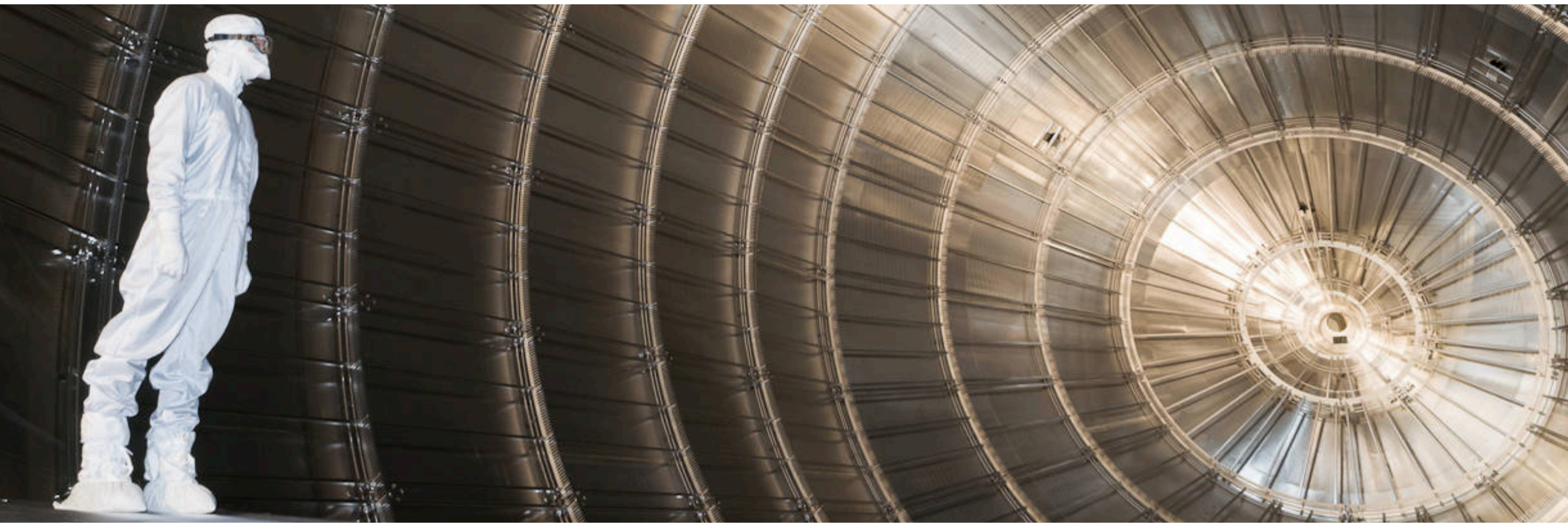
KATRIN: Measuring Neutrino Mass

Björn Lehnert
for the KATRIN Collaboration



KATRIN Karlsruhe Tritium Neutrino Experiment

BERKELEY LAB

Lake Louise Winter Institute
Chateau Lake Louise, Canada
Feb 19 2023

Different Neutrino Mass Observables

β-decay (kinematic)
model independent

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

cosmology
model dependent
- ΛCDM

$$m_\Sigma = \sum_i m_i$$

mass eigenstate
mixing

m_1 m_2 m_3

m_β — m_Σ — $m_{\beta\beta}$

double beta decay
model dependent
- lepton number violation
- light Majorana neutrino exchange

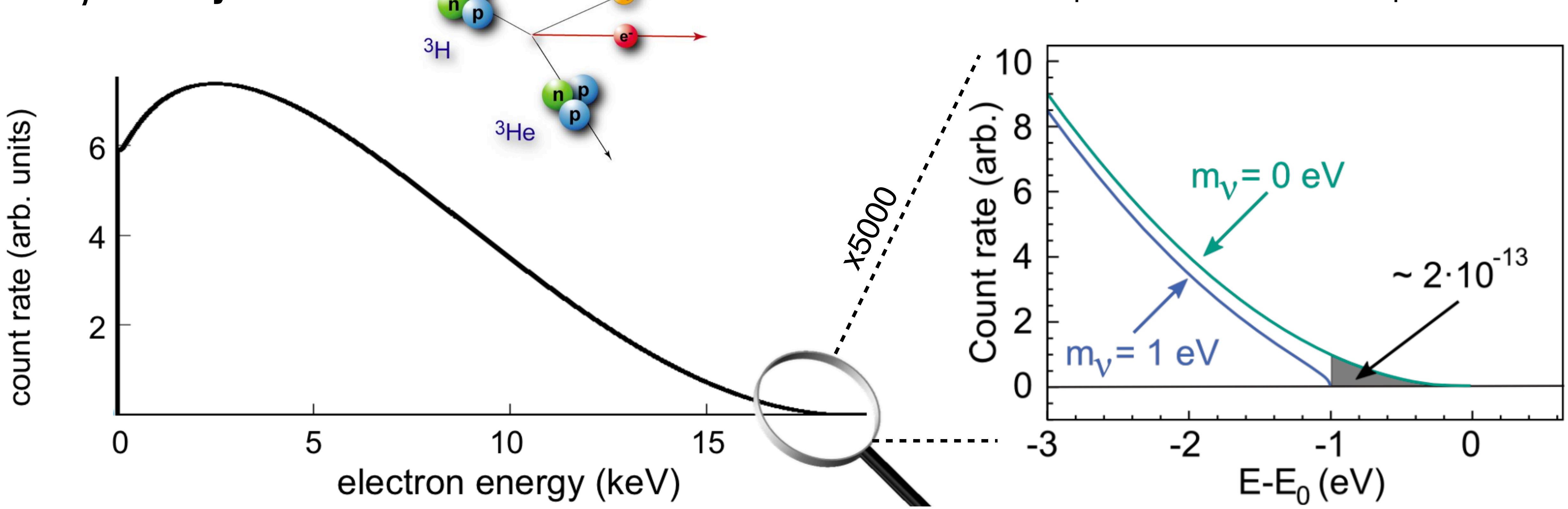
$$m_{\beta\beta} = |\sum_i m_i U_{ei}^2|$$

Beta Decay Measurements

Precision spectroscopy of β-decays

Experimental signature:

- Spectral distortion at endpoint



Observable: $m_\beta^2 = \sum_i m_i^2 |U_{ei}|^2$

- Appears in β-spectrum:

$$\frac{d\Gamma}{dE_e}(m_{\nu_i}) = C \cdot p_e E_e \cdot \sqrt{(E_e - E_0)^2 - m_{\nu_i}^2} \cdot (E_e - E_0) \cdot F(E_e, Z)$$

normalization — Observable — Relativistic Fermi function

- No model dependence (only kinematics)

Experimental Challenges:

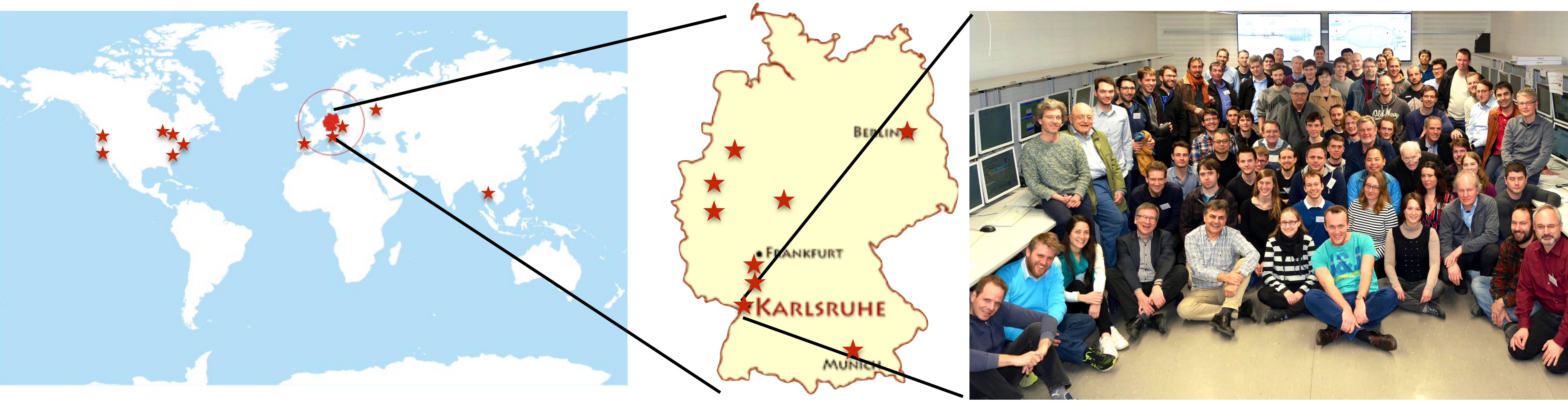
- High resolution
- Strong source & low background
- Convenient isotope: half-life, Q-value

^{3}H (12 yr, 18.6 keV), ^{163}Ho (4600 yr, 2.8 keV)

Other kinematic limits [pdg]**:**

- SN1987: $m_{\nu_e} < 5.8$ eV
- π-decay: $m_{\nu_\mu} < 190$ keV
- τ-decay: $m_{\nu_\tau} < 18.2$ MeV

KATRIN - KArlsruhe TRItium Neutrino Experiment



≈150 scientists in 24 institutions from 7 countries

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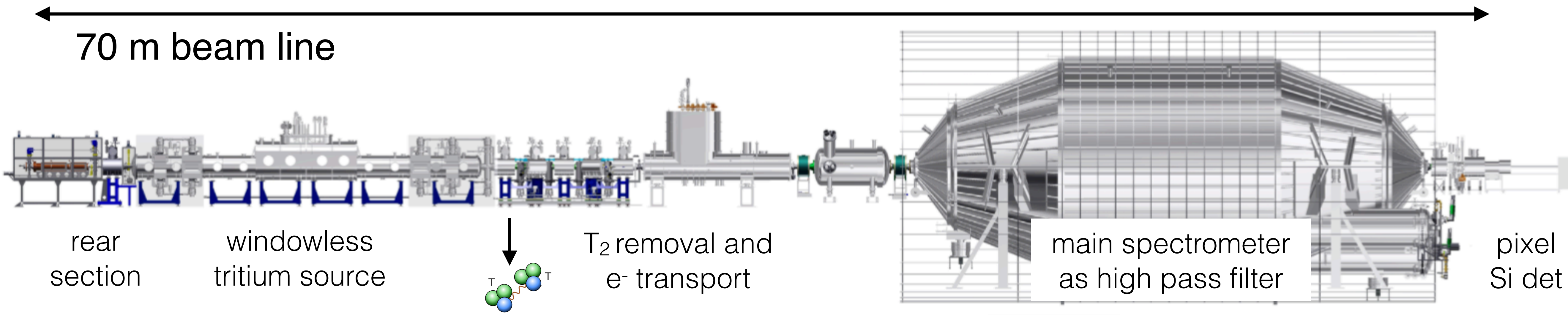
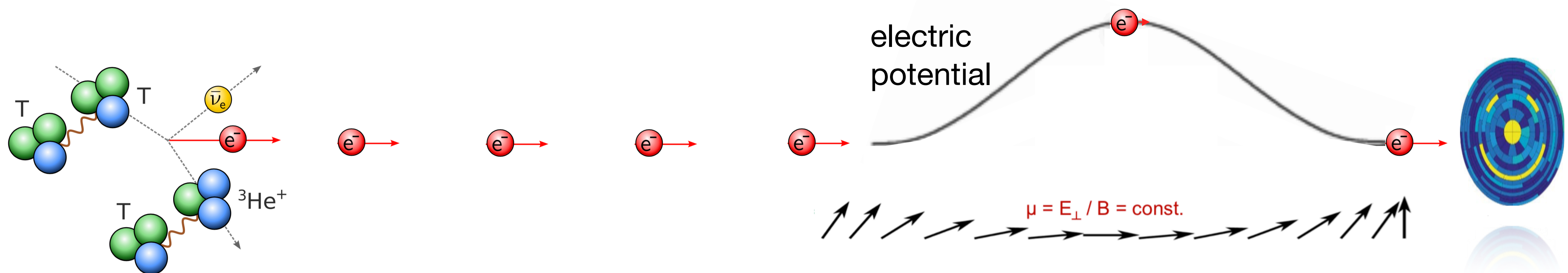
The Experiment

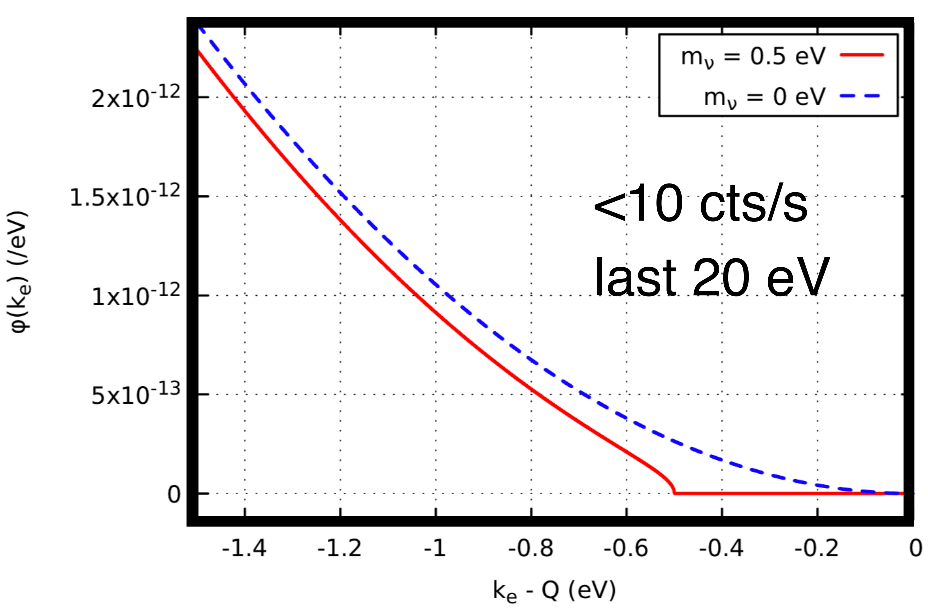


molecular tritium T_2



10^{11} Bq

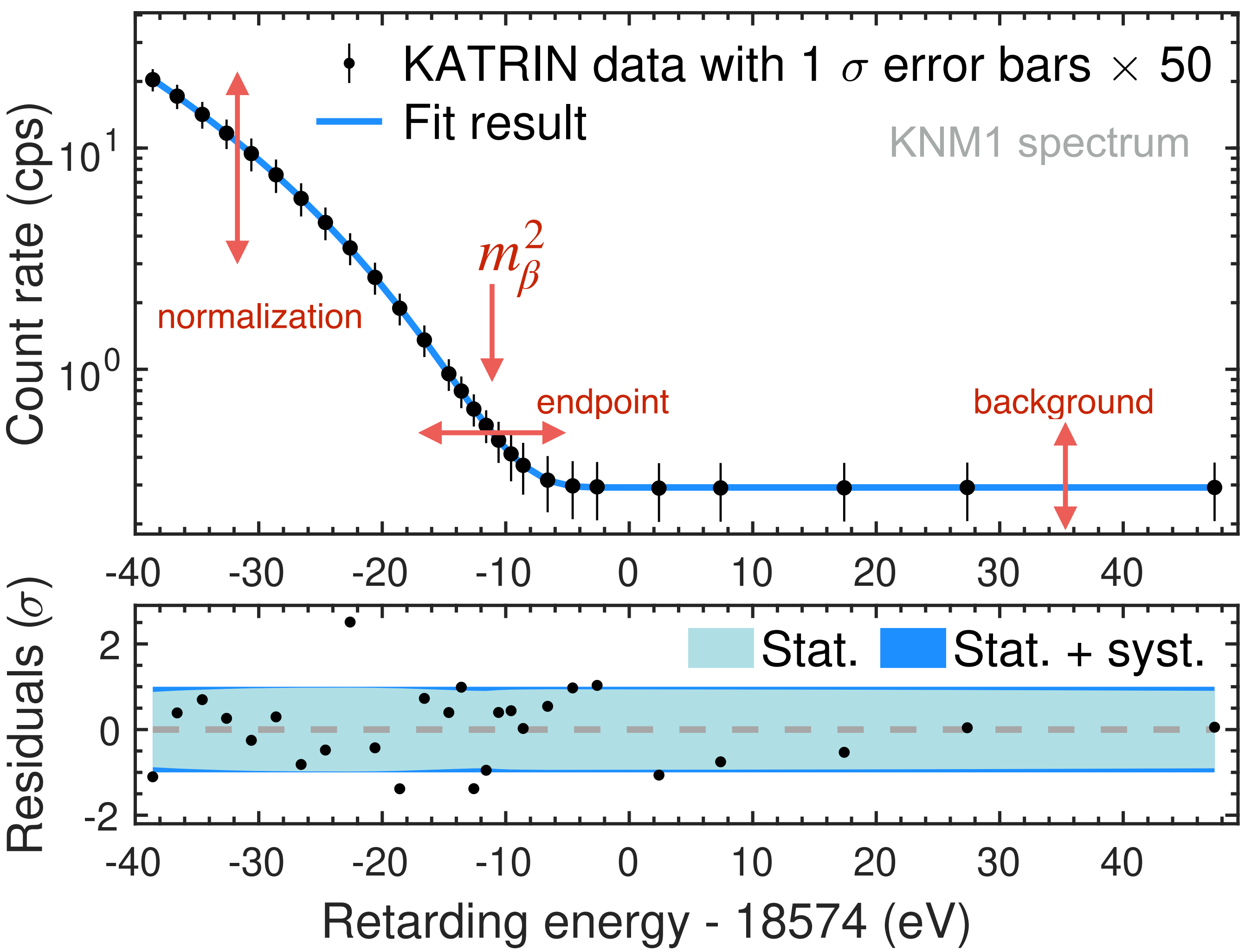
resolution: O(1 eV)

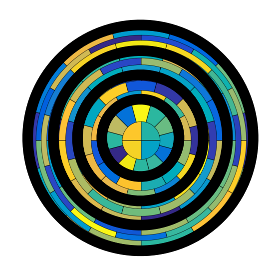


integral spectrum measured close to endpoint

Analysis Strategy

2 Datasets:	**KNM1**	**KNM2**
Date	04-05 2019	09-11 2019
Number scans	274	361
Measurement time	21.7 d	31.0 d
Source activity	25 GBq	95 GBq
Background rate	0.29 cts/s	0.22 cts/s
Signal-to-bg ratio	3.7	9.9



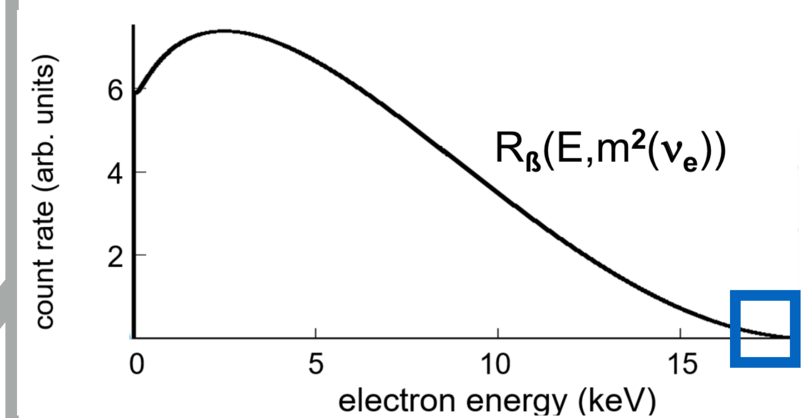


detector segmentation

Model ingredients and systematics

Beta spectrum:

- Multiple spectra from T_2, DT, HT
- Various final states

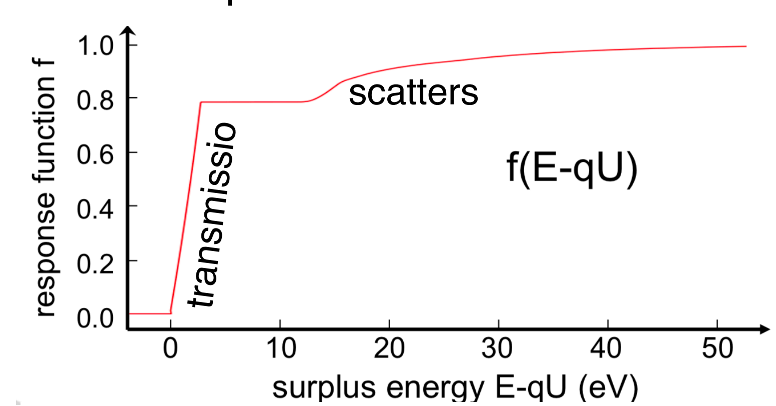


Constant background

- Time varying component
- Potential slope

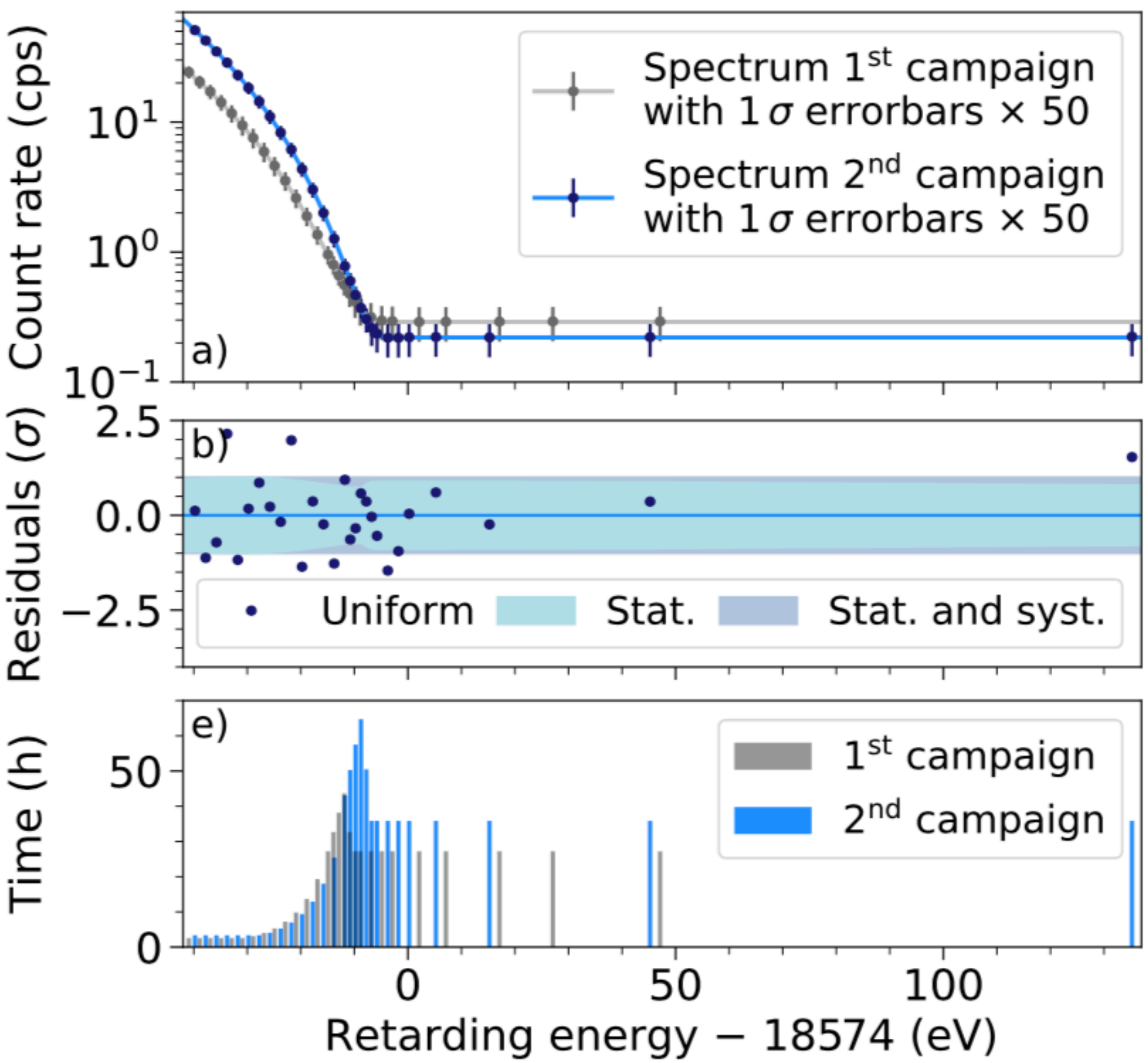
Response function:

- Transmission: B-fields
- Source density: Probability of scatter
- Electron energy loss: If scatter occurs
- Source potential: Plasma effects



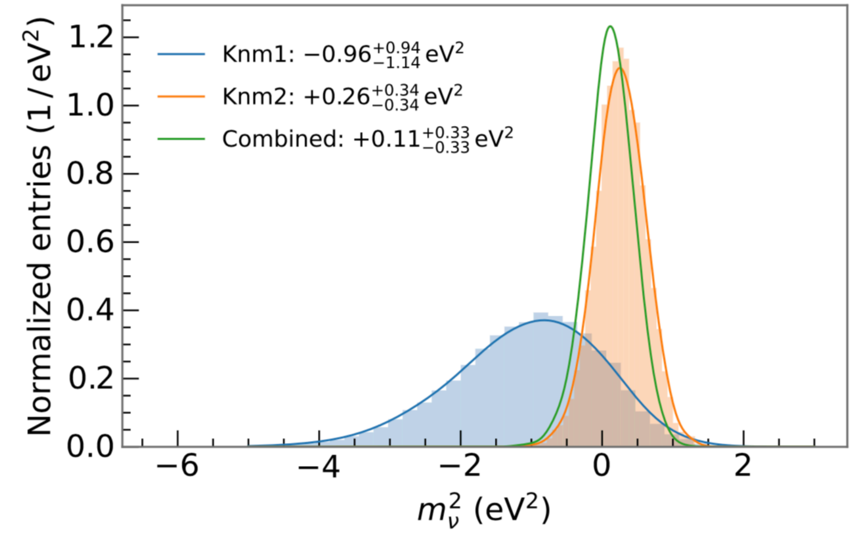
Results Combined KNM1 + KNM2

Nature Physics
18, 160 (2022)



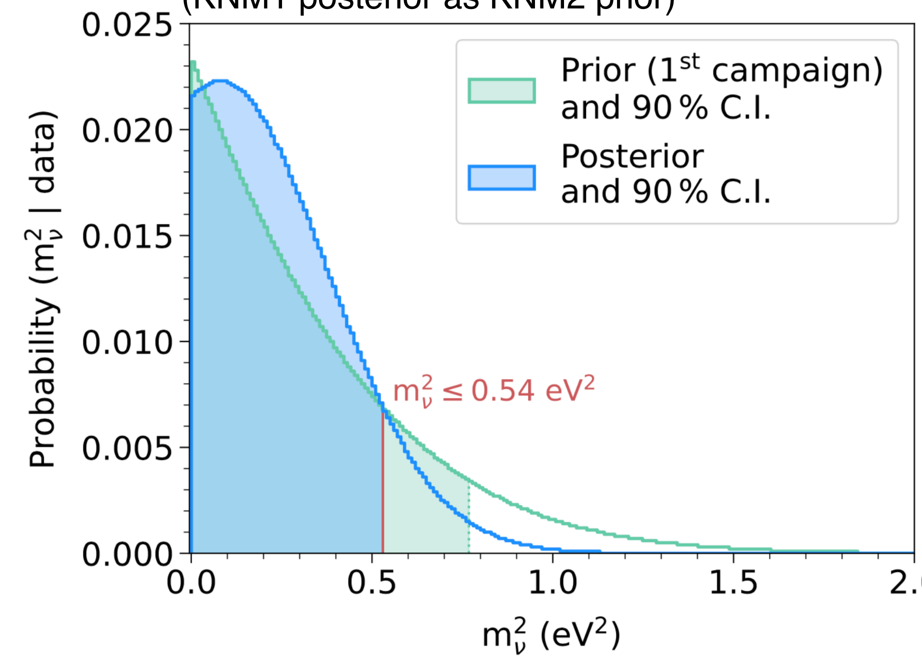
Frequentist likelihoods

(multiplication or combined fit)



Bayesian posteriors

(KNM1 posterior as KNM2 prior)



Cross check of Q-value:

	KNM1 [eV]	KNM2 [eV]
endpoint	18573.7 ± 0.1	18573.69 ± 0.03
Q-value	18575.2 ± 0.5	18575.2 ± 0.6

literature Q-value = 18575.72 ± 0.07 eV

good agreement illustrating stability of energy scale

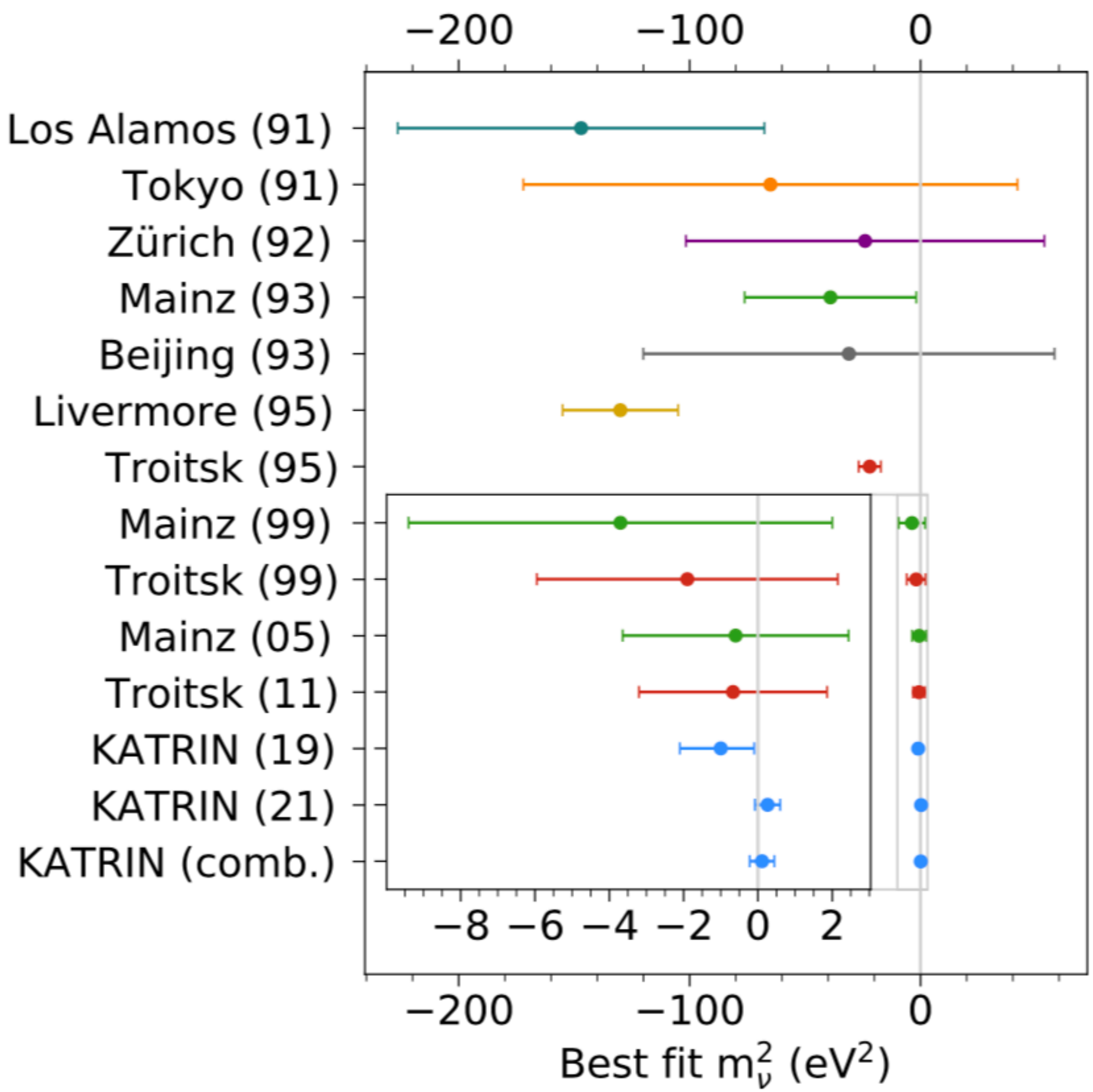
Best fit: $m_\beta^2 = 0.1 \pm 0.3\ \mathrm{eV}^2$

Limits LT and FC: $m_\beta < 0.8\ \mathrm{eV}$ (90% CL)

Limits Bayesian: $m_\beta < 0.73\ \mathrm{eV}$ (90% CI)

Results Combined KNM1 + KNM2

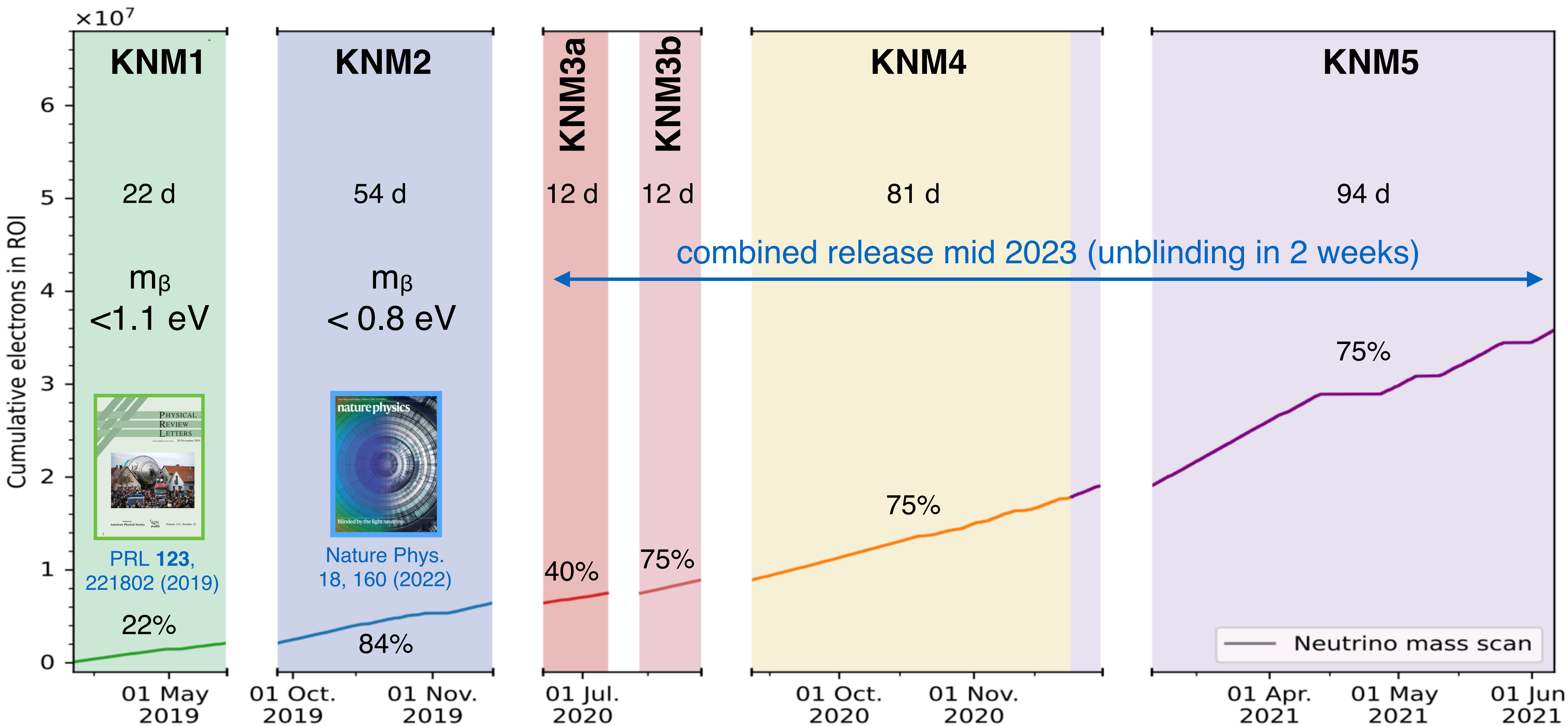
Nature Physics
18, 160 (2022)



3 months KATRIN data better than Mainz, Troitsk

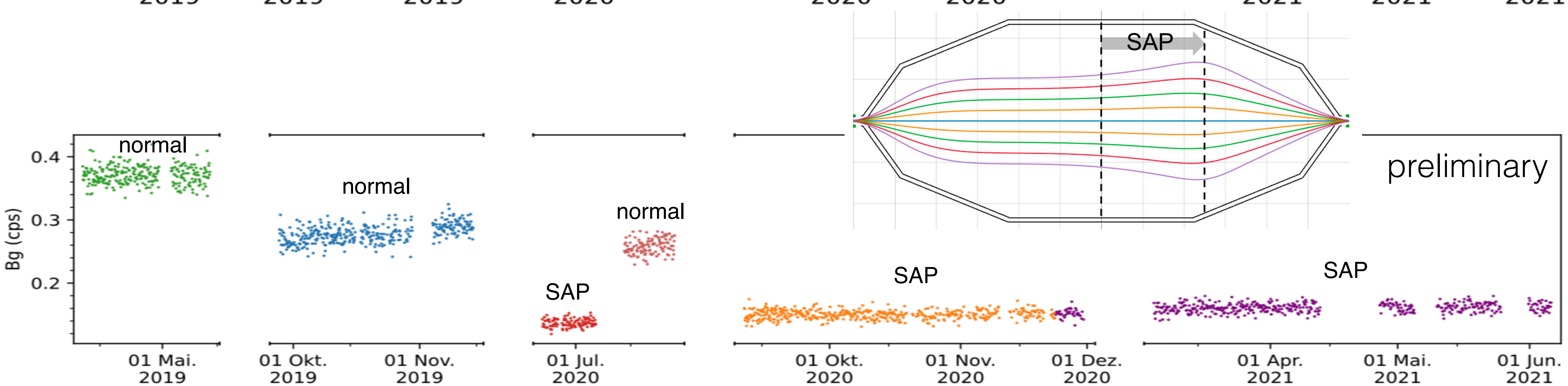
- Statistics x6, systematics x12
- Multiple independent blind analyses
- First sub-eV neutrino mass sensitivity in lab
- Neutrino x500.000 times lighter than electron

Future Datasets

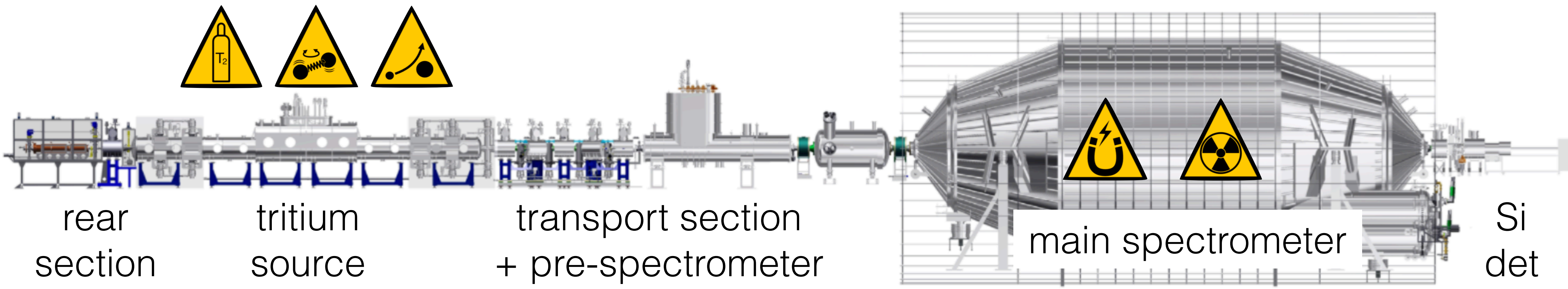


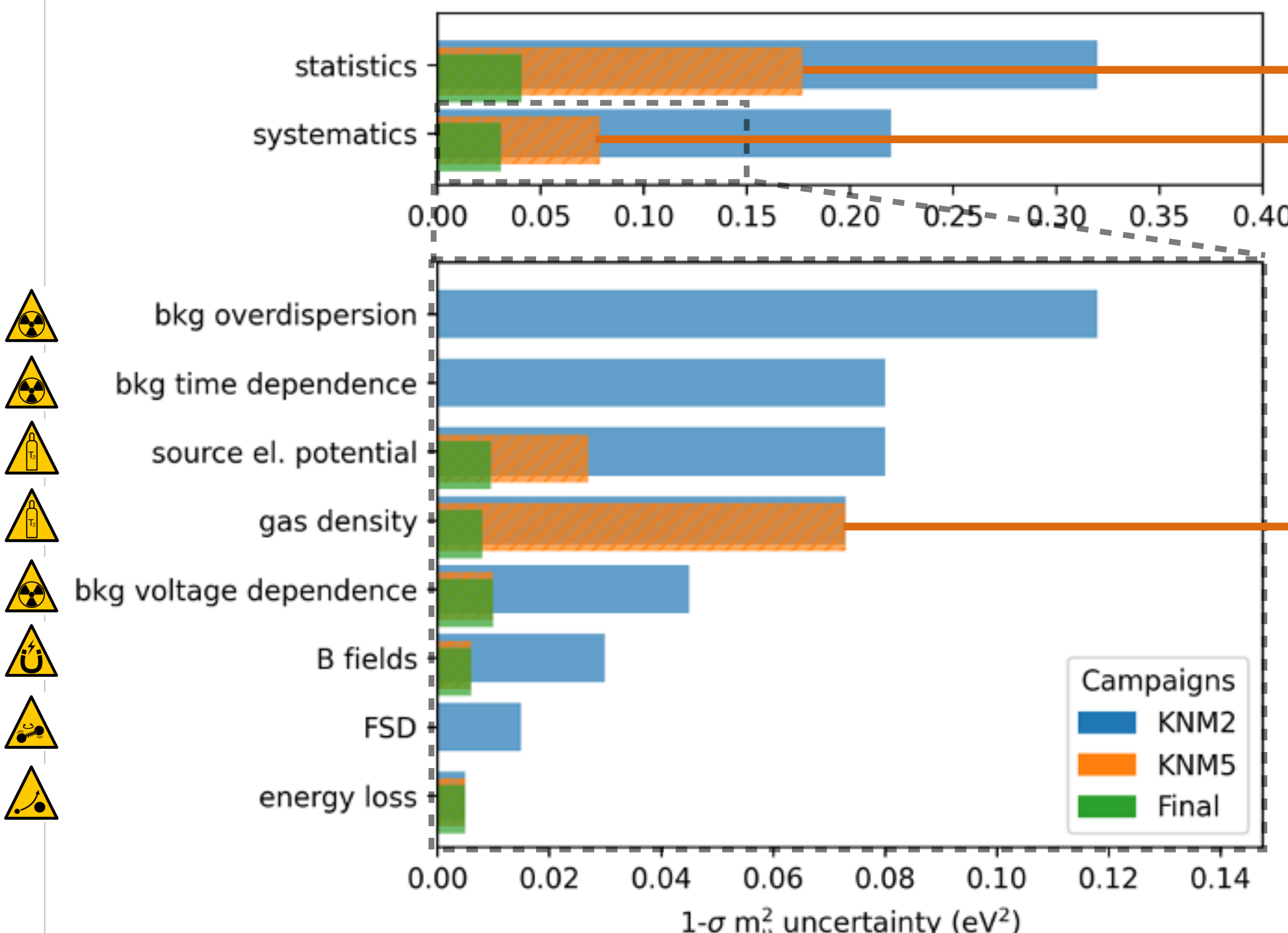
KNM6, 7 on disk

KNM8 ongoing



Current and Future Systematics





Higher statistics (longer run)

Reduced systematics (x6)
- SAP mode
- Source operation

Largest systematic in next dataset: Gas density

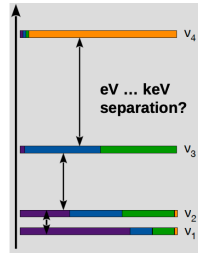
Final sensitivity:
- **1000 days** in 5 yr (end of 2024)
- Sensitivity: 0.2 eV (90% CL)
- Discovery potential: 0.35 eV

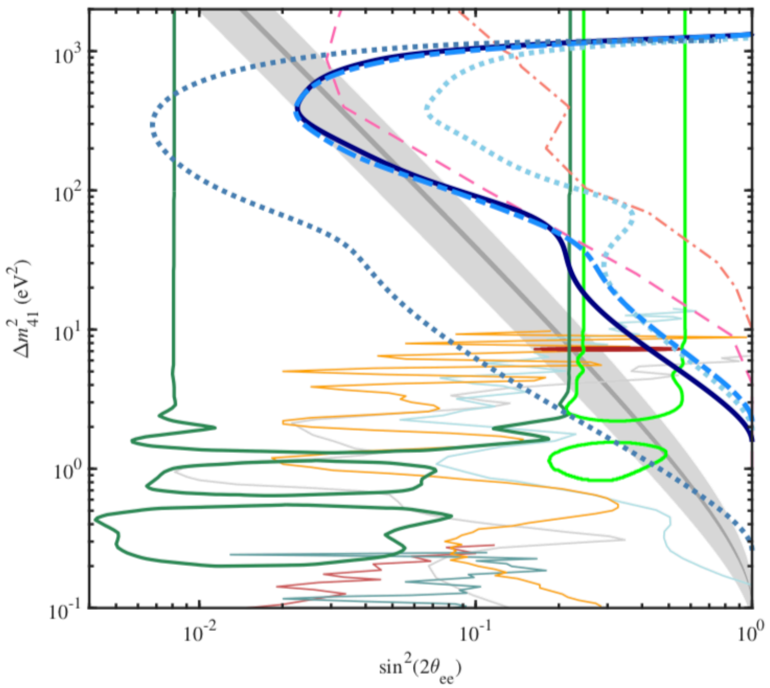
Other Searches With KATRIN Data

Sterile Neutrinos 3+1

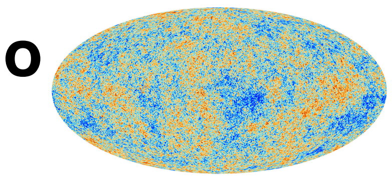
eV Phys. Rev. D 105, 072004

keV arXiv:2207.06337 [nucl-ex]

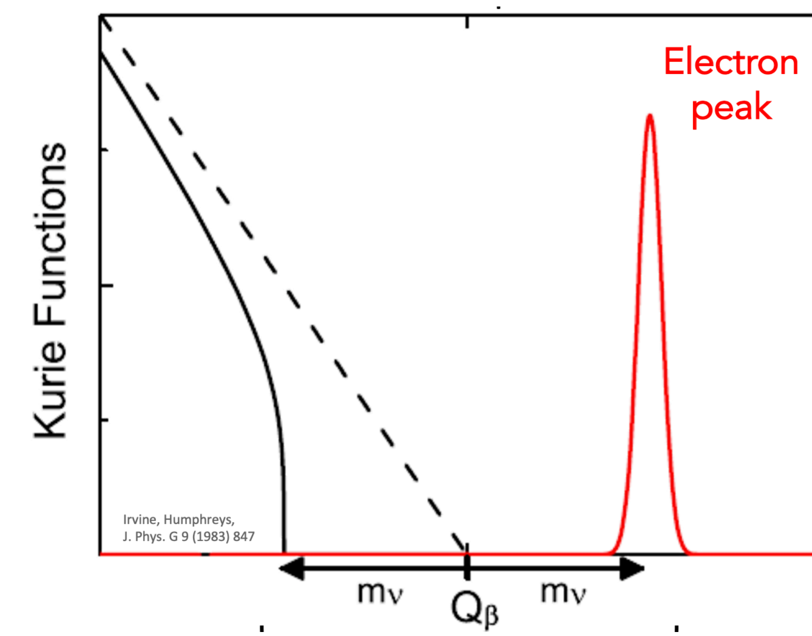




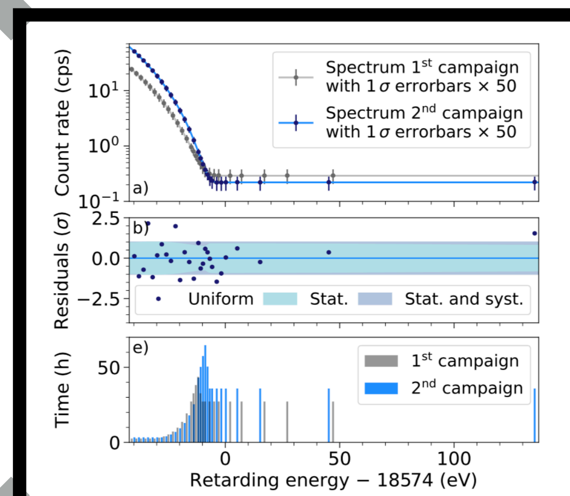
Cosmic Neutrino Background



Phys. Rev. Lett. 129, 011806

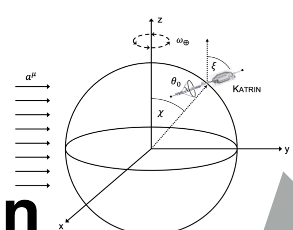


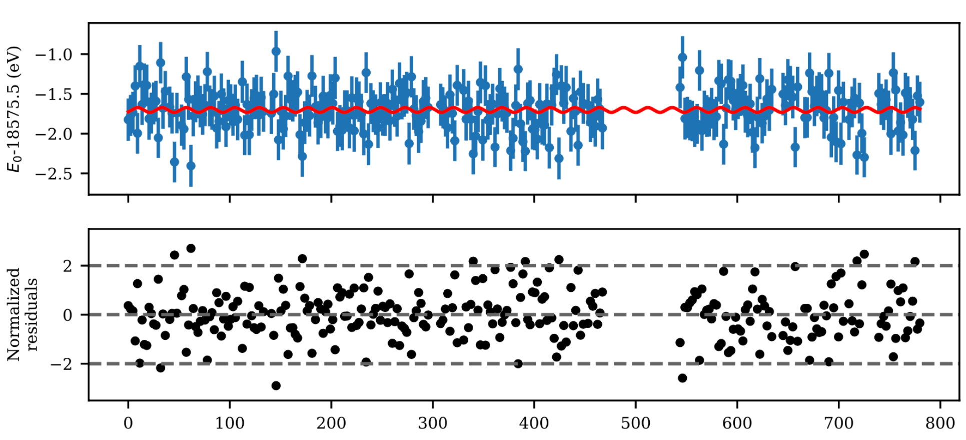
High precision beta decay data



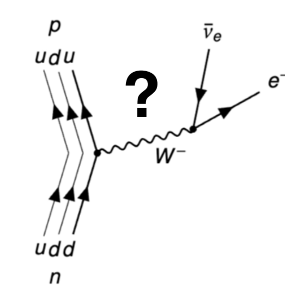
Lorentz Invariance Violation

arXiv:2207.06326 [nucl-ex]





Exotic Weak Interactions



in progress…

Conclusions & Outlook

KATRIN measures neutrino mass

- $m_\beta = \sqrt{\sum_i m_i^2 |U_{ei}|^2}$
- Complementary with Cosmology and Double Beta Decay
- Currently only leading experiment (Future: Project8, ECHo, HOLMES)

Current best limit from all data [1-2]

- $m_\beta^2 = 0.1 \pm 0.3\ \text{eV}^2$
- $m_\beta < 0.8\ \text{eV}\ (90\,\%\ \text{CL})$
- Statistics dominated, largest systematic from background

Nature Physics 18, 160 (2022)

Coming next:

- Next data release [1-5] ETA mid 2023
- Final sensitivity: 0.2 eV (90% CL)
- Final discovery potential: 0.35 eV

Backup

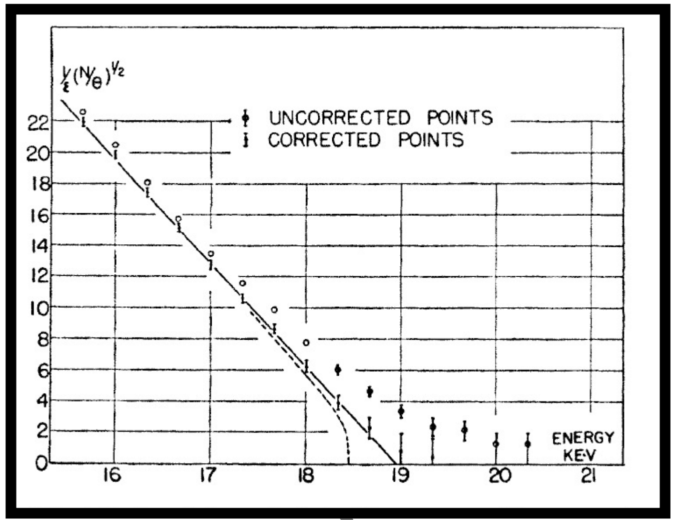
History of Neutrino Mass Measurements

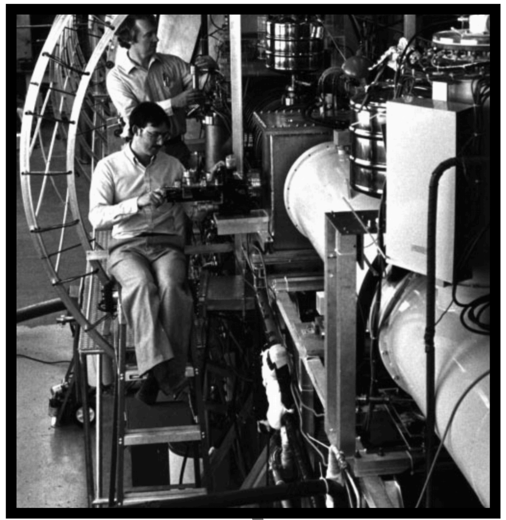
Hanna & Pontecorvo 1949
Proportional counter
$m_\nu < 500$ eV

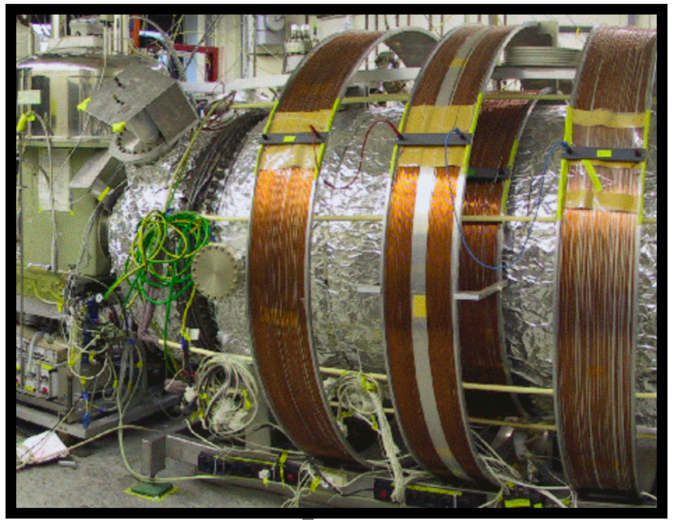
Los Alamos Experiment
Gaseous T_2 source
$m_\nu < 9.3$ eV

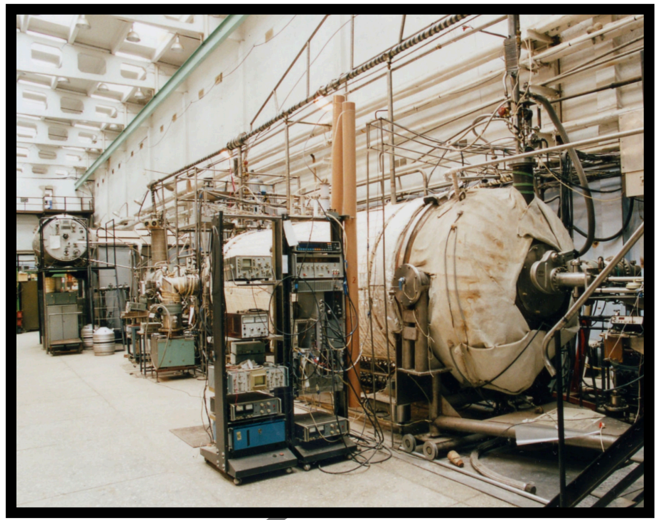
Mainz Experiment
MAC-E filter, solid state T_2
$m_\nu < 2.3$ eV

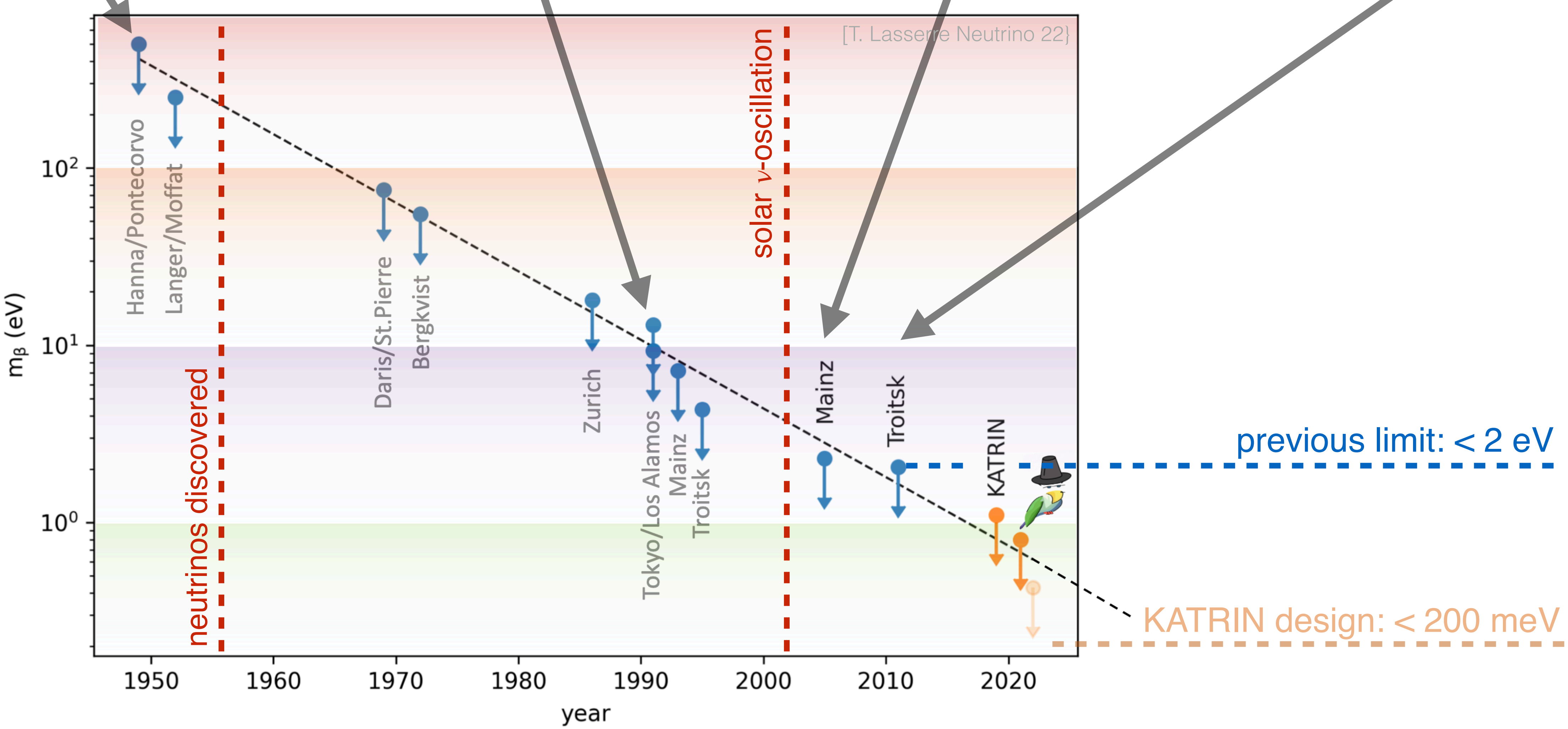
Troitsk Experiment
MAC-E filter, gaseous T_2
$m_\nu < 2.05$ eV







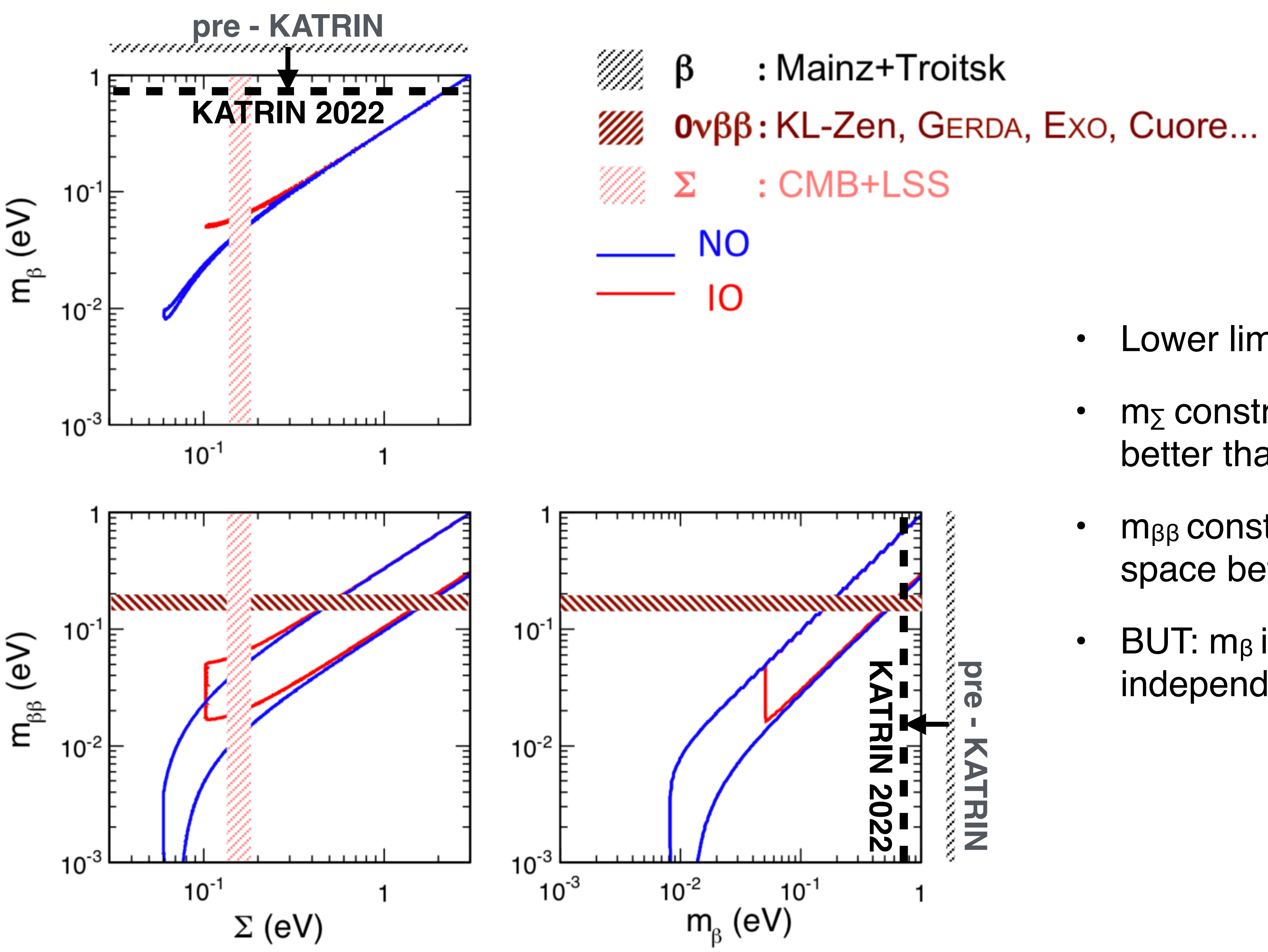




Global Picture 2022

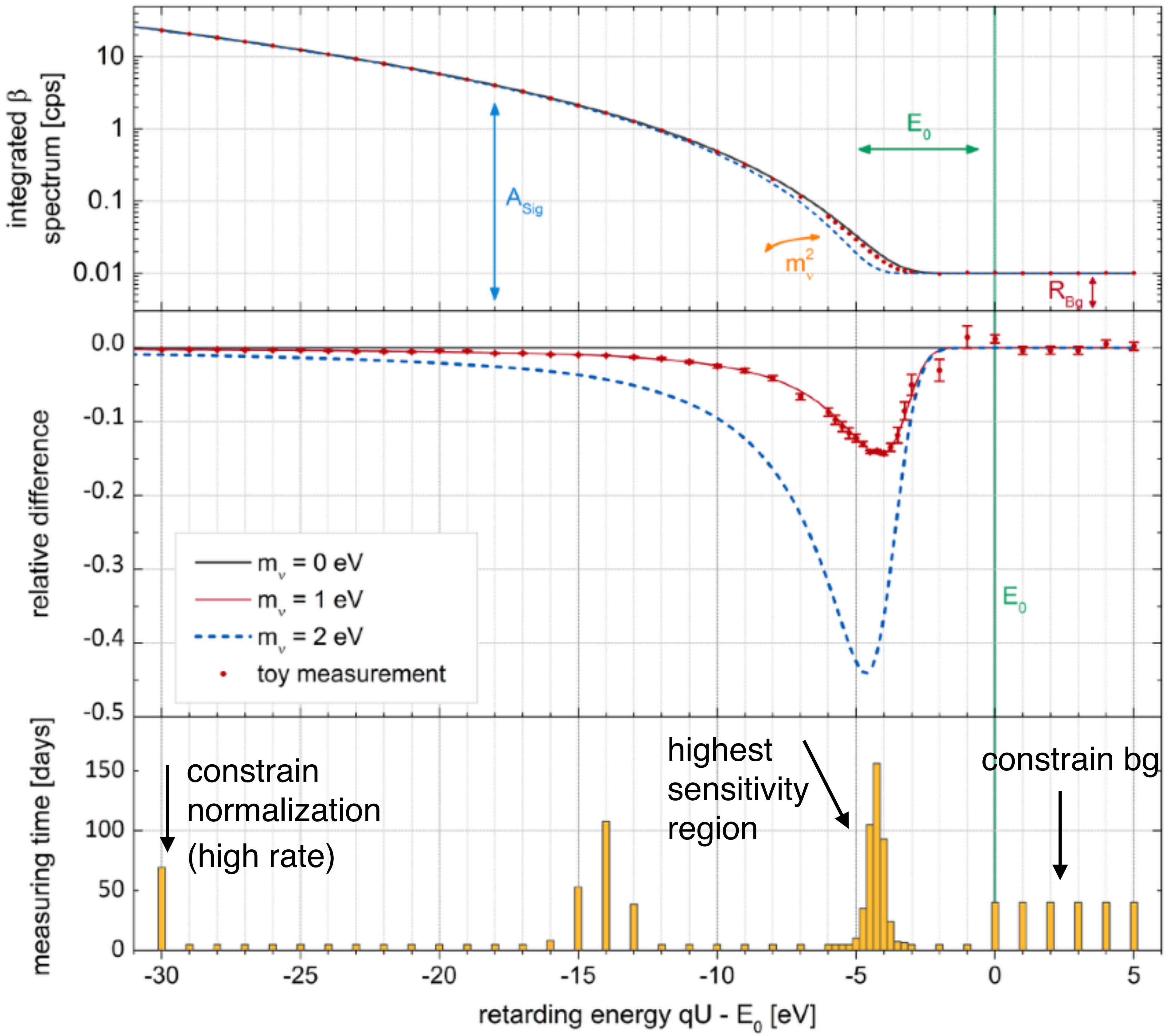
(assuming no sterile neutrinos)

[from Eligio Lisi, TAUP19]



- Lower limit on m_β at 8 - 50 meV
- m_Σ constrains parameter space better than m_β
- $m_{\beta\beta}$ constrains parameter space better than m_β
- BUT: m_β is the only model independent measurement

Measurement Concept



Integral spectrum

- Run: complete scan of all HV points
- 4 fit parameters to describe spectrum
- Background is flat

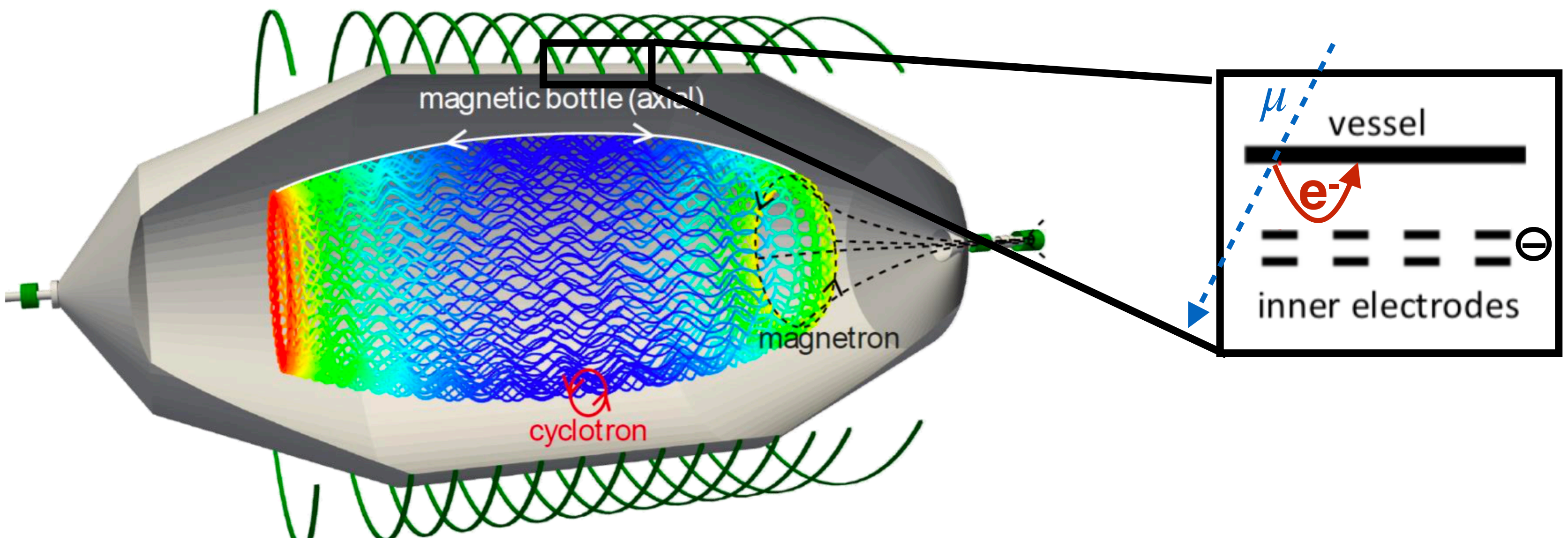
Residuals

- Most sensitive region around endpoint
- Statistical fluctuations can result in "negative m²"

Measuring time distribution

- Choose HV points and statistics in each point
- Optimize for sensitivity e.g. constrain background, normalization

Backgrounds



Main expected electron source:

- e^- from muon interaction in vessel (above ground)
- Effectively mitigated by inner electrode system

Signal:

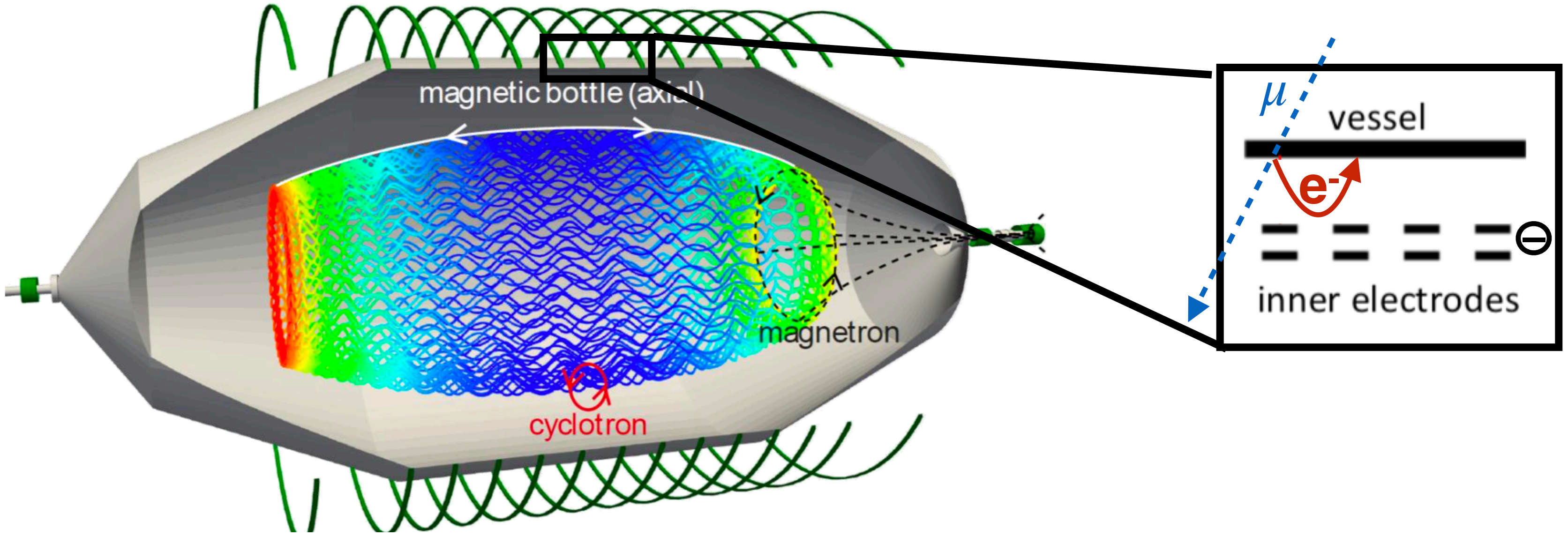
- e^- have $E \approx 0$ keV in analyzing plane

Background:

- All low energy e^- in main spectrometer volume can mimic signal
- Background e^- are detected independent of qU: background flat in integral spectrum

Initially observed background 50x higher than expected!

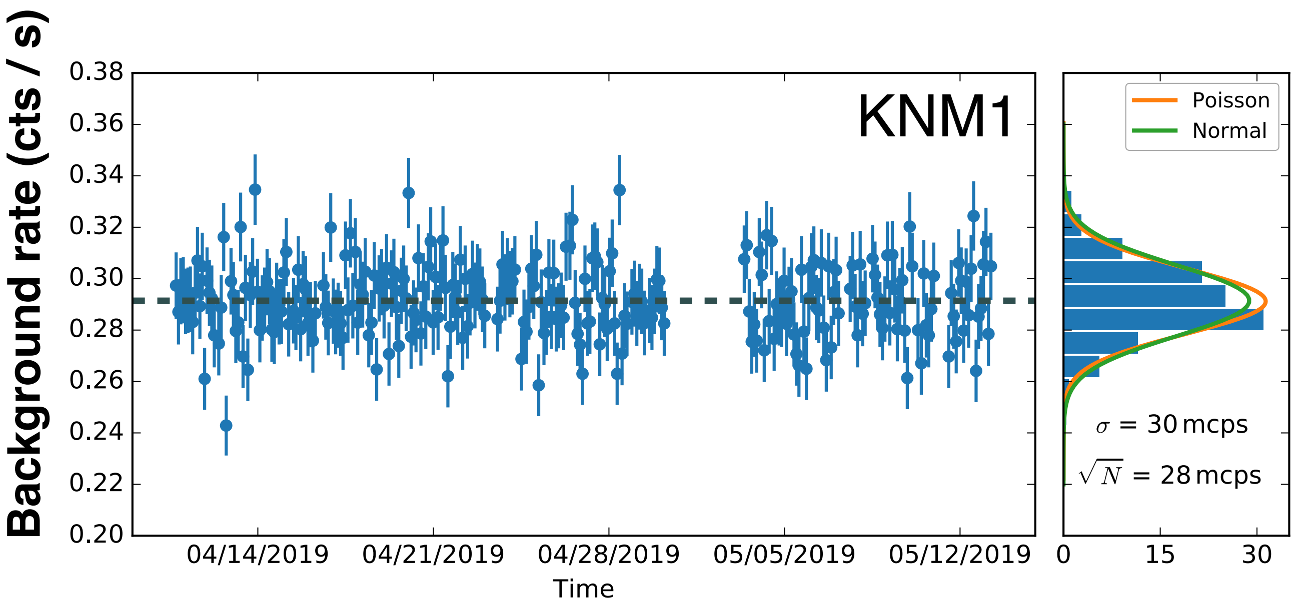
Backgrounds



- MAC-E filter can store fast e- through "magnetic bottle" effect
- Stored e- ionize residual gas creating low e- secondary electrons

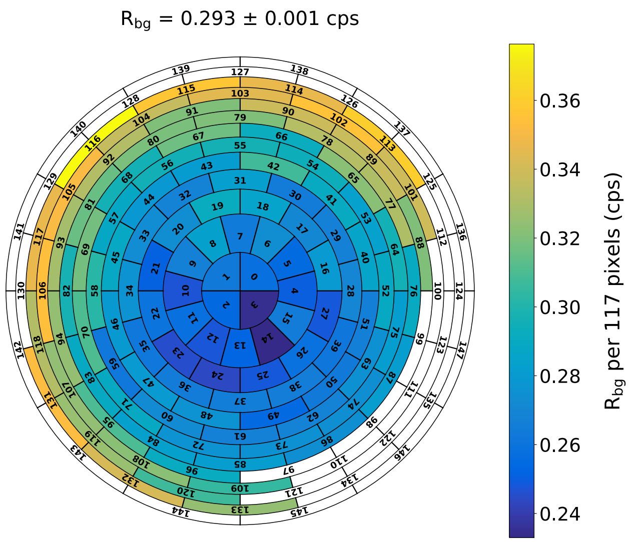
1. ^{219}Rn ($T_{1/2}$ = 4s) from getter material in pumps

- Decays in spectrometer create fast e- which are stored
- Creates time varying background rate
- Largest systematic



2. Rydberg atoms from vessel walls

- ^{210}Pb / ^{210}Po decays spatter out atoms in highly excited Rydberg states
- Ionize in main volume creating radial dependent background



Change of measurement and analysis strategy largely mitigates impact on sensitivity

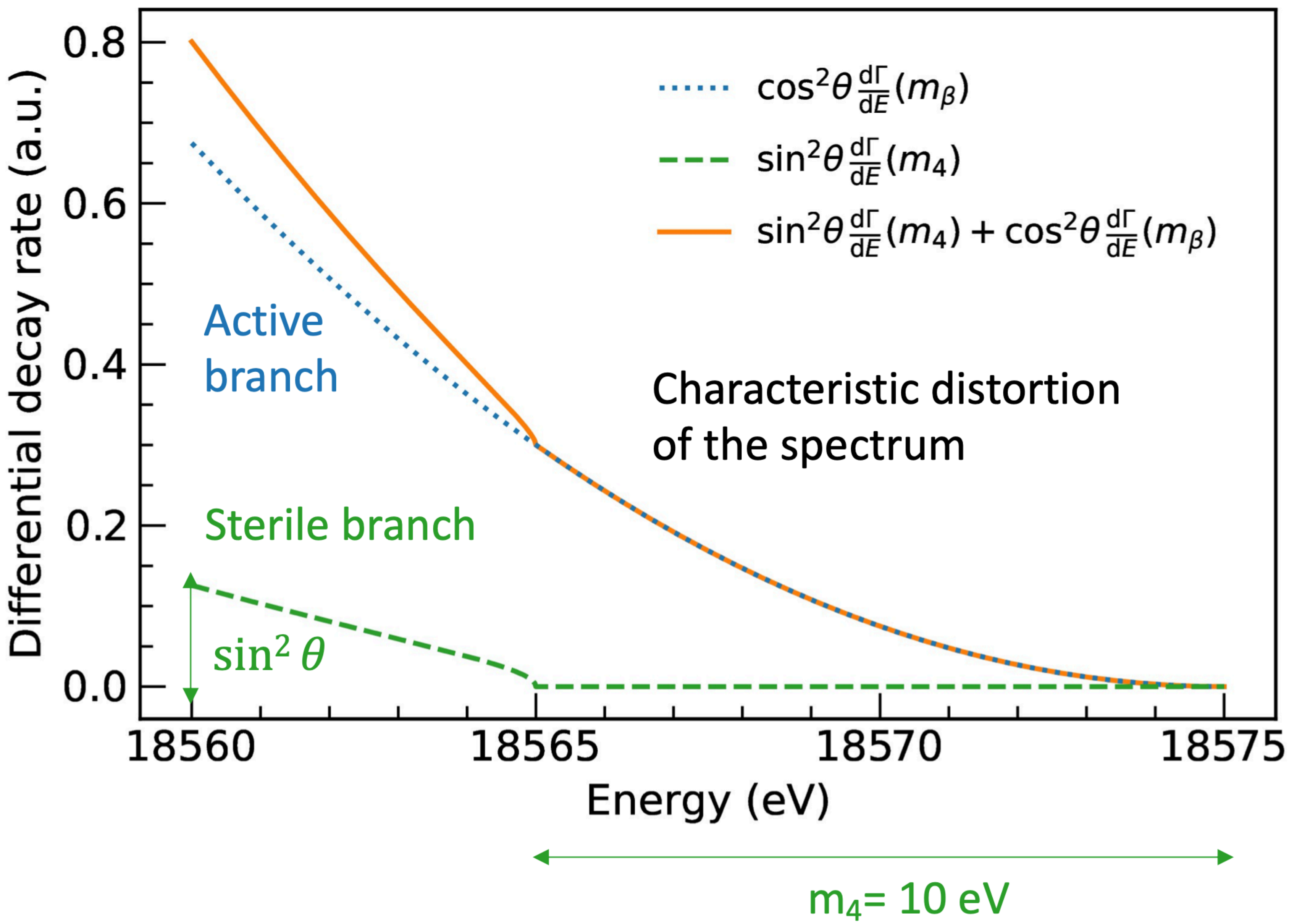
eV Sterile Neutrinos: Experimental signature

Additional mass eigenstate ν_4

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

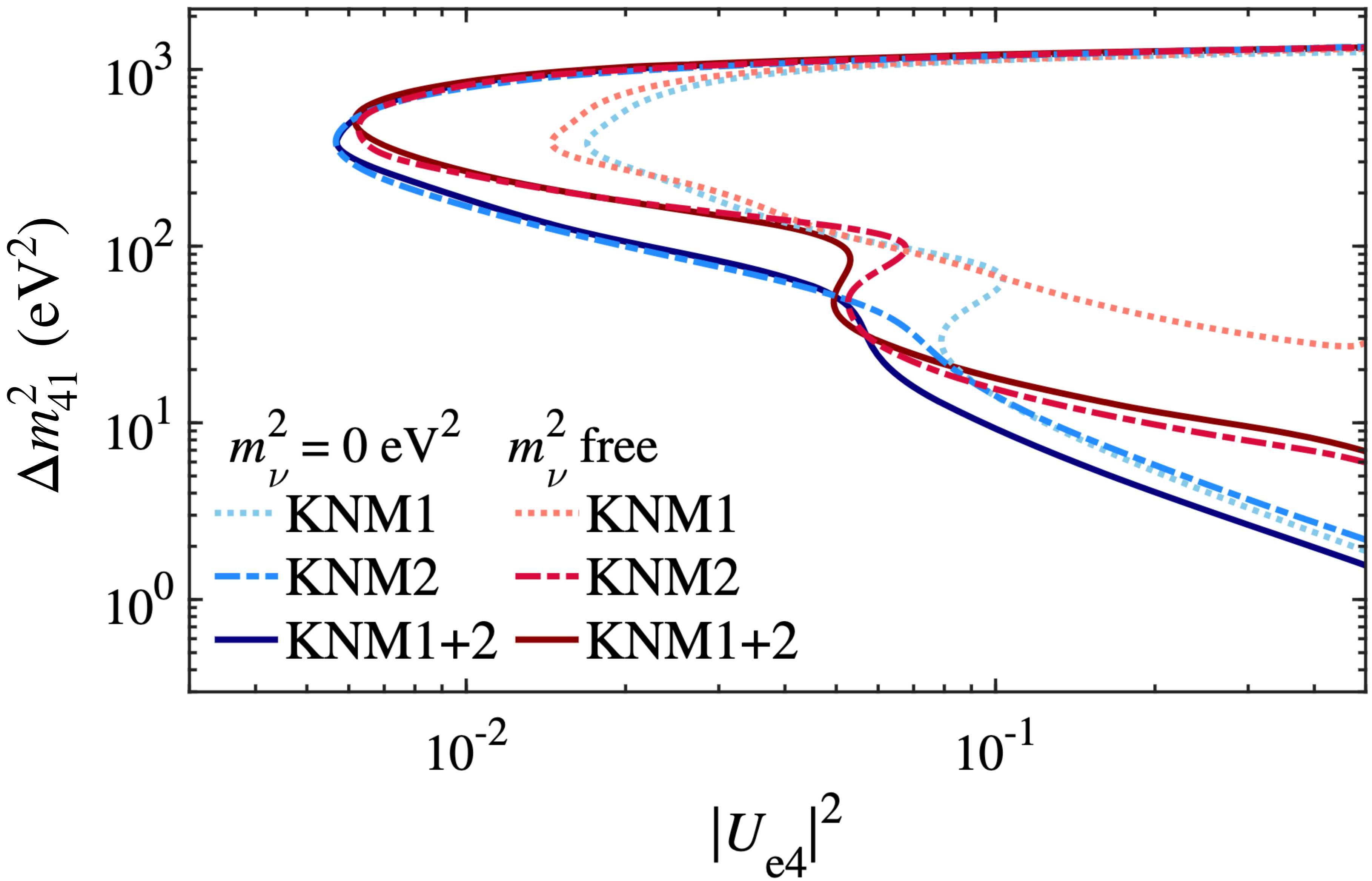
Analysis:

- Same dataset as for neutrino mass
- Two additional parameters
  - m_4: 4th neutrino mass
  - U_{e4}^2: 4th neutrino mixing
- Grid search in m_4^2 - U_{e4}^2 plane



eV Sterile Neutrinos: Results

PRD 105, 072004 (2022)



Interplay between m_β^2 and m_4^2

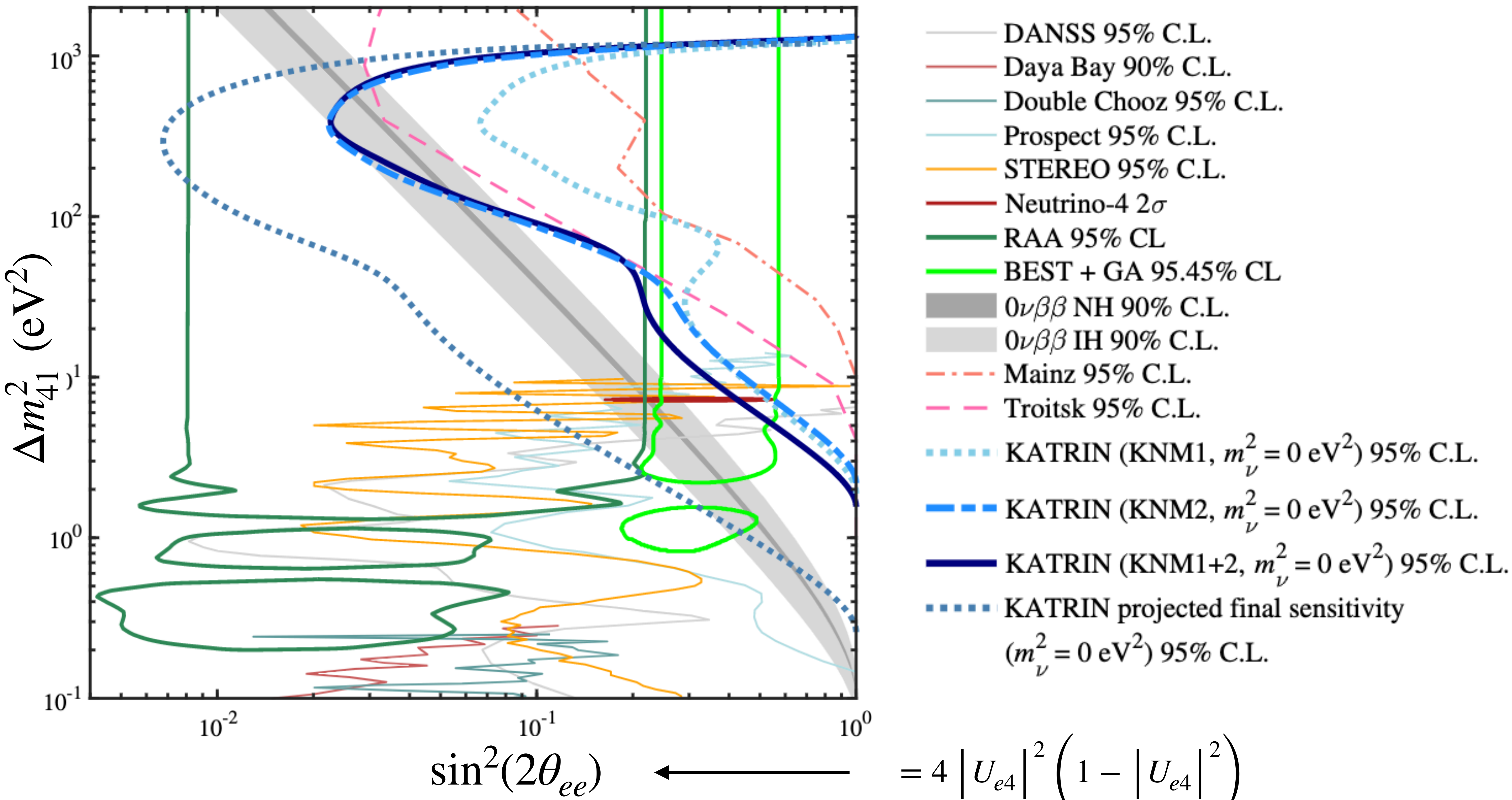
- $|U_{e4}|^2 < 0.5$ (otherwise $m_4^2 \rightarrow m_\beta^2$)
- Strong correlation at low m_4 reducing sensitivity

Analysis details

- χ^2 fit with covariance matrix for systematics
- 95% limits using Wilk's: $\Delta\chi^2 = 5.99$
- Statistics dominated
- Structures caused by MTD

eV Sterile Neutrinos: Comparison with other Experiments

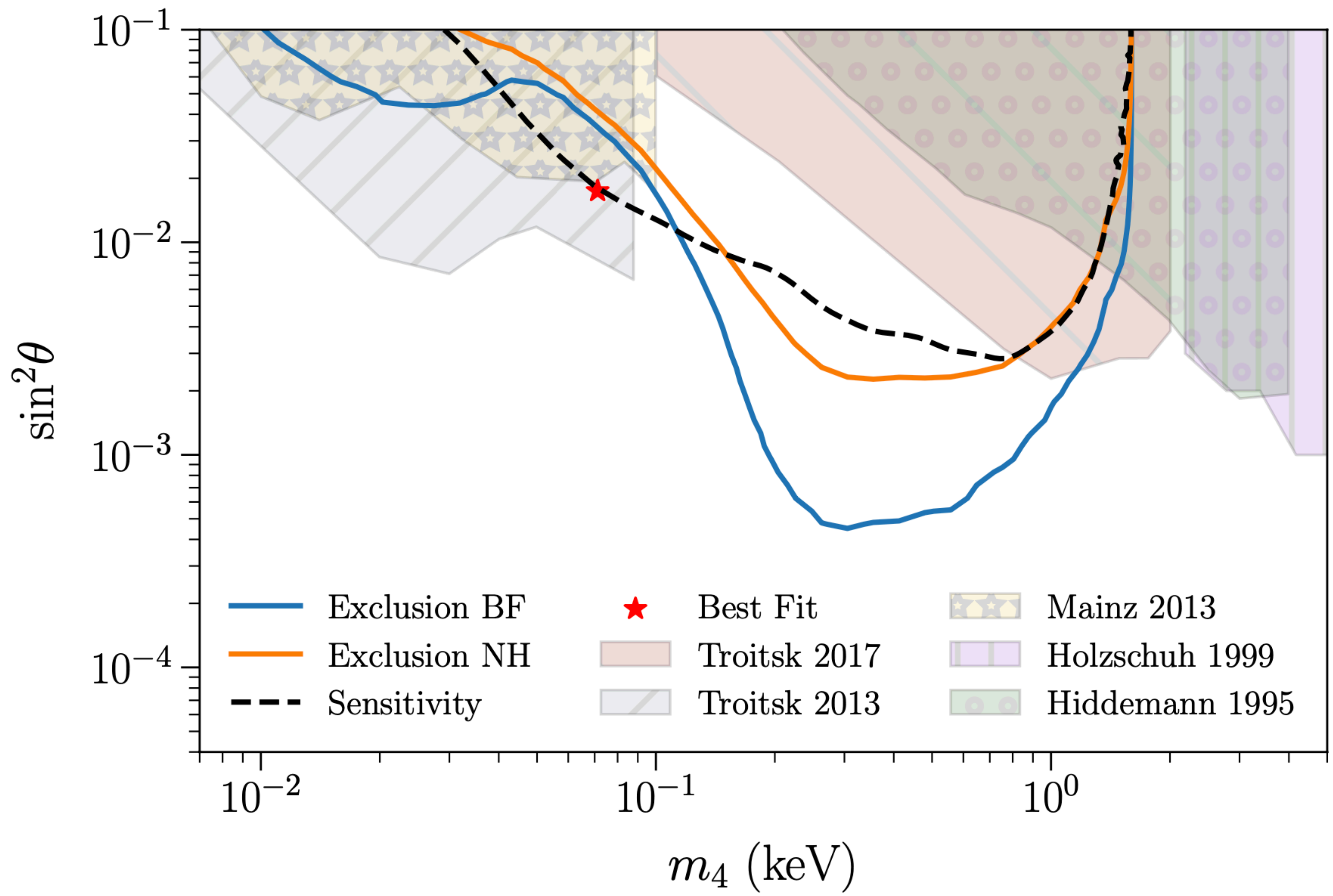
PRD 105, 072004 (2022)



$$= 4\left|U_{e4}\right|^2\left(1 - \left|U_{e4}\right|^2\right)$$

- Different perspective on short baseline anomalies
- Final KATRIN dataset will test large regions of RAA, BEST and Neutrino-4

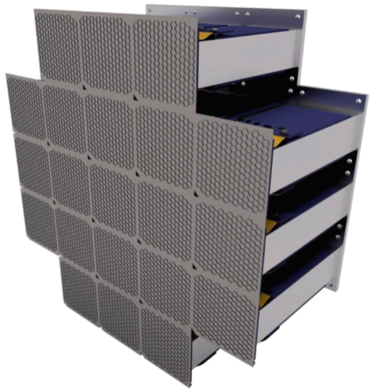
keV Sterile Neutrinos



arXiv:2207.06337 (2022)

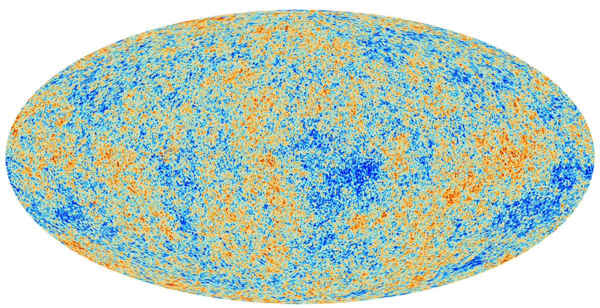
New results (last week):
- Commissioning data 2018
- 0.5% T_2 in 12 day measurement
- Scan 1.6 keV deep into spectrum

Future: Tristan
- Dedicated runs post KATRIN (≥ 2025)
- New detector
  - >1000 pixel Si drift detector
  - Accept higher rate



Cosmic Neutrino Background (CNB)

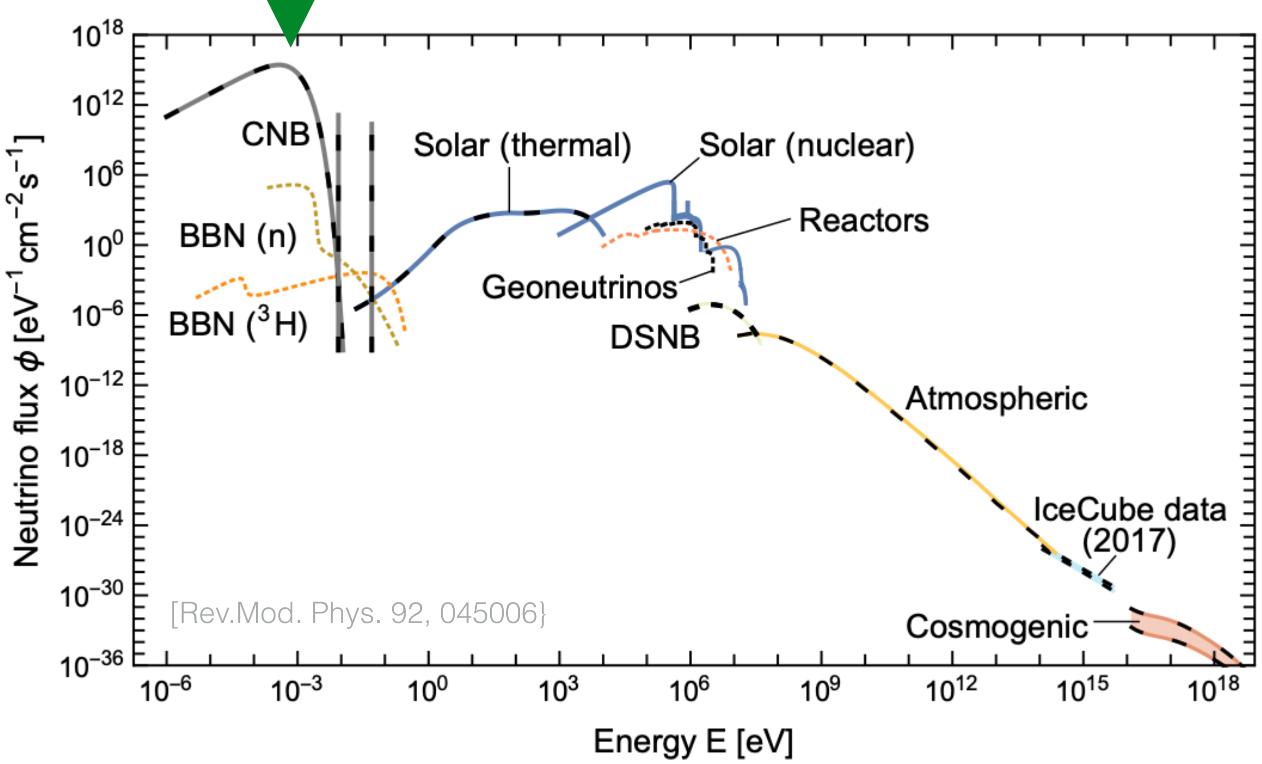
- Window into 1 sec after big bang
- 336 neutrinos / cm³ (56 per specie)
- Potentially clustered in galaxies (sub-relativistic)

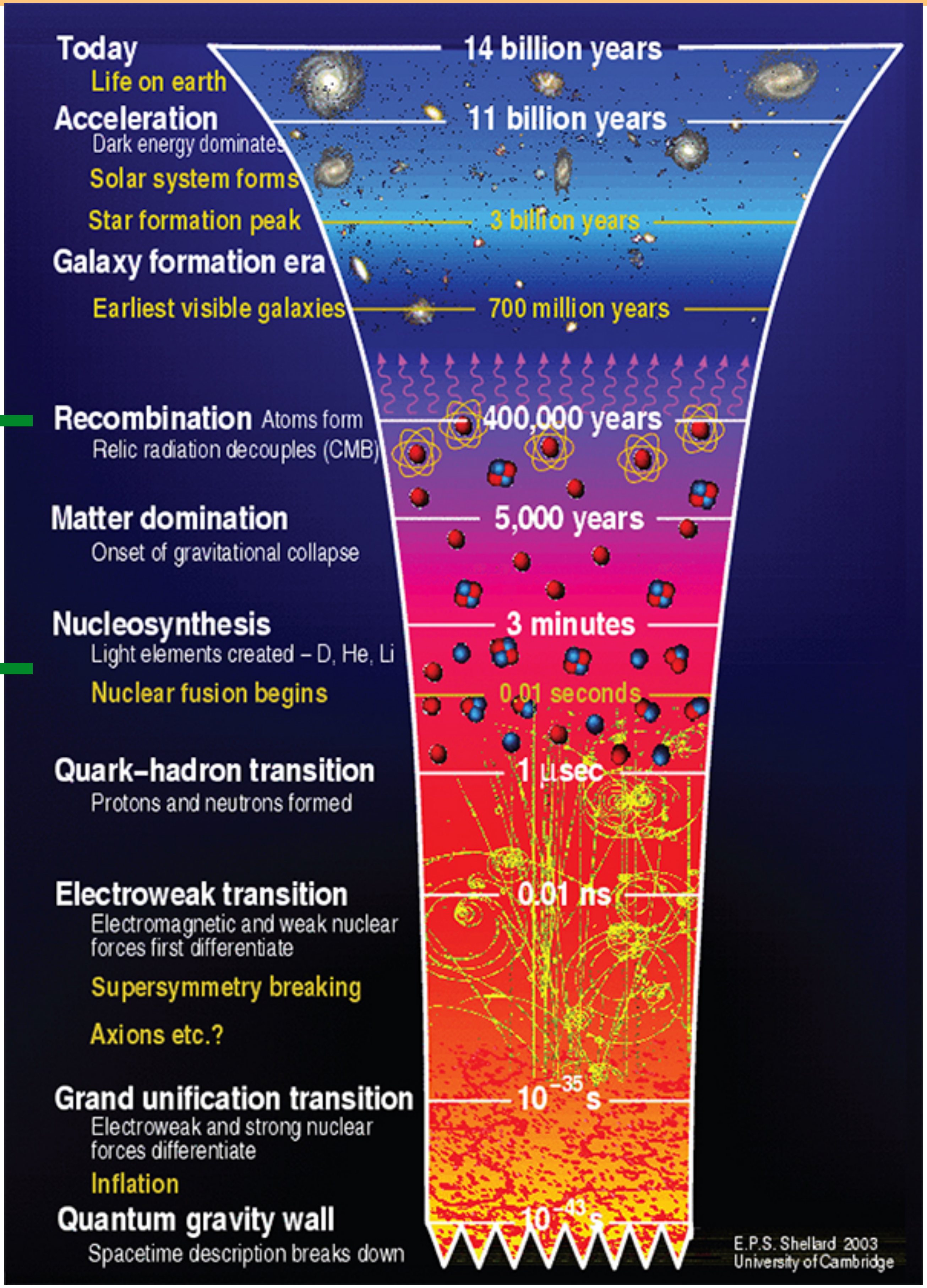


CMB: 370,000 yr, 2.7 K

CNB: 1 sec ,1.9 K

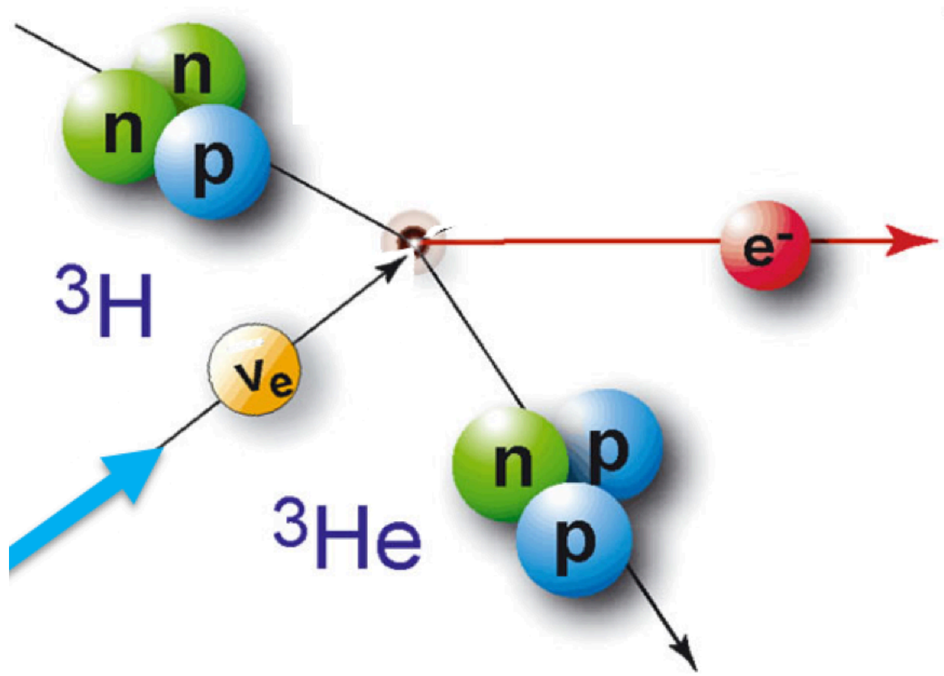
highest flux of neutrinos but at very low energy





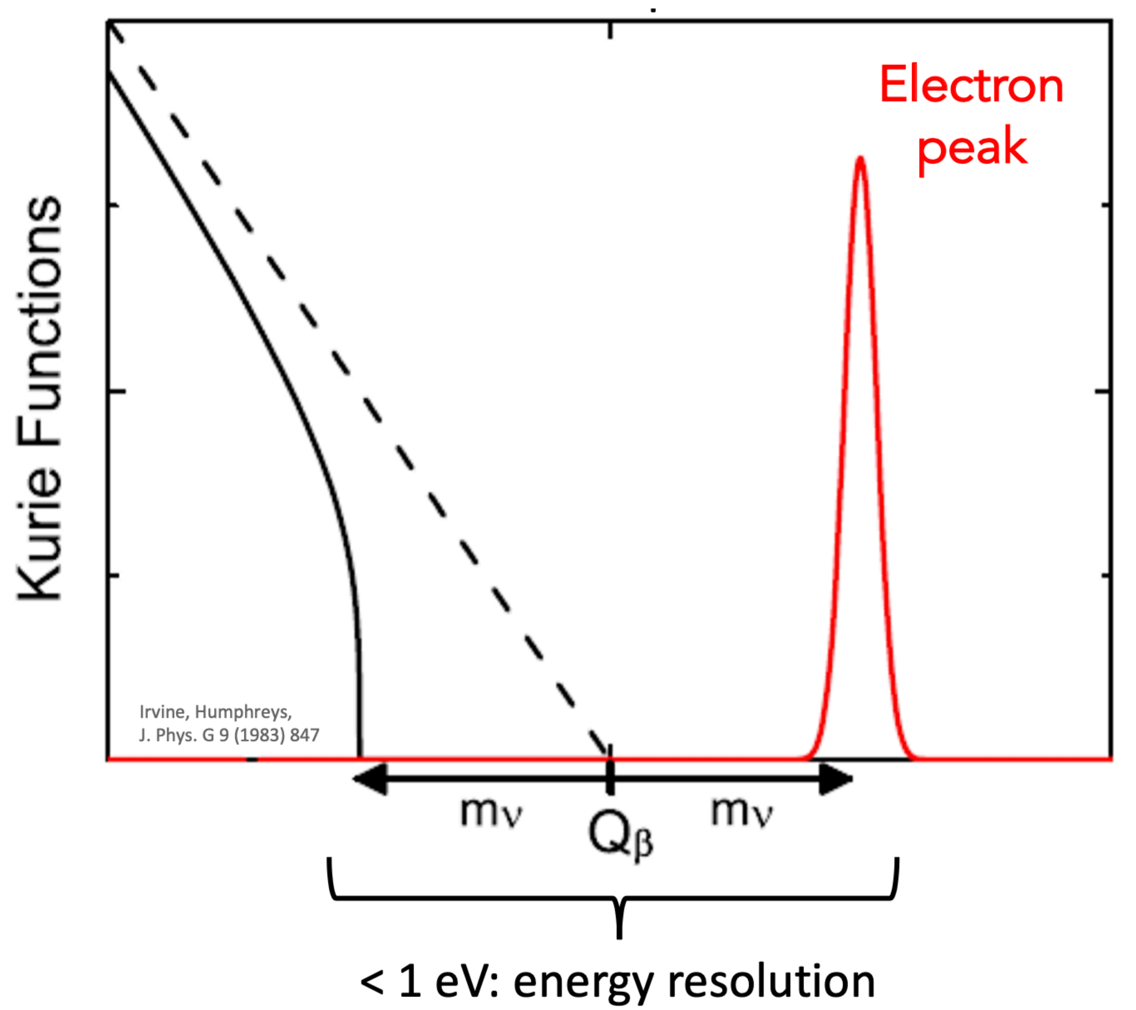
CNB: Experimental Signature

Neutrino capture on tritium:



Experimental signature:

Peak above endpoint (differential spectrum)

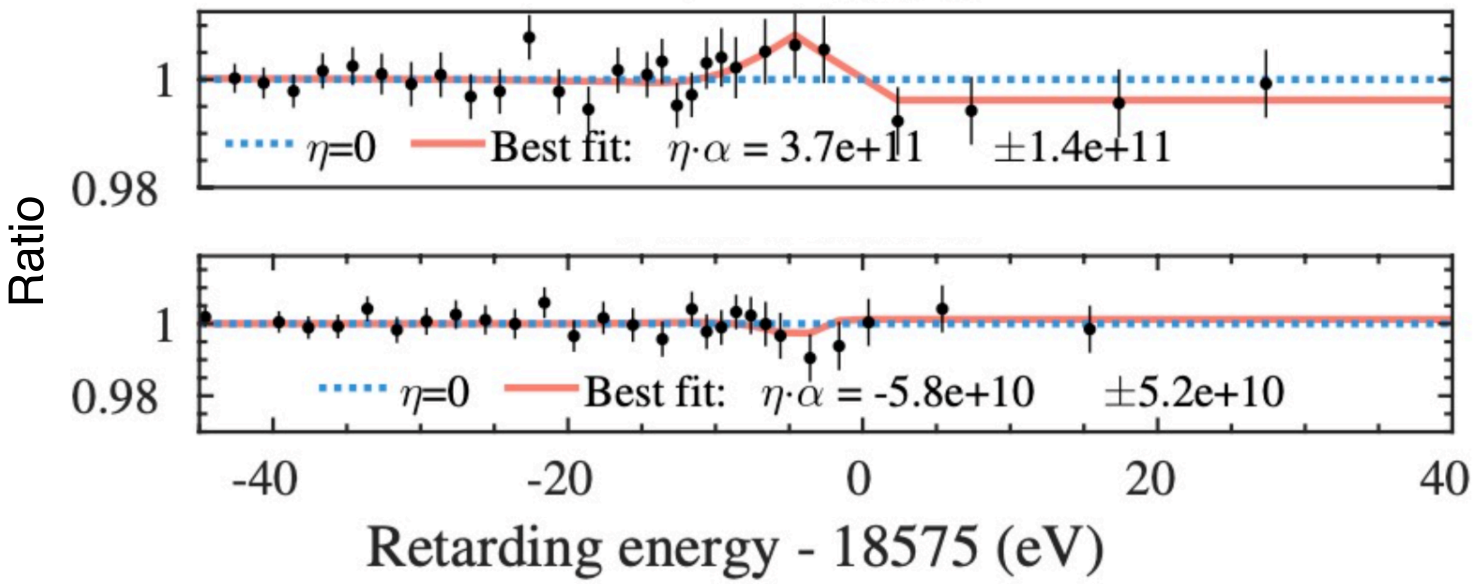


Expected interaction rate:

- 100 g tritium: 10 ν per year
- 13 μg tritium in KATRIN (3 month)

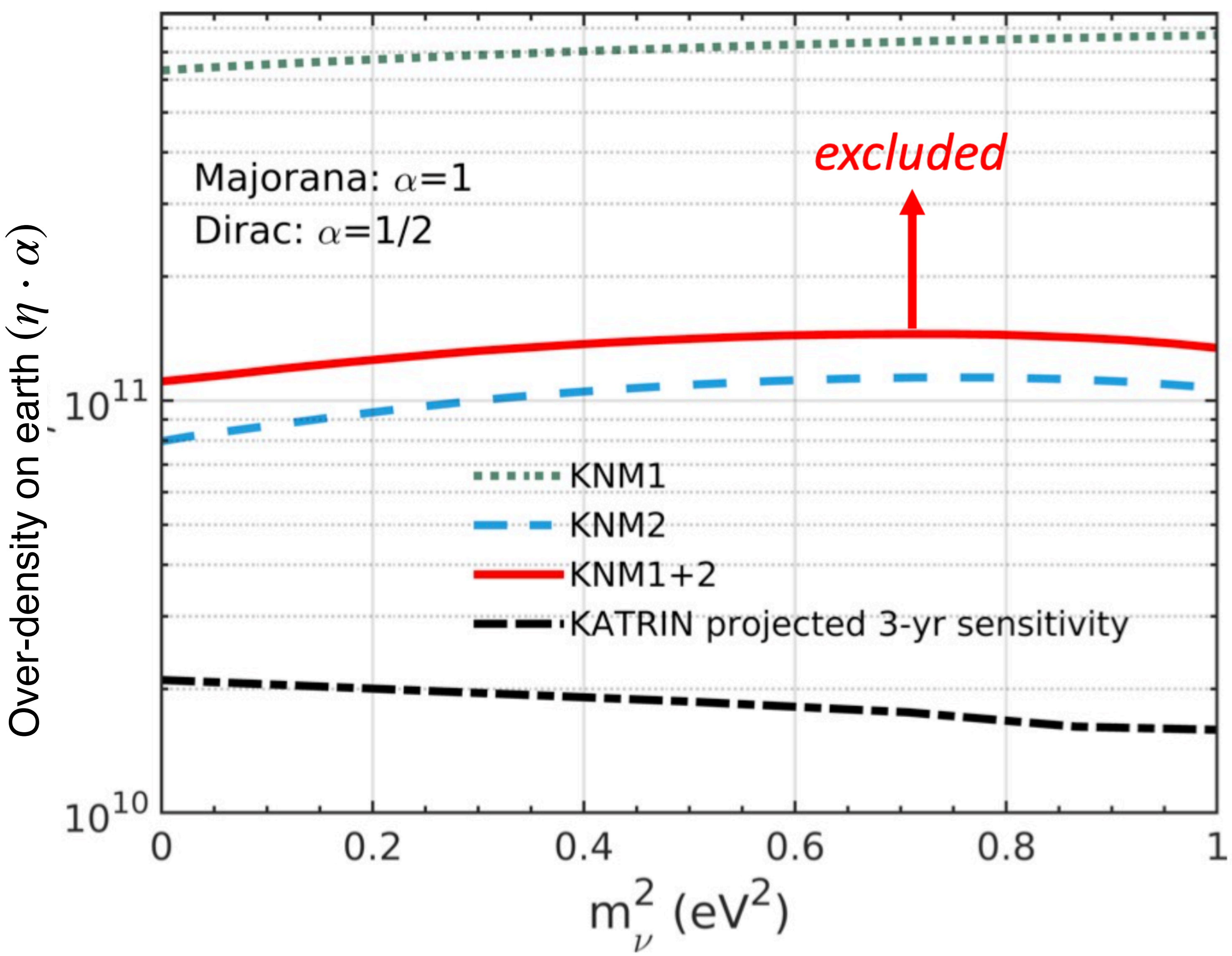
CNB: Results

PRL 129, 011806 (2022)



KNM1 data

KNM2 data



Results:

- Exclude large (10^{11}) CNB over-densities on earth

Needed for observation:

- Much more tritium
- Better energy resolution
- …