Present and future of direct neutrino mass experiments

Angelo Nucciotti

Università di Milano-Bicocca e INFN - Sezione di Milano-Bicocca

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA
AUDENTES FORTUNA IUVAT

INFN
Istituto Nazionale di Fisica Nucleare

NEUTRINO 2024

XXXI International Conference on Neutrino Physics and Astrophysics

June 16-22, 2024 Milan, Italy

The question of the neutrino mass

neutrino **flavor** weak eigenstate

neutrino mixing matrix

neutrino **mass** eigenstate

$$|\nu_l\rangle = \sum_i U_{li}|\nu_i\rangle$$

known from oscillation experiments

$\Delta m_{ij}^2 = |m_i^2 - m_j^2|$

$\sin^2 2\vartheta_{li} = f(|U_{li}|^2)$

http://www.nu-fit.org/
Particle Data Group, Prog. Theor. Exp. Phys. 2022, 083C01 (2022) and 2023 update

Open questions:

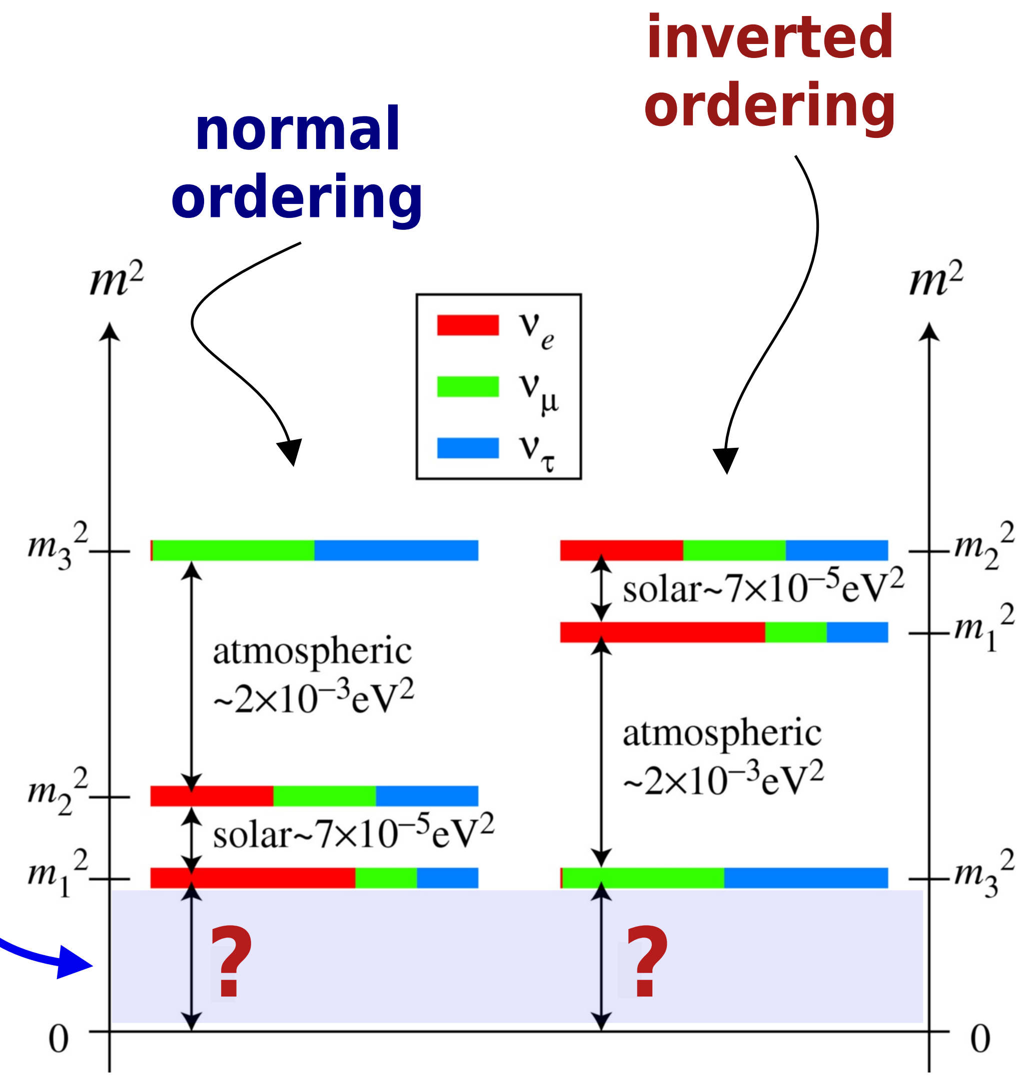
mass scale: i.e. mass of the lightest neutrino m_{light}?

mass ordering

degenerate ($m_1 \approx m_2 \approx m_3$)

or hierarchical ($m_1 < m_2 \ll m_3$ or $m_3 \ll m_1 \approx m_2$)?

nature: $\nu = \bar{\nu}$? i.e. Dirac or Majorana particle?



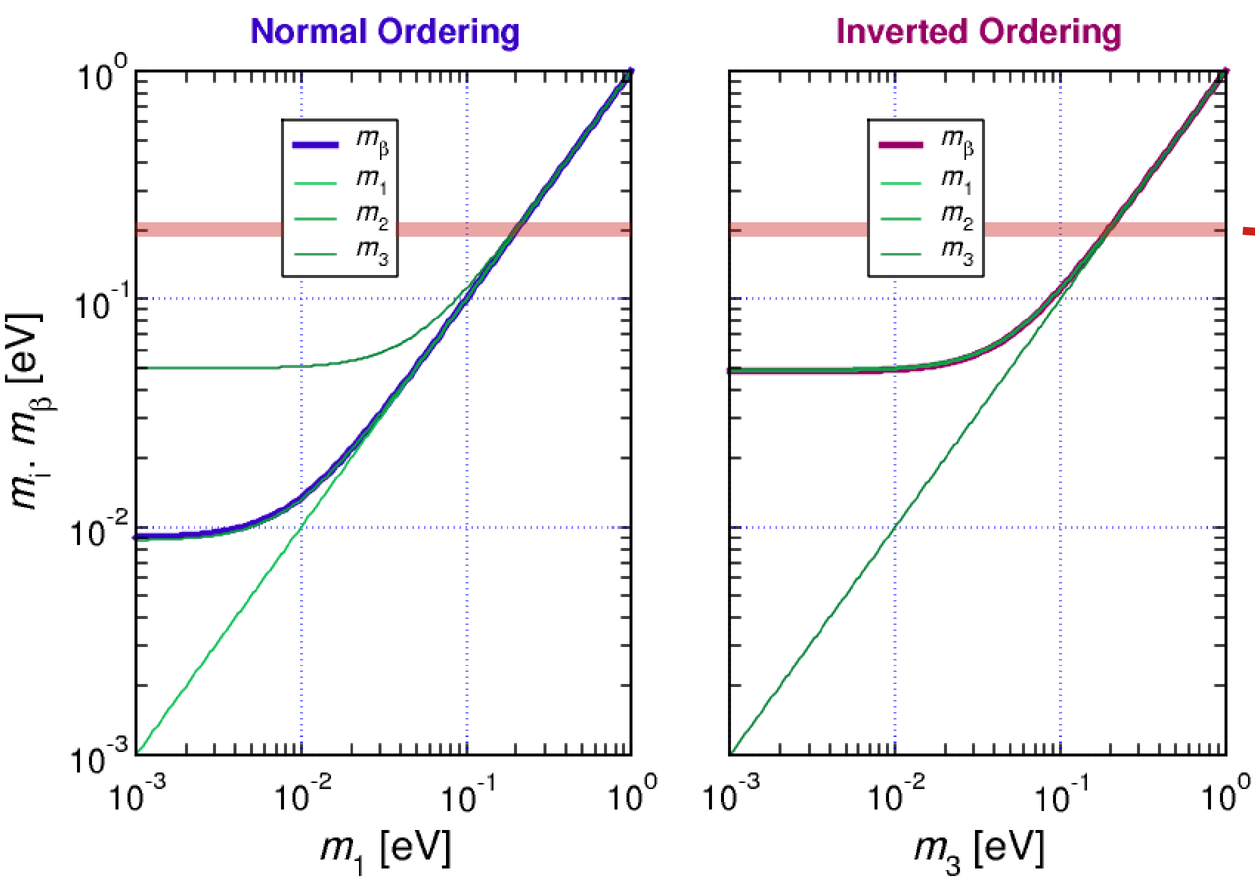
Direct neutrino mass measurements

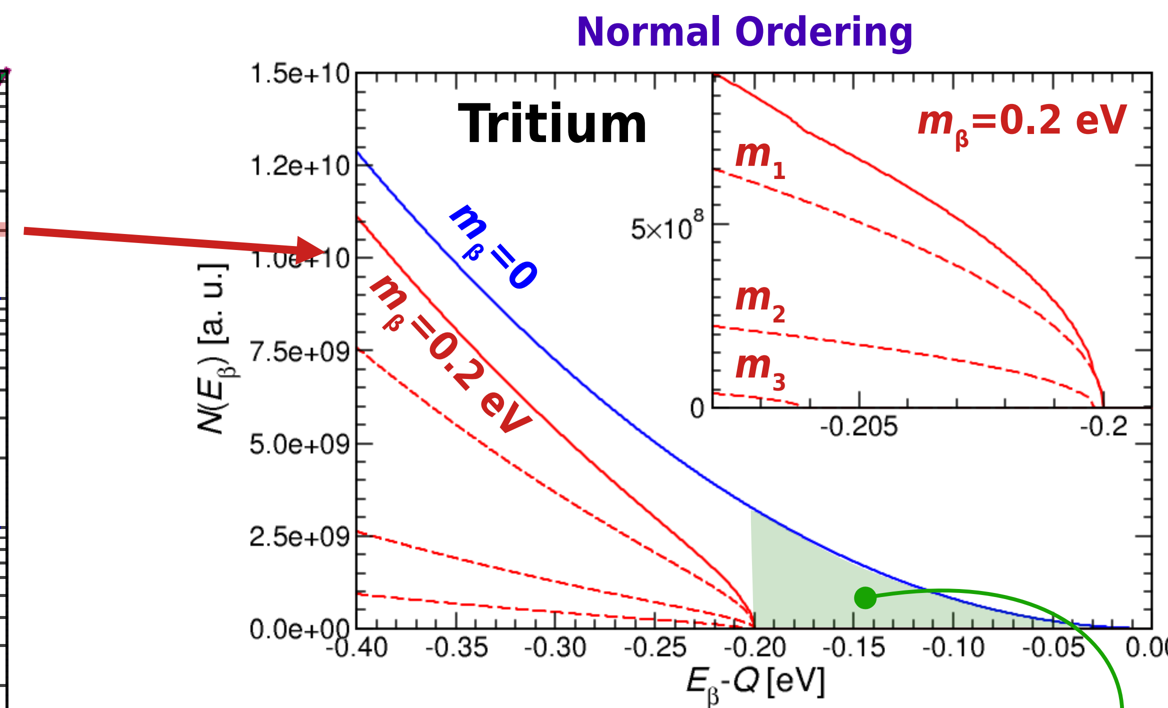
model independent approach: study the kinematics of weak decays

beta and electron capture decays where $\bar{\nu}_e$ or ν_e are emitted

for nuclear β decay and **degenerate masses** (i.e. m_{light}>≈0.1 eV → $m_1 \approx m_2 \approx m_3$)

$$N(E_\beta) \approx p_\beta E_\beta (Q-E_\beta)\sqrt{(Q-E_\beta)^2 - \boldsymbol{m_\beta}^2}\, F(Z,E_\beta) S(E_\beta) \quad \text{with} \quad \boldsymbol{m_\beta = \sqrt{\sum_i m_i^2 |U_{ei}|^2} \equiv m_\nu}$$





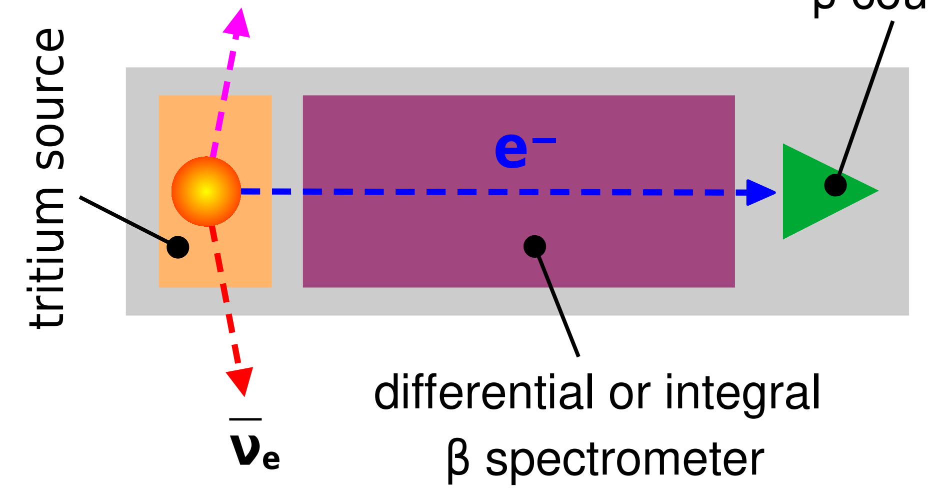
fraction of T decays in **[*Q*-Δ*E*, *Q*]**

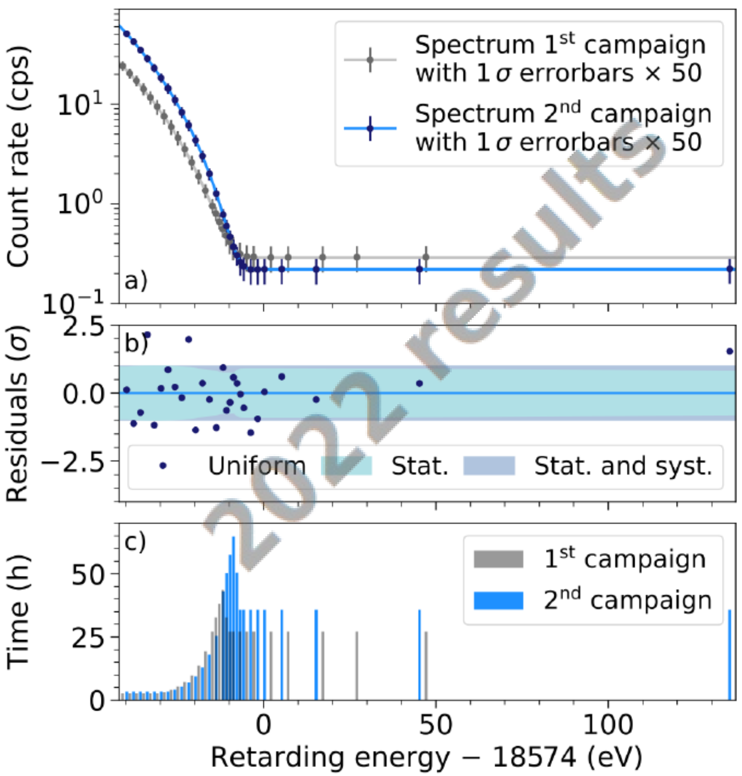
$f(\Delta E) \propto (\Delta E/Q)^3 \rightarrow f(m_\beta) \approx 10^{-15}$

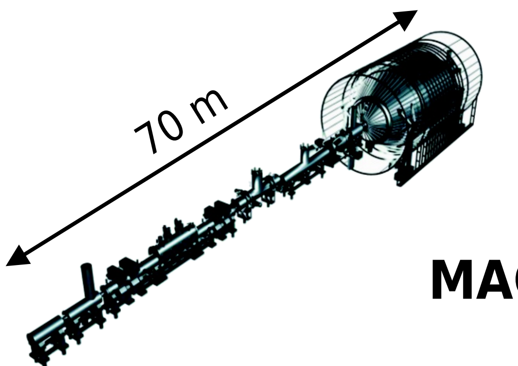
for m_β = 0.2 eV and Q = 18.6 keV

Spectrometric direct neutrino mass experiments

- since 1970 direct measurements used **Tritium and spectrometric** approach
  - low endpoint: Q = 18.6 keV
  - fast super-allowed β decay: $\tau_{1/2} = 12.3$ y
- various Tritium source types: solid and gaseuos







MAC-E filter with **windowless gaseous T_2 source**

→ ultimate integral spectrometer experiment

running since 2019, completing data taking in 2025

sensitivity goal: 0.3 eV 90% CL

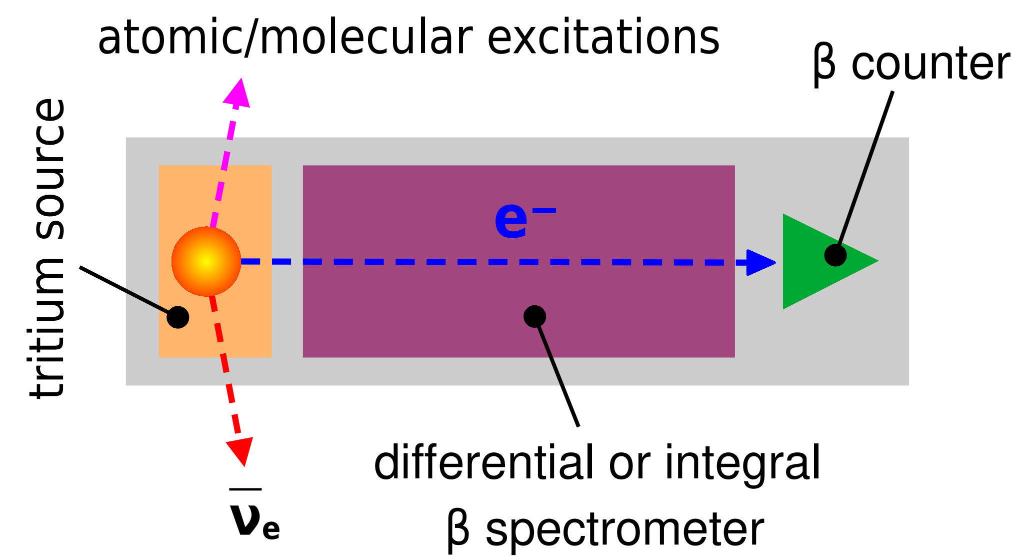
energy resolution <3 eV @18 keV.

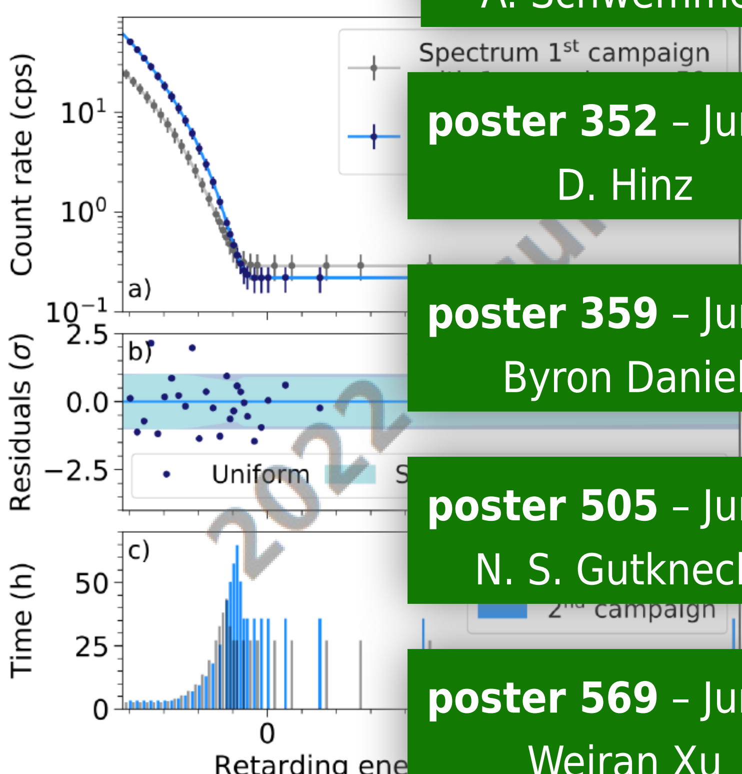
in 2022 ***m*** m_ν **< 0.8 eV** 90% CL *Nat. Phys. 18, 160–166 (2022)*

new data in 2024 → 0.5 eV sensitivity expected

Spectrometric direct neutrino mass experiments

- since 1970 direct measurements used **Tritium and spectrometric** approach
  - low endpoint: Q = 18.6 keV
  - fast super-allowed β decay: $\tau_{1/2}$ = 12.3 y
- various Tritium source types: solid and gaseuos





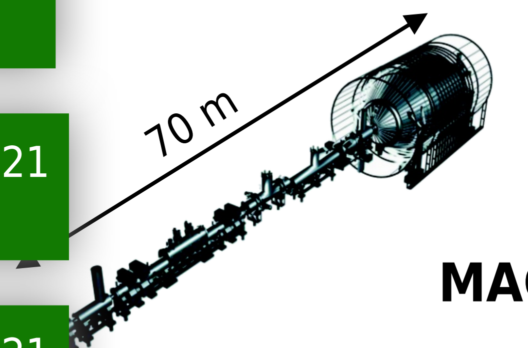
poster 12 – Jun 21
A. Schwemmer

poster 352 – Jun 21
D. Hinz

poster 359 – Jun 21
Byron Daniel

poster 505 – Jun 21
N. S. Gutknecht

poster 569 – Jun 21
Weiran Xu



KATRIN – Karlsruhe Tritium Neutrino Experiment

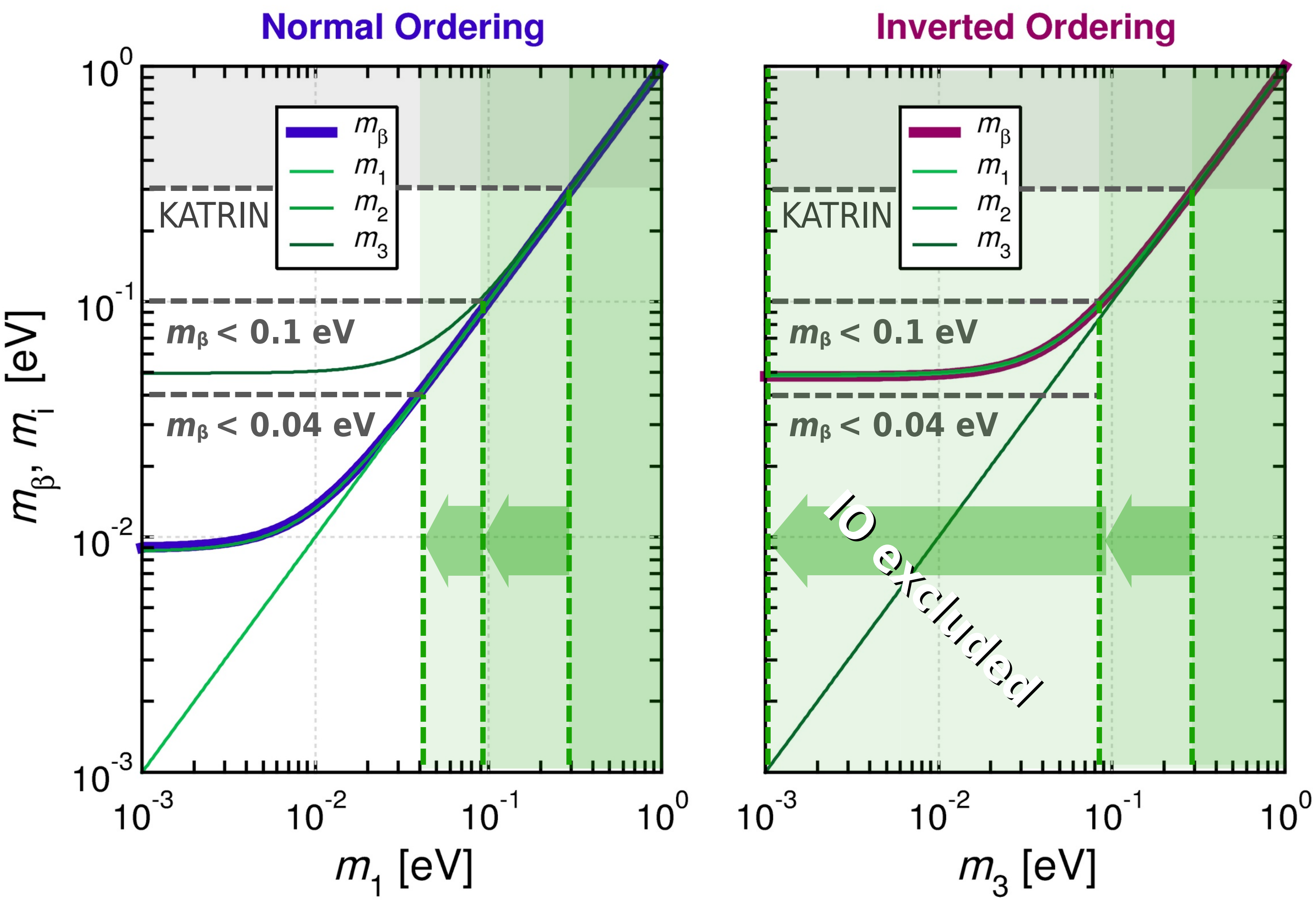
MAC-E filter with **windowless gaseous T_2 source**
→ ultimate integral spectrometer experiment
running since 2019, completing data taking in 2025
sensitivity goal: 0.3 eV 90% CL
energy resolution <3 eV @18 keV.
in 2022 ***m_ν* < 0.8 eV** 90% CL *Nat. Phys. 18, 160–166 (2022)*
new data in 2024 → 0.5 eV sensitivity expected

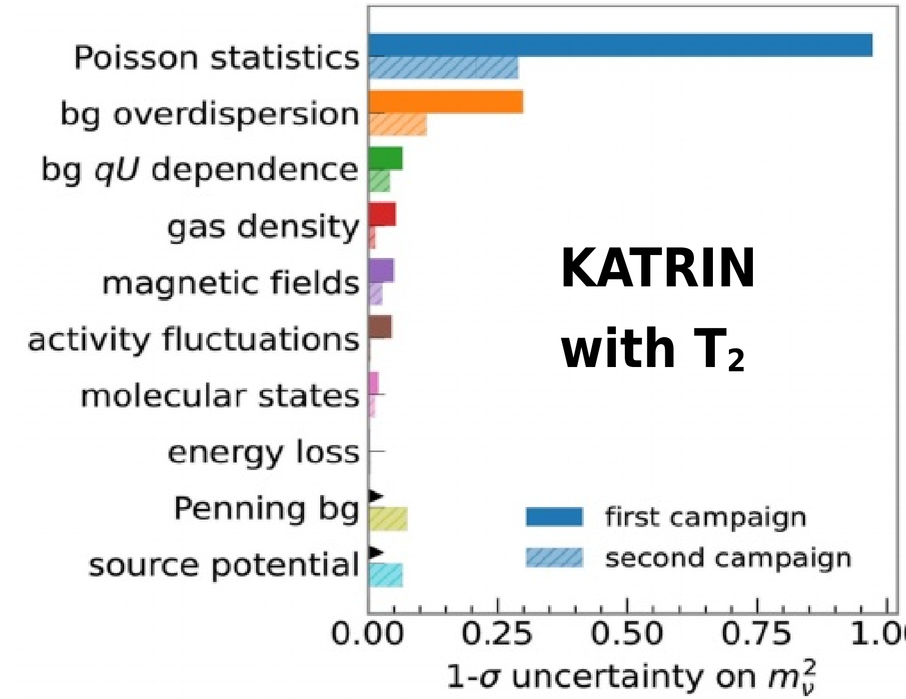
Direct measurements: future goals

determine mass scale from m_β

constrain the ordering for $m_\beta \lesssim 0.05$ eV (also from Δm_{ij}^2, $|U_{ei}|^2$)

A. A. Esfahani et al., Phys. Rev. C, 103 (2021) 065501





Statistics $\sigma_{stat}(m_\beta) \propto N^{-1/4}$

- source strength
- efficiency/duty cycle
- energy resolution
- background

Systematics $\sigma_{sys}(m_\beta) < \sigma_{stat}(m_\beta)$

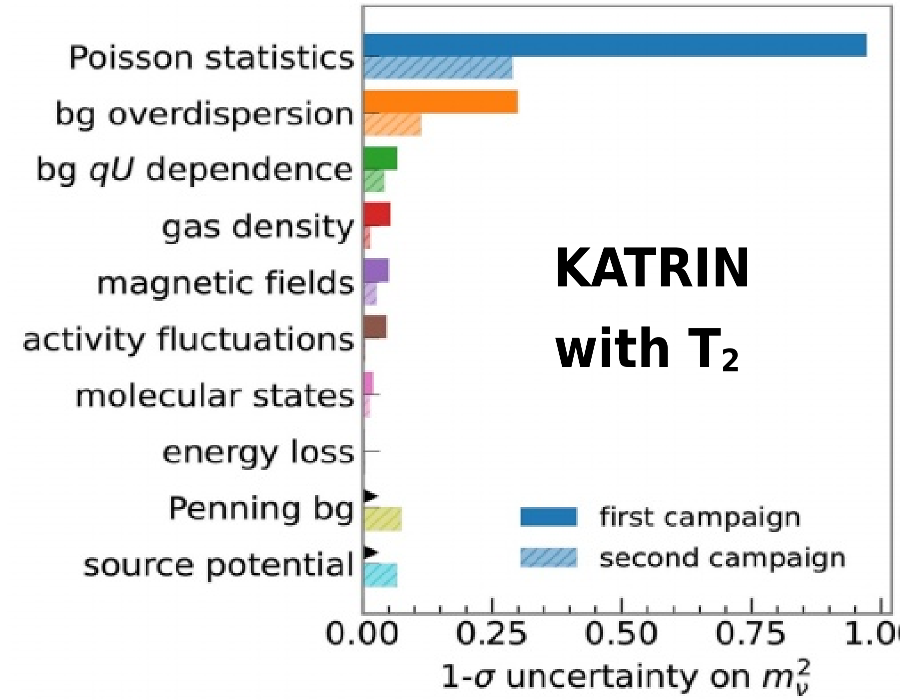
- atomic/molecular final states
- source
- background

Direct measurements: future goals

determine mass scale from m_β

constrain the ordering for $m_\beta \lesssim 0.05$ eV (also from Δm_{ij}^2, $|U_{ei}|^2$)

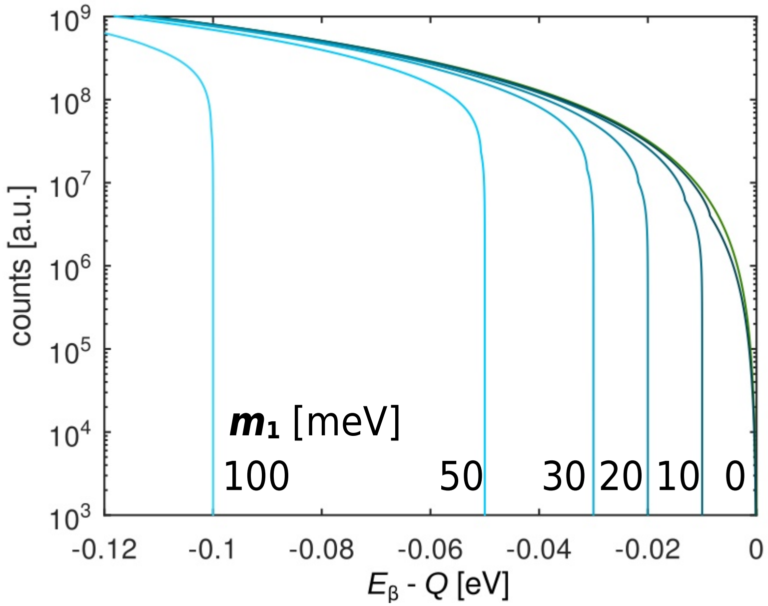
A. A. Esfahani et al., Phys. Rev. C, 103 (2021) 065501



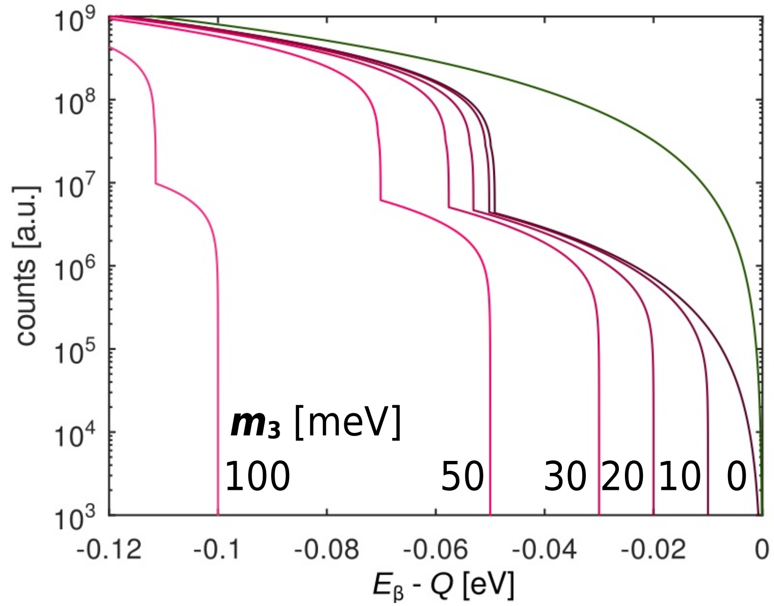
for $\boldsymbol{m_{light}} \ll$ **0.1 eV**

$$N(E_\beta) \propto p_\beta E_\beta (Q-E_\beta) \sum_k |\boldsymbol{U_{ei}}|^2 \sqrt{(Q-E_\beta)^2 - \boldsymbol{m_i}^2} F(Z,E_\beta) S(E_\beta)$$

Normal Ordering



Inverted Ordering



Statistics $\sigma_{stat}(m_\beta) \propto N^{-1/4}$

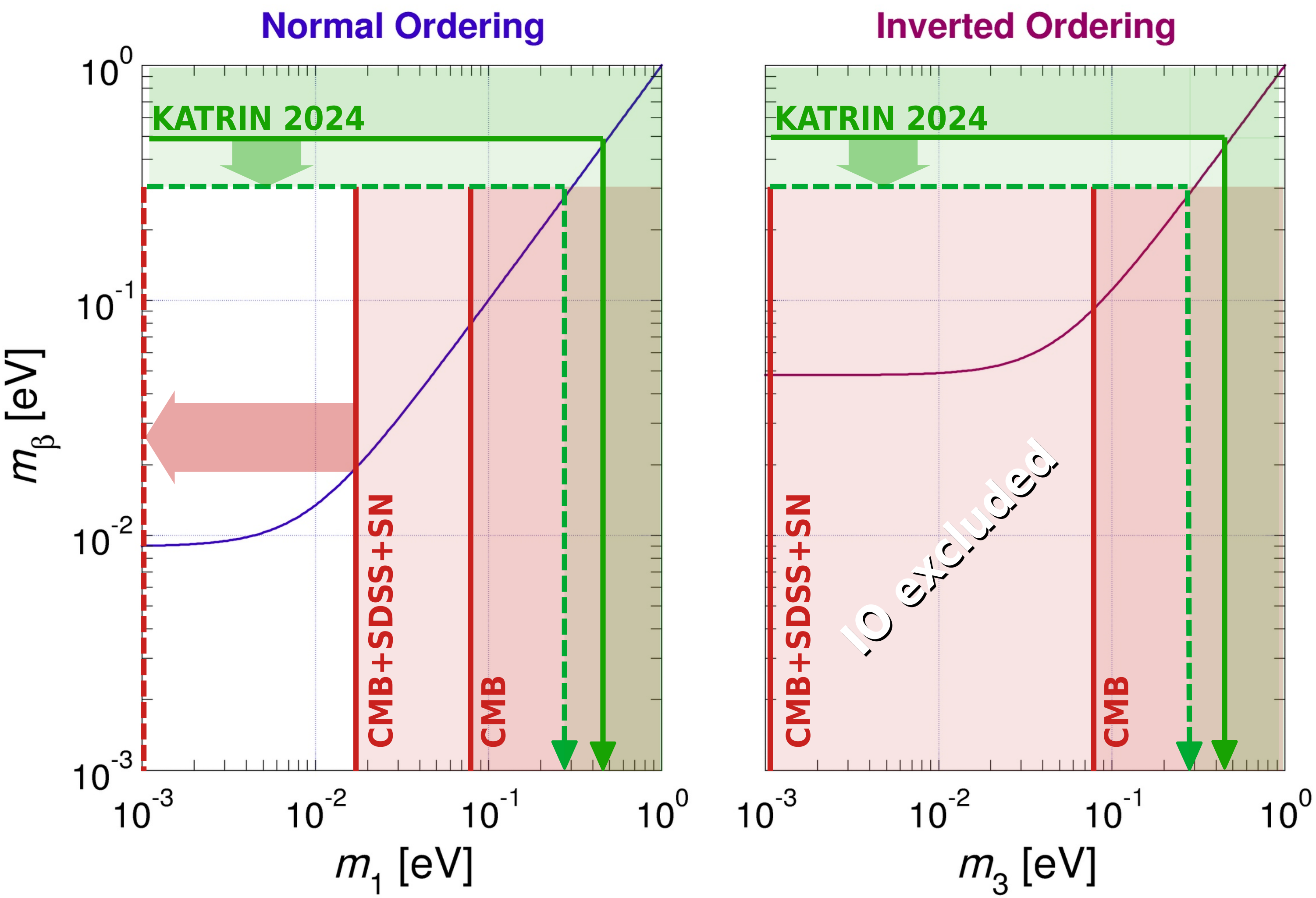
- source strength
- efficiency/duty cycle
- energy resolution
- background

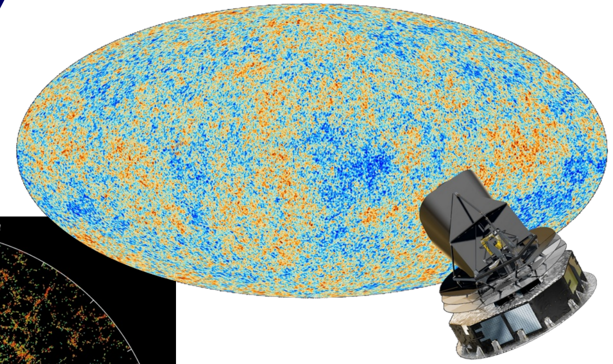
Systematics $\sigma_{sys}(m_\beta) < \sigma_{stat}(m_\beta)$

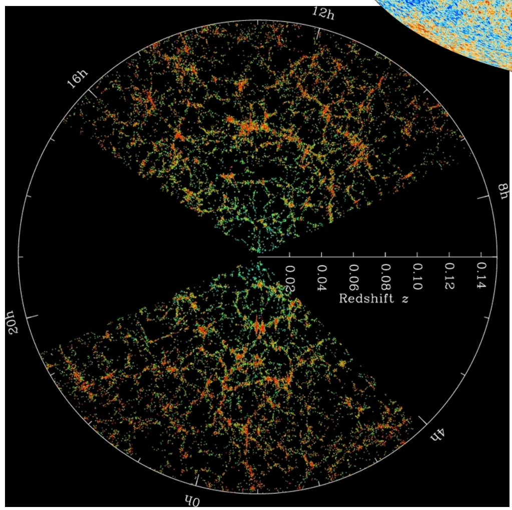
- atomic/molecular final states
- source
- background

Direct vs indirect measurements: cosmology

present upper limits on m_{light} from cosmological observations







Observable $m_\Sigma = \sum_i m_i$

from CMB, BAO, LSS, SN-Ia...

Assumes **ΛCDM**

Degeneracy with other observables

(h, A_s, sterile ν, ...)

N. Aghanim et al., A&A, 641 (2020)

E. Di Valentino et al., Phys. Rev. D, 104 (2021) 083504

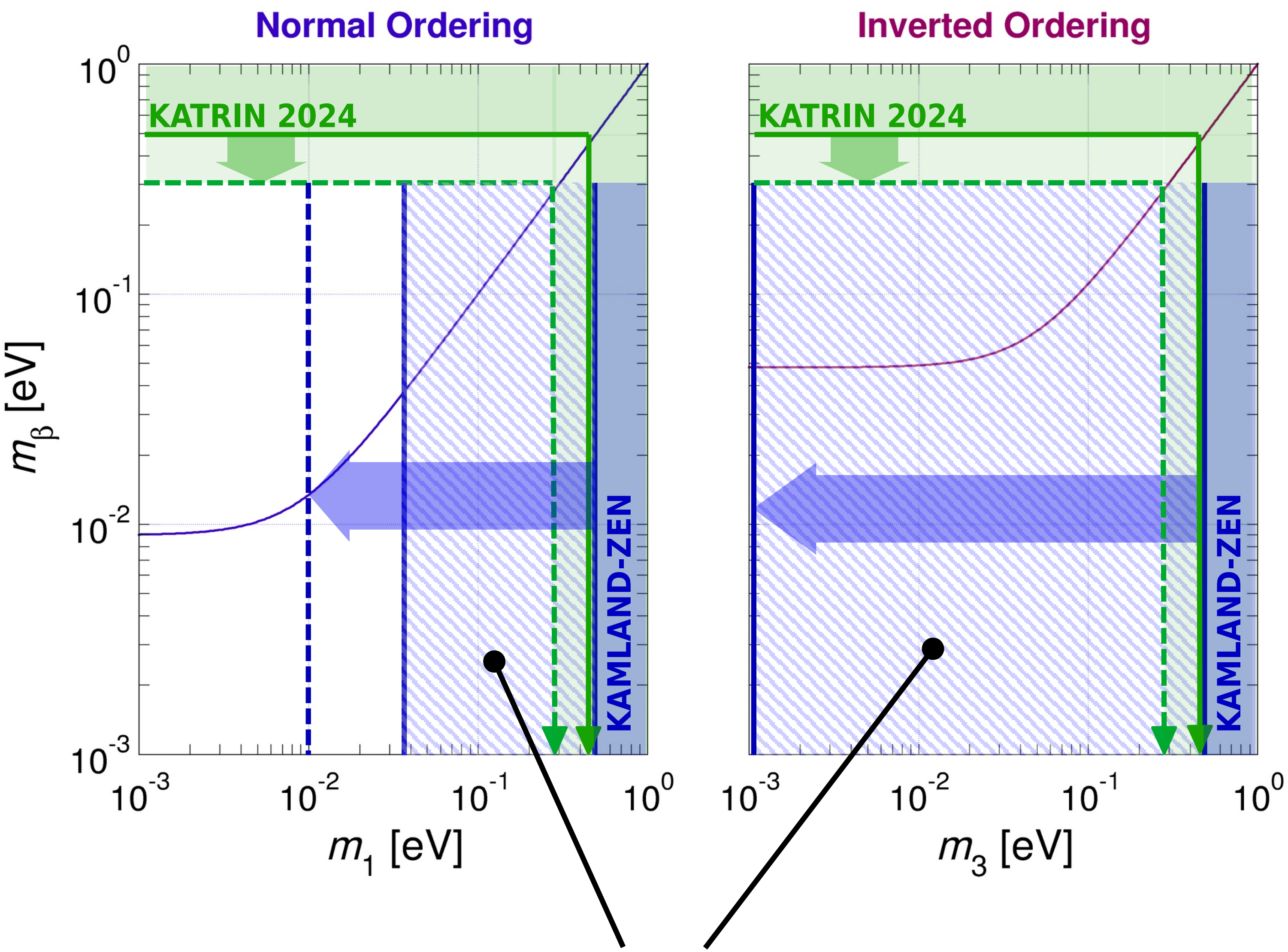
D. Wang et al., arXiv:2405.03368 (!)

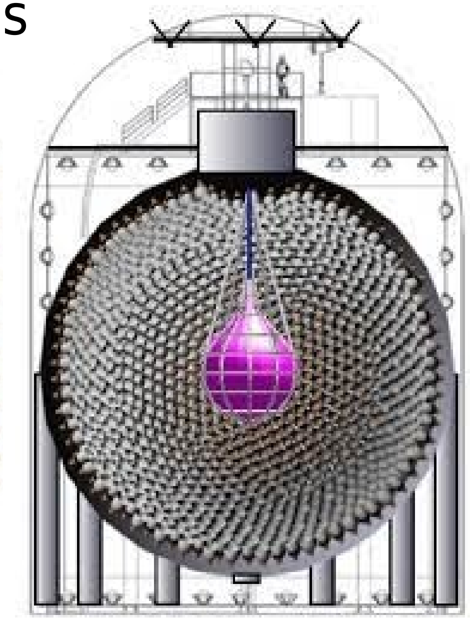
direct measurements can

- help confirming **ΛCDM** assumption
- provide m_{light} as input for model analysis

Direct vs indirect measurements: neutrinoless ββ decay

present upper limits on $\boldsymbol{m_{light}}$ from neutrinoless double beta decay searches





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

$\boldsymbol{m_{\beta\beta}} \leftrightarrow \boldsymbol{\tau_{1/2}}$ of $\beta\beta0\nu$ of ^{136}Xe, ^{76}Ge, ^{130}Te...

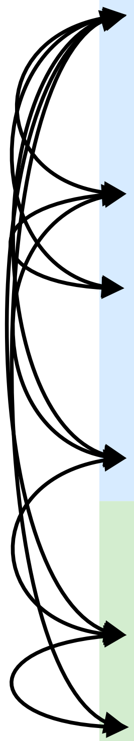
Requires **Majorana neutrinos**

Uncertainty on $\boldsymbol{m_{light}}$ due to

- Majorana phases φ_1 and φ_2 in U_{ei}
- nuclear matrix elements F_N
- axial coupling g_A

KamLAND-Zen Collaboration et al., Phys. Rev. Lett., 130 (2023) 051801

Direct measurements: alternatives for the future



Tritium

KATRIN follow up

- KATRIN++

Cyclotron Radiation Emission Spectroscopy

- Project 8
- QTNM

Hybrid spectroscopic techniques

- PTOLEMY

^{163}Ho

Low Temperature Calorimetry

- HOLMES
- ECHo
  - → a future ^{163}Ho based experiment

collaborative community
complementary approaches
many synergies
→ solid programs
→ robust results

Workshop NuMass 2024

D. Castelvecchi, "How heavy is a neutrino? Race to weigh mysterious particle heats up," Nature, Mar. 2024

KATRIN++

2019-2025 (PoF-IV) — **Phase 1 (integral) neutrino mass**

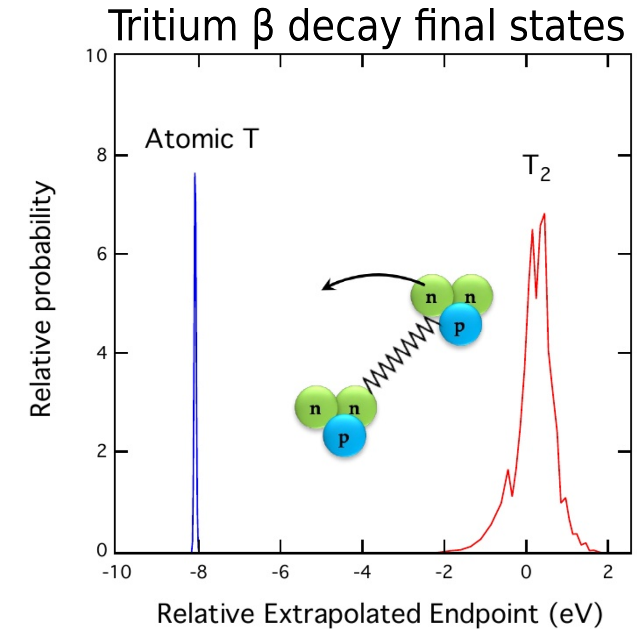
2026-2027 (PoF-IV) — Phase 2 (differential) keV-sterile

- Differential detection R&D
- Atomic tritium R&D

2028-2034 (PoF-V) — **R&D phase for KATRIN++**

- Differential detection demonstrators
- Atomic tritium demonstrator

Scientific goal — Neutrino mass



R&D program for a sensitivity on ***m*$_\beta$ < 40 meV**

- the Tritium Laboratory Karlsruhe **TLK** can handle **50 g of Tritium**
- KATRIN's **MAC-E filter** and **WTGS** as platforms for R&Ds
- call to community for a collaborative effort at TLK

R&D objectives (until 2027)

differential spectrometry to improve statistical sensitivity

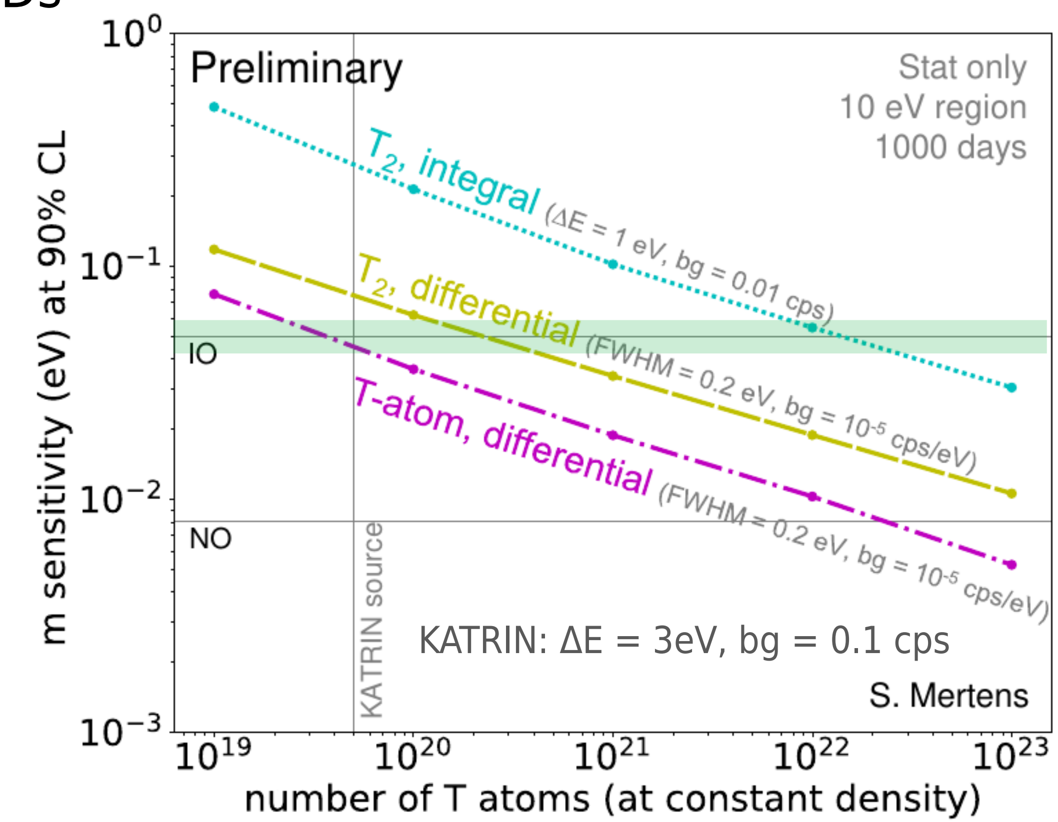
→ higher measuring efficiency

→ lower background

atomic T source to reduce broadening and systematics

→ only atomic excited state broadening

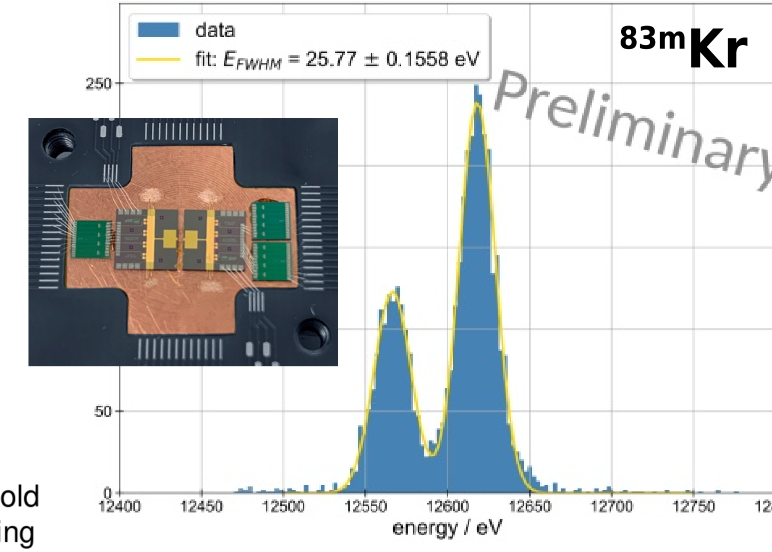
KATRIN++ demonstrators from 2028

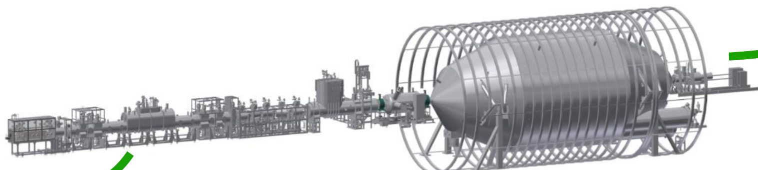


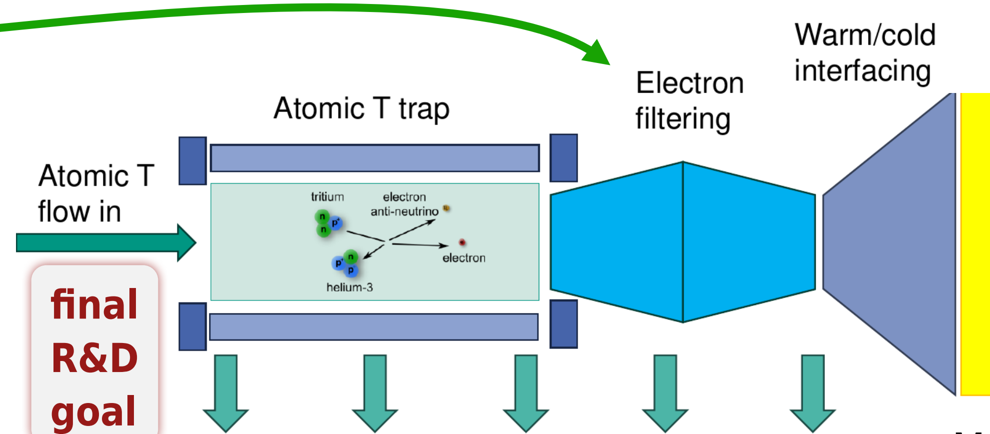
KATRIN++

two R&D lines for **differential spectrometry** with $\Delta E_{FWHM} \approx 0.2$ eV

- high-resolution low temperature detectors arrays (≈10^6 pixels)
- time-of-flight: single electron tagging (start/stop) is challenging
- other options from community?

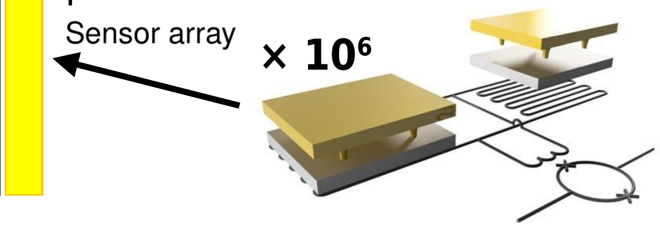






credits: M.Schloesser

hi-res differential spectroscopy of βs above threshold



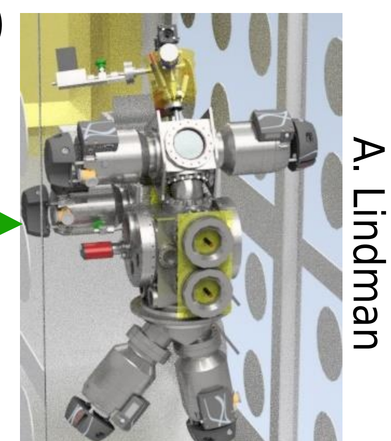
Magnetic Metallic Calorimeters (MMC)

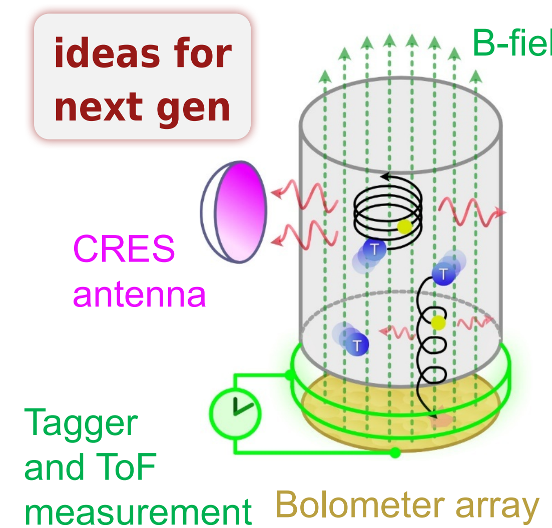
cold **atomic T** source → KAMATE (TLK/U. Mainz)

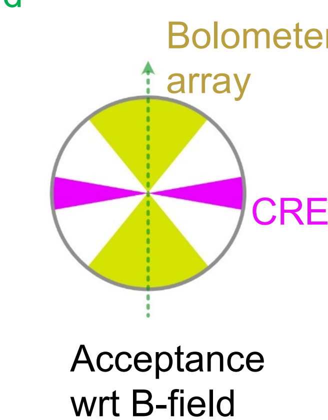
R&Ds to replace WTGS

- atomic T cooling&trapping
- atomic T absorbed on graphene

→ potential for synergies and/or collaborations with Project8 and PTOLEMY





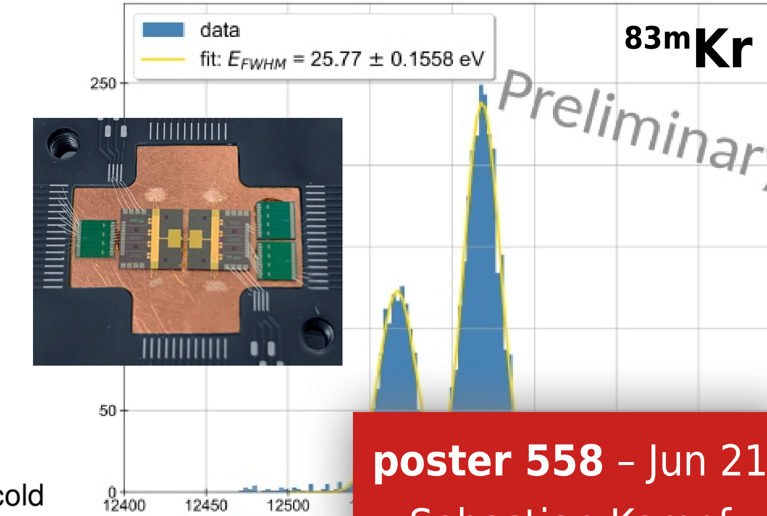


credits: M.Schloesser

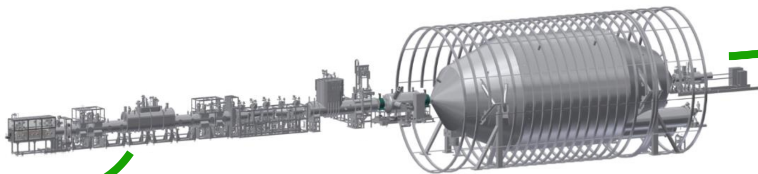
KATRIN++

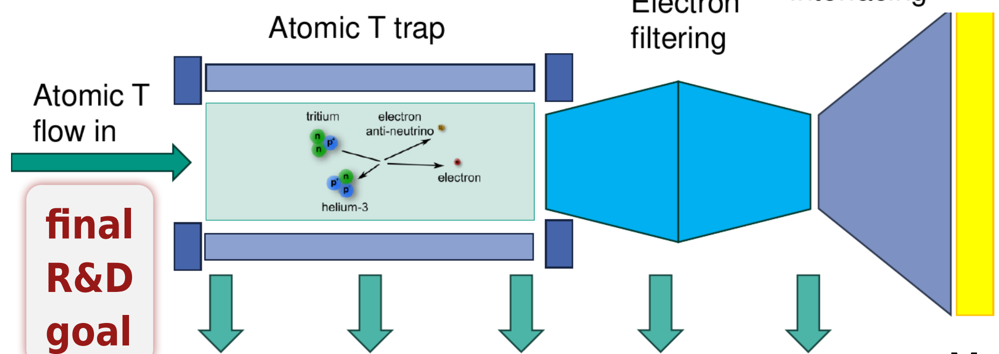
two R&D lines for **differential spectrometry** with $\Delta E_{FWHM} \approx 0.2$ eV

- high-resolution low temperature detectors arrays ($\approx 10^6$ pixels)
- time-of-flight: single electron tagging (start/stop) is challenging
- other options from community?



poster 558 – Jun 21
Sebastian Kempf

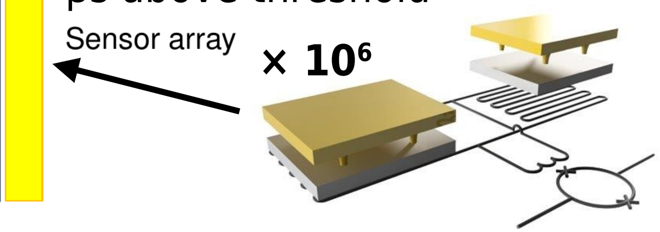




final R&D goal

credits: M.Schloesser

hi-res differential spectroscopy of βs above threshold



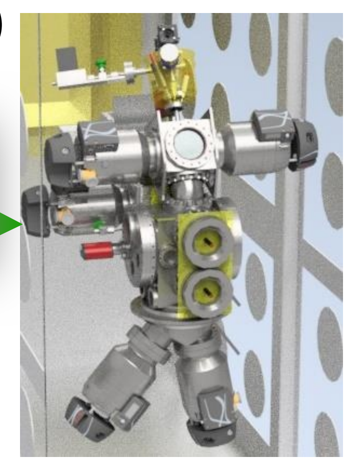
Magnetic Metallic Calorimeters (MMC)

cold **atomic T** source → KAMATE (TLK/U. Mainz)

R&Ds to replace WTGS

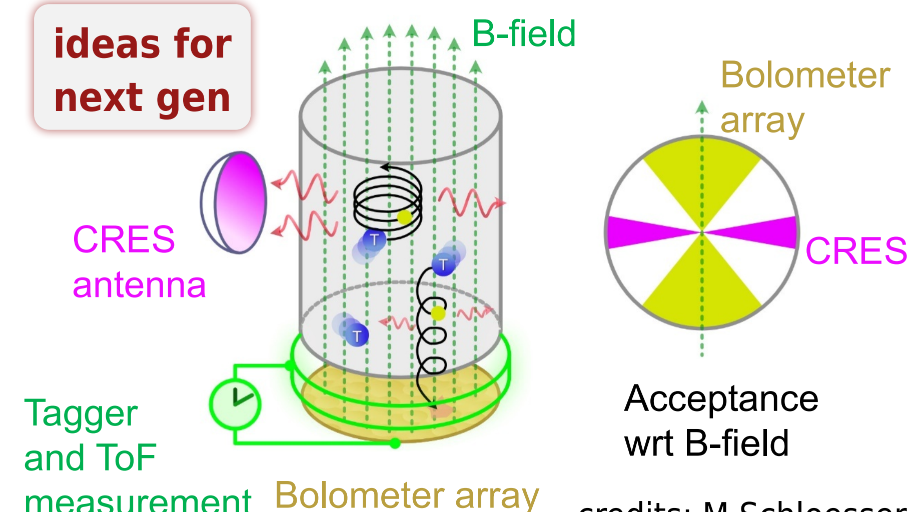
- atomic T cooling&trapp[ing]
- atomic T absorbed on g[raphene]

poster 548 – Jun 21
C Rodenbeck, L Thorne



→ potential for synergies and/or collaborations with Project8 and PTOLEMY

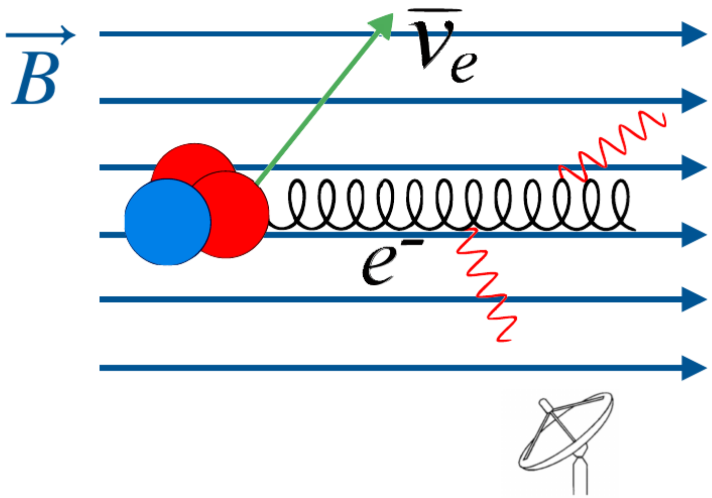
ideas for next gen



credits: M.Schloesser

CRES: Project8 and others

Cyclotron **R**adiation **E**mission **S**pectroscopy



B. Monreal and J. A. Formaggio, Phys. Rev. D 80, 051301 (2009)

cyclotron emission frequency

$$2\pi f(E_\beta) = \frac{eB}{E_\beta + m_e} = \frac{eB}{\gamma m_e}$$

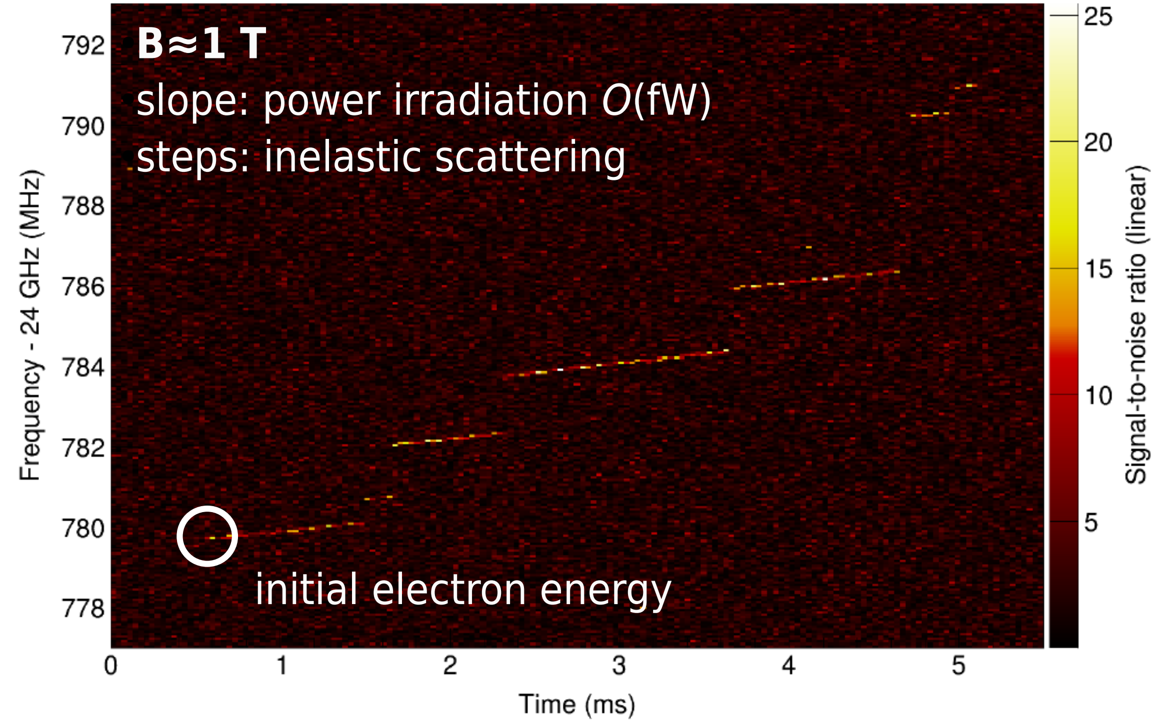
energy resolution $$\frac{\Delta E}{m_e} = \frac{\Delta f}{f}$$

PROJECT 8

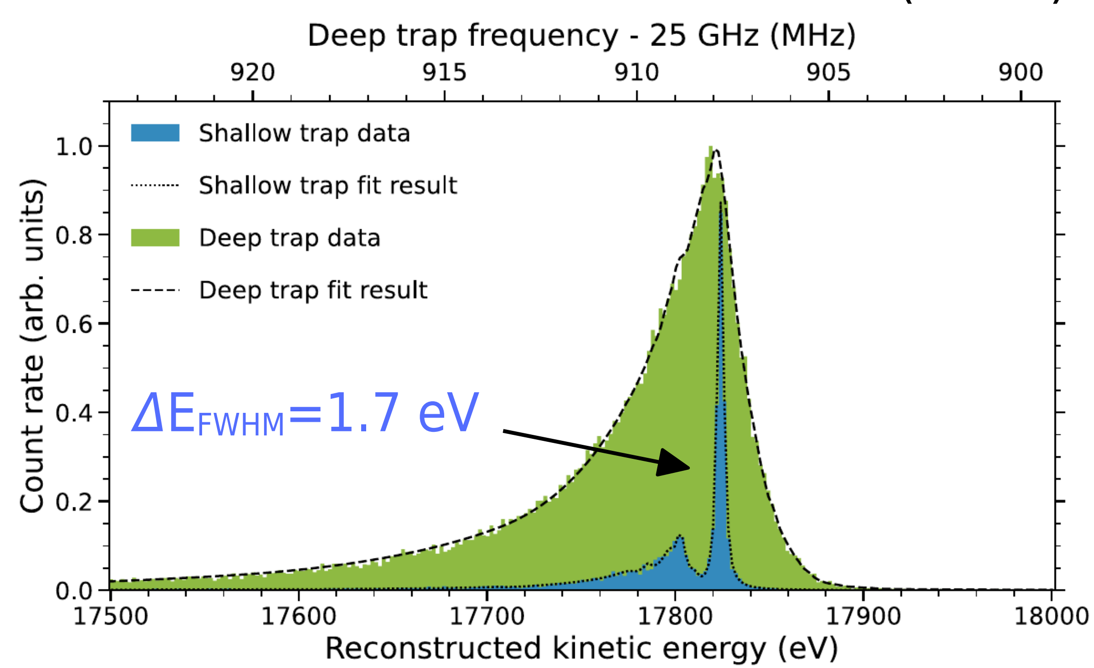
CRES technique demonstrated by **Project8**

for electrons magnetically trapped inside a wave guide

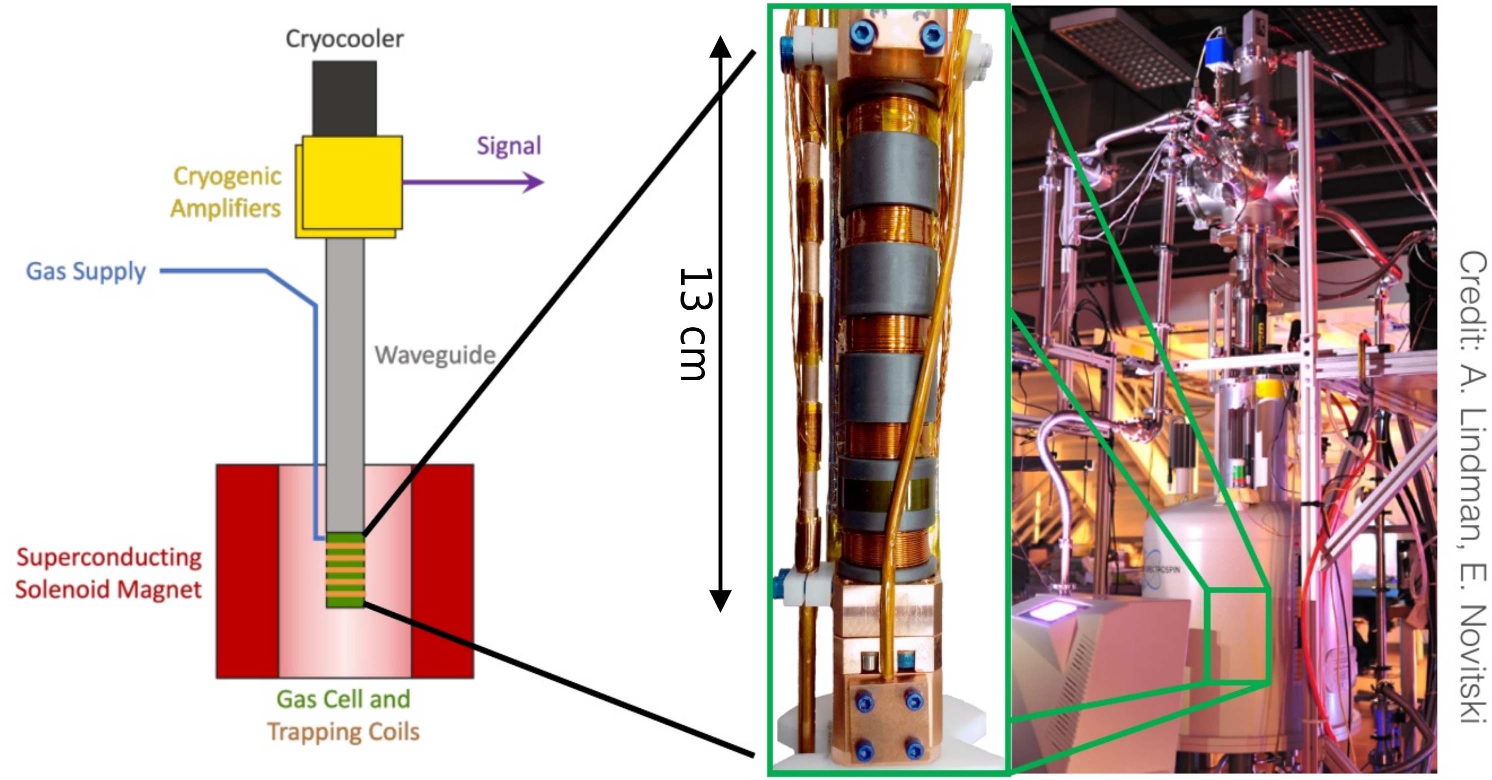
best energy resolution ΔE_{FWHM}= 1.7 eV at 18 keV

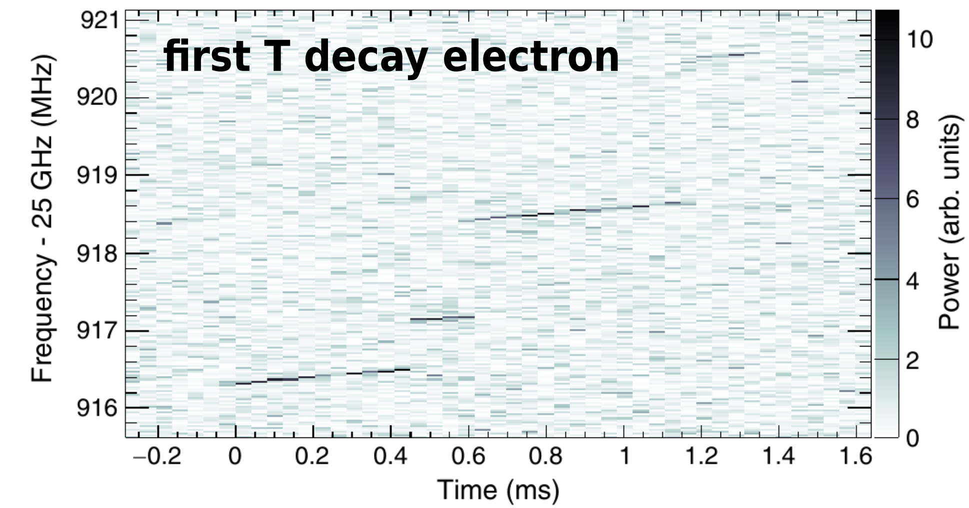


^{83m}Kr internal conversion electron (K line)

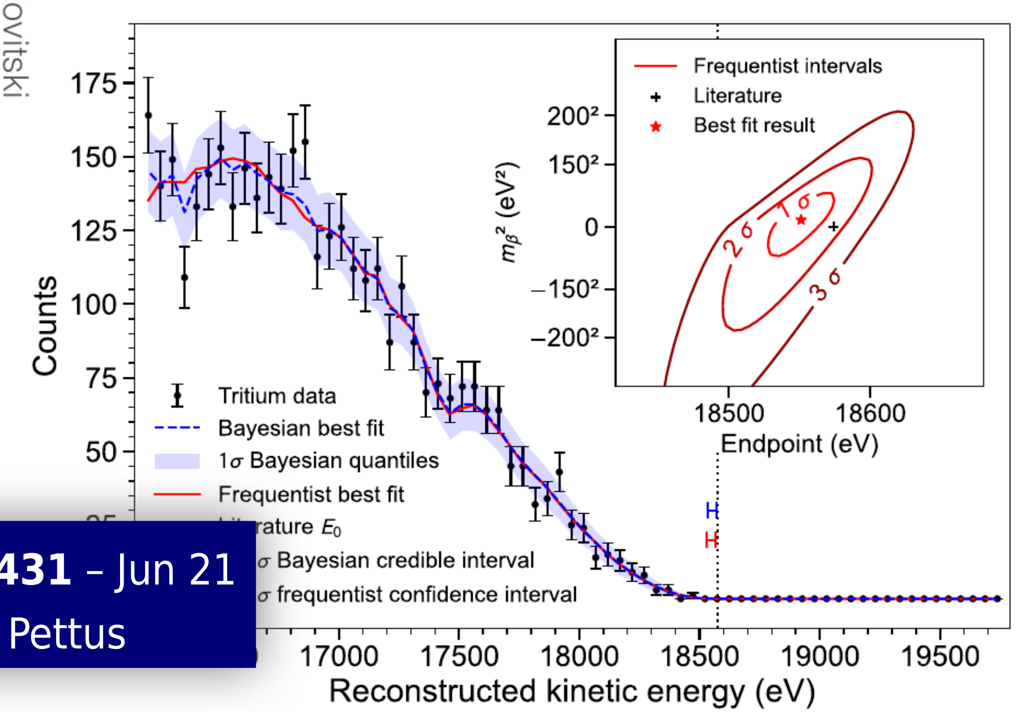


Project8: phase II results





A. Ashtari Esfahani et al. Phys. Rev. C 109, 035503



4 different experimental phases since 2009

long term sensitivity goal: 40 meV 90% CL (phase IV)

phase II with T_2 adsorbed in getter

- demonstrated T decay spectroscopy with **0 background**
- ΔE_{FWHM}=54 eV (deep trap configuration)
- 3770 T decays within wave guide in 82 days
- → $\boldsymbol{m_\nu}$ **< 152 eV** 90% CL *Project 8 Collaboration, PRL 131 (2023) 102502*

poster 431 – Jun 21
W. Pettus

Project8: phase III and IV

Phase III (in progress now)

CRES with T_2 or magnetogravitationally trapped T atoms

goal m_ν < 0.2 eV (with T_2)

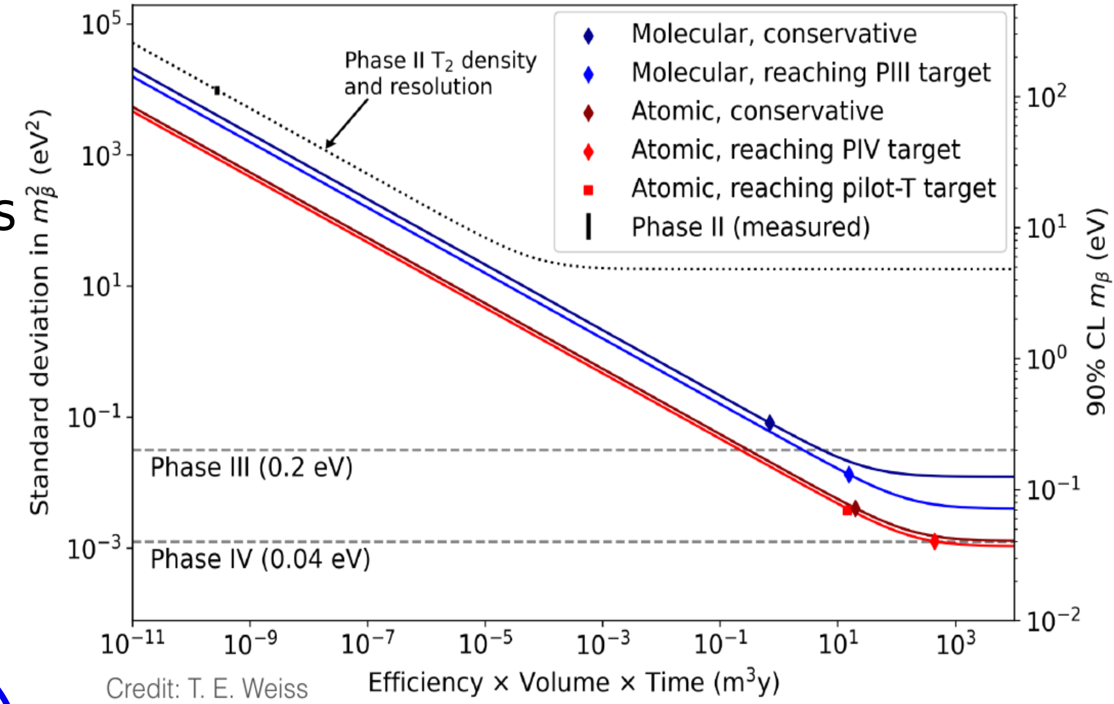
R&D on atomic Tritium source well advanced

R&D on cavity RF readout (f_c <1GHz for T trapping)

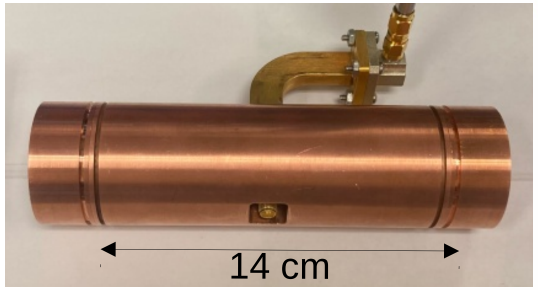
Phase IV

scaling up phase III trap

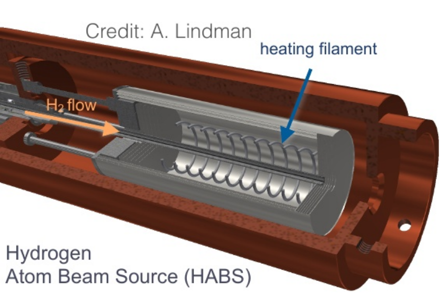
goal m_ν < 0.04 eV

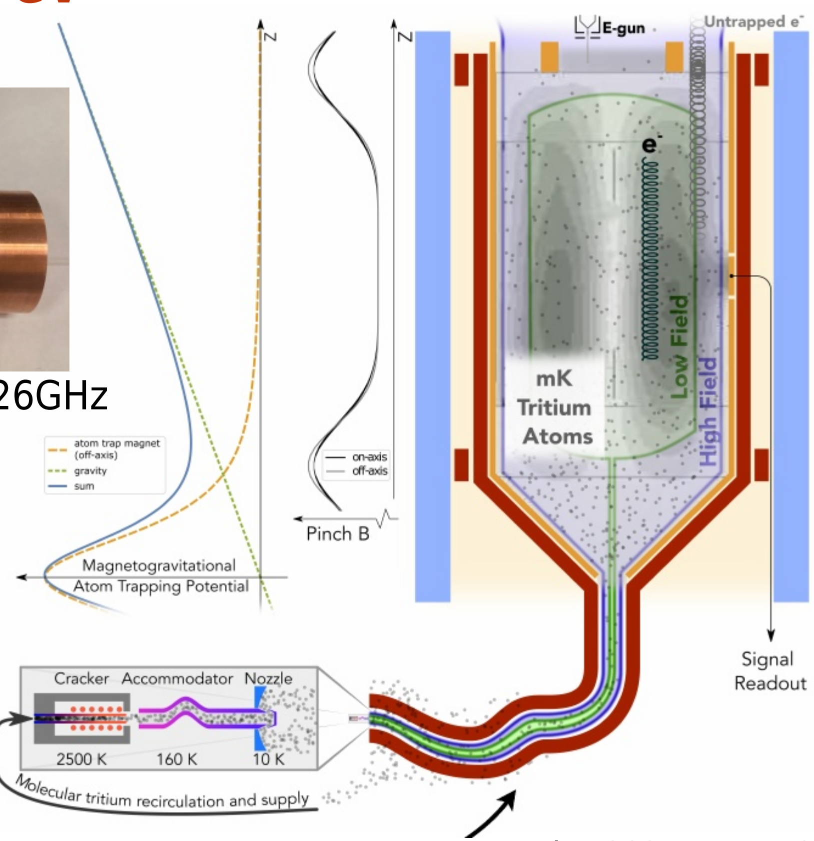


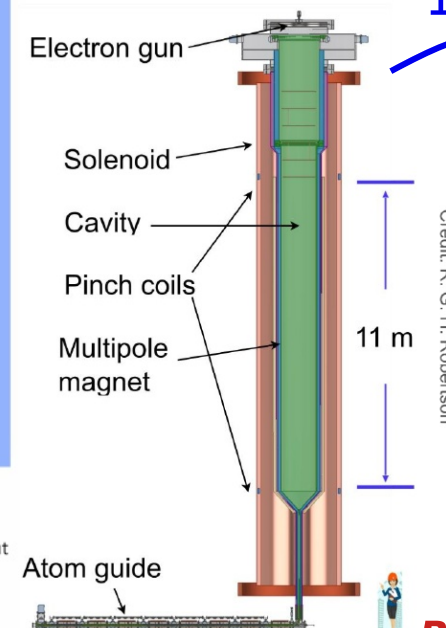
conceptual design



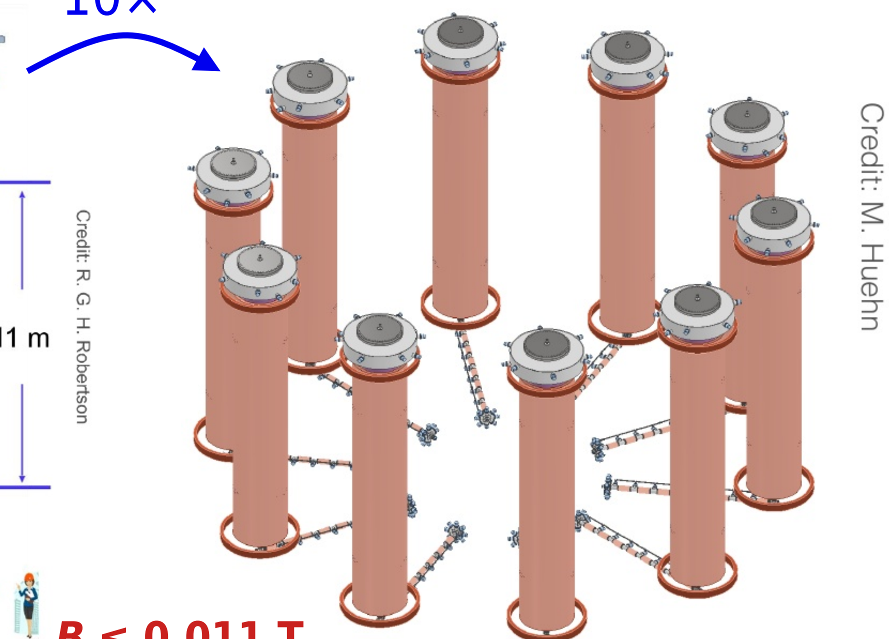
CRES cavity prototype at 26GHz







10×



$B \lesssim$ 0.011 T
$f_c \lesssim$ 325 MHz

Project8: phase III and IV

Phase III (in progress now)

CRES with T_2 or magnetogravitationally trapped T atoms

goal m_ν < 0.2 eV (with T_2)

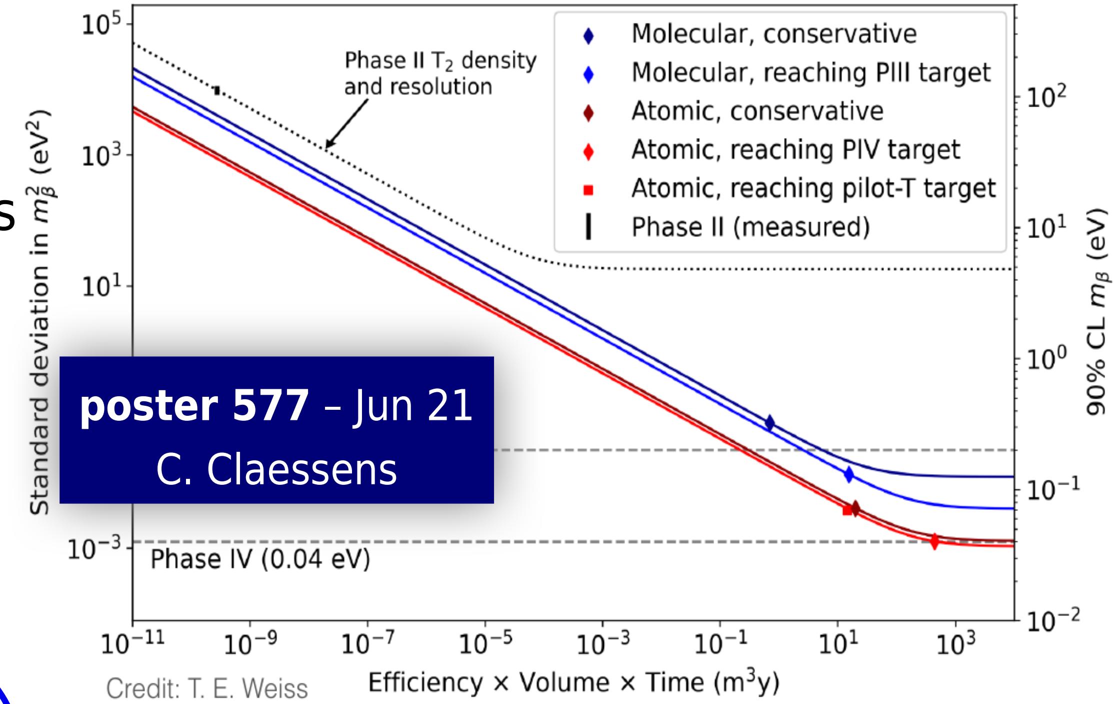
R&D on atomic Tritium source well advanced

R&D on cavity RF readout (f_c <1GHz for T trapping)

Phase IV

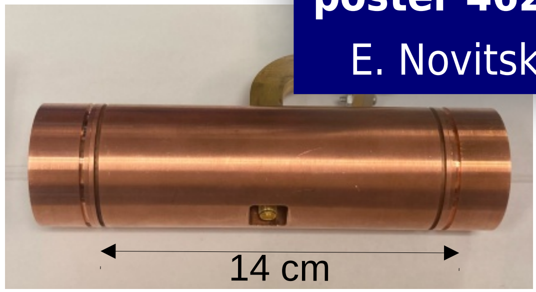
scaling up phase III trap

goal m_ν < 0.04 eV



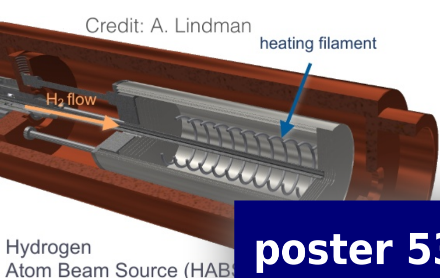
poster 577 – Jun 21
C. Claessens

conceptual design

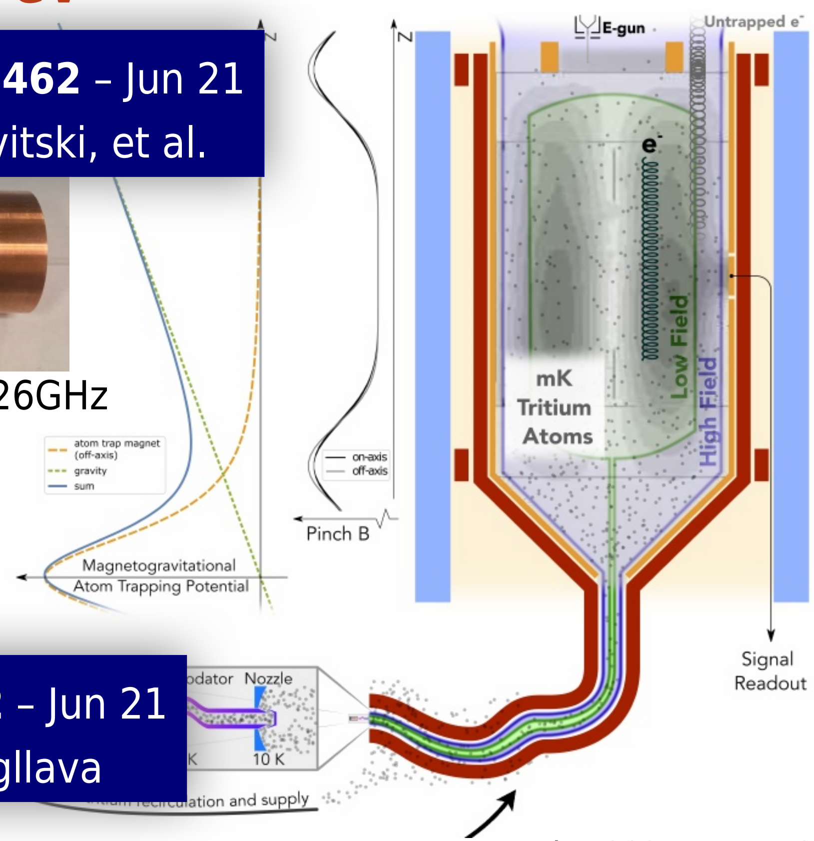


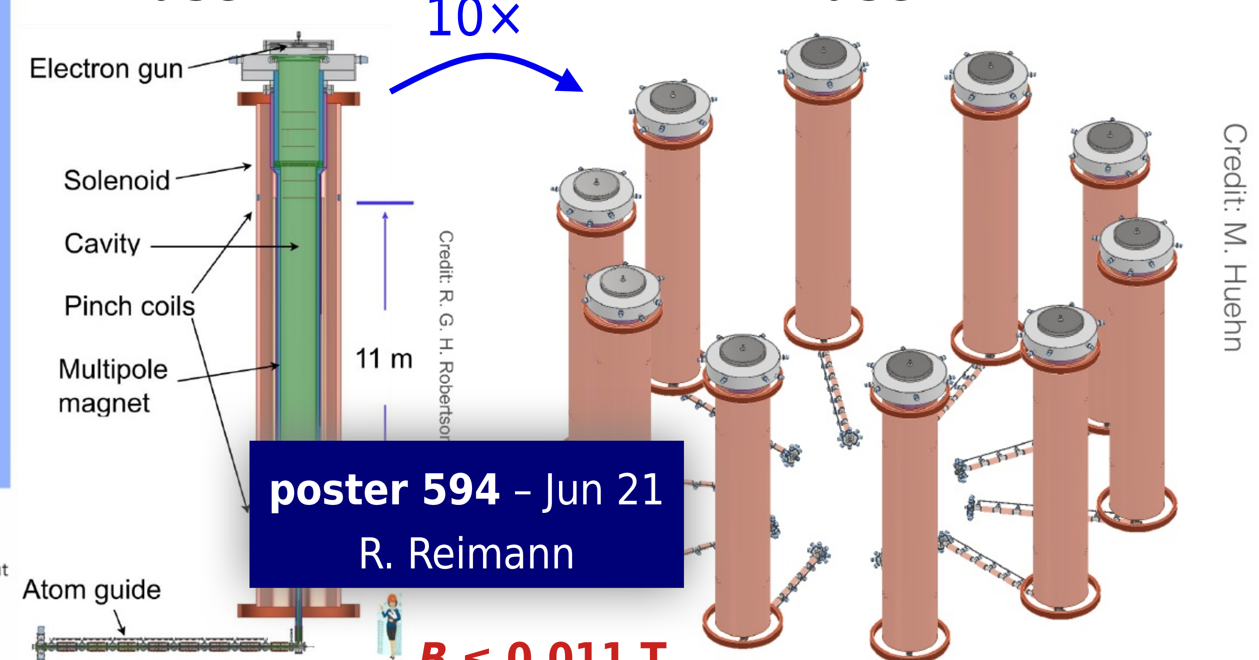
CRES cavity prototype at 26GHz

poster 462 – Jun 21
E. Novitski, et al.



poster 532 – Jun 21
B. Muçogllava





poster 594 – Jun 21
R. Reimann

***B* ≲ 0.011 T**
f_c ≲ 325 MHz

QTNM - Quantum Technologies for Neutrino Mass

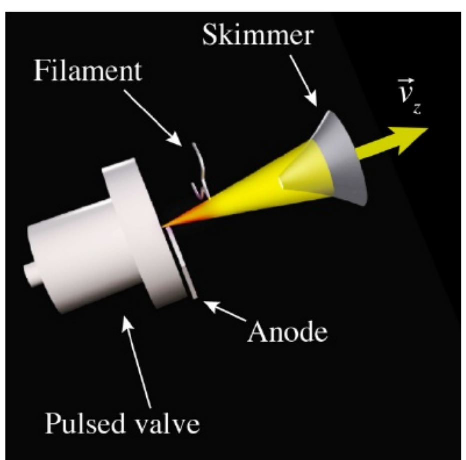
CRESDA demonstrator apparatus for determining neutrino mass via CRES from tritium

first phase (to 2025)

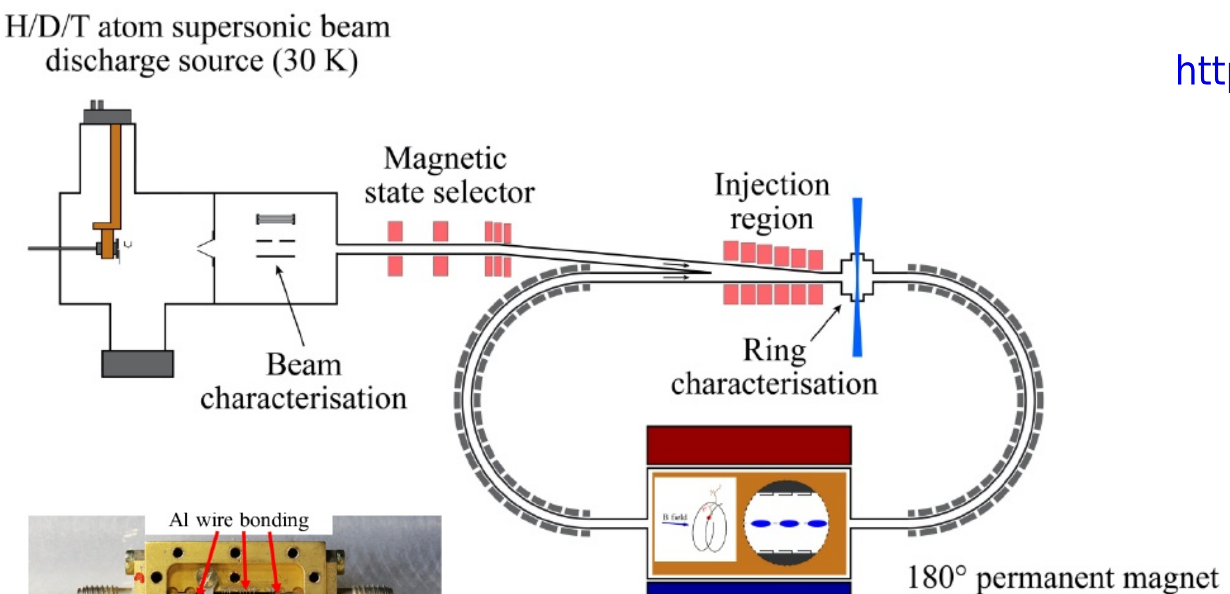
- quantum-noise-limited microwave sensors for a high resolution, high efficiency CRES
- magnetic field mapping with < 1 μT absolute precision and
  ≈1 mm spatial resolution using Rydberg states as quantum sensors
- demonstration of production and confinement of H/D atoms with densities of $O(10^{12}\ \text{cm}^{-3})$

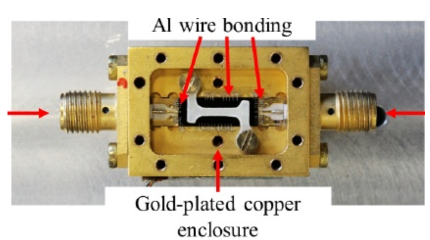
Tritium demonstrations at Culham (beyond 2025)

Final neutrino mass experiment with 0.01~0.05 eV m_ν sensitivity (2030–2040)

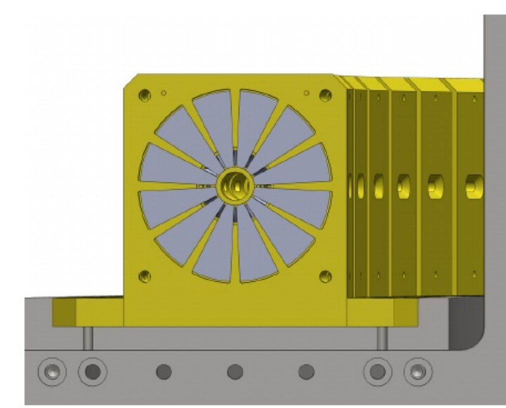


Hogan, Habilitation Thesis ETH Zurich (2012)





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



PTOLEMY

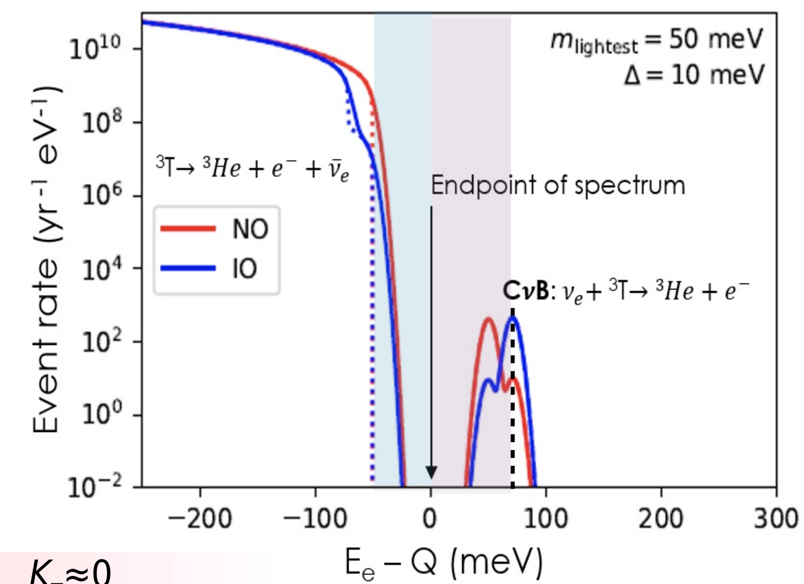
project to detect the **Cosmic Neutrino Background** via neutrino capture on tritium

differential spectrometer combining:

- CRES to determine electron energy and pitch angle
- transverse drift filter to select and decelerate end-point electrons
- low temperature microcalorimeters for hi-res spectroscopy

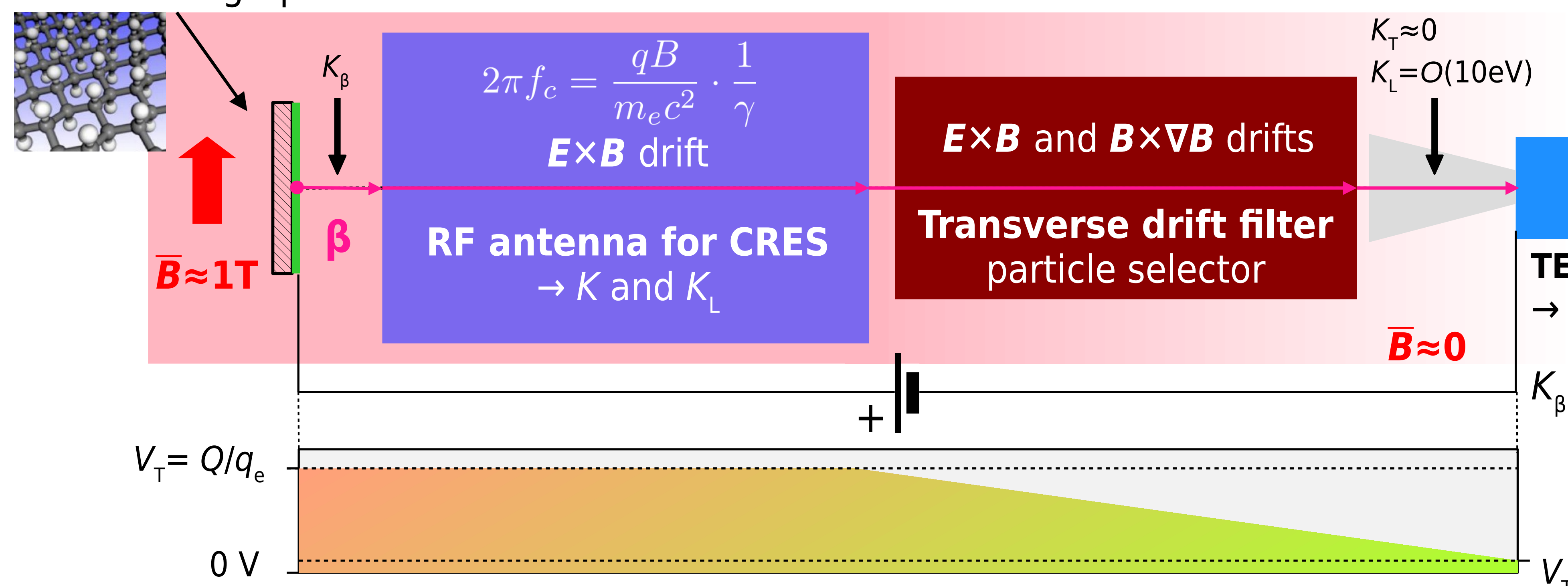
capture target is also a T source → direct $\boldsymbol{m_\nu}$ measurement

→ *O*(100 mV) sensitivities could be achievable with 1 μg T



M. G. Betti et al., Journal of Cosmology and Astroparticle Physics, 2019 (2019)

atomic T on graphene



TES μcalorimeters

→ $\boldsymbol{E}_{\mathbf{cal}}=K_T+K_L$

$K_\beta=q_e(V_{TES}-V_T)+\Delta E_{RF}+\boldsymbol{E}_{\mathbf{cal}}$

V_{TES} = O(10eV)/q_e

M. G. Betti et al., Progress in Particle and Nuclear Physics, 106 (2019) 120

PTOLEMY

Full scale demonstrator with superconducting magnets

- magnet, drift filter and interfaces design
- end-to-end electron transport simulation
- to be installed at LNGS in 2025

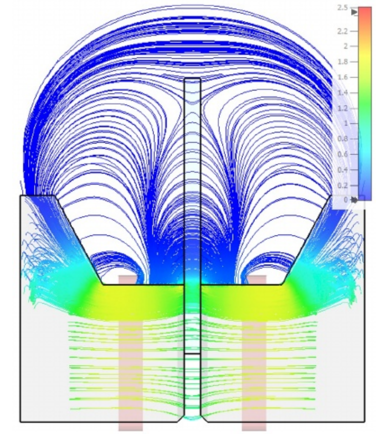
R&D in progress on

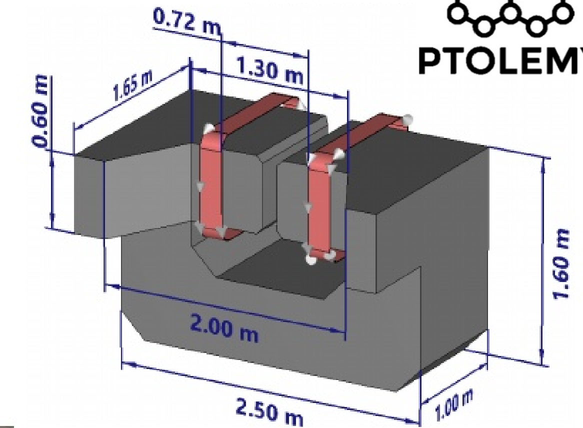
- T loading on graphene
- CRES detection
- TES microcalorimeters for high res electron spectroscopy

poster 374 – Jun 18
J. V. Mead

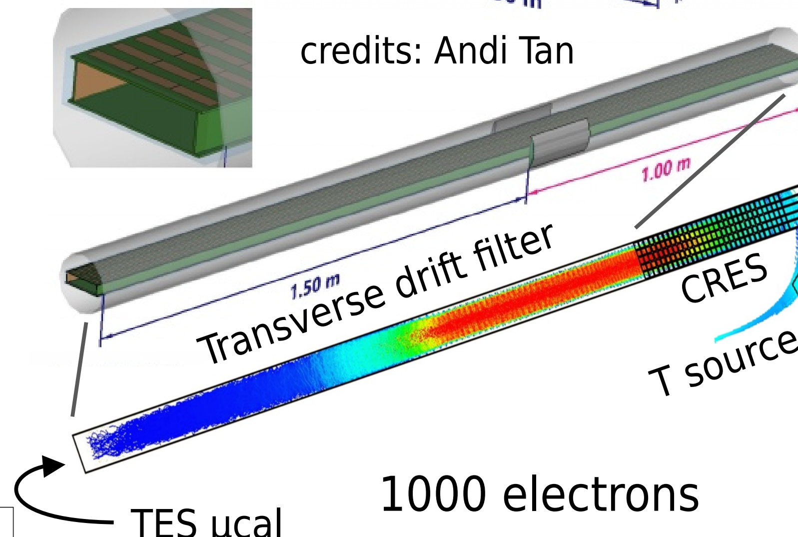
neutrino mass sensitivity studies

- theoretical study of β decay spectral shape for T on graphene
- investigation of alternatives to graphene

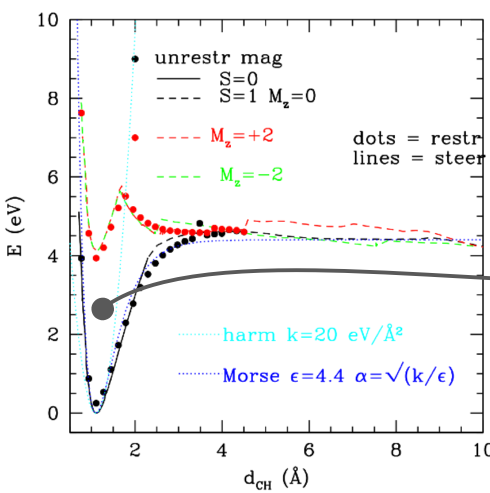


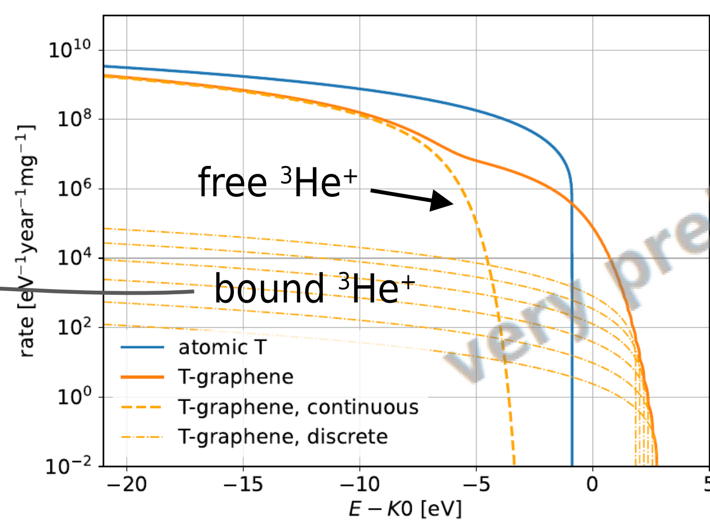


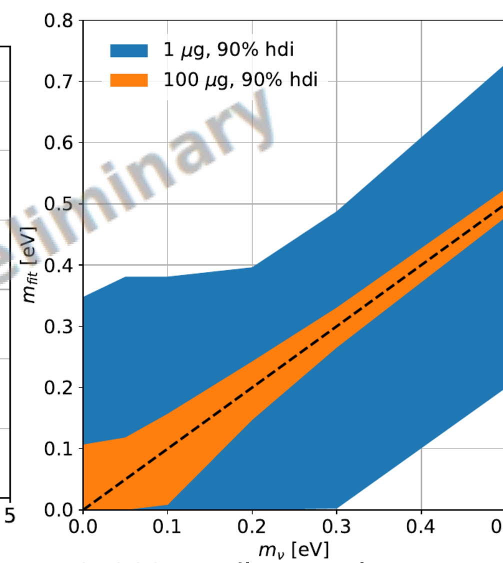
credits: Andi Tan



1000 electrons
18.6 keV
pitch 15° - 45°







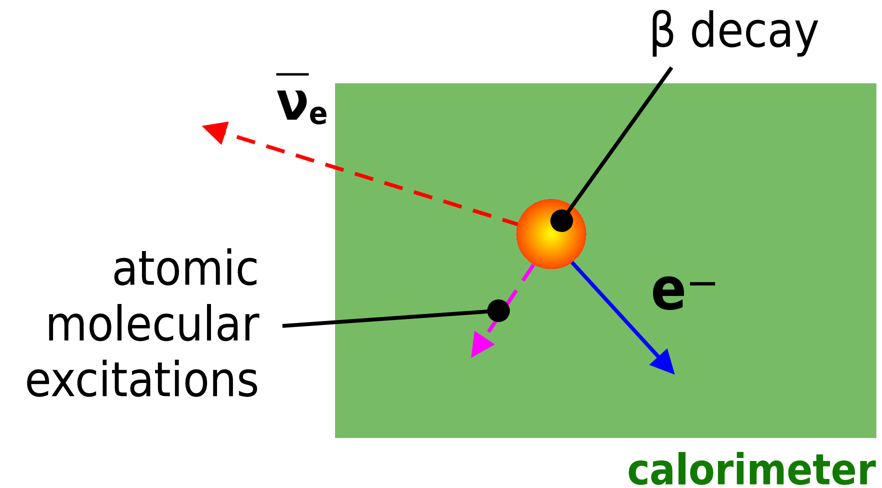
A. Apponi et al., J. Inst., 17 (2022)
A. Apponi et al., Phys. Rev. D, 106 (2022)

Calorimetric experiments

ideal calorimetric experiment

- radioactive source embedded in the detector(s)
- only the neutrino energy escapes detection

→ $E_c = Q - E_\nu$



- ▲ no backscattering
- ▲ no energy losses in source
- ▲ no decay final state effects
- ▲ no solid state excitation
- ▼ low activity → limited statistics
- ▼ pile-up background

ideal isotope has

- low *Q*
  - → larger fraction *f* of decays in ROI
  - → easier calorimetry
- for EC: capture peak close to *Q*
- short $\tau_{½}$

isotope	*Q* [eV]	$\tau_{½}$ [y]	decay	B.R.	experiments
^{3}H	18592.01(7)	12	β⁻	1	Simpsons's
^{187}Re	2470.9(13)	4.3×10^{10}	β⁻	1	MANU, MIBETA
^{163}Ho	2863.2(6)	4570	EC	1	Holmes, ECHo
^{135}Cs	440	8.0×10^{11}	β⁻	1.6×10^{-6}	-
^{115}In	155	4.3×10^{20}	β⁻	1.1×10^{-6}	-

A. Nucciotti, Adv. High Energy Phys., 2016 (2016) 9153024

for an udated analysis of low *Q* candidates *D. K. Keblbeck et al., Phys. Rev. C, 107 (2023) 015504*

Electron capture calorimetric experiments

$^{163}Ho \rightarrow {}^{163}Dy[H_i] + \nu_e$

$^{163}Dy[H_i] \rightarrow {}^{163}Dy + E_c$

- calorimetric measurement of Dy atomic de-excitations (E_c)
- Q = 2863.2±0.6 eV *Ch. Schweiger et al. Nat. Phys. (2024)*
  - end-point rate and **m_ν sensitivity depend on $Q-E_b$(M1)**
- $\tau_{1/2} \approx$ 4570 years → 2×10^{11} ^{163}Ho nuclei ↔ 1 Bq

shell binding energy:

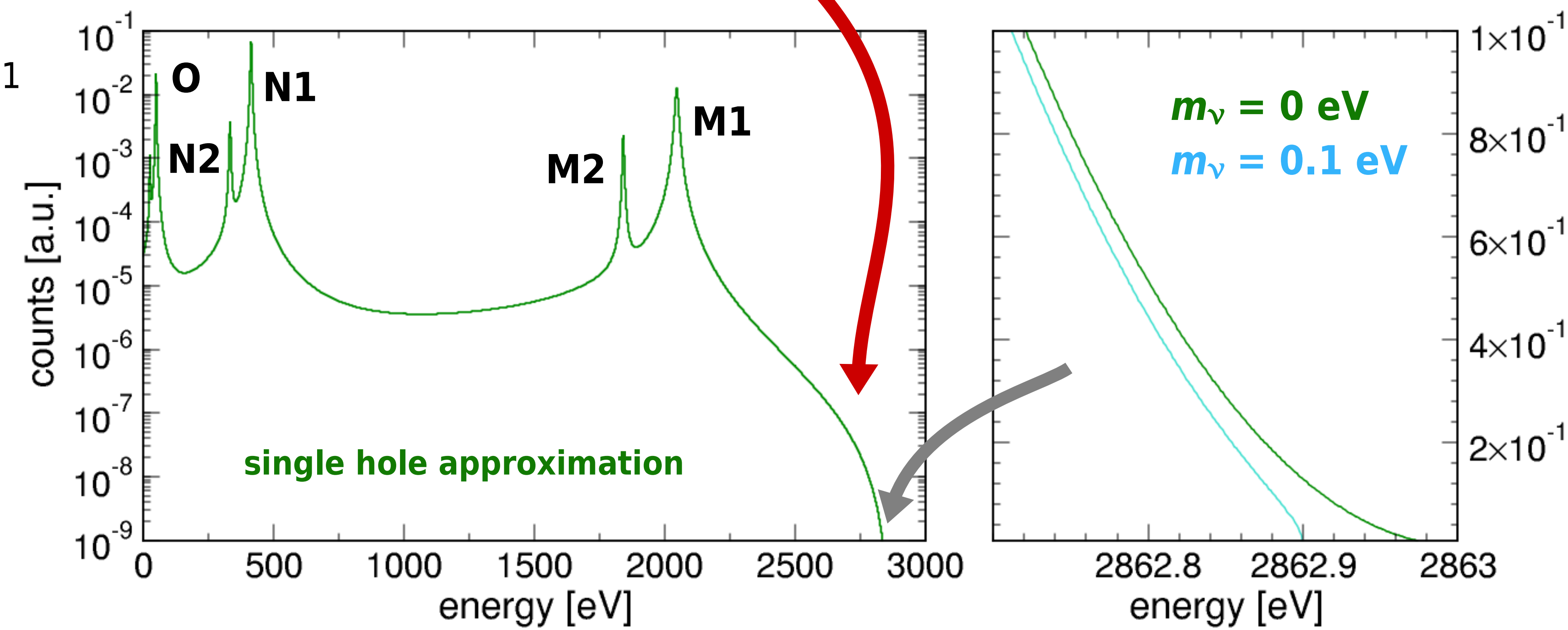
E_b(M1)=2.05 keV

$\Gamma_{M1}\approx$13 eV

→ EC from shell ⩾M1

→ H_i=M1, M2, N1, N2, O1, O2, P1

$$N(E_c) = \frac{G_\beta^2}{4\pi^2}(Q-E_c)\sqrt{(Q-E_c)^2 - m_\nu^2} \times \sum_i n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi} \frac{1}{(E_c - E_b(H_i))^2 + \Gamma_{H_i}^2/4}$$

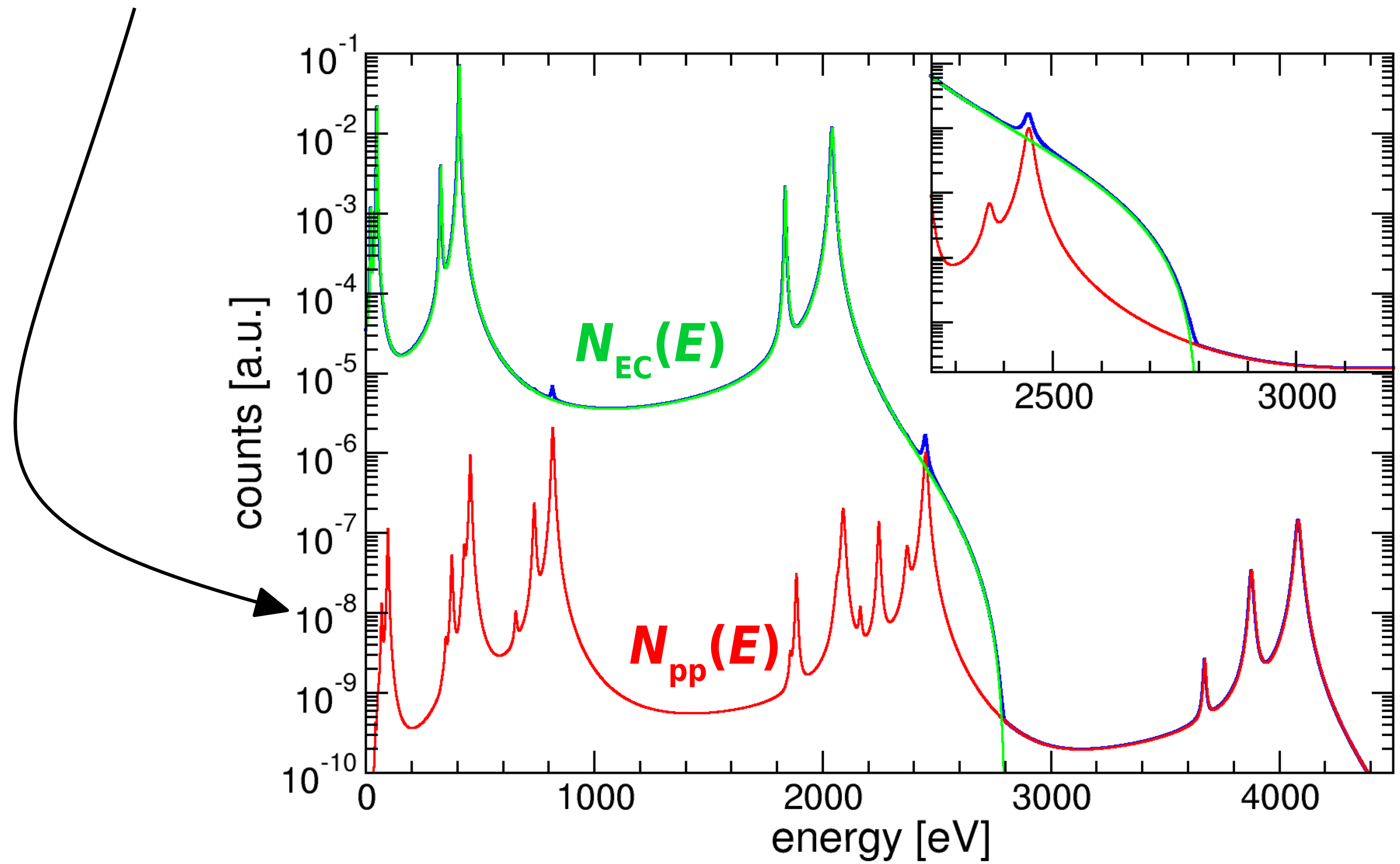


A. De Rújula and M. Lusignoli, Phys. Lett. B 118 (1982) 429

Pile-up in ^{163}Ho EC calorimetric experiments

- accidental coincidences → complex pile-up spectrum
- calorimetric measurement → **detector speed is critical**
  - $N_{pp}(E) = f_{pp}\, N_{EC}(E) \otimes N_{EC}(E)$ with $f_{pp} \approx A_{EC}\, \tau_R$

A_{EC} EC activity per detector
τ_R time resolution (≈rise time)

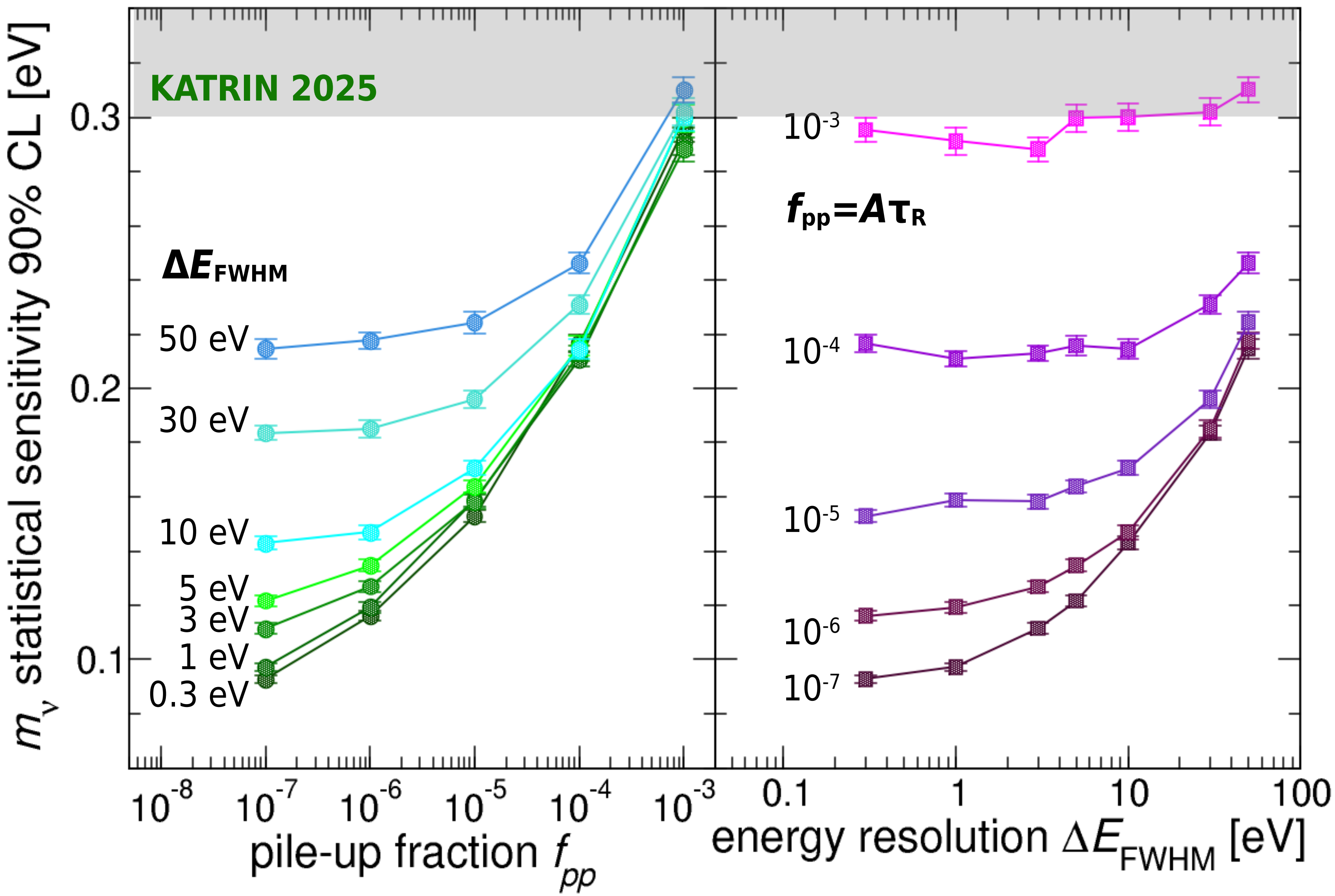


Q = 2.8 keV

$f_{pp} = 10^{-4}$

Statistical sensitivity: pile-up and energy resolution

- Montecarlo simulations for statistical sensitivity with **single-hole spectrum**
- simulations confirm that sensitivity **$\Sigma(m_\nu)$ scales as $1/(N_{ev})^{1/4}$**



$N_{ev} = 5\times10^{16}$

$N_{ev} = A\, t_M\, N_{det}$

$\Sigma_{90}(m_\nu) \propto \sqrt[4]{1/N_{ev}}$

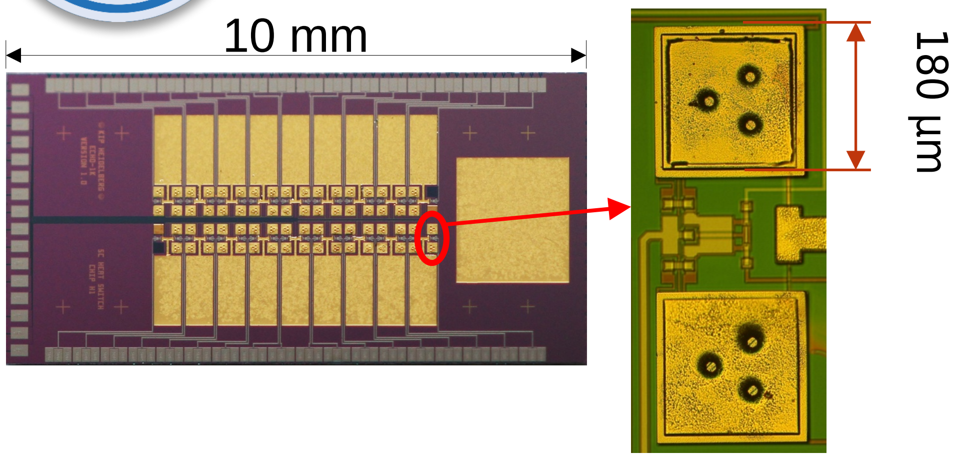
A. Nucciotti, Eur. Phys. J. C 74.11 (2014)

The ECHo and HOLMES experiments

low temperature **microcalorimeter arrays** with ion-implanted ^{163}Ho

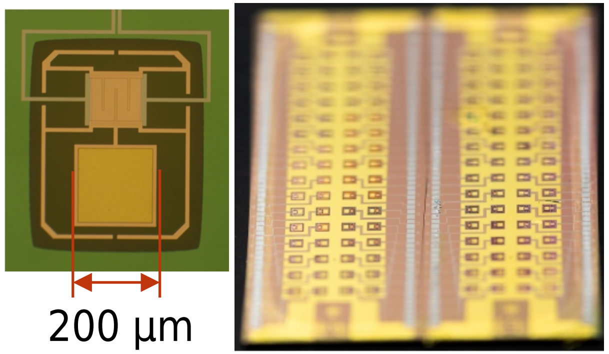
scalable proof-of-principles for an experiment with **≲0.1 eV m_ν sensitivity**

L. Gastaldo et al. Eur. Phys. J. Special Topics 226, 1623 (2017)



HOLMES

Transition Edges Sensors TESs
multiplexed TESs
1000 detectors
300 Bq(^{163}Ho)/pixel
$\Delta E_{FWHM} \approx 1$ eV
→ $\Sigma_{90\%}(m_\nu) < \approx 2$ eV



B. Alpert et al., Eur. Phys. J. C, (2015) 75:112

ECHo-1k

Magnetic Metallic Calorimeters MMCs
60~100 detectors
1~5 Bq(^{163}Ho)/det
$\Delta E_{FWHM} < 10$ eV
→ $\Sigma_{90\%}(m_\nu) < \approx 20$ eV

ECHo-100k

multiplexed MMCs
12000 detectors
10 Bq(^{163}Ho)/det
$\Delta E_{FWHM} < 5$ eV
→ $\Sigma_{90\%}(m_\nu) < \approx 1.5$ eV

both started R&D around **2010**
now running arrays with
≈60 detectors
≈1Bq/det of implanted ^{163}Ho

^{163}Ho isotope production

^{162}**Er (n,γ)** ^{163}**Er** $\sigma_{thermal} \approx 20$ b

^{163}**Er →** ^{163}**Ho +** ν_e $\tau_{1/2}^{EC} \approx 75$ min

^{162}Er irradiation at **ILL nuclear reactor** (Grenoble, France)

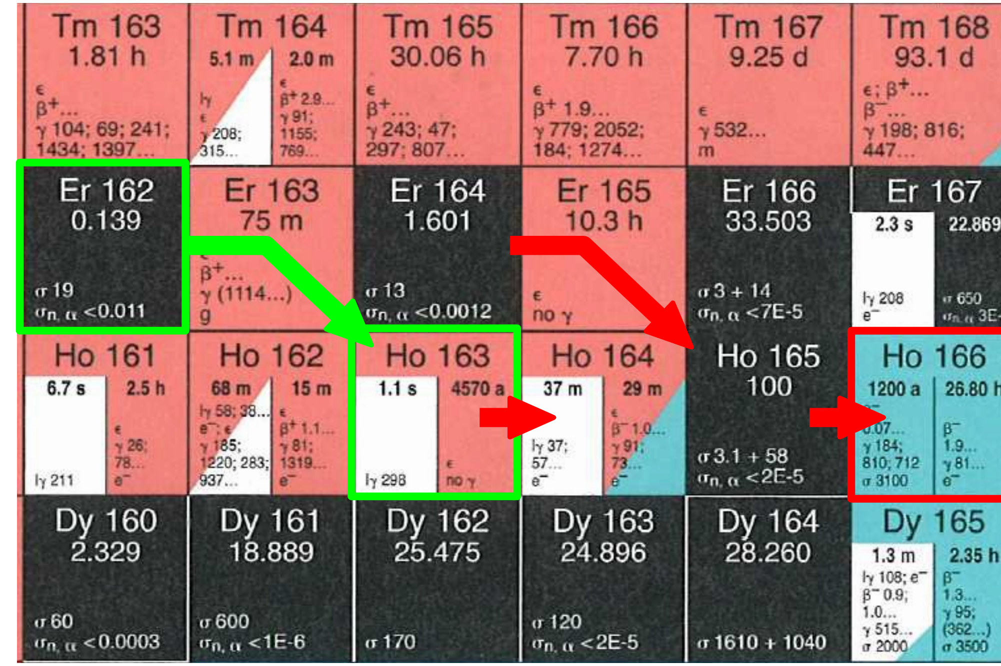
Ho chemical purification with ion-exchange resins in hot-cell

side production of ^{166m}**Ho**

- β⁻, Q=1.8 MeV, $\tau_{1/2}$=1200 y → background in ROI
- ≈2 kBq(^{166m}Ho)/MBq(^{163}Ho)

  → requires mass separation

HOLMES and **ECHo** has collected **≈250 MBq of** ^{163}**Ho**

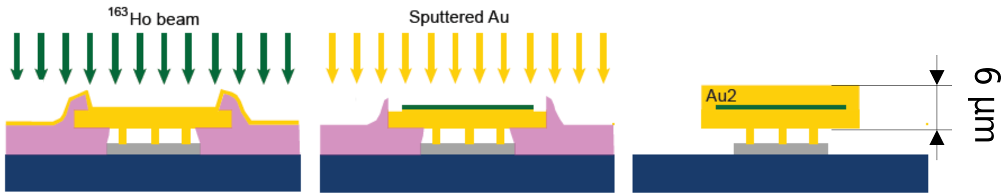


H. Dorrer et al., Radiochimica Acta, 106 (2018) 535

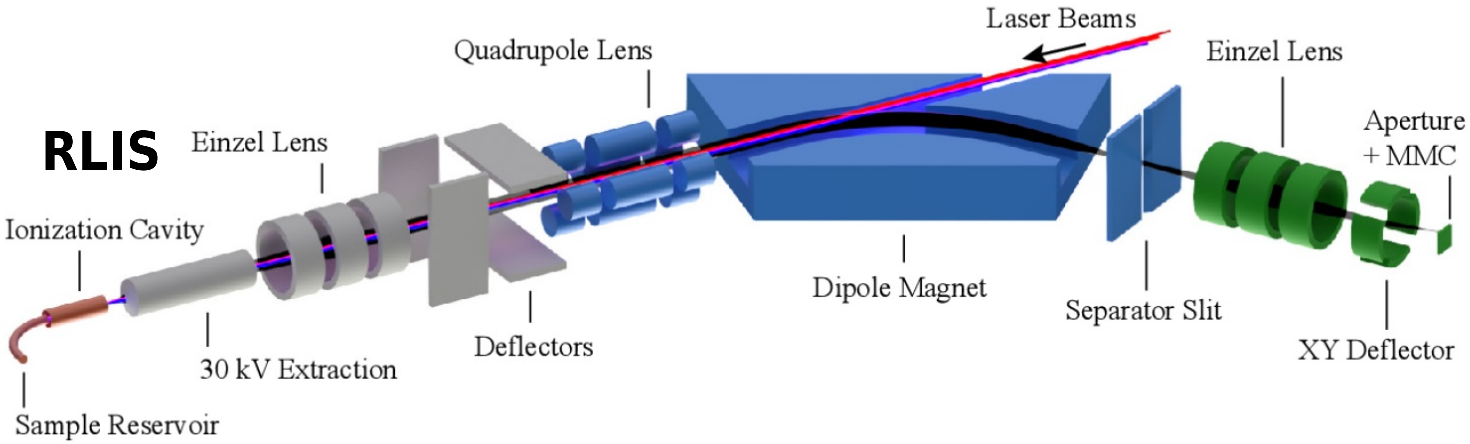
S. Heinitz et al., PLoS ONE 13(8): e0200910

Mass separation and isotope embedding

^{166m}Ho must be separated by magnetic mass spectrometer requires high current, high source and geometrical efficiency



T. Kieck et al., Rev. Sci. Instrum., 90, 2019



ECHo: resonant laser ionization source

- RISIKO at Mainz University
- efficiency: (69 ± 5stat ± 4syst)%

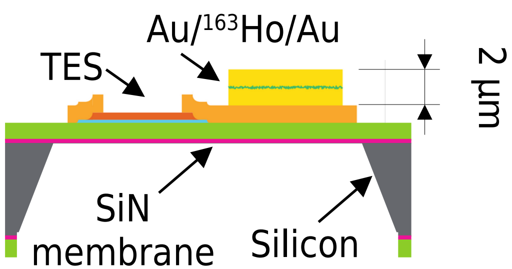
→ demonstrated **A(^{163}Ho)$_{max}$≈ 3 Bq/det**

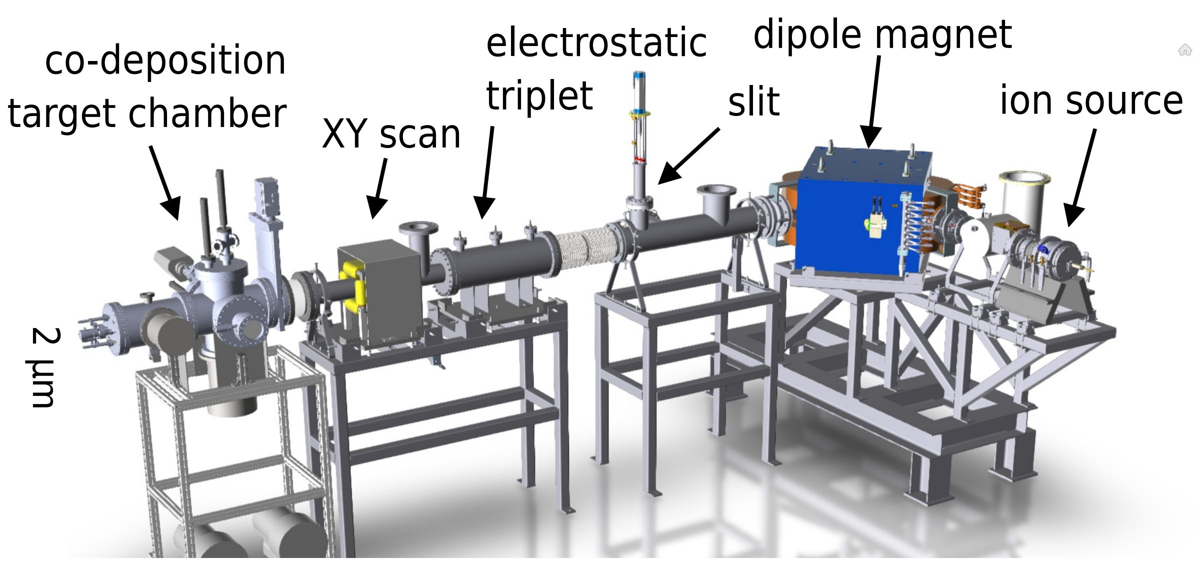
T. Kieck et al., NIM A, 945, 2019, 162602.

HOLMES: Ar plasma sputter ion source

- installed at INFN Genova
- efficiency ≈0.2%
- w/o triplet/XY-scan and chamber

→ **A(^{163}Ho)$_{max}$≈ 1 Bq/det**

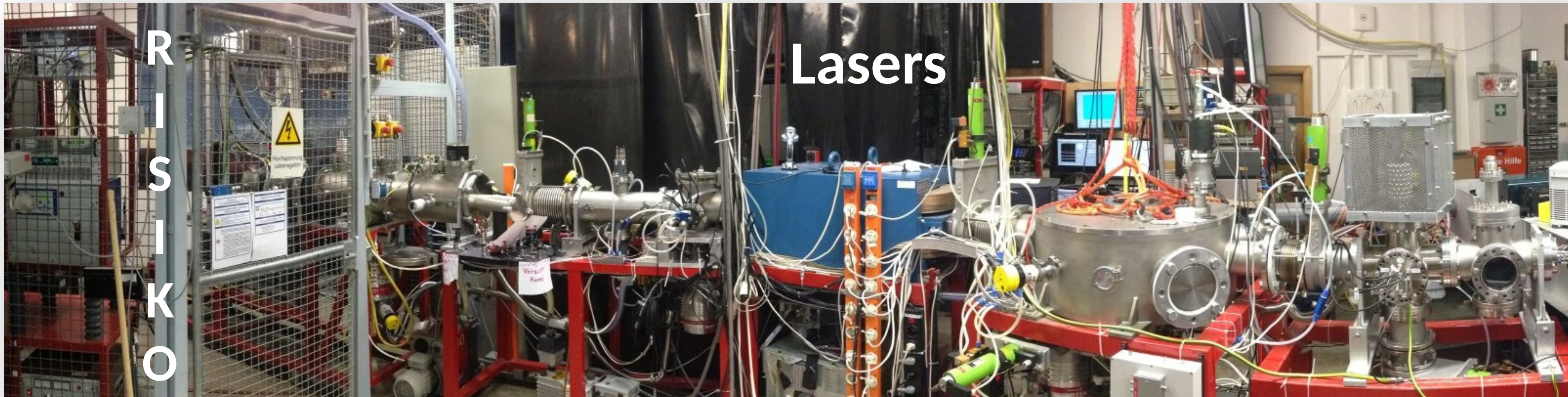




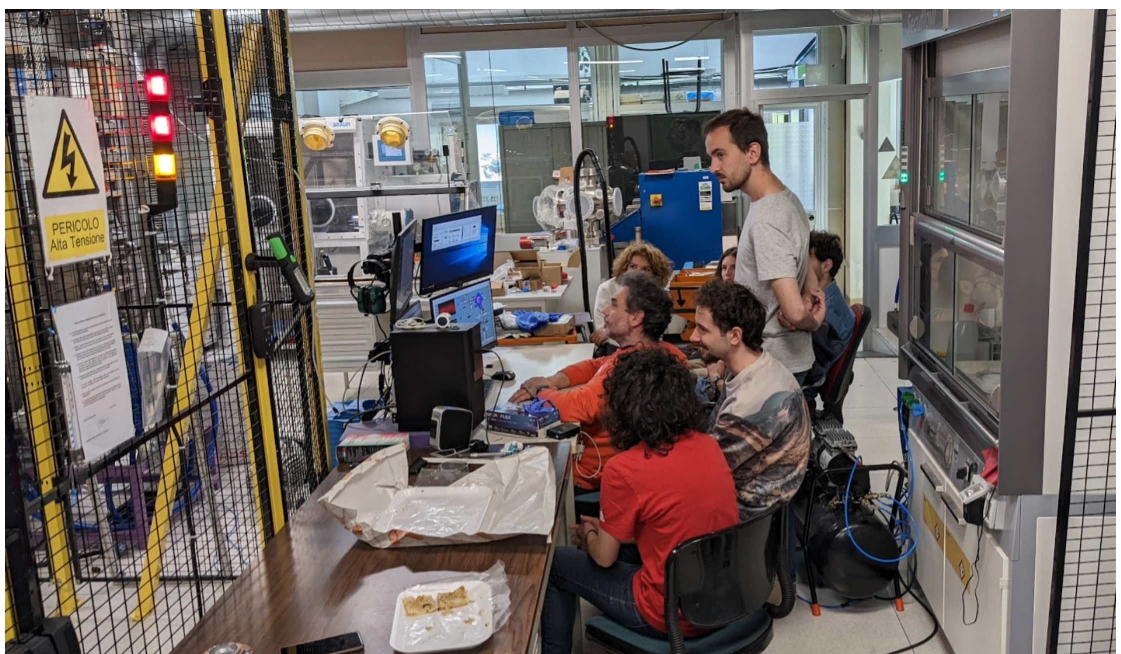
Mass separation and isotope embedding

Ion Source 30 keV Acceleration Magnet Slits Focalization Implantation

U. Mainz



INFN Genova



Microcalorimeters arrays readout

TES and MMC readout by SQUIDs

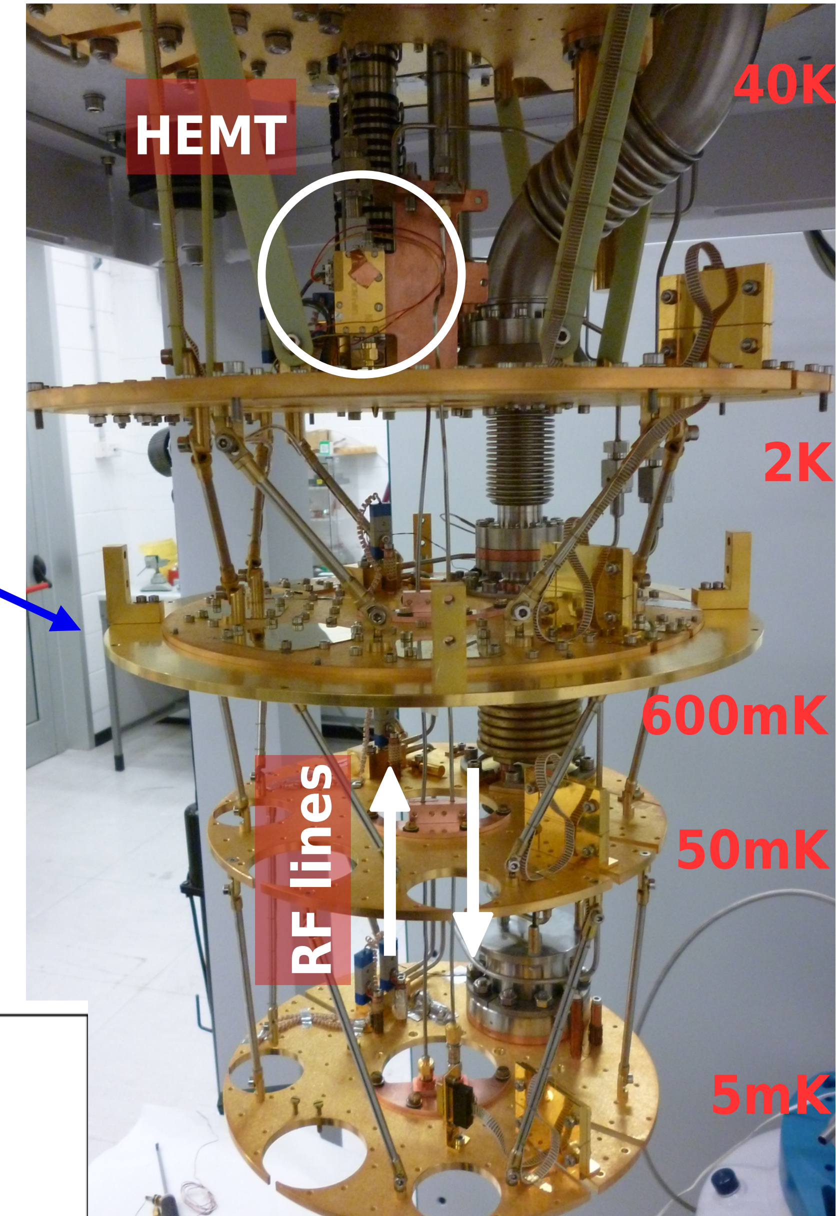
high BW **microwave multiplexing** of rf-SQUIDs

Software Defined Radio (SDR) for heterodyne readout

D. T. Becker et al., JINST, 14 (2019) P10035

O. Sander et al., IEEE Trans. Nucl. Sci., 66 (2019) 1204

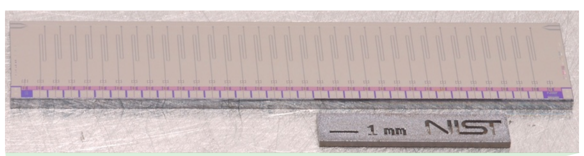
HOLMES → **256** detectors in 4 GHz: 1 RF line / 1 HEMT amplifier



For arrays of ≈10^6 detectors

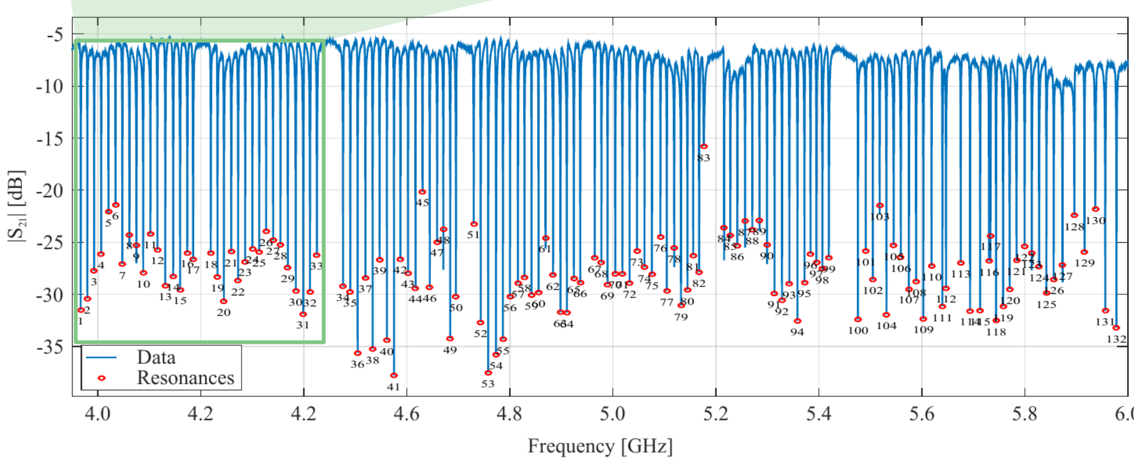
signal multiplexing → reduced impact on cryogenic systems

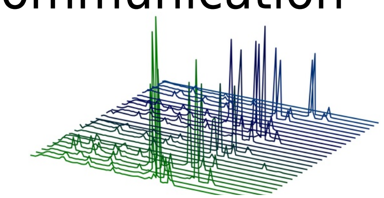
SDR → low costs per channel with RFSoCs for telecommunication

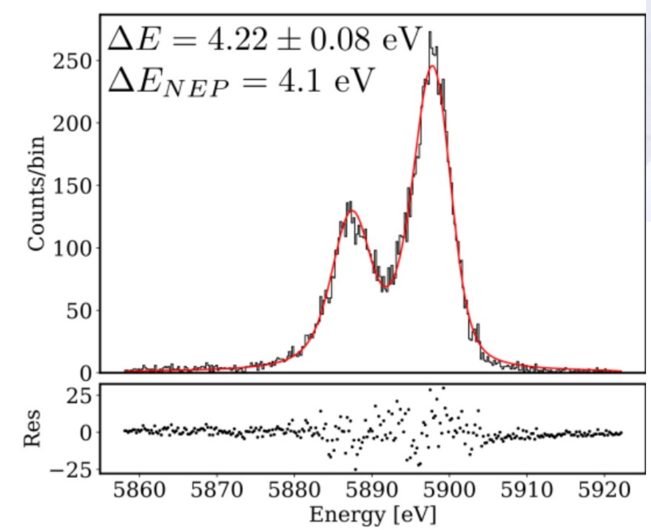


4 μmux chips in series

→ 132 tones in 2 GHz







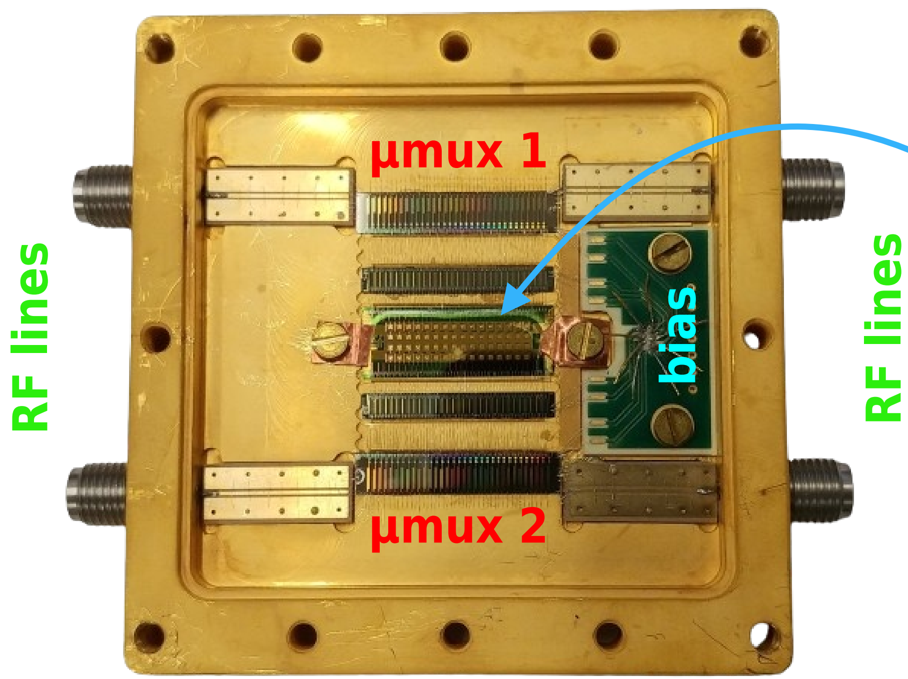
32 multiplexed TESs w/o ^{163}Ho

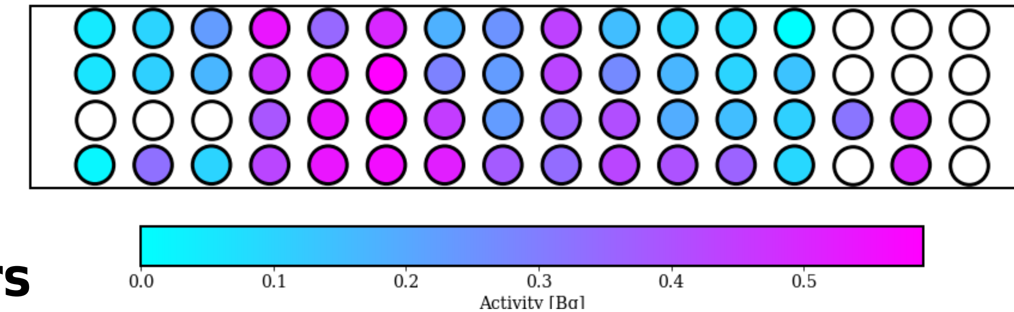
→ ΔE_{FWHM}≈4-6 eV

→ τ_R≈1.5 μs

B. Alpert at al., EPJ C, 79 (2019) 304

HOLMES high statistics measurement





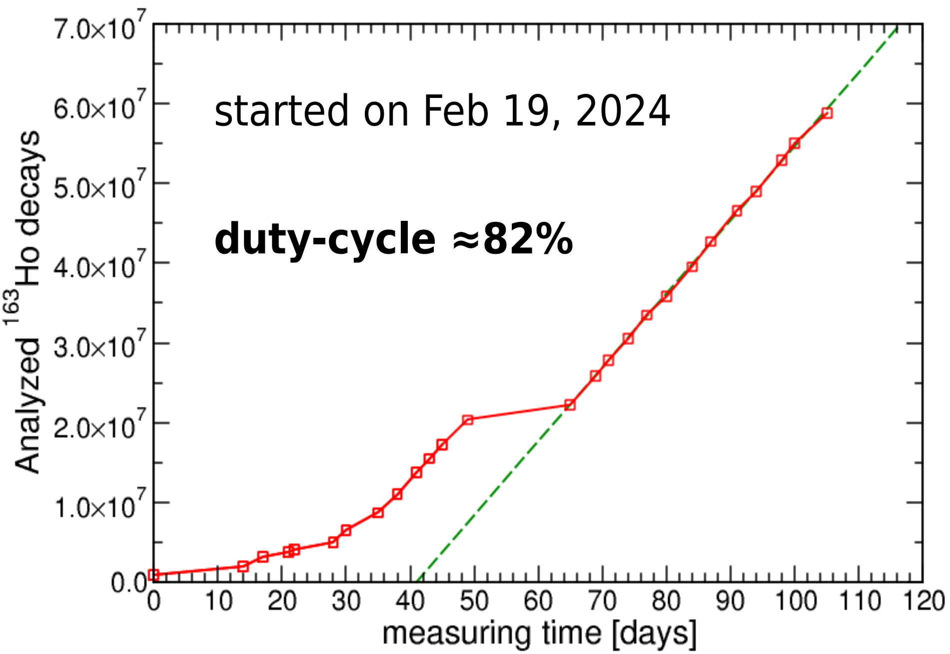
48 active detectors

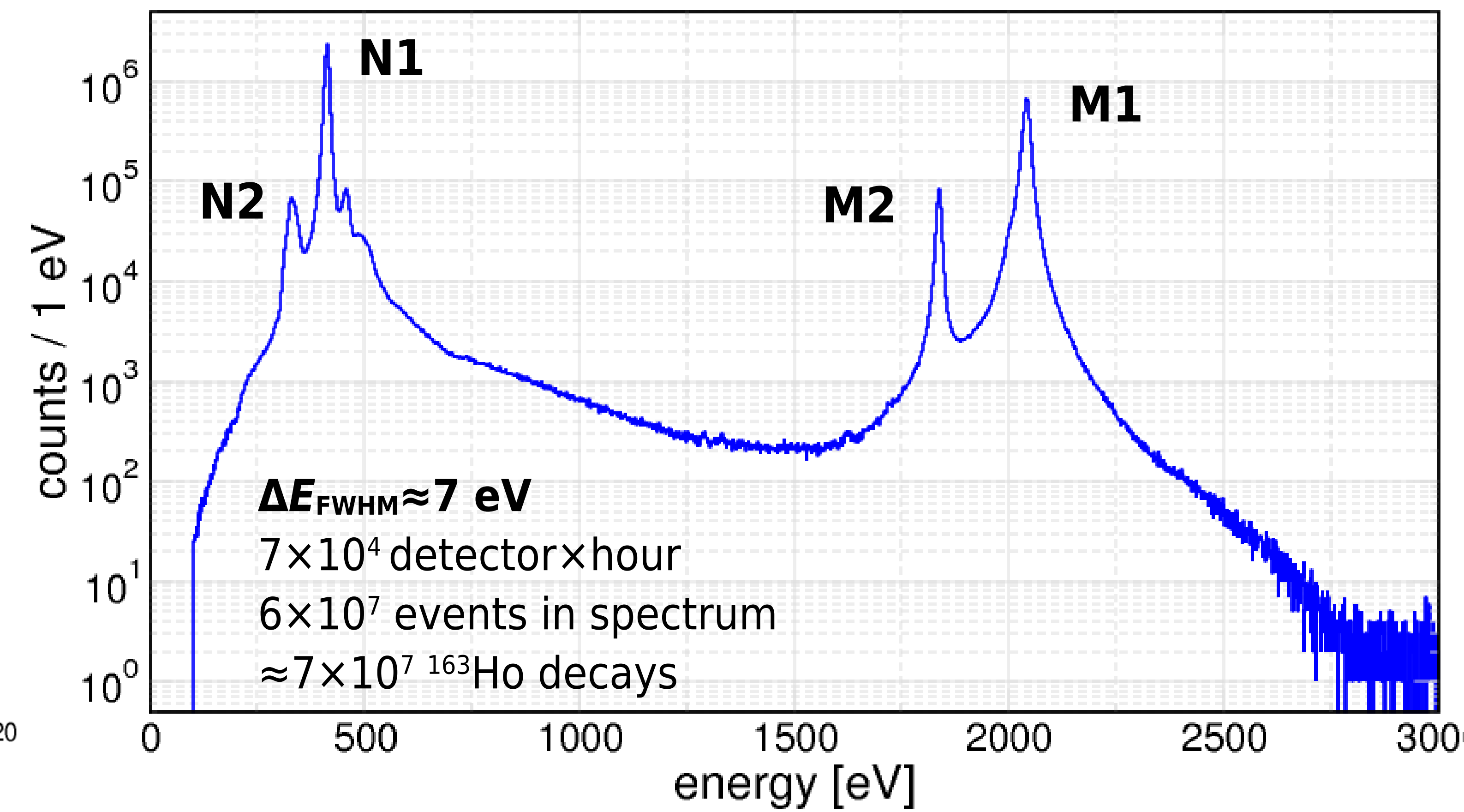
average activity* $\langle A \rangle$ **= 0.27 Bq**

total activity* A_{tot} **= 13 Bq**

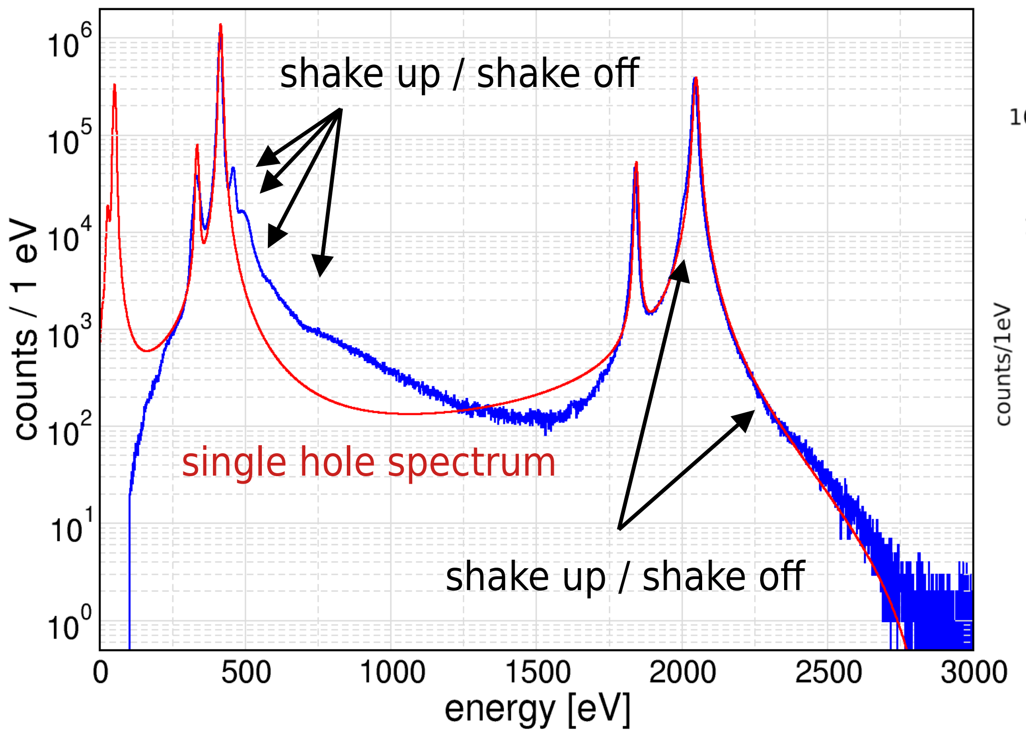
peak activity* A_{max}**≈0.6 Bq**

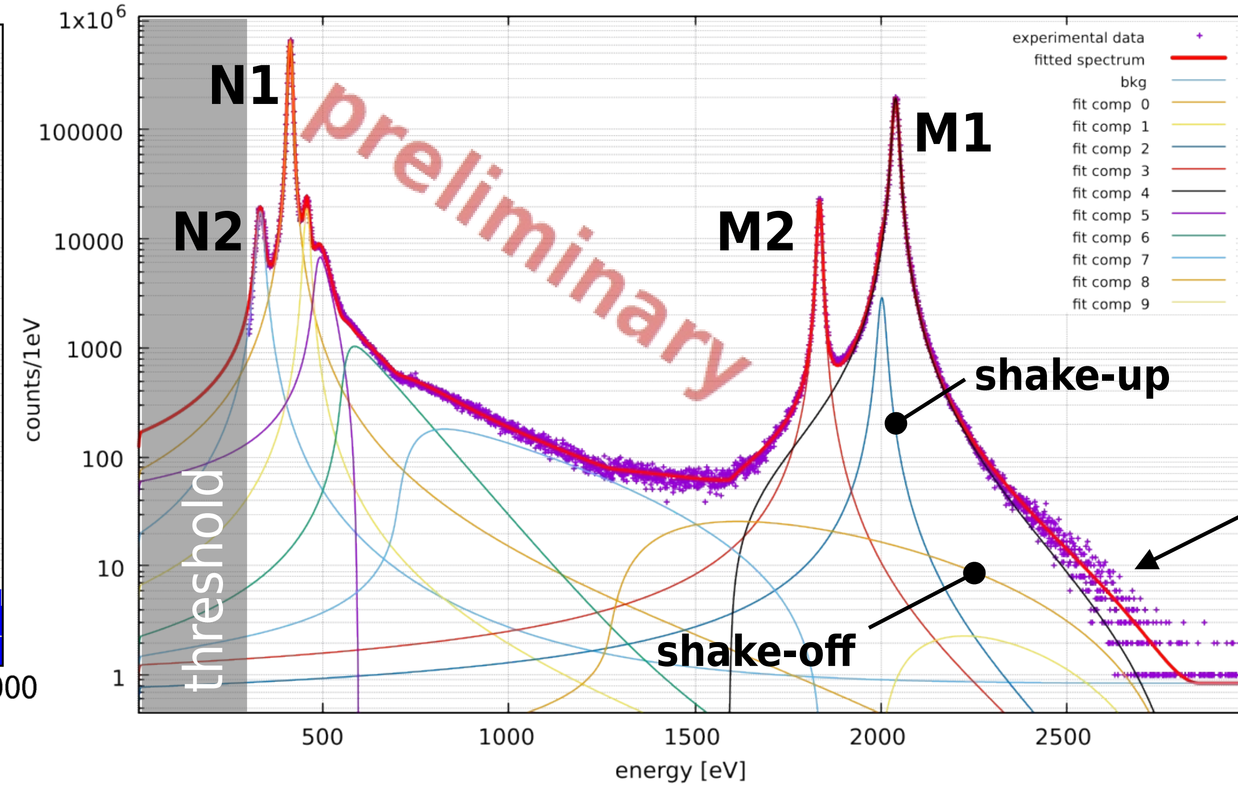
* all activities above thershold





HOLMES high statistics measurement: spectral shape





signal rate higher than single-hole

impact on m_β sensitivity?

experimental EC spectrum deviates from all theoretical predictions

→ **phenomenological description** of the EC spectrum

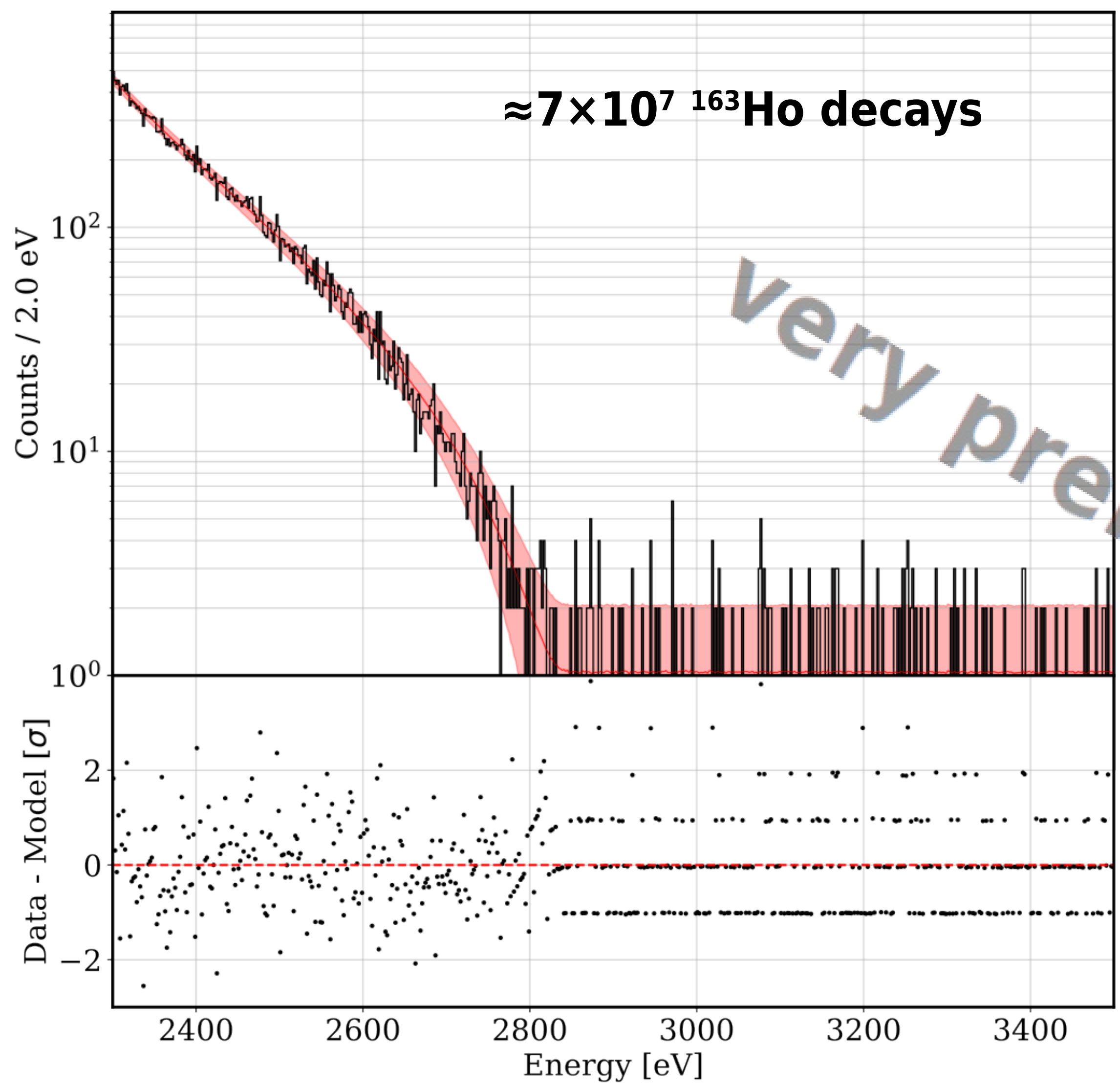
- shake-up peaks and shake-off spectra
- strongly asymmetric Lorentzians (Fano-like interference?)

needed for assessing sensitivity of future ^{163}Ho experiments

end-point region is smooth and featureless

A. De Rújula et al., J. High Energ. Phys., 2016 (2016) 15
A. Faessler et al., Phys. Rev. C, 95 (2017) 045502
M. Brass et al.t, New J. Phys., 22 (2020) 093018
R. G. H. Robertson, Phys. Rev. C, 91 (2015) 035504

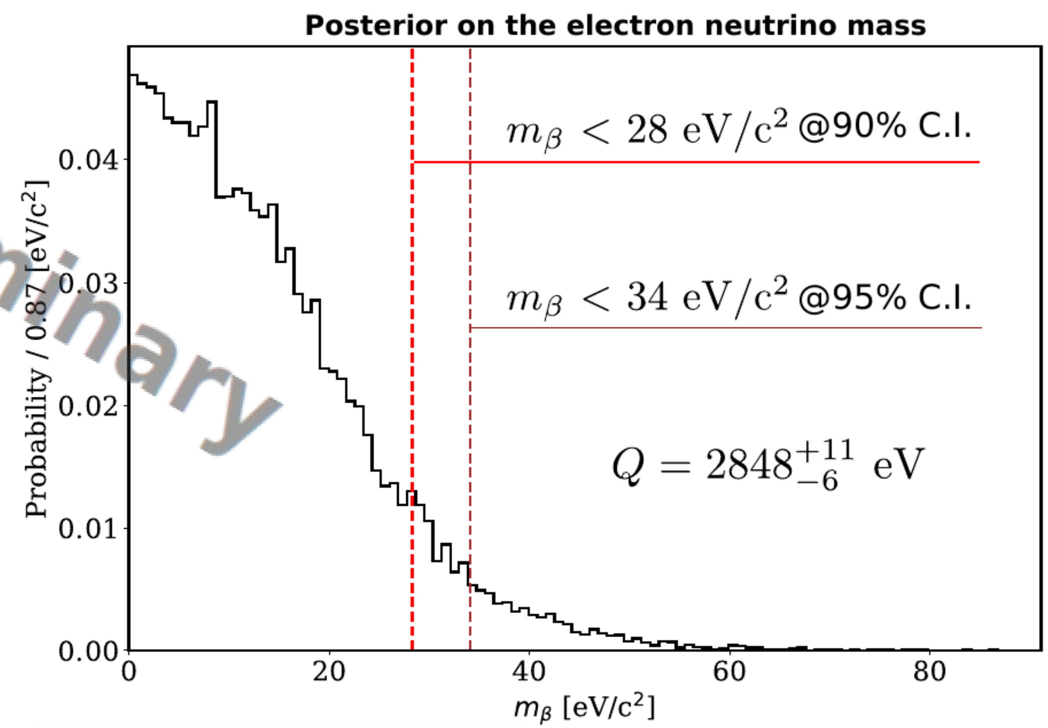
HOLMES high statistics measurement: end-point analysis



preliminary Bayesian end-point analysis
with phenomenological model

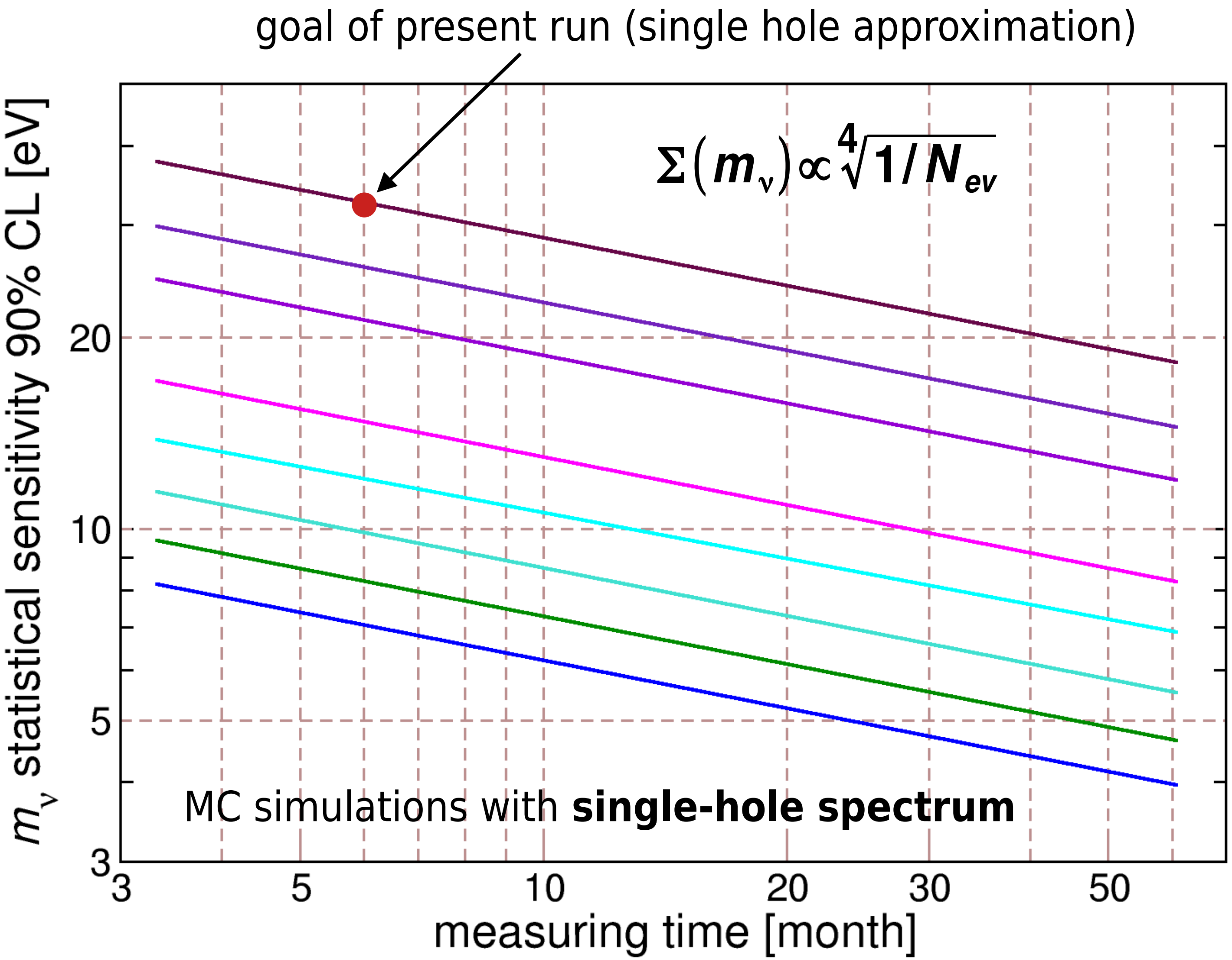
***m_β* < 28 eV @ 90% CI**

***Q* = 2848+11−6 eV (only stat error)**



poster 534 – Jun 21
M. Borghesi

HOLMES sensitivity evolution vs. pixel activity



64 detectors

ΔE = 7 eV

$\tau_R \approx$ 2 µs

bkg = 2×10^{-4} c/eV/d/det

***A* = 0.3 Hz/det**

***A* = 0.5 Hz/det** low dose

***A* = 1 Hz/det**

***A* = 3 Hz/det**

***A* = 5 Hz/det**

***A* = 10 Hz/det**

***A* = 30 Hz/det**

***A* = 50 Hz/det**

...
beam focusing
...
lower *T*
...

now **upgrading ion implanter** with focusing stage and co-deposition chamber

→ better uniformity and higher detector activity (starting with 3~5 Bq)

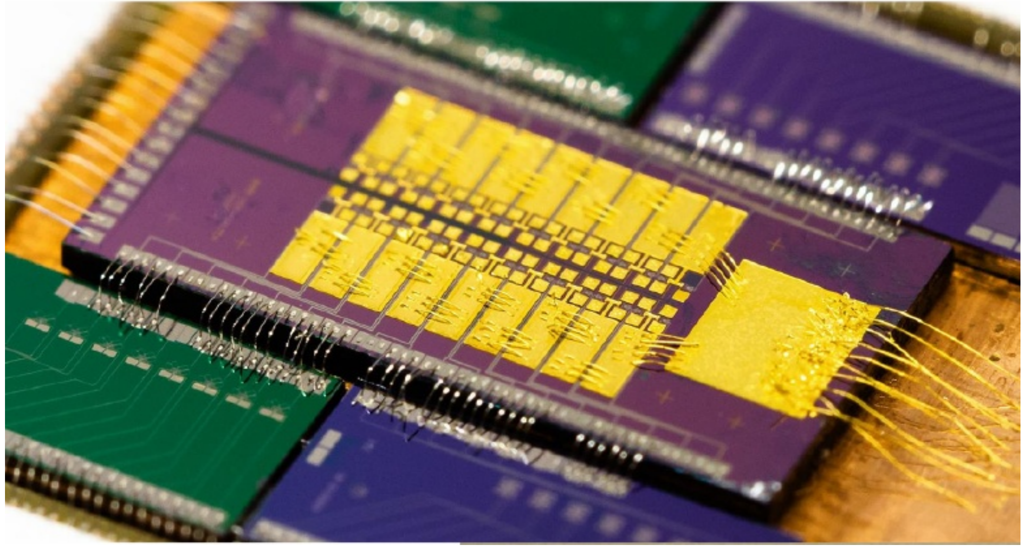
operate at **lower temperatures** to reduce the impact of implanted ^{163}Ho on detector performance

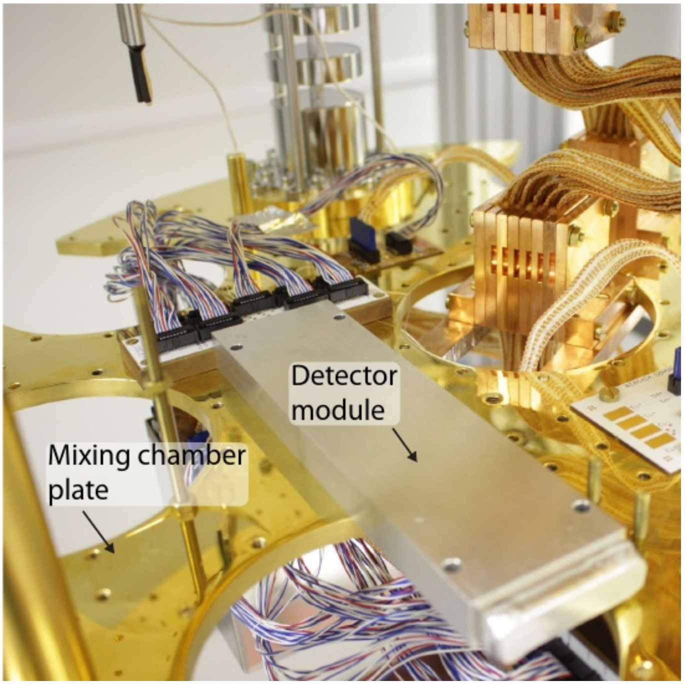
ECHo-1k status: detectors

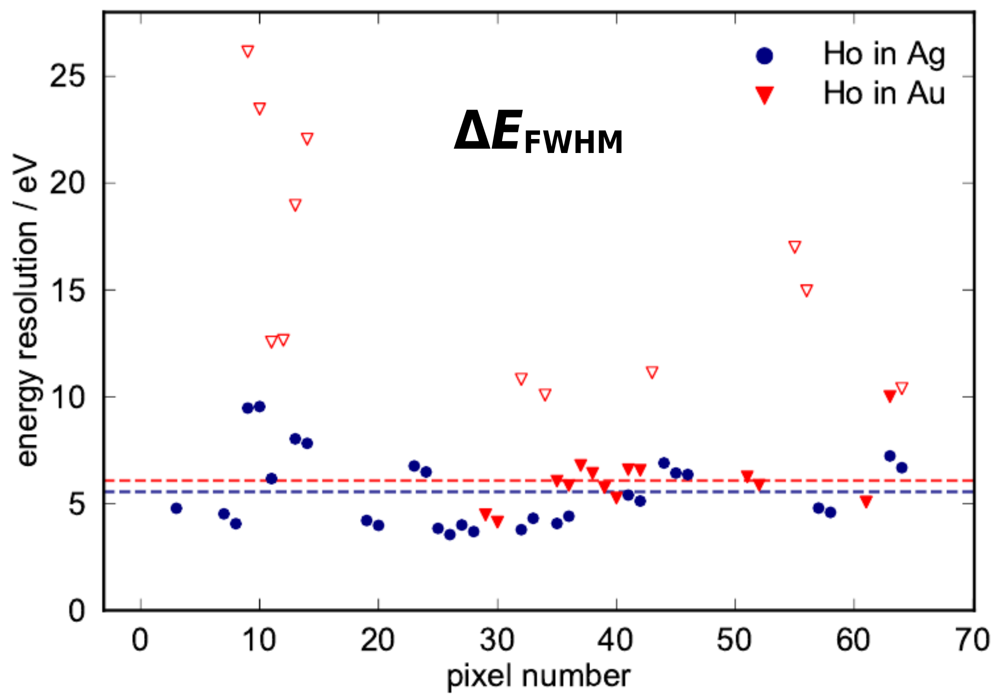
2 64 detector modules with ^{163}Ho in Au and Ag host material

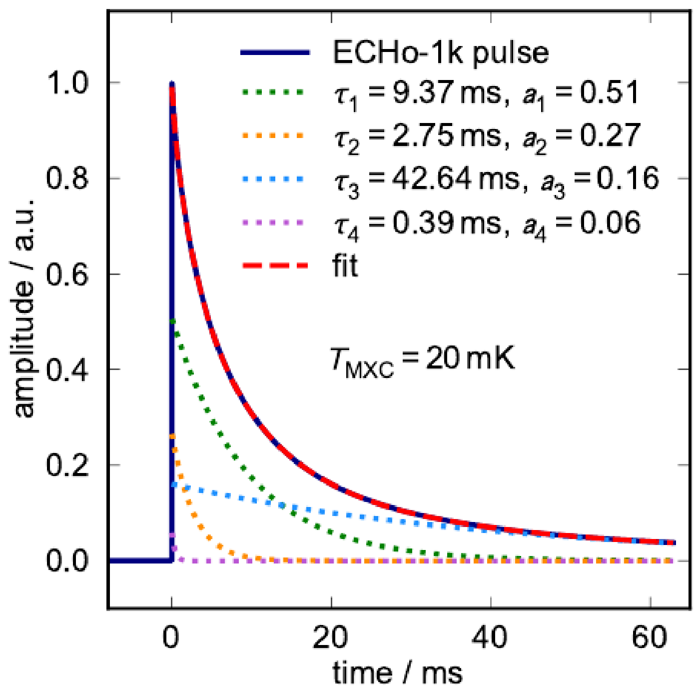
parallel dc-SQUID readout

host	^{163}Ho pixels	bkg pixels	⟨A⟩ [Bq]	A_{tot} [Bq]
Au	23	3	0.94	28.1
Ag	34	6	0.71	25.9









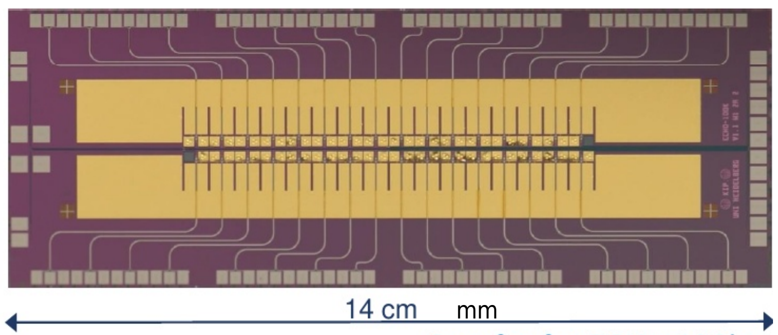
F. Mantegazzini et al, NIM A 1030 (2022) 166406

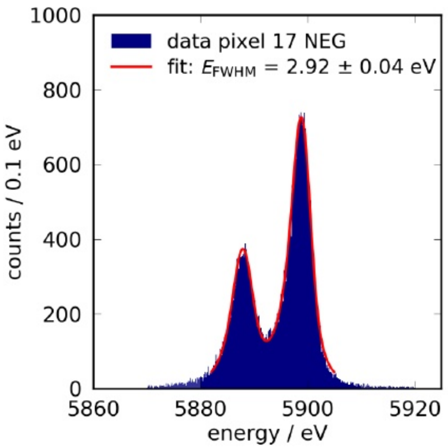
F. Mantegazzini et al., J. Inst. 16 (2021) P08003

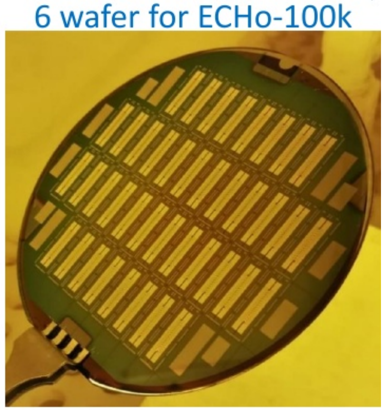
- τ_{rise}≈1 µs limited by SQUID bandwidth
- complex decays time: mostly τ_1≈10 ms

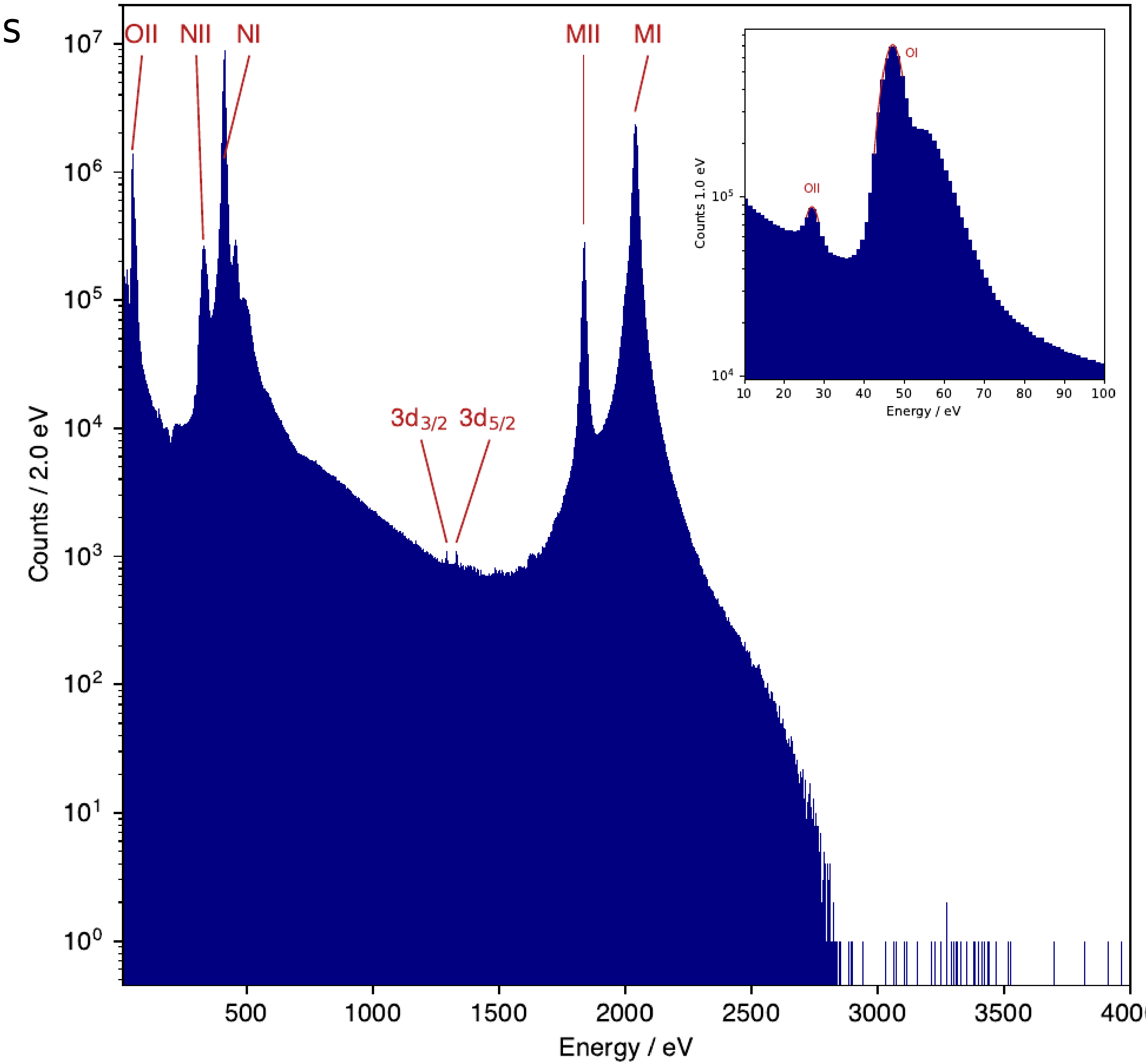
ECHo-1k status: 10^8 events spectrum

- Bayesian end-point analysis in progress
- **1.26×10^8** events from detectors with ^{163}Ho in **Ag** host material
- now preparing **ECHo-100k**









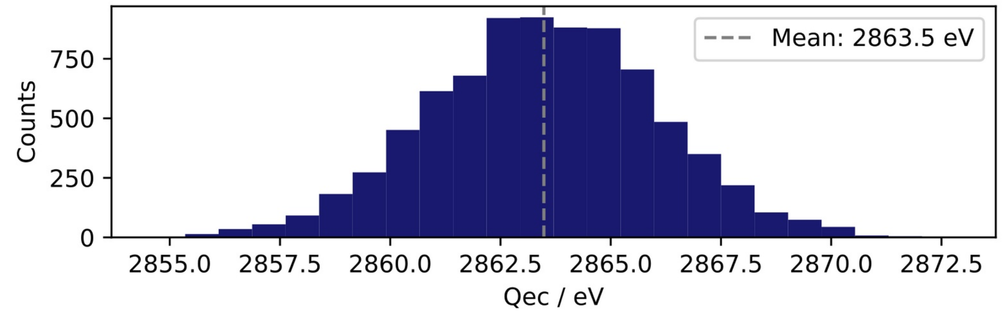
poster 336 – Jun 21
L. Gastaldo

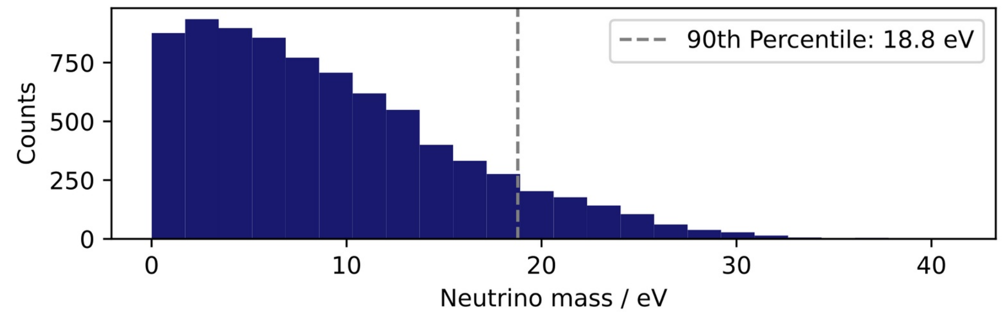
poster 566 – Jun 21
L. A. Perez

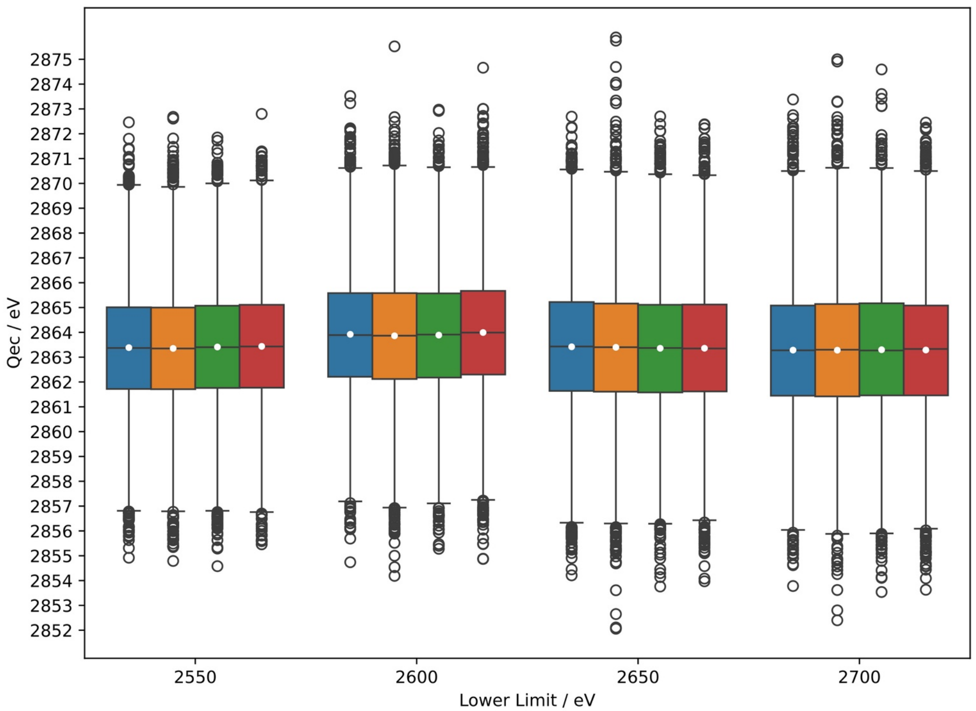
ECHo-1k status: 10^8 events spectrum

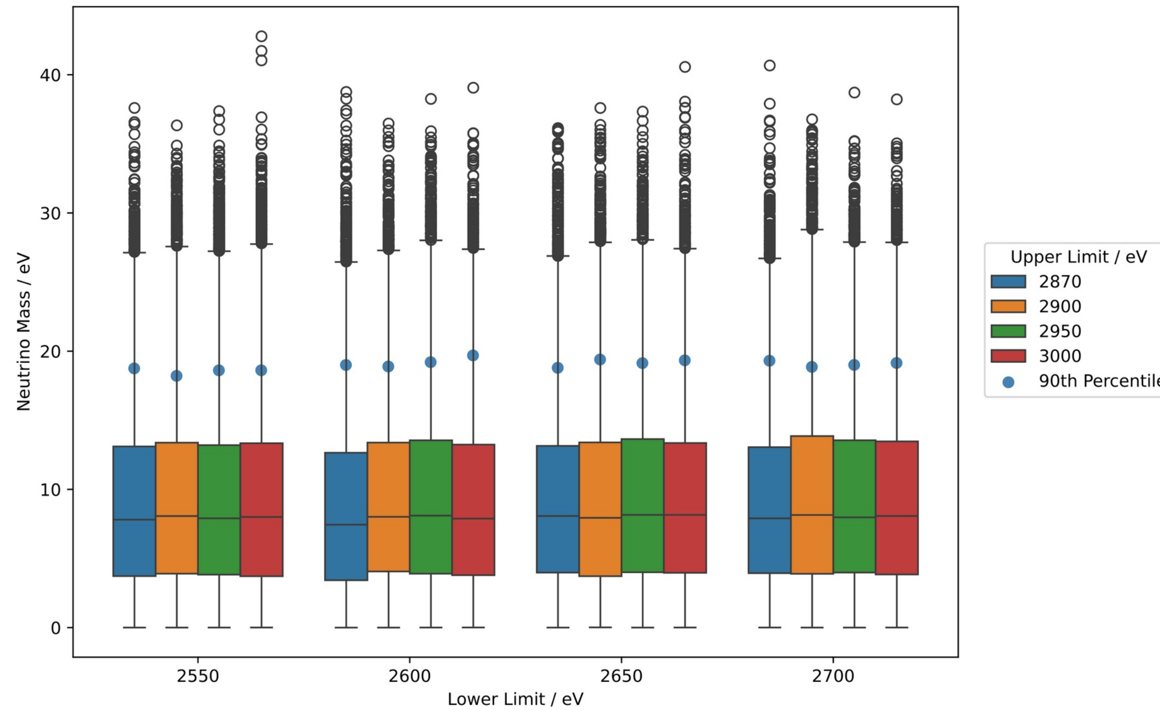
Q = (2862.1 ± 1.7) eV

m_ν < 19 eV 90% CL









Beyond ECHo and HOLMES: a sub-eV experiment

ECHo and **HOLMES** proved

- production of large and pure ^{163}Ho isotope samples
- efficient embedding technology
- large bandwith array multiplexed readout
- performing microcalorimeters with implanted absorber
- high duty-cyle high-statistics data taking
- spectrum endpoint analysis

Synergy with other EC experiments: BeEST

BeEST *K.G. Leach and S. Friedrich, J. Low Temp. Phys. 209, 796 (2022)*

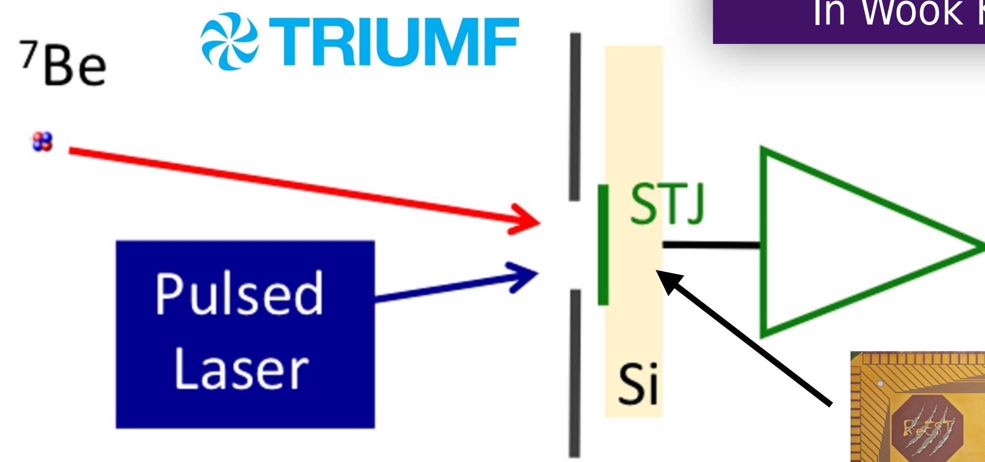
study **EC decay** of ^{7}**Be implanted** in **low temperature detectors** to search for

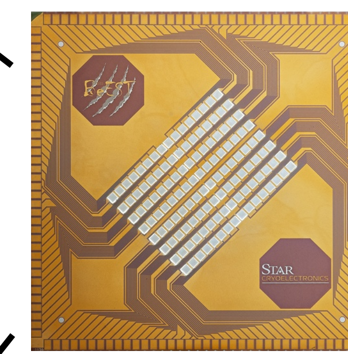
- sterile neutrinos with ≈0.1-1 MeV masses
- other sub-MeV ν-coupled particles

also probe

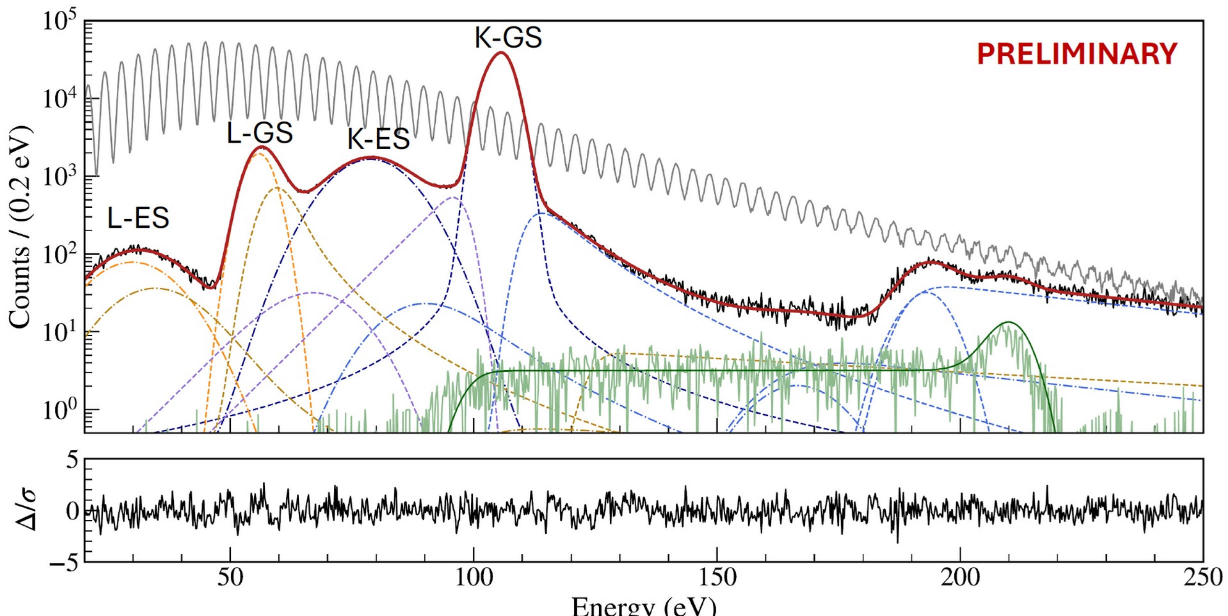
- neutrino quantum properties
- precision nuclear and atomic structure

poster 275 – Jun 18
In Wook Kim

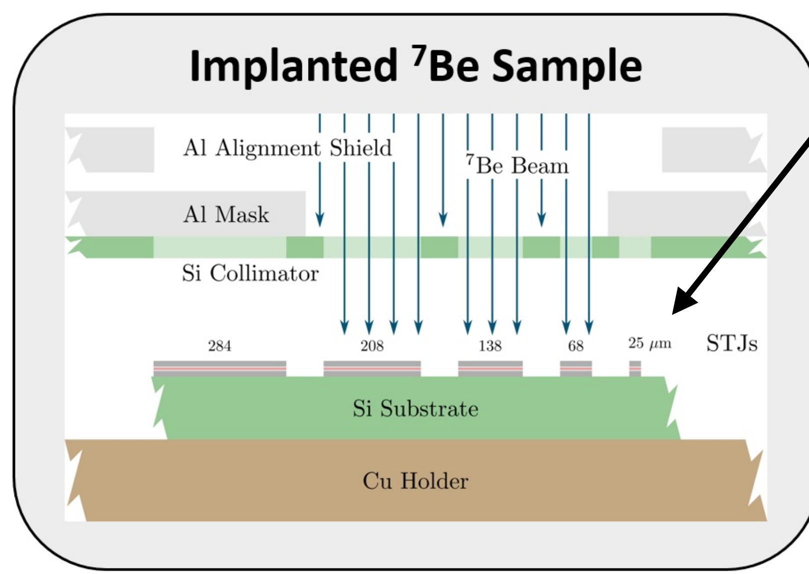




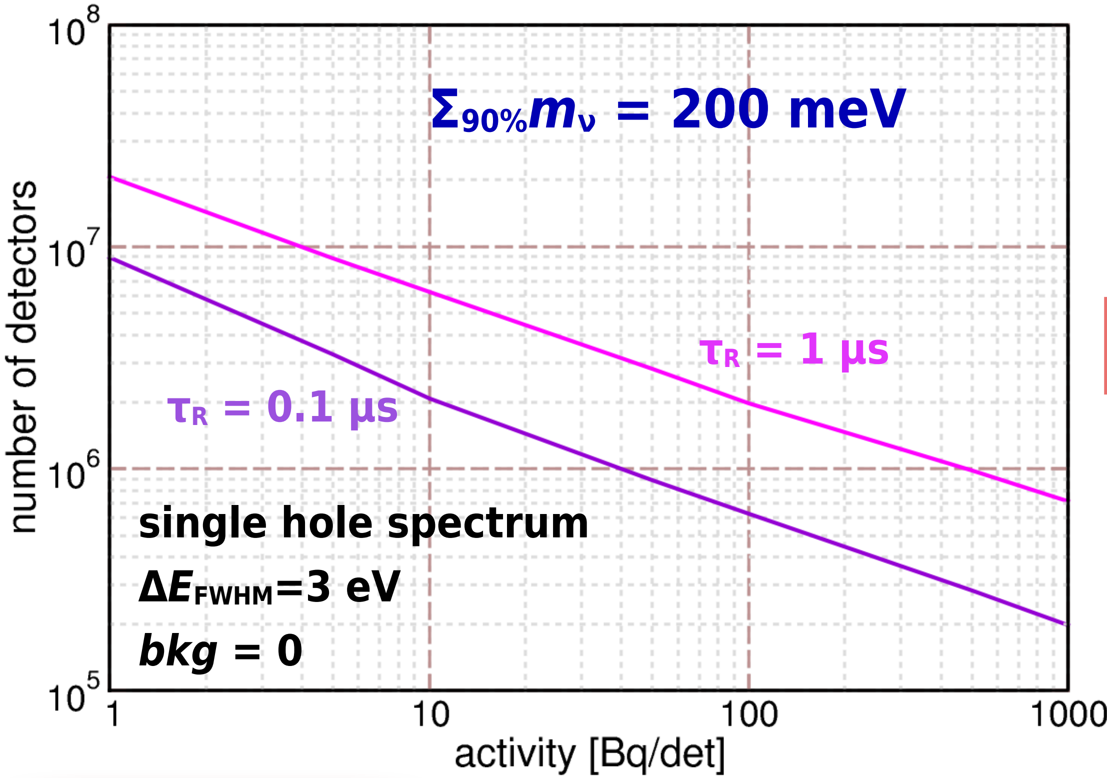
superconducting tunnel junction array



Lawrence Livermore National Laboratory



Beyond ECHo and HOLMES: a sub-eV experiment



10 years measuring time

$\Sigma_{90} m_\nu$ [meV]	200	100
A [Bq/det]	30	300
τ_R [µs]	1.0	0.1
f_{pp}	3.0E-05	3.0E-05
N_{det}	3.6E+06	5.8E+06
A total [Bq]	1.1E+08	1.7E+09
^{162}Er [mg] *	820	13200

* ^{162}Er/A(^{163}Ho) = 3790 mg/GBq + 50% usage efficiency

HOLMES
ECHo
BeEST
NIST
LANL
...

contacts are in progress for a collaboration for a **sub-eV** experiment

- increased pixel activity ≈100 Bq/det ↔ impact of ^{163}Ho heat capacity
- ^{163}Ho activity ≳10^8 Bq ↔ implantation efficiency and precision
- multiplexing and DAQ bandwidth ↔ cost/channel
- about 1M pixels ↔ cost/channel

- estimated cost is *only* *O*(10M€)

Conclusions

direct neutrino mass experiments are unavoidable to assess the lightest neutrino mass

many options to go beyond KATRIN using tritium

- still in a R&D phase
- presently reaching 150 eV sensitivity on m_β

^{163}Ho-based experiments are a solid and readily available alternative

- low temperature calorimeters with different systematics
- individual projects are reaching order of 10 eV sensitivities on m_β
- ready to reach statistical sensitivities of order of 1 eV on m_β in few years
- potential to go beyond KATRIN with more R&D and a large international collaboration