Karlsruhe Institute of Technology

Tritium Laboratory Karlsruhe

Direct neutrino mass measurement

Caroline Rodenbeck

HOLMES

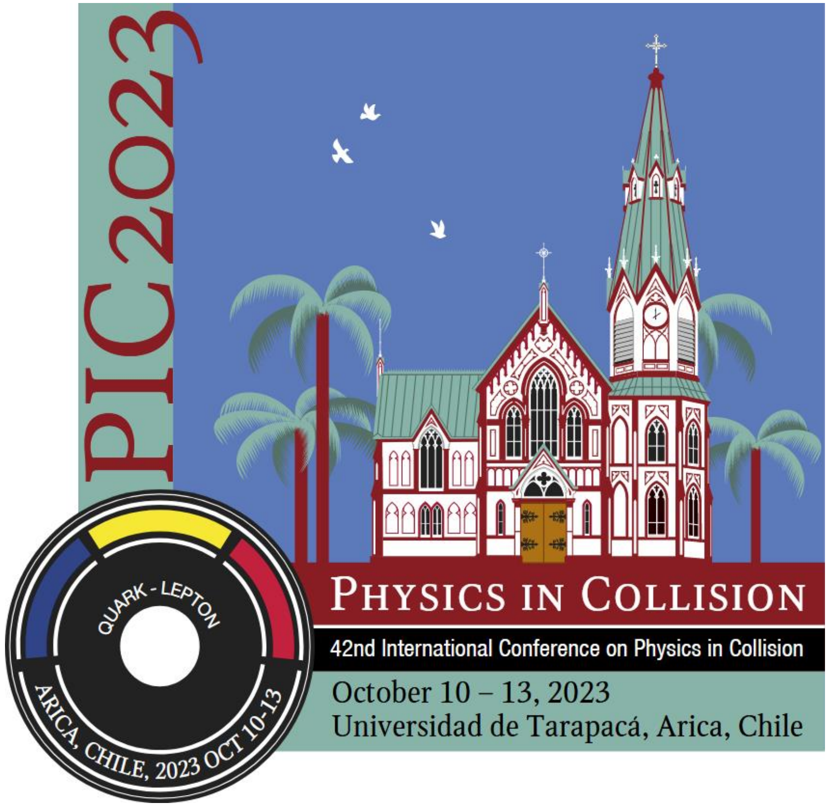
KATRIN — Karlsruhe Tritium Neutrino Experiment

ECHo

QTNM — Quantum Technologies for Neutrino Mass

PTOLEMY

PROJECT 8

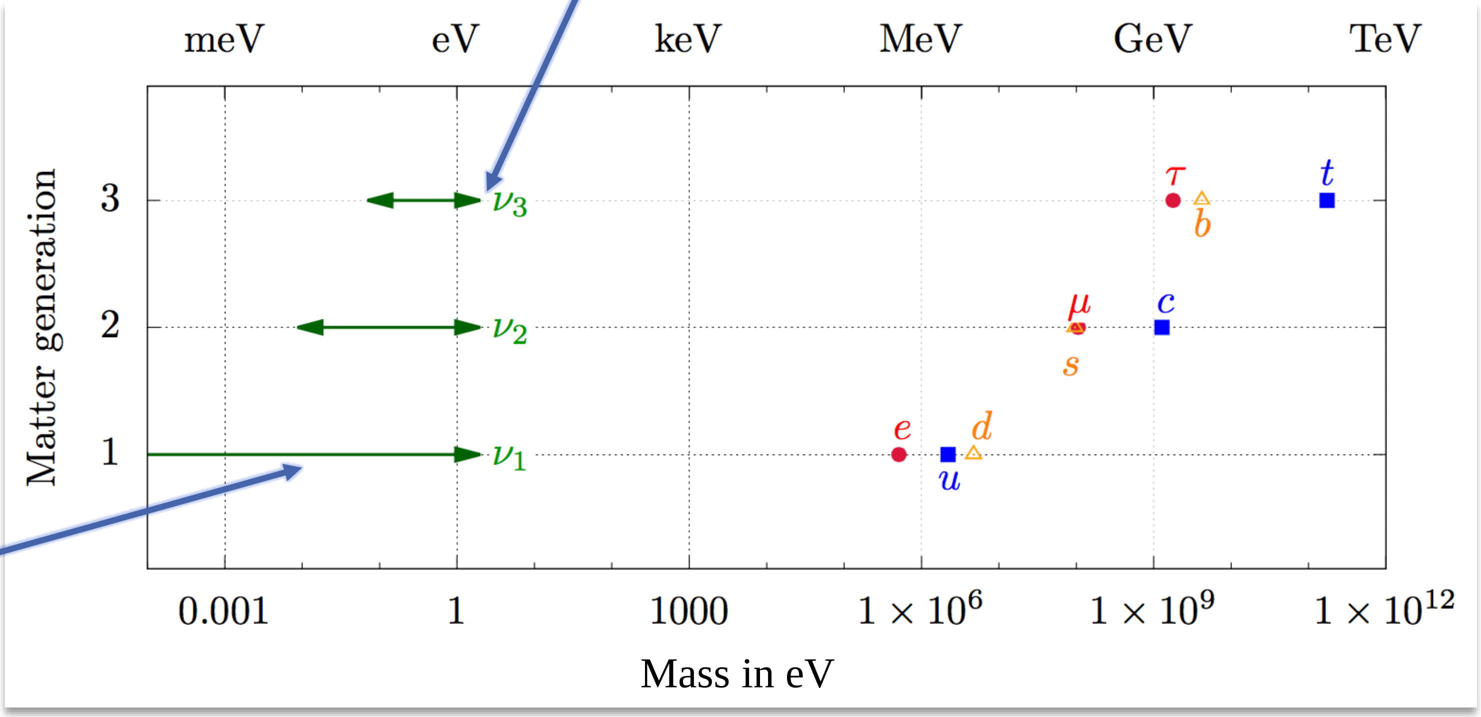


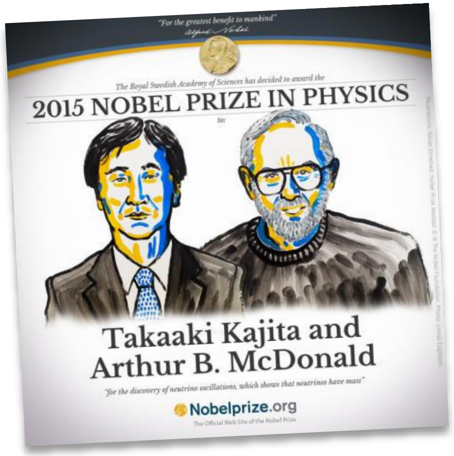
With material from the KATRIN, ECHo, HOLMES, Project 8, PTOLEMY and QTNM Collaborations

Neutrino mass

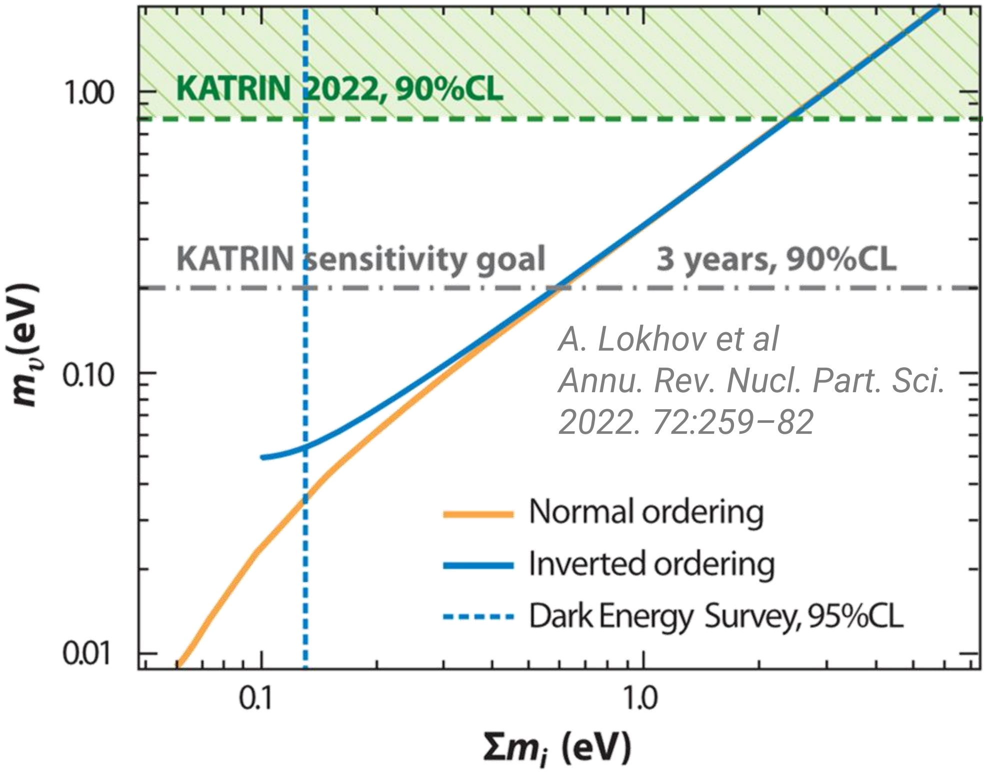
- Neutrino mass ≠ 0: proof from observation of neutrino oscillations
- Neutrino oscillation experiments:
  - sensitive on mixing angles and squared mass differences only
  - provide **lower bound** for masses

Upper bound from direct measurements



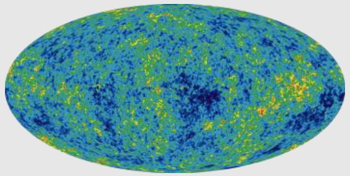


Complementary ways of determining the neutrino mass



Cosmology

- $m_\Sigma = \sum_i m_i$



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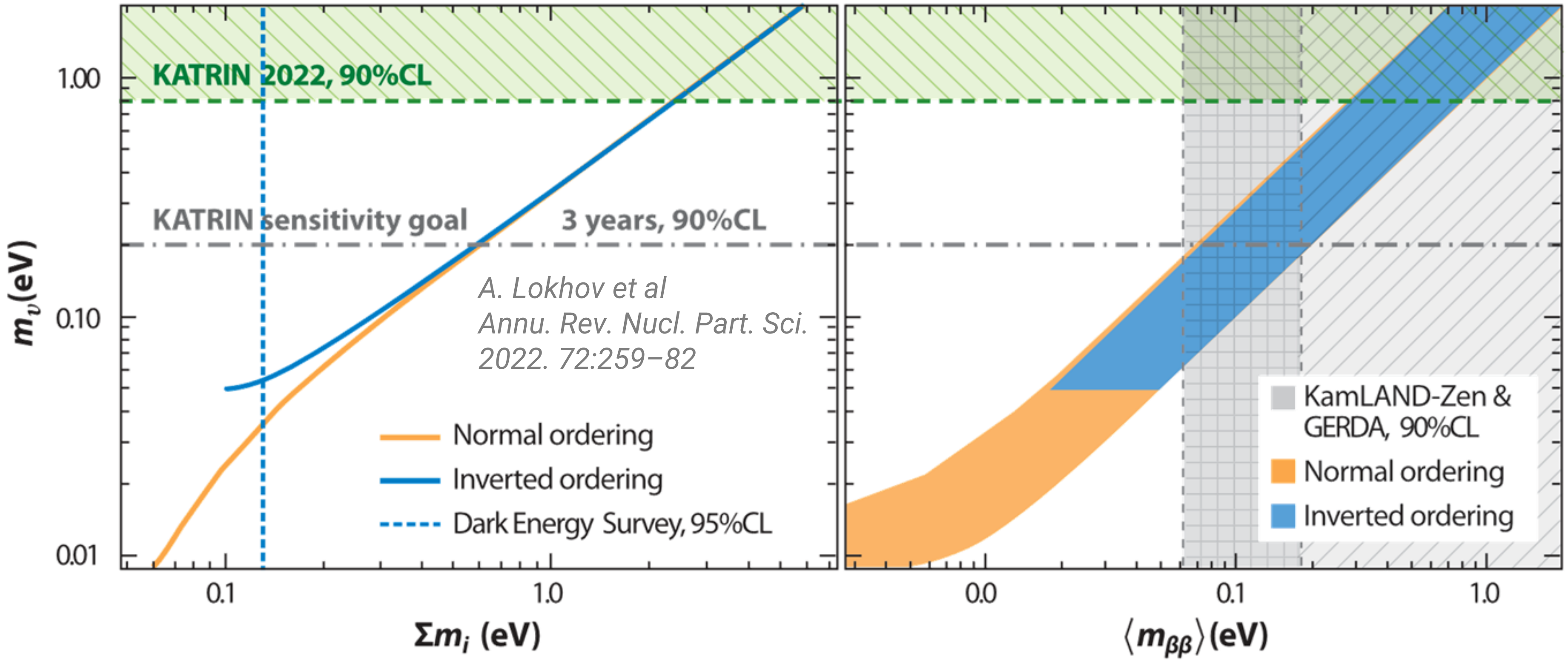

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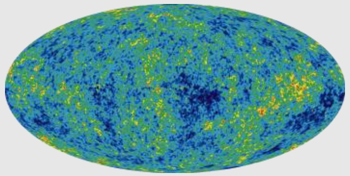
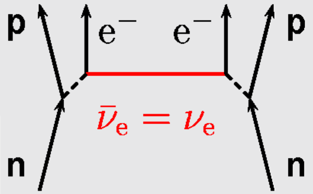


0νββ

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



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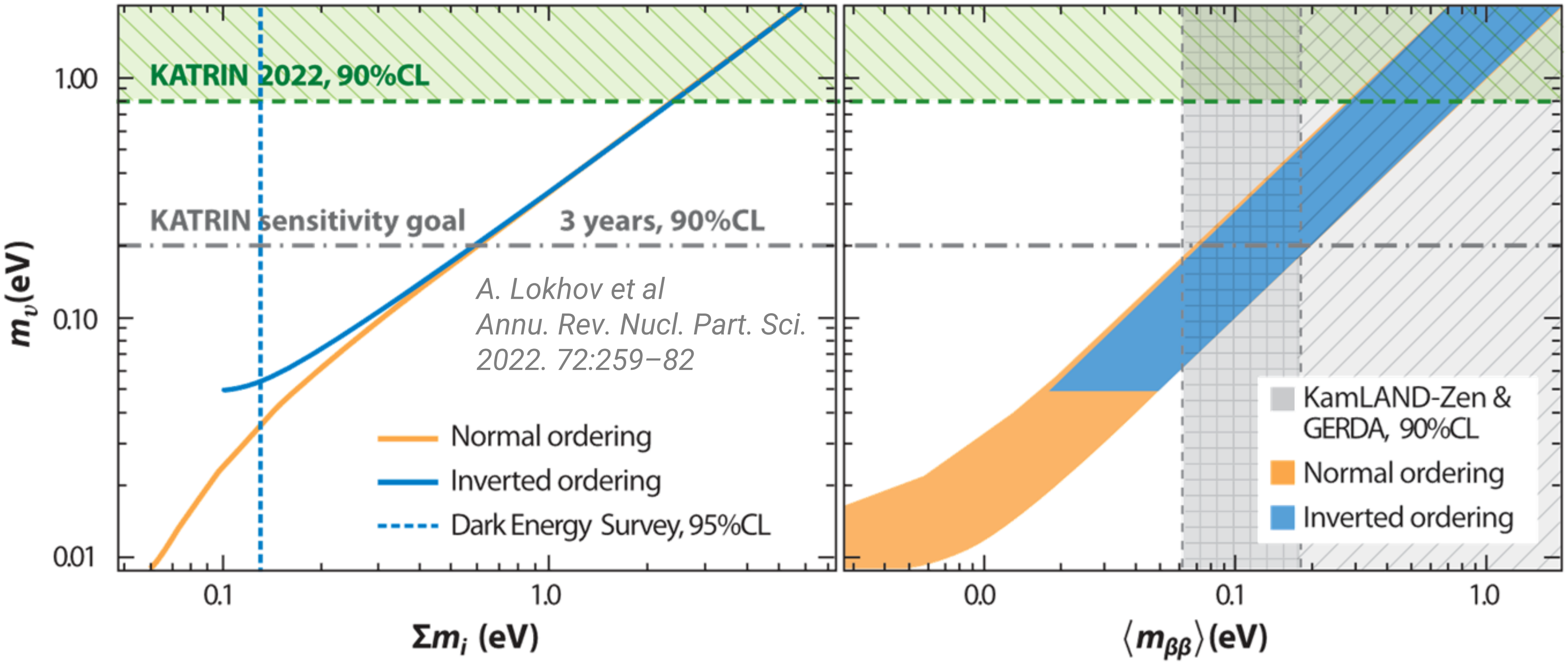

Kinematic investigations

- $m_\nu = \sqrt{\sum_i m_i^2 |U_{ei}|^2}$
- flight-time measurements (νs from supernovae)
- kinematics of weak decays

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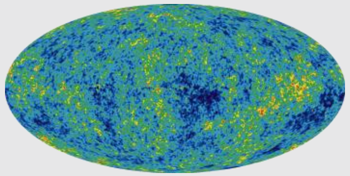

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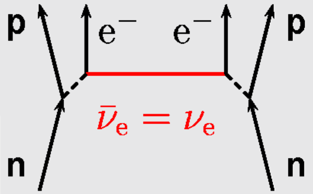

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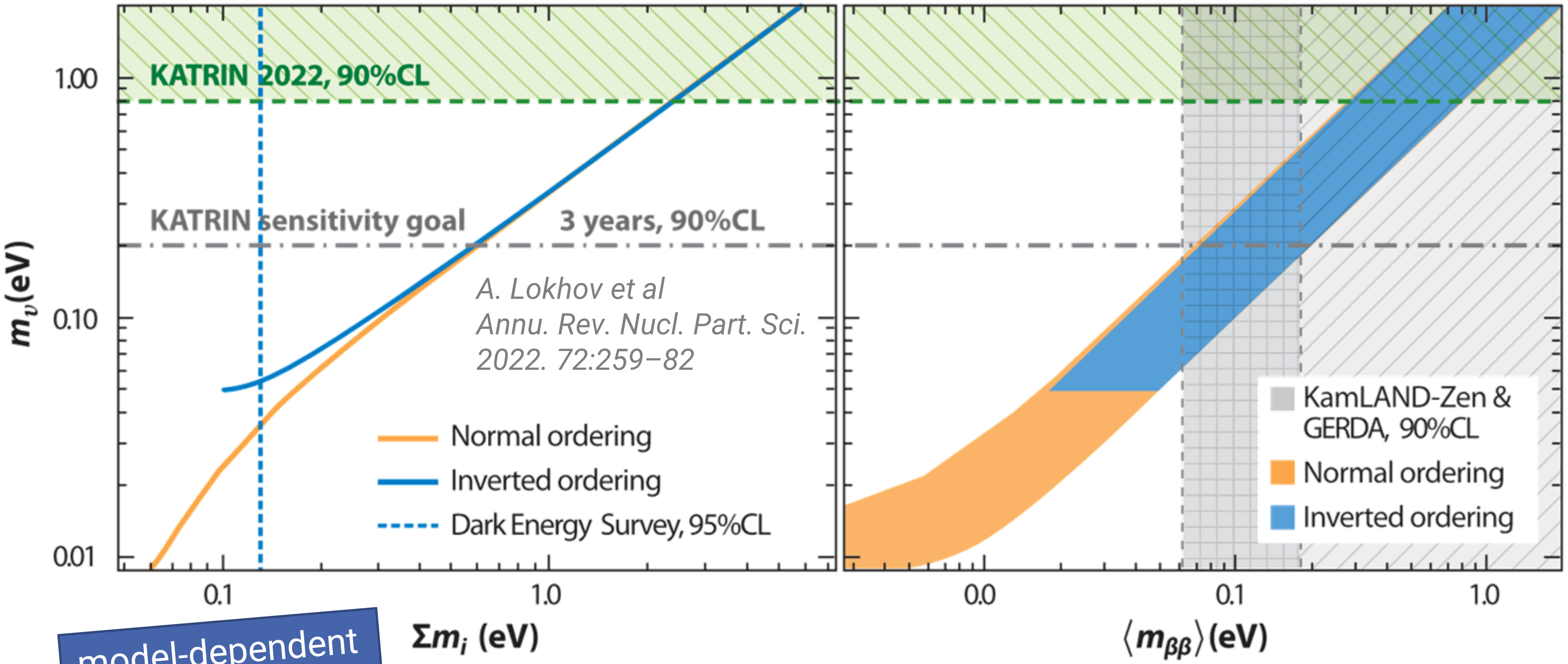

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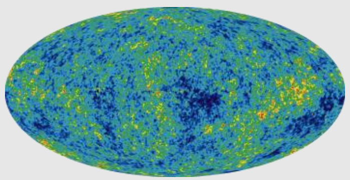

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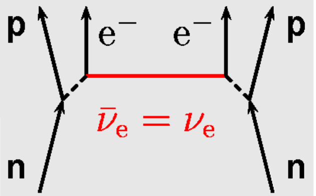
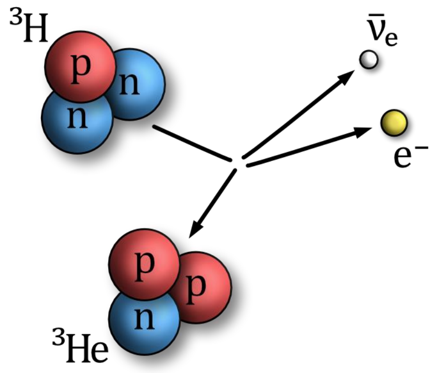


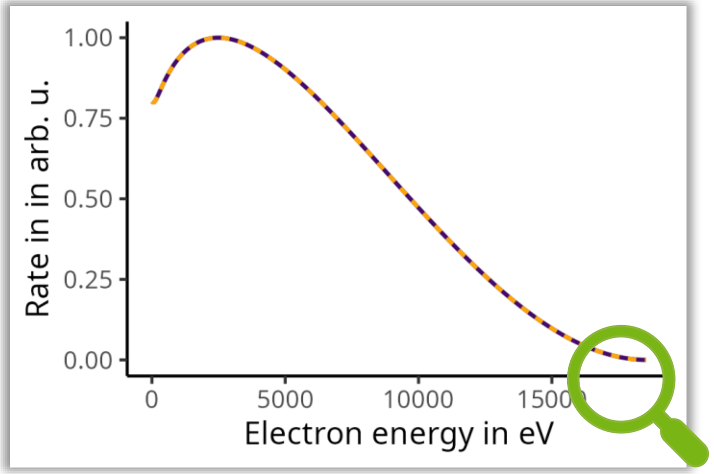
Neutrino mass determination from beta decay

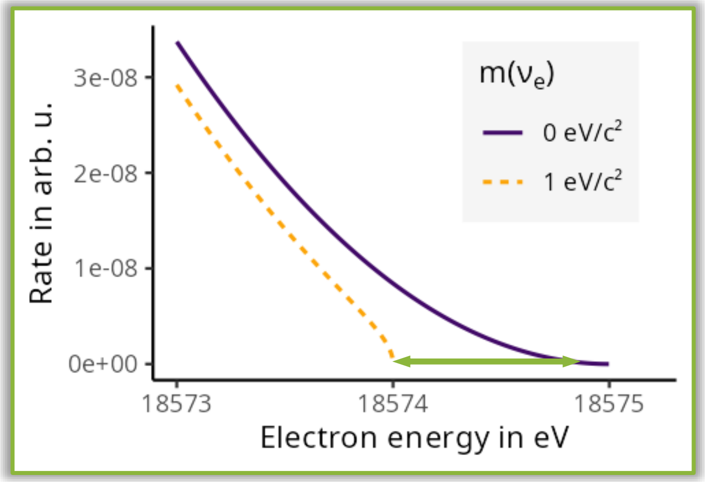
- Possible beta-decay source: tritium
  - Simple structure of atomic/nuclear shell
  - Low endpoint (18.6 keV)
  - Super-allowed transition
    - High-decay rate ($T_{1/2}$ = 12.3 years)
- Neutrino mass influences decay spectrum, especially at the endpoint ($E \approx E_0$)



$$\left(\frac{dN}{dE}\right) \sim (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - \sum_i m_i^2 |U_{ei}|^2}$$

Measure kinetic energy of beta-decay electrons





Neutrino mass determination from electron capture (EC)

- Possible EC source: Holmium-163
  - Very low endpoint (2.8 keV)
  - $T_{1/2} \approx 4570$ years

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

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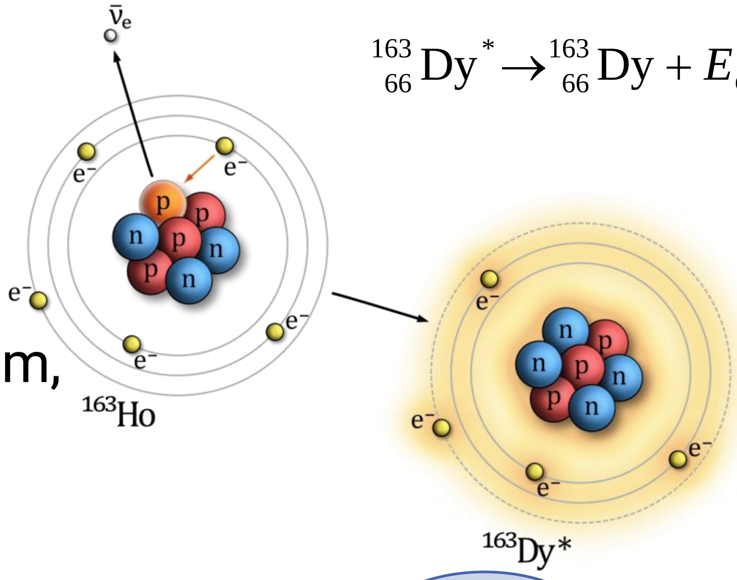

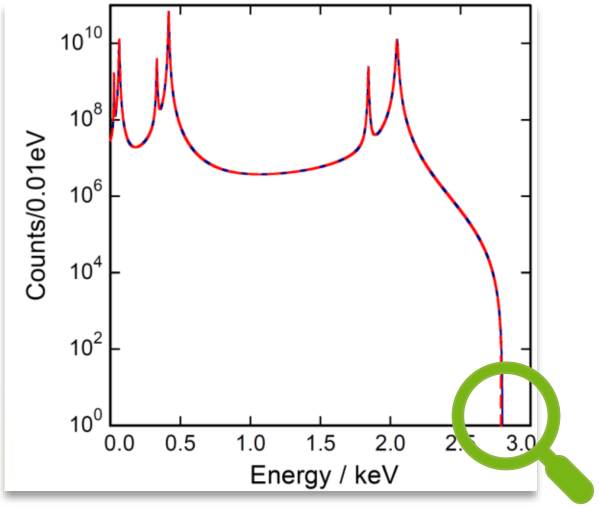

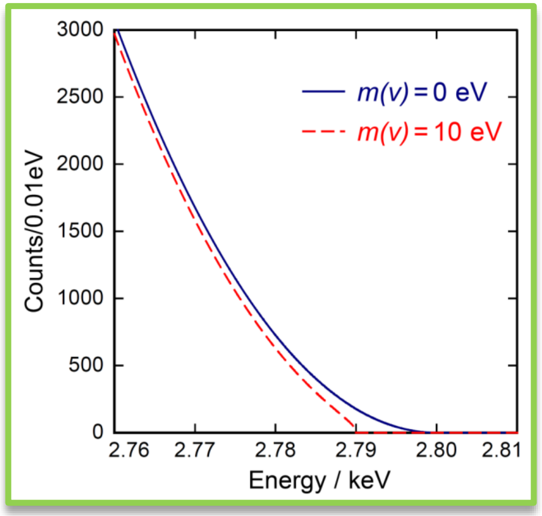

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$$\left(\frac{dN}{dE}\right) \sim (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - \sum_i m_i^2 |U_{ei}|^2}$$

Measure internal excitation energy of daughter atom

Beta decay and electron capture – common challenges

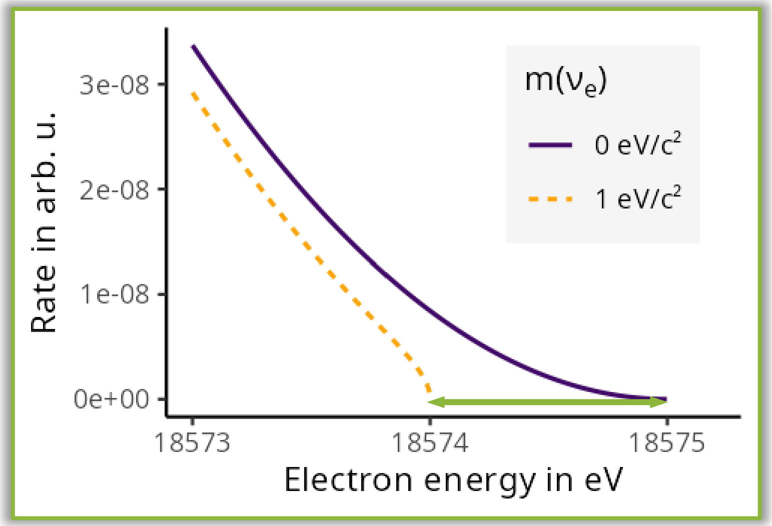
For resolving signature of the neutrino mass:

- Low endpoint and high decay rate
- High source activity needed
- High resolution in endpoint region

✓ ^3H, ^{163}Ho

Source design

Detector design



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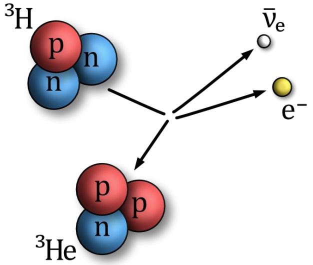

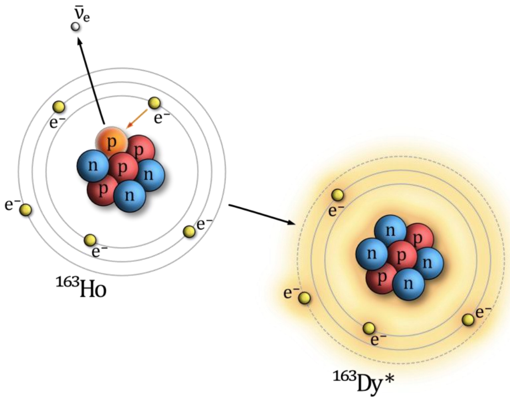

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Isotope	^3H = T	^{163}Ho
Endpoint	18.6 keV	2.8 keV
Half-life	12.3 years	4570 years
Production	n-capture in D_2O	n-irradiation of ^{162}Er

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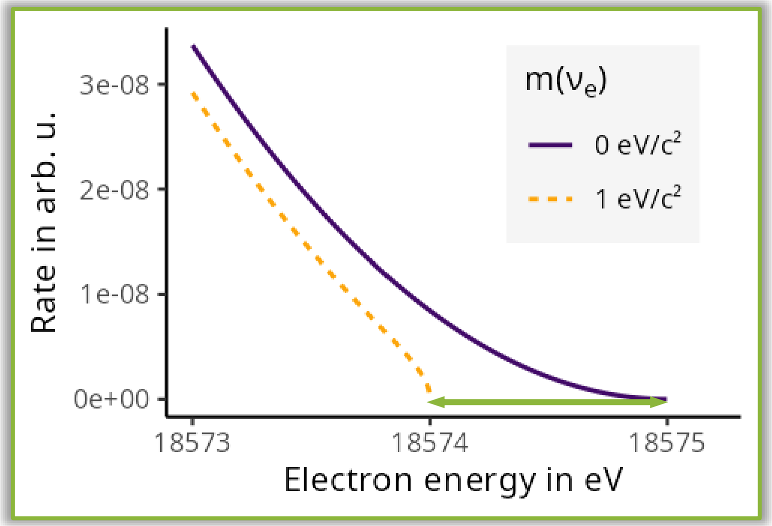

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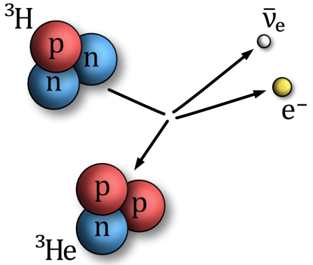

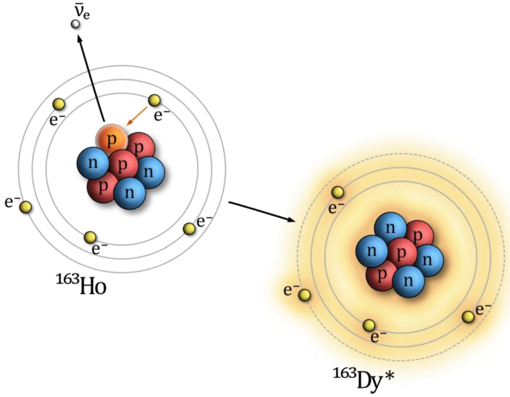

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- Magnetic Adiabatic Collimation with an Electrostatic Filter
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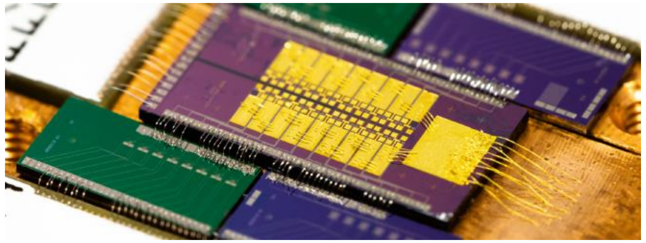
Calorimeters

- Low-temperature micro calorimeters
- Measuring energy by **temperature change**



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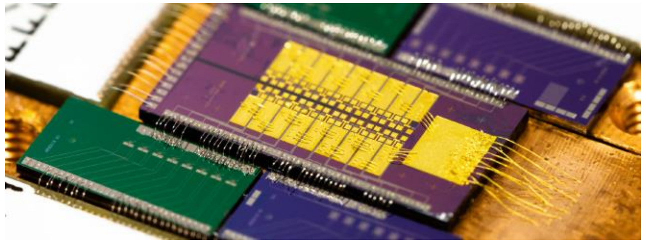

CRES

- Cyclotron Radiation Emission Spectroscopy
- Measuring energy via **frequency**

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Karlsruhe Institute of Technology

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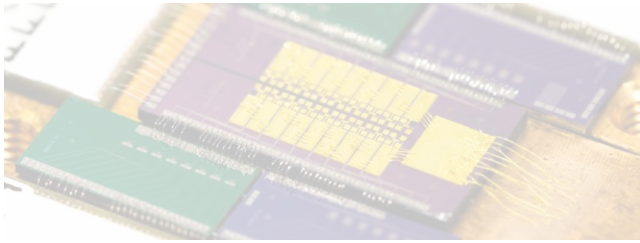

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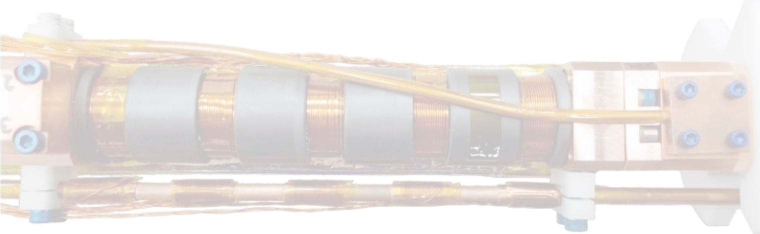
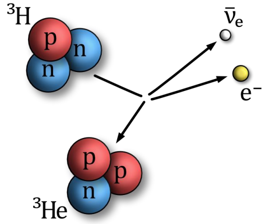
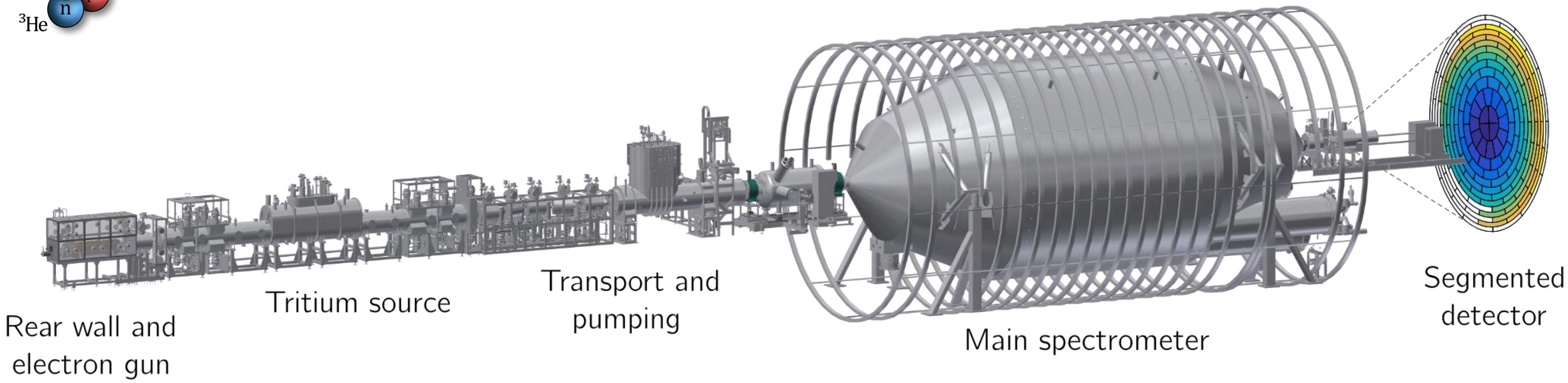
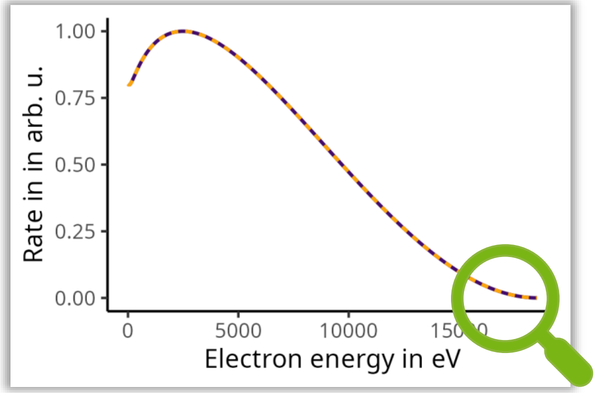


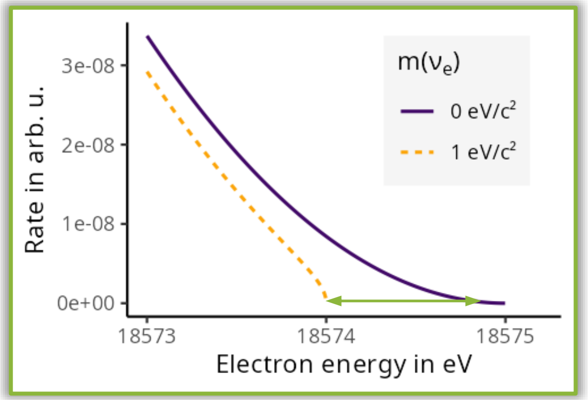
Karlsruhe Tritium Neutrino Experiment (KATRIN)

- **Goal**: Determining the neutrino mass with a sensitivity of 0.2 eV/c² (90% CL)









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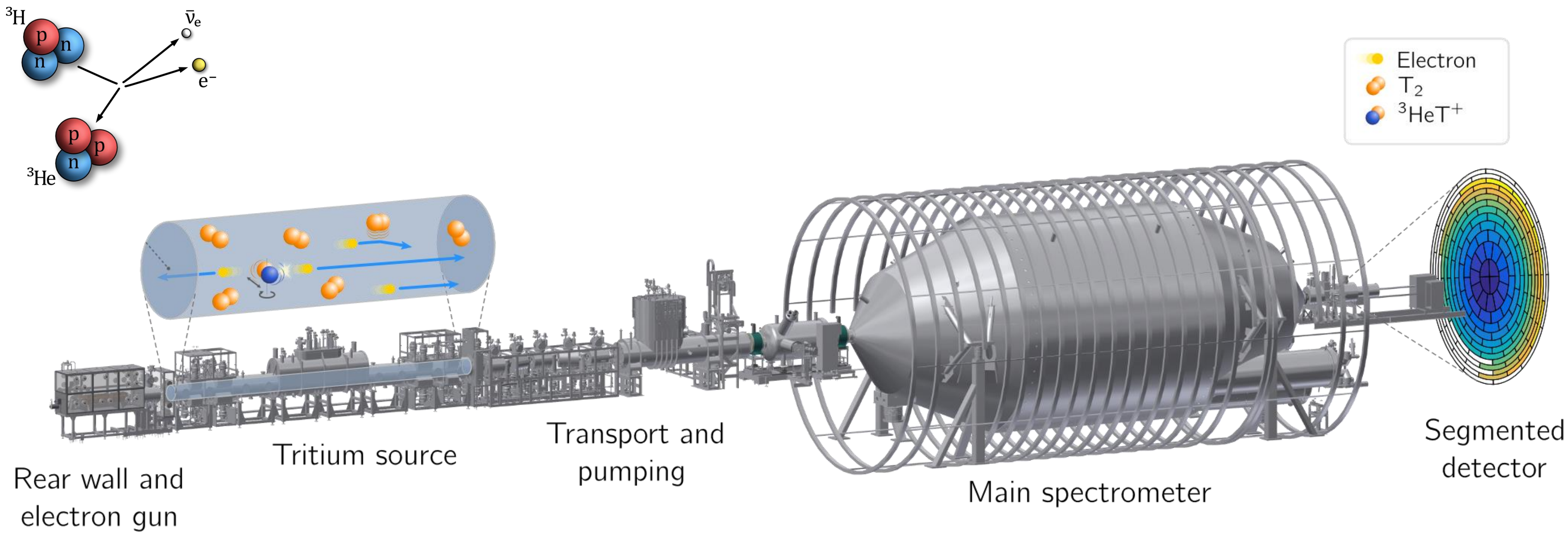

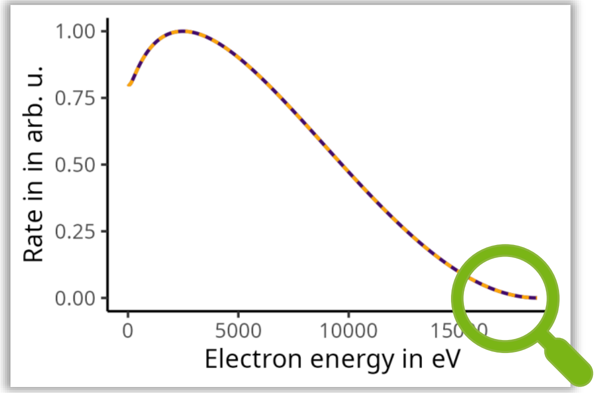

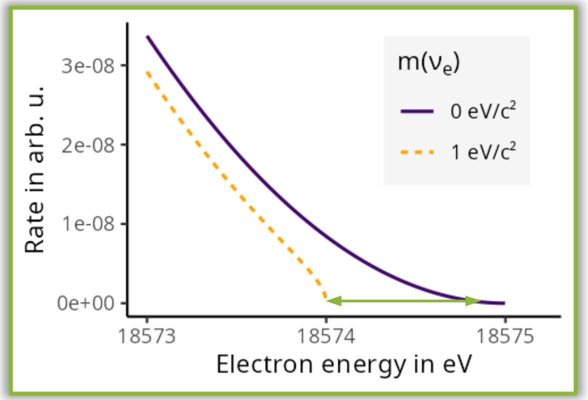

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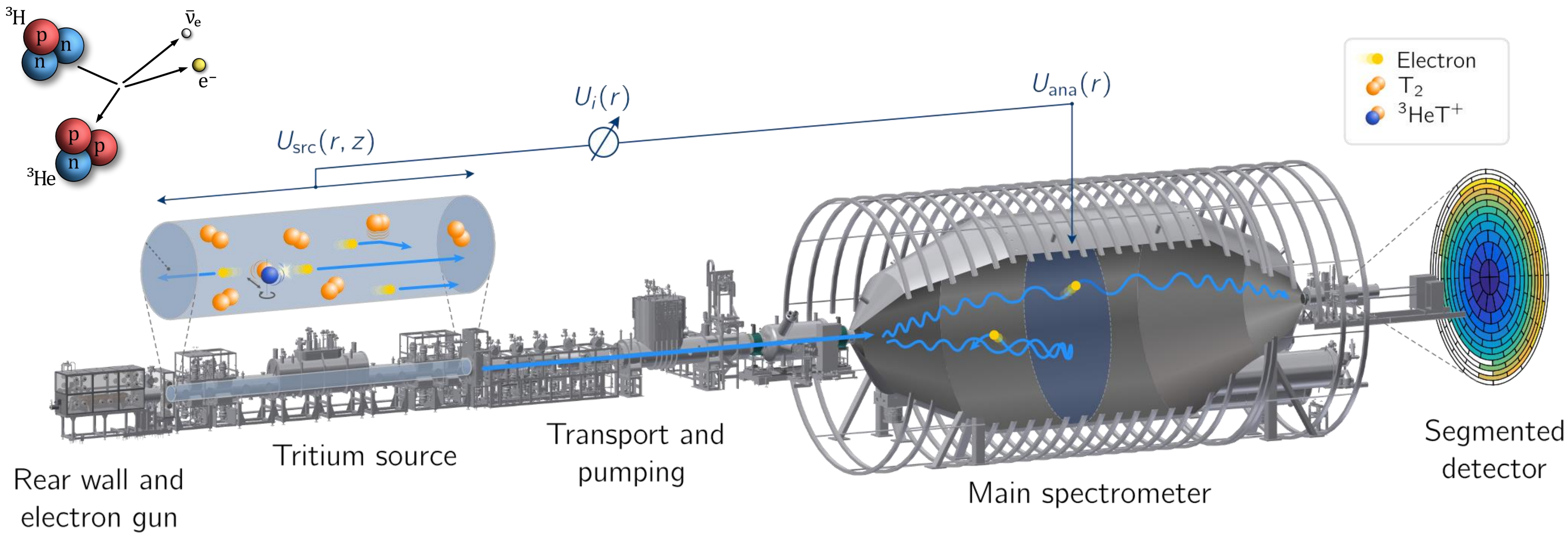

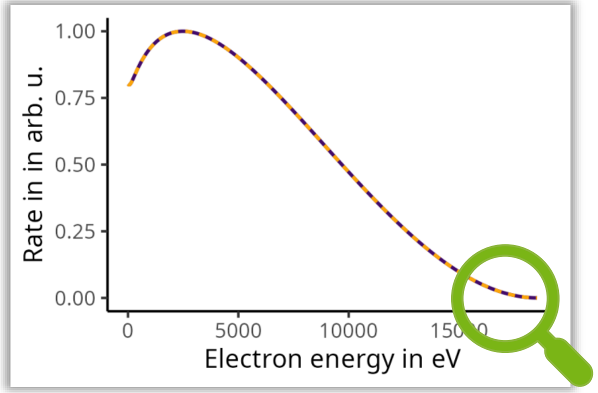

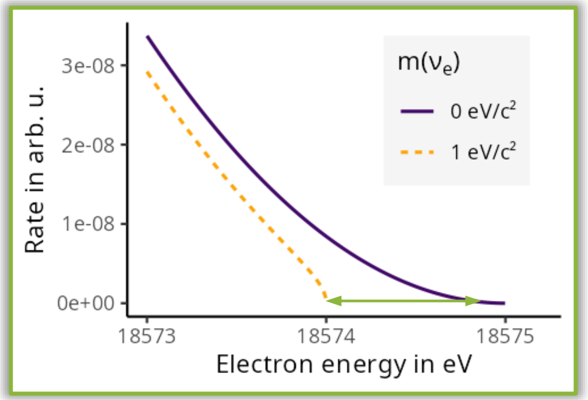

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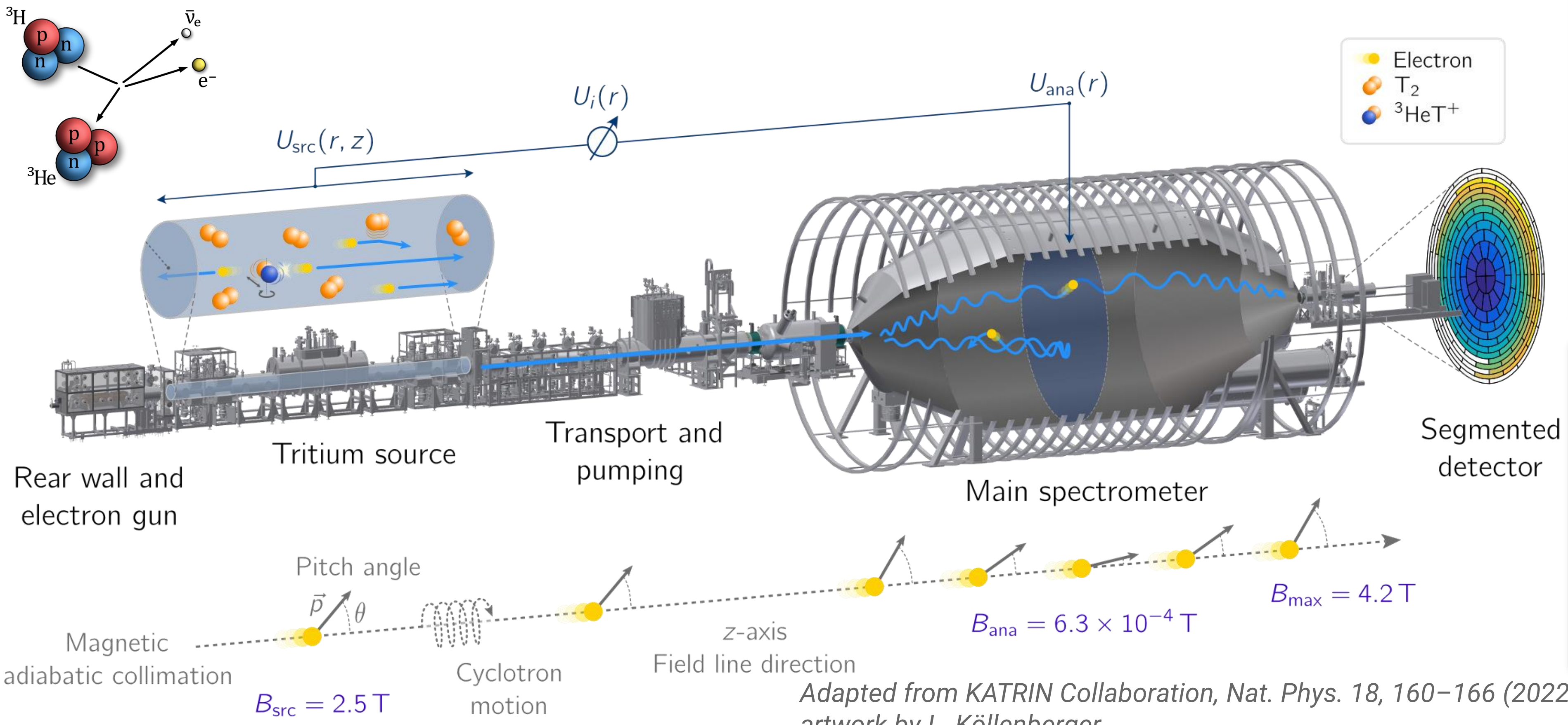

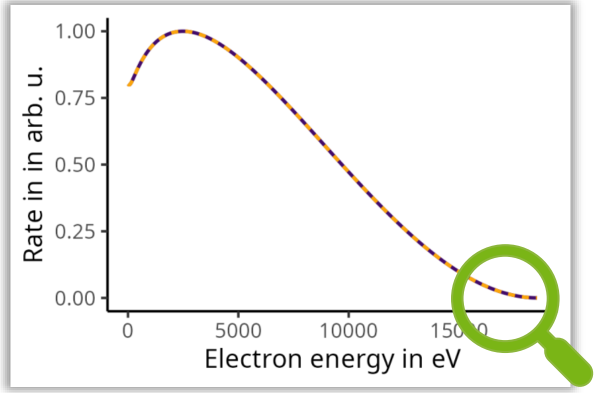

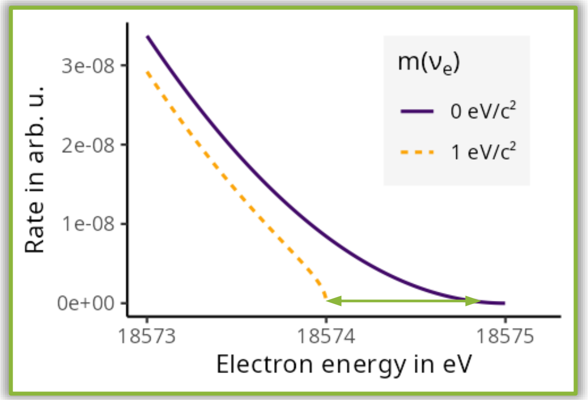

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Recent results from KATRIN

- First campaign
  (“KNM1”, spring 2019)
  - total stat.: 2 million events
  - best fit: $m^2(\nu_e) = -1.0^{+0.9}_{-1.1} \text{eV}^2$
  - limit: $m(\nu_e) < 1.1$ eV (90% C.L.)

Phys. Rev. Lett. 123, 221802 (2019)
Phys. Rev. D. 104 (1), 012005 (2021)

- Second campaign
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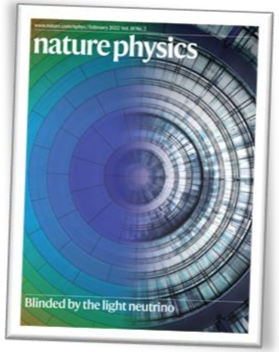

- **Combined result:**
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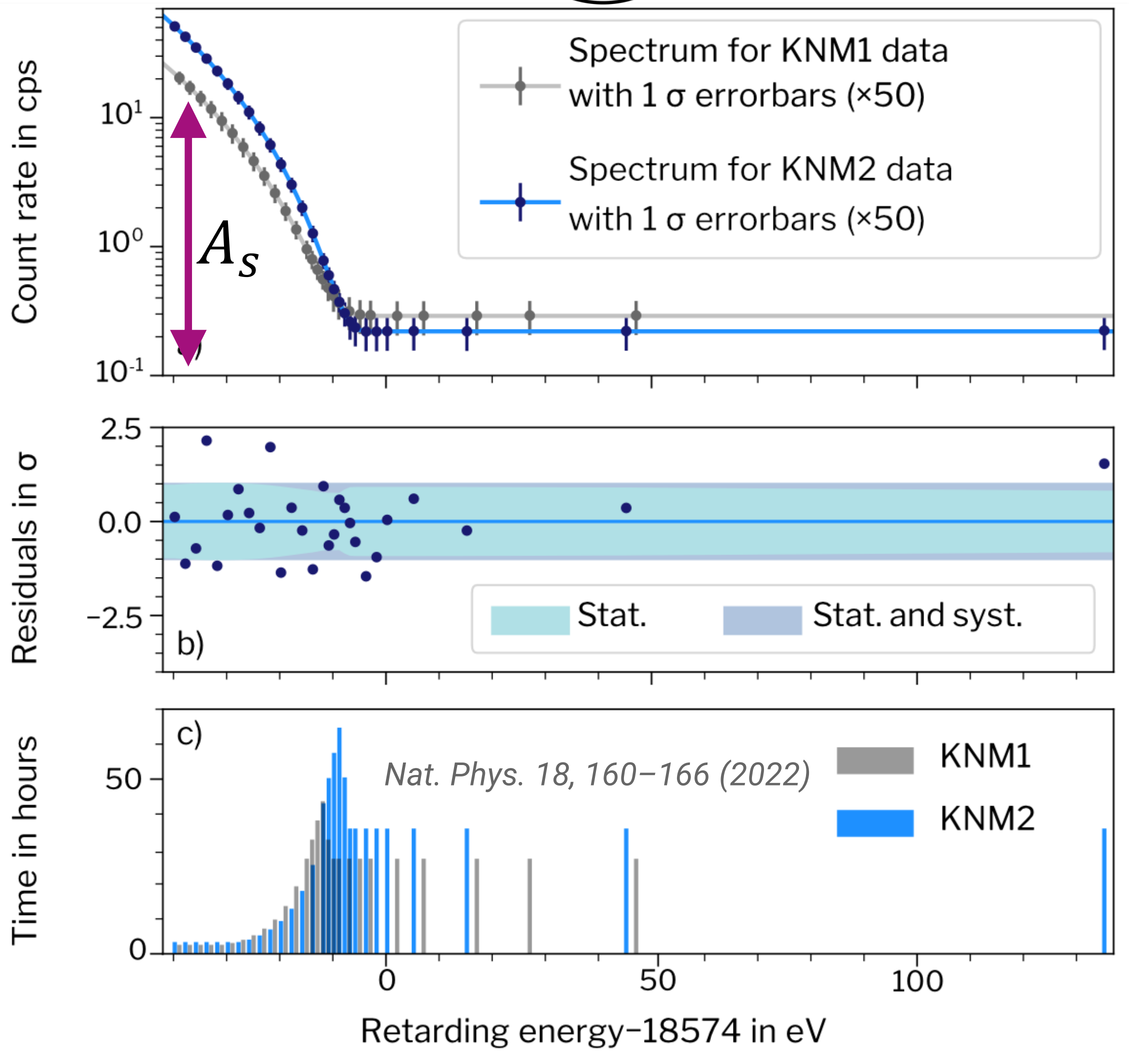
Nat. Phys. 18, 160–166 (2022)

KNM: KATRIN Neutrino Mass measurement



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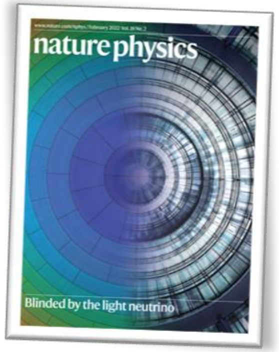

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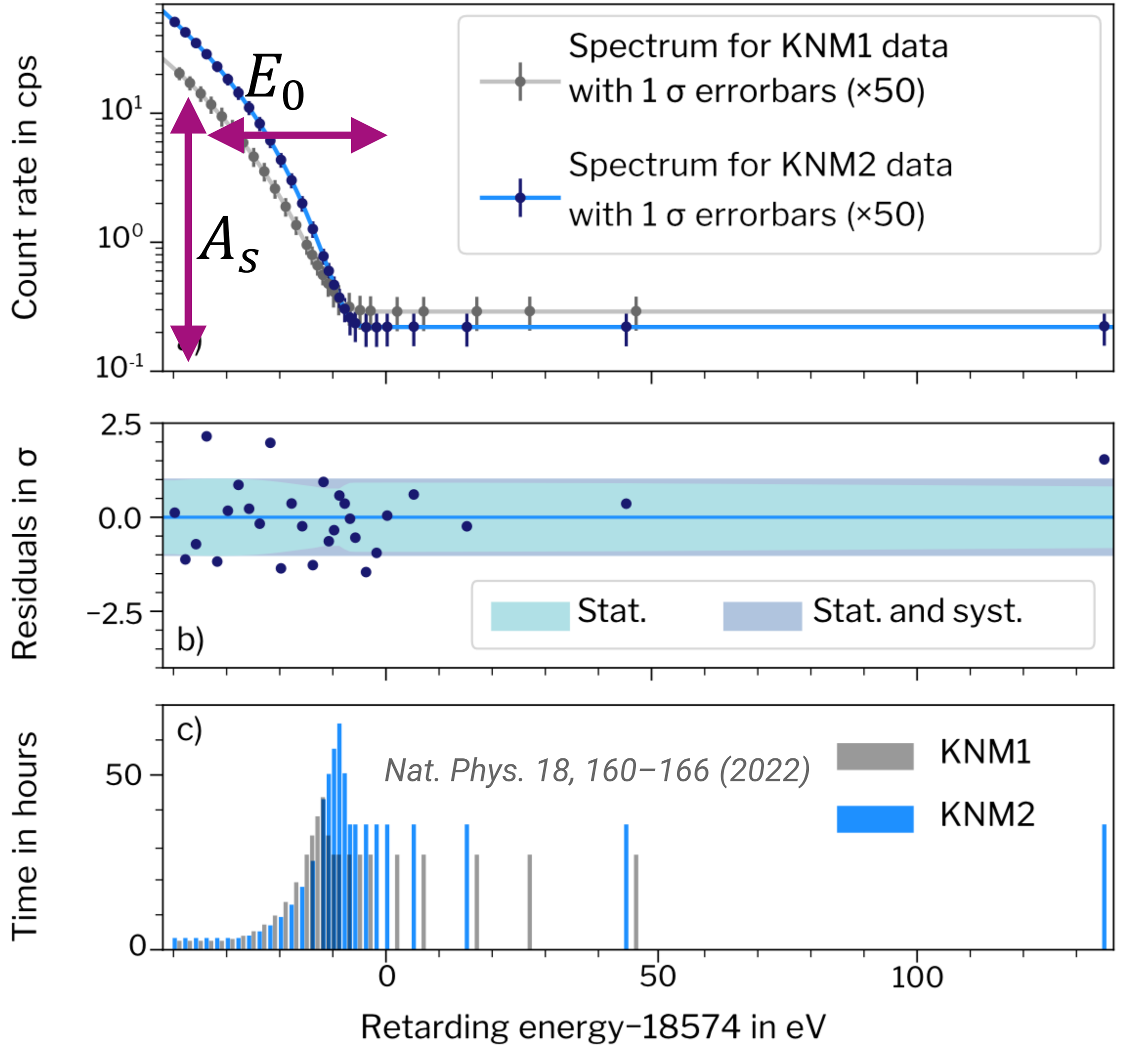

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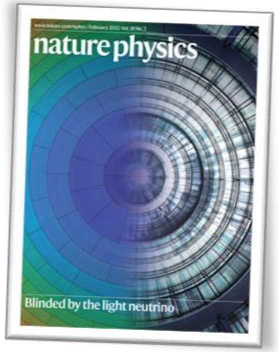

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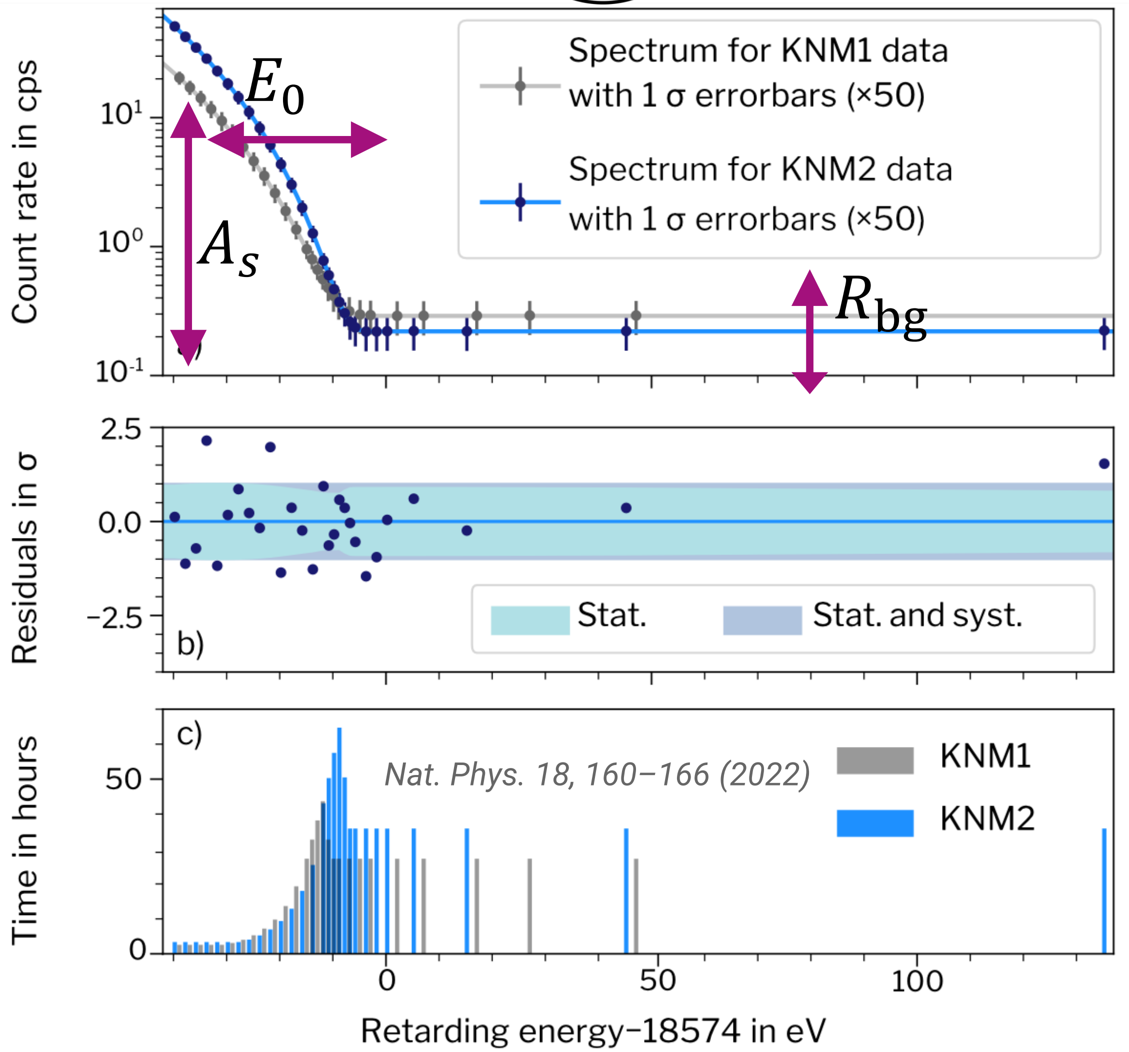

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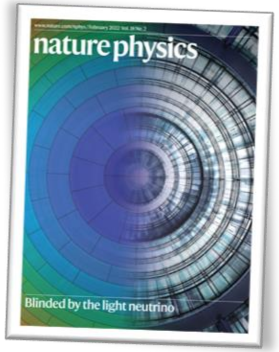
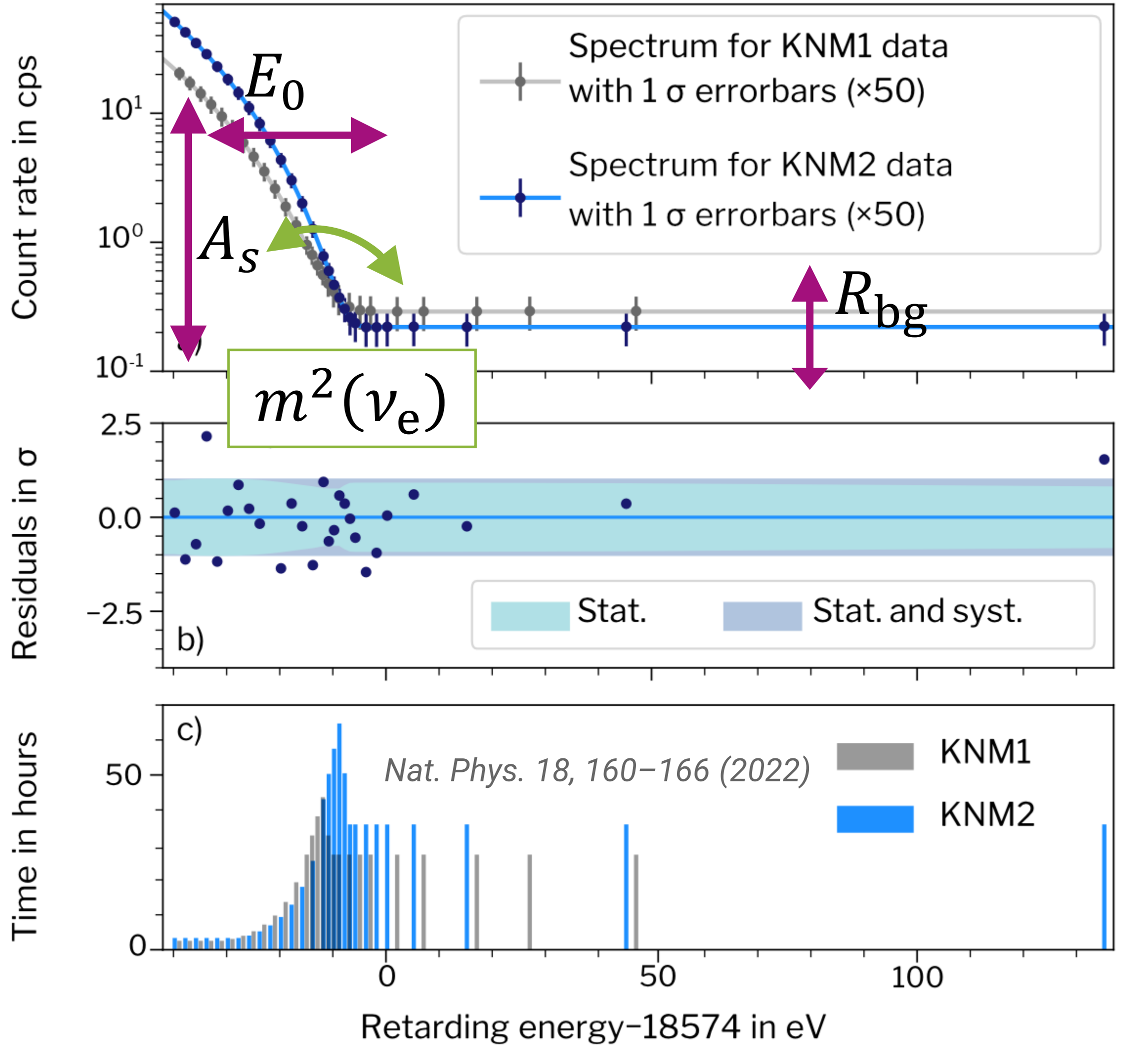


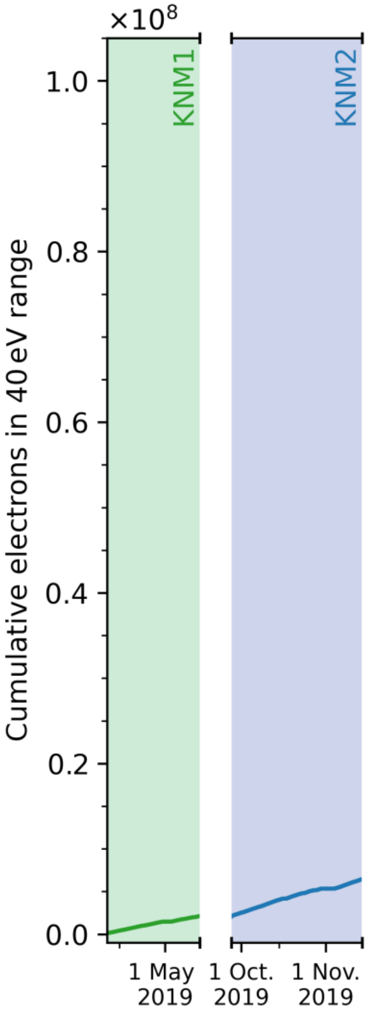
- **Combined result:**
  $m(\nu_e) <$ 0.8 eV (90% C.L.)

Nat. Phys. 18, 160–166 (2022)

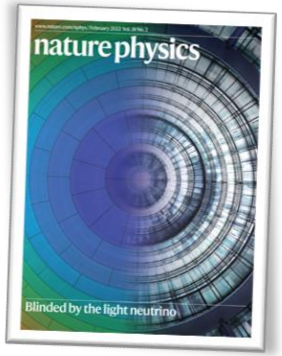
KNM: KATRIN Neutrino Mass measurement



KATRIN data taking



Phys. Rev. Lett. 123, 221802 (2019)
Phys. Rev. D. 104 (1), 012005 (2021)



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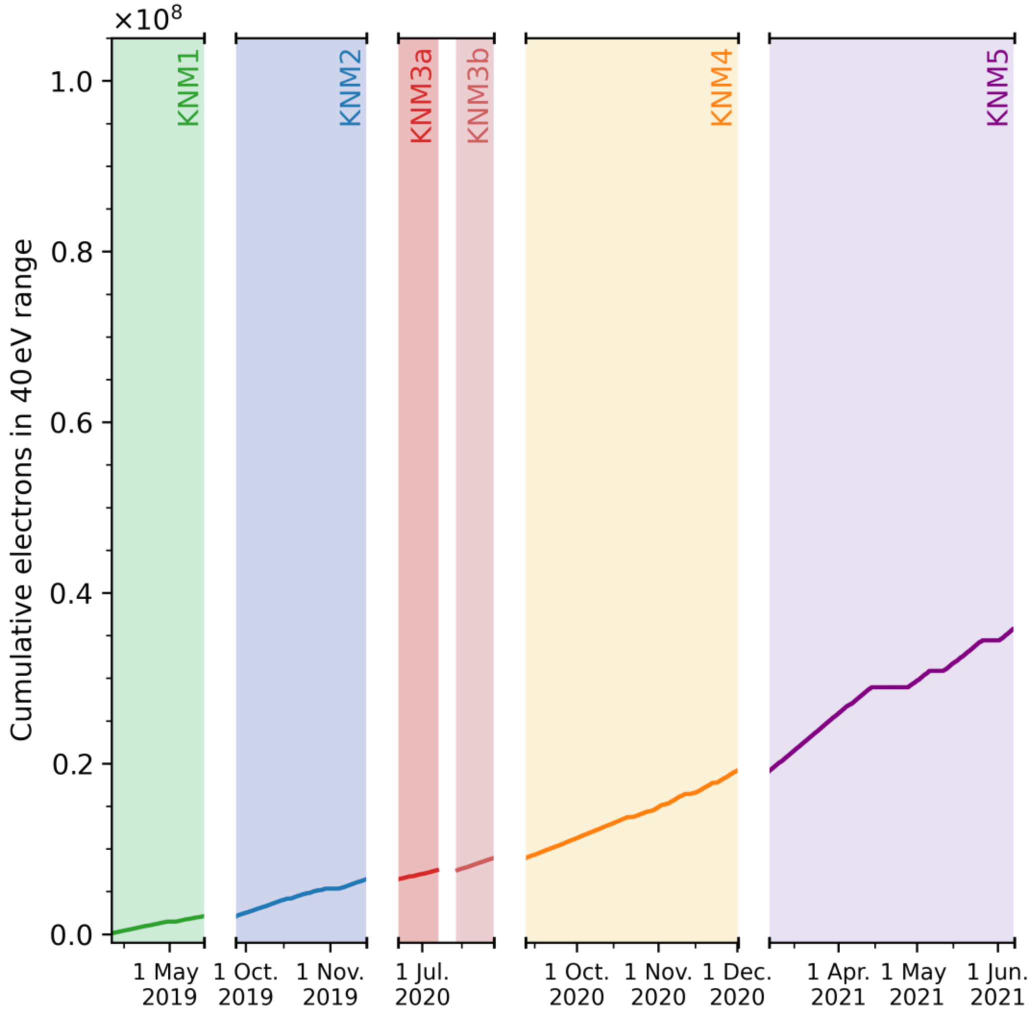
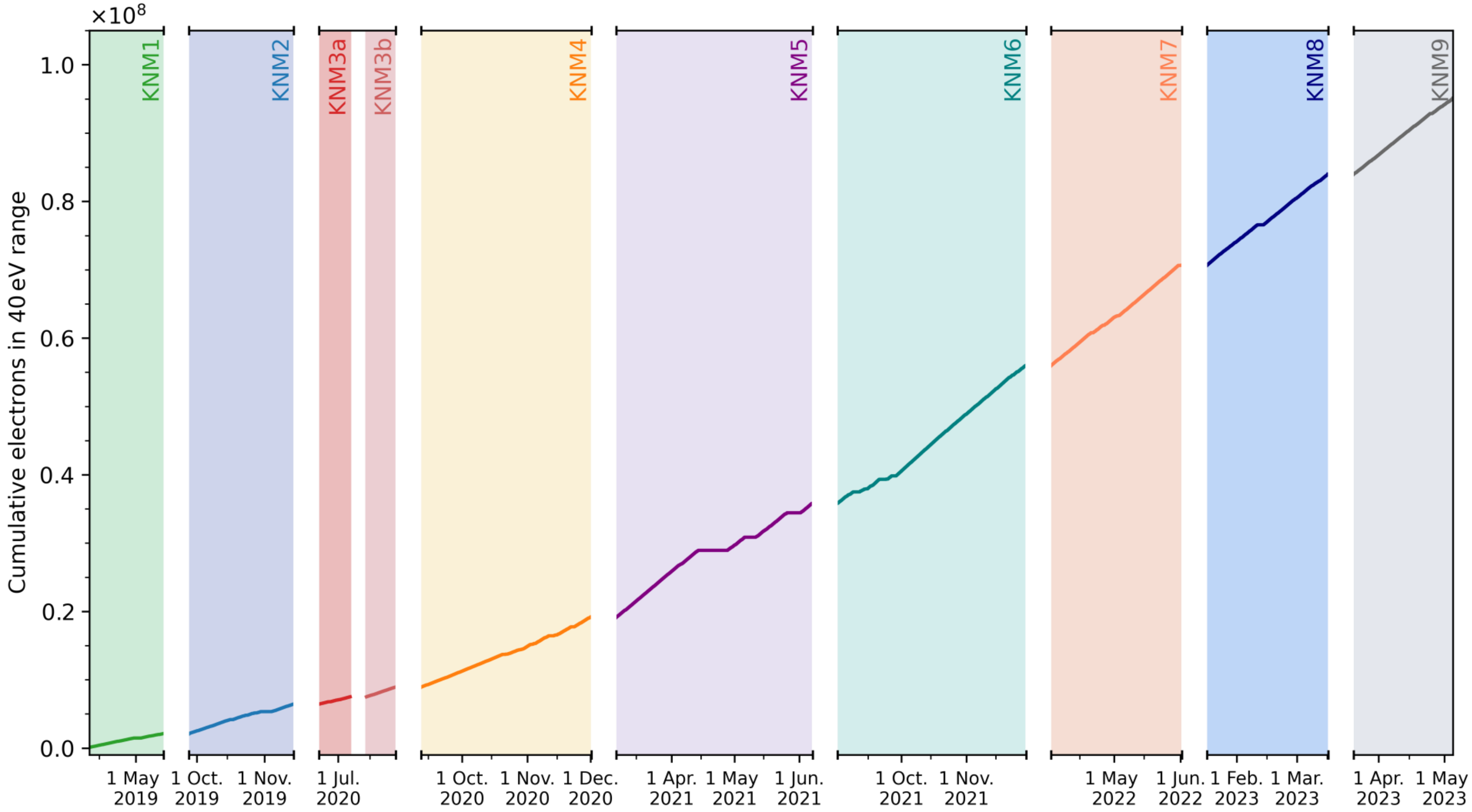
KATRIN data taking



Analysis of **first five runs** is being finalized:

- Statistical sensitivity **~ 0.5 eV (90% C.L.)**

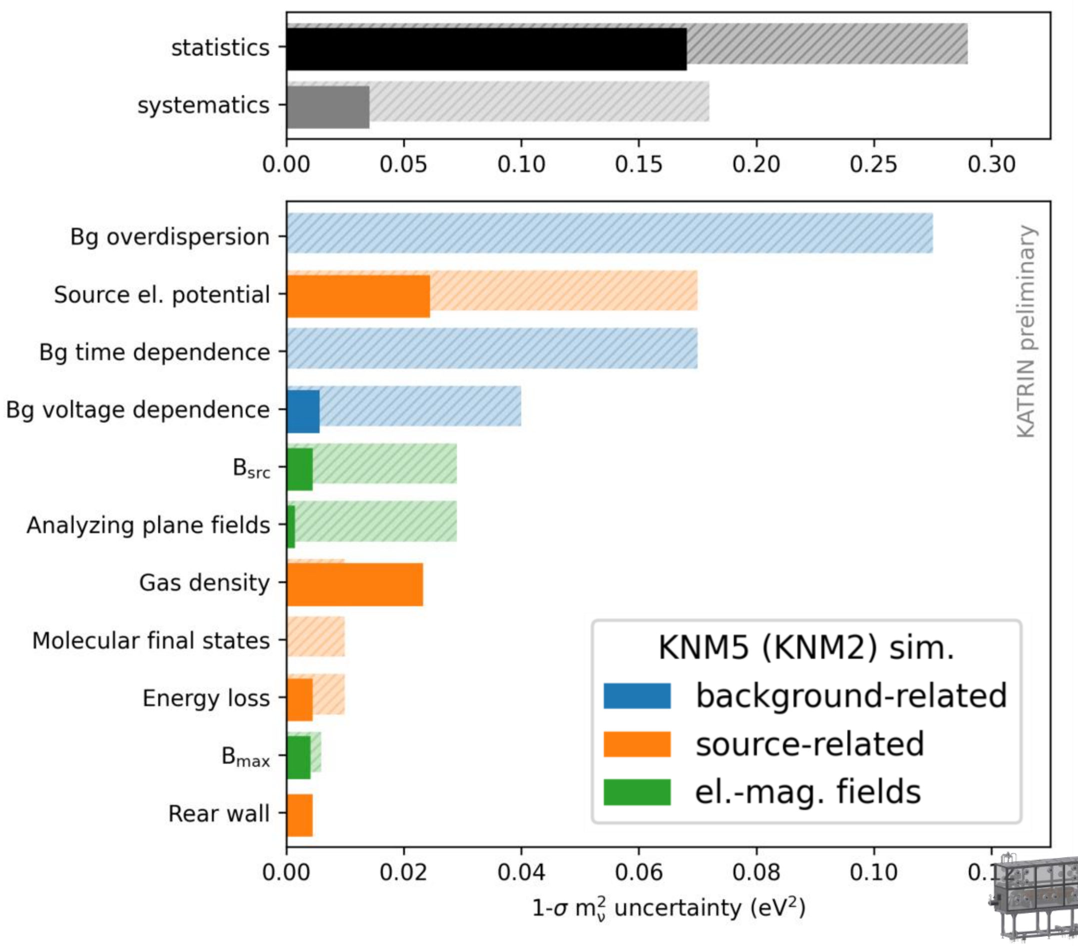
KATRIN data taking

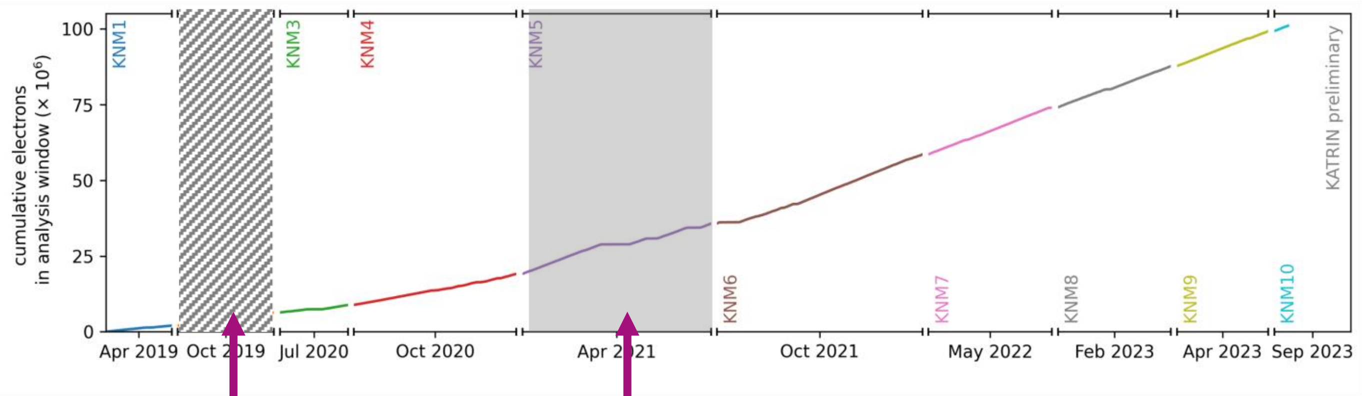


Analysis of **first five runs** is being finalized:

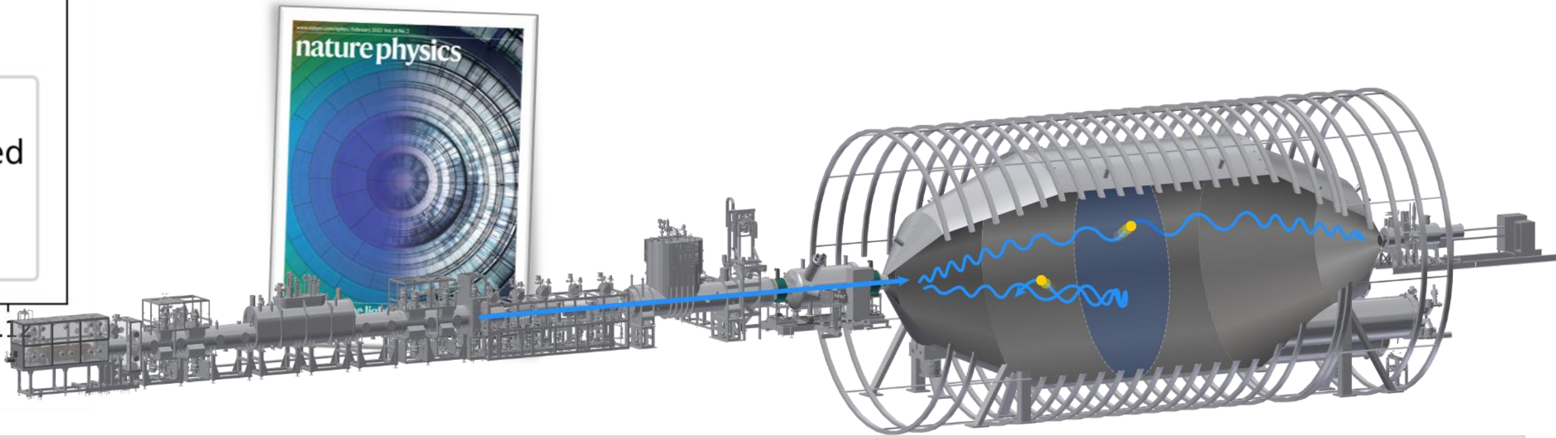
- Statistical sensitivity **~ 0.5 eV (90% C.L.)**
- KNM11 data taking ongoing
- Planned data taking until 2025 to complete **1000 measurement days**

Improvements from 2nd to 5th campaign

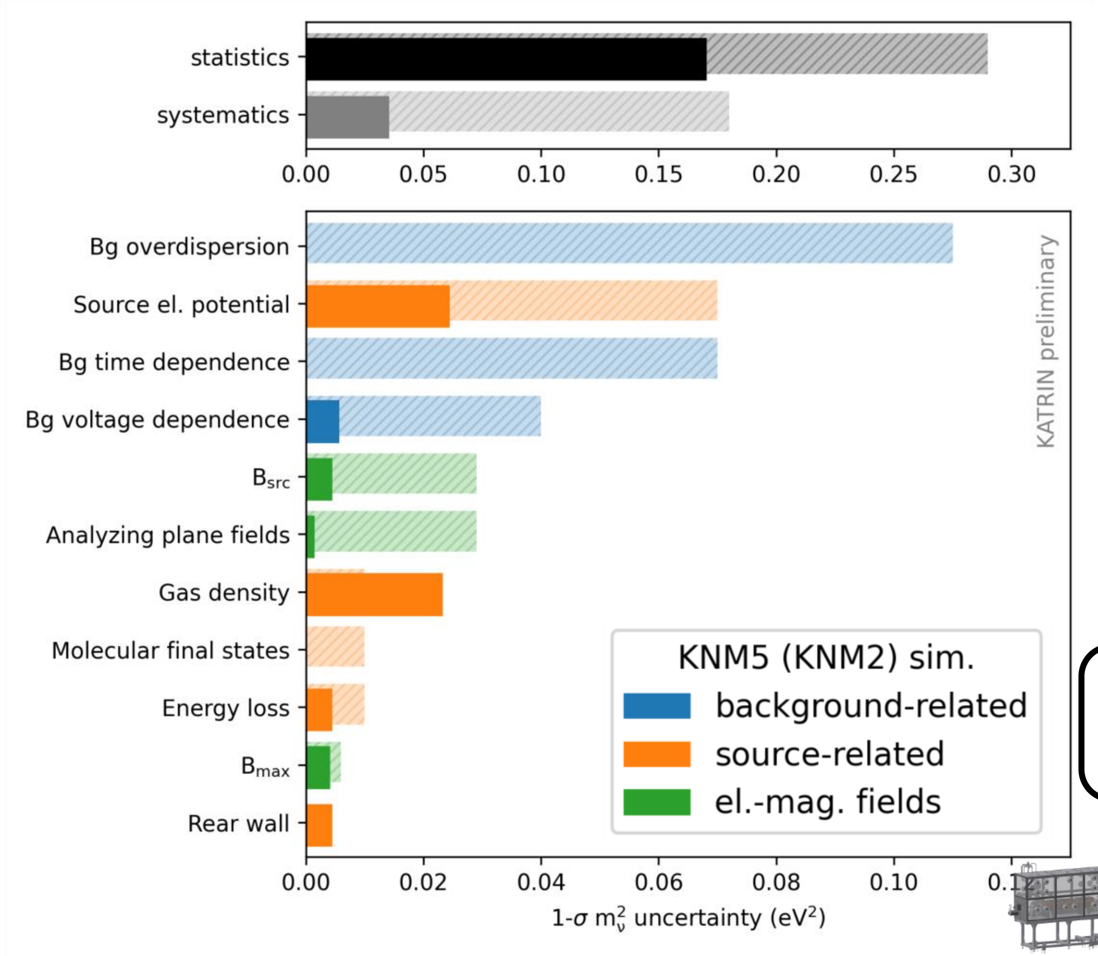




2nd campaign 5th campaign



Recent improvements on systematics



High-statistics ^{83m}Kr calibration
*A. Marsteller et al. JINST **17** P12010 (2022)*

Shifted analyzing plane
A.Lokhov et al. Eur. Phys. J. C 82:258 (2022)

Absolute energy scale calibration
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Removal of the penning trap
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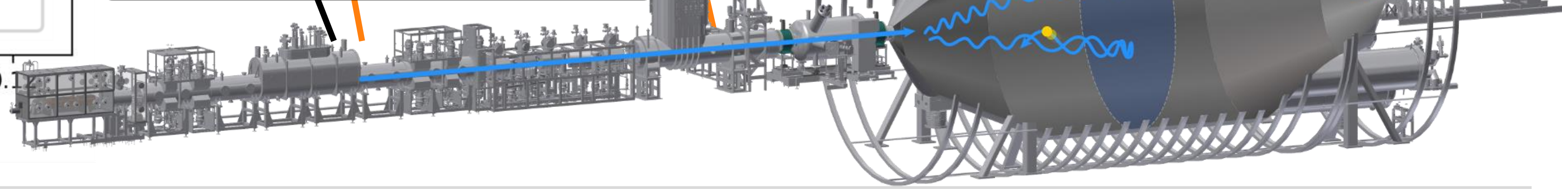
Improved evaluation of theoretical uncertainties



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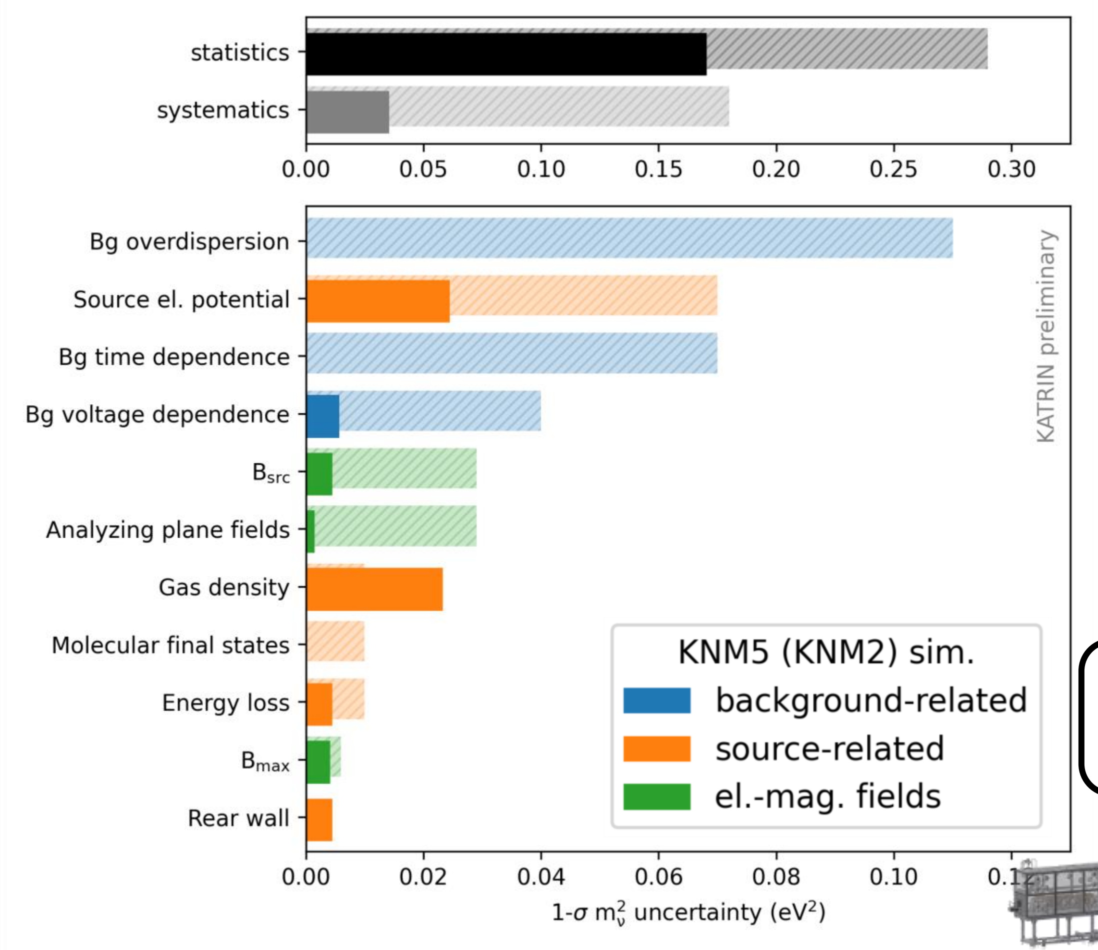

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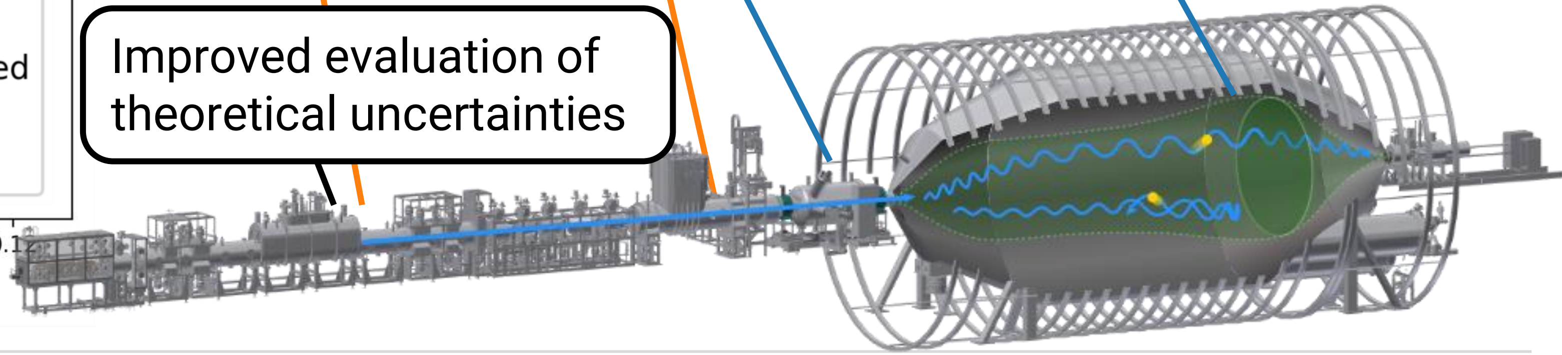

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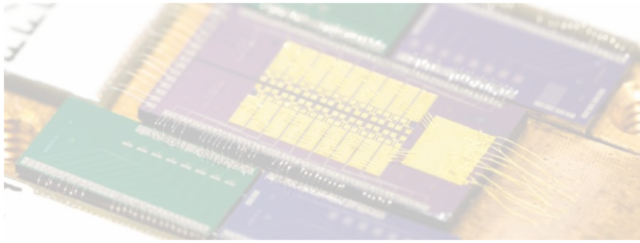
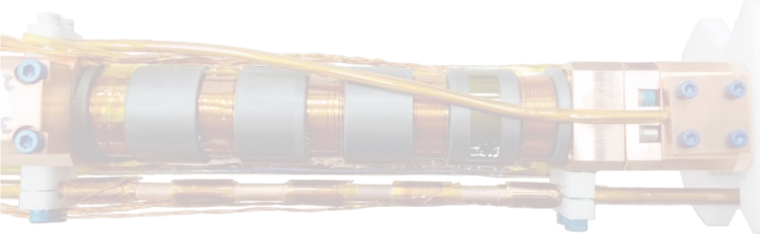
Calorimeters

- Low-temperature micro calorimeters
- Measuring energy by **temperature change**



CRES

- Cyclotron Radiation Emission Spectroscopy
- Measuring energy via **frequency**



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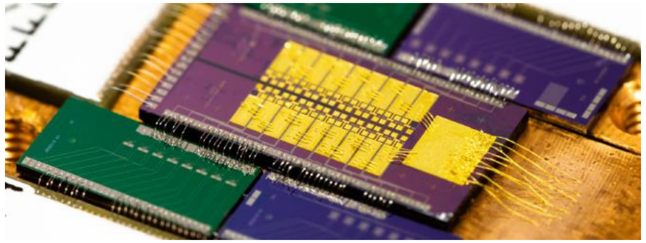

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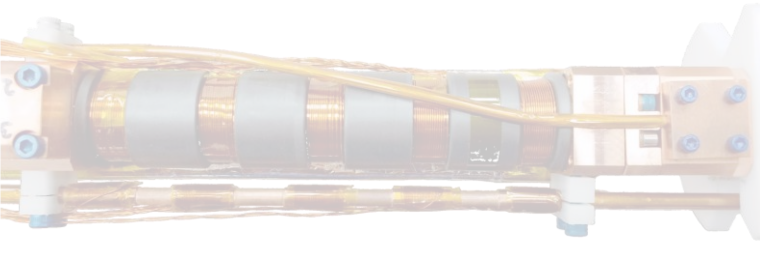
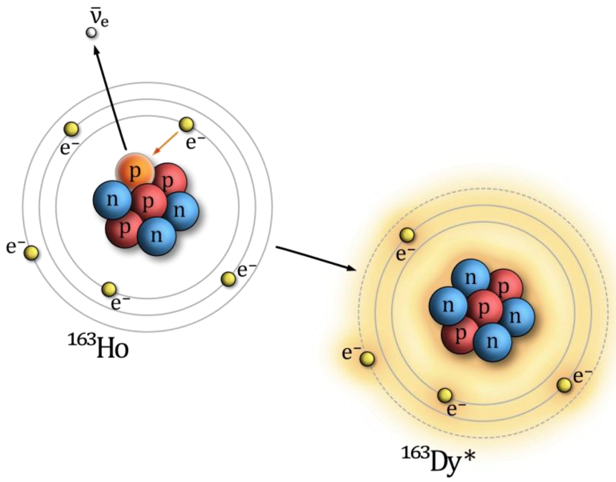
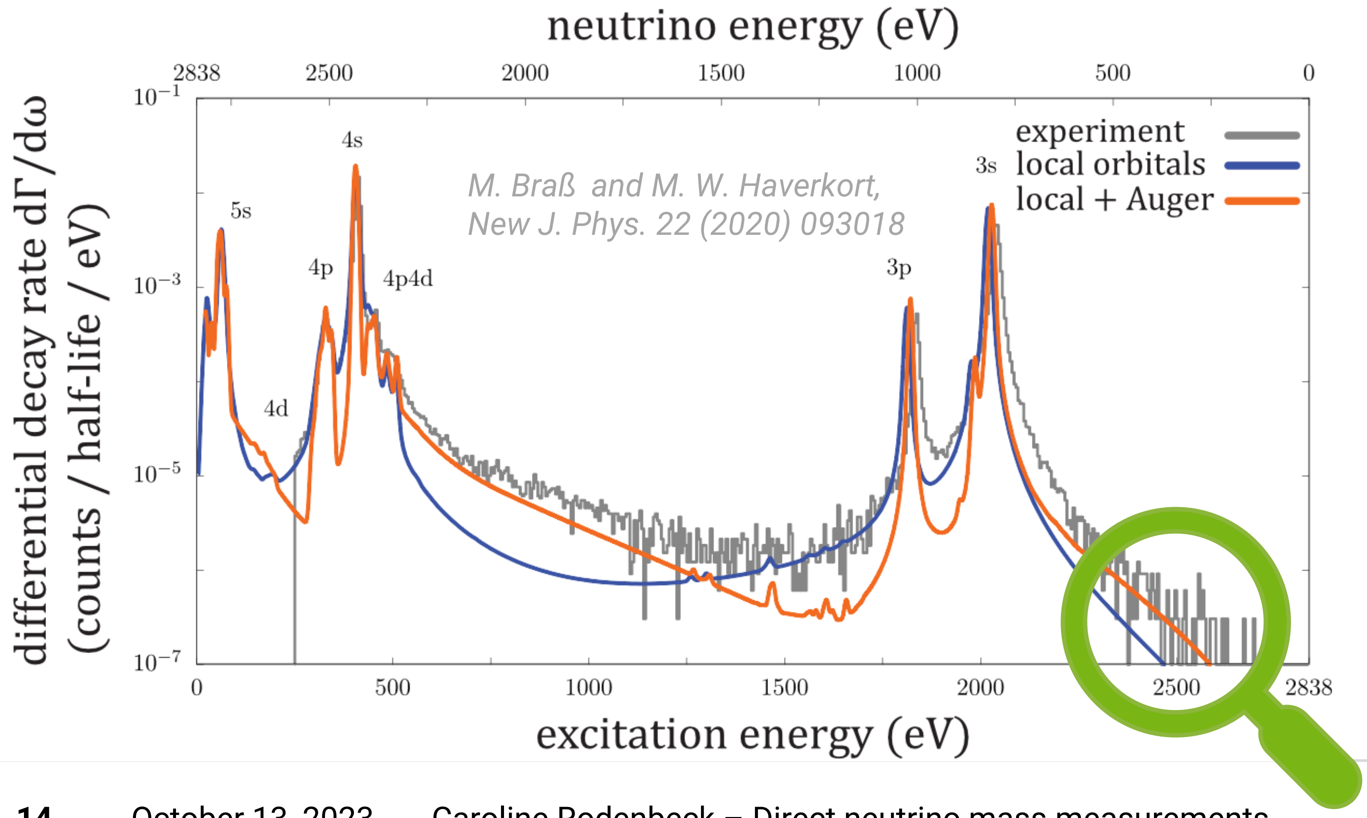


Electron capture in holmium-163

- Measure internal excitation energy of daughter atom (dysprosium-163)





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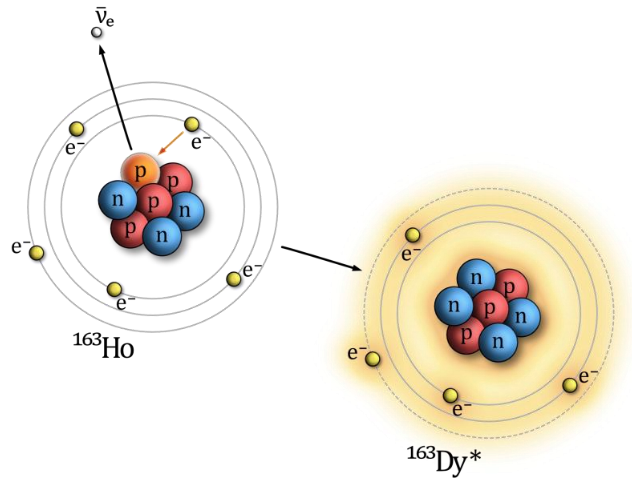
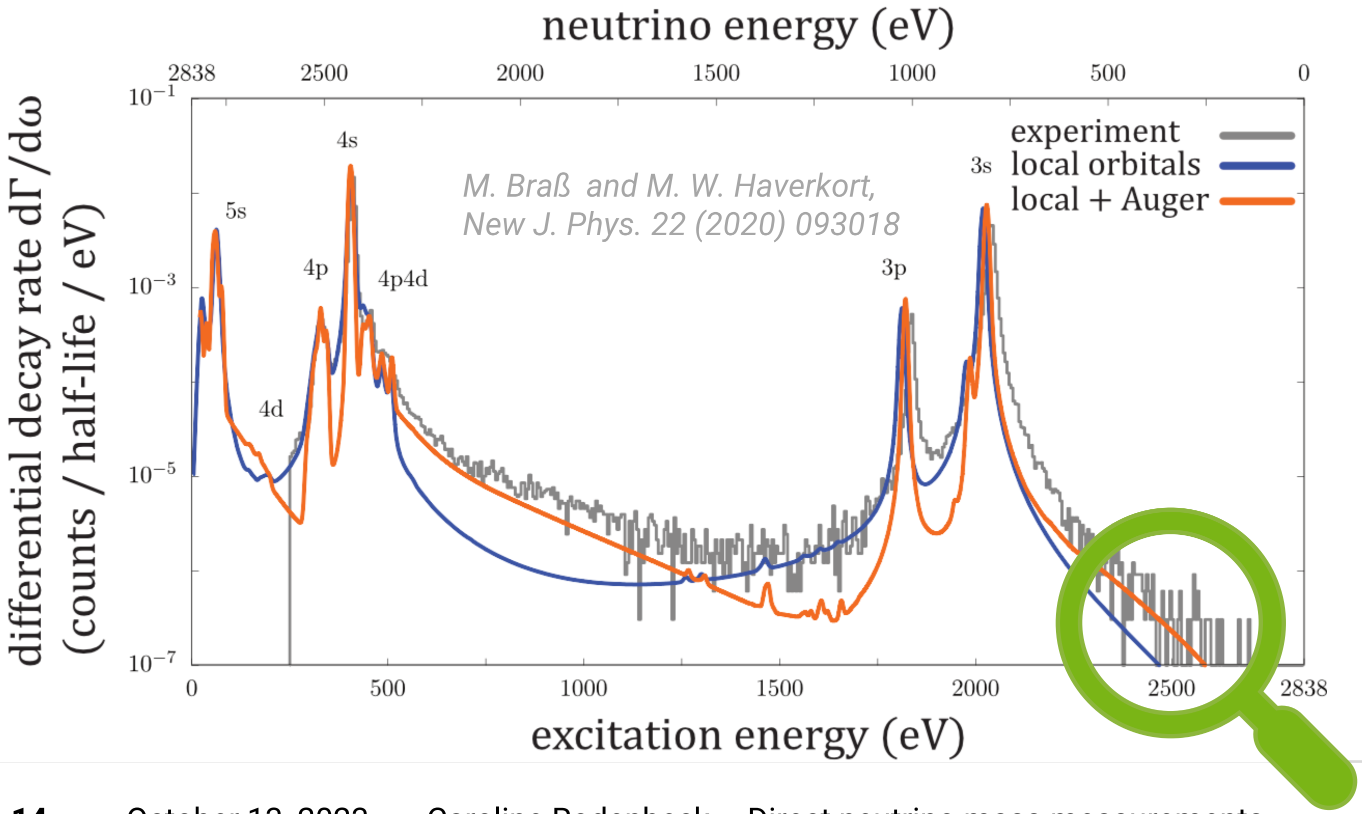
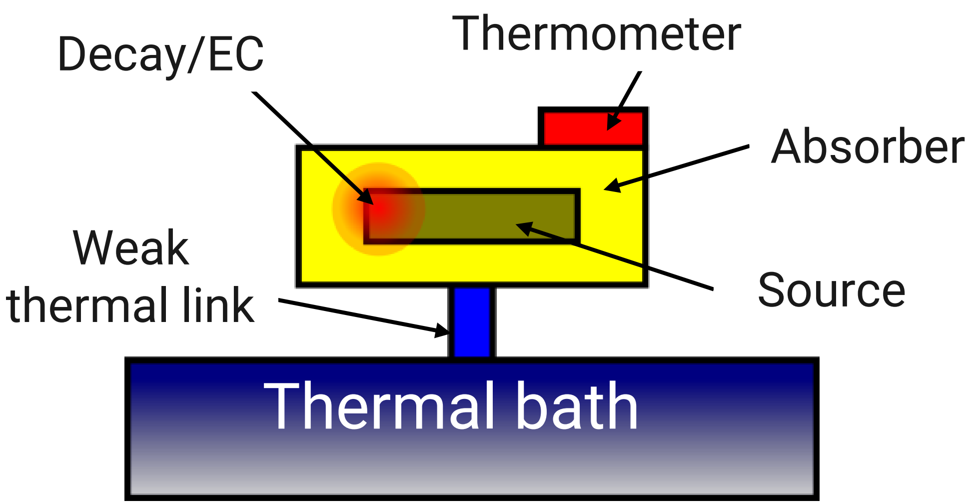


- Measure internal excitation energy of daughter atom (dysprosium-163)
- Source implanted into detector

4π geometry



Cryogenic microcalorimeter



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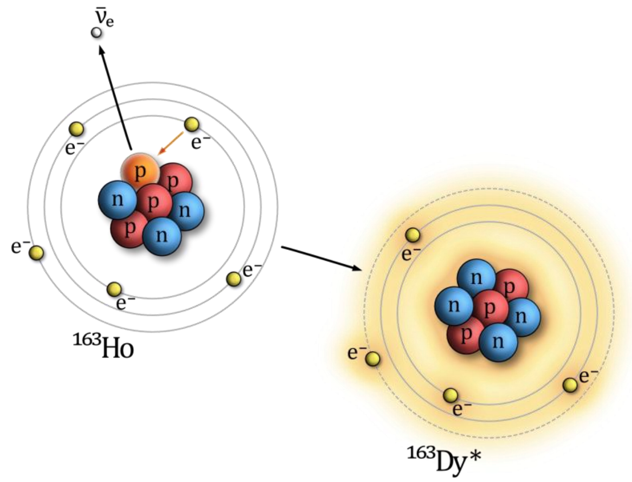
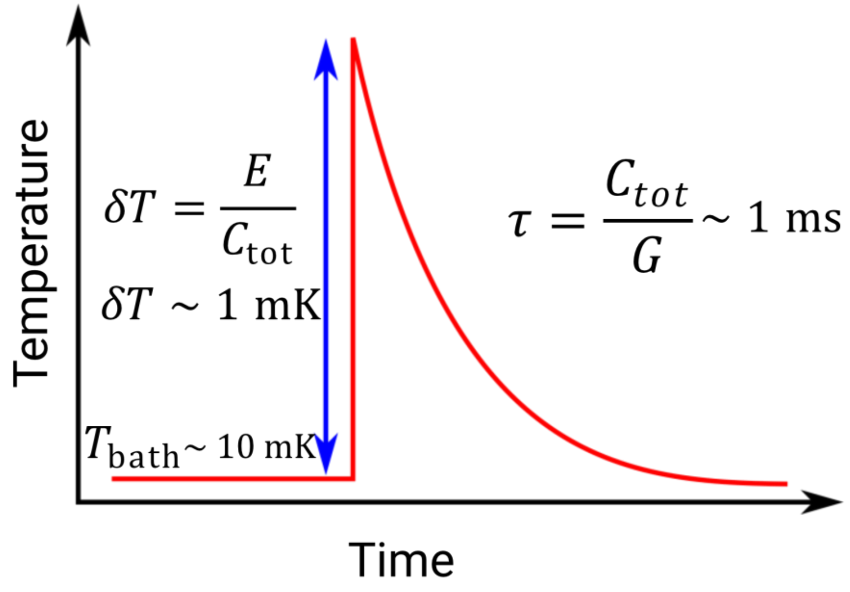
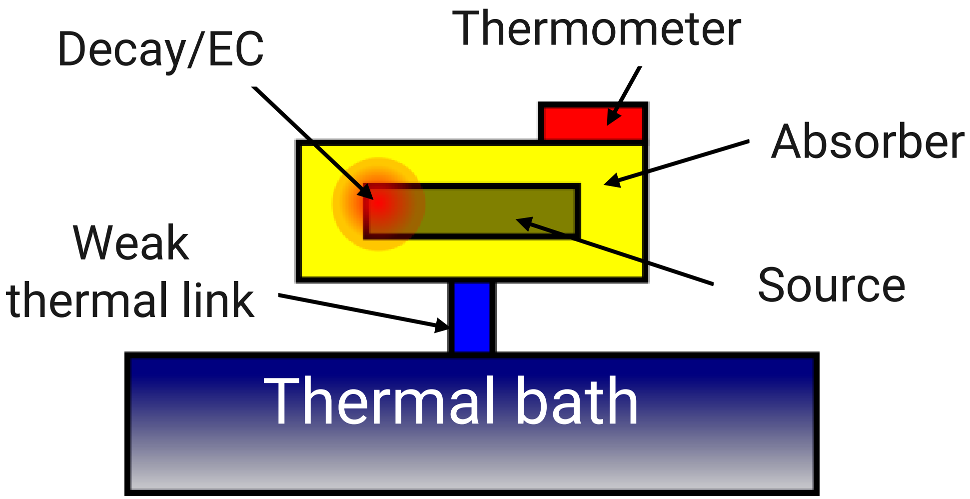


Measurement of temperature change via:

- Metallic Magnetic Calorimeters (MMC) ECHo
- Transition Edge Sensors (TES) HOLMES



Cryogenic microcalorimeter

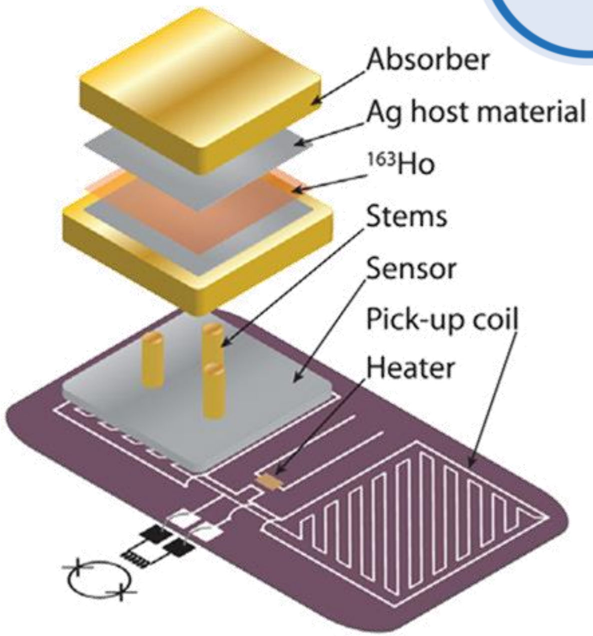


ECHo detectors

F. Mantegazzini et al., *Nucl. Instrum. Meth. A* **1030** (2022) 166406

- large arrays of low temperature **metallic magnetic calorimeters** with enclosed ^{163}Ho

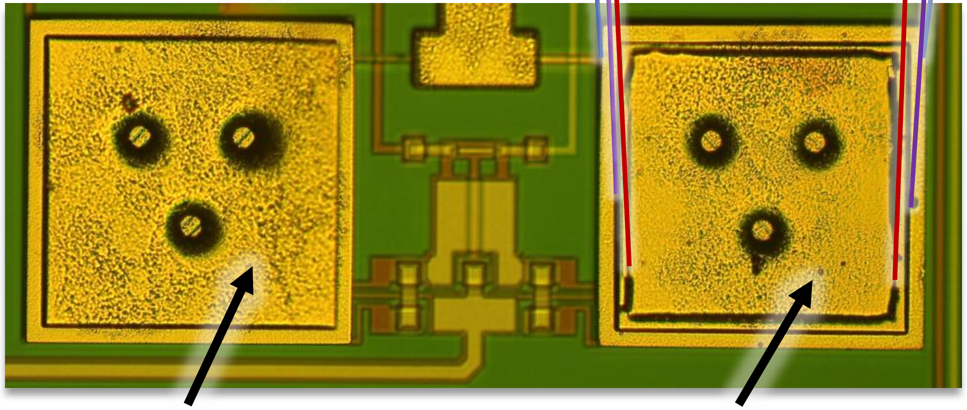
Content provided by L. Gastaldo (ECHo Collaboration)



First absorber: 180 µm x 180 µm

Second absorber: 165 µm x 165 µm

Implantation square: 150 µm x 150 µm



not implanted

implanted

ECHo detectors

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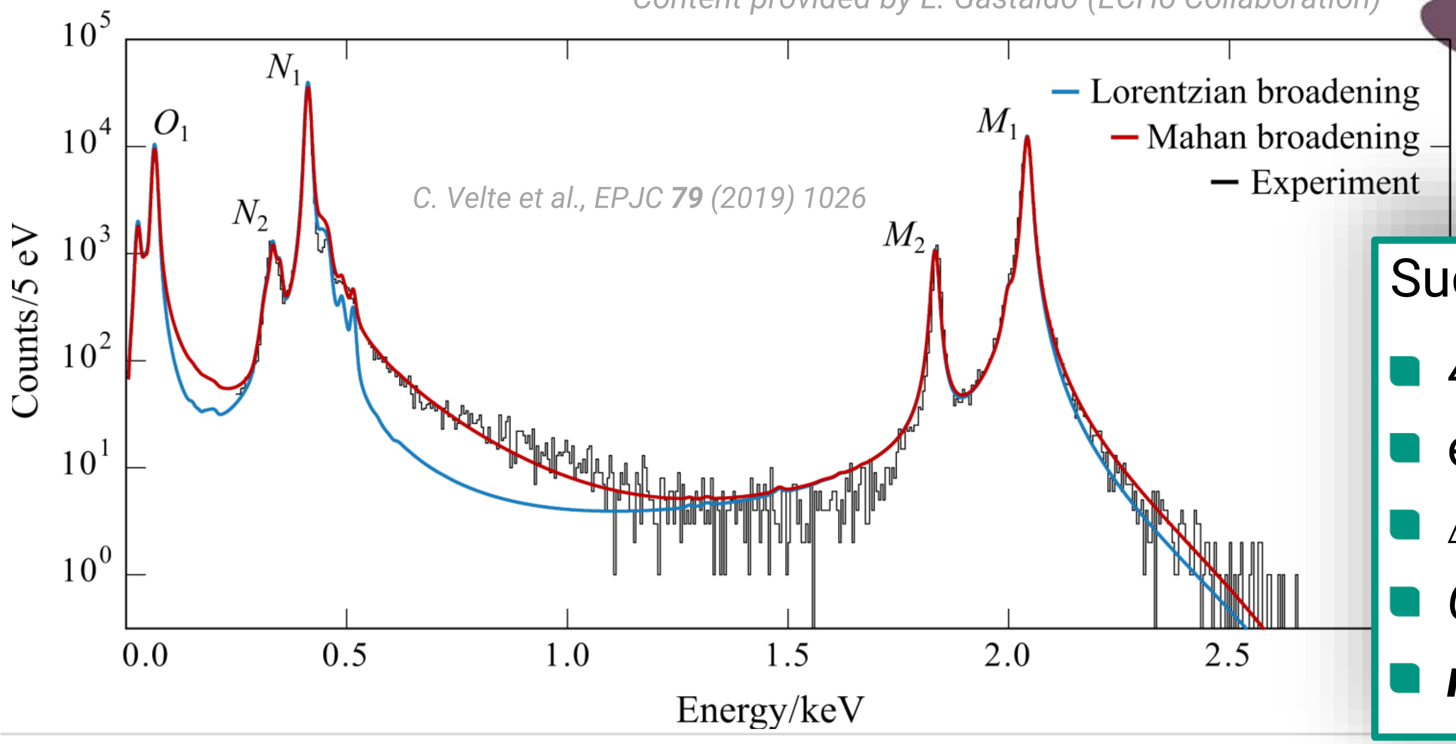

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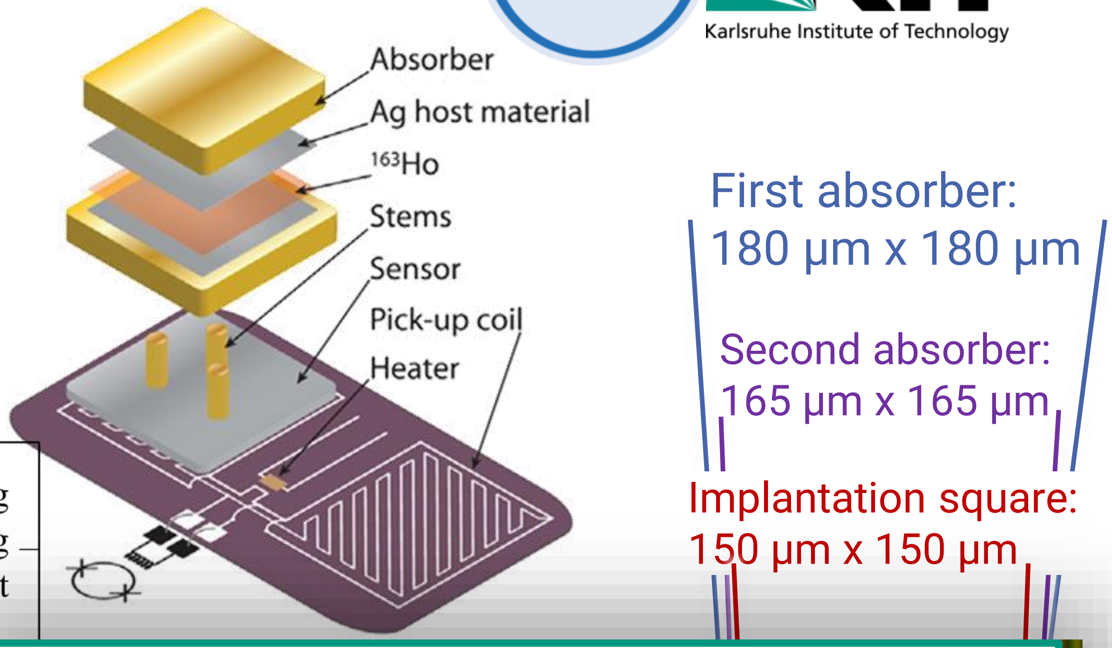
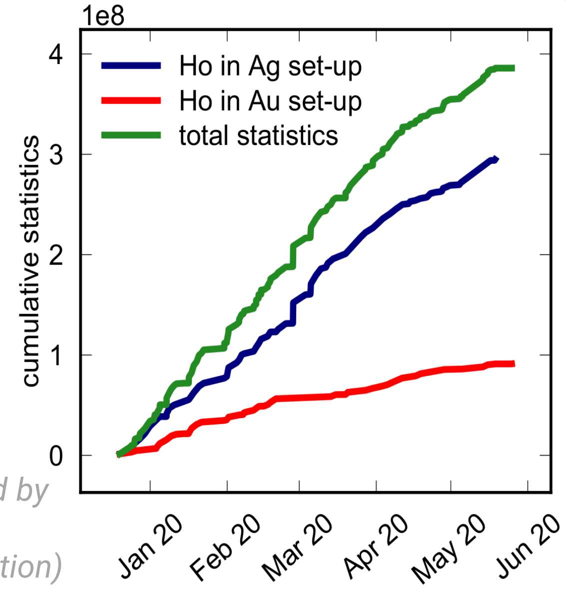


Successful proof of concept measurements:

- 4 days, with 4 pixels
- each pixel loaded with ~ 0.2 Bq ^{163}Ho
- ΔE_{FWHM} = 9.2 eV
- Q_{EC} = (2838 ± 14) eV
- **$m(\nu_e)$ < 150 eV (95% C.L.)**

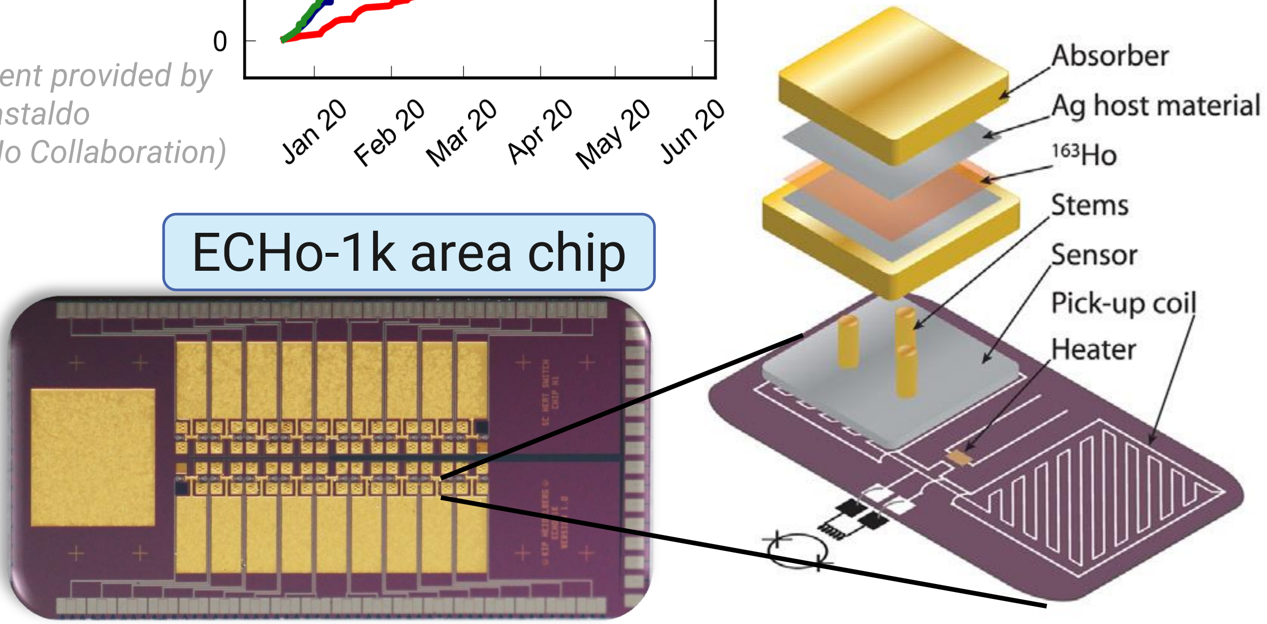
ECHo-1k – high-statistics spectrum

- Analysis of about 10^8 events ongoing
- Quantification of systematic uncertainties for precise endpoint region analysis with experiments and simulations
  - Detector response and theoretical model
- Achievable neutrino mass sensitivity with ECHo-1k data ~ **20 eV/c²**



Content provided by L. Gastaldo (ECHo Collaboration)

ECHo-1k chip-Au	23 pixel with implanted ^{163}Ho 3 background pixels average activity = 0.94 Bq **total activity of 28.1 Bq**
ECHo-1k chip-Ag	34 pixel with implanted ^{163}Ho 6 background pixels average activity = 0.71 Bq **total activity of 25.9 Bq**



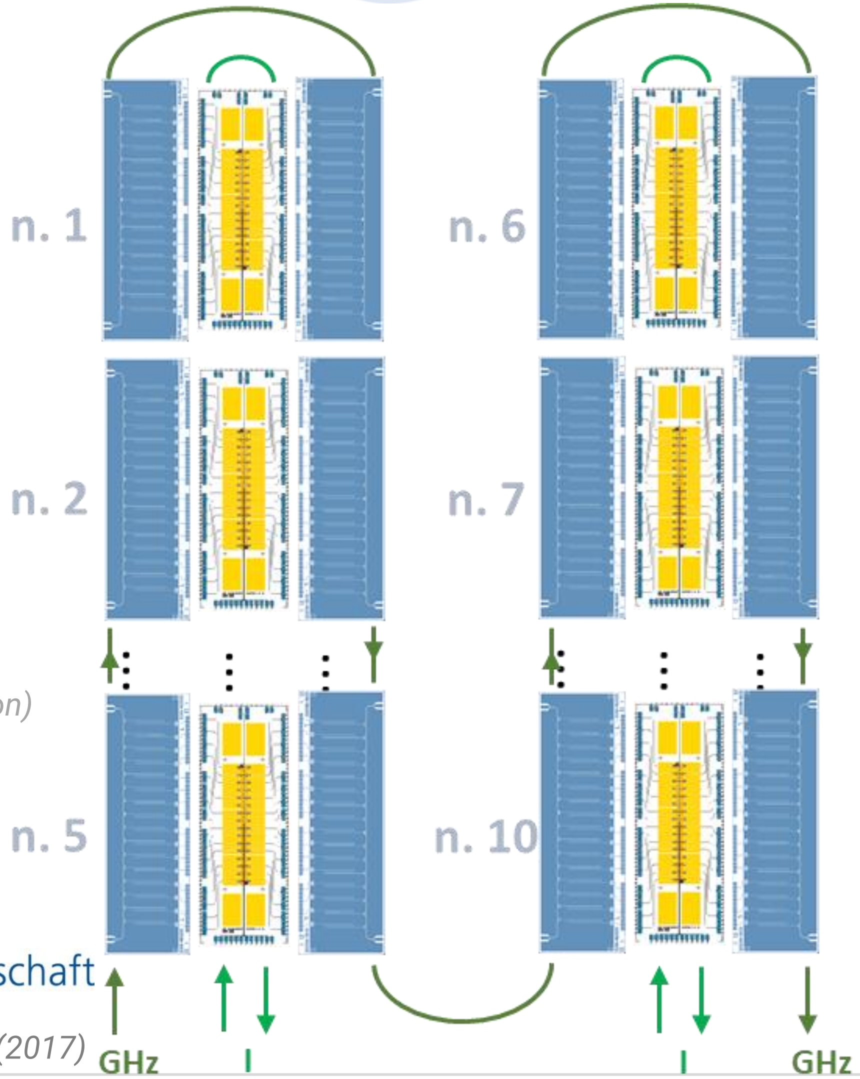
F. Mantegazzini et al., *Nucl. Instrum. Meth. A* **1030** (2022) 166406

ECHo-100k – for eV-scale sensitivity

- **1200** detectors
- **10 Bq** acitivity per pixel (2 × 10^{12} ^{163}Ho atoms)
- High-purity ^{163}Ho source: available about 30 MBq
- Ion implantation system:
  - Demostrated and continuously optimized
- Metallic magnetic calorimeters (MMC)
  - Reliable fabrication of large MMC array
  - Successful characterization of arrays with ^{163}Ho
- Multiplexing and data acquisition:
  - Demostrated for 8 channels
  - Development of the SDR electronics
  - Still to show scaling of the system
- Data reduction
  - Optimized energy-independent algorithm to identify spurious trace

Present status

Content provided by L. Gastaldo (ECHo Collaboration)

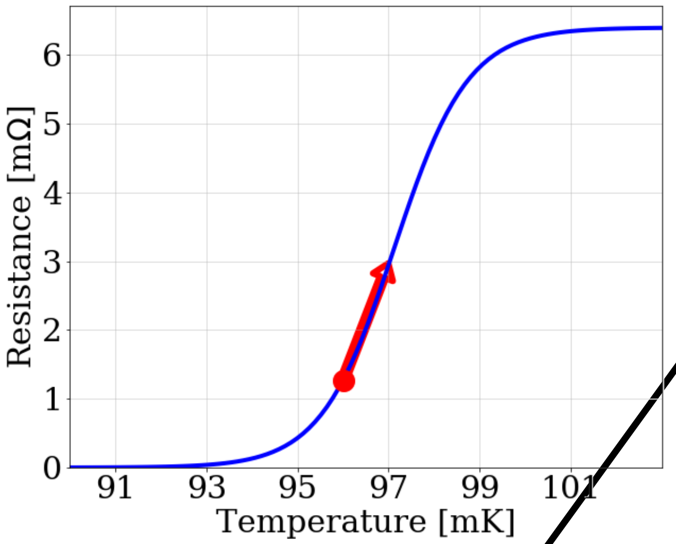


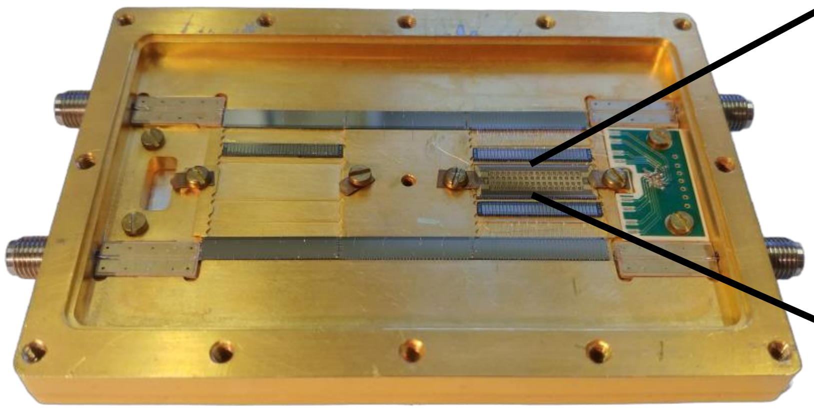
Deutsche Forschungsgemeinschaft

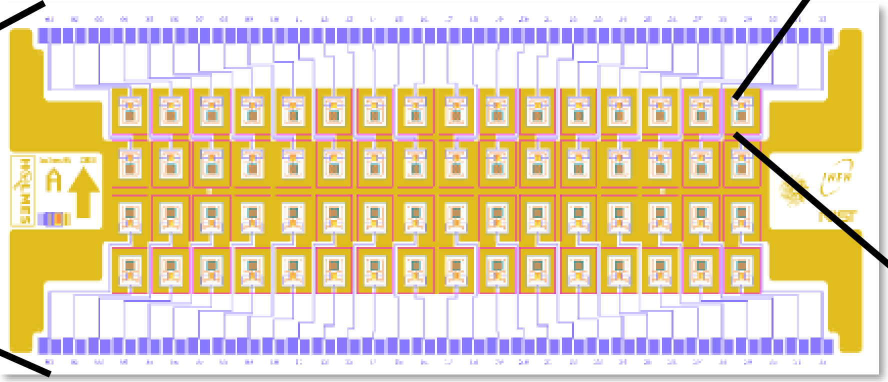
The ECHo Collaboration EPJ-ST 226 8 1623 (2017)

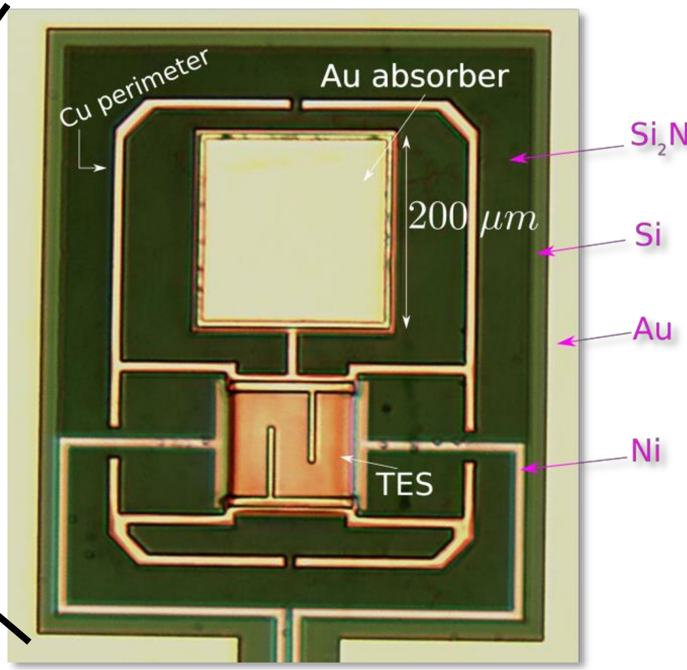
HOLMES – Detectors

- Transition edge sensors:
  - superconductor film **operated** in the narrow temperature region **between resistive and the superconducting** state
  - Very sensitive thermometer, able to detect a **temperature variation** on the order of **a fraction of mK**





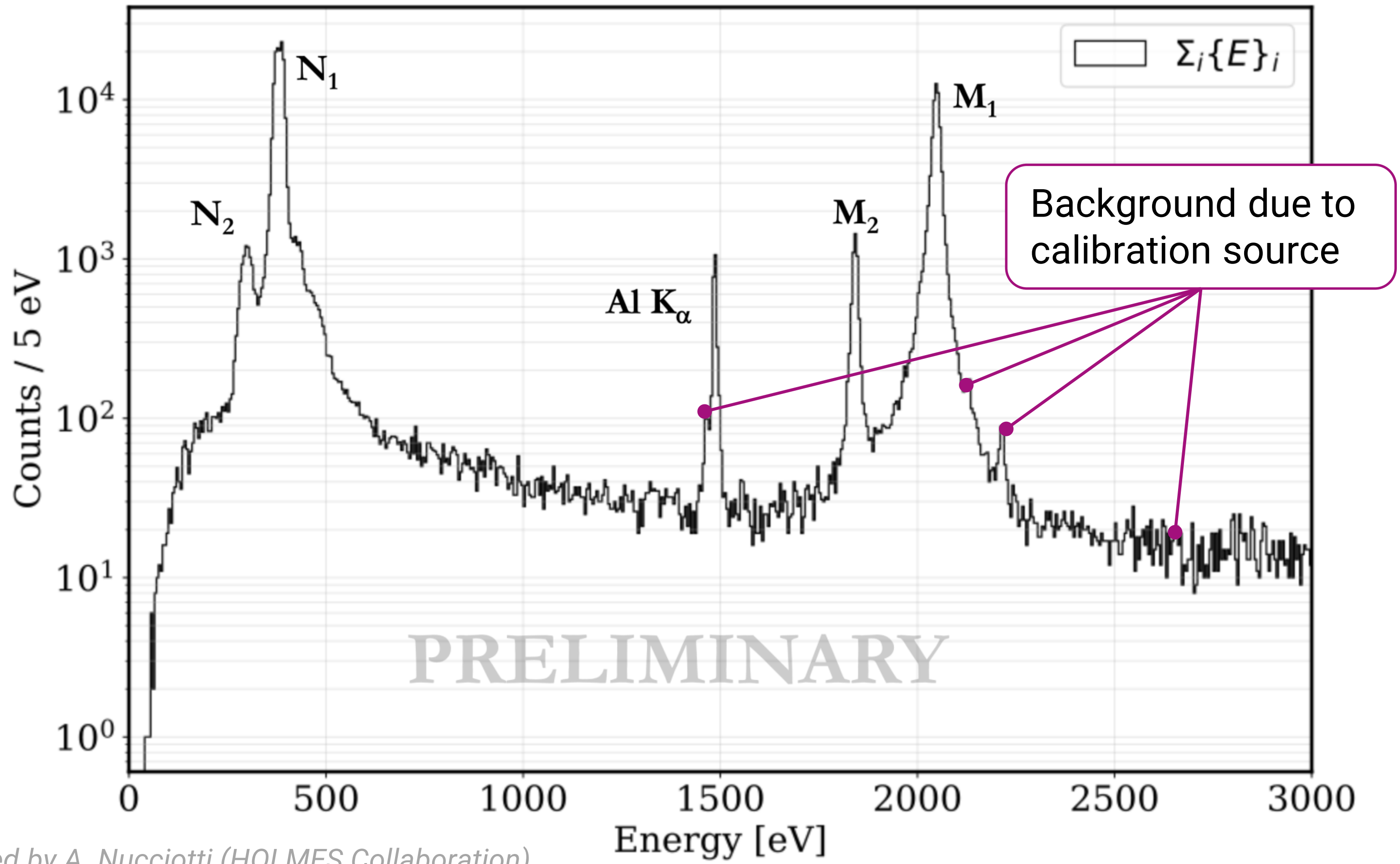




Content taken from presentation by M. Borghesi, TAUP23, Vienna, 29 Aug2023

First HOLMES ^{163}Ho spectrum

- First detector array finalized in mid-June 2023
- First spectrum shows:
  - Acquisition time: **48.5 hours**
  - sum over **4 pixels**
  - $< A > \approx$ 0.5 Bq (0.1 –1 Bq)
  - ΔE_{FWHM}= 6–8 eV @6keV
- Expected background due to cosmic rays in ROI lower than 0.01 counts/5eV
- High background due to measurements with ^{55}Fe calibration source and Al fluorescence



Content provided by A. Nucciotti (HOLMES Collaboration)

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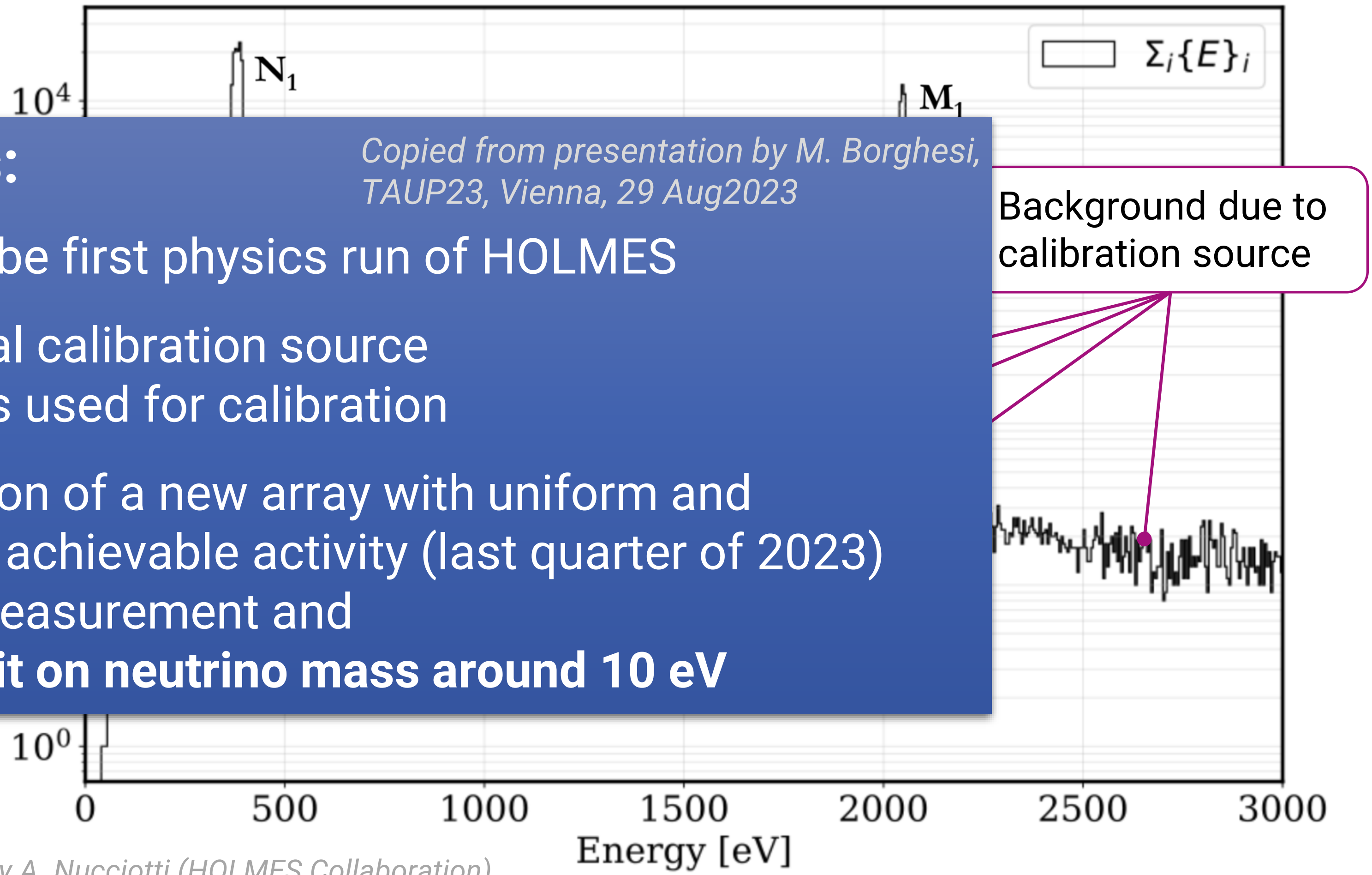

Next steps:

Copied from presentation by M. Borghesi, TAUP23, Vienna, 29 Aug2023

- Run 3 will be first physics run of HOLMES
- No external calibration source
  → Ho lines used for calibration
- Implantation of a new array with uniform and maximum achievable activity (last quarter of 2023)
  → Long measurement and
  first limit on neutrino mass around 10 eV

Content provided by A. Nucciotti (HOLMES Collaboration)

Established measurement principles

MAC-E filter

- Magnetic Adiabatic Collimation with an Electrostatic Filter
- Measuring energy by applying a **high-pass filter**

Calorimeters

- Low-temperature micro calorimeters
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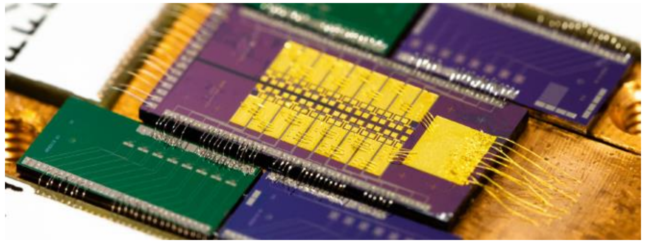
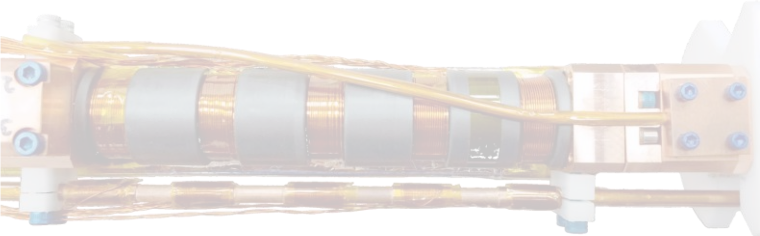
ECHo HOLMES



CRES

- Cyclotron Radiation Emission Spectroscopy
- Measuring energy via **frequency**

PROJECT 8 QTNM



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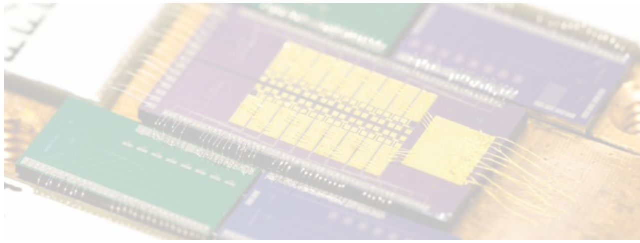

CRES

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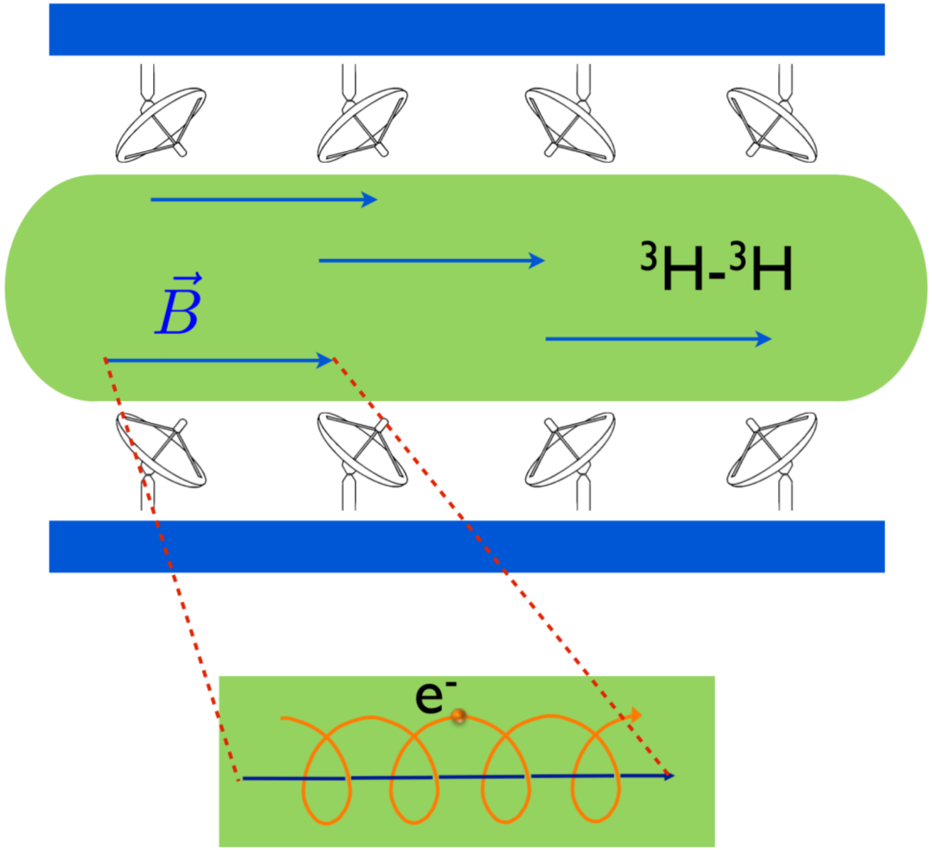
Cyclotron radiation emission spectroscopy (CRES)

- Cyclotron radiation is emitted by accelerated electrons in a magnetic field:

$$\omega = \frac{\omega_0}{\gamma} = \frac{qB}{m_e + E_{kin}}$$



B. Monreal and J. Formaggio, Phys. Rev. D80 051301 (2009)

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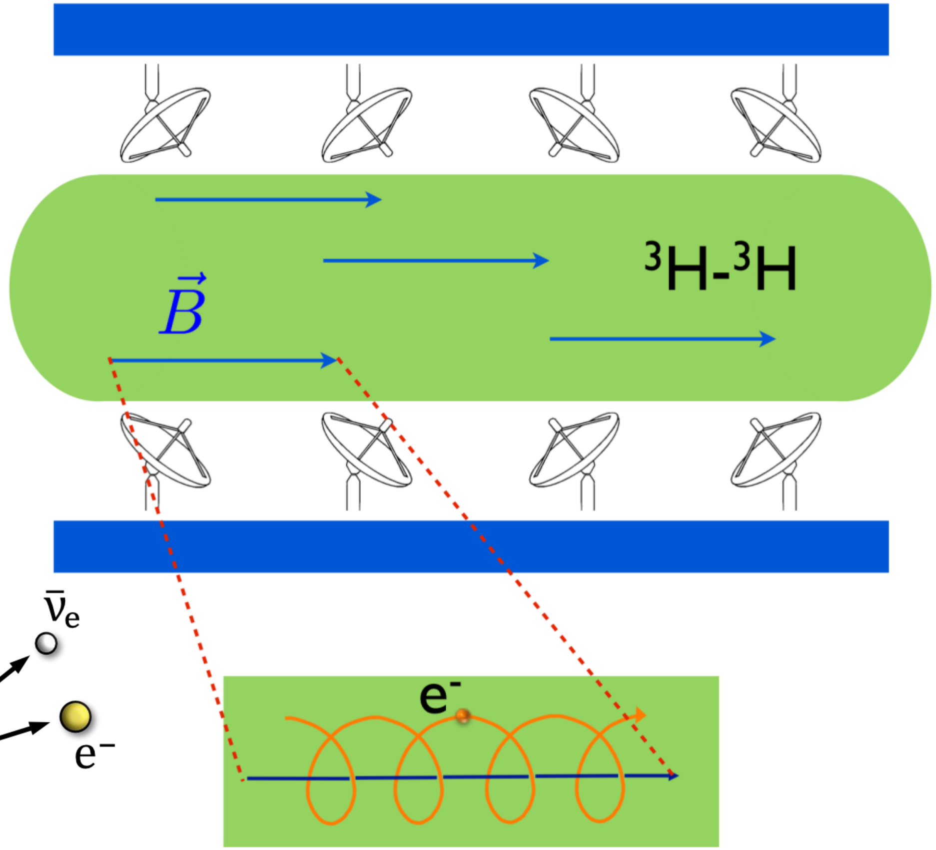

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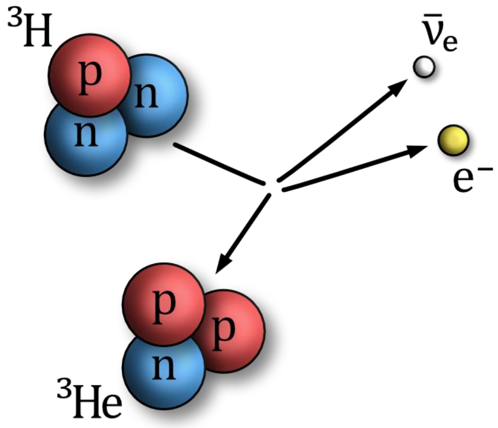

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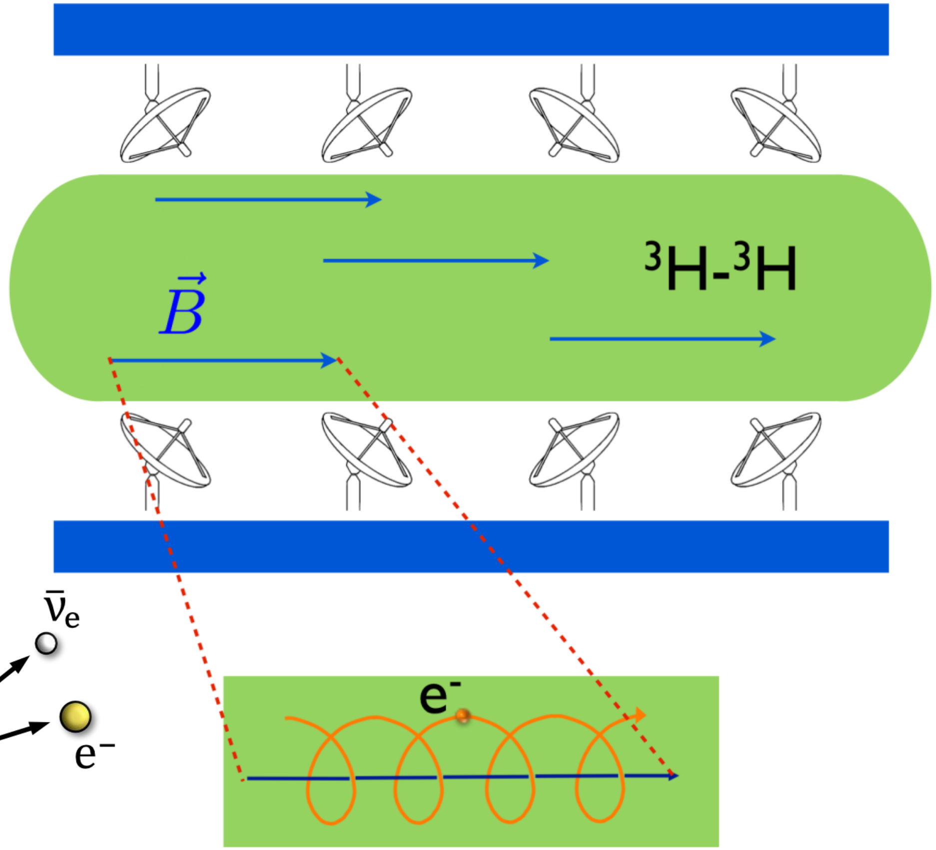
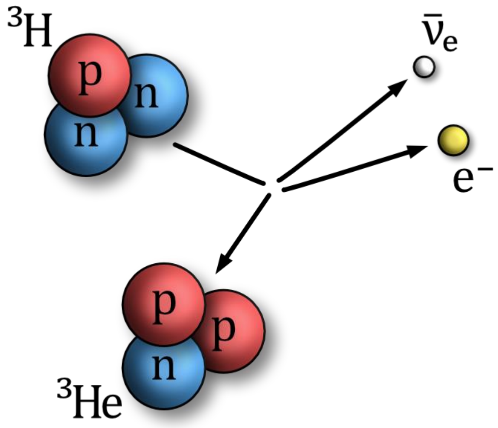
- Place tritium in magnetic field and measure ω with antennas
- Challenges:
  - Sub-eV energy resolution: →B-field homogeneity at the 10^{-7}-level
  - High statistics → large volume
  - Detection of femto – zetta Watt radiation





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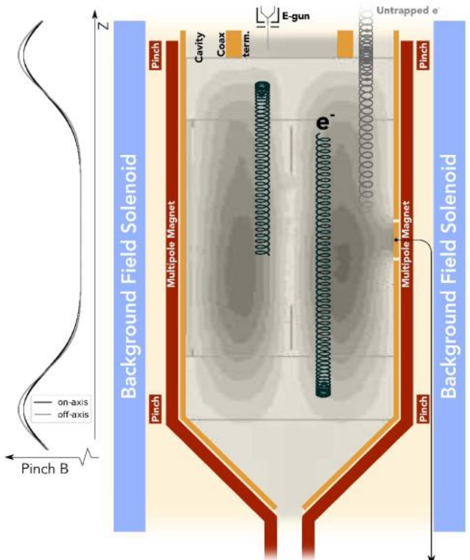
Experiments using CRES

Project 8

- Cavity-based CRES experiment



Copied from presentation by J. Stachurska TAUP 2023

Photo by M. Guigue

Experiments using CRES

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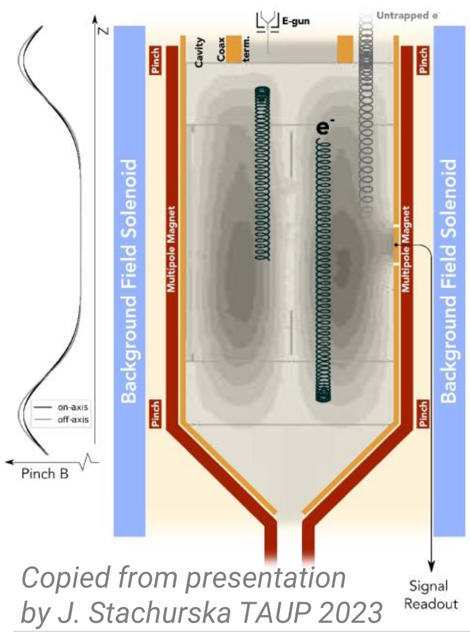


Copied from presentation by J. Stachurska TAUP 2023

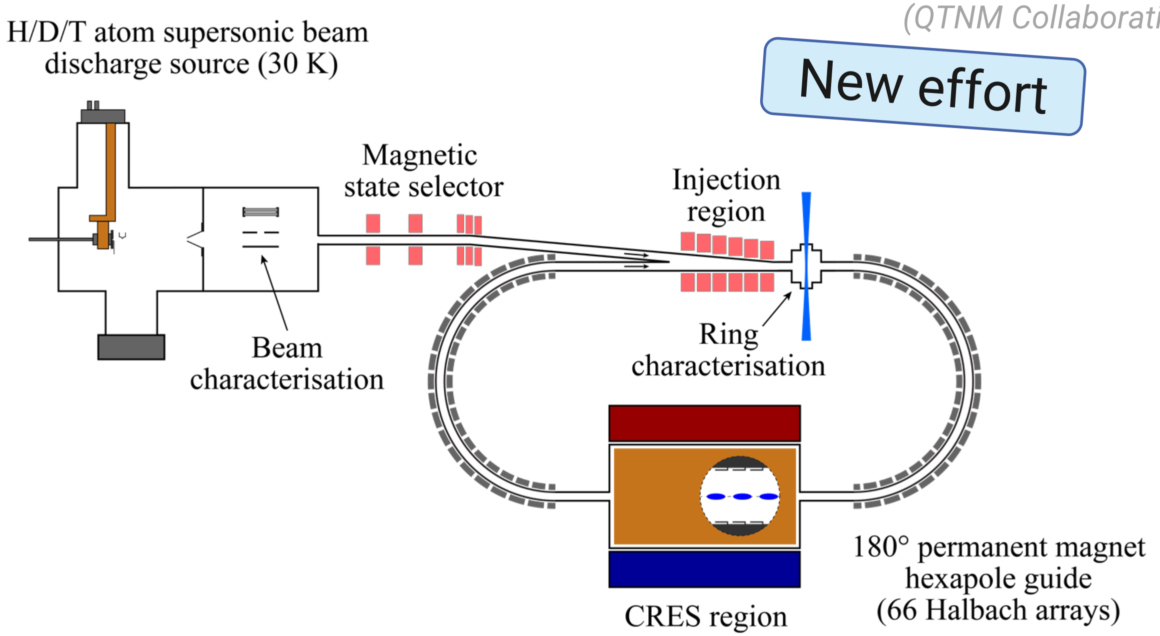
Photo by M. Guigue

QTNM / CRESDA

- CRESDA = CRES demonstration apparatus
- Confinement of H-Atoms in storage ring

Content provided by R. Saakyan (QTNM Collaboration)

New effort



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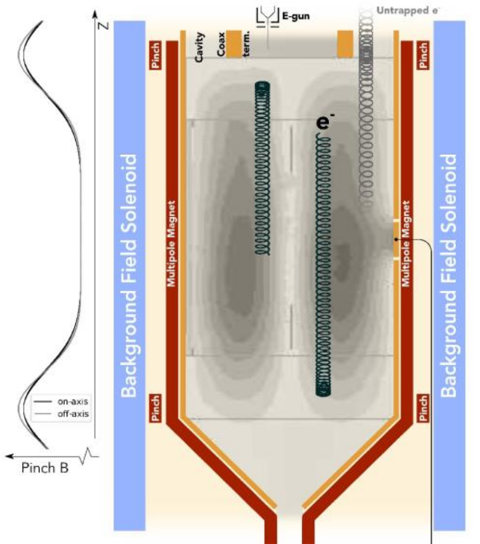

Copied from presentation by J. Stachurska TAUP 2023

Photo by M. Guigue

He-6–CRES

- Measuring CRES from MeV-scale electrons

W. Byron et al. Phys. Rev. Let. 131, 082502 (2023)

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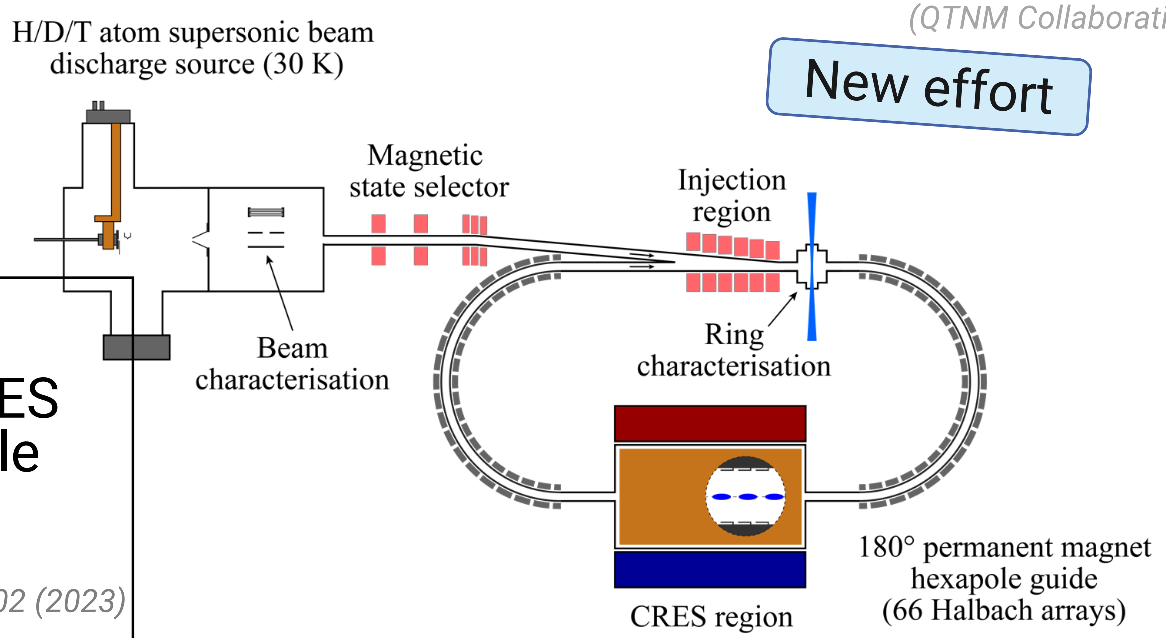
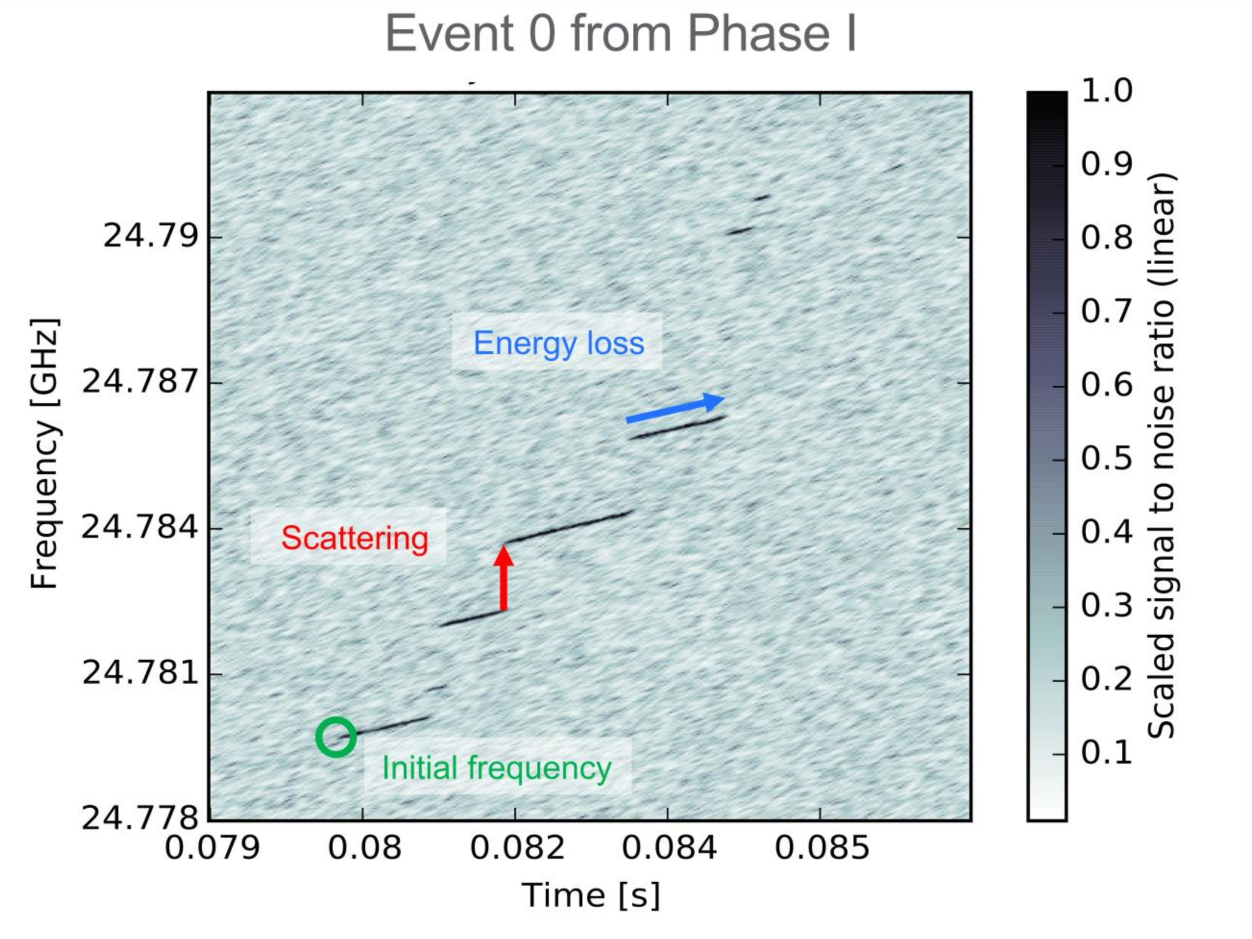
Content provided by R. Saakyan (QTNM Collaboration)

New effort



Project 8 – Results

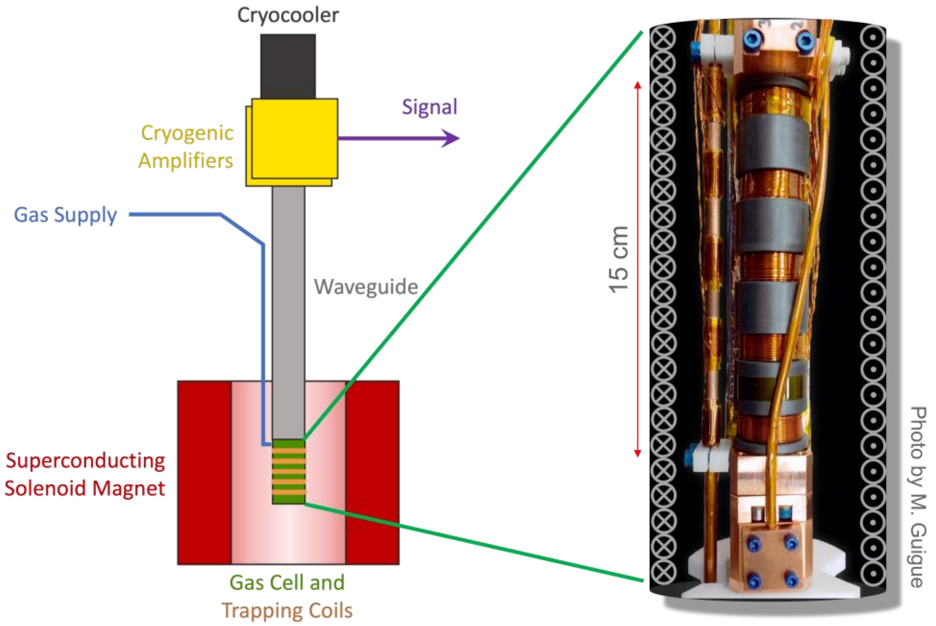
- **Phase I:** First use of CRES for electron spectroscopy (^{83m}Kr)



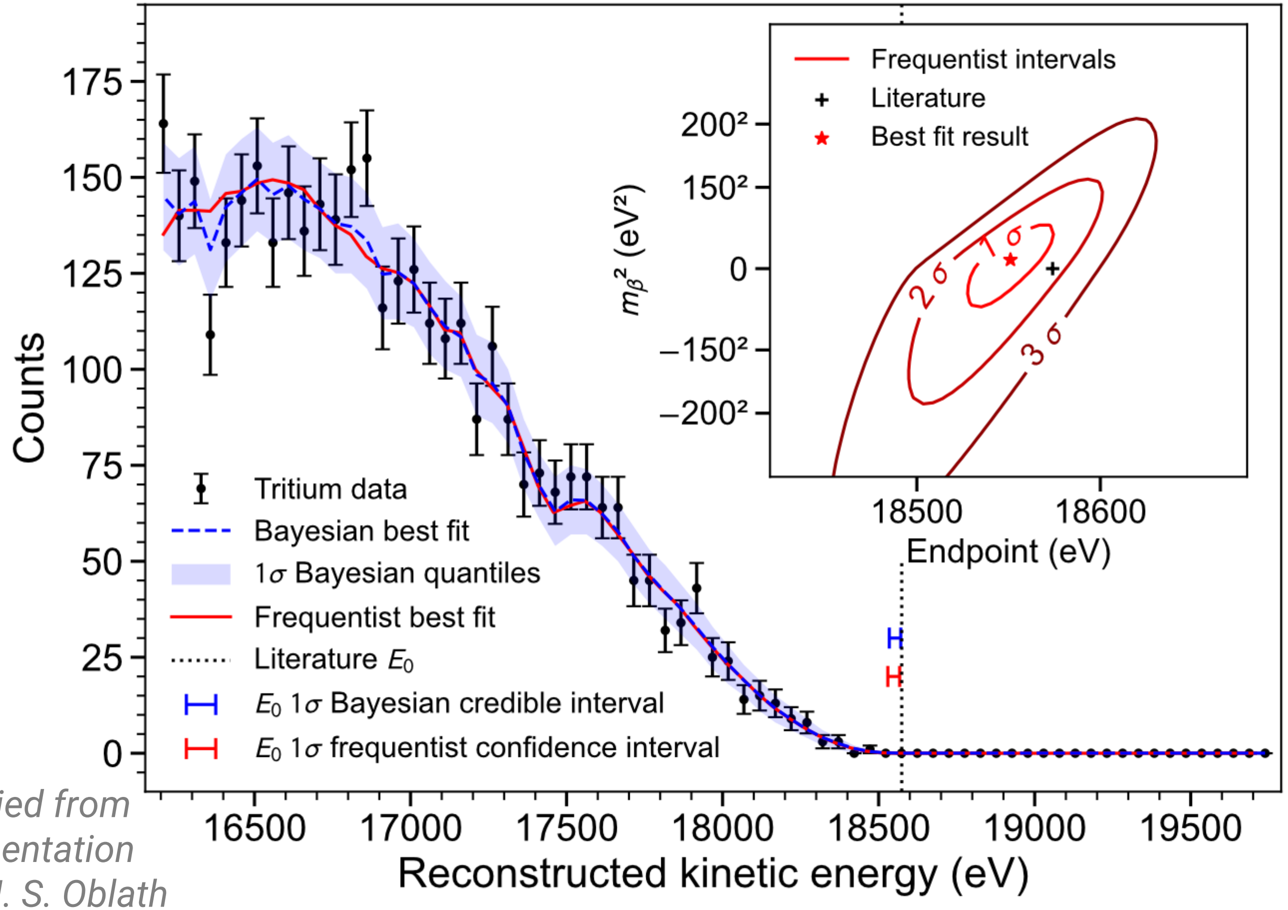
D. M. Asner, et al., Phys. Rev. Lett. 114, 162501 (2015)

Project 8 – Results

- **Phase I:** First use of CRES for electron spectroscopy (^{83m}Kr)
- **Phase II:** First use of CRES for tritium beta-decay electron spectroscopy
  → Neutrino mass limit ($m_\beta < 155$ eV)



Copied from presentation by N. S. Oblath TAUP 2023

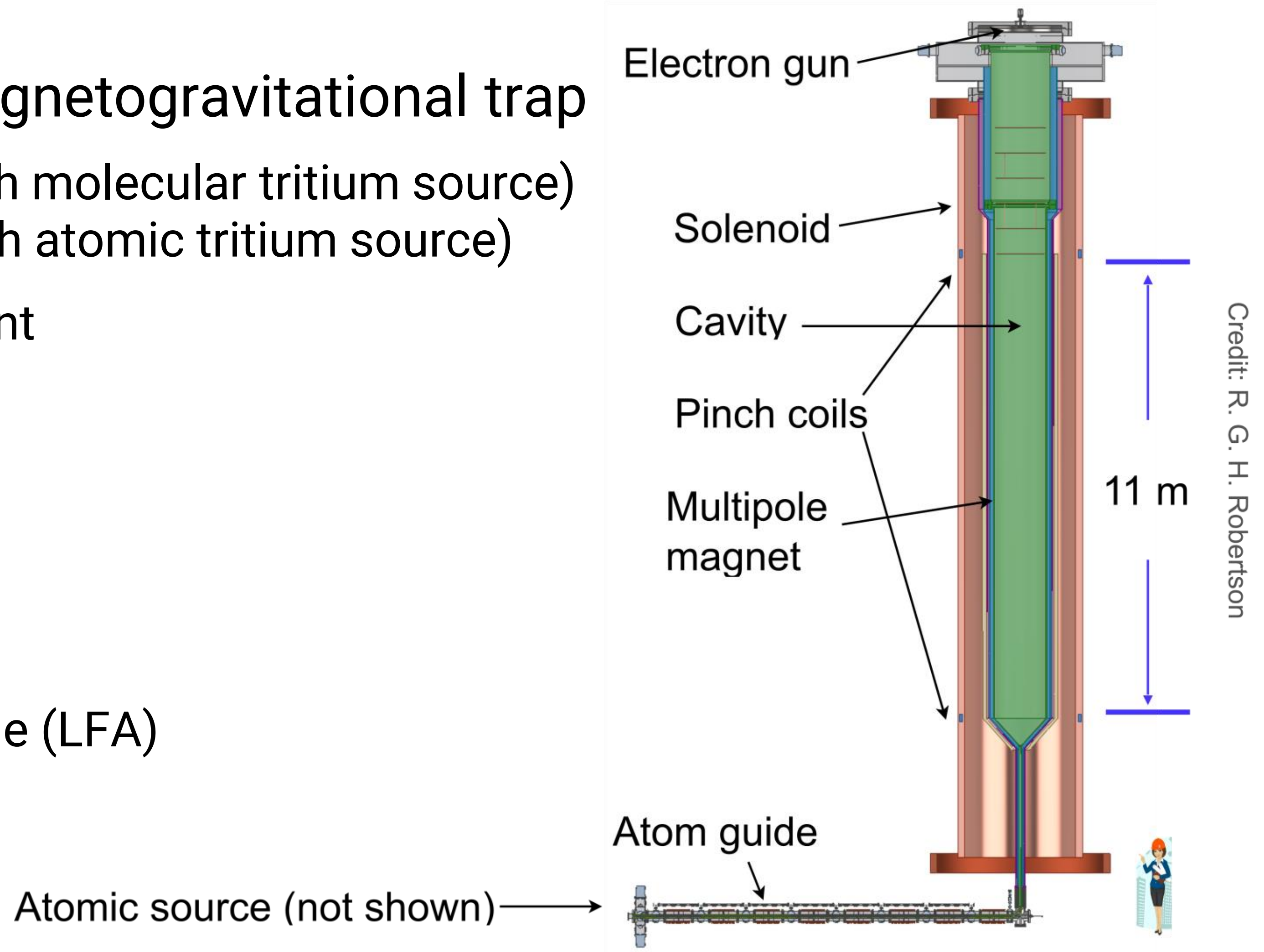


A. Ashtari Esfahani et al.Phys. Rev. Lett. 131, 102502 (2023)

Project 8 – Future

- **Phase III:** Tritium trapped in magnetogravitational trap
  - Sensitivity aim: $m_\beta < 200\ \mathrm{meV}$ (with molecular tritium source)
    $m_\beta < 100\ \mathrm{meV}$ (with atomic tritium source)

  → Blueprint for full 40 meV experiment
- **Next steps:**
  - Set of demonstrators:
    - High resolution (CCA)
    - Large volume (LUCKEY)
    - High resolution and large volume (LFA)
  - Develop atomic tritium source



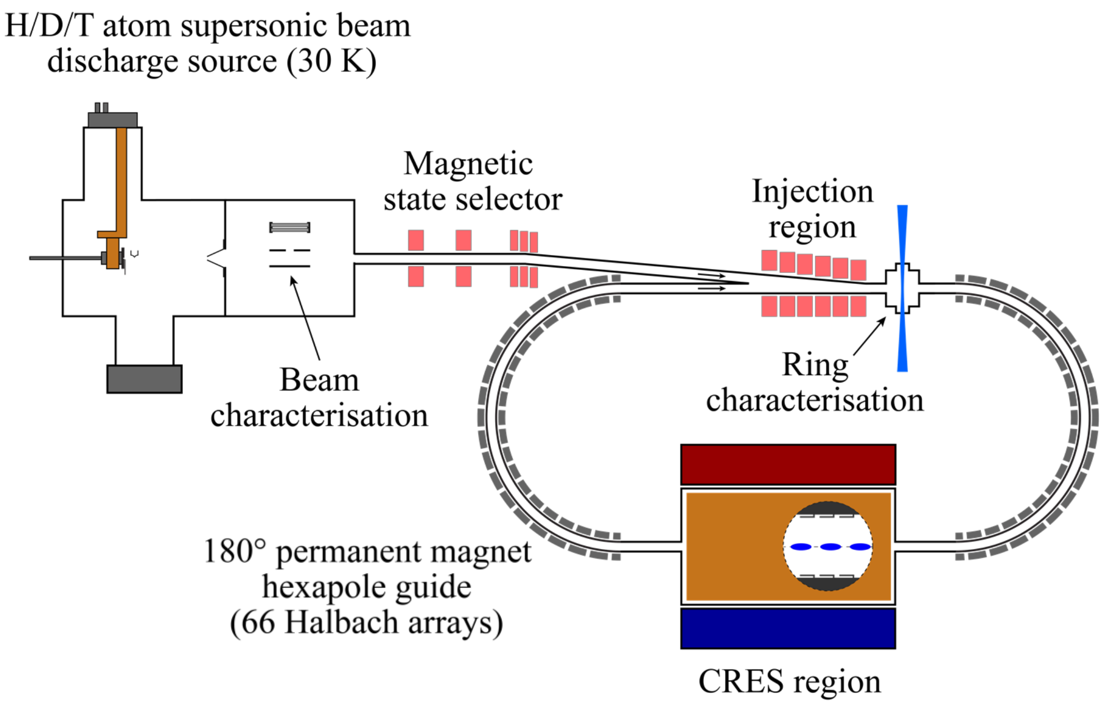
Content copied from presentation by J. Stachurska TAUP 2023

CRES demonstration apparatus (CRESDA)

- **Goal:** Neutrino mass measurement from tritium beta decay via CRES using **latest advances in quantum technologies**
- **Technology Demonstration:**
  - Production and confinement of H-atoms, ≥ 10^{12} cm^{-3}
  - B-field mapping with $\lesssim 1\ \mu$T precision, using H-atoms as quantum sensors (Rydberg Magnetometry)
  - CRES detection of single electrons with quantum limited micro-wave electronics (CRESDA0)
- **Phased approach**

CRESDA0 → CRESDA-Tritium → 100 meV → 50 meV → O(10 meV)

current | Culham Centre for Fusion Energy



Content provided by R. Saakyan (QTNM Collaboration)

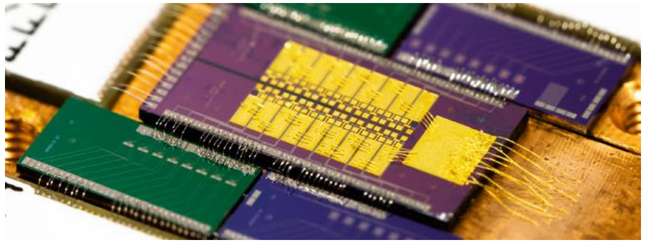
Established measurement principles

MAC-E filter

- Magnetic Adiabatic Collimation with an Electrostatic Filter
- Measuring **kinetic energy**

Calorimeters

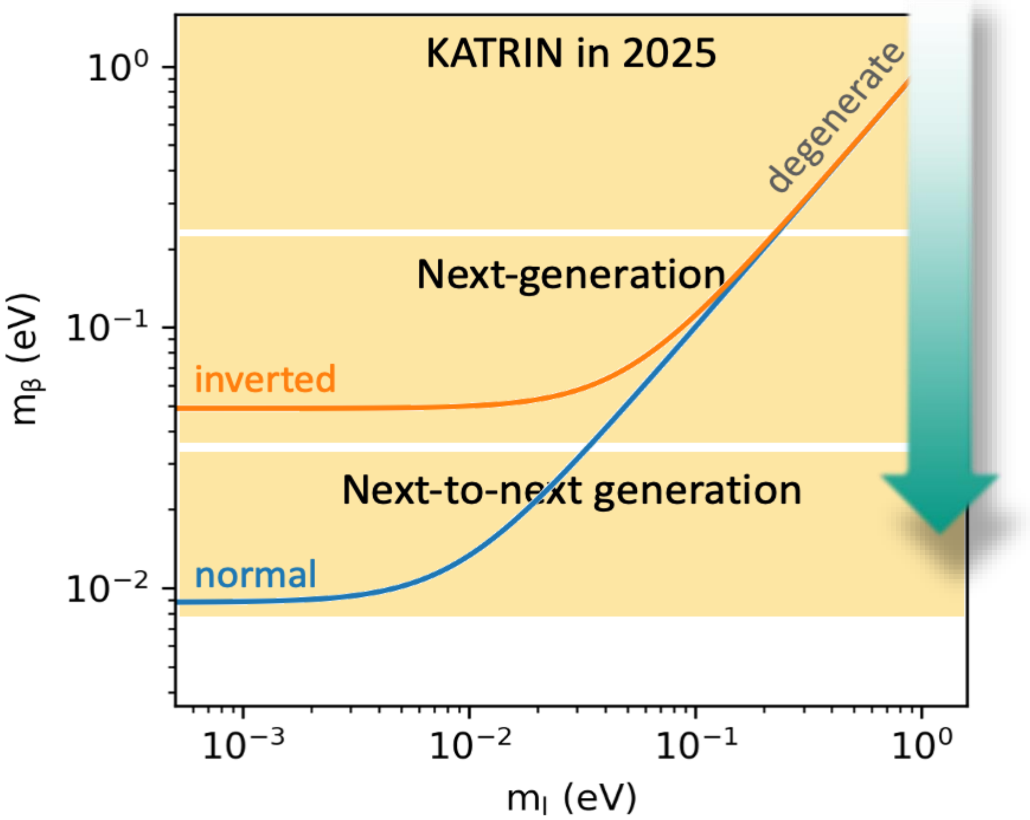
- Low temperature micro-calorimeters
- Measuring **temperature**



CRES

- Cyclotron Radiation Emission Spectroscopy
- Measuring **frequency**

Future of direct neutrino mass detection

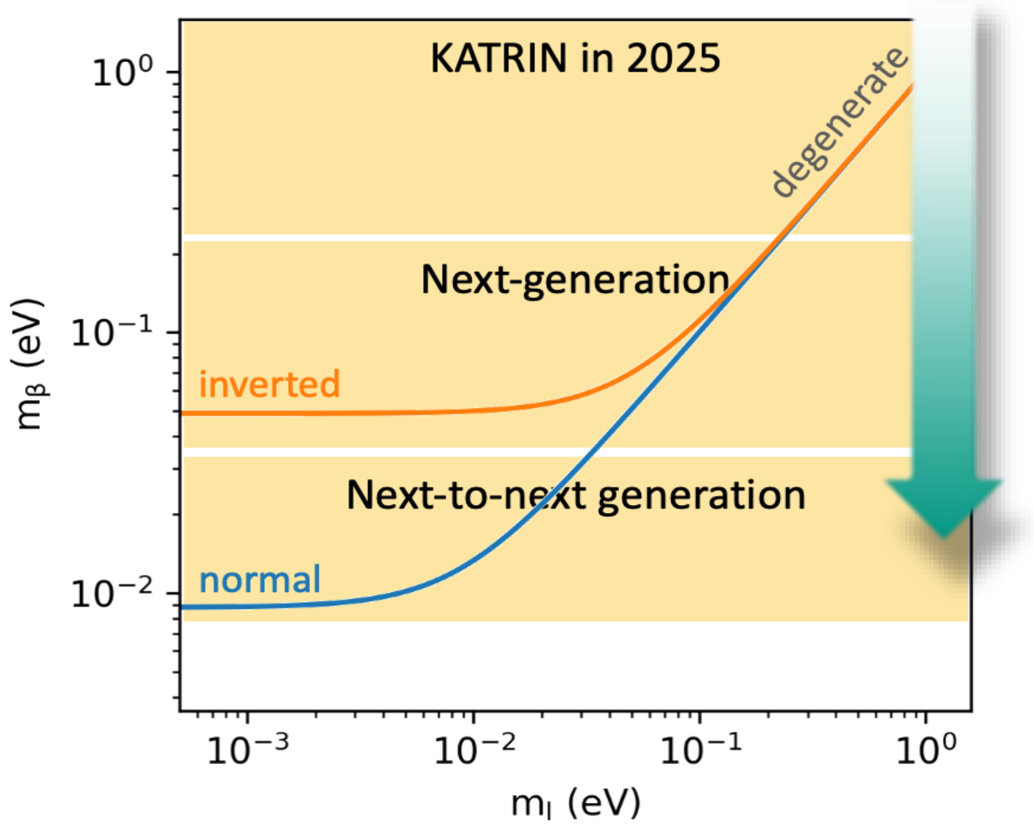


Future: combine technologies (MAC-E filter, MMCs, TES, CRES, …) to go below the inverted mass scale

Mission of CRES experiments

- Experiments using CRES technologies aiming at inverted ordering (or even beyond) → **technology demonstration required**

Future of direct neutrino mass detection



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Mission of CRES experiments

- Experiments using CRES technologies aiming at inverted ordering (or even beyond) → **technology demonstration required**

Beyond KATRIN

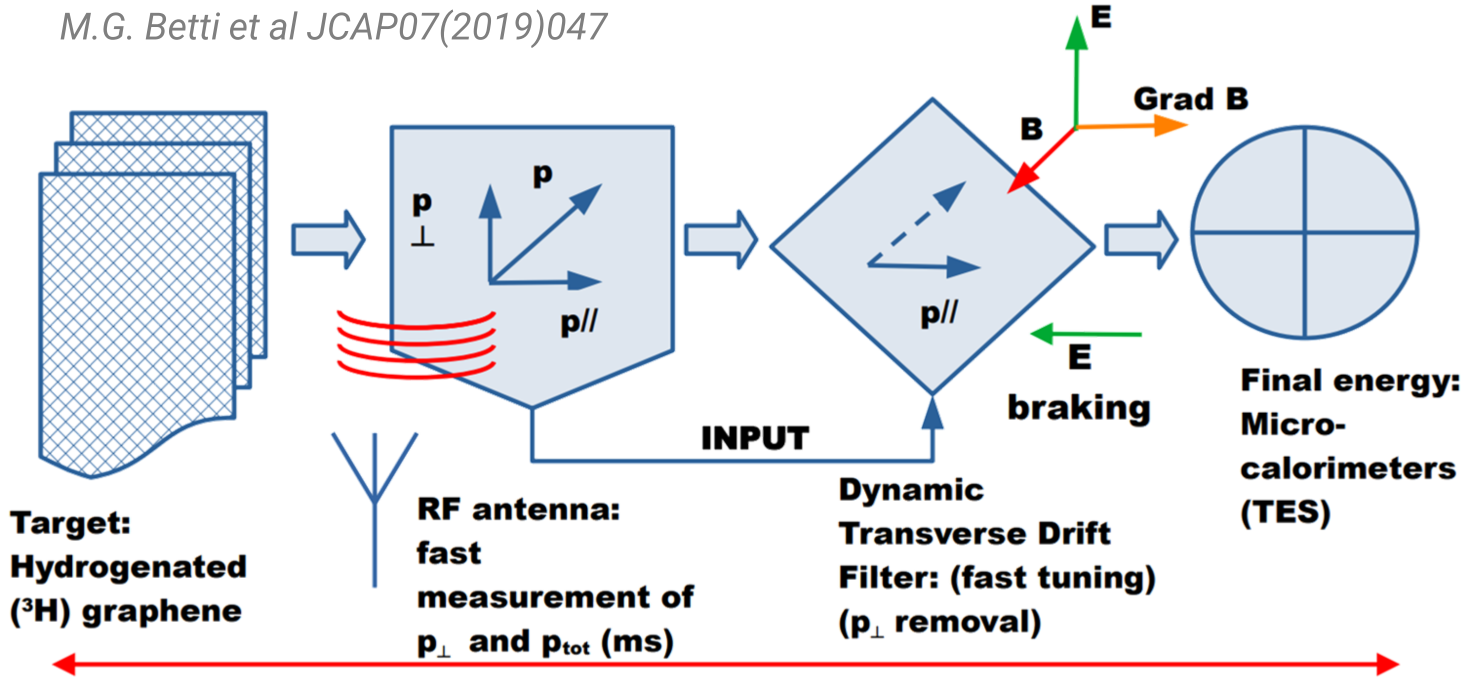
- Data taking until 2025 (1000 measurement days)
- **R&D for differential measurement ongoing** significant sensitivity increase is possible: more statistics, elimination of background, better resolution
- *Option 1:* large area, high-resolution, multi-pixel quantum sensor array
- *Option 2:* Time-of-flight measurement with electron tagger technology

Future of direct neutrino mass detection

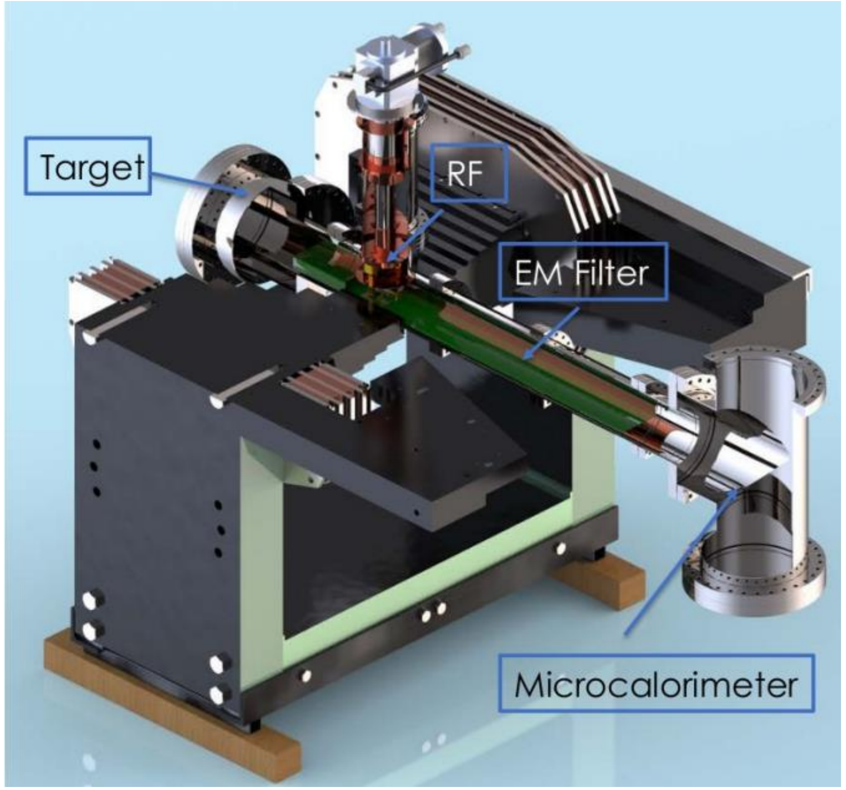
PTOLEMY

Karlsruhe Institute of Technology

- **Aim:** direct detection of big-bang neutrinos; determination of neutrino mass is „by-product“
  M.G. Betti et al JCAP07(2019)047



Content from N. Rossi, EPS-HEP July 2023 Hamburg



Combine technologies (TES, CRES, novel drift filter) with large scale *O*(100g) tritiated graphene target

Setup of technology demonstrator probably at LNGS in the next years

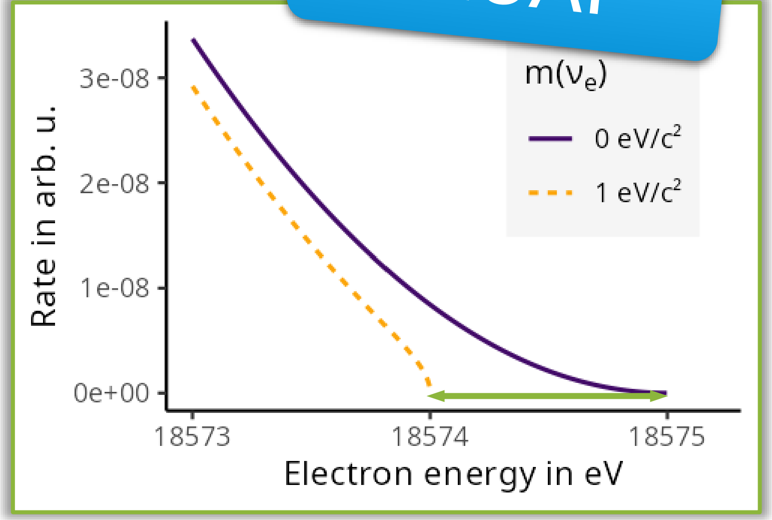
Beta decay and electron capture – common challenges

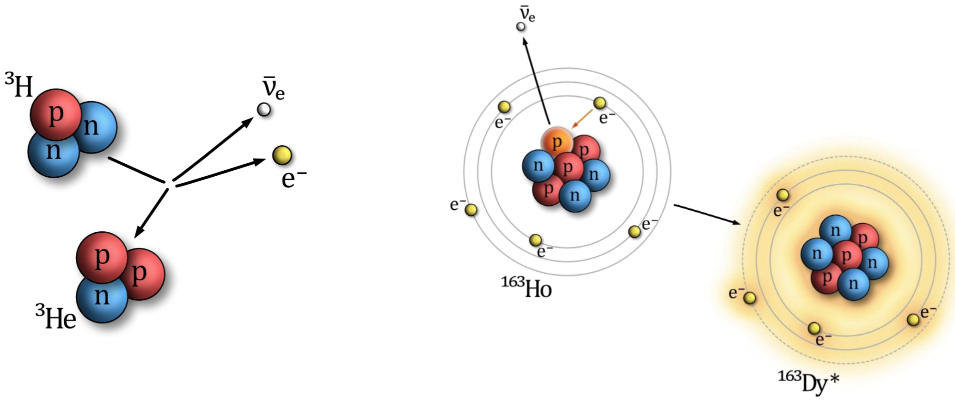
RECAP

For resolving neutrino mass signal:

- Low endpoint and high decay rate ✓ ^3H, ^{163}Ho
- High source activity needed — Source design
- High resolution in endpoint region — Detector design ✓

$$\left(\frac{dN}{dE}\right) \sim (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - \sum_i m_i^2 |U_{ei}|^2}$$





	Beta decay	Electron capture
Isotope	^3H = T	^{163}Ho
Endpoint	18.6 keV	2.8 keV
Half-life	12.3 years	4570 years
Production	n-capture in D_2O	n-irradiation of ^{162}Er

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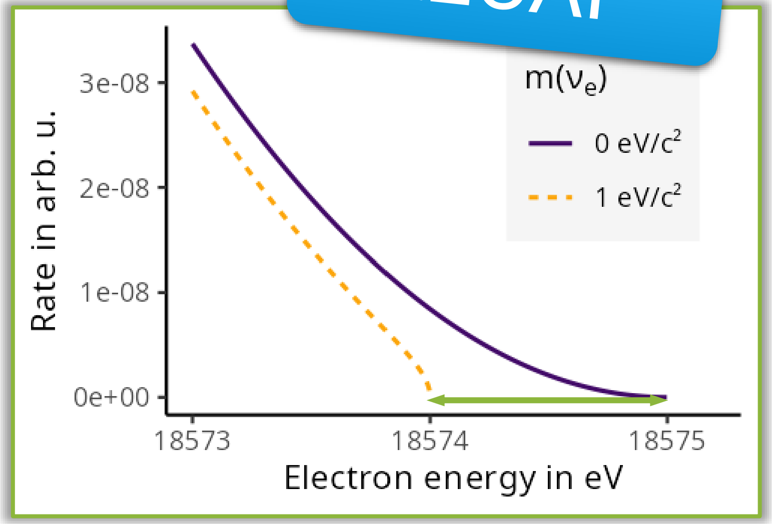

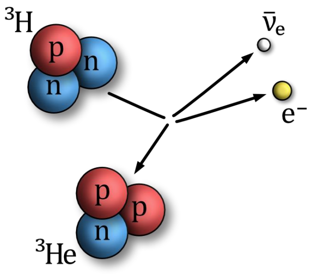

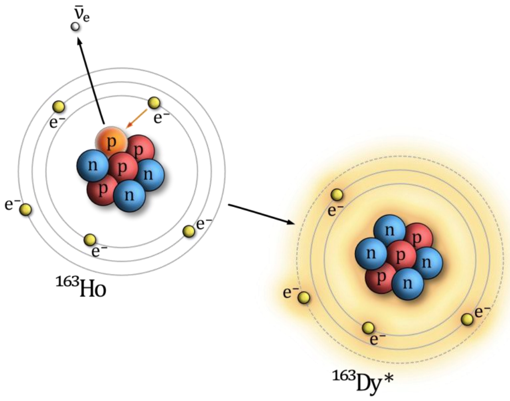

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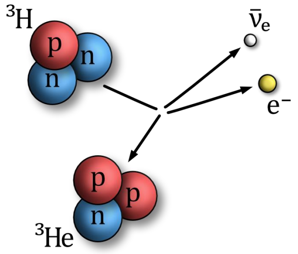
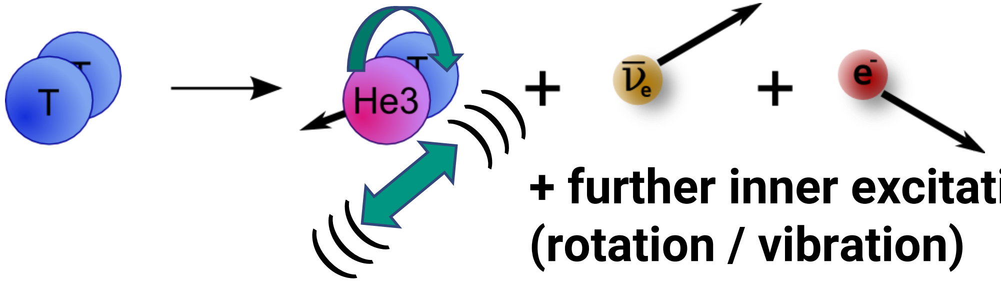
Tritium source – molecular vs. atomic

- So far, tritium neutrino mass experiments with tritium use **molecular** tritium
- Daughter molecule $^{3}HeT^{+}$ exhibits inner excitations after tritium beta decay → “Final states”

Atomic decay



Molecular decay



+ further inner excitations (rotation / vibration)

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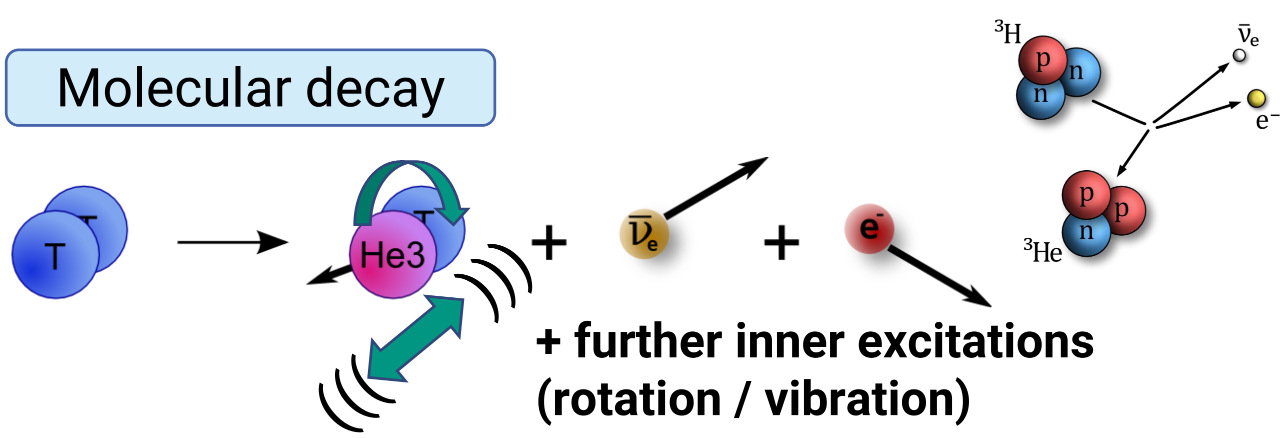

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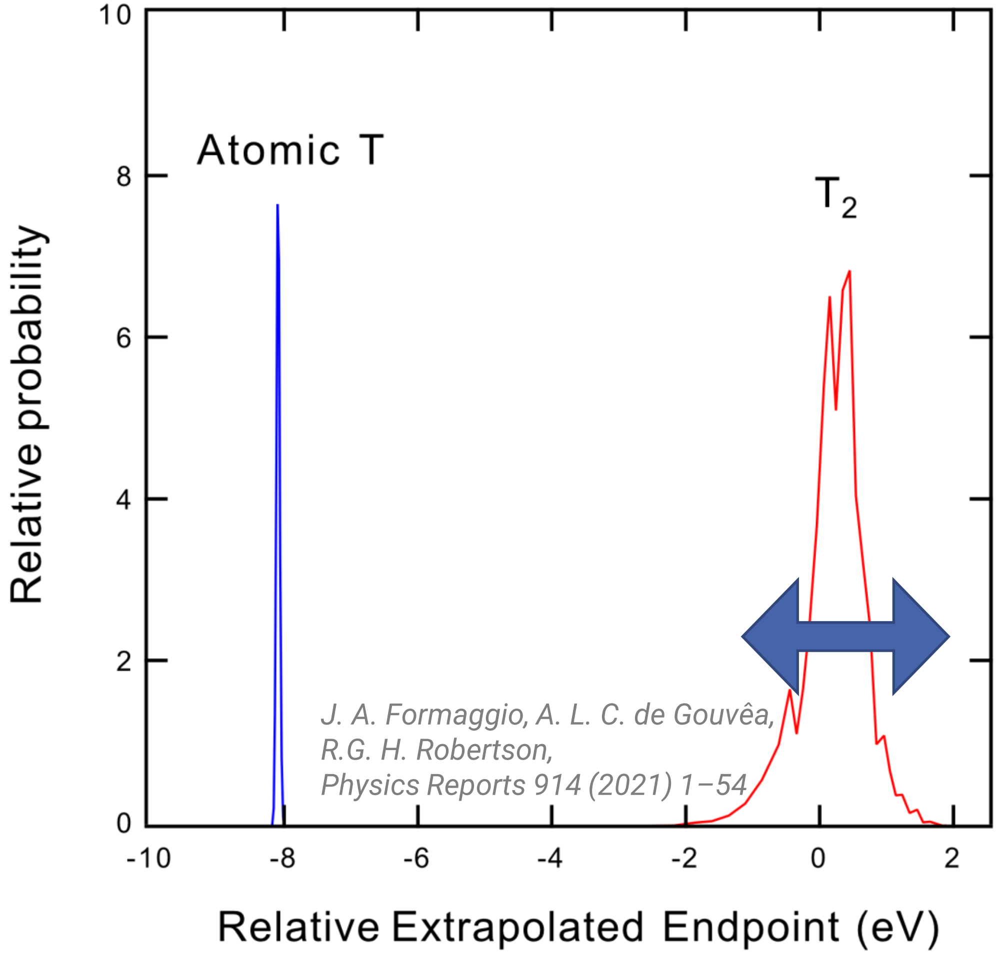
Final-state distribution



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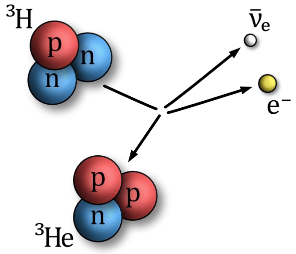
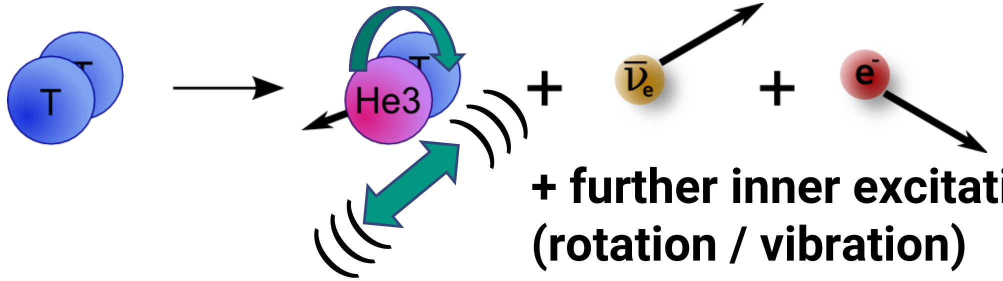


Molecular decay



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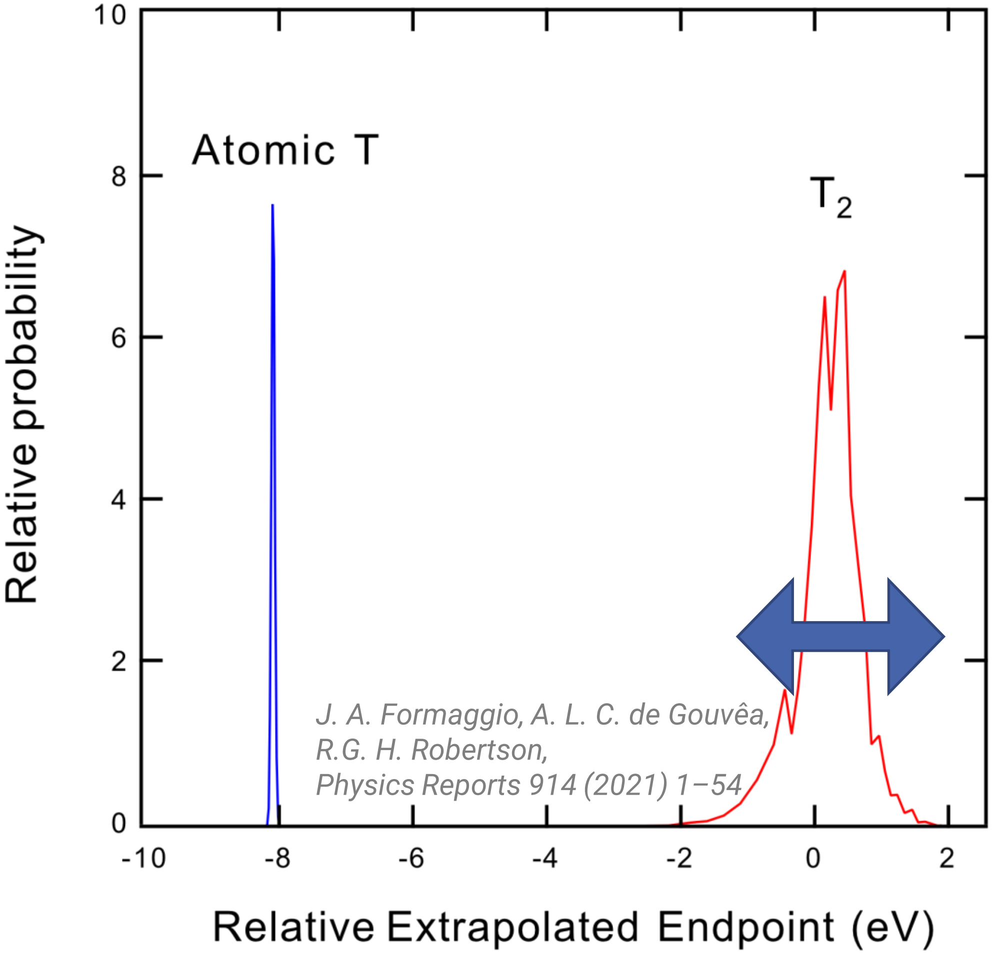
Future: Use atomic tritium source to avoid limitations by molecular broadening

Final-state distribution



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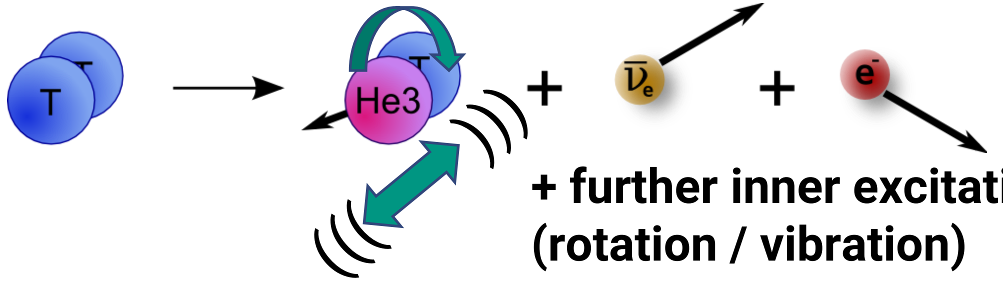

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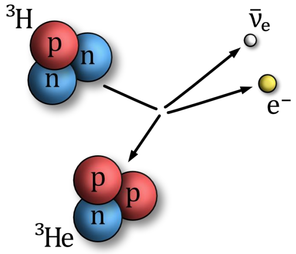
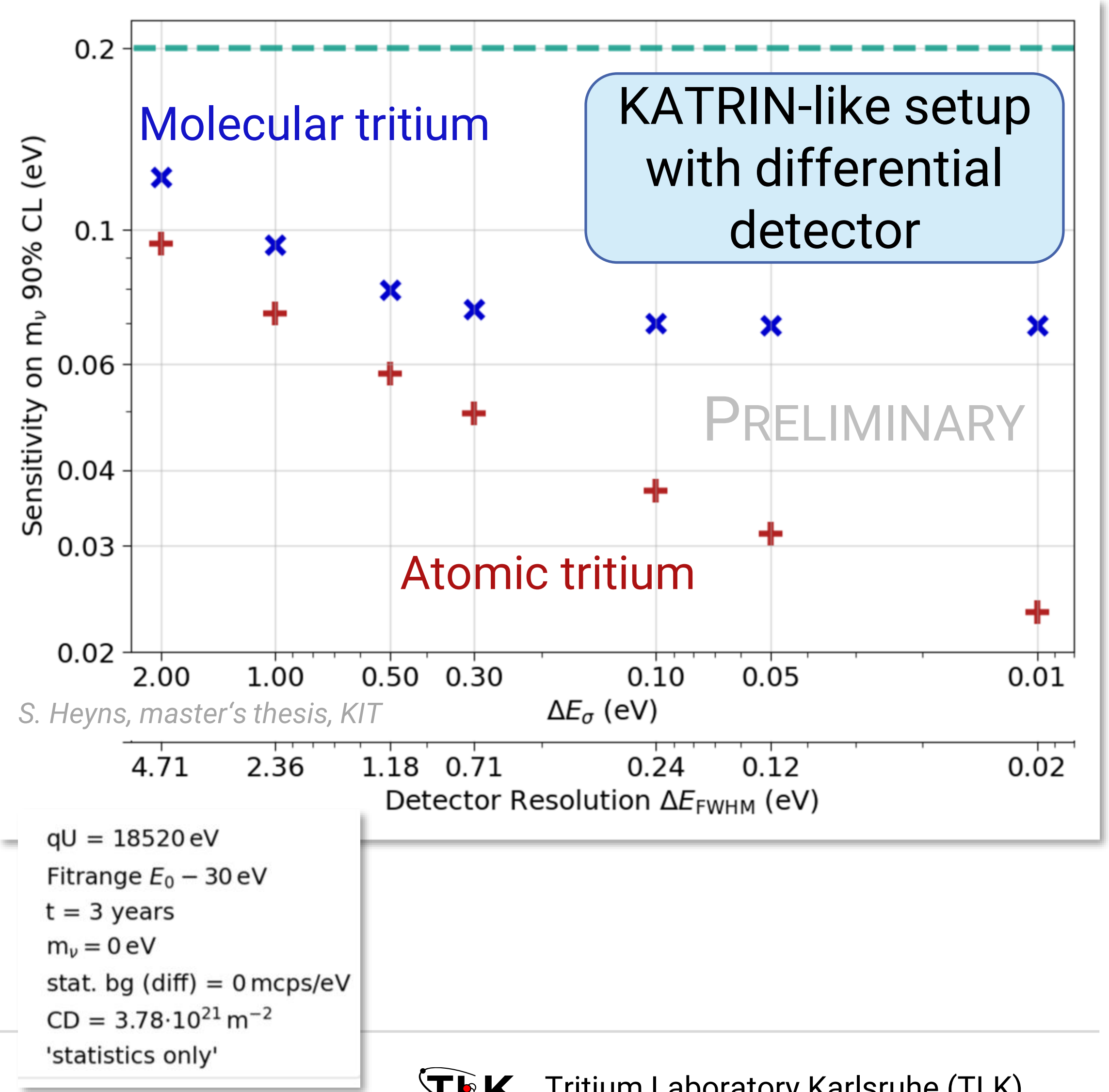
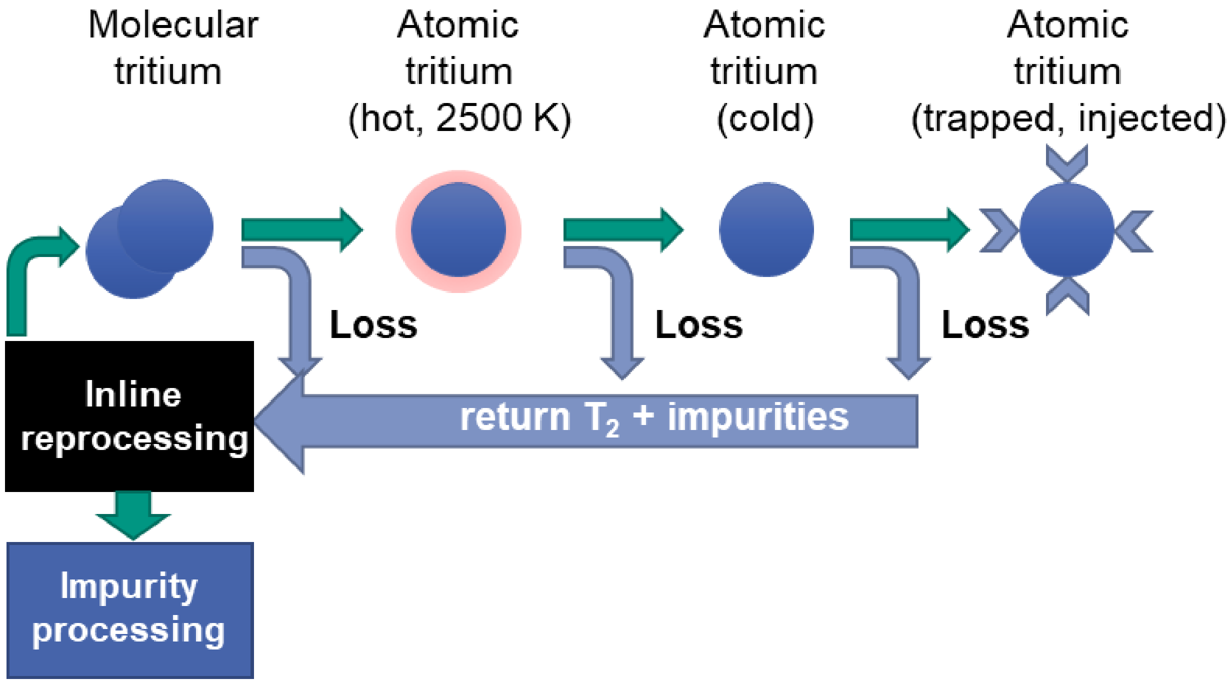




Future: Use atomic tritium source to avoid limitations by molecular broadening

R&D efforts for an atomic tritium source

- **Aim:** Generate mK-cold tritium atoms as source for ultimate neutrino mass experiments



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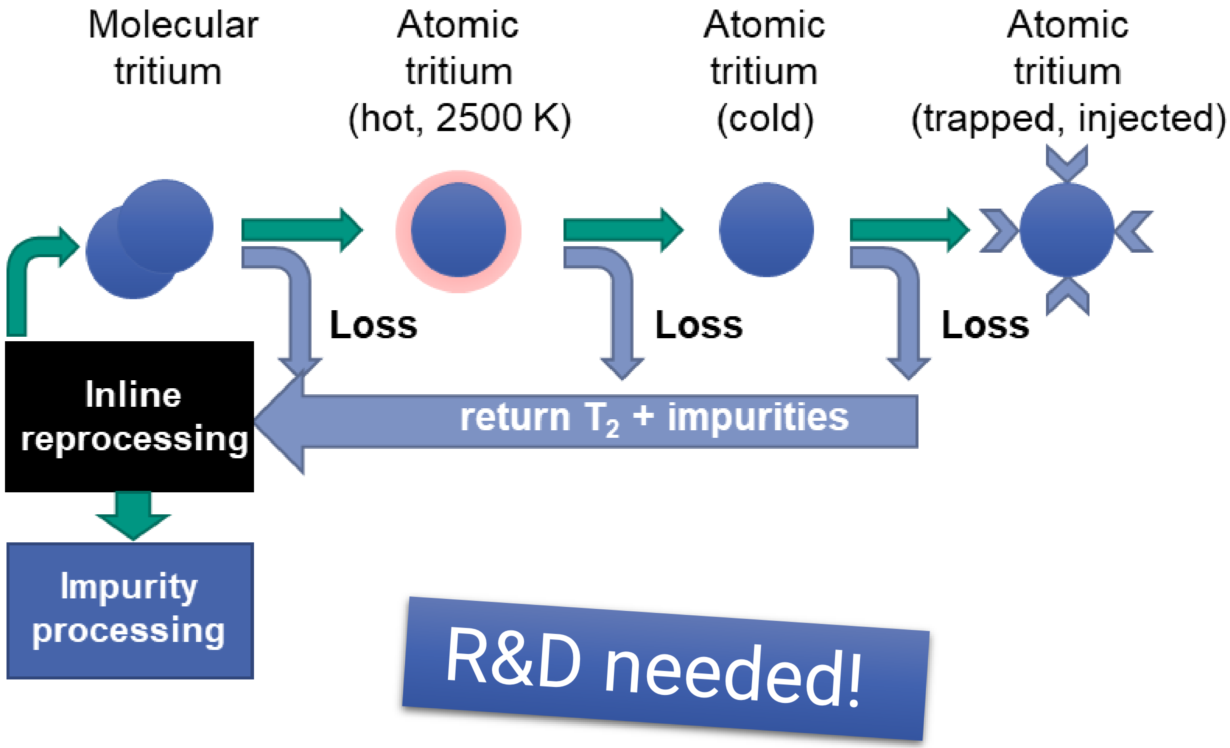

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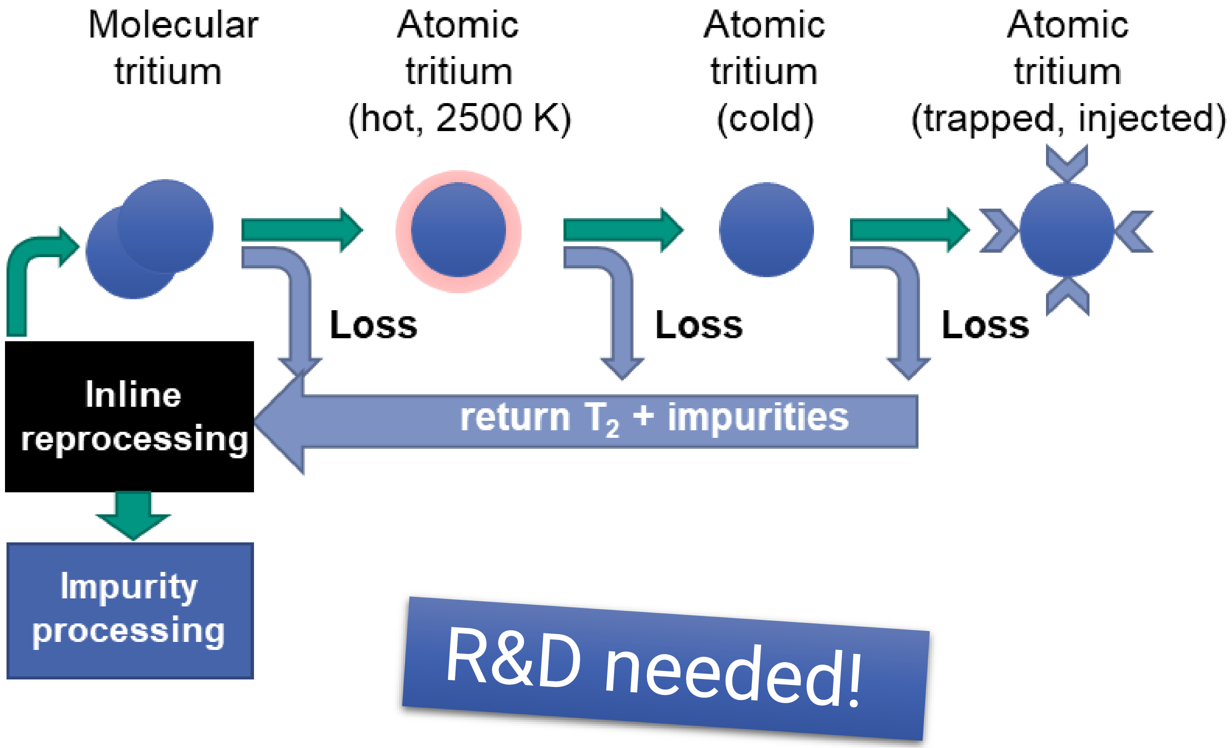
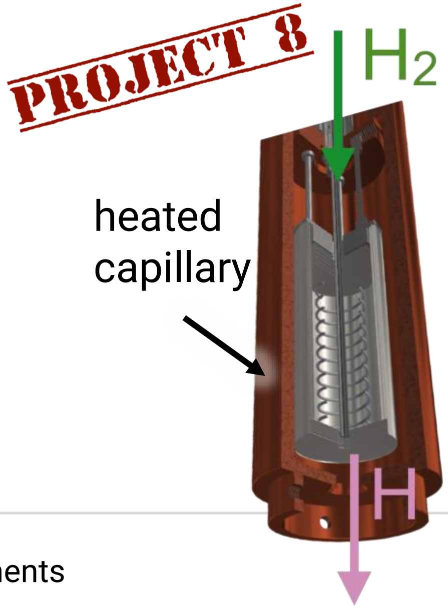
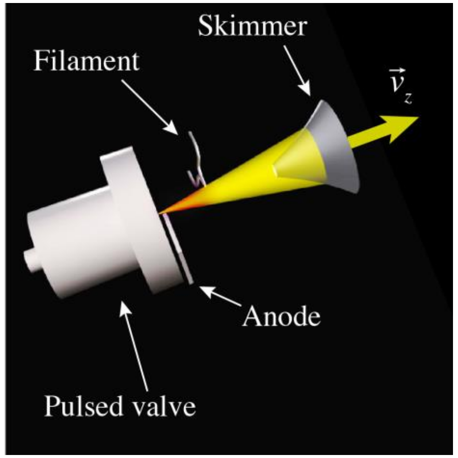


- R&D on different source types:
  - RF plasma,
  - DC discharge with pulsed valve,
  - Thermal dissociation in a capillary, …





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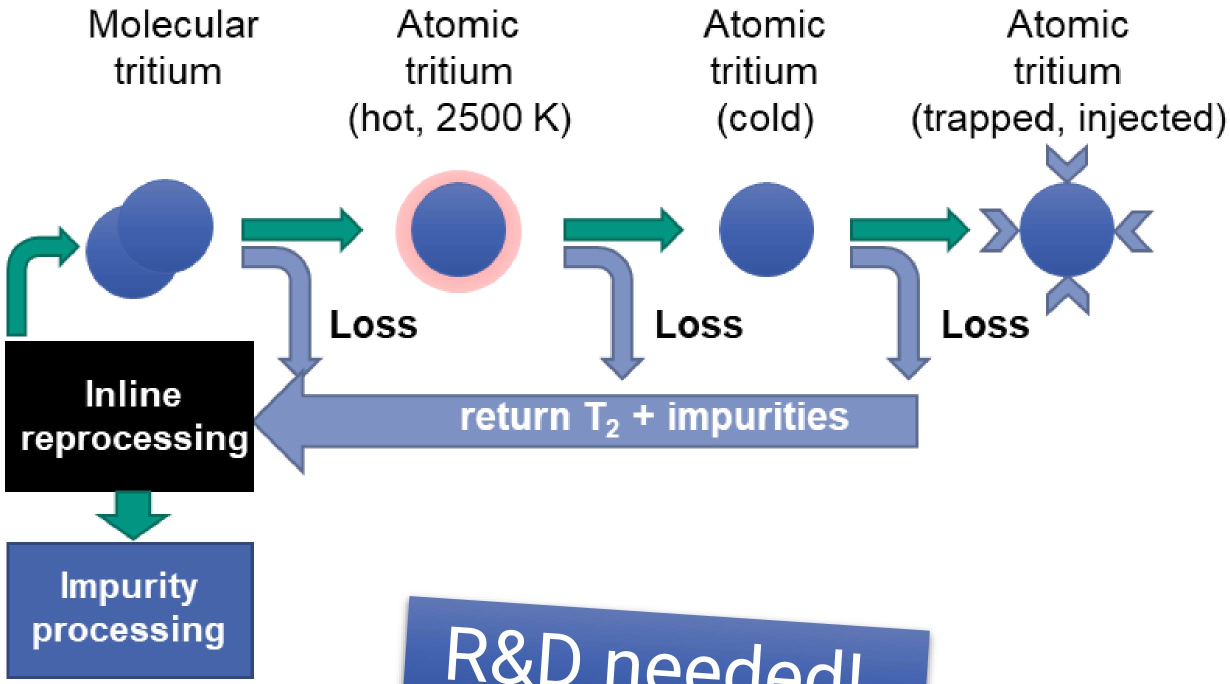

R&D needed!

- R&D on different source types:
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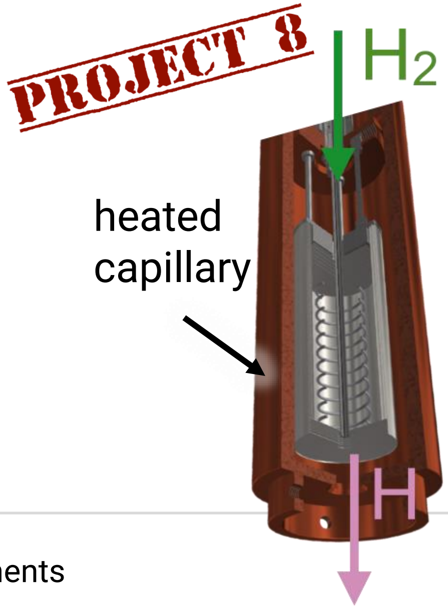
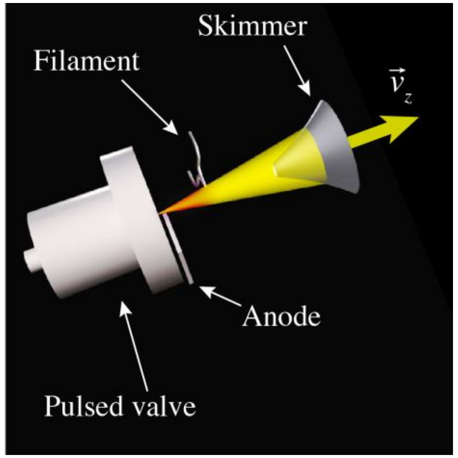
- Avoid recombination of tritium atoms
  → Magnetic trapping





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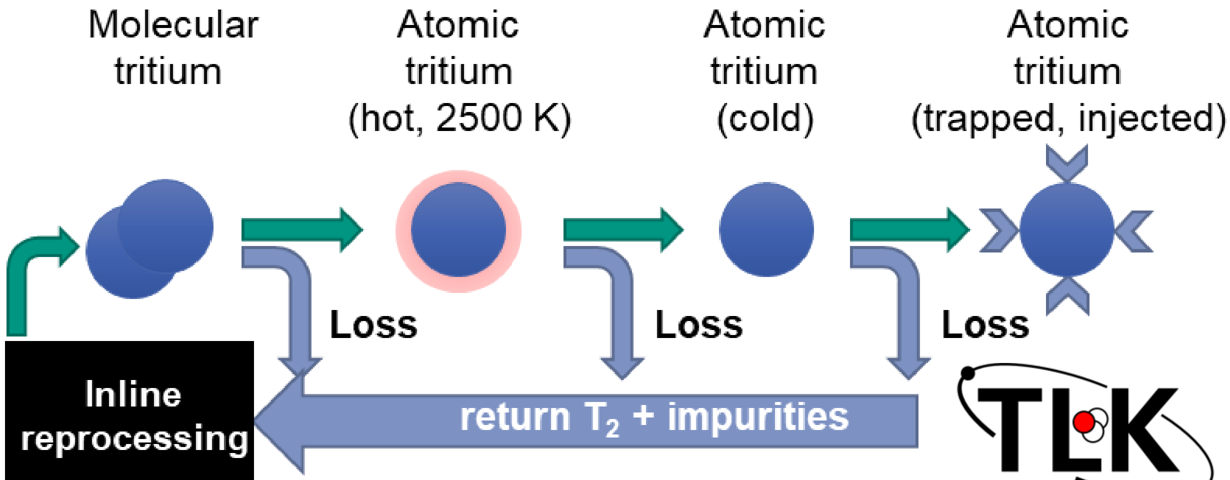

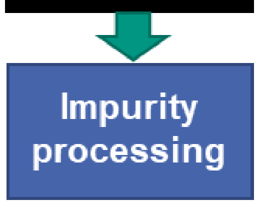

- KATRIN-like T_2 throughput (40 g T / day) or above
- Efficiency of each processing step needs to be optimized to achieve a high total efficiency

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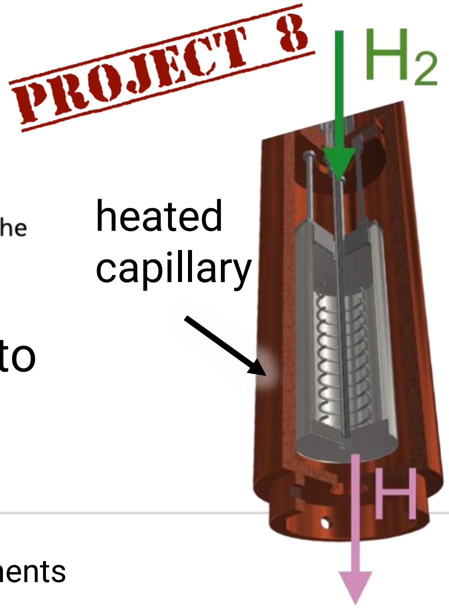

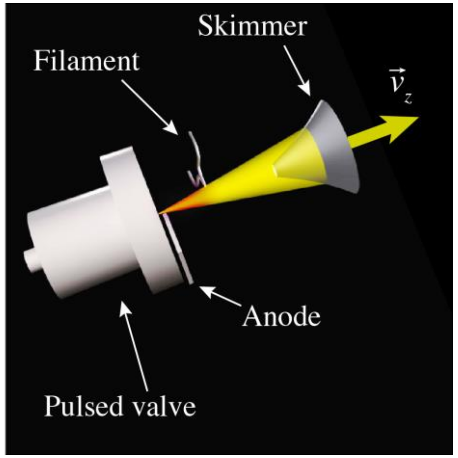

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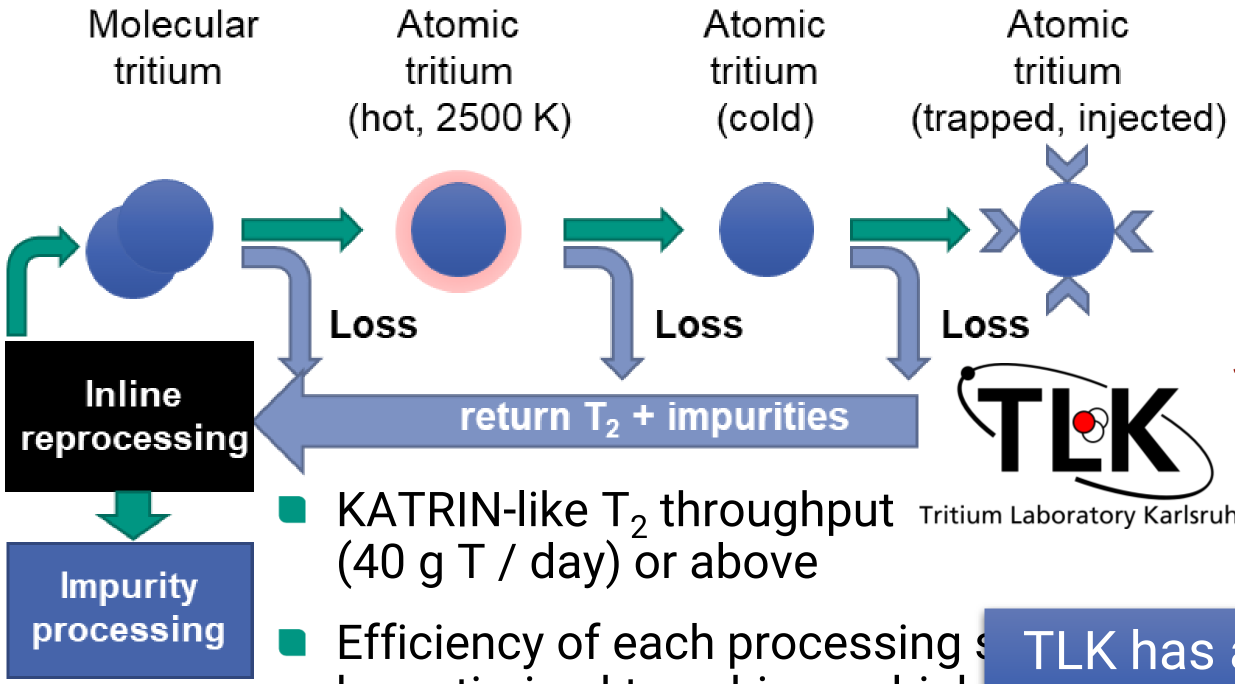

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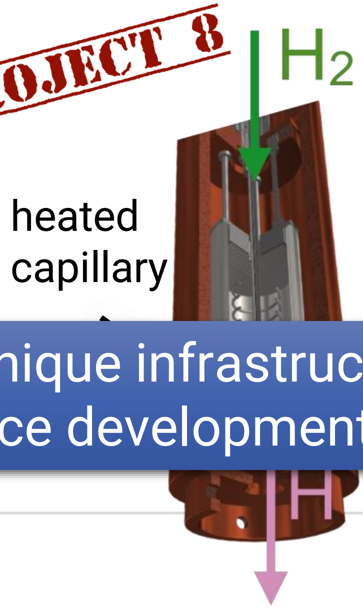
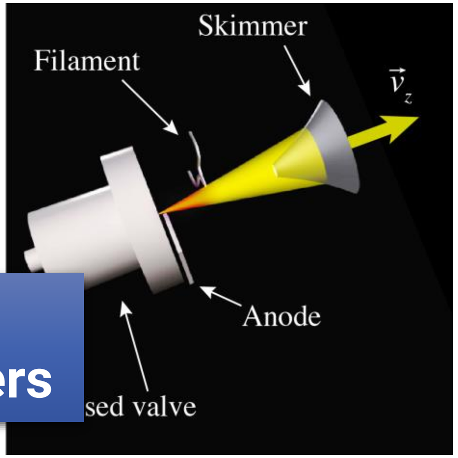
PROJECT 8

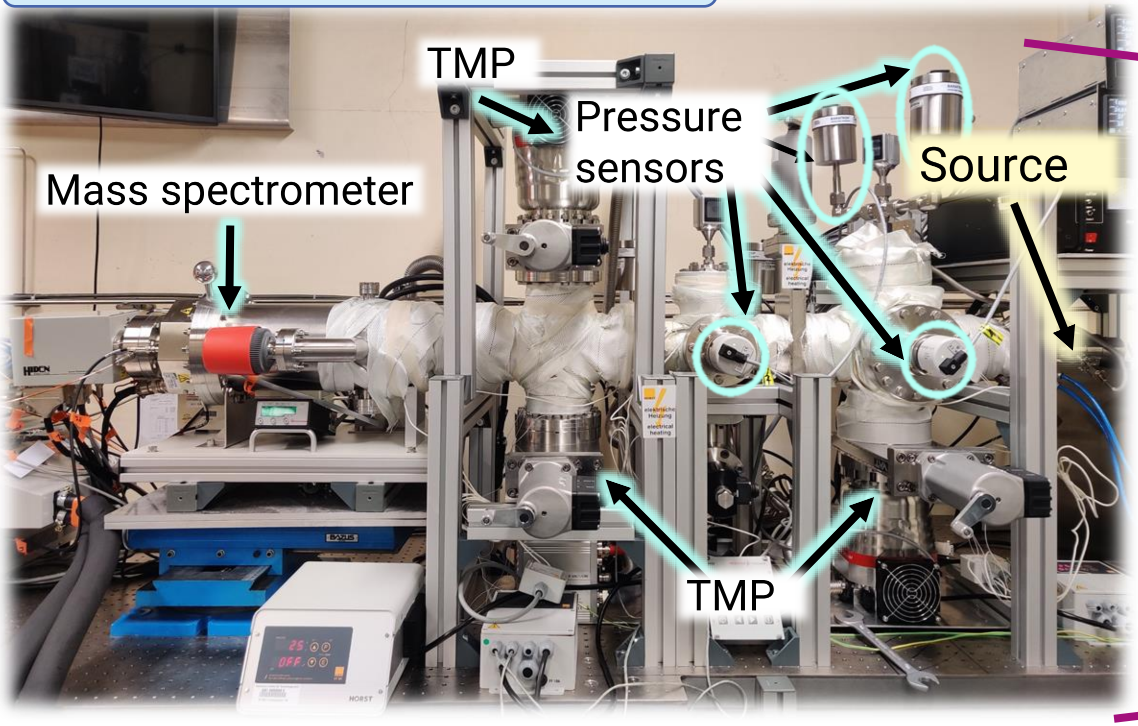




TLK has a unique infrastructure for atomic source development with **partners**

R&D efforts for an atomic tritium source

Atomic hydrogen test stand



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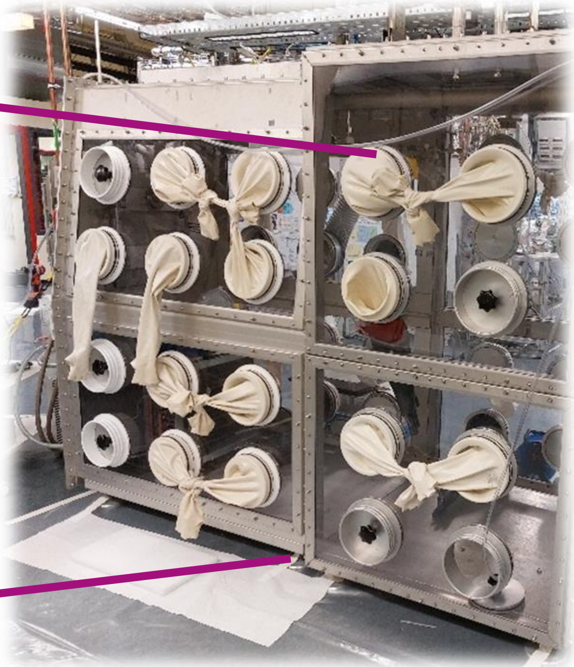

- Currently preparing the glovebox for integration of the **first atomic tritium** experiment
- Simple cracker-based test experiment

R&D efforts for an atomic tritium source

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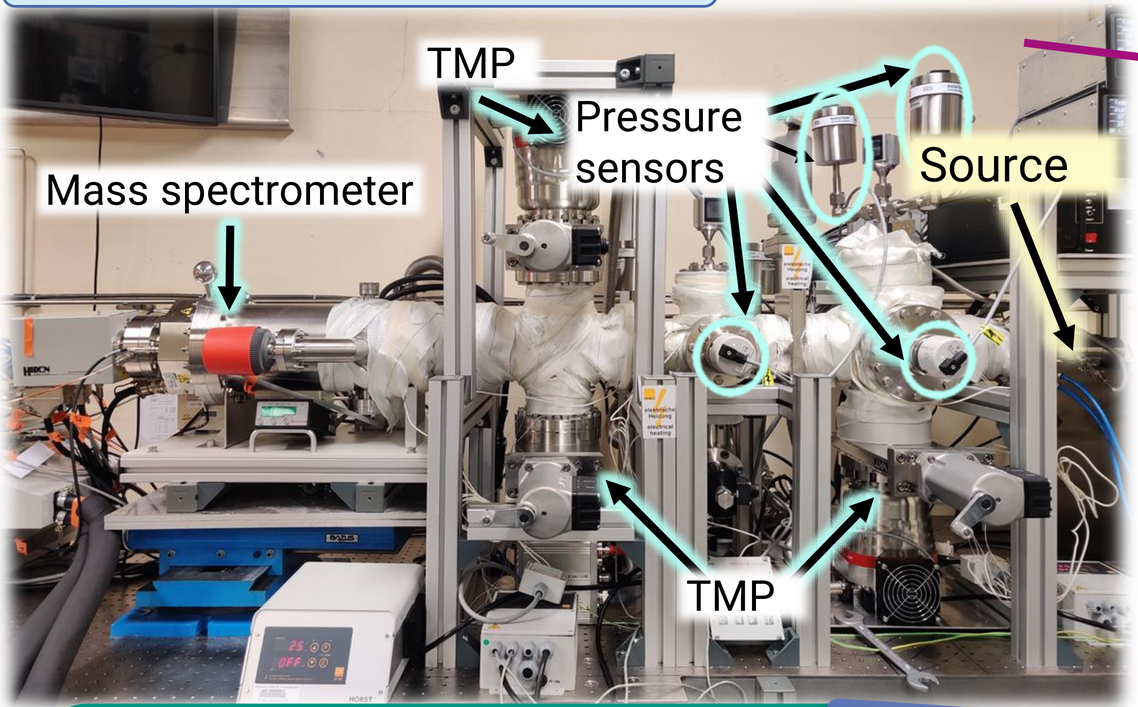

Goals

- Proof-of-principle experiment
- Atomic fraction / isotopic effects
- Tritium operation experience

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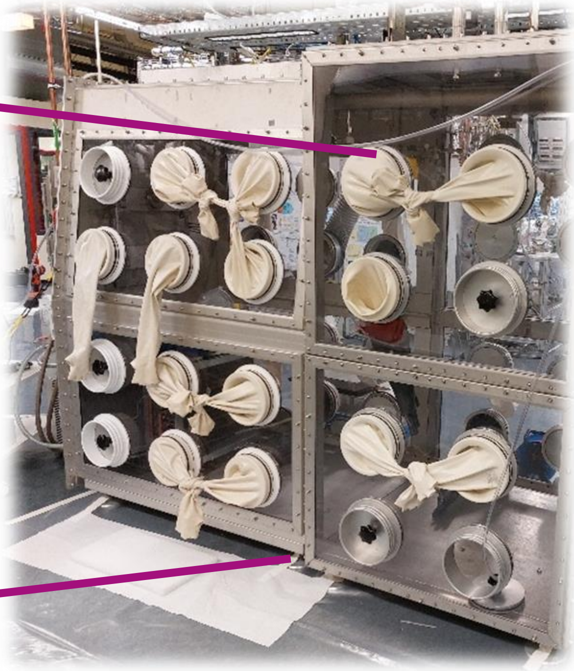

First experiments planned in 2024

R&D efforts for an atomic tritium source

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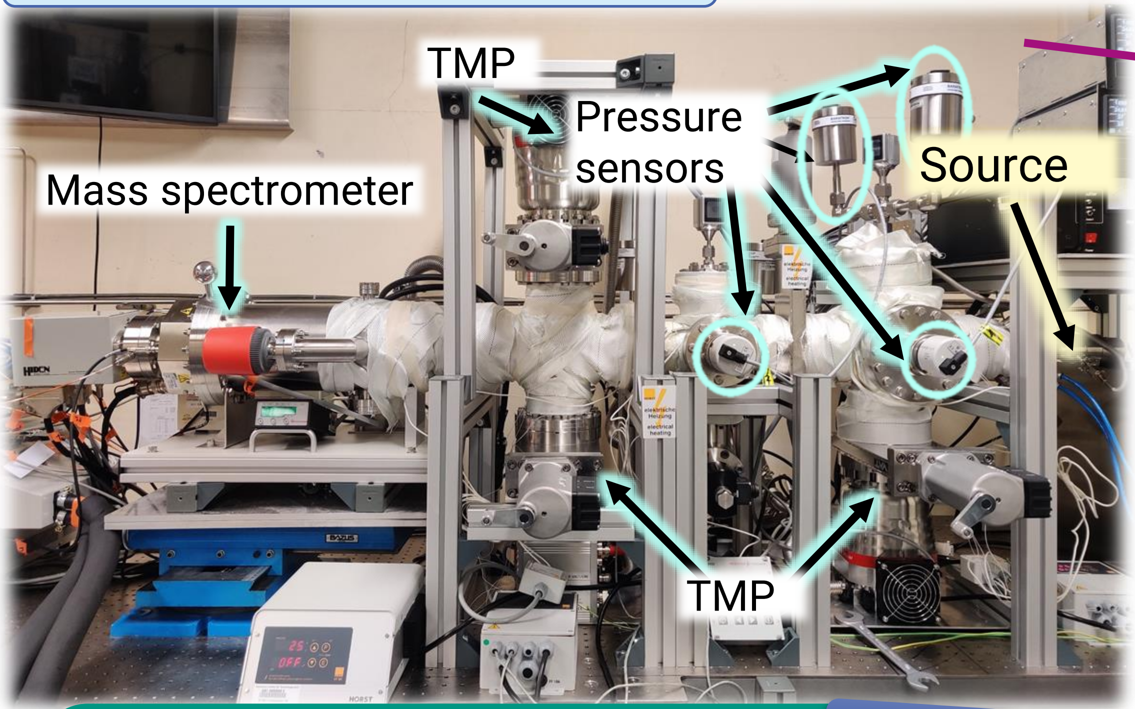

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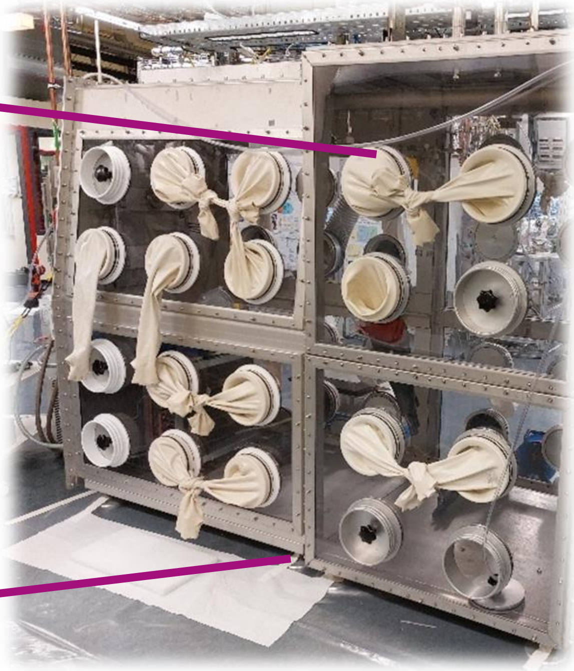


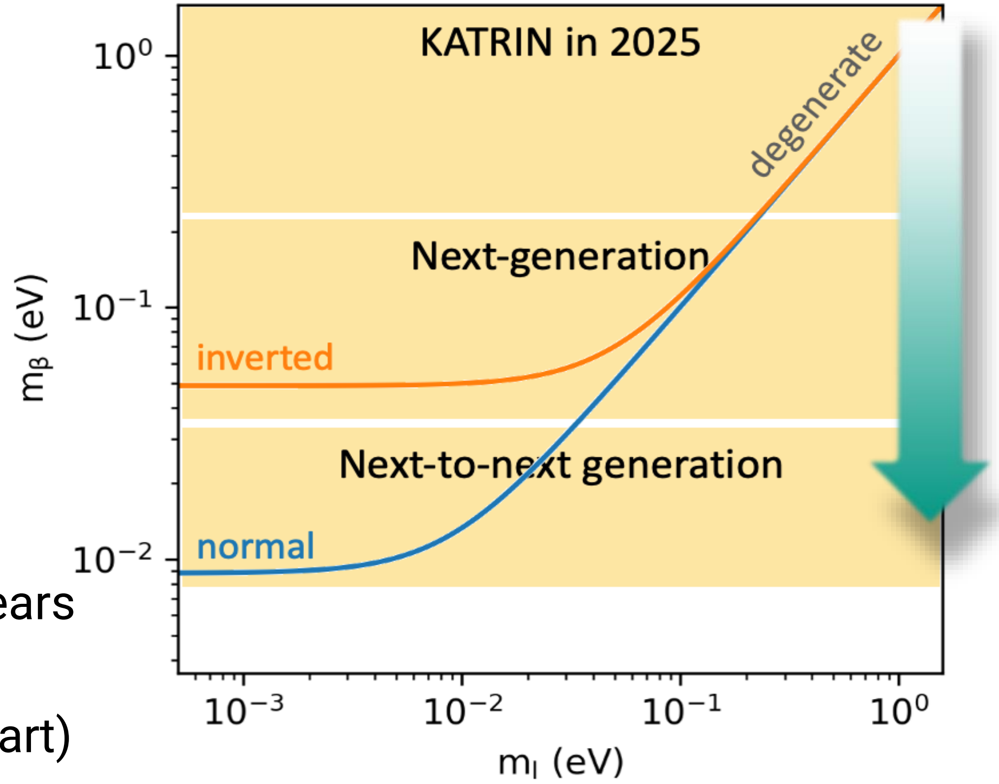
First experiments planned in 2024

To achieve the final stages –atom guiding, cooling and trapping– a laboratory with tritium handling expertise is essential

Summary and outlook

Tritium

- **KATRIN** currently provides leading neutrino mass limit ($m_\nu < 0.8$ eV)
  - Final goal (after 2025) : sensitivity better than 0.3 eV
- **Project 8** published first tritium data
- **QTNM** and **PTOLEMY** in pre-tritium technology demonstration stages



Holmium

- Micro calorimeters technology progressed in in the last few years
- O(10 eV) sensitivities in reach (**ECHo** data being analysed; **HOLMES** science runs about to start)

Community pushes onward

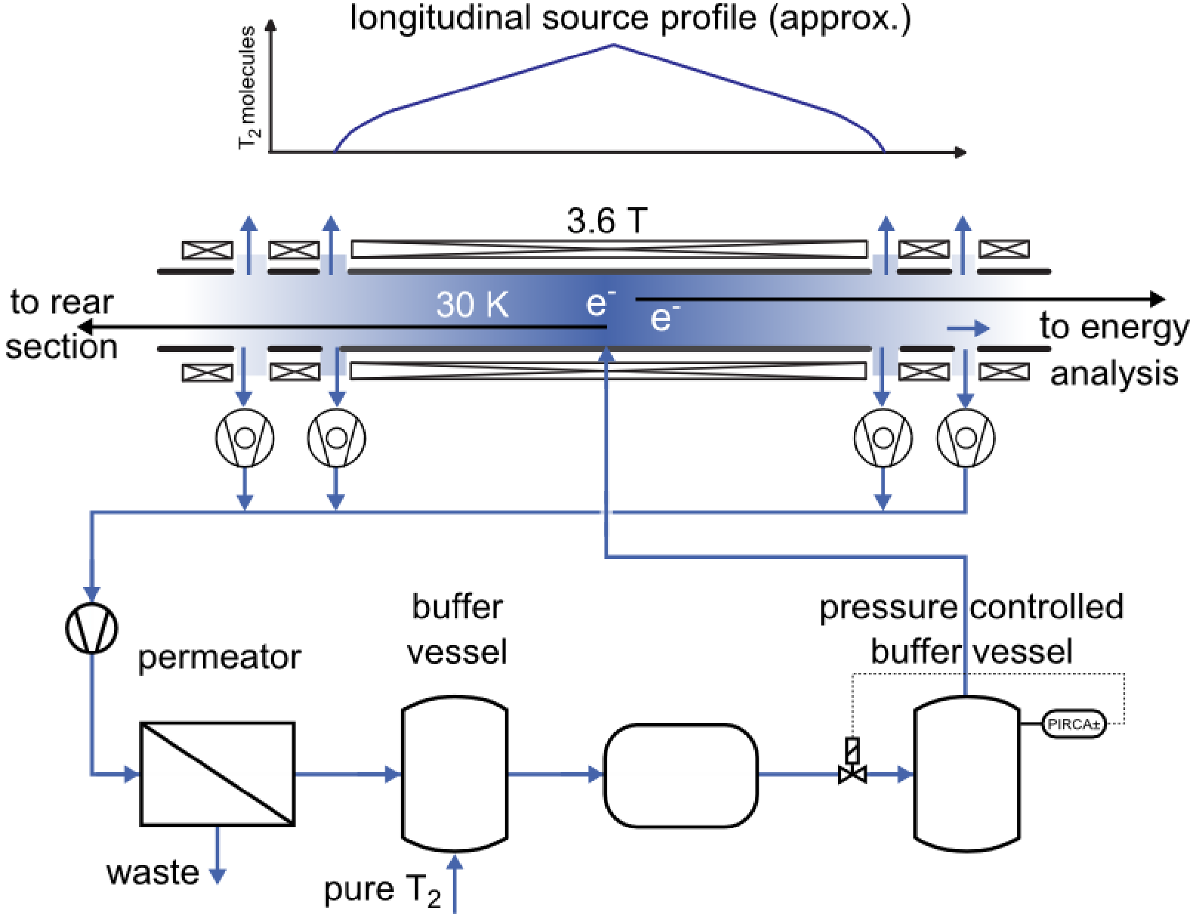
- **Active R&D of more sensitive technologies** (CRES, MMC, ToF, …) ongoing
- Efforts toward employing **atomic tritium**

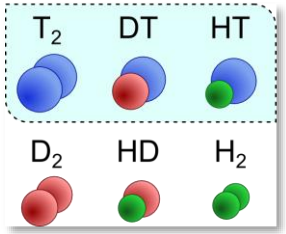
Develop new technologies to reach sensitivities **beyond the inverted ordering!**

Backup slides

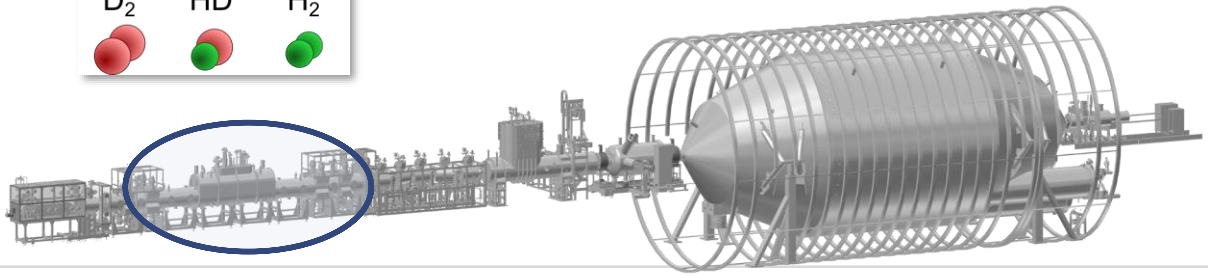
Windowless gaseous tritium source

- Source activity: 10^{11} Bq
  - Tritium throughput ~40 g/day
  - Operation 24/7, 60 days/run
  - Necessary inventory > 15 g
- Source profile stable to 10^{-3} level
- T_2 purity > 95%





Hydrogen isotopologs



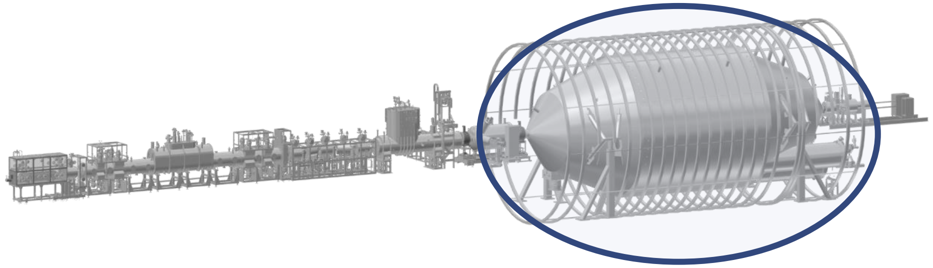
Measurement principle of the MAC-E filter spectrometer

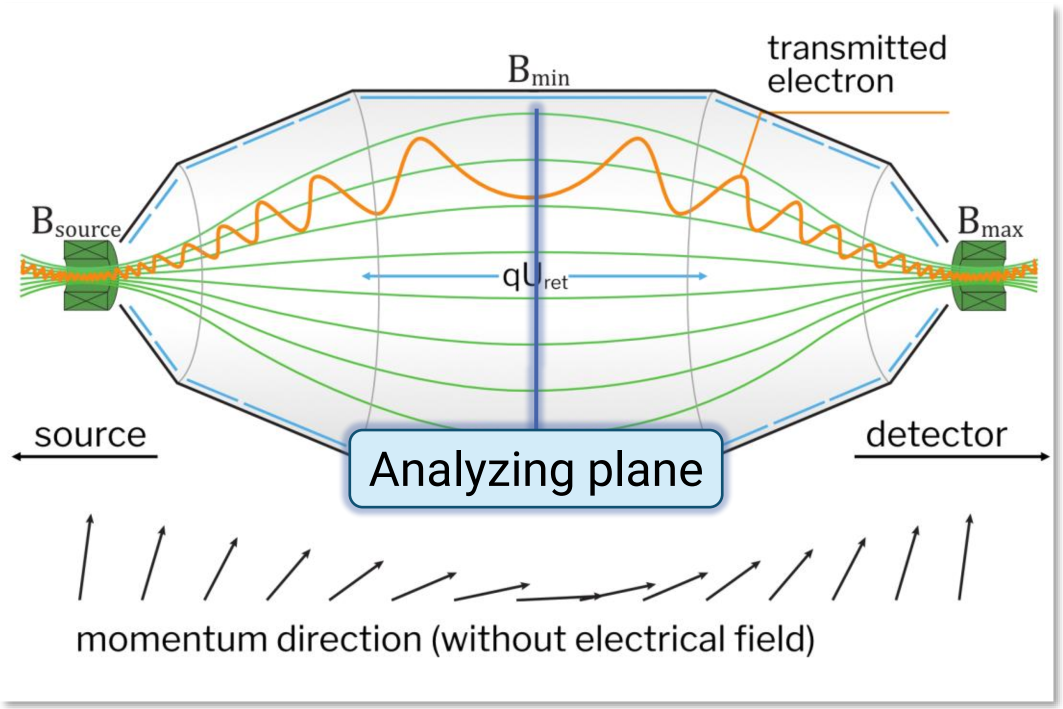
MAC Magnetic adiabatic collimation:

- Axially symmetric and smoothly diverging magnetic field
- Magnetic moment $\mu = \frac{e}{2m_e}|\vec{L}| = \frac{E_\perp}{B}$ is invariant
- At analyzing plane, transversal energy $E_\perp$ is minimal and $E_{\perp,\mathrm{Ana}} = E_{\mathrm{kin}} \cdot \sin^2\theta_{\mathrm{source}} \frac{B_{\mathrm{min}}}{B_{\mathrm{source}}}$

E Electrostatic filter

- High-pass filter: $E_\parallel \geq qU_{\mathrm{ret}}$





Measurement principle of the MAC-E filter spectrometer

Karlsruhe Institute of Technology

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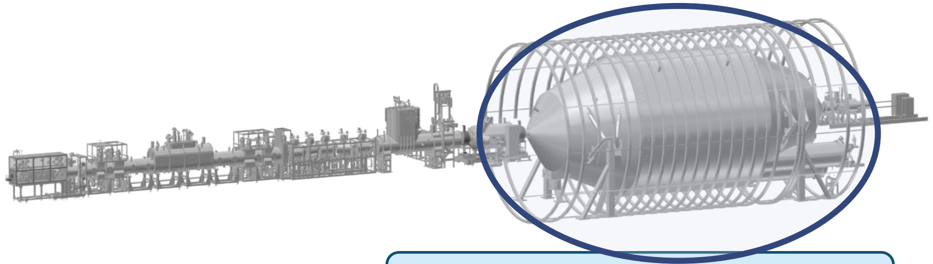
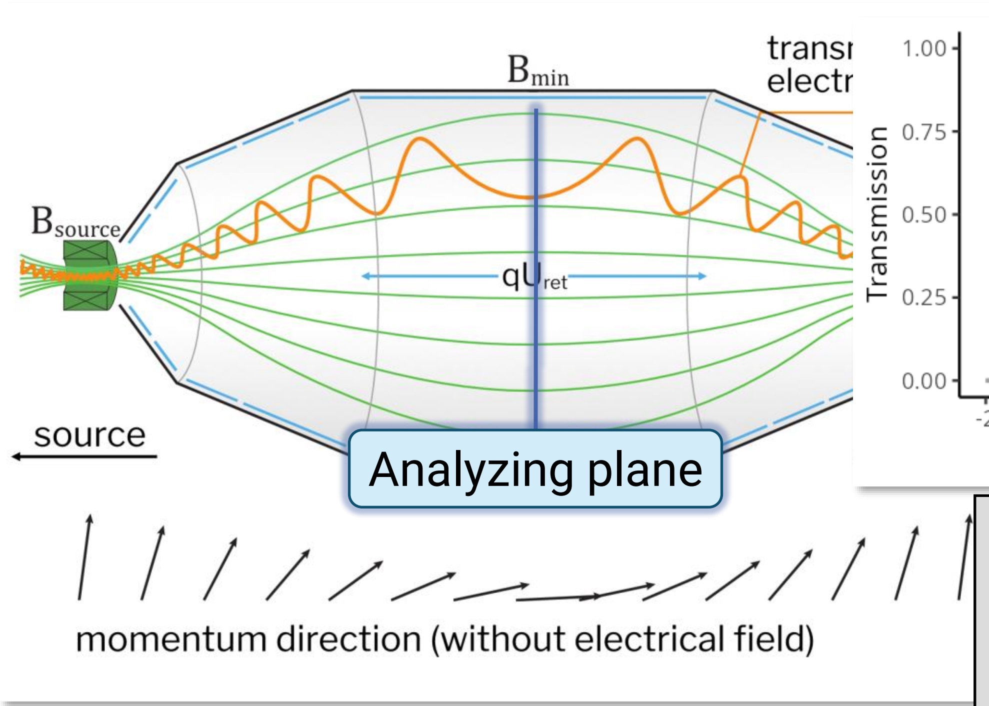
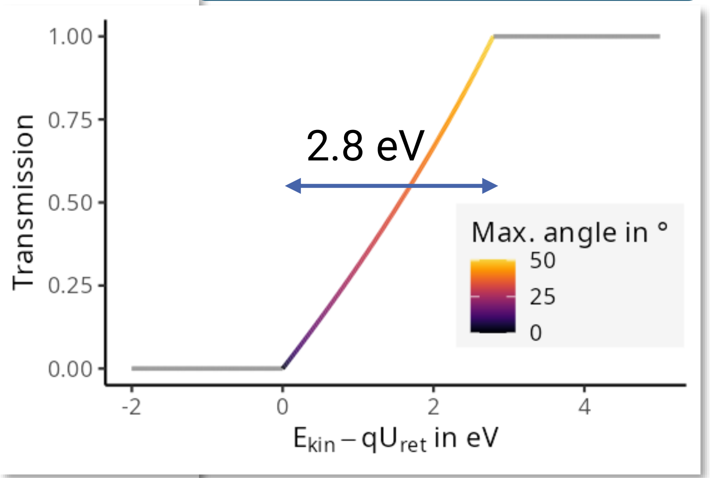


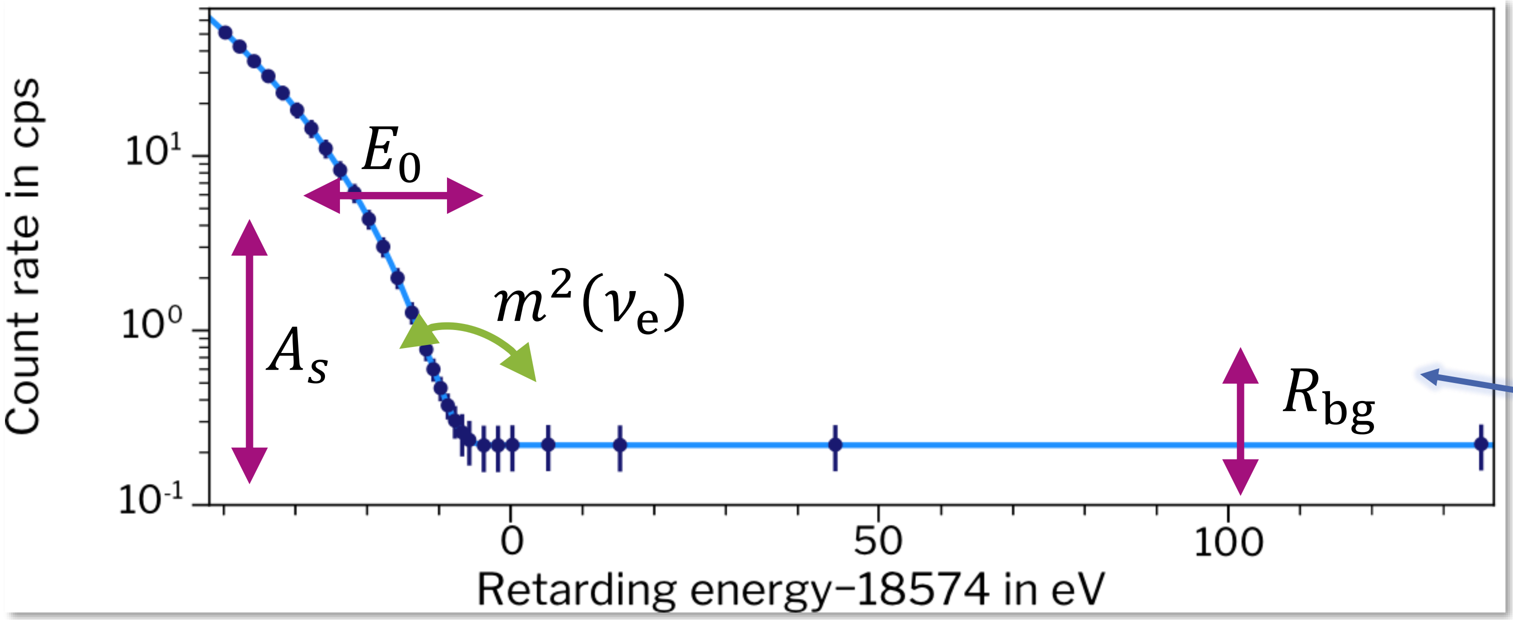
Transmission function



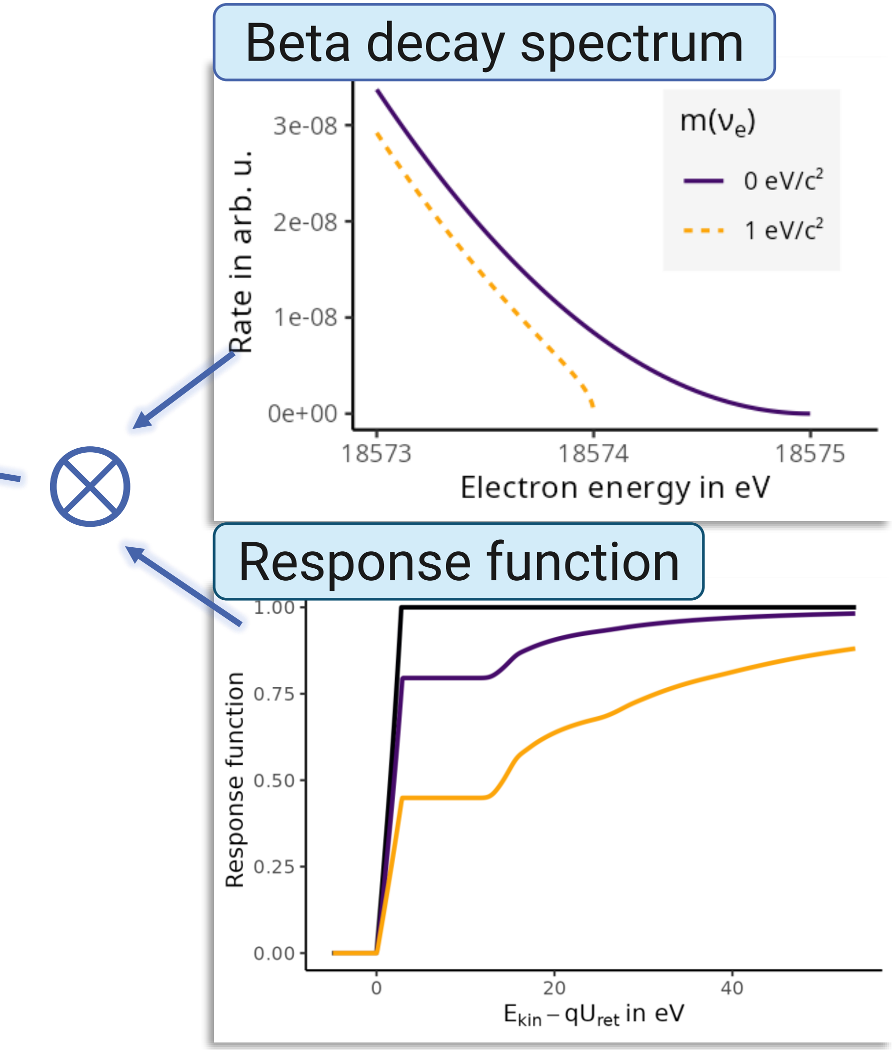


- isotropic source ($\theta_{\mathrm{max}} = 51°$)
- standard magnetic fields
- $U_{\mathrm{ret}} = -18.6\ \mathrm{kV}$

Measurement of the neutrino mass



KATRIN Collaboration, Nat. Phys. 18, 160–166 (2022)



$$R(qU_{\text{ret}}) = A_s \cdot N_T \int_{qU}^{E_0} R_\beta(E, m^2(\nu_e)) \cdot f(E, qU_{\text{ret}}) \mathrm{dE} + R_{\text{bg}}(qU_{\text{ret}})$$