

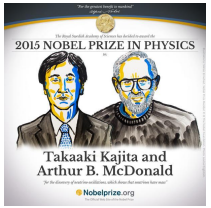
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Latest results from the KATRIN experiment and future prospects of direct neutrino mass experiments

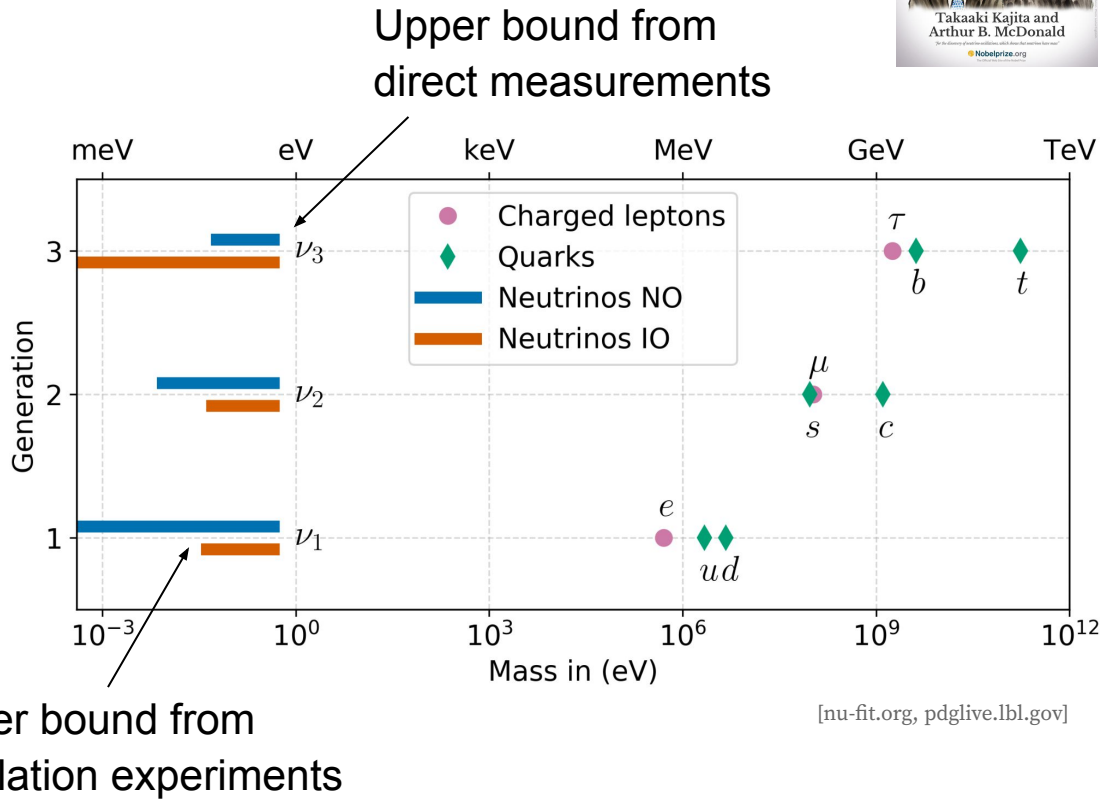
Christoph Köhler (MPIK) for the KATRIN collaboration, DISCRETE, Bratislava, 16.11.2026

DISCRETE 2026

Neutrino mass



- Neutrino oscillations → non-zero mass
- Smallness, ordering and origin of mass?

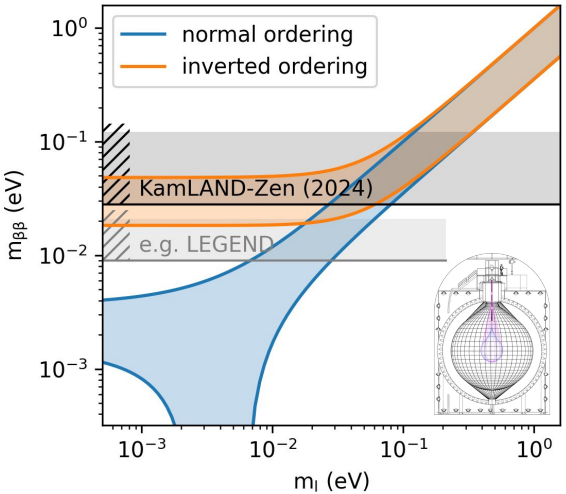


[nu-fit.org, pdglive.lbl.gov]

Determination method

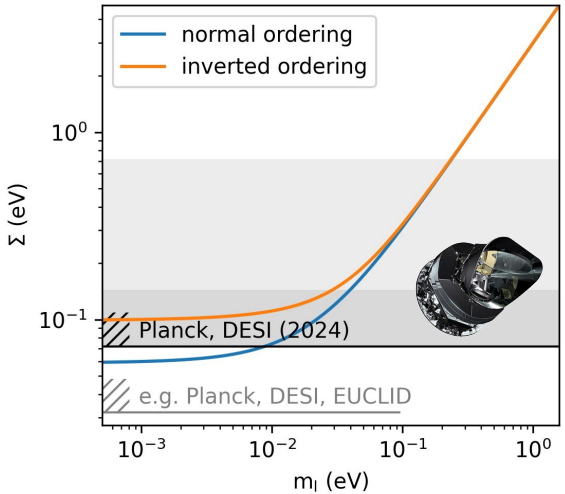
Neutrinoless ββ-decay

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



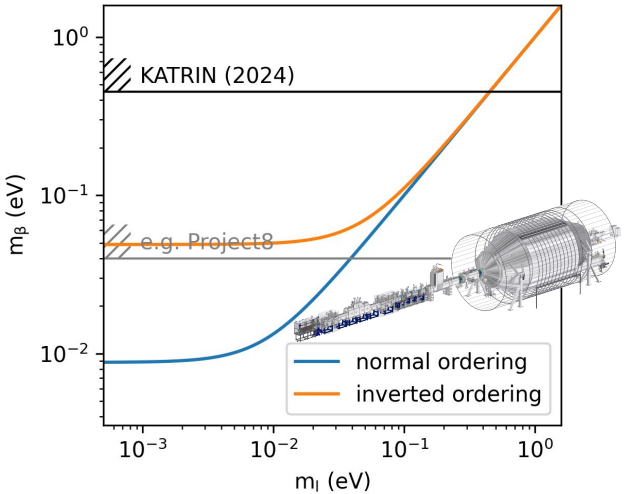
Cosmology

$$\Sigma = \sum_i m_i$$



β-decay kinematics

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

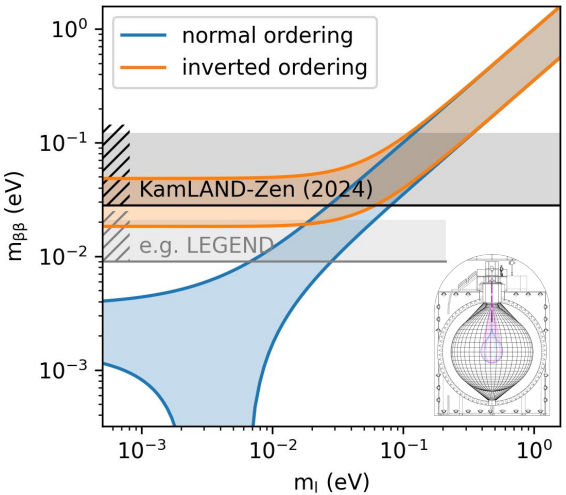


[NuFIT 5.3, nu-fit.org]

Neutrinoless ββ-decay

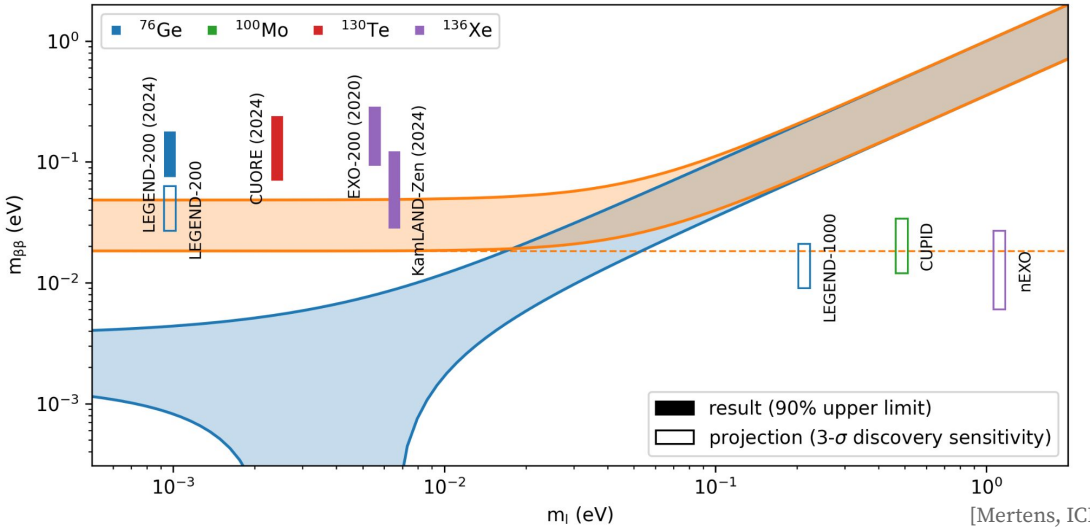
Neutrinoless ββ-decay

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



World leading: KamLAND-Zen

$T_{1/2}$ **> 3.8e26 y ⇒** $m_{\beta\beta}$ **28-122 meV**



[Mertens, ICHEP 2024]

- Majorana nature!?
- Nuclear matrix elements?



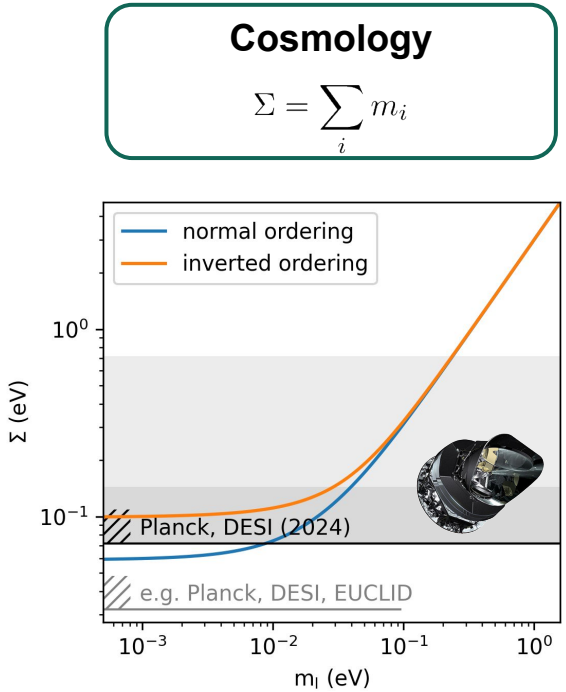
Cosmology

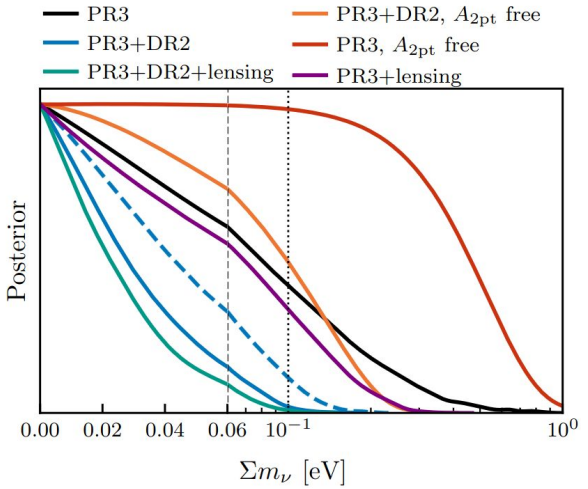
- Stringent bound from Planck, DESI and ACT data

  [Adame et al., arXiv:2404.03002]

  $\Sigma < \mathbf{0.07\ eV}$ (95% CI)

- Model and dataset dependence can weaken bounds

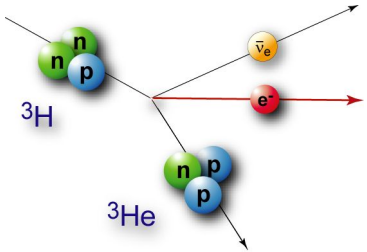




[Lynch et al., Phys.Rev.D 112 (2025) 8]

β-decay* kinematics

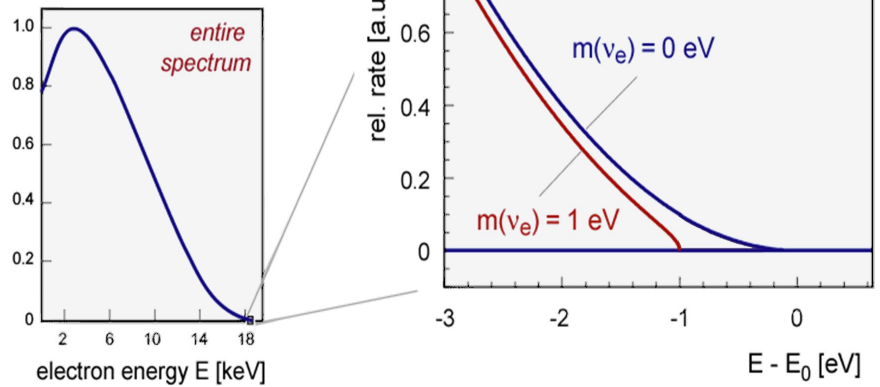
* or electron capture

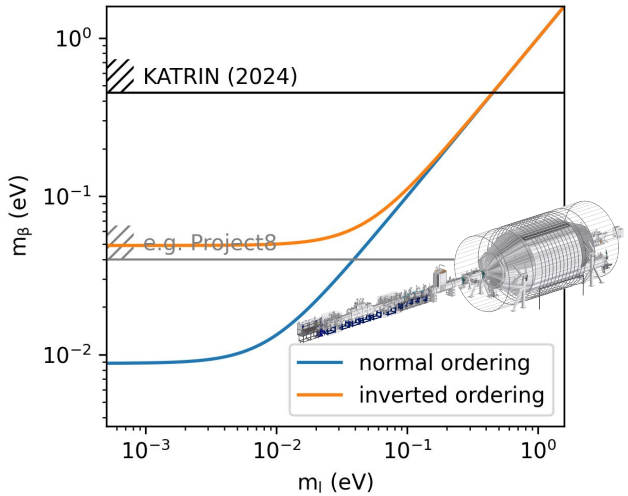


- Independent of cosmology
- Independent of neutrino nature

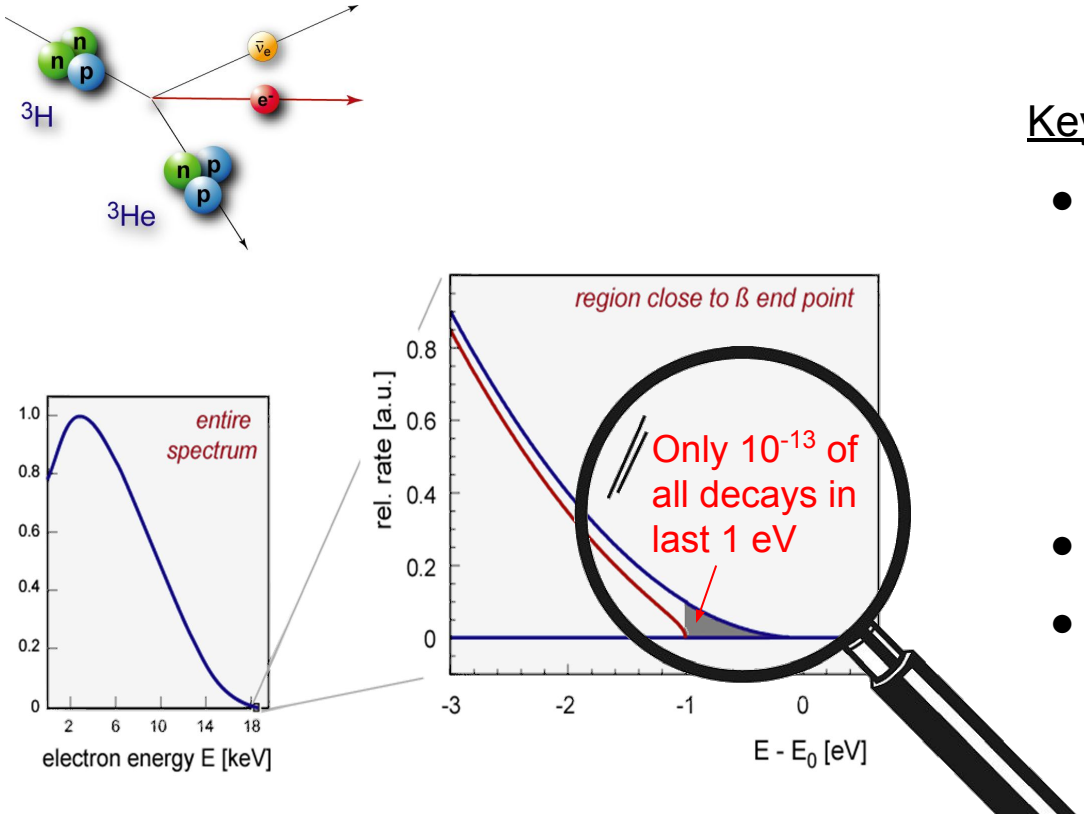
β-decay kinematics

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





The challenge

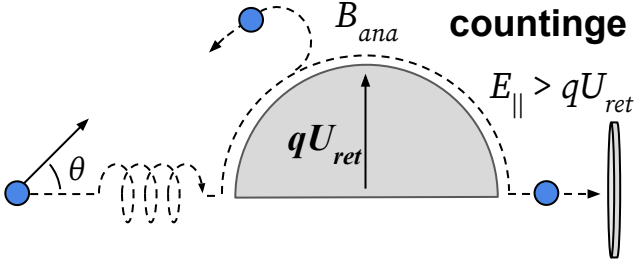


Key requirements:

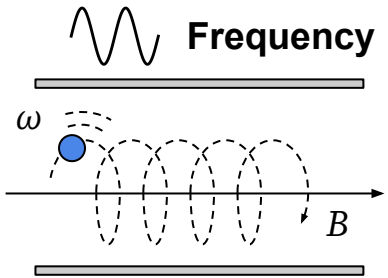
- Strong β-decaying source
  - Tritium: **12.3 years, E_0 = 18.6 keV**
  - Holmium: **4500 years, E_0 = 2.8 keV**
- Low background (< 0.1 cps)
- Excellent energy resolution (1 eV)

Experimental approaches

Retarding potential: countinge above threshold

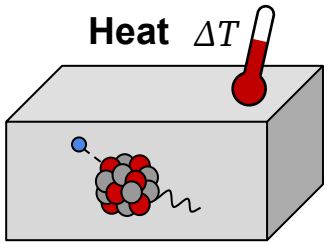


Electrostatic filter (MAC-E)

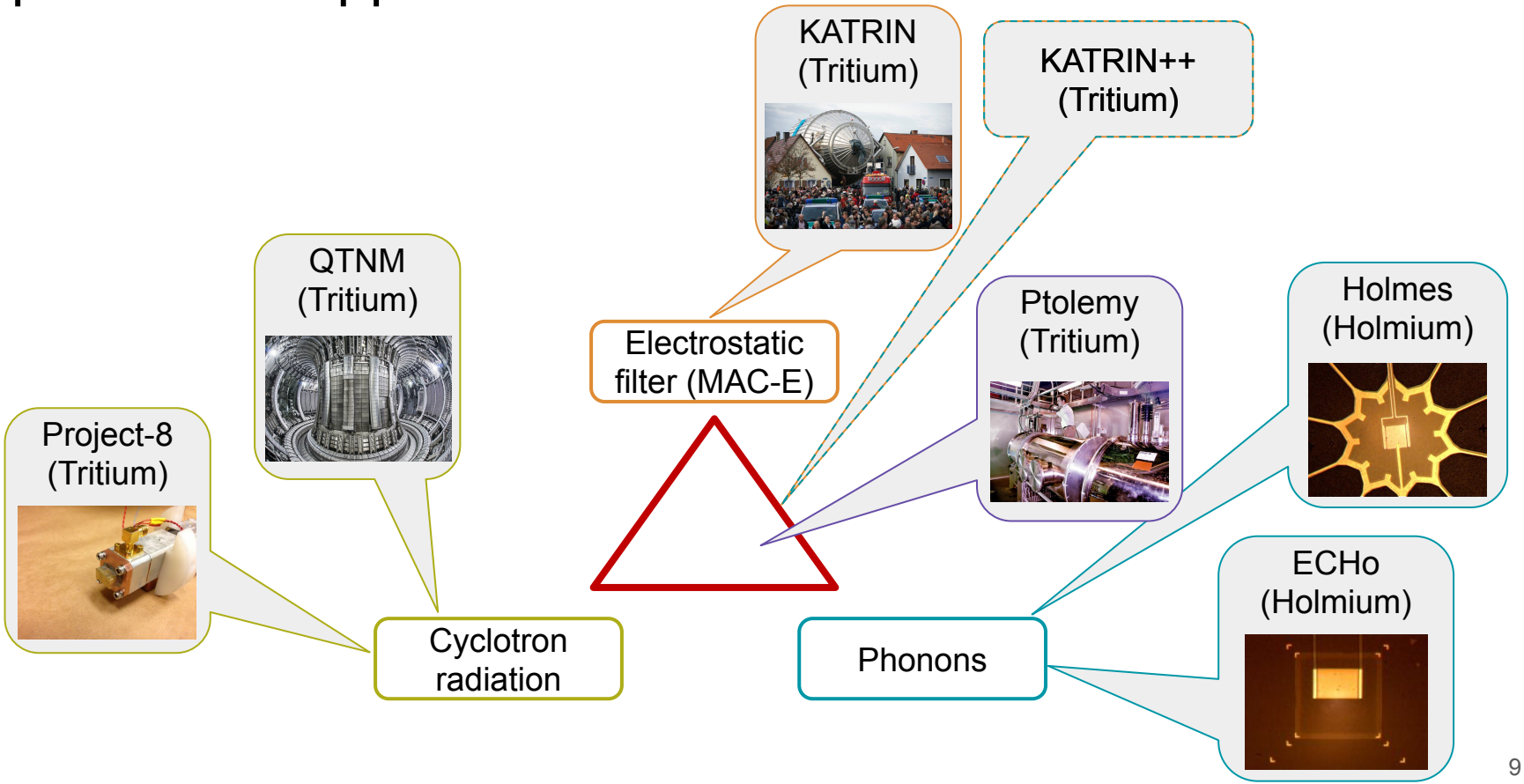


Cyclotron radiation

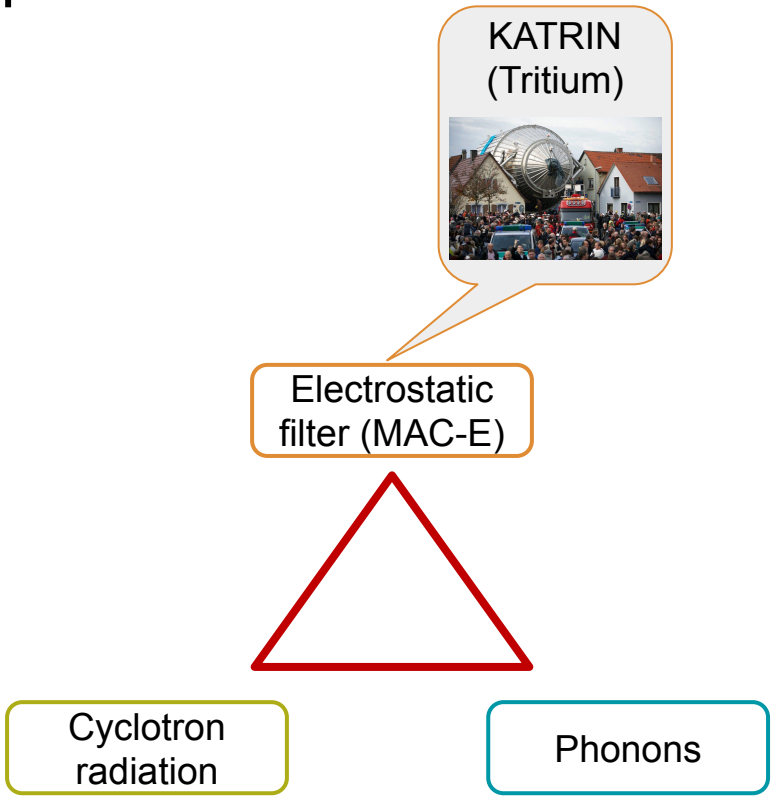
Phonons



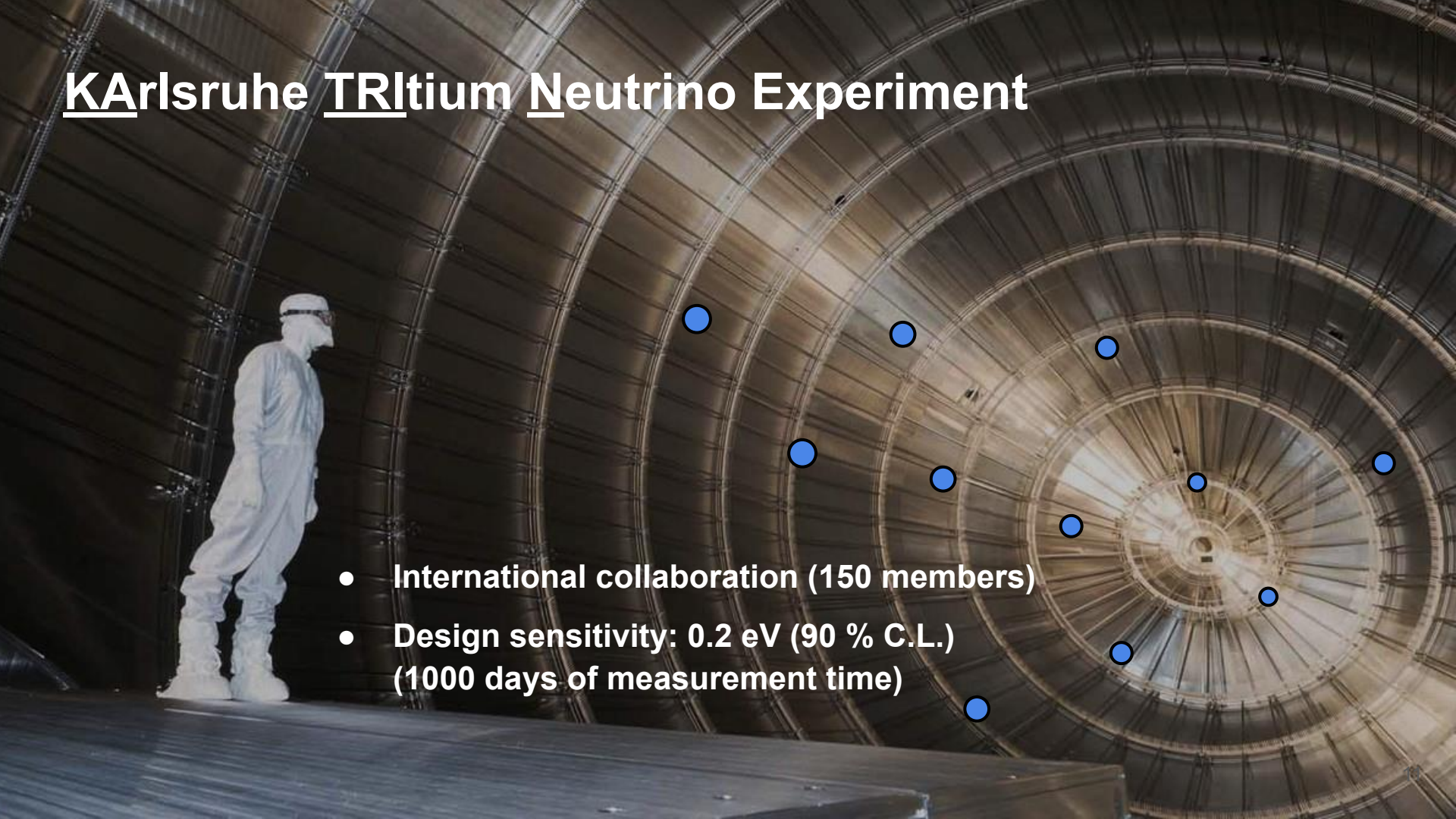
Experimental approaches



Experimental approaches



KArlsruhe TRItium Neutrino Experiment

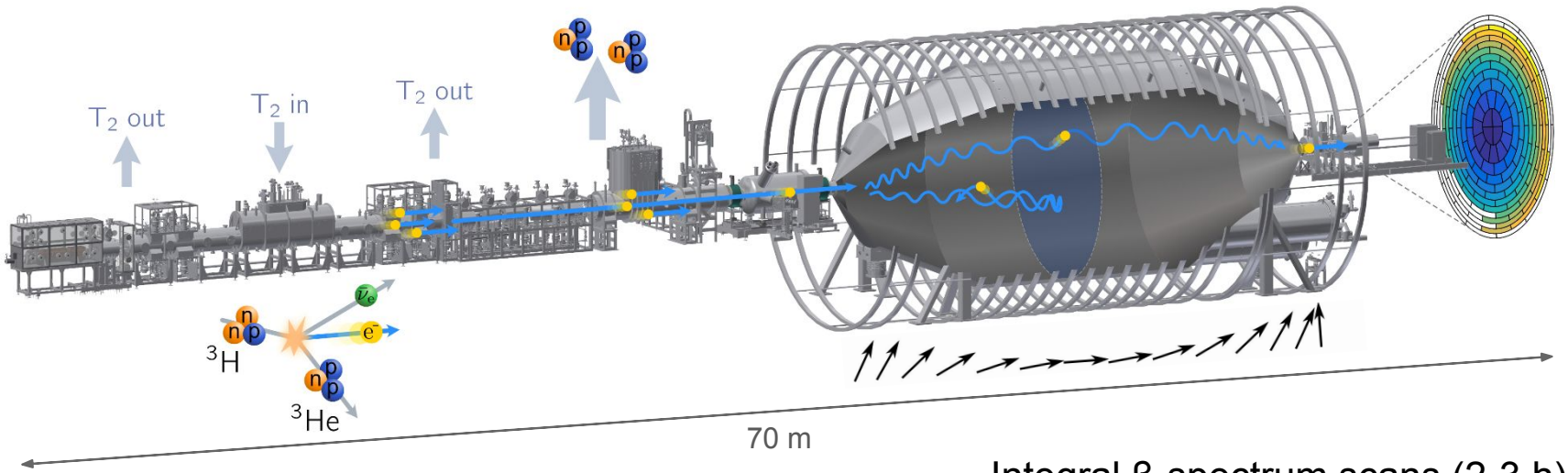


- International collaboration (150 members)
- Design sensitivity: 0.2 eV (90 % C.L.)
  (1000 days of measurement time)

Experimental overview

[Aker et al., JINST 16 (2021), 08, T08015]

Windowless gaseous tritium source: ~200 μg T_2 → 10^{11} decay/s	Tritium gas/ion removal > 10^{14}	High-resolution O(1) eV MAC-E spectrometer system	Electron counting with 148 pixel silicon PIN-diode

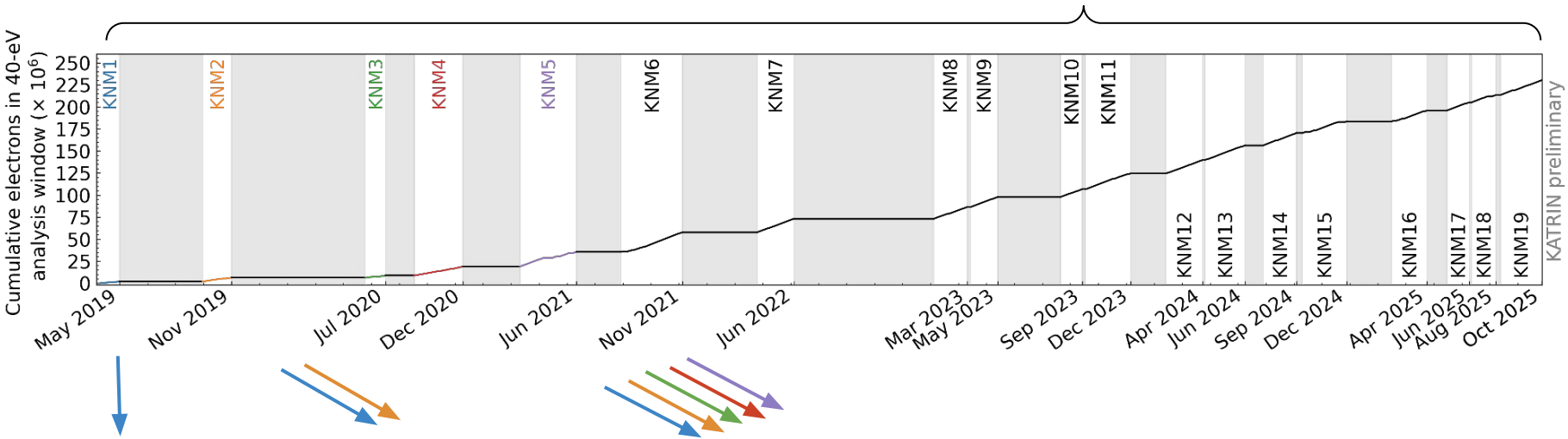


Integral β-spectrum scans (2-3 h)
[E_0 - 40 eV, E_0 + 135 eV]

Data taking overview

*in last 40 eV

Final dataset, 1000 days of measurement, 231 million electrons*



1st result
$m_\beta < 1.1$ eV
(90% C.L.)



[PRL. 123, 221802 (2019)]
[Phys. Rev. D 104, 012005 (2021)]

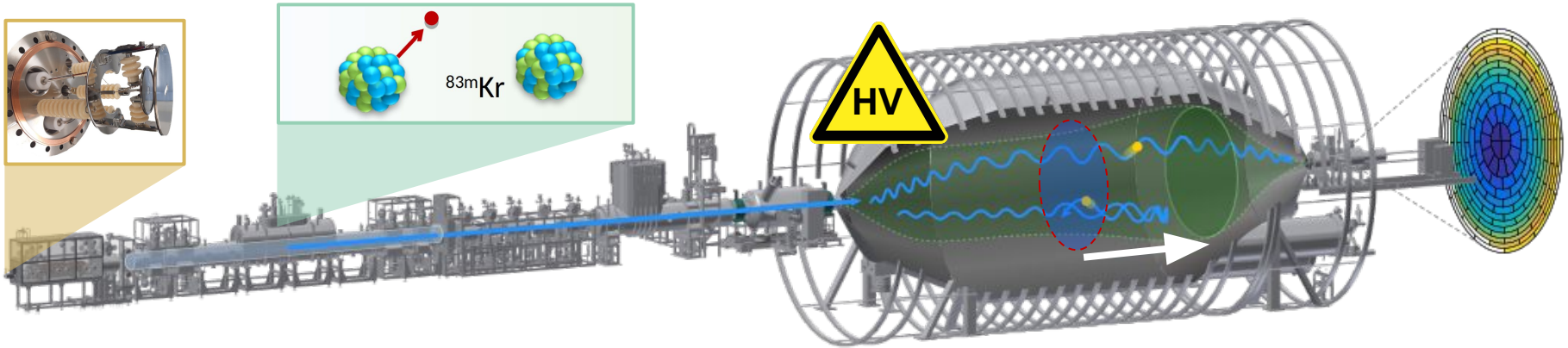
2nd result
$m_\beta < 0.8$ eV
(90% C.L.)



[Nat. Phys. 18, 160–166 (2022)]

3rd result
(in the following slides)
259 days of measurement,
36 million electrons*

Experimental improvements

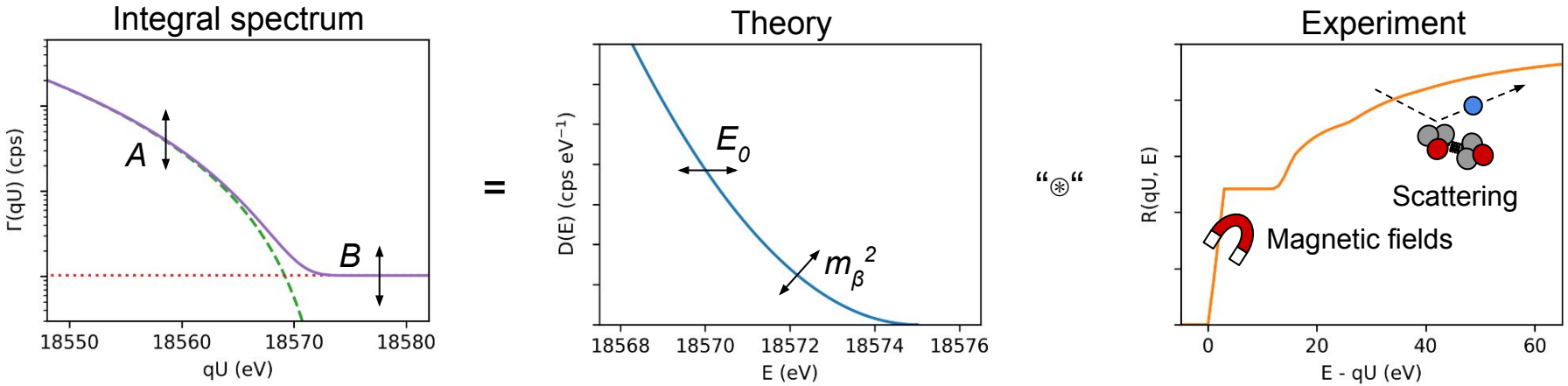


- **Background reduction by a factor of 2** with “shifted analyzing plane” configuration [Lokhov et al., EPJ C 82 (2022) 3, 258]
- Determination of source potential and spectrometer fields with ^{83m}Kr [Altenmüller et al., J.Phys.G 47 (2020), 6, 065002]
- Probe source scattering (gas density, energy loss) with improved **electron gun**

[Schneidewind et al., Eur.Phys.J.C 86 (2026) 7, 773]

Analysis strategy

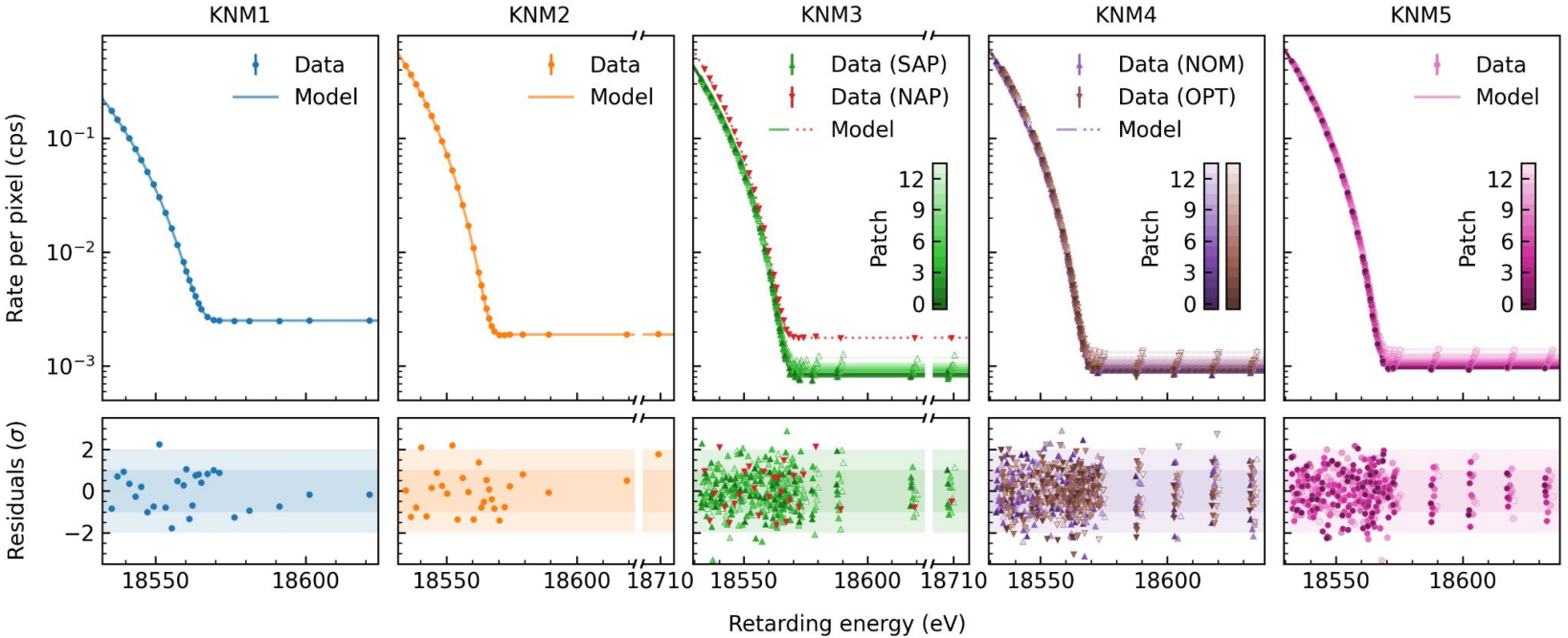
- Maximum likelihood fit of model $\Gamma(qU) \propto A \int_{qU}^{E_0} D(E; m_\beta^2, E_0)\, R(qU, E)\, \mathrm{d}E + B$



- Free parameters: **squared neutrino mass** m_β^2, **effective endpoint** E_0, **amplitude** A and **background** B
- Theoretical (Fermi theory, molecular excitations) and experimental inputs (calibration measurements)

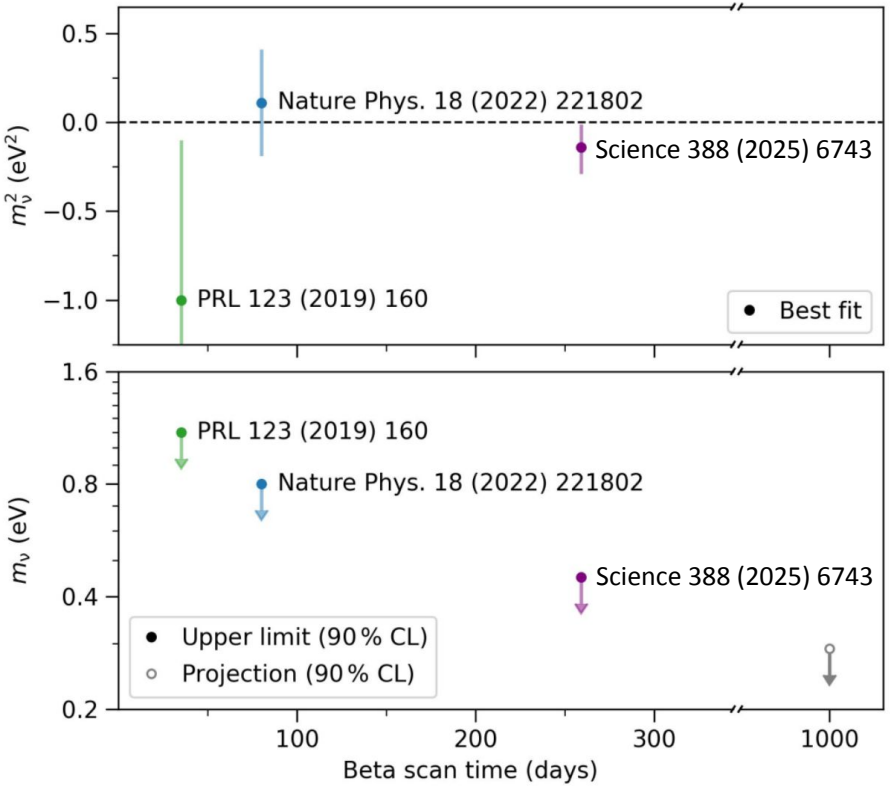
3rd KATRIN result

[Aker et al., Science 388 (2025) 6743]



- **Data set:** first 5 campaigns, 59 spectra, 1609 data points
- **Best fit result:** $m_\beta^2 = -0.14^{+0.13}_{-0.15}$ eV^2 (stat. dom.), upper limit $\boldsymbol{m_\beta < 0.45}$ **eV** (90% C.L.)

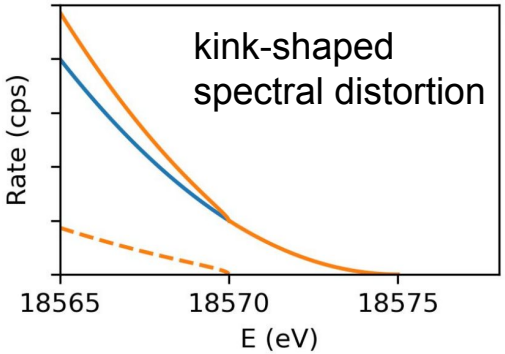
KATRIN results



- 3rd KATRIN release with 259 measurement days and 36 million electrons → improvement on upper limit by a factor of 2

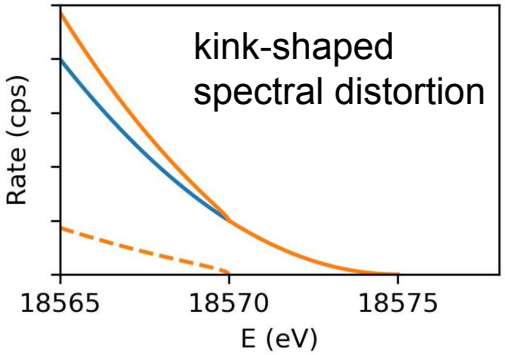
- Final result:
  - based on 1000 measurement days and 231 million electrons
  - statistical sensitivity: m_β **< 0.28 eV**
  - systematics budget in preparation, goal to reach m_β **< 0.3 eV**

Beyond neutrino mass analyses

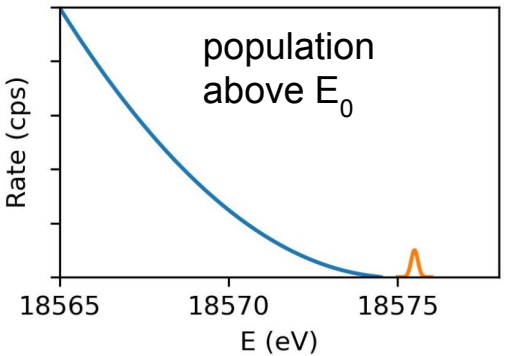


- Sterile neutrinos: eV- to keV-scale
  [Acharya et al., Nature 648 (2025) 8092, 70-75]
- Extra dimensions
  [Antoniadis et al., JHEP 02 (2026) 015]

Beyond neutrino mass analyses

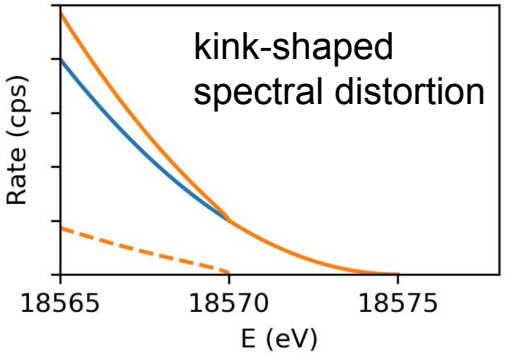


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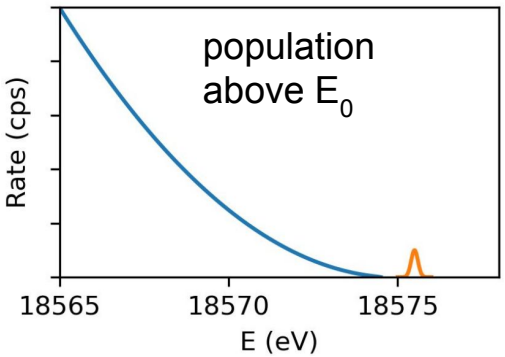


- Relic neutrino overdensity
  [Aker et al., PRL 129 (2022) 1, 011806]

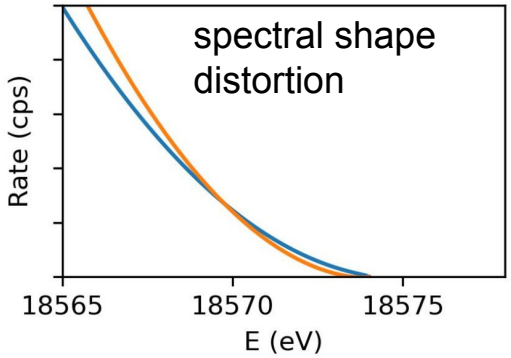
Beyond neutrino mass analyses



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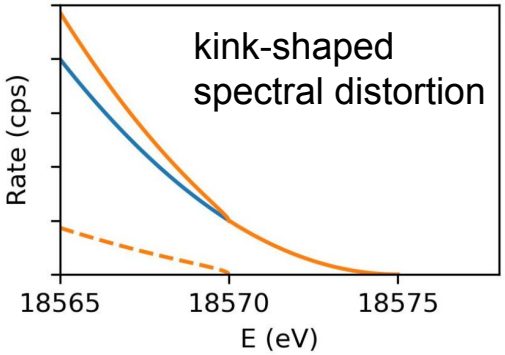


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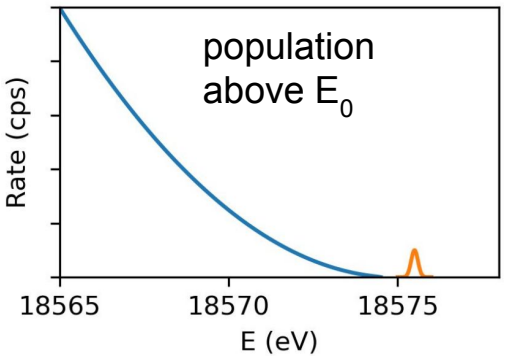


- General neutrino interactions
  [Aker et al., PRL 134 (2025) 25, 251801]
- Light bosons
  [Lauer, PoS ICHEP2024 (2025) 326]

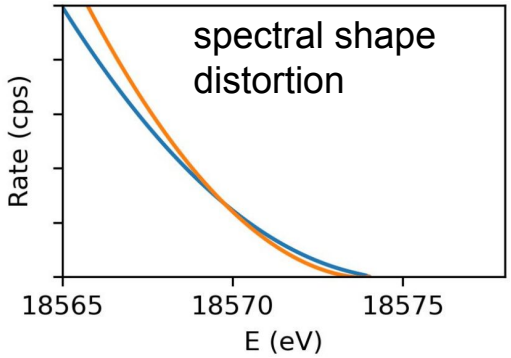
Beyond neutrino mass analyses



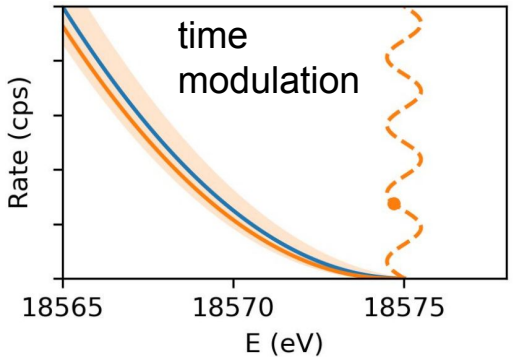
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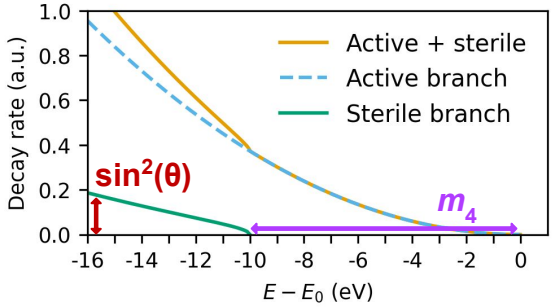
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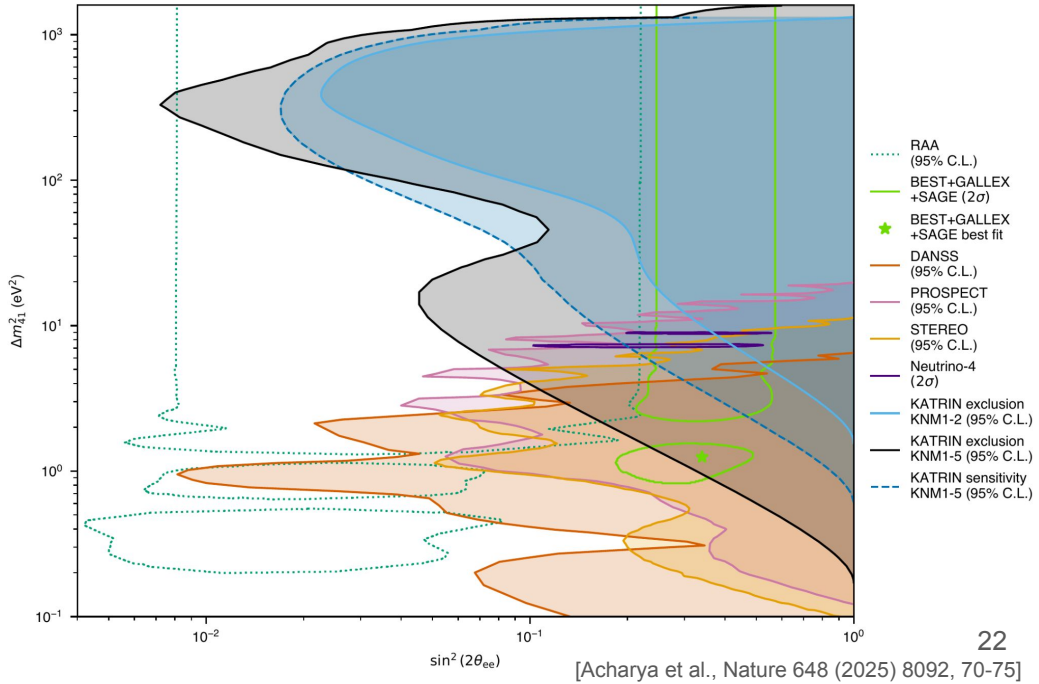


- Lorentz invariance violation
  [Aker et al., PRD 107 (2023) 8, 082005]
- Ultra-light axion oscillations

Light sterile neutrino search

- KATRIN can probe eV-scale sterile neutrinos, motivated by anomalies
- 3+1 model (m_4, $\sin^2(\theta)$) applied to grid search analysis
- Data from first 5 campaigns
- KATRIN exclusion limit:
  - challenges almost whole Gallium anomaly
  - complementary to short baseline oscillation experiments
- Possible solution to GA: neutrino capture cross section calculation

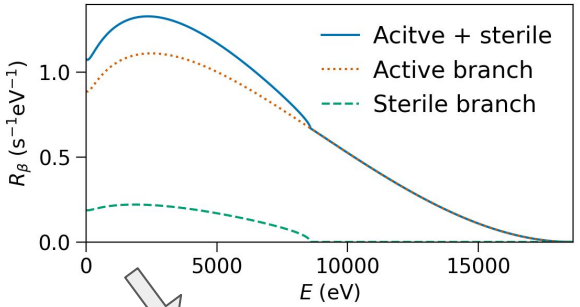




[Cadeddu et al. Phys.Rev.Lett. 137 (2026) 13]

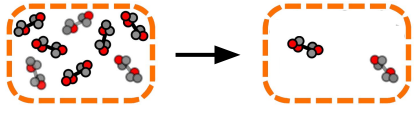
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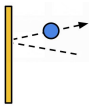
keV-scale sterile neutrino search



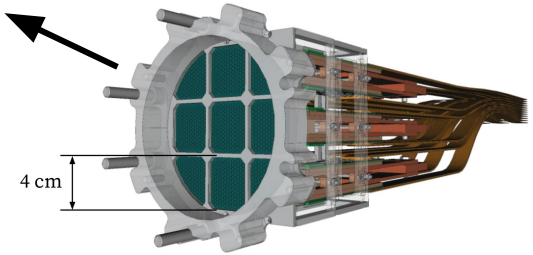
10^5 counts/s/pixel

Source activity reduction: 100% → O(1)%





Rear wall: Au to Be



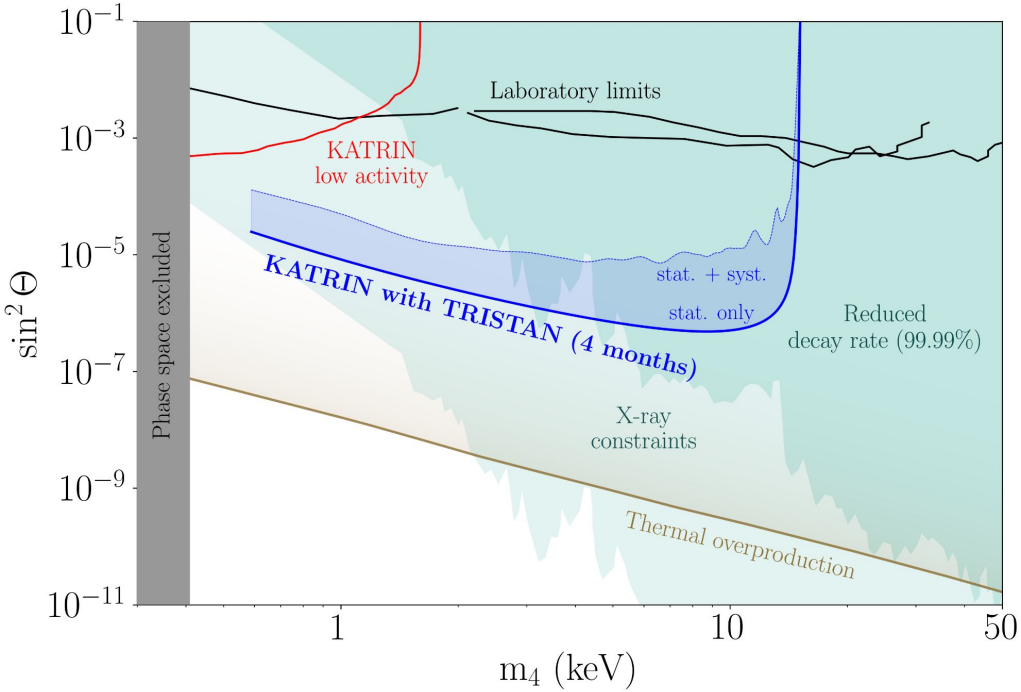
[Siegmann et al., J.Phys.G 51 (2024) 8, 085202]

- Upgrade of beamline and installation of new TRISTAN detector: silicon drift detector (SDD), 9 x 166 pixels [Mertens et al., J.Phys.G 46 (2019) 6, 065203]
- By the end of 2027: First measurements with new detector and tritium in the source

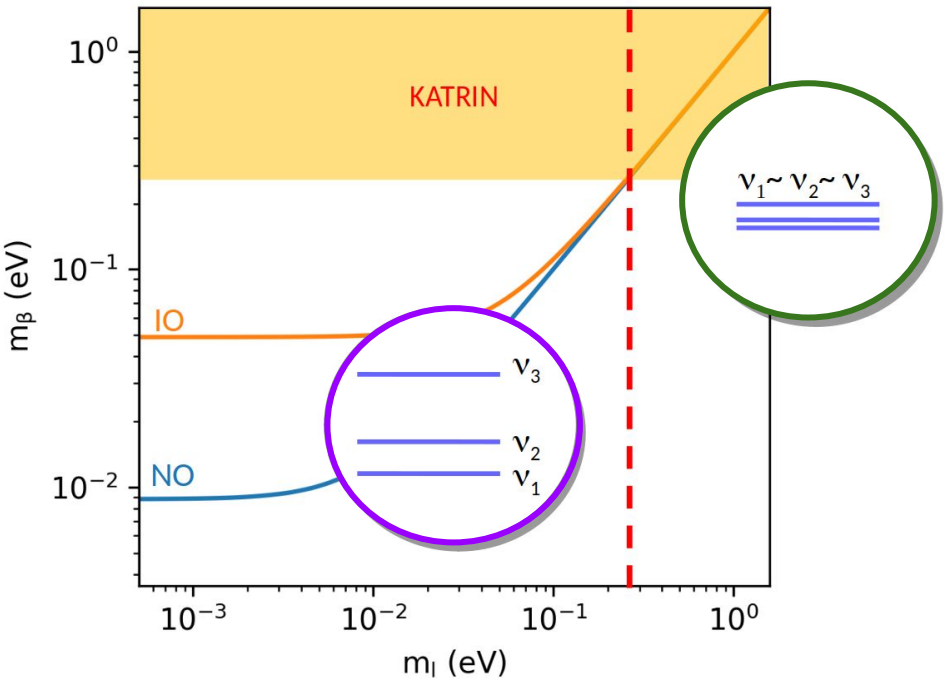
keV-scale sterile neutrino sensitivity

- With 4 months of measurement: 4 x 10^{14} electrons
- Statistical sensitivity reaching $\sin^2(\theta) < 10^{-6}$ but limited by systematic uncertainties
- Extensive calibrations to control systematic effects
- Precise simulation of full beamline needed

[Acharya et al., arXiv:2603.23256]

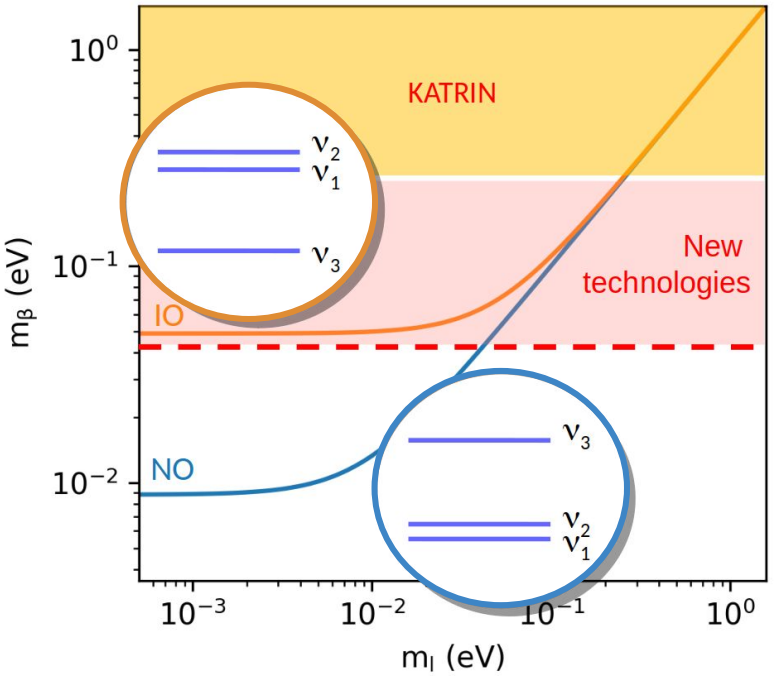


Going beyond KATRIN



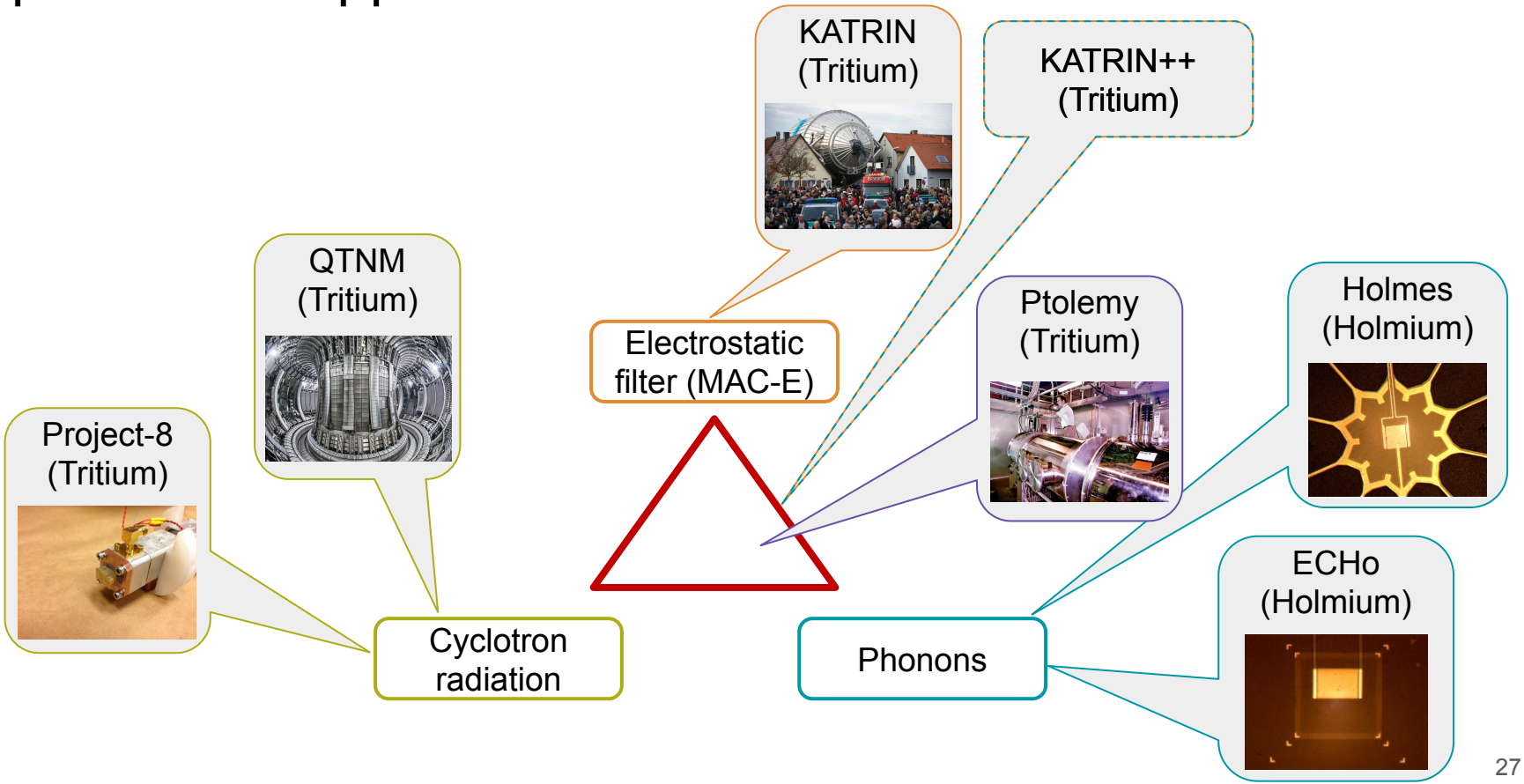
- KATRIN final: < **0.3 eV** (90% C.L.)
  Distinguish between **degenerate** and **hierarchical** scenario

Going beyond KATRIN

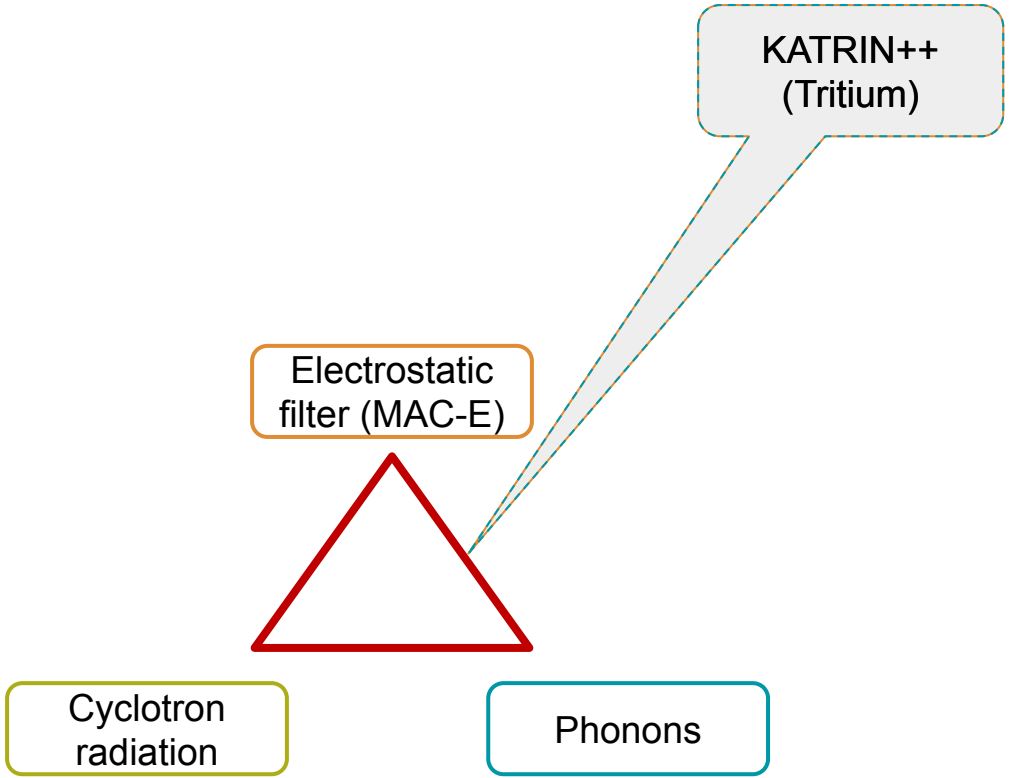


- KATRIN final: < **0.3 eV** (90% C.L.)
  Distinguish between **degenerate** and **hierarchical** scenario
- New technologies: < **0.05 eV**
  Cover **inverted ordering**

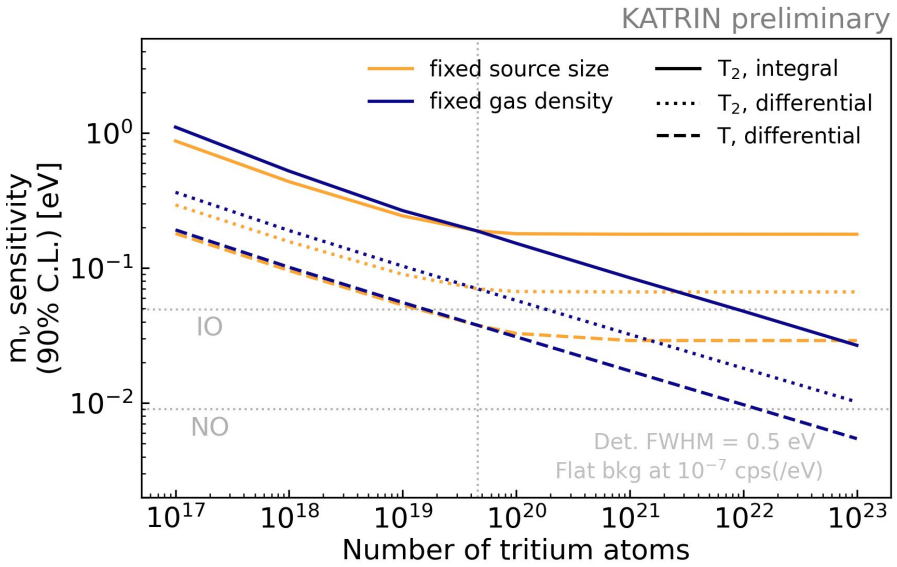
Experimental approaches

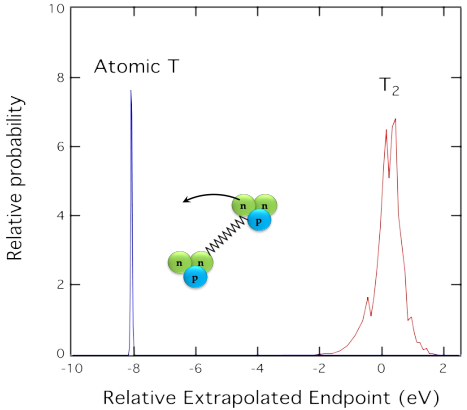


Experimental approaches



Going beyond KATRIN





..... Differential measurement (FWHM < 1 eV)
- better use of statistics ✅
- lower background ✅

--- Atomic tritium
- avoid broadening (~ 1eV) ✅
- avoid limiting systematics of T_2 ✅

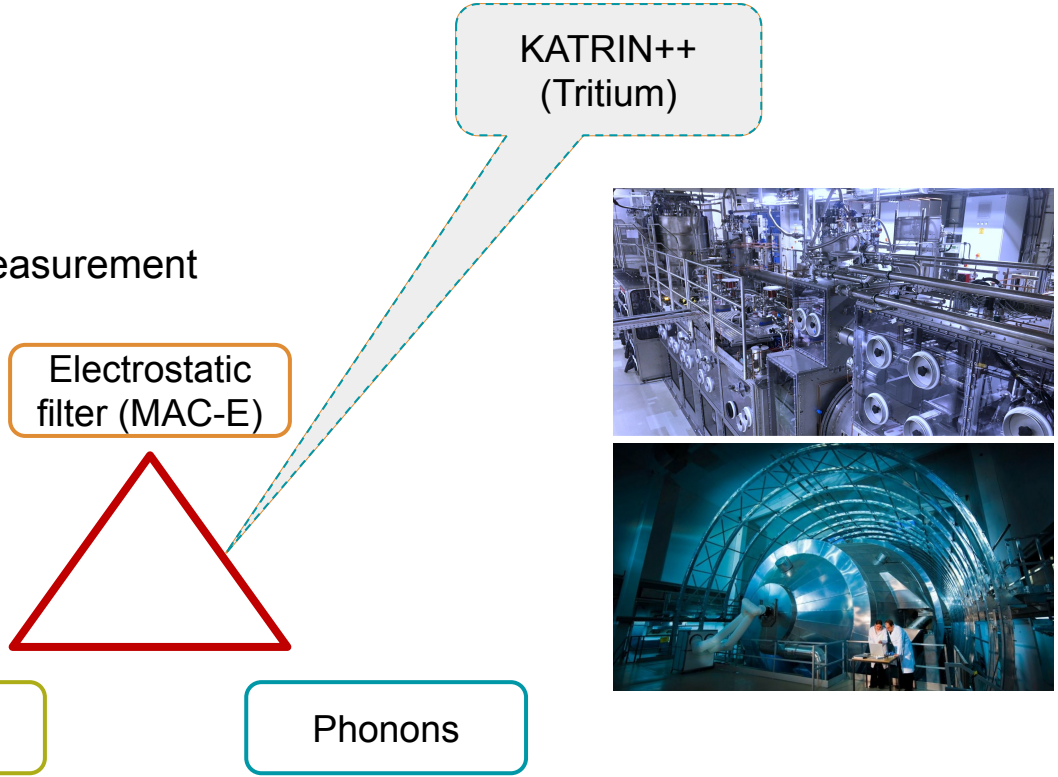
Experimental approaches

R&D launched:

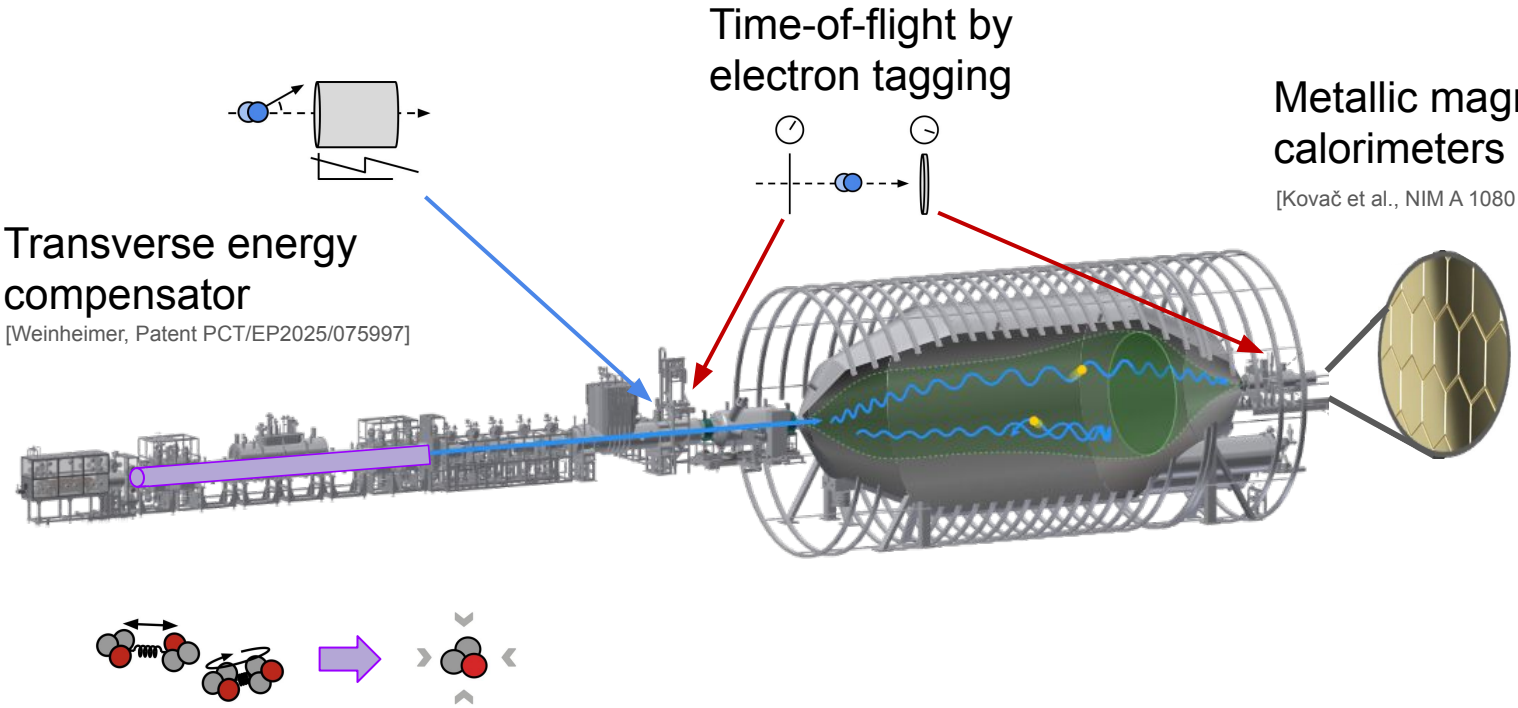
- Atomic tritium source concepts
- Techniques to enable differential measurement

Leverage unique infrastructures:

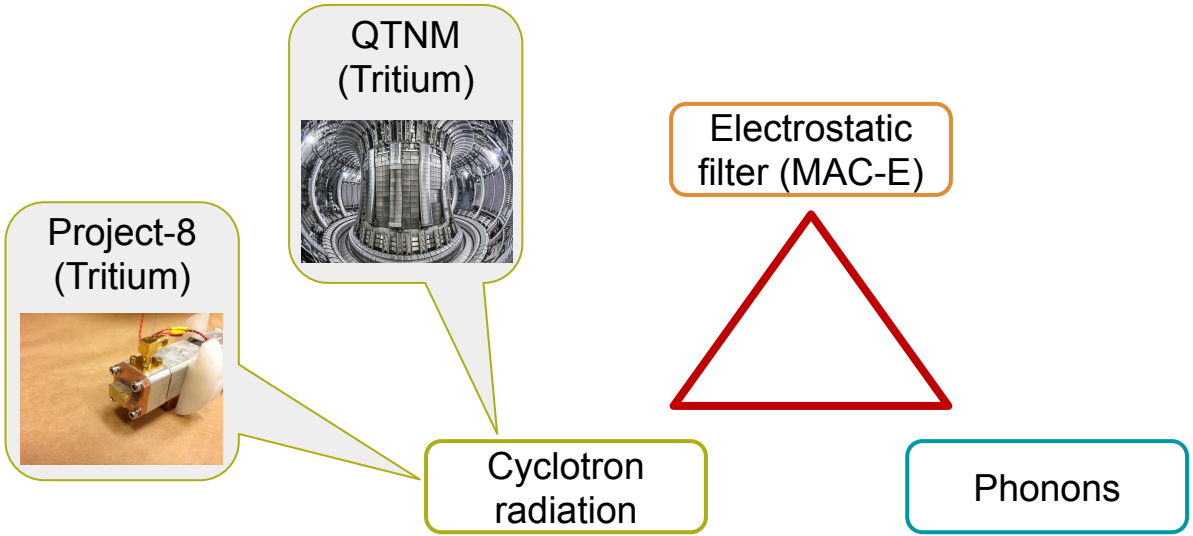
- Tritium Laboratory Karlsruhe
- KATRIN beamline



Towards KATRIN++



Experimental approaches



Cyclotron Radiation Emission Spectroscopy (CRES)

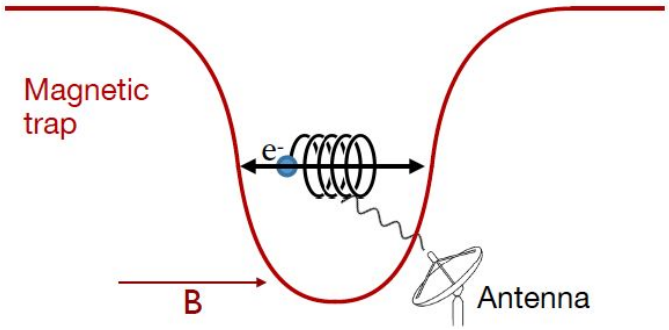
- Precise frequency measurement: $\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{E + m_e}$

Advantages:

- (sub)-eV-scale differential measurement
- No electron beamline

Challenges:

- Weak signal: ~1fW
- B-field homogeneity at the 10^{-7} level
- Large volume (~m^3) atomic trap for < 0.04 eV sensitivity

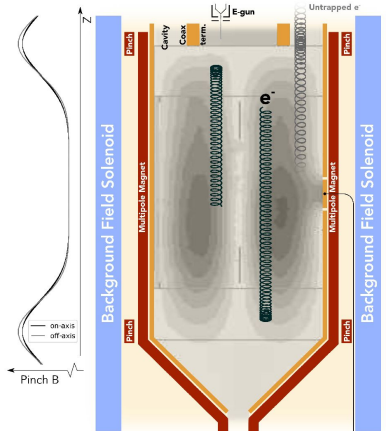


Experiments

Project-8

PROJECT 8

- Cavity CRES + cold atomic tritium trap



QTNM

QTNM
Quantum Technologies for Neutrino Mass

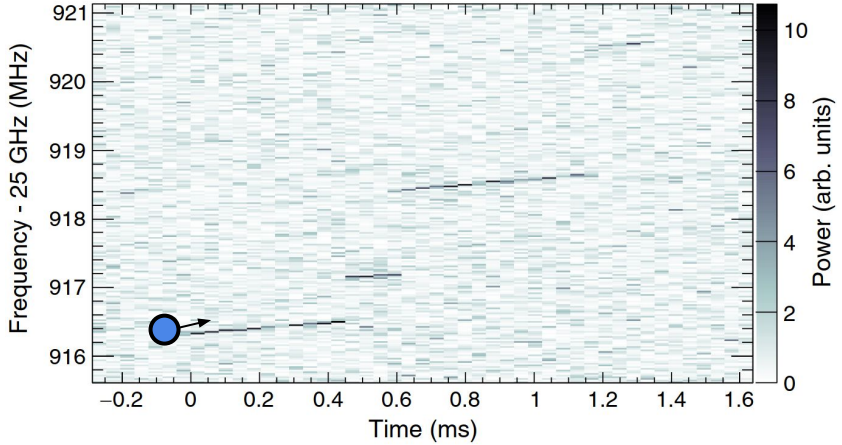
- Storage ring confinement
- New effort, conceptual stage



Project 8

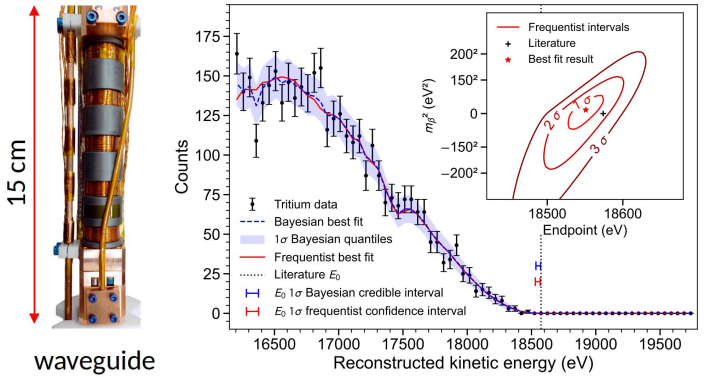
- Phase I: Proof of CRES concept

  [Asner et al., Phys.Rev.Lett. 114 (2015) 16, 162501]



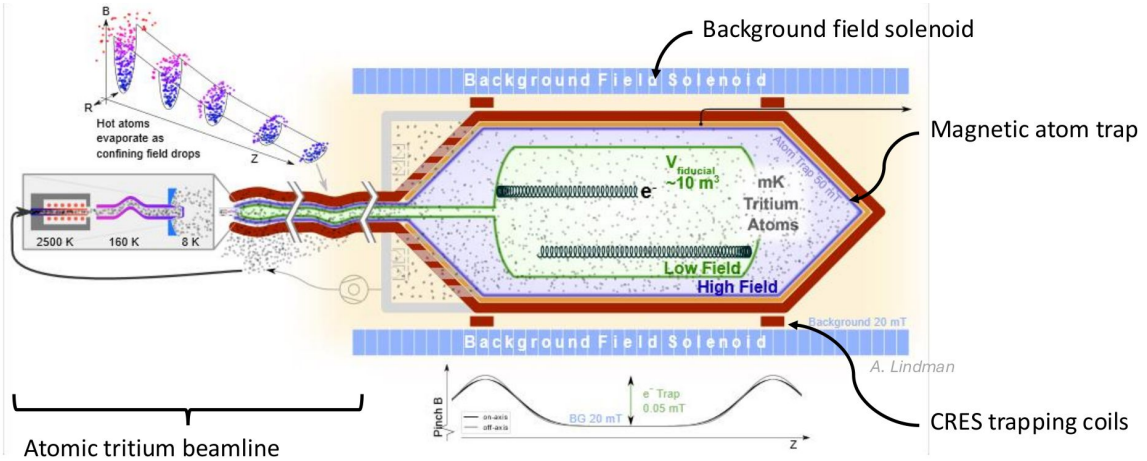
- Phase II: First neutrino mass limit $m_\beta < 155$ eV (90% C.L.)

  [Ashtari Esfahani *et al.*, Phys.Rev Lett. 131 (2023) 10, 102502]



Project 8

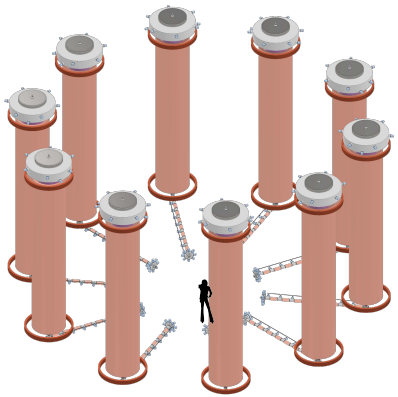
[Binney, NuMass 2026]



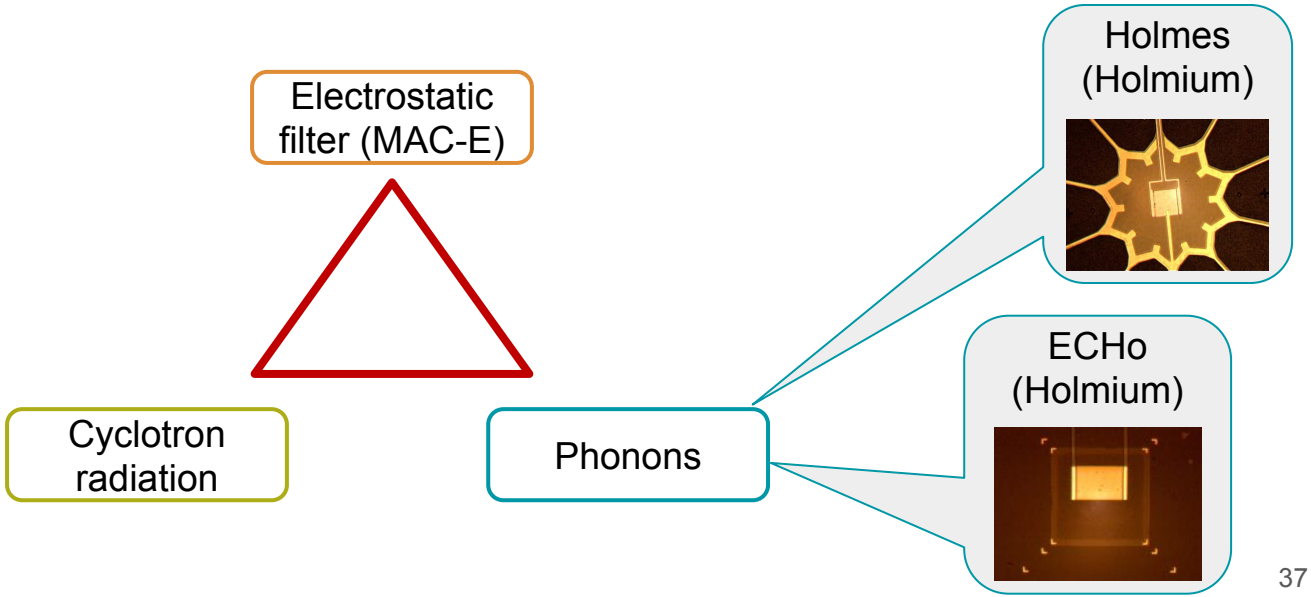
You are here

- Phase III:
  - large-volume (m^3) cavity resonator
  - development of atomic tritium source
- Phase IV: Ultimate goal to cover inverted ordering having 40 meV sensitivity

[Ashtari Esfahani et al., arXiv:2203.07349]



Experimental approaches



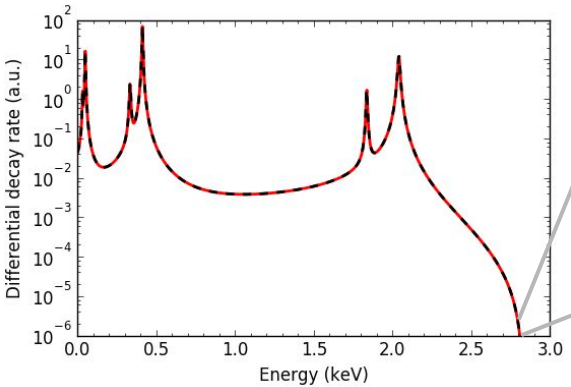
Working principle

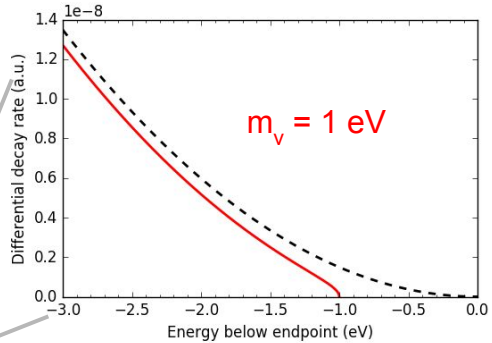
Low-temperature micro-calorimetry with holmium

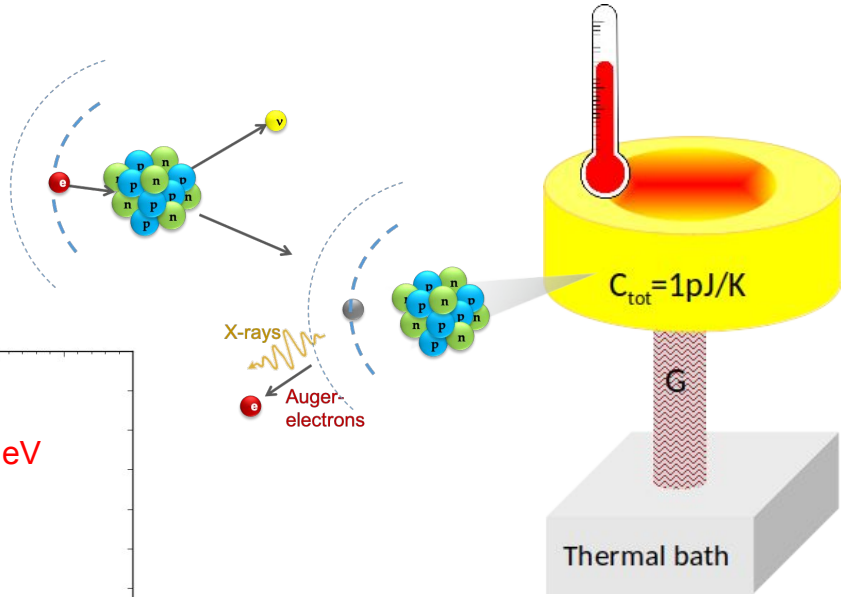
[De Rujula et al., *Phys. Lett.B* 118 (1982) 429]

$$^{163}_{67}\mathrm{Ho} \rightarrow ^{163}_{66}\mathrm{Dy}^{*} + \nu_{\mathrm{e}}$$

$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow ^{163}_{66}\mathrm{Dy} + E_{\mathrm{C}}$$







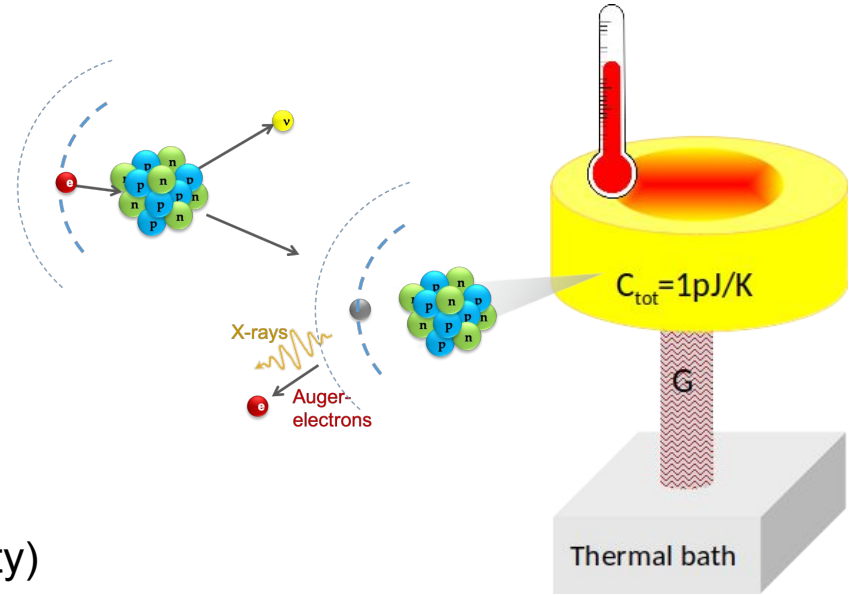
Working principle

Advantages:

- eV-scale differential measurement
- Source implanted in detector

Challenges:

- eV-resolution
  - operation at low temperature (mK)
  - small pixels (µm-scale)
- Collecting data (> 10^{13} decay for eV sensitivity)
  - high as possible activity per pixel (10 Bq)
  - many (> 10,000) pixels (multiplexed read-out)

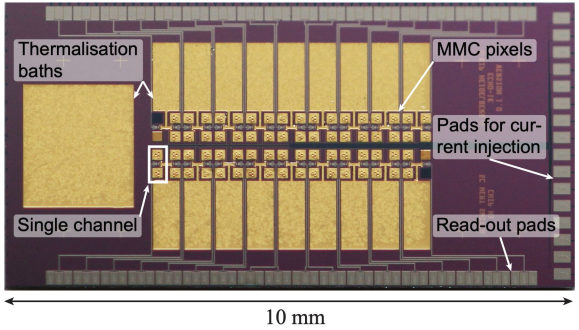


Experiments

ECHo

- Metallic magnetic calorimeters (MMC)

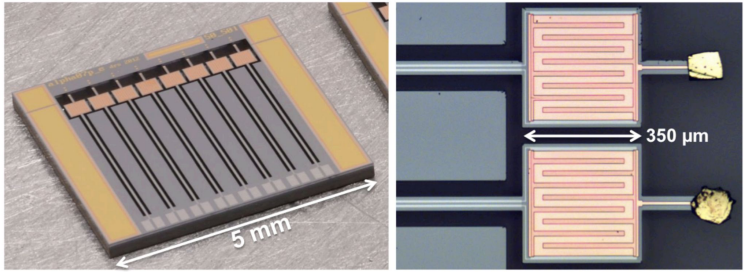
[Gastaldo et al. *Eur.Phys.J.ST*. 226 (2017) 8]



Holmes

- Transition edge sensors (TES)

[Hays–Wehle et al., *J.Low Temp.Phys* **184** (2016) 1-2]



ECHo

Achievements

- **Prototype**: m_β < 150 eV (95% C.L.)

  [Velte et al., *Eur.Phys.J.C* 79 (2019) 12]

- **ECHo-1k:** m_β < 15 eV (90% C.L.)

  ~1 Bq/pixel, 60 pixels, 10 eV FWHM

  [Adam et al., *Phys.Rev.Lett.* 136 (2026) 12, 121801]

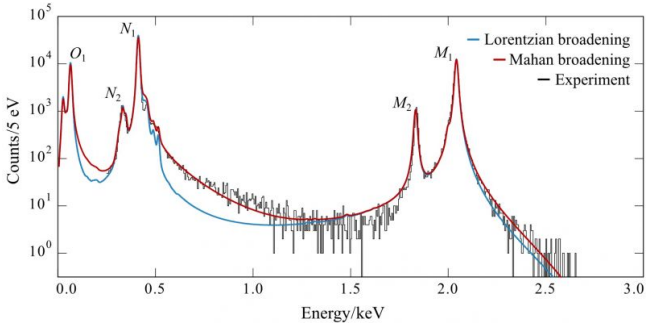
Next steps (2026-2030)

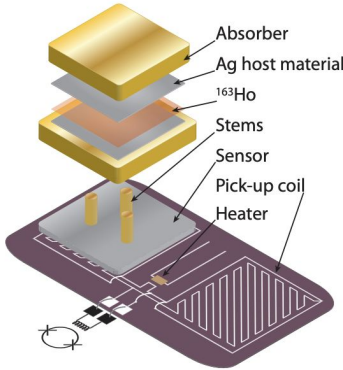
- **ECHo-LE**: m_β < 0.8 eV (90% C.L.)

  ~10 Bq/pixel, 20000 pixels, 5 eV FWHM

Ultimate goal:

- 10 MBq (100,000 pixels) → low sub-ev sensitivity







60 pixel, ~1 Bq each

Holmes

Achievements:

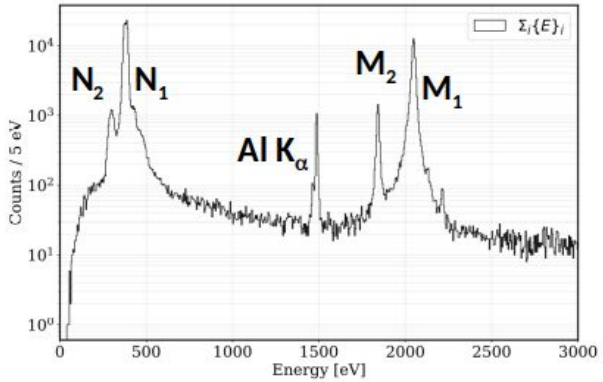
- **First result:** m_β < 27 eV (90% CL)
- 52 active pixels (64 total)
- <A> ≈ 0.3 Bq, ΔE_{FWHM} = ~4 eV @ 6 keV
  [Borghesi, Neutrino (2024)]

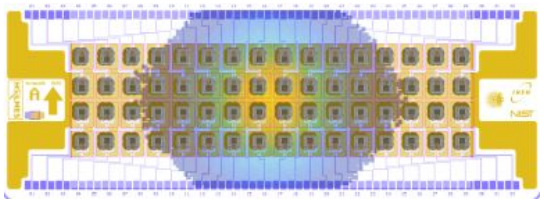
Next steps (2025-2027)

- m_β < 5.6 eV (2y, 256 pixel, 3 Bq/pixel)
- m_β < 3.6 eV (2y, 16 pixel, 30 Bq/pixel)
  [Nucciotti, NuMass (2026)]

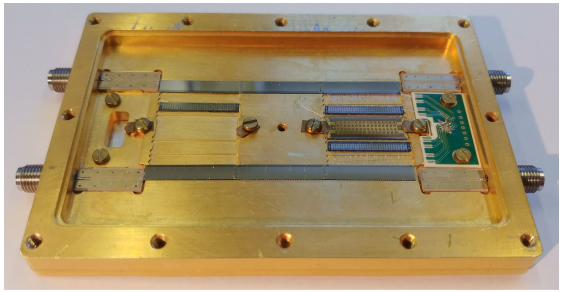
Goal:

- 0.3 MBq (1000 pixels) → 1 eV sensitivity
  [Borghesi et al., *Nucl.Instrum.Meth.A* 1051 (2023) 168205]



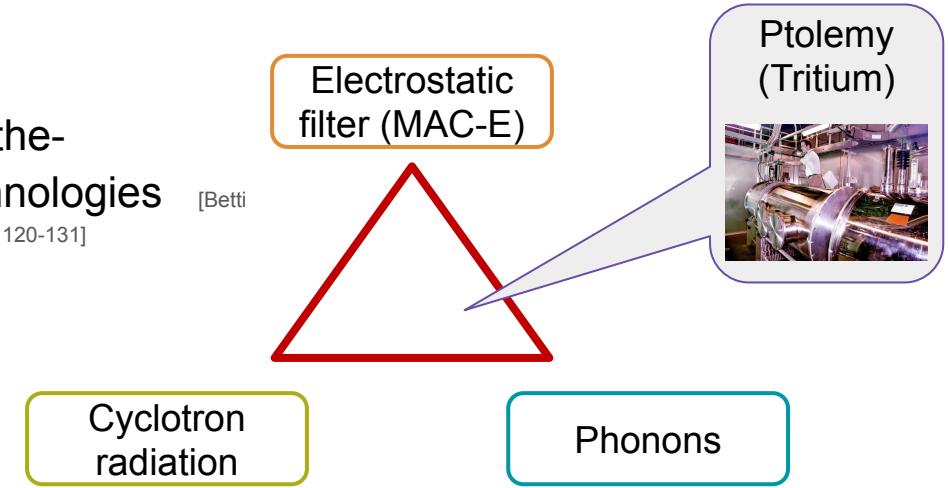


64 pixel detector: ~0.5 Bq activity/pixel



Experimental approaches

- Science goal:
  Search for **Big Bang neutrinos**
  [Betts et al, arXiv:1307.4738]
- Sensitivity to neutrino mass of
  m_β **< 10 meV**
  [Betti et al., *JCAP* 07 (2019) 047]
- Combined beyond-the-state-of-the-art technologies [Betti et al., *Prog.Part.Nucl.Phys.* 106 (2019) 120-131]

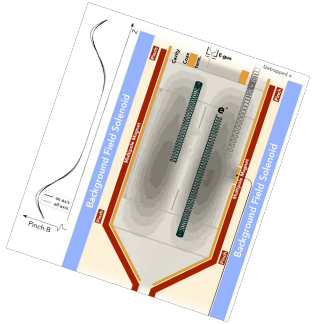


Summary



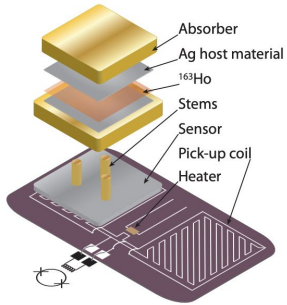
KATRIN

- Leading direct limit: m_β **< 0.45 eV** with 259 measurement days
- Final 1000 day dataset on disk → aiming for data release in 2027
- eV-scale sterile neutrino search: challenges anomalies
- Preparation for keV-scale sterile neutrino search



Cyclotron Radiation Emission Spectroscopy (CRES): Project-8 & QTNM

- First neutrino mass limit m_β < 150 eV (Project-8)
- Next step: scaling up to large-volume traps, develop atomic tritium source



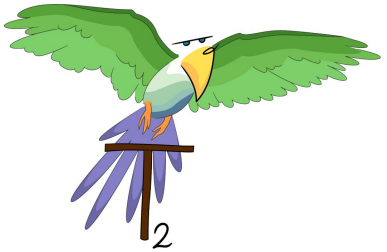
Microcalorimeter (MMC, TES): ECHo, Holmes & KATRIN++

- New limits m_β < 15 eV (ECHo) and m_β < 27 eV (Holmes)
- Next step: scaling up to high-activity and large number of detectors

Thank you

and thanks to the KATRIN collaboration
and the ECHo, Holmes, Project-8,
Ptolemy and QTNM collaboration





KATRIN collaboration meeting, April 2026, Heidelberg