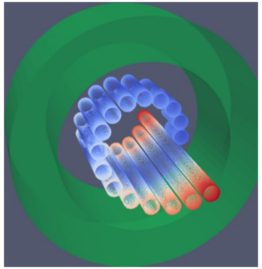
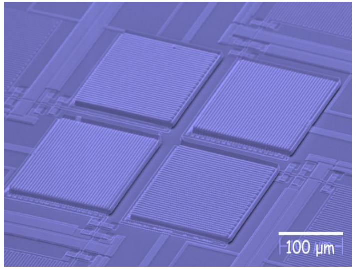
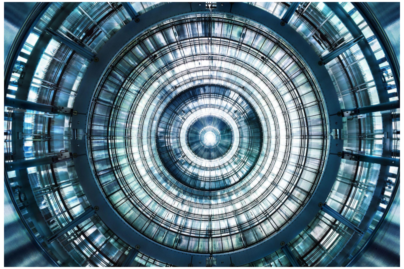


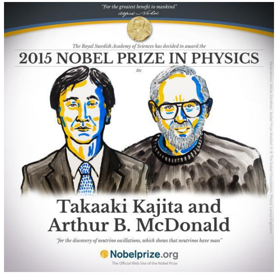




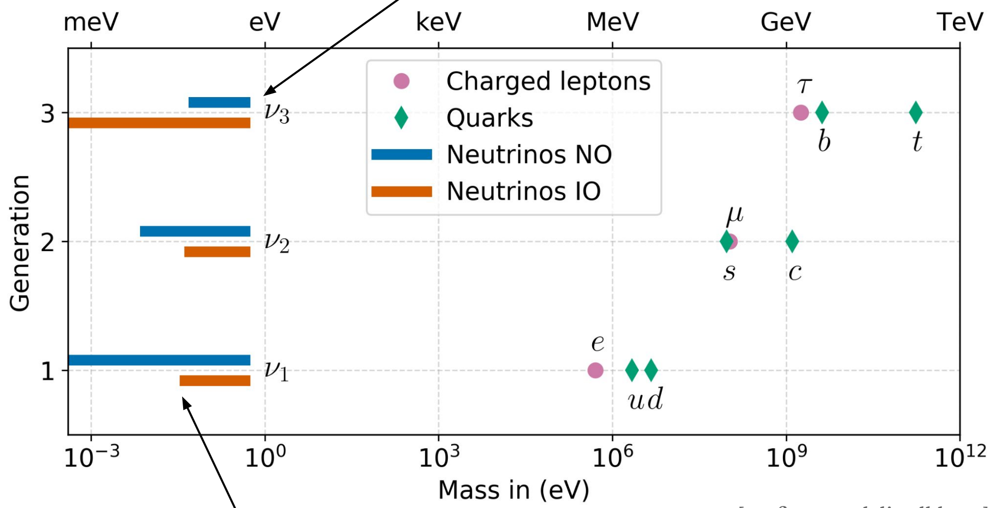
Direct Neutrino Mass Measurement

Christoph Köhler (TUM), PIC 2024, 23.10.2024

Neutrino mass



Upper bound from direct measurements



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

Lower bound from oscillation experiments

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

Determination method

Neutrinoless ββ-decay

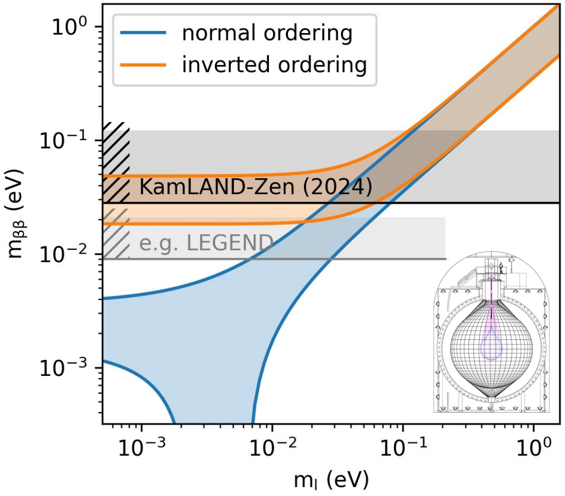
$$m_{\beta\beta} = |\sum_i U_{ei}^2 m_i|$$

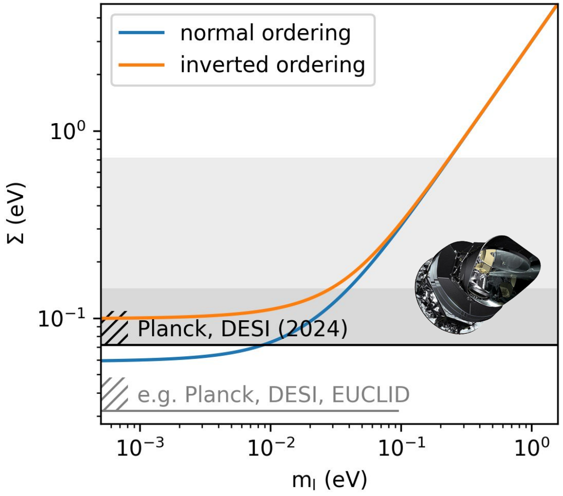
Cosmology

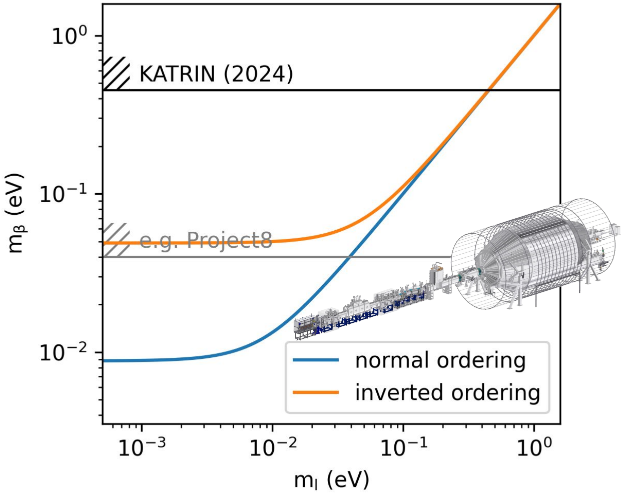
$$\Sigma = \sum_i m_i$$

β-decay kinematics

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



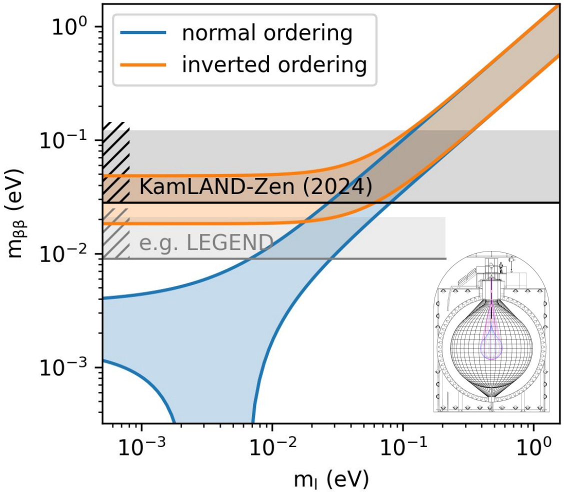




Neutrinoless ββ-decay

Neutrinoless ββ-decay

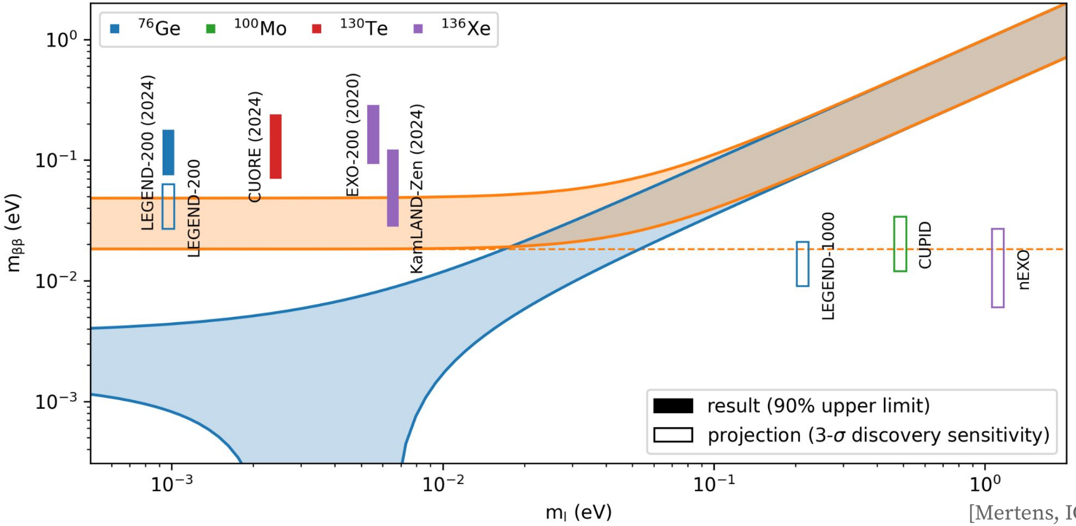
$$m_{\beta\beta} = |\sum_i U_{ei}^2 m_i|$$



World leading: KamLAND-Zen

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

- Majorana nature!?
- Nuclear matrix elements?



[Mertens, ICHEP 2024]

Neutrinoless ββ-decay

- Majorana nature!? Nuclear matrix elements?

Neutrinoless ββ-decay

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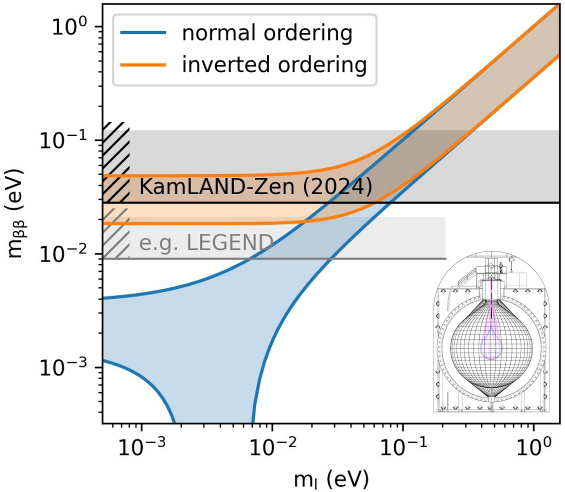
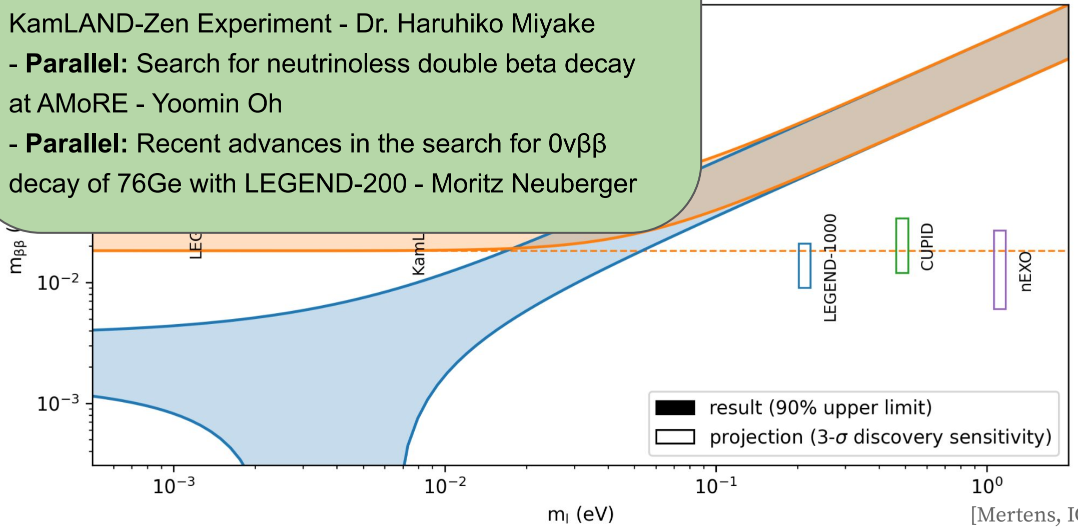


For more details see on Wednesday:

- **Plenary:** Neutrinoless Double Beta Decay: The Current Status and Future Prospects - Dr. Vivek Singh
- **Parallel:** Latest Results and Future Prospects of the KamLAND-Zen Experiment - Dr. Haruhiko Miyake
- **Parallel:** Search for neutrinoless double beta decay at AMoRE - Yoomin Oh
- **Parallel:** Recent advances in the search for 0νββ decay of 76Ge with LEGEND-200 - Moritz Neuberger



[Mertens, ICHEP 2024]

Cosmology

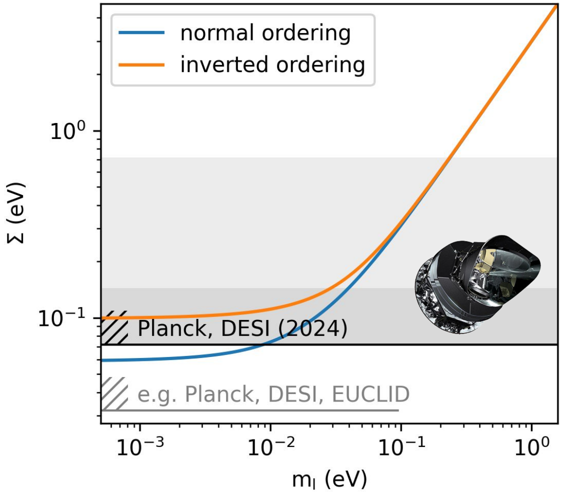
- Most stringent bound driven by Planck and DESI data
[Adame et al., arXiv:2404.03002]

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

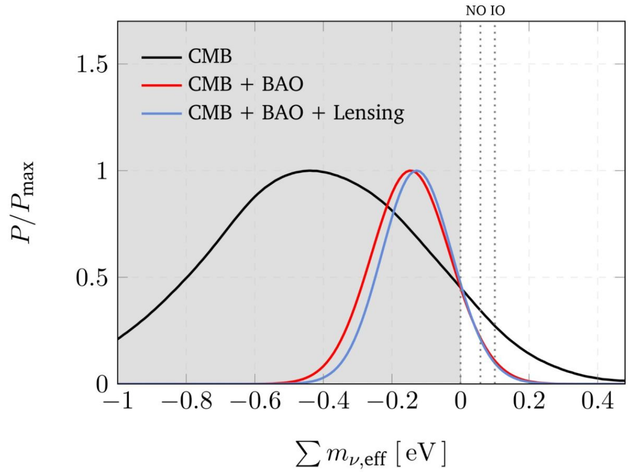
- Model dependence can weaken bounds

Cosmology

$$\Sigma = \sum_i m_i$$



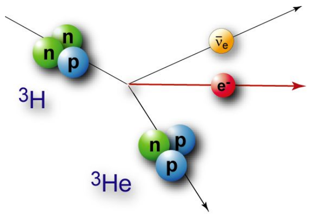
Introducing effective neutrino mass → ~3σ tension



[Elbers, Neutrino 2024]

β-decay* kinematics

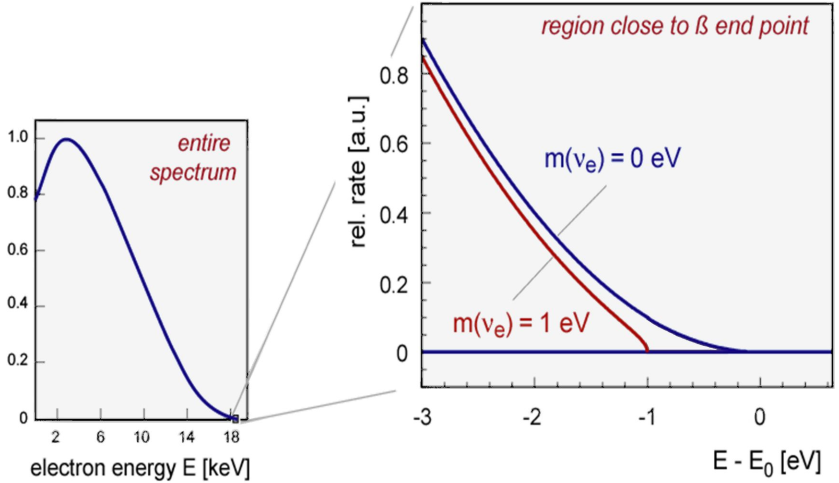
* or electron capture

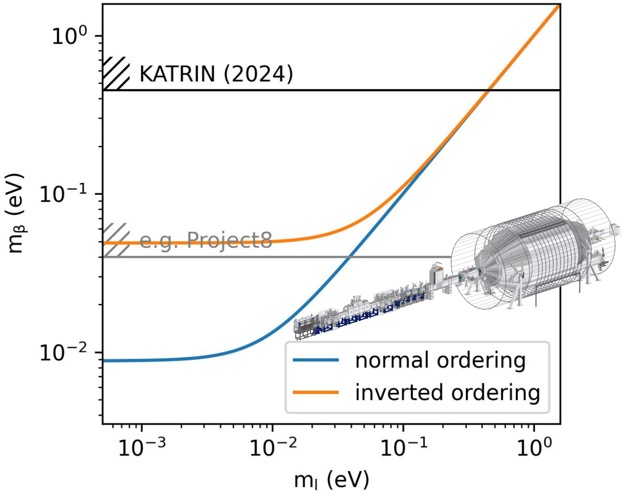


- Independent of cosmology
- Independent of neutrino nature

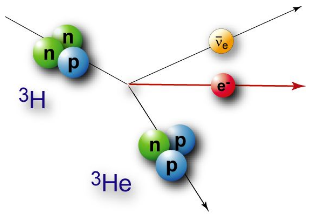
β-decay kinematics

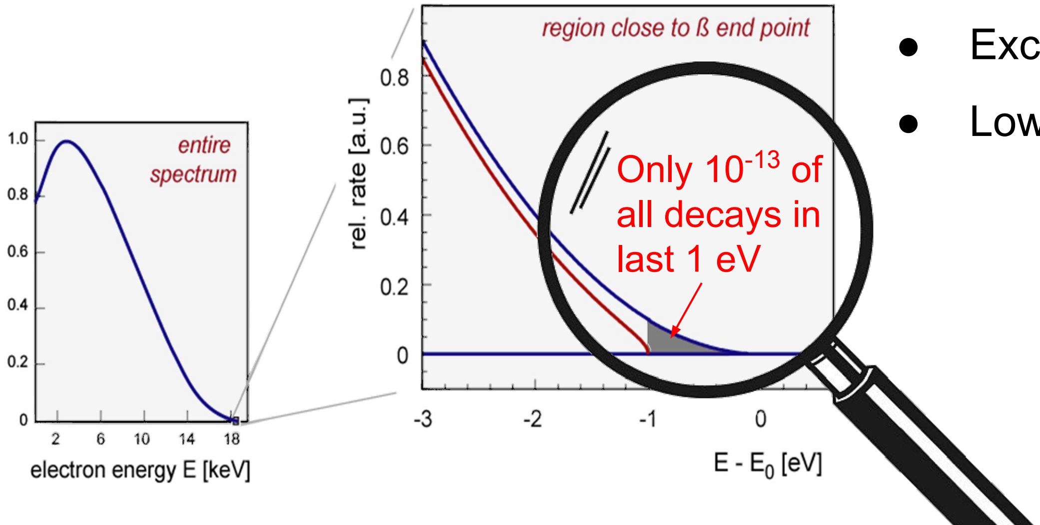
$$m_\beta = \sqrt{\sum_i |U_{ei}^2| m_i^2}$$





The challenge

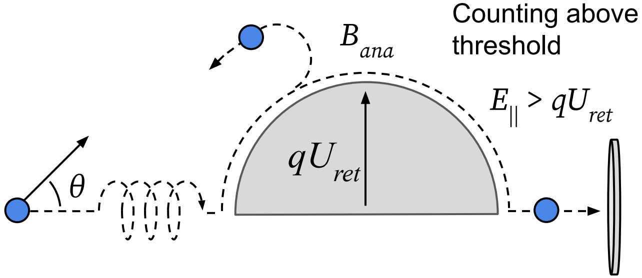




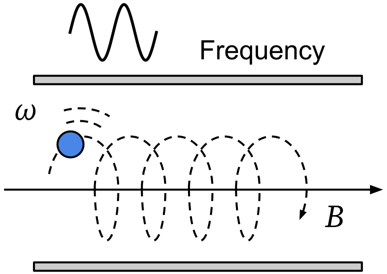
<u>Key requirements:</u>

- Strong β-decaying source
  - Tritium: **12.3 years, E_0 = 18.6 keV**
  - Holmium: **4500 years, E_0 = 2.8 keV**
- Excellent energy resolution (1 eV)
- Low background (< 100 mcps)

Experimental approaches

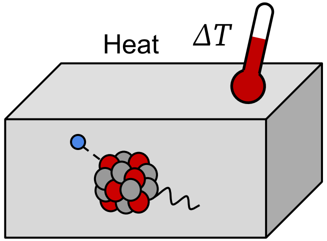


Electrostatic filter (MAC-E)

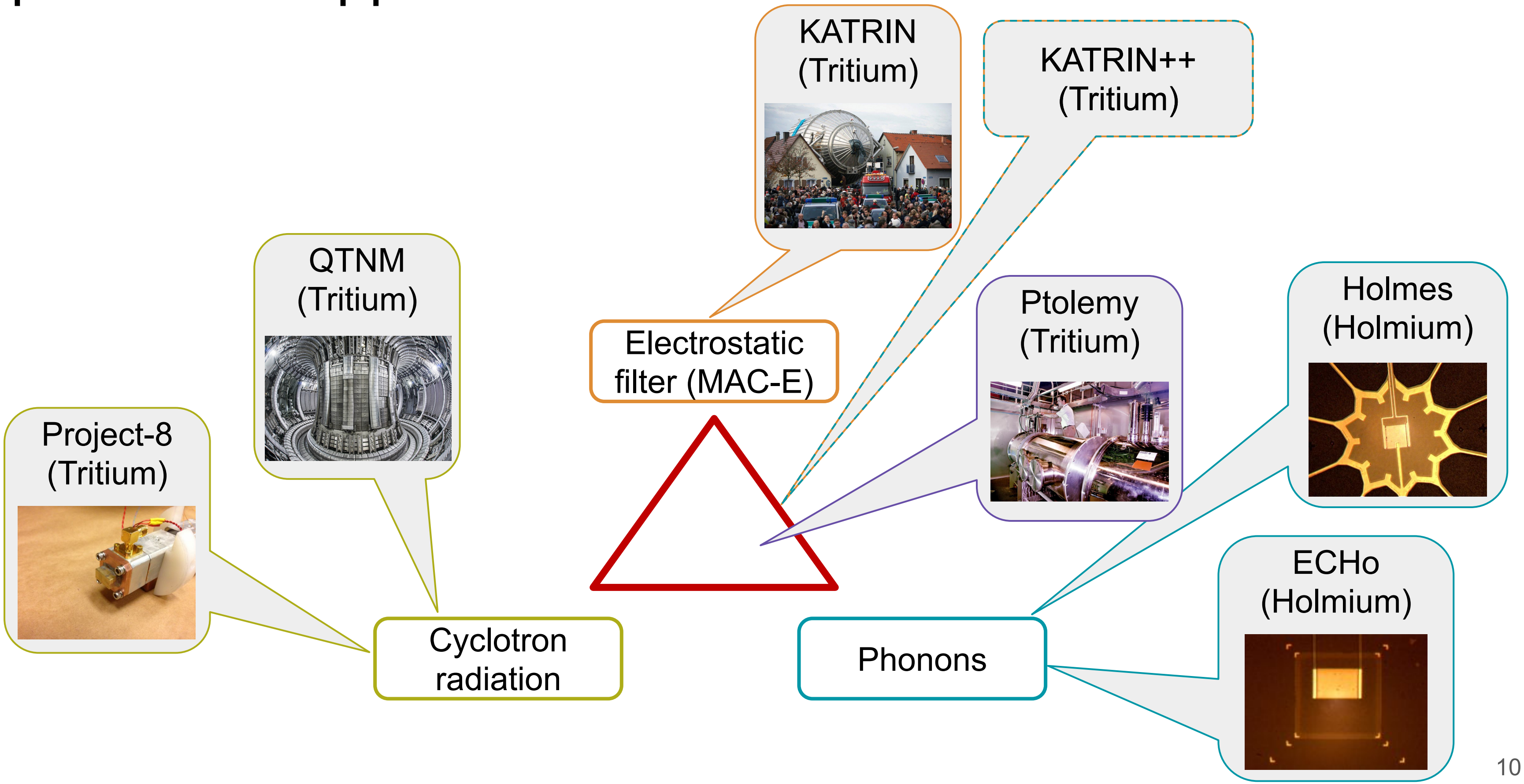


Cyclotron radiation

Phonons



Experimental approaches



Experimental approaches

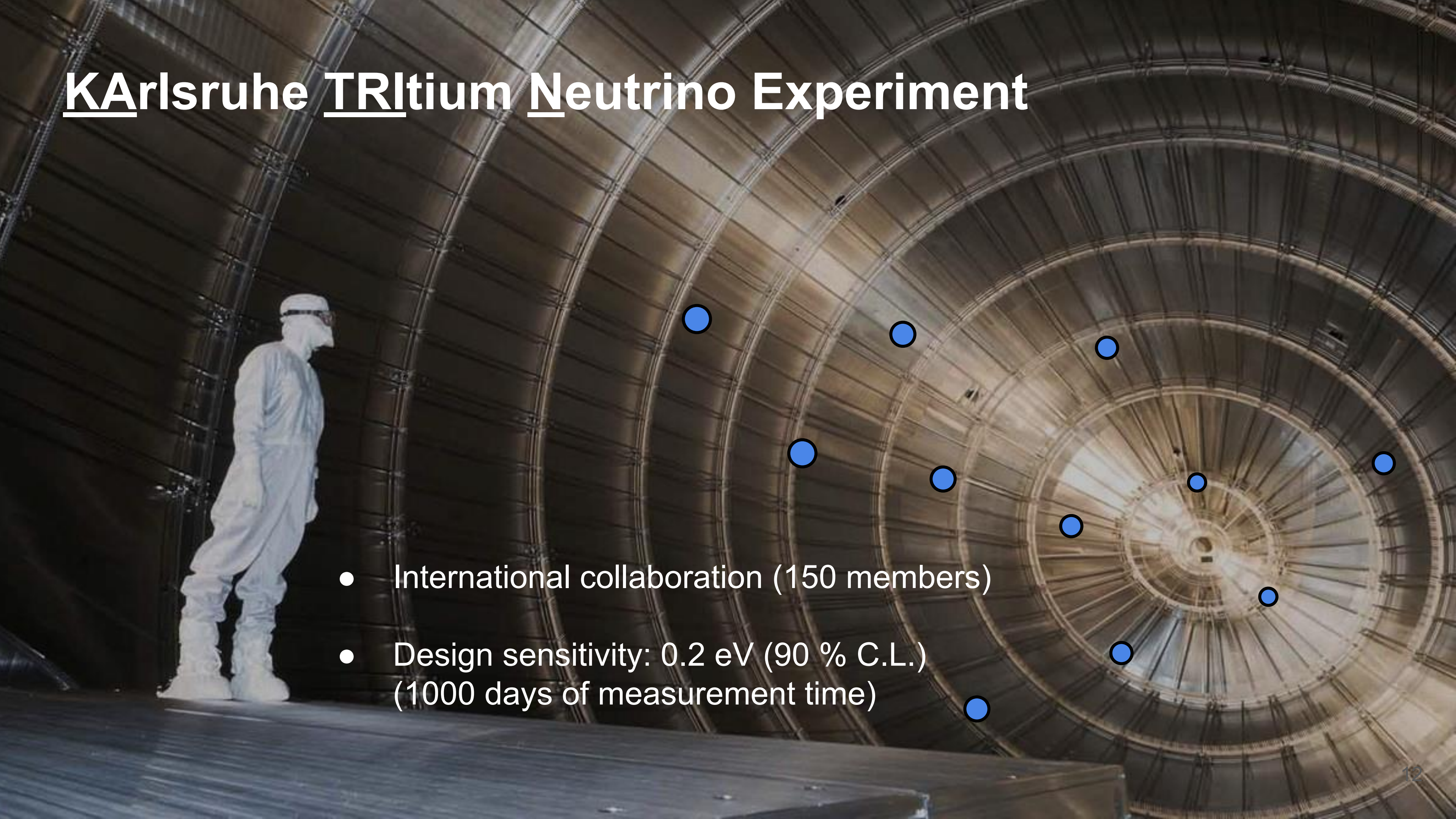
KATRIN
(Tritium)

Electrostatic filter (MAC-E)

Cyclotron radiation

Phonons

KArlsruhe TRItium Neutrino Experiment



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

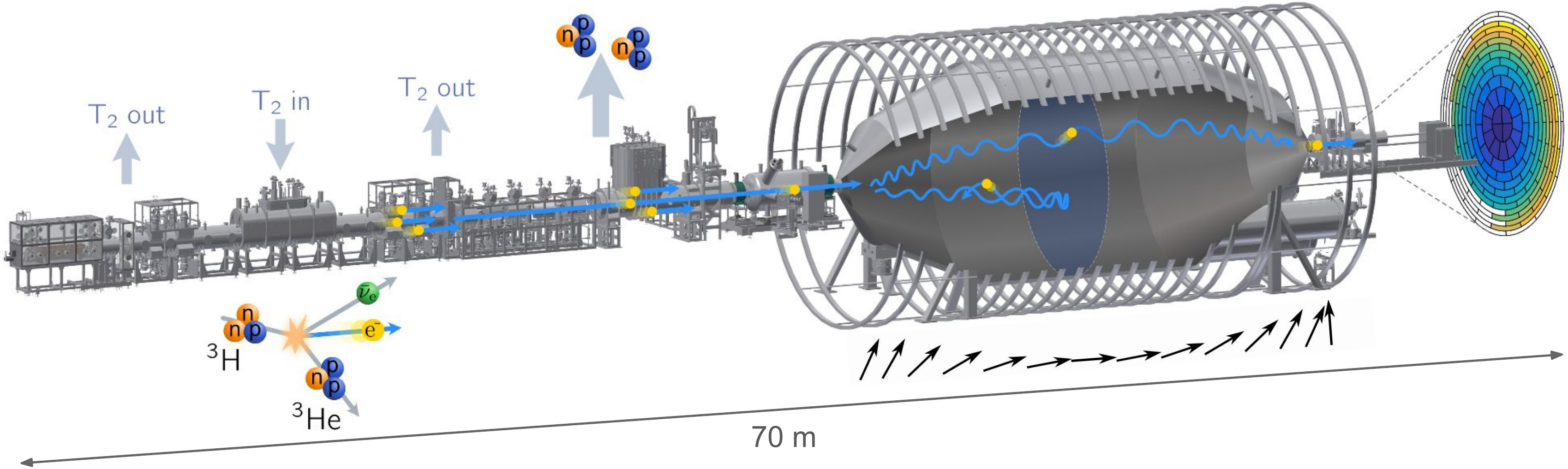
Experimental overview

Windowless gaseous tritium source
- 30 µg molecular tritium in closed loop
- **10^{11} T_2 decay/s**

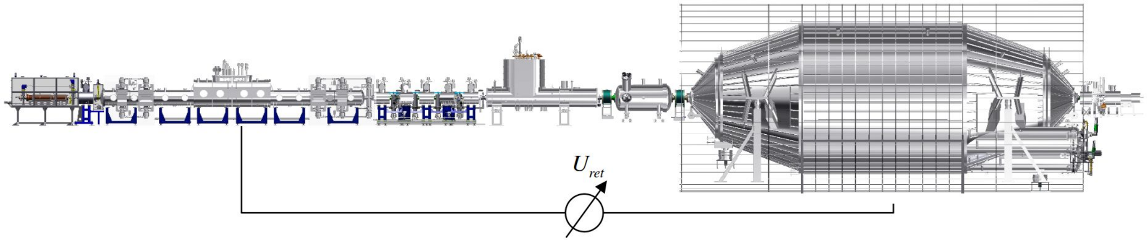
Transport section
- Tritium gas/ion removal > **10^{14}**

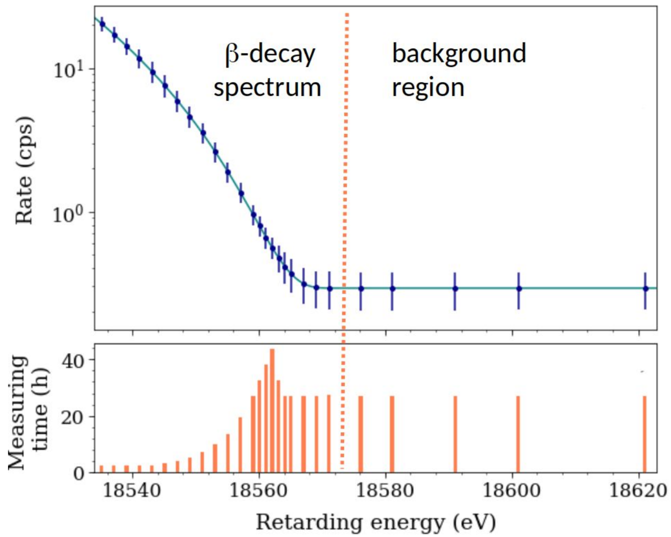
Spectrometer
- MAC-E filter principle
- High resolution: **O(1) eV**

Detector
- Focal plane detector, **148 pixel** PIN-diode
- Counts electrons



Measurement strategy

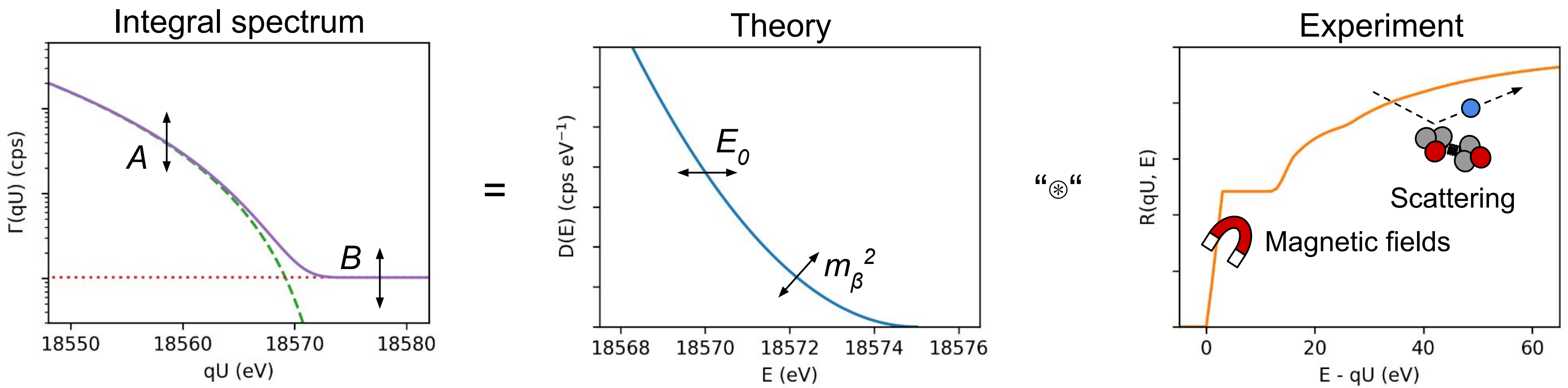




- ~30 HV set points with varying duration
- Scan interval: E_0 - 40 eV, E_0 + 135 eV
- 2-3 h scan time
- Several campaigns per year with O(100) scans

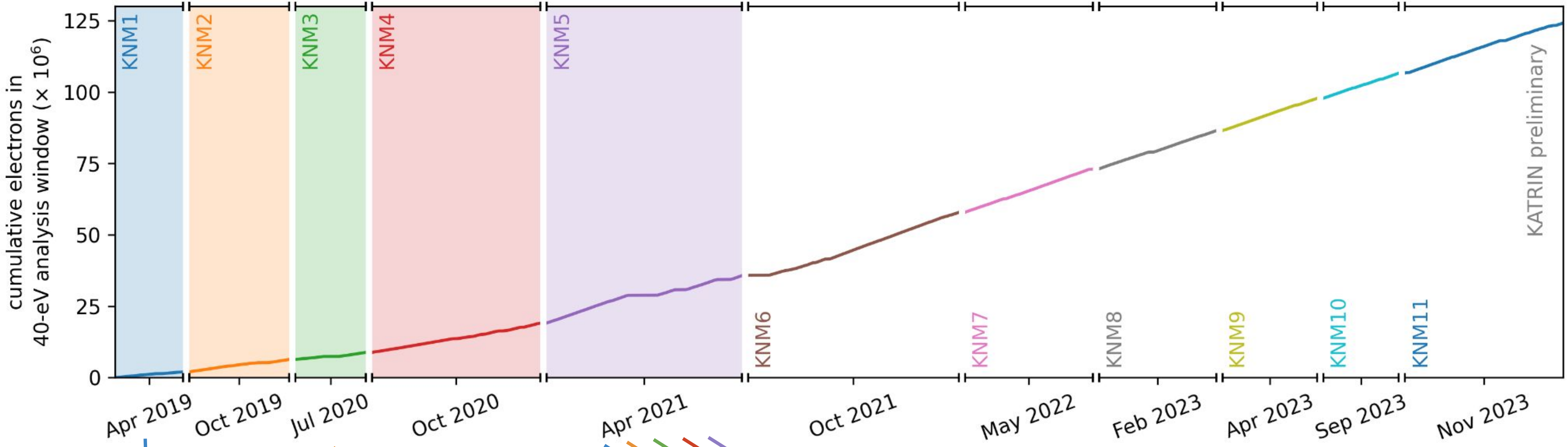
Analysis strategy

- 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)

Data taking overview



1st m_ν campaign

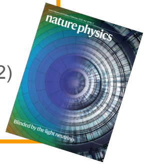
m_ν < 1.1 eV

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

1st & 2nd campaign

m_ν < 0.8 eV

Nat. Phys. 18, 160–166 (2022)



1st to 5th campaigns

m_ν < 0.45 eV

arXiv:2406.13516

Will be published soon

New KATRIN result

Data set:

- 250 days of data (5 campaigns)

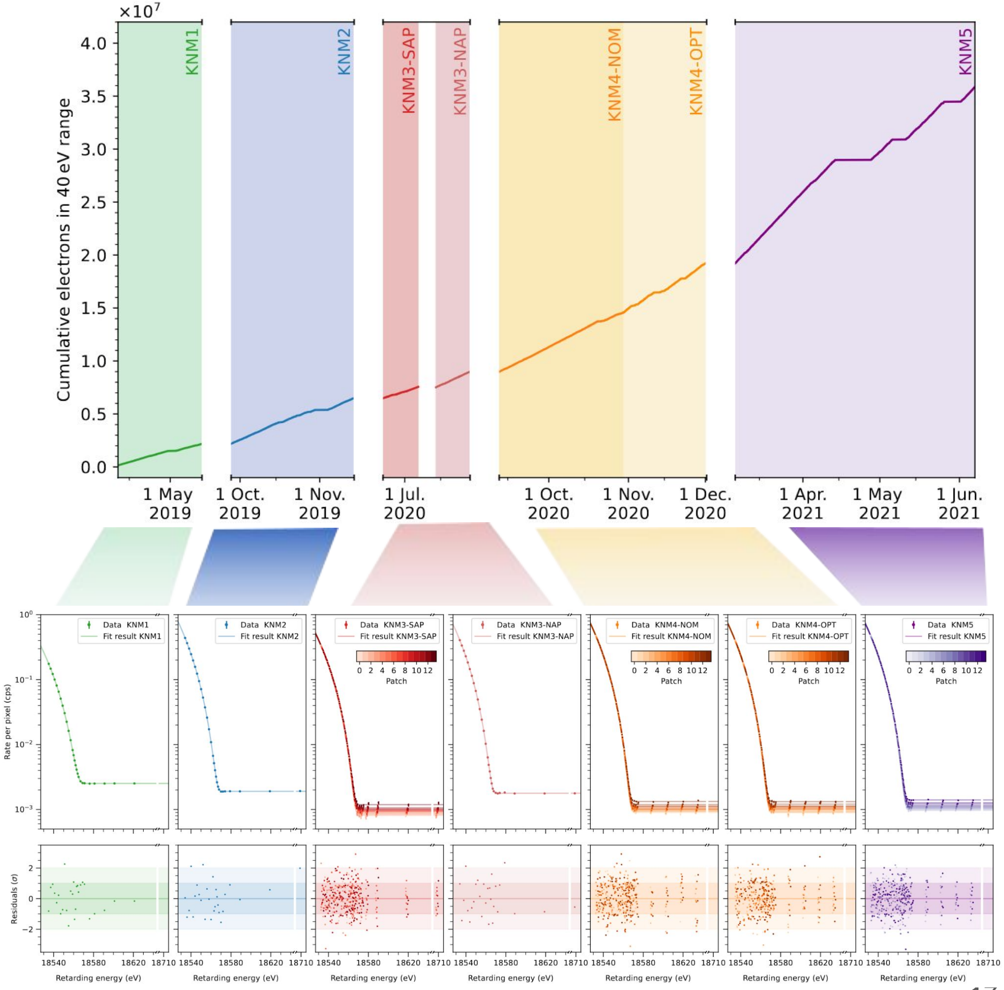
Result:

- Best fit: $m_\nu^2 = -0.14^{+0.13}_{-0.15}$ eV^2 (stat. dom.)
- New limit: $m_\nu < 0.45$ eV (90% CL)

Neutrino-24 (2024), arXiv:2406.13516 (2024)

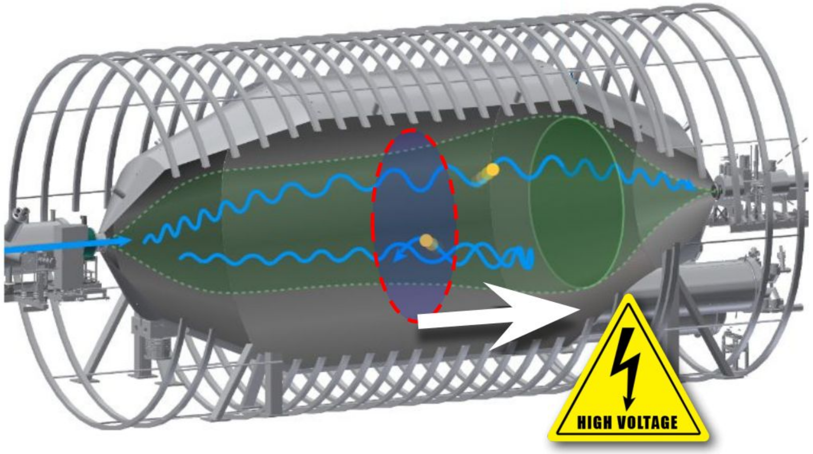
Final goal (in 2026):

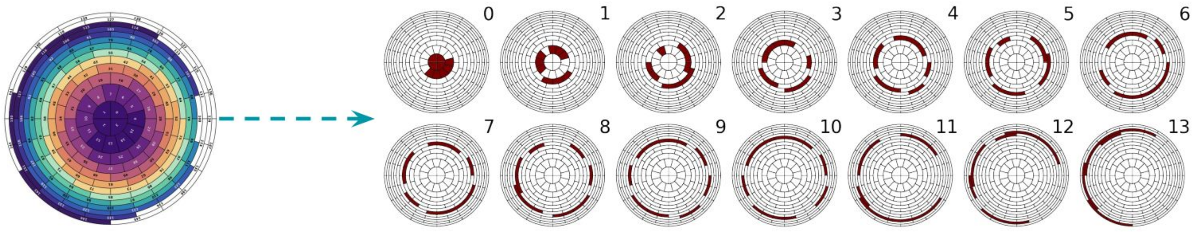
- < 0.3 eV sensitivity



Experimental improvements

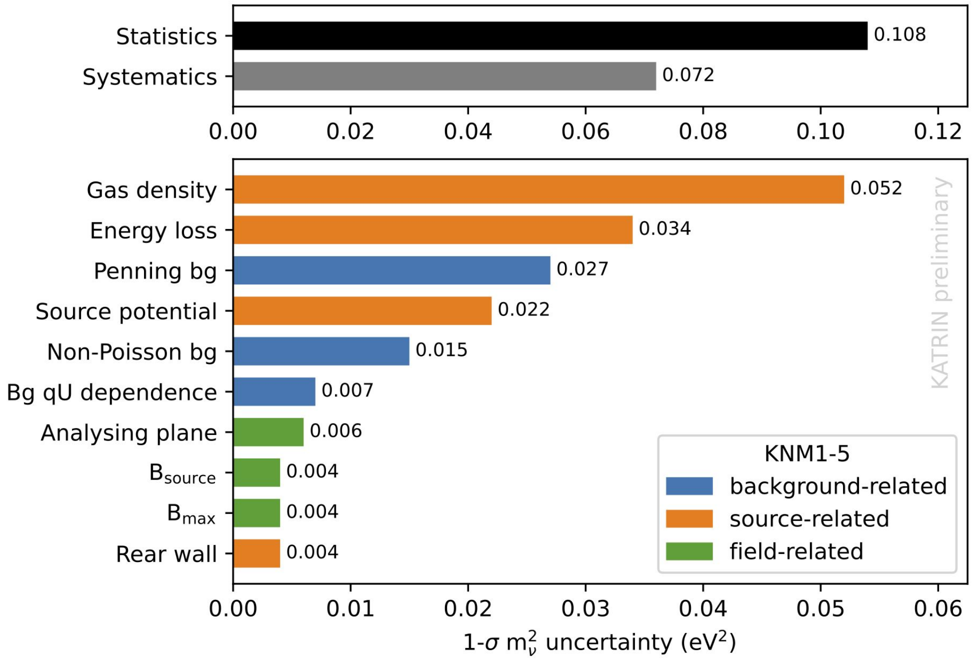
- **Background reduction by a factor of 2** with "shifted analyzing plane" configuration
- Mapping of smaller volume on detector
- Inhomogeneous EM-fields
  - Segmentation in **14** patches
  - Calibration of fields needed



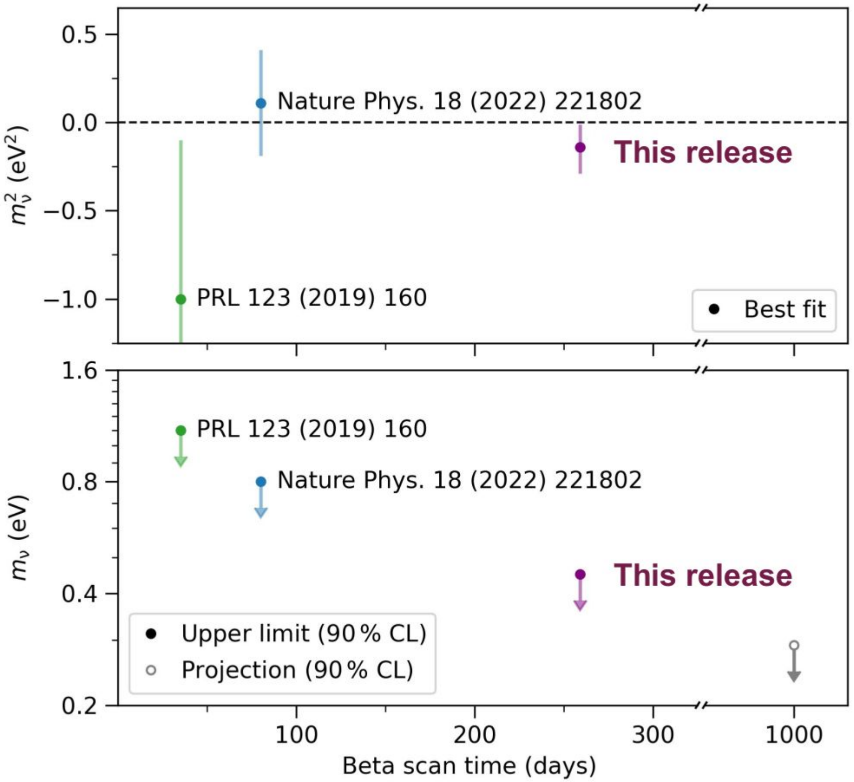


Systematic uncertainties

- Statistical uncertainties dominate
- Significant reduction of **background-related** systematics
- **Source-related** uncertainties reduced in current data



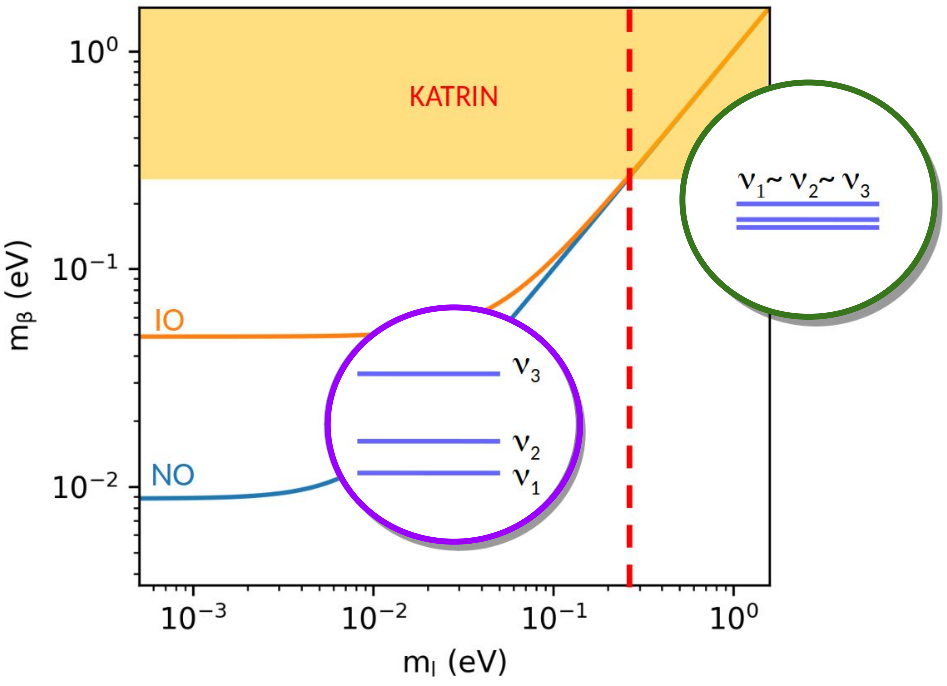
KATRIN results



- New KATRIN release improves direct neutrino-mass bound by a factor of 2: $m_v < 0.45$ eV (90% CL)

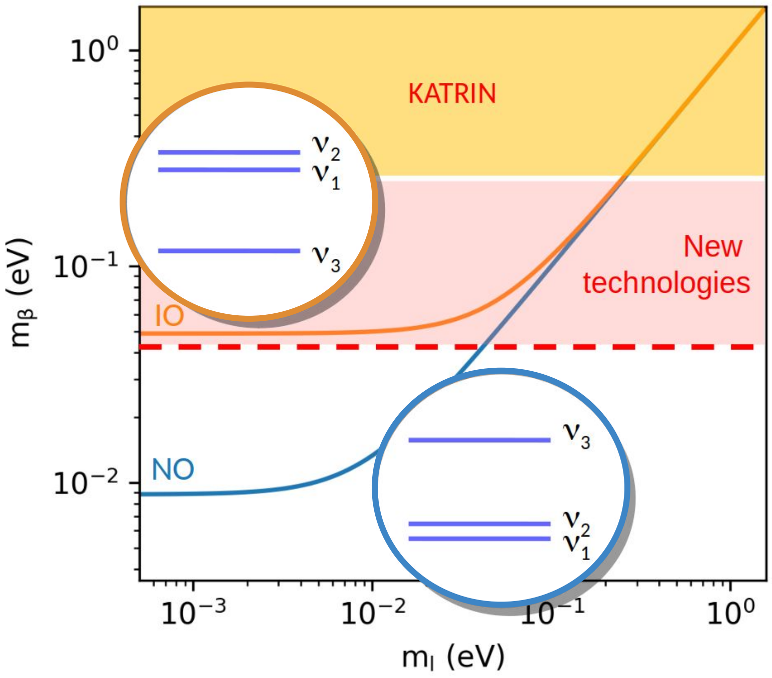
- Final result:
  - based on 1000 days of data taking (completed end of 2025)
  - sensitivity better than $m_v < 0.3$ eV

Going beyond KATRIN



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

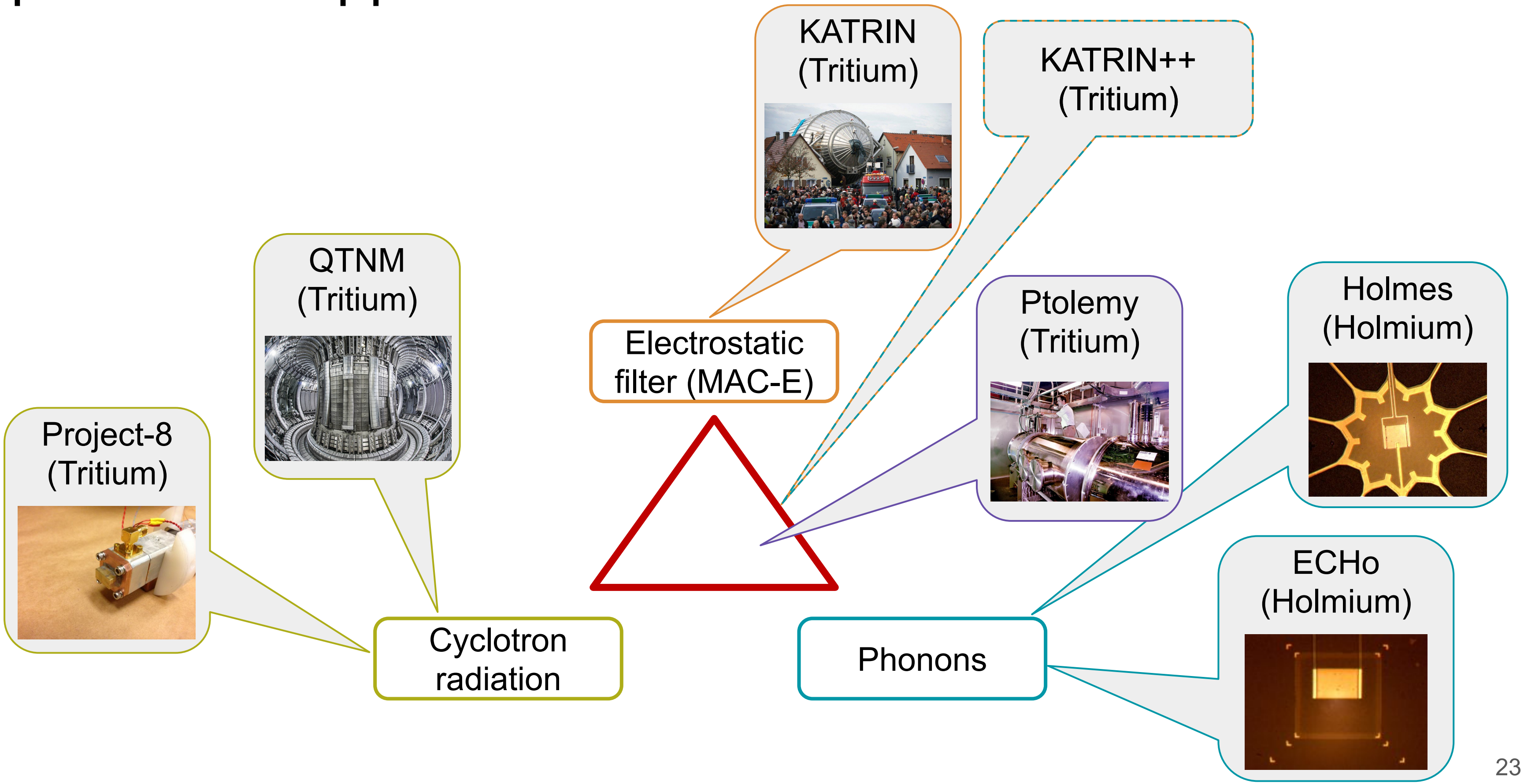
Going beyond KATRIN



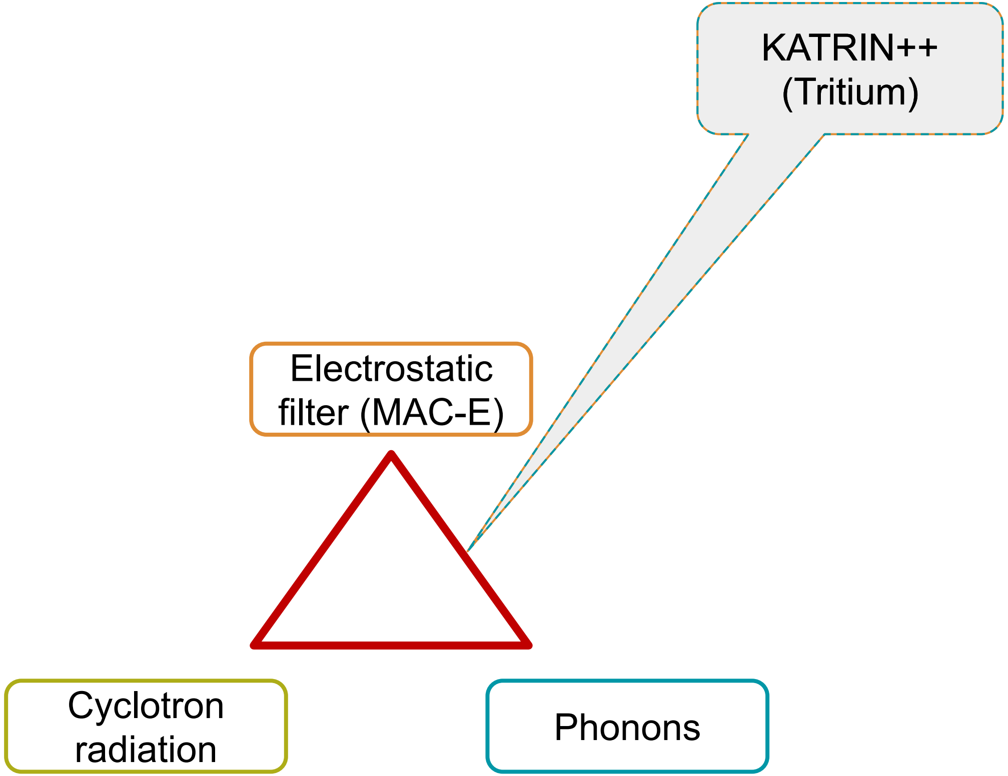
- KATRIN final: < **0.3 eV** (90% CL)
  Distinguish between **degenerate** and **hierarchical** scenario

- New technologies: < **0.05 eV**
  Cover **inverted ordering**

Experimental approaches



Experimental approaches



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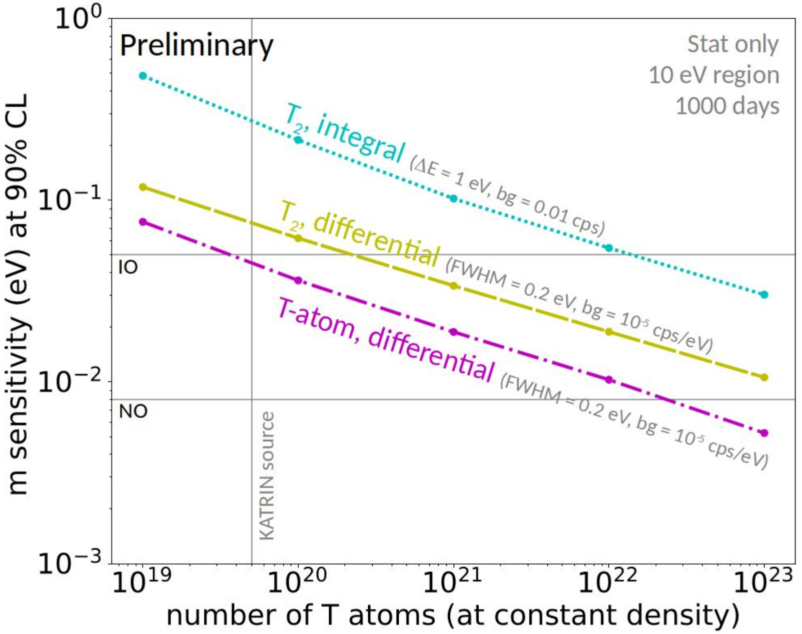
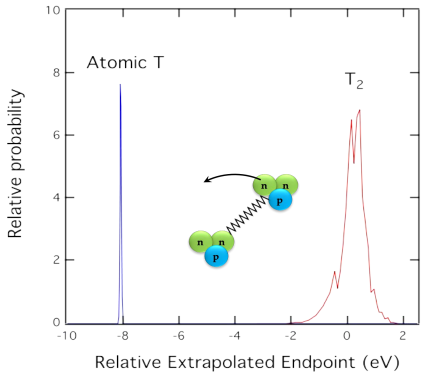


- Differential measurement (FWHM < 1 eV)
  - Better use of statistics ✅
  - Lower background ✅
- Atomic tritium
  - Avoid broadening (~ 1eV) ✅
  - Avoid limiting systematics of T_2 ✅



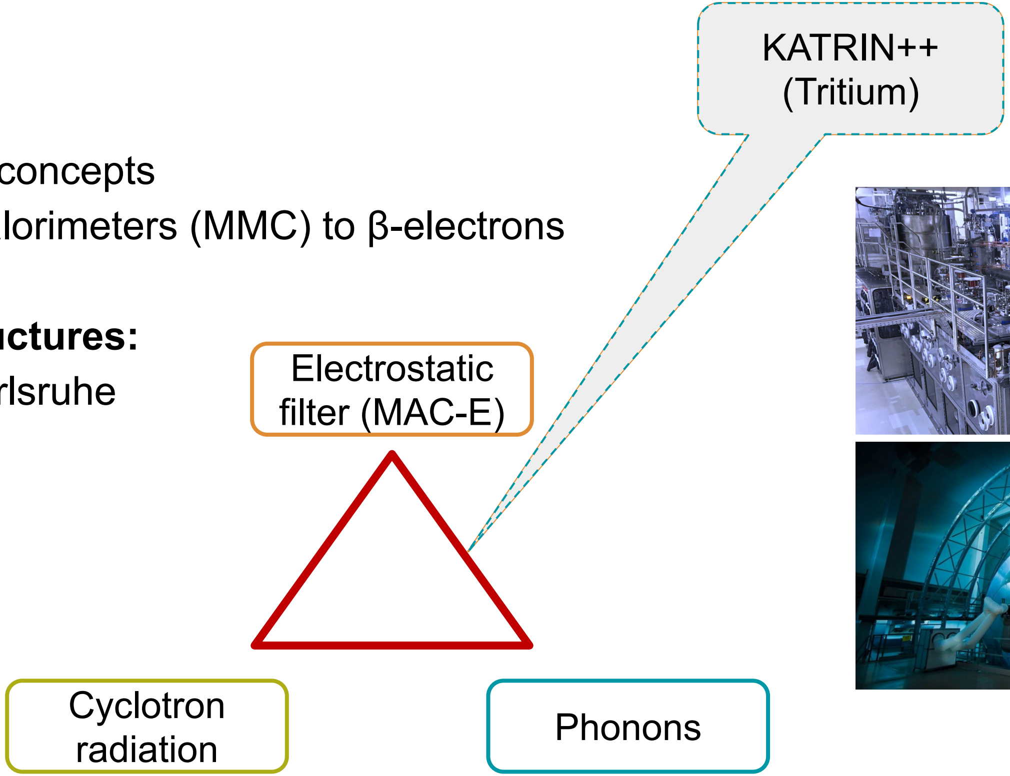
Experimental approaches

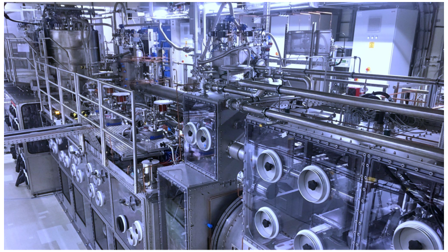
R&D launched:

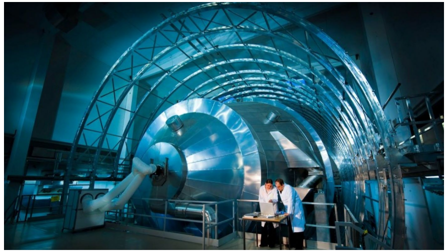
- Atomic tritium source concepts
- Application of microcalorimeters (MMC) to β-electrons

Leverage unique infrastructures:

- Tritium Laboratory Karlsruhe
- KATRIN beamline







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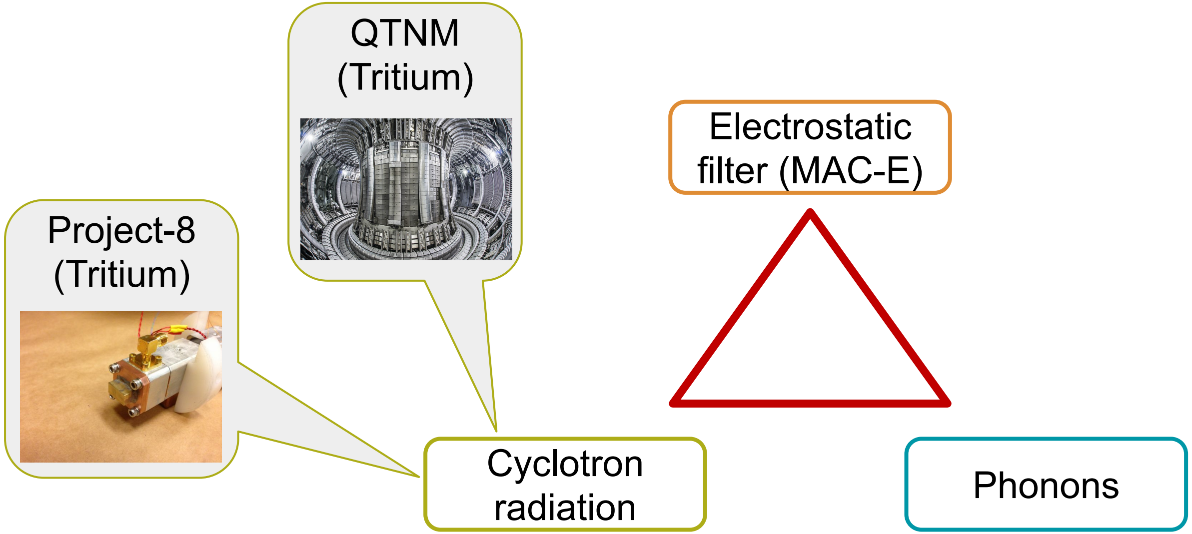


Cyclotron Radiation Emission Spectroscopy (CRES)

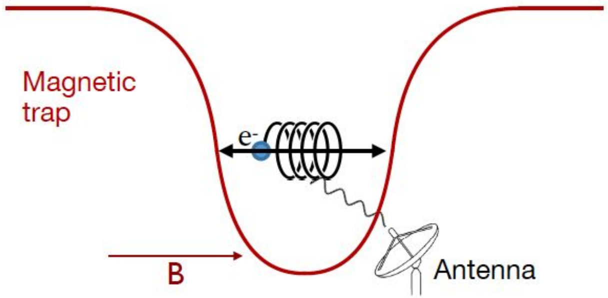
- Precise frequency measurement: $$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{\boldsymbol{E} + m_e}$$

Advantages:

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

Challenges:

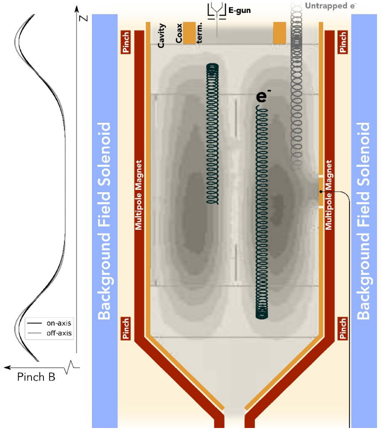
- Weak signal: ~1fW
- B-field homogeneity at the 10^{-7} level
- Large volume (~m^3) atomic trap for < 0.04 eV sensitivity
- …



Experiments

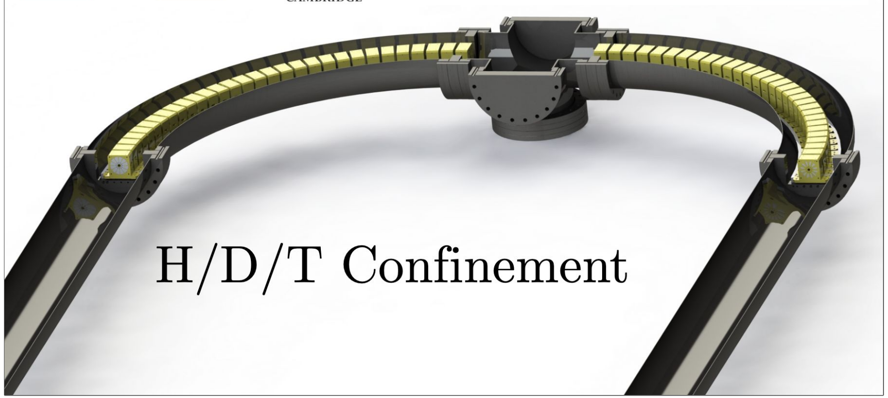
Project-8

- Cavity CRES + cold atomic tritium trap



QTNM

- Storage ring confinement
- New effort, conceptual stage

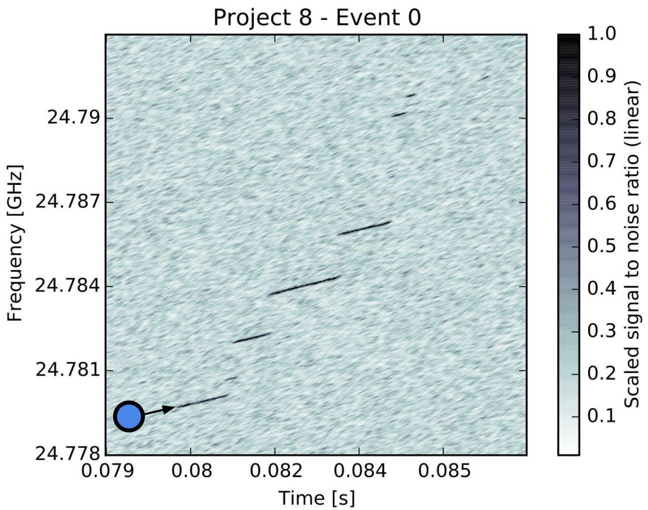


Project 8

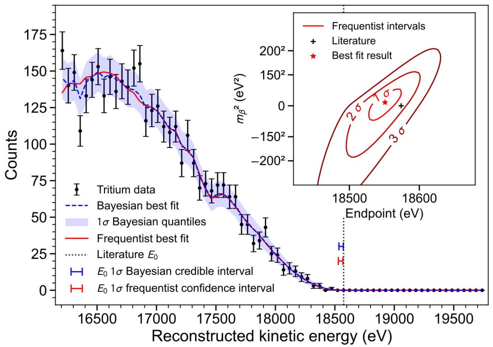
- Achievements:
  - Proof of CRES concept
    D.M. Asner et al., Phys. Rev. Lett. 114, 162501 (2015)
  - First neutrino mass limit: m_ν < 155 eV (90% CL)
    A. Ashtari Esfahani *et al.*, Phys. Rev. Lett. 131, 102502 (2023)

- Next steps /challenges:
  - large-volume (m^3) cavity resonator
  - development of atomic tritium source

- Ultimate goal to cover inverted ordering:
  40 meV sensitivity arXiv:2203.07349 (2022)



waveguide



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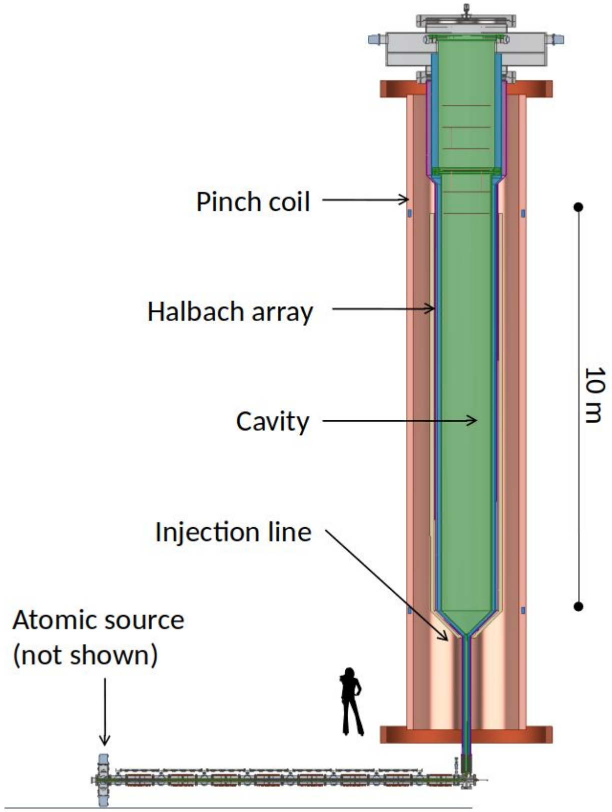

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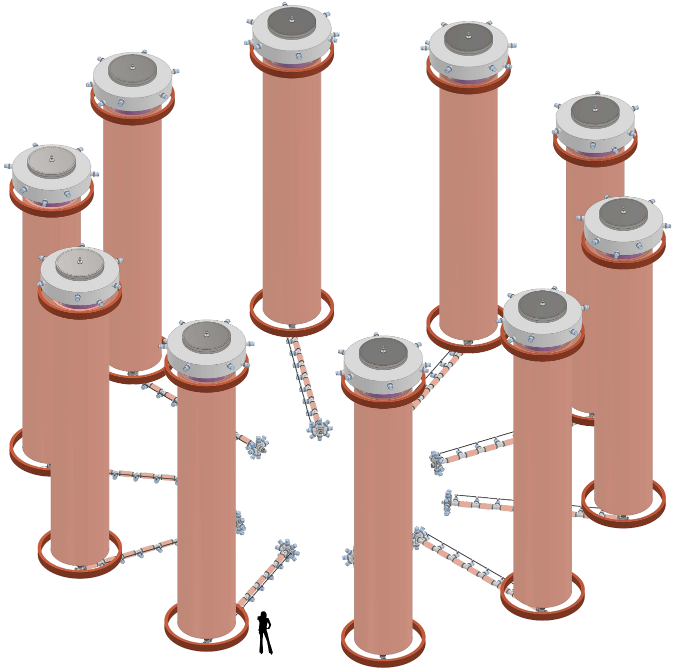
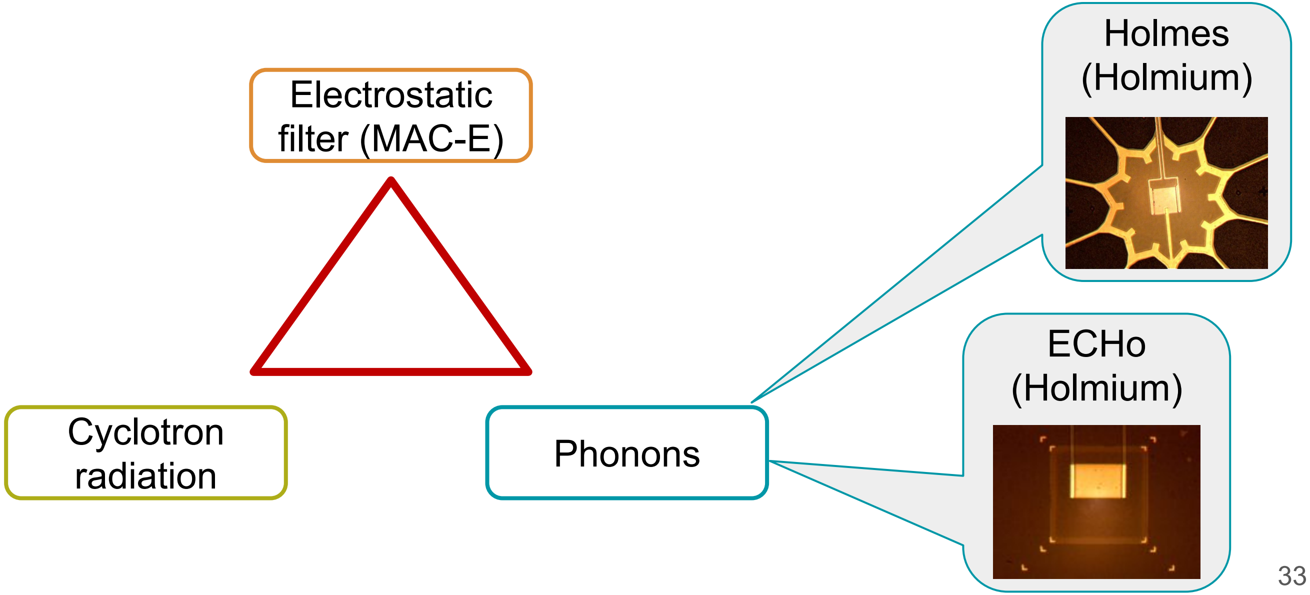


Experimental approaches



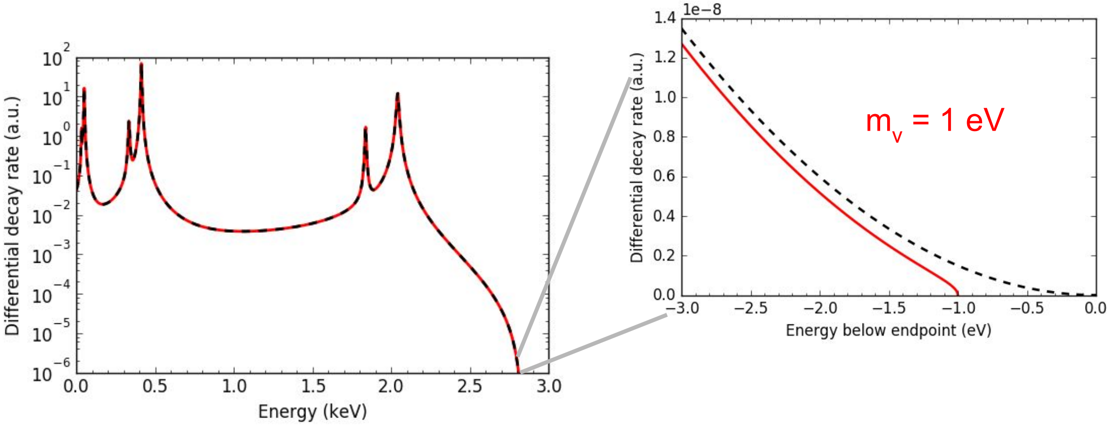
Working principle

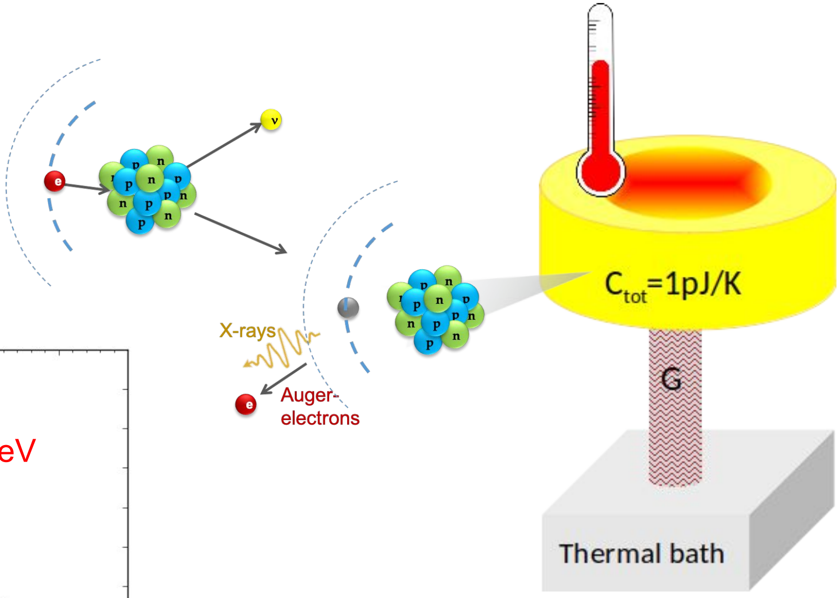
Low-temperature micro-calorimetry with holmium

A. De rujula and M. Lusignoli, *Phys. Lett.* **118B** (1982)

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

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





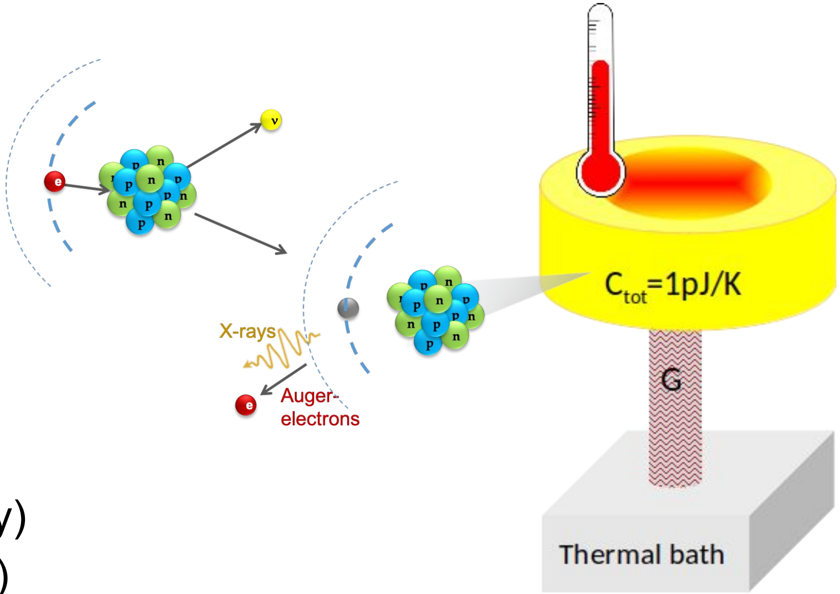
Working principle

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

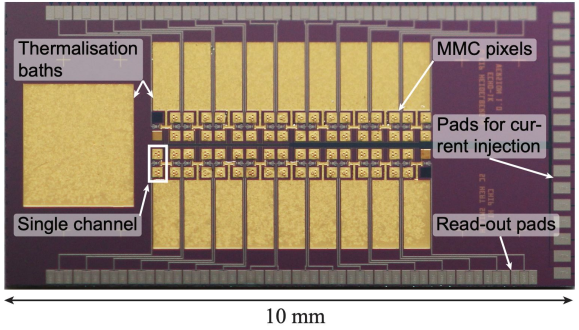


Experiments

ECHo

- Metallic magnetic calorimeters (MMC)

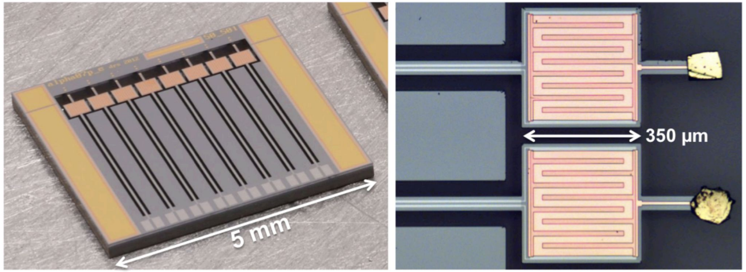
L. Gastaldo et al. Eur. Phys. J. Spec. Top. 226 (2017)



Holmes

- Transition edge sensors (TES)

J Low Temp Phys **184**, 492-497 (2016)



ECHo

Achievements

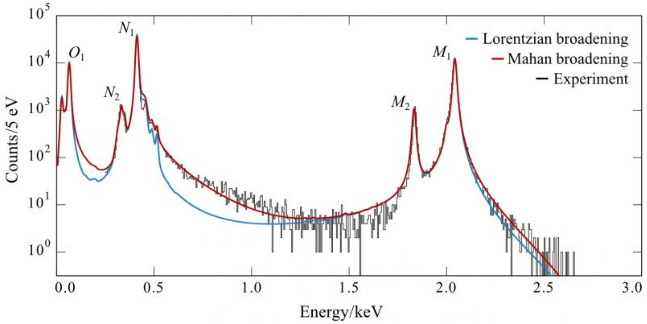
- **Prototype**: m_v < 150 eV (95% CL)
  EPJ-C 79 1026 (2019)
- **ECHo-1k:** m_v < 19 eV (90% CL)
  ~1 Bq/pixel, 60 pixels, 10 eV FWHM
  Neutrino (2024)
- **ECHo-100k:** excellent performance demonstrated:
  ~10 Bq/pixel, 12000 pixels, 1 eV sensitivity
  Neutrino (2024)

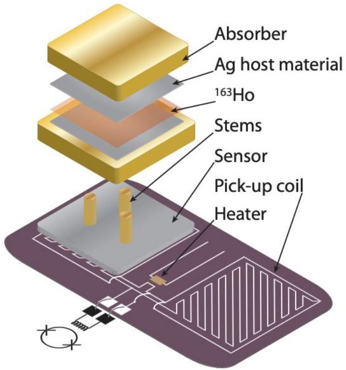
Next steps/challenges:

- Scaling up to more activity and pixels

Ultimate goal:

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





60 pixel, ~1 Bq each

Holmes

Achievements:

- **First result:** $m_\nu < 28$ eV (90% CL)
- 52 active pixels (64 total)
- <A> ≈ 0.3 Bq, ΔE_{FWHM} = ~4 eV @ 6 keV

Neutrino (2024)

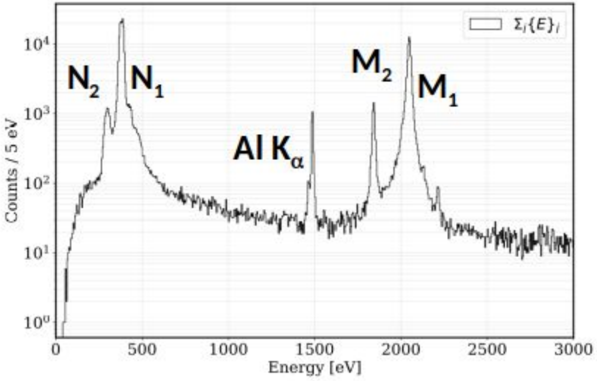
Next steps/challenges:

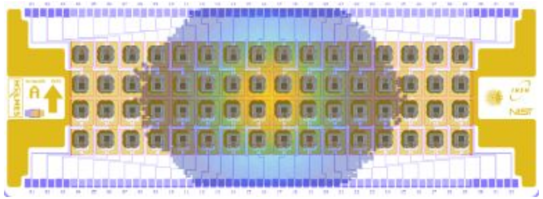
- Scaling to more activity and pixels

Goal:

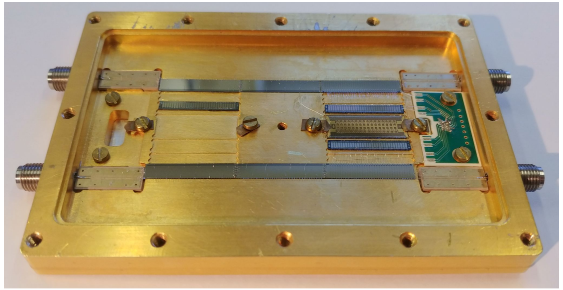
- 0.3 MBq (1000 pixels) → 1 eV sensitivity

Nuclear Inst. and Methods in Physics Research, A 1051 (2023) 168205



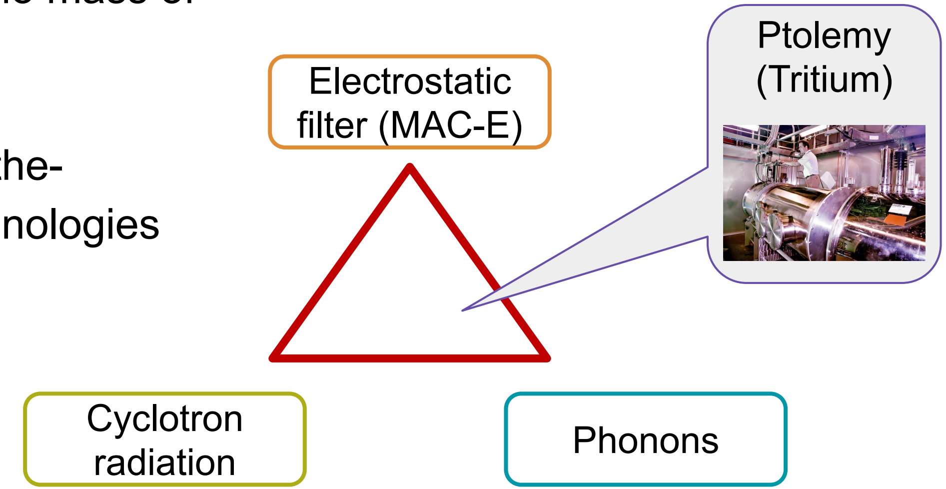


64 pixel detector: ~0.5 Bq activity/pixel



Experimental approaches

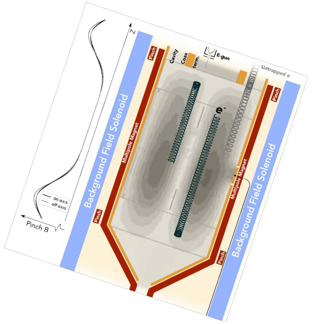
- Science goal:
  Search for **Big Bang neutrinos**
  arXiv:1307.4738 [astro-ph.IM]
- Sensitivity to neutrino mass of
  $m_\nu < 10$ meV
  JCAP 07 (2019) 047
- Combined beyond-the-state-of-the-art technologies
  PPNP 106, 2019, 120-131



Summary

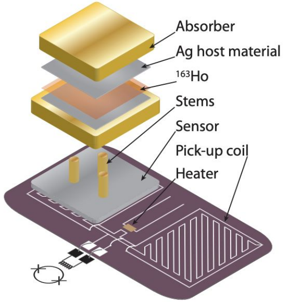
KATRIN

- Leading neutrino mass limit (m_v < 0.45 eV) from direct measurements
- Final goal: sensitivity m_v < 0.3 eV



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

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

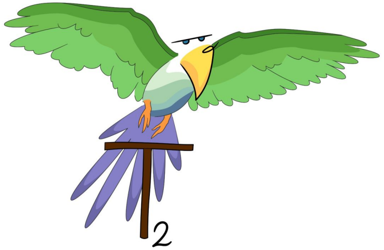


Microcalorimeter (MMC, TES): ECHo, Holmes & KATRIN++

- New limits m_v < 19 eV (ECHo) and m_v < 28 eV (Holmes)
- Next step: scaling up to high-activity and large number of detectors

Thank you

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



Collaboration meeting, October 2024, Karlsruhe

KIT Karlsruher Institut für Technologie
MIT
BERKELEY LAB
Humboldt-Universität zu Berlin
Nuclear Physics Institute
cea
TUM
BERGISCHE UNIVERSITÄT WUPPERTAL
UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386
Max-Planck-Institut für Physik
THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL
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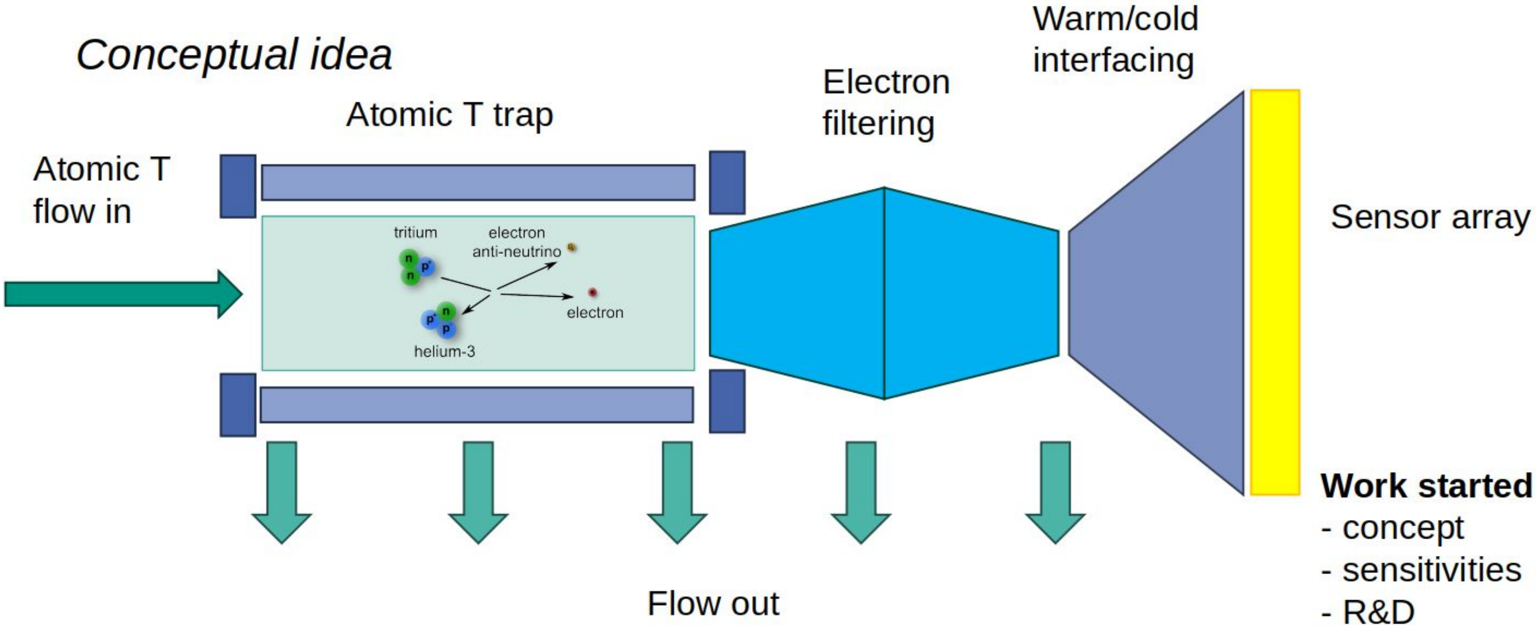
Chula Chulalongkorn University

Bundesministerium für Bildung und Forschung
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES
DFG
MAX PLANCK GESELLSCHAFT
U.S. DEPARTMENT OF ENERGY
Office of Science
Czech Republic: MŠMT MINISTRY OF EDUCATION, YOUTH AND SPORTS
erc
INFN

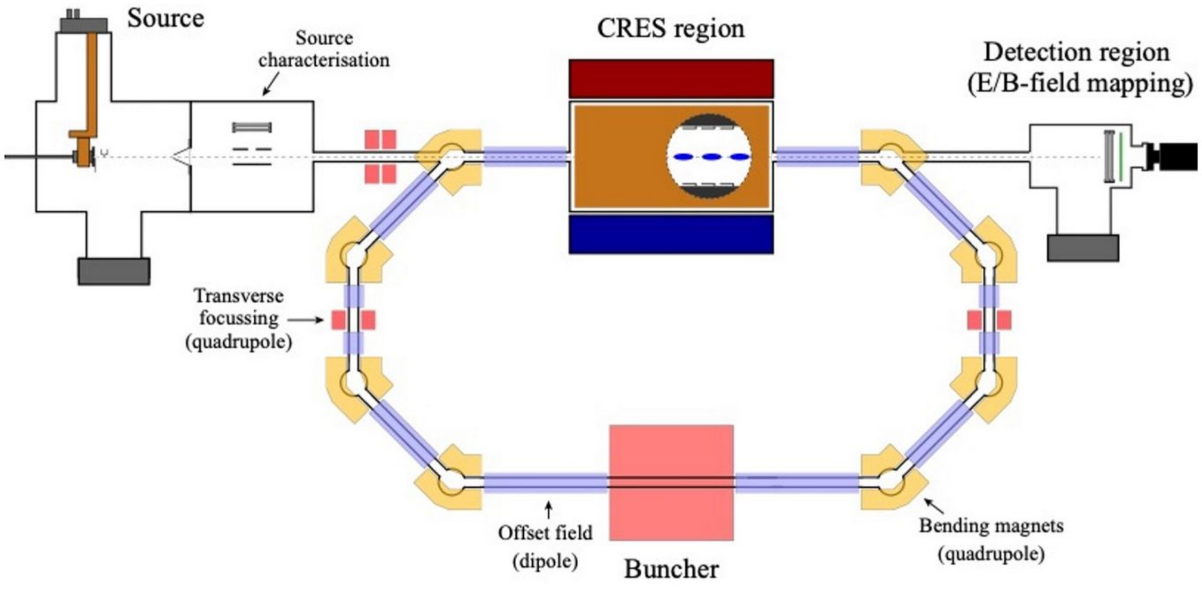
Backup

KATRIN++



Work started
- concept
- sensitivities
- R&D

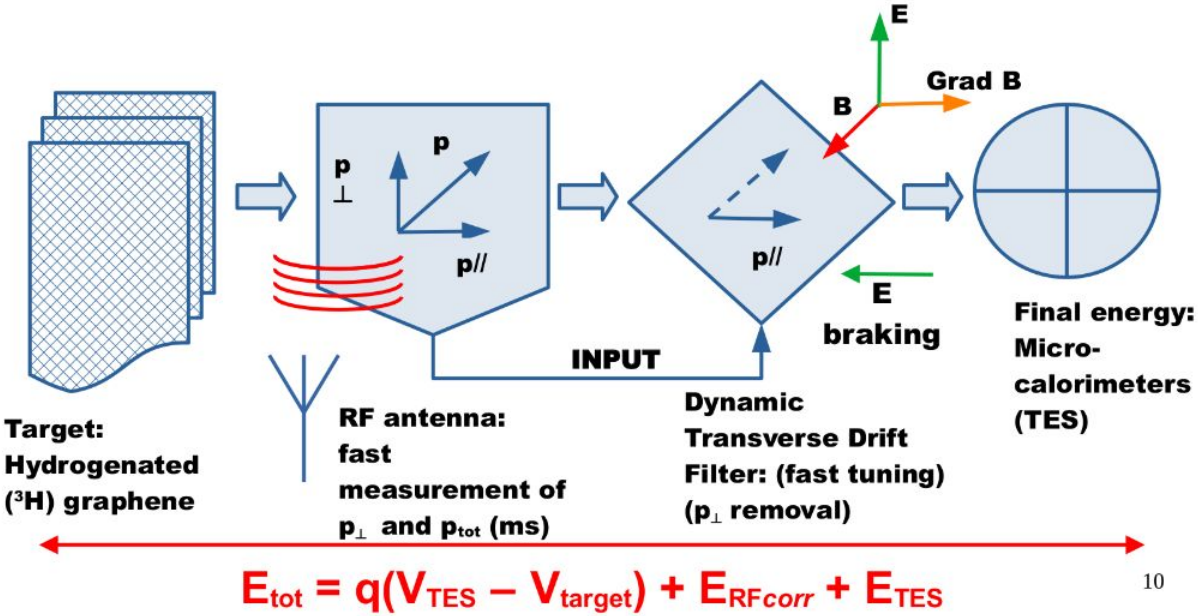
QTNM



Conceptual design of CRESDA

https://www.hep.ucl.ac.uk/qtnm/

Ptolemy



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