Direct Neutrino Mass Measurements

(with emphasis on KATRIN)

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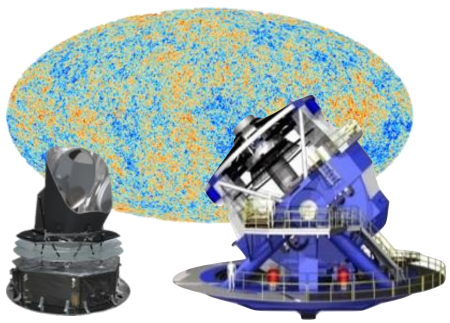
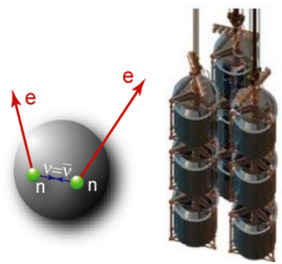
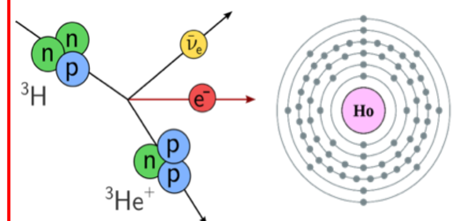
for the KATRIN Collaboration

DBD18, Waikoloa, HI, 21 Oct 2018

Direct Measurement Using Kinematics Only

Methods to measure Neutrino Mass

	Cosmology	0νββ	β decay / EC
			
Observable	$M_\nu = \sum_i m_i$	$m_{\beta\beta}^2 = \left\vert \sum_i U_{ei}^2 m_i \right\vert^2$	$m_\beta^2 = \sum_i \vert U_{ei}\vert^2 m_i^2$
Relies on	ΛCDM	Majorana	Kinematics

Model Independent
Direct Measurement

Direct Measurement Using Weak Decays

Wish List for Direct Measurements

- low end-point → relatively large spectrum deformation
- short life → small source amount / less scattering in source

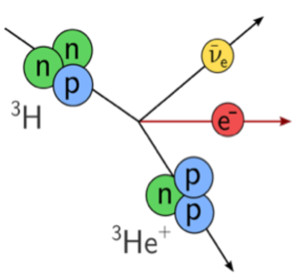
- (super) allowed transition → matrix element reliably calculable
- simple molecular → molecular states calculable

- high isotopic purity
- source stability
- established procurement

⇒ Only two isotopes of choice:

Beta Decay (Tritium)

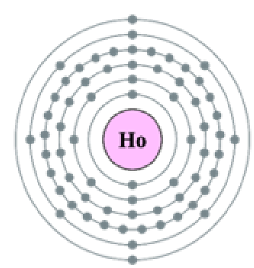
$$^{3}\mathrm{H} \longrightarrow \; ^{3}\mathrm{He} + e^{-} + \bar{\nu}_e$$



E_0 = 18.6 keV
$T_{1/2}$ = 12.3 y
super-allowed

Electron Capture (Holmium)

$$^{163}\mathrm{Ho} + e^{-} \longrightarrow \; ^{163}\mathrm{Dy}* + \nu_e$$



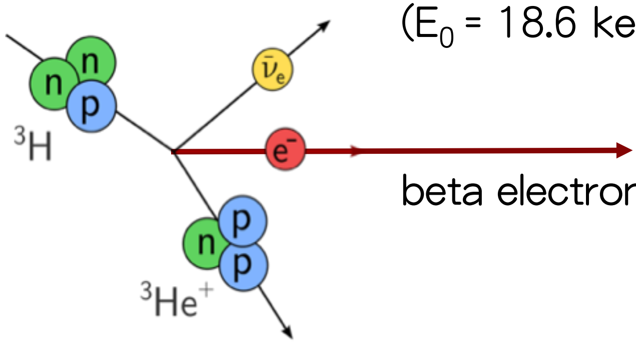
Q_{EC} = 2.8 keV
$\tau_{1/2}$ = 4570 y

Neutrino Mass Measurements with Weak Decays

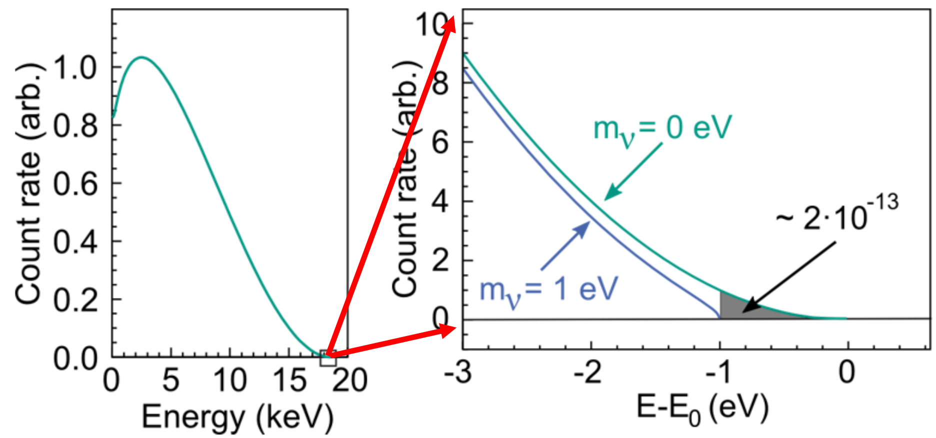
Beta Decay (Tritium)

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

(E_0 = 18.6 keV)



Electron Spectrum



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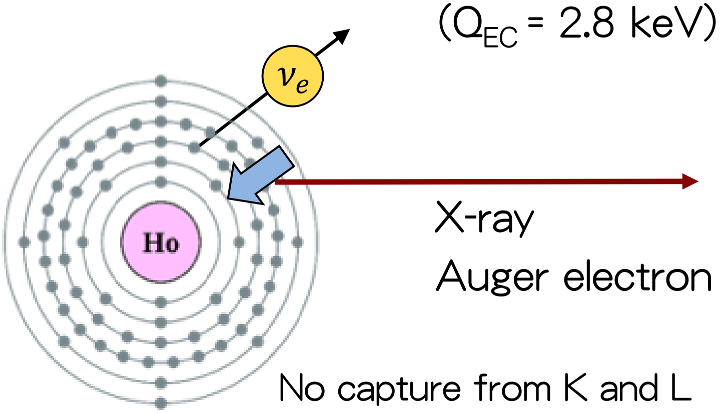
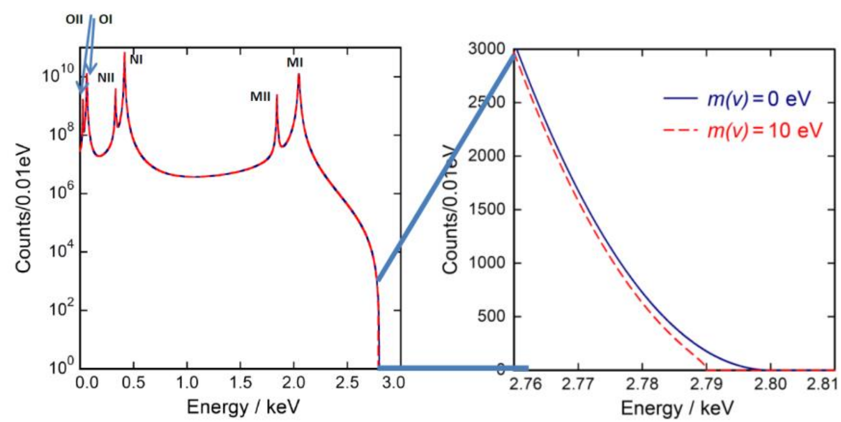


De-excitation Spectrum



Weak Decay Spectroscopy

Beta Decay (Tritium)

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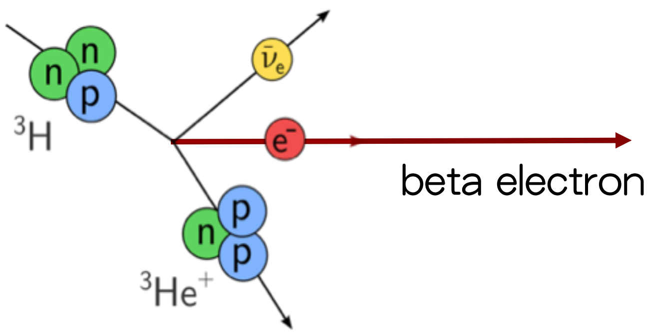
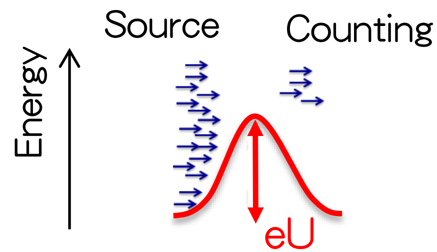
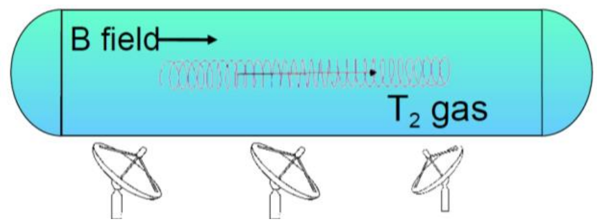


Electro-Static Filter



2018:
construction completed

Cyclotron Radiation Emission Spectroscopy



2018:
proof-of-concept

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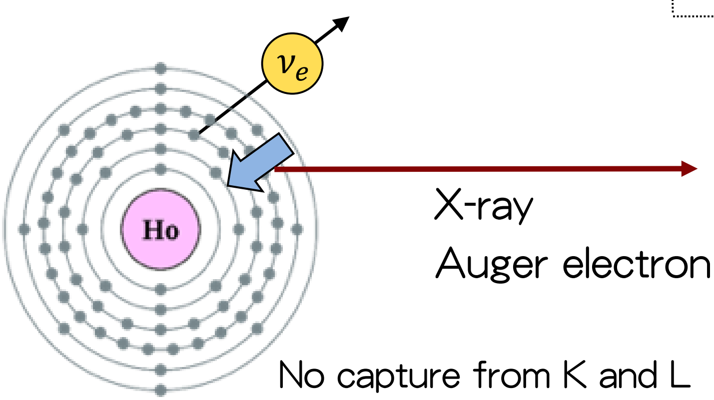
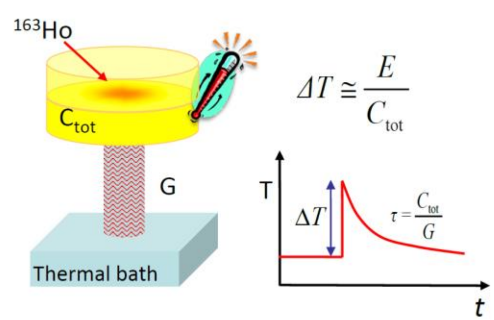


Calorimetry (bolometer)



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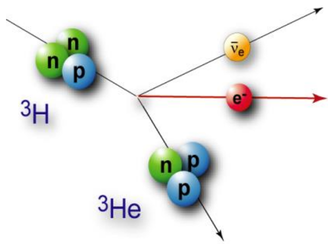
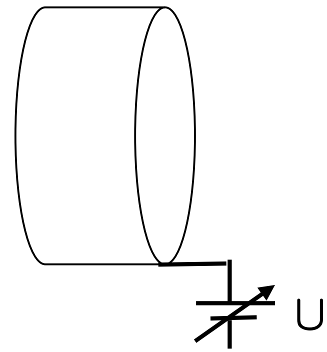
Electron Spectroscopy with Electro-Static Filter

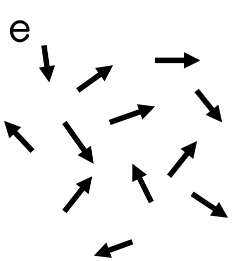


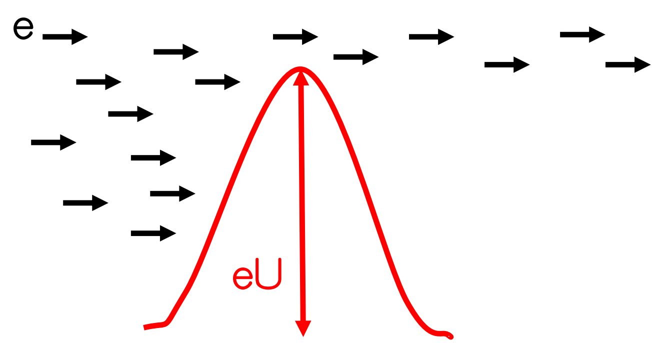
tritium
source



electro-static
retarding potential

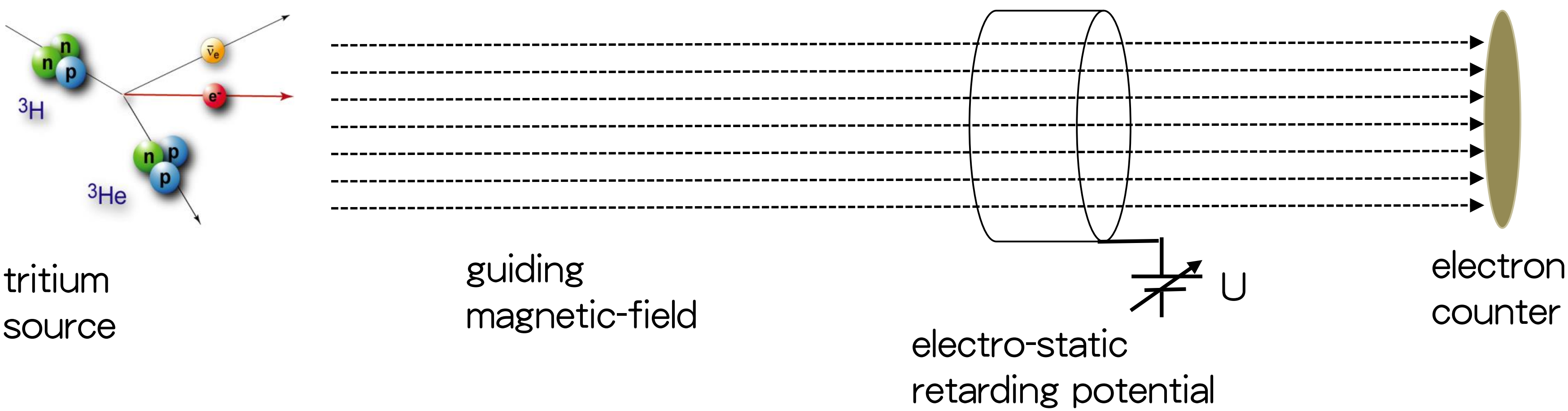
electron
counter

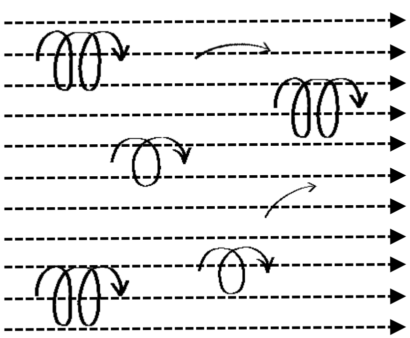




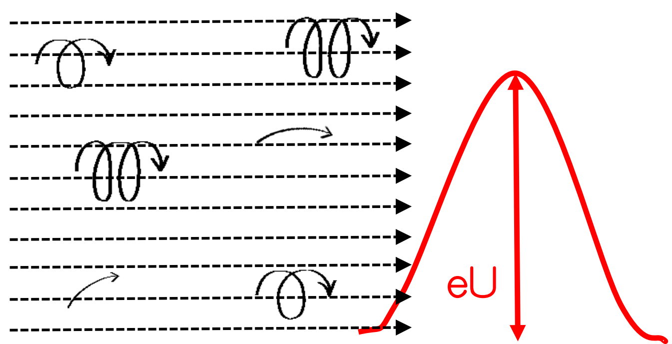
Problem: only small fraction of electrons reach this
→ guiding magnetic field

Electron Spectroscopy with Electro-Static Filter



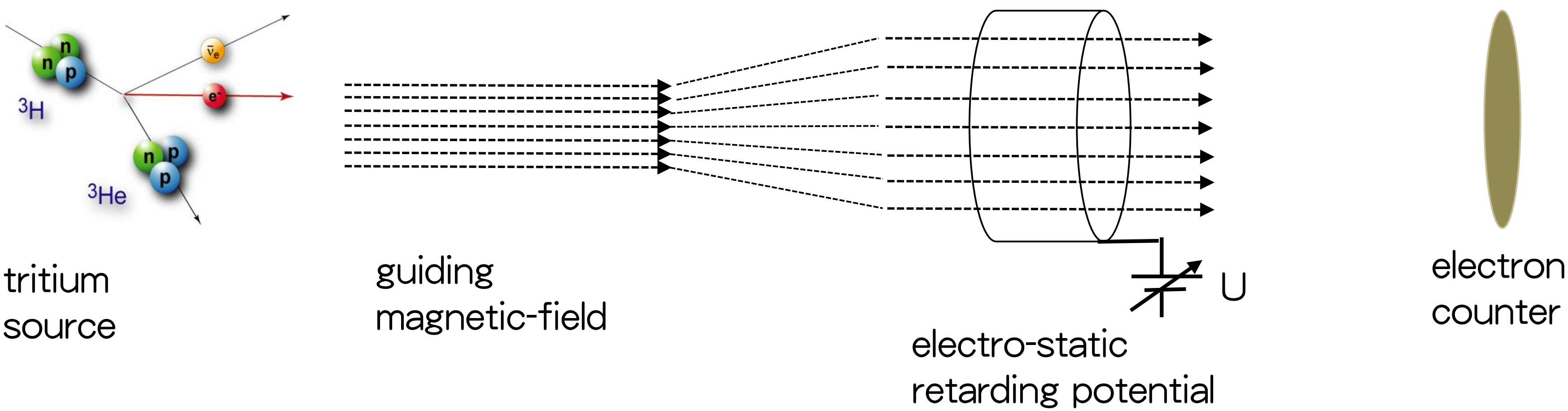


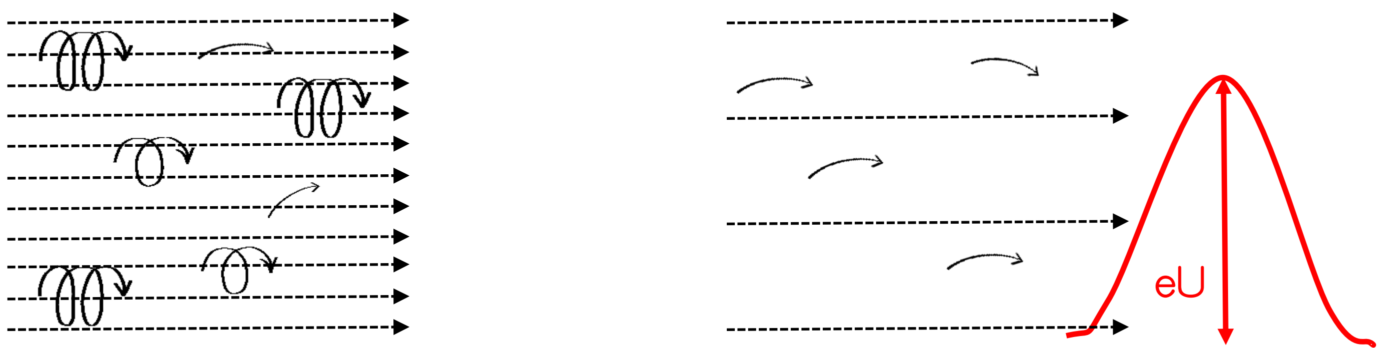
$E_{parallel}$ / $E_{transversal}$ depends on initial emission angle



Problem: only $E_{parallel}$ is measured
→ adiabatic collimation

Electron Spectroscopy with Electro-Static Filter

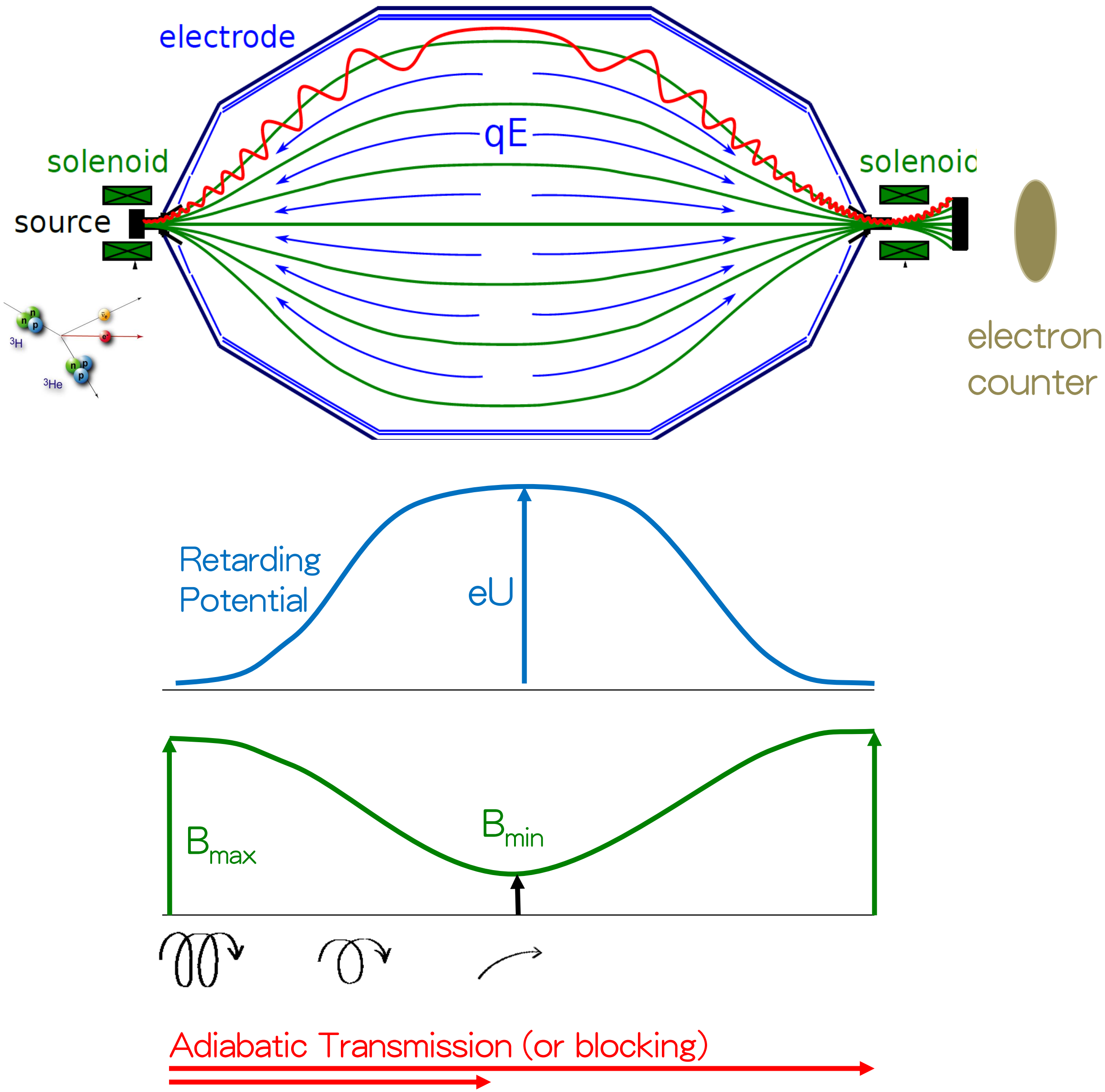




reduce magnetic field adiabatically

$\Rightarrow$ magnetic moment conserves: $\mu = \dfrac{E_\perp}{B} = \text{const}$ $\Rightarrow$ collimation

MAC-E (Magnetic-Adiabatic-Collimation Electro-static) Filter



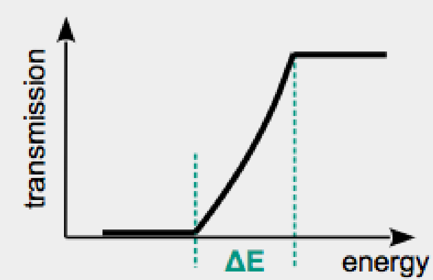
Adiabatic Transmission
(constant magnetic moment)

$$\mu = \frac{E_\perp}{B} = \text{const}$$

Energy resolution is determined by B-Ratio

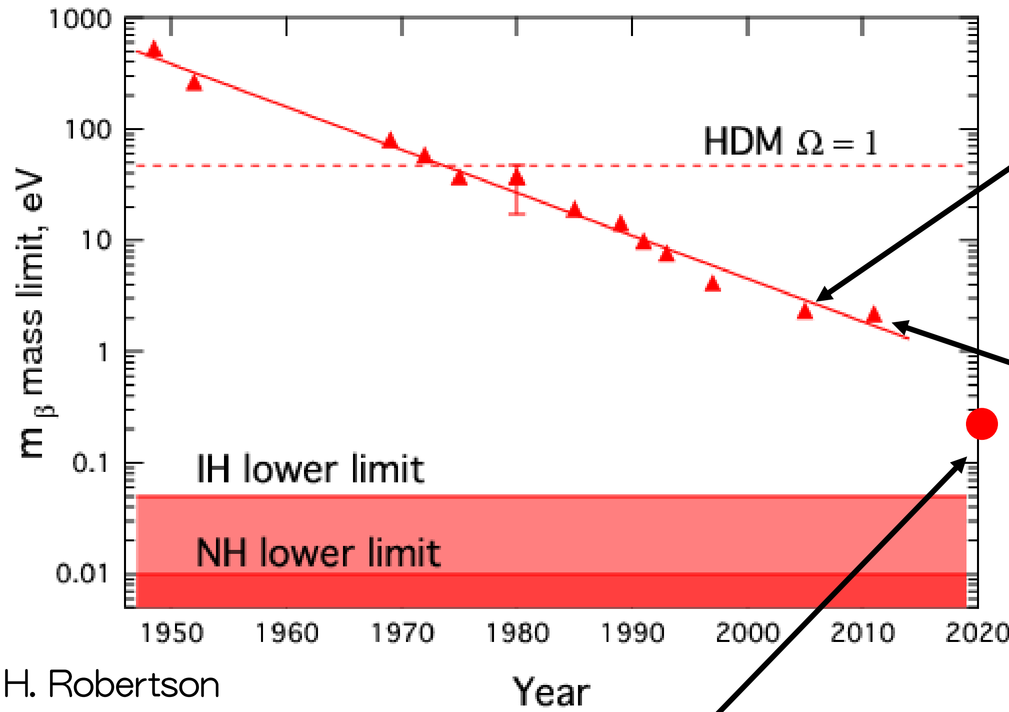
$$\frac{\Delta E}{E} = \frac{B_{\text{min}}}{B_{\text{max}}}$$

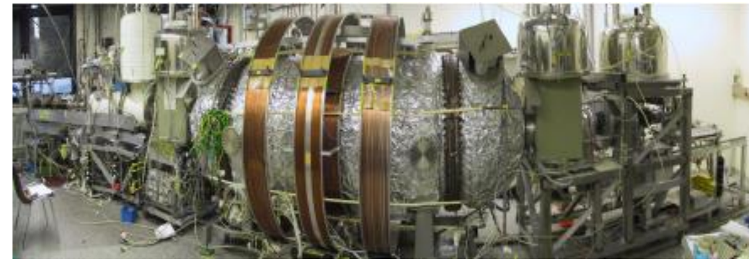
Sharp high-pass filter:



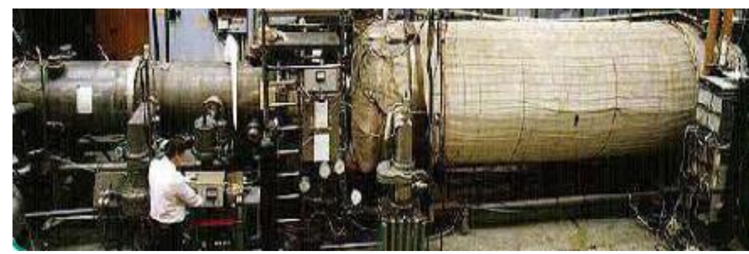
Steps of filter potential
→ integrated β spectrum

Present Mass Limit and KATRIN Experiment





Mainz (2005, final result)
$m(\nu_e) < 2.3$ eV (95%CL)



Triosk (2011, re-analysis)
$m(\nu_e) < 2.05$ eV (95%CL)

KATRIN
design sensitivity: $m(\nu_e) < 0.2$ eV (90%CL)

sensitivity 1/10 on m_e

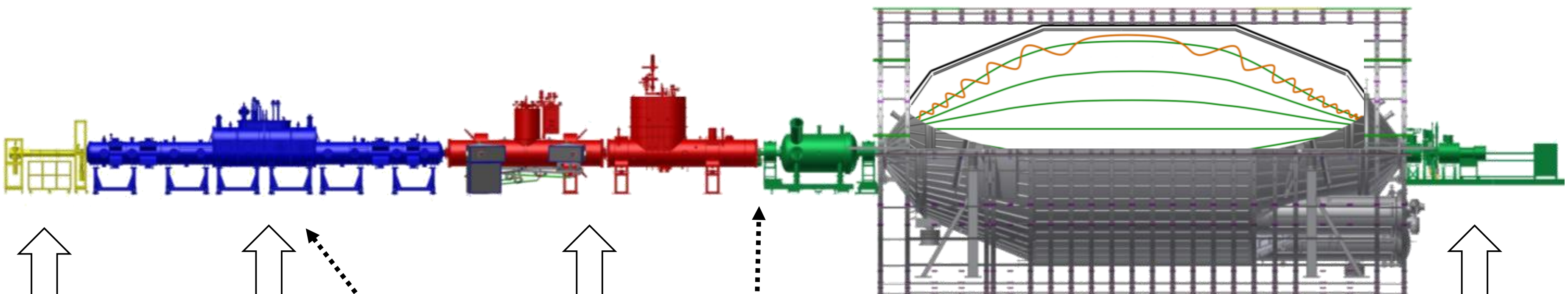
$\Rightarrow$ sensitivity 1/100 on m_e^2

$\Rightarrow$ ×100 statistics, 1/100 systematics

KATRIN Experiment

KArlsruhe TRItium Neutrino Experiment

- located at Karlsruhe Institute of Technology, Karlsruhe, Germany
- design sensitivity: $m(\nu_e) < 0.2$ eV (90%CL, 3 years)



Calibration E-Gun

Injection 1.8 mbar l/s

10^{-14} mbar l/s

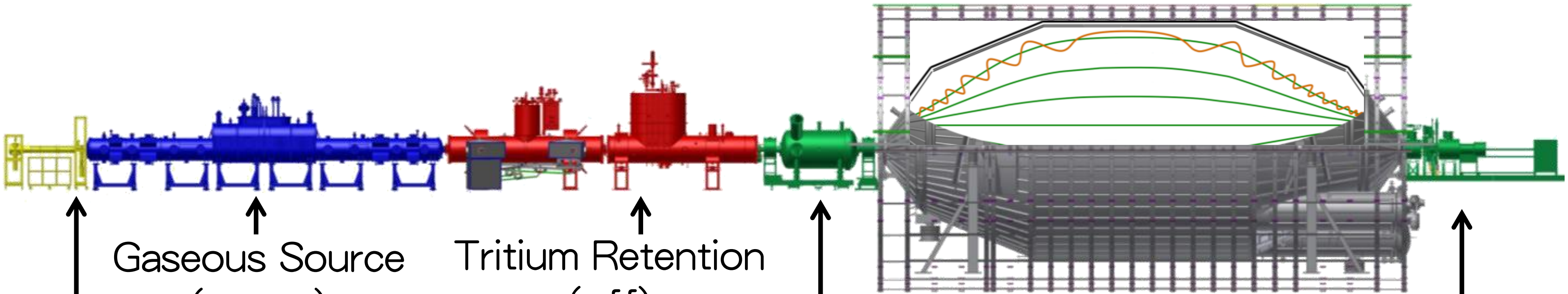
Tritium Retention (electrons guided by B)

Electron Counter (~10 mHz)

10^{11} Bq Gaseous Tritium Source

0.9 eV Resolution MAC-E Filter

Oct 2016: KATRIN “First Light” (just before DBD16)



Gaseous Source (empty)

Tritium Retention (off)

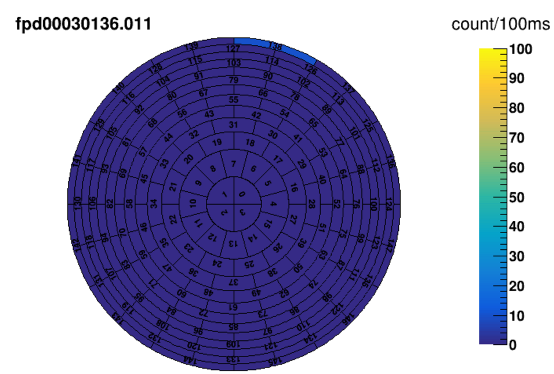
Spectrometer

Pre-Spectrometer

Photo-Electron Source

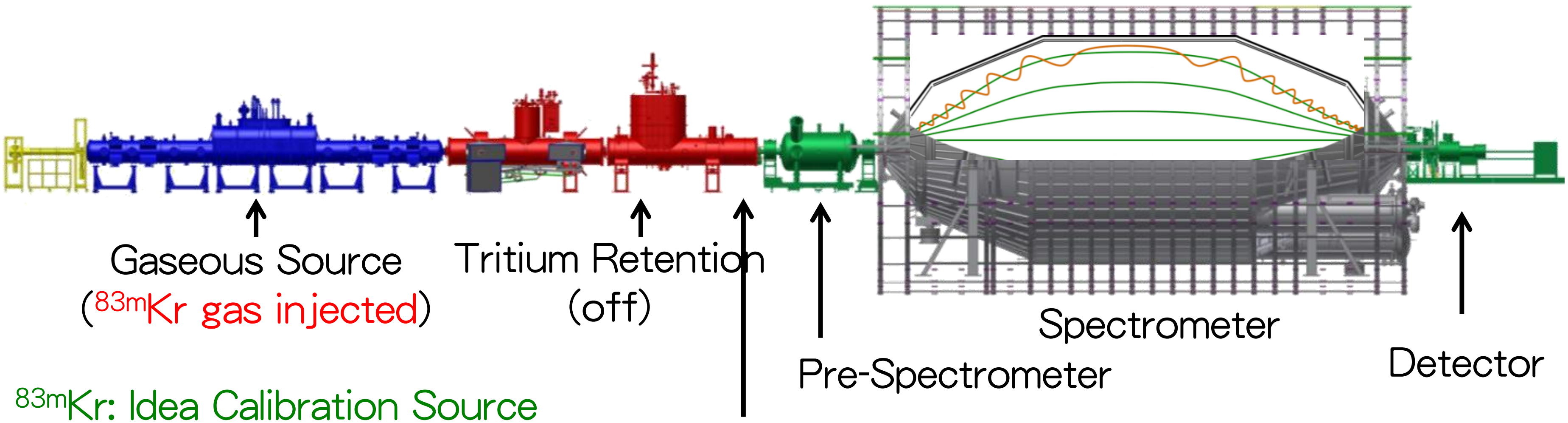
Detector

end-to-end transmission of electrons



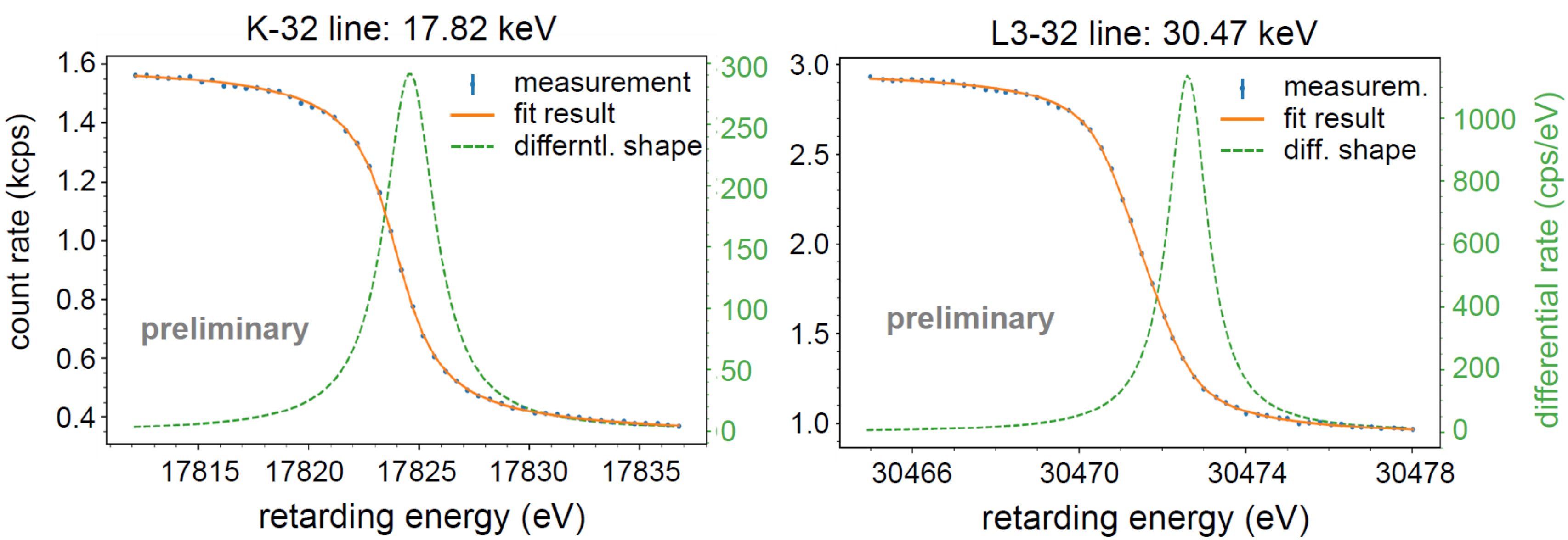
- ✓ Adiabatic transmission throughout beamline
- ✓ Beam steering with electrodes
- ✓ Ion blocking tests

Jul 2017: Krypton Campaign



^{83m}Kr: Idea Calibration Source

- ✓ Quasi monoenergetic electrons from internal-conversion
- ✓ 1.8 h life



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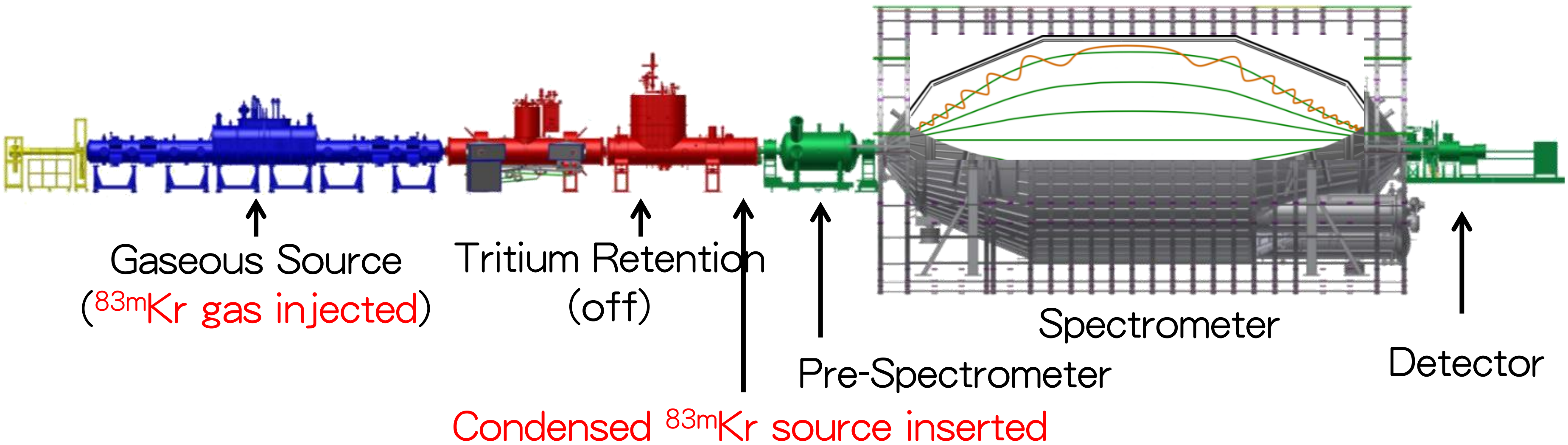
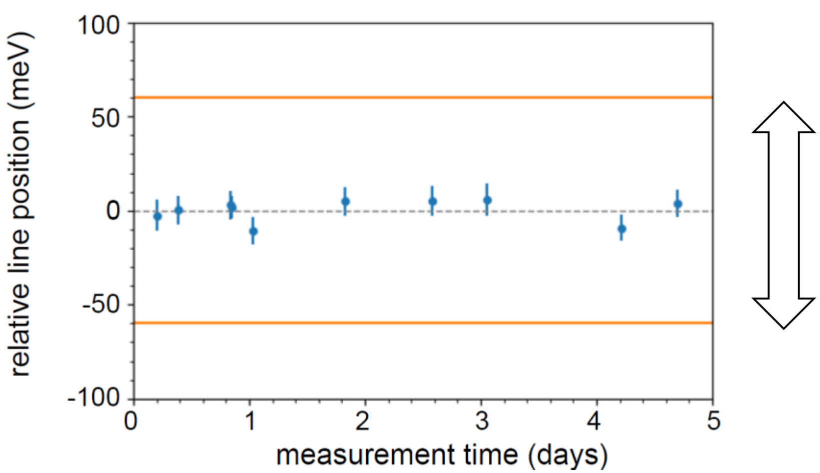
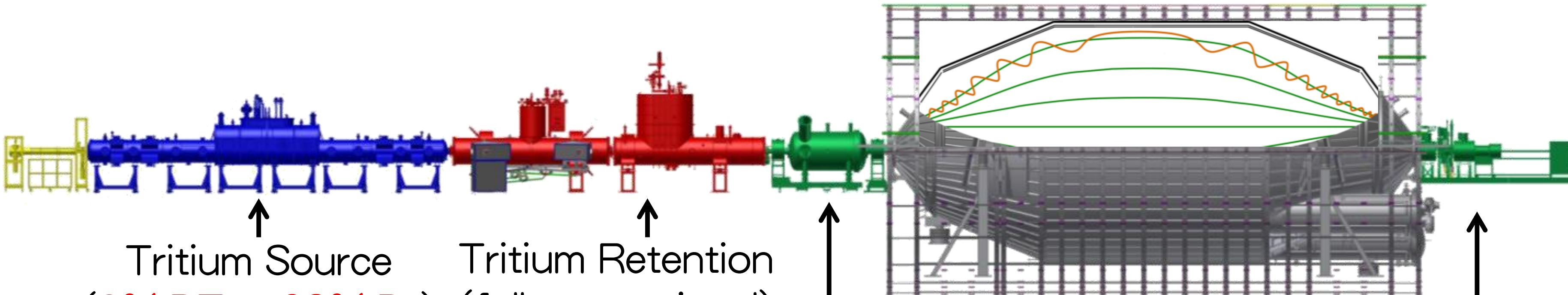


- Repeated scans of L3-32 line (30.47 keV) over a week
- Demonstrates stability of KATRIN energy scale



KATRIN stability goal: ±60 mV

Jun 2018: “The Very First Tritium”



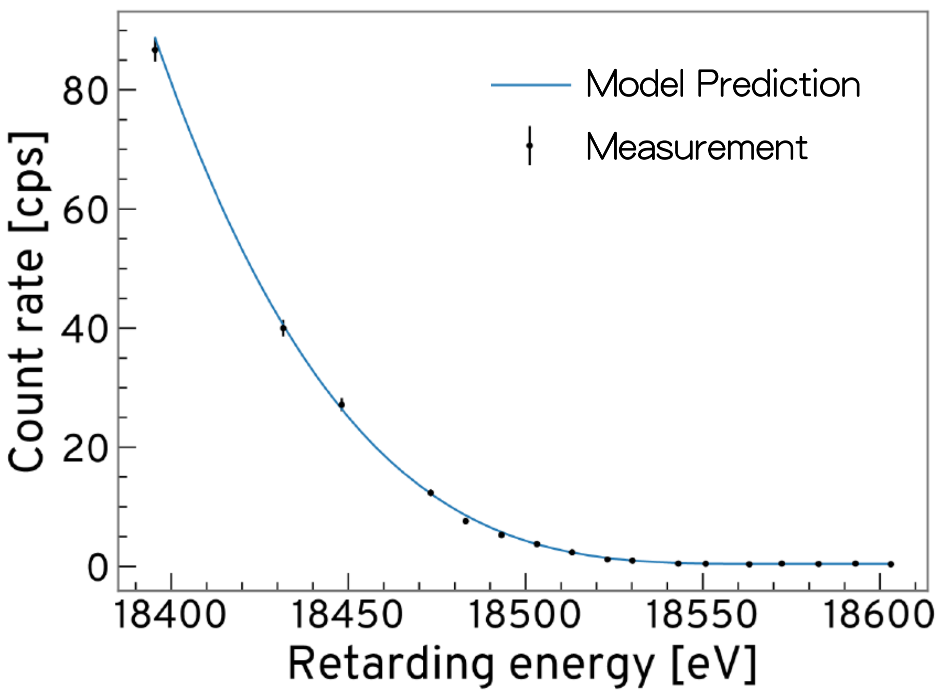
Tritium Source
(2% DT + 98% D_2)

Tritium Retention
(fully operational)

Pre-Spectrometer

Spectrometer

Detector



Observed rates look like “just as predicted”

Jun 2018: KATRIN "Inauguration"

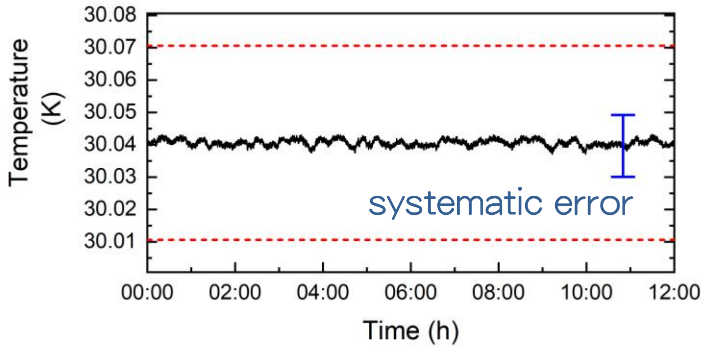
Successful start of long-term tritium data taking

operation room, official photo

operation room, in reality

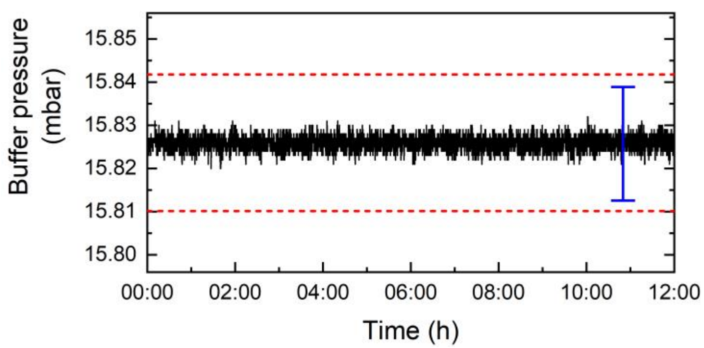
First Tritium Highlights: Source Stability

WGTS Temperature



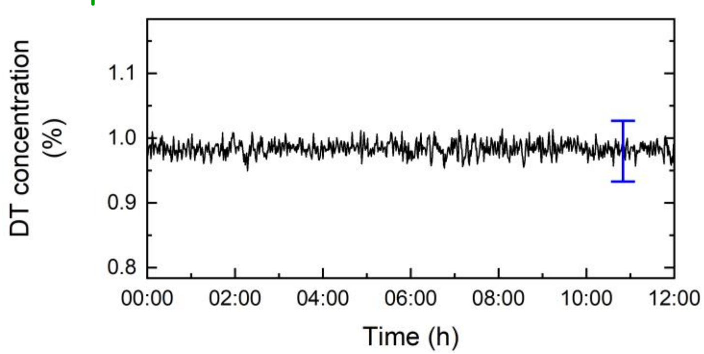
KATRIN Stability Goal
± 30 mK @ 30 K

Buffer Pressure (affects Gas Throughput)



KATRIN Stability Goal
0.1% stability

Isotopic Composition

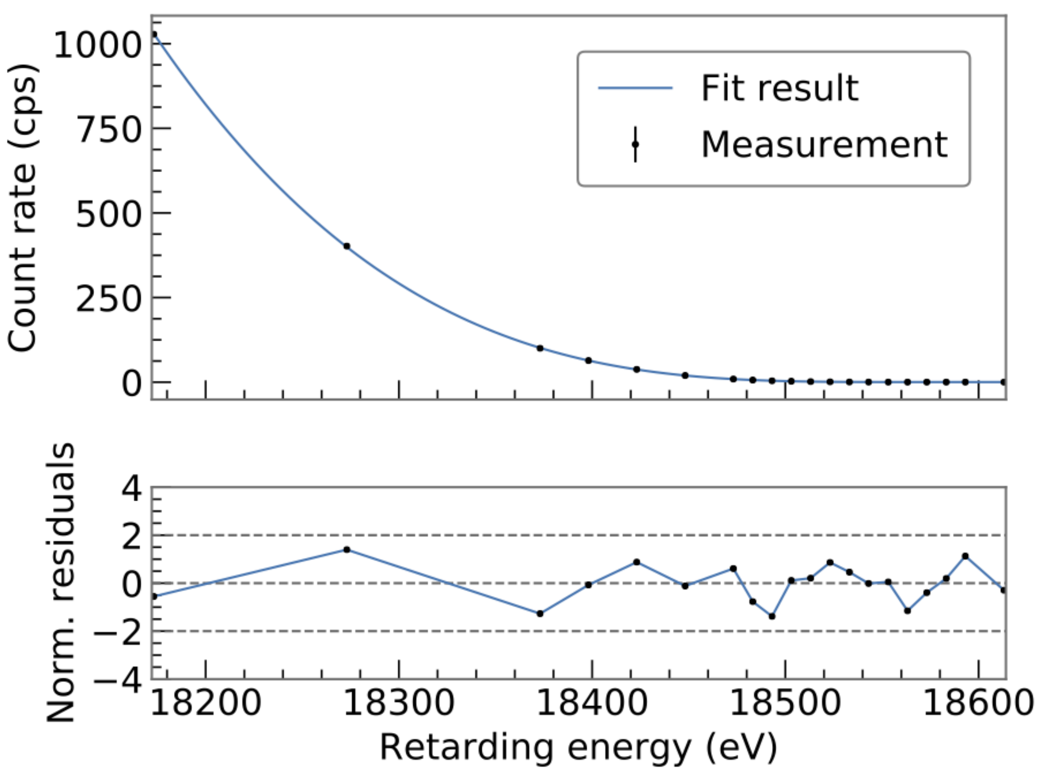


(this is not nominal KATRIN operation range)

First Tritium Highlights: Spectrum Fitting

Free Parameters:
- End-point energy
- Normalization
- Backgrounds

m_ν is fixed to zero



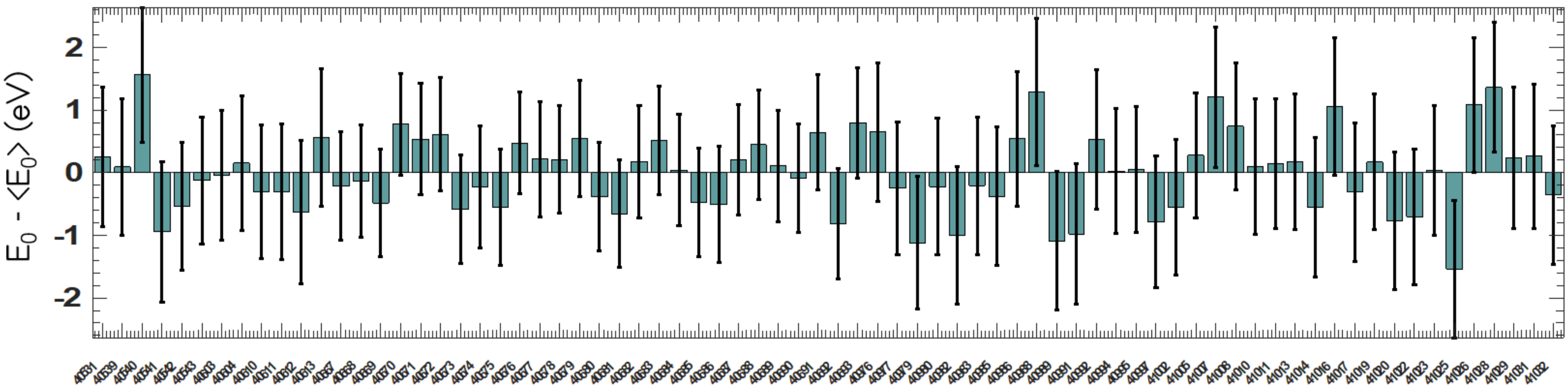
- Single 3-hour run
- Statistical errors only

- Works on-going:
  Correlations on systematics
  - combining runs, pixels
  - drifting quantities

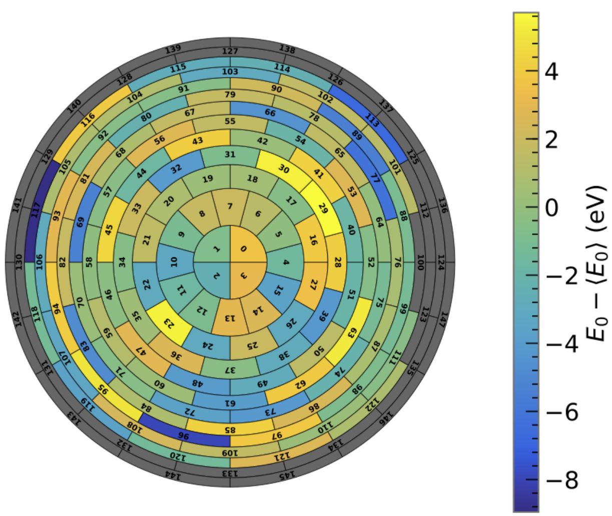
Deviance:
11.44 @ 17 dof
$\Rightarrow$ 83.28%

First Tritium Highlights: End-point Stability

Estimated end-point energies over measurement period (72 scans in 5.3 days)

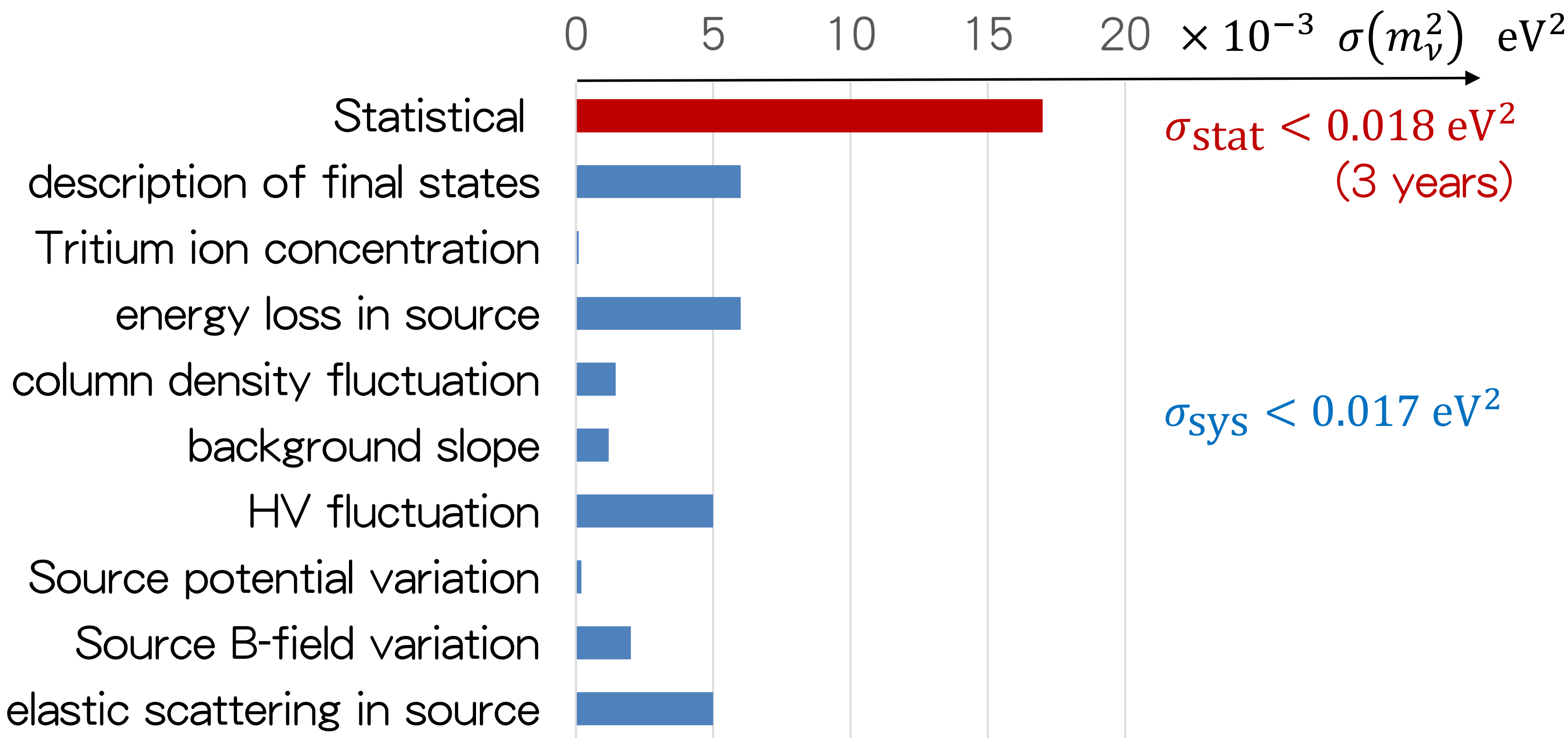


Estimated end-point energies for each pixel

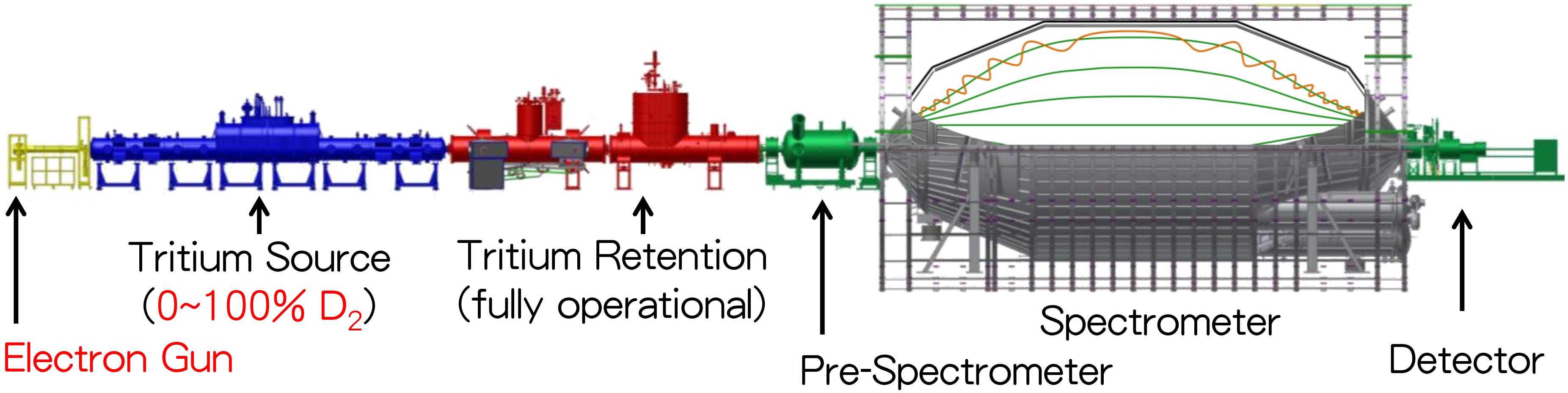


KATRIN Error Budget

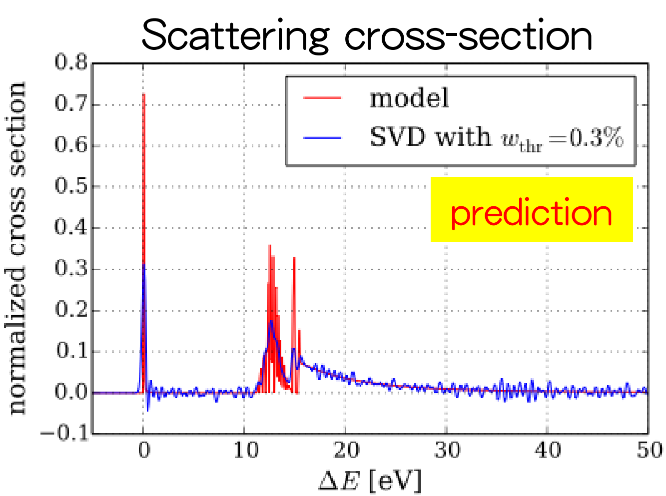
(KATRIN Design Report 2004)

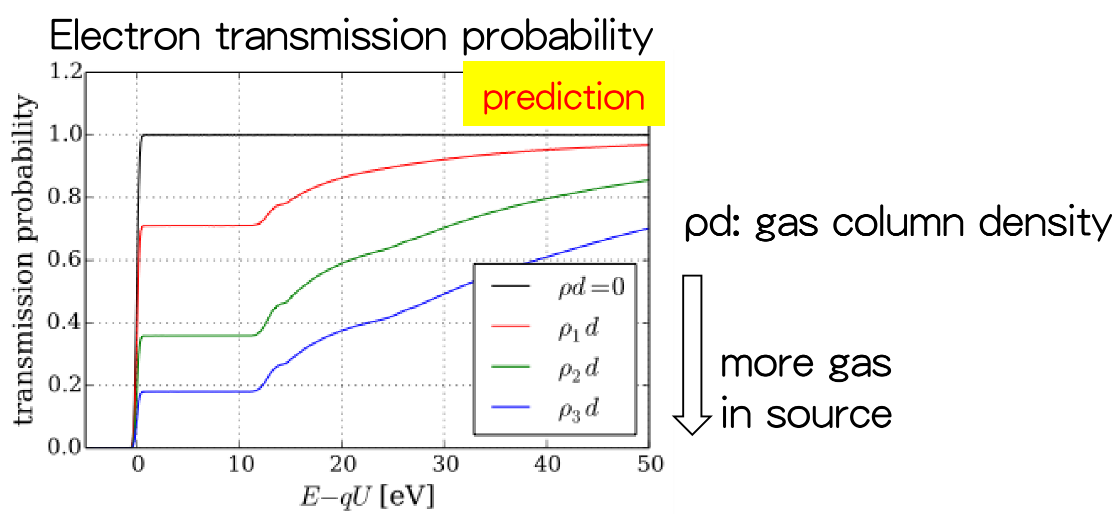


Oct 2018: Source Section Characterization



- Characterize ion creation, detection ad blocking
- Measure inelastic scattering energy-loss

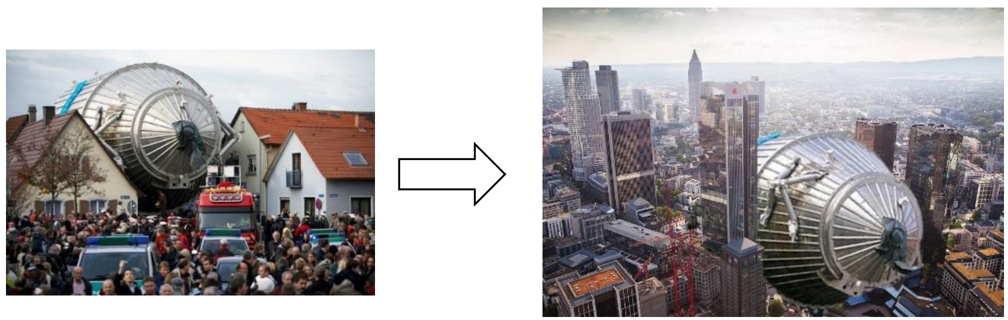




Going Further

(in case KATRIN does not see anything...)

Improving Statistics / Resolution / Backgrounds

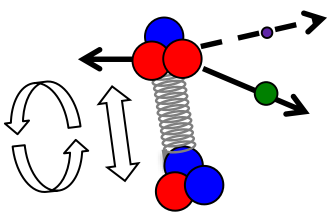


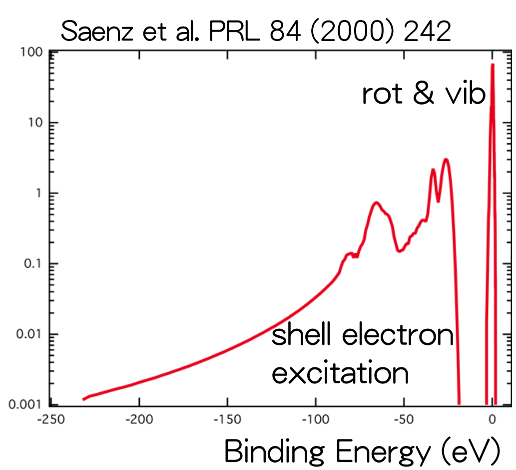
Source column-density is already at maximum

- Only possible extension is source pipe diameter
- Spectrometer diameter scales

Improving Systematics

Final state uncertainty limits the sensitivity





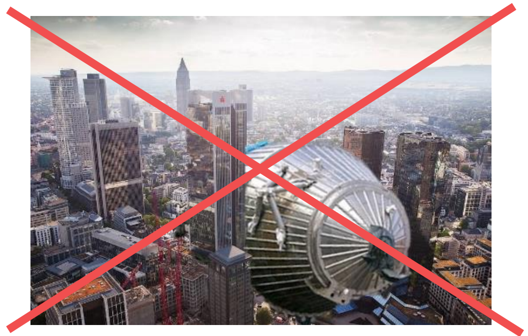
Excitations

- Rotational
- Vibrational
- Shell electron

Going Further

(in case KATRIN does not see anything...)

Improving Statistics / Resolution / Backgrounds



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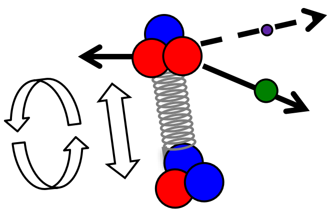

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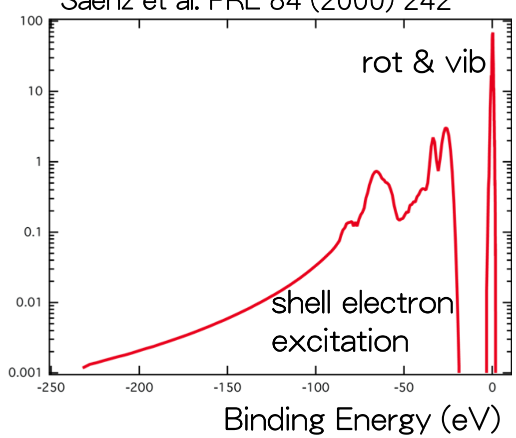
Saenz et al. PRL 84 (2000) 242



Possible Ways Out

KATRIN Differential-Mode

- MAC-E Time-of-Flight
- MAC-E + End-point Bolometer

No Electron Extraction

- Calorimetry
- Cyclotron Radiation Detection

Improve FS Understanding

No Molecular Tritium

Weak Decay Spectroscopy

Beta Decay (Tritium)

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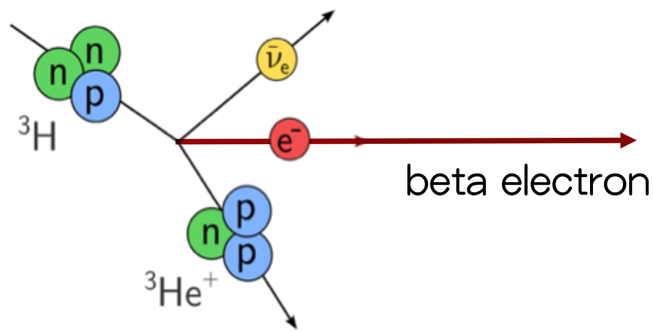

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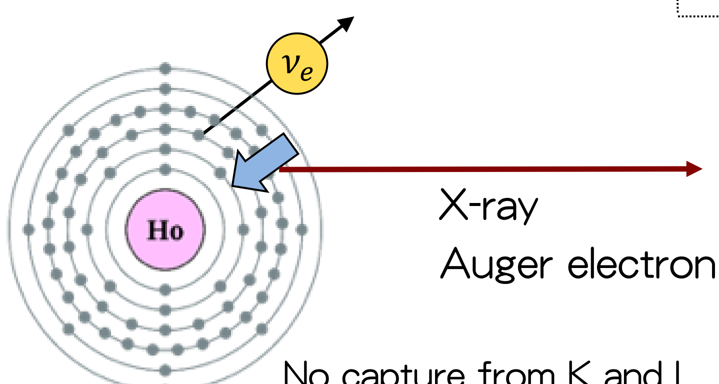
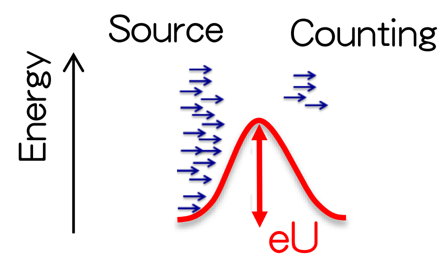
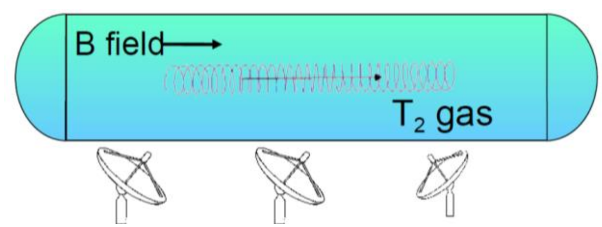


Electro-Static Filter



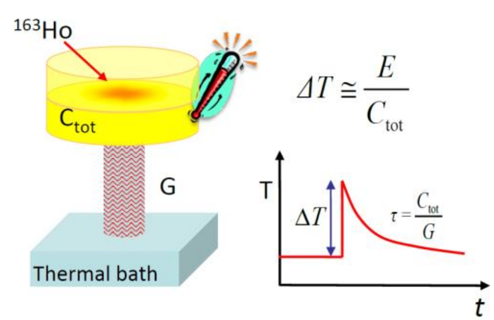
2018:
construction completed

Cyclotron Radiation Emission Spectroscopy



2018:
proof-of-concept

Calorimetry (bolometer)

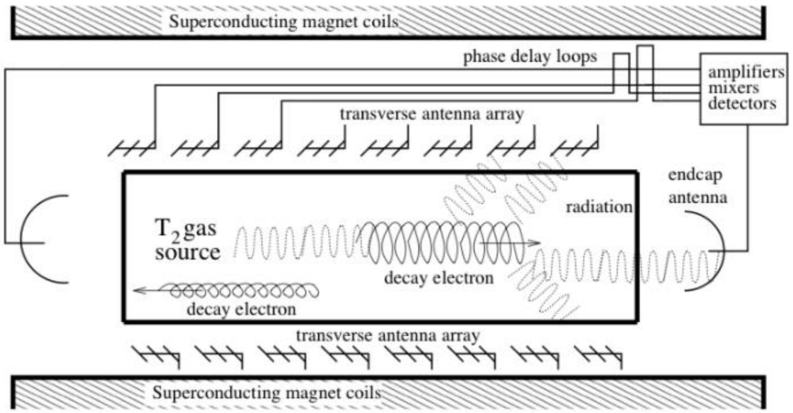


ECHo

HOLMES

2018:
proof-of-concept

Project 8: Cyclotron Radiation Emission Spectroscopy



$$f = \frac{f_0}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e + E_{\rm kin}/c^2}, \qquad P = \frac{2\pi e^2 f_0^2}{3\epsilon_0 c} \frac{\beta^2 \sin^2\theta}{1-\beta^2}$$

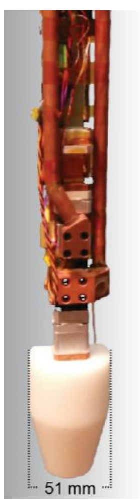
for E =18.6 keV in B = 1 T, θ = 90°
⇒ ~1 fW @ ~26 GHz

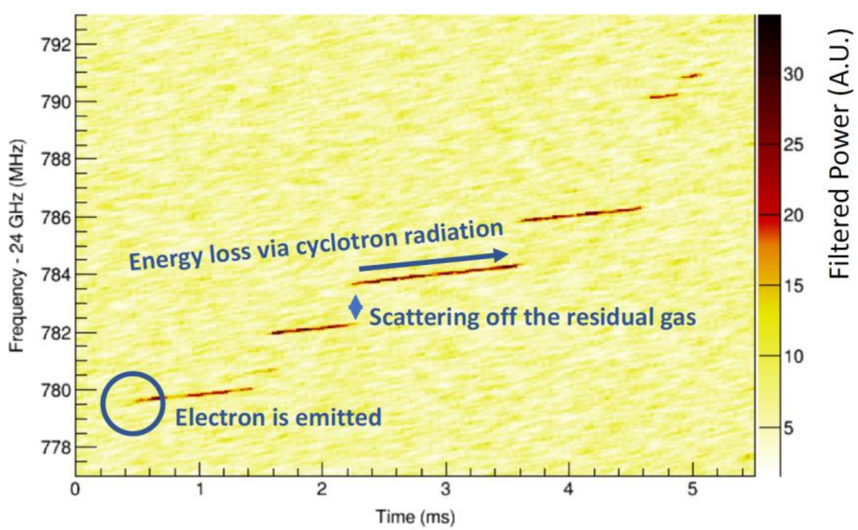
$$\Delta f = 1/\tau$$

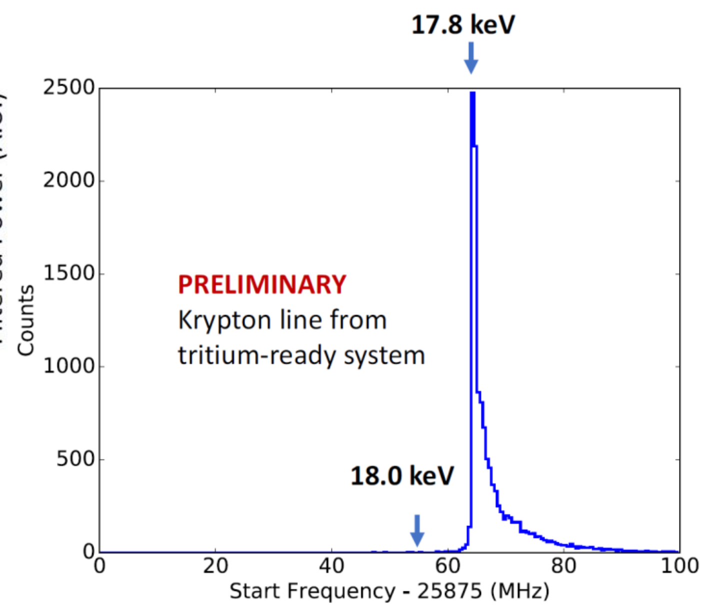
several μs ⇔ ΔE ~1 eV

Proof-of-principle, single electron detection form Krypton

(G. Rybka, Neutrino 2018)



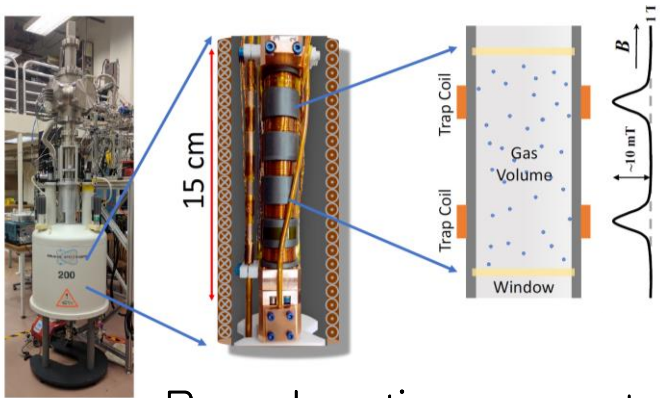




Project 8: Phased Approach

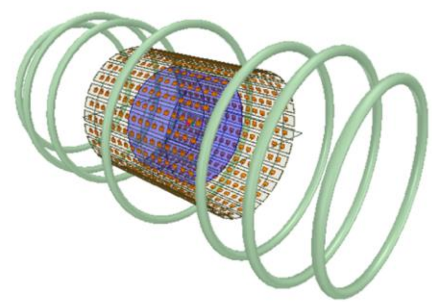
(G. Rybka, Neutrino 2018)

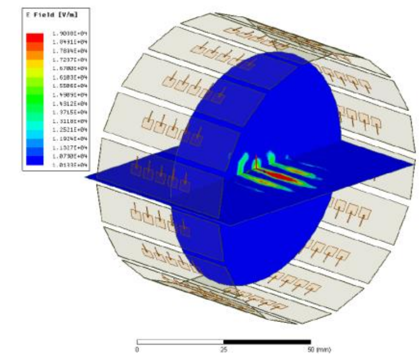
Phase 2: Electrons from Tritium



Record continuous spectrum
m_ν ~ 10 .. 100 eV

Phase 3: Large Volume

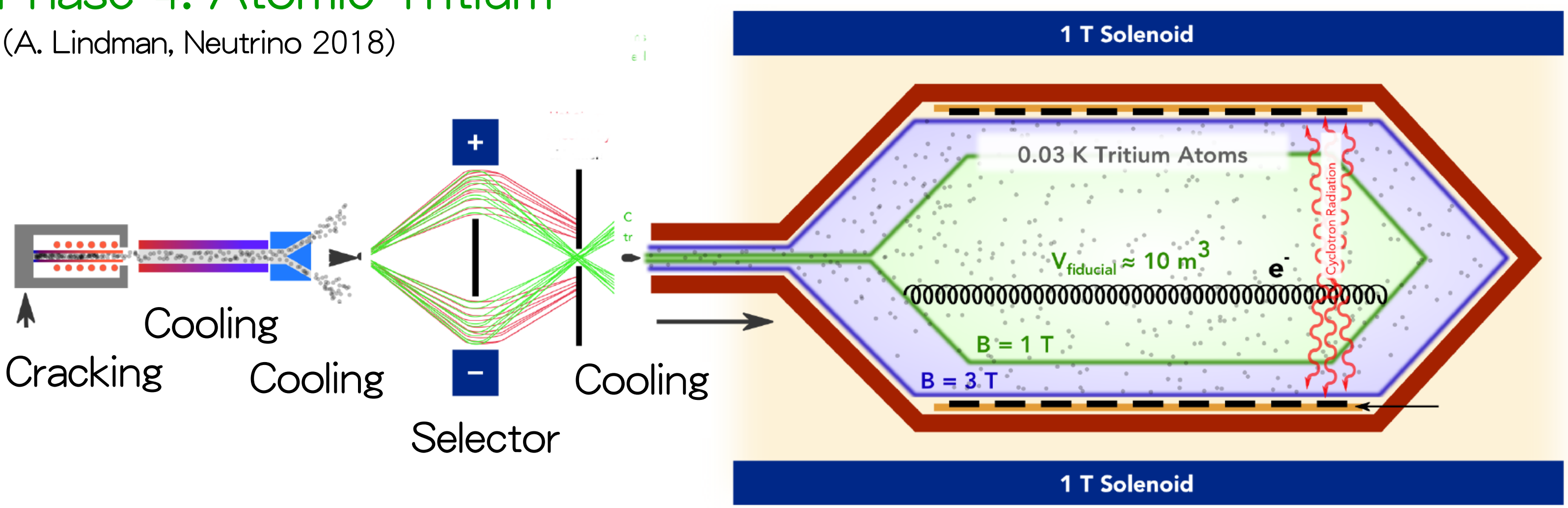




Antenna array, interferometry to localize
m_ν ~ 2 eV

Phase 4: Atomic Tritium

(A. Lindman, Neutrino 2018)

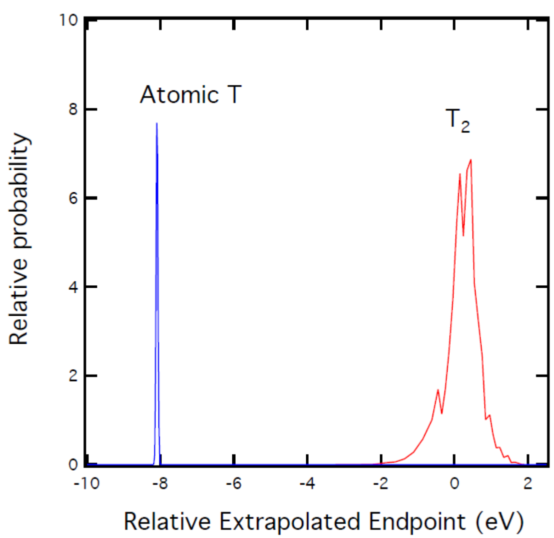


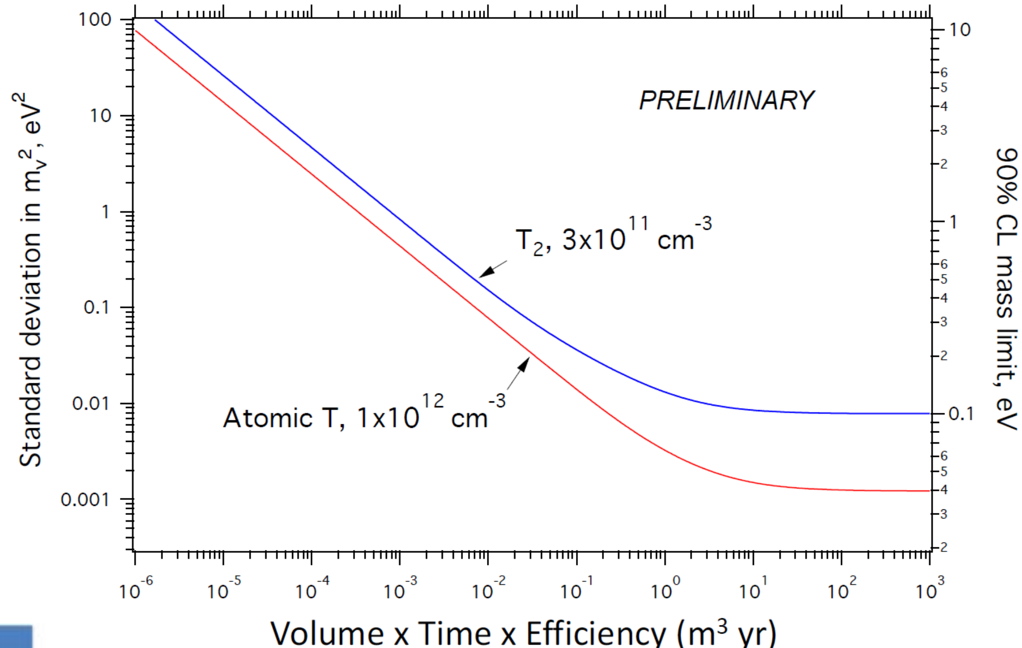
Trapping & Decay Volume

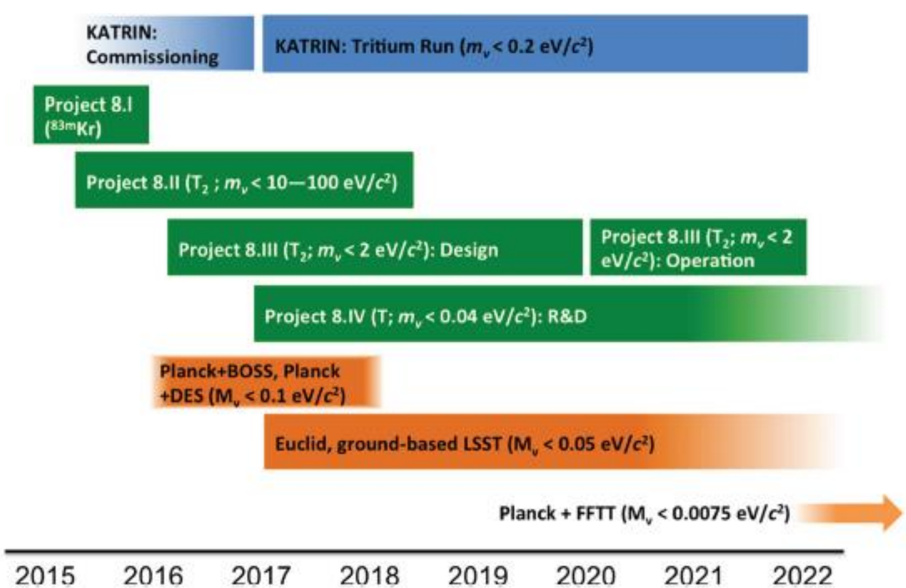
$T_2/T < 10^{-6}$

Project 8: Sensitivity with Atomic Tritium

(G. Rybka, Neutrino 2018)







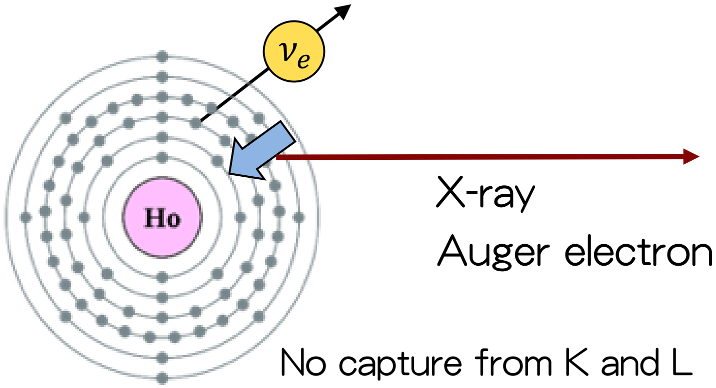
With 10 ~ 100 m^3 yr,
m_ν sensitivity 40 meV

J. Phys. G 44 (2017) 054004

ECHo & HOLMES

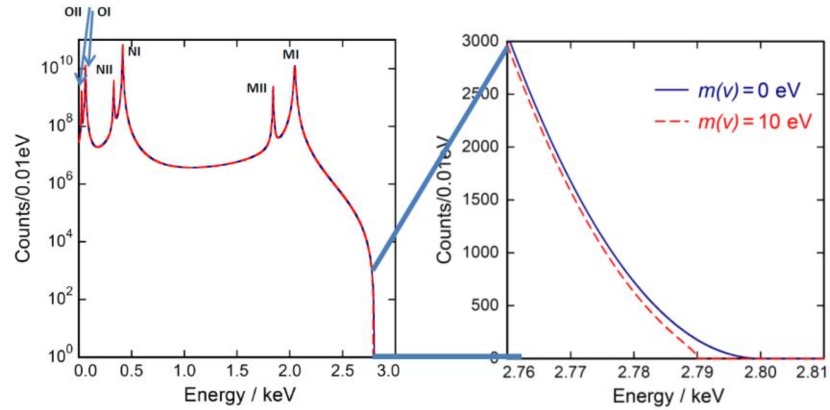
(L. Gastaldo, Neutrino 2018)

Calorimetry for EC De-excitation



No capture from K and L

De-excitation Spectrum



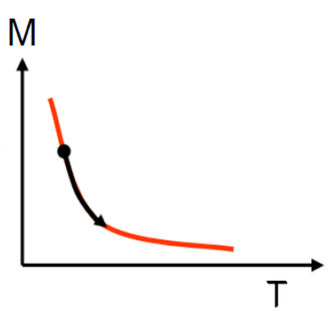
- ✓ Source inside / contact to detector
- ✓ No molecular final states

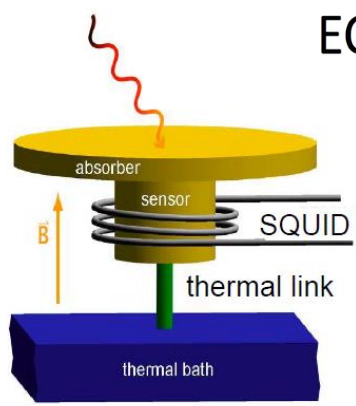
Metallic Magnetic Calorimeters (MMC)

Magnetization of para-magnetic material

$\delta T \;\Rightarrow\; \delta M$

ECHo

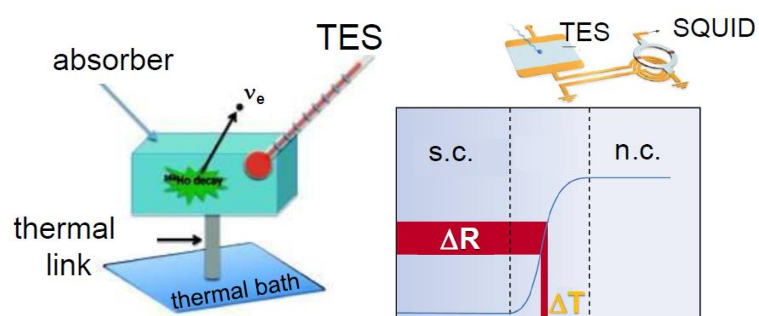




Transition Edge Sensors (TES)

Resistance at super-conducting transition

HOLMES

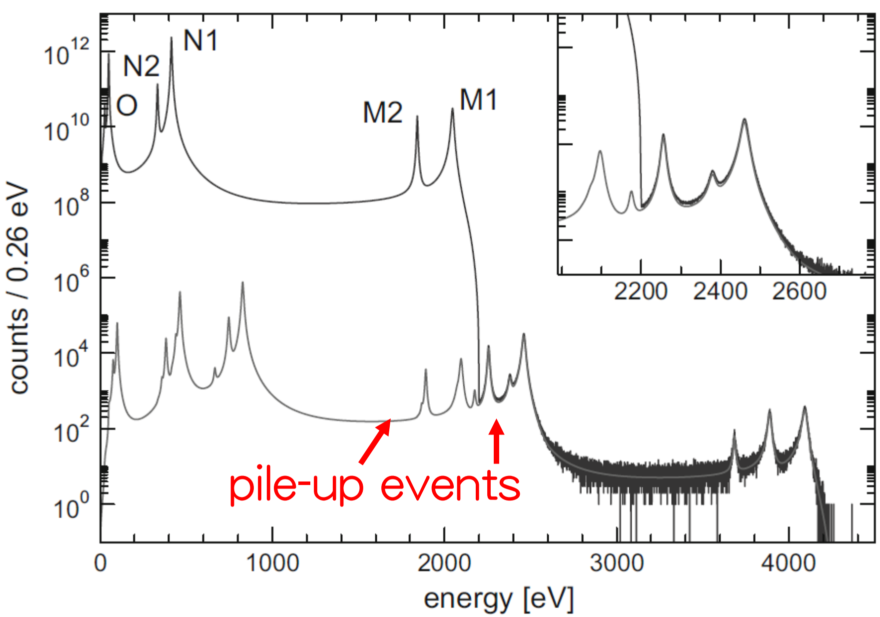


ECHo & HOLMES: Challenges and Goals

(L. Gastaldo, Neutrino 2018 / G. Drexlin, NOW 2018)

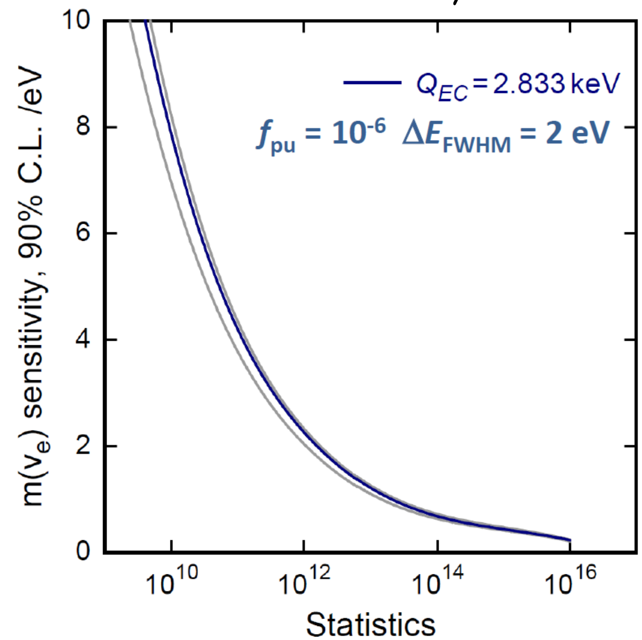
- Energy resolution: $\Delta E < 2\sim3$ eV
- Statistics sub-eV sensitivity: $N_{ev} > 10^{14} \Rightarrow A = 1\sim10$ MBq
- Small pile-up fraction: $f_{pu} < 10^{-6} \Rightarrow \tau < 1$ µs and 10^6 pixels
- Background level: $< 10^{-5}$ events/eV/pixel/day

de-excitation spectrum with pile-up



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

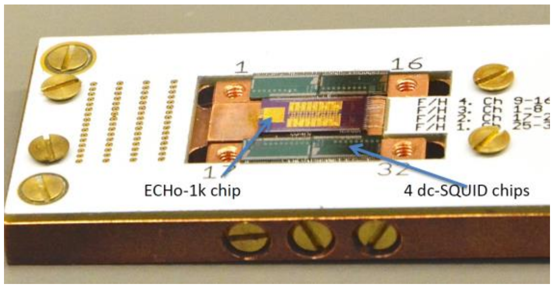
sensitivity



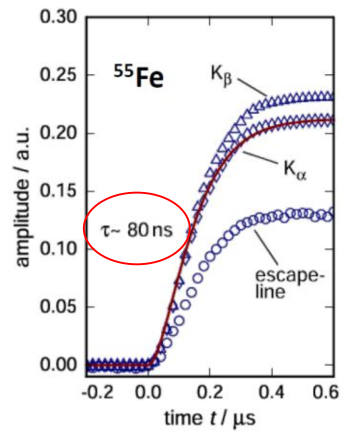
ECHo & HOLMES: Achievements and Status

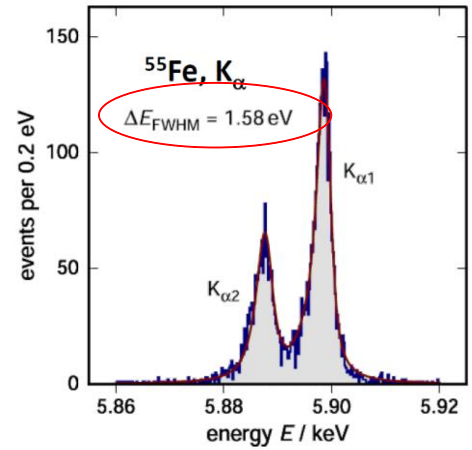
(L. Gastaldo, Neutrino 2018)

ECHo



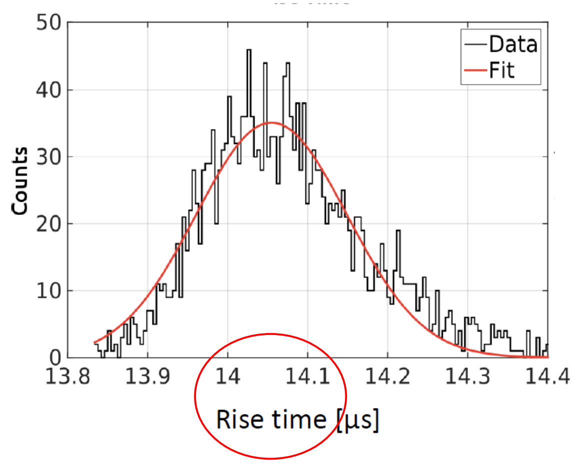
- 5 Bq/pixel chip
- 60 produced

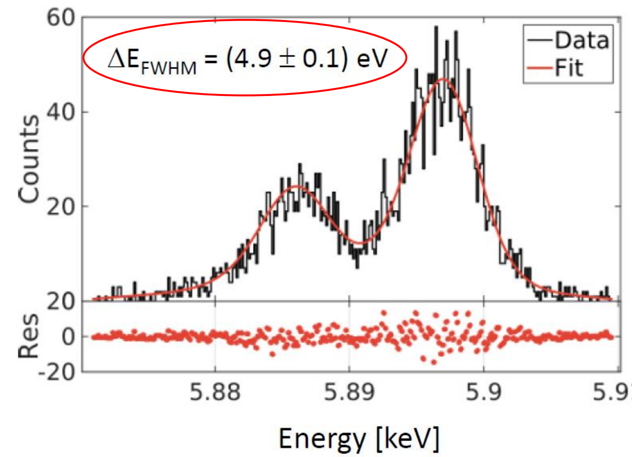




HOLMES

- 300 Bq/pixel chip
- 1000 produced





ECHo and HOLMES: Sensitivity and Plans

ECHo

(L. Gastaldo, Neutrino 2018 / G. Drexlin, NOW 2018)

2015-2018: ECHo 1k

- 5 Bq / pixel × 60 pixels
- 1 year
- m_ν sensitivity: 10 eV

2018-2021: ECHo 100k

- 10 Bq / pixel × 12,000 pixels
- 3 years
- m_ν sensitivity: 1.5 eV

2021-2027: ECHo 1M

- 1 M pixels (10 MBq)
- m_ν sensitivity: 0.3 eV

HOLMES

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

2013-2018: Proof-of-concept

- 300 Bq/pixel × 64 pixels
- 1 month
- m_ν sensitivity: 10 eV

2019~: Full scale

- 300 Bq/pixel × 1000 ch
- 3 years
- m_ν sensitivity: 1 eV

Conclusions

Direct Measurement with Weak Decay Kinematics

- Model independent
- Current limit: 2 eV (Mainz & Triosk)

KATRIN

- 0.2 eV sensitivity (90% CL) in 3 years
- Construction completed
- Excellent performance in commissioning runs

Going Further

- To overcome: statistics & molecular final-state uncertainty
- Next Generation Projects:

PROJECT 8: Cyclotron Radiation Spectroscopy, Atomic Tritium
- Single electron detection demonstrated

ECHo, HOLMES: EC on ^{163}Ho and Calorimetry
- >MBq ^{163}Ho produced, technology demonstrated
- Currently ~10 eV sensitivity, pushing down

KATRIN Collaboration

- ~130 Collaborators
- 18 Institutions
- 6 Countries
  DE, US, CZ, RU, UK, FR