First Relic Neutrino Search with the KATRIN experiment

Thierry Lasserre

on behalf of the KATRIN collaboration

NOW 2022

Neutrino Oscillation Workshop


Karlsruhe
Tritium
Neutrino
Experiment

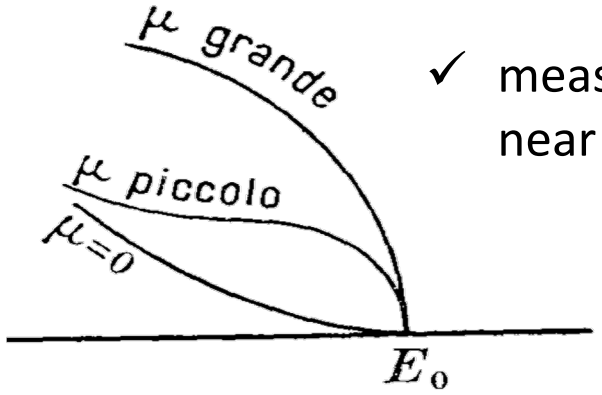
- ✓Experimental site:

  Karlsruhe Institute of Technology

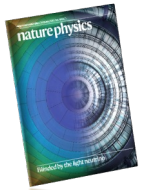
- ✓International Collaboration (150 members)

- ✓Main goal: neutrino mass with 0.2 eV sensitivity

Precision β-decay spectroscopy



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



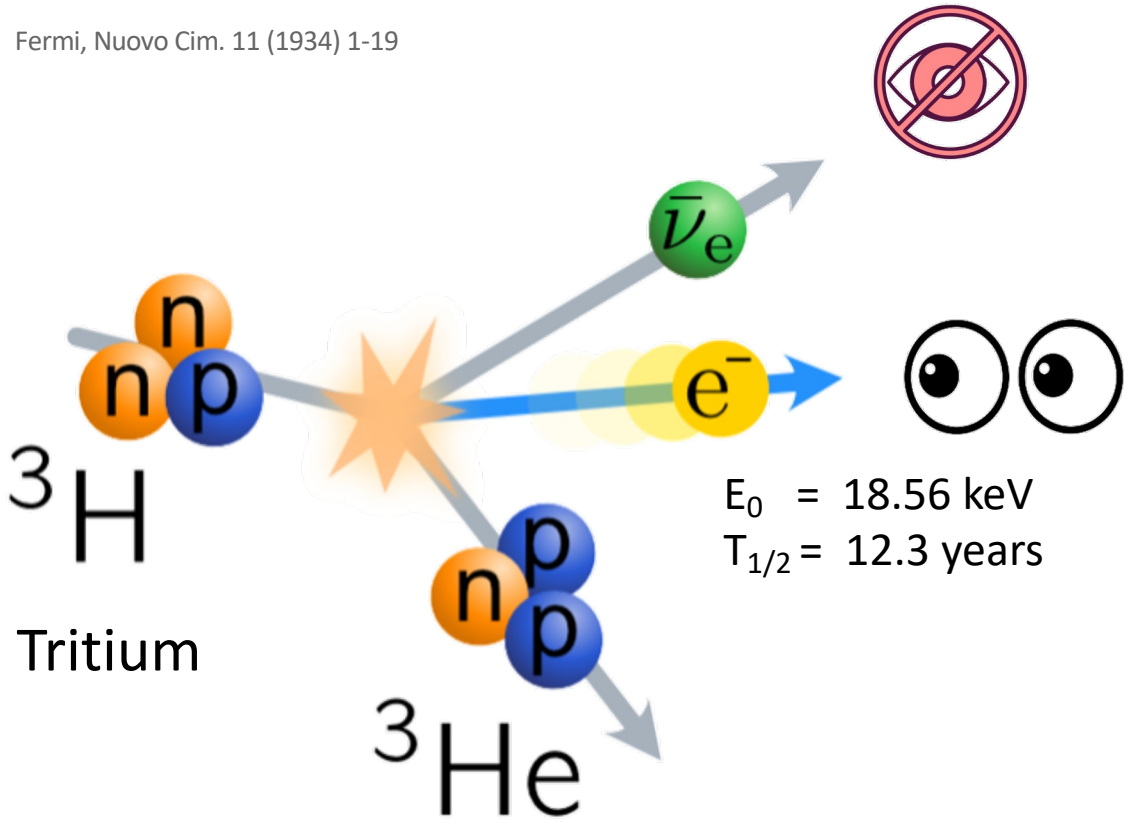
✓ incoherent neutrino mass

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

see **Guido Drexlin's talk** (Friday)

✓ Sterile neutrino searches

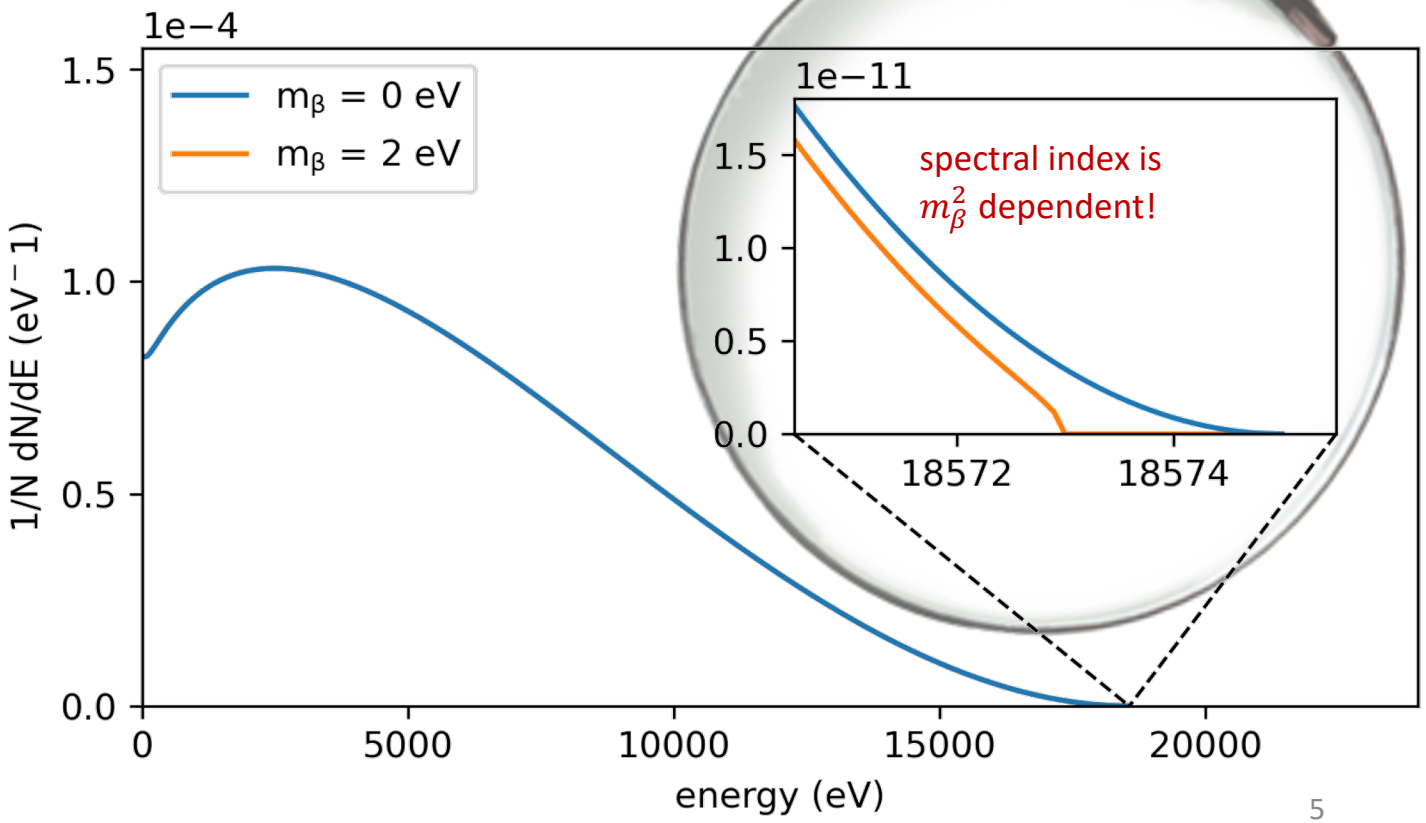
✓ Relic neutrino search → this talk



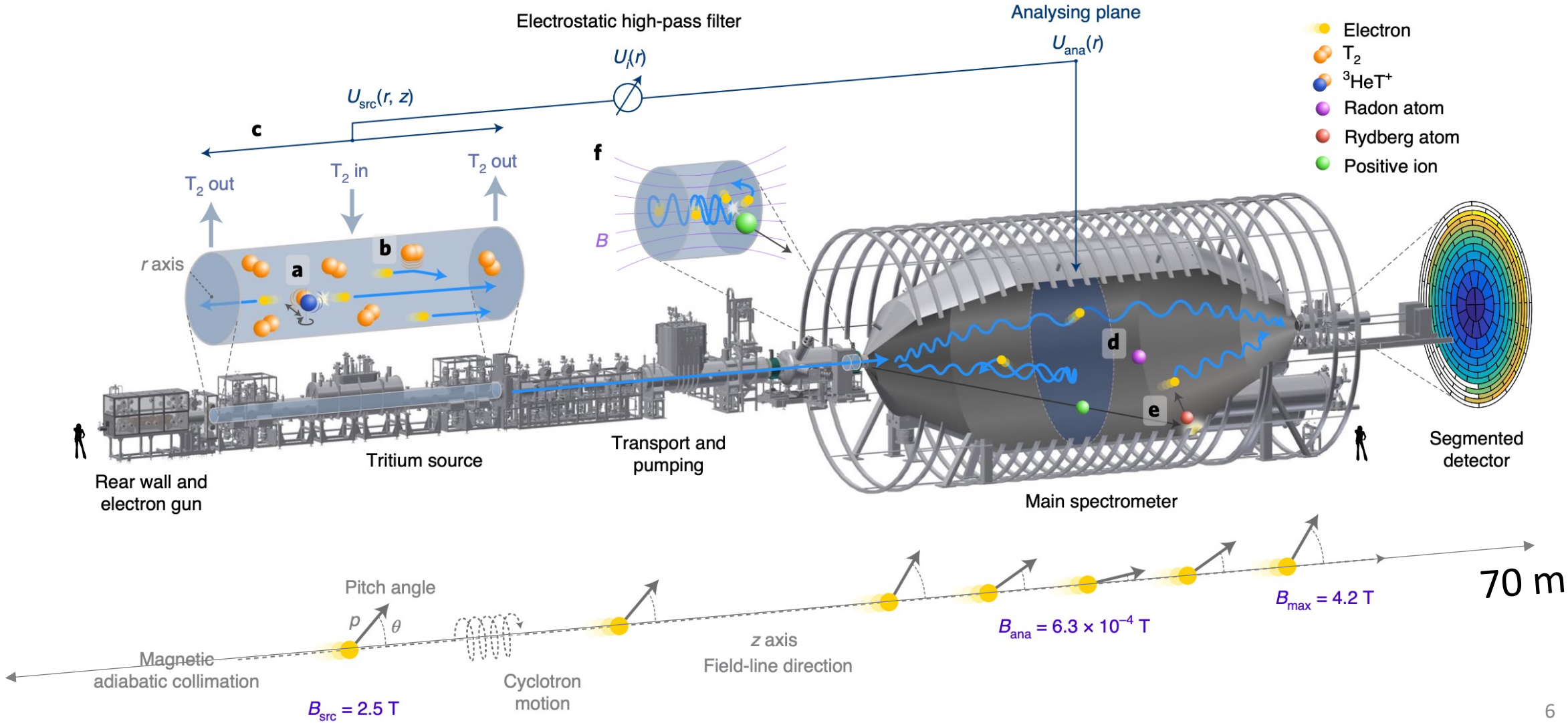
KATRIN experimental challenges

- ✓ 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



KATRIN Working Principle

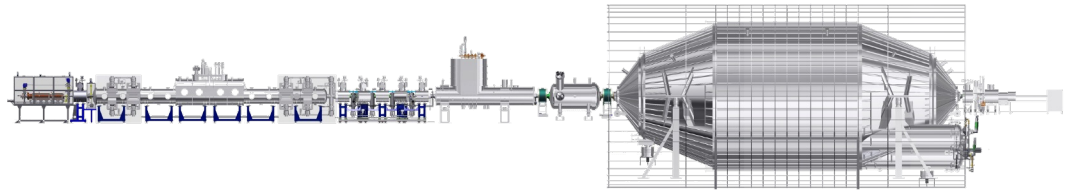


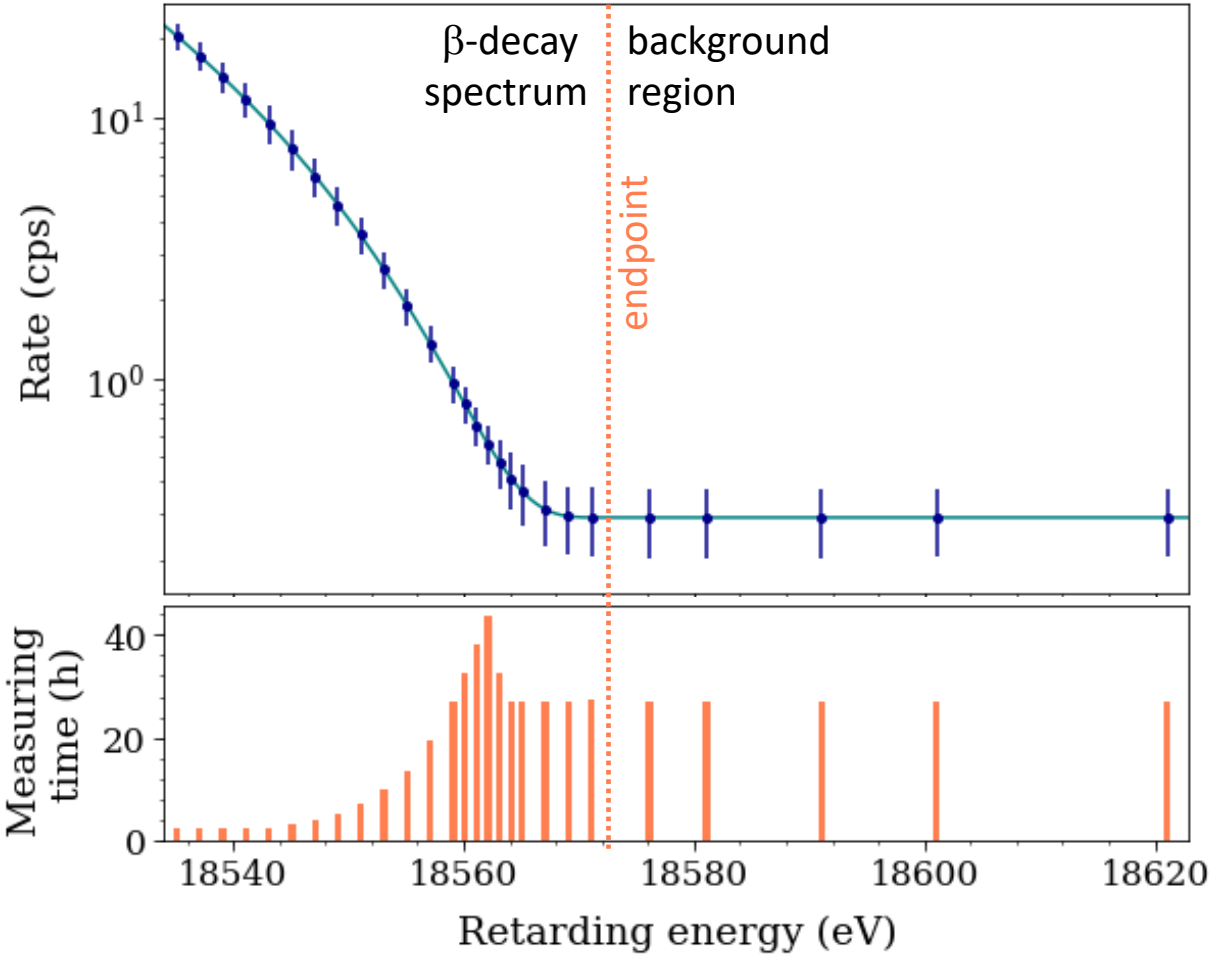
Measurement strategy

Integral spectral measurement !
around the endpoint

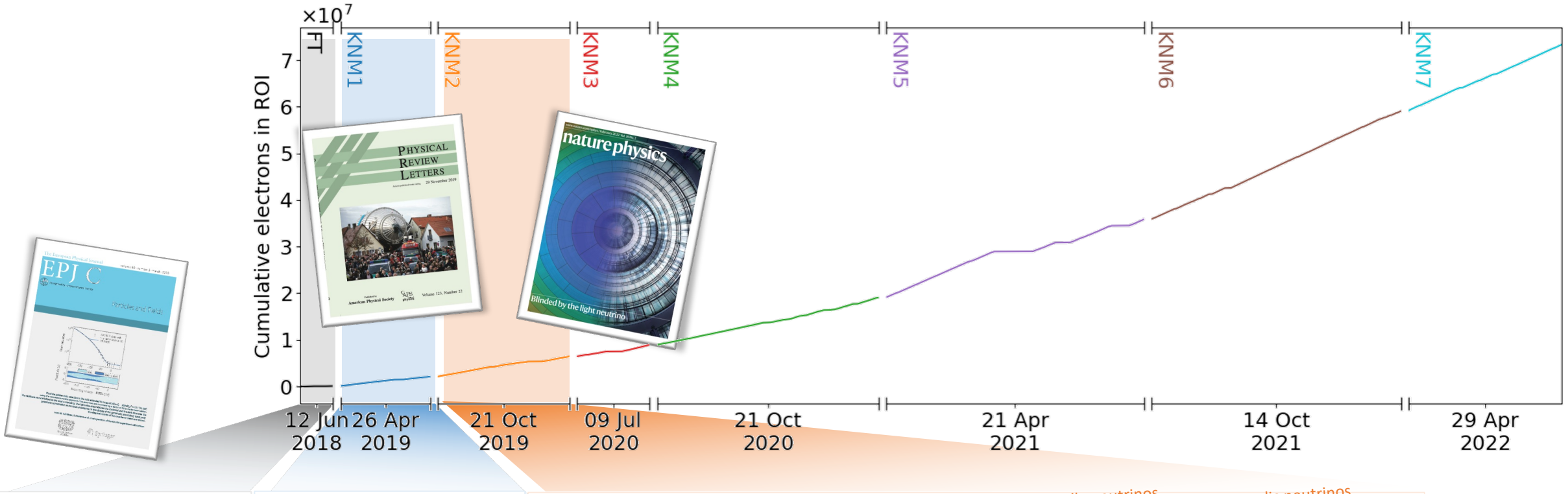
β-scans illustration:

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





KATRIN Data Taking Overview



- Commissioning
- Only 0.5% tritium

EPJ C 80, 264 (2020)

- 1st m_ν campaign
- $m_\nu < 1.1$ eV

PRL. 123, 221802 (2019)

Phys. Rev. D 104, 012005 (2021)

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

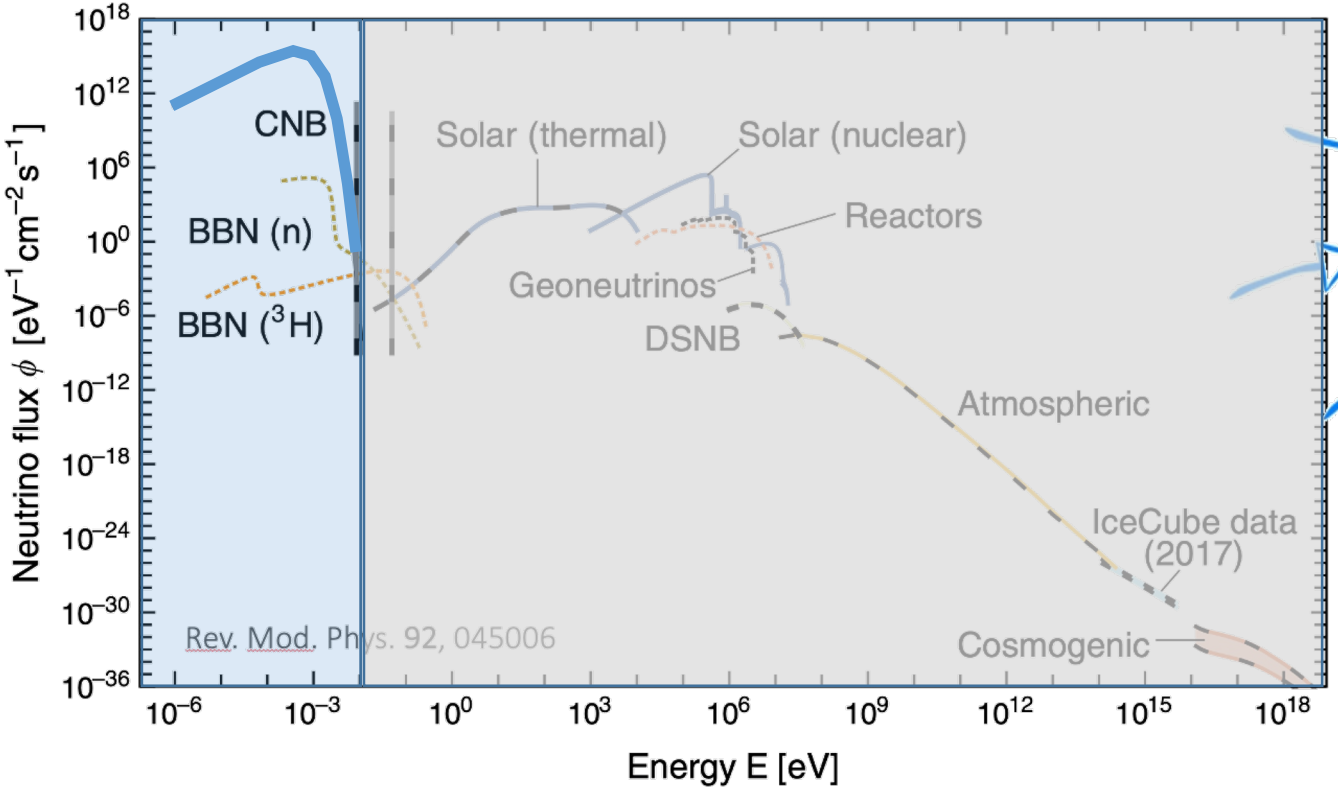
Nat. Phys. **18,** 160–166 (2022)

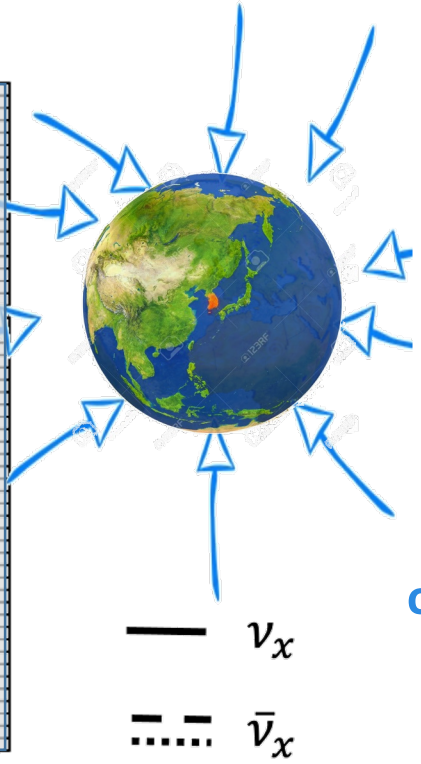
light sterile neutrinos

relic neutrinos

Cosmic neutrino background

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

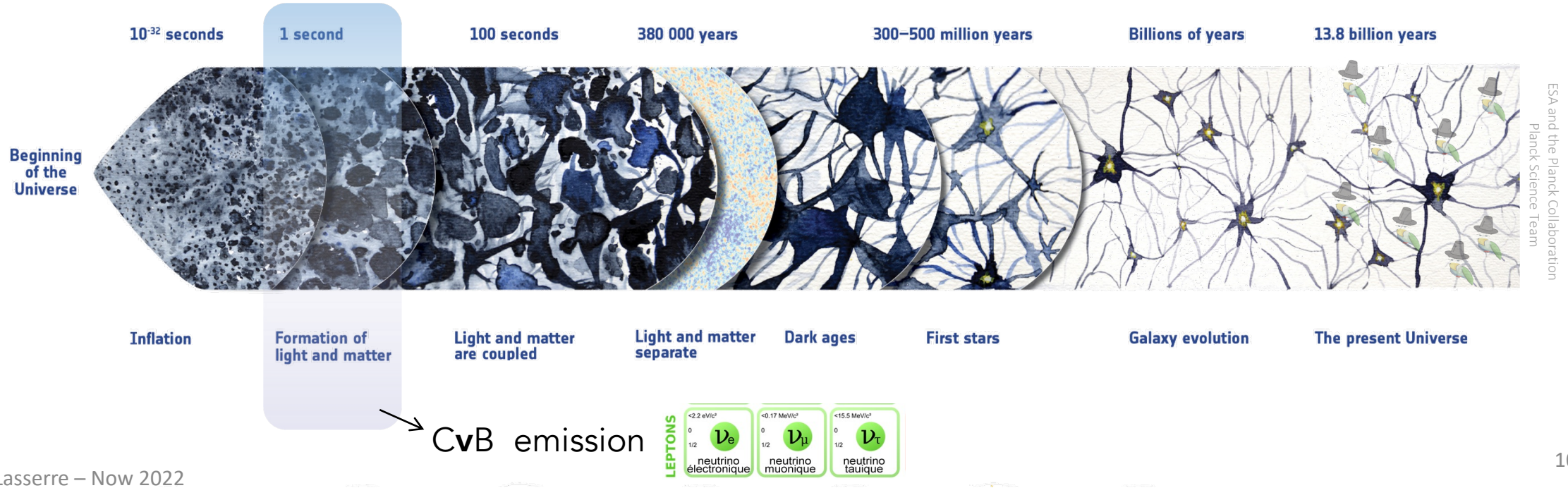




KATRIN restricts the maximum overdensity ratio η of relic neutrinos on Earth

Cosmic neutrino background figures

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



Dataset for CNB analysis

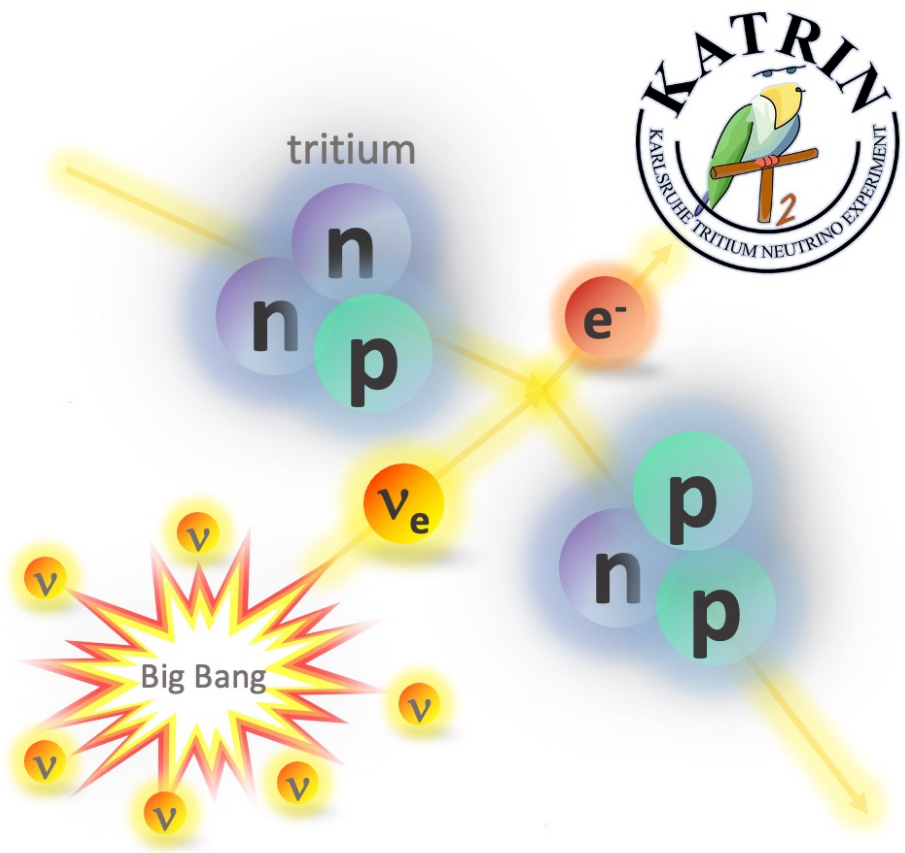
as in the case of neutrino mass analysis

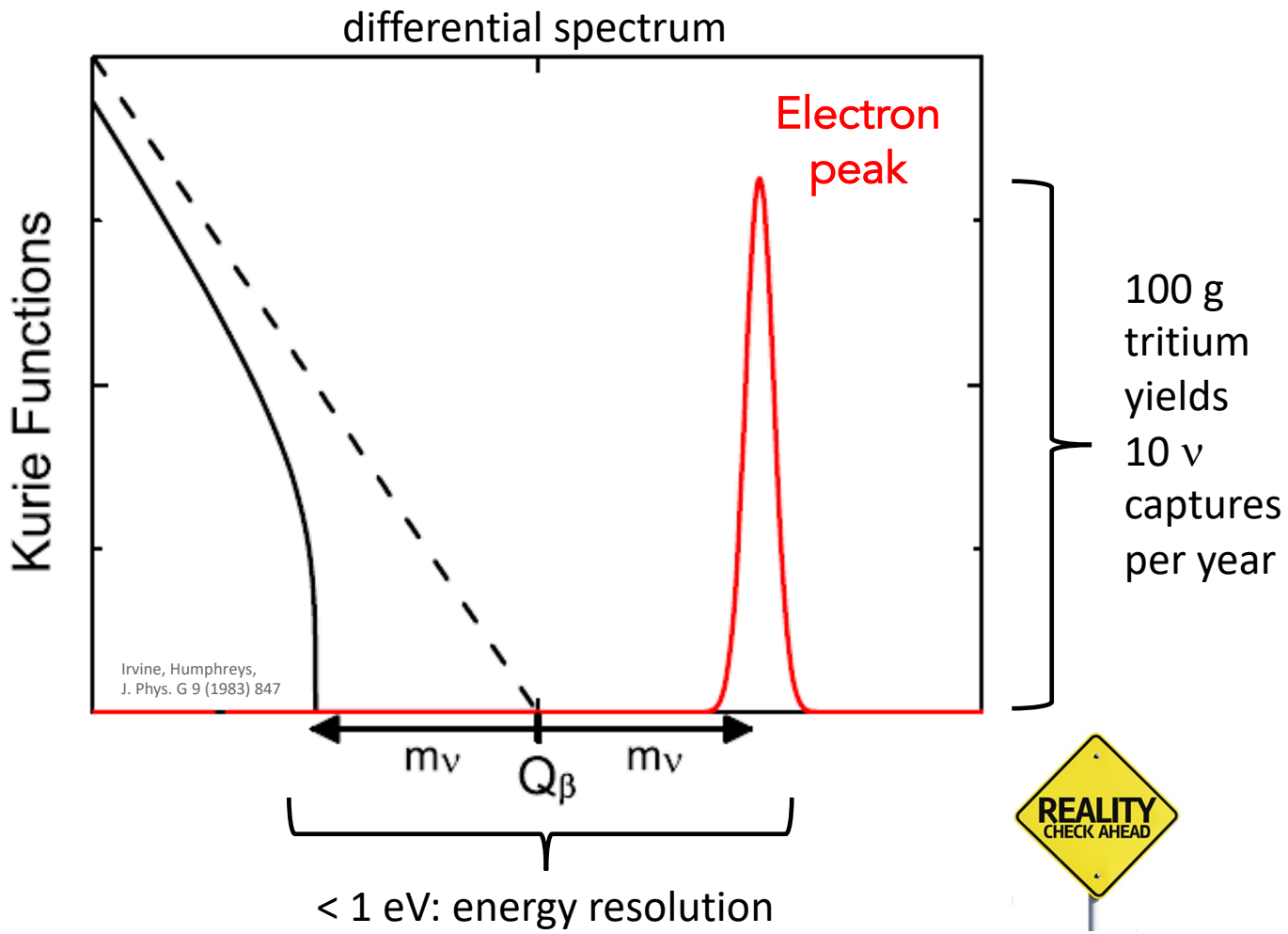
	1st campaign PRL 123 (2019) & PRD 104 (2021)	2nd campaign Nat. Phys. (2022) & PRL 129 (2022)
Campaign date	April-May 2019	Sept-Nov 2019
Total scan time	522 h	744 h
Source activity	25 GBq	98 GBq
Background	290 mcps	220 mcps
Tritium purity	97.6%	98.7%
Electrons in RoI	2 Mio	4.3 Mio

Thresholdless neutrino capture on Tritium

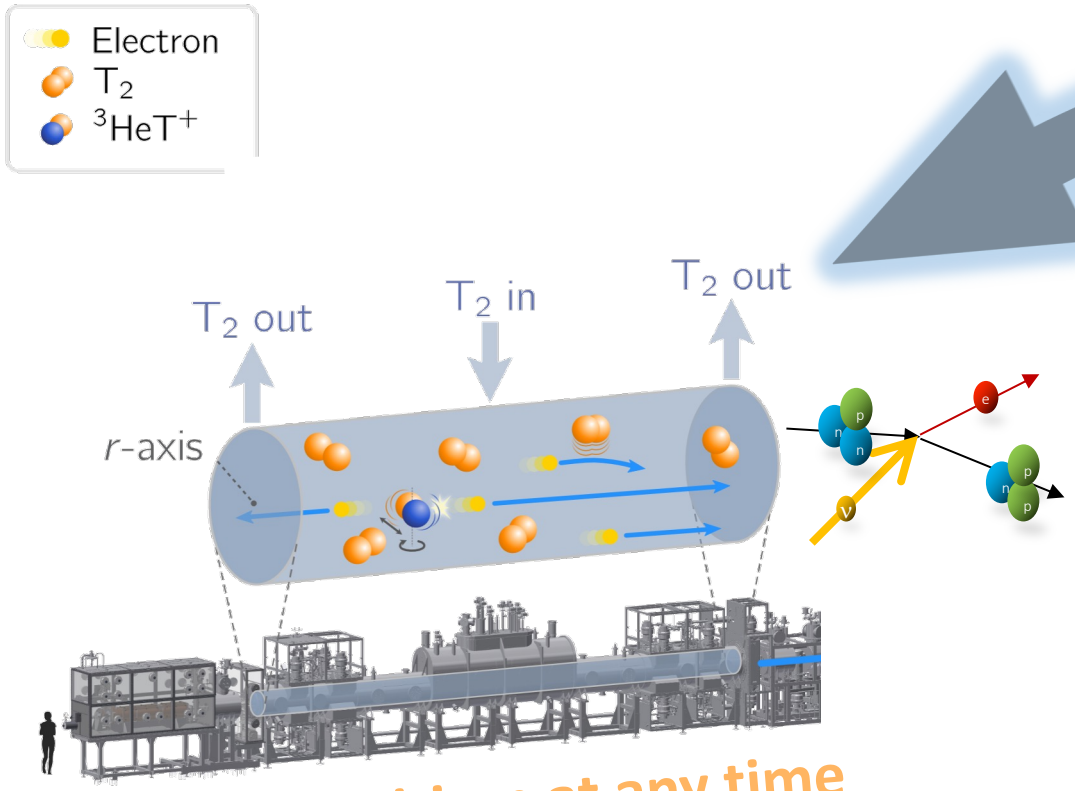
$$^3\mathrm{H} + \nu_e \longrightarrow {}^3\mathrm{He}^+ + e$$

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





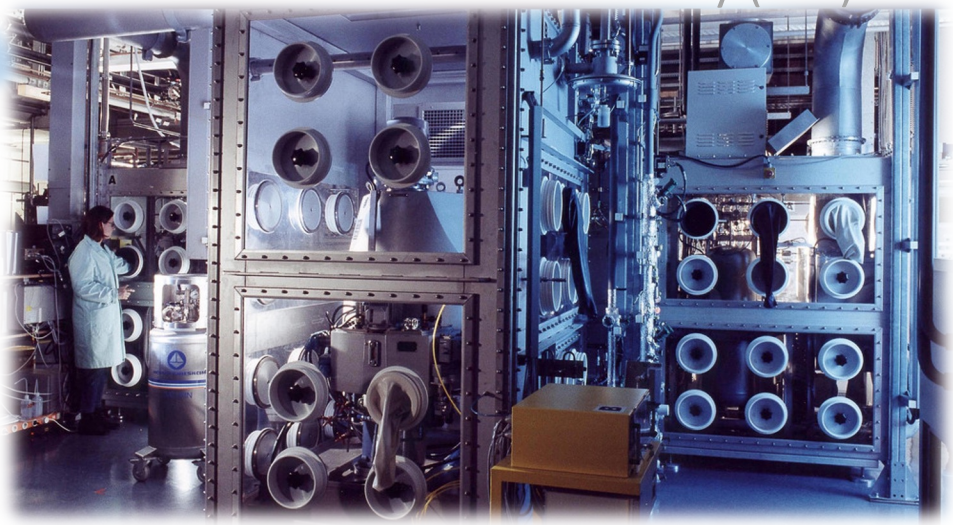
Sensitivity to the overdensity ratio η



30 µg of tritium at any time

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

Karlsruhe Tritium Laboratory (TLK)



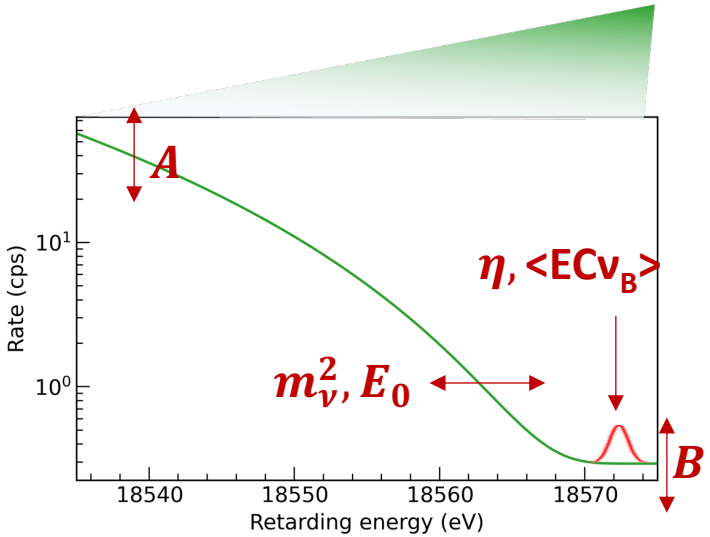
Overall gaseous tritium quantity at TLK: currently 25 g

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

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

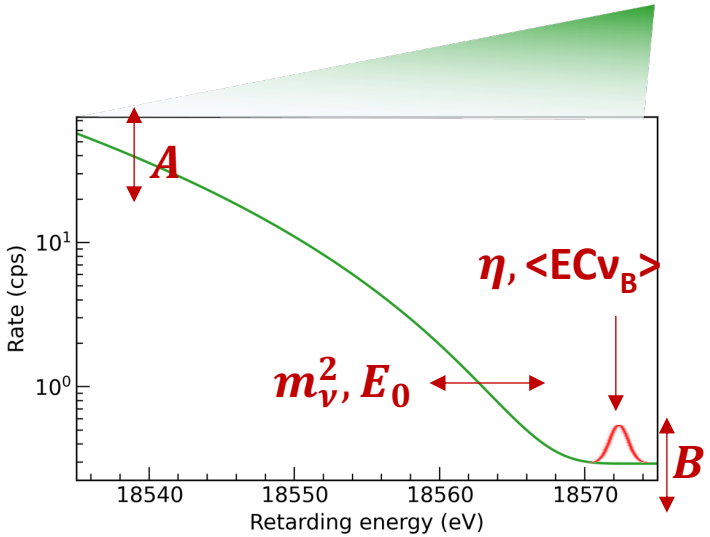
Analysis strategy

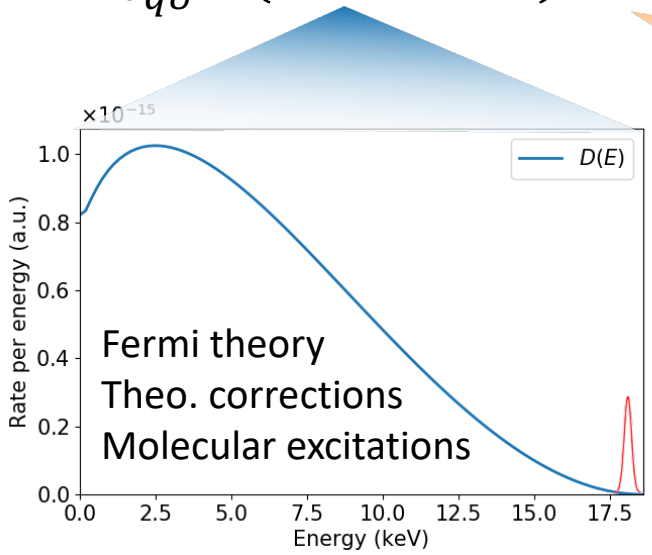
✓ fit of theoretical prediction: $\Gamma(qU)$

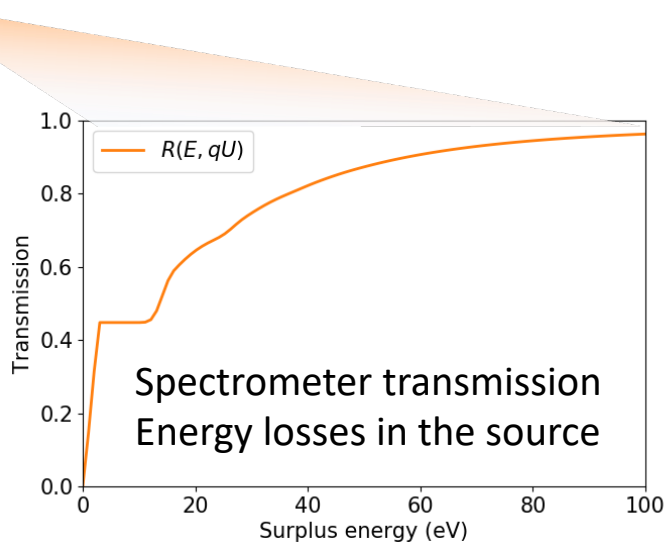


Analysis strategy

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



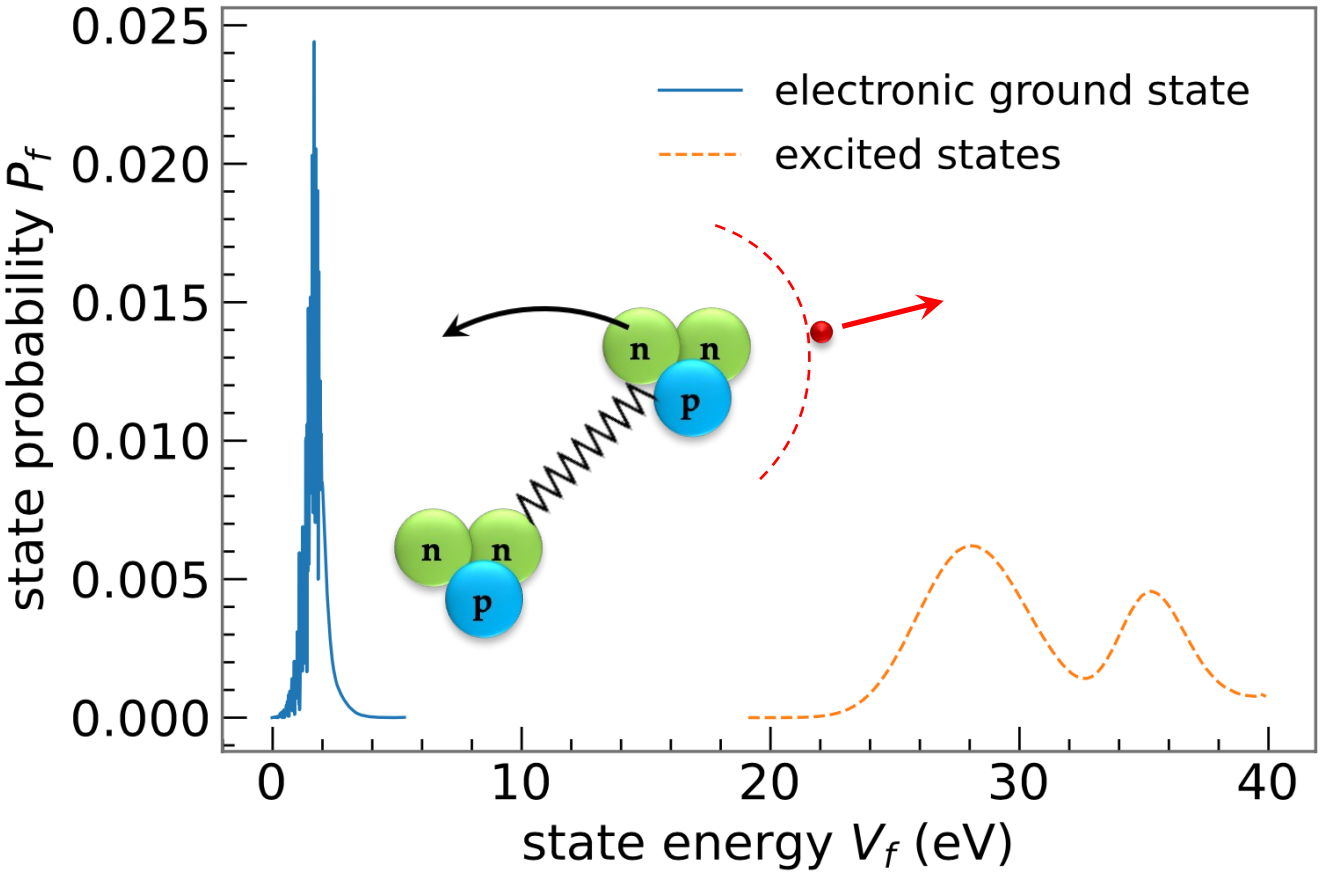




✓ Relic neutrino fit parameters: $\boldsymbol{\eta}$, $\boldsymbol{\langle ECv_B \rangle}$, $\boldsymbol{E_0}$, $\boldsymbol{B}$, $\boldsymbol{A}$, $\boldsymbol{m_\nu^2}$

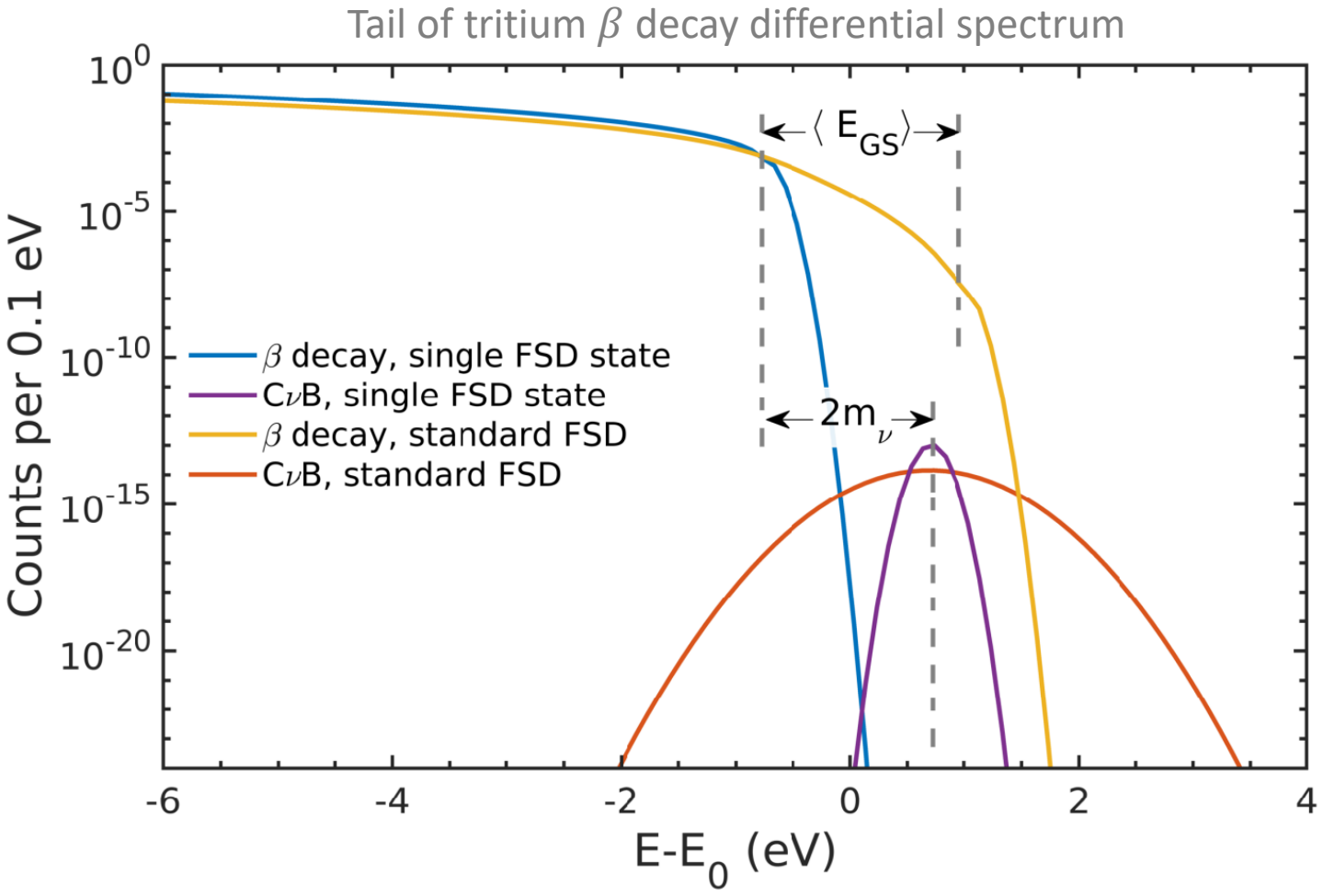
✓ fit model informed by **theoretical** and **experimental** inputs (e-gun, krypton, monitoring, …)

Theoretical input: molecular final states



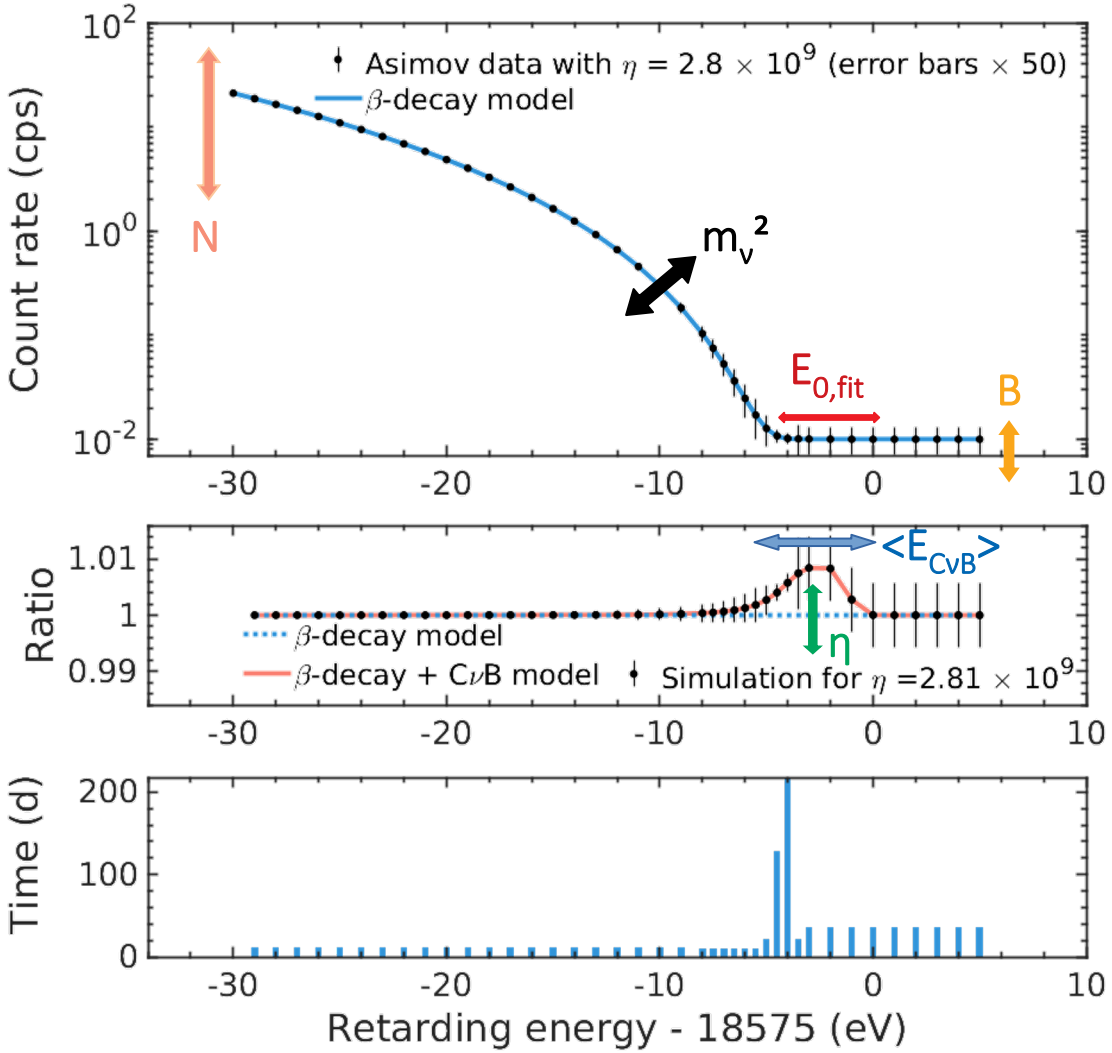
- ✓ β −electron and tritium molecule share the energy released in the decay
- ✓ precise calculation of molecular ground and excited final states
  A. Saenz et al, Phys. Rev. Lett. 84, 242 (2000)
  + KATRIN updates
- ✓ unavoidable energy broadening due to molecular effects
- ✓ zero-point energy broadening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

Impact of molecular Tritium on CNB search



- ✓ **Free Atomic Tritium**: relic peak $2m_\nu$ above E_0
- ✓ **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

Relic neutrino analysis fit

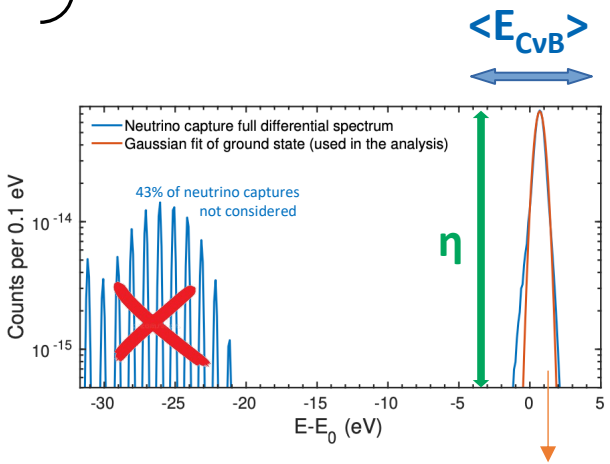


Fit Parameters:

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

} Tritium β – decay + background

- ✓ η overdensity
- ✓ $<E_{CvB}>$ peak position



Relic neutrino capture peak on the differential spectrum

Relic neutrino search fit with systematics

✓ Standard χ^2 minimization

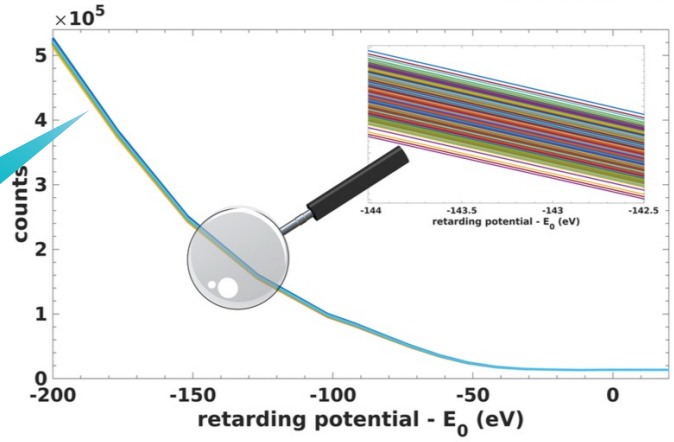
m_ν^2, E_0, B, A
+ RNB peak position & overdensity η

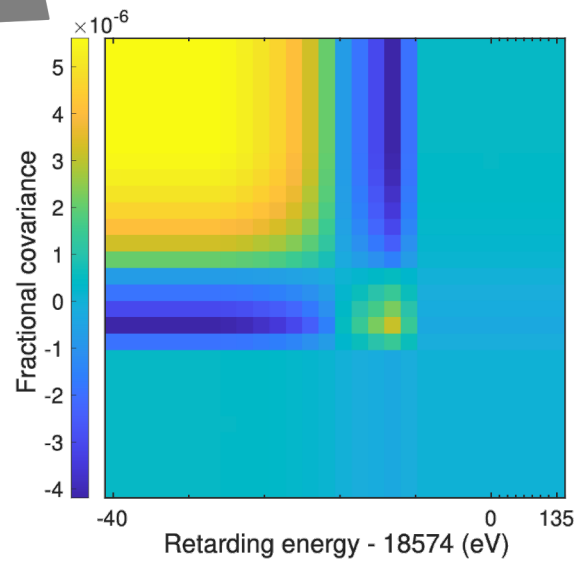
$$\chi^2 = \left(\vec{R}_{\text{data}}(q\vec{U},\vec{r}) - \vec{R}(q\vec{U},\vec{r}|\vec{\Theta},\vec{\eta})\right)^T C^{-1} \left(\vec{R}_{\text{data}}(q\vec{U},\vec{r}) - \vec{R}(q\vec{U},\vec{r}|\vec{\Theta},\vec{\eta})\right)$$

✓ Uncertainty propagation with covariance matrices

B-fields, ρd, plasma, …

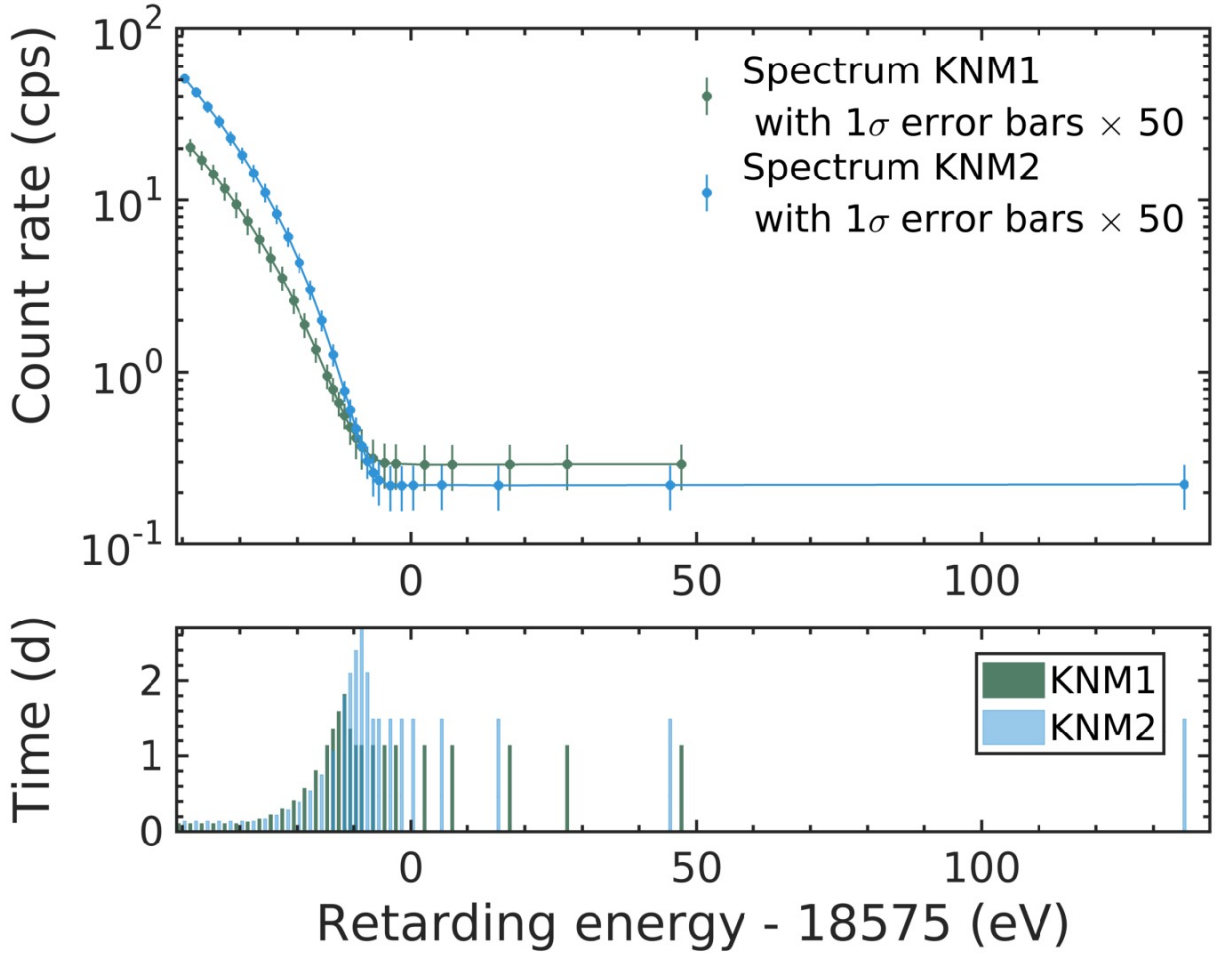
Compute 10^4 spectra with different systematic configurations





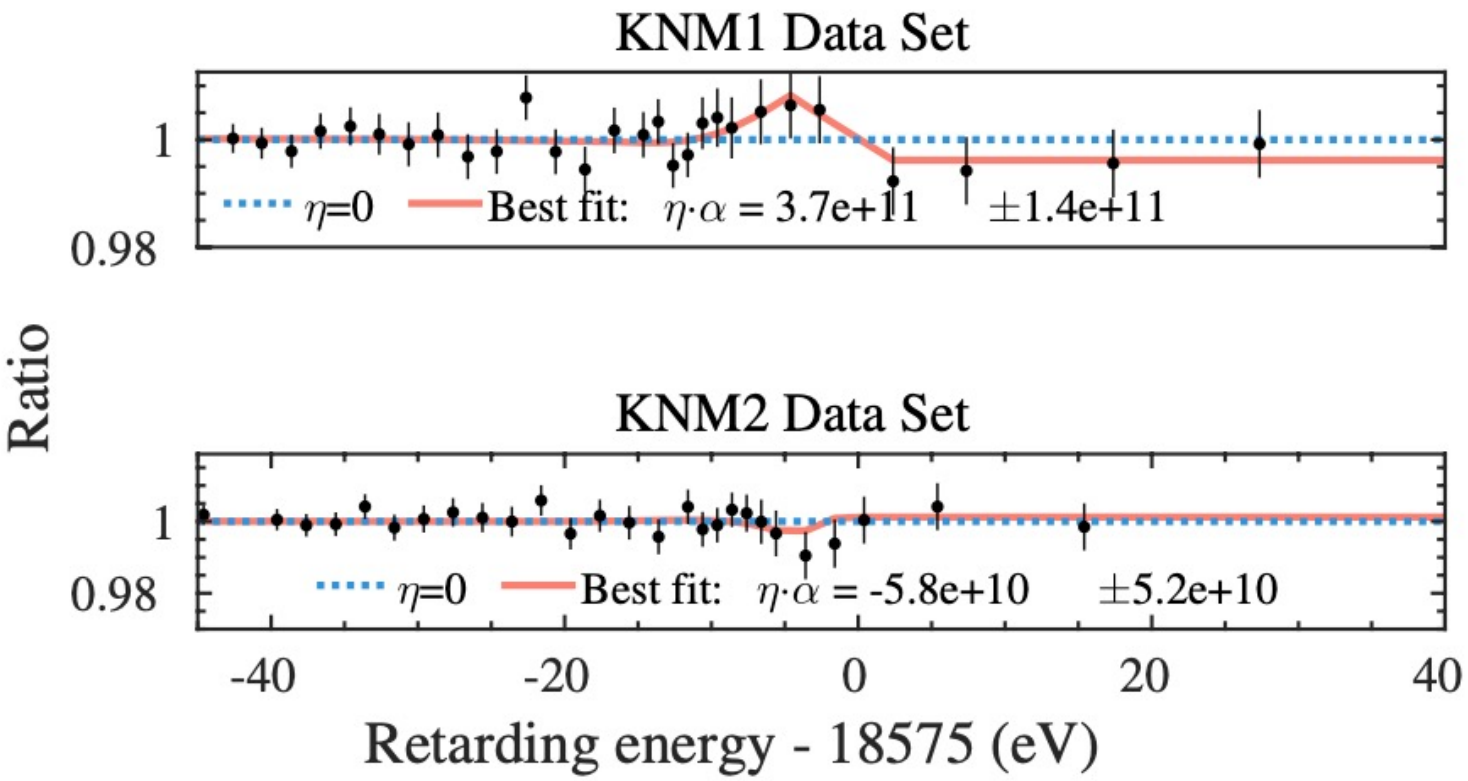
✓ Blinding: analysis validated & fixed on mockup data

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

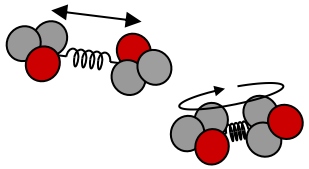
Relic neutrino fit results (best fit)



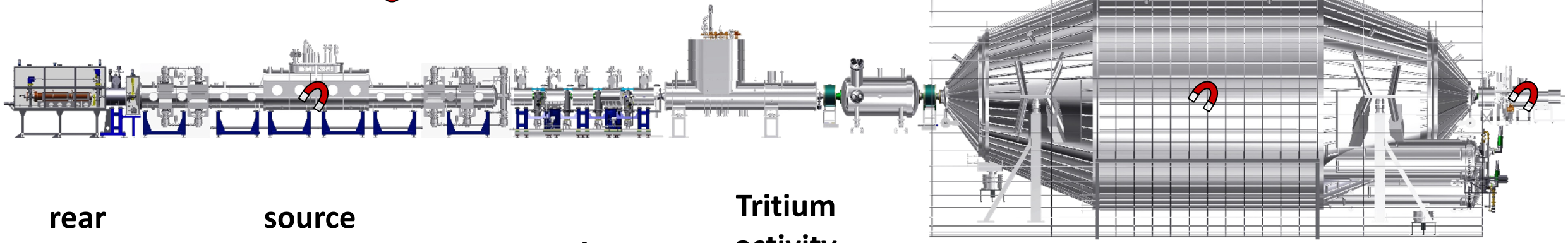
- ✓ KNM1 2019 dataset:
  - ✓ 522 hours
  - ✓ 3.4 μg for capture on tritium
- ✓ KNM2 2019 dataset
  - ✓ 744 hours
  - ✓ 13.0 μg for capture on tritium
- ✓ no evidence for relic neutrino overdensity → upper limits
- ✓ KNM 1+2 combination

Systematics uncertainties overview

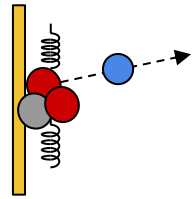
molecular final states



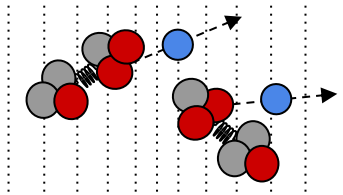
magnetic fields



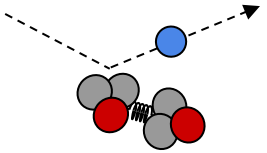
rear wall



source potential

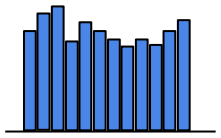


scattering

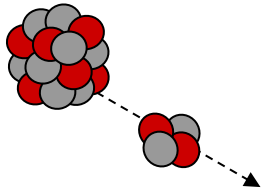


- energy loss
- source density

Tritium activity fluctuations

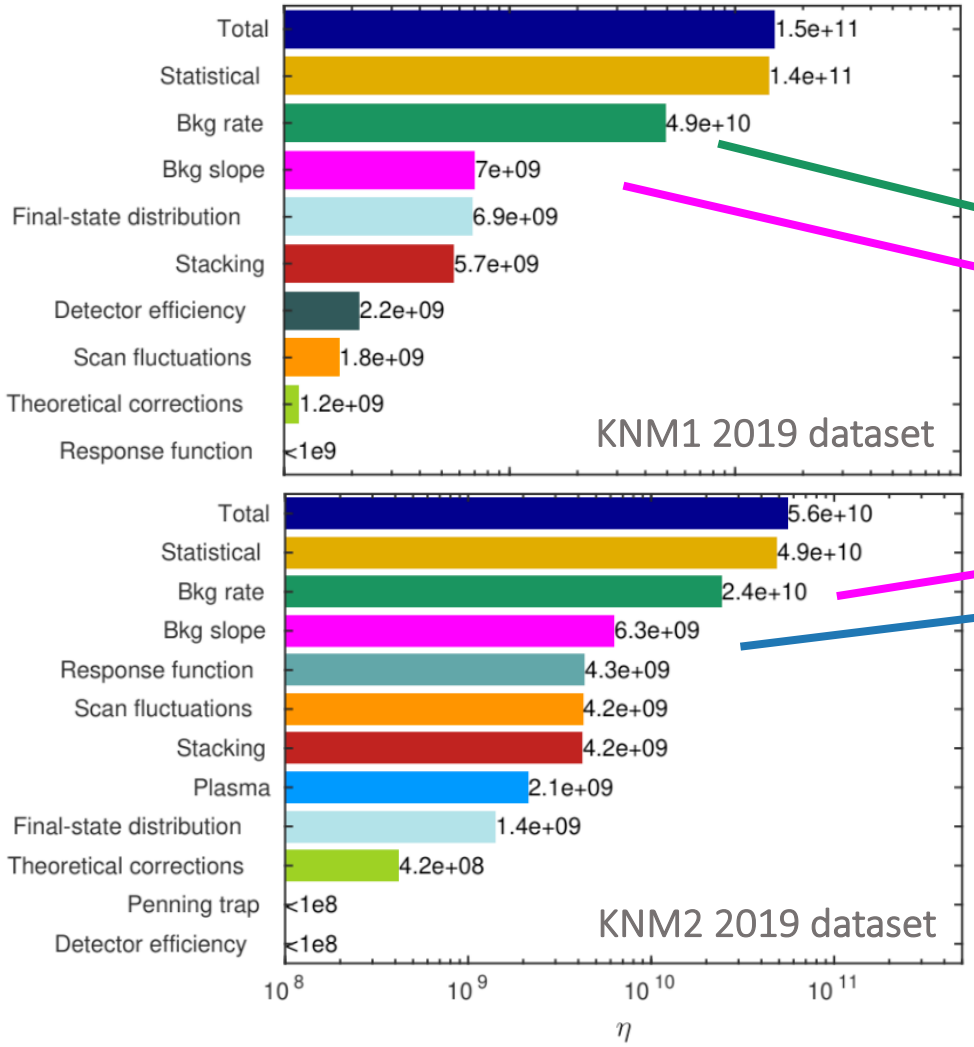


background

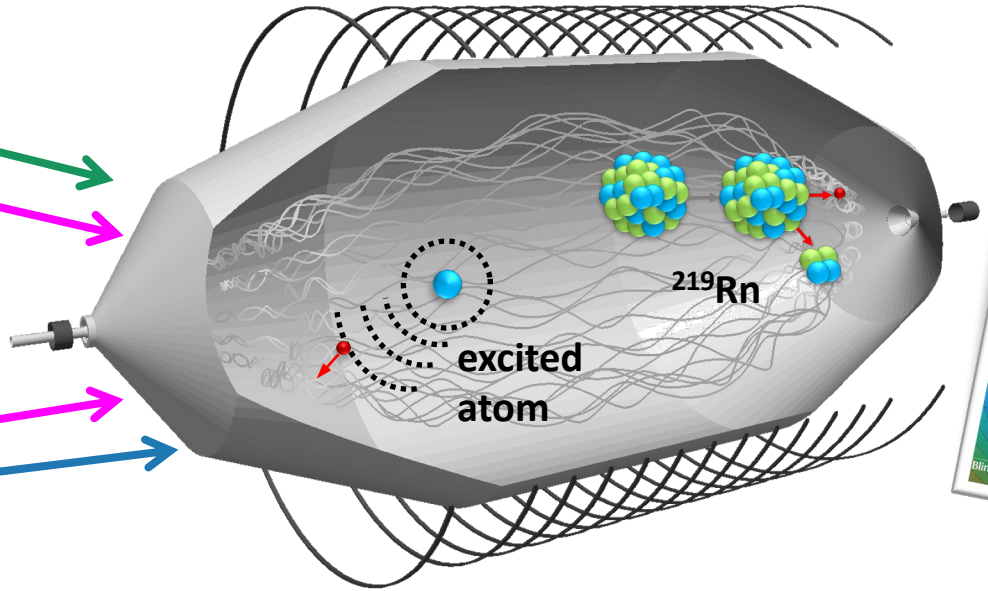


- overdispersion
- oime variation
- spectral variation

Uncertainty budget for relic neutrino search

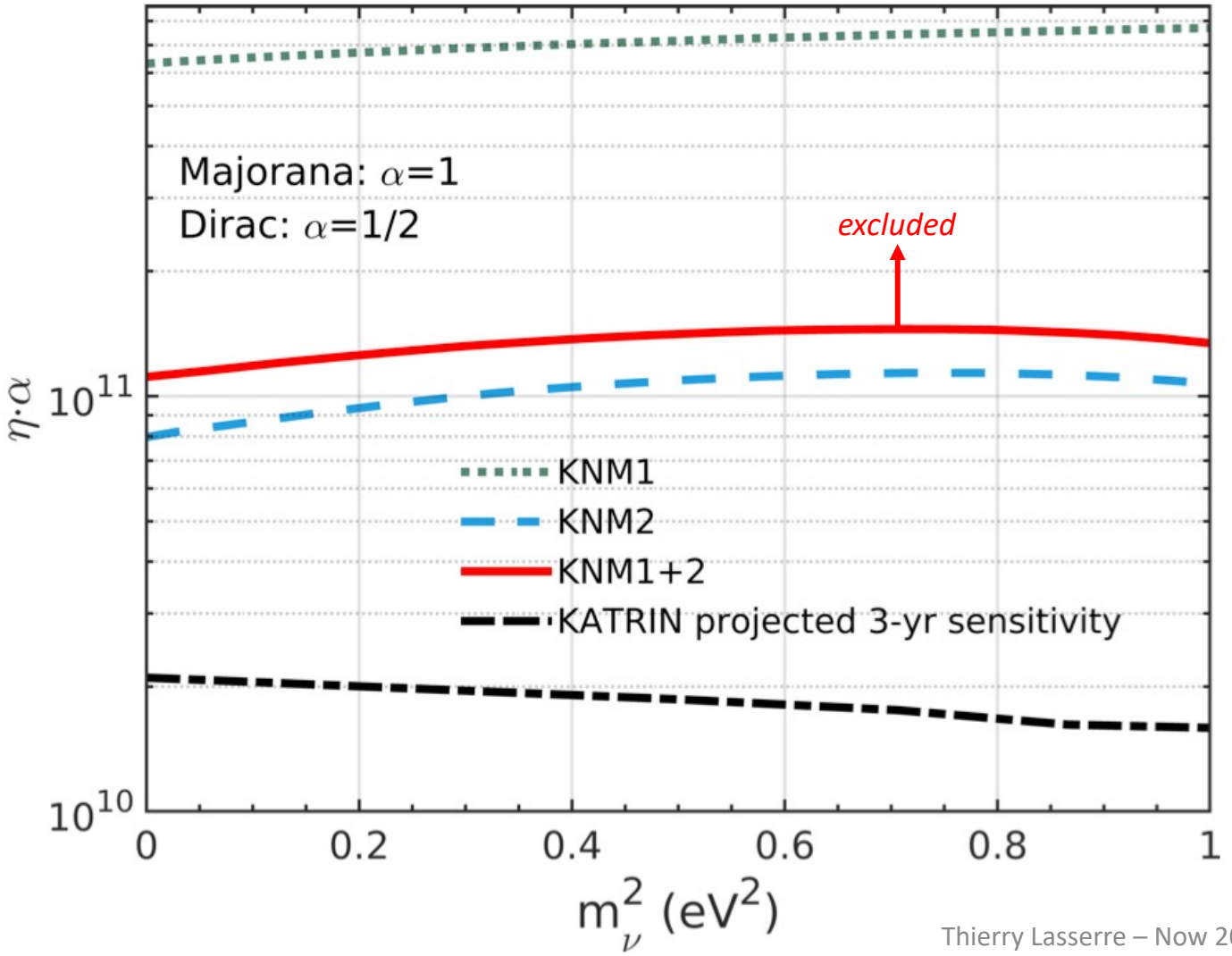


inner surface: 650m^2
volume: 1400m^3



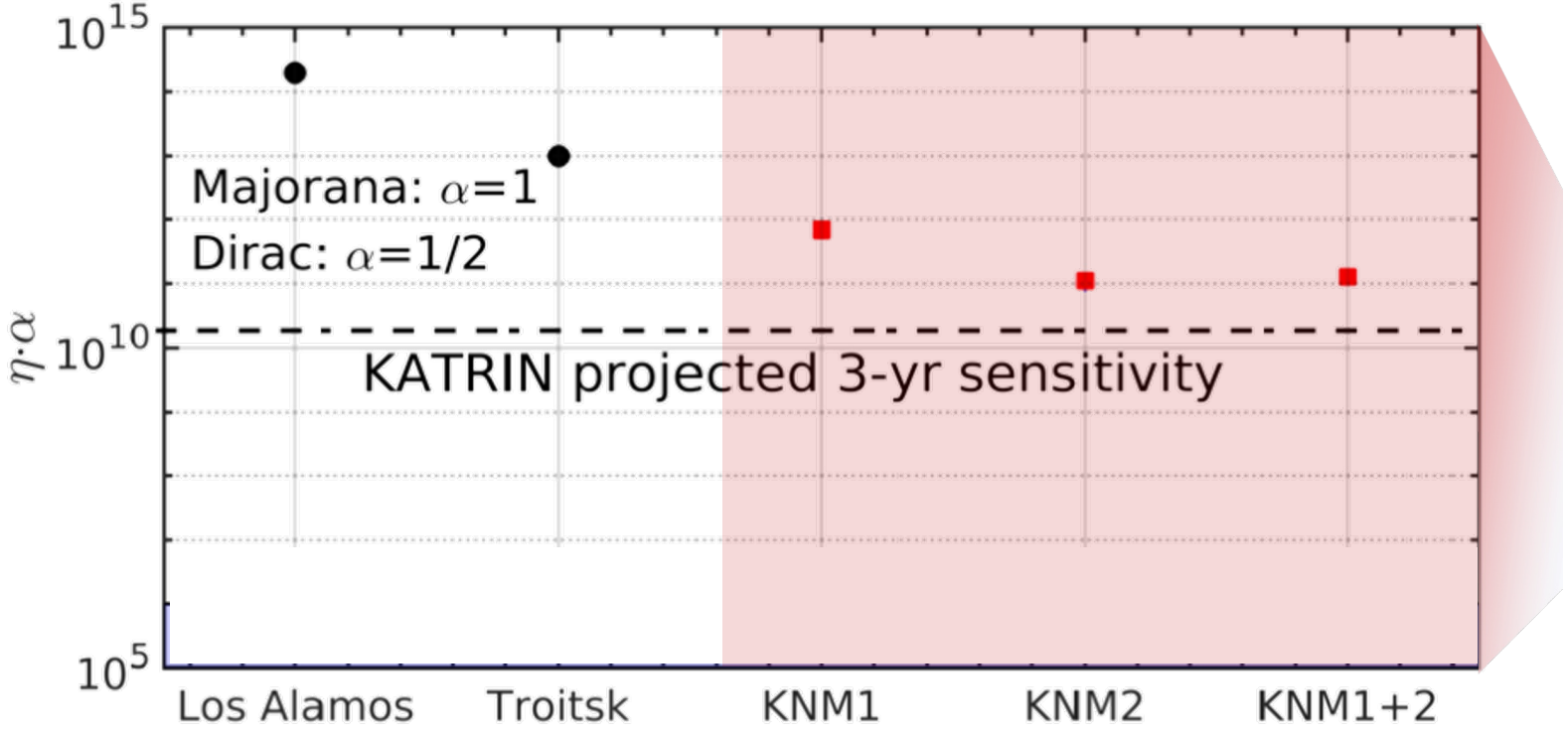
- ✓ **Both analyses are statistics dominated**
- ✓ Largest systematics: Background rate & Background slope

New Relic Neutrino Upper Limits (2022)



- ✓ test for <u>large overdensity η</u> of relic neutrinos in our surrounding
  - ✓ First campaign KNM1
  - ✓ Second campaign KNM2
- ✓ combined limit
  - ✓ $\eta < 1.1 \cdot 10^{11}/\alpha$ at 95% CL
- ✓ the search is statistically limited

Conclusion & Outlook

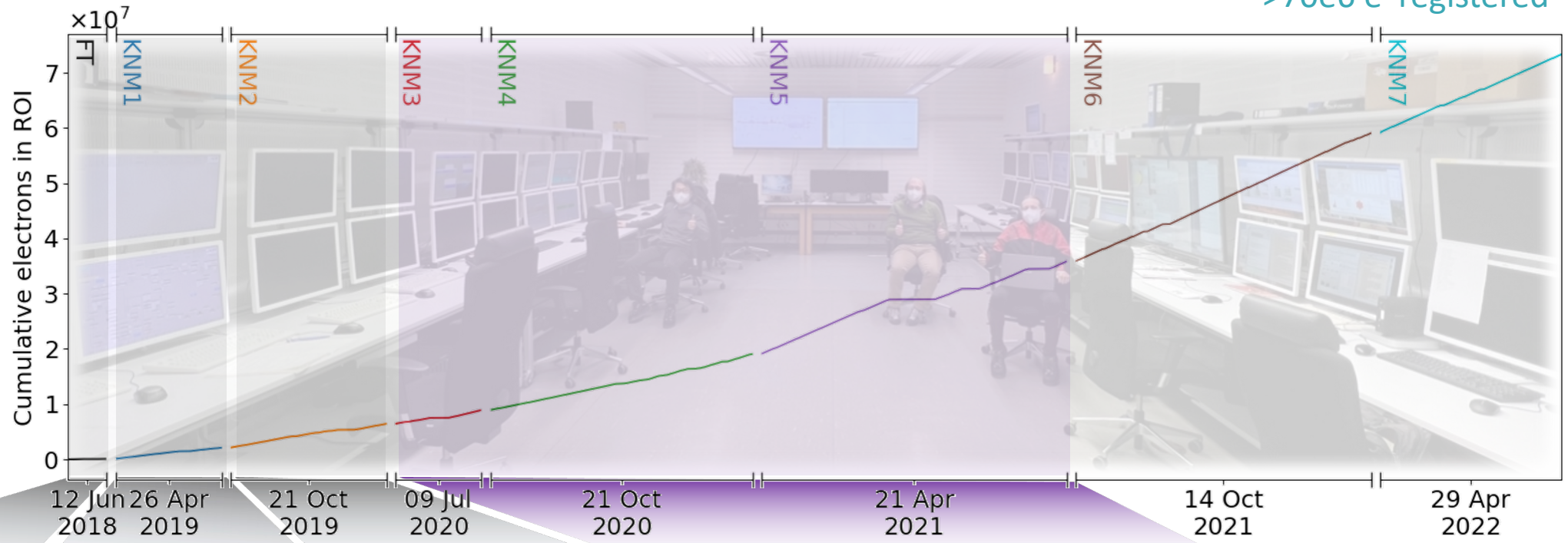


- ✓ first KATRIN search for relic neutrinos: Phys. Rev. Lett. **129**, 011806 (2022)
- ✓ new limit on relic neutrino overdensity ratio:
  - ✓ $\eta < 1.1 \cdot 10^{11}/\alpha$ at 95% C.L.
  - ✓ improved limit by 2 orders of magnitude compared to previous laboratory limits
- ✓ new KATRIN forecast: $\eta < 1 \cdot 10^{10}$ (90% C.L., 130 mcps background)

Don’t miss the KATRIN plenary talk by G. Drexlin on Friday!

Outlook: dataset available in 2022

>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 dataset available in 2022
- 1st, 2nd, 3rd, 4th, 5th campaigns
- ~30e6 e⁻ in ROI

Thank you for your attention