Overview on Direct Neutrino Mass Experiments

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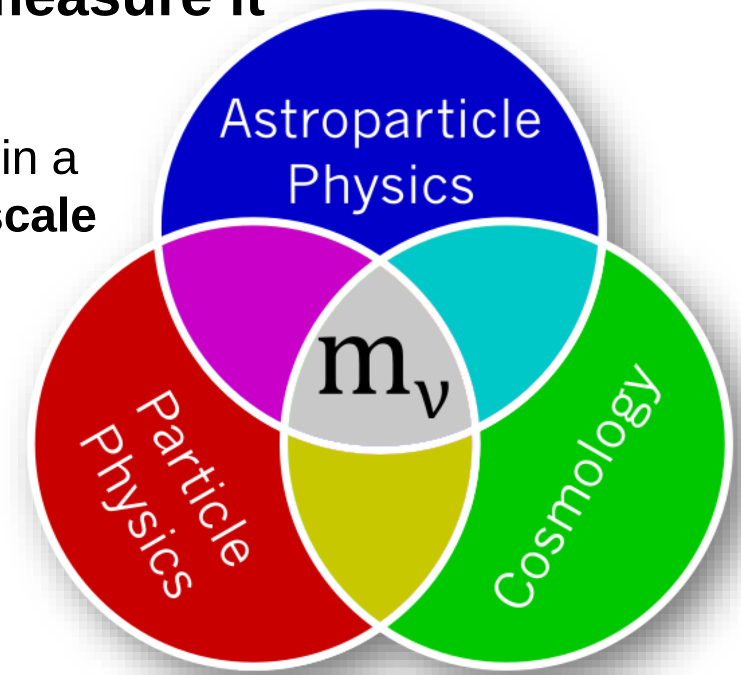
The 40th International Symposium on Physics in Collision 2021, RTWH Aachen

With material from the KATRIN, ECHo, HOLMES, Project8 and PTOLEMY Collaborations

The role of massive neutrinos and motivations to measure it

Neutrino masses bring in a **fundamental energy scale** (besides Higgs scale)



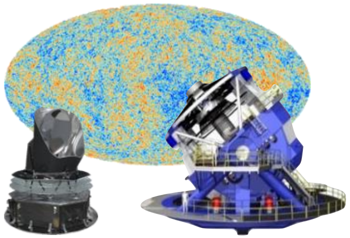
Cosmology and the role of neutrinos therein **may be more complex** (what is DE, …?)

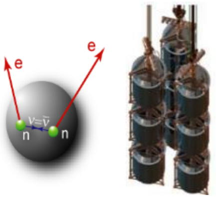
0νββ observation **not necessarily** points to an **neutrino mass**

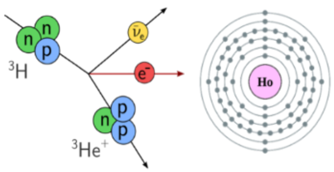
Model for mass generation needs: mixing matrix **AND mass scale**

Signal is „in reach“: Minimal mass scales exist!
“$m(\nu_e)$“ > 10 meV (normal mass ordering)
“$m(\nu_e)$“ > 50 meV (inverted mass ordering)

Ways to access the neutrino mass





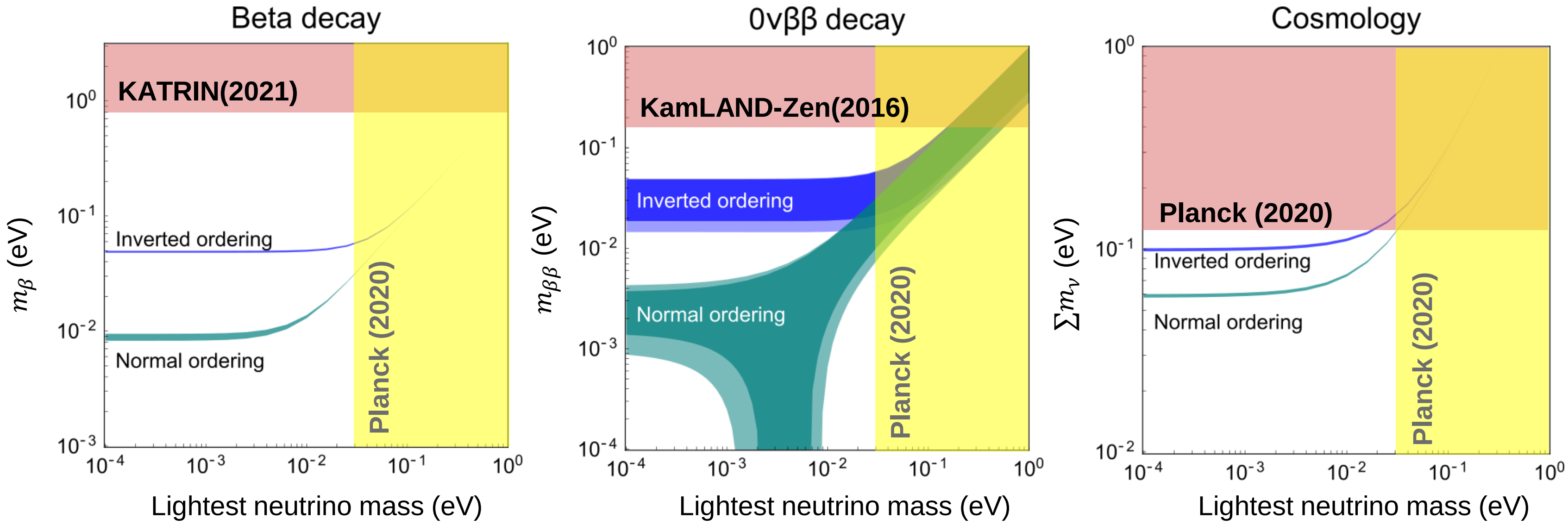


	Cosmology	Search for 0νββ	β-decay & electron capture
Observable	$M_\nu = \sum_i m_i$	$m_{\beta\beta}^2 = \left\vert\sum_i U_{ei}^2 m_i\right\vert^2$	$m_\beta^2 = \sum_i \vert U_{ei}\vert^2 m_i^2$
Present upper limit	0.12 eV*	0.18 eV*	1.1 eV
Model dependence	Multi-parameter cosmological model	- Majorana ν - contributions other than m(ν)? - nuclear matrix elements, g_A	**Direct,** only kinematics; no cancellations in incoherent sum

This talk

Complementarity and need for direct mass measurements

Standard neutrino picture: ***observations have to be found in colored regions***



NuFit, J. High Energ. Phys. 2020, 178 (2020).

Tie-breaker needed to exclude exotic models in neutrino nature or cosmology

KATRIN, arXiv:2105.08533

KamLAND-Zen, PRL **117,** 082503 (2016)

Planck, Astron. Astrophys. **641** (2020) A6

Inspired by IUPAP neutrino panel white paper, www.iupapneutrinopanel.org

Direct mass experiments

- Direct, model-independent access to neutrino mass

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

$\beta^{(-)}$ decay

$$X \rightarrow Y + e^- + \bar{\nu}_e$$

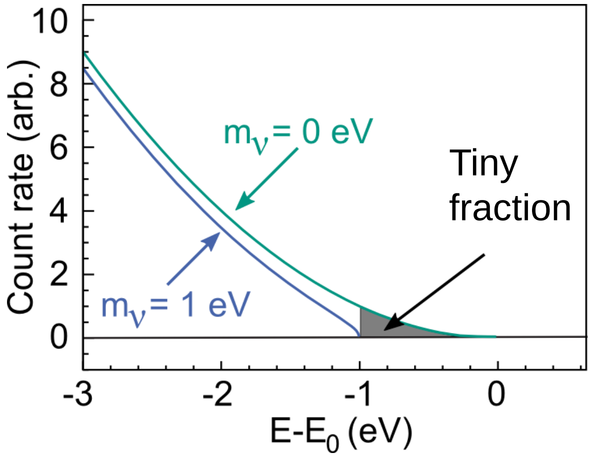
Measurement of kinetic energy of electron

Electron capture

$$X + e^-(\text{shell}) \rightarrow Y^* + \nu_e \qquad Y^* \rightarrow Y + E_C$$

Measurement of internal excitation of daughter atom

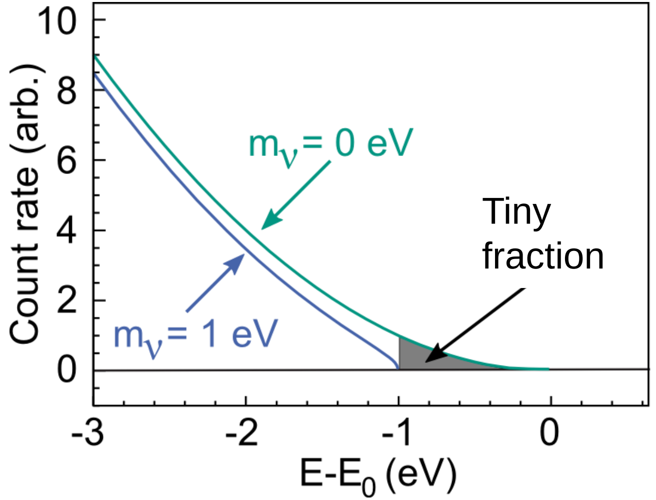
$$\frac{dN}{dE} \propto \sqrt{(E_0 - E)^2 - m_{\bar{\nu}_i}^2 c^4}$$



(Anti-) neutrino mass determined from shape distortion near kinematic endpoint

Challenges for achieving low sensitivity

$$\frac{dN}{dE} \propto \sqrt{(E_0 - E)^2 - m_{\bar{\nu}_i}^2 c^4}$$



- Low kinematic endpoint, high decay rate

	β-decay	Electron capture
Chosen isotope	$^3H = T$	^{163}Ho
Endpoint	18.6 keV	2.8 keV
Half life	12.3 years	4570 years
Typ. production	n-capture in D_2O	n-irradiation of ^{162}Er

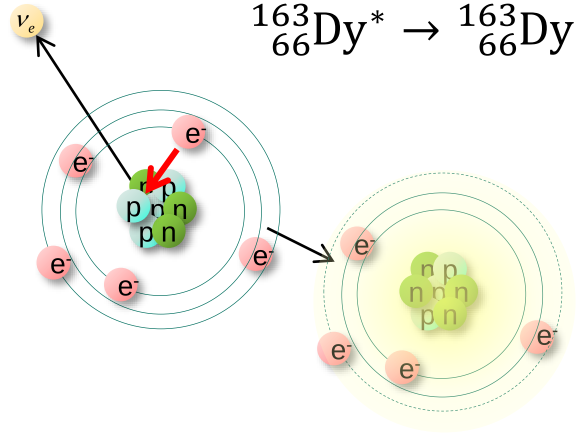
High signal (→ statistics)
Low background (→ statistics)

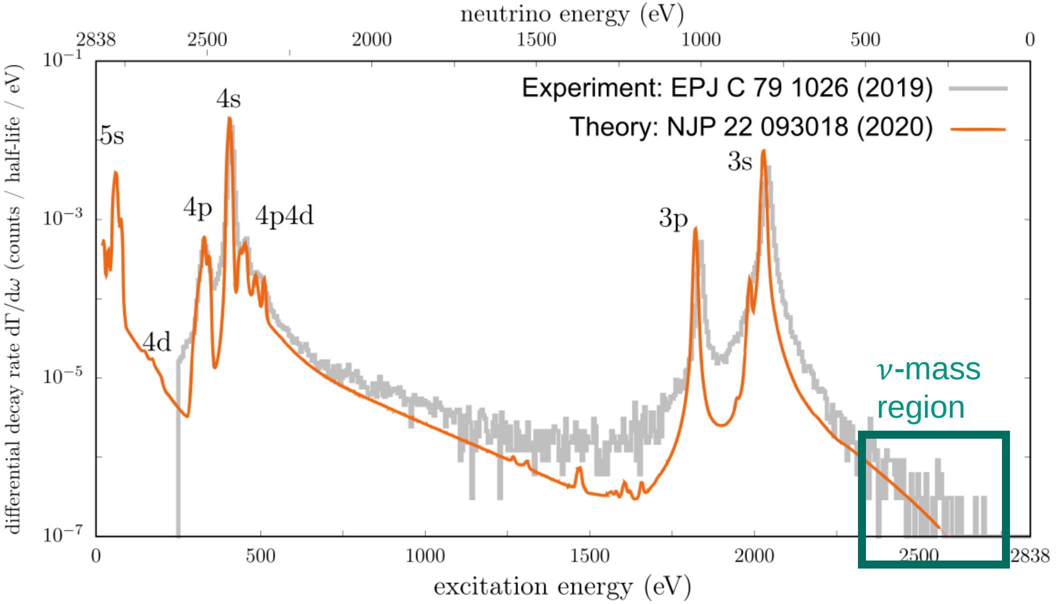
High energy resolution (→ sensitivity)
Low and quantified systematic effects

Electron capture experiments with holmium

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

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





M. Braß and M. W. Haverkort, *New J. Phys.* **22** (2020) 093018

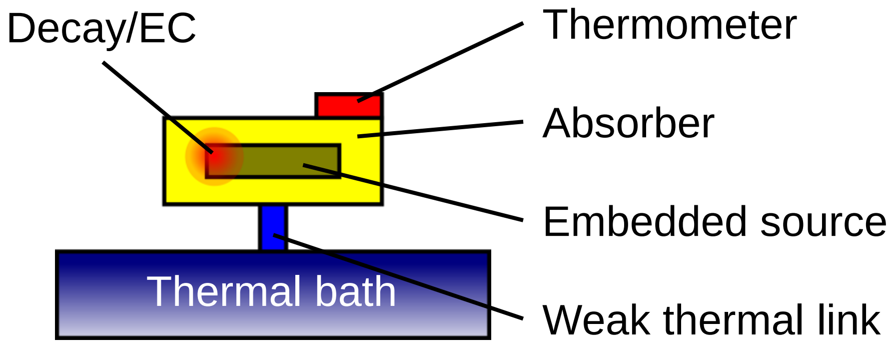
- $\tau_{1/2}$ ≅ 4570 years (2x10^{11} atoms for 1 Bq)
- Q_{EC} = $(2.833 \pm 0.030^{stat} \pm 0.015^{syst})$ keV

Sub-eV neutrino mass sensitivity requirement:
Events > 10^{14}, Ener. Res. < 3 eV, BG rate < 10^{-6} $eV^{-1}det^{-1}d^{-1}$

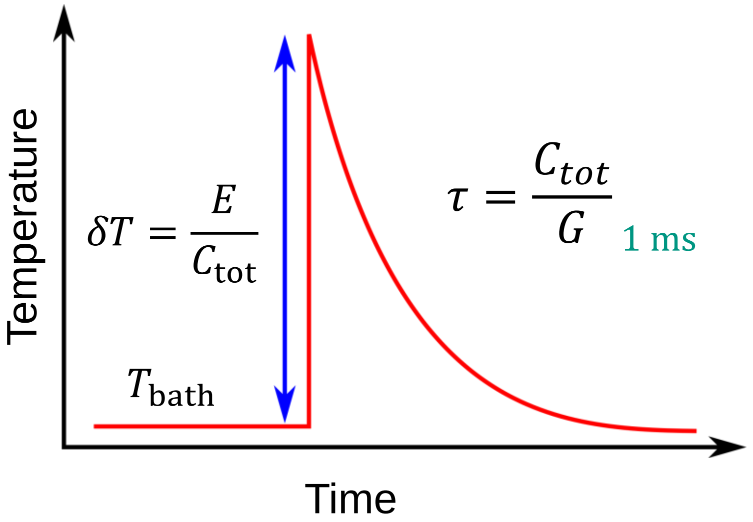
Cryogenic microcalorimeters (4π acceptance)

Karlsruhe Institute of Technology

Detector schematics



Single event



ECHo (Magnetic Microcalorimeter)

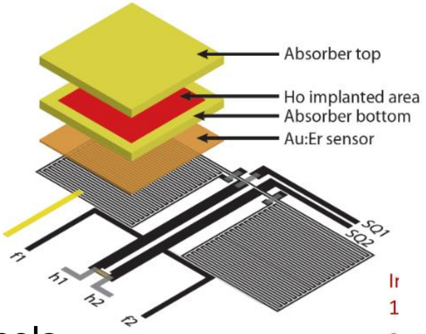
HOLMES (Transition edge detector)

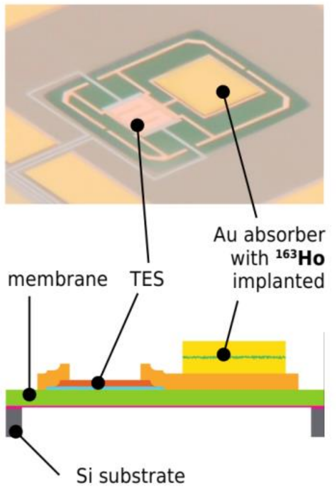
ECHo and Holmes (Different strategies)

EPJ Special Topics 226, 1623–1694 (2017)

EPJ C 75(3), (2015)

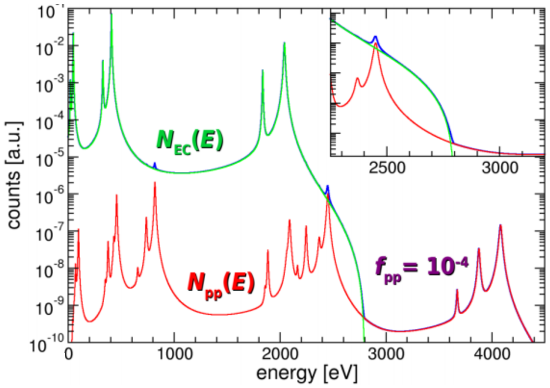
Currently *(planned)*	ECHo		HOLMES	
Channels	60	*(12000)*	64	*(1000)*
Activity per pixel	1 Bq	*(10 Bq)*	-	*(300 Bq)*
Energy resolution	5 eV	*(~1 eV)*	4.1 eV	*(~1 eV)*
m_ν sensitivity	20 eV	*(< 2 eV)*	-	*(~2 eV)*
Detector layout				

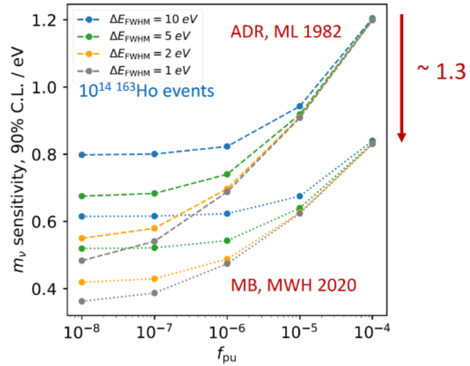




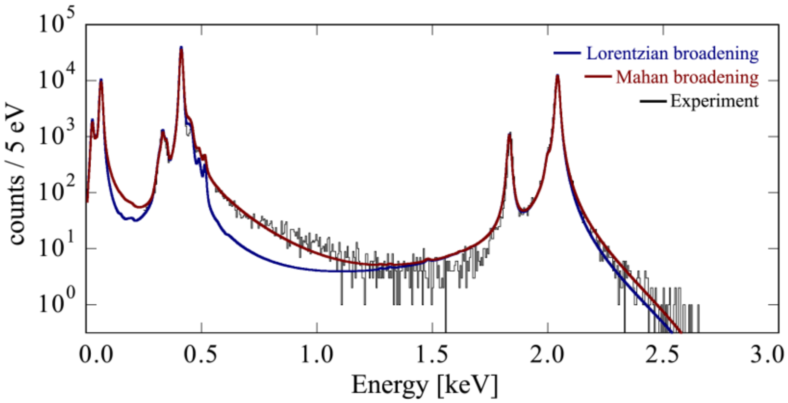
Large number of channels requires RF-multiplexing

Unresolved pile-up





ECHo-1k results



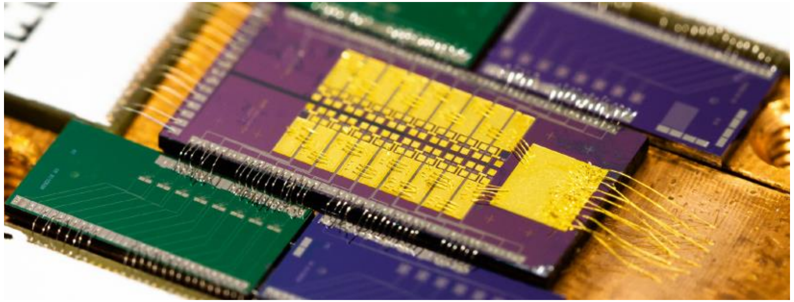
C. Velte et al., EPJC **79** (2019)1026

4-day measurement with 4 pixels loaded with ~0.2 Bq ^{163}Ho

Energy resolution $\Delta E_{FWHM} = 9.2$ eV
Background level $b < 1.6 \times 10^{-4}$ events/eV/pixel/day

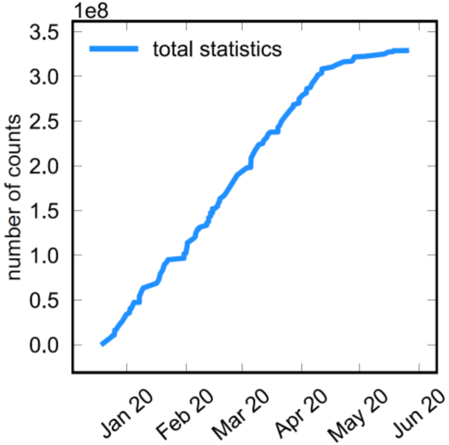
- $Q_{EC} = (2838 \pm 14)$ eV
- $m(\nu_e) < 150$ eV (95% C.L.)

!

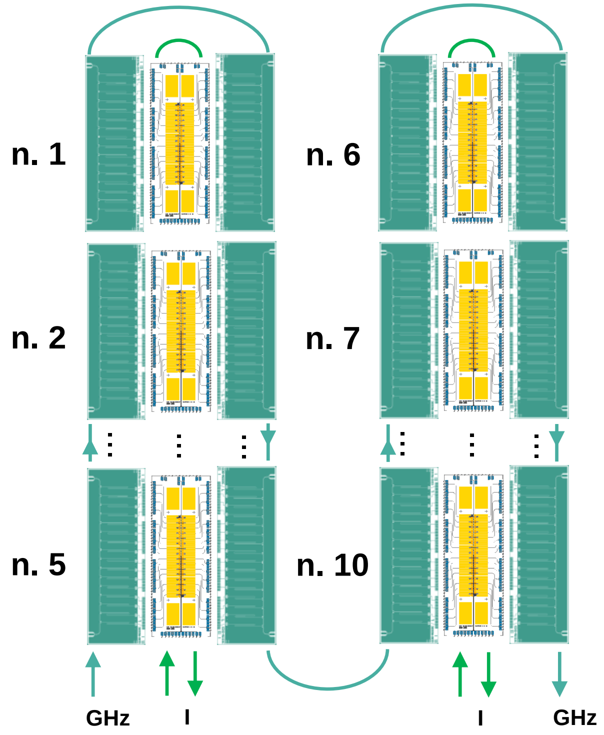


60 MMC pixels with about 1 Bq ^{163}Ho
parallel 2-stage SQUID readout
more that 10^8 ^{163}Ho events

Achievable sensitivity
$m(\nu_e) < 20$ eV (95% C.L.)



ECHo-100k: sub-2eV sensitivity



ECHo-100k baseline: large arrays of metallic magnetic calorimeters

Number of detectors: 12000
Activity per pixel: 10 Bq (2 × 10^{12} ^{163}Ho atoms)

Present status:

High Purity ^{163}Ho source:
- available about 18 MBq

Ion implantation system:
- demonstrated on single chip → next stage: wafer scale implantation

Metallic magnetic calorimeters
- reliable fabrication of large MMC array
  → next stage: ECHo-100k wafers in production
- successful characterization of arrays with ^{163}Ho

Multiplexing and data acquisition:
- demonstrated for 8 channels
  → next stage: ^{163}Ho spectrum and test on larger arrays

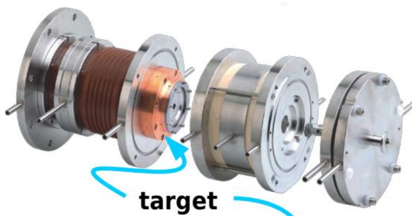
Data reduction
- optimized energy independent algorithm to identify spurious traces

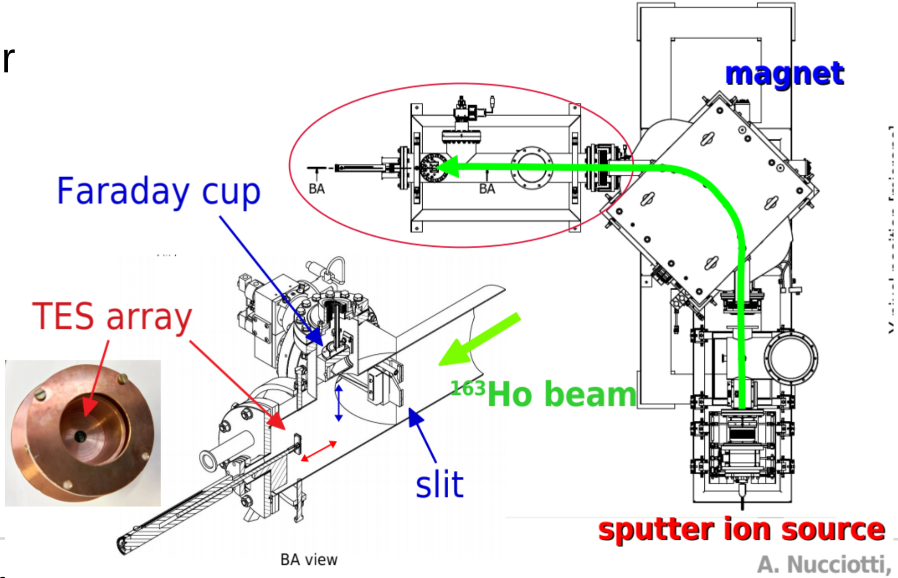
DFG Deutsche Forschungsgemeinschaft

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

Source ^{163}Ho implantation progress

- 180 MBq of ^{163}Ho available for first implantation
- ^{163}Ho / ^{166m}Ho mass separation > 10^5
- Ongoing:
  - Beam optimization with ^{nat}Ho
  - Study of optimal target (sintered target or molecular plating (e.g. $Ho(OH)_3$)



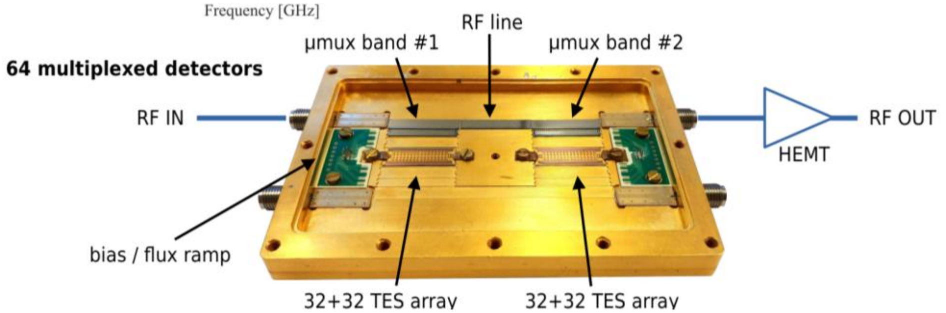


Aim after switching to enriched ^{163}Ho

Low dose implantation of 1 Bq/det

Detector performance

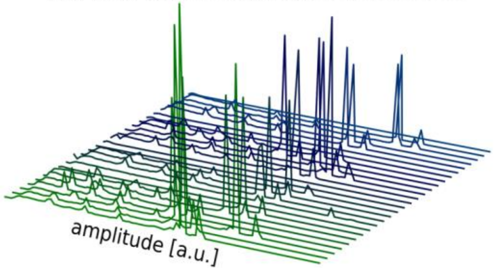
Multiplexing of 64 pixels with RF modulation (4-8 GHz)



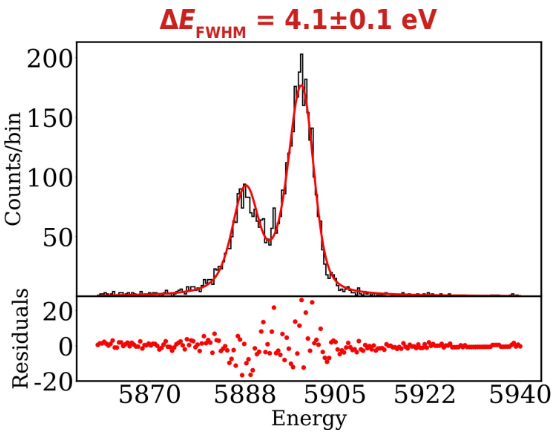
D.T. Becker et al. JINST 14.10 (2019)

Alpert B. et al., Eur. Phys. J. C (2019) 79:304

raw data from 26 multiplexed detectors



Energy resolution after multiplexing unchanged



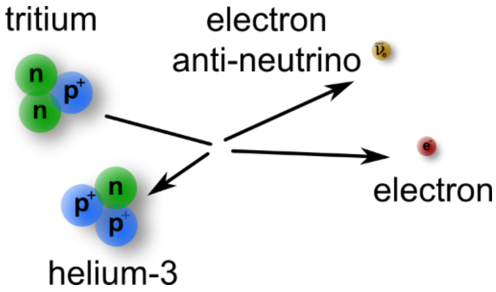
M. Borghesi et al., Eur. Phys. J. C 81.5 (2021)

Multiplexing successful

Detectors ready for implantation

Tritium beta decay experiments

- Direct, model-independent access to neutrino mass

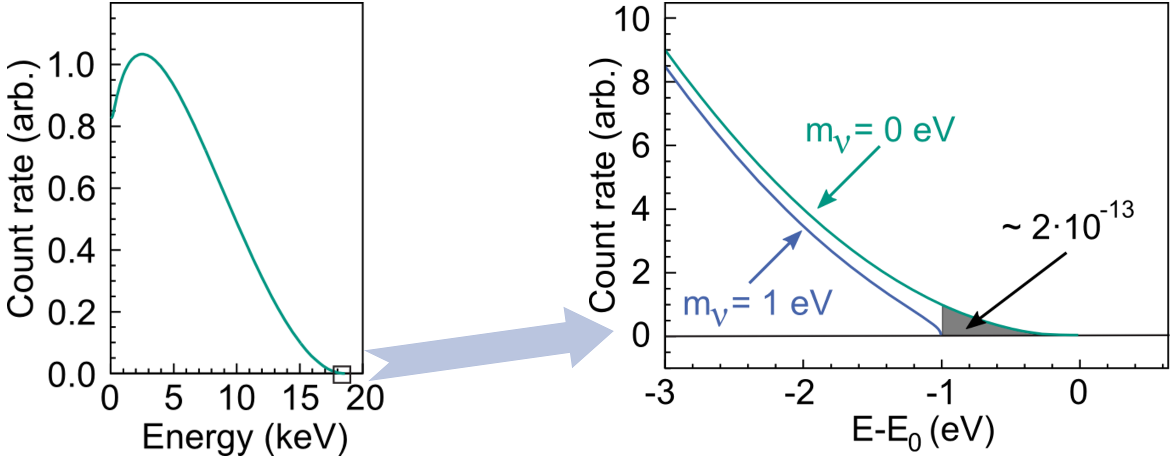


$$m_\beta^2 = \sum_i |U_{ei}|^2 \, m_i^2$$

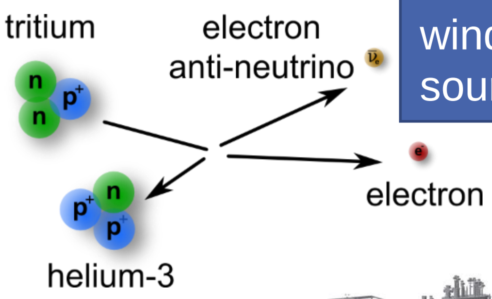
$$\frac{dN}{dE} \propto \sqrt{(E_0 - E)^2 - m_{\bar{\nu}_i}^2 c^4}$$

E_0 = 18.6 keV

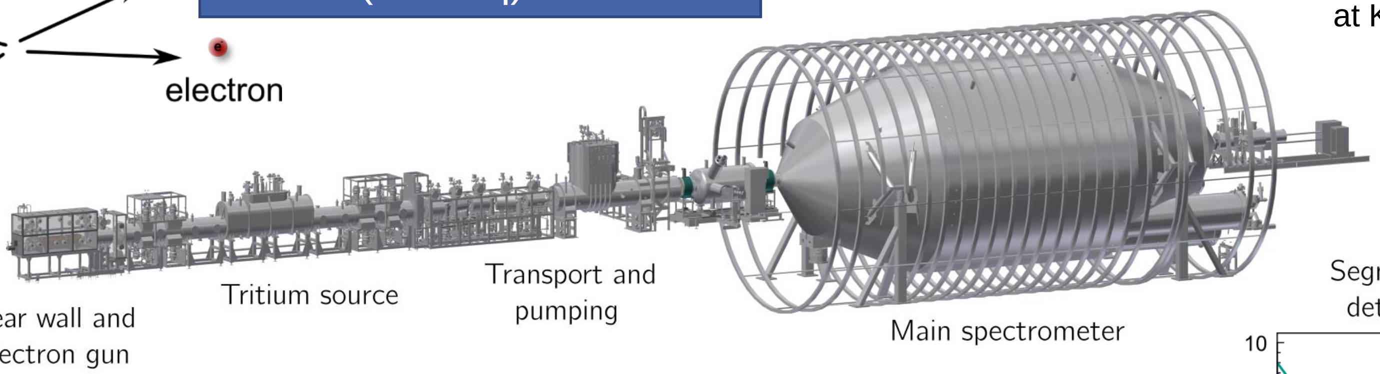
$T_{1/2}$ = 12.3 y



Karlsruhe Tritium Neutrino Experiment (KATRIN)



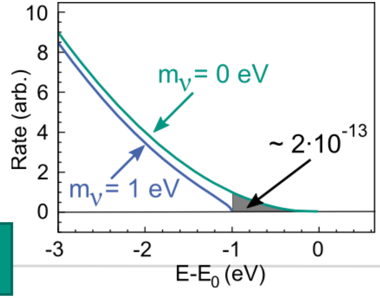
ultra-stable high-luminosity windowless gaseous tritium source (10^{11} Bq)



70 m long setup
at KIT campus north

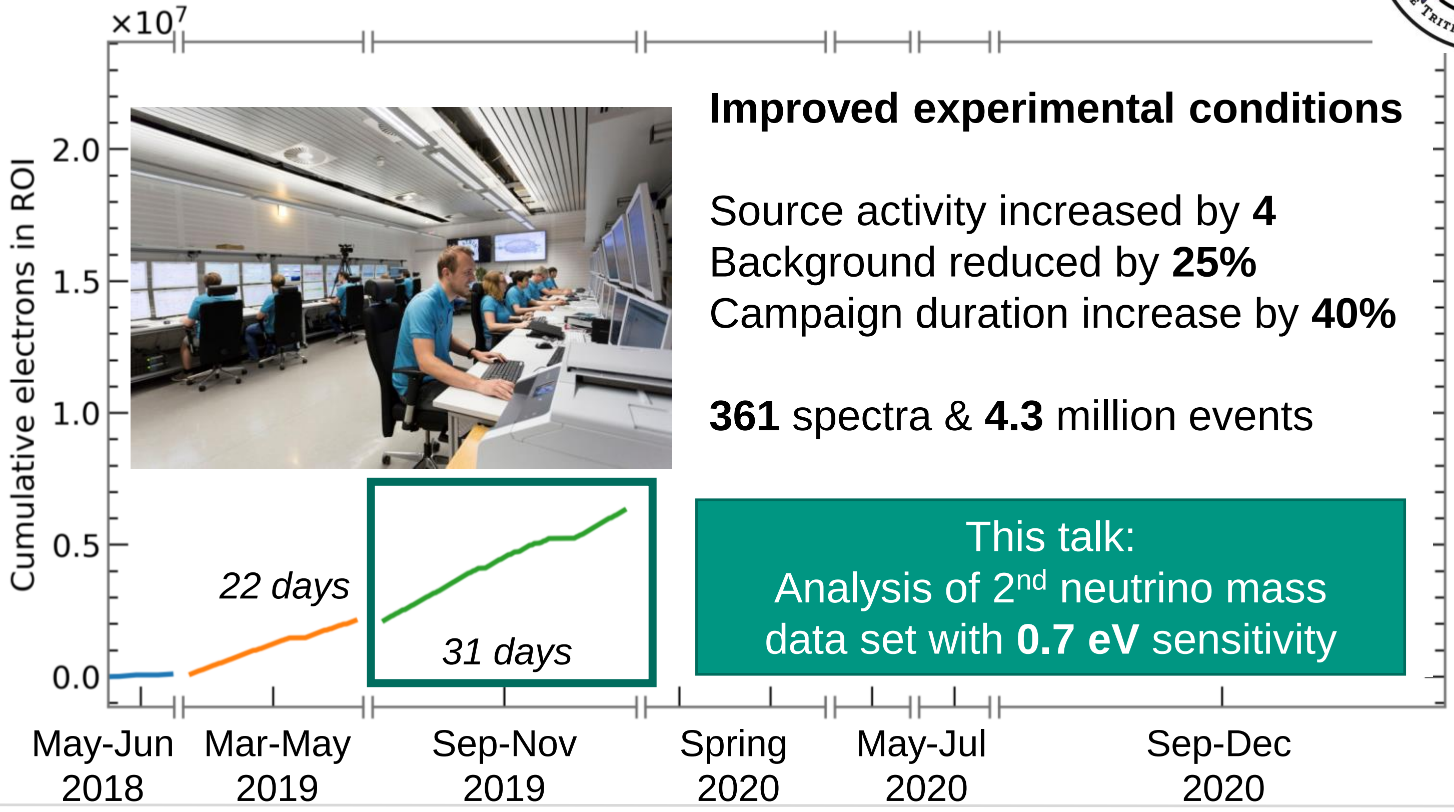
JINST **16** T08015 (2021)

high-resolution MAC-E filter with < 1 eV energy resolution



KATRIN's aim: Direct measurement of m_ν with a sensitivity of 0.2 eV/c²

New data set with the KATRIN experiment



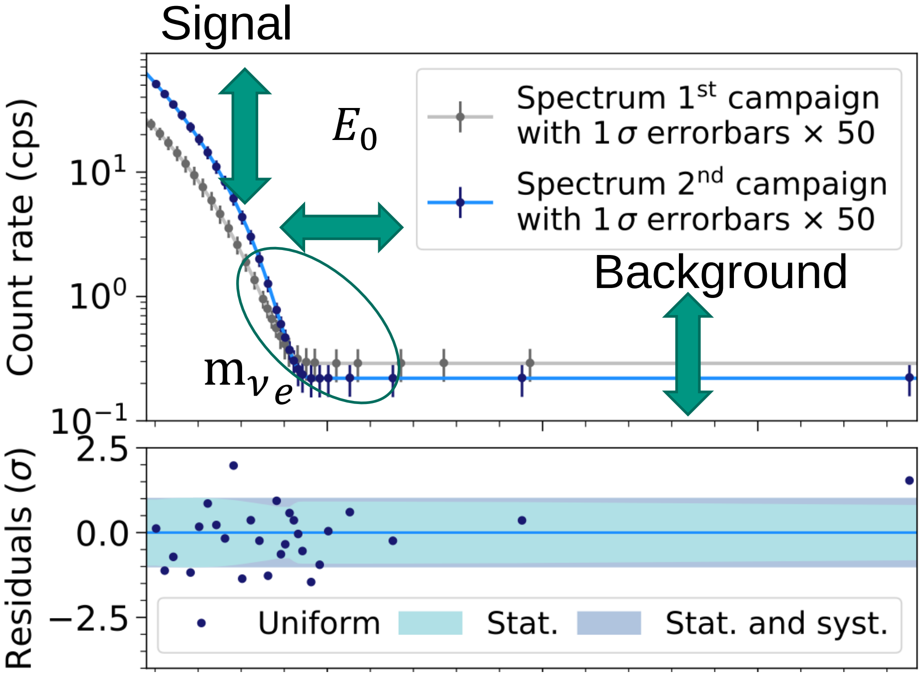
Improved experimental conditions

Source activity increased by **4**
Background reduced by **25%**
Campaign duration increase by **40%**

361 spectra & **4.3** million events

This talk:
Analysis of 2nd neutrino mass data set with **0.7 eV** sensitivity

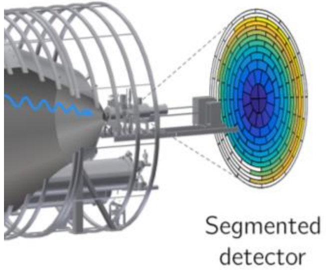
New high-statistics beta-spectrum



arXiv:2105.08533

- **Ring wise fitting**
  (allowing for radial effects
  in source and spectrometer)

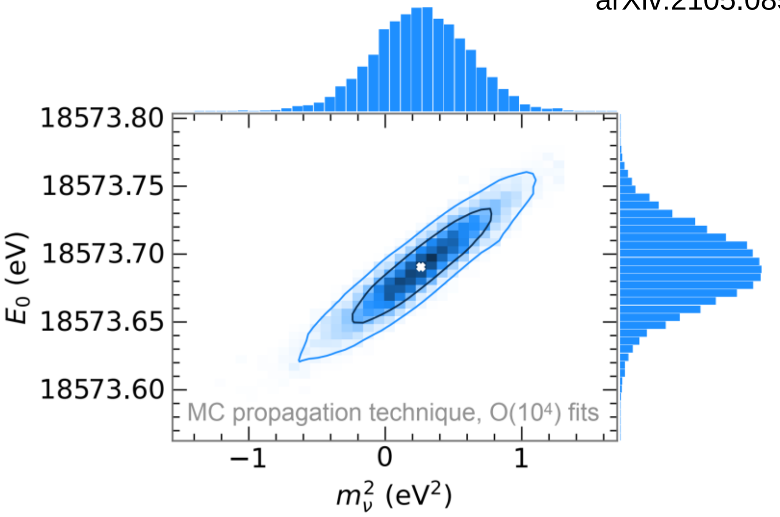
12 x endpoint
12 x signal normalization
12 x background rate
1x neutrino mass
→ **37 parameters**

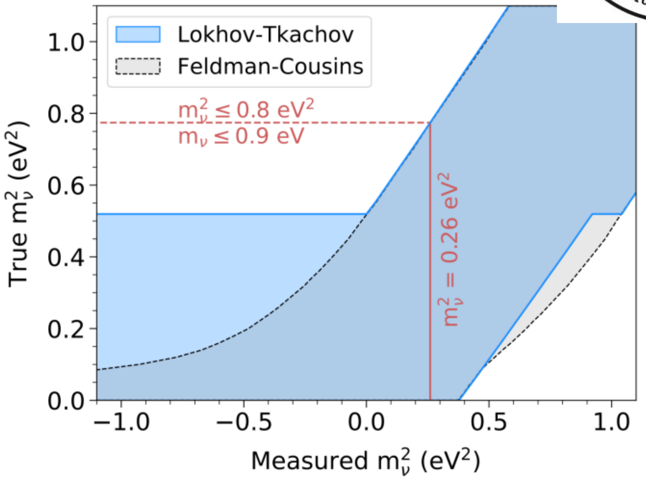


- **Excellent agreement of fit-model to data** $\chi^2/\mathrm{ndof} = 277/299$
- Statistics dominated dataset
- Significant systematics (background and source plasma)

Results

arXiv:2105.08533





- **Value from ring-wise best-fit**

$$m_\nu^2 = 0.26 \pm 0.34\ \text{eV}^2$$ (90% CL)

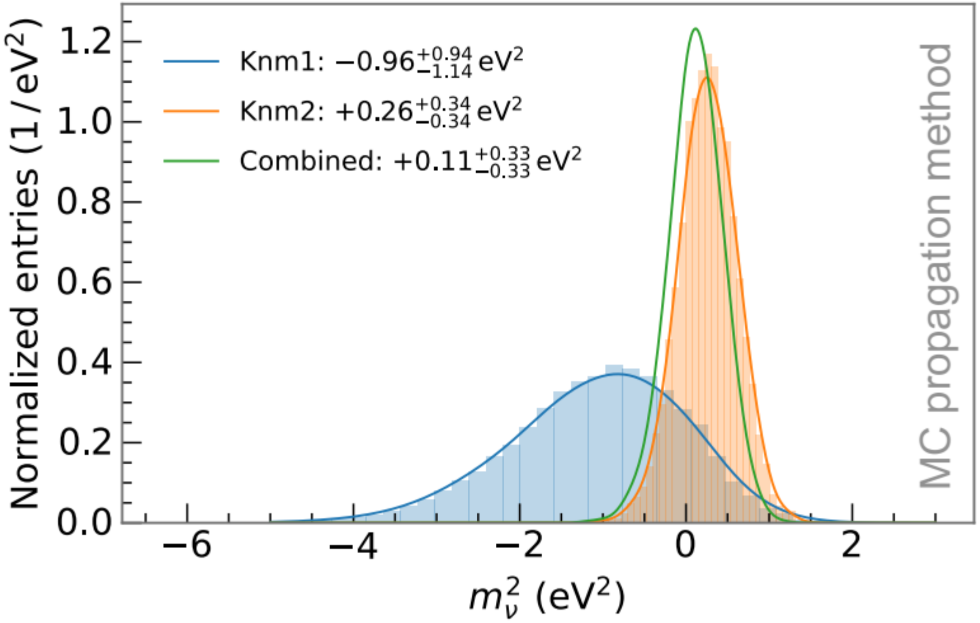
First campaign $m_\nu^2 = (-1.0^{+0.9}_{-1.1})\ \text{eV}^2$ (90% CL)

New limit from 2nd campaign
$m_\nu < 0.9$ eV (90% CL)

First campaign $m_\nu < 1.1$ eV (90% CL)

Combination of 1st and 2nd KATRIN data sets

arXiv:2105.08533



- Combination of likelihoods (χ^2) of both data sets

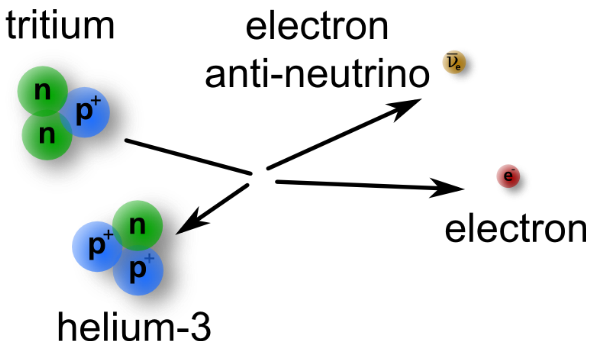
New limit from KATRIN
$m_\nu < 0.8$ eV (90% CL)

- Further methods studied
  - Simultaneous fit to both data sets
  - Bayesian analysis using posterior from first campaign as prior

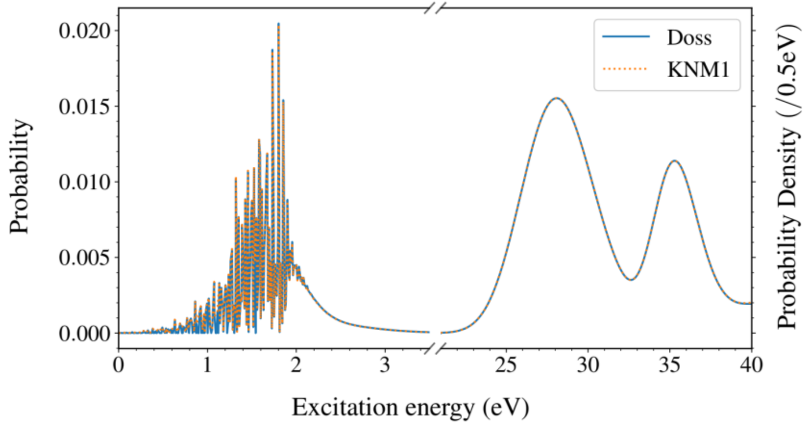
First sub-electronvolt sensitivity from direct neutrino mass experiment

Molecular decay

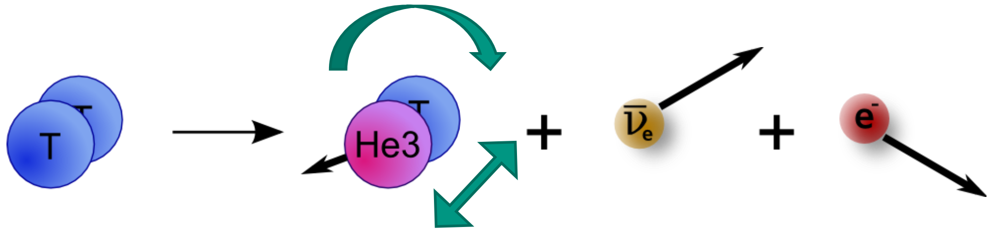
Atomic decay



Final-state distribution



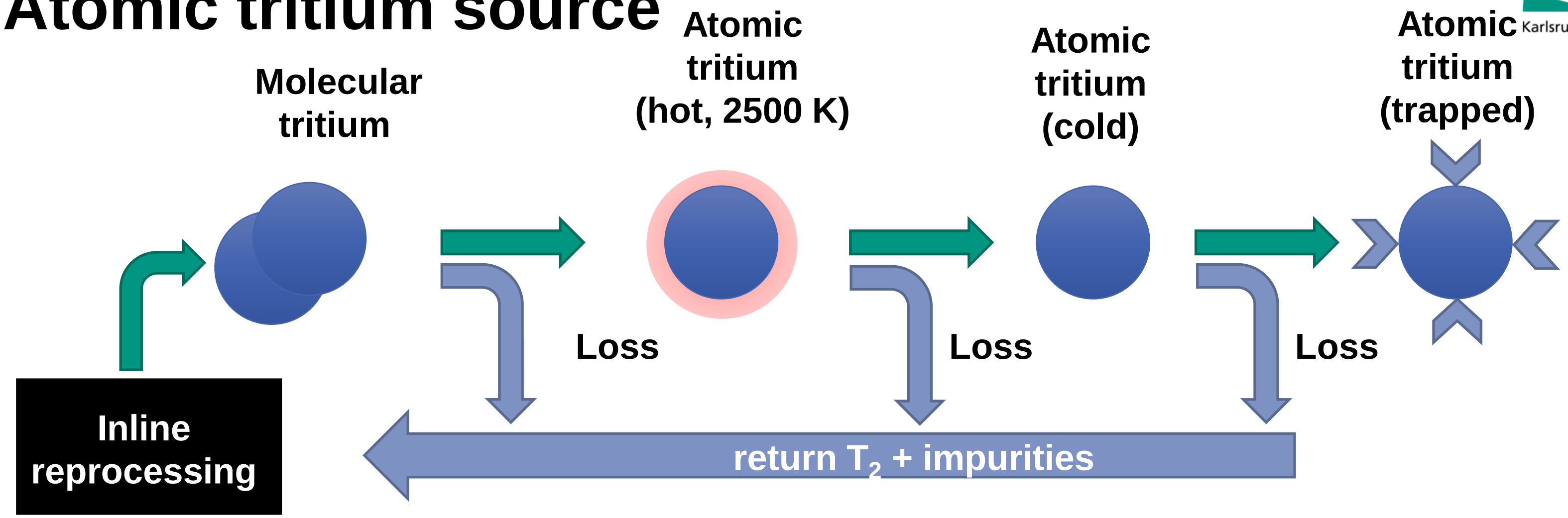
Decay from a molecule

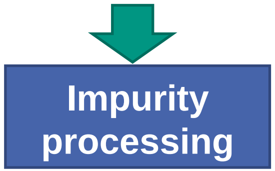


Molecular effects effectively broaden the energy resolution and add model-dependence

+ further inner excitations (rotation / vibration)

Atomic tritium source





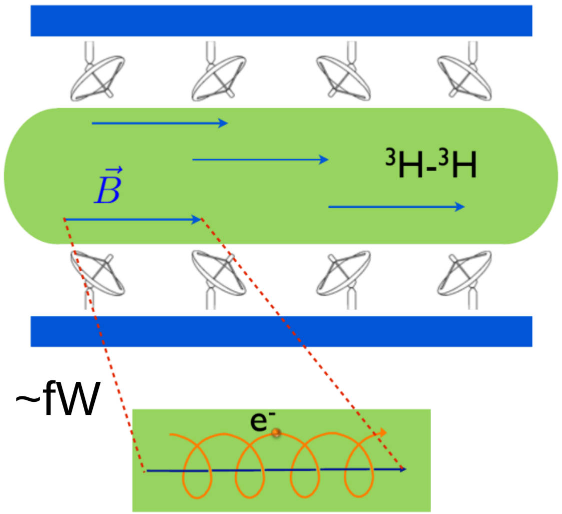
- Avoid recombination on surfaces
- The efficiency of each processing step needs to be optimized (➔ High total efficiency)

Use magnetic dipole (s=1/2) to manipulate T-atoms (stear, cool, trap)

High efficiency important to minimize return fluxes and inventories

Project8 principle and projected sensitivity

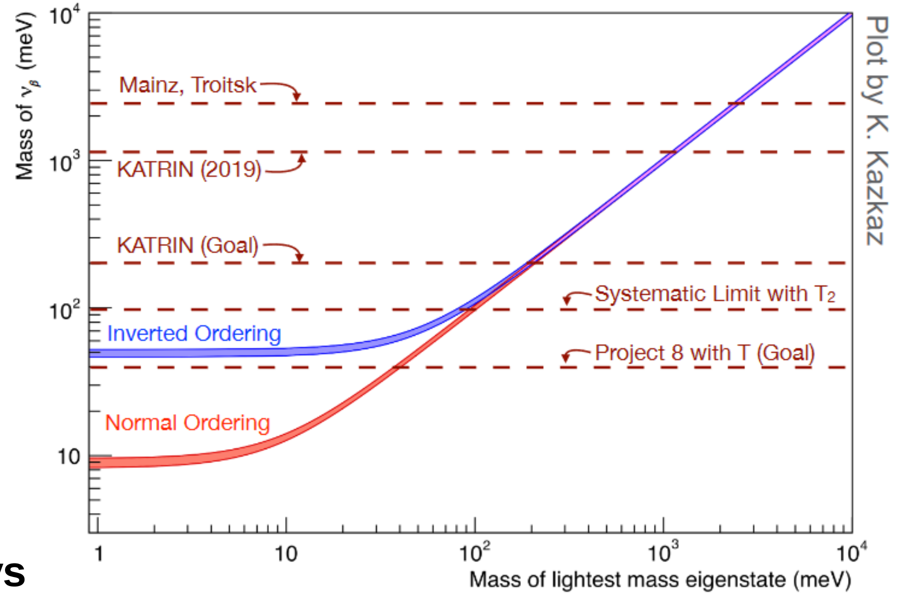
Cyclotron Radiation Emission Spectroscopy



$$f_\gamma = \frac{f_c}{\gamma} = \frac{1}{2\pi}\frac{eB}{m_e + E_{\mathrm{kin}}}$$

Differential measurement with antenna arrays around a (atomic) tritium source

Atomic tritium required to cross the 100 meV line.



Neutrino mass sensitivity aim: 40 meV

Phased approach

2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027

Phase I

→ Single-electron detection; spectroscopy
→ ^{83m}Kr conversion-electron spectrum

First CRES demonstration: PRL 114: 162501, 2015
~eV Resolution J. Phys. G. 44, 2017
Machine learning: New J. Phys. 22 (2020)

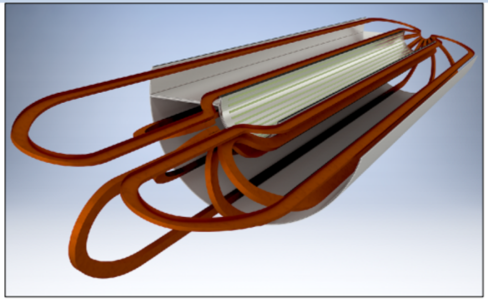
Phase II

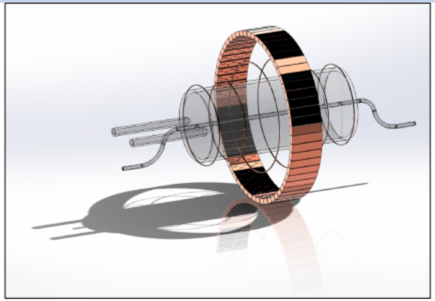
→ Systematic & background studies
→ T_2 spectrum and endpoint measurement

Phenomenology: Phys. Rev. C. 99 (2019) 055501
RF simulation: New J. Phys. 21 (2019) 113051

Phase III R&D — **Phase III**

→ ≈10-100s cm^3 volume; free-space detection with antenna array; $m_\beta < 5$ eV/c^2
→ Demonstration of atomic tritium production, cooling, and trapping





Phase IV

→ $m_\beta < 40$ meV/c^2
→ Mass hierarchy

First tritium measurement (Phase II)

- T_2 gas cell in 1 T solenoid

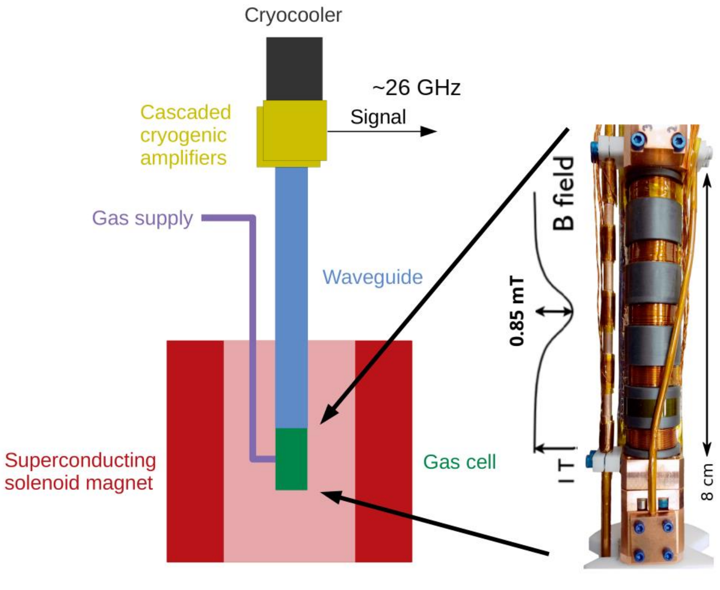
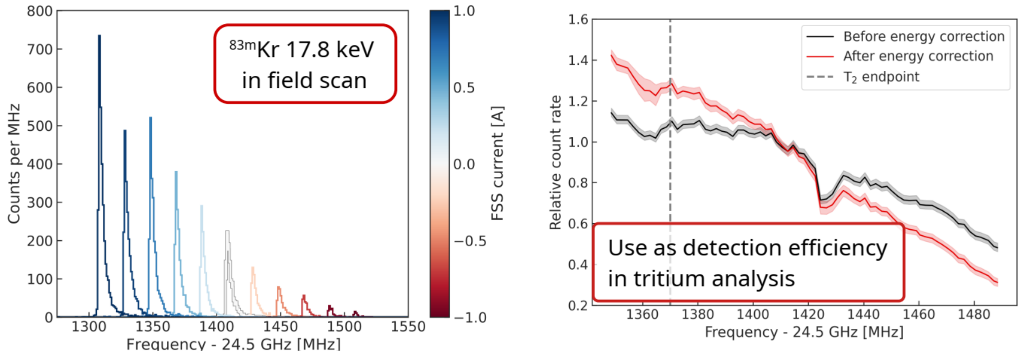


Image: Project 8

- Acquisition: 82 days (12/19-03/20)
- Event: 6017 events
- Background: No events beyond endpoint
  → $\dot{N}_{\mathrm{Bg}} < 3 \cdot 10^{-10}\ \mathrm{eV}^{-1}\mathrm{s}^{-1}$

Detector efficiency calibration with K-line from ^{83m}Kr



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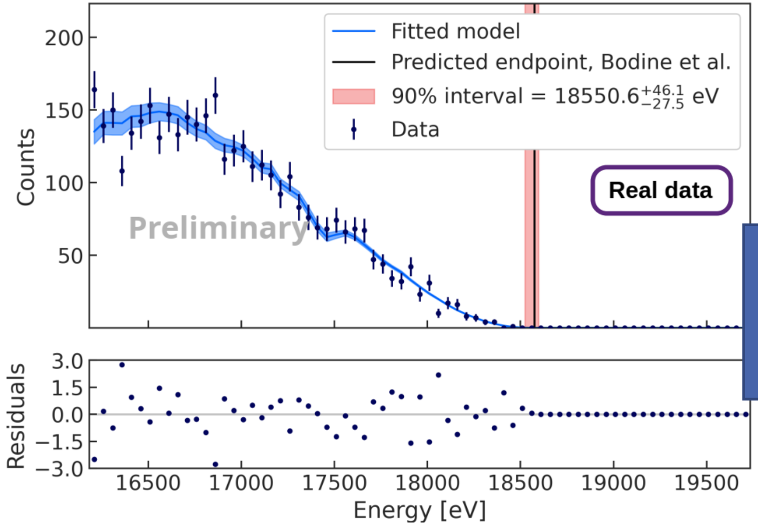
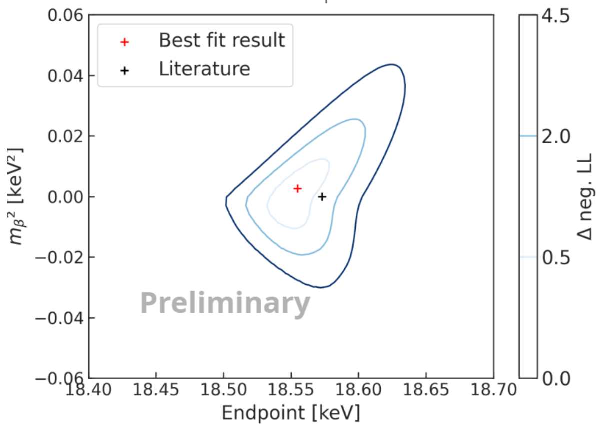
First tritium results from Phase II

- **Preliminary results**



Agreement with literature value (18573 eV)

Preliminary limit: m_β< 185 eV/c² (90% CL)*



*Analysis is being finalized

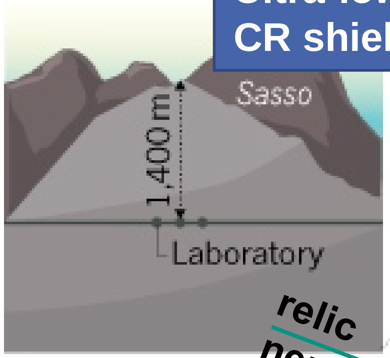
17

Next steps

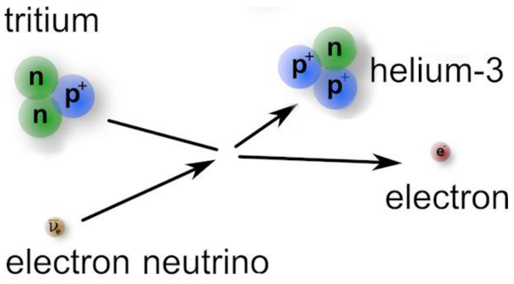
- Last systematic simulation studies under way
- Expected to decrease uncertainty on detector response
- Finalize frequentist and Bayesian analysis

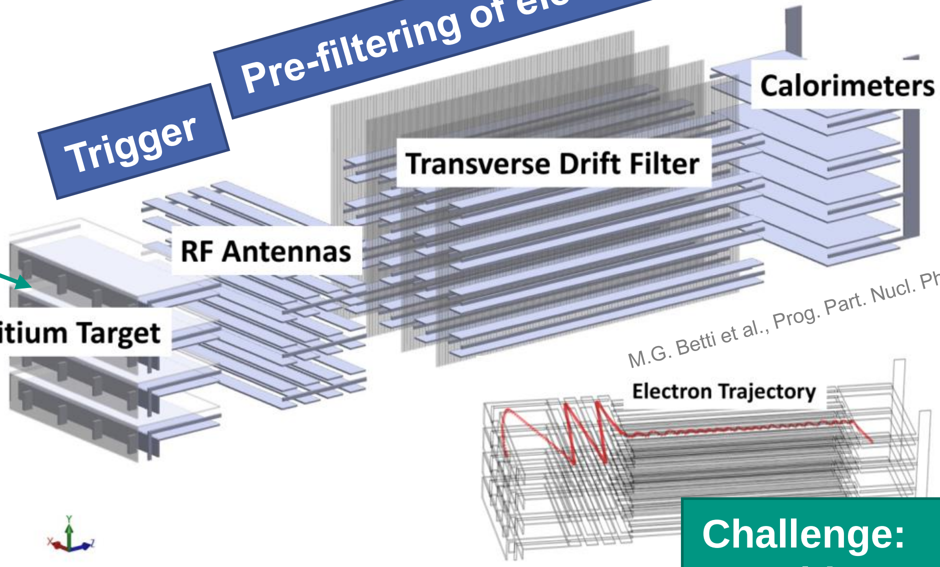
Relic Neutrino detection with PTOLEMY

Ultra-low background
CR shielding, radio-pure components



Capture of relic nu in T





TES with
σ(E) = 0.05eV

M.G. Betti et al., *Prog. Part. Nucl. Phys.* 106 (2019) 120-131

100 g tritium
on graphene
~ 500,000 m²

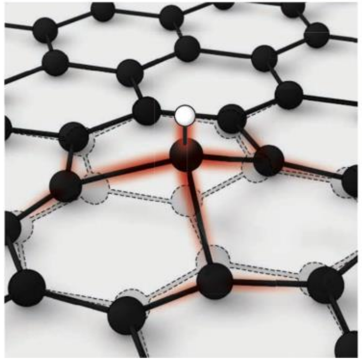
Challenge:
Resulting rate = 10 events / year

Neutrino mass with PTOLEMY

- **Smaller version (mg-scale) may be used for neutrino mass measurement**
- **R&D planned or ongoing**

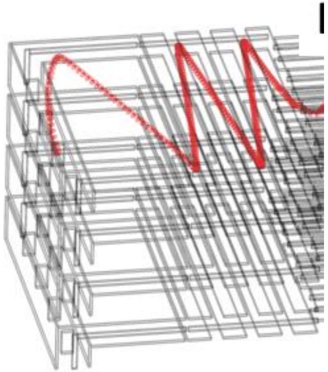
M.G. Betti *et al* JCAP07(2019)047

Tritiated graphene	**CRES signal**	**Compact dynamic filtering**	**TES detector**



L. Hornekær Science 364 (6438), 2019, 331-332

Quasi-atomic T-source?



Pre-measurement of electron energy and pitch angle

Select particle and reduce E_{kin}

Differential meas. of electron (σ_E ~50 meV)

Overview on current direct neutrino mass activities

Karlsruhe Institute of Technology

ECHo
- Analysis of ~5 month of 60 pixel measurement ongoing (20 eV sensitivity)
- Preparation of next detector generation with 12000 pixels x 10 Bq

HOLMES
- Multiplexing of channels successful w/o loss of energy resolution
- Detectors ready to be loaded with ^{163}Ho after final implantation optimizations

KATRIN
- **New neutrino mass limit by KATRIN**
- Analysis of ~20% of total data ongoing

$m_\nu < 0.8$ eV (90% CL)

arXiv:2105.08533

~5% of total statistics

PROJECT 8
- First preliminary tritium results by Project 8: $m_\nu < 185$ eV (90% CL)
- R&D for large volume CRES and atomic tritium ongoing

PTOLEMY
- Various R&D projects on crucial technologies ongoing
- Smaller experimental version for neutrino mass measurement considered

Direct neutrino mass measurement overview

Thank you!

earlier | 2005 | 2010 | 2015 | 2020 | 2025 | **Future**

- Holmium-based (neutrino mass)

150 eV

< 225 eV
1987

ECHO-1K | ECHO-100K < 2 eV

HOLMES | <? eV

sub eV
R&D

# of channels

- Tritium-based (anti-neutrino mass)

1.1 eV

0.8 eV

Study of key systematics

Mainz & Troitsk < 2eV

KATRIN R&D / construction | Meas. < 0.2 eV

Project8 R&D | Meas. < 5 eV

PTOLEMY R&D

< 40 meV
R&D

- atomic T
- diff. measurement

The next high sensititivity experiments require substantial R&D efforts