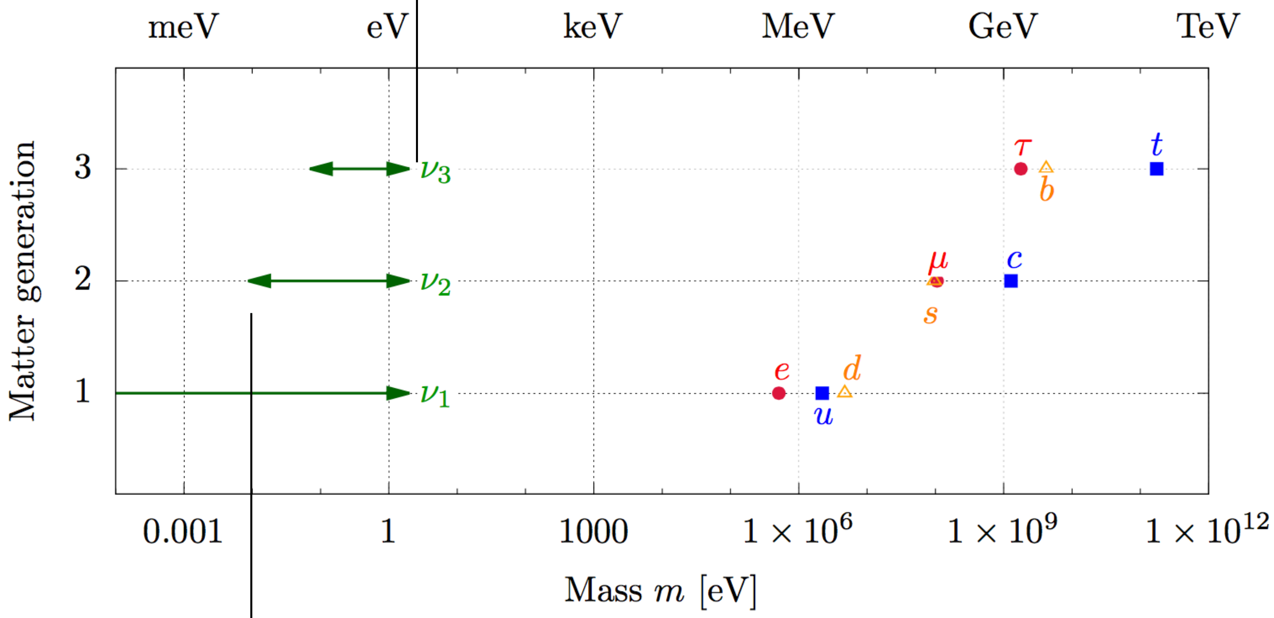
Direct Neutrino Mass Measurements

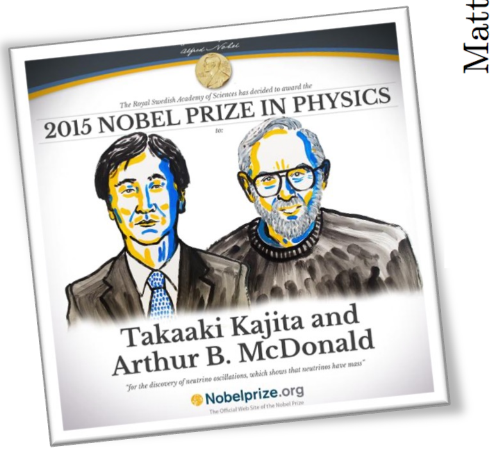
22nd International Workshop on Next Generation Nucleon Decay and Neutrino Detectors

Thierry Lasserre (CEA & TUM)
Procida, 12/10/2023

Neutrino mass

Upper bound
from direct measurements





Lower bound
from oscillation experiments

Neutrino mass

Cosmology

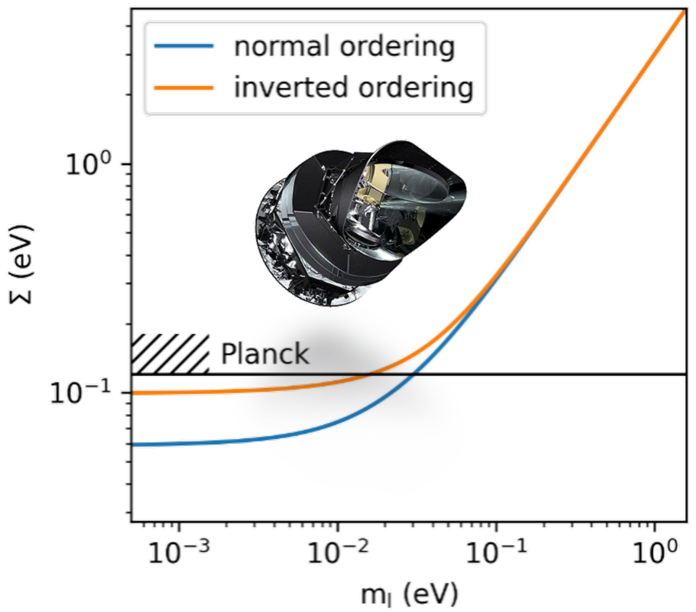
$$\Sigma = \sum_i m_i$$

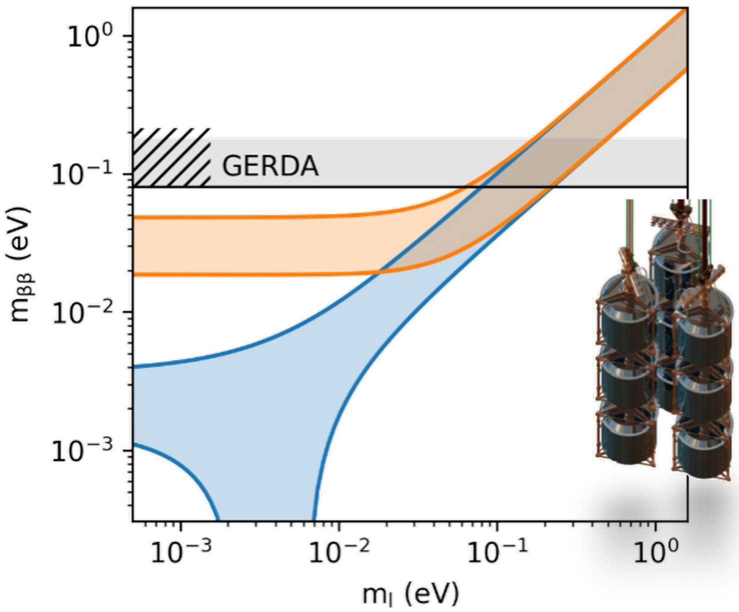
Neutrinoless ßß decay

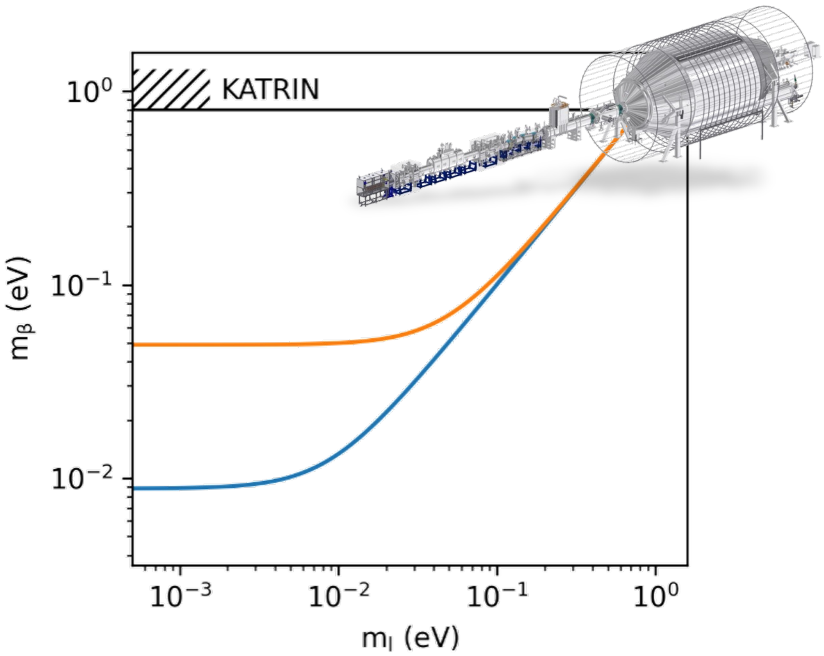
$$m_{\beta\beta} = |\sum_i U_{ei}^2 m_i|$$

ß-decay kinematics

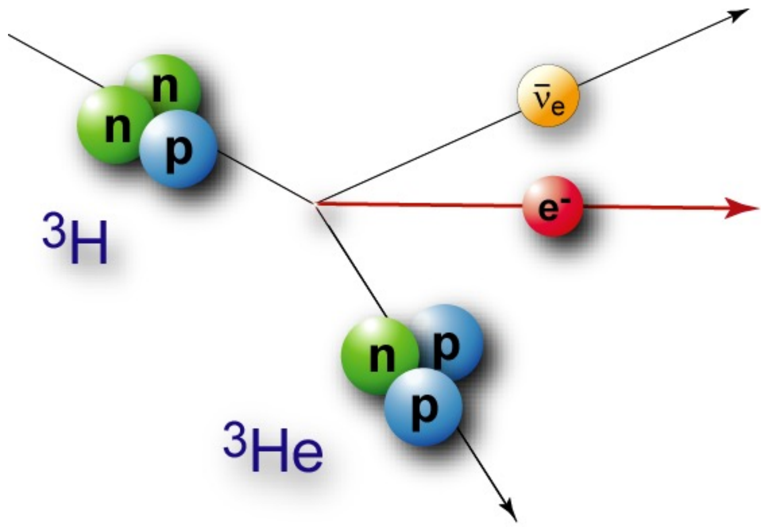
$$m_\beta = \sqrt{\sum_i |U_{ei}^2| m_i^2}$$







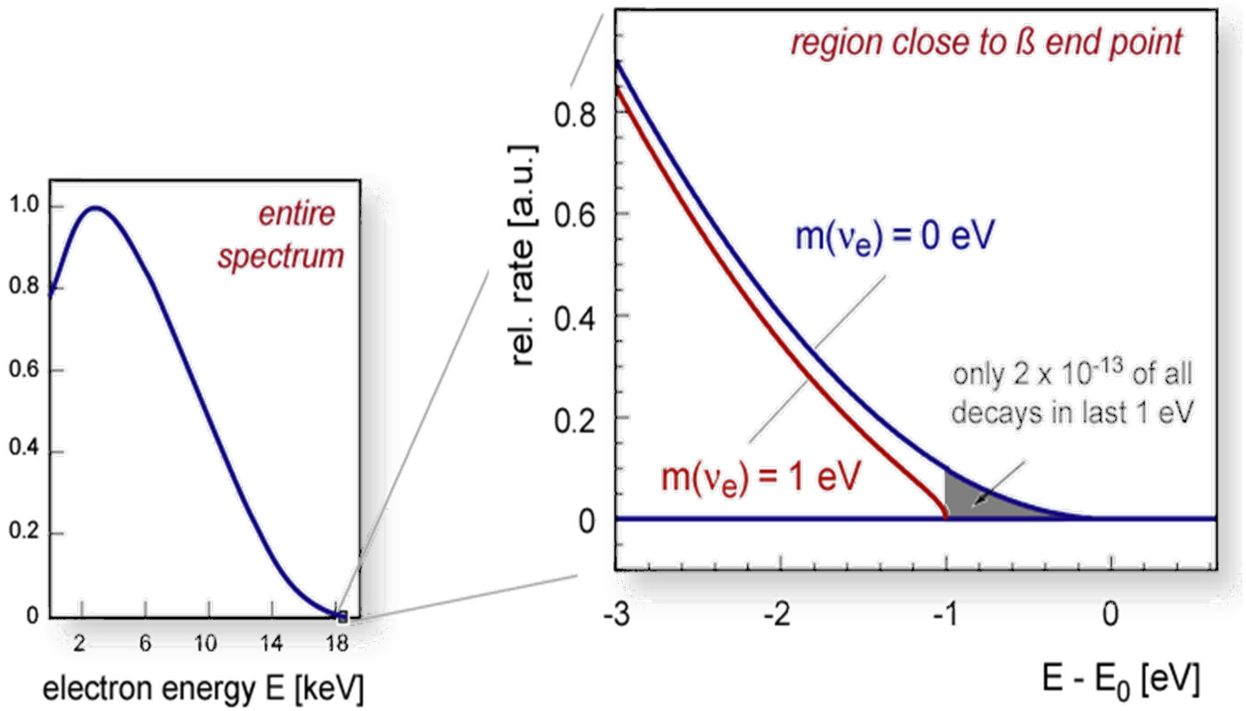
General idea



✓ Independent of cosmology

✓ Independent of neutrino nature

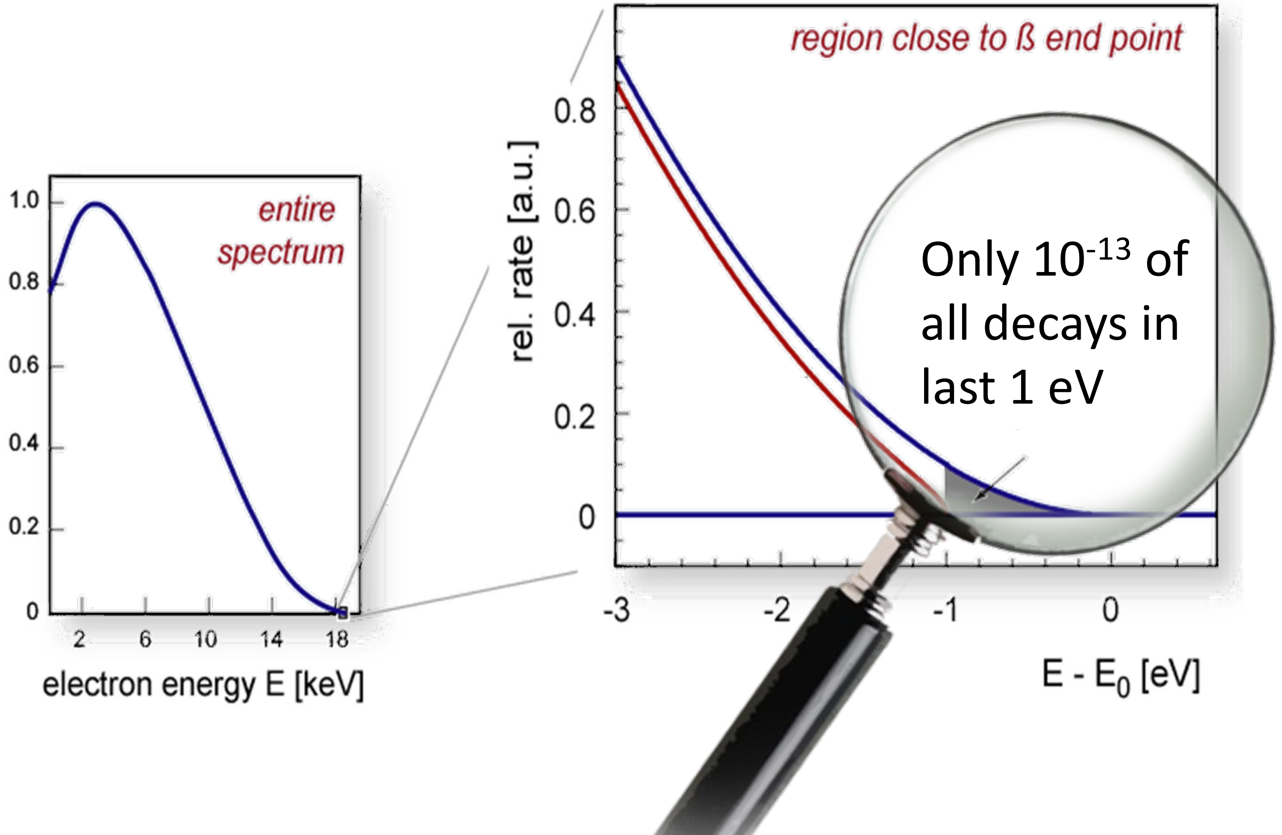
$$m^2(\nu_e) = \sum_i |U_{ei}|^2 \cdot m_i^2$$



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

Electrostatic filter (MAC-E)

counting above threshold

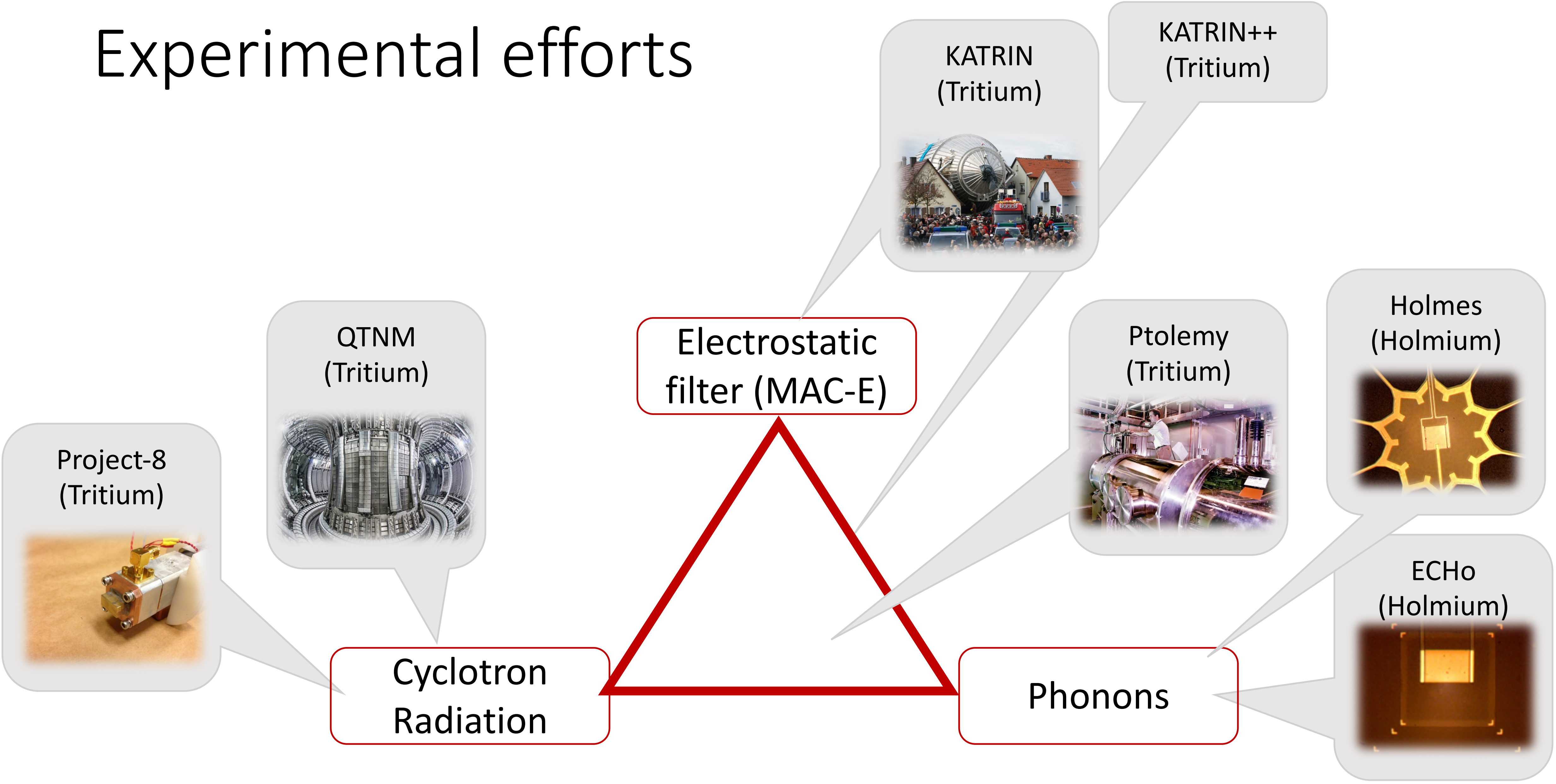
frequency

Cyclotron Radiation

heat

Phonons

Experimental efforts



Experimental efforts

KATRIN
(Tritium)

Electrostatic filter (MAC-E)

Cyclotron Radiation

Phonons

KATRIN

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

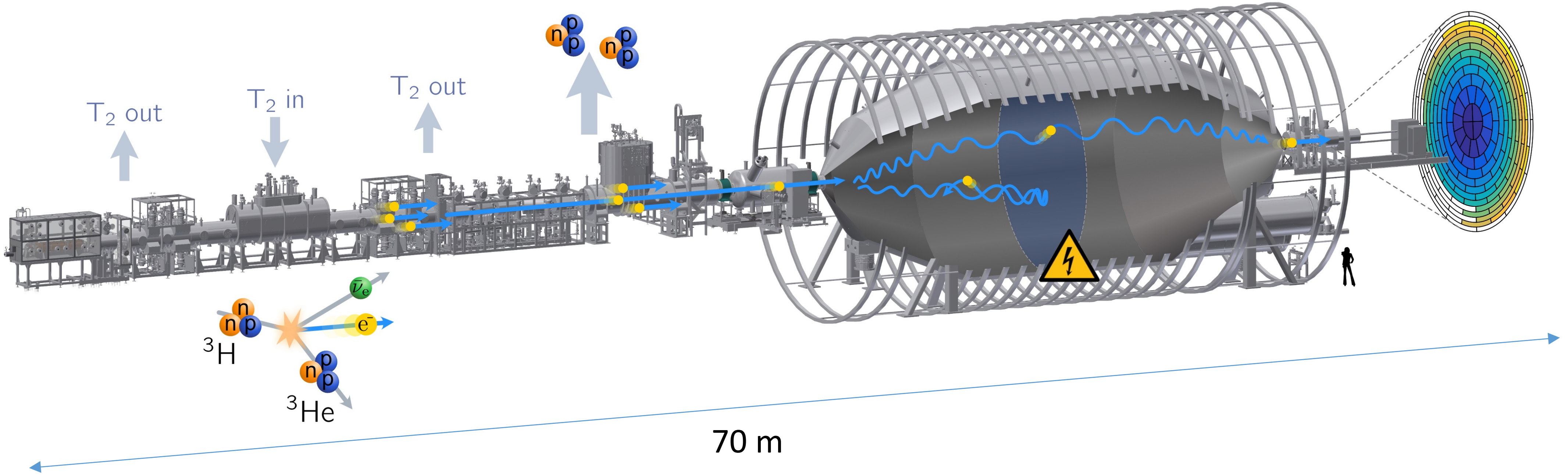
KIT Karlsruher Institut für Technologie
Max-Planck-Institut für Kernphysik Heidelberg
University of Washington
Case Western Reserve University EST. 1826 think beyond the possible
Westfälische Wilhelms-Universität Münster
Massachusetts Institute of Technology
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)
The University of North Carolina at Chapel Hill
The Czech Academy of Sciences
Hochschule Fulda University of Applied Sciences
Carnegie Mellon University Pittsburgh Pennsylvania 1900
Universidad Complutense Madrid
Università degli Studi di Milano Bicocca
cea
JG|U Johannes Gutenberg Universität Mainz
TUM Technische Universität München
universitätbonn
Politecnico Milano 1863
Humboldt-Universität zu Berlin
Bergische Universität Wuppertal
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



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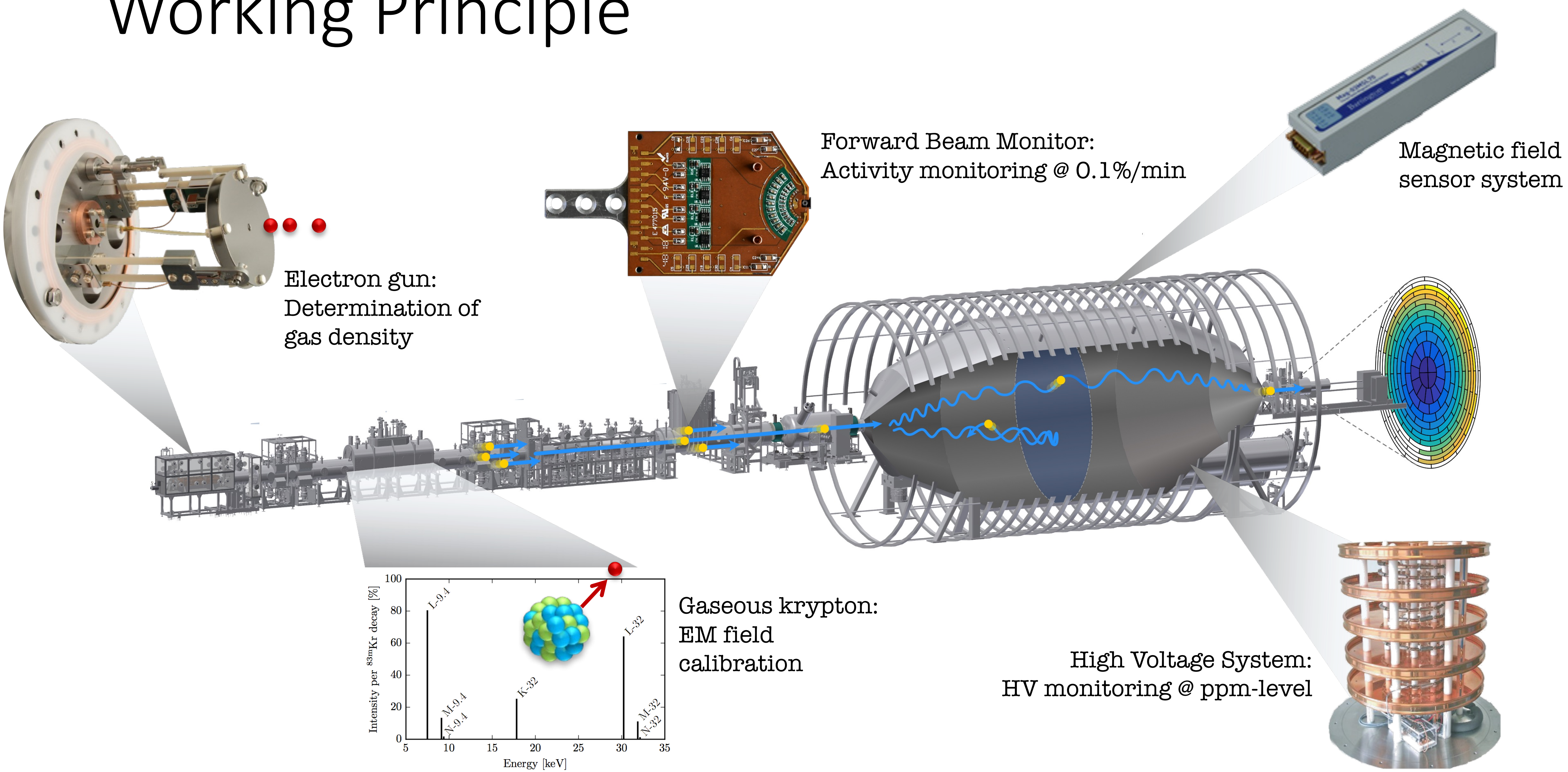
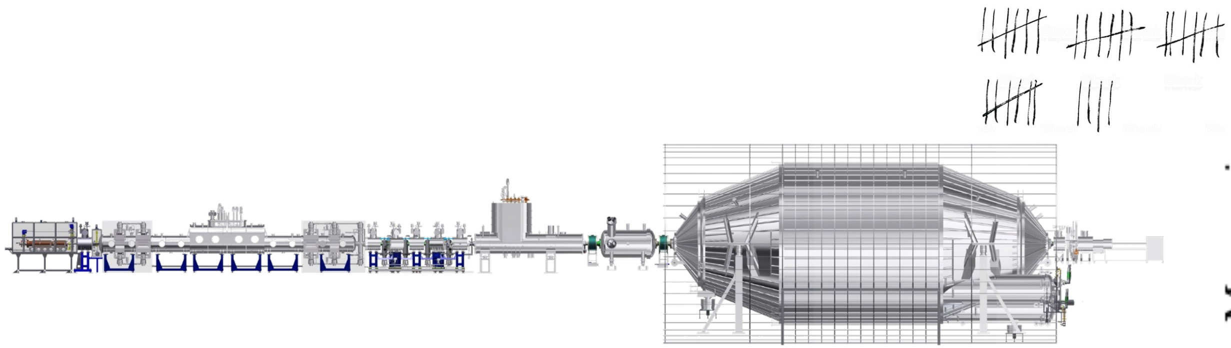


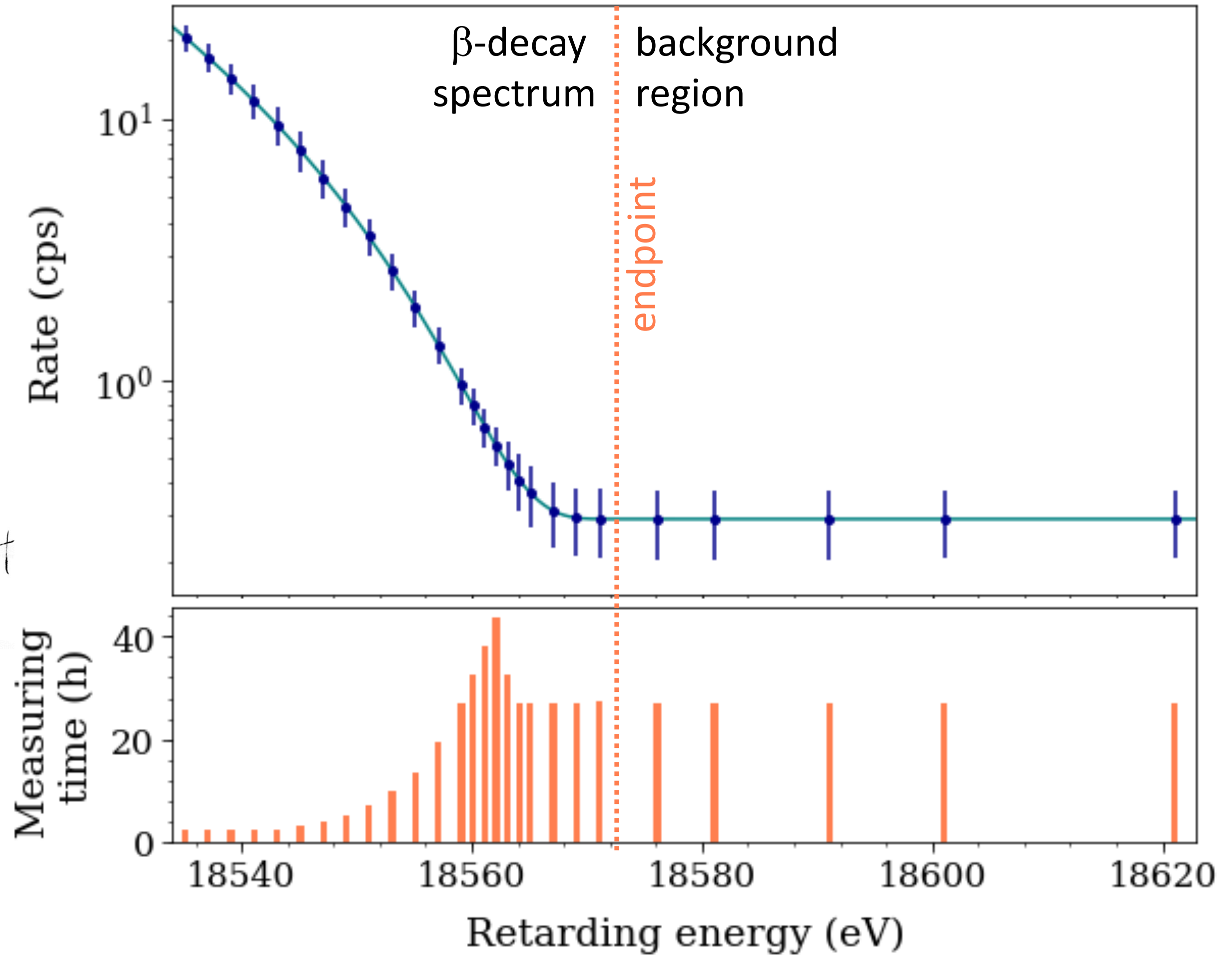
Measurement strategy

β-scans:

- Scan points: **30 HV set points**
- Scan interval: **E_0 – 40 eV , E_0 + 130 eV**
- Scan time: **3 hours**

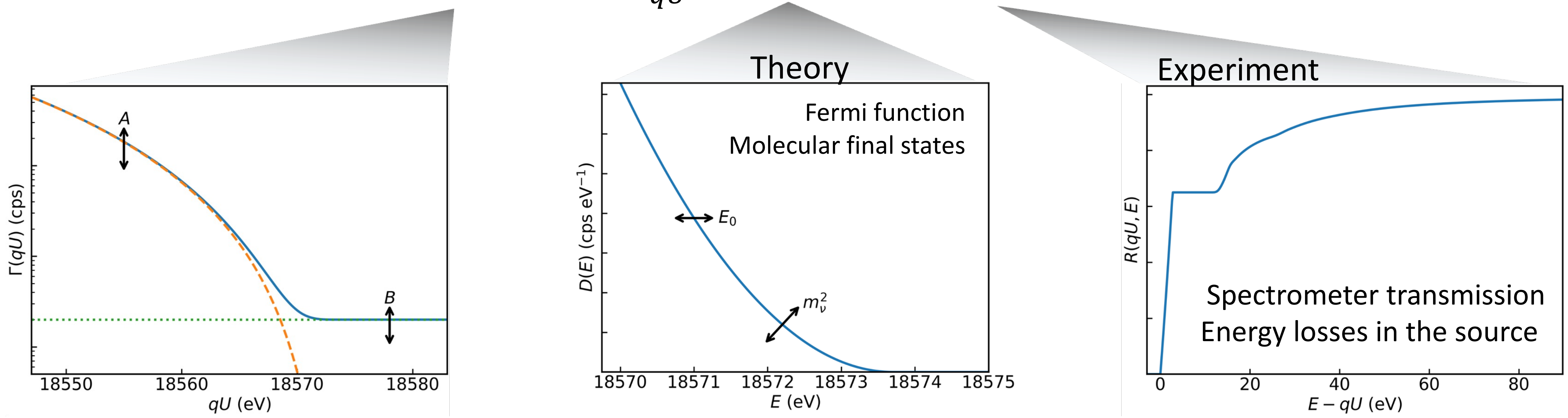


Integral spectrum



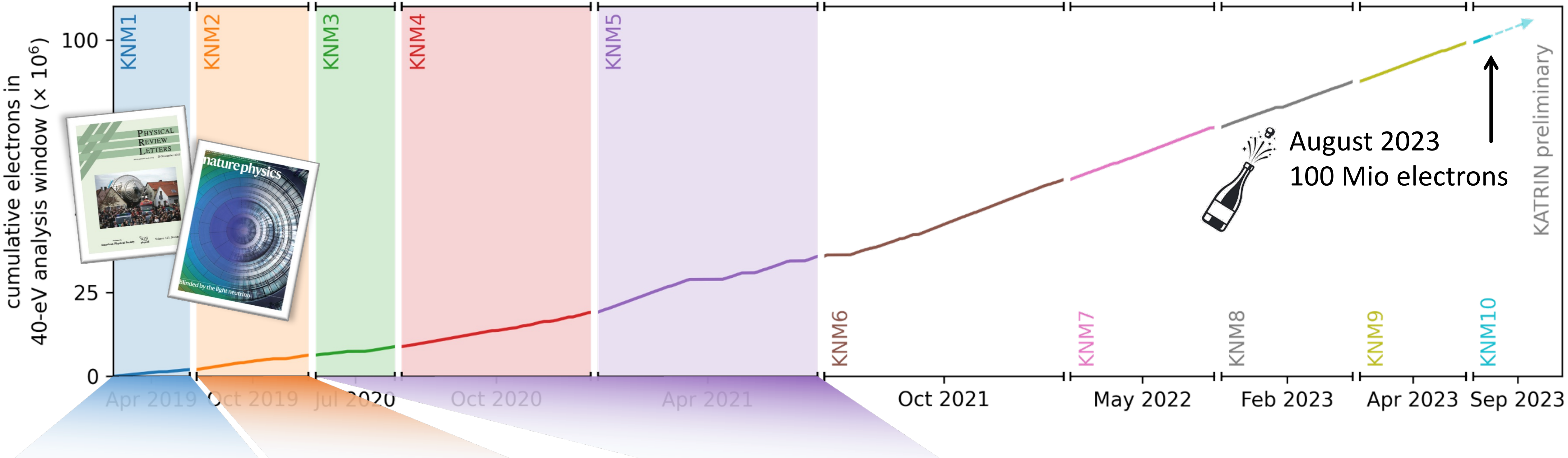
Analysis strategy

- Fit of theoretical prediction: $\Gamma(qU) \propto \boldsymbol{A} \cdot \int_{qU}^{\boldsymbol{E_0}} D\left(E; \boldsymbol{m_\nu^2}, \boldsymbol{E_0}\right) \cdot R(qU, E)\, dE + \boldsymbol{B}$



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

KATRIN Data Taking Overview



- 1^{st} m_ν campaign
- $m_\nu < 1.1$ eV

PRL. 123, 221802 (2019)

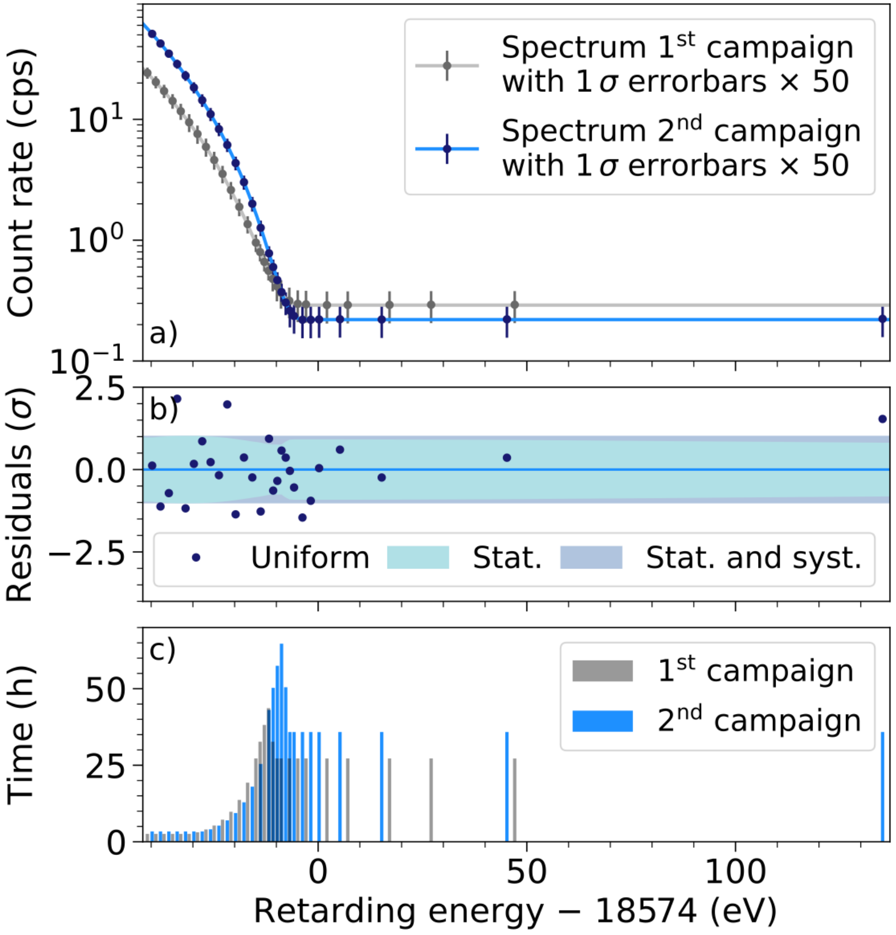
Phys. Rev. D 104, 012005 (2021)

- 2^{nd} m_ν campaign
- $m_\nu < 0.8$ eV

Nat. Phys. **18,** 160–166 (2022)

- 1^{st} to 5^{th} campaigns
- Unblinded, will be released soon

1st and 2nd campaign



First campaign:

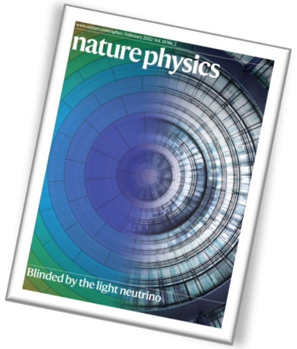
- total statistics: 2 million events
- best fit: $m_\nu^2 = \left(-1.0^{+0.9}_{-1.1}\right)$ **eV² (stat. dom.)**
- limit: $m_\nu < 1.1$ **eV (90% CL)**

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

Second campaign:

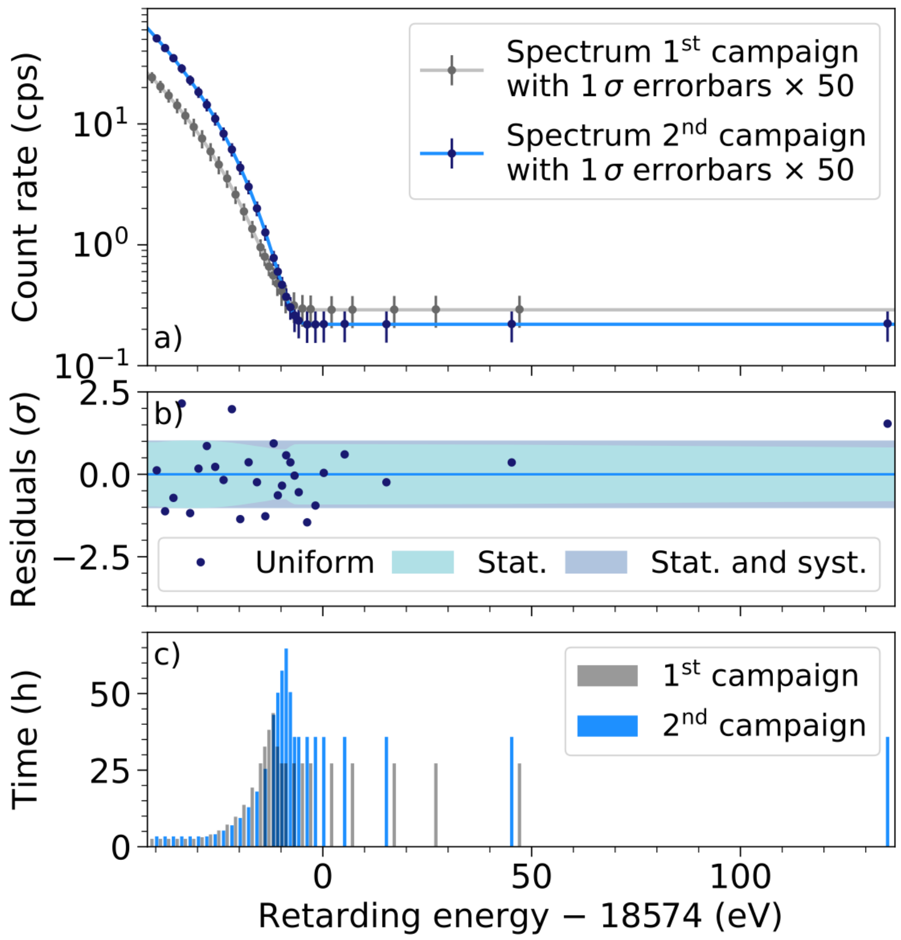
- total statistics: 4 million events
- best fit: $m_\nu^2 = \left(0.26^{+0.34}_{-0.34}\right)$**eV² (stat. dom.)**
- limit: $m_\nu < 0.9$ **eV (90% CL)**

Nat. Phys. ***18,*** *160–166 (2022)*



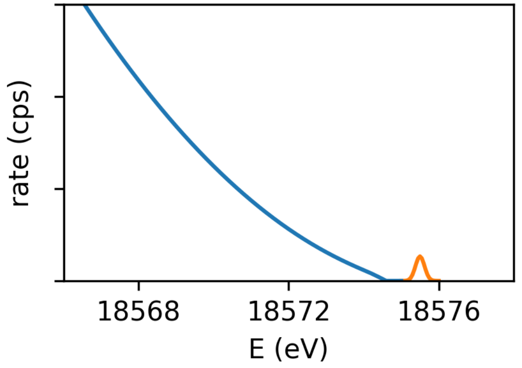
- **Combined result:** $m_\nu < 0.8$ **eV (90% CL)**

1^{st} and 2^{nd} campaign



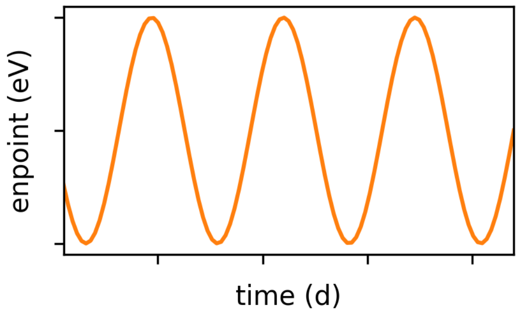
✓ Search for relic big-bang neutrinos

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



✓ Search for violation of Lorentz invariance

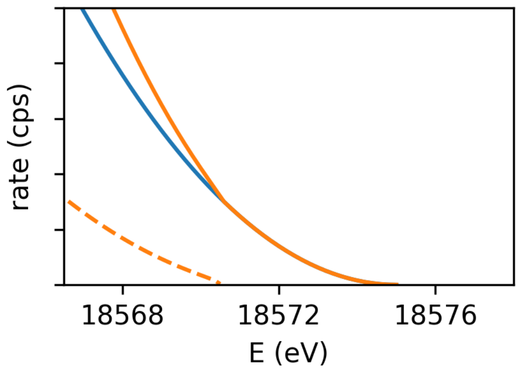
Phys. Rev. D **107**, 082005 (2023)



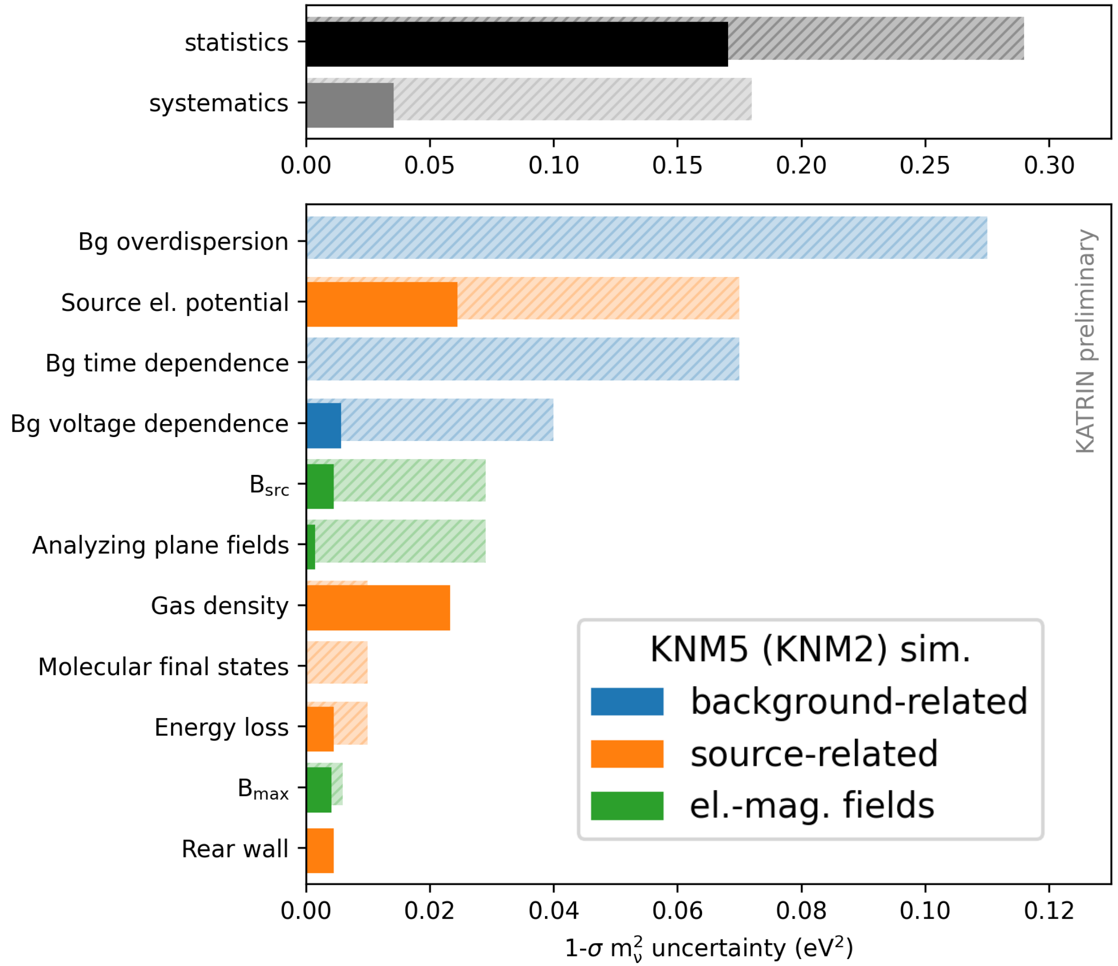
✓ Search for light sterile neutrinos

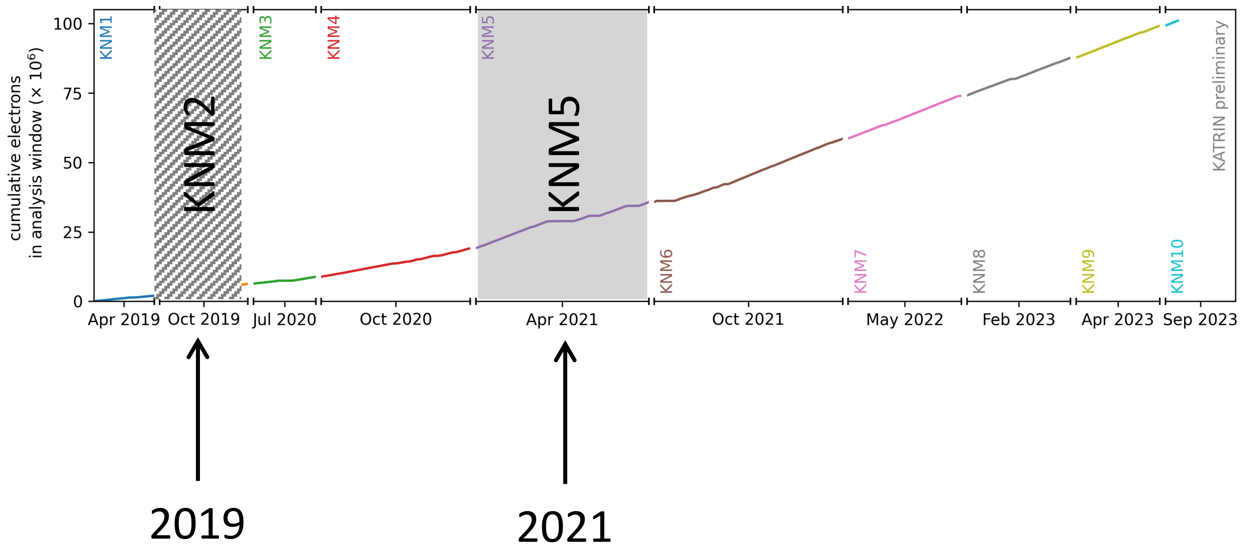
Phys. Rev. Lett. **126**, 091803 (2021)

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



Improvements: 2^{nd} vs 5^{th} campaign





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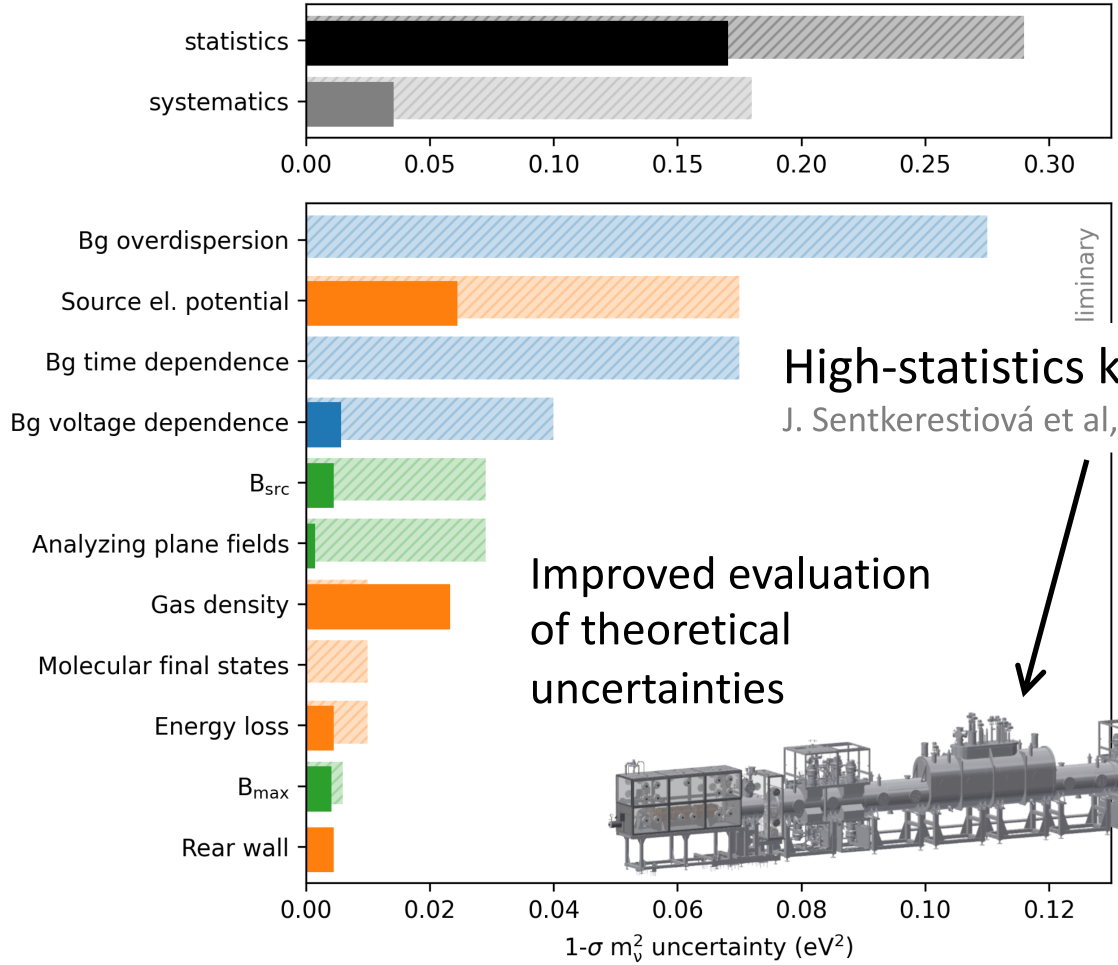


Improved evaluation of theoretical uncertainties

High-statistics krypton calibration

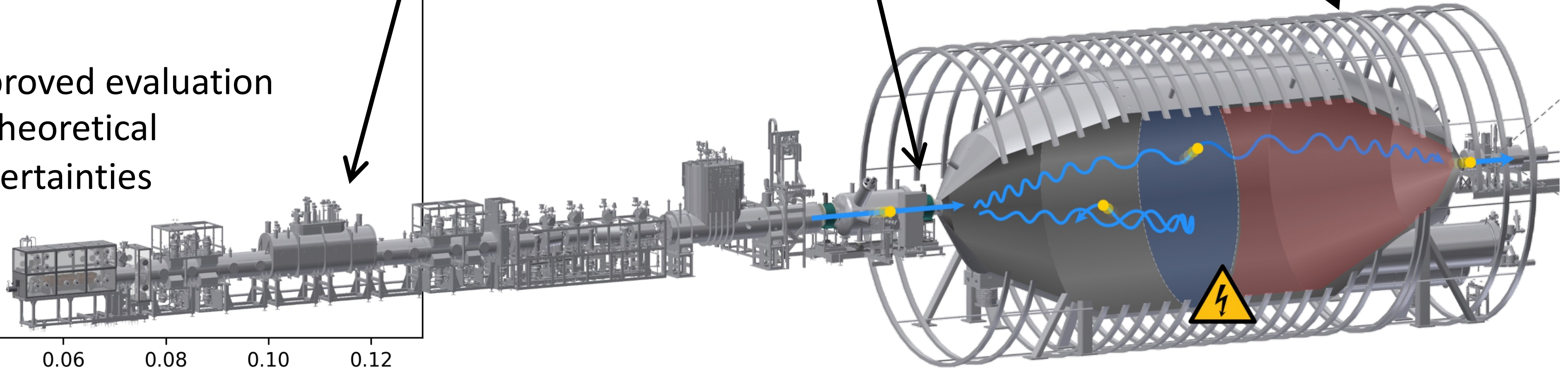
J. Sentkerestiová et al, JINST 13 (2018)

Elimination of penning trap

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

Shifted analzing plane

Lokhov et al arXiv:2201.11743 (2022)



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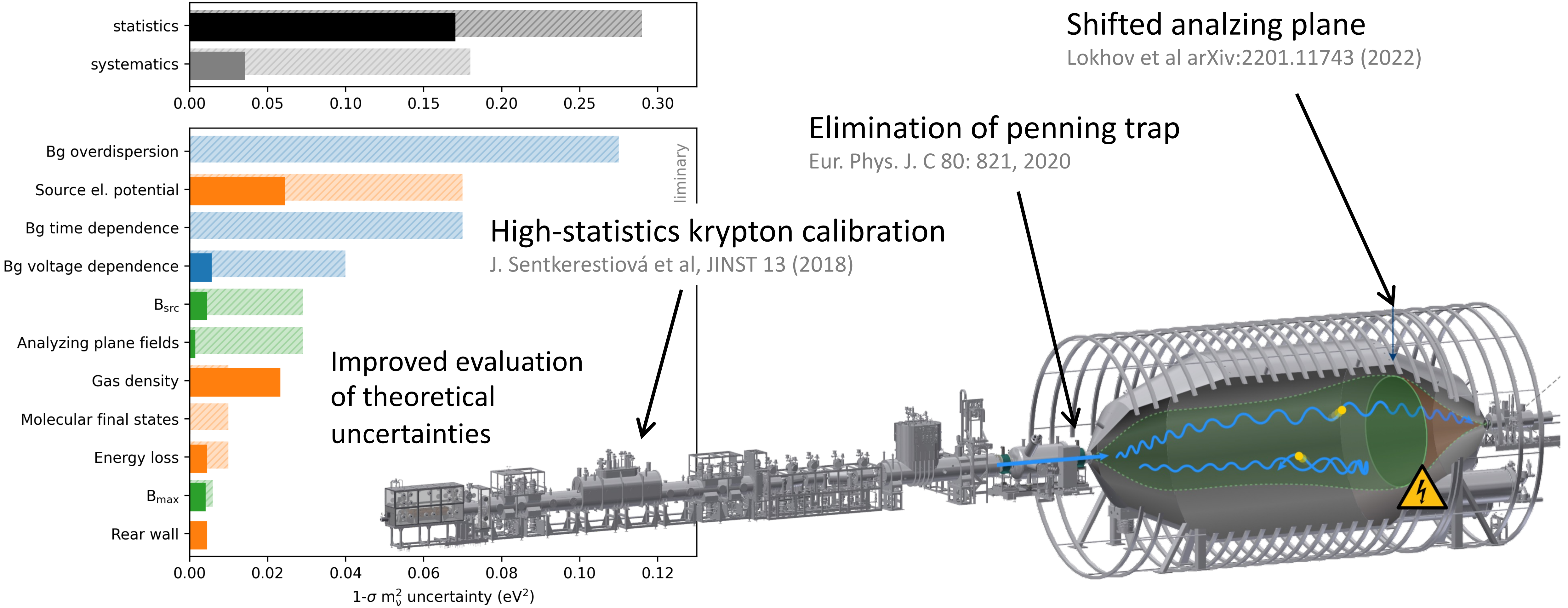

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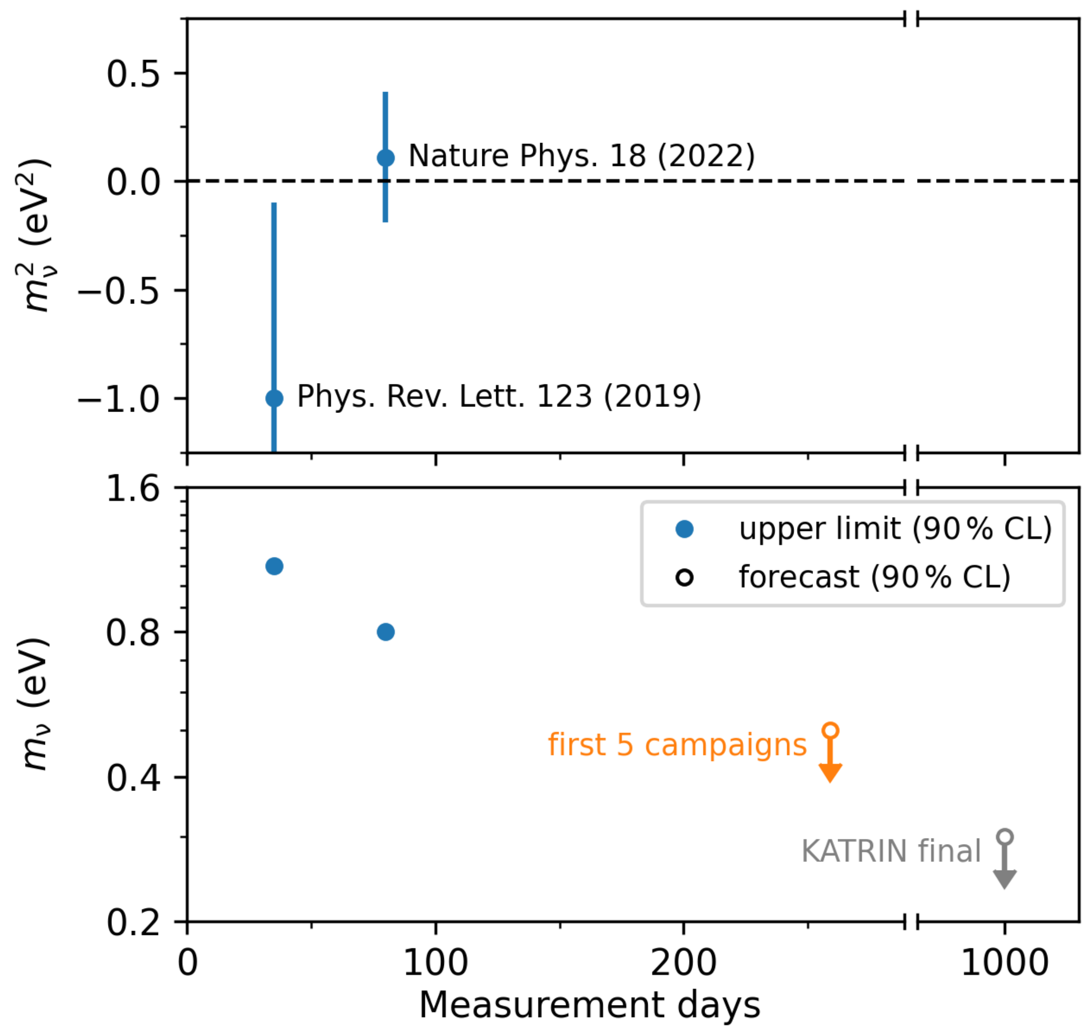
Upcoming KATRIN results



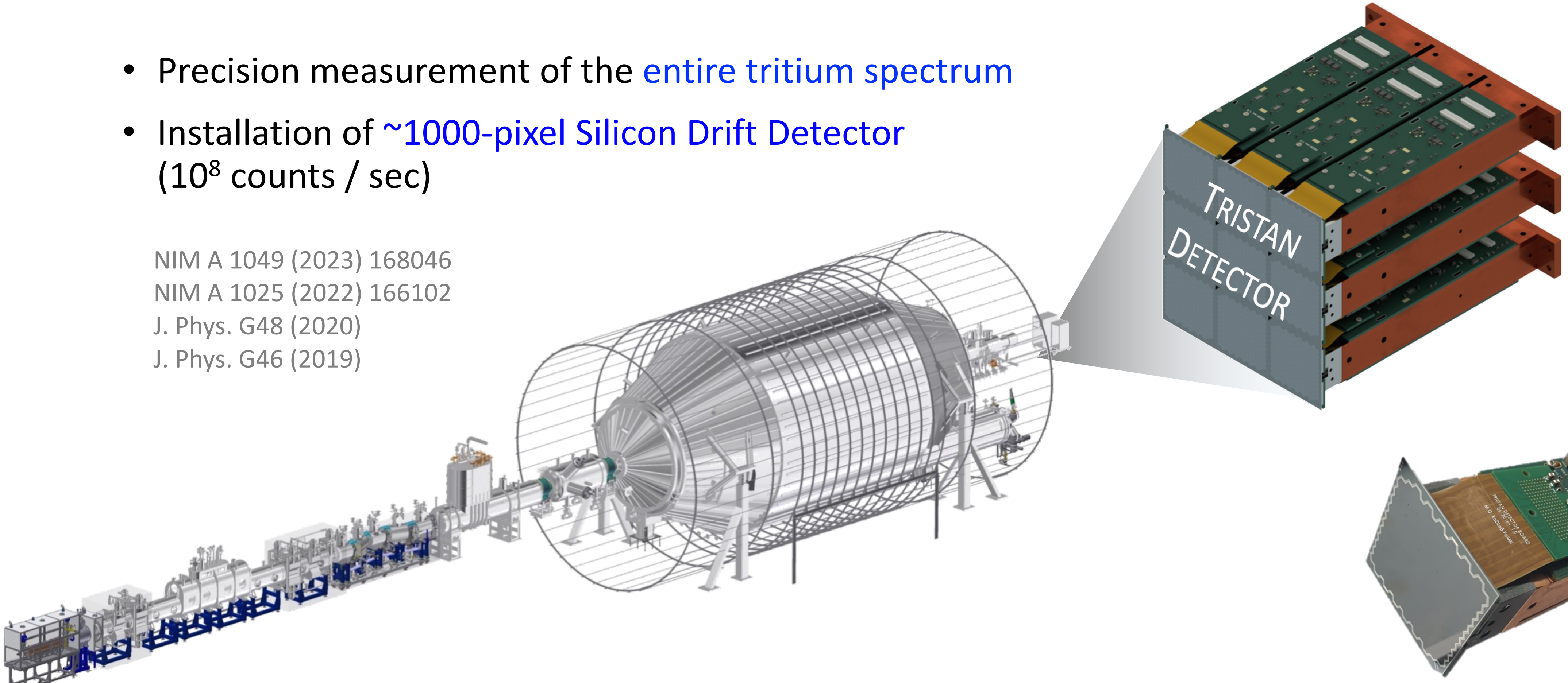
- **Upcoming result (this year):**
  - Based on first five campaigns
  - Statistics x 6, Systematics ÷ 3
  - Sensitivity better than **m_ν < 0.5 eV**
  - Paper (almost) ready for submission
- **Final result:**
  - Based on 1000 days of data taking (completed end of 2025)
  - Sensitivity better than **m_ν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

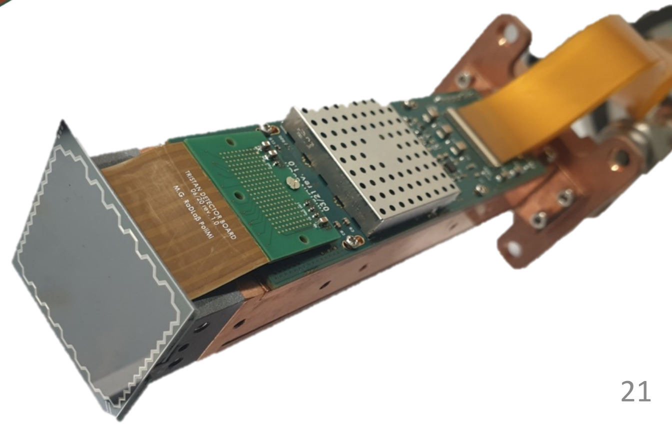
KATRIN timeline

neutrino mass	2026- 2027: keV-sterile neutrinos (TRISTAN)	**KATRIN ++**

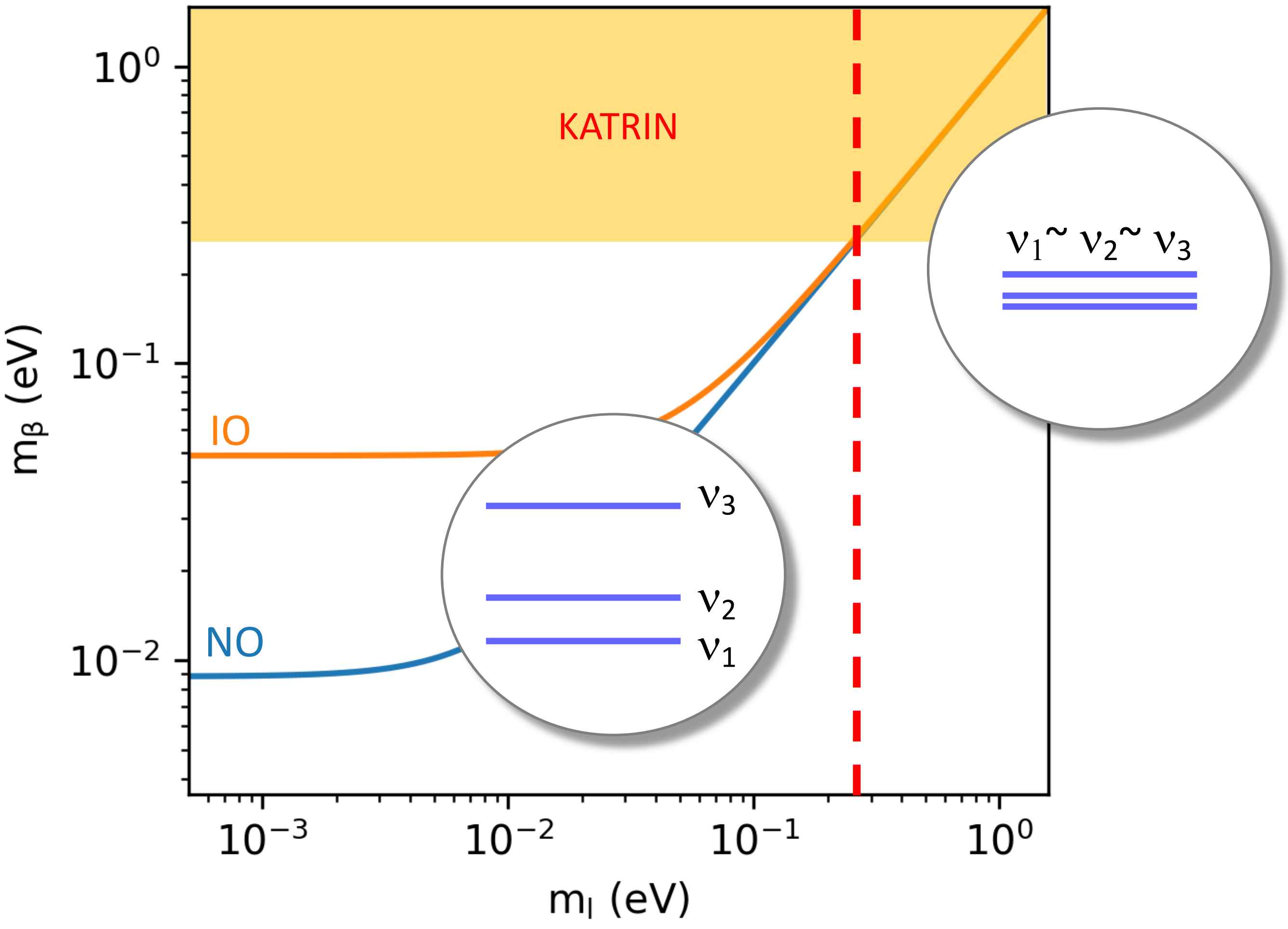
- Precision measurement of the entire tritium spectrum
- Installation of ~1000-pixel Silicon Drift Detector (10^8 counts / sec)

NIM A 1049 (2023) 168046
NIM A 1025 (2022) 166102
J. Phys. G48 (2020)
J. Phys. G46 (2019)



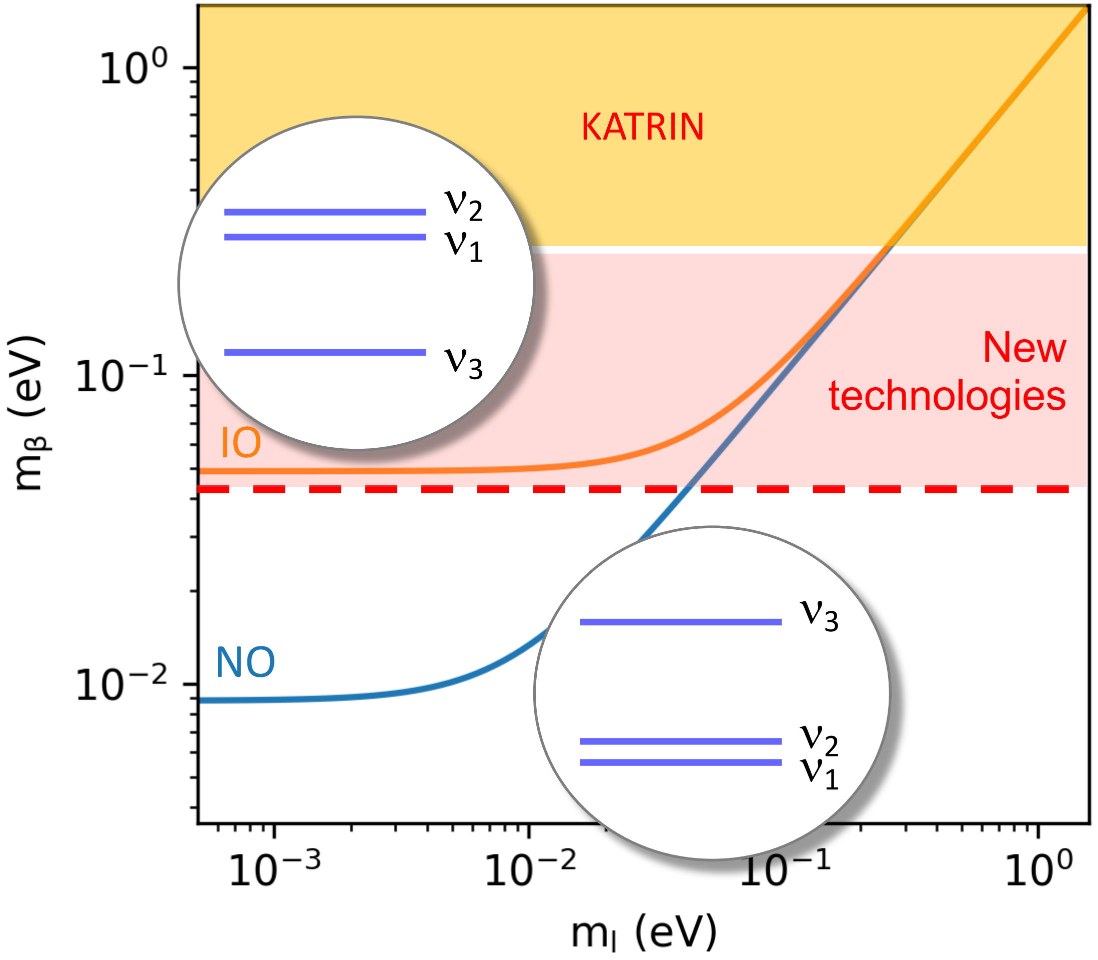


Going beyond KATRIN



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

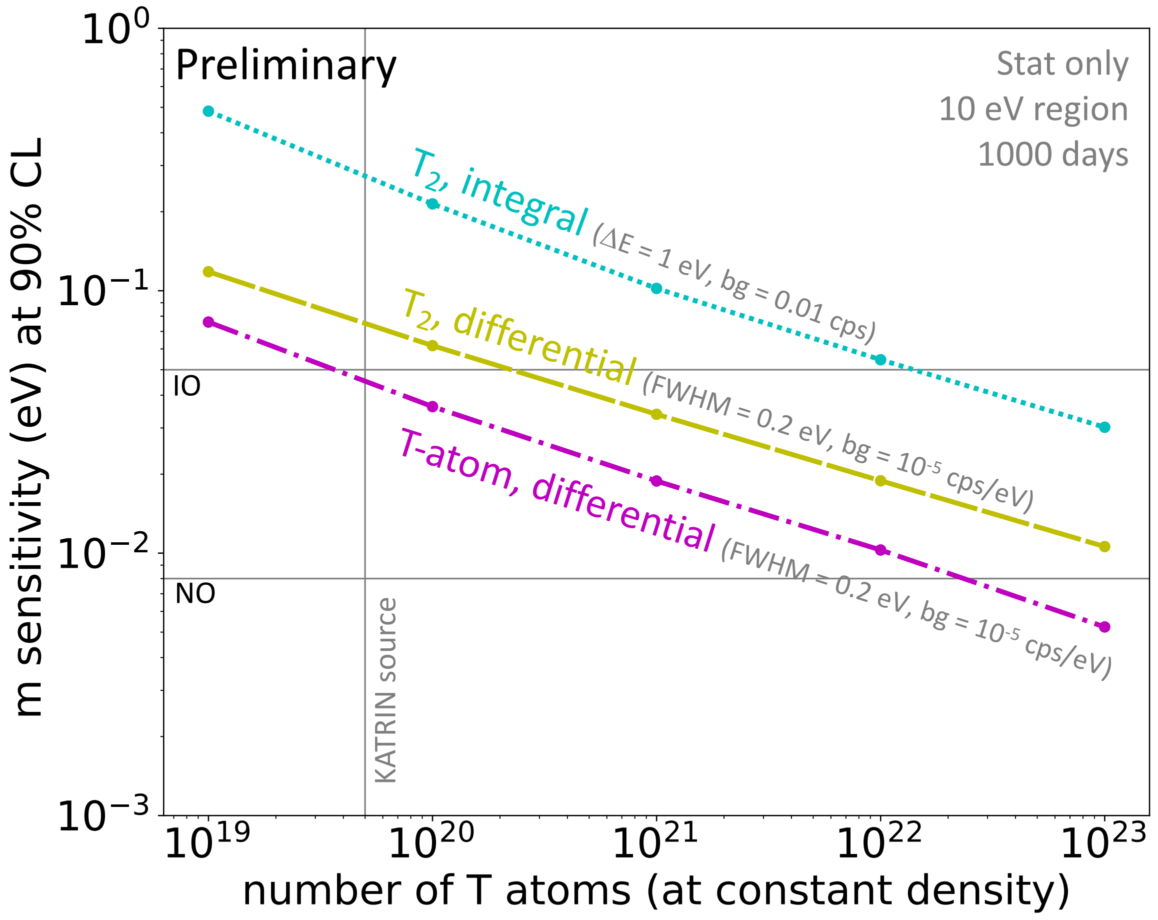
Going beyond KATRIN



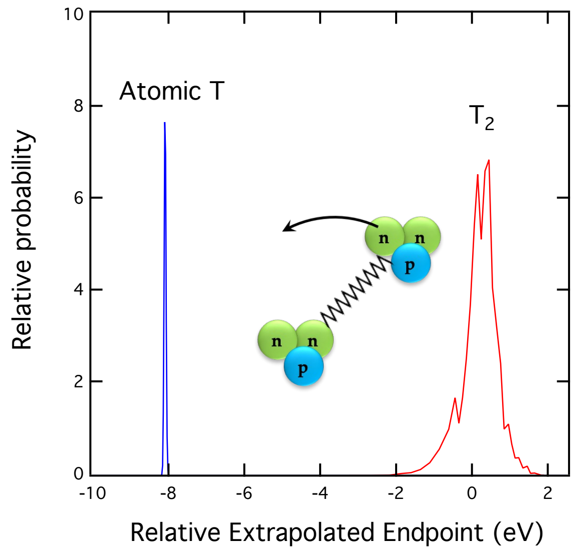
- KATRIN final: < **0.3 eV** (90% CL)
  Distinguish between **degenerate** and **hierarchical** scenario

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

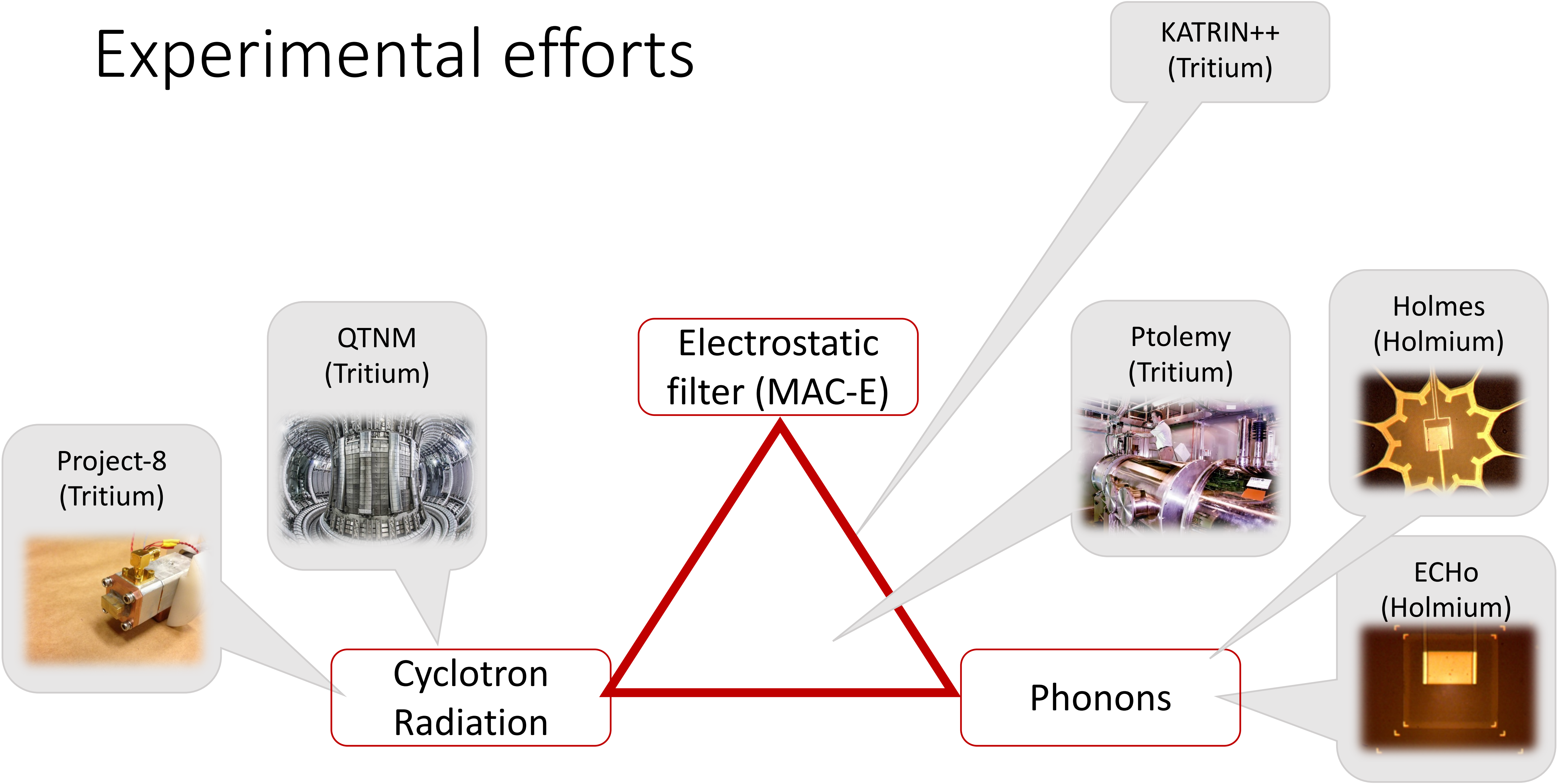
Going beyond KATRIN



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



Experimental efforts



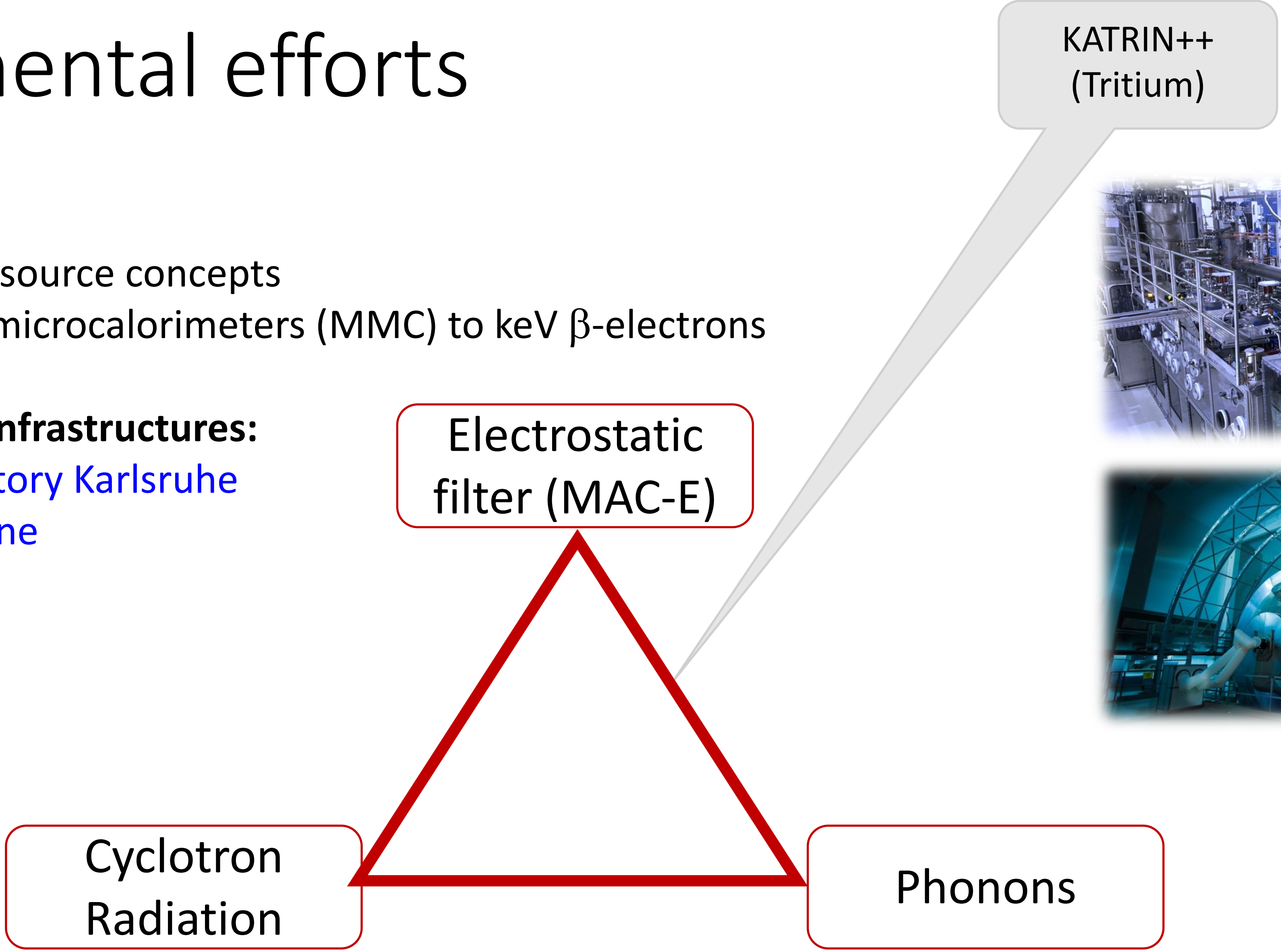
Experimental efforts

R&D launched:

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

Leverage unique infrastructures:

- ✓ Tritium Laboratory Karlsruhe
- ✓ KATRIN beamline



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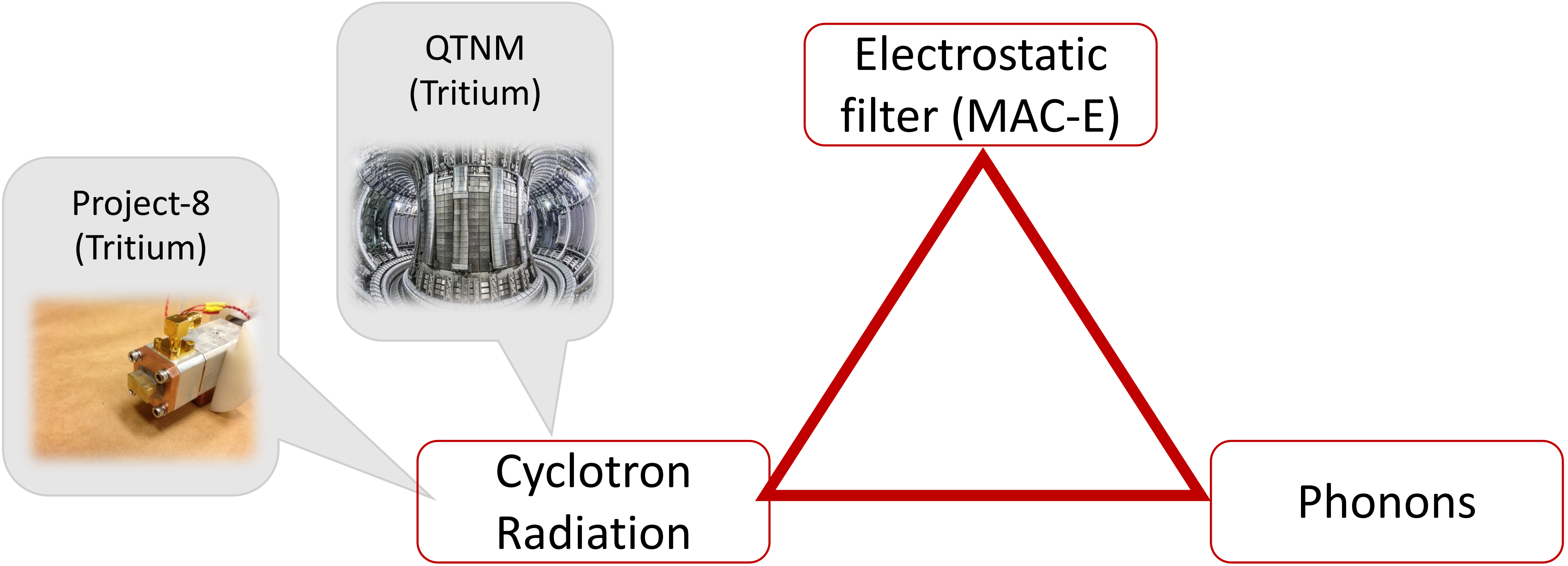
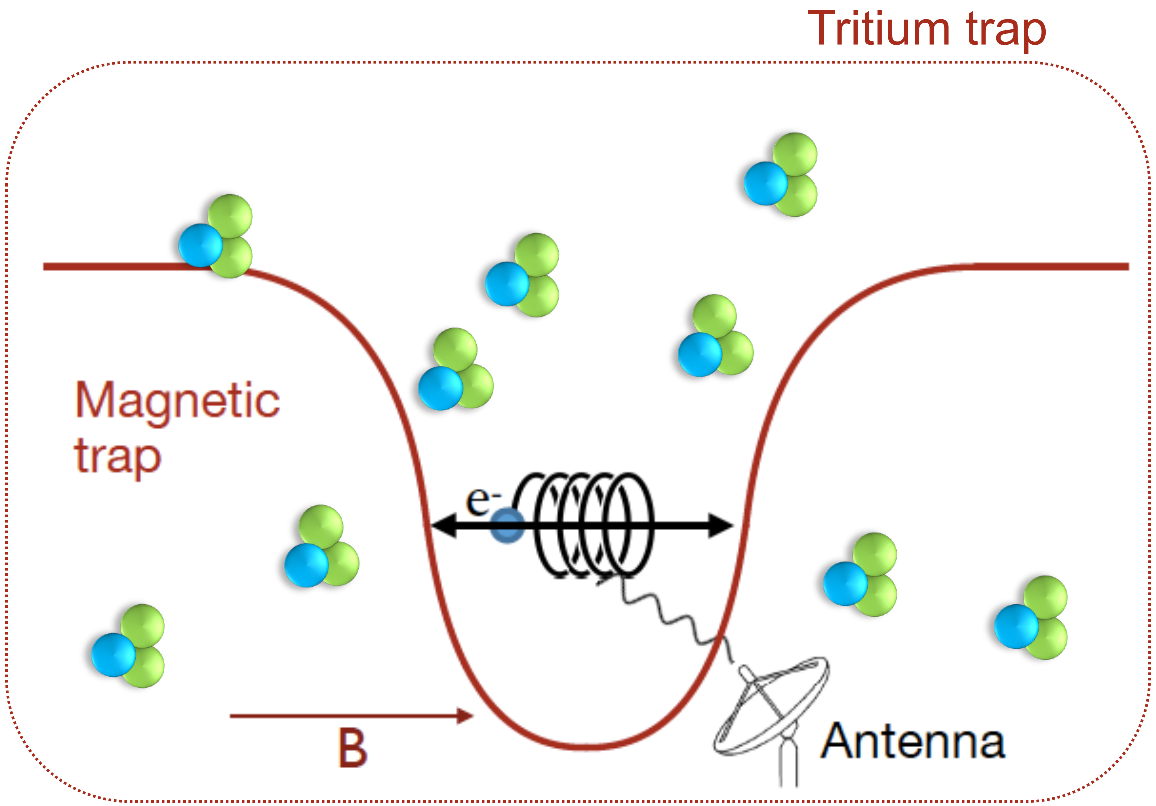


Working principle

Cyclotron Radiation Emission Spectroscopy (CRES)

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

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



Working principle

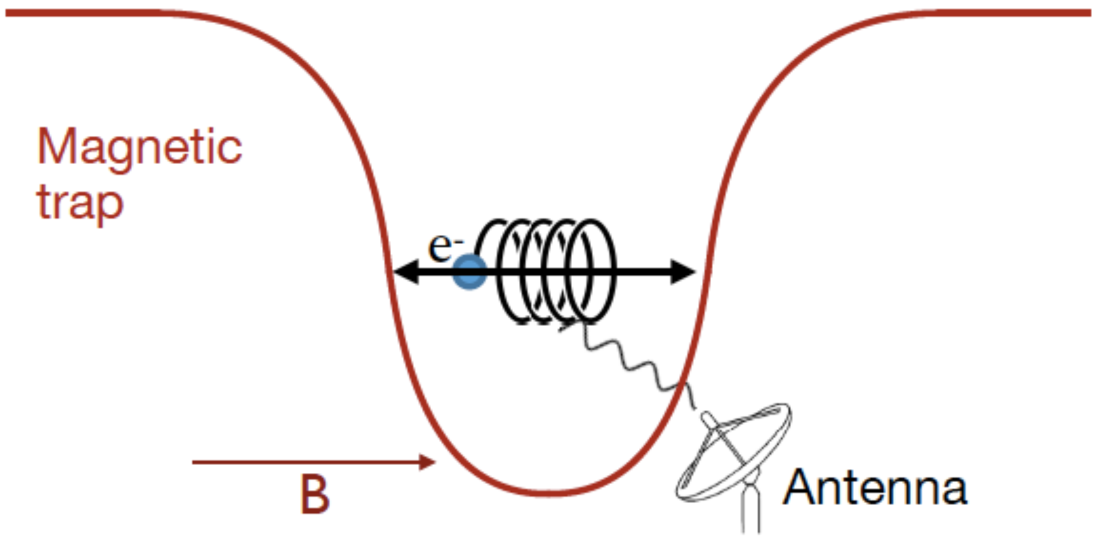
Advantages:

✓ (sub)-eV-scale differential measurement

✓ no electron beamline

Challenges:

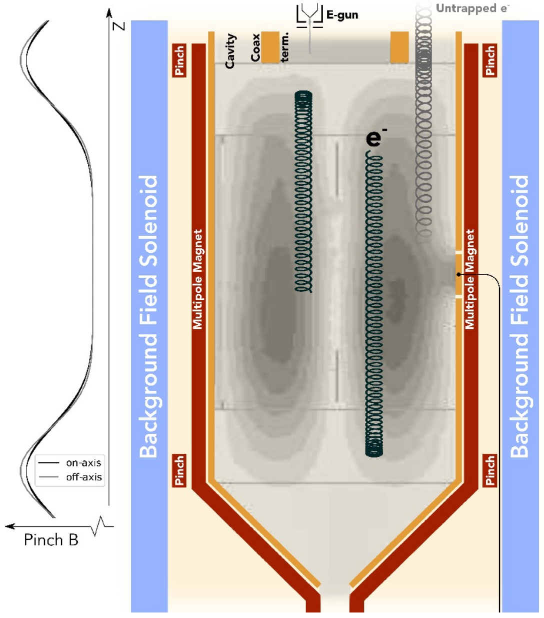
- Sub-eV energy resolution
  → B-field homogeneity at the 10^{-7}-level
- High statistics (~10^{19} T-atoms for < 0.04 eV sensi)
  → large volume (~m^3) atomic tritium trap
- Detection of femto - zetta Watt radiation
- …



Experiments

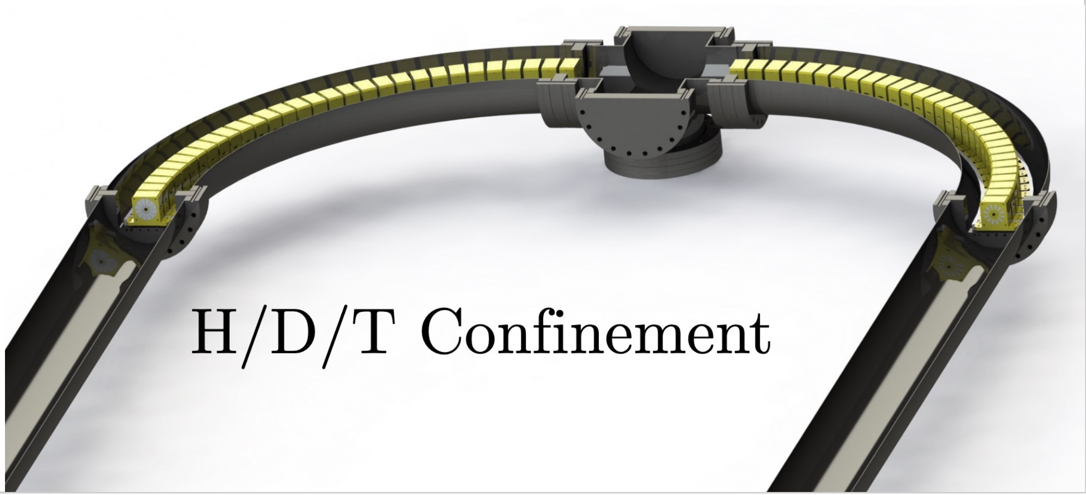
Project-8

- Cold tritium atom trap + resonant cavity



QTNM

- Storage ring confinement
- New effort, conceptual stage

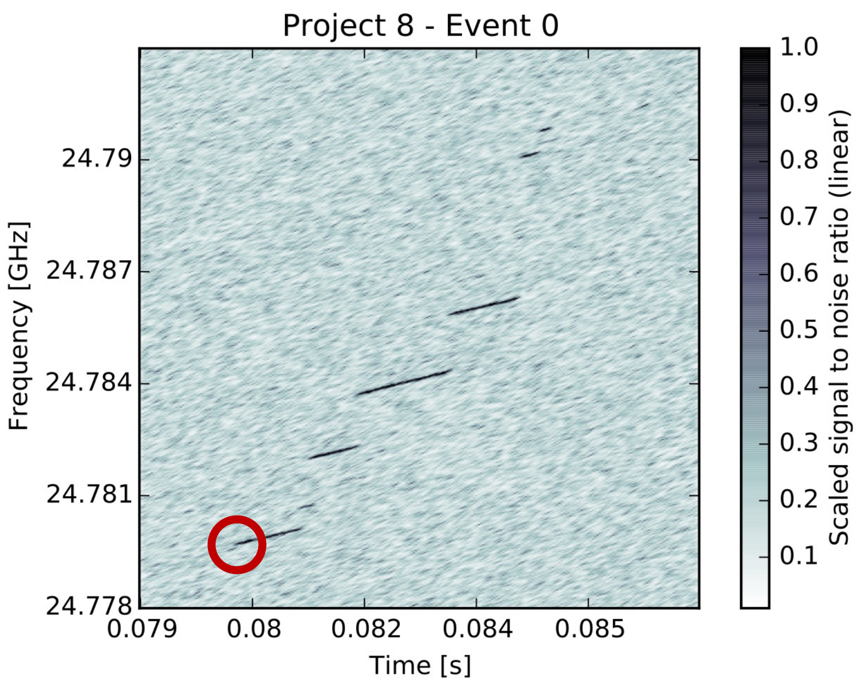


Project 8

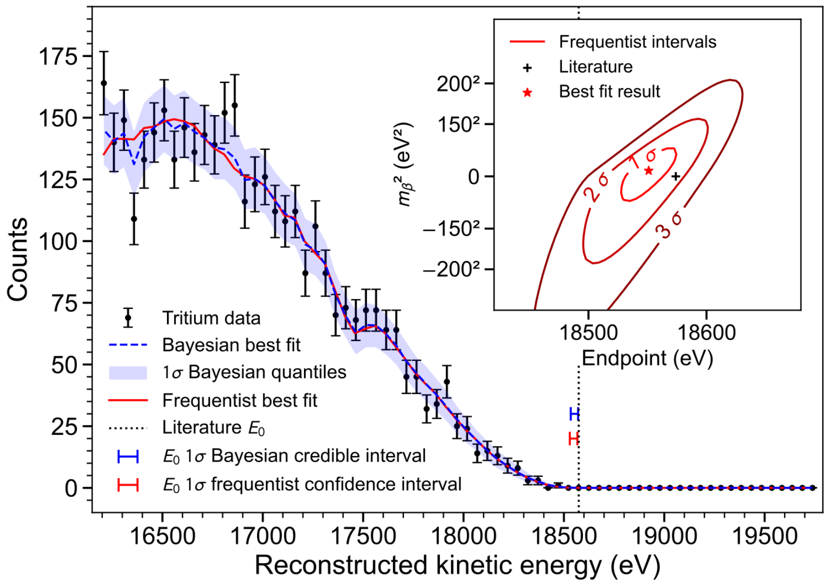
- **Achievements:**
  - ✓ **Proof of CRES concept**
    D.M. Asner et al., Phys. Rev. Lett. 114, 162501 (2015)
  - ✓ **First neutrino mass limit: m_ν < 185 eV (90% Cl.)**
    arXiv:2212.05048 (2022)

- **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)



waveguide



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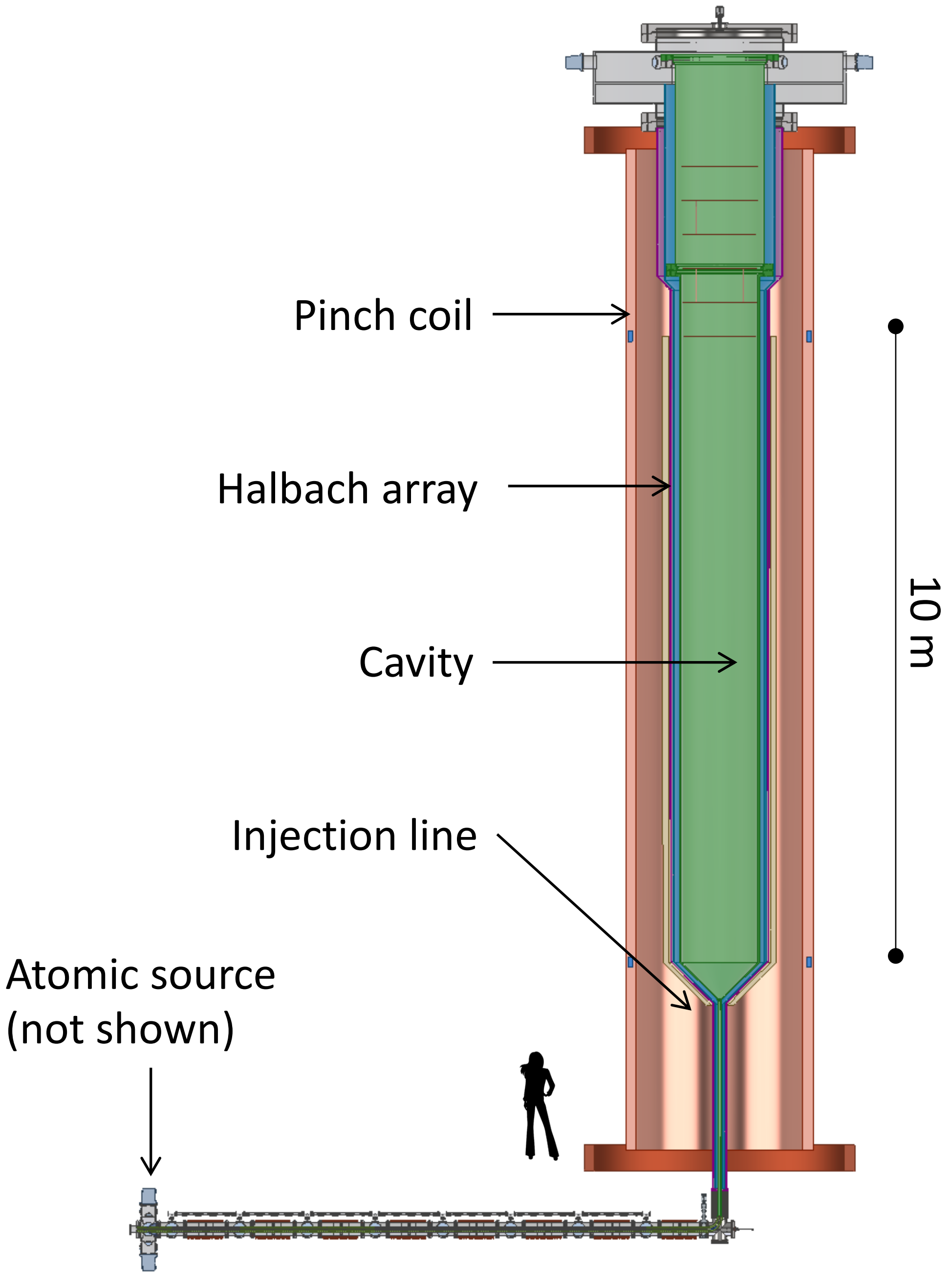

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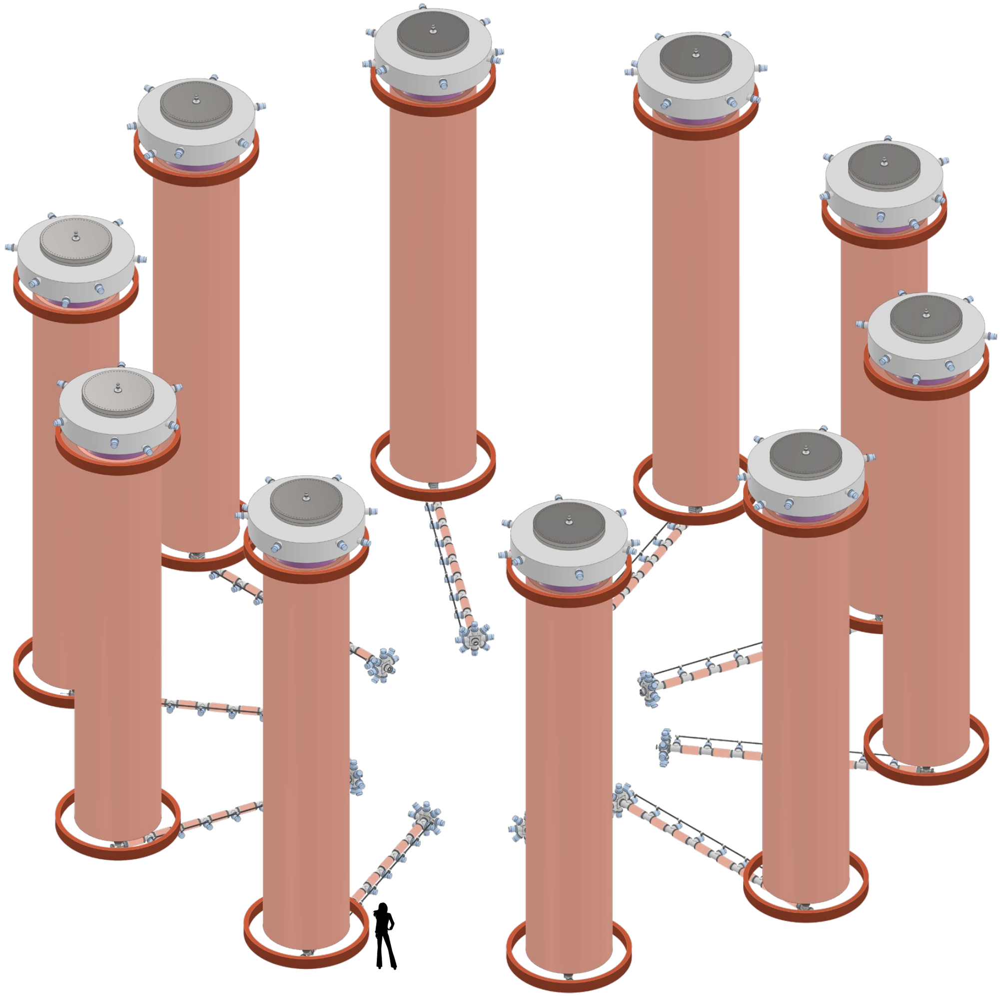
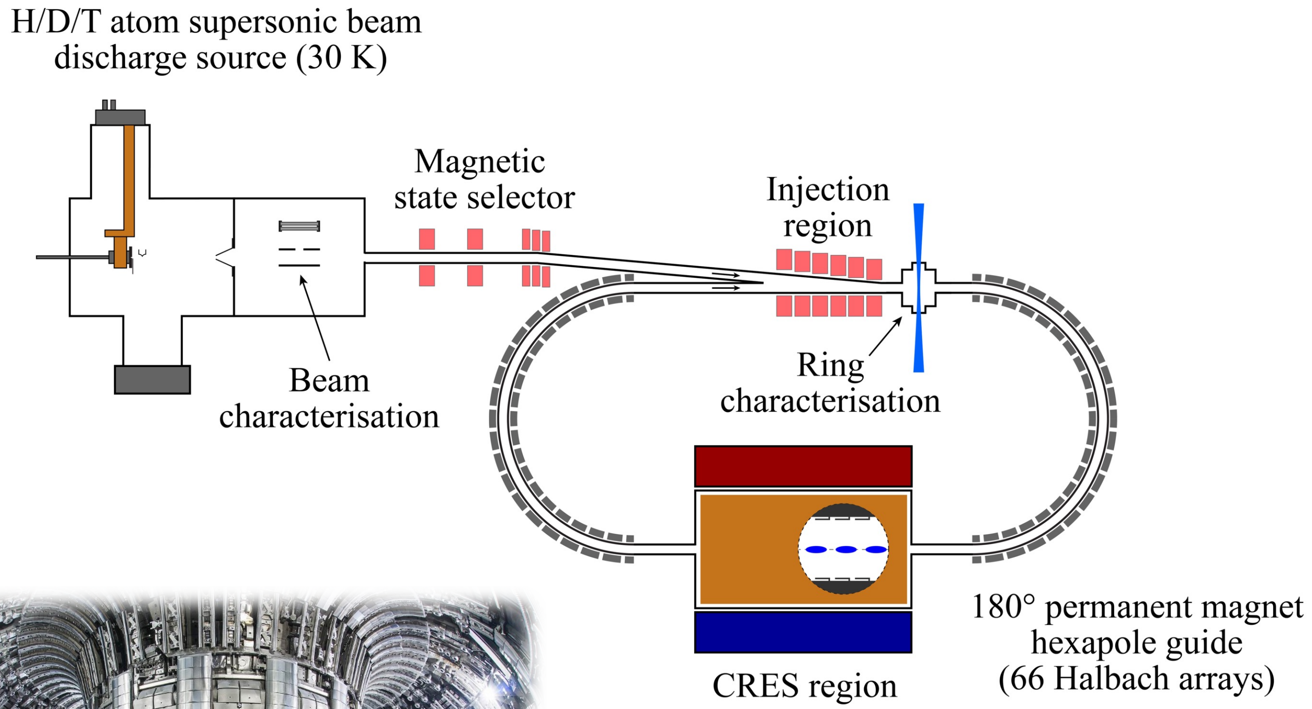
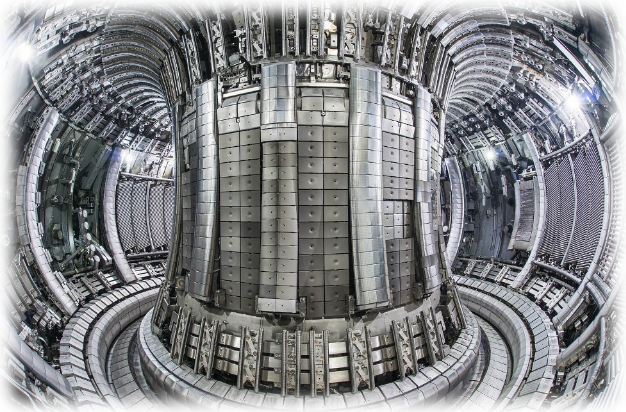


QTNM: Quantum Technology for Neutrino Mass

- **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)





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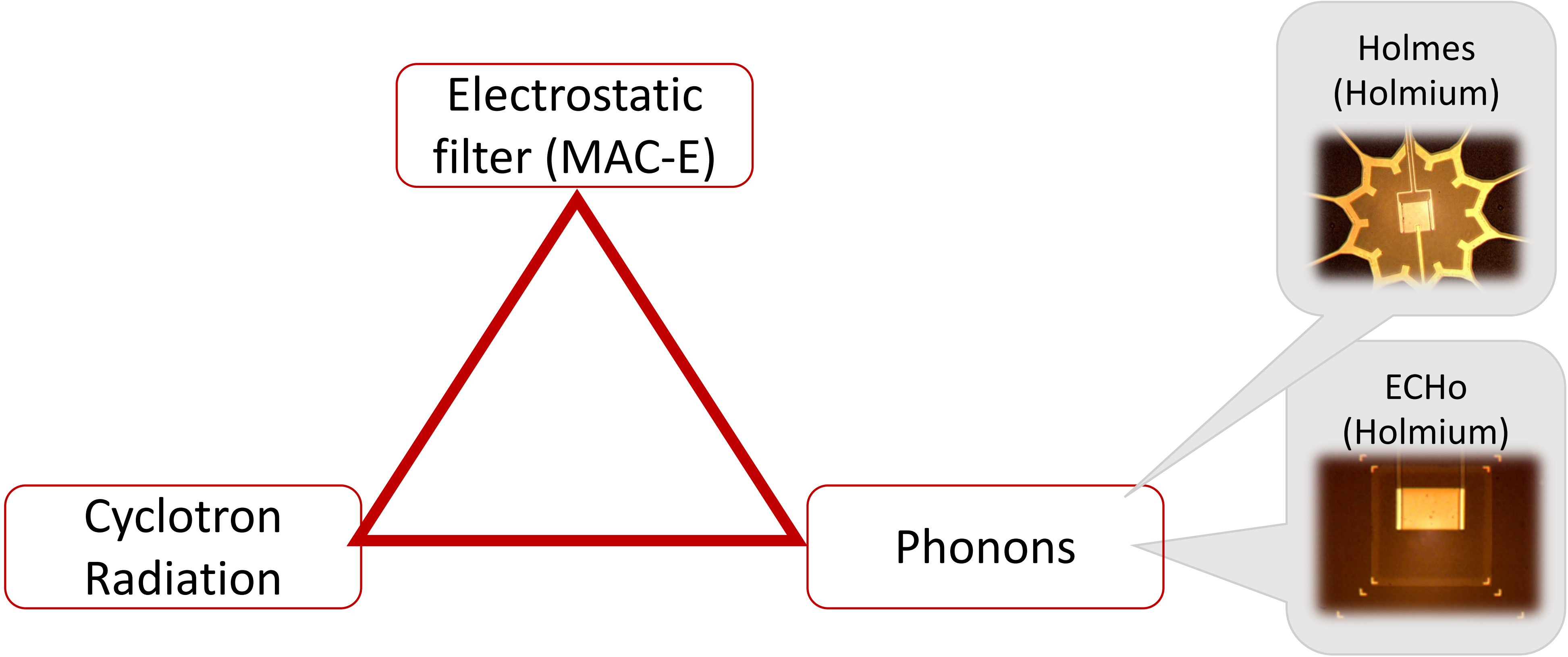
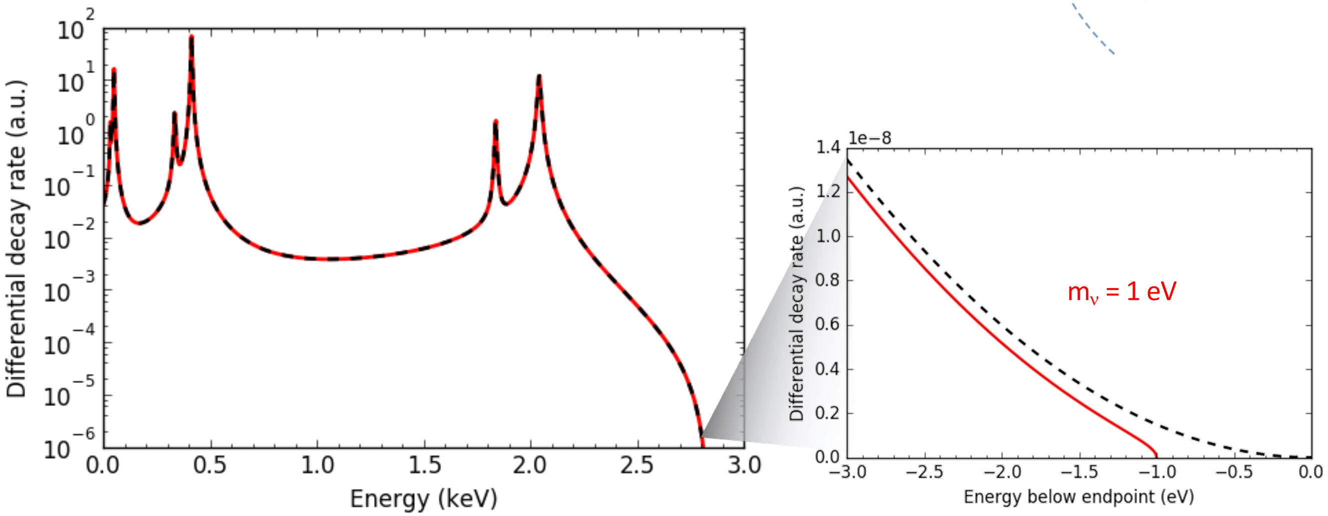


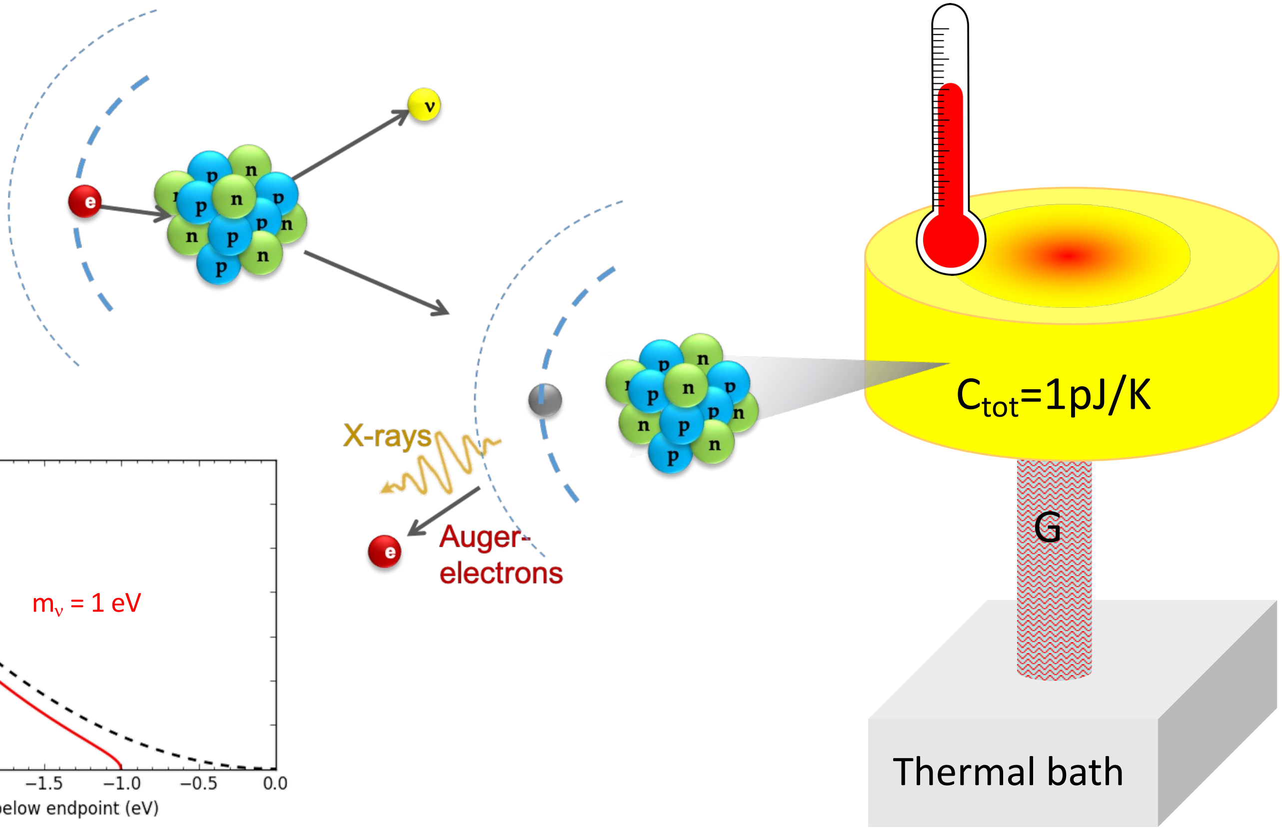
Working principle

Low-temperature micro-calorimetry with holmium

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

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





Working principle

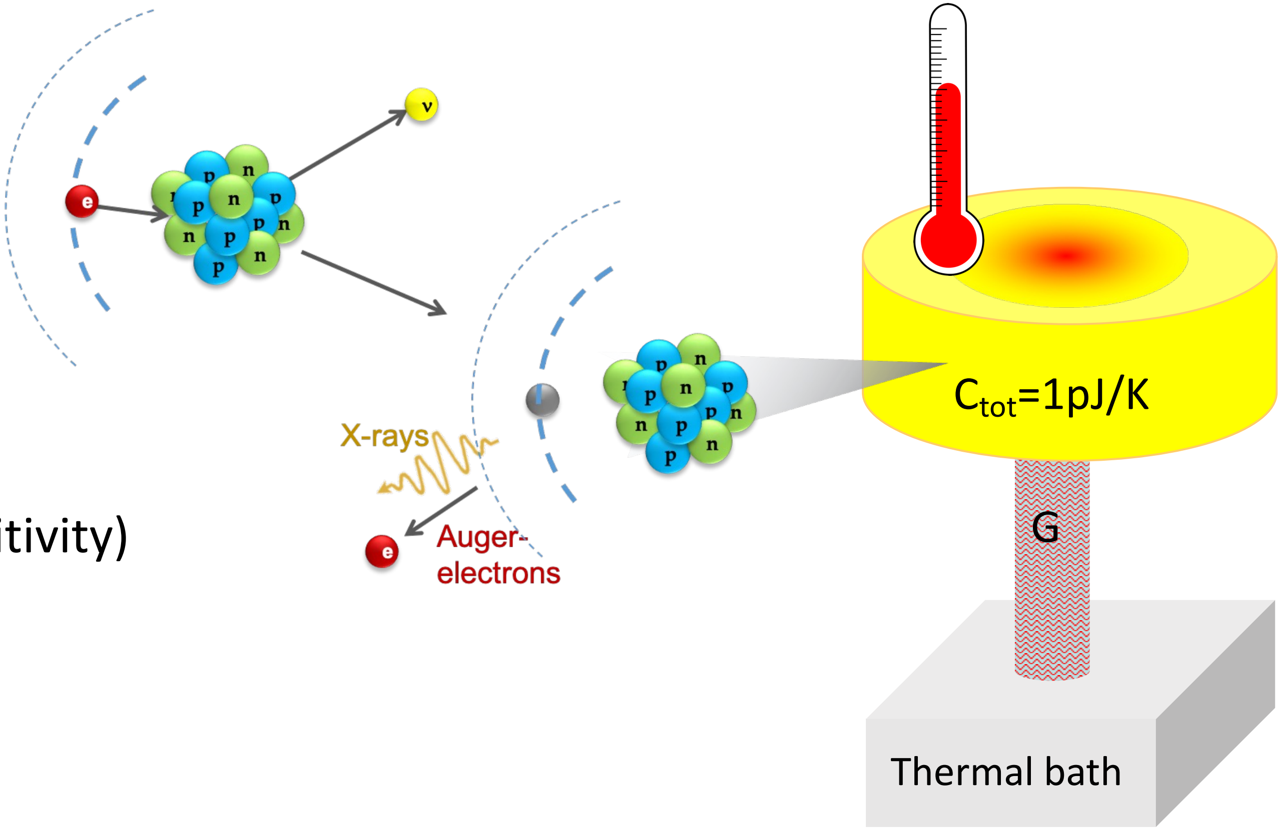
Advantages:

✓ eV-scale differential measurement

✓ „source = detector“ concept

Challenges:

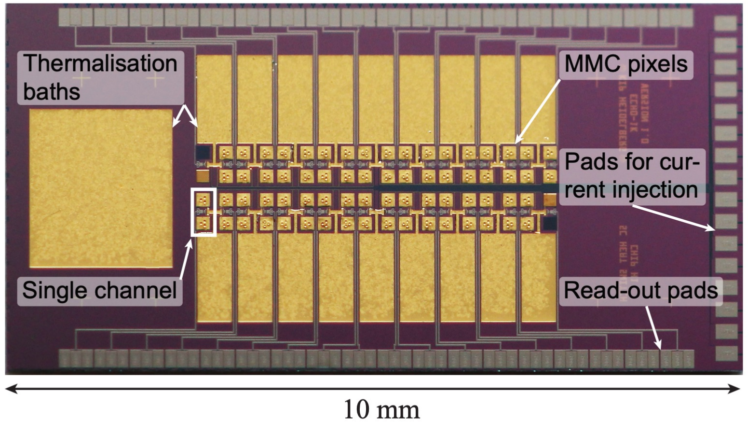
- eV-resolution
  → operation at low temperature (mK)
  → small pixels (μm-scale)
- High statistics (> 10^{13} decays for eV sensitivity)
  → high as possible activity per pixel (10 Bq)
  → many (> 10 000) pixels
  → multiplexed read-out



Experiments

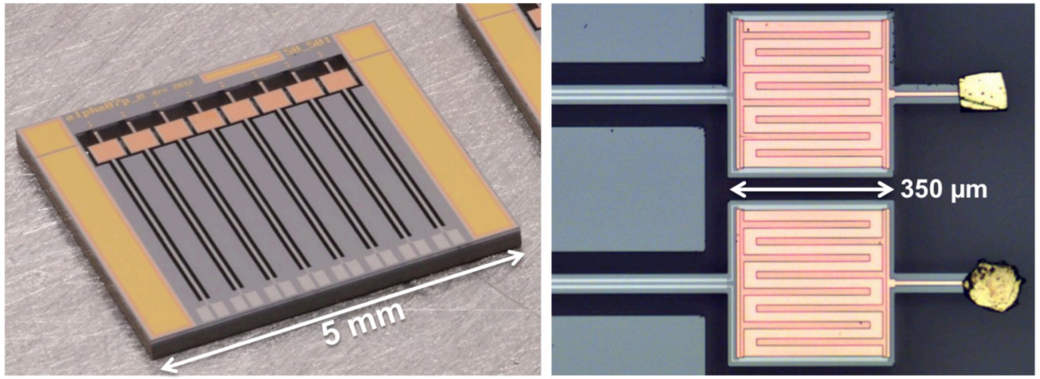
ECHo

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



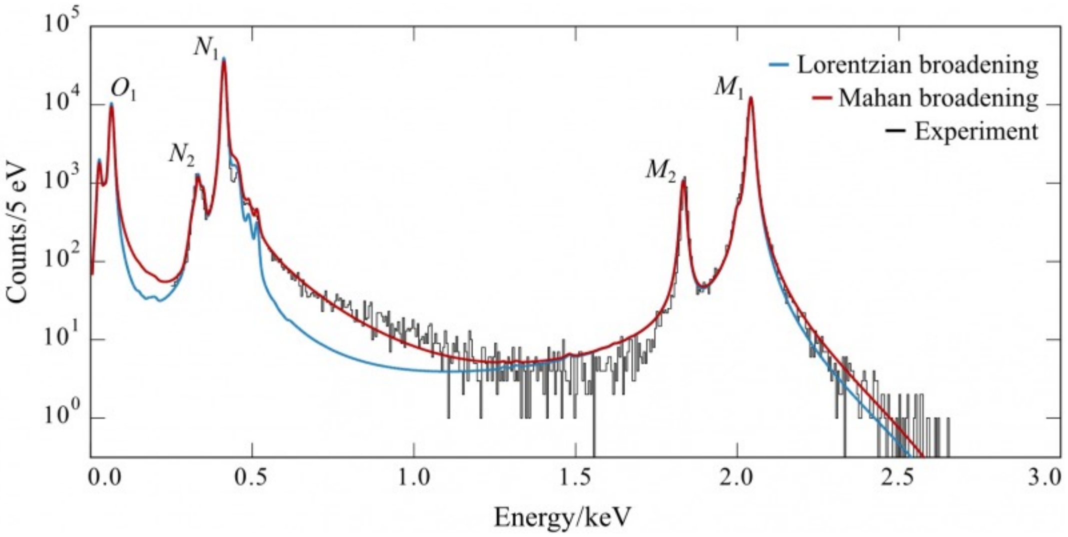
HOLMES

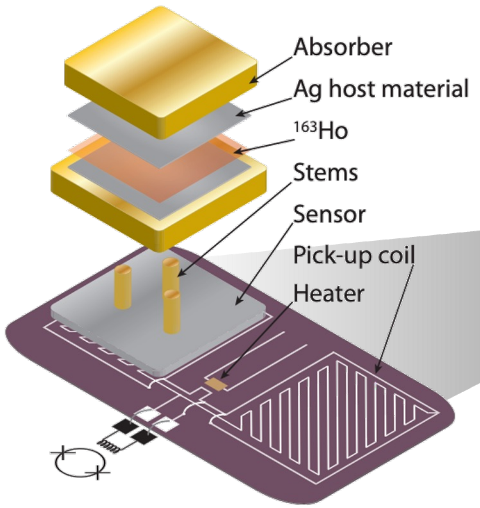
- transition edge sensors (TES)
  J Low Temp Phys **184,** 492–497 (2016)



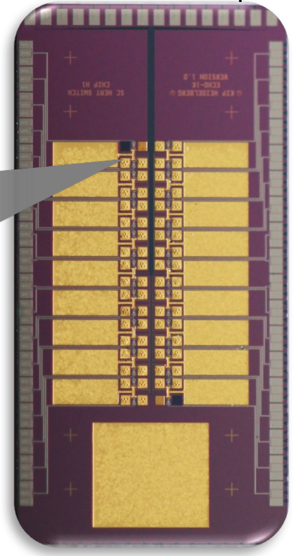
ECHo

- **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 → 60 pixels → <10 eV FWHM → 20 eV sensitivity
    EPJ-C 81, 963 (2021)
  - ✓ *ECHo-100k:* excellent performance demonstrated
    ~10 Bq/pixel → 12000 pixels → 5 eV FWHM → 2 eV sensitivity
    NIMA, 1055, 2023, 168564
- **Next steps/challenges**
  - Scaling to more activity and pixels
- **Ultimate goal:**
  - 10 MBq (= 10^5 pixels) → low sub-eV sensitivity





60 pixel,
each about 1 Bq



ECHo

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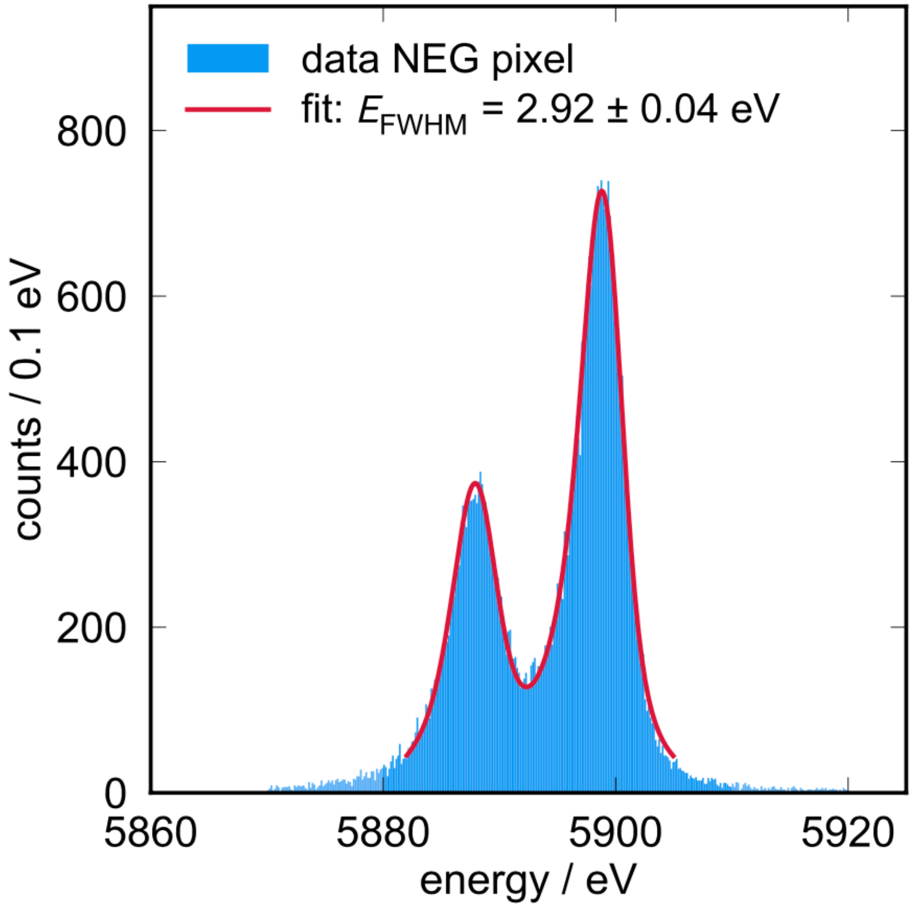
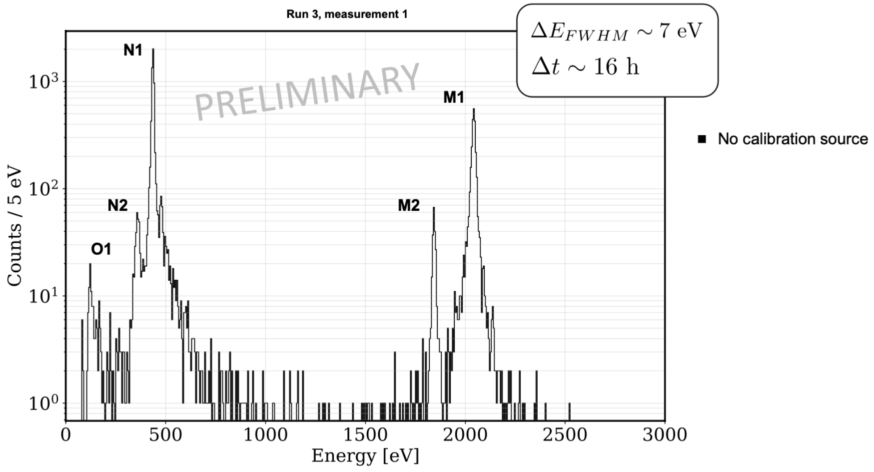
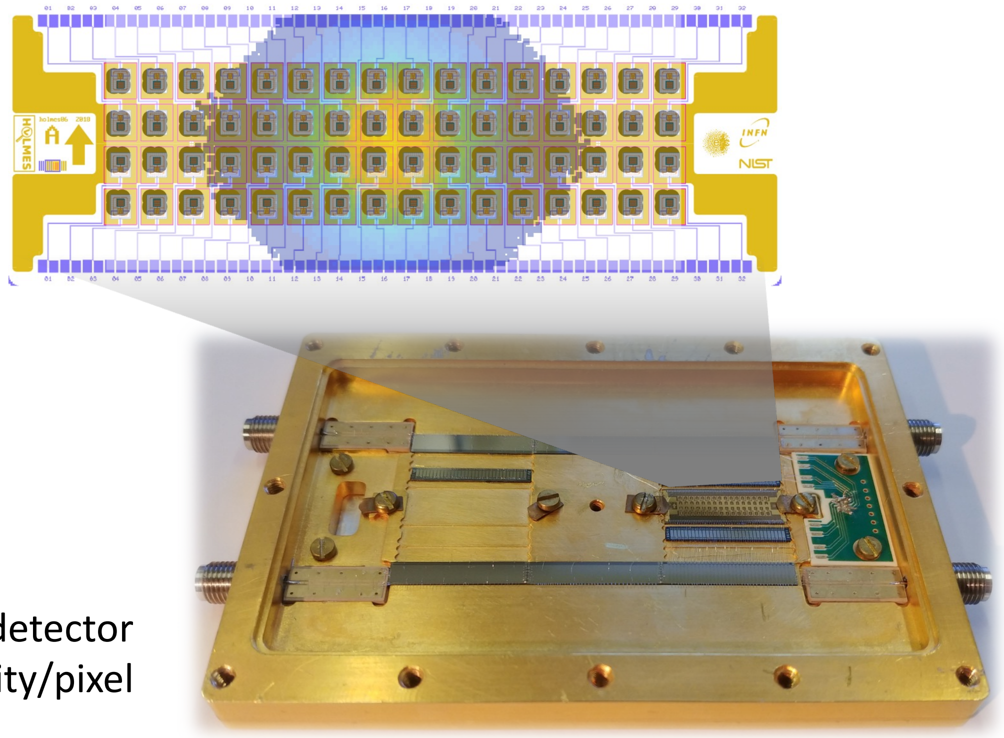


Holmes

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

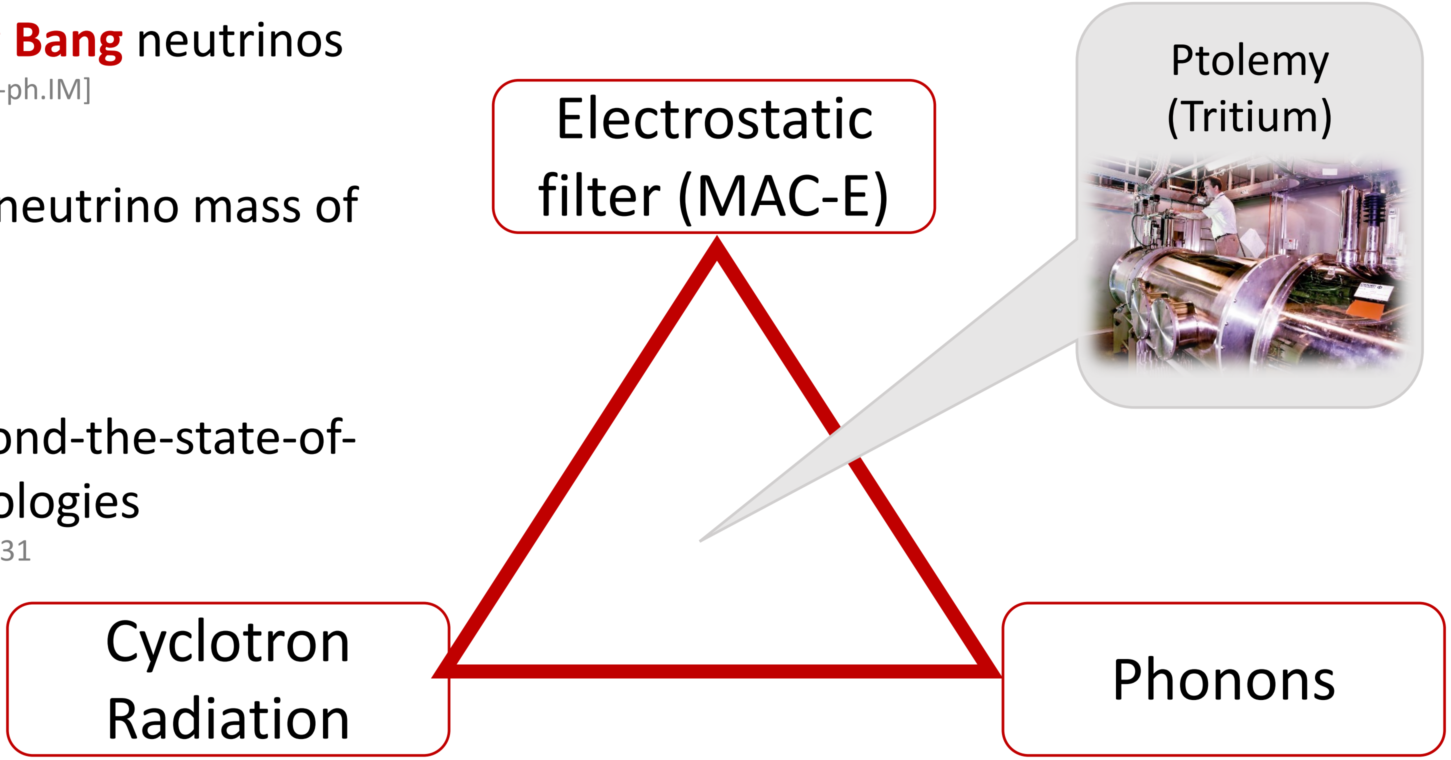




64 pixel detector
0.5 Bq average activity/pixel

Experimental efforts

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



Summary

KATRIN (integral)

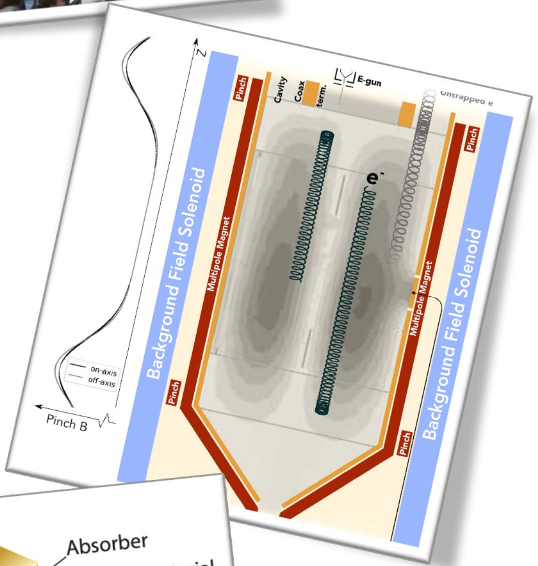
- Leading neutrino mass limit (m_ν < 0.8 eV) from direct measurements
- Upcoming data release this year: sensitivity better than 0.5 eV
- Final goal: sensitivity better than 0.3 eV

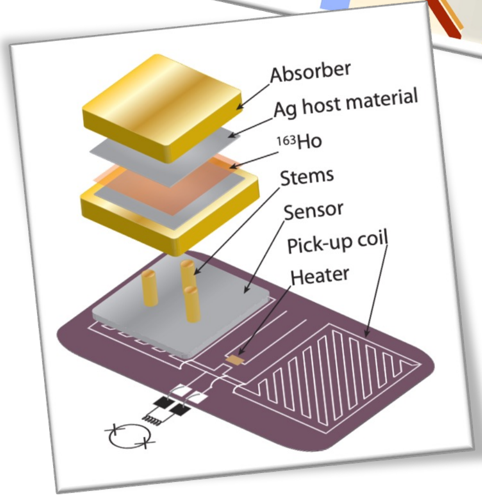
Cyclotron Radiation Emission Spectroscopy (differential)**:** Project-8 & QTNM

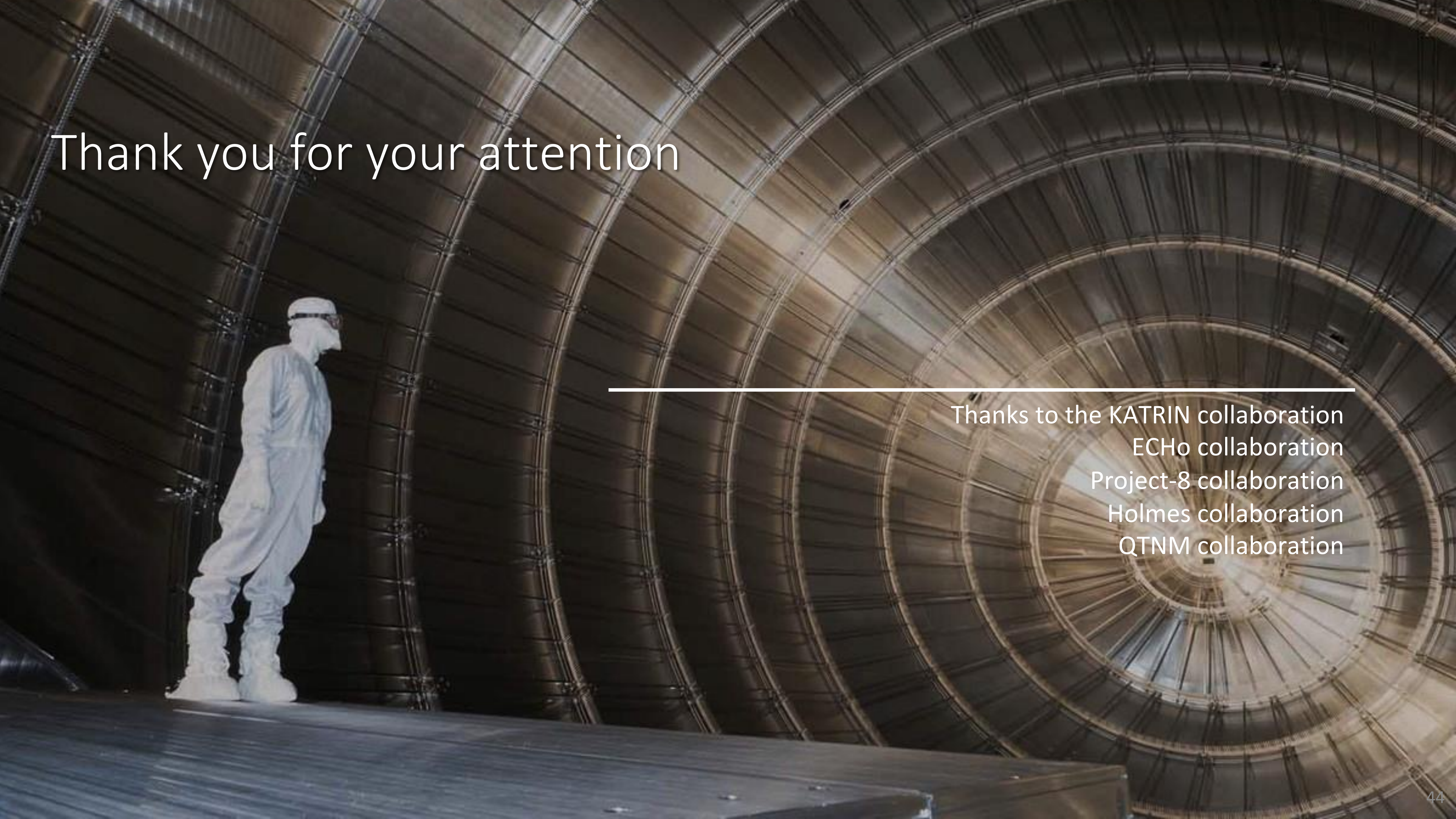
- First neutrino mass limit m_ν < 150 eV (Project-8)
- Next step: Scaling up to **large-volume traps,** develop **atomic tritium source**

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

- First neutrino mass limit m_ν < 150 eV (ECHo) and m_ν < 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