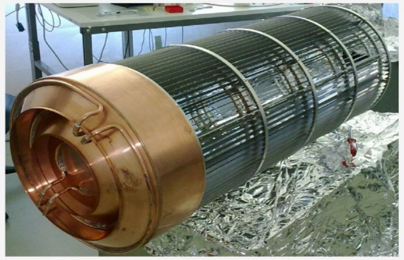
Removal of trapped particles
(dipole mode, HF excitation)

Removal of Radon induced background
(LN2 baffle)

Remaining background ≈ **20 mHz**

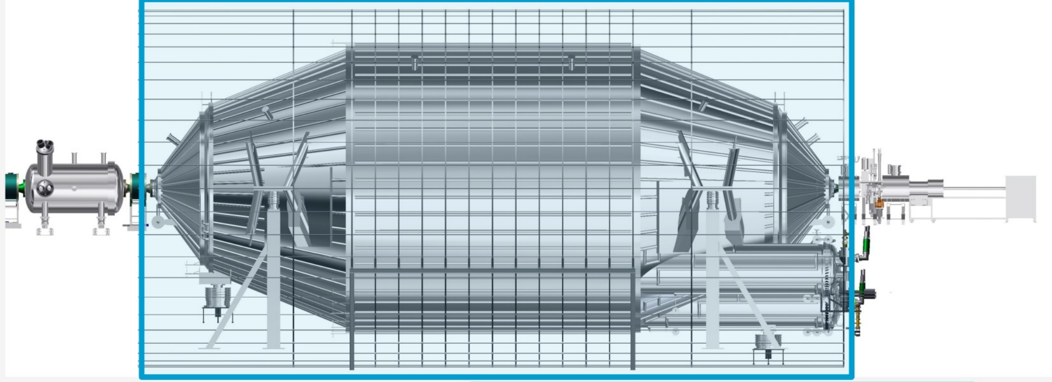






Main spectrometer

- 18.6 kV retardation voltage, $\sigma < 60$ meV
- 0.93 eV resolution
- pressure $< 10^{-11}$ mbar
- Air coils for earth magnetic field compensation
- Double layer wire electrode for background reduction and field shaping



LN$_2$ baffles in pump ports for radon trapping

Huge spectrometer:
High energy resolution & acceptence

Air coil system:
Background suppression & B field shaping

Inner electrode system:
Background suppression & potential shaping

Energy filtering with a MAC-E filter

Magnetic adiabatic collimation with electrostatic filter (MAC-E)

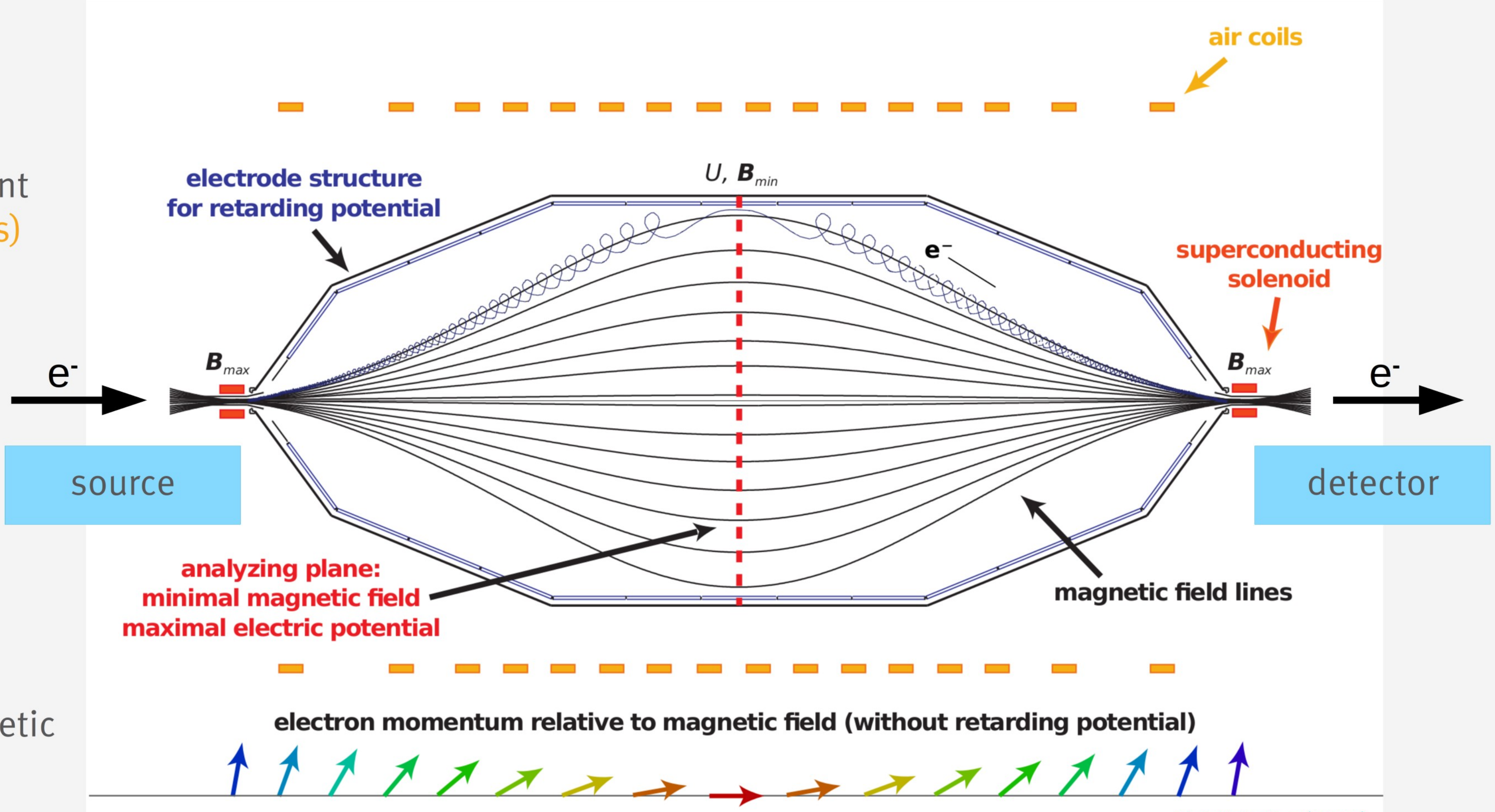
- Adiabatic collimation of electron momentum by magnetic field gradient (superconducting selenoid / air coils)

$$\mu = \frac{E_\perp}{B} = \text{const.}$$

- Energy filtering by applying electric potential (electrode structure)

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

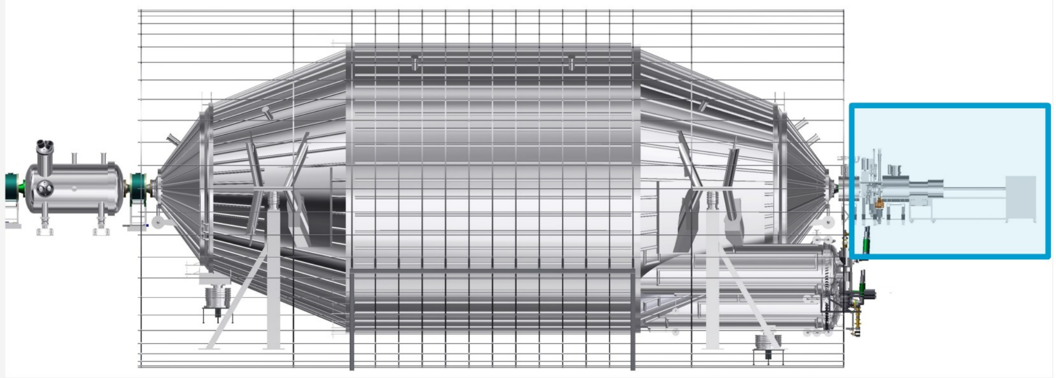
- Analyzing plane defined by maximal electric potential and minimal magnetic field

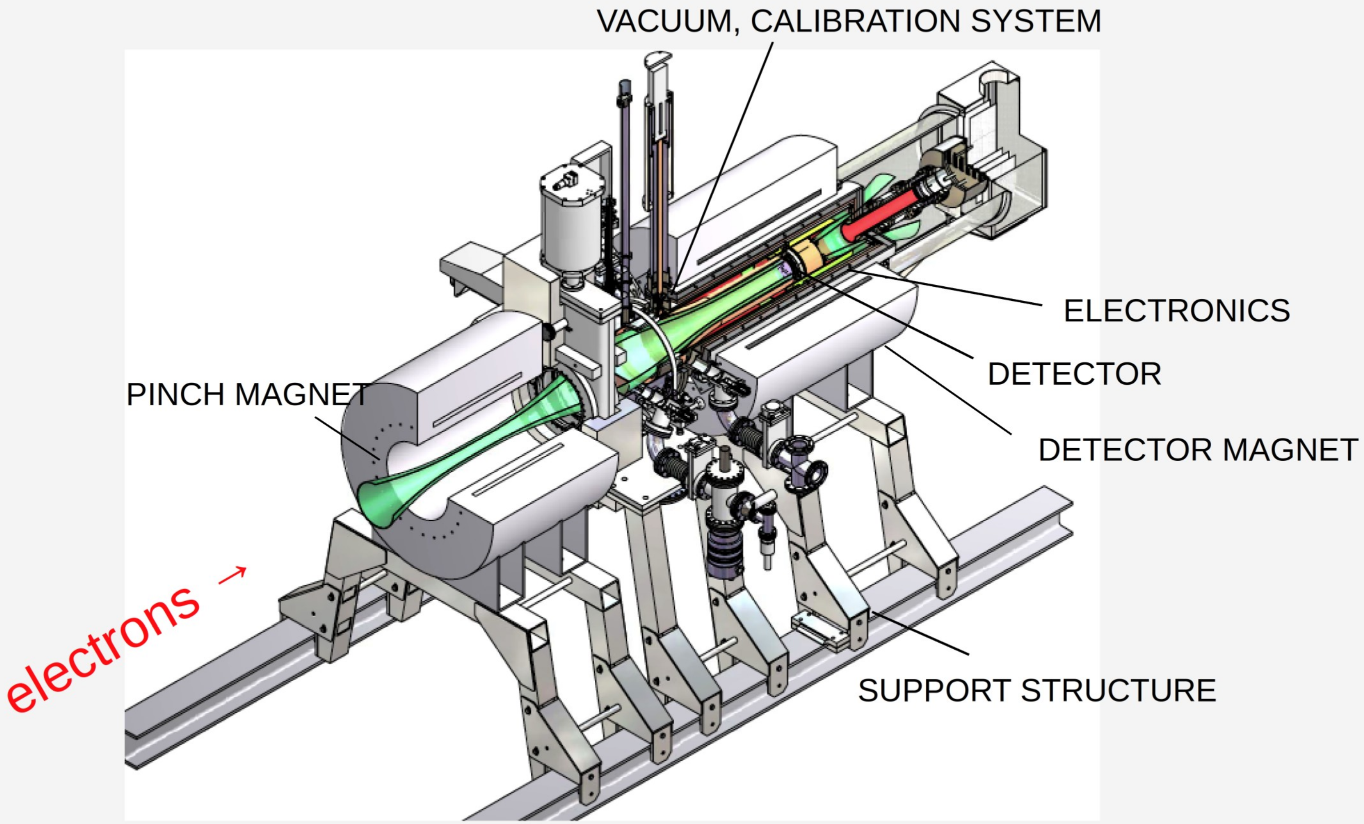


PhD Valerius (2009)

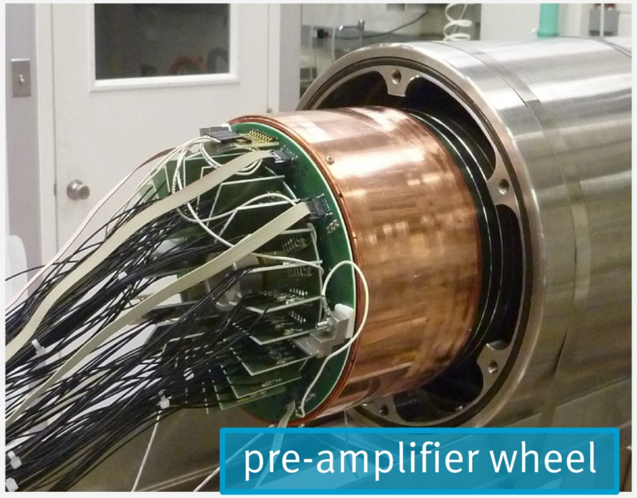
Focal Plane Detector

- segmented Si-PIN diode:
  90 mm Ø, 148 pixels, 50 nm dead layer
- energy resolution ≈ 1 keV
- pinch and detector magnets up to 6 T
- post acceleration (10kV)
- active veto shield

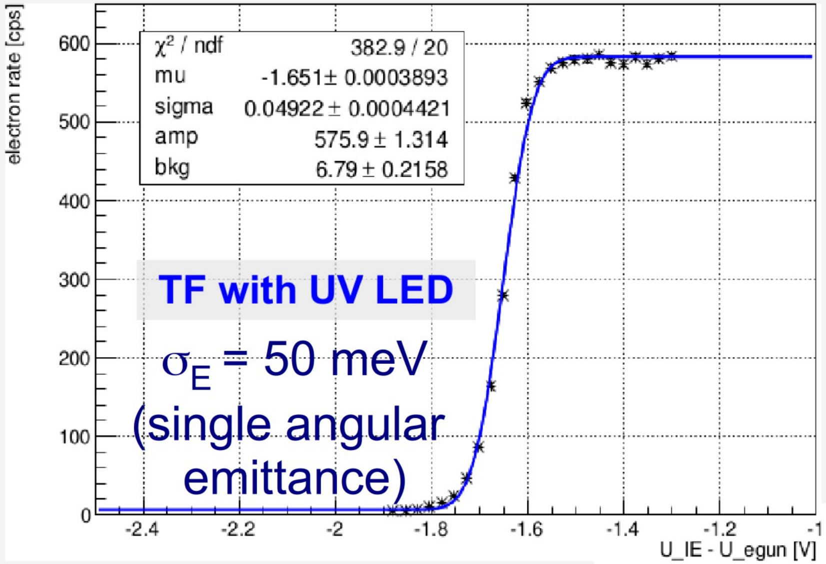





segmented Si-PIN wafer


pre-amplifier wheel

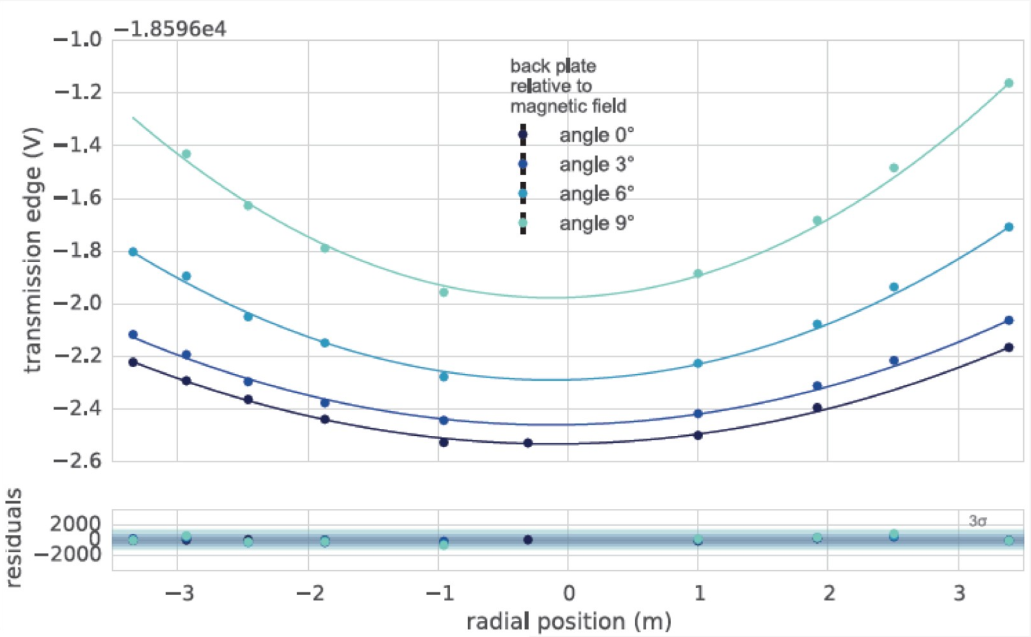
Characterizing the Main Spectrometer

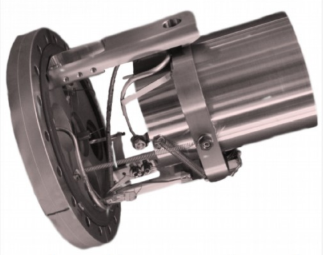


TF with UV LED

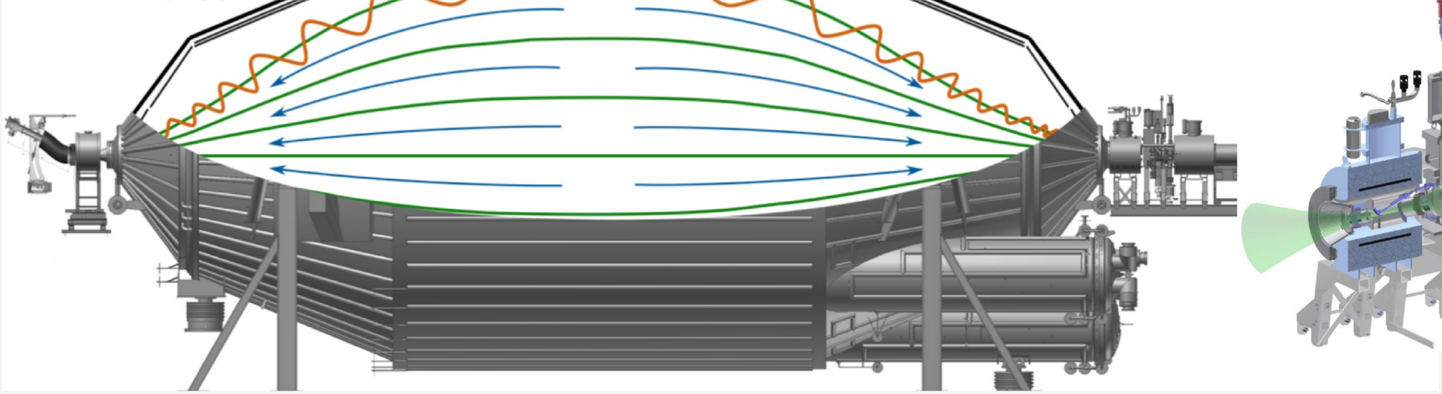
σ_E = 50 meV (single angular emittance)

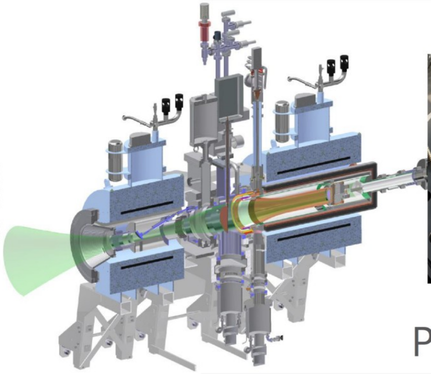
double layer wire electrode

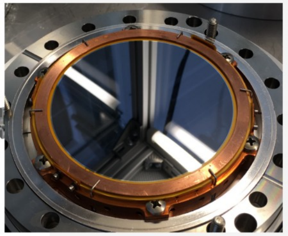




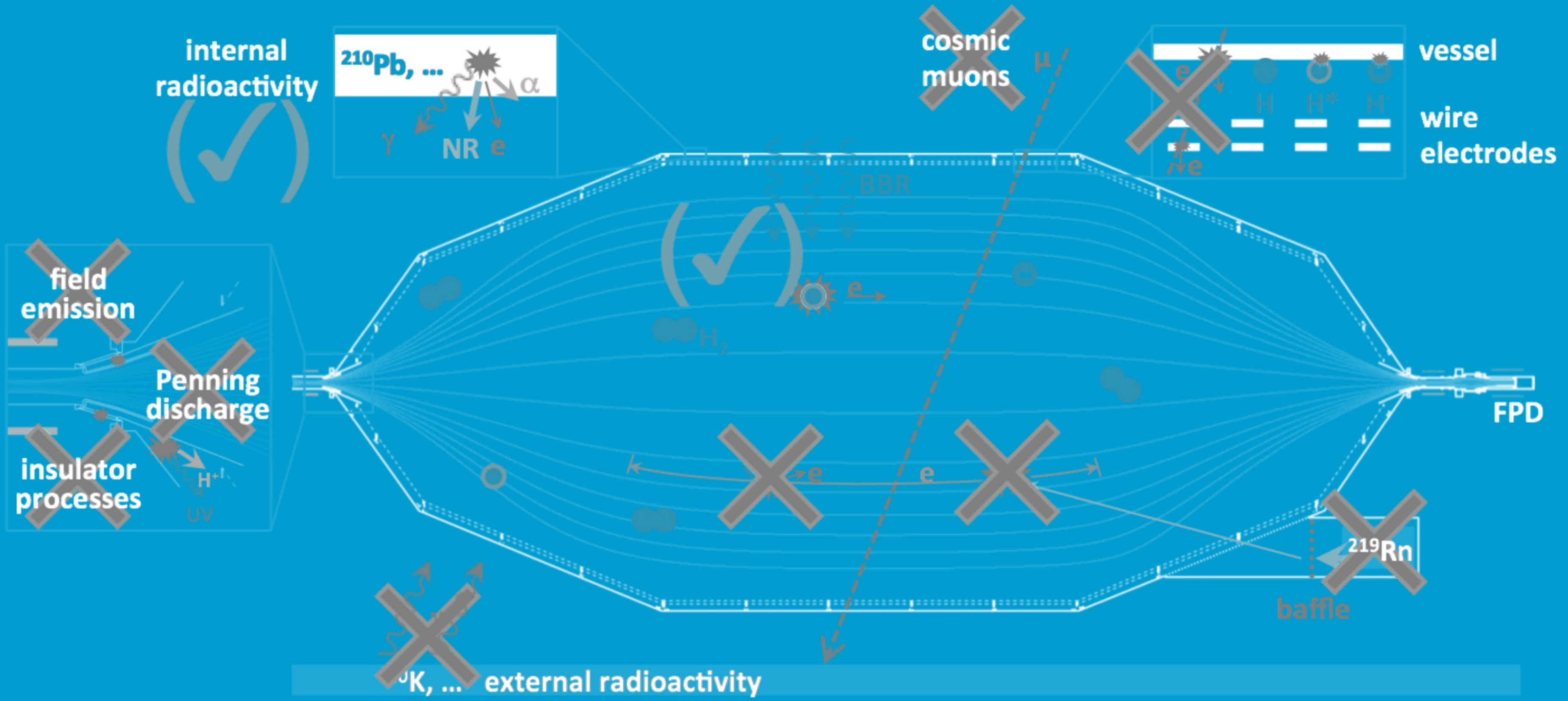
Angular-selective pulsed Photo-electron source





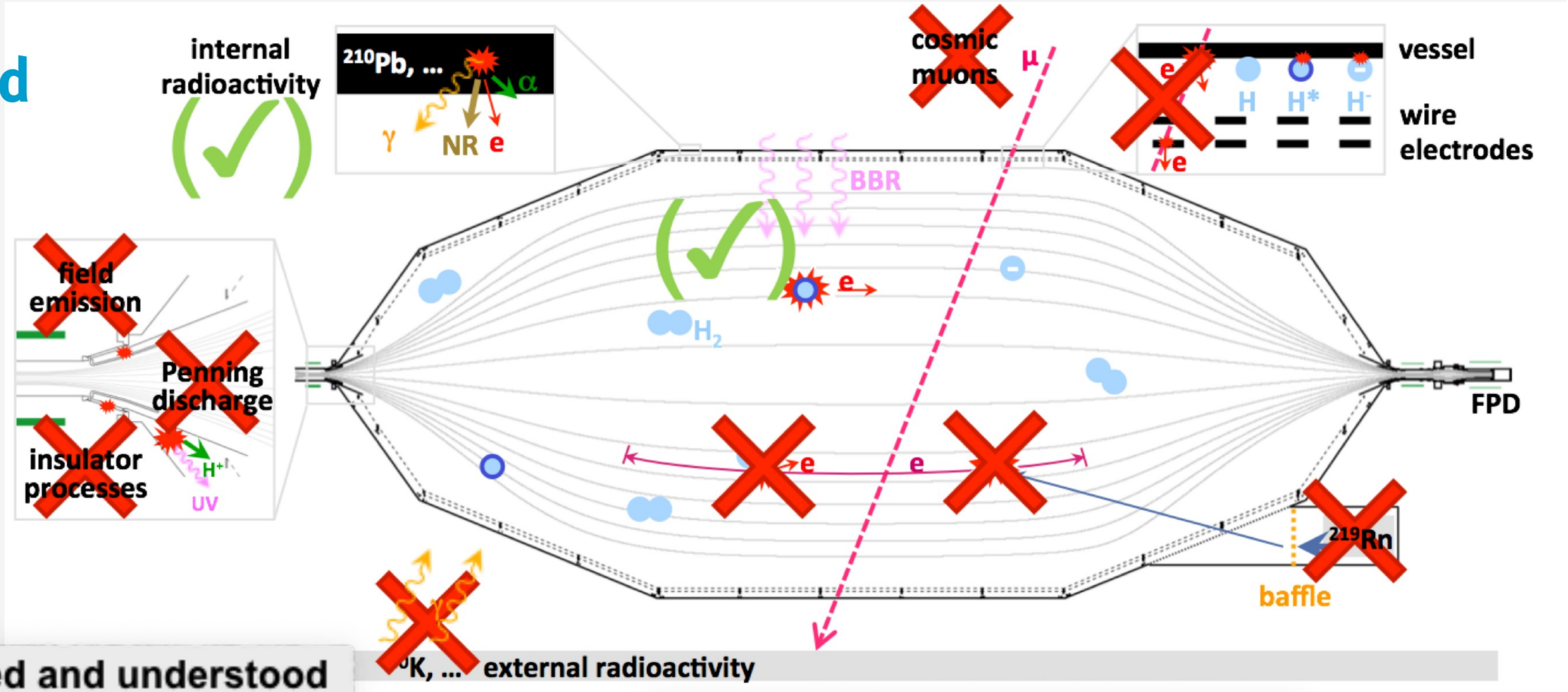


Pixel detector section



Spectrometer background

Spectrometer Background



- **8 sources of background investigated and understood**
- **7 out of 8 avoided or actively eliminated by**
  - fine-shaping of special electrodes
  - symmetric magnetic fields
  - LN$_2$-cooled baffles (cold traps)
  - wire electrode grids

- **1 out of 8 remaining:** caused by ^{210}Pb on spectrometer walls (neutral H* atoms ionised by black-body radiation in spectrometer)

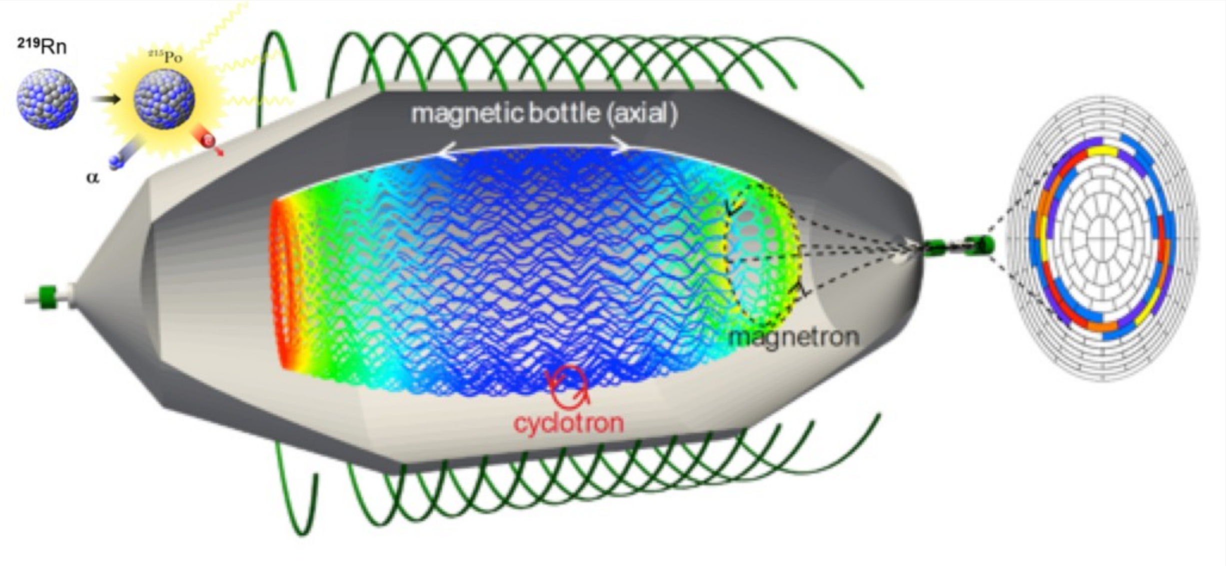
Neutral decays in Spectrometer - ^{219}Rn (getter) and ^{220}Rn (artificial source)

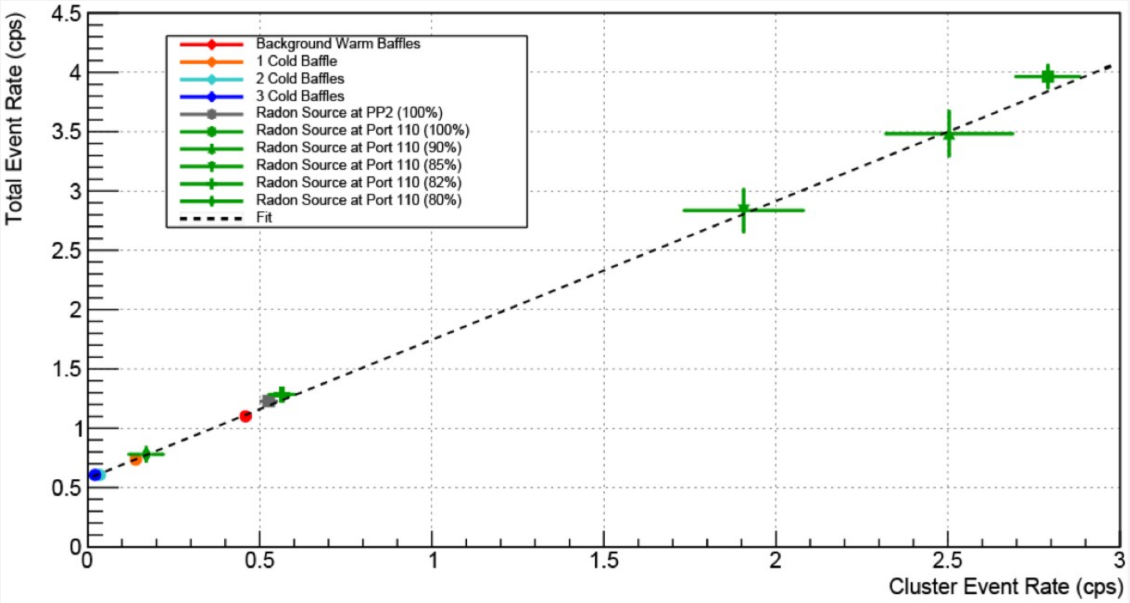
^{219}Rn atoms:

- ^{219}Rn emanates from NEG
- stored electrons eV…keV
- bg-rate: ~500 mcps

countermeasure (passive):

- cryotraps in front of NEG
- 3 LN$_2$-cooled Cu-baffles eliminate ~97% of emanated ^{219}Rn atoms





Ionization of Rydberg atoms sputtered off by alpha decays

Rydberg (or autoionsing) atoms:

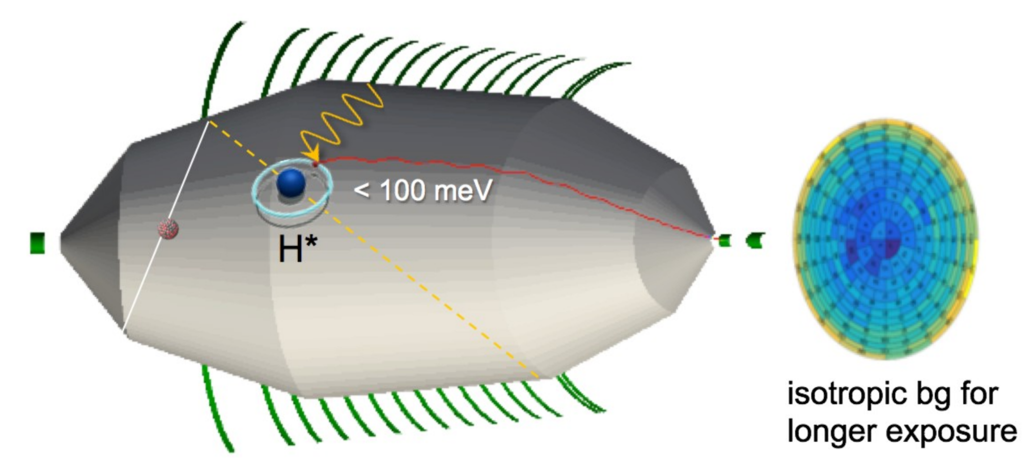
- ejected from walls due to ^{206}Pb recoil ions from ^{210}Po decays
- ionized by black body radiation (291 K)
- non-trapped electrons on meV-scale
  ⇢ bg-rate: ~0.5 cps

counter measures:

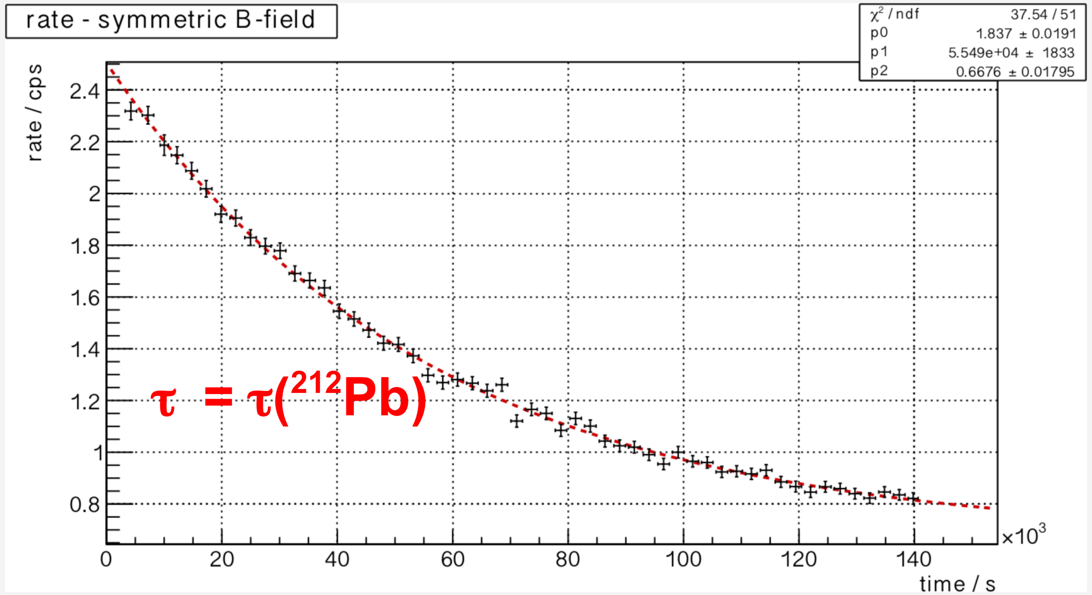
- apply stronger voltage (field ionisation) at wire electrode system
- reduce flux tube
- cover main spectrometer walls (maybe in future)

Testing this hypothesis:

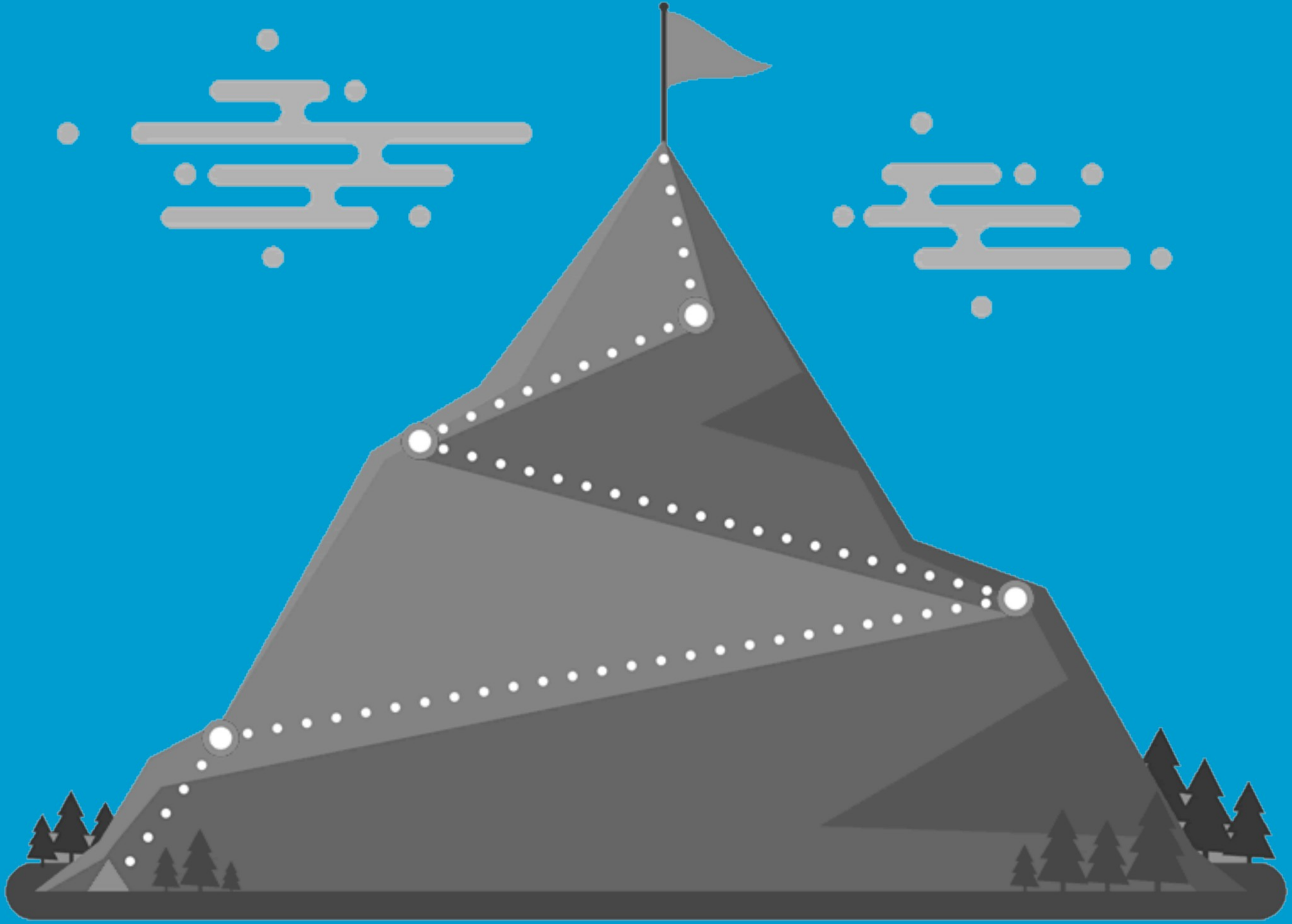
artifically contaminating the spectrometer with implanted short-living daughters of ^{220}Rn (and ^{219}Rn)



isotropic bg for longer exposure

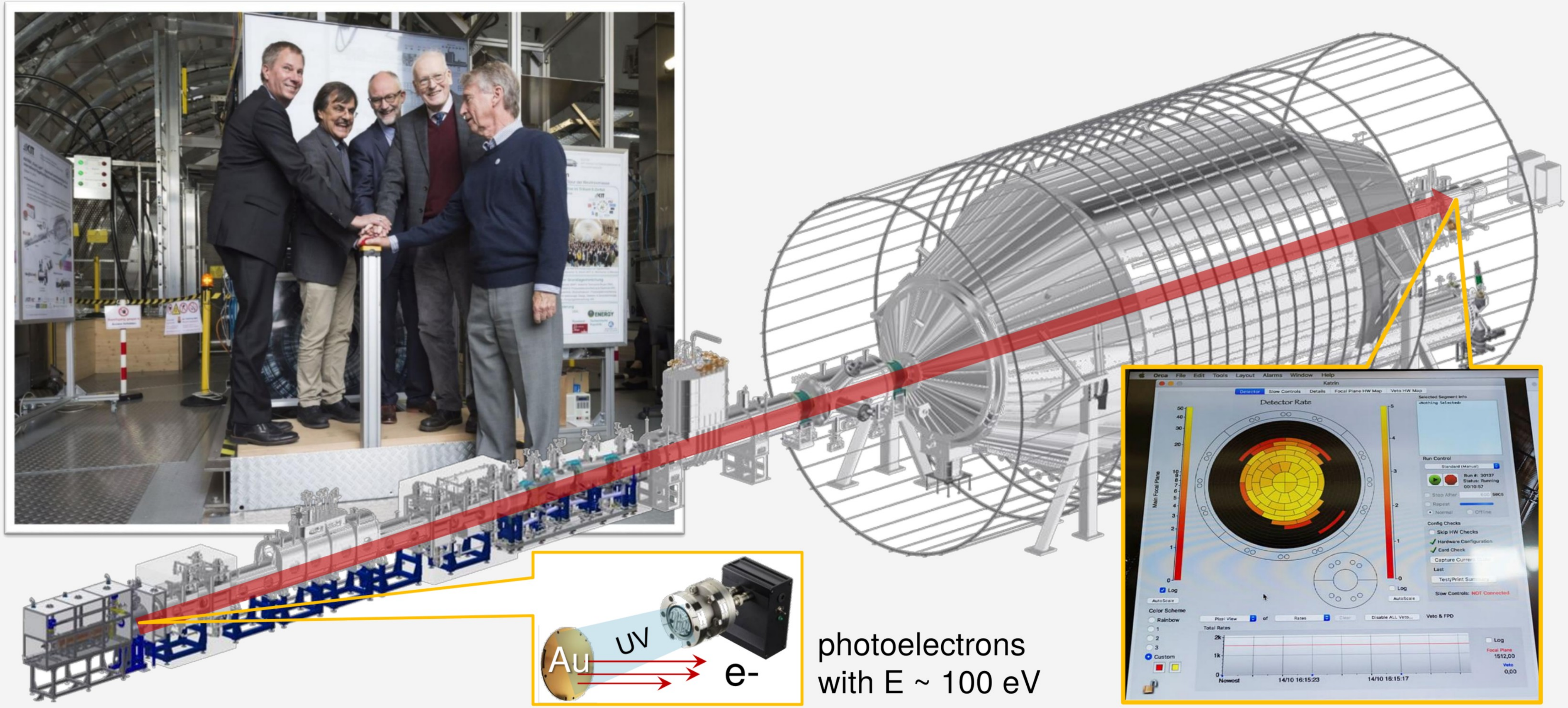


χ² / ndf	37.54 / 51
p0	1.837 ± 0.0191
p1	5.549e+04 ± 1833
p2	0.6676 ± 0.01795



Milestones towards the Neutrino Mass

Technical inauguration of KATRIN – October 2016



photoelectrons
with E ~ 100 eV

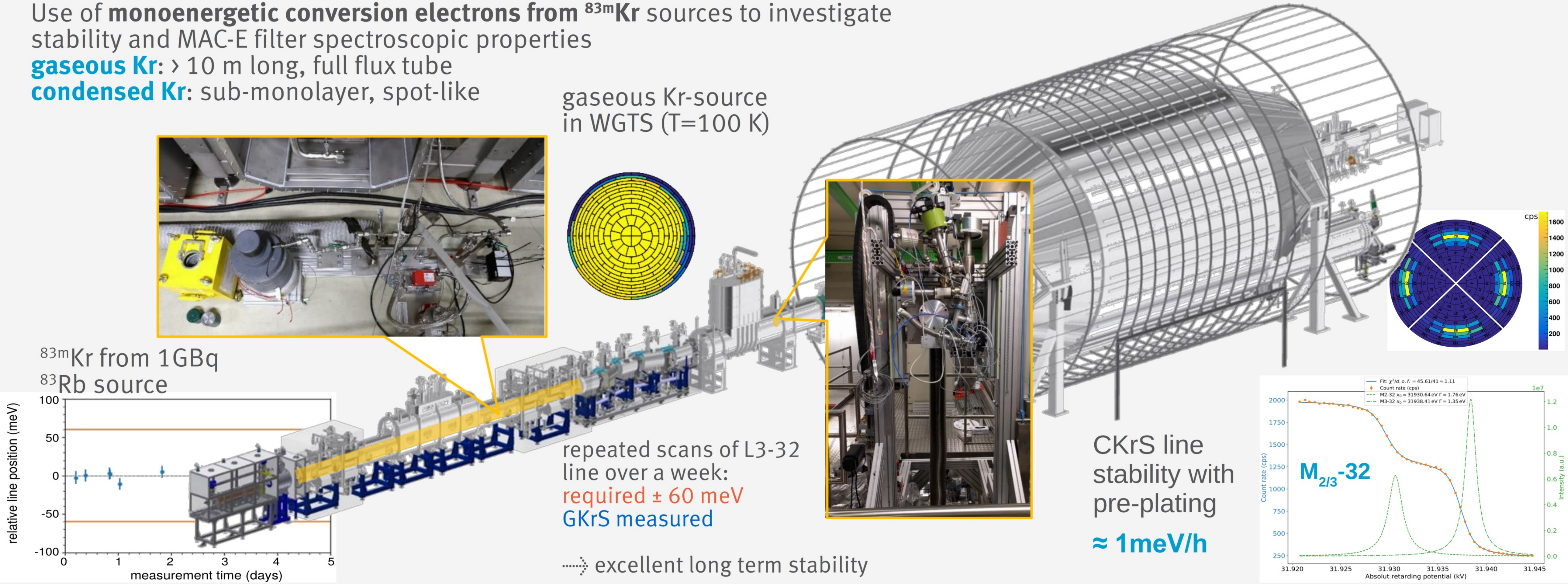
Krypton summer 2017

*KATRIN collab.,
JINST 13 P04020 (2018)*

Use of **monoenergetic conversion electrons from ^{83m}Kr** sources to investigate stability and MAC-E filter spectroscopic properties

gaseous Kr: › 10 m long, full flux tube

condensed Kr: sub-monolayer, spot-like



gaseous Kr-source
in WGTS (T=100 K)

^{83m}Kr from 1GBq
^{83}Rb source

repeated scans of L3-32
line over a week:
required ± 60 meV
GKrS measured

⇢ excellent long term stability

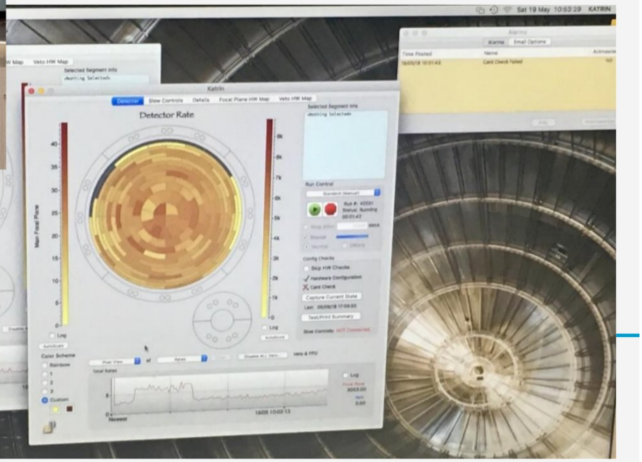
CKrS line
stability with
pre-plating

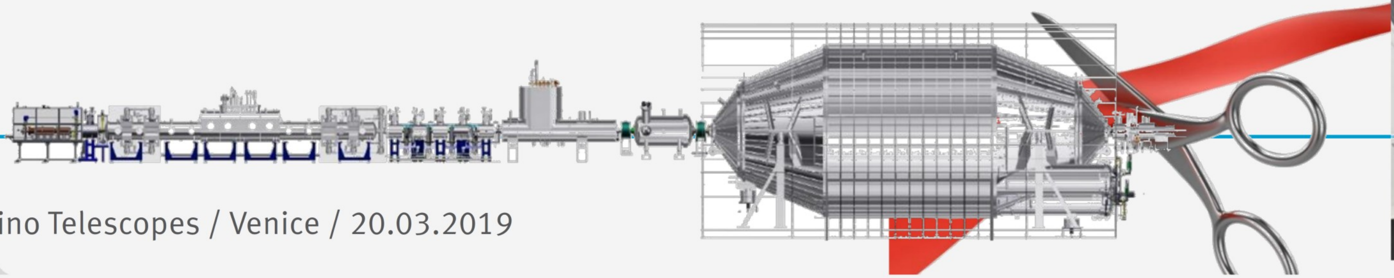
≈ 1meV/h

Official inauguration in 2018 – First tritium (engineering run)

method:

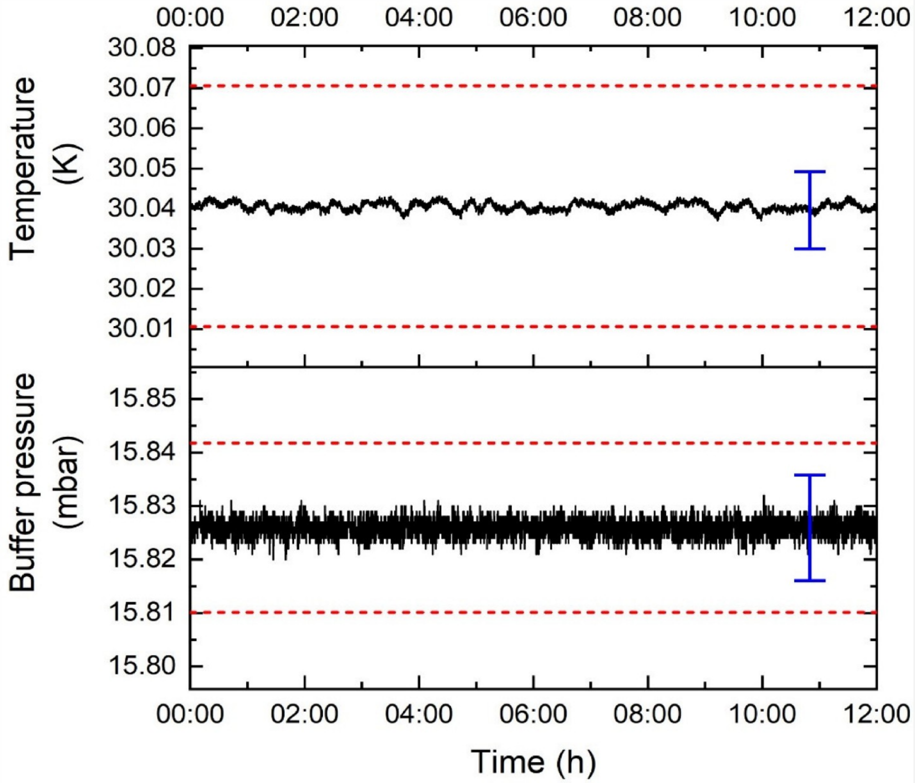
- inject known gas mix from prepared cylinders (80% of nominal ρd, ~1% DT and ~99% D_2 corresponds to <1% of nominal activity ≈ 500 Mbq)
- verify functionality of all system components and demonstrate 0.1% global stability
- study beta spectrum for systematic effects and test analysis strategies





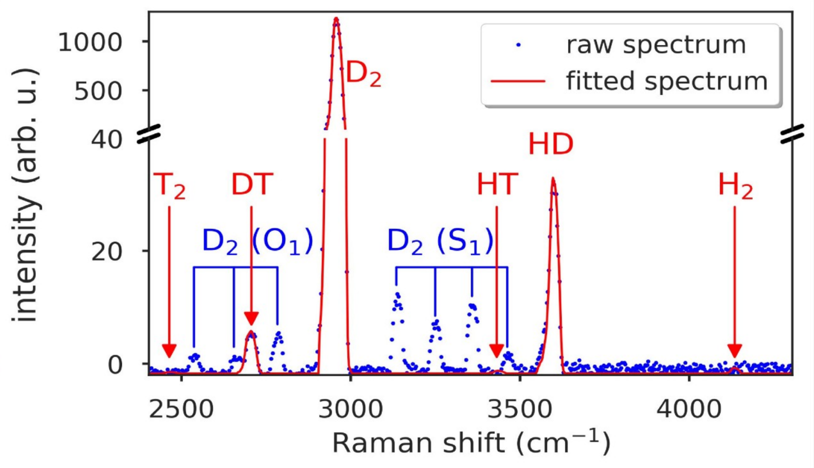
System stability and next steps

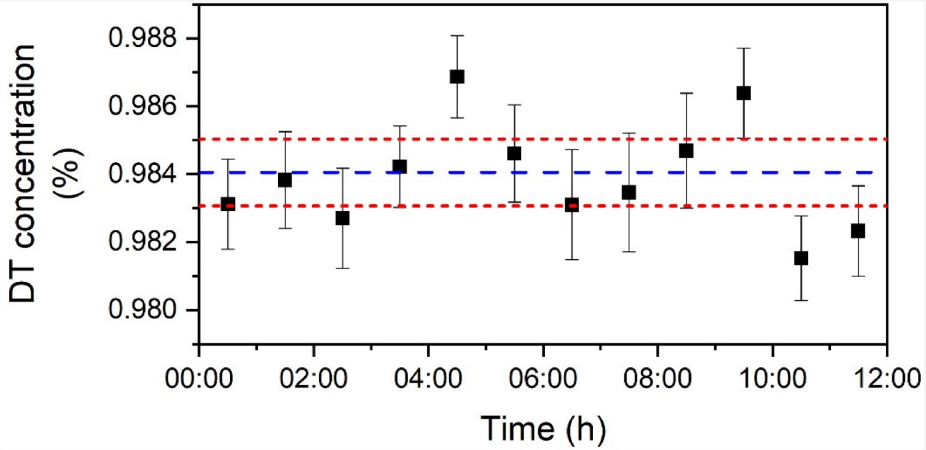
Source stability over 12 h



Blue arrow: systematic uncertainty
Red dashed line: ± 0.1 % stability required for neutrino mass taking

Source parameters are stable and within the specifications





Schlösser et al.,
J. Mol. Spect. 1044 61 (2013)

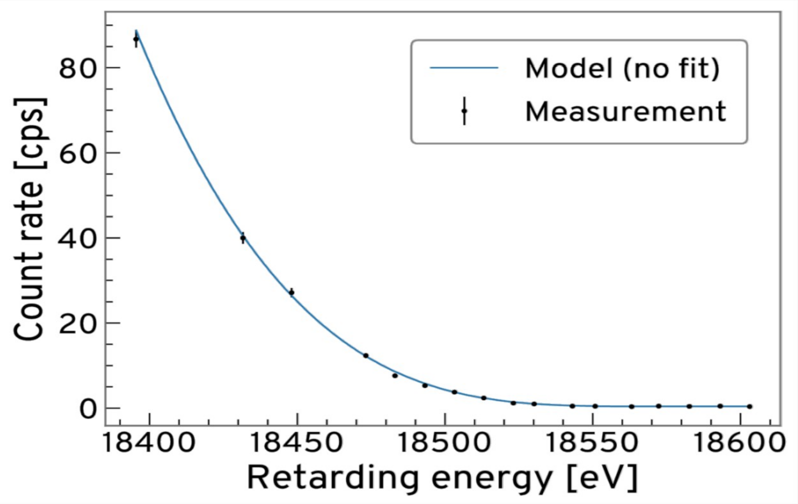
DT concentration measured by laser Raman spectroscopy

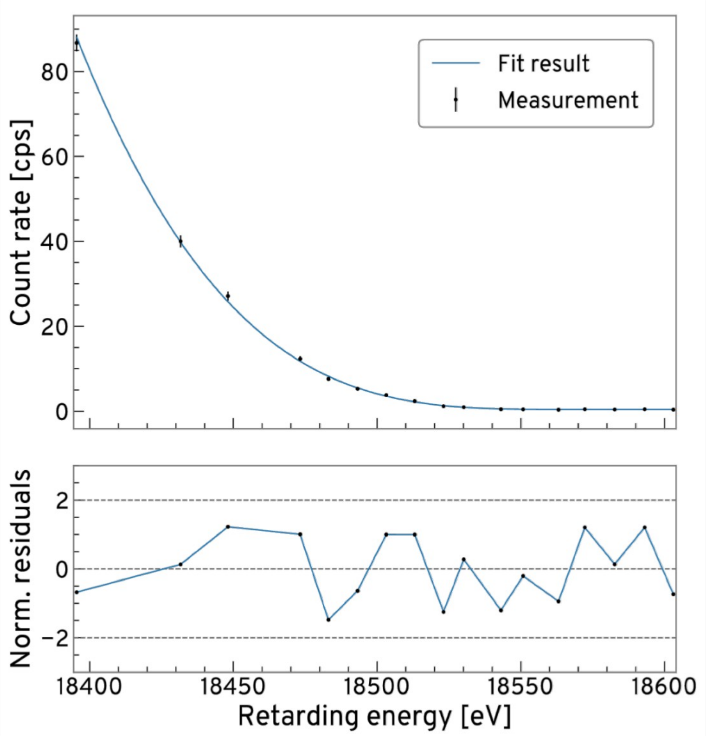
First tritium - Model fits

Analysis of first tritium scan (200 eV):

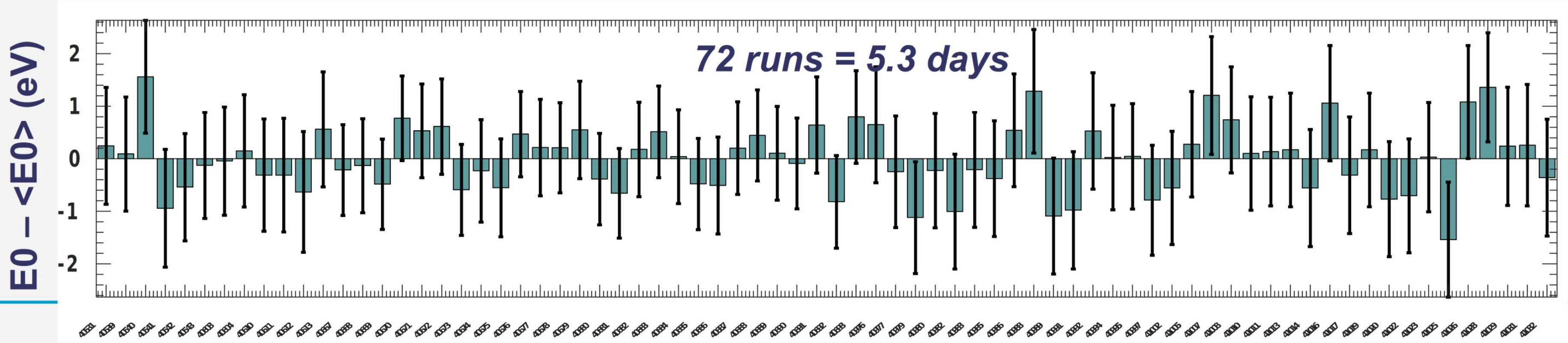
model gives very good understanding of both rate and shape (even up to 2 keV!!)

fit (E0, bckg., Amp.) results agree with expectations





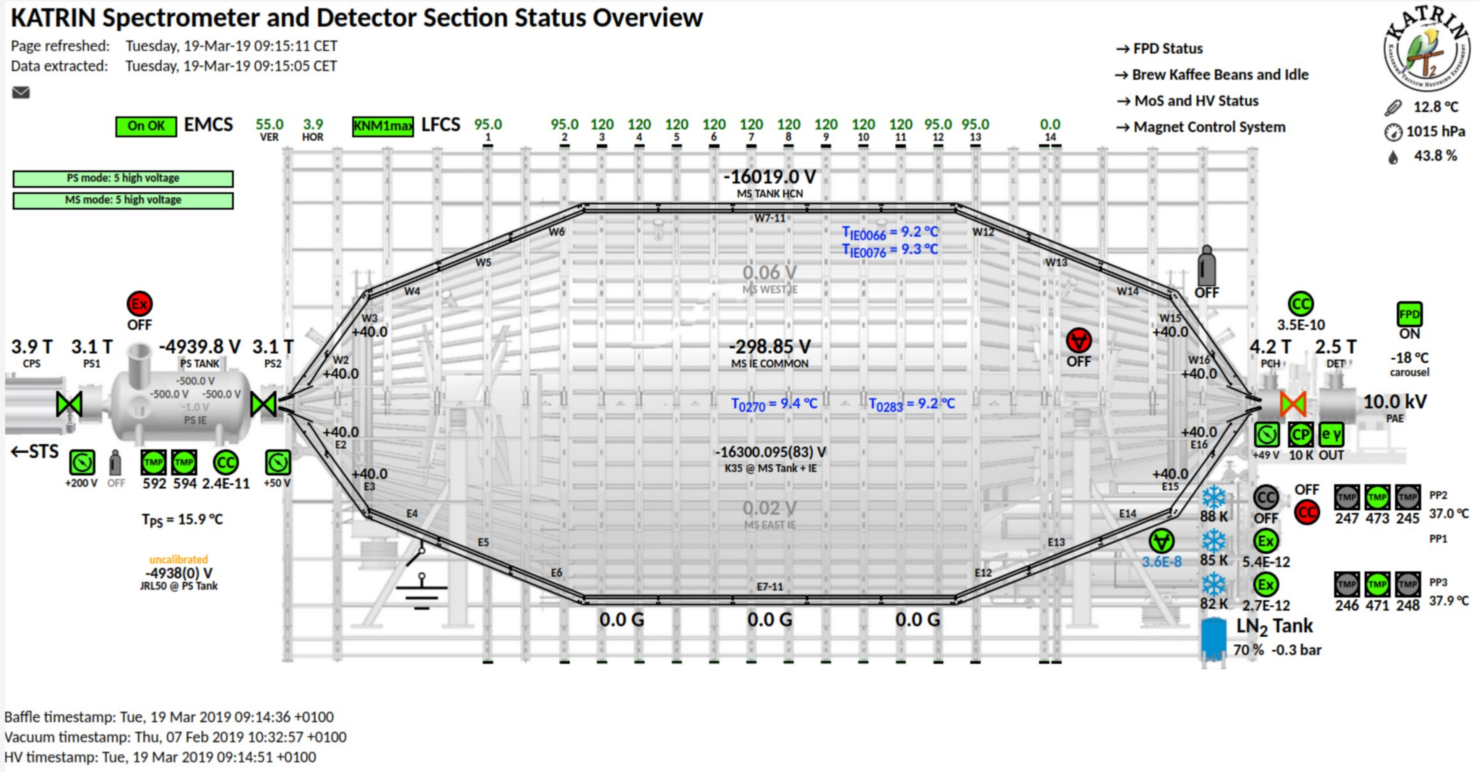
Endpoint stability



Science Run 0

- Ramping up system to full column density
- First scientific run in March/April 2019
- 30 days of data taking
- Expected mass sensitivity ‹ 1eV

KATRIN started!



KATRIN Spectrometer and Detector Section Status Overview

Page refreshed: Tuesday, 19-Mar-19 09:15:11 CET
Data extracted: Tuesday, 19-Mar-19 09:15:05 CET

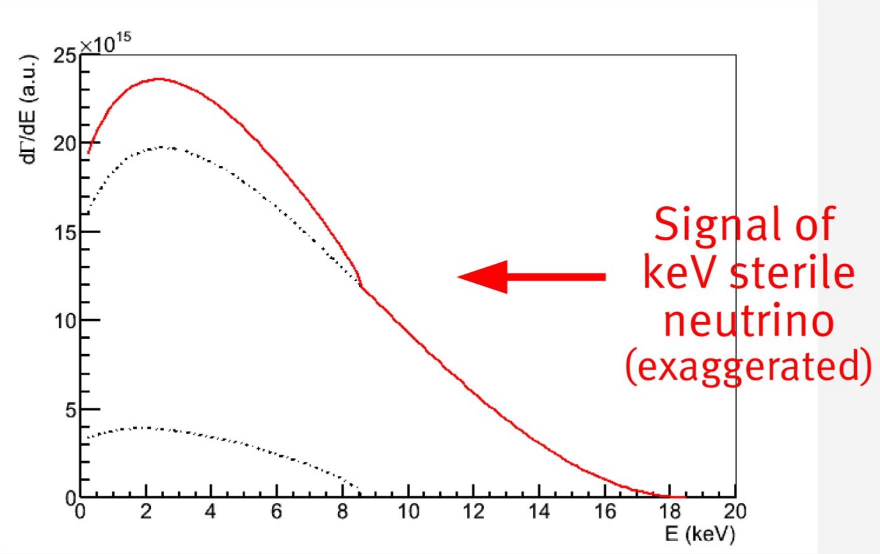
→ FPD Status
→ Brew Kaffee Beans and Idle
→ MoS and HV Status
→ Magnet Control System

PS mode: 5 high voltage
MS mode: 5 high voltage

Baffle timestamp: Tue, 19 Mar 2019 09:14:36 +0100
Vacuum timestamp: Thu, 07 Feb 2019 10:32:57 +0100
HV timestamp: Tue, 19 Mar 2019 09:14:51 +0100

Next steps - Sterile Neutrinos

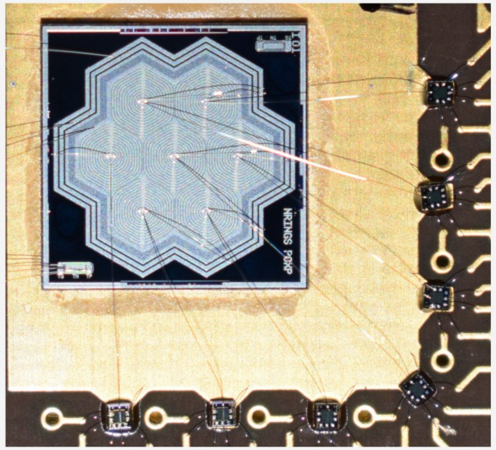
- Extension of KATRIN to search for eV – keV sterile neutrinos
  - ⇢ Tiny, but characteristic signal further away from the endpoint
- Challenge: ppm sensitivity needed (high statistics, small systematics)
  - ⇢ New detector system!
- R&D of multi-pixel Silicon Drift Detector (SDD) system ongoing
  - ⇢ Excellent performance demonstrated with prototype detector system



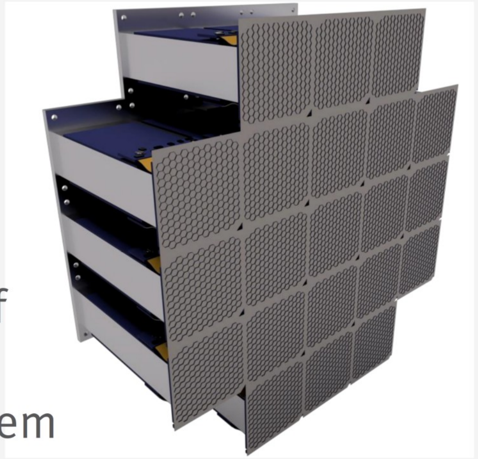
Signal of keV sterile neutrino (exaggerated)

S. Mertens, T. Lasserre *et. al.* Phys.Rev. D91 (2015) 4, 042005
S. Mertens, K. Dolde, M. Korzeczek, *et al.* JCAP 1502 (2015) 02, 020
K. Dolde, S.Mertens, D. Radford et. al. NIM-A 848 (2017)
M. Drewes *et. al.*, JCAP 1701 (2017) no.01, 025
A. Boyarsky, M. Drewes, T. Lasserre, S. Mertens, O. Ruchayskiy, arXiv:1807.07938
S. Mertens, et al.: arXiv:1810.06711 [physics.ins-det] (2018)

7 pixel TRISTAN prototype



Design of 3500 ch SDD system



Conclusion and outlook

Neutrino oscillations showed that neutrinos obtain mass but absolute mass scale is unknown

⇢ Different approaches to measure the absolute mass

KATRIN aims to measure electron anti-neutrino mass with 0.2 eV sensitivity (90% C.L.)

⇢ Precise measurement of the endpoint region of tritium β decay

KATRIN beamline consisting of a high luminosity windowless gaseous tritium source, transport, spectrometer and detector section

⇢ System is fully comissioned and in 2018 the official inauguration took place

Currently the KATRIN system gets ramped up

⇢ Perform the first science run in March/April

Future KATRIN measurement possibilities

⇢ New detector design for sterile neutrino search

Thank you for your attention