Bandwidth requirements and effective time resolution in HOLMES

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Determination of the absolute electron (anti-)neutrino mass
4-7 April 2016, Trento, Italy

Outline

- ^{163}HO EC spectrum experiment
- ^{163}HO pile-up spectrum
- HOLMES
  - HOLMES sensitivity
  - RF-SQUID read out with multiplexing microwave
  - Bandwidth budget
- Time resolution
  - Simulation of TES respose
  - Pile-up simulations
  - Effective time resolution

HO Electron capture experiments

HOLMES

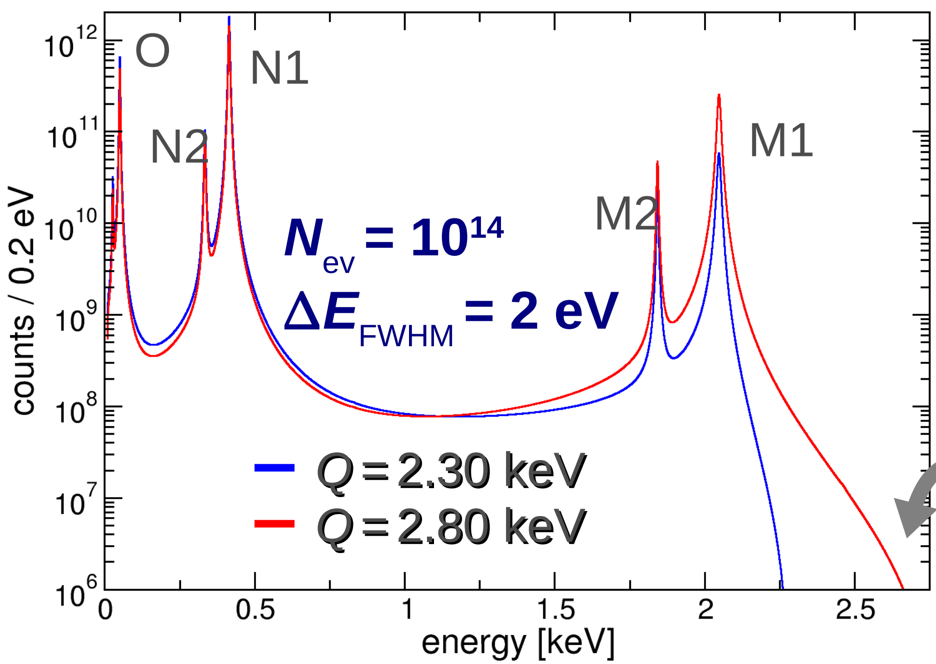
$^{163}\mathbf{Ho} + \mathbf{e}^- \rightarrow {}^{163}\mathbf{Dy}^* + \nu_e$

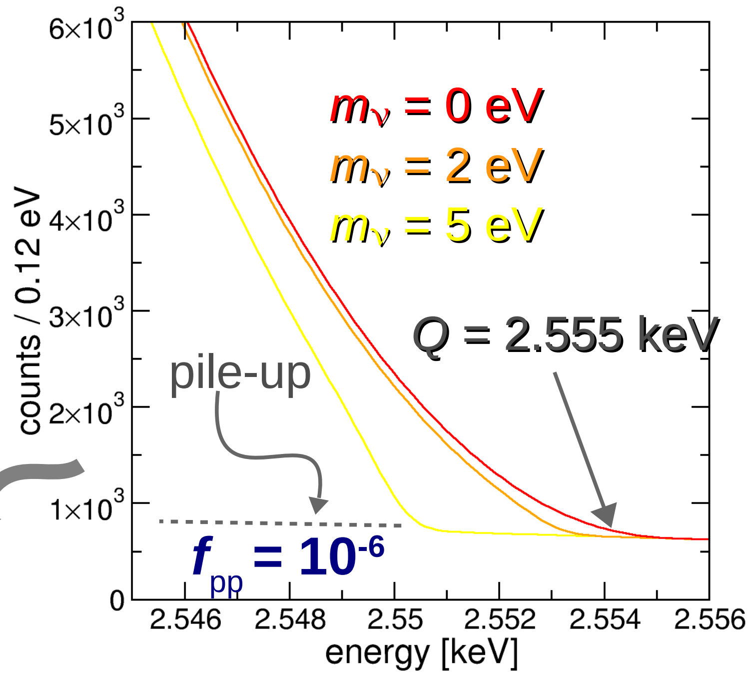
electron capture from shell ≥ M1

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

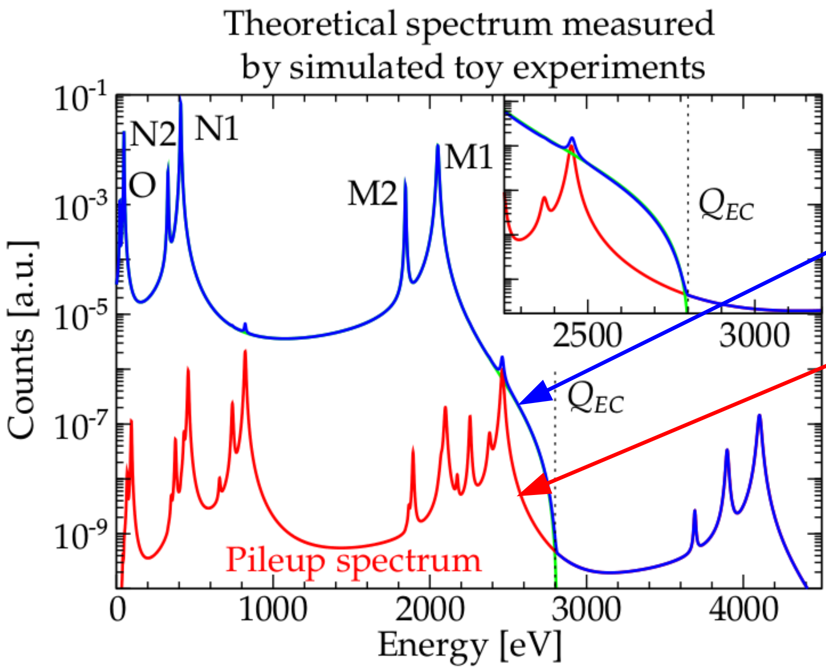
- calorimetric measurement of Dy atomic de-excitations (mostly non-radiative)
- rate at end-point and ν mass sensitivity depend on Q
  - Past measurements: Q= 2.3-2.8 keV. Recently measured $\boldsymbol{Q = 2.83 \pm 0.04}$ **keV**
- $\tau_{1/2} \approx 4570$ years → few active nuclei are needed

$$\frac{d\lambda_{EC}}{dE_c} = \frac{G_\beta^2}{4\pi^2}(Q-E_c)\sqrt{(Q-E_c)^2-m_\nu^2} \times \sum_i n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi} \frac{1}{(E_c-E_i)^2+\Gamma_i^2/4}$$





Ho Pile-up spectrum



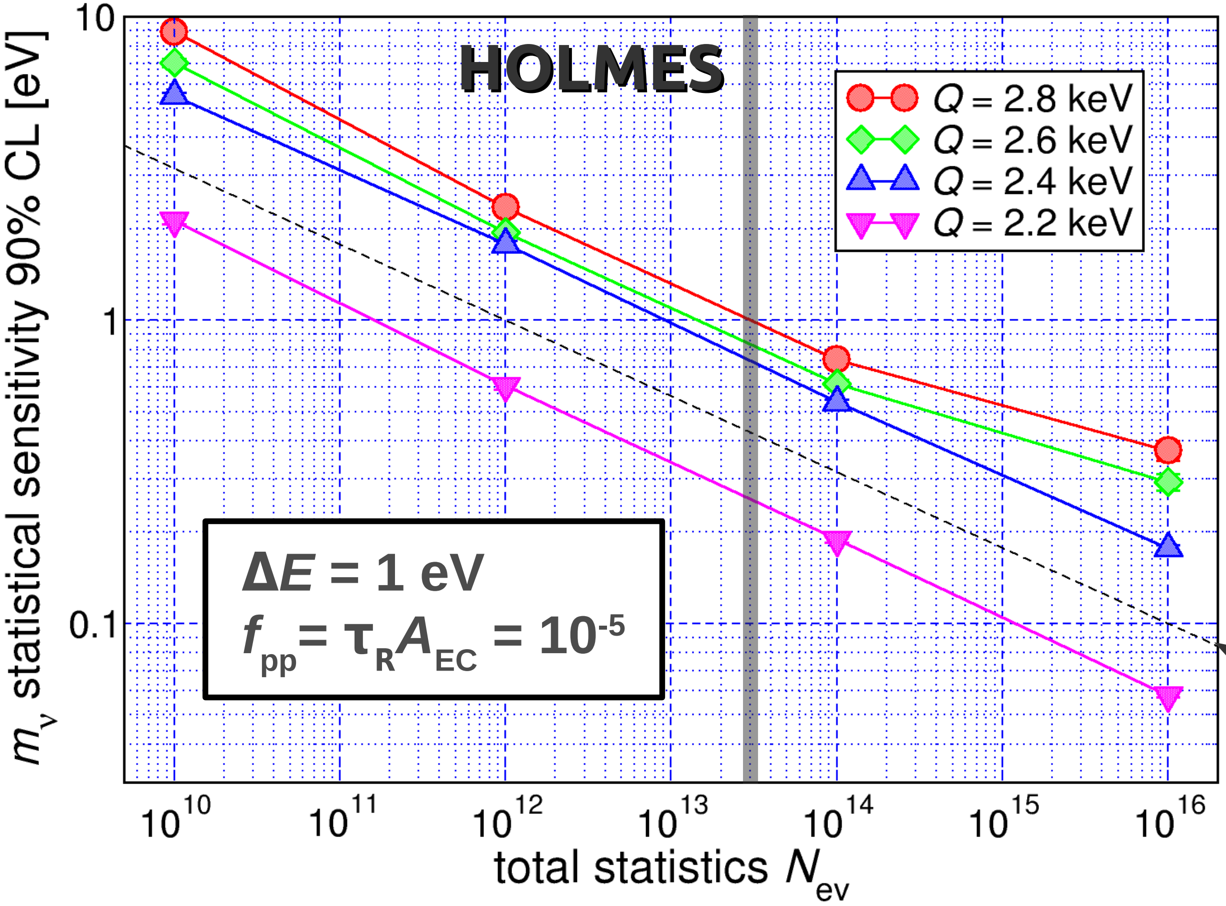
$Q_{EC} = 2800$ eV, $\Delta E = 2$ eV, $N_{ev} = 10^{14}$, $f_{pp} = 10^{-4}$

$$S(E_c) = [N_{ev}(N_{EC}(E_c, m_\nu) + f_{pp} \times N_{EC}(E_c, 0) \otimes N_{EC}(E_c, 0)) + B(E_c)] \otimes R_{\Delta E}(E_c)$$

N_{ev}	: total number of events
$N_{EC}(E_c, m_\nu)$	: ^{163}Ho spectrum
$B(E)$	: background energy spectrum
$R_{\Delta E}(E_c)$	: detector energy response function
f_{pp}	: fraction of pile-up events
$R_{\Delta E}(E_c)$	: detector energy response function
ΔE	intervall of energy

- Pile-up pulse occurs when multiple events arrive within the temporal resolving time of the detector;
- Unresolved pile-up produces background close to the end-point;
- The 163 Ho pile-up events spectrum is quite complex and presents a number of peaks right at the end-point of the decay spectrum;
- To resolve pile-up:
  - Detector with fast signal rise-time τ_{rise};
  - Pulse pile-up recovery algorithm;

^{163}Ho statistical sensitivity - Montecarlo simulations



Requirements:

- high energy resolution ≈1eV
- fast response ≈1µs
- large multiplexable array ≈1000

$$\propto \sqrt[4]{1/N_{ev}}$$

M. Galeazzi et al., arXiv:1202.4763v2
A. Nucciotti, Eur. Phys. J. C, (2014) 74:3161

HOLMES (ERC-Advanced Grant n. 340321)

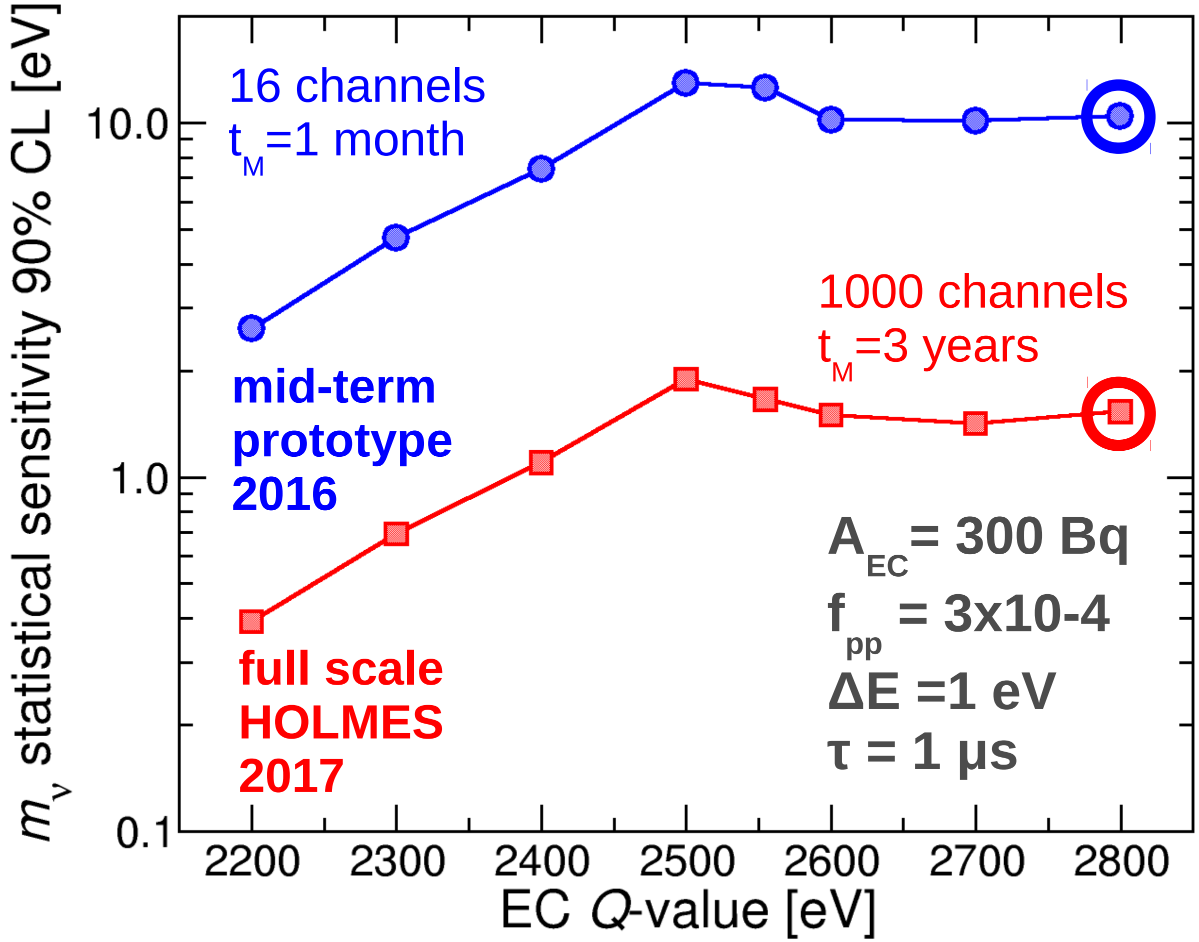
HOLMES

Goal

- neutrino mass measurement: m_ν statistical sensitivity as low as 0.4 eV
- prove technique potential and scalability:
  - assess EC *Q*-value
  - assess systematic errors

Baseline

- TES with implanted ^{163}Ho
  - 6.5×10^{13} nuclei per pixel → 300 dec/sec
  - $\Delta E\approx1$eV and $\tau_R\approx1\mu$s
- 1000 channel array
  - 6.5×10^{16} ^{163}Ho nuclei → ≈18μg
  - 3×10^{13} events in 3 years



B. Alpert et al., Eur. Phys. J. C, (2015) 75:112
http://artico.mib.infn.it/holmes

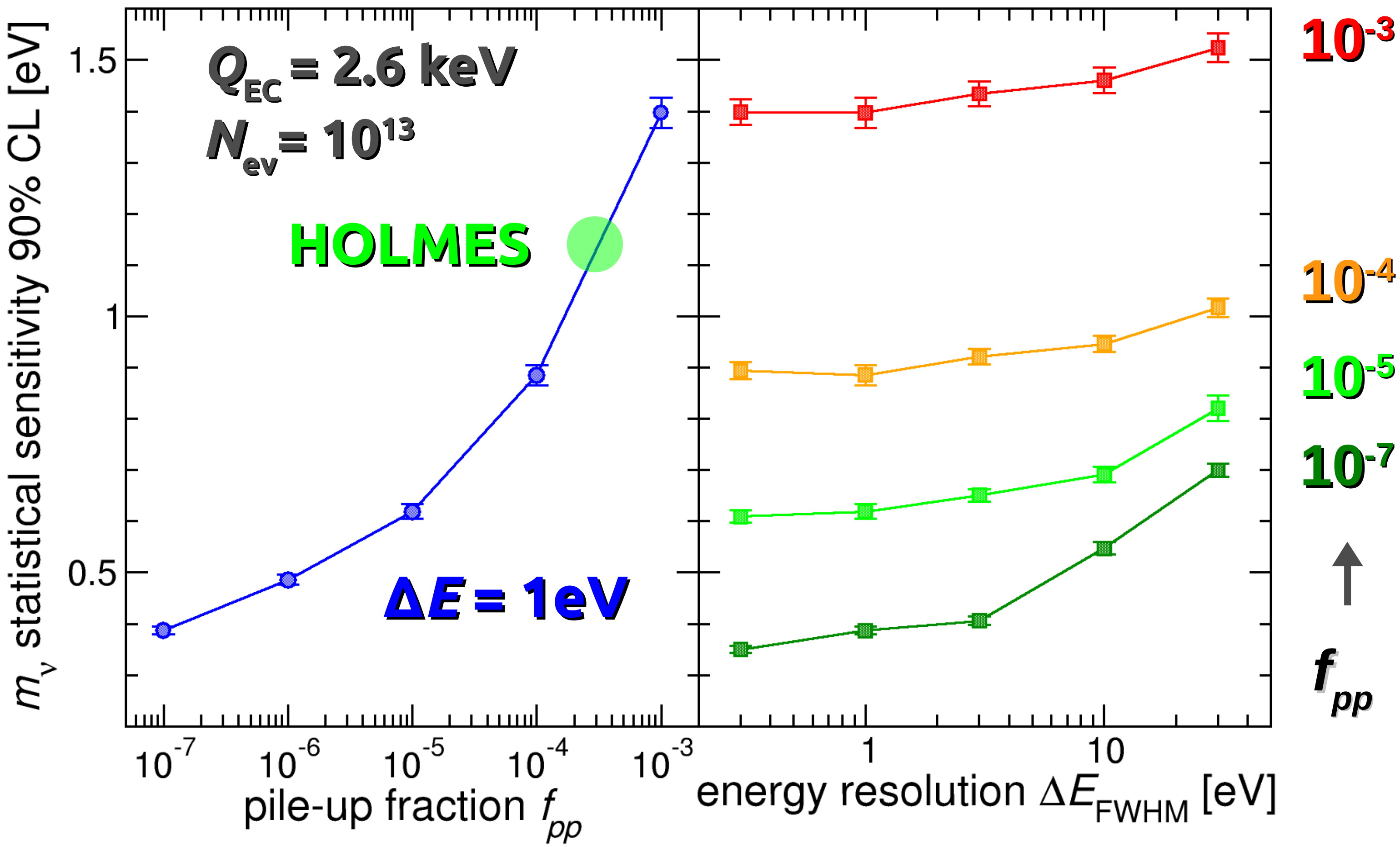
→ Project Started on February 1st 2014

HOLMES sensitivity: montecarlo simulation

Statistical sensitivity $\Sigma(m_\nu)$ dependencies from MC simulations

- **strong** on statistics $N_{ev}=A_{EC}N_{det}t_M$: $\boldsymbol{\Sigma(m_\nu) \propto N_{ev}^{1/4}}$
- **strong** on rise time pile-up (probability $f_{pp} \approx A_{EC}\tau_R$)
- **weak** on energy resolution ΔE

t_M measuring time
N_{det} number of detectors
A_{EC} EC activity per detector
τ_R time resolution (≈rise time)



RF-Squid read out with multiplexing microwave

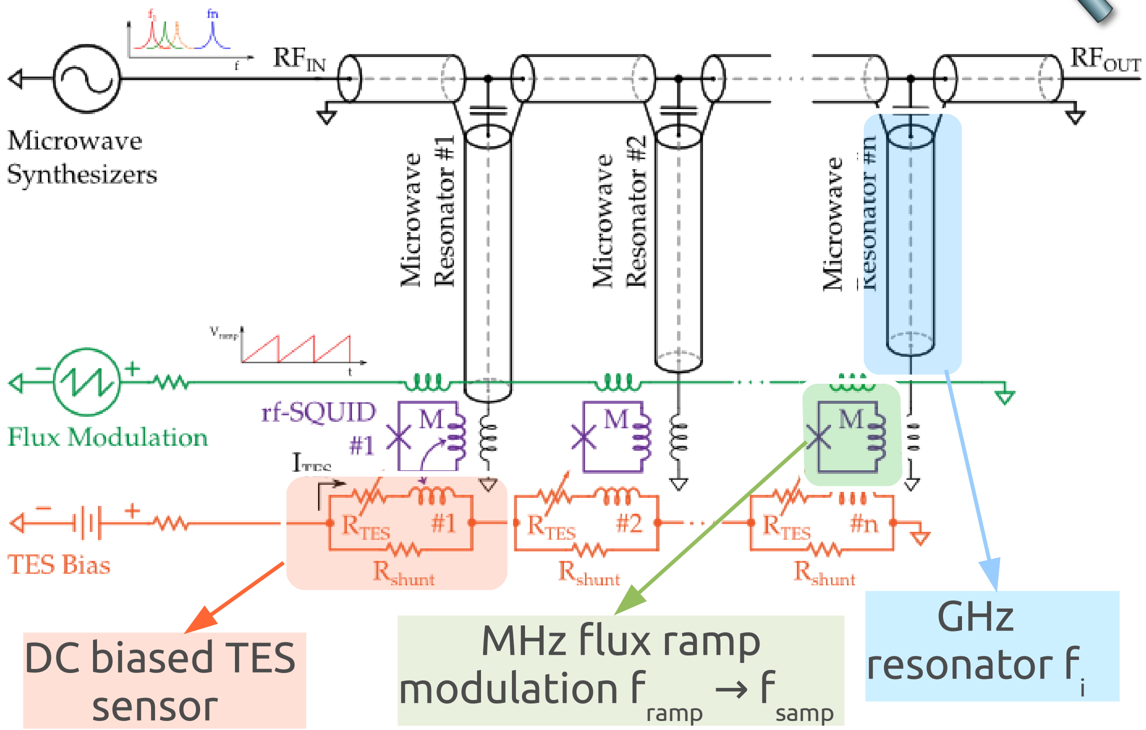
- RF- SQUID coupled with DC biased TES and a $\lambda/4$-wave resonant circuit
- RF-SQUID read out with flux ramp demodulation (common flux line inductively coupled to all SQUIDs)
- Signal reconstructed with homodyne detection and demodulation

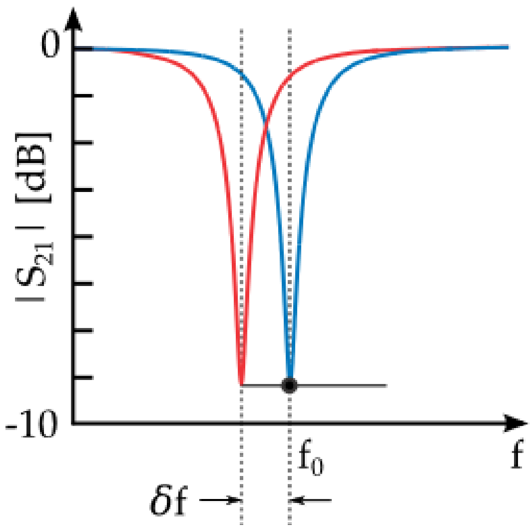
1. An event in the absorber increases the temperature and therefore the resistance of the TES;

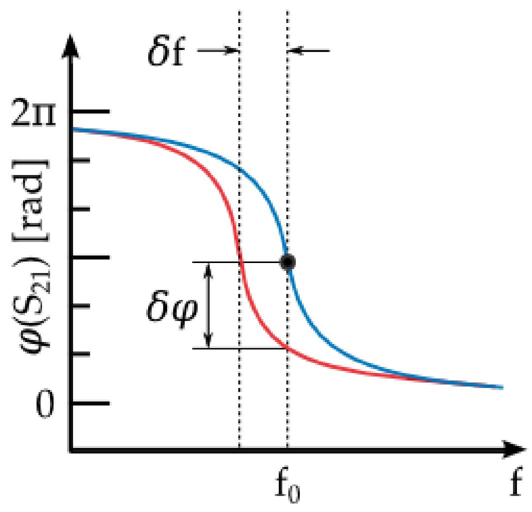
2. Change in TES current ⇒ change in the input flux to the SQUID;

3. The RF-SQUID transduces a change in input flux into a variation of resonant frequency and phase;

4. The ramp induces a controlled flux variation in the rf-SQUID, which is crucial for linearizing the response.



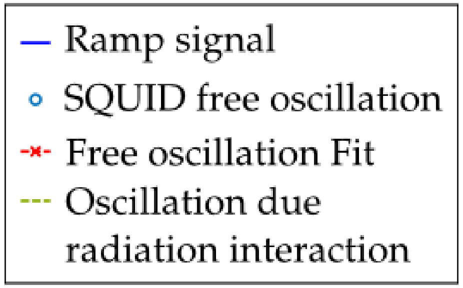


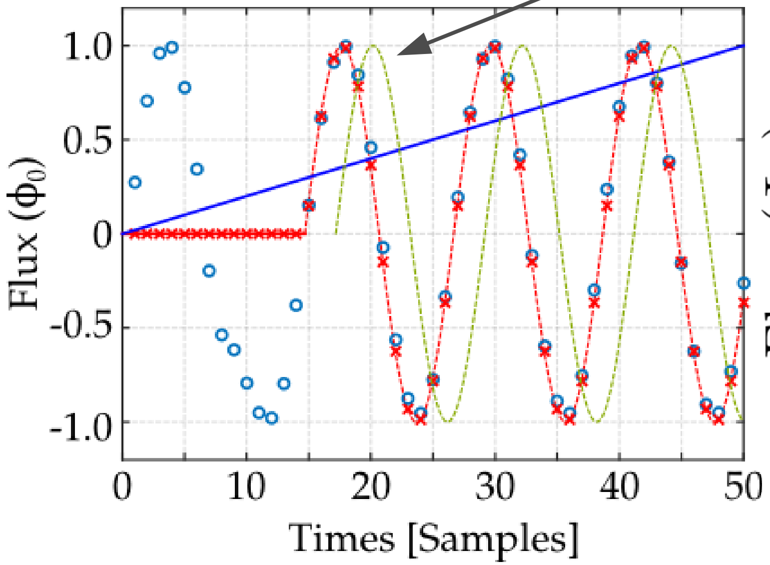


Signal reconstruction

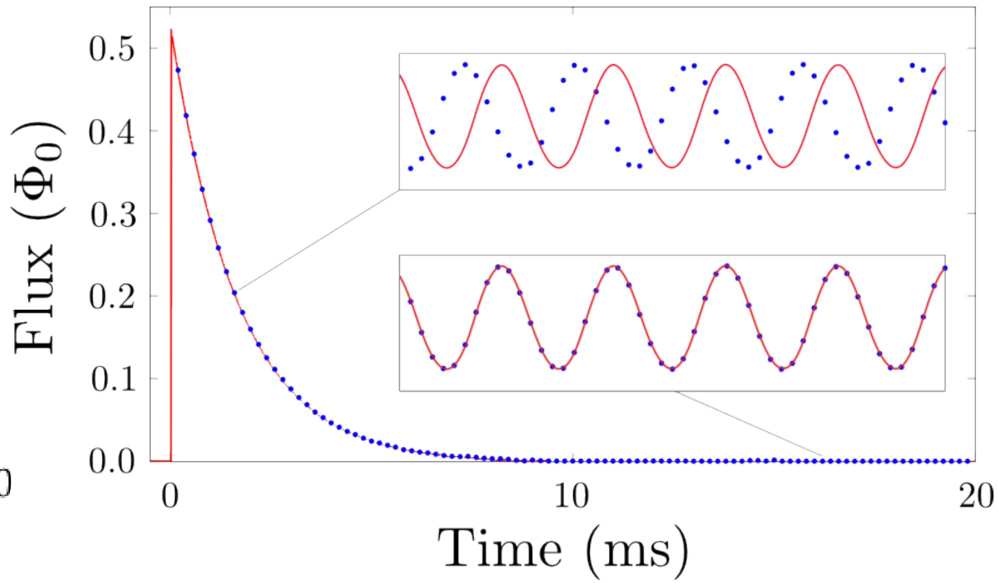
$n_{\Phi_0}=3$ ($n_{\Phi_0}\geq 2$)

$f_{mod}=n_{\Phi_0} f_{ramp}$





Each ramp acquisition represents a sample in the reconstructed phase signal



The signal is reconstructed by comparing the phase shift caused by the interaction of the radiation in the TES, with the free oscillation of the SQUID, when the TES is not biased.

TES microwave multiplexing with RF-SQUID ramp modulation + ROACH2-based Software Defined Radio (SDR)

Bandwidth budget

The detector design is mostly driven by the read-out bandwidth requirements.

- Effective sampling rate is set by the ramp: $f_{ramp} = f_{samp}$
- Necessary resonator bandwidth per flux ramp (resonator bandwidth): $f_{res} \geq 2 n_{\Phi_0} f_{samp}$
- To avoid cross talk spacing between resonances: $f_n \geq g_f f_{res} \quad [g_f = 10]$
- To avoid distortions (signal BW): $f_{samp} \geq \frac{R_d}{\boldsymbol{\tau}_{rise}} \approx \frac{5}{\boldsymbol{\tau}_{rise}}$ [τ_{rise} exponential]
- Available ADC bandwidth f_{ADC} with ROACH2 system 550 MHz
- Multiplexing factor:

$$n_{TES} = \frac{f_{ADC}}{f_n} \leq \frac{f_{ADC}\, \tau_{rise}}{2 R_d g_f n_{\Phi_0}} \approx \frac{f_{ADC}\, \boldsymbol{\tau}_{rise}}{200}$$

for fixed $\boldsymbol{f}_{ADC}$**=550MHz** and $\boldsymbol{n}_{TES}$**≈30 ↔** $\boldsymbol{\tau}_{rise}$**≈10μs** with $\boldsymbol{f}_{samp}$**=0.5MHz**

→ check for τ_{eff} and ΔE...

Simulation of TES response 1

Pulse profile:

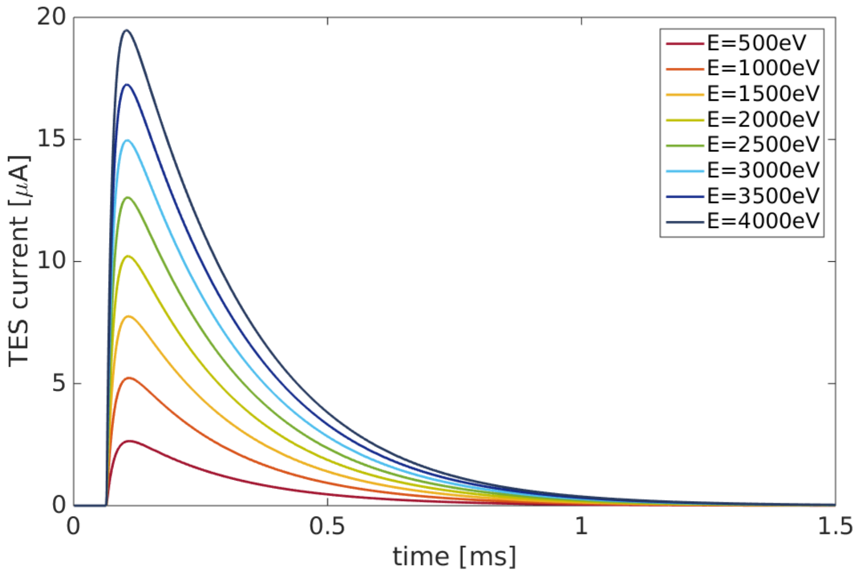
obtained by solving the two coupled differential equations (Irwin-Hilton model).

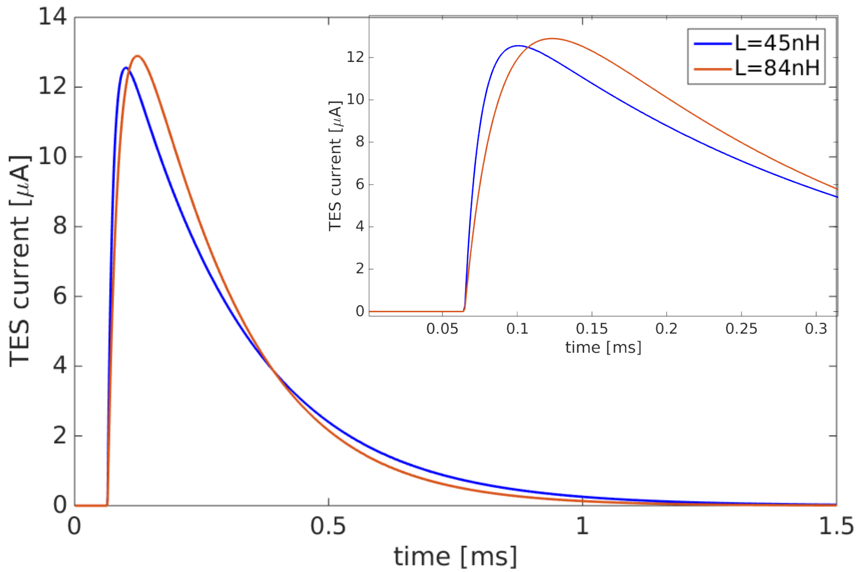
→ fourth order Runge-Kutta method (RK4)

→ the non-linearity behaviour is automatically taken into account

$$C\frac{dT}{dt} = -P_{bath} + P_j + \delta(t - t_0)E$$

$$L\frac{dI}{dt} = V + IR_L - IR(T, I)$$





TES parameters

n=3.3

C = 0.86 pJ/K

G = 0.44 nW/K

R_L=0.3 mΩ

R_N=10 mΩ

R_0=1.5 mΩ

L=45,84 nH

α_I=90, β_I=1.5

T_c=0.1K

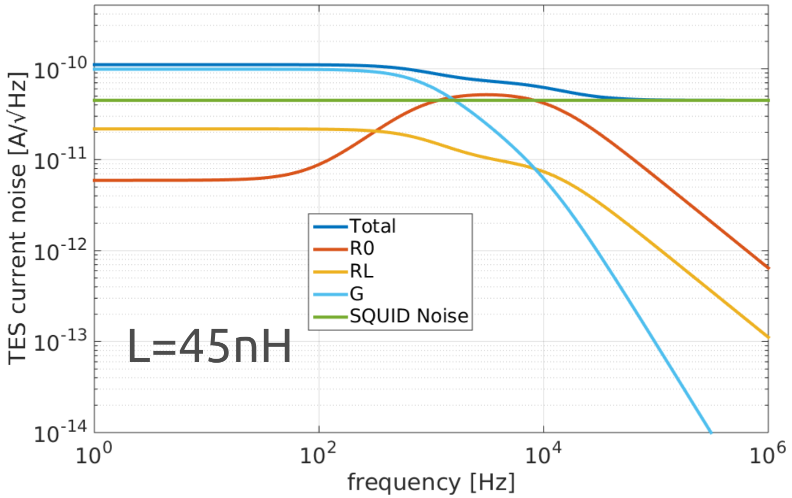
T_{bath}=0.06K

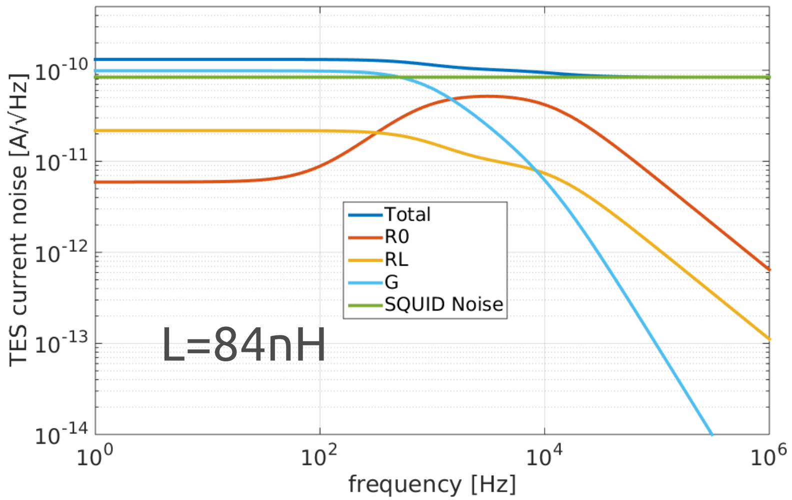
Simulation of TES response 1

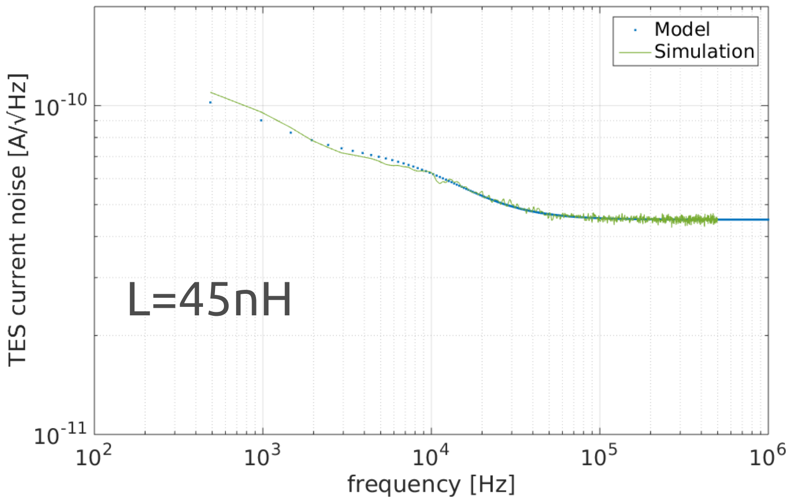
Noise profile:

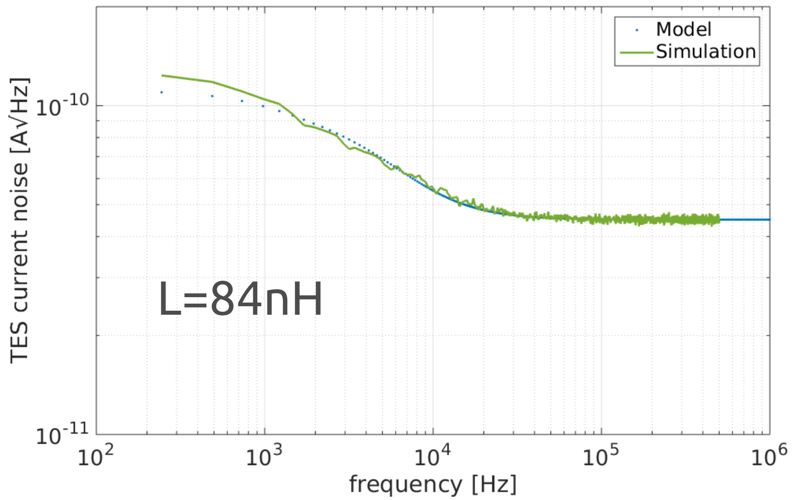
thermodynamic fluctuations of its state variables (I,T) + Johnson noise of shunt resistance R_L and SQUID amplifier noise (Irwin-Hilton model).

→ double roll off from the separate roll-off of the Johnson and thermal fluctuation noise







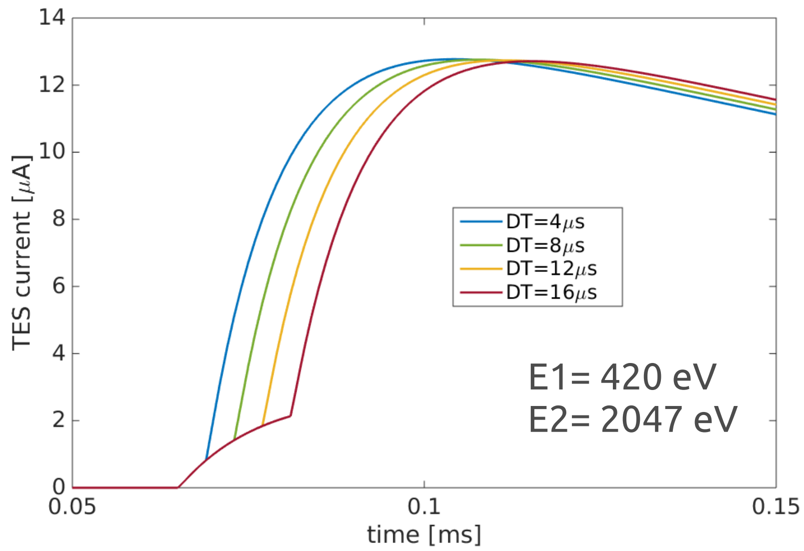


Pile-up Simulations

Simulation of sets of pile-up events with random time distances and with known time distances.
In first approximation → pile up of two events (i.e. two decays in one detector too close in time so that they are mistaken as a single one with an apparent energy equal to the sum of the two decays)

Events:

- ^{163}Ho spectrum (Q=2.5 keV,m_ν=0 eV) energy distribution (only considered the one-hole electron excitation spectrum)
- event pairs with $E_1 + E_2 \in$ [2.4 keV, 2.6 keV]
- delay of the pile up events from 0 to 16μs
- the arrival time does not match with the sampling (i.e. the simulated signals are originally oversampled and the arrival time is generated randomly)



ADC:

- 12 bit in a dynamic range 0-40 μA
- sample frequency of 0.5 and 1 MHz
- record length 2048 or 4096 points (1/8 for pre-trigger)

Effective time resolution

For subsequent (Δt) events with energy E_1 and E_2: time resolution $\tau_R = \tau_R(E_1, E_2)$

$$N_{pp}(E) = A_{EC} \int_0^{\infty} \tau_R(E, \epsilon) N_{EC}(\epsilon) N_{EC}(E-\epsilon) d\epsilon$$

We evaluate the **effective time resolution τ_{eff}** from **pile-up detection efficiency $\eta(\Delta t)$**

$$f_{pp} = A_{EC} \Delta t_{max} \left[1 - \int_0^{\Delta t_{max}} \frac{\eta(x)}{\Delta t_{max}} dx\right] = A_{EC} \boldsymbol{\tau_{eff}}$$

where

$\eta(x)$ rejection efficiency (0 - 1)

ΔT_{max} is the time interval used [0 – 18μs]

τ_{eff} *is an effective time resolution*

- Pile-up detection algorithms:
  - Wiener Filter WF or Single Value Decomposition SVD (**→ B. Alpert's talk this afternoon**)

Discrimination with Wiener Filter

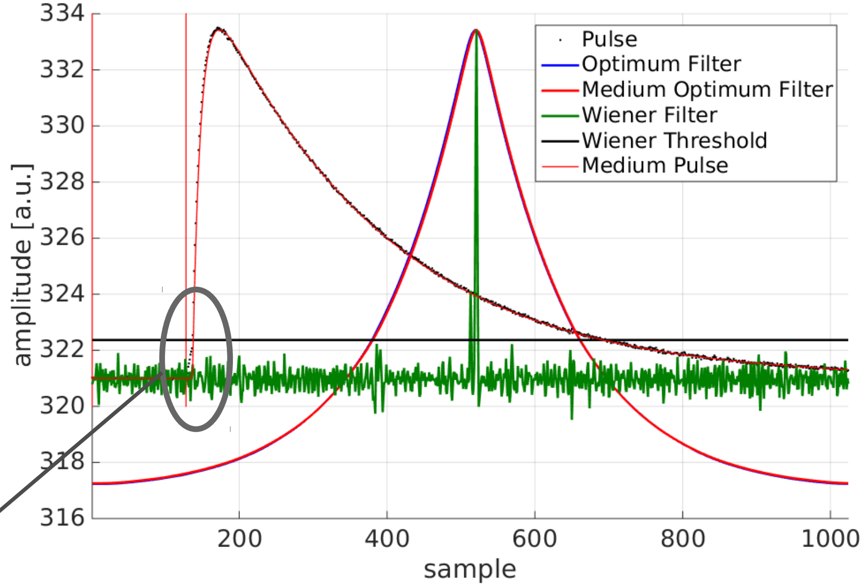
In our analysis the pile-up discrimination algorithms are based on the Optimum Filter and on the Wiener Filter. The OF provides the best estimate for the signal amplitude while the WF is a digital filter to gain time resolution.

signal $S(\omega)$

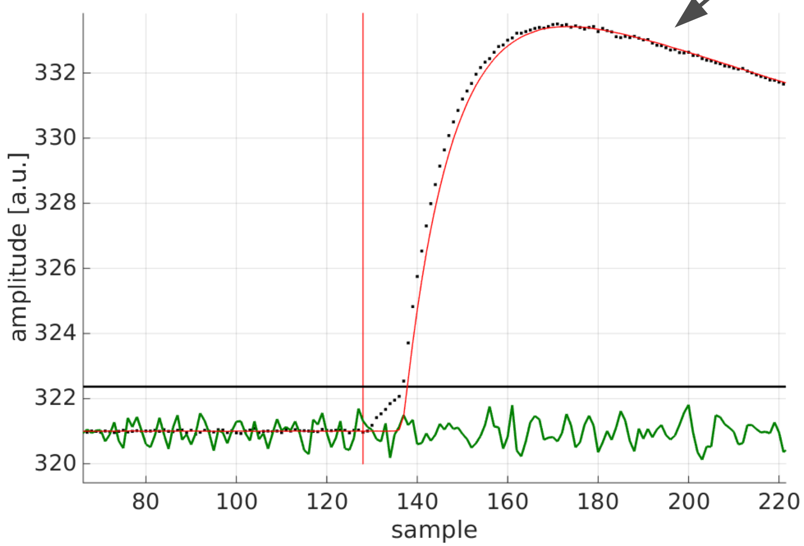
noise $N(\omega)$

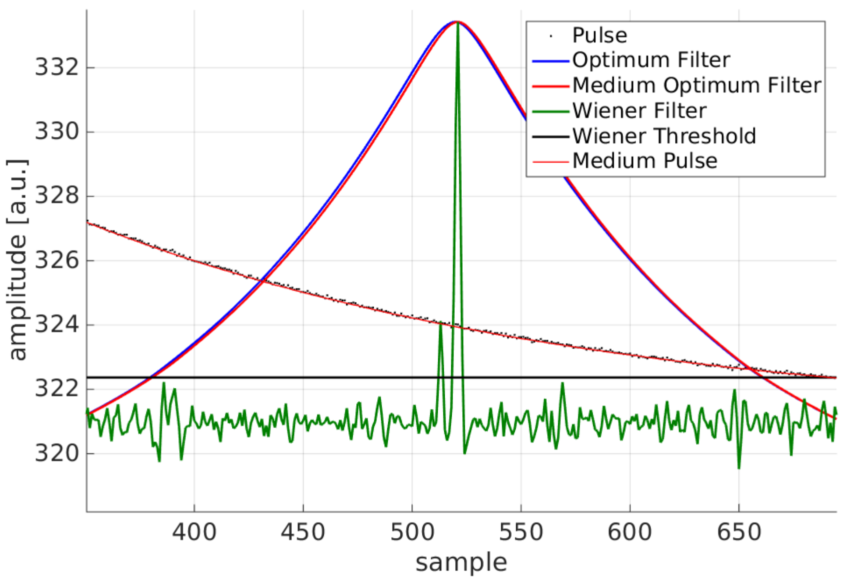
$$H_{OF}(\omega) \propto \frac{S^*(\omega)}{N(\omega)}$$

$$H_{WF}(\omega) \propto \frac{S^*(\omega)}{|S(\omega)|^2 + |N(\omega)|^2}$$

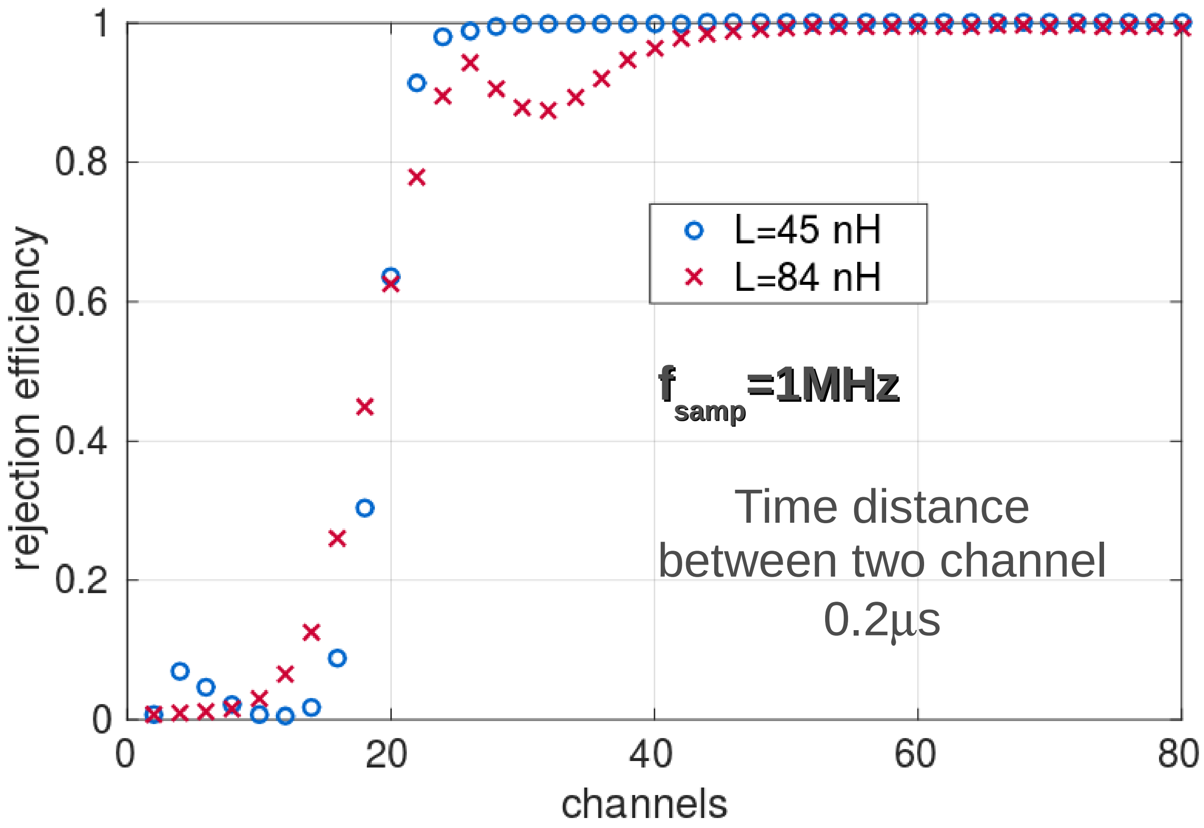


Trigger threshold is n-times the rms noise of the Wiener Filter.





Pile-up rejection efficiency

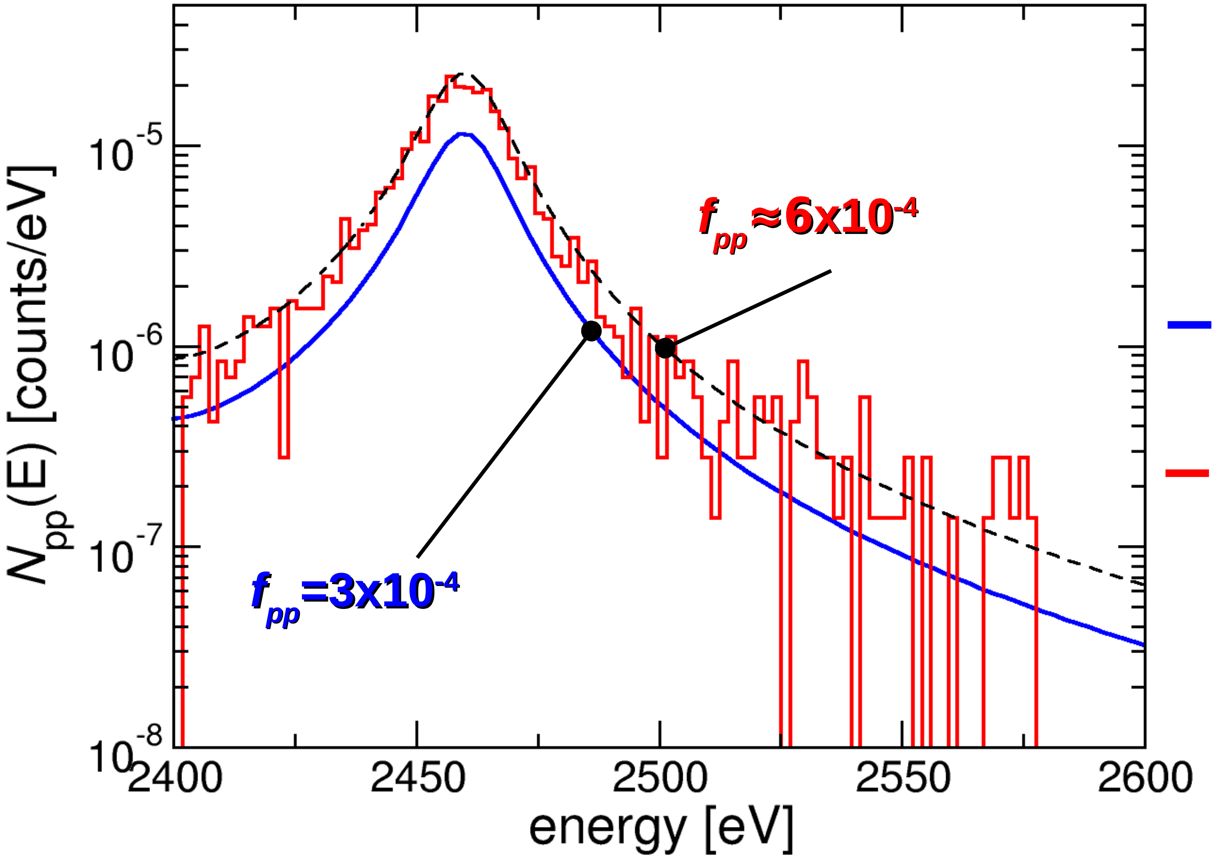


For lower sampling frequencies a more efficient trigger on the Wiener filter is required

f_{sam}	reclen	L	$\tau_{rise\ (10\text{-}90)}$	τ_{decay}	false +	τ_{eff}	ΔE
[MHz]	[sample]	[nH]	[us]	[us]	%	[us]	[eV]
1	1024	45	18	262	3	3.4	2.4
1	1024	84	31	225	4.5	3.7	2.4

Random events

Random pile-up events with time distance between 0 and 16 μs



— $f_{pp}\, N_{EC}(E) \otimes N_{EC}(E)$ with A = 300 Bq and τ_R = 1 μs

— **WF simulation** with f_{samp} = 1 MHz, $\tau_{rise} \approx$ 10 μs, and A = 300 Bq

→ estimated $\tau_{eff} \approx$ **3 μs**

Conclusion

- Detector design driven by readout bandwidth
- Pile-up is a strong source of background at the end-point
- Wiener filtering has proven to be a viable solution for pile-up identification
- We are running new simulations considering the two-hole de-excitation spectrum with Q=2833 eV
- We are working on a new trigger for the Wiener Filter