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DESY.

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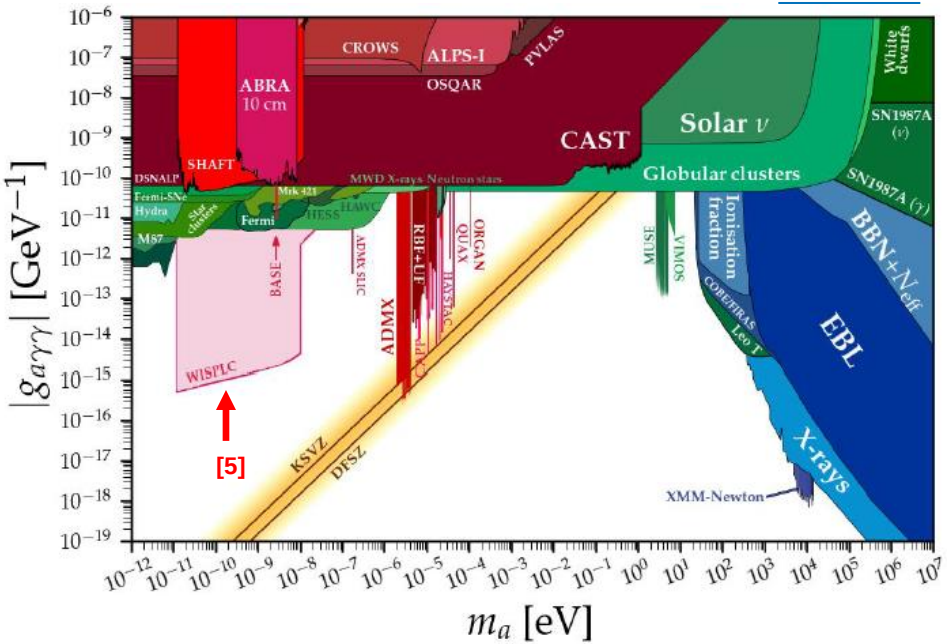
Dark Matter searches with WISPLC experiment

Motivation

- **Axions** solve the strong CP problem and are prominent candidates for CDM [1].
- QCD axion parameter space can be extended in the neV range [2,3].
- Cavity-type experiments are very sensitive in μeV range but:
  A. They are not **broadband**.
  B. Not feasible for **low frequencies**.
- Experiments based on lumped elements [4] can be both broadband and resonant thus covering more efficiently a large part of the axion parameter space.

Source: C. O'Hare



Theoretical Background

- In the presence of axions, Maxwell's equations are modified as [4]:

$$\nabla \cdot \boldsymbol{E} = g\boldsymbol{B} \cdot \nabla a + \rho_{el}$$

$$\nabla \times B - \frac{\partial E}{\partial t} = g_{a\gamma\gamma}\left(E \times \nabla a - \boldsymbol{B}\frac{\partial a}{\partial t}\right) + j_{el}$$

- For m_a ~ neV, axion behaves as a coherent oscillating scalar field ($\lambda \sim 10^5$ m):

$$a(t) = a_0 cos(m_a t) = \frac{\sqrt{2\rho_{DM}}}{m_a} cos(m_a t)$$

- An external B-field induces an axion sourced current density oscillating at the Compton freq. of axions:

$$\boldsymbol{j_a}(t) = -g_{a\gamma\gamma}\boldsymbol{B}\frac{\partial a}{\partial t}$$

- This generates an oscillating perpendicular toroidal magnetic field such that: $\nabla \times \boldsymbol{B_a} = \boldsymbol{j_a}$

Detection Scheme – WISPLC

1. External $\boldsymbol{B_0}$- field converts axions to an oscillating displacement current $\boldsymbol{j_a}$:

$$\boldsymbol{j_a} = -g_{a\gamma\gamma}\boldsymbol{B_0}\frac{\partial a}{\partial t} = g_{a\gamma\gamma}\sqrt{2\rho_{DM}}\boldsymbol{B_0}sin(m_a t)$$

2. The oscillating current induces a toroidal magnetic field $\mathbf{B_a} \perp \mathbf{j_a}$:

$$\boldsymbol{B_a} = g_{a\gamma\gamma}\sqrt{2\rho_{DM}}sin(m_a t)\int\frac{\boldsymbol{B_0}\times(\boldsymbol{r}-\boldsymbol{r}')}{|\boldsymbol{r}-\boldsymbol{r}'|^3}dV$$

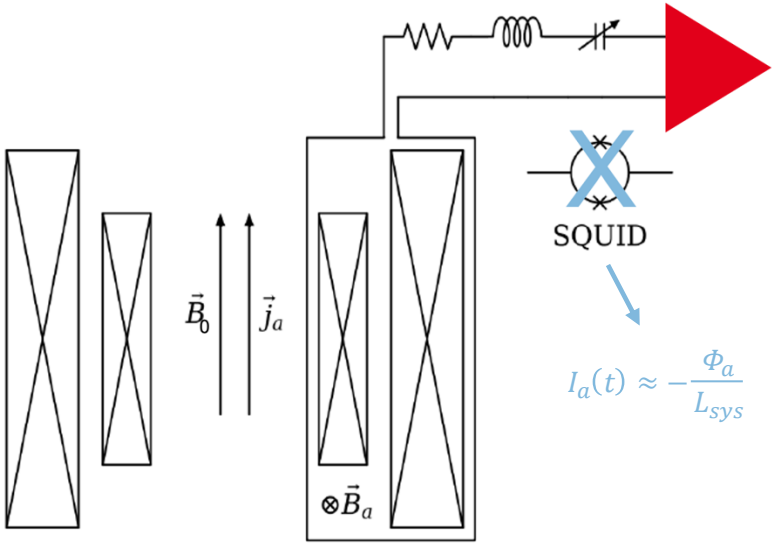
$$\Phi_a = g_{a\gamma\gamma}\sqrt{2\rho_{DM}}sin(m_a t)\int_{loop}dA\int\frac{\boldsymbol{B_0}\times(\boldsymbol{r}-\boldsymbol{r}')}{|\boldsymbol{r}-\boldsymbol{r}'|^3}dV\cdot\hat{\boldsymbol{n}}_{loop}$$

3. The toroidal magnetic field creates an AC $\mathrm{EMF} = -d\Phi_a/dt$.
4. EMF induces a voltage in a pickup loop (with N windings):

$$V_a(t) = N\cdot\frac{d\Phi_a(t)}{dt}$$

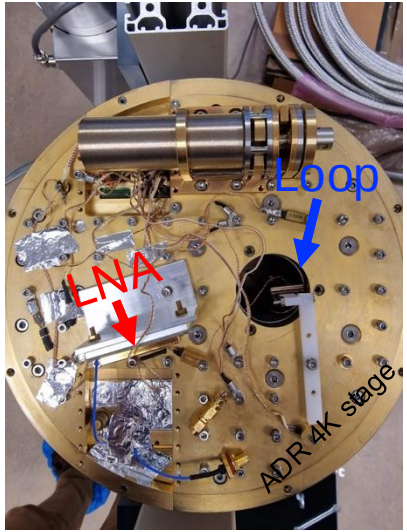
5. An LC circuit can tune and resonantly enhance the expected signal by Q at $\omega = \frac{1}{\sqrt{LC}}$.

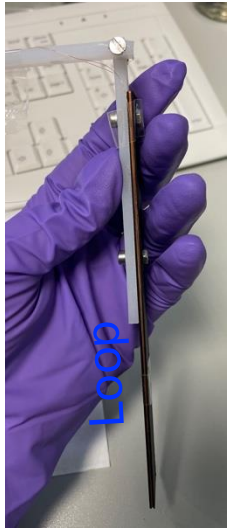
- WISPLC [5] employs voltage detection instead of current using a LNA instead of a SQUID.
- **Axion mass / frequency-dependent sensitivity!**

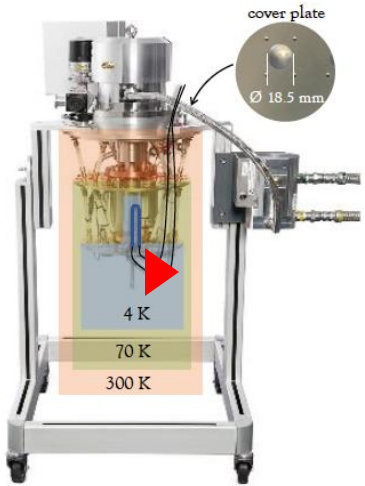


WISPLC Prototype – Setup (Broadband Case)

- A **250 cm** pickup loop from **0.1 mm Cu** wire is used winded 7 times around a rectangular 16 x 2 cm PTFE holder.
- The loop is placed inside the bore of a dipole **6 T** magnet of an ADR parallel to the magnetic field.
- Loop connected to a high-input impedance Stahl CX4 LNA providing **~67 dB** amplification @ 4K with a noise temperature **< 1K**.
- Post-amplification of ~40 dB via a room-temp Femto HSA LNA and **readout through an** SPCM **ADC**.

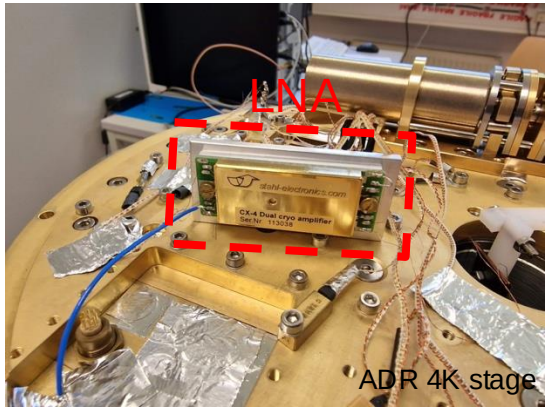


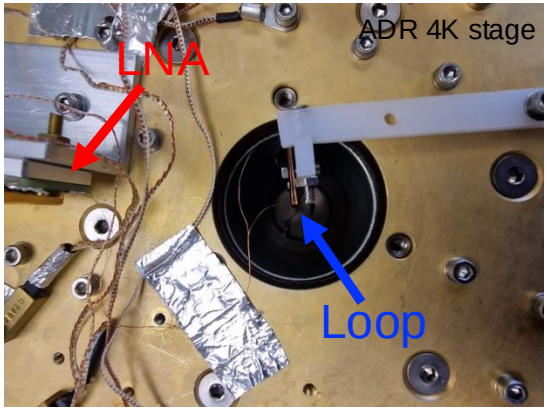




WISPLC Prototype – LNA

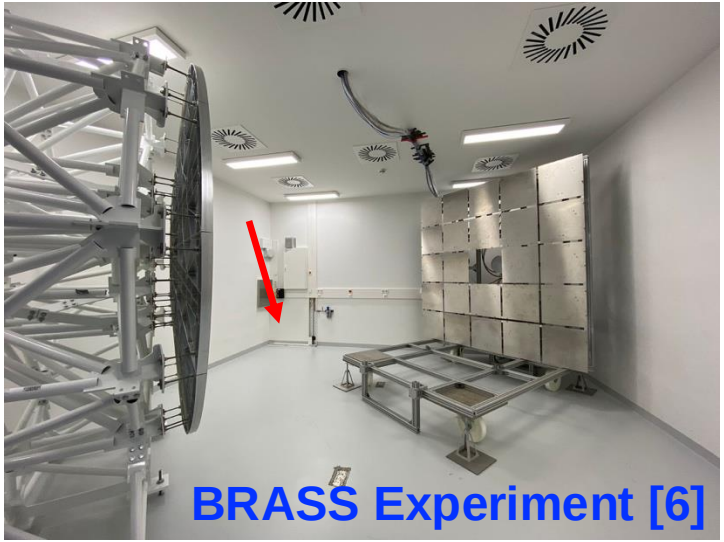
- SQUID magnetometers are very sensitive to stray magnetic fields in comparison to HEMTs
- LNA has MΩ input resistance to reject current noise so only the voltage is amplified.
- LNA mounted with optimum orientation to the stray static magnetic field.



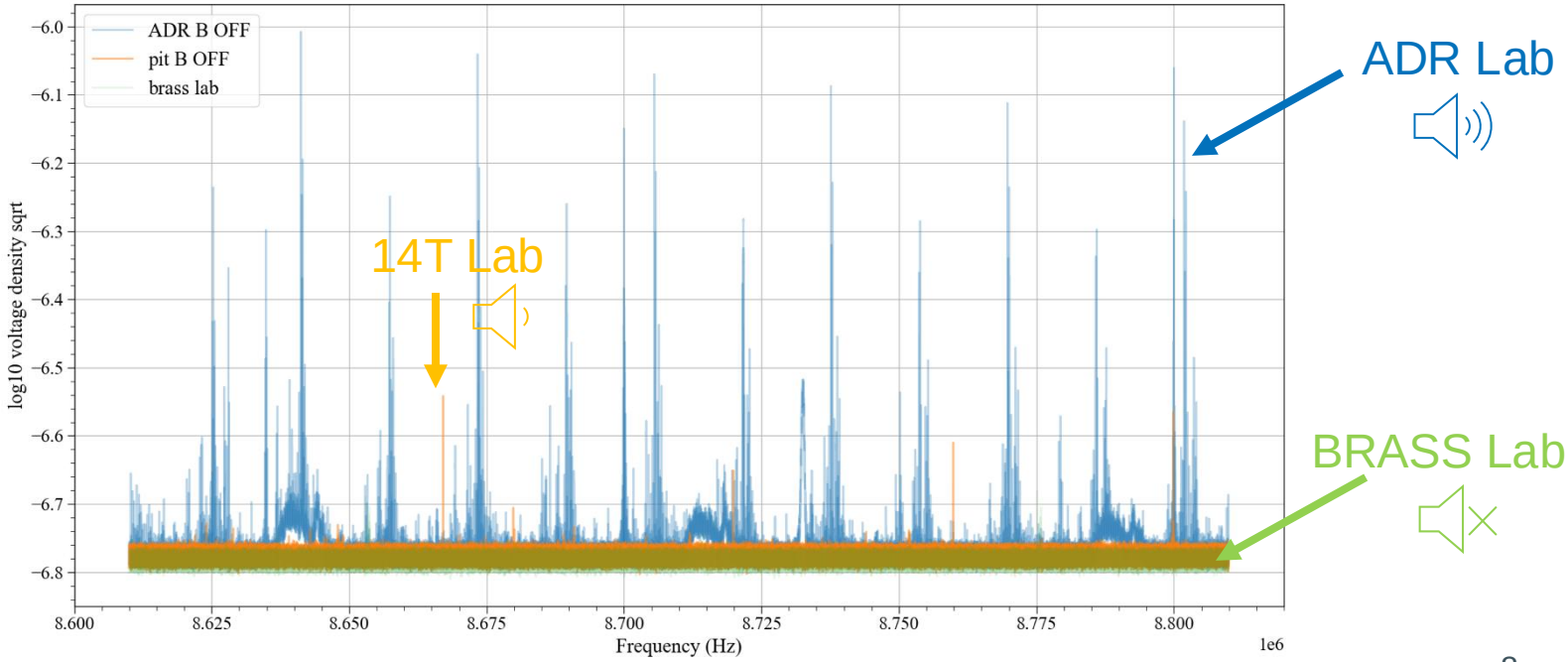


WISPLC Prototype – Shielding

- Setup installed inside the **radiation-shielded BRASS lab** [6] to reduce external EMI/EMC parasites.
- Compressors, chillers and control/monitoring rack placed outside.



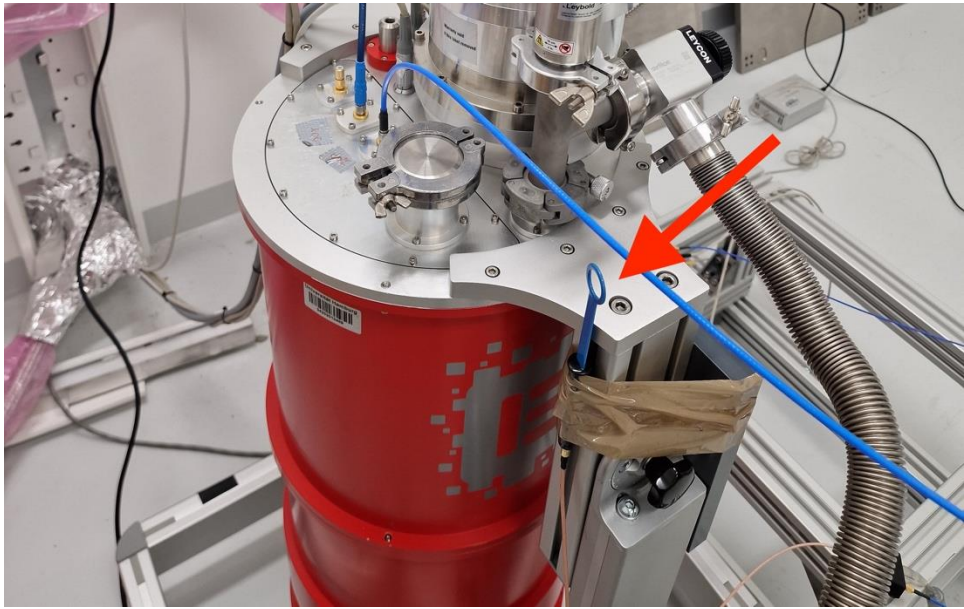
WISPLC Prototype – Shielding



WISPLC Prototype – EMI/EMC Identification

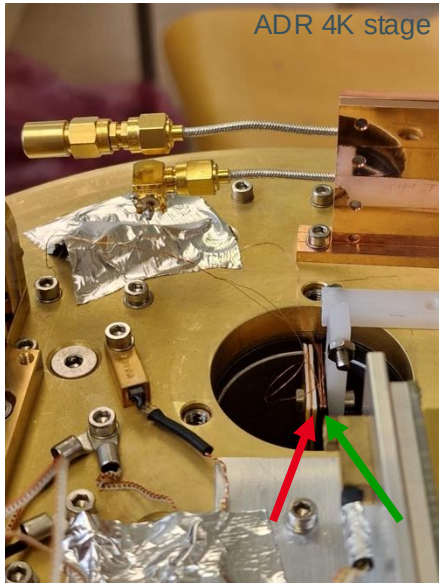
- Installation of an additional external antenna next to the ADR, measuring together with the pick-up probe channel & at the same frequency band to reject any incoming as well as **self-created** EMI/EMC.

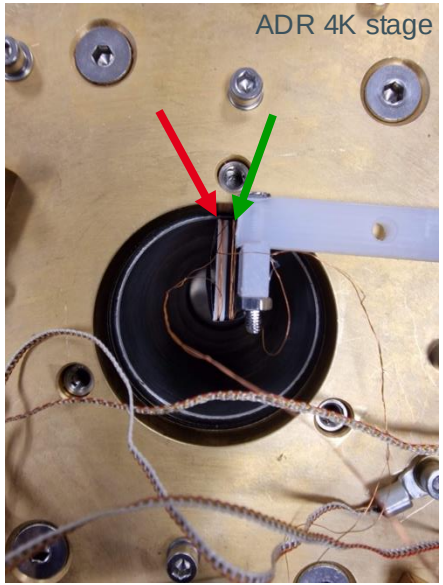
see slide 14



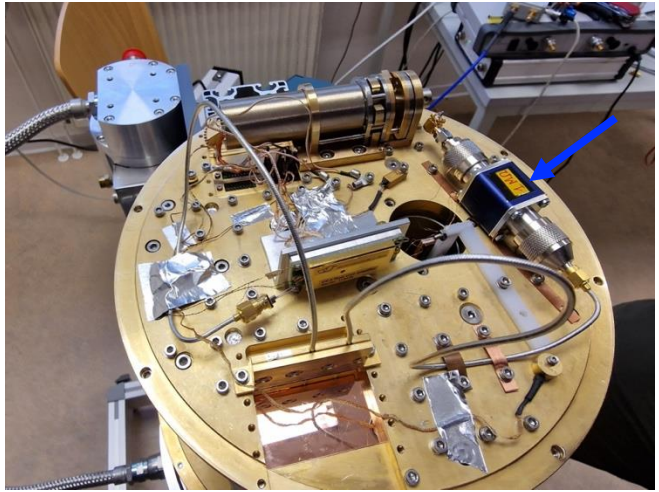
WISPLC Prototype – Calibration

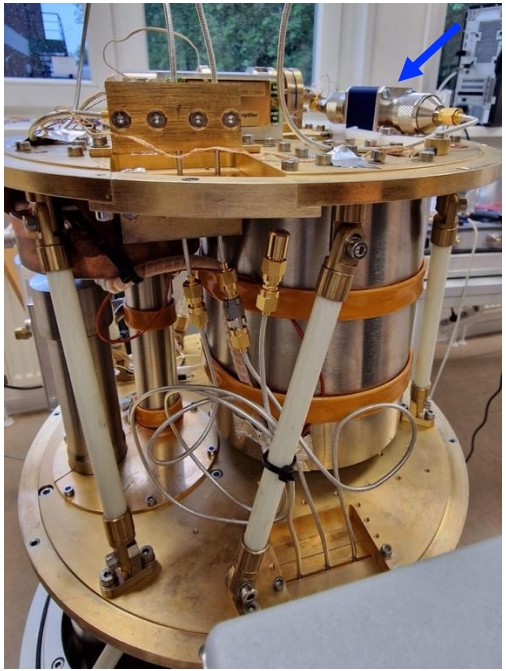
- Installation of a secondary similar Cu injection loop parallel to the pickup loop for injected signal coupling via mutual inductance.
- Synthetic signal injections for calibration and verification of the data acquisition procedure.





WISPLC Prototype – Calibration

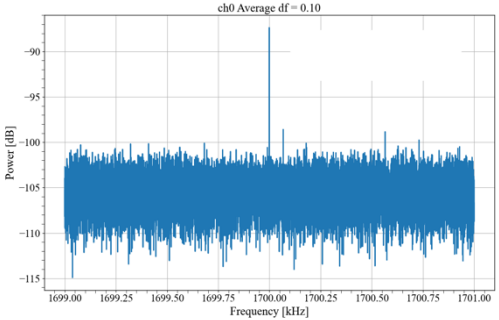




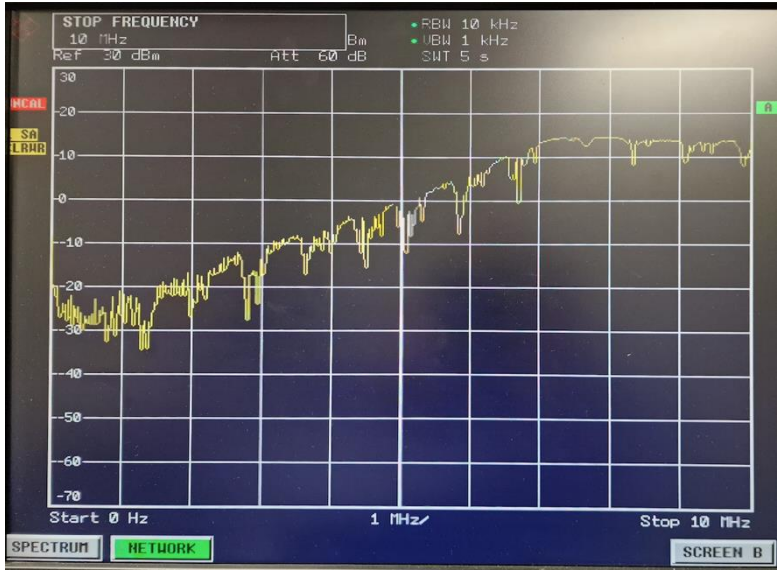
1 MOhm resistor placed in series to transform the injected voltage source into current source.

WISPLC Prototype – Calibration

- Sweeping from 0 - 10 MHz with a spectrum analyzer at -30 dBm in data-taking conditions.
- As expected, with the LNA and voltage detection setup, we have increased sensitivity with increasing frequency.

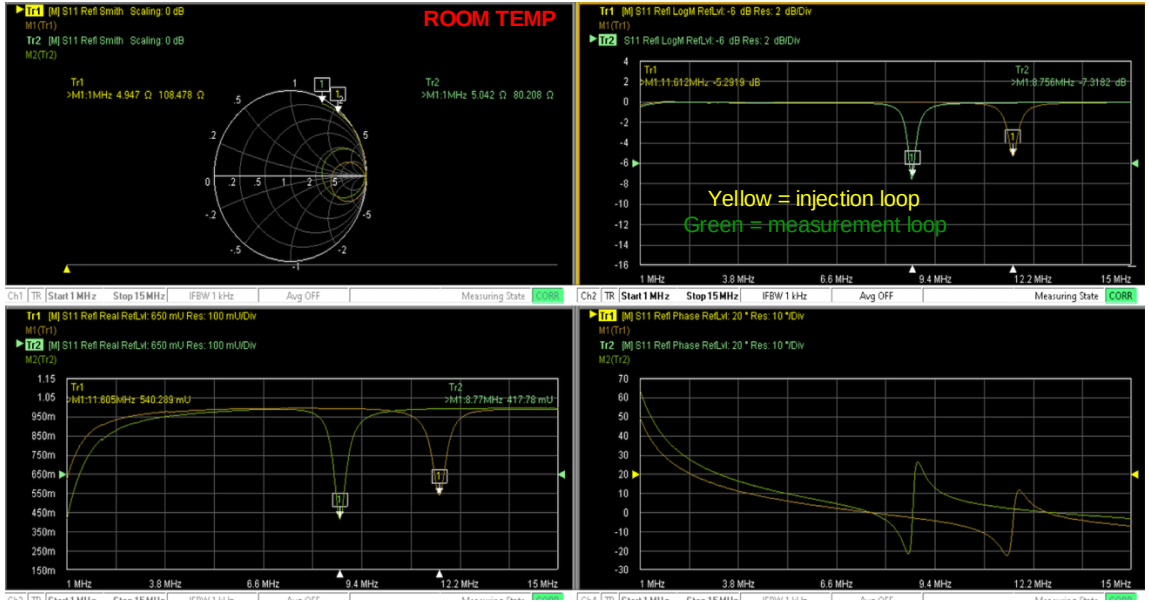


+ Hardware-injected CW signals for DAQ sanity check.



WISPLC Prototype – Characterization

- Impedance & inductance measurement @ room temp + data-taking conditions.
  - Expected values (@ room temp): Z_r = 5.5 Ohm L=20 μH
  - Measured values: Z_r = 5 Ohm L=13 μH
- Loop inductive up to 10 MHz @ 4K + 6T.
- Similar values for both injection and measurement loops

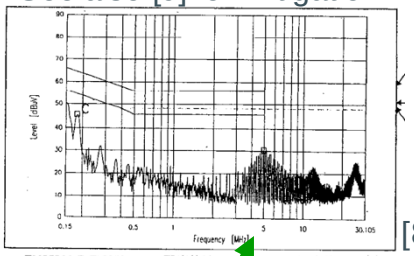


Data Acquisition Results

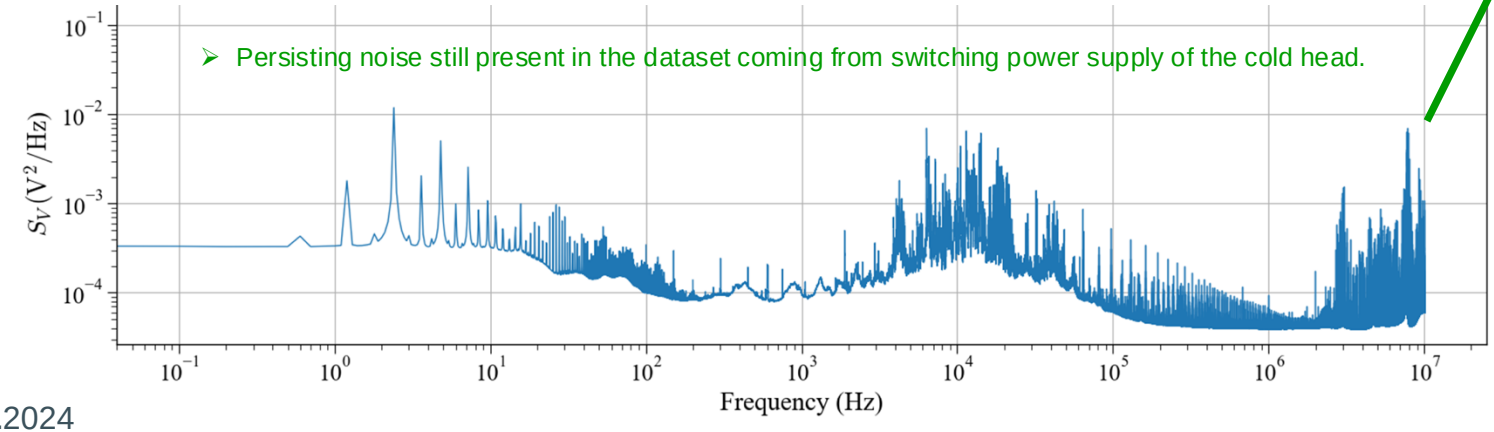
- **Measured for 84 h with B = 6T → for axion signal search.**

- Measured for 48 h with B = 3 T → for EMI/EMC signal elimination.
- Measured for 24 h with B = 0 T → for EMI/EMC signal elimination.
- Measured for 48 h with external probe → for EMI/EMC signal elimination

See also [9] for mitigation

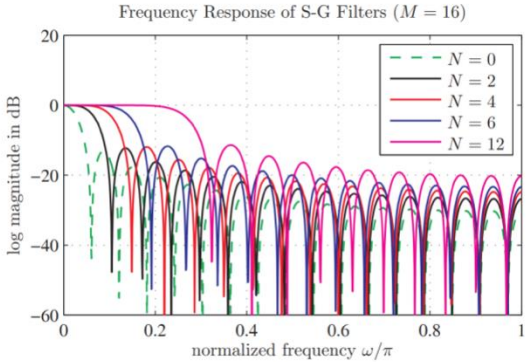


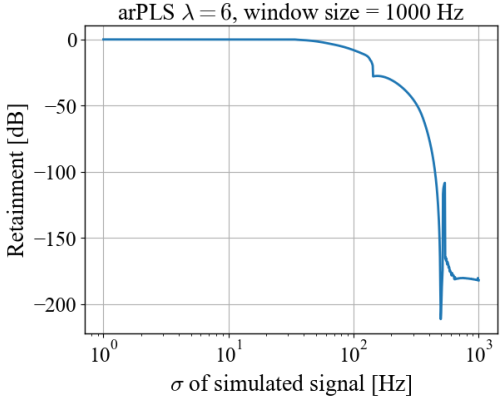
[8]



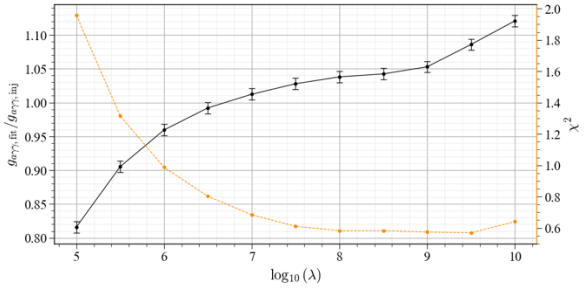
Data Analysis – Background subtraction

- Use of the asymmetrically-reweighted-Penalized-Least-Squares-Smoothing (arPLS) filter [7] instead of the Savitsky-Golay (SG) due strong EMI/EMC parasites distorting the spectrum shape.
- arPLS filter originally introduced for Raman Spectroscopy.
- SG not suitable for broadband searches due to limited attenuation in the stopband region (see also K. Ozbozduman's talk + poster).

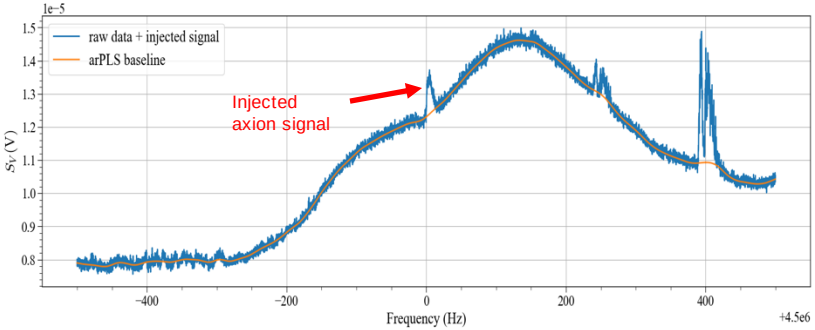


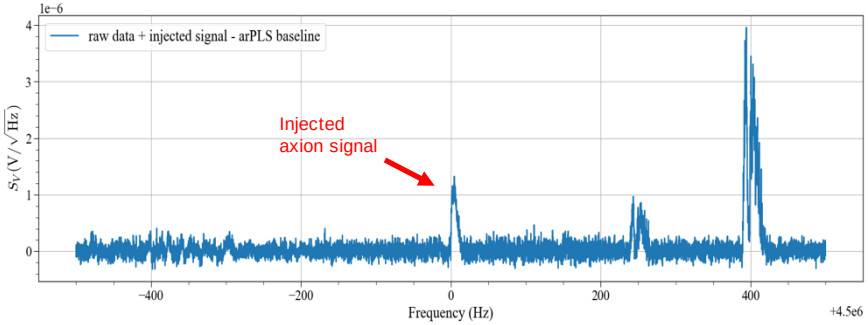


Data Analysis – Background subtraction

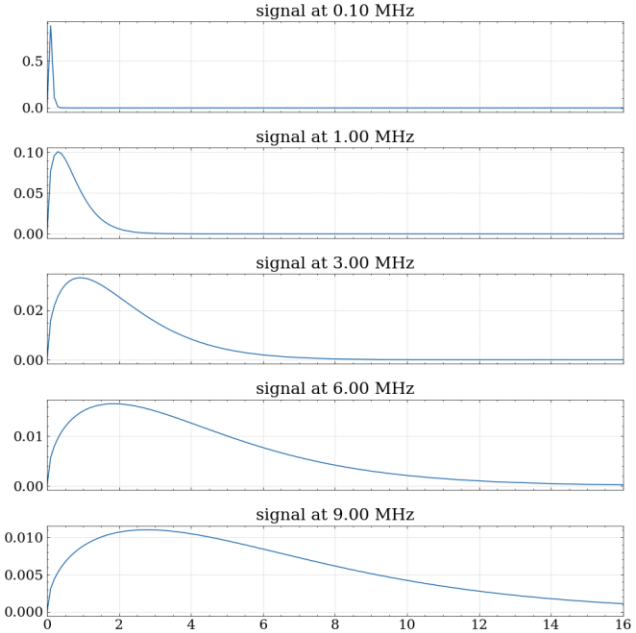


- Optimization of the smoothing parameter λ via Monte-Carlo simulations in order to have the minimum χ^2, and the correct axion-photon coupling.

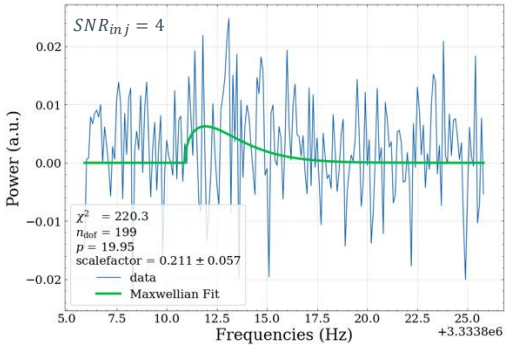


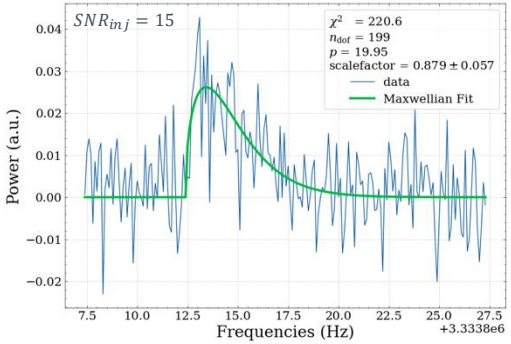


Data Analysis – Axion signal expectation



- **Varying axion linewidth** from ~ 0.1 Hz to 10 Hz for WISPLC useable 0.1 MHz – 10 MHz frequency range.
- Selected FFT RBW: **0.1 Hz**.
- **Dynamic λ** on arPLS filter for background fitting based on frequency.
- Blind signal injections for verification of the analysis procedure.





Data Analysis – Axion signal search

Signal elimination through the following procedure:

1. Appearance of a signal in the **external probe** dataset.
2. Incompatibility with expected **Maxwellian shape** and/or better linear fit.
3. Appearance of a signal in the **B = 0T** dataset.
4. Incorrect scaling of a signal in the **B = 3T** dataset.
5. Incorrect scaling of a signal with **time** (requires re-running of FFT on existing time-domain data).

Signal characterization procedure underway!

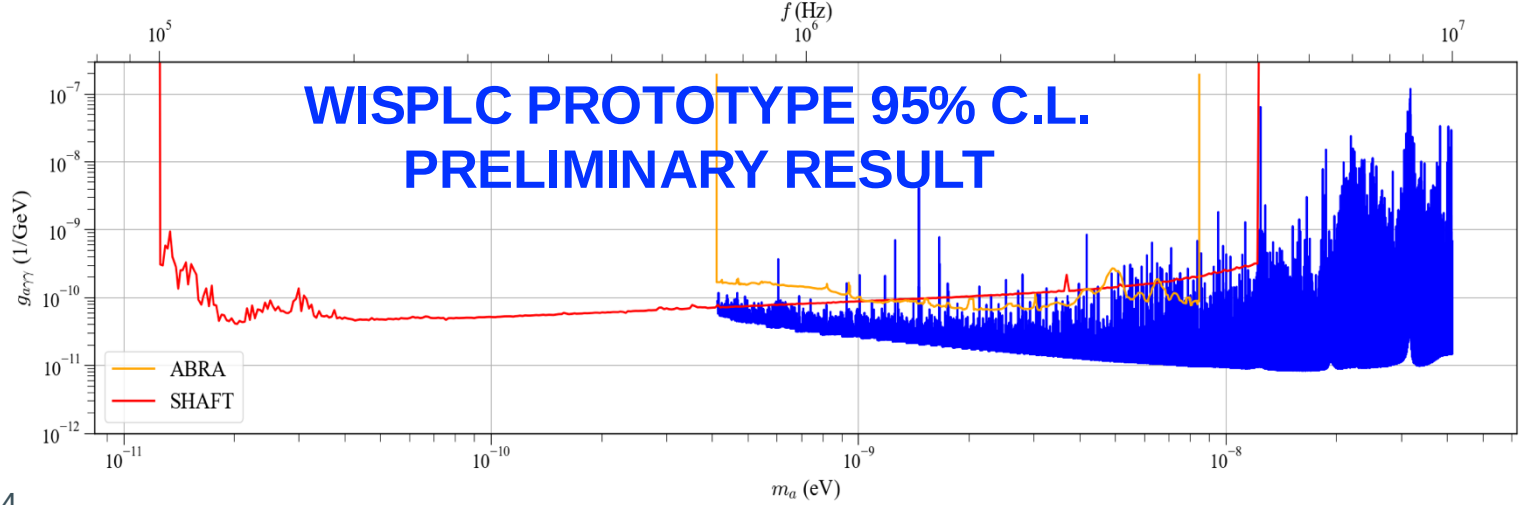
↓

Stay tuned!!

Data Analysis – Exclusion plot

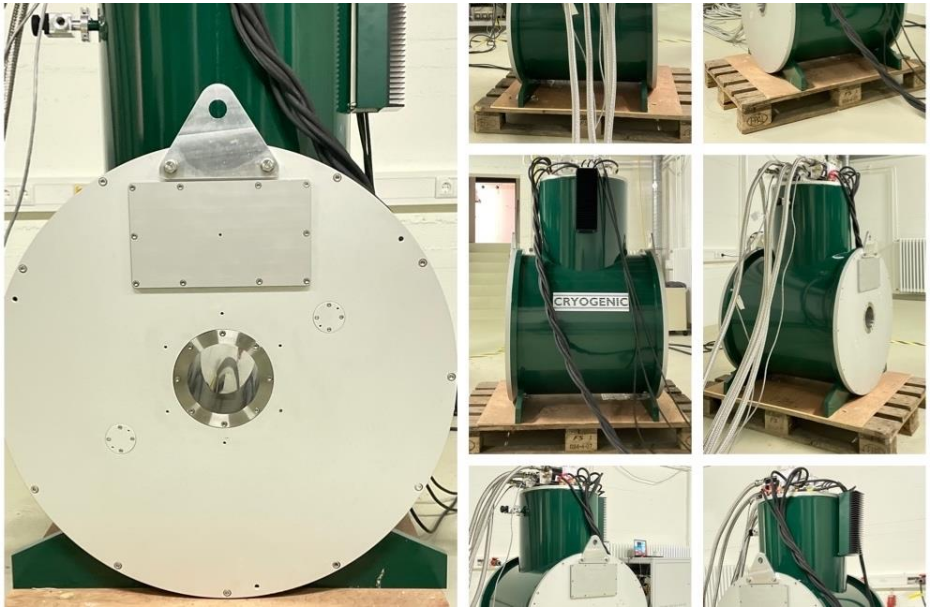
- Assuming no Axion/ALP signal is present in the collected dataset: ☹

$$g_{a\gamma\gamma} = \frac{\mathrm{SNR}\ \sigma_\Phi\ (t\tau_a)^{-1/4}}{BV_B\sqrt{2\rho_{\mathrm{DM}}}} = \frac{\mathrm{SNR}\ \sigma_V\ (t\tau_a)^{-1/4}}{m_a G N_{\mathrm{loop}} BV_B\sqrt{2\rho_{\mathrm{DM}}}}$$



Future steps

- **Publish** current physics results.
- Replace cold head switching DC power supply with a linear one or use copper mesh on supply line [8] to **reduce self-imposed noise**.
- Modify loop geometry and wire thickness to increase the inductive behavior of the pickup loop to **higher frequencies**.
- Introduction of a tuned capacitor in series with the loop for measurement under the **resonant scheme**.
- Implementation of WISPLC in our **14 T warm-bore magnet** for increased sensitivity.
- **GW and transient signal search** in the broadband mode.



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References

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