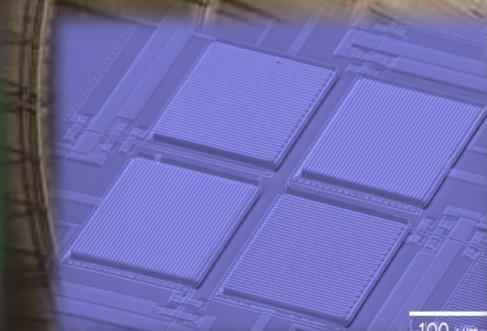
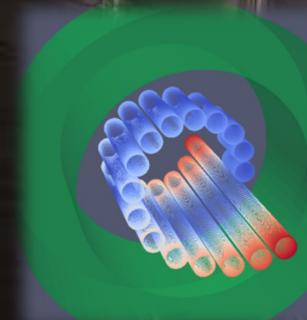


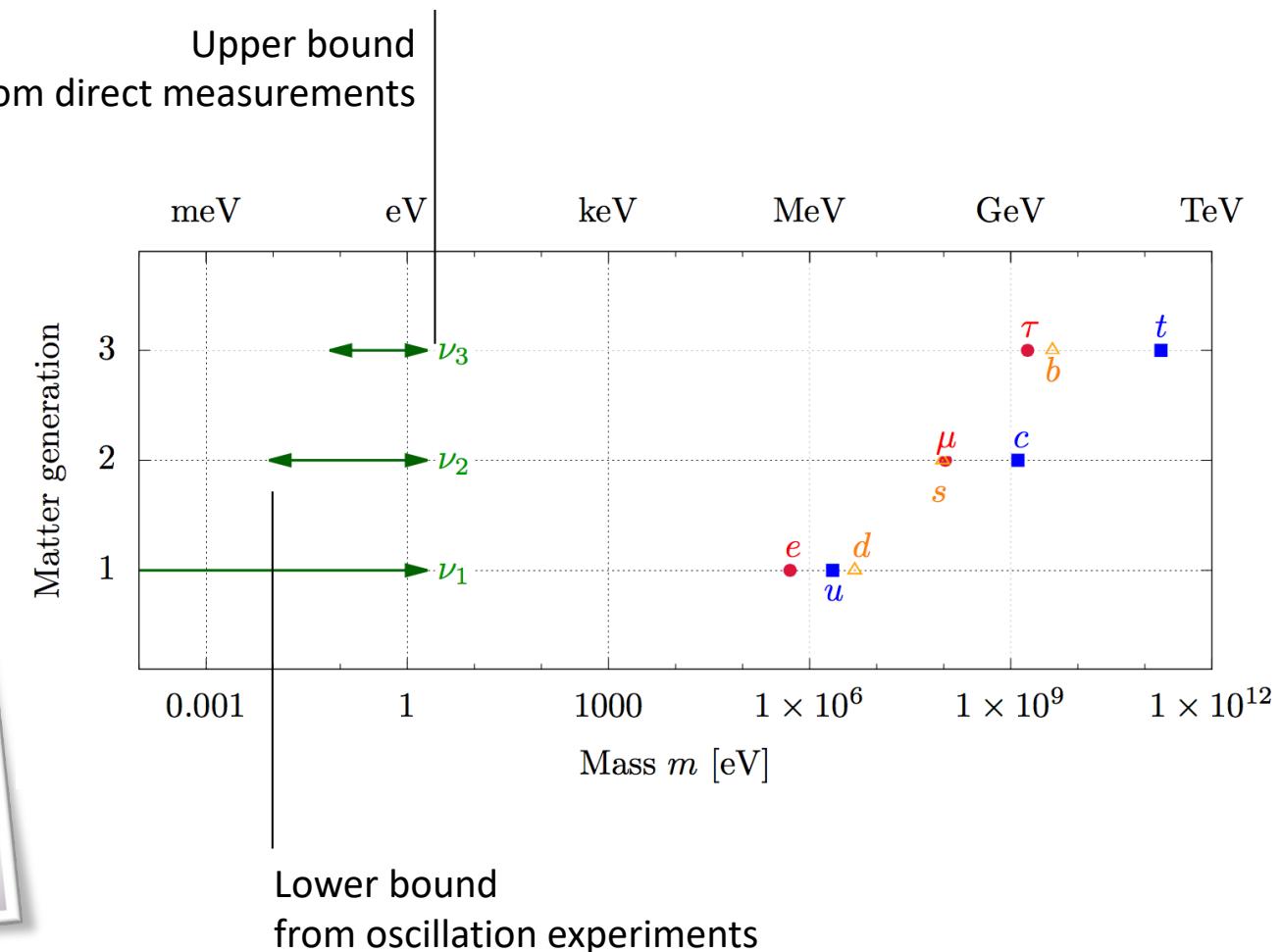
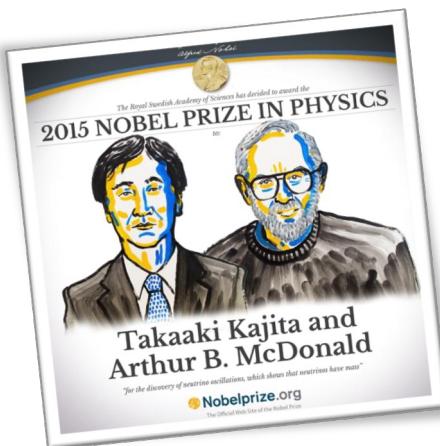
Direct Neutrino Mass Measurements

TAUP 2023



- Thierry Lasserre (CEA)
- On behalf of Susanne Mertens (TUM)

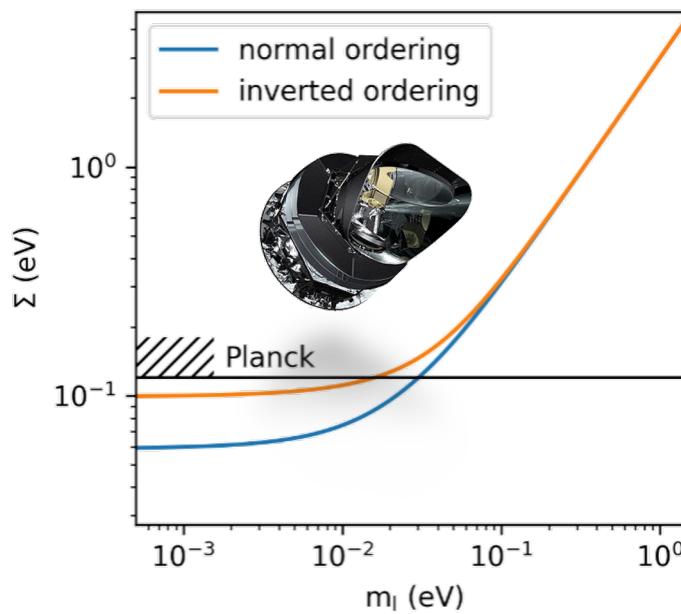
Neutrino mass



Neutrino mass

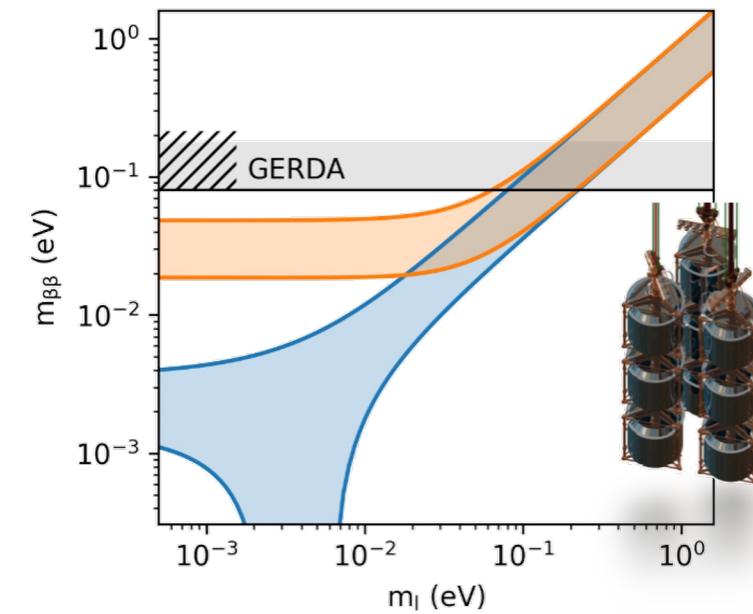
Cosmology

$$\Sigma = \sum_i m_i$$



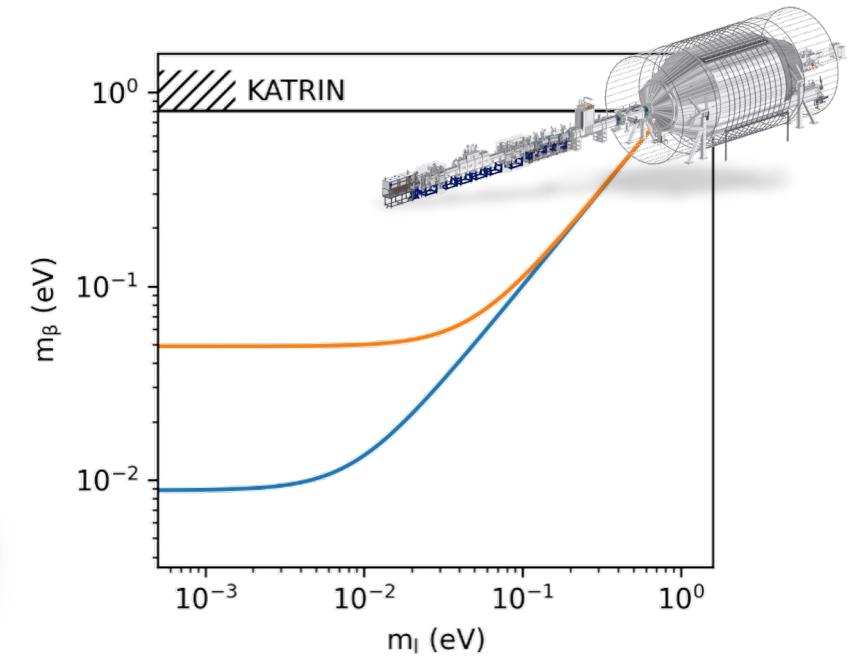
Neutrinoless $\beta\beta$ decay

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

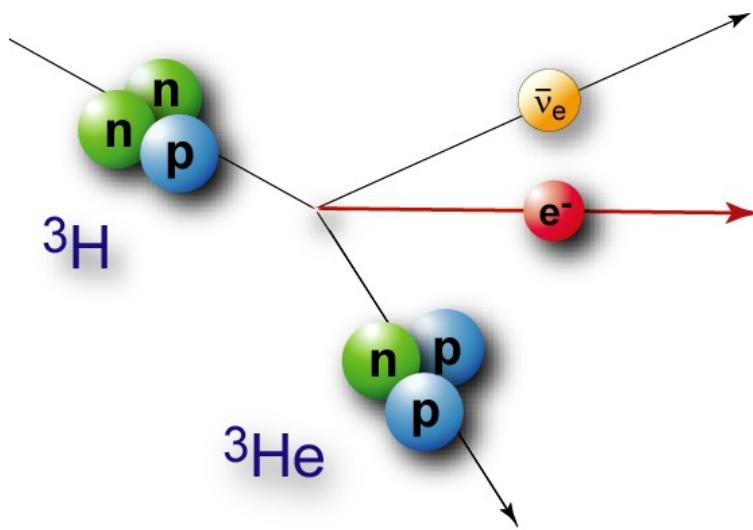


β -decay kinematics

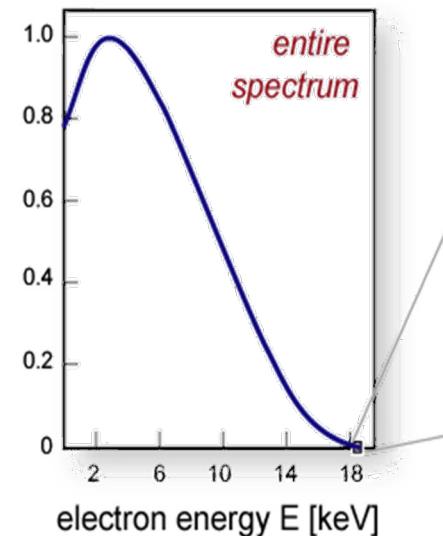
$$m_\beta = \sqrt{\sum_i |U_{ei}^2| m_i^2}$$



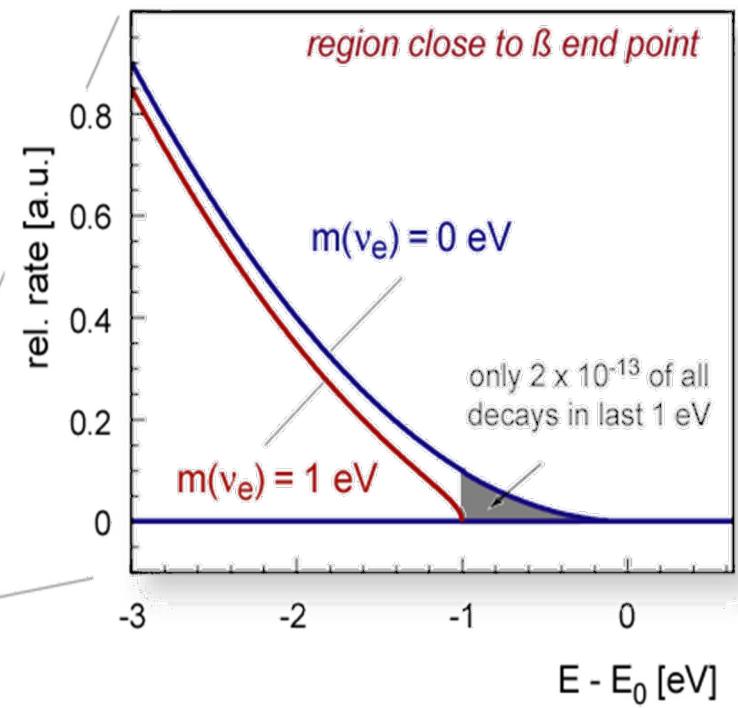
General idea



- ✓ Independent of cosmology
- ✓ Independent of neutrino nature



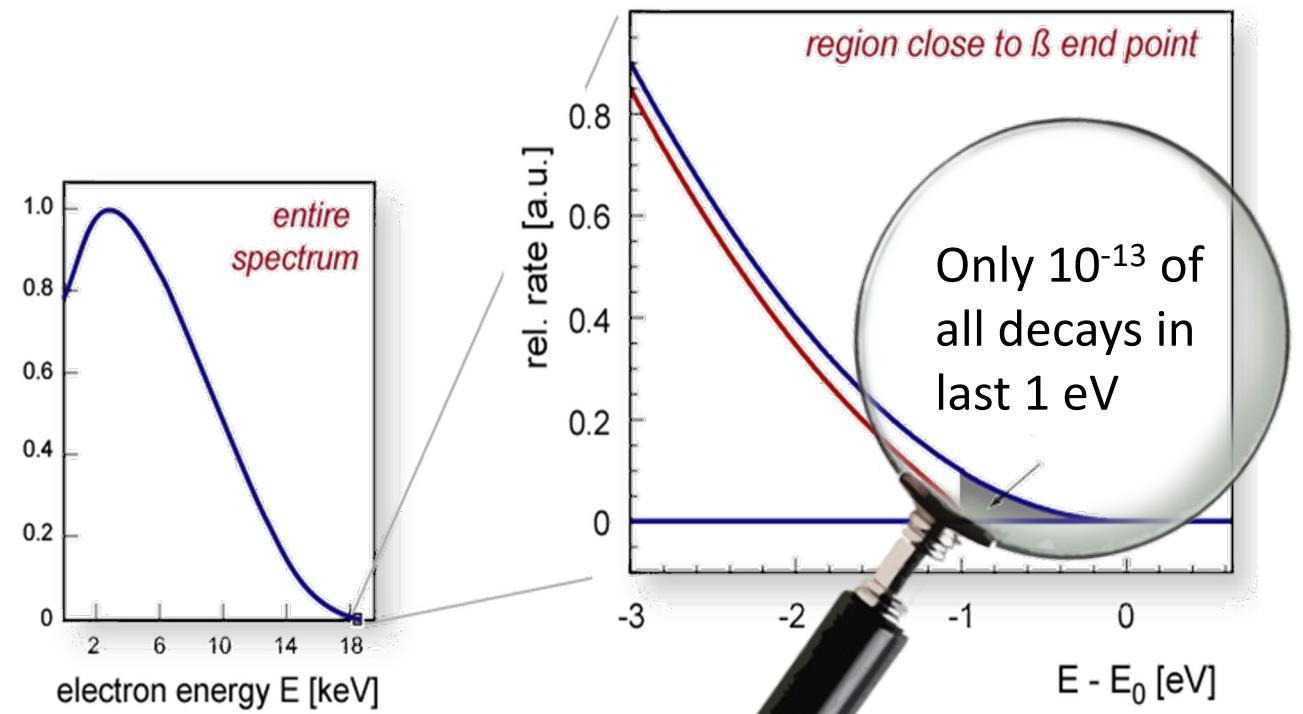
$$m^2(\nu_e) = \sum_i |U_{ei}|^2 \cdot m_i^2$$



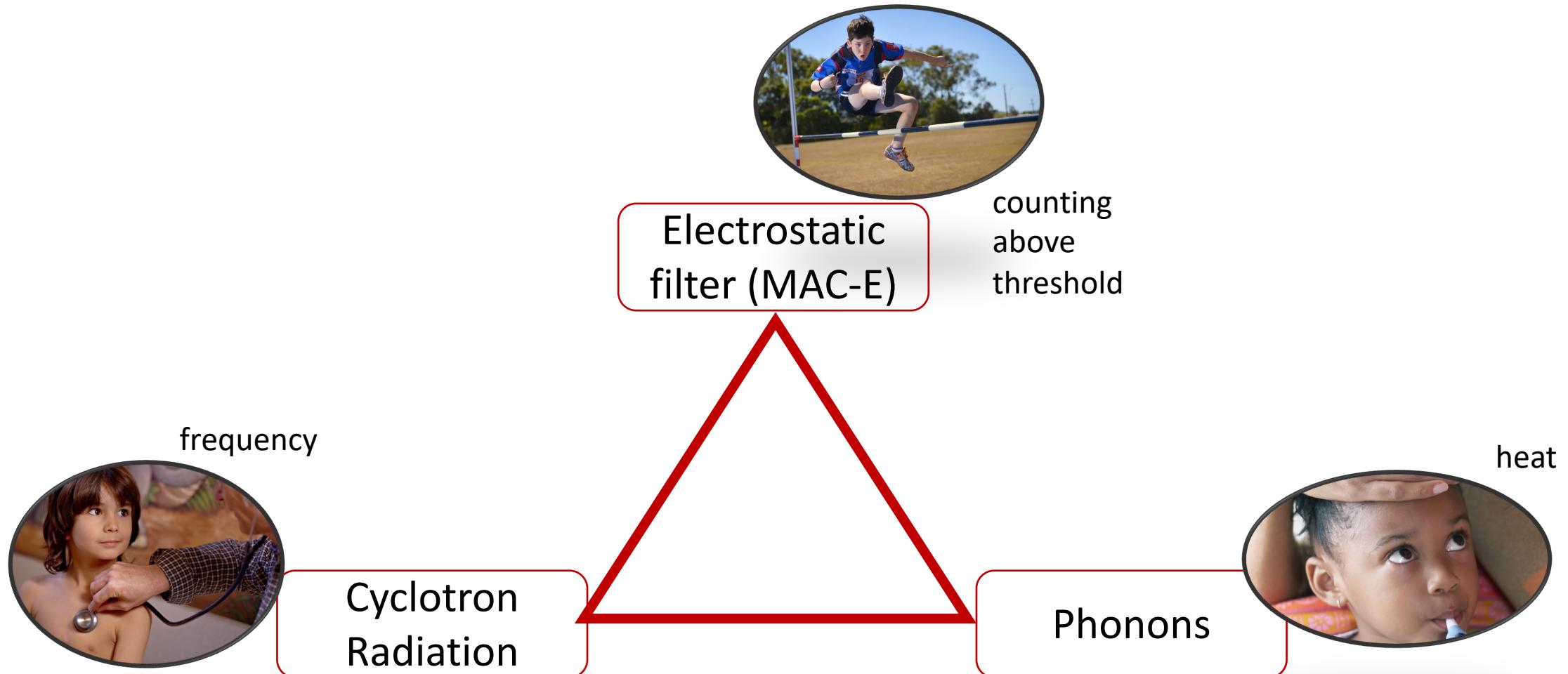
The challenge

Key requirements:

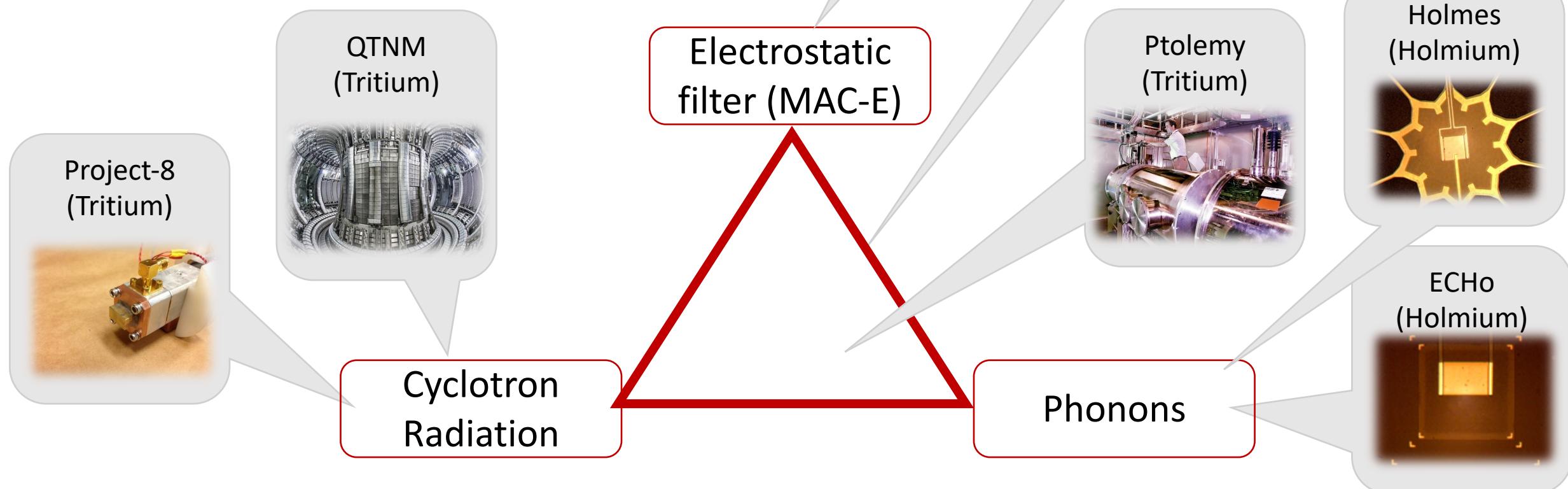
- Strong β -decaying source
 - Tritium (12.3 years, $E_0 = 18.6$ keV)
 - Holmium (4500 years, $E_0 = 2.8$ keV)
- Excellent energy resolution (~ 1 eV)
- Low background (< 100 mcps)



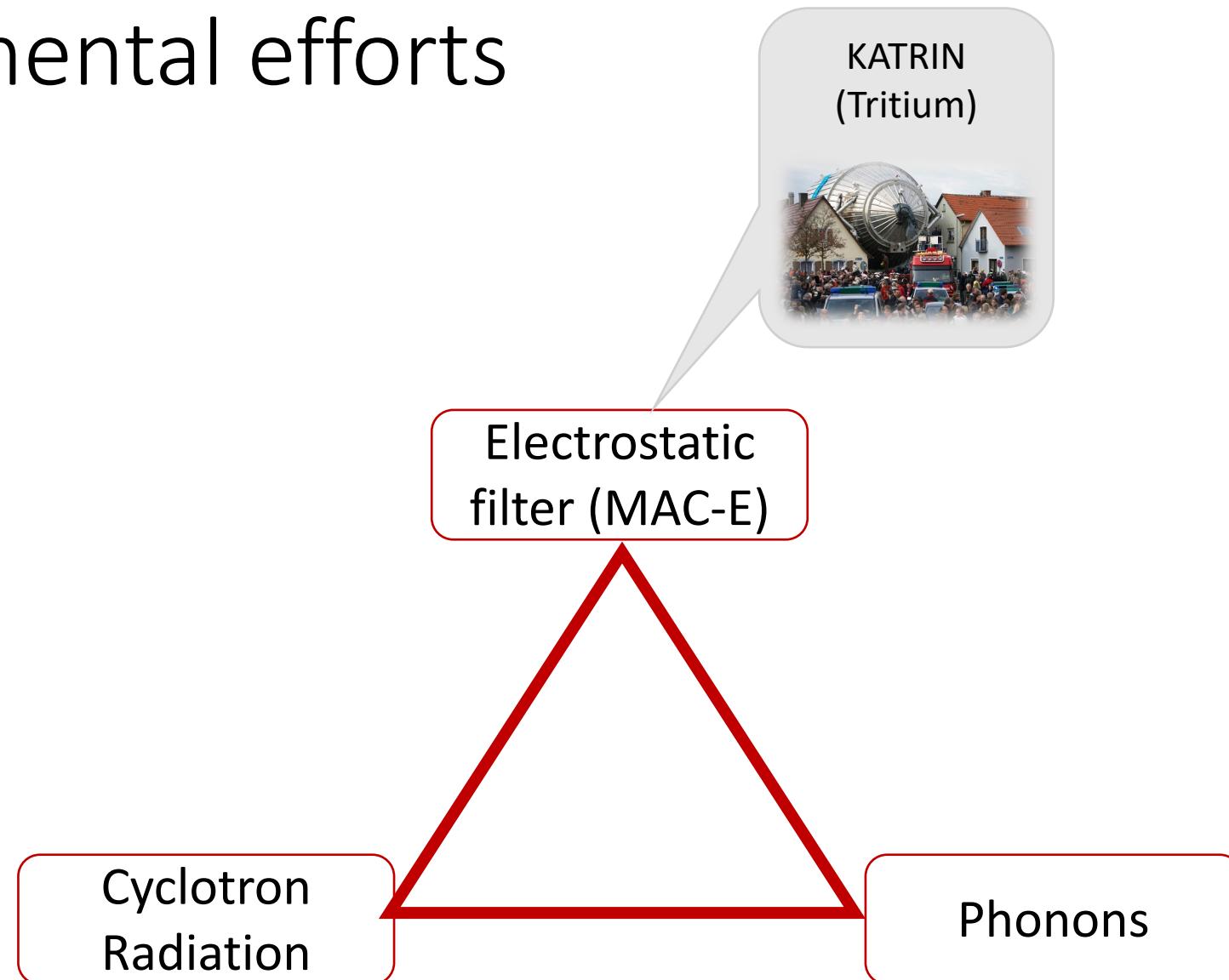
Experimental efforts



Experimental efforts



Experimental efforts



KATRIN

- Experimental site: Karlsruhe Institute of Technology (KIT)
- International Collaboration (150 members)
- Design sensitivity: 0.2 eV (90% CL)
(1000 days of measurement time)



Karlsruher Institut für Technologie



MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK
HEIDELBERG

WESTFÄLISCHE
WILHELMS-UNIVERSITÄT
MÜNSTER



Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)



THE UNIVERSITY
of NORTH CAROLINA
at CHAPEL HILL



Massachusetts
Institute of
Technology



The Czech Academy
of Sciences



UNIVERSIDAD
COMPLUTENSE
MADRID



Hochschule Fulda
University of Applied Sciences



BICOCCA



POLITECNICO
MILANO 1863



DE LA RECHERCHE À L'INDUSTRIE



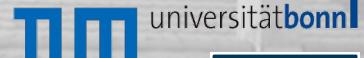
JOHANNES GUTENBERG
UNIVERSITÄT MAINZ



HUMBOLDT-UNIVERSITÄT
ZU BERLIN



BERGISCHE
UNIVERSITÄT
WUPPERTAL



universität bonn



TECHNISCHE
UNIVERSITÄT
MÜNCHEN



BERKELEY LAB



Russian Academy
of Sciences

Working Principle



Tritium source

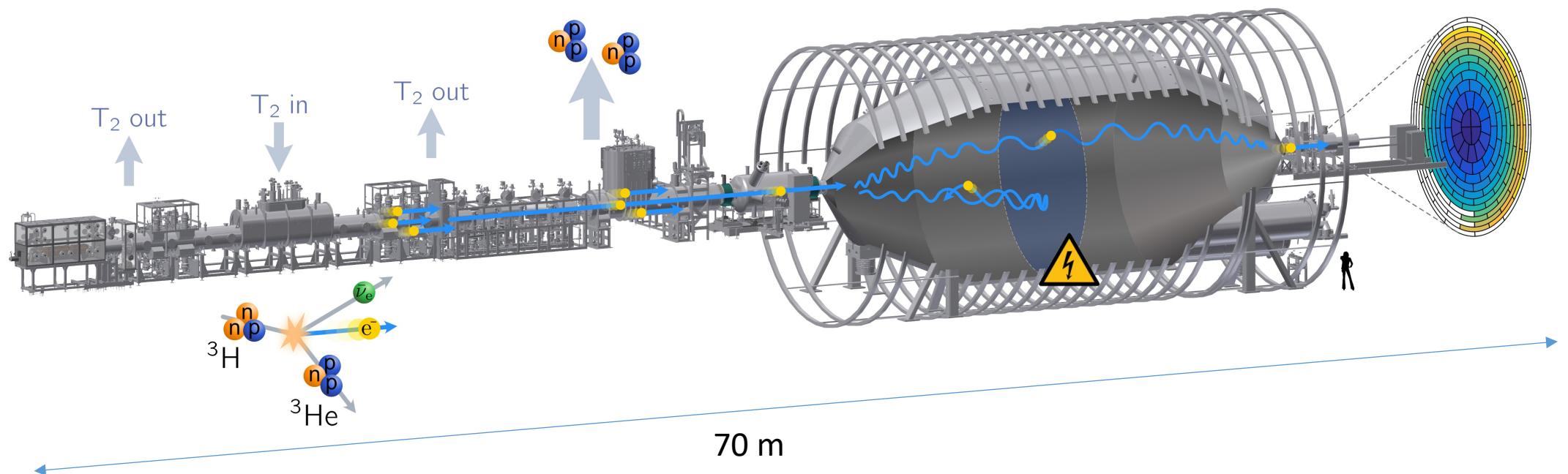
- Gaseous T_2
- $10^{11} T_2$ decays/s

Spectrometer

- Electrostatic filter
- MAC-E filter principle

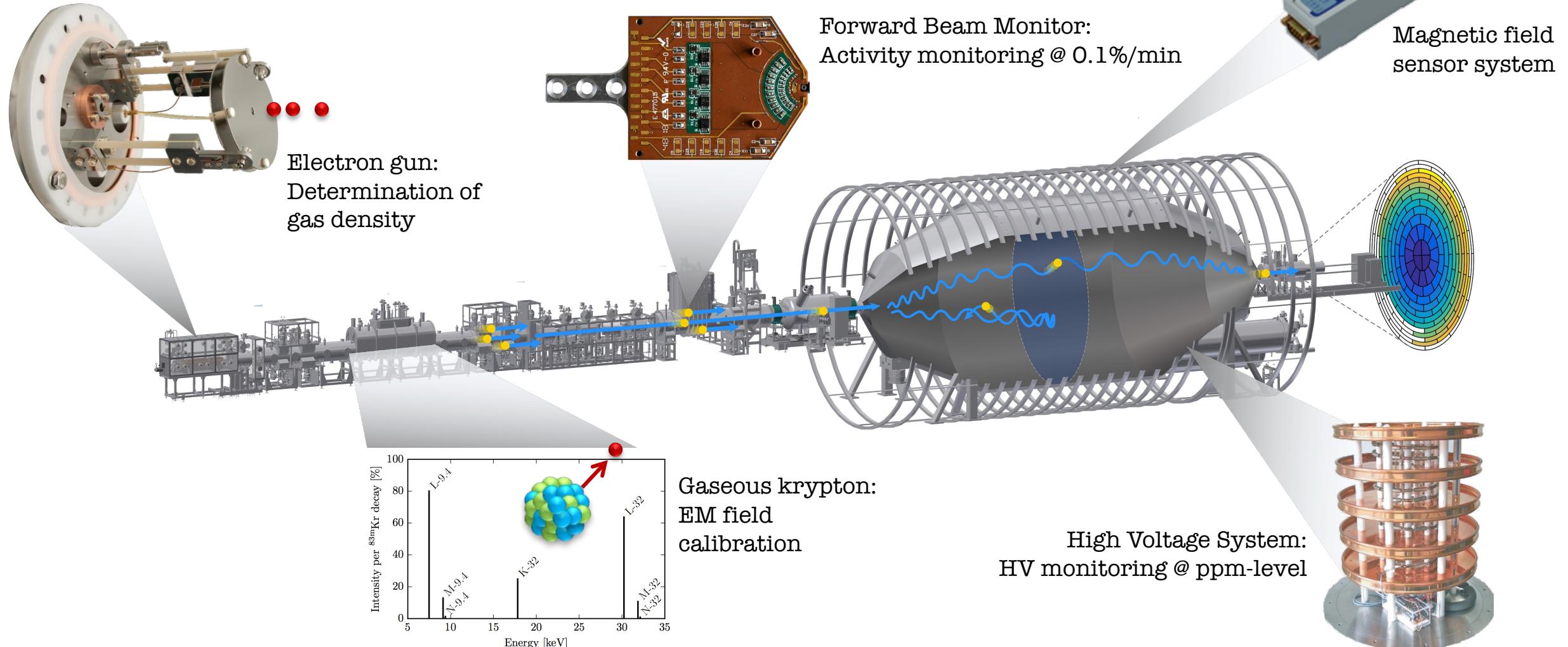
Detector

- Si-PIN detector
- Rate vs filter voltage



Working Principle

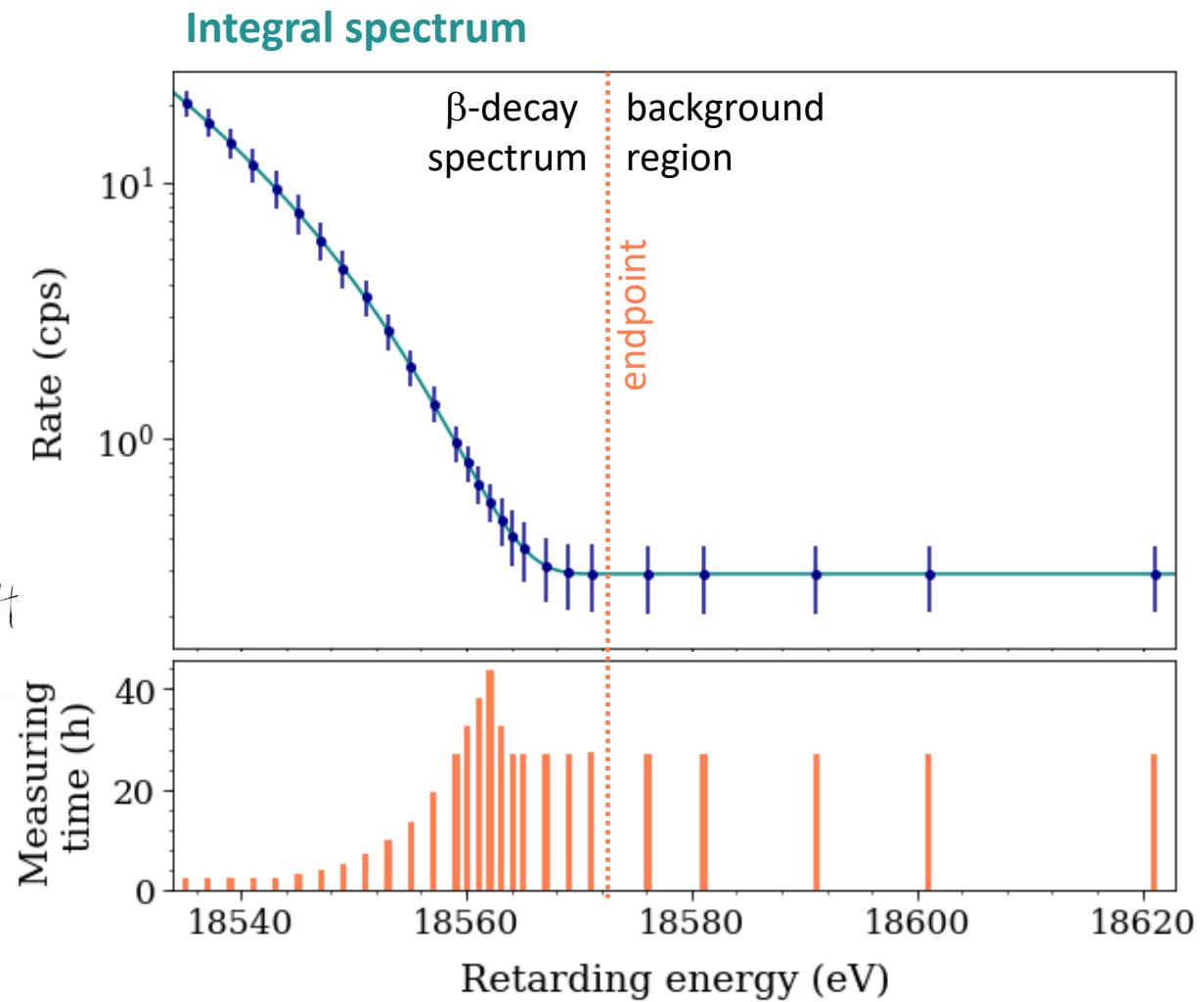
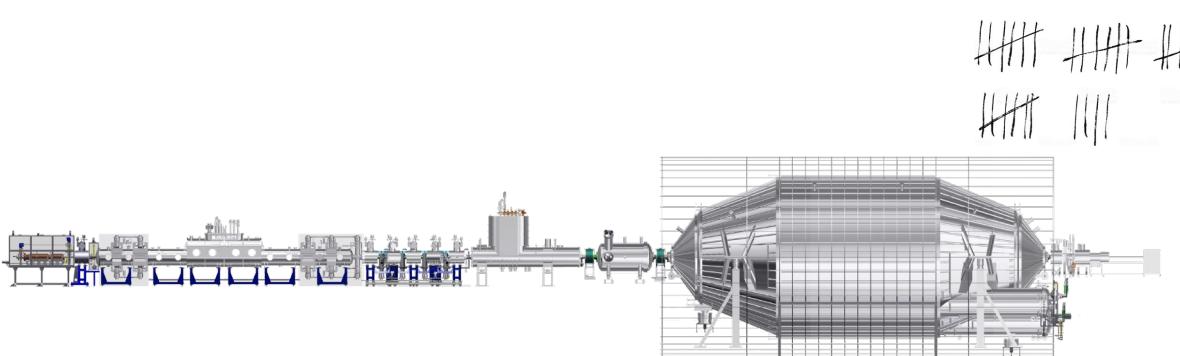
B. Bieringer, M. Böttcher
28 August, poster A



Measurement strategy

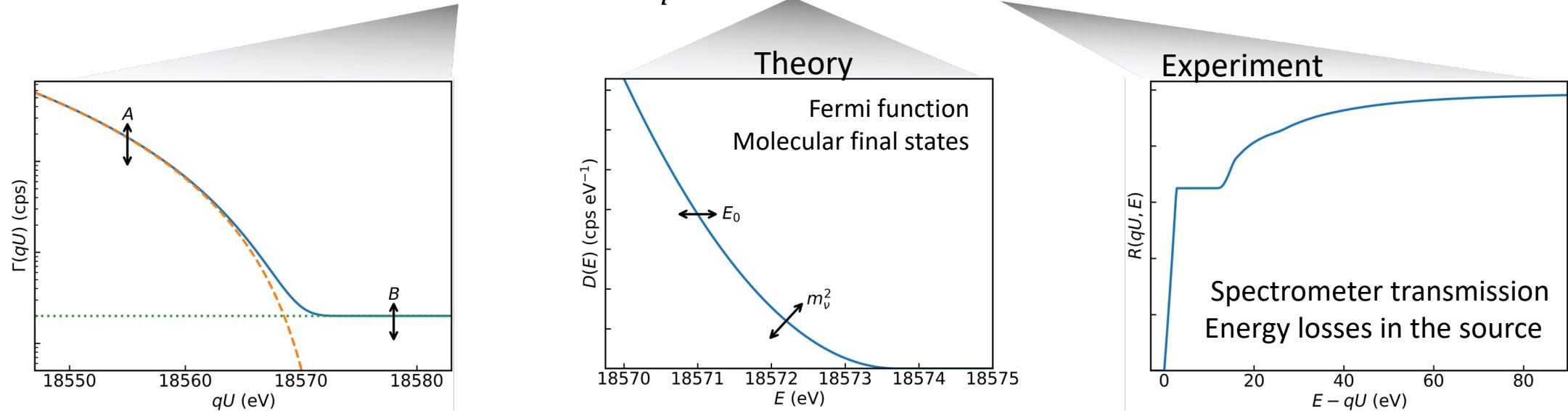
β -scans:

- Scan points: **30 HV set points**
- Scan interval: **$E_0 - 40 \text{ eV}, E_0 + 130 \text{ eV}$**
- Scan time: **3 hours**



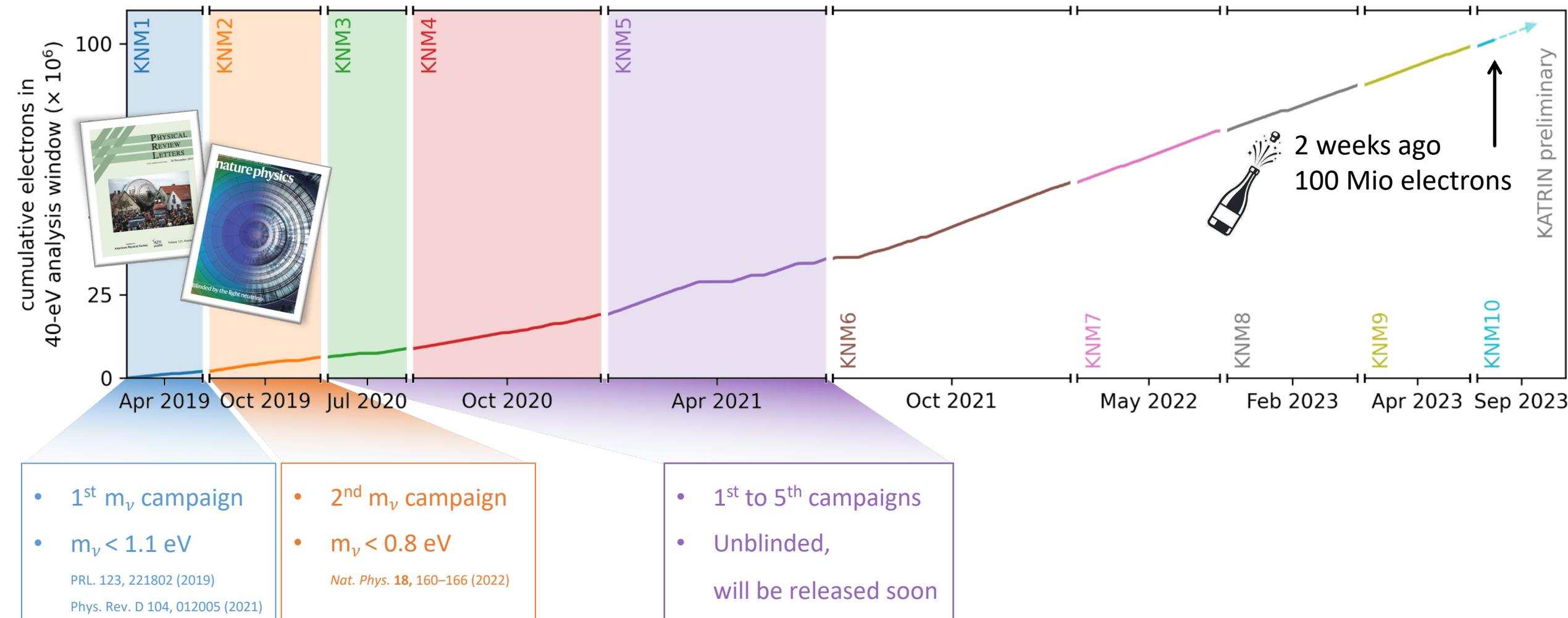
Analysis strategy

- Fit of theoretical prediction: $\Gamma(qU) \propto \mathbf{A} \cdot \int_{qU}^{E_0} D(E; \mathbf{m}_v^2, E_0) \cdot R(qU, E) dE + \mathbf{B}$

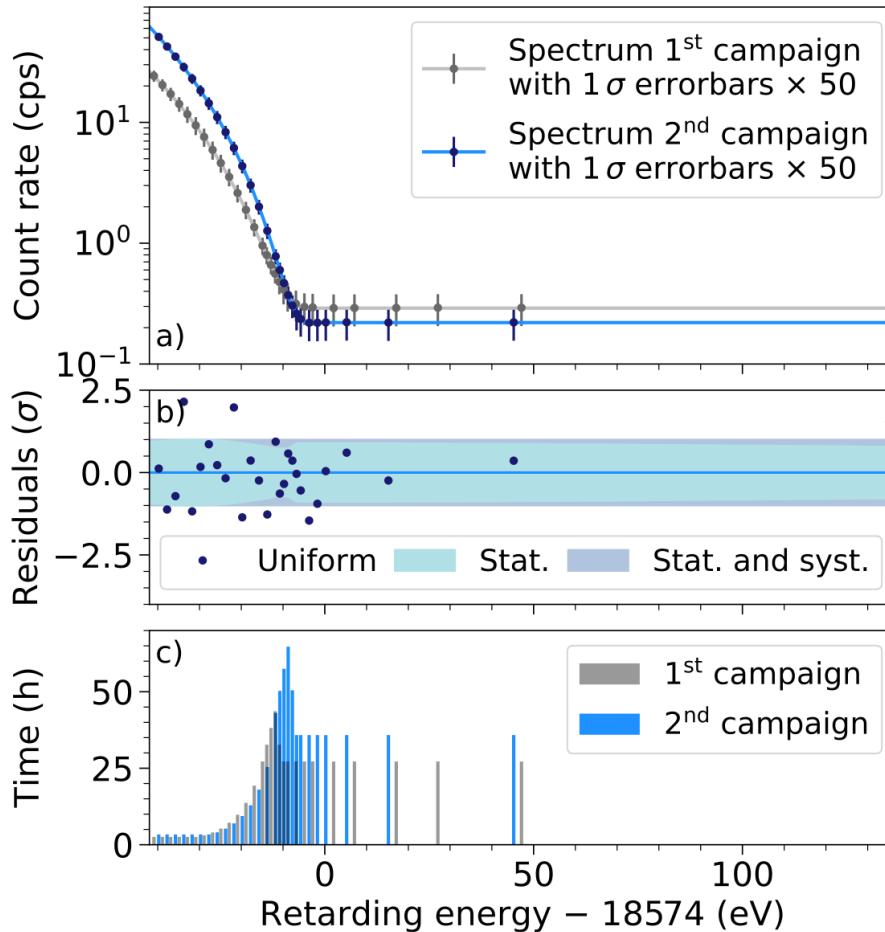


- Free parameters: $\mathbf{m}_v^2 + E_0, \mathbf{B}, \mathbf{A}$ + nuisance parameters (constrained via calibrations)
- Blinded analysis: 1. independent analysis teams, 2. MC twin data, 3. model blinding

KATRIN Data Taking Overview



1st and 2nd campaign



First campaign:

- total statistics: 2 million events
- best fit: $m_\nu^2 = (-1.0^{+0.9}_{-1.1}) \text{ eV}^2 (\text{stat. dom.})$
- limit: $m_\nu < 1.1 \text{ eV (90% CL)}$

PRL. 123, 221802 (2019)

Phys. Rev. D 104, 012005 (2021)



Second campaign:

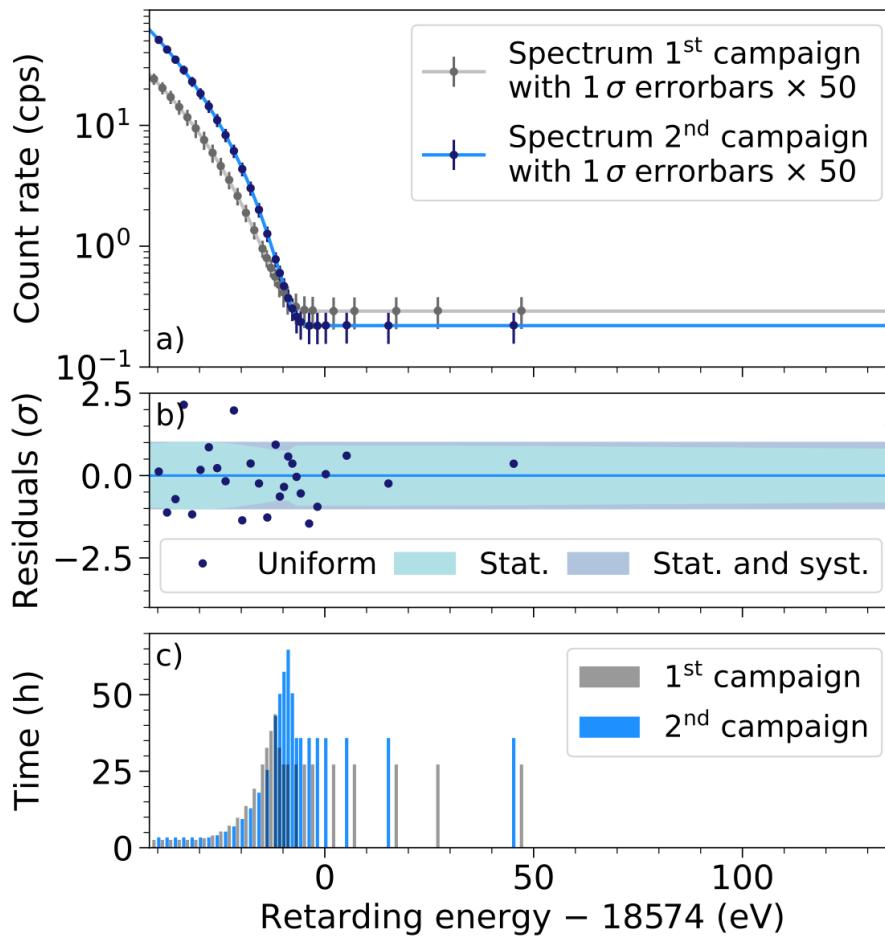
- total statistics: 4 million events
- best fit: $m_\nu^2 = (0.26^{+0.34}_{-0.34}) \text{ eV}^2 (\text{stat. dom.})$
- limit: $m_\nu < 0.9 \text{ eV (90% CL)}$

Nat. Phys. 18, 160–166 (2022)

- Combined result: $m_\nu < 0.8 \text{ eV (90% CL)}$**



1st and 2nd campaign



✓ Search for relic big-bang neutrinos

Phys. Rev. Lett. **129**, 011806 (2022)

✓ Search for violation of Lorentz invariance

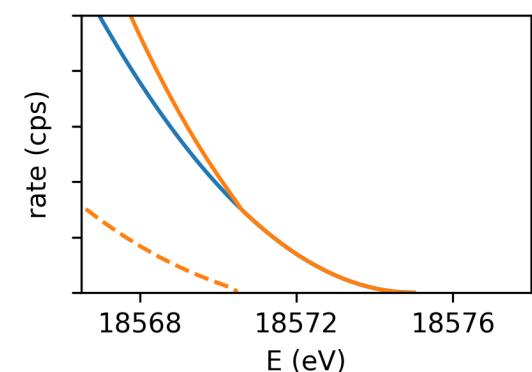
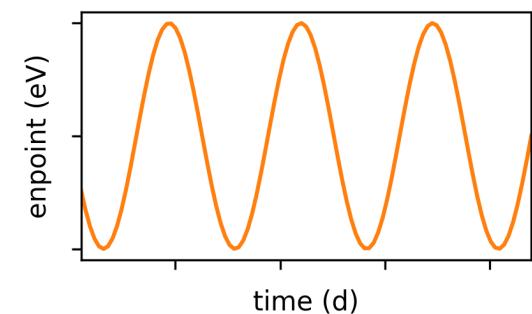
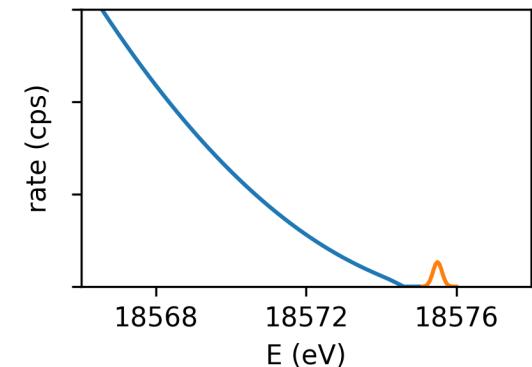
Phys. Rev. D **107**, 082005 (2023)

✓ Search for light sterile neutrinos

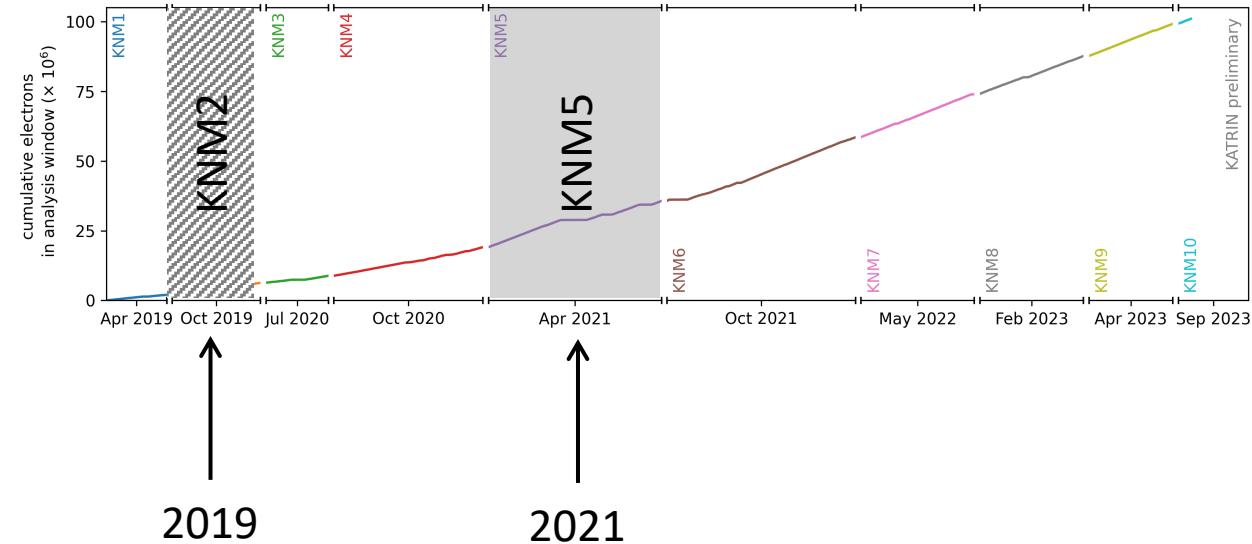
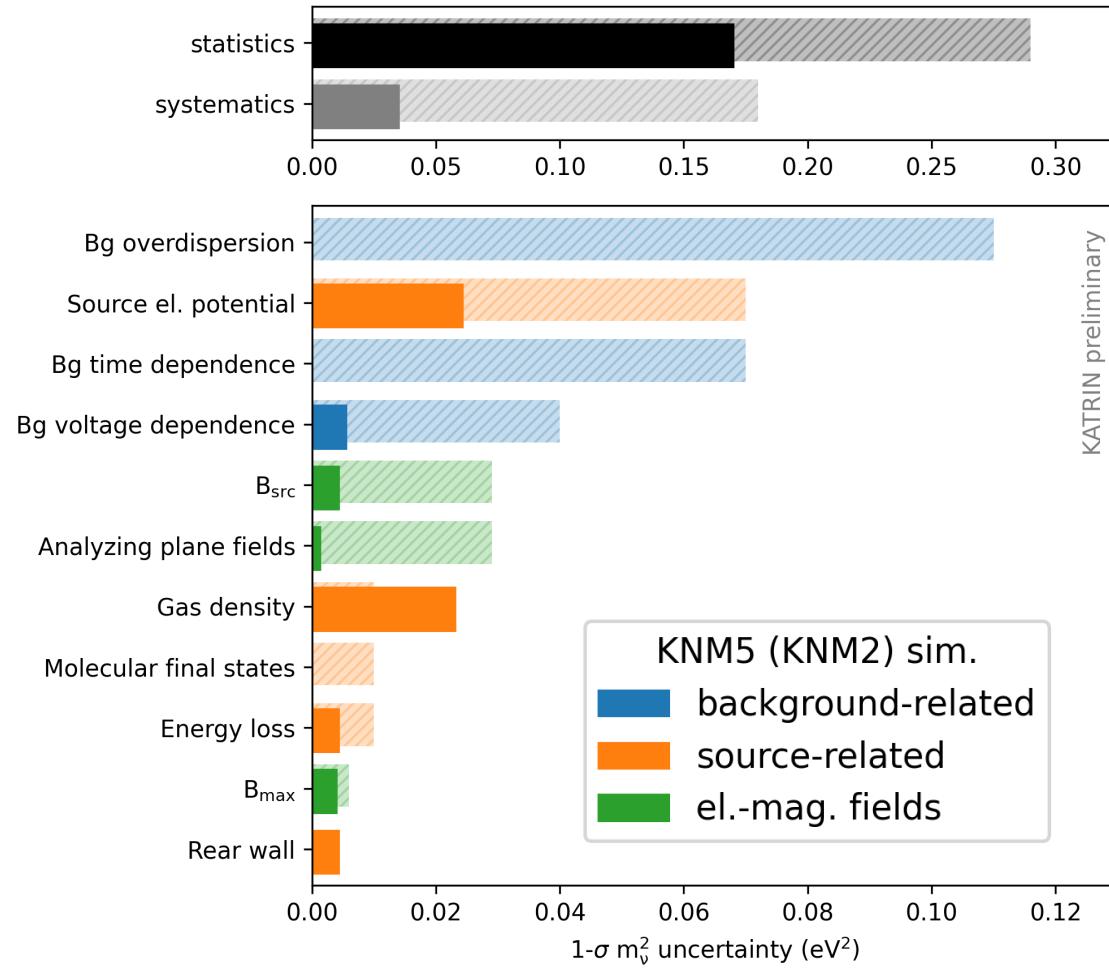
Phys. Rev. Lett. **126**, 091803 (2021)

Phys. Rev. D **105**, 072004 (2022)

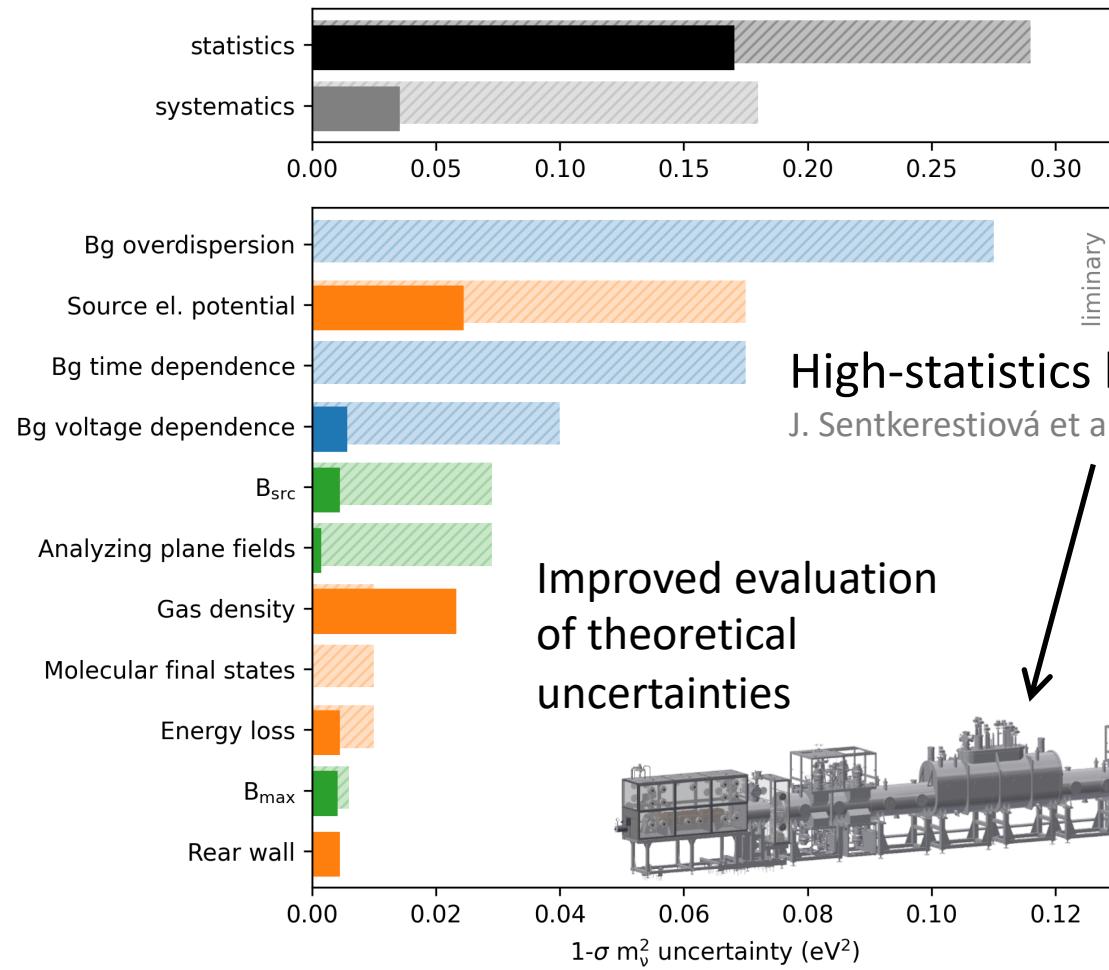
*L. Köllenberger
30 August, poster B*



Improvements: 2nd vs 5th campaign

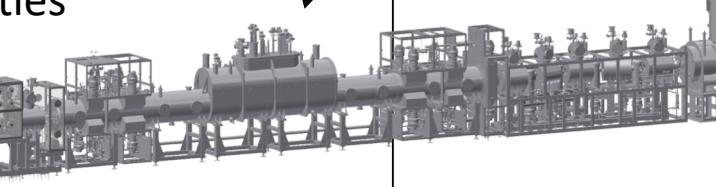


Improvements: 2nd vs 5th campaign



High-statistics krypton calibration
J. Sentkerestiová et al, JINST 13 (2018)

Improved evaluation
of theoretical
uncertainties

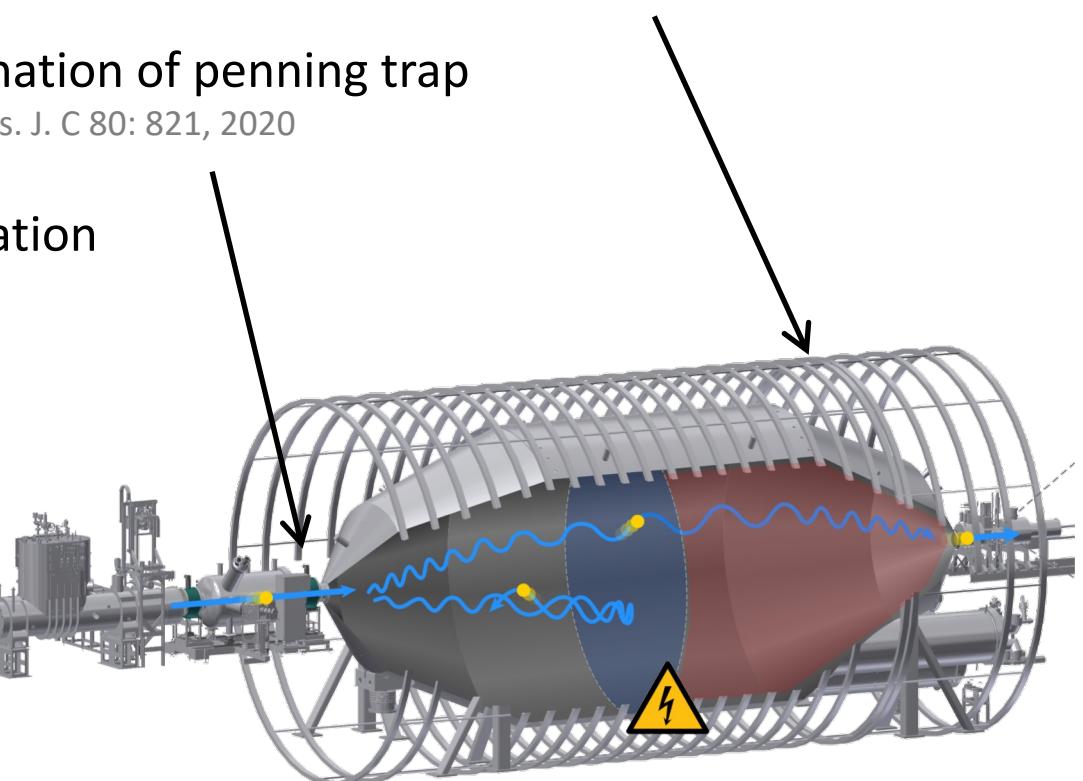


Shifted analyzing plane

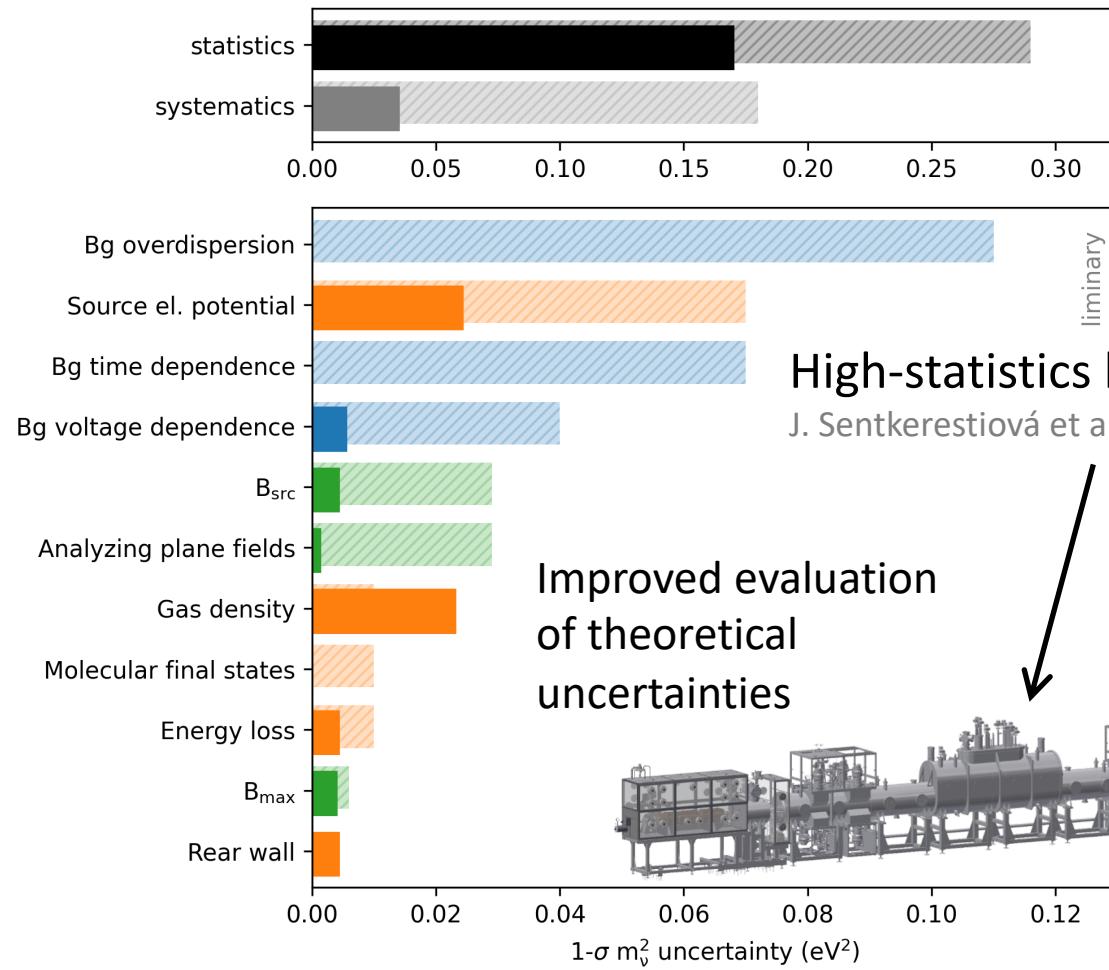
Lokhov et al arXiv:2201.11743 (2022)

Elimination of penning trap

Eur. Phys. J. C 80: 821, 2020



Improvements: 2nd vs 5th campaign



High-statistics krypton calibration

J. Sentkerestiová et al, JINST 13 (2018)

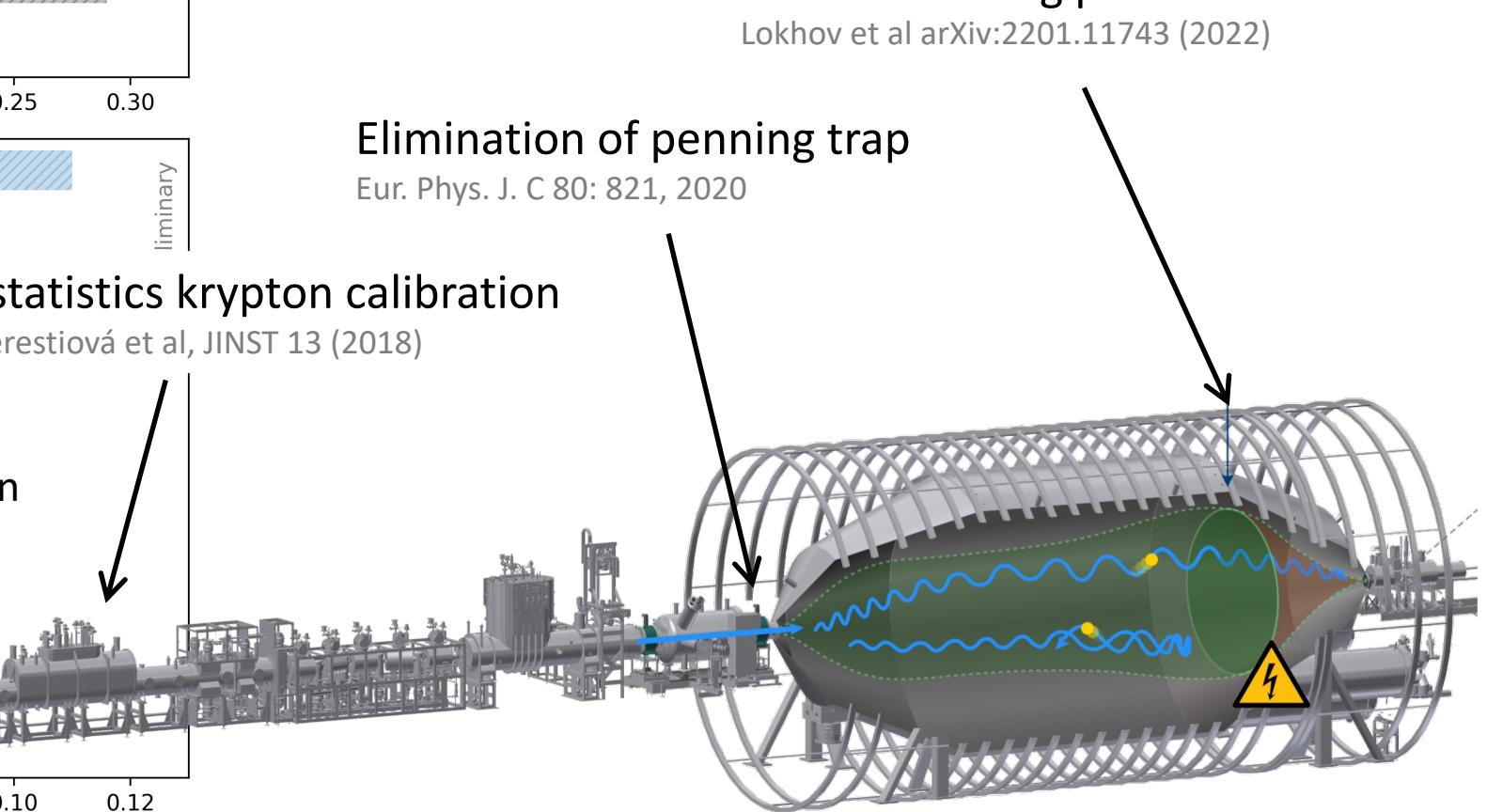
Improved evaluation
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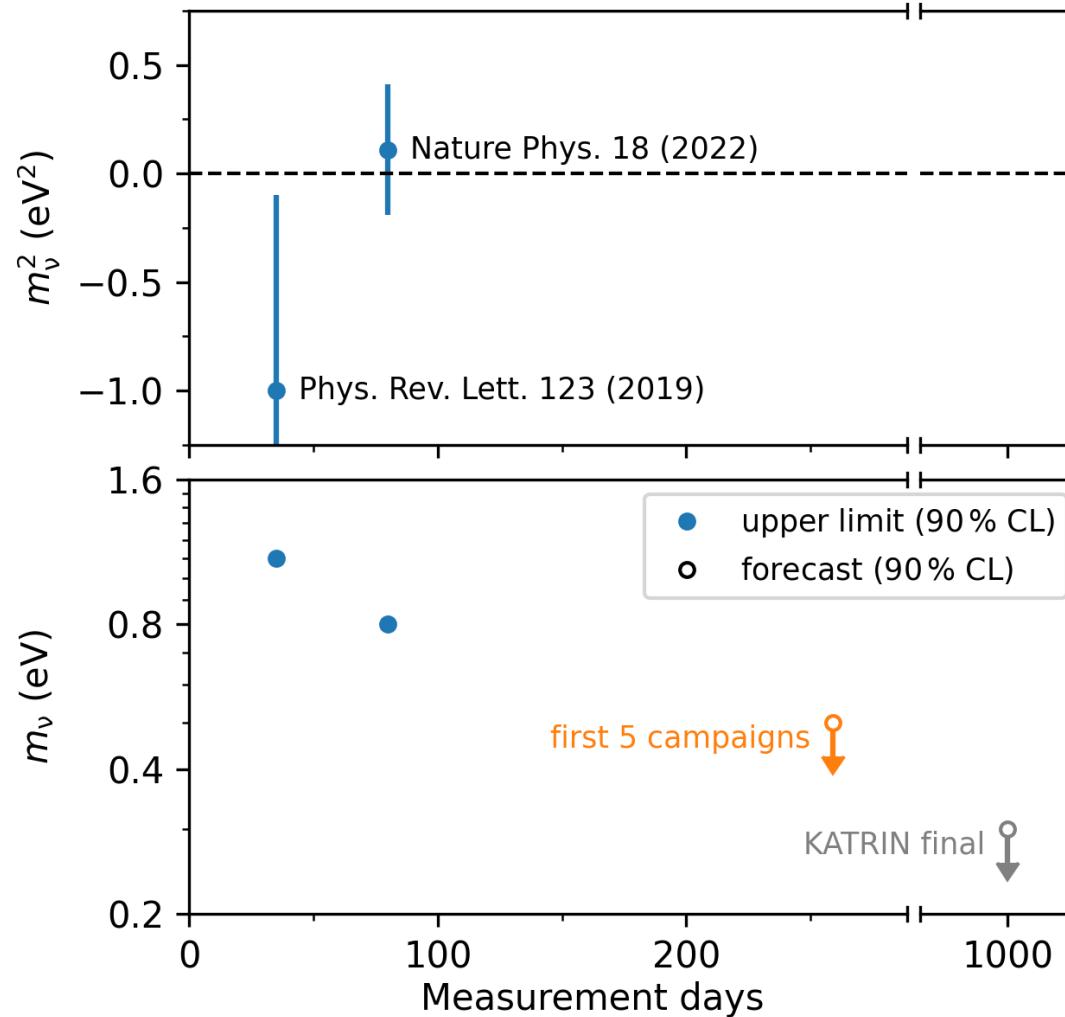
Eur. Phys. J. C 80: 821, 2020

Shifted analyzing plane

Lokhov et al arXiv:2201.11743 (2022)



Upcoming KATRIN results



- **Upcoming result (this year):**
 - Based on first five campaigns
 - Statistics $\times 6$, Systematics $\div 3$
 - Sensitivity better than $m_\nu < 0.5$ eV
 - Paper (almost) ready for submission
- **Final result:**
 - Based on 1000 days of data taking (completed end of 2025)
 - Sensitivity better than $m_\nu < 0.3$ eV

KATRIN timeline



A. Onillon
30 August, 14:00

A. Nava
28 August, poster A

K. Urban
28 August, poster A

A. Huber
30 August, poster B

neutrino mass

2026- 2027: keV-sterile neutrinos (TRISTAN)

KATRIN ++

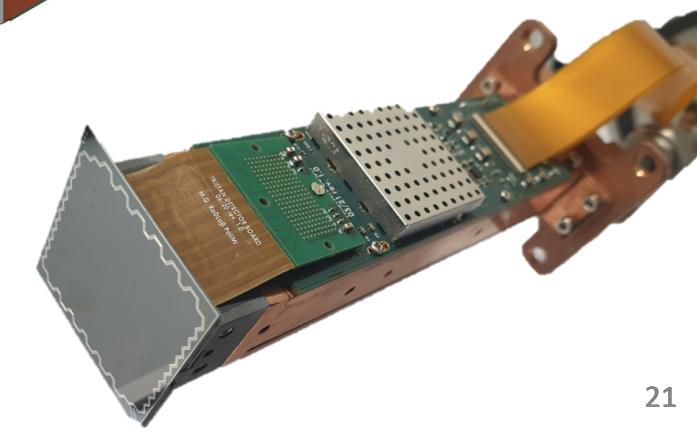
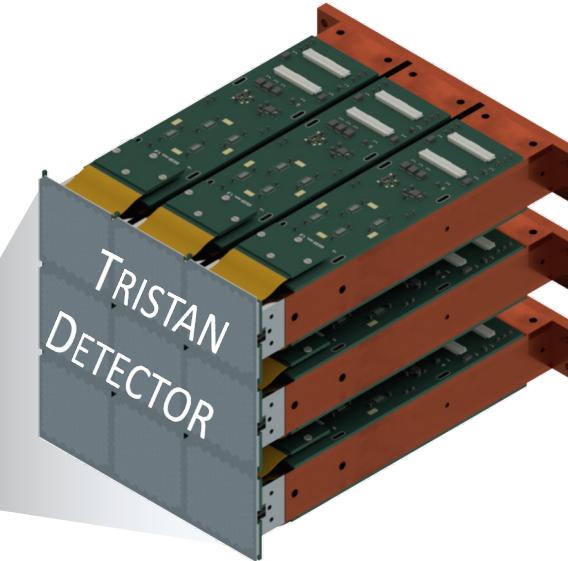
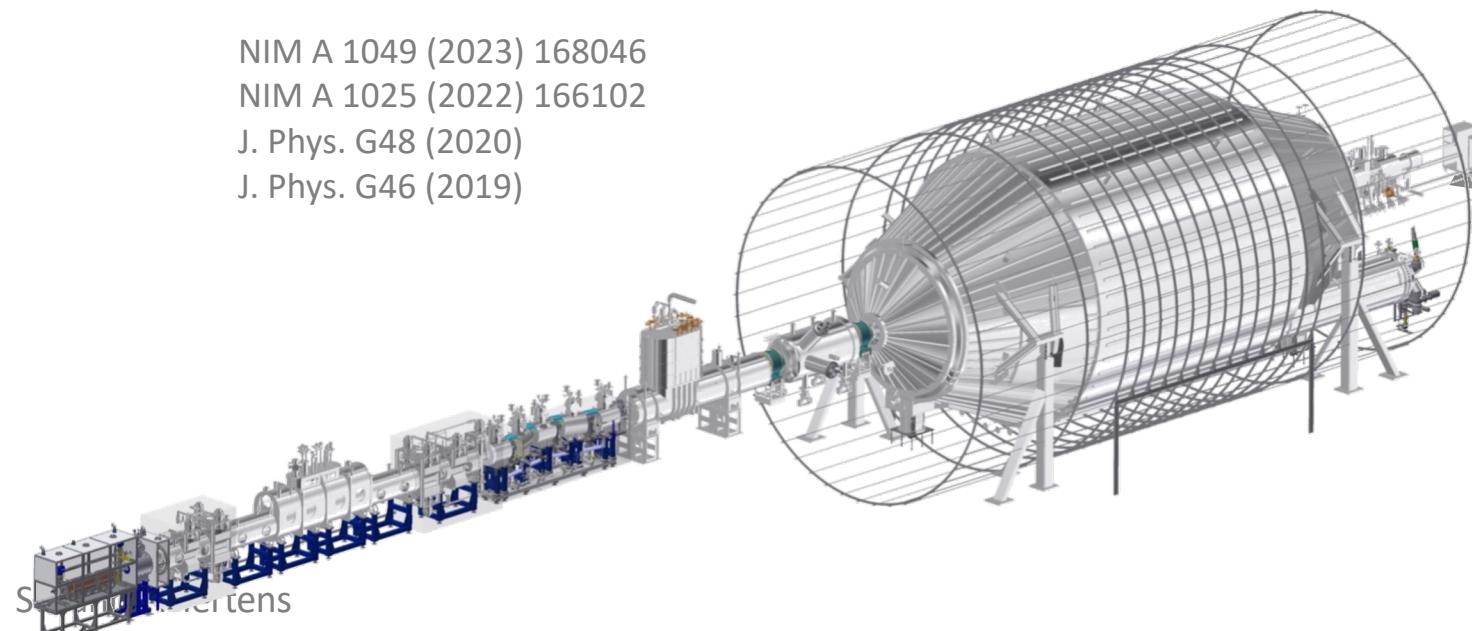
- Precision measurement of the entire tritium spectrum
- Installation of ~1000-pixel Silicon Drift Detector
(10^8 counts / sec)

NIM A 1049 (2023) 168046

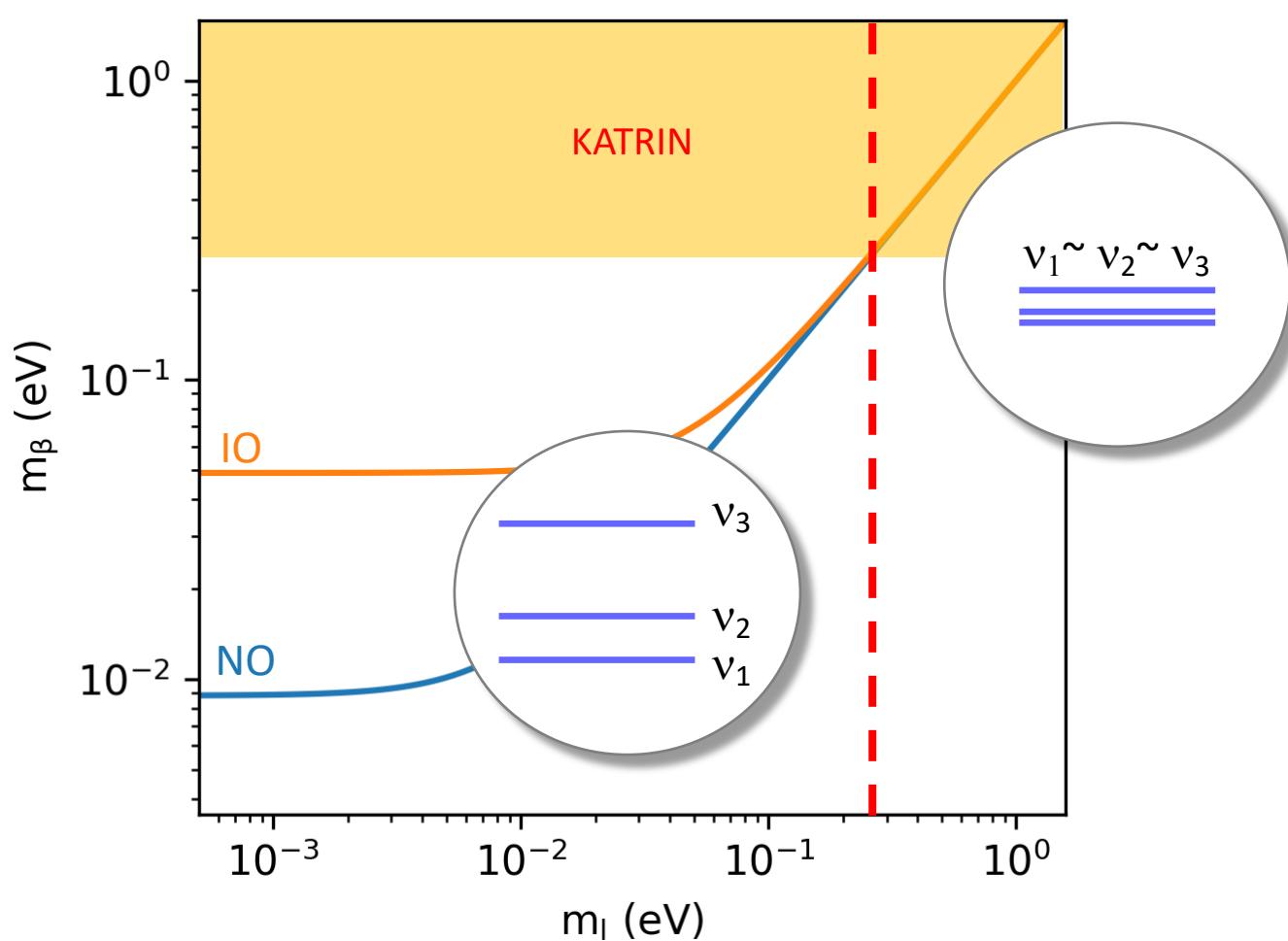
NIM A 1025 (2022) 166102

J. Phys. G48 (2020)

J. Phys. G46 (2019)

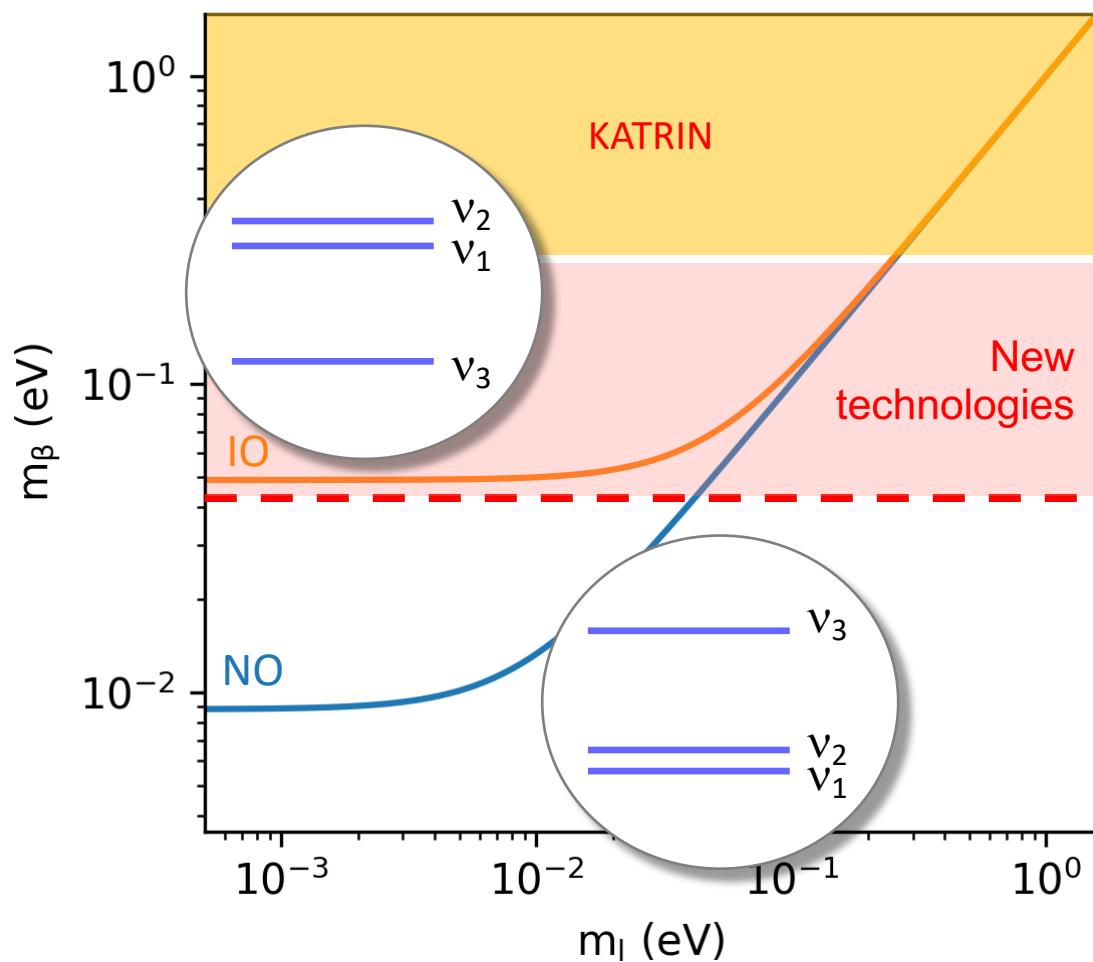


Going beyond KATRIN



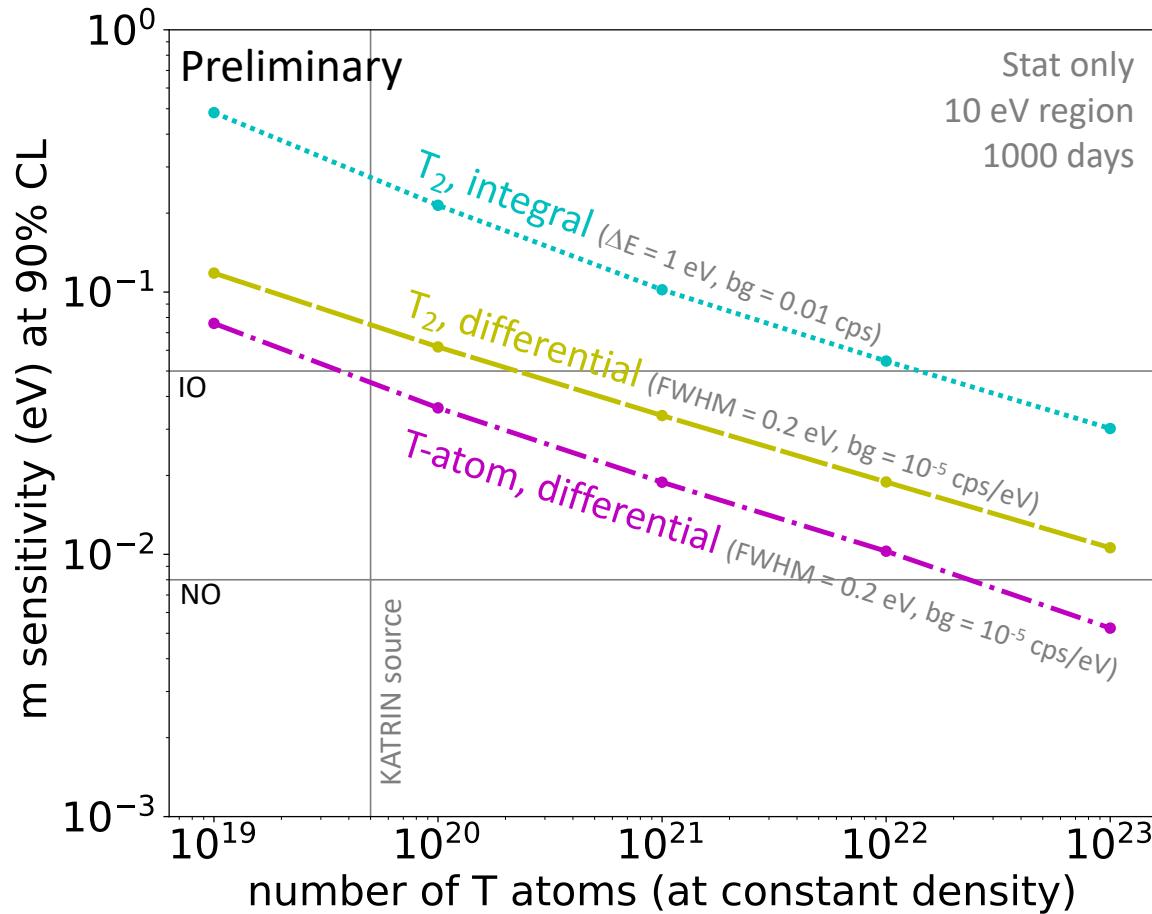
- KATRIN final: **< 0.3 eV (90% CL)**
Distinguish between **degenerate** and **hierarchical** scenario

Going beyond KATRIN

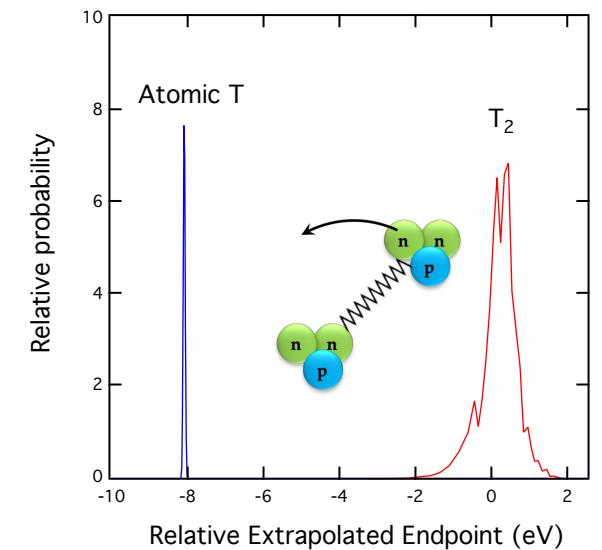


- KATRIN final: < 0.3 eV (90% CL)
Distinguish between **degenerate** and **hierarchical** scenario
- New technologies: < 0.05 eV
Cover **inverted** ordering

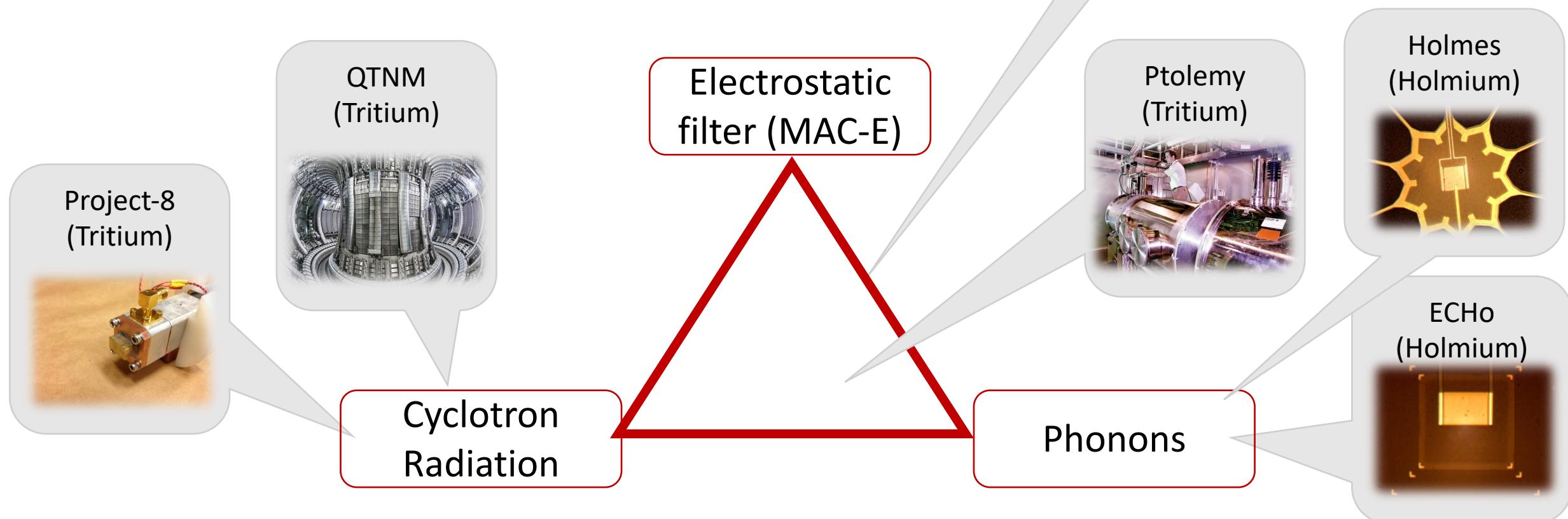
Going beyond KATRIN



- **Differential measurement (FWHM < 1 eV)**
 - ✓ Better use of statistics
 - ✓ Lower background
- **Atomic tritium**
 - ✓ Avoid broadening ($\sim 1 \text{ eV}$)
 - ✓ Avoid limiting systematics of T_2



Experimental efforts



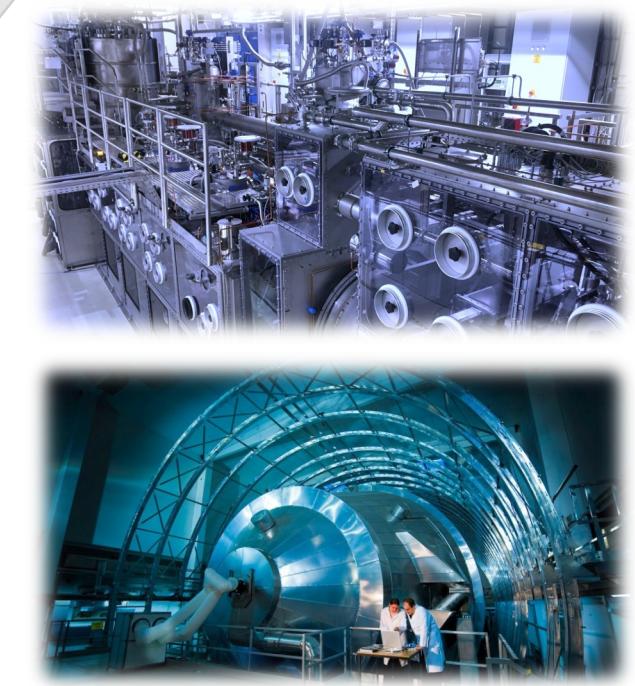
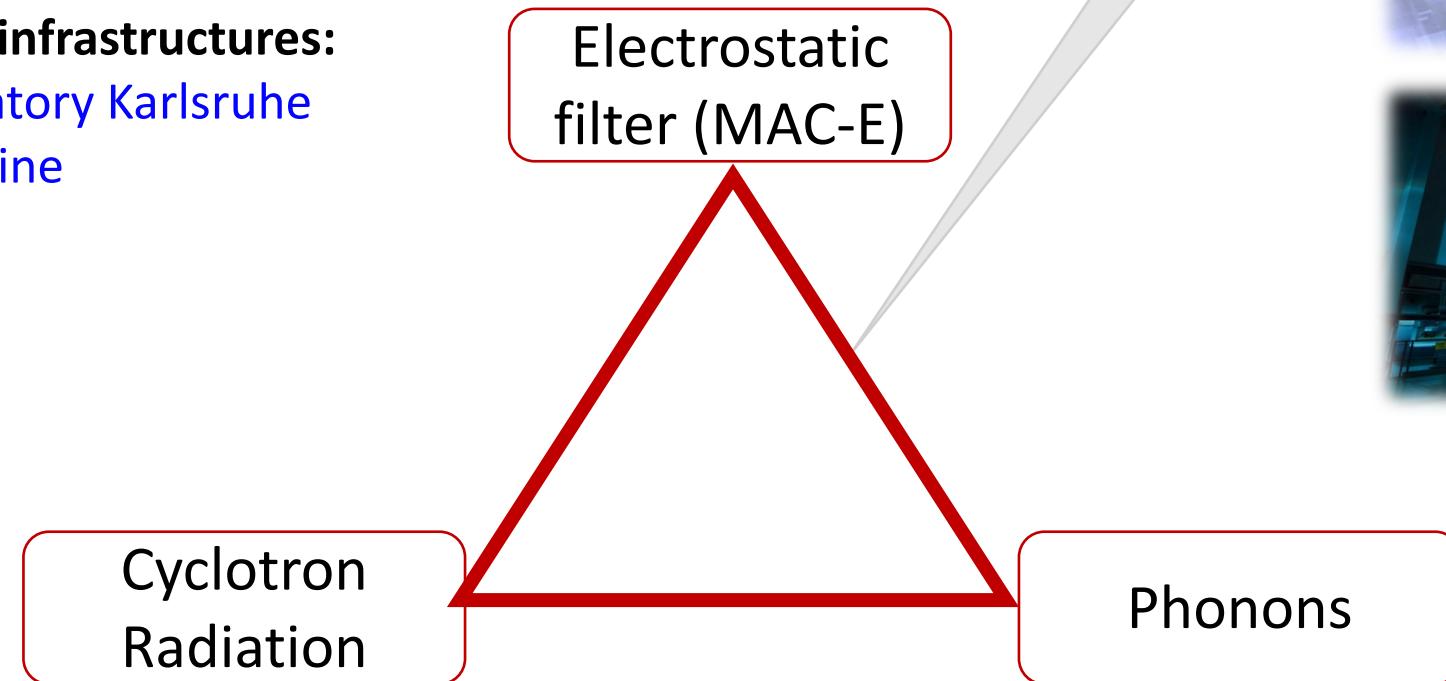
Experimental efforts

R&D launched:

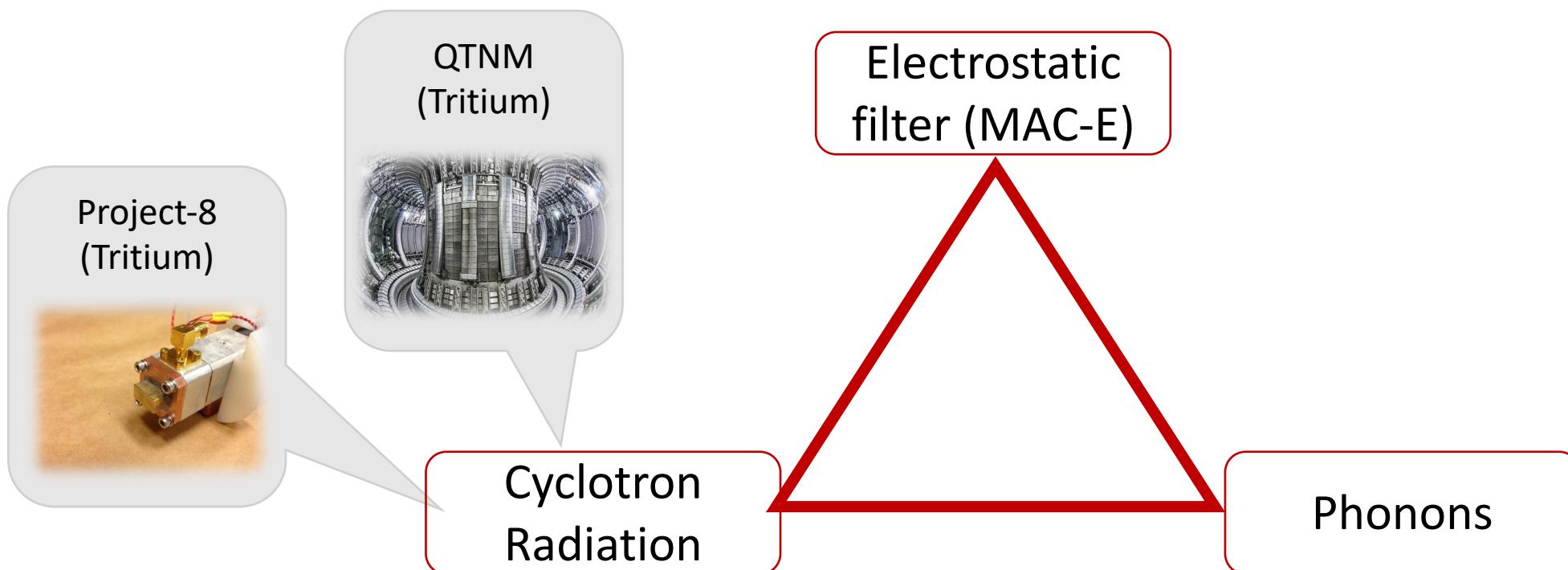
- ✓ atomic tritium source concepts
- ✓ application of microcalorimeters (MMC) to keV β -electrons

Leverage unique infrastructures:

- ✓ Tritium Laboratory Karlsruhe
- ✓ KATRIN beamline



Experimental efforts

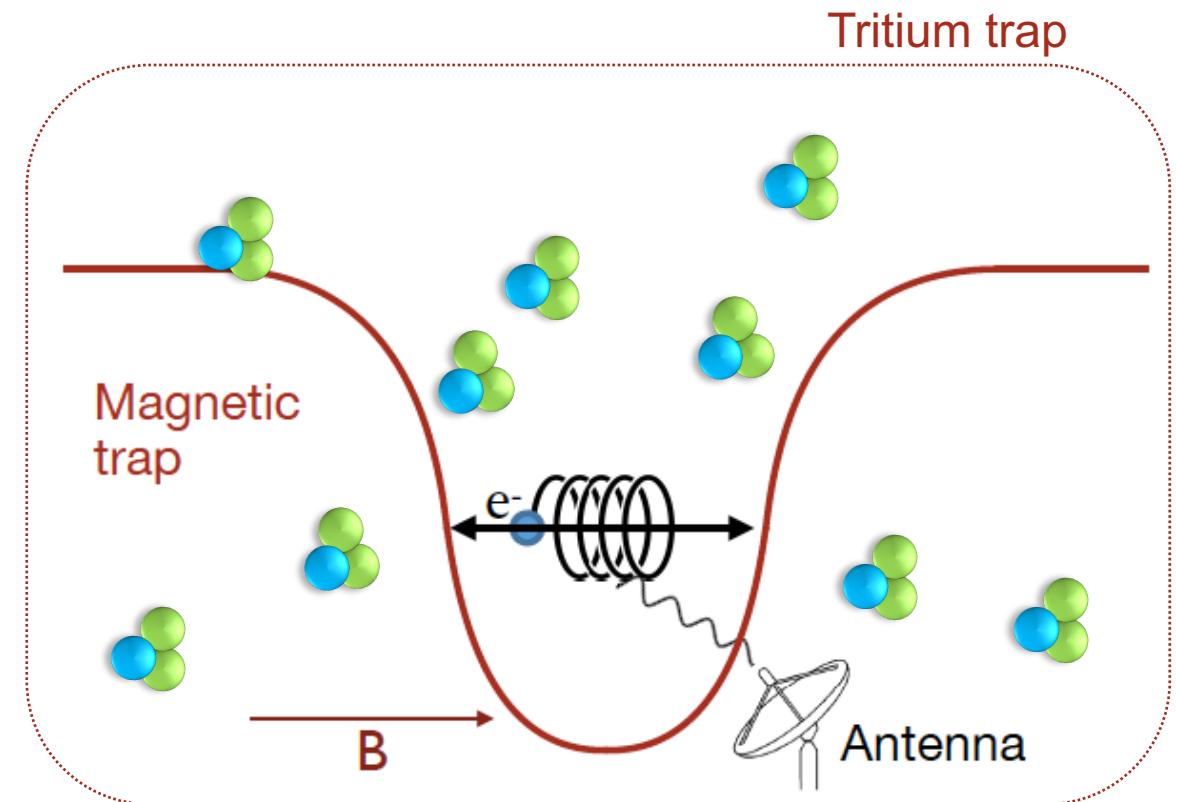


Working principle

Cyclotron Radiation Emission Spectroscopy (CRES)

B. Montreal and Joe Formaggio, Phys. Rev D 80:051301

$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{E + m_e}$$



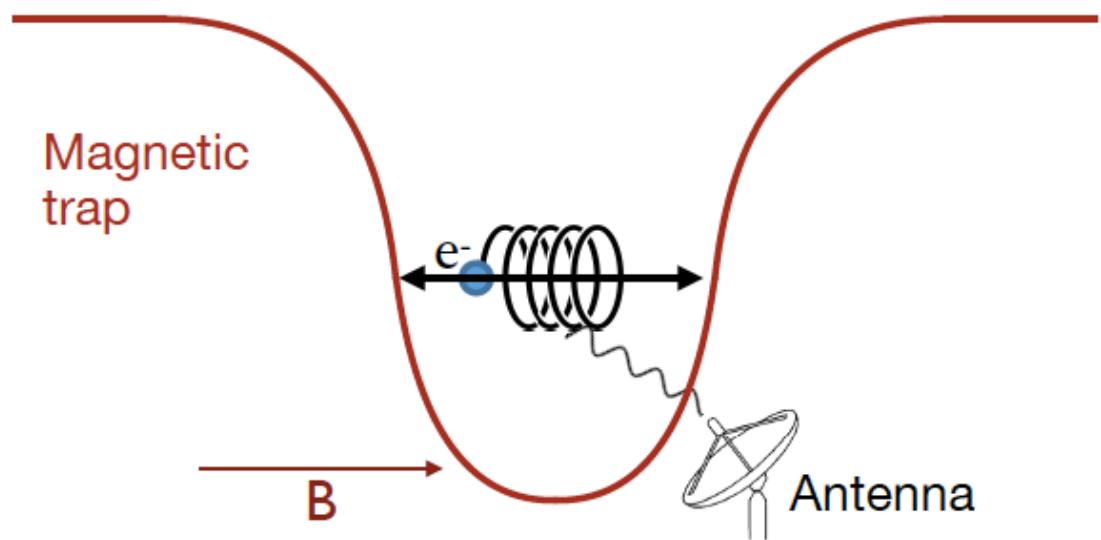
Working principle

Advantages:

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

Challenges:

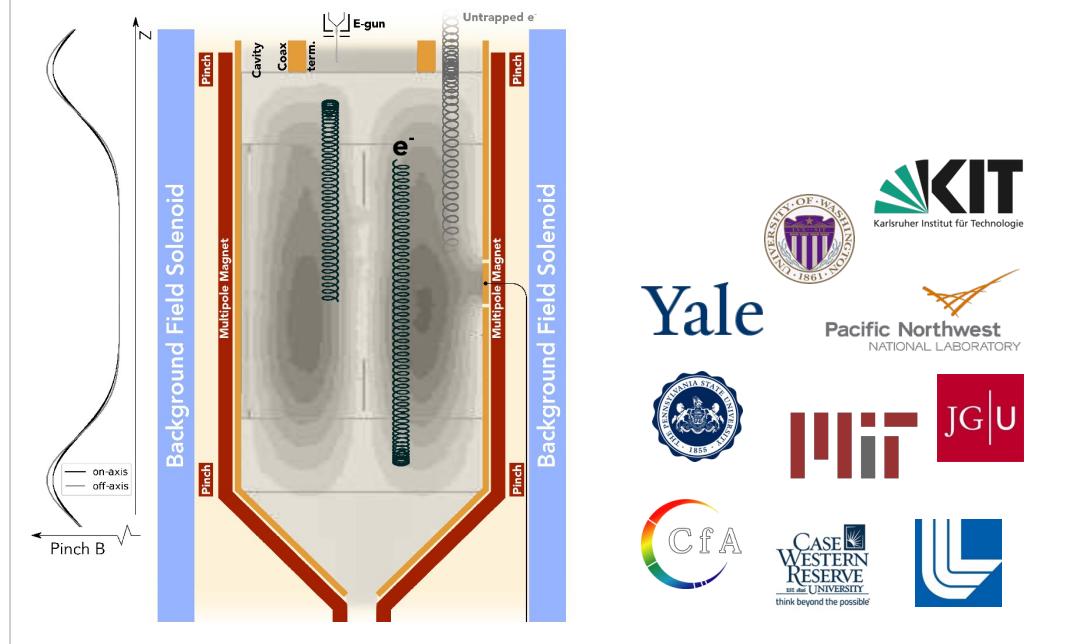
- Sub-eV energy resolution
→ **B-field homogeneity at the 10^{-7} -level**
- High statistics ($\sim 10^{19}$ T-atoms for < 0.04 eV sensi)
→ **large volume ($\sim m^3$) atomic tritium trap**
- Detection of femto - zetta Watt radiation
- ...



Experiments

Project-8

- Cold tritium atom trap + resonant cavity

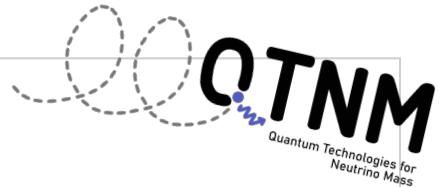


PROJECT 8



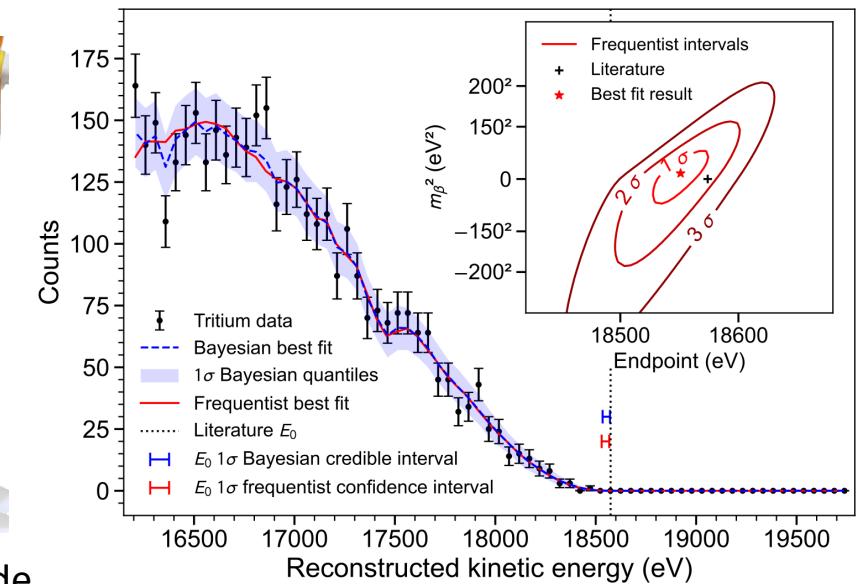
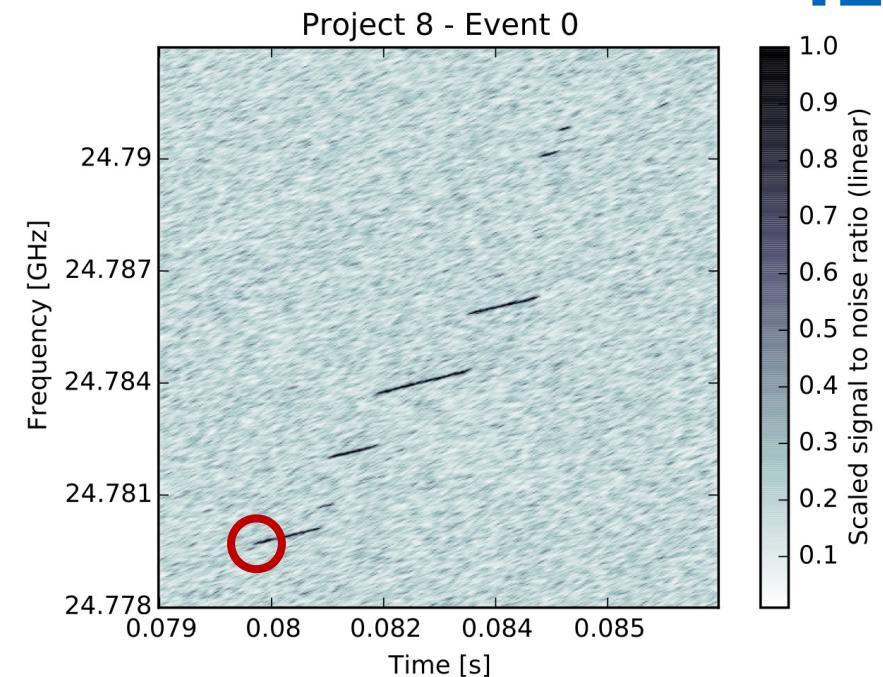
QTNM

- Storage ring confinement
- New effort, conceptual stage



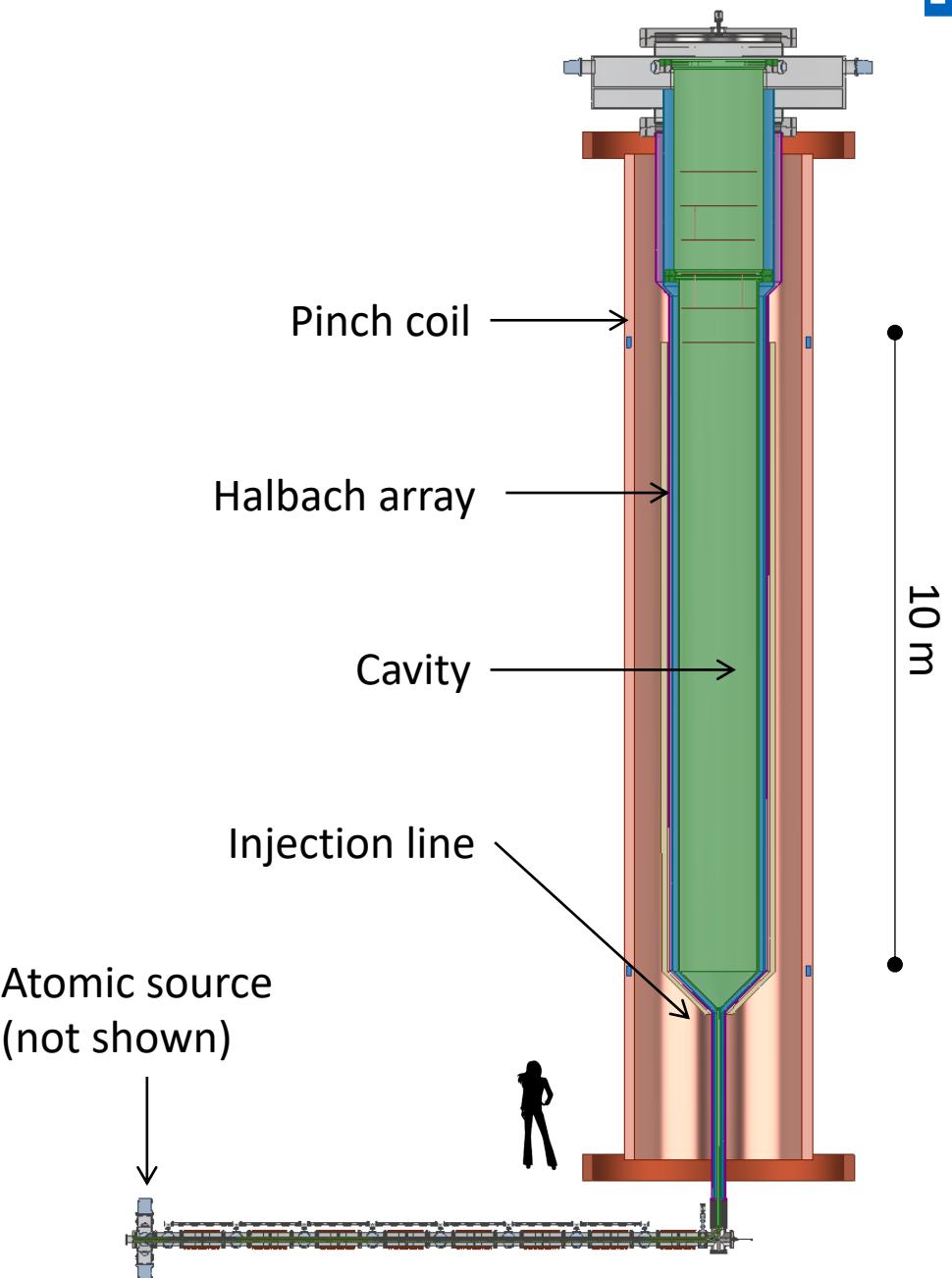
Project 8

- **Achievements:**
 - ✓ **Proof of CRES concept**
D.M. Asner et al., Phys. Rev. Lett. 114, 162501 (2015)
 - ✓ **First neutrino mass limit: $m_\nu < 185$ eV (90% CI.)**
arXiv:2212.05048 (2022)
- **Next steps / challenges:**
 - large-volume (m^3) cavity resonator
 - develop atomic tritium source
(atoms stored in magneto-gravitational trap)
- **Ultimate goal:**
 - Cover inverted ordering: 40 meV sensitivity
arXiv:2203.07349 (2022)



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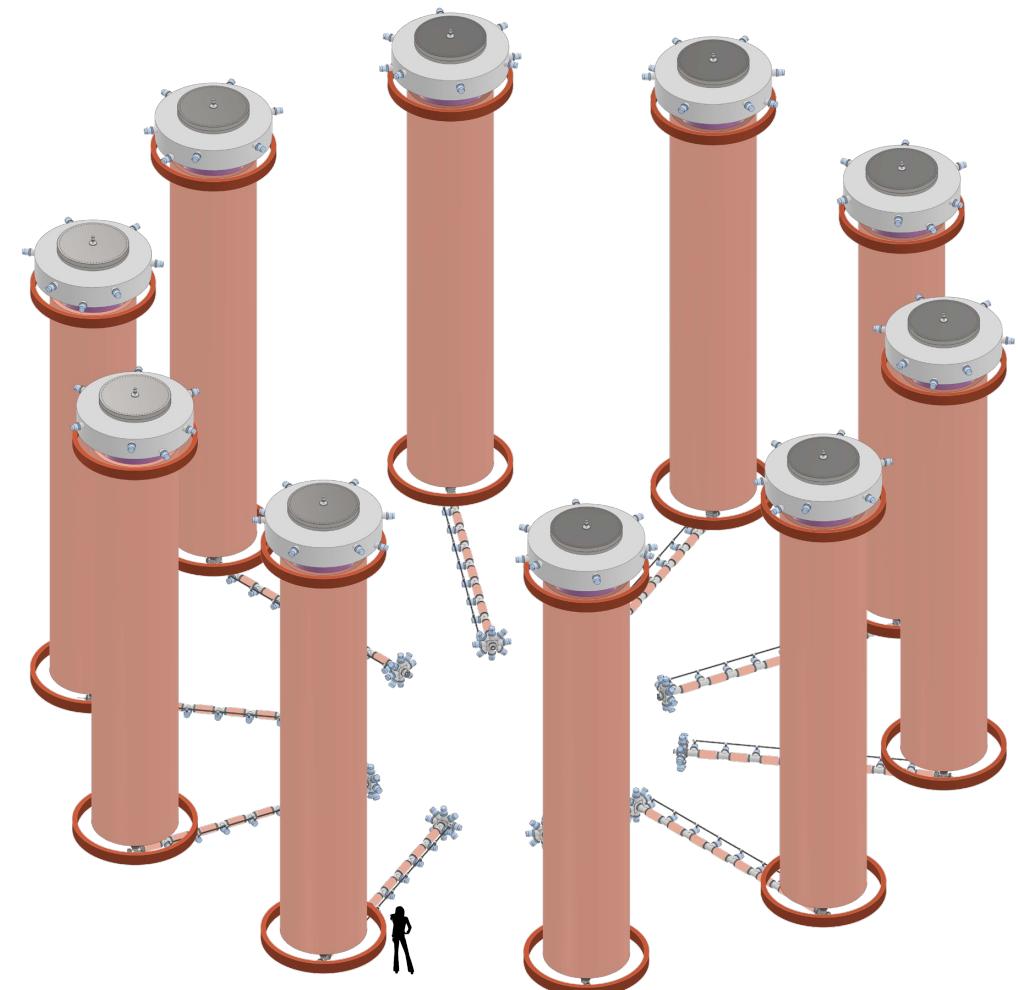
Project 8

N. Oblath
30 August, 16:45

L. Thorne
30 August, 15:15

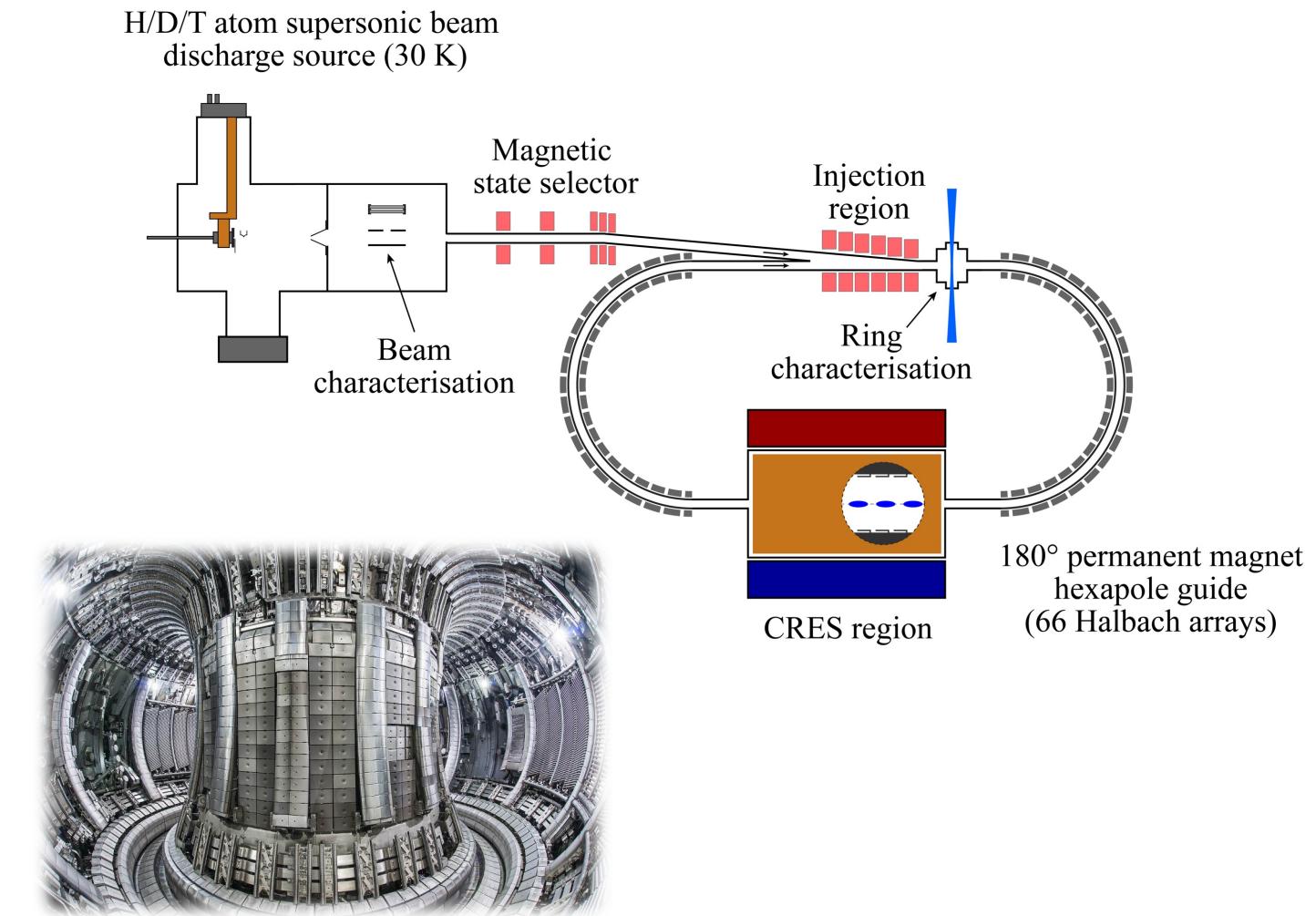
J. Stachurska
29 August, 17:30

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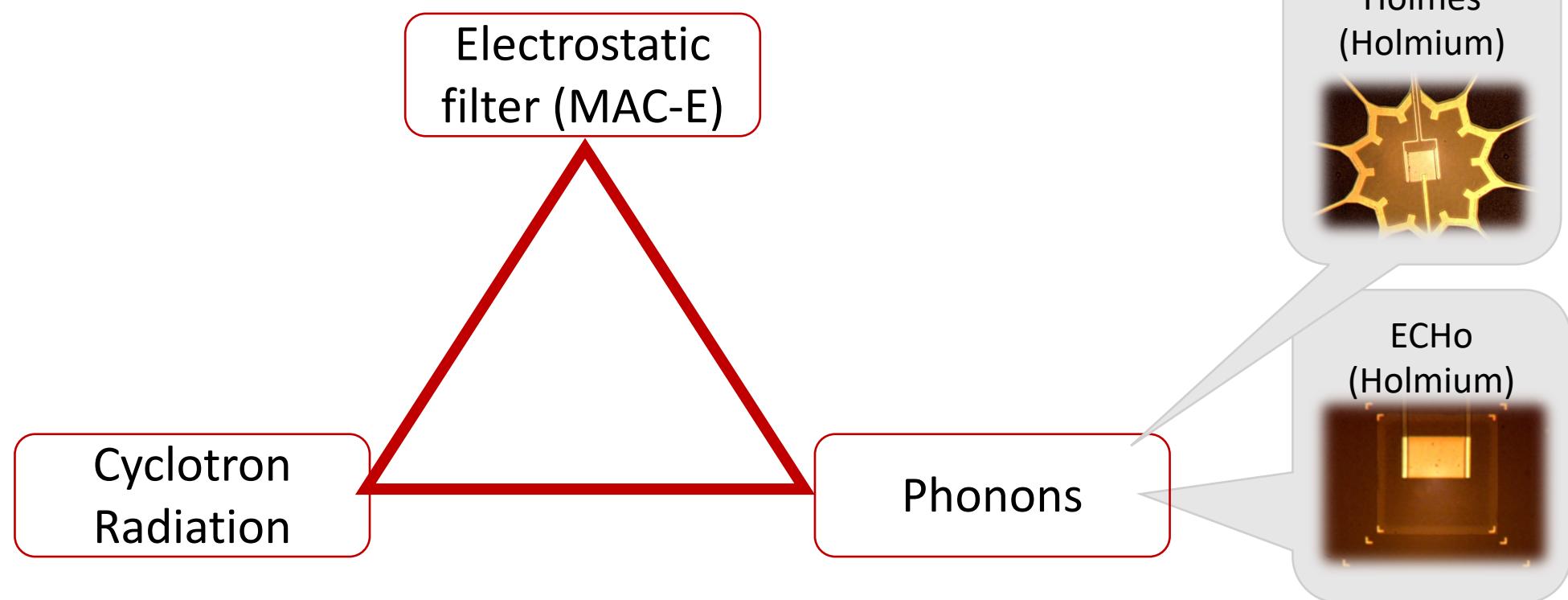


QTNM: Quantum Technology for Neutrino Mass

- **Current effort:**
 - Key technology demonstration:
e.g. H-storage, B-field mapping,
CRES with quantum limited
micro-wave electronics
- **Mid-term future:**
 - Demonstrator (CRESDA) at
tritium facility (strong
engagement with Culham, UK)



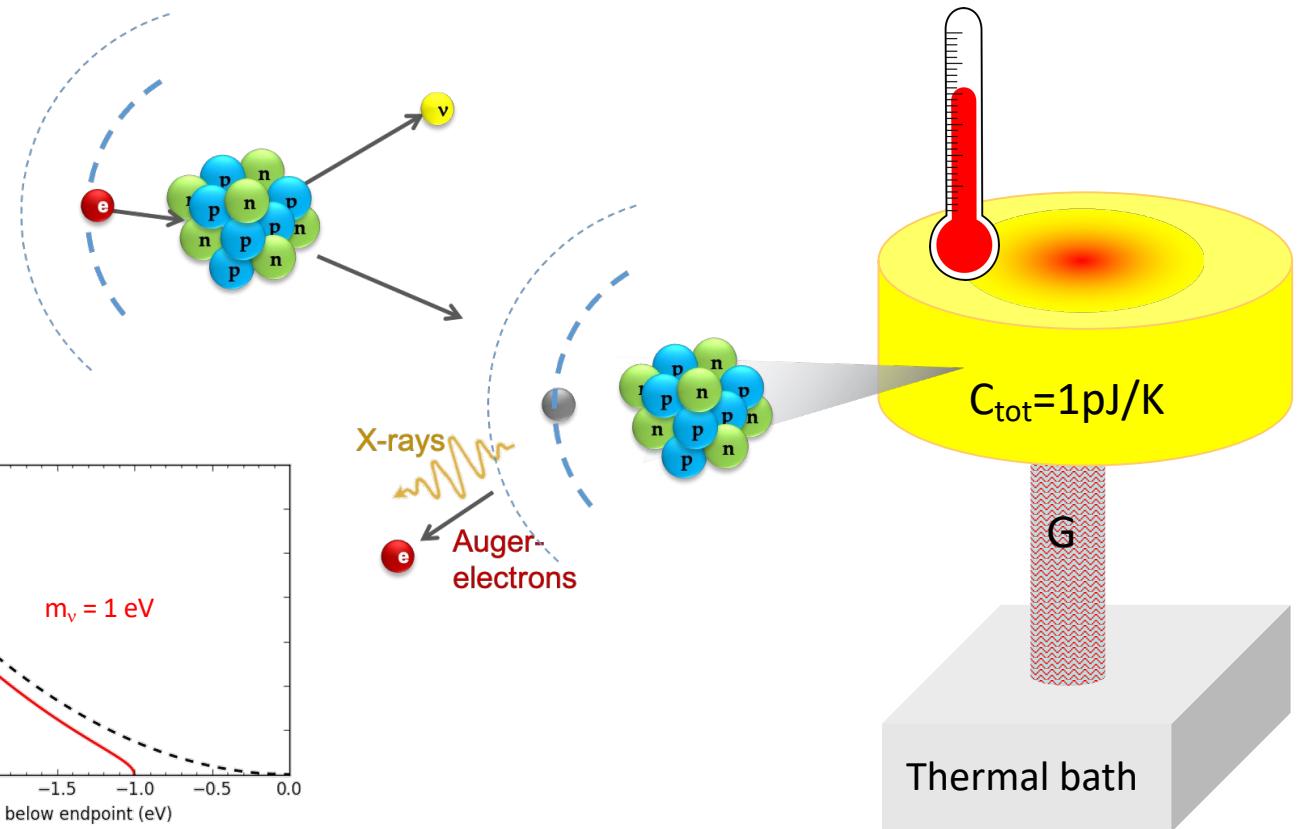
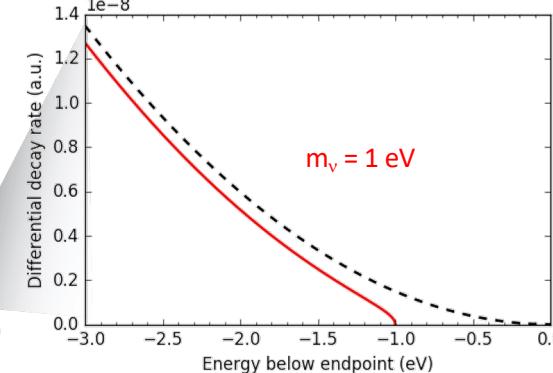
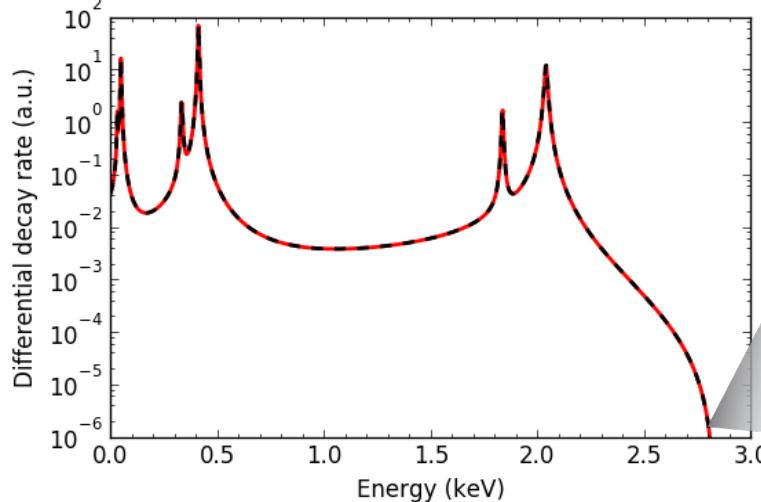
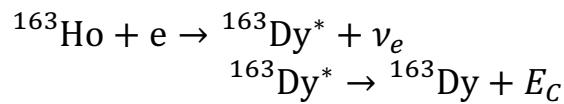
Experimental efforts



Working principle

Low-temperature micro-calorimetry with holmium

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



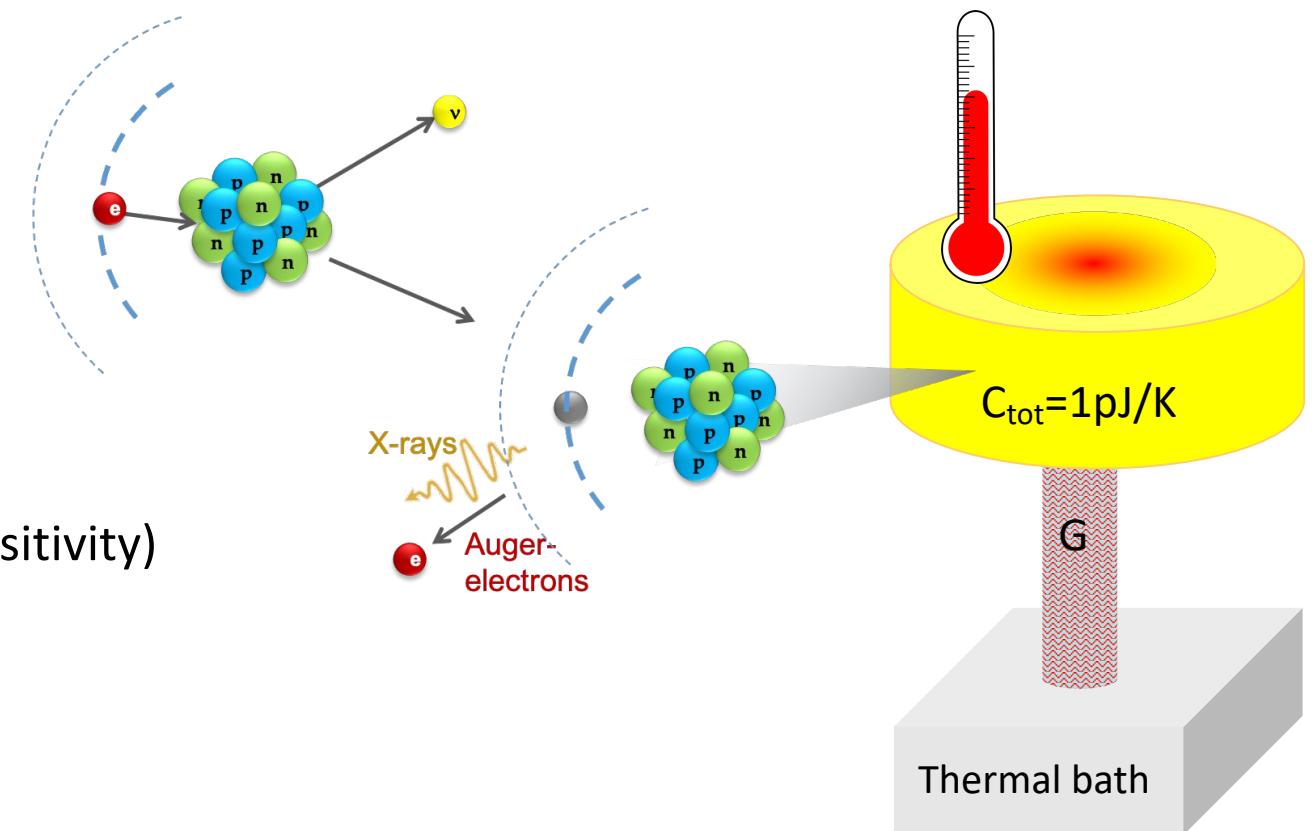
Working principle

Advantages:

- ✓ eV-scale differential measurement
- ✓ „source = detector“ concept

Challenges:

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

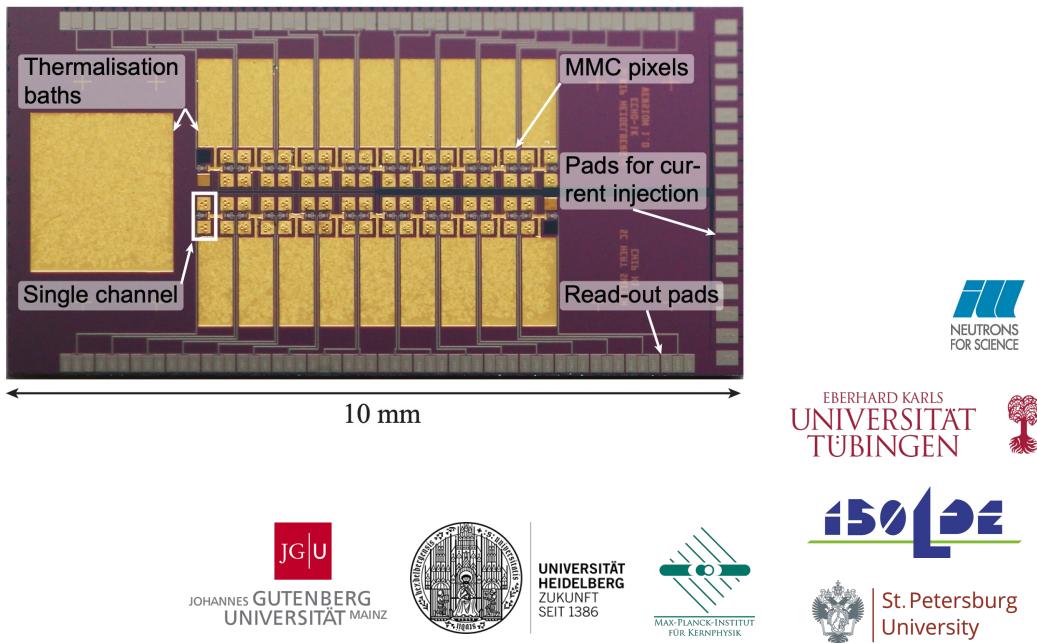


Experiments



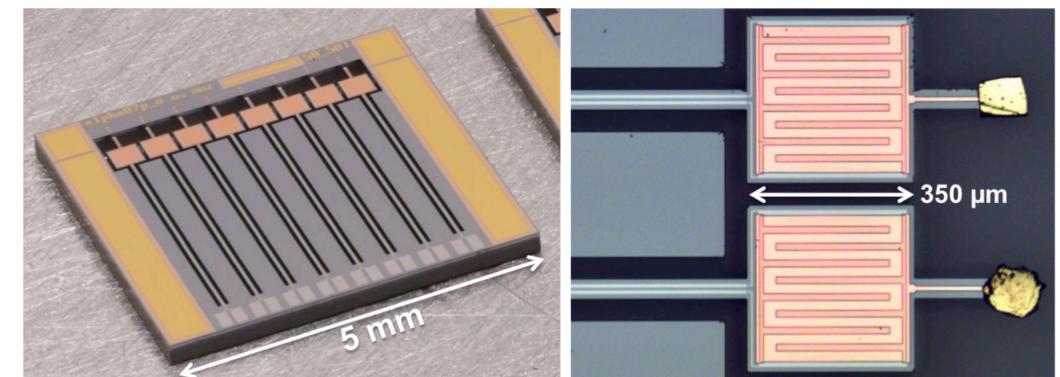
ECHo

- metallic magnetic calorimeters (MMC)
- L. Gastaldo et al. Eur. Phys. J. Spec. Top. 226 (2017)



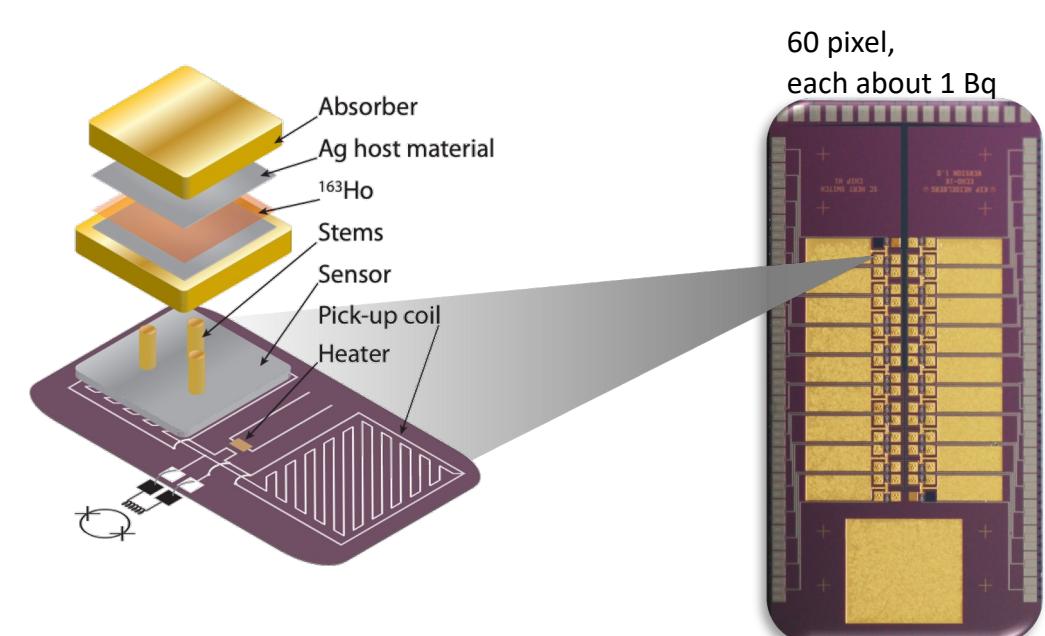
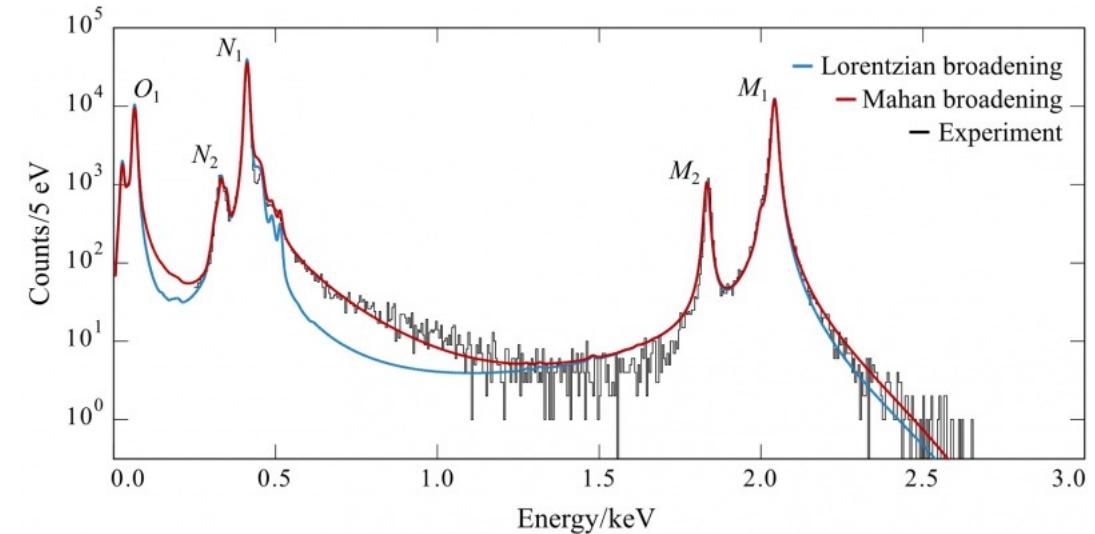
HOLMES

- transition edge sensors (TES)
- J Low Temp Phys* **184**, 492–497 (2016)



ECHo

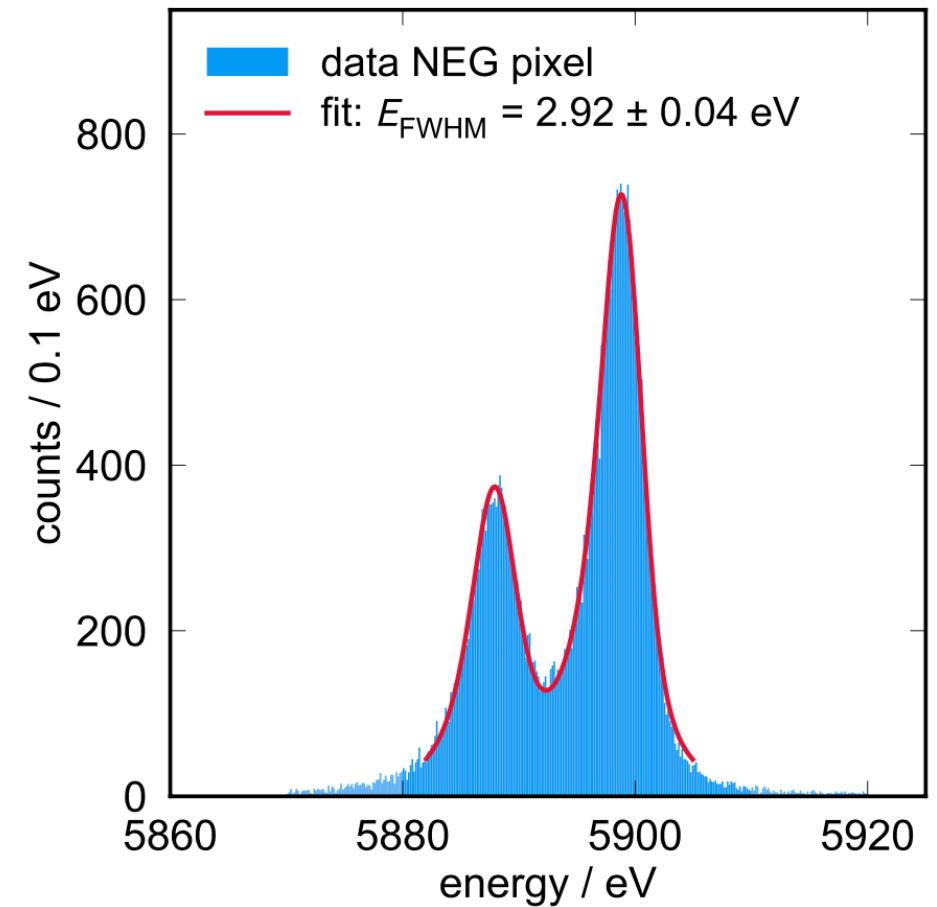
- **Achievements**
 - ✓ **Prototype:** nu-mass limit: $m < 150$ eV (95% C.L.)
EPJ-C 79 1026 (2019)
 - ✓ **ECHo-1k:** completed (10^8 counts)
 ~ 1 Bq/pixel \rightarrow 60 pixels \rightarrow <10 eV FWHM \rightarrow 20 eV sensitivity
EPJ-C 81, 963 (2021)
 - ✓ **ECHo-100k:** excellent performance demonstrated
 ~ 10 Bq/pixel \rightarrow 12000 pixels \rightarrow 5 eV FWHM \rightarrow 2 eV sensitivity
NIMA, 1055, 2023, 168564
- **Next steps/challenges**
 - Scaling to more activity and pixels
- **Ultimate goal:**
 - 10 MBq (= 10^5 pixels) \rightarrow low sub-eV sensitivity



L. Gastaldo,
29 August, 16:30

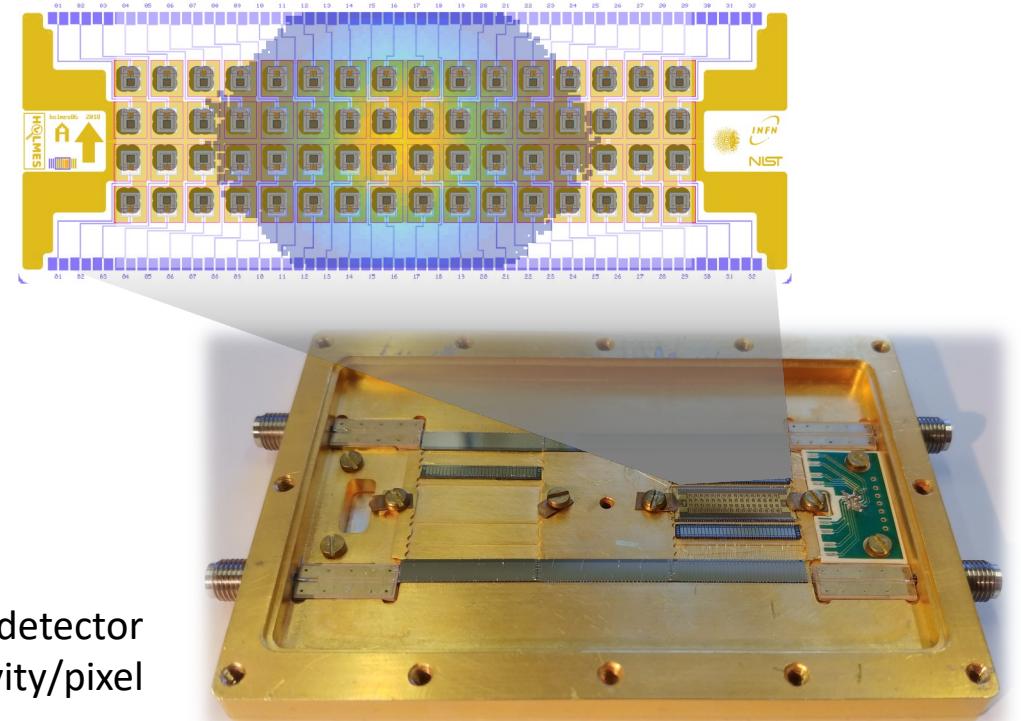
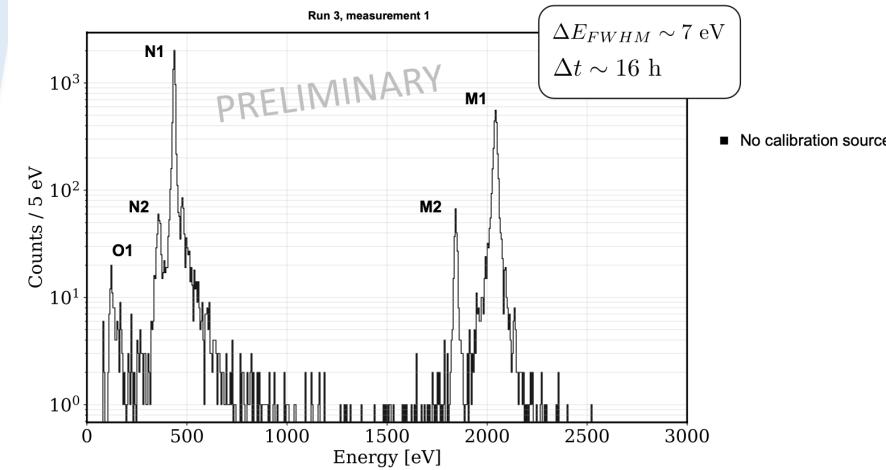
ECHo

- **Achievements**
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NIMA, 1055, 2023, 168564
- **Next steps/challenges**
 - Scaling to more activity and pixels
- **Ultimate goal:**
 - 10 MBq (= 10^5 pixels) → low sub-eV sensitivity



Holmes

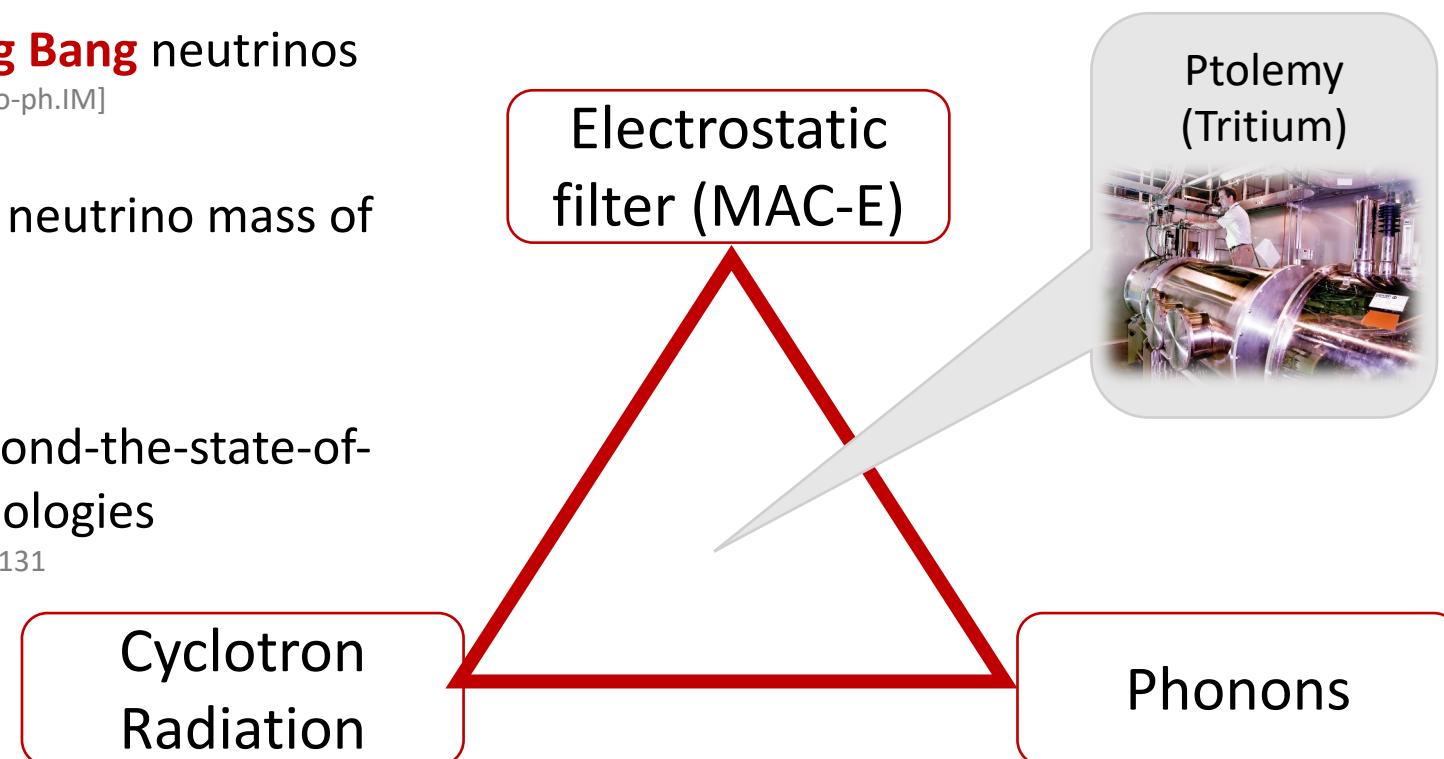
- **Approach:**
 - Maximize activity per pixel (if possible)
→ reduce number of pixels
- **Achievements**
 - ✓ Mid June 2023:
First detector array finalized
 - ✓ First holmium spectra measured
 $\langle A \rangle \approx 0.5 \text{ Bq}$, $\Delta E_{\text{FWHM}} = 7 \text{ eV}$ @6keV
- **Next steps:**
 - Scaling to more activity and pixels



Experimental efforts

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

J. Mead
28 August, 15:15



Summary

KATRIN (integral)

- Leading neutrino mass limit ($m_\nu < 0.8$ eV) from direct measurements
- Upcoming data release this year: sensitivity better than 0.5 eV
- Final goal: sensitivity better than 0.3 eV

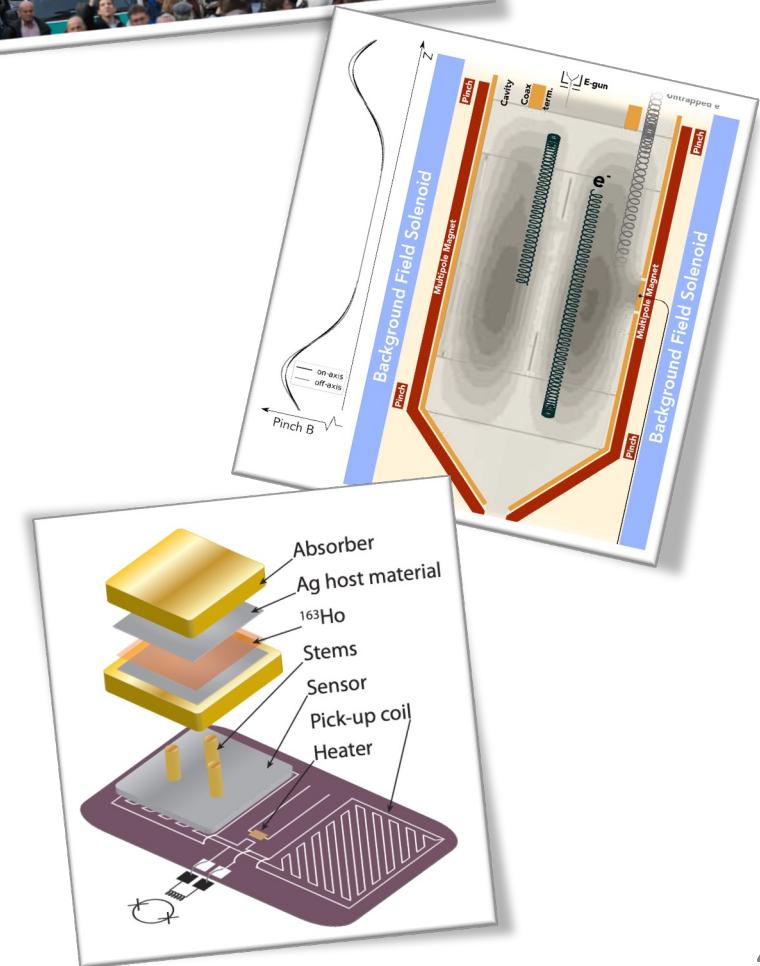


Cyclotron Radiation Emission Spectroscopy (differential): Project-8 & QTNm

- First neutrino mass limit $m_\nu < 150$ eV (Project-8)
- Next step: Scaling up to **large-volume traps**, develop **atomic tritium source**

Microcalorimeter (differential): ECHo & Holmes & KATRIN++

- First neutrino mass limit $m_\nu < 150$ eV (ECHo) and $m_\nu < 10$ eV is in reach
- Next step : Scaling-up to **high-activity** and **large number of detectors**



Thank you for your attention



Thanks to the KATRIN collaboration
ECHO collaboration
Project-8 collaboration
Holmes collaboration
QTNM collaboration

Dr. Susanne Mertens

Technical University Munich