WWU MÜNSTER

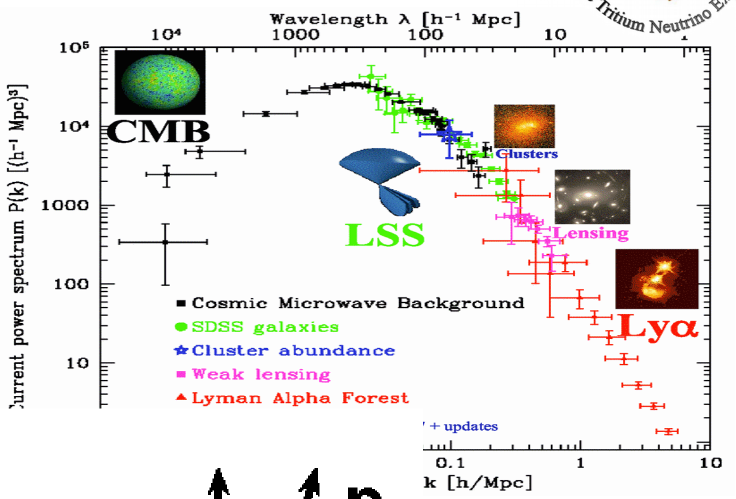
KATRIN experiment: recent results and future prospects

Alexey Lokhov *on behalf of KATRIN collaboration*
(University of Muenster & INR RAS)

KAT Strategy meeting
December 3-4, 2020

KAT. Komitee für Astro.Teilchen.Physik

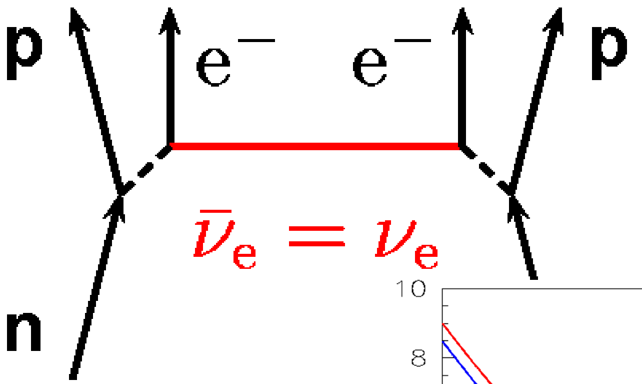
Three ways to assess the absolute neutrino mass scale



1) Cosmology

- very sensitive: era of precision cosmology
- compares power at different scales
- current sensitivity: **$\Sigma m(\nu_i) \approx$ 0.12 eV (Planck)**

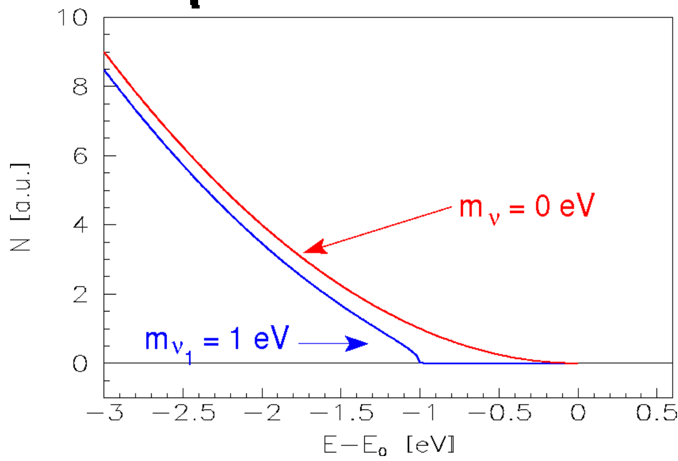
2) Search for $0\nu\beta\beta$



- Sensitive to Majorana neutrinos, model-dependent, LNV
- Upper limits by CUORE, EXO-200, GERDA, KamLAND-Zen: **$m_{\beta\beta}$ < 0.1-0.4 eV**

3) Direct neutrino mass determination

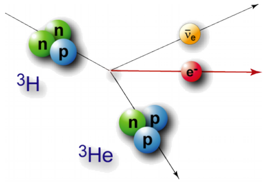
- No further assumptions needed, use $E^2 = p^2c^2 + m^2c^4$ $\Rightarrow m^2(\nu)$
- Time-of-flight measurements (ν from supernova)
- Kinematics of weak decays / beta decays, e.g. tritium, ^{163}Ho best upper limit: **$m(\nu)$ < 1.1 eV (90% CL) (KATRIN)**



N. Aghanim et al. (**Planck**), (2018), arXiv:1807.06209; ***CUORE*** *Collab, PRL 124 (2020) 122501;*
GERDA Collab, Science 365 (2019) 1445, PRL 120 (2018) 132503; Nature 544 (2017) 47;
EXO-200 *Collab, PRL 123 (2019) 161802;* ***KamLAND-Zen*** *Collab, PRL 117 (2016) 082503;* ***KATRIN*** *Collab, PRL 123 (2019) 221802*

Tritium β-decay

- continuous β-spectrum described by Fermi´s Golden Rule, measurement of effective mass m(ν_e) based on **kinematic parameters & energy conservation**



$$\frac{d\Gamma}{dE} = C \cdot p \cdot (E + m_e) \cdot (E_0 - E) \cdot \sum_{i=1}^{3} \left|U_{ei}^2\right| \cdot \sqrt{(E_0 - E)^2 - m_{\nu_i}^2} \cdot F(E, Z) \cdot \theta(E_0 - E - m_{\nu_i})$$

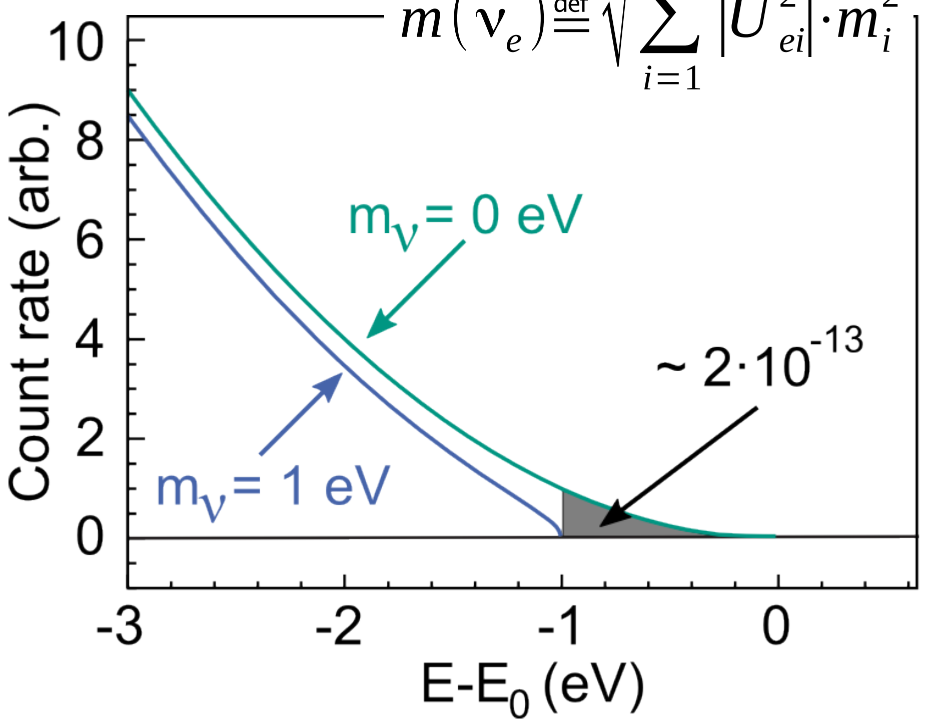
$$m(\nu_e) \stackrel{\text{def}}{=} \sqrt{\sum_{i=1}^{3} \left|U_{ei}^2\right| \cdot m_i^2}$$

Need:

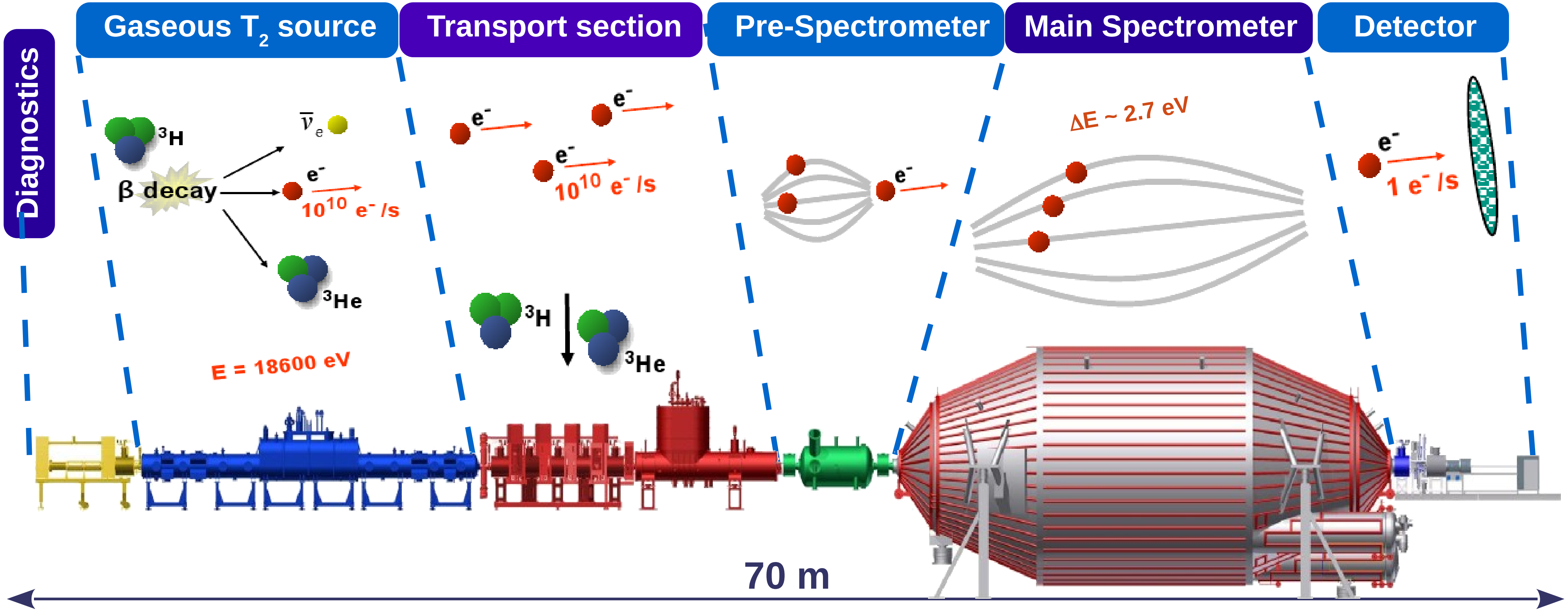
low endpoint energy ⇒ **Tritium ^{3}H – 18.6 keV**
short half-life (superallowed) **– 12.3 yr**
(^{163}Ho electron capture)
very high energy resolution &

very high luminosity & ⇒ **MAC-E-Filter** ⇒ **KATRIN**
cryogenic bolometers
very low background ⇒ **ECHo, HOLMES**
CRES ⇒ **PROJECT 8**

graphene substrate of T target+TES+... ⇒ **PTOLEMY**



The KATRIN experiment at Karlsruhe Institute of Technology



First ν-mass result

- ν-mass: best fit result

$$m^2_{\nu_e} = -1.0^{+0.9}_{-1.1}\,\mathrm{eV}^2$$

- ν-mass: new upper limit

$$m_{\nu_e} < 1.1\,\mathrm{eV}\,(90\,\%\,\mathrm{CL})$$

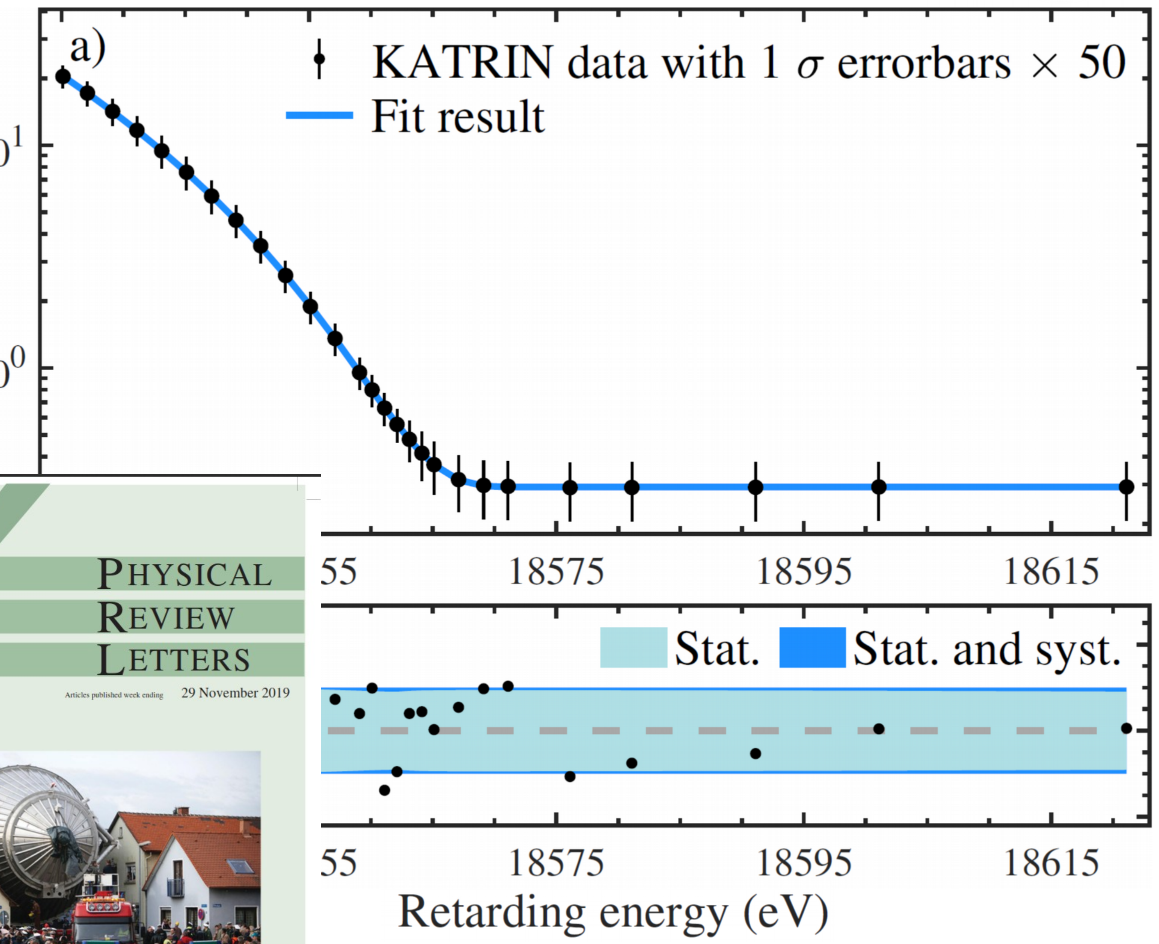
Lokhov - Tkachov

Feldman-Cousins $m_{\nu_e} < 0.8\,\mathrm{eV}\,(90\,\%\,\mathrm{CL})$

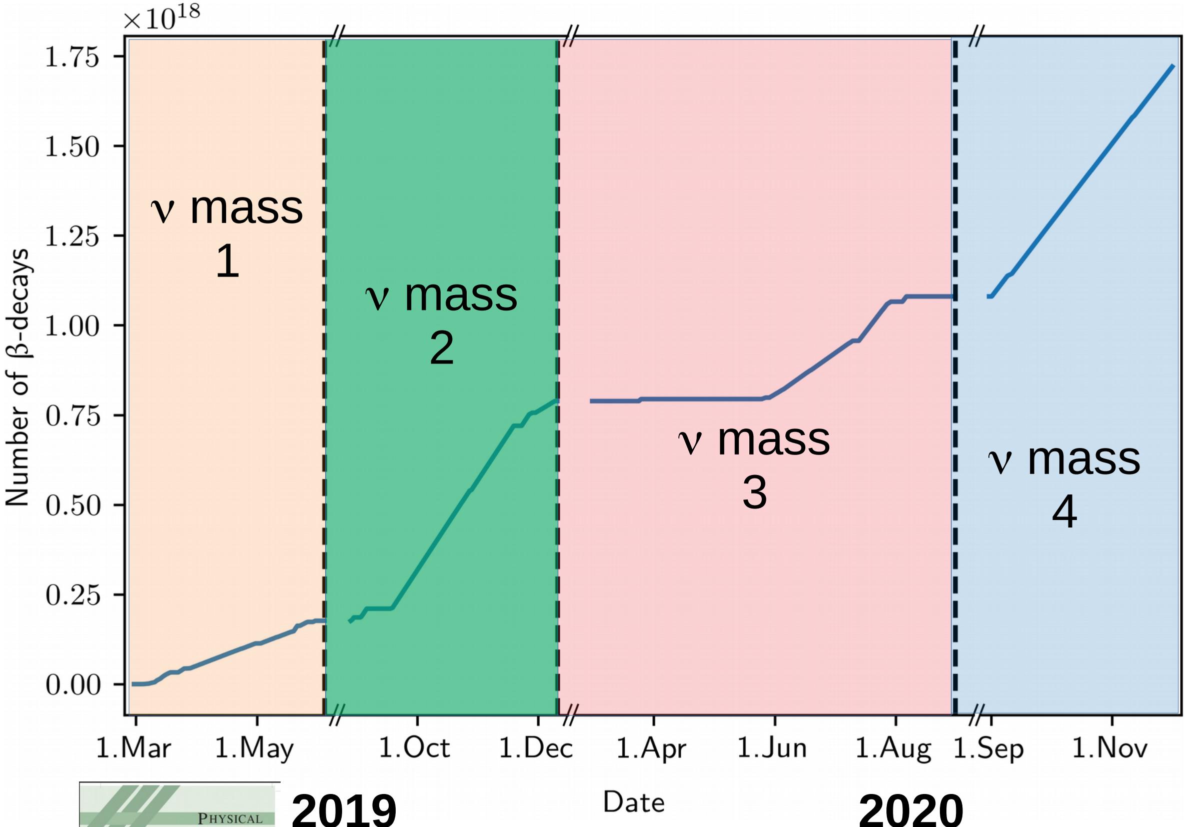
Bayesian $m_{\nu_e} < 0.9\,\mathrm{eV}\,(90\,\%\,\mathrm{CI})$

flat prior, *$m^2 > 0$*

- ✓ Excellent data quality
- ✓ Improvement of statistics (x2)
- ✓ Reduction of systematics (÷6)
- ✓ Only 5 days out of 1000 live days!



KATRIN data taking & analysis



2^{nd} neutrino mass campaign

- Measurement time: 31 days
- Gas density: 84% (x4 "ν mass 1")
- Isotopic purity: 98.6% tritium
- Source activity: $9.8 \cdot 10^{10}$ Bq
- Total statistics: $4 \cdot 10^{6}$
- Reduced background (÷1.3 of "ν mass 1")

» Finalizing analysis → stay tuned

Unbiased ν-mass analysis:

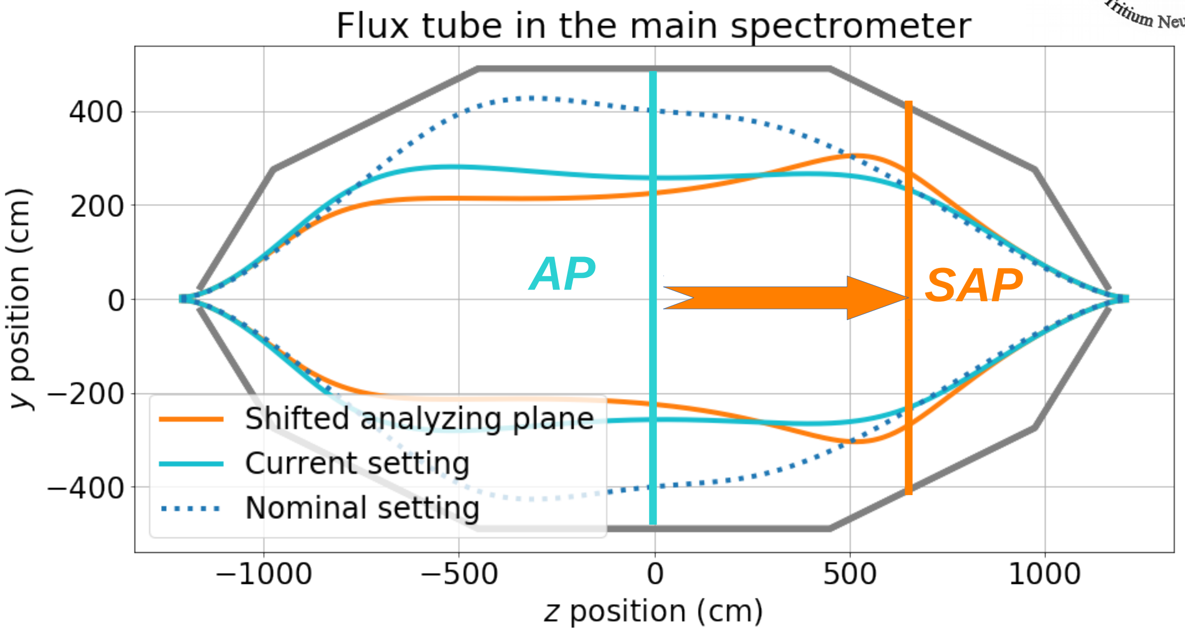
- Bias protection by Monte Carlo
  - Apply whole analysis chain to MC-copy of data
  - Analysis procedure is fixed on MC data
- Model-blinding scheme
  - Artificial smearing of the T_2 molecular final states
  - All parameters except for m^2 are not affected
- Two independent methods to treat systematics
  - Covariance matrix (χ^2 estimator)
  - Monte Carlo propagation (ML estimator)

Improving background 1

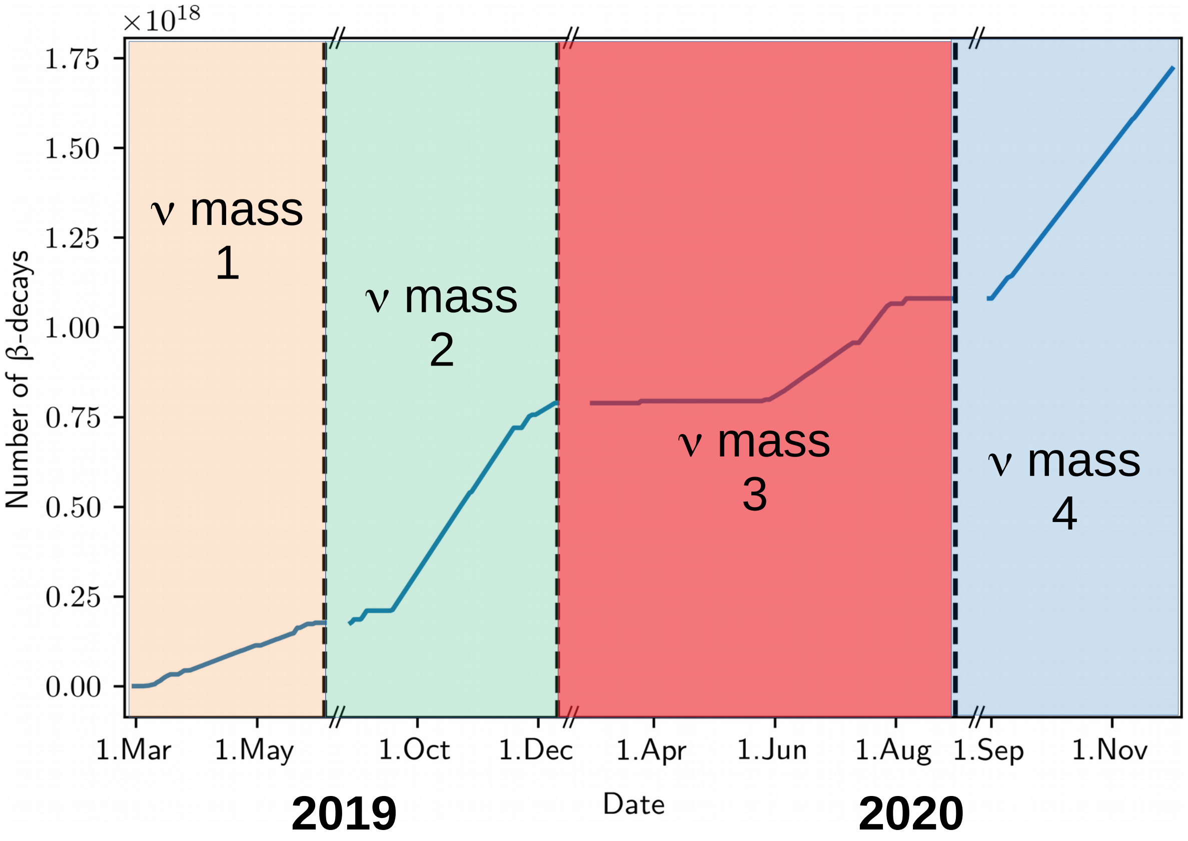
- **Background reduction**
  - ⇨ spectrometer bake-out successful ☑
  - ⇨ more effective ^{219}Rn retention ☑

- **Volume dependent background rate**
  - **Reduce the volume of the flux**
  - ⇨ upgraded air coil system ☑
  - ⇨ modified EM-fields configuration ☑
  - ⇨ „shifted analyzing plane“ (SAP) ☑
    - – factor **2 signal/background** improvement ☑
    - – background & calibration & tritium scans ☑

⇨ **implemented in neutrino mass scans of 2020** ☑



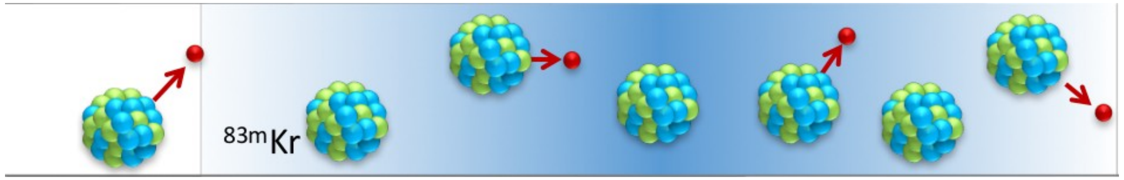
2020: Status & Improvements



In 2020 KATRIN is taking data through CoVid-19 times with all the necessary precautions!

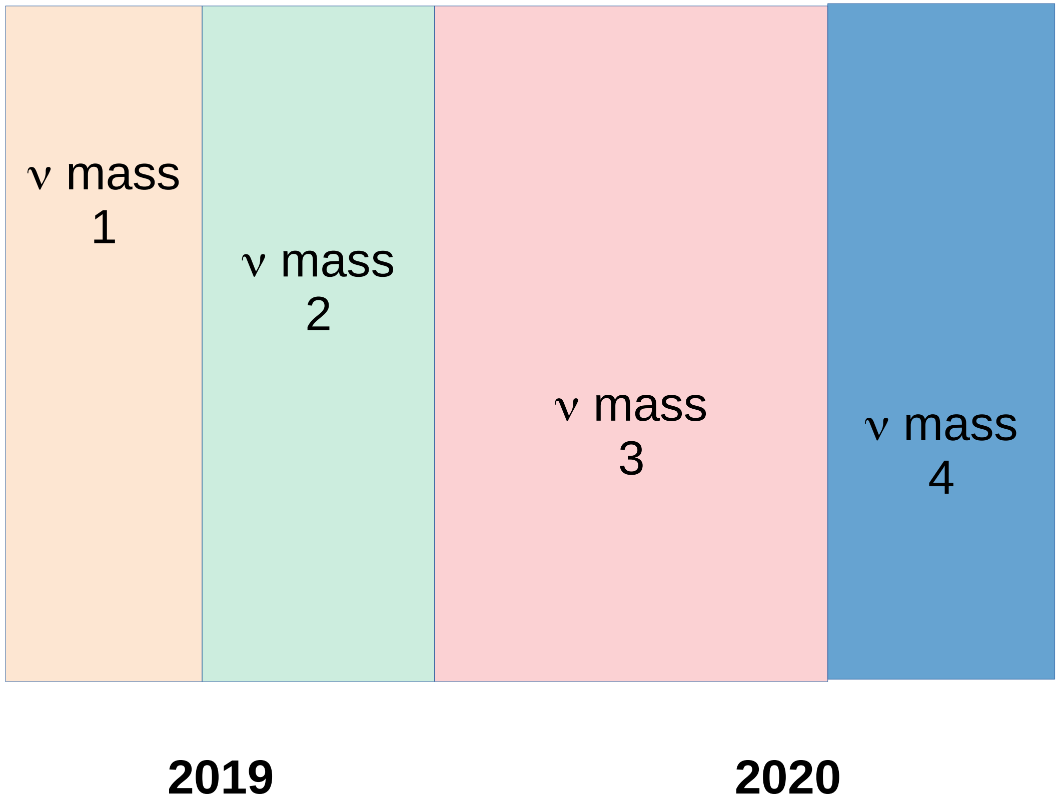
3rd neutrino mass campaign

- Neutrino mass scans & calibration measurements
- Optimized configuration of tritium source
  - T = 80 K (nominal: 30 K), stabilization with LN_2
  - In situ calibration of the source properties using ^{83m}Kr: well-controlled systematics, same mode for ν mass measurements and calibration



- Extensive study of plasma properties at different gas densities, temperature and boundary conditions
- Reduced background rate using “shifted analyzing plane” (SAP) configuration

2020: Status & Improvements



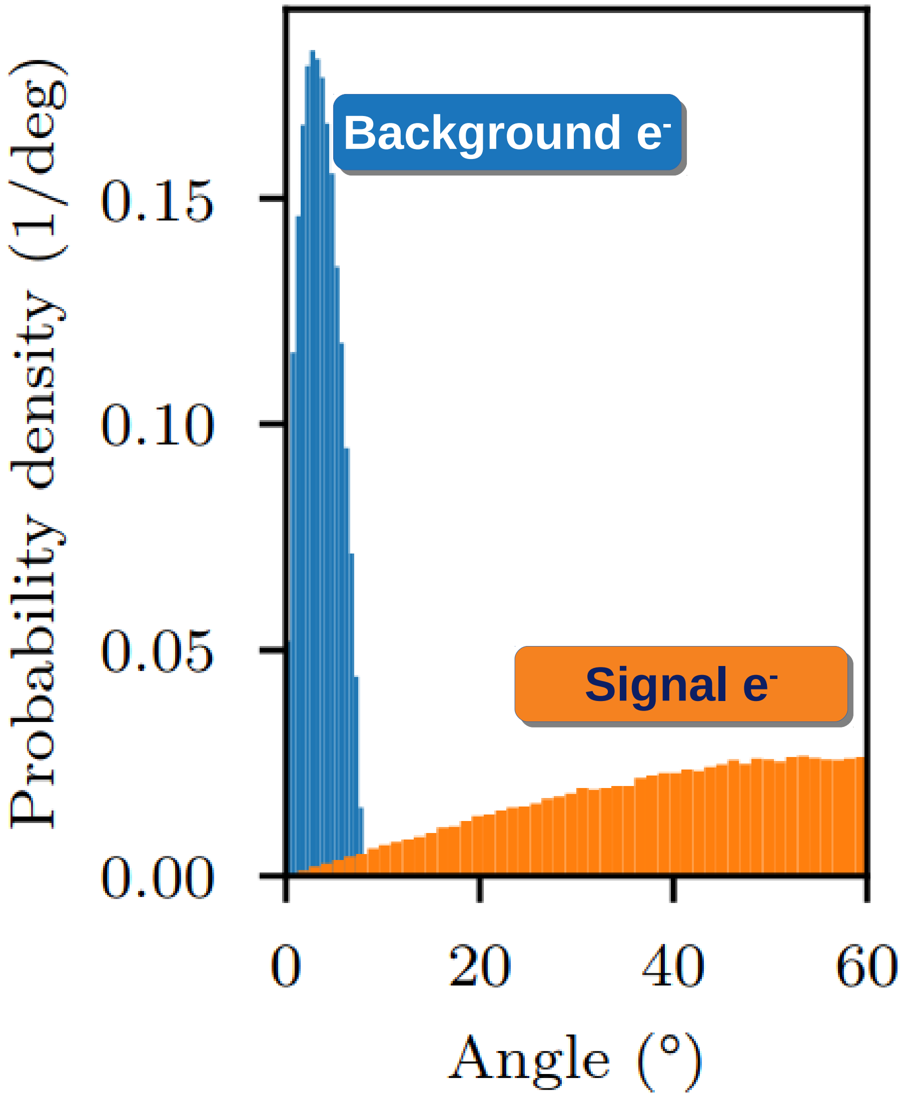
In 2020 KATRIN is taking data through CoVid-19 times with all the necessary precautions!

4^{th} neutrino mass campaign

- Completed on Tuesday
- Long science run of 2020, 90 days
- High quality data collected
  - T_2 purity above 98 %
  - Source @ 80 K, 75% nominal column density
  - Background reduction **x2** with "shifted analyzing plane" (SAP) EM-field configuration
  - Signal-to-background ratio **x5** (to "ν mass 1")
  - Much better control of systematics
- Analysis ongoing

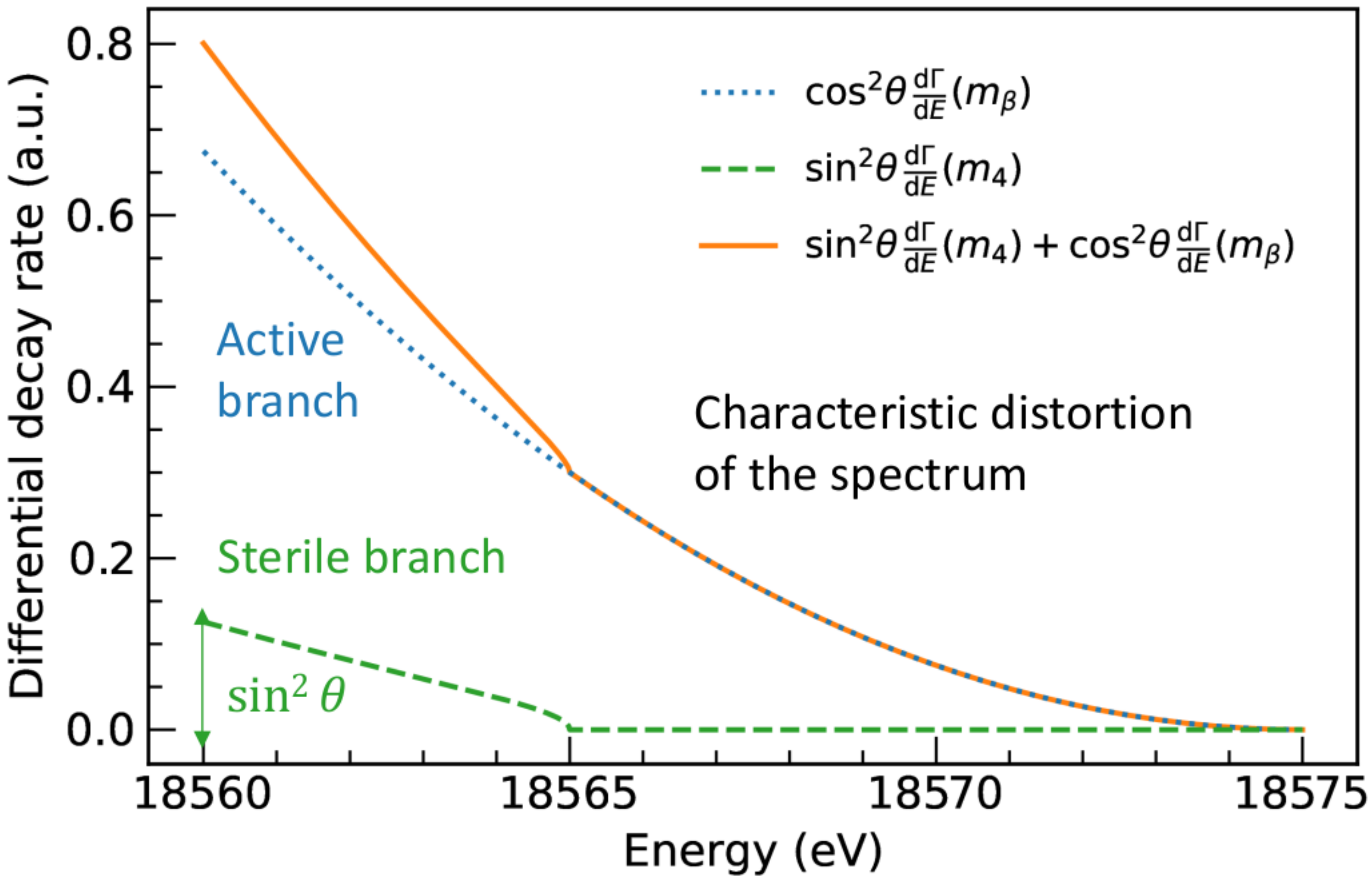
Improving background 2

- **Main component of background:**
  - Highly excited (neutral) Rydberg atoms ionized in the volume of main spectrometer
  - Very low kinetic energy of background e^-
- **Further reduction of background planned:**
  - Use angular distribution of background electrons
  - a very new idea: angular threshold filter (“*active transverse energy filter*”, aTEF)
  - filter electrons with different cyclotron radii
  - R&D ongoing, promising first test and simulation results → expect factor 5

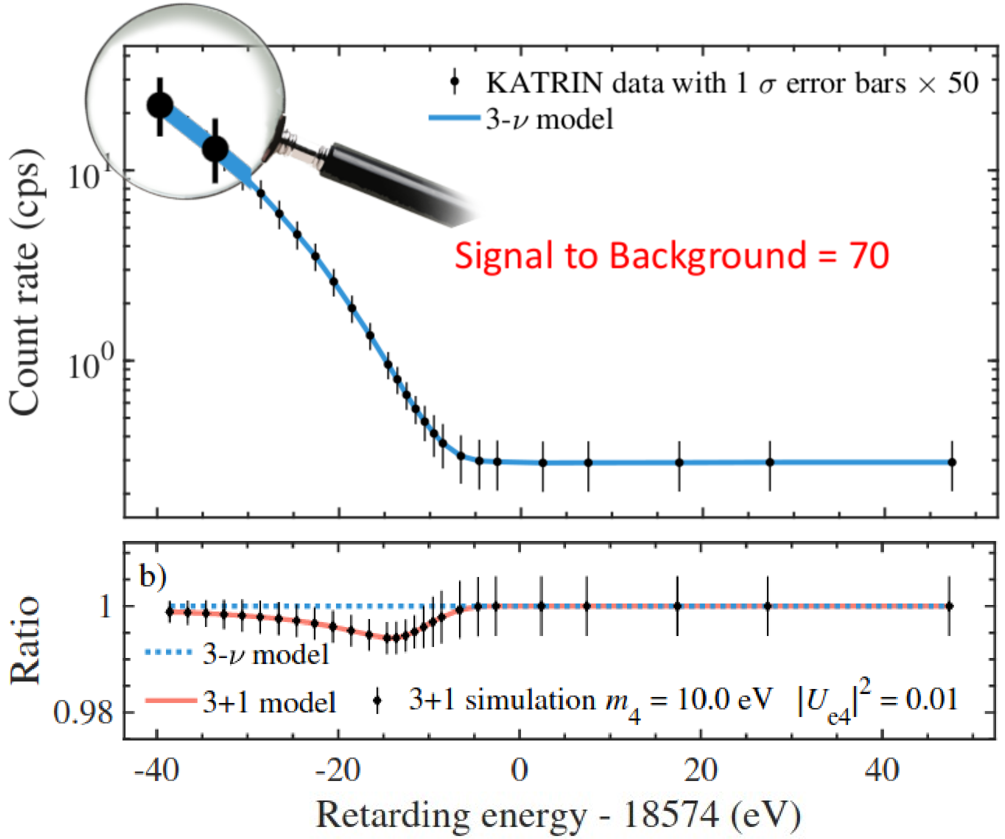


A. Fulst et al., Eur.Phys.J.C 80 (2020) 10, 956

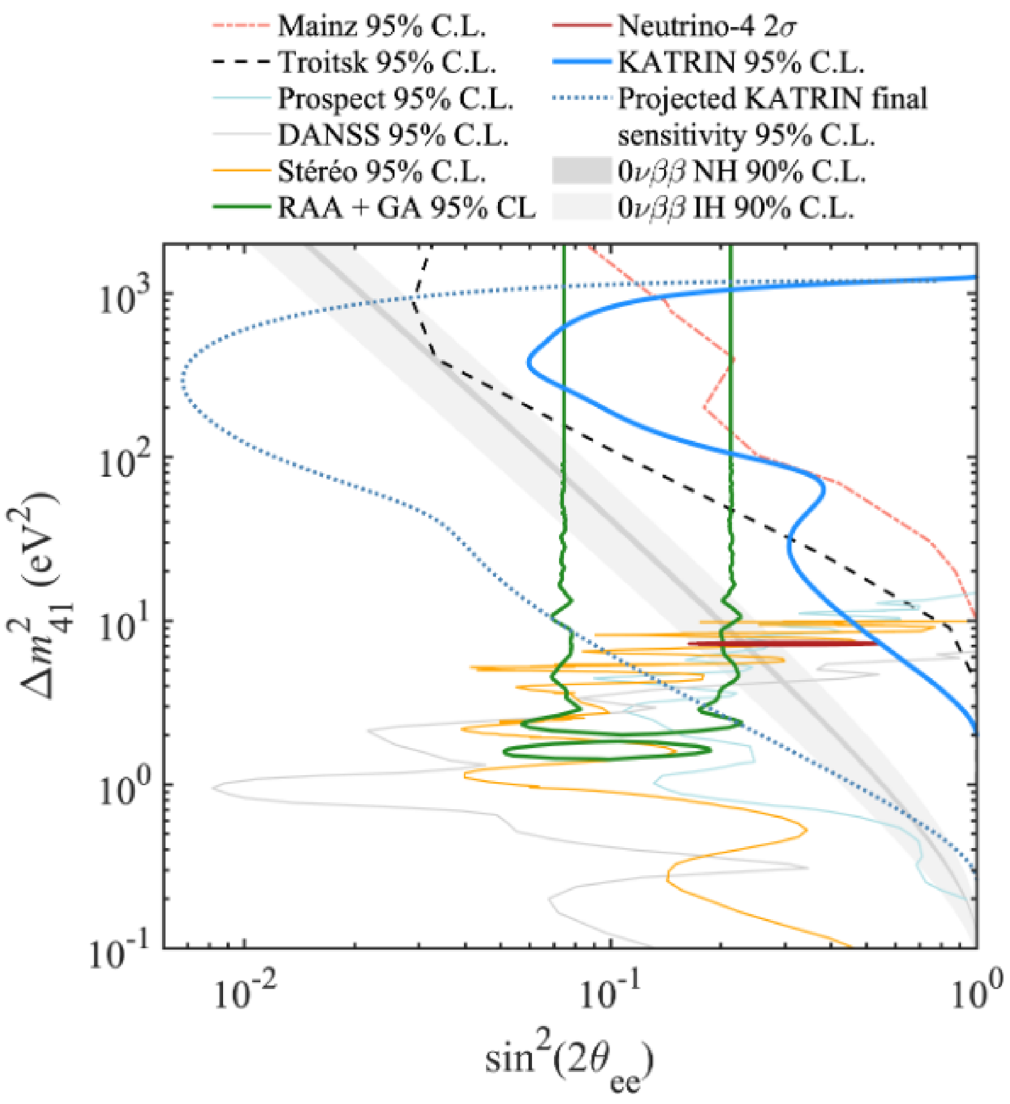
Sterile neutrino searches with KATRIN



- Same data-set as for the neutrino mass
- 3+1 sterile neutrino model
- Grid search in m_4, $|U_{e4}|^2$ plane



eV-scale sterile neutrino

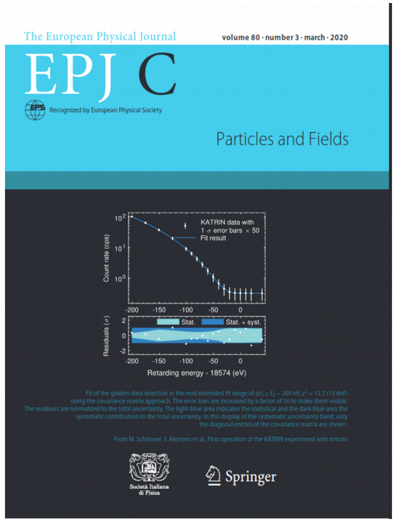


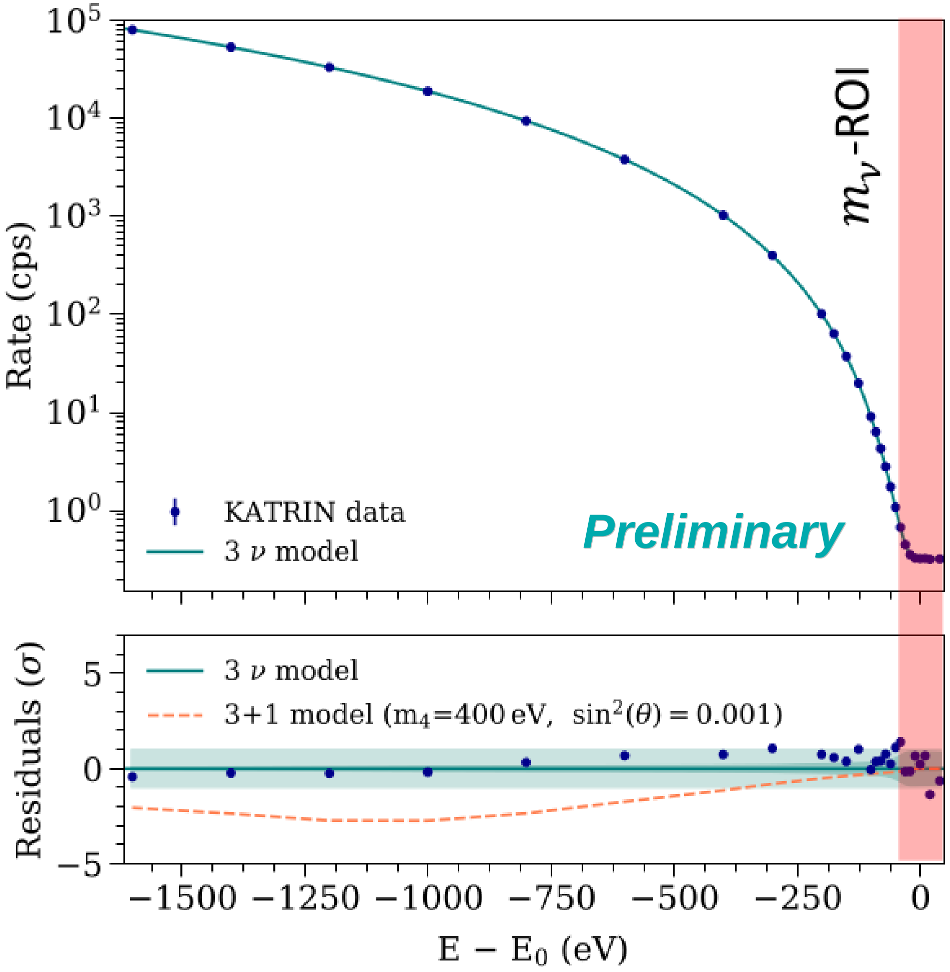
- Data of the first science run of KATRIN
- Complementary probe of sterile ν with KATRIN
- High Δm^2_{41} values:
  - Improve exclusion with respect to DANSS, PROSPECT, STEREO
  - Exclude parameter space of Reactor Antineutrino Anomaly (RAA)
- Low Δm^2_{41} values:
  - Improve on Mainz and Troitsk limit
  - Approaching Neutrino-4 hint
- Probe a large fraction of RAA with the full 1000 live days of data
- KATRIN's light sterile neutrino search is competitive with $0\nu\beta\beta$ experiments

KATRIN collaboration, "Bound on 3+1 active-sterile neutrino mixing from the first four-week science run of KATRIN", arXiv:2011.05087

KATRIN search for keV sterile neutrinos

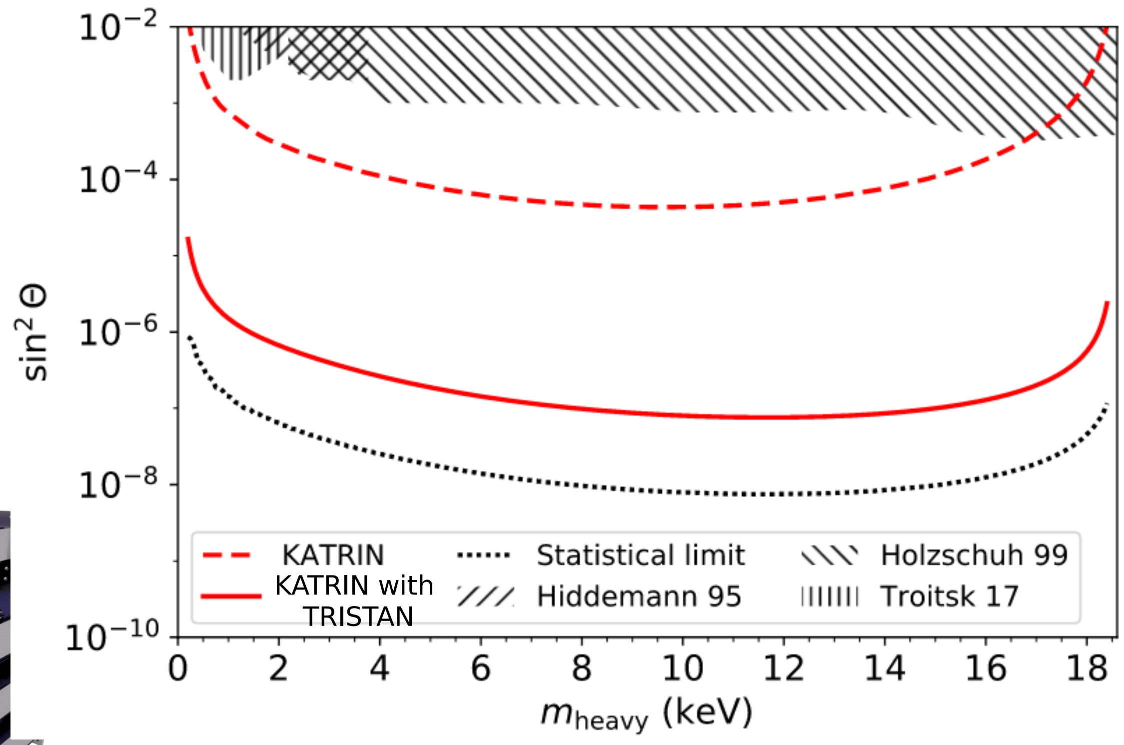
- **Deep scans (1.6 keV below E_0) with low-activity**
  - Excellent agreement of model and data
  - Sensitivity to the mixing of 0.001 @ m_4 = 400 eV
- **Reminder: First Tritium commissioning campaign:**
  - Low tritium concentration: 1% DT and ~99% D_2
  - Excellent stability of the source parameters
  - Analysis range of 400 eV below E_0

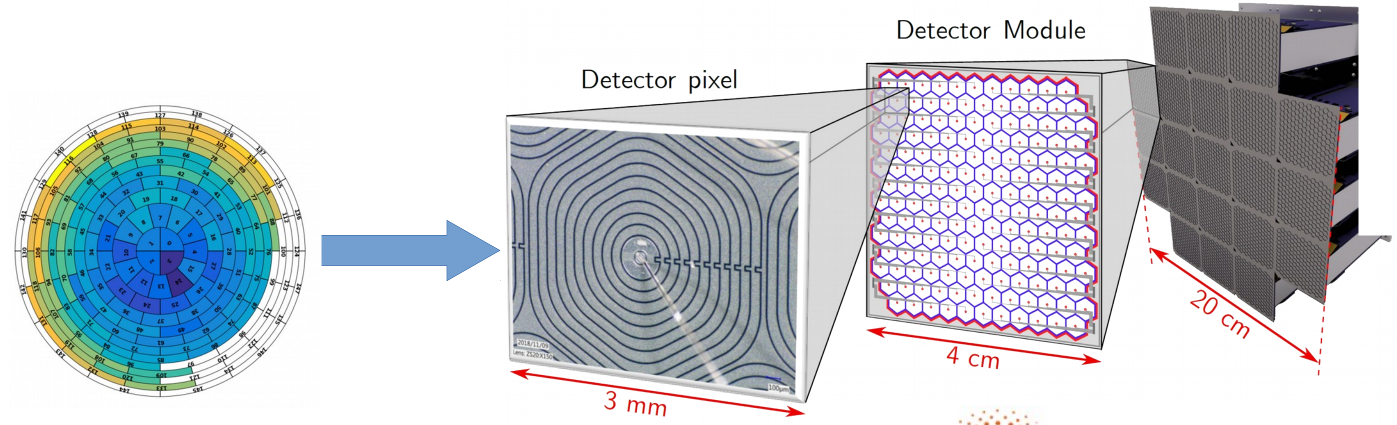




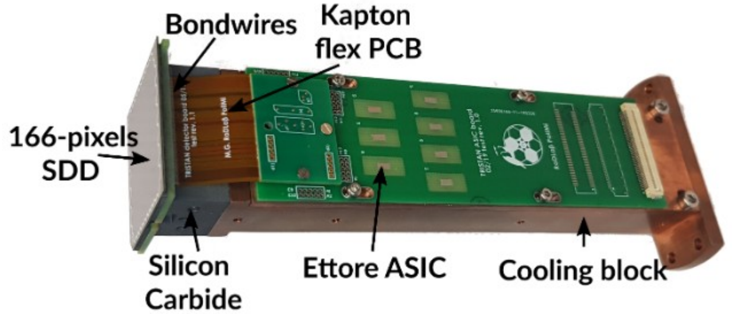
KATRIN search for keV sterile neutrinos

- **TRISTAN project in KATRIN:**
  - novel multi-pixel Silicon Drift Detector array
  - large count rates
  - excellent energy resolution
  - Prototypes installed as monitoring devices @ KATRIN
  - Target sensitivity: $\sin^2\theta < 10^{-6}$





segmented Si-PIN wafer



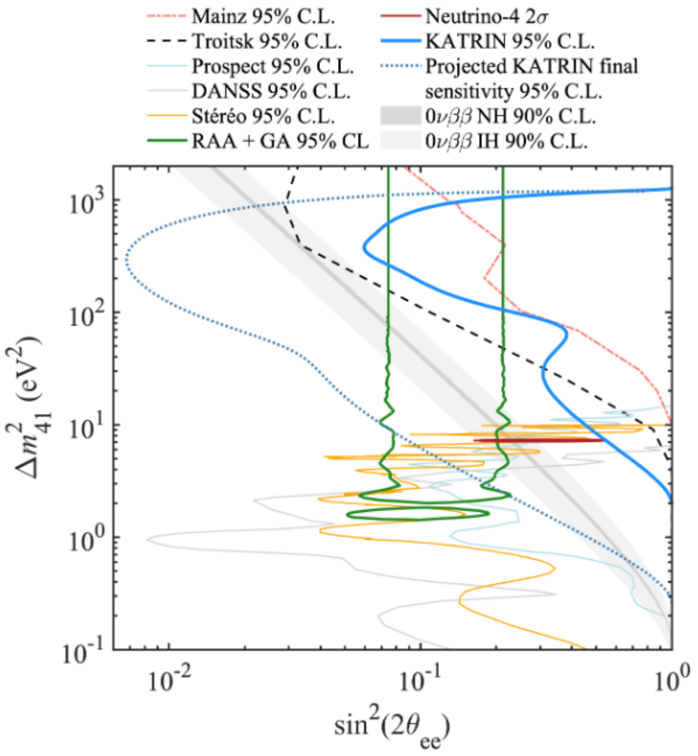
erc S. Mertens, TUM & MPP

Outlook

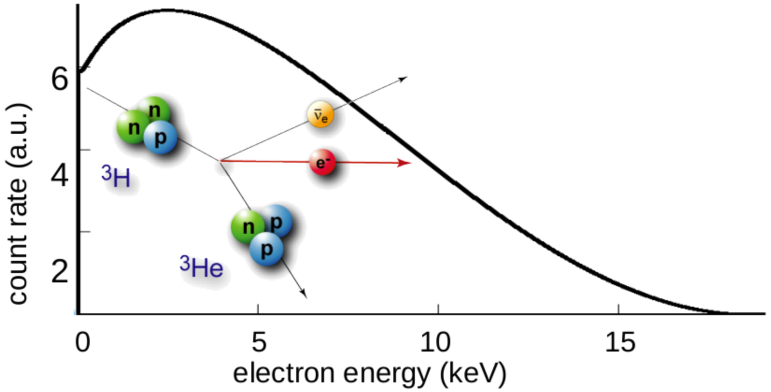
- **Recent results and improvements**
  - New world-best direct neutrino mass measurment
    - Next release: early 2021
  - First search for eV- and keV- scale sterile neutrinos
  - Optimized configuration of EM-fields → background reduction
  - Optimized source operation mode → reduction of source systematics
- **KATRIN is continuosly taking data**
  - 200 days/year, also in 2020 with all Corona precautions
  - Scheduled neutrino mass campaigns until the end of 2024
  - Further improvement of background by a factor 5 expected by "active transverse energy filter" (aTEF), reduction of systematics
- **Physics programme beyond ν mass**
  - eV-scale sterile neutrino, other BSM physics (light bosons, RH currents)
  - keV sterile neutrino searches with a novel silicon drift detector (SDD) to start in ~2024

Neutrino Properties

See the note on "Neutrino properties listings" in the Particle Listings.
Mass $m <$ 1.1 eV, CL = 90% (tritium decay)



Today 90 years ago: Wolfgang Pauli‘s letter



$$m_\nu < 10^{-2} m_p \, (\text{Pauli})$$

$$m_\nu < 1.17 \cdot 10^{-9} m_p \, (\text{KATRIN})$$

Stay tuned!

Zürich, 4. Dez. 1930
Gloriastrasse

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

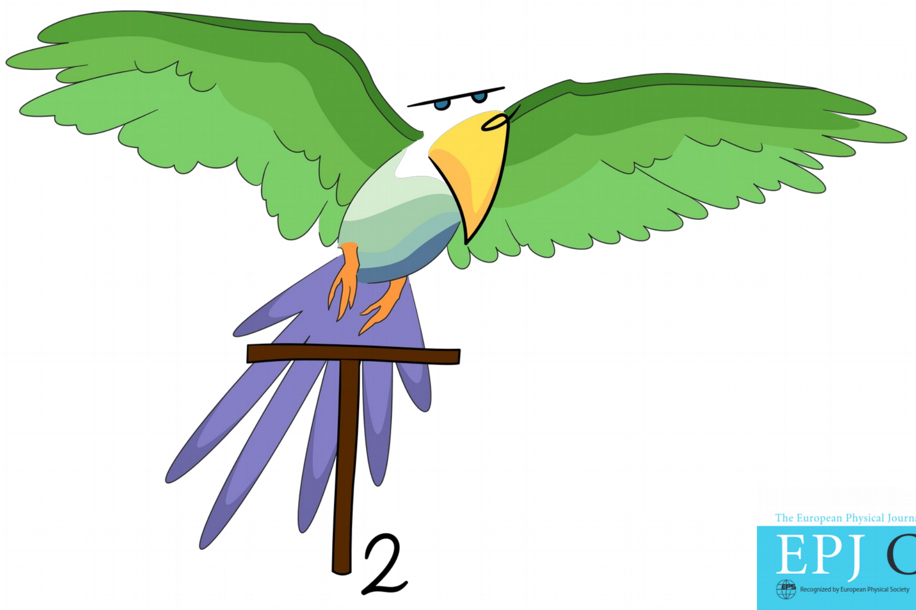
Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

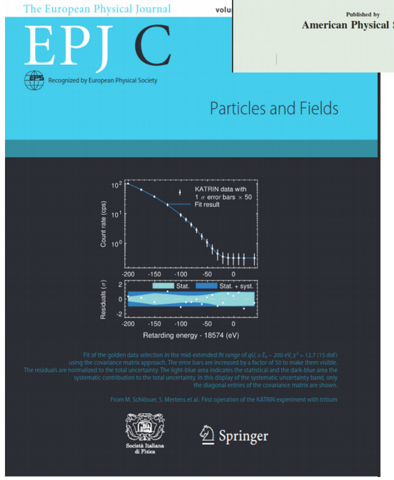
Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

Thank you for your attention!





Neutrino Properties

See the note on "Neutrino properties listings" in the Particle Listings.

Mass $m < 1.1$ eV, CL = 90% (tritium decay)

We acknowledge the support of Helmholtz Association (HGF), Ministry for Education and Research BMBF (05A17PM3, 05A17PX3, 05A17VK2, 05A17PDA, and 05A17WO3), Helmholtz Alliance for Astroparticle Physics (HAP), the doctoral school KSETA at KIT, and Helmholtz Young Investigator Group (VH-NG-1055), Max Planck Research Group (MaxPlanck@TUM), and Deutsche Forschungsgemeinschaft DFG (Research Training Groups Grants No. GRK 1694, GRK 1694 and GRK 2149, Graduate School Grant No. GSC 1085-KSETA, and SFB-1258 in Germany ; Ministry of Education, Youth and Sport (CANAM-LM2015056, LTT19005) in the Czech Republic; and the Department of Energy through grants DE-FG02-97ER41020, DE-FG02-94ER40818, DE-SC0004036, DE-FG02-97ER41033, DE-FG02-97ER41041, DE-AC02-05CH11231, and DE-SC0011091 in the United States. This project has received funding from the European Research Council (ERC) under the European Union Horizon 2020 research and innovation programme (grant agreement No. 852845).