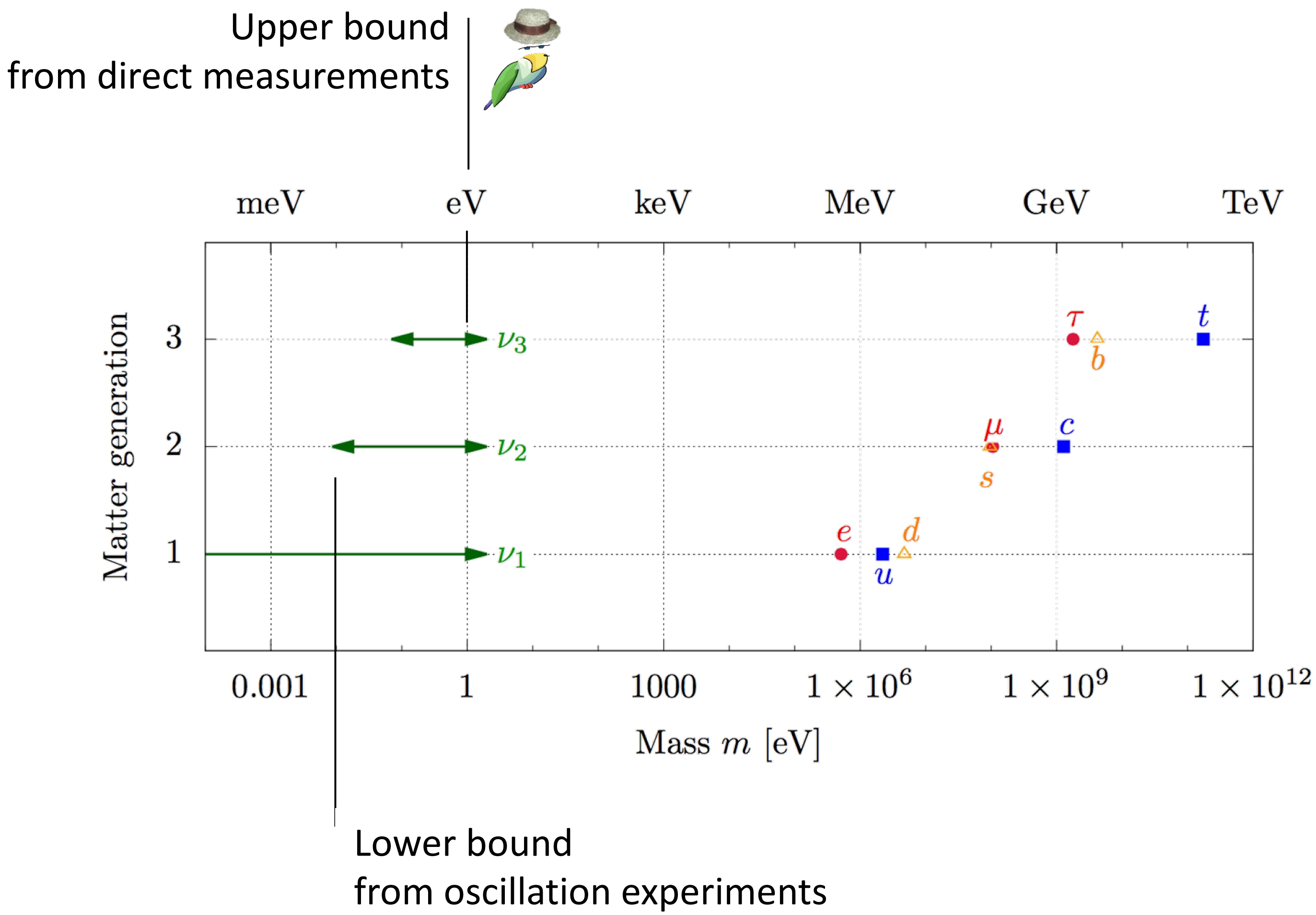
Recent Results from the KATRIN experiment

Thierry Lasserre
on behalf of the KATRIN collaboration

SFB 1258 Neutrinos Dark Matter Messengers

4^{th} World Summit conference (EDSU2022)
La Réunion on the 7^{th}-11^{th} November 2022

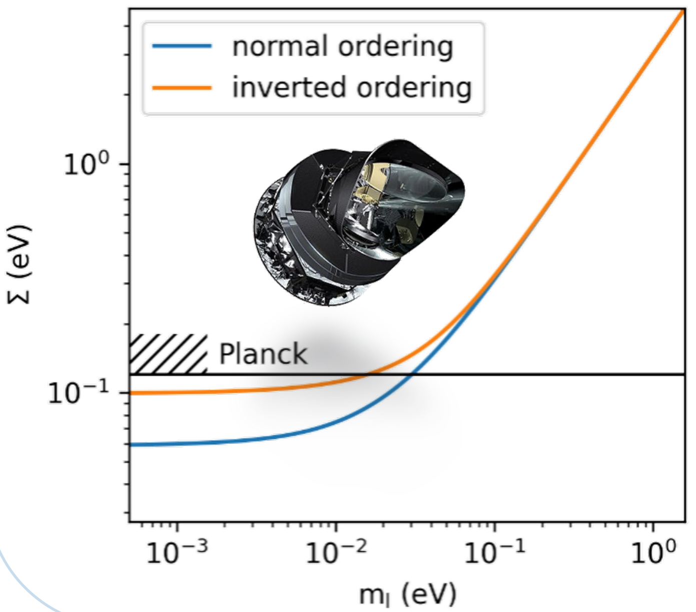
Direct Neutrino Mass Measurement



Neutrino mass(es)

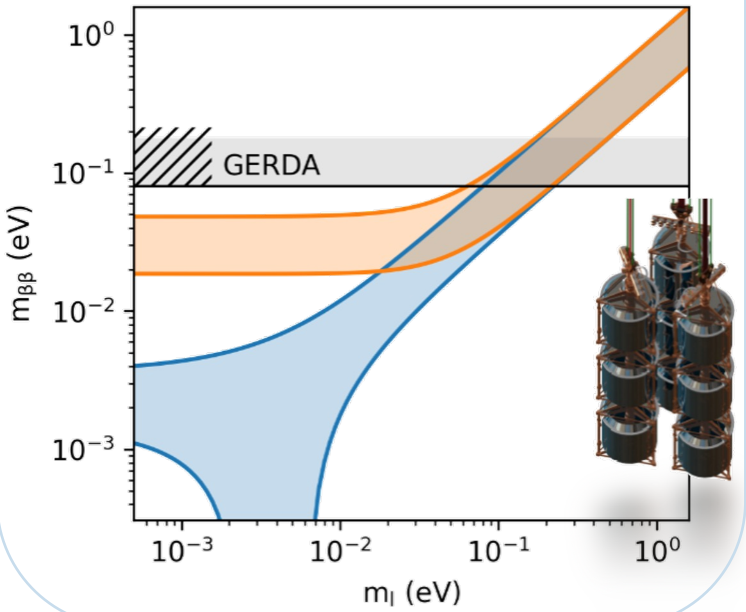
Cosmology

$$\Sigma = \sum_i m_i$$



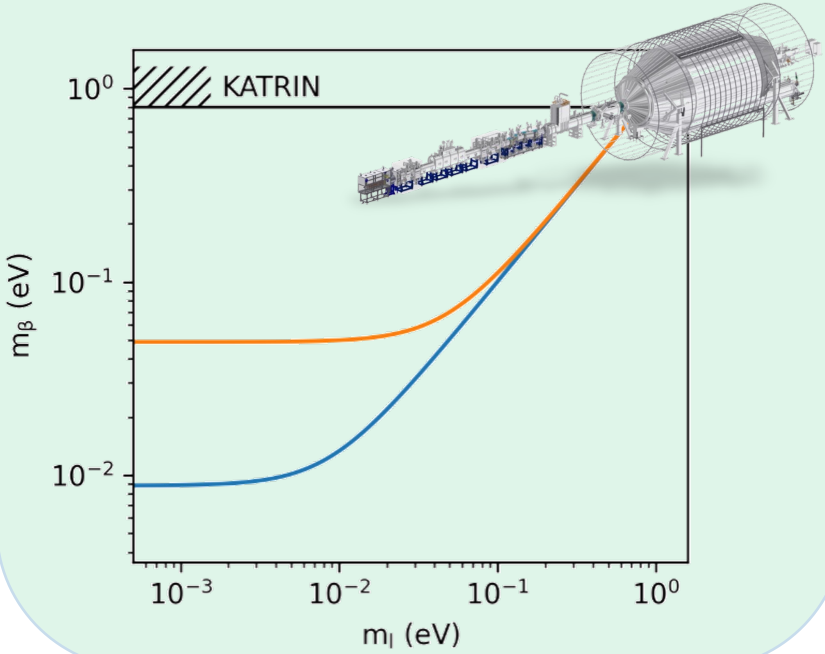
Neutrinoless ßß decay

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

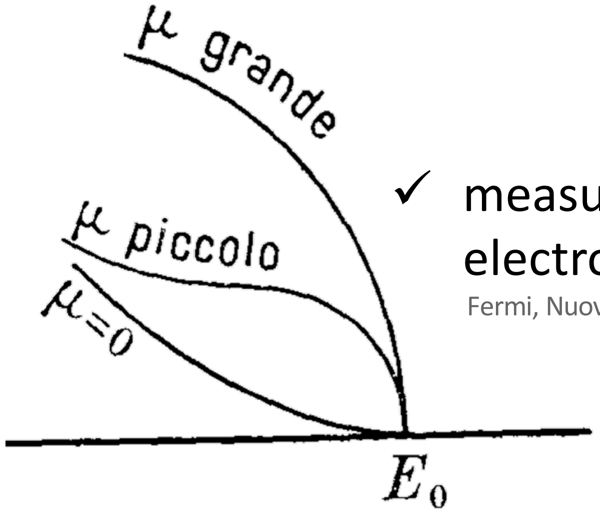


ß-decay kinematics

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

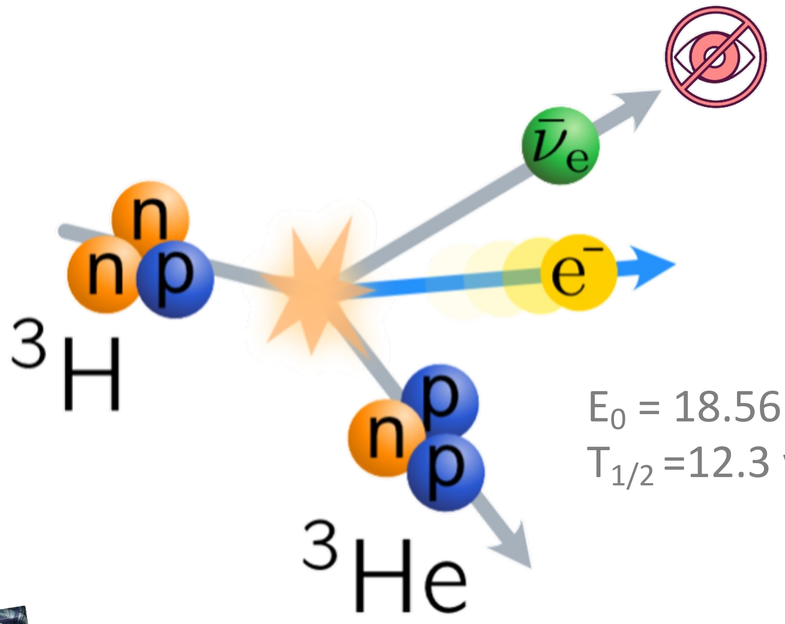


Kinematic neutrino mass measurement



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

- ✓ independent of cosmology
- ✓ independent of neutrino nature

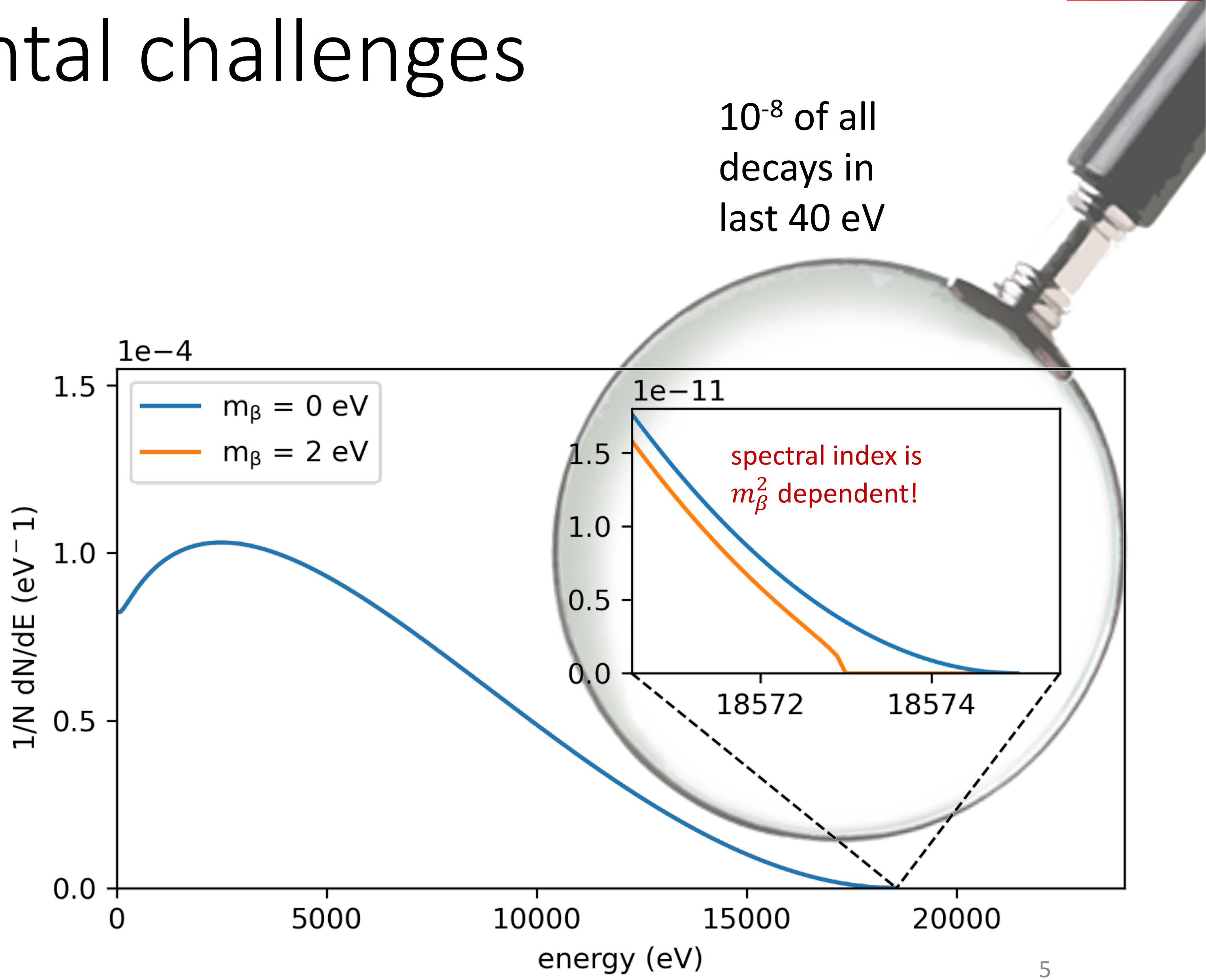


E_0 = 18.56 keV
$T_{1/2}$ =12.3 years

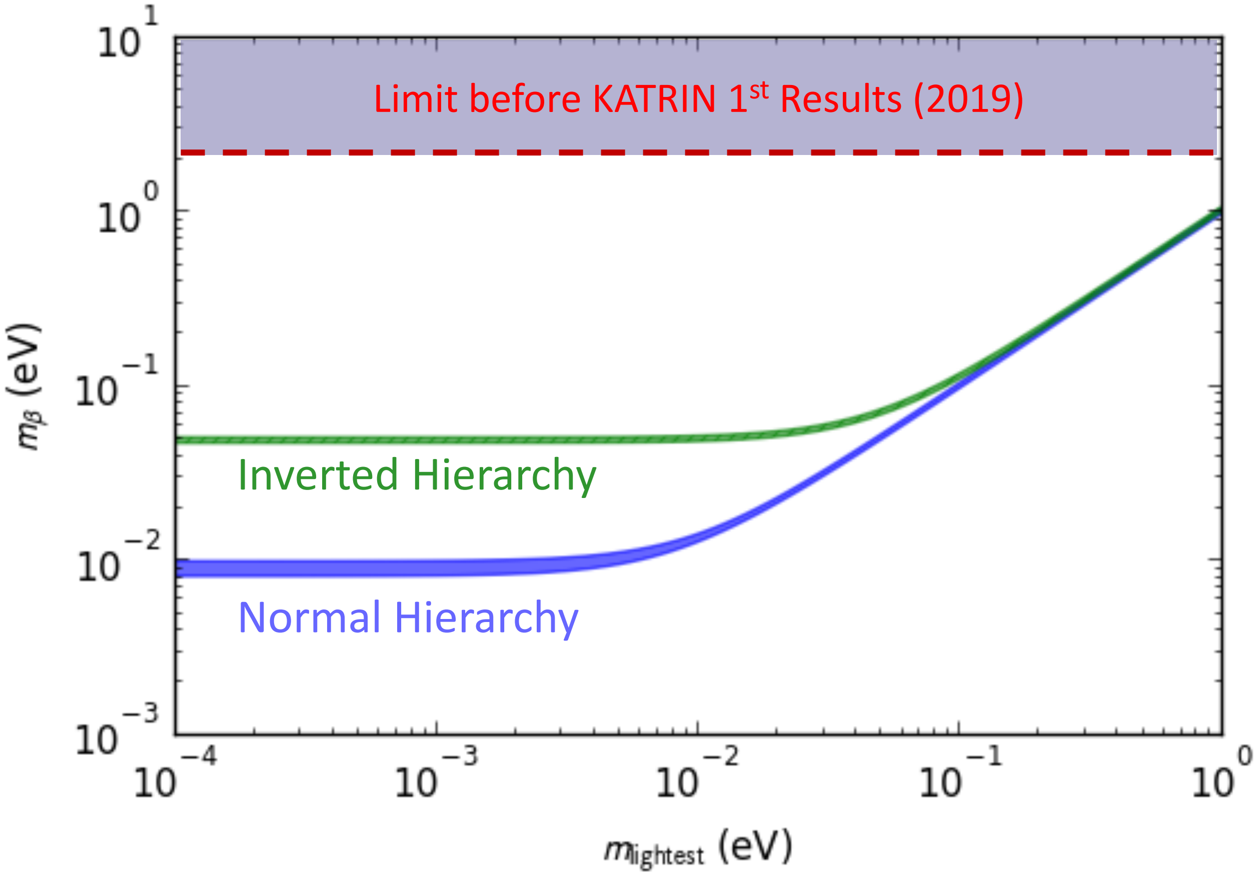
- ✓ based on kinematics and energy conservation
- ✓ m_ν^2 spectral distortion, maximal at endpoint energy E_0
- ✓ incoherent neutrino mass : $m_\nu^2 = \sum_i |U_{ei}|^2 \cdot m_i^2$

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



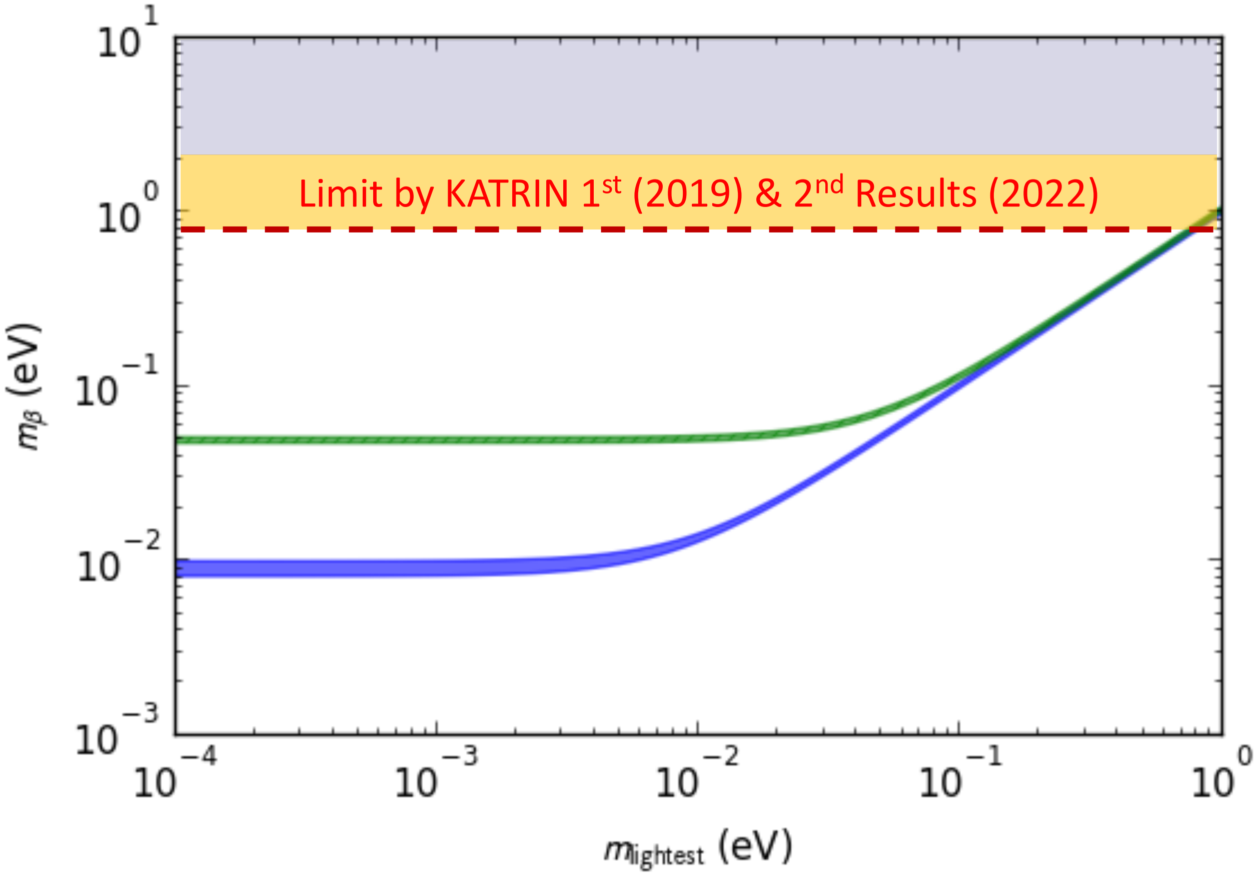
Where did we stand?



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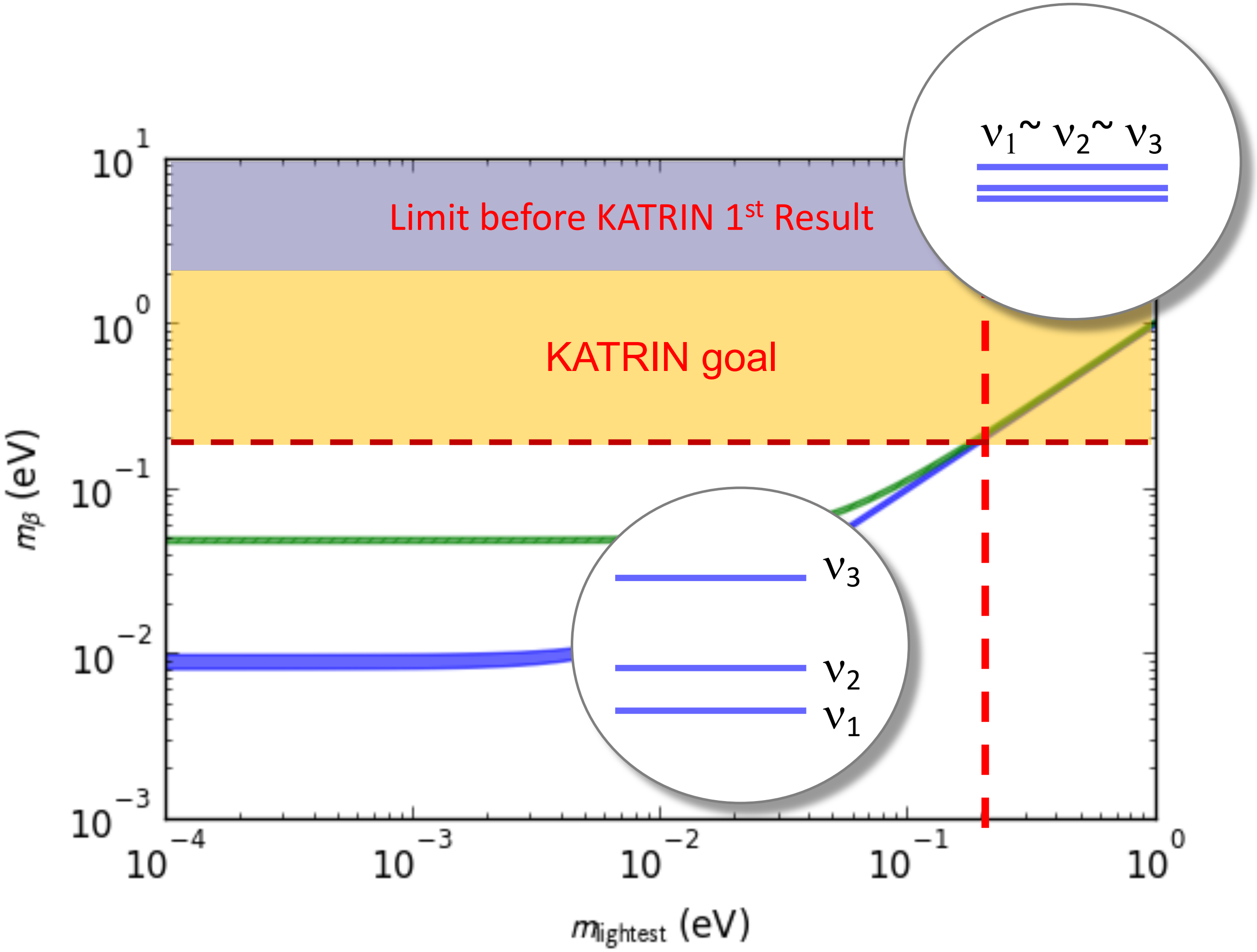
  V. N. Aseev et al., Phys. Rev. D 84 (2011) 112003
  Kraus, C., Bornschein, B., Bornschein, L. et al. Eur. Phys. J. C (2005)
- ✓ intermediate KATRIN results (~5% of the total expected statistics) – This Talk

Where will we stand by 2025?



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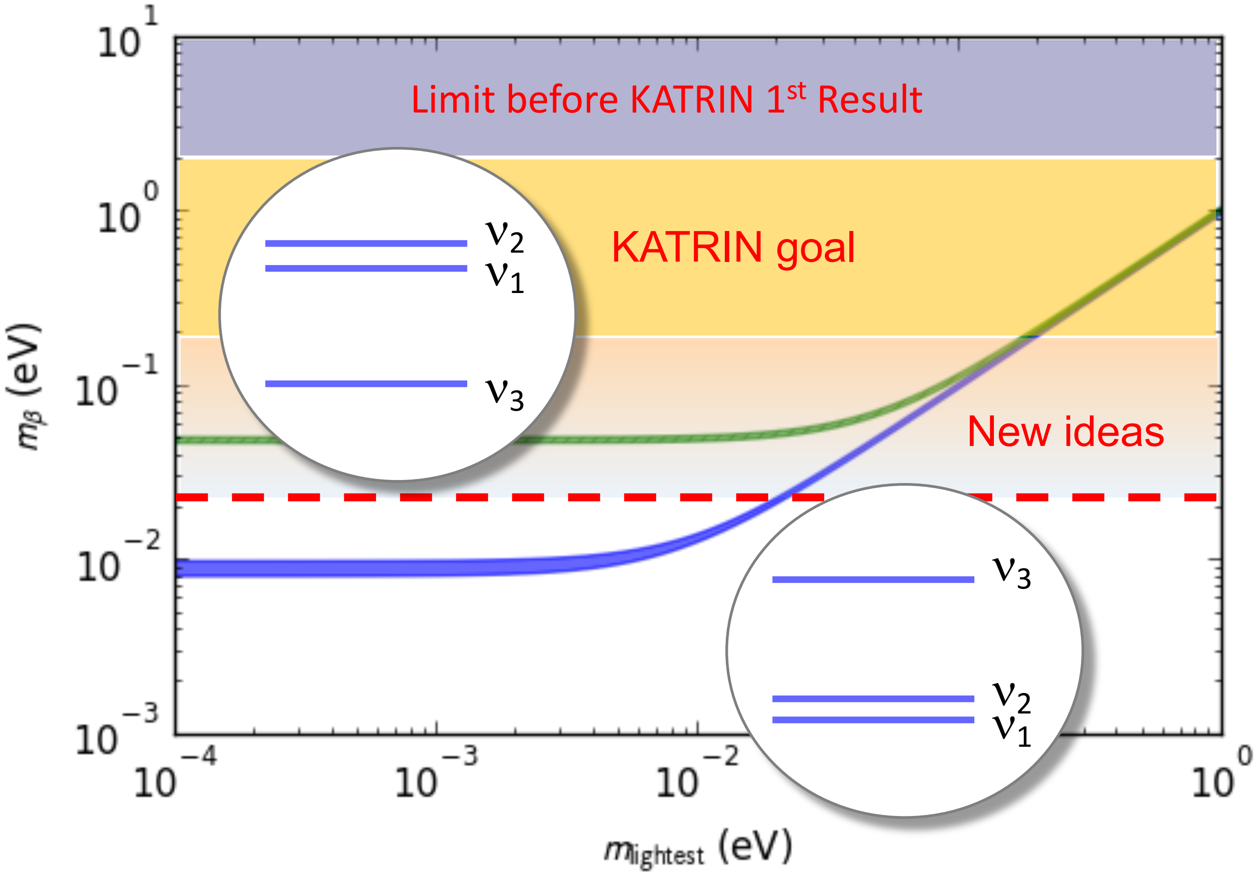
- ✓ intermediate KATRIN results (~5% of the total expected statistics) – This Talk
- ✓ KATRIN goal: distinguish between **degenerate** and **hierarchical** scenario

Where could we stand by 203X?



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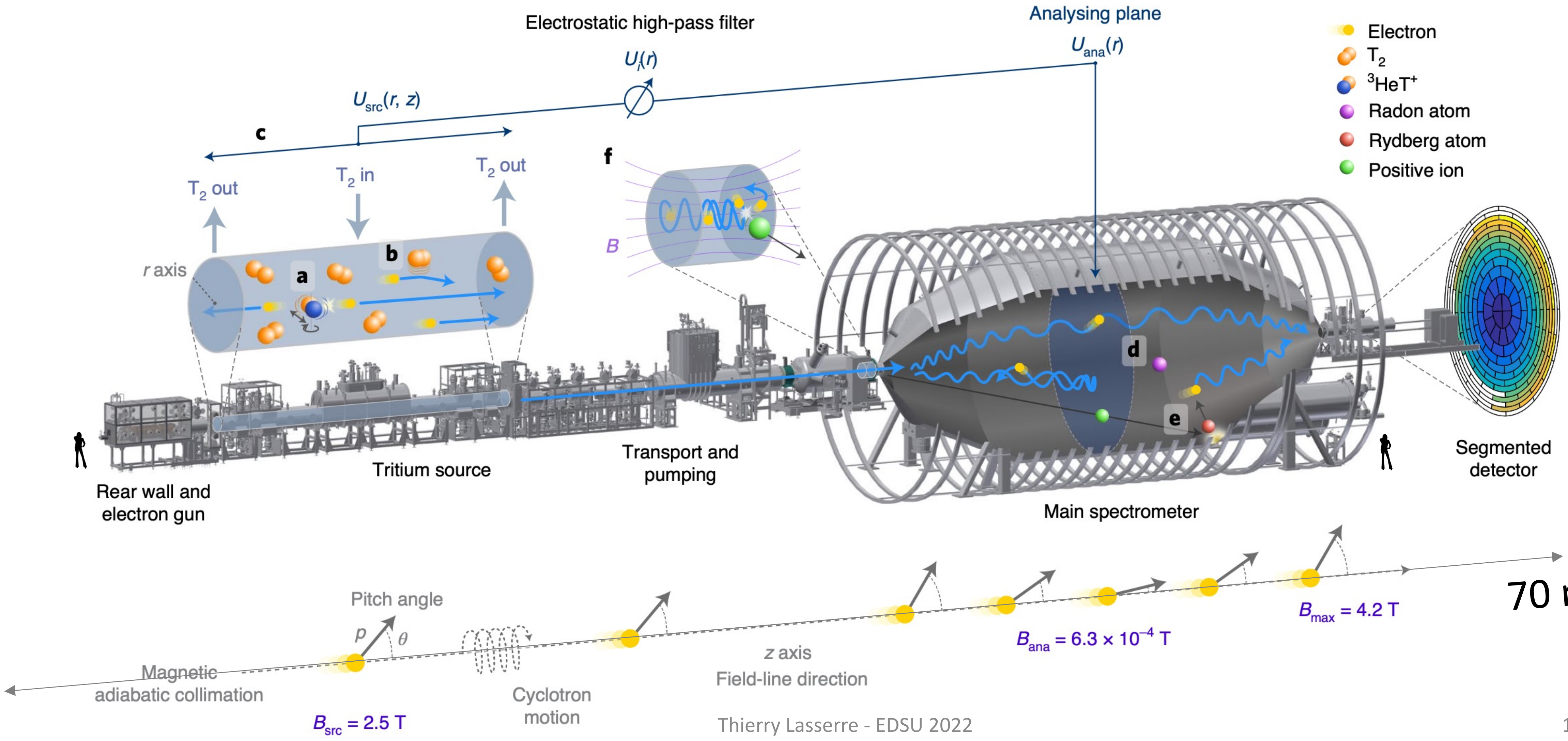
  V. N. Aseev et al., Phys. Rev. D 84 (2011) 112003
  Kraus, C., Bornschein, B., Bornschein, L. et al. Eur. Phys. J. C (2005)
- ✓ intermediate KATRIN results (~5% of the total expected statistics) – This Talk
- ✓ KATRIN goal: distinguish between **degenerate** and **hierarchical** scenario
- ✓ beyond KATRIN: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



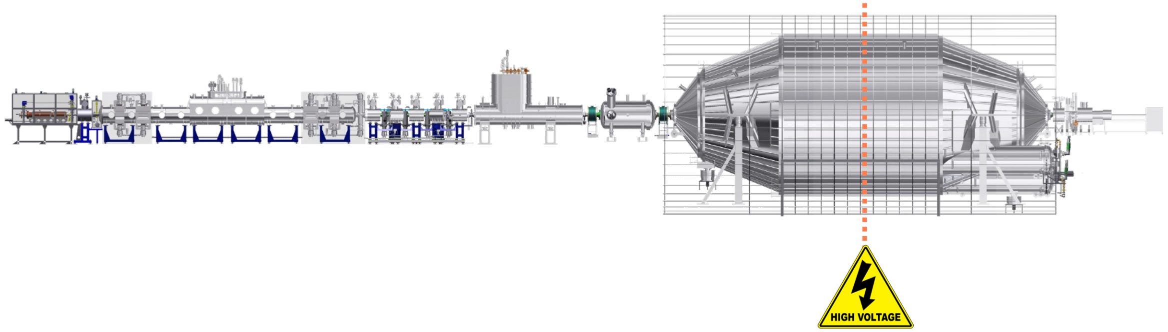
70 m

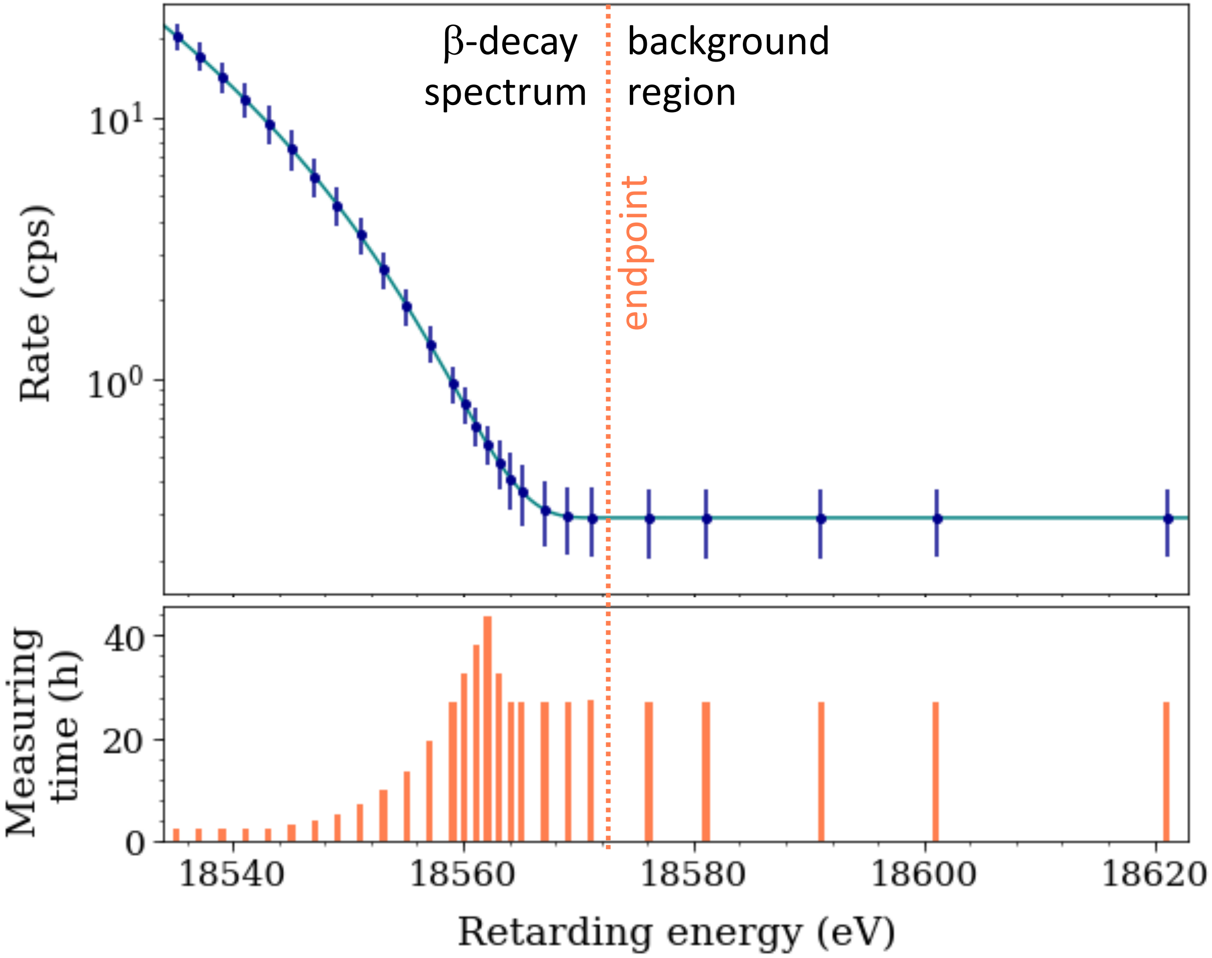
Measurement strategy

Integral spectral measurement !

β-scans illustration:

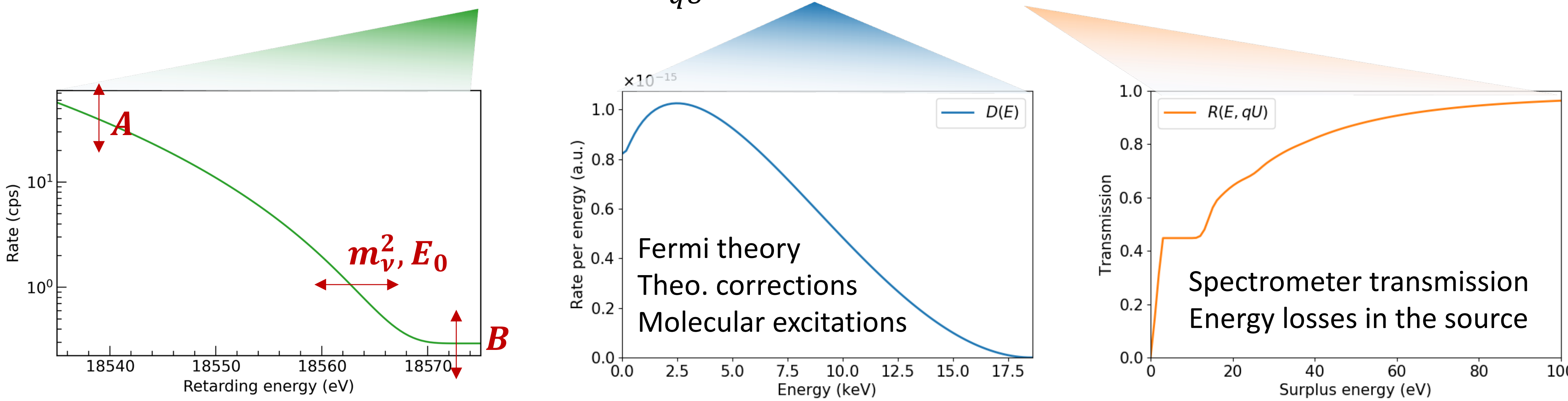
- ✓ scan points: **~30 HV set points**
- ✓ scan interval: **E_0 – 40 eV , E_0 + 135 eV**
- ✓ scan time: **~2 hours**





Analysis strategy

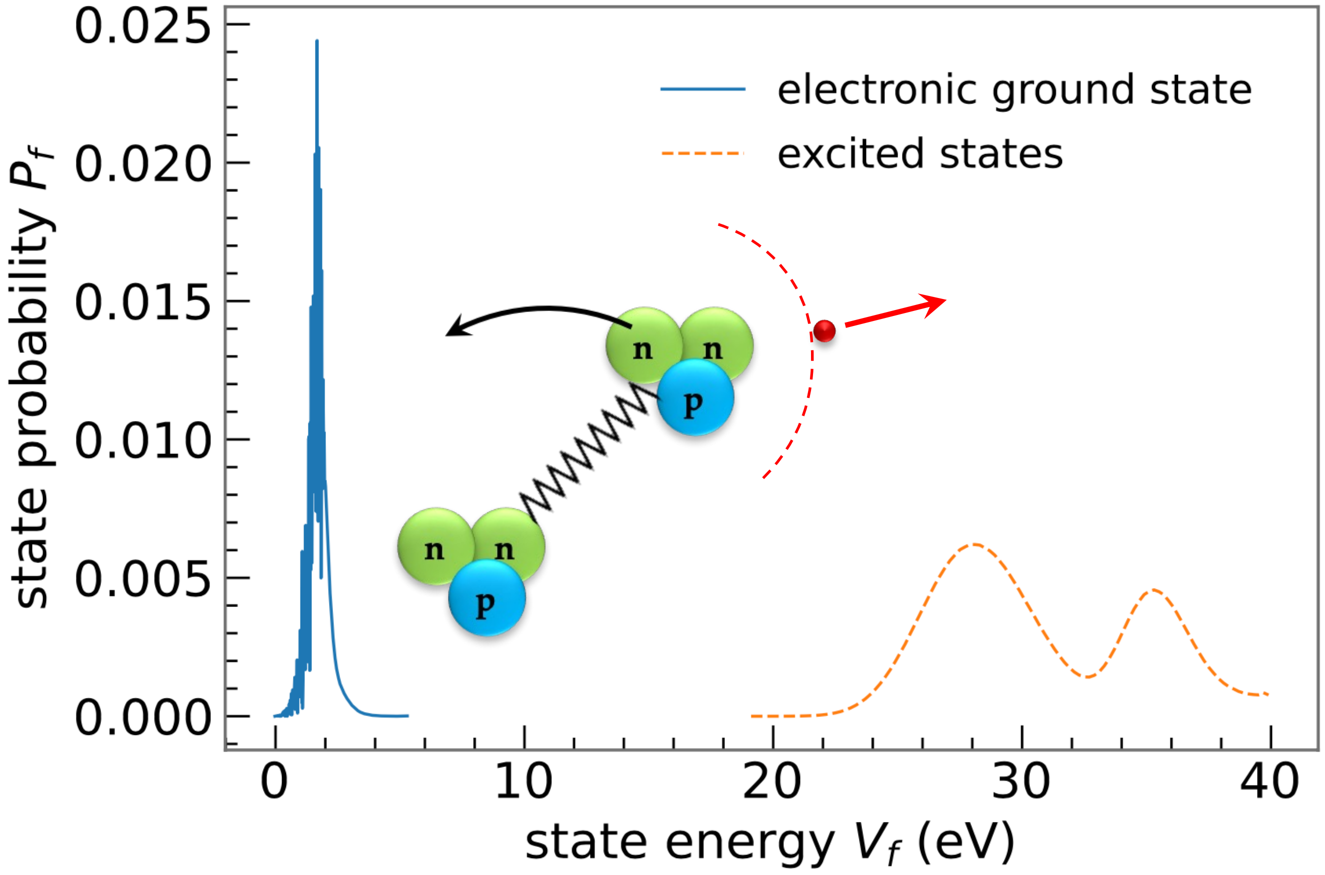
✓ fit of theoretical prediction: $\Gamma(qU) \propto \boldsymbol{A} \cdot \int_{qU}^{\boldsymbol{E_0}} D(E; \boldsymbol{m_\nu^2}, \boldsymbol{E_0}) \cdot R(qU, E)\, dE + \boldsymbol{B}$



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

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

Theoretical input: molecular final states

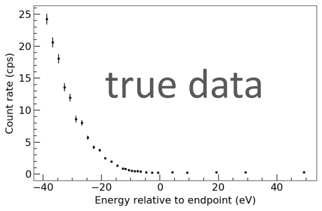


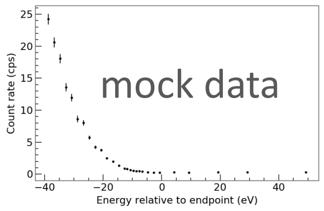
- ✓ β −electron and tritium molecule share the energy released in the decay
- ✓ precise calculation of molecular ground and excited final states
  A. Saenz et al, Phys. Rev. Lett. 84, 242 (2000)
  + updates
- ✓ unavoidable energy broadening
- ✓ no limitation for KATRIN

3-tiered blind analysis

Freeze analysis on MC-twin data

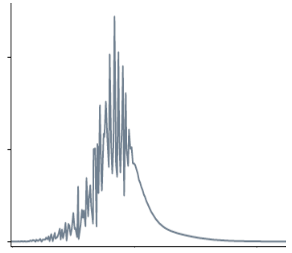
- mock data mimicking each scan

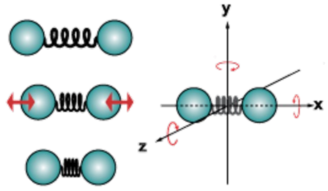




Blinded model

- modified molecular final state dist.

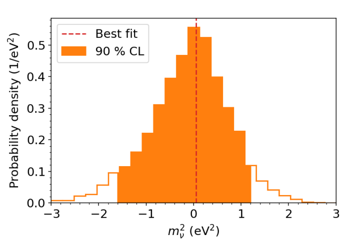


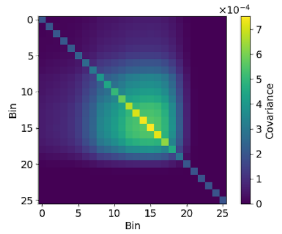


m_ν^2

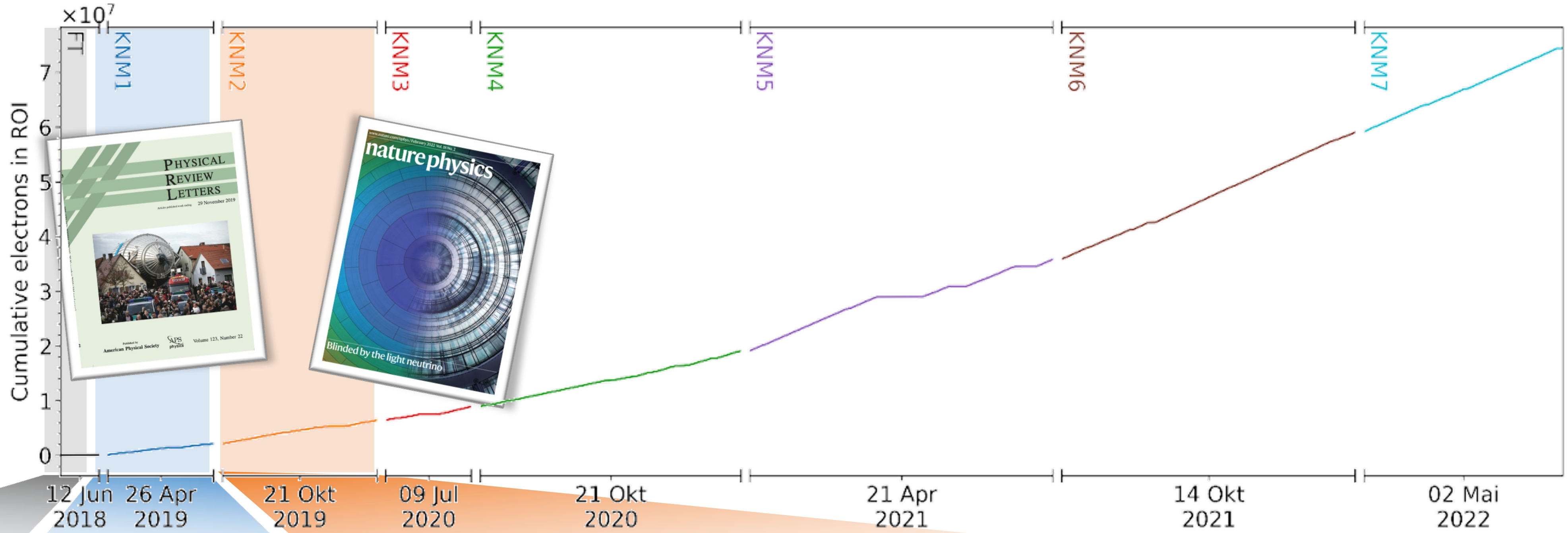
Three independent analysis teams

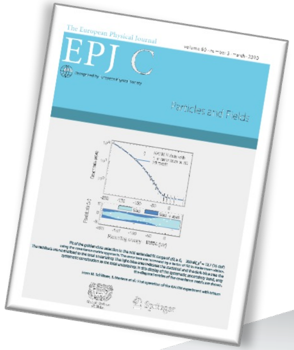
- different strategies and codes





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)

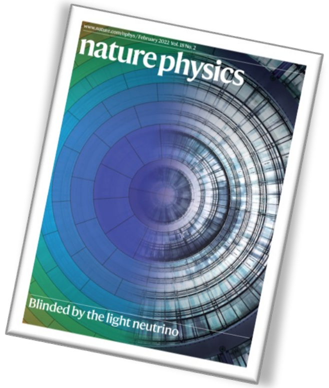
- 1^{st} + 2^{nd} m_ν campaign
- $m_\nu < 0.8$ eV

Nat. Phys. **18,** 160–166 (2022)

light sterile neutrinos

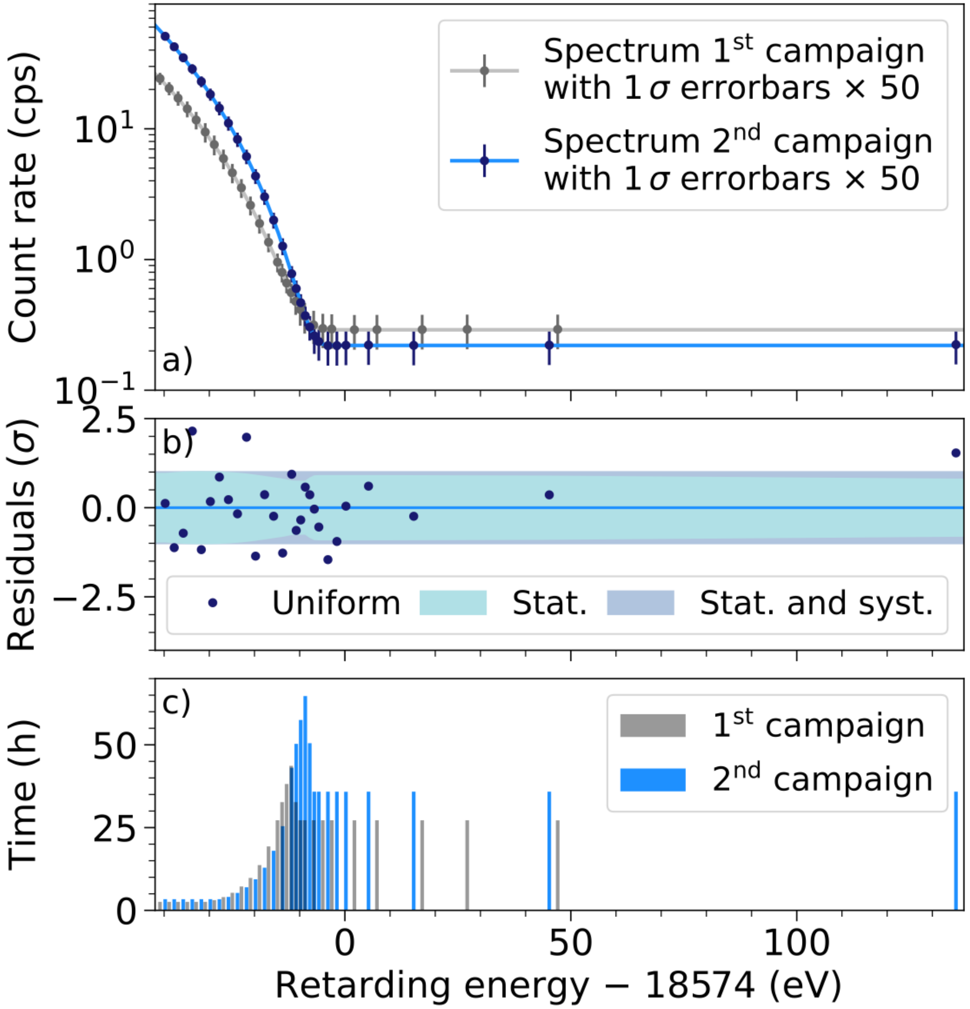
relic neutrinos

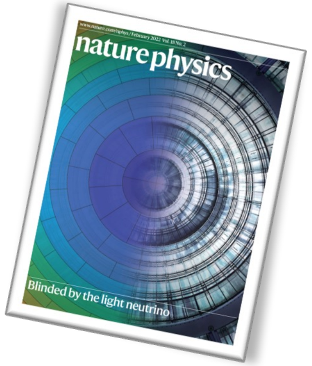
1st & 2nd campaigns figures



	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):

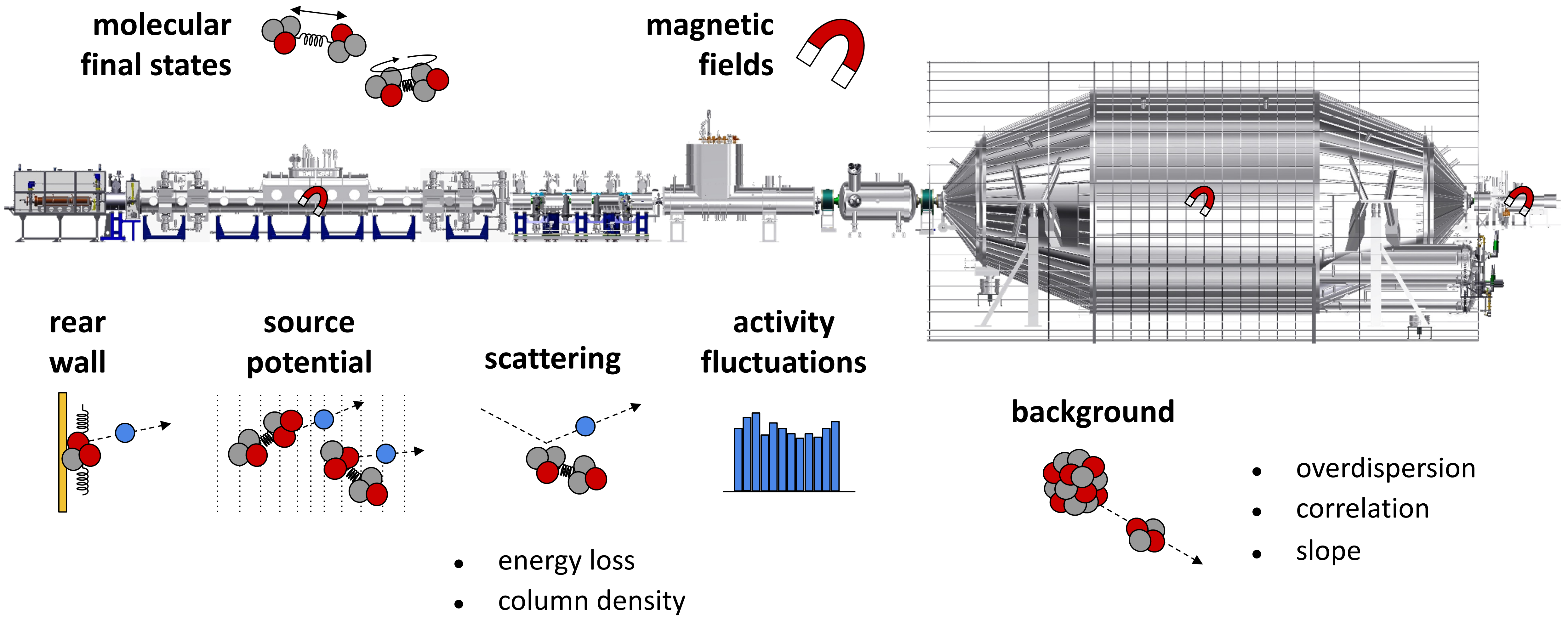
✓ total statistics: 4.3 million events

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

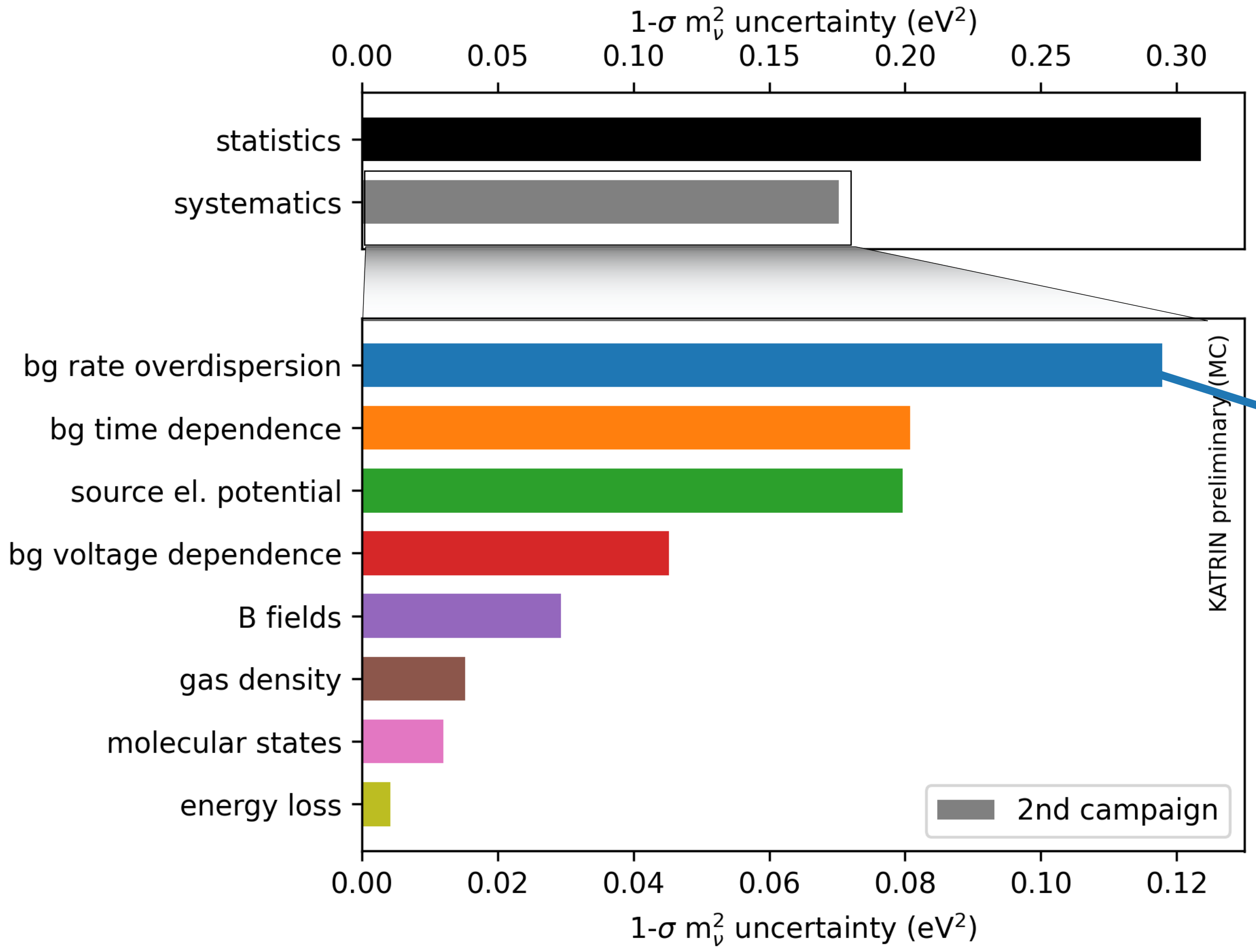
✓ limit: $m_\nu < 0.9$ eV (90% CL)

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

Systematics uncertainties overview

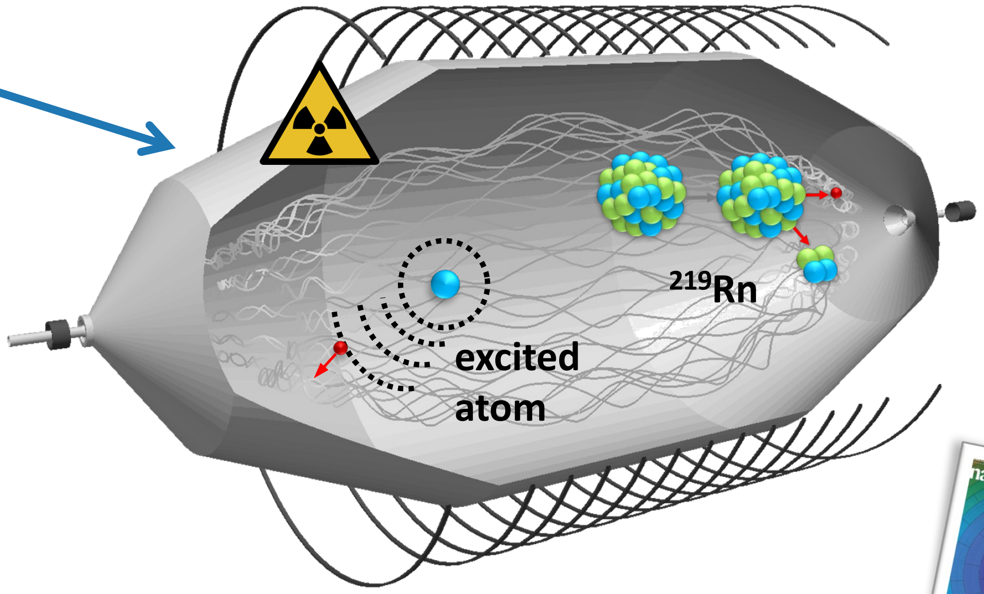


Uncertainty budget in second campaign

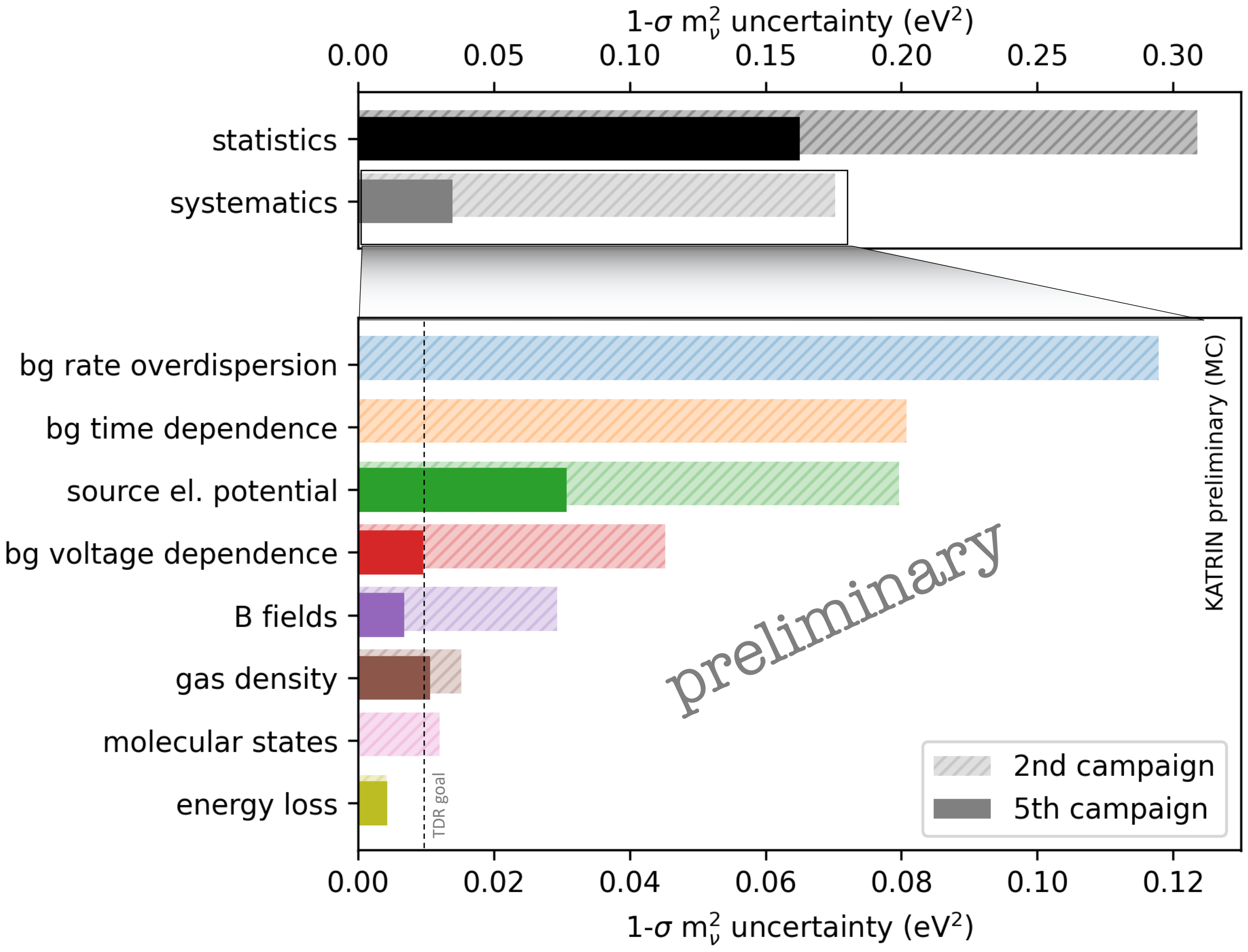


inner surface: $650 m^2$

volume: $1400 m^3$



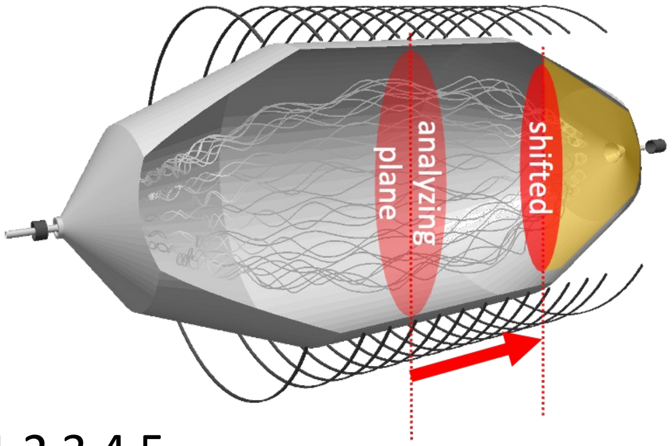
Improvements achieved by 2022



Major improvements:

✓ background reduction (÷2) via new EM field layout

A. Lokhov et al, EPJC 82, 258 (2022)

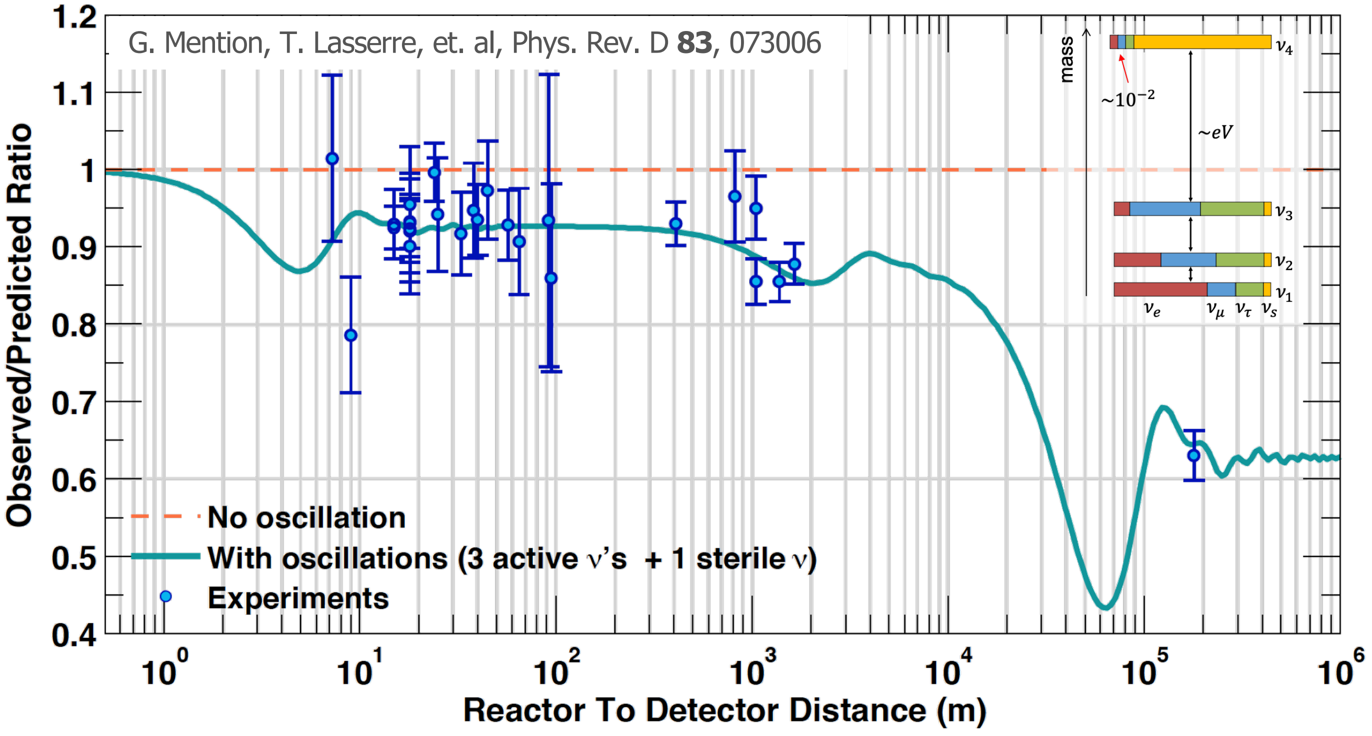


✓ KNM 1 2 3 4 5

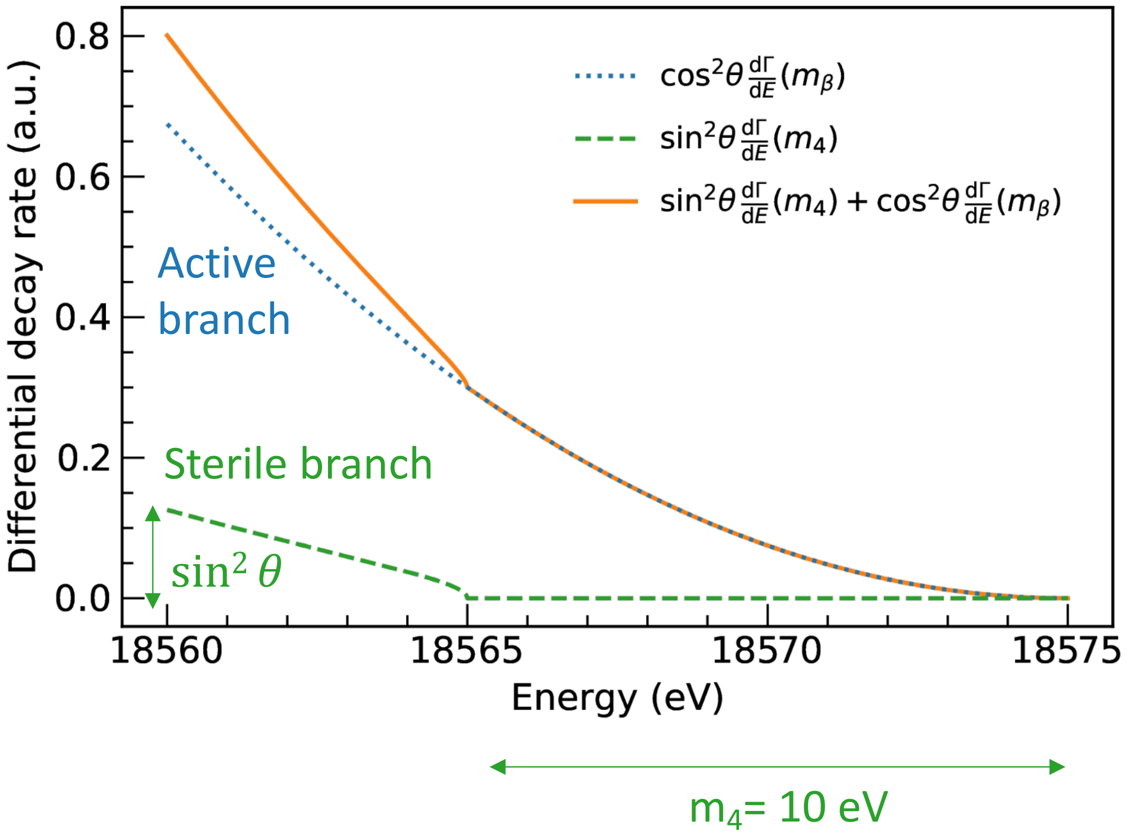
- ✓ 30 millions of electrons in ROI
- ✓ 0.5 eV sensitivity
- ✓ New results in 2023

Search for eV-scale sterile neutrinos

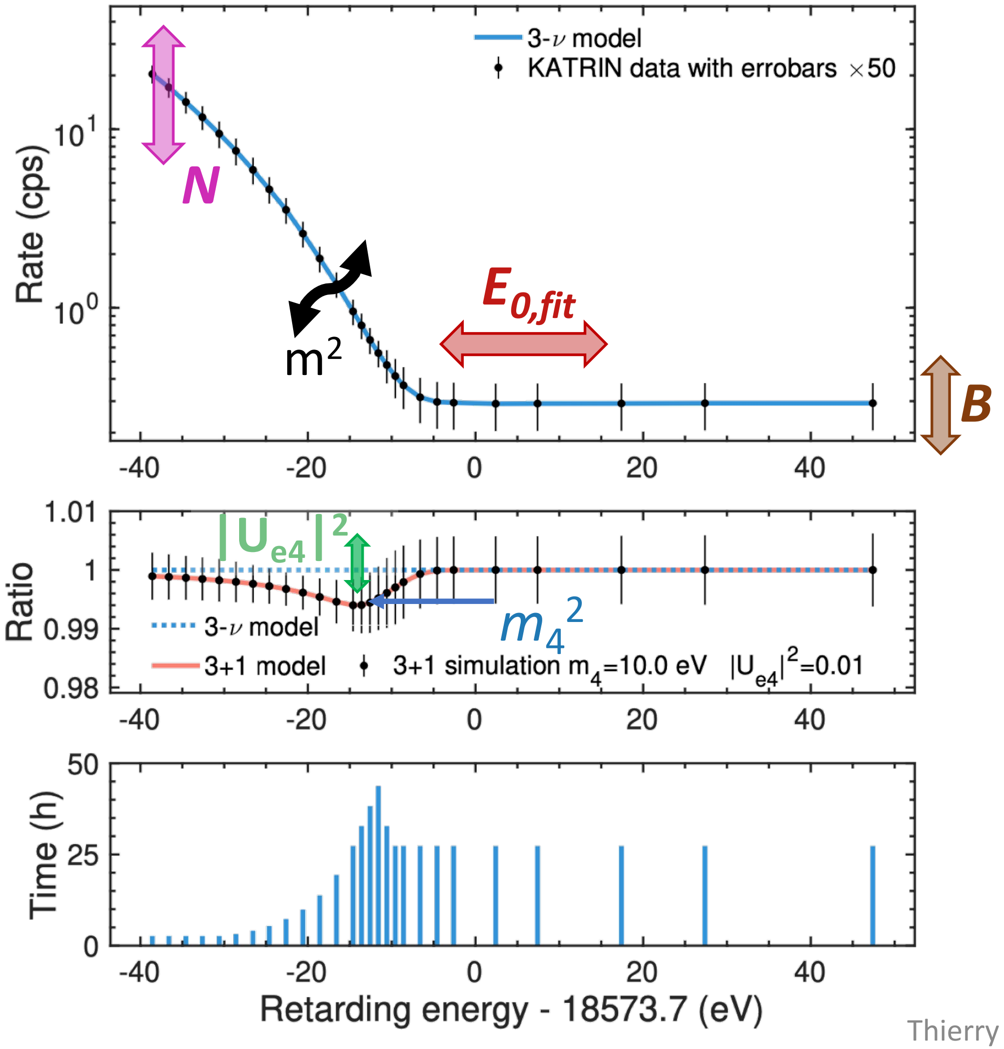
Anomalies in oscillation experiments



Expected signature in KATRIN



Sterile neutrino modeling

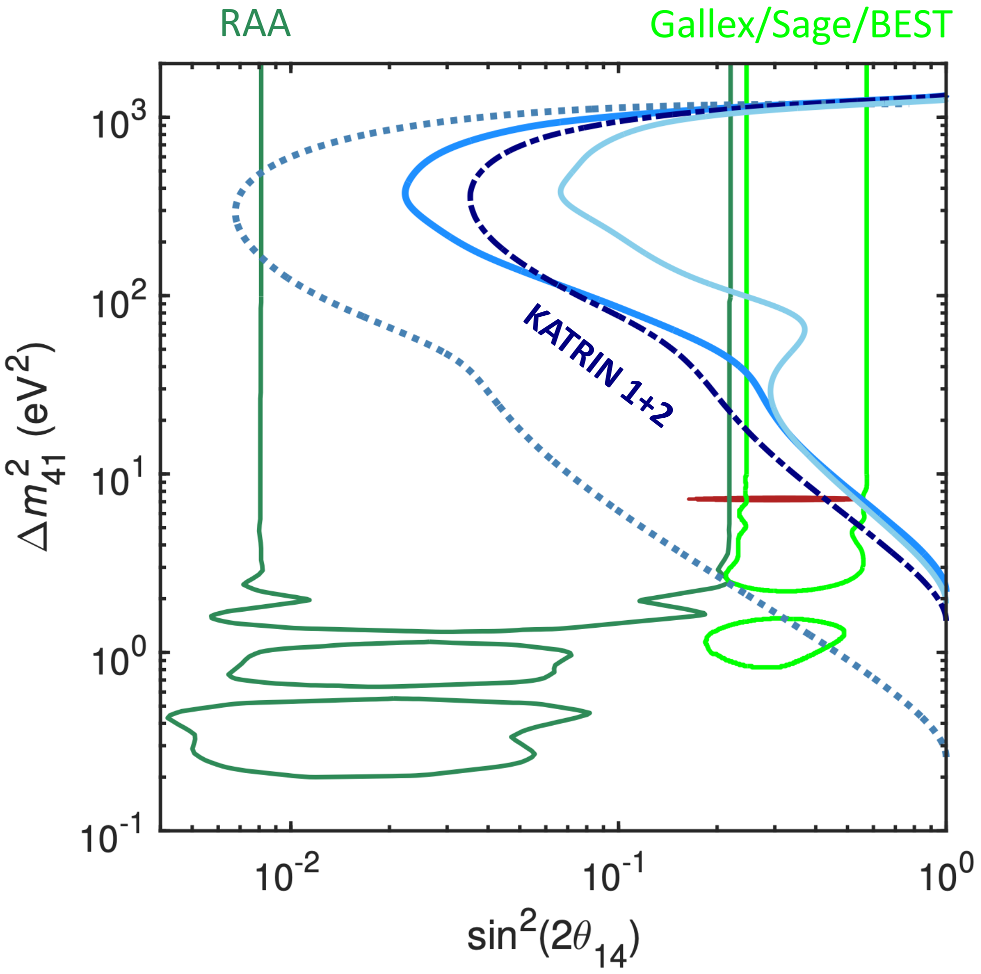


$$\frac{d\Gamma}{dE} = \underbrace{\left(1-|U_{e4}|^2\right)\frac{d\Gamma}{dE}(m_\beta^2)}_{\text{light neutrino}} + \underbrace{|U_{e4}|^2\frac{d\Gamma}{dE}(m_4^2)}_{\text{heavy neutrino}}$$

<u>Fit Parameters:</u>

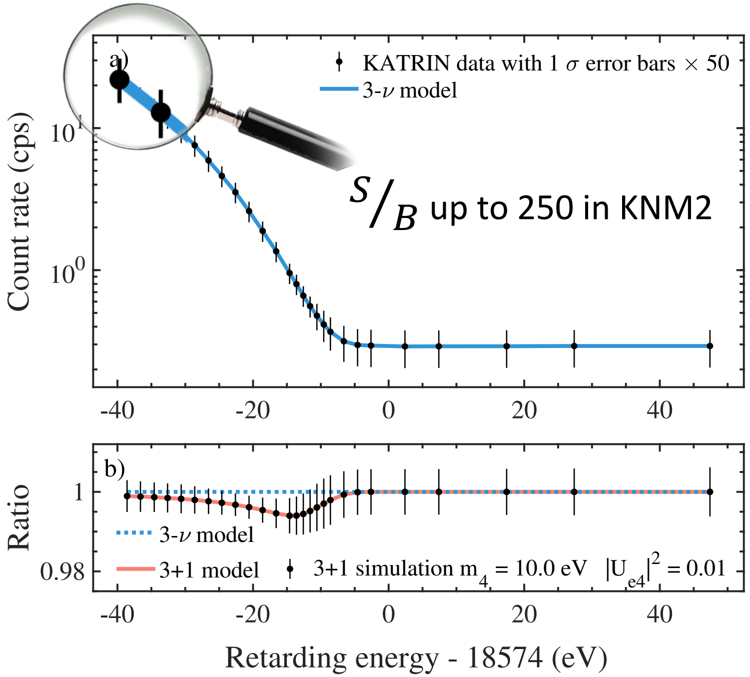
m^2	neutrino mass (fixed/free/constrained)
$E_{0,fit}$	endpoint
N	signal normalization
B	background rate
$m_4{}^2$	4th neutrino mass
$\lvert U_{e4}\rvert^2$	4th neutrino mixing

Comparison to oscillation experiments

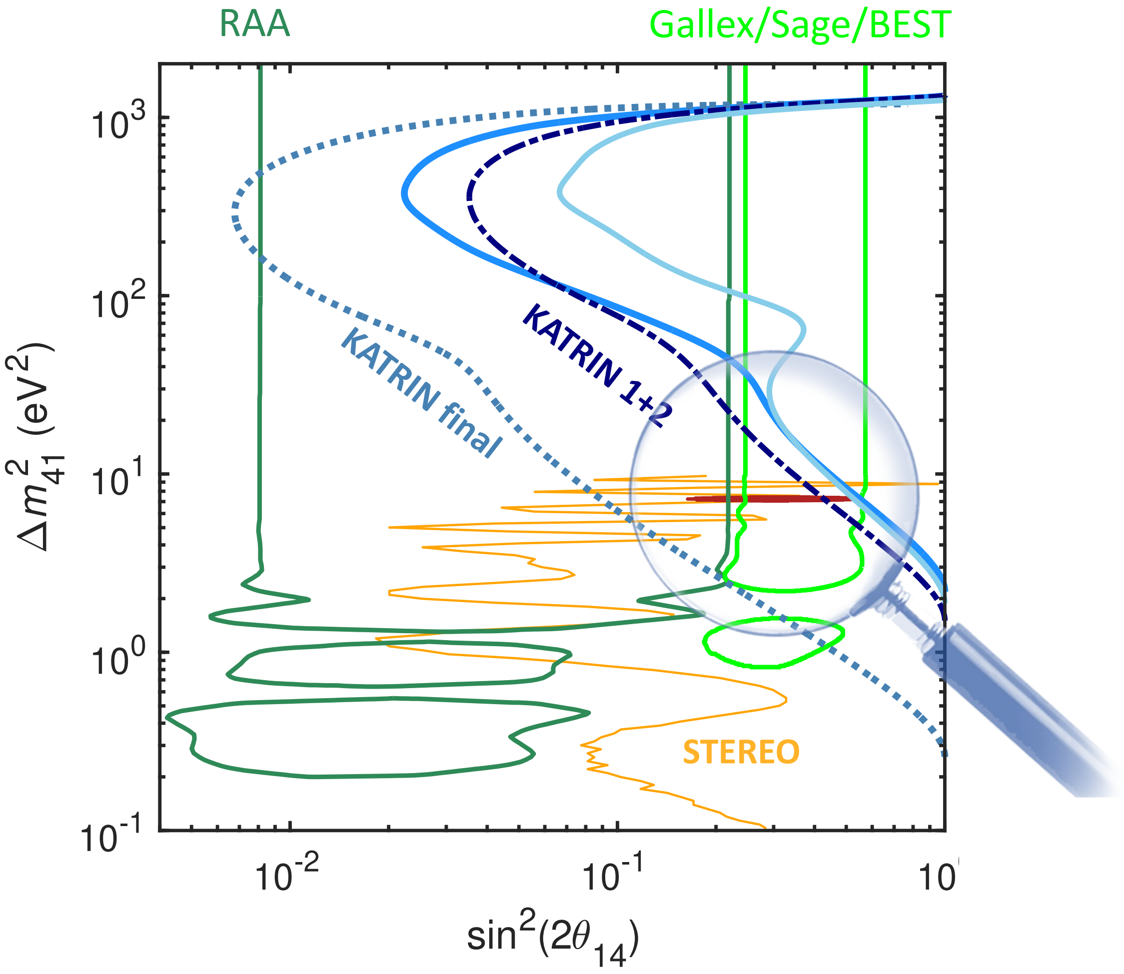


- ✓ tackling short baseline oscillation anomalies from a different perspective (shape-only search)
- ✓ start probing interesting parameter space

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



Sterile neutrino search in KATRIN



✓ 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)

✓ 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
...

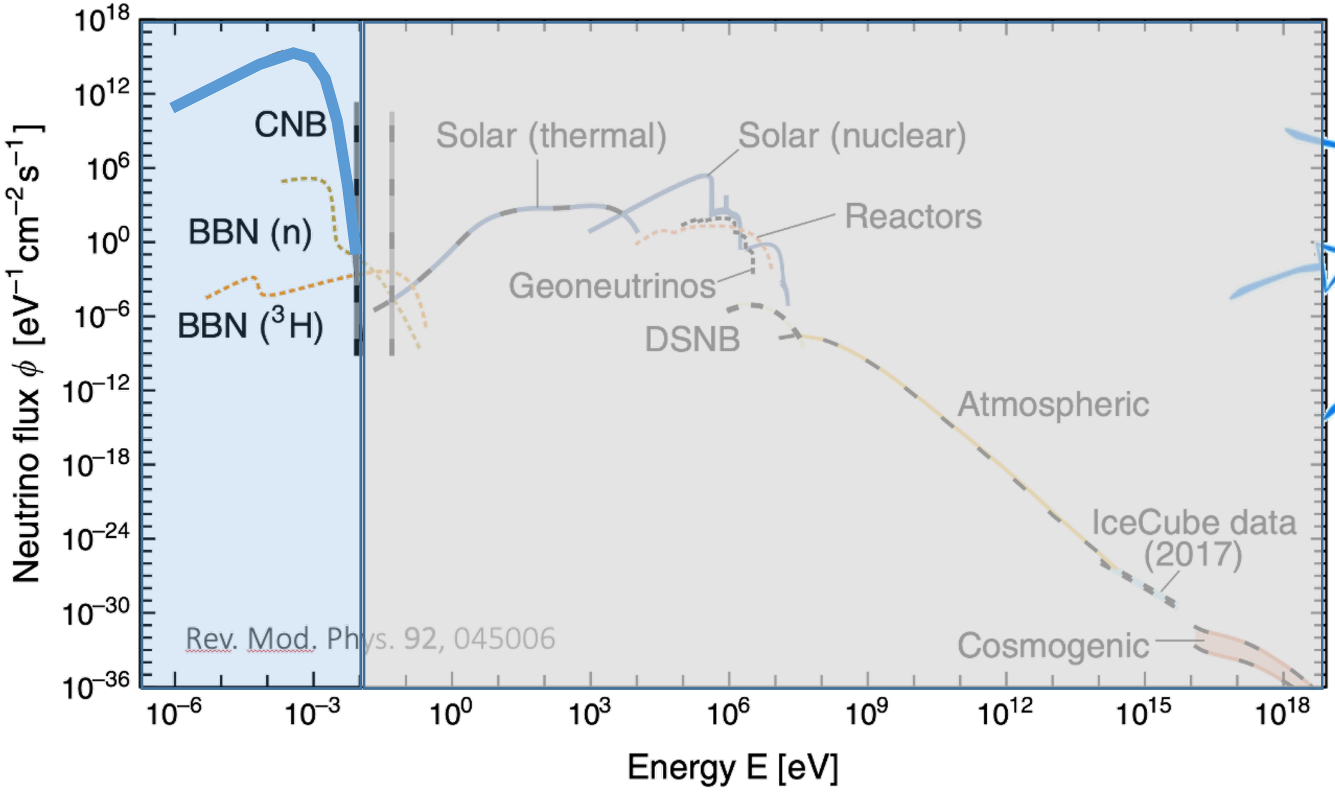
✓ KATRIN will soon probe the favored regions at $\Delta m^2 > 5\ \text{eV}^2$

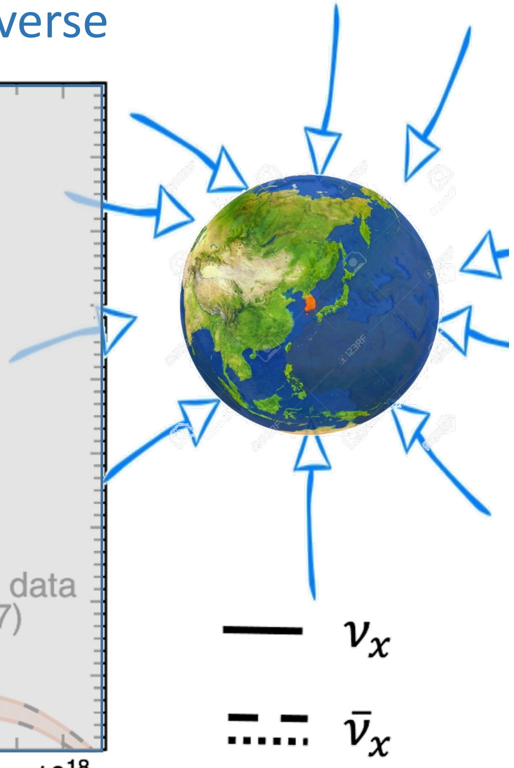
Cosmic neutrino background overdensity

✓ in the very early Universe, ν's are in thermal equilibrium with matter/radiation

✓ Big-Bang + 1 sec: ν decouple ⟶ Cosmic Neutrino Background emission

340 relic neutrinos of all species /cm^3 in today's Universe



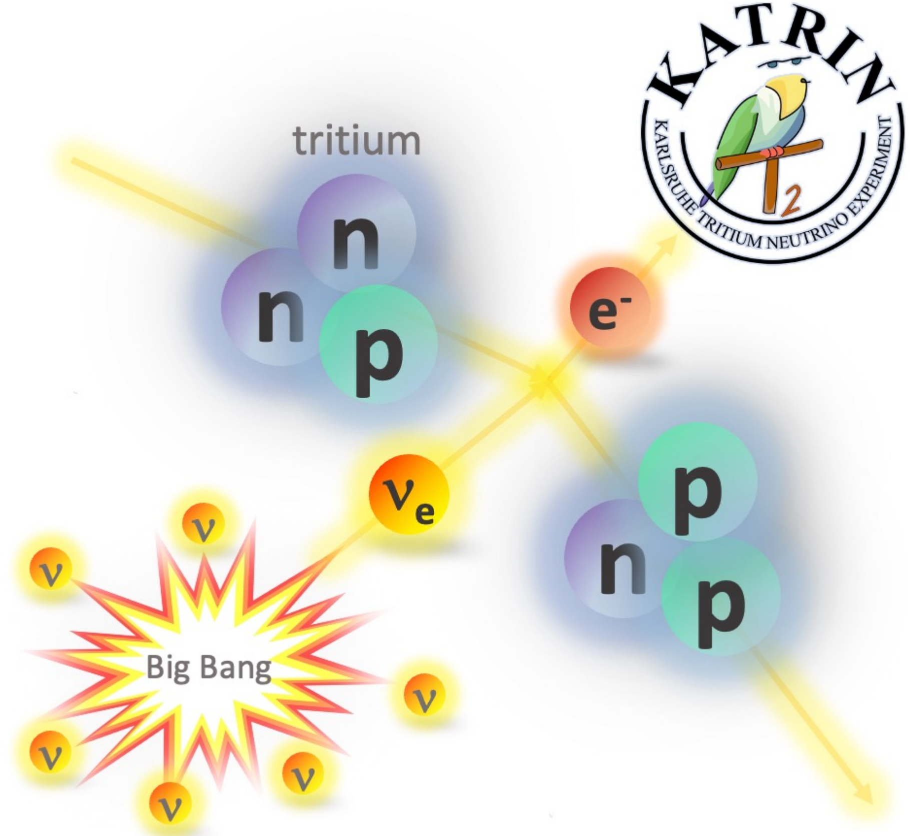


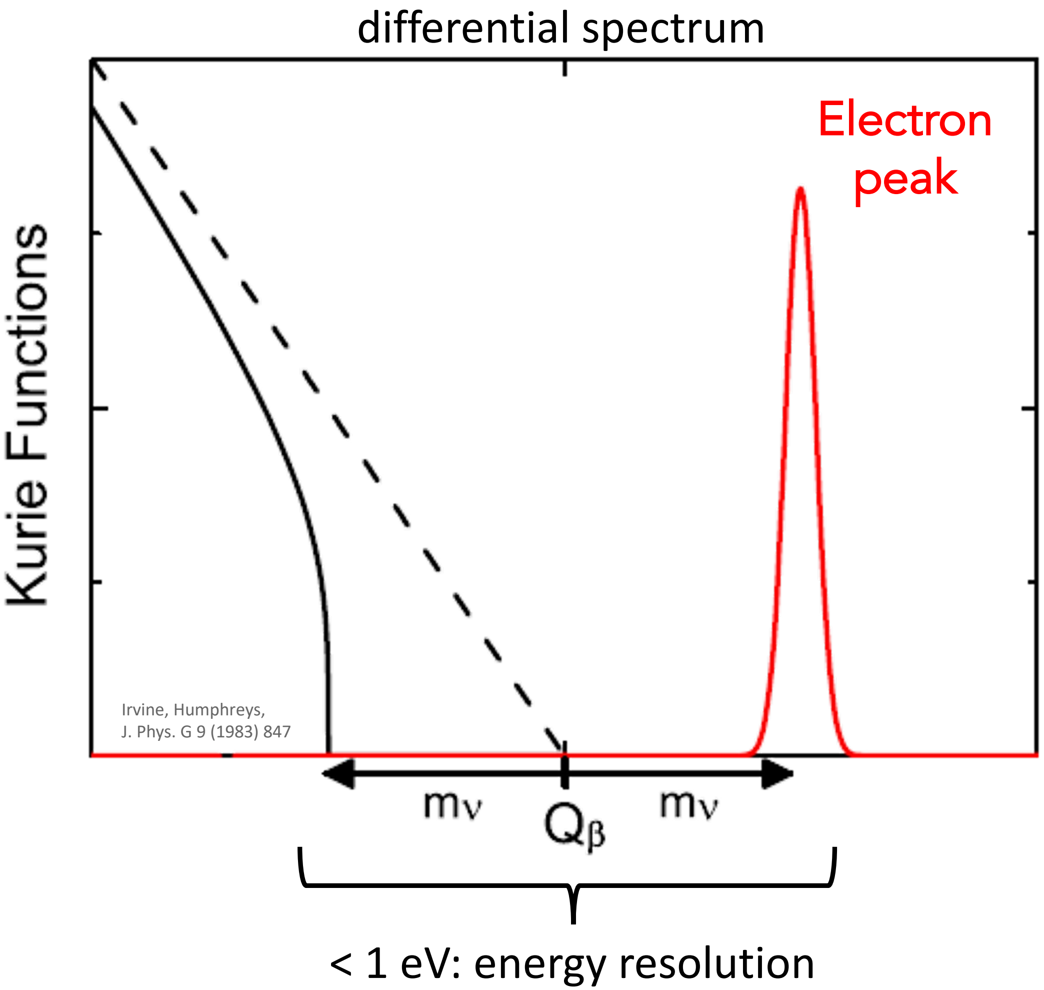
KATRIN restricts the maximum overdensity ratio η of relic neutrinos on Earth

Thresholdless meV-ν capture on Tritium

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

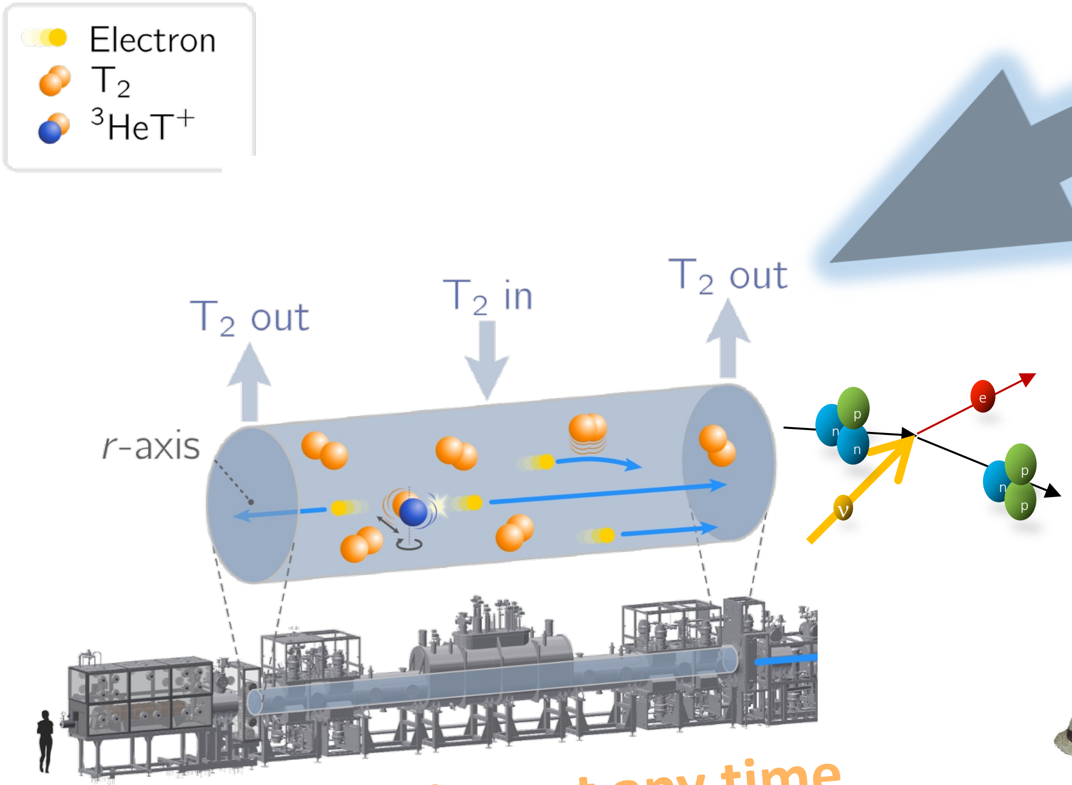
S. Weinberg, Phys.Rev. 128 (1962) 1457–1473





100 g tritium yields 10 ν captures per year

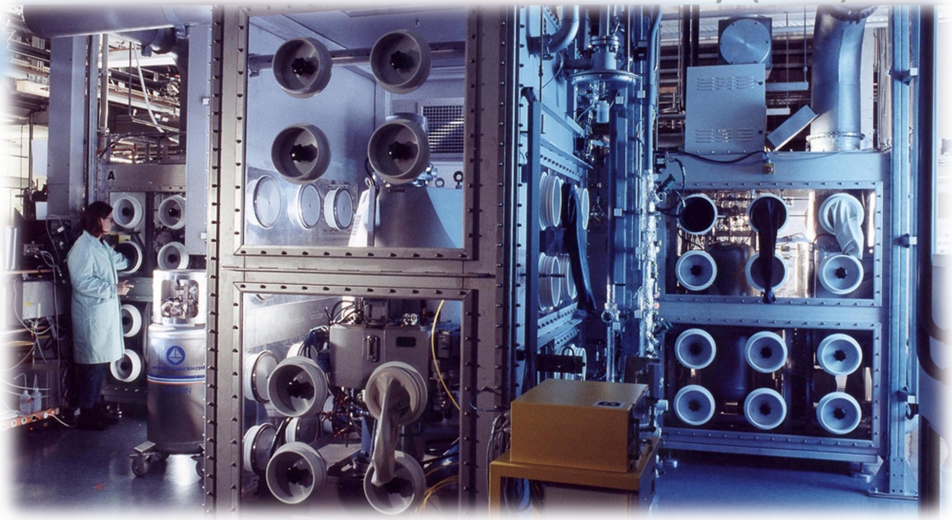
Sensitivity to the overdensity ratio η



30 μg of tritium at any time

10^{-6} ν capture/year
(depends on Dirac/Majorana nature)

Karlsruhe Tritium Laboratory (TLK)

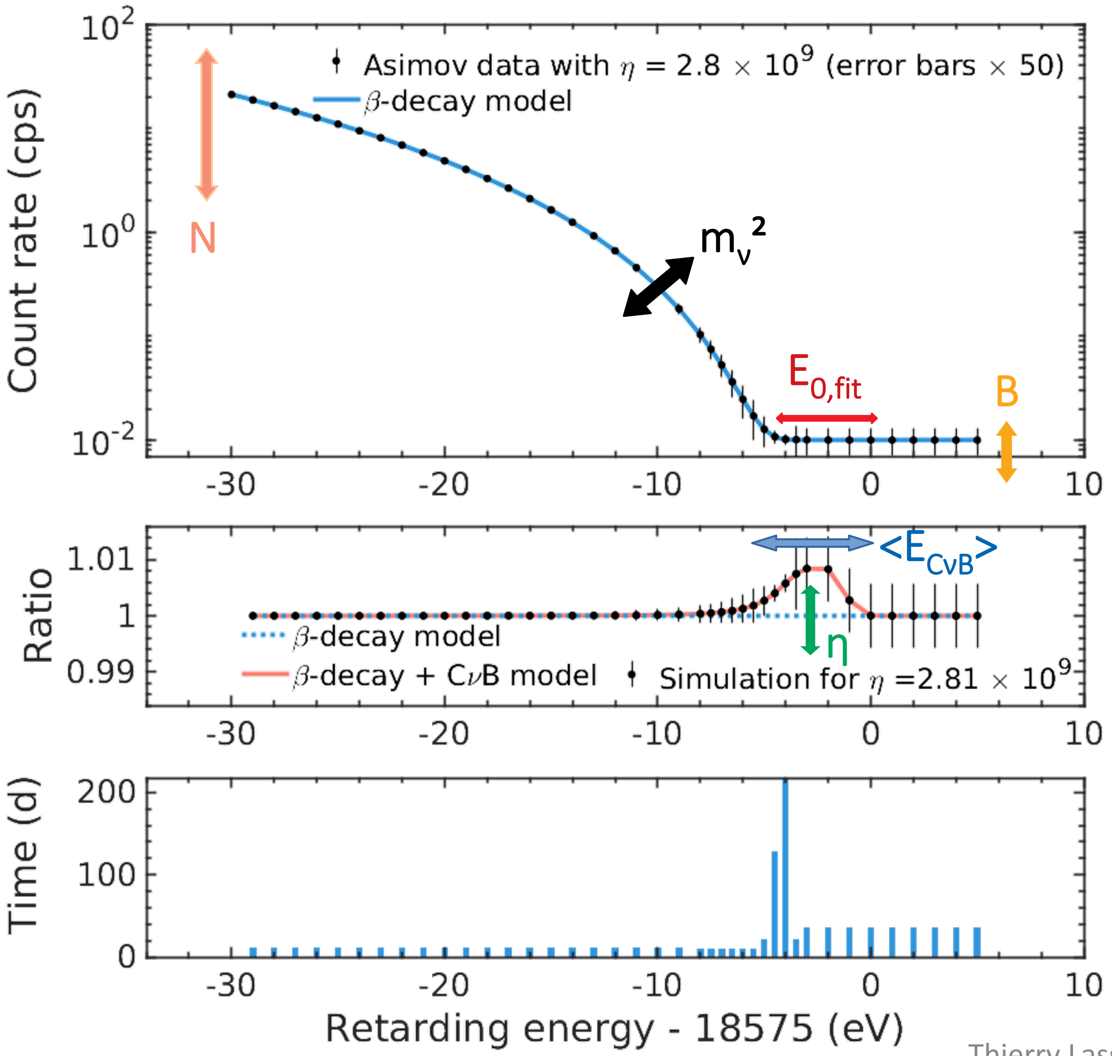


Overall gaseous tritium quantity at TLK: currently 25 g

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

$$\eta = n_\nu / < n_\nu >$$

Relic neutrino modeling

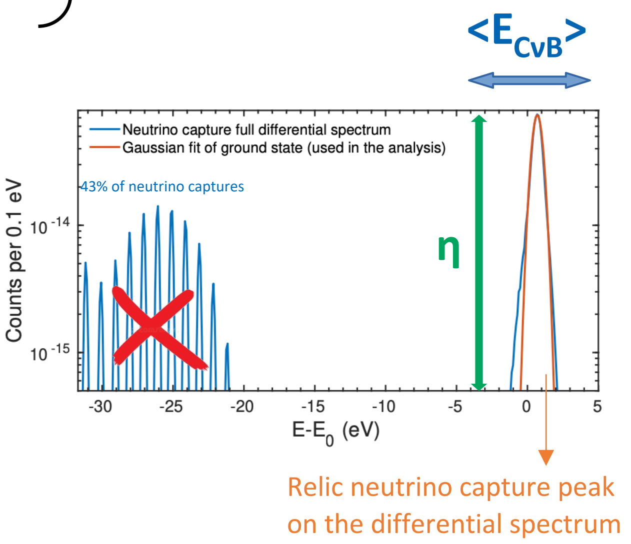


Fit Parameters:

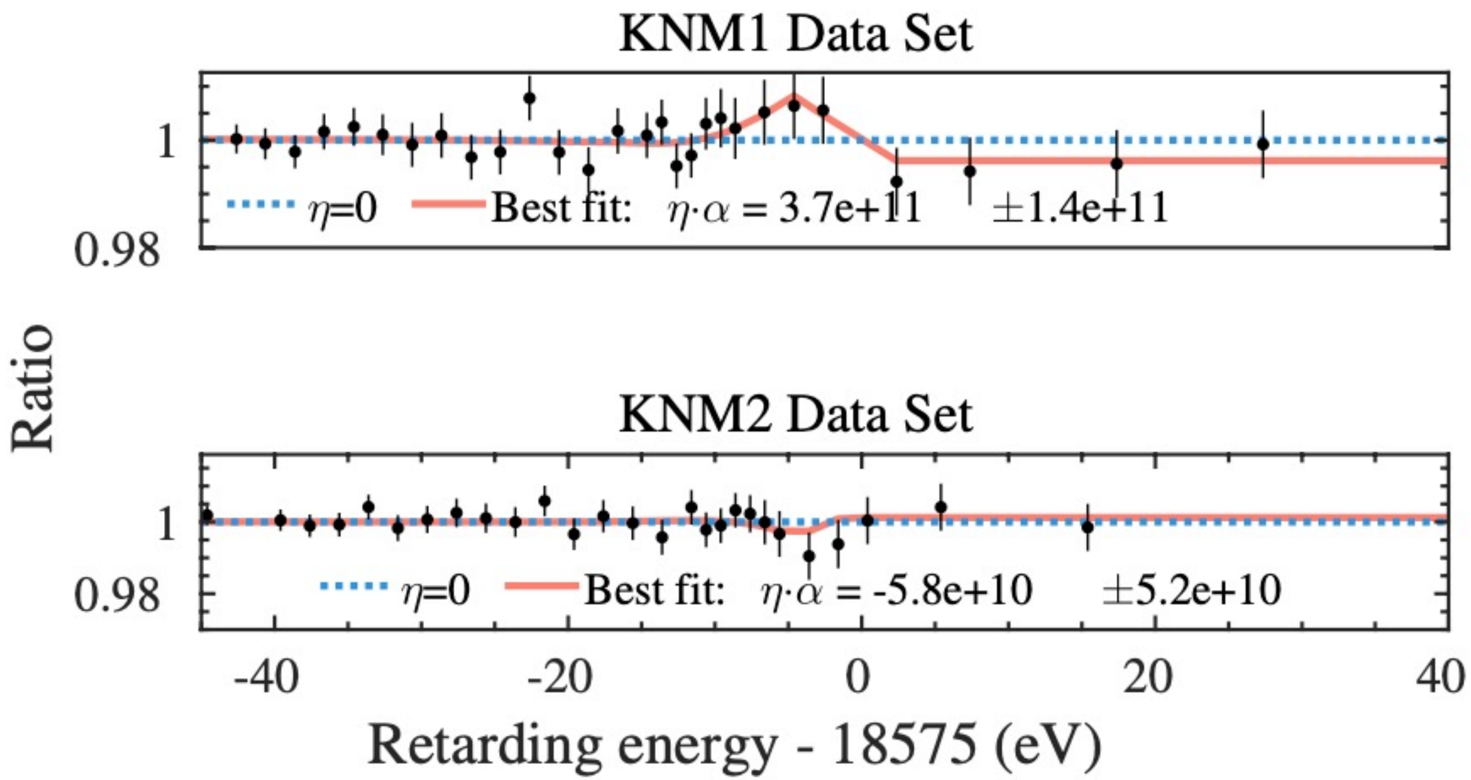
- ✓ m_ν^2 neutrino mass
- ✓ $E_{0,fit}$ endpoint
- ✓ N signal normalization
- ✓ B background rate

Tritium β – decay
+
background

- ✓ η overdensity
- ✓ $\langle E_{C\nu B} \rangle$ peak position



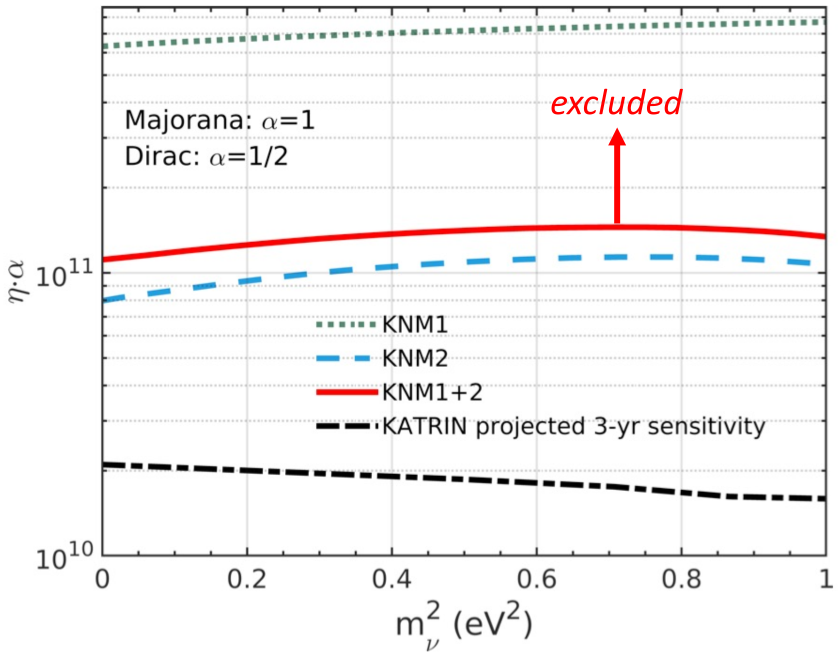
Relic neutrino fit results (best fit)



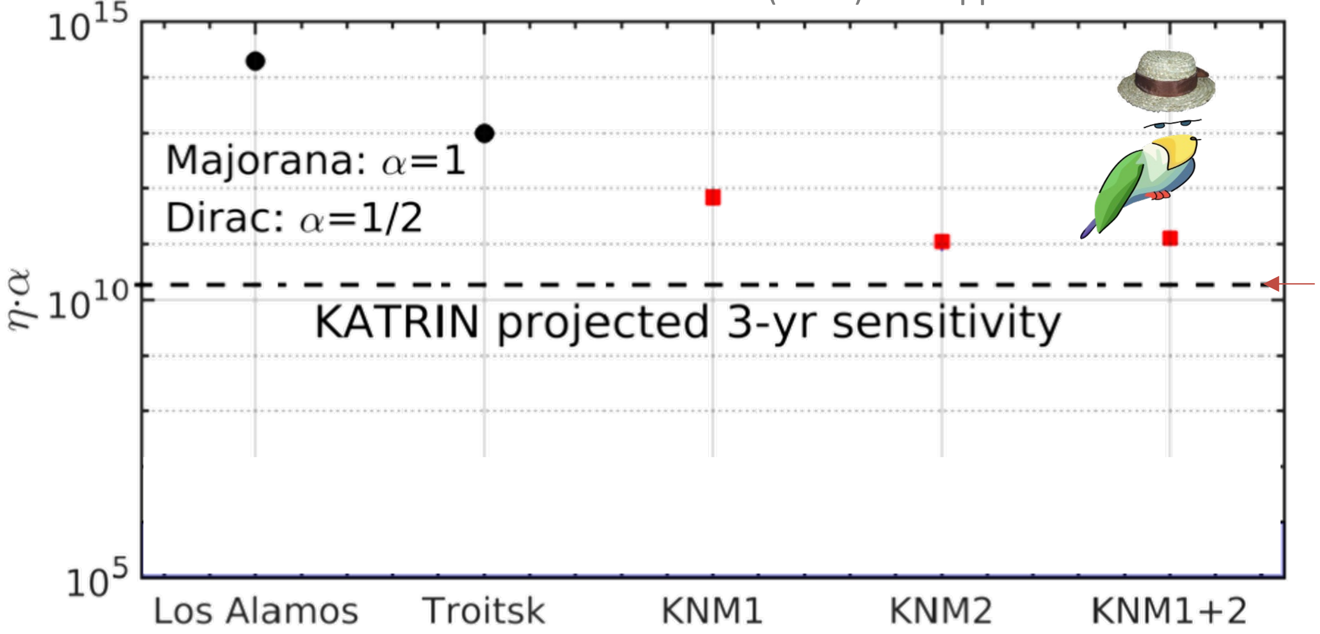
- ✓ KNM1 2019 dataset:
  - ✓ 522 hours
  - ✓ 3.4 μg for capture on tritium
- ✓ KNM2 2019 dataset
  - ✓ 744 hours
  - ✓ 13.0 μg for capture on tritium
- ✓ no evidence for relic neutrino overdensity → upper limits
- ✓ KNM 1+2 combination

Relic Neutrino Results (2022)

- ✓ test for large overdensity η of relic neutrinos in our surrounding (based on **1st** and **2nd** campaigns)
- ✓ $\eta < 1.1 \cdot 10^{11}/\alpha$ at 95% CL – 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**
- ✓ target 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

Thank you for your attention