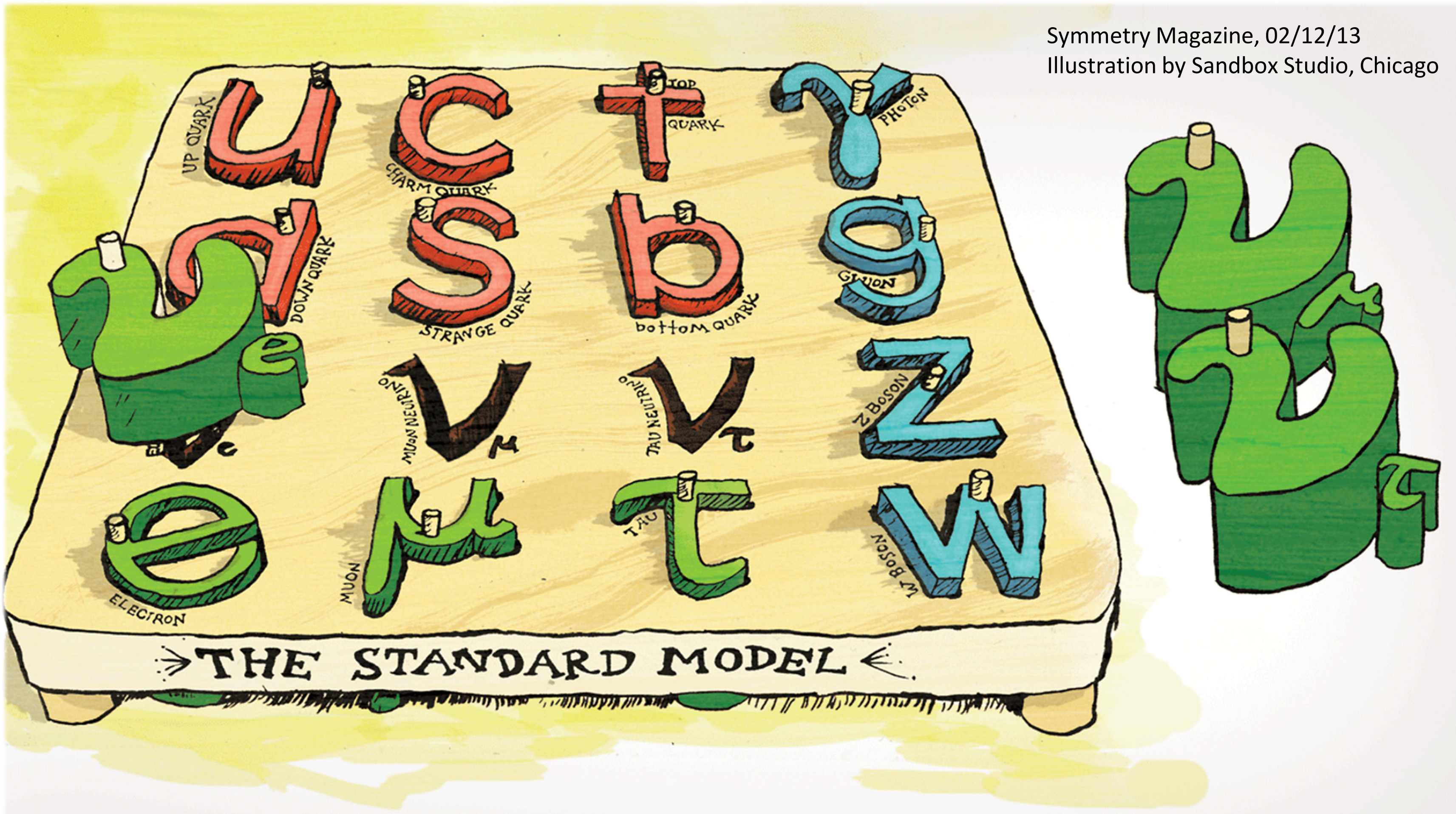
Invisibles18

Direct neutrino mass measurements

Loredana Gastaldo

Kirchhoff Institute for Physics, Heidelberg University

Massive Neutrinos

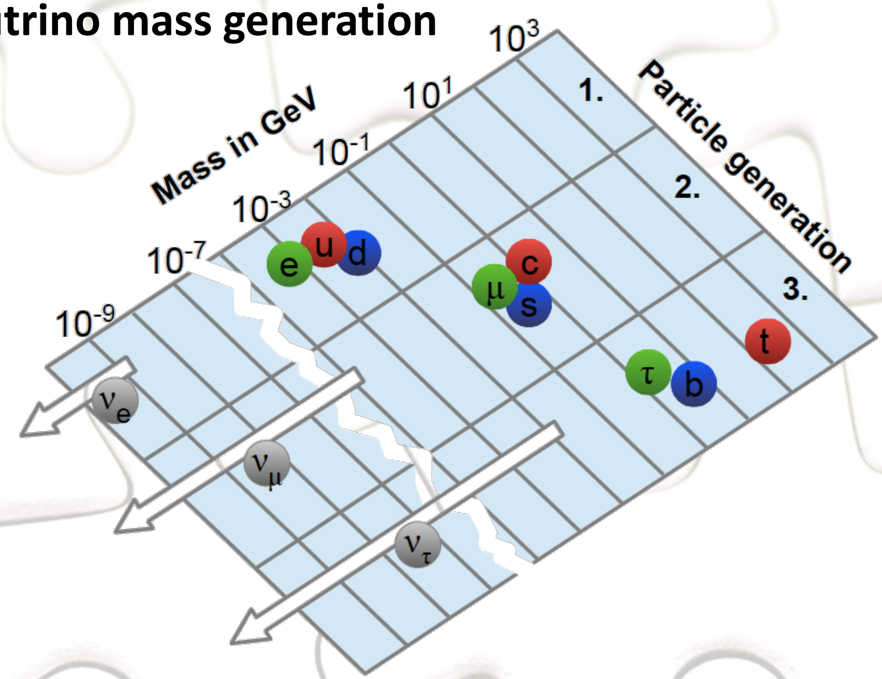


Symmetry Magazine, 02/12/13
Illustration by Sandbox Studio, Chicago

Knowing neutrino mass scale….

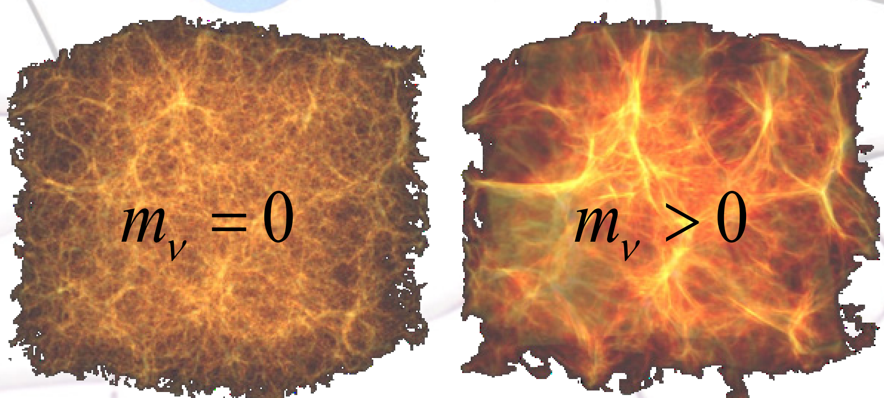
Particle Physics

Neutrino mass generation



Astrophysics

Supernova netrinos



Cosmology

Matter distribution in the Universe

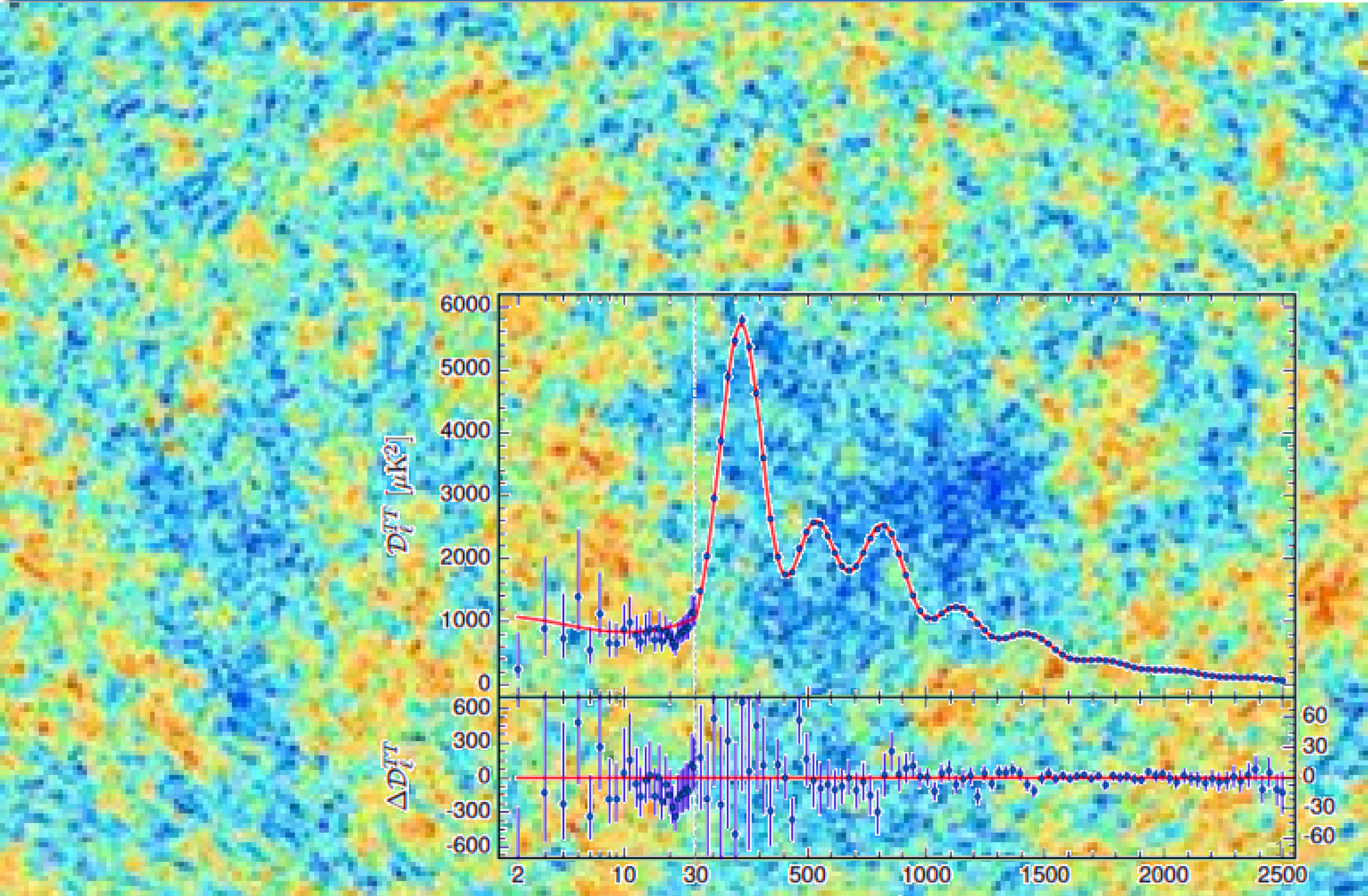
Outline

- Observable sensitive to finite neutrino masses
- Direct neutrino mass measurements through kinematic approach

Beta decay of ^{3}H and electron capture in ^{163}Ho

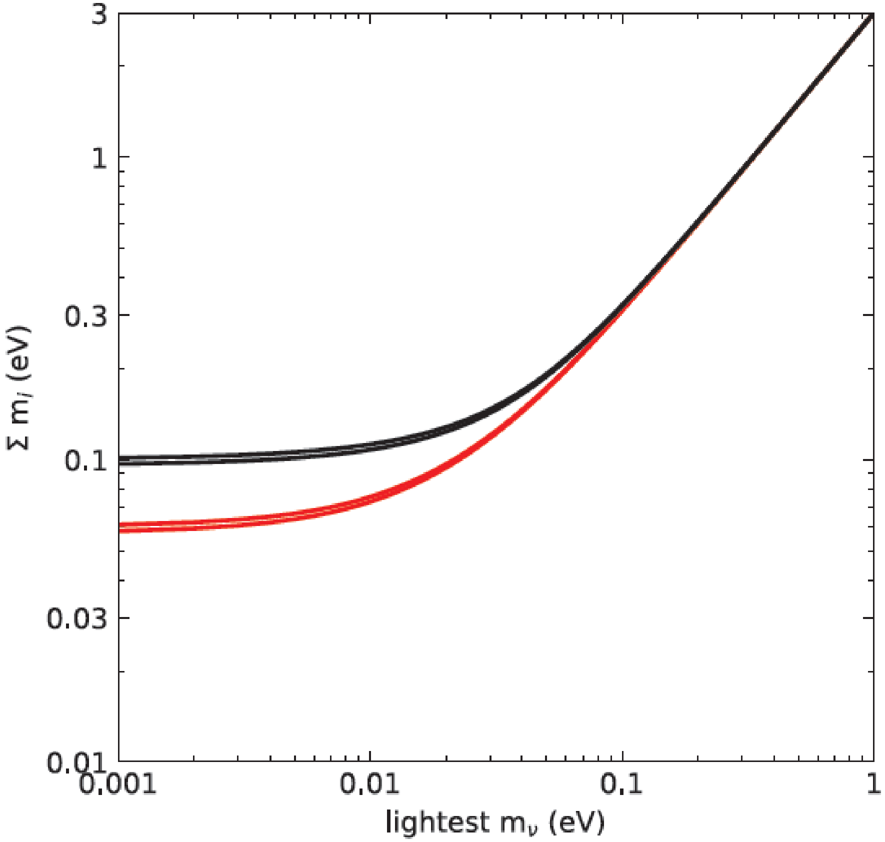
- ^{3}H-based experiments
- ^{163}Ho-based experiments
- Conclusions and outlook

Cosmology



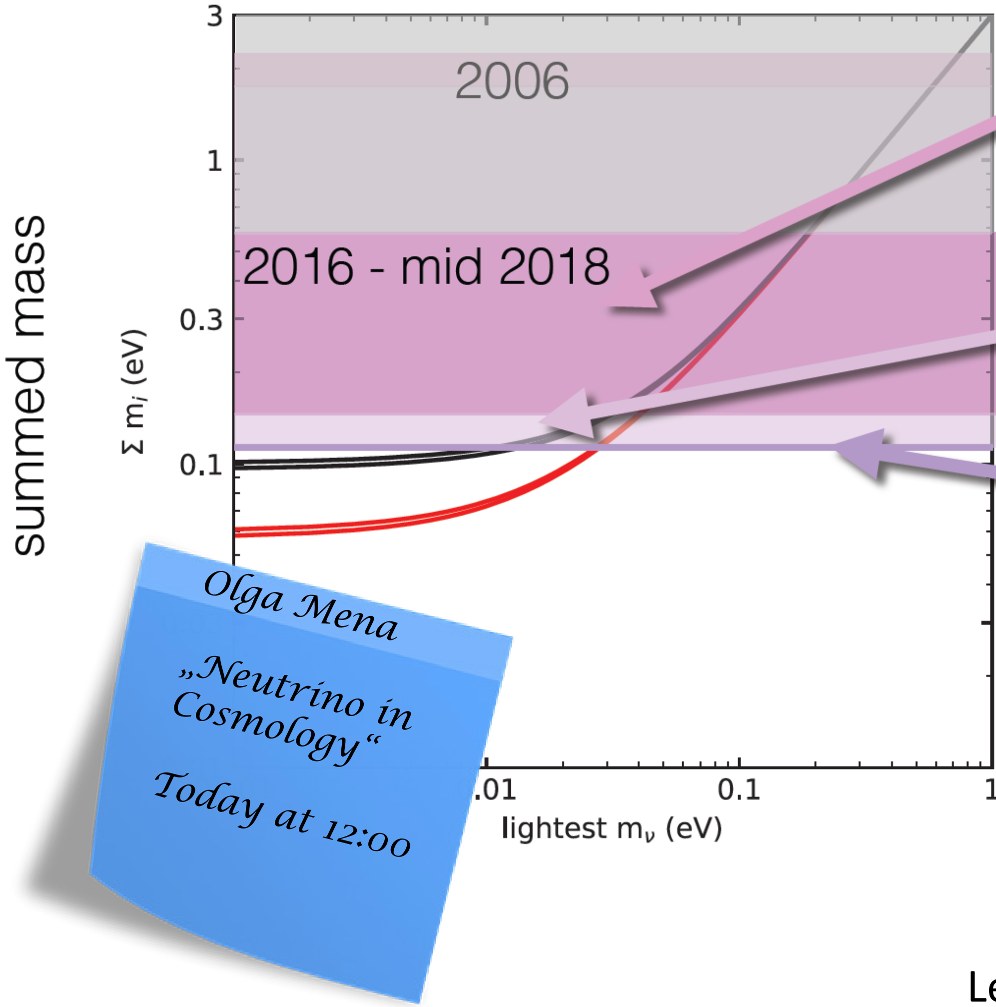
6000
5000
4000
3000
2000
1000
0
600
300
0
-300
-600
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500

Cosmology



Cosmology

95%CL upper bounds on $\Sigma_i m_i$ for 7 parameters



CMB only: Planck,
w/o high-l polarisation and lensing…
$\Sigma_i m_i$ < 590 to 140 meV (95%CL)

CMB + conservative LSS :

- Planck 2016 {TT+SIMLow+lensing} + BAO:
  $\Sigma_i m_i$ < **170 meV** (95%CL)
- Planck 2016 {TTTEEE+SIMLow} + BAO:
  $\Sigma_i m_i$ < **120 meV** (95%CL)

- Planck 2015 + Lyman-α:
  $\Sigma_i m_i$ < **120 meV** (95%CL)

[Planck col.] 1605.02985; Cuesta et al. 2016;
Palanque-Delabrouille et al. 1506.05976;
Vagnozzi et al. 1701.08172;
PDG "Neutrino Cosmology" [JL & Verde]

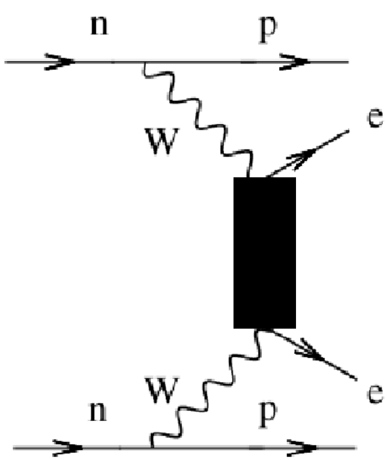
… harder to avoid bounds with simple cosmological model extensions

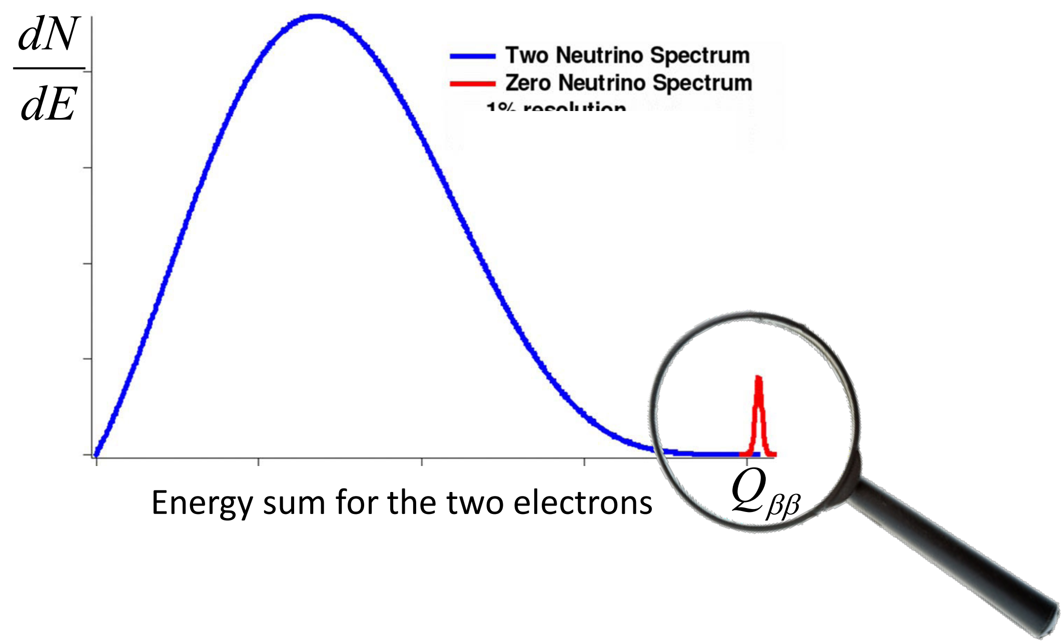
Lesguorgues Neutrino 2018

Neutrinoless double beta decay

- If neutrinos are massive
- If neutrinos are Majorana particles

$(A,Z) \rightarrow (A, Z+2) + 2e^{-}$





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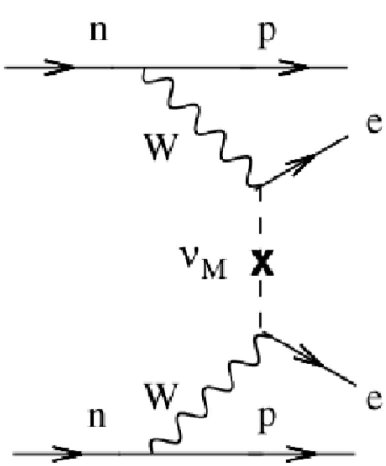
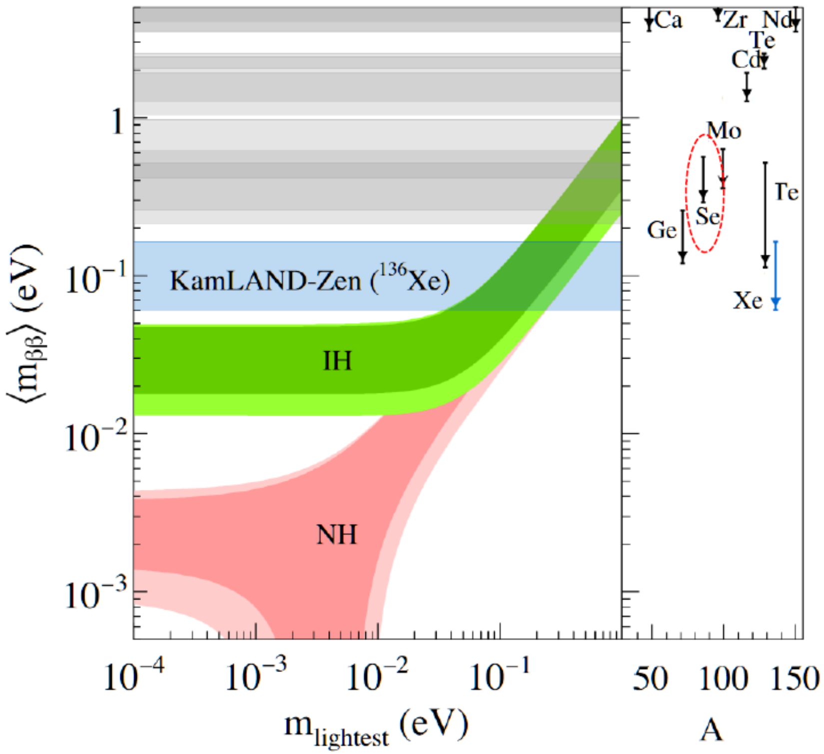


- If exchange light Majorana neutrino

→ Sensitivity to effective Majorana mass



$$\left(\tau_{1/2}^{0\nu}\right)^{-1} = \left|\frac{m_{\beta\beta}}{m_e}\right|^2 \left|M_\nu^{0\nu}\right|^2 G^{0\nu}$$

$$m_{\beta\beta}^2 = \left|\sum U_{ei}^2 m(\nu_i)\right|^2$$

Neutrinoless double beta decay

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- If neutrinos are Majorana particles

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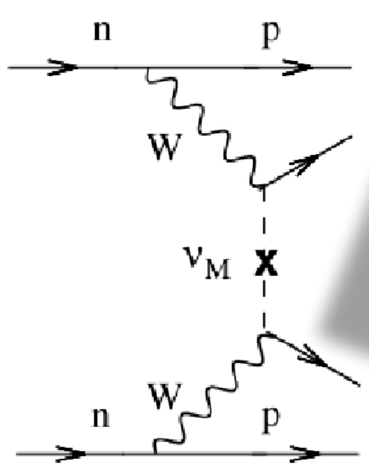
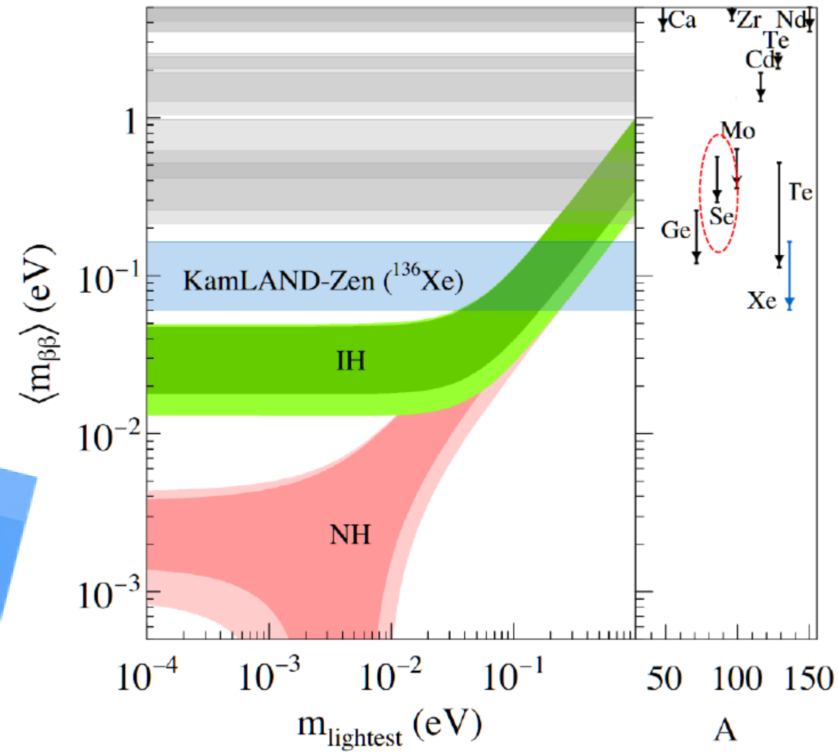


Chiara Brofferio
„Review of 0ν2β experiments“
Today at 11:00



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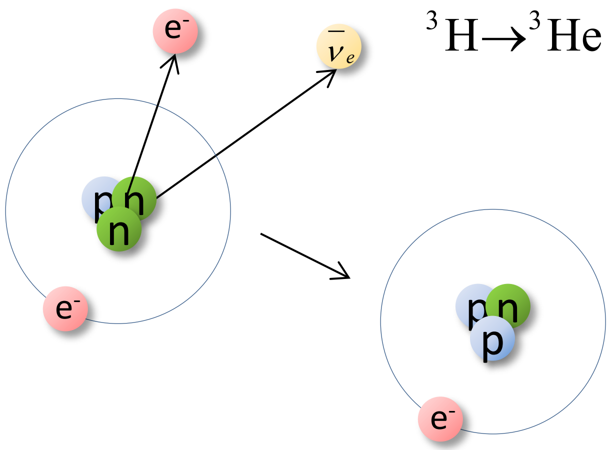
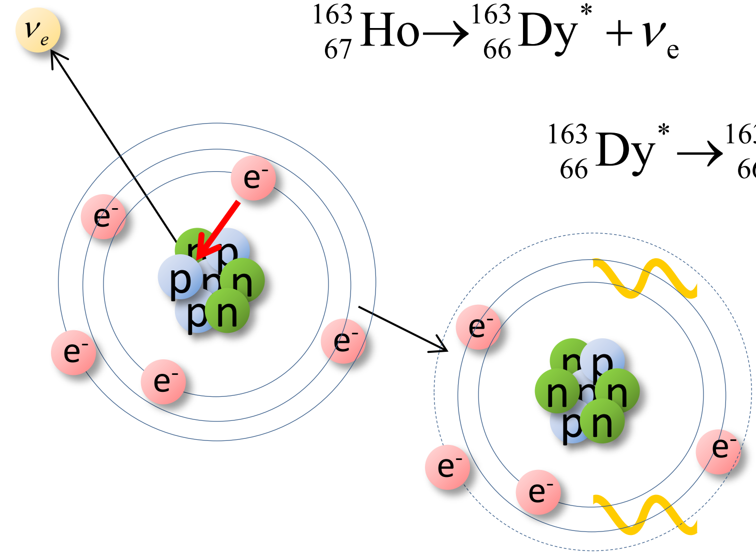
Beta decay and electron capture

$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-} + \overline{\nu}_e$$



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

$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow {}^{163}_{66}\mathrm{Dy} + E_{\mathrm{C}}$$



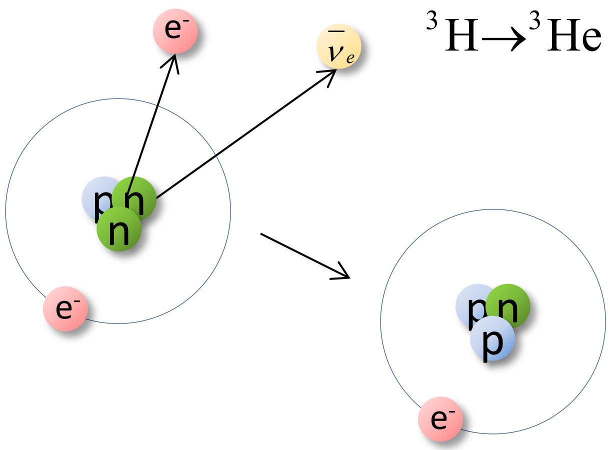
- $\tau_{1/2} \cong 12.3$ years (4*10^8 atoms for 1 Bq)
- Q_{β} = 18 592.01(7) eV

E.G. Myers et al., *Phys. Rev. Lett.* **114** (2015) 013003

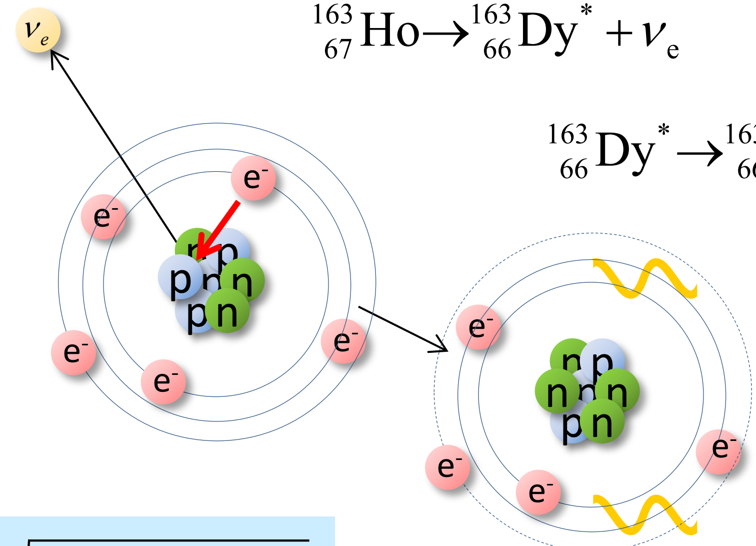
- $\tau_{1/2} \cong 4570$ years (2*10^11 atoms for 1 Bq)
- Q_{EC} = $(2.833 \pm 0.030^{stat} \pm 0.015^{syst})$ keV

S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501

Beta decay and electron capture



$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-} + \overline{\nu}_e$$



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$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow {}^{163}_{66}\mathrm{Dy} + E_{\mathrm{C}}$$

$$\frac{dW}{dE} \propto (Q - E)^2 \sqrt{1 - \frac{m_\nu^{\,2}}{(Q - E)^2}}$$

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E.G. Myers et al., *Phys. Rev. Lett.* **114** (2015) 013003

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S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501

Beta decay and electron capture

Kinematics of beta decay

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

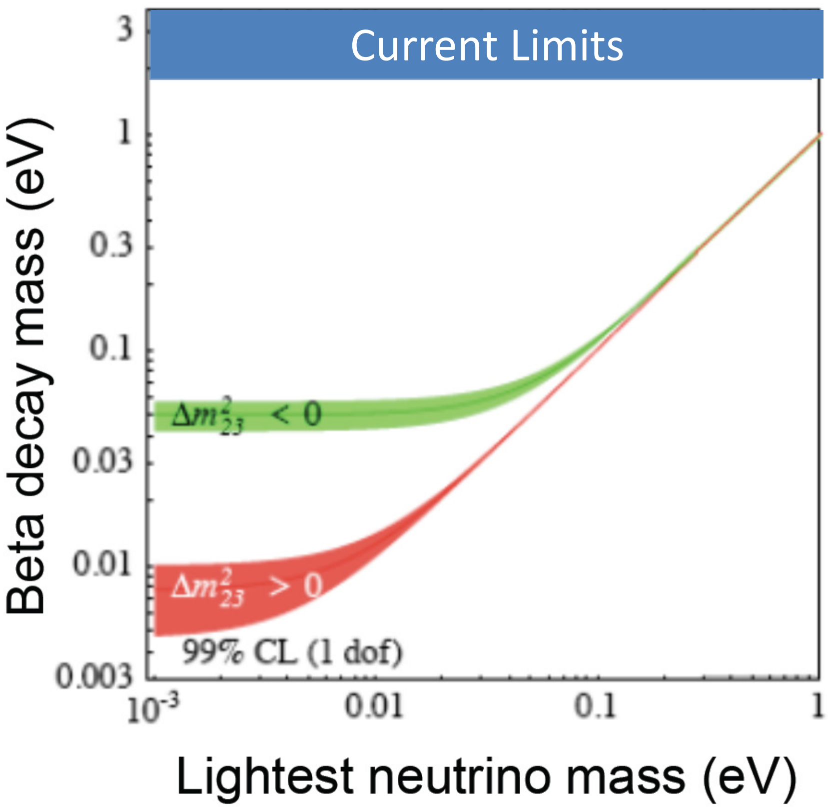
- Model independent
- Laboratory experiments

$$m(\overline{\nu}_e) < 2\ eV$$

^3H (1)

$$m(\nu_e) < 225\ eV$$

^{163}Ho (2)



(1) Ch. Kraus *et al.*, Eur. Phys. J. C **40** (2005) 447
N. Aseev *et al.*, Phys. Rev D **84** (2011) 112003

(2) P. T. Springer, C. L. Bennett, and P. A. Baisden Phys. Rev. A 35 (1987) 679

Beta decay and electron capture

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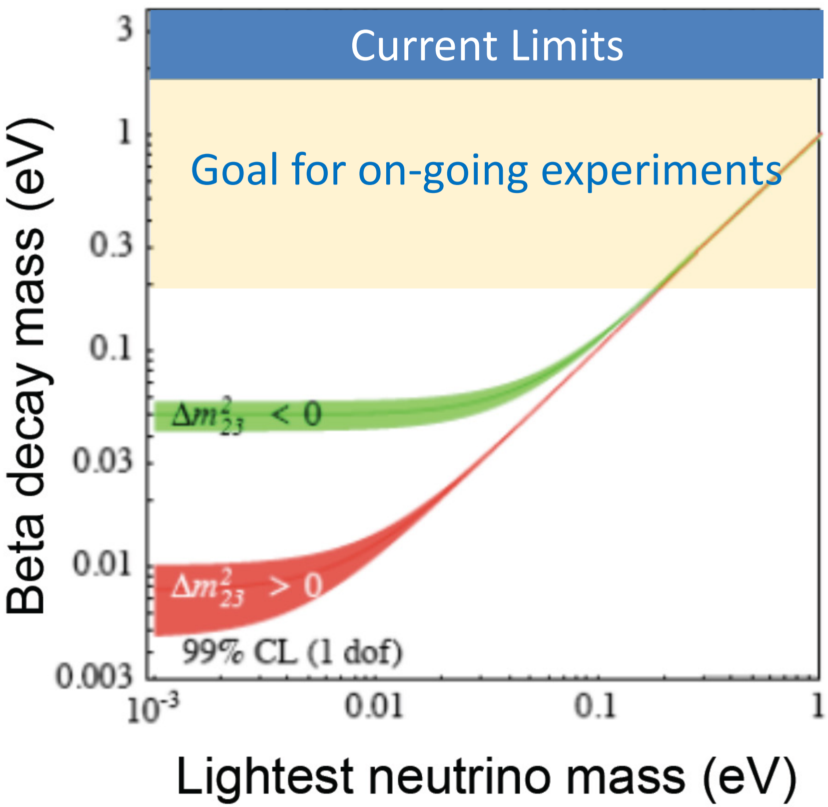
- Model independent
- Laboratory experiments

$m(\bar{\nu}_e) < 2\ eV$ ^{3}H   (1)

$m(\nu_e) < 225\ eV$ ^{163}Ho   (2)

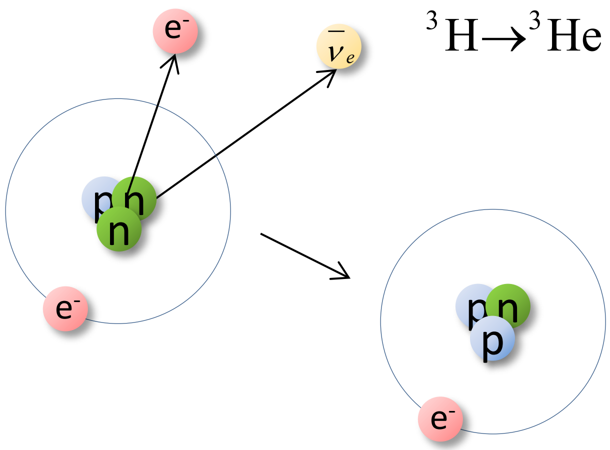
- **Next future 200 meV**



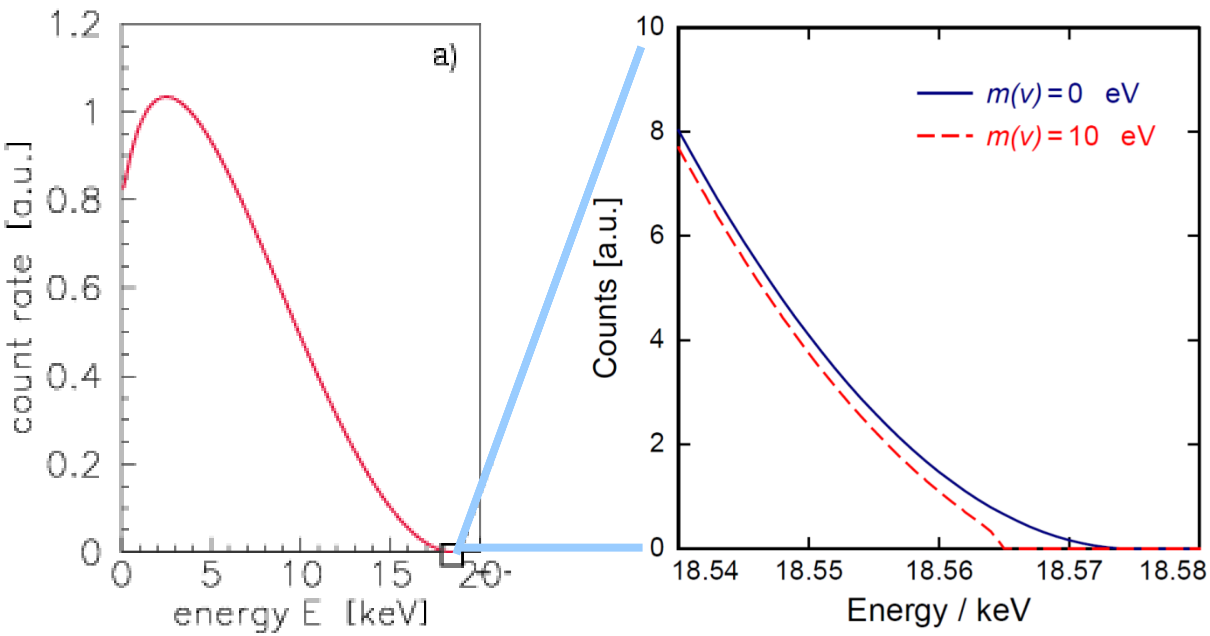
(1) Ch. Kraus *et al.*, Eur. Phys. J. C **40** (2005) 447
N. Aseev *et al.*, Phys. Rev D **84** (2011) 112003

(2) P. T. Springer, C. L. Bennett, and P. A. Baisden Phys. Rev. A 35 (1987) 679

Beta decay of ^{3}H



$$^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^- + \overline{\nu}_e$$



Only a small fraction of events in the last eV below the endpoint: **$2 * 10^{-13}$**

^{3}H based experiments

❖ The Karlsruhe Tritium Neutrino Experiment – **KATRIN**

Main ideas:

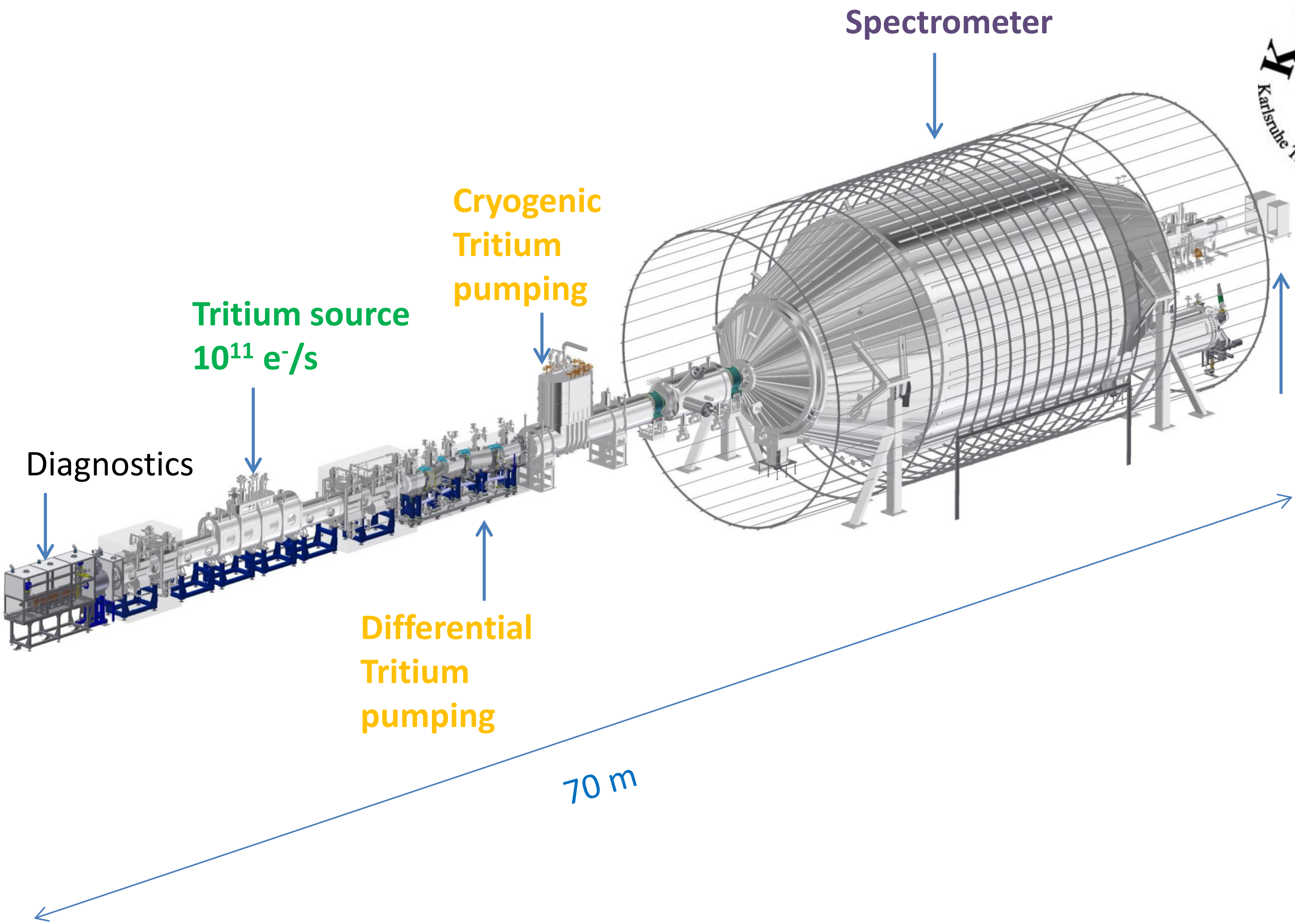
- high activity source 10^{11} e^{-}/s
- high resolution MAC-E filter to select electrons close to the end point
- count electrons as function of retarding potential
  → integral spectrum

❖ **Project8**

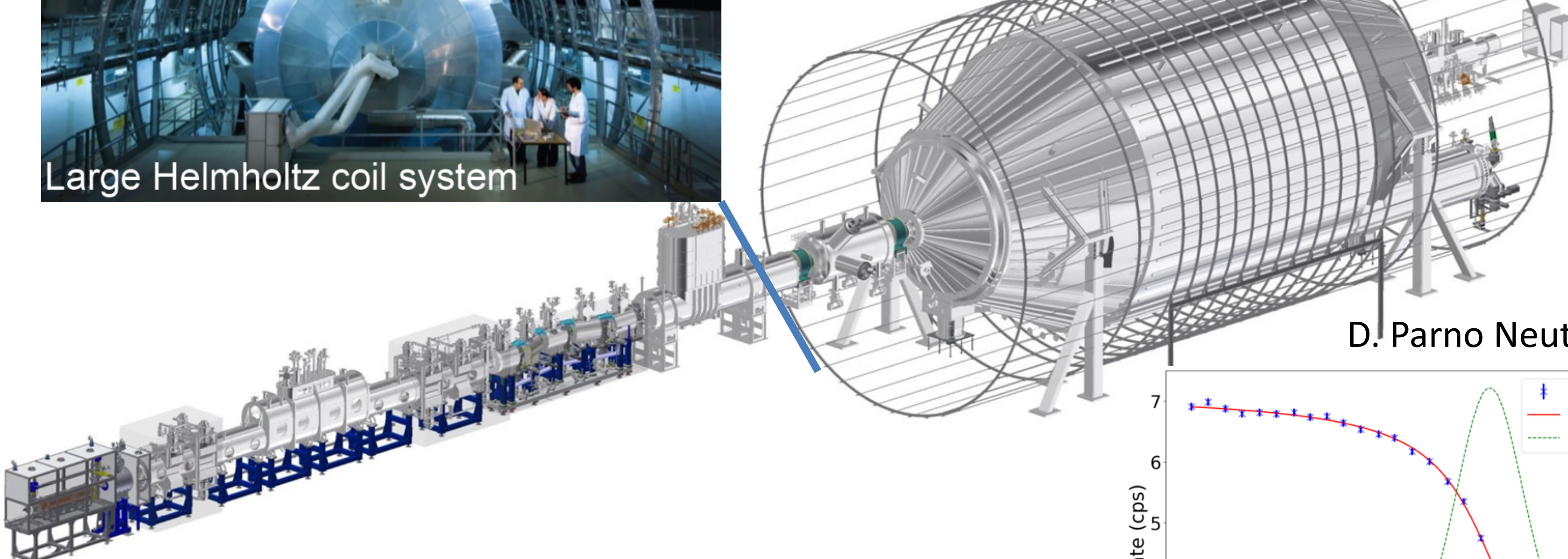
Main ideas:

- Source = detector $10^{11} – 10^{13}$ $^{3}H_2$ molecules /cm^3
- Use cyclotron frequency to extract electron energy
- Differential spectrum

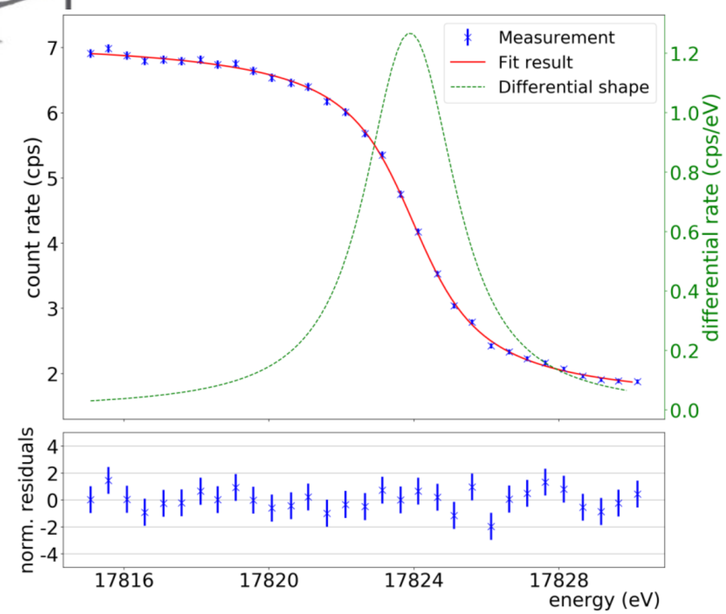
The KATRIN experiment



The KATRIN experiment: present status



D. Parno Neutrino 2018

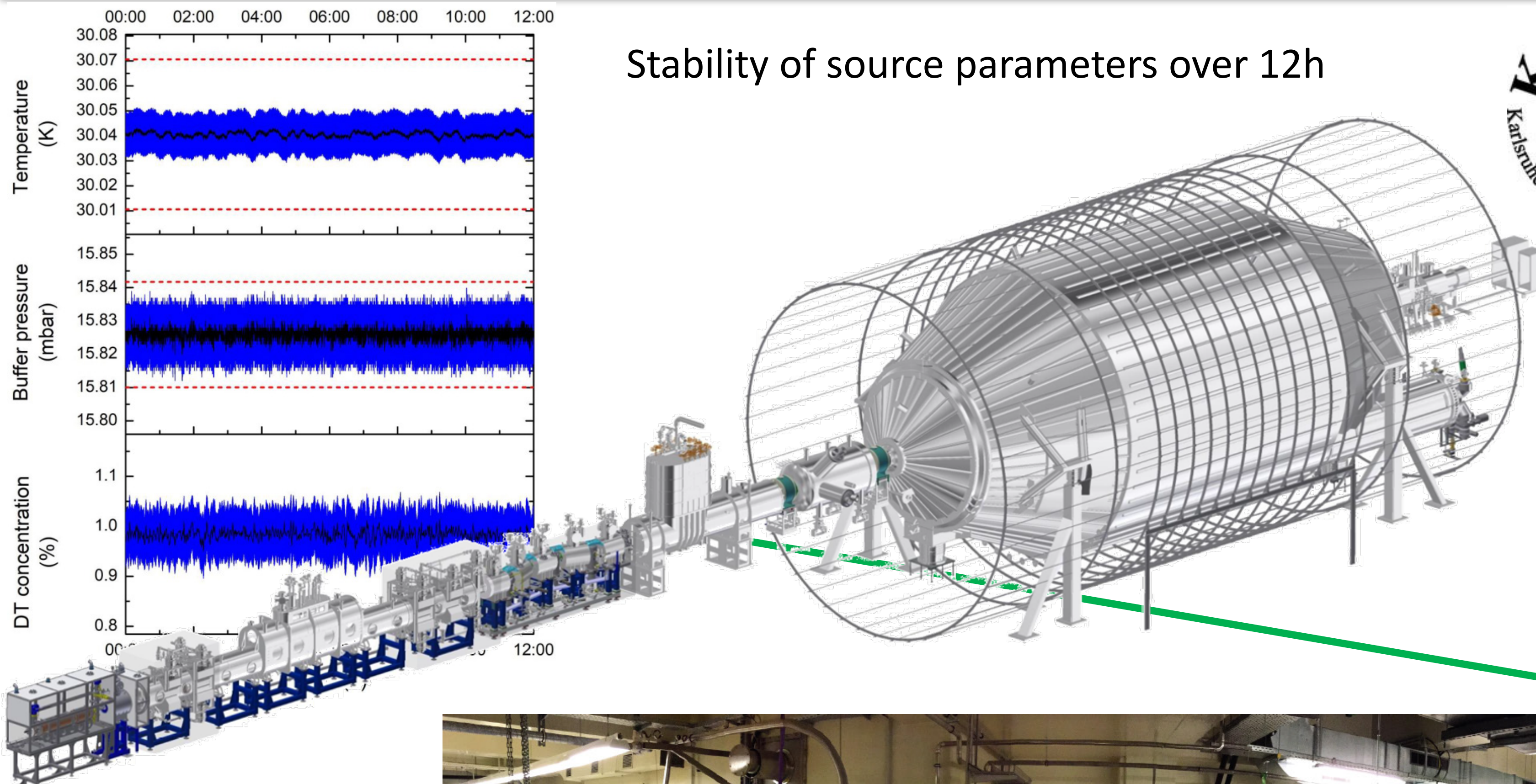


Validation of high (<1 eV) spectroscopic resolution of KATRIN spectrometer with a gaseous ^{83m}Kr source

*KATRIN collab., JINST **13** P04020 (2018),*
*KATRIN collab., EPJ C **78** 368 (2018)*

The KATRIN experiment: present status

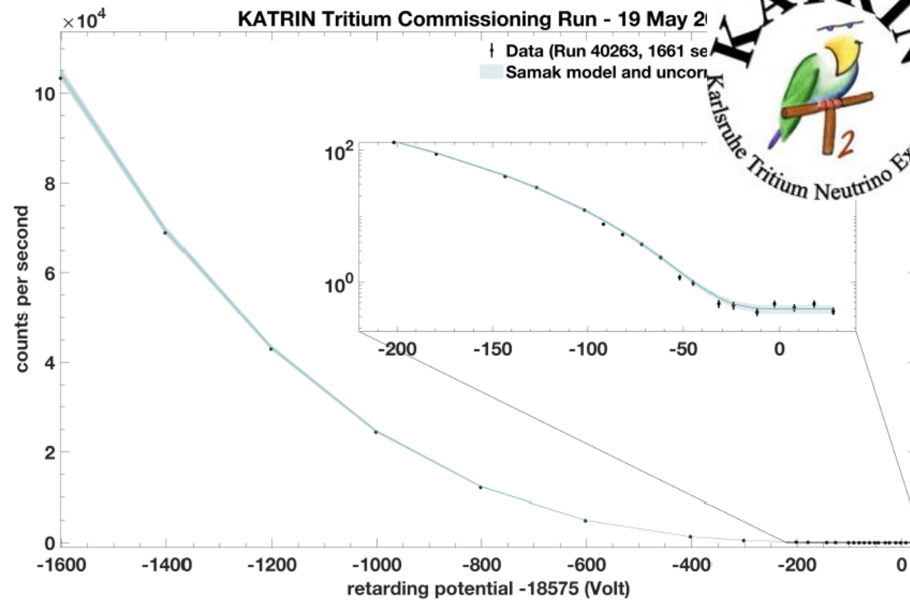
Stability of source parameters over 12h



The KATRIN experiment: m_υ measurement

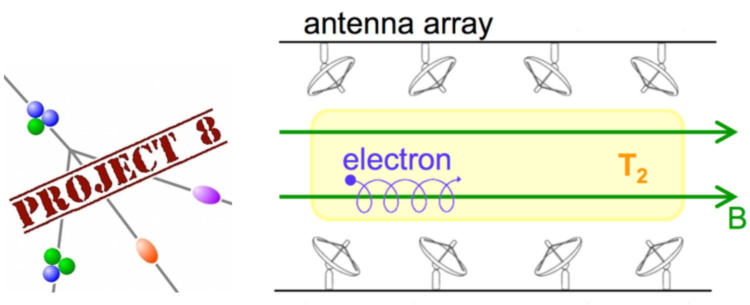
First tritium campaign May/June 2018

- Commissioning of system with tritium (1% of nominal activity)
- Demonstrate 0.1% global system stability
- Investigate ion generation and retention
- Study beta spectrum for systematic effects and test analysis strategies



D. Parno Neutrino 2018

PROJECT 8



- Enclosed volume filled with **tritium molecular gas**
- Add a **magnetic field** → **Decay electrons spiral around field lines**
- Add **antennas** to detect the cyclotron radiation

Cyclotron Radiation Emission Spectroscopy (CRES)

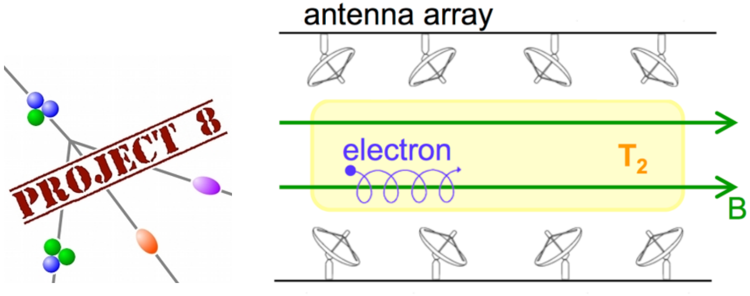
- Non-destructive measurement of electron energy

$$\omega_\gamma = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$

@ 1 Tesla	ω(18 keV) ~ 26 GHz P(18 keV) = 1.2 fW

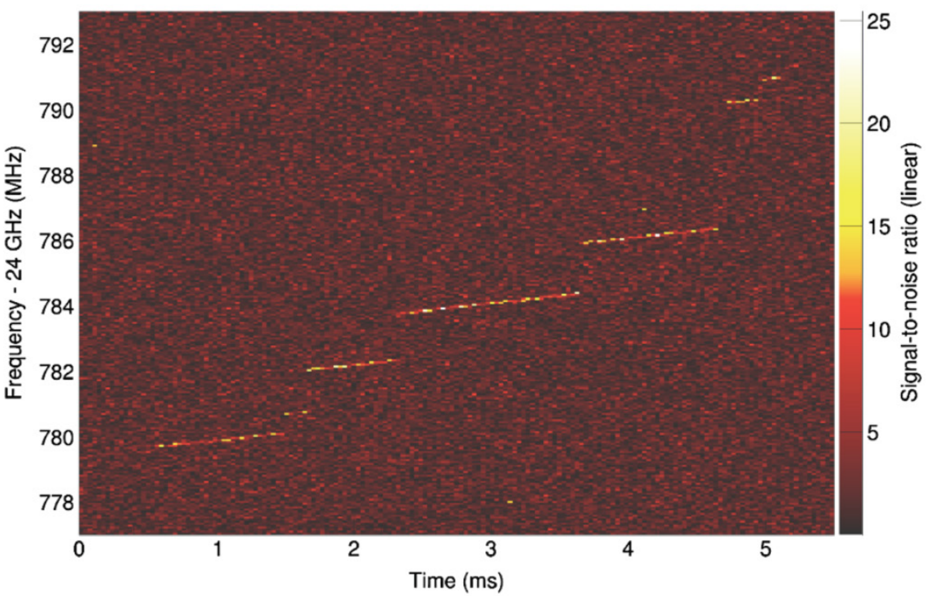
B. Monreal & J. Formaggio PRD 80 (2009) 051301

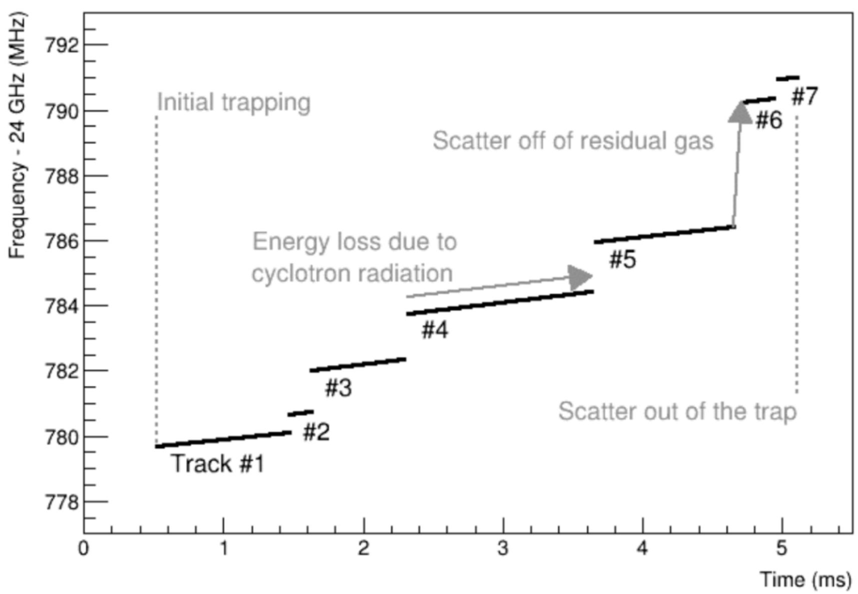
PROJECT 8



- Enclosed volume fill with ^{83m}Kr gas
- Waveguide & cryogenic amplifiers to detect the cyclotron radiation

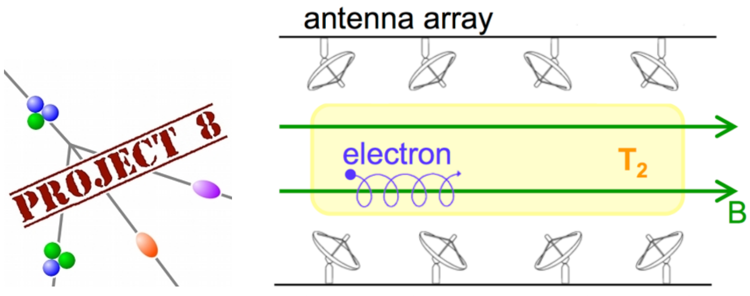
First observation of cyclotron radiation from single electrons June 2014





Asner et al., *PRL* **114** (2015) 16501

PROJECT 8



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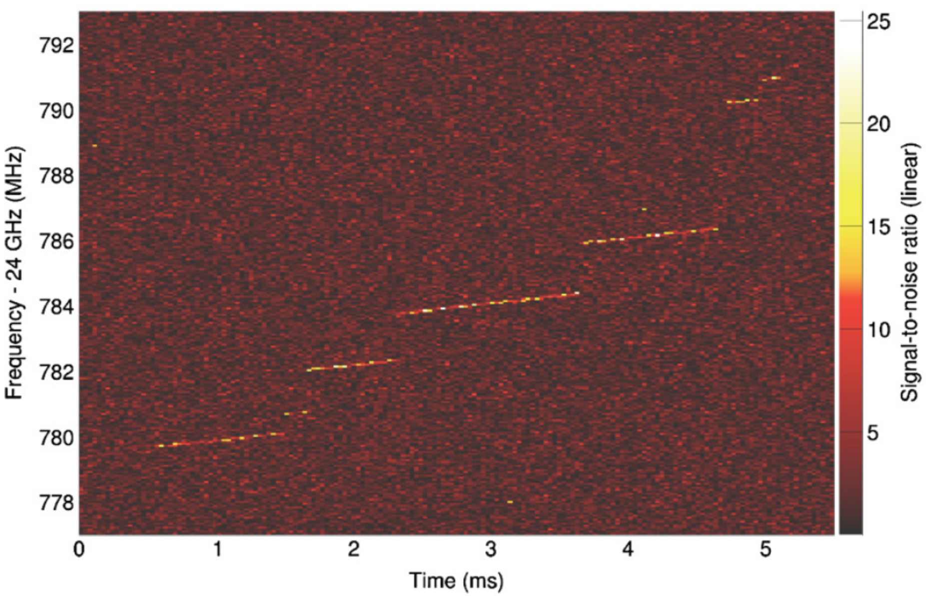
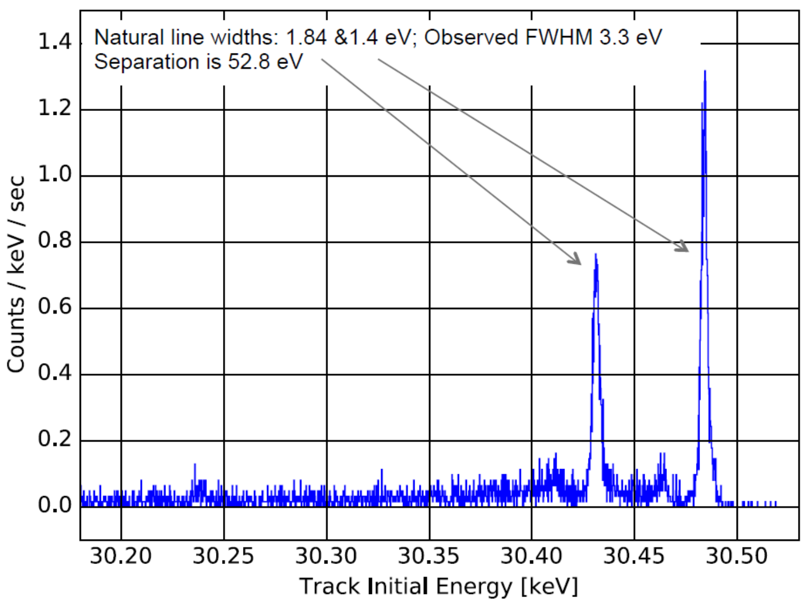




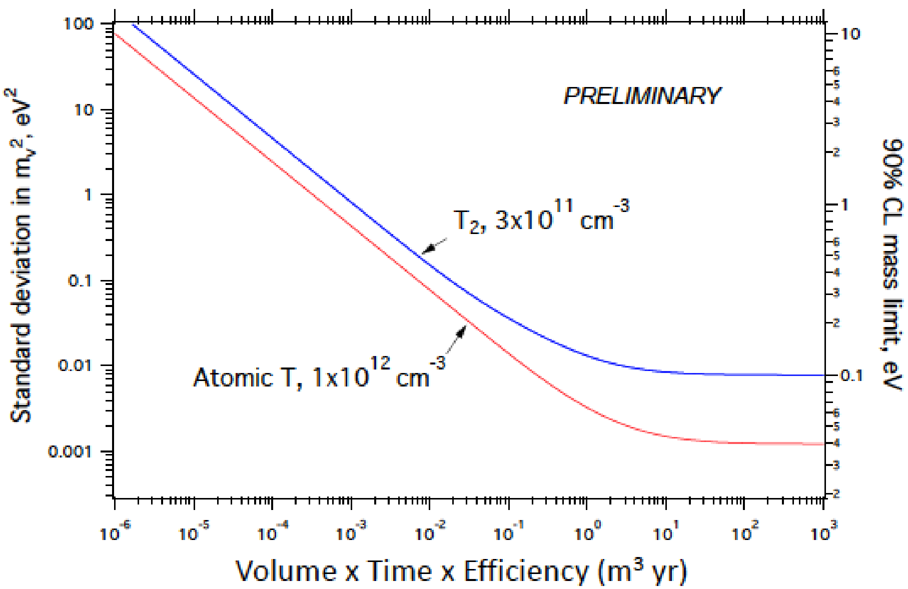
A. A. Esfahani et al., *JPhysG* **44** (2017) 5

PROJECT 8: schedule

Phase I (2010 - 2016)
Demonstration of the CRES method ✓
Conversion electron lines from ^{83m}Kr source

Phase II (Present)
Spectroscopy of continuous T_2 spectrum
Study of systematics
improvement of the energy resolution

Phase III (near future)
Large volume system (1 year)
Phased array antenna
Sensitivity goal: $m(\nu_e) < 2$ eV 90% C.L.



Phase IV (2018 +)
Large scale exp. with atomic ^3H source for sub-eV sensitivity

^3H based experiments

❖ KATRIN - Karlsruhe Tritium Neutrino Experiment

Main ideas:
- high activity source: 10^{11} e^-/s
- high resolution MAC-E filter to select electrons close to the end point
- count electrons as function of retarding potential
  → integral spectrum

❖ Project8

Main ideas:
- Source = detector: $10^{11} – 10^{13}$ $^3H_2$ molecules /cm^3
- Use cyclotron frequency to extract electron energy
- Differential spectrum

Future Project

❖ PTOLEMY - Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield

Main ideas:

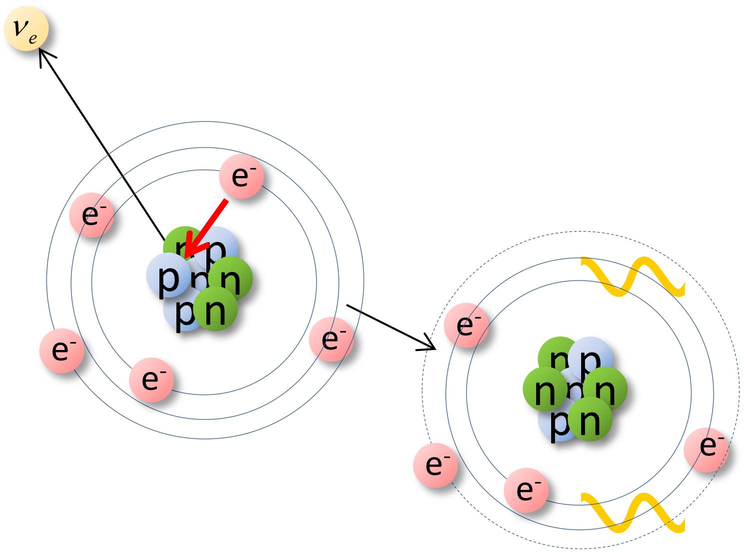
large area tritium source: 100 g atomic ^3H

MAC-E lter methods

RF tracking and time-of-flight systems

cryogenic calorimetry → differential spectrum

^{163}Ho electron capture



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Q_{EC} = $(2.833 \pm 0.030^{stat} \pm 0.015^{syst})$ keV

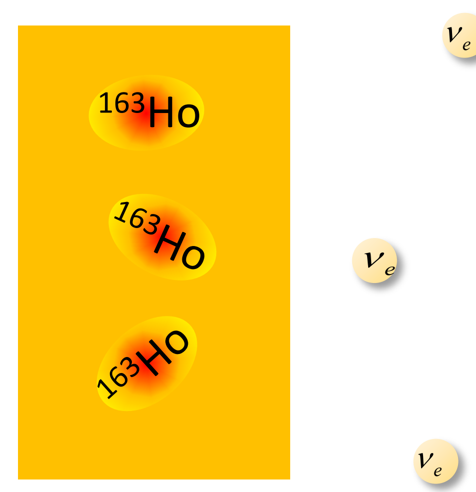
S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501

- $\tau_{1/2} \cong 4570$ years (2*10^{11} atoms for 1 Bq)

Atomic de-excitation:

- X-ray emission
- Auger electrons
- Coster-Kronig transitions

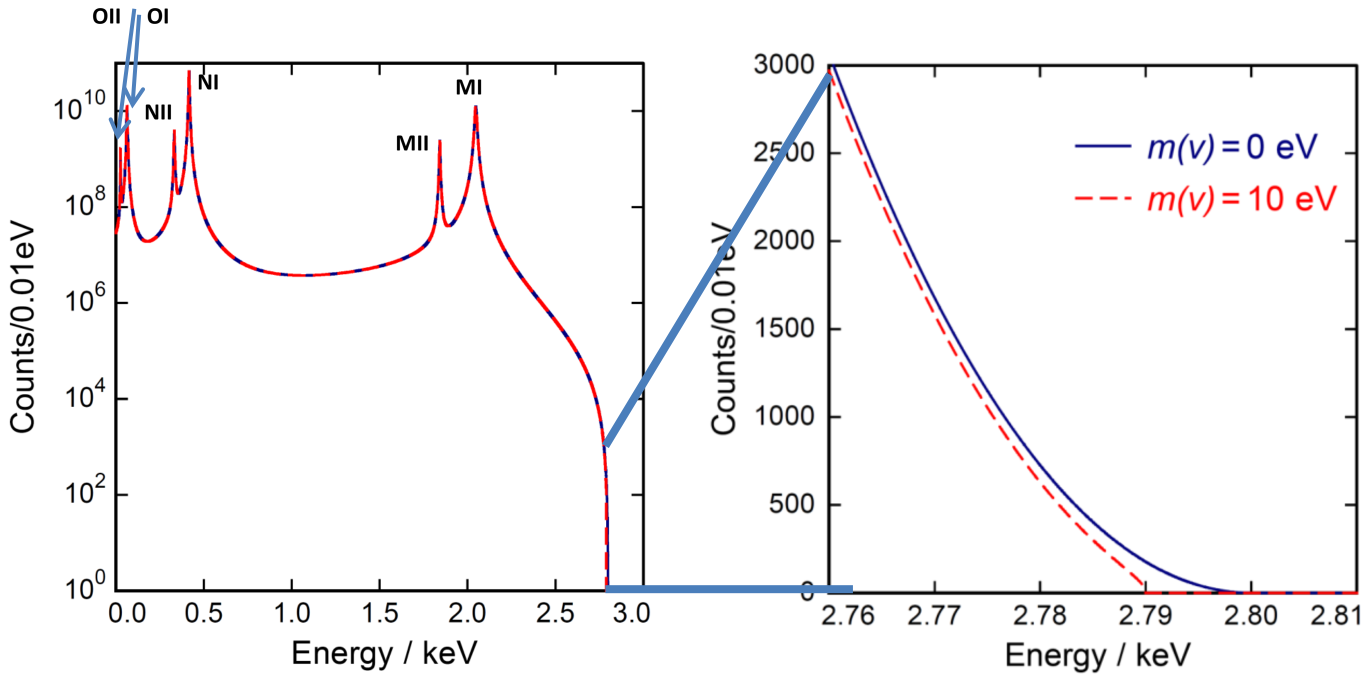
Calorimetric measurement



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

^{163}Ho calorimetrically measured spectrum

$$\frac{dW}{dE_C} = A(Q_{EC} - E_C)^2 \sqrt{1 - \frac{m_\nu^{\,2}}{(Q_{EC} - E_C)^2}} \sum_H B_H \varphi_H^{\,2}(0) \frac{\frac{\Gamma_H}{2\pi}}{(E_C - E_H)^2 + \frac{\Gamma_H^{\,2}}{4}}$$



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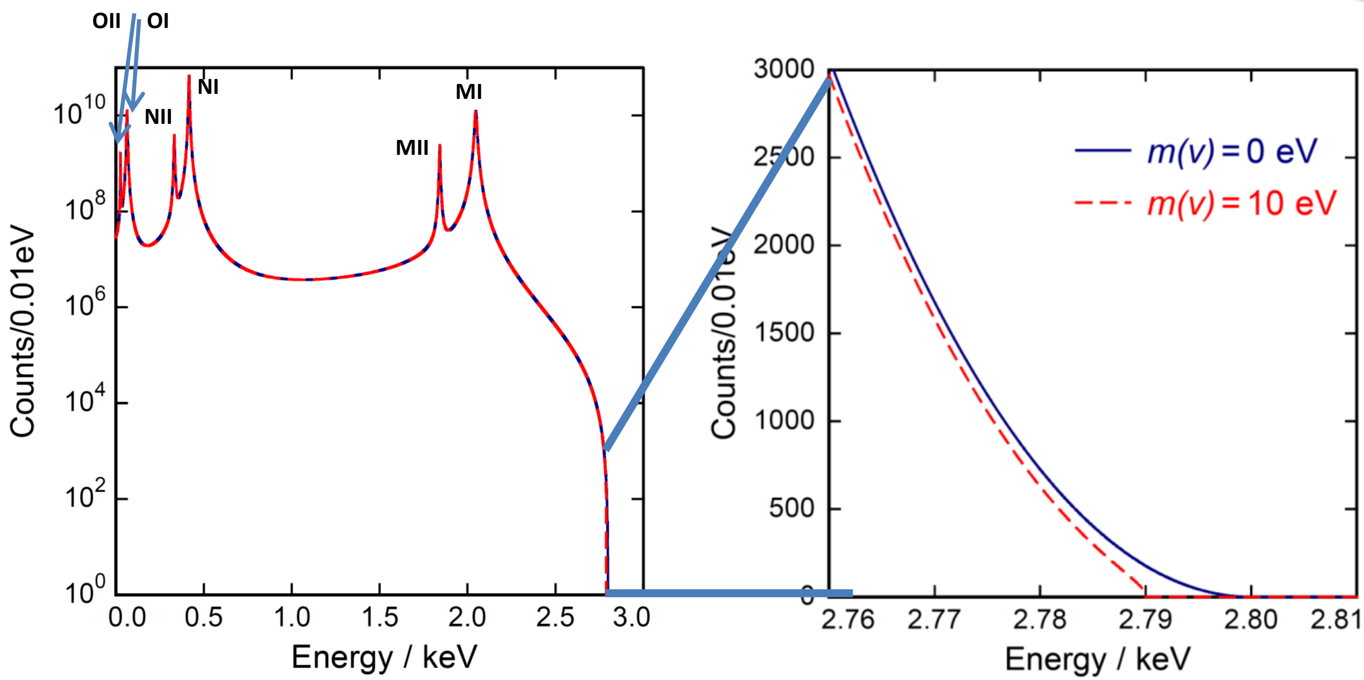


The ECHo Collaboration, *EPJ-ST* **226** 8 (2017) 1623

The Holmes Collaboration Phys. J. C 75 (2015) 112

Sub-eV sensitivity: a possible scenario

Statistics in the end point region

- $N_{ev} > 10^{14}$ → **A ≈ 1 MBq**

Unresolved pile-up ($f_{pu} \sim a \cdot \tau_r$)

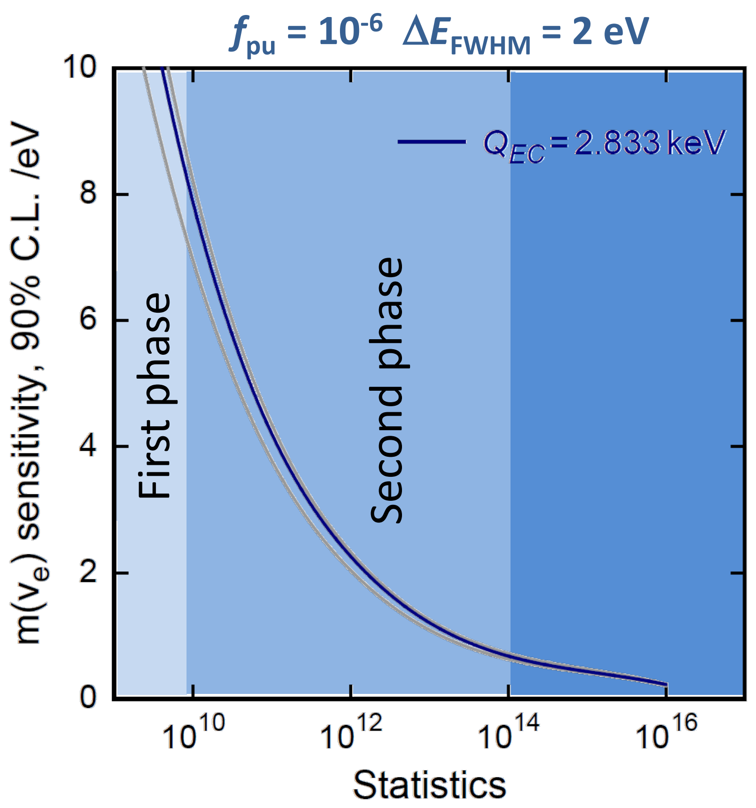
- $\boldsymbol{f_{pu} < 10^{-5}}$
- $\tau_r < 1\ \mu s$ → $a \sim 10$ Bq
- 10^5 pixels → **multiplexing**

Precision characterization of the endpoint region

- $\boldsymbol{\Delta E_{FWHM} < 3}$ **eV**

Background level

- **< 10^{-5} events/eV/det/day**



^{163}Ho high purity source

Required activity in the detectors: Final experiment → >10^{6} Bq → >10^{17} atoms

- Neutron irradiation

  (n,γ)-reaction on ^{162}Er

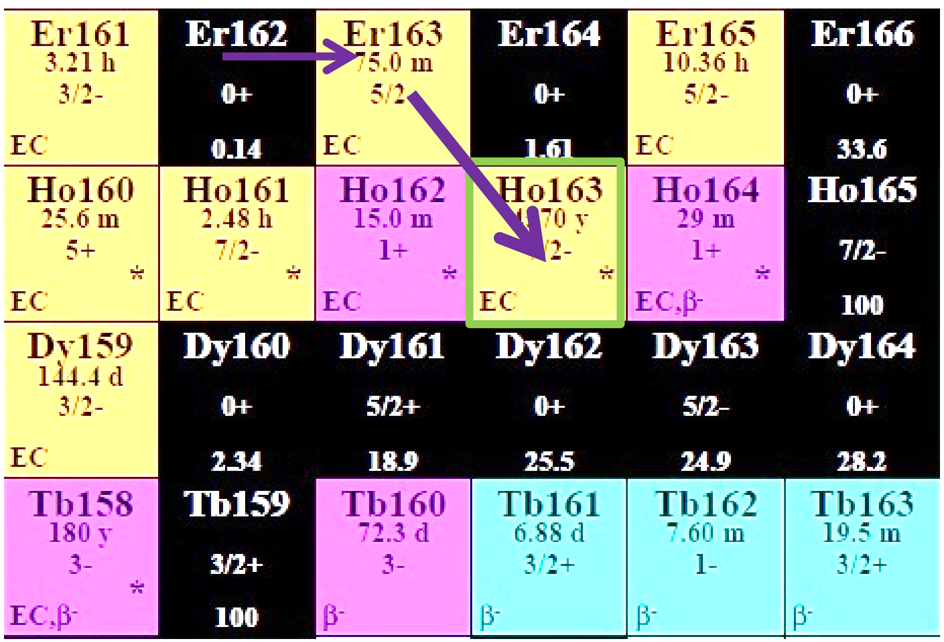
  High cross-section

  Radioactive contaminants

Very selective chemical separation

Leads to pure Ho samples

But ^{166m}Ho is still present…



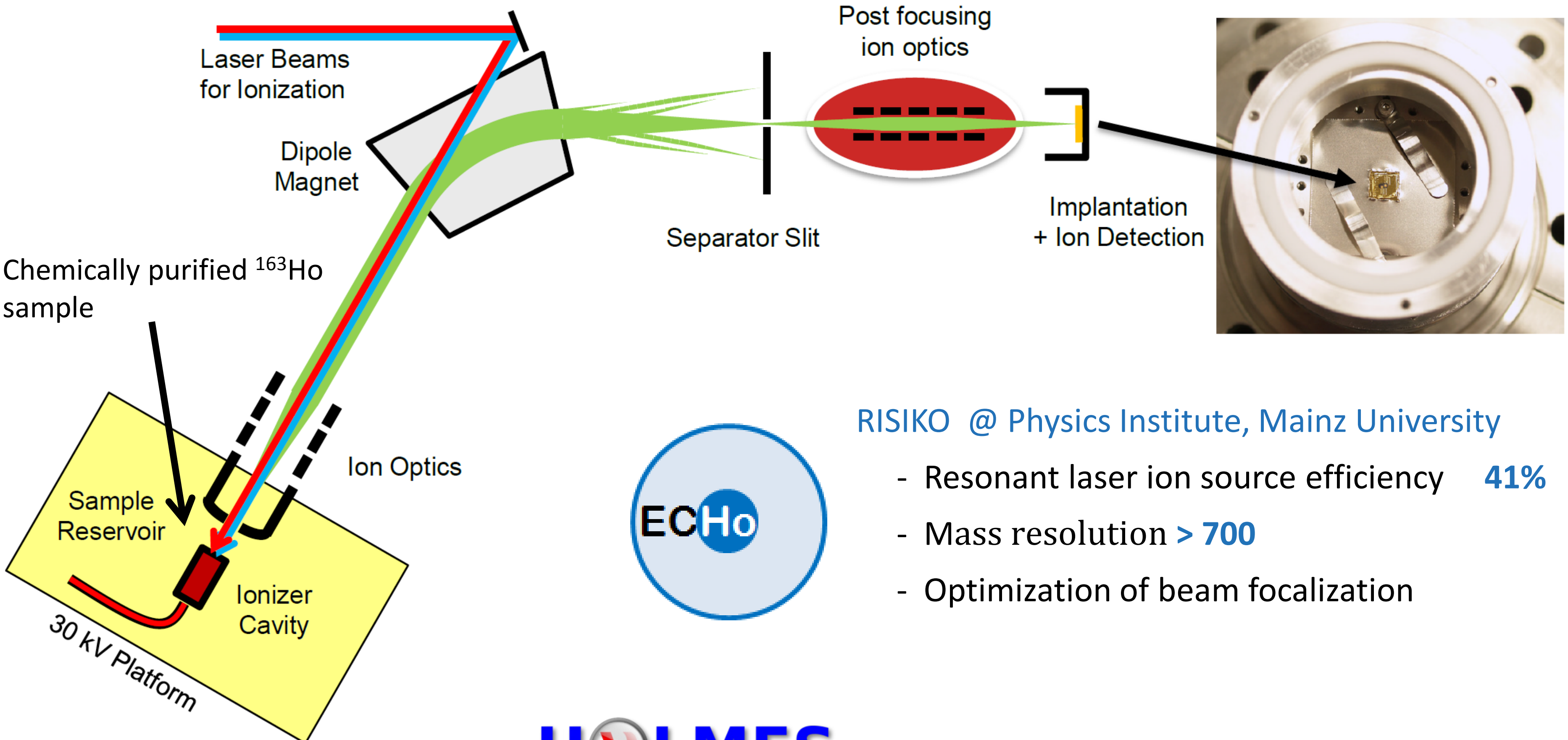
H. Dorrer et al, Radiochim. Acta 106 (2018) 535

HOLMES

ECHo

S. Heinitz et al. (2018)
PLoS ONE 13(8): e0200910.
https://doi.org/10.1371/journal.pone.0200910

Mass separation and ^{163}Ho ion-implantation



RISIKO @ Physics Institute, Mainz University

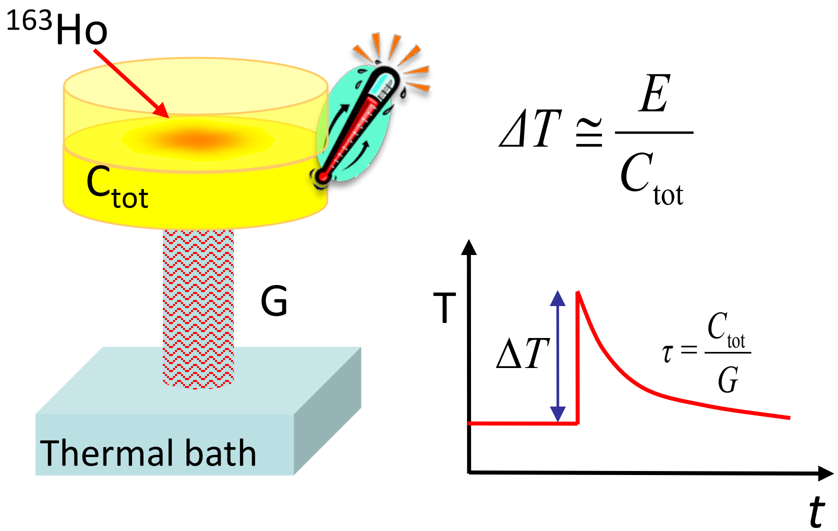
- Resonant laser ion source efficiency **41%**
- Mass resolution **> 700**
- Optimization of beam focalization

HOLMES Custumed system under commissioning

F. Schneider et al ., *NIM B* **376** (2016) 388

High energy resolution detectors

Low temperature microcalorimeters



$$\Delta T \cong \frac{E}{C_{tot}}$$

- Very small volume

- Working temperature below 100 mK
  small specific heat
  small thermal noise

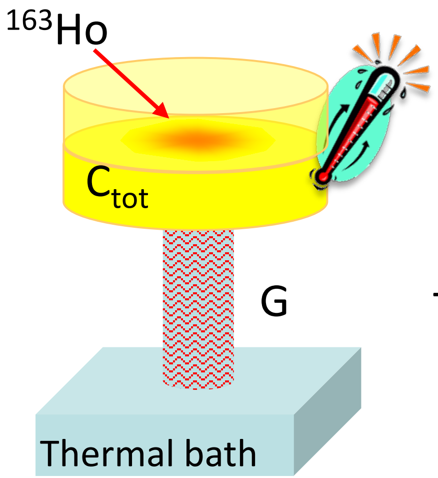
- **Very sensitive temperature sensor**

F. Gatti et al., Physics Letters B 398 (1997) 415

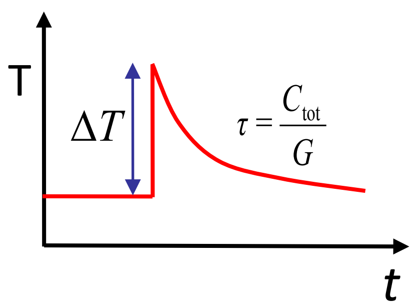
Cryogenic Particle Detection
Springer Topics in Applied Physics 99 ed. C. Enss (2005)

High energy resolution detectors

Low temperature microcalorimeters

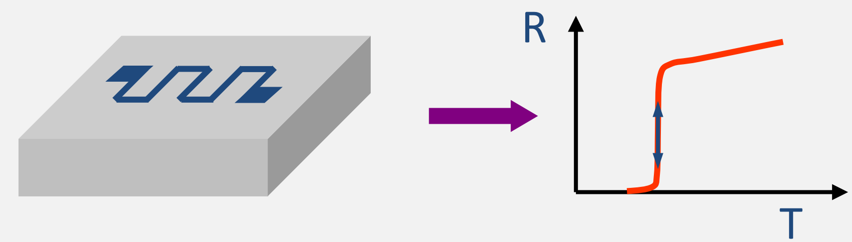


$$\Delta T \cong \frac{E}{C_{tot}}$$



- Very small volume
- Working temperature below 100 mK
  small specific heat
  small thermal noise
- **Very sensitive temperature sensor**

Resistance at superconducting transition,TES



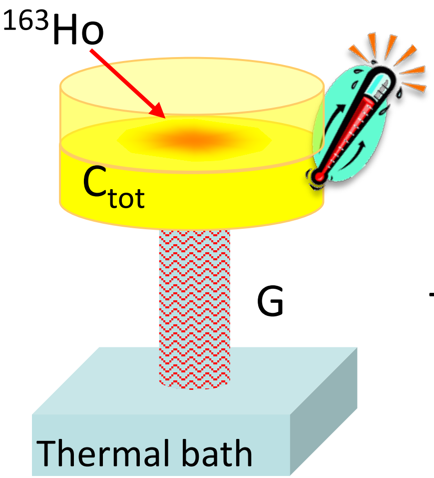
K.D. Irwin and G.C. Hilton, Topics in Applied Physics 99 (2005) 63

Magnetization of paramagnetic material, MMC

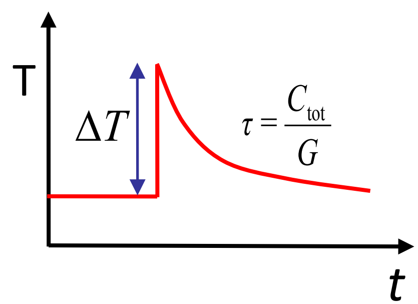
A.Fleischmann, C. Enss and G. M. Seidel, Topics in Applied Physics 99 (2005) 63

High energy resolution detectors

Low temperature microcalorimeters

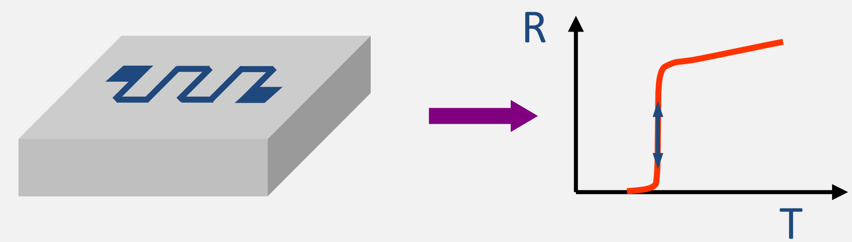


$$\Delta T \cong \frac{E}{C_{tot}}$$

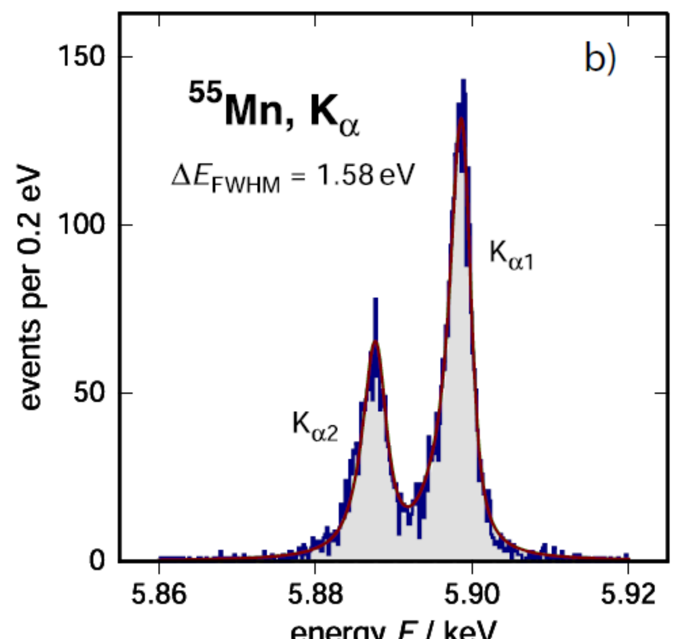


- Very small volume
- Working temperature below 100 mK
  - small specific heat
  - small thermal noise
- **Very sensitive temperature sensor**

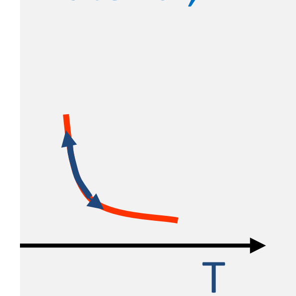
Resistance at superconducting transition,TES



K.D. Irwin and G.C. Hilton, Topics in Applied Physics 99 (2005) 63

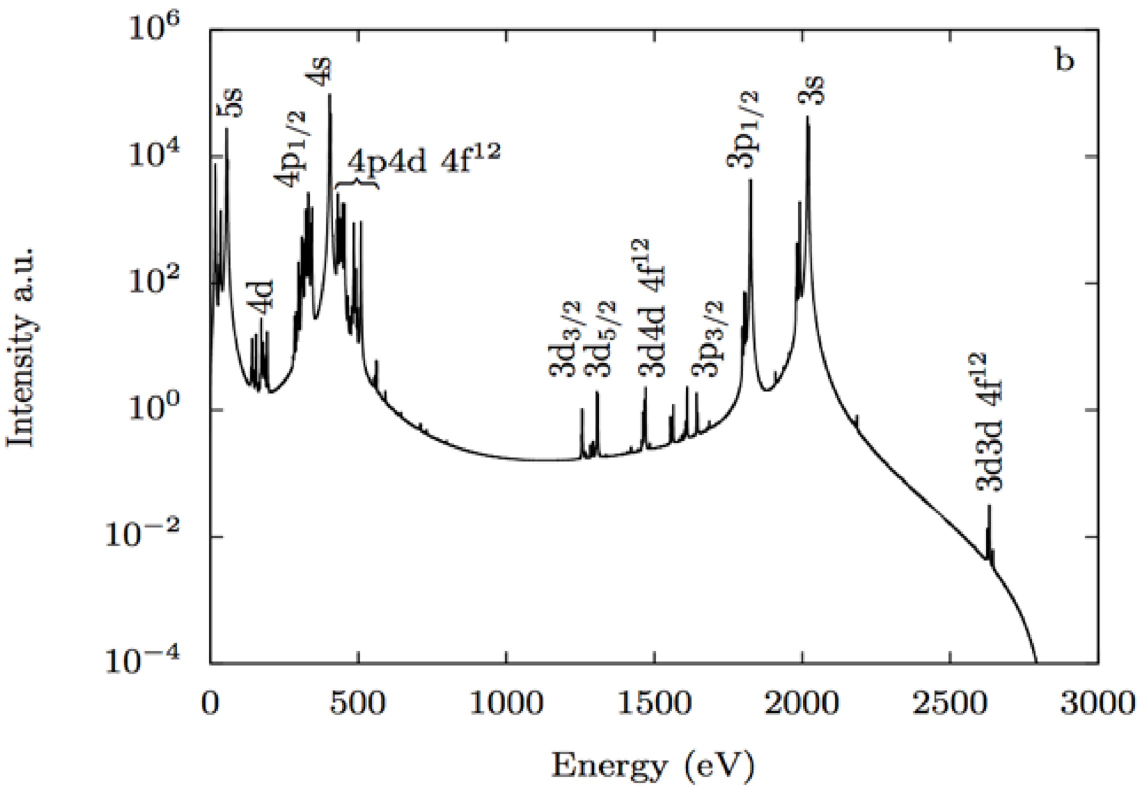


material, MMC



s and G. M. Seidel,
sics 99 (2005) 63

Calorimetric spectrum - theory



New approach

Ab inito calculation of the ^{163}Ho electron capture spectrum

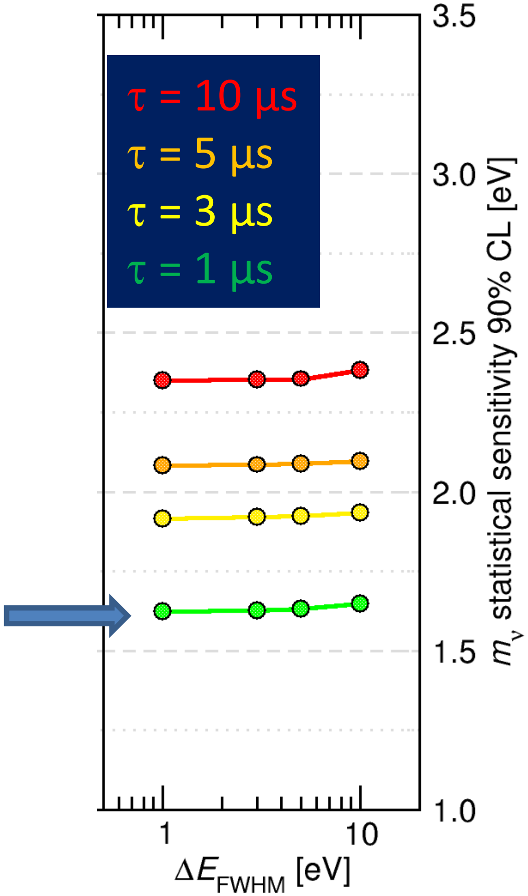
Calorimetrically measured spectra from other EC unstable nuclides as ^{193}Pt, ^{157}Tb (LANL group)

Restricted to bound-states only, i.e. the spectrum is given by a finite number of resonances

→ Include decay to the continuum states
→ Study the effect of metallic host

Brass et al., *Phys. Rev. C* **97** (2018) 054620

Holmes: sensitivity and timeplan



HOLMES baseline:

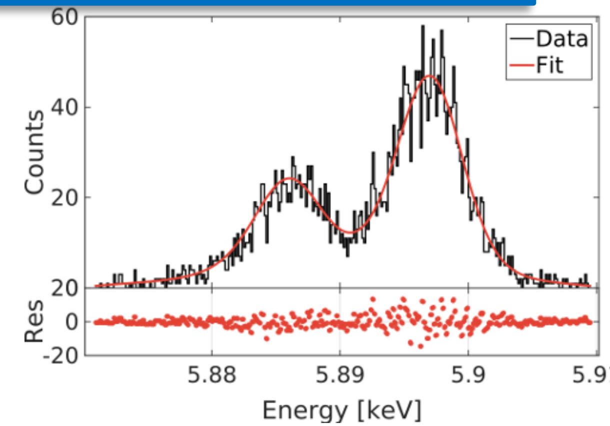
Activity per pixel: 300 Bq (6×10^{13} ^{163}Ho atoms)
Number of detectors: 1000

Two steps approach:

- Proof of concept (2013 – 2018):
  64 channels mid-term prototype
  t_M= 1 month
  → $m(\nu_e) < 10$ eV
- full scale (starting 2019):
  1000 channels,
  t_M= 3 years (3×10^{13} events)
  → $m(\nu_e) < 1$ eV

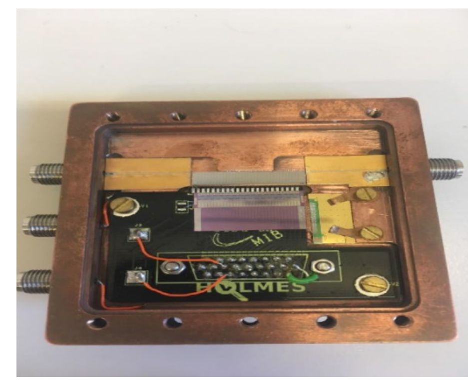
B. Alpert et al, Eur. Phys. J. C (2015) 75:112
A. Nucciotti, Eur. Phys. J. C (2014) 74:3161

Holmes: present status

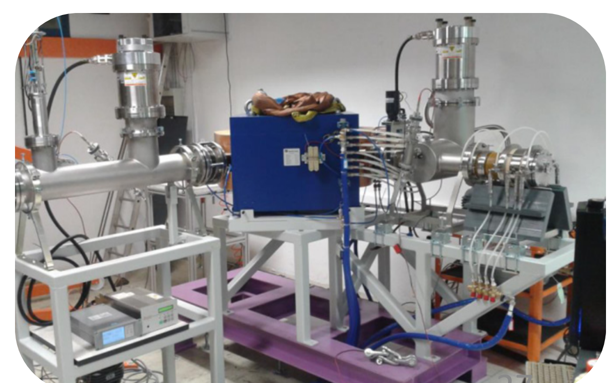


Source production and purification:
130 MBq available for tests and experiments ✓

Detector arrays characterization:
very good single pixel performance ✓
operating microwave SQUID multiplexing
next challenge → load TES arrays with ^{163}Ho !

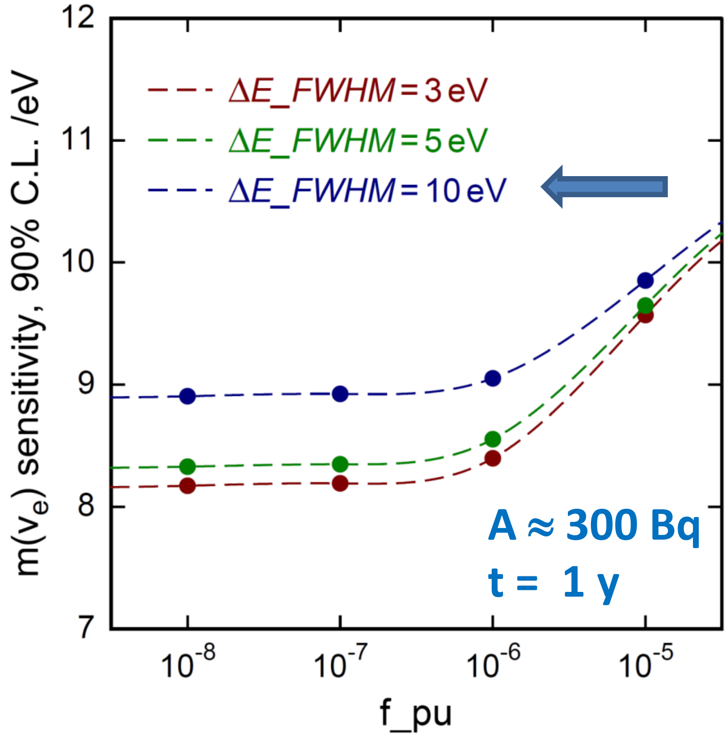


Dedicated mass separator:
facility installed
tests of the ion source on-going
commissioning on-going !



ECHo: sensitivity and timeplan

ECHo-1k (2015 – 2018)

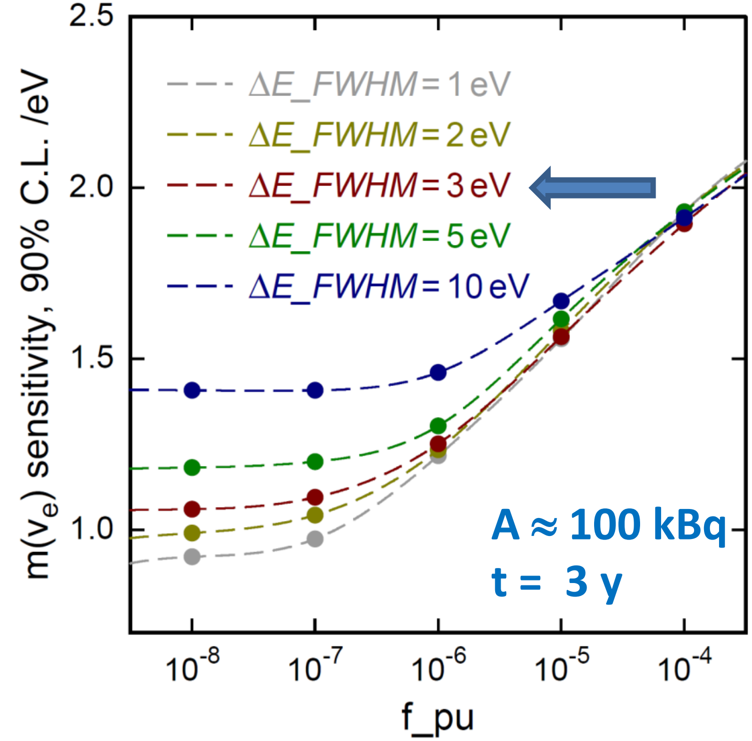


$m(\nu_e) < 10$ eV 90% C.L.

Activity per pixel 5 Bq
Number of detectors 60
Readout: parallel two stage SQUID

Supported by DFG Research Unit FOR 2022/1

ECHo-100k (2018 – 2021)

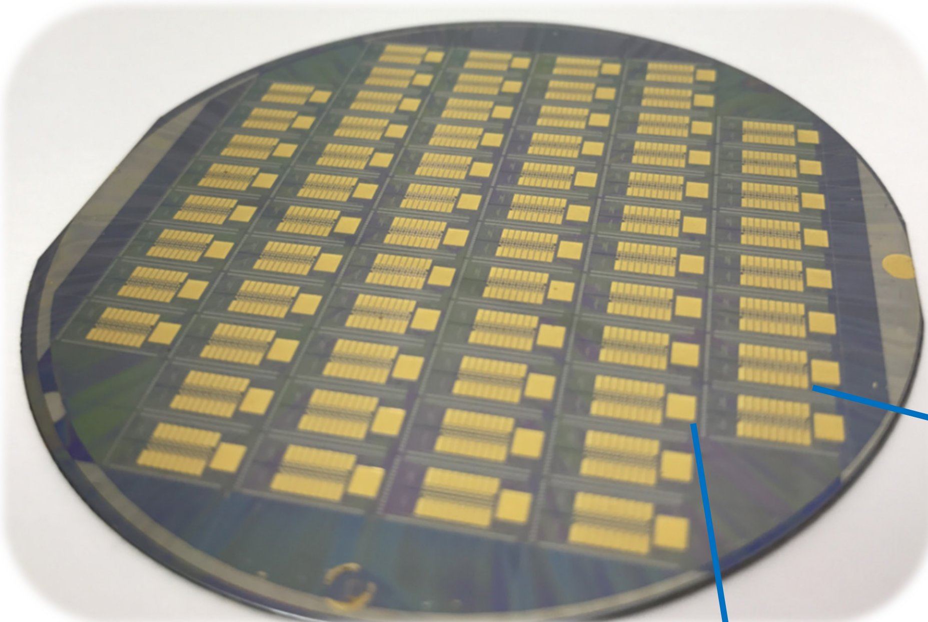


$m(\nu_e) < 1.5$ eV 90% C.L.

Activity per pixel 10 Bq
Number of detectors 12000
Readout: microwave SQUID multiplexing

Supported by DFG Research Unit FOR 2022/2

ECHo-1k array

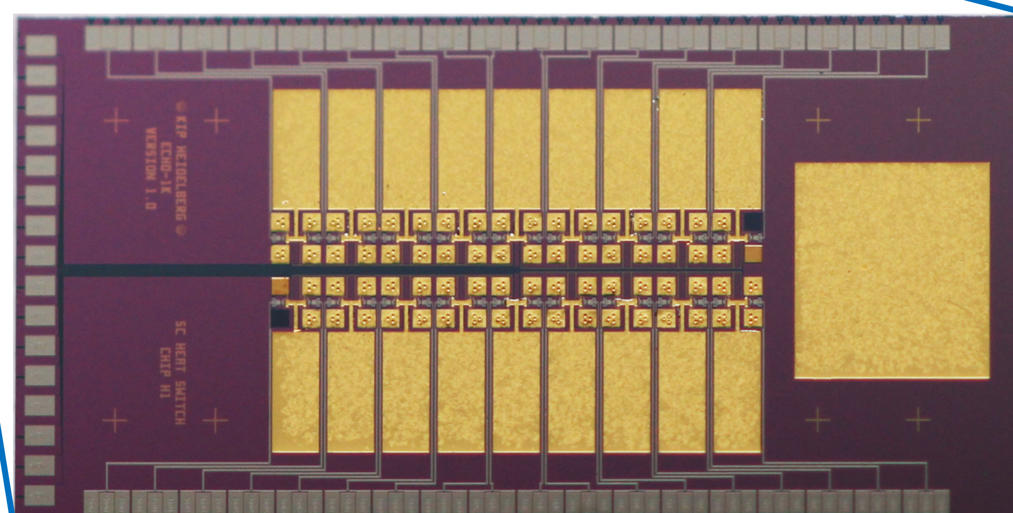


3“ wafer with 64 ECHo-1k chip

Suitable for
parallel and multiplexed readout

64 pixels which can be loaded with ^{163}Ho
+ 4 detectors for diagnostics

Design performance:
ΔE_{FWHM} ~ 5 eV
τ_r ~ 90 ns (single channel readout)
τ_r ~ 300 ns (multiplexed read-out)



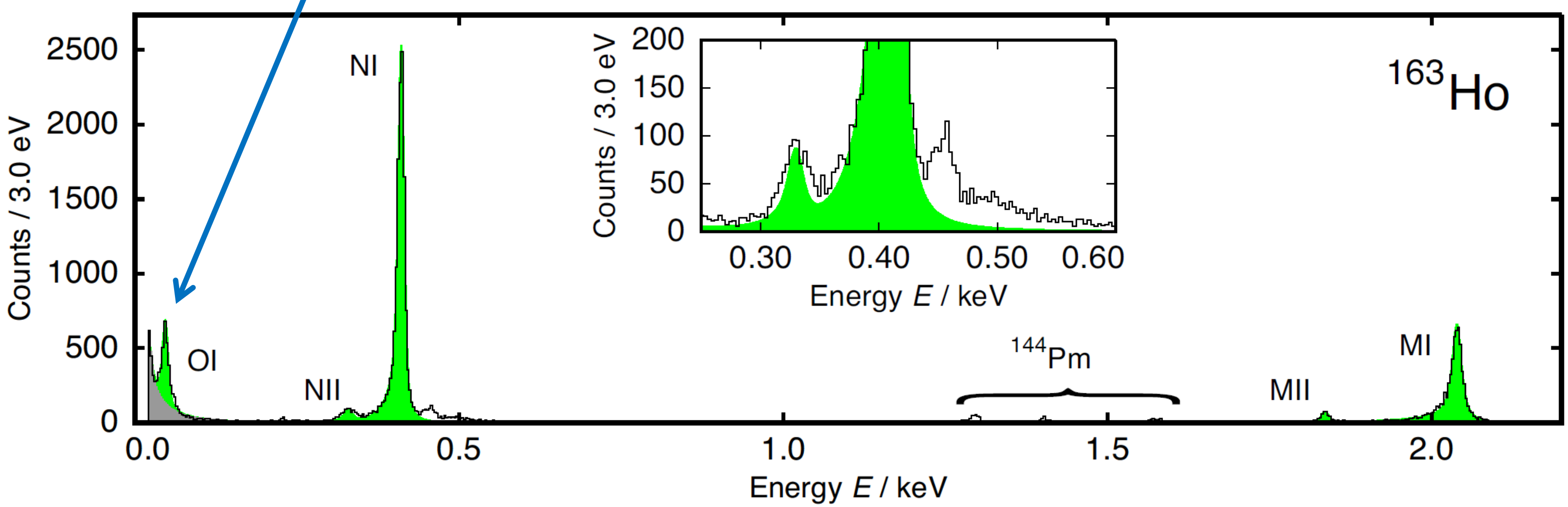
S.Kempf *et al.*, *J. Low. Temp. Phys.* **176** (2014) 426

Calorimetric spectrum

- Rise Time ~ 130 ns
- ΔE_{FWHM} = 7.6 eV @ 6 keV
- Non-Linearity < 1% @ 6keV

	E_H bind.	E_H exp.	Γ_H lit.	Γ_H exp
MI	2.047	2.040	13.2	13.7
MII	1.845	1.836	6.0	7.2
NI	0.420	0.411	5.4	5.3
NII	0.340	0.333	5.3	8.0
OI	0.050	0.048	5.0	4.3

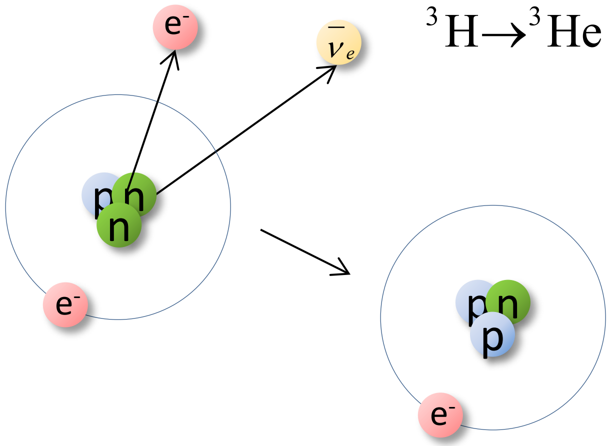
First calorimetric measurement of the OI-line



P. C.-O. Ranitzsch et al., *Phys. Rev. Lett.*, 119, 122501 (2017)

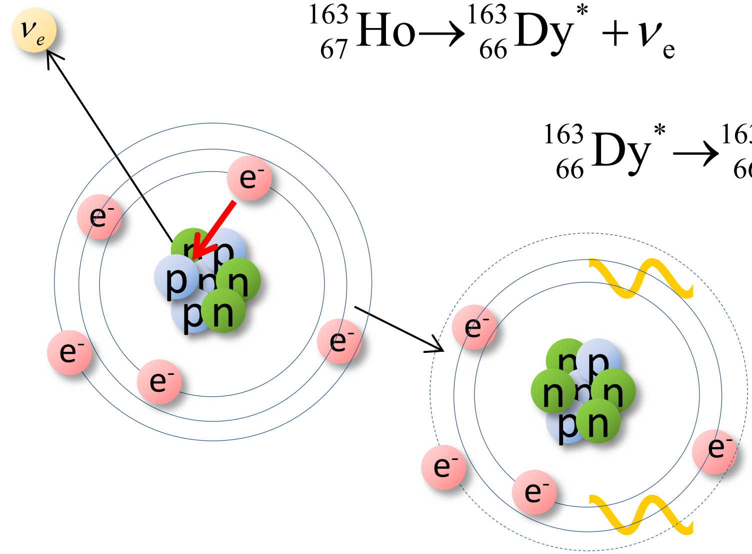
Conclusions and outlook

$${}^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-} + \overline{\nu}_{e}$$



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

$${}^{163}_{66}\mathrm{Dy}^{*} \rightarrow {}^{163}_{66}\mathrm{Dy} + E_{\mathrm{C}}$$



KATRIN

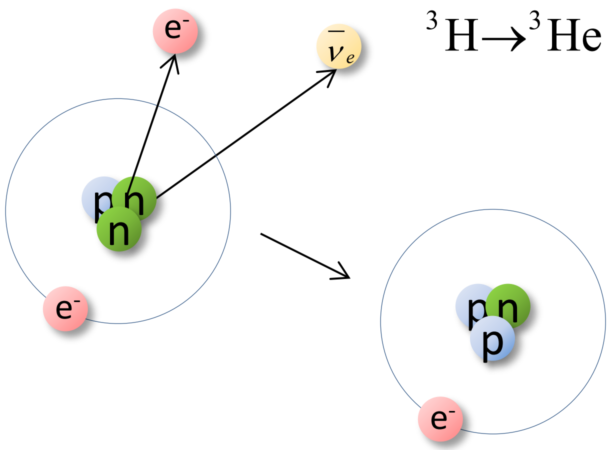
PROJECT8

PTOLEMY

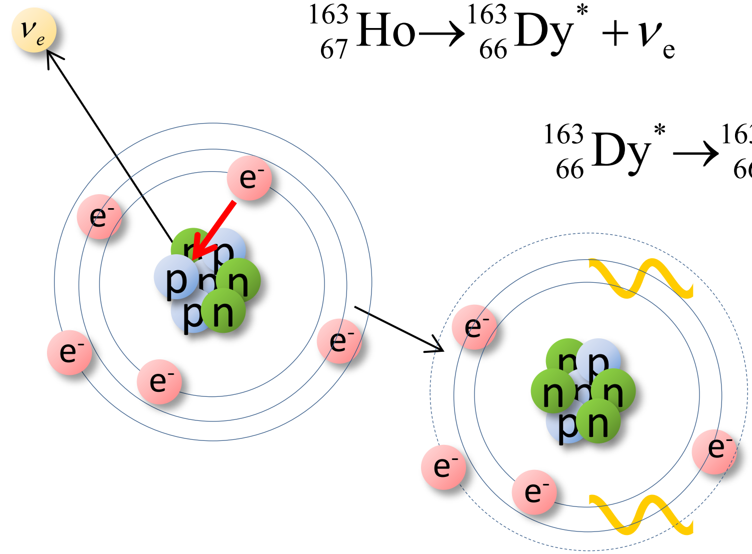
ECHo

HOLMES

Conclusions and outlook



$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-} + \bar{\nu}_e$$



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

$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow {}^{163}_{66}\mathrm{Dy} + E_{\mathrm{C}}$$

KATRIN

PROJECT8

PTOLEMY

m(ν_e) < 200 meV (90% CL)

ECHo

HOLMES

Determination of the absolute (anti-)neutrino mass

ECT* Trento 04 – 08 April 2016

1st edition

ECT* Trento 26 – 30 March 2018

2nd edition

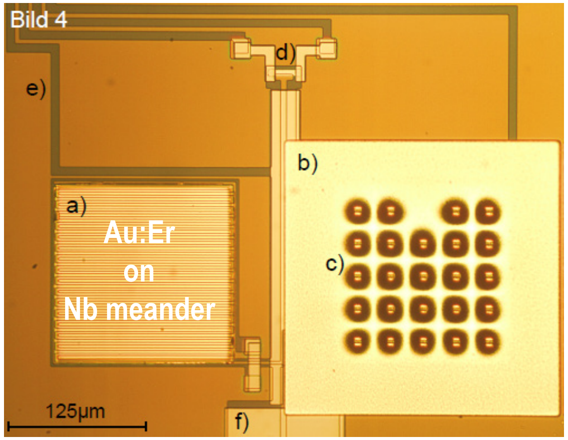
Determination of the absolute (anti-)neutrino mass

ECT* Trento 04 – 08 April 2016

ECT* Trento 26 – 30 March 2018

Thank you!

Metallic magnetic calorimeters (MMCs)



Fast risetime

→ Reduction un-resolved pile-up

Extremely good energy resolution

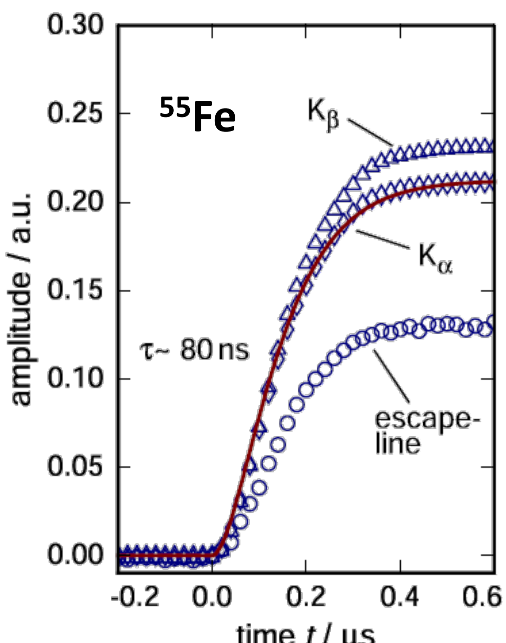
→Reduced smearing in the end point region

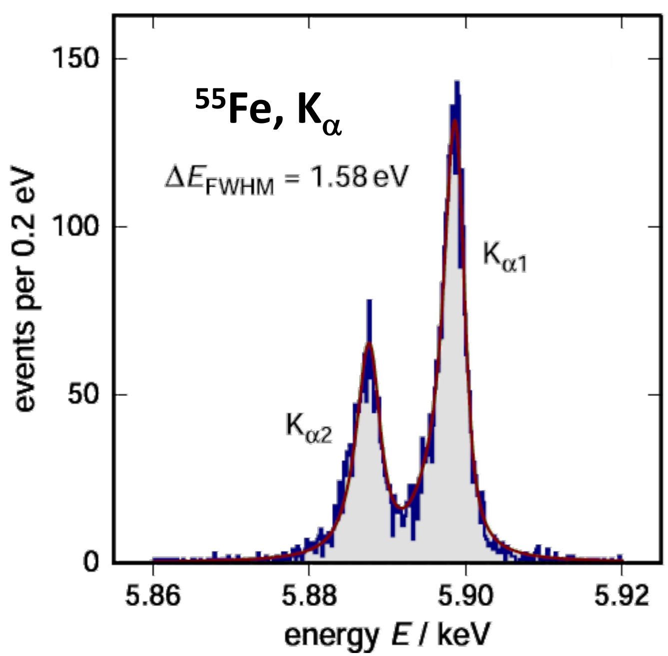
Excellent linearity

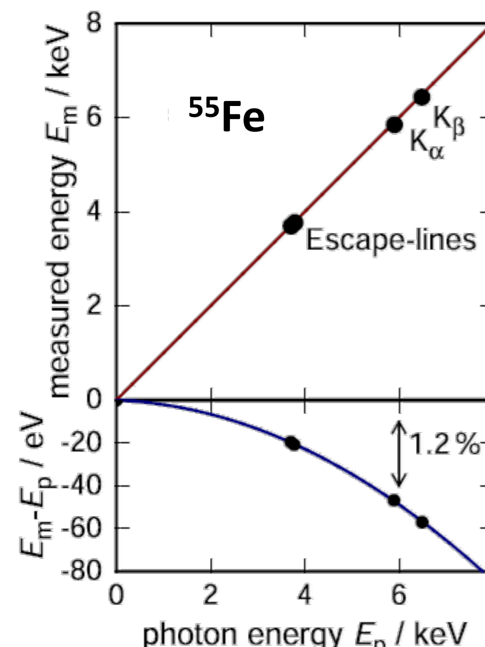
→ precise definition of the energy scale

A. Fleischmann et al., *AIP Conf. Proc.* **1185** (2009) 571

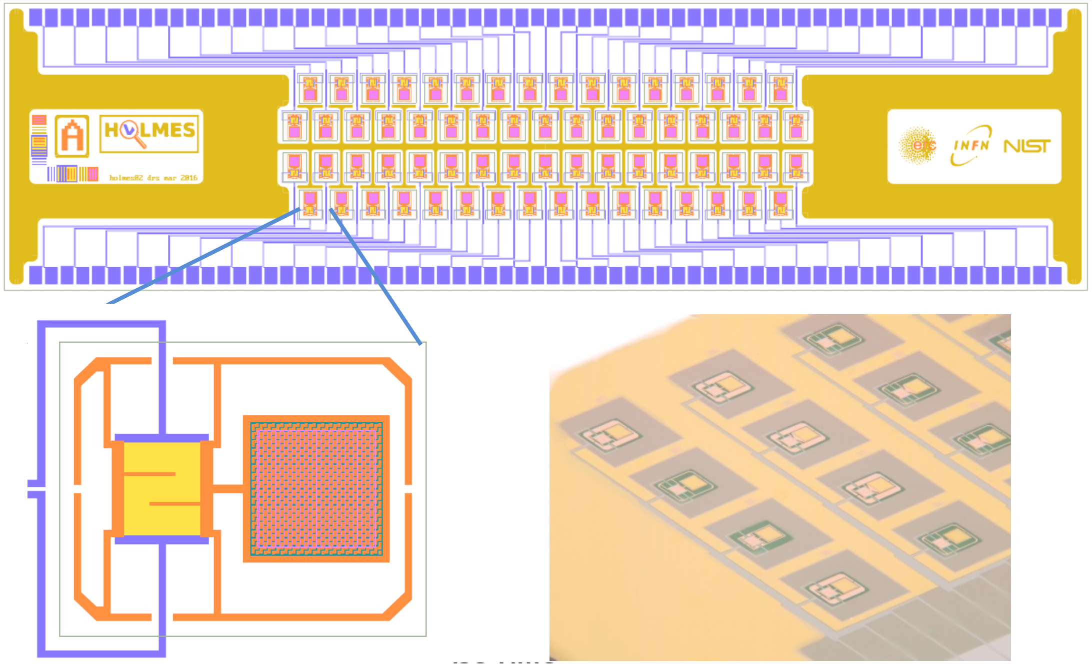
L. Gastaldo et al., Nucl. *Inst. Meth. A*, **711** (2013) 150







Transition Edge Sensors (TESs)



NIST arrays operated in HOLMES cryogenic platform:

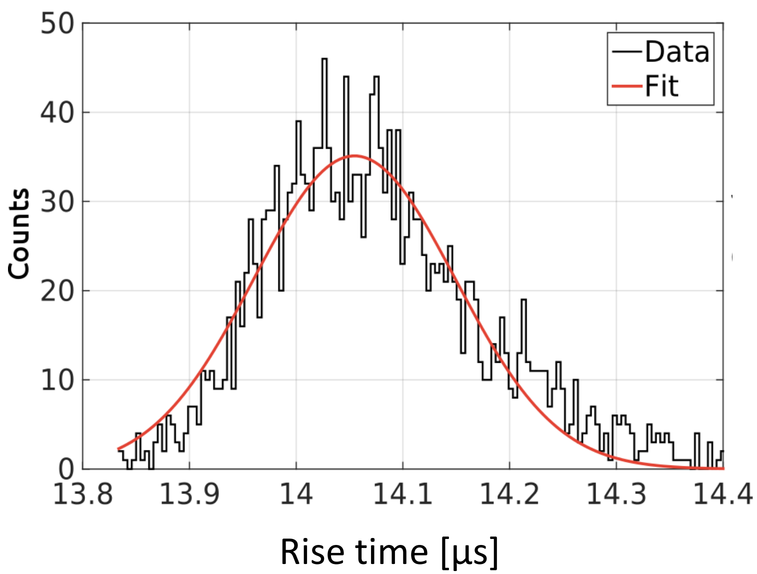
Extremely good energy resolution

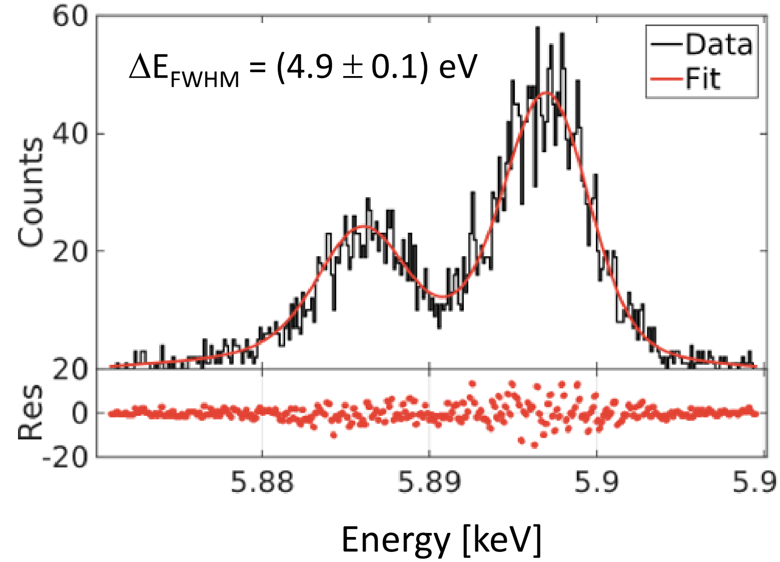
Risetime

Goal: reaching 1 μs

A. Orlando, et al. J Low Temp Phys (2018).

A. Puiu, et al. J Low Temp Phys (2018).





^{163}Ho Q_{EC} determination

$$Q_{EC} = m(^{163}\mathrm{Ho}) - m(^{163}\mathrm{Dy})$$

Penning Trap Mass Spectroscopy

@TRIGA TRAP (Uni-Mainz)

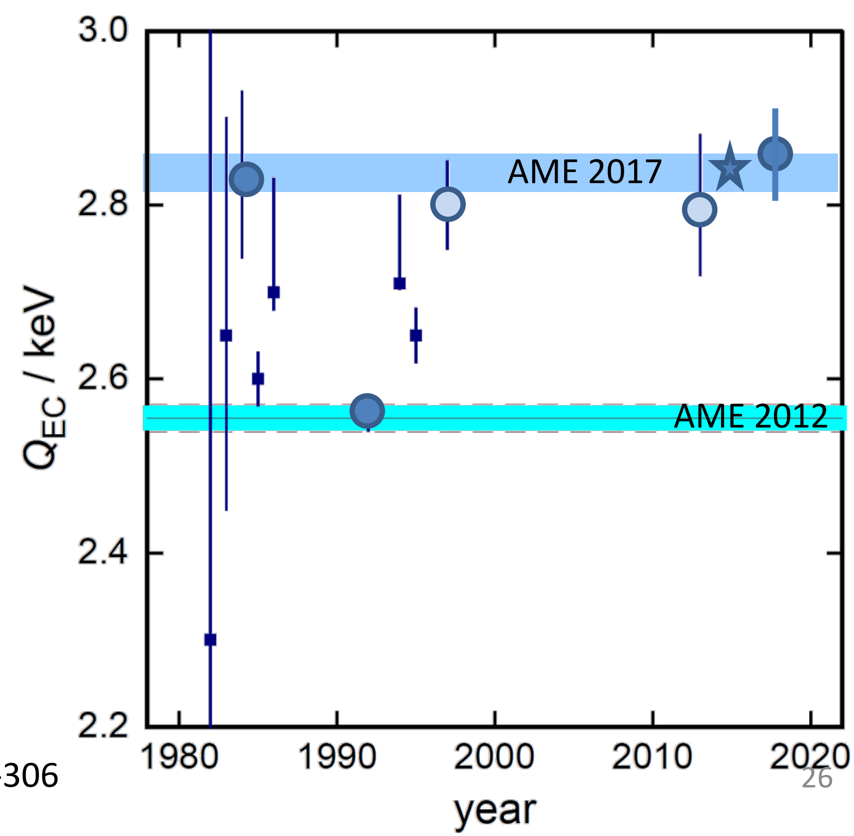
@SHIPTRAP (GSI – Darmstadt)

$$\nu_c = \frac{qB}{m}$$

$Q_{EC} = (2.833 \pm 0.030^{stat} \pm 0.015^{syst})$ keV

Perfect agreement with Q_{EC} from ^{163}Ho spectrum

$Q_{EC} = (2.858 \pm 0.010^{stat} \pm 0.05^{syst})$ keV



Future goal: 1 eV precision

PENTATRAP @MPIK, Heidelberg (D) (*)

CHIP-TRAP @CMU Mount Pleasant (US) (**)

(*) J. Repp et al., Appl. Phys. B 107 (2012) 983

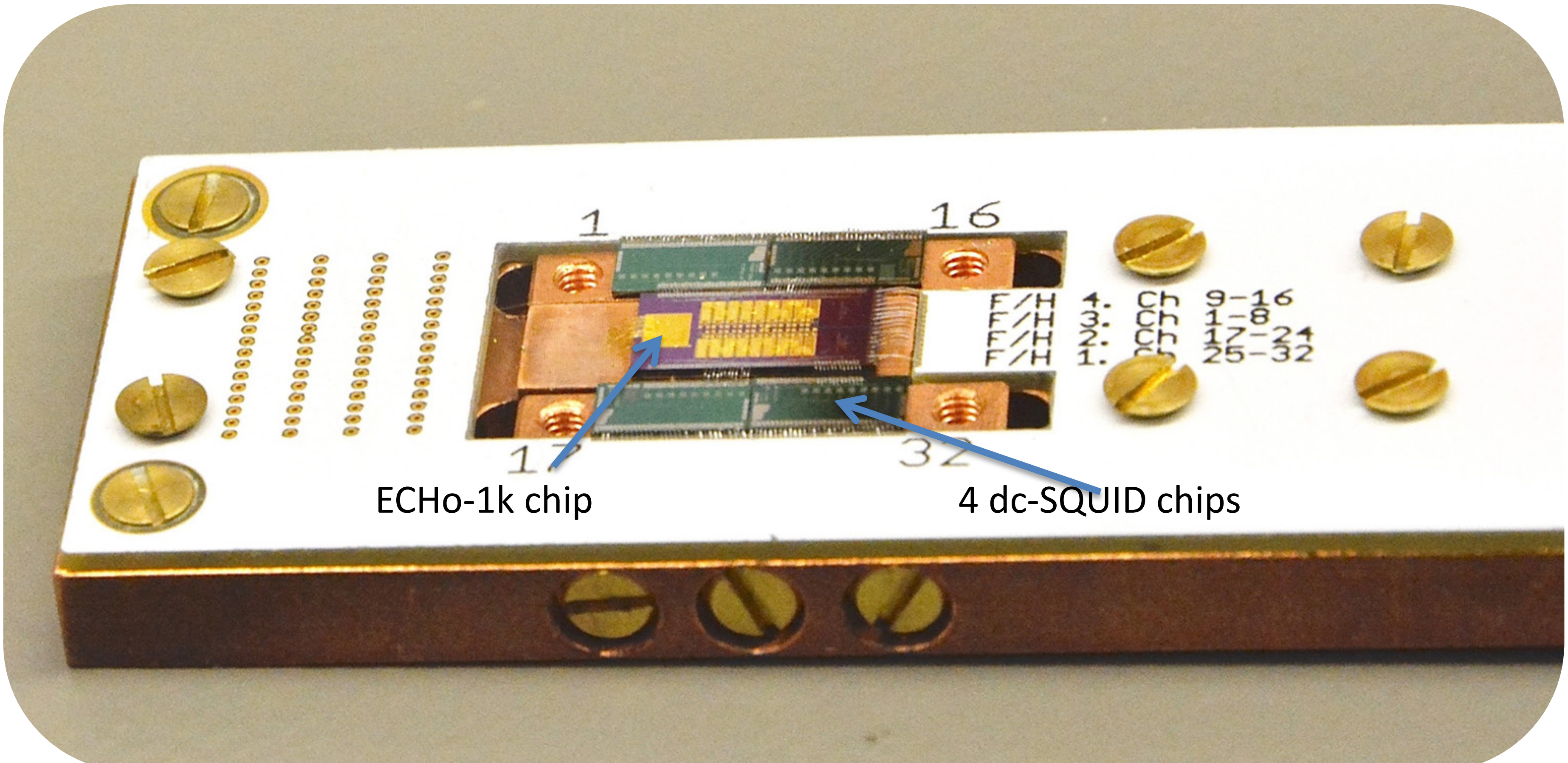
(*) C. Roux et al., Appl. Phys. B 107 (2012) 997

(**) M. Redshaw et al Nucl.Instrum.Meth. B376 (2016) 302-306

ECHo-1k array and read-out

- ECHo-1k chip implanted at RISIKO Uni-Mainz

  → ^{163}Ho activity per pixel $a \approx 1.5$ Bq (total activity $A \approx 100$ Bq)
- 4 Front-end chips each with 8 dc-SQUIDs



ECHo-1k experimental set-up