Recent Results from the KATRIN experiment

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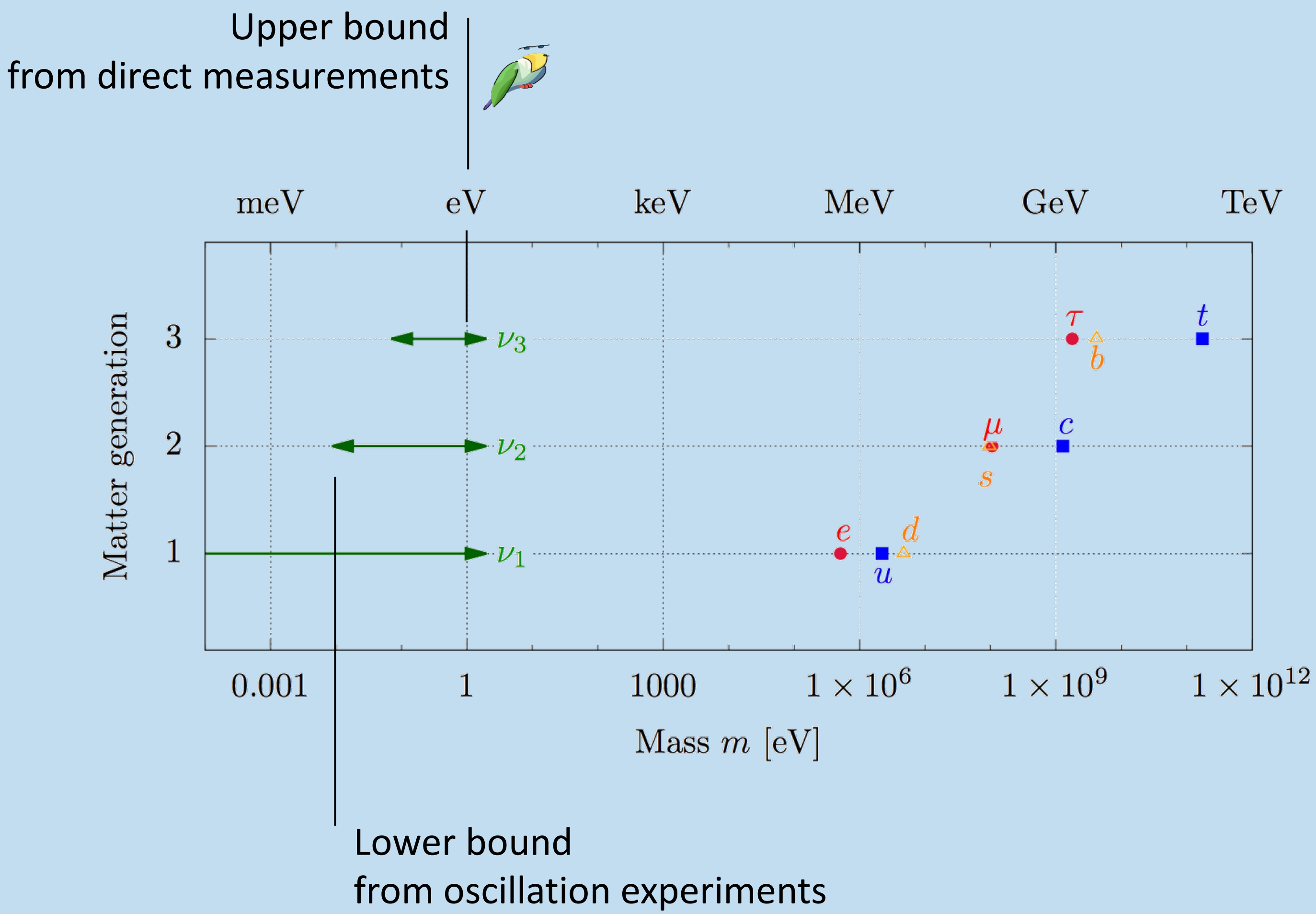
on behalf of the KATRIN collaboration

Gentner-series on astroparticle physics
Max-Planck-Institute für Kernphysik
January 11th 2023

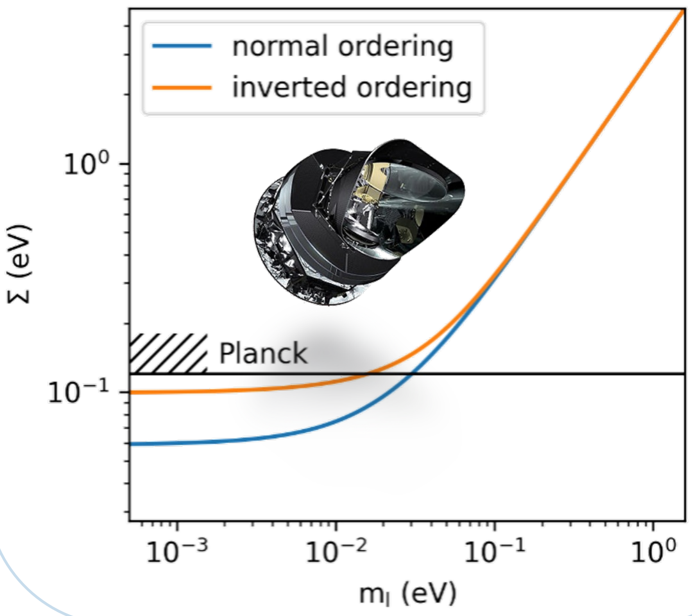
Direct Neutrino Mass Measurement



Neutrino mass(es)

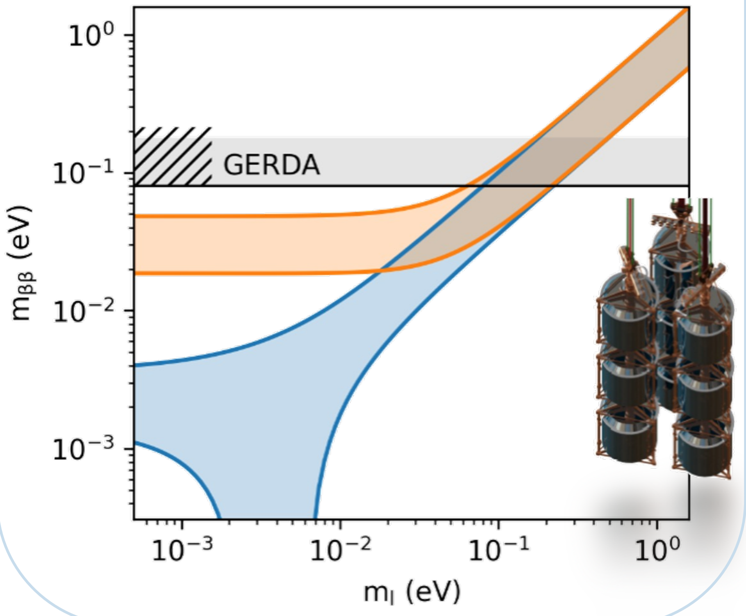
Cosmology

$$\Sigma = \sum_i m_i$$



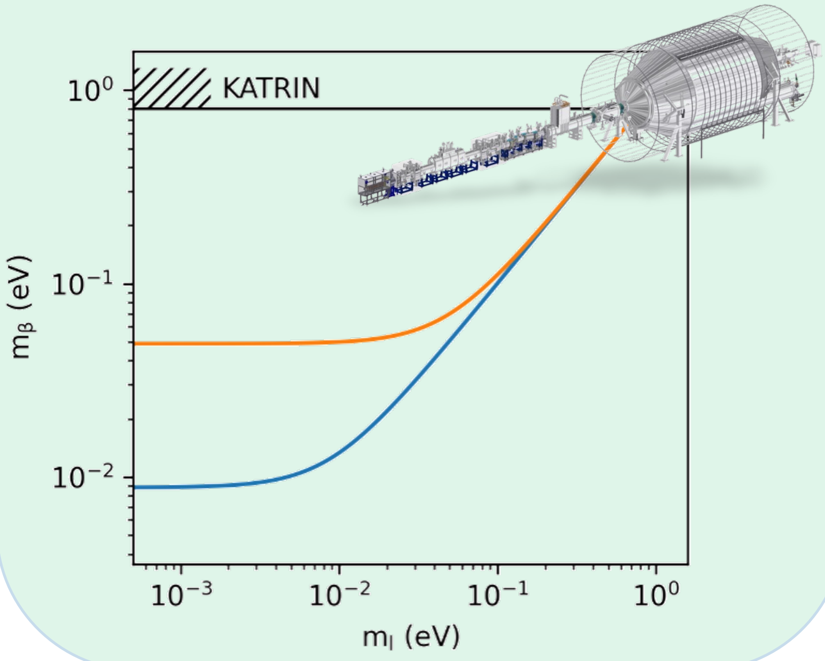
Neutrinoless ßß decay

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

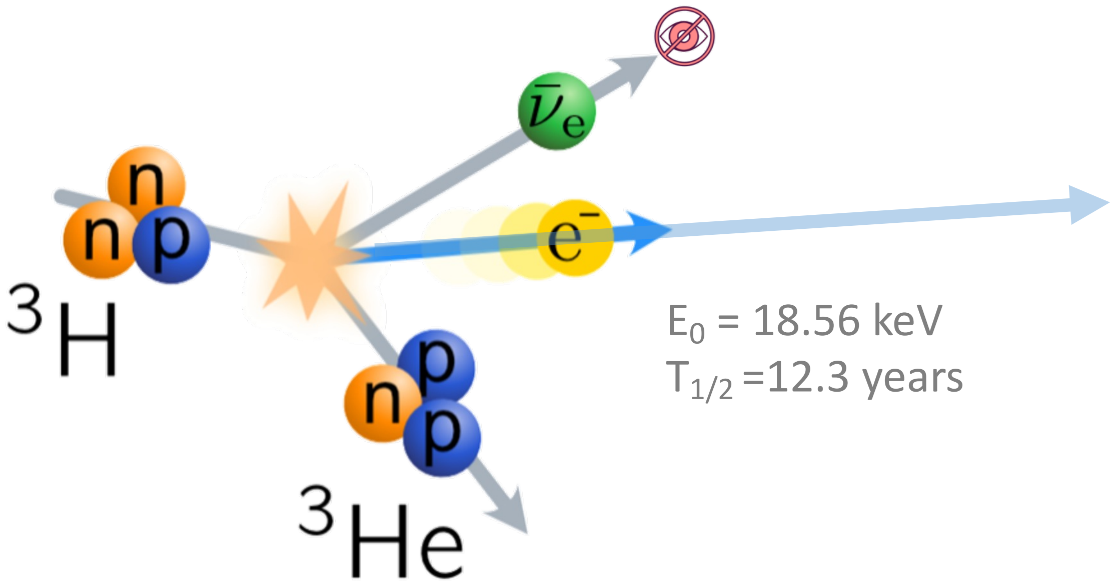


ß-decay kinematics

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

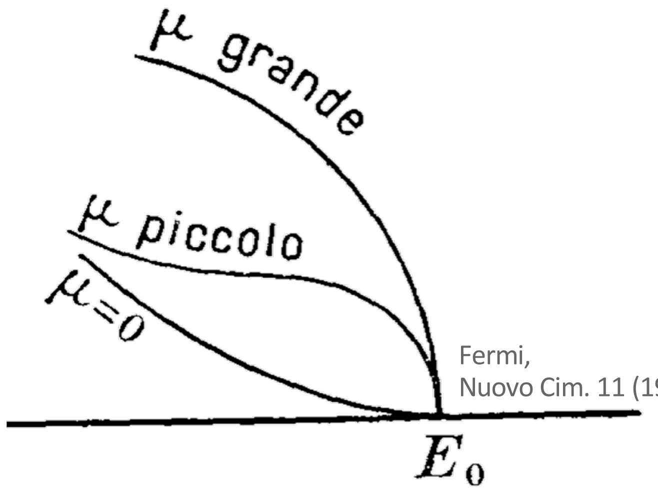


Kinematic neutrino mass measurement



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

✓ measurement of the electron β −spectrum
- independent of cosmology
- independent of neutrino nature



Fermi,
Nuovo Cim. 11 (1934) 1-19

✓ based on kinematics and energy conservation

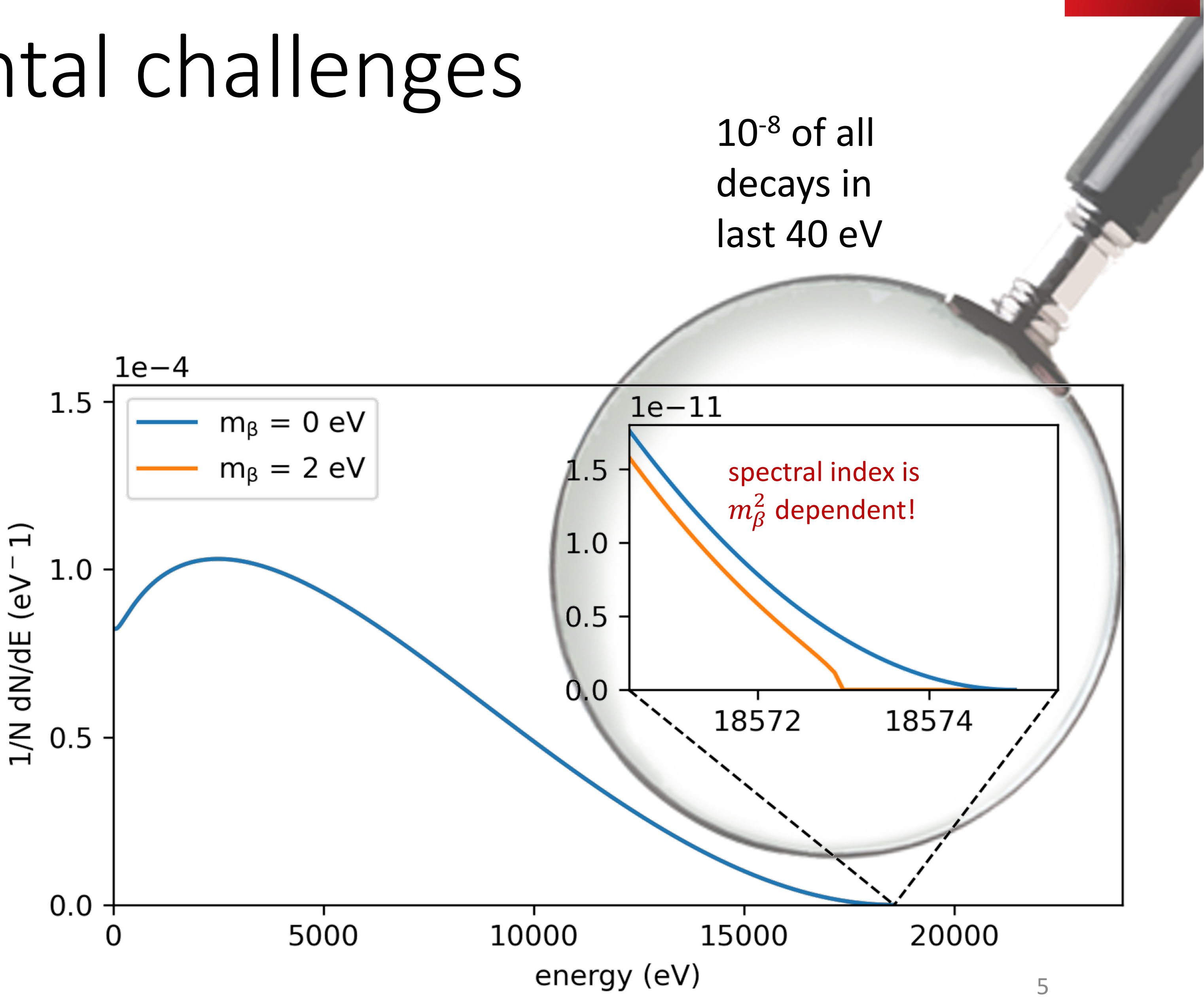
✓ m_ν^2 spectral distortion, maximal at endpoint energy E_0

✓ incoherent neutrino mass : $m_\nu^2 = \sum_i |U_{ei}|^2 \cdot m_i^2$

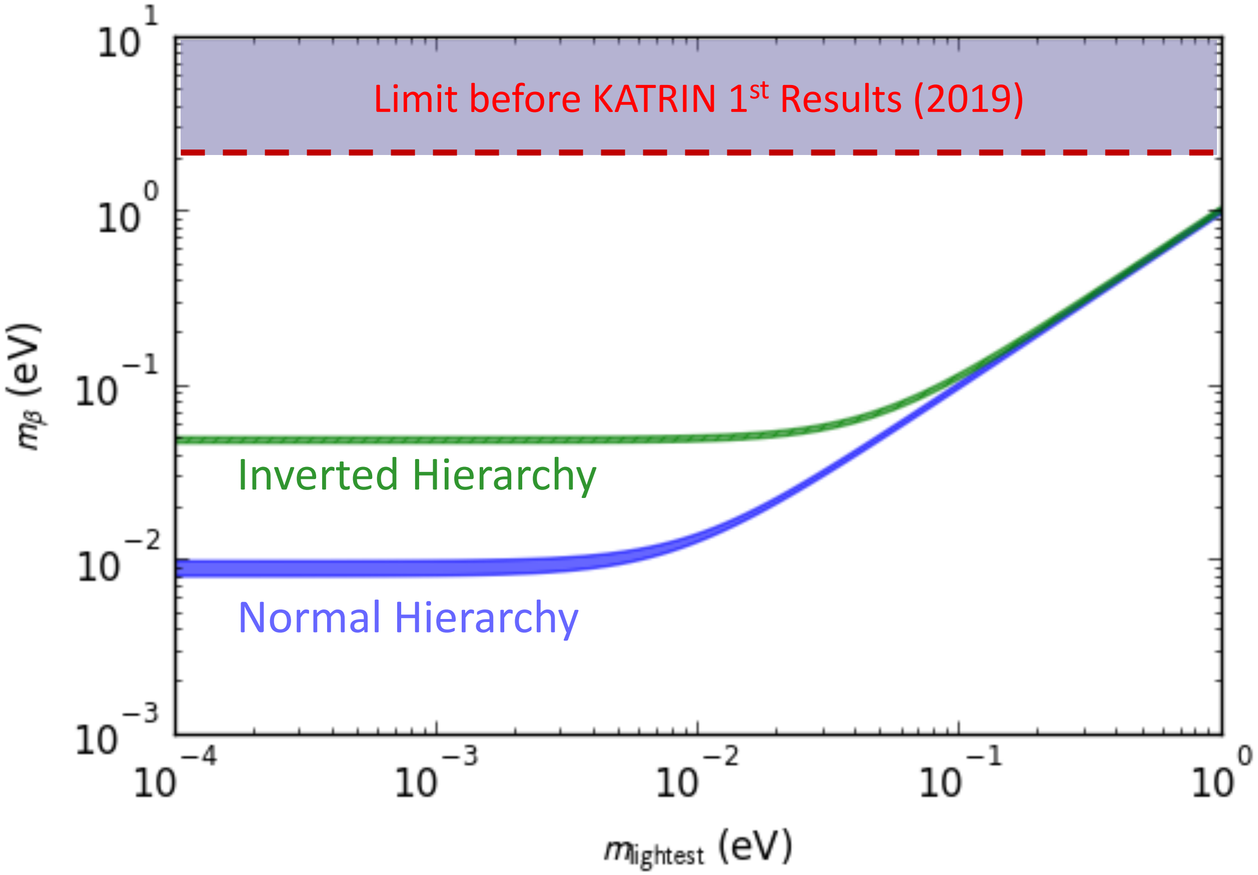
KATRIN experimental challenges

- ✓ 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

10^{-8} of all decays in last 40 eV



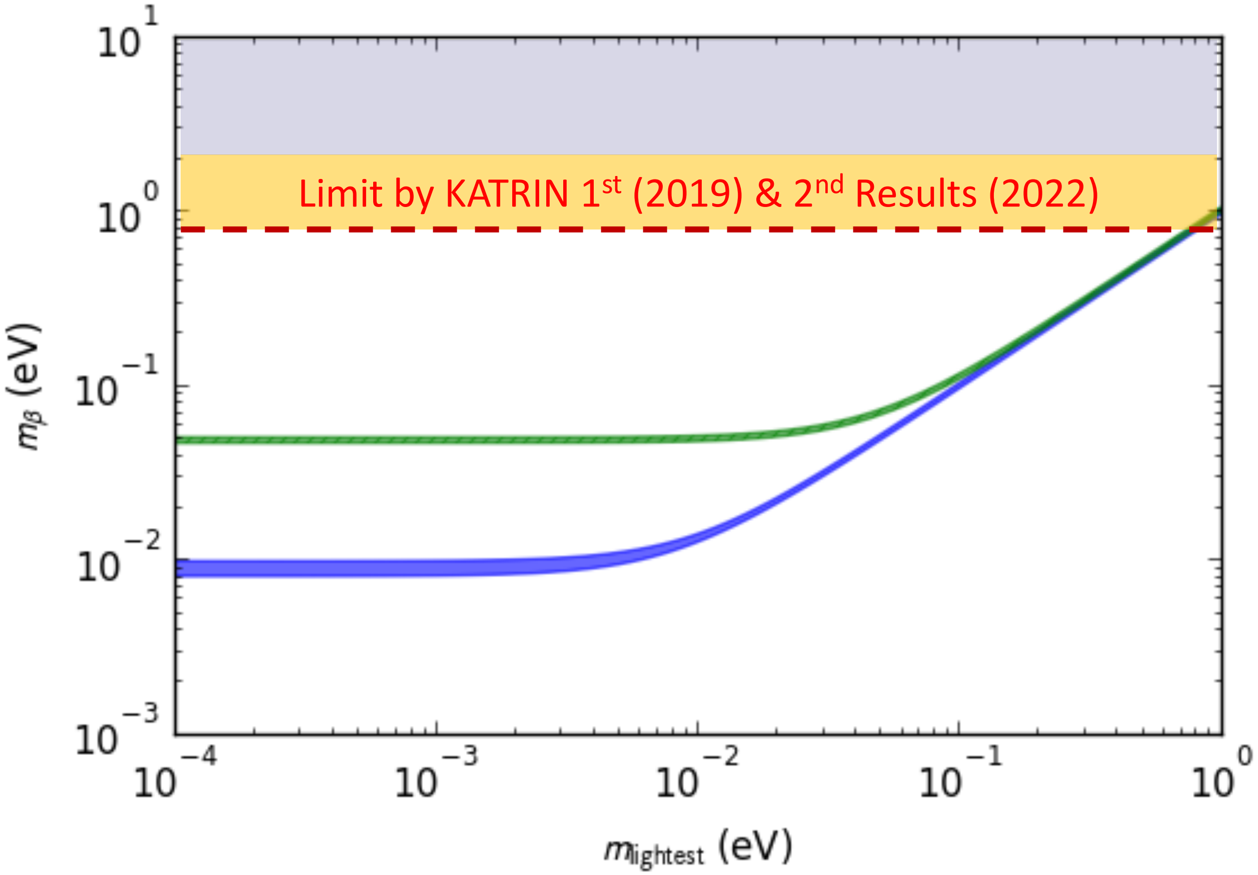
Where did we stand?



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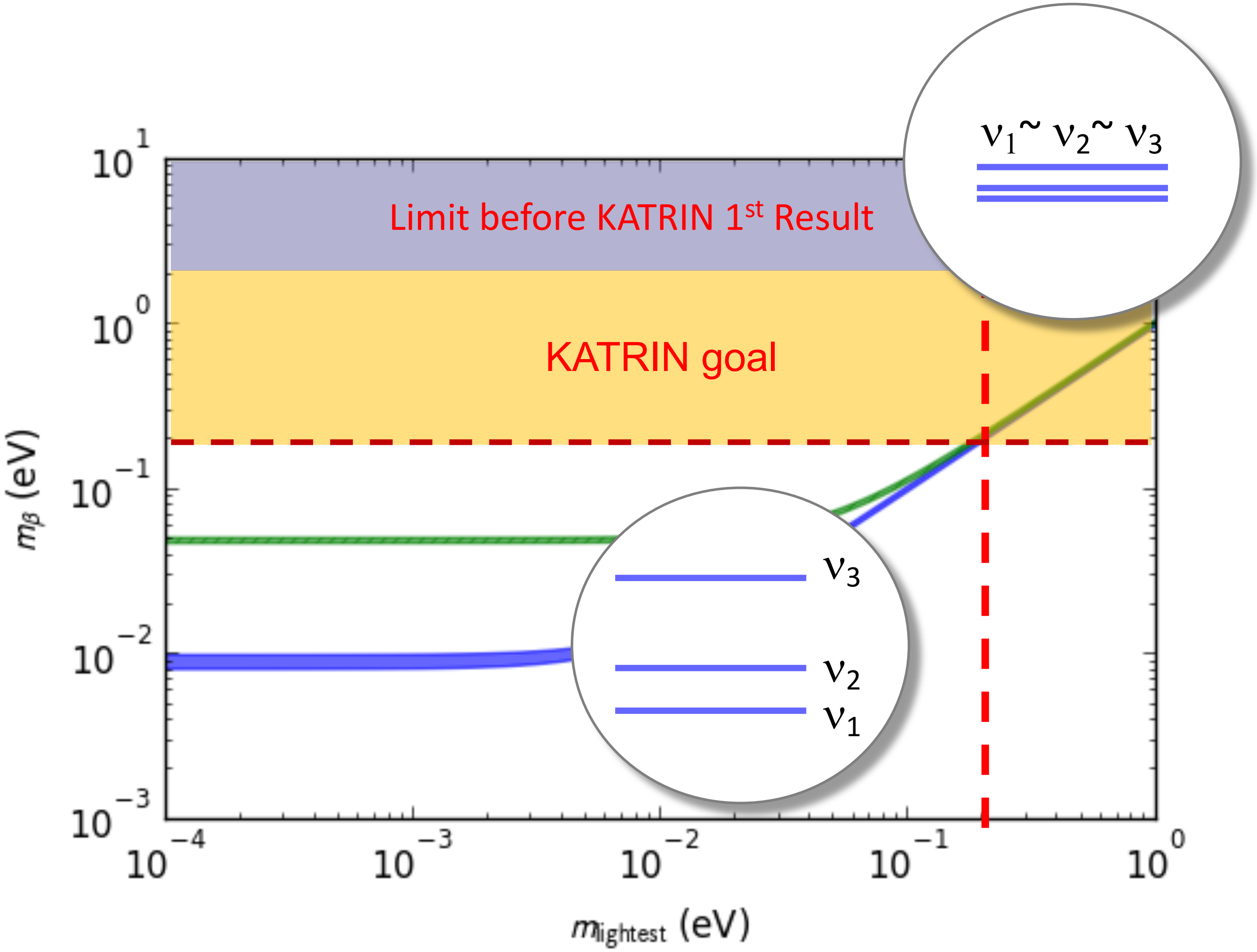
  V. N. Aseev et al., Phys. Rev. D 84 (2011) 112003
  Kraus, C., Bornschein, B., Bornschein, L. et al. Eur. Phys. J. C (2005)
- ✓ intermediate KATRIN results (~5% of the total expected statistics) – This Talk

Where will we stand by 2025?



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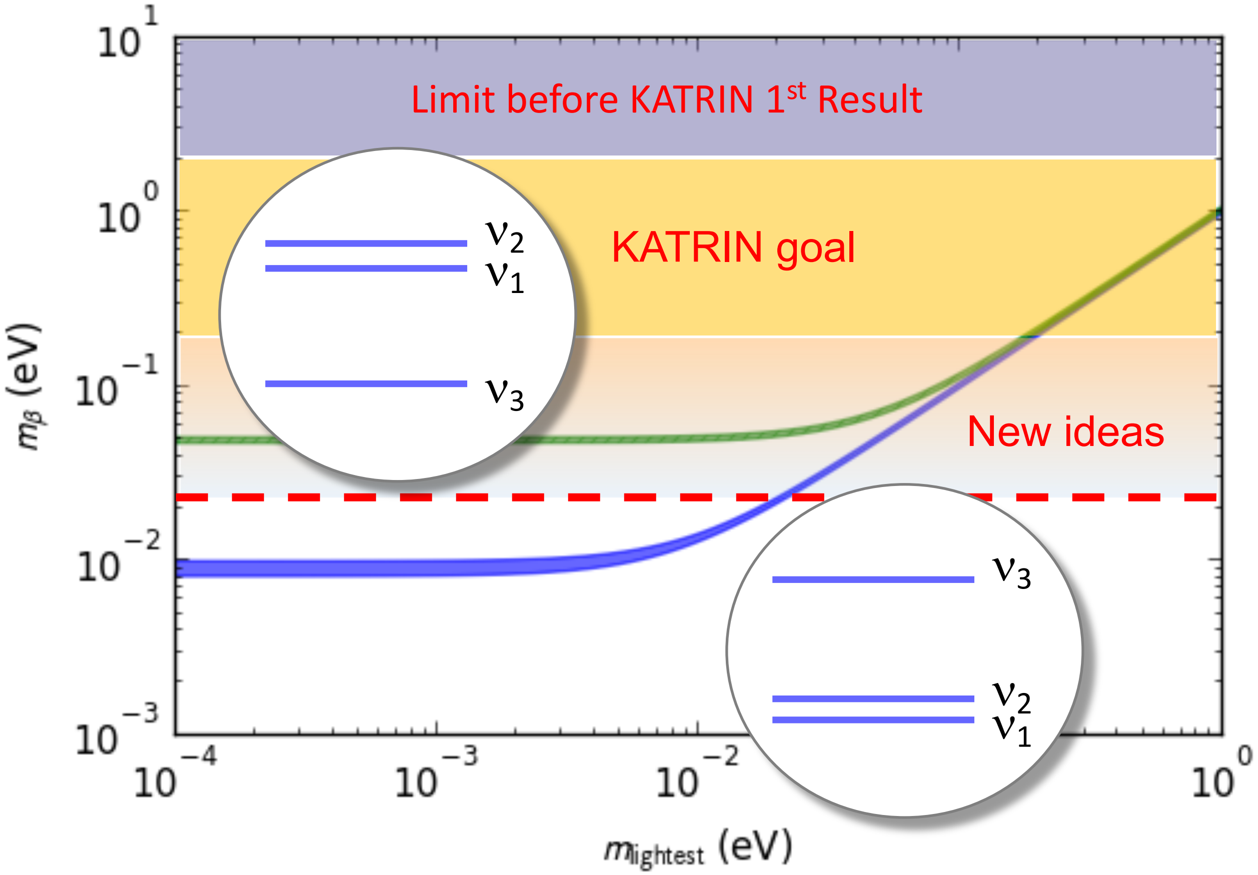
- ✓ intermediate KATRIN results (~5% of the total expected statistics) – This Talk
- ✓ KATRIN goal: distinguish between **degenerate** and **hierarchical** scenario

Where could we stand by 203X?



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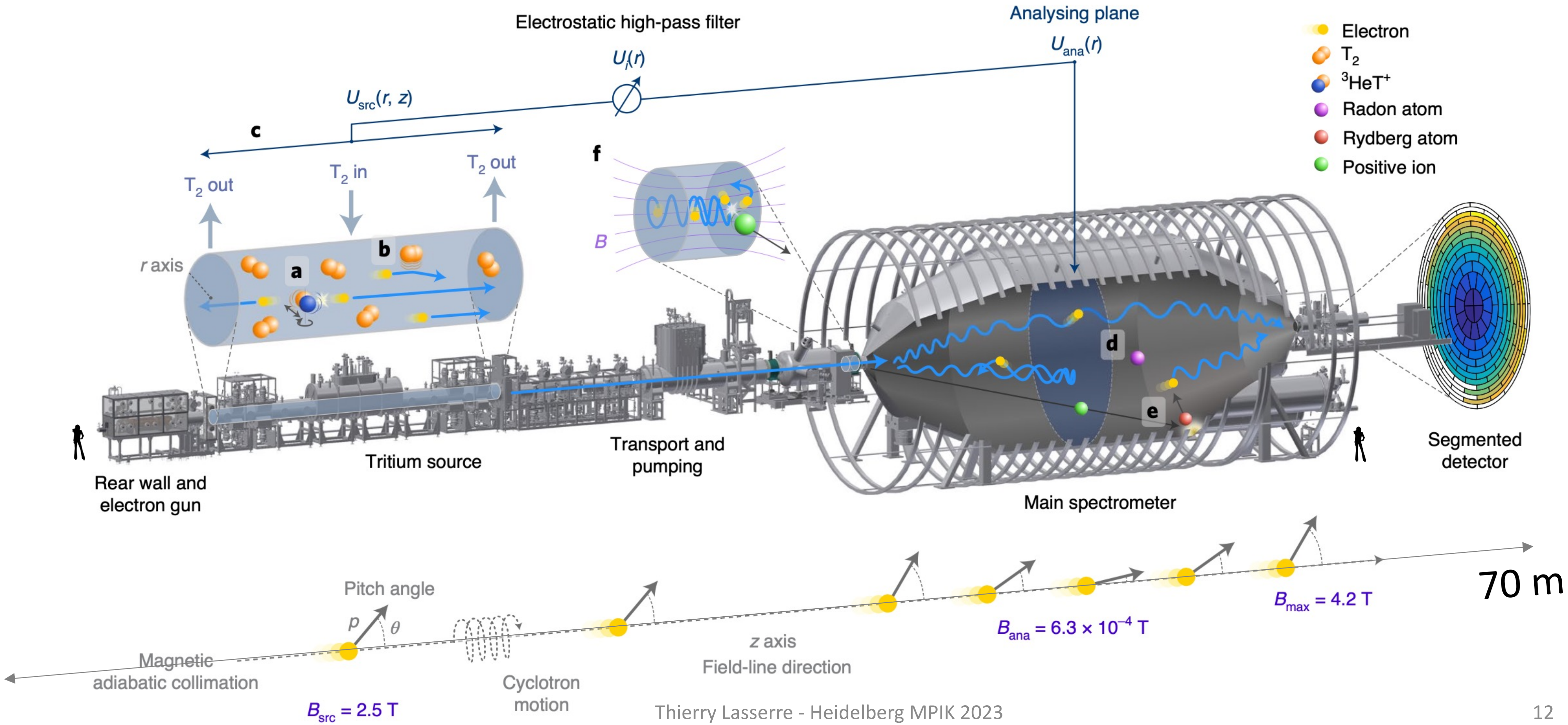
  V. N. Aseev et al., Phys. Rev. D 84 (2011) 112003
  Kraus, C., Bornschein, B., Bornschein, L. et al. Eur. Phys. J. C (2005)
- ✓ intermediate KATRIN results (~5% of the total expected statistics) – This Talk
- ✓ KATRIN goal: distinguish between **degenerate** and **hierarchical** scenario
- ✓ beyond KATRIN: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



Measurement strategy

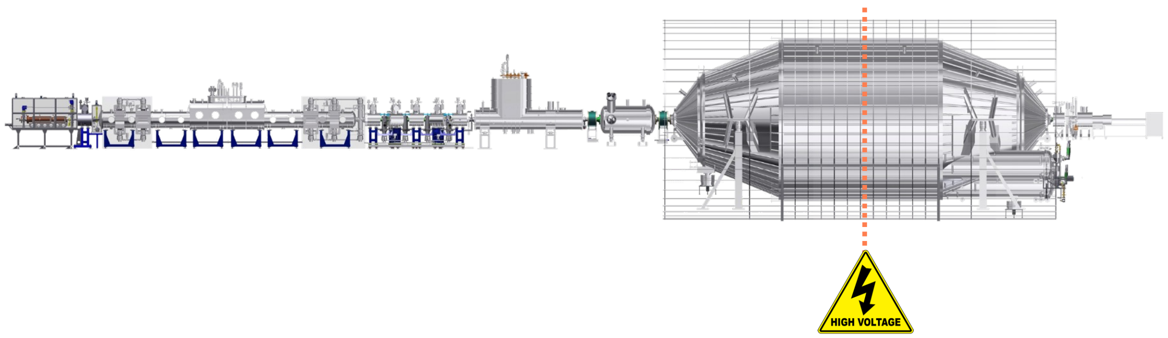
Integral spectral measurement !

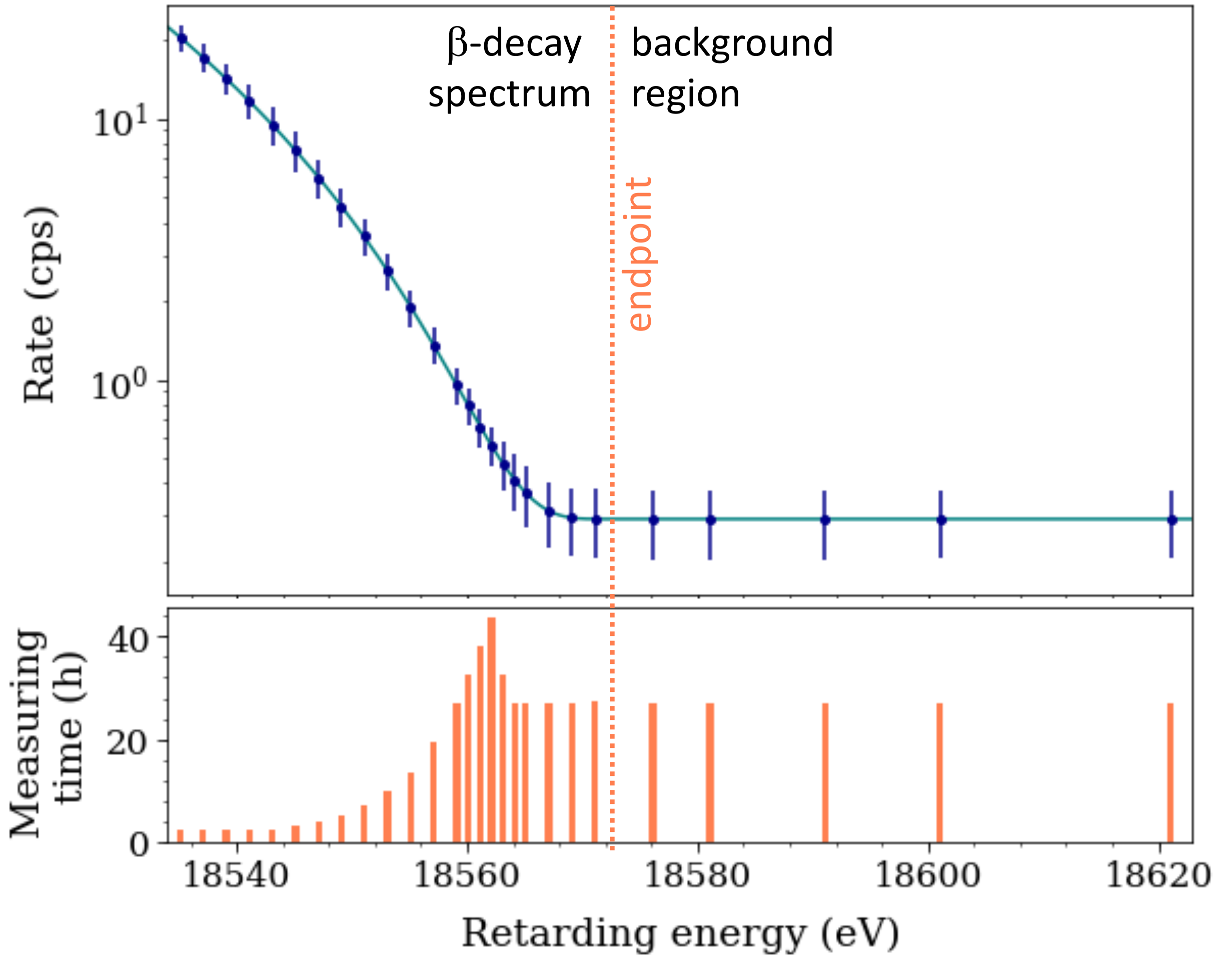
β-scans illustration:

✓ scan points: **~30 HV set points**

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

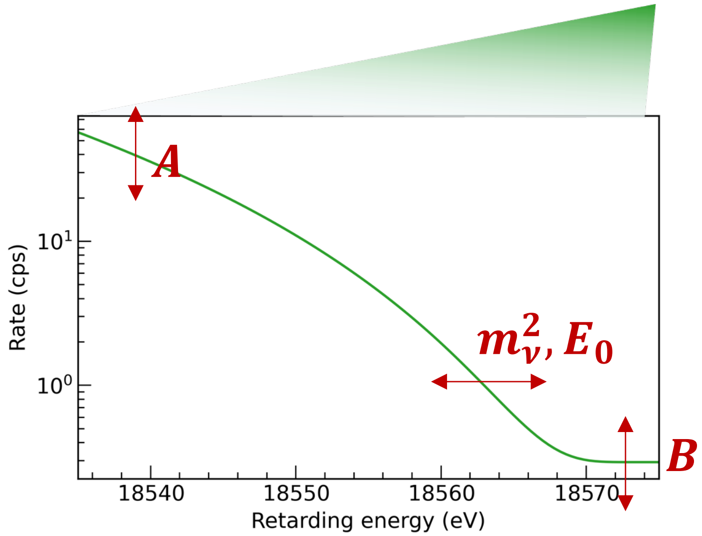
✓ scan time: **~2 hours**

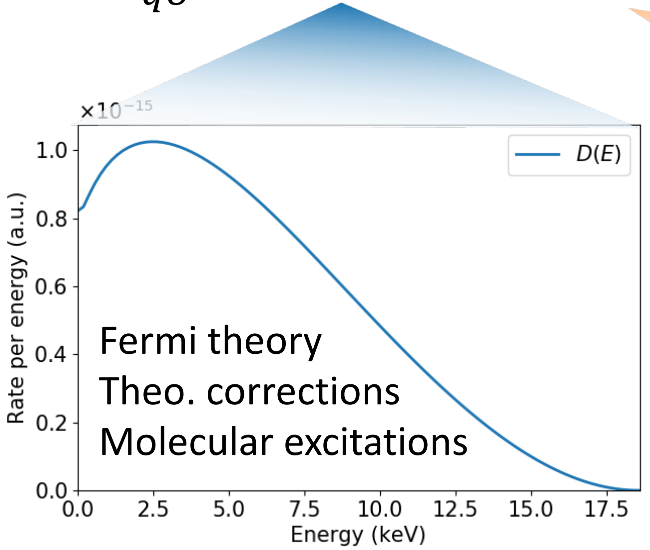


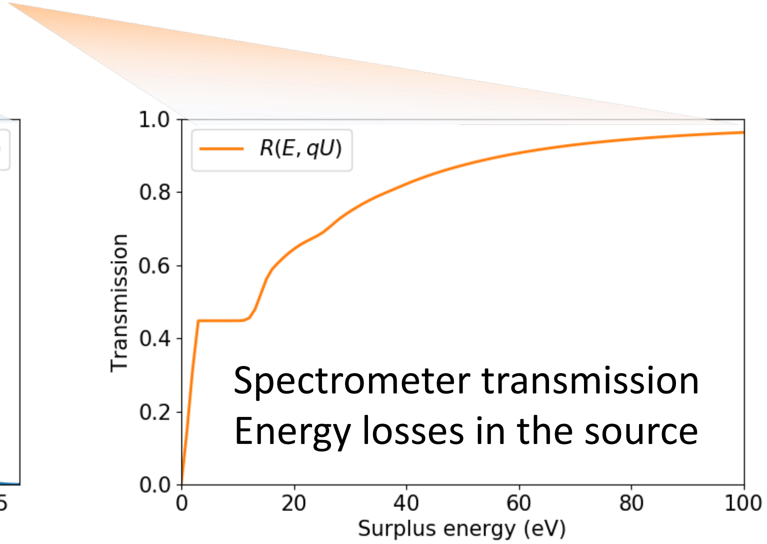


Analysis strategy

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



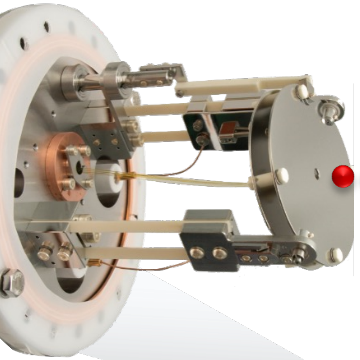


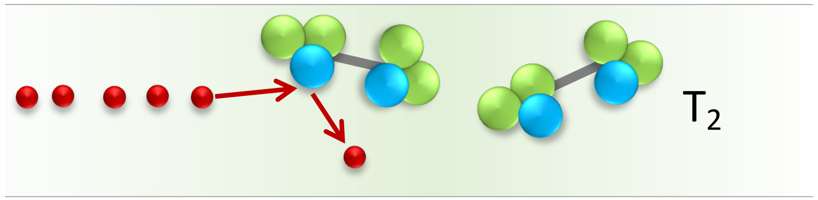


✓ neutrino mass fit parameters: $\boldsymbol{m_\nu^2}, \boldsymbol{E_0}, \boldsymbol{B}, \boldsymbol{A}$

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

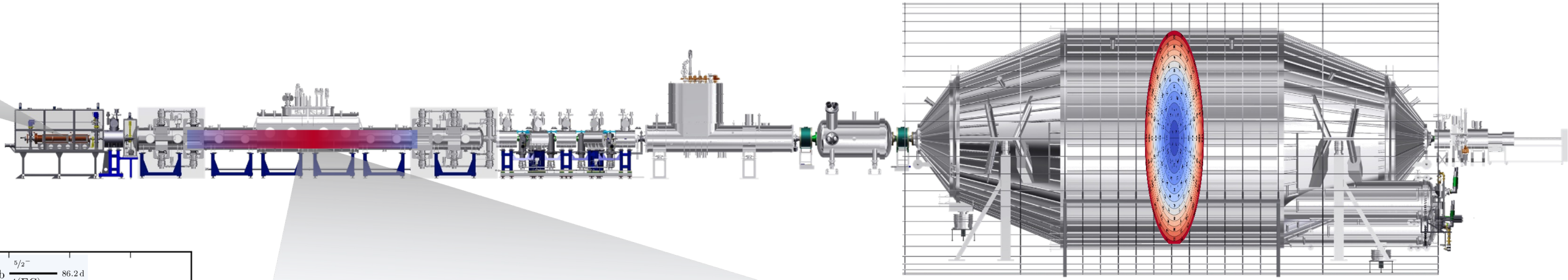
Experimental inputs: e-gun, ^{83m}Kr

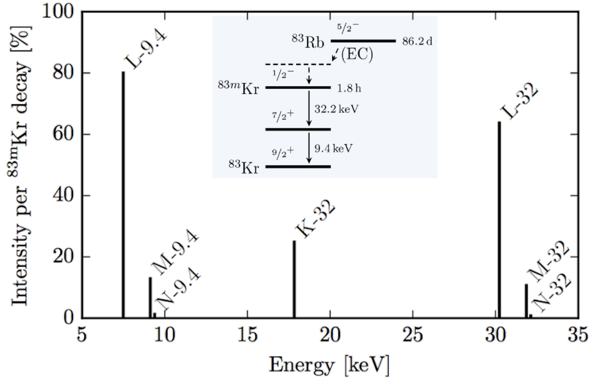


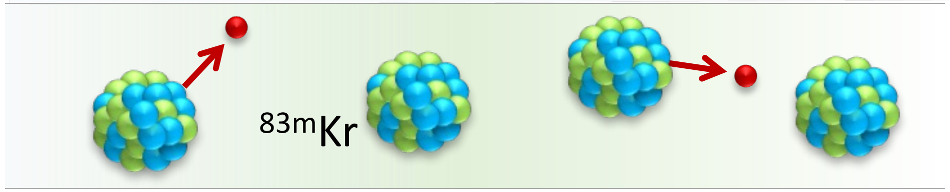


- ✓ measurement of gas density and energy losses

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



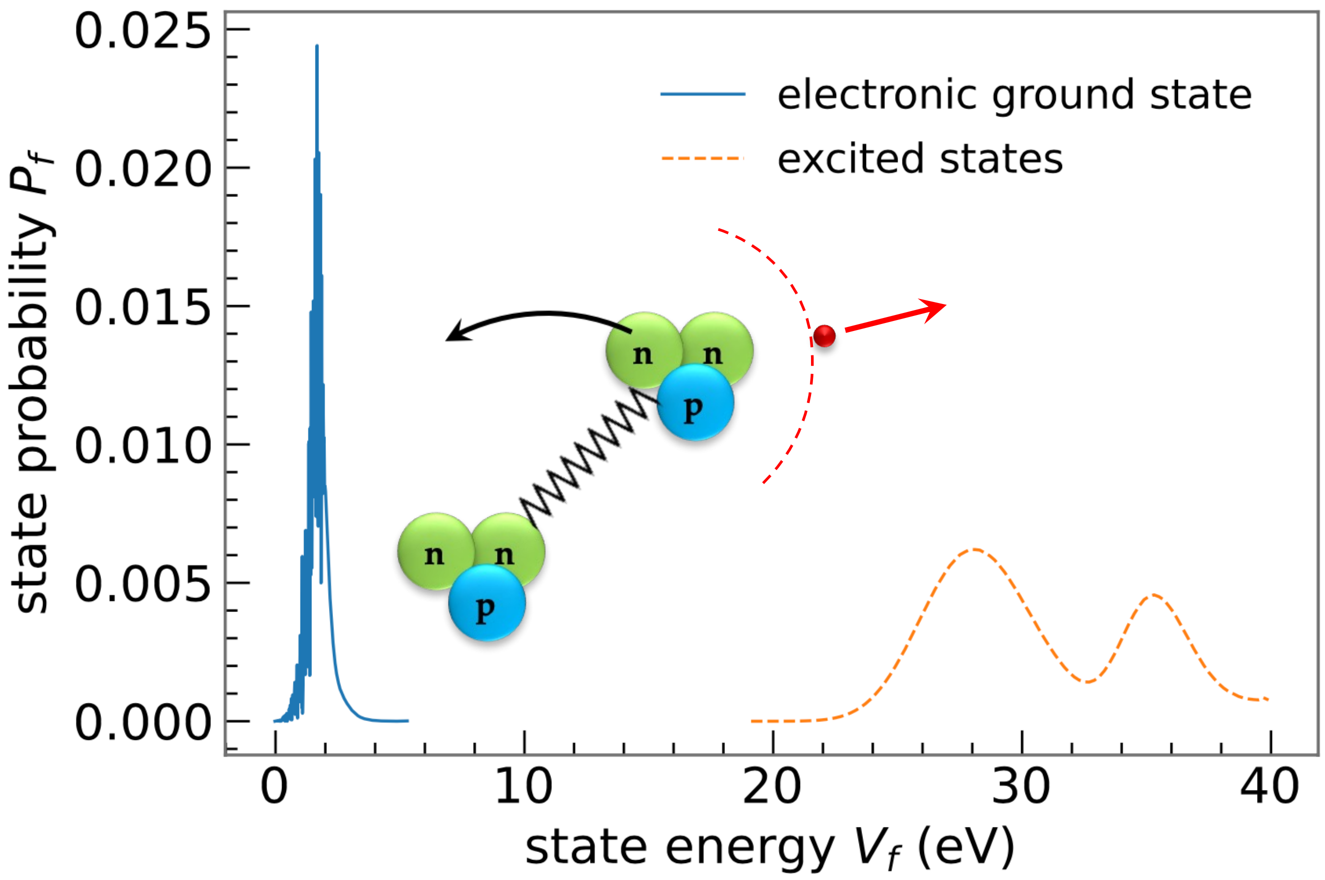




- ✓ measurement of E/M fields var. in the source and spectrometer

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

Theoretical input: molecular final states

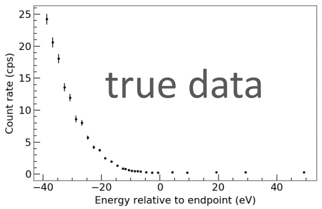


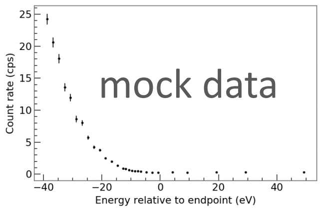
- ✓ β −electron and tritium molecule share the energy released in the decay
- ✓ precise calculation of molecular ground and excited final states
  A. Saenz et al, Phys. Rev. Lett. 84, 242 (2000)
  + updates
- ✓ unavoidable energy broadening
- ✓ no limitation for KATRIN

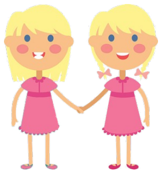
3-tiered blind analysis

Freeze analysis on MC-twin data

- mock data mimicking each scan

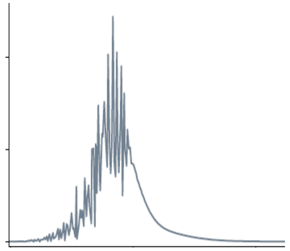


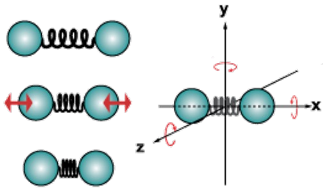




Blinded model

- modified molecular final state dist.

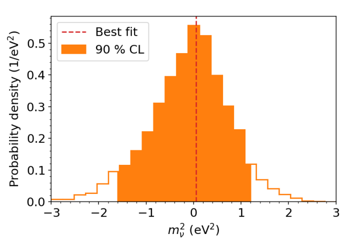


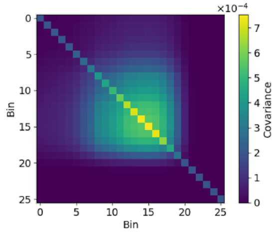


$$m_\nu^2$$

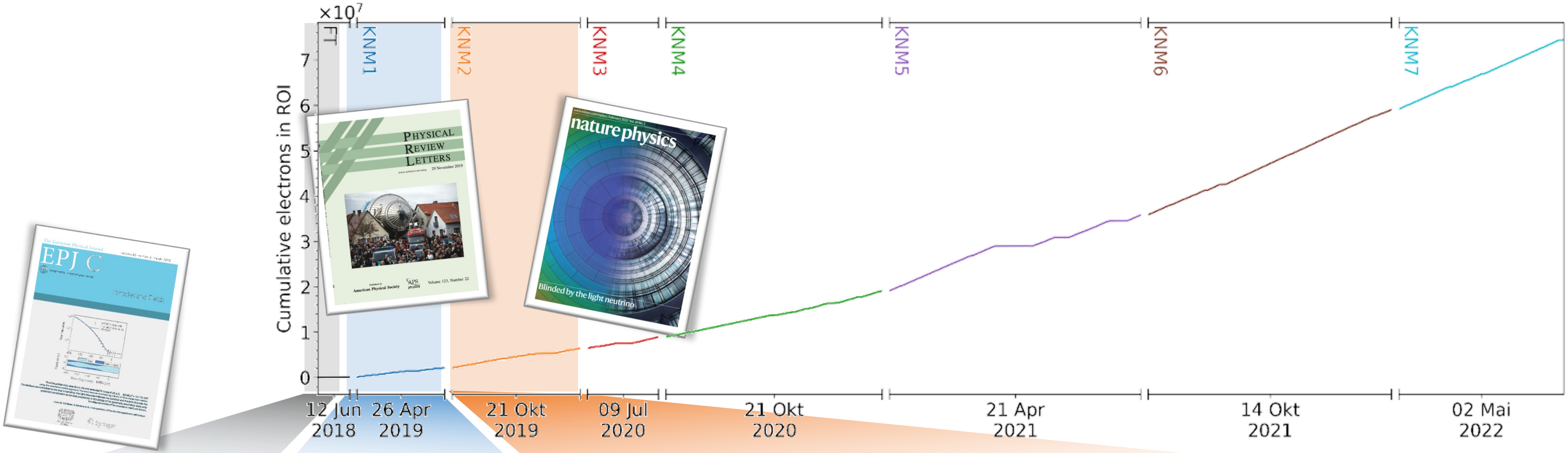
Three independent analysis teams

- 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)

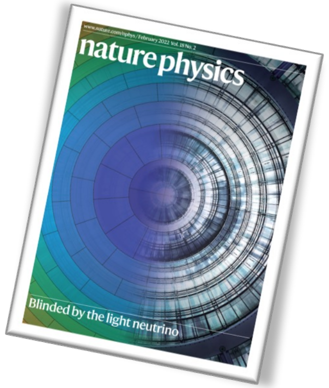
- $1^{st} + 2^{nd}$ m_ν campaign
- $m_\nu < 0.8$ eV

Nat. Phys. **18,** 160–166 (2022)

light sterile neutrinos

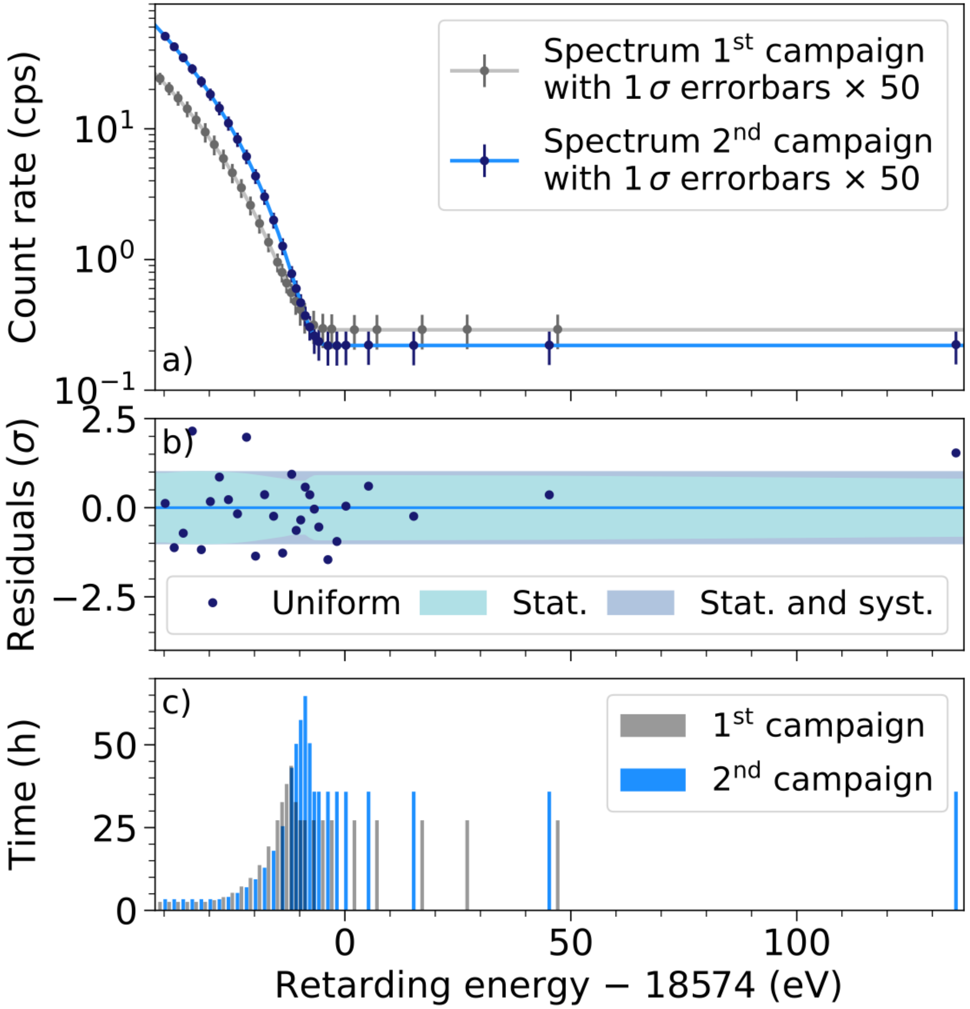
relic neutrinos

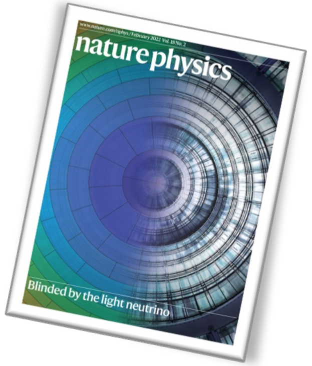
1^{st} & 2^{nd} campaigns figures



	1^{st} campaign **PRL 123 (2019) & PRD 104 (2021)**		**2^{nd} 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):

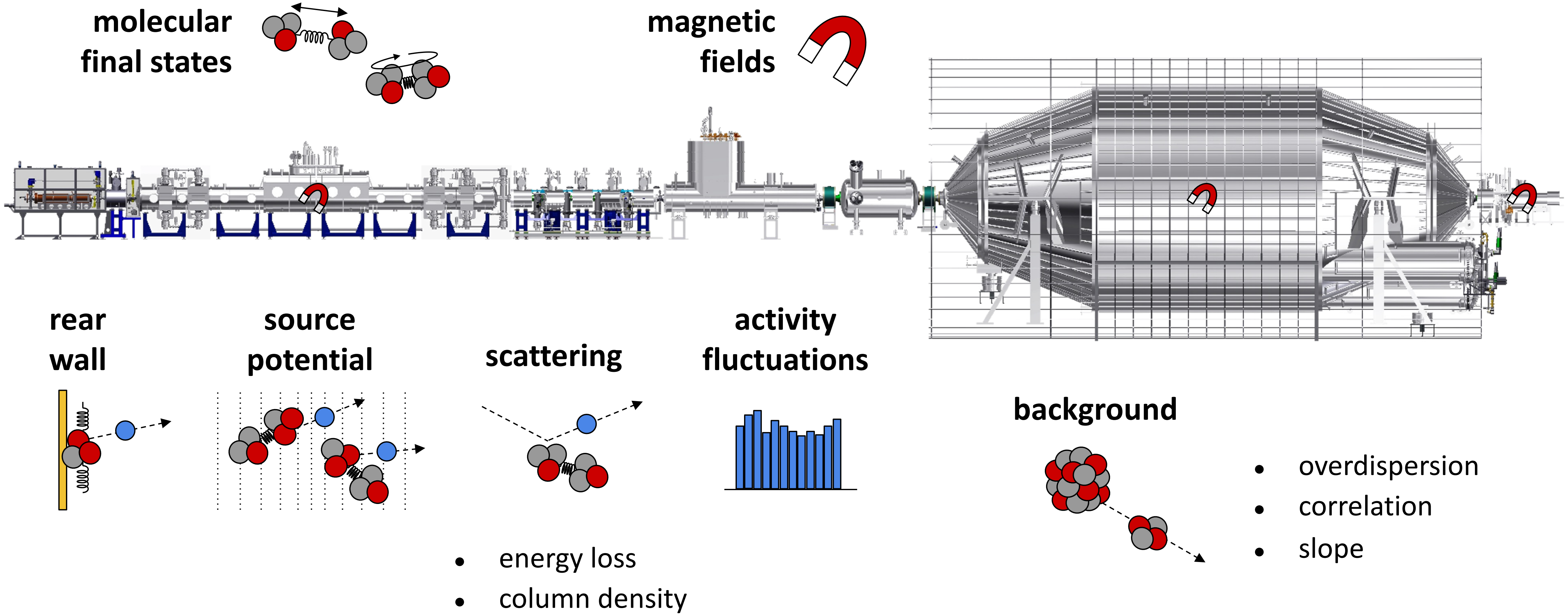
- ✓ total statistics: 2 million events
- ✓ best fit: $m_\nu^2 = \left(-1.0^{+0.9}_{-1.1}\right)$ **eV² (stat. dom.)**
- ✓ limit: $m_\nu < 1.1$ **eV (90% CL)**

Second campaign (autumn 2019):

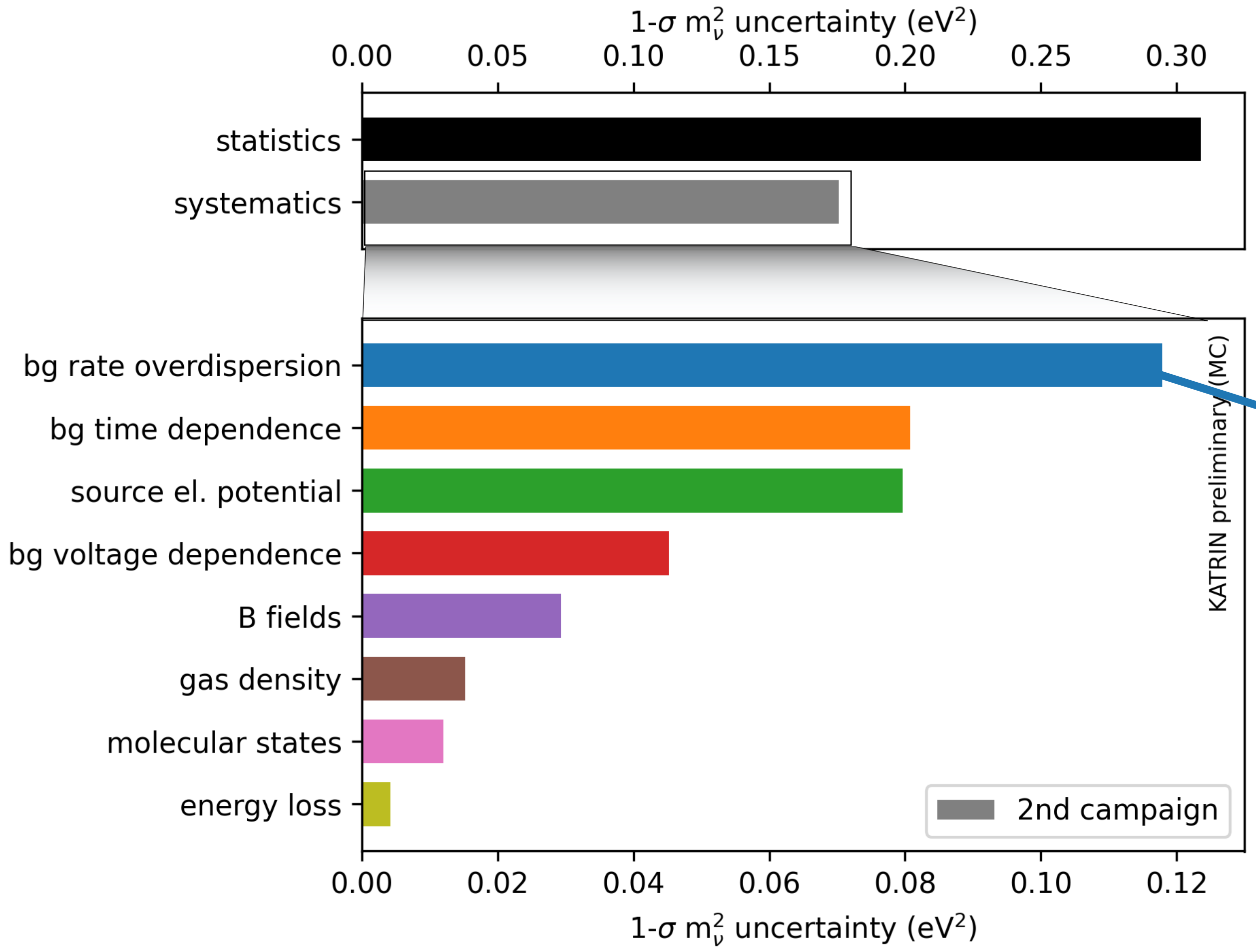
- ✓ total statistics: 4.3 million events
- ✓ best fit: $m_\nu^2 = \left(0.26^{+0.34}_{-0.34}\right)$ **eV² (stat. dom.)**
- ✓ limit: $m_\nu < 0.9$ **eV (90% CL)**

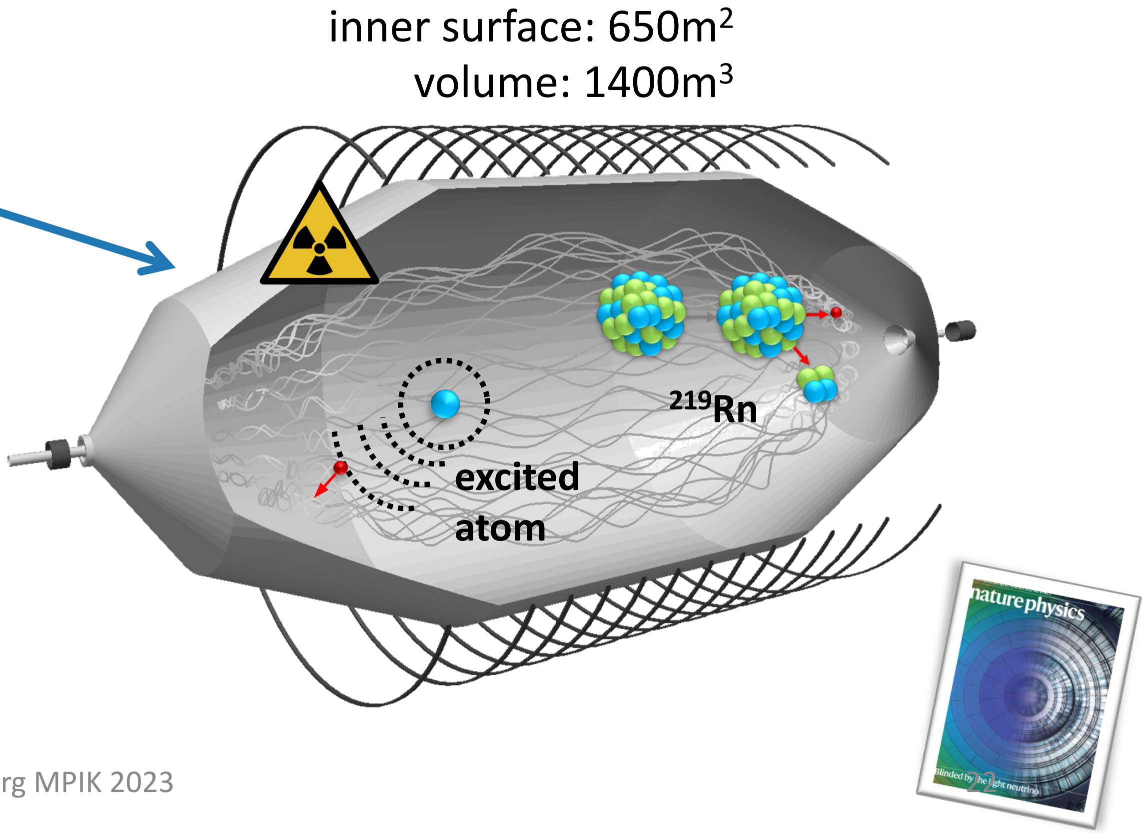
Combined result: $m_\nu < 0.8$ eV (90% CL)

Systematics uncertainties overview

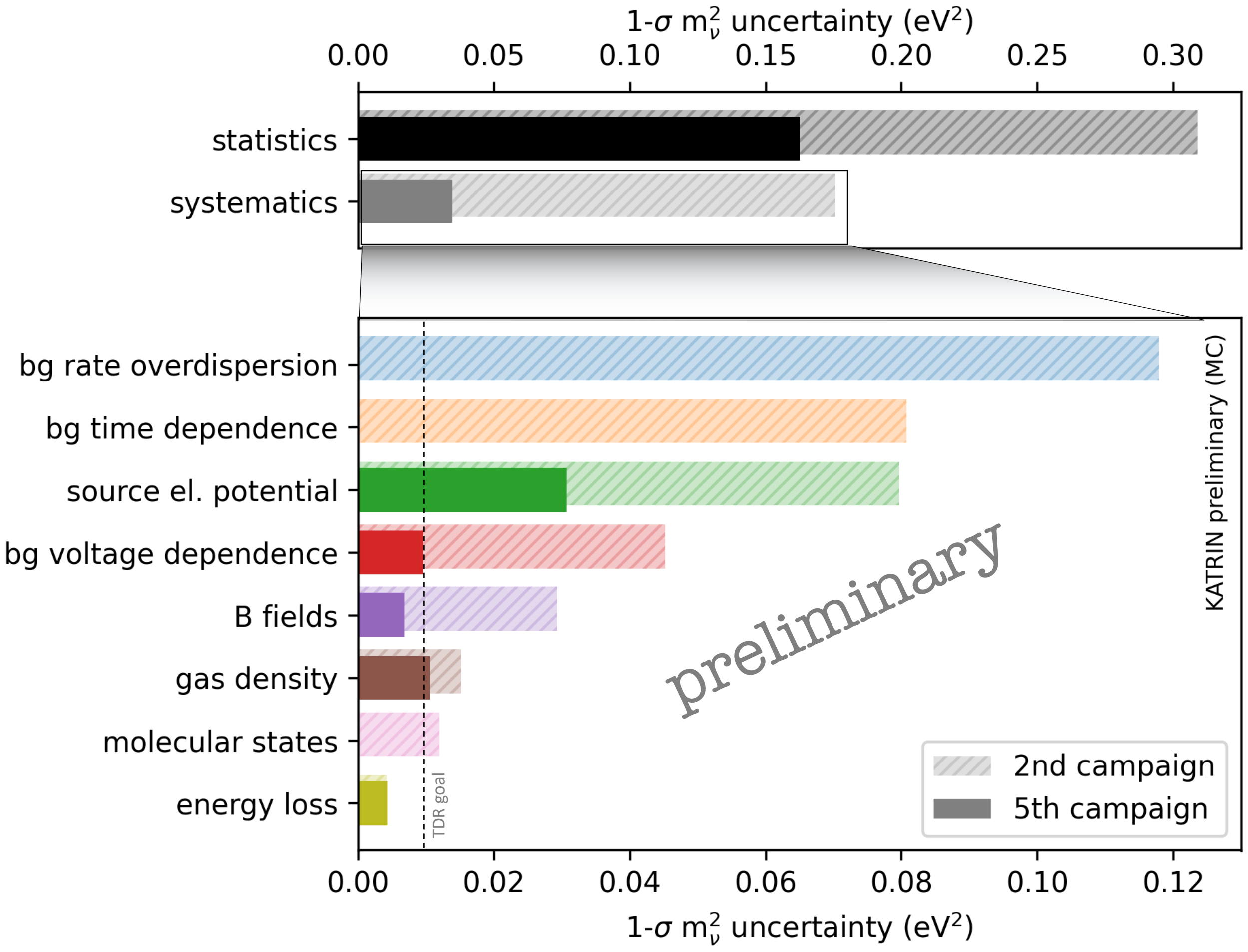


Uncertainty budget in second campaign





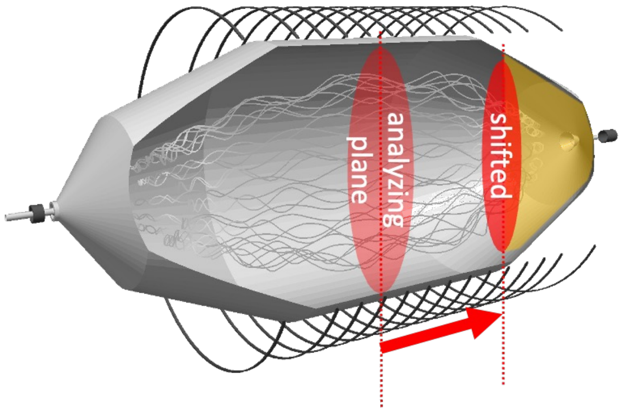
Improvements achieved by 2022



Major improvements:

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

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

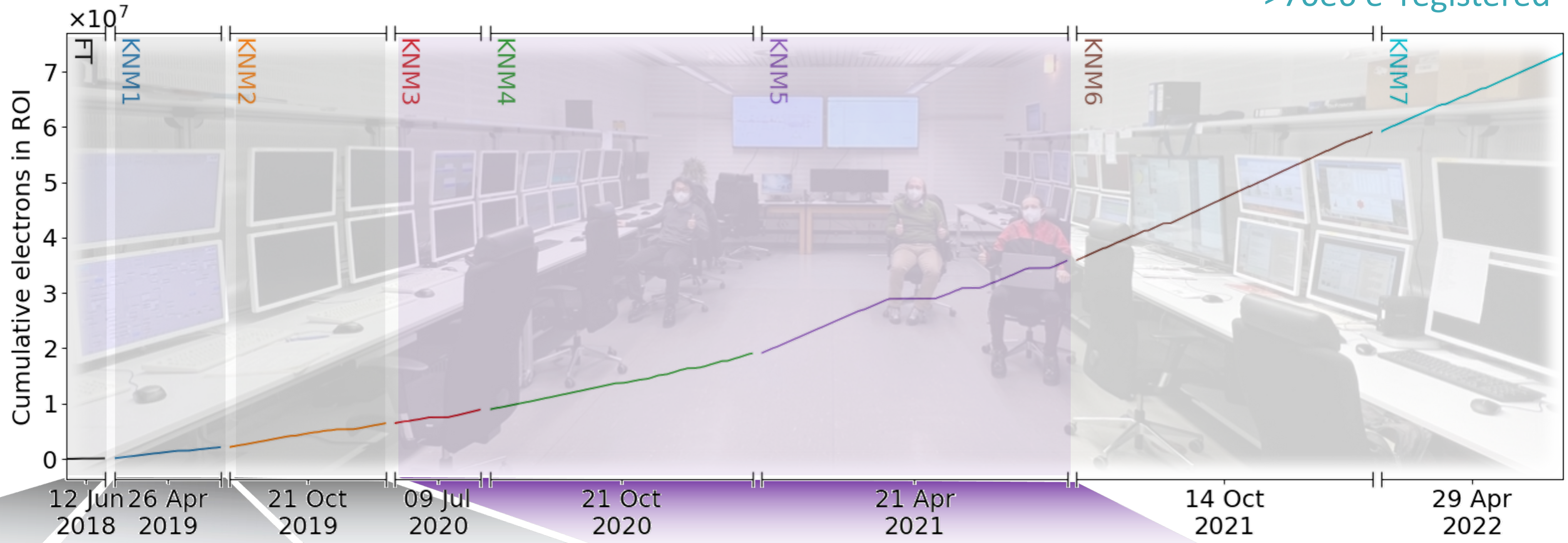


✓ KNM 1 2 3 4 5 (20219 – 2022 data)

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

Outlook –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 2023
- 1st, 2nd, 3rd, 4th, 5th campaigns
- ~30e6 e⁻ in ROI – sensitivity <0.5 eV (90% C.L.)

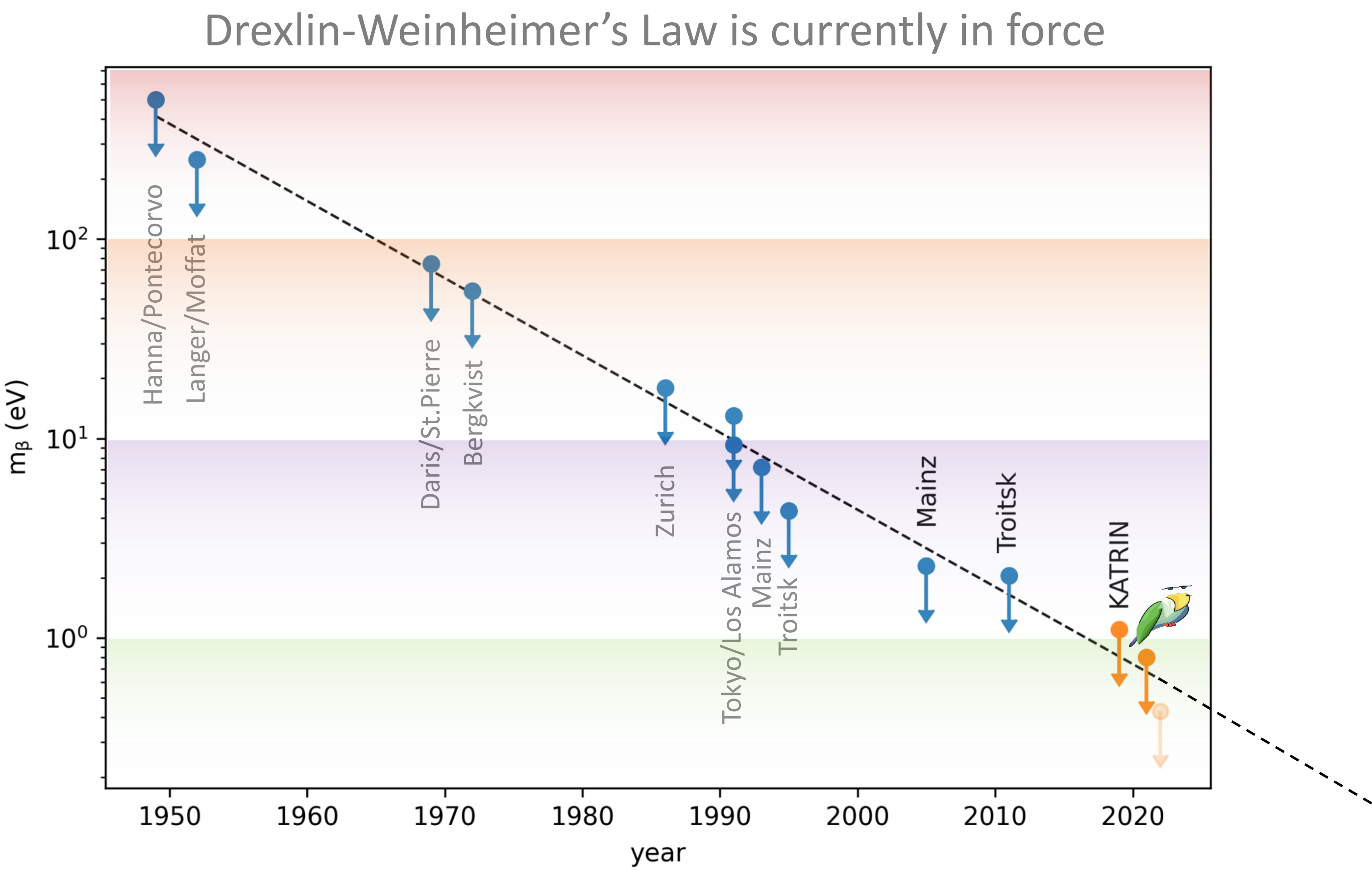
Outlook – 2025

2022:

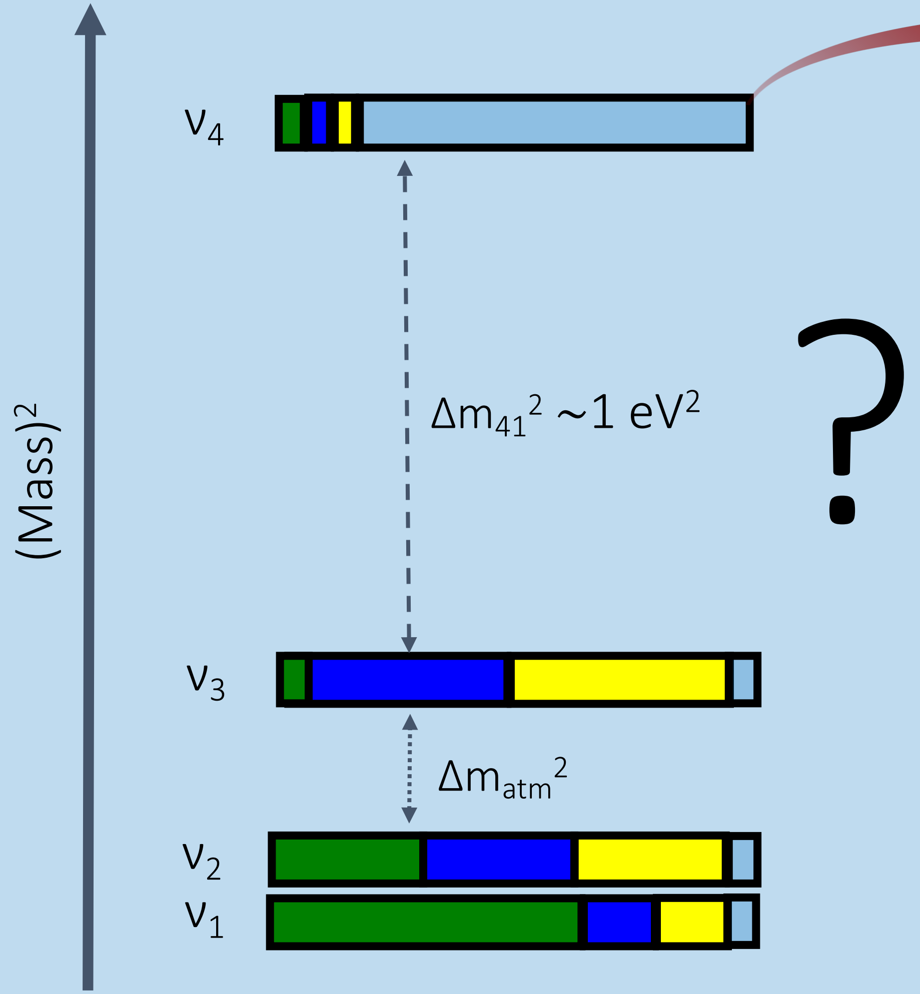
- ✓ first direct neutrino-mass experiment to reach sub-eV sensitivity and limit
- ✓ $m_\nu < 0.8$ eV (90% CL)
  KATRIN Collab. Nat. Phys. **18,** 160–166 (2022)
- ✓ statistics dominated

2025:

- ✓ targeted sensitivity
  $m_\nu < 0.2 - 0.3$ eV (90% CL)
- ✓ measurement or upper limit ?



Are there additional neutrinos (mainly steriles) ?



- New eV-scale massive neutrino?
  - No – or extra-weak SM interaction
  - Mixing with active ν's

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix}$$

$\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$

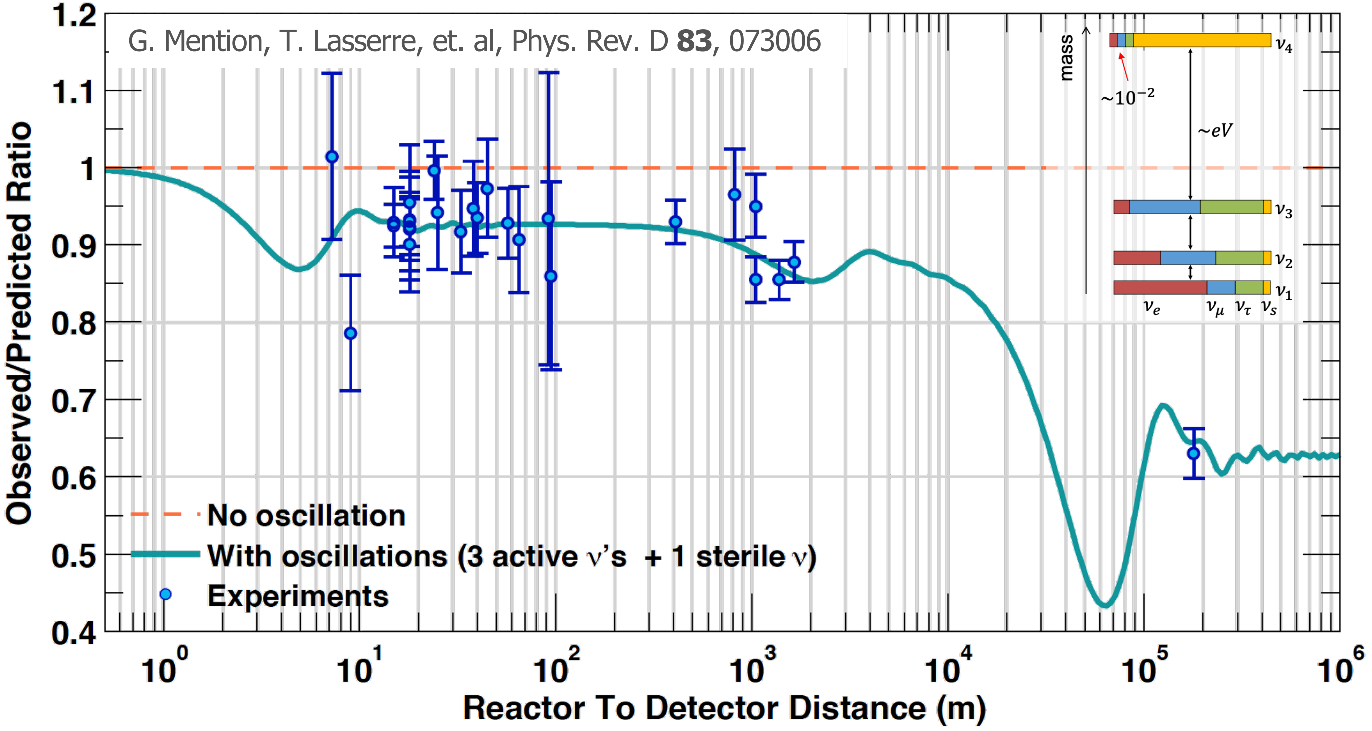
$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$

$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$

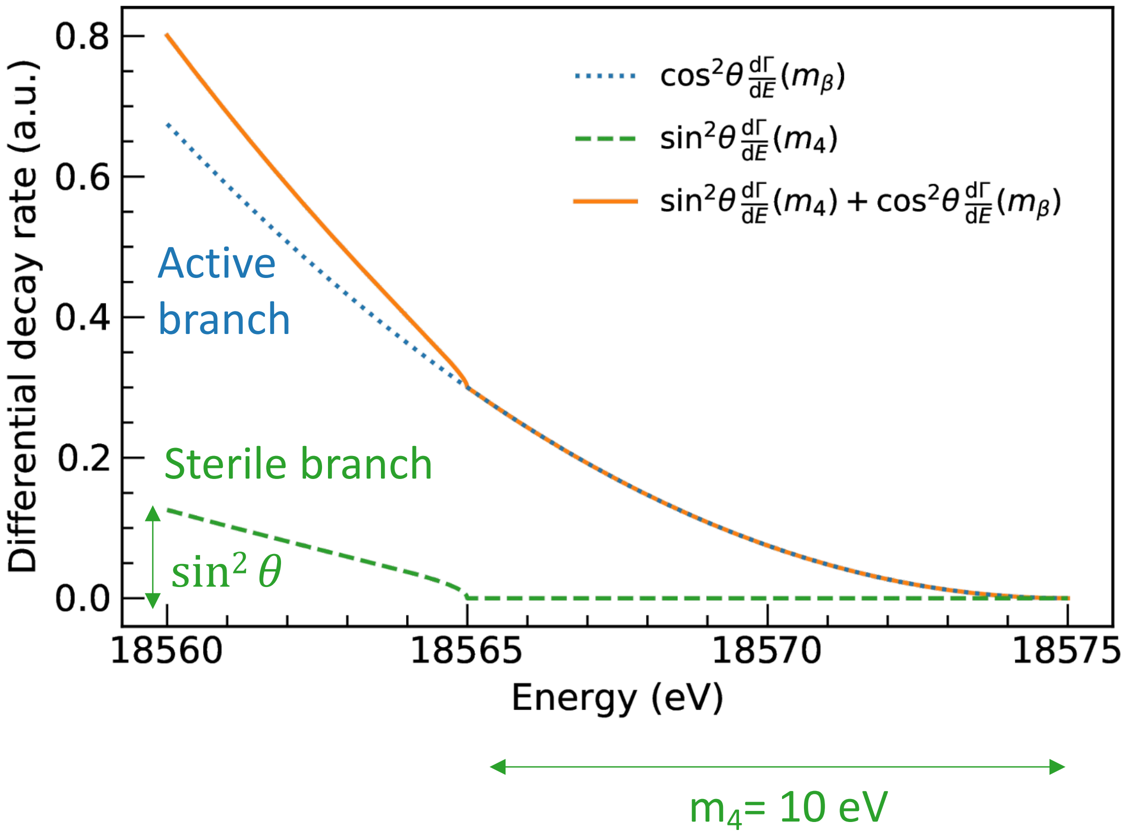
ν_e $|U_{ei}|^2$ ν_μ $|U_{\mu i}|^2$ ν_τ $|U_{\tau i}|^2$ ν_s $|U_{si}|^2$

Search for eV-scale sterile neutrinos

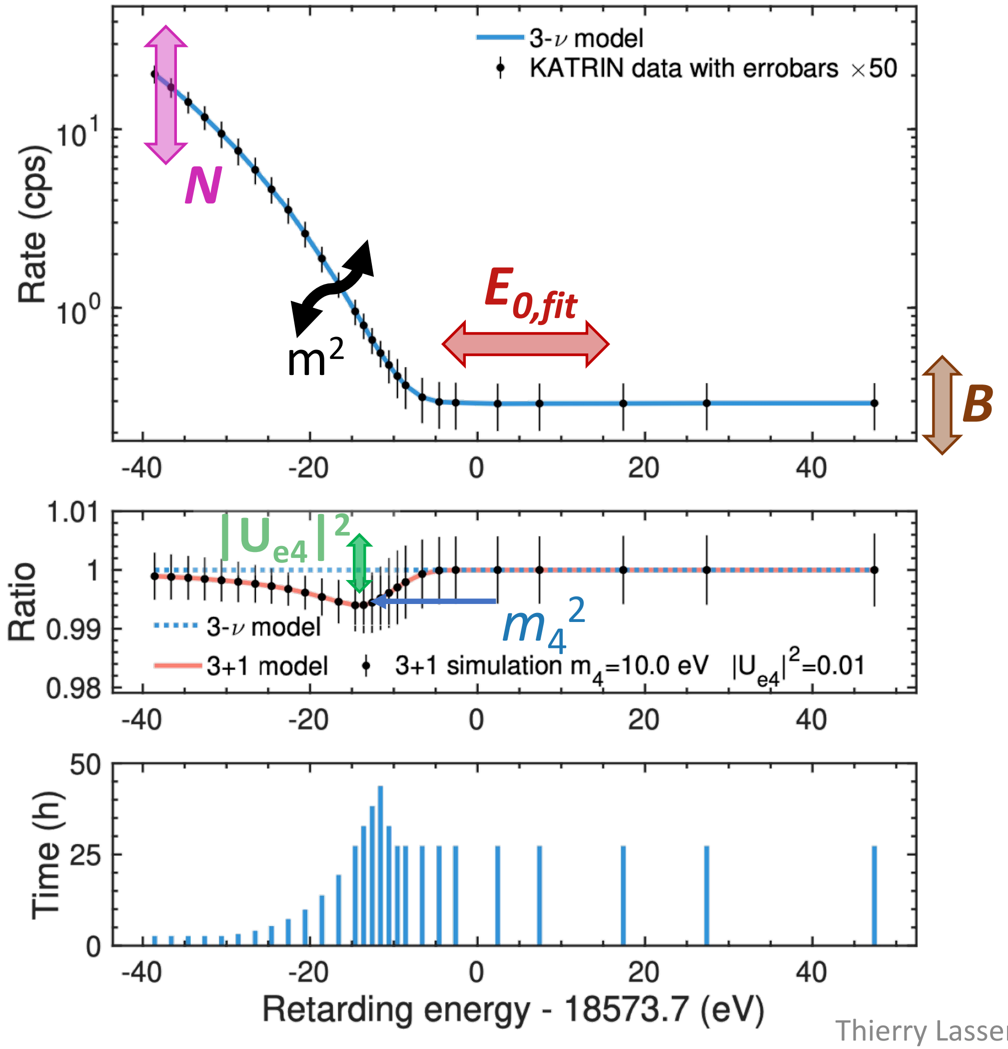
Anomalies in oscillation experiments



Expected signature in KATRIN



Sterile neutrino modeling

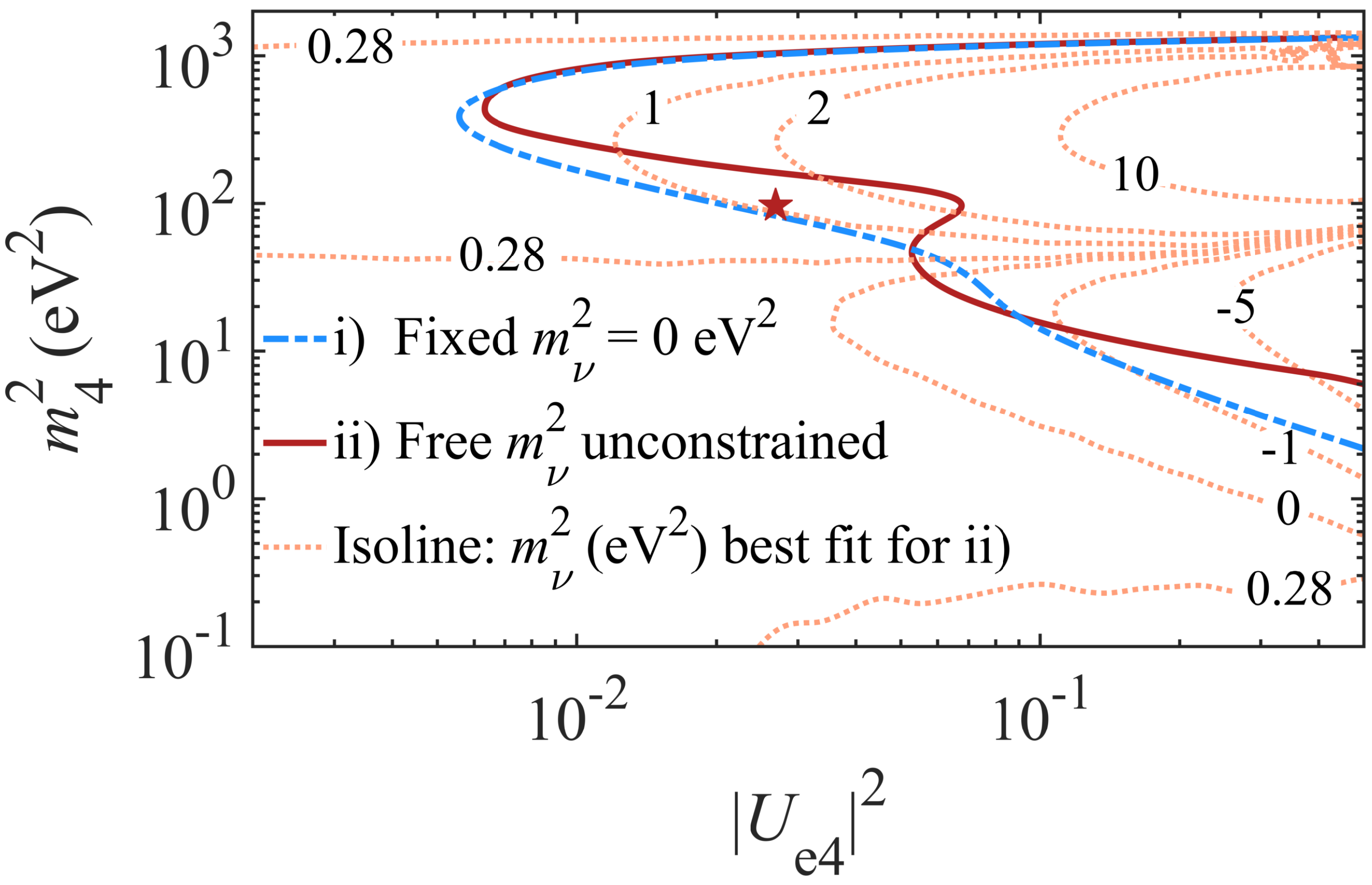


$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} = \underbrace{\left(1 - |U_{e4}|^2\right) \frac{\mathrm{d}\Gamma}{\mathrm{d}E}(m_\beta^2)}_{\text{light neutrino}} + \underbrace{|U_{e4}|^2 \frac{\mathrm{d}\Gamma}{\mathrm{d}E}(m_4^2)}_{\text{heavy neutrino}}$$

<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
$\|U_{e4}\|^2$	4th neutrino mixing

KSN2 Results: no evidence for light sterile neutrinos

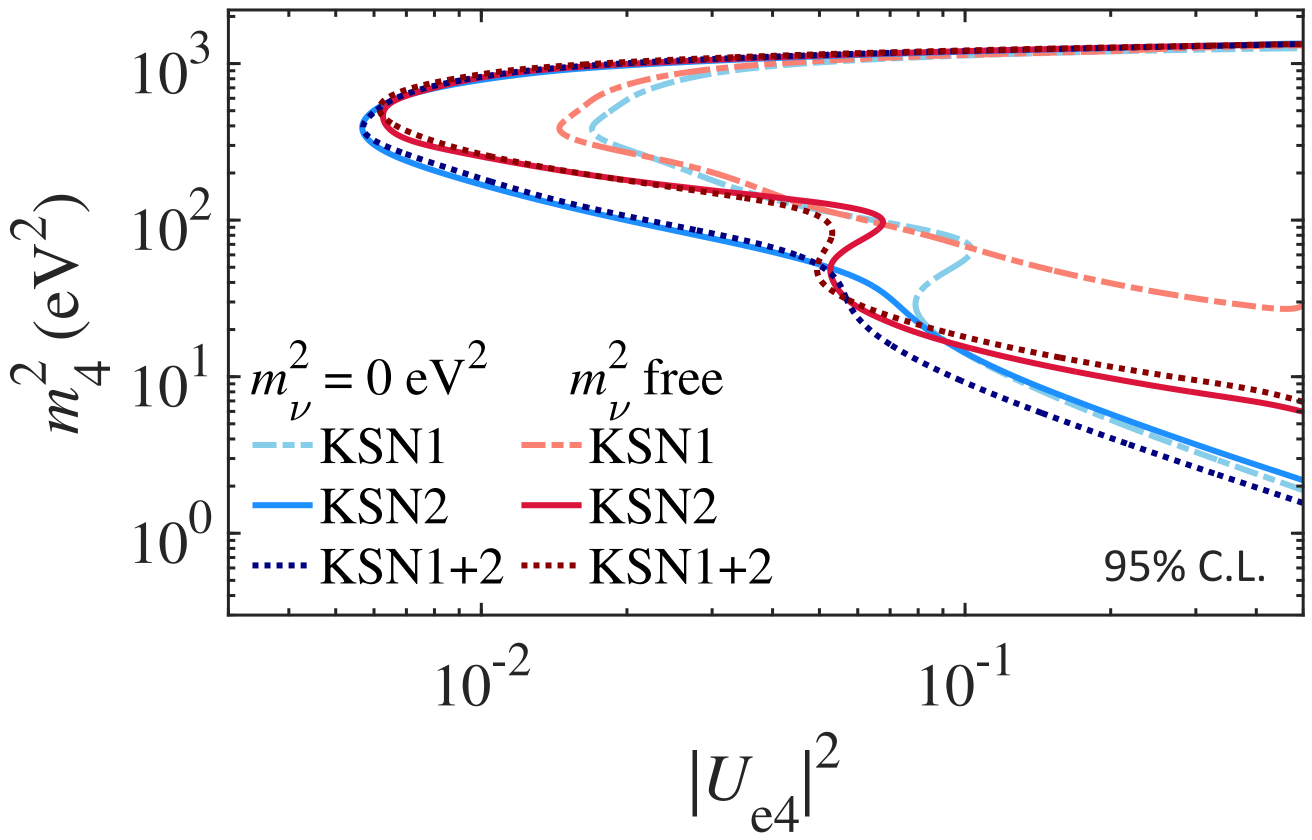


- Scenario i) : $\boldsymbol{m_{1,2,3} \ll m_4}$: $\boldsymbol{m_\nu^2 = 0}$ **eV^2**
  - Best fit:
  - $|U_{e4}|^2 = 1.0$, $m_4^2 = 0.28$ eV^2 → KNM-2
  - $\chi^2_{\rm min} = 27.5$ (23 dof) , $p = 0.24$
  - $\Delta\chi^2 = \chi^2_{\rm Null} - \chi^2_{\rm bf} = 0.7$
  - → No significant improvement (0.8σ) over no-sterile hypothesis

- Scenario ii) : $\boldsymbol{m_\nu^2}$ unconstrained nuisance parameter
  - Best fit:
  - $|U_{e4}|^2 = 0.027$, $m_4^2 = 98$ eV^2 & $m_\nu^2 = 1.1$ eV^2
  - $\chi^2_{\rm min} = 25.0$ (22 dof) , $p = 0.30$
  - $\Delta\chi^2 = \chi^2_{\rm Null} - \chi^2_{\rm bf} = 2.5$
  - → No significant improvement (1.4σ) over no-sterile hypothesis

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

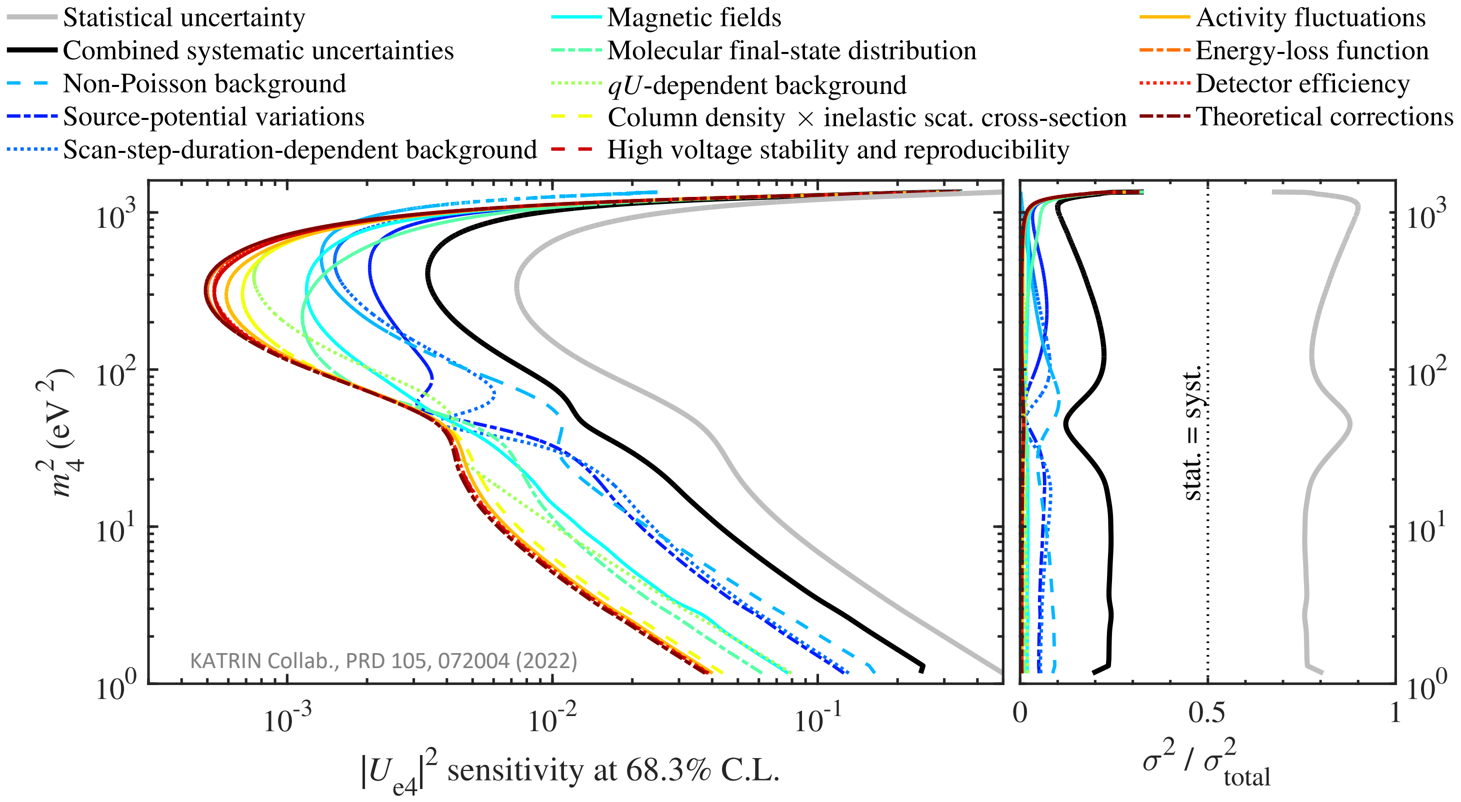
✓ **scenario ii) : m_ν^2 as a free parameter**

- ✓ 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

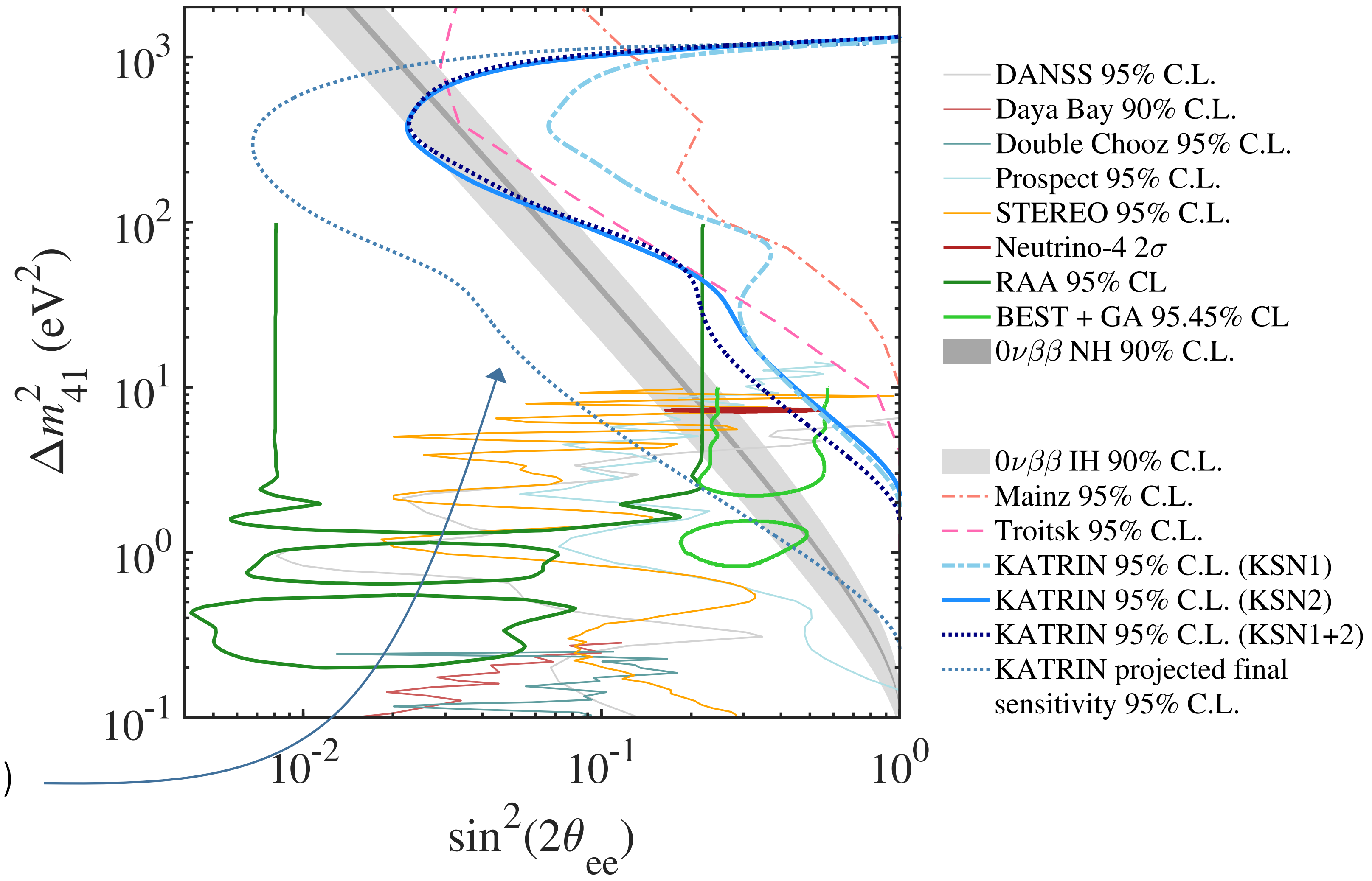
Systematic uncertainties

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

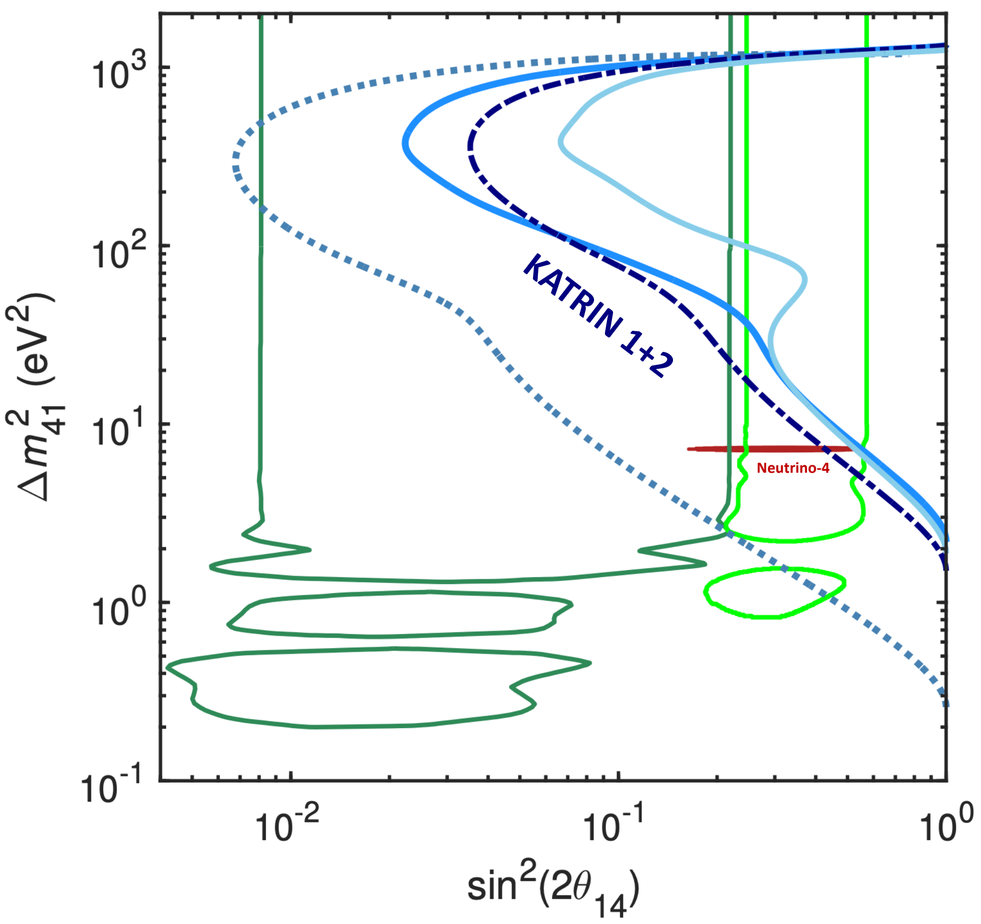


Complementarity with oscillation experiments

- **Oscillation Electron Disappearance Experiments**
  - $\Delta m_{41}^2 = m_4^2 - m_1^2 \approx \Delta m_{42}^2 \approx \Delta m_{43}^2$
  - $\sin^2 2\Theta = 4|U_{e4}|^2(1-|U_{e4}|^2)$
- **KATRIN**
  - m_β and m_4
  - $\sin^2\Theta = |U_{e4}|^2$
- Conversion KATRIN -to- Oscillation
  - $\Delta m_{41}^2 \simeq m_4^2 - m_\beta^2$
  - $\sin^2 2\Theta = 4 \sin^2\Theta(1- \sin^2\Theta)$
- Projected KATRIN final sensitivity (1000 days of data – reduced background)

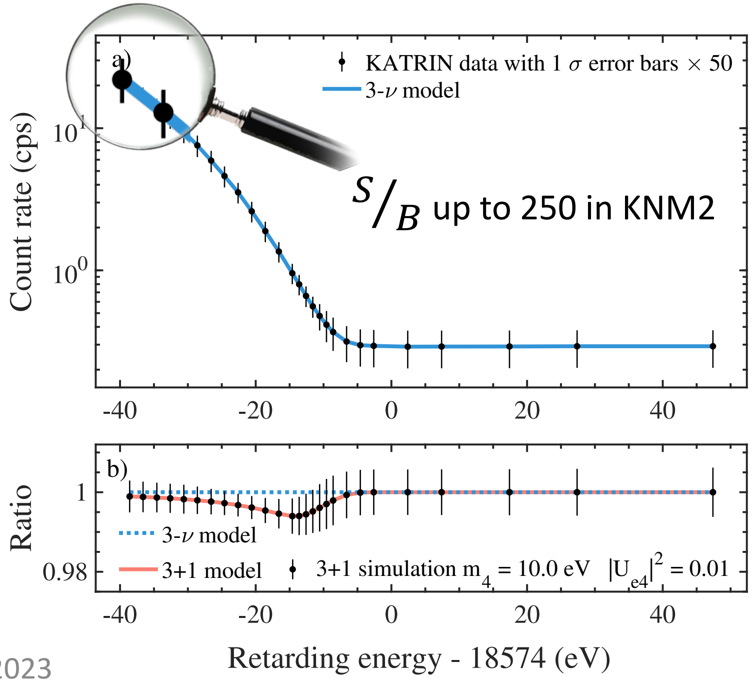


Comparison to anomalies



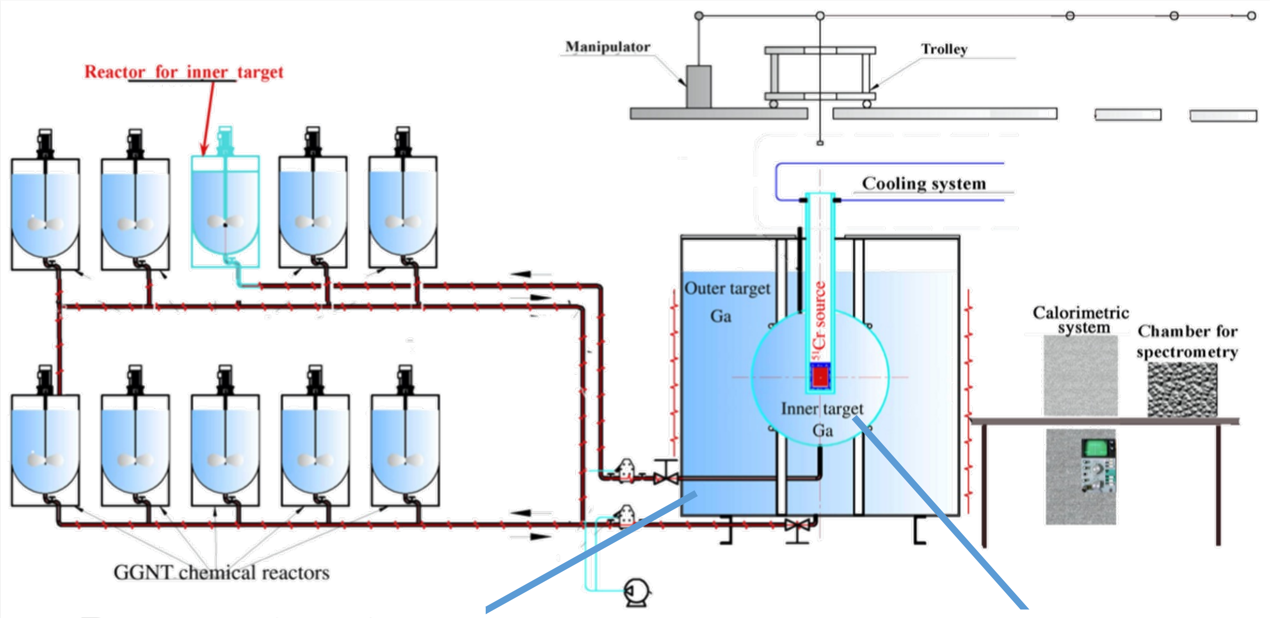
- ✓ tackling short baseline oscillation anomalies from a different perspective (shape-only search)
- ✓ start probing interesting parameter space

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

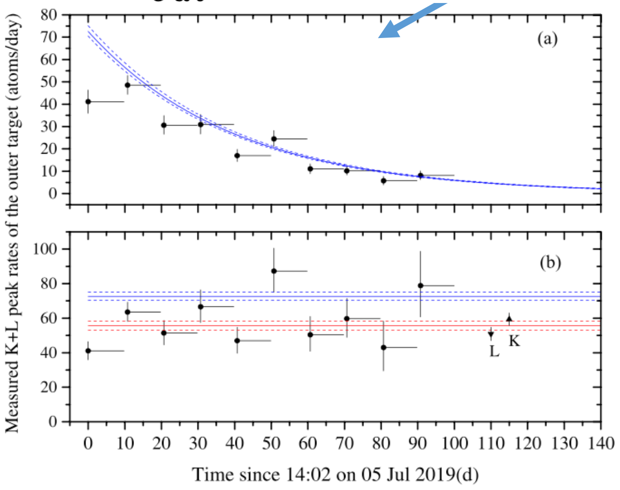


Remark on the Gallium Anomaly – BEST results

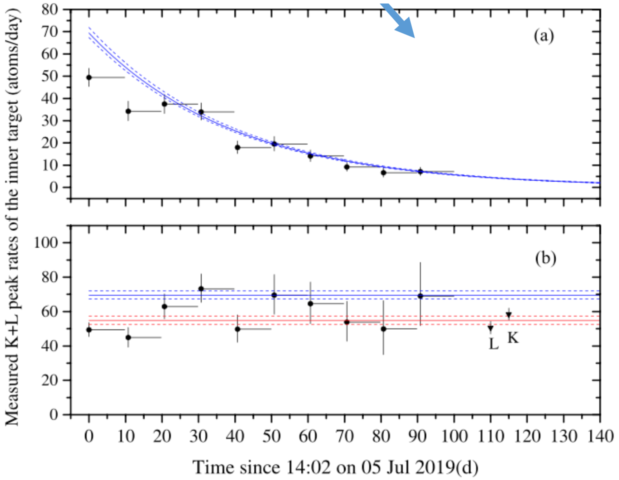
Proofed technology & methodology. BEST results are robust



$R_{out} = 0.766 \pm 0.05$

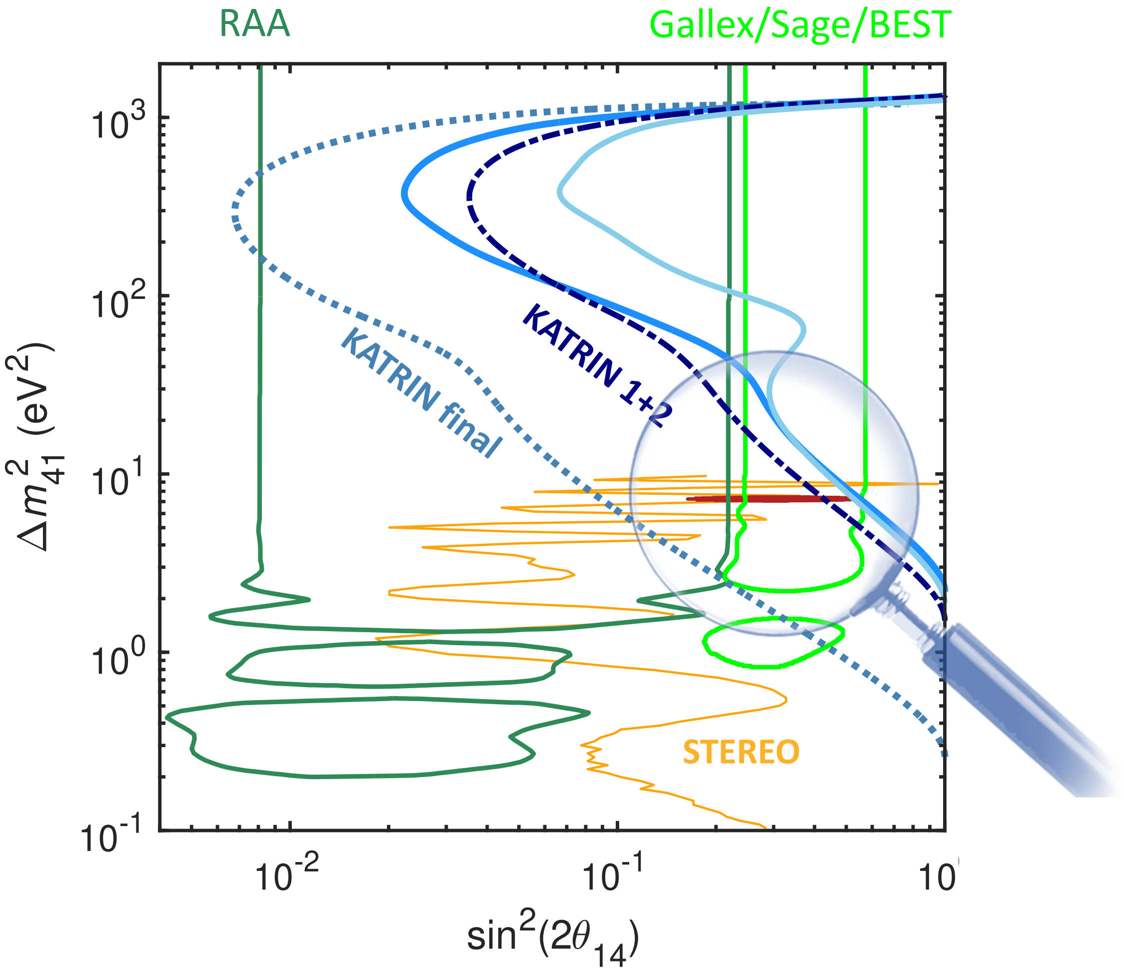


$R_{in} = 0.791 \pm 0.05$



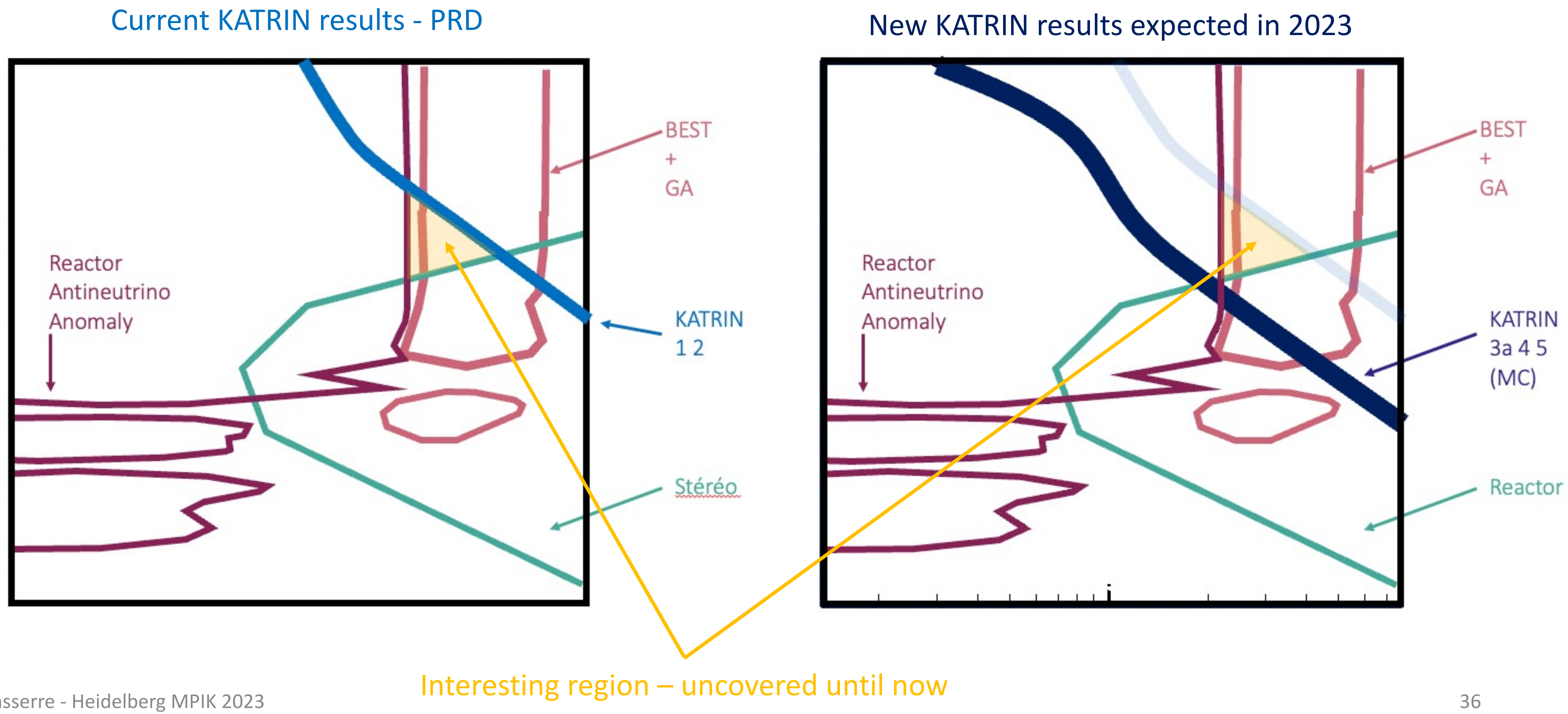
- BEST investigate the Gallium Anomaly (GA) with high-intensity ^{51}C sources
- 3.4-MCi ^{51}Cr ν_e source at the center of two nested Ga volumes. ^{71}Ge production through the CC reaction, $^{71}Ga(\nu_e, e^-)^{71}Ge$
- $R_{in/prediction}$ = 0.791±0.05 ! Significant Deficit
- $R_{out/prediction}$ = 0.766±0.05 ! Significant Deficit
- R_{out}/R_{in} = .97±0.07 → but no specific sterile neutrino signature
- Puzzling…

Synergy with oscillation experiments

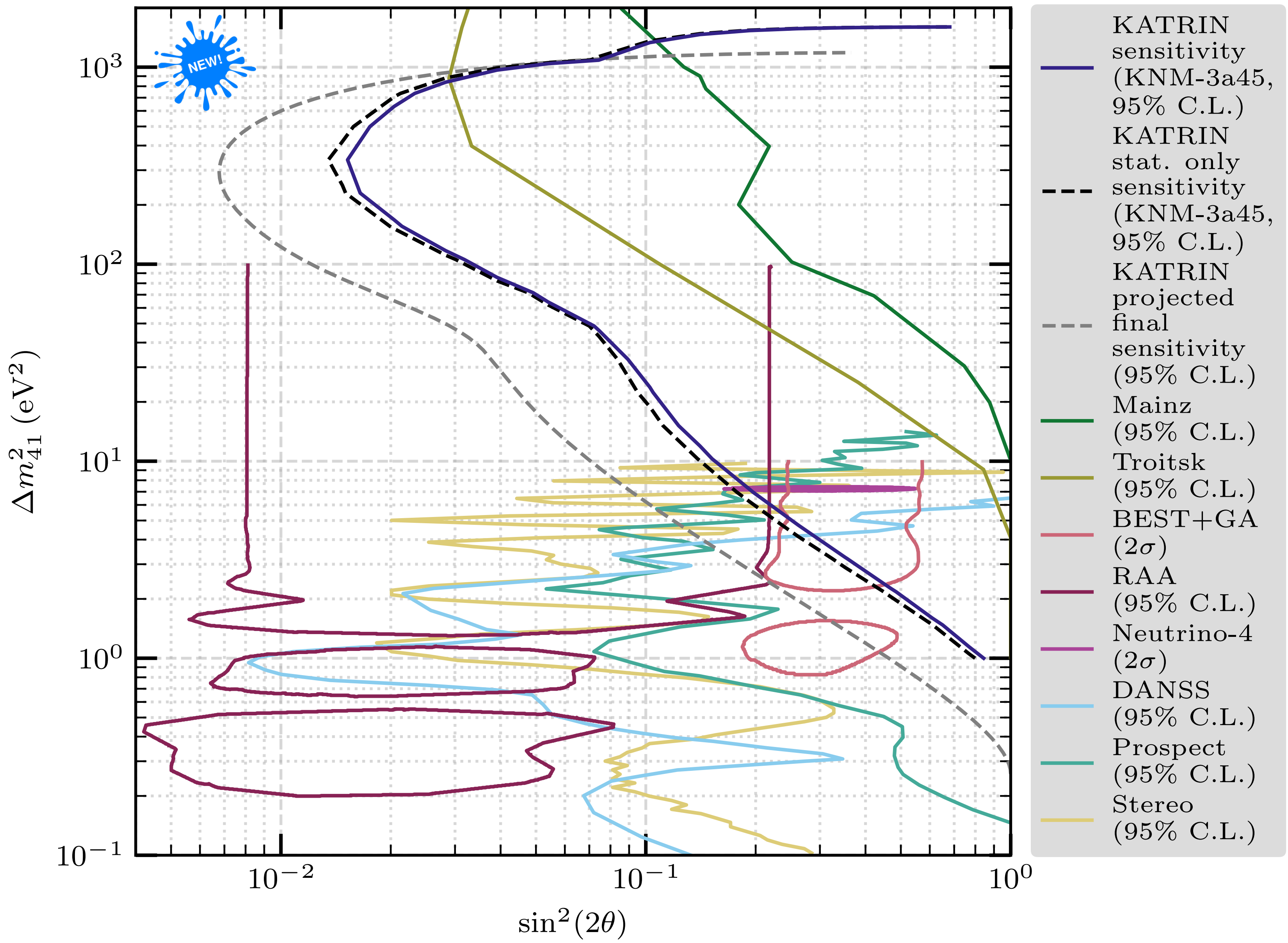


- ✓ tackling short baseline oscillation anomalies from a different perspective (shape-only search)
- ✓ start probing interesting parameter space
  KATRIN Collab., PRL. 126, 091803 (2021)
  KATRIN Collab., PRD 105, 072004 (2022)
- ✓ complementary probe to oscillation-based experiments
  DANSS, arXiv:1911.10140 (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 $\Delta m^2 > 5$ eV^2

Forthcoming sterile neutrino results in 2023



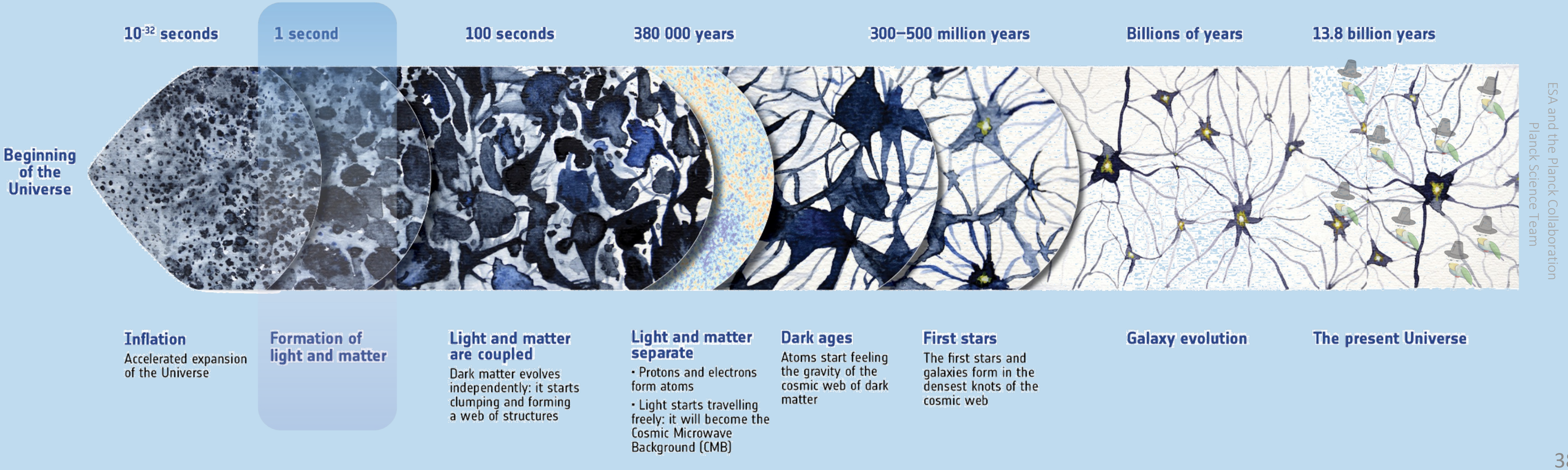
KATRIN Sensitivity Study – data 2019 - 2022



- 30-ish millions of events in ROI
- Reduced background
  - Improvement at low Δm_{41}^2
- Significant improvement with respect to KSN 1+2
- Neutrino-4 claim fully covered
- Significant constraint for $\Delta m_{41}^2 < 10$ eV^2

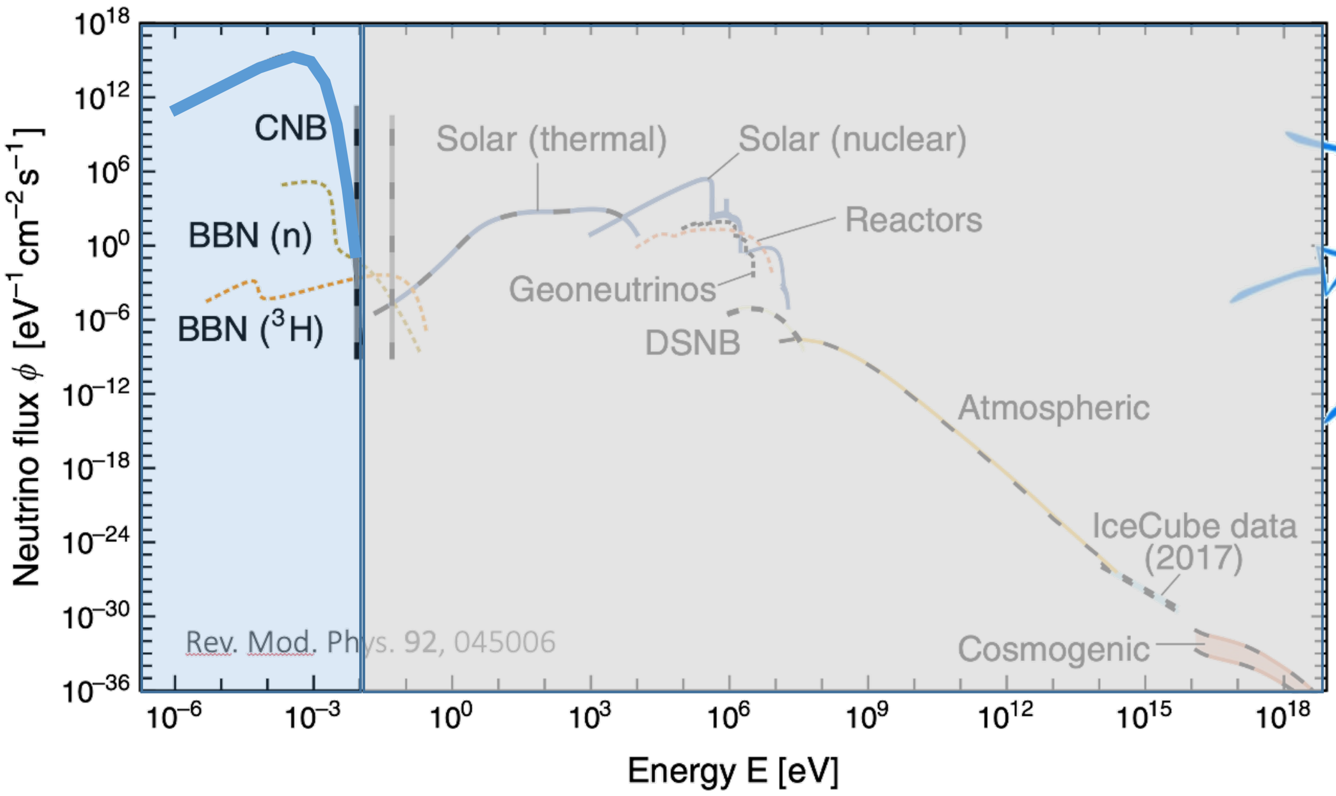
Cosmic neutrino background

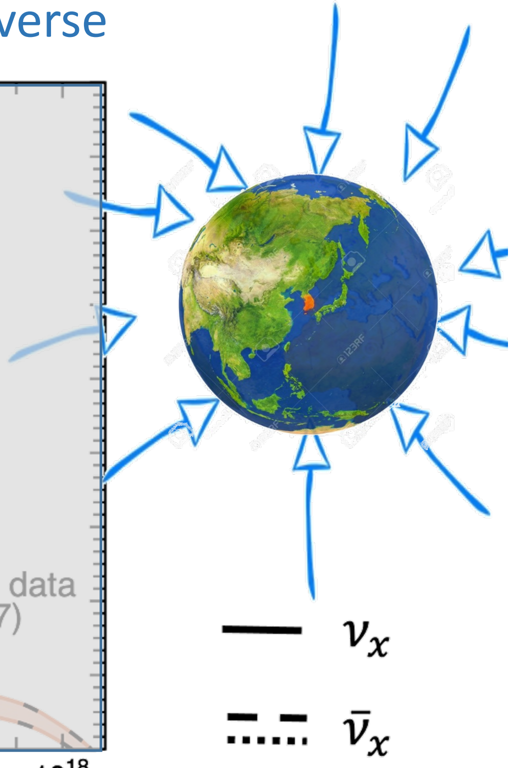
- ✓ in the early Universe, ν's are in thermal equilibrium with matter
- ✓ Big-Bang+1 sec (1 MeV) ν decouple ⟶ Relic (Cosmic) Neutrino Background emission
- ✓ today: $\langle n_\nu \rangle \sim 56$ O(meV) ν per cm^3 per specie
- ✓ Not yet directly detected on Earth



Cosmic neutrino background overdensity

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



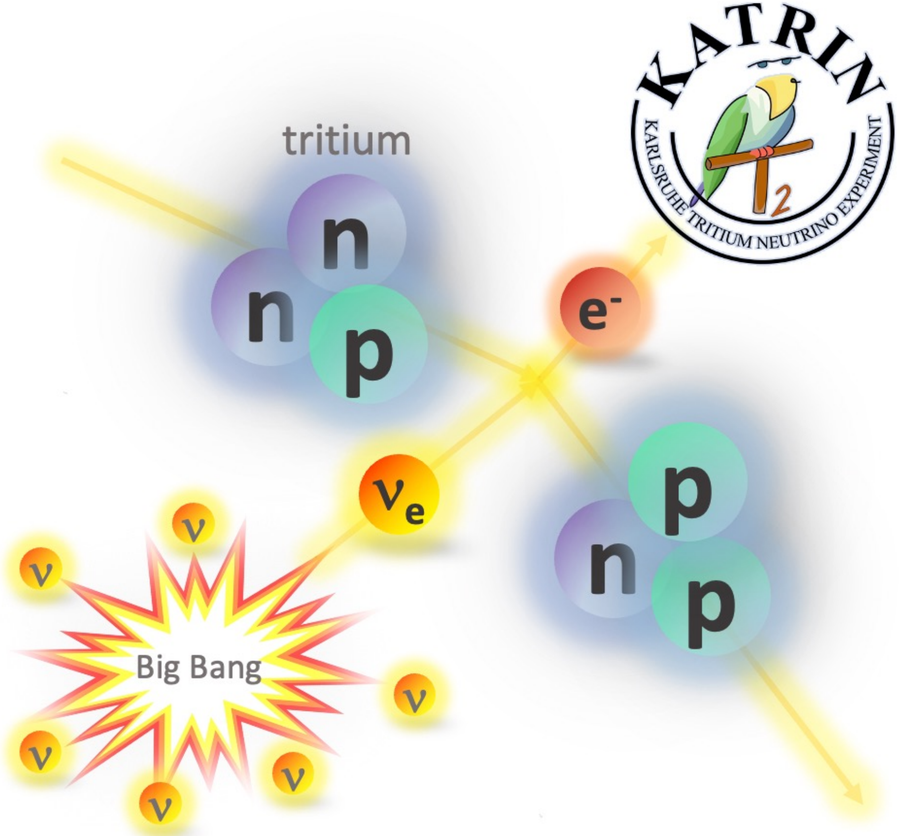


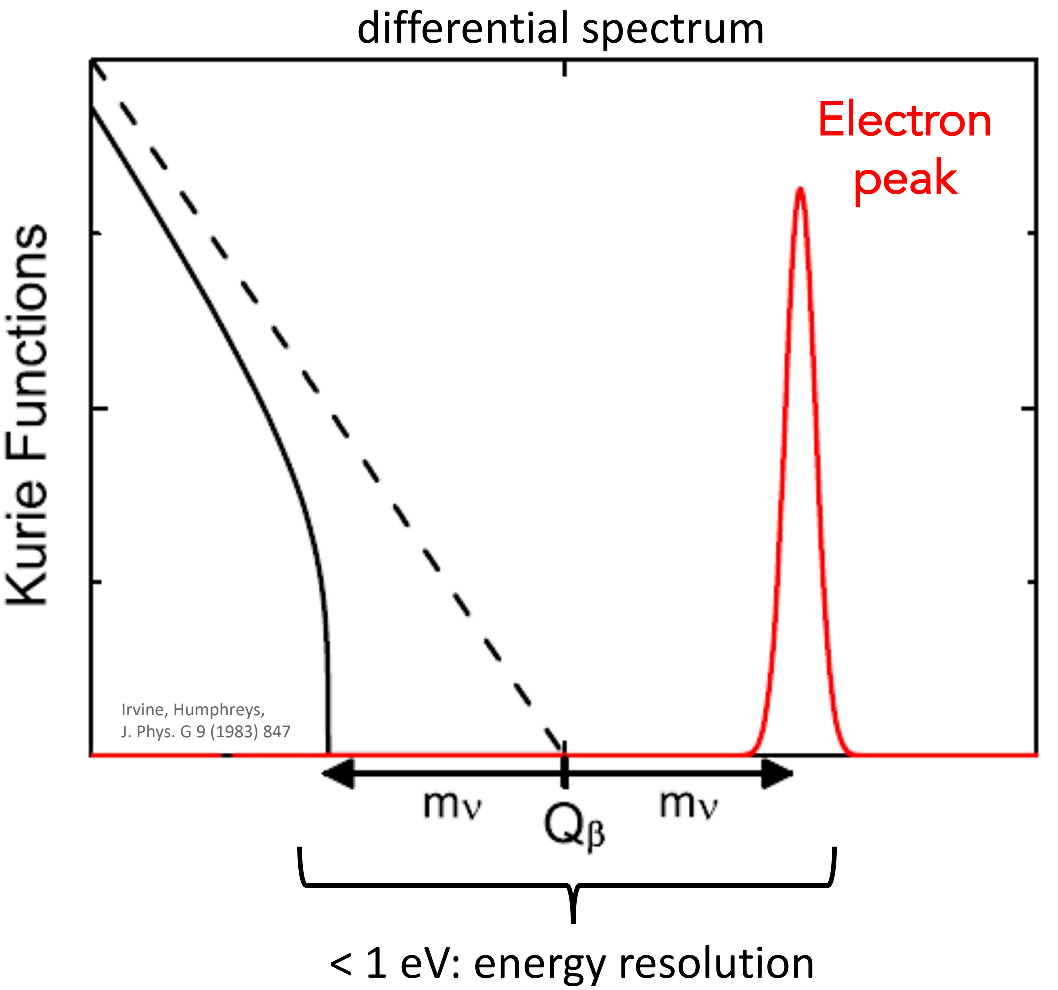
KATRIN restricts the maximum overdensity ratio η of relic neutrinos on Earth

Thresholdless meV-ν capture on Tritium

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

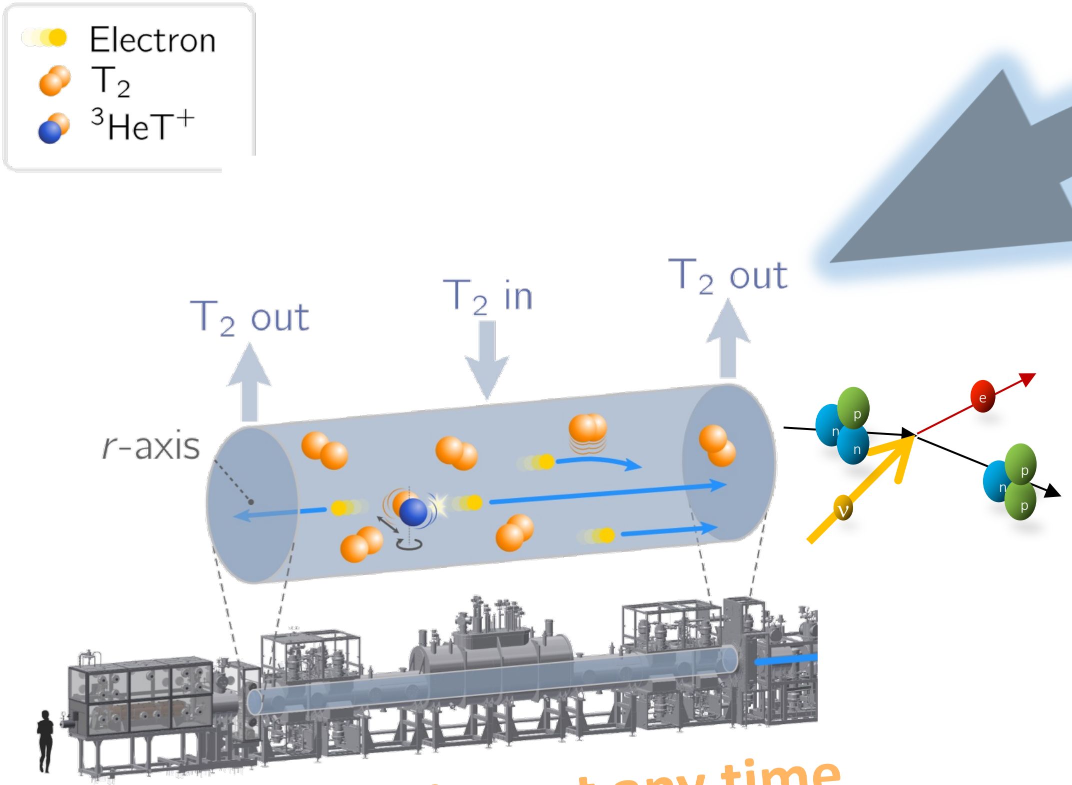
S. Weinberg, Phys.Rev. 128 (1962) 1457–1473





100 g tritium yields 10 ν captures per year

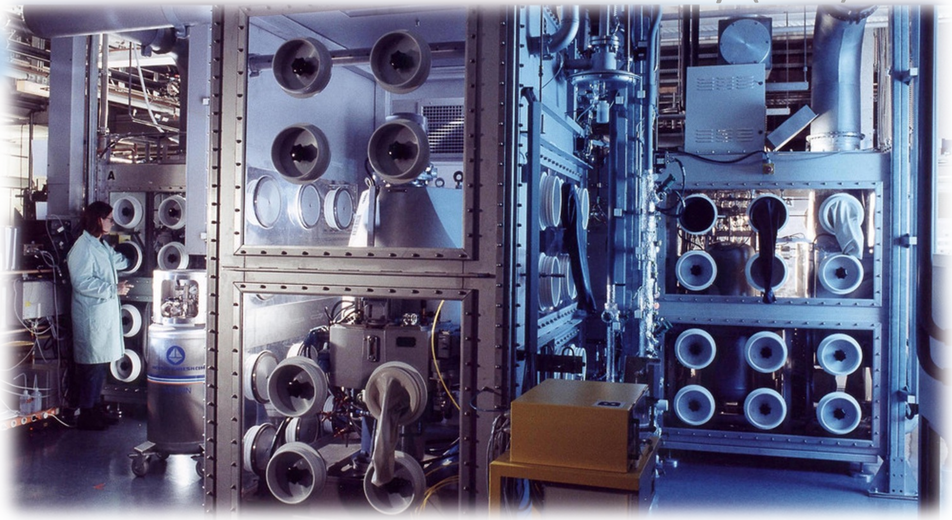
Sensitivity to the overdensity ratio η



30 μg of tritium at any time

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

Karlsruhe Tritium Laboratory (TLK)

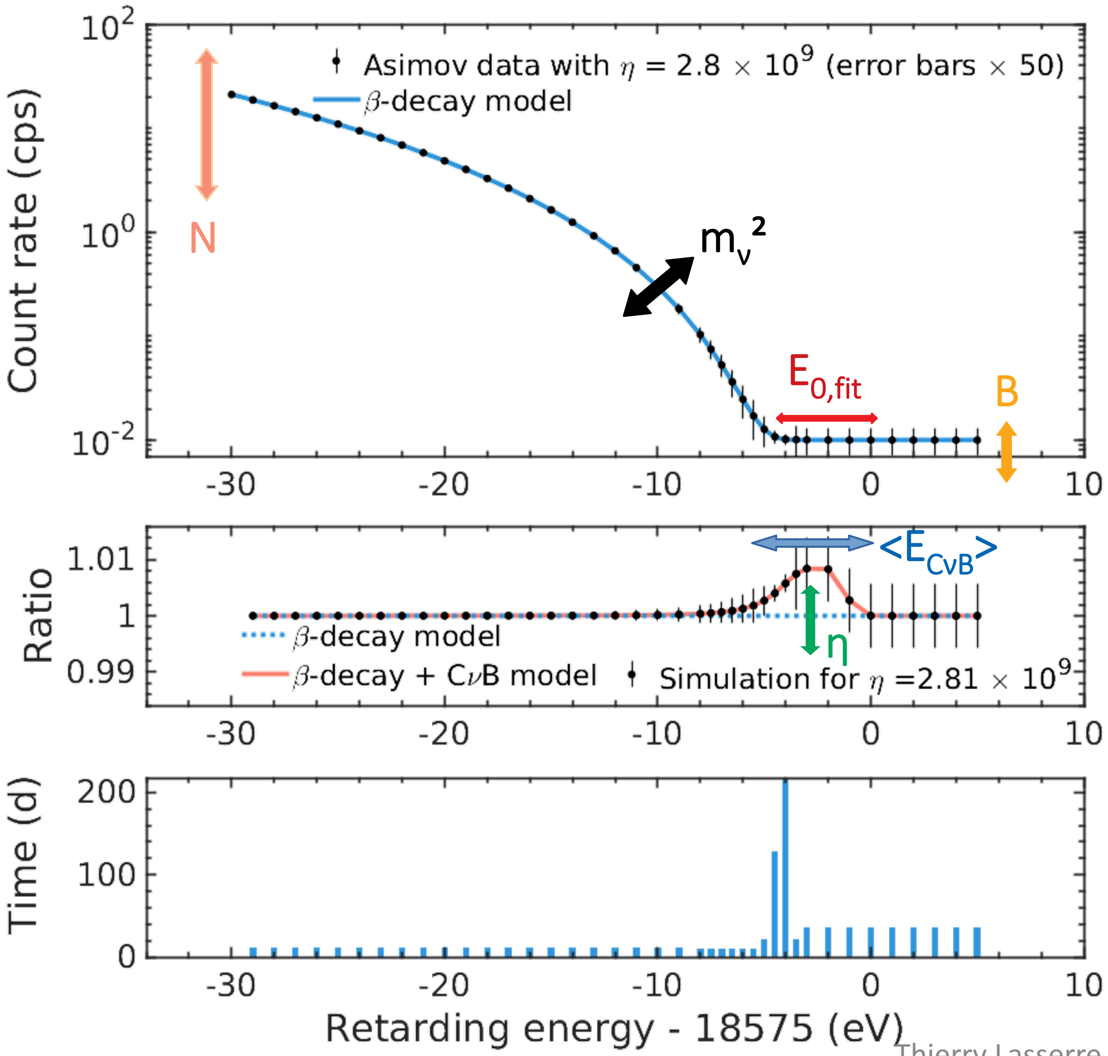


Overall gaseous tritium quantity at TLK: currently 25 g

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

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

Relic neutrino modeling

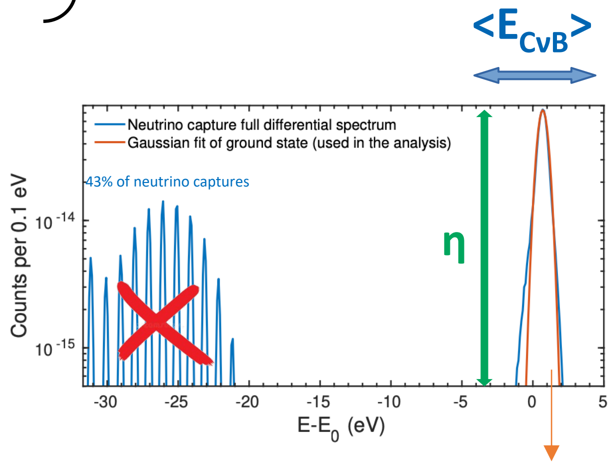


Fit Parameters:

- ✓ 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 capture peak on the differential spectrum

Relic neutrino search fit with systematics

✓ Standard χ^2 minimization

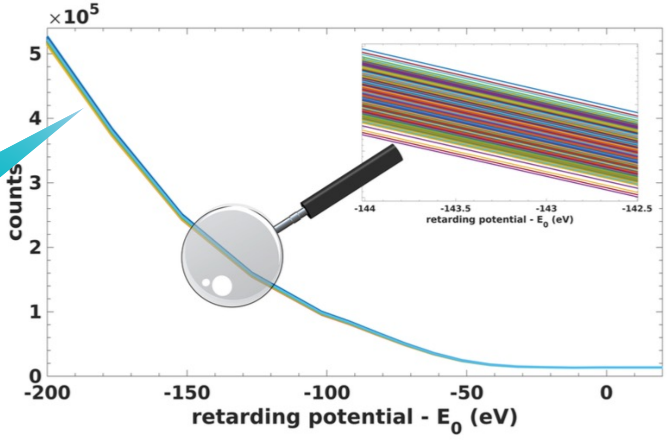
m_ν^2, E_0, B, A
+ RNB peak position & overdensity η

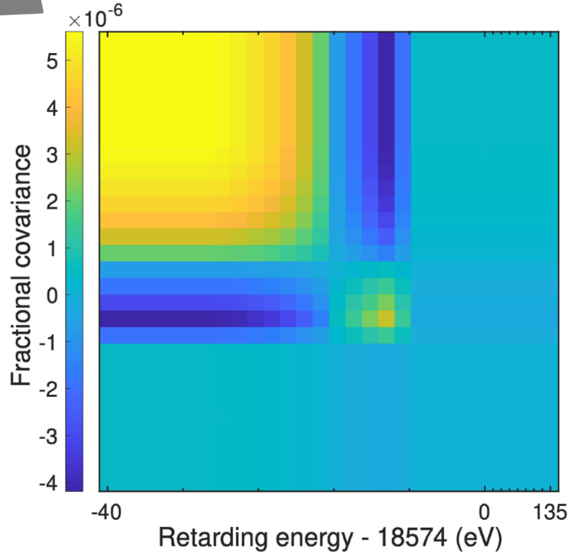
$$\chi^2 = \left(\vec{R}_{\rm data}(q\vec{U},\vec{r}) - \vec{R}(q\vec{U},\vec{r}|\vec{\Theta},\vec{\eta})\right)^T C^{-1} \left(\vec{R}_{\rm data}(q\vec{U},\vec{r}) - \vec{R}(q\vec{U},\vec{r}|\vec{\Theta},\vec{\eta})\right)$$

B-fields, ρd, plasma, …

✓ Uncertainty propagation with covariance matrices

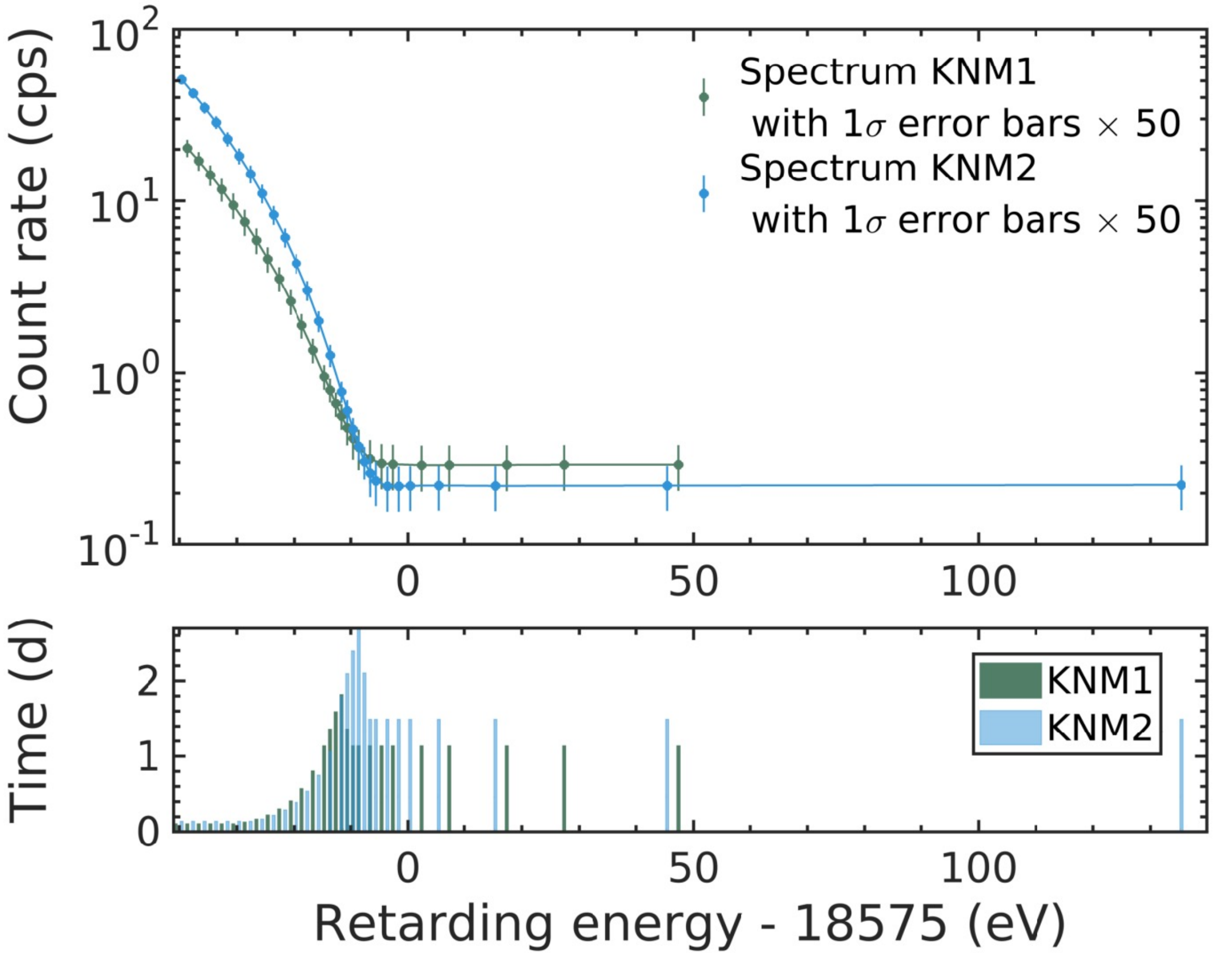
Compute 10^4 spectra with different systematic configurations





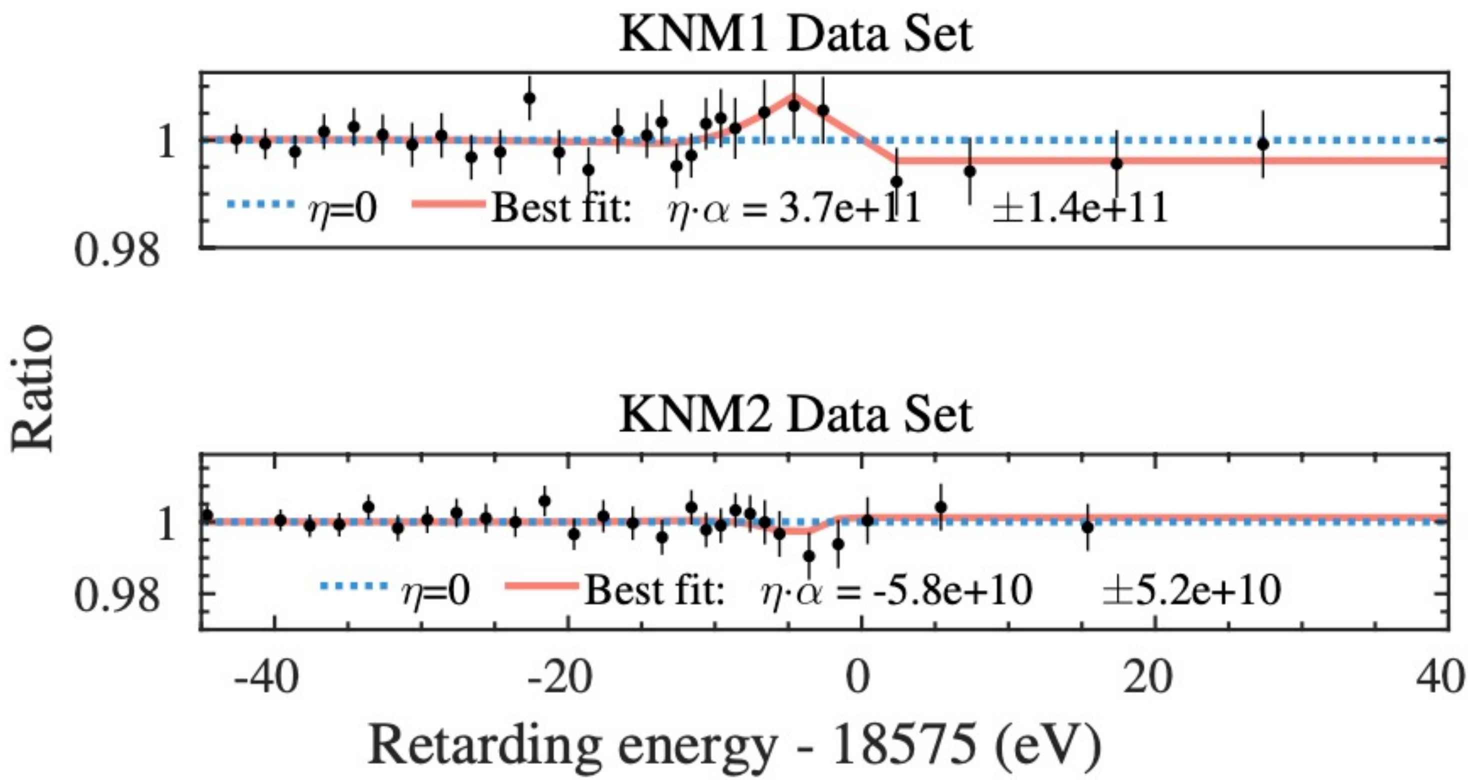
✓ Blinding: analysis validated & fixed on mockup data

Relic neutrino fit results (best fit)



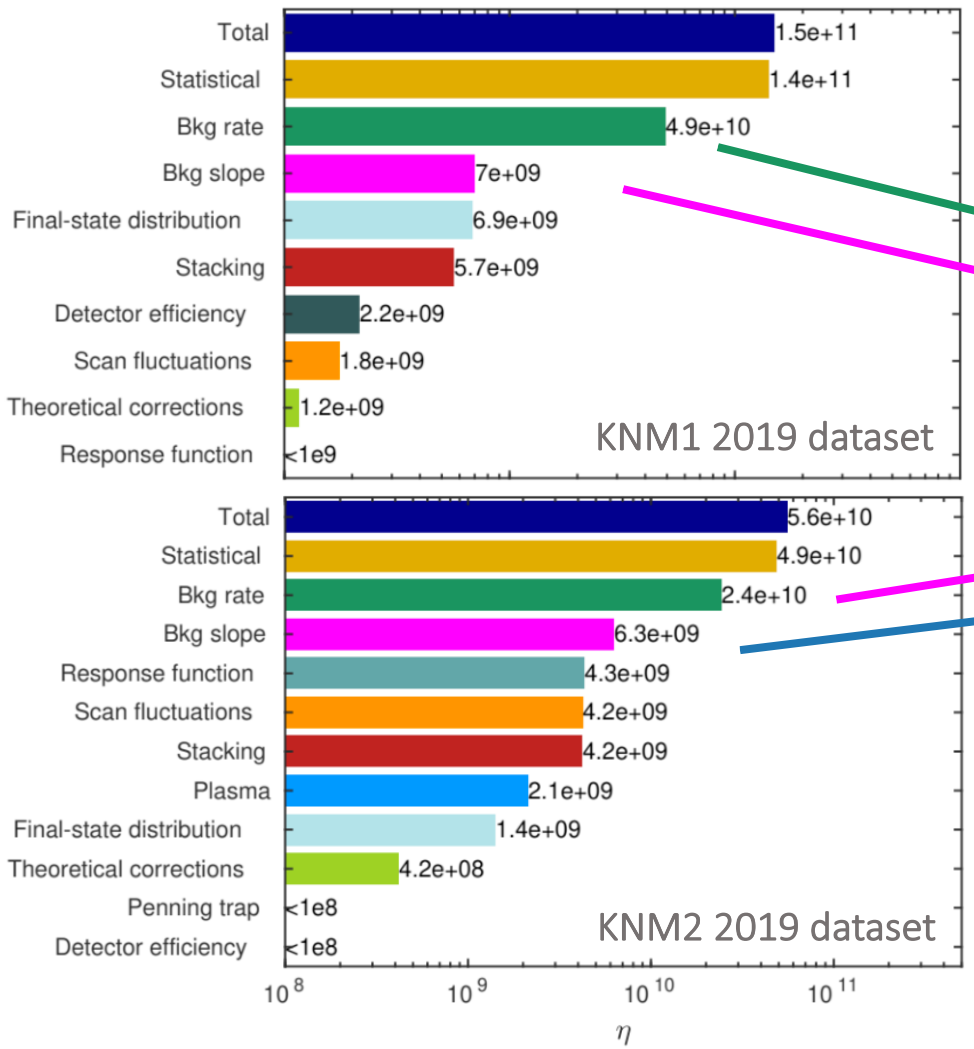
- ✓ KNM1 2019 dataset:
  - ✓ 522 hours
  - ✓ 3.4 μg for capture on tritium
- ✓ KNM2 2019 dataset
  - ✓ 744 hours
  - ✓ 13.0 μg for capture on tritium

Relic neutrino fit results (best fit)

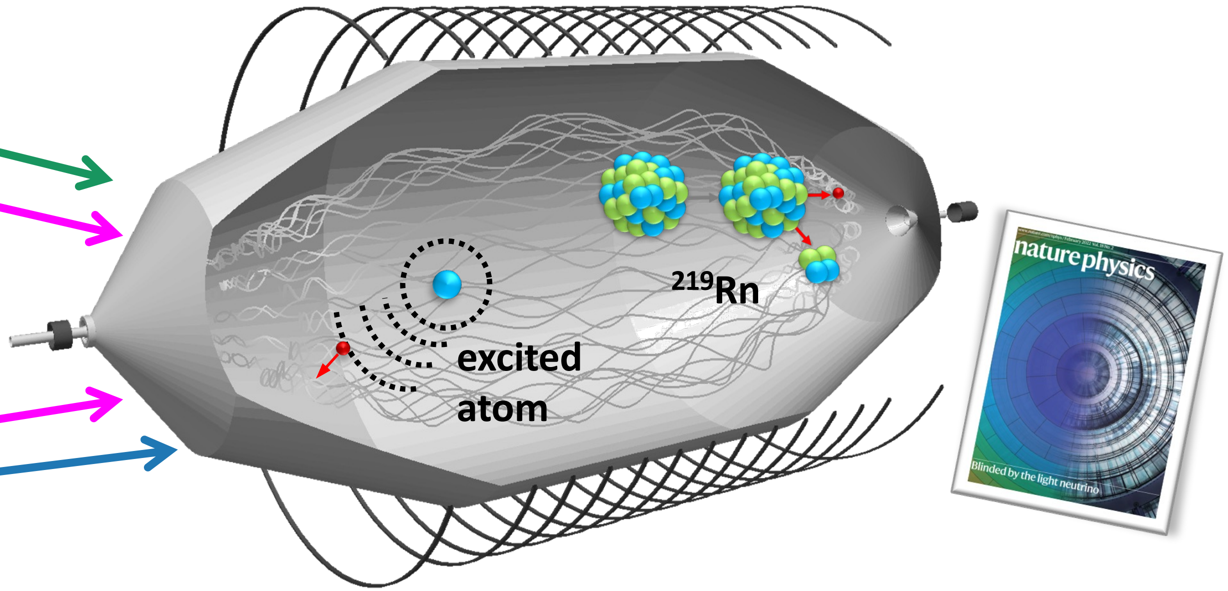


- ✓ KNM1 2019 dataset:
  - ✓ 522 hours
  - ✓ 3.4 μg for capture on tritium
- ✓ KNM2 2019 dataset
  - ✓ 744 hours
  - ✓ 13.0 μg for capture on tritium
- ✓ no evidence for relic neutrino overdensity → upper limits
- ✓ KNM 1+2 combination

Uncertainty budget for relic neutrino search



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

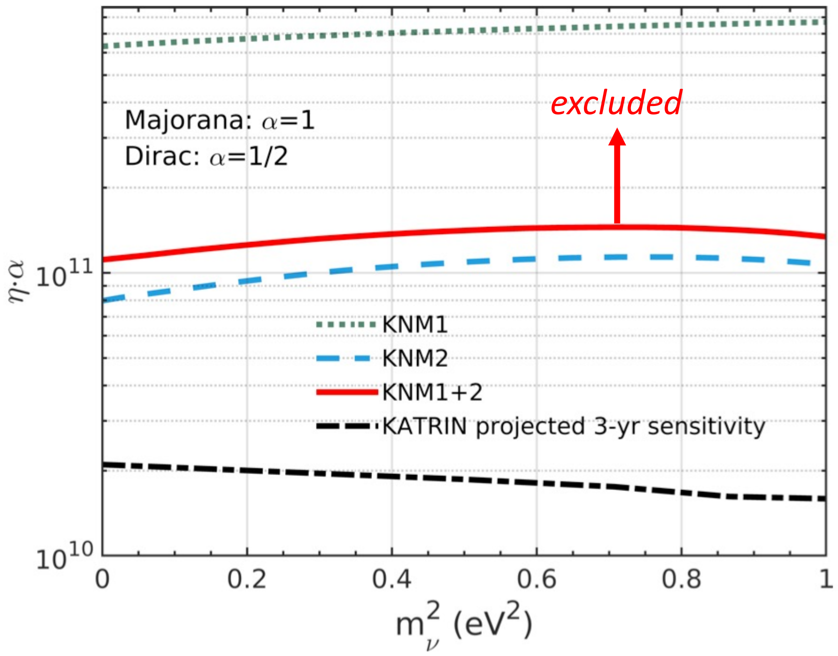


✓ **Both analyses are statistics dominated**

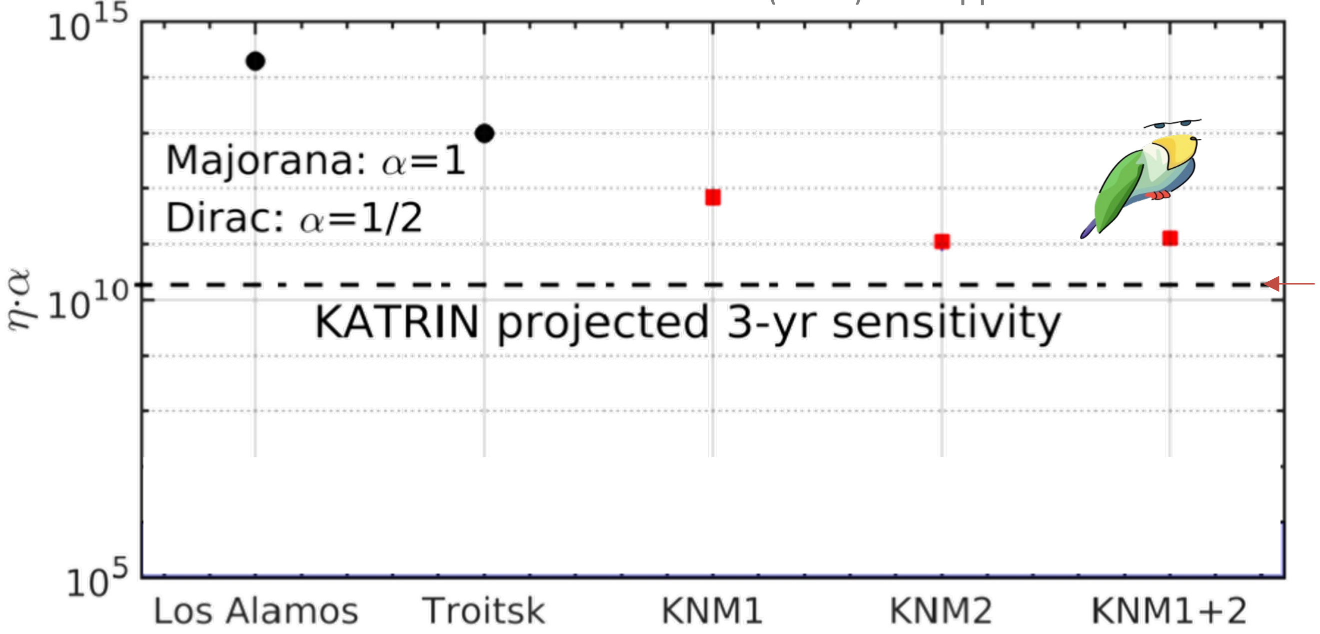
✓ Largest systematics: Background rate & Background slope

Relic Neutrino Results (2022)

- ✓ test for <u>large overdensity η</u> of relic neutrinos in our surrounding (based on **1st** and **2nd** campaigns)
- ✓ $\eta < 1.1 \cdot 10^{11}$ at 95% CL – the search is statistically limited
- ✓ improved limit by 2 orders of magnitude compared to previous laboratory limits

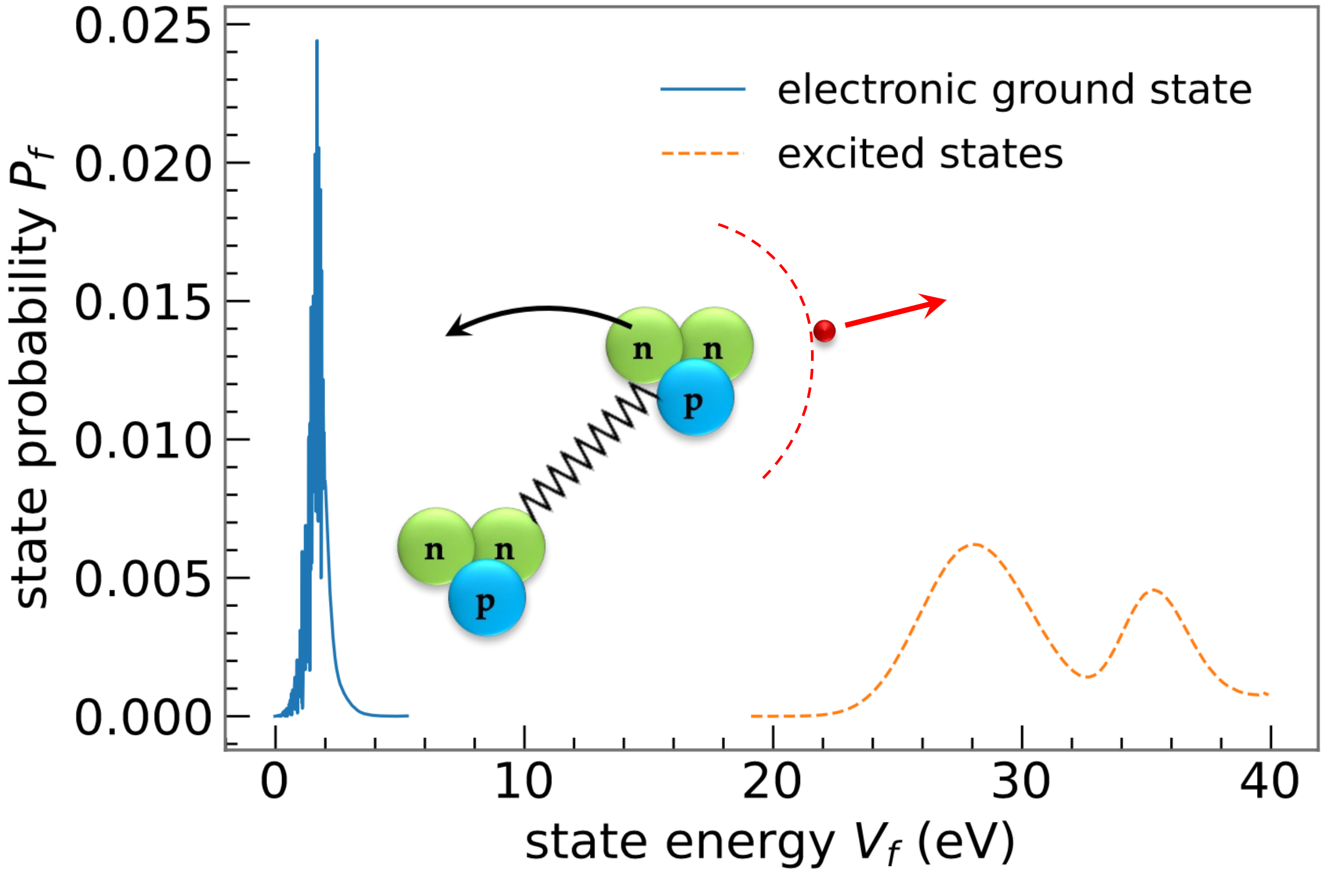


KATRIN Collab. arXiv:2202.04587 (2022) – to appear in PRL



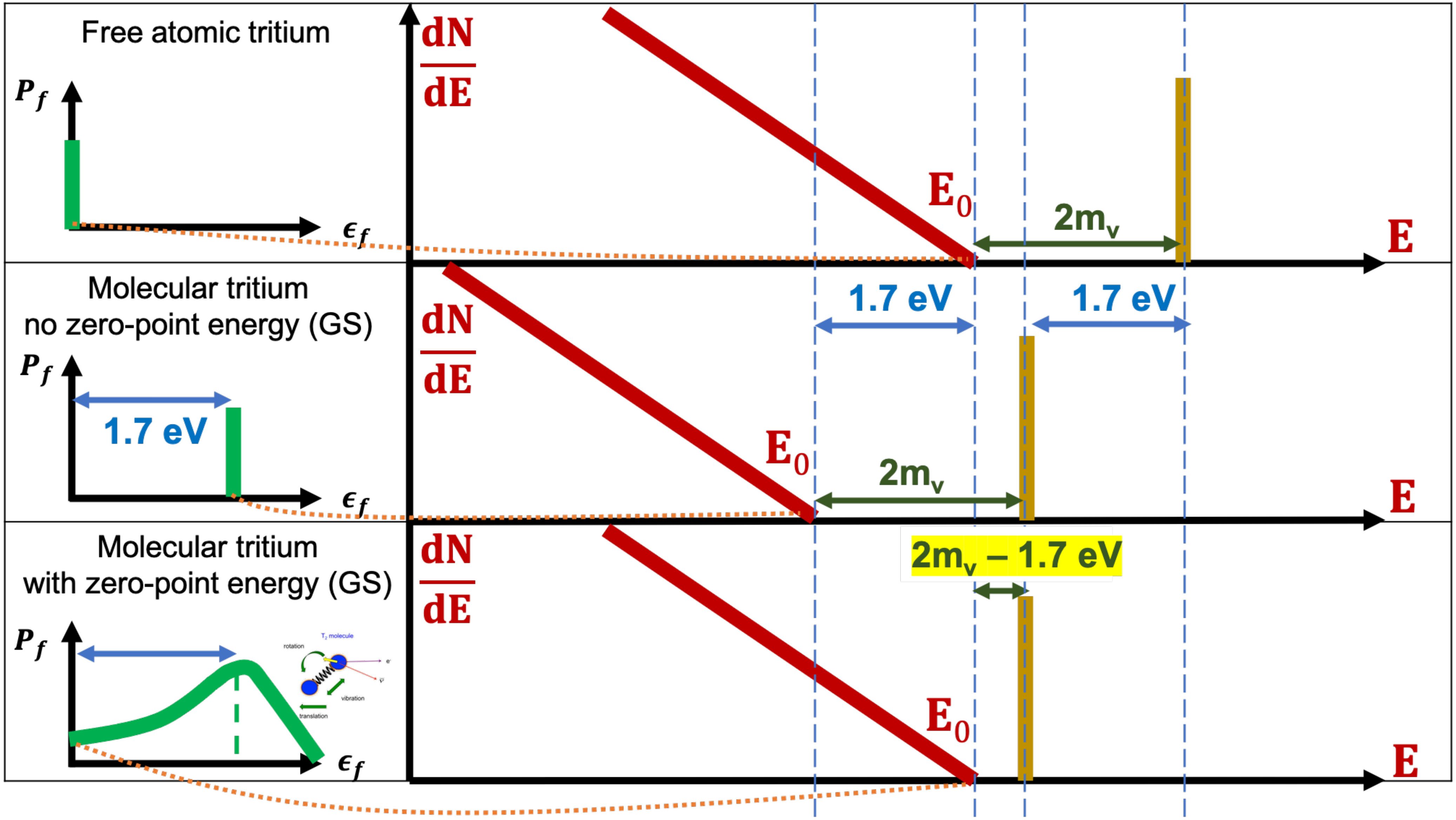
KATRIN 1000 days sensitivity: $\eta \lesssim 1.4 \cdot 10^{10}/\alpha$

Theoretical input: molecular final states



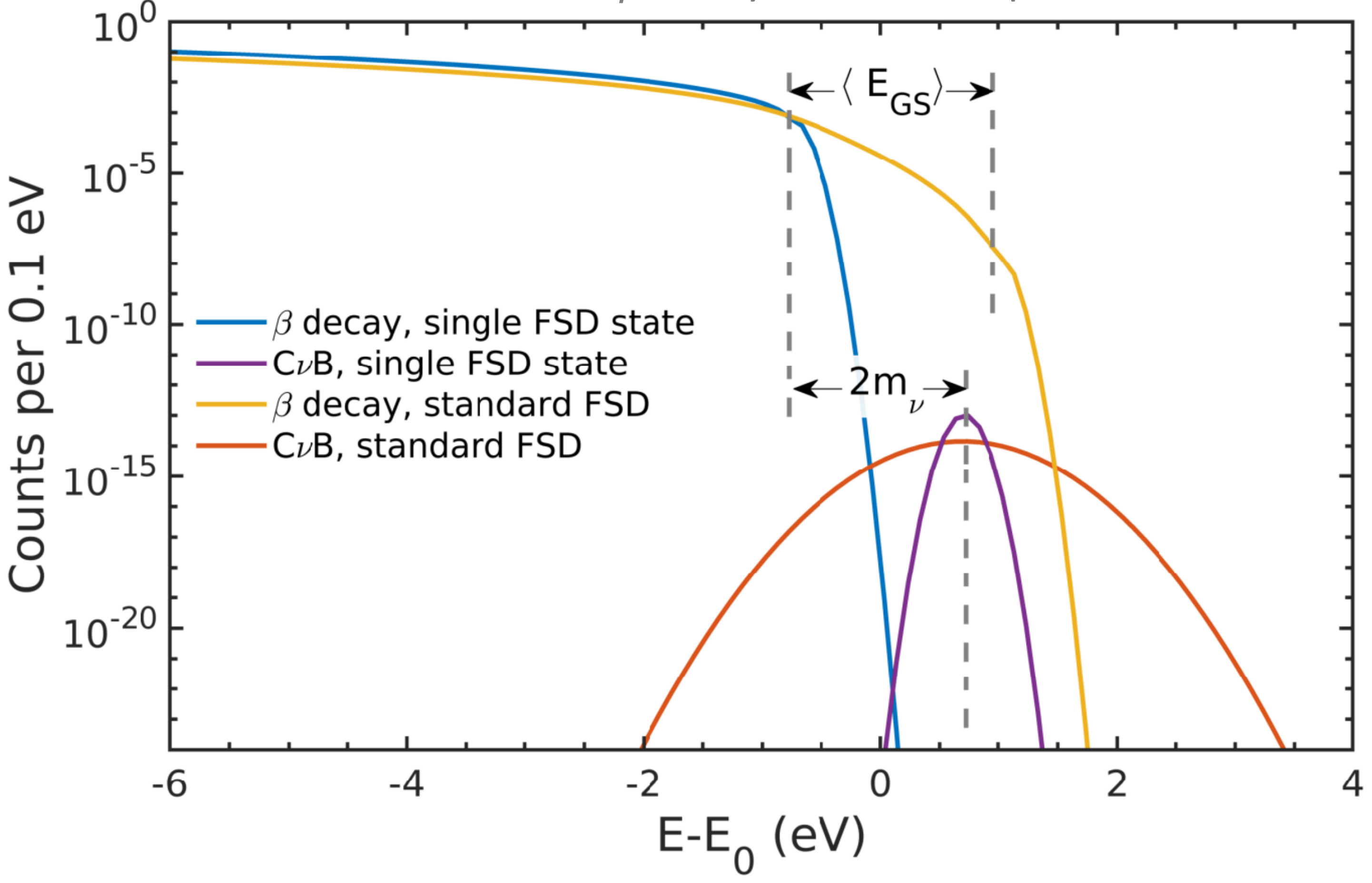
- ✓ β −electron and tritium molecule share the energy released in the decay
- ✓ precise calculation of molecular ground and excited final states
  A. Saenz et al, Phys. Rev. Lett. 84, 242 (2000)
  + KATRIN updates
- ✓ unavoidable energy broadening due to molecular effects
- ✓ zero-point energy broadening (irreducible)

Impact of Molecular Tritium (zero-point energy)



Impact of molecular Tritium on CNB search

Tail of tritium β decay differential spectrum



- ✓ **Free Atomic Tritium**: relic peak $2m_\nu$ above $E_0(m)$
- ✓ **Molecular Tritium**:
  - ✓ FSD ground state smears out the tritium spectrum → relic peak separation in the data reduced to: $2m_\nu - E_{GS}$
  - ✓ **For $m_\nu < 0.85$ eV:**
    - ✓ relic signal with β electrons overlap
    - ✓ for η = 1: S/B ratio = 10^{-7}
    - ✓ the detection of relic neutrinos with molecular tritium is deemed infeasible

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