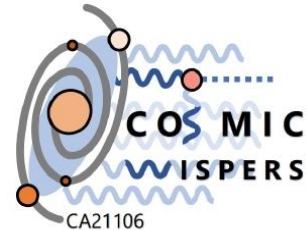# The Daily Modulations And Broadband Strategy In Axion Searches:
An Application With CAST-CAPP Detector

Kaan Özbozduman & Marios Maroudas
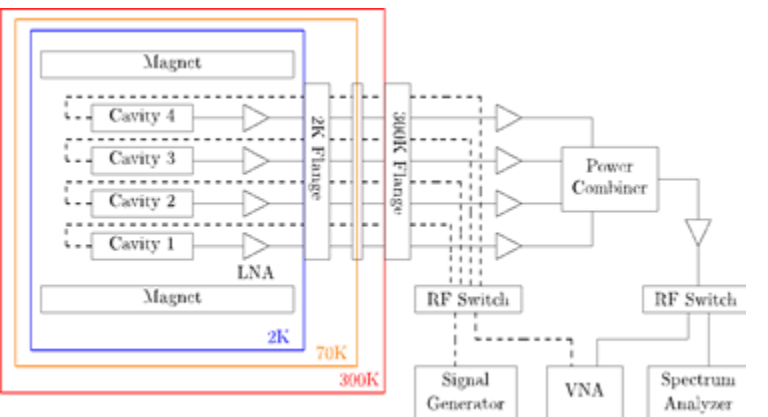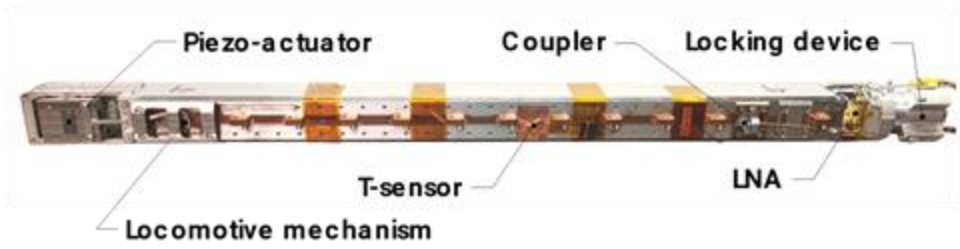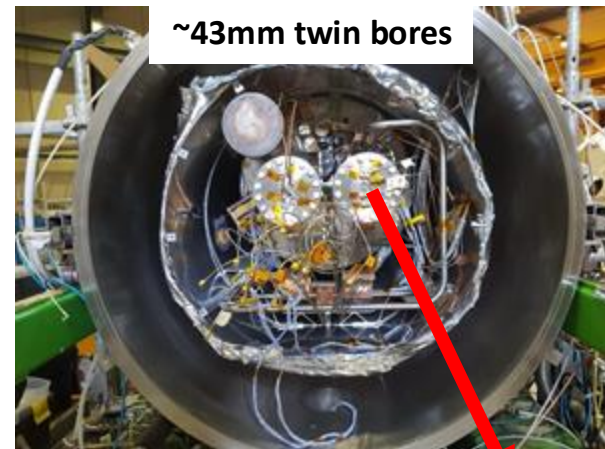on behalf of the CAST Collaboration
Sep 5, 2024

https://arxiv.org/abs/2405.10972

2nd General Meeting of COST Action COSMIC WISPers (CA21106)

CAST-CAPP Detector

Four identical stainless steel **tunable** cavities electroplated with ~30μm of copper installed in one of the two twin bores of CAST magnet with the split plane parallel to the magnetic field.
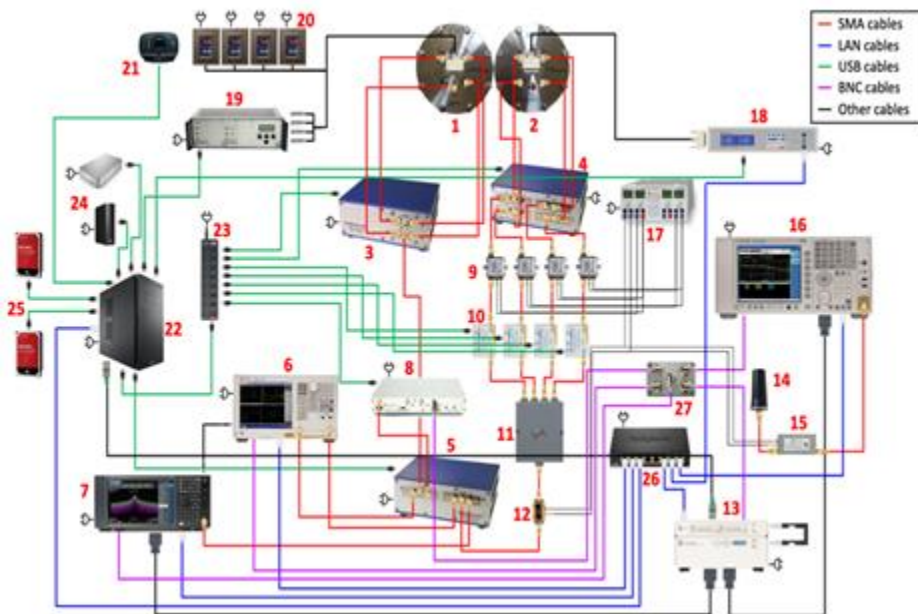

~43mm twin bores
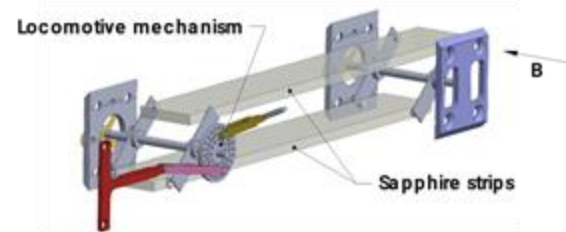
CAST-CAPP

<u>Tuning mechanism</u>: 2 dielectric sapphire bars symmetrically placed parallel to the longitudinal sides, moving simultaneously towards the center and activated by a piezoelectric motor.

CAST-CAPP Data Acquisition

- 1-min measurements
- Bandwidth = 5 MHz
- Tuning step size = 200 kHz
- Size = ~ 3 GB / file !!

QUALITY CHECKS:

Main source→Vibrations

| Nr.	Parameters	Criteria
1	Frequency stability	$\Delta \nu_0 < 100\,\mathrm{kHz}$
2	Amplitude variation	$\Delta A_0 < 3\,\mathrm{dB}$
3	Quality factor	$10^3 < Q_L < 4 \times 10^4$
4	Quality factor shift	$\Delta Q_L < 7 \times 10^3$
5	Temperature variation	$\Delta T_{\mathrm{cav}} < 3\,\mathrm{K}$
6	Temperature	$1\,\mathrm{K} < T_{\mathrm{cav}} < 273\,\mathrm{K}$
7	Magnetic field variation	$\Delta \vec{B} < 0.1\,\mathrm{T}$
8	Frequency mismatch	$< 20\,\mathrm{kHz}$ (before) & $< 80\,\mathrm{kHz}$ (after)
9	Amplitude mismatch	$< 1\,\mathrm{dB}$
10	Temperature mismatch	$< 3\,\mathrm{K}$

RESULTS:

- Data-taking time: 4124 h (172 d)
- Frequency range: 660.15 MHz
- Axion Masses: 4.77 - 5.43 GHz
- Data size: ~ 650 TB !!

CAST-CAPP Results → Alternative analyses

- Total data-taking time: 4124 h (172 d)
- Data size: ~ 650 TB
- Frequency range: 660.15 MHz
- Axion masses: 19.74 µeV - 22.47 µeV
- Present sensitivity: $g_{a\gamma\gamma} = 8 \times 10^{-14}\,GeV^{-1}$
- Confidence level: 90 %
- Total uncertainty: 7.4%

New analysis options:
1. Dark photons
2. Transient events (high resolution time series measurements)
3. AQN daily modulations (24h, Low Q, fixed frequency measurements, temperature isolation of complete datataking chain.)
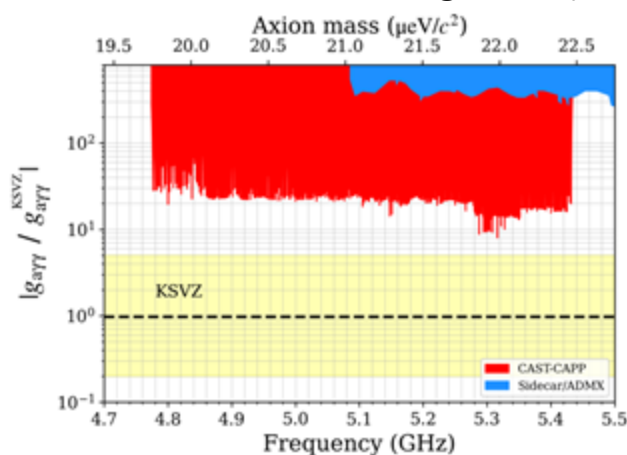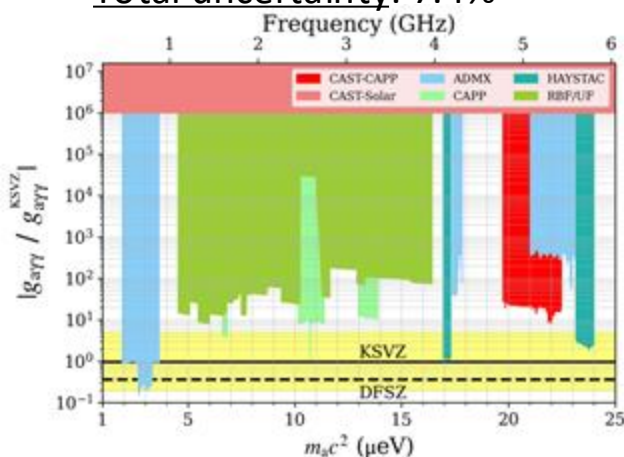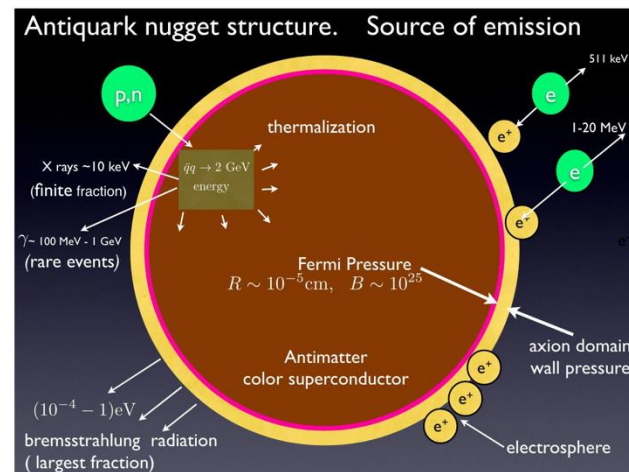

CAST is closed in 2022 ☹

CAST-CAPP was not designed for daily modulation analysis. We present an analysis model on retrospective data that will pave the way for future experiments.

CAST Collab., Search for Dark Matter Axions with CAST-CAPP. *Nat Commun* 13, 6180 (2022).

Axion Quark Nugget (AQN) Model

- Originally proposed by Ariel Zhitnitsky (2003) to explain $\Omega_{DM} \sim \Omega_{visible}$.
- Also explain other mysteries (core-cusp, solar corona etc).
- Composite particles with axion domain walls.
- Relativistic axions with **$<\upsilon_a> \sim 0.6c$** are emitted from AQNs as they penetrate the Earth.
- Production mechanism would cause:
  1. **Daily modulation (~10-20%).**
  2. **Seasonal phase shift.**

DFSZhitnitsky

Antiquark nugget structure.   Source of emission

p,n

thermalization

511 keV

1-20 MeV

X rays ~10 keV
(finite fraction)

$\bar{q}q \rightarrow 2$ GeV
energy

$\gamma \sim 100$ MeV - 1 GeV
(rare events)

Fermi Pressure
$R \sim 10^{-5}$ cm, $B \sim 10^{25}$

axion domain
wall pressure

Antimatter
color superconductor

$(10^{-4} - 1)$ eV

bremsstrahlung radiation
(largest fraction)

electrosphere

Axion Quark Nugget (AQN) Model

- AQN induced Axions have **$<\upsilon_a>$ ~0.6c** opposed to **$<\upsilon_a>$ ~10^{-3}c** of galactic DM axion $\Longrightarrow$ **broadband** detection strategy for haloscopes.

- AQNs interact with Earth and lose its mass $\Longrightarrow$ **Daily modulation (~10-20%)**

$$\rho_{\mathrm{a}}^{\mathrm{AQN}}(t) \equiv A_{\mathrm{(d)}}(t)\langle\rho_{\mathrm{a}}^{\mathrm{AQN}}(R_{\oplus})\rangle$$
$$A_{\mathrm{(d)}}(t) \equiv [1 + \kappa_{\mathrm{(d)}}\cos(\Omega_d t - \phi_0)]$$

Seasonal phase shift

$$\Omega_d = 2\pi\,\mathrm{day}^{-1}$$

$$\phi_0 \simeq \pi$$

For opposite seasons

Any haloscope experiment can analyze for AQN induced modulations without interfering with conventional searches
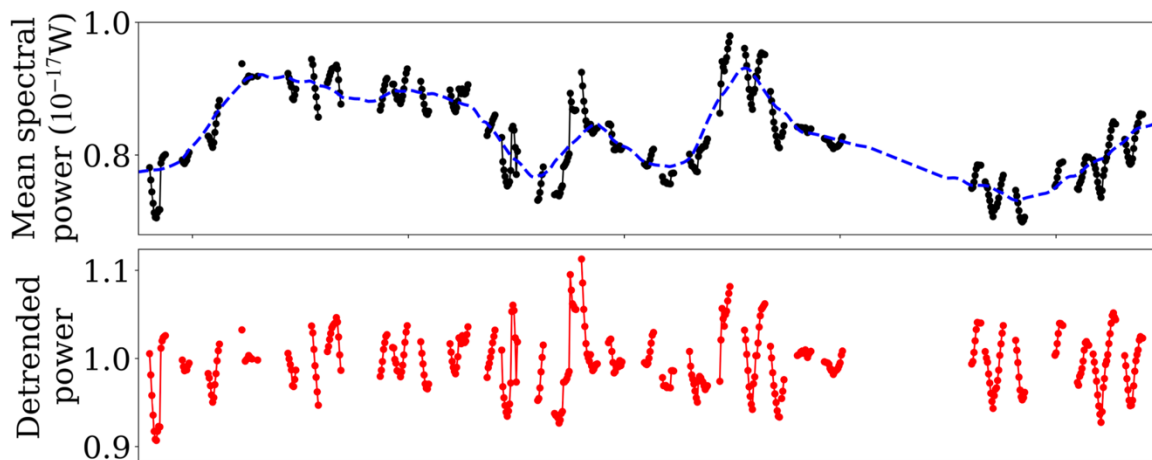
Simulations

- AQN power= 0.7% of the mean spectrum power
- 1-min spectra created by real background + random noise + AQN power
- 5 days / 1 min = 7200 simulated spectra
- Create a periodogram using Lomb Scargle method
- ML algorithm to find the best decision threshold

5 days
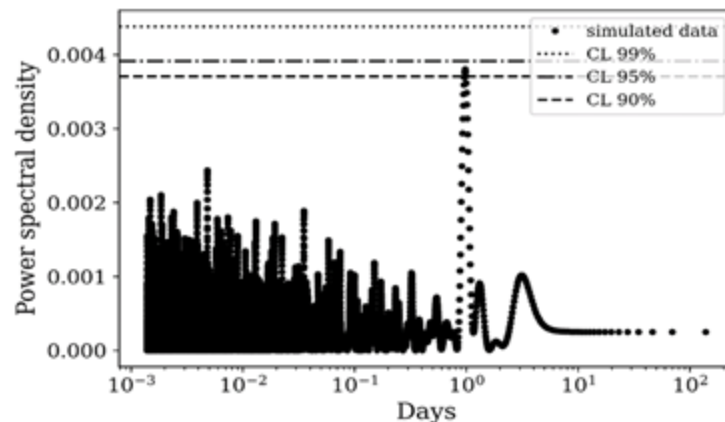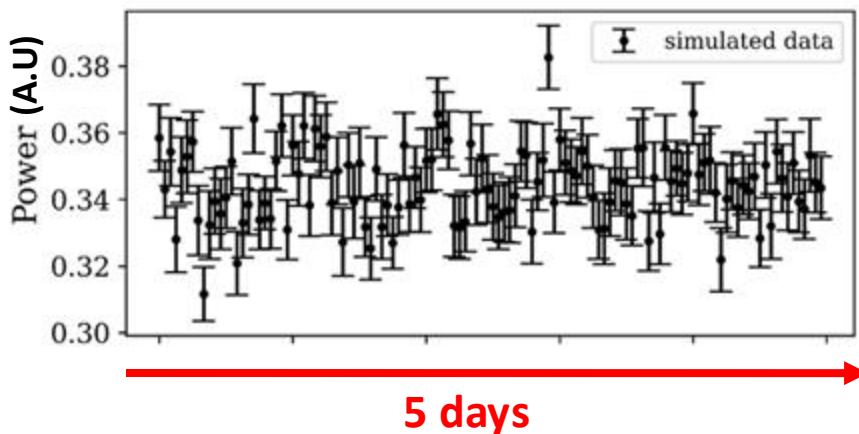
Data Treatment

- Phase-matched data can not be used (attenuation added).
- Fast-tuning data can not be used.

❖ Single cavity data in fixed-frequency measurements.
❖ Use of high-quality data (clean from mechanical vibrations).
❖ Use of both B=ON & B=OFF data.
❖ **All data are detrended before analysis**

Aug 15 - Sep 16, 2020

Data Analysis - B=ON

Time trace (2020/08/13 - 2020/09/20)

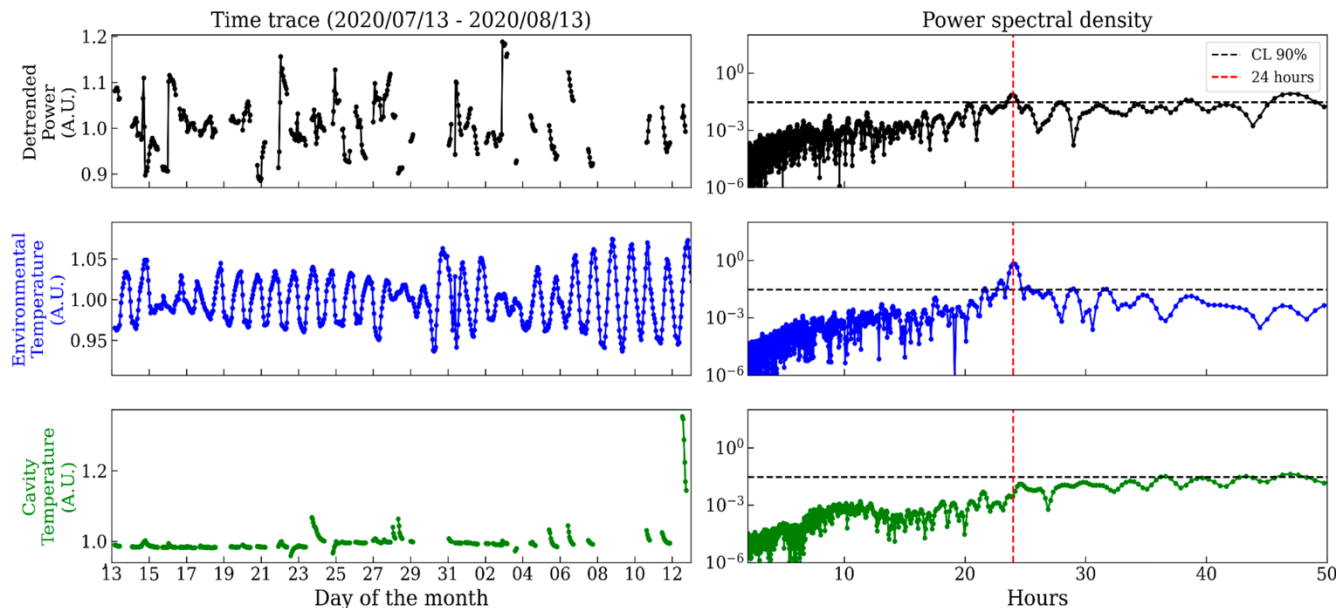Power spectral density
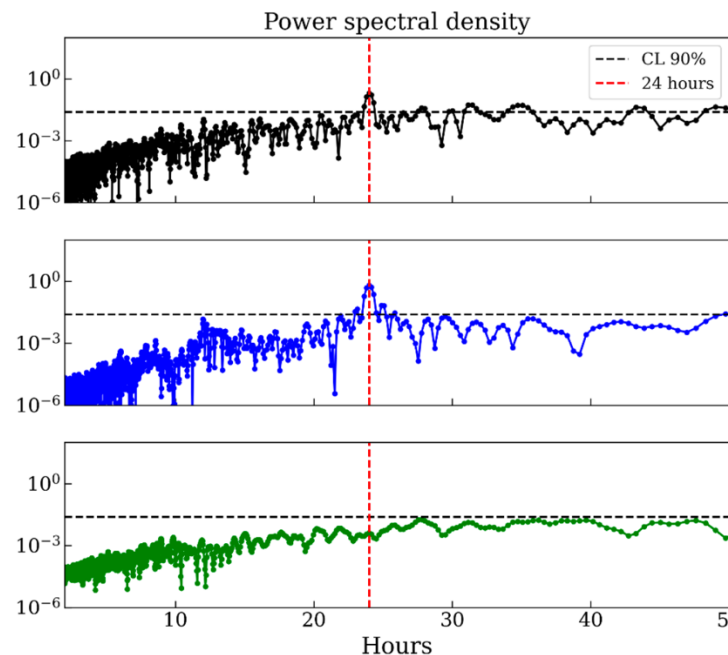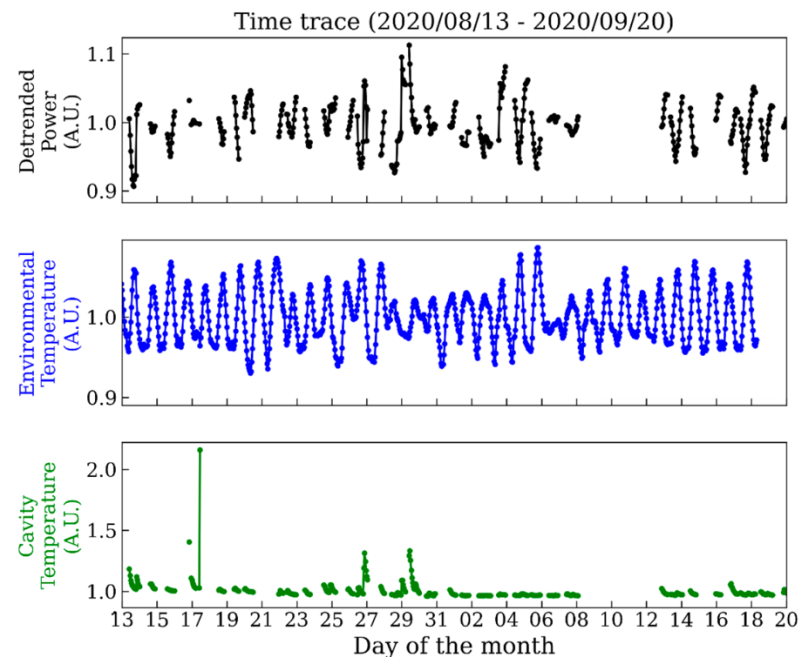
Cavity 3:
B=ON data shows daily periodicity.

CAST hall temperature shows strong daily modulations.

No periodicity for cavity temperature.

13 Aug - 20 Sep 2020

Data Analysis - B=OFF

13 July - 13 Aug 2020

Cavity 2:
Both B=ON and B=OFF show daily variations.

Origin may not be due to ==temperature variation==s OR temperature dependency might be more complex than anticipated

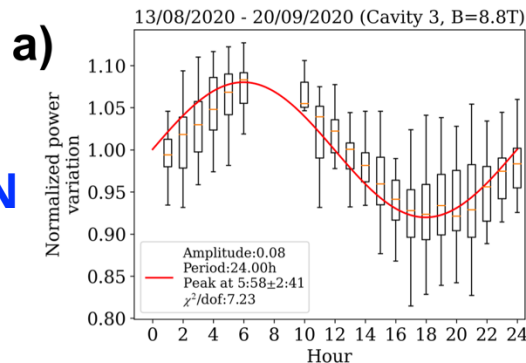**Further investigation required.**

We cannot verify the AQN induced daily modulations without first understanding the daily variations included in B=OFF data.
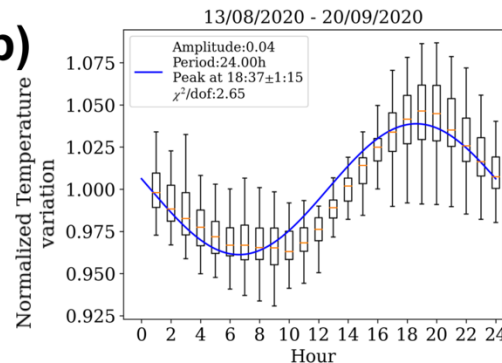
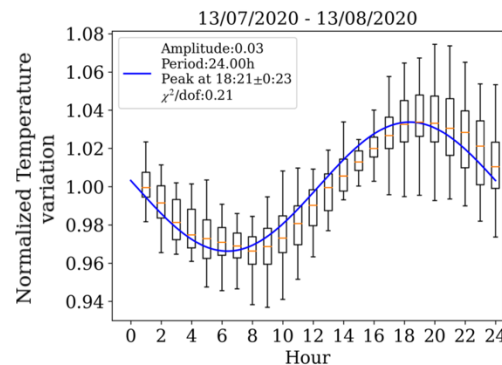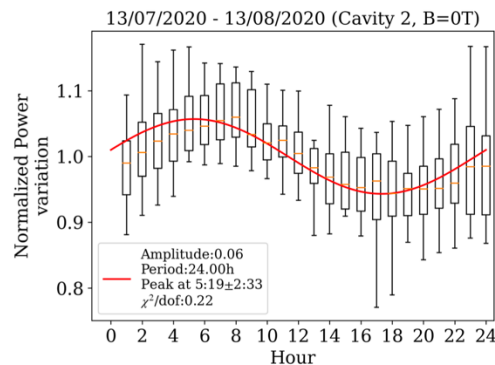# Data Analysis – Hourly Distributions

Cavity Power   **Ambient Temp**

~12 hours phase shift

A similar dependence is expected for the electronic gain of the amplifier chain of the DAQ system

Discussion / Conclusions

CAST-CAPP data analyzed for signatures (daily modulation) as expected from the AQN model:

- Daily modulation observed in both B=ON and B=OFF data.
- Temperature dependency of the gain of 2nd stage (room temp) LNAs is the most probable scenario.
- Voltage drifts less probable due to the existence of a line-interactive UPS.
- Other parameters need to be checked. But CAST is closed.

❖ **Proof of principle → Done**
❖ **No conclusive result.**

Any haloscope experiment can analyze for AQN induced modulations without interfering with conventional searches.