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Direct neutrino mass search with the KATRIN experiment and beyond

Intern. School of Nuclear Physics, Ettore Majorana Foundation and Centre for Scientific Culture, Erice, 16.-22.9.2026

- Direct search for absolute neutrino mass with KATRIN
- Search for keV sterile neutrinos with KATRIN phase 2 and the TRISTAN detector
- Much higher neutrino mass sensitivity: KATRIN++
- Conclusions

erc

living.knowledge

Christian Weinheimer* – University of Münster

* reporting at this school at Erice before in 1997, 2001, 2005, 2009 and 2013

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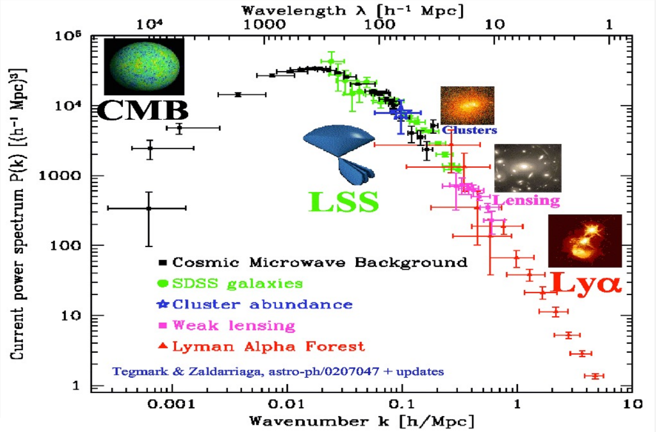
Three complementary ways to the absolute neutrino mass scale

1) **Cosmology:** $\sum_i m(\nu_i) = 3 \cdot \overline{m(\nu_i)}$

very sensitive, but model dependent, compares power at different scales

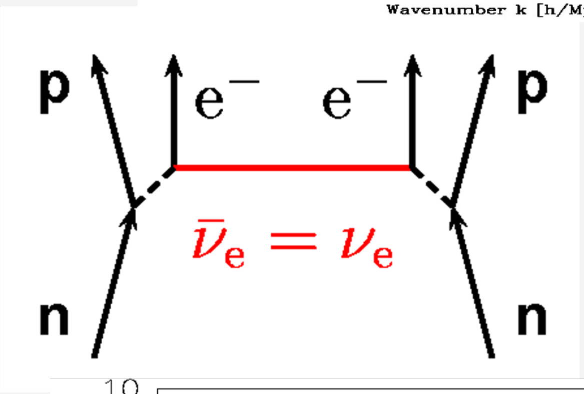


2) **Search for 0νββ:** $m_{\beta\beta} := \left|\sum_i U_{ei}^2 \cdot m(\nu_i)\right|$

sensitive to Majorana neutrinos only, challenge of nuclear matrix elements

disclaimer: $m_{\beta\beta}$ are valid only, if 0νββ works dominantly via ν exchange

Discovery of 0νββ would proof lepton number violation !



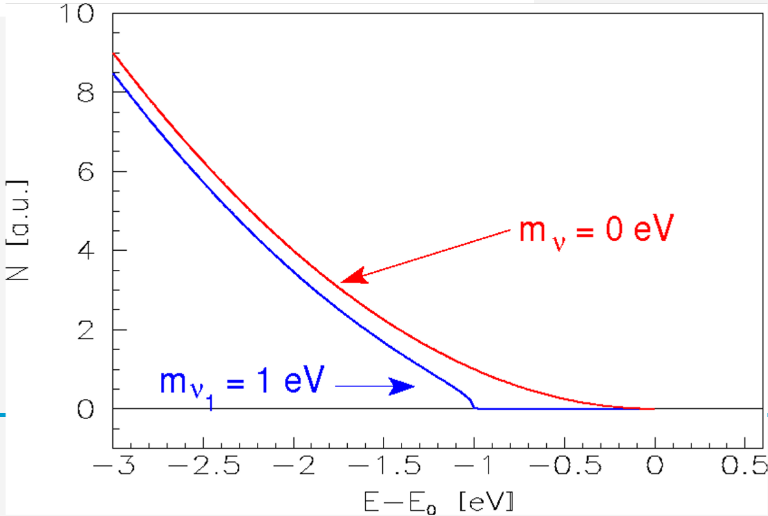
3) **Direct neutrino mass determination:** $m^2(\nu_e) := m_\beta^2 := \sum_i |U_{ei}|^2 \cdot m^2(\nu_i)$

no further assumptions needed, use $E^2 = p^2c^2 + m^2c^4$ → $m^2(\nu)$

Time-of-flight measurements (ν from supernova)

Kinematics of weak decays / beta decays, e.g. tritium, ^{163}Ho

measure charged decay prod., E-, p-conservation

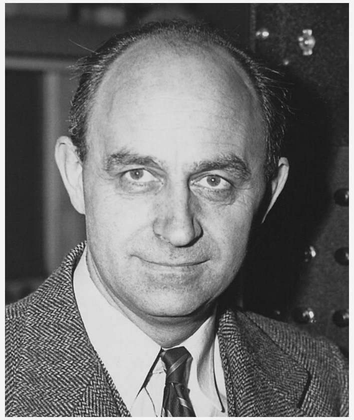


Direct determination of "$m(\nu_e)$" from β-decay (EC)

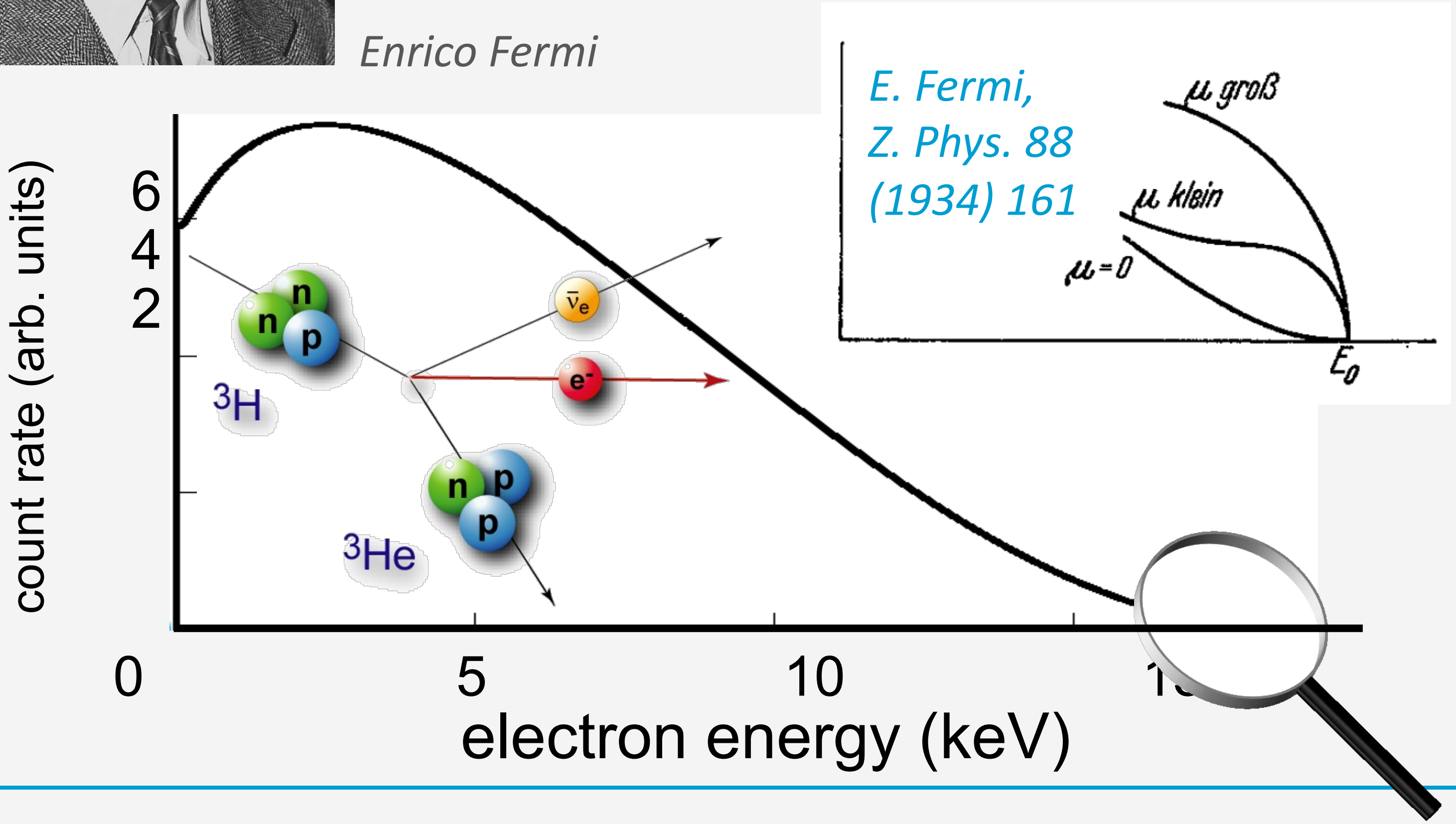
β-spectrum: $\frac{dN}{dE} = K \cdot F(E,Z) \cdot \underbrace{p}_{p_e} \cdot \underbrace{E_{tot}}_{E_e} \cdot \underbrace{(E_0 - E_e)}_{E_\nu} \cdot \sum_i |U_{ei}|^2 \cdot \underbrace{\sqrt{(E_0 - E_e)^2 - m^2(\nu_i)}}_{p_\nu}$

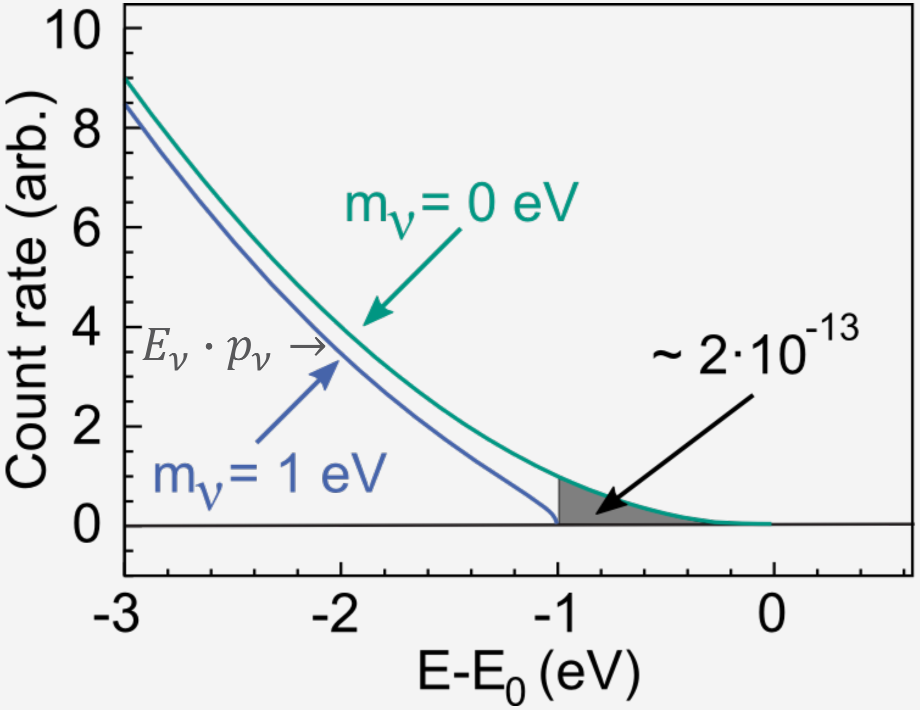
essentially phase space: p_e E_e E_ν p_ν

with "electron neutrino mass": $m_\beta^2 = m^2(\nu_e) := \sum_i |U_{ei}|^2 \cdot m^2(\nu_i)$, complementary to 0νββ & cosmology

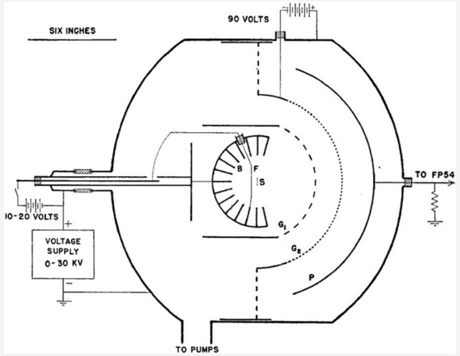


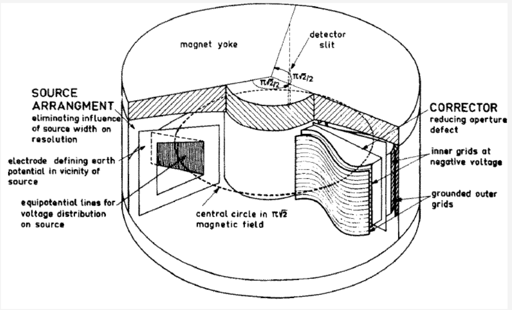
Enrico Fermi

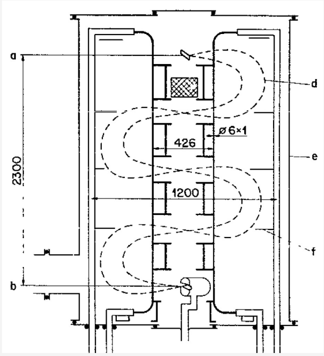


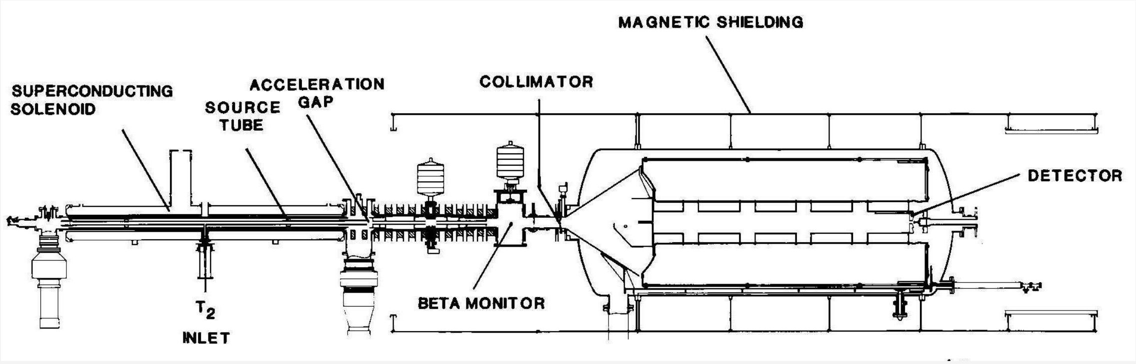


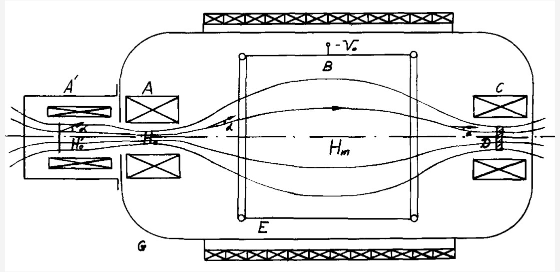
Direct neutrino mass experiments - history

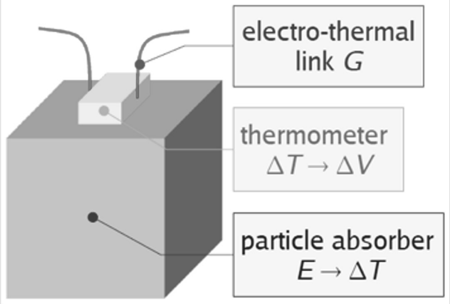


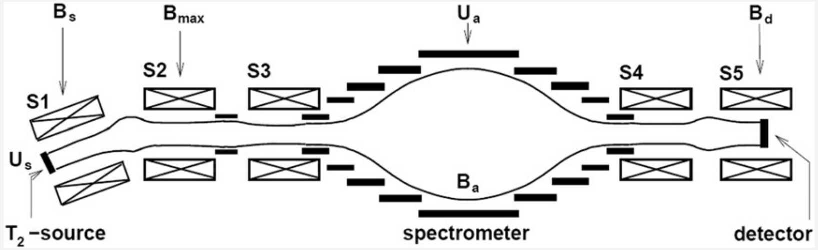


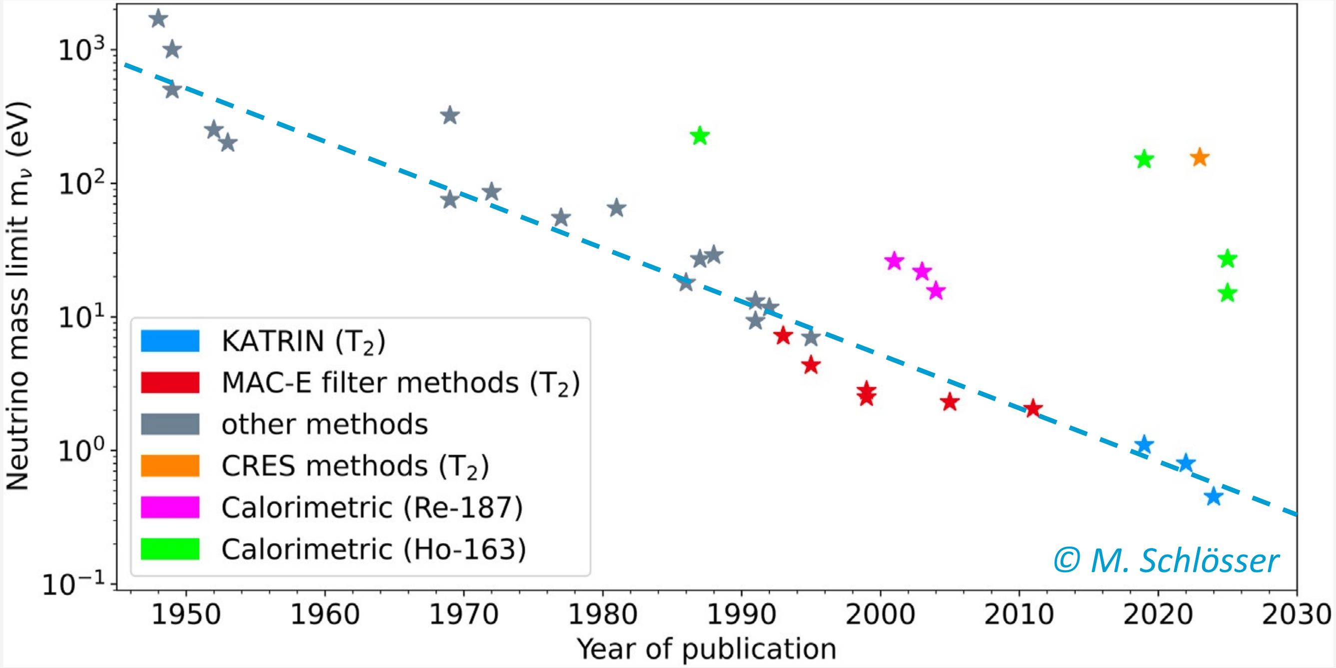












NIM A240 (1985) 30, Rep. Prog. Phys. 55 (1992) 1035, Rep. Prog. Phys. 71 (2008) 086201, Phys. Rep. 914 (2021) 1, Encyclopedia Part. Phys. 4 (2026) 438

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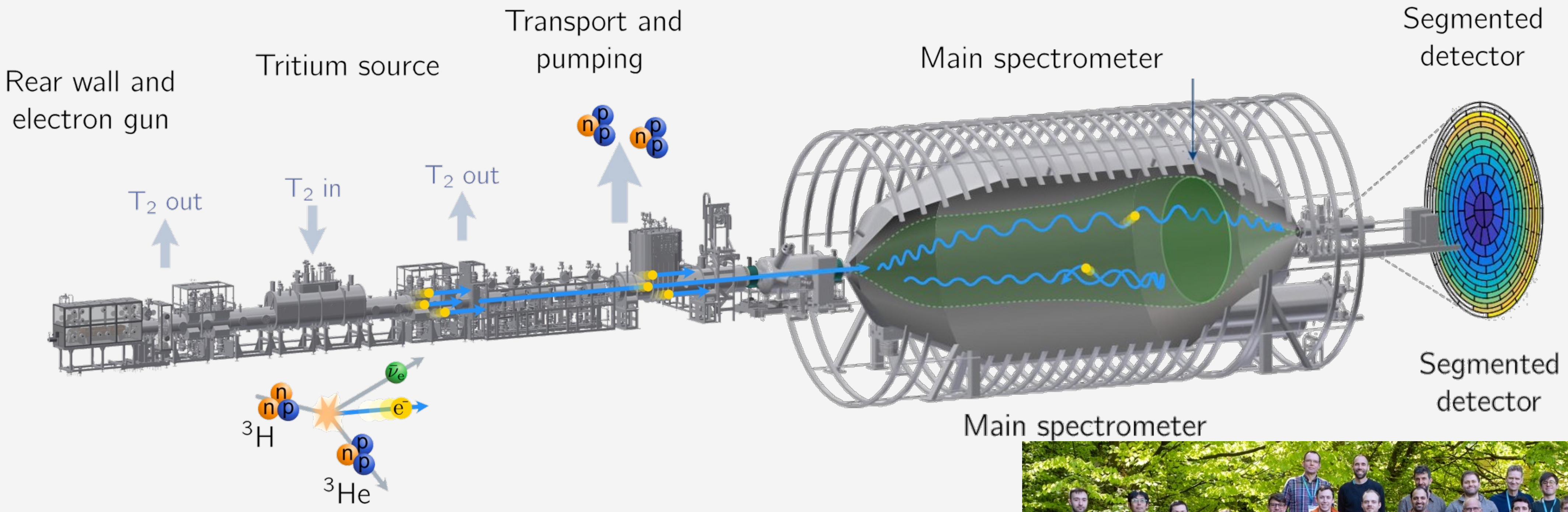
KArlsruhe TRItium Neutrino experiment KATRIN

A **10^{11} Bq windowless T_2** source with an **high acceptance & eV-resolution integrating spectrometer**

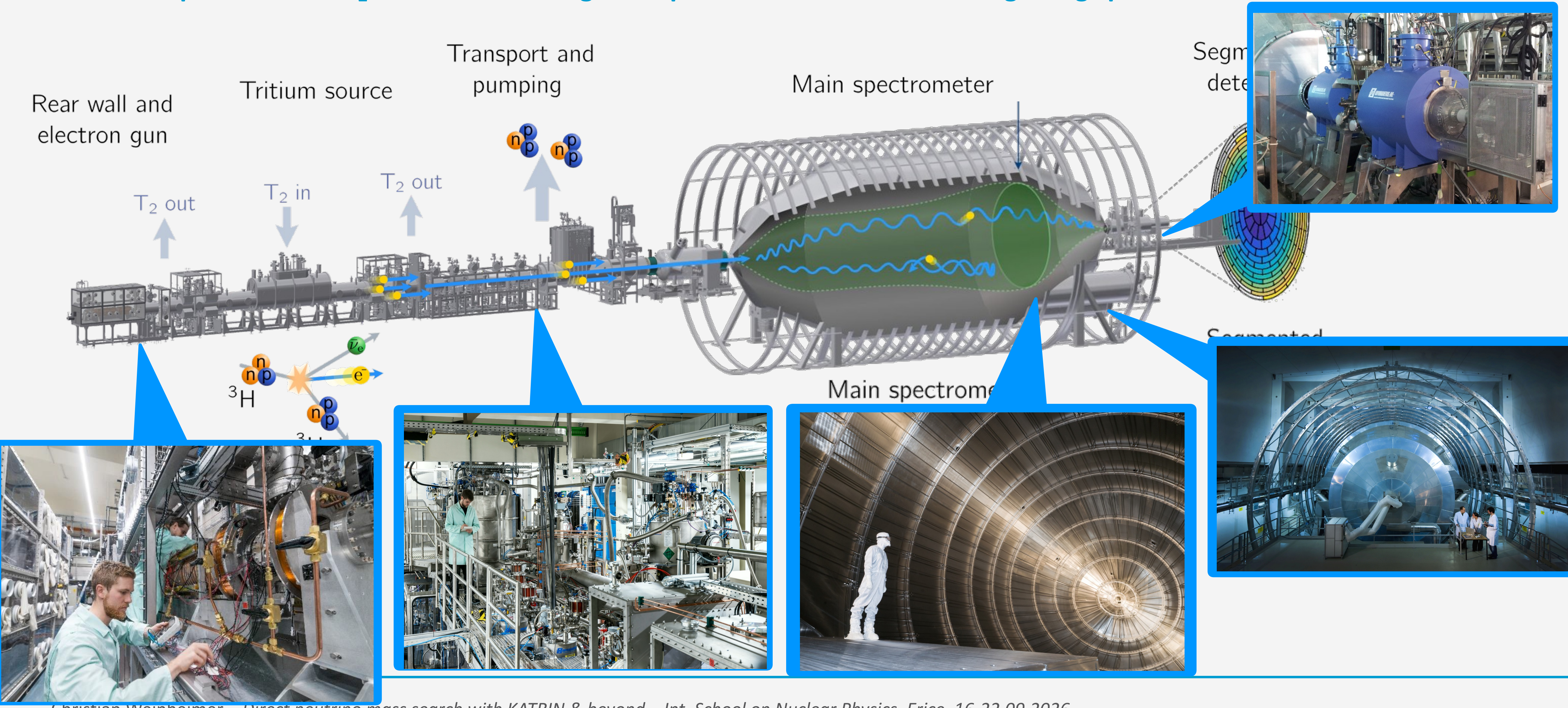


The international KATRIN Collaboration:

150 authors from 24 institutions from 8 countries

KArlsruhe TRItium Neutrino experiment KATRIN

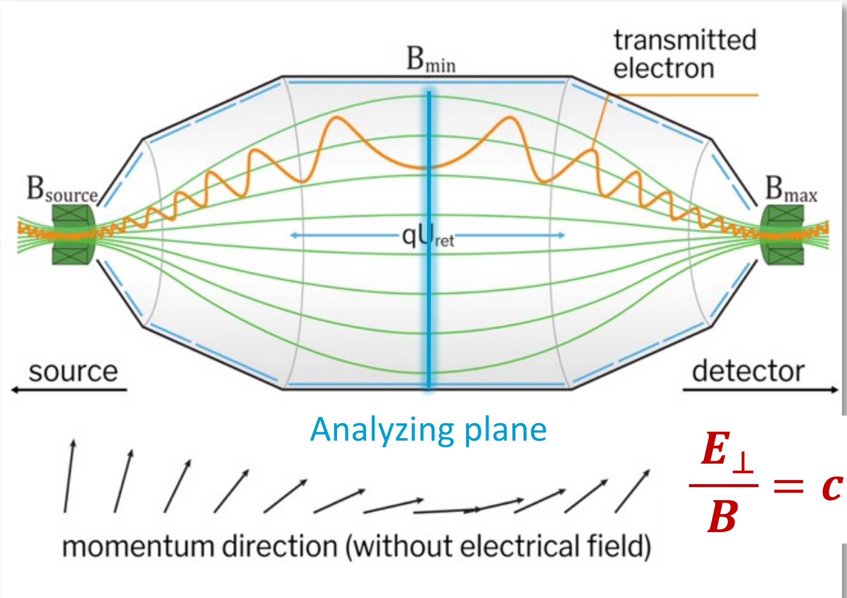
A **10^{11} Bq windowless T_2** source with an **high acceptance & eV-resolution integrating spectrometer**



Main spectrometer of MAC-E-filter type

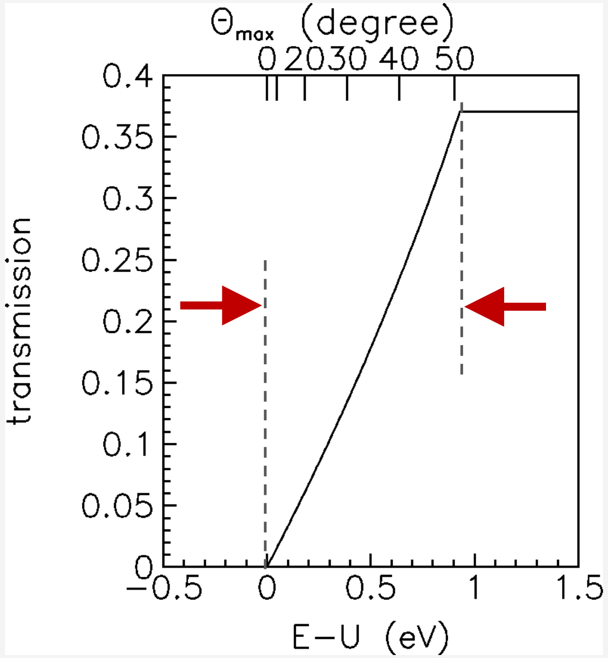
Magnetic gradient force: transforms transversal energy $E_\perp$ into longitudinal energy $E_{||}$ ($\frac{E_\perp}{B} = const.$, non-rel.)

Electrostatic filter: retarding voltage U let electrons through above a certain energy $E \sim E_{||} \geq qU$

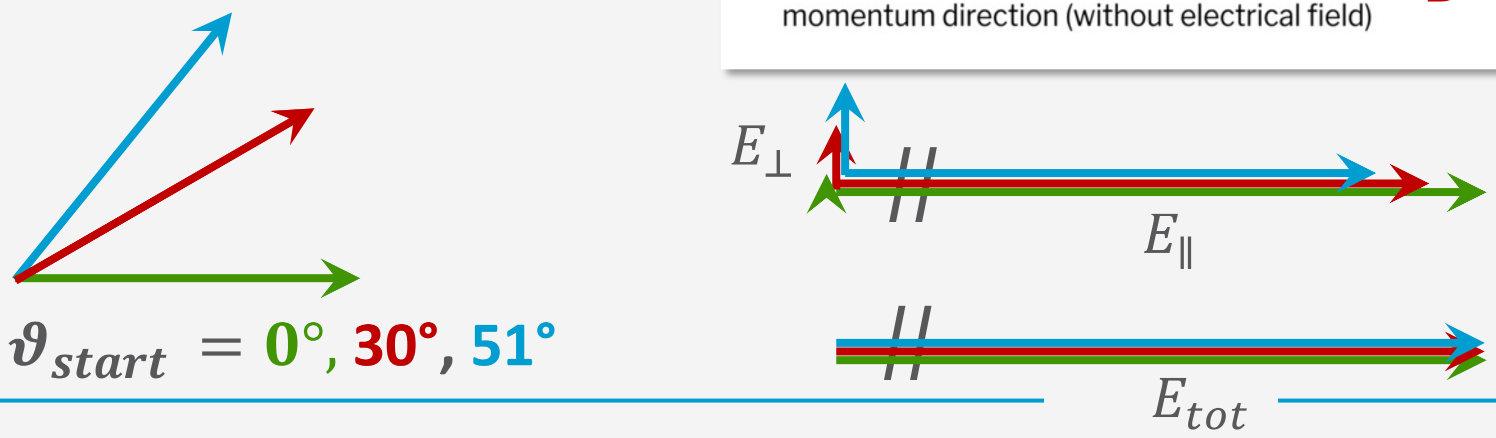


$$\frac{E_\perp}{B} = const.$$

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



e⁻ angles at source



$\vartheta_{start} = 0°, 30°, 51°$

Very high energy resolution

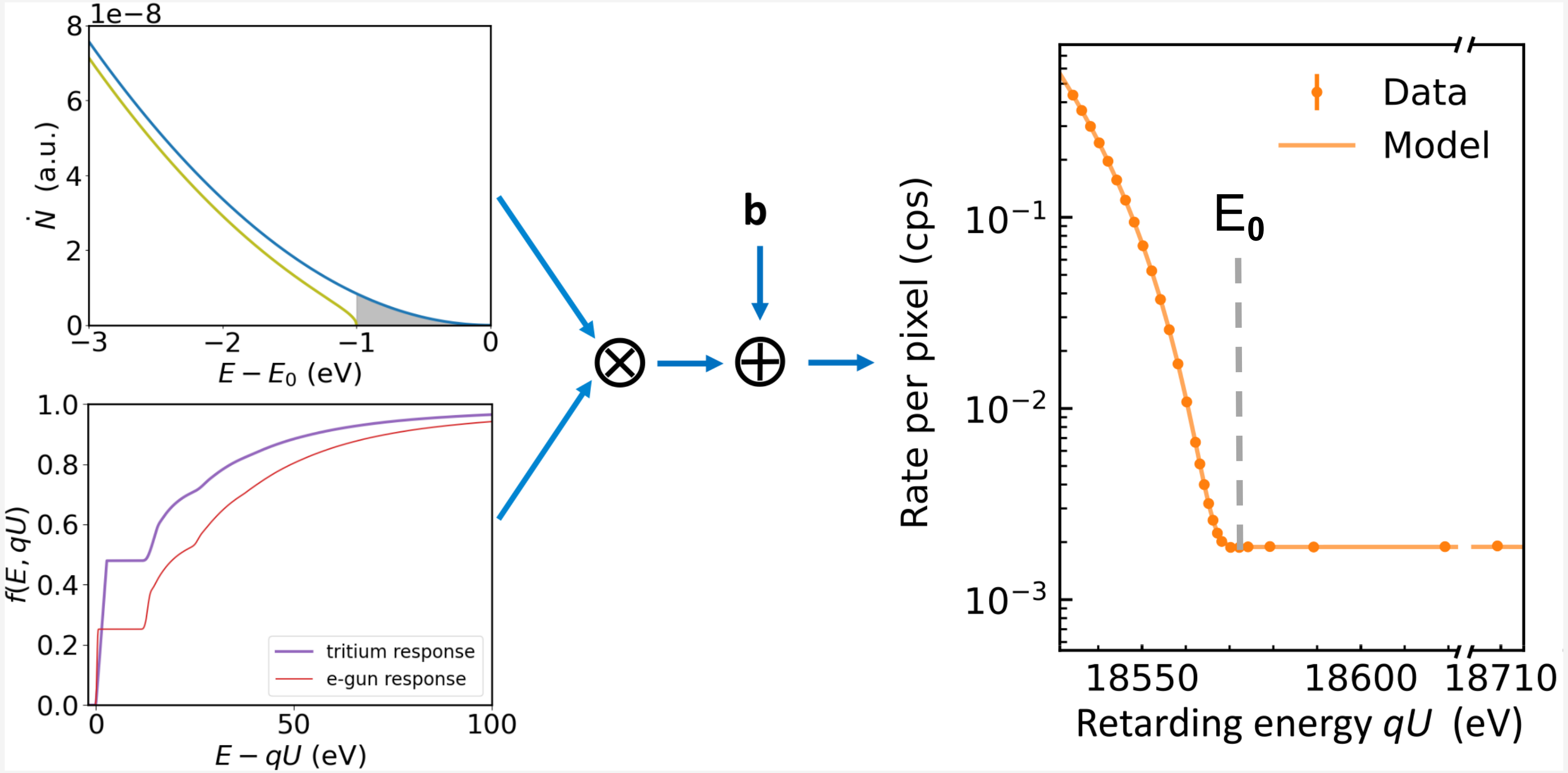
$\Delta E = \mathcal{O}(1\text{eV})$: 2.6 eV

Very high angular acceptance:

$\Delta\Omega \sim \pi$

Model of the experimental spectrum

- **Beta spectrum: $R_\beta(E, m^2(\nu_e))$**



PRL 123 (2019) 221802,
EPJ C 79 (2019) 204

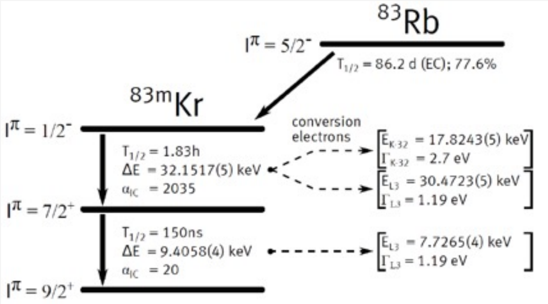
+ detailed analysis:
PRD 104 (2021) 012005

+ energy loss measurement:
EPJ C 81 (2021) 579

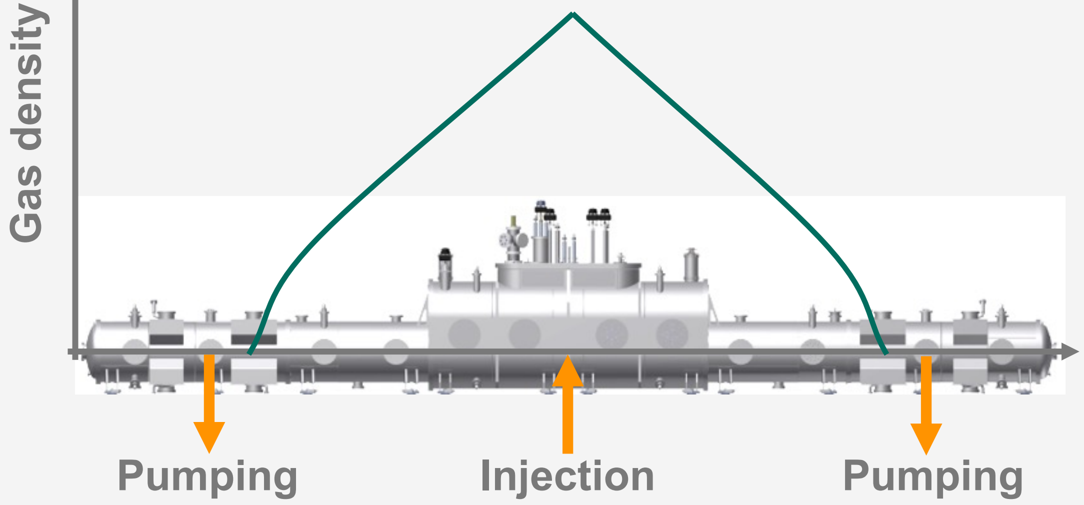
- **Experimental response: f(E-qU)**

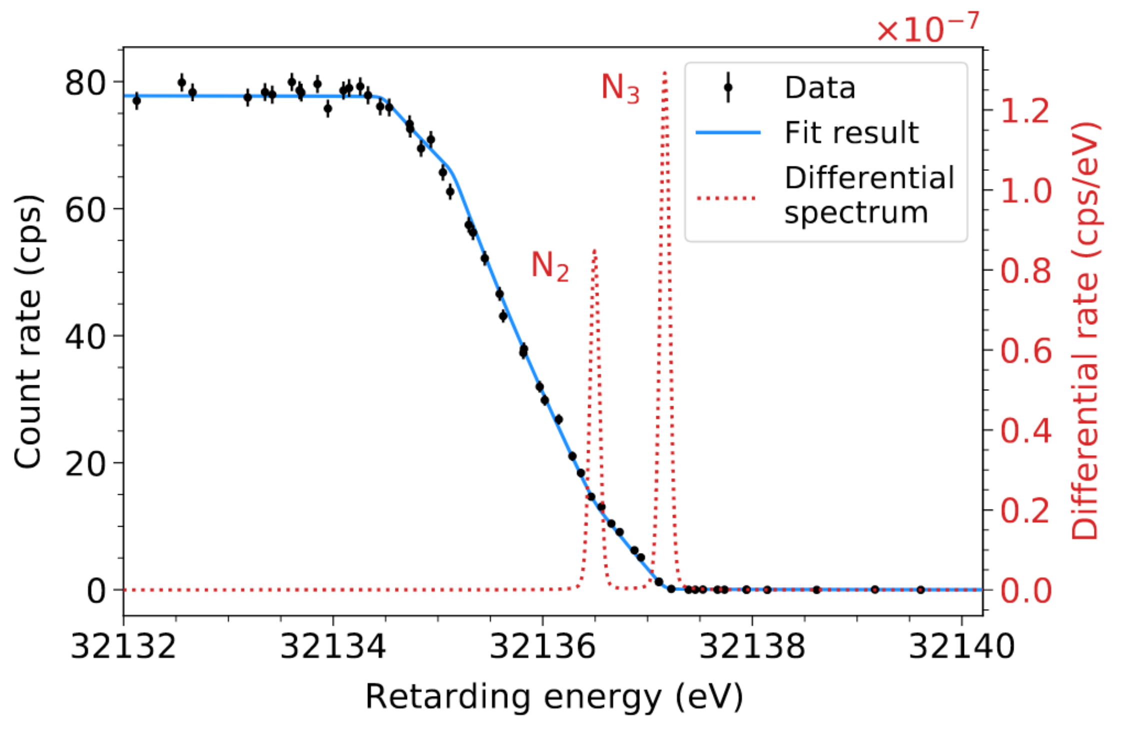
$$R(qU) = A_s \cdot N_T \int_{qU}^{E_0} R_ß(E, m^2(\nu_e)) \cdot f(E - qU)\, dE + R_{bg}$$

Improving source-related systematics



Co-circulation of tritium and ^{83m}Kr at 80 K





Data of 2020 krypton run at 40% tritium column density used to constrain systematics in 2nd campaign *Nature Phys. 18 (2022) 160*

Since then: New operation mode with stable co-circulation of both T_2 and ^{83m}Kr at high column density at 80 K

From summer 2021 on: **10 GBq Krypton generator (activity x6) ➜ further reduction of plasma systematics**

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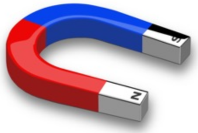
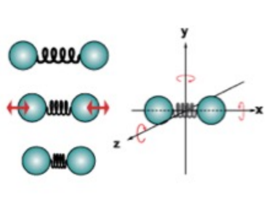
Systematic effects and uncertainties

Magnetic fields
- source
- spectrometer
- detector JINST 13 (2018) P02003



Molecular final states
- quantum-chemical computations

Eur. Phys. J. C 84 (2024) 494

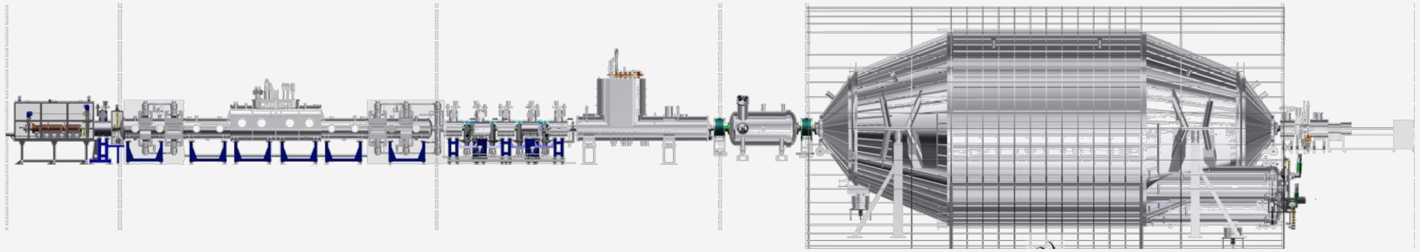


Source electric potential
- plasma properties
- surface conditions

JINST **17** (2022) P06029

Spectrometer voltage
- compensation of fluctuations
- absolute calibration

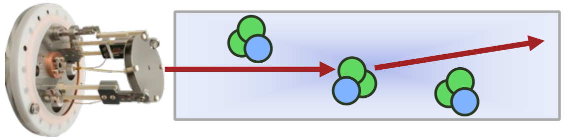
JINST 17 (2022) P06003
Metrology 56 (2019) 045007



Detection efficiency

Nucl. Inst. Meth. A 778 (2015) 40-60

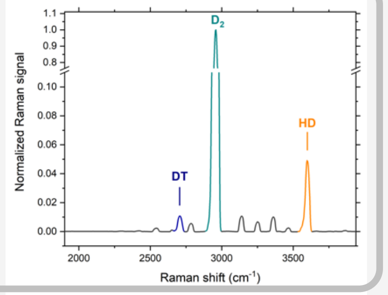
Energy loss by scattering



Eur. Phys. J C 79 (2019) 204
Eur. Phys. J C 81 (2021) 579

Activity fluctuations
- column density
- tritium (T_2, DT, HT)
- concentration

Sensors 20 (2020) 4827



Background
- dependence on retarding potential
- time structure due to trapped electrons

JINST 13 (2018) T10004 , Eur. Phys. J. A 44 (2010) 499
Astropart. Phys. 138 (2022) 102686

Three complementary strategies to include systematics in the fit:
(a) covariance matrix, (b) Monte-Carlo propagation, (c) pull-term method

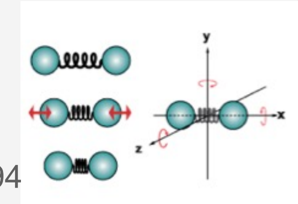
see PRL 123 (2019) 221802 + detailed analysis PRD 104 (2021) 012005 + Nature Physics 18 (2022) 160, Science 388 (2025) 180-

see talks by Karo Erhardt and Sonja Schneidewind on Sunday

Systematic effects and uncertainties

Molecular final states
- quantum-chemical computations

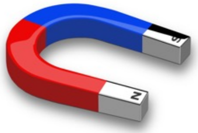
Eur. Phys. J. C 84 (2024) 494



Source electric potential
- plasma properties
- surface conditions

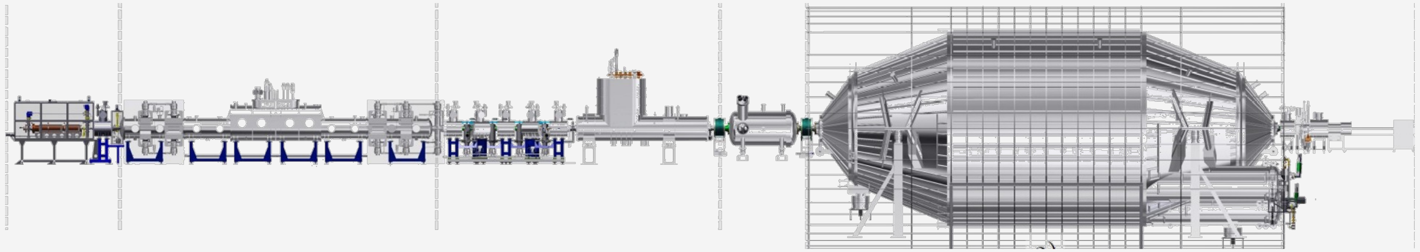
JINST **17** (2022) P06029

Magnetic fields
- source
- spectrometer
- detector JINST 13 (2018) P02003



Spectrometer voltage
- compensation of fluctuations
- absolute calibration

JINST 17 (2022) P06003
Metrology 56 (2019) 045007



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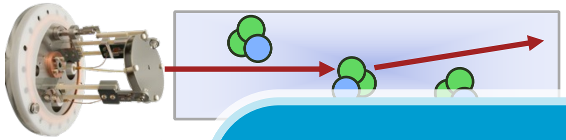

Eur. Phys. J
Eur. Phys. J

Activity fluctuations
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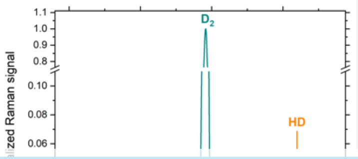

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A 44 (2010) 499

Three co
(a) cov
see PRL 12

KATRIN's success is to a big part based on
extensive intra and interdisciplinary collaboration between physicists specialising
in nuclear, particle and astroparticle physics, atomic, molecular and plasma physics,
surface science as well as metrology, vacuum, detector, radiation safety and
data science experts, electronics and mechanical engineers,
and theorists in the fields of AMO physics, particle and nuclear physics

see talks by Karo Erhardt and Sonja Schneidewind on Sunday

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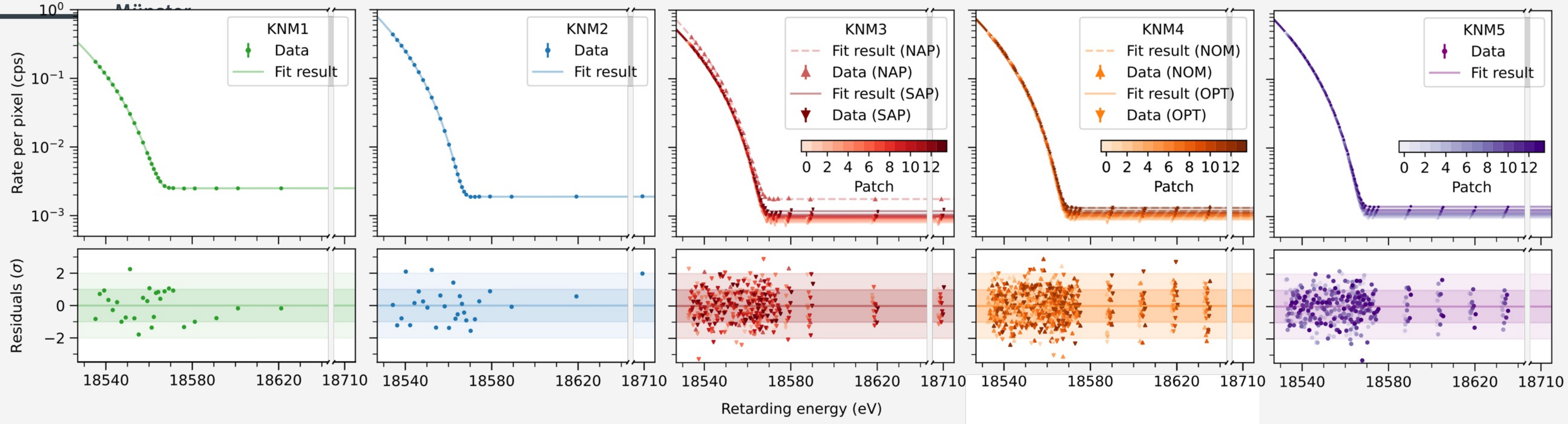
KATRIN KNM1-5



KNM1: *Phys. Rev. Lett. 123 (2019) 221802* KNM2: *Nature Physics 18 (2022) 160*

KNM1-5: ***Science* 388 (2025) 180-185**

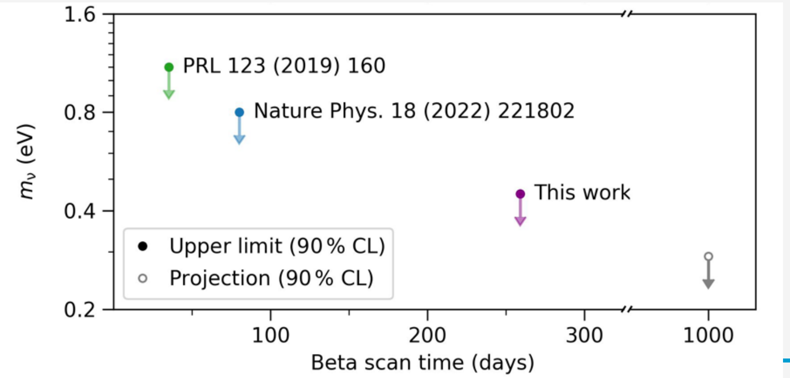
KNM1 to KNM5 campaigns:

$$m^2(\nu) = \left(-0.14^{+0.13}_{-0.15}\right) \text{ eV}^2$$

→ compatible with zero

Lokhov-Tkachov: $m_\nu < 0.45$ **eV (90% CL)**

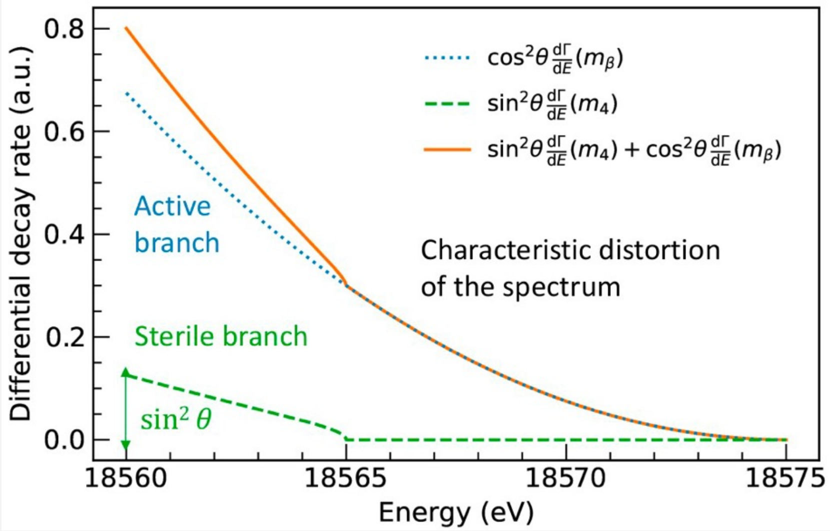
Feldman-Cousins: $m_\nu < 0.31$ eV (90% CL)



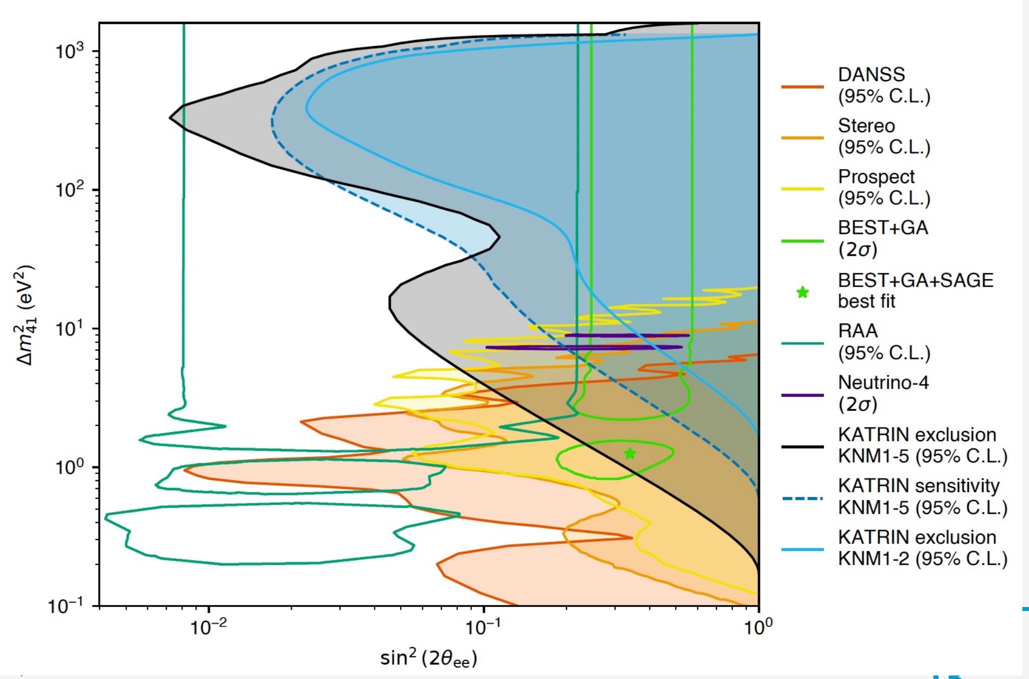
Search for a 4th light sterile neutrino

Sterile neutrinos at eV-scale: a 4[th] state? $\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = U'_{PMNS} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \boldsymbol{\nu_4} \end{pmatrix}$

The motivation comes from
anomalies in short baseline oscillation
accelerator, solar and reactor
neutrino experiments



KATRIN is probing
very interesting parameter space and
challenging the Neutrino-4 claim,
complementary to oscillation searches



Phys. Rev Lett. 126, 091803 (2021)
Phys. Rev. D 105 (2022) 072004
Nature 648 (8092) (2025) 70

Search for physics beyond the neutrino mass

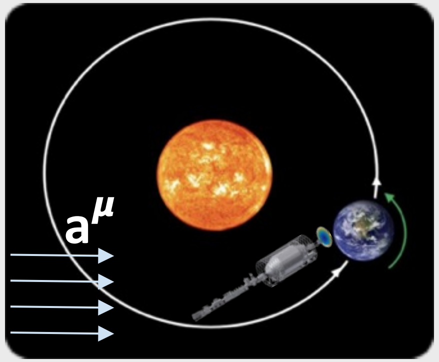
β-spectroscopy at high precision & high stability

Search for **shape distortion** through exotic weak interactions

→ PRL **134** (2025) 251801

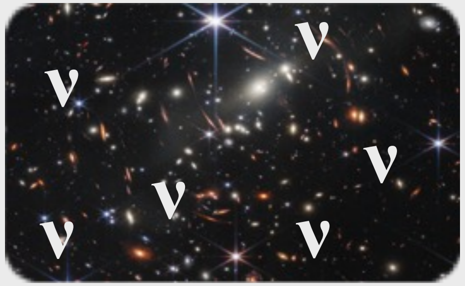
Search for Lorentz violation through **sidereal modulation**

→ PRD **107** (2023) 082005

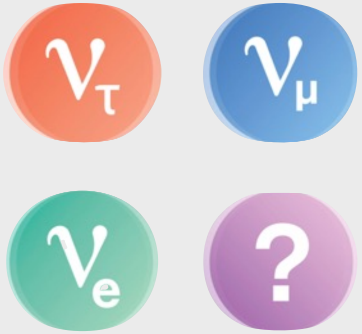


Peak search for capture of local cosmic relic ν search for overdensities

→ PRL **129** (2022) 011806



“Kink” search for fourth (sterile) neutrino



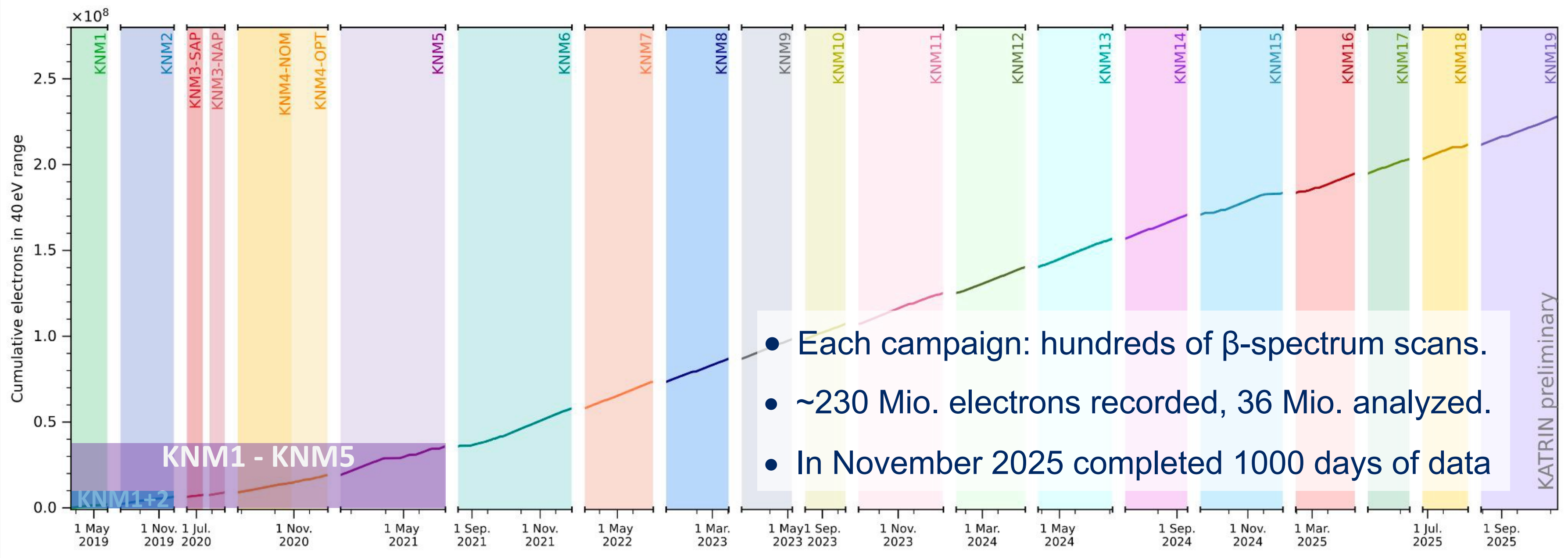
eV mass scale:

→ PRL **126** (2021) 091803
Nature **648**, 8092 (2025) 70

keV mass scale:

→ EPJ C **83** (2023) 763

KATRIN final data sensitivity with 1000days of measurement up to end of 2025: $m_\nu < 0.3$ eV



April 2026: Celebrating the 1000 days of KATRIN data and transition to KATRIN phase 2 with the TRISTAN detector

166-pix module

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Next measurement phase of KATRIN:
dedicated search for sterile keV neutrinos 2026-2028

4^{th} mass eigenstate of neutrino mixed with flavour eigenstates

➞ BSM particle, dark matter candidate

Look for the kink in the β-spectrum

Target sensitivity of $sin^2\,\theta < 10^{-6}$

➞ dedicated search for sterile keV neutrinos in 2026/27

Requires a new detector & DAQ system "TRISTAN" with

- large count rates
- **excellent energy resolution:**

  >1000 pixels silicon drift detector (SDD)

  with an energy resolution of 300 eV (FWHM)

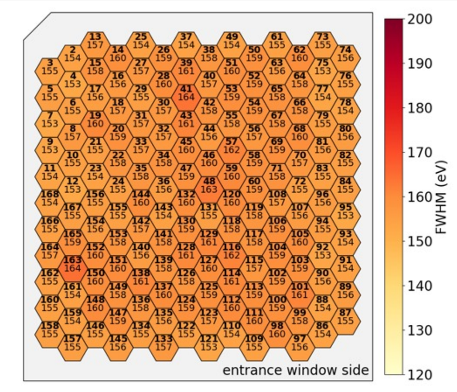
NIM A 1049 (2023) 168046

NIM A 1025 (2022) 166102

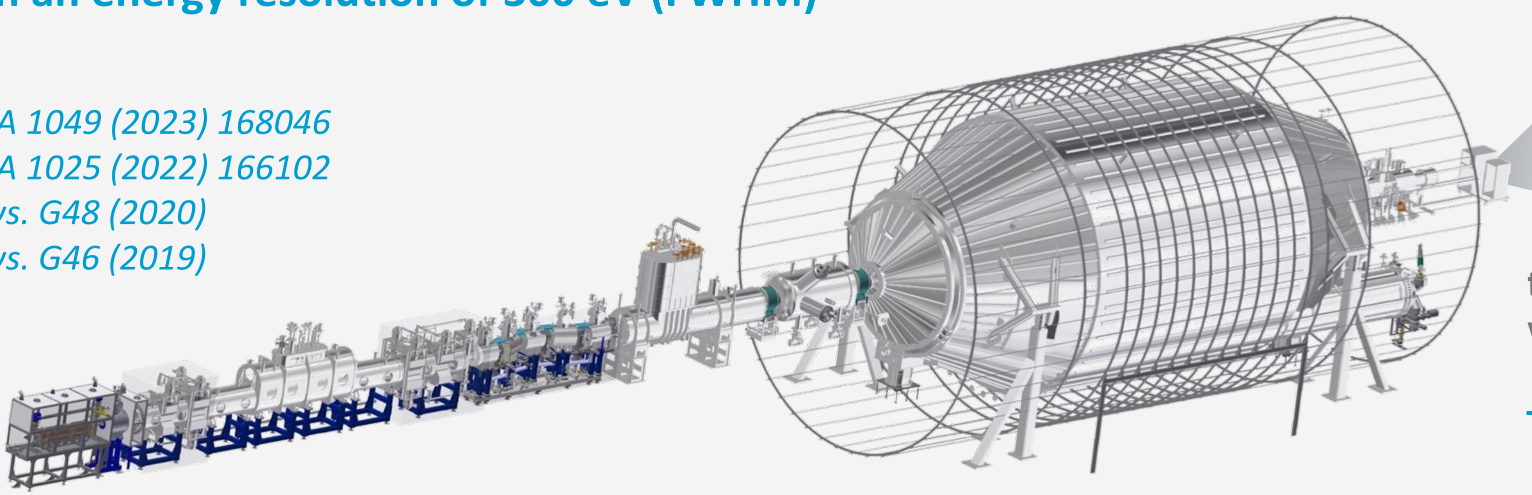
J. Phys. G48 (2020)

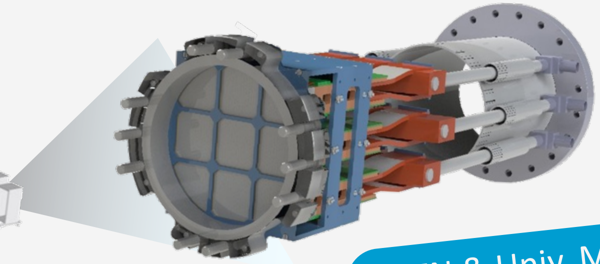
J. Phys. G46 (2019)

Successfully tested first prototype module at KATRIN's monitor spectrometer



replica beamline for system characterization

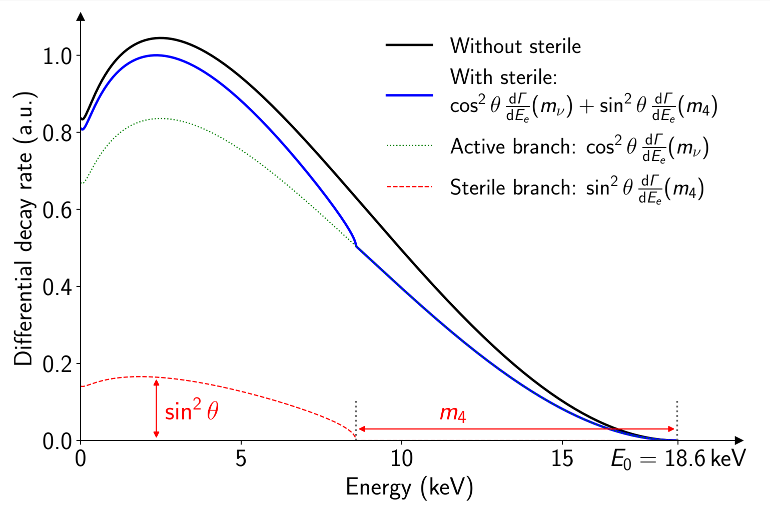


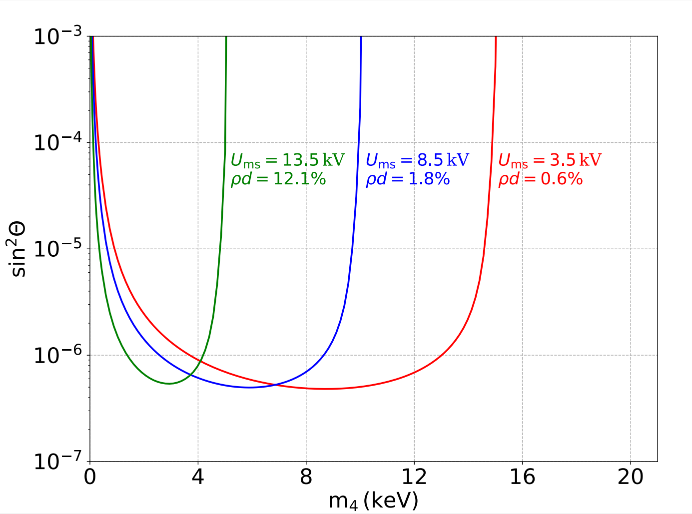


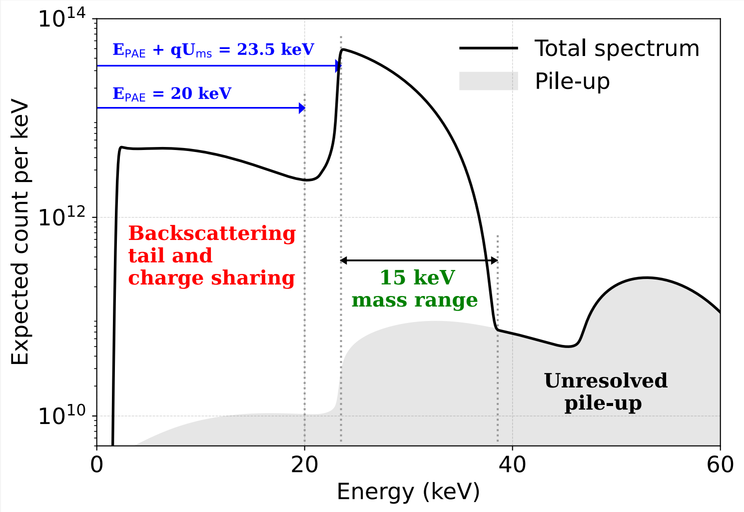
tower assembly with 9 modules

INFN & Univ. Milano Bicocca, Politecnico di Milano: Frontend ASICs incl. "ETTORE" boards

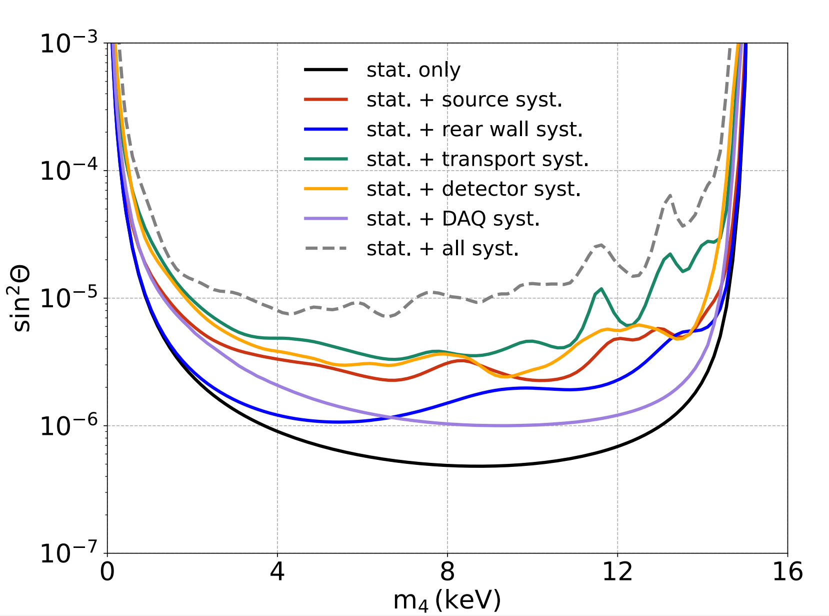
Sterile keV neutrino sensitivity: KATRIN with TRISTAN

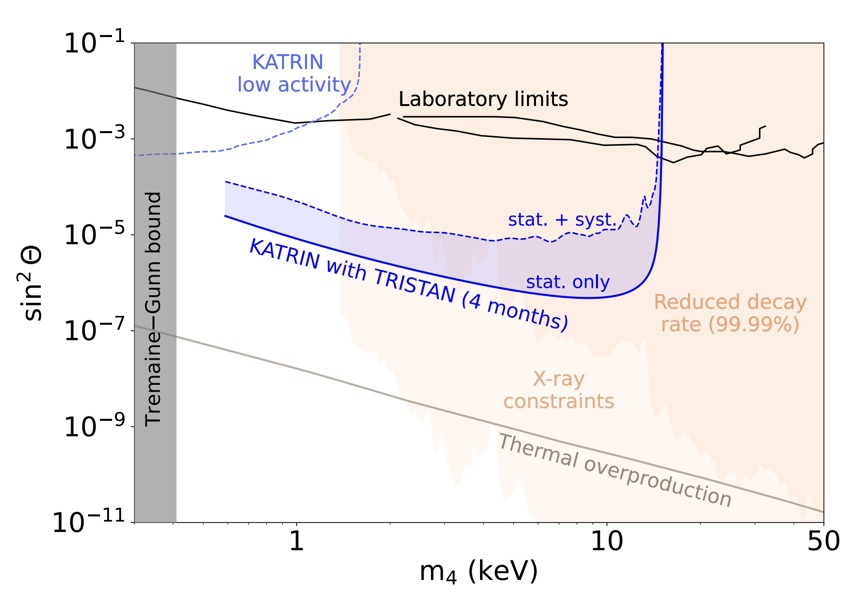






arXiv:2603.23256, accepted for publication by EPJ C





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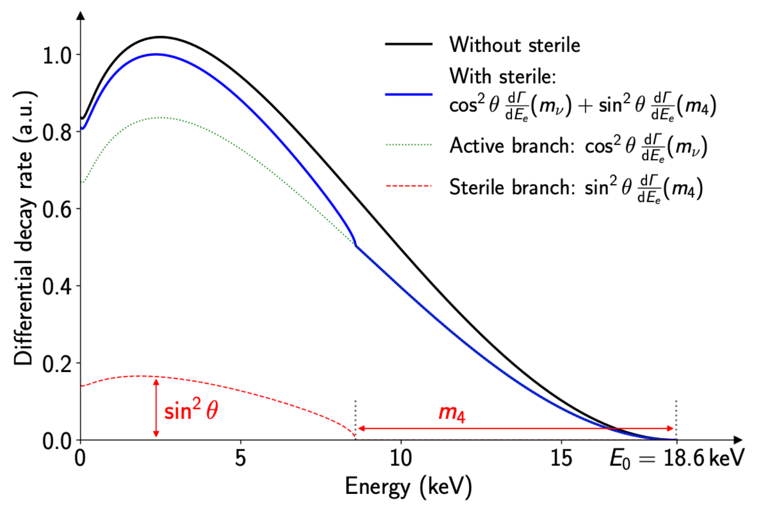
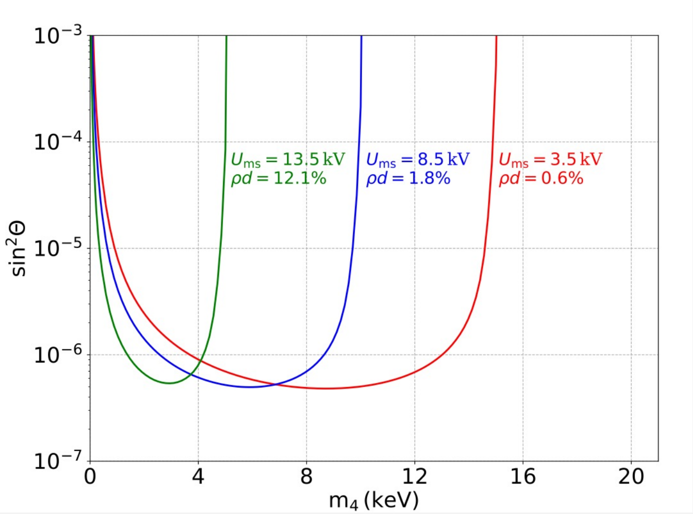
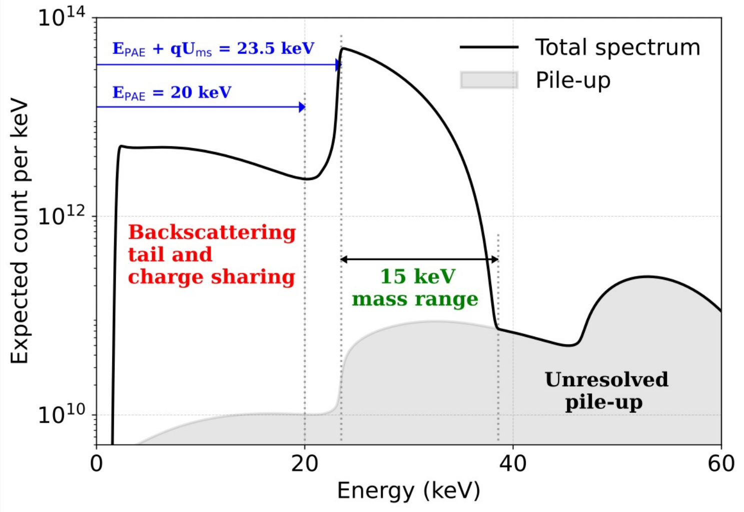
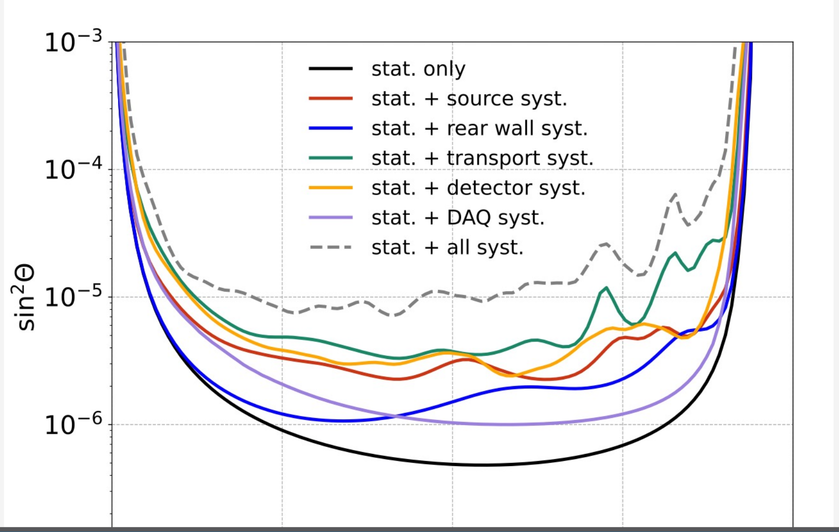
Sterile keV neutrino sensitivity: KATRIN with TRISTAN

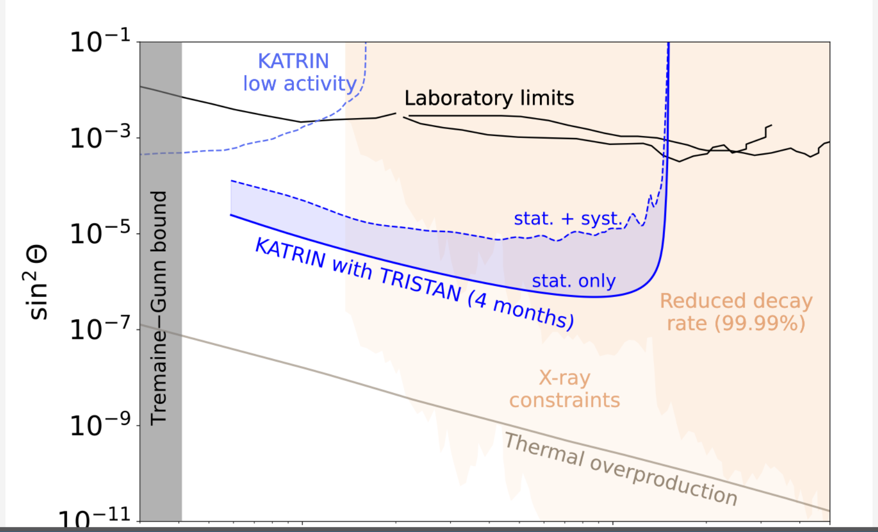






arXiv:2603.23256, accepted for publication by EPJ C





Implement in KATRIN beamline for measurements starting 2026-2027

Next steps in direct neutrino mass searches ?

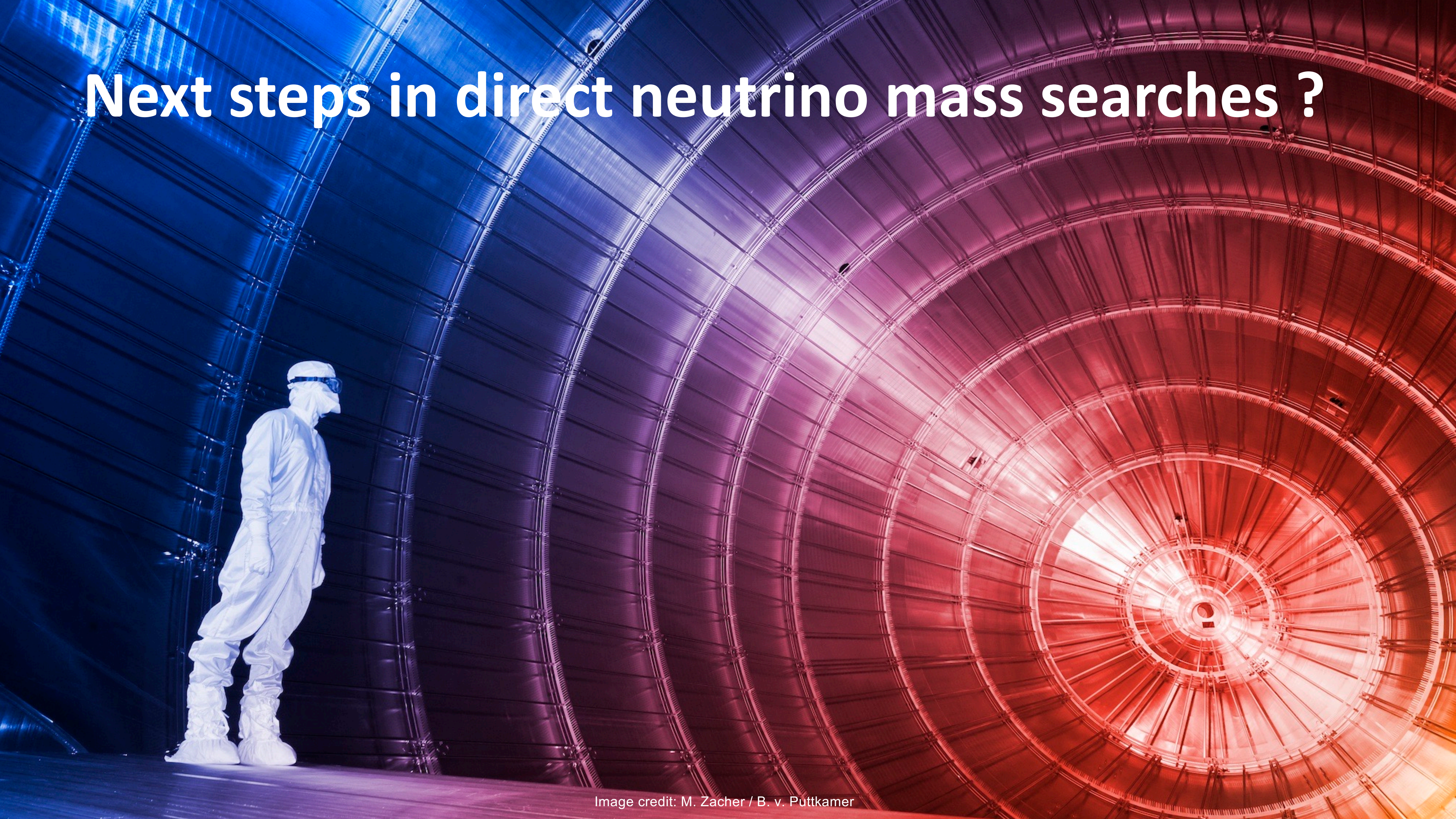


Image credit: M. Zacher / B. v. Puttkamer

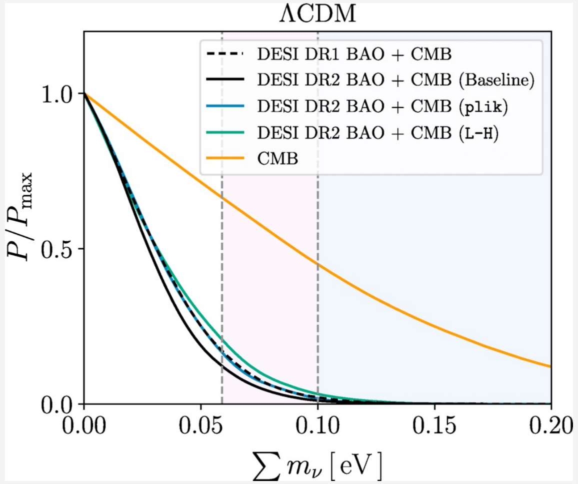
Next steps in direct neutrino mass searches

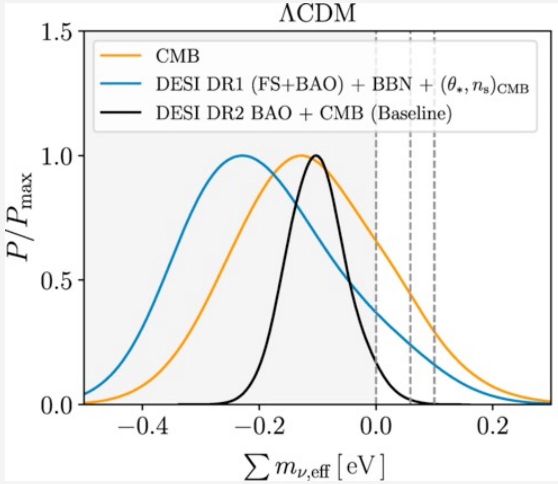
FEATURED IN PHYSICS | EDITORS' SUGGESTION | OPEN ACCESS

Constraints on neutrino physics from DESI DR2 BAO and DR1 full shape

W. Elbers[1], A. Aviles[2,3], H. E. Noriega[2,4], D. Chebat[5], A. Menegas[1], C. S. Frenk[1], C. Garcia-Quintero[6,*], D. Gonzalez[7], M. Ishak[8] *et al.* (DESI Collaboration)

Phys. Rev. D 112, 083513 (2025)



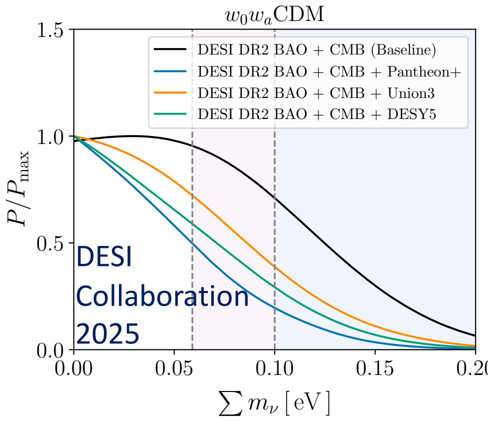


$\Sigma m_\nu < 0.064$ **eV (at 95% C.L.) from DESI+CMB (Planck)**

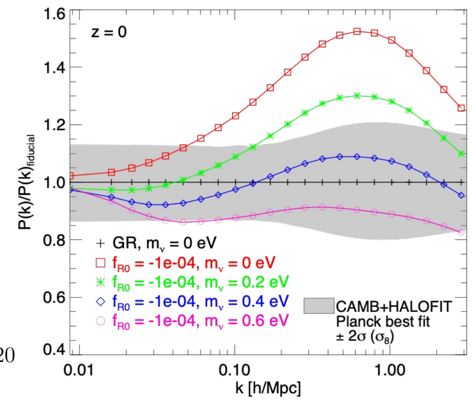
Maria Archidiacono, Erice 2026:

Cosmology is a remarkably powerful laboratory for neutrino physics, but its constraints are model–dependent and affected by astrophysics and observational systematics.

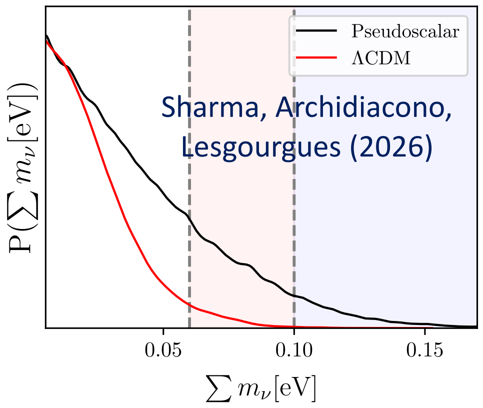
→ The complementarity with terrestrial neutrino experiments is therefore key to a robust determination of neutrino properties.



Beyond ΛCDM

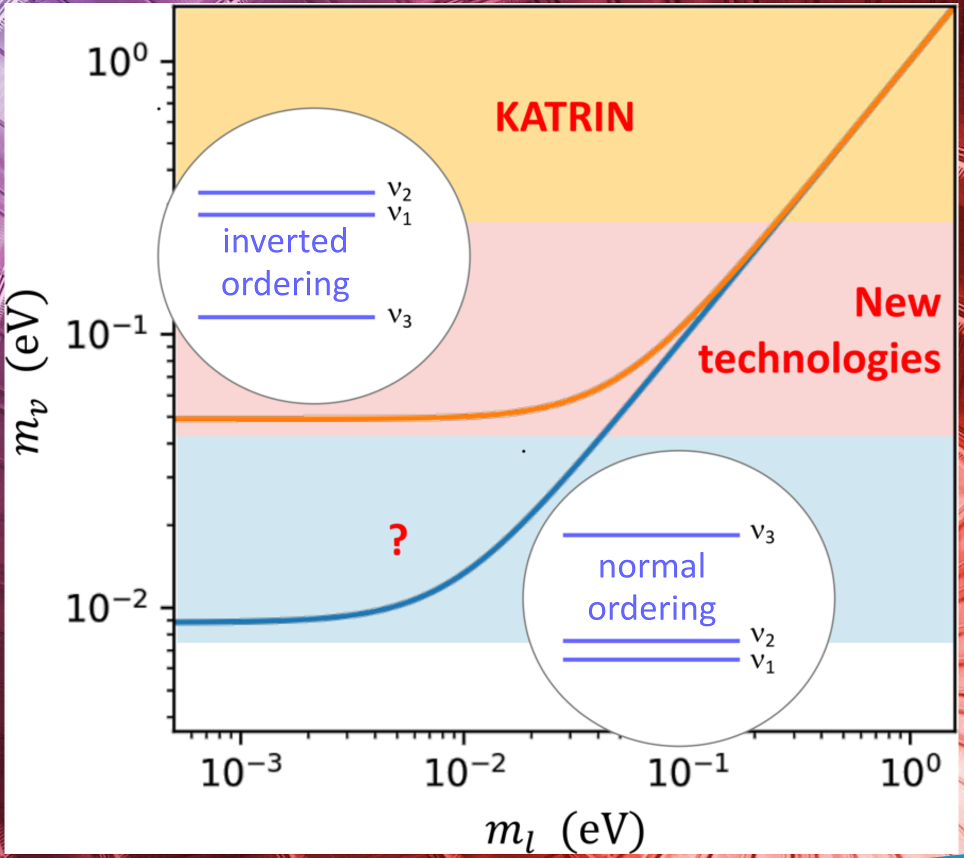


Beyond GR



Beyond SM

Next steps in direct neutrino mass searches ?

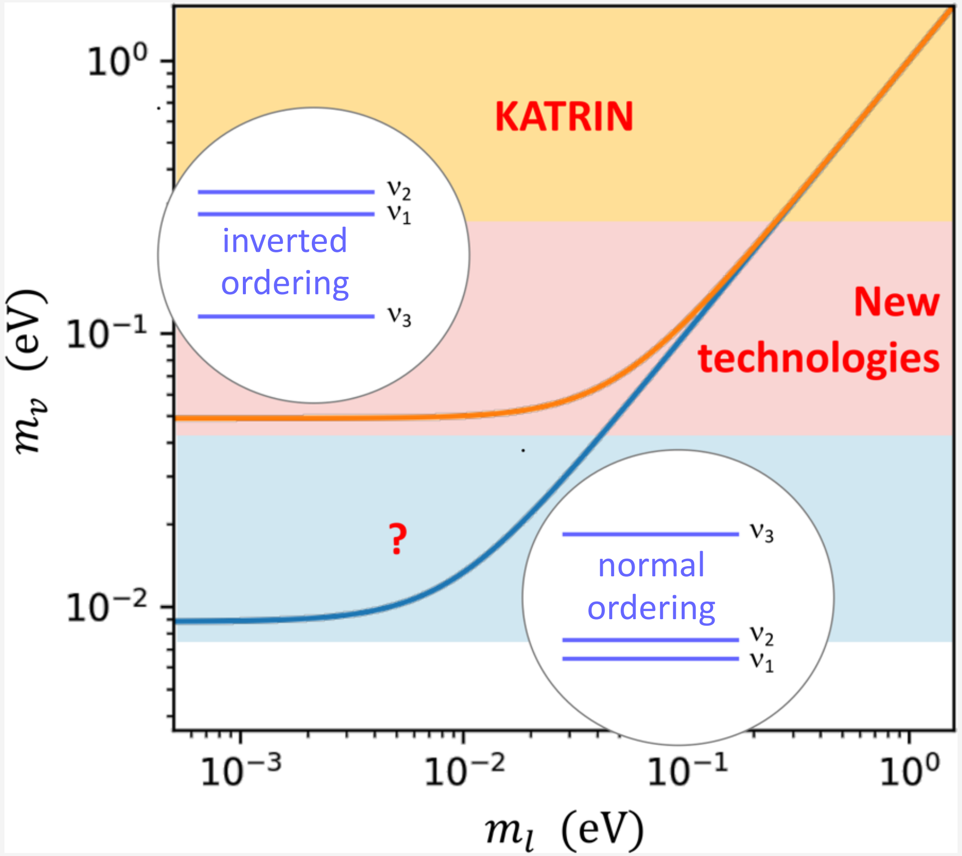


see talk by Juliana Stachurska on Thursday

Image credit: M. Zacher / B. v. Puttkamer

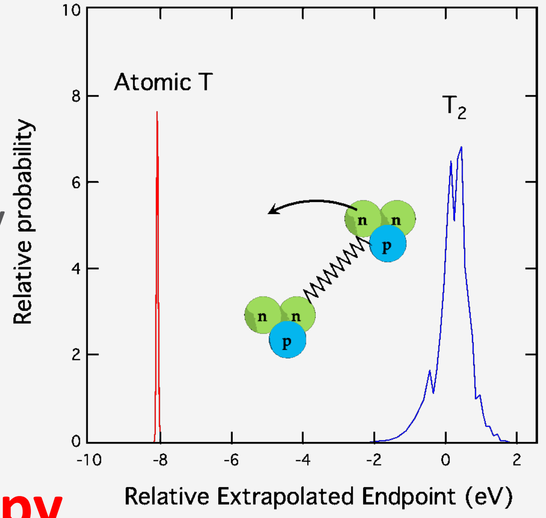
KATRIN++: smart upgrade of KATRIN with an atomic tritium source and a sub-eV differential spectrosopy by quantum technology

Universität Münster



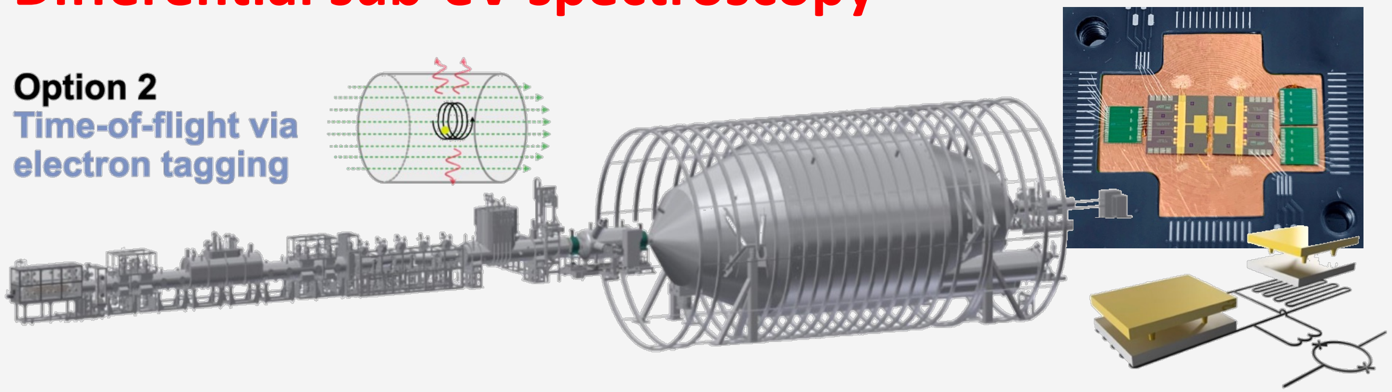
A) Atomic tritium source

to avoid ro-vibrational broadening of final states of T_2-decay



B) Differential sub-eV spectroscopy

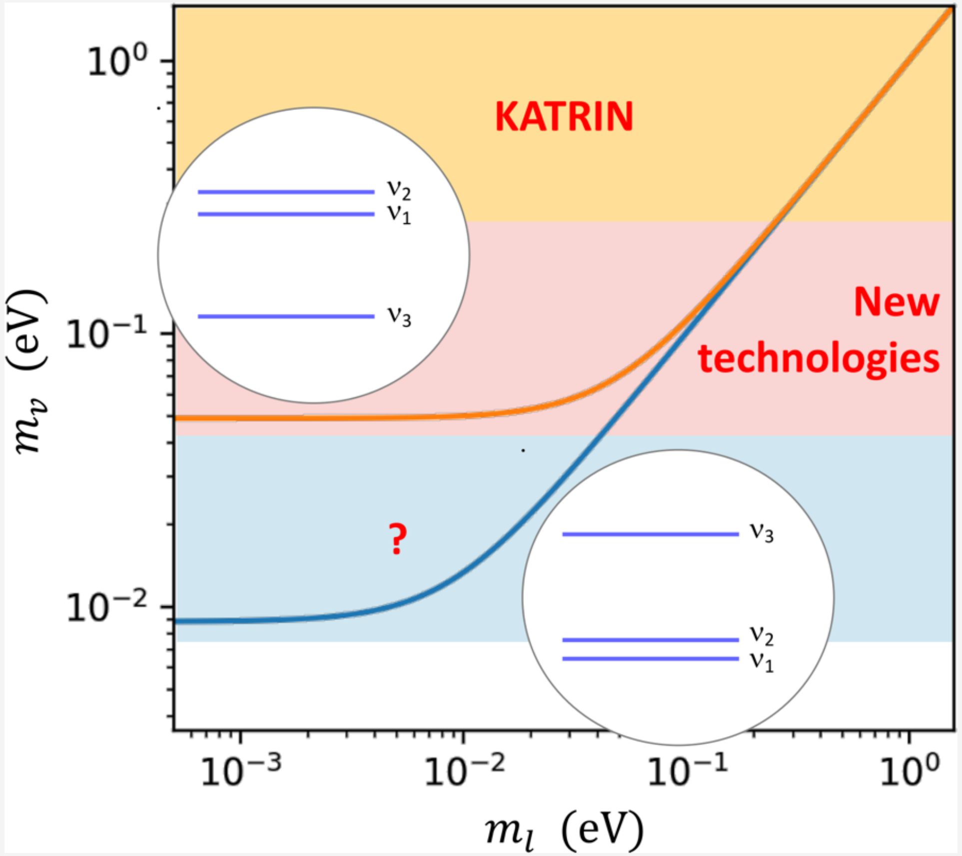
Option 2
Time-of-flight via electron tagging

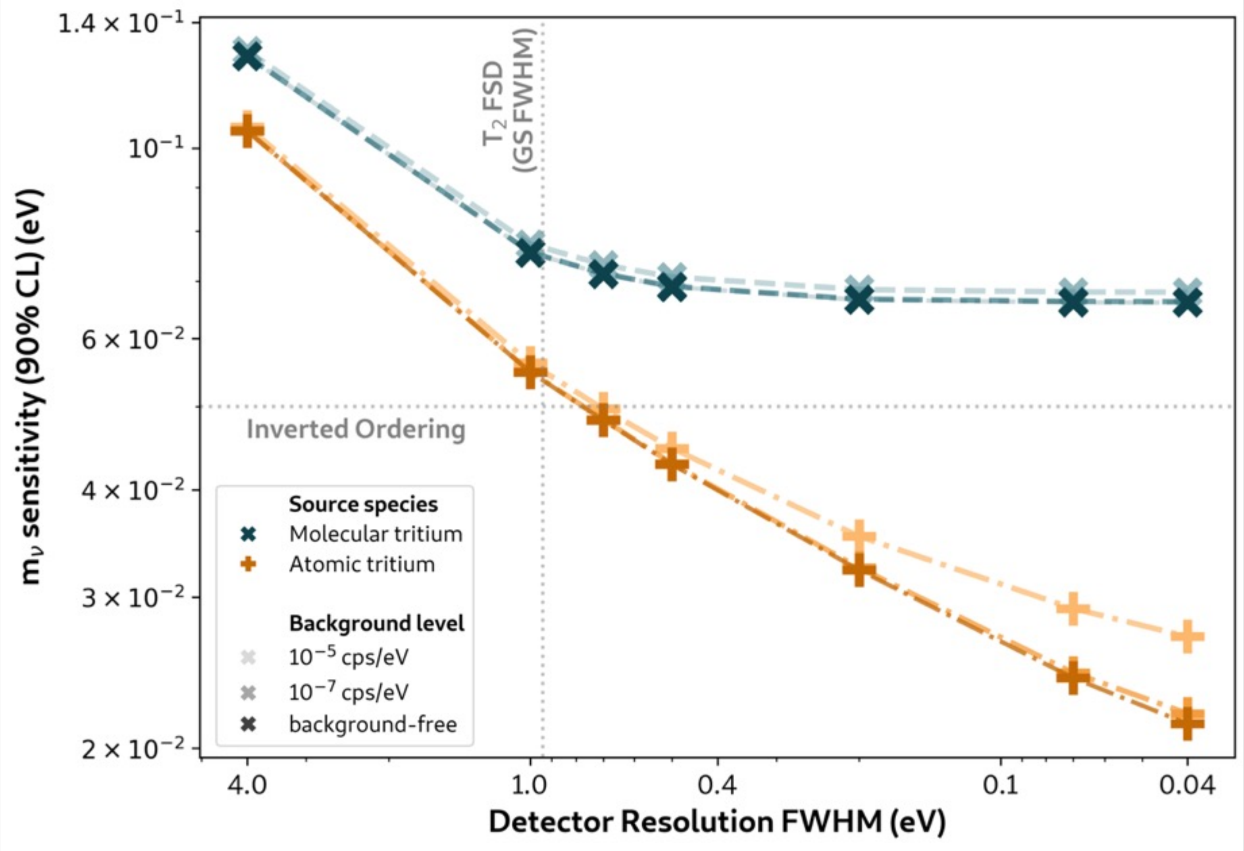


- eV resolution for **differential** detection
- **immune to** Rydberg-like **backgrounds**

Option 1
Micro-calorimeters / Quantum sensor

KATRIN++: smart upgrade of KATRIN with an atomic tritium source and a sub-eV differential spectrosopy by quantum technology





studies by S. Heyns, N. Kovac, C. Goupy, S. Mertens et al.

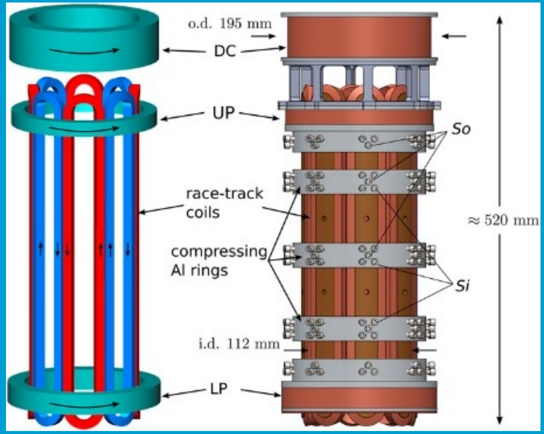
Atomic tritium pathfinder

Goal: Demonstration of production of cryogenic T-atom (>10^{15} s^{-1}) and trapping at relevant (>10^{13} cm^{-3})

Cryogenic source of atomic tritium & multipole trap

- Cryogenic discharge in 100 mK-cryostate for T-generation
- T-cooling with He-gas
- T-Trapping in liter-size multipole trap

A. Semakin et al, Phys. Rev. Research 8 (2026) 033096



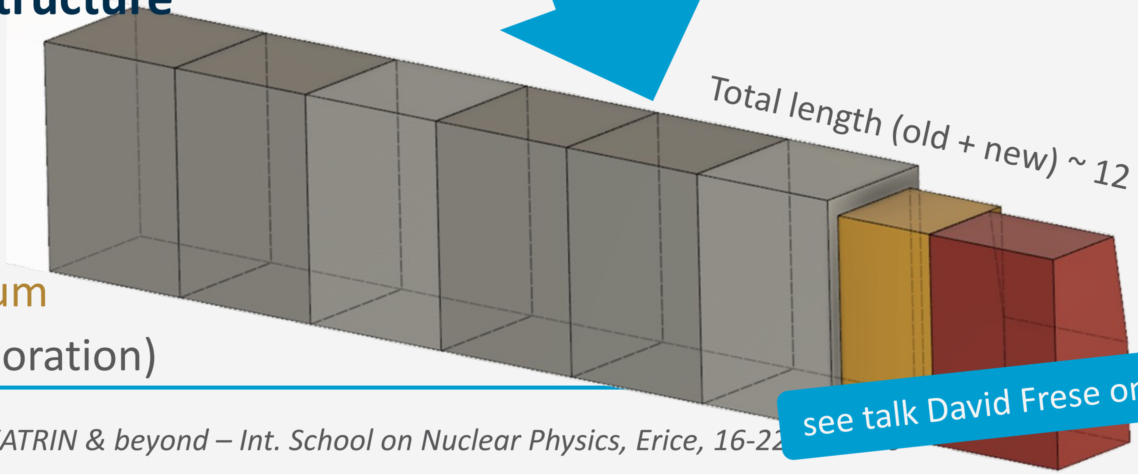
J. Ahokas *et al.*, *Rev. Sci. Instrum.* **93** (2022) 023201

Partnered with world-leading experts

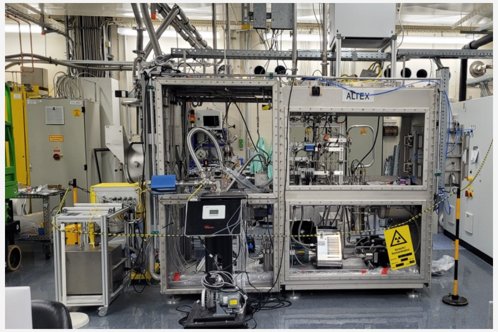
- Atomic hydrogen (U Turku, LKB Paris, SMI Vienna)
- Project 8, QTNM
- Tritium plasma (IPP Garching)

Atomic Tritium Pathfinder infrastructure

- 12 m glove box train
- 1:10 KATRIN tritium circulation loop
- TLK infrastructure connection
- Ongoing experiments with atomic tritium (**Karlsruhe Mainz AtomicTritium** collaboration)



TLK infrastructure



Simple dissociator + tritium supp

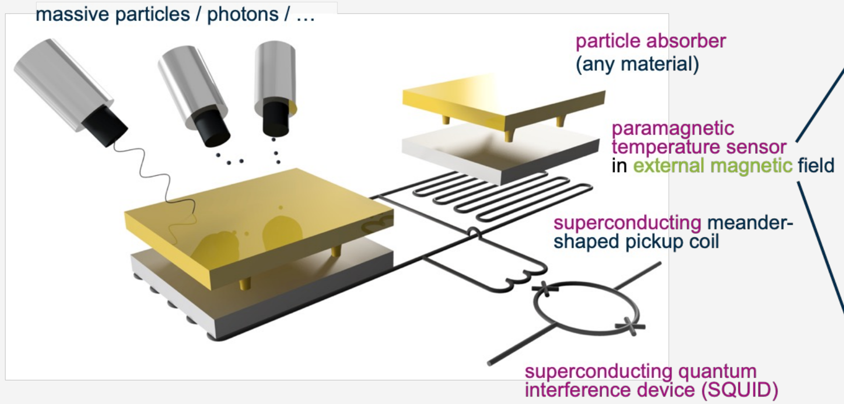
courtesy M. Schlösser

see talk David Frese on Sunday

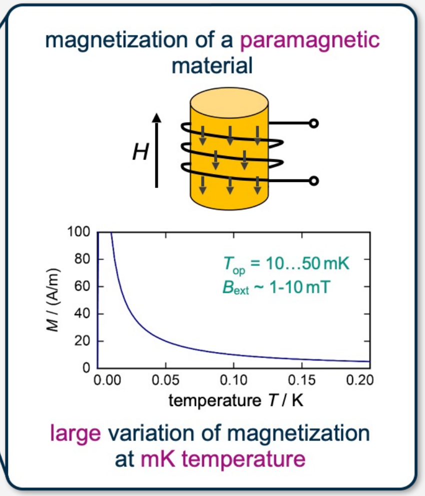
Universität Münster

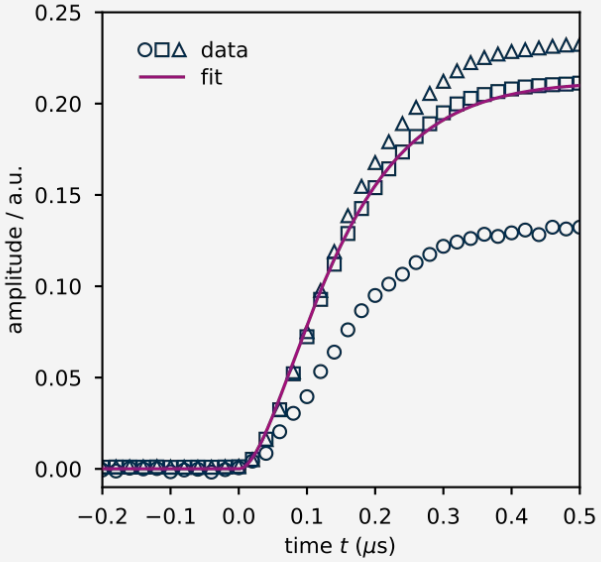
MMC detectors at KIT

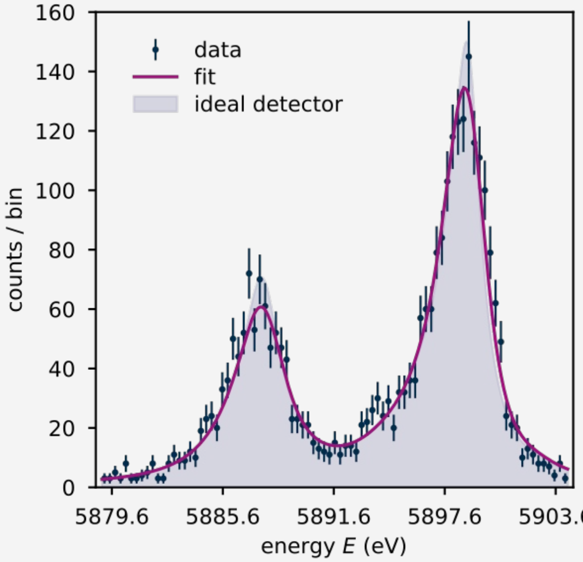
Karlsruhe Institute of Technology

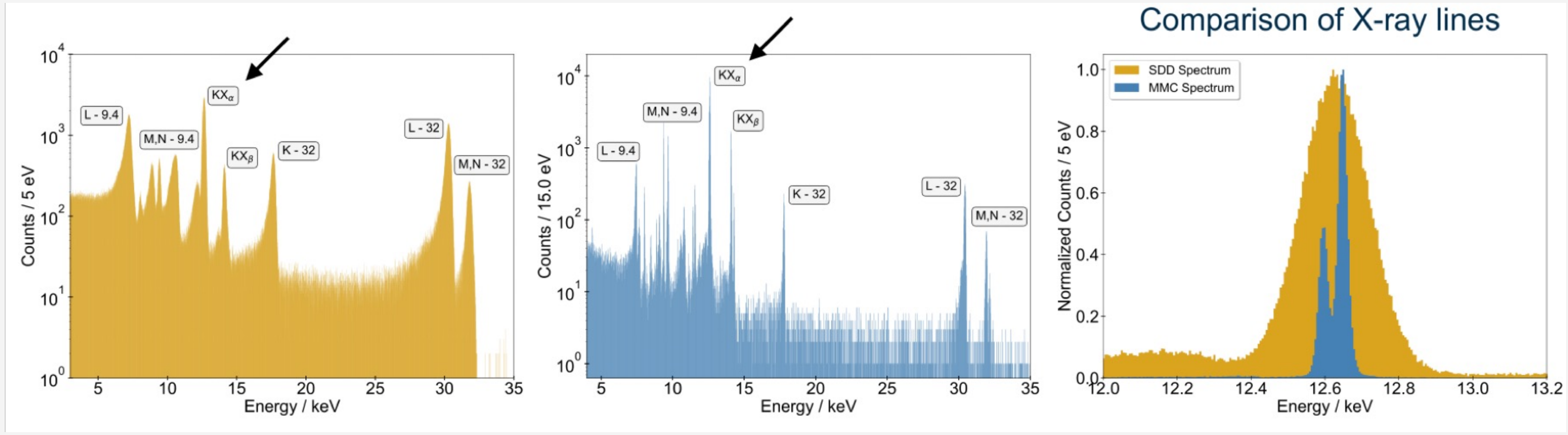


energy resolution: $\Delta E_{\mathrm{FWHM}} \simeq 2.36\sqrt{4k_{\mathrm{B}}C_{\mathrm{abs}}T^2}\sqrt{2}\left(\frac{\tau_0}{\tau_1}\right)^{\frac{1}{4}}$









N. Kovač et al., NIM A 1080 (2025)

*M. Krantz et al, Appl. Phys. Lett. **124** (2024) 032601*

*F. Toschi et al, Phys. Rev. D **109** (2024) 043035*

*S. Kempf et al, J. Low Temp. Phys. **193** (2018) 365*

courtesy S. Kempf

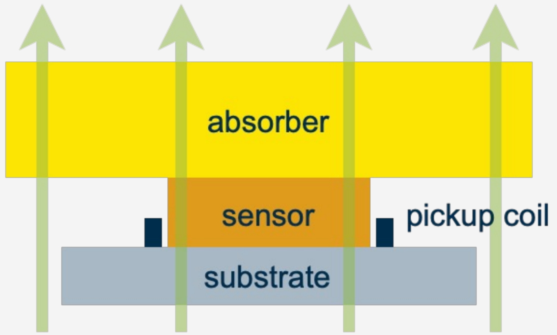
MMC detector array for KATRIN++

Requirements:

- sub eV detector energy resolution (FWHM)
- detection of external electrons: backscattering, detector response, …
- QSA operation in ambient magnetic field (required for adiabatic electron guiding)
- flux tube conservation: area vs. *B*-field strength → many pixels with multiplexing readout
- room-temperature electron ‚source': windowless warm-cold interface (cryo-chicane)
- energy resolution must be known to a level better than 1% (for all pixels): calibration challenge

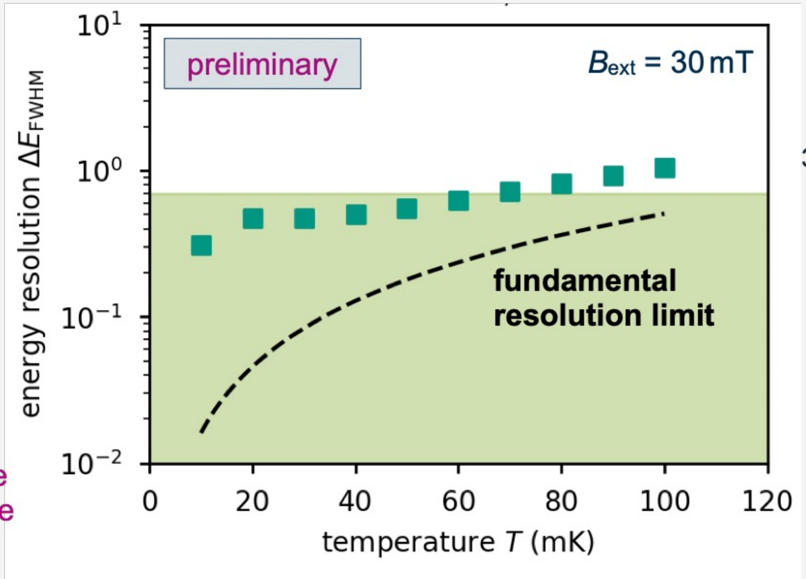
cylindrical temperature sensor

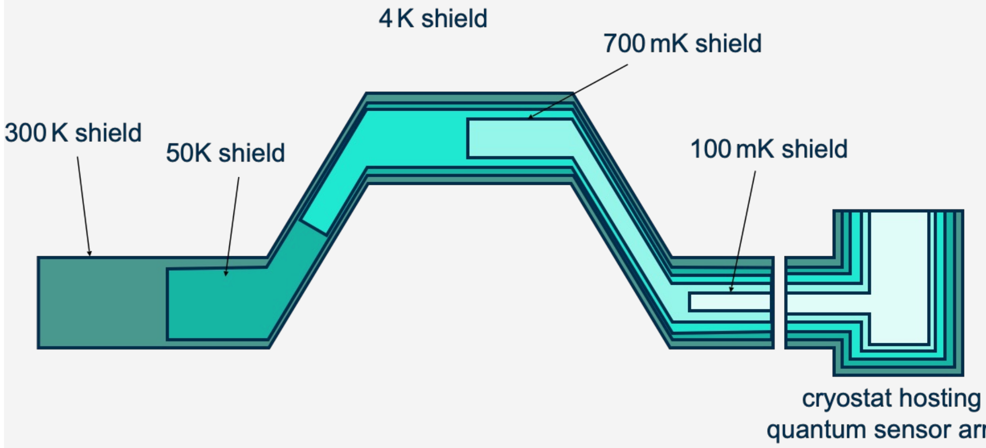
exploit magnetic background field for temperature sensor biasing



more sophisticated sensor geometries and alternative absorber materials might allow to significantly advance energy resolution and enlarge active pixel area

example: bismuth absorber with $V_{\mathrm{abs}} = 200\,\mu\mathrm{m} \times 200\,\mu\mathrm{m} \times 2\,\mu\mathrm{m}$

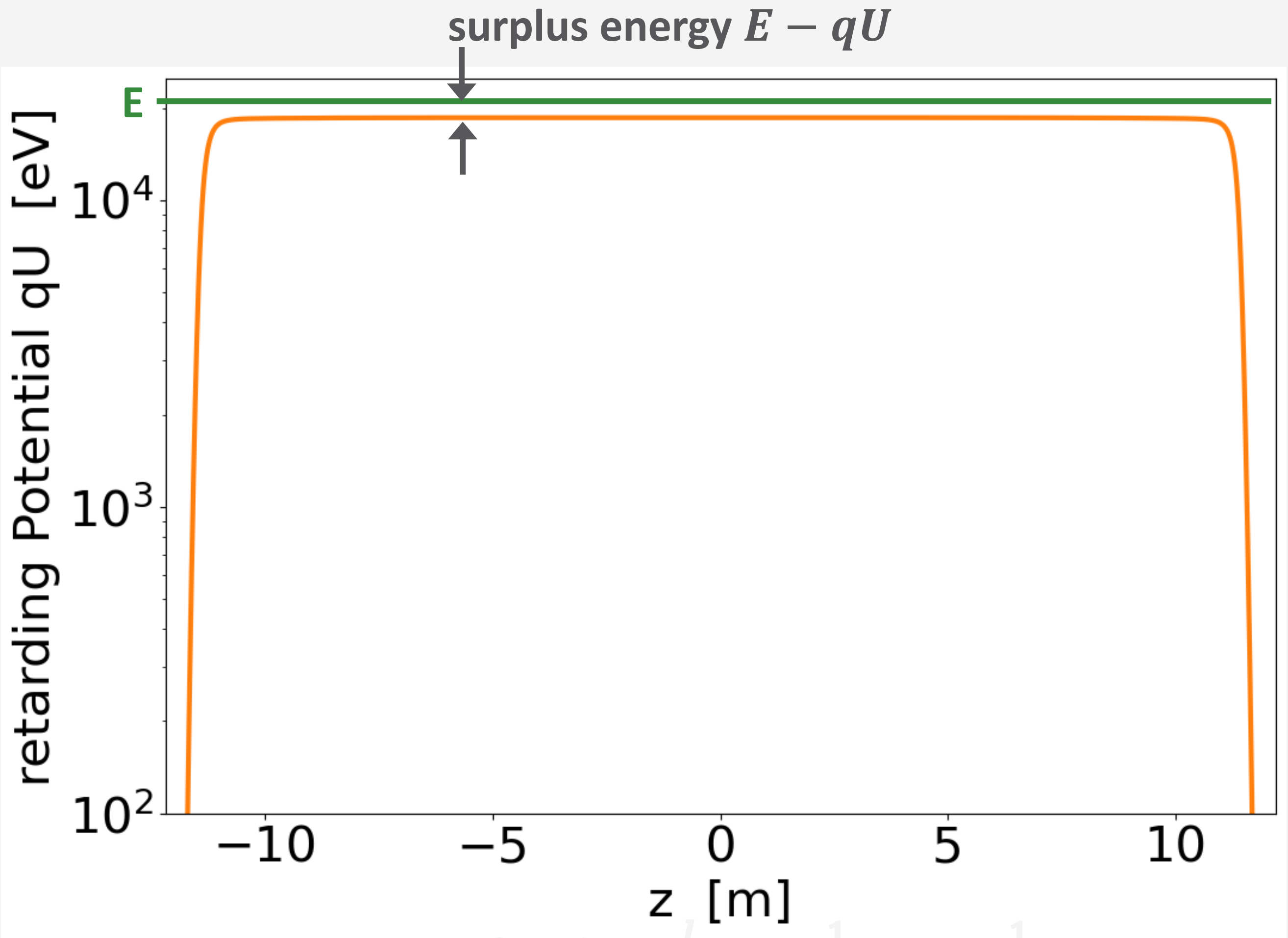




courtesy S. Kempf

MAC-E-filter with retarding potential

→ time-of-flight is long and can provide differential spectrum



Electrons at the tritium endpoint (18.6 keV) have a velocity of $v \approx {}^1/_4\, c = 13\ {}^{ns}/_{\mu s}$ but they are strongly retarded in the main spectrometer

→ time-of-flight (tof) depends strongly on the surplus energy respect to the retarding potential qU

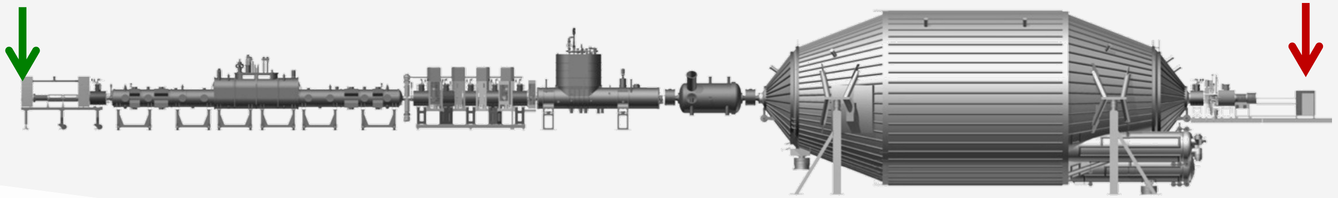
$$\text{tof} \coloneqq \Delta t = \frac{l}{v} \propto \frac{1}{\sqrt{E - qU}} = \frac{1}{\sqrt{E_{\parallel,ana}}}$$

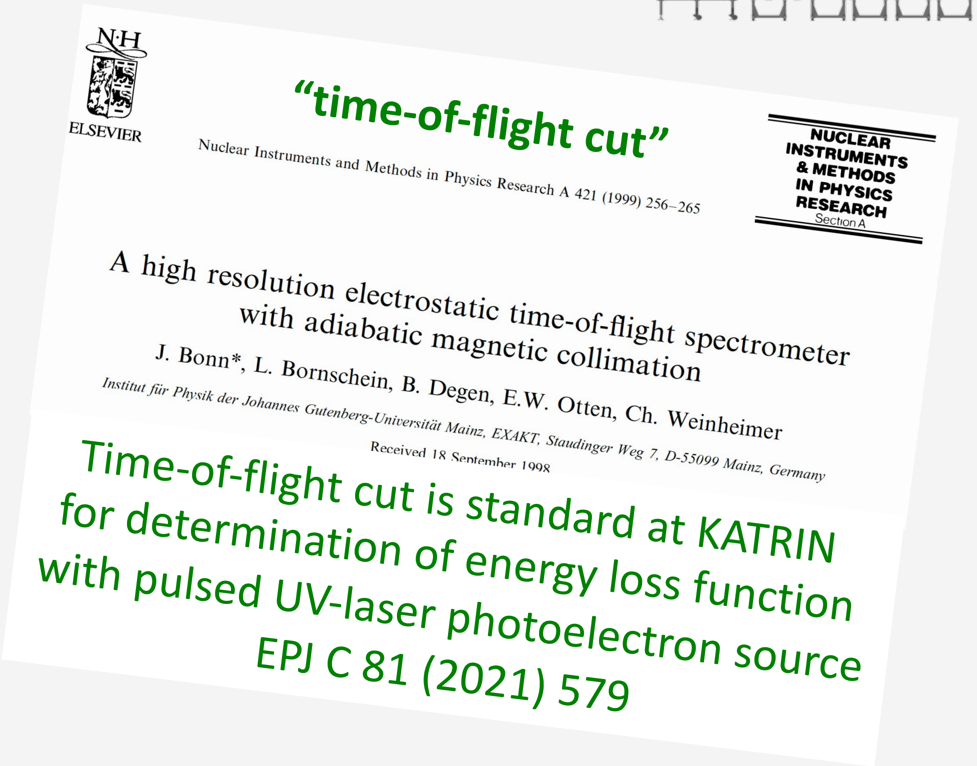
New ideas towards differential spectroscopy

Alternative path: Time-of-flight is quasi-differential due to the strong retarding in spectrometer

pulsed e-gun

stop signal by detector




"time-of-flight cut"

Nuclear Instruments and Methods in Physics Research A 421 (1999) 256–265

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

A high resolution electrostatic time-of-flight spectrometer with adiabatic magnetic collimation

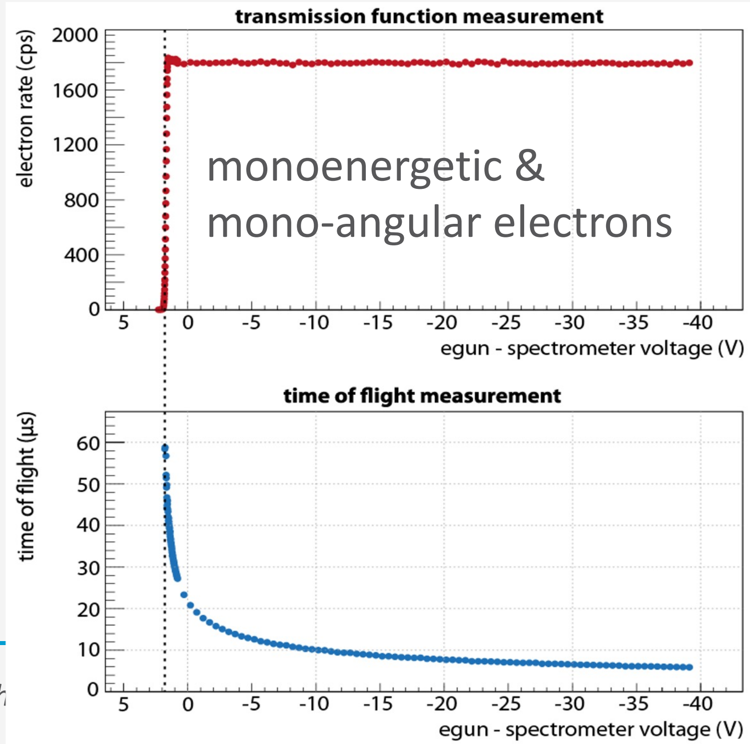
J. Bonn*, L. Bornschein, B. Degen, E.W. Otten, Ch. Weinheimer

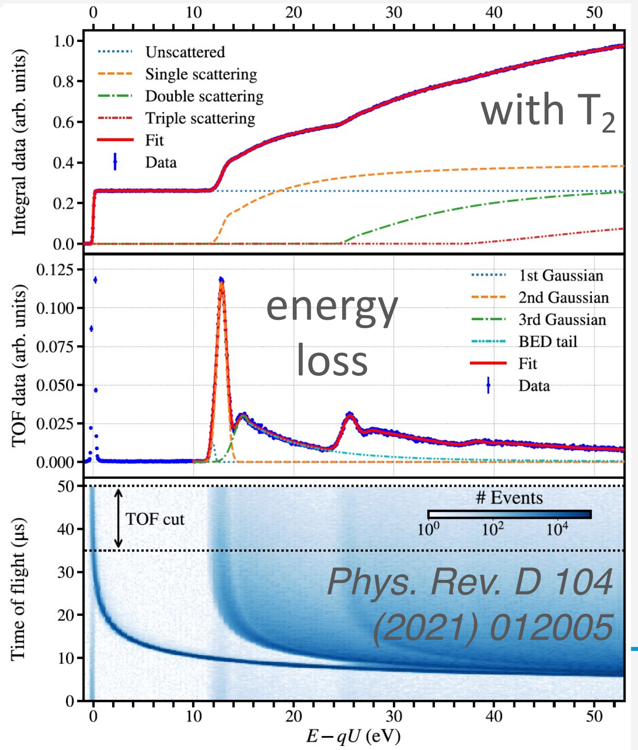
Institut für Physik der Johannes Gutenberg-Universität Mainz, EXAKT, Staudinger Weg 7, D-55099 Mainz, Germany

Received 18 September 1998

Time-of-flight cut is standard at KATRIN for determination of energy loss function with pulsed UV-laser photoelectron source

EPJ C 81 (2021) 579





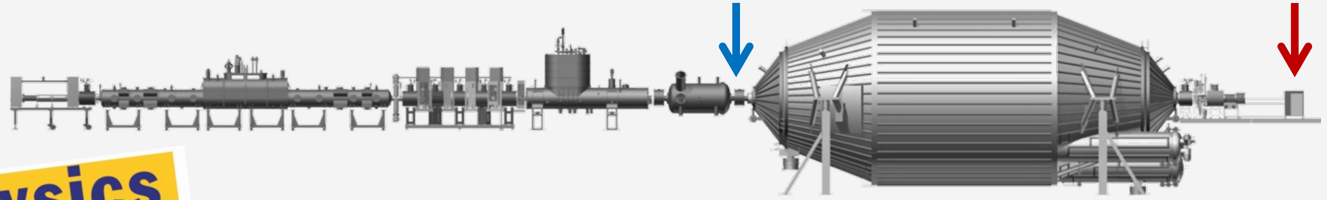
Universität Münster

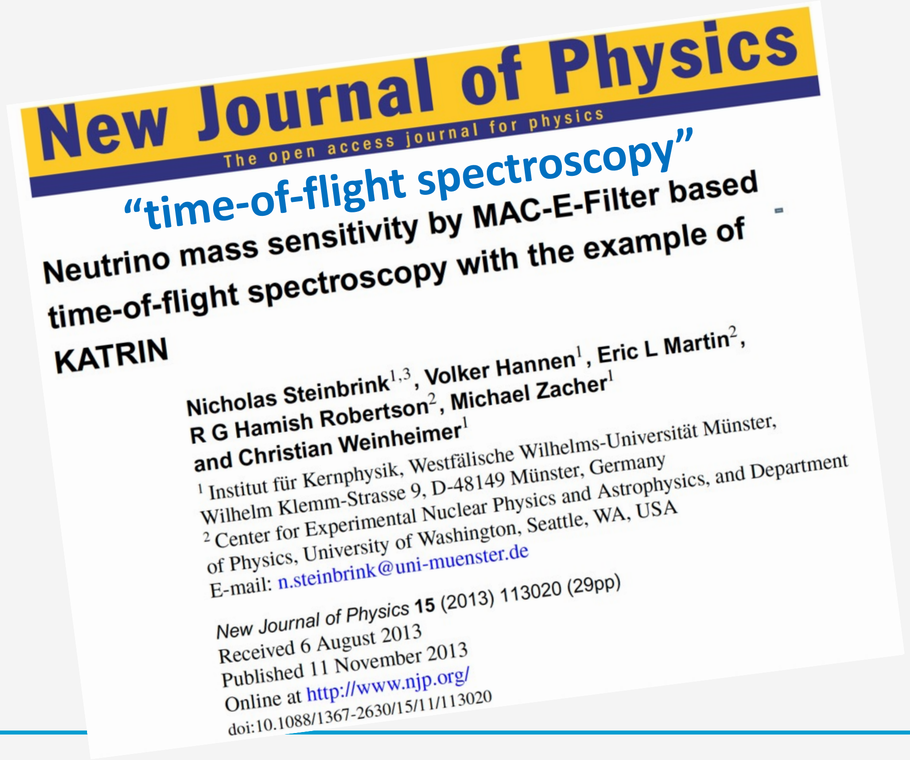
New ideas towards differential spectroscopy

Alternative path: Time-of-flight is quasi-differential due to the strong retarding in spectrometer

rate: ≈ 1000 cps
start signal by ``electron tagger”

stop signal
by detector




New Journal of Physics
The open access journal for physics

“time-of-flight spectroscopy”

Neutrino mass sensitivity by MAC-E-Filter based time-of-flight spectroscopy with the example of KATRIN

Nicholas Steinbrink[1,3], Volker Hannen[1], Eric L Martin[2], R G Hamish Robertson[2], Michael Zacher[1] and Christian Weinheimer[1]
[1] Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, Wilhelm Klemm-Strasse 9, D-48149 Münster, Germany
[2] Center for Experimental Nuclear Physics and Astrophysics, and Department of Physics, University of Washington, Seattle, WA, USA
E-mail: n.steinbrink@uni-muenster.de

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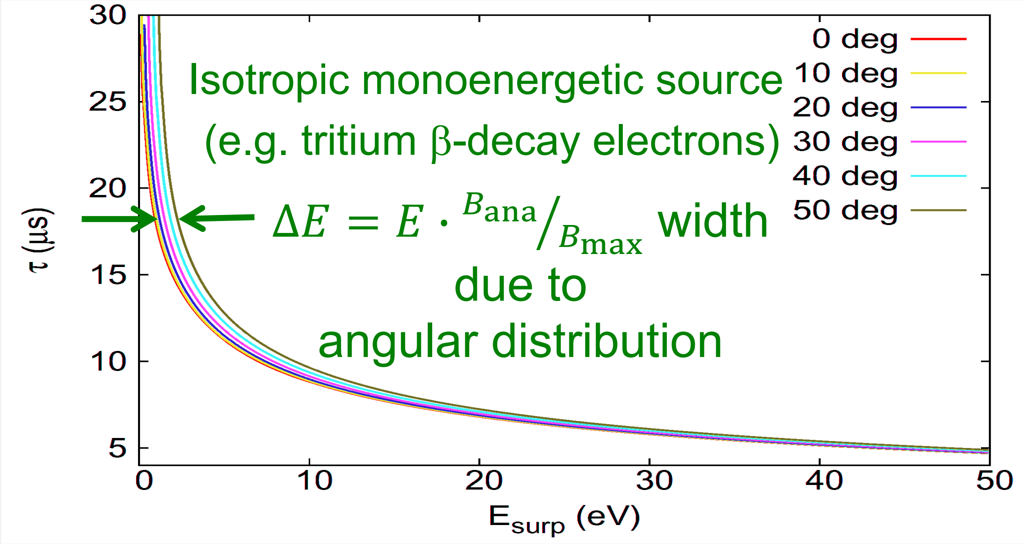
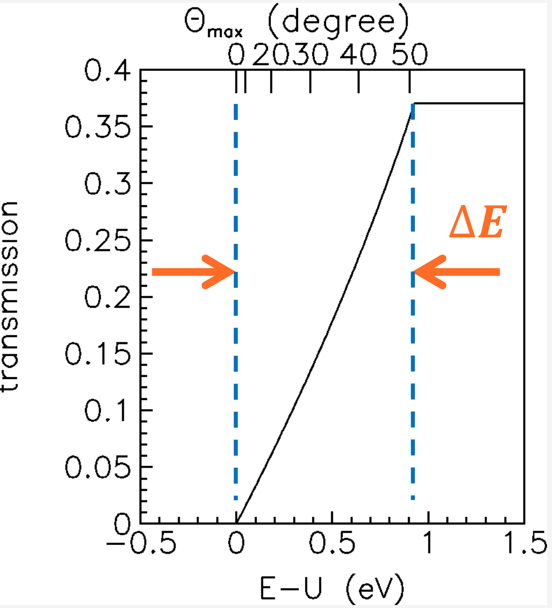
Received 6 August 2013
Published 11 November 2013
Online at http://www.njp.org/
doi:10.1088/1367-2630/15/11/113020



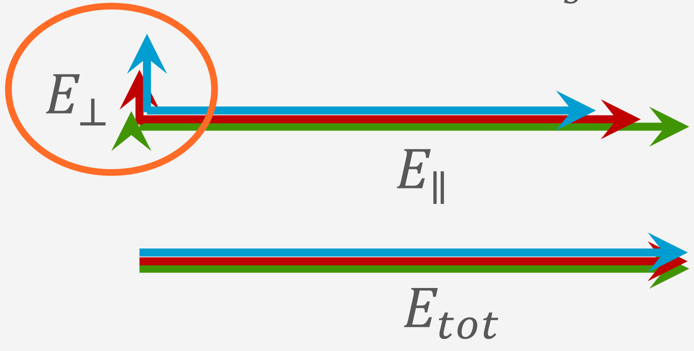
→ about a factor 2 improvement on m_ν possible

Overcome the energy resolution limit of a MAC-E-Filter

by a TEC for an isotropically emitting source with angles $\vartheta_s \leq \vartheta_{max}$



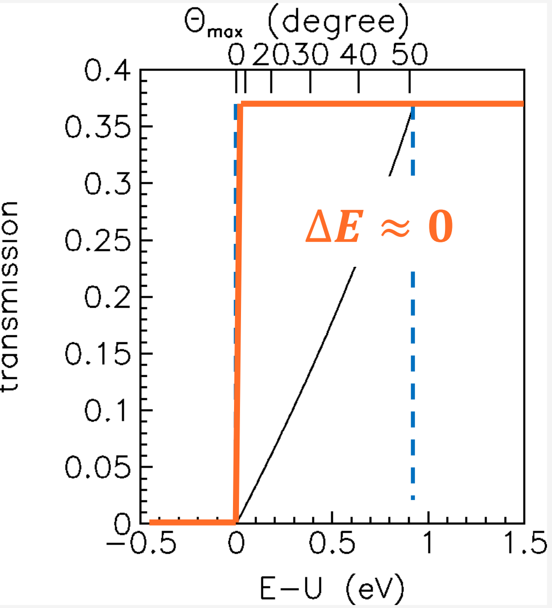
Problem: $E_{\parallel,missing,\vartheta_s} = E_{\perp,ana,\vartheta_s} = \frac{B_A}{B_S} \cdot E_{\perp,s} = \frac{B_A}{B_S} \cdot sin^2\vartheta_s \cdot E \propto sin^2\vartheta_s \approx \vartheta_s^2 - \mathcal{O}(\vartheta_s^4)$



$\vartheta_{start} = 0°, 30°, 51°$

Overcome the energy resolution limit of a MAC-E-Filter

by a TEC for an isotropically emitting source with angles $\vartheta_s \leq \vartheta_{max}$



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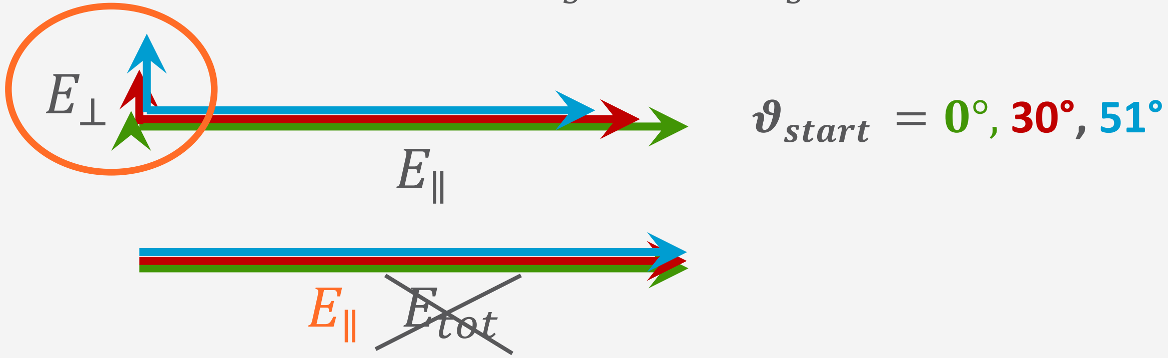

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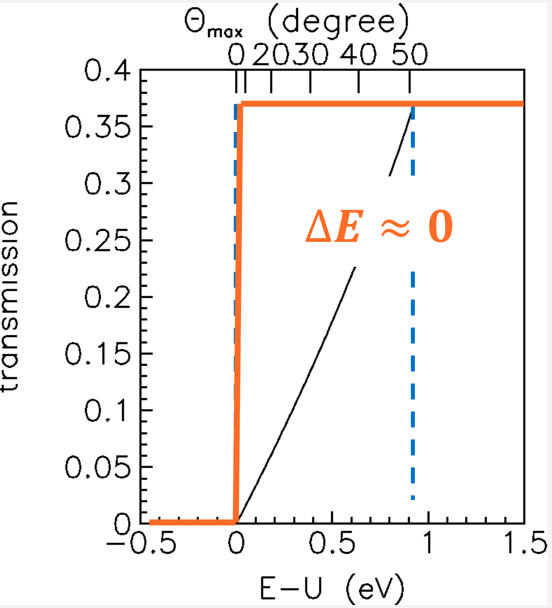

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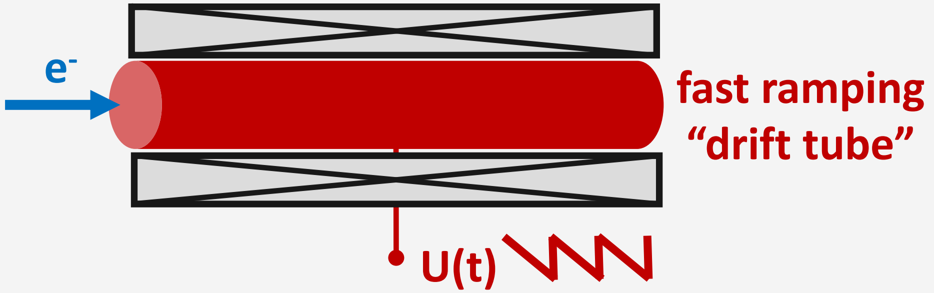
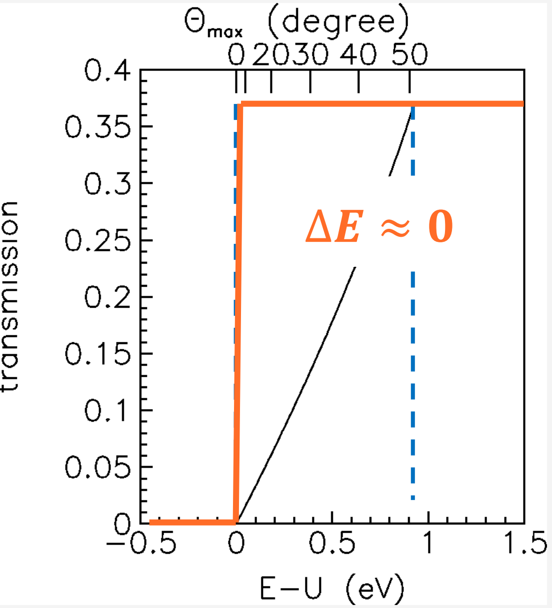
Idea for a solution: Compensate the missing $E_{\parallel,missing,\vartheta_s}$ by an **additional longitudinal energy boost $\Delta E_{\parallel,boost,\vartheta_s}$** with a drift tube featuring slightly different potentials when electron is at entrance and at exit



Overcome the energy resolution limit of a MAC-E-Filter
by a TEC for an isotropically emitting source with angles $\vartheta_s \leq \vartheta_{max}$



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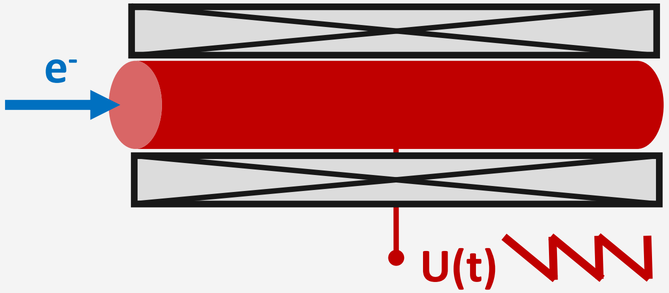


$$E_{\parallel,boost,\vartheta_s} = t_{\text{drift}} \cdot \frac{\partial U}{dt} = \frac{l}{v_\parallel} \cdot \frac{\partial U}{dt} \propto \frac{1}{v_\parallel} \propto a \cdot \frac{1}{\cos\vartheta_s}$$

for linear ramping: $\frac{\partial U}{dt} = \text{const.}$

$$\Delta E_{\parallel,boost,\vartheta_s} \propto \left(\frac{1}{\cos\vartheta_s} - 1\right) = \left(\frac{1-\cos\vartheta_s}{\cos\vartheta_s}\right) \approx \left(\frac{1-\left(1-\vartheta_s^2/_2\right)}{\left(1-\vartheta_s^2/_2\right)}\right) = \left(\frac{\vartheta_s^2/_2}{\left(1-\vartheta_s^2/_2\right)}\right) = \left(\frac{\vartheta_s^2/_2 \cdot \left(1+\vartheta_s^2/_2\right)}{\left(1-\vartheta_s^4/_2\right)}\right) \propto \vartheta_s^2 + \mathcal{O}(\vartheta_s^4)$$

Compensation to 1st order is possible !

→ Idea of "Transverse Energy Compensator" (TEC)*

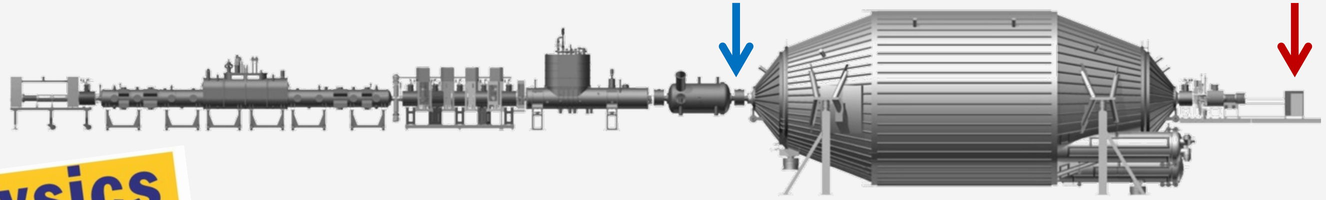
* This idea from C. Weinheimer *has been submitted as a patent application under no. WO2026/057763 A1*

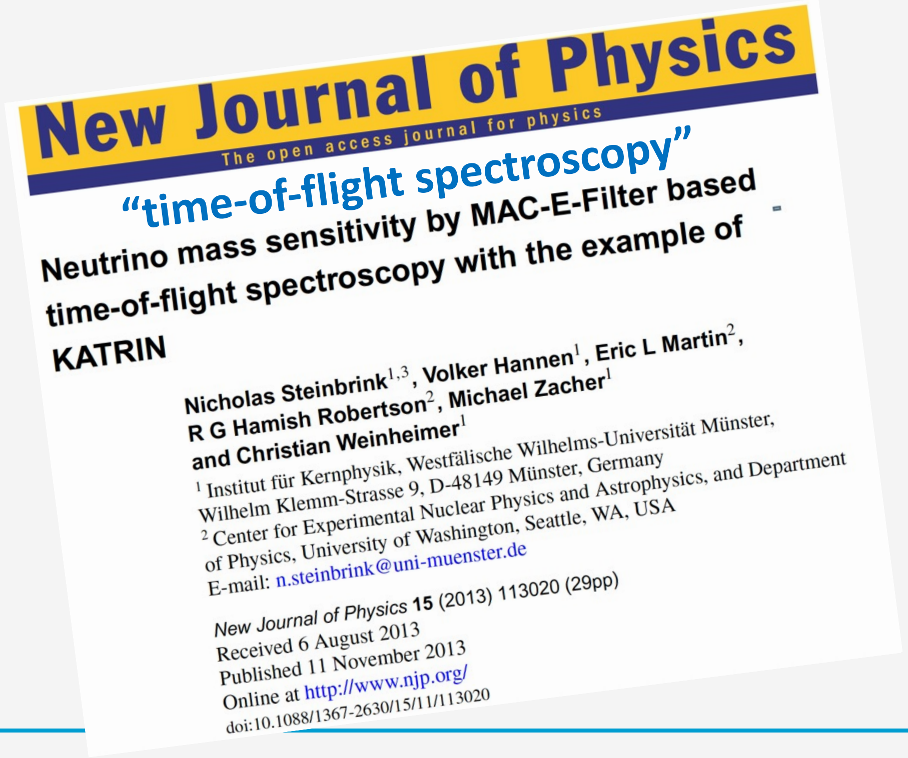
R&D towards differential spectroscopy

Alternative path: Time-of-flight is quasi-differential due to the strong retarding in spectrometer

rate: ≈ 1000 cps
start signal by ``electron tagger"

stop signal by detector




"time-of-flight spectroscopy"

New Journal of Physics
The open access journal for physics

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[1] Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, Wilhelm Klemm-Strasse 9, D-48149 Münster, Germany
[2] Center for Experimental Nuclear Physics and Astrophysics, and Department of Physics, University of Washington, Seattle, WA, USA
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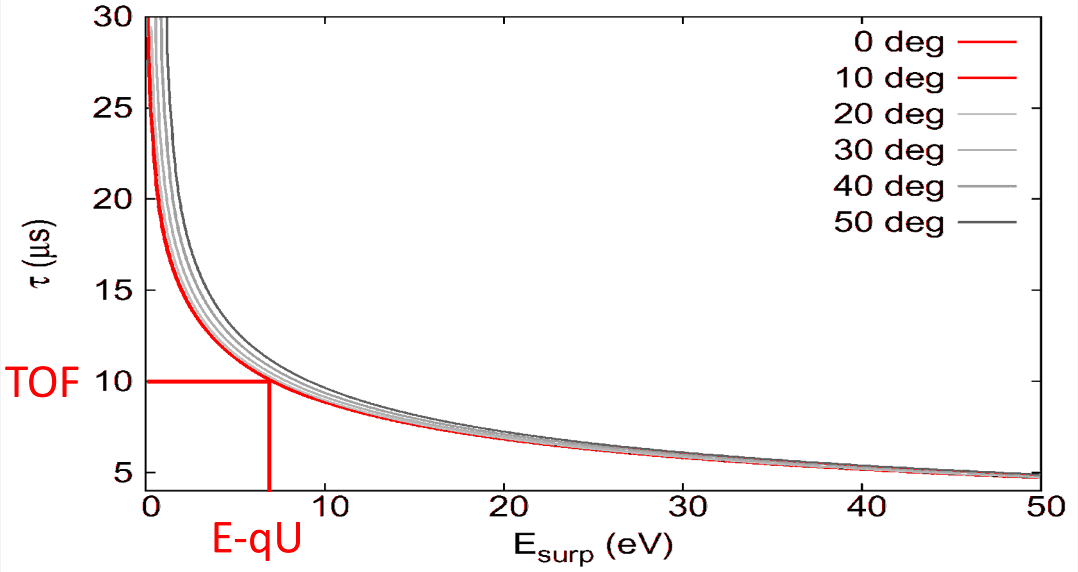
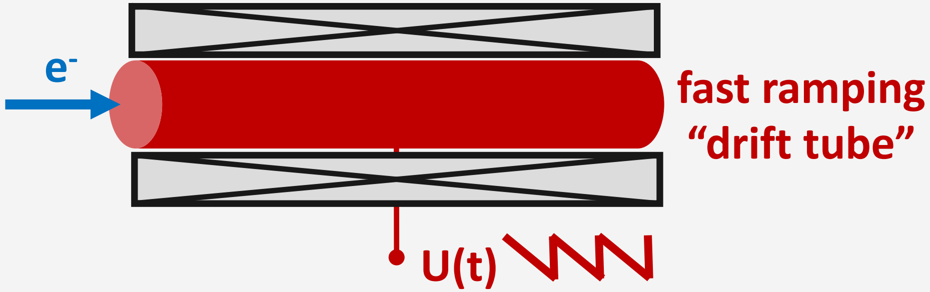
Online at http://www.njp.org/
doi:10.1088/1367-2630/15/11/113020

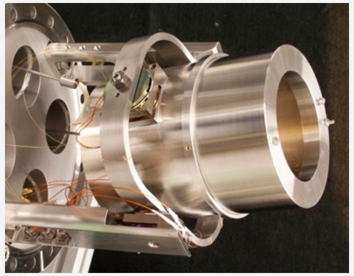


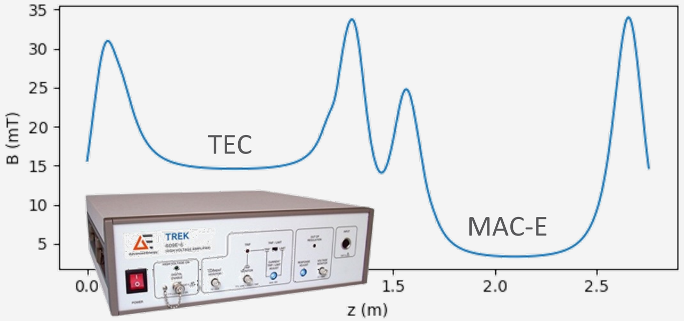
→ for vanishing angular time-of-flight width by "TEC" much better m_ν^2

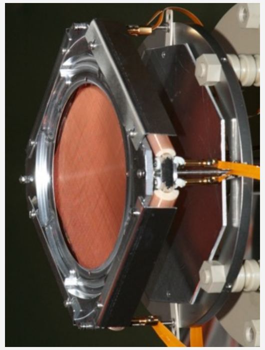
Successful TEC demonstration at 15eV to a few 100 eV

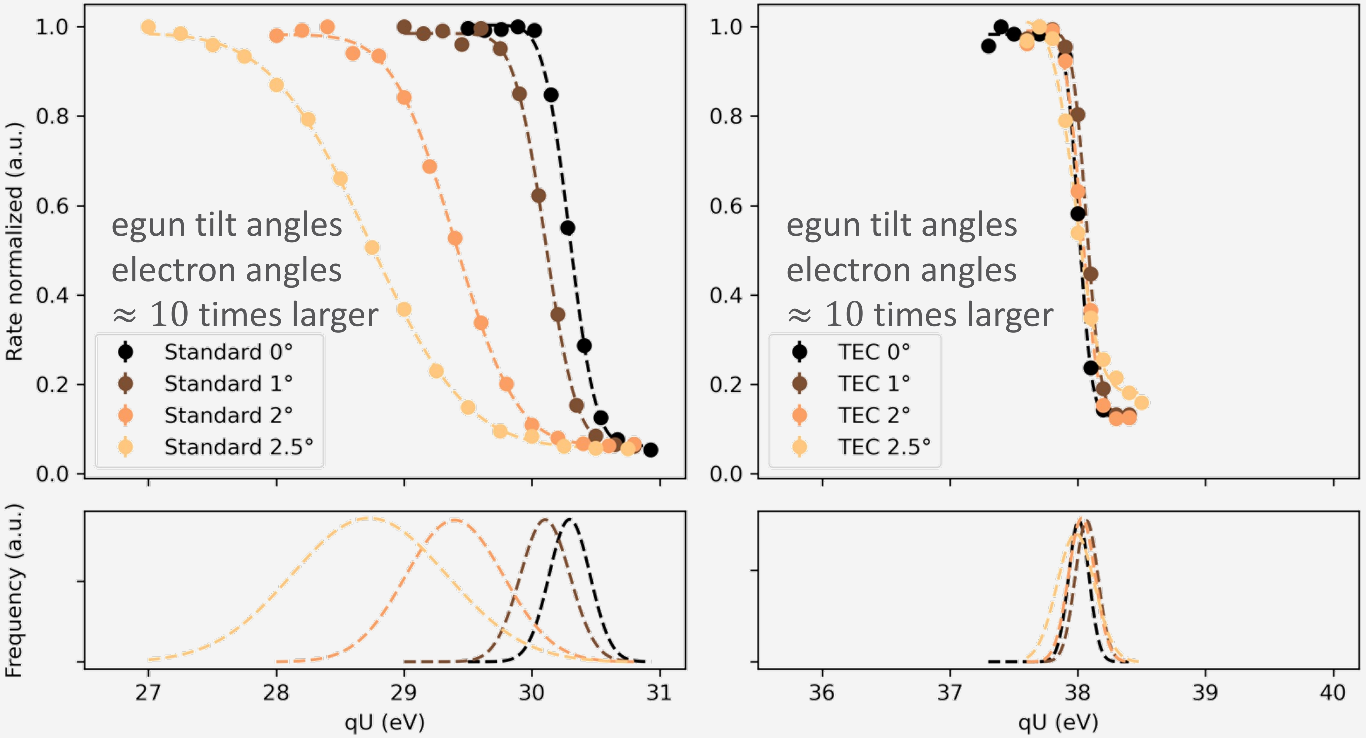
Universität Münster











→ TEC could turn the KATRIN spectrometer into a “virtual ø30m spectrometer”

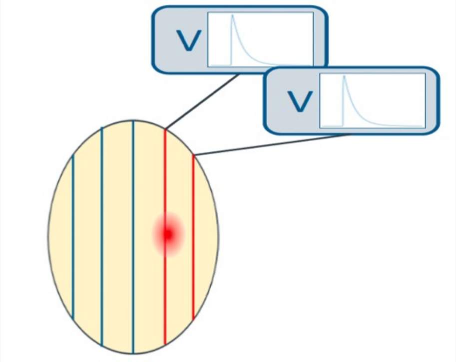
TEC: Patent application has been submitted as a patent application under: WO2026/057763 A1

TEC publication is on its way

Ideas for an electron tagger

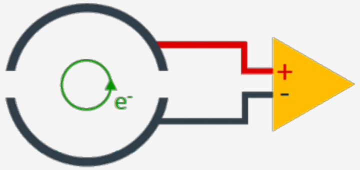
tagger: start signal, but minimal invasive on electron energy/momentum

2d membrane with SNSPDs



- Electron passes a 2d membrane covered by a net of super-conducting nanowires (SNSPD)
- Electron deposites nearly fix amount of energy therein (e.g. plasmon excitation)
- Quasi-particle travels to a SNSPD which changes to normal conducting → tag

Image current detection



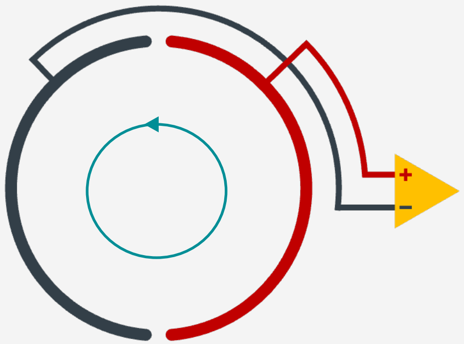
- In precision Penning traps: Electron on cyclotron motion gives rise to image current on surrounding electrodes
- Signal from multiple turns should be added coherently
- Read out image current by quantum-limited quantum-technology → tag

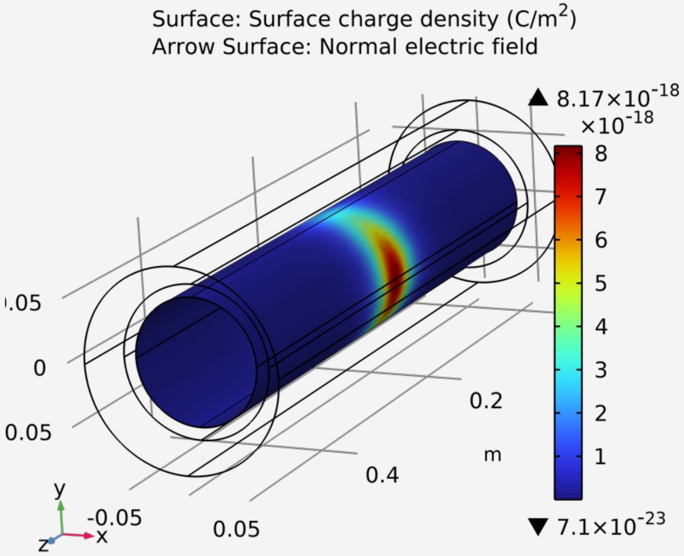
Other tagger ideas

- Cyclotron Radiation Emission Spectroscopy (CRES)
- Cryogenic Current Comparator (CCC) with SQUID readout
- Matrix of Rydberg atoms
- 2d membrane with SNSPDs and cryobolometer readout

Cooperation with leading experts in quantum technology at Delft, Heidelberg, KIT, MPIK and Münster

Electron tagging by measuring image charge/current induced by cylotron motion





Simulation: Patrick Unkhoff

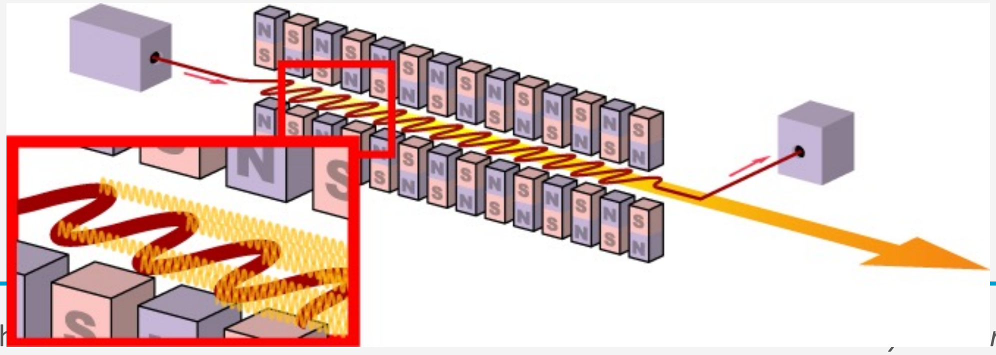
Collaboration with **Sven Sturm**, MPIK

Compare **to image charge measurements** in Penning traps, introduced by
D.J. Wineland, H.G. Dehmelt, J. Appl. Phys. 46, 919 (1975)

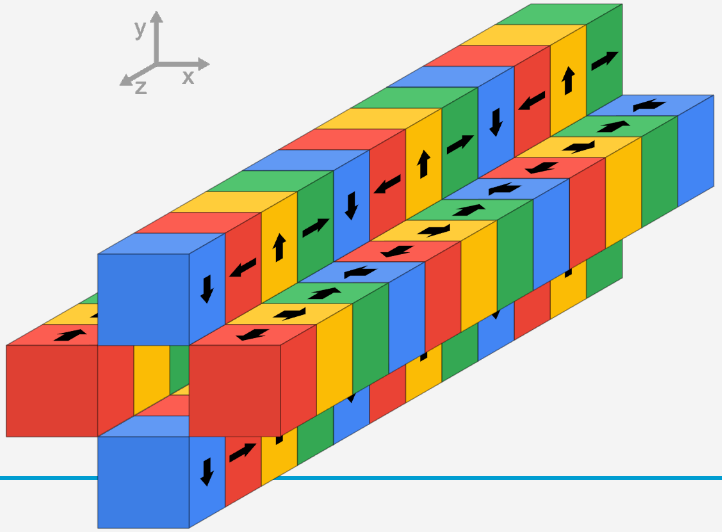
But does not work in the Telsa field of KATRIN → Idea with help from Sven Sturm, MPIK:

Force the electron on some oscillating trajectory using static (electro-)magnetic fields

Found such a solution: undulator (see synchrotron sources, FEL)



Undulator in 2 dimensions
see Apple-type undulator, DESY



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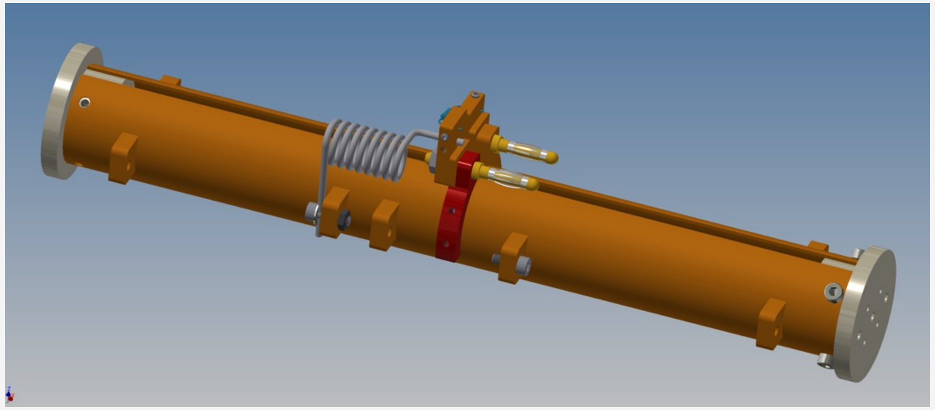
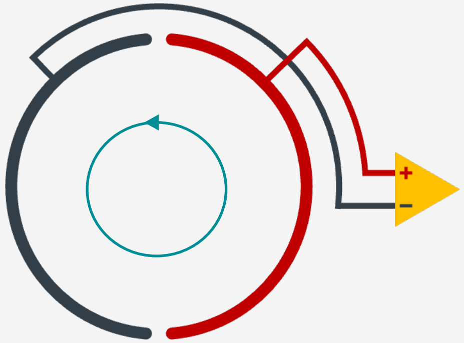
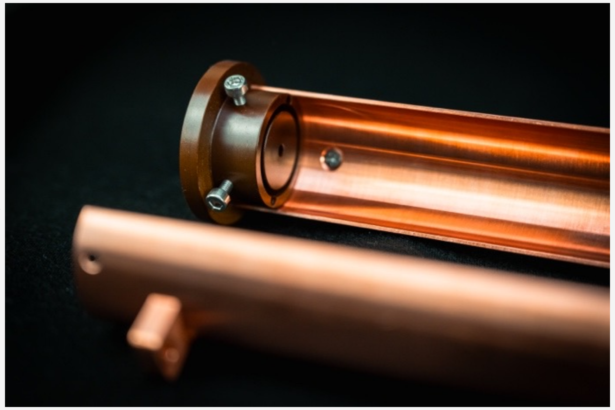
Demonstrator for image current eTagger, v0



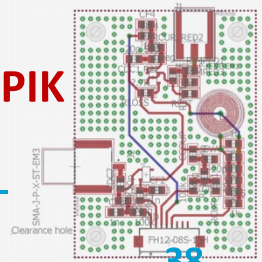




Zigzag-line to simulate circulating electron pulses at 50 MHz

Two-stage GaAs MESFET JFET cryogenic amplifier with on-board resonator by S. Sturm, Blaum div., MPIK

higher freq. SQUID, maybe by Sebastian Kempf, KIT

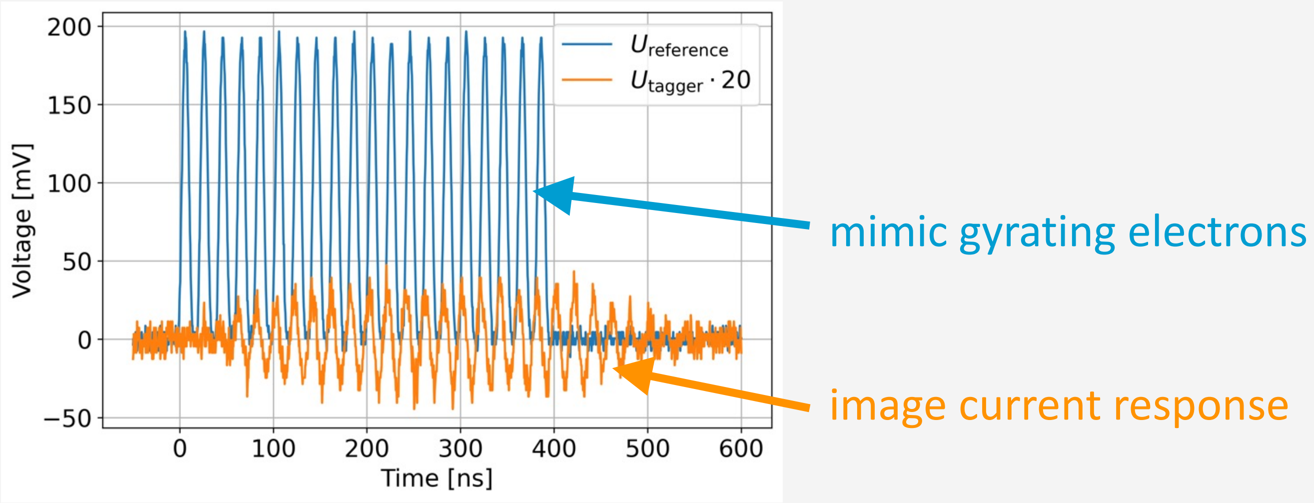


Demonstrator for image current eTagger: 1st signals

Signal to zigzag via pulse generator

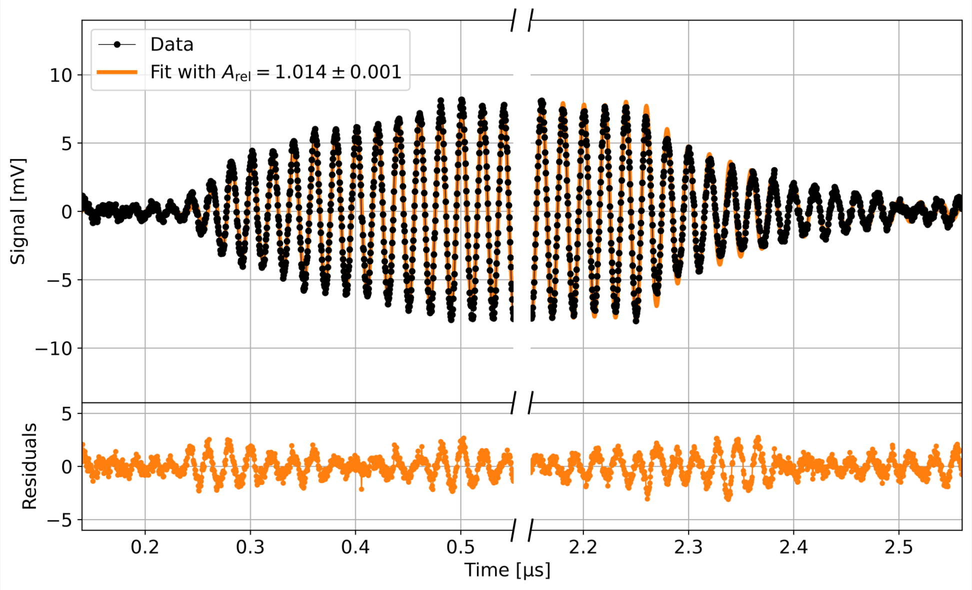
1) at room temperature

- Burst of 20 pulses
- Pulse length: 8ns
- Pulse height: 200mV
  (much more than 1 electron)



2) at 5 K

- Burst of 100 pulses
- Pulse length: 8ns
- Pulse height: 20mV
- digital high pass filter
  & template fit to data



Conclusions

- **The scale of the neutrino mass is one of the timely questions of neutrino physics and cosmology**
- **KATRIN has finished its phase 1 and delivered an neutrino mass upper limit of 0.45 eV**
  still 6 times more data and itis looking for other science channels beyond neutirno mass, e.g. sterile neutrinos
- **KATRIN will start in 2026/2027 to look deeper into the beta spectrum searching for keV sterile neutrinos with the TRISTAN detector**
- **KATRIN++ is an R&D project to improve the sensivitiy on m_β by a factor 5 (on observable m_β^2 by factor 25)**
  to measure the neutrino mass for inverted ordering and to go deeply into the normal ordering scenarios
  by upgrading the KATRIN hardware
  with a quantum technology for a differential, sub-eV spectroscopy and an atomic tritium source

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Thank you for your attention !