

Focused topical session 'Data Analysis'

NuMass, KIT, 15 April 2026

Contributors:

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- Pranava Teja Surukuchi, Elise Novitski (Project 8)
- Seb Jones (QTNM)
- Raghav Pandey (ECHO)
- Matteo Borghesi (HOLMES)
- Alfredo Cocco, Federico Virzi (PTOLEMY)



Outline

- Overview and shared questions
- Signal processing and data analysis
 - MAC-E
 - CRES
 - Holmium
- Sensitivity

Signal processing and data analysis: from phenomena to limits

Weak decay

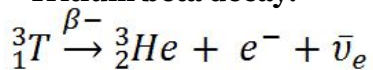
Signature of energy spectrum

Signal processing

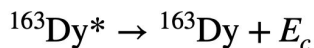
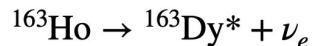
Constructing end-spectrum

Fitting for effective neutrino mass

Tritium beta decay:



Electron Capture Holmium-163



Phase space factor determines energy available to remaining decay products:

“ENERGY SPECTRUM”

- Integral count rate (KATRIN)

- Frequency chirp (PROJECT 8/QTNM)

- Temperature pulse (ECHO/HOLMES)

- Track + calorimeter (PTOLEMY)

“SIGNAL”

Signal processing extracts a proxy for energy: retarding potential, frequency, pulse height, etc.

- Differential mode: histogram of reconstructed energies
- Integral mode: count rate vs. retarding potential

This session

- Tritium experiments (KATRIN, PROJECT 8, QTNM, PTOLEMY): Fit the exact theoretical β -spectrum known from first principles.
- Holmium experiments (ECHO, HOLMES): Fit a phenomenological model of the EC de-excitation spectrum.

Shared big questions and challenges

Endpoint, fixed or not?

How precise does one need to be on the absolute energy calibration?

Fit using m_β^2 or m_β ? m_β or (m_1, m_2, m_3) ?

Overlooked broadening \rightarrow negative m^2

What happens when m is forced to be positive?

Which unmodelled effects could bias the neutrino mass estimation?

How do we spot them?

Multiple endpoints?

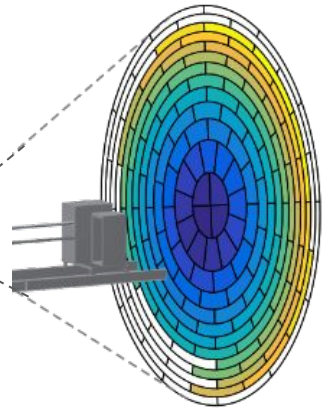
Deformation in the energy spectrum?

Additional backgrounds?

How can we perform reliable (and fast!) sensitivity studies?

KATRIN beamline: Galactic View

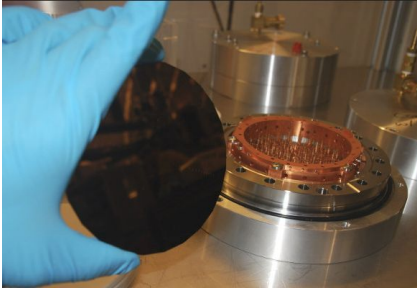
Signal Processing □ Data Analysis & Strategies



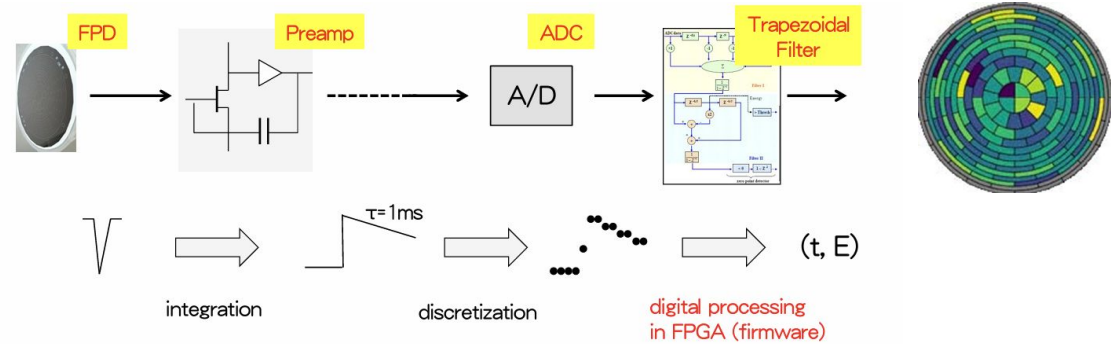
Focal plane detector (FPD)
148 pixel silicon PIN diode

KATRIN: Signal processing

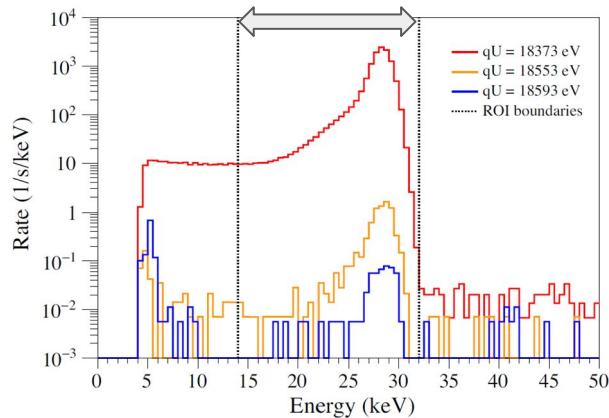
Focal Plane Detector (FPD):
Segmented PIN diode wafer



Readout Chain: Precision Analog + Digital Signal Processing



FPD Energy Spectra & Counting in ROI

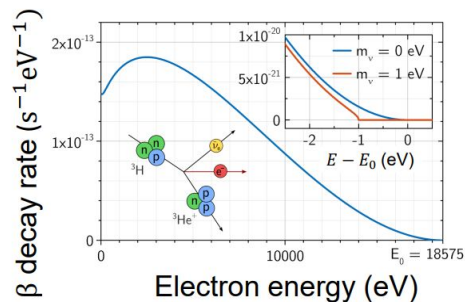


Detection Efficiency Corrections include:

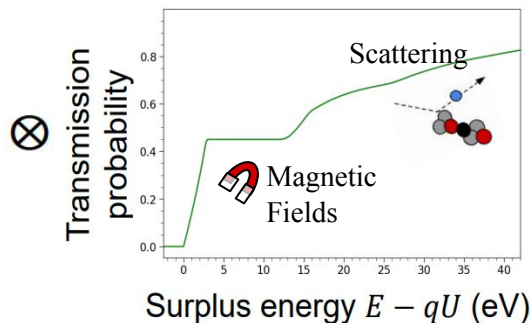
- **Back-scattering** & reflection of back-scattered electrons
 - Signal **charge sharing** among pixels
 - Multiple electrons in an event (peak **pile-up**)
 - Electronics **baseline shift** depending on rates (tail pile-up)
 - Finite resolution and **drift** of the gain
- Electron rates vary from 0.1 cps (typ. beta signals) to 100 kcps (e-gun)
 - **Accurate detection efficiency** is the key → appendix

Integral Measurement: Modeling of the tritium spectrum

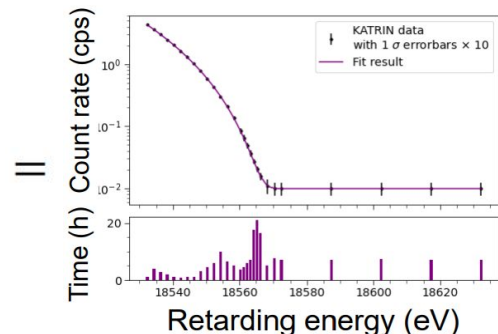
T₂ Beta spectrum $R_\beta(E; m^2(\nu_e))$



Response function: $f(E - qU)$



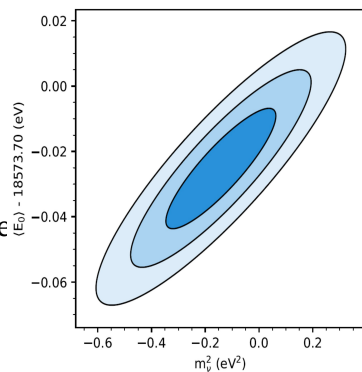
Observed spectrum



Cross check: Endpoint energy

- $E_0 = 18573.66 \pm 0.01$ eV
- Q-value: 18575.0 ± 0.3 eV
- Good agreement with Penning trap ϵ 18575.78 ± 0.02 eV

Phys. Rev. Lett. 131 (2023) 243002



Science 388, 180–185 (2025)

$$R(qU) = A_s \cdot N_T \int_{qU}^{E_0} R_\beta(E; m^2(\nu_e)) \cdot f(E - qU) dE + R_{bg}$$

Four free fit parameters:

Spectrum amp. A_{sig}

Spectrum Endpoint E_0

Background rate R_{bg}

Squared mass m_ν^2

$\sim 10^{-8}$ of all β -decays in scan region
 ~ 40 eV below endpoint

Data combination

Beta scans:

- One integral scan: ~ **2-3 hours of data**
- One measurement campaign: **few 100 scans**

Challenge

- ~1000 runs \times 148 pixels \rightarrow large data volume
- High number of fit parameters

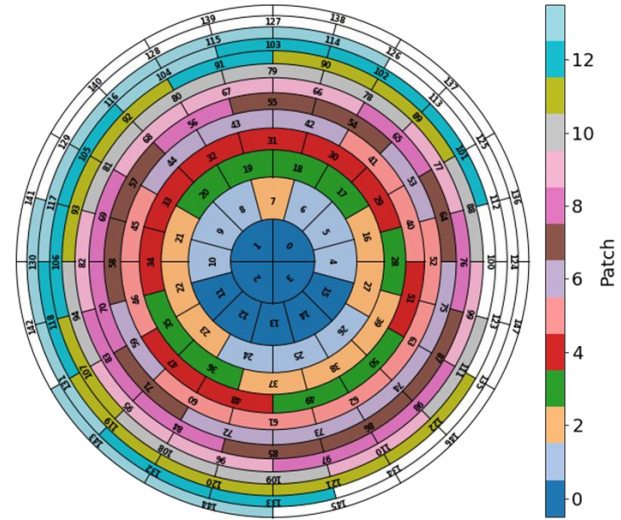
Strategy

- Stack pixel-wise data at same HV set points
- Group pixels with similar transmission \rightarrow *patches*

Implementation

- Use **14-patch configuration** b/c of **SAP settings**
- Accounts for radial inhomogeneity in electromagnetic fields

14-patch configuration



A. Lokhov et al., Eur. Phys. J. C 82, 258 (2022)

Data Analysis Challenges & Approaches

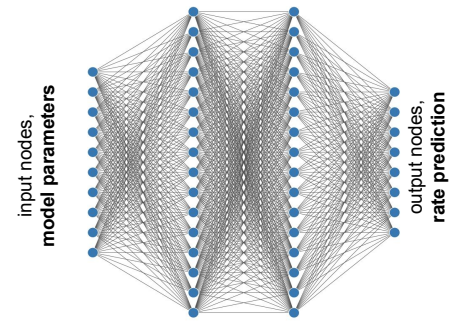
Challenges

- **Larger datasets:** multiple campaigns, >1500 data points
- **Complex modeling:** ~ 180 fitting parameters
- **Strong correlations:** ~ 150 correlated systematic param.
- **High computational cost:** expensive model evaluation and fitting procedures

Frameworks

Two independent analysis teams with different analysis frameworks

- **KaFit team:** Highly optimized, direct model evaluation with block caching of response function & tritium decay spectrum
- **The Netrium Team:** Neural network-assisted fast model predictions
[Karl et al., EPJ C 82 (2022)]



Data Analysis: Two-step Blinding Strategy

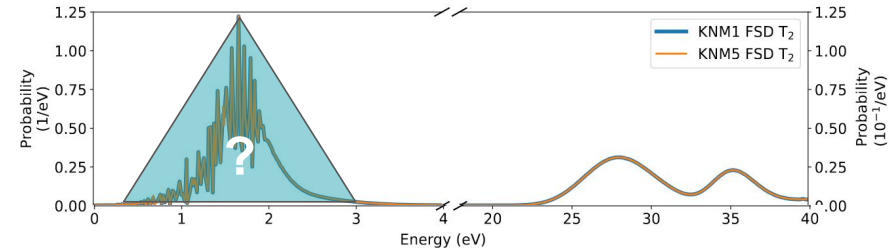
Hide the data

1. Analysis of Asimov twin (MC simulation)
 - Data-like twins
 - Investigation on systematic effects
 - Freeze all inputs to the model



Hide the result

2. Analysis of data with blind model
 - Unknown modification of **final state distributions**, unknown bias on neutrino mass
 - Data blinding limited ability to effectively monitor the apparatus -> adopted model blinding



3. Unblind neutrino mass with real data

- Analysis on the data with true FSDs performed

Experimental Data and results: Campaigns 1-5

- 7 different configurations with 59 stacked spectra, 1609 data points
- Simultaneous **maximum likelihood fit** performed, using a common m_ν^2 parameter
- Best fit value:

$$m_\nu^2 = -0.14_{-0.15}^{+0.13} \text{ eV}^2$$

Limit on neutrino mass

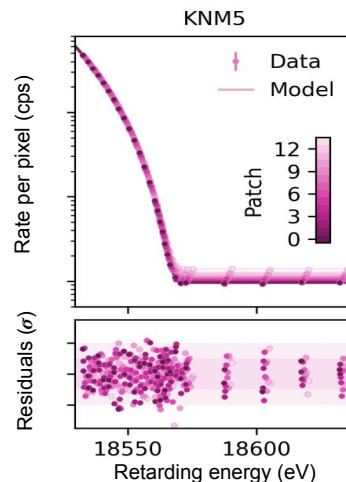
- **Frequentist limit:** Upper limit for m_ν^2 based on the best-fit result:

$$m_\nu < 0.45 \text{ eV (90\% CL)}$$

based on **Likhov-Tkachov** confidence interval construction

[Likhov, Tkachov, Phys.Part.Nucl. 46 (2015)]

- **Feldman-Cousins limit:** $m_\beta < 0.31 \text{ eV (90\% CL)}$, benefits from negative best-fit
- **Bayesian limit:** Publication in preparation

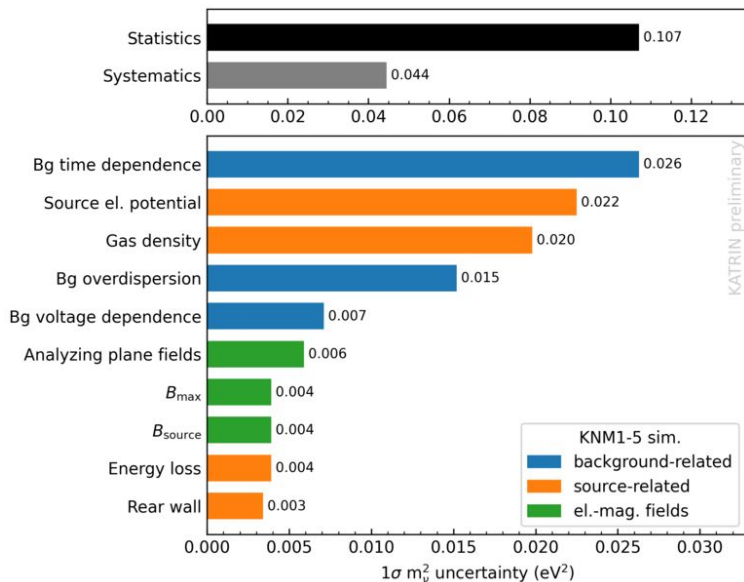


See full spectra from
KATRIN overview
talk by C. Goupy

KATRIN Main Systematic uncertainties

How we propagate systematic (Nuisance param. method)

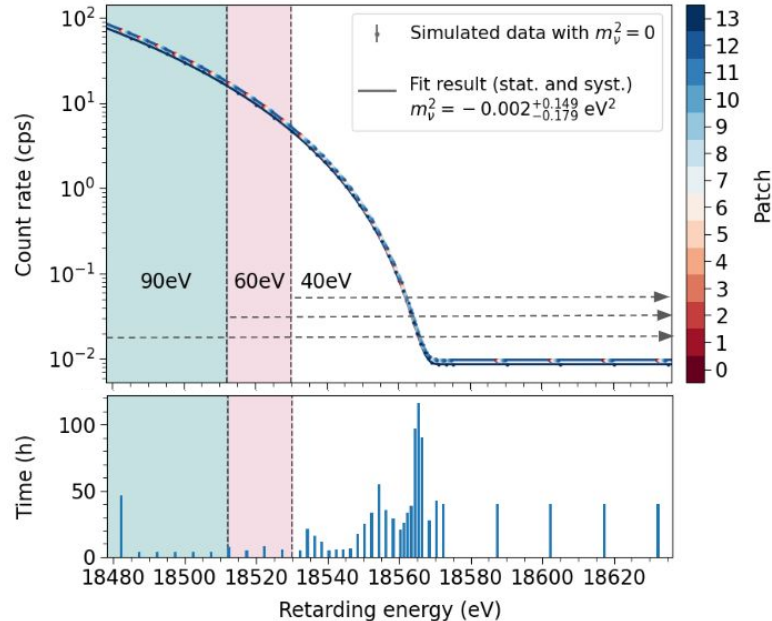
- $-2\log\mathcal{L}_{\text{total}} = -2\log\mathcal{L}_{\text{stat}} + (\vec{\eta} - \vec{\eta}_{\text{ext}})^T \Theta_{\text{cov}}^{-1} (\vec{\eta} - \vec{\eta}_{\text{ext}})$
- Individual contribution of systematic effect by fitting only relevant parameter and fixing everything else



See Topical Session of
'Background & Systematics' on
Tuesday

Extended Range Analysis: 60 eV & 90 eV below E_0

- KATRIN records data in wider energy window (such as 60 eV and 90 eV) below the E_0
- Only use 40 eV for the standard analysis
 - FSDs only available for 40 eV
 - Some systematic uncertainties increase, some decreases (i.e. column density, loss & plasma)
 - For 60 eV and 90 eV → FSDs studies on-going



BSM studies:
sterile & relic neutrino searches, new
light bosons, lorentz invariance &
exotic weak searches

See posters by C. Koehler, A.
Schwemmer, J.Lauer

Road map to the final KATRIN release: Campaigns 1-19

KATRIN has completed 1000 days of data-taking

- collected statistics: >230 million electrons (in 40 eV range)
- Established analysis procedure
- Need to ensure that it is feasible, robust and applicable to final dataset

Challenges:

- **optimizing** the analysis while maintaining a **bias-free** neutrino mass result
 - Stacking data granularity
 - Reducing computing time
- With large statistics, careful propagation of systematic uncertainty becomes crucial

Planned Improvements:

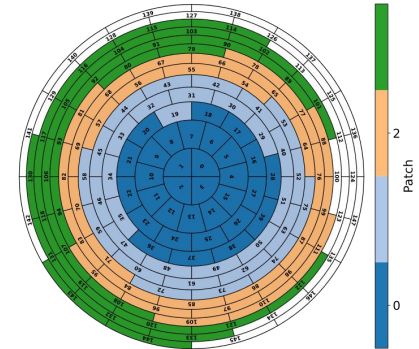
- **smart Patching:** 4-patch conf. Immediate reduction of fitting parameters by factor 3
- **combining campaigns:** combine param. sets that are in good agreement through campaigns

~1400 fit parameters,
Analysis already feasible
w/o combining campaigns



~260 parameter
reduced computing time by x25
w. combining campaigns

4-patch configuration



See Poster by
K. Erhardt

CRES

CRES (Project 8, QTNM)

- ❑ **Principle:** Cyclotron radiation emission spectroscopy
- ❑ Measuring energy via **frequency**

PROJECT 8

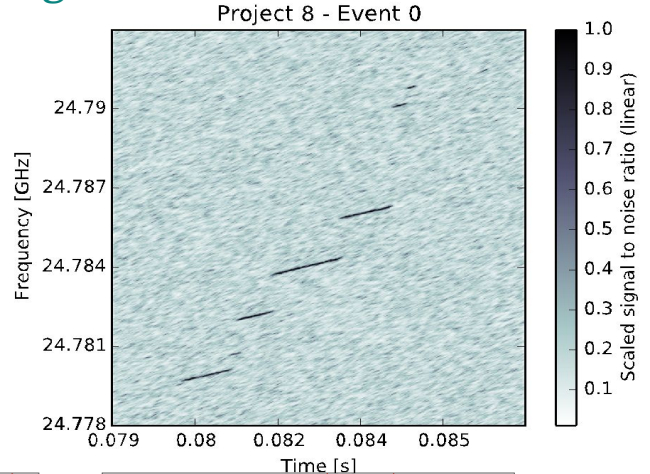
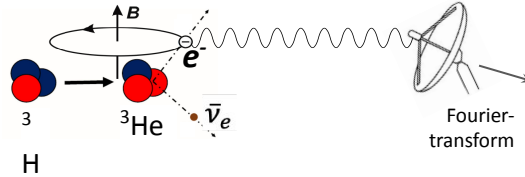
QTNM
Quantum Technologies for
Neuroimaging



CRES signal processing: identifying and characterizing events

To 0th order, a CRES signal is a sine wave at the cyclotron frequency, ranging from 100MHz - 27GHz for QTNM and Project 8.

$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e + E_{kin}/c^2}$$

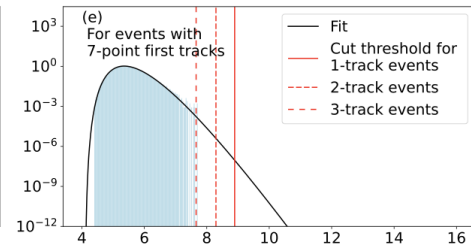
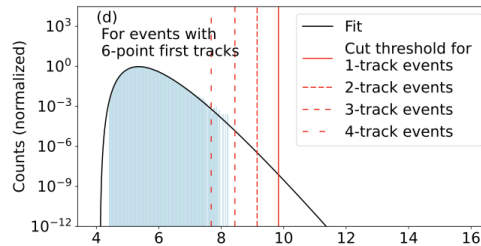
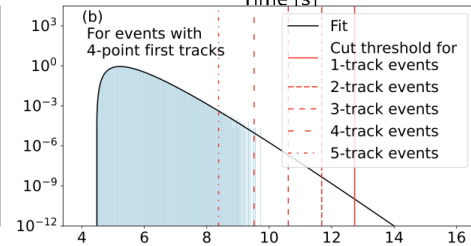
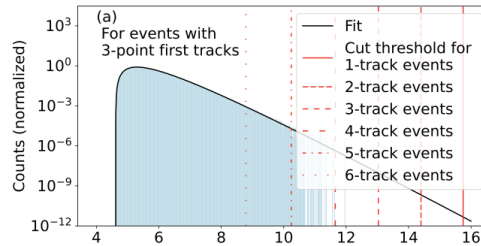


Challenges:

- **Must exclude false events from RF noise.**

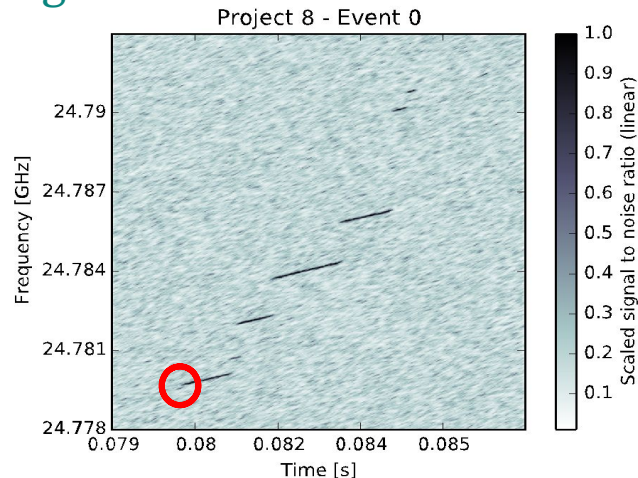
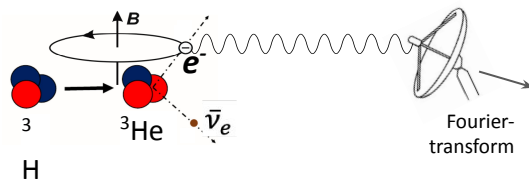
An example from Phase II of how this background can be characterized and excluded:

- Set a lower threshold on power in pixels that are to be considered as part of signals. Noise signals left over follow gamma distributions in power.
- Separate tracks into groups based on number of bins in first track, number of tracks in event
- Apply group-dependent cut to power in first track
- Gave us zero background in Phase II!



CRES signal processing: identifying and characterizing events

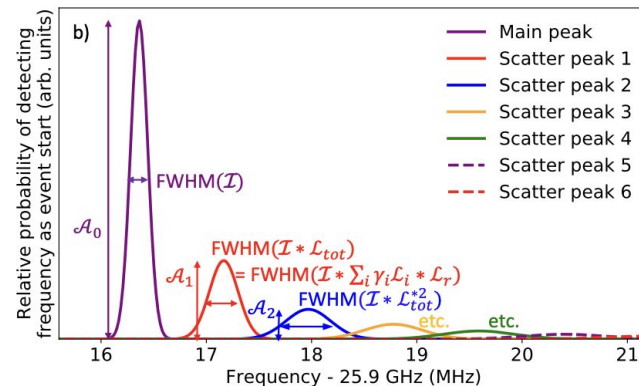
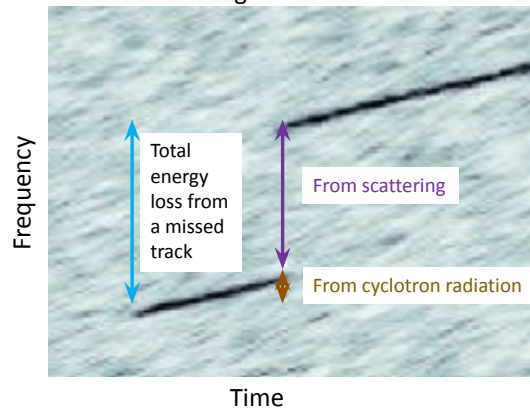
$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e + E_{kin}/c^2}$$



Challenges:

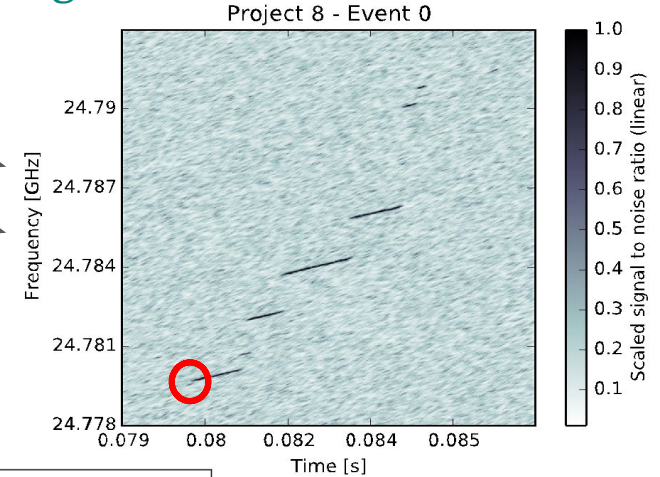
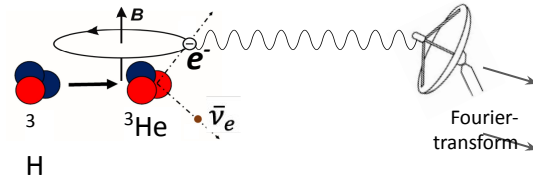
- Must exclude false events from RF noise
- Must accurately **find the first track** of each event, and account in analysis for the fact that sometimes scattering will happen too quickly to detect the first track
 - Can understand this via simulation and account for it in predicted spectrum

For a single missed track:



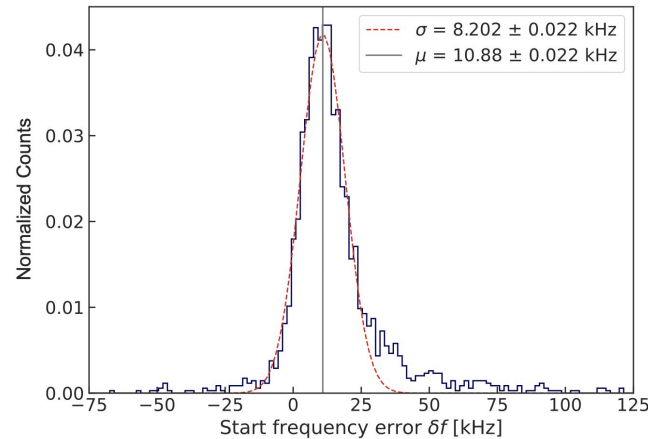
CRES signal processing: identifying and characterizing events

$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e + E_{kin}/c^2}$$



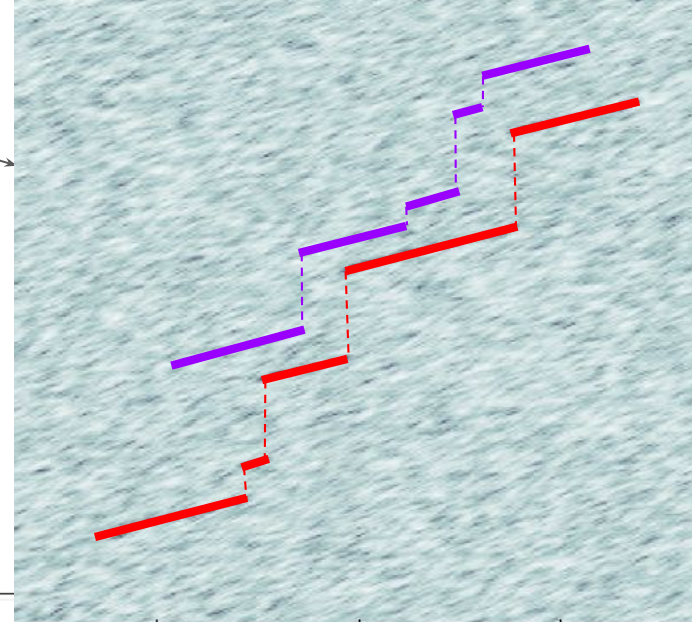
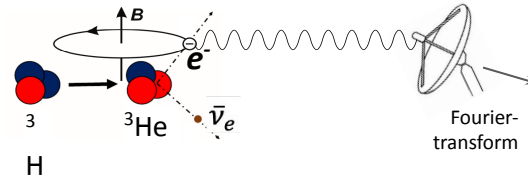
Challenges:

- Must exclude false events from RF noise
- Must account for scattering
- Must accurately reconstruct the start frequency of first track in event
 - Can characterize reconstruction algorithm's precision and accuracy with simulated data



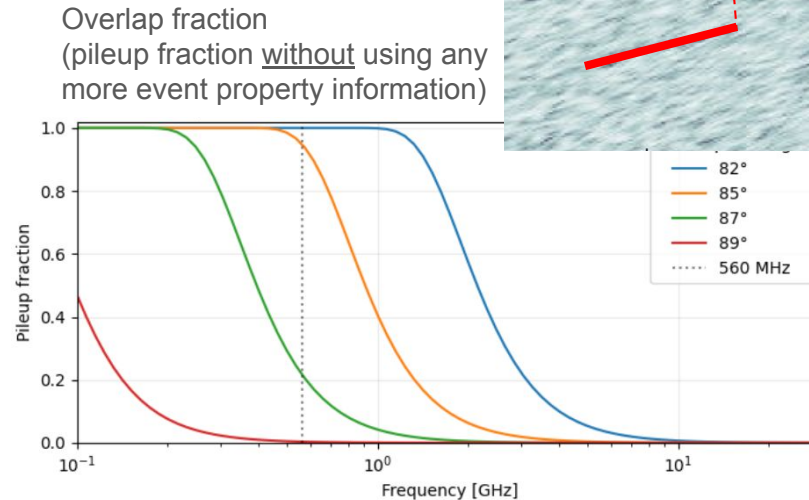
CRES signal processing: identifying and characterizing events

$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e + E_{kin}/c^2}$$



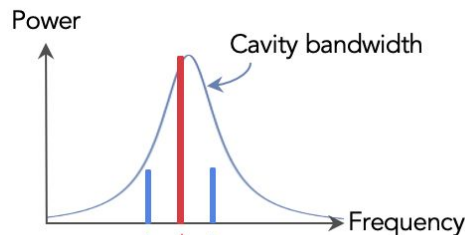
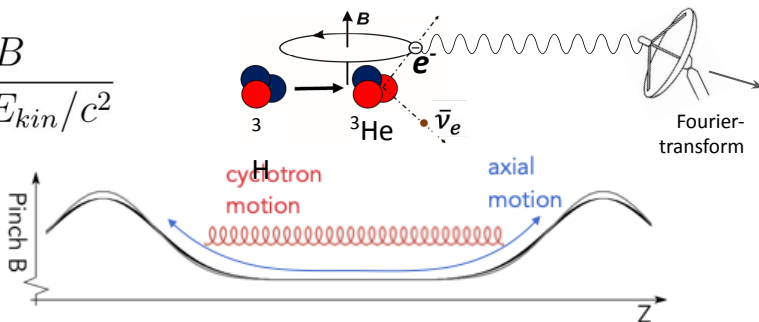
Challenges:

- Must exclude false events from RF noise
- Must account for scattering
- Must accurately reconstruct the start frequency of first track in event
- Must **exclude pileup**
 - Mitigated by information-richness of events; low likelihood of one event starting precisely as another ends



CRES signal processing: identifying and characterizing events

$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e + E_{kin}/c^2}$$

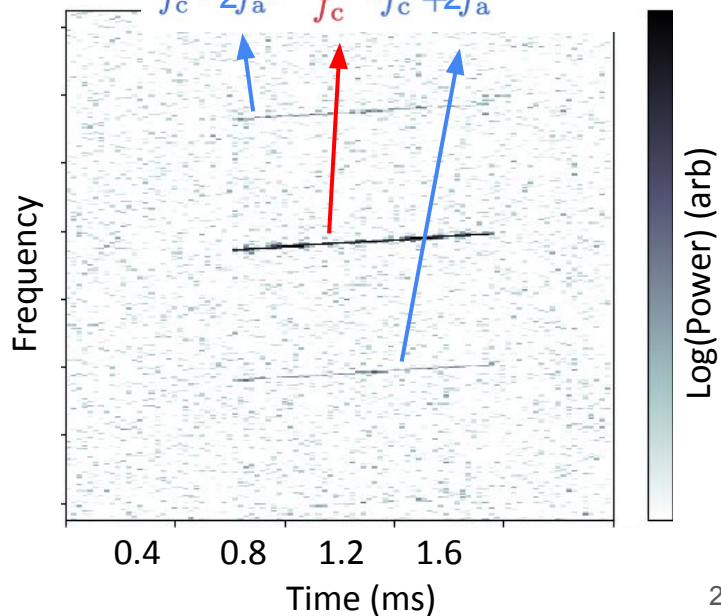


Signal is modulated, causing **sidebands** to appear. Due to:

- Amplitude modulation: variation of coupling to RF receiver
- Frequency modulation: variation of magnetic field from trap; Doppler effect (in some geometries)

Challenge:

- Must correctly identify which RF signal is the **main carrier** (at the cyclotron frequency) and which are **sidebands**. Must design trapping field to enable predictable, interpretable patterns of sidebands.



CRES signal processing: converting frequency to energy

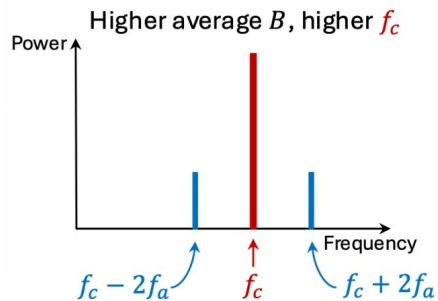
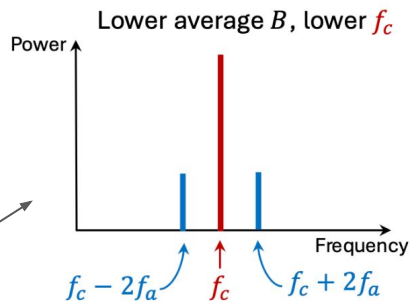
Challenge: Electrons that explore different regions of the magnetic trap experience slightly different average magnetic fields B_{avg} ! This directly affects the conversion of cyclotron frequency to kinetic energy.

$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB_{avg}}{m_e + E_{kin}/c^2}$$

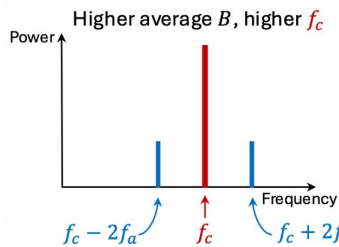
Fortunately, the CRES sideband spacing contains the information needed to correct for this.

To mitigate:

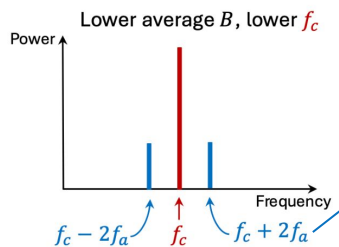
- Must map the magnetic field $\mathbf{B}(\vec{x})$ inside the trap, AND
- Must extract electron trajectory information \vec{x} encoded in the sideband spacing of the CRES signal to determine which region a given electron explores.
- Combine for event-by-event B_{avg}
- Expected to enable sub-eV resolution



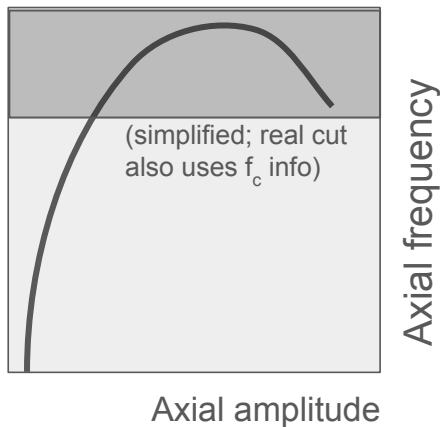
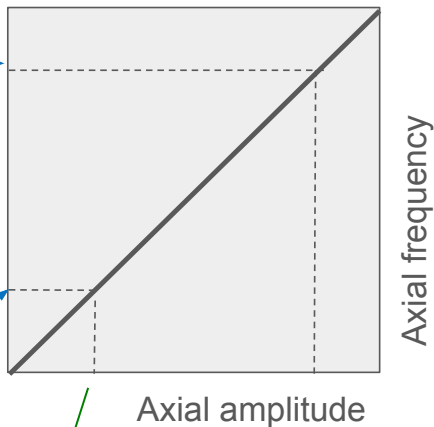
CRES signal processing: converting frequency to energy



It would be convenient if the relationship looked like this:



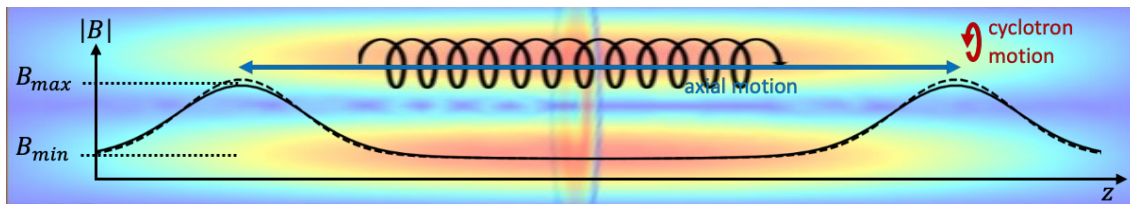
But reality is messier:



$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi m_e} \frac{eB_{avg}}{c^2 + E_{kin}}$$

To mitigate:

- Design trap to minimize fraction of electrons in double-valued region
- Cut double-valued region (statistics hit)
- Use additional signal features to distinguish, e.g., amplitude modulation from different coupling to cavity mode(s)
 - This could also help with radial position reconstruction



CRES signal processing pipeline

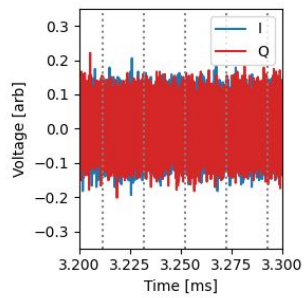
And possible signal-processing-related systematic effects

Cyclotron radiation from electrons from tritium β^- decay

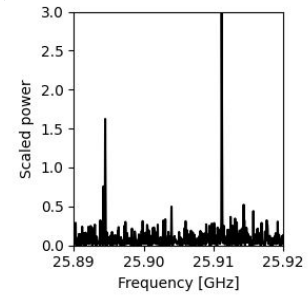
- plus any signals from trapped electrons whose true start energies differ from the ideal spectrum (covered by Hamish Robertson in the Background and Systematics focus session):
- Plasma effects
 - Patch effects
 - Molecular tritium decay in trap volume
 - Cosmic ray interactions with tritium resulting in trapped electrons (extremely rare!)



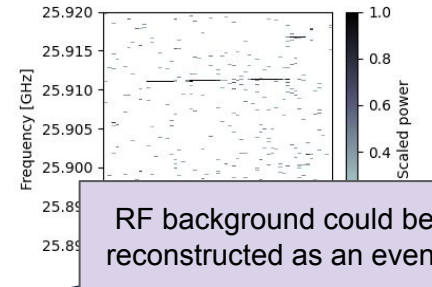
Voltage vs. time



Short time Fourier transform



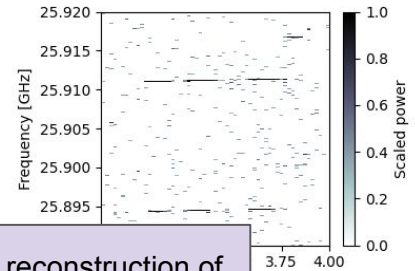
Spectrogram construction and background removal



RF background could be reconstructed as an event



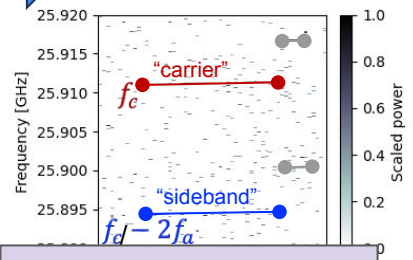
Track finding and event building



Imperfect reconstruction of the beginning of an event



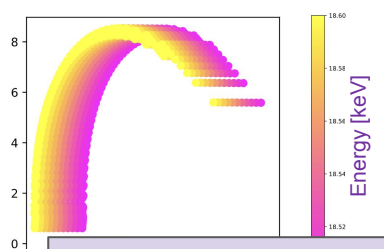
Track classification



Sideband could be mistaken for main carrier



Conversion to energy



Imperfection in magnetic field mapping and trajectory reconstruction



Measured spectrum of electron kinetic energies

CRES spectrum model+fit: example from Project 8's Phase II

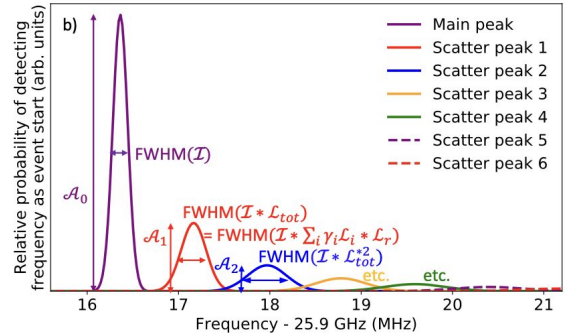
	Bayesian	Frequentist	Unit
Endpoint	18553 ⁺¹⁸ ₋₁₉	18548 ⁺¹⁹ ₋₁₉	eV
m_β	57 ⁺⁶¹ ₋₃₉		eV
m_β^2		2440 ⁺¹⁰¹⁷⁵ ₋₁₃₃₅₄	eV ²
90% C.L.	$m_\beta < 155$	$m_\beta < 152$	eV

A_j : probability that a detected electron has scattered j times before detection

\mathcal{L} : spectrum of energy losses due to scattering

* represents convolution over energy

j : scatter #



N : counts at a given energy

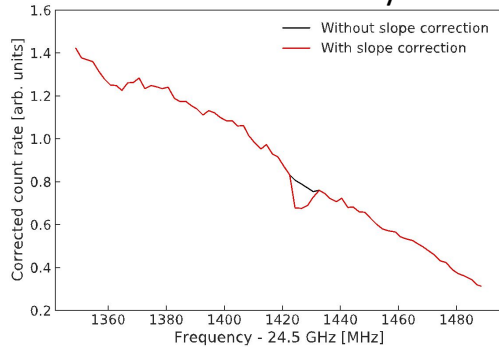
$$N = r_s \epsilon \left(y * \sum_{j=0} A_j (I * \mathcal{L}^{*j}) \right) + r_F \mathcal{F}$$

r_s : overall event rate

\mathcal{F} : flat background (due to false events from RF noise)

r_F : background rate

ϵ : detection efficiency



Y : true underlying β^- spectrum

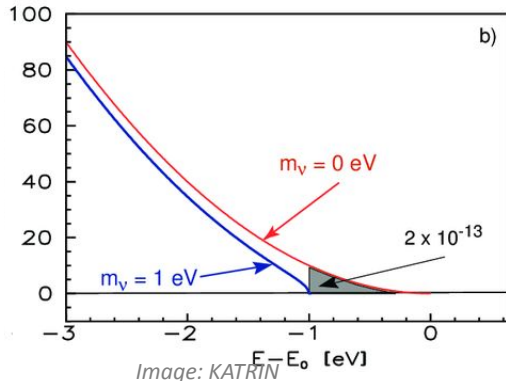
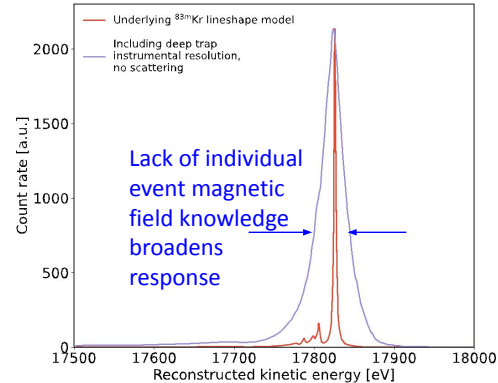


Image: KATRIN

I : instrumental resolution



CRES spectrum model+fit: future outlook

- E_0 and mass variable(s) will both be left free
- With resolution this good, may need to fit more than one mass state.

A_j : probability has scattered

Scattering effects will be much smaller!

- Inelastic scatters will all leave ROI! Only elastic scatters will be relevant (very small energy loss)
- Cyclotron energy losses before first detected scatter will be much smaller because of lower magnetic field ($P \propto B^2$)

Remaining scattering effects will still be accounted for in analysis.

* represents convolution over energy

N : counts at a given energy

r_s : overall event rate

ϵ : detection efficiency

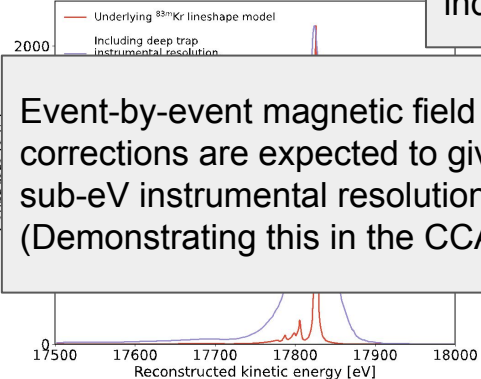
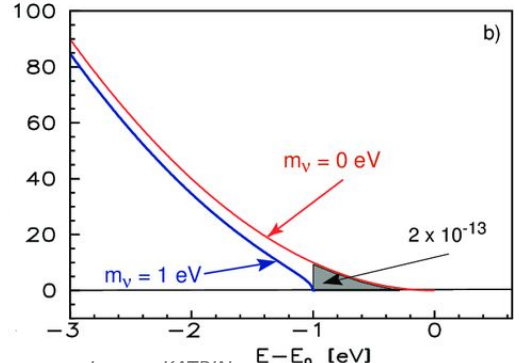
ROI will be much narrower, focused around the endpoint. Detection efficiency will be characterized with electron gun, other methods.

$$N = r_s \epsilon \left(y * \sum_{j=0} A_j (I * \mathcal{L}^{*j}) \right) + r_F \mathcal{F} + r_{T_2} y_{T_2}$$

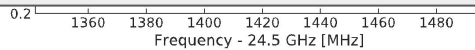
Y : true underlying β^- spectrum

I : instrumental resolution

Molecular tritium spectrum. Will reduce as much as possible, and measure independently.



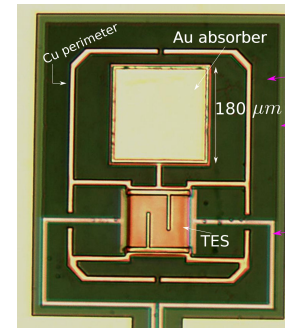
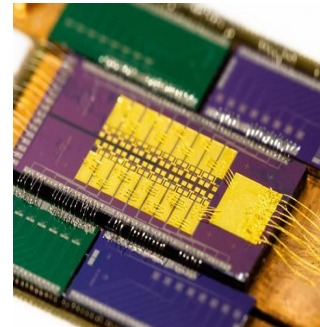
Event-by-event magnetic field corrections are expected to give sub-eV instrumental resolution (Demonstrating this in the CCA)



Holmium-163

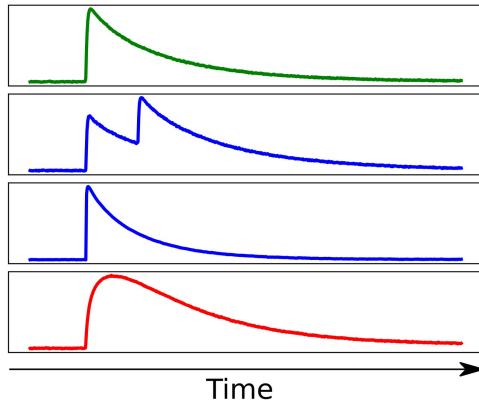
Calorimeters (ECHO, HOLMES)

- ❑ Principle: Low-temperature micro-calorimeters
- ❑ Measuring energy by **temperature change**

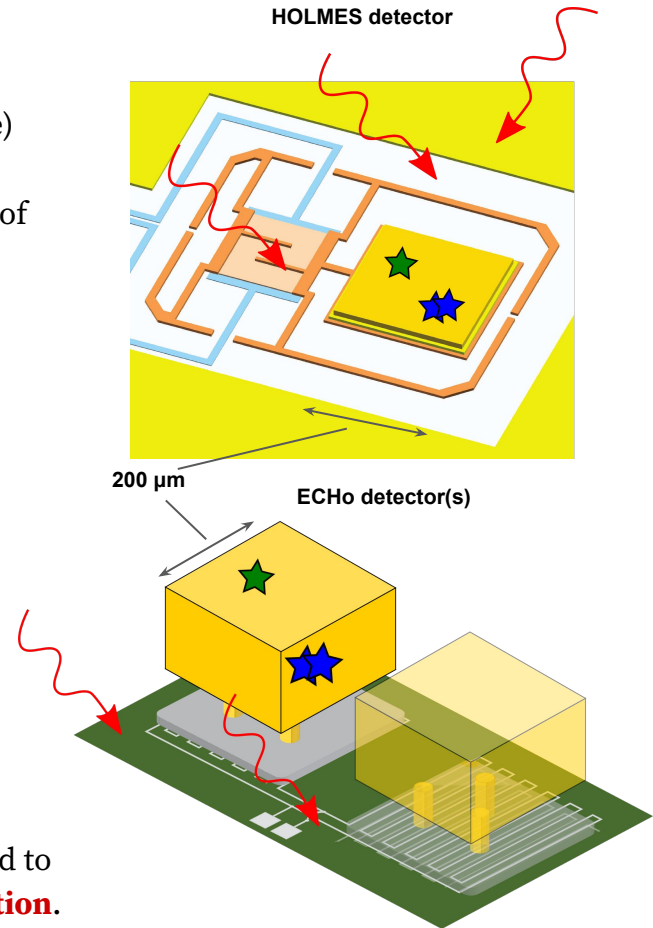


Low Temperature Detectors: signal processing

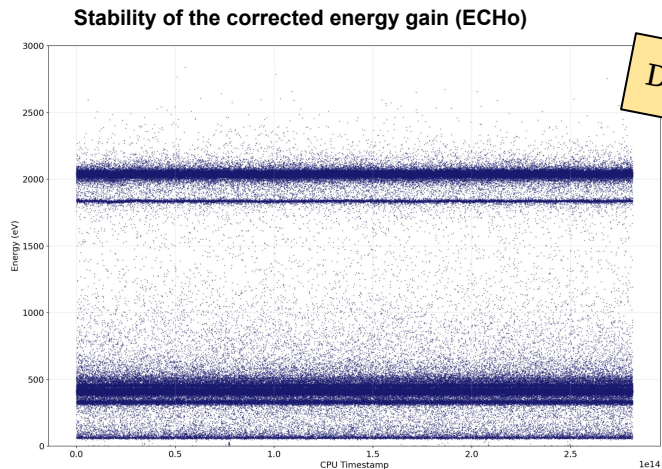
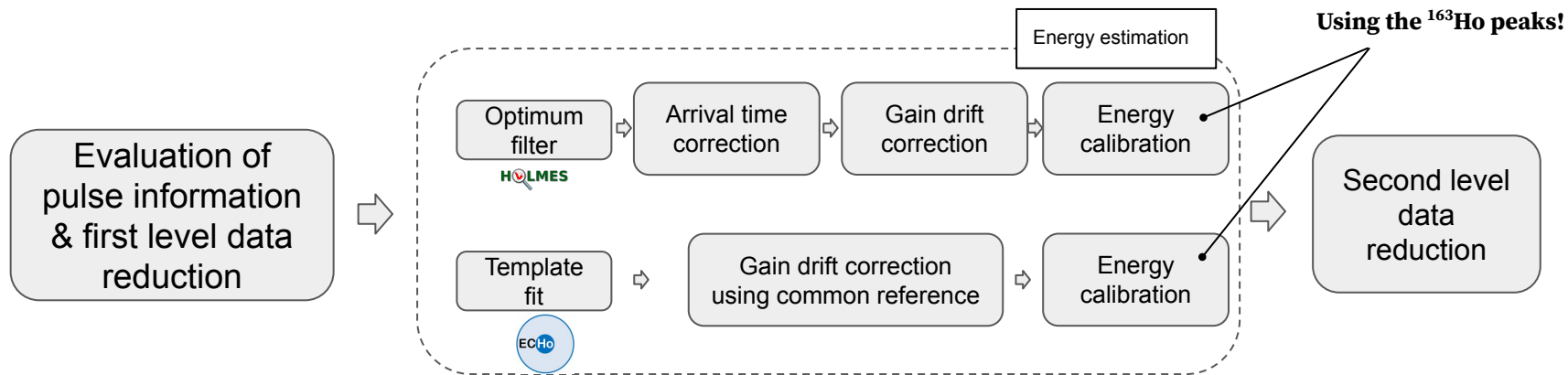
- **Event** := waveform representing the variation of the current (temperature) inside the detector.
 - **The energy of the event is proportional** to the amplitude/integral of the signal
 - Estimating these quantities with high accuracy is essential to preserve the exquisite energy resolution of the devices.



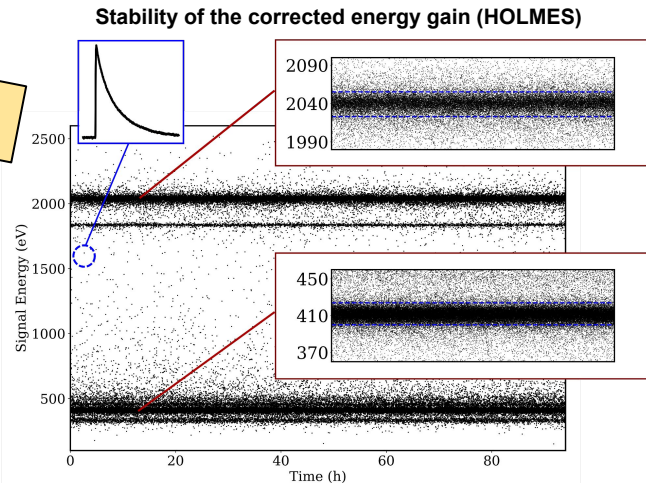
- **Data reduction techniques** (**pulse-shape analysis** with analytic filters, unsupervised learning methods, coincidences between pixels etc.) are used to distinguish **bulk holmium events** from **pile-up events** and **external radiation**.



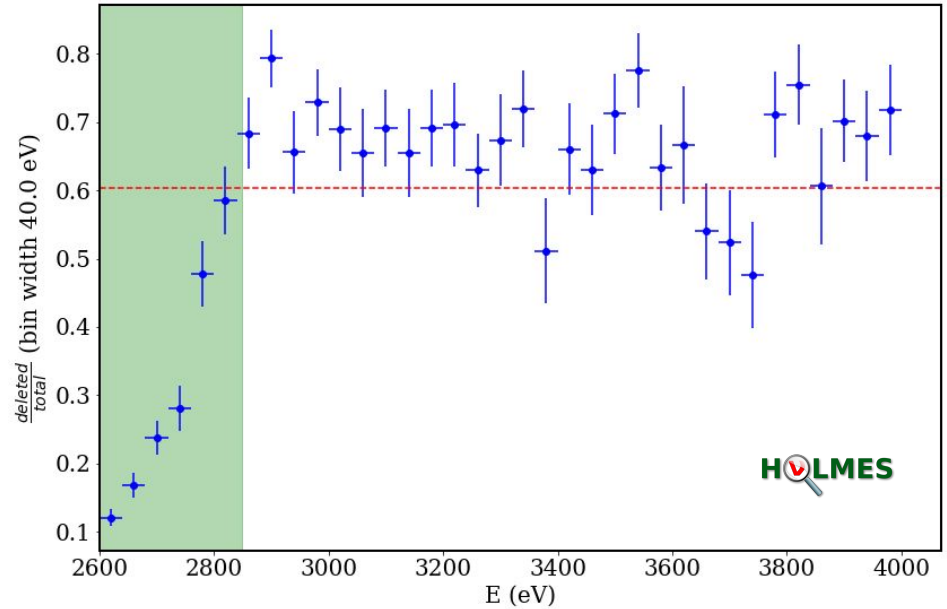
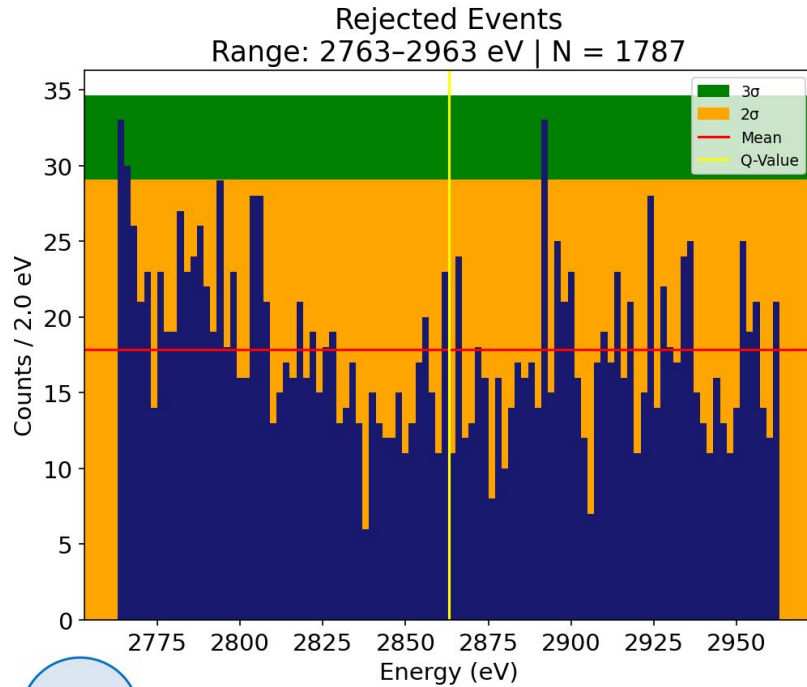
Low Temperature Detectors: data analysis pipeline (now)



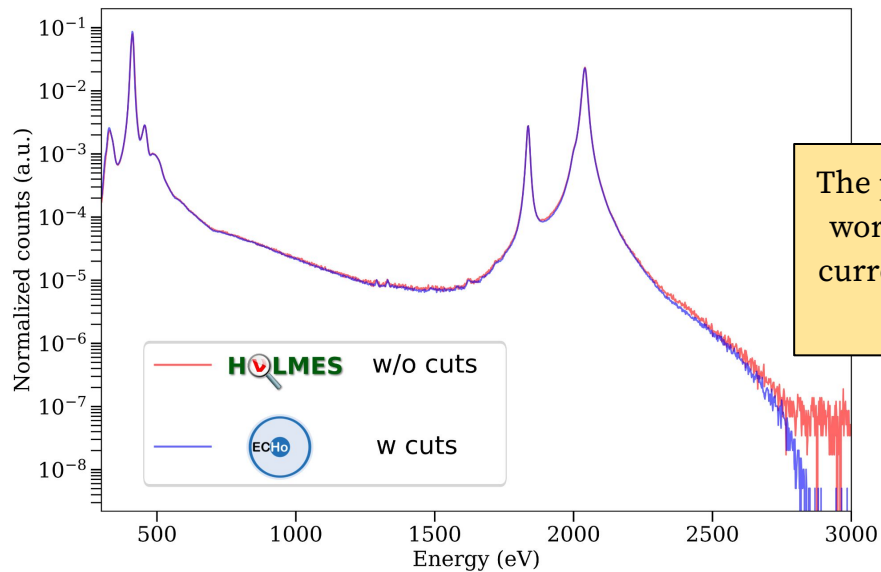
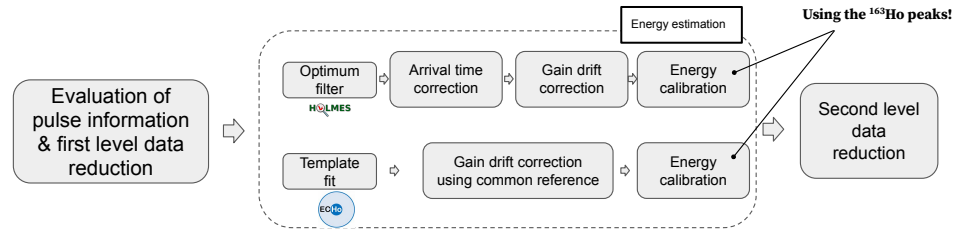
Dead time < 1%



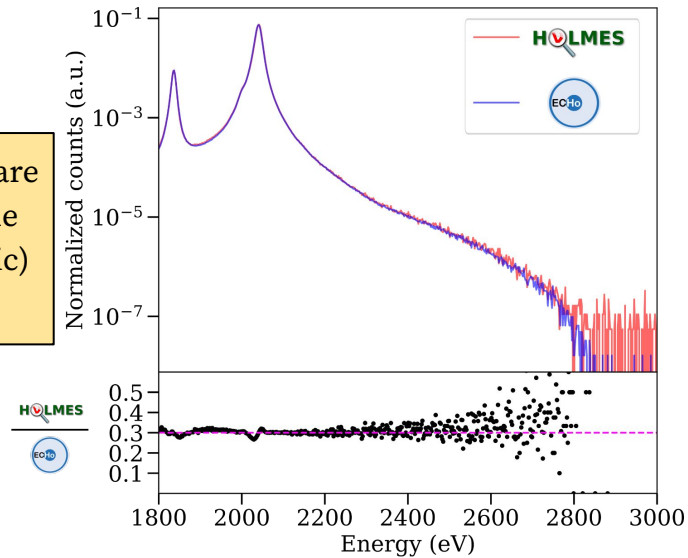
Low Temperature Detectors: data analysis pipeline (now)



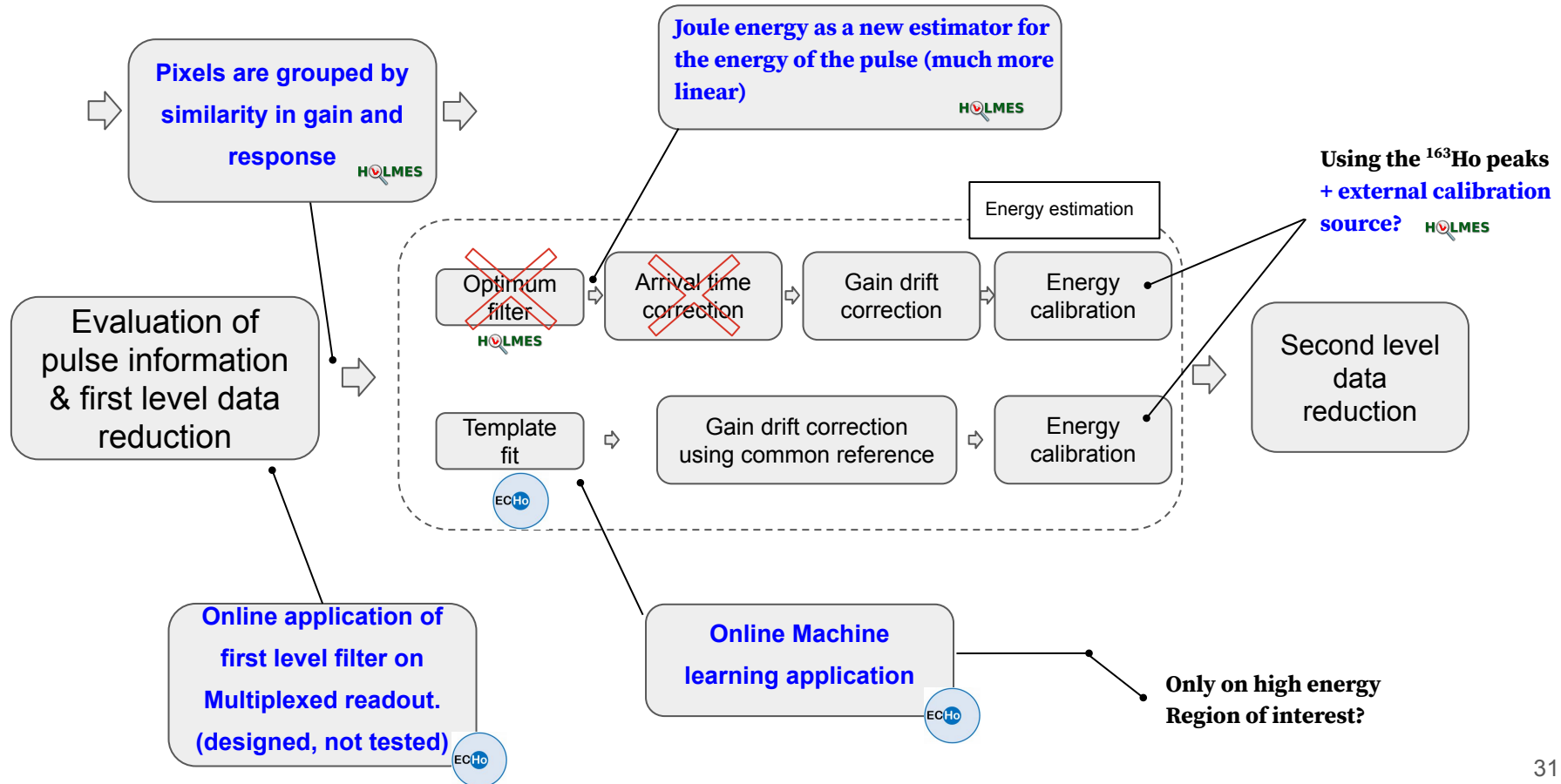
Low Temperature Detectors: data analysis pipeline (now)



The pipelines are working (w the current statistic)



Low Temperature Detectors: data analysis pipeline (future)



HOLMIUM current fit strategy

- The final spectrum (S_{exp}) is the sum of m $O(1000)$ different spectra with different energy resolution and background level

Very good approximation

163Ho spectrum

Pileup spectrum

(flat) background

gaussian response

$$S_{exp} = \sum_i^m [N_i(S_{Ho} + f_i^{pp} S_{Ho}^{pp}) + B_i] * R_i$$

➔

Effective gaussian

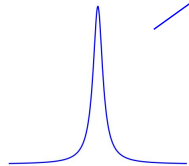
$$S_{exp} = [N_{tot}(S_{Ho} + f_{eff}^{pp} S_{Ho}^{pp})] * R_{eff} + b_{eff}$$

- The full shape of the ^{163}Ho calorimetric spectrum is unknown(*), but **in the ROI the spectrum can be modelled as a sum of two (three) simple terms**

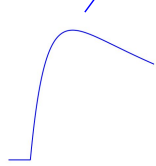
$$S_{Ho} \Big|_{ROI} \sim k_0(k_{BW} S_{BW} + k_{SO} S_{SO} + S_{pol}) \times F$$

The ROI must be chosen *cum grano salis*

$$F = (Q - E) \sqrt{(Q - E)^2 - m_\beta^2}$$



2 parameters



3 parameters



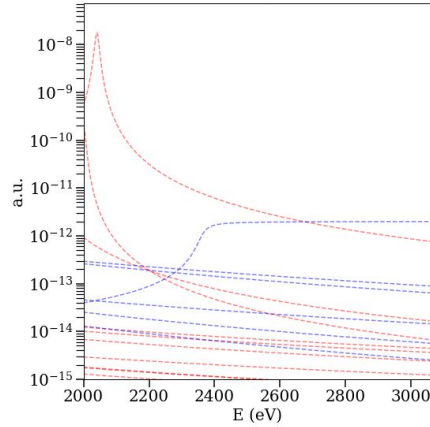
1 parameter



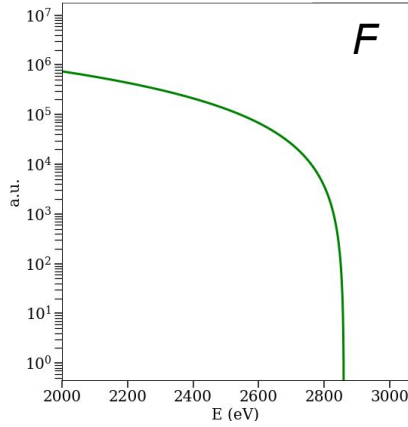
HOLMIUM current fit strategy. Is it safe?

①

$S_{Ho} =$

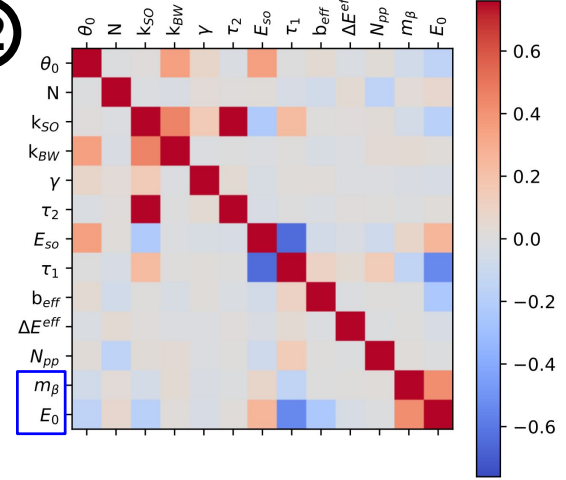


\times



②

Pearson correlation coefficient



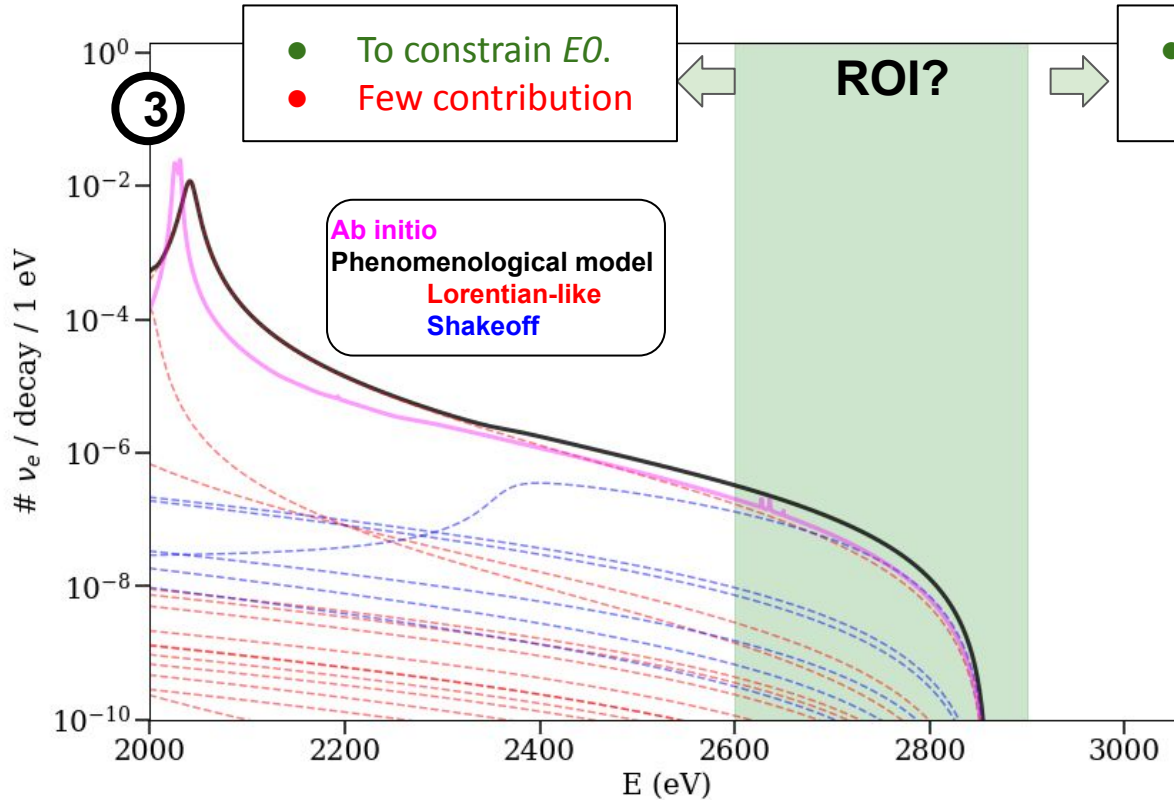
①

All models, to date, predicts a smooth ROI

②

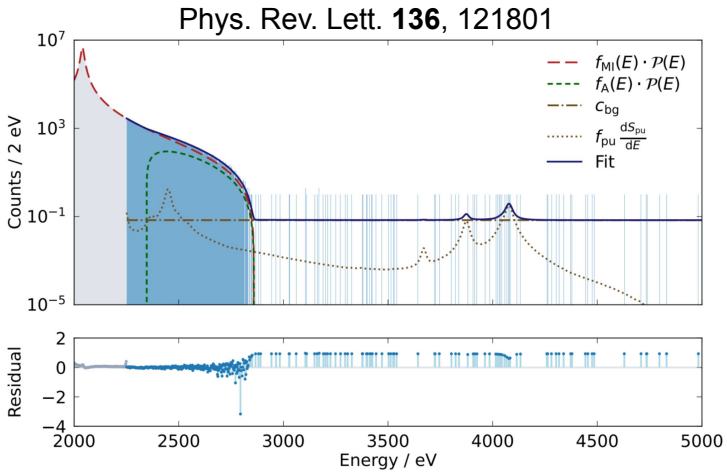
No strong correlation between m_β and the parameters describing the ^{163}Ho spectral shape (To be checked with increasing stat)

HOLMIUM current fit strategy. Is it safe?



- 3 increasing statistics \rightarrow smaller ROI \rightarrow fewer Ho spectral components are relevant
- ... also, these components will be better constrained by the data!

HOLMIUM fit results



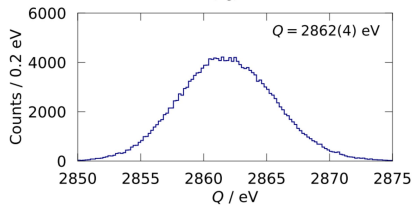
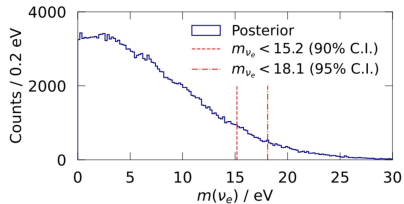
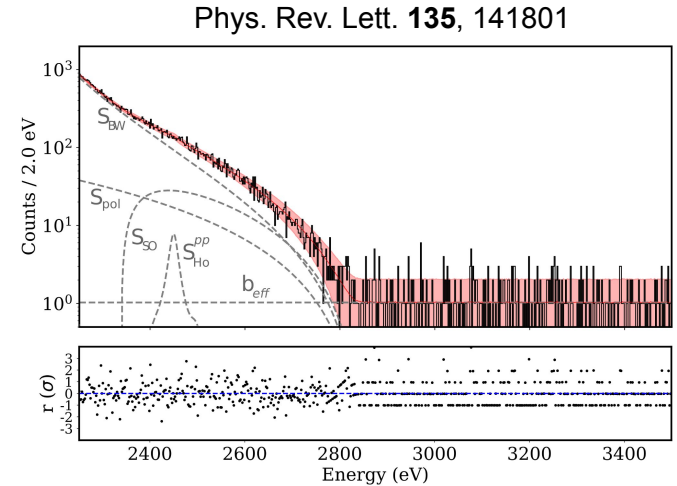
ECHo

200M $\rightarrow m_\beta < 15.2$ eV (90%)

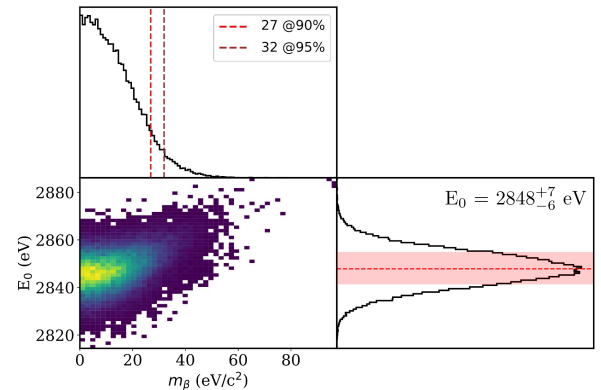


HOLMES

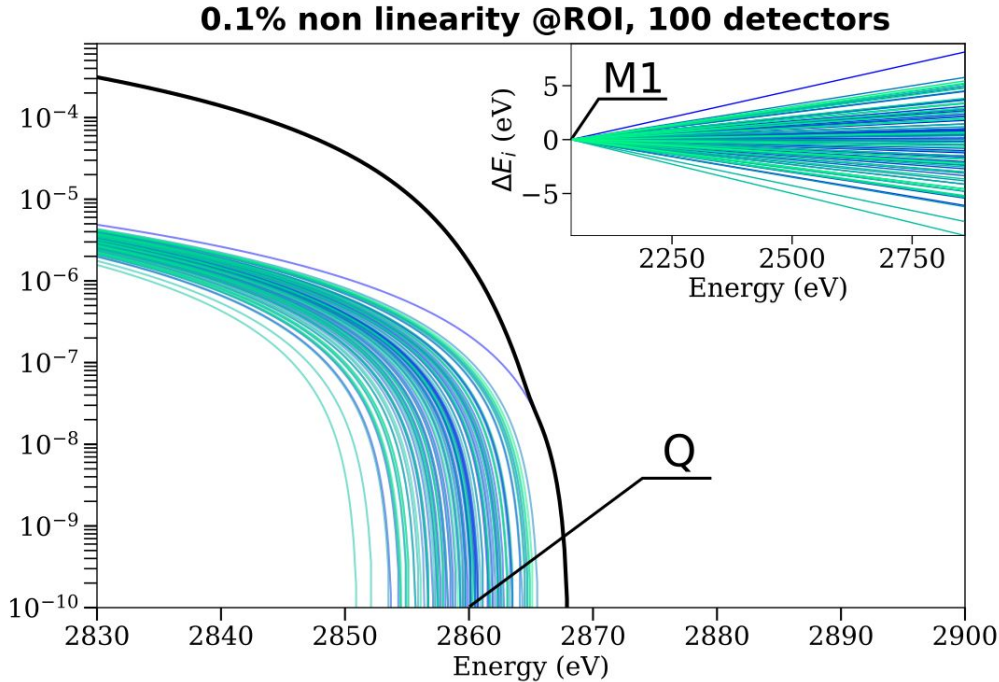
70M $\rightarrow m_\beta < 27$ eV (90%)



Both collaborations proved that it is feasible to perform a calorimetric measurement of the neutrino mass using ^{163}Ho (even without knowing the ^{163}Ho spectral shape)



HOLMIUM main analysis challenges



- Open question: how to handle the pixel by pixel variability in the detector response (i.e. nonlinearity)
- Possible mitigations:
 - Group and analyze the pixel by their response
 - Use a more linear energy estimator
 - Additional calibration source
 - ...

Sensitivity Studies

HOLMES recipe for sensitivity studies:

1. Set an experimental configuration (# detectors, lifetime, resolutions, non-linearity, time resolution, background...)
2. generate N toys from a reference ^{163}Ho spectrum (and hypothesis to test)
3. Bayesian parameter estimation on each of the N spectra using a certain model...
 - a. ... that depends on the study that you are performing/systematic that you are studying
4. Select only the results ($M \leq N$) in which the fit converges(*)
 - a. (*) Look at residuals, durbin wilson test etc..
5. On the M "good" fits, plot the distribution of the 90% C.R. for m_{β}
6. The mean and standard deviation of that distribution is the 90% sensitivity on the m_{β} using that experimental configuration



Very long!

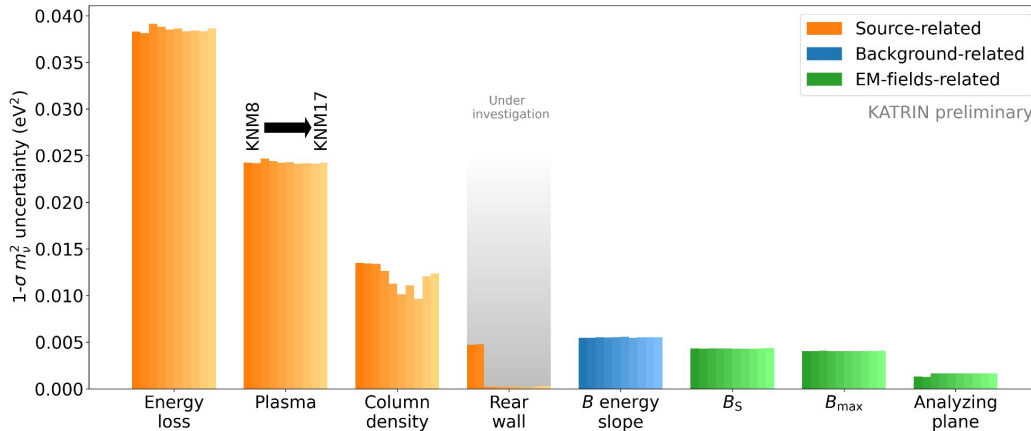
Many different experimental configuration / hypothesis to test

KATRIN recipe for sensitivity studies

- Generate Asimov data with relevant statistics
- Fit the data and extract the uncertainties on m_ν^2
- Compare uncertainties for stat. only and stat+sys
- Consider diff. scenarios of statistics, systematics and analysis ranges



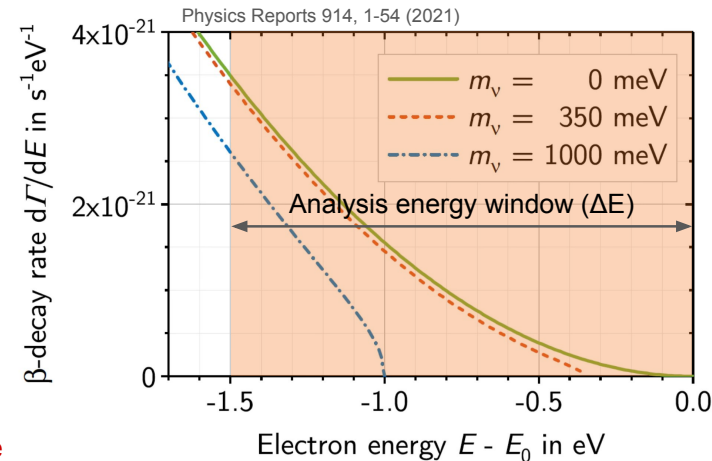
Very Happy!



See Poster by
J. Ploessner

Analytic sensitivity prediction

- Idea: The number of events in a well-defined analysis window provides the uncertainty on the square of neutrino mass
 - Validity: frequency-based, calorimetric, and MAC-E experiments
 - Requirements:
 - i. Analysis window (ΔE) has to be carefully chosen
 - ii. Rate, time, endpoint energy, and backgrounds need to be determined separately
 - iii. Systematic contributions (assumed Gaussian), and associated uncertainties, to energy broadening (in ΔE) determined separately
- Can convert the uncertainty into 90% limit



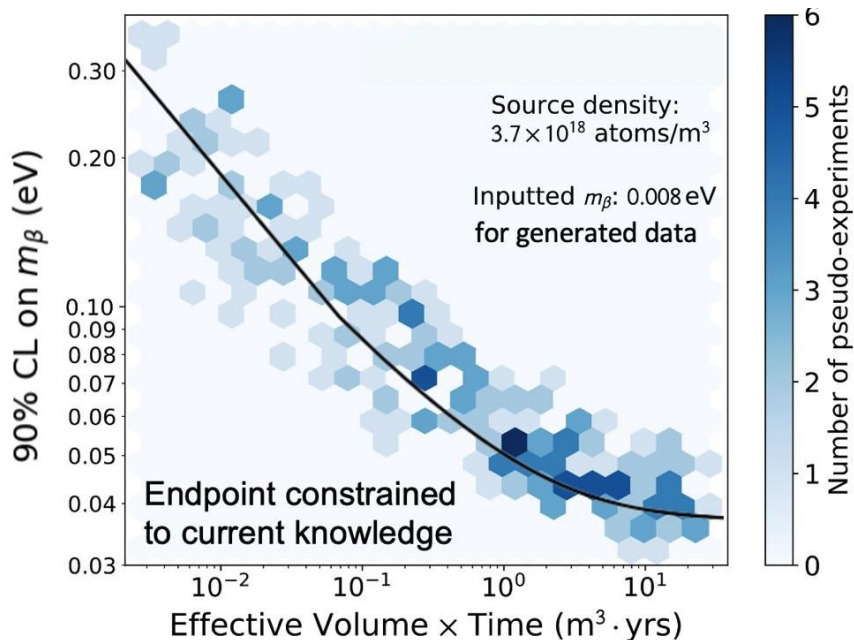
$$\text{Neutrino mass uncertainty } \sigma_{m_\beta^2} = \frac{2}{3} \sqrt{ \frac{1}{rt} \left[\Delta E + \frac{b}{r\Delta E} \right] + 4 \sum_i \sigma_i^2 \cdot \delta\sigma_i^2 }$$

Labels in the diagram:

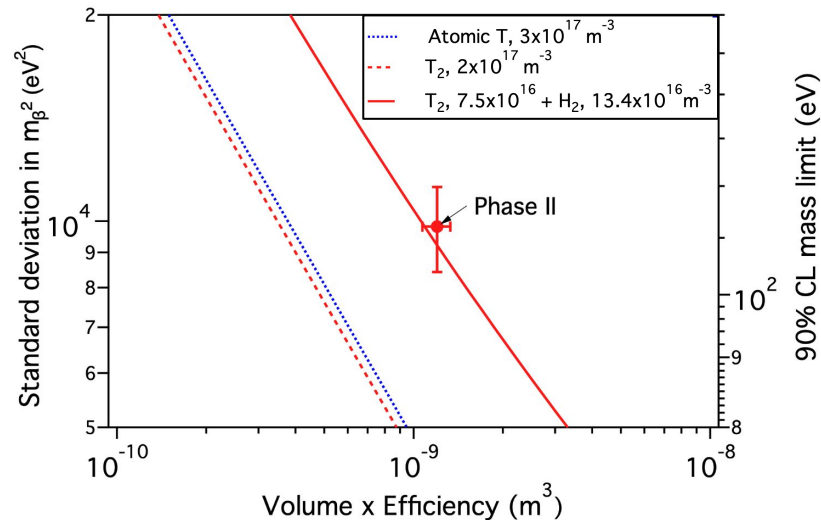
- Total detected event rate**: points to the $1/rt$ term.
- background rate**: points to the b term.
- Measurement time**: points to t .
- Optimized energy window**: points to ΔE .
- Energy broadening contribution i** : points to σ_i^2 .
- Uncertainty on energy broadening contribution i** : points to $\delta\sigma_i^2$.

Analytic sensitivity prediction: a validation example from Project 8

Analytic sensitivity in good agreement with Monte Carlo sensitivity



Exclusion limit from **analytic** approach in good agreement with **Project 8 Phase-II limit**



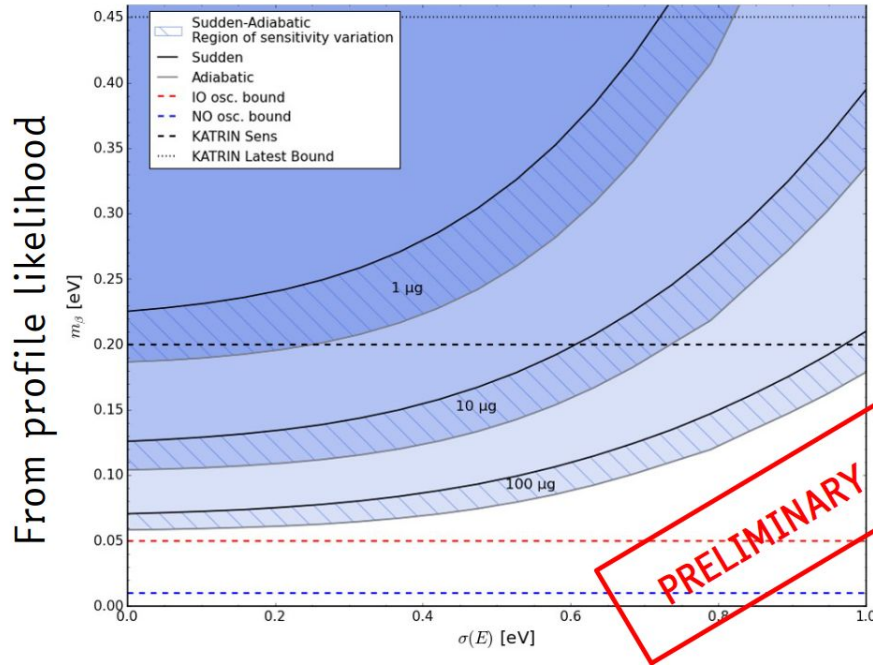
See:

Project 8: PRC 103, 065501 (2021)

Project 8: PRC 109, 035503 (2024)

PTOLEMY sensitivity estimates

$$N_{dec} = \left(\frac{m_{\text{source}} \mathcal{N}_A}{A_{(3H)}} (1 - e^{-t_{\text{expo}}/\tau_{3H}}) \right) \times 0.5 \simeq 2.2 \cdot 10^{16} \text{ events}$$



- Profile likelihood combined with toy MC
- Compare β -decay spectra with and without endpoint deformation
- Sensitivity defined as the median of the alternative hypothesis exceeding the 90% quantile of the null hypothesis distribution

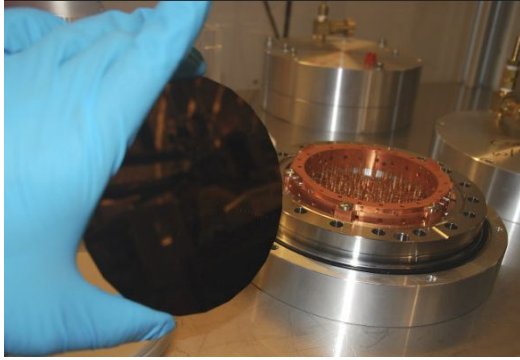
Signal processing challenges for m_β estimation

MAC-E	CRES	CALORIMETRY
<p>Requirements: Invisible HV ripples</p> <ul style="list-style-type: none">- Stable HV- Constant/known detection efficiency <p>Challenges:</p> <ul style="list-style-type: none">- Invisible HV ripples- Large rate variations- Non-Poisson arrivals	<p>Requirements:</p> <ul style="list-style-type: none">- Strong signal; low RF noise- Well-characterized detector response and reconstruction algorithm <p>Challenges:</p> <ul style="list-style-type: none">- Not so bad:<ul style="list-style-type: none">- Excluding RF noise- Accounting for scattering- Finding precise event start frequency- Excluding pileup- Sideband/mainband classification- Most challenging: reconstructing electron trajectory for event-by-event magnetic field correction	<p>Requirement:</p> <ul style="list-style-type: none">- Low dead time- Highly effective selection algorithms (PSA)- Very low nonlinearity <p>Challenges:</p> <ul style="list-style-type: none">- Pixel-by-pixel variability in detector response- Temperature/Gain drift- Selection algorithms with negligible energy dependence

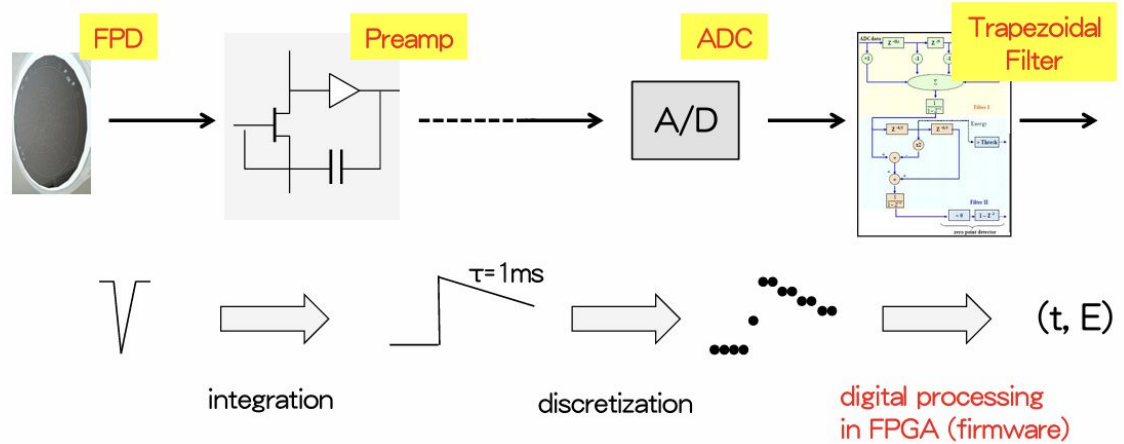
KATRIN Backup

KATRIN: Signal processing - Overview

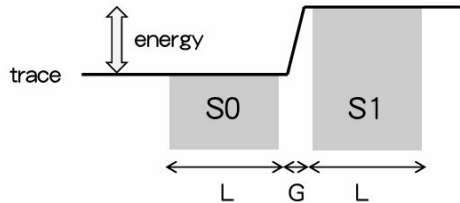
Focal Plane Detector (FPD):
Segmented PIN diode wafer



Readout Electronics



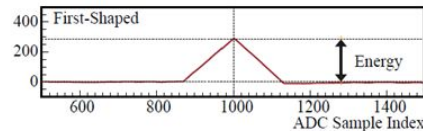
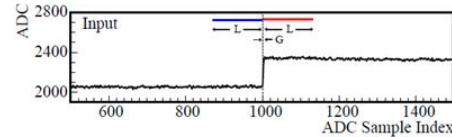
Trapezoidal Filter: digital energy estimator



$$E = \frac{S1 - S0}{L}$$

L: shaping length, 1.6 μ s

Trapezoidal Shaping: Applying this continuously



Basically
digital version of
Gaussian shaping

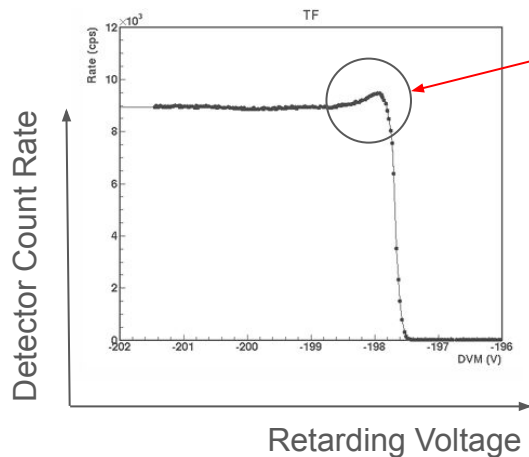
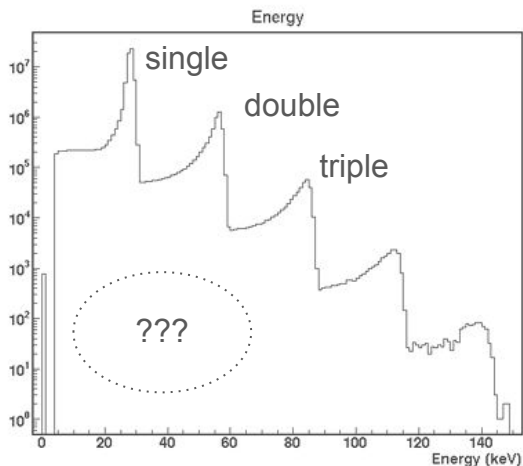
KATRIN: Signal processing - Problem

Problem: FPD was optimized for precision measurements at ~ 100 mcps.
e-gun calibrations are at $10\sim 100$ kcps \rightarrow pile-up

 $\times 10^6$



Example of an e-gun **pulse-mode** run: electrons emitted in bunches



Small surplus energy



Large velocity variations



Large arrival time spread



Less chance of pile-up

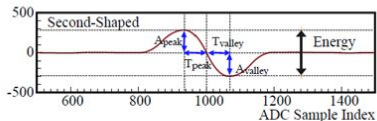
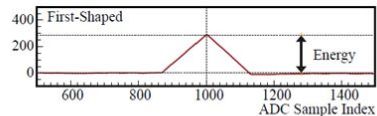
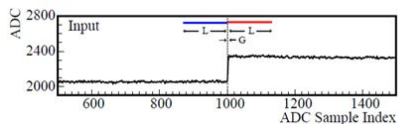
“Pile-up Rejection” is not an option for us

- Estimating the rejection ratio for non-Poisson events (bunches!) is very tricky
- Some signal and BG electrons are also non-Poisson (due to back-scattering & reflection etc.)
- At a high rate, a large fraction of electrons pile-up; too many to remove

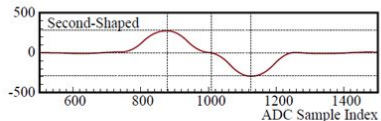
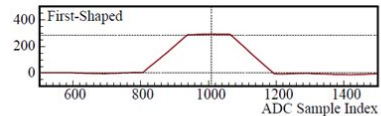
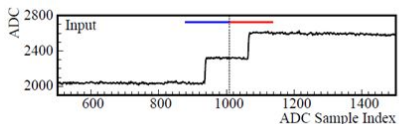
KATRIN: Signal processing - New Method

Pile-up Resolving Trapezoidal Filter (KATRIN invention)

Trapezoidal Filter Simulation, single electron



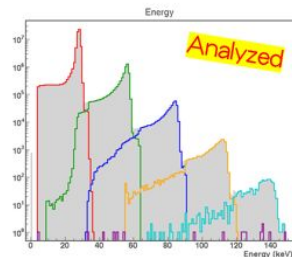
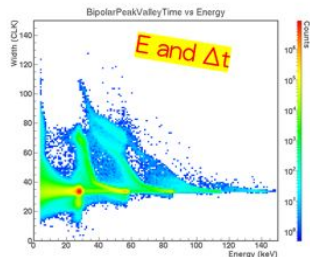
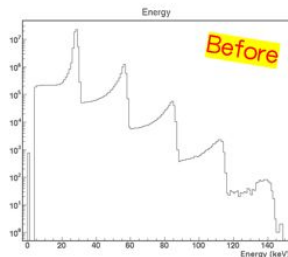
Trapezoidal Filter Simulation, two electron pile-up



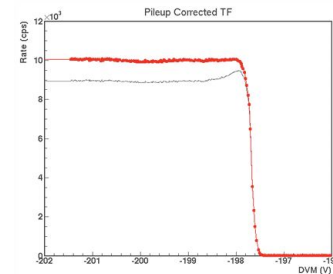
Trapezoidal shaping is basically blurred-differentiation

Do it again to convert it to a pair of bipolar pulses
→ then measure peak-to-valley time

In Action (Real Data)

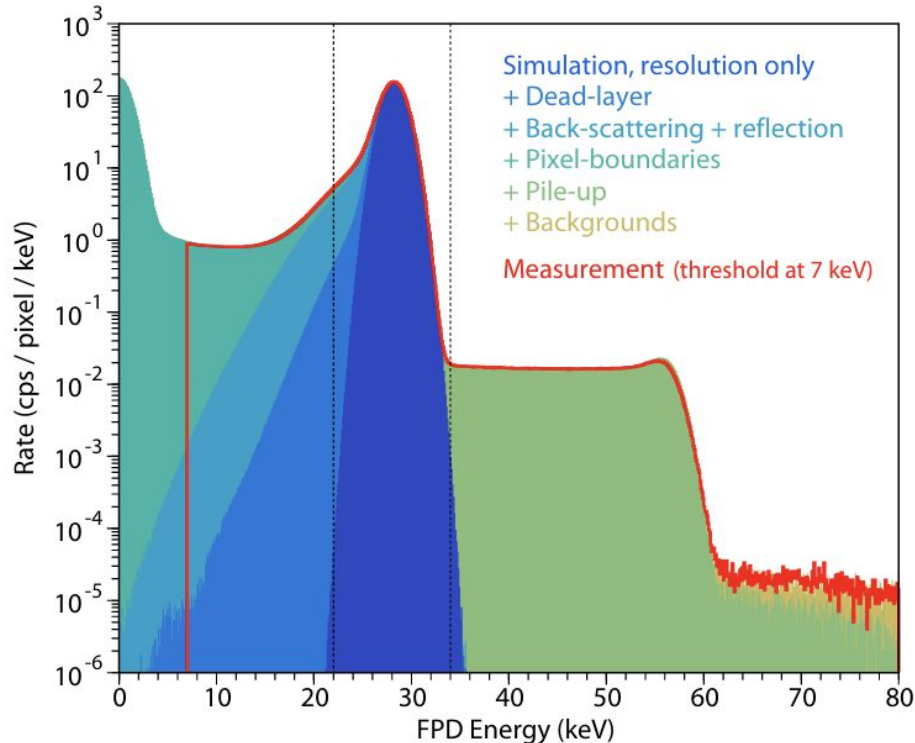


<0.1% counting error!!



KATRIN: Signal processing - Characterization

Simulation: End-to-end chain of first principles



Kassiopeia

- Field calculation
- Electron tracking

KESS

- Electron energy loss in Silicon
- Dead-layer shape
- Plasmon excitation
- Electron back-scattering

DRIPS

- Analog electronics transfer functions
- Noise sources and spectra
- Simulation twin of digital electronics

Data Quality Workflow

- **Before the campaign:**

- Quality criteria defined by subsystem experts for quality evaluation
- Stored in the database
- Criteria use to automatic flags for runs not meeting standards

- **During the campaign:**

- On-site operators review each run for automatic flags set for auto. Quality evaluation
- Remote shifters review runs as well

- **After the campaign:**

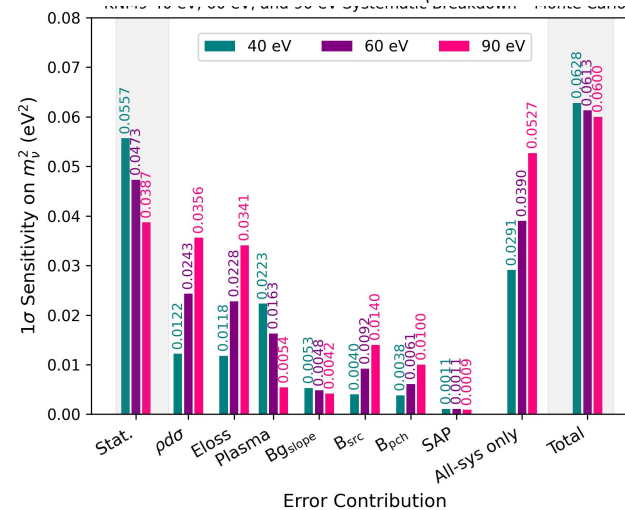
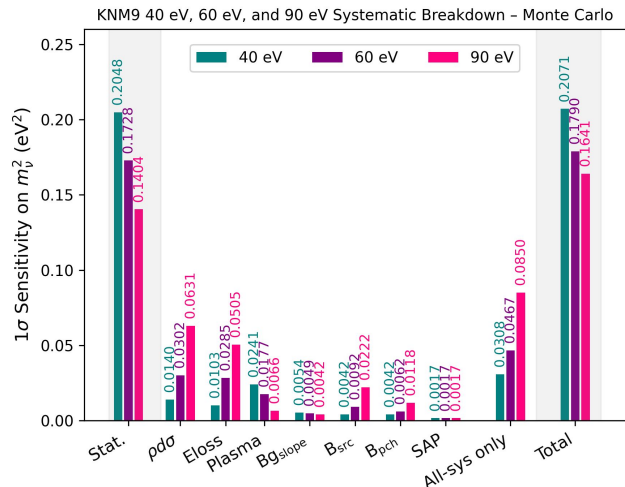
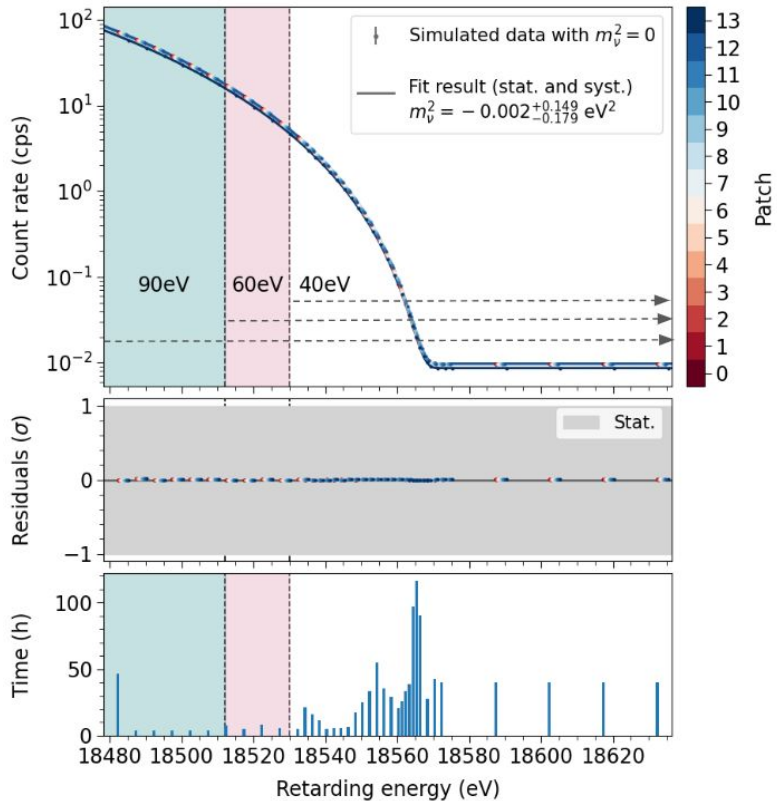
- Data quality working group reviews flagged runs (**R / Y**) marked by operators
- Post campaigns expert hardware review for each sub-system
- **Additional checks:** High voltage consistency, Column density stability
- **Golden run list** generated



Data Cleaning



Extended range studies



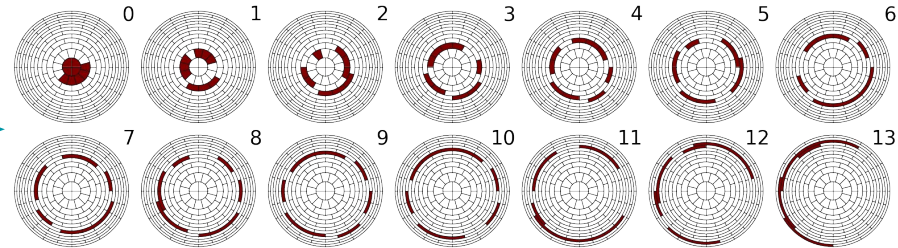
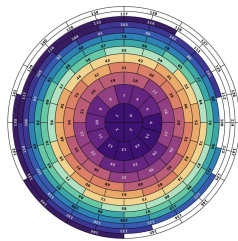
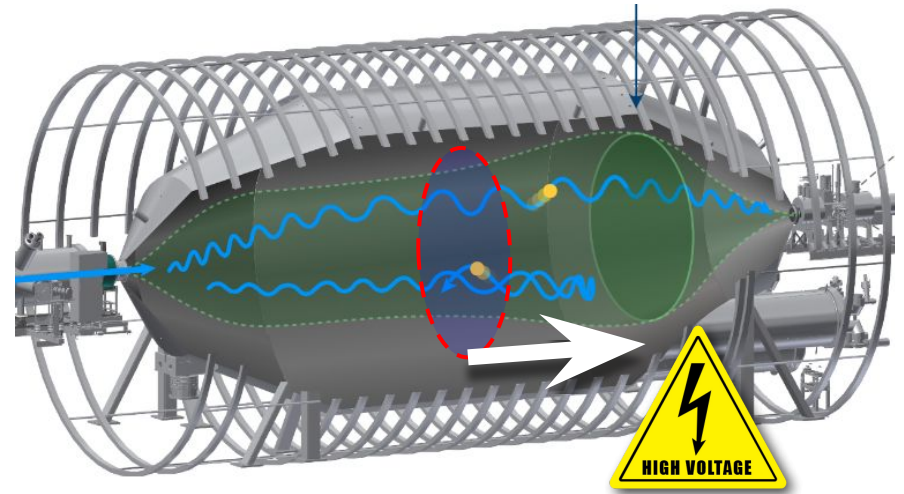
One campaign

600 days of data

Experimental improvements in new data (I)

Factor 2 lower background using “*shifted analyzing plane*” configuration

- Smaller volume mapped onto detector
- Inhomogeneous EM-fields
 - More segmented data **x 14**
 - **Calibration** of fields needed

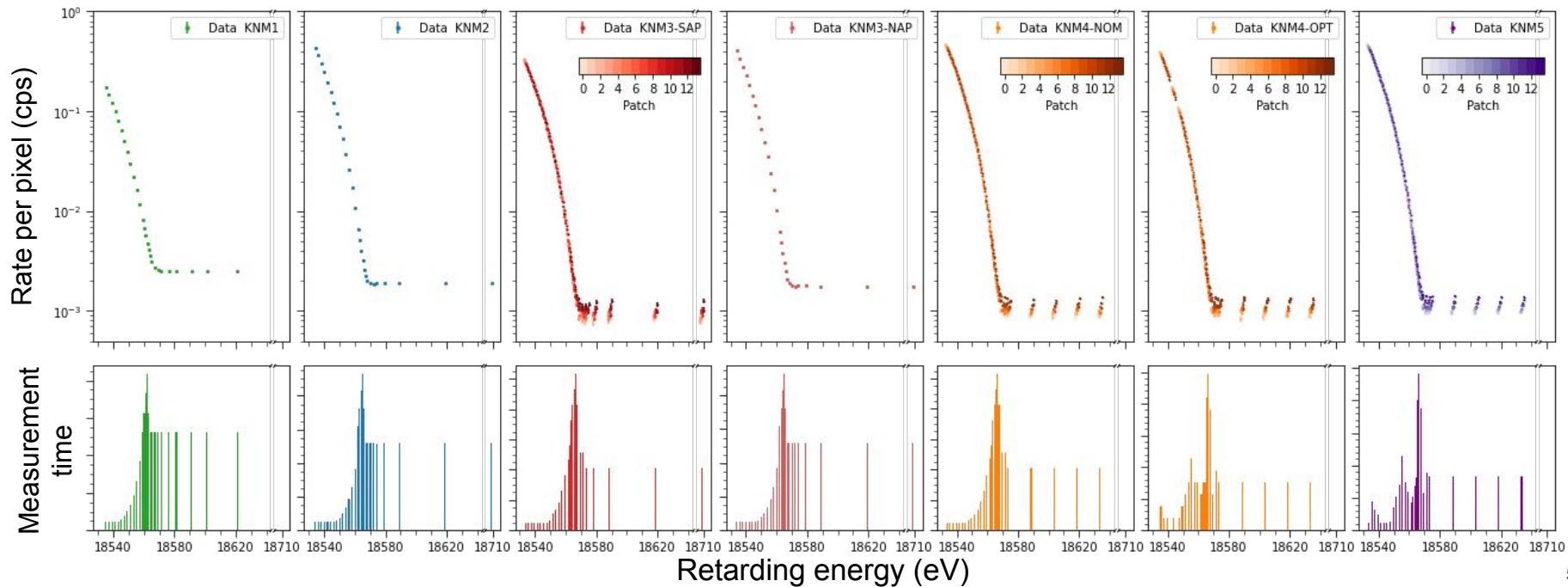


Data

36 Mio counts in total

59 stacked spectra with

27 + 28 + 14 x 28 + 28 + 14 x 28 + 14 x 25 + 14 x 28 =
1609 data points

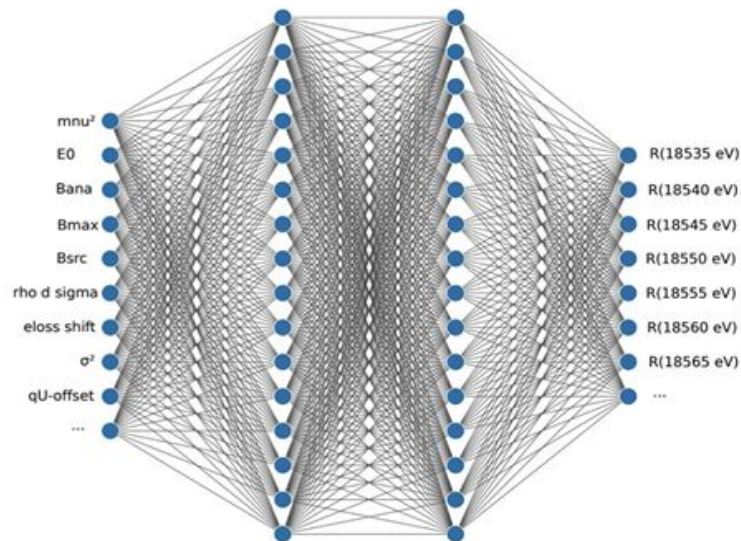


KaFit optimisation

- Block caching of detector response function and tritium decay spectrum
- Convolution of multiple scattering energy loss in Fourier space
- Shared dependent models among detector pixels
- Numerical Gauss-Legendre integration
- Fitting time reduced by a factor of $\sim 10k$ for one campaign, $O(100)$ CPU hours
for combined analysis using $O(10)$ cores

Model prediction with Neural network

- Network training with $O(10^6)$ Monte Carlo spectra
– $\sim 100\text{k}$ CPU hours in network preparation
- Fast analytical model prediction in given parameter range
– $O(10)$ CPU hours in fitting
- Regenerate neural networks for new parameter ranges



See *Eur. Phys. J. C* 82, 439 (2022)
for more details

Neutrino-mass limit: For campaigns 1-5

- New World-leading direct upper limit on the neutrino mass:

$$m_{\beta} < 0.45 \text{ eV (90\% CL)}$$

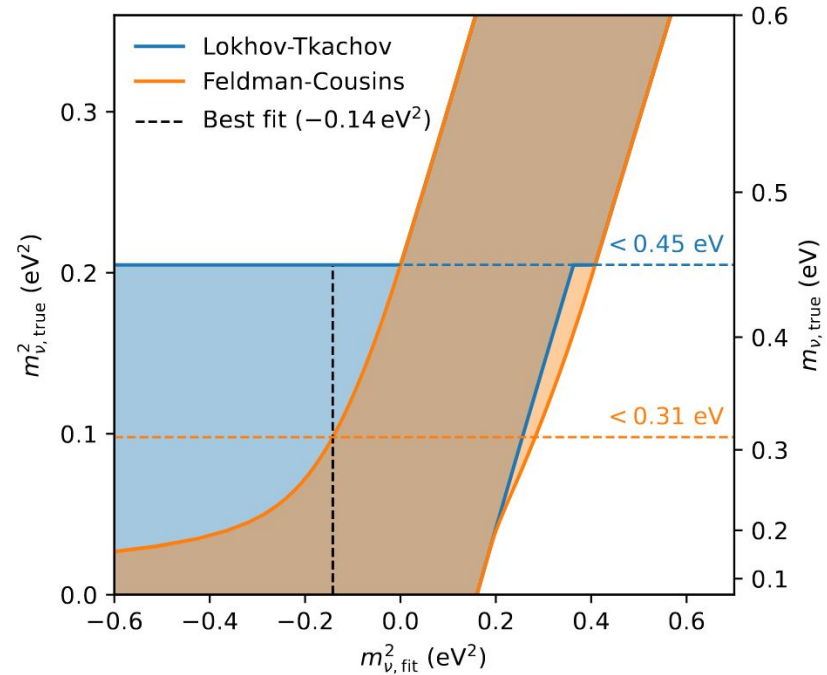
based on **Lokhov-Tkachov** confidence interval construction [Lokhov, Tkachov, Phys.Part.Nucl. 46 (2015)]

- **Feldman-Cousins limit:**

$m_{\beta} < 0.31 \text{ eV (90\% CL)}$, benefits from negative best-fit

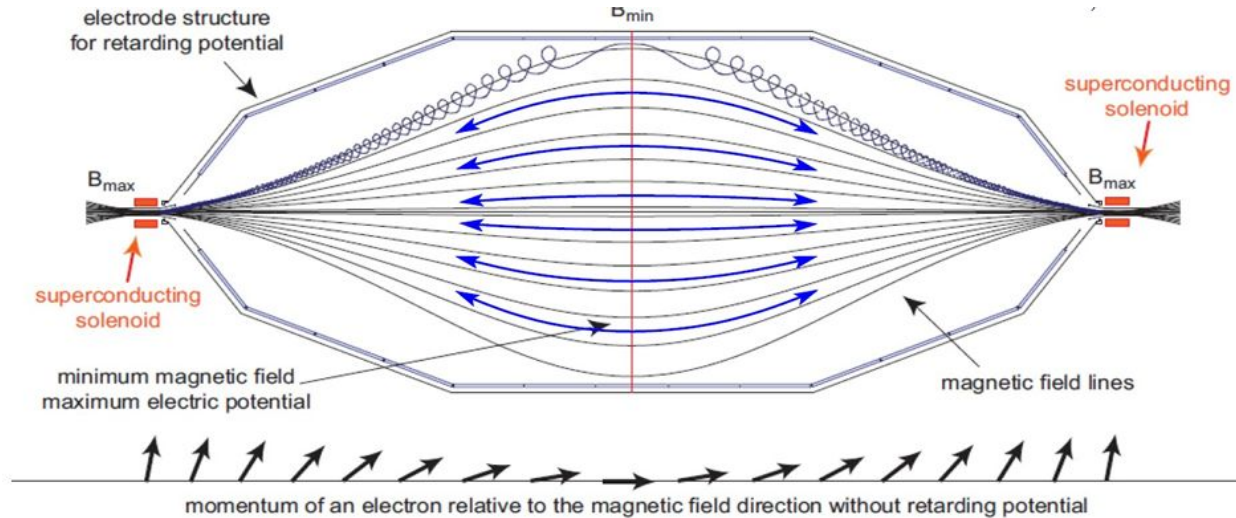
- **For BSM physics searches:** sterile neutrinos, relic neutrinos, Lorenz invariance, exotic weak interactions

See Posters



MAC-E filter concept

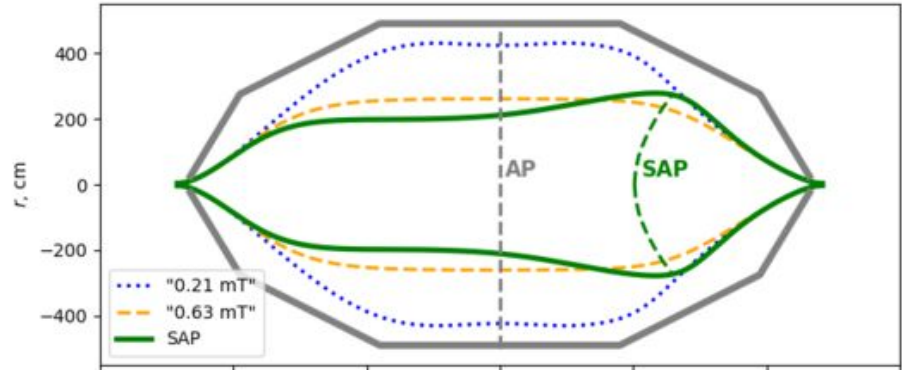
Magnetic Adiabatic Collimation with Electrostatic Filter



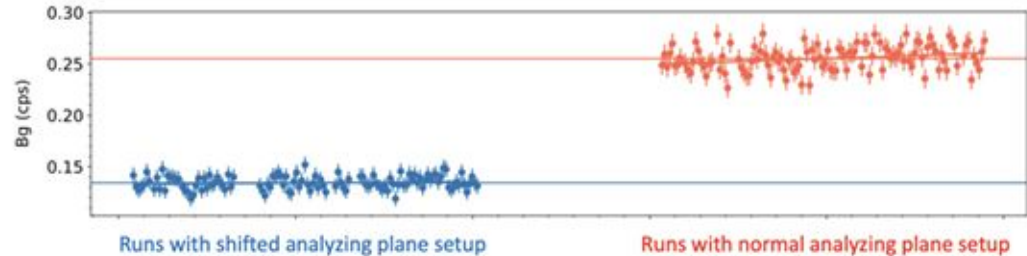
- adiabatic transport $\rightarrow \mu = E_{\perp} / B = \text{const.}$
- B drops by $2 \cdot 10^4$ from solenoid to analyzing plane $\rightarrow E_{\perp} \rightarrow E_{\parallel}$
- only electrons with $E_{\parallel} > eU_0$ can pass the retardation potential
- Energy resolution $\Delta E = E_{\parallel, \text{max, start}} \cdot B_{\min} / B_{\max} < 1 \text{ eV}$

The Shifted Analyzing plane configuration

- A shifted analyzing plane configuration has been adopted since April 2020, leading to a higher radial inhomogeneity in the magnetic fields
- Uniform pixel combination no longer valid; instead use 14 "patches" for each campaign → model evaluation complicated
- New spectrometer field configuration (shifted analysis plane) reduced background by factor 2 and removes non-poissonian backgrounds



Eur. Phys. J. C 82 (2022) 258



FSD Systematic for Extended Fit-ranges

- Uncertainty estimate as described by Schneidewind et al. [EPC 84, 494 (2024)]
- **Required:** systematic converged FSDs
- **Problem:** systematically converged FSDs above 40 eV: not generated yet
 - **Between 40 and 55 eV:** electronic bound & continuum states contribute
 - **Above 55 eV:** spectrum dominated by autoionizing states
- Preliminary uncertainty (order of magnitude!) estimate based on three FSDs obtained with completely **different methods**
 - **Saenz** == **GEM: Geminals**/ Complex Scaling for continuum [PRL 84, 242 (2000)]
 - **Doss** == **GEM+Dc:** gaussians/ **R-matrix**/ only continuum/ bound states from **Saenz**/ some flaws [Phys. B 41, 125701 (2008)]
 - **Schulz** == **CI: B-spline CI**/ box discretization for continuum [to be published]

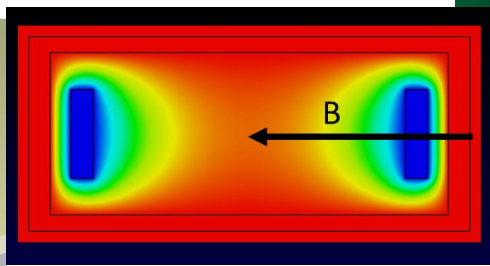
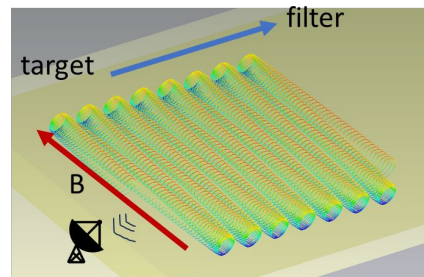
Note: Schulz FSD serves as reference (“true”) FSD.

PTOLEMY Backup

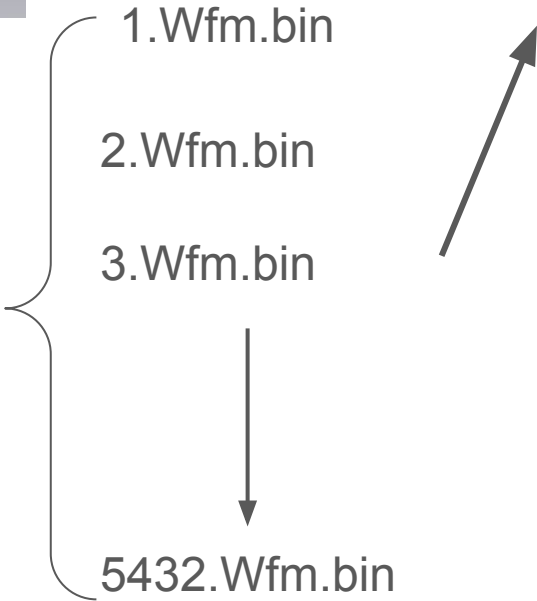
PTOLEMY- signal processing and data analysis challenges beyond those already described for MAC-E and CRES

- Doing CRES on a single-pass electron
- Analyzing data in real-time to adjust filter and direct each electron to the detector

PTOLEMY RF analysis: Electron Trap



Data:
1 event =
1 triggered event
in the trigger
frequency range



Data analysis input:

- Threshold SNR
- Avg FFT of start RUN

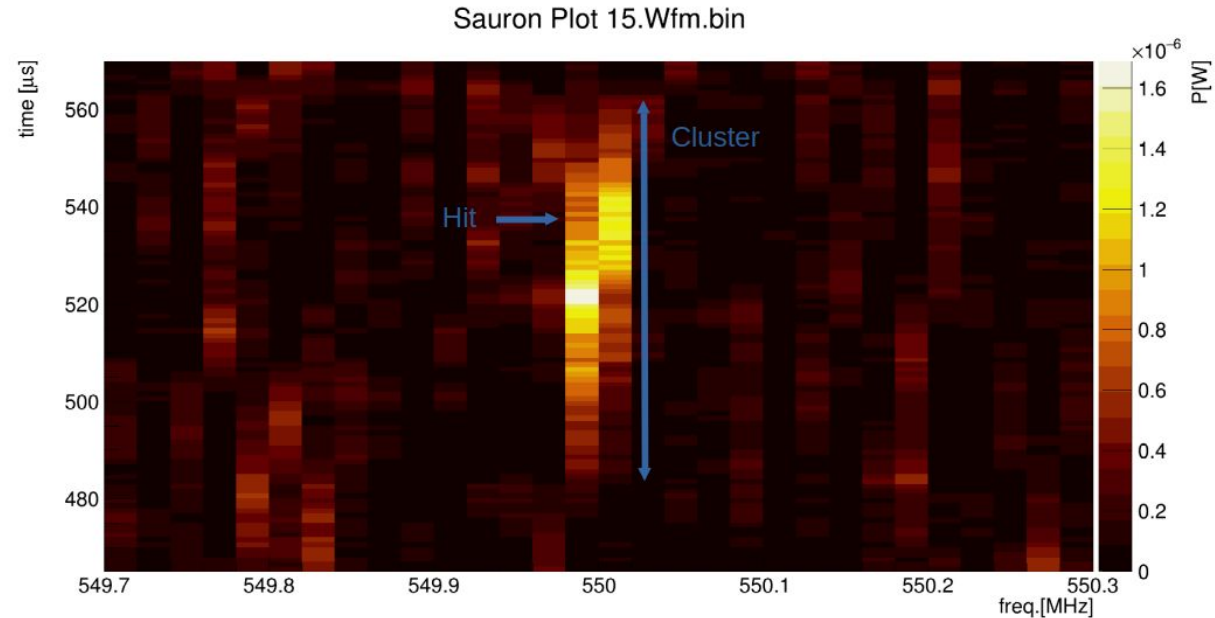
Root Tree with data, what in particular?

PTOLEMY RF analysis: The Sauron Plot

From the time series (CH1 oscilloscope)



- Sauron Plot (spectrogram with sliding fourier)
- Key parameter: ResolutionBandWidth
- Search for Hit and clusters (collection of hits at same freq.)
- Analysis in SNR basis
- Several clusters/event possible->Data cuts

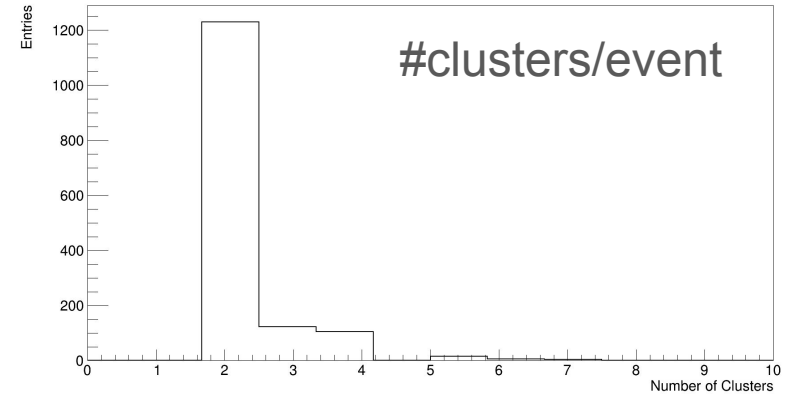
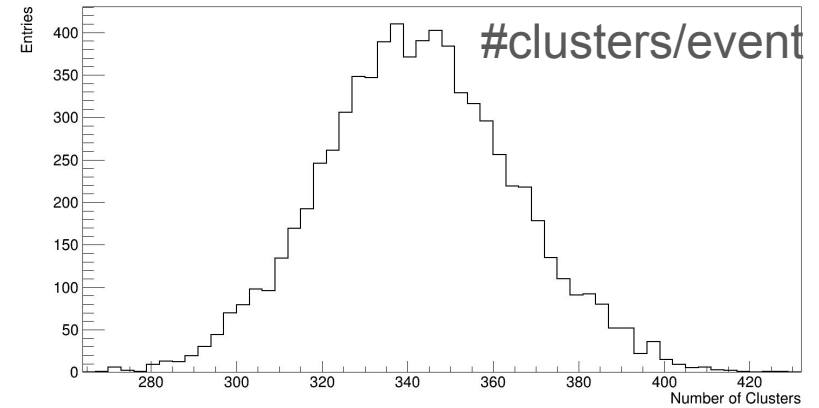
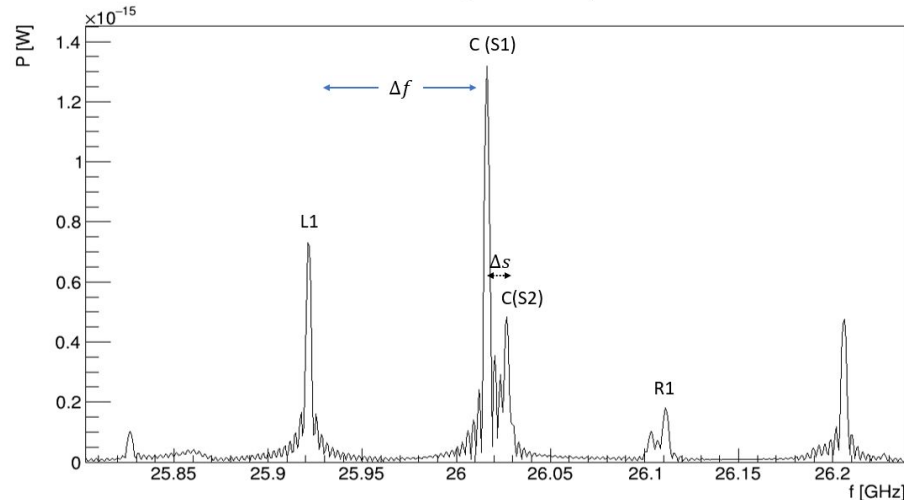


PTOLEMY RF analysis: Electron Trap Data

Data cuts:

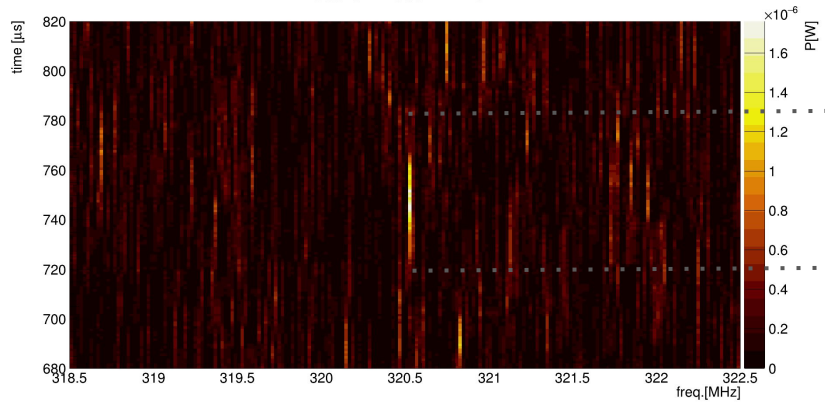
- SNR
- Drift time
- Average cluster SNR
- Cluster peak power
- Time coincidence between Carrier and sideband

CST simulation: single electron RF-pattern

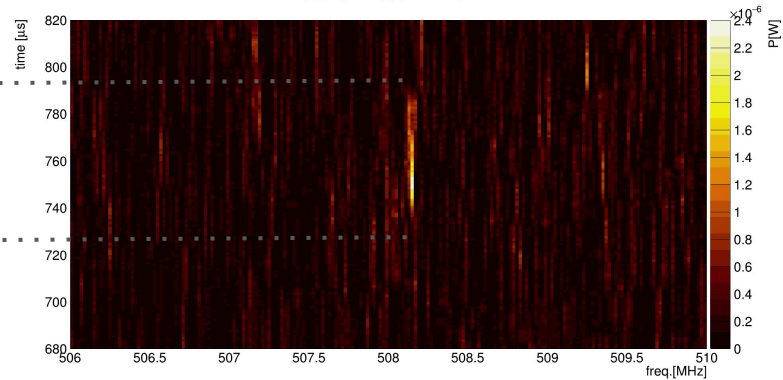


PTOLEMY RF analysis: Electron Trap Data

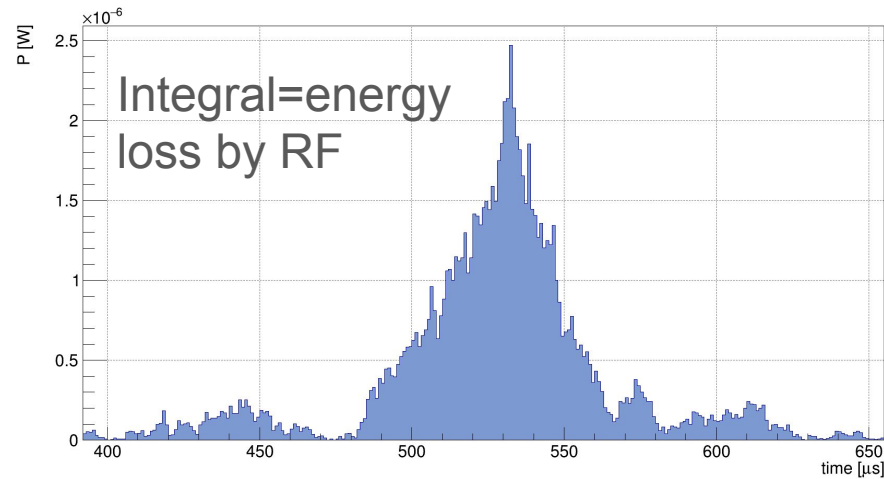
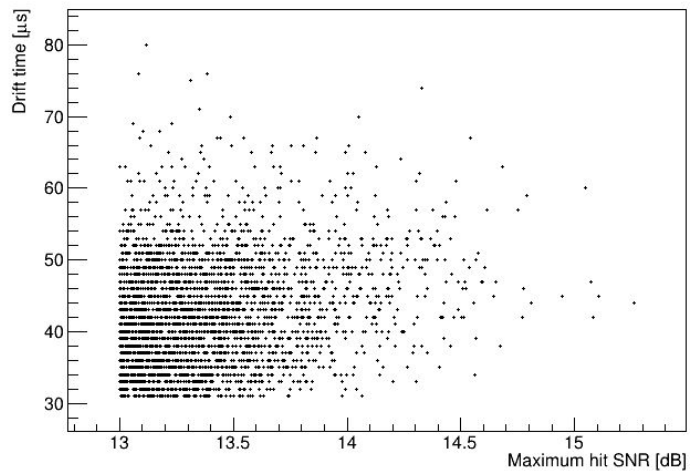
Sauron Plot 9.Wfm.bin



Sauron Plot 9.Wfm.bin

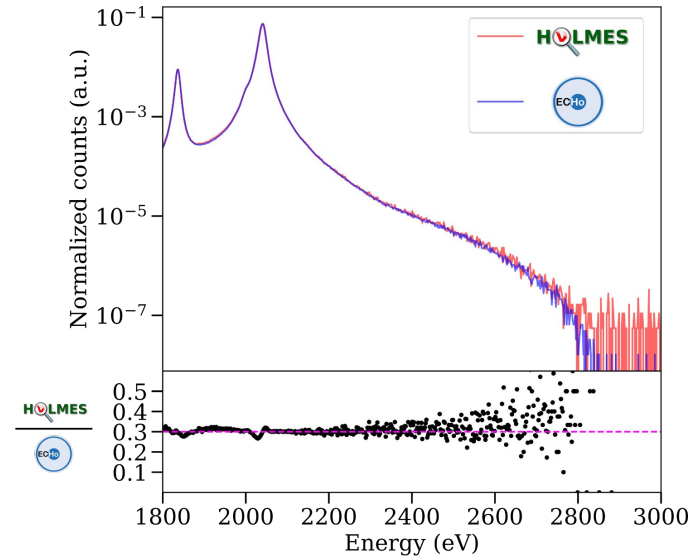
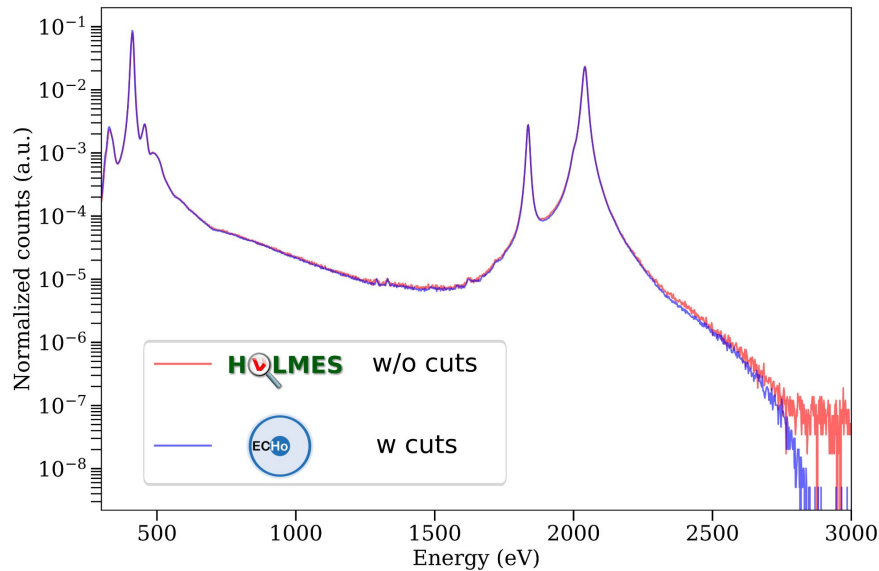


maximum hit SNR vs Drift time



Low Temperature Detectors: duty cycle and data comparison

- **ECHo and HOLMES** have completed their first data-taking stages, collecting approximately 200M (ECHo) and 70M (HOLMES) ^{163}Ho events...
 - ...using **different detector technologies, experimental setups and analysis!**
 - Efficiency: ~89% (ECHo), 99% (HOLMES)
- Two independent experiments produced a **consistent and fully compatible ^{163}Ho calorimetric spectrum.**



HOLMIUM data analysis approach

- For the first physics campaign, **one-man analysis team**
 - Bayesian analysis framework
 - STAN MCMC software



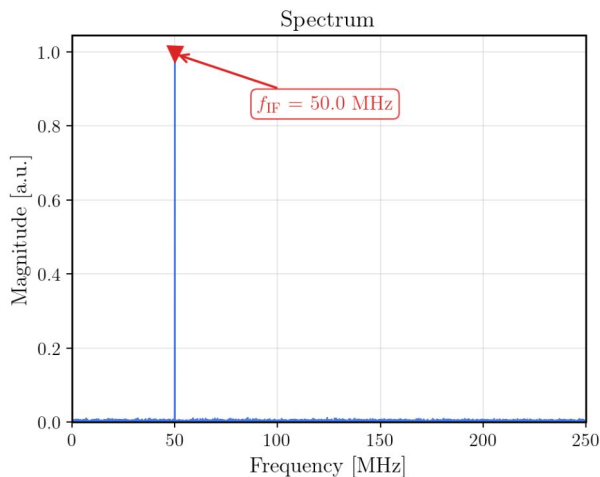
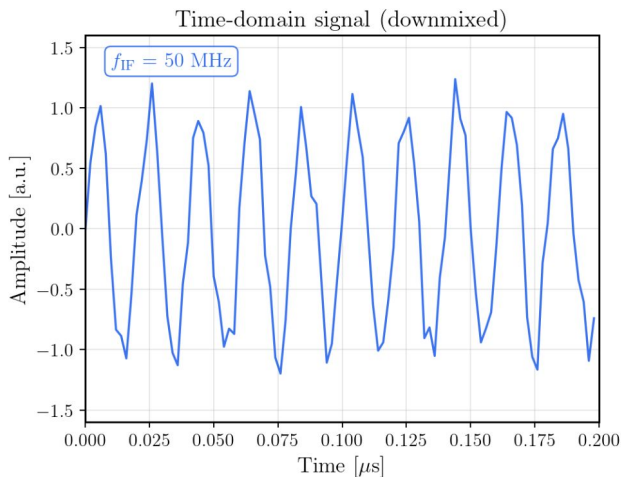
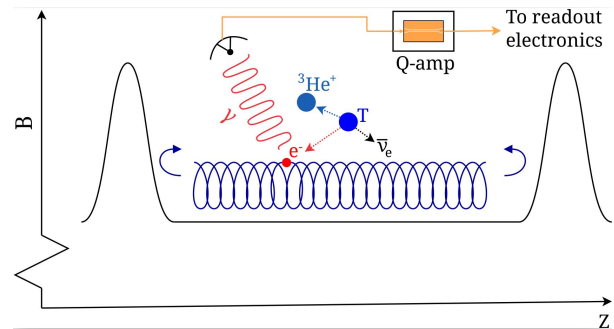
- **No blinding strategy, but:**
 - The impact of each assumption/approximation was tested using toy data
 - Calibration
 - Nonlinear energy response
 - Response function
 - ^{163}Ho model
- **In the future, a common platform/database shared between the two experiments could be established:**
 - Shared data?
 - Shared analysis framework?
 - **TBD during this numass!**

CRES Backup

CRES detectors: signal processing

To 0th-order our CRES signal is a sine wave at the (downmixed) cyclotron frequency

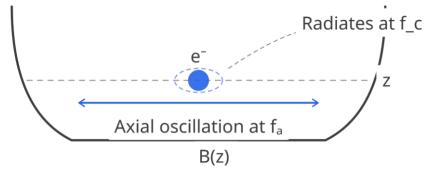
$$f_c = \frac{1}{2\pi} \frac{eB}{\gamma m_e}$$



At the fields QTNM and Project 8 are interested in, we have f_c in the range 100MHz - 27GHz

CRES detectors: signal processing

Magnetic trap



Same axial motion causes both:

FM — frequency modulation

Doppler effect
Velocity along z

Varying B-field
 $B(z)$ changes f_c

Both modulate instantaneous freq.

Observed frequency vs time:



Frequency modulated at f_a

→ FM sidebands in spectrum

AM — receiver coupling

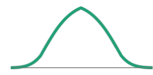
Coupling to receiver depends on
electron position along z

Cavity

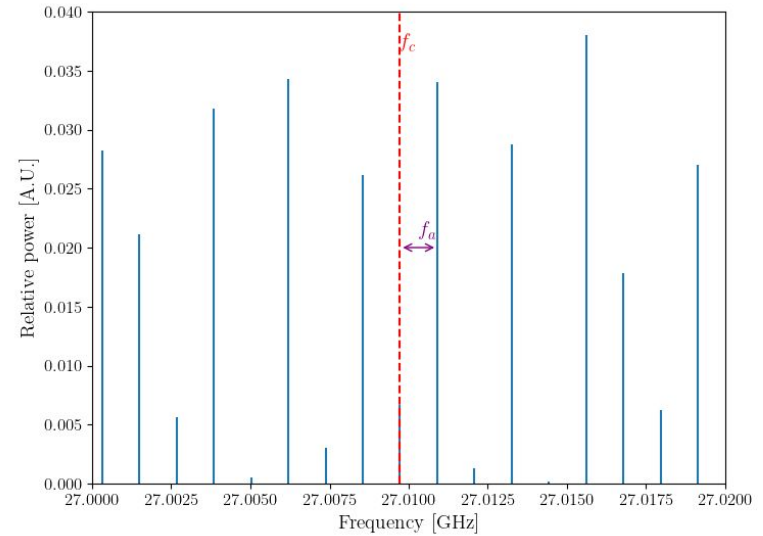
Antenna

Mode amplitude vs z:

Power pattern vs z:



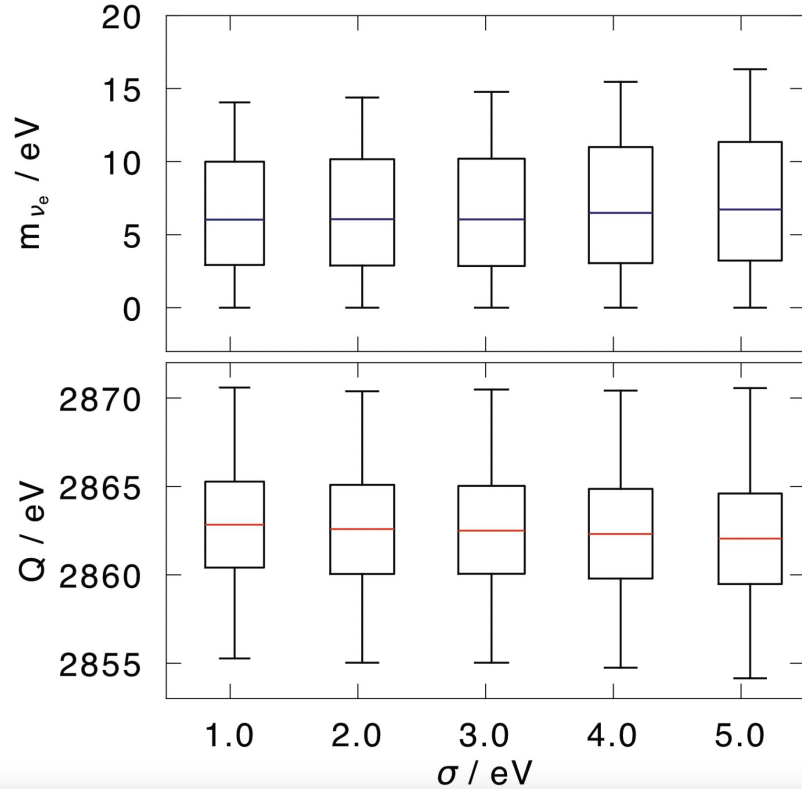
→ AM sidebands in spectrum



Modulation creates sidebands spaced at f_a . Can be both **problematic** (harder to see signals) and **useful** (can be used to deduce axial frequency and electron motion)-- see next slide

Holmium-163 Backup

Energy resolution | Posterior Distributions



Box plot of posterior distributions for m_{ν_e} (top) and Q (bottom) derived from MCMCs with biased energy resolution σ . The horizontal position and width of the boxes correspond to the median and standard deviation of $P(\sigma)$. The bottom and top edge of each box mark the first and third quartile. The whiskers on the boxes for $P(m_{\nu_e})$ mark the 0th and 90th percentile and for $P(Q)$ the 3σ range.

Master Thesis, Lorenzo Calza (2025)

Big questions and challenges

- Endpoint, fixed or not?
- Fit using m_2 or m
 - $M_2 < 0 \rightarrow$ what happens when m is forced to be greater than 0? Do you lose the ability to detect some systematic effects?
- Fit using m_{beta} or m_1, m_2 and m_3 ? Where and when?
- How to treat different endpoints in the spectrum?
- How much do you need to be precise on the absolute energy calibration?
 - This could be related to the free endpoint
- Overlooked broadening \rightarrow negative m^2 . How to handle this in the future?
(Sanshiro could make slide about how KATRIN has dealt with this)
- How to perform sensitivity studies
 - Can we use Asimov dataset?
 - Project 8's comparison of analytical and Monte Carlo sensitivity forecasting tools (Pranava could make this slide)