Axion-like particle and hidden photon search with a microwave shining through the wall experiment

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DESY ALPS Seminar

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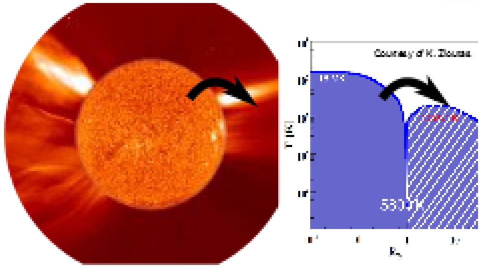
Outline

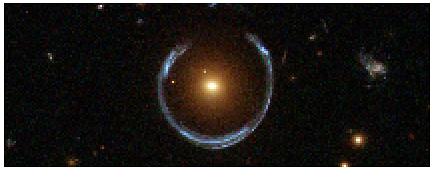
- **Overview** of “microwaves (not) shining through the wall” at CERN
- Design of the **cavities**
  - Some WISP radiation patterns
- Electromagnetic **shielding**
- Analog and digital **signal processing**
  - Crash course: Mixers and the superhetrodyne receiver
- The HSP measurement run in 03/2012
- The axion measurement run in 09/2012
- Outlook

Motivation for WISP search

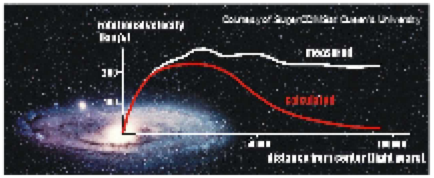
- WISP = Weakly Interacting sub-eV particles
  - *Axion like particles (ALPs), hidden sector photons (HSPs), chameleons etc.*
  - **Very weak coupling to standard model particles**, they live in a "hidden sector"
- The axion was proposed to "wash away" the strong CP problem
  - still a popular (theoretical) solution
- Some WISPs are excellent candidates for **cold dark matter**



How is energy transferred into the solar corona over a cold spot?



Why is there stronger "gravitational lensing" than expected?



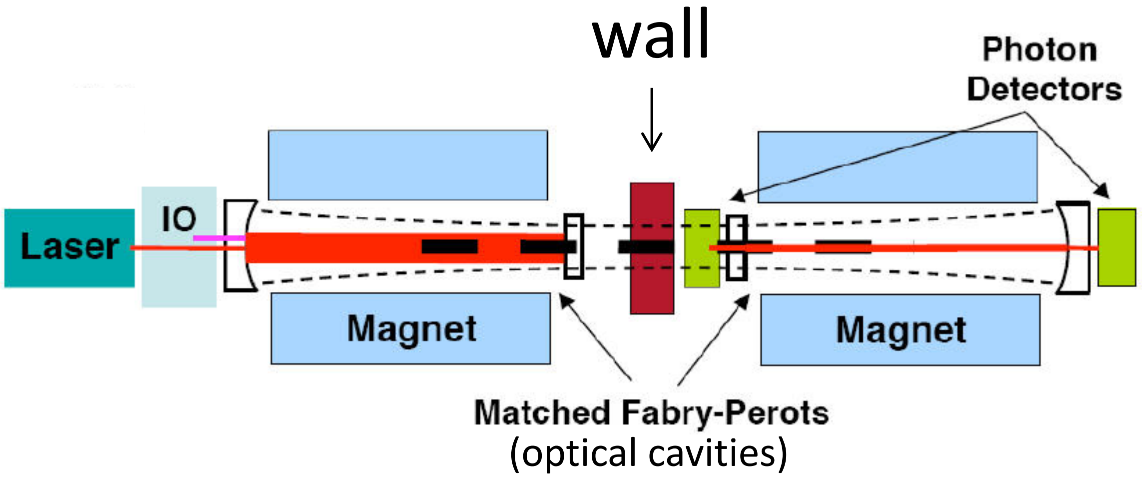
Why do clusters of stars rotate faster on their outskirts than predicted?

Weakly interacting Sub-eV particles (WISPs) like *axions* or *hidden sector photons* **could be the answer!**

Motivation for using microwaves

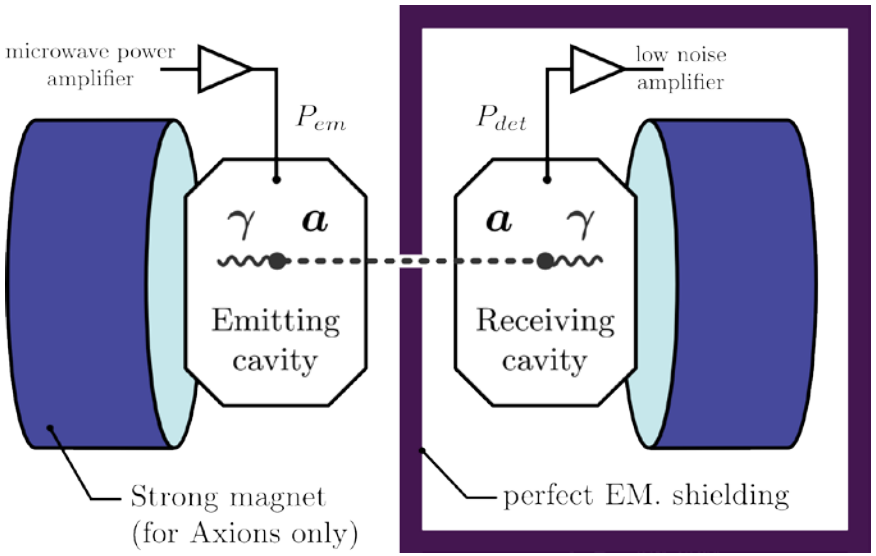
Optical LSW

- ✓ A simple **wall** blocks photons but not WISPs
- High Q resonators are possible **but expensive and delicate (nm tolerances)**



Microwave LSW

- ✓ Q-factors around 10^5 are no problem (mm tolerances)
- ✓ Powerful detection methods!
- The "**wall**" becomes a **3D EM. shielding challenge**
- Photon energy is limited!



γ → Photon a → Axion EM. → Electromagnetic

Motivation for using microwaves

Optical LSW

- ✓ A simple **wall** blocks photons but not axions / paraphotons
- High Q resonators are possible **but expensive and delicate (nm tolerances)**

Microwave LSW

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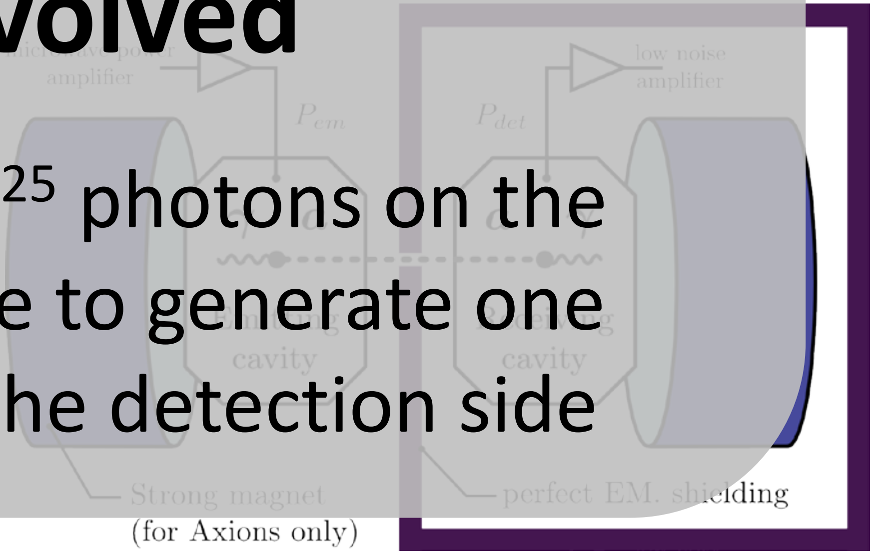
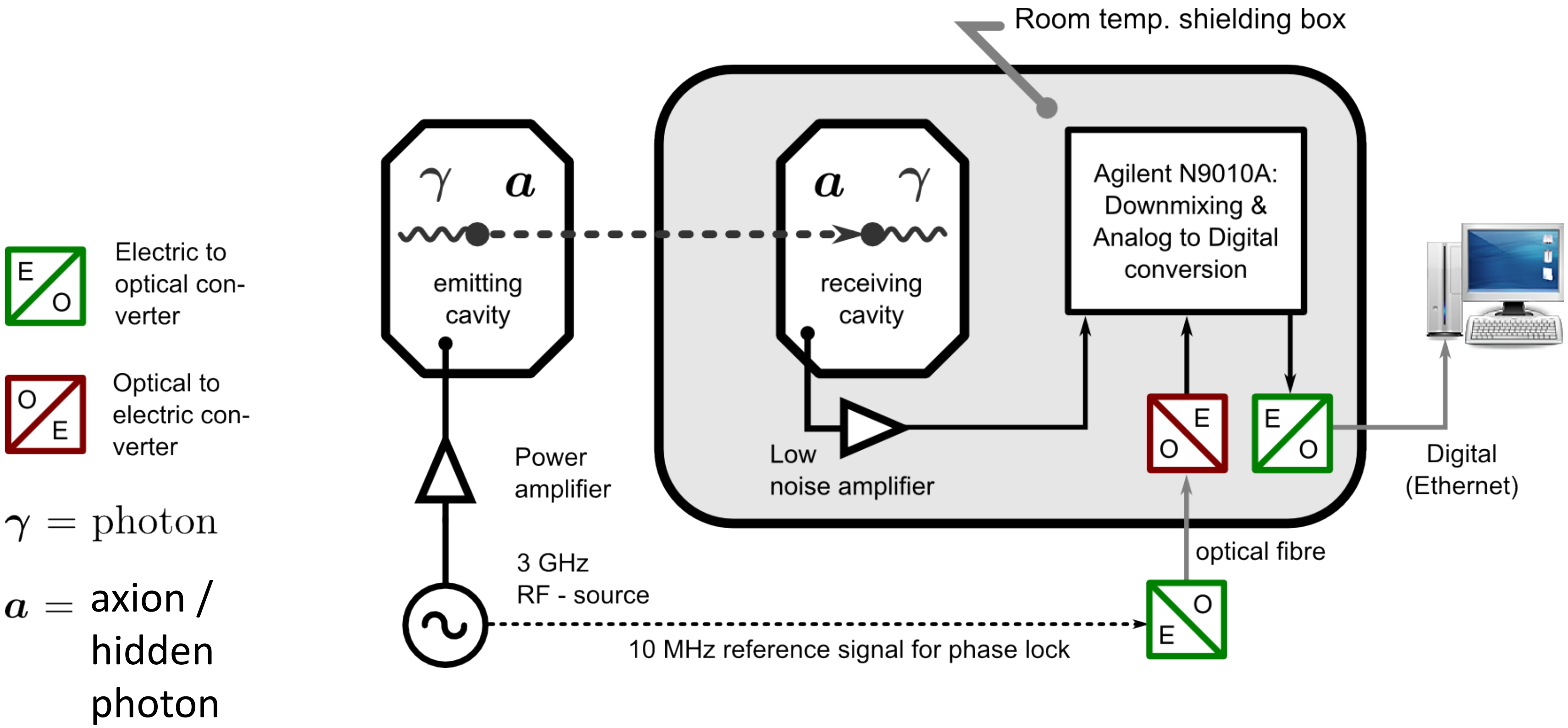


The biggest challenge in both cases is the tiny probabilities involved

It takes > 10^{25} photons on the emitting side to generate one photon on the detection side

γ → Photon a → Axion EM. → Electromagnetic

Overview of the HSP setup



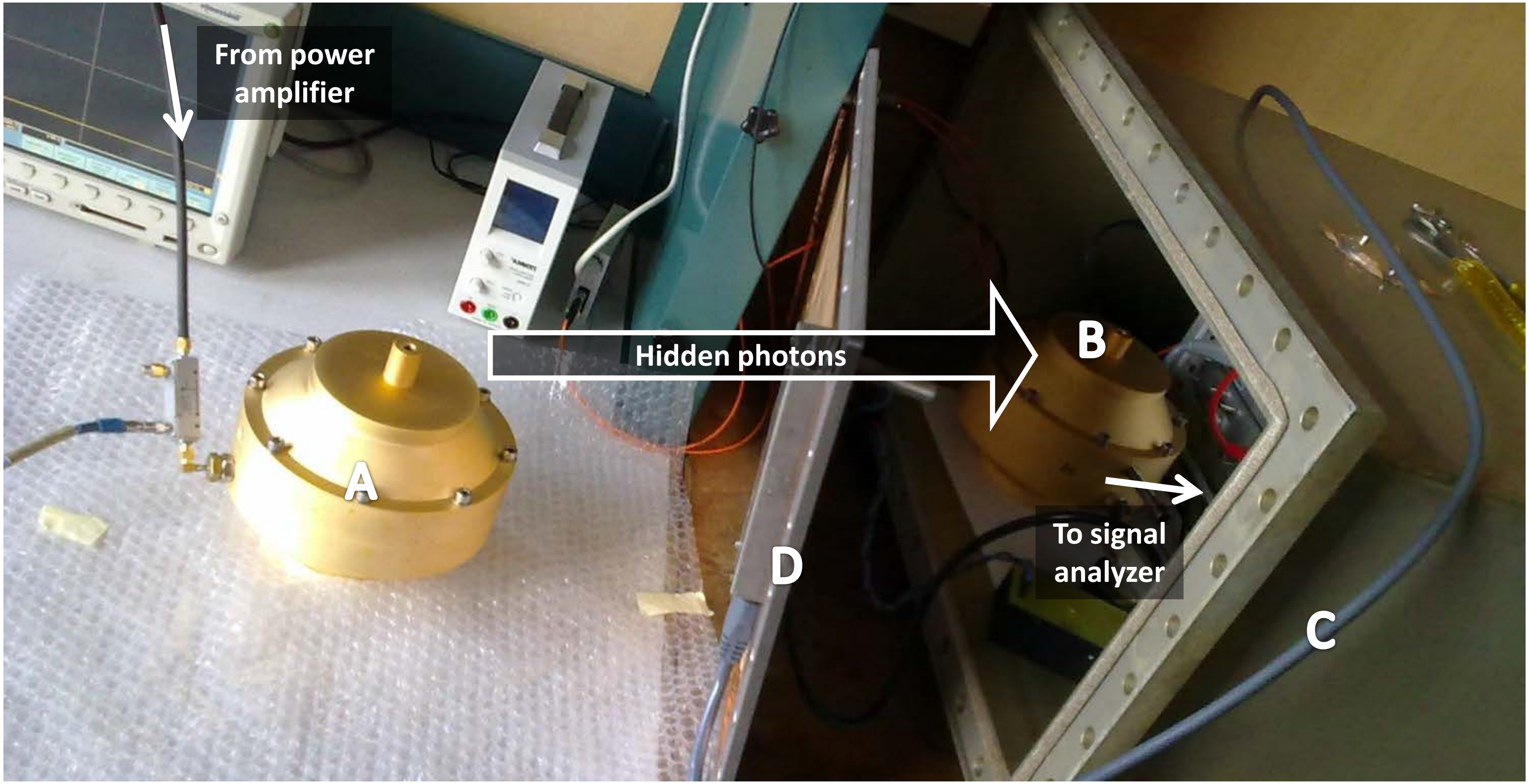
$\gamma = \text{photon}$

$a =$ 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, containing the signal receiver
(**D**) Custom feed-trough filter for 230 V mains

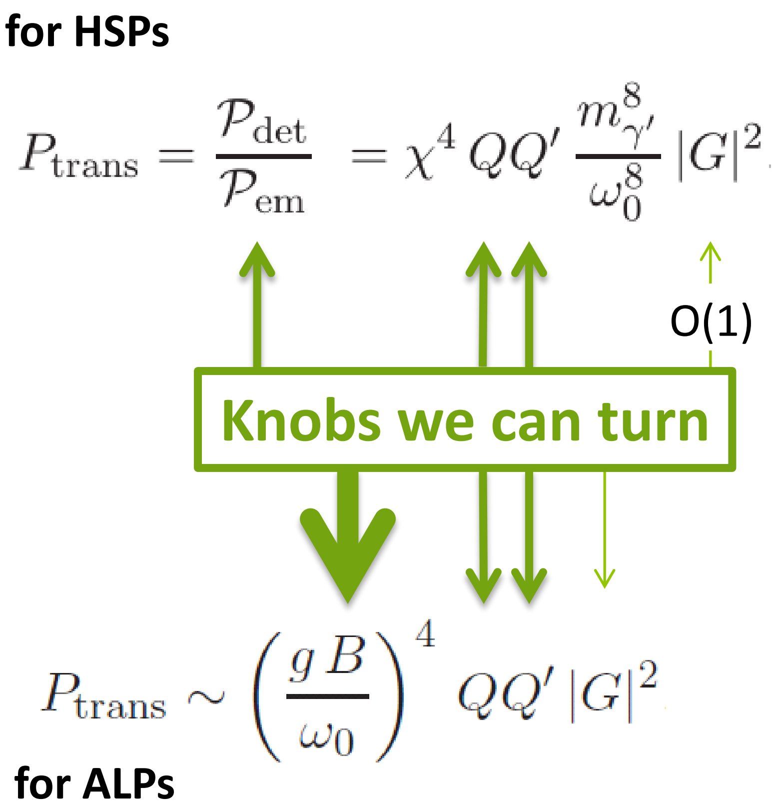
Engineering aspects

1. Designing the cavities

2. EM. Shielding

3. Signal detection

Choice of cavity technology



for HSPs

$$P_{\rm trans} = \frac{\mathcal{P}_{\rm det}}{\mathcal{P}_{\rm em}} = \chi^4\, QQ'\, \frac{m_{\gamma'}^8}{\omega_0^8}\, |G|^2$$

O(1)

Knobs we can turn

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

for ALPs

- $P_{\rm trans}$ = Power transferred between the cavities due to WISPs
- Most significant parameters to optimize:
  - Q – factors
  - Magn. field B (for ALPs)
- Quality factor (Q) of a cavity = circulating power / power loss per cycle
- **We want high Q factors!**

Equations from "A Cavity Experiment to Search for Hidden Sector Photons", J. Jaeckel, A. Ringwald

Choice of cavity technology

Normalcond.

$Q = O(10^4)$

Bottleneck: resistive losses through wall currents

Easy to handle

To optimize Q: Internal silver coating

Choice of a low loss resonating mode

Superconducting

$Q = O(10^9)$

Bottleneck: criticality / sensitivity to vibrations

Nearly impossible to keep on tune!!!

Field emission and breakdown (emitting cavity)

Cryogenics necessary

Not compatible with static magnetic fields

How much mechanical deviation (Δl) can we tolerate ?

due to vibrations, therm. Expansion, etc.

$$Q = \frac{f}{\Delta f} = \frac{l}{\Delta l}$$

f=3 GHz, l=10 cm

Normalconducting

$Q = 10^4$

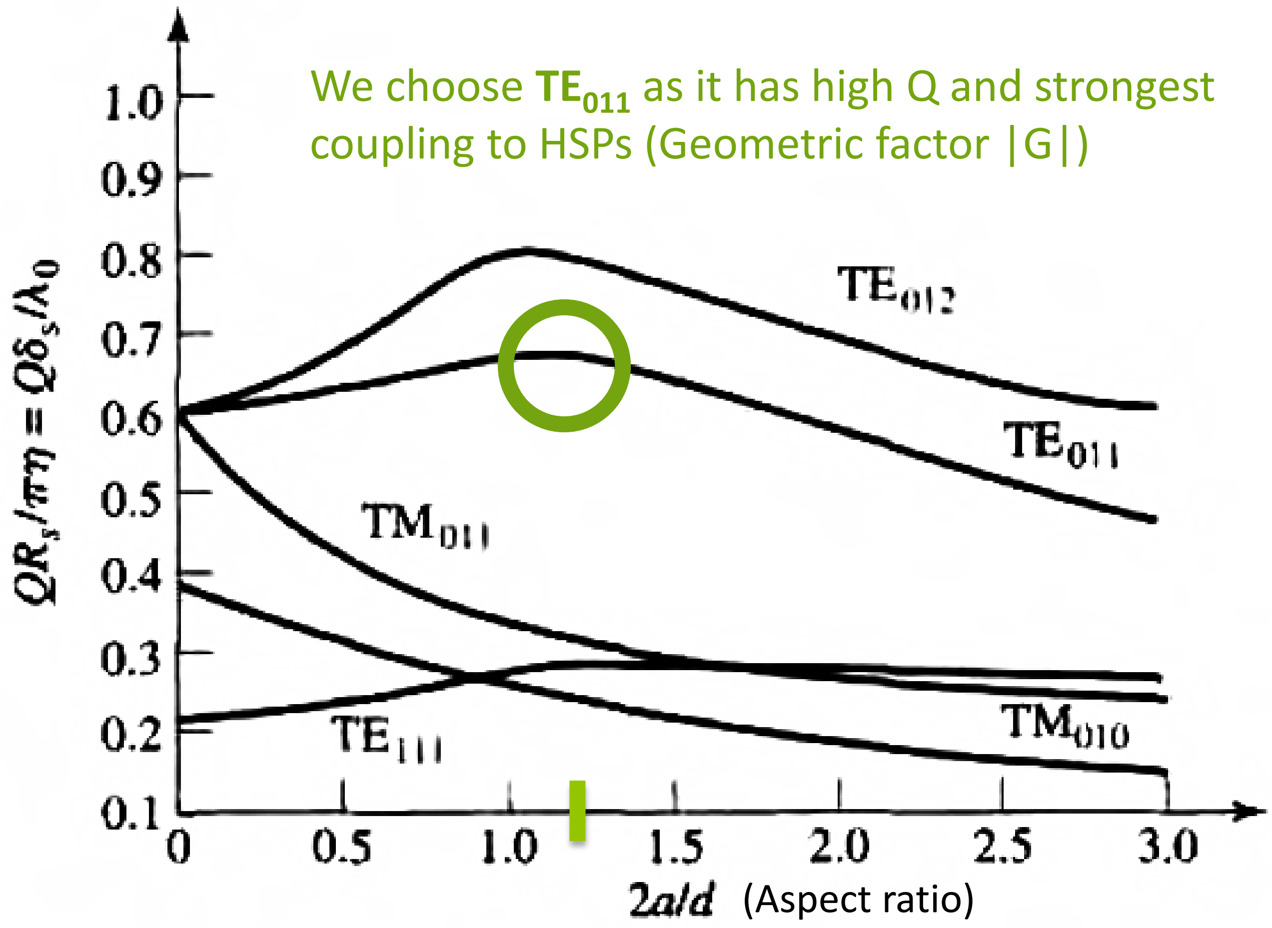
$\boldsymbol{\Delta l = 10^{-5}\ \mathrm{m}}$ $\}$ **realistic**

Superconducting

$Q = 10^9$

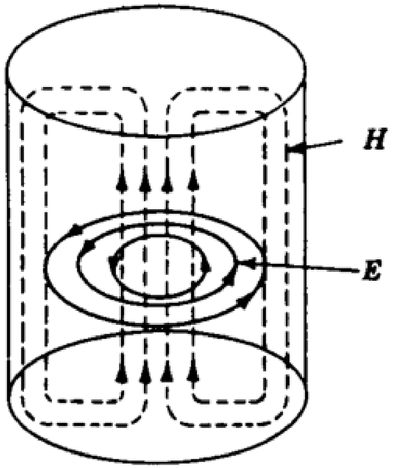
$\boldsymbol{\Delta l = 10^{-10}\ \mathrm{m}}$ $\}$ That's about the size of a **hydrogen atom**!

Choice of cavity mode

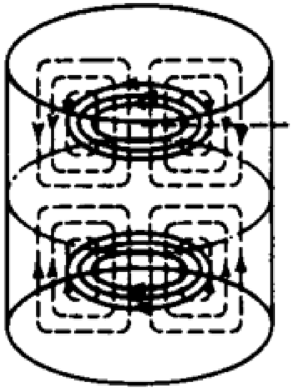


We choose **TE$_{011}$** as it has high Q and strongest coupling to HSPs (Geometric factor |G|)

(Aspect ratio)



(a) TE$_{011}$ mode

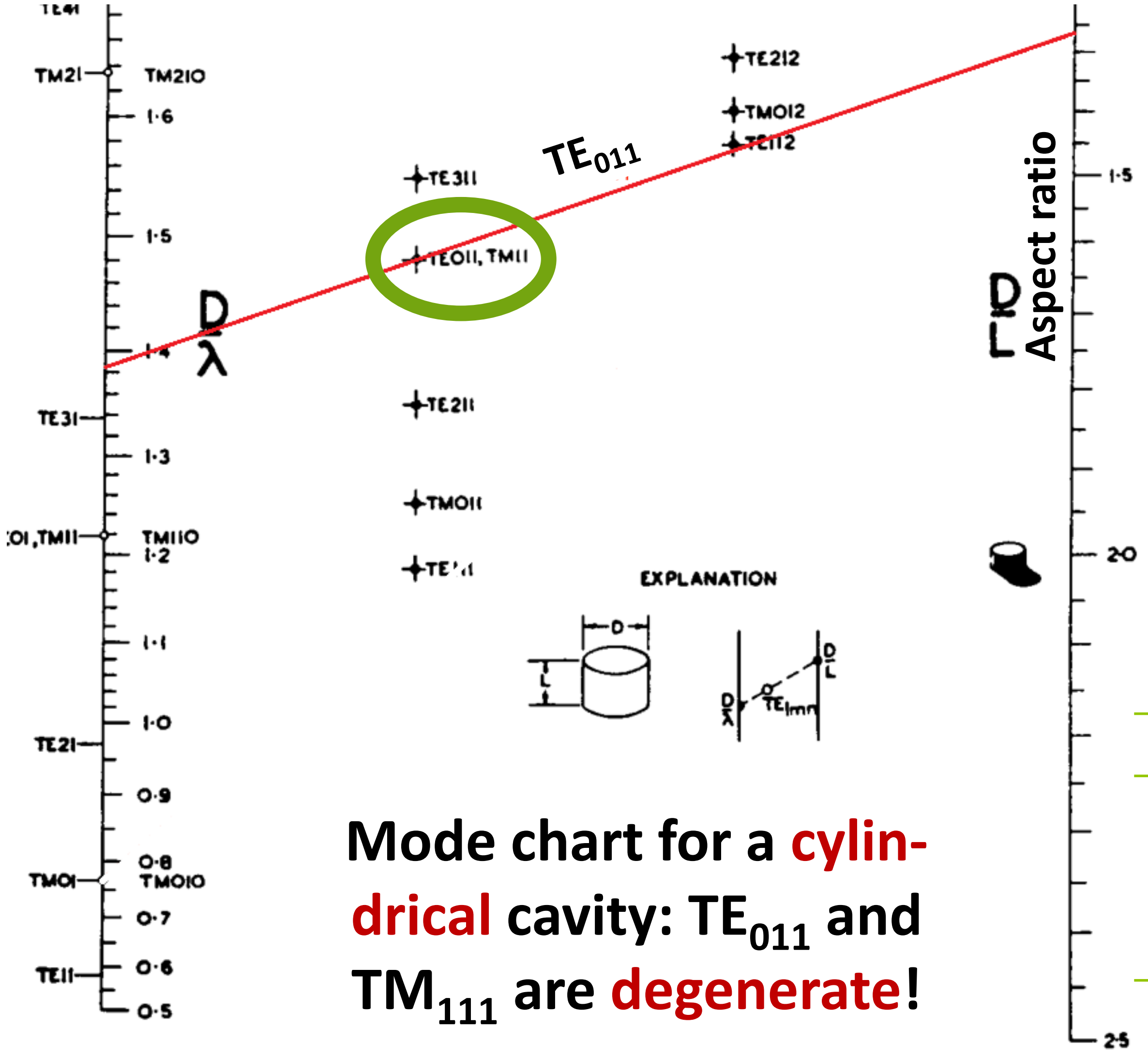


TE$_{012}$

Normalized Q for various cylindrical cavity modes (air-filled).

From: D. Pozar, Microwave Engineering

Choice of cavity geometry



Mode chart for a cylin-drical cavity: TE$_{011}$ and TM$_{111}$ are degenerate!

Figure 15. Mode lattice for cylindrical resonators [3, p. 832]. [© 1947 IRE (now IEEE)].

We use a different geometry: Cylindrical cavity with beveled edges

From simulation:

Cylindrical

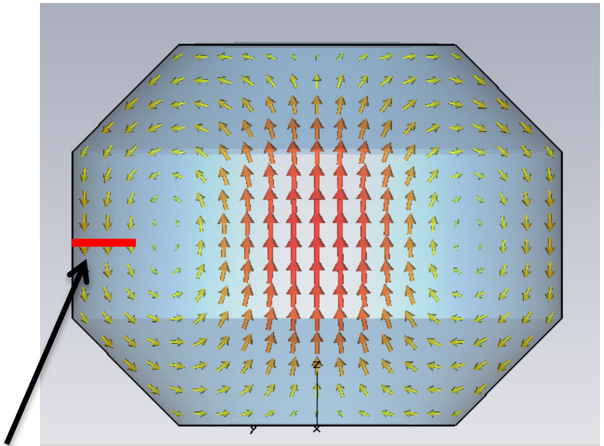
Mode	f_{res} [GHz]
TM$_{111}$	2.863
TE$_{011}$	2.863
TE$_{112}$	2.890

Bevelled

Mode	f_{res} [GHz]
TM$_{111}$	2.629
TE$_{011}$	2.955
TE$_{112}$	3.022

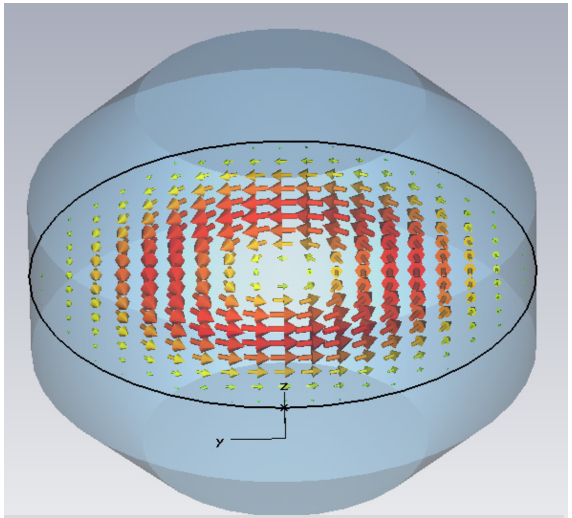
Bevelled edges break degeneration!

Fields in the cavity

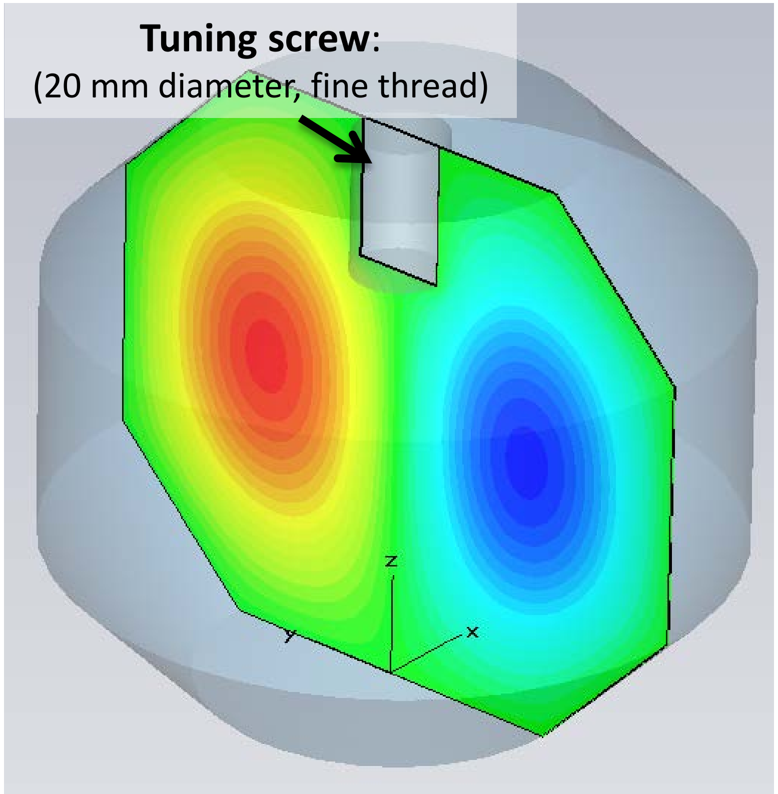


TE$_{011}$ mode, **H–field** on YZ-plane

Possible location of an inductive coupling loop for the TE$_{011}$ mode (The loop extends on the XY-plane)



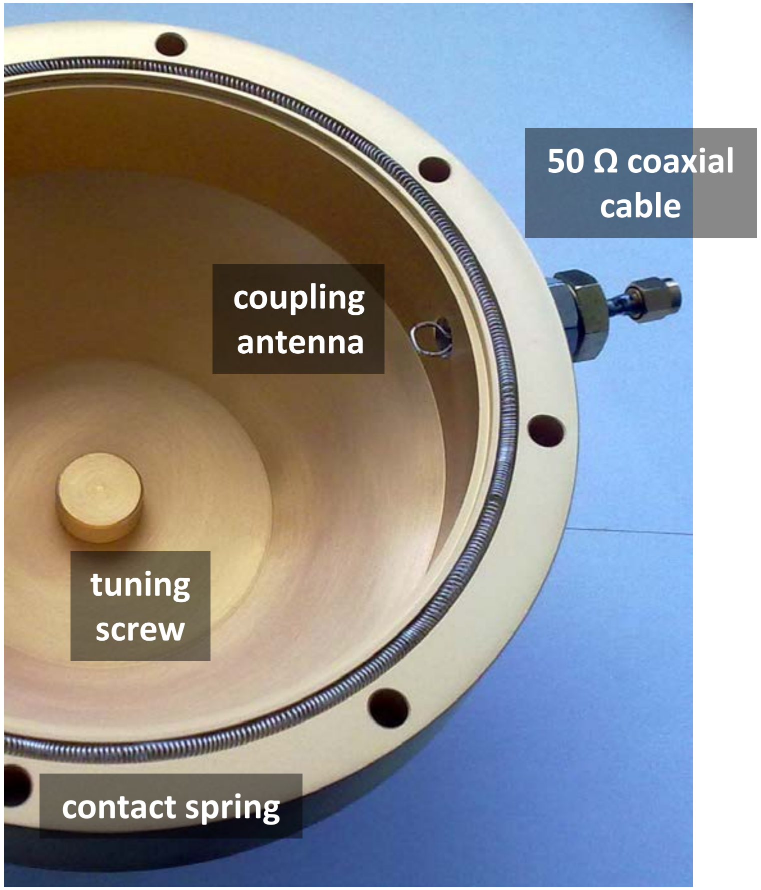
TE$_{011}$ mode, **E–field** on XY-plane



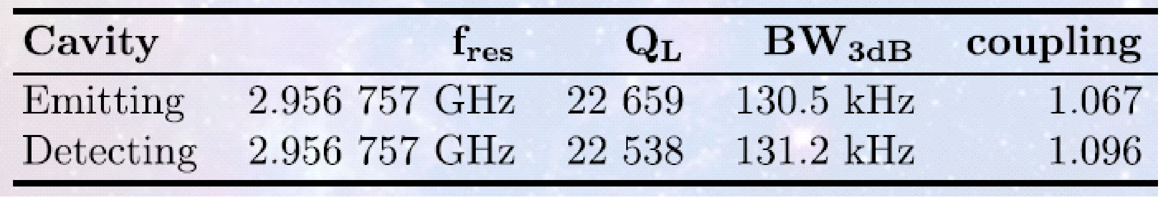
Tuning screw:
(20 mm diameter, fine thread)

TE$_{011}$ mode, **E–field** in X-direction

Cavity	f_{res}	Q_L	BW_{3dB}	coupling
Emitting	2.956 757 GHz	22 659	130.5 kHz	1.067
Detecting	2.956 757 GHz	22 538	131.2 kHz	1.096



Material: Silver coated brass (non magnetic) with a flash of gold to prevent oxidation



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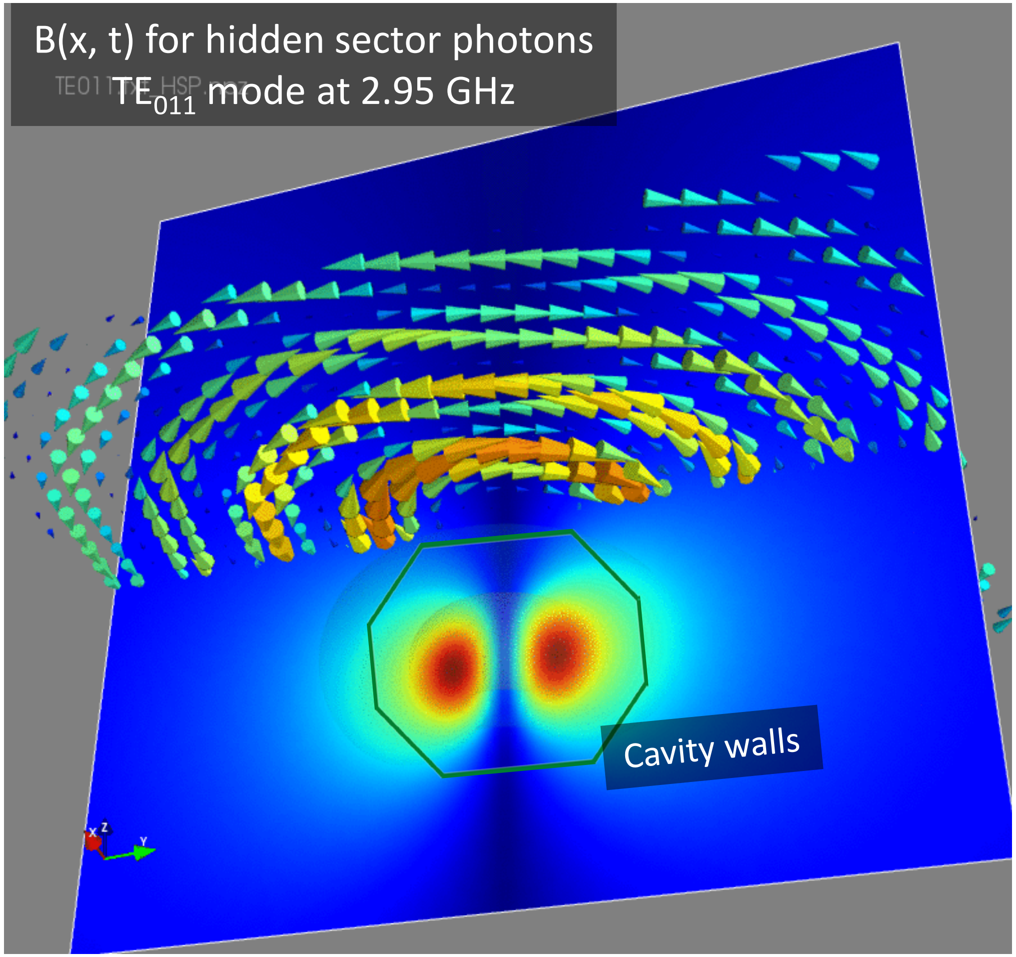
The radiated field outside the cavity

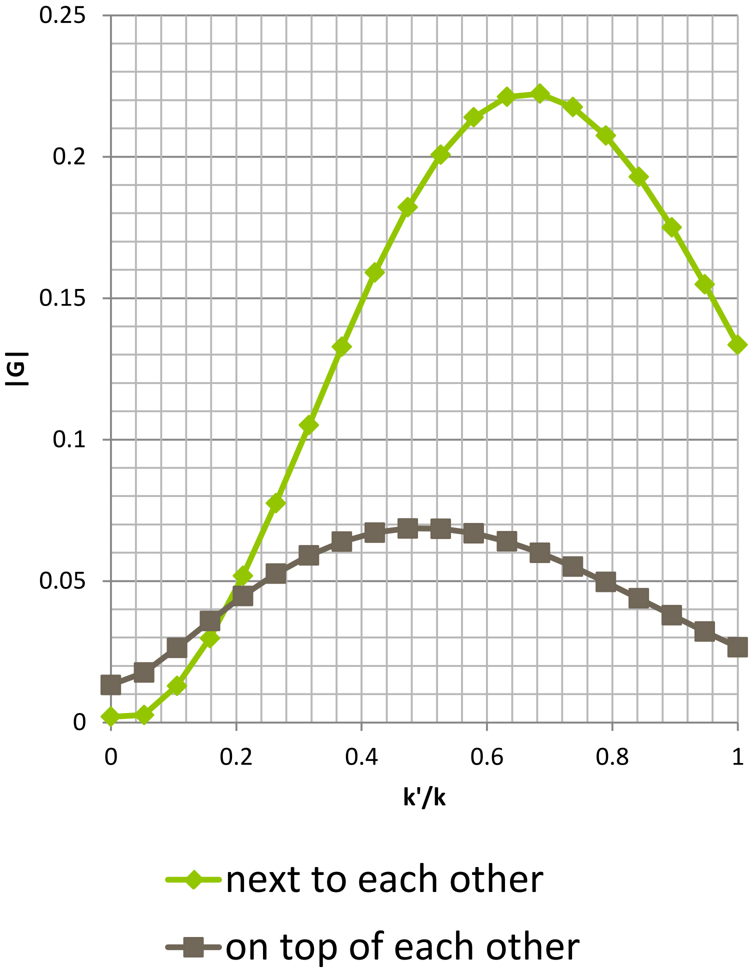


B(x, t) for hidden sector photons

TE_{011} mode at 2.95 GHz

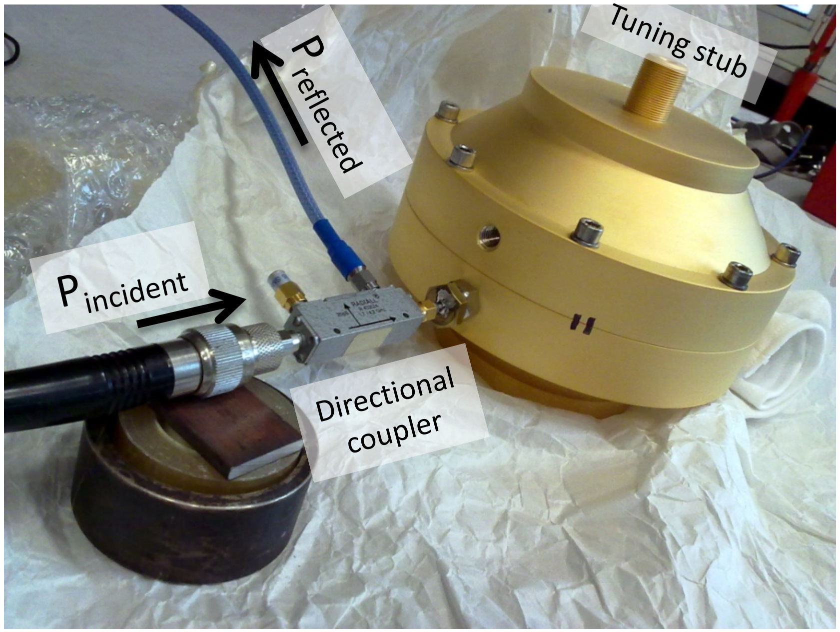
Cavity walls

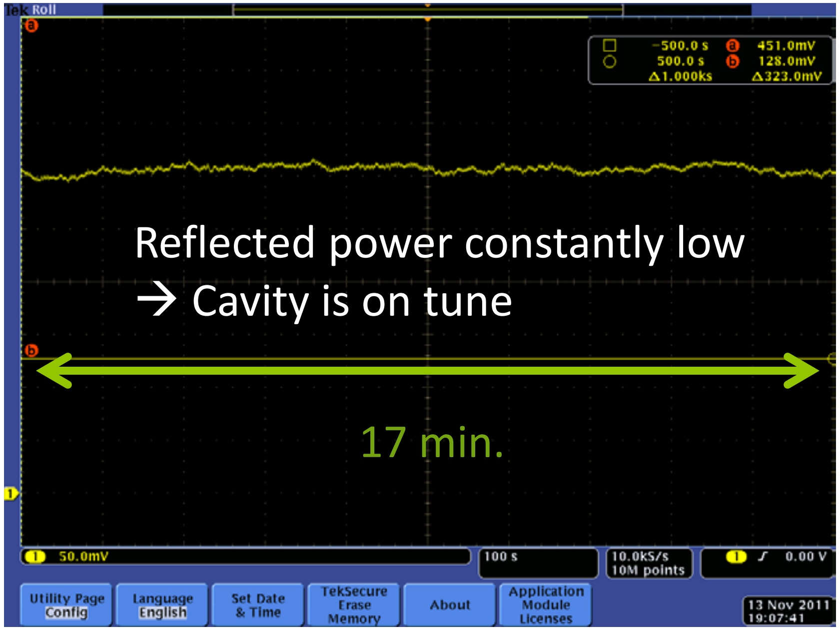
Geometric form factor of 2 cavities with 15 cm spacing between them



$$B(\mathbf{x}, t) = \chi m_{\gamma'}^{2} \int_{V} d^{3}\mathbf{y} \frac{\exp(ik|\mathbf{x}-\mathbf{y}|)}{4\pi|\mathbf{x}-\mathbf{y}|} a_{\rm em}(t) A_{\omega_0}(\mathbf{y}),$$

Tune of the **emitting** cavity

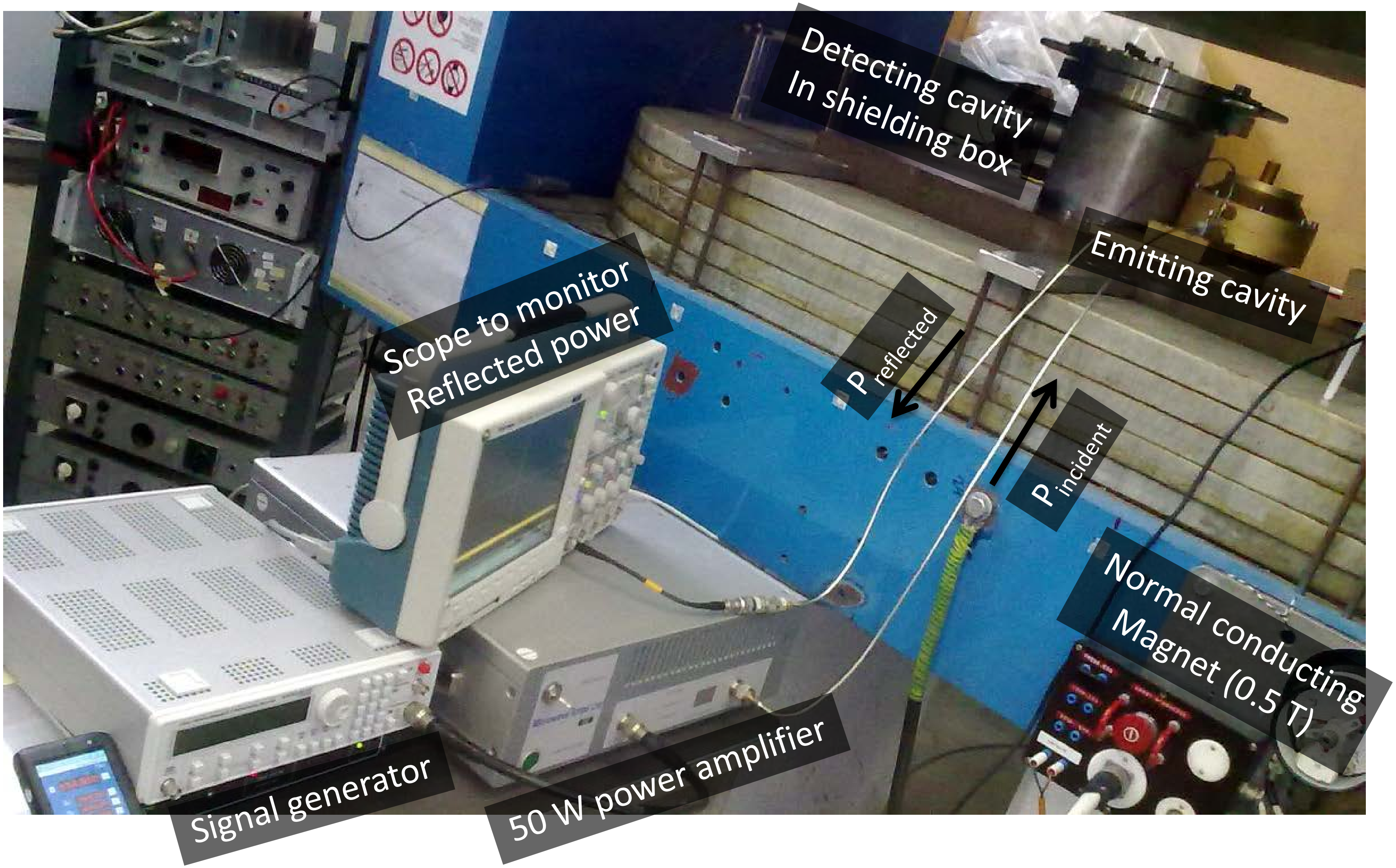




- If the cavity is on tune, reflected power should be **close to zero**
- We monitor and record this during the whole experimental run

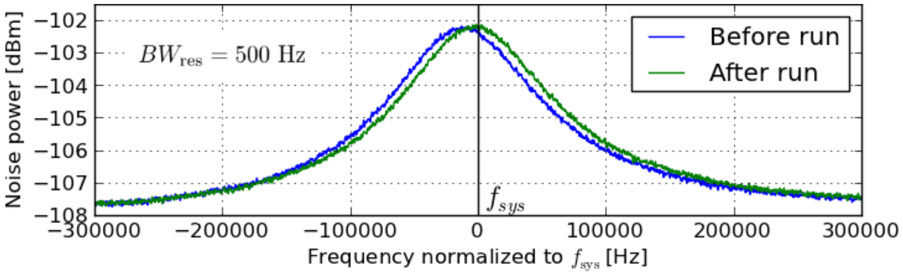
- During **warm up**, the cavity drifts by ≈ 1 MHz, this is significant!
(3 dB bandwidth ≈ 130 kHz)
- the drift is compensated by the tuning screw manually
- Once in thermal equilibrium, the cavity is stable

How it looks like in practice (for axions)

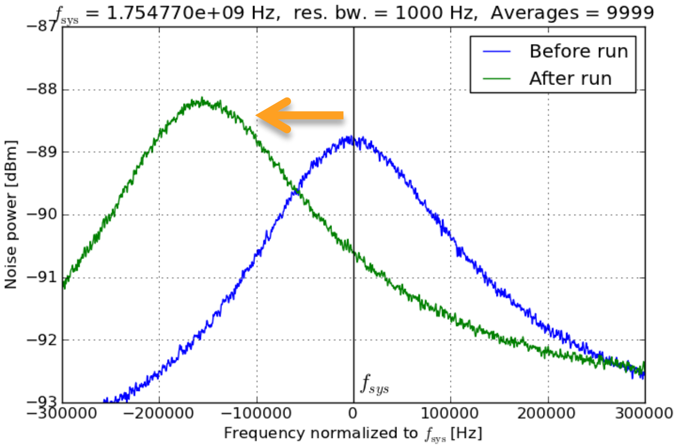


Tune of the **detecting** cavity (1)

- 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 ✓

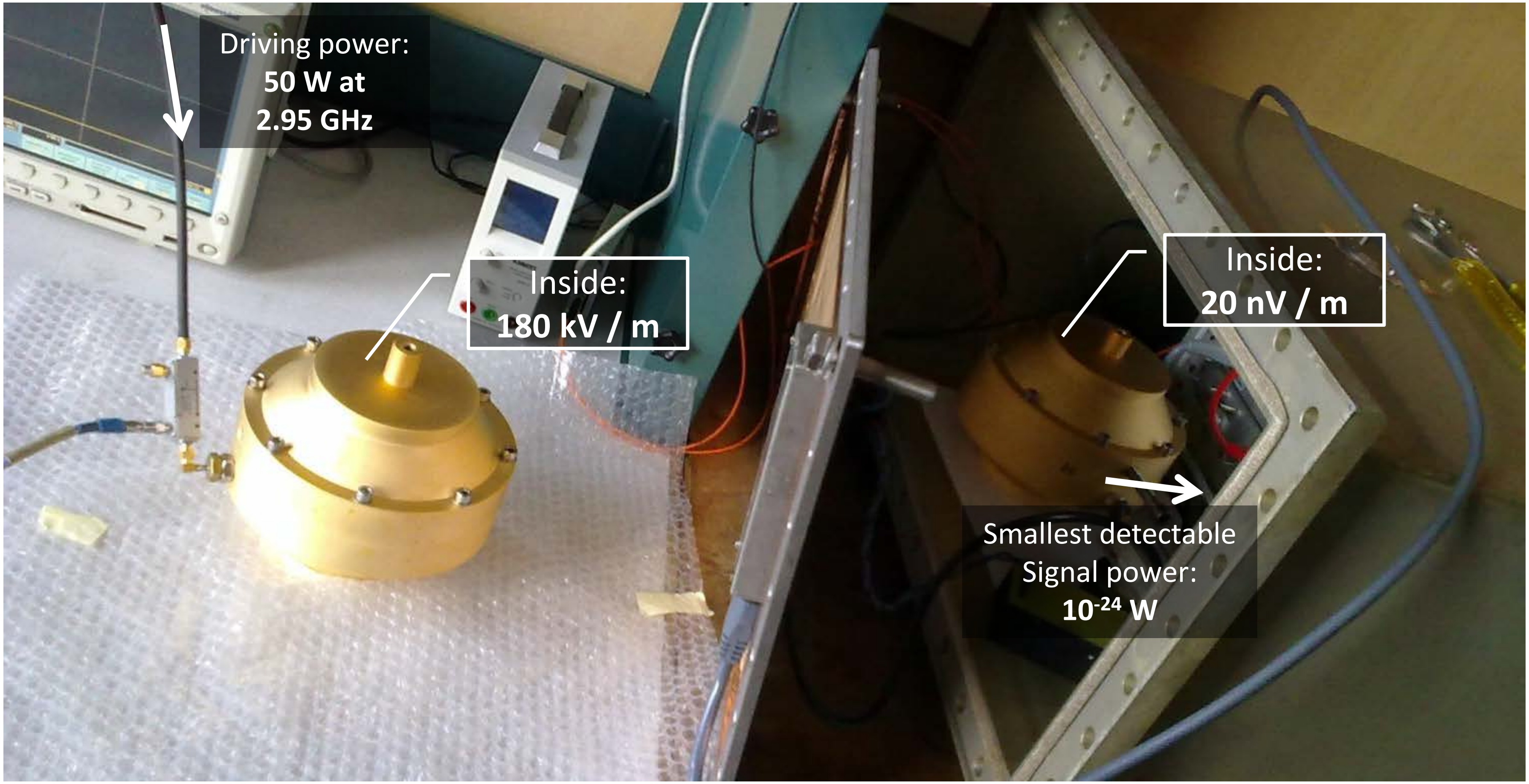


The detecting cavity did not have enough time to warm up, a drift of the tune can be observed, we loose some signal power

Engineering aspects

1. Designing the cavities
2. EM. Shielding
3. Signal detection

Electromagnetic shielding (for HSPs)



Driving power:
50 W at
2.95 GHz

Inside:
180 kV / m

Inside:
20 nV / m

Smallest detectable
Signal power:
10^{-24} W

We **need** to reduce the field strenght by a factor of 10^{13}
That is 20*log(10^{13}) = **260 dB**

The cavities are not perfect,
they provide **≈ 110 dB** of shielding each,
which is not enough

Electromagnetic shielding

- EM shielding is a 2 step process:
  1. Construction of a shielding box
  2. Filtering of **all** cables going in and out of the box

- For **step 1** we use a big piece of waveguide with custom made end caps
- It will contain the detection cavity and signal analyzer
- **Air circulation!**

How to measure screening attenuation

- A **magnetic near field probe** (HP 11940A) connected to a spectrum analyzer is used to determine local field-strength
- Essentially a **calibrated antenna**
- A signal source was placed inside the shielding box, radiating a test signal at 3 GHz
- We measured outside the box in 20 cm distance:
  - With open shielding box (H_0)
  - With closed shielding box (H_1)
- The screening attenuation (SA) is the difference in received power (in dBm)
- The probe is also very useful to localize leaks

$$SA = 20 \ * \log\left|\frac{H_0}{H_1}\right|$$

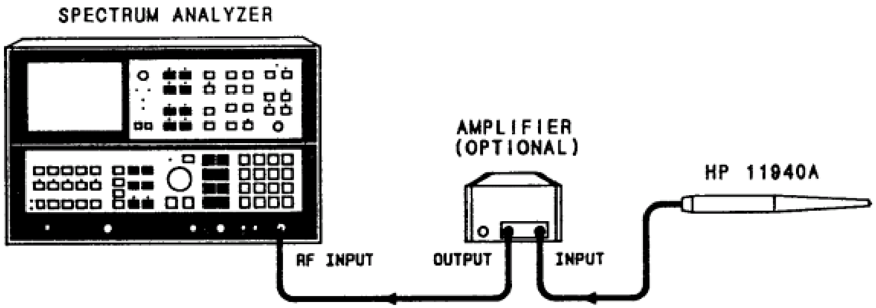
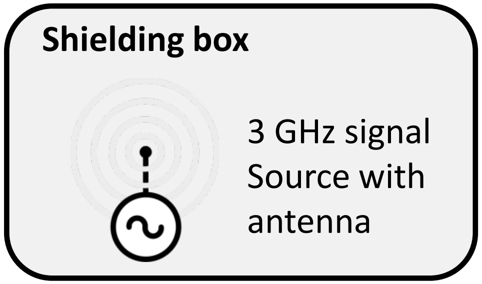
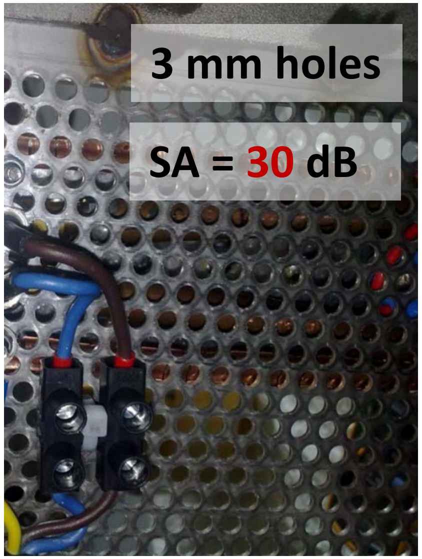


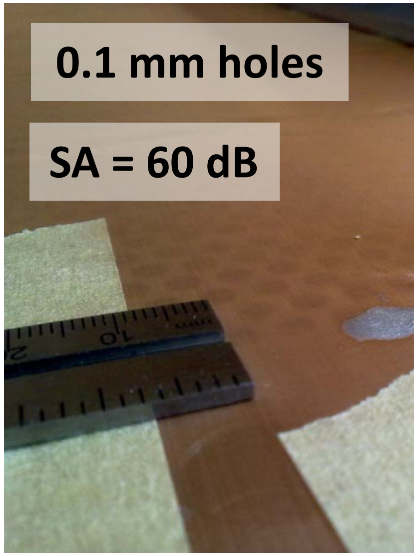
Figure 4. Emissions Test Setup



EM shielding: Lessons learned


3 mm holes

SA = 30 dB


0.1 mm holes

SA = 60 dB


Microwave absorbing material


Leakage


Contact - resistance is critical

A better solution:
Wire mesh gasket

Most important:

The **weakest spot** of the shielding determines its **overall performance**!

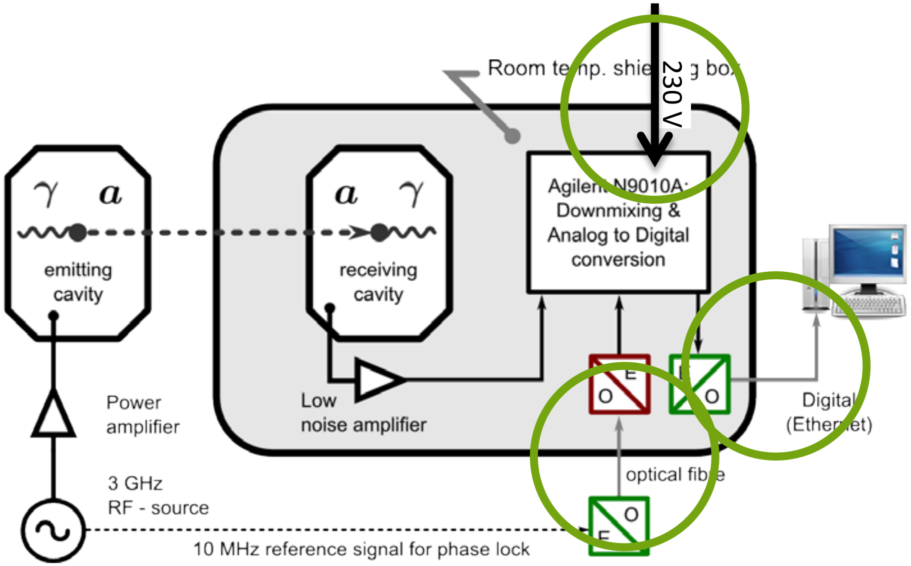
Only when **<u>ALL</u>** the lights are turned out, the room becomes **really** dark

Electromagnetic shielding

- EM shielding is a 2 step process:
  1. Construction of a shielding box
  2. Filtering of **all** cables going in and out of the box

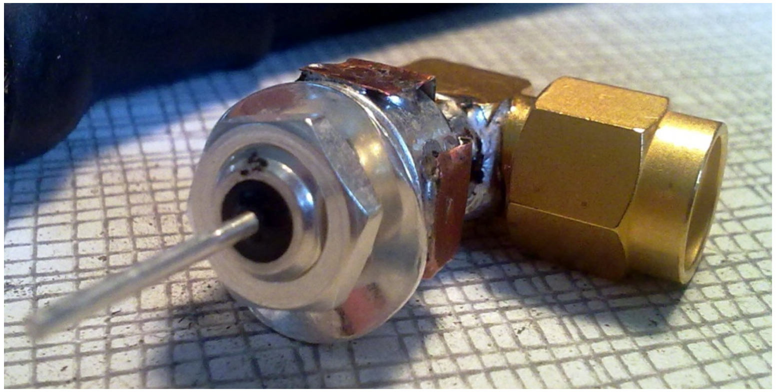
- Our plan for step 2:

Which cables do we have	How to filter them
230 V AC power	Custom low pass filter
10 MHz reference signal	Transmission over optical fibre
Ethernet	Transmission over optical fibre



Feeding **power** in the shielding enclosure

A second order low-pass filter was built from an inductive and a capacitive element



Capacitive element

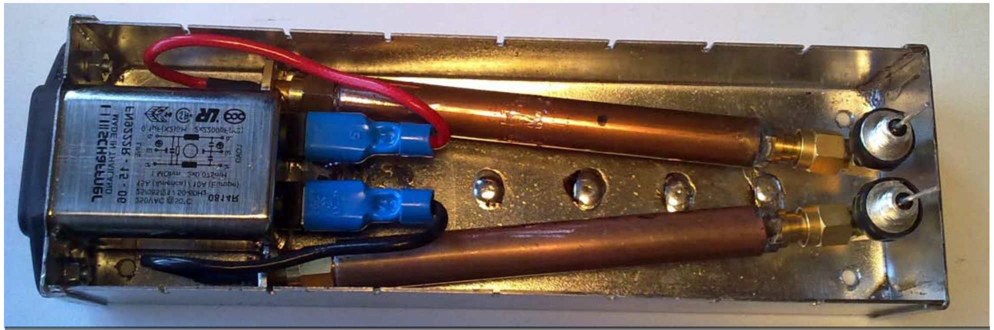
100 nF feed-trough capacitor, **IL = 90 dB**

RF connectors on **each component** allow to measure them **individually** on a Network Analyzer.

Thus we can estimate the performance of the complete filter

Inductive element:

tube made from lossy ferrite **IL = 60 dB**



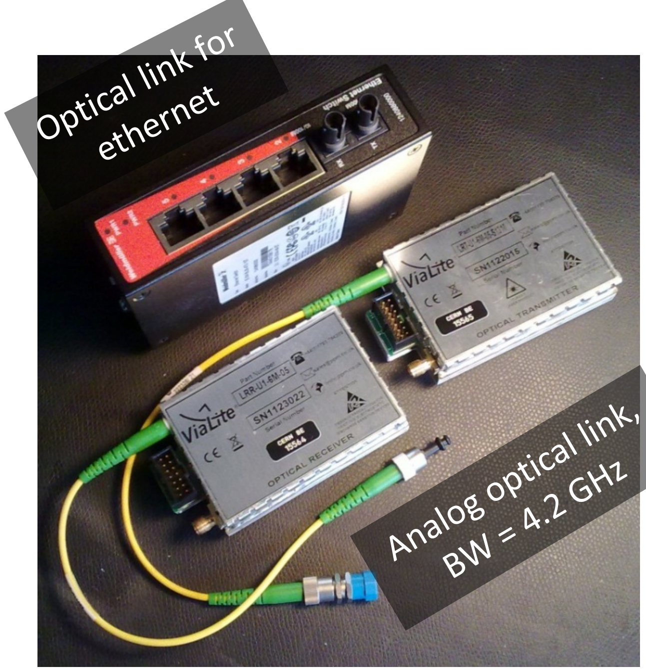
DC and 50 Hz can pass, GHz signals are attenuated by **≈150 dB**

Optical feed-troughs

- Analog and digital (Ethernet) optical transceivers are commercially available
- We use a short metal pipe for feeding the fibres in the shielding box
- ... we have a **hole in the shielding**, what is the effect on screening attenuation?
- Pipe = **Circular waveguide** of length ***l*** and diameter ***d***:
  - **$f > f_c$** → Wave propagation, barely any attenuation
  - **$f << f_c$** → Aperiodic propagation, attenuation increases exponentially with ***l***: $IL\,[\text{dB}] \approx 32\, l / d$

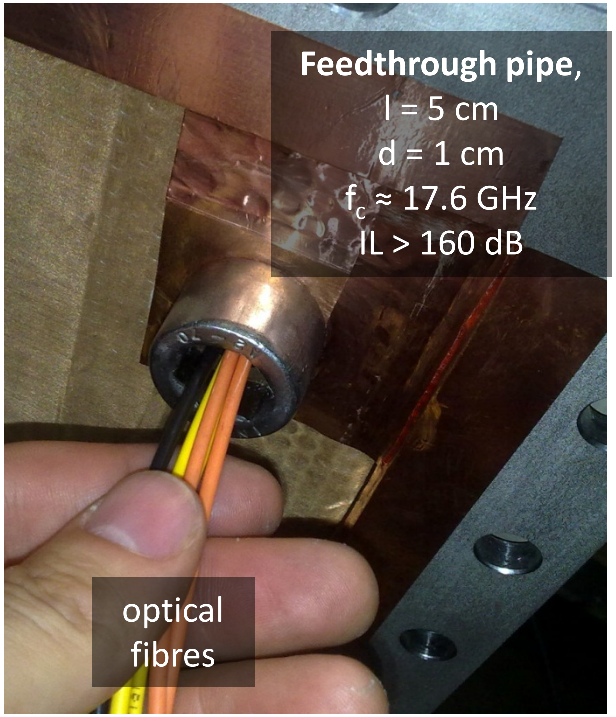
$$f_c \approx \frac{17.6\ GHz}{d\ [cm]}$$

- Any kind of **metallic conductor** can not be fed through this pipe!!! This would allow TEM waves to propagate at any frequency



Optical link for ethernet

Analog optical link, BW = 4.2 GHz



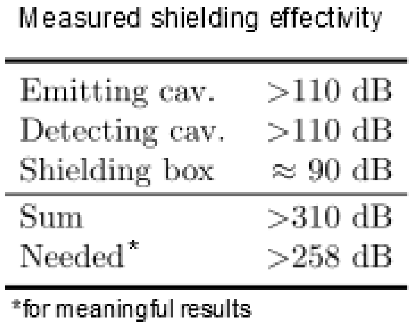
Feedthrough pipe,
l = 5 cm
d = 1 cm
$f_c \approx 17.6$ GHz
IL > 160 dB

optical fibres

Electromagnetic shielding

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

The background signal in the experiment will be thermal noise, not EM crosstalk between the cavities



Measured shielding effectivity

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

*for meaningful results

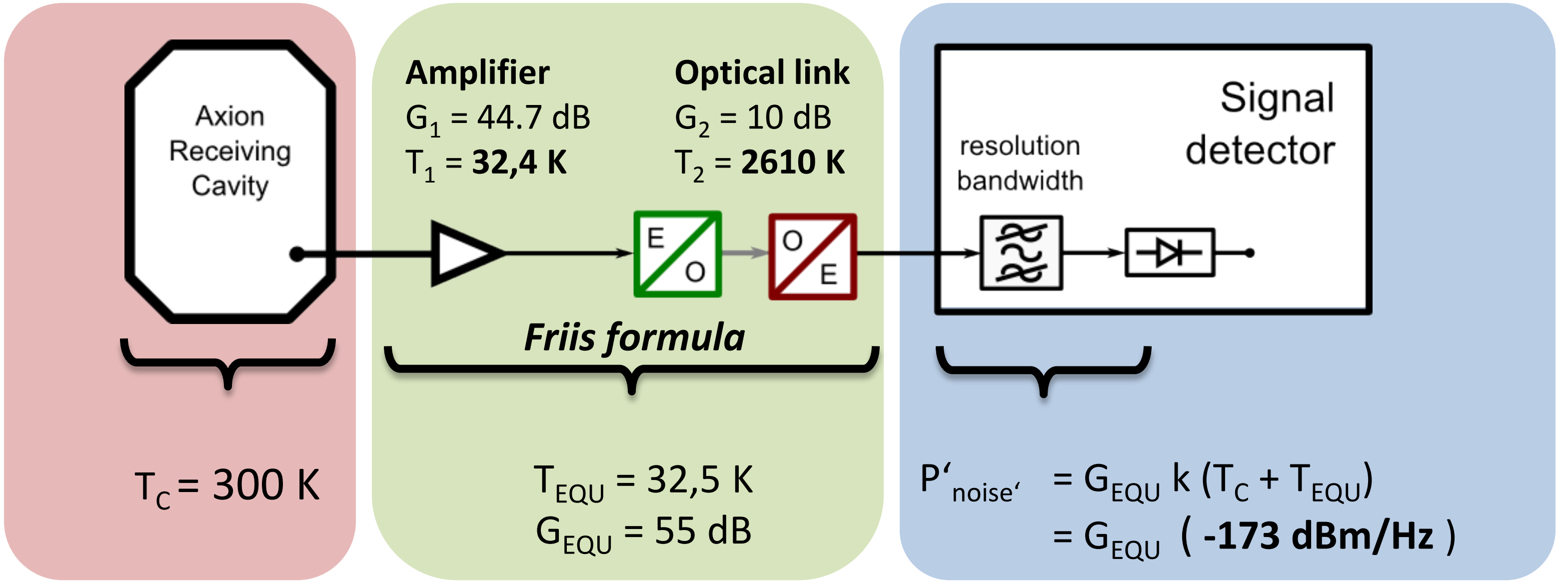
We will soon implement a reference transmitter, inside the shielding, which allows us to measure the screening attenuation in real-time during the measurement run

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

Engineering aspects

1. Designing the cavities
2. EM. Shielding
3. Signal detection

Signal processing: Noise temp.



Amplifier
G_1 = 44.7 dB
T_1 = **32,4 K**

Optical link
G_2 = 10 dB
T_2 = **2610 K**

Friis formula

T_C = 300 K

T_{EQU} = 32,5 K
G_{EQU} = 55 dB

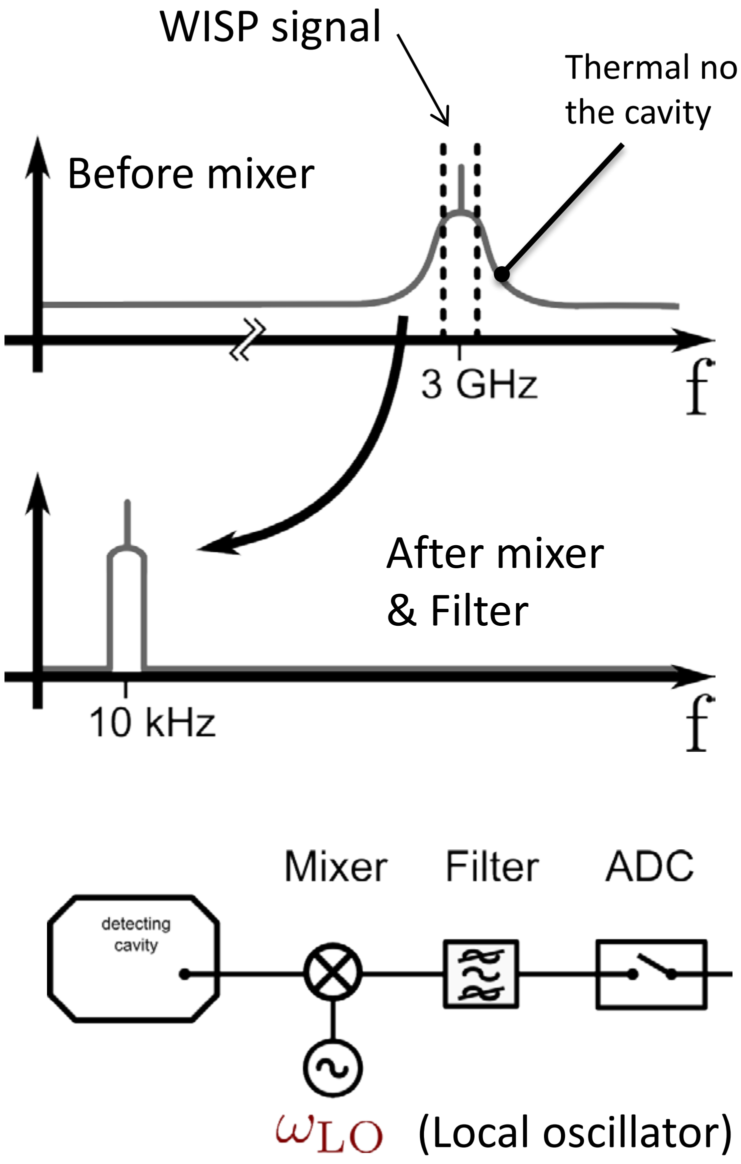
$P'_{noise'} = G_{EQU}\, k\, (T_C + T_{EQU})$
$= G_{EQU}$ (**-173 dBm/Hz**)

- On its resonant frequency, the cavities noise temp = its physical temp. = 300 K
- We expect a system noise temperature of 32.5 K
- For the added noise from the receiver, **Friis formula** applies:

$$T_{total} = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \ldots$$

  - The performance of the **first amplifier** determines the noise temperature of the whole receiving chain

Superhet receiver


WISP signal

Thermal noise from the cavity

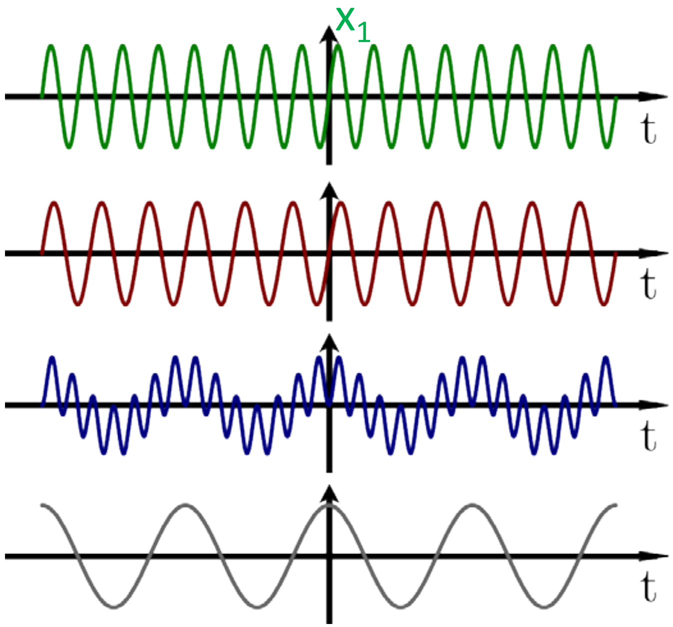
Before mixer

After mixer & Filter

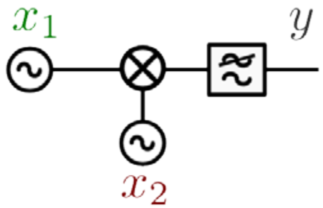
ω_{LO} (Local oscillator)

- As we expect a sinusoidal WISP signal at known frequency, we are only interested in a narrow band of the received spectrum
- Goal: cut out a certain window of the input spectrum (at 3 GHz) and shift it down to a frequency the ADC can handle (< 48 kHz)
- Superhetrodyne = Greek for “another force becomes superimposed”
- Mixer (=signal multiplier) + local oscillator = “frequency shifter”

Superhet receiver: Mixers



$$x_1 = A\sin(\omega_1 t)$$



$$x_2 = B\sin(\omega_2 t)$$

$$x_1 \cdot x_2 = \frac{AB}{2}\left[\cos((\omega_1 - \omega_2)t) - \cancel{\cos((\omega_1 + \omega_2)t)}\right]$$

Elliminated by Lowpass filter

$$y = \frac{AB}{2}\cos\left[(\omega_1 - \omega_2)t\right]$$

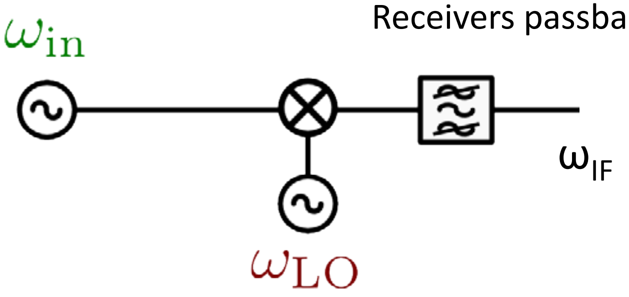
- **x_1** is the **signal of interest** (radio station, reconverted axions, etc.)
- **x_2** is the "**local oscillator**" (ω_{LO}): A sinusoidal signal of known and adjustable frequency
- The goal is to shift x_1 to a **fixed** "Intermediate frequency" (ω_{IF})
- All components after the mixer can now be implemented for the fixed IF while the receiver is still tuneable by changing ω_{LO}

Superhet receiver: Mixers

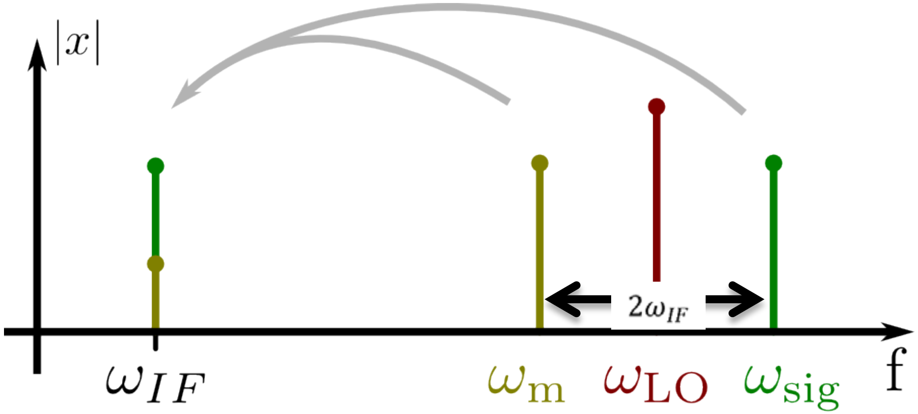
- For a simple mixer, frequency conversion is **ambiguous**!
- Input signals with the frequency **ω_{sig}** and **ω_m** will both end up at the **same** intermediate frequency
- **ω_{sig}** is the signal of interest
- **ω_m** is called the image or mirror frequency and not wanted

$$|\omega_1 - \omega_{LO}| = \omega_{IF}$$

$$\omega_{\mathrm{sig}} = \omega_{\mathrm{LO}} + \omega_{\mathrm{IF}}$$
$$\omega_{\mathrm{m}} = \omega_{\mathrm{LO}} - \omega_{\mathrm{IF}}$$

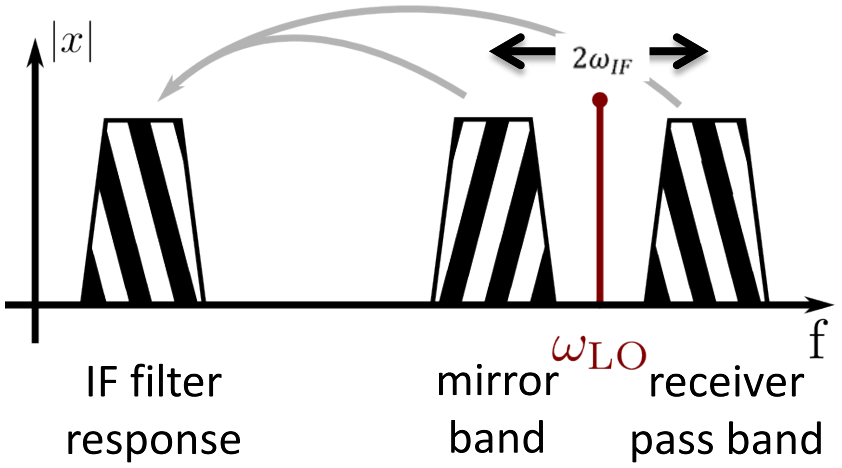


Filter determining the Receivers passband



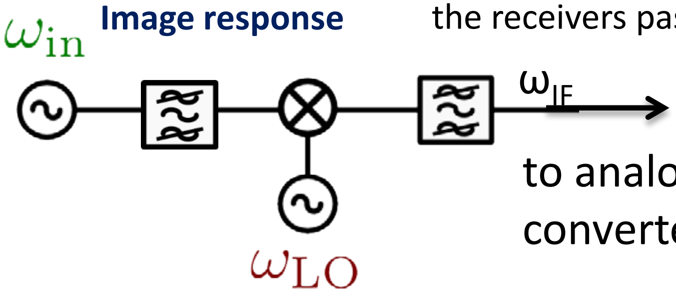
Superhet receiver: Mixers

- So for a given pass band of the IF – filter on the mixers output, there are always two pass bands on the mixers input
- The unwanted one being called the “mirror” or “image“ band
- It can be mitigated by a filter on the mixers input

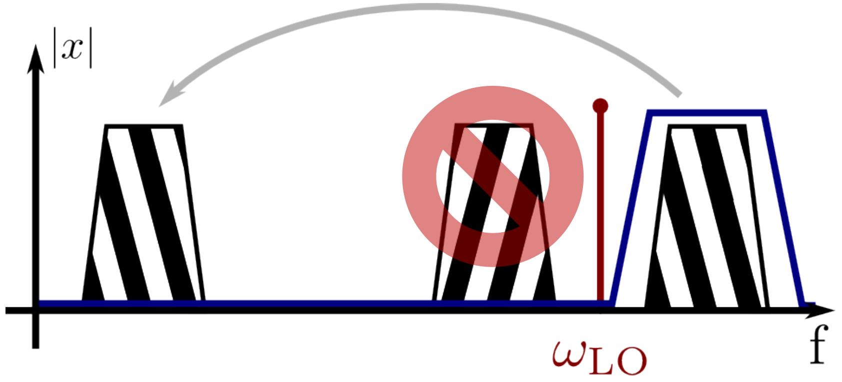


Filter to mitigate the Image response

IF filter determining the receivers passband



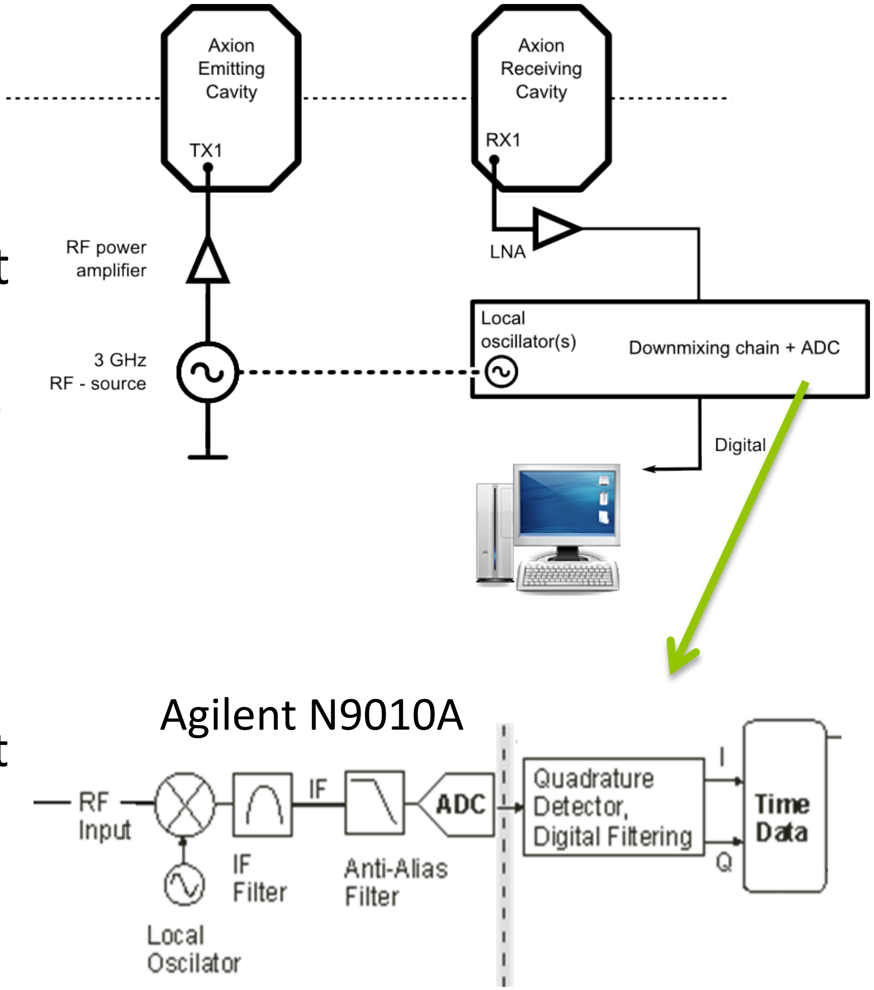
to analog – digital converter (ADC)



Blue line = response of a bandpass filter at the mixers input to mitigate the image response

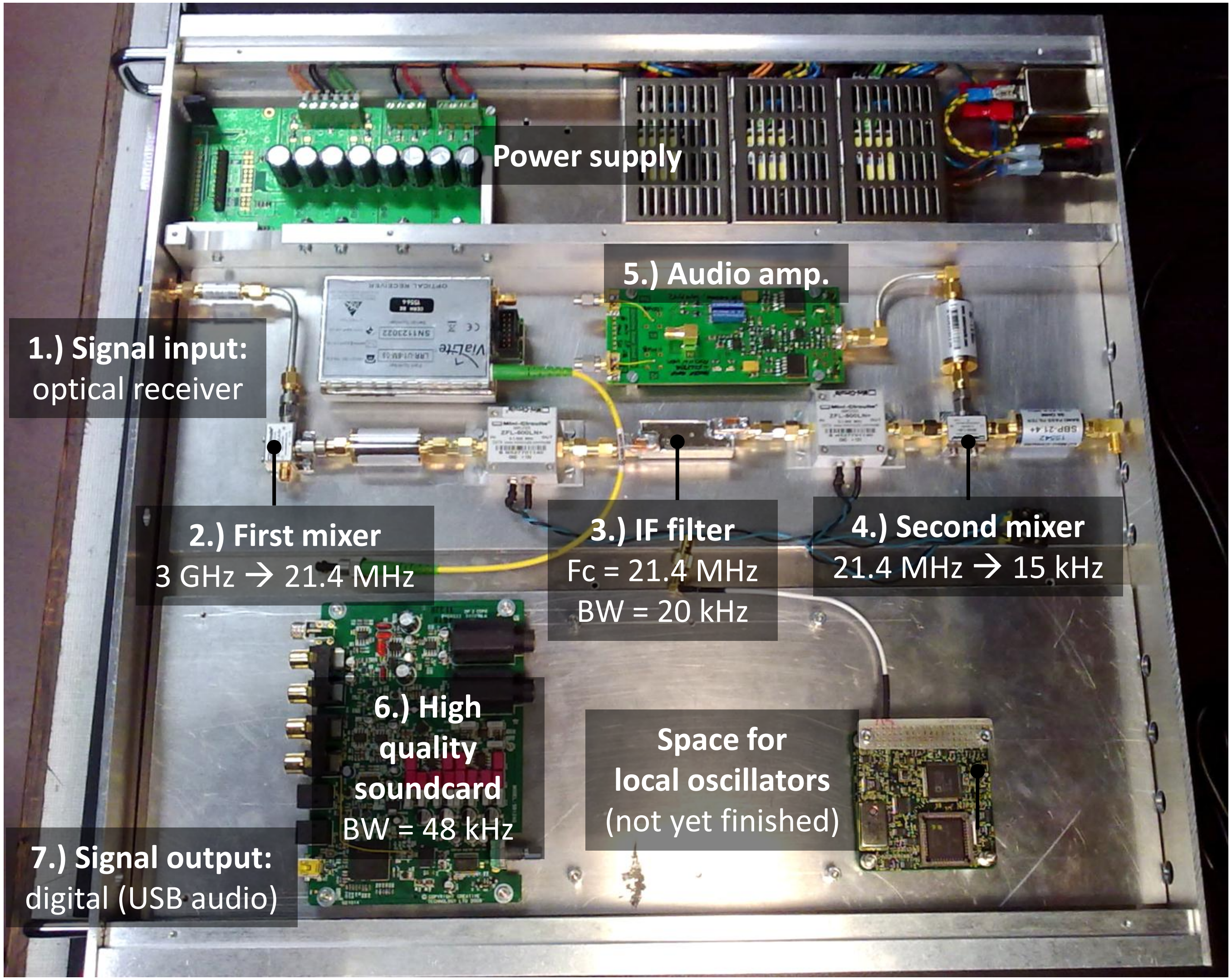
The commercial receiver

- So far we used the Agilent N9010A vector spectrum analyser to record data
- Essentially a (very expensive) superhet receiver
- Versatile but complex hardware (black box) optimized for large dynamic range
- **Bottleneck**: Can not acquire more than $5 \cdot 10^8$ samples in one recording
  - We'd like to record up to 10^{10} samples (in 12 h at BW = 100 kHz), that's about 40 Gigabyte of data
- We need simple hardware optimized on frequency stability and low noise performance



The homebrew receiver (work in progress …)

- 2 mixer stages (to reject the image response!)
- Optical input of the 3 GHz signal from the detecting cavity
- Allows indefinite recording time at 20 kHz BW
- High quality 16 bit audio ADC
- The two local oscillators and the ADC clock are phase locked to a common 10 MHz reference



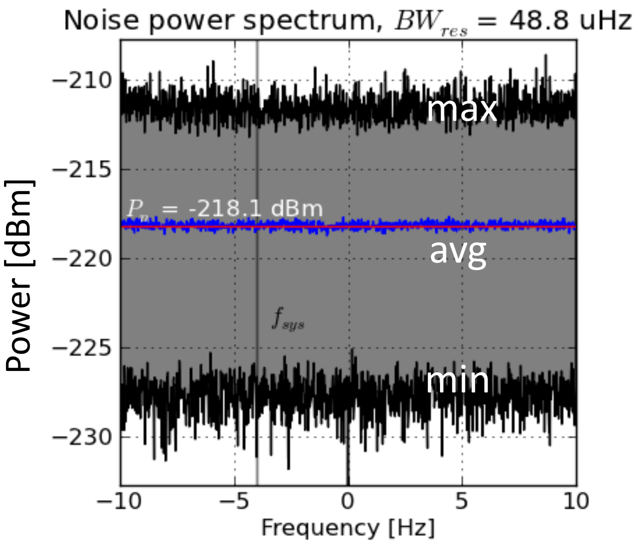
Data processing

Signal analyzer: frequency conversion, digitizing, **recording** to disk

Offline python script**:** Multiply the time trace with a **window** function

Fourier transformation
(of the whole time trace)

Squared magnitude = **Power spectrum** Search for peaks at the right frequency



Resulting spectrum of a 11.5 h measurement run

Fourier transformation is the optimum detection method for sinusoidal signals in white noise (Matched filter!)

Data processing: pushing the noise floor

Average noise power:

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

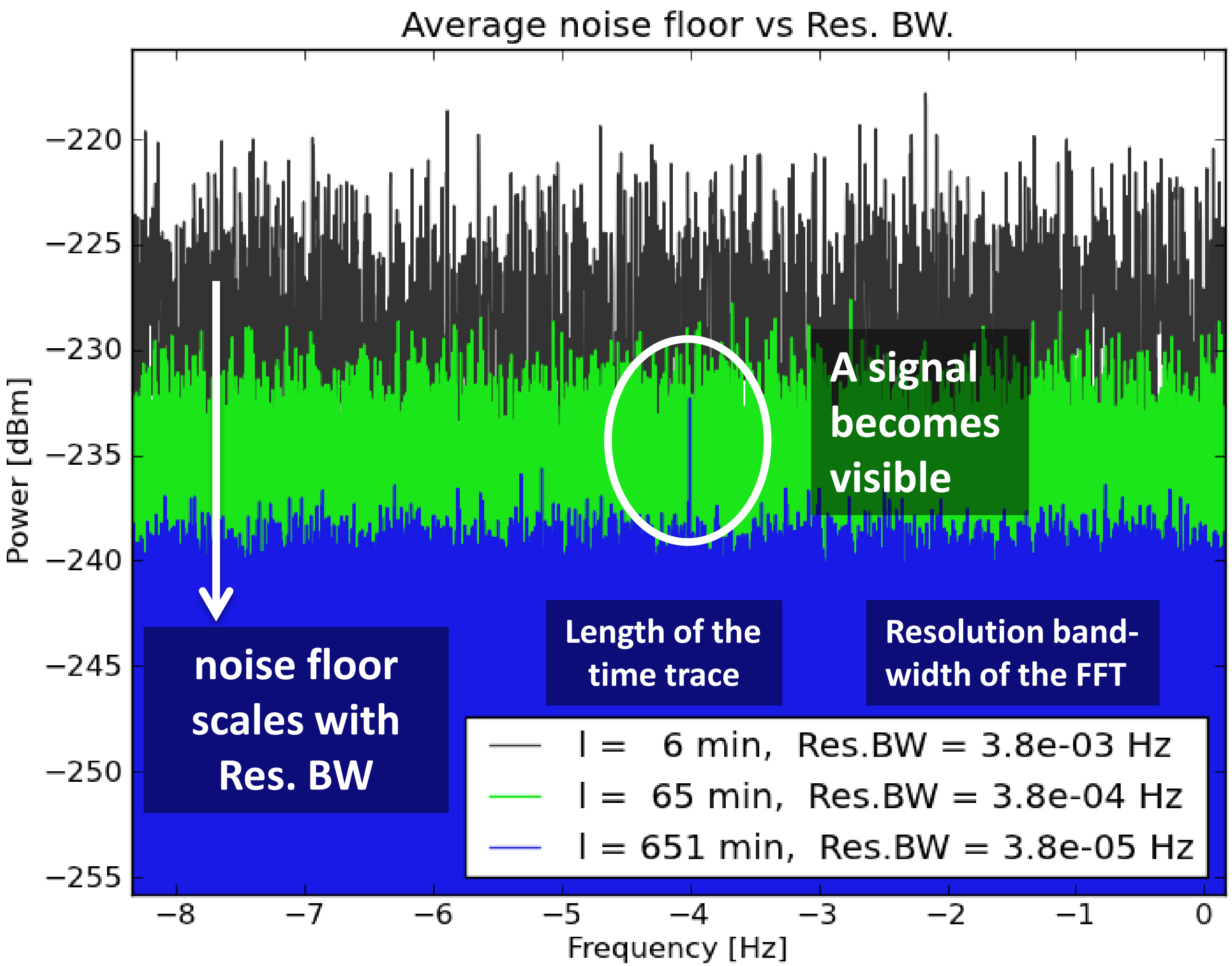
k_B = Boltzmann const.

BW_{res} = 1.5 / l
resolution bandwidth

l = length of the recorded time trace

T_{sys} = system noise temp.

Linear increase of signal to noise ratio with measurement time



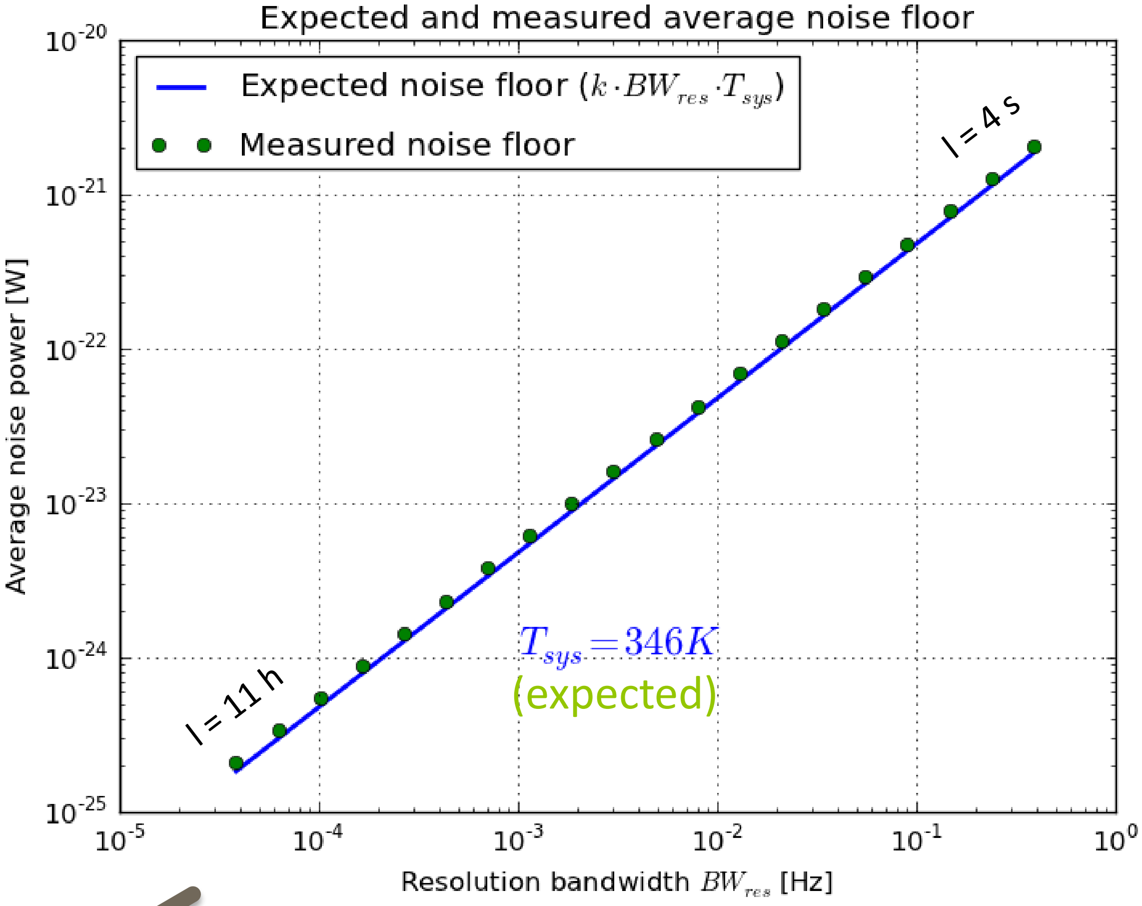
A signal becomes visible

noise floor scales with Res. BW

Length of the time trace

Resolution band-width of the FFT

Data processing: pushing the noise floor



l = length of one time segment

Average noise power:

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

k_B = Boltzmann const.

T_{sys} = system noise temp.

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

Data processing: pushing the noise floor

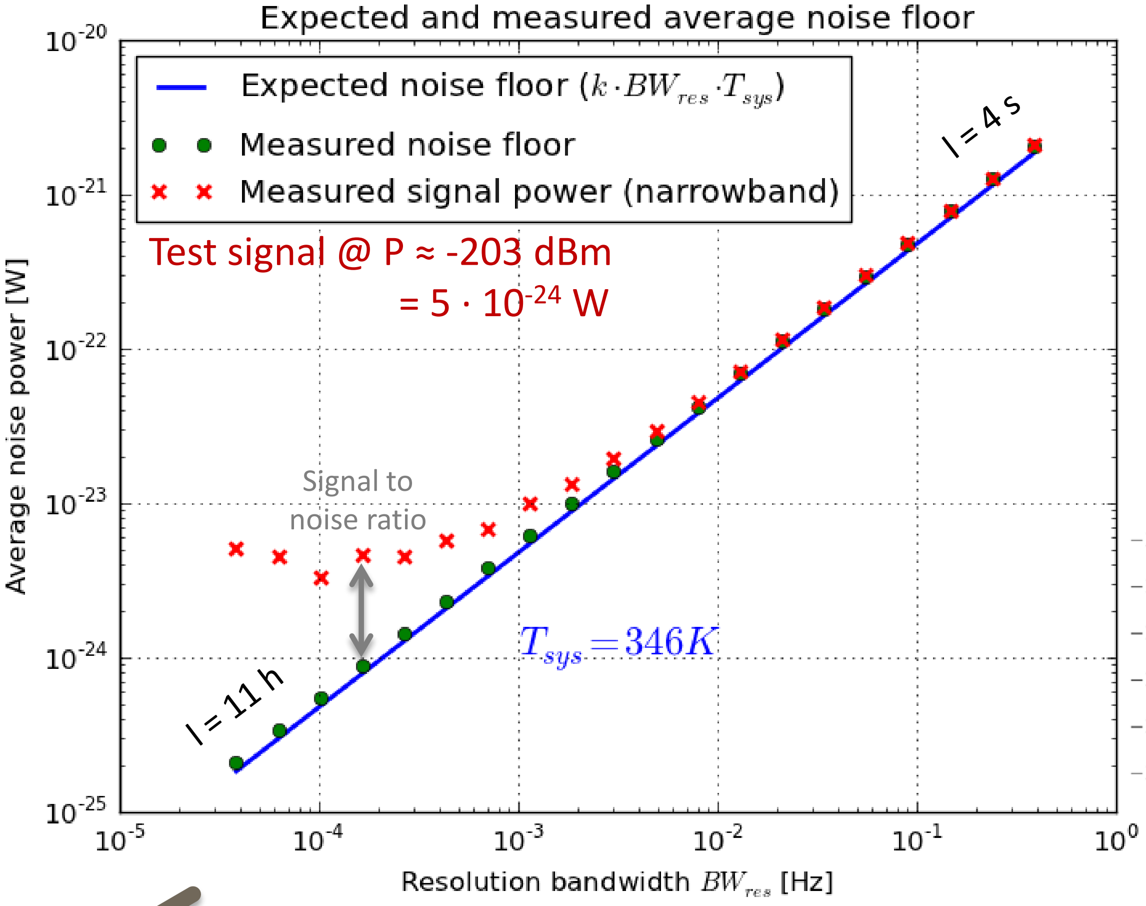
We can detect microwave signals below :

-210 dBm

= 10^{-24} W

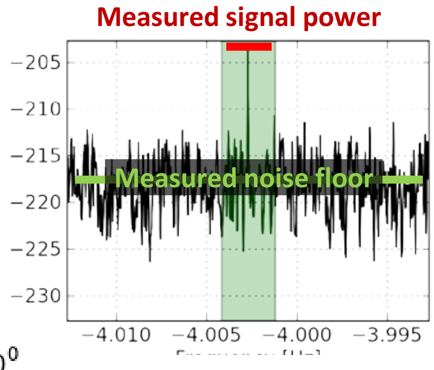
= 1 photon every 2 seconds

At room temperature, without any cryogenics!



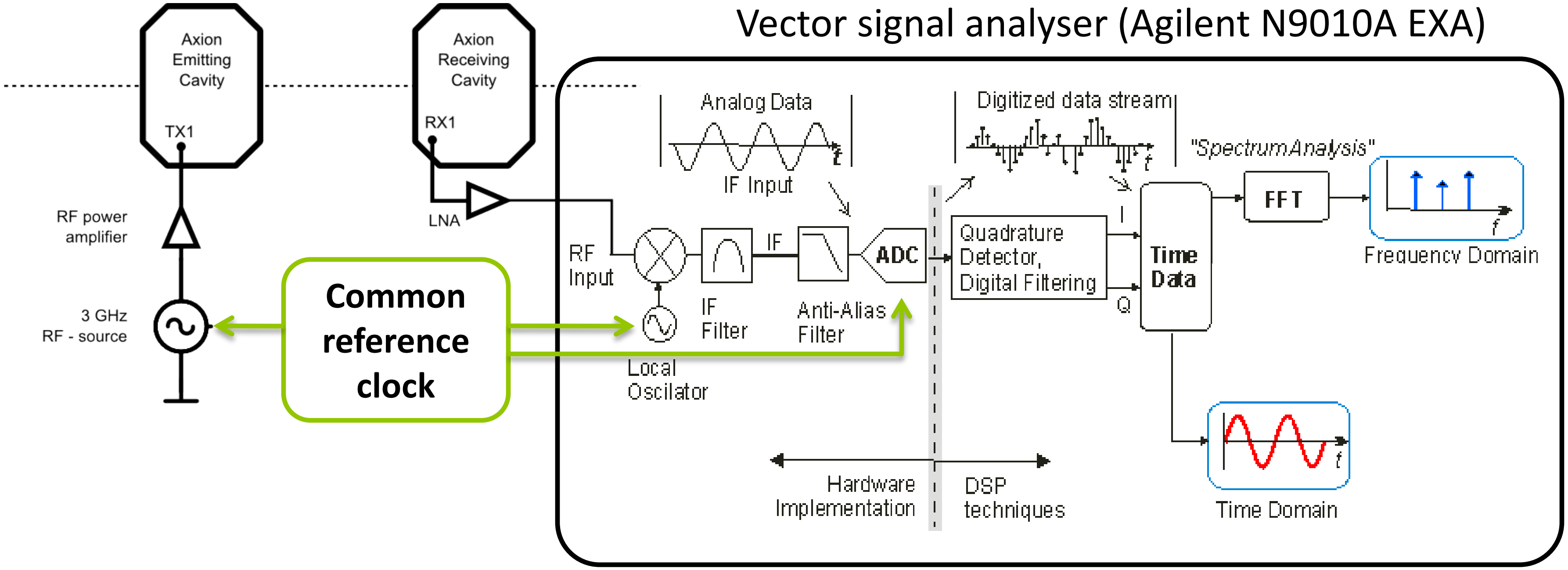
Test signal @ P ≈ -203 dBm = 5 · 10^{-24} W

l = length of one time segment



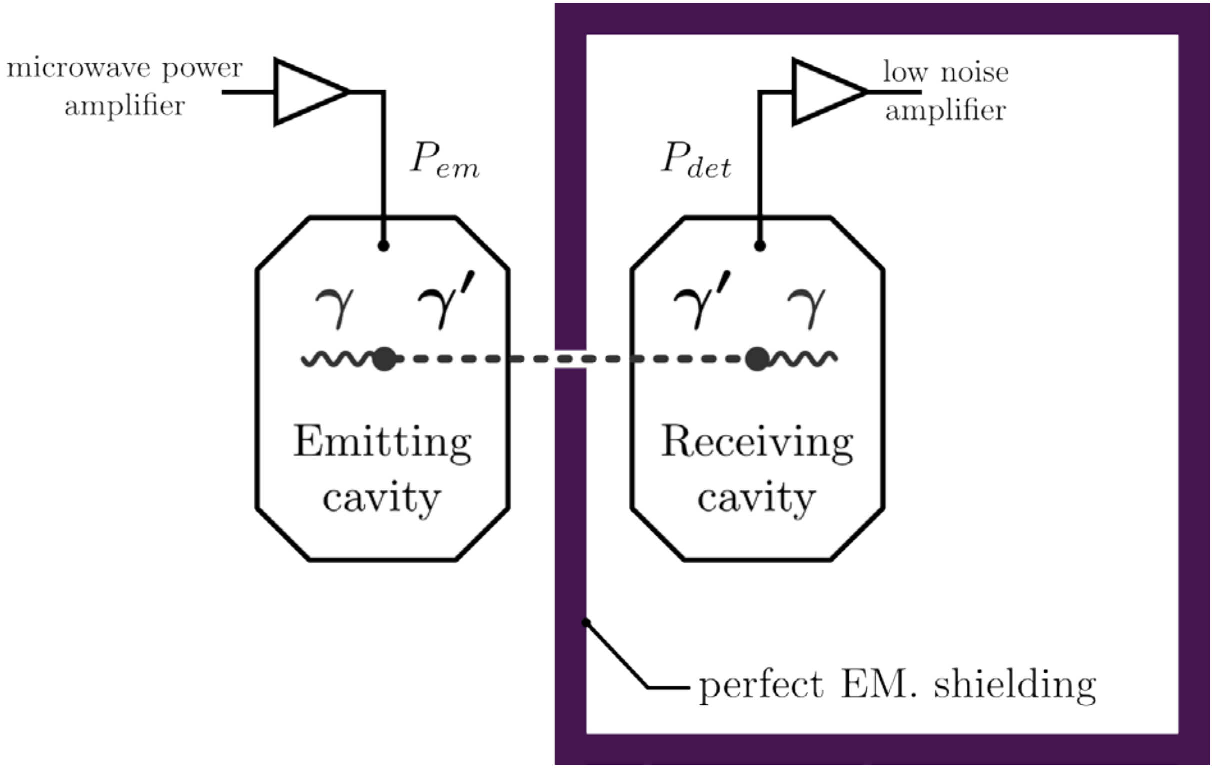
The signal power stays constant

Frequency drifts


Vector signal analyser (Agilent N9010A EXA)

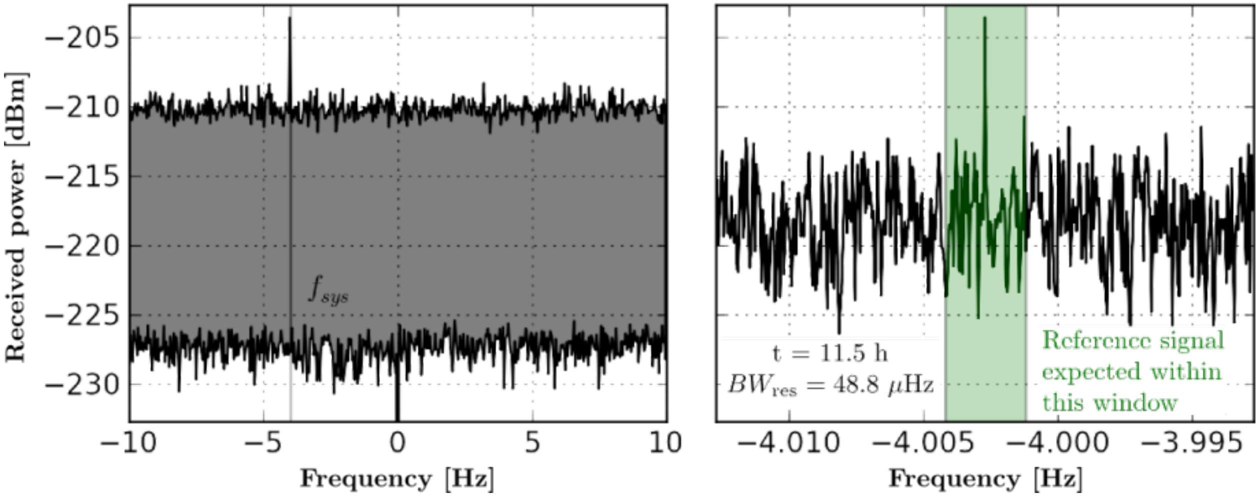
- To detect signals down to -230 dBm we need resolution bandwidths in the 10 µHz range
- This can be achieved with a FFT on a 24 h time trace
- Frequency drifts are unavoidable!
- But by phase locking source and analyzer we can eliminate relative frequency errors

The first HSP measurement run in March 2012



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.



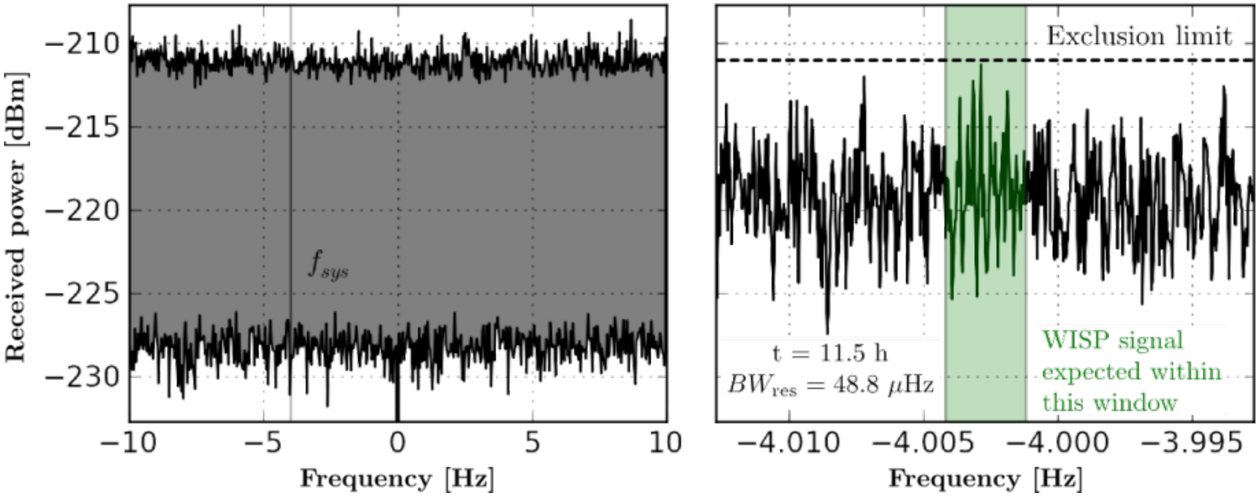
Full span

Zoomed in

First HSP measurement run, March 2012

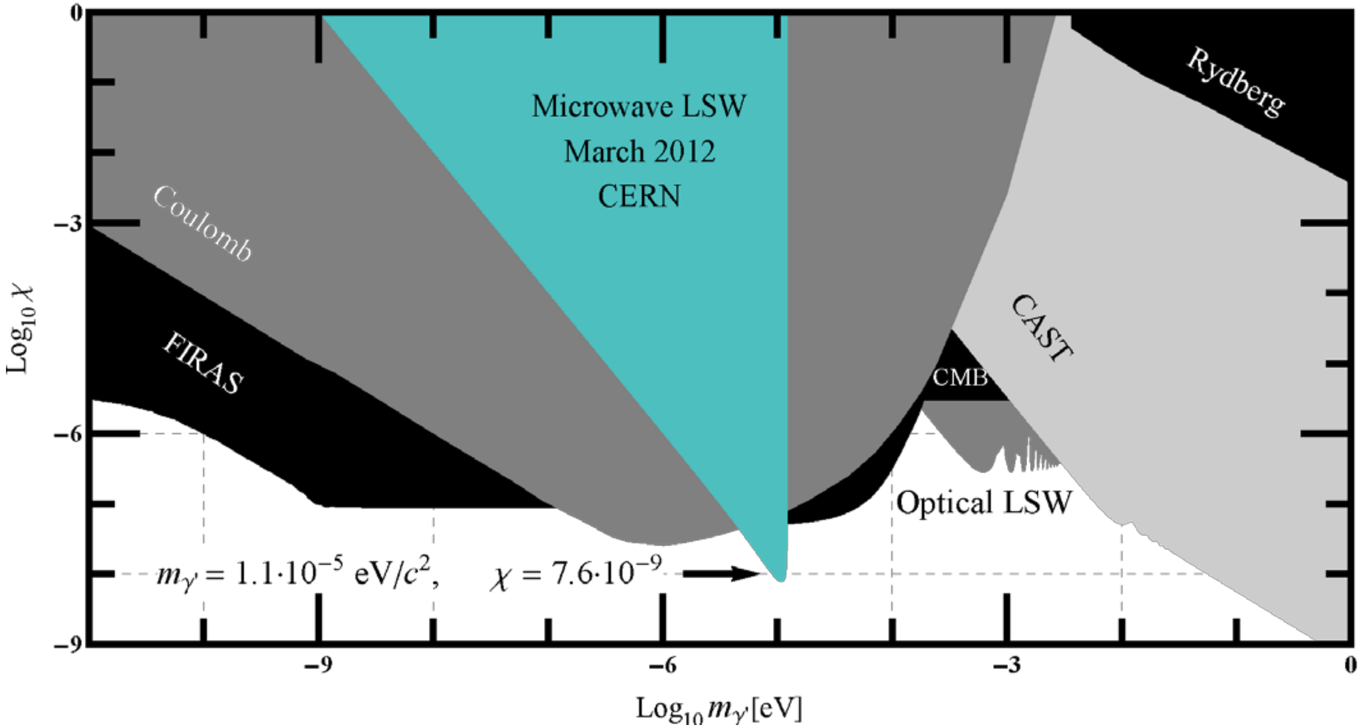
- 11.5 h measurement run with **closed shielding box**
  - peaks within the window do not significantly exceed the peaks in other parts of the spectrum
  - No signal detected → exclusion result

Full span *Zoomed in*



First HSP measurement run, March 2012

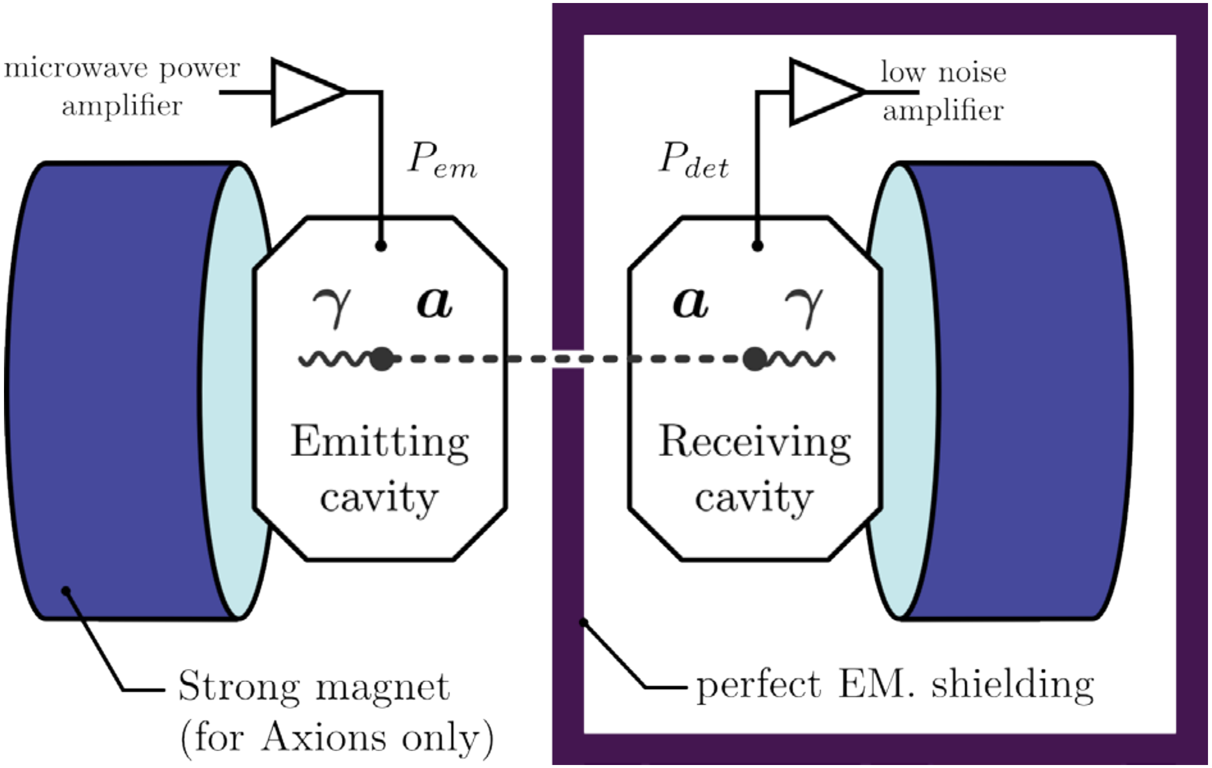
- We were sensitive enough to improve over current exclusion limits [1]



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

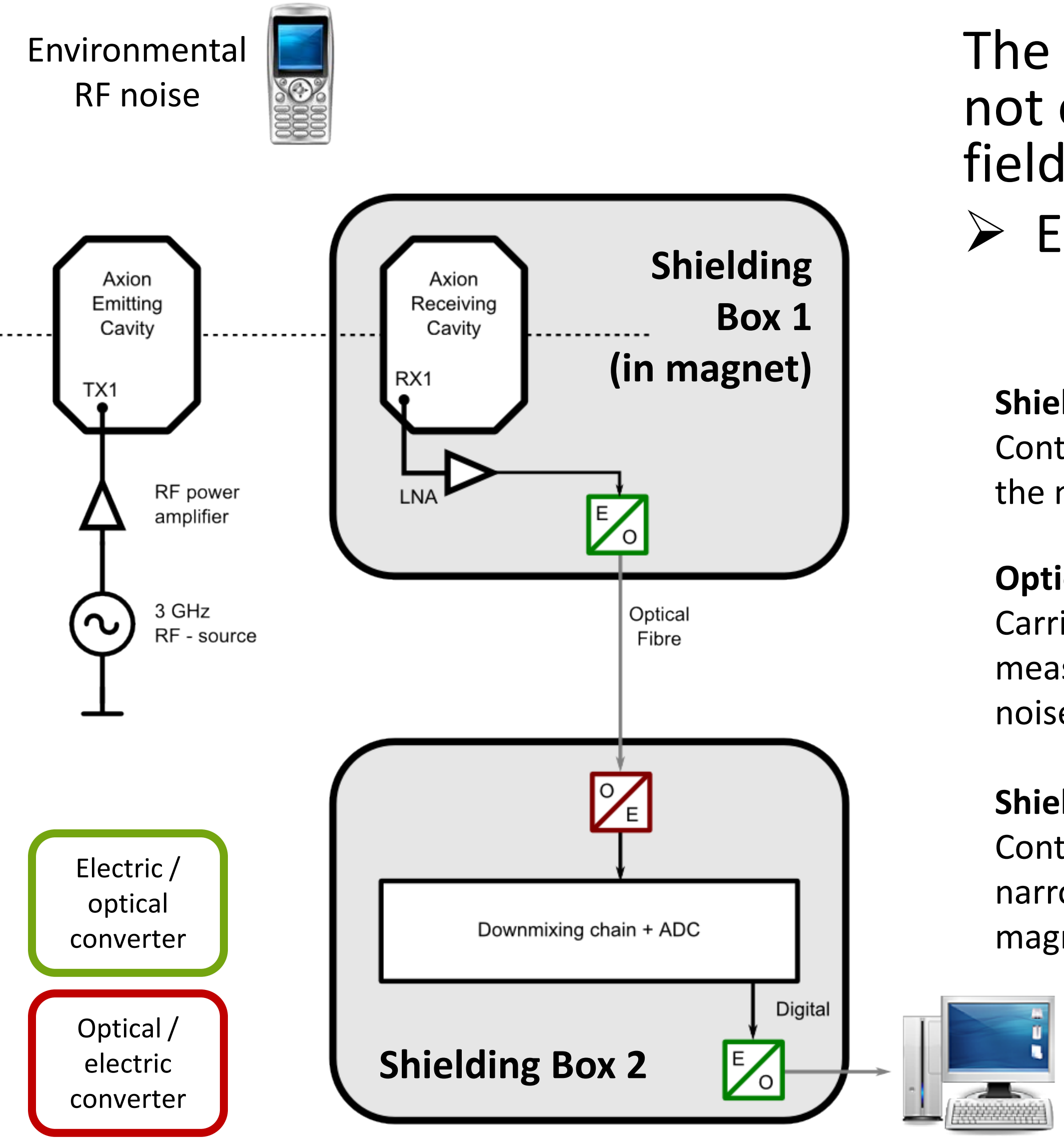
The first axion LSW measurement run in June 2012



Axion LSW measurements (June 2012)

- We got a 1 week timeslot to use a large 0.5 T magnet at CERN
- Things which had to be done before:
  - Adjust the cavity couplers to the **$\mathbf{TM_{010}}$ 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

Electromagnetic shielding



The signal processing electronics can not easily operate in strong magnetic fields

- ➢ Experiment is split into two parts

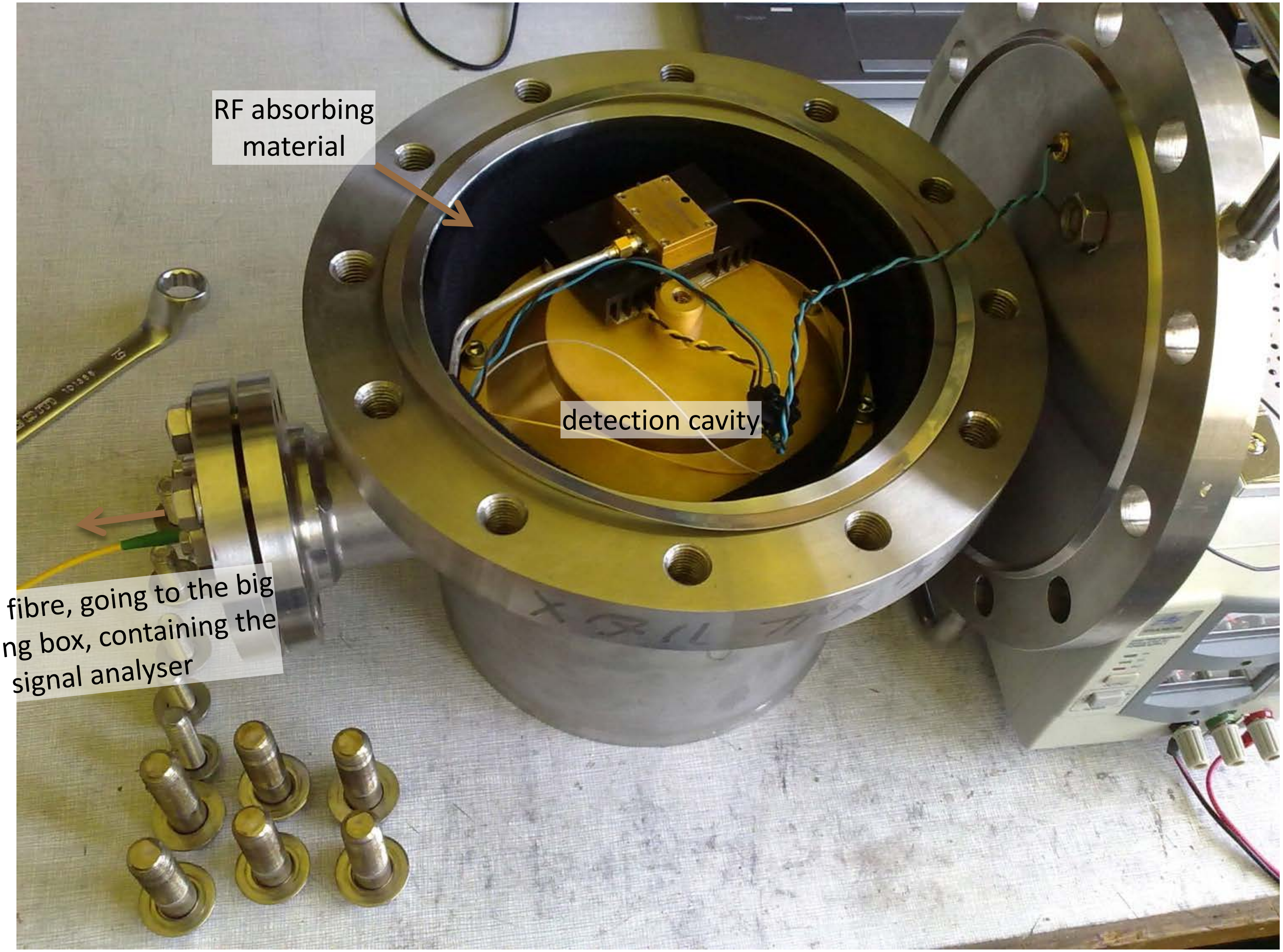
Shielding Box 1
Contains the axion detection cavity and will be placed in the magnet

Optical Fibre
Carries the weak signal from axion conversion to the measurement instruments, unaffected by ambient EM. noise and without comprising the shielding boxes

Shielding Box 2
Contains instruments for the detection of weak narrowband microwave signals and will be outside the magnet

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

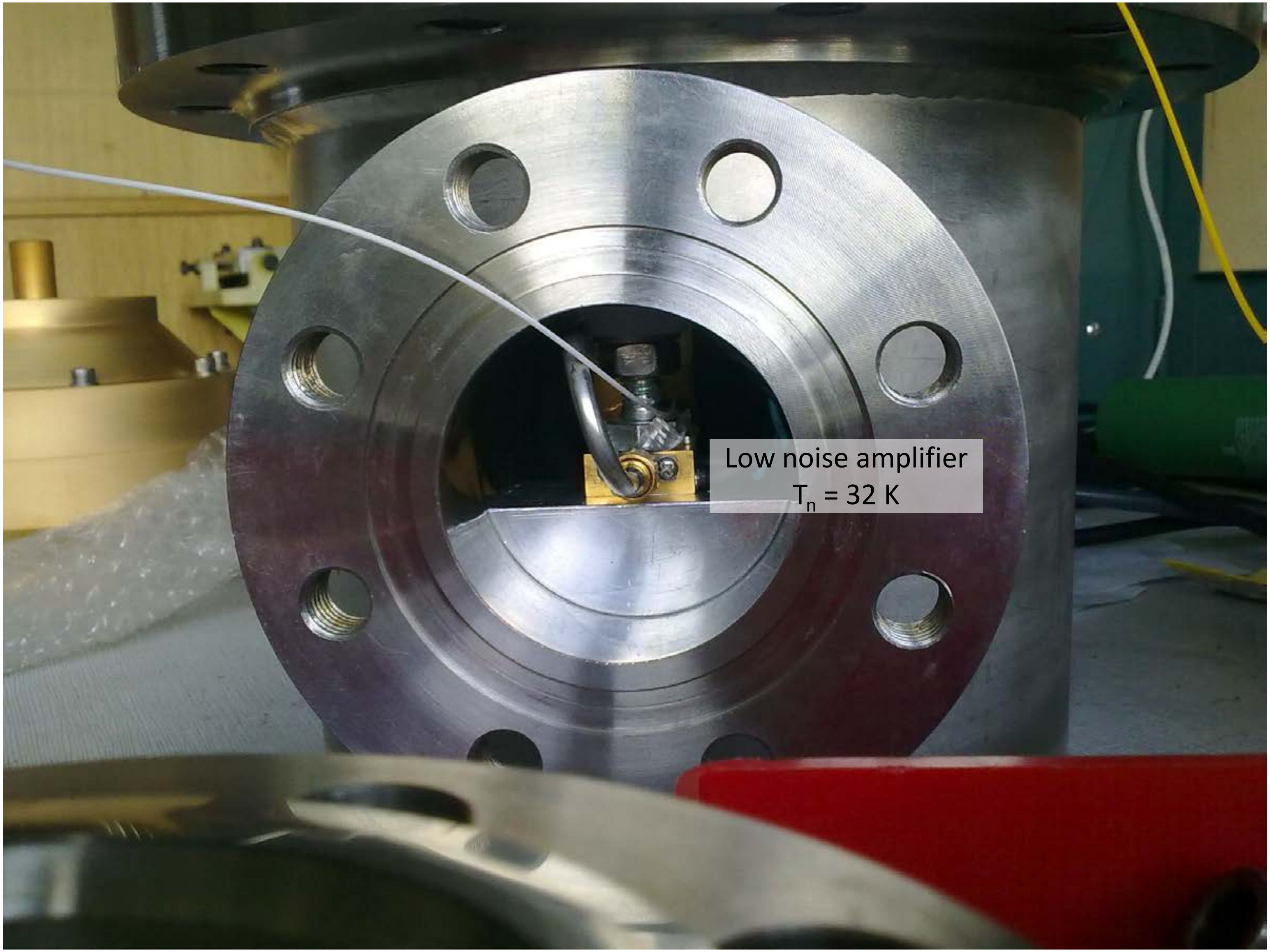
The secondary shielding enclosure, ready to be placed in the magnet



RF absorbing material

detection cavity

optical fibre, going to the big shielding box, containing the signal analyser

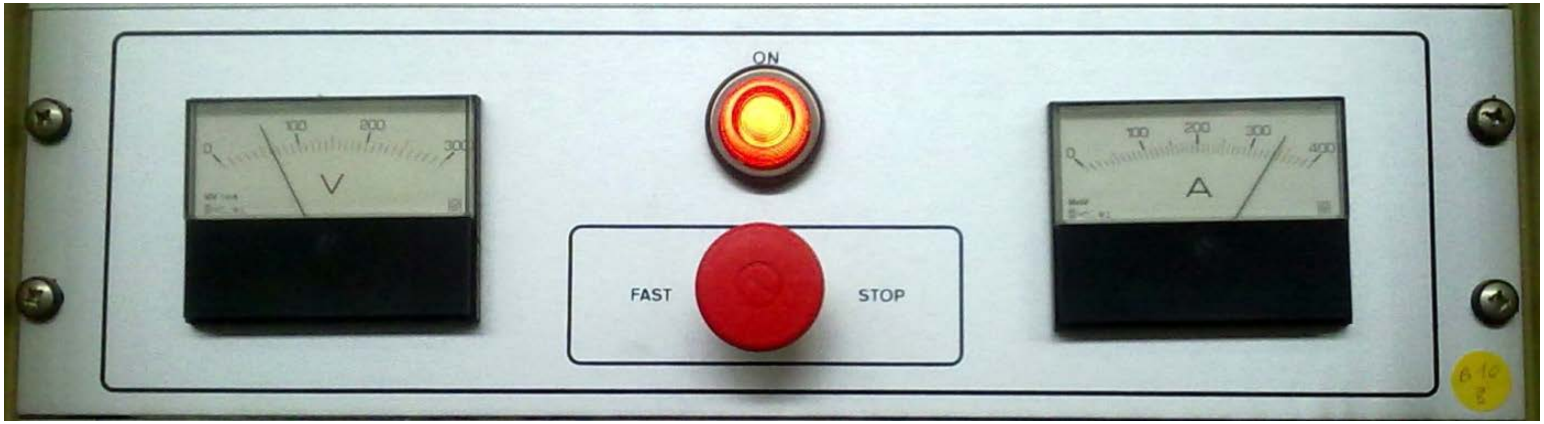


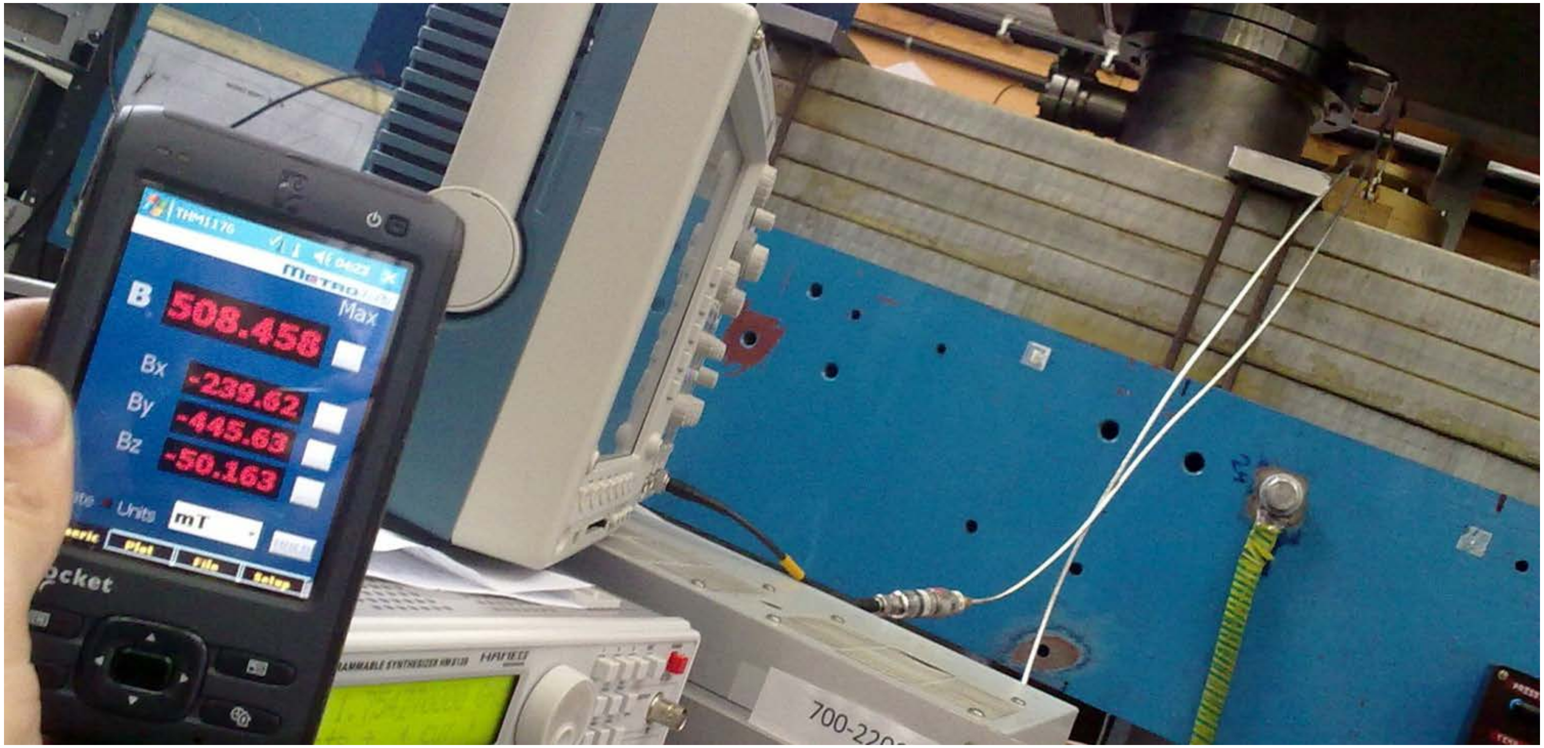
Low noise amplifier
T_n = 32 K

Moving to the magnet hall

$|B_{max}| = 0.5$ T

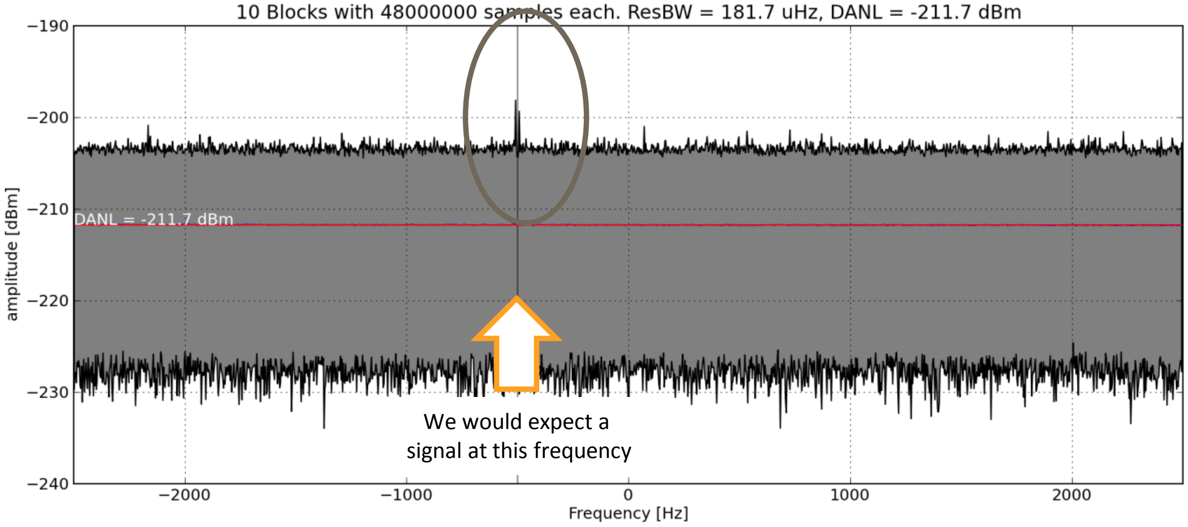
Resonant frequency: **1.754 GHz**
Incident RF power: **7.3 W**
Avg. reflected power: **0.7 W**


ON
0
100
200
300
V
0
100
200
300
400
A
FAST
STOP
B 10
8


THM1176
METROLAB
B
508.458
Max
Bx
-239.62
By
-445.63
Bz
-50.163
Units
mT
Plot
File
Setup
700-220

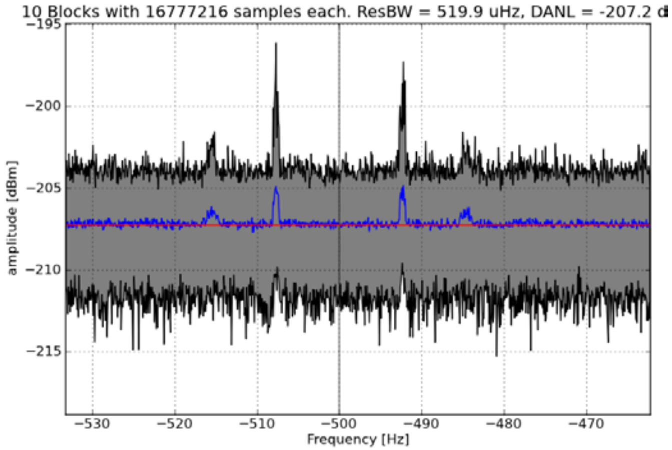
Results from the first run

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



10 Blocks with 48000000 samples each. ResBW = 181.7 uHz, DANL = -211.7 dBm

We would expect a signal at this frequency



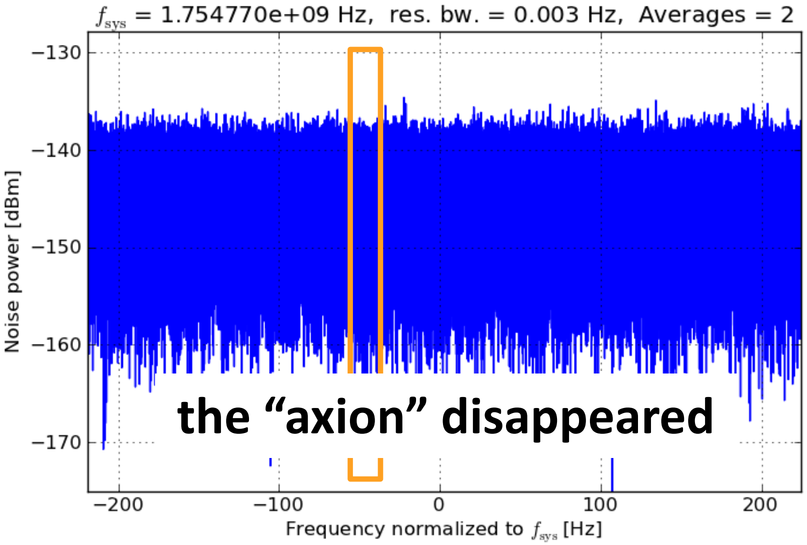
10 Blocks with 16777216 samples each. ResBW = 519.9 uHz, DANL = -207.2 d

Did the axion finally reveal itself?

Strange sidebands! But no signal where we would expect it

Results from the first run

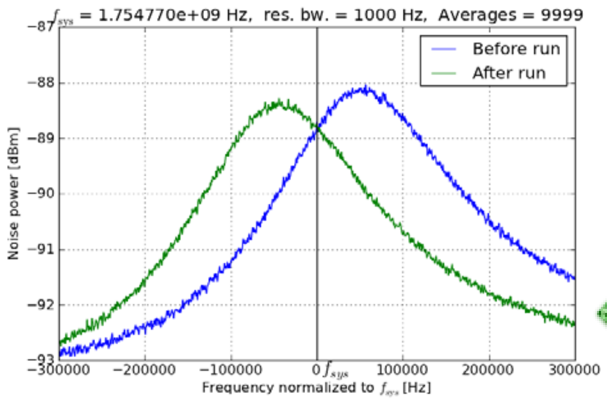
- It turned out to be 2 problems:
  - **EM. leakage**
  - A different (cheaper) RF source was used, which did not lock cleanly to the 10 MHz reference signal
- Stuffing copper mesh in the seam and using a different RF source fixed the problem

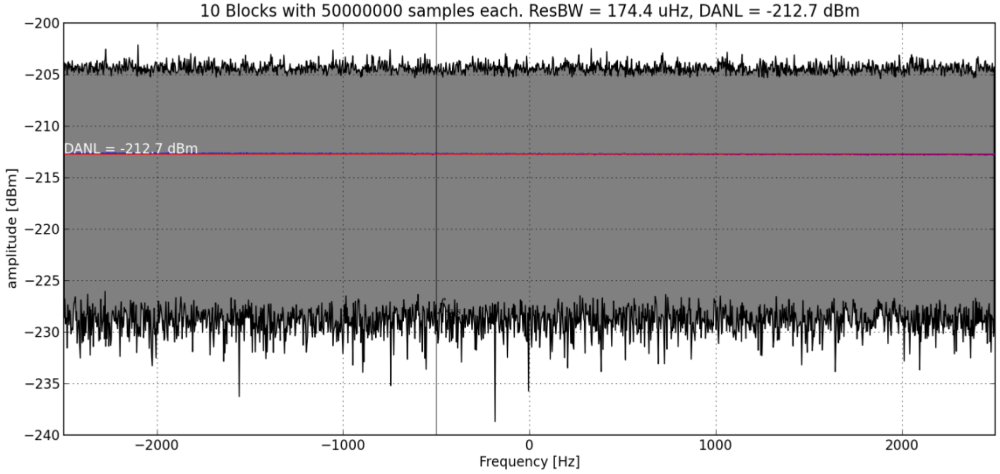


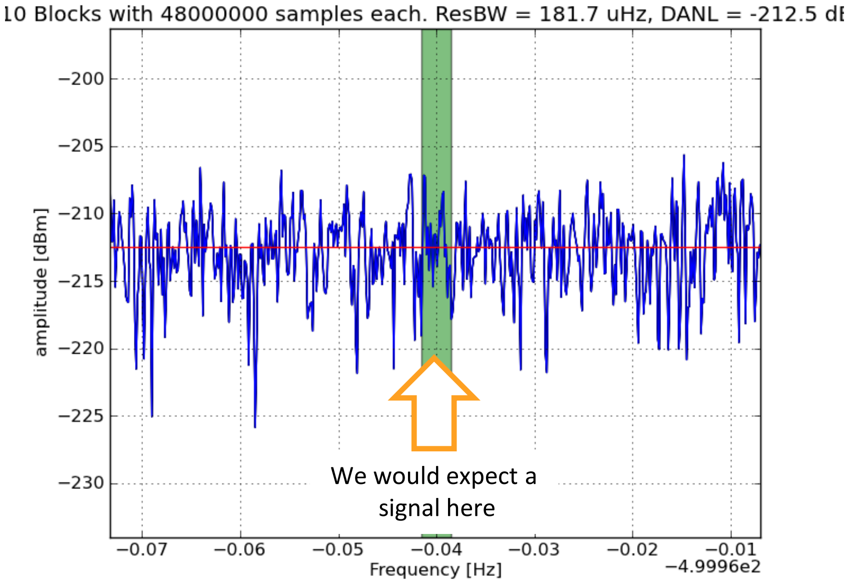
Results from the second run

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

Tune of the detecting cavity



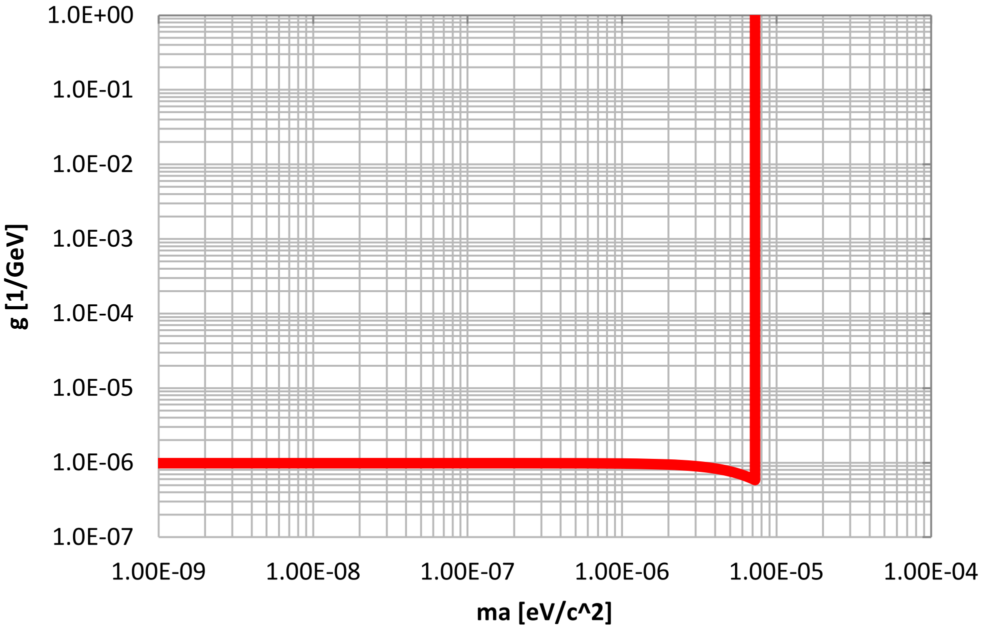


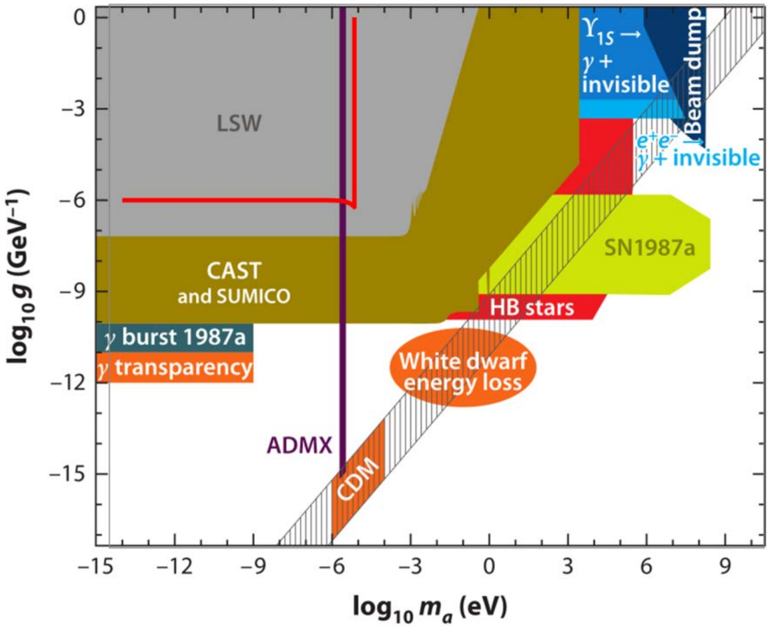


We would expect a signal here

Results from the second run

expressed as an exclusion limit for ALPs





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

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

Preliminary!

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

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

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

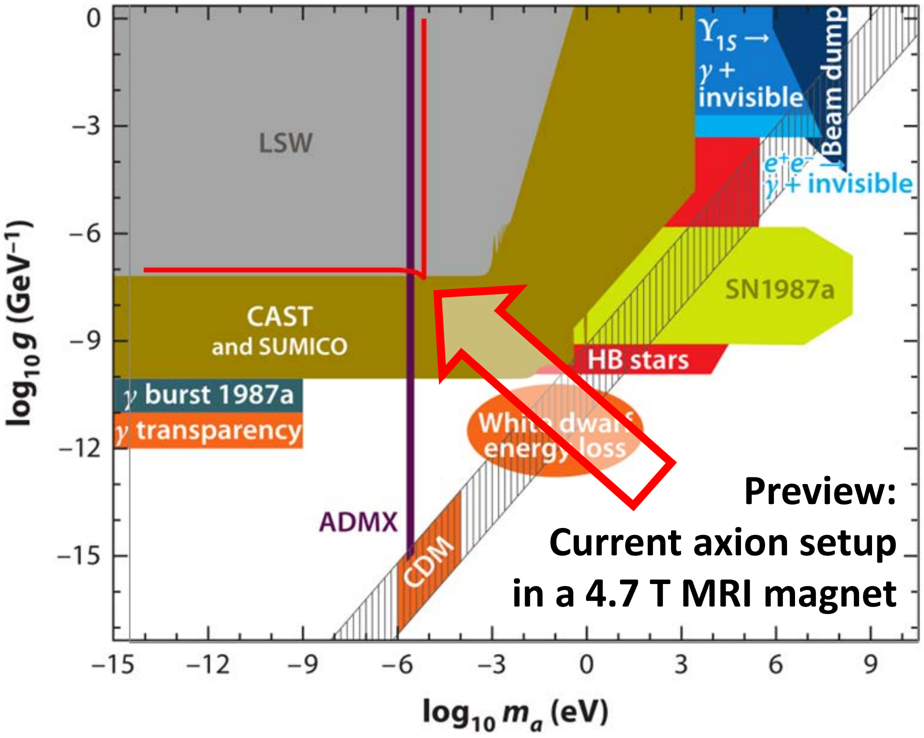
Outlook

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

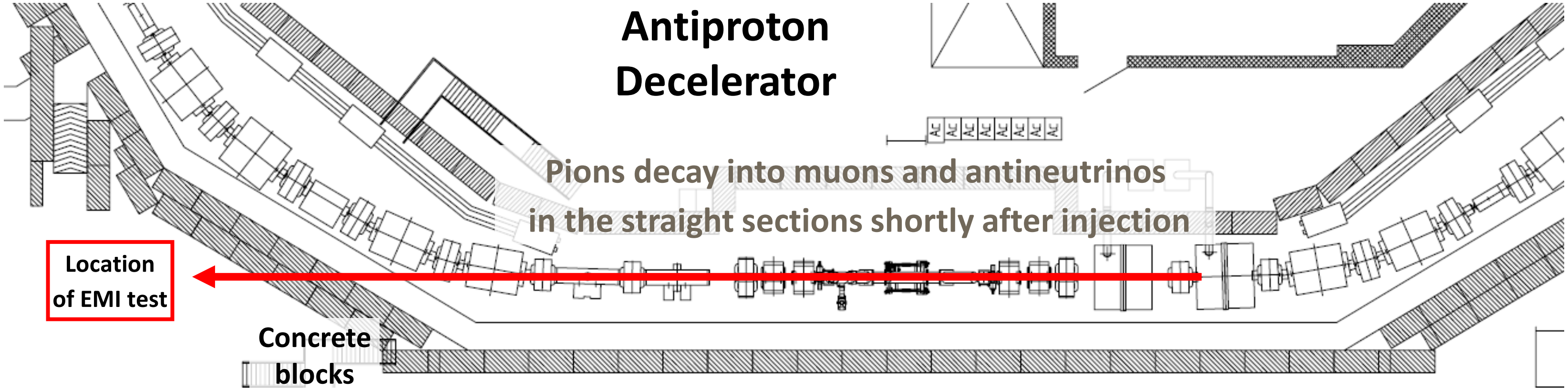


Preview:
Current axion setup
in a 4.7 T MRI magnet

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)



Pions decay into muons and antineutrinos in the straight sections shortly after injection

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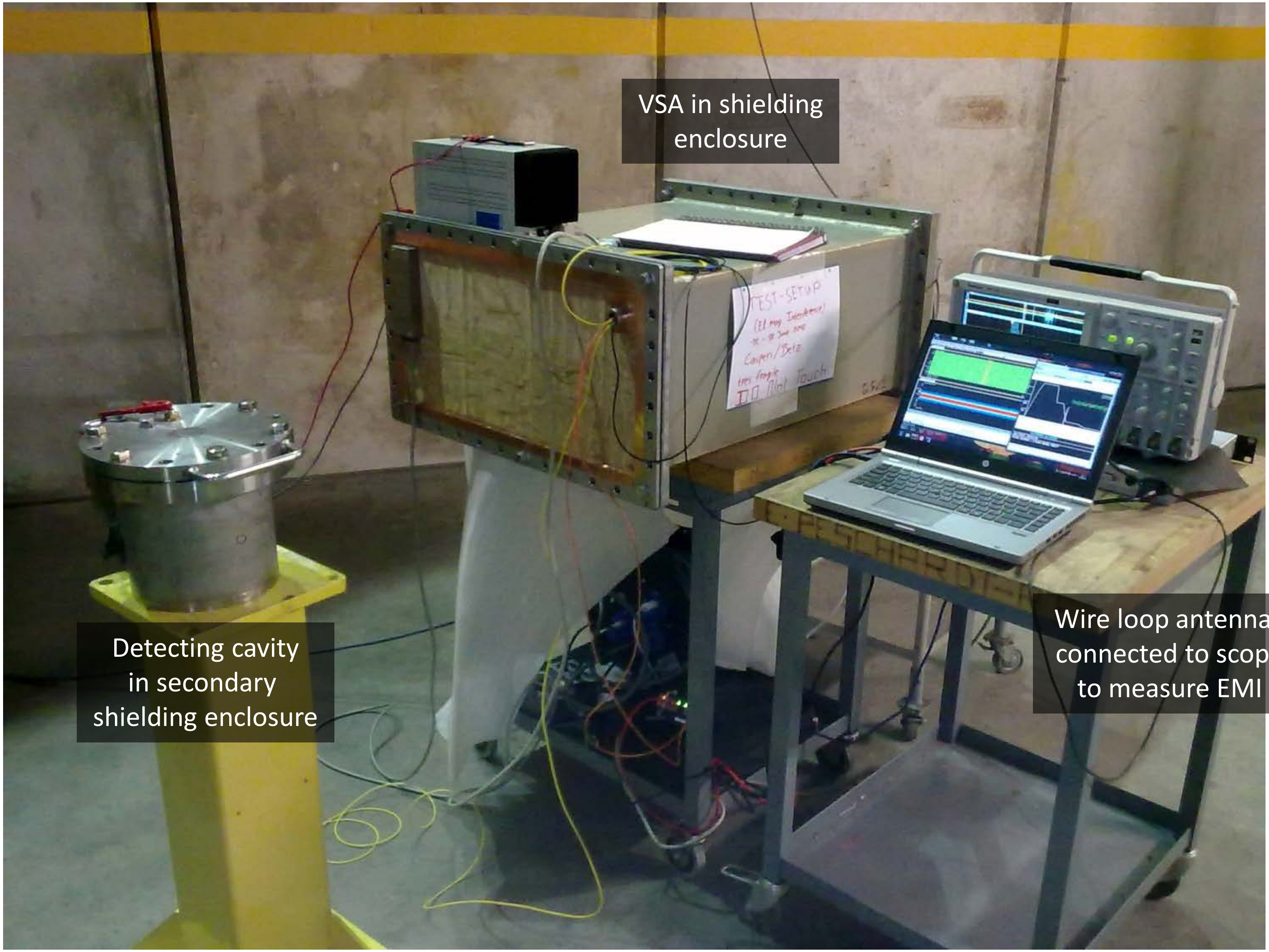
[1] I. I. Kalikinski , *“On microwave transition radiation”,* TECHNICAL PHYSICS VOLUME 43, NUMBER 2 FEBRUARY 1998



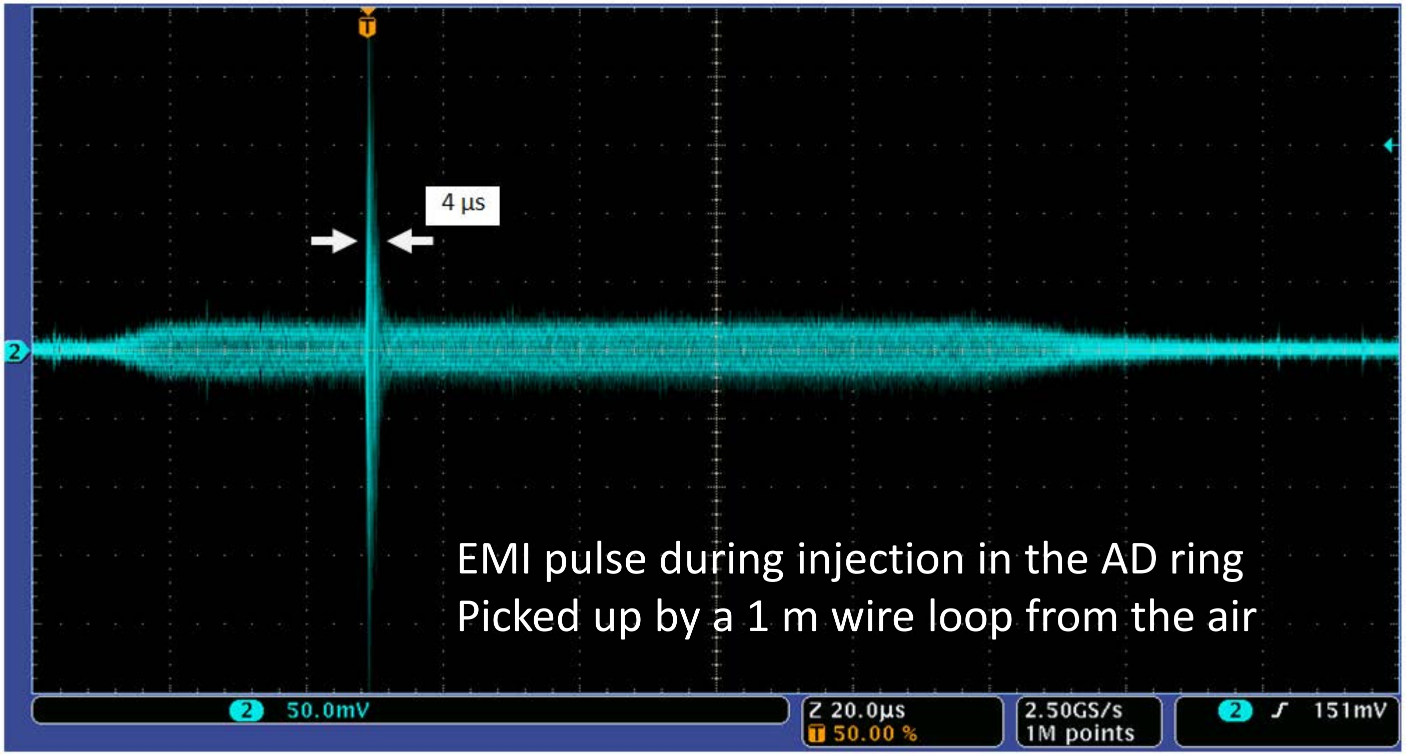
VSA in shielding enclosure

Detecting cavity in secondary shielding enclosure

Wire loop antenna, connected to scope to measure EMI

Results

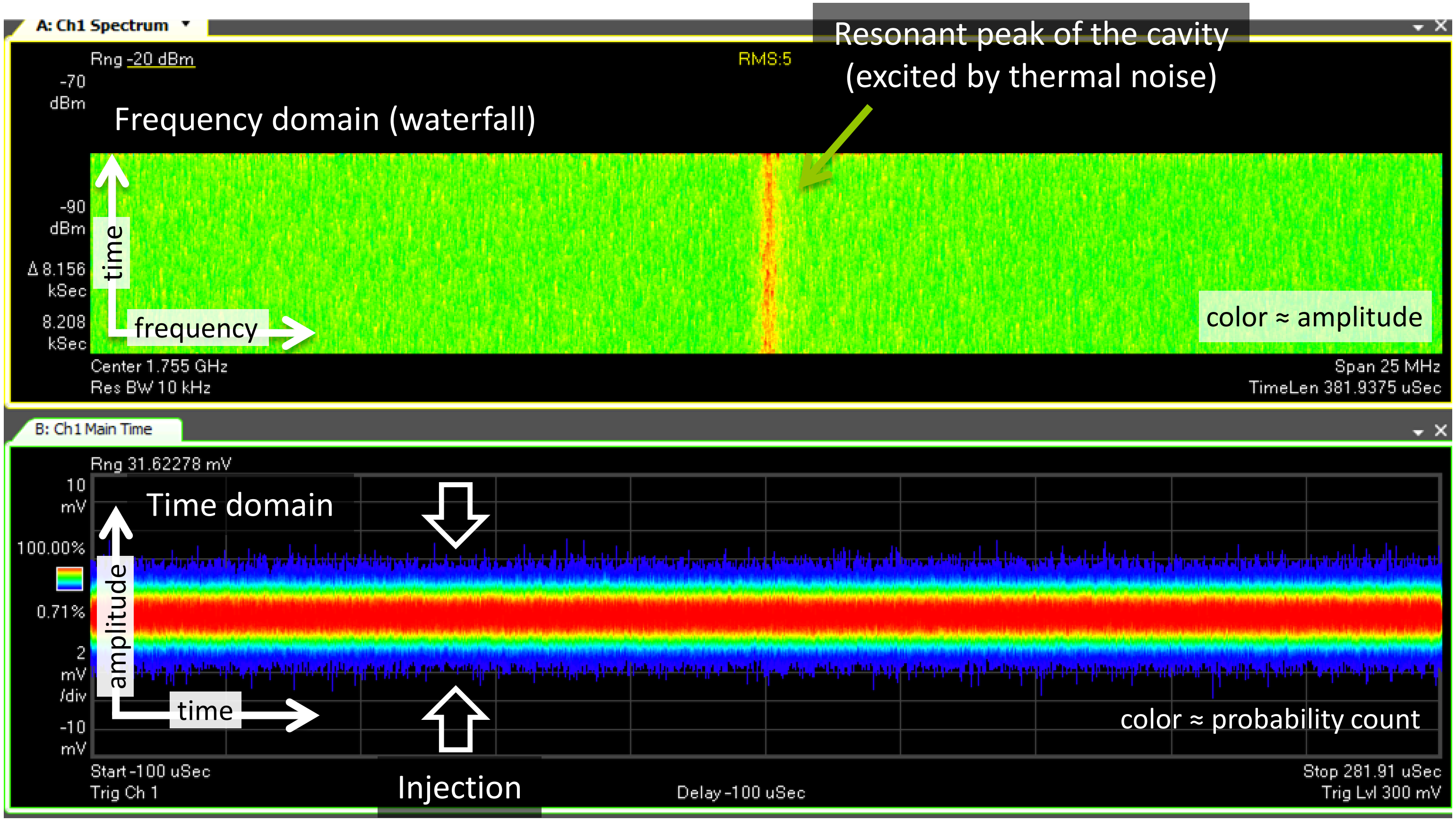
- There is strong pulsed EMI in the hall



4 µs

EMI pulse during injection in the AD ring
Picked up by a 1 m wire loop from the air

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



Resonant peak of the cavity (excited by thermal noise)

Frequency domain (waterfall)

color ≈ amplitude

Time domain

Injection

color ≈ probability count

Rng -20 dBm

RMS:5

Center 1.755 GHz

Res BW 10 kHz

Span 25 MHz

TimeLen 381.9375 uSec

Rng 31.62278 mV

Start -100 uSec

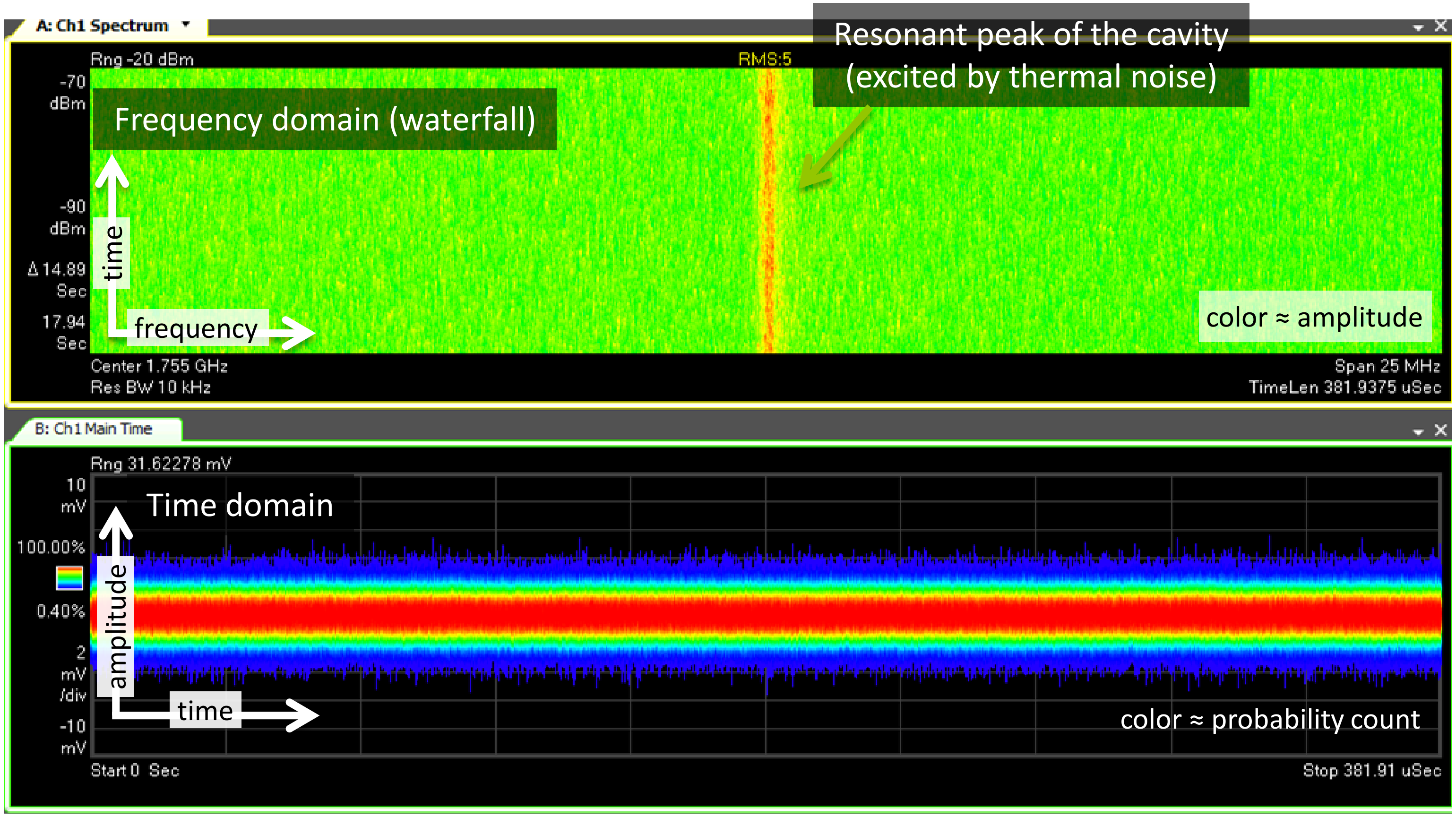
Trig Ch 1

Delay -100 uSec

Stop 281.91 uSec

Trig Lvl 300 mV

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



The system is EMI leak tight

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

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

Acknowledgements

- Thanks to F. Caspers, M. Gasior and M. Thumm for making this work possible

- Thanks to Babette for organizing these seminars

- 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

Thank you!