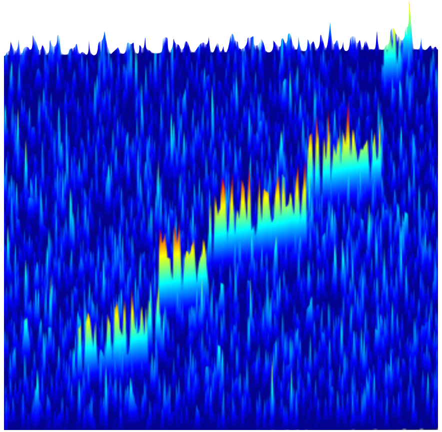
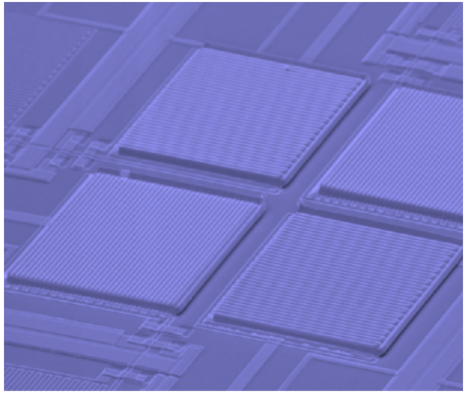
International Neutrino Summer School
Bologna, June 3-14, 2024

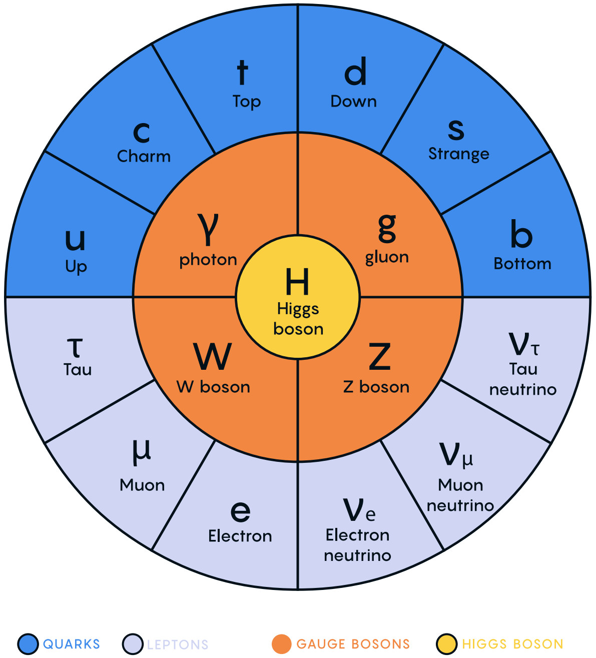
Neutrino mass measurements

Kathrin Valerius, KIT, Institute for Astroparticle Physics
kathrin.valerius@kit.edu

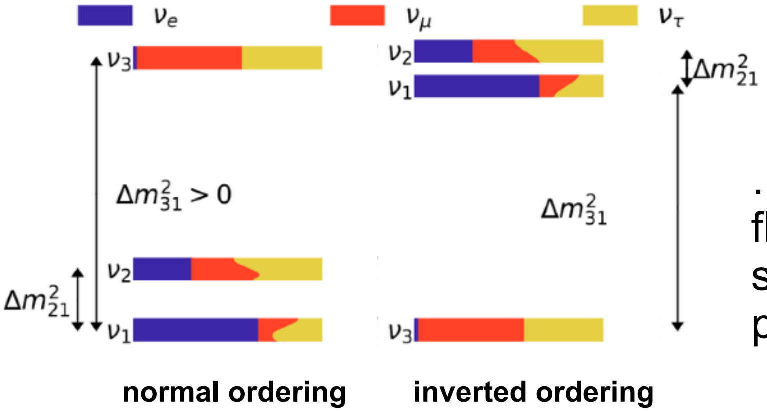




Neutrinos in the Standard Model



- Neutrinos are the only electrically neutral fermions
- Neutrinos participate only in the weak interaction
- Neutrinos are massless in the Standard Model …



… but neutrino flavour oscillations show that this picture is too simple!

image: Quanta Magazine

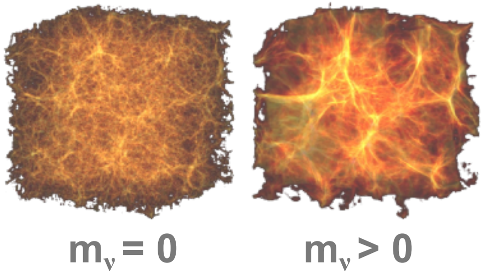
image: globalfit.astroparticles.es

Motivation: Why measure the neutrino mass?

- Neutrino oscillations: Measure leptonic mixing matrix and squared-mass pattern
- Absolute neutrino mass not accessible through oscillations, but bears important relevance:

Massive neutrinos as “cosmic architects”

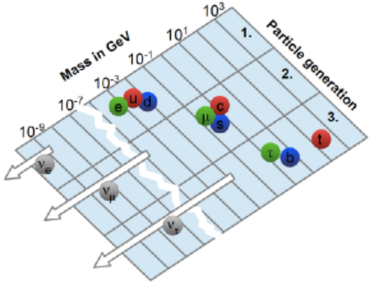
336 ν/cm^3 in the Universe today



Cosmology

Massive neutrinos as “misfits” of the Standard Model

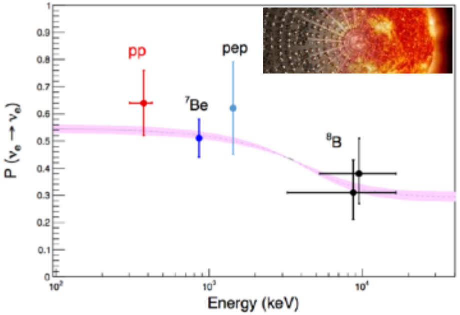
New mass-generating mechanism?



Particle physics

Massive neutrinos as key to astrophysical processes

e.g., ν as probes of fusion in the sun

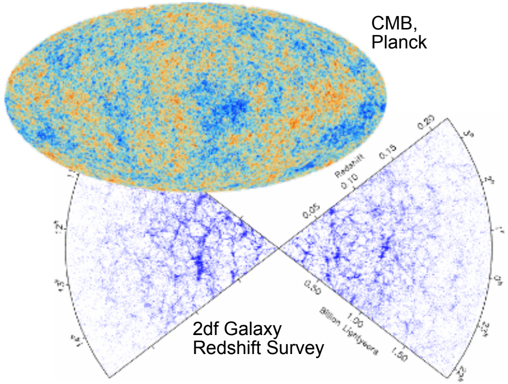


Astrophysics

Three paths to the neutrino mass scale

Cosmology

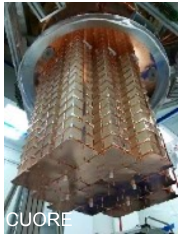
Method: Evolution of structures from the early Universe to today

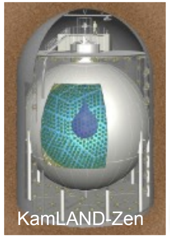


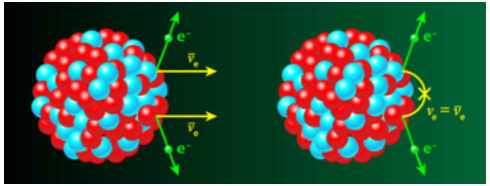
Interpretation within
ΛCDM cosmological paradigm

Nuclear/particle physics

Method: Search for neutrinoless double beta decay



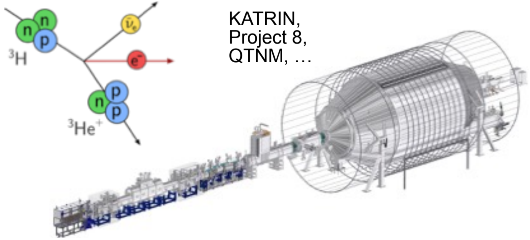


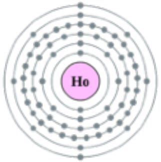


Assume Majorana nature of ν

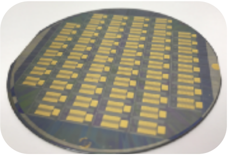
Nuclear/particle physics

Method: Kinematics of weak decays





ECHo,
HOLMES



Only relies on energy & momentum conservation

Only the kinematic method is independent of fundamental model assumptions.

Three paths to the neutrino mass scale

Cosmology

Sum of neutrino masses

$$M_\nu = \sum_i m_i$$

Nuclear/particle physics

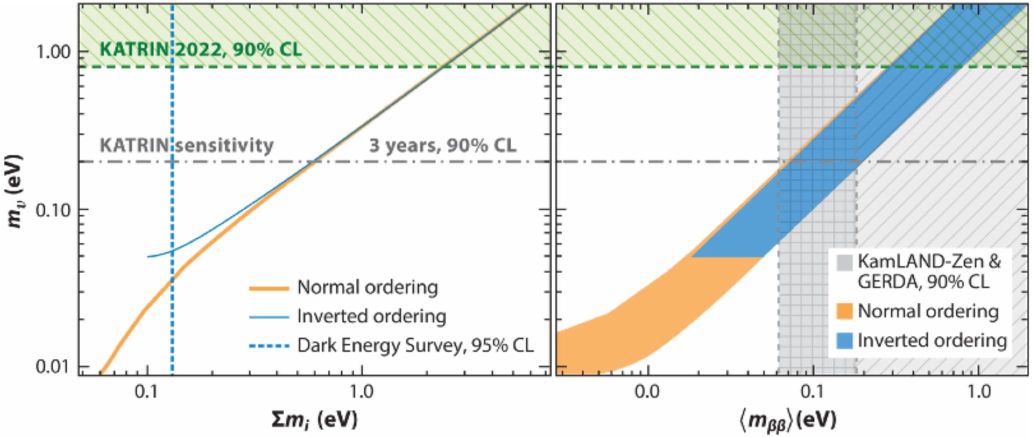
Effective Majorana neutrino mass

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

Nuclear/particle physics

Effective electron neutrino mass

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



compilation: Lokhov et al., Ann. Rev. Nucl. Part. Phys. **72** (2022) 259

The three methods probe different ν-mass observables.

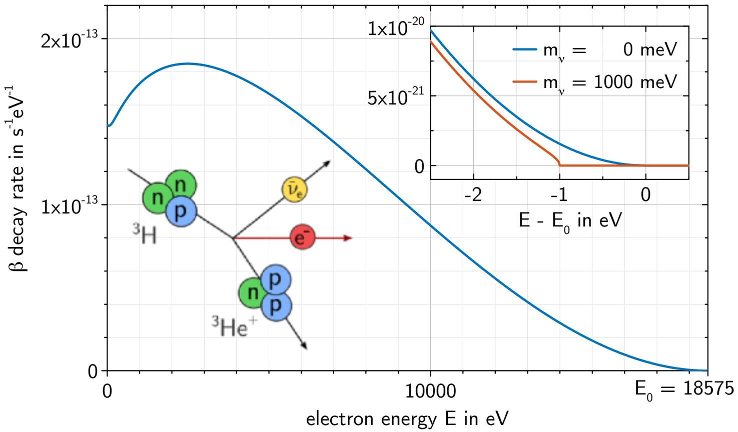
Neutrino mass from β-decay kinematics

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} = K \cdot F(Z,E) \cdot \underbrace{p}_{p_\mathrm{e}} \cdot \underbrace{E_\mathrm{tot}}_{E_\mathrm{e}} \cdot \underbrace{(E_0 - E)}_{E_\nu} \cdot \underbrace{\sum\nolimits_i |U_{\mathrm{e}i}|^2 \sqrt{(E_0 - E)^2 - m_i^2}}_{p_\nu}$$

similar for electron capture

Fermi's phase space for β-decay

Modern twist: mass eigenstates m_i and neutrino mixing matrix U

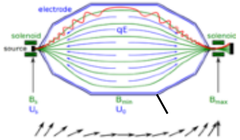


Key requirements:

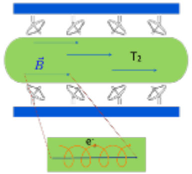
- Strong β-decaying source
  - ✓ **Tritium:** E_0 = 18.6 keV, $T_{1/2}$ = 12.3 yr (4×10^8 atoms for 1 Bq)
  - ✓ **^{163}Ho:** E_0 = 2.8 keV, $T_{1/2}$ = 4570 yr (2×10^{11} atoms for 1 Bq)
- Excellent energy resolution
- Low background

Experimental approaches

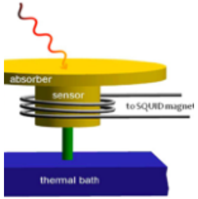
Spectroscopy method



integral: counting above threshold
→ electrostatic filter (MAC-E)



differential: frequency measurement
→ microwave detection (CRES)



differential: calorimetric measurement
→ low-temp. sensors (MMC, TES)

Source technology

tritium: gaseous molecular (T_2)

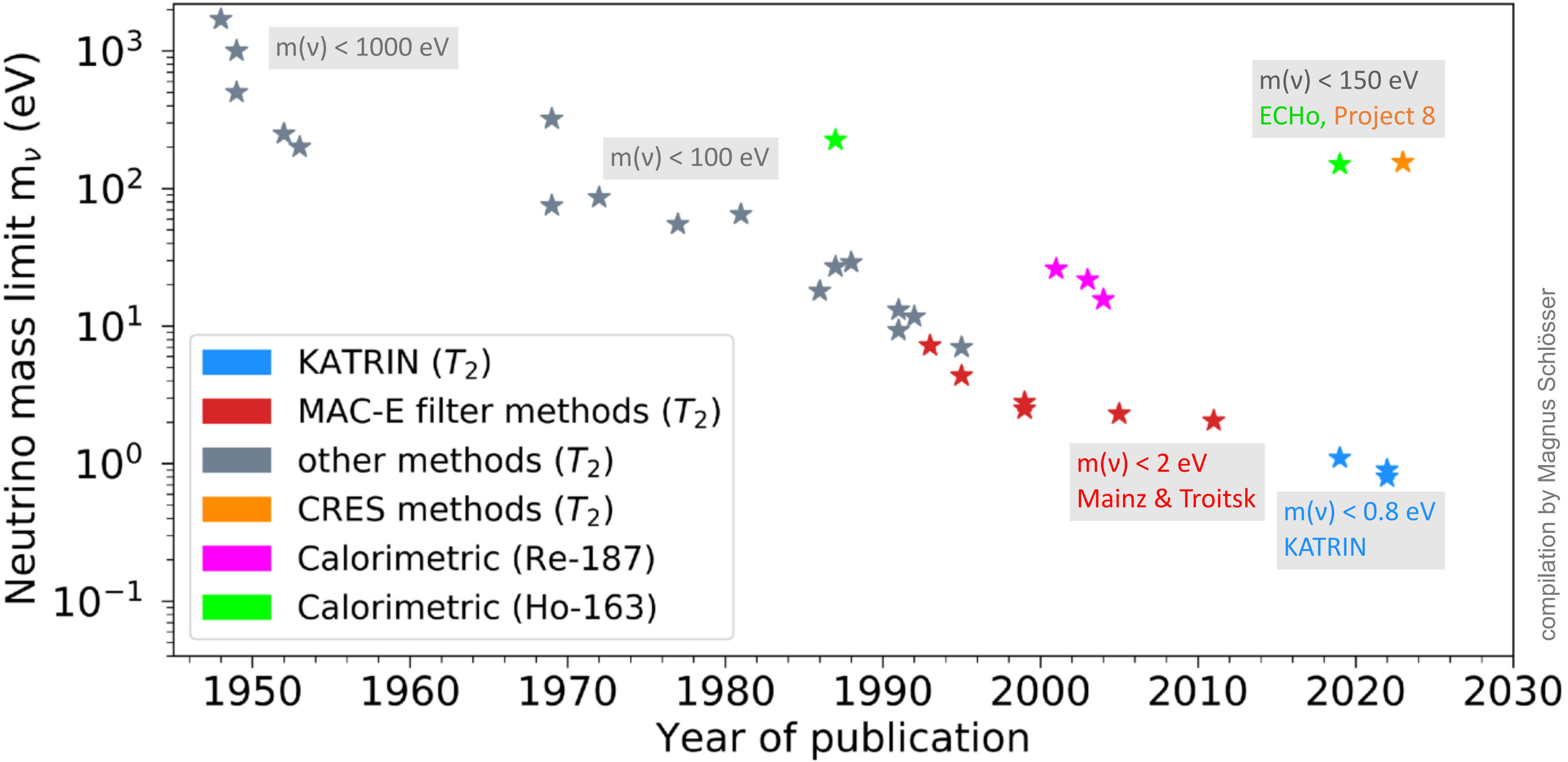
tritium: gaseous atomic (T)

tritium: surface-bound, quasi-atomic (T)

holmium: implanted

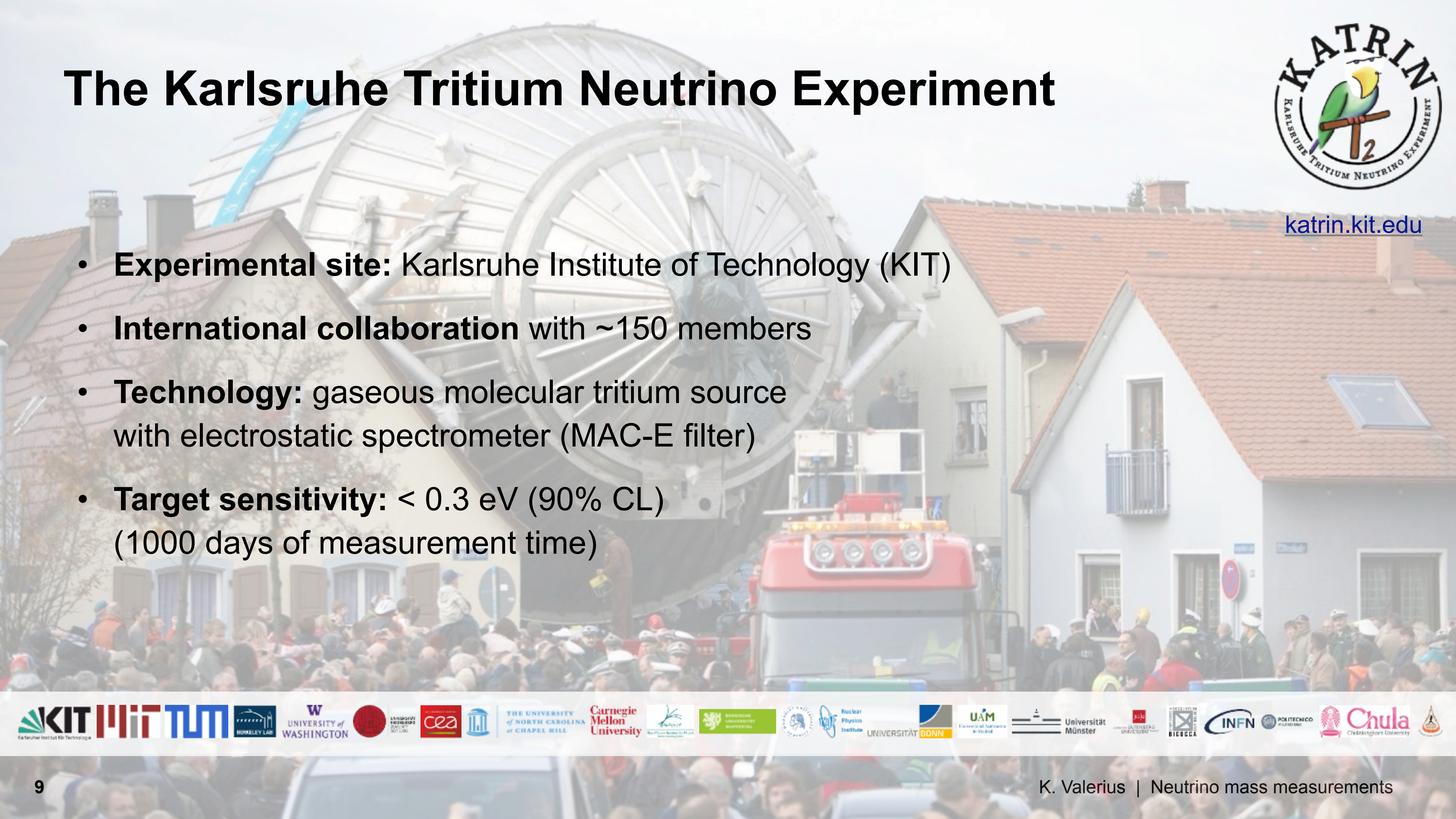
Combinations in varying states of development; offer complementing systematic uncertainties.

Development and status of the field



compilation by Magnus Schlösser

The Karlsruhe Tritium Neutrino Experiment

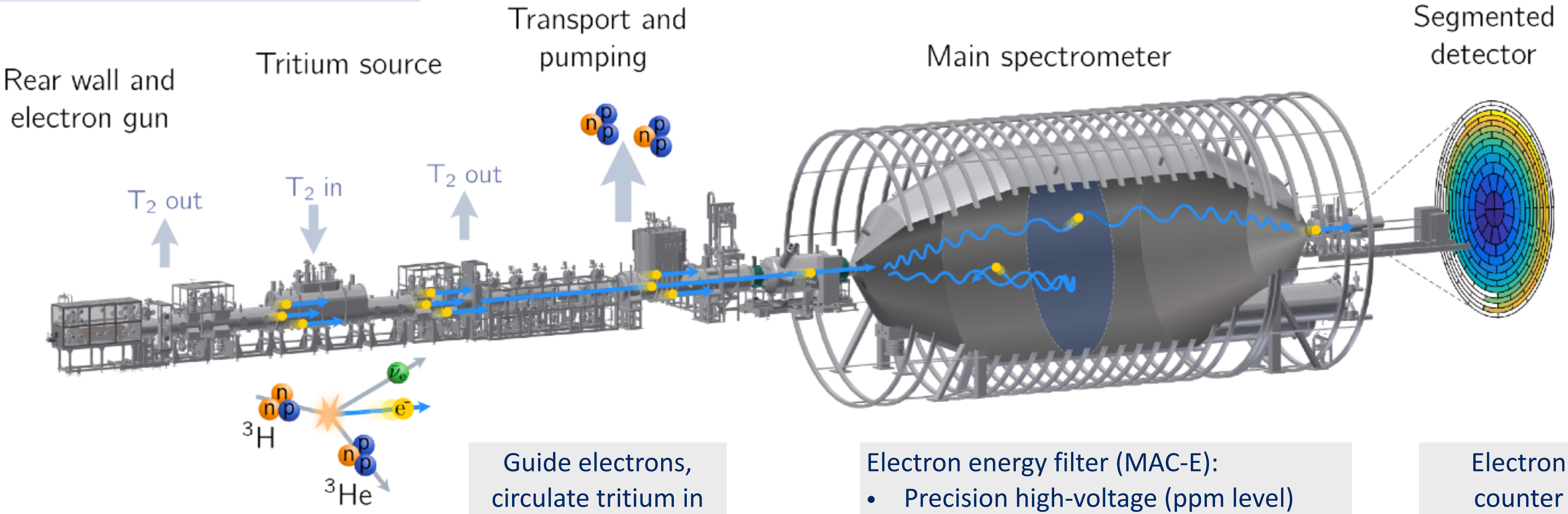


katrin.kit.edu

- **Experimental site:** Karlsruhe Institute of Technology (KIT)
- **International collaboration** with ~150 members
- **Technology:** gaseous molecular tritium source
  with electrostatic spectrometer (MAC-E filter)
- **Target sensitivity:** < 0.3 eV (90% CL)
  (1000 days of measurement time)

Working principle of KATRIN

Overall: 70 m long beamline



100 billion β-decays per second

Guide electrons, circulate tritium in closed loop

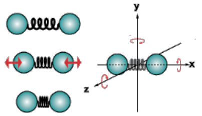
Electron energy filter (MAC-E):
- Precision high-voltage (ppm level)
- Magnetic fields (0.1 mT – few T)
- Ultra-high vacuum (10^{-11} mbar in $1240\ m^3$ recipient)

Electron counter

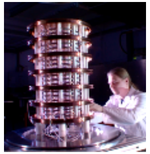
Ingredients of precision ν-mass measurement

Fit model is informed by **theoretical** and **experimental inputs**, with all key systematic uncertainties determined by **dedicated measurements**.

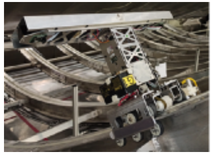
Molecular final states
quantum-chemical computations

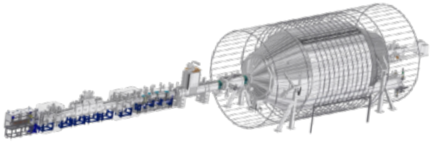


Energy scale
- spectrometer potential
- source plasma
- surface conditions

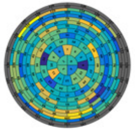


Magnetic fields
- source
- spectrometer
- detector

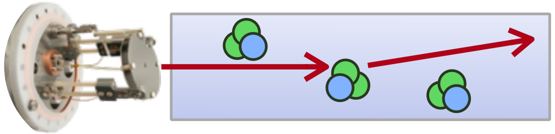




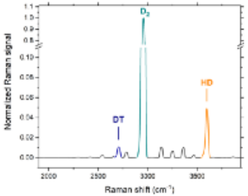
Detection efficiency



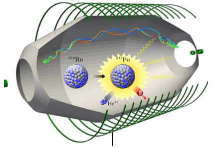
Energy loss by scattering



Activity fluctuations
- column density
- tritium concentration



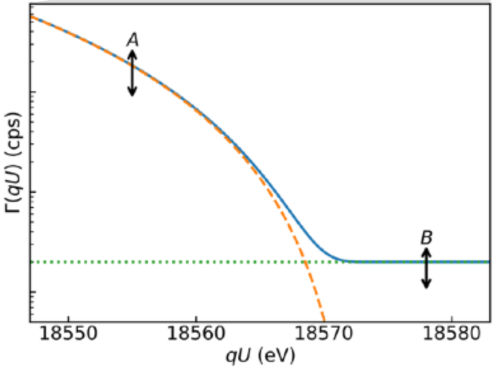
Background
- energy dependence
- time structure due to trapped electrons

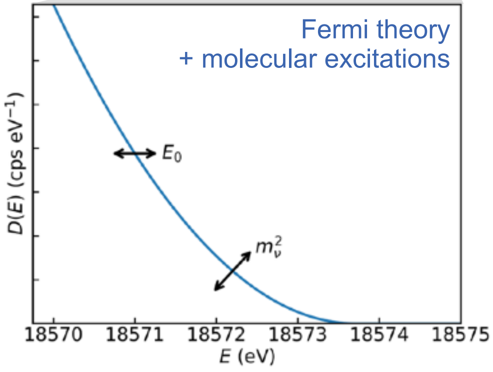


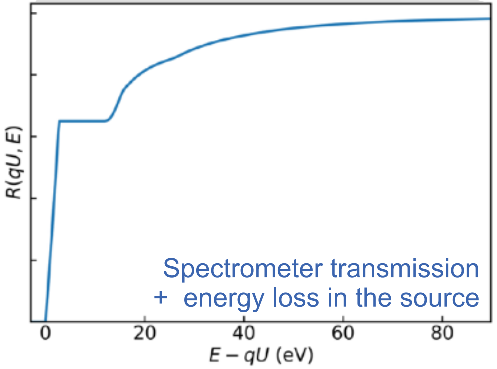
Analysis methods

Fit of theoretical model:

$$\Gamma(qU) \propto A \cdot \int_{qU}^{E_0} D\left(E; m_\nu^2, E_0\right) \cdot R\left(qU, E\right)\, dE + B$$

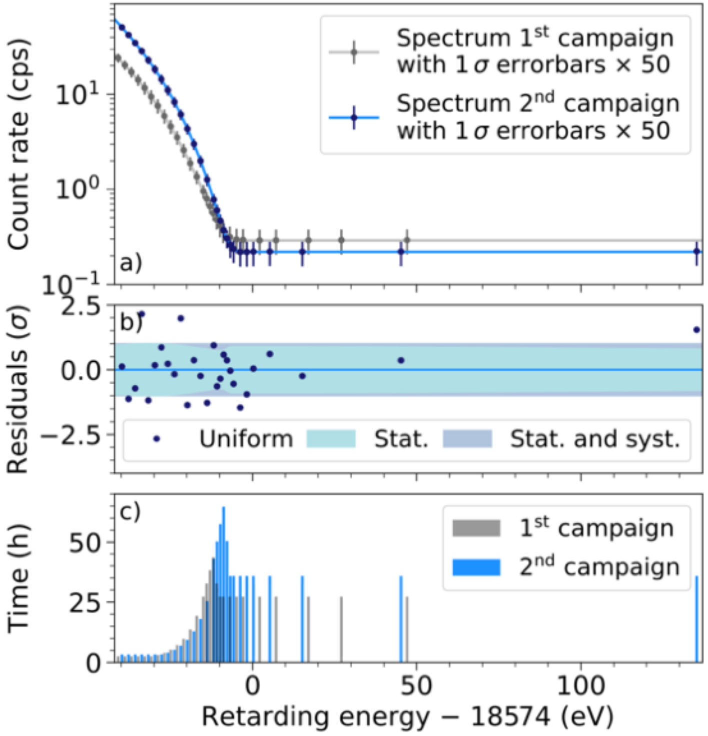



Fermi theory
+ molecular excitations


Spectrometer transmission
+ energy loss in the source

- Free parameters: m_ν^2 + *O*(10-100) nuisance parameters (most constrained via calibrations)
- Blind analysis: **1.** independent teams, **2.** “simulated twin” data sets, **3.** model blinding
- Frequentist and Bayesian inference

Neutrino-mass results from initial data



1st campaign:

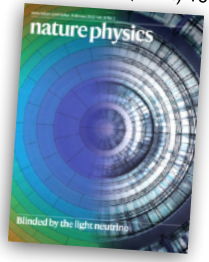
- 522 hours (2 million electrons)
- Best fit: $m_\nu^2 = \left(-1.0^{+0.9}_{-1.1}\right)\,\mathrm{eV}^2$
- Limit: $m_\nu < 1.1\ \mathrm{eV}\ (90\%\ \mathrm{CL})$

PRL 123 (2019) 221802

1st + 2nd campaign:

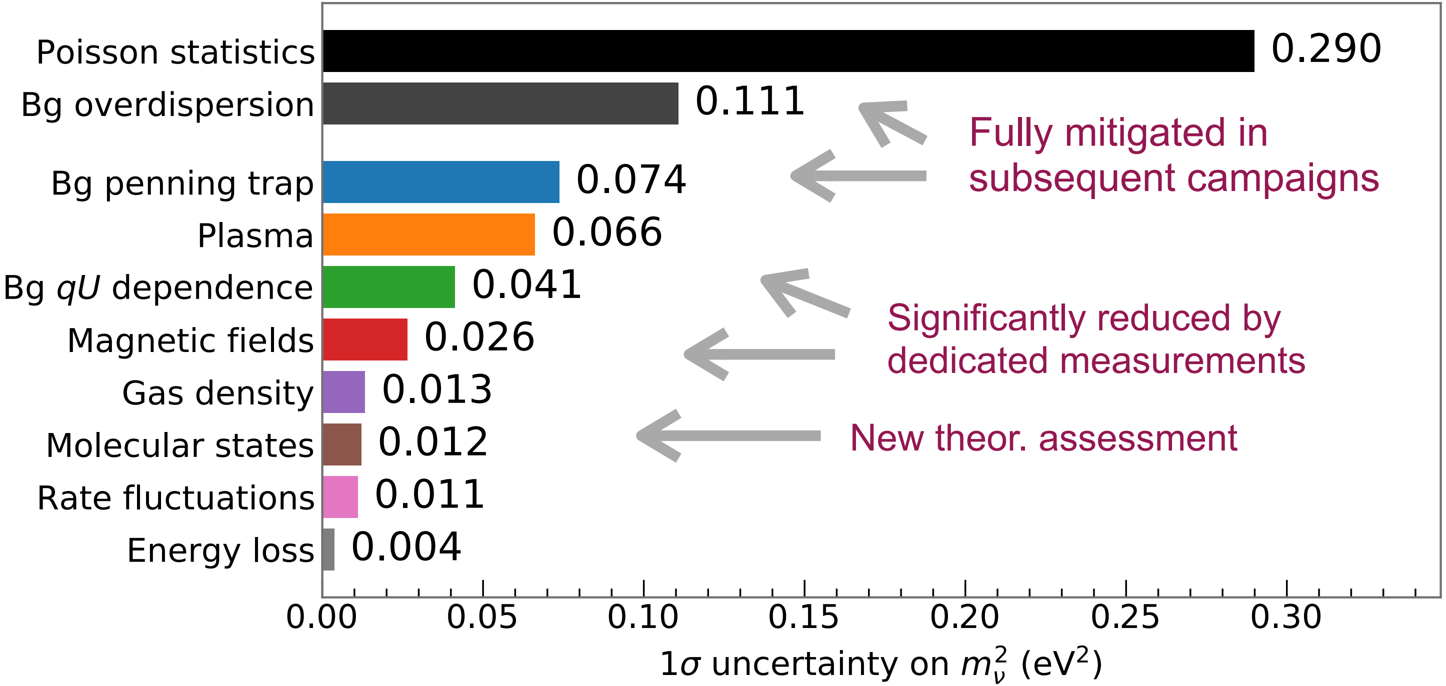
- 1266 hours (6.3 million electrons)
- Combined result: $m_\nu^2 = (0.1 \pm 0.3)\,\mathrm{eV}^2$
- Combined limit: $m_\nu < 0.8\ \mathrm{eV}\ (90\%\ \mathrm{CL})$

Nat. Phys. 18 (2022) 160



Uncertainties strongly dominated by statistics.

Systematic uncertainties (2^{nd} campaign)



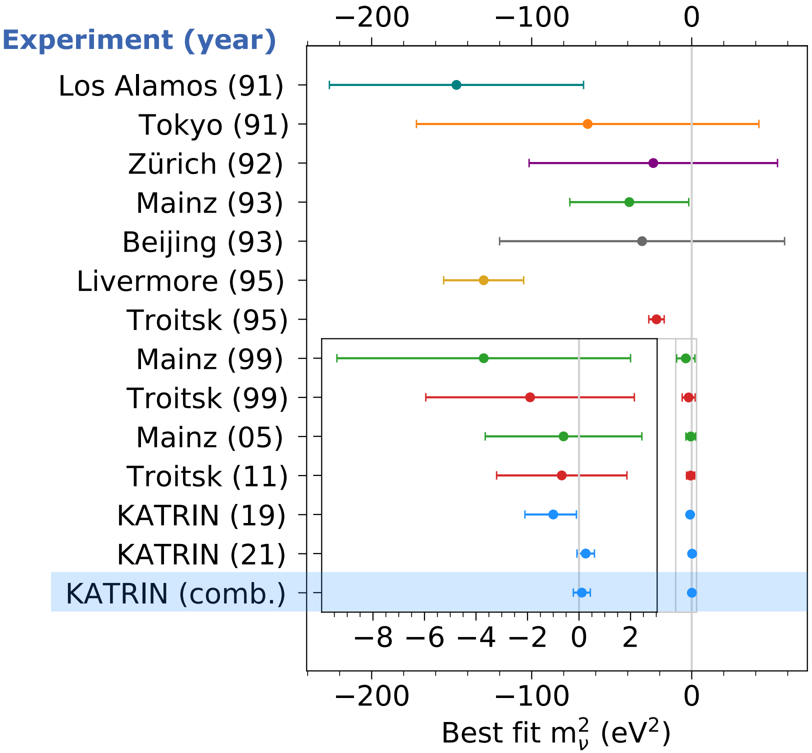
Fully mitigated in subsequent campaigns

Significantly reduced by dedicated measurements

New theor. assessment

Here: status for initial data-taking. Substantial improvements from 3^{rd} campaign on.

Tritium-based neutrino-mass measurements



Instrument development
+ dedicated systematics experiments
+ theoretical model

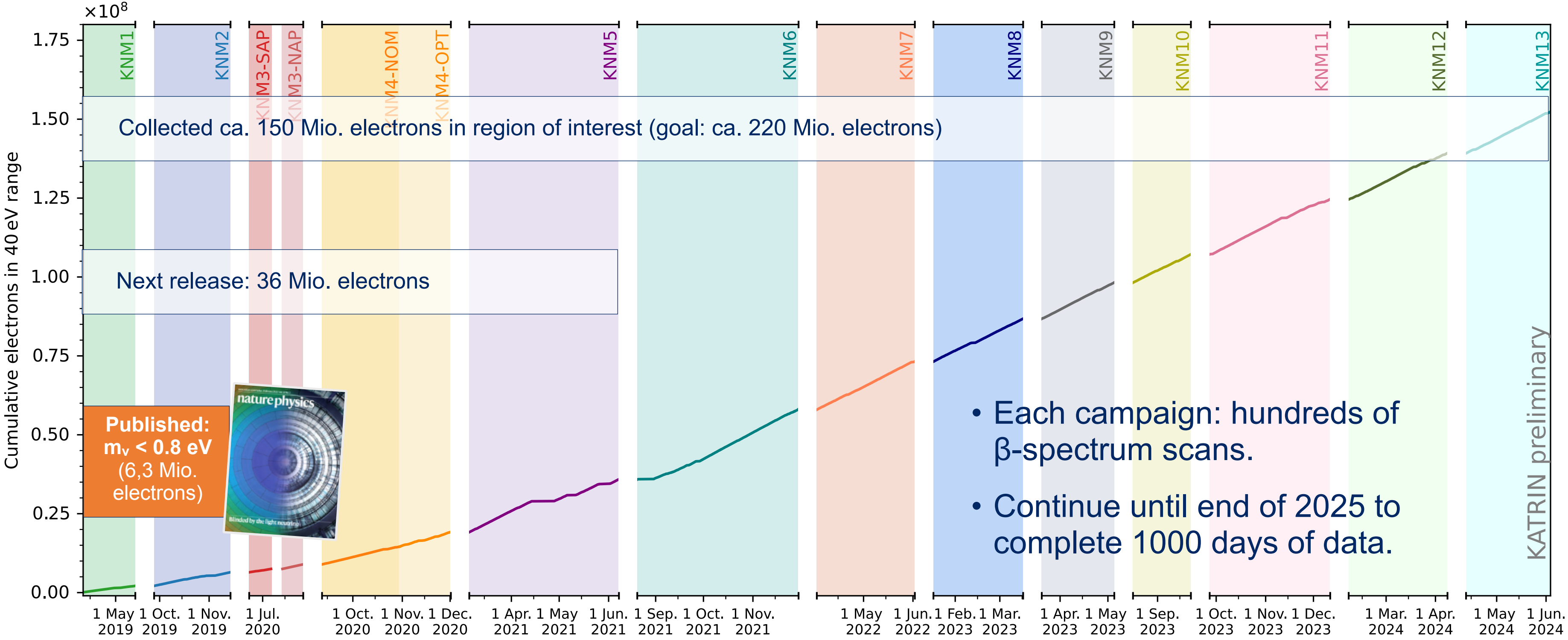
Scale-up & further development
of MAC-E technique
with gaseous source

KATRIN (2022): first direct neutrino-mass measurement to reach sub-eV sensitivity

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

[Nat. Phys. **18** (2022) 160]

Progress of data-taking and analysis



Collected ca. 150 Mio. electrons in region of interest (goal: ca. 220 Mio. electrons)

Next release: 36 Mio. electrons

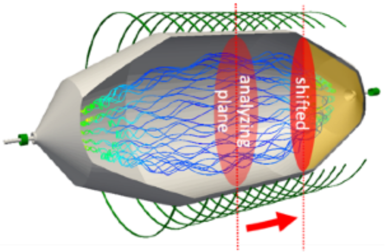
Published:
m_ν < 0.8 eV
(6,3 Mio. electrons)

- Each campaign: hundreds of β-spectrum scans.
- Continue until end of 2025 to complete 1000 days of data.

Preview: Upcoming release

New data & analysis with many improvements, e.g.:

Background reduction by ~50% through fiducialization: “shifted analyzing plane”



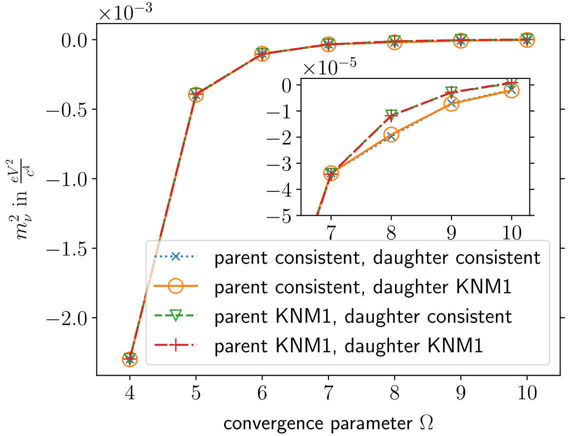
smaller flux-tube volume imaged onto detector
➜ A. Lokhov et al., EPJ C **82** (2022) 258

Optimized scan-time distribution of HV set points

Penning-trap background eliminated by operating pre-spectrometer at low voltage

Tritium source operated at high throughput and at elevated temperature (30K → 80K)

new co-circulation mode of ^{83m}Kr as powerful probe of electric potential variation in source
➜ A. Marsteller et al., JINST **17** (2022) P12010

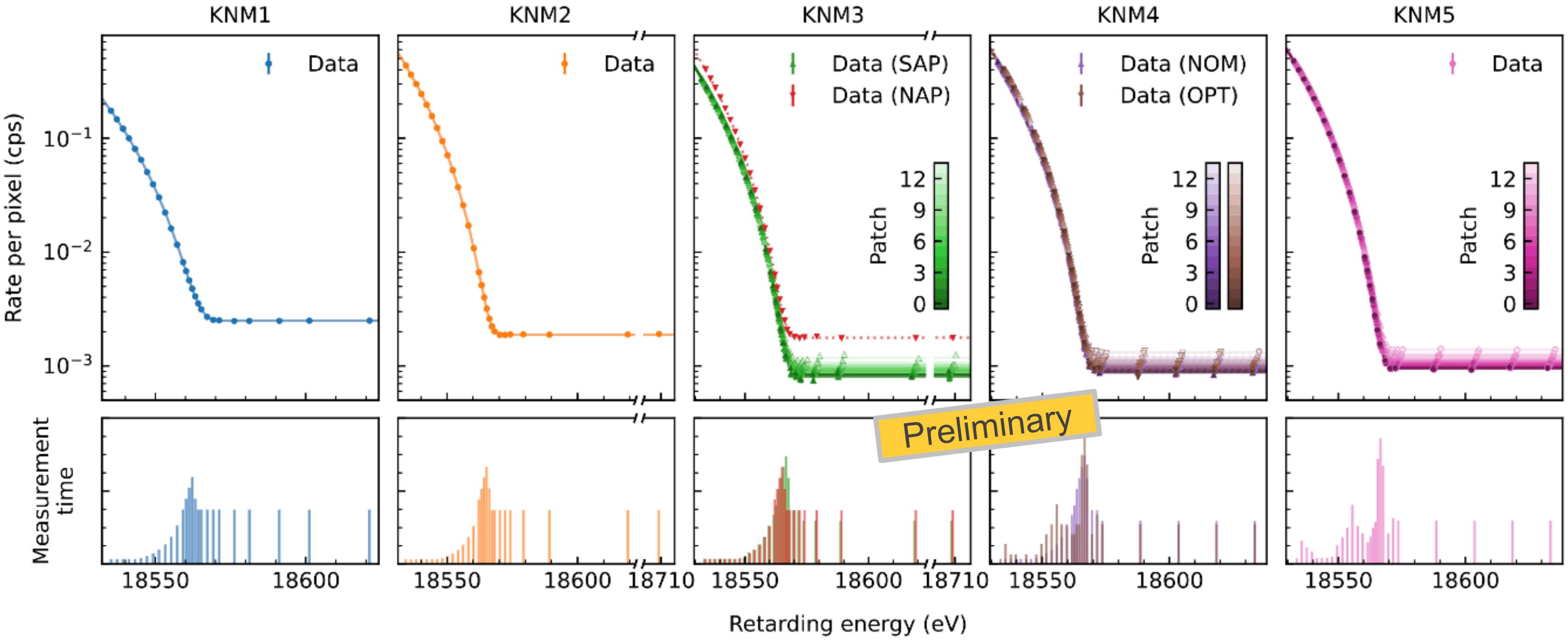


Dedicated assay of molecular final-states uncertainty (ab-initio calc. & simulation)

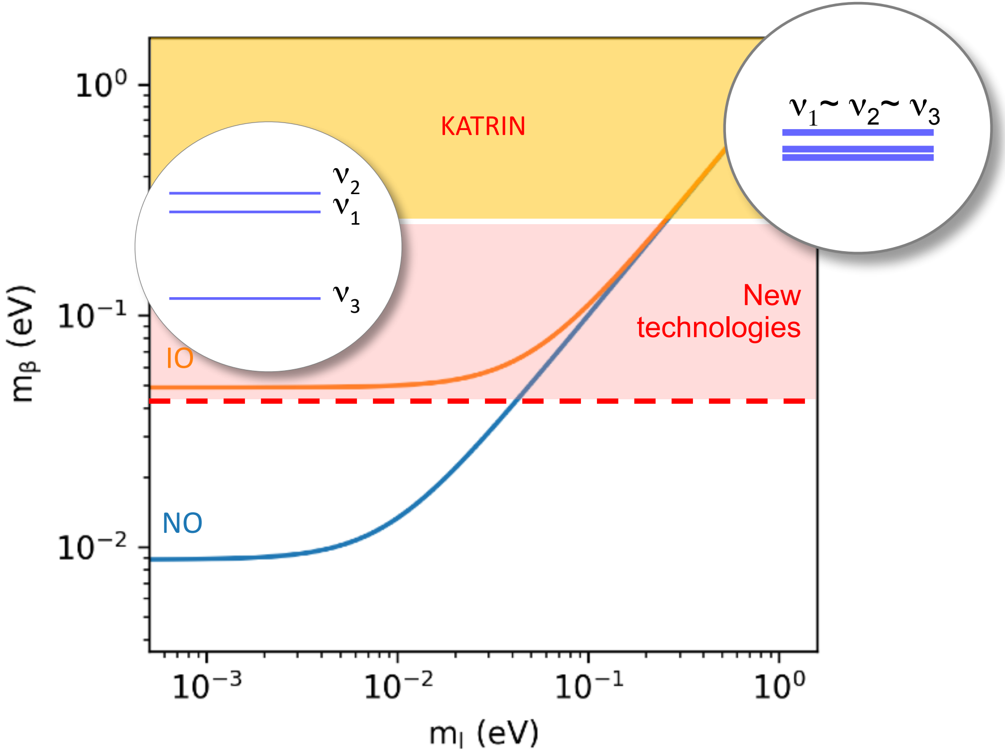
replaces conservative estimate based on gaussian approx.
➜ S. Schneidewind et al., EPJ C **84** (2024) 494

Preview: Upcoming release

Analysis of first 5 campaigns (statistics x 6, improved systematics and lower background)

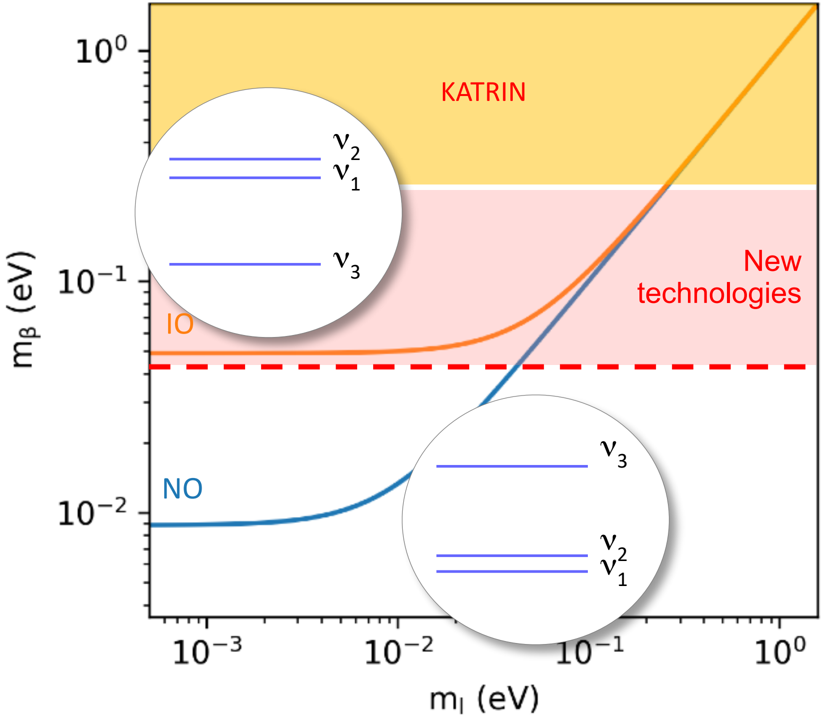


Going beyond KATRIN



- KATRIN reach by 2025: **< 0.3 eV** (90% CL) Distinguish between degenerate and hierarchical neutrino mass scenarios

Going beyond KATRIN

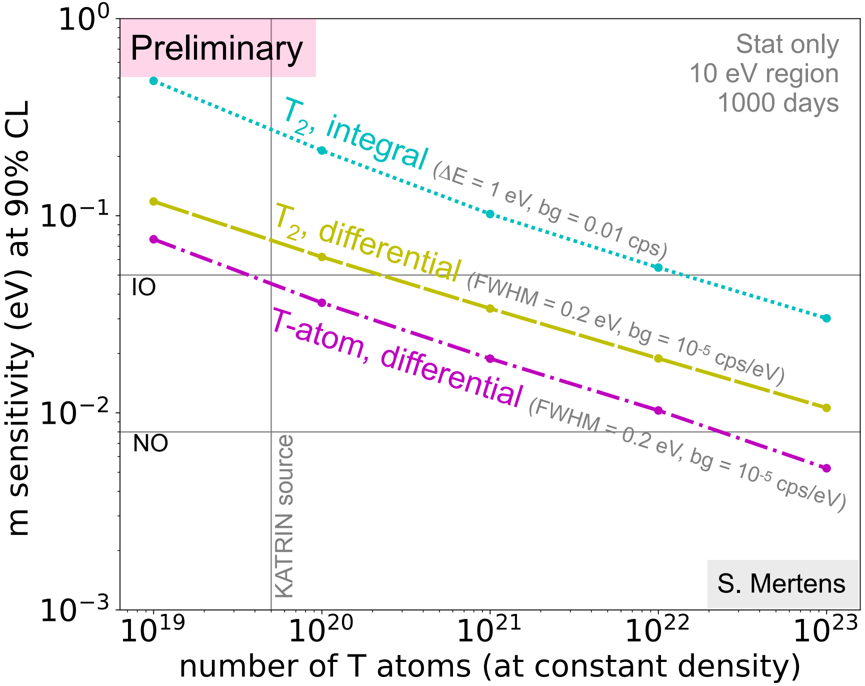


- KATRIN reach by 2025: **< 0.3 eV** (90% CL) Distinguish between degenerate and hierarchical neutrino mass scenarios
- New technologies: < **0.05 eV** to cover inverted ordering

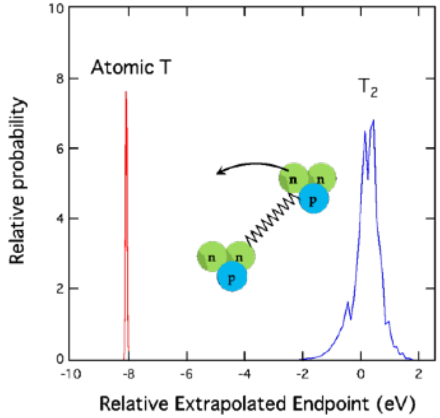
Going beyond KATRIN requires:

- New source concepts (molecular ➛ atomic tritium)
- New detector technologies (differential, high-resolution measurement)

Going beyond KATRIN

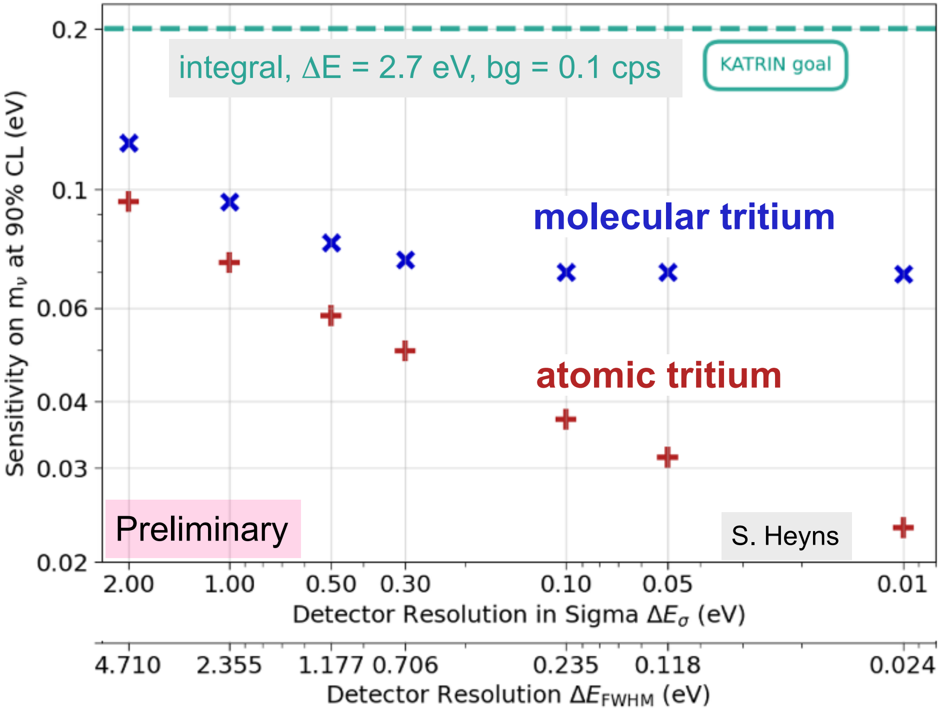


- **KATRIN now:**
  integral, ΔE = 2.7 eV, bg = 0.1 cps
- **Differential measurement (FWHM < 1 eV)**
  - ✓ Better use of statistics
  - ✓ Lower background
- **Atomic tritium**
  - ✓ Avoid broadening (~ 1 eV)
  - ✓ Avoid final-state systematics of T_2



R.G.H. Robertson

Sensitivity beyond KATRIN



Differential measurement

- stat. uncertainty only: 30 eV range,1000 days
- tritium density ~KATRIN now, background-free

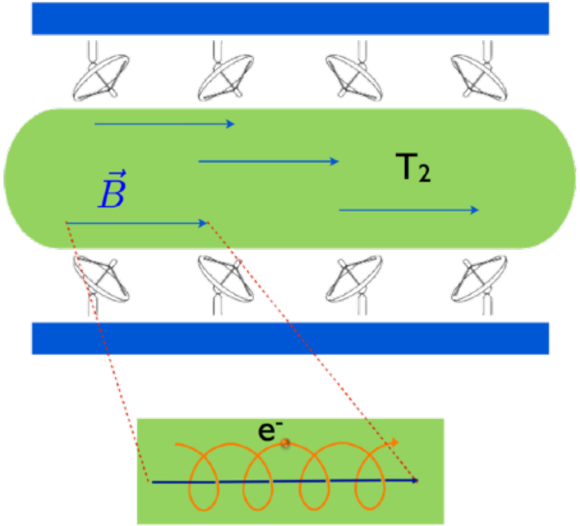
Started R&D programme towards KATRIN++

- *atomic tritium source:* cooperation with Project 8 (Mainz group) ➜ seed funding for test setup at Tritium Laboratory Karlsruhe
- *differential measurement:* pursuing two options
  - time-of flight via electron tagging ➜ concept studies ongoing
  - micro-calorimeter array (TES, MMC, …) ➜ test setup for detection of external electrons, concept studies of electron transport

Experimental technique: frequency measurement

Working principle: Cyclotron radiation emission spectroscopy (CRES)

Idea: B. Monreal and J. Formaggio, Phys. Rev. D **80** (2009) 429



- β-electrons immersed in B-field emit EM radiation
- Frequency encodes kinetic energy:

$$f = \frac{1}{2\pi}\frac{eB}{m_e + E_{\mathrm{kin}}/c^2}$$

- For $E_{kin} = Q_\beta = 18.6$ keV and $B = 1$ T: microwave radiation $f = 27$ GHz, $\lambda \sim 1$ cm
- Radiation collected with antenna, waveguide, or resonant cavity

The Project 8 experiment

Proof CRES concept:

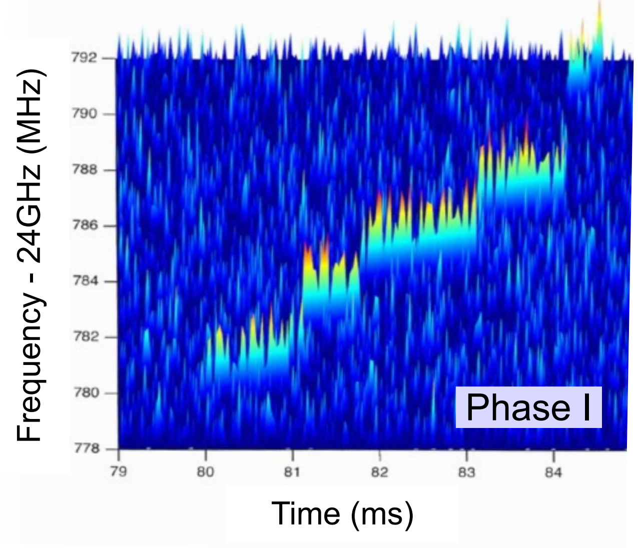
- ✓ differential measurement with eV resolution
- ✓ “source = detector”, magnetic electron trap

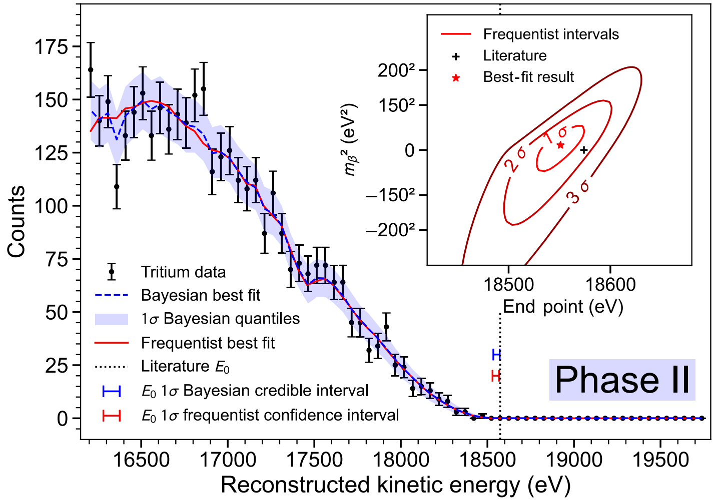
PRL **114** (2015) 1162501; J. Phys. G **44** (2017) 05400

First frequency-based ν-mass limit:

- ✓ m(ν) < 155 eV (90% CI)
- ✓ no background observed above endpoint

A. Ashtari *et al.* (Project 8 Coll.), PRL **131** (2023) 102502



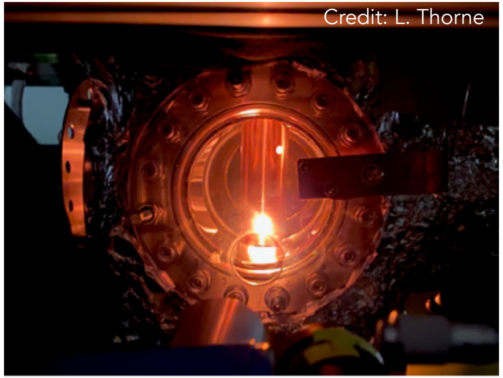


from Sebastian Böser & Martin Fertl

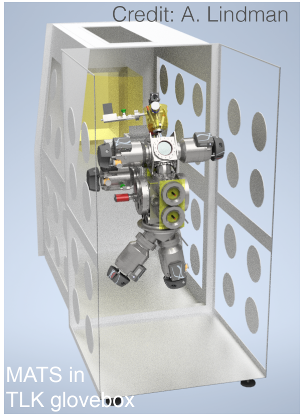
The Project 8 experiment

Phase III **Major technology developments:**

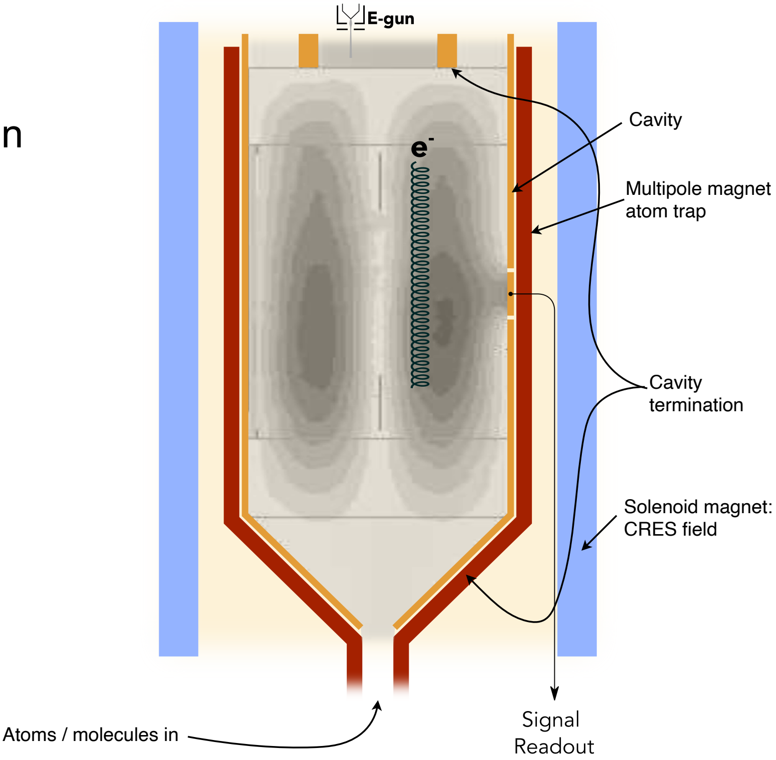
- Large-volume (~10 m^3 scale) **cavity** for CRES detection
  ➜ resonance enhancement of electron signal
- High-intensity source of **cold atomic tritium**
- Magneto-gravitational **trap** for tritium atoms


Credit: L. Thorne

Mainz Atomic Test Stand (MATS)


Credit: A. Lindman

MATS in TLK glovebox

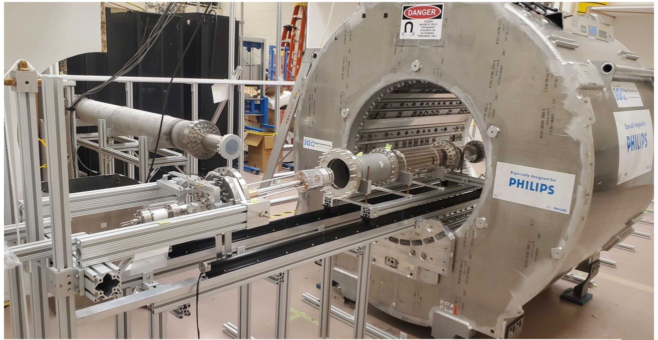


from Sebastian Böser & Martin Fertl

The Project 8 experiment

Phase III **Sensitivity projection,** 1-yr data:
200 meV for molecular source,
100 meV) for atomic) source

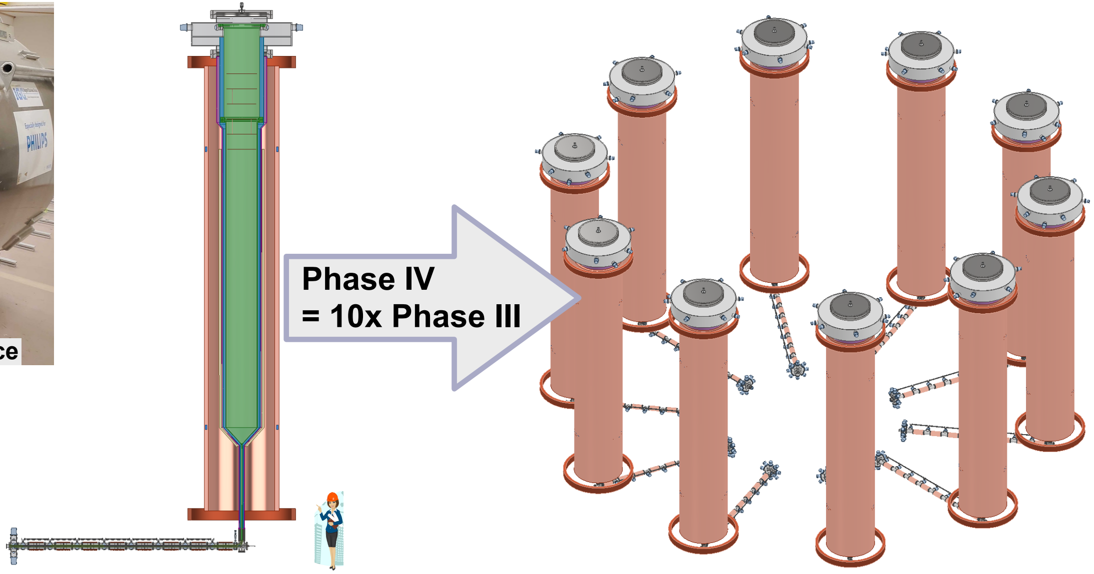
Phase IV **Ultimate goal:** Cover inverted mass ordering at **40 meV** sensitivity
Snowmass paper, arXiv:2203.07349



Development of cavity prototype and electron source

~2030: Compatibility of CRES and atom trapping demonstrated

2030s: First atomic tritium neutrino-mass extraction



Phase IV
= 10x Phase III

Credit: M. Huehn

from Sebastian Böser & Martin Fertl

QTNM: Quantum Technologies for Neutrino Mass

QTNM
Quantum Technologies for Neutrino Mass

UCL
UNIVERSITY OF CAMBRIDGE
Swansea University Prifysgol Abertawe
NPL National Physical Laboratory
Queen Mary University of London
UNIVERSITY OF OXFORD
WARWICK THE UNIVERSITY OF WARWICK

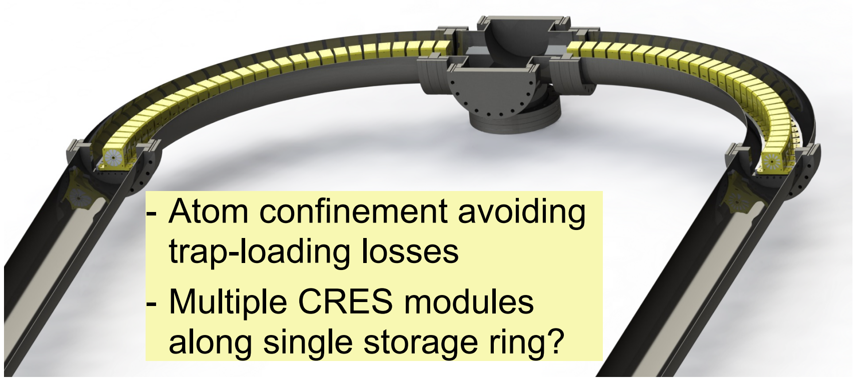
Recent effort, addressing **key challenges of CRES**:

- Very small radiated powers ~ fW
- Need to observe ~10^{20} tritium atoms for ~year
- Magnetic and electric fields seen by electron need to be constrained at extreme precision

Leverage quantum technologies:

- Quantum-noise-limited microwave sensors for high-res & high efficiency CRES
- Magnetic field mapping (< 1 μT absolute precision, ~1 mm spatial resolution) using Rydberg states as quantum sensors

Storage ring concept instead of atom trap:



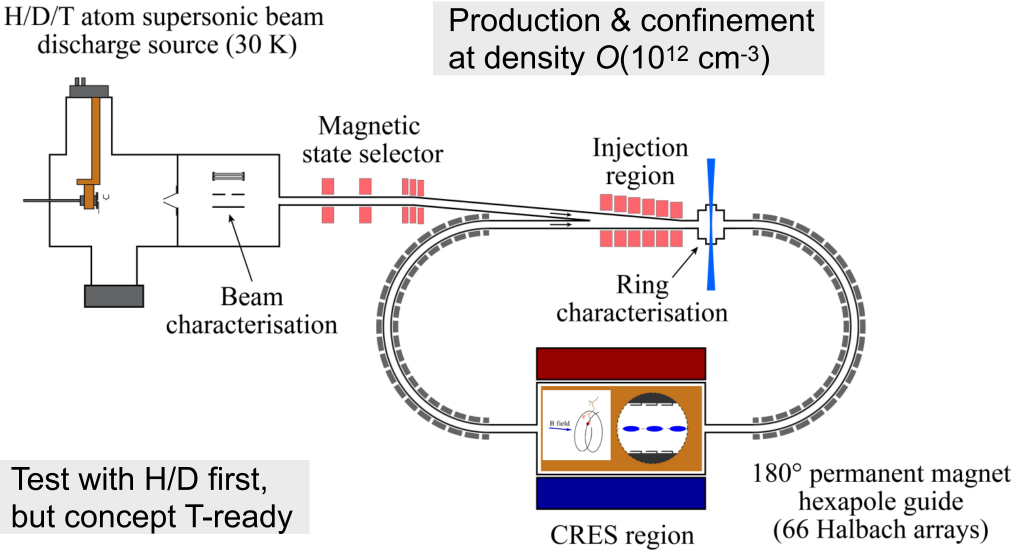
- Atom confinement avoiding trap-loading losses
- Multiple CRES modules along single storage ring?

from Ruben Saakyan & Seb Jones

QTNM: Quantum Technologies for Neutrino Mass

CRES Demonstrator Apparatus (**CRESDA**)

Phased approach: CRESDA0 → CRESDA Tritium → 100 meV → 50 meV → O(10 meV)

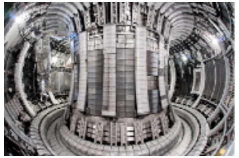


Production & confinement at density *O*(10^{12} cm^{-3})

Test with H/D first, but concept T-ready

- **2021-2025:** Basic technology demonstration
- **Beyond 2025**: Tritium demonstrations at Culham
- **2030-2040:** Neutrino mass experiment at Culham or similar facility

CCFE CULHAM CENTRE FOR FUSION ENERGY

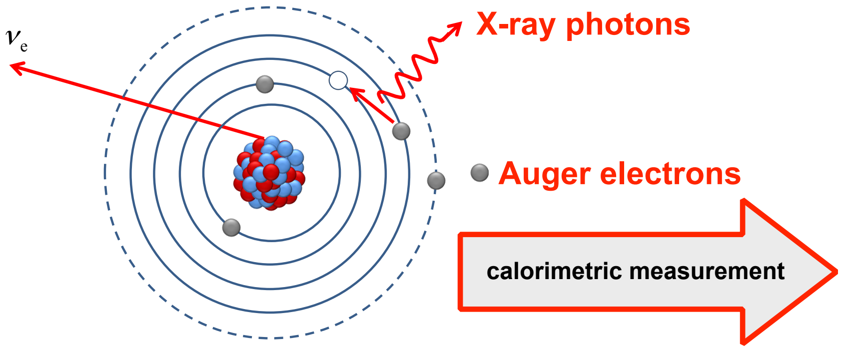


from Ruben Saakyan & Seb Jones

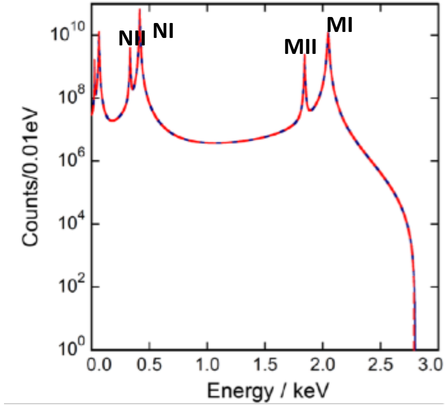
Experimental technique: micro-calorimetry with holmium

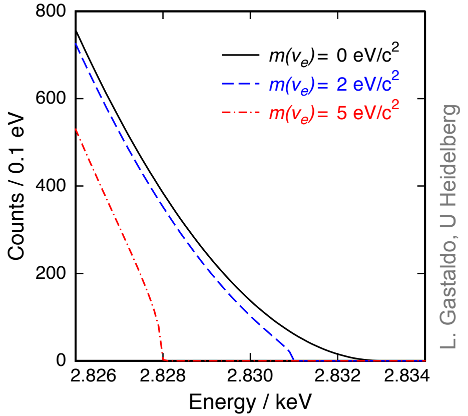
Working principle: Low-temperature calorimetry with ^{163}Ho embedded in absorber

Idea: A. De Rujula and M. Lusignoli, Phys. Lett. B **118** (1982) 429

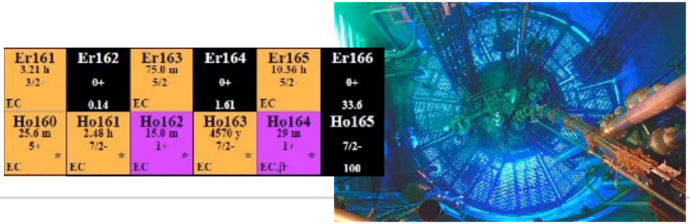


$^{163}\text{Ho} \rightarrow {}^{163}\text{Dy}^* + \nu_e$





L. Gastaldo, U Heidelberg



Er161 3.21 h 3/2- EC	Er162 0+ 0.14	Er163 75.0 m 5/2- EC	Er164 0+ 1.61	Er165 10.36 h 5/2- EC	Er166 0+ 33.6
Ho160 25.6 m 5+ * EC	Ho161 2.48 h 7/2- * EC	Ho162 15.0 m 1+ * EC	Ho163 4570 y 7/2- * EC	Ho164 29 m 1+ * EC,β-	Ho165 7/2- 100

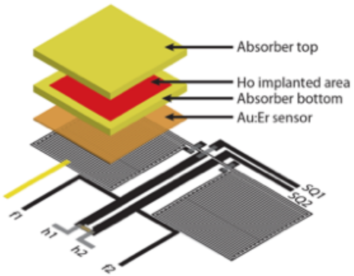
ECHo: EPJ-ST **226** (2017) 1623

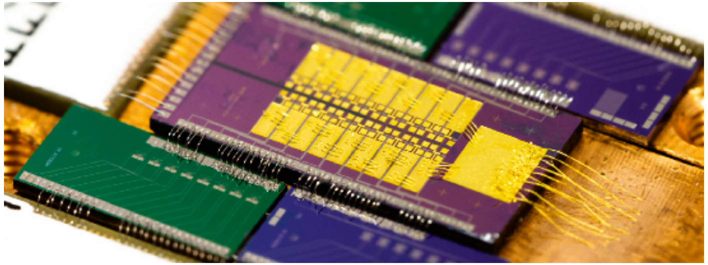
HOLMES: Eur. Phys. J. C **75** (2015) 112

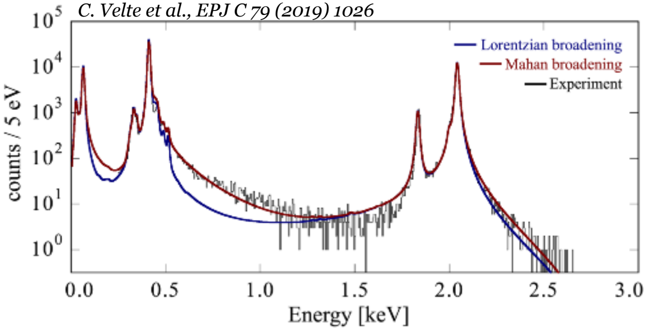
The ECHo experiment

Detector technology: Metallic Magnetic Calorimeters (MMC)

[Fleischmann, Enss, Seidel 2005; Fleischmann *et al.* 2009; Gastaldo *et al.* 2013]; activity goal **~few Bq** per pixel





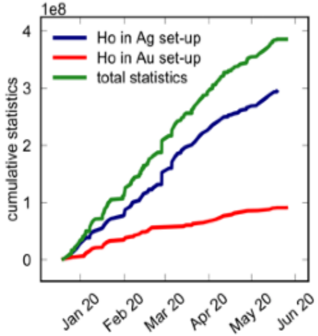

C. Velte et al., EPJ C 79 (2019) 1026

ECHo-1k phase (data analysis ongoing):

- present upper limit: $m(\nu_e) < 150$ eV (95% CL)
- expected sensitivity: $m(\nu_e) \sim 20$ eV

ECHo-100k phase (started):

- expected sensitivity: $m(\nu_e) \sim 1.5$ eV



$\sim 10^8$ events collected

ongoing studies:

- *detector response*
- *theoretical spectrum*

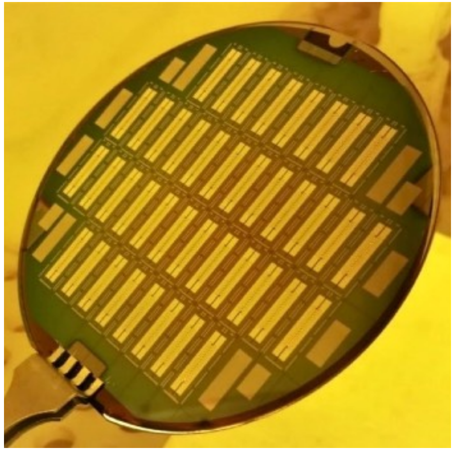
from Loredana Gastaldo

The ECHo experiment

ECHo-100k baseline: multiplexing to read out large number of MMCs

- Detector array of ~12000 pixels with activity of 10 Bq each

6" wafer for ECHo-100k



Current status:

- High Purity ^{163}Ho source:
  ~30 MBq available, wafer-scale ion implantation demonstrated
- Metallic magnetic calorimeters:
  reliable fabrication, successful characterization with ^{163}Ho
- Multiplexing and data acquisition:
  demonstrated for 8 channels, further scaling still to show

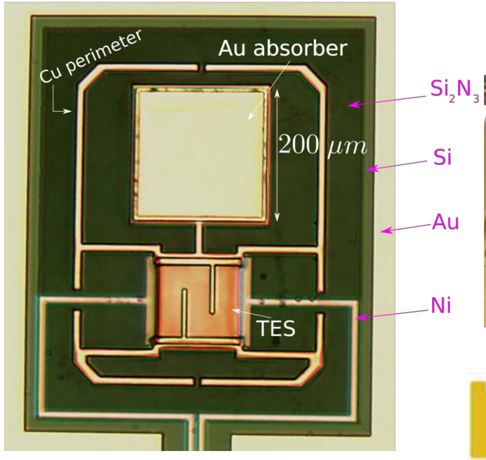
Timeline:

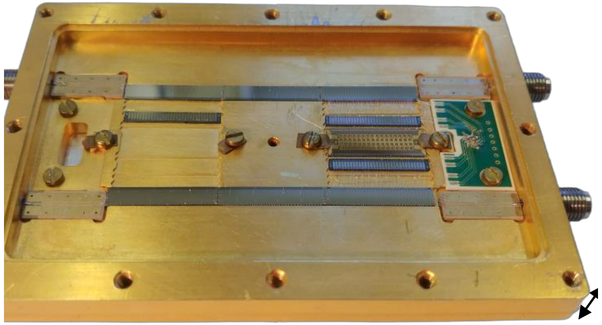
- Complete detector fabrication in 2024
- Start of data-taking in 2025 ➜ data collection and analysis 2026-27

from Loredana Gastaldo

The HOLMES experiment

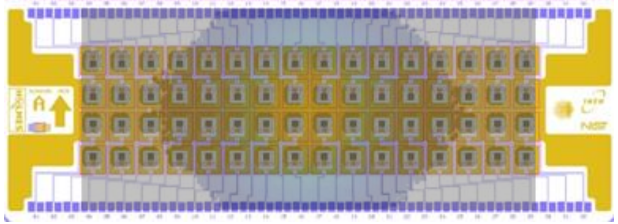
Technology: Mo/Cu bilayer Transition Edge Sensors (TES)
[J. Low Temp. Phys. **184** (2016) 492], activity **~few 100 Bq** per pixel





Current phase: 2x32 pixel array

- Low-activity implantation (~0.5 Bq)
- First holmium spectra measured
- Detector characterization
- Sensitivity m(ν_e) ~ 10 eV expected



Custom implanter at Genova:
multi-spot vs single spot irradiation

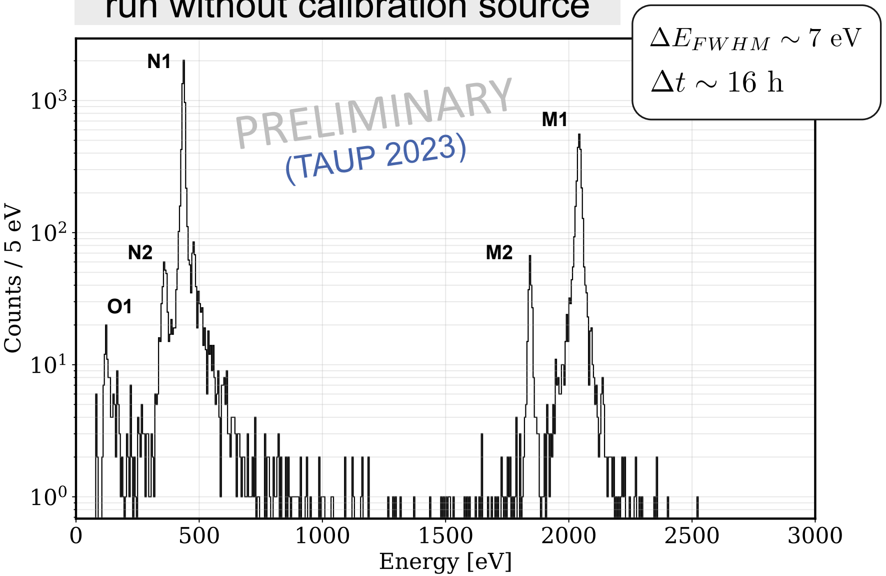
Array readout: microwave
SQUID multiplexing

from Matteo Borghesi

The HOLMES experiment

Technology: Mo/Cu bilayer Transition Edge Sensors (TES)
[J. Low Temp. Phys. **184** (2016) 492], activity **~few 100 Bq** per pixel

run without calibration source



Current phase: 2x32 pixel array

- Low-activity implantation (~0.5 Bq)
- First holmium spectra measured
- Detector characterization
- Sensitivity m(ν_e) ~ 10 eV expected

Future phase: 1000 pixel array

- Adjust pixel activity based on detector performance with ^{163}Ho
- Sensitivity m(ν_e) ~ 1.5 eV expected

➜ Explore potential for holmium-based sens. m(ν_e) ~ 0.1 eV

from Matteo Borghesi

Take-aways

Stay tuned!

- Massive neutrinos represent physics beyond the Standard Model
- Kinematic measurements are a direct, model-agnostic way to determine the absolute neutrino mass scale
- **Current lead:** KATRIN with integral MAC-E spectrometer and molecular tritium
  → Initial data: $m(\nu) < 0.8$ eV; target sensitivity better than 0.3 eV
  → R&D towards KATRIN++ has started
- **Cyclotron resonance emission spectroscopy (differential):** Project 8 & QTNM
  → First neutrino mass limit: $m(\nu) < 150$ eV (Project 8)
  → Next step: scaling up large-volume trap, develop atomic tritium source
- **Low-temperature detectors for ^{163}Ho (differential):** ECHO & HOLMES
  → First neutrino mass limit: $m(\nu) < 150$ eV (ECHo), $m(\nu) < 10$ eV is in reach
  → Next step: scaling up to high activity and large number of detectors

Many thanks to:

Stay tuned!

- The ECHo Collaboration
- The HOLMES Collaboration
- The KATRIN Collaboration
- The Project 8 Collaboration
- The QTNM Collaboration