WWU
MÜNSTER

The neutrino mass experiment KATRIN

GSI-FAIR Colloquium, GSI-FAIR, Darmstadt, April 25, 2023

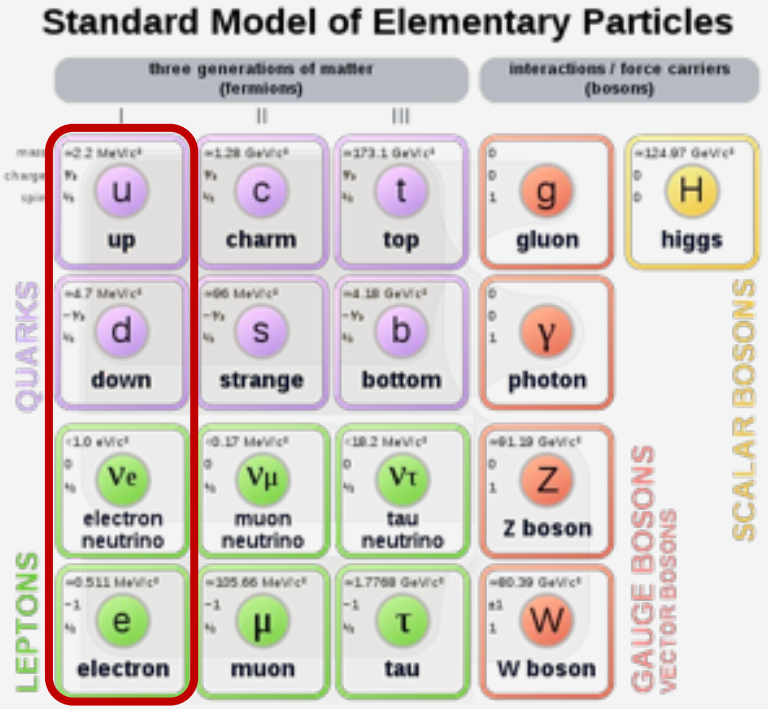
Christian Weinheimer – Institute for Nuclear Physics, University of Münster

erc

- Introduction – search for $m(\nu)$
- The direct neutrino mass experiment KATRIN
- Recent sub-eV results from KATRIN
- Improvements and future goals of KATRIN
- Conclusions

Happy birthday, Jürgen Kluge !

Neutrinos in the Standard Model of particle physics



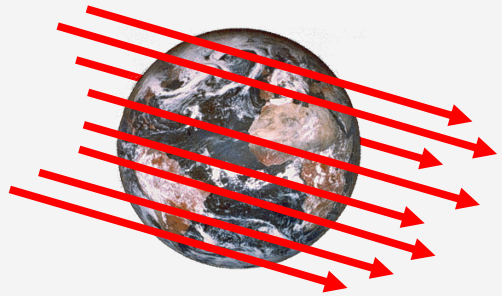
modified from en.wikipedia.org

Neutral, spin ½,

Only weak interaction (W,Z very heavy):

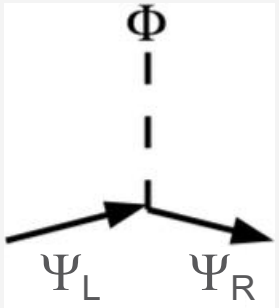
$\lambda_\nu \approx$ light years at MeV scale

interaction rate increases linearly with E_ν usually



The most abundant particle in the universe:

Cosmic neutrino background: 336 / cm^3 (similar to CMB photons)

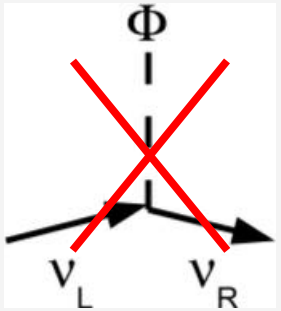


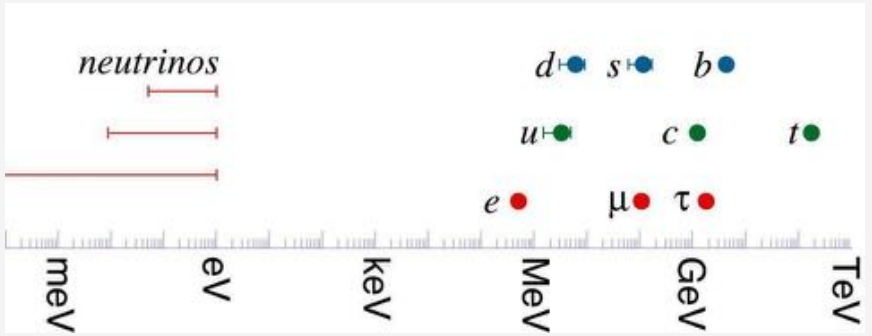
In original SM ν only left-handed: ν_L

→ difficult to account for mass term:

Yukawa coupling to the Higgs

did not exist in the SM up to 1998





http://hitoshi.berkeley.edu

Discovery of neutrino oscillations → m(ν)≠0

Super Kamiokande experiment (1998)

atmospheric neutrinos: $\nu_\mu \rightarrow \nu_\tau$

Sudbury Neutrino Observatory SNO (2001/02)

solar neutrinos: $\nu_e \rightarrow \nu_\mu/\nu_\tau$

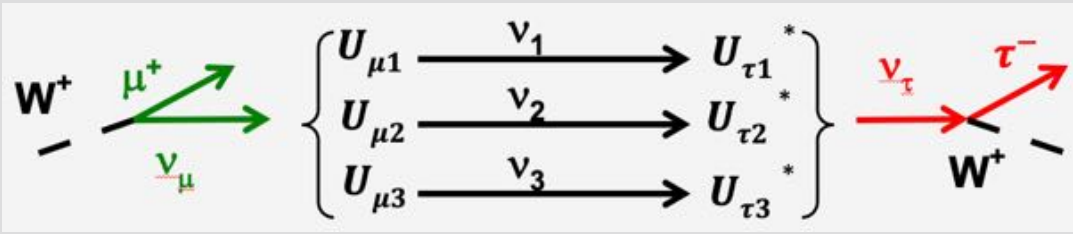
Nobel Prize in physics 2015

Neutrino oscillation:

3 flavor ν_e, ν_μ, ν_τ & 3 mass eigenstates ν_1, ν_2, ν_3
mixed by a unitary 3×3 matrix U_{PMNS}

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U_{PMNS}\cdot\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

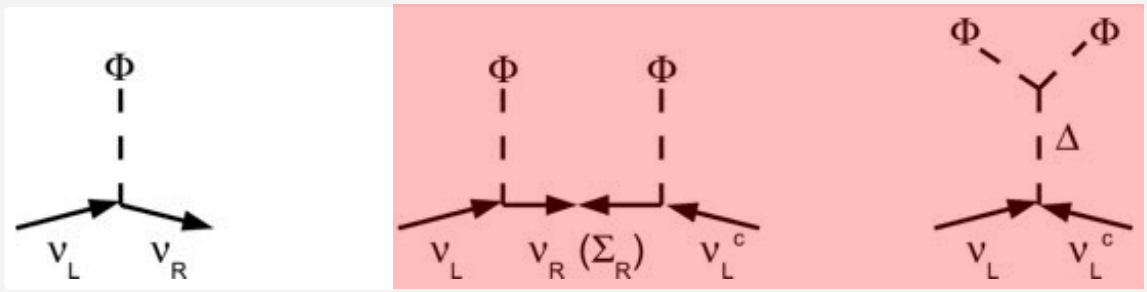
→ **„tripple slit" exp.**: solar $\nu_e \rightarrow \nu_\mu, \nu_\tau$, atmospheric $\nu_\mu \rightarrow \nu_\tau$



Motivations to search for the neutrino mass scale

Why are so neutrinos so light compared to the other fermions in the Standard Model of particle physics?

The very small neutrino masses are probably due to more than just the Yukawa coupling to the Higgs



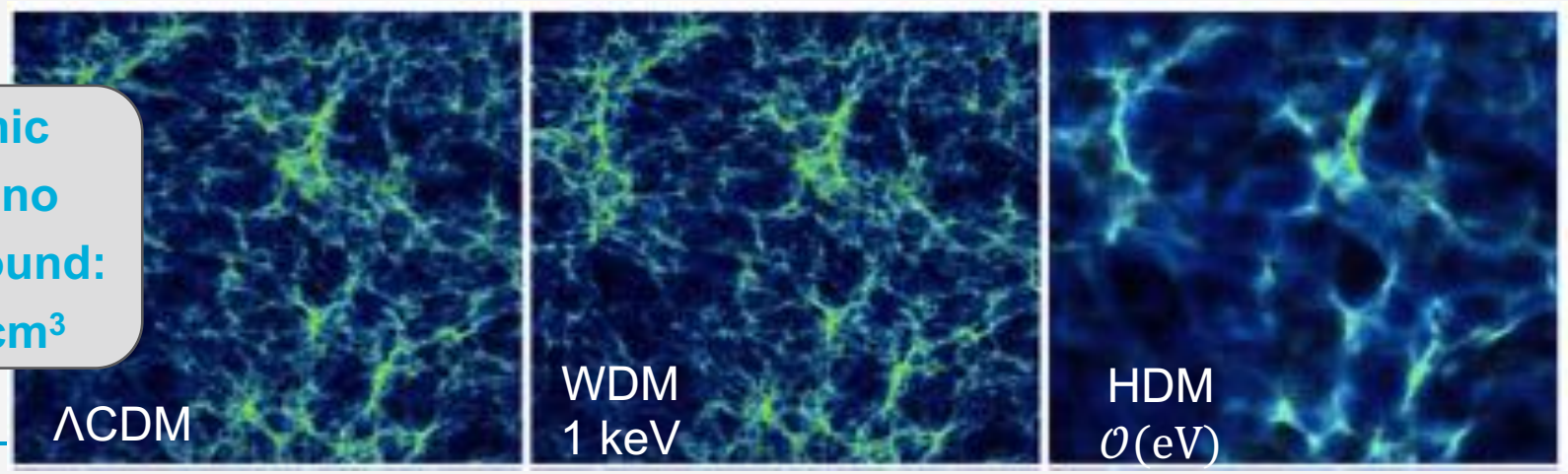
"Seesaw"-mechanism

Physics beyond the Standard Model at very large energy scales

How do the neutrinos influence the evolution of the universe?

Even small neutrino masses count, since a billion times more neutrinos than atoms in the universe

Cosmic neutrino background: 336 / cm³

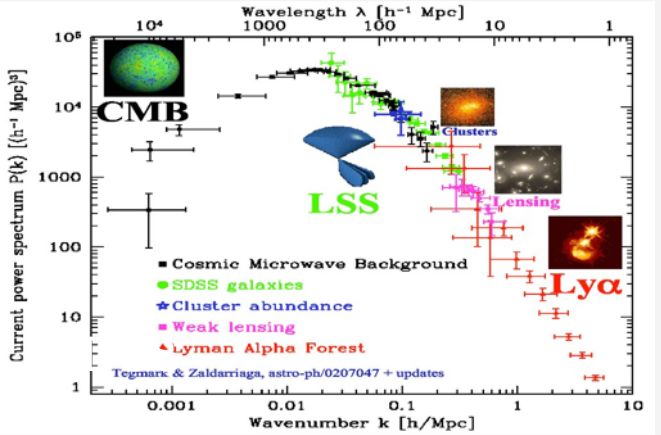


Structure formation in the early universe: depending on their mass neutrinos had smeared out different scales

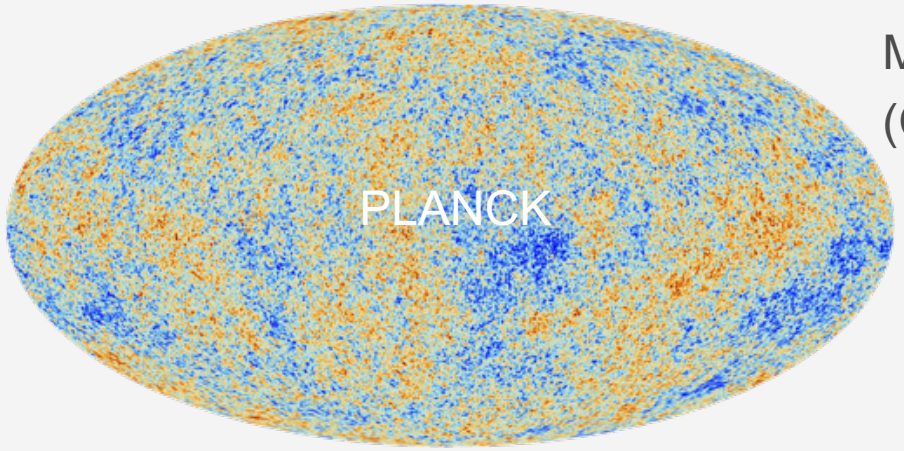
Three complementary ways to the absolute neutrino mass scale

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

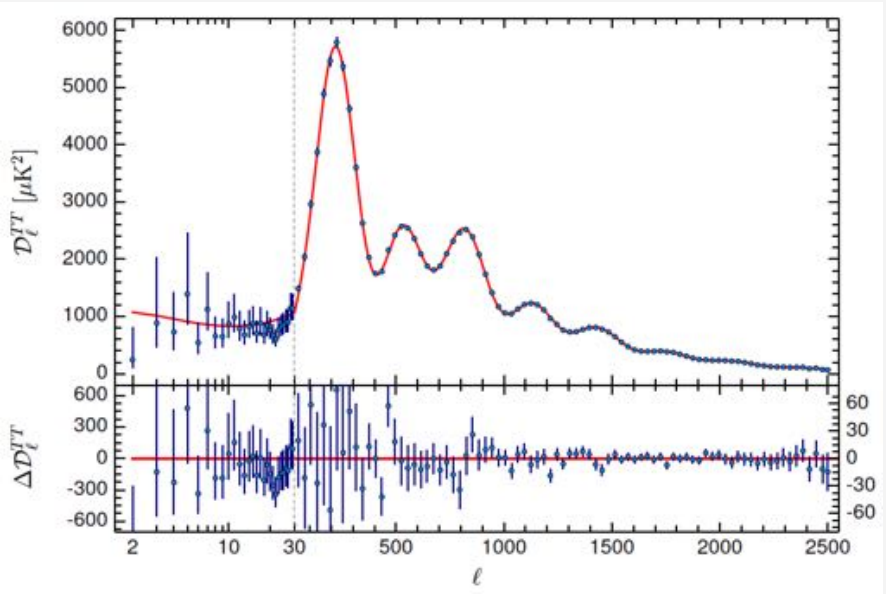
very sensitive, but model dependent, compares power at different scales



Neutrino mass from cosmology

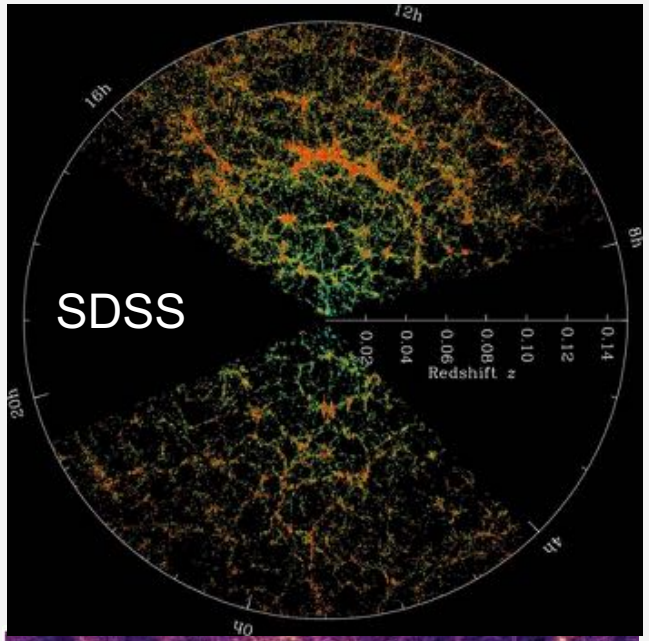


Measurement of CMB
(Cosmic Microwave Background radiation)

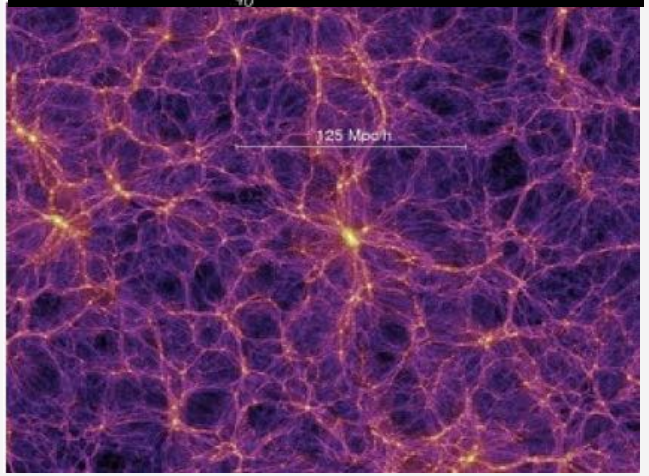


Planck Collaboration:
P. A. R. Ade et al., arXiv:1502.01589

Measurement of matter density distribution LSS (Large Scale Structure) by 2dF, SDSS, ...



Compare to numerical models including relic neutrino densitiy of 336 cm^{-3}



Millenium simulation
http://www.mpa-garching.mpg.de/galform/presse/

→ within the ΛCDM model:

$$\sum m(\nu_i) < 0.12 \text{ eV}$$

Planck Collaboration, A&A 641, A6 (2020)

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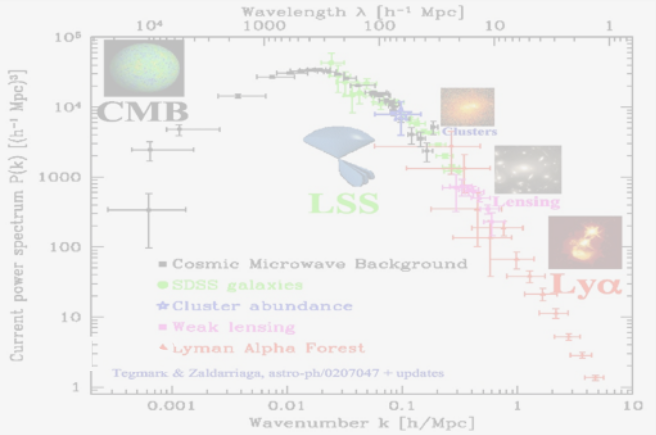
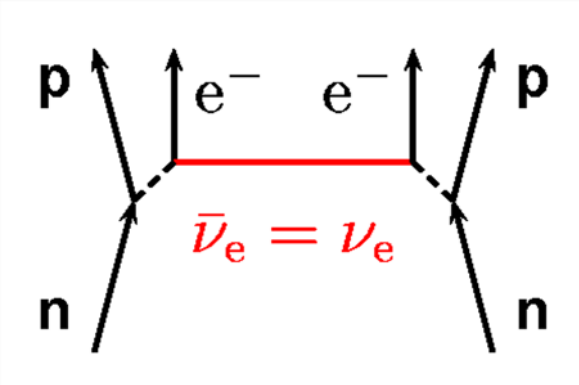


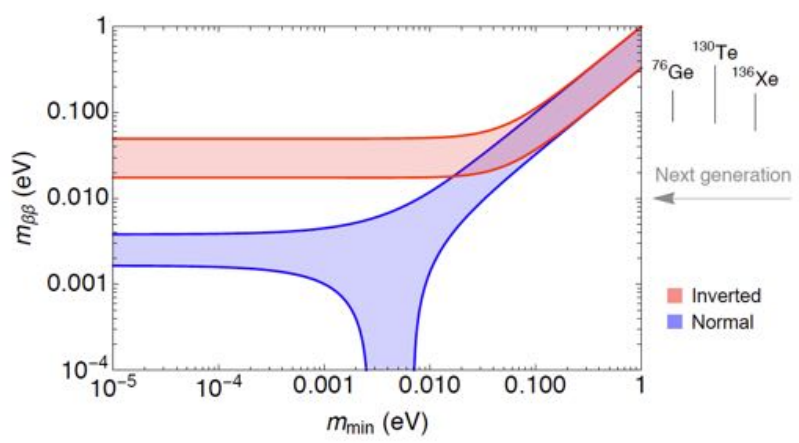
2) **Search for 0νββ:** $m_{\beta\beta} := \left|\sum_i U_{ei}^2 \cdot m(\nu_i)\right|$

sensitive to Majorana neutrinos only, challenge of uncertainties of nuclear matrix elements

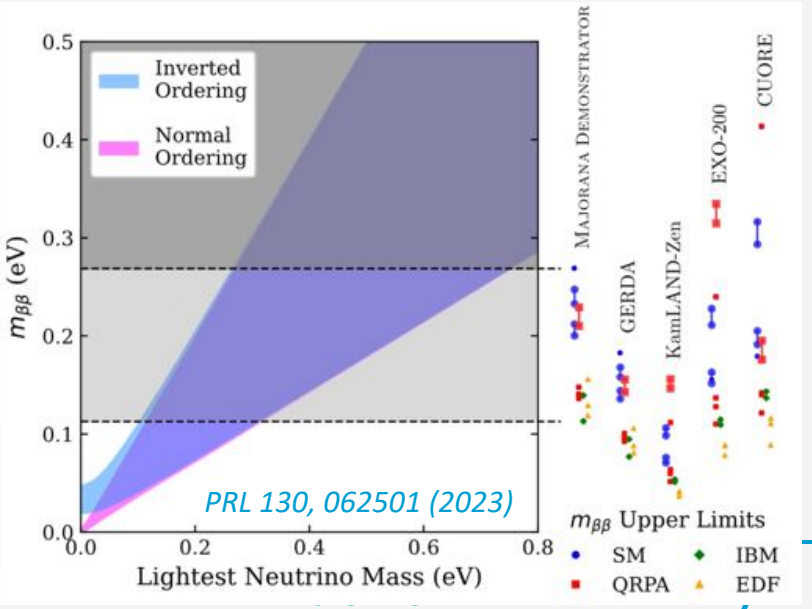
disclaimer: $m_{\beta\beta}$ are valid only, if 0νββ works dominantly via ν exchange

Discovery of 0νββ would proof lepton number violation !





log → lin scale



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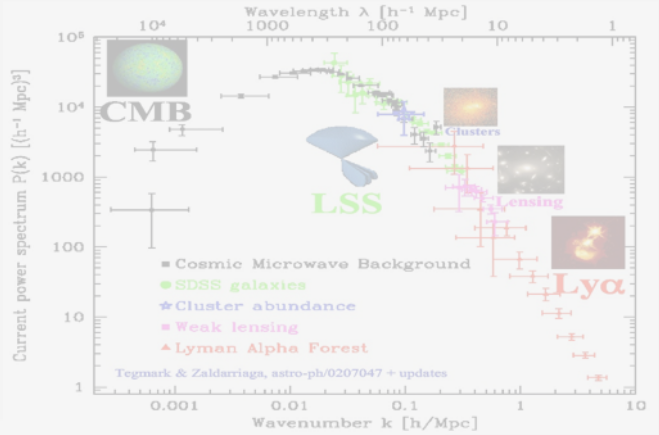

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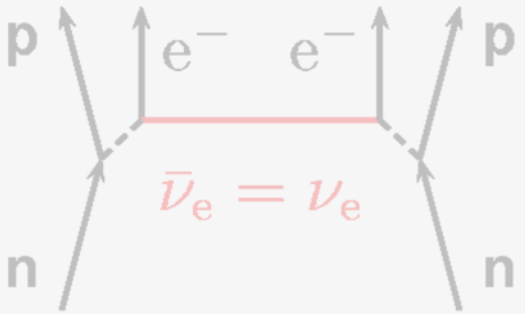


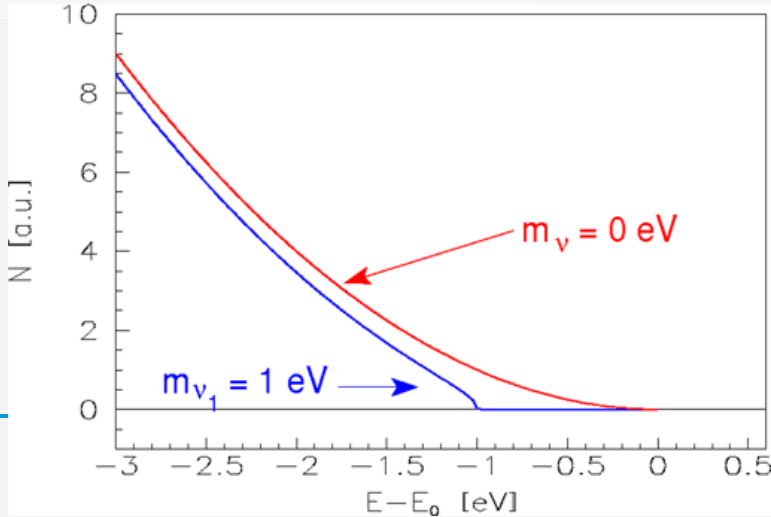
3) **Direct neutrino mass determination:** $m^2(\nu_e) := m_\beta^2 := \sum_i |U_{ei}|^2 \cdot m^2(\nu_i)$

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

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

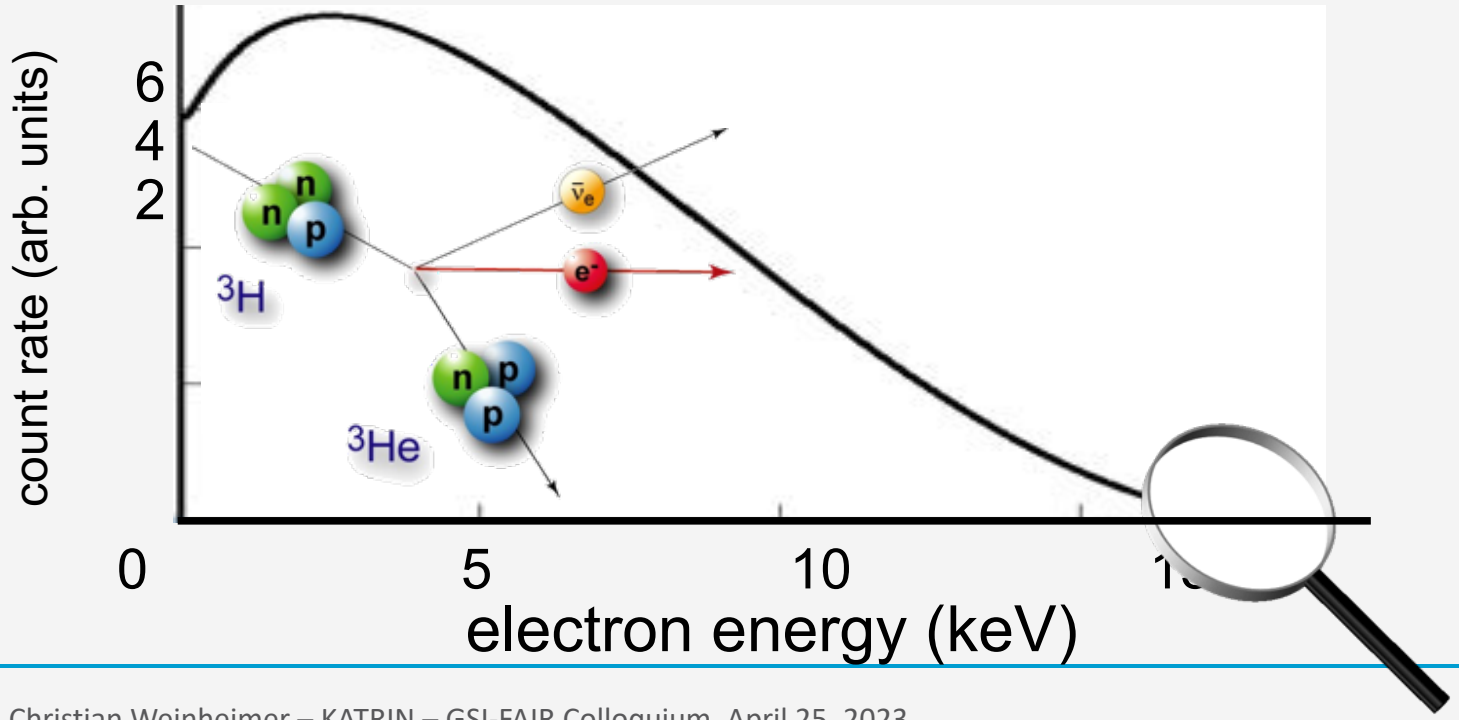


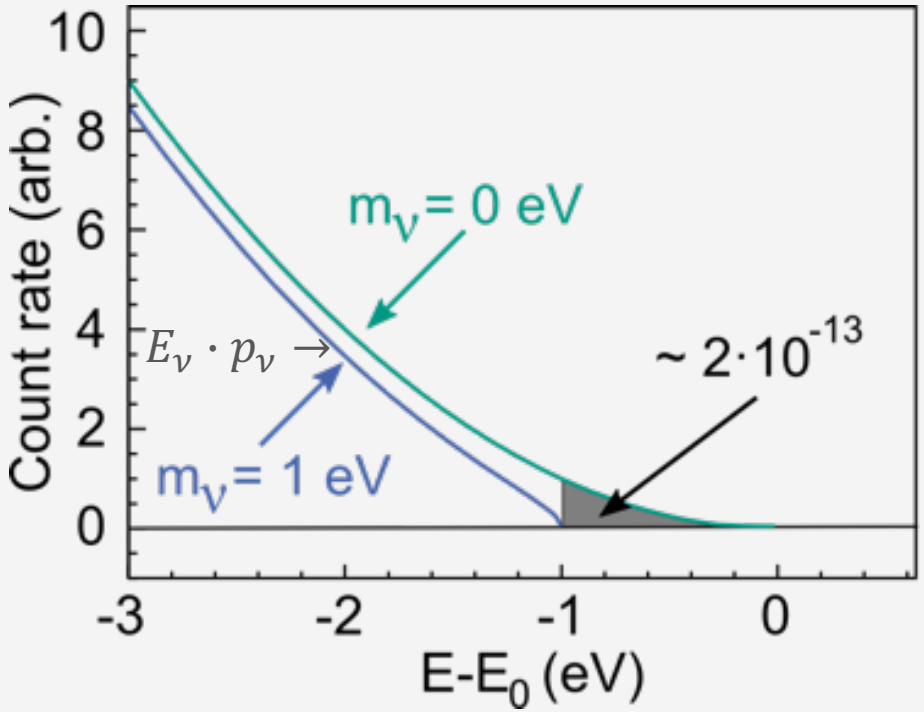
Direct determination of "$m(\nu_e)$" from β-decay (EC)

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

essentially phase space: p_e E_e E_ν p_ν

with "electron neutrino mass": $\boldsymbol{"m^2(\nu_e)" := \sum_i |U_{ei}|^2 \cdot m^2(\nu_i)}$, complementary to 0νββ & cosmology
(modified by electronic final states, recoil corrections, radiative corrections)





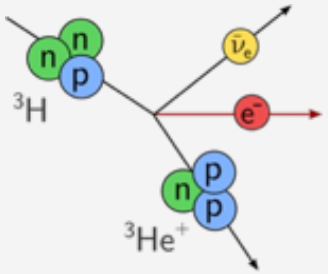
The KArlsruhe TRItium Neutrino experiment KATRIN at Karlsruhe Institute of Technology (KIT)

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

tritium pumping & e^- transport
T_2 flow reduction $>10^{14}$

high-pass energy filters
MAC-E filter

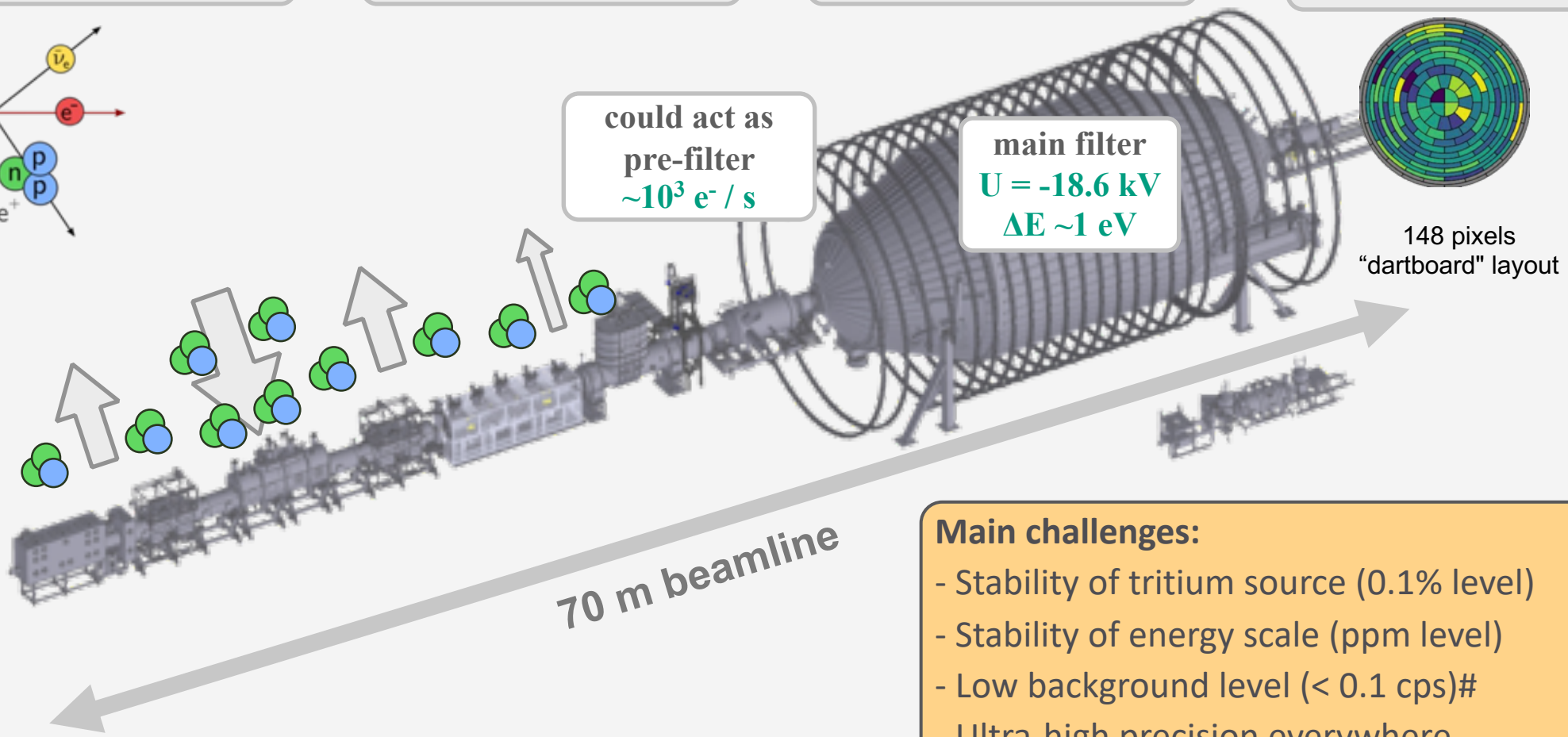
counting detector
< 1 e^- / s



could act as pre-filter
~10^3 e^- / s

main filter
U = -18.6 kV
ΔE ~1 eV

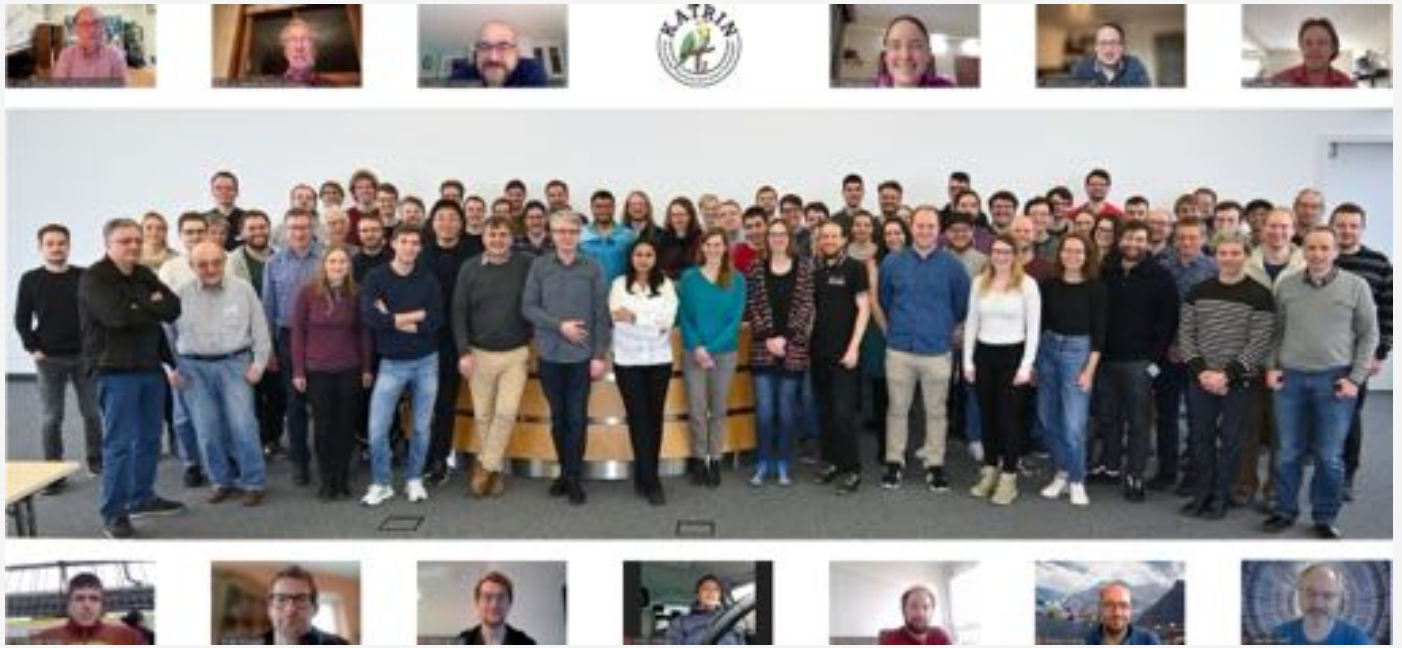
148 pixels
"dartboard" layout



Main challenges:
- Stability of tritium source (0.1% level)
- Stability of energy scale (ppm level)
- Low background level (< 0.1 cps)#
- Ultra-high precision everywhere

The KArlsruhe TRItium Neutrino experiment KATRIN

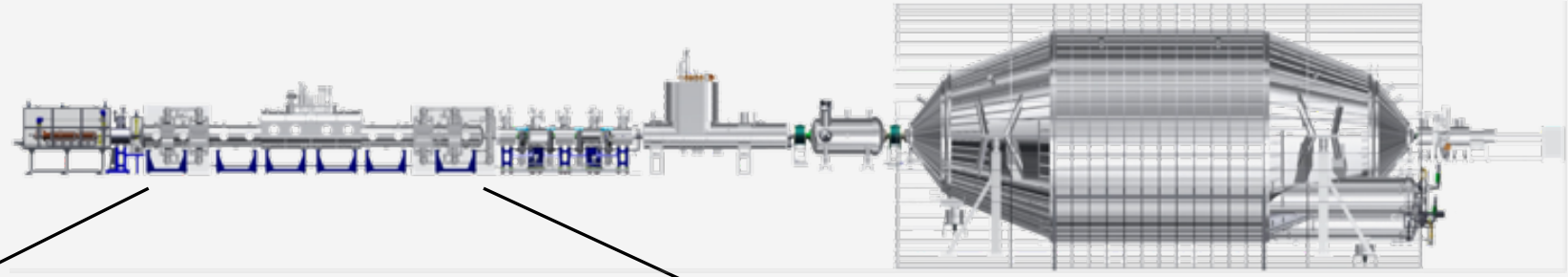
The international KATRIN Collaboration:
150 people
from 24 (8) institutions (countries)

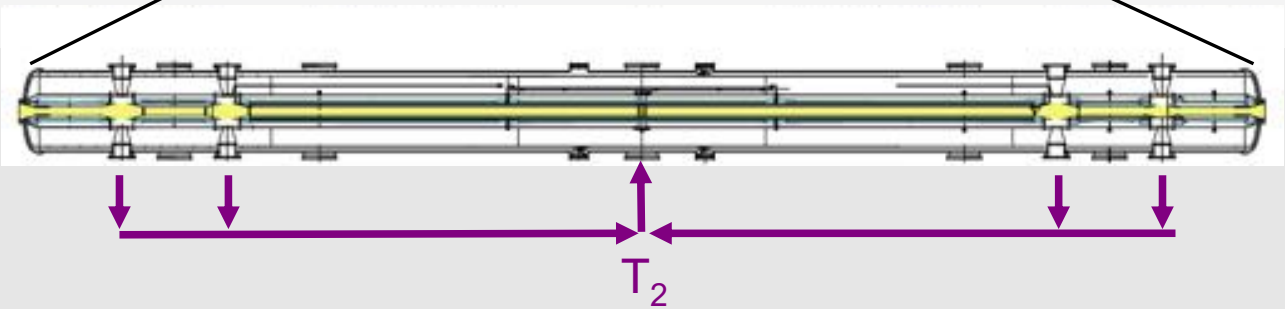


Collaboration Meeting
Spring 2023

Funded by:

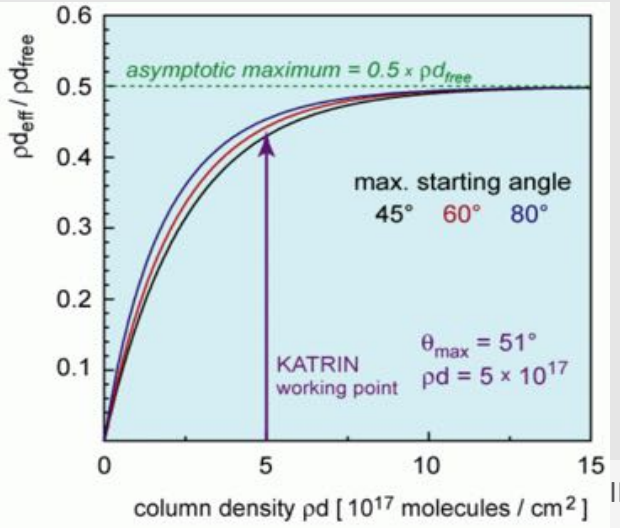
Windowless Gaseous Molecular Tritium Source





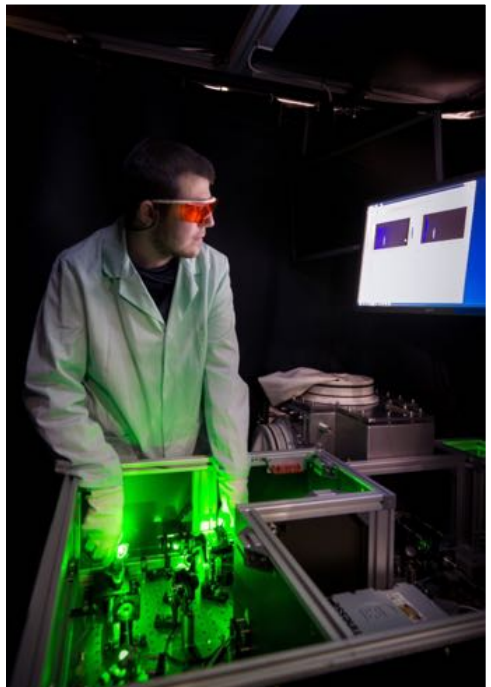
column density $5 \cdot 10^{17}$ T_2 /cm^2 luminosity $1.7 \cdot 10^{11}$ Bq

beam tube	Ø = 9 cm , L = 10 m
guiding field	3.6 T (2.52 T)
temperature	T = 30 K ± 30 mK (80 K),
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 %



WGTS at Tritium Laboratory Karlsruhe

Photos: source & transport section



Main spectrometer: an integrating high resolution MAC-E Filter

Ultra-high vacuum, pressure < 10^{-11} mbar

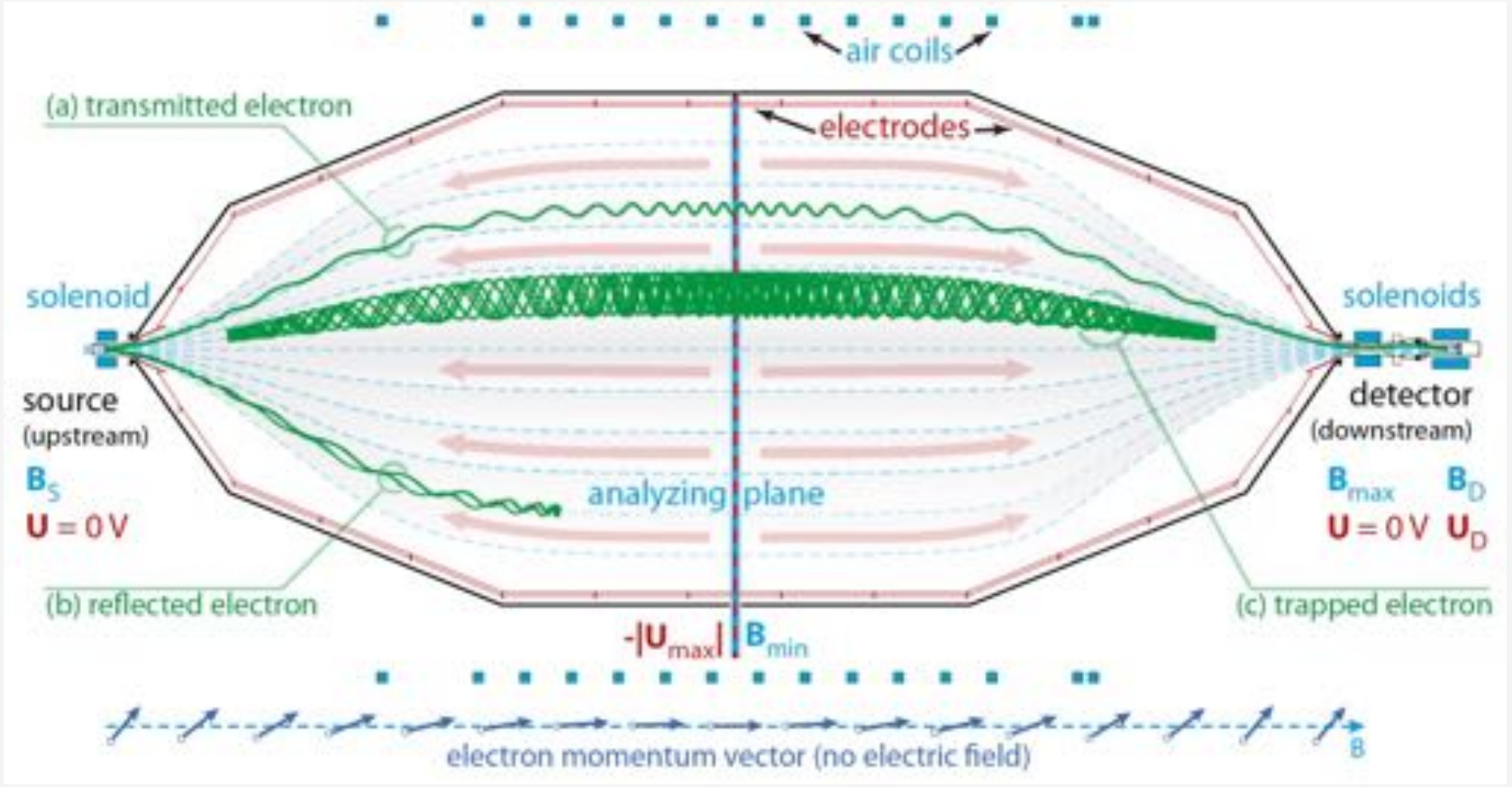
Precision retardation voltage of -18.6 kV (ppm)
at vessel (, σ < 60 mV/years)
and double layer wire electrode system
for background reduction
and field shaping

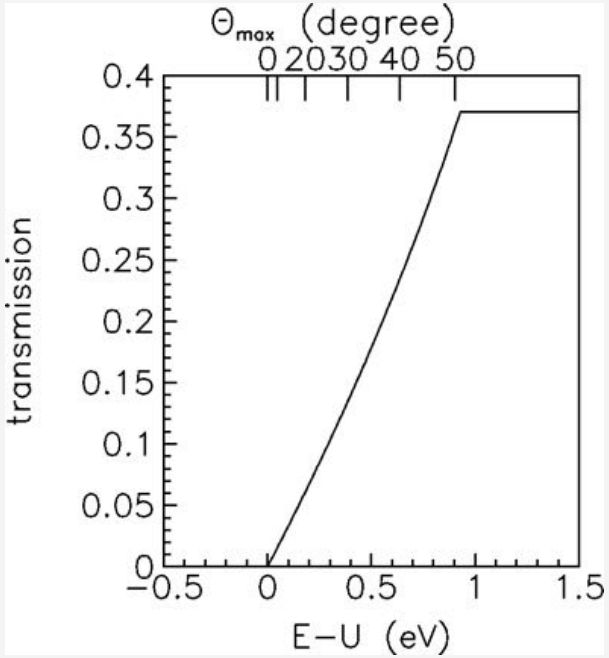
Air coils for earth magnetic
field compensation

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 $E \sim E_{||} \geq qU$





Very high energy resolution

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

Very high angular acceptance:

$\Delta\Omega \sim \pi$

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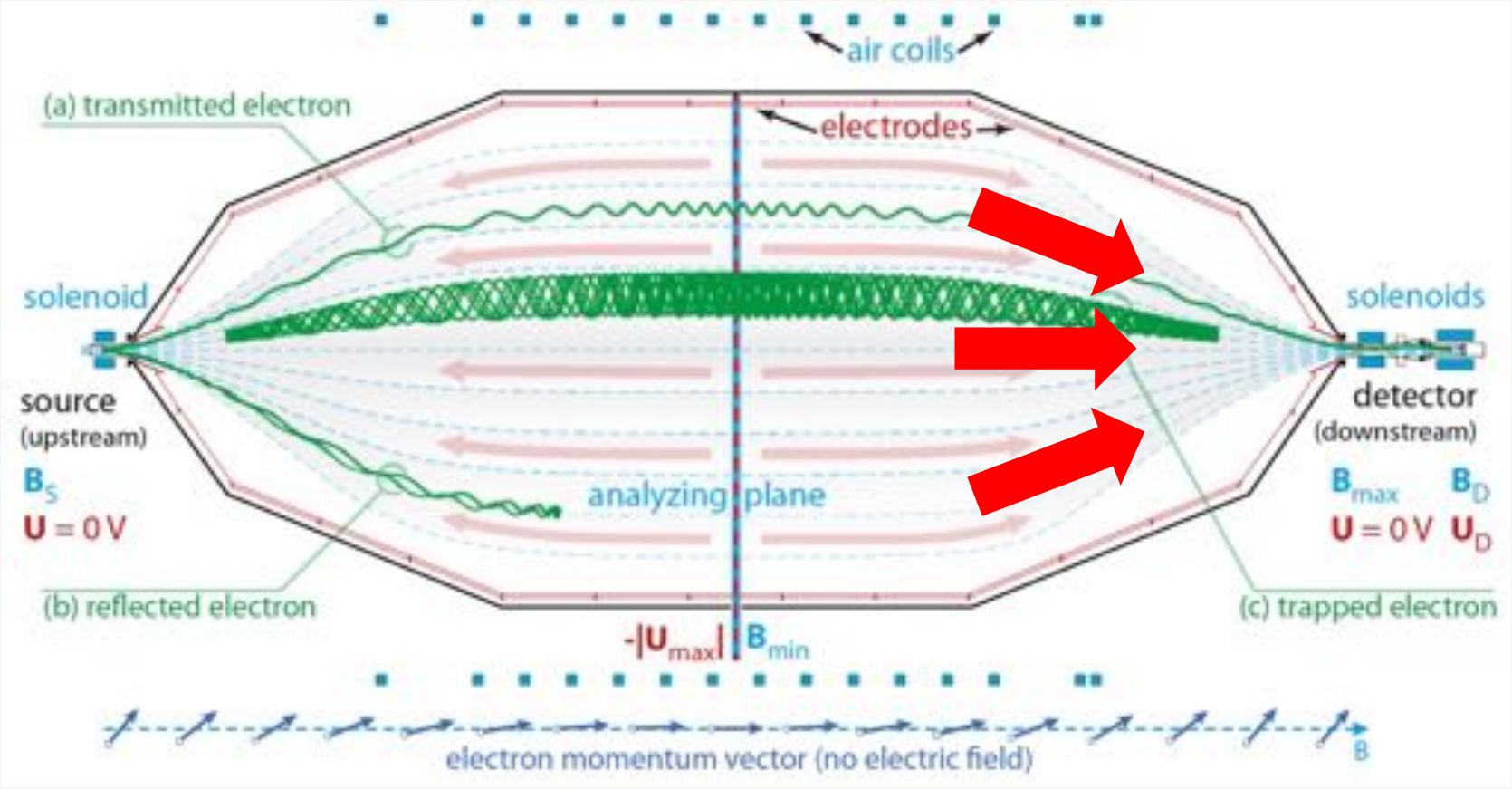


Sensitive to backgrounds:

- Low energy electrons "born" in the spectrometer volume will be accelerated to detector (same energy as signal electrons)
- Electrons can be trapped in the magnetic bottle of MAC-E-Filter or in local Penning traps
  → secondary electrons

Very high energy resolution

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

Very high angular acceptance:

$$\Delta\Omega \sim \pi$$

The KATRIN electron detector FPD

Focal plane detection system

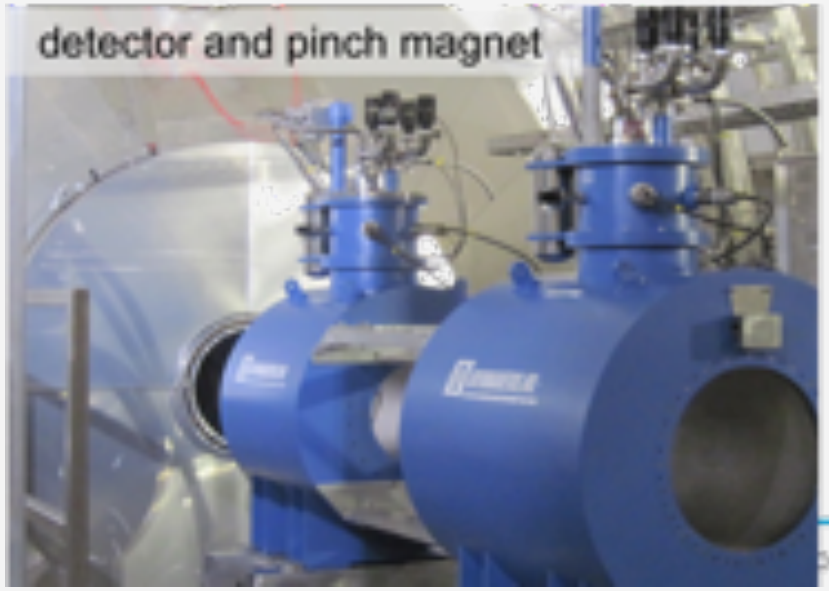
segmented Si PIN diode:
90 mm Ø, 148 pixels, 50 nm dead layer

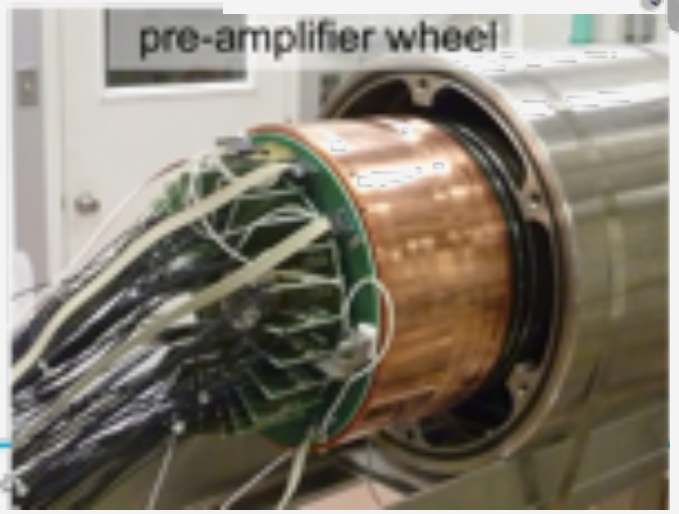
energy resolution ≈ 1 keV

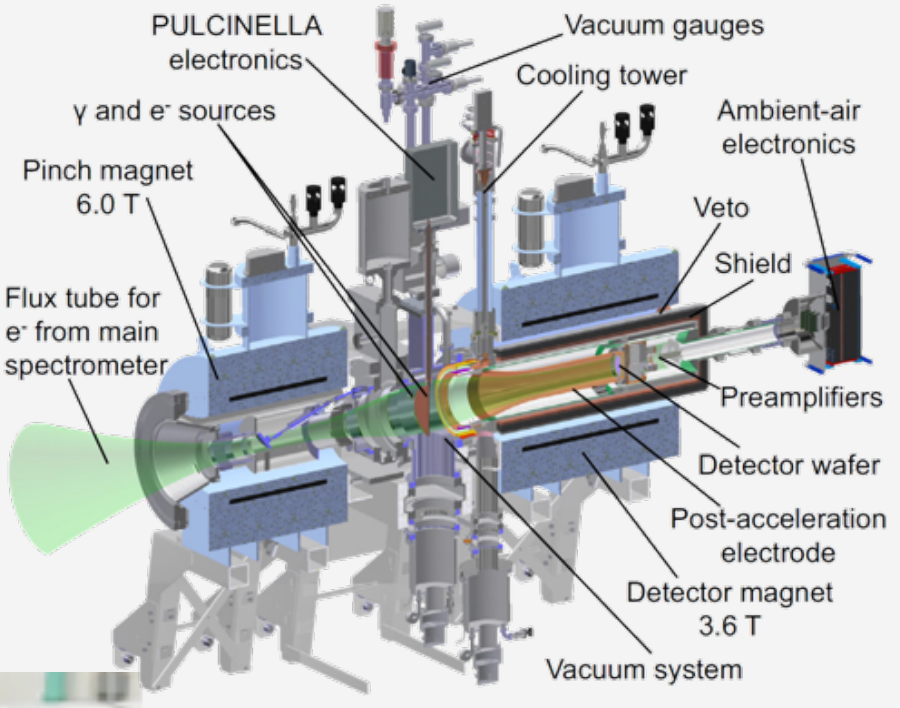
pinch and detector magnets up to 6 T

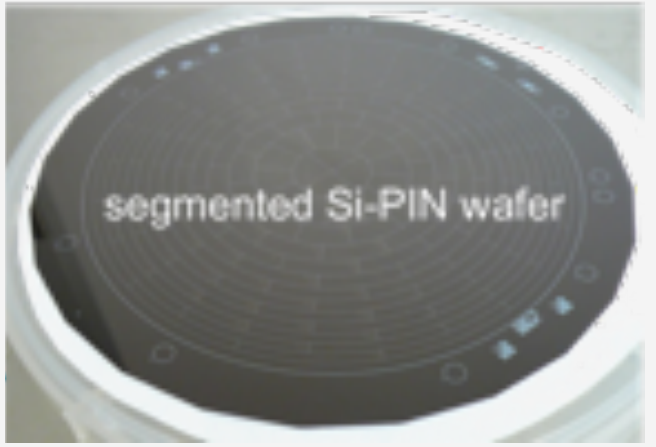
post acceleration (10kV)

active veto shield

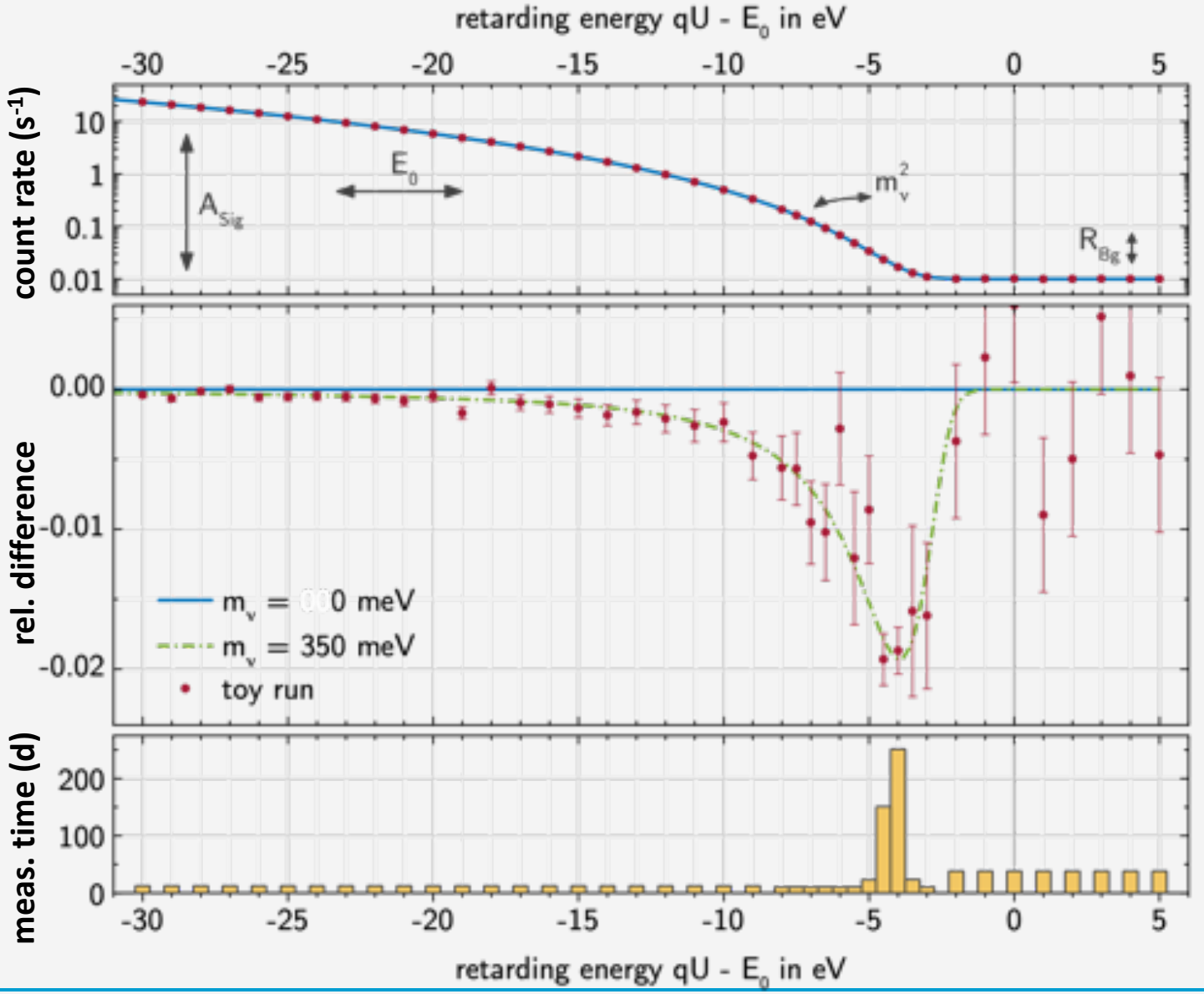








The measurement principle



Direct **shape** measurement of
integral β-spectrum
rate for various **minimal energies** qU

→ essentially 4 fit parameters:

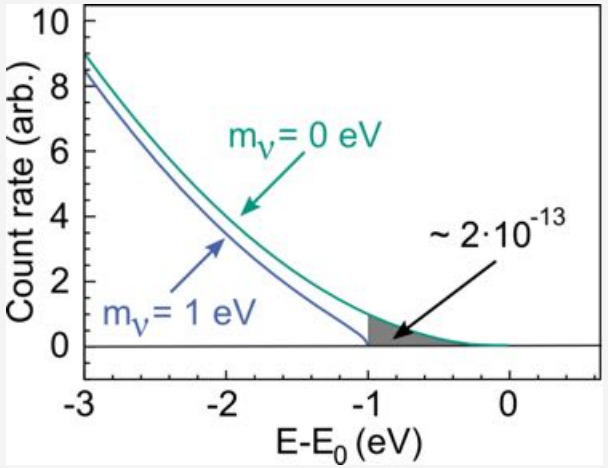
- spectrum norm. A_{sig}
- spectrum endpoint **E0**
- background rate R_{Bg}
- squared mass m_ν^2

~10^{-8} of all β-decays in scan region
~40 eV below endpoint

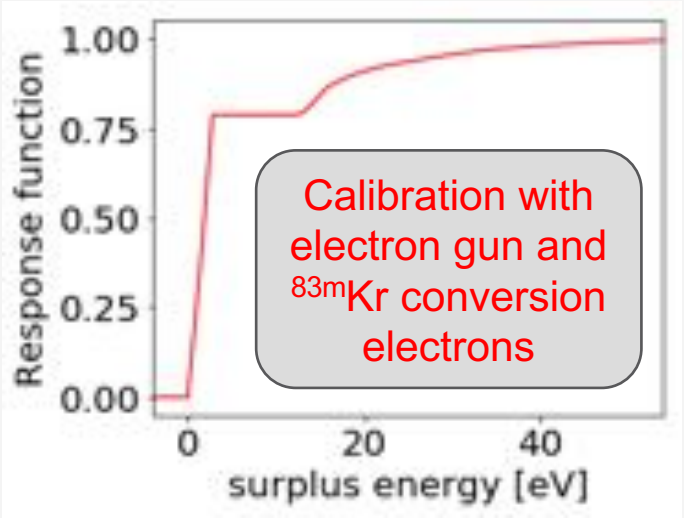
Eur. Phys. J. C 79 (2019) 204

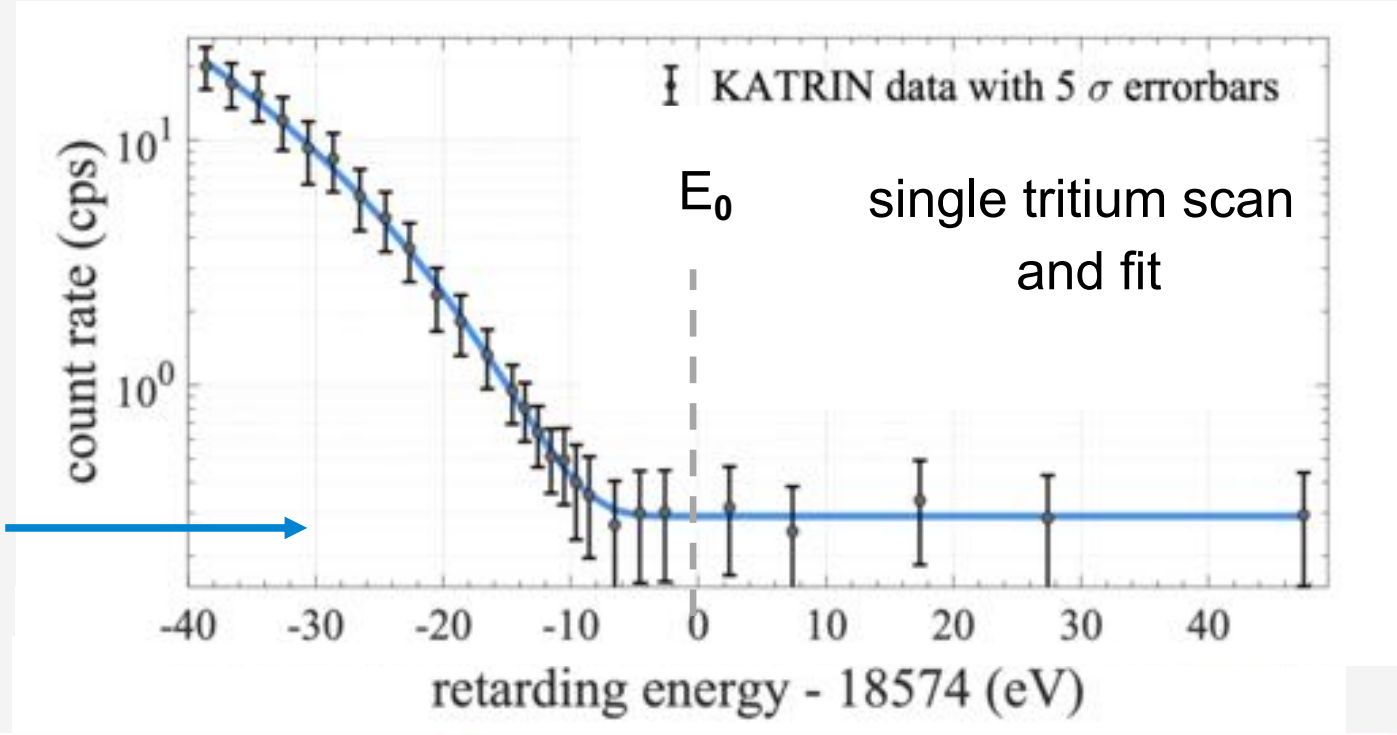
Model of the experimental spectrum

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



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





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

PRL 123 (2019) 221802, EPJ C 79 (2019) 204
+ detailed analysis PRD 104 (2021) 012005
+ energy loss measurement EPJ C 81 (2021) 579

First neutrino mass result

1st science run of KATRIN in spring 2019

- ν-mass: best fit result

  $m^2(\nu_e) = -1.0^{+0.9}_{-1.1}$ eV²

- ν-mass: new upper limit

  $m(\nu_e) < 1.1$ eV (90% C.L. Lokhov – Tkachov)

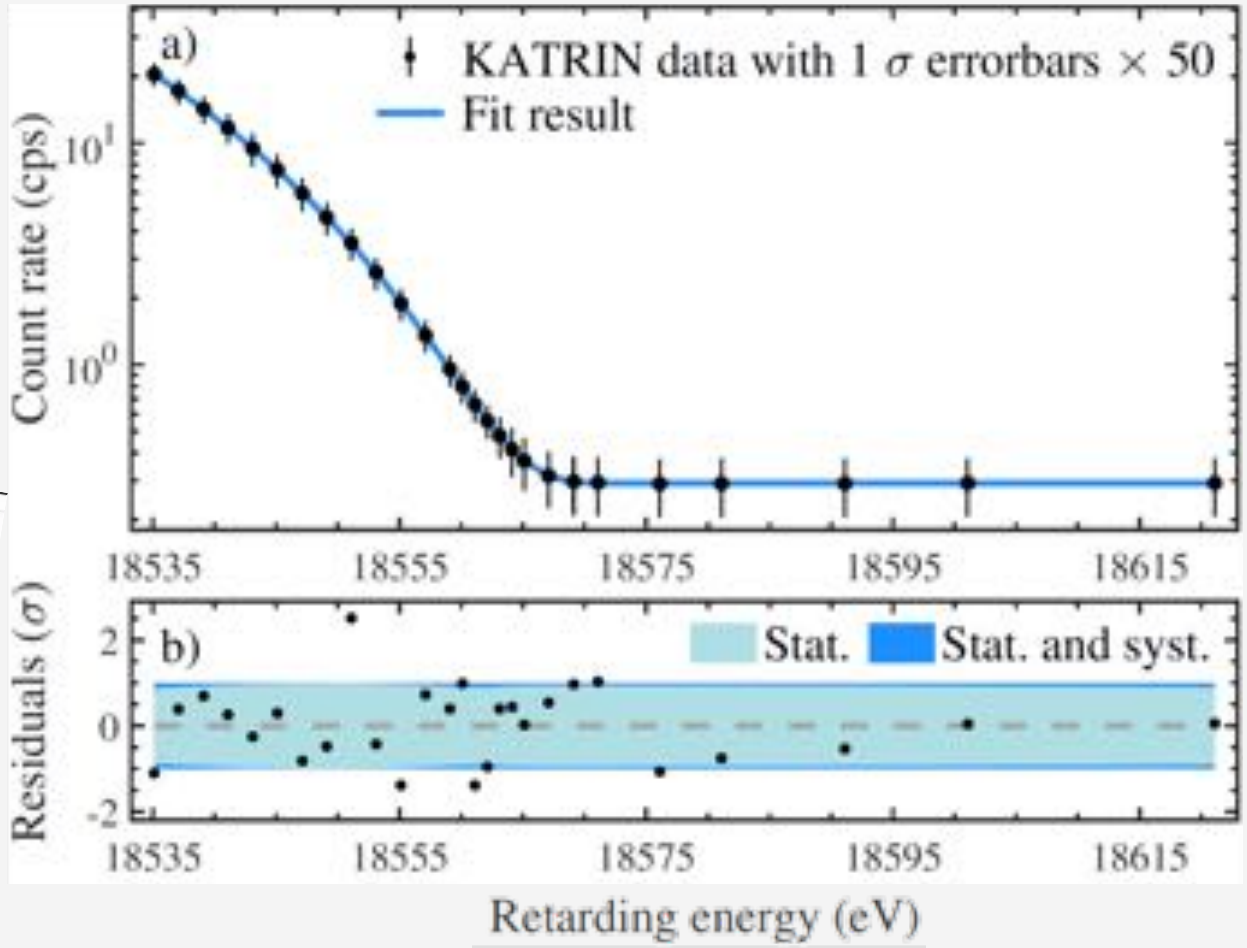
  $m(\nu_e) < 0.8$ eV (90% C.L. Feldman-Cousins)

  $m(\nu_e) < 0.9$ eV (90% C.L. Bayesian, flat prior m^2>0

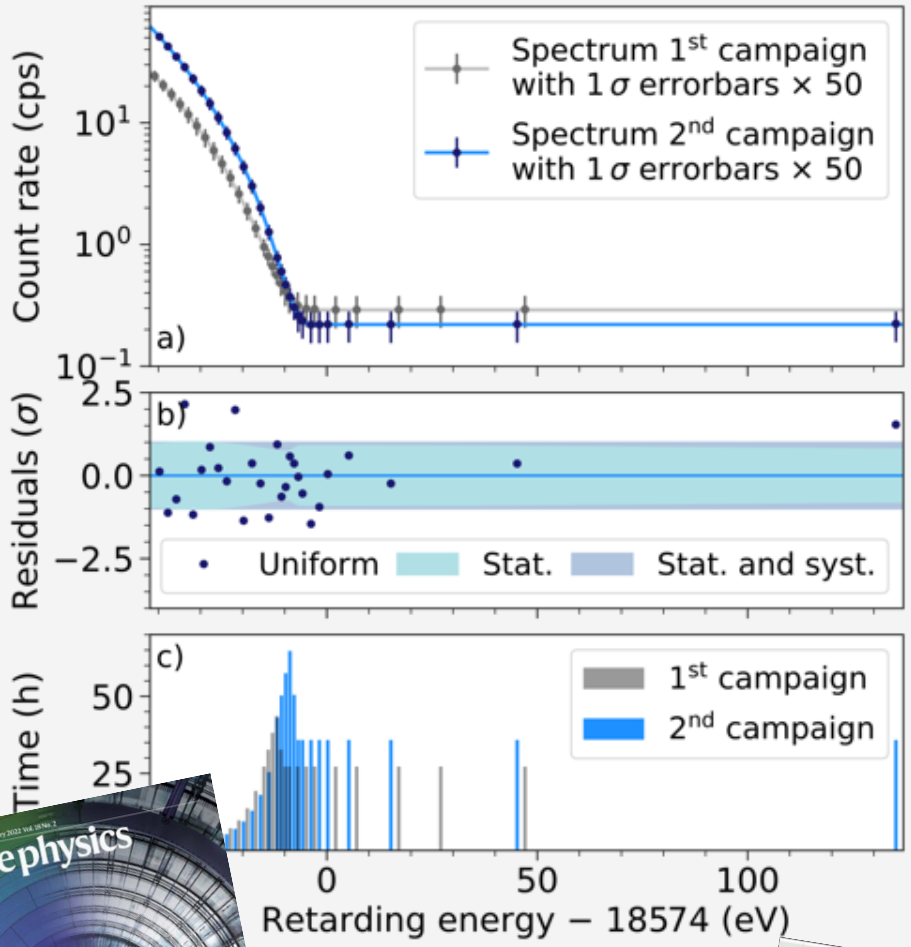
Excellent data quality

Only 9 days out of 1000 live days!

PRL 123 (2019) 221802
+ detailed analysis:
PRD 104 (2021) 012005



Recent KATRIN result of 2nd neutrino mass campaign



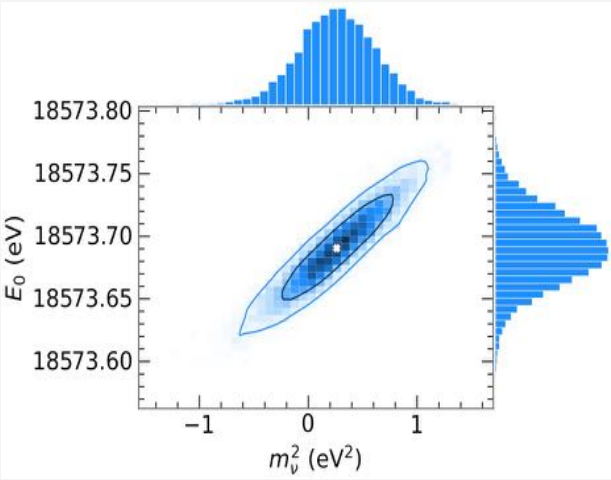
$m^2(\nu) = \left(0.26^{+0.34}_{-0.34}\right)$ eV²

→ compatible with zero

$E_0 = 18573.69 \pm 0.03\ eV$

→ Q-value : 18575.2 ± 0.5 eV

good agreement with Penning trap exp.:
Q = 18575.72 ± 0.07 eV, PRL 114 (2015) 013003



Frequentist limit: $m_\nu < 0.9$ eV (90% CL)

Same for Feldman & Cousins and Lokhov & Tkachov
less than sensitivity, due to positive fit result

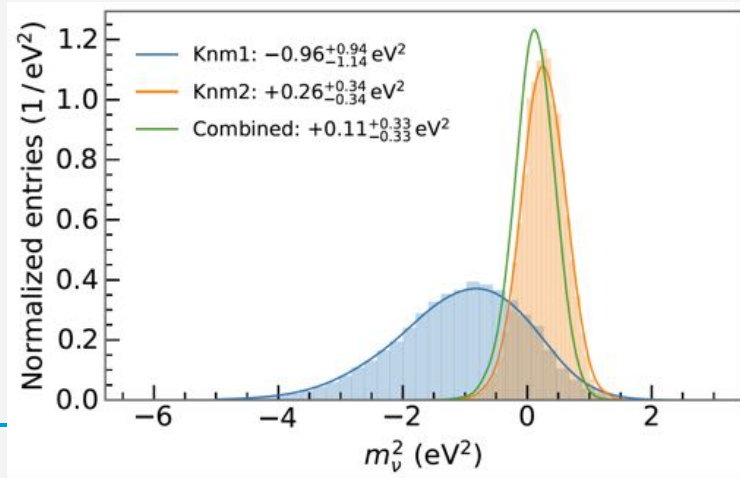
Bayesian: $m_\nu < 0.85$ eV (90% CI)

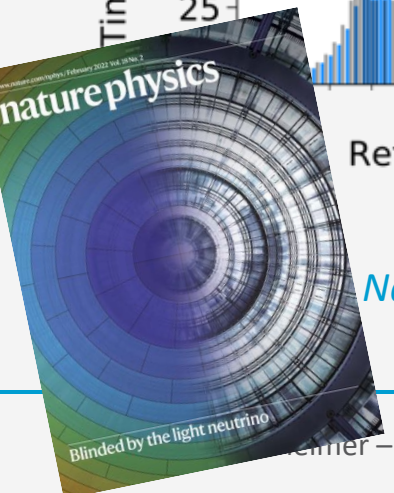
Lokhov & Tkachov, Phys. Part. Nucl. 46 (2015) 347
Feldman & Cousins, Phys. Rev. D57 (1998) 3873

Combine 1st & 2nd campaign:

Frequentist: $m_\nu < 0.8$ eV (90% CL)

Bayes: $m_\nu < 0.7$ eV (90% CL)

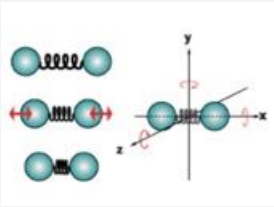




PRL 123 (2019) 221802
Nature Phys. 18 (2022) 160

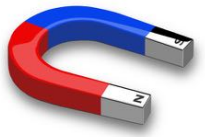
Systematic effects and uncertainties

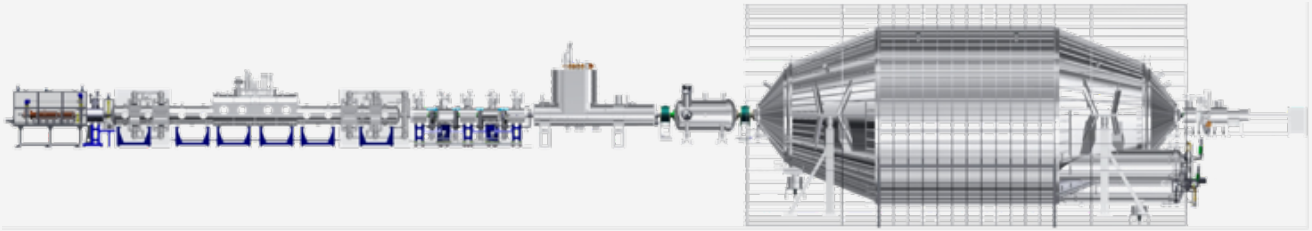
Molecular final states
- quantum-chemical
- computations



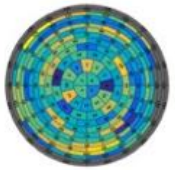
Source electric potential
- plasma properties
- surface conditions

Magnetic fields
- source
- spectrometer
- detector



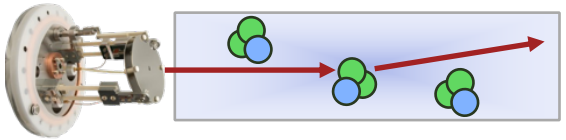


Detection efficiency



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

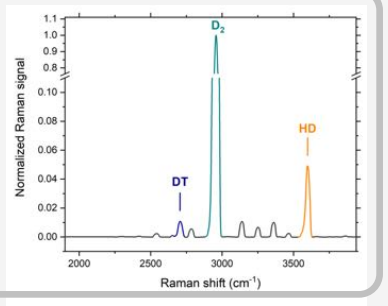
Energy loss by scattering



EPJ C 79 (2019) 204
EPJ 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

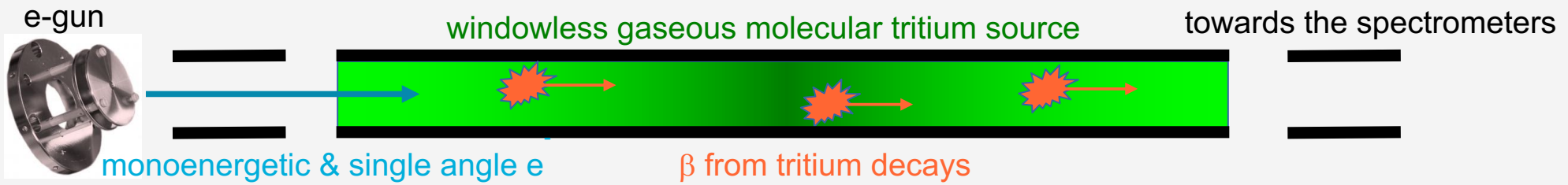
JINST 13 (2018) T10004
Eur. Phys. J. A 44 (2010) 499
Astropart. Phys. 138 (2022) 102686

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

Determination of response function



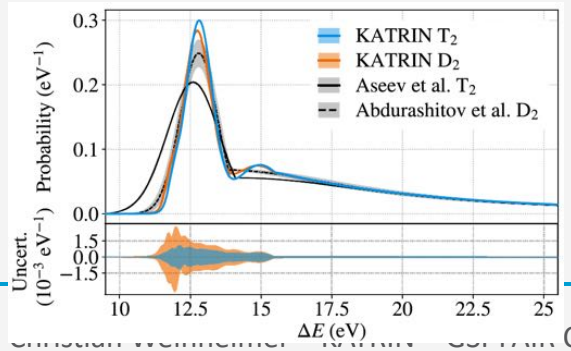
- **Shooting electrons from monoenergetic pulsed UV-laser photoelectron source through tritium column density**

Eur. Phys. J. C77 (2017) 410, Astropart. Phys. 89 (2017) 30

Normal integral MAC-E-Filter mode

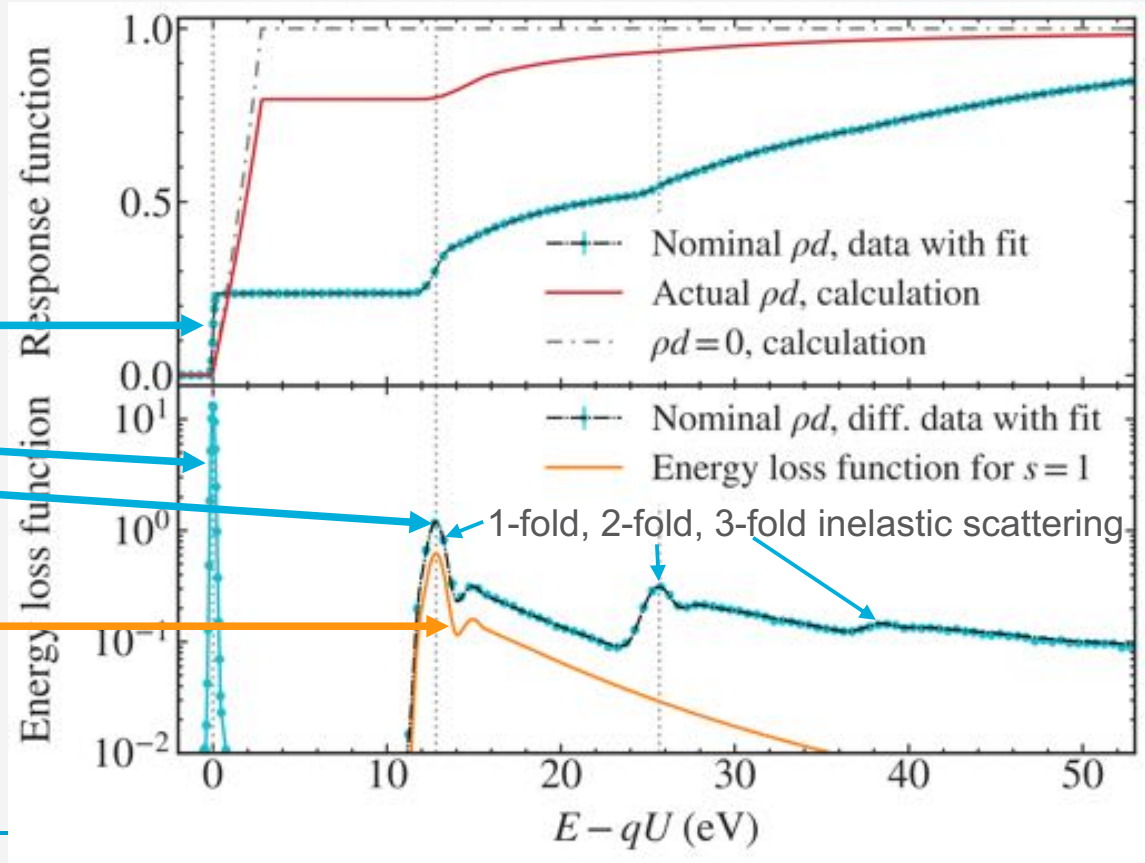
Differential Time-of-flight mode

Nucl. Inst. Meth. A 421 (1999) 256



Deconvoluted differential energy loss function

Eur. Phys. J. C 81 (2021) 579

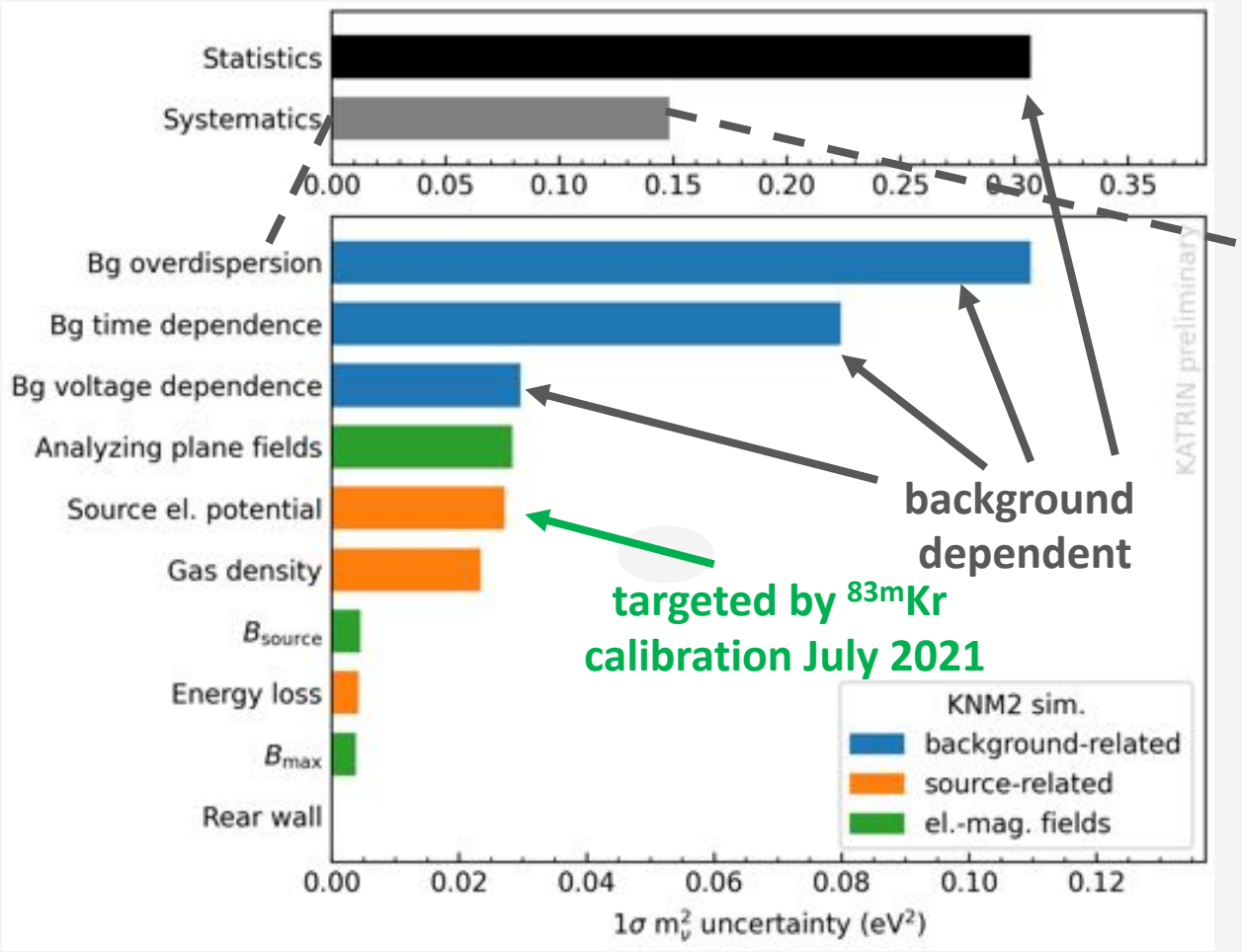


Uncertainty breakdown: published run (KNM2)

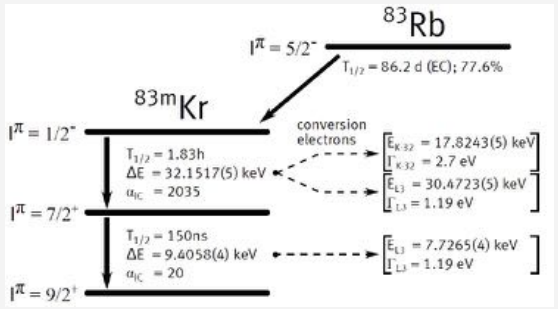
- **Budget for KNM2 (autumn 2019)**

Budget is statistics dominated,
but various contributions by **background**
and source systematics are still too high

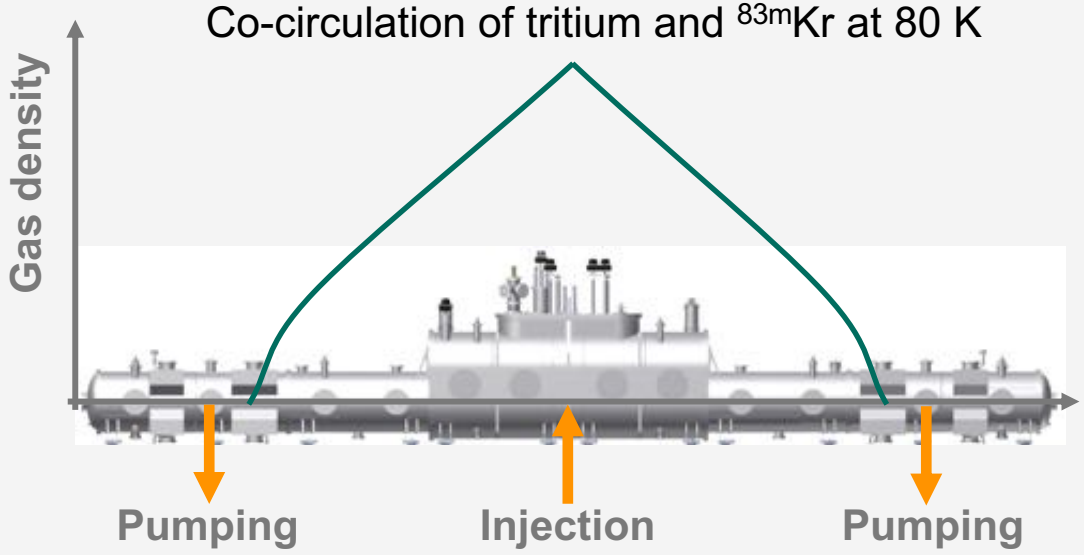
Nature Phys. 18 (2022) 160

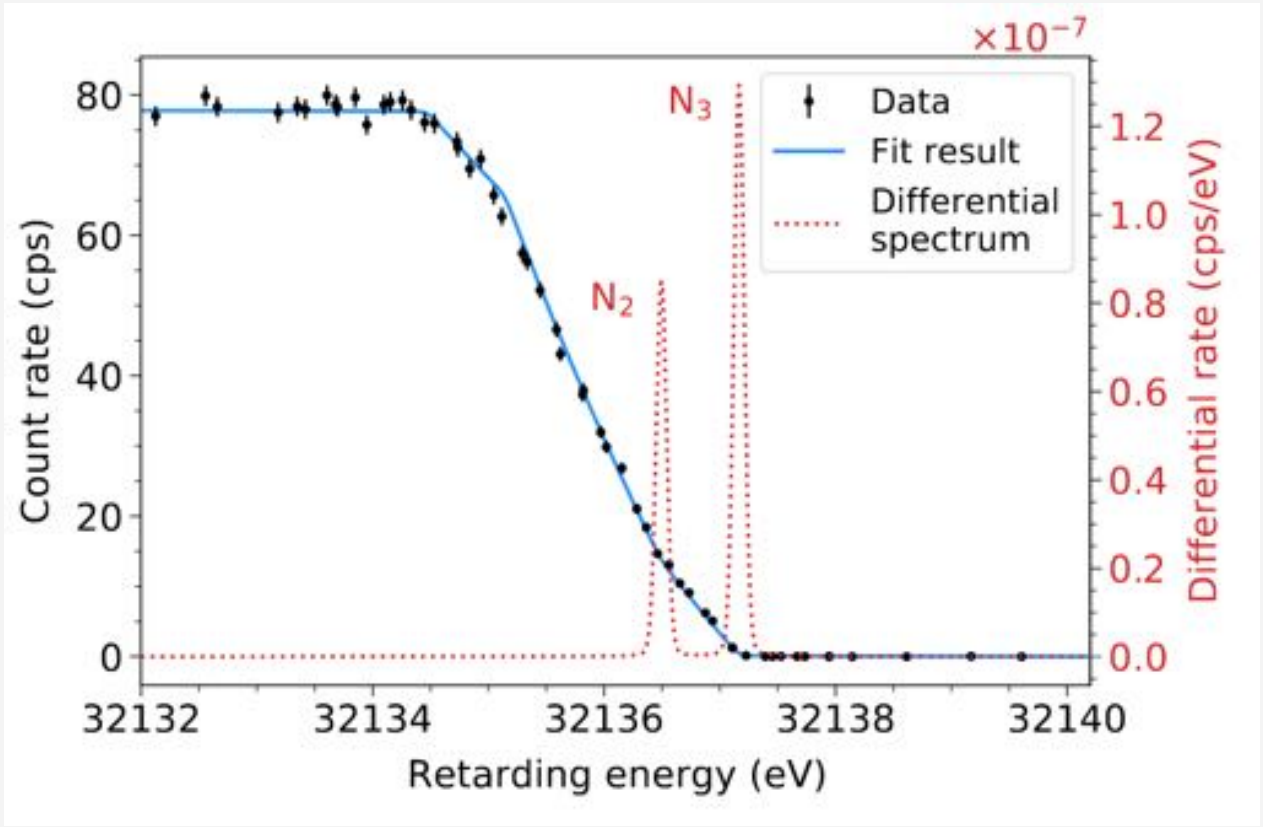


Improving source-related systematics



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





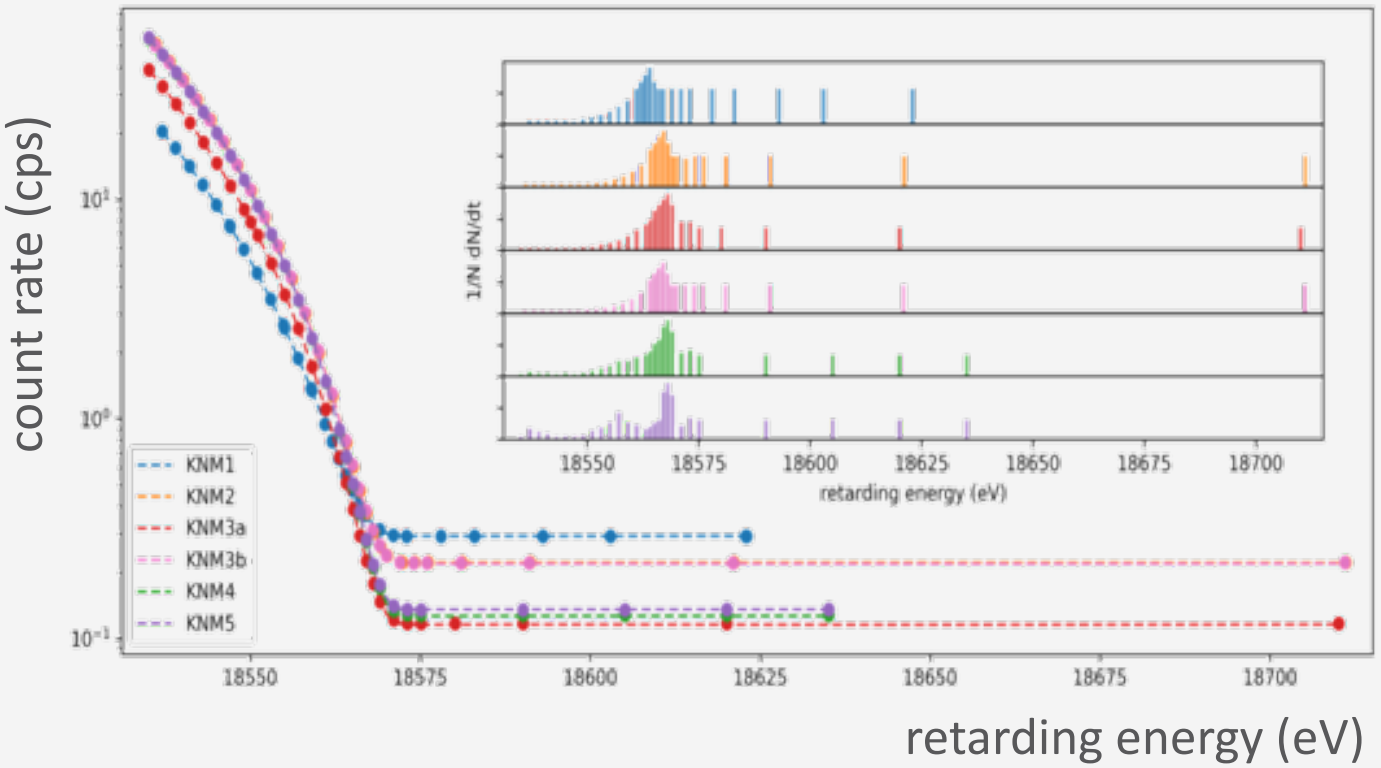
Data of 2020 krypton run at 40% tritium column density used to constrain systematics in 2nd campaign *Nature Phys. 18 (2022) 160*

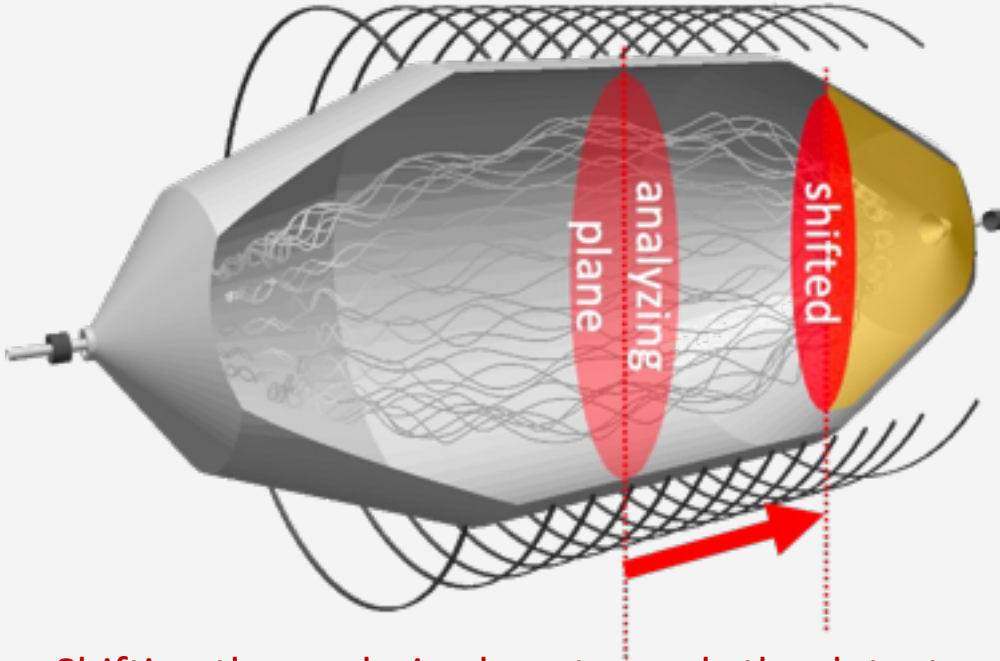
Since then: New operation mode with stable co-circulation at high column density at 80 K

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

KATRIN signal & background impovements

- continuous improvement of signal-to-background ratio

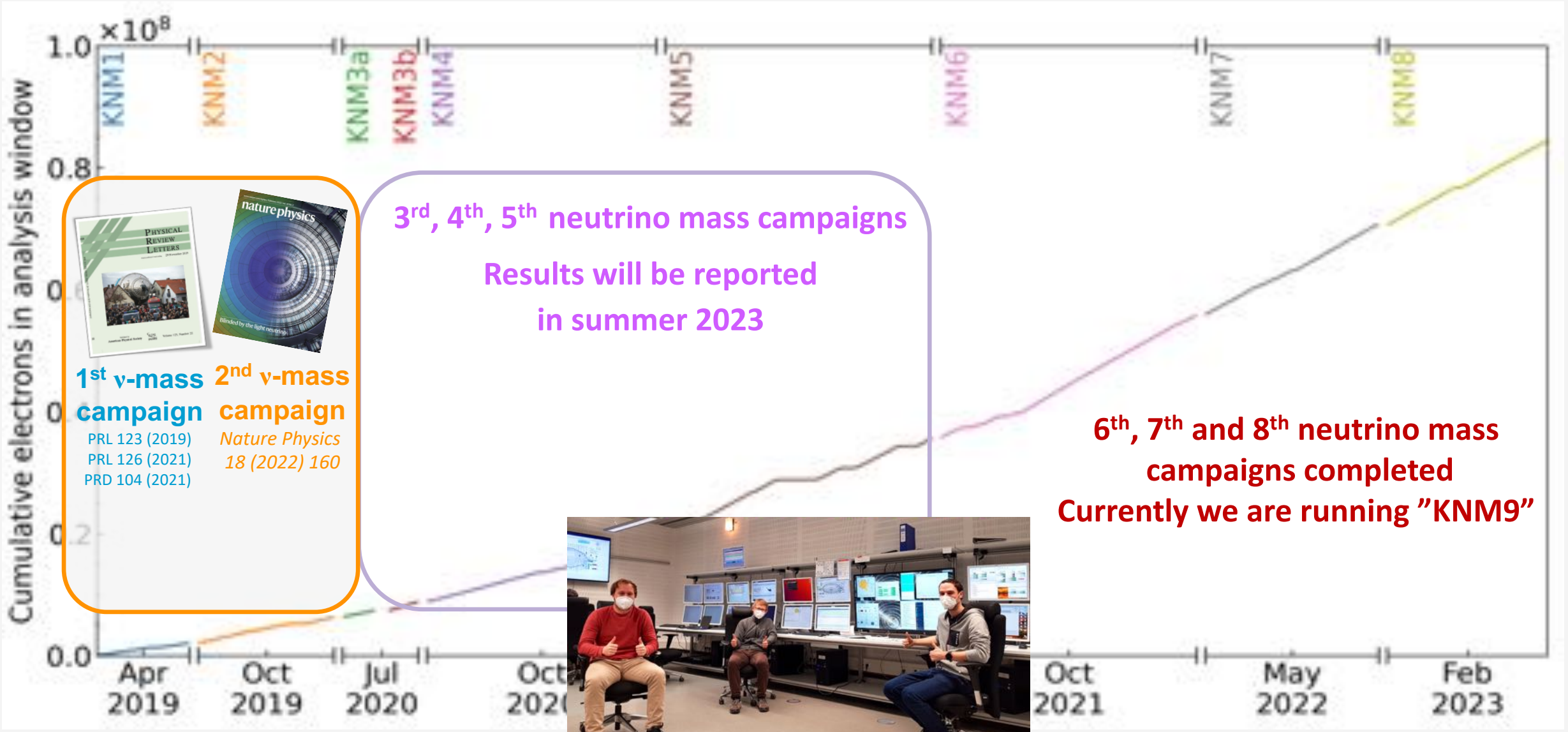




Shifting the analysis plane towards the detector reduced background by factor of 2

Eur. Phys. J. C 82 (2022) 258

KATRIN data taking continues



1st ν-mass campaign
PRL 123 (2019)
PRL 126 (2021)
PRD 104 (2021)

2nd ν-mass campaign
Nature Physics 18 (2022) 160

3rd, 4th, 5th neutrino mass campaigns

Results will be reported in summer 2023

6th, 7th and 8th neutrino mass campaigns completed
Currently we are running "KNM9"

Uncertainty breakdown: later runs (here KNM5)

- **Budget for KNM5 (spring 2021)**

budget is statistics dominated, but

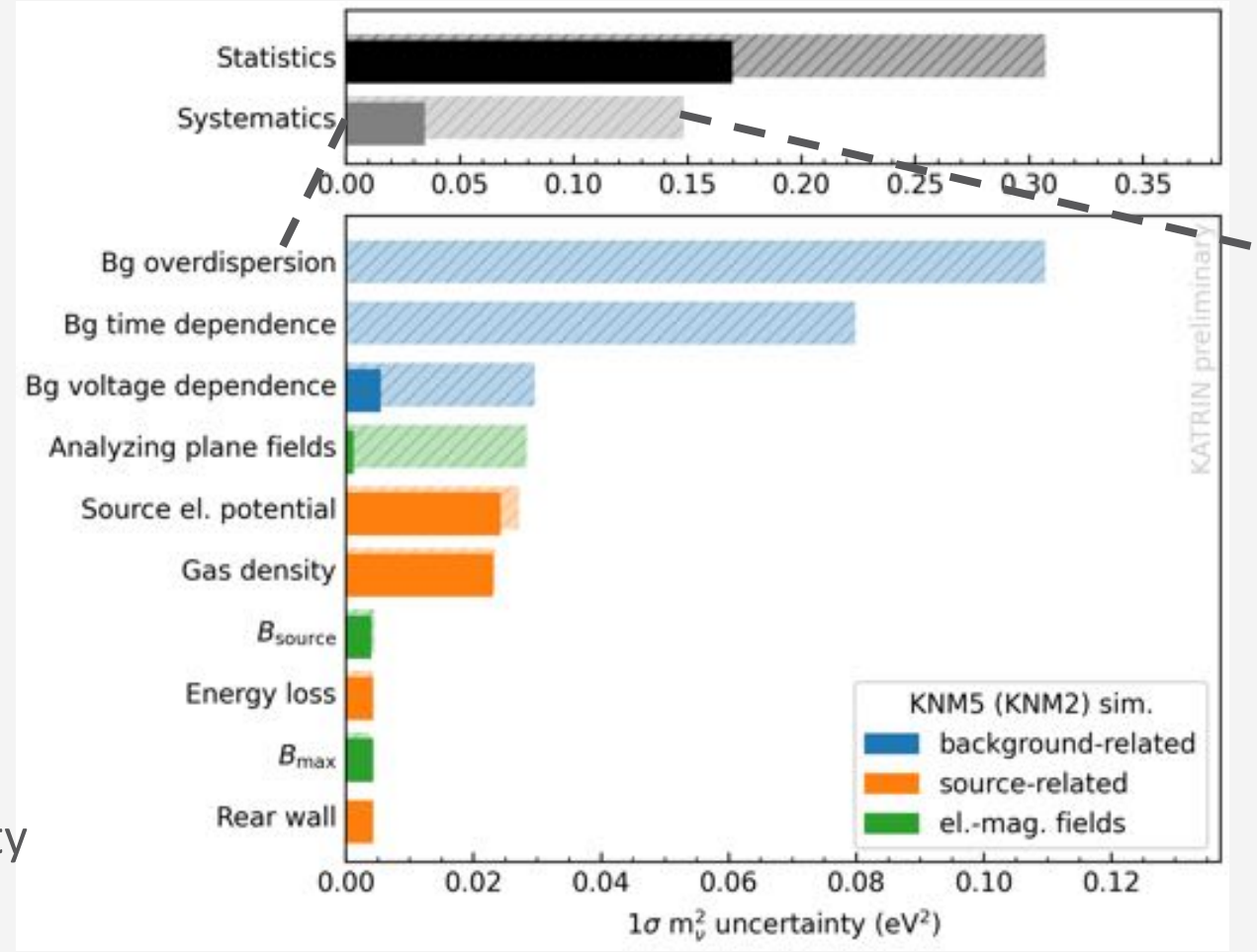
background-mitigation techniques:
avoid Penning trap,
shifted analyzing plane (SAP)

Lokhov et al., Eur.Phys.J. C 82 (2022) 258

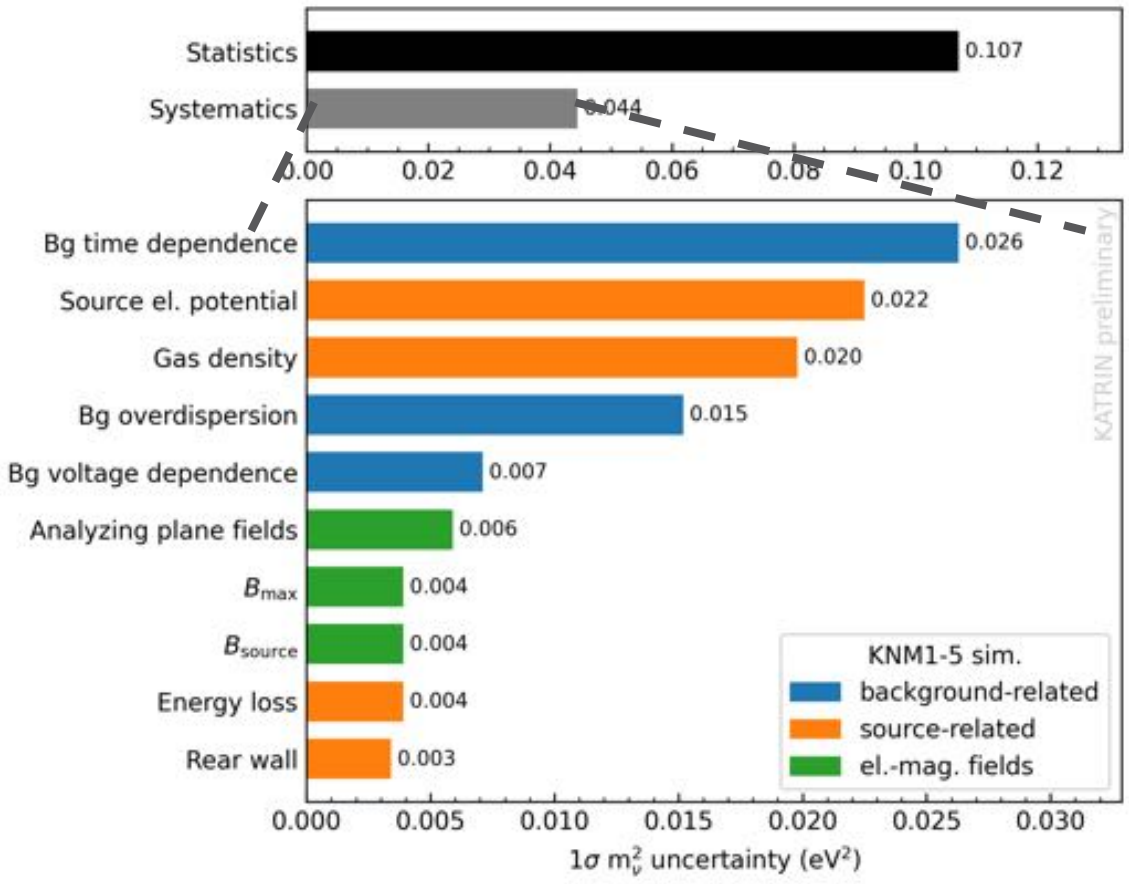
high-statistics ^{83m}**Kr campaign**,

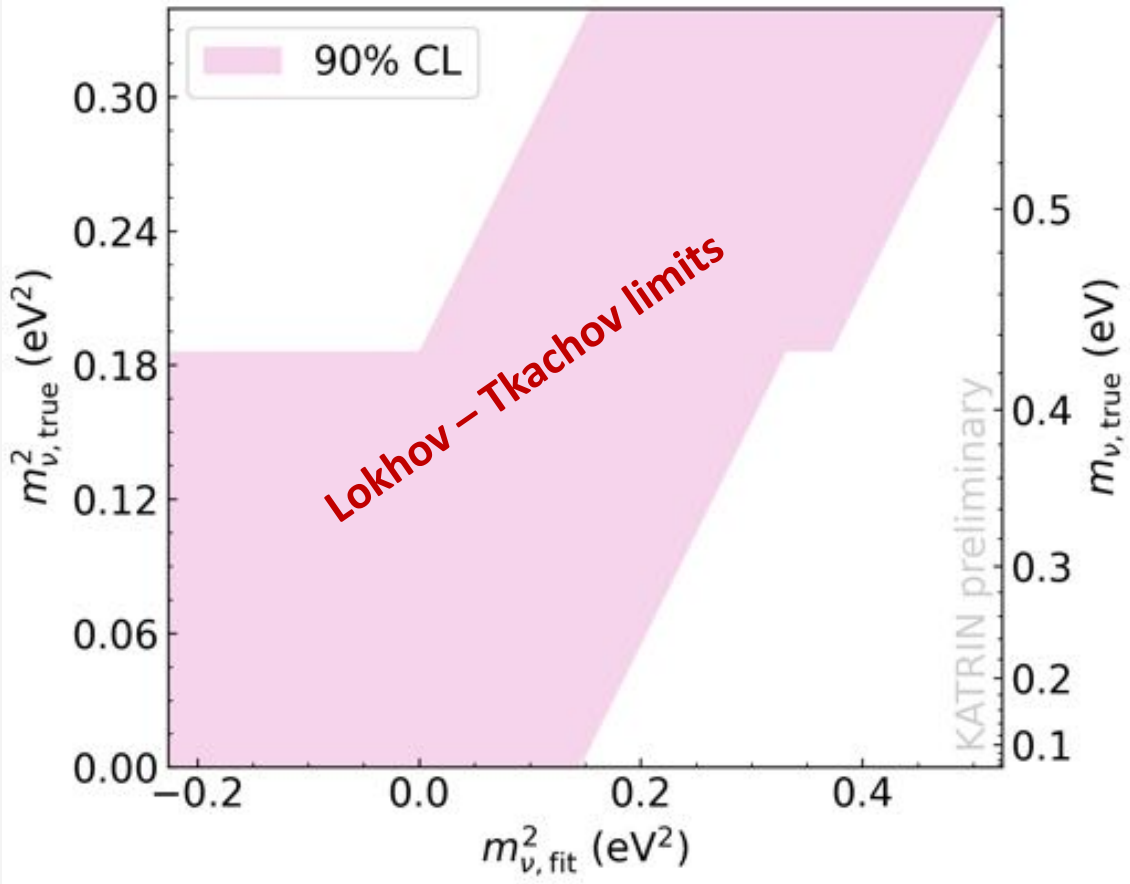
tritium scans at identical temperature / gas density

Altenmüller et al., J.Phys.G 47 (2020) 6, 065002



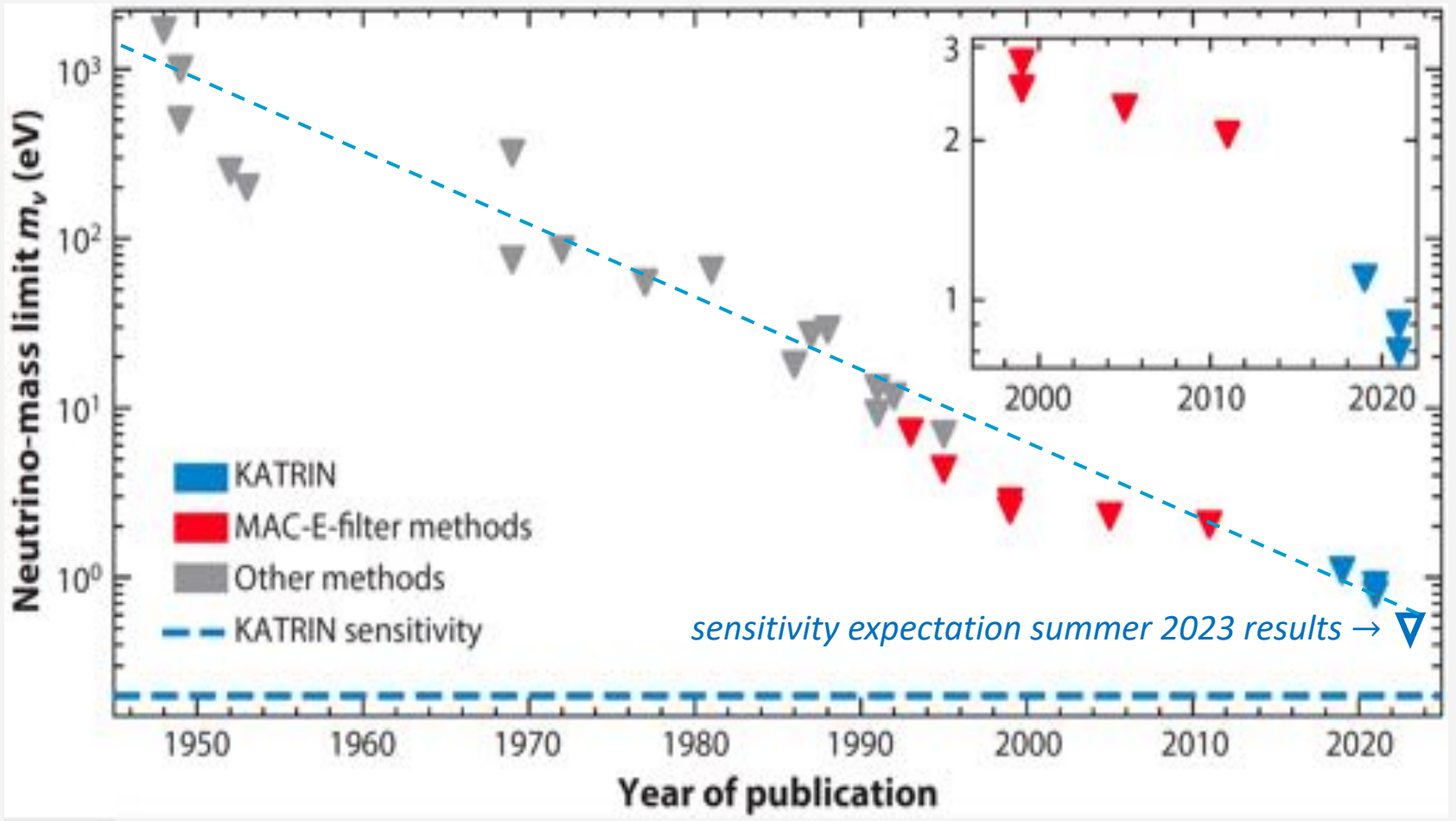
Sensitivity estimate of runs to be presented in summer 2023





→ **expect sensitivity to neutrino mass scale ≈ $0.45\ eV$**

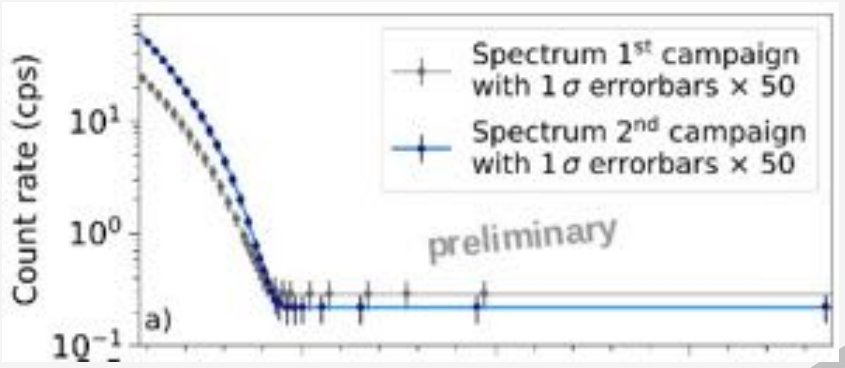
KATRIN's sensitivity improvements on neutrino mass



Annu. Rev. Nucl. Part. Sci. 72 (2022) 259

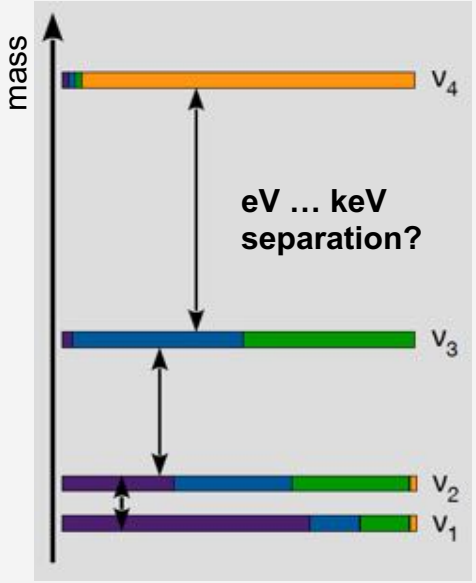
→ expect sensitivity to neutrino mass scale $\approx 0.45\ eV$

KATRIN „beyond the neutrino mass“



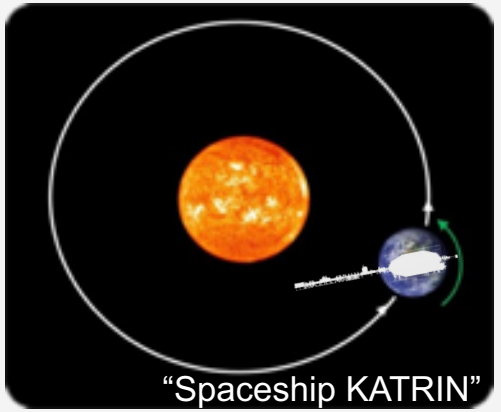
Is there a fourth (sterile) neutrino?

Search for exotic weak interactions (spectrum shape)



β-spectrum of high statistics and precision

Search for Lorentz invariance violation (sidereal modulation)



Neutrino mixing: “Kink” in normal β-spectrum (eV scale) or deep β-spectrum (keV scale)

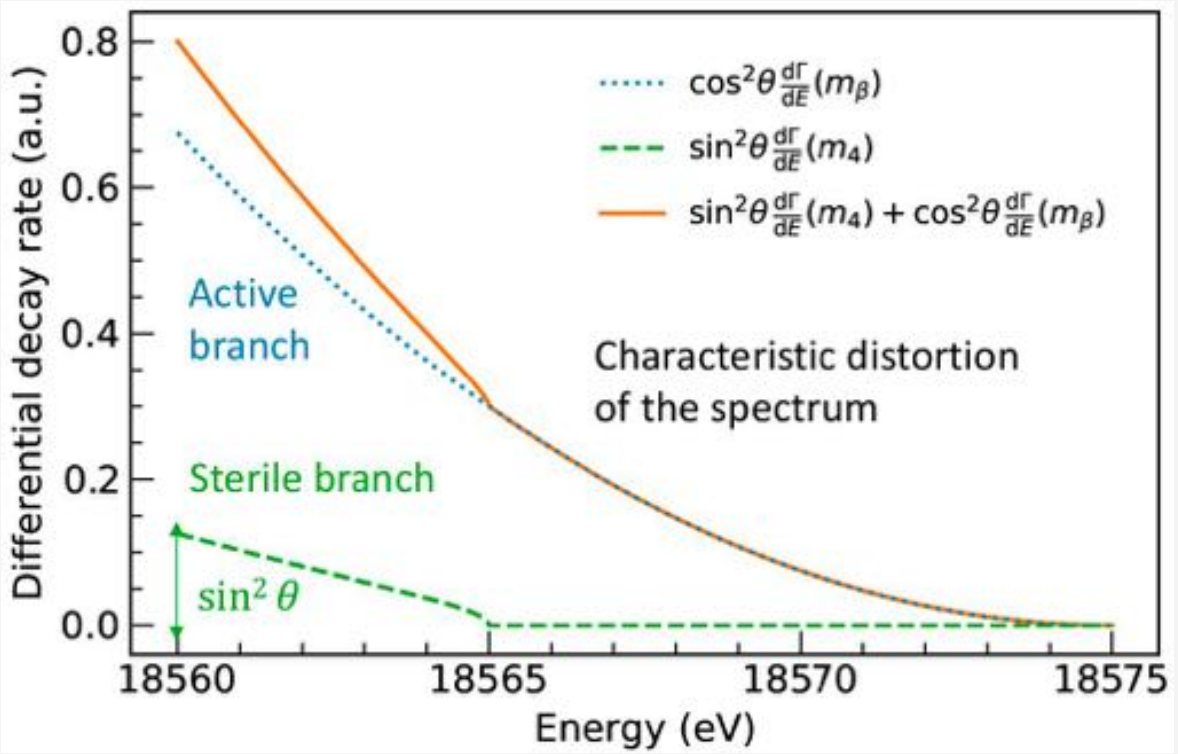
Constrain local overdensity of cosmic relic neutrinos (peak search)

Constraints on light sterile neutrinos

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

The 4th neutrino mass state ν_4
would manifest in a kink in the beta spectrum

$$\frac{d\Gamma}{dE} = \underbrace{\left(1 - |U_{e4}|^2\right) \frac{d\Gamma}{dE}(m_\beta^2)}_{\text{light neutrino}} + \underbrace{|U_{e4}|^2 \frac{d\Gamma}{dE}(m_4^2)}_{\text{heavy neutrino}}$$



Constraints on light sterile neutrinos

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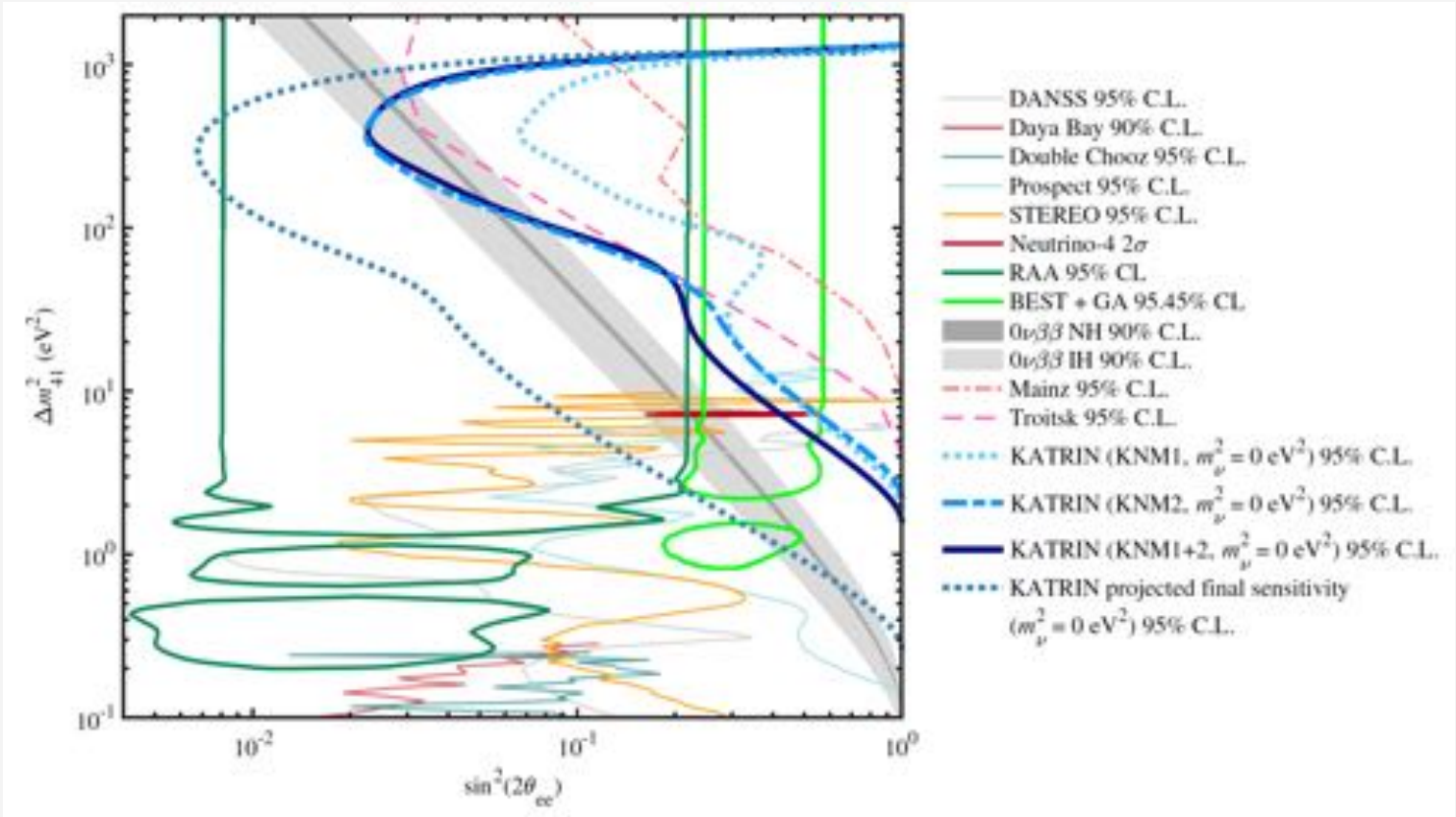
The motivation comes from anomalies in short baseline oscillation accelerator, solar and reactor neutrino experiments

KATRIN starts to probe very interesting parameter space, complementary to oscillation searches



Phys. Rev Lett. 126, 091803 (2021)
Phys. Rev. D 105 (2022) 7, 072004

Expected sensitivities on light sterile neutrinos

Sterile neutrinos at eV-scale: a 4th state?

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = U'_{PMNS} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \boldsymbol{\nu_4} \end{pmatrix}$$

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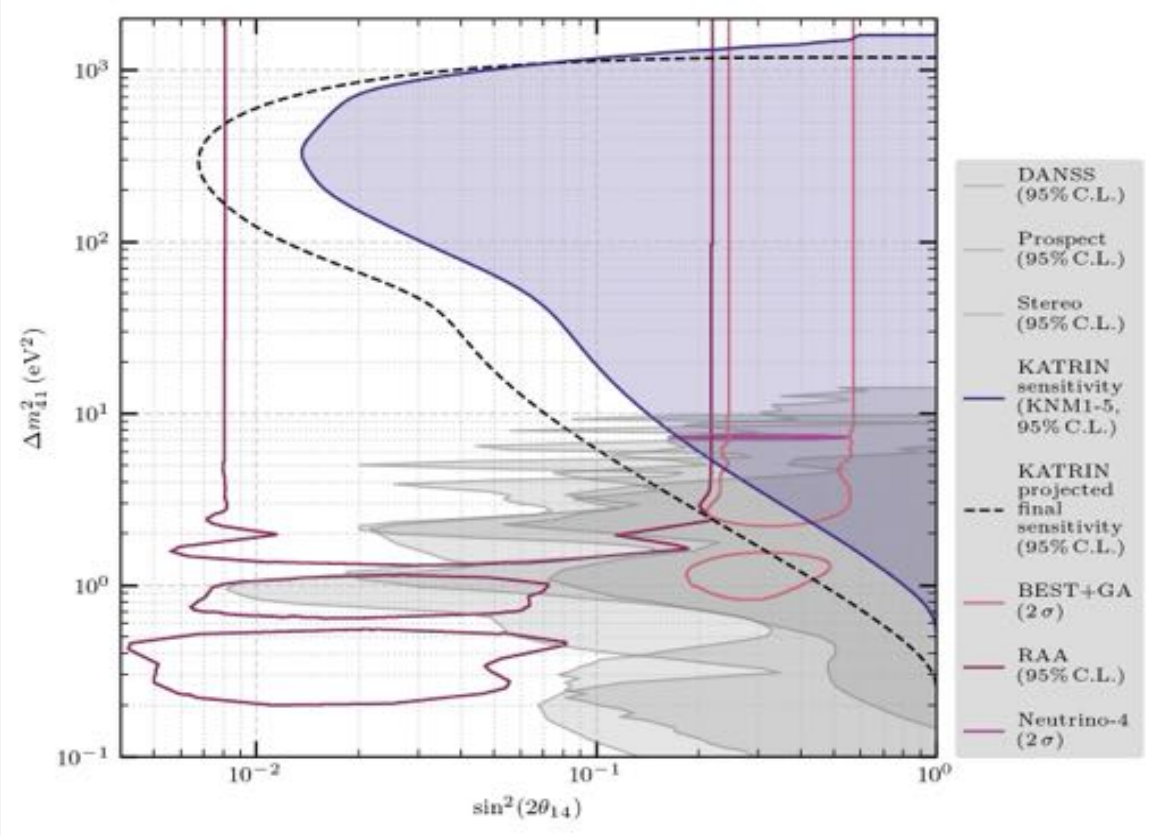


Phys. Rev Lett. 126, 091803 (2021)
Phys. Rev. D 105 (2022) 7, 072004

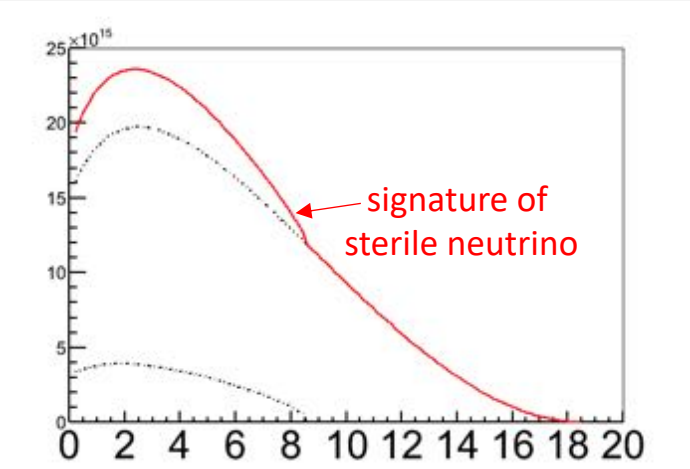
KATRIN: search for sterile neutrinos at keV-scale

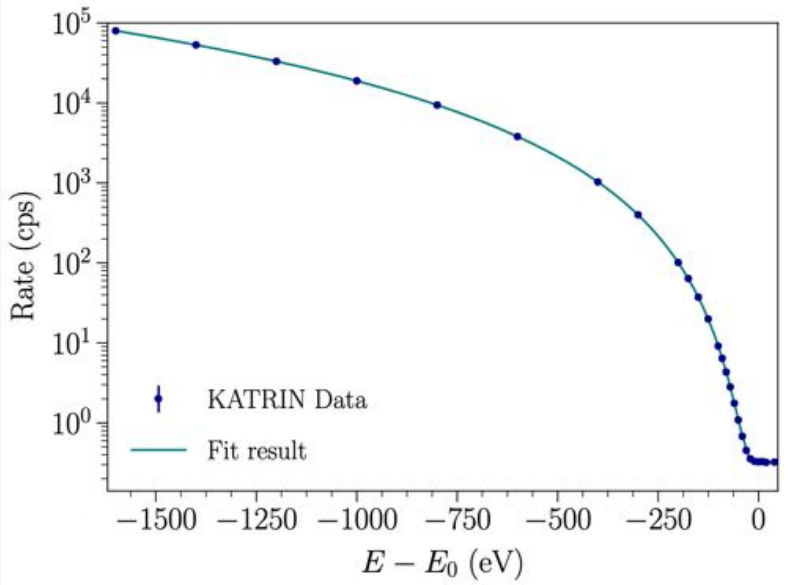
- **Strong physics impact**

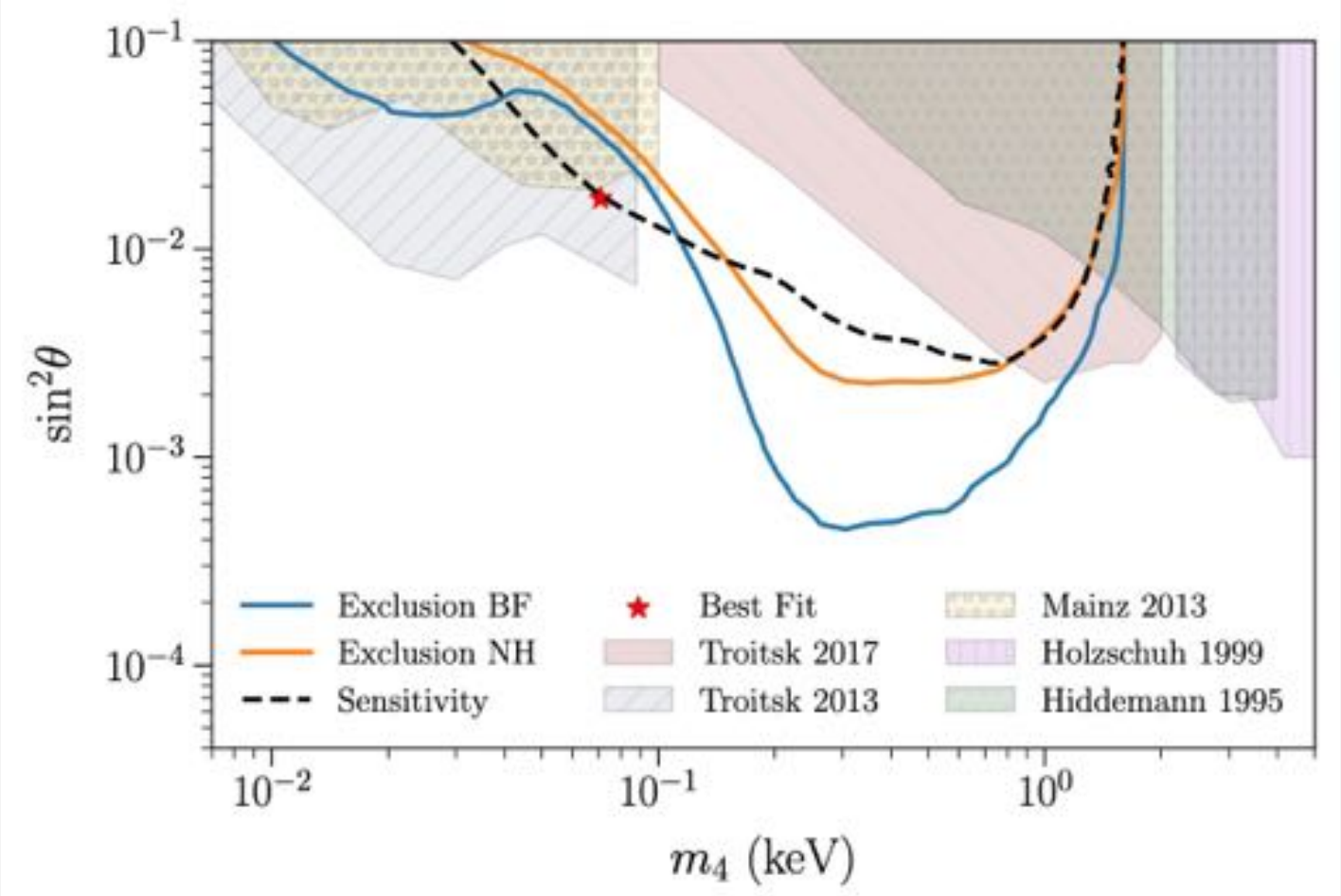
  - sterile neutrinos on keV-scale are a viable candidate for dark matter in the universe (WDM)

see recent CERN Courier issue 3-4/2022

KATRIN: search for sterile neutrinos at keV-scale







arXiv:2207.06337

Future: search for sterile keV neutrinos with KATRIN

4th mass eigenstate, dark matter candidate

Look for the kink in the β-spectrum

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

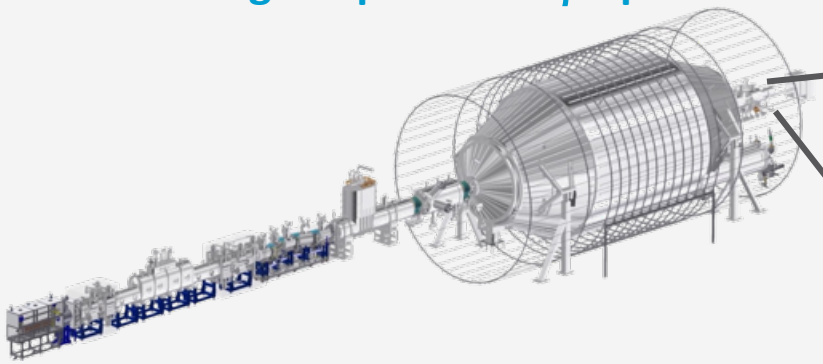
requires developing a new detector & DAQ system with

- **large count rates**
- **good energy resolution**

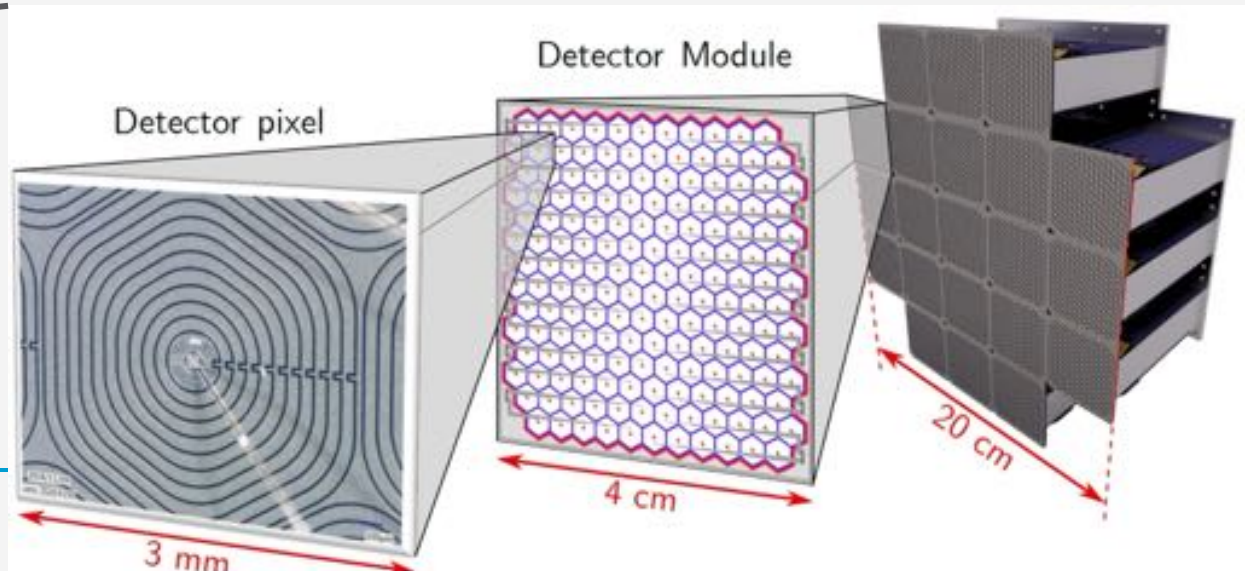
➞ highly pixelized silicon drift detector (SDD): TRISTAN detector'

- **data taking deep into the β-spectrum from 2026 on**

Successfully tested first prototype module at KATRIN's monitor spectrometer

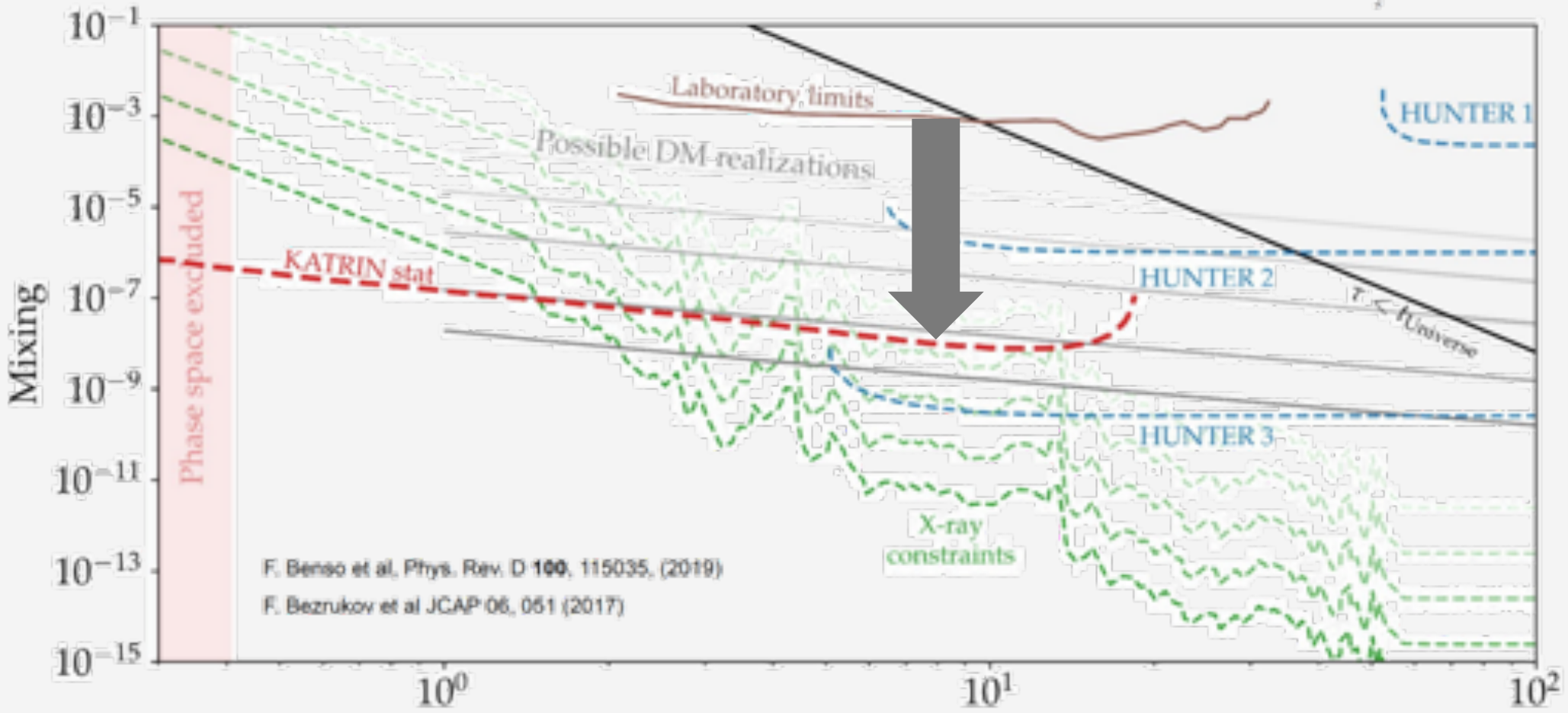


S. Mertens et al., J.Phys. G46 (2019) 065203
T. Brunst et al., JINST 14 (2019) P11013

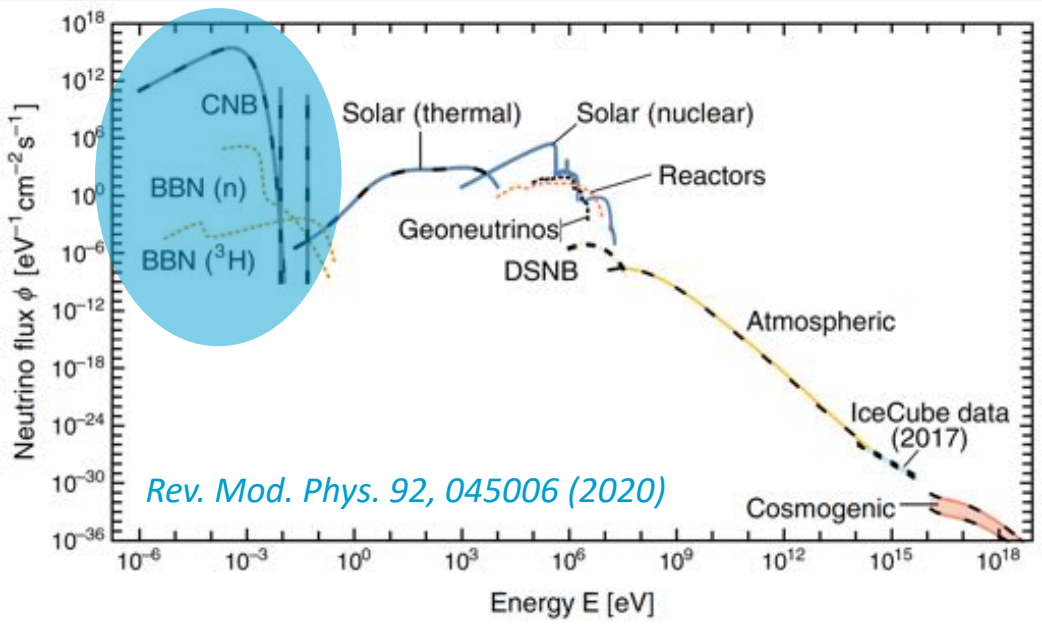


Physics reach for sterile neutrinos at keV-scale

- KATRIN will advance experimental sensitivity by many orders

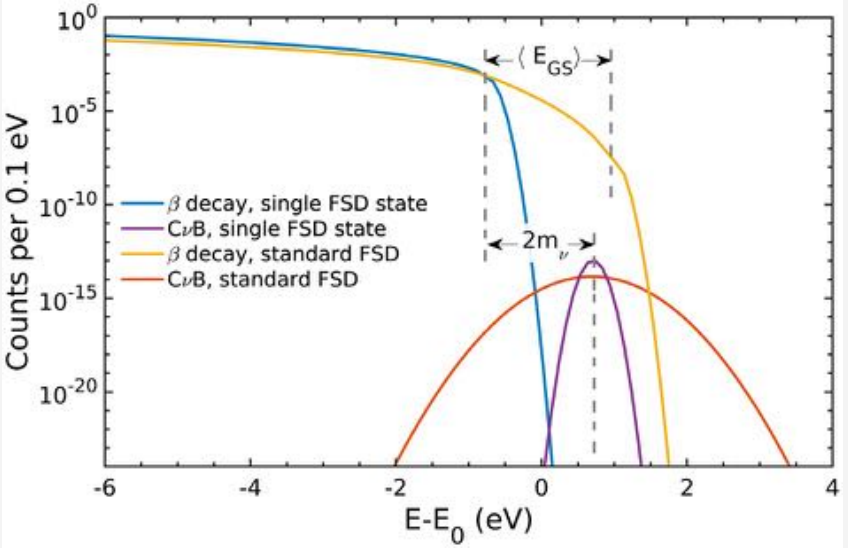


Search for overdensity of cosmic relic neutrinos



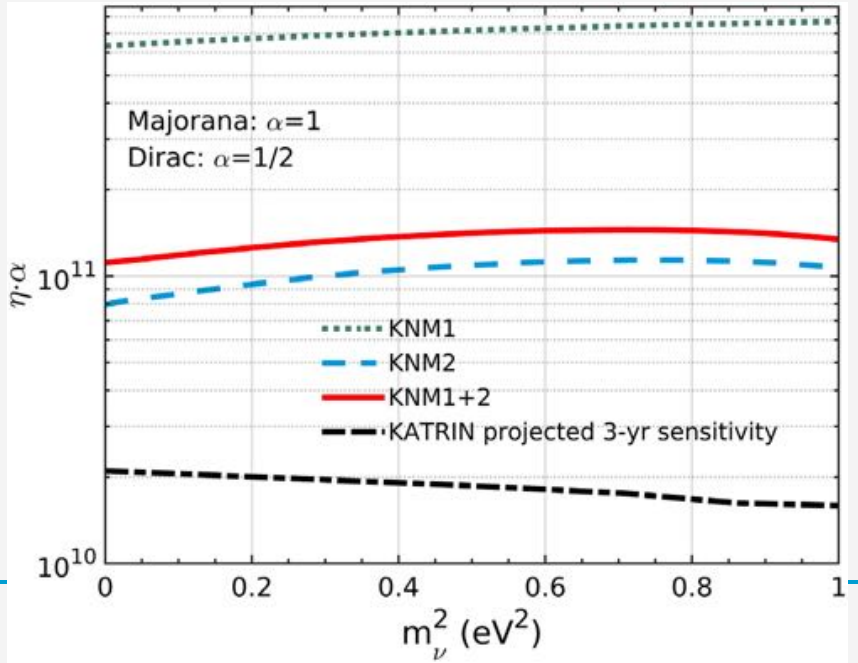
Rev. Mod. Phys. 92, 045006 (2020)

Signature at KATRIN



Results by KATRIN

Phys. Rev. Lett. 129 (2022) 011806



Detection via inverse β-decay on tritium:

$$\nu_e + \mathrm{T} \rightarrow {}^3\mathrm{He} + \mathrm{e}^-$$

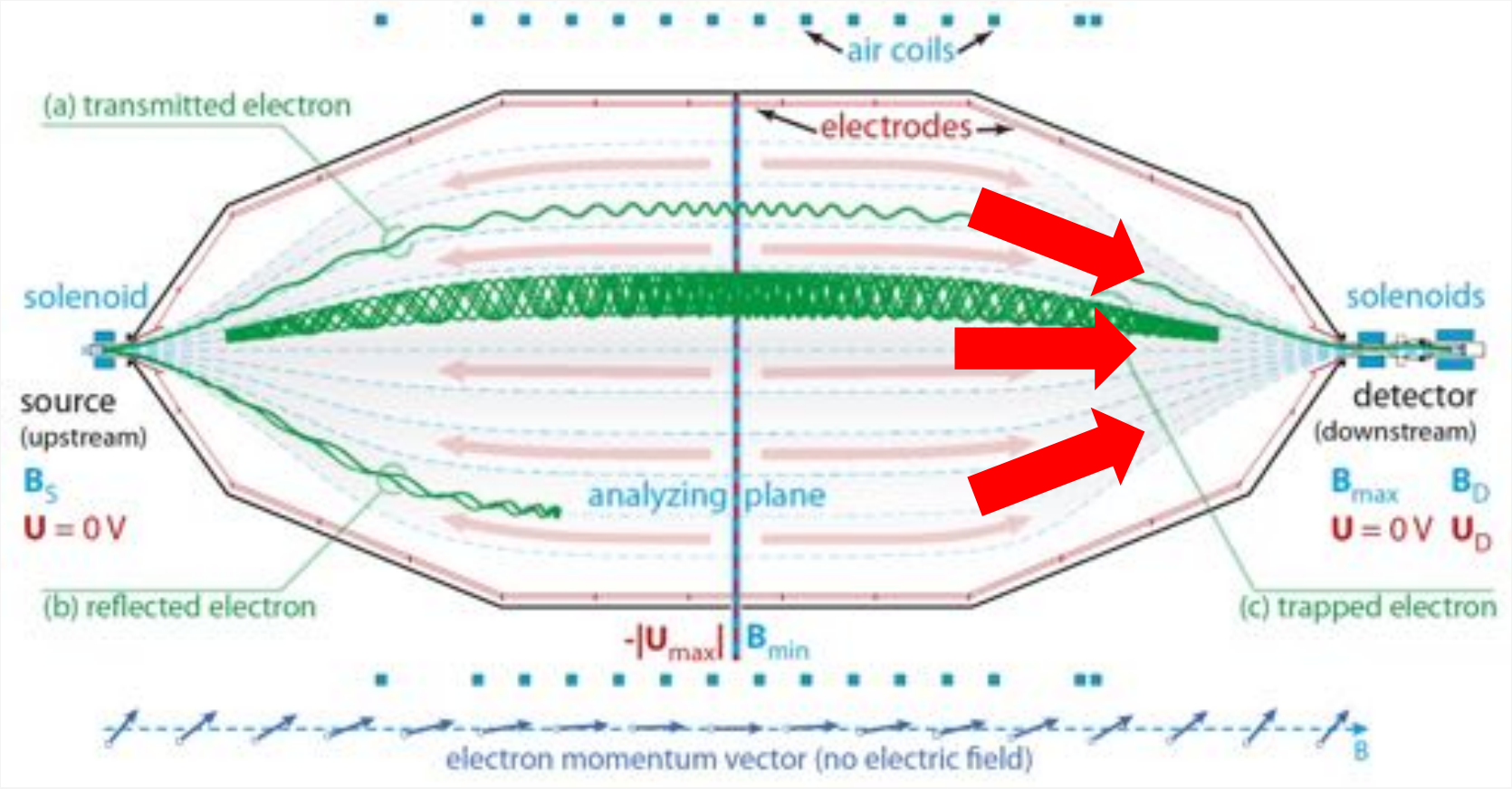
→ monoenergetic electron

Further reduction of background rate

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 $E \sim E_{||} \geq qU$



Sensitive to backgrounds:

- Low energy electrons "born" in the spectrometer volume will be accelerated to detector (same energy as signal electrons)
- Electrons can be trapped in the magnetic bottle of MAC-E-Filter or in local Penning traps → secondary electrons

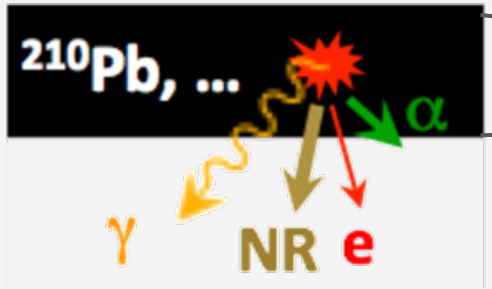
Very high energy resolution

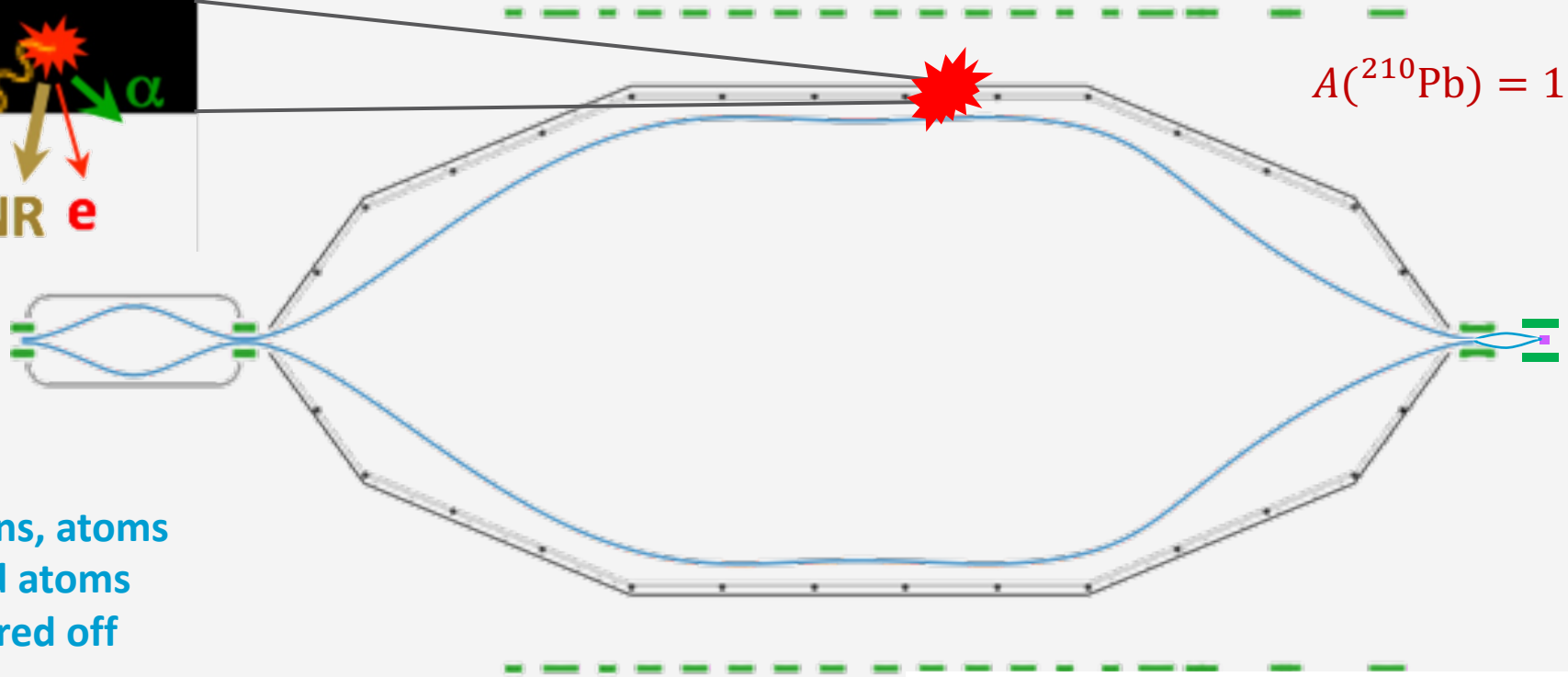
$\Delta E = \mathcal{O}(1\text{eV})$

Very high angular acceptance:

$\Delta\Omega \approx \pi$

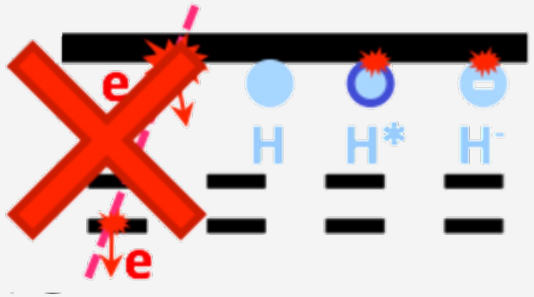
An unexpected background ^{210}Pb in wall → ^{210}Po α decays from installing the spectrometer under ambient air (^{222}Rn)

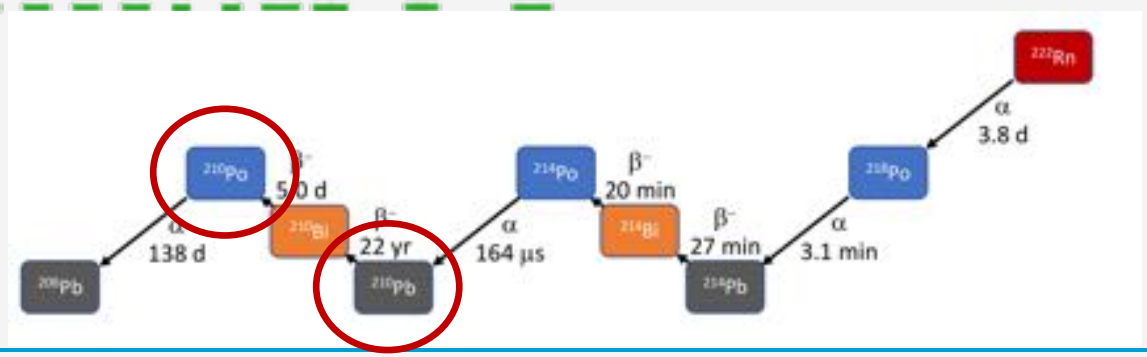




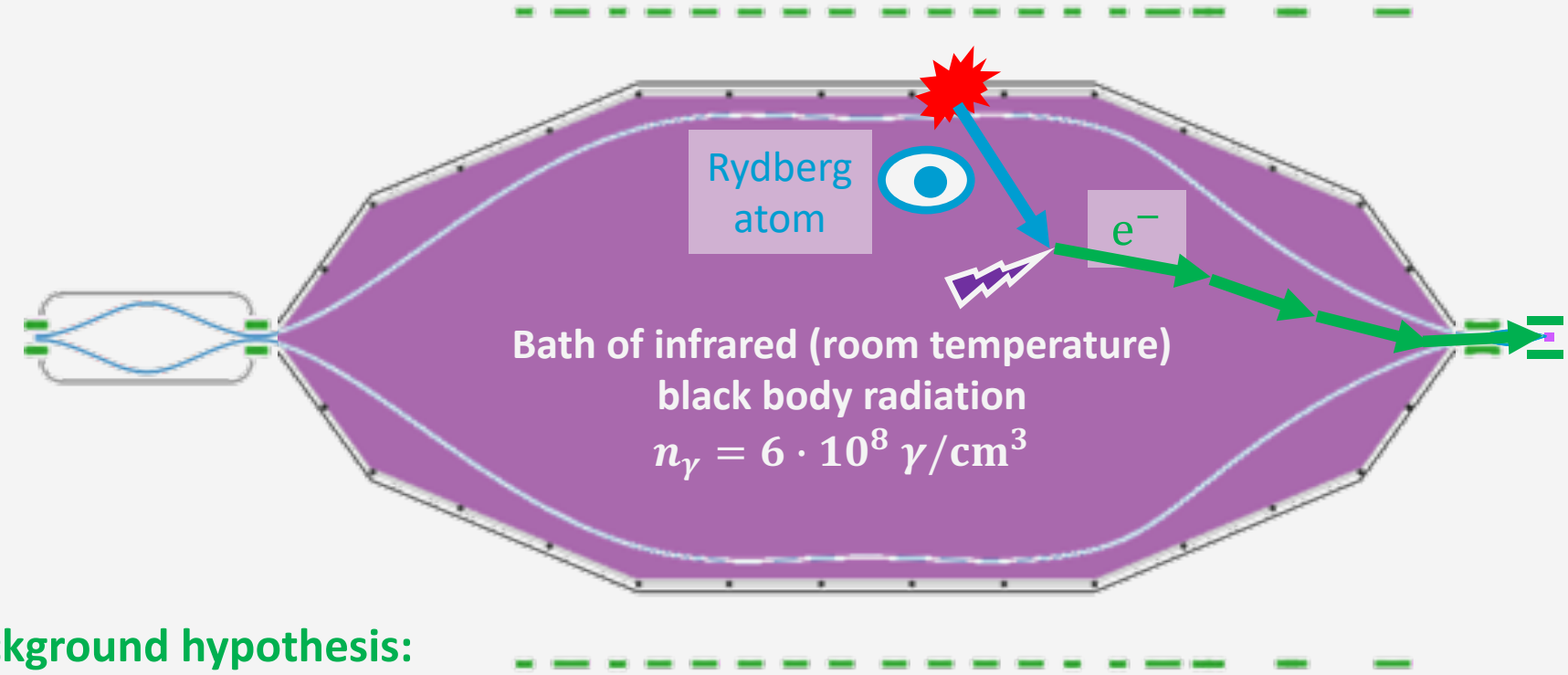
$$A(^{210}\mathrm{Pb}) = 1\,\frac{\mathrm{Bq}}{\mathrm{m}^2} \sim 1\ \mathrm{kBq\ in\ total}$$

Also a few ions, atoms and excited atoms get sputtered off





^{210}Po α decays create “Rydberg” atoms → background electrons



Rydberg background hypothesis:

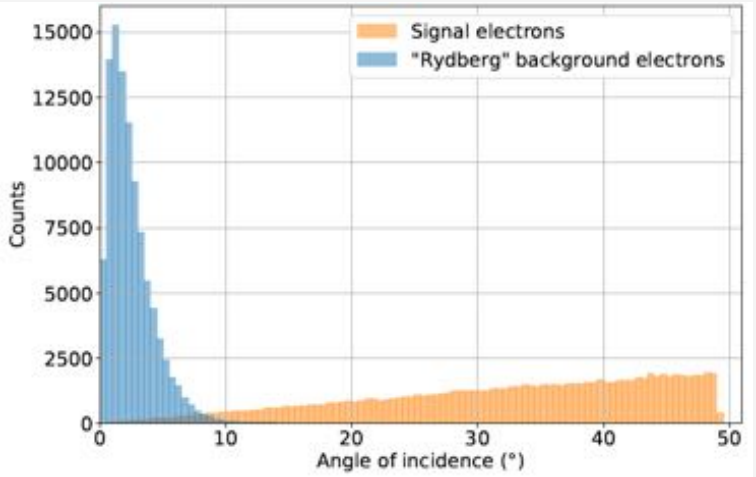
Neutral Rydberg atom overcomes electromagnetic barriers,
is ionized in the flux tube by infrared photons,
electron follows the electric potential gradient following the magnetic field lines to the detector.
Energetically practically indistinguishable from β electrons.

Astropart. Phys. 138 (2022) 102686

Different angular distributions → transverse energy filter

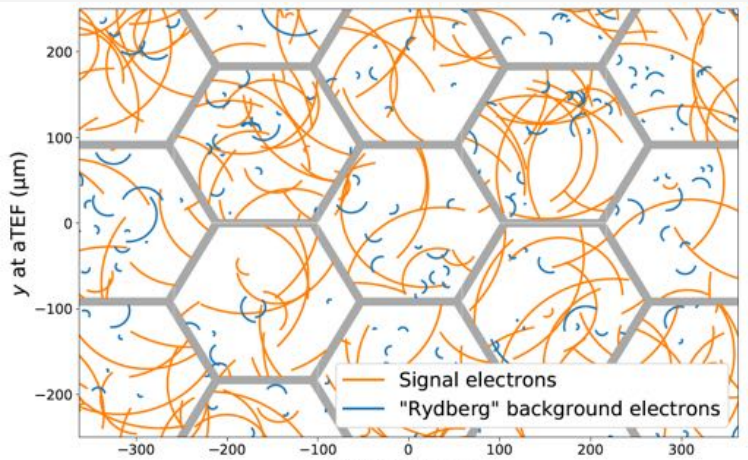
"Rydberg electrons" are released in spectrometer volume
with very little starting energy $\mathcal{O}(k_B T)$,
and accumulate practically only longitudinal energy $E_{||}$, but $E_{\perp} \approx k_B T$

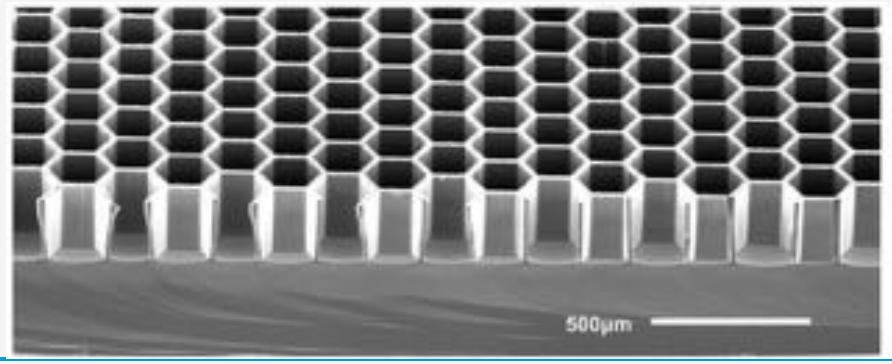
→ sharp angular distribution at detector,
in contrast to β electrons, which have $E_{\perp}$ up to $\Delta E \sim 2.7$ eV

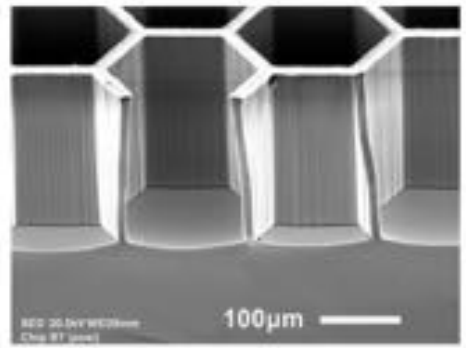


Eur. Phys. J. C 82 (2022) 922

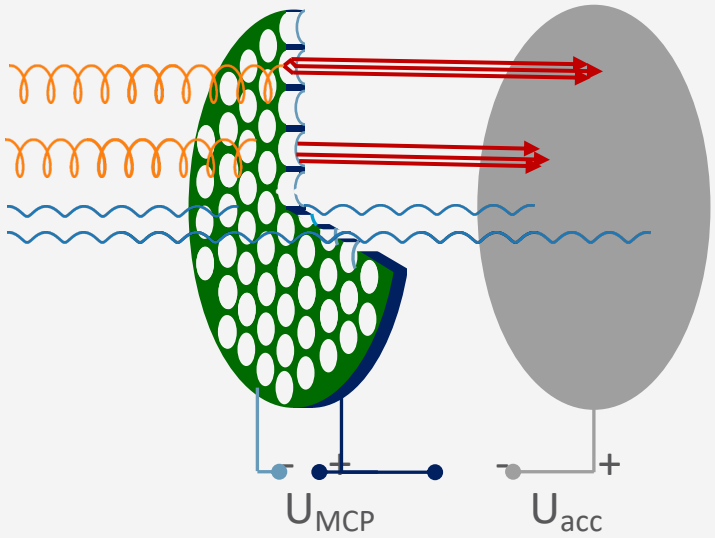
To suppress background need a detector which can distinguish large and small angles
at very low energies (18.6 keV) and at strong magnetic fields (2.5 T at KATRIN detector)
→ make use of the different cyclotron radii (R.G.H. Robertson)
→ develop an **"active transverse energy filter" (aTEF)** by hexagonal shaped active detector surfaces (CW)



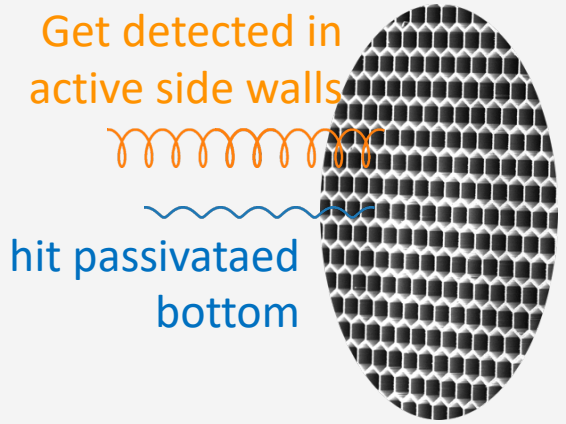




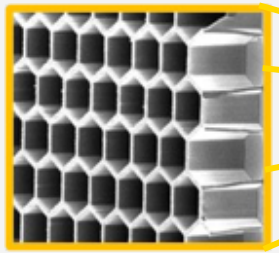
MCP-aTEF and Si-aTEF

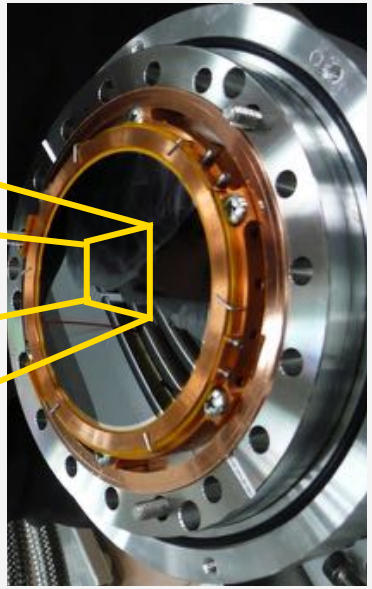


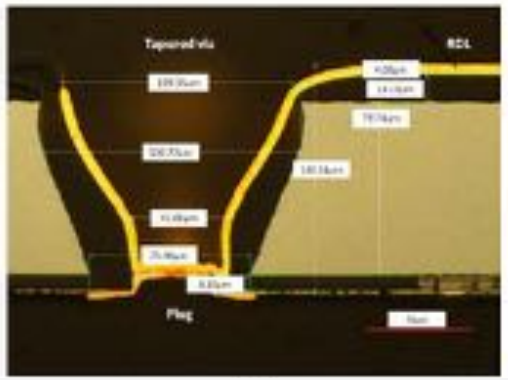
Principle demonstrated:
Eur. Phys. J. C 82 (2022) 922

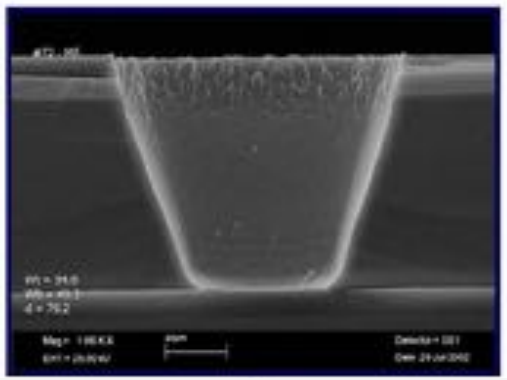


Idea: micro-structure directly KATRIN detector (PIN-diode array)



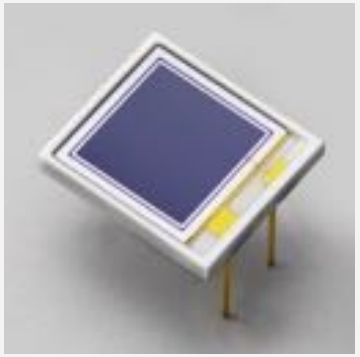


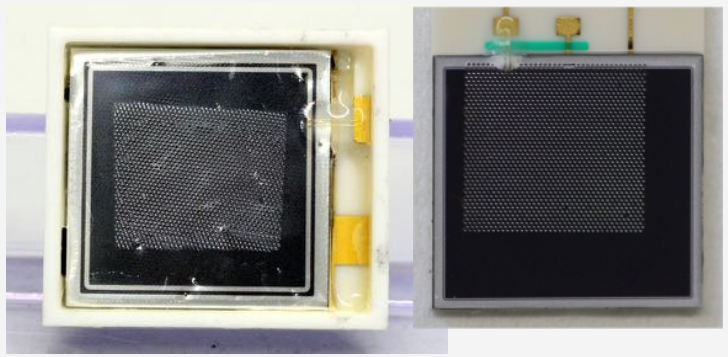


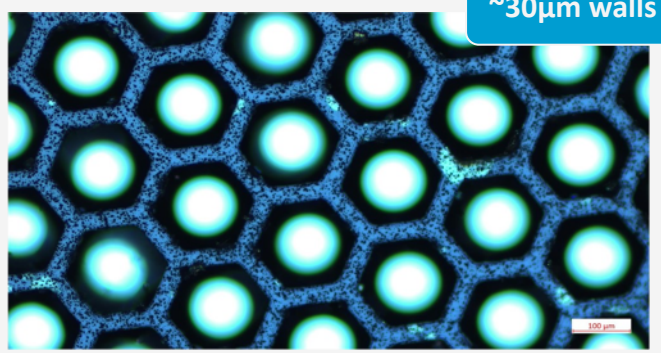


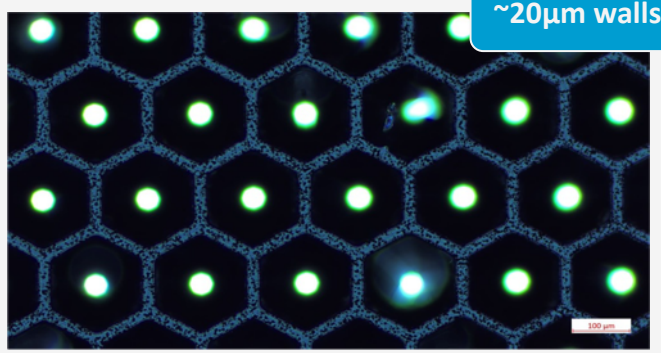
Etching of holes into Si-semiconductor detectors has been already successfully demonstrated for other purposes
Rep. Prog. Phys. 81 (2018) 066101

Si-aTEF: yes it works but not perfect yet





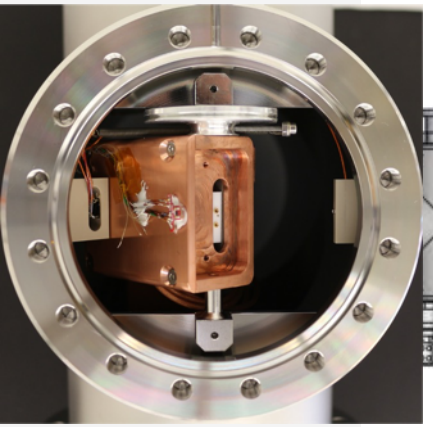


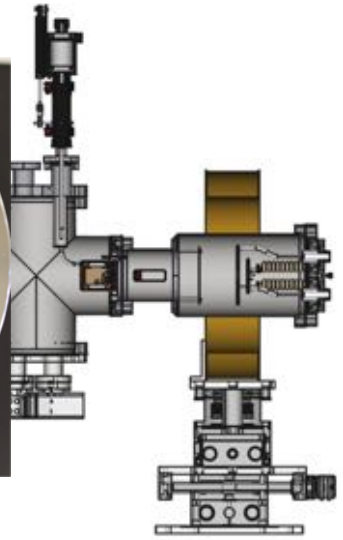


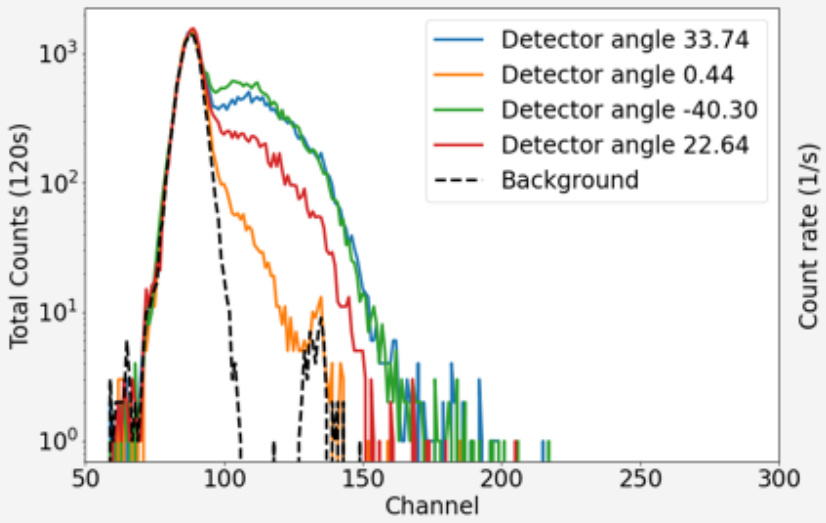
Hamamatsu PIN diodes S3590 (partly with special housing)

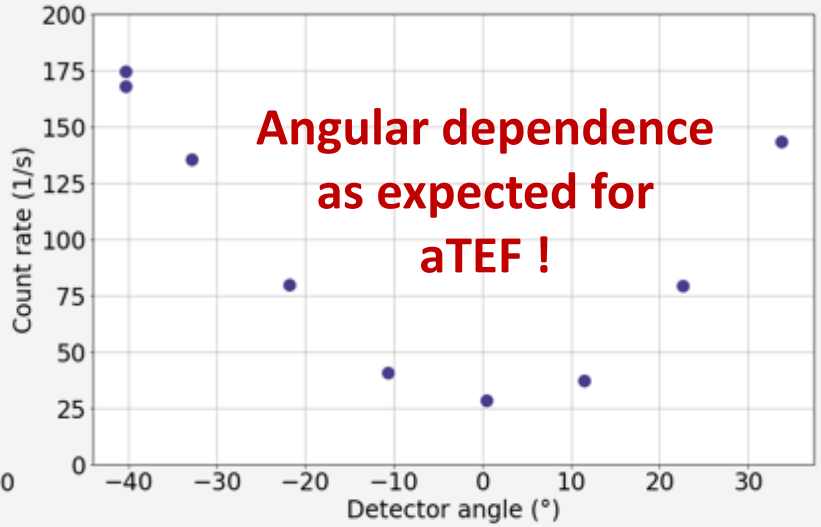
(different thickness of walls)

Test whether electrons can be detected in the side walls by changing angle of incidence by turning detector:





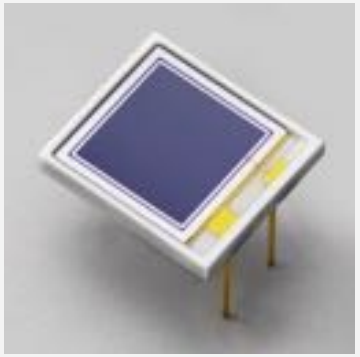


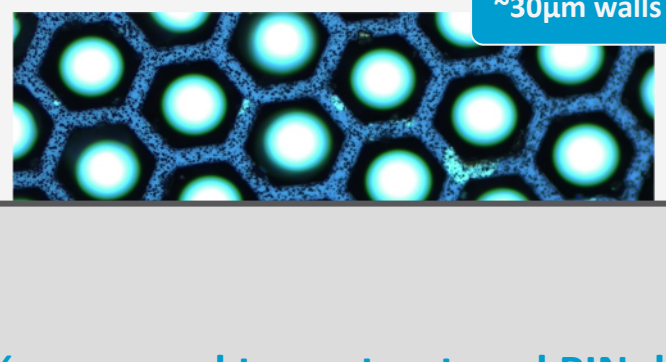


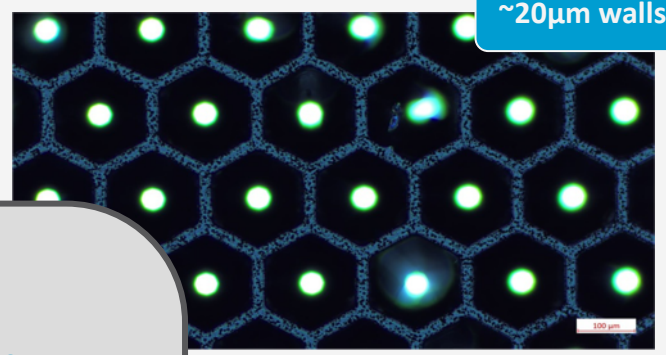
Angular dependence as expected for aTEF !

absolut detection efficiency: >80% compared to unstructured PIN diodes

Si-aTEF: yes it works but not perfect yet







Hamamatsu PIN dio

s of walls)

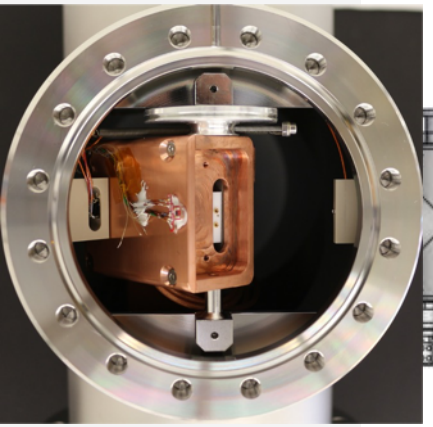
Test whether electr

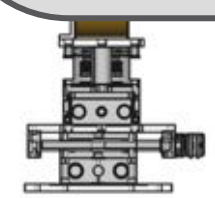
by turning detector:

Si-aTEF prototypes:

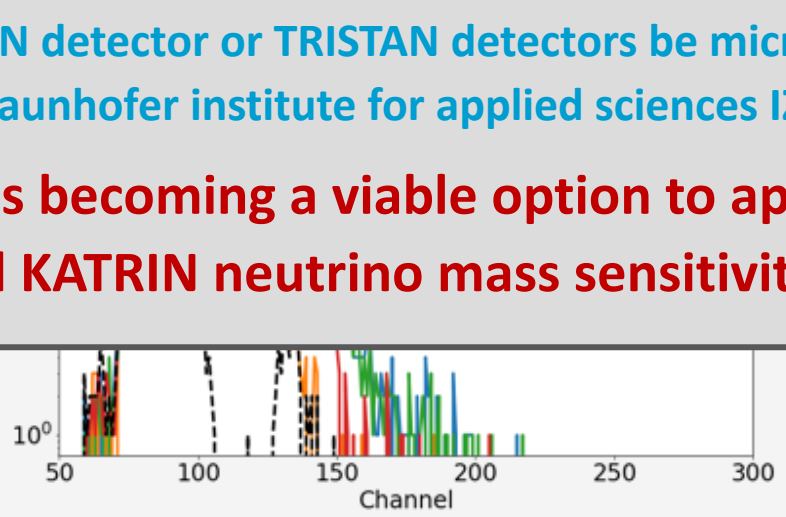
- Detection efficiency: >80% compared to unstructured PIN diodes
- Passiviation layer allows to operate at -40 °C
- Mechanical stability?
- Can KATRIN detector or TRISTAN detectors be microstructured?
  Help by Fraunhofer institute for applied sciences IZM

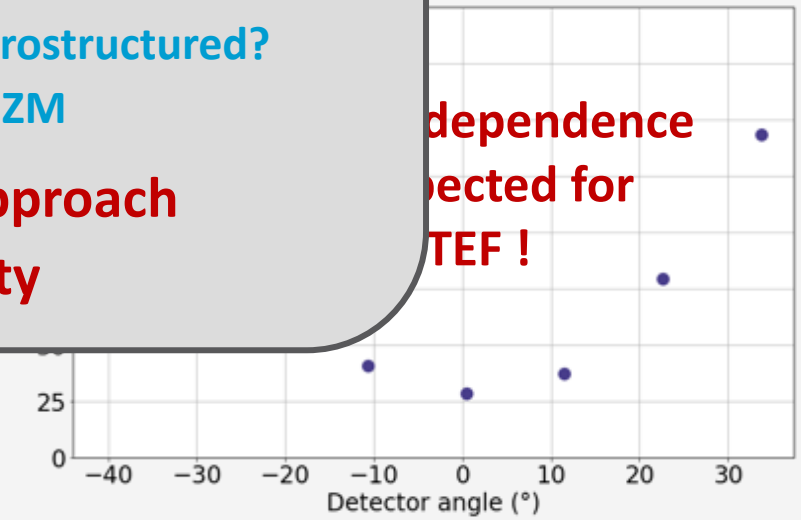
→ **Si-aTEF is becoming a viable option to approach the final KATRIN neutrino mass sensitivity**





dependence
ected for
TEF !





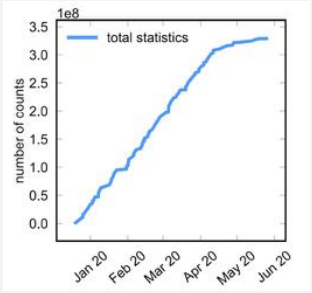
absolut detection efficiency: >80% compared to unstructured PIN diodes

Direct $m(\nu_e)$ searches with cryogenic bolometers: ECHo, HOLMES

$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e \rightarrow {}^{163}Dy + \gamma/e^- + \nu_e$

$$\Delta T \cong \frac{E}{C_{tot}} \xrightarrow{\text{MMC}} \Delta\Phi_S \propto \frac{\partial M}{\partial T}\Delta T \rightarrow \Delta\Phi_S \propto \frac{\partial M}{\partial T}\frac{E}{C_{tot}}$$

ECHo: metallic magnetic calorimeters (MMC):



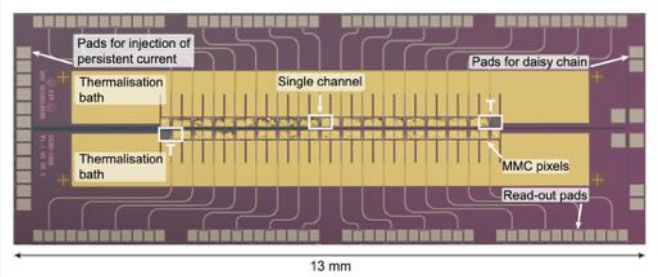
ECHo-1k phase:

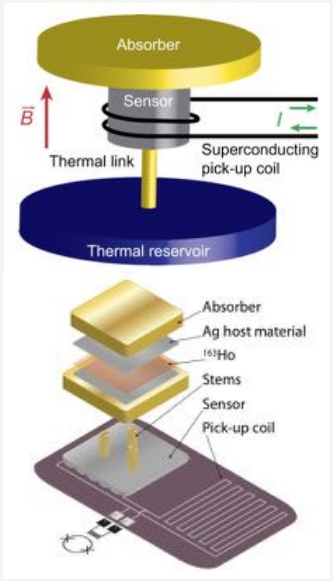
$m(\nu_e) < 20$ eV

ECHo-100k phase: 10 Bq per pixel

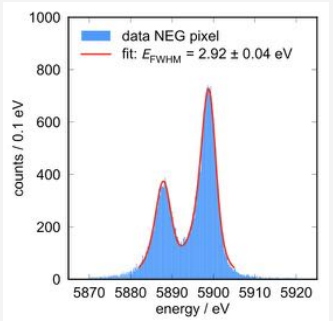
production of chips and wafers on-going

expected sensitivity: $m(\nu_e) \approx 2$ eV

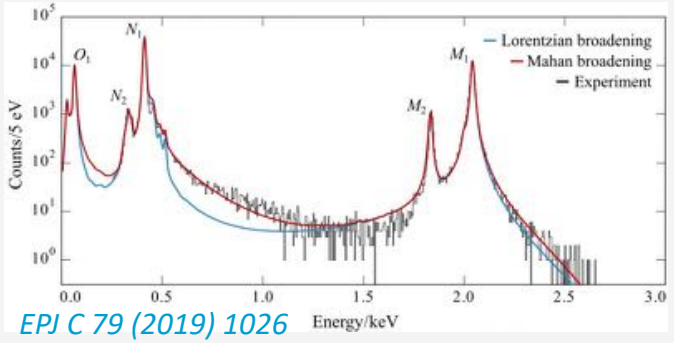




N. Kovac, poster, EPS HEP 2021



Understanding the em. deexcitation spectrum:

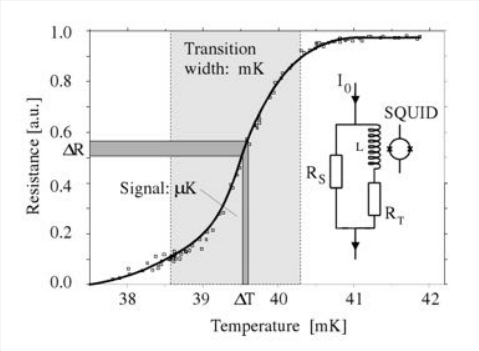


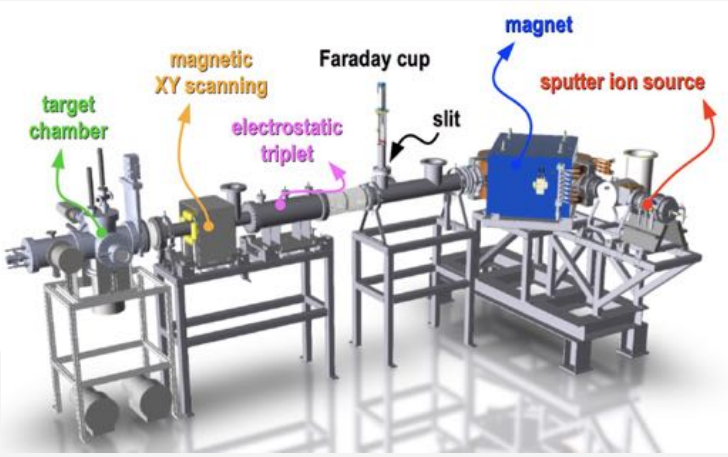
EPJ C 79 (2019) 1026

ECHo: $Q_{EC} = (2838 \pm 14)$ eV

Ship- trap: $Q_{EC} = (2833 \pm 30_{stat} \pm 15_{syst})$ eV

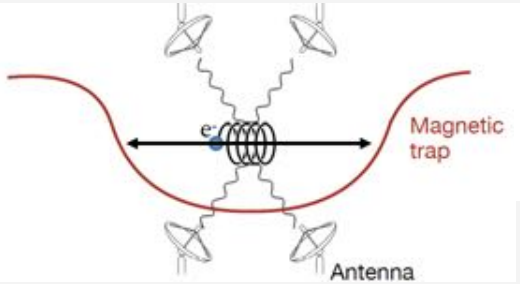
HOLMES: superconducting transition edge sensors (TES)





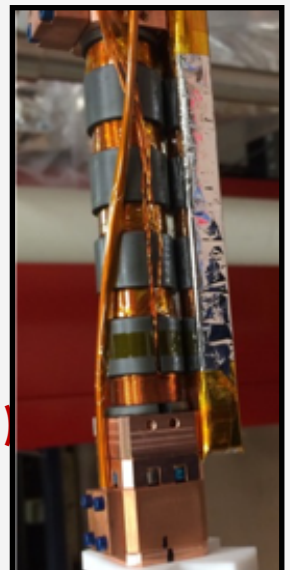
JLTP 193 (2018) 1137

Direct m(ν) beyond KATRIN: Project 8



$$\omega = \frac{\omega_0}{\gamma} = \frac{qB}{m_e + E}$$

Uses the principle of
Cyclotron Radiation EmissionSpectroscopy (CRES)
to reconstruct total energy of electrons.

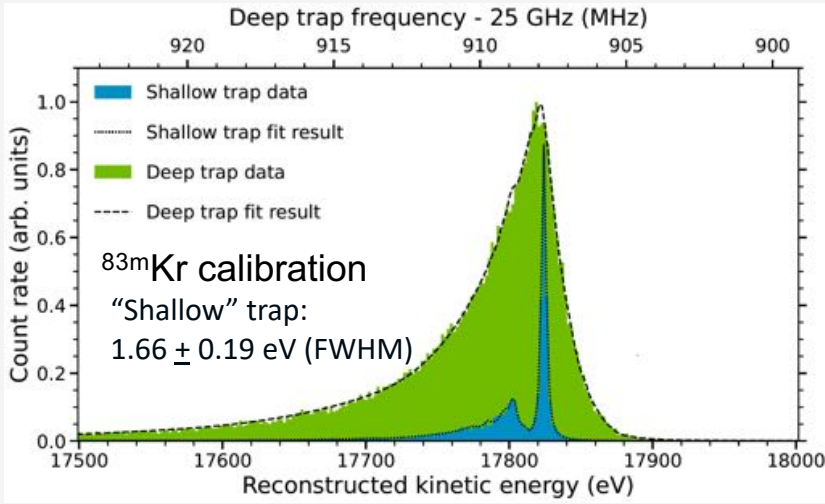


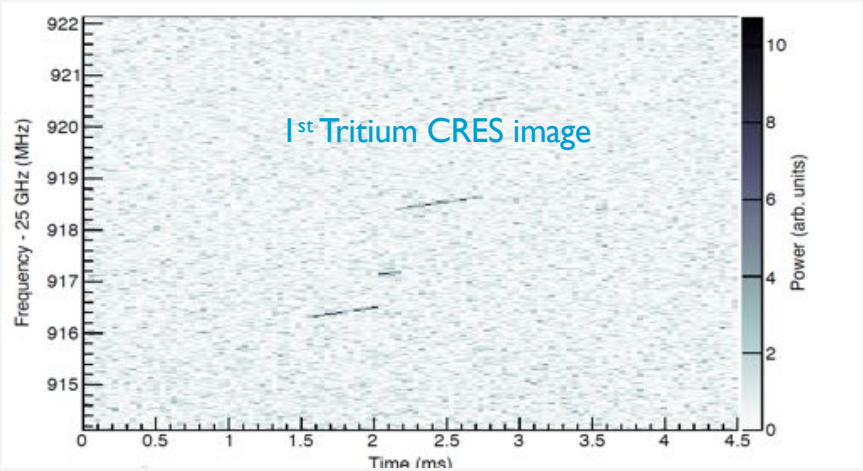
Phase I & II

First tritium run using CRES in 2019-2020

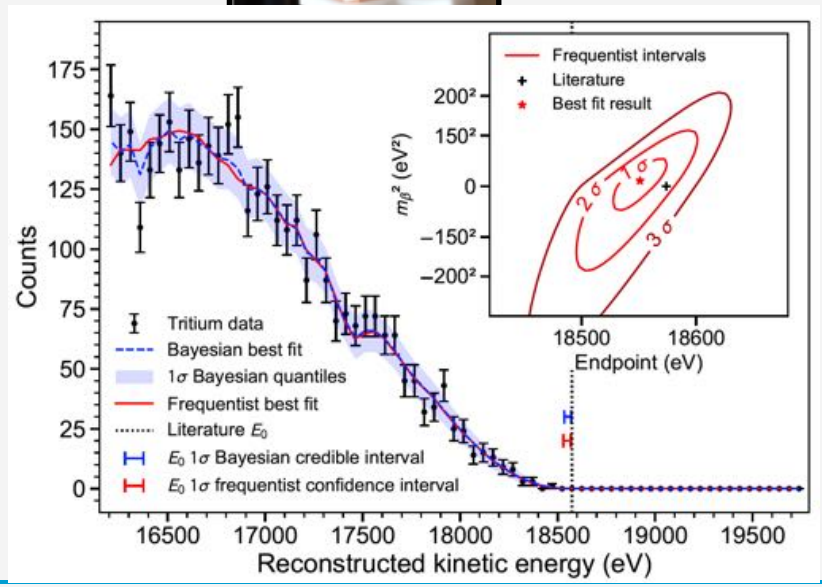
Low background achieved

arXiv:2212:05048





$m_\nu < 155\ (152)$ eV



Phase III & IV

A future CRES experiment will require large volumes and an atomic tritium source.

Eventually, Project 8 wants to build an experiment with sensitivity O(40 meV).

Conclusions

- Direct neutrino mass search
  - very important for astrophysics & cosmology and for nuclear & particle physics (BSM physics)
  - complementary to cosmological analyses and $0\nu\beta\beta$ searches
- Direct neutrino mass experiment KATRIN
  - is taking data with unprecedented precision since 2019
  - is continuously improving statistical and systematic uncertainties
  - has presented **1st sub-eV limit: "$m(\nu_e)$" < 0.8 eV and will report on data soon with < 0.5 eV sensitivity**
- KATRIN measures β-spectrum with unprecedented statistics and precison
  - beyond the Standard Model physics searches: eV and keV sterile neutrinos, CMB neutrinos, …
- KATRIN's background is dominated by "Rydberg electrons" (and from auto-ionizing states)
  -> efforts to lower background further towards sensitivity goal of 0.2 eV: aTEF, …
- New direct neutrino mass projects have started: ECHo, HOLMES, Project 8, …
- KATRIN will go on: TRISTAN detector for dedicated keV sterile neutrino search, starting to think of KATRIN^{++}