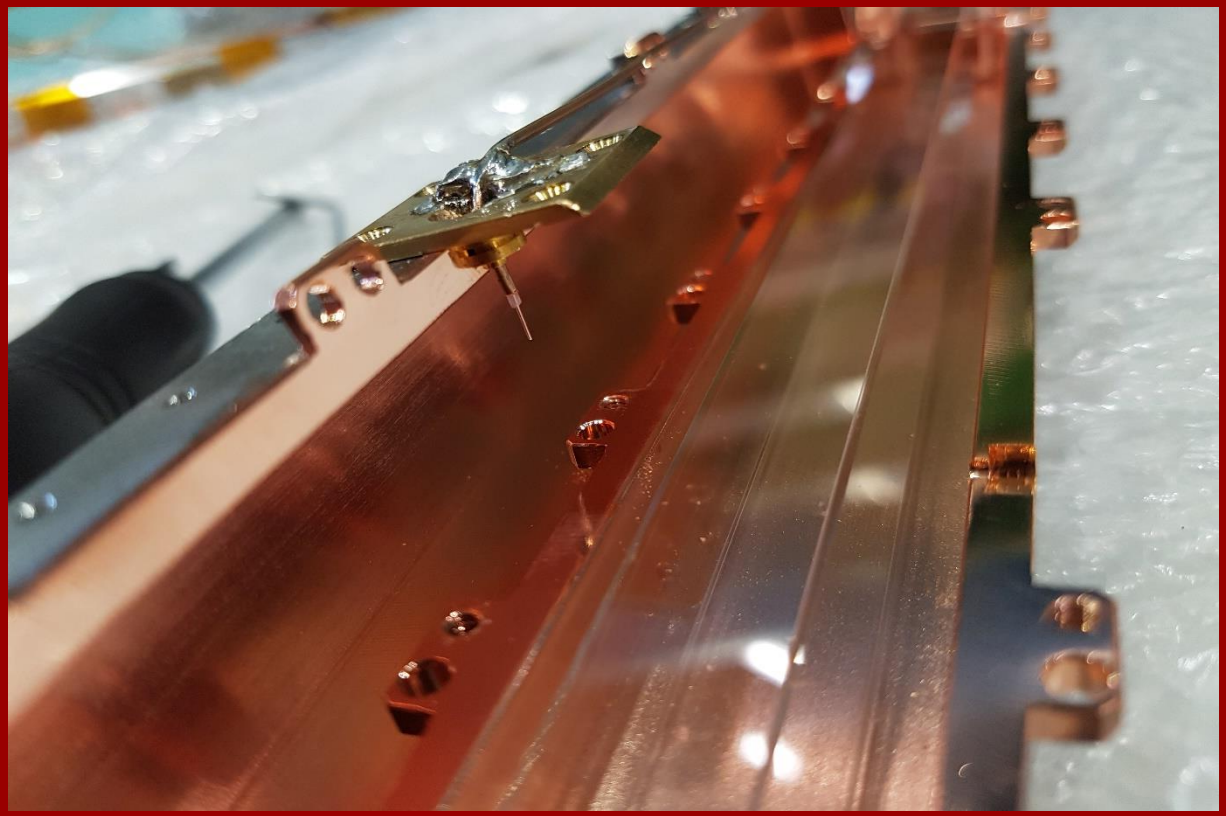
CAST



CAST EXPERIMENT

10th June 2021

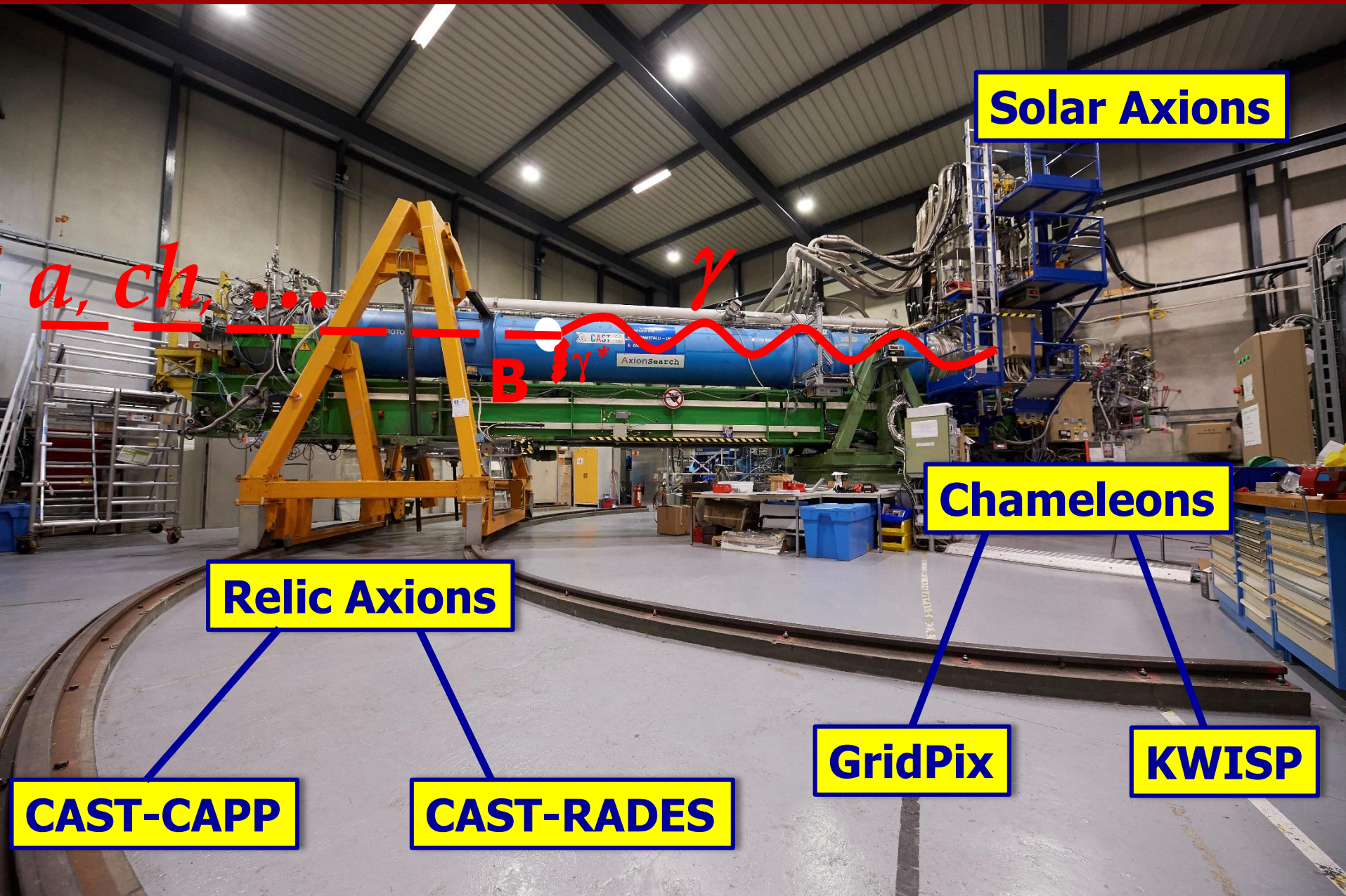
Status Report to the SPSC for the 142nd Meeting

Horst Fischer on behalf of

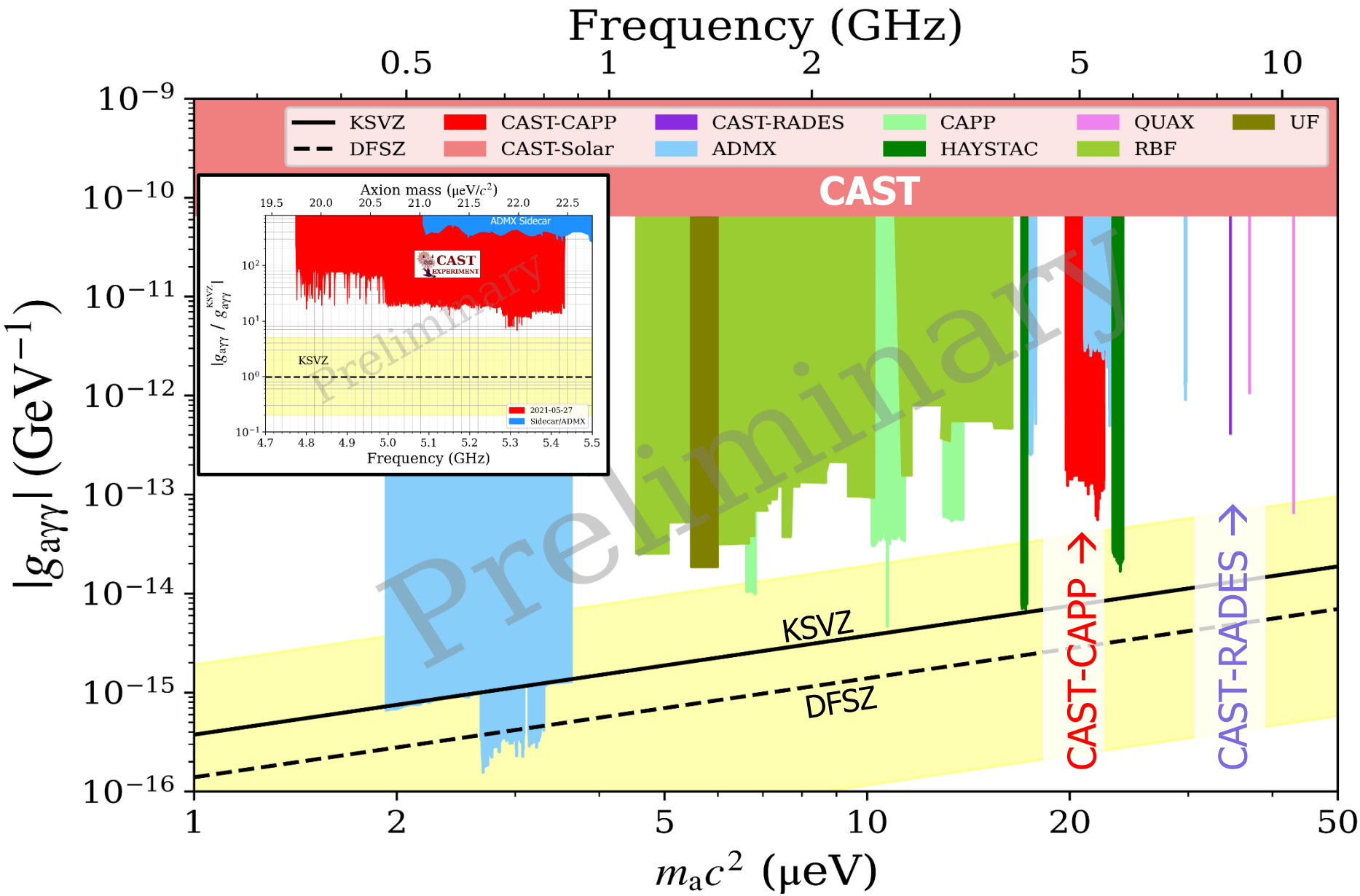
the CAST Collaboration

UNI FREIBURG

The CAST Physics Programme



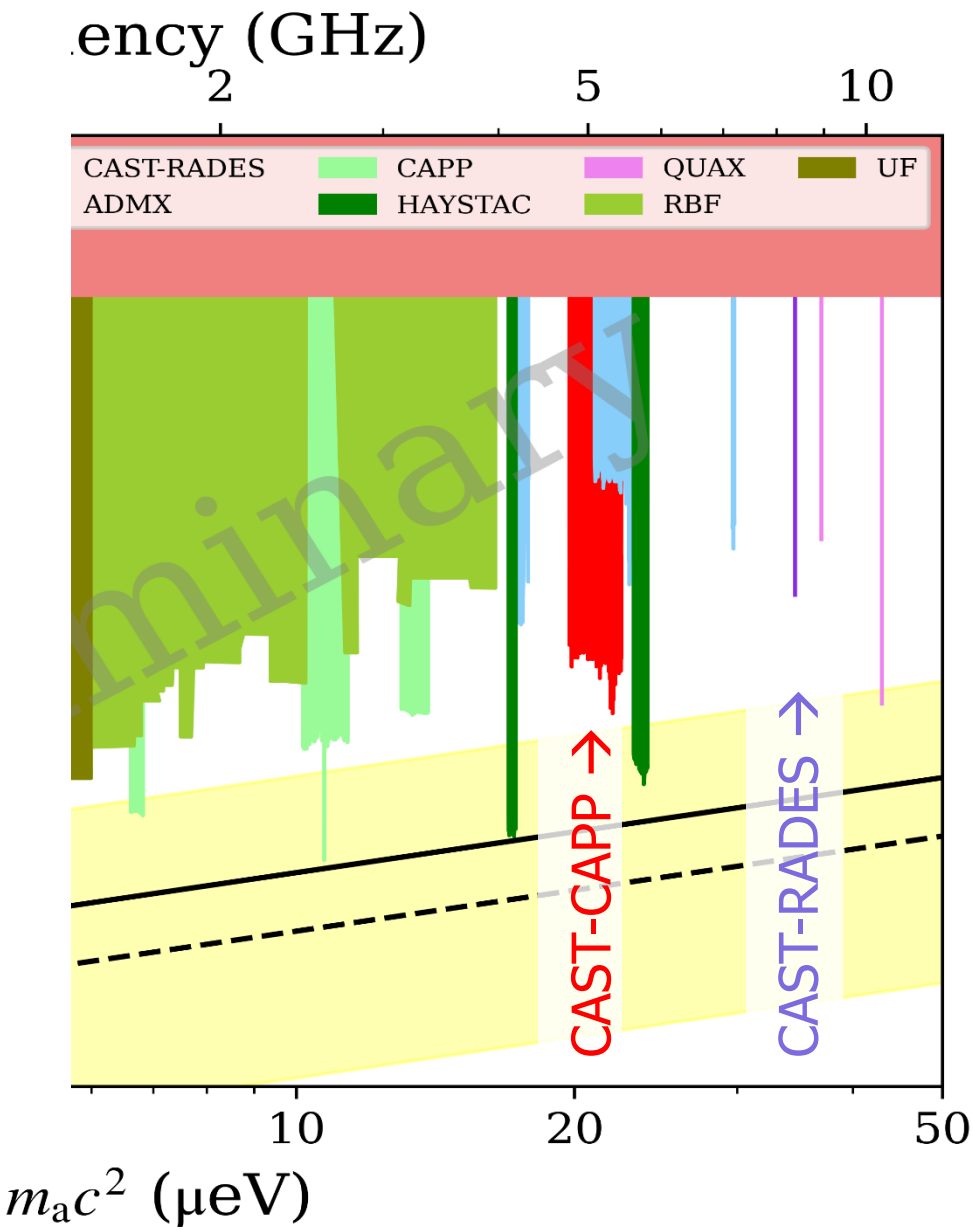
CAST on Halo Axions



CAST on Halo Axions

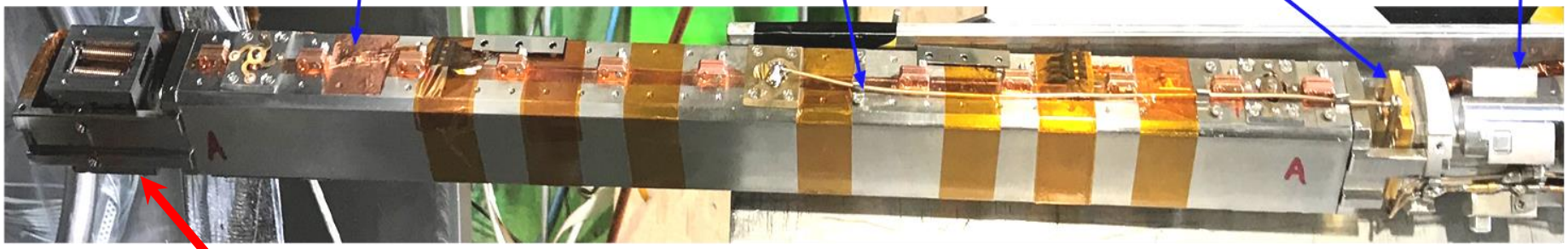
Outline:

- **Status of CAST-CAPP**
- **R&D towards BabyIAXO**
  - CAST-RADES (relic Axions)
  - MicroMegas (solar Axions)
- **Chameleon Search**
  - InGrid (photon coupling)
  - KWISP (matter coupling)



Status of CAST-CAPP

CAST-CAPP: A Fast Tuning Broadband Cavity



55 cm

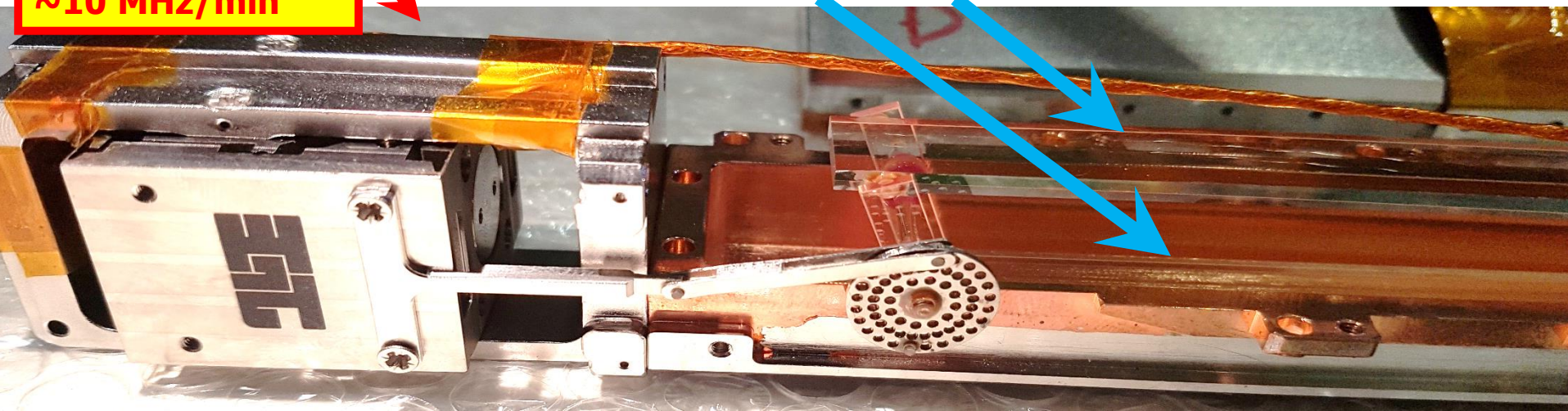
Cavity volume: (23 x 25 x 390) mm³

Fast tuning mechanism

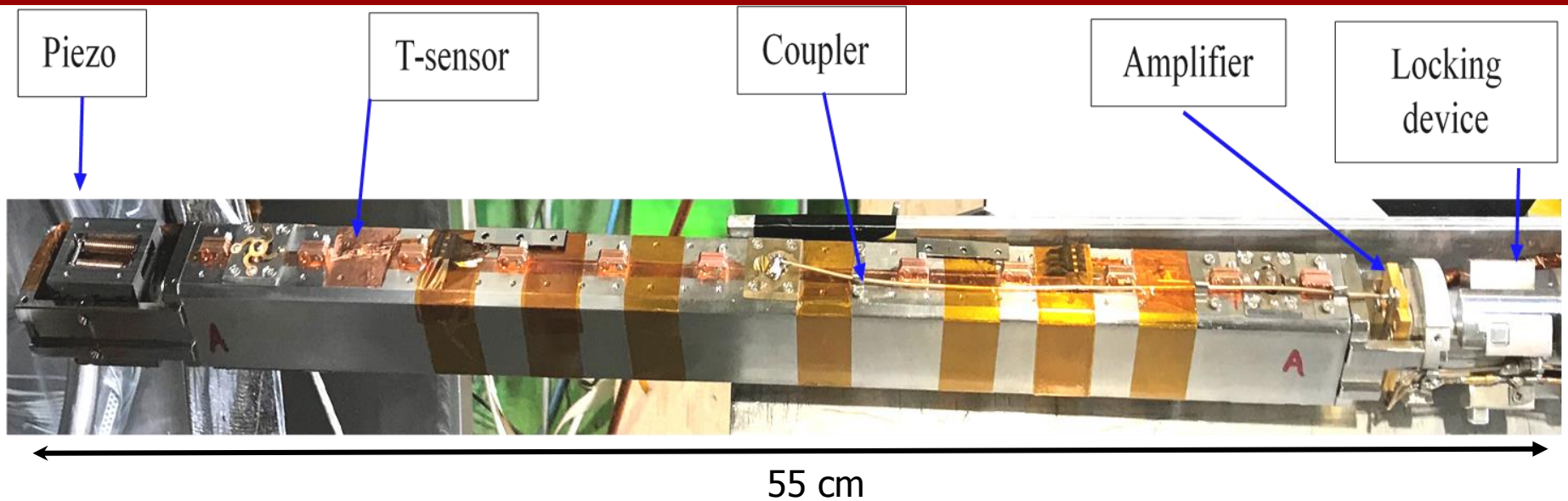
~10 MHz/min

Fast tuning allows for transient search

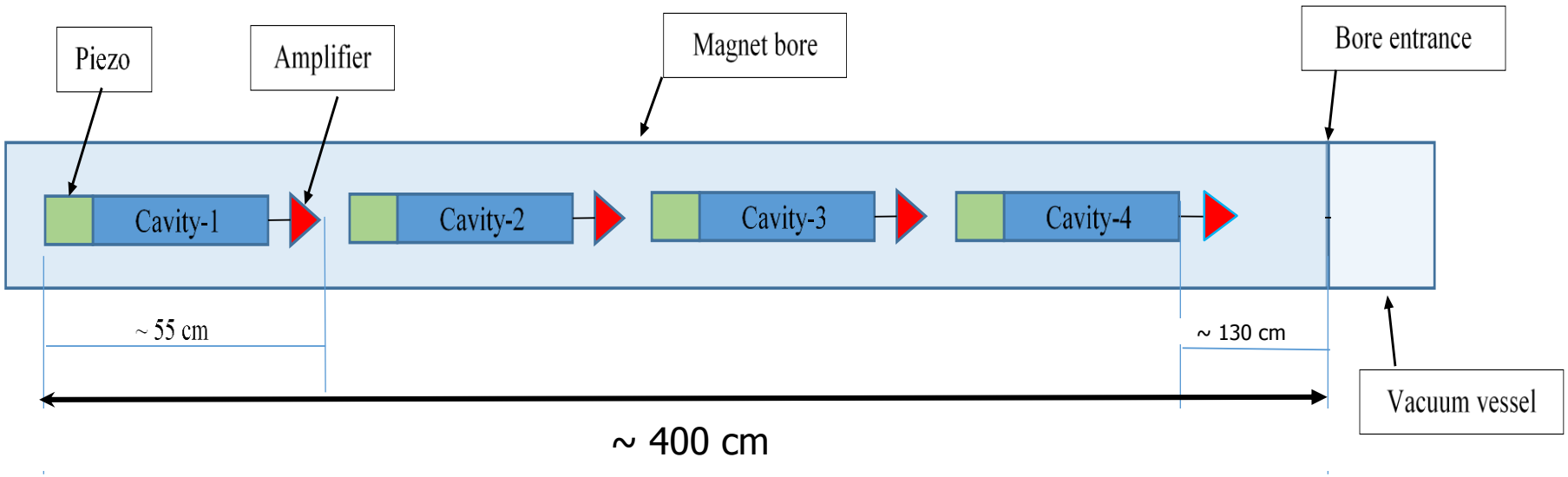
2 Sapphire plates



CAST-CAPP: A Fast Tuning Broadband Cavity



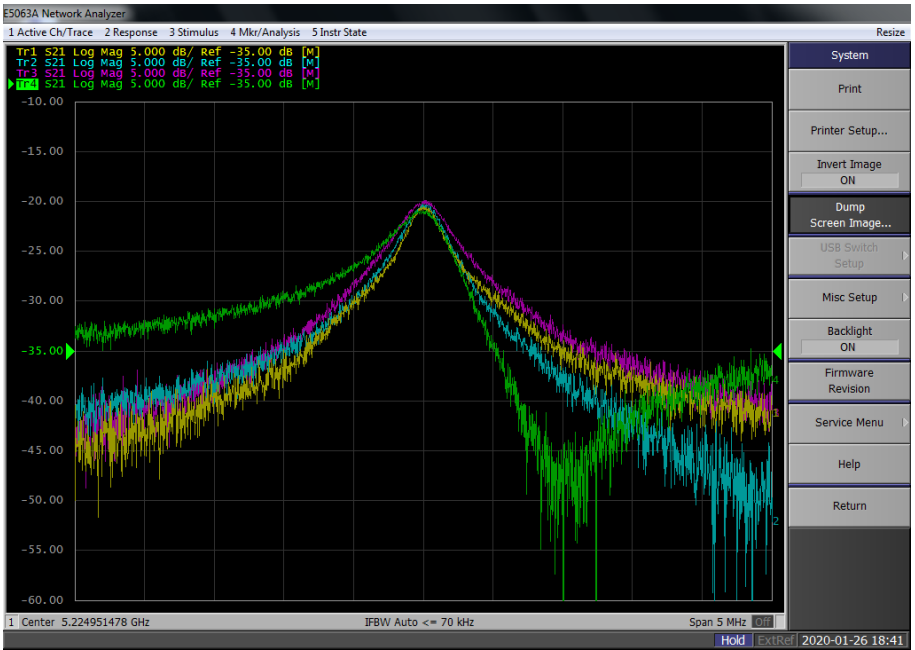
- Installations inside CAST magnet:

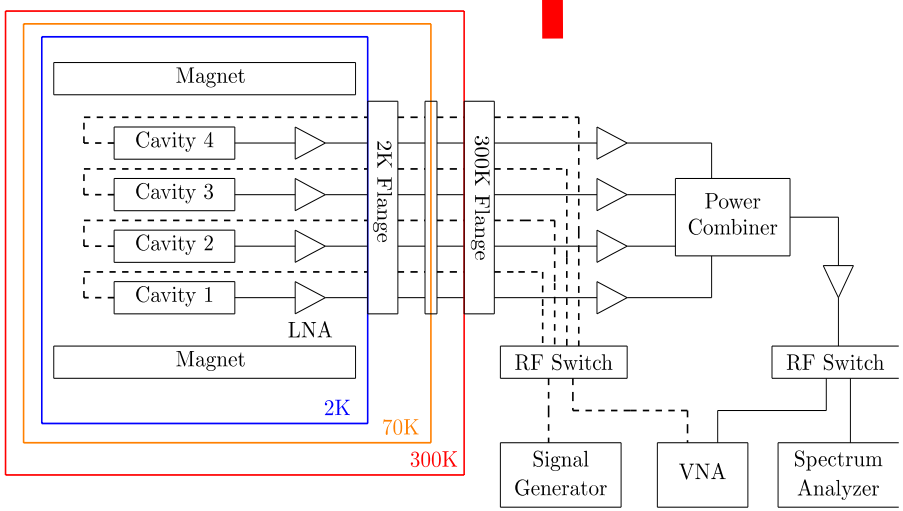


Adjustable Phase Matching

- Novel method, **first** and **uniquely** applied **in an Axion Experiment**
- Axion signals from cavities combined coherently (larger cavity volume, better SNR)
- Alignment in **Amplitude** (0.25dB) and **Frequency** (10 kHz)

- No phase-matching: $\mathrm{SNR}_N = \sqrt{N} \times \mathrm{SNR}_{\mathrm{single}}$
- With phase-matching: $\mathrm{SNR}_N = N \times \mathrm{SNR}_{\mathrm{single}}$





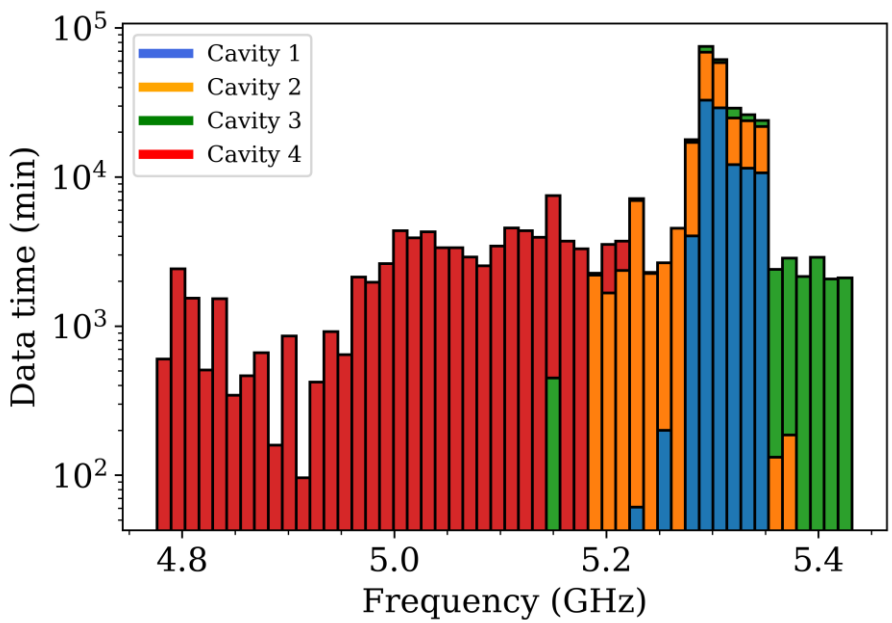
- System noise temperature: T_S=~10K

CAPP: Data Taking Statistics (25.05.2021)

- Effective time: **3670.3h**
- 2160h since SPSC 10/2020
  (X-mas break: ~50d)

- 1-min files: 233311

- $19.7\ \mu eV < m_a < 22.4\ \mu eV$ (~660MHz)



Phase matched:

- 130MHz (5.2224GHz – 5.3525GHz)
- **1543.7h**

- 2 PM Cavities: 1345.4h, 76.0MHz
- 3 PM Cavities: 198h, 37.7MHz
- 4 PM Cavities: 0.3h, 5.0MHz

Single Cavity:

- 660MHz (4.7739GHz – 5.4341GHz)
- 2126.6h

- Cavity 1: 26.7h, 127.6MHz
- Cavity 2: 653.7h, 199.0MHz
- Cavity 3: 304.5h, 211.7MHz
- Cavity 4: 1141.7h, 471.9MHz

Analysis of RF Cavity Data (1/2)

✓ Procedure is used by both, CAST-CAPP and the CAST- RADES

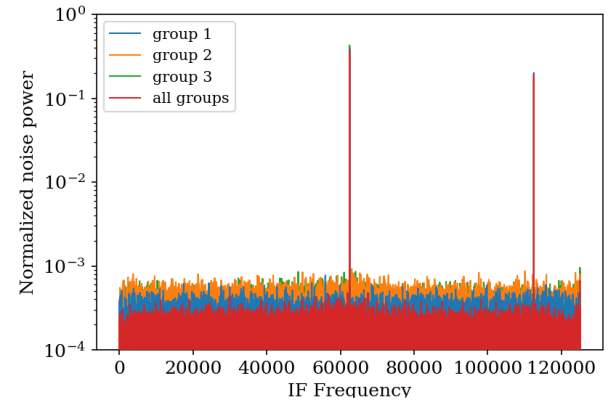
➡ Remove intermediate frequency noise:

(1) split all FFT spectra in 3 groups

→ bins contain data from different frequencies

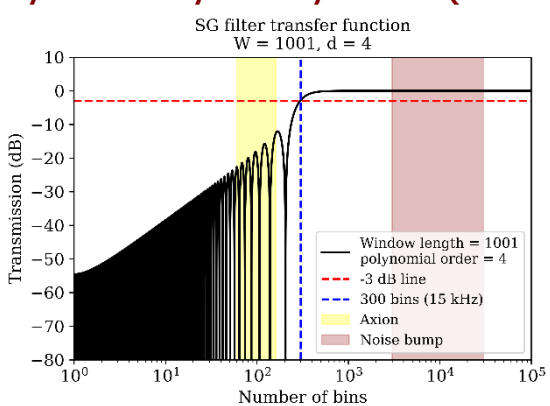
(1) remove bin with excessive spike in >2 groups

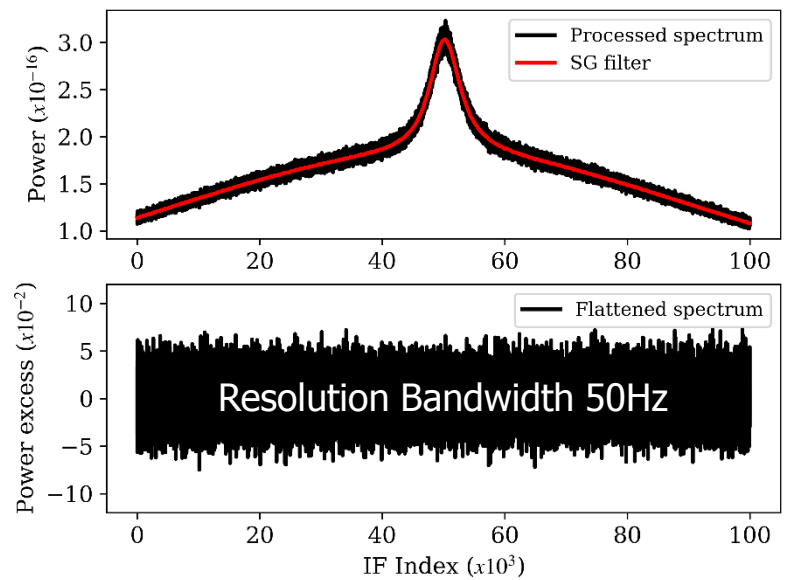
(2) average with neighbored bins



➡ Flattening:

(1) apply Savitzky-Golay filter (4th order, 1001bins)





(2) divide FFT spectrum by SG-fit, shift to Zero

➡ Combine multiple spectra

Grand Spectrum

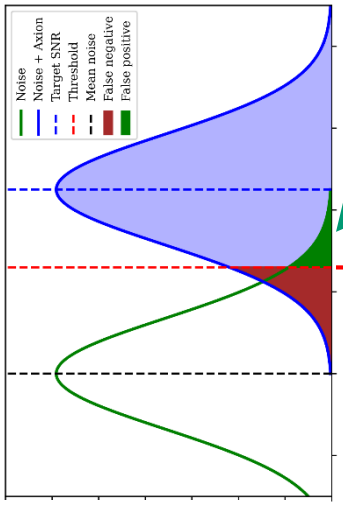
- Horizontal averaging and weighting of bins → optimize for 7kHz axion linewidth
- Combining all ~230k Spectra into one single Spectrum

Expectation: 47 bins showing "false positive" power excess

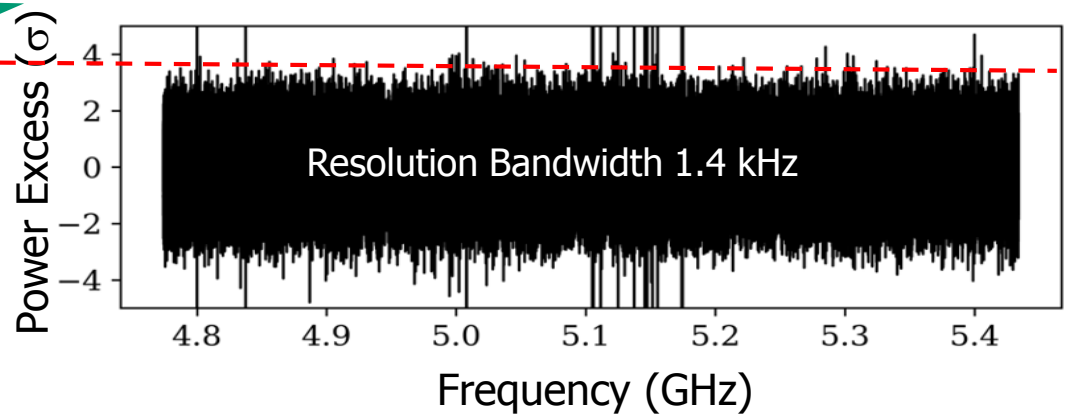
(dubbed: "outliers")

Target: SNR = 5σ

Threshold = 3.72 σ
(CL=90%)



Gaussian PDF

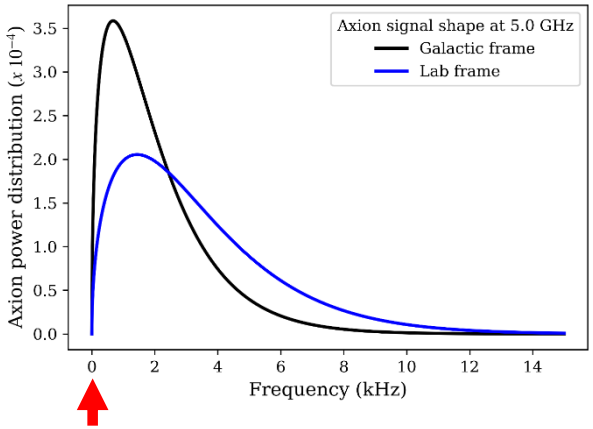


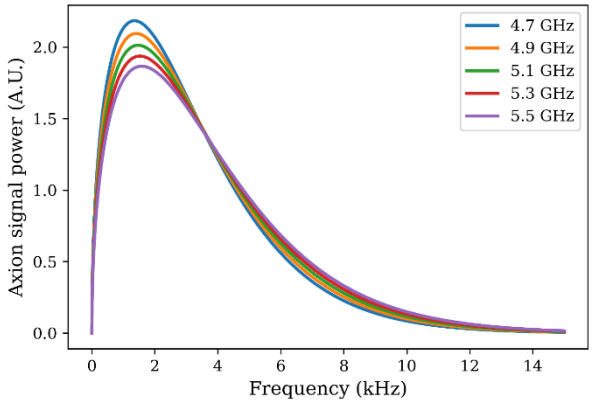
- **measurement:** outliers in 60 frequency bins
- all outlier frequency bins need special attention
- additional contribution to outliers by ambient EMI/EMC

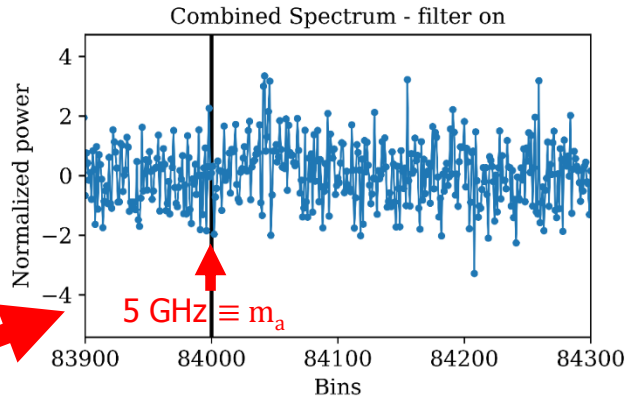
Data Analysis Test – Software Injection of Artificial Axion

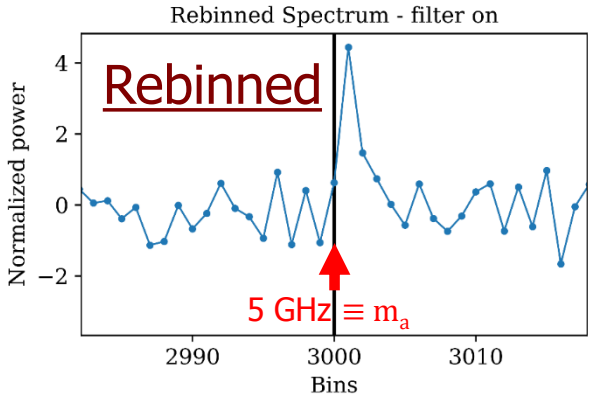
- data-driven Monte Carlo background noise
- axion signal, $g_{a\gamma\gamma}$=20 x $g_{a\gamma\gamma}$(KSVZ)

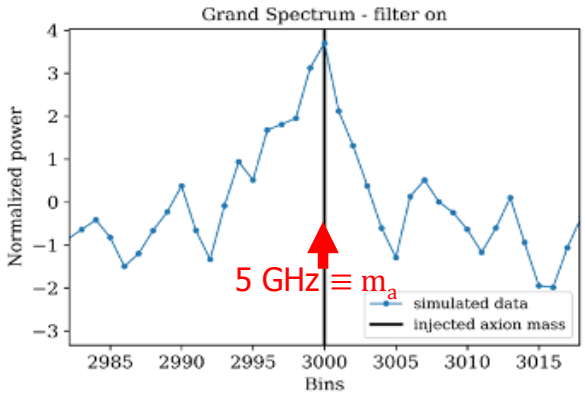
→ Signal should become visible when averaging 90 minutes











➡ 110 minutes of data generated (top right plot)

➡ same analysis steps as for measured data

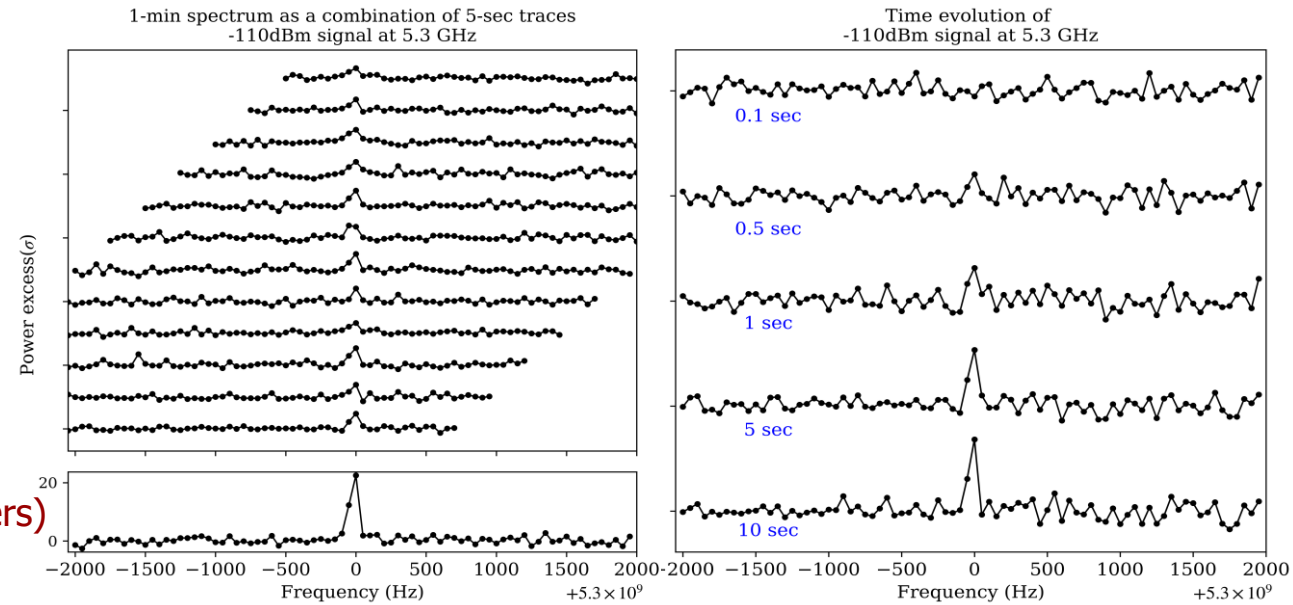
➡ **Peak frequency (m_a) and linewidth recovered**

(line shape due to convolution with expected Maxwell distribution)

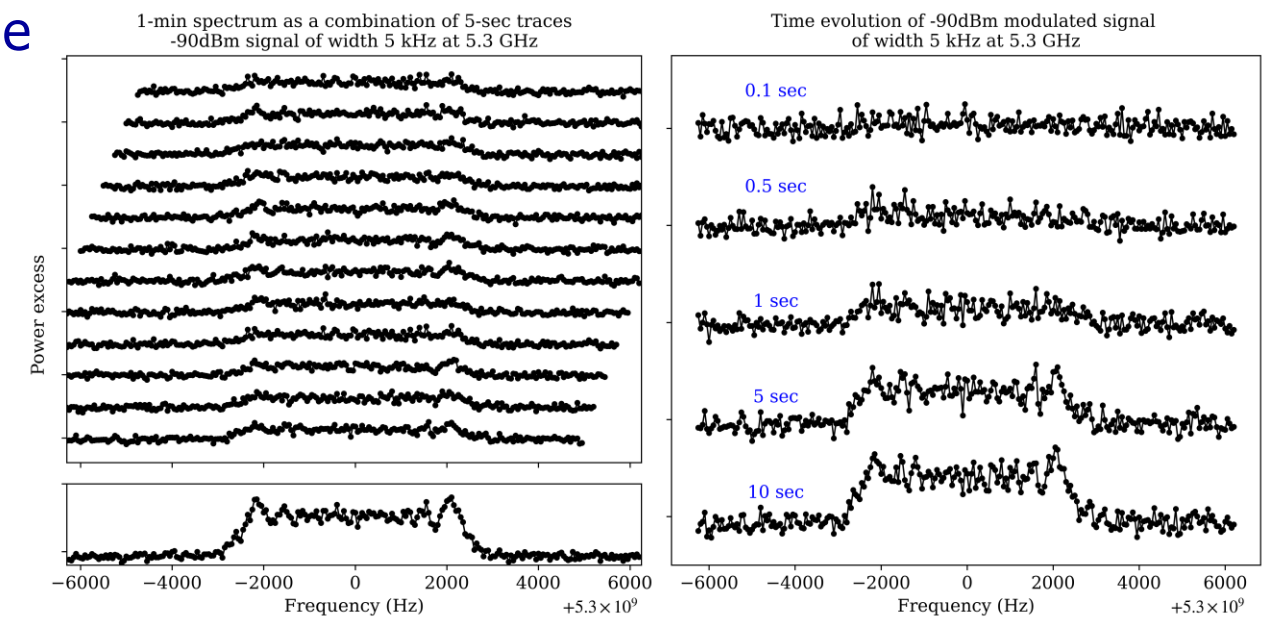
Data Analysis Test – Hardware Injection of Artificial Axion

Injected to cavities:

- -110dBm pilot tone
- single frequency
- 11 signals secretly injected to data (=outliers)



- -110dBm modulated tone
- 5 kHz frequency band

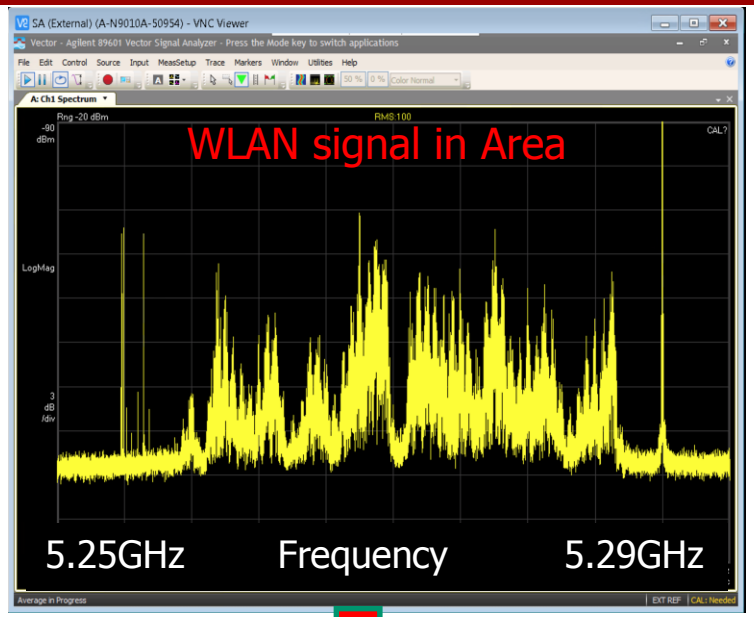


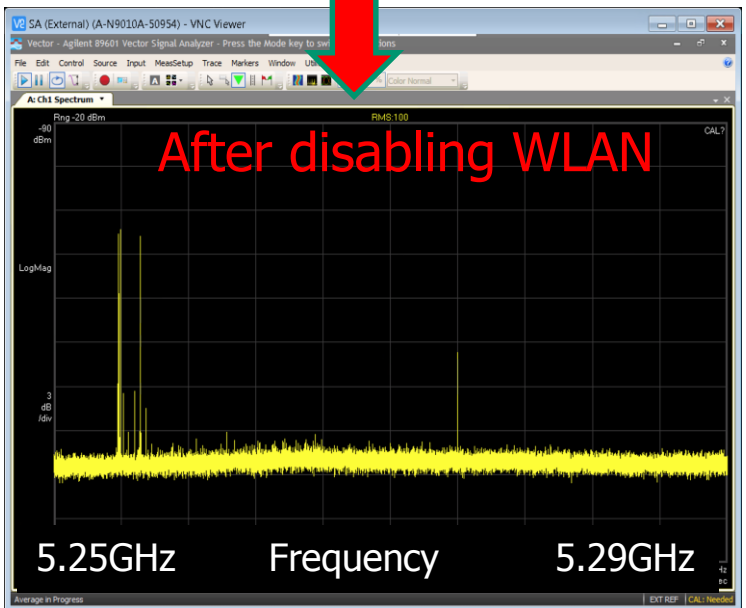
➡ Pilot tone & modulation recovered in analysis

➡ Noise model confirmed

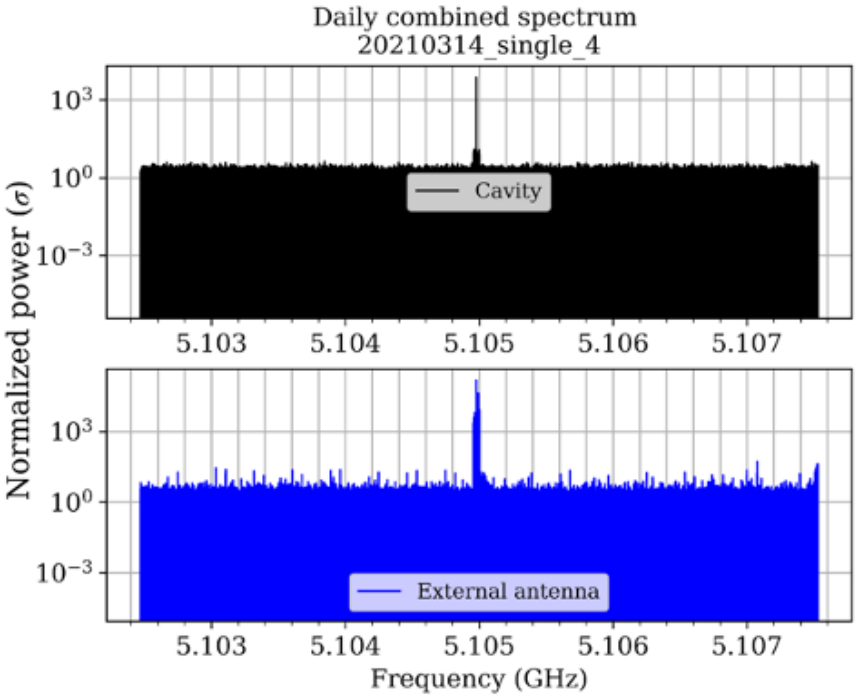
$$\sigma_{noise} = k_B T_s \sqrt{\frac{\Delta\nu}{t}}$$

Fighting EMC/EMI Noise in the CAST Area





- simultaneous measurement of ambient EMC/EMI signals with antenna outside of magnet



- ~30dB margin due to magnet shielding
- **9** outliers verified as EMI/EMC parasites

Investigating Outliers

Identifying Axions:

- 60 frequency bins are above detection threshold
  - **11** blindly injected hardware pilot tones
  - **9** verified EMI/EMC parasites (simultaneous measurement outside magnet)
  - **40** "statistically expected" outliers

    ➡ Predefined protocol for axion detection:

    (1) Persistence after rescanning with same cavity

    (2) " " rescanning with different cavity

    (3) Persistent when tuning to different resonant mode

    (4) Correct line shape 5…7 kHz

    (5) Signal $\propto B^2$

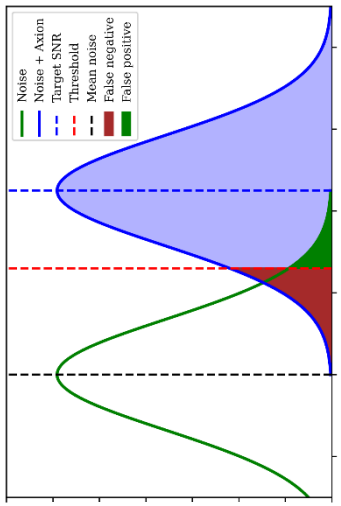
    - all 40 outliers disappeared by step (1) and (2)

➢ **0** outliers **remain** above threshold (3.72 σ)

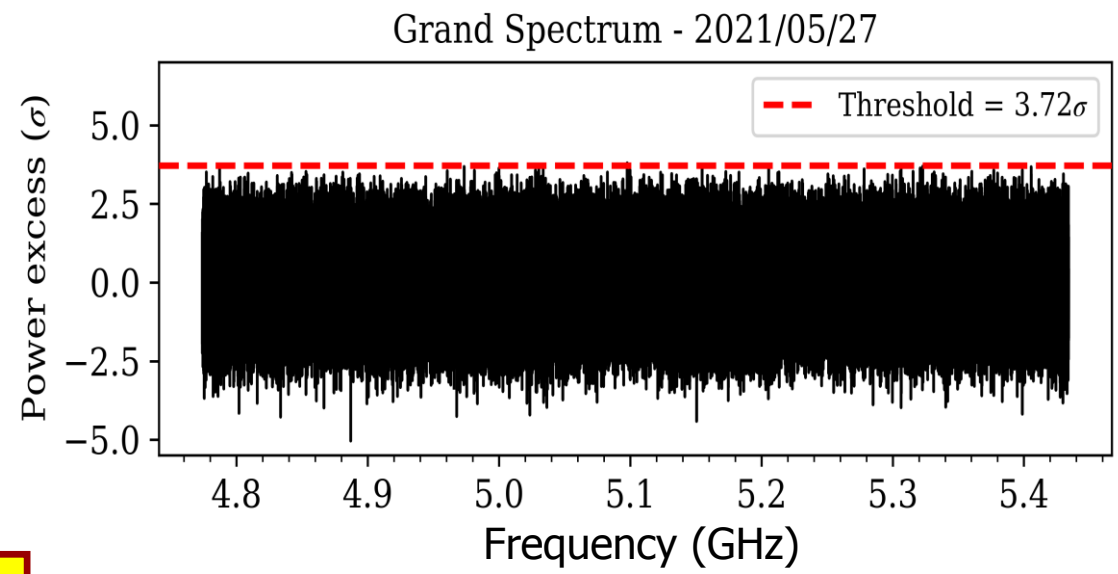
Analysis of RF Cavity Data (1/2): Grand Spectrum

Target: SNR = 5σ

Threshold = 3.72 σ
(CL=90%)



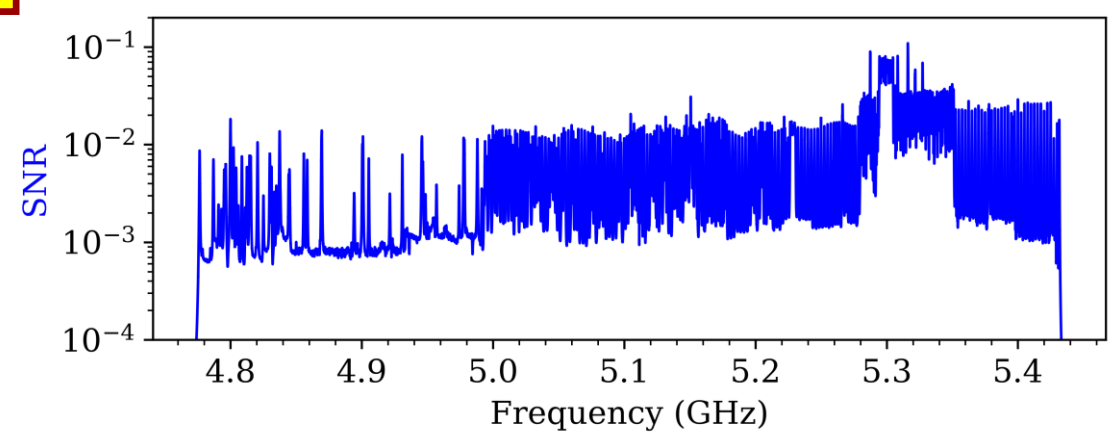
Gaussian PDF



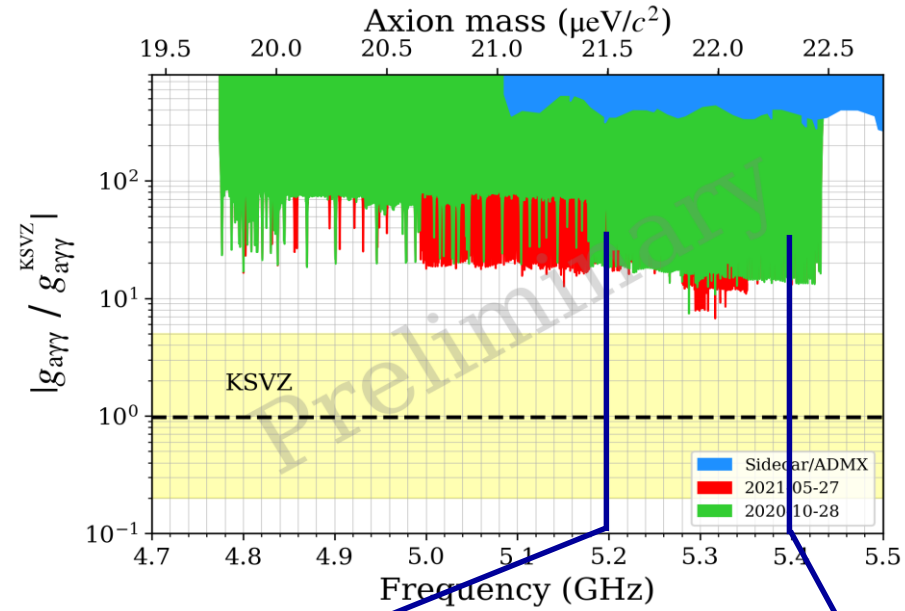
- Axion Signal:

$$P_S = (g_{a\gamma\gamma})^2 \rho_a \frac{1}{m_a} B^2 CV \, min[Q_c, Q_a]$$

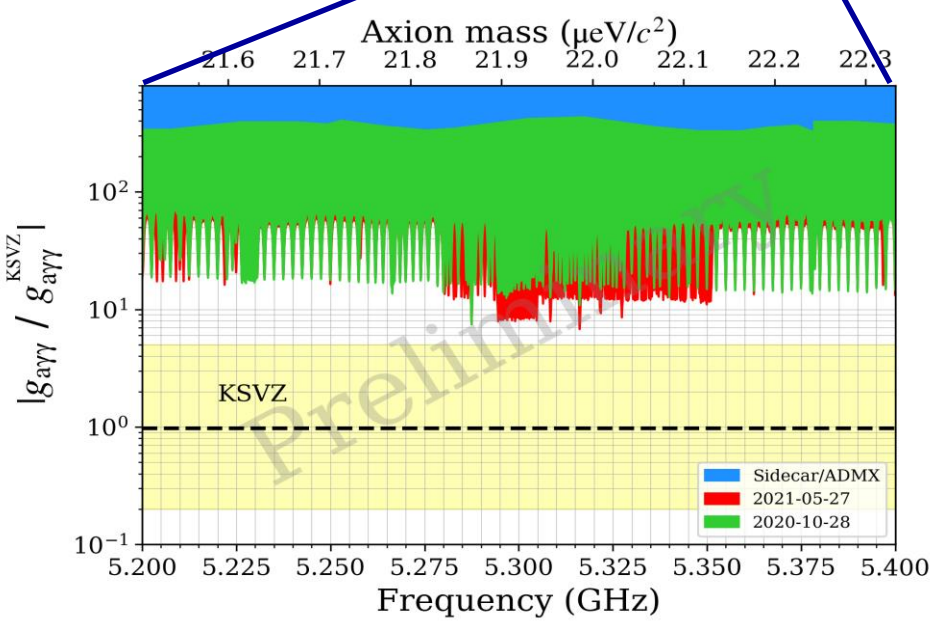
$$\mathrm{SNR} = \frac{P_S}{\sigma_{noise}} = \frac{P_S}{k_B T_S}\sqrt{\frac{t}{\Delta\nu}}$$



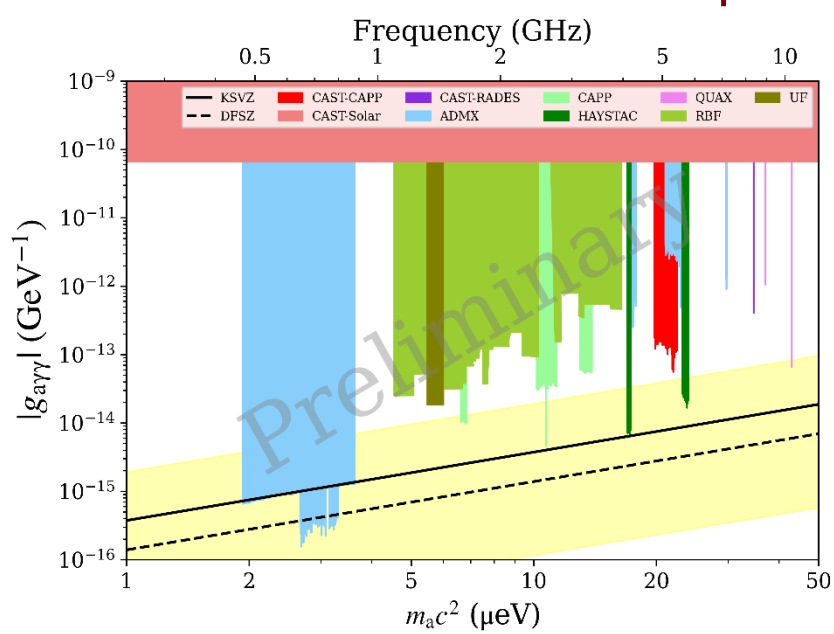
Preliminary Results as of 27th May 2021



- 3670 h data taking
- 19.7 μeV < m_a < 22.4 μeV (~660MHz)
- present sensitivity: 8 x $g_{a\gamma\gamma}$(KSVZ)

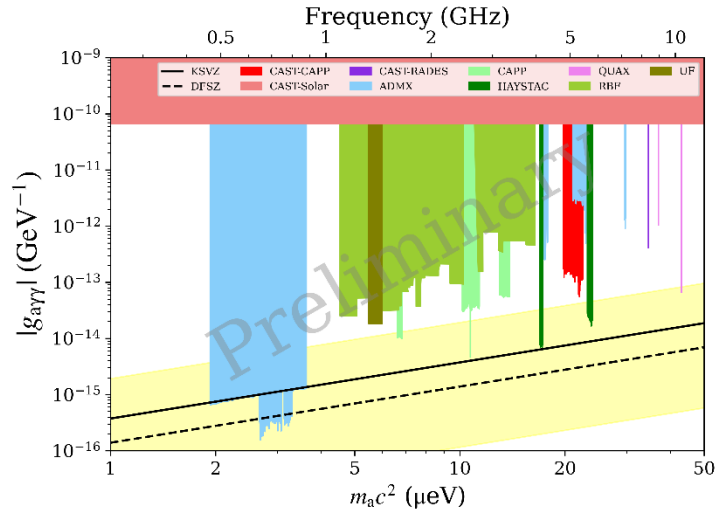


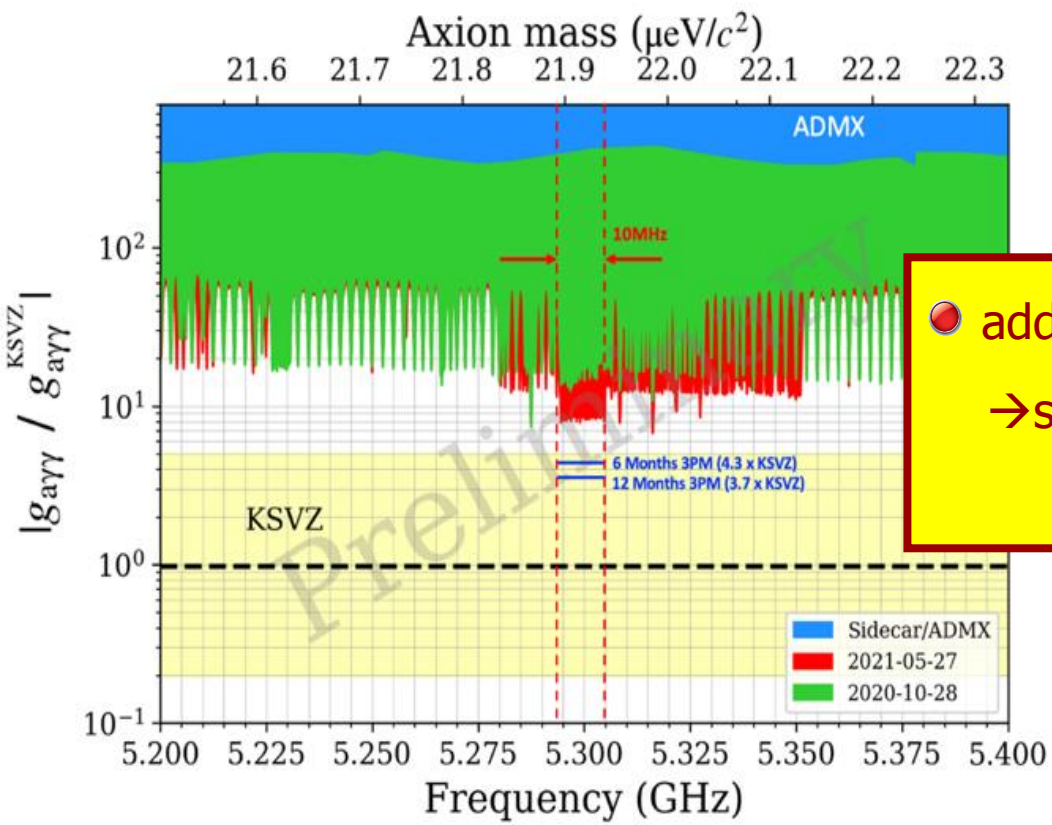
CAST in the axion landscape



Summary on CAST-CAPP

- 3670h with adjustable phase matching and fast scanning techniques on tape
- complementary, competitive, cutting edge results
- smooth data taking
- almost real time data analysis
- publication close to final





- additional 12 months of data taking
  →sizably reach into the theoretical band for 10 MHz bandwidth

Status of CAST-RADES

CAST-RADES – First Results

- higher Masses → smaller cavities → less sensitivity ☹
- **RADES:** sub-structured, diaphragm separated cavity → restore sensitivity ☺

Prepared for submission to JHEP

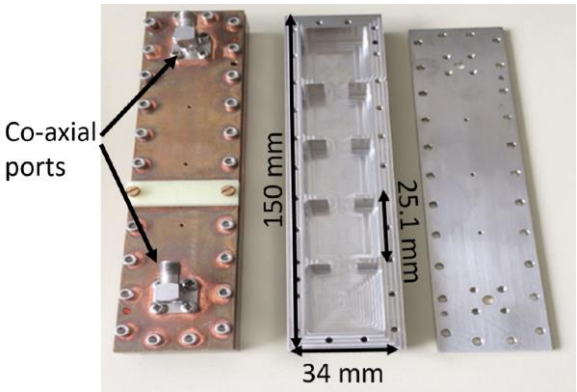
First results of the CAST-RADES haloscope search for axions at 34.67 μeV

A. Álvarez Melcón,[1] S. Arguedas Cuendis,[*,2] J. Baier,[3] K. Barth,[2] H. Bräuninger,[4] S. Calatroni[2] G. Cantatore,[5,6] F. Caspers,[2,7] J.F. Castel,[8] S.A. Cetin,[9] C. Cogollos,[10] T. Dafni,[8] M. Davenport,[2] A. Dermenev,[11] K. Desch,[12] A. Díaz-Morcillo,[1] B. Döbrich,[2] H. Fischer,[3] W. Funk,[2] J.D. Gallego,[13] J.M. García Barceló,[1] A. Gardikiotis,[14,15] J.G. Garza,[8] B. Gimeno,[16] S. Gninenko,[11] J. Golm[2,17] M.D. Hasinoff,[18] D.H.H. Hoffmann,[19] I.G. Irastorza[8] K. Jakovčić,[20] J. Kaminski,[12] M. Karuza,[5,21,22] B. Lakić [†,20] J.M. Laurent,[2] A.J. Lozano-Guerrero,[1] G. Luzón,[8] C. Malbrunot,[2] M. Maroudas,[14] J. Miralda-Escudé,[10,32] H. Mirallas[8] L. Miceli,[23] P. Navarro,[1] A. Ozbey,[9,24] K. Özbozduman,[9,25] C. Peña Garay,[26,27] M.J. Pivovaroff,[a,28] J. Redondo,[8,29] J. Ruz,[28] E. Ruiz Chóliz,[8] S. Schmidt,[12] M. Schumann,[3] Y.K. Semertzidis,[23,30] S.K. Solanki,[31] L. Stewart,[2] I. Tsagris,[14] T. Vafeiadis,[2] J.K. Vogel,[28] W. Wuensch,[2] and K. Zioutas[2,14]

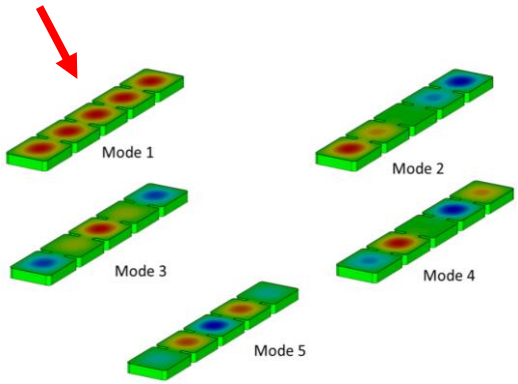
[1] *Department of Information and Communications Technologies, Technical University of Cartagena, 30203 - Murcia, Spain*
[2] *European Organization for Nuclear Research (CERN), 1211 Geneva 23, Switzerland*
[3] *Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, 79104 Freiburg, Germany*
[4] *Max-Planck-Institut für Extraterrestrische Physik, Garching, Germany*
[5] *Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Trieste, Trieste, Italy*
[6] *Universita di Trieste, Trieste, Italy*
[7] *European Scientific Institute, Archamps, France*
[8] *Center for Astroparticle and High Energy Physics (CAPA) & Departamento de Física University de Zaragoza, 50009 - Zaragoza, Spain*
[9] *Istanbul Bilgi University, High Energy Physics Research Center, Fi*
[10] *Institut de Ciències del Cosmos, Universitat de Barcelo Spain.*
[11] *Institute for Nuclear Research (INR), R*
[12] *Physikalisches Institut, Univ*
[13] *Yebes Observatory, N Geospace Applications, 19080 - Guadalaj*
[14] *Physics Departme ece*
[15] *Universität Hambur*
[16] *Instituto de Física C IFIC), CSIC-University of Valencia, 46071 - Valencia, Spain*

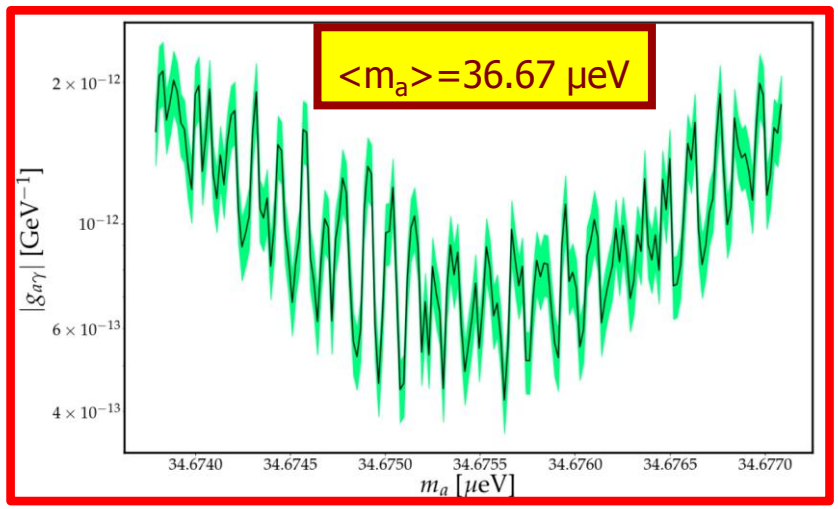
[†] deceased
[a] Current address: SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA.

Paper under review at JHEP

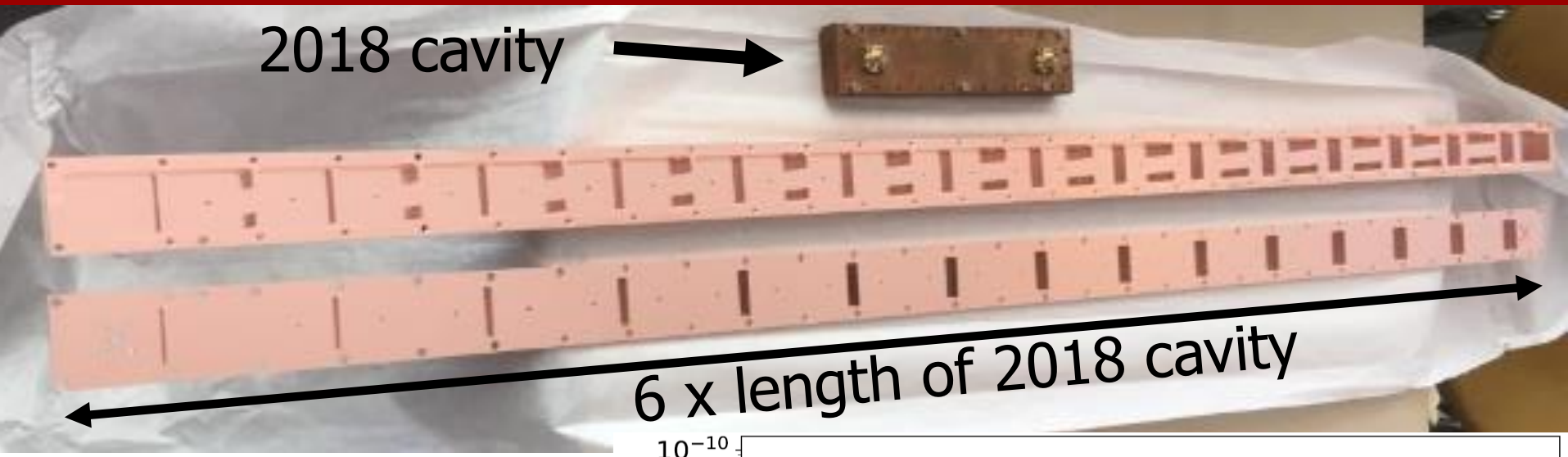


E || B → Axion Mode



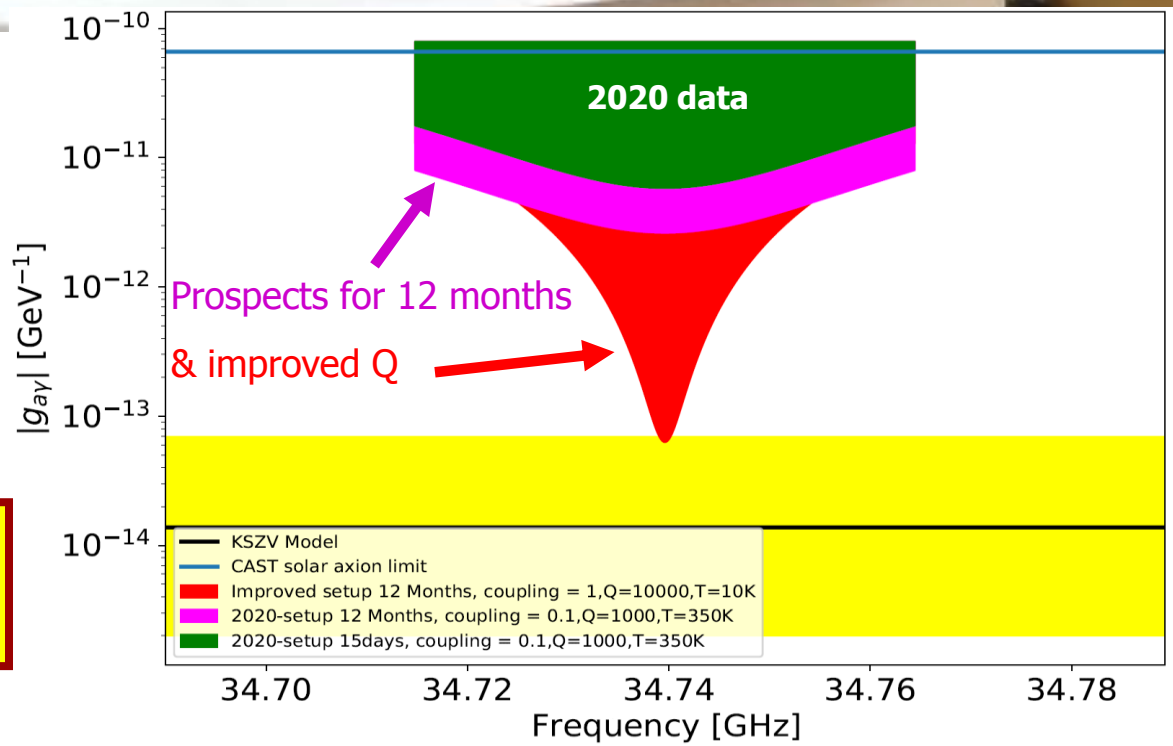


Further Improving on Sensitivity



Status:

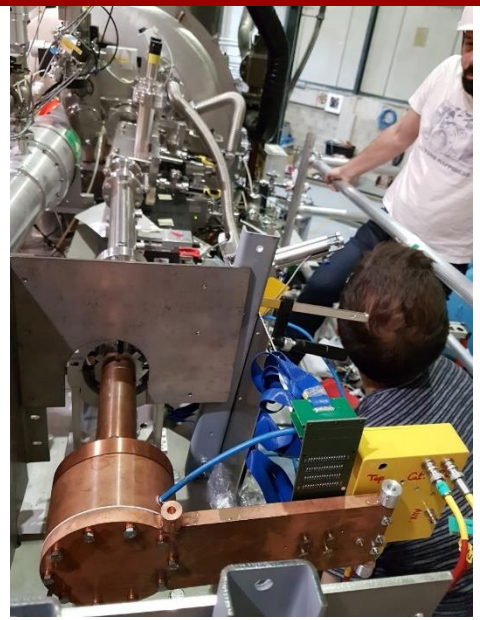
- commissioning in 2020
- 15 days of data taken in 2020
- 2021: broken connection between Cavity and LNA inside magnet bore

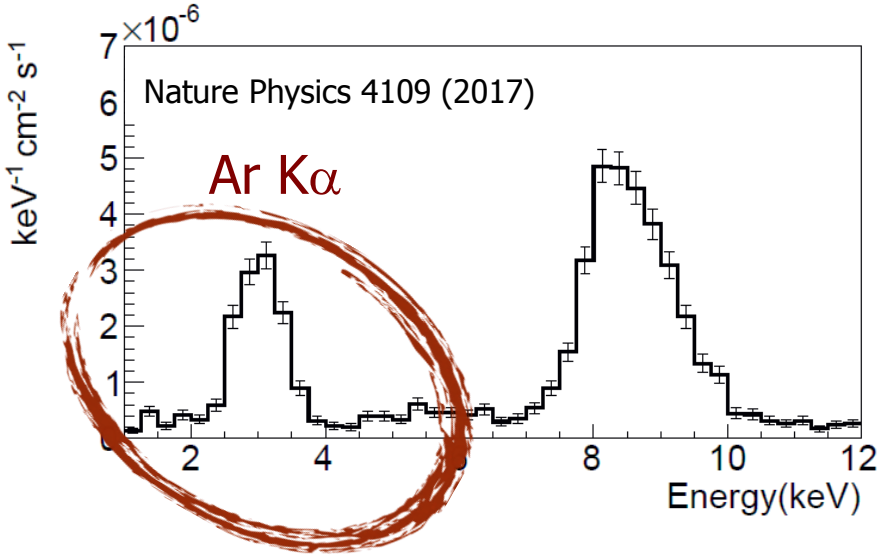


Important R&D for future high-mass cavity experiments like babyIAXO

Status of MicroMegas – Solar Axions

Search for Solar Axions with Microbulk MicroMegas

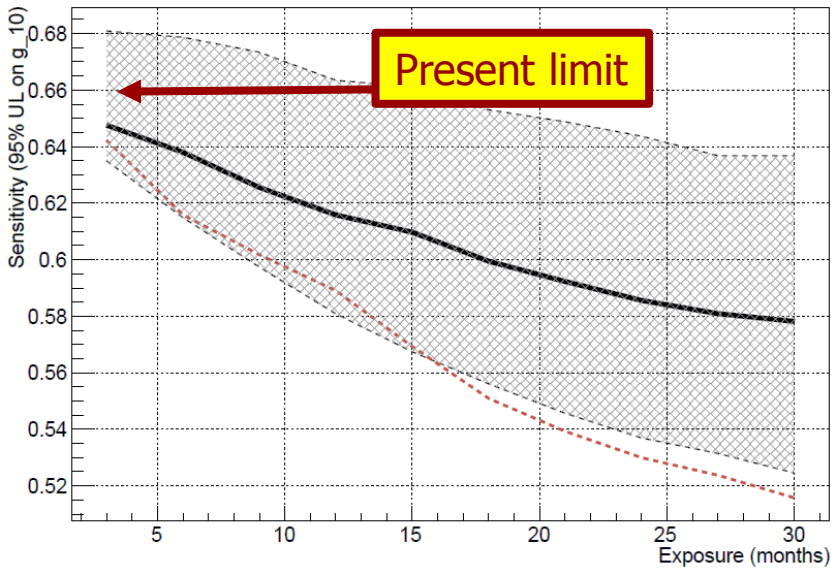




Scientific goals:

➡ **Physics:**

- improve sensitivity to $g_{a\gamma\gamma}$
- clarify origin of 2σ-excess in 2013-2015 results (290 h solar tracking)



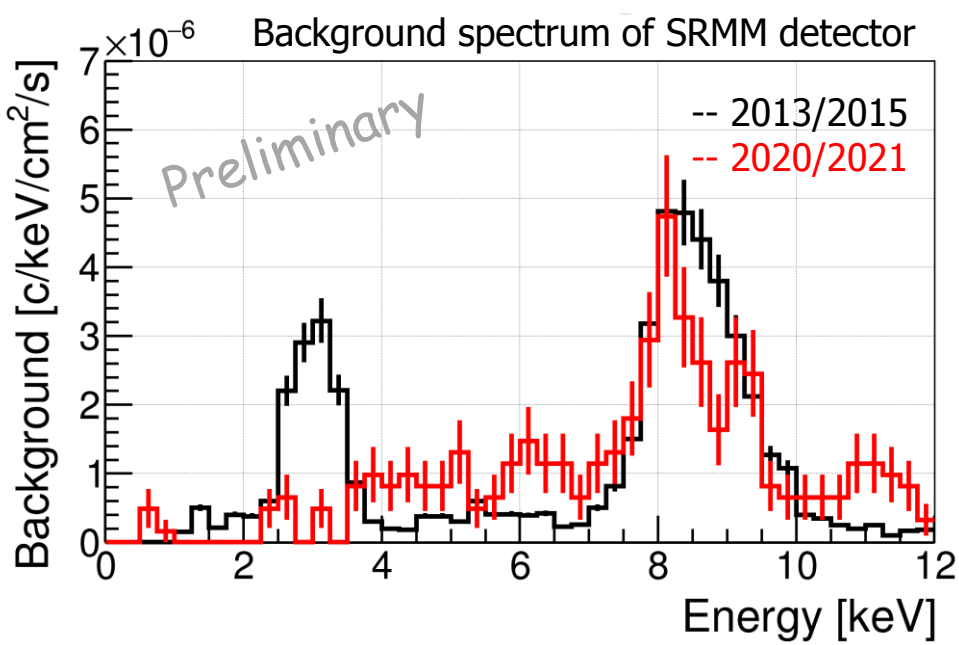
➡ **R&D for babyIAXO & IAXO**

- closed loop Xe gas system (48.85% Xe + 48.85% Ne + 2.3% Isobutane)
- insight into limitations of background and threshold
- provide technical and operational experience

MicroMegas Operation 2020/2021

- background level for 1 track events after preliminary cuts (i.e. not optimized)
- ^{55}Fe calibrations with Xenon, calibration with X-ray source after data taking
- efficiency ~85% (all 1 track events), studies for 2 track events ongoing
- 132 h tracking, 2170 hours background (runs with relative gain >0.8, >25th Jan 2021)
- no veto cut applied yet

→ no fluorescence peak in background at 3 keV



Important achievement for solar axion search!

(Maximum in spectrum of Primakoff photons expected in that energy)

Chameleon Searches
GridPix and KWISP Detectors

Chameleon Search

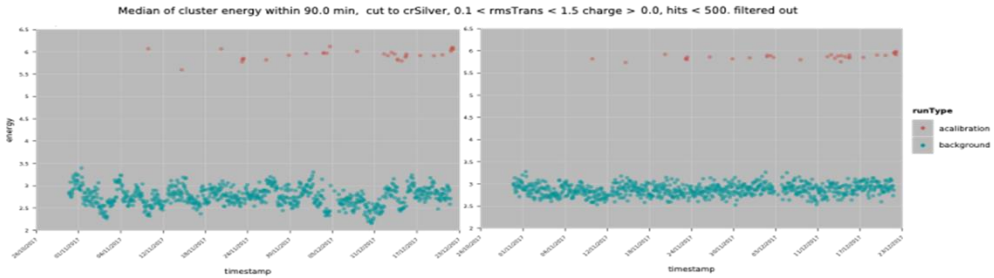
- Chameleons provide particle physics solution to Dark Energy
- mass depending on ambient matter density ρ

matter coupling photon coupling

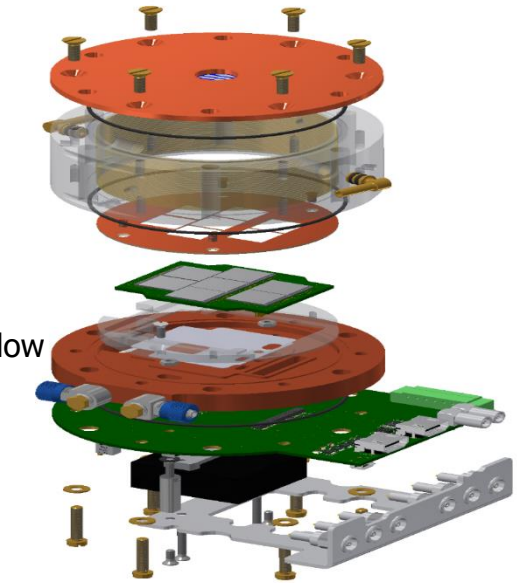
$$V_{\text{eff}}(\phi) = \frac{\Lambda^{4+n}}{\phi^n} + e^{\frac{\beta_m}{M_{\text{Pl}}}\phi}\rho_m + e^{\frac{\beta_\gamma}{M_{\text{Pl}}}\phi}\rho_\gamma$$

Better understanding of GridPix data & analysis is important R&D for babyIAXO

- **detection through coupling to photons a'la Primakoff (β_γ)**
  - data taken 2017/2018
  - analysis ongoing, considerable progress since 10/2020
    - accommodate for p, T, n_i dependence in calibration
    - optimization of likelihood selection (energy dependence)



InGrid/GridPix



- low energy axions & ALPS share same analysis
  - ➡ benefit from smaller spot size (less background)

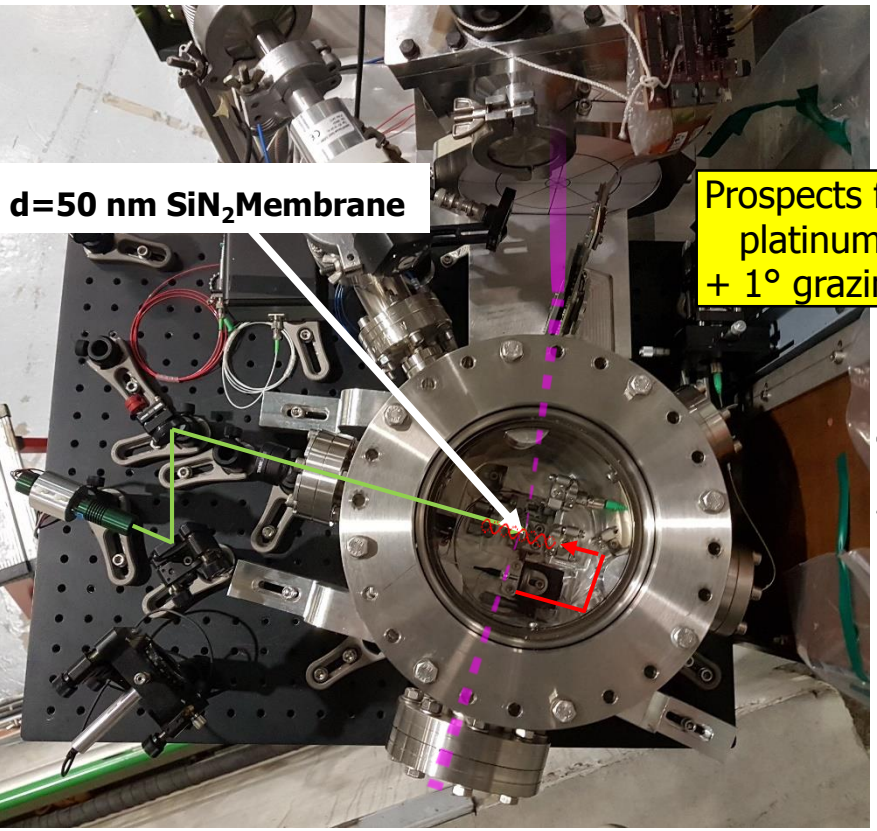
KWISP - Optomechanical Sensor for Chameleon Hunting

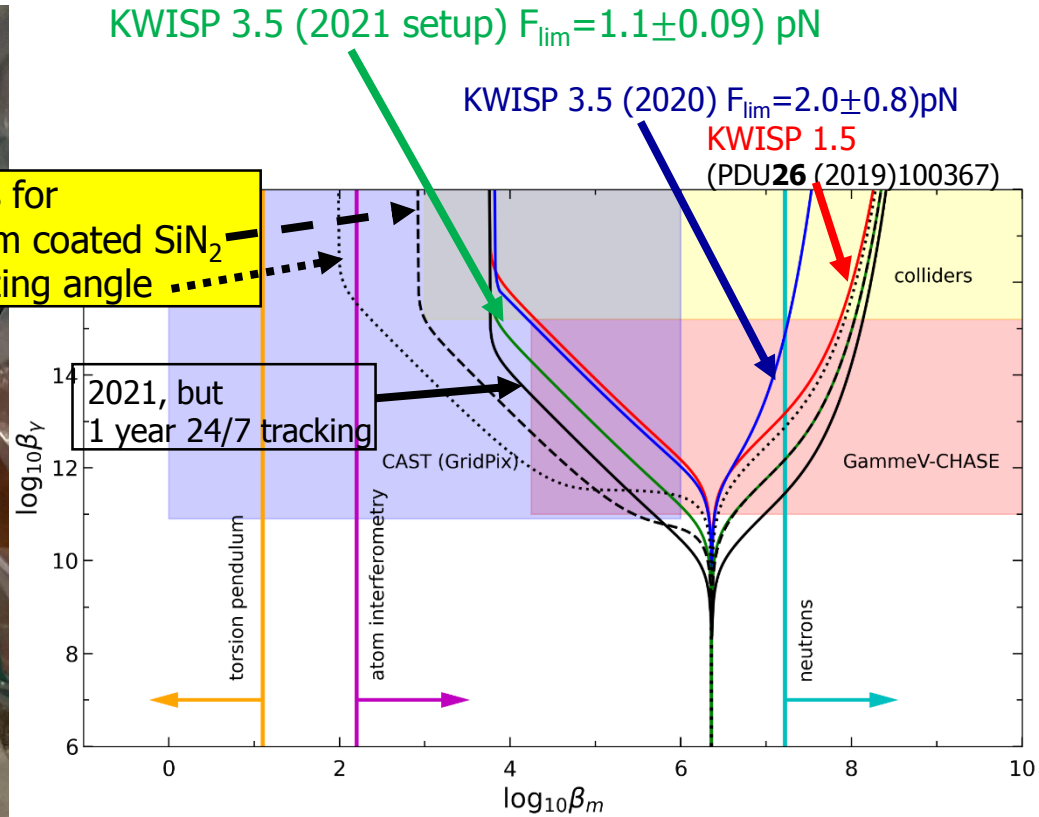
- **coupling to matter, if $m_{chameleon} > E_{chameleon}$ (β_m)**
- continuous efforts to improve on force sensitivity

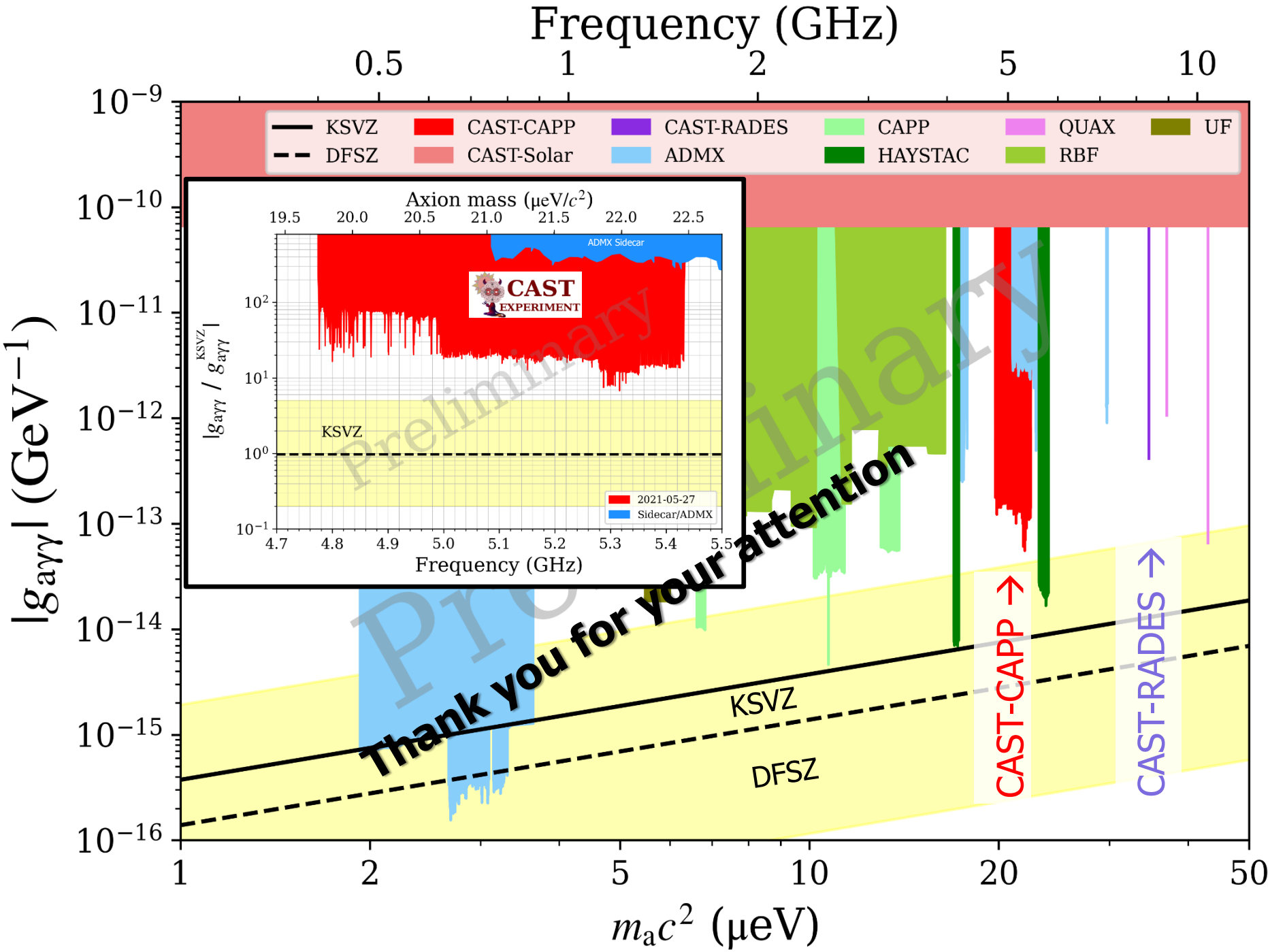
matter coupling photon coupling

$$V_{\rm eff}(\phi) = \frac{\Lambda^{4+n}}{\phi^n} + e^{\frac{\beta_m}{M_{\rm Pl}}\phi}\rho_m + e^{\frac{\beta_\gamma}{M_{\rm Pl}}\phi}\rho_\gamma$$

2021:
- SiN_4 scattering membrane adjustable in z-Position
- new calibration laser
- Digital Micro-Mirror Device → platinum covered platter (improve acceptance)






Frequency (GHz)
0.5
1
2
5
10
KSVZ
DFSZ
CAST-CAPP
CAST-Solar
CAST-RADES
ADMX
CAPP
HAYSTAC
QUAX
RBF
UF
Axion mass (μeV/c²)
19.5
20.0
20.5
21.0
21.5
22.0
22.5
ADMX Sidecar
CAST EXPERIMENT
KSVZ
2021-05-27
Sidecar/ADMX
Frequency (GHz)
Preliminary
Thank you for your attention
KSVZ
DFSZ
CAST-CAPP →
CAST-RADES →
$|g_{a\gamma\gamma}|$ (GeV^{-1})
$m_a c^2$ (μeV)