Impact of marine microseisms in the Mediterranean Sea on the performance of CUORE detectors

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Introduction

From CUORE to CUPID

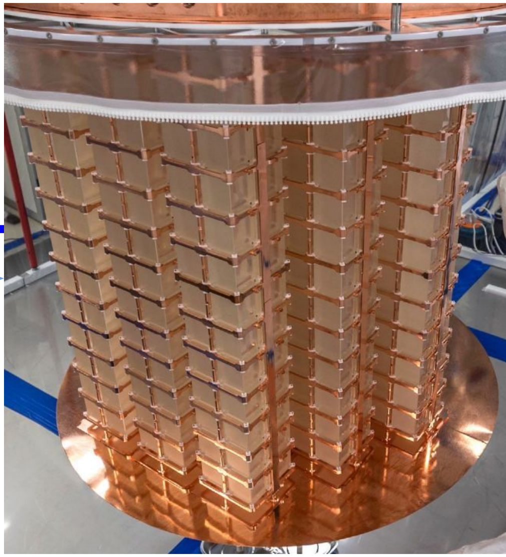
- CUORE:
  - search for $0\nu\beta\beta$ decay of ^{130}Te with 988 TeO_2 crystals operated at ∼15 mK as low-temperature calorimeters;
  - sensitivity to $0\nu\beta\beta$ decay:

$$S^{0\nu} \propto \sqrt{\frac{\boxed{MT}}{\boxed{B}\boxed{\Delta}}}$$

Exposure = ββ-isotope mass · measure time

Background index in the ROI: $Q_{\beta\beta}(^{130}Te)$ = 2528 keV

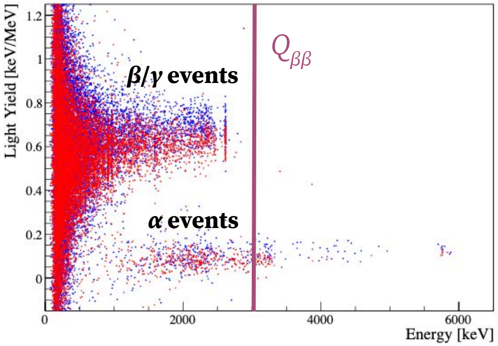
Energy resolution in the ROI

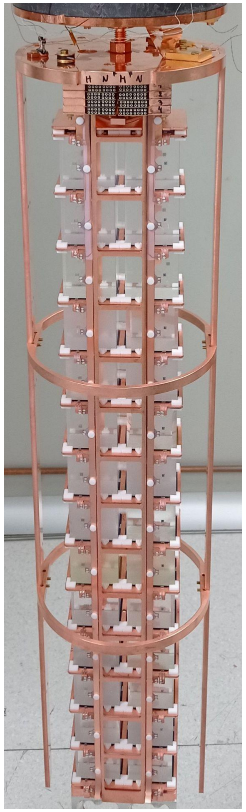


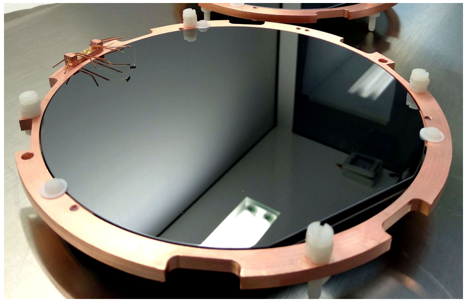
- Improve $S^{0\nu}$ by reducing the background index:
  - 90% of CUORE bkg in ROI is due to degraded-α

    ↓

    CUPID: α-rejection with heat-light double read-out from scintillating crystals;
  - **first CUPID full-tower**:
    - new structure to reduce contaminated material near detectors;
    - test performance of crystals and light detectors;
  - **SURFACE**:
    - novel bolometric detectors for surface α-contamination screening.



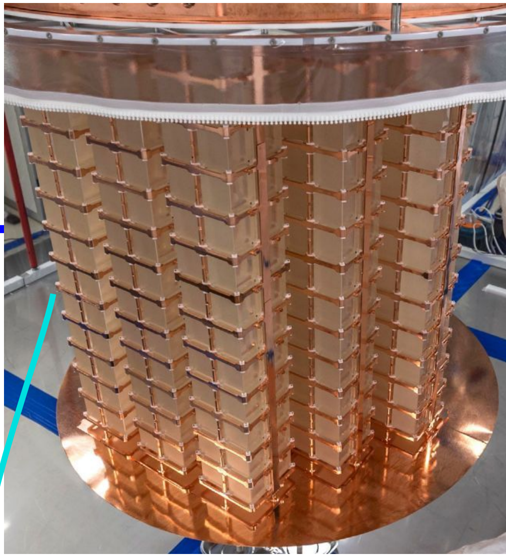


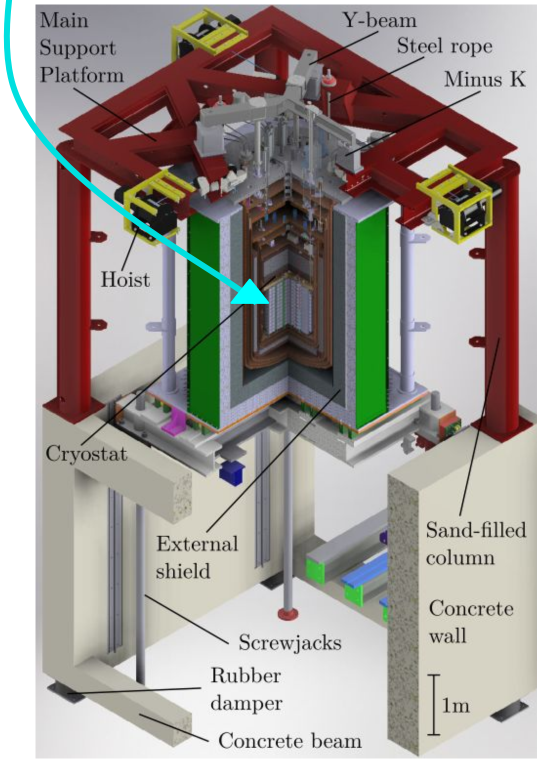


Introduction

Marine microseisms

- Can we improve $S^{0\nu}$ by improving the CUORE energy resolution?
- CUORE is enclosed in a complex suspension system
  to decouple detectors from external vibrations.
- Energy resolution can be affected by low-frequency noise ($\lesssim$ 2 Hz).
- **Marine microseisms** (faint seisms caused by sea waves motion
  and marine storms) **are a source of sub-Hz noise.**
- Study the impact of marine microseisms-induced vibrations on CUORE:
  1) impact on the low-frequency noise;
  2) impact on the baseline resolution during storms;
  3) correlation between CUORE energy resolution and
     seasonal modulation of Mediterranean Sea activity.





1) Study of low-frequency noise

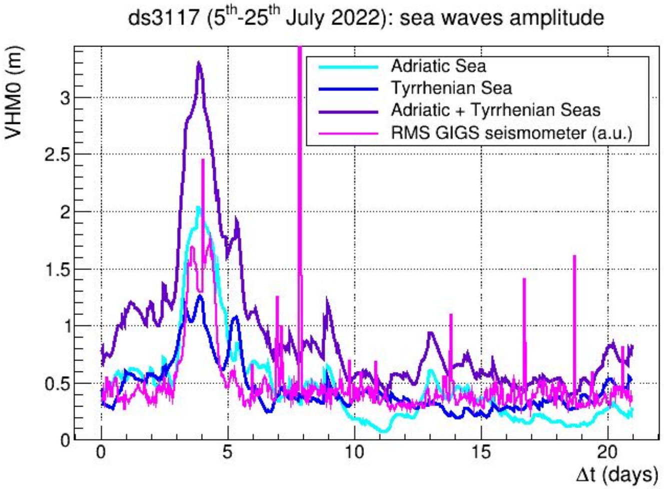
Copernicus and Seismometers

Data selection

- Multi-detector approach:
  - ➢ **Copernicus Marine Service**: E.U. program for marine monitoring (satellites + in-situ data)
  - ➢ **seismometers**: to detect and reject earthquakes;
  - ➢ **CUORE** low-temperature detectors.

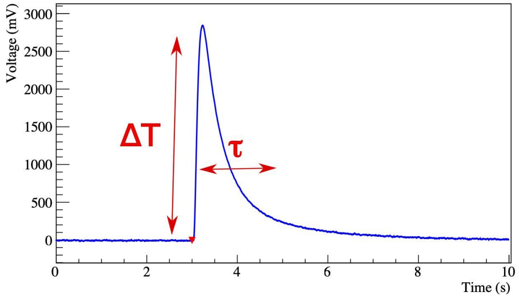
- Copernicus Marine Service:
  - ➢ select data in two regions of Adriatic and Tyrrhenian Seas;
  - ➢ in each sea region evaluate the hourly average of VHM0: (average of the highest ⅓ of recorded wave heights);
  - ➢ identify storms from the time profile of VHM0.

- Seismometers:
  - ➢ seismometers detect vibrational noise from both earthquakes and marine microseisms;
  - ➢ identify earthquakes and reject them from the analysis.

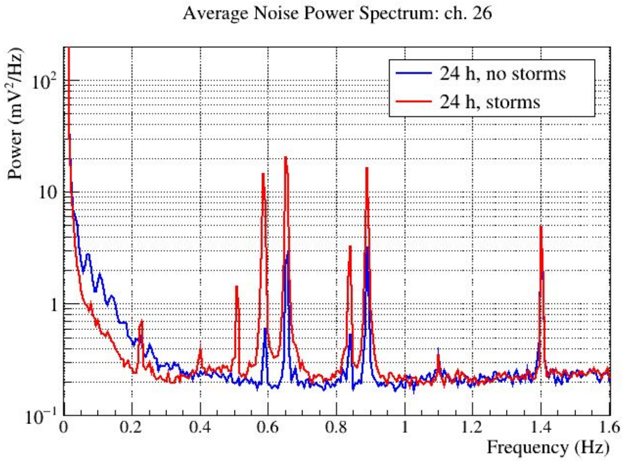


Bolometric analysis

Data selection and ANPS production



- CUORE:
  - ➢ increase events time window from (standard) 10 s to 60 s
    ↓
    higher sensitivity to low-frequency noise components after FFT;
  - ➢ data selection:
    - select noise events (no signals);
    - reject time periods with earthquakes and detectors instabilities;
  - ➢ for each detector, apply FFT to produce noise power spectra (ANPS) averaged on ~12 h of data;
  - ➢ low-frequency noise ($\nu < 1.4$ Hz):
    - peaks position is stable over time;
    - peaks position is stable along CUORE columns;
    - peaks amplitude changes over time
      ↓
      low-frequency noise is time-dependent.



Time evolution of low-frequency noise

Analysis

- For each detector, integrate the ANPS in several frequency intervals

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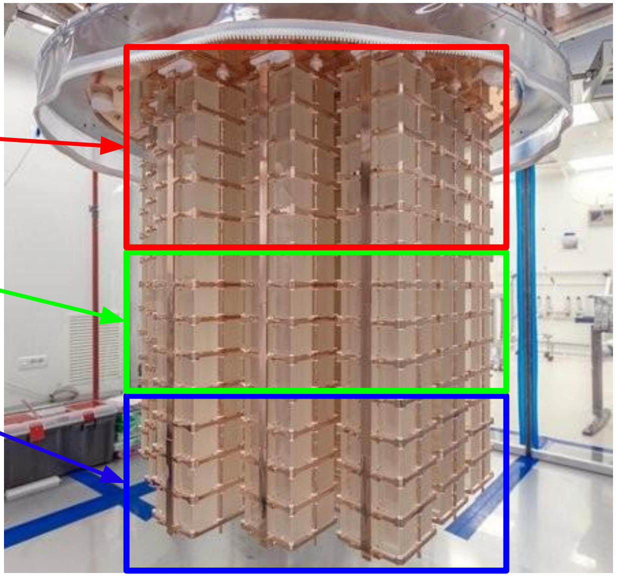
  evaluate the power of the noise P_ν for each frequency component ν.

- How does the low-frequency noise change in time w.r.t. the marine conditions?
  - ➢ for each detector and for each frequency component ν, evaluate $R_\nu = \frac{P_{i,\nu}}{P_{ref,\nu}}$

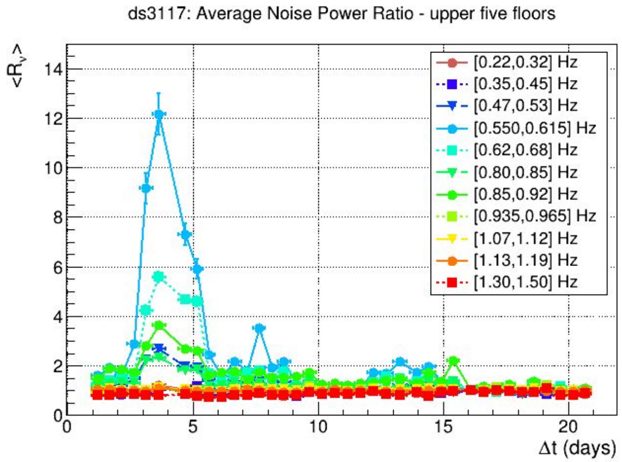
    as the the noise power ratio between each 12 h-time period and a reference period with quiet marine condition;
  - ➢ define three geometric subsets of CUORE:
    - upper five floors;
    - central four floors;
    - lower four floors.

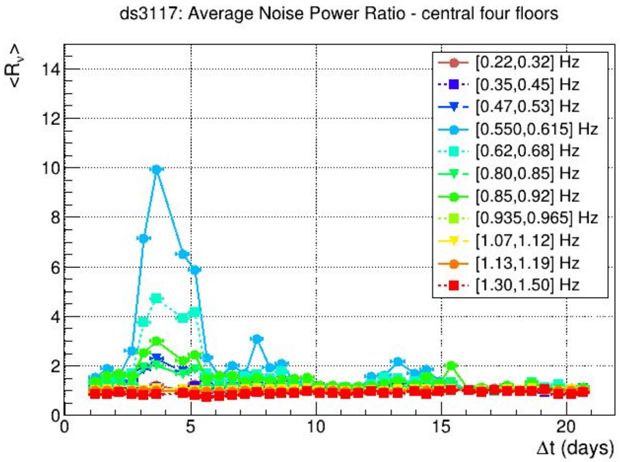


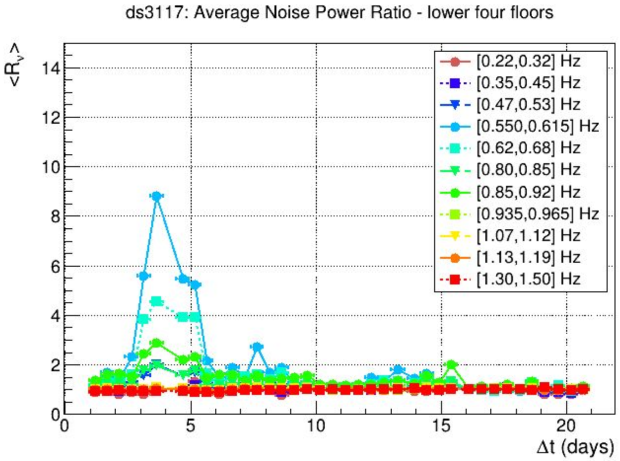
Time evolution of low-frequency noise

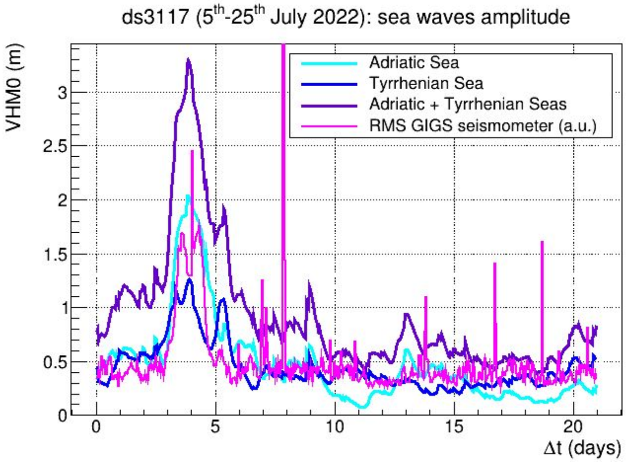
Results

- Time evolution of R_ν, averaged on each of the three CUORE geometric subsets:









- Comments:
  - ➢ **CUORE low-frequency noise increases during a storm identified by Copernicus.**
  - ➢ noise components at ~0.6 Hz vary the most over time;
  - ➢ noise components ≳ 0.9 Hz are mostly unaffected.

Noise sensitivity to marine microseisms

Analysis

- Goal: for each frequency component and geometric subset, evaluate the sensitivity of noise power P_v to marine microseisms.

- Sea waves intensity:
  - ➢ integral over each 12 h-time period of the VHM0 time profiles of Adriatic and Tyrrhenian Seas:

$$I_S = \int_{t_i}^{t_f} [VHM0_A(t) + VHM0_T(t)]dt$$

- For each frequency - geometric subset configuration, **<P_v> and I_S are linearly correlated**

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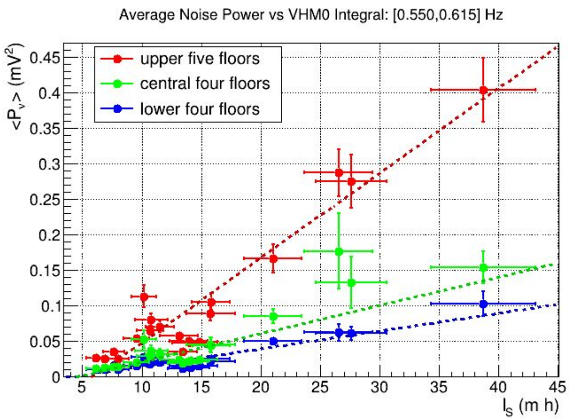
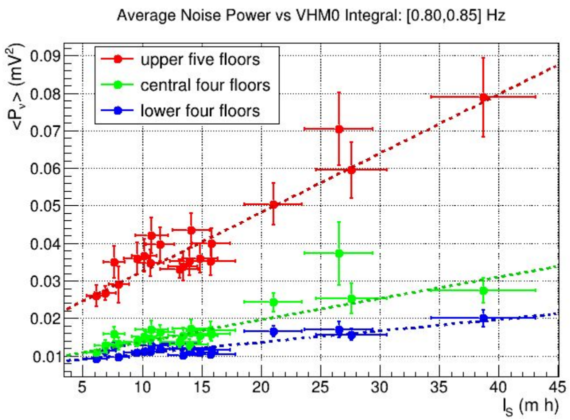
  - ➢ the relative angular coefficient **$m_v^{rel} = m_v / \min(<P_v>)$ quantify the sensitivity of the noise power of a frequency component w.r.t. changes of sea wave intensity**.

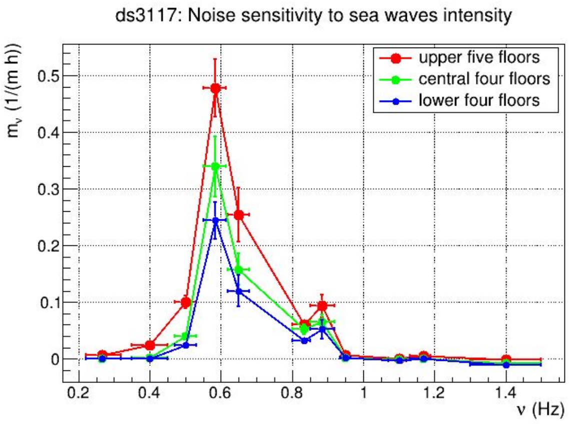




Noise sensitivity to marine microseisms

Results

- For each geometric subset, compare the sensitivity m_ν^{rel} for different frequency components of the noise:
  - ➢ the noise sensitivity to marine microseisms decreases along the CUORE towers from top floors to bottom floors;
  - ➢ noise components above ~0.9 Hz are mostly unaffected;
  - ➢ **the most sensitive noise components to marine microseisms-induced noise are at ~0.6 Hz**



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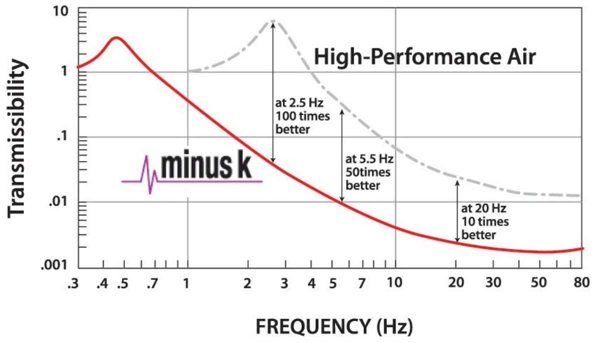
hypothesis: marine microseisms-induced vibrations excite a resonance frequency of the CUORE suspension system at ~0.6 Hz, enhancing the corresponding frequency components in the detectors noise.



2) Study of baseline resolution during storms

Baseline resolution and marine microseisms

Correlations

- Baseline resolution: contribution to the detector energy resolution due to noise-induced baseline fluctuations.

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  Is the baseline resolution of CUORE detectors affected by marine microseisms-induced noise?

- CUORE is stably taking data since 2019

  ↓

  select six stormy time periods over two years (from September 2020 to November 2022).

- For each CUORE geometric subset, evaluate average baseline resolution <FWHM$_{\text{baseline}}$> over 12 h-time intervals for each stormy period.

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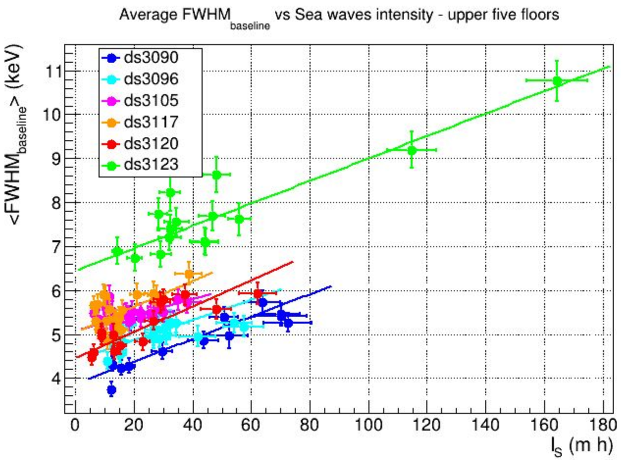
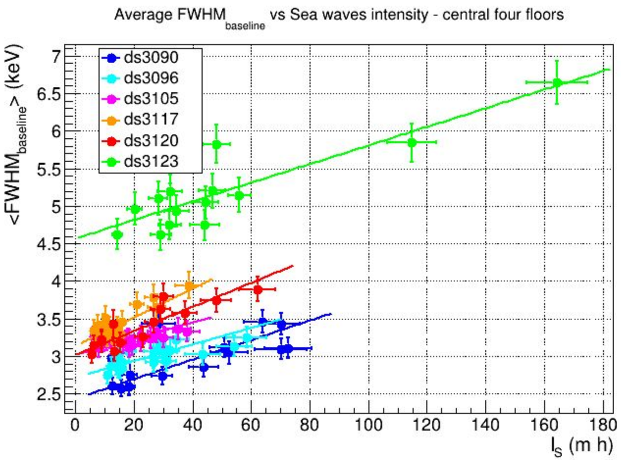
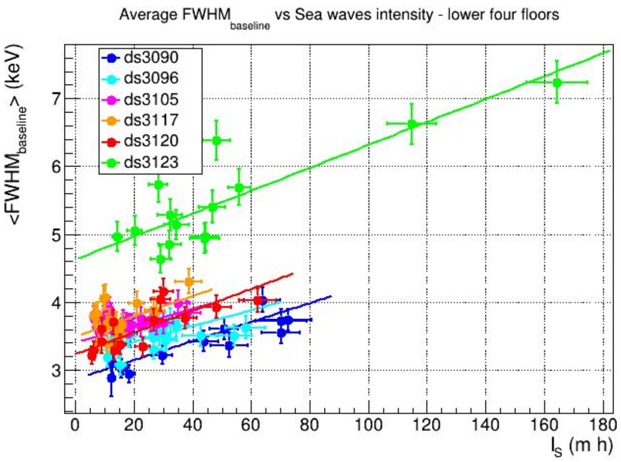
  <FWHM$_{\text{baseline}}$> and sea waves intensity I_s are linearly correlated.



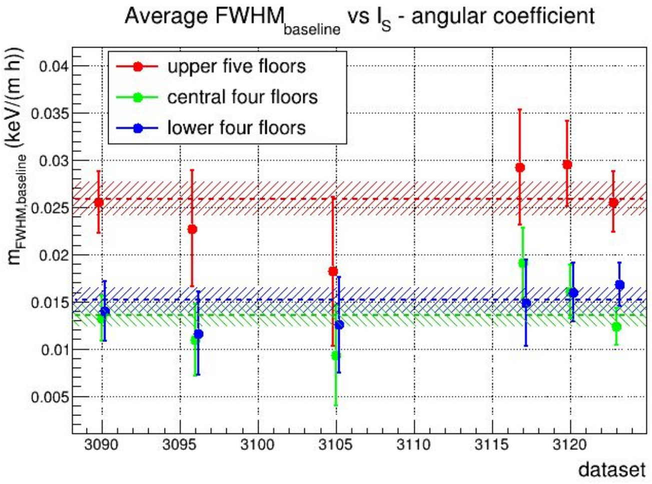




Baseline resolution and marine microseisms

Results

- **The angular coefficient $m_{baseline}$ quantify the $\langle FWHM_{baseline} \rangle$ sensitivity w.r.t changes of sea waves intensity**:
  - the baseline resolution is affected by storms;
  - within each geometric subset, the baseline sensitivity is stable over two years of data taking;
  - **the baseline of detectors in the upper five floors is the most sensitive to marine microseisms-induced noise.**



Geometric subset	<m> (keV/(m h))
Upper 5 floors	**0.026 ± 0.002**
Central 4 floors	**0.014 ± 0.001**
Lower 4 floors	**0.015 ± 0.001**

3) Seasonal modulation of energy resolution

Seasonal modulation

Analysis

- The Mediterranean Sea shows a seasonal modulated activity, being more quiet during summer and more stormy during winter.

- CUORE is stably taking data since 2019

  ↓

  is the baseline/peaks energy resolution of CUORE affected by the marine seasonal modulation?

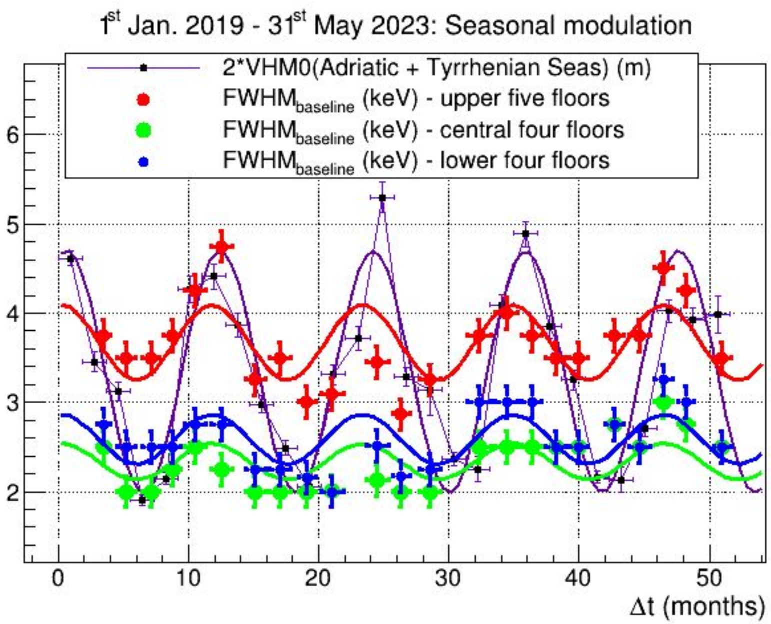
- Analysis procedure:
  - ➢ 4 yr of CUORE data (2 t · yr exposure): April 2019 → April 2023;
  - ➢ evaluate baseline/peaks resolution for each dataset (∼2 months) and each geometric subset;
  - ➢ perform sinusoidal fit of Copernicus data (<VHM0> over 2 months):

$$f(t) = A\sin\left(\frac{2\pi}{T}t + \phi\right) + c$$

  - ➢ perform simultaneous fit of CUORE data (T, ϕ in common):

$$\begin{cases} \mathcal{L} = \prod_{j,i} \frac{1}{\sqrt{2\pi}\sigma_{j,i}} \exp\left[-\frac{(y_{j,i}-\mu_{j,i})^2}{2\sigma_{j,i}^2}\right] \\ \mu_{j,i} = \frac{1}{\Delta t_{j,i}} \int_{t_{j,i}^{in}}^{t_{j,i}^{in}+\Delta t_{j,i}} \left[A_j \sin\left(\frac{2\pi}{T} + \phi\right) + c_j\right] dt \end{cases}$$

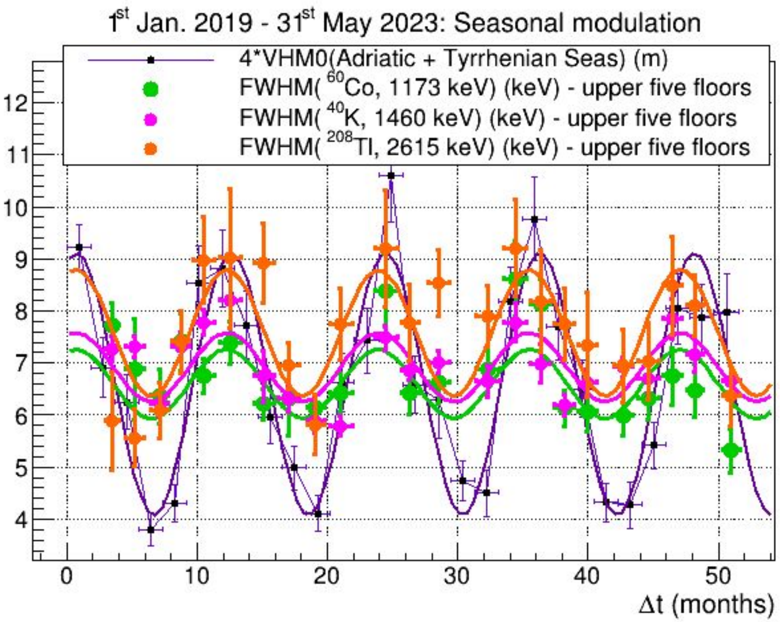
Seasonal modulation of baseline resolution



	Sea	**upper 5 floors**	**central 4 floors**	**lower 4 floors**
A	(0.63 ± 0.05) m	(0.42 ± 0.06) keV	(0.20 ± 0.06) keV	(0.28 ± 0.06) keV
T	**(11.8 ± 0.2) months**	**(11.6 ± 0.2) months**		
φ	**1.2 ± 0.2**	**1.4 ± 0.2**		
c	(1.65 ± 0.04) m	(3.67 ± 0.04) keV	(2.34 ± 0.04) keV	(2.59 ± 0.04) keV
χ^2_{red}	0.73	1.16		

- Comments:
  - ➢ both Copernicus and CUORE data show seasonal modulation, in phase within each others: minimum in summer-time, maximum in winter-time;
  - ➢ ∼1 yr oscillation periods evaluated from Copernicus and CUORE data are consistent;
  - ➢ better FWHM$_{baseline}$ w.r.t. sinusoidal modulation in Δt = 13 → 28 months (Febr. 2020→April 2021) (due to different suspension system configuration?)
  - ➢ baseline in upper five floors is factor ∼1.5-2 more sensitive w.r.t. central/lower floors.

Seasonal modulation of baseline resolution



	Sea	^{208}Tl (2615 keV)	^{40}K (1460 keV)	^{60}Co (1173 keV)
A	(0.63 ± 0.05) m	**(1.21 ± 0.23) keV**	(0.66 ± 0.07) keV	(0.66 ± 0.14) keV
T	**(11.8 ± 0.2) months**	**(11.6 ± 0.1) months**		
ϕ	**1.2 ± 0.2**	**1.2 ± 0.1**		
c	(1.65 ± 0.04) m	**(7.58 ± 0.15) keV**	(6.92 ± 0.05) keV	(6.60 ± 0.09) keV
χ^2_{red}	0.73	1.97		

- Comments:
  - ➢ both Copernicus and CUORE data show seasonal modulation, in phase within each others: minimum in summer-time, maximum in winter-time;
  - ➢ ~1 yr oscillation periods evaluated from Copernicus and CUORE data are consistent;
  - ➢ **FWHM(^{208}Tl, 2615 keV):**
    - ■ **average value ~7.6 keV;**
    - ■ **seasonal oscillation ~3 keV (summer minumum ~6 keV, winter maximum ~9 keV)**

↓

~50% FWHM summer-winter variation → same effect at $0\nu\beta\beta$ decay ROI = 2528 keV.

Conclusions

- CUORE detectors are sensitive to the vibrational noise induced by marine microseisms in the Mediterranean Sea:
  - ➢ excitation of a ∼0.6 Hz resonance in the CUORE suspension system;
  - ➢ sensitive to both transient storms and seasonal modulation of sea activity;
  - ➢ FWHM(^{208}Tl, 2615 keV) varies by 50% from summer to winter

↓

affect the sensitivity to $0\nu\beta\beta$ decay at $Q_{\beta\beta}(^{130}\text{Te}) = 2528$ keV

$$S^{0\nu} \propto \sqrt{\frac{MT}{B\boxed{\Delta}}} \rightarrow$$

Energy resolution in the ROI

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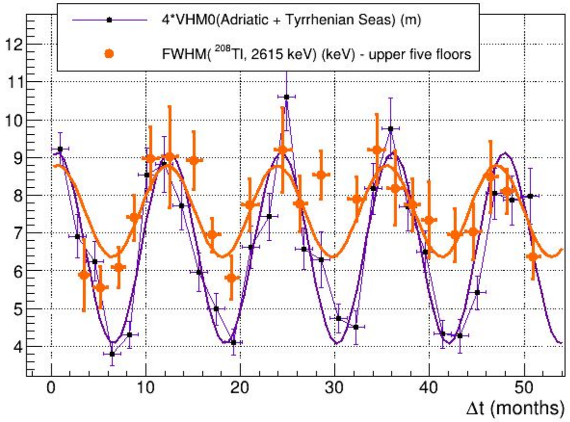
improvements in decoupling/suspension systems for CUPID.

1st Jan. 2019 - 31st May 2023: Seasonal modulation



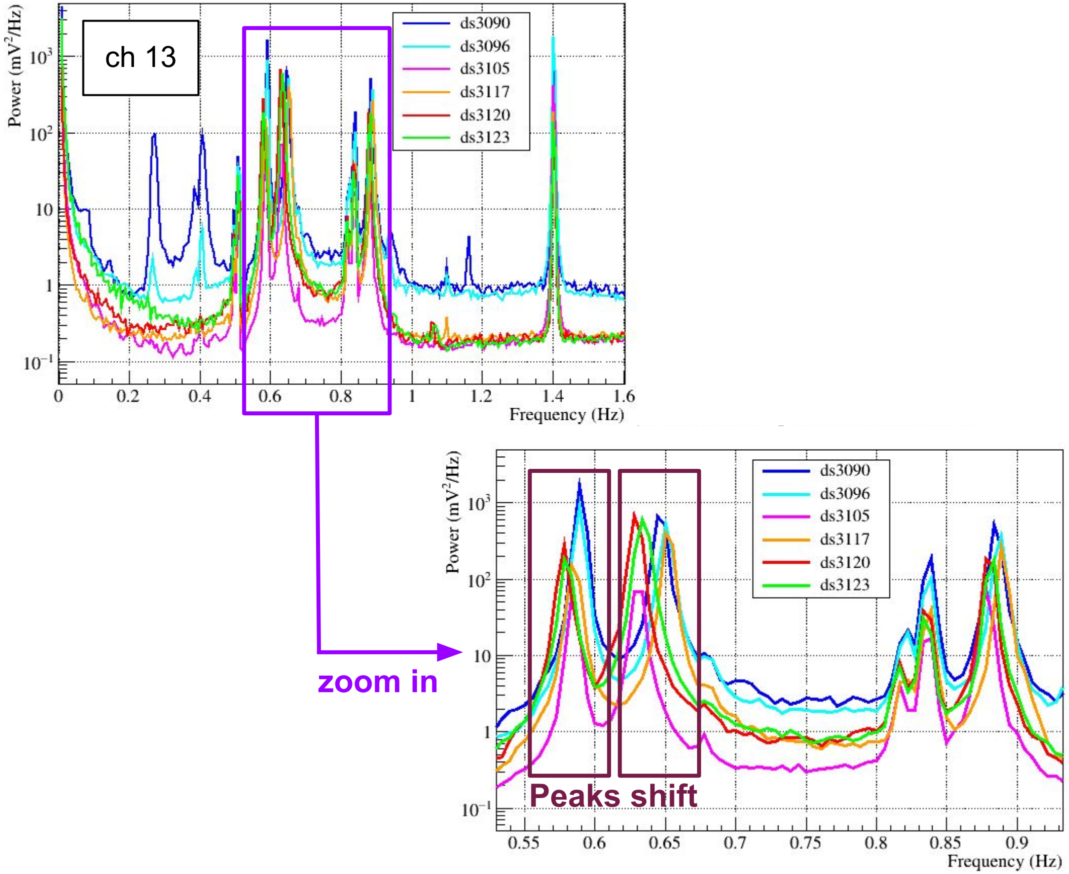
Thanks for your attention!

Backup slides

Low-frequency noise

Shift of noise peaks

- By comparing ANPS of different datasets:
  - the **0.6 Hz-doublet shifts between different datasets**;
  - the shift of 0.6 Hz-doublet is consistent for all ds;
  - the position of the other peaks is not changed.



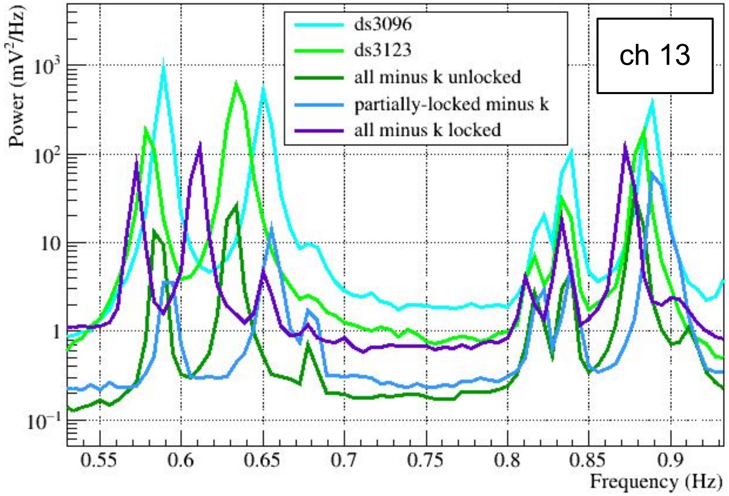
Peak center (Hz) (ds3090-3096-3117) (ds3105-3120-3123)	**Integration range (Hz)** (ds3090-3096-3117) (ds3105-3120-3123)
0.267	[0.22, 0.32]
0.400	[0.35, 0.45]
0.500	[0.47, 0.53]
0.588 → 0.580	[0.550, 0.615] → [0.54, 0.60]
0.650 → 0.630	[0.62, 0.68] → [0.60, 0.67]
0.835	[0.80, 0.85]
0.885	[0.85, 0.92]
0.950	[0.935, 0.965]
1.10 → 1.05	[1.07, 1.12] → [1.03, 1.09]
1.17	[1.13, 1.19]
1.40 (PT-induced)	[1.30, 1.50]

Low-frequency noise

Tests on minus-k

- Hypothesis: shift of 0.6 Hz-doublet due to change of minus-k suspension configuration.

- Compare selected data with reference runs of known minus-k config:
  - ➢ bkg run acquired after unlocking minus-k in August 2021;
  - ➢ test run with partially-locked minus-k (June 2022);
  - ➢ test run with all the three minus-k locked (June 2022).



- Results:
  - ➢ ds3090-3096-3117: minus-k partially-locked (1/3);
  - ➢ ds3105-3120-3123: all three minus-k unlocked;
  - ➢ starting from unlocked minus-k, locking one minus-k causes the 0.6 Hz-peak doublet to shift toward higher frequencies;
  - ➢ starting from unlocked minus-k, locking all minus-k causes the 0.6 Hz and 0.8 Hz-peak doublets to shift toward lower frequencies.

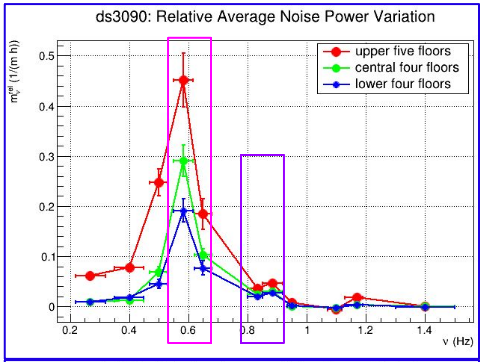
↓

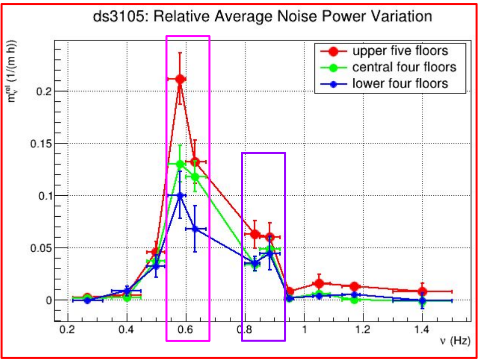
The comparison with reference runs allows to reconstruct the minus-k config along datasets.

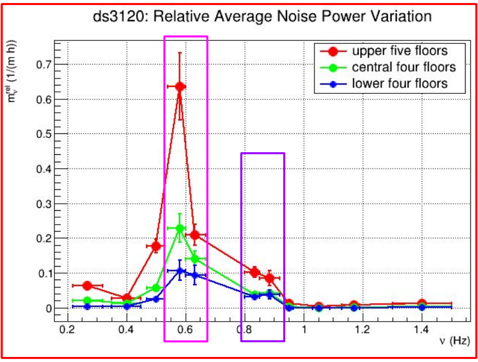
Noise sensitivity to marine microseisms

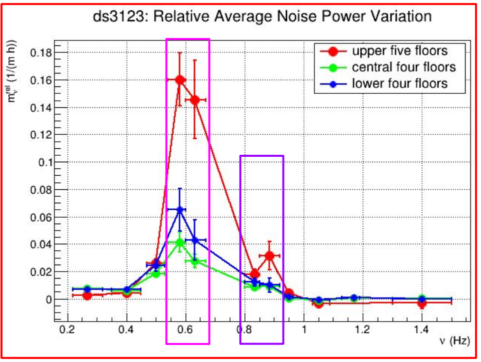
Compare different datasets

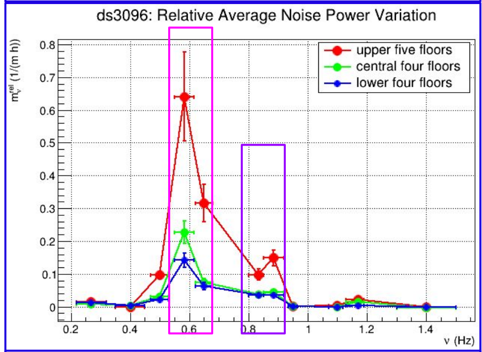
- Compare $m_\nu^{rel} = m_\nu / \min(<P_\nu>)$ vs frequency for each ds - frequency - geometric subset

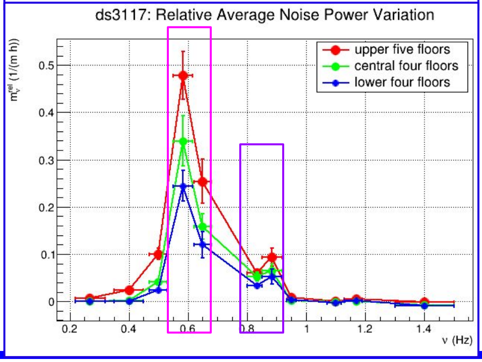

ds3090: Relative Average Noise Power Variation


ds3105: Relative Average Noise Power Variation


ds3120: Relative Average Noise Power Variation


ds3123: Relative Average Noise Power Variation


ds3096: Relative Average Noise Power Variation


ds3117: Relative Average Noise Power Variation

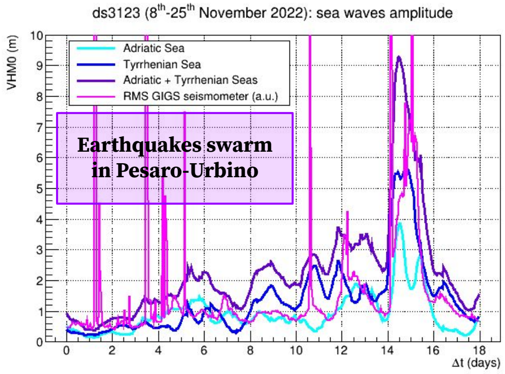
Partially-locked minus-k

Unlocked minus-k.

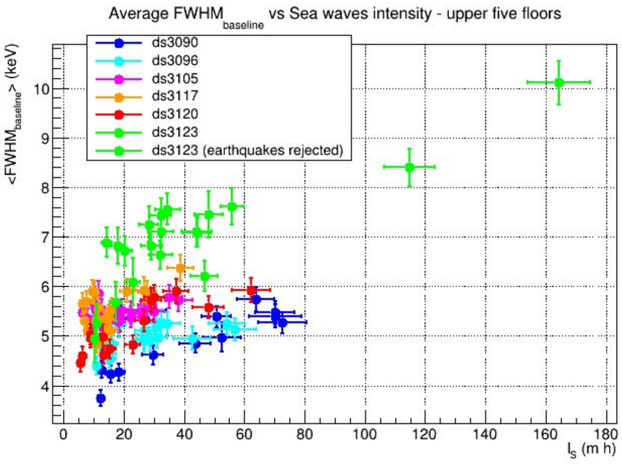
- Comments:
    - ➢ the **sensitivity of noise power variations w.r.t. sea waves intensity decreases along the towers from top to bottom**, and is strongly damped from upper five floors to central-lower floors;
    - ➢ the **0.6 Hz-doublet is the most sensitive to wave intensity variations**: the **first peak is more sensitive** w.r.t. the second peak;
    - ➢ the two peaks of 0.8 Hz-doublet are mostly equally sensitive;
    - ➢ peaks ≳ 0.935 Hz are mostly unaffected (including the 1.4 Hz peak);
    - ➢ **hints for identifying the 0.6 Hz as the CUORE vibration mode.**

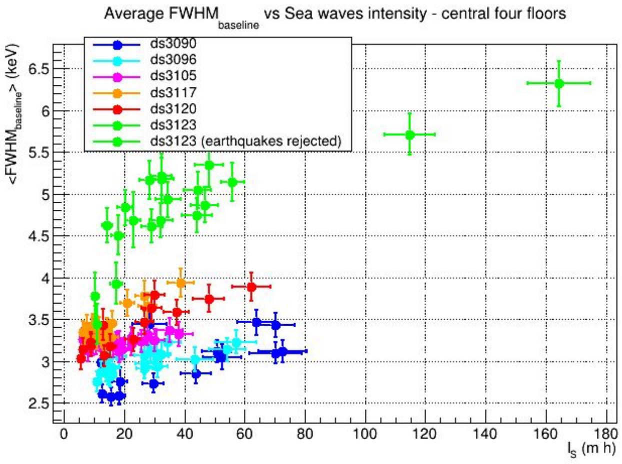
Baseline resolution vs Sea waves intensity

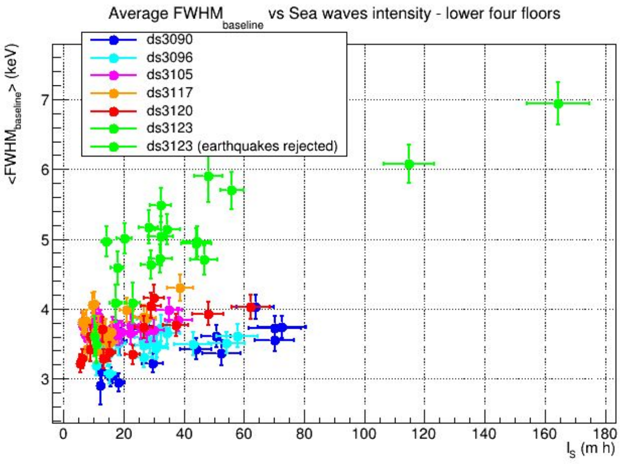
ds3123



- Why is $\langle FWHM_{baseline} \rangle$ systematically higher in ds3123?
- Plot $\langle FWHM_{baseline} \rangle$ vs sea waves intensity:
  - ➢ include runs in ds3123 during earthquakes swarm;
  - ➢ for runs in ds3123, add time cuts to reject earthquakes.







- Comments:
  - ➢ $\langle FWHM_{baseline} \rangle$ drops for runs during earthquakes swarm (at low I_S)

    ↓

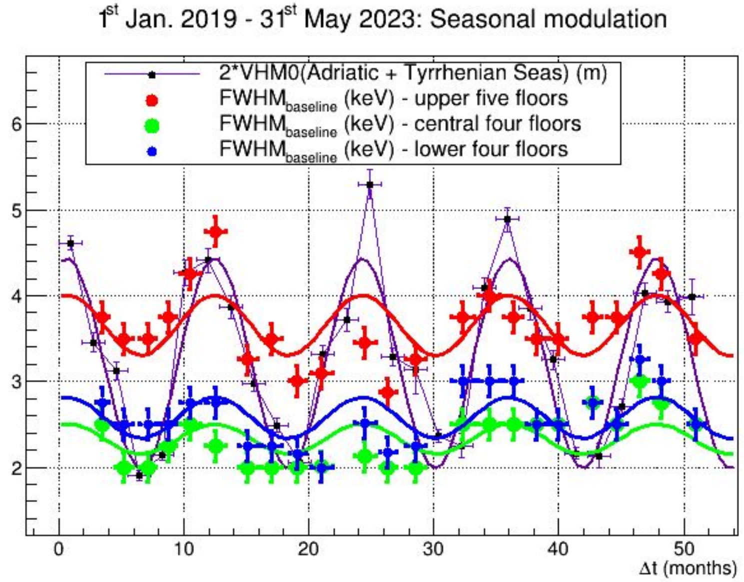
    compatible with ds3105-3117-3120 (@ $T_{base} \sim 15$ mK);
  - ➢ runs after earthquakes swarm still have a systematically higher $\langle FWHM_{baseline} \rangle$

    ↓

    additional source of noise not rejected with time cuts → low-intensity seismic activity?

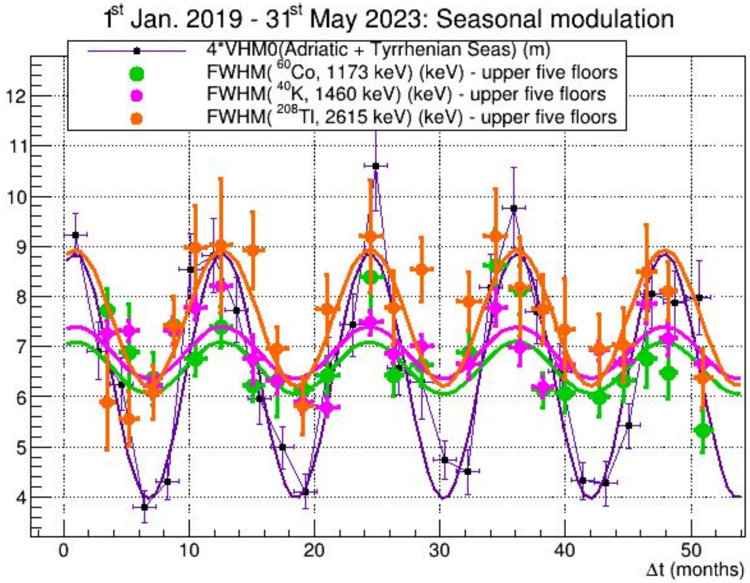
Seasonal modulation of the energy resolution

Global fit of CUORE and Copernicus data



1st Jan. 2019 - 31st May 2023: Seasonal modulation

	Sea	**upper 5 floors**	**central 4 floors**	**lower 4 floors**
A	(0.61 ± 0.06) m	(0.35 ± 0.06) keV	(0.17 ± 0.06) keV	(0.24 ± 0.06) keV
T	**(11.8 ± 0.1) months**			
Φ	**1.2 ± 0.1**			
c	(1.60 ± 0.03) m	(3.66 ± 0.04) keV	(2.33 ± 0.04) keV	(2.58 ± 0.04) keV
χ^2_{red}	1.05			

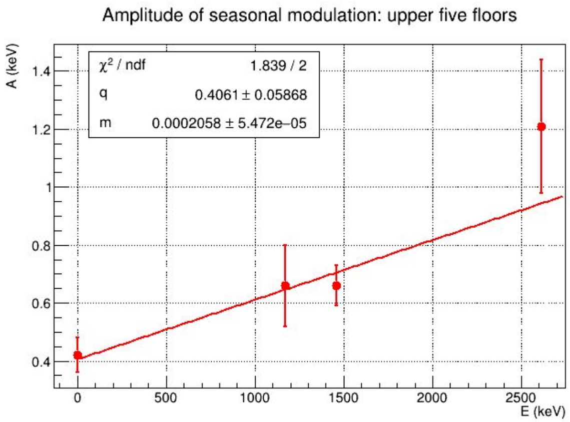


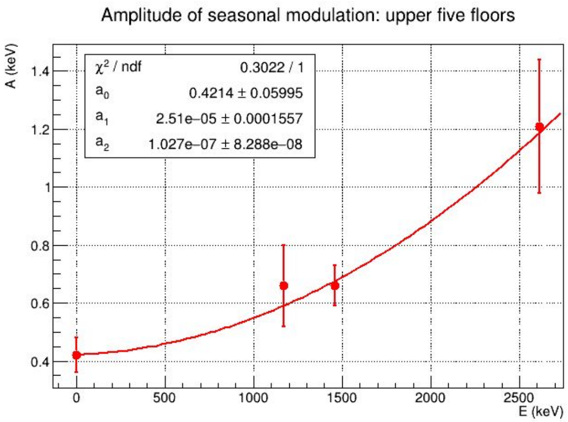
1st Jan. 2019 - 31st May 2023: Seasonal modulation

	Sea	**^{208}Tl (2615 keV)**	**^{40}K (1460 keV)**	**^{60}Co (1173 keV)**
A	(0.61 ± 0.03) m	**(1.38 ± 0.09) keV**	(0.51 ± 0.07) keV	(0.52 ± 0.14) keV
T	**(11.7 ± 0.1) months**			
Φ	**1.1 ± 0.1**			
c	(1.61 ± 0.03) m	**(7.57 ± 0.14) keV**	(6.88 ± 0.05) keV	(6.58 ± 0.09) keV
χ^2_{red}	1.94			

Amplitude of seasonal modulation

- The amplitude of the seasonal modulation appears to be energy-dependent.
  - ➢ plot the oscillation amplitude A, from the simultaneous fit of CUORE upper five floors data, as a function of the energy of baseline (0 keV) and physics peaks (^{60}Co, ^{40}K, ^{208}Tl);
  - ➢ perform linear and quadratic fit:





- Why the seasonal modulation amplitude is energy-dependent? Still unknown.

Seasonal variation of $0\nu\beta\beta$ decay sensitivity

- CUORE $0\nu\beta\beta$ decay sensitivity can vary due to the seasonal modulation of the sea activity:

$$S^{0\nu} \propto \sqrt{\frac{MT}{B\boxed{\Delta}}}$$

Energy resolution in the ROI (affected by seasonal modulation of marine activity)

- CUORE upper five floors are more sensitive to season modulation

↓

$S^{0\nu}$ can vary between two extreme cases:

1) all the detectors are equally sensitive to sea activity → same energy resolution modulation;
2) central-lower floors are unaffected by sea activity → their resolution is constant over time;

- **Case 1:** equally-sensitive detectors
  - ➢ ^{208}Tl resolution at summer minimum sea activity: $\mathrm{FWHM}_S(^{208}\mathrm{Tl}) \sim 6$ keV;
  - ➢ ^{208}Tl resolution at winter maximum sea activity: $\mathrm{FWHM}_W(^{208}\mathrm{Tl}) \sim 9$ keV;

Seasonal variation of $0\nu\beta\beta$ decay sensitivity

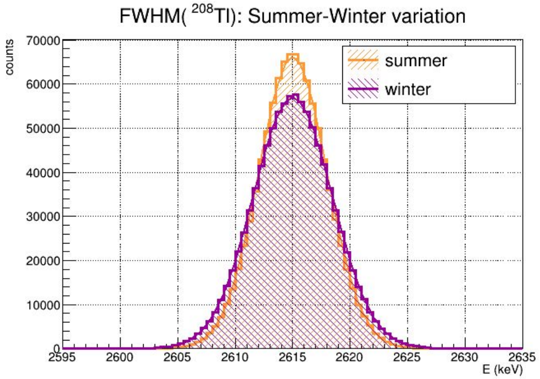
- **Case 2:** central-lower floors detectors unaffected
  - ➢ perform 5000 MC to estimate ^{208}Tl resolution in summer and winter:
    - ■ for each detector, generate 1000 events at ^{208}Tl peak with gaussian distribution;
    - ■ for upper floors: $\mathrm{FWHM_S}^{\mathrm{MC}}(^{208}\mathrm{Tl}) \sim 6$ keV , $\mathrm{FWHM_W}^{\mathrm{MC}}(^{208}\mathrm{Tl}) \sim 9$ keV;
    - ■ for central-lower floors: $\mathrm{FWHM_S}^{\mathrm{MC}}(^{208}\mathrm{Tl}) = \mathrm{FWHM_W}^{\mathrm{MC}}(^{208}\mathrm{Tl}) \sim 7.6$ keV;
  - ➢ for each MC, sum the summer/winter energy distributions

    ↓

    evaluate the average all-floors energy resolution in summer/winter among all the MC:

    $\mathrm{FWHM_S}^{\mathrm{MC}}(^{208}\mathrm{Tl}) \sim 7.02$ keV

    $\mathrm{FWHM_W}^{\mathrm{MC}}(^{208}\mathrm{Tl}) \sim 8.17$ keV



- Scale the energy resolutions from E(^{208}Tl) to $Q_{\beta\beta}(^{130}\mathrm{Te})$:
  - ➢ **Case 1:** $\mathrm{FWHM_S}(Q_{\beta\beta}) \sim 5.80$ keV , $\mathrm{FWHM_W}(Q_{\beta\beta}) \sim 8.70$ keV;
  - ➢ **Case 2:** $\mathrm{FWHM_S}^{\mathrm{MC}}(^{208}\mathrm{Tl}) \sim 6.79$ keV , $\mathrm{FWHM_W}^{\mathrm{MC}}(^{208}\mathrm{Tl}) \sim 7.90$ keV.

- Summer-winter $0\nu\beta\beta$ decay sensitivity variation: $$\sqrt{\frac{FWHM_W^{MC}(Q_{\beta\beta})}{FWHM_S^{MC}(Q_{\beta\beta})}} - 1 < \frac{S_S^{0\nu} - S_W^{0\nu}}{S_W^{0\nu}} < \sqrt{\frac{FWHM_W(Q_{\beta\beta})}{FWHM_S(Q_{\beta\beta})}} - 1$$

$$7.9\% < \frac{S_S^{0\nu} - S_W^{0\nu}}{S_W^{0\nu}} < 22.4\%$$

Mechanical fuses

- Mechanical fuses:
  - ➢ beam elements connecting CUORE concrete walls with ground, installed to block oscillation of the structure;
  - ➢ supposed to jump away from their housing in case of high-intensity earthquakes, isolating the structure of CUORE from the environment for structural safety;
  - ➢ they are probably the main mechanical link between the CUORE structure and the ground → → they can possibly be a major path for external vibrations to propagate to the CUORE structure and detectors.