Status Report to the SPSC for the 142nd Meeting

Horst Fischer on behalf of the CAST Collaboration
The CAST Physics Programme

- Solar Axions
- Chameleons
- Relic Axions
- CAST-CAPP
- CAST-RADES
- GridPix
- KWISP
CAST on Halo Axions

CAST -> CAPP

CAST -> RADES

CAST

ADMX Sidecar

\[ |g_{a\gamma\gamma}| \text{ (GeV}^{-1}) \]

\[ m_a c^2 \text{ (\mu eV)} \]

Axion mass (\mu eV/c^2)

|g_{a\gamma\gamma}| vs. Frequency (GHz)

CAST

CAST-CAPP

CAST-RADES

KSVZ

DFSZ

CAPP

HAYSTAC

RBF

PRELIMINARY
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

- Piezo
- T-sensor
- Coupler
- Amplifier
- Locking device

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: \( \text{SNR}_N = \sqrt{N} \times \text{SNR}_{\text{single}} \)
- With phase-matching: \( \text{SNR}_N = N \times \text{SNR}_{\text{single}} \)

**System noise temperature:** \( T_s = \sim 10K \)
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
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
2. Remove bin with excessive spike in >2 groups
3. Average with neighbored bins

Flattening:

1. Apply Savitzky-Golay filter (4th order, 1001 bins)
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%)

measurement: outliers in 60 frequency bins
all outlier frequency bins need special attention
additional contribution to outliers by ambient EMI/EMC
data-driven Monte Carlo background noise

- axion signal, $g_{a\gamma\gamma} = 20 \times g_{a\gamma\gamma}$ (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)
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

\[ \sigma_{\text{noise}} = k_B T_s \sqrt{\frac{\Delta \nu}{t}} \]
Fighting EMC/EMI Noise in the CAST Area

- **WLAN signal in Area**

- **After disabling WLAN**

- **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 $\sigma$)
Analysis of RF Cavity Data (1/2): Grand Spectrum

Target: SNR = 5\sigma
Threshold = 3.72 \sigma \ (CL=90\%)

Axion Signal:
\[ P_S = (g_{\alpha\gamma\gamma})^2 \rho_a \frac{1}{m_a} B^2 CV \min[Q_c, Q_a] \]

SNR = \frac{P_S}{\sigma_{\text{noise}}} = \frac{P_S}{k_B T_S} \sqrt{\frac{t}{\Delta \nu}}
Preliminary Results as of 27th May 2021

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

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 $\rightarrow$ smaller cavities $\rightarrow$ less sensitivity 😞
- RADES: sub-structured, diaphragm separated cavity $\rightarrow$ restore sensitivity 😊

$E \parallel B \rightarrow$ Axion Mode

$\langle m_a \rangle = 36.67 \mu$eV

Paper under review at JHEP
Further Improving on Sensitivity

2018 cavity

6 x length of 2018 cavity

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

Nature Physics 4109 (2017)

Present limit
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 $\sim 85\%$ (all 1 track events), studies for 2 track events ongoing

132 h tracking, 2170 hours background (runs with relative gain $>0.8$, $>25^{th}$ Jan 2021)

no veto cut applied yet

$\rightarrow$ 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 $\rho$

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

Detection through coupling to photons \textit{a\'la Primakoff} ($\beta_\gamma$)

- data taken 2017/2018
- analysis ongoing, considerable progress since 10/2020
- accommodate for $\rho$, $T$, $n_i$ dependence in calibration
- optimization of likelihood selection (energy dependence)

InGrid/GridPix

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

Low energy axions & ALPS share same analysis

$\rightarrow$ benefit from smaller spot size (less background)
**KWISP - Optomechanical Sensor for Chameleon Hunting**

- **coupling to matter, if** $m_{\text{chameleon}} \geq E_{\text{chameleon}}$ ($\beta_m$)
- continuous efforts to improve on force sensitivity

2021: ➡️ SiN$_4$ scattering membrane adjustable in z-Position

➡️ new calibration laser

➡️ Digital Micro-Mirror Device ➔ platinum covered platter (improve acceptance)

$V_{\text{eff}}(\phi) = \frac{\Lambda^{4+n}}{\phi^n} + e^{\frac{\beta_m}{M_P}} \phi_m + e^{\frac{\beta_\gamma}{M_P}} \phi_\gamma$

KWISP 3.5 (2021 setup) $F_{\text{lim}}=1.1\pm0.09$ pN

KWISP 3.5 (2020) $F_{\text{lim}}=2.0\pm0.8$ pN

KWISP 1.5 (PDU26 (2019)100367)

Prospects for platinum coated SiN$_2$ + 1° grazing angle

2021, but 1 year 24/7 tracking