Status report and first results of the microwave LSW experiment at CERN

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Chicago 2012

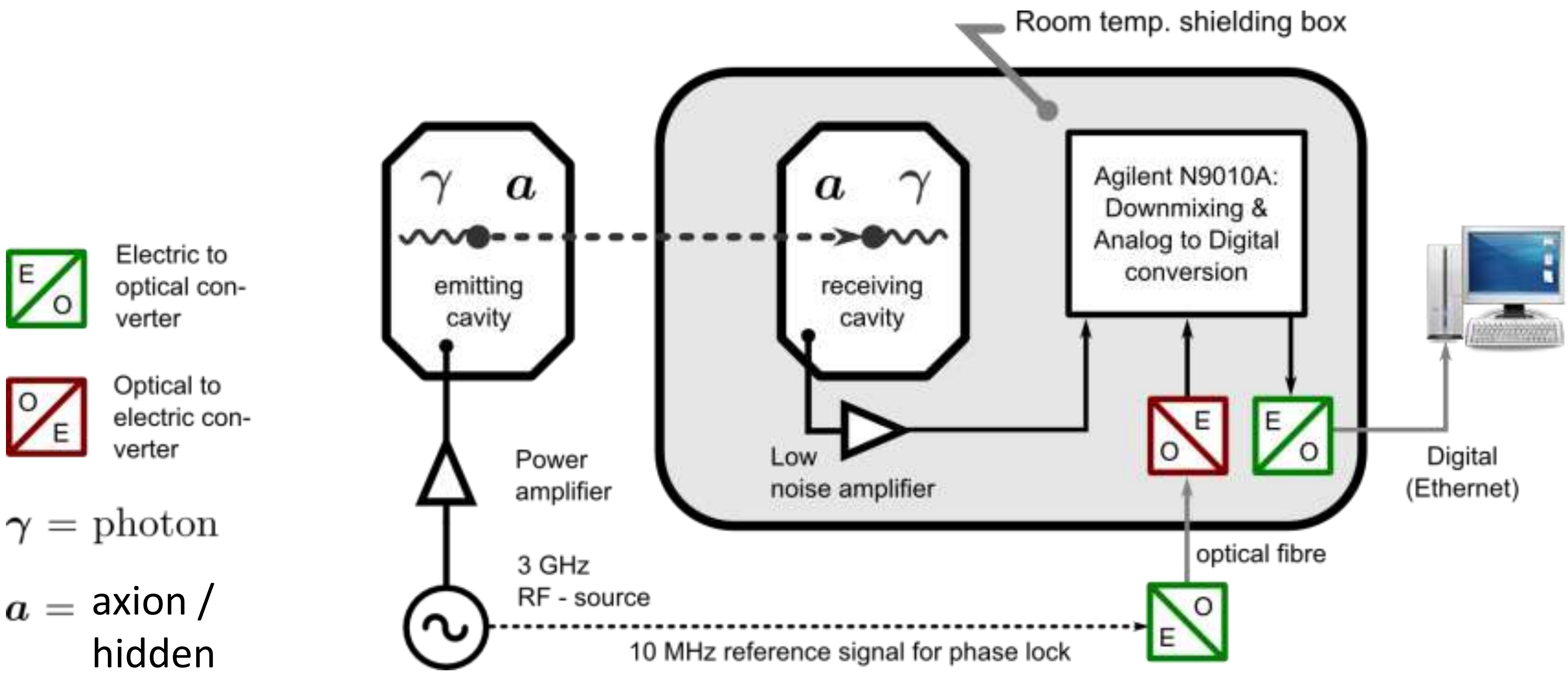
Outline

- "Microwaves shining through the wall" at CERN
  - Hardware setup
  - Engineering challenges
  - Signal processing

- Searching for Hidden sector photons (HSP), new exclusion limit

- Searching for ALPs in a magnet

Overview of the HSP setup



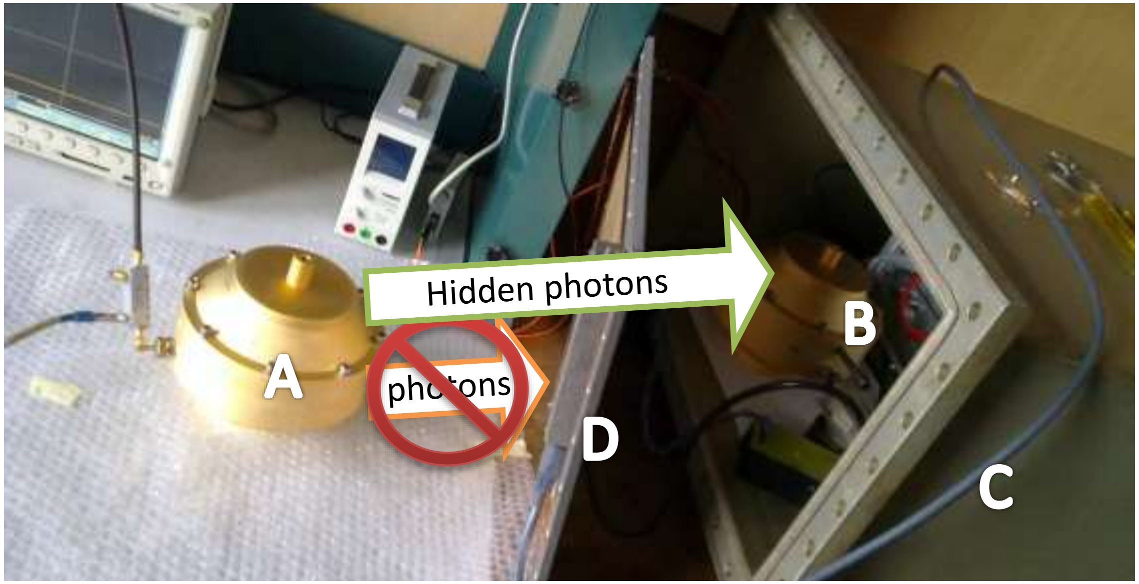
γ = photon

a = axion / hidden photon

Some of the challenges involved:

- Detecting a microwave signal below **-210 dBm** **(10^{-24} W)**
- Providing electromagnetic shielding of **> 300 dB** at 3 GHz within 15 cm
- Keeping both cavities on tune for **> 11 h**

The setup in the laboratory



(**A**) Emitting cavity
(**B**) Detecting cavity
(**C**) EM. Shielding enclosure, contains the signal receiver
(**D**) Custom feed-trough filter for 230 V mains

We achieved **> 300 dB** electromagnetic shielding at 3 GHz within 15 cm distance, that's a reduction in signal power by a factor of $\mathbf{10^{30}}$

Measured shielding effectivity

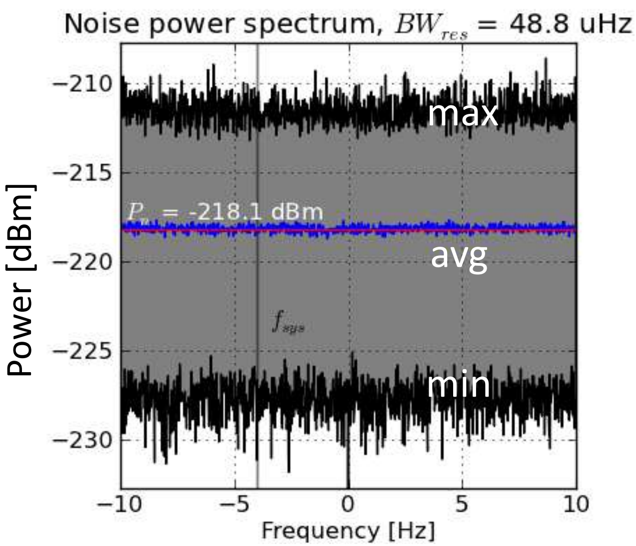
Emitting cav.	>110 dB
Detecting cav.	>110 dB
Shielding box	≈ 90 dB
Sum	>310 dB
Needed*	>258 dB

*for meaningful results

See also: M. Betz, F. Caspers, "A microwave paraphoton and axion detection experiment with 300 dB electromagnetic shielding at 3 GHz", proc. of IPAC 2012

Data processing

- **Signal analyser:** frequency conversion, digitizing, recording
- **Offline python script:** Windowing, **Fourier Transform (FFT),** estimates spectral power
- **Important property of the FFT:**
  Longer time trace (l) = narrower resolution bandwidth (BW_{res}) of one frequency bin
- Avg. noise power goes down, **signal power stays constant** (always within 1 bin)
- We can show: **FFT** = matched filter for sinusoidal signals = **optimum detector**



Resulting spectrum of a 11.5 h measurement run

Average noise power:

$$P_n = k_B \, BW_{res} \, T_{sys}$$

k_B = Boltzmann const.

BW_{res} = 1.5 / **l**
resolution bandwidth
(the width of one spectral bin)

l = length of the recorded time trace

T_{sys} = system noise temp.

With the FFTW software library, a **$130 \cdot 10^6$** points FFT calculates in ≈ 10 sec using 8 GB of RAM.

Even bigger FFTs can be calculated by the "**6 – step**" algorithm, making FFT size independent of available memory

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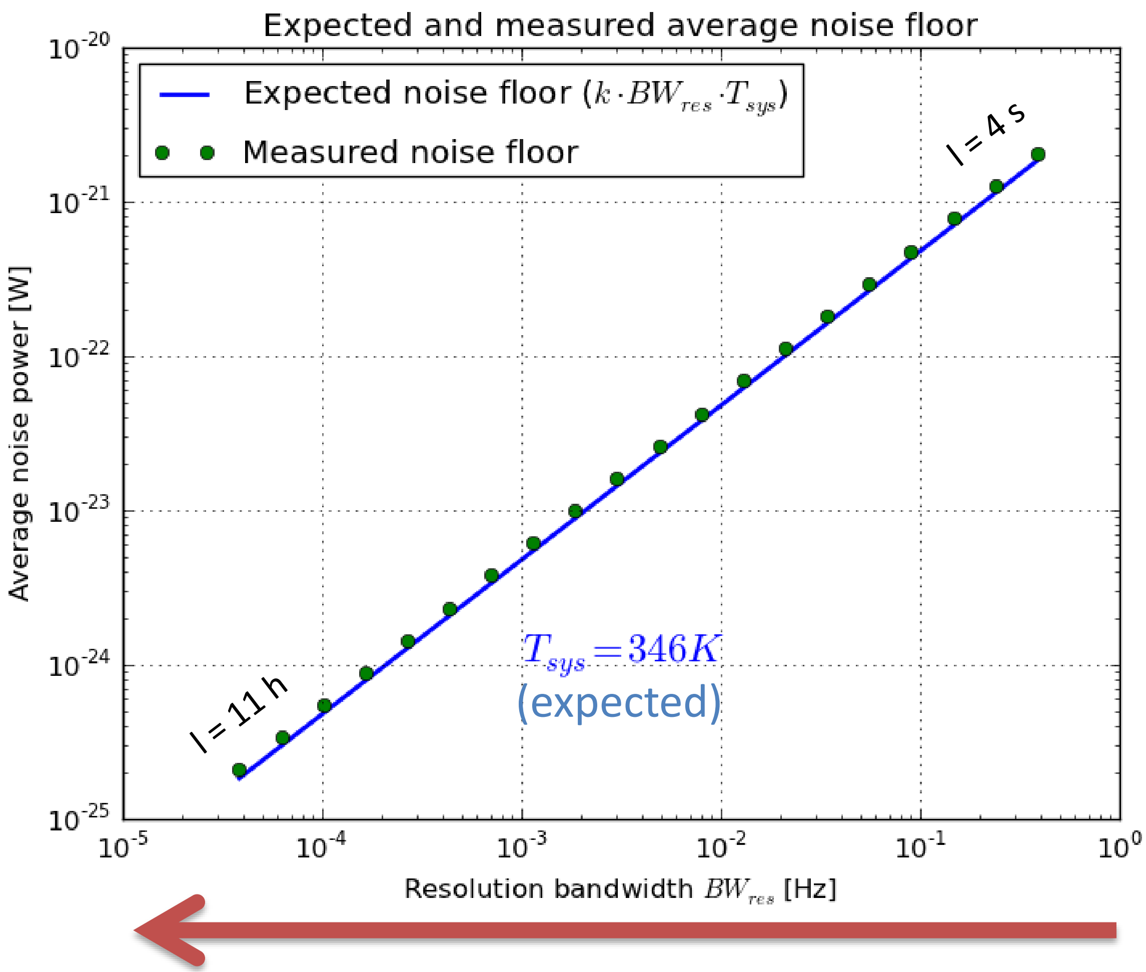
Data processing: pushing the avg. noise floor



l = length of one time segment

Average noise power:

$$\mathbf{P_n = k_B \, BW_{res} \, T_{sys}}$$

$\mathbf{k_B}$ = Boltzmann const.

$\mathbf{T_{sys}}$ = system noise temp.

Longer time trace (l) = narrower resolution bandwidth = lower noise floor

Data processing: pushing the avg. noise floor

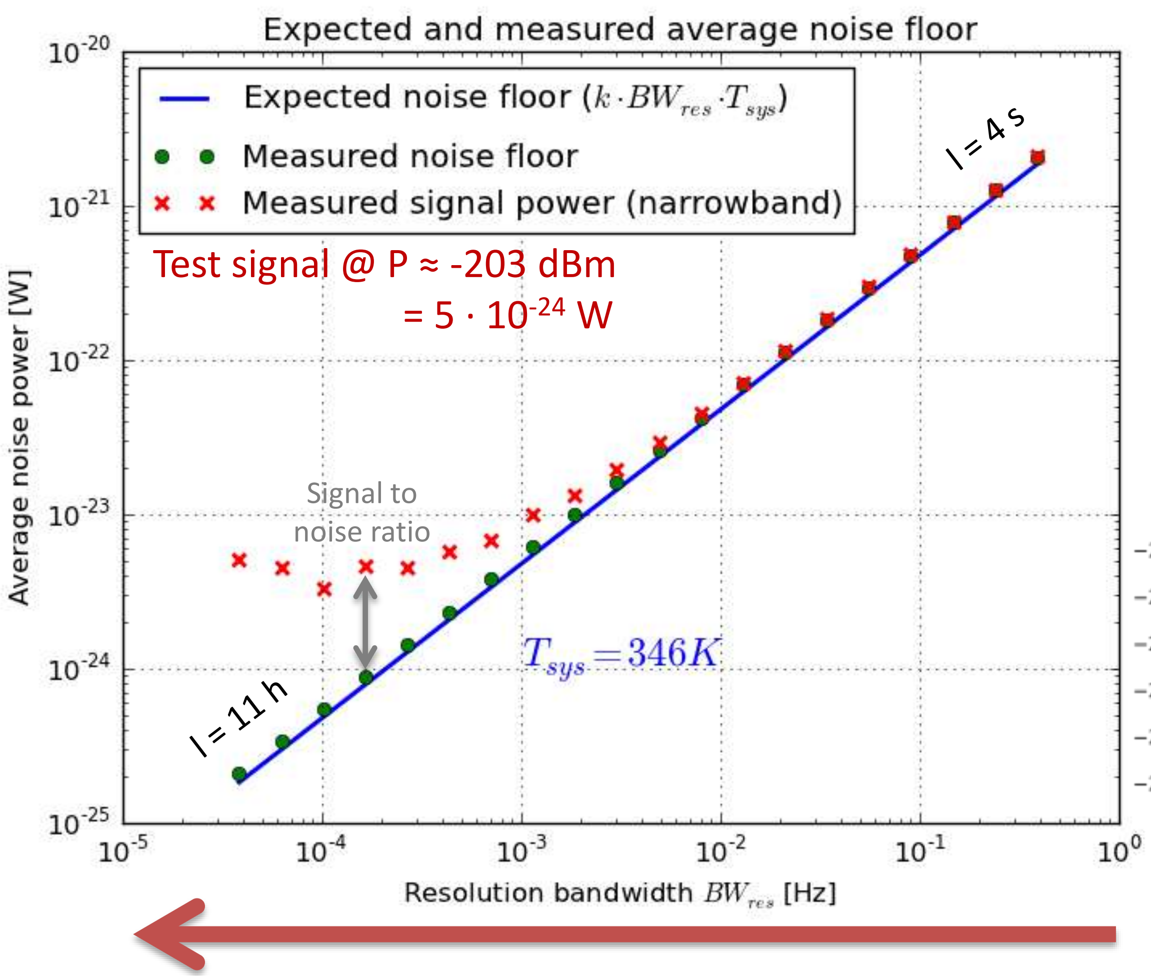
We can detect microwave signals below :

-210 dBm

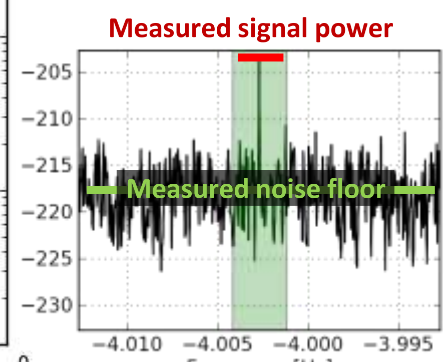
= 10^{-24} W

= 1 photon every 2 seconds

At room temperature, without any cryogenics!



l = length of one time segment



The signal power stays more or less constant

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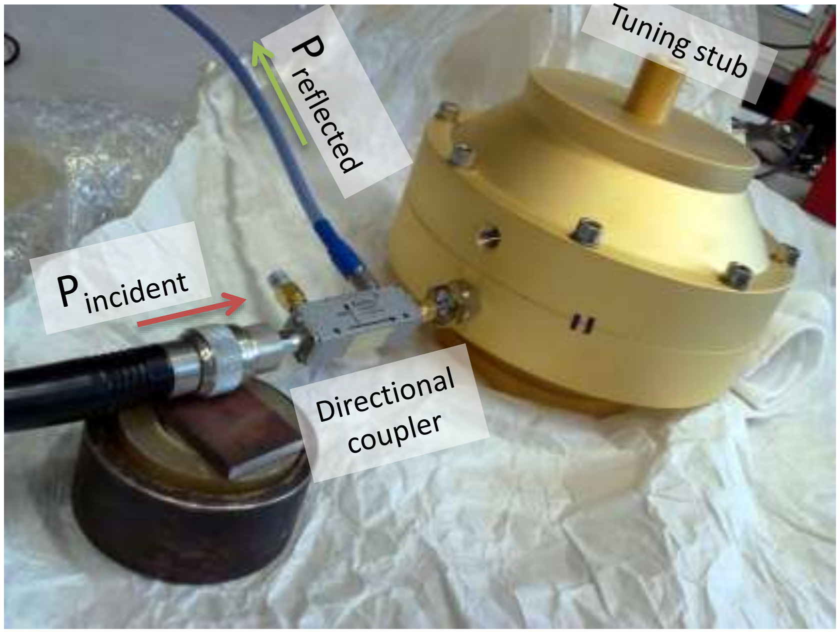
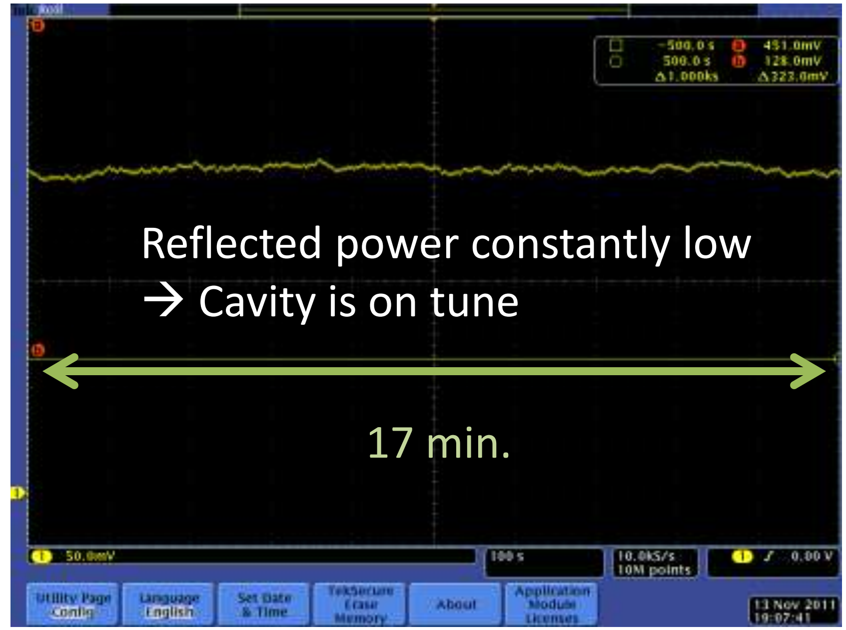
Tune of the **emitting** cavity



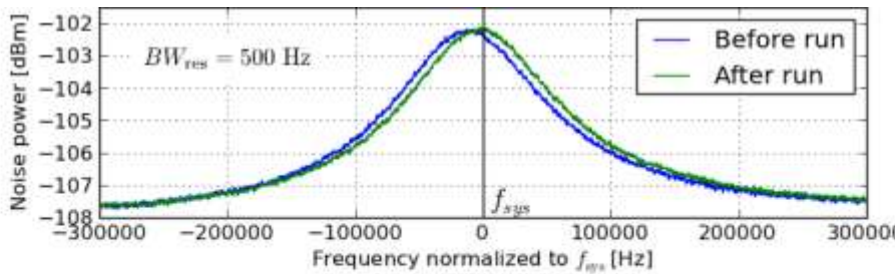


- If the cavity is on tune, reflected power should be **close to zero**
- We monitor and record this during the whole experimental run

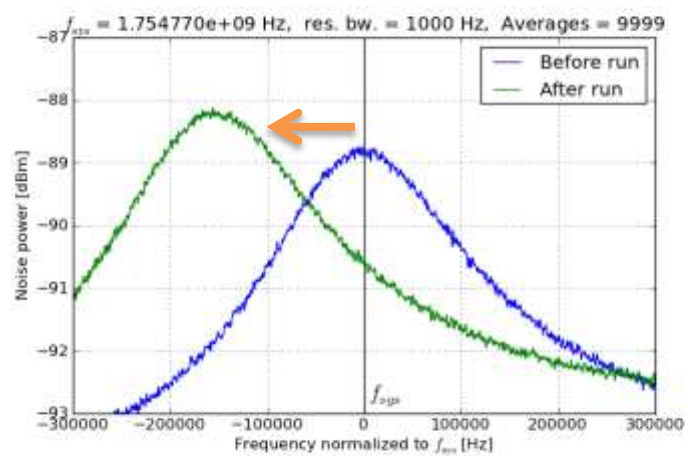
- During **warm up**, the cavity drifts by ≈ 1 MHz, this is significant! (3 dB bandwidth ≈ 130 kHz)
- the drift is compensated by the tuning screw manually
- Once in thermal equilibrium, the cavity is stable

Tune of the **detecting** cavity (1)

- Tune is less critical as there is no power dissipation
- The most significant noise source in our setup is thermal noise from the cavity walls
- The cavity's spectral noise power is measured before and after each run by the VSA
- Its maximum indicates the resonant frequency



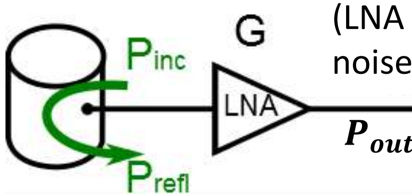
Measured thermal noise power from the detecting cavity, indicating little drift of its tune



The detecting cavity did not have enough time to warm up, a drift of the tune can be observed, we loose some signal power

Tune of the **detecting** cavity (2)

Γ(f) is the frequency dependent reflection coefficient of the cavity



(LNA = Low noise amplifier)

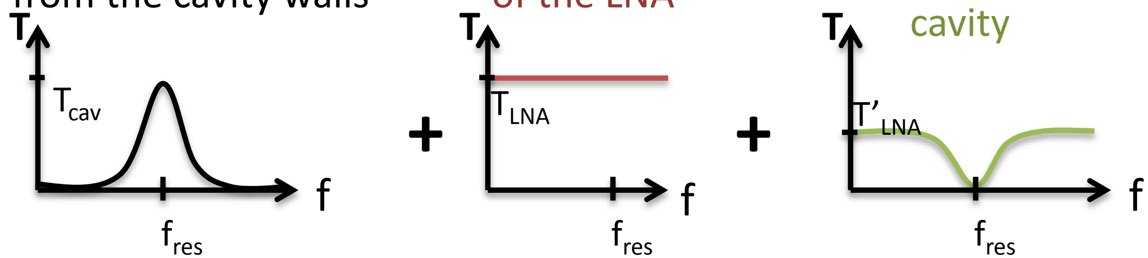
$$P_{out} = G \cdot k_B \cdot BW \cdot T_{sys}$$

$$T_{sys} = T_{cav}(1 - |\Gamma|^2) + T_{LNA} + T'_{LNA} \cdot |\Gamma|^2$$

"Blackbody" noise from the cavity walls

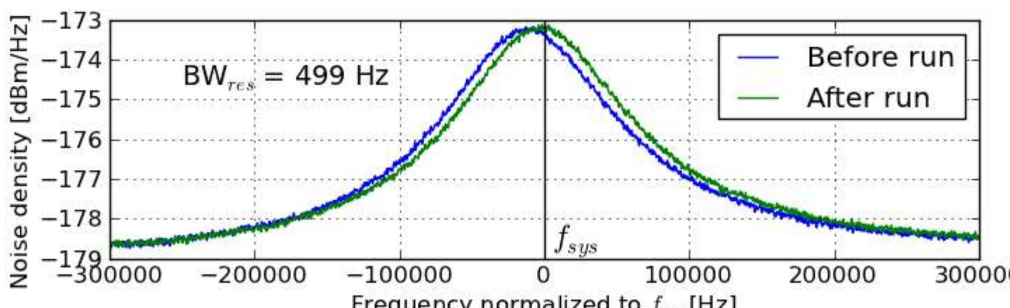
Intrinsic noise of the LNA

Noise from the LNA's input, reflected by the cavity



We either see a dip or a peak at the resonant frequency in the spectral noise power, depending if the noise temperature of the amplifiers input is larger or smaller than the physical temperature of the cavity

We don't consider any mismatch effects except **Γ** of the cavity



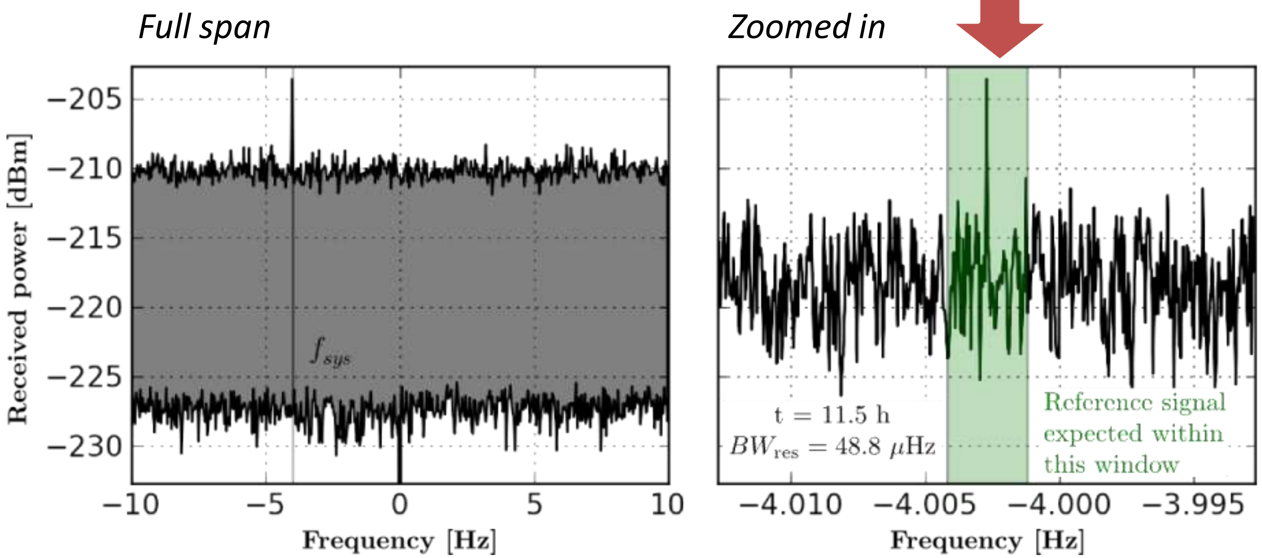
Measured thermal **noise power density** from the detecting cavity, indicating little drift of its tune

Outline

- Our “microwaves shining through the wall” setup
- Searching for Hidden sector photons (HSP), new exclusion limit
- Searching for ALPs in a magnet

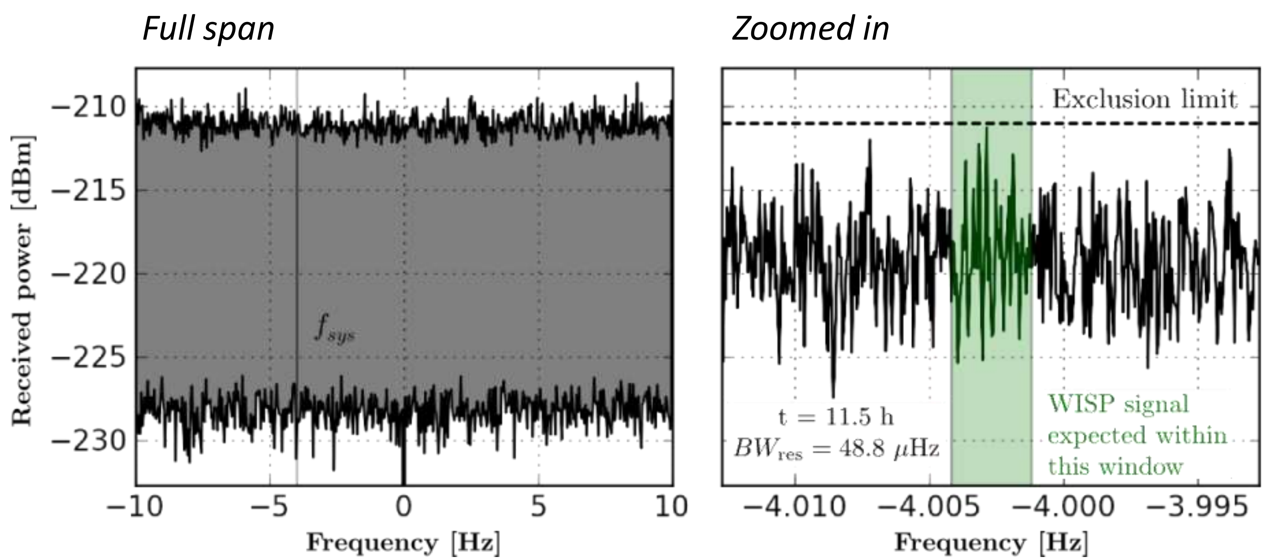
First HSP measurement run, March 2012

- 11.5 h reference run with **open shielding box**
  - We expect some **EM. leakage**
  - Proof that our setup is working
  - We define a window of +-1.5 mHz around the observed signal freq.



First HSP measurement run, March 2012

- 11.5 h measurement run with **closed shielding box**
  - peaks within the window do not significantly exceed the peaks in other parts of the spectrum
  - No signal detected → exclusion result



First HSP measurement run, March 2012

Expressing the result as an exclusion limit:

- Geometry factor G depends on frequency / HSP mass and has been determined numerically for the exact cavity geometry
- Results for G have been cross-checked by the YMCE group
- The formula for the exclusion limit X as a function of HSP mass was taken from [1]

Sampling points for the E-field of the TE_{011} mode for the numerical calculation of G

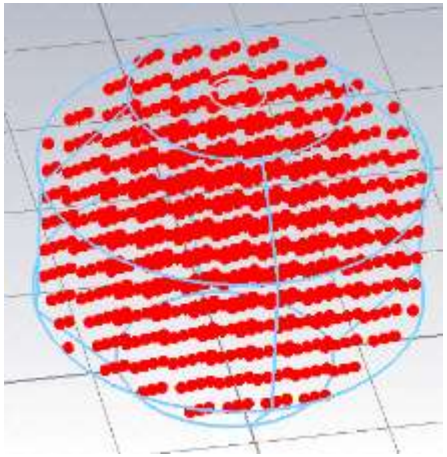


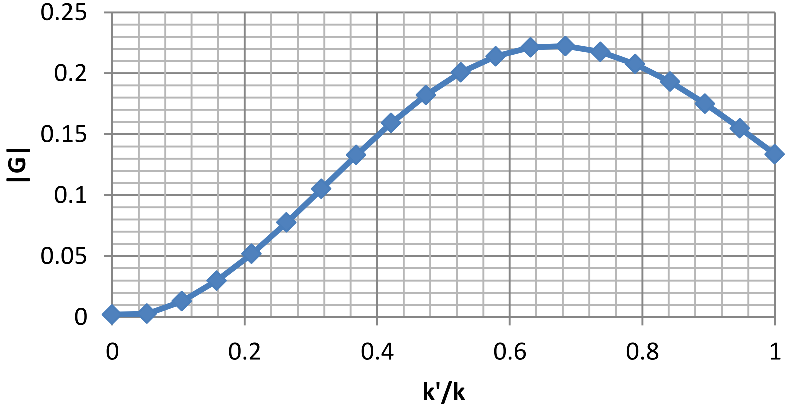
Table 1: parameters of the paraphoton run in March 2012

$f_{sys} = 2.9565$ GHz	$Q_{det} = 23620$	$Q_{em} = 23416$
$P_{det} = 8.51 \cdot 10^{-25}$ W	$P_{em} = 37$ W	$\|G\| = 0.222$

$$G(k'/k) \equiv k^2 \int_{V'} \int_{V} d^3\mathbf{x}\, d^3\mathbf{y}\, \frac{\exp(ik'|\mathbf{x}-\mathbf{y}|)}{4\pi|\mathbf{x}-\mathbf{y}|} A_{\omega_0}(\mathbf{y}) A'_{\omega_0}(\mathbf{x})$$

$$\chi^4_{excl}(m_{\gamma'}) \geq \frac{m_\gamma^8 \; P_{det}}{m_{\gamma'}^8 \, |G|^2 \, Q_{det} \, Q_{em} \, P_{em}}$$

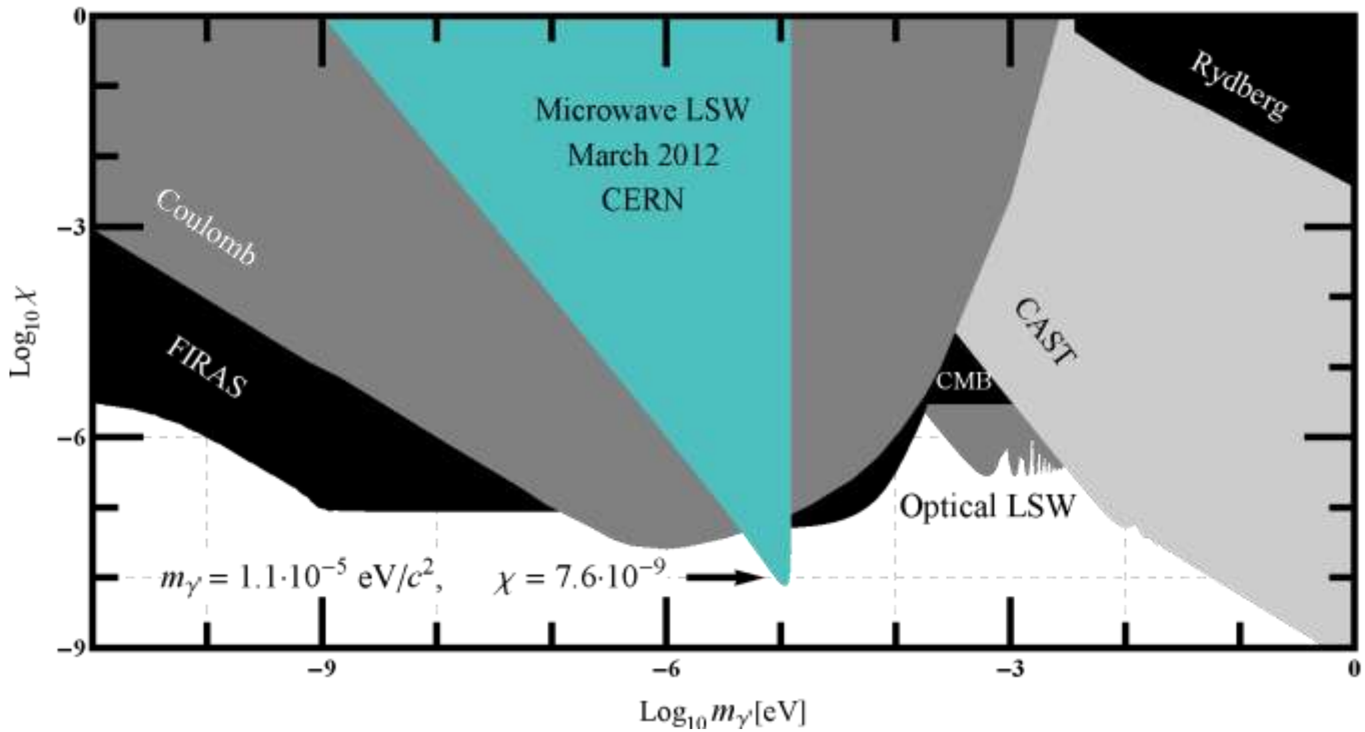
Geometry factor for the TE_{011} mode



[1] J. Jaeckel, A. Ringwald, "A Cavity Experiment to Search for Hidden Sector Photons"

First HSP measurement run, March 2012

- We were sensitive enough to improve over current exclusion limits [1]



Thanks to J. Jaeckel for the collection of exclusion plot data

[1] M. Betz, F. Caspers, "A microwave paraphoton and axion detection experiment with 300 dB electromagnetic shielding at 3 GHz", proc. of IPAC 2012

Outline

- Our “microwaves shining through the wall” setup
- Searching for Hidden sector photons (HSP), new exclusion limit
- Searching for ALPs in a magnet

Axion LSW measurements (June 2012)

- We got a 1 week timeslot to use a large 0.5 T magnet in July

- Things which had to be done before:

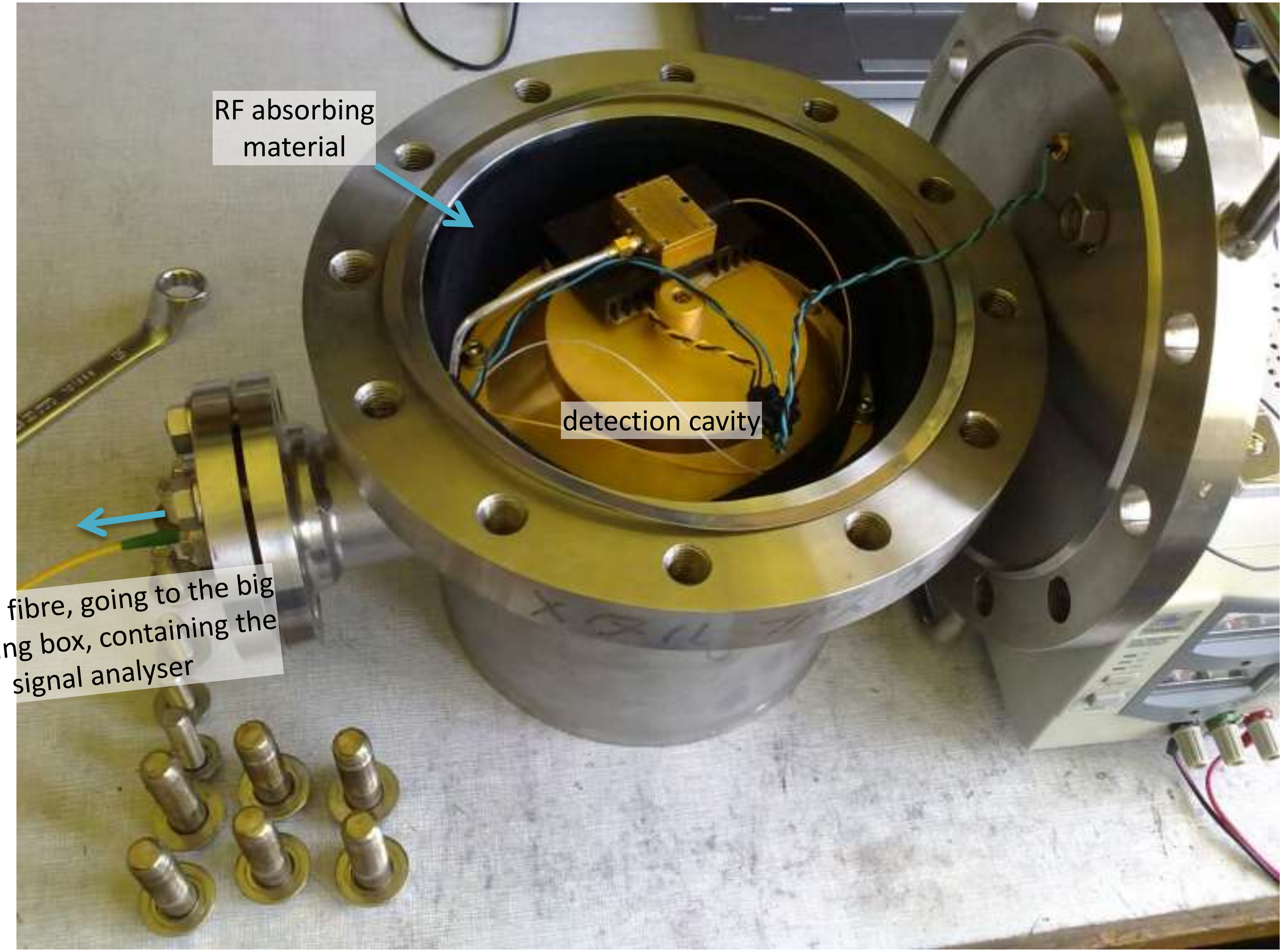
  - Adjust the cavity couplers to the **TM_{010} mode** at 1.755 GHz, which couples to ALPs

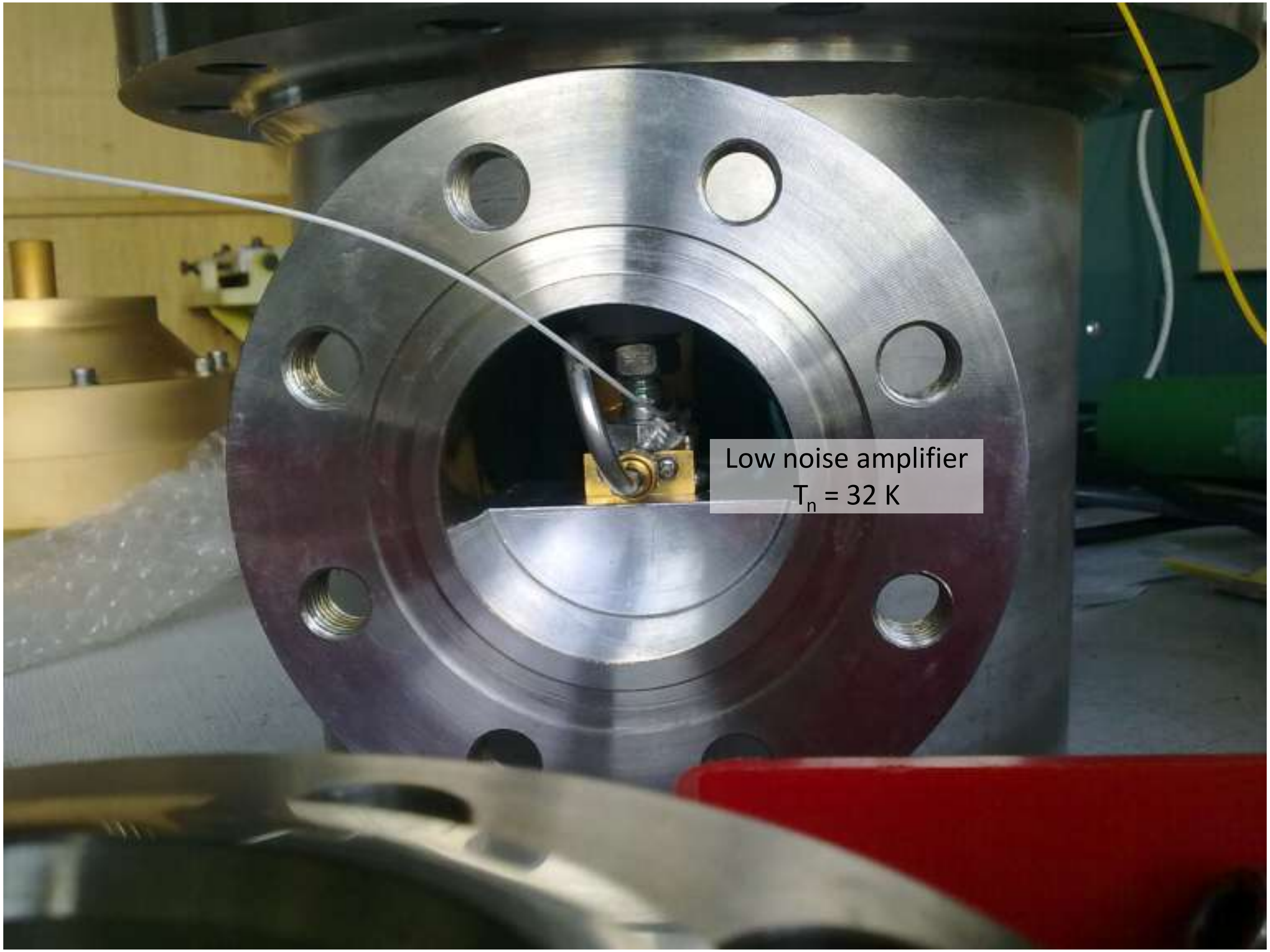
  - Find a new power amplifier for 1.755 GHz

  - Construct a smaller **secondary shielding enclosure** which fits inside the magnet

The secondary shielding enclosure, ready to be placed in the magnet


DC feed-through capacitor,
DC can pass, EMI is blocked

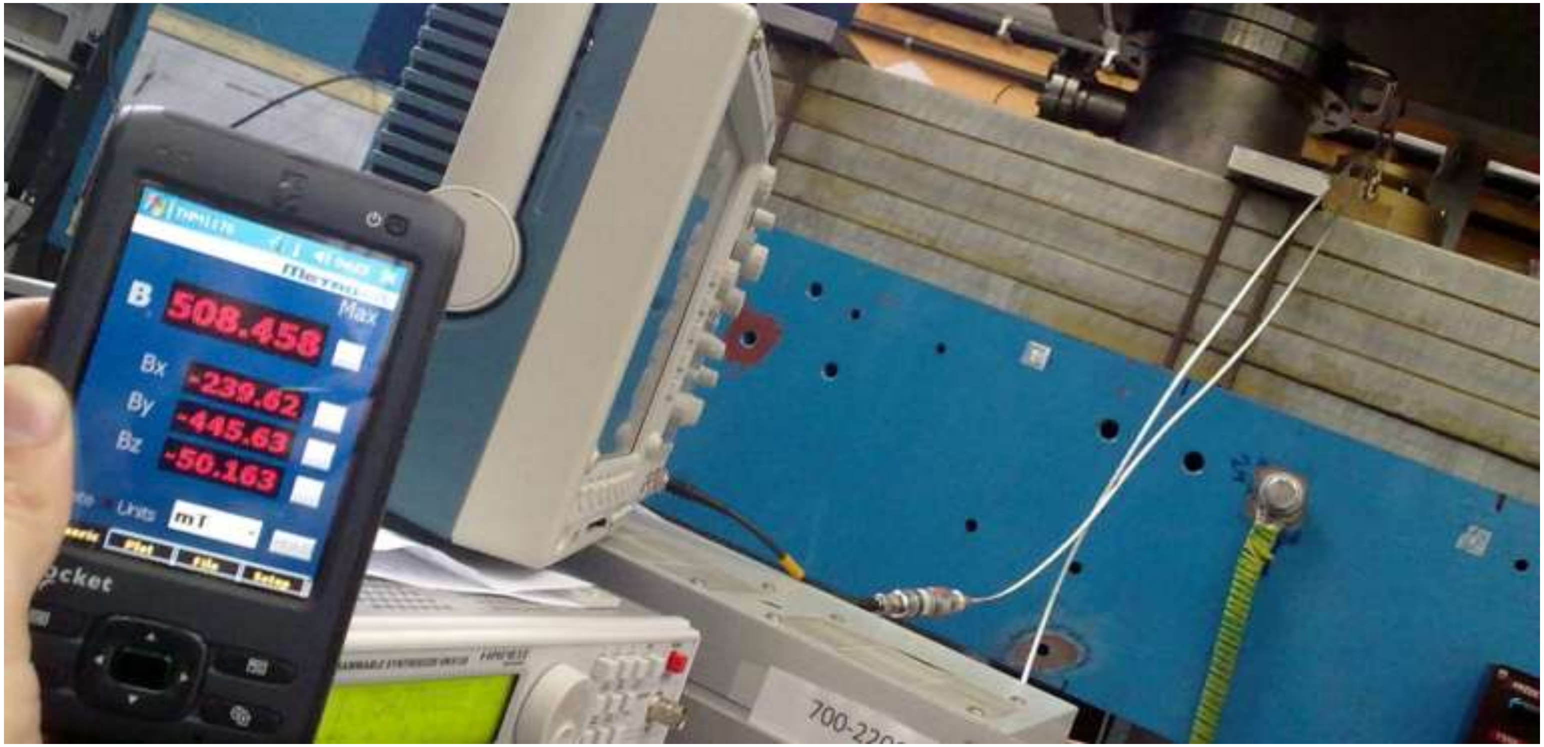

RF absorbing material
detection cavity
optical fibre, going to the big shielding box, containing the signal analyser


Low noise amplifier
T_n = 32 K

Moving to the magnet hall

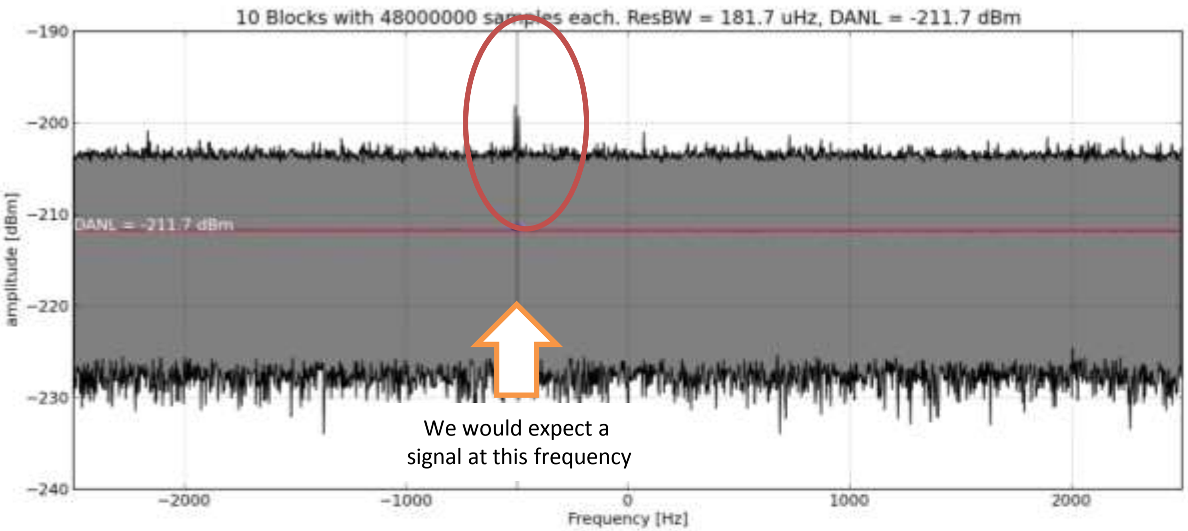

|B$_{max}$| = 0.5 T
Resonant frequency: **1.754 GHz**
Incident RF power: **7.3 W**
Avg. reflected power: **0.7 W**

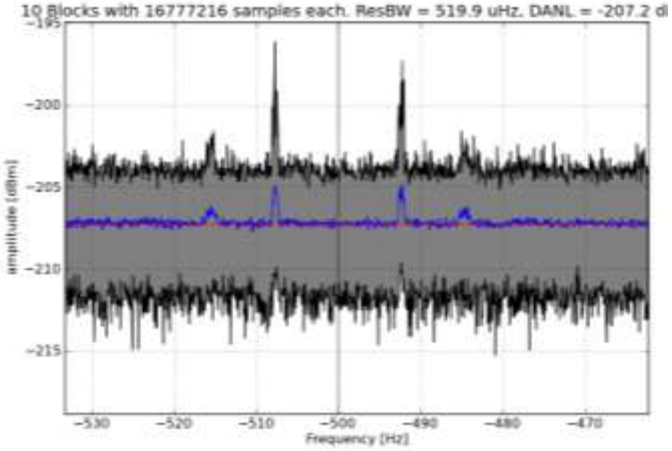

ON
FAST
STOP
V
A


B
508.458
Max
Bx
-239.62
By
-445.63
Bz
-50.163
Units
mT
Plot
File
Setup
700-220

Results from the first run

- After the first 4h of recorded data, a surprise

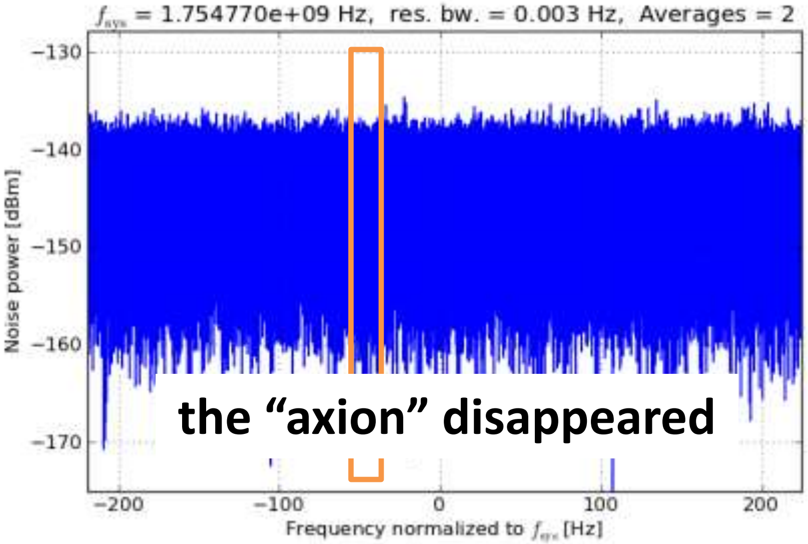




Did the axion finally reveal itself?

Results from the first run

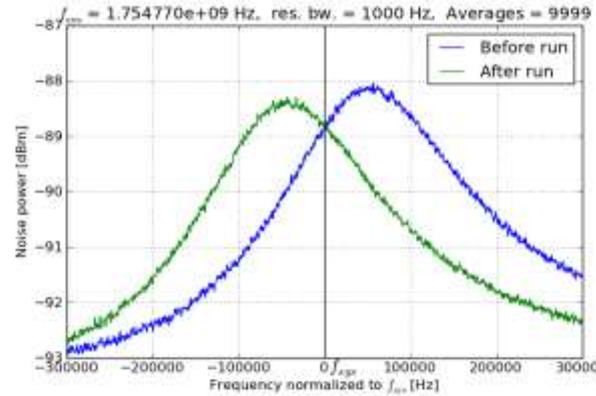
- It turned out to be just **EM. leakage**
- The strange modulation came from the RF source, which struggled to lock to the 10 MHz reference
- Stuffing copper mesh in the seam and using a different RF source fixed the problem

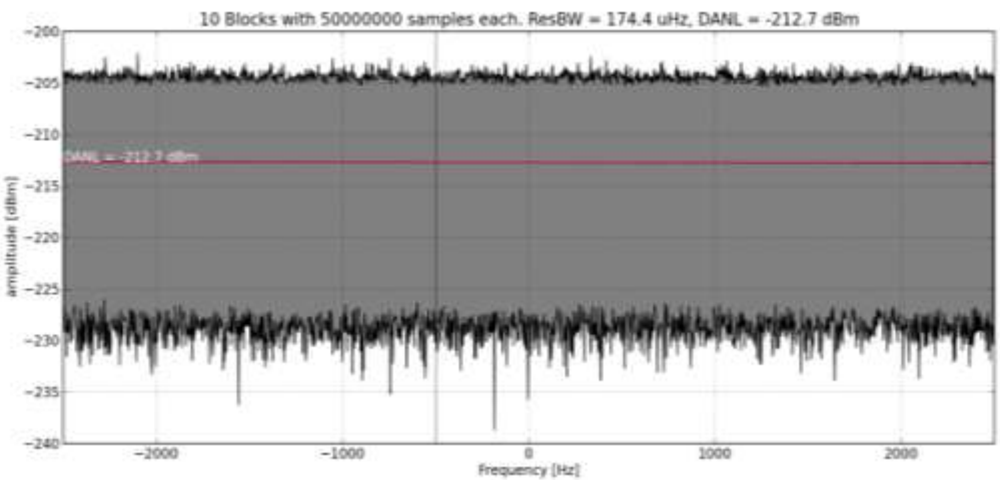


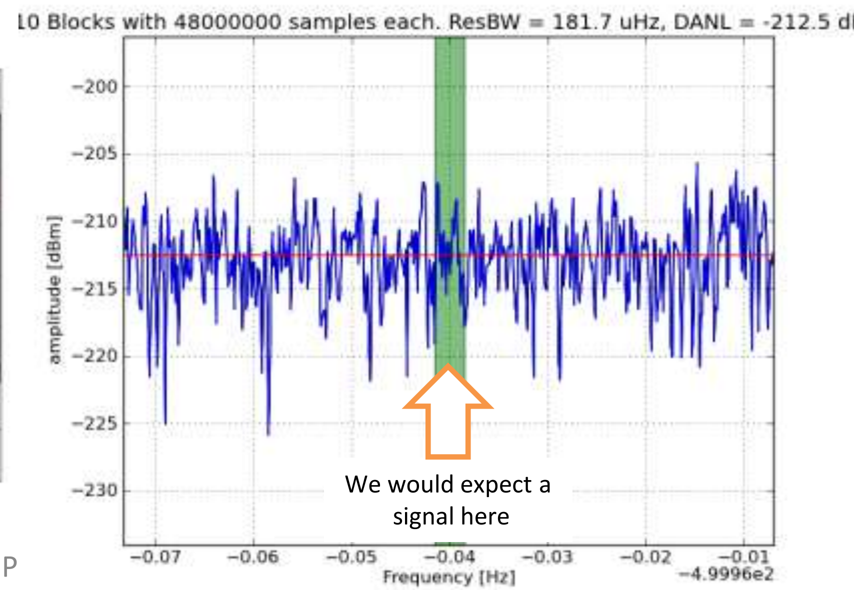
Results from the second run

- After another 4h of recorded data
- Nothing visible, except thermal noise
- Smallest detectable signal: ≈ -205 dBm

Tune of the detecting cavity

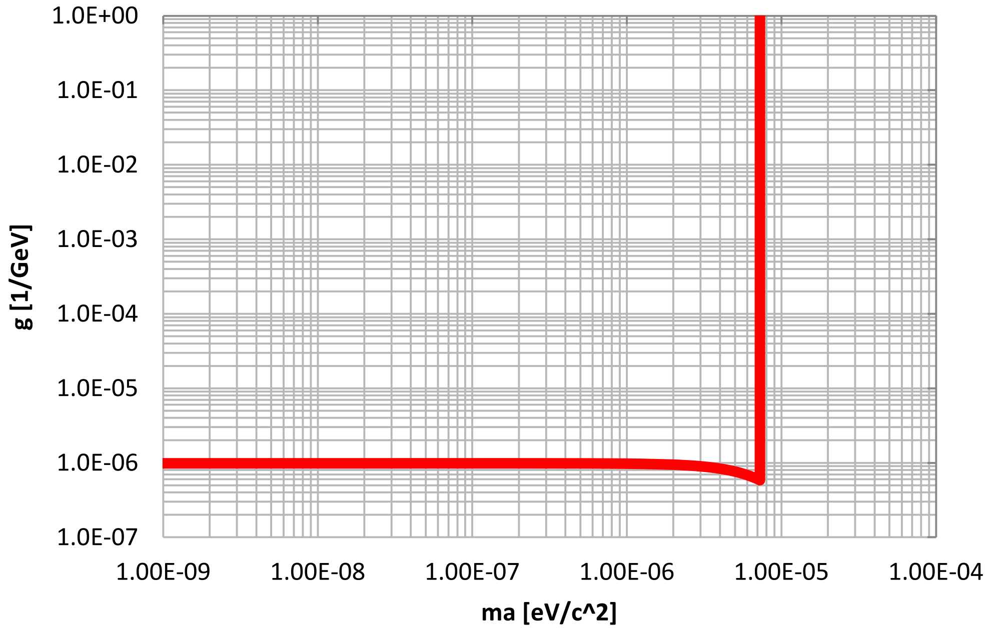


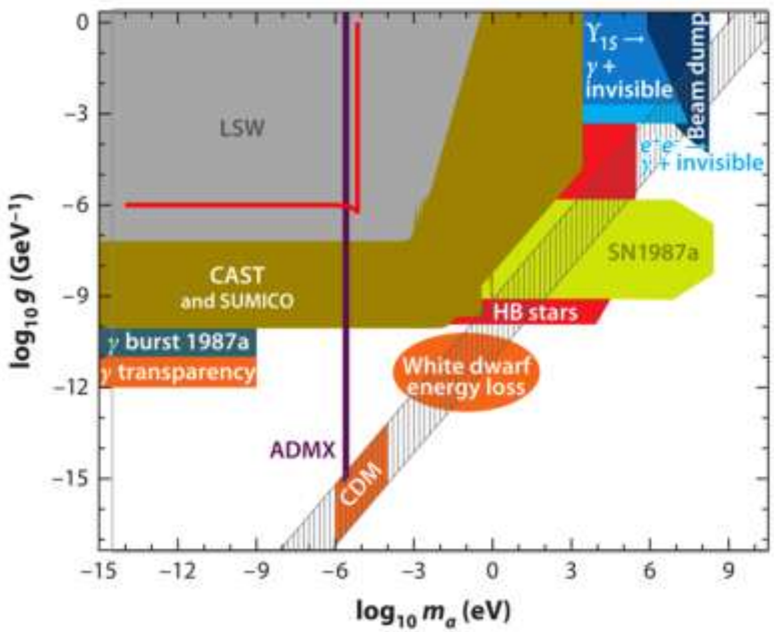




Results from the second run

expressed as an exclusion limit for ALPs





Same principle as for HSP but with a different formula [1]

$$P_{\text{trans}} \sim \left(\frac{g\,B}{\omega_0}\right)^4 QQ'\,|G|^2.$$

[1] J. Jaeckel, A. Ringwald, A Cavity Experiment to Search for Hidden Sector Photons, arXiv:0707.2063v1

Preliminary!

Plot from J. Jaeckel and A. Ringwald, Ann. Rev. of Nuc. and Particle Sci., 60, 405, 2010.

Conclusion

- Only exclusion results so far
- All in all, the microwaves shining through a wall experiment is a success
- We got the EMI issues under control and have a running experiment
- World record sensitivity for hidden sector photons at 10 μeV

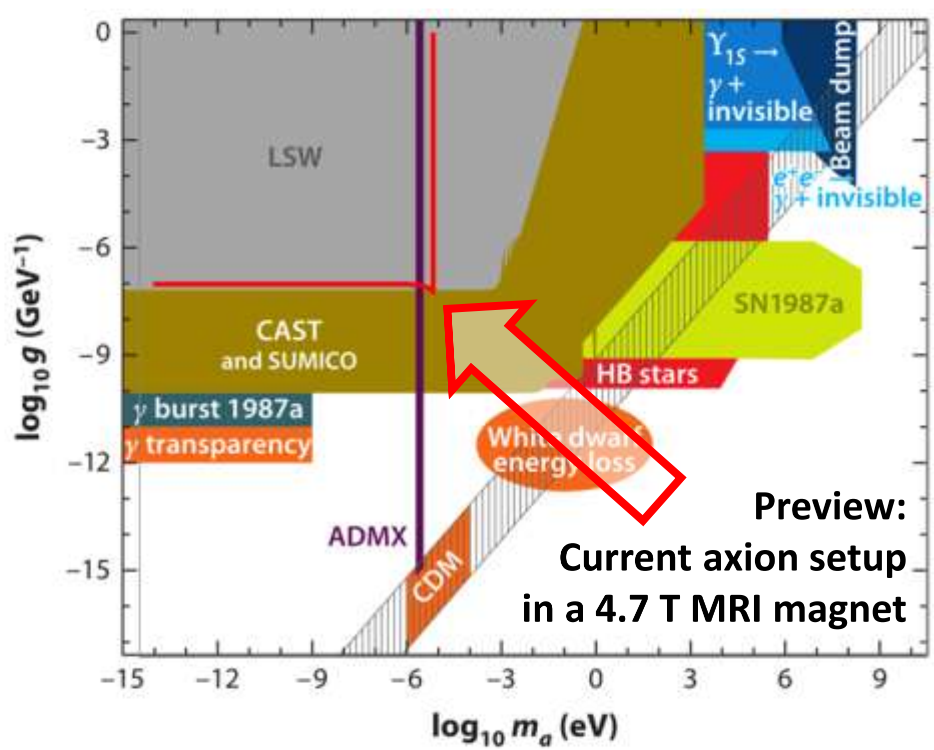
$$P_{\text{trans}} \sim \left(\frac{g B}{\omega_0}\right)^4 QQ' |G|^2.$$

Outlook

Superconducting MRI magnet from Bruker BioSpin

We need a stronger magnet for the ALPs search:

- We are in contact with *Bruker BioSpin* in Karlsruhe
- They manufacture and test MRI magnets
- Warm bore = no problems with power dissipation
- Our current setup would fit in a **4.7 T** magnet
- With some small modifications we could even use a 9.4 T magnet

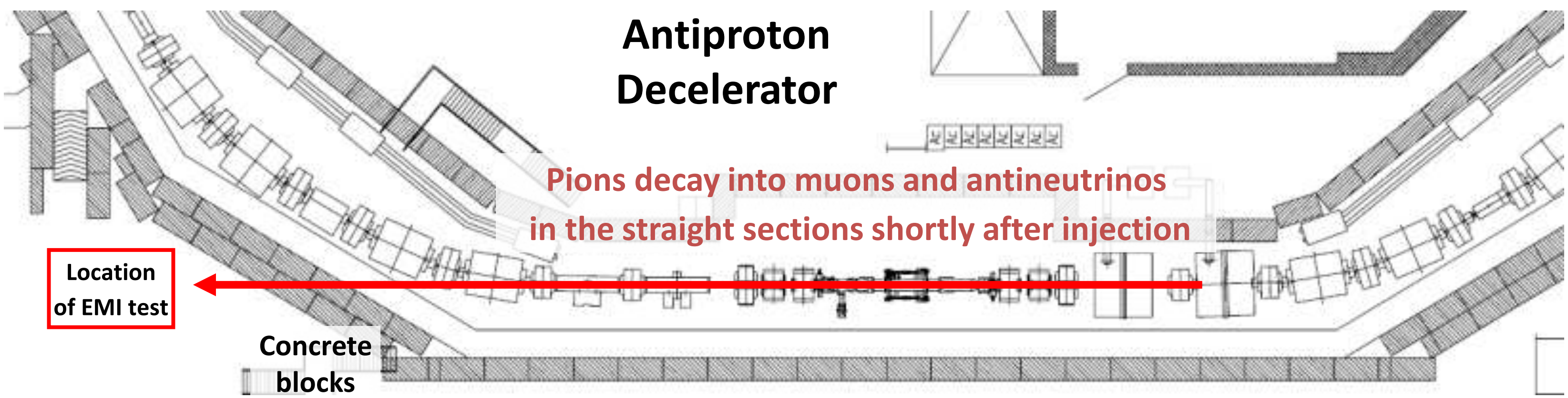


More work needs to be done to understand the behaviour of the cavities & LNA in a strong magnetic field

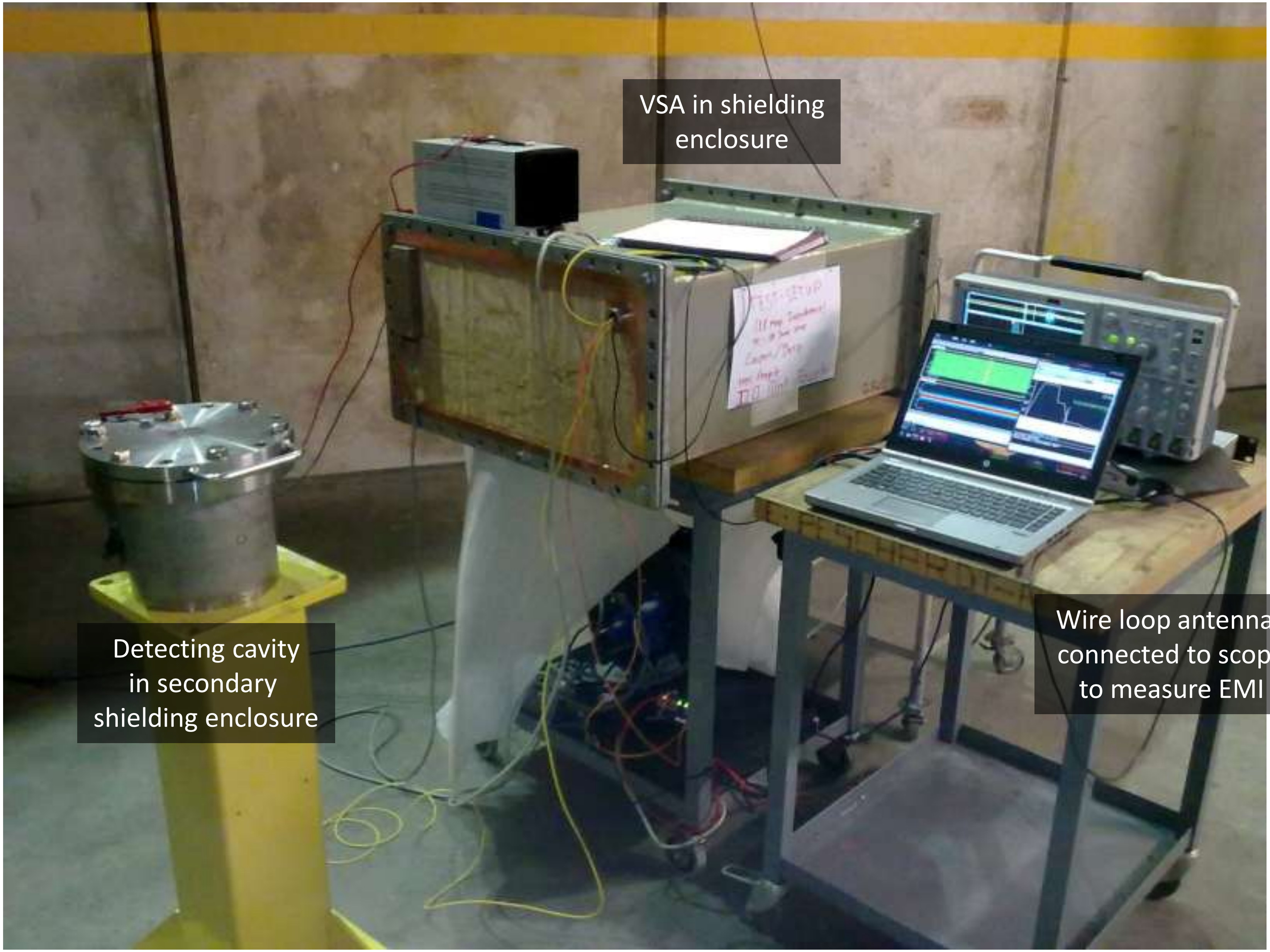
Bonus slides: An EMI stress test

- Is our shielding good enough to do measurements next to an accelerator?
- Can we see any influence from ionizing radiation? [1]
- To do a first test, we operated our setup next to the Antiproton Decelerator (AD) at CERN

- $5 \cdot 10^{10}$ **parasitic** pions are injected in the ring every 100 s [2]
  - They decay within several turns (10^{-5} s) into muons and antineutrinos
  - **Strong radiation peaks for a few μs**, especially in line with the straight sections, even behind the concrete shielding
  - Average radiation level is ≈ 2*background (safe)

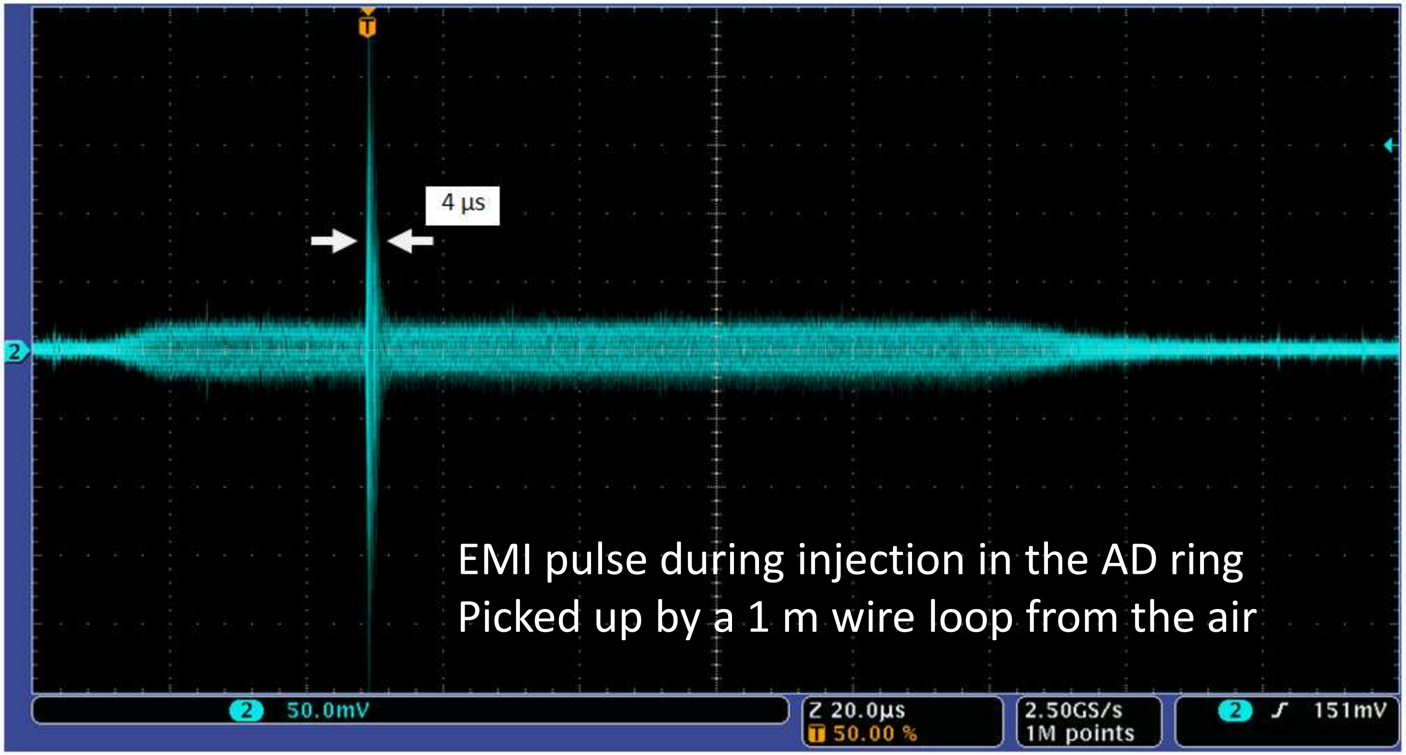


[1] I. I. Kalikinski , *"On microwave transition radiation",* TECHNICAL PHYSICS VOLUME 43, NUMBER 2 FEBRUARY 1998
[2] E. Wilson, *"Design study of an antiproton collector for the antiproton accumulator (ACOL)"*, CERN 83-10

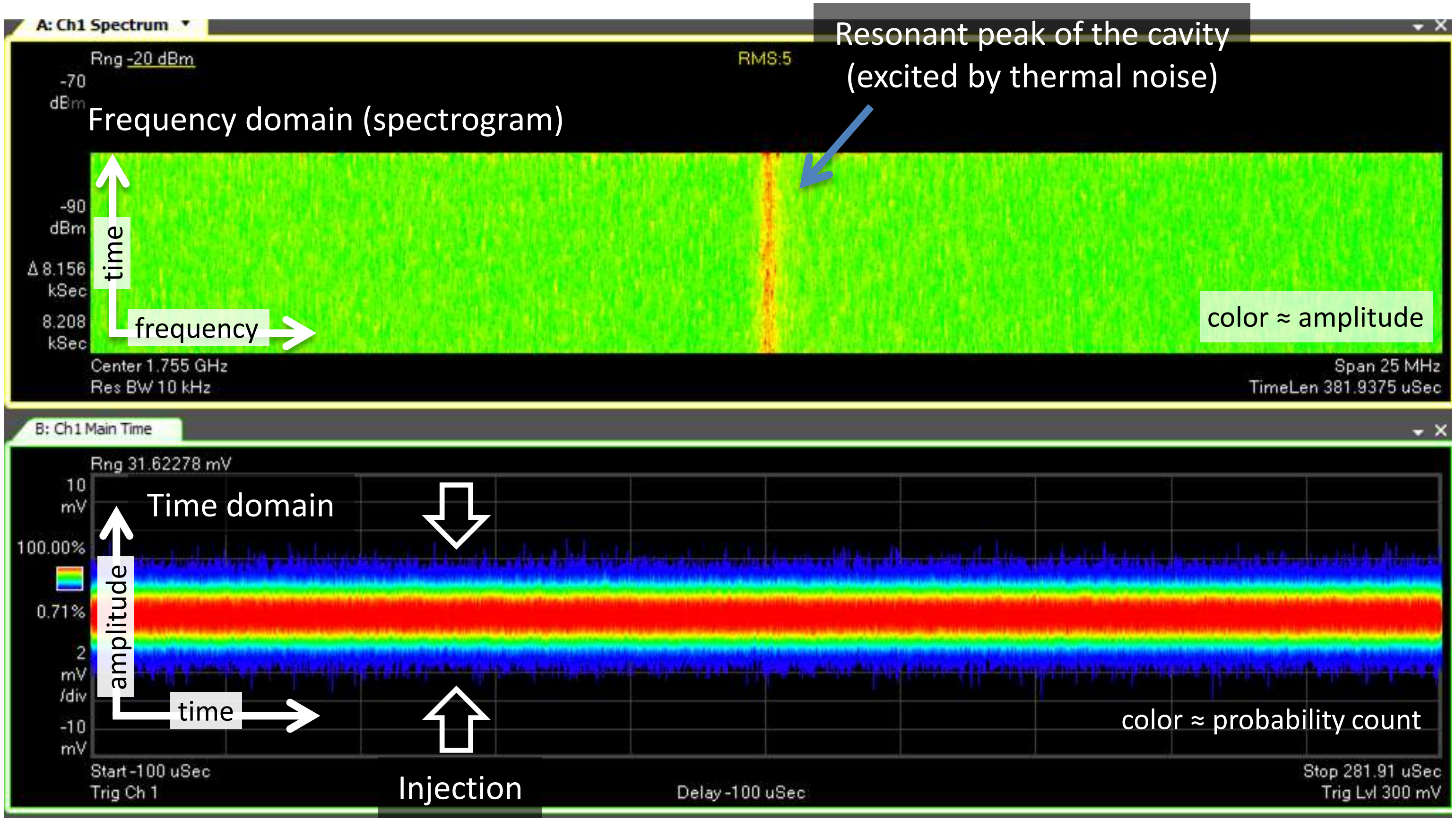

VSA in shielding enclosure
Detecting cavity in secondary shielding enclosure
Wire loop antenna, connected to scope to measure EMI

Results

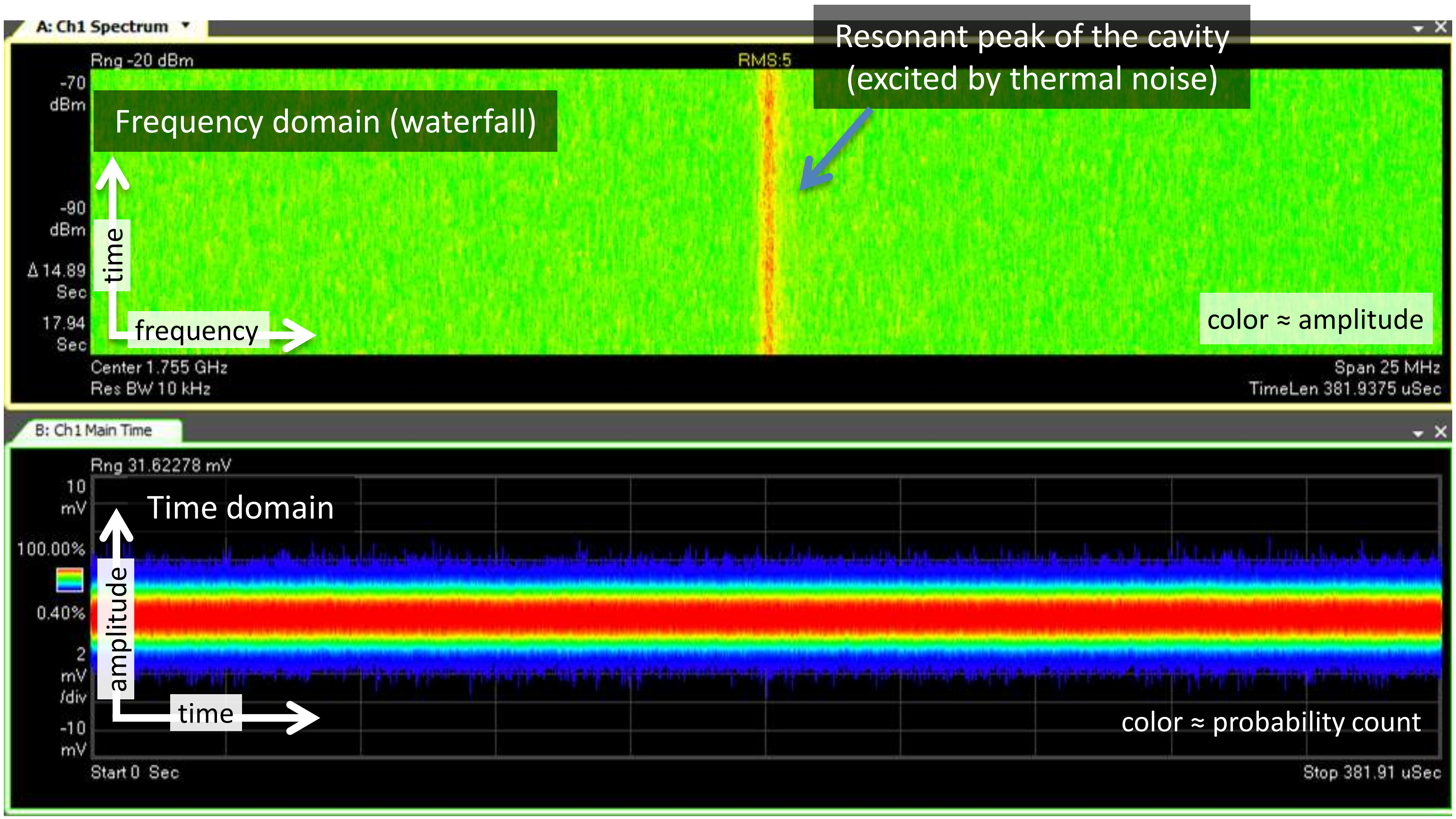
- There is strong pulsed EMI in the hall



Triggered on each injection (radiation peaks), data taken during 81 injections



For comparison:
Data taken while the AD was not active (no radiation)



The system is EMI leak tight

The neutrinos and the pulsed ionizing radiation **did not interfere** with the measurement

This proofs that HSP measurements next to operational accelerating cavities are feasible

Thank you!

Acknowledgements

- Many thanks for a large number of hints and inspiring discussions to K. Baker, A. Deveau, F. Hehl, J. Jäckel, A. Malagon, A. Martin, A. Ringwald, P. Slokum and K. Zioutas

- We are grateful for support from R. Jones, E. Jensen and the BE department management