Recent Results from the KATRIN experiment

Thierry Lasserre

on behalf of the KATRIN collaboration

SFB 1258 Neutrinos Dark Matter Messengers

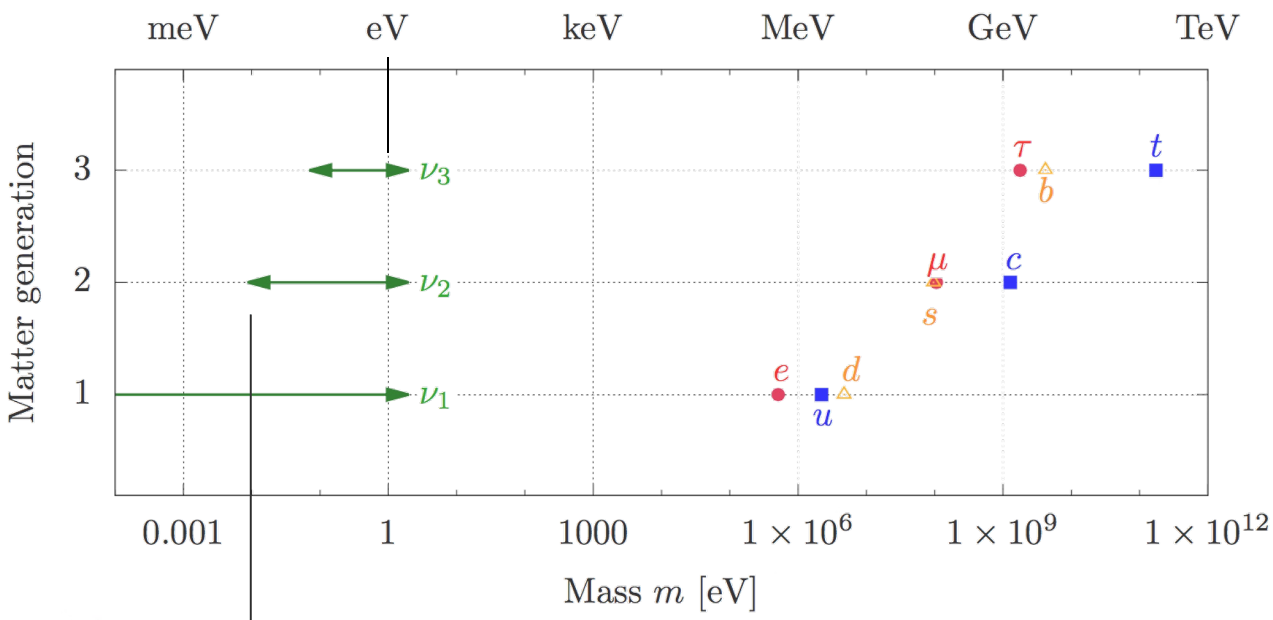
Neutrino2022

XXX International Conference on Neutrino Physics and Astrophysics

May 30 (Mon) - June 4 (Sat), 2022 | Virtual Seoul, Korea

Direct Neutrino Mass Measurement

Upper bound
from direct measurements

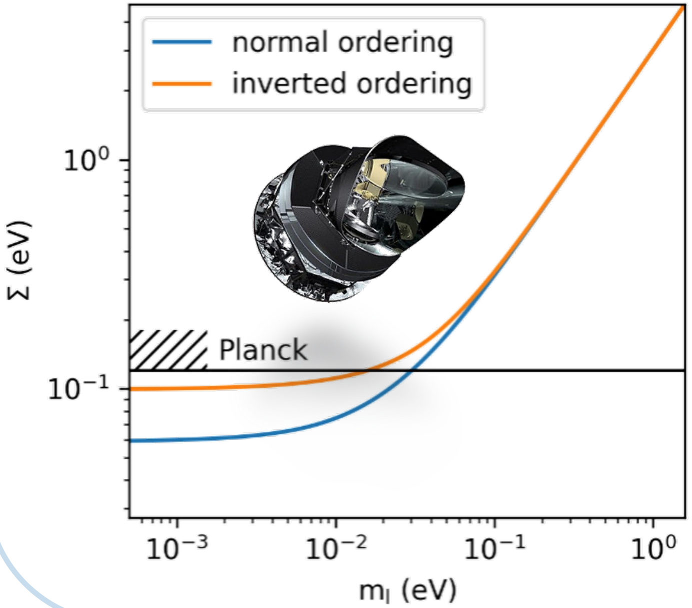


Lower bound
from oscillation experiments

Neutrino mass(es)

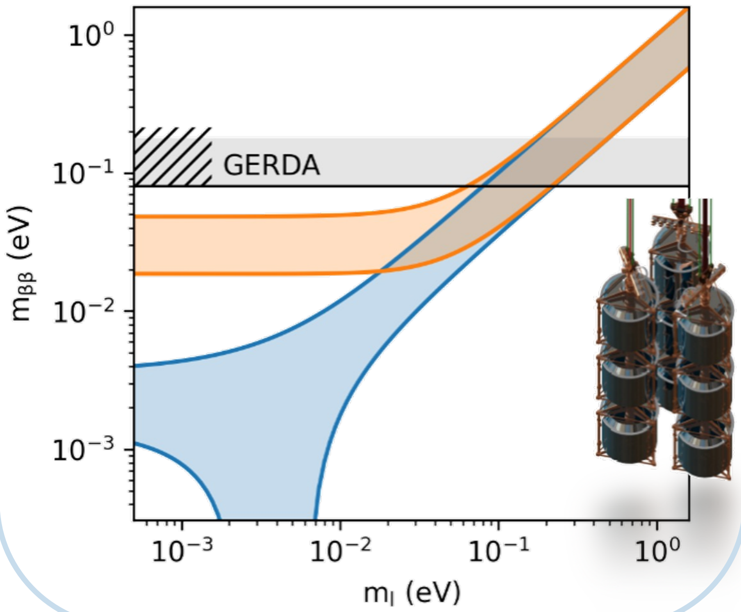
Cosmology

$$\Sigma = \sum_i m_i^2$$



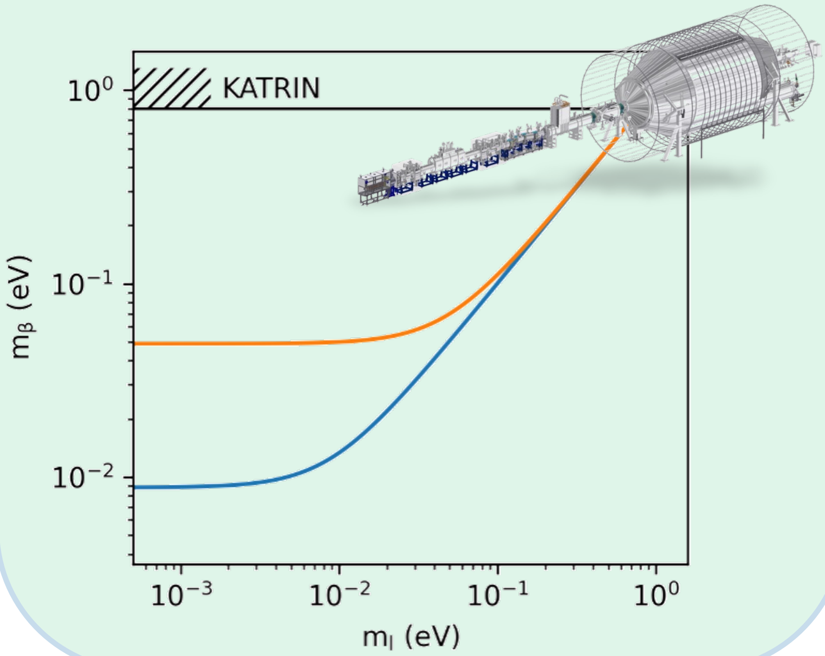
Neutrinoless ßß decay

$$m_{\beta\beta} = \sum_i U_{ei}{}^2 \cdot m_i$$

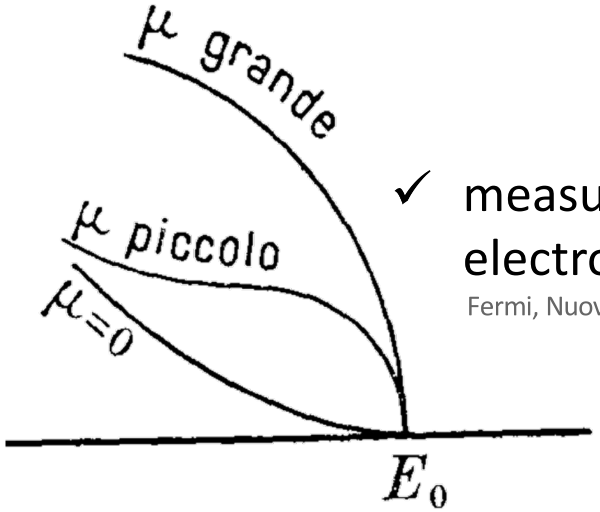


ß-decay kinematics

$$m^2_{\nu\,/\,\beta} = \sum_i |U_{ei}|^2 \cdot m_i^2$$

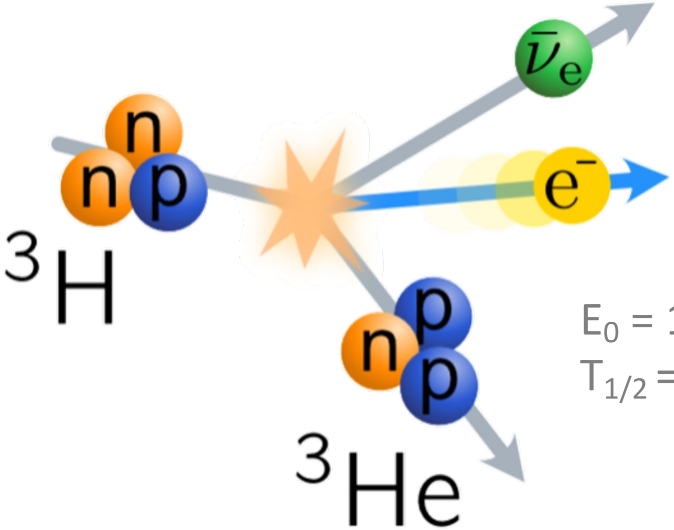


Kinematic neutrino mass measurement



- ✓ measurement of the electron β −spectrum
  Fermi, Nuovo Cim. 11 (1934) 1-19

- ✓ independent of cosmology
- ✓ independent of neutrino nature



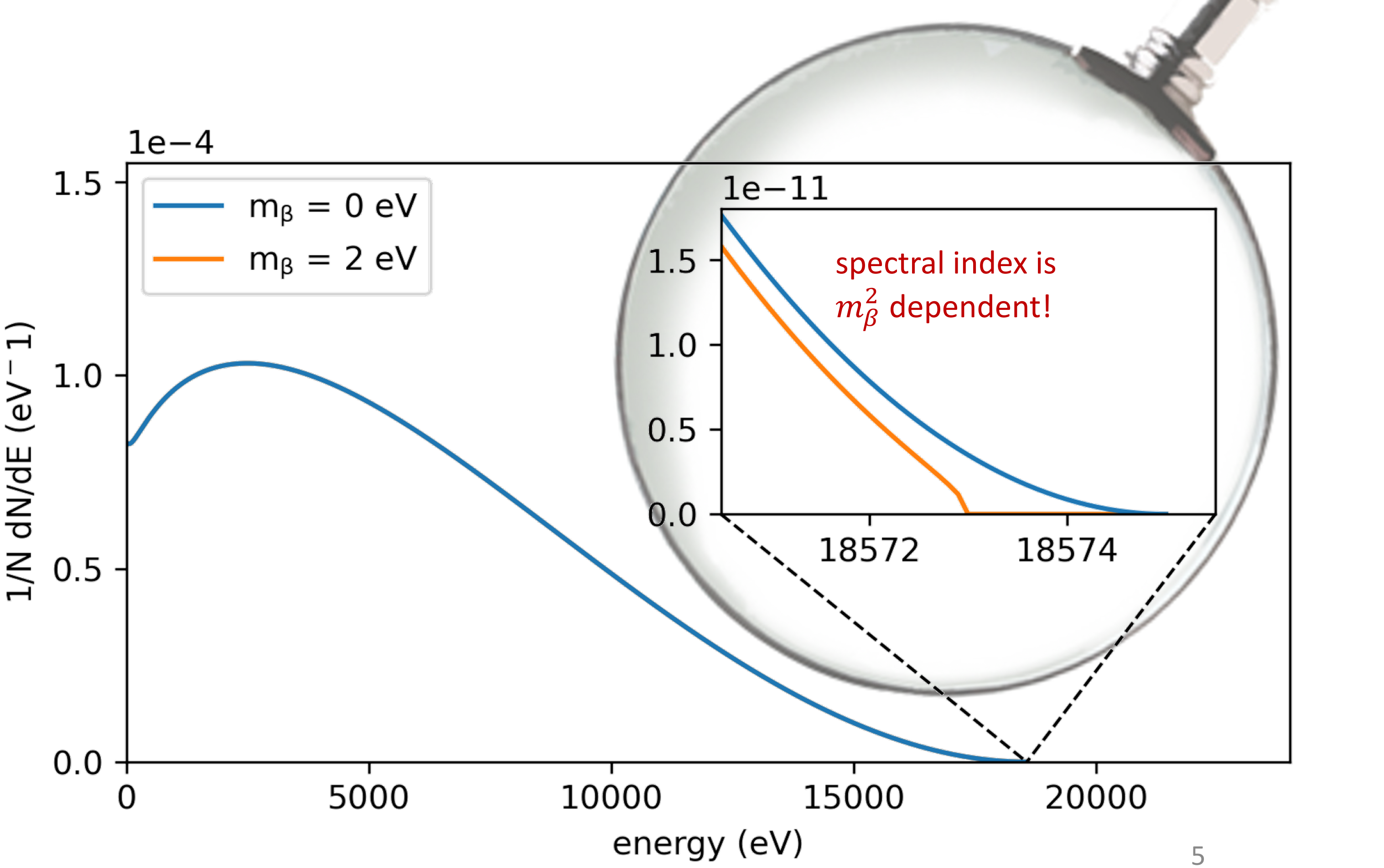
E_0 = 18.56 keV
$T_{1/2}$ =12.3 years

- ✓ based on kinematics and energy conservation
- ✓ m_ν^2 spectral distortion, maximal at endpoint energy E_0
- ✓ incoherent neutrino mass : $m_\nu^2 = \sum_i |U_{ei}|^2 \cdot m_i^2$

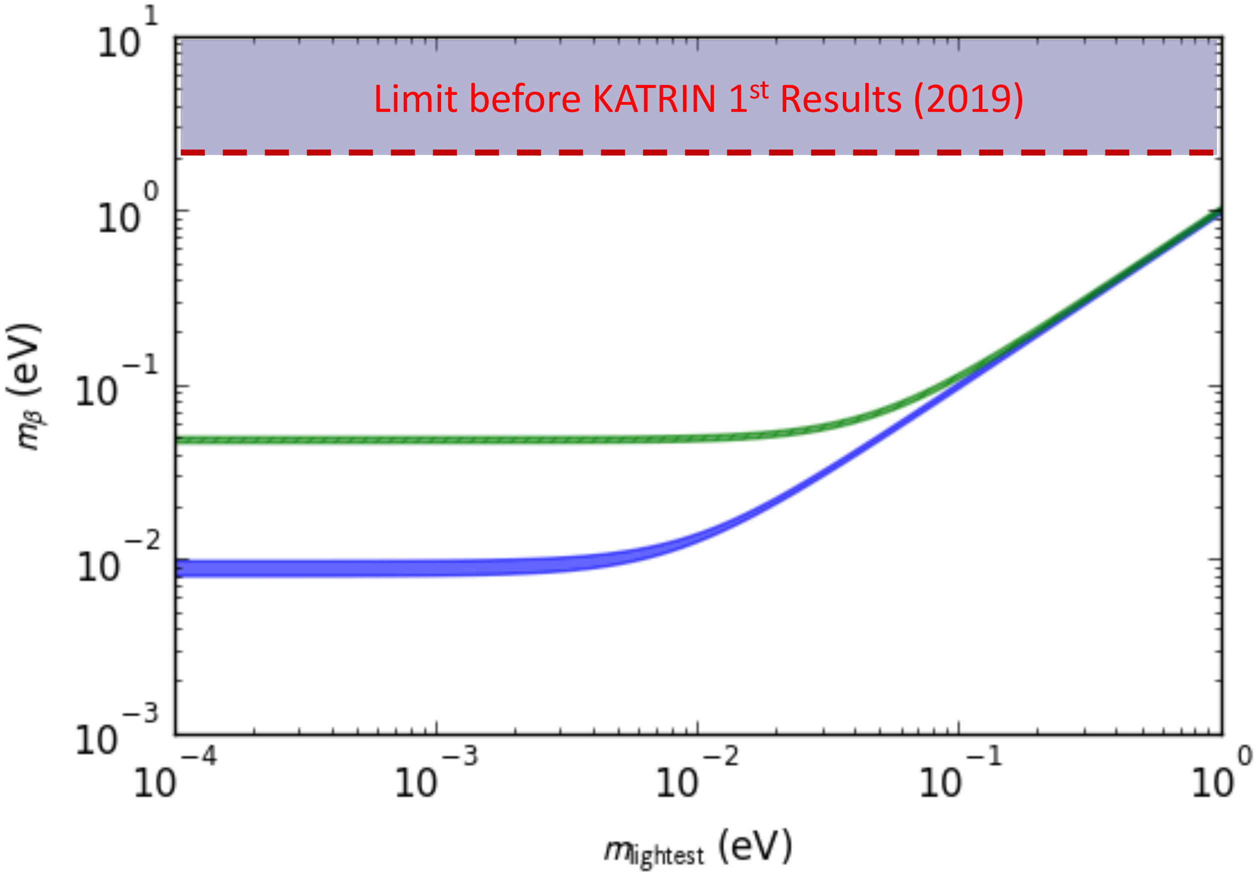
KATRIN experimental challenges

- ✓ strong tritium source: 10^{11} decays/s
- ✓ < 0.1 cps background level
- ✓ ~1 eV energy resolution
- ✓ 0.1% level understanding of the spectrum shape
- ✓ 0.1% level hardware stability controlled over the years

Only 10^{-13} of all decays in last 1 eV



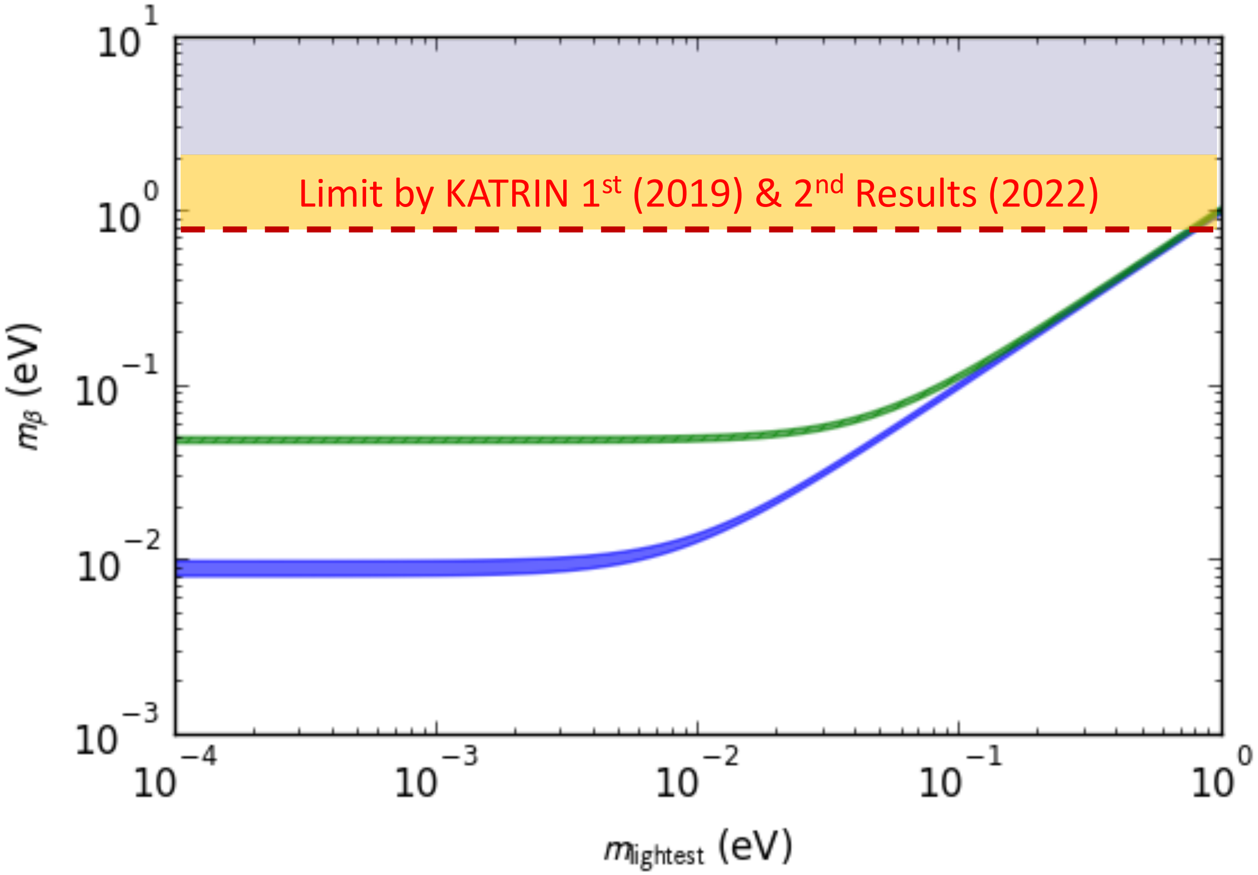
Where did we stand?



✓ limit before KATRIN 1st Results: Mainz and Troitsk Experiments

V. N. Aseev et al., Phys. Rev. D 84 (2011) 112003
Kraus, C., Bornschein, B., Bornschein, L. et al. Eur. Phys. J. C (2005)

Where do we stand now (this talk)?



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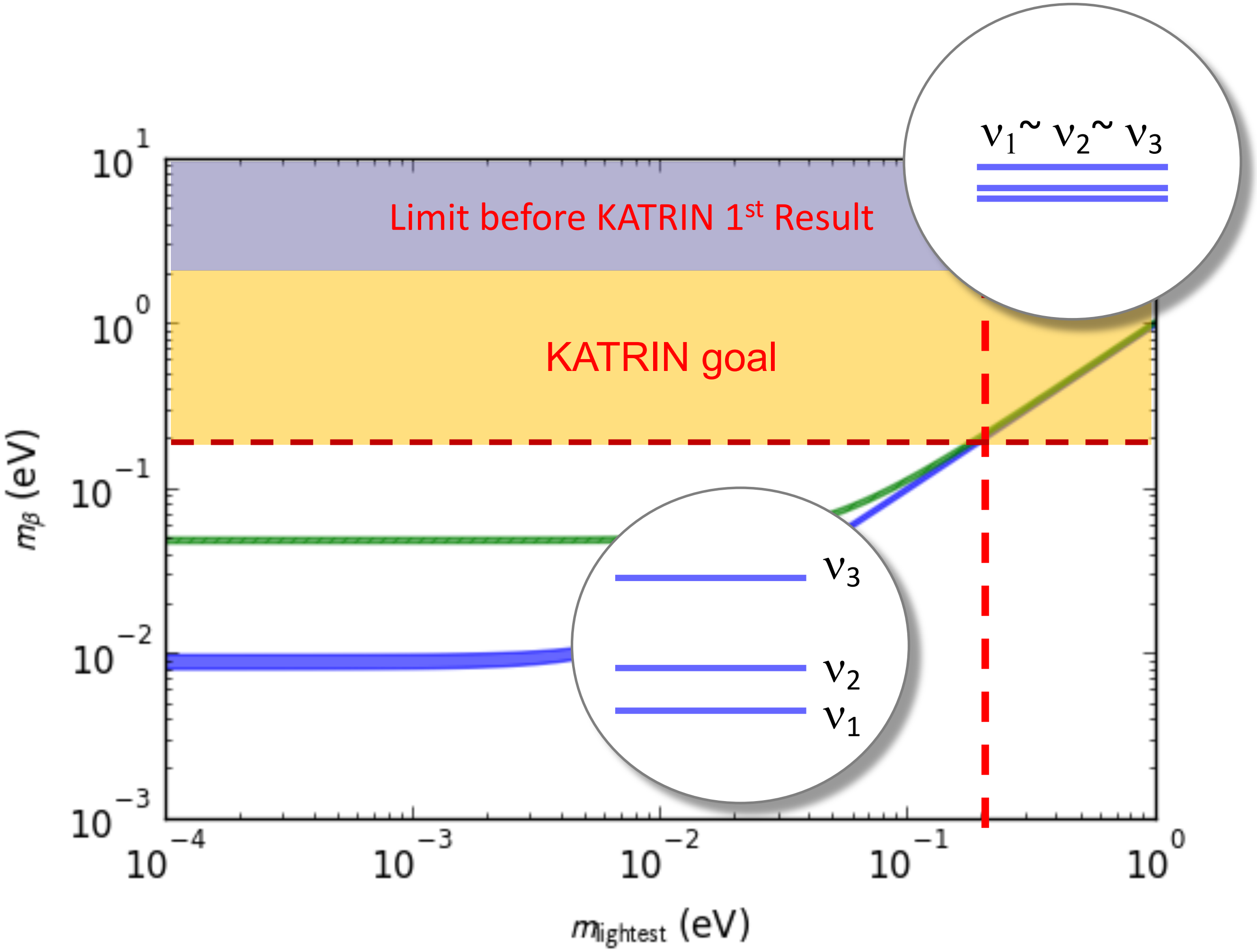
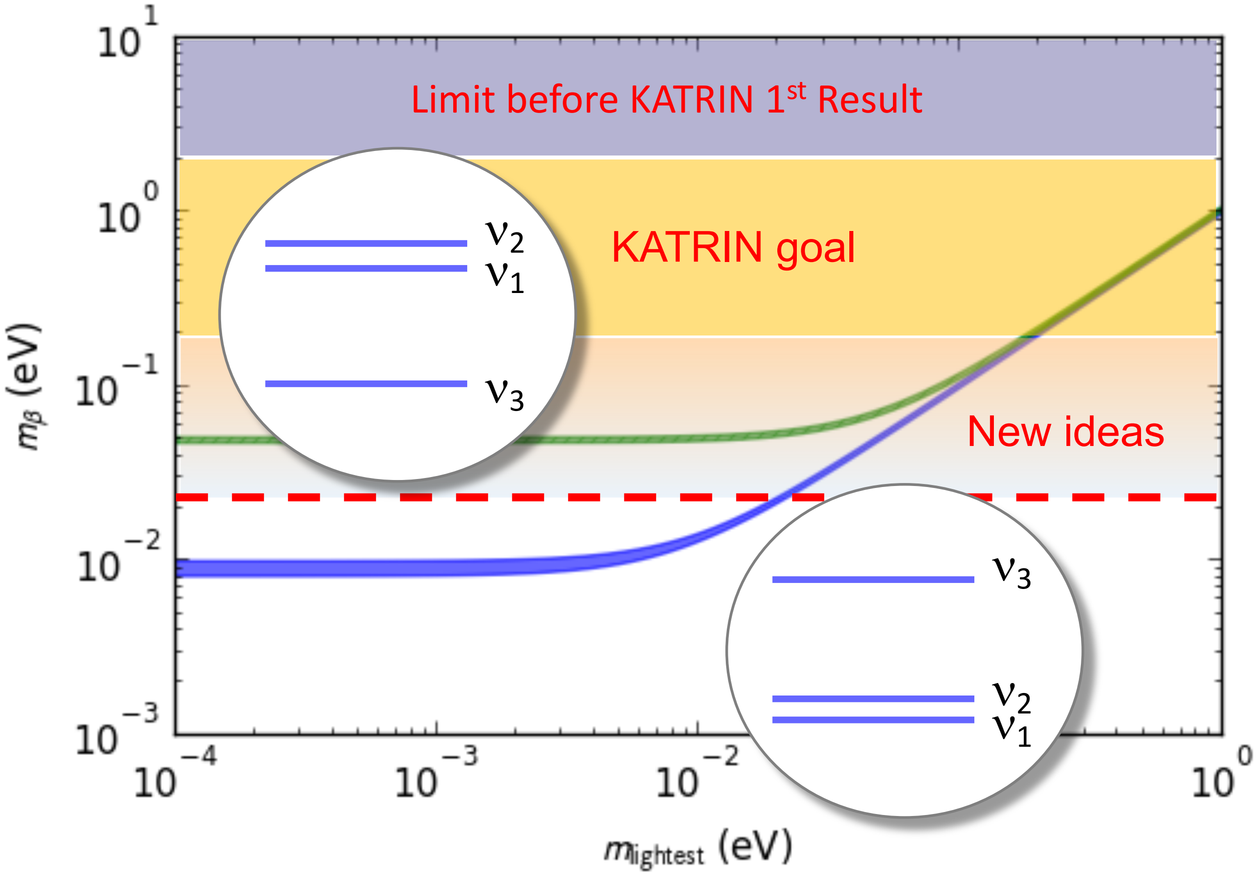
  V. N. Aseev et al., Phys. Rev. D 84 (2011) 112003
  Kraus, C., Bornschein, B., Bornschein, L. et al. Eur. Phys. J. C (2005)
- ✓ intermediate KATRIN results (~5% of the total expected statistics) – This Talk

Where will we stand by 2025?



- ✓ limit before KATRIN 1st Results: Mainz and Troitsk Experiment
  V. N. Aseev et al., Phys. Rev. D 84 (2011) 112003
  Kraus, C., Bornschein, B., Bornschein, L. et al. Eur. Phys. J. C (2005)
- ✓ intermediate KATRIN results (~5% of the total expected statistics) – This Talk
- ✓ KATRIN goal: distinguish between **degenerate** and **hierarchical** scenario

Where could we stand by 203X?



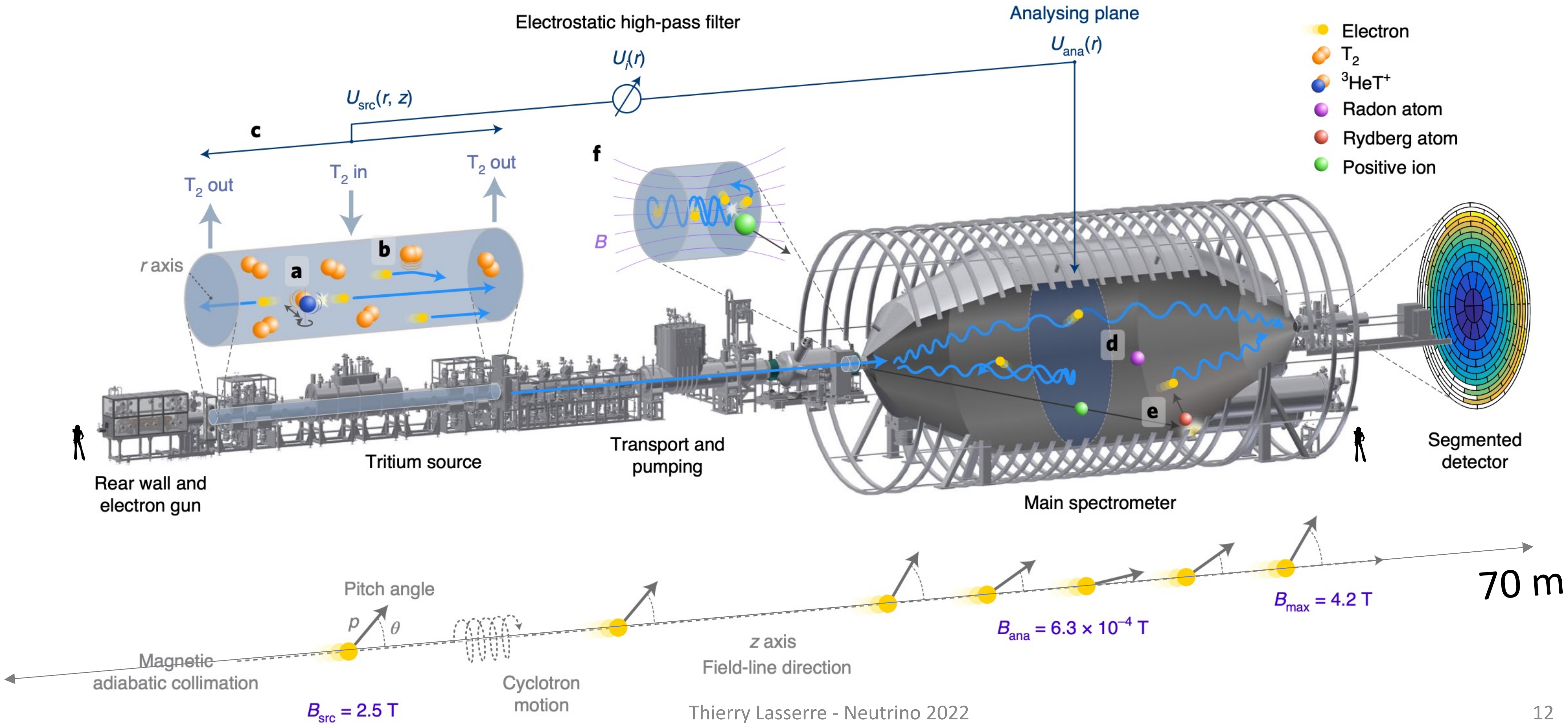
- ✓ limit before KATRIN 1st Results: Mainz and Troitsk Experiment
  V. N. Aseev et al., Phys. Rev. D 84 (2011) 112003
  Kraus, C., Bornschein, B., Bornschein, L. et al. Eur. Phys. J. C (2005)
- ✓ intermediate KATRIN results (~5% of the total expected statistics) – This Talk
- ✓ KATRIN goal: distinguish between **degenerate** and **hierarchical** scenario
- ✓ beyond KATRIN: resolve **normal** vs **inverted** neutrino mass hierarchy


Karlsruhe
Tritium
Neutrino
Experiment

KATRIN

- ✓ **Experimental site: Karlsruhe Institute of Technology (KIT)**
- ✓ **International Collaboration (150 members)**
- ✓ **Design sensitivity: 0.2 eV (90% CL)**
  (1000 days of measurement time)

Working Principle



Measurement strategy

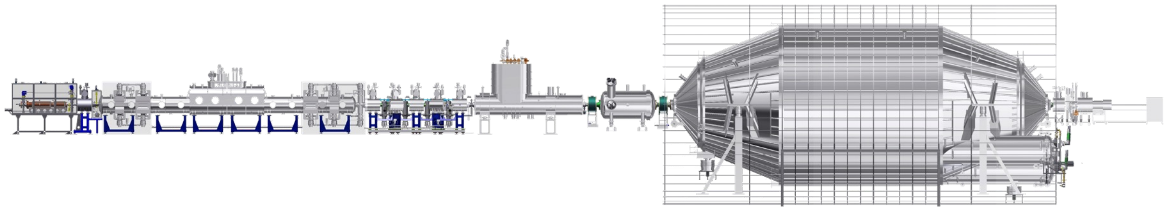
Integral spectral measurement !

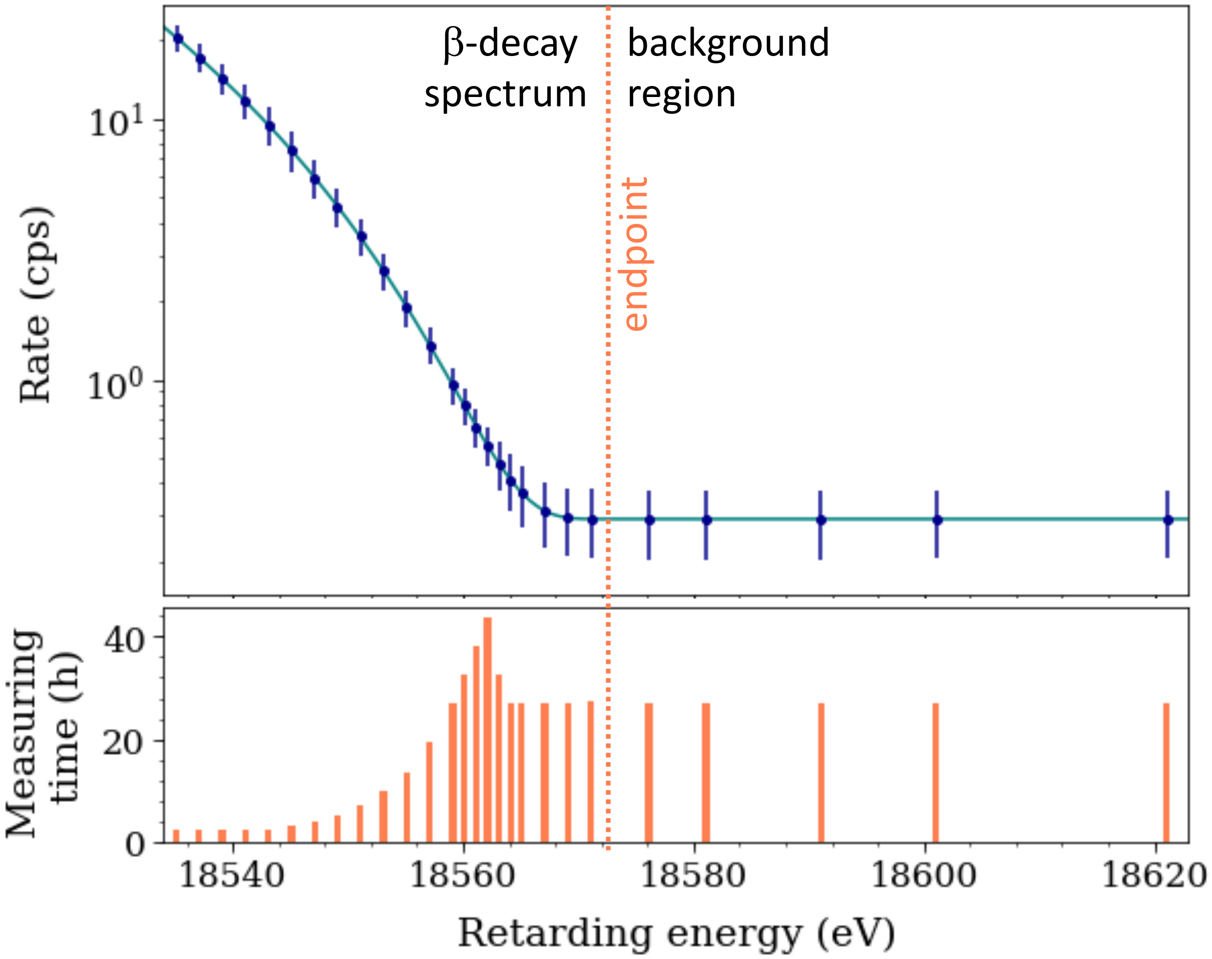
β-scans illustration:

✓ scan points: **~30 HV set points**

✓ scan interval: **E_0 – 40 eV , E_0 + 135 eV**

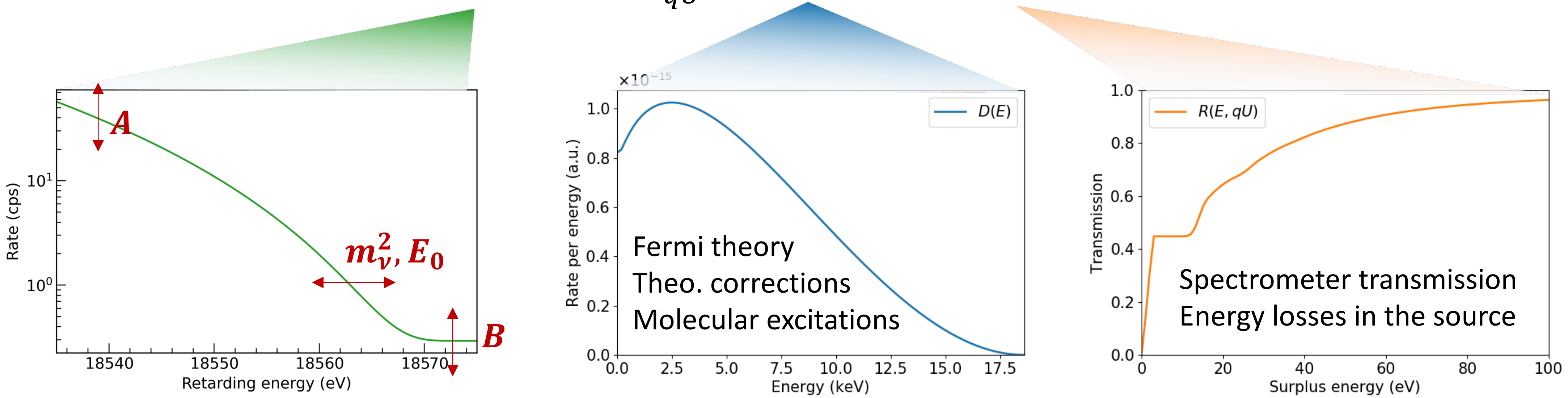
✓ scan time: **~2 hours**





Analysis strategy

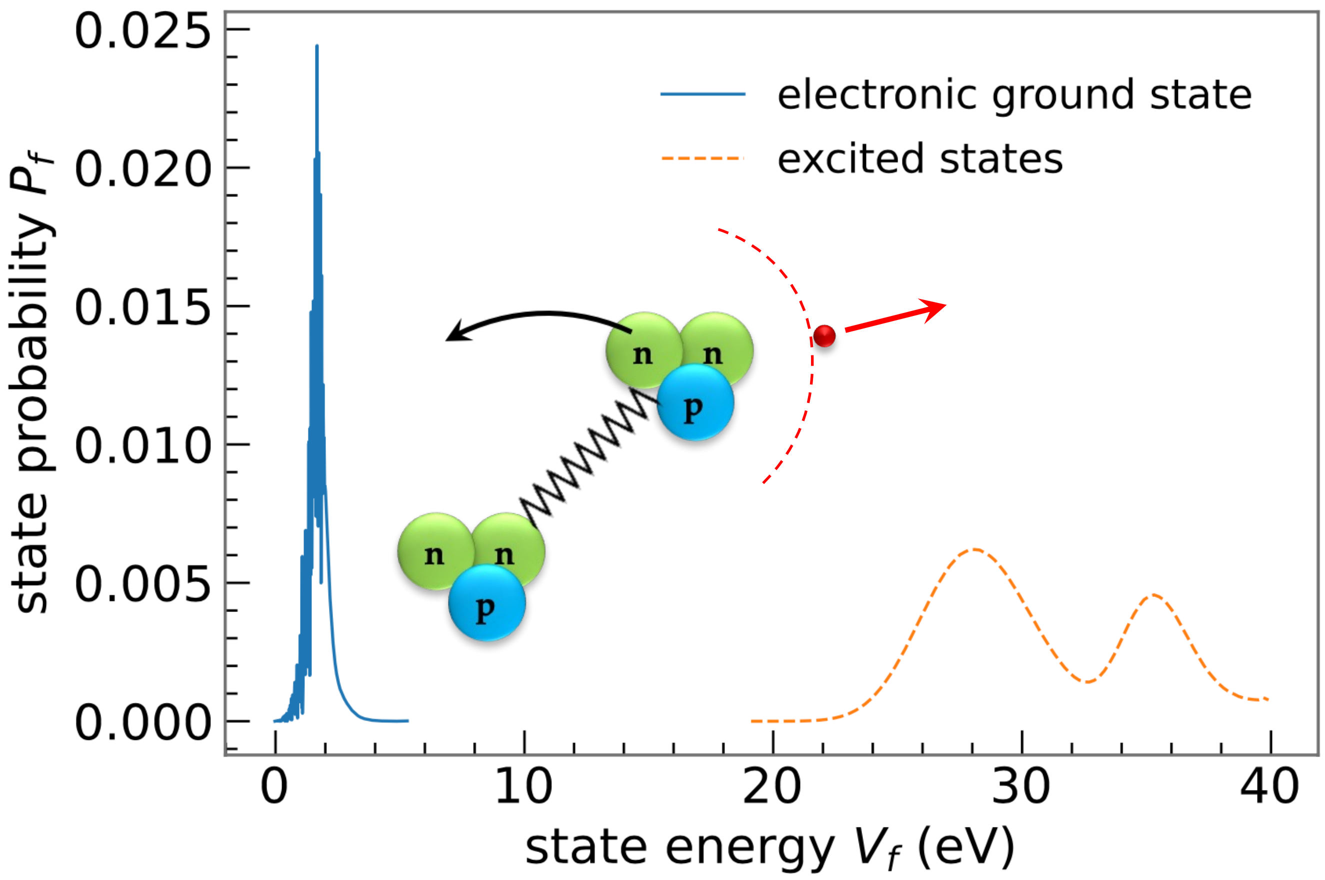
✓ fit of theoretical prediction: $\Gamma(qU) \propto \boldsymbol{A} \cdot \int_{qU}^{\boldsymbol{E_0}} D(E; \boldsymbol{m_\nu^2}, \boldsymbol{E_0}) \cdot R(qU, E)\, dE + \boldsymbol{B}$



✓ neutrino mass fit parameters: $\boldsymbol{m_\nu^2}, \boldsymbol{E_0}, \boldsymbol{B}, \boldsymbol{A}$

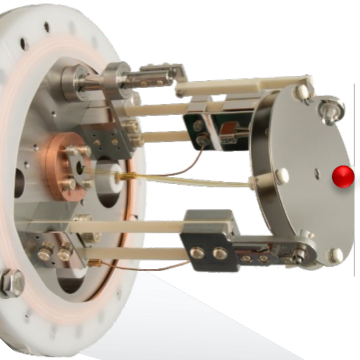
✓ fit model informed by **theoretical** and **experimental** inputs (e-gun, krypton, monitoring, …)

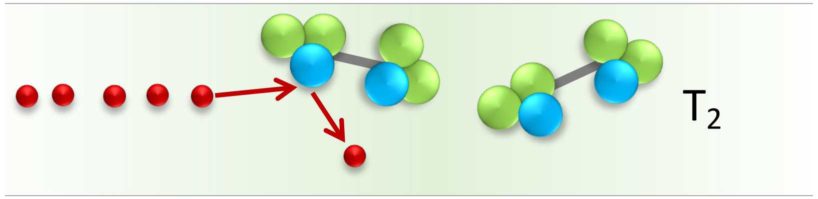
Theoretical input: molecular final states



- ✓ β −electron and tritium molecule share the energy released in the decay
- ✓ precise calculation of molecular ground and excited final states
  A. Saenz et al, Phys. Rev. Lett. 84, 242 (2000)
  + updates
- ✓ unavoidable energy broadening
- ✓ no limitation for KATRIN

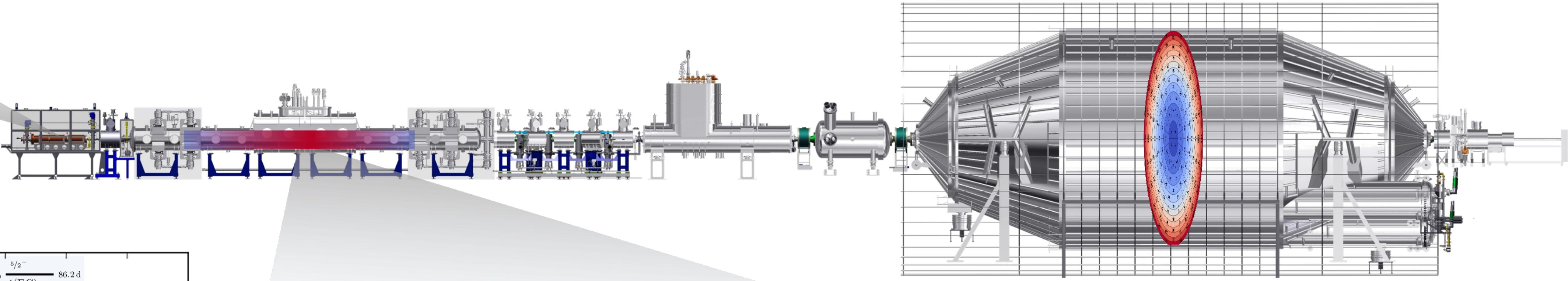
Experimental inputs: e-gun, ^{83m}Kr

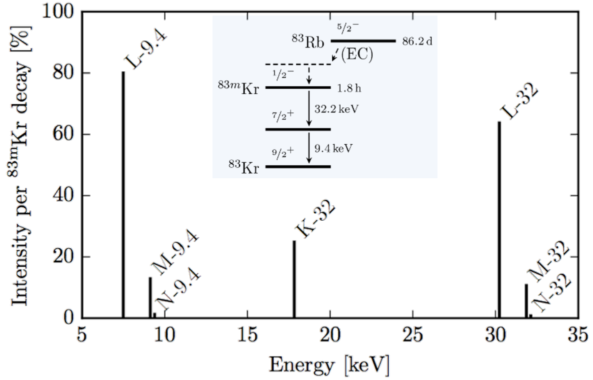


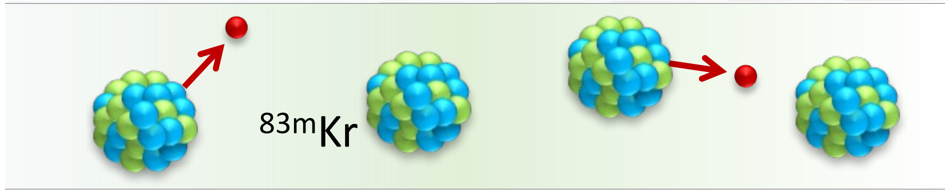


- ✓ measurement of gas density and energy losses

Behrens et al., EPJC 77 (2017) 6, 410
Hannen et al., Astropart.Phys. 89 (2017) 30-38
Aker et al., EPJC 81 (2021) 7, 579







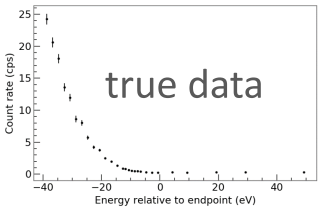
- ✓ measurement of E/M fields var. in the source and spectrometer

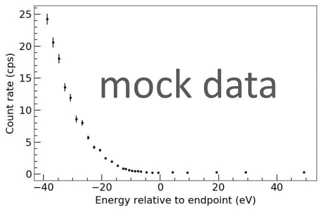
Sentkerestiová et al., J.Phys.Conf.Ser. 888 (2017) 1, 012072
Arenz et al., Eur.Phys.J.C 78 (2018) 5, 368
Arenz et al., JINST 13 (2018) 04, P04020

3-tiered blind analysis

Freeze analysis on MC-twin data

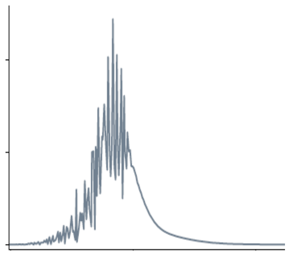
- mock data mimicking each scan

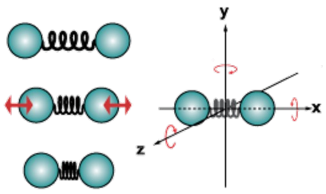




Blinded model

- modified molecular final state dist.

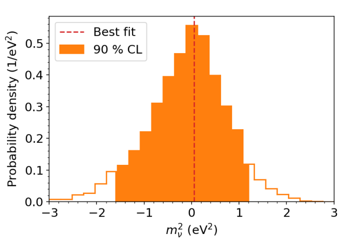


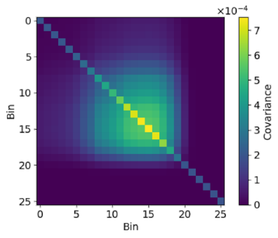


$$m_\nu^2$$

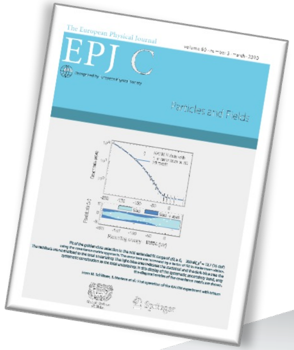
Three independent analysis teams

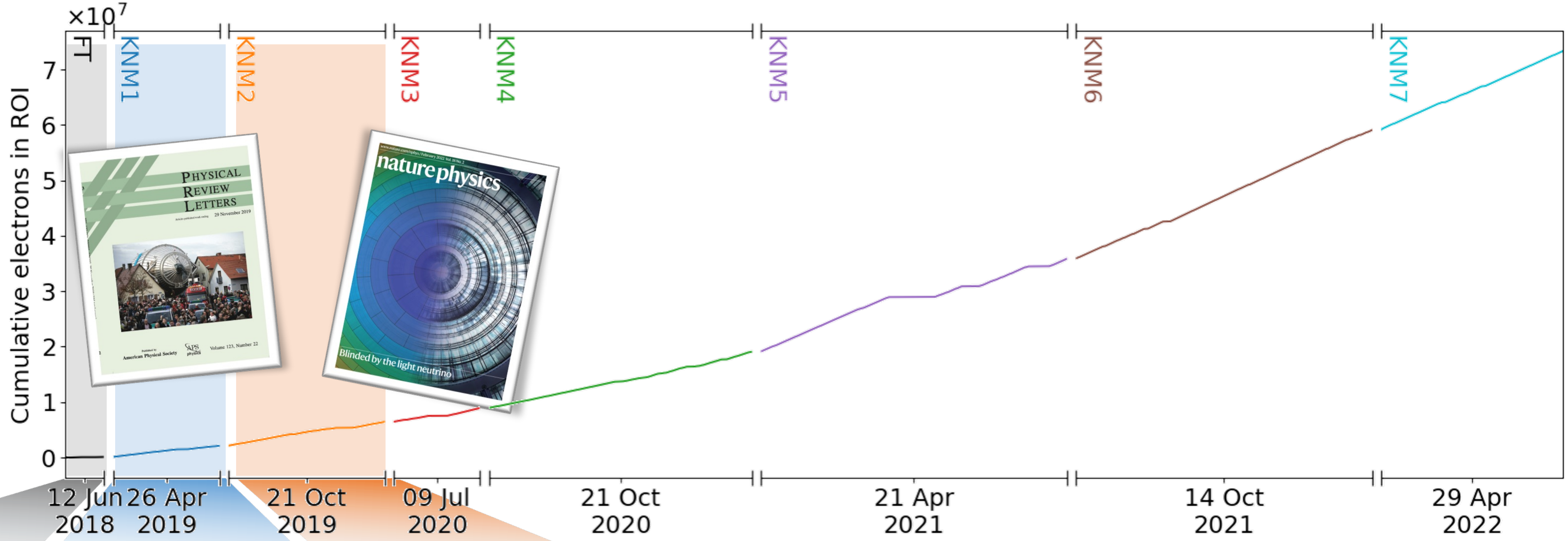
- different strategies and codes





KATRIN Data Taking Overview





- Commissioning
- Only 0.5% tritium

EPJ C 80, 264 (2020)

- 1^{st} m_ν campaign
- $m_\nu < 1.1$ eV

PRL. 123, 221802 (2019)

Phys. Rev. D 104, 012005 (2021)

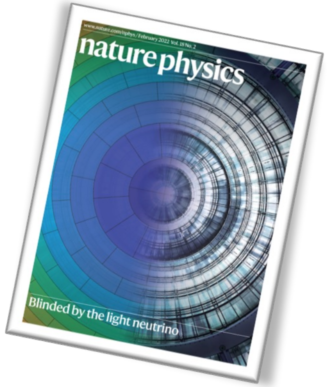
- 1^{st} + 2^{nd} m_ν campaign
- $m_\nu < 0.8$ eV

Nat. Phys. **18,** 160–166 (2022)

light sterile neutrinos

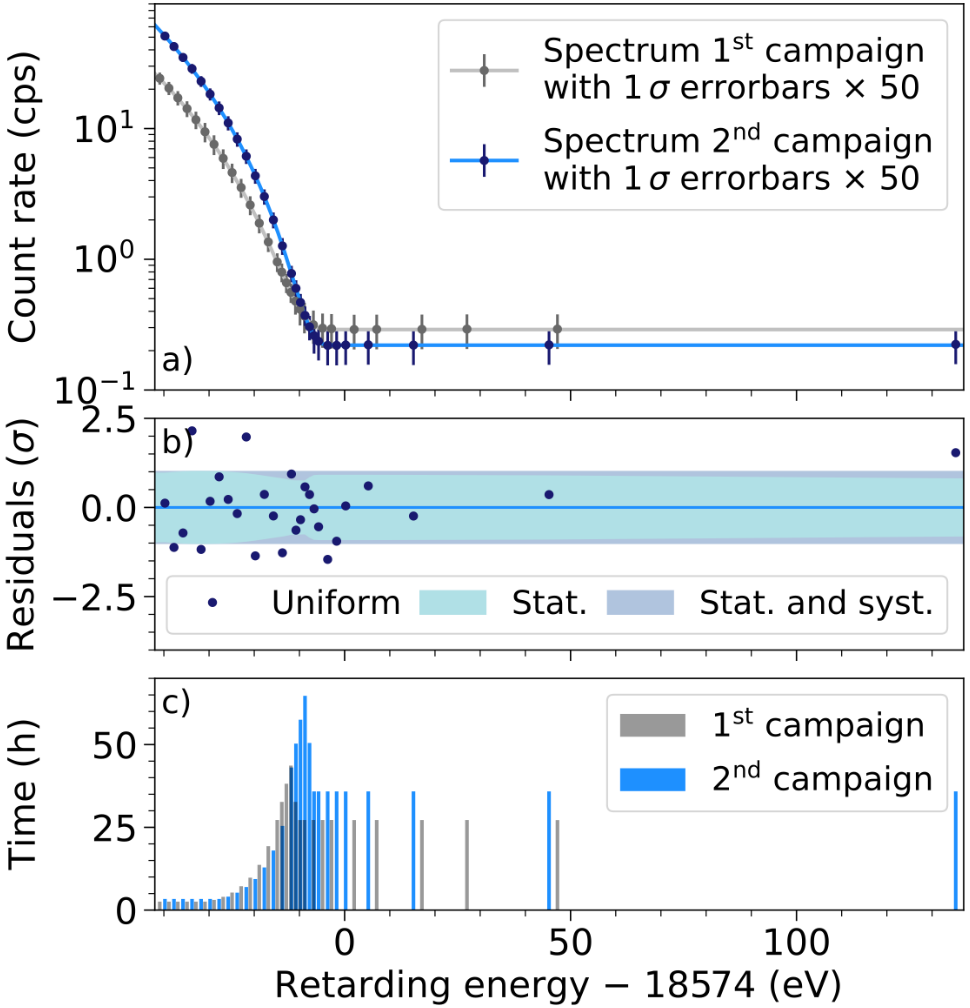
relic neutrinos

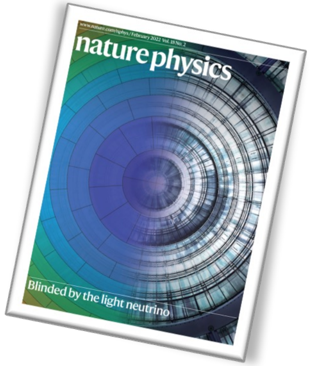
1st & 2nd campaigns figures



	1st campaign PRL 123 (2019) & PRD 104 (2021)		2nd campaign Nat. Phys. (2022)
Campaign date	April-May 2019		Sept-Nov 2019
Total scan time	522 h		744 h
Source activity	25 GBq	nominal activity →	98 GBq
Background	290 mcps	reduction -25% →	220 mcps
Tritium purity	97.6%		98.7%
Electrons in RoI	2 Mio		4.3 Mio

Latest ν −mass results





First campaign (spring 2019):

✓ total statistics: 2 million events

✓ best fit: $m_\nu^2 = \left(-1.0^{+0.9}_{-1.1}\right)$ **eV² (stat. dom.)**

✓ limit: $m_\nu < 1.1$ **eV (90% CL)**

Second campaign (autumn 2019):

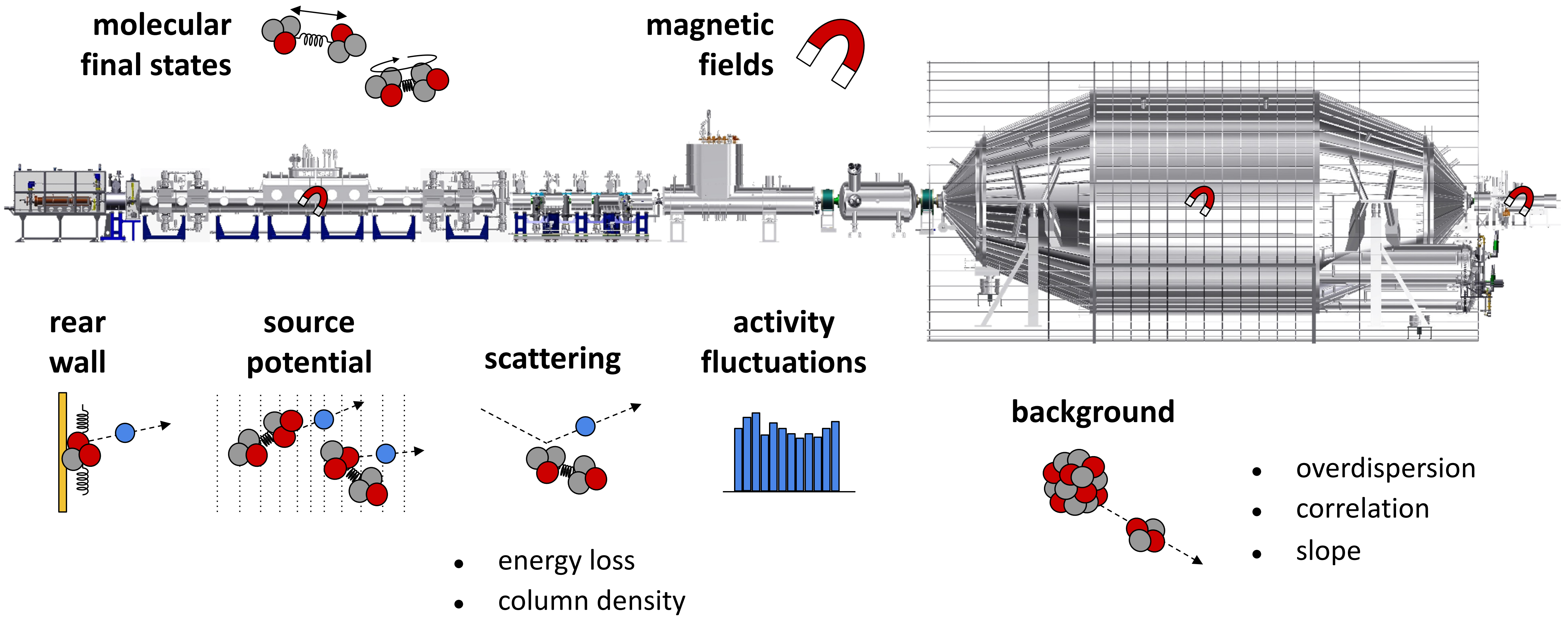
✓ total statistics: 4.3 million events

✓ best fit: $m_\nu^2 = \left(0.26^{+0.34}_{-0.34}\right)$ **eV² (stat. dom.)**

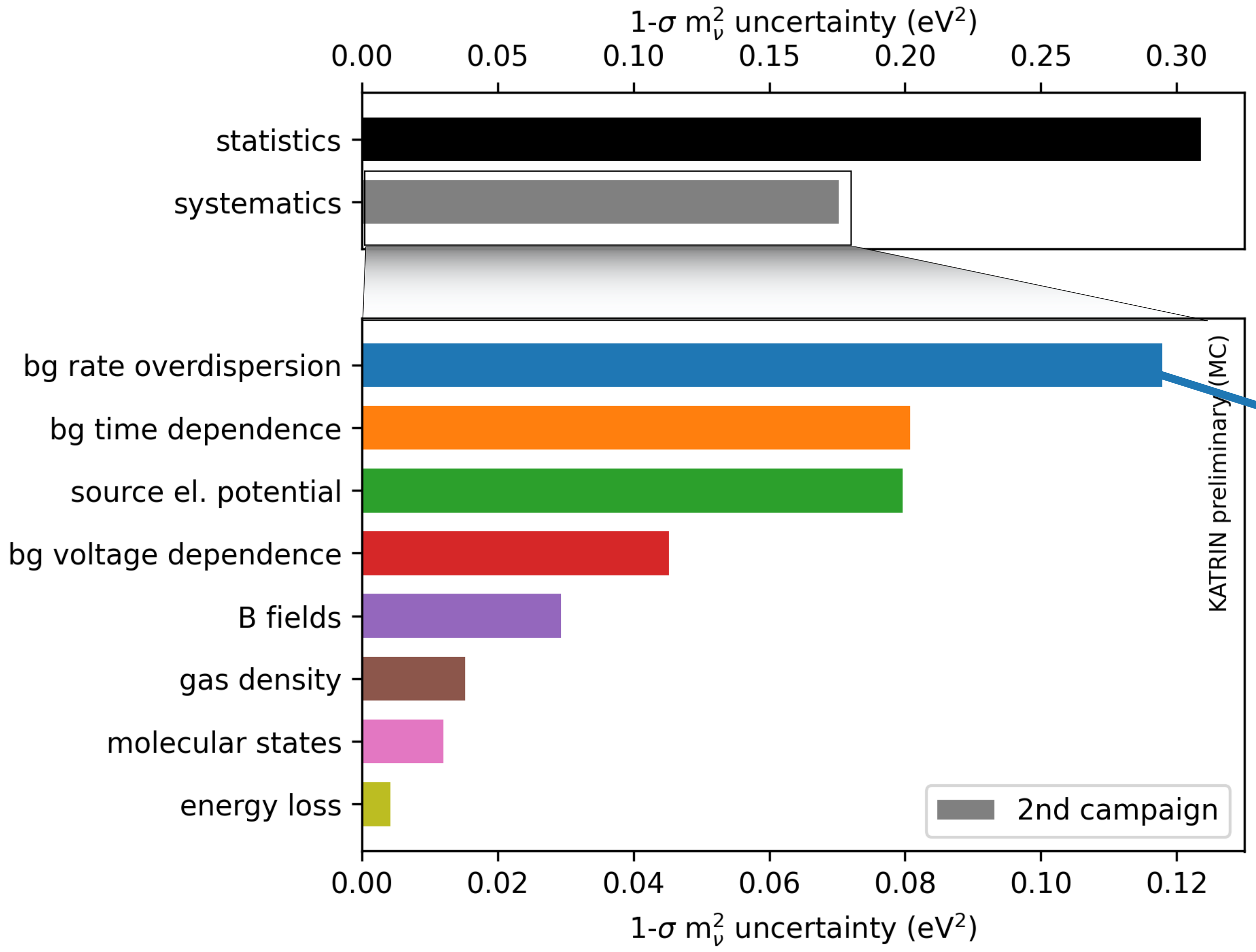
✓ limit: $m_\nu < 0.9$ **eV (90% CL)**

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

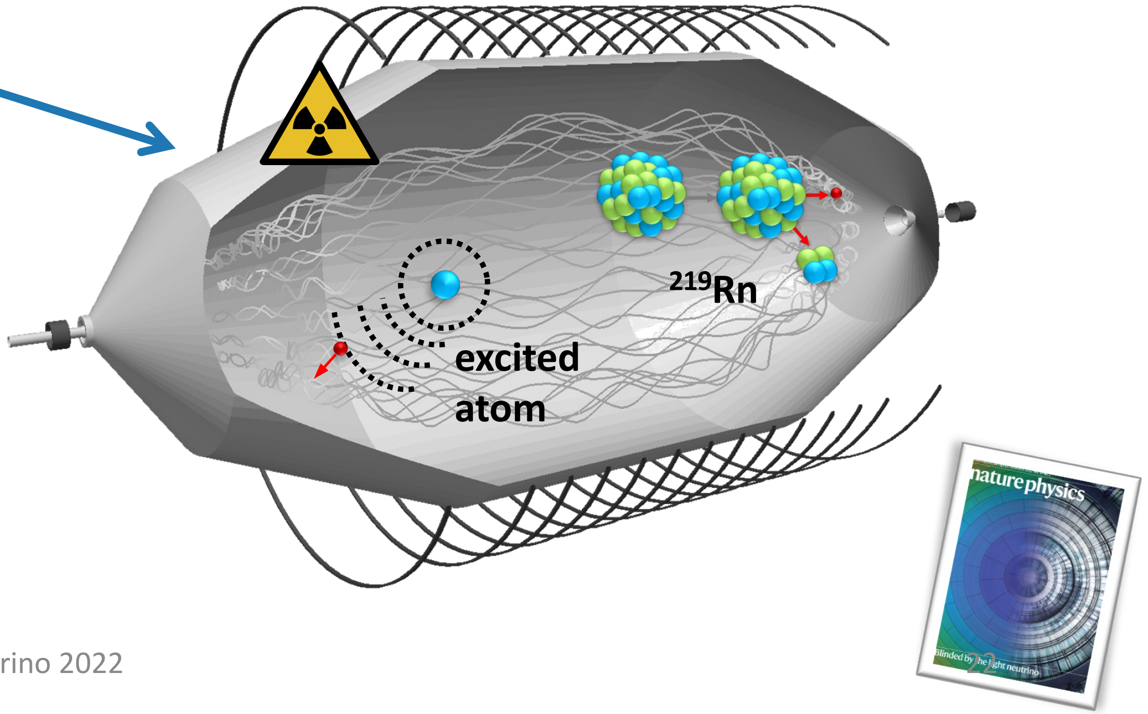
Systematics uncertainties overview



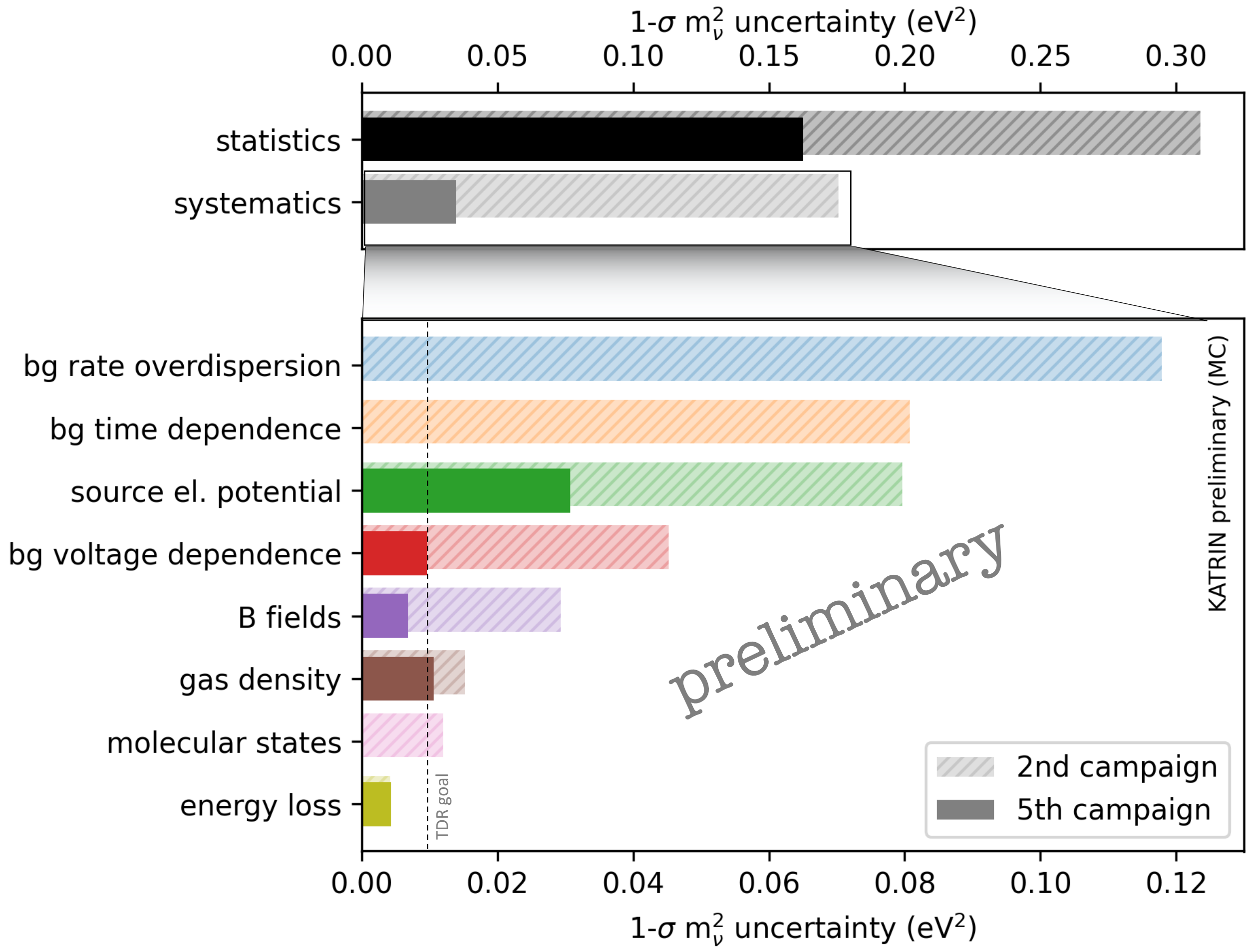
Uncertainty budget in second campaign



inner surface: $650m^2$
volume: $1400m^3$



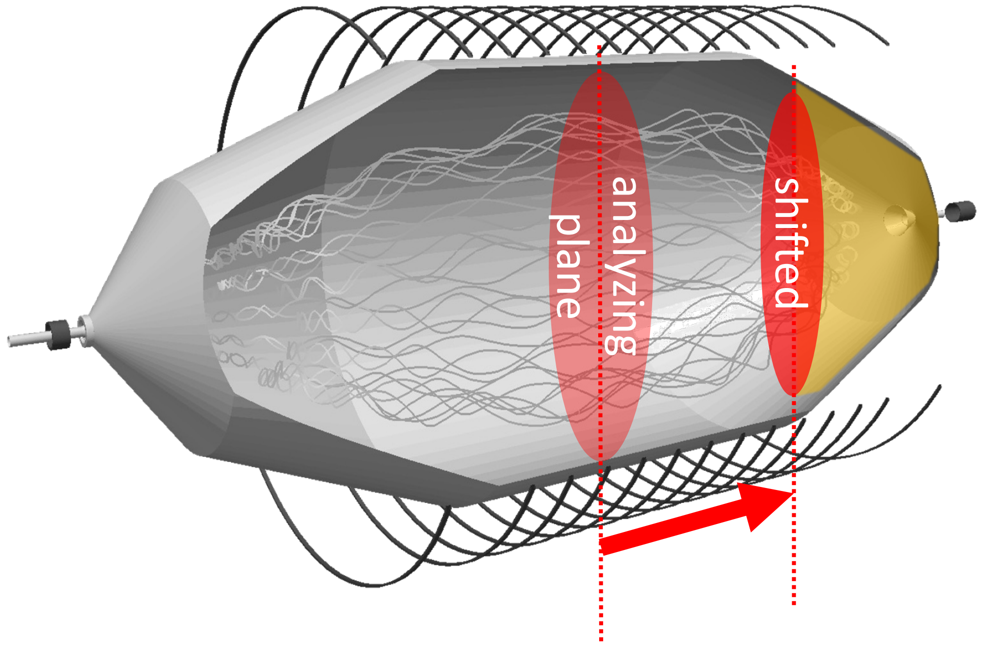
Improvements achieved by 2022



Major improvements:

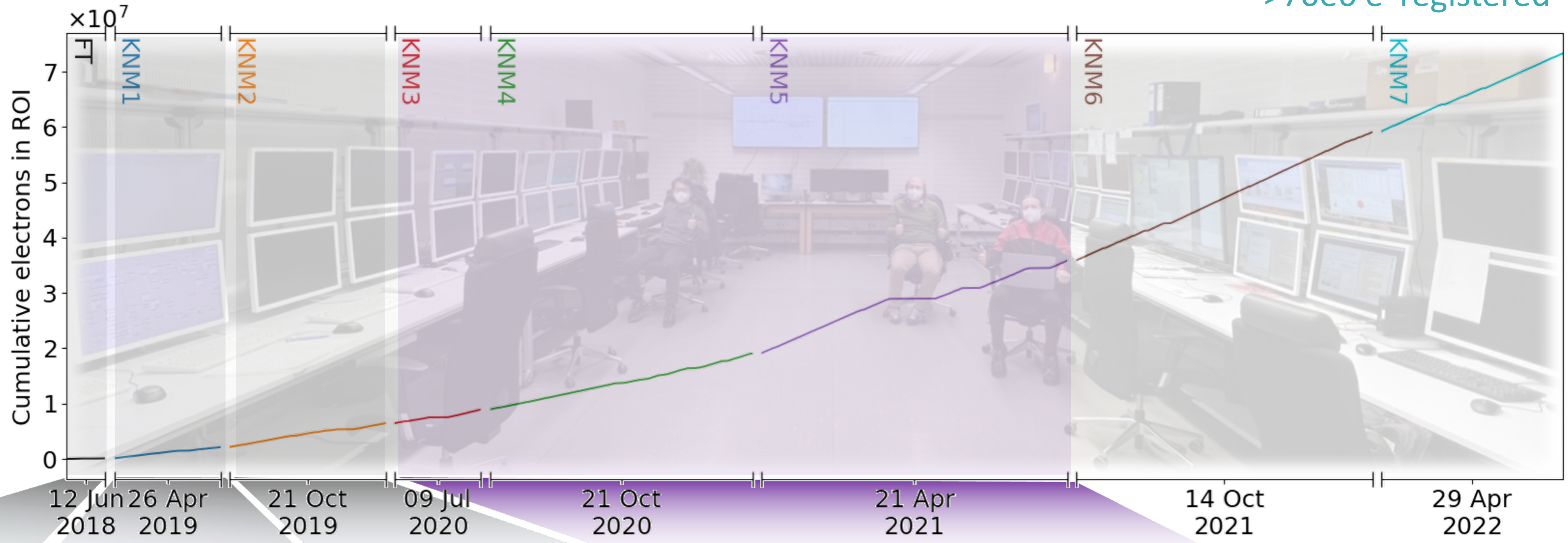
✓ background reduction (÷2) via new EM field layout
A. Lokhov et al, EPJC 82, 258 (2022)

✓ 10 GBq ^{83}Rb/^{83m}Kr calibration (ν –mass scan conditions)
J. Sentkerestiová et al, JINST 13 (2018)



Outlook – 2022/2023

>70e6 e^- registered



- commissioning
- only 0.5% tritium

EPJ C 80, 264 (2020)

- 1st campaign
  2e6 e^- in ROI
- $m_\nu < 1.1$ eV

PRL. 123, 221802 (2019)
PRD. D 104, 012005 (2021)

- 1st + 2nd campaigns
- 6e6 e^- in ROI
- $m_\nu < 0.8$ eV

Nat. Phys. **18,** 160–166 (2022)

- next data unblinding in summer 2022
- 1st, 2nd, 3rd, 4th, 5th campaigns
- ~30e6 e^- in ROI

Outlook – 2025

2022:

✓ first direct neutrino-mass experiment to reach sub-eV sensitivity and limit

✓ $m_\nu < 0.8$ eV (90% CL)
KATRIN Collab. Nat. Phys. **18,** 160–166 (2022)

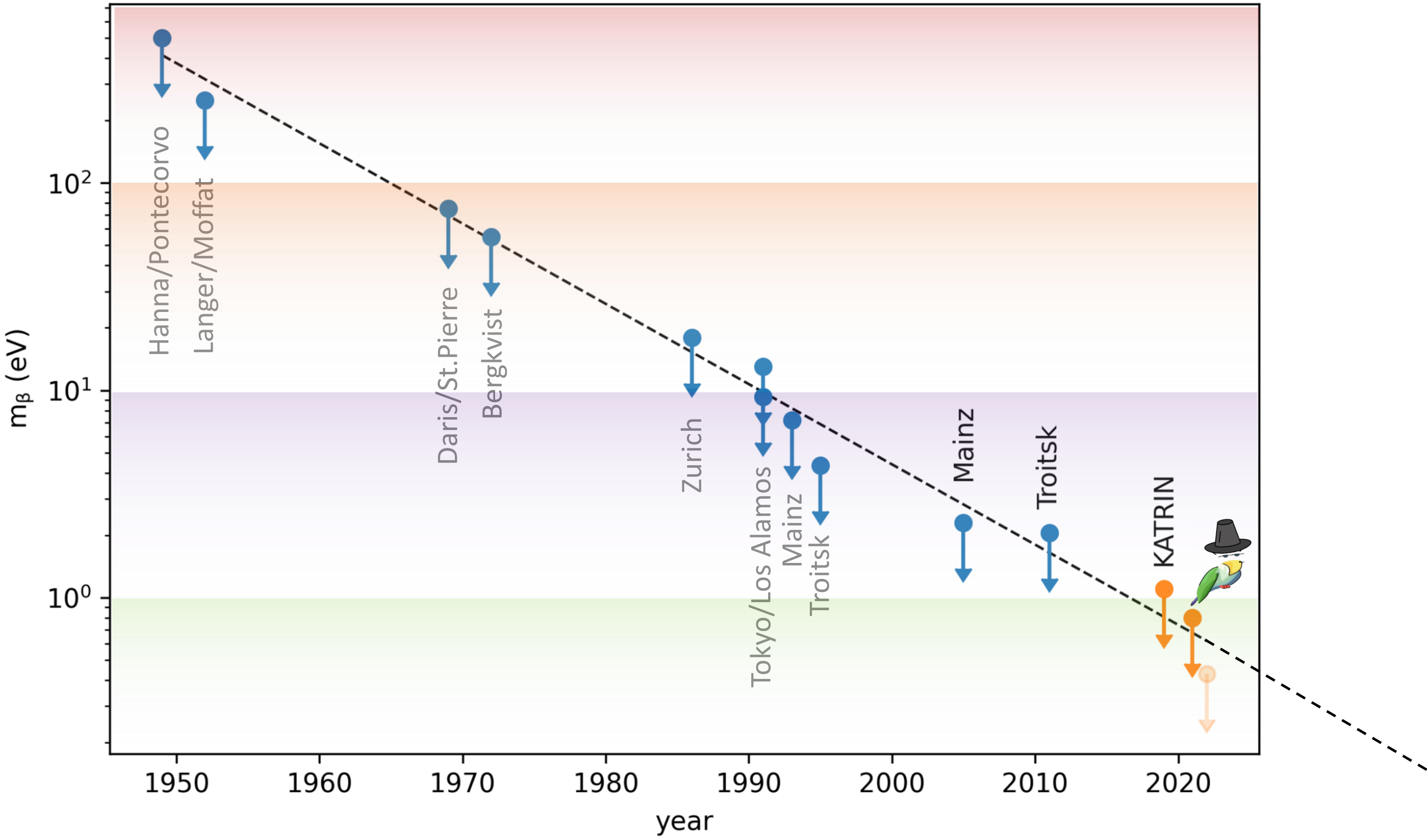
✓ statistics dominated

2025:

✓ targeted sensitivity
$m_\nu < 0.2 - 0.3$ eV (90% CL)

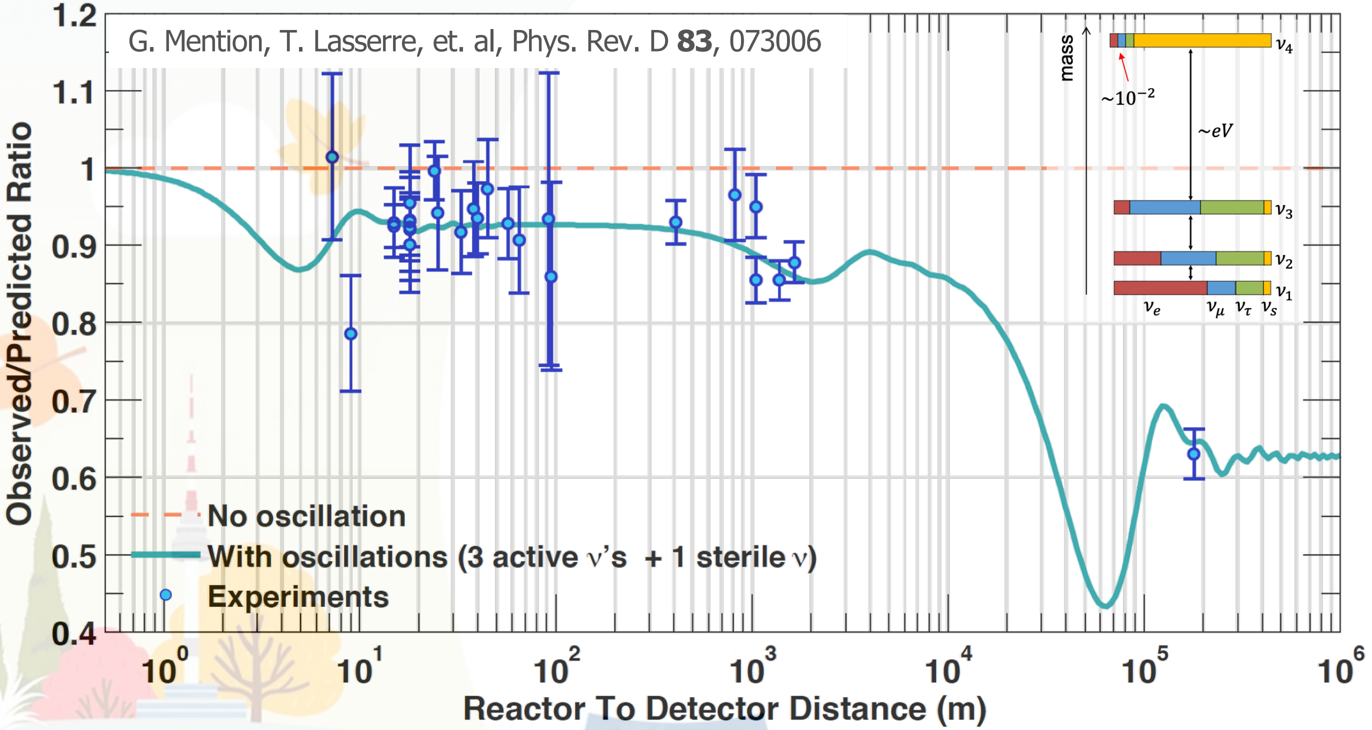
✓ measurement or upper limit ?

Drexlin-Weinheimer's Law is currently in force

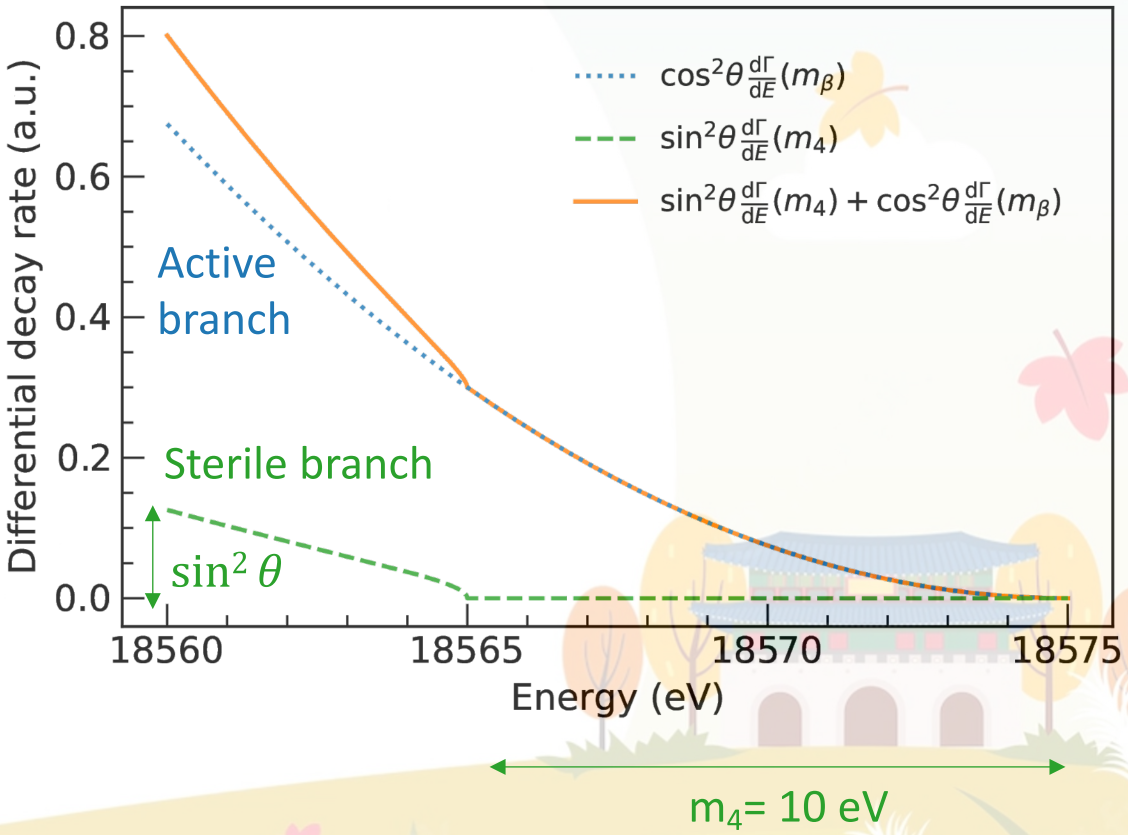


Search for eV-scale sterile neutrinos

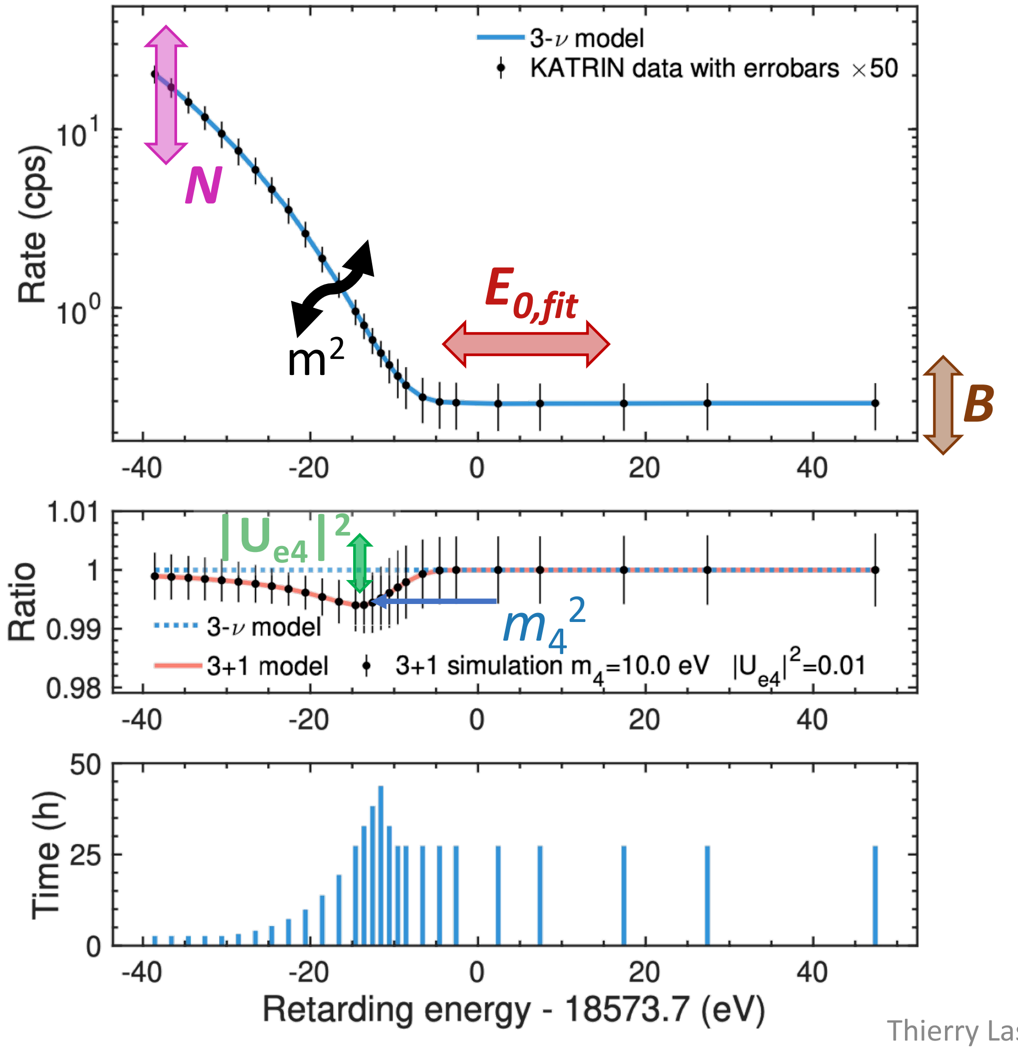
Anomalies in oscillation experiments



Expected signature in KATRIN



Sterile neutrino modeling



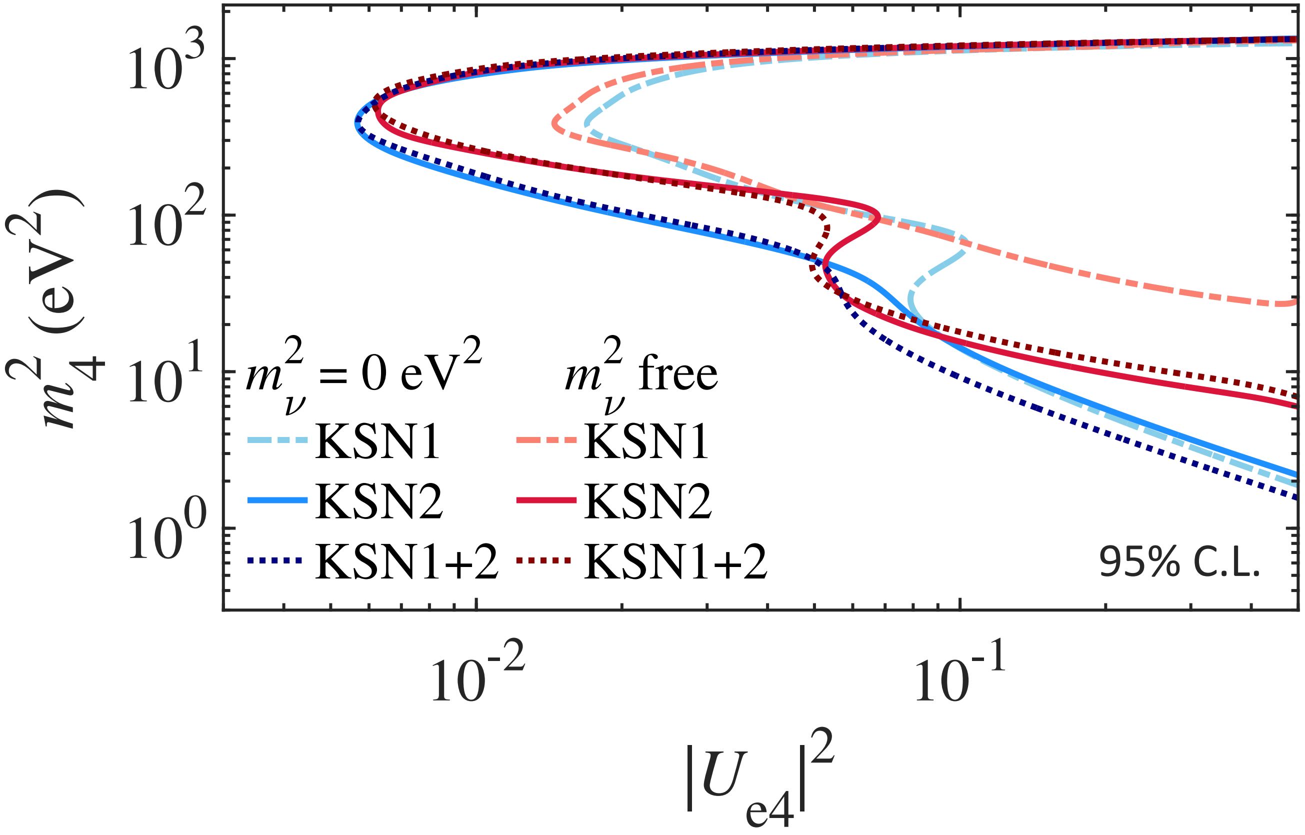
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} = \underbrace{\left(1 - |U_{e4}|^2\right) \frac{\mathrm{d}\Gamma}{\mathrm{d}E}(m_\beta^2)}_{\text{light neutrino}} + \underbrace{|U_{e4}|^2 \frac{\mathrm{d}\Gamma}{\mathrm{d}E}(m_4^2)}_{\text{heavy neutrino}}$$

Fit Parameters:

m^2	neutrino mass (fixed/free/constrained)
$E_{0,fit}$	endpoint
N	signal normalization
B	background rate
$m_4{}^2$	4th neutrino mass
$\lvert U_{e4}\rvert^2$	4th neutrino mixing

3+1 neutrino fit (1st & 2nd campaign, 2019)

KATRIN Collab., PRD 105, 072004 (2022)



✓ **scenario i) : $0 = m_\nu \equiv m_{1,2,3} \ll m_4$**

- ✓ best fit KNM2: $|U_{e4}|^2 = 1.0, m_4^2 = 0.28$ eV^2 *p-value* = 0.24

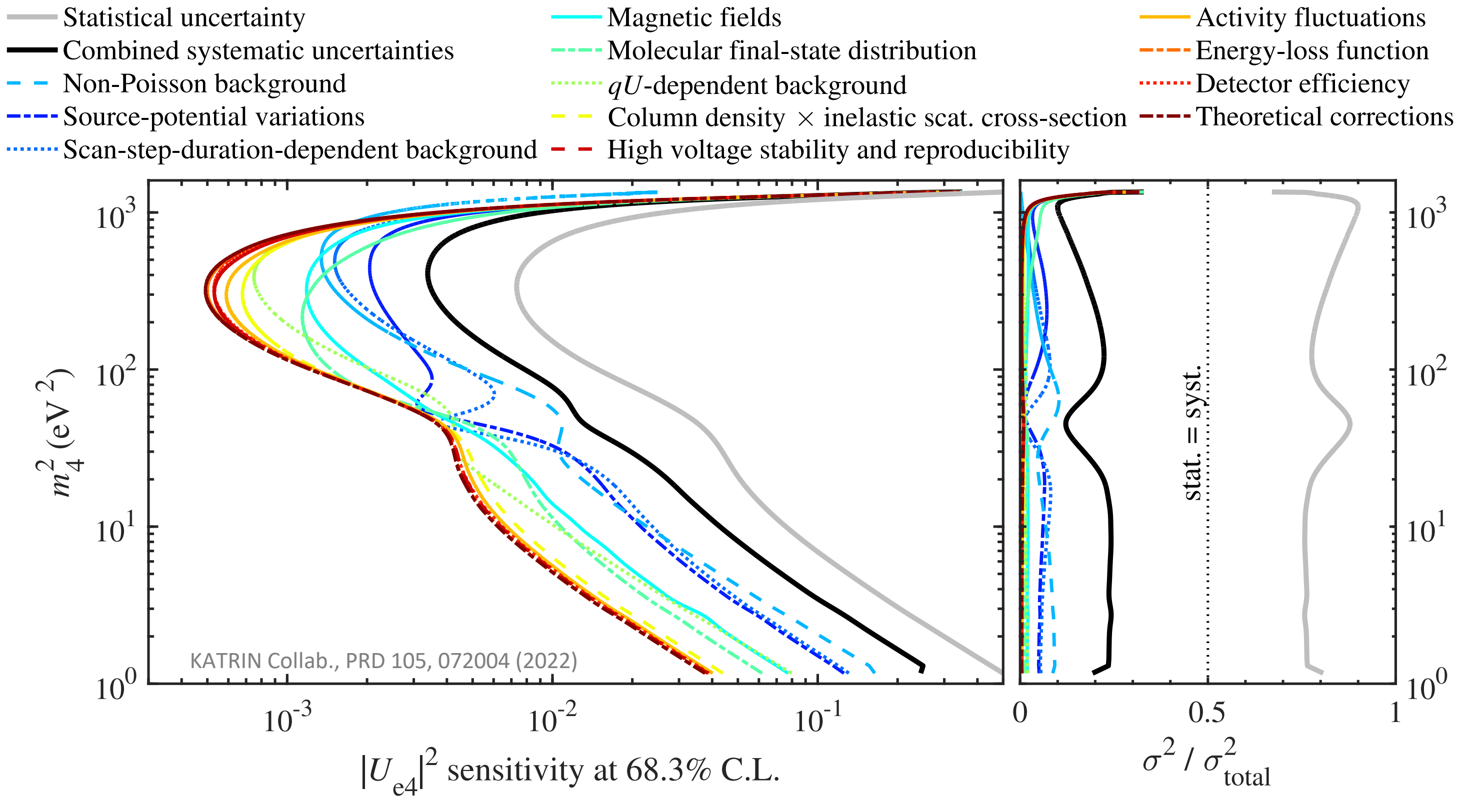
✓ **scenario ii) : m_ν^2 as a free parameter**

- ✓ best fit KNM2: $|U_{e4}|^2 = 0.027, m_4^2 = 98$ eV^2, *p-value* = 0.30
  $m_\nu^2 = 1.1$ eV^2 (unconstrained nuisance parameter)

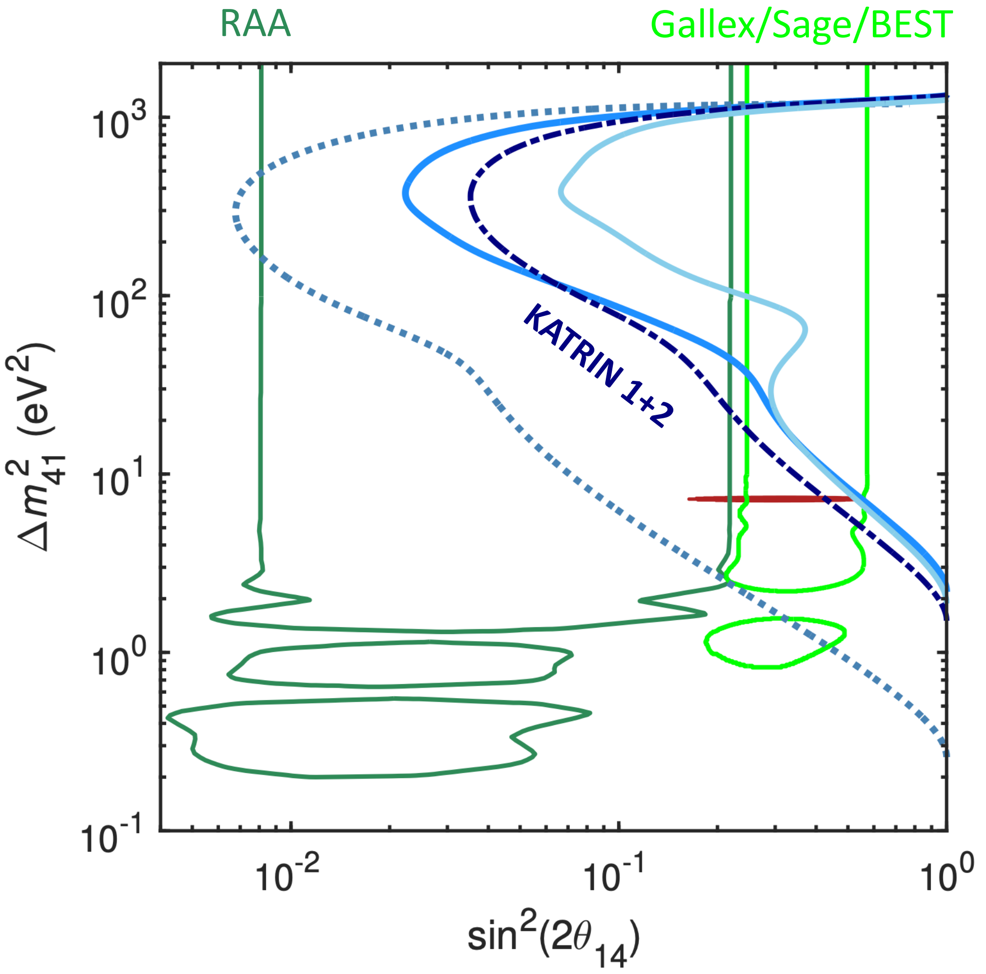
✓ no significant improvement over the no-sterile ν hypothesis (1.4σ) → exclusion limits

Systematic uncertainties

- ✓ $\sigma_{\text{syst}}(|U_{e4}|^2) = \sqrt{\sigma^2_{\text{stat+syst}} - \sigma^2_{\text{stat}}}$
- ✓ statistics dominated for all m_4^2
- ✓ dominant syst. effects
  - ✓ background overdispersion
  - ✓ time-dependent background
  - ✓ T-source plasma potential

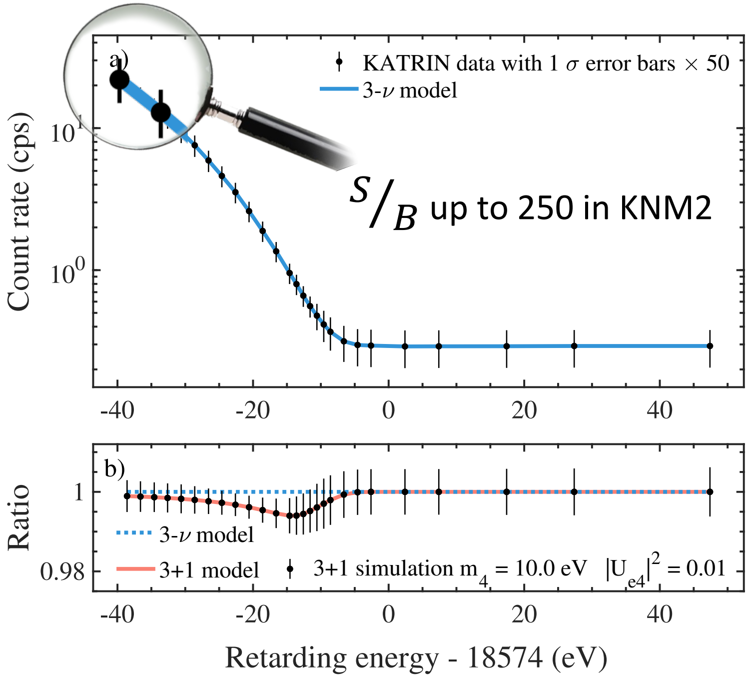


Comparison to oscillation experiments

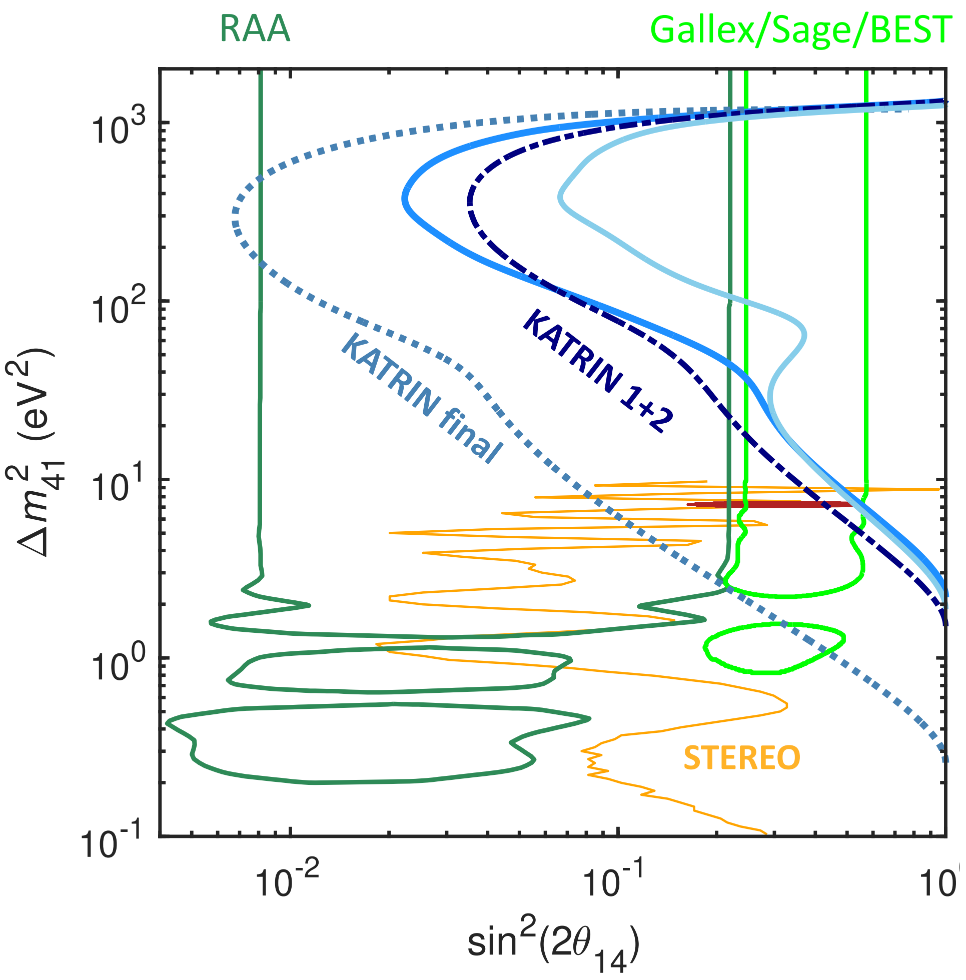


- ✓ tackling short baseline oscillation anomalies from a different perspective (shape-only search)
- ✓ start probing interesting parameter space

KATRIN Collab., PRL. 126, 091803 (2021)
KATRIN Collab., PRD 105, 072004 (2022)



Sterile neutrino search in KATRIN



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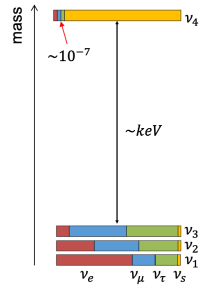
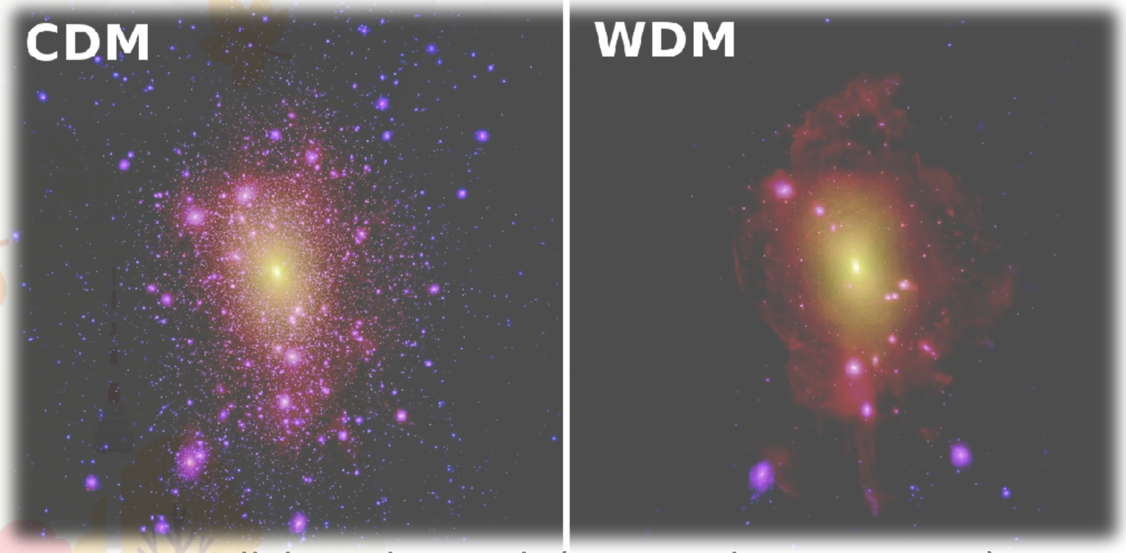
- ✓ start probing interesting parameter space
  KATRIN Collab., PRL. 126, 091803 (2021)
  KATRIN Collab., PRD 105, 072004 (2022)
- ✓ complementary probe to oscillation-based experiments
  DANSS, arXiv:1911.10140 (2019)
  STEREO, Phys. Rev. D 102, 052002 (2020)
  PROSPECT, Phys. Rev. D 103, 032001 (2021)
  Neutrino-4, JETP Lett. 109 (2019) 4, 213-221
  Gallex, Phys. Lett. B 342, 440 (1995); 420, 114 (1998)
  Sage, Phys. Rev. Lett. 77, 4708 (1996); Phys. Rev. C 59, 2246 (1999)
  BEST, arXiv:2109.11482, to appear in PRL
  …
- ✓ KATRIN will soon probe the favored regions at $\Delta m^2 > 5\ \mathrm{eV}^2$

Search for keV-scale sterile neutrinos



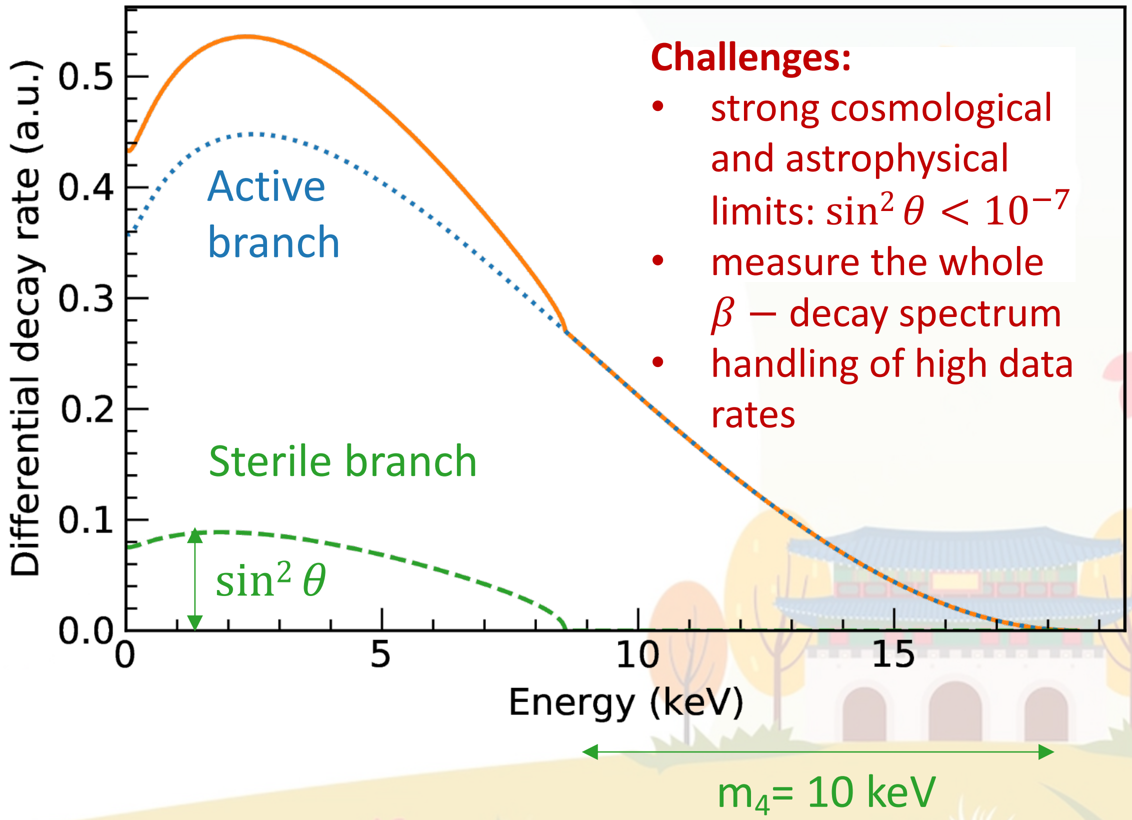
Dark matter candidate

Boyarsky, Drewes, Lasserre, Mertens, Ruchayskiy, PPNP (2018)



see talk by Kyle Leach (S3: Sterile Neutrino 3)

Expected signature in KATRIN

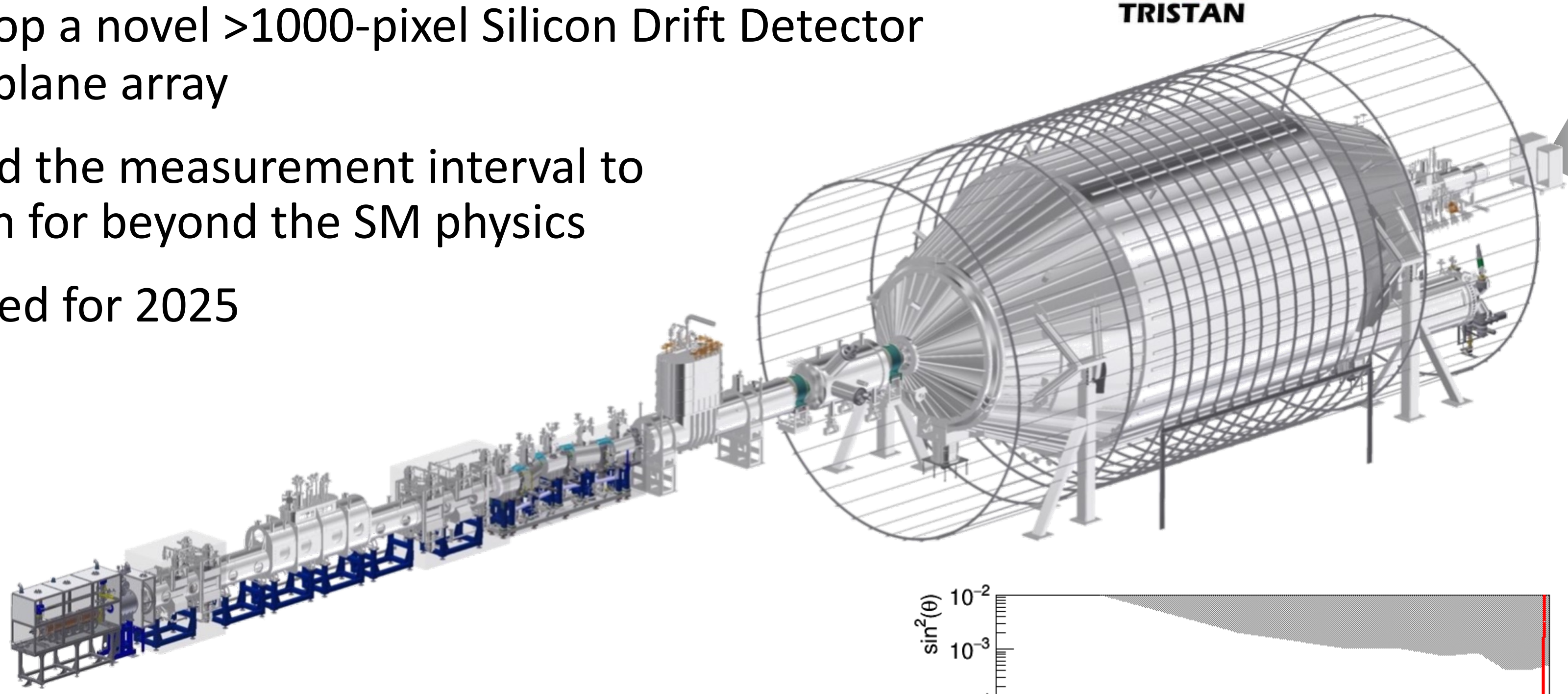


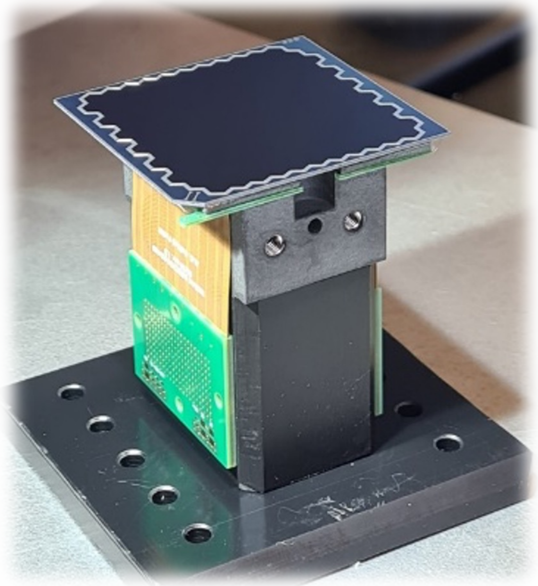
Challenges:

- strong cosmological and astrophysical limits: $\sin^2\theta < 10^{-7}$
- measure the whole β – decay spectrum
- handling of high data rates

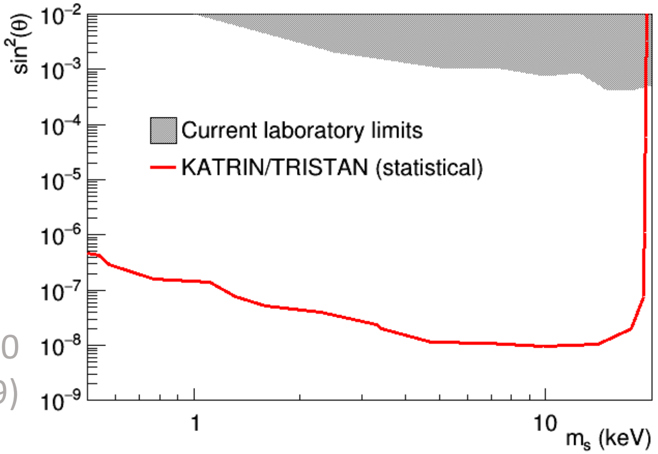
The TRISTAN project

- ✓ develop a novel >1000-pixel Silicon Drift Detector focal plane array
- ✓ extend the measurement interval to search for beyond the SM physics
- ✓ planned for 2025





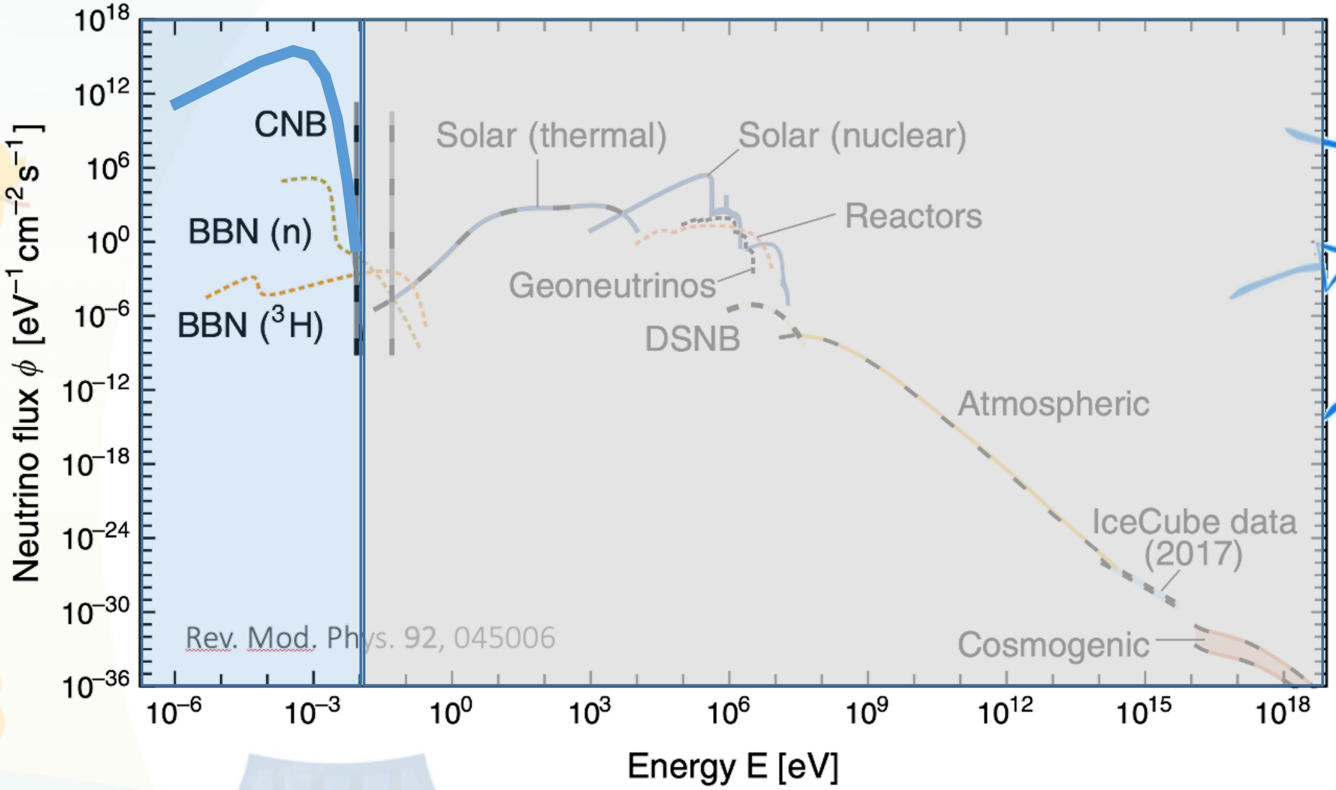
- ✓ see talk by Kyle Leach (S3: Sterile Neutrino 3)

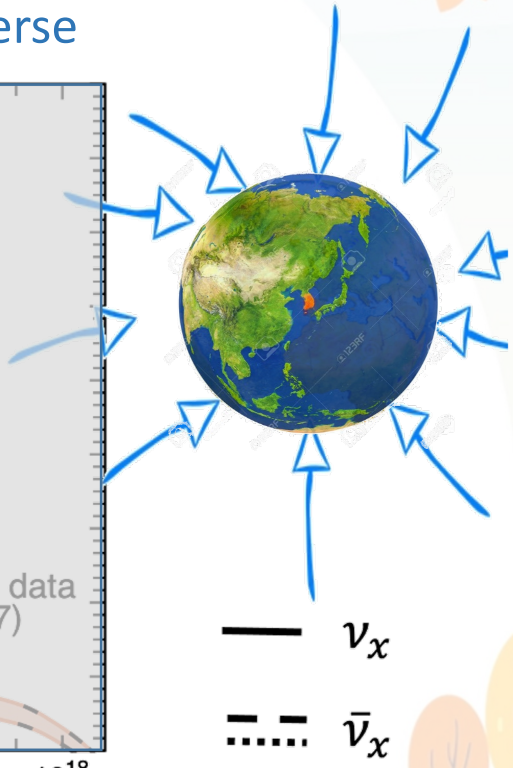


Mertens, Lasserre et al, JCAP 02 (2015) 020
Mertens et al, J. Phys. G46 (2019)

Cosmic neutrino background overdensity

340 relic neutrinos of all species /cm^3 in the Universe

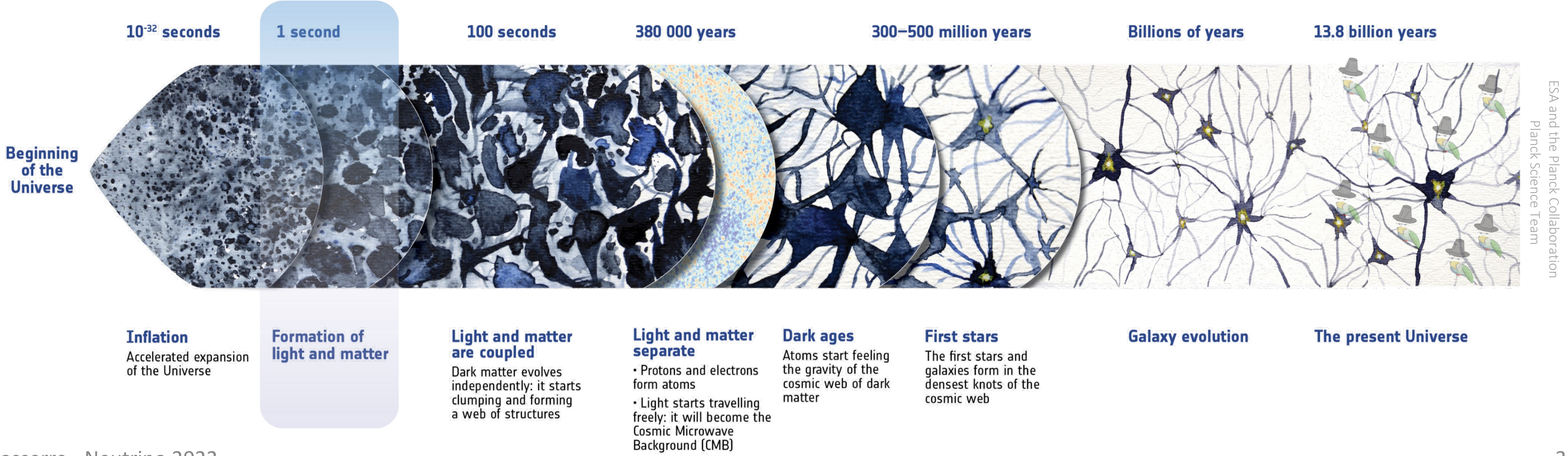




KATRIN restricts the maximum overdensity ratio on Earth η

Cosmic neutrino background

- ✓ in the early Universe, ν's are in thermal equilibrium with matter
- ✓ Big-Bang+1 sec (1 MeV) ν decouple ⟶ Relic (Cosmic) Neutrino Background emission
- ✓ today: $<n_\nu> \sim 56$ O(meV) ν per cm^3 per specie
- ✓ **local ν clustering possible → overdensity ratio η can be constrained by KATRIN**

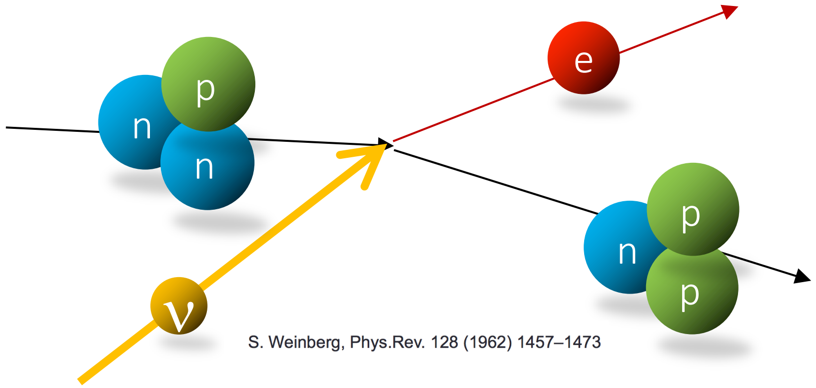


Relic neutrino capture in KATRIN

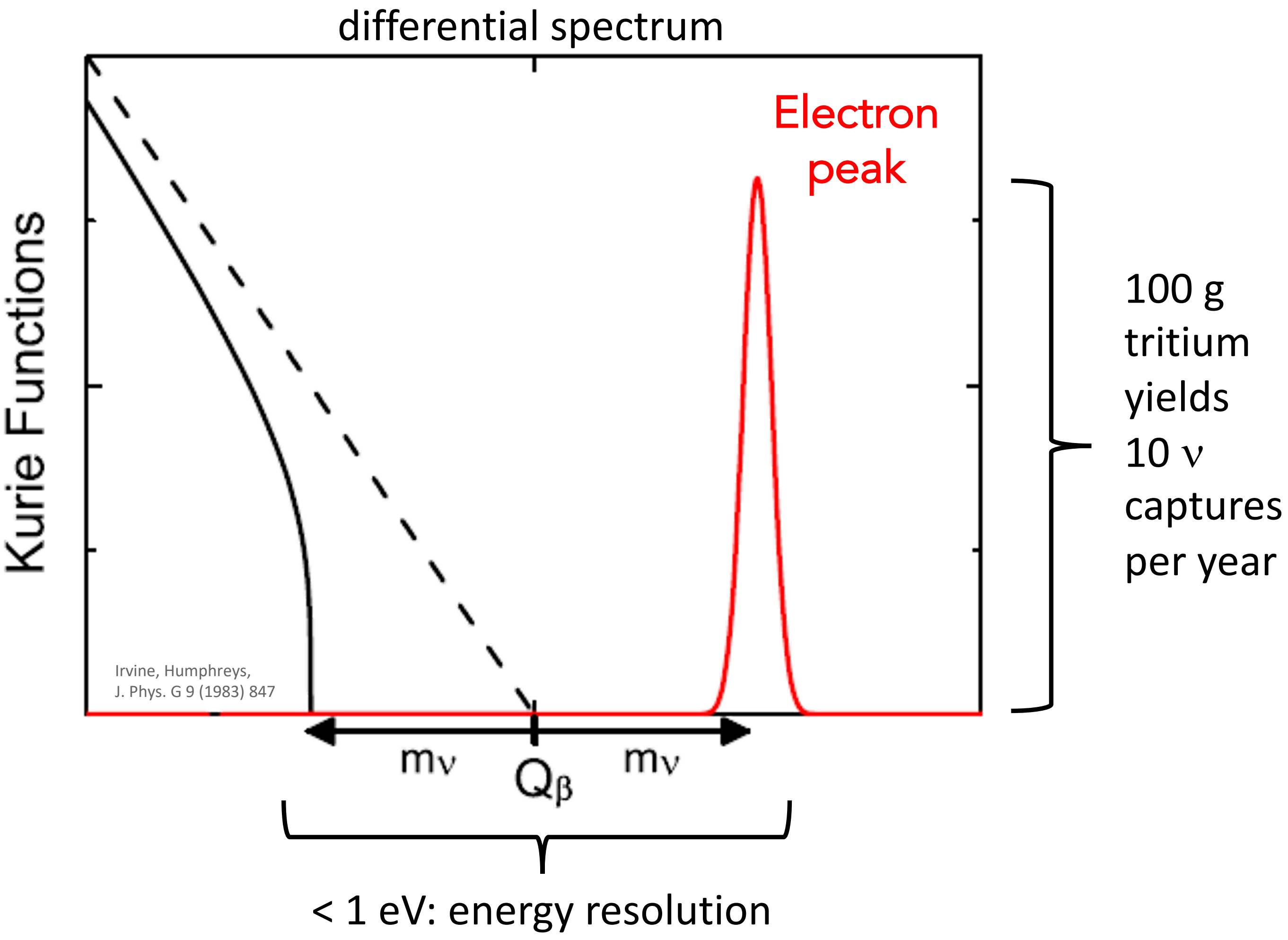
- ✓ meV relic neutrinos…
- ✓ neutrino capture on tritium:

$$^3\mathrm{H} + \nu_e \longrightarrow \ ^3\mathrm{He}^+ + e$$

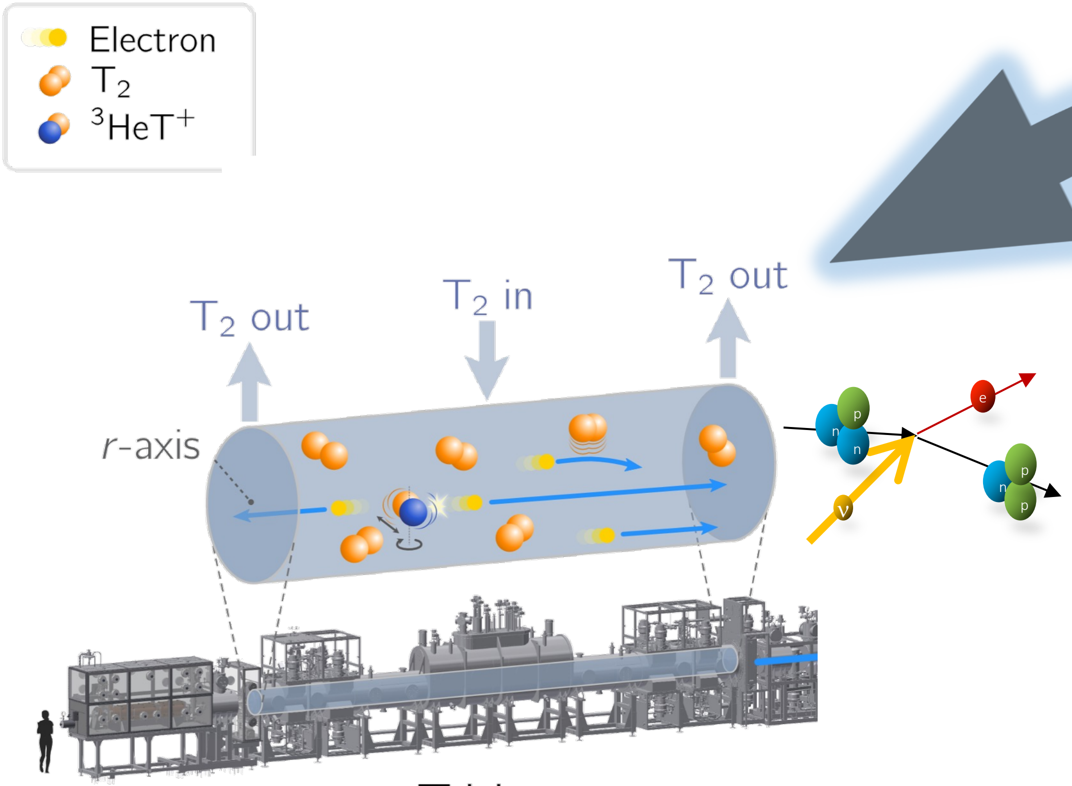
no energy threshold



- ✓ electron peak right above endpoint (in the differential spectrum)



Sensitivity to the overdensity ratio



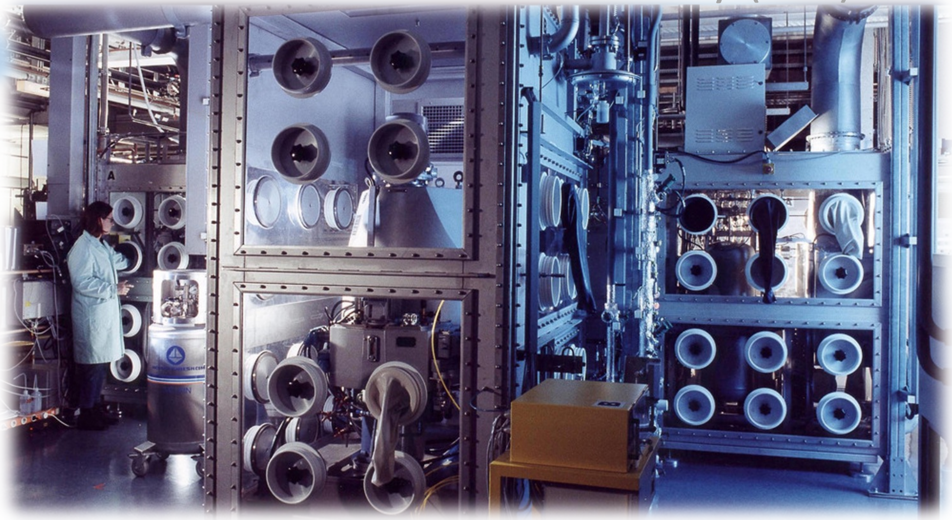
Tritium source

30 µg of tritium

10^{-6} ν capture/year

(depends on Dirac/Majorana nature)

Karlsruhe Tritium Laboratory (TLK)

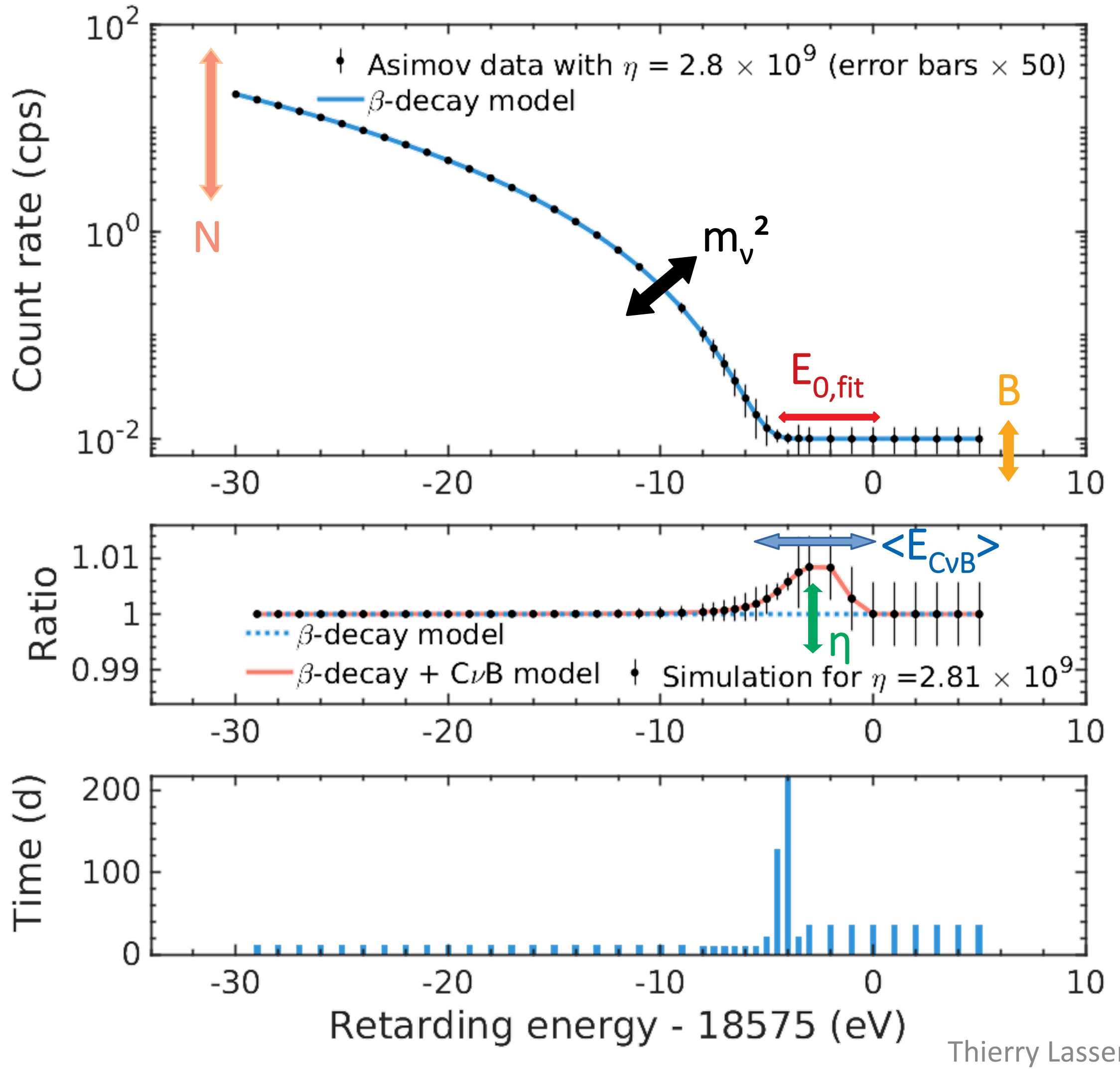


Overall gaseous tritium quantity at TLK: currently 25 g

KATRIN has only the sensitivity to probe large clustering of cosmic neutrinos around the solar system

$\eta = n_\nu / \langle n_\nu \rangle$

Relic neutrino modeling

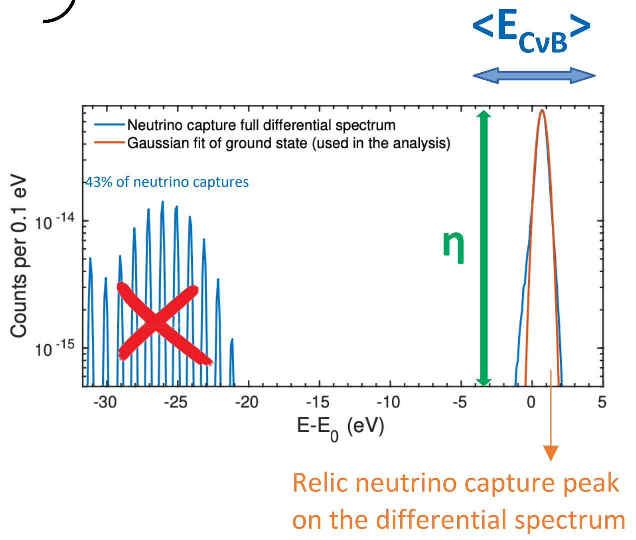


Fit Parameters:

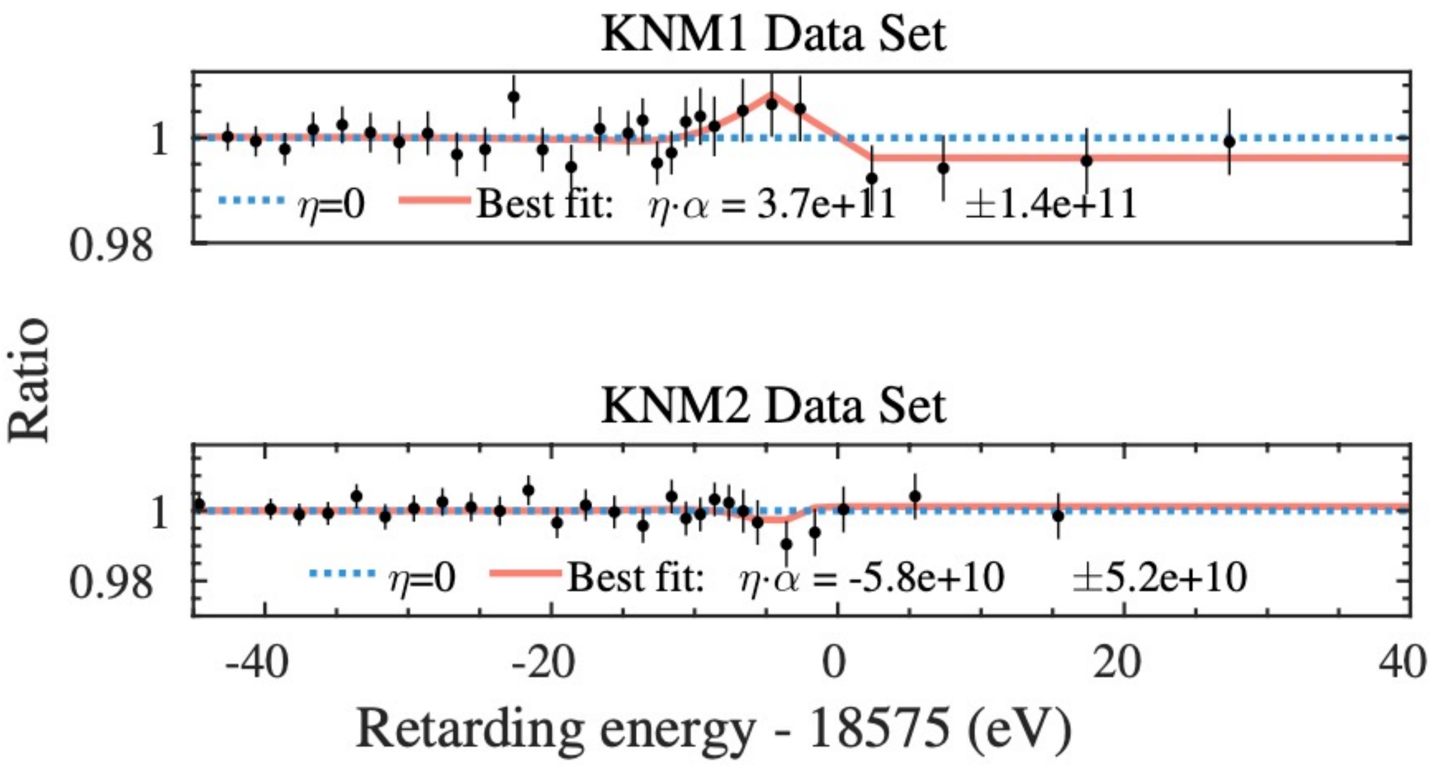
- ✓ m_ν^2 neutrino mass
- ✓ $E_{0,fit}$ endpoint
- ✓ N signal normalization
- ✓ B background rate

Tritium β − decay
+
background

- ✓ η overdensity
- ✓ <$E_{C\nu B}$> peak position



Relic neutrino fit (1st & 2nd campaigns)



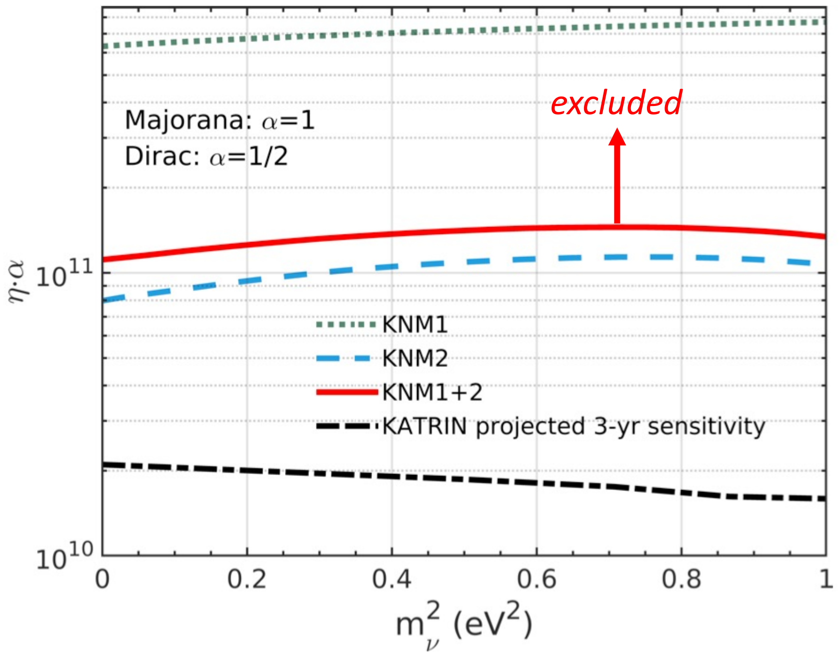
- ✓ KNM1 2019 dataset:
  - ✓ 522 hours
  - ✓ 3.4 μg for capture on tritium
- ✓ KNM2 2019 dataset
  - ✓ 744 hours
  - ✓ 13.0 μg for capture on tritium
- ✓ no evidence for relic neutrino overdensity → upper limits

Relic Neutrino Results (2022)

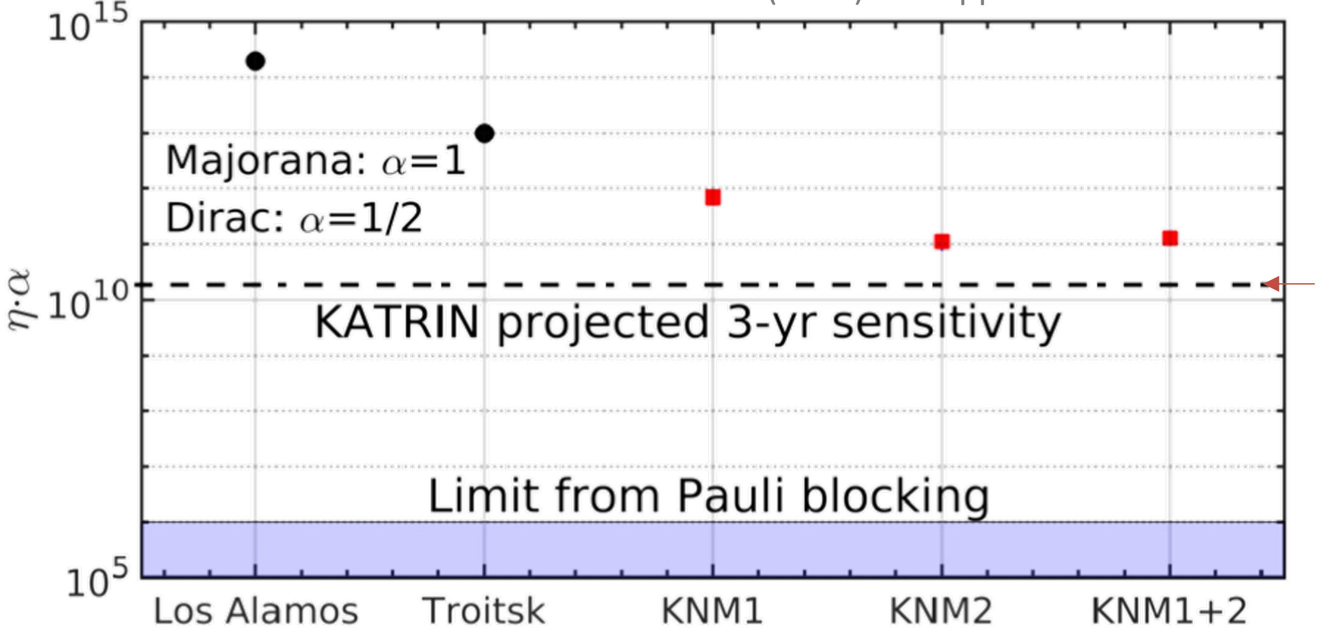
✓ test for <u>large overdensity η</u> of relic neutrinos in our surrounding (based on **1st** and **2nd** campaigns)

✓ $\eta < 1.1 \cdot 10^{11}/\alpha$ at 95% C.L. – the search is statistically limited

✓ improved limit by 2 orders of magnitude compared to previous laboratory limits



KATRIN Collab. arXiv:2202.04587 (2022) – to appear in PRL



KATRIN
1000 days
sensitivity:
$\eta \lesssim 1.4 \cdot 10^{10}/\alpha$

Conclusion & Outlook

- ✓ first **sub-eV neutrino mass limit** from a direct experiment, m_ν < 0.8 eV (90% C.L.). Currently running with various **improvements on background and systematics**
- ✓ targeted sensitivity: m_ν < 0.2-0.3 eV by 2025
- ✓ complementary limits for **eV-scale sterile** neutrinos
- ✓ new limit on **relic neutrino** overdensity
- ✓ search for **keV-scale sterile** neutrinos will follow

CLICK HERE posters: P0191, P0713, P0715, P0169, P0247, P0423, P0513, P0518, P0529, P0532, P0587, P0603, P0714, P0778, P0737

Thank you for
your attention

Working Principle

Windowless Tritium source
- ✓ 30 µg of gaseous T_2
- ✓ 10^{11} T_2 decays/s

Spectrometer
- ✓ electrostatic filter
- ✓ MAC-E filter principle

Detector
- ✓ counts electrons
- ✓ Rate vs HV