SEARCH FOR DARK MATTER AXIONS WITH CAST-CAPP

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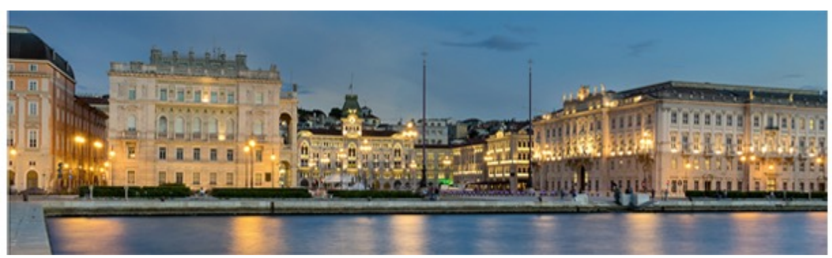
on behalf of the CAST Collaboration

16th Patras Workshop on Axions, WIMPs and WISPs

14-18/06/2021



Ευρωπαϊκή Ένωση
European Social Fund

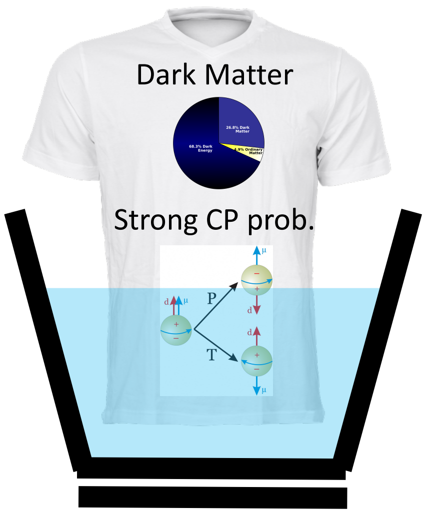
Operational Programme
Human Resources Development,
Education and Lifelong Learning
Co-financed by Greece and the European Union

ΕΣΠΑ
2014-2020
ανάπτυξη - εργασία - αλληλεγγύη

CAST EXPERIMENT

CAPP
Center for Axion and Precision Physics Research

AXIONS

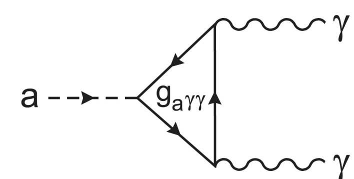


Axion Characteristics:

- Pseudo-Goldstone boson
- No charge
- Small mass: $1\mu eV < m_\alpha < 10 meV$
- Weakly interacting
- Local density: $0.45 GeV / cm^3$

Coupling to photons:

$$\mathcal{L}_{\alpha\gamma\gamma} = -g_{\alpha\gamma\gamma}\alpha\vec{E}\cdot\vec{B}$$



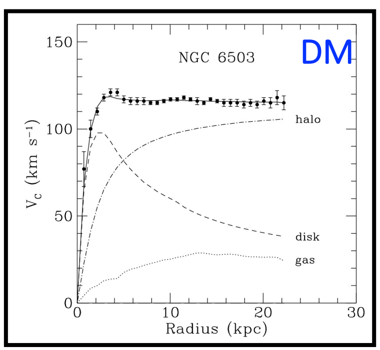
CP problem

$$\mathcal{L}_\theta^{QCD} = \theta\frac{g_s^2}{32\pi^2}G_a^{\mu\nu}\tilde{G}_{\alpha\mu\nu}$$

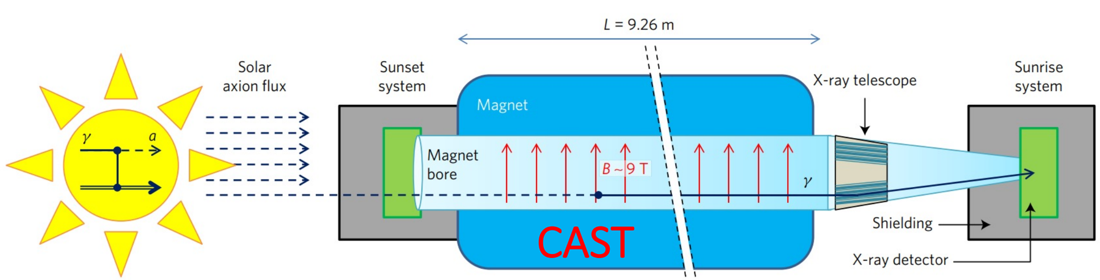
$$d_n \simeq 10^{-16}\cdot\theta \text{ e cm}$$

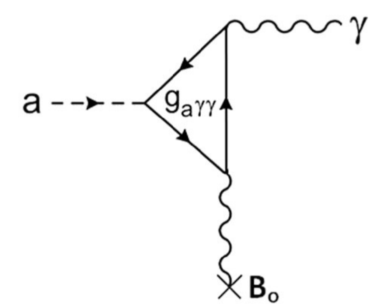
$$\left|d_n^{obs}\right| < 2.9\times10^{-26} \text{ e cm} \longrightarrow \theta < 10^{-10}$$

Axions convert to photons in a strong magnetic field!



Inverse Primakoff effect:





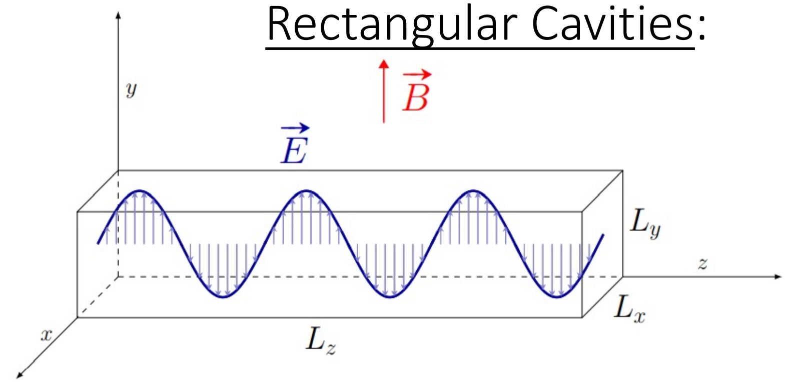
AXION HALOSCOPES a la Sikivie

The on-resonance axion conversion power in a microwave cavity is:

$$P_{sig} \approx g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} \boxed{B^2 \cdot V} \cdot Q_L \cdot C_{mnl}$$

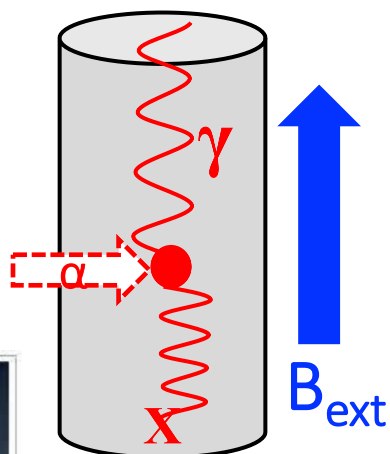
Magnet Strength, Size Matters!

Rectangular Cavities:

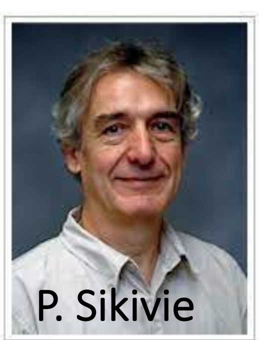


Mode frequency: $f_{lmn} \propto \sqrt{\left(\frac{l}{L_x}\right)^2 + \left(\frac{m}{L_y}\right)^2 + \left(\frac{n}{L_z}\right)^2}$

Higher frequencies → smaller cavities



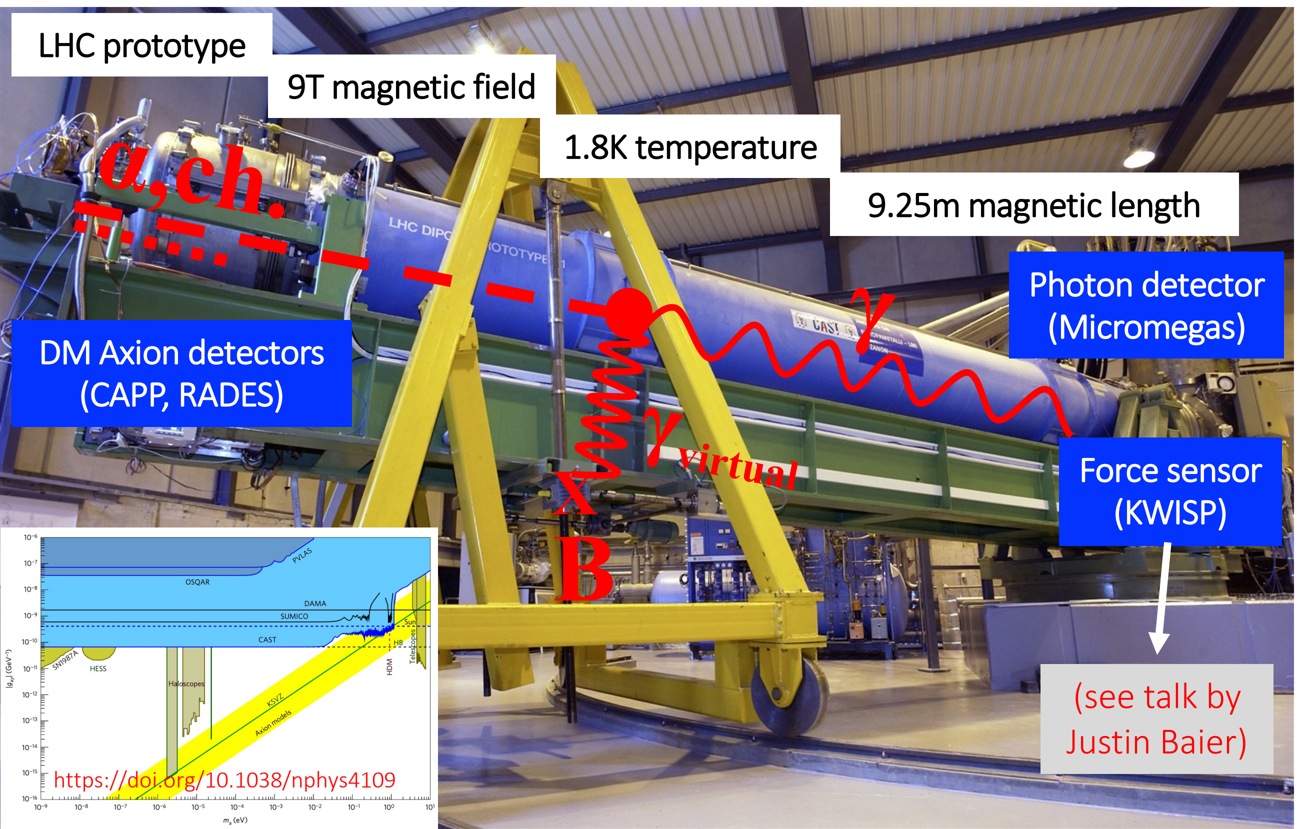
$$SNR = \frac{P_{sig}}{\sigma_{noise}} = \frac{P_{sig}}{k_B T_S} \sqrt{\frac{t}{\Delta v}}$$



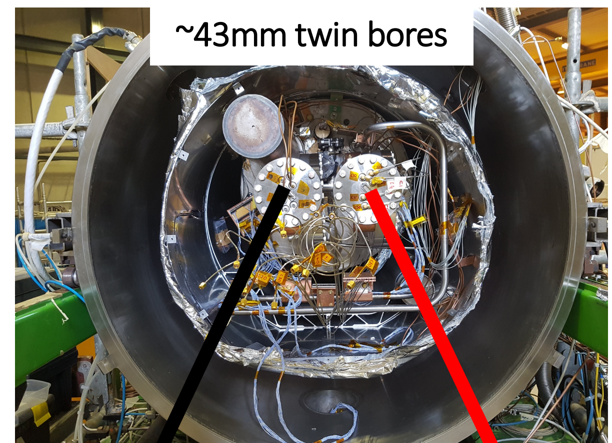
For CAST-CAPP: $P_{sig} \sim 10^{-24} W$ $T_S = T_{cav} + T_{LNA} =\sim 10\ \mathrm{K}$

CAST EVOLUTION

Axion Helioscope (Solar Axions) → **2019** → **Axion Haloscope** (Dark Matter Axions)



(see talk by Justin Baier)



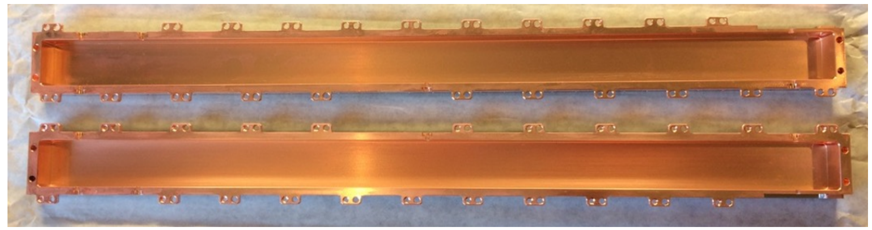
CAST-RADES
(see talk by Sergio Arguedas Cuendis)

CAST-CAPP
(this talk)

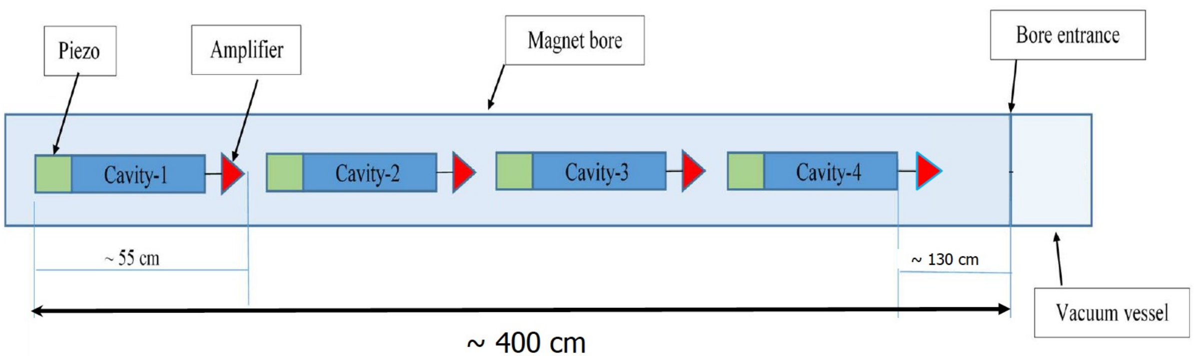
CAST-CAPP CAVITIES

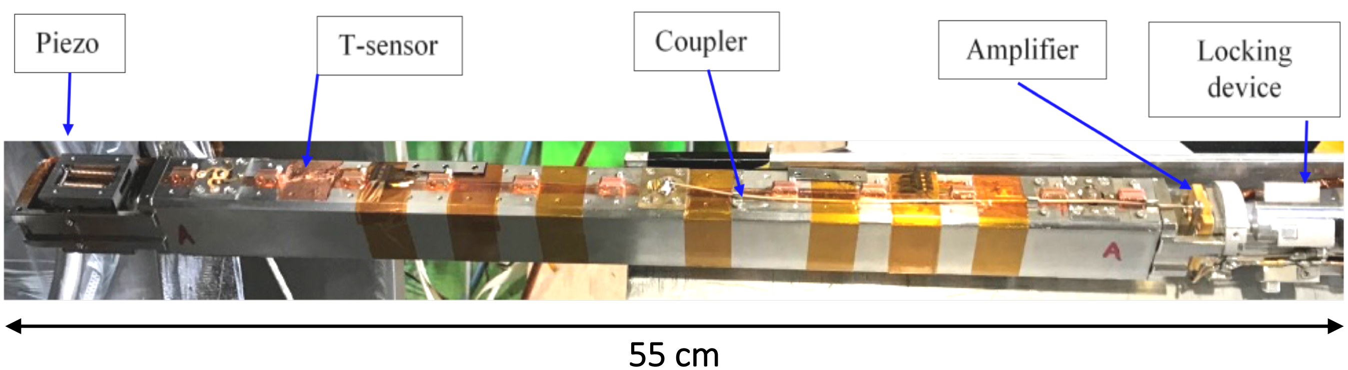
4 identical stainless steel tunable cavities electroplated with ~30µm of copper installed in one of the two twin bores of CAST magnet.

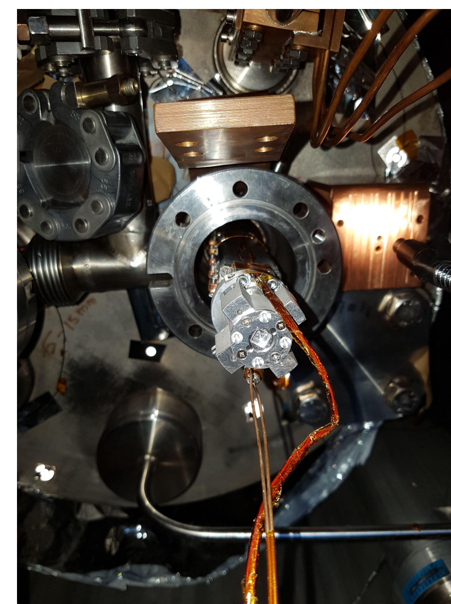
Longitudinally split into two identical halves.



$$23 \times 25 \times 390 \text{ mm}$$
$$V = 224 \times 10^{-6} m^3$$
$$Q_L \sim 20000$$
$$T_S \sim 10K$$
$$C \sim 0.53$$

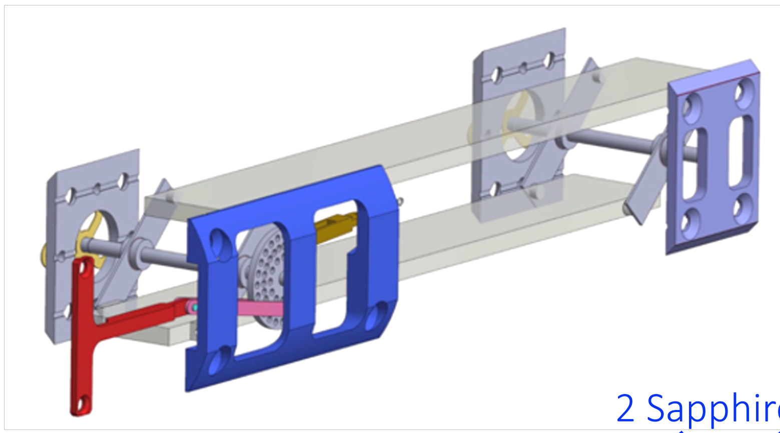






AXION MASS UNKNOWN → TUNING IS REQUIRED

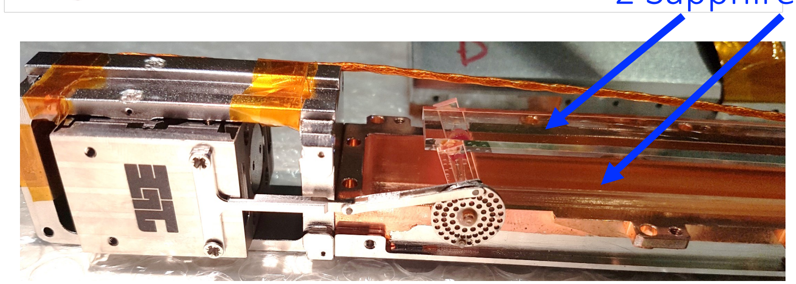
Tuning mechanism: 2 dielectric sapphire bars symmetrically placed parallel to the longitudinal sides, moving simultaneously towards the center and activated by a piezoelectric motor.

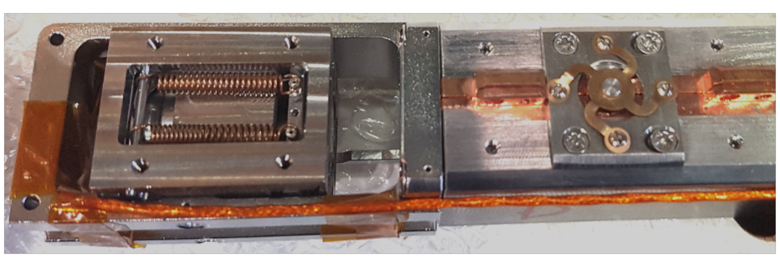


Mode of interest: TE_{101}

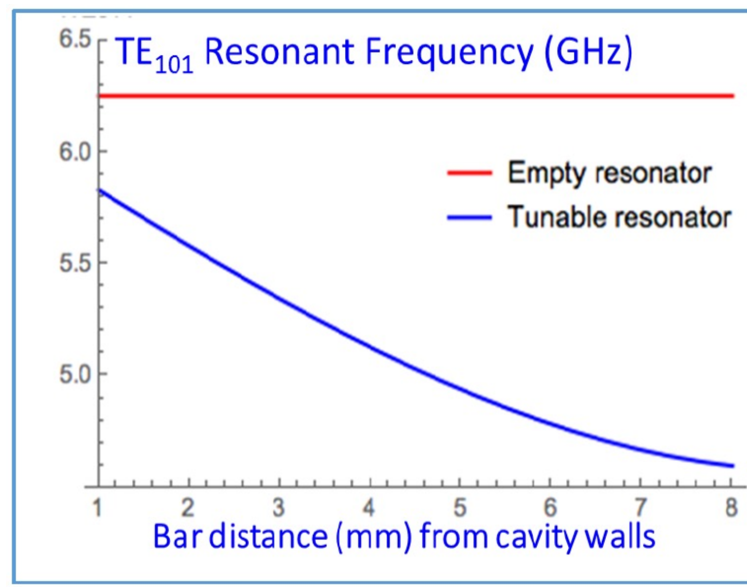
- Frequency Range: ~4.8 – 5.4 GHz (660 MHz)
- Axion mass range: ~19.7 – 22.4 μeV

2 Sapphire plates





Resolution: 100 Hz



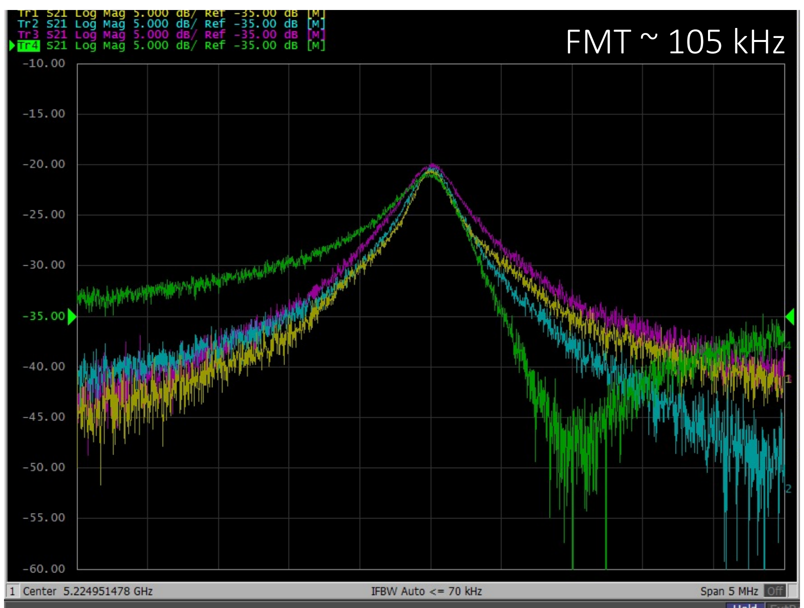
PHASE MATCHING

Increase the sensitivity via *coherent* combination of the power outputs of each frequency-matched cavity *after* individual signal amplification.

- No phase-matching: $SNR_N = \sqrt{N} \cdot SNR_{single}$
- With phase-matching: $SNR_N = N \cdot SNR_{single}$

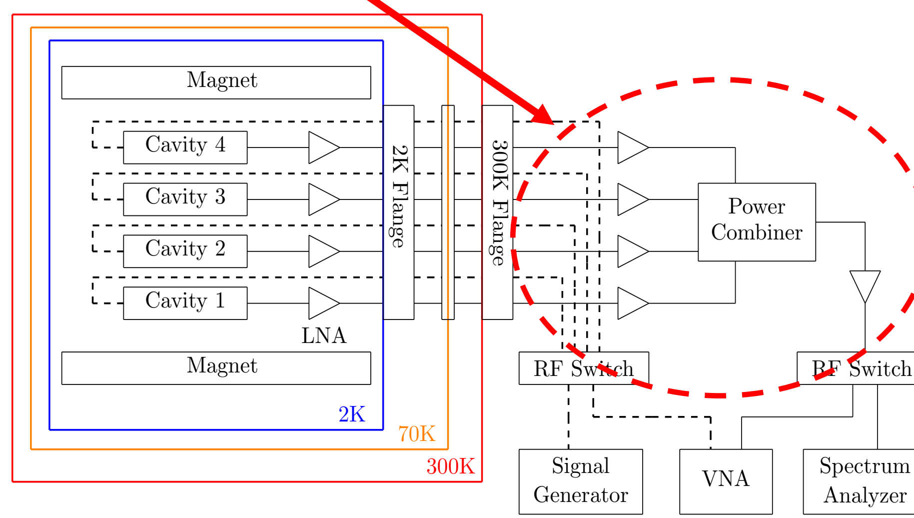
$$\lambda_{\text{deBroglie}} \sim 62m$$

- ➢ Frequency accuracy: ±10 kHz
- ➢ Amplitude accuracy: ± 0.25 dB



https://doi.org/10.1016/j.astropartphys.2017.10.012

Configuration	1	2	3
Schematic			
Components	N complete chains	N amplifiers 1 combiner	1 amplifier 1 combiner
Sensitivity	$\sqrt{N} \cdot \mathrm{SNR_{sgl}}$	$N \cdot \mathrm{SNR_{sgl}}$	$\lesssim N \cdot \mathrm{SNR_{sgl}}$
Characteristic	Individual accessibility	Hightest sensitivity	Simplest design



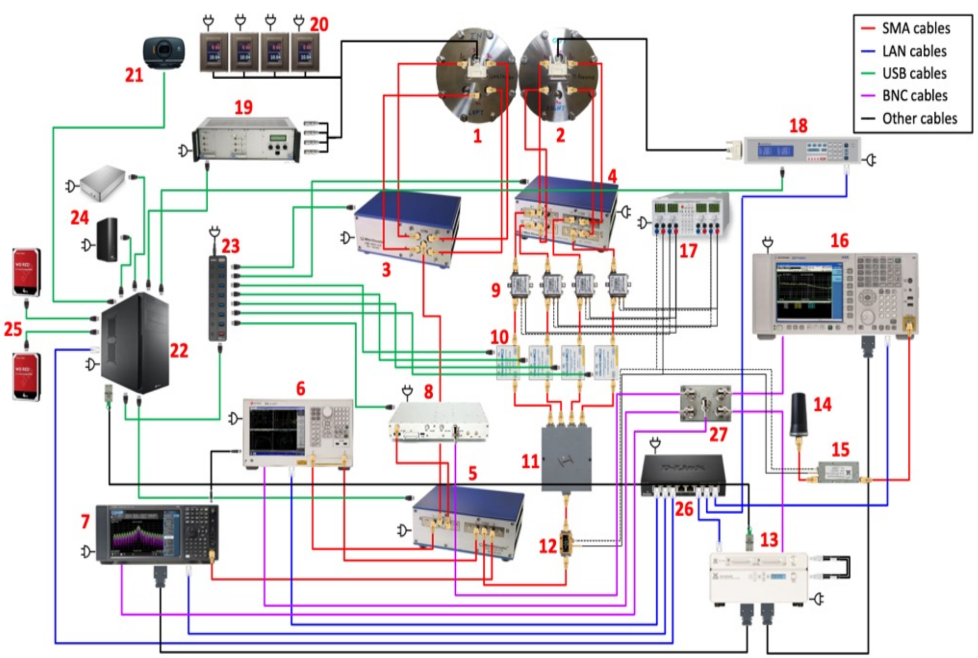
DAQ SYSTEM

Data acquisition system installed on CAST magnet and allows a fast semi-autonomous data-taking for 20 h / day.

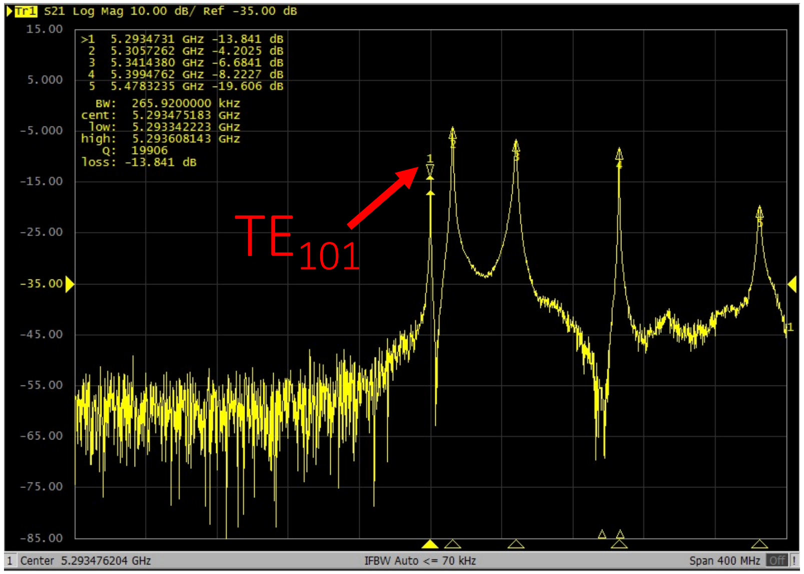
- 1-min measurements
- Bandwidth = 5 MHz
- Tuning step size = 200 kHz
- Size = ~ 3 GB / file !! → CERN Tape Archive (CTA) storage

- Daily offloading/uploading
- Daily processing
- Daily analysis

ONLY 37 instruments!



Transmission measurement through VNA:



WAIT… THERE IS MORE!

CAST-CAPP is ALSO sensitive to transient events such as streams, mini clusters etc.

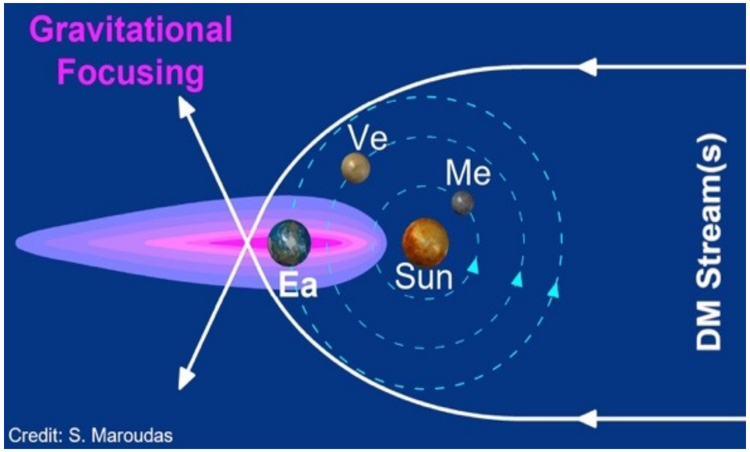
(see talk by Abaz Kryemadhi)

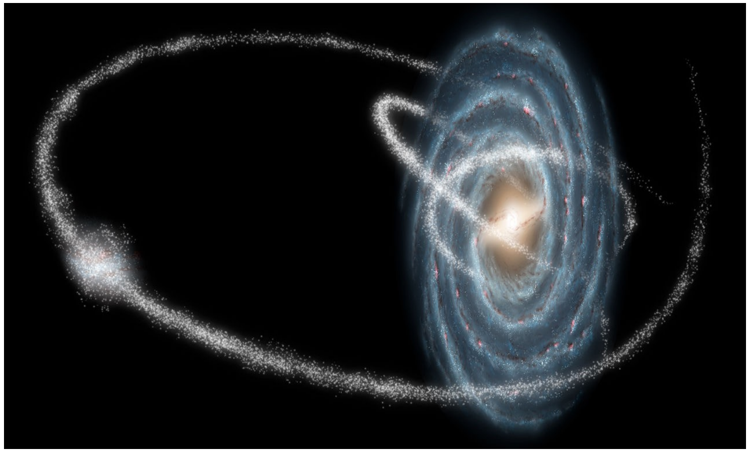
Gravitational (self-)focusing → Flux enhancement!!

- ✓ Fast scanning
- ✓ Wide band electronics
- ✓ Fast analysis & elimination procedures
- ✓ Maximum duty cycle

Current piezo speed: (10 MHz / min)

The faster the scanning the shorter axion burst can be probed





DATA TAKING RESULTS

RESULTS:

- Data-taking time: 3876 h (161.5 d)
- Frequency range: 660.15 MHz (4.77 - 5.43 GHz)
- Data size: ~ 650 TB !!

✓ Phase-matching of all four cavities
✓ Fast resonance scanning
✓ Unexplored parameter space

QUALITY CHECKS:

Nr.	Parameters	Criteria
1	Frequency stability	$\Delta\nu_0 < 100\,\text{kHz}$
2	Amplitude variation	$\Delta A_0 < 3\,\text{dB}$
3	Quality factor	$10^3 < Q < 4 \times 10^4$
4	Quality factor shift	$\Delta Q < 7 \times 10^3$
5	Frequency mismatch	$< 20\,\text{kHz}$ (before)
6	Frequency mismatch	$< 80\,\text{kHz}$ (after)
7	Amplitude mismatch	$< 1\,\text{dB}$
8	Temperature mismatch	$< 3\,\text{K}$

Total discarded Files: (~4.72%)

Data Processing: FFT

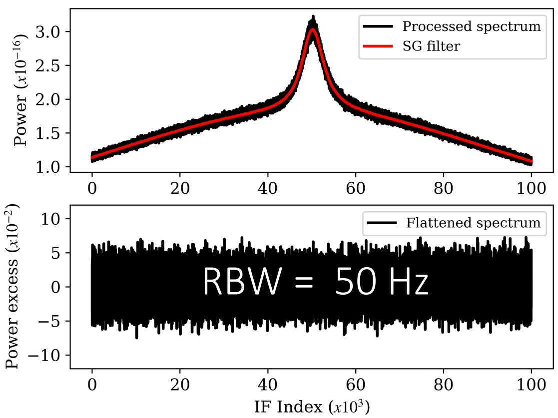
Time domain I(t), Q(t) → Frequency domain I(f), Q(f)

- RBW = 50 Hz

DATA ANALYSIS

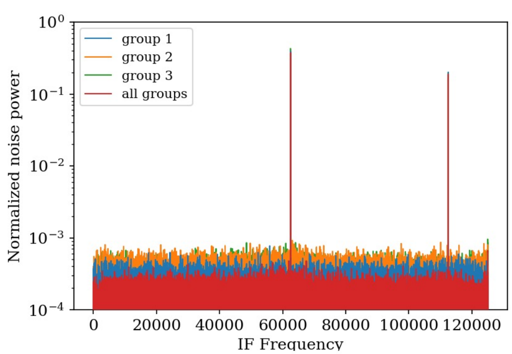
1. Spectrum Flattening:

- Divide spectrum by SG filter output to remove noise baseline of processed spectra



2. IF interference check:

- Constant index, narrow line
- Flagged IF bins are discarded



3. Combining multiple spectra:

a. Scaling of the spectra by P_{noise}/P_{axion} to get axion SNR

b. Vertical averaging (weights by ML estimates)

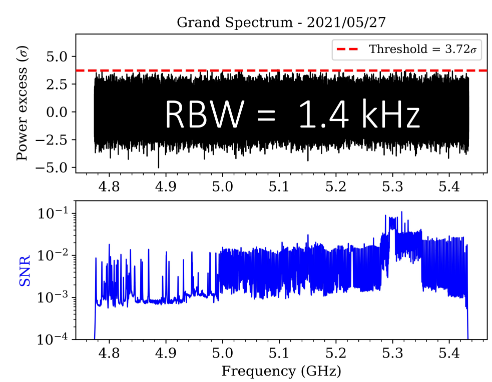
c. Normalization of bins via division by its σ

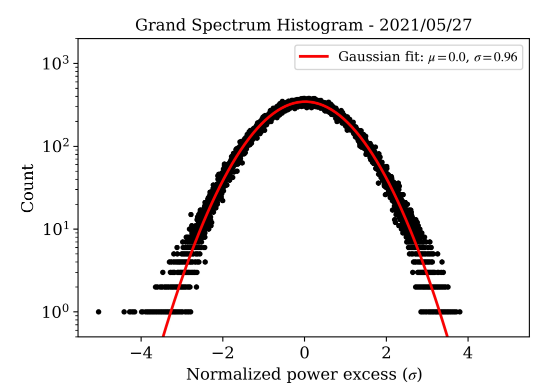
4. Rebinned spectrum:

- Horizontal averaging of 28 adjacent bins with ML weights to increase SNR of ~ 7kHz axion

5. Grand spectrum:

- Convolution with expected axion signal shape in the lab frame.

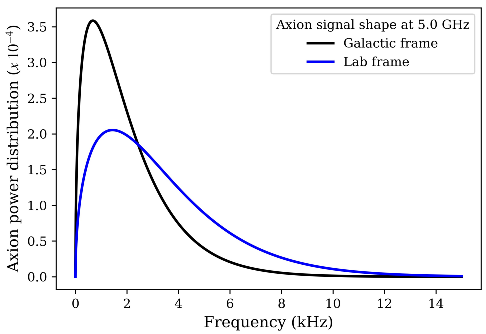


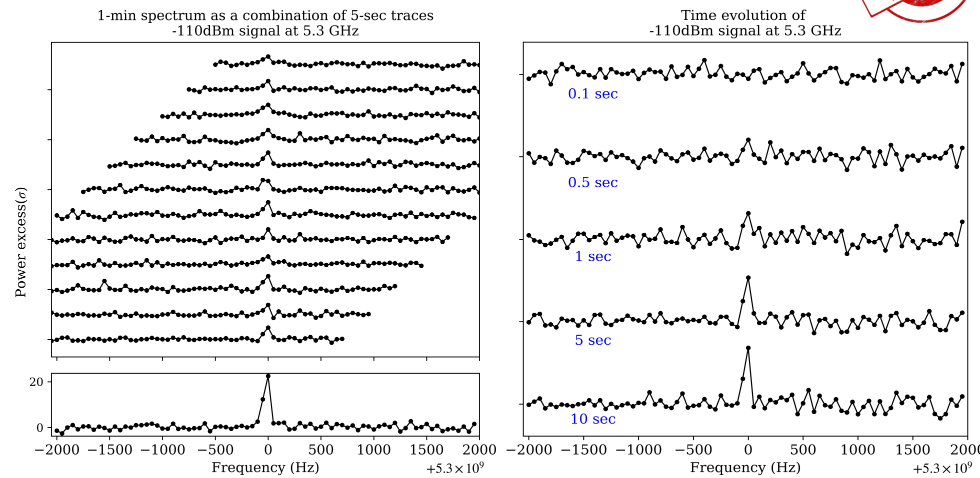


HARDWARE AND SOFTWARE SIGNAL INJECTIONS

- Blind injection of well-defined "fake" axion signals.
- Identification from analysis + stability and calibration.
- Behavior and characteristics as expected.

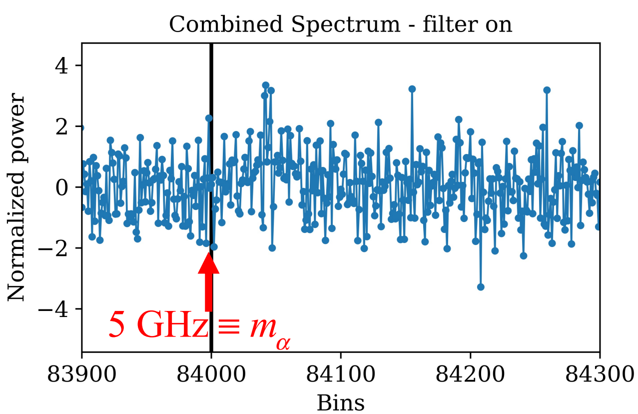
Hardware Injections:

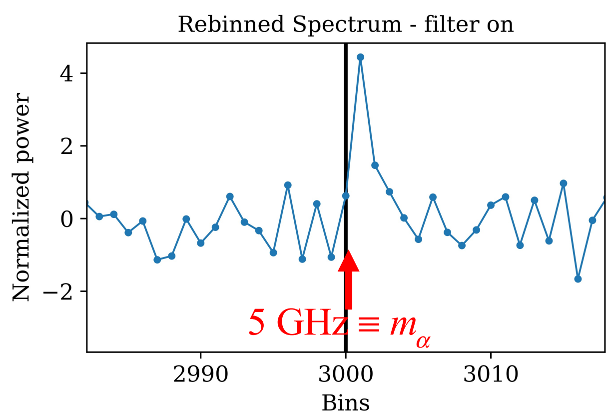


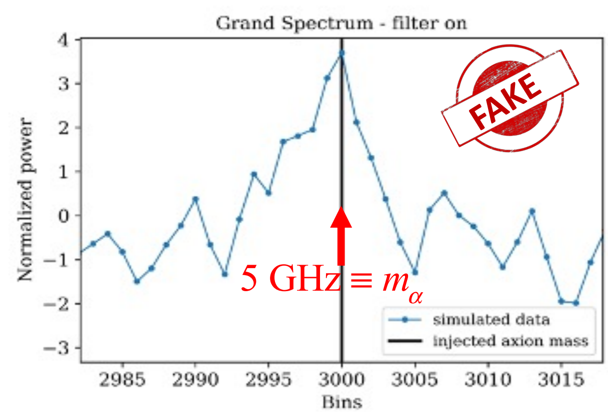


- ❖ Injected power: $g_{\alpha\gamma}^{injected} = 20 \times g_{\alpha\gamma}^{KSVZ}$
- ❖ Should be visible after 90-min averaging
- ❖ 110-min of data generated

Monte Carlo synthetic axion signal:



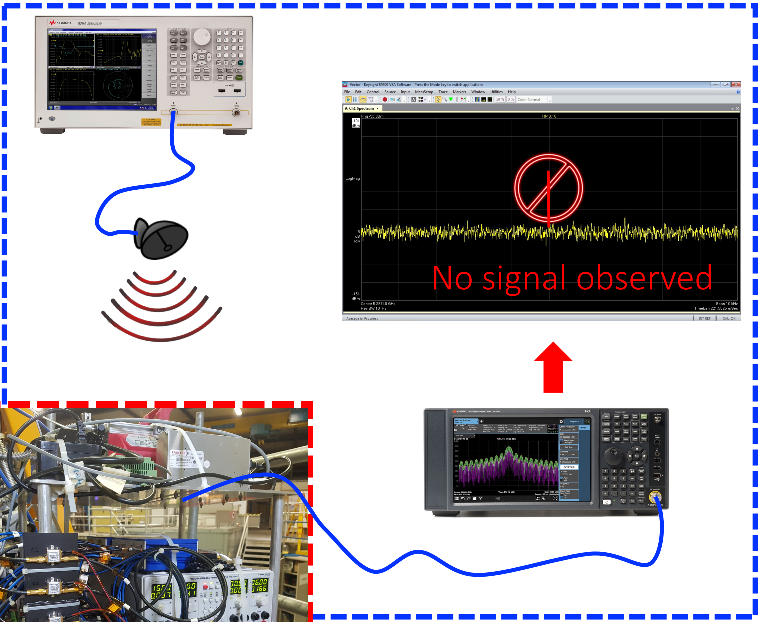


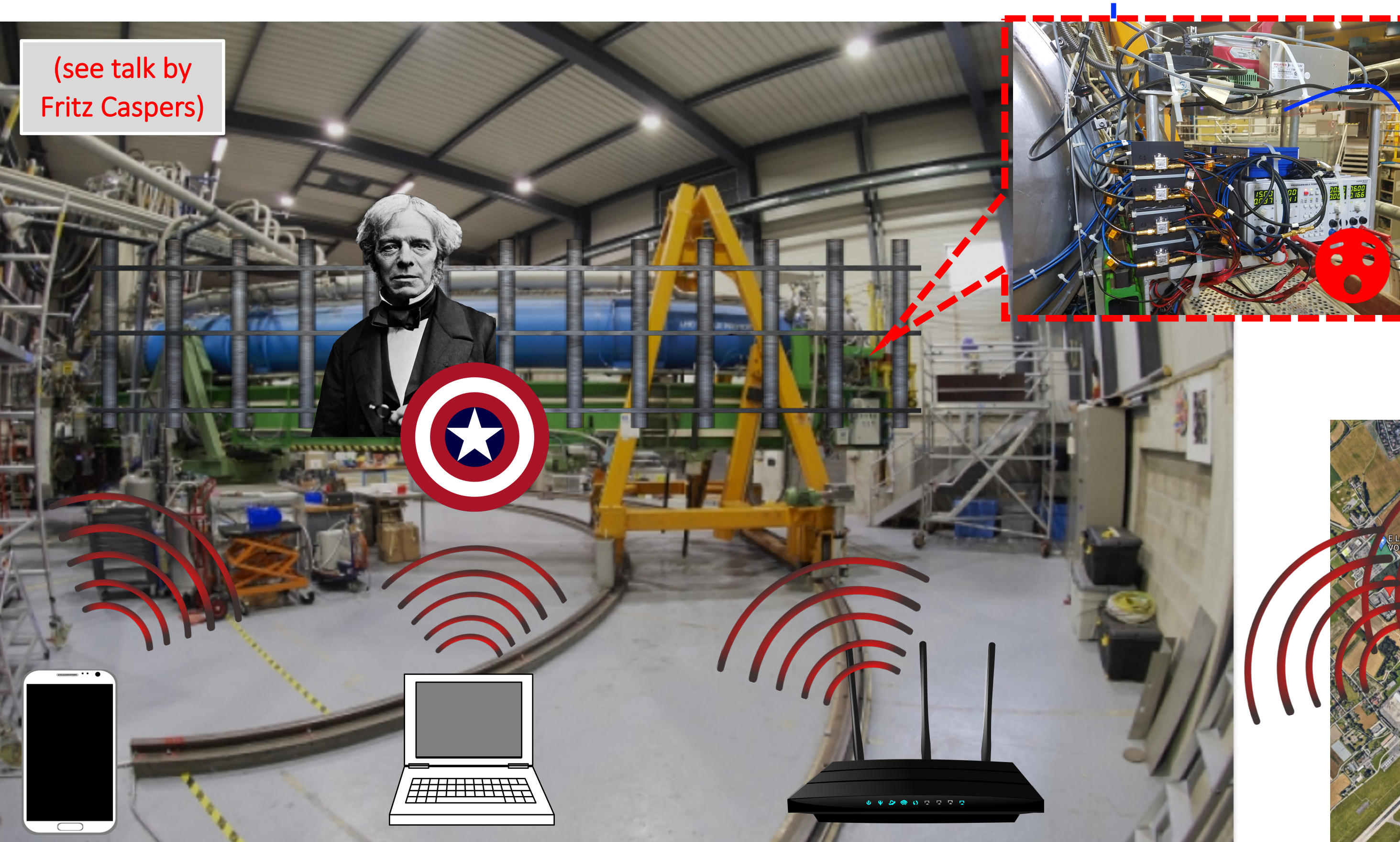


BUT… WHAT ABOUT AMBIENT INTENDED/UNINTENDED EMITTERS?

- Magnet body acts as a Faraday "S.H.I.E.L.D."
- Outside-the-cryostat connections are unprotected.

GOOD NEWS:
Margin of ~30 dB above the noise!



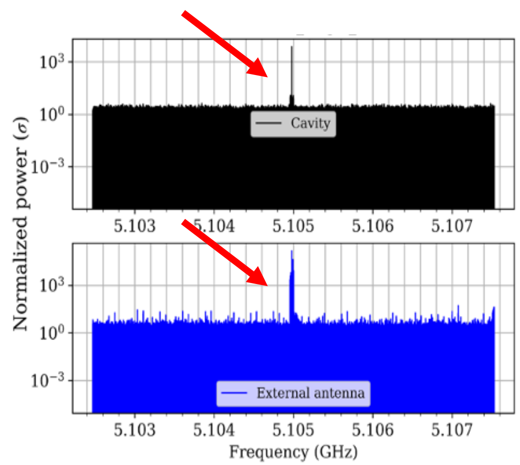


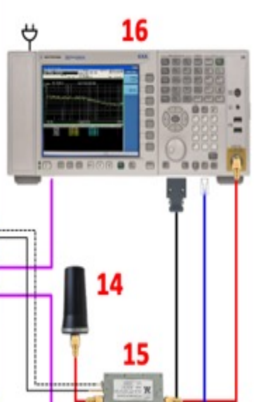
BUT… WHAT ABOUT AMBIENT INTENDED/UNINTENDED EMITTERS?

Solution A:

Simultaneous measurements at the same frequency band with a second *independent* channel looking for ambient EMI/EMC signals in the CAST area.

Important for signal identification & characterization



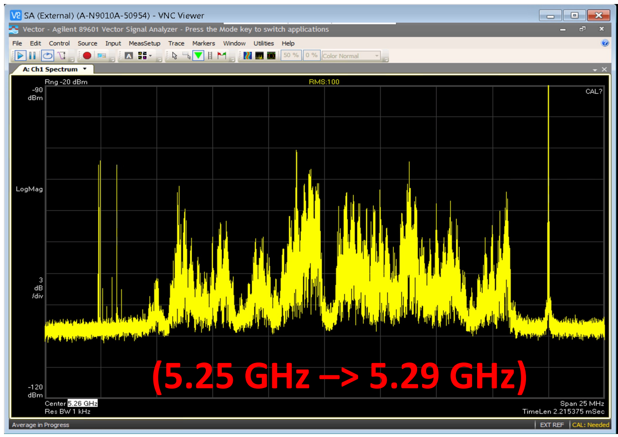


Second vector spectrum analyzer connected to an omnidirectional antenna

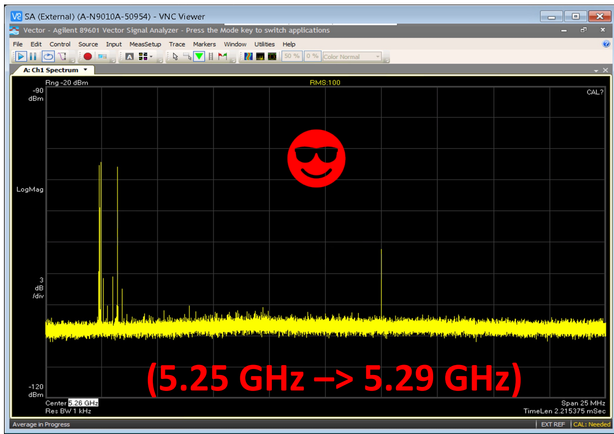
Solution B:

Disabling of *intervening* WLAN channels in 5GHz band of the surrounding Aps.

BEFORE



AFTER

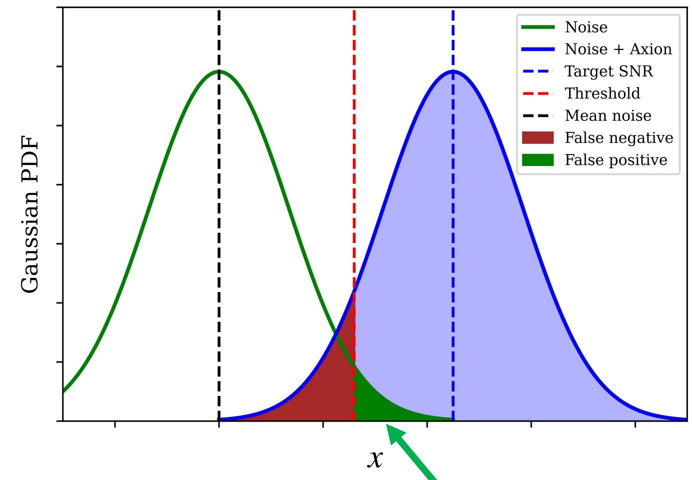


DATA ANALYSIS – HYPOTHESIS TESTING

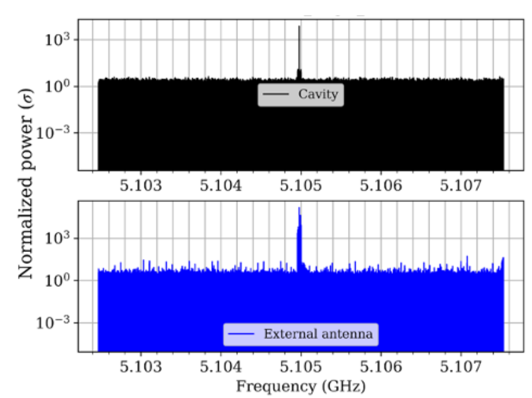
- Target SNR = 5 σ
- Confidence Level: 90%

Threshold: 3.72 σ

60 outliers

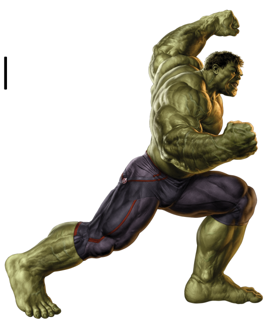


- 40 statistical outliers (~47 expected)
- 11 verified as blind signal injections
- 9 verified as EMI/EMC parasites



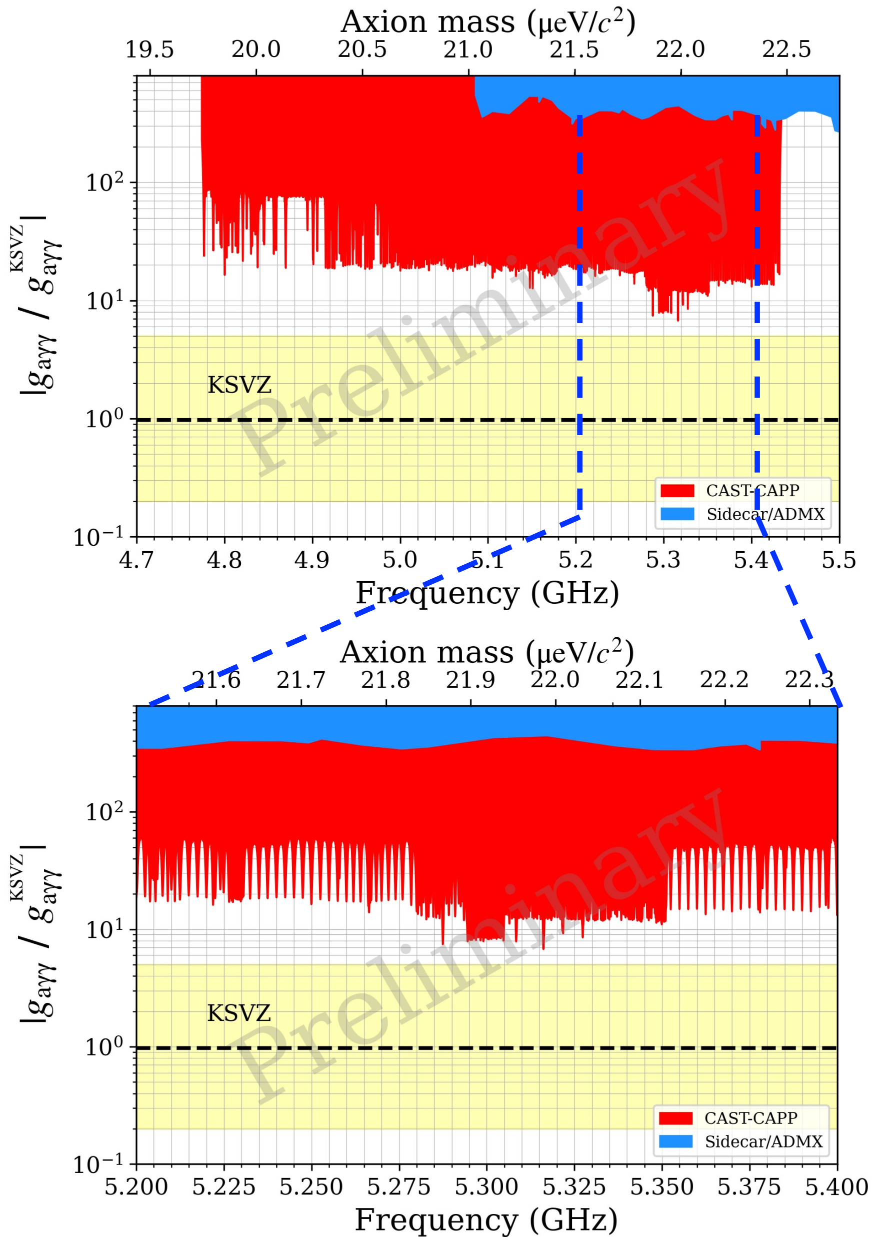
Elimination Procedure:

1. No EMI/EMC parasite in 2nd channel
2. Persistence during re-scanning
3. Re-scanning with different cavities
4. Tuning to different resonant mode
5. Correct axion line shape (5-7 kHz)
6. Signal ∝ B



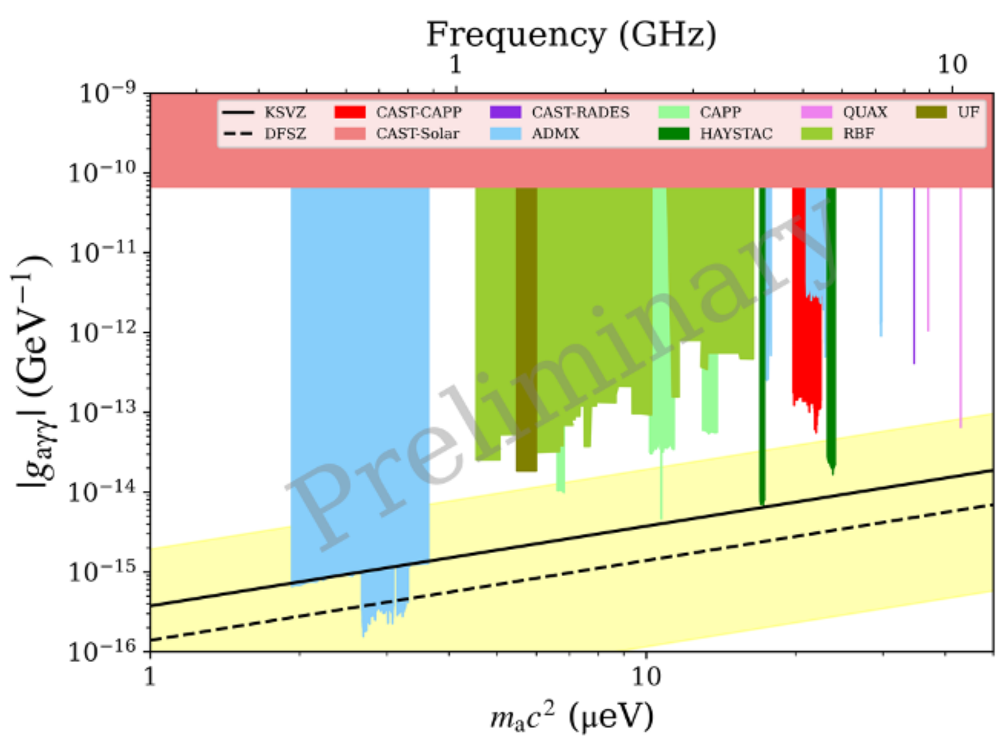
No remaining outliers!

DATA ANALYSIS – EXCLUSION PLOT

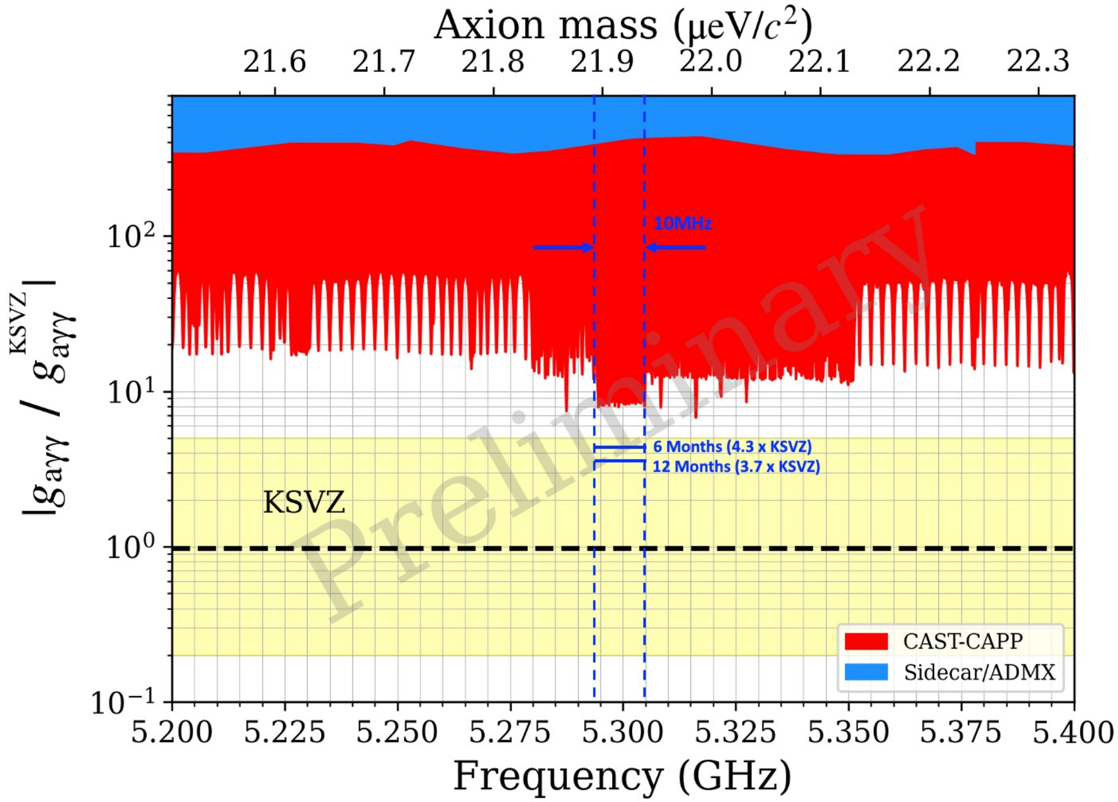


- Total time: 3670.3 h
- Frequency range: 660.15 MHz
- Axion masses: 19.7 μeV < m_α < 22.4 μeV
- Present sensitivity: $8 \times g_{\alpha\gamma\gamma}^{KSVZ}$

No axions here…



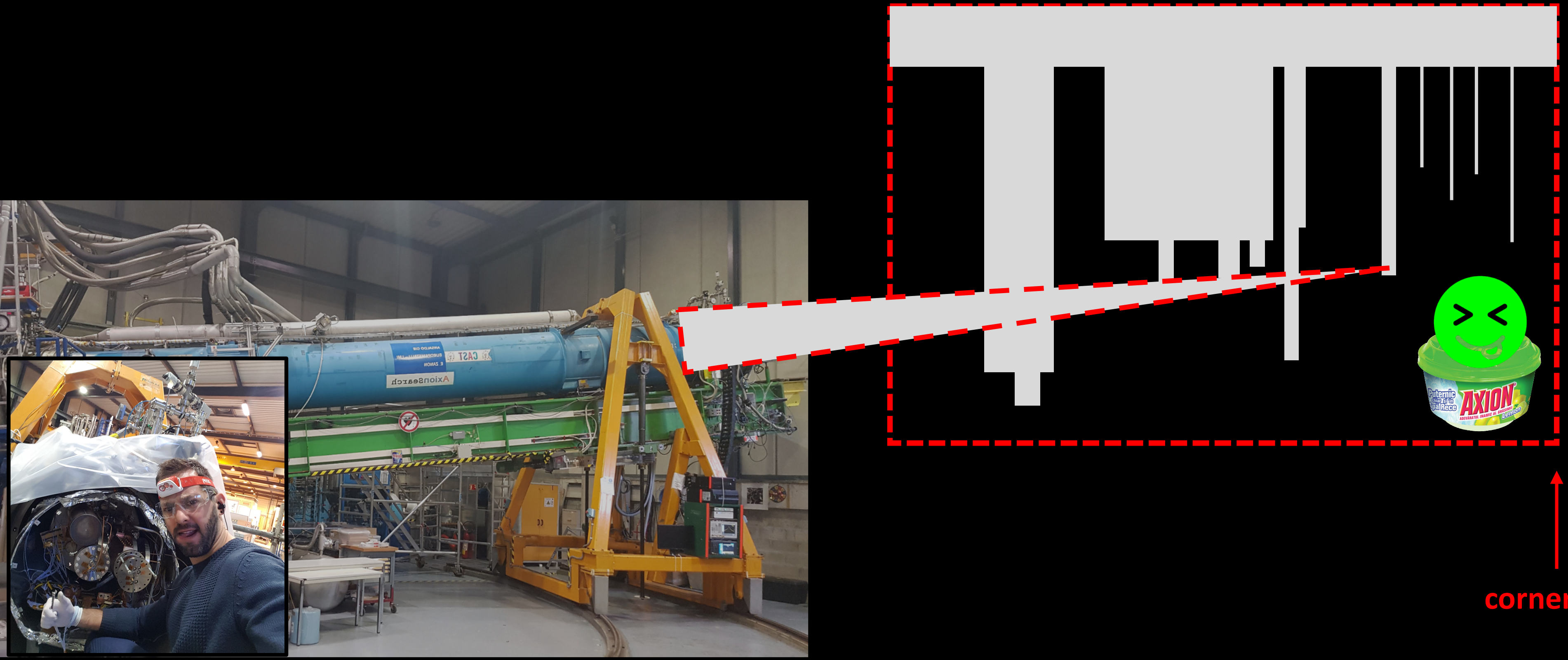
PROSPECTS



+ MORE ?

- Improve analysis results with optimization of parameters.
- Increase tuning range up to 1GHz.
- Optimizations on tuning speed & cryo-contact of the cavities.
- Superconducting cavities using HTS YBCO tape on the inner surface.
- Extension of transient-signal data-taking & analysis.
- Search for signal modulations.

THANK YOU!

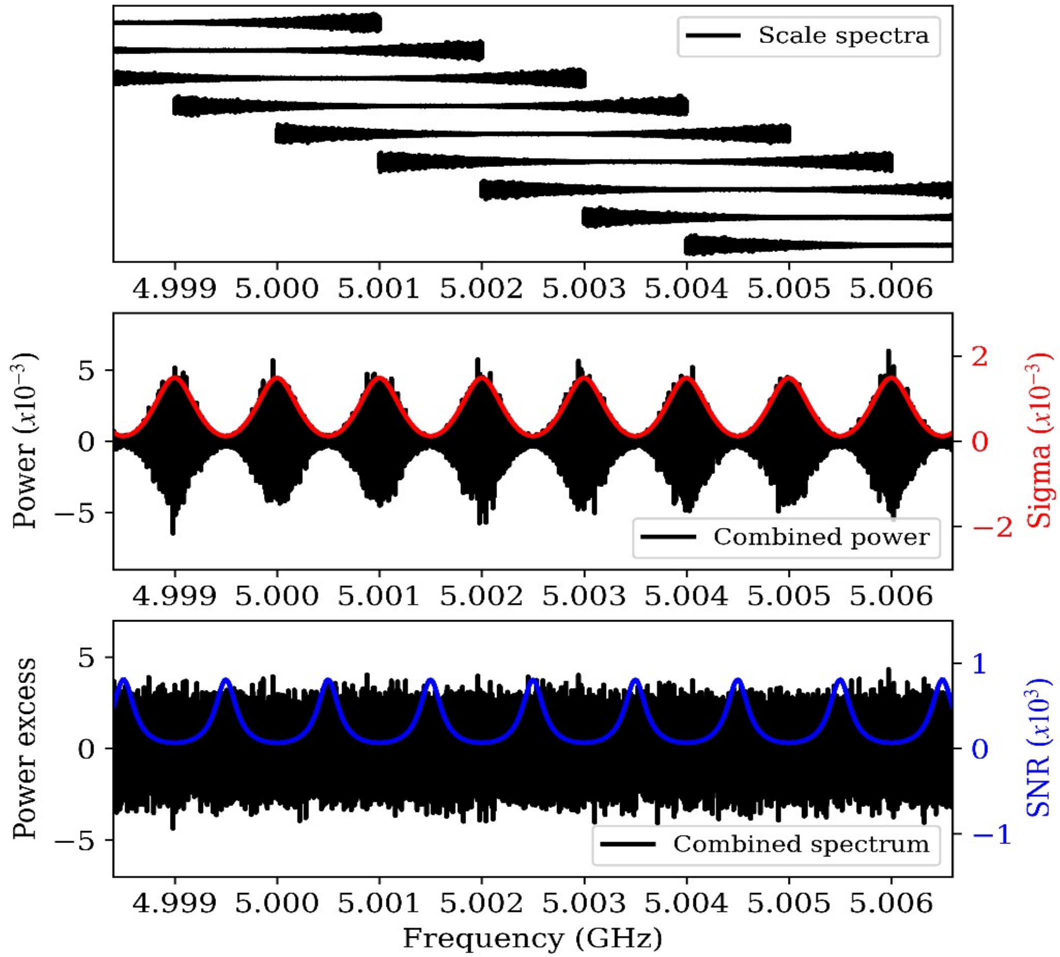


AXION HUNTING PERIOD IS STILL ON!!

BACKUP SLIDES

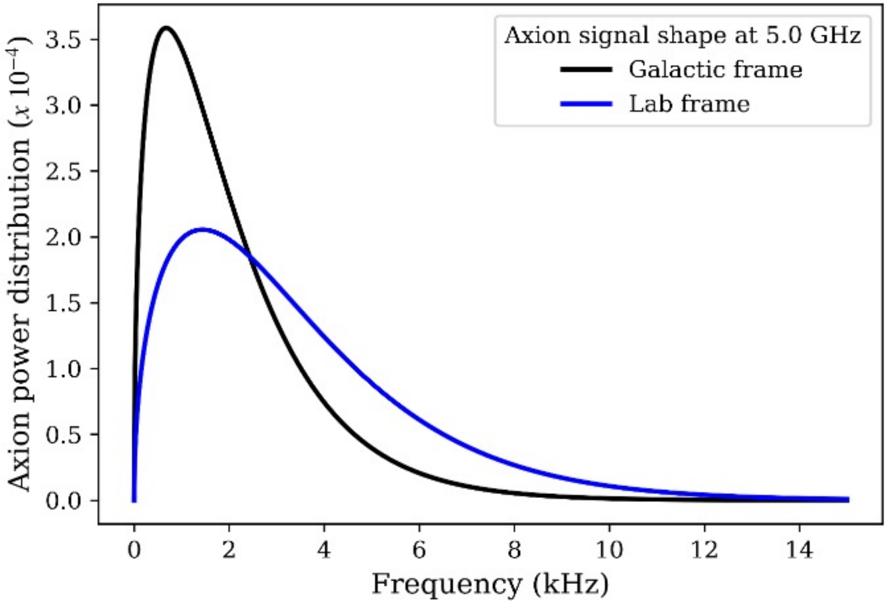
DATA ANALYSIS

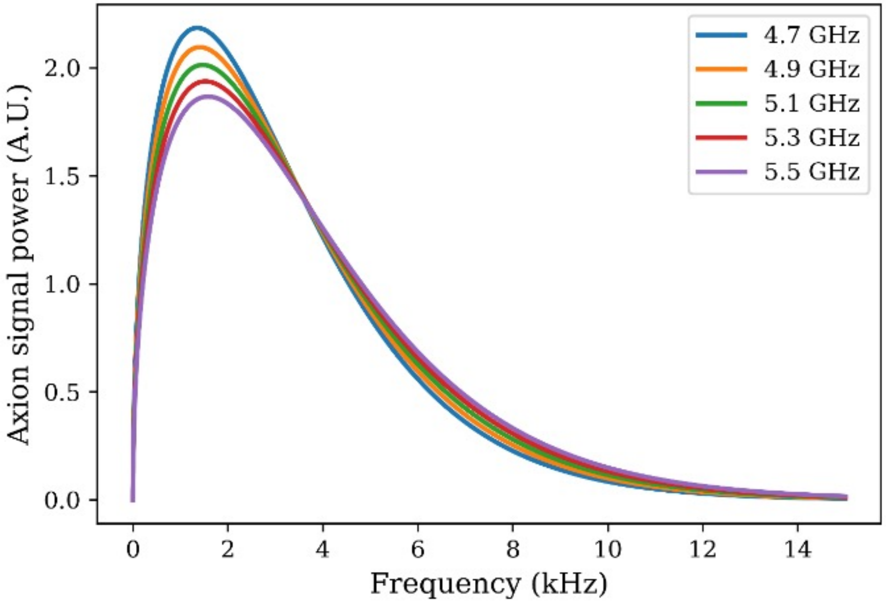
3. Combining multiple spectra:



DATA ANALYSIS

Expected axion line shape on galactic and lab frame





PROSPECTS

Projections to reach KSVZ limit with phase-matched cavities.