CAST Proposal and Status Report
139th Meeting of the CERN SPSC

K. Zioutas,
University of Patras,

on behalf of **CAST Collaboration**
and external collaborators
M. Vogelsberger (MIT) & **A. Kryemadhi** (Messiah U.)

(CERN-SPSC-2020-022 / SPSC-SR-277 02/10/2020
http://cds.cern.ch/record/2738387)

CERN, 13th October 2020

About CAST

↓

Presently: 10 theses

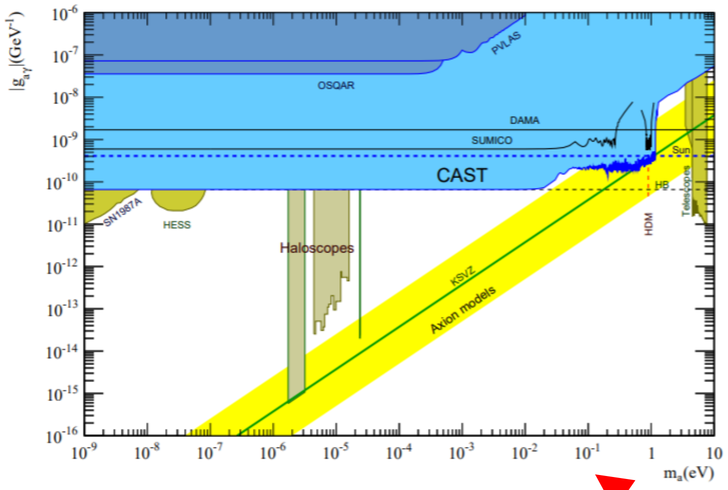
ABSTRACT

With less than 2 months of data taking, **the CAST-CAPP cavity experiment** managed to cover a significant fraction of previously unexplored parameter DM axion space in the range 19.7 to 22.4 μeV (4.7 to 5.5 GHz), and exceeded the previous limits by ADMX-Sidecar by far. **CAPP is a sub-detector of CAST with 4 resonance cavities.** It is the full realization of the conceptual idea from 2011 and transforms CAST from an axion helioscope to an axion haloscope. Since 2019 data are taken with individual cavities as well as with all 4 cavities phase matched (=coherently). The experiment is not yet running under optimal conditions and further optimizations are already being prepared. These will improve the sensitivity even further and will lead to world-leading results. **The full previously granted data taking time of 6 months,** which due to the COVID19 pandemic would extend into 2021, **is essential to achieve the planned sensitivity.** To fully exploit its sensitivity, we have recently installed a second spectrum analyser which measures simultaneously the ambient electromagnetic noise. CAST-CAPP has pioneered the new technology of fast scanning and phase-matching of multiple cavities, which is capable to detect transient events from streaming dark matter or axion mini-clusters. An unambiguous detection of such events requires an independent detector at another location. We are currently in contact with the IBS Korea on the possibilities to facilitate establishment of a second detector there.

From the CAST report to SPSC: http://cds.cern.ch/record/2738387/files/**SPSC-SR-277**.pdf

CAST Motivation:

Solar axions: NATURE Phys.13(**2017**)584



Dark Universe …. **Axions** ➔ strong CP problem **&** **DM** **&** **solar axions**

…. **Chameleons** ➔ **DE**

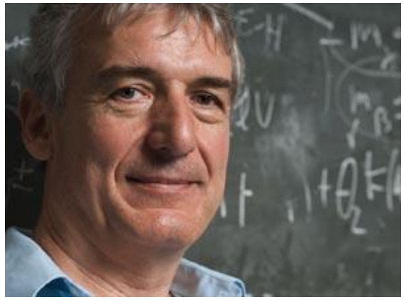
Direct DM search

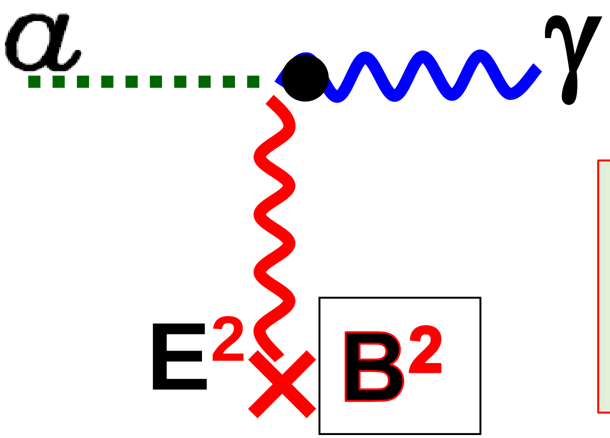
@ CERN

CAST's approach: 1 out of 3 methods

CAST

P. Sikivie



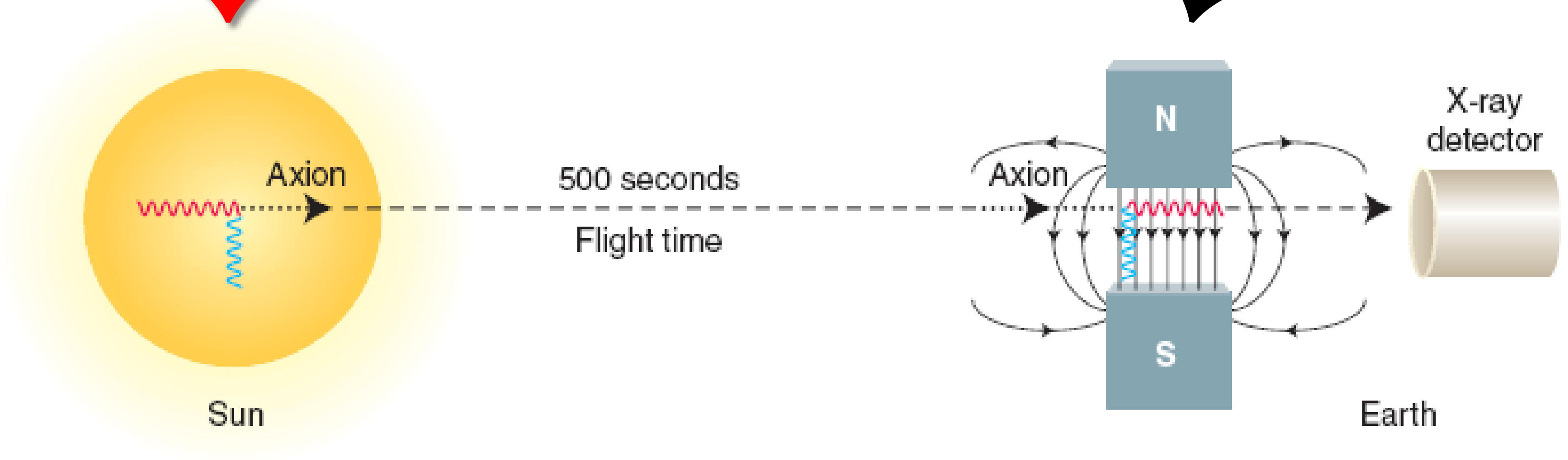


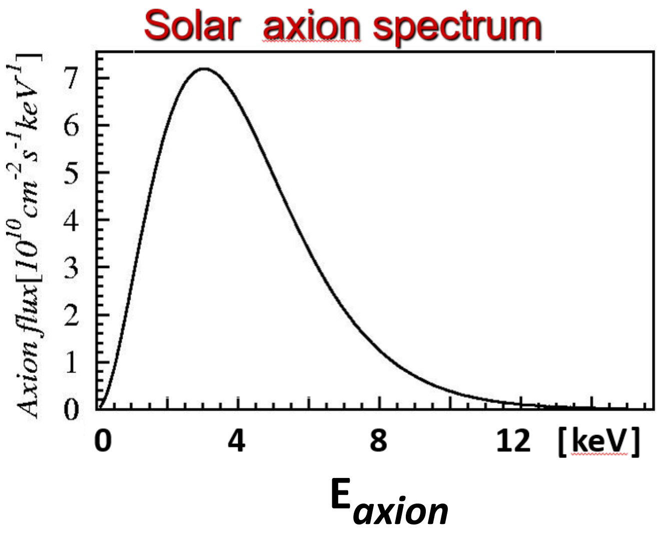
Working principle:
- *a*-helioscope
- *a*-haloscope

Axion - source

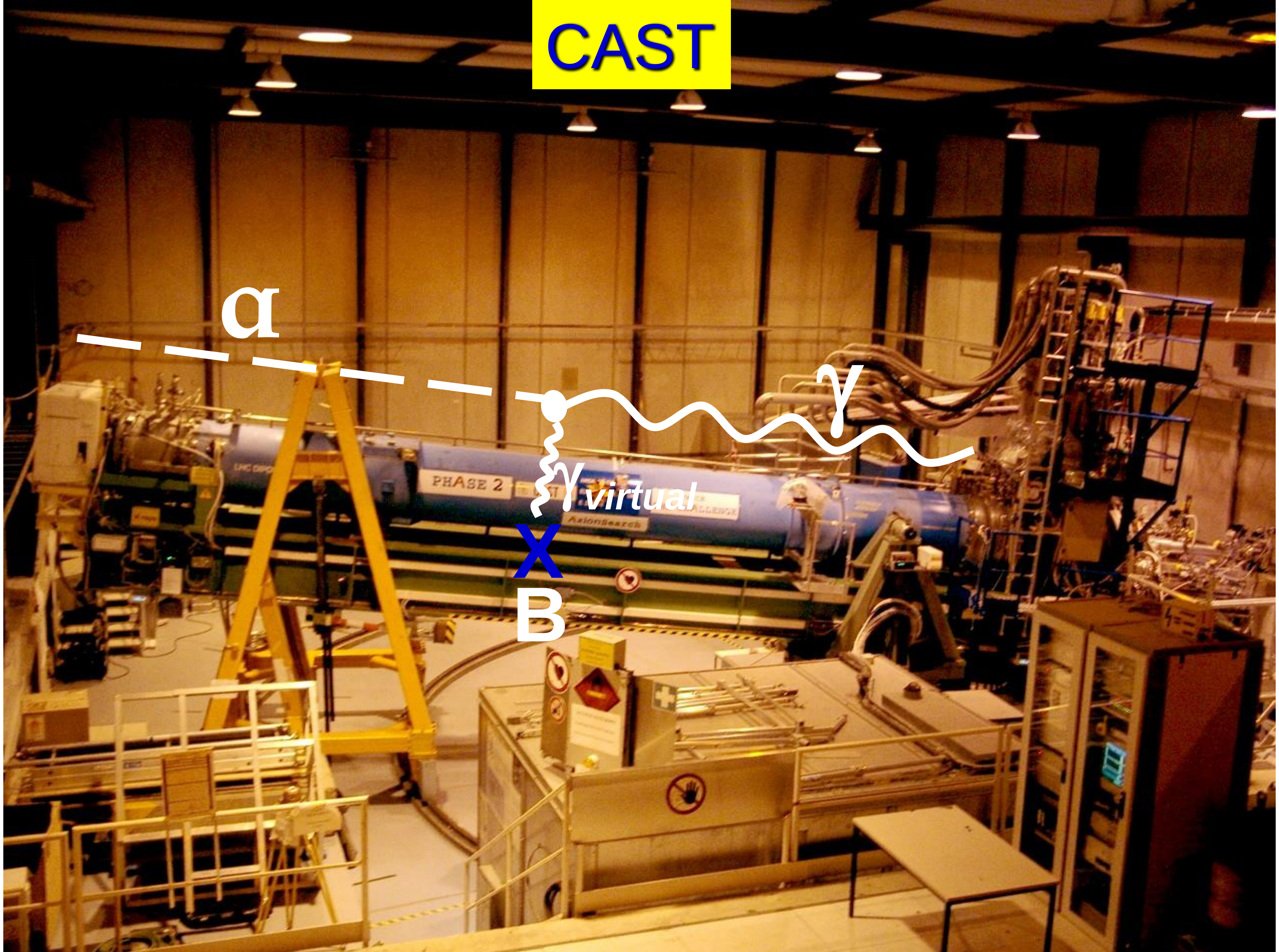
~100 ktons of axions/s overlooked?

Axion - conversion

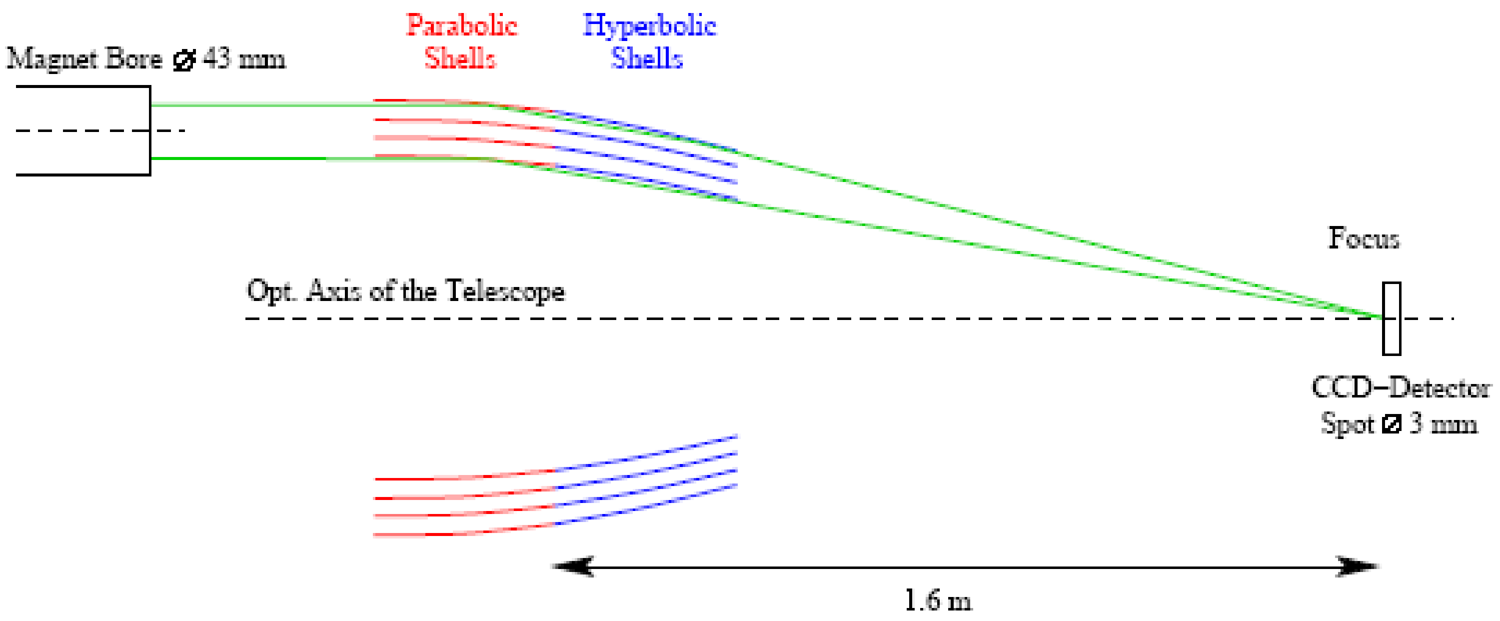




CAST



The X-ray Telescope of CAST >>> + 2nd XRT



still
a CAST "first"
in astroparticle physics

Wolter I type grazing incident optics (Prototype for *ABRIXAS* space mission):

- 27 nested gold coated nickel shells, on-axis resolution ≈ 43 arcsec
- Telescope aperture 16 cm, used for CAST 43 mm
- Only one sector of the full aperture is used for CAST

⌀43 mm (LHC Magnet aperture) $\Longrightarrow$ ⌀3 mm (spot of the sun)
Significantly improves the signal to background ratio !

Initially:

Solar axions (DM) → **solar chameleons** (DE) 2013-

<4 keV>   <1 keV>

2003-

K.Z., P. Brax PR D85(**2012**)043014

↓

DM axions (<meV) → **CAST**

2019-

with dipole magnet:

OK.Baker, …, K.Z.
PR D85(**2012**)035018
9authors **/** **7**Institutes

3 "first" done:

- Fast tuning ⇔ *a*-transients
- Phase matched cavities
  → coherence
- Unexplored axion mass

<1999 **CAST** **2020**

Axion**Phobia** → Axion**Euphoria**

CAST – CAPP >> DM axions

+ transients

Cavity axion-haloscope

https://arxiv.org/abs/1703.01436
https://doi.org/10.1111/j.1365-2966.2011.18224.x
https://doi.org/10.1088/0004-637X/814/2/122
https://doi.org/10.1093/mnras/stx1474

Theses: Marios Maroudas
Kaan Özbozduman

DATA-TAKING RESULTS
FAST TUNING & 4 PHASE-MATCHED CAVITIES!

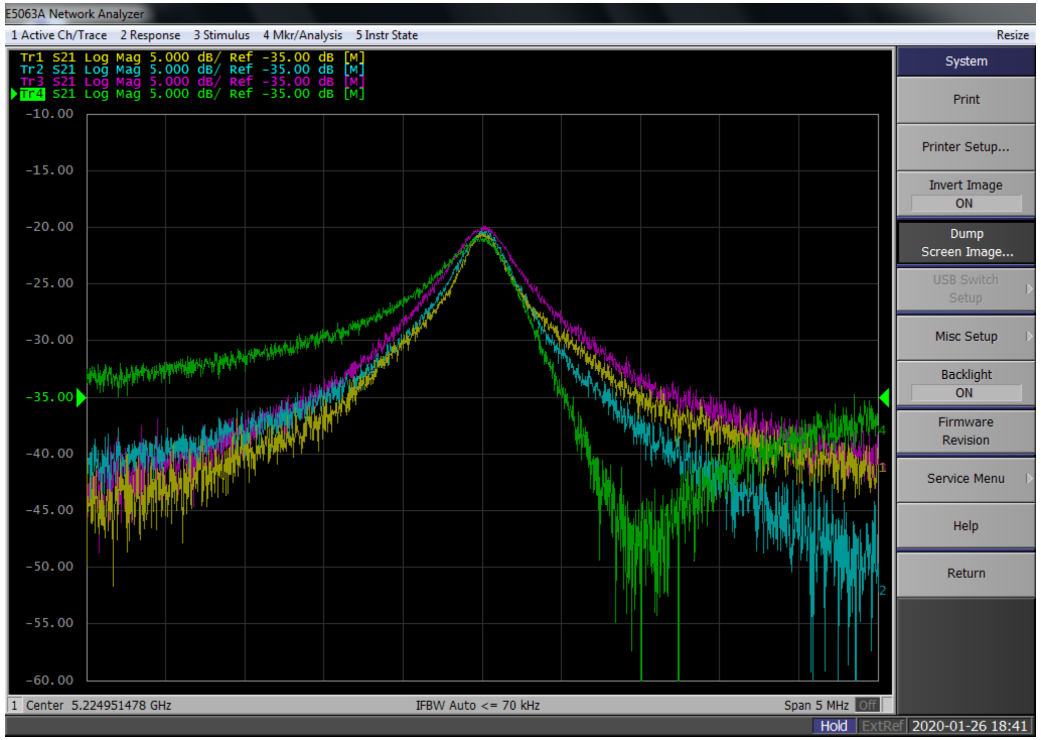
Increase sensitivity by combining coherently the read-outs from several cavities:

$$SNR_N = N \cdot SNR_{single}$$

So far:

<u>TOTAL Phase Matched cav's</u>:

448.9 h (18.7days) & 125 MHz



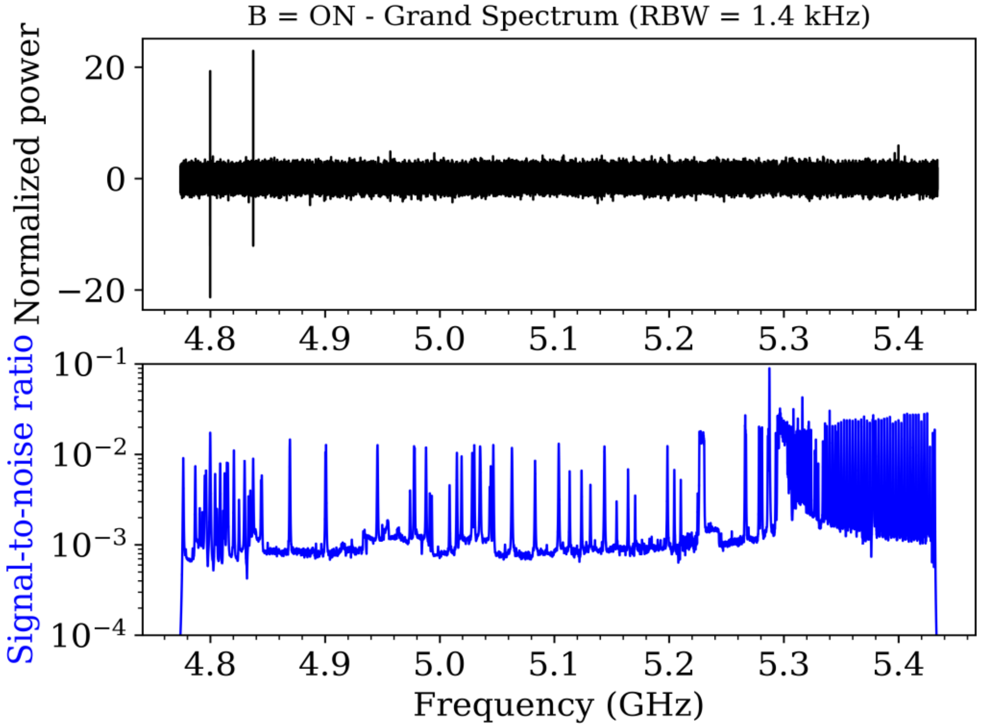
DATA-TAKING RESULTS
BACKGROUND DATA (B=OFF)

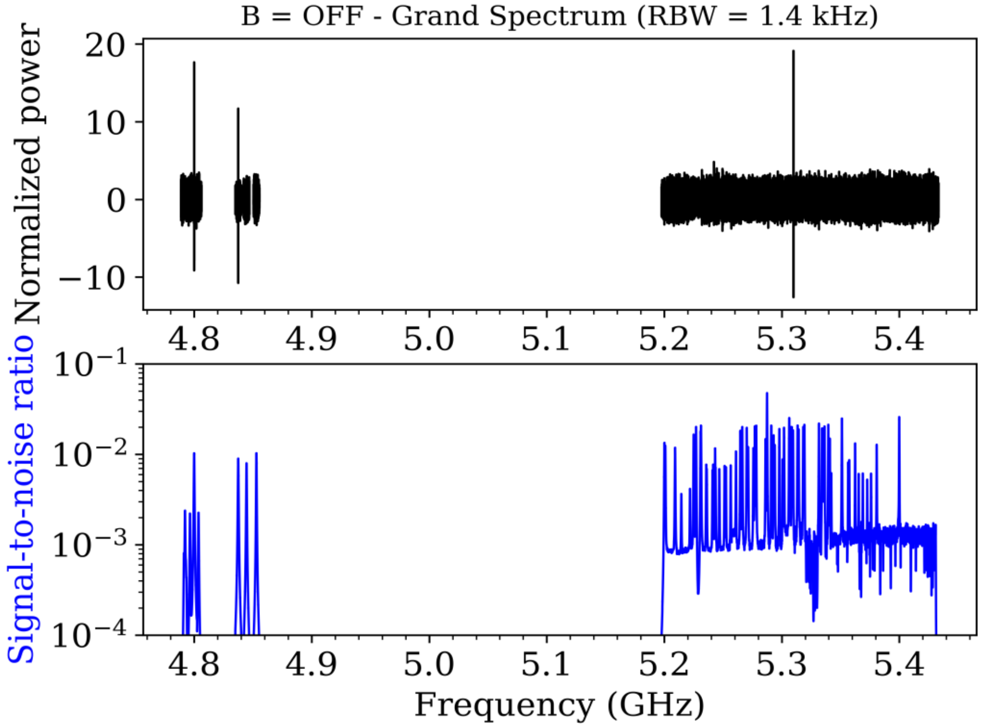
Goal: Comparison of frequencies with significant power excesses between B=ON & OFF

So far:

TOTAL BKG: 442.9 h (17.6 days) & ~150MHz

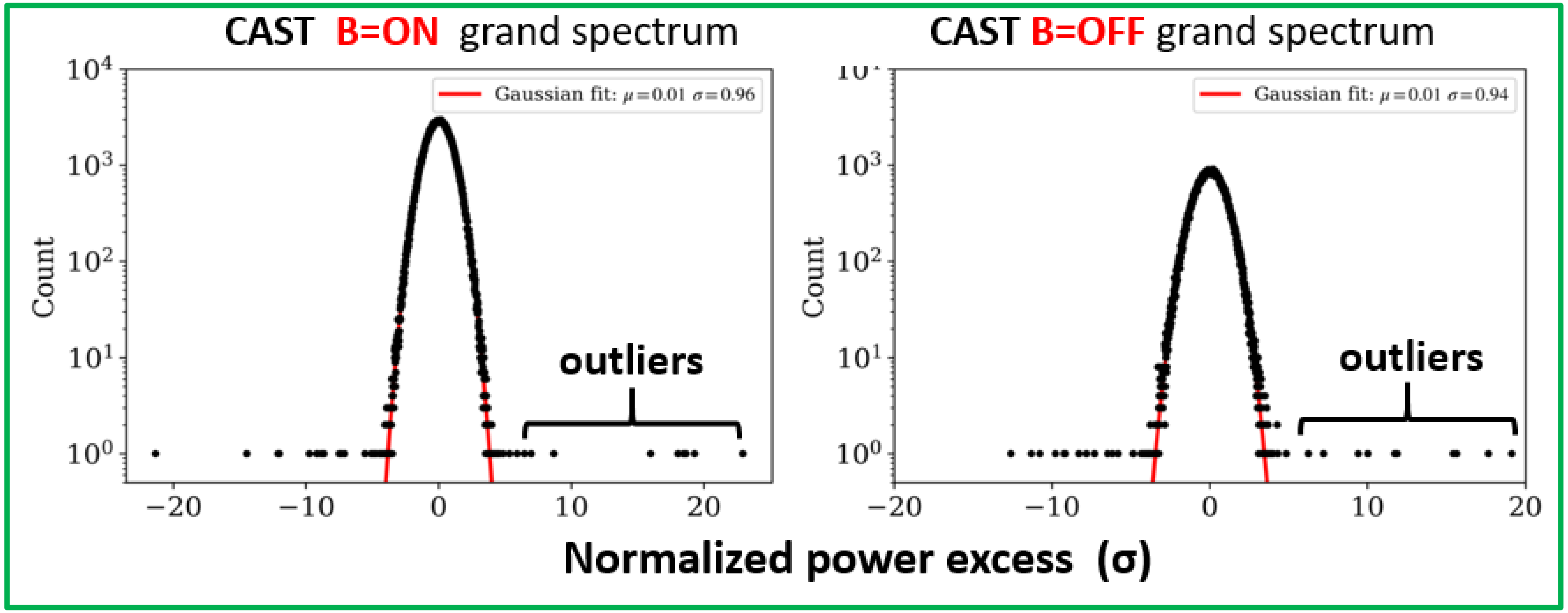
DATA ANALYSIS
RESULTS FROM ALL DATA

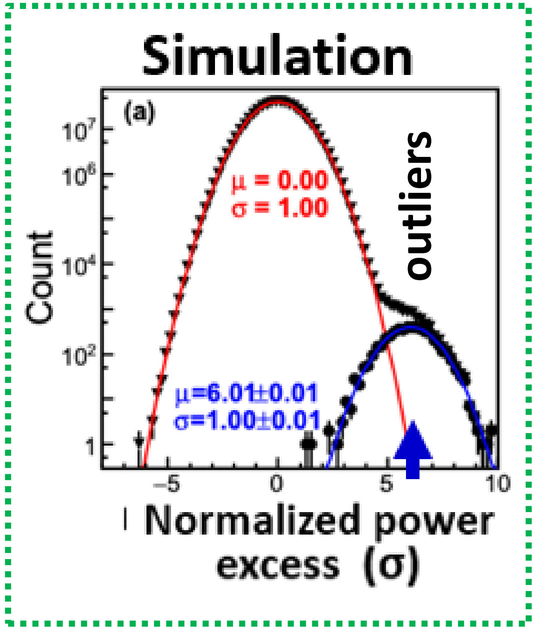




DATA ANALYSIS
RESULTS

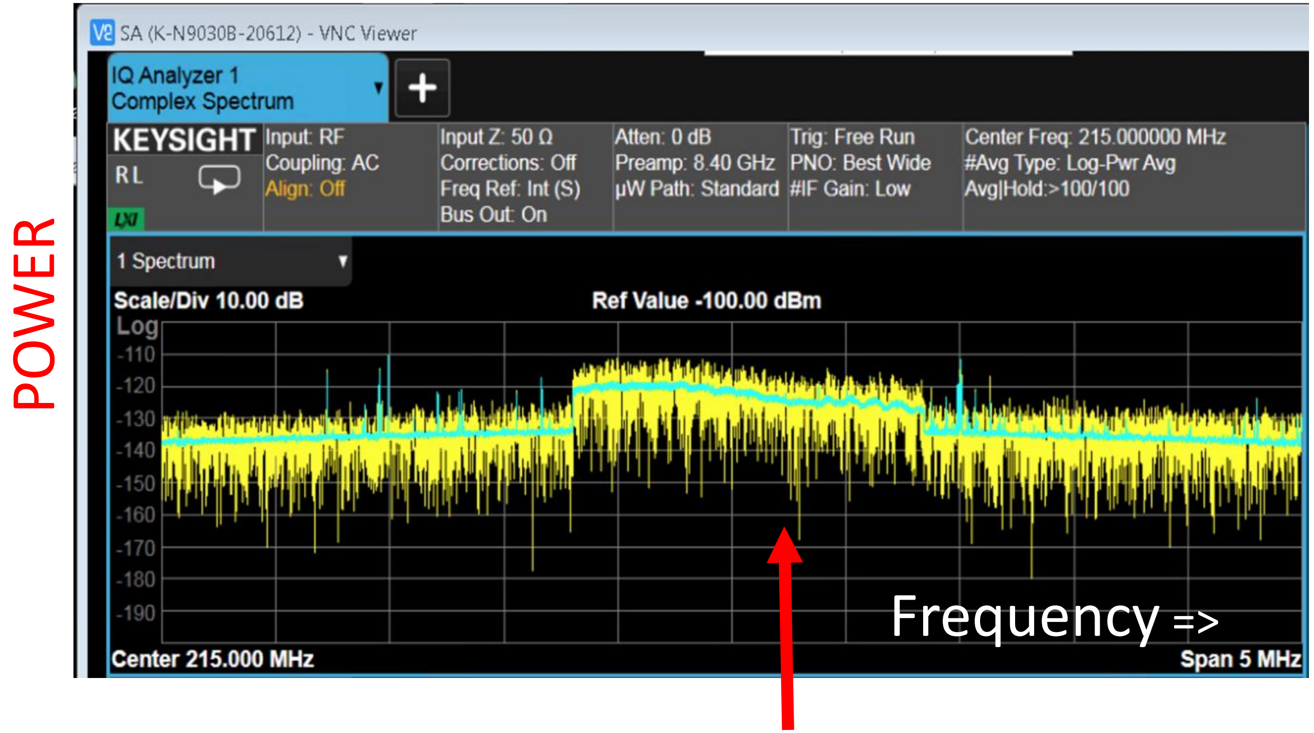
Histogram of the grand spectrum with a gaussian fit (in red). The outliers being scrutinized are the ones on the right side of the red curve.





DATA-TAKING RESULTS
BACKGROUND (ENVIRONMENTAL EMC NOISE)

07/2020



Therefore: A <u>simultaneous</u> independent measurement with a second spectrum analyzer connected to an external antenna measuring the EM noise in the CAST area = A MUST: NOW INSTALLED!

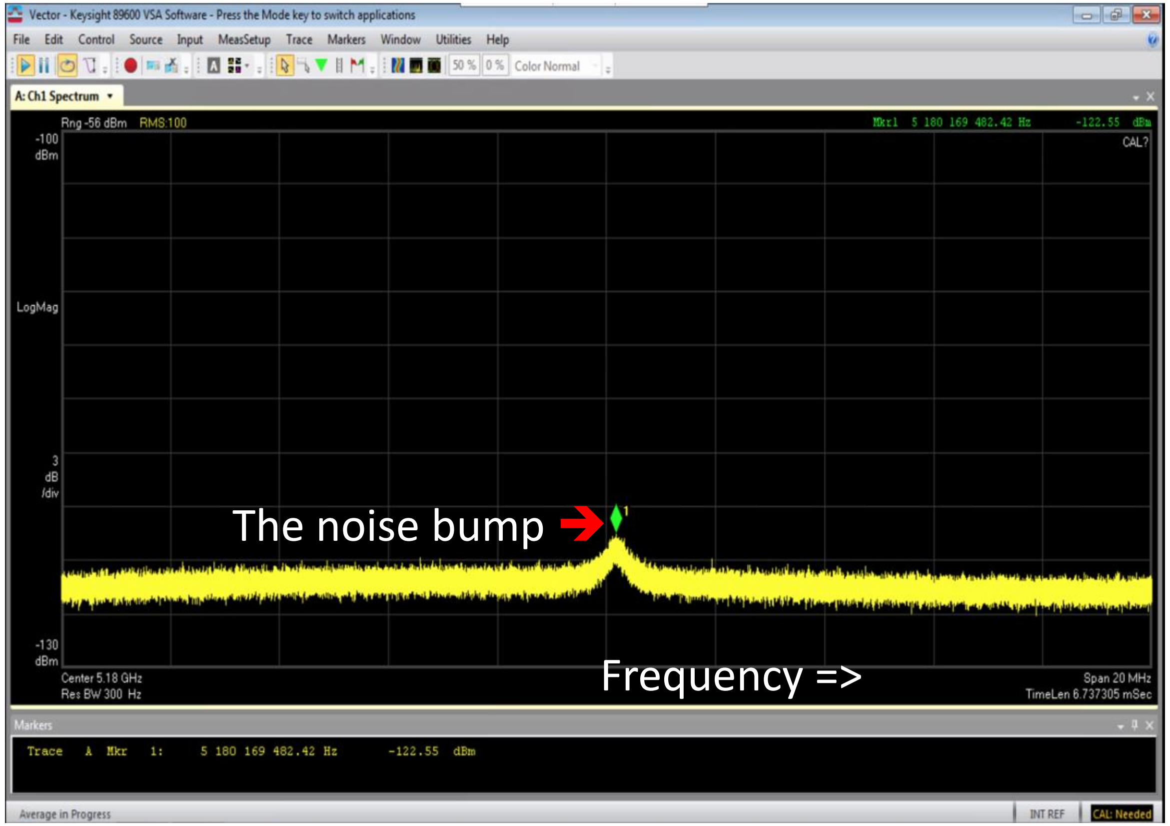
DATA-TAKING & ENVIRONMENTAL EMC NOISE

Simultaneous comparison of data from cavities with EMC data

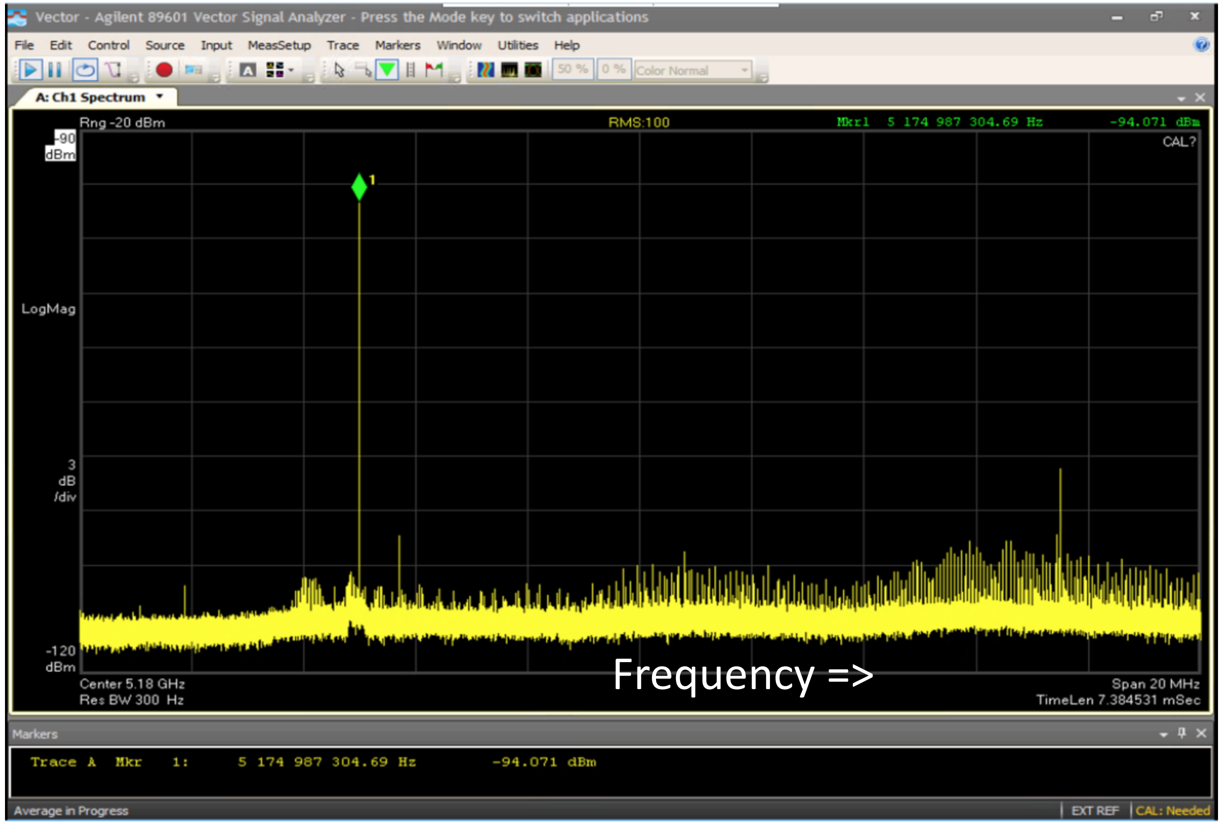
Both are in the frequency domain: FFT by the SA

Power excess

Cavity 4



EMC noise in CAST area



DATA ANALYSIS

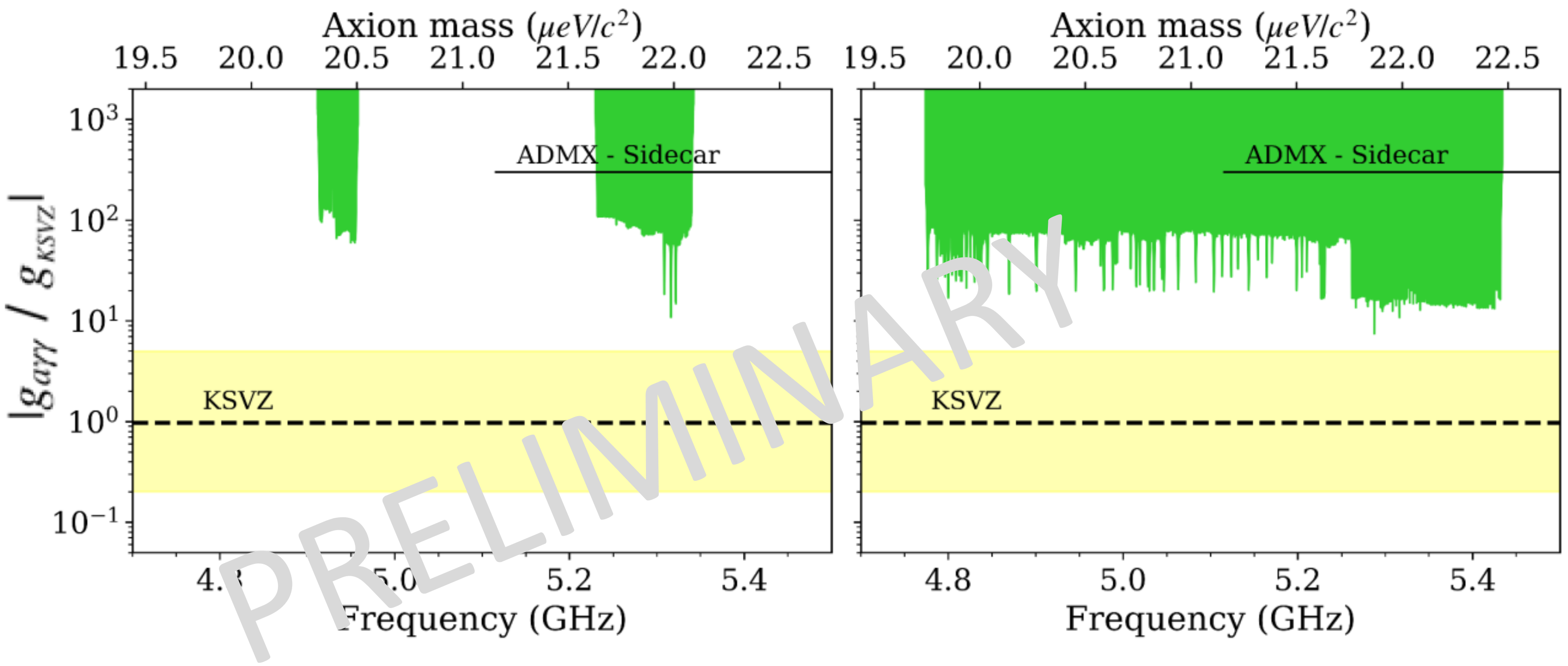
EXCLUSION PLOT ASSUMING GALACTIC DM AXIONS

So far data-taking time with single & PM cavities and **B=ON**: **1461 hours** (**60.9 days**).

Spikes correspond to longer measurement times.
For comparison **ADMX** is also given

progress

09/2019 → **10/2020**

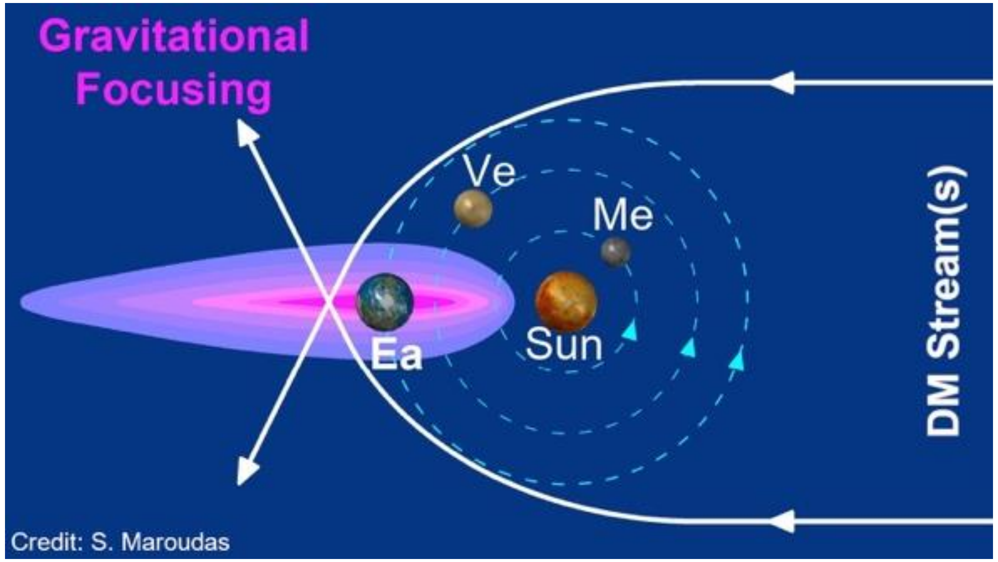


DATA-TAKING RESULTS
FAST TUNING (SINGLE CAVITIES)

Fast cavity tuning takes advantage of possible DM transients: streams / clusters
➔ gravitational (self-)focusing ➔ flux enhancement.
Special case free fall with low speed: ~46 km/s at 1 AU! [Adrien Leleu]

In total with single cavity and **B=ON:** 1013.2h (42.2 days) & ~660 MHz

Tidal streams



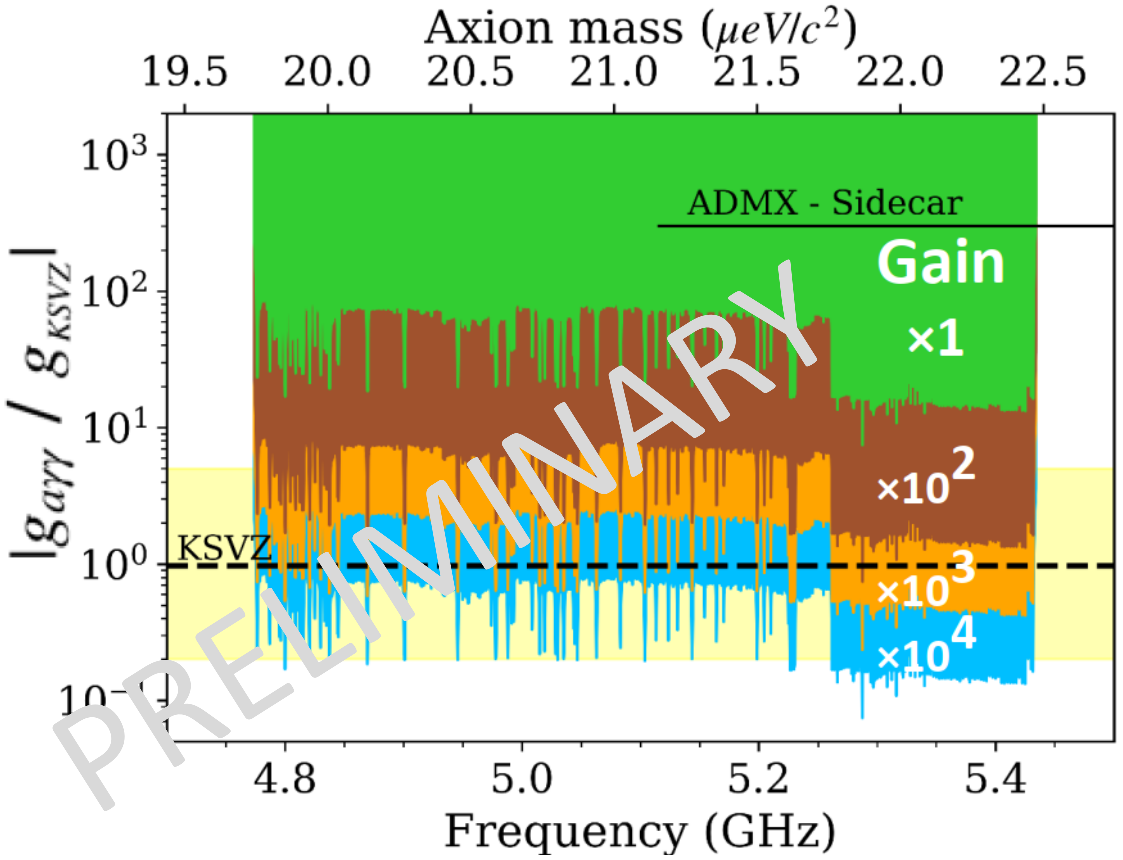
DATA ANALYSIS

SENSITIVITY PLOT FOR DM AXIONS INCLUDING FLUX ENHANCEMENT

Due to gravitational lensing (by sun, …., Moon) or axion mini-clusters

Improvement due to streaming DM axions or axion-miniClusters lasting ~1 hour and for an increased flux by factor $10^{3\pm1}$ ➔ **parasitically sensitive** also to cosmological axion transients

10/2020



Comparison with **ADMX** around 0.5 - 0.8 GHz

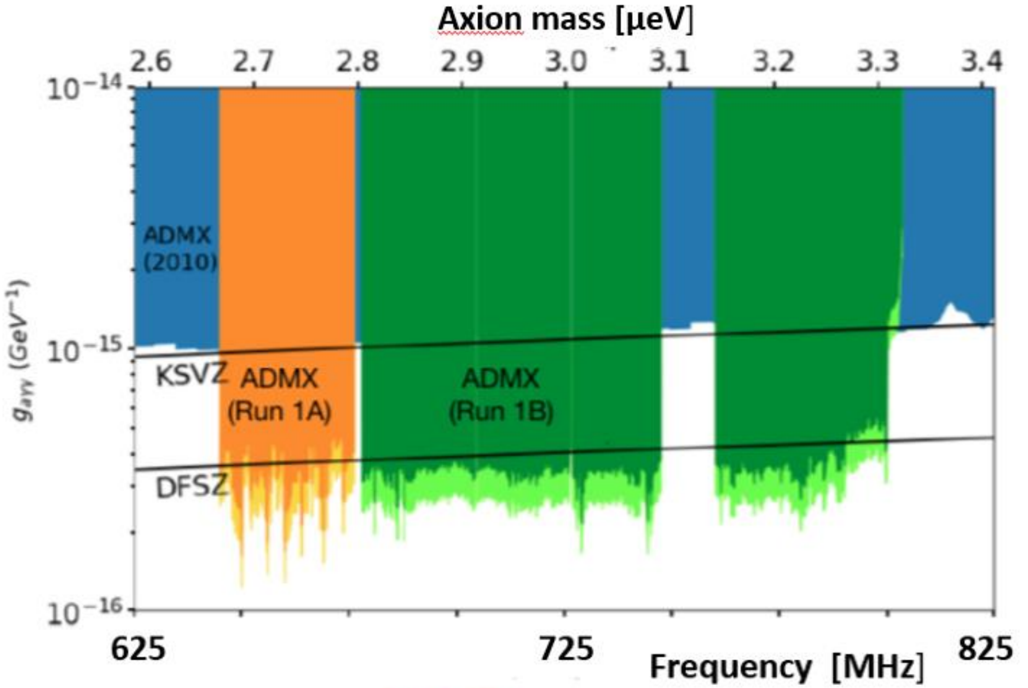


FIG. 28. Recent limits **ADMX** 90% confidence exclusion on axion-photon coupling as a function of axion mass for the Maxwell-Boltzmann (MB) dark-matter model (dark green) and N-body model (light green) from Ref[2]. Blue and Orange denote limits reported in [64] and [1] respectively.

https://arxiv.org/abs/2010.00169 **Oct 2020**

CAST (660 MHz) *vs.* **ADMX (200 MHz)**

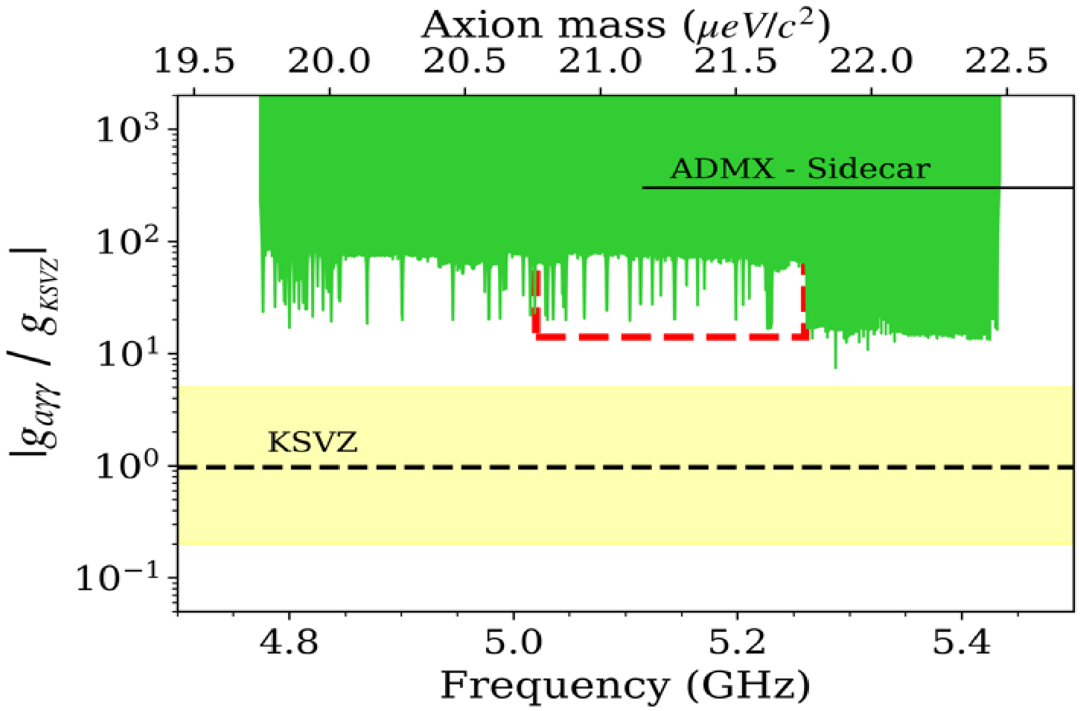
@~5 GHz **@ <0.8 GHz**

Higher axion mass ➔ *a*-Haloscopes less sensitive

=> volume effect

FUTURE PROSPECTS
DATA TAKING

- Projected relic axion detection sensitivity with the remaining 4 months (of the previously granted 6 months in total) of data taking.
- Modest Flux enhancement due to streams / clusters reaches sensitivity to QCD axions.



CAST – CAPP conclusions

1. **~2 months of data taken** over the summer. We managed to cover a significant fraction of previously unexplored parameter axion space in the range of 19.7 to 22.4 μeV and exceeded the previous limits by ADMX-Sidecar by far.
2. Data taken with individual cavities as well as with all 4 cavities **phase matched** (=coherently).
3. More **optimizations** to extend the sensitivity even further are already being prepared and will result to world-leading results.
4. The full **previously granted data taking time of 6 months**, which due to COVID-19 would extend into 2021, is essential to achieve the planned sensitivity.
5. To fully exploit its sensitivity, we have recently installed a second spectrum analyser which measures **simultaneously the ambient EM noise**.
6. CAST-CAPP has pioneered the new technology of **fast scanning** and **phase-matching** of multiple cavities, which is capable to detect transient events from streaming dark matter or axion miniclusters.
7. an **unambiguous detection** of such events requires an independent detector at another location, therefore we are currently in contact with IBS Korea on the possibilities to facilitate the establishment of a 2^{nd} detector there.

Other CAST activities

in parallel and **parasitically** to CAST-CAPP

CAST – Rades >> DM axions

>>> R&D for **babyIAXO**.

Cavity axion haloscope

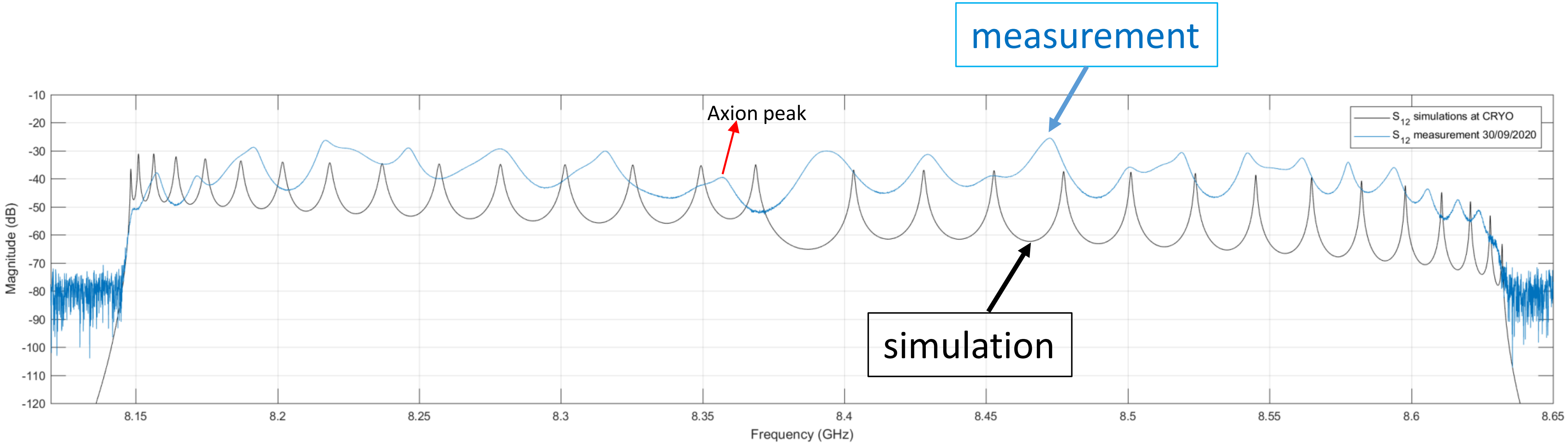
Theses: Sergio Arguedas Cuendis
Jessica Golm
José María García Barceló

RADES 1m long cavity

For 2020 data taking

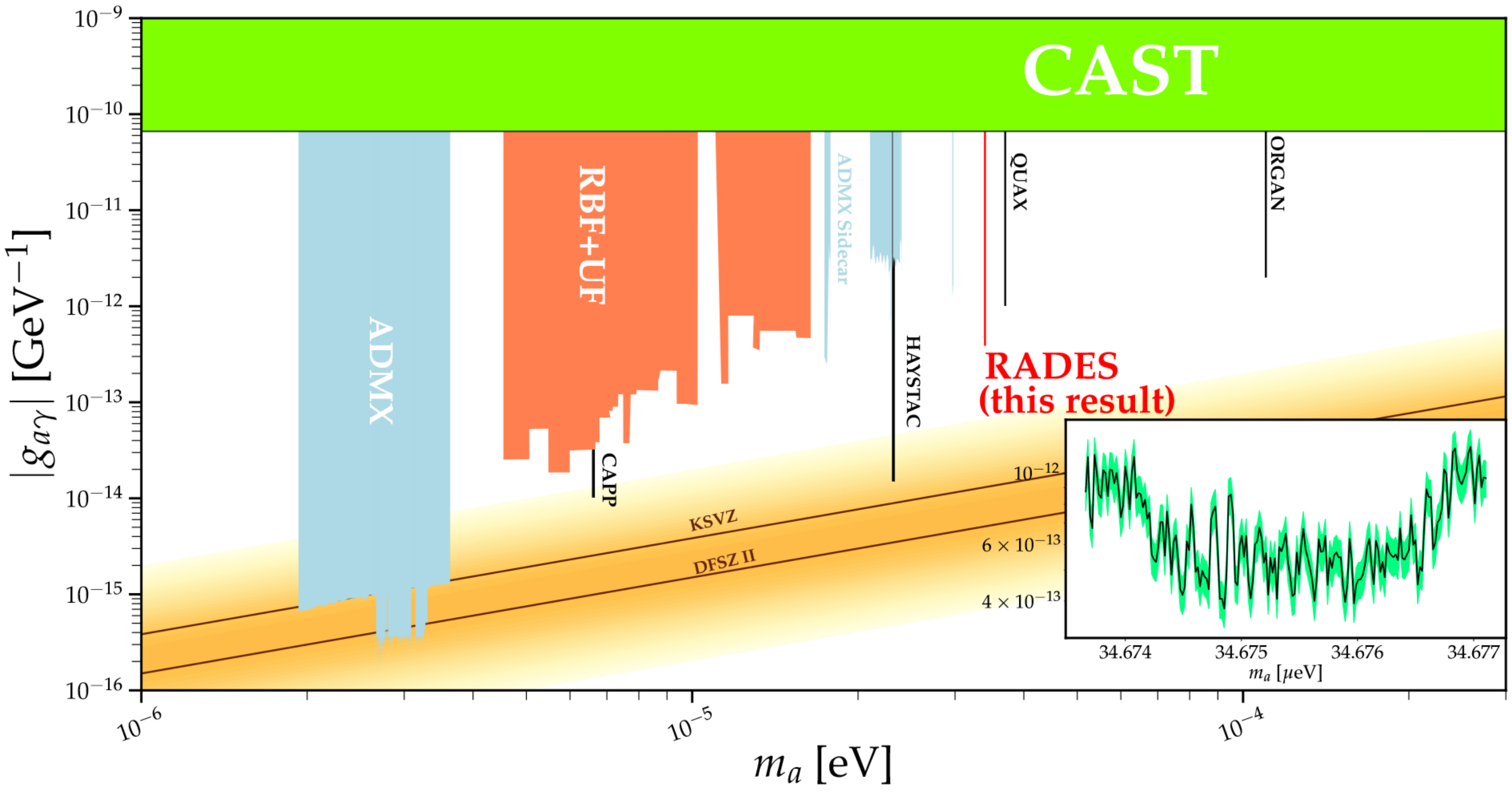
- Increase of the detection volume by a factor 5 using a more complex cavity geometry relying on alternating irises theoretically shown to be more scalable than the previous cavity. The damaged cryogenic amplifier was replaced and has been functioning as expected.

RADES 1m long cavity



- The 2020 cavity Q-value is lower than expected.
- Its EM response is also more complex and requires further characterization which are currently taking place.
- Data taking with this cavity is ongoing.
- Important R&D for **babyIAXO**.

CAST-RADES preliminary exclusion limit



CAST-RADES exclusion limit using 2018 data-set in the context of other haloscope experimental results.
Our result provides the strongest exclusion limit for an axion mass above 30 μeV.

CAST Micromegas detector

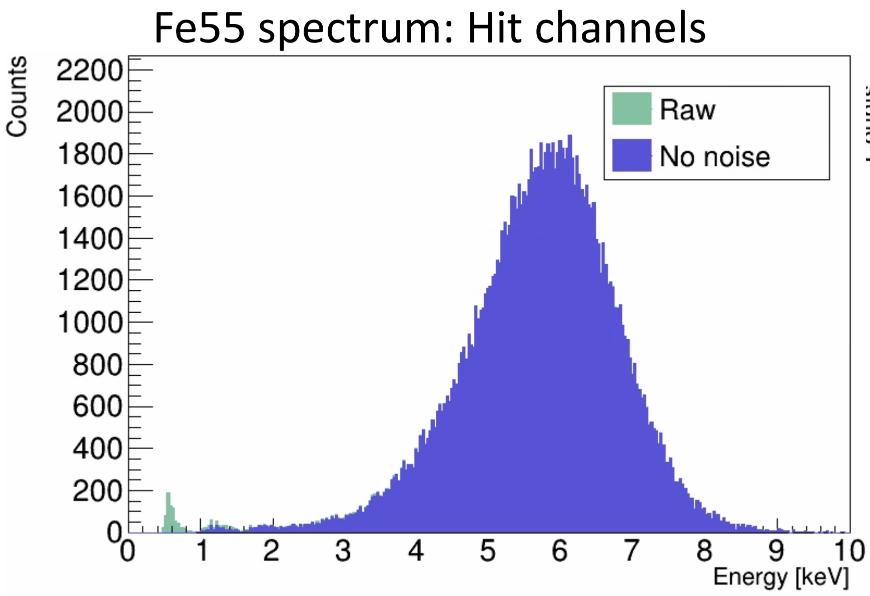
Solar axion search(DM)

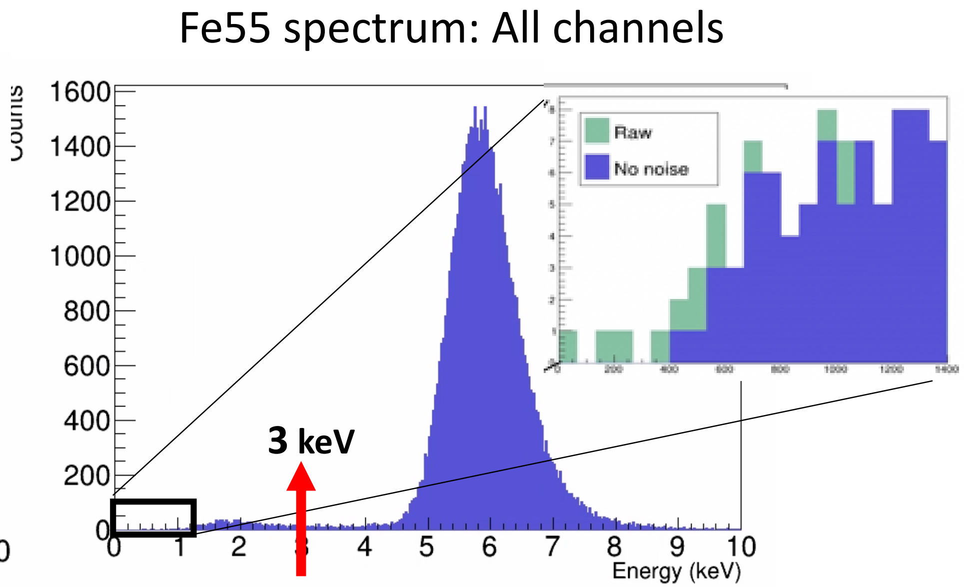
with a new detector & the 2nd XRTelescope: first xenon data →

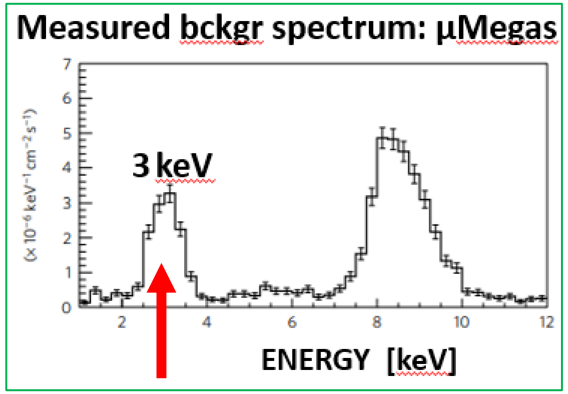
Important R&D for any future solar axion search , e.g. babyIAXO.

Theses: Cristina Margalejo Blasco,
Héctor Mirallas

Xenon runs - calibration







NATURE Phys.13(**2017**)584

Xe + 50% Ne + 2.3% isobutane	Energy threshold	Resolution @ 5.9keV	Gain (5.9 keV peak in ADC)
Hit channels	1100 eV	37%	5000
All channels	700 eV	19%	8000

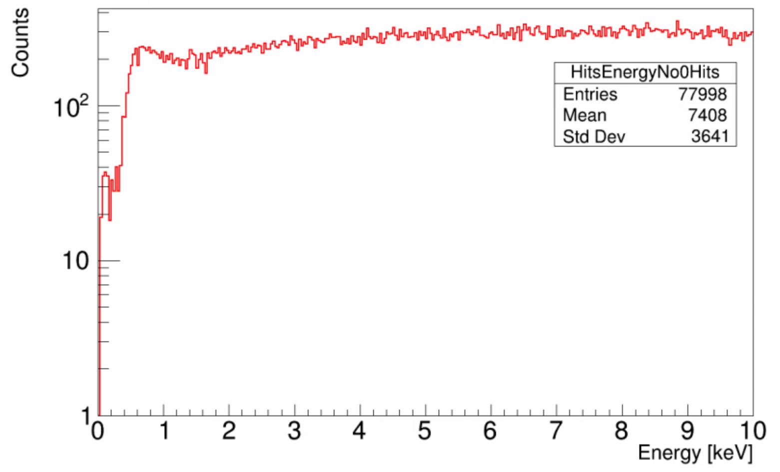
- Small peak at low energies (1 - 1.5keV). Possible fluorescence?
  - Simulations will help define its energy.
  - It will be useful for a better energy calibration at low energies.
  - **The argon fluorescence peak at ~3 keV no longer appears, reducing background level in that energy range. >> IMPORTANT!**

Xenon runs – **background** spectrum **224.5 h**

Preliminary

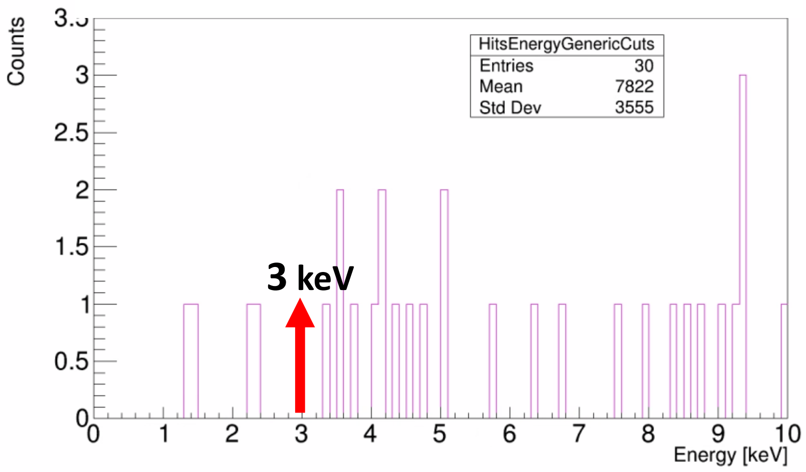
Includes only 1-prong events

Raw spectrum (**113.5h**)



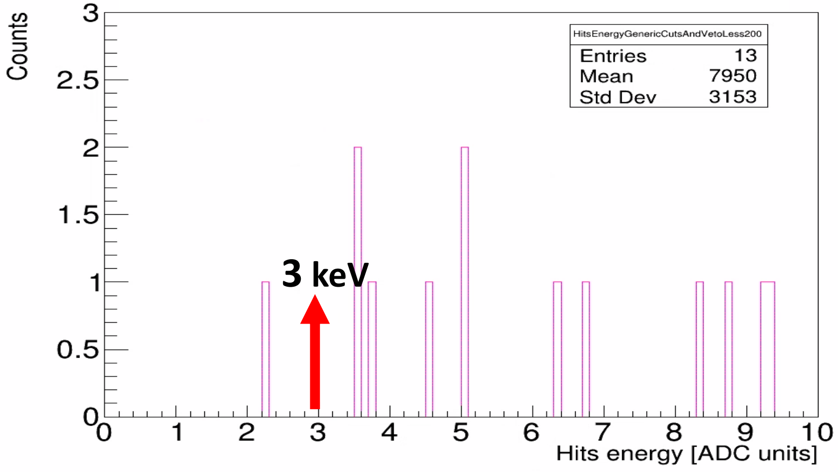
$6x10^{-3}$ c/keV/cm²/s

Generic cuts



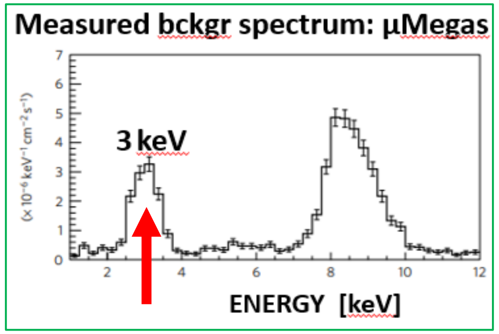
$2.1x10^{-6}$ c/keV/cm²/s

Generic cuts and veto



$1.2x10^{-6}$ c/keV/cm²/s

Background level **for 1-prong events** after generic cuts based on ^{55}Fe calibrations with Xenon



NATURE Phys.13(**2017**)584

Summary

- Ar+2.3% isobutane 2019 data taking campaign
  - ~120 hours of tracking
  - Background ~$2x10^{-6}$ c/keV/cm^2/s
  - Analysis tools under development to achieve higher efficiency
- Ar+2.3% isobutane 2020 data taking campaign
  - ~35 hours of tracking
  - Improved electronics configuration
- **Xe+50%Ne+2.3% isobutane 2020 data taking campaign**
  - **35 hours & 23 trackings**
  - Saving all channels allows us to have higher gain, better energy resolution, lower energy threshold, and potentially better X-ray selection algorithms

Next steps

- Develop new analysis strategy that matches the new electronics configuration
- Understand the differences we observe among different data taking campaigns and with the X-ray tube
- Perform simulations for the different phenomena we observed
- Possible re-calibration of the detector in the X-ray tube

InGrid

Integrated Grid

solar chameleons (dark energy) & low energy solar axions (DM)
with a sensitive low energy x-ray detector

InGrid

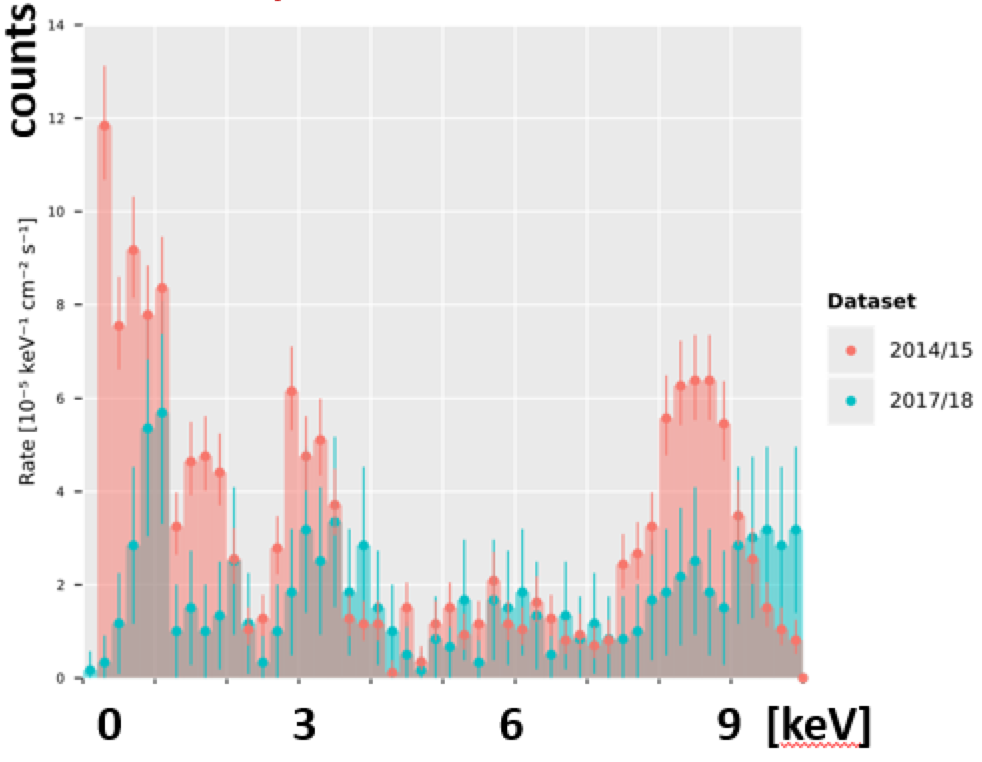
Data analysis of the 2017/18 data nearing completion on the software side.

Analysis framework **including limit calculation is done**.
Background rate still preliminary, due to:

- usage of detector vetoes via scintillators to be finalized (cut values to be fixed)
- GridPix(= Timepix + InGrid). Outer 6 GridPix validation for background rate over whole chip outstanding (=> understand clusters near chip edges
  - data lossy, gap between chips)
- Possible improvement from better FADC utilization
- significant variation of photo peak position (in charge or pixels) of ^{55}Fe calibration data observed. Current energy calibration suffers possible bias because of this. Excess of 2017/18 in plot near 4 and 9.5 keV likely due to overestimate of energy in part of dataset.

Finally, a structured check of the whole analysis pipeline is ongoing to verify no major bugs are hiding, by validating all intermediate steps.

Background rate (2017/2018) compared with 2014/2015



Status of the KWISP detector

>>> Solar Chameleons

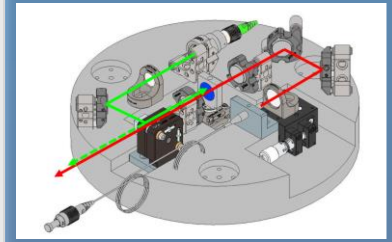
<u>Working group</u>: *J. Baier, D. Božičević, G. Cantatore, S. Cetin, H. Fischer, A. Gardikiotis, M. Karuza, Y. Semertzidis, K. Zioutas*

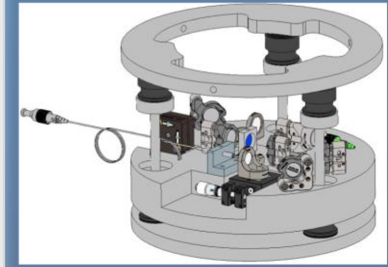
Detection by ***radiation pressure*** on a Si_3N_4 nano-membrane

Theses: Justin Baier
Martin Markanovic
Dorotea Bozicevic

KWISP current version overview

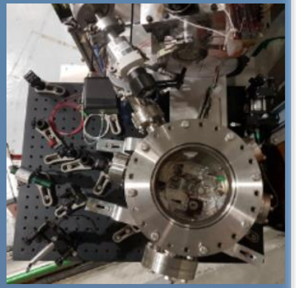
KWISP 3.5



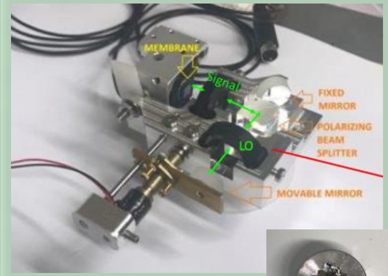


- **Fabry-Pérot interferometer** with full fiber-optic beam transport
- improved monolithic optics design
- uncoated membrane
- “sandwich-type” passive vibration isolation
- built-in force calibration with auxiliary beam
- DMD chopper

- Already acquired ~ 9h of sun-tracking data
- **Data taking continues**

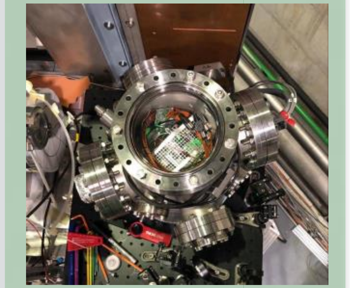


KWISP 1.5



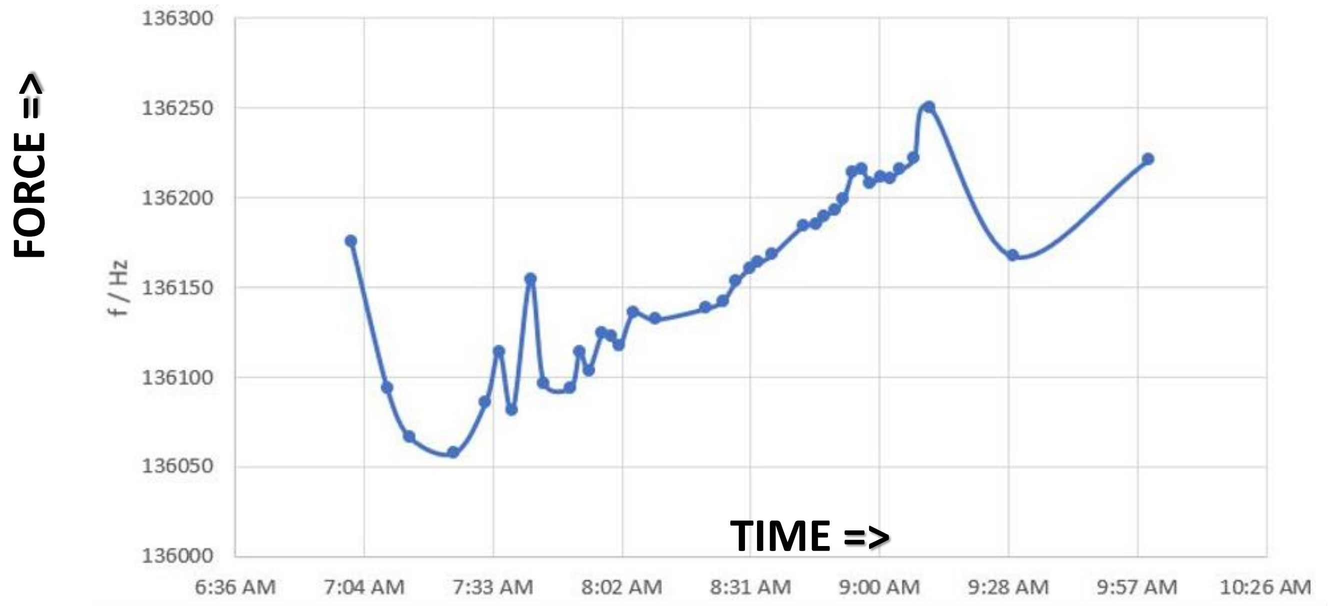
- **Michelson interferometer**
- monolithic design
- high density Pt coated membrane
- “sandwich-type” passive vibration isolation
- “chopper-less” detection

- Short sun-tracking run in January 2020
- Presently under test and calibration in the laboratory



KWISP 1.5 status

- **Parasitic** tracking performed in January 2020 with **KWISP 1.5**
  - Sensitive to a static force ⇒ change in the frequency of the membrane mechanical resonant mode
  - Now under calibration in the laboratory to check for long term pressure and temperature effects
  - Preliminary force sensitivity in the **pN** range



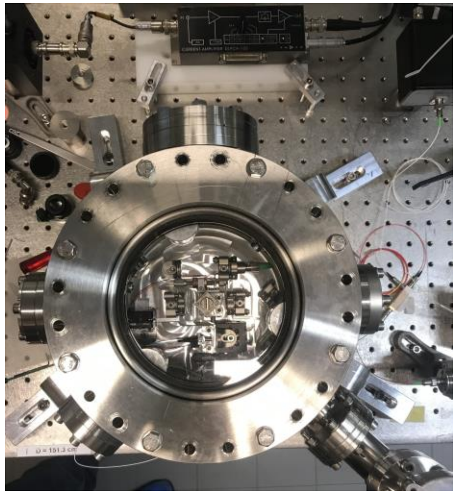
Sample KWISP 1.5 data from the 23/1/2020 sun tracking run

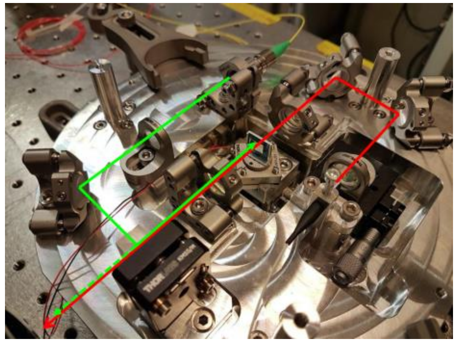
The linear trend can be interpreted as due to the variation of the component of the gravity force normal to the membrane surface when the CAST magnets tilts vertically

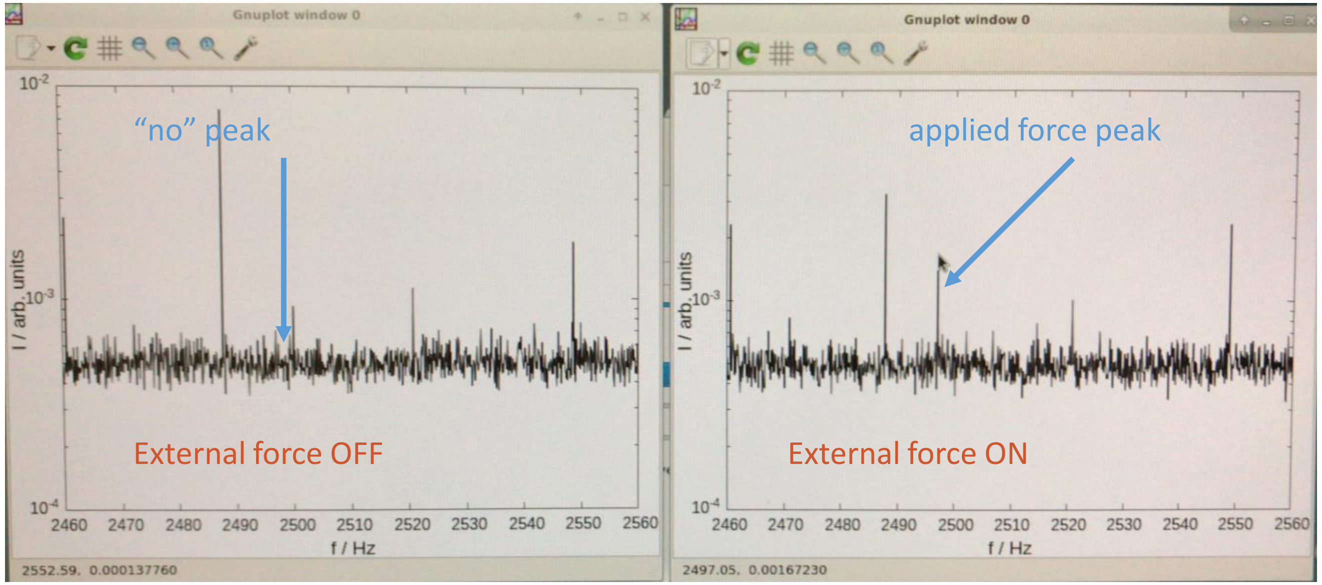
KWISP 3.5 calibration

- **KWISP 3.5** is home made
  - stable lock under vacuum
  - **successful direct force calibration** with built in auxiliary 532 nm laser beam (amplitude-modulated at a controlled frequency)
  - **Preliminary sensitivity estimate from direct calibration**

    $8 \cdot 10^{-12}$ N/ √Hz @ 2.5 kHz



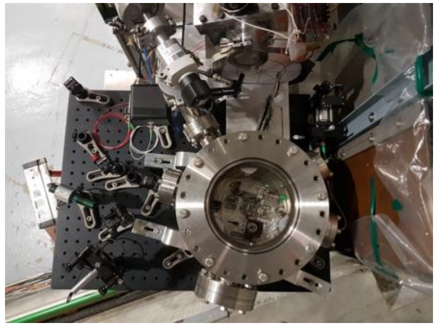




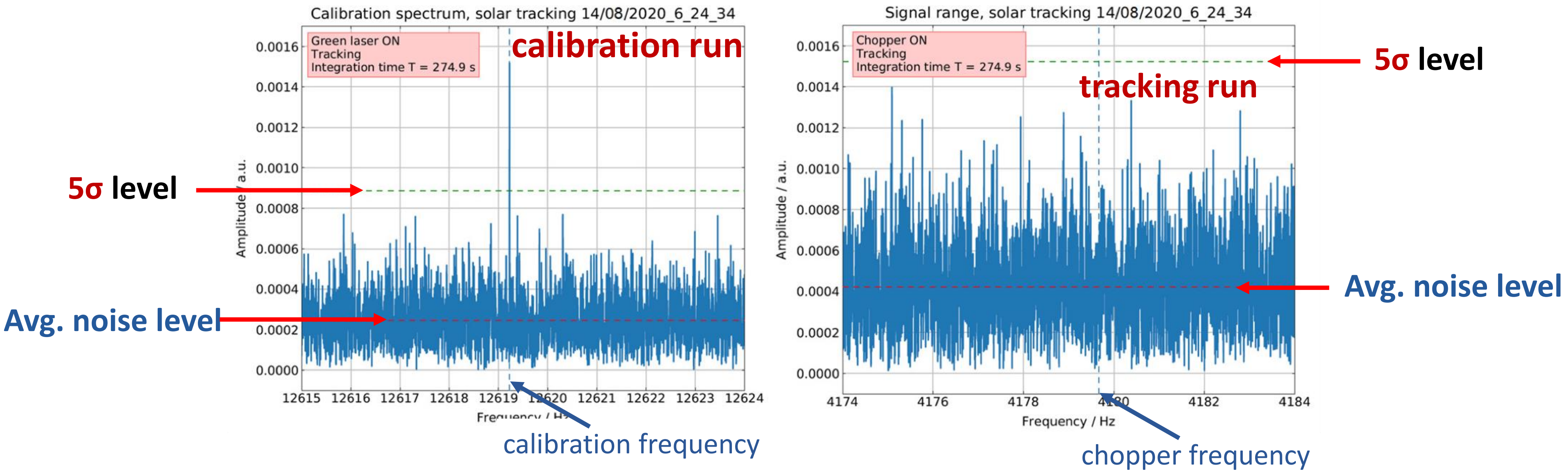
Direct force calibration near the chopper expected frequency of operation (~2.5 kHz)

KWISP 3.5 preliminary sun-tracking runs

- **July 2020: Installation**
- **August 2020: Sun-tracking-** parasitically, no magnetic field needed
  - Sun **tracking data: 11 hours.**
  - **Background & Calibration: 21.3 hours.**
  - **Preliminary sensitivity 28 pN/√Hz**
- **No solar signal yet**
- Minimum force detected in 275 s was **~3.3 pN**, MORE DATA AVAILABLE: ~30000 sec. Therefore,
- **>10× better min detected force**



	Chopper (4202 Hz)		Green (12619 Hz)	
	ON	OFF	ON	ON, blocked
Tracking	31886 s (8,9 h)	7697 s (2,1 h)	21166 s (5,9 h)	-
Parking	20616 s (5,7 h)	56350 s (15,7 h)	19791 s (5,5 h)	20066 s (5,6 h)



KWISP next steps >>> parasitically

- **KWISP 3.5**
  - **Complete analysis** of taken data
  - **faster online calibration** (under way)
  - **continue taking solar data** as long as possible
- **KWISP 1.5**
  - **study long term stability**

CAST conclusions

- **~2 months of data taken** over the summer, now stopped up to mid of November due to water tower maintenance (not related to CAST).

- **Fast tuned & phase matched cavities** pioneered by CAST.

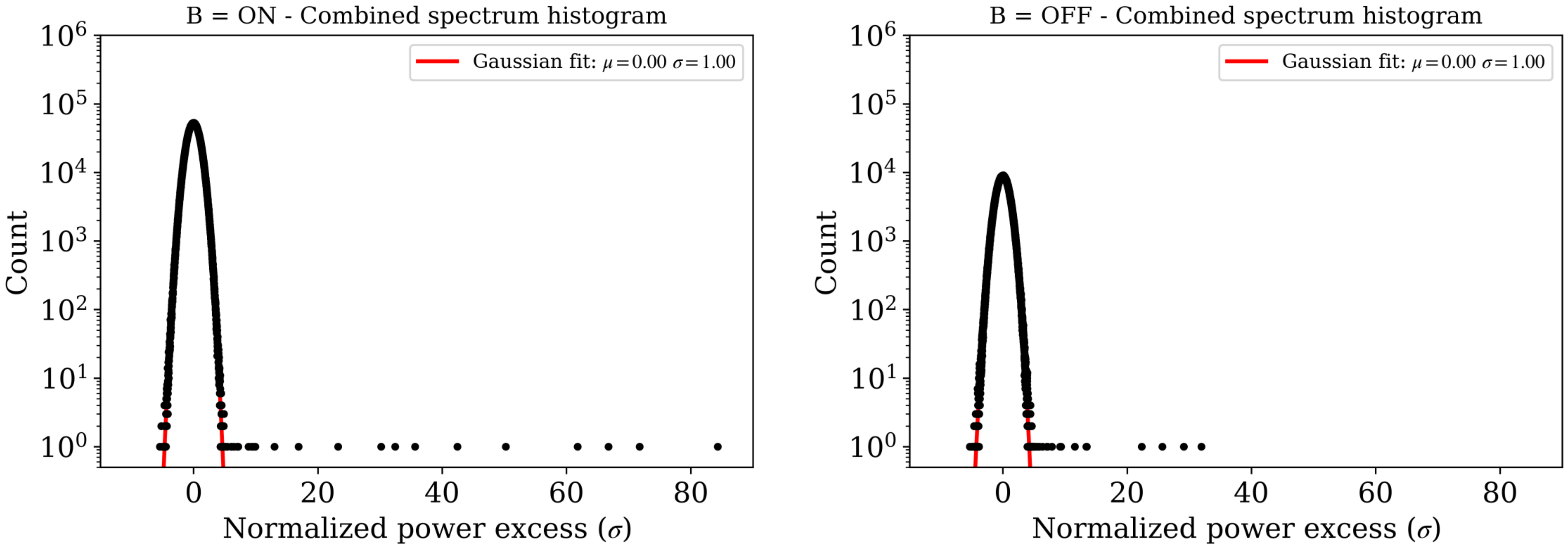
- The **full previously granted data taking time of 6 months**, which due to **COVID-19** would **extend into 2021**, is **essential** to achieve the planned sensitivity.

- The **missing 4 months** of data taking are **extremely important for the theses of our students**.
The estimated remaining data taking time for 2020 is less than 1 month. For the DM search the efficiency is ~18h/24.

Backup slides

DATA ANALYSIS
BEYOND THE ~5KHZ SIGNAL SEARCH

Histogram of the **combined** spectrum with a gaussian fit (in red). Combined spectra are more appropriate for DM transients due to non-restriction to a ~5kHz signal search.



DATA ANALYSIS
RESULTS

Combined spectra are more appropriate for transients (no width constraint).