Status report of the CERN microwave axion experiment

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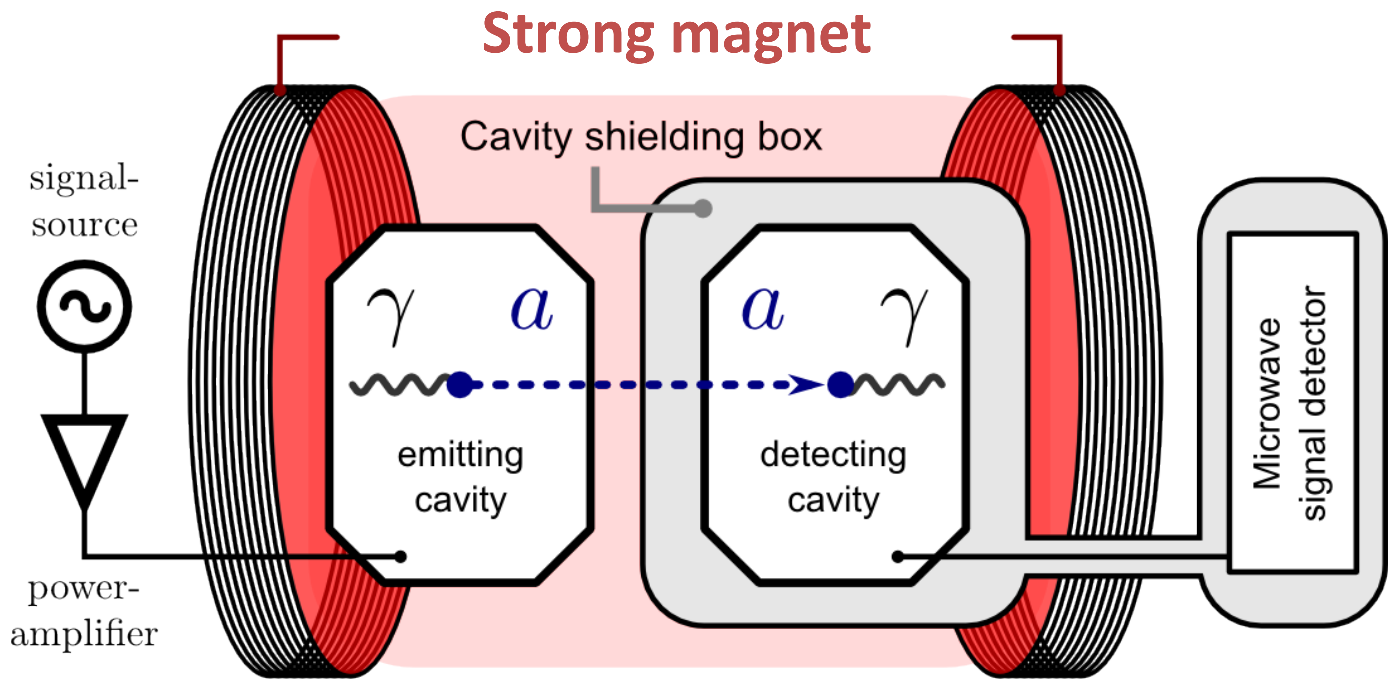
9th Patras Workshop on Axions, WIMPs and WISPs
Mainz (Germany), 2013

Outline

- Short introduction: Principle of the experiment
- Making it happen
  - Microwave cavities
  - RF shielding
  - Narrowband signal detection
  - Finding a suitable magnet
- Latest ALPs results
- Outlook / Future plans

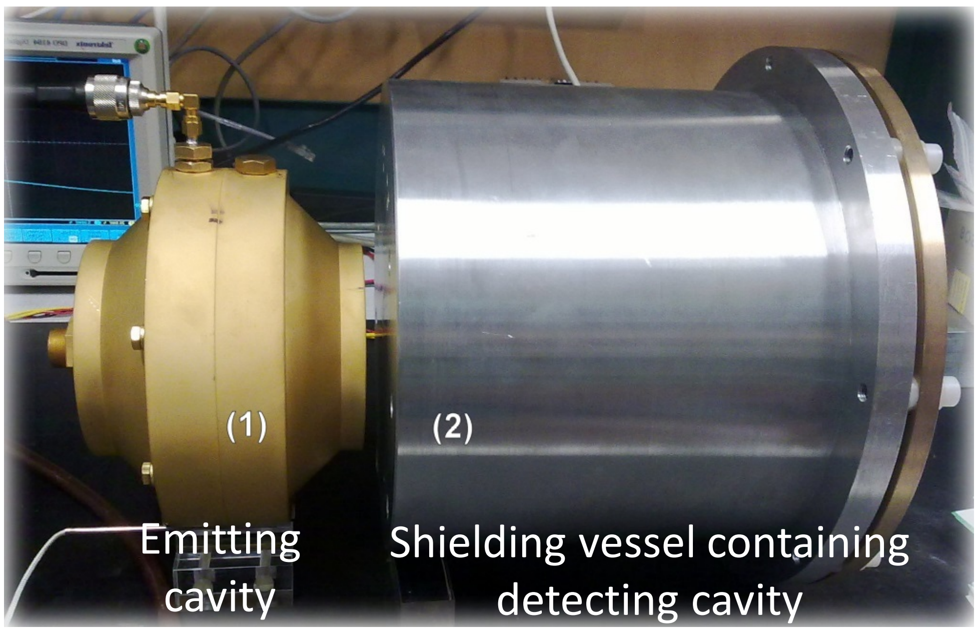
Principle

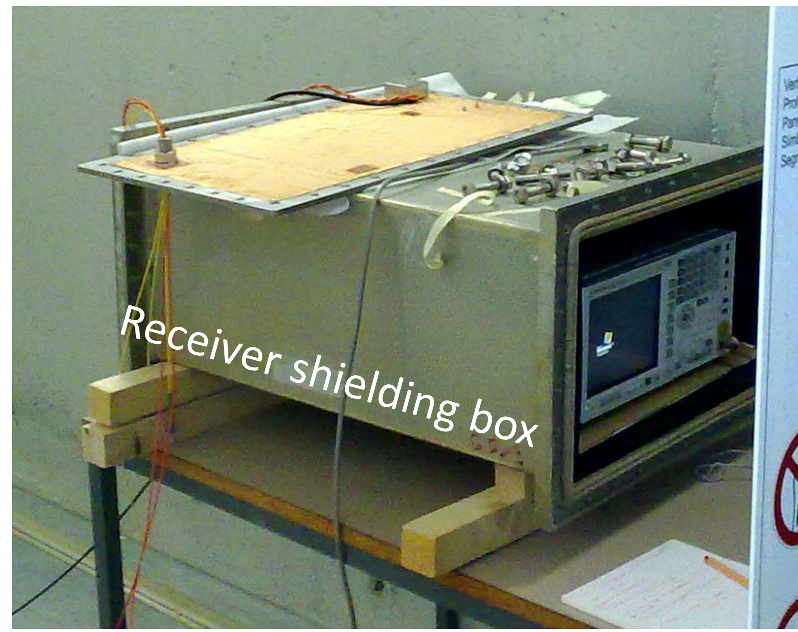


Critical points

- Electro-magnetic **shielding**
- **Detecting** faint micro-wave signals
- Keeping both cavities on **tune**
- Operating in a strong **magnetic** field

How it looks like in real life

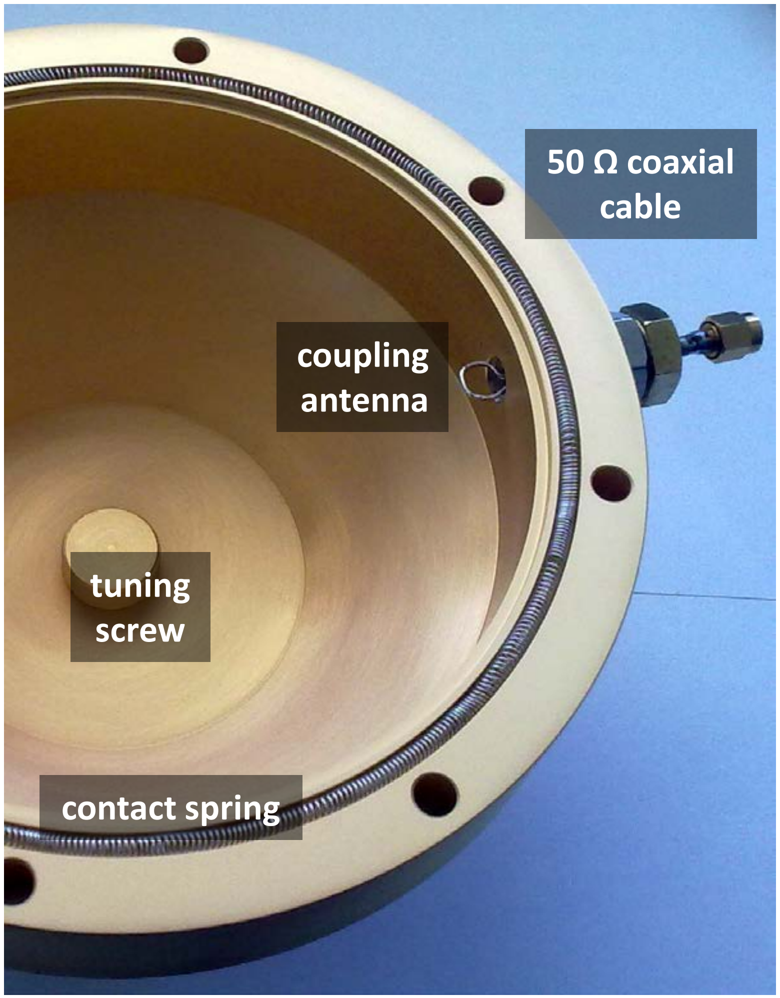




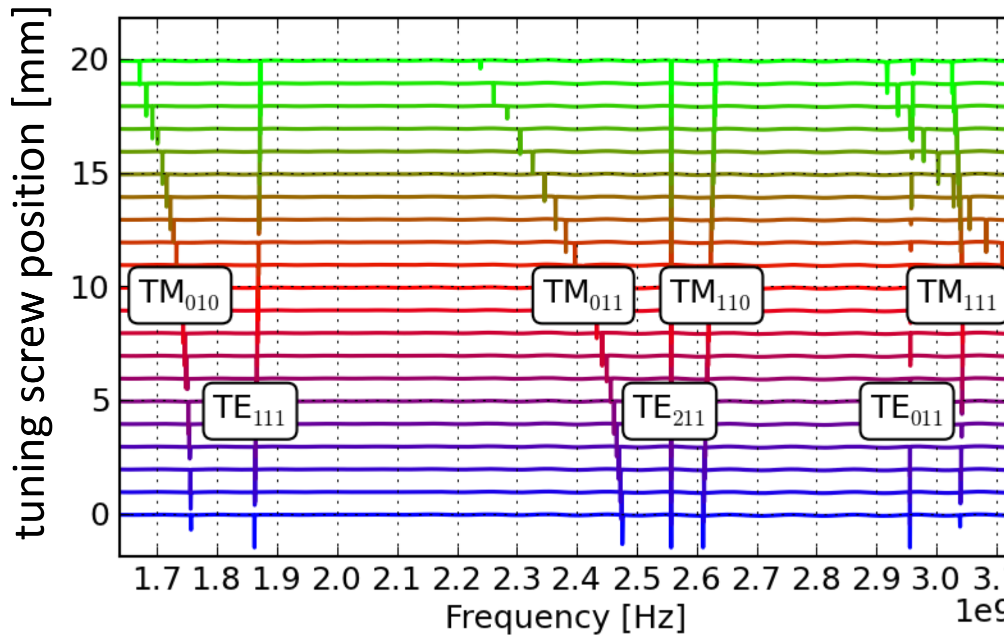
↔

Connected by optical fibres

The WISP conversion cavities



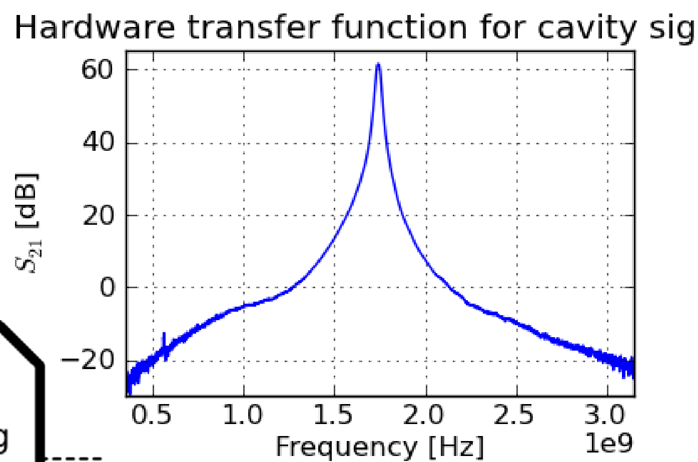
Measured mode chart



Mode	f_{res} [GHz]	meas. Q_L	|G| HSP[1]	|G| ALPs[1]
TM_{010}	1.75	12 000	0.77	0.76
TE_{011}	2.96	23 000	0.52	0.09

[1] *Result of numerical calculation, only the max value of |G(k'/k)| is shown. Cav. next to each other, 20 mm separation*

Components of the receiving chain

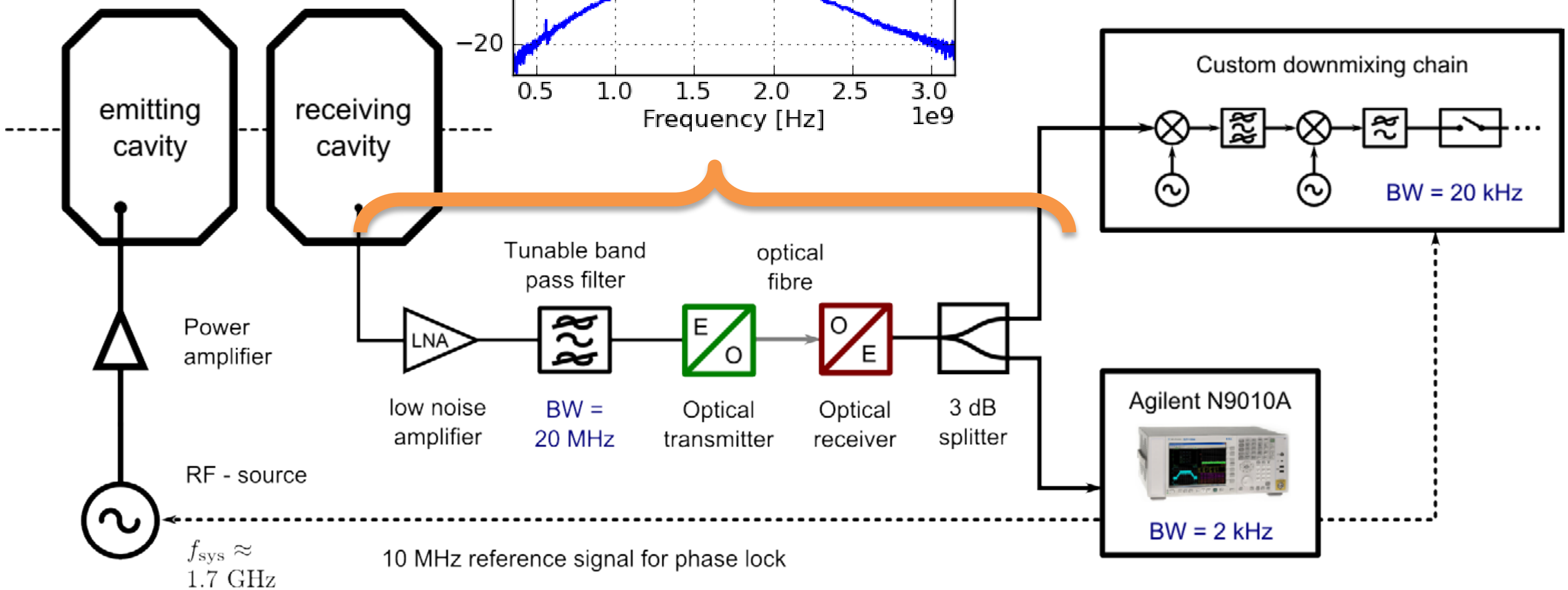


<u>HTF at 1.7 GHz:</u>

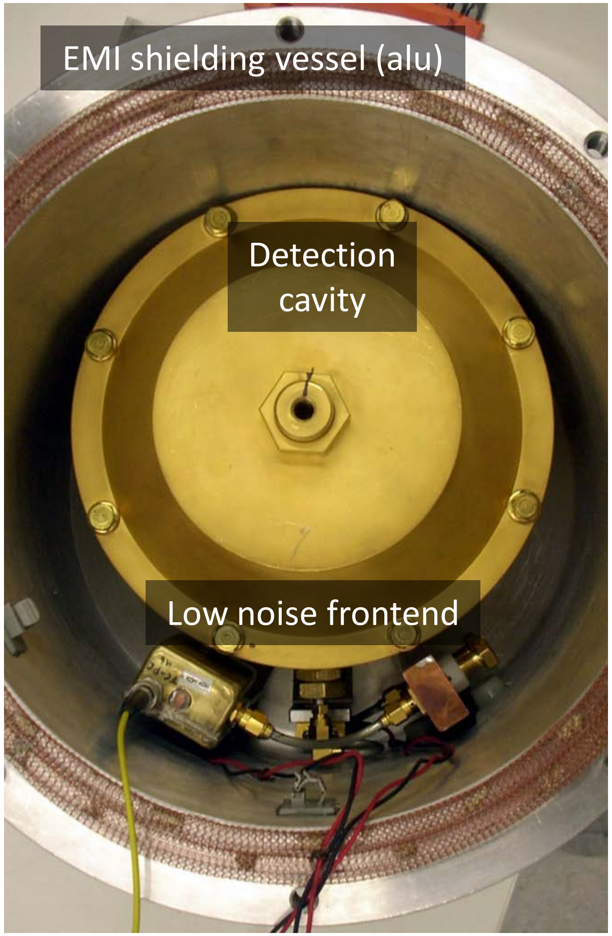
Gain = 60.4 dB +- 1 dB

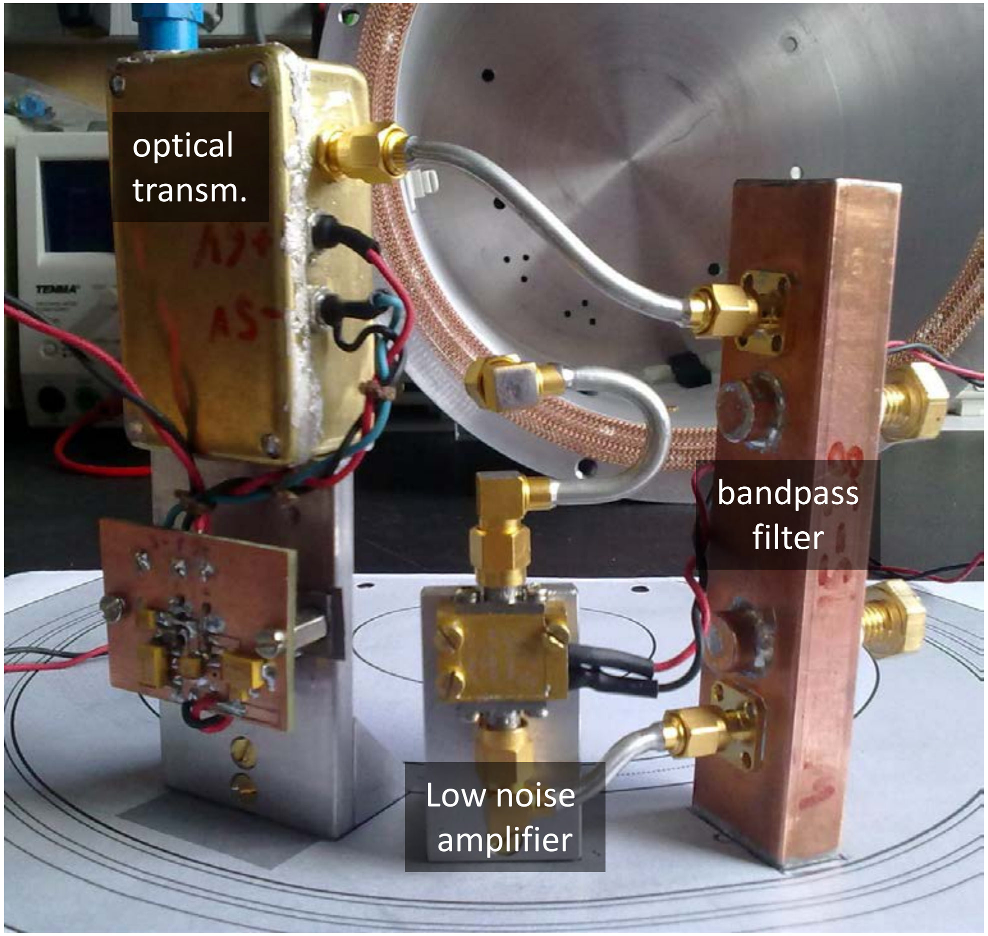
Noise Figure = 0.6 dB

Equ. noise temp. = 43 K



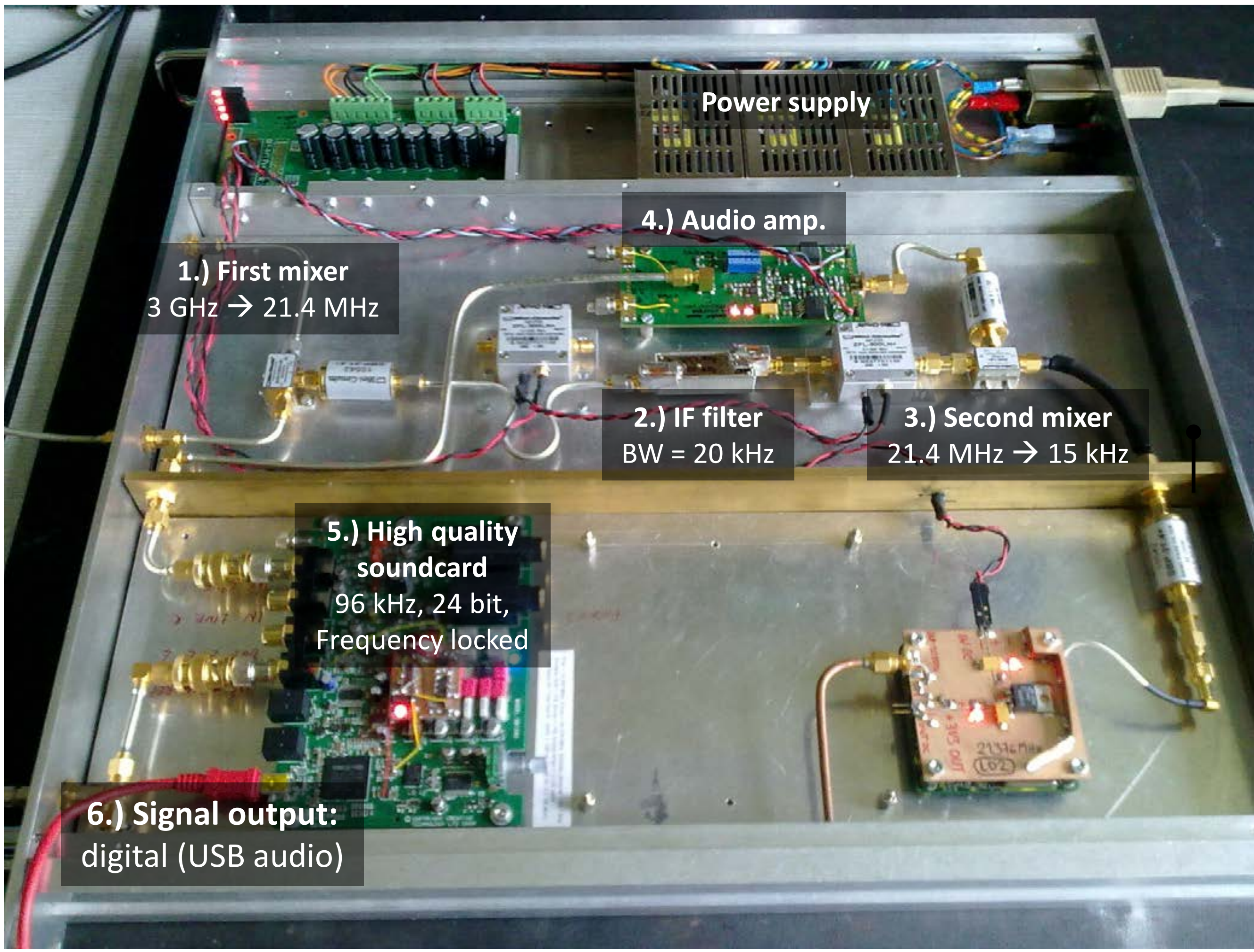
Low noise frontend

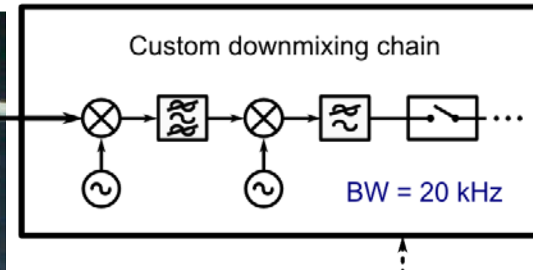




Needs to function **in the magnet** at 3 Tesla! Many design iterations were necessary!

Custom downmixing chain

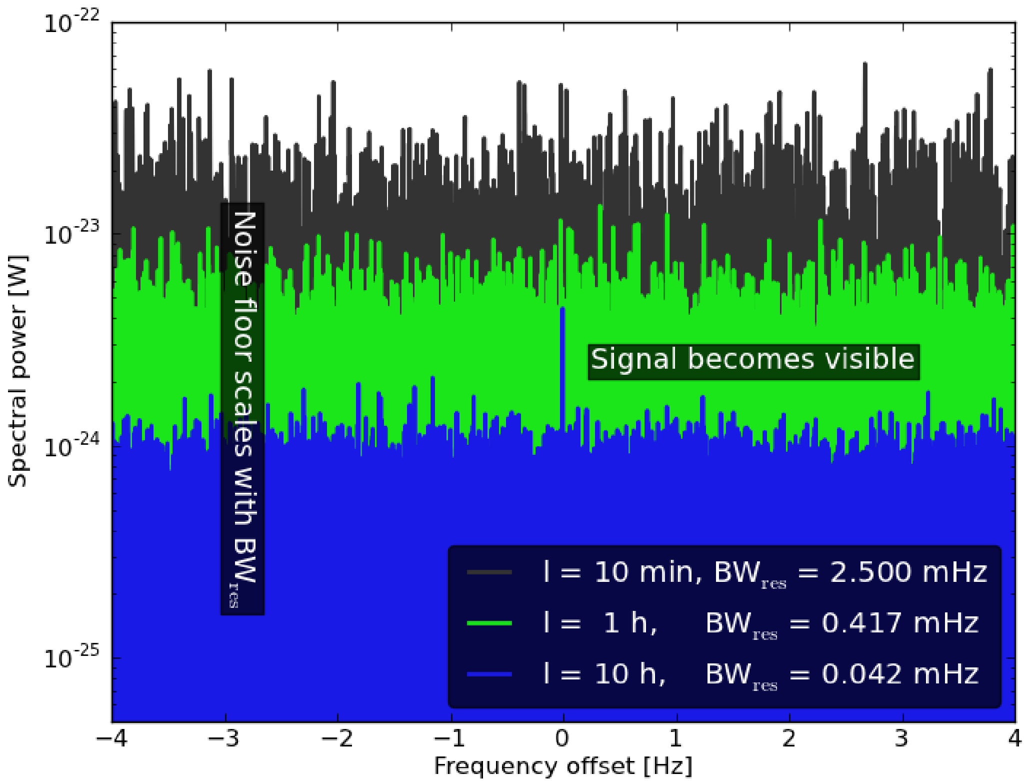




- 2 mixer stages
- Boundless recording time at 20 kHz BW
- Optimized for **low noise** and minimum **frequency drift**

Narrowband signal detection

- Calculate **power spectrum** by a Fast Fourier Transform (FFT)
- Spectral bins ≈ array of Bandpass filters
- longer time trace ≈ **narrower** filter ≈ **lower noise floor**
- We search for a **monochromatic** signal, it's power should always be concentrated within one bin



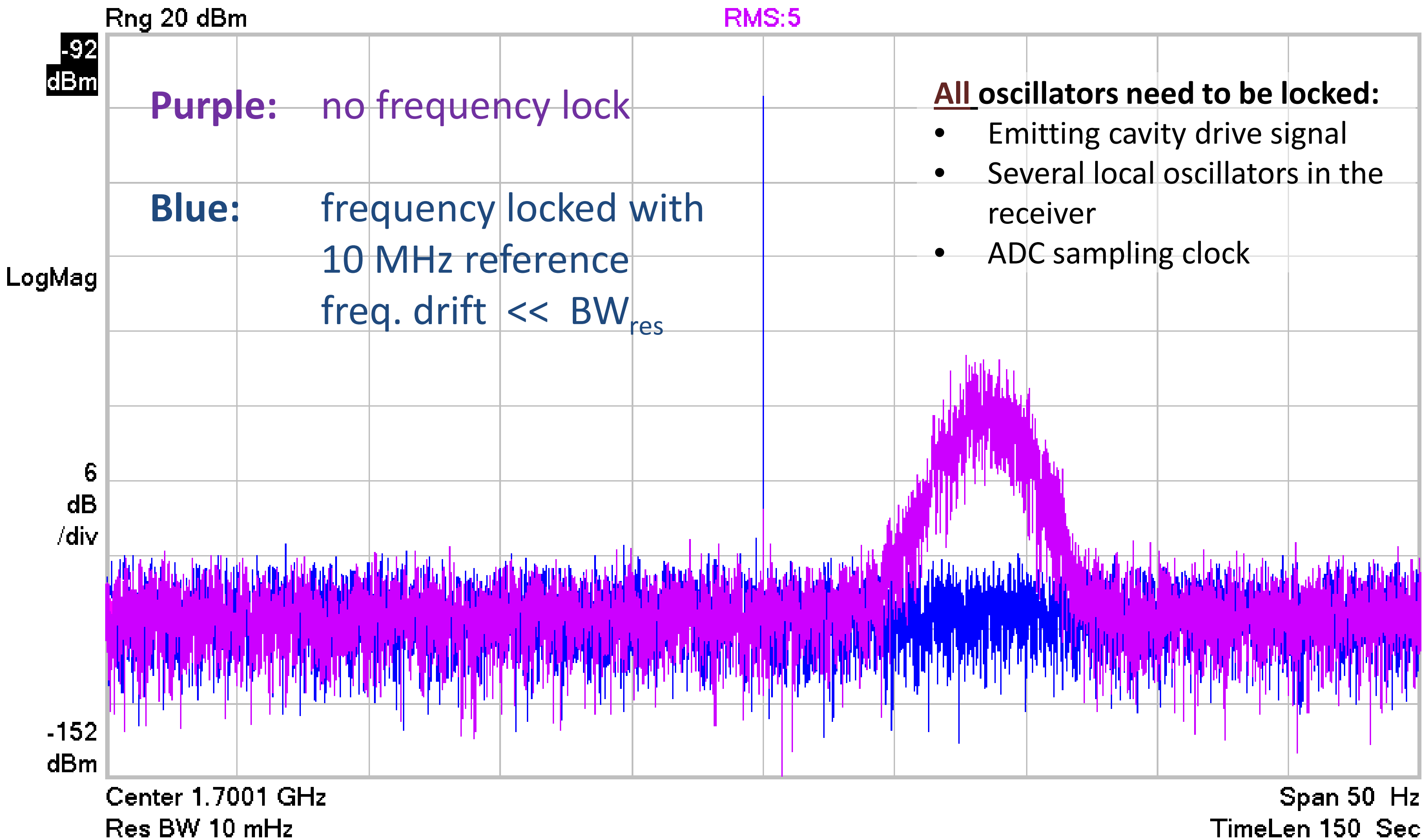
Linear increase of signal to noise ratio with measurement time

But:

Oscillators suffer from frequency drifts!

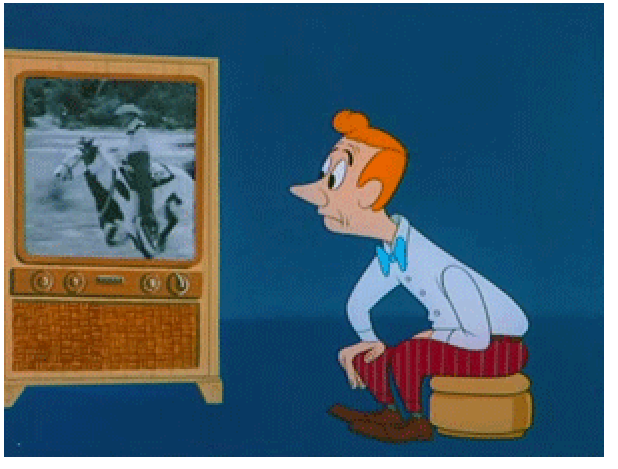
How to keep the ≈ 1.7 GHz signal within the ≈ 30 μHz „filter" bandwidth?

Effect of frequency lock



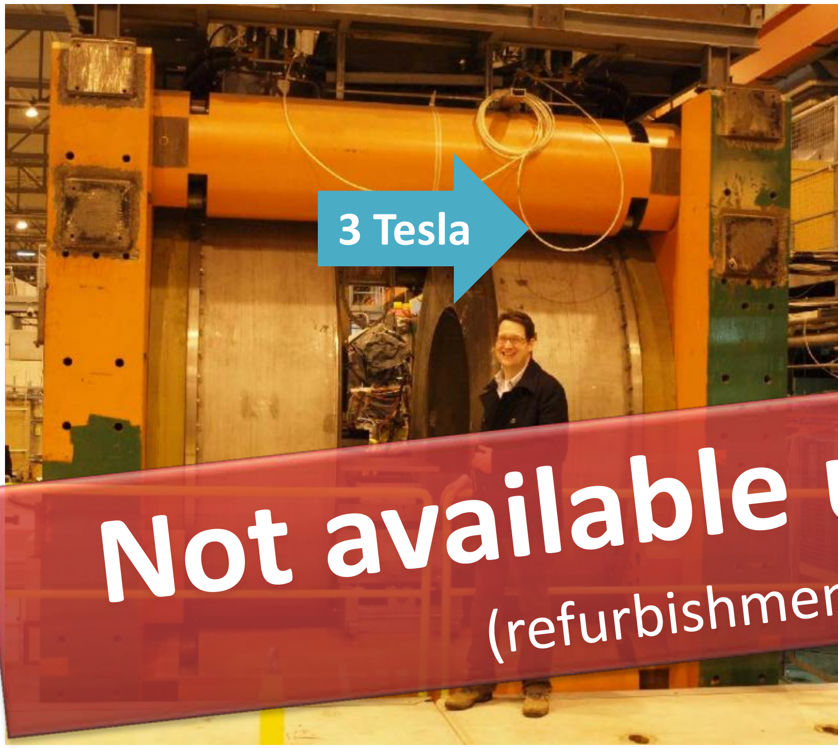
See also: *F. Caspers, S. Federmann and D. Seebacher, Demonstration of 10^{-22} W Signal Detection Methods in the Microwave Range, Internal RF technical Note CERN-BE-Note-2009-026.*

Effect of frequency lock



Next step:
searching for a magnet

M1 magnet at CERN

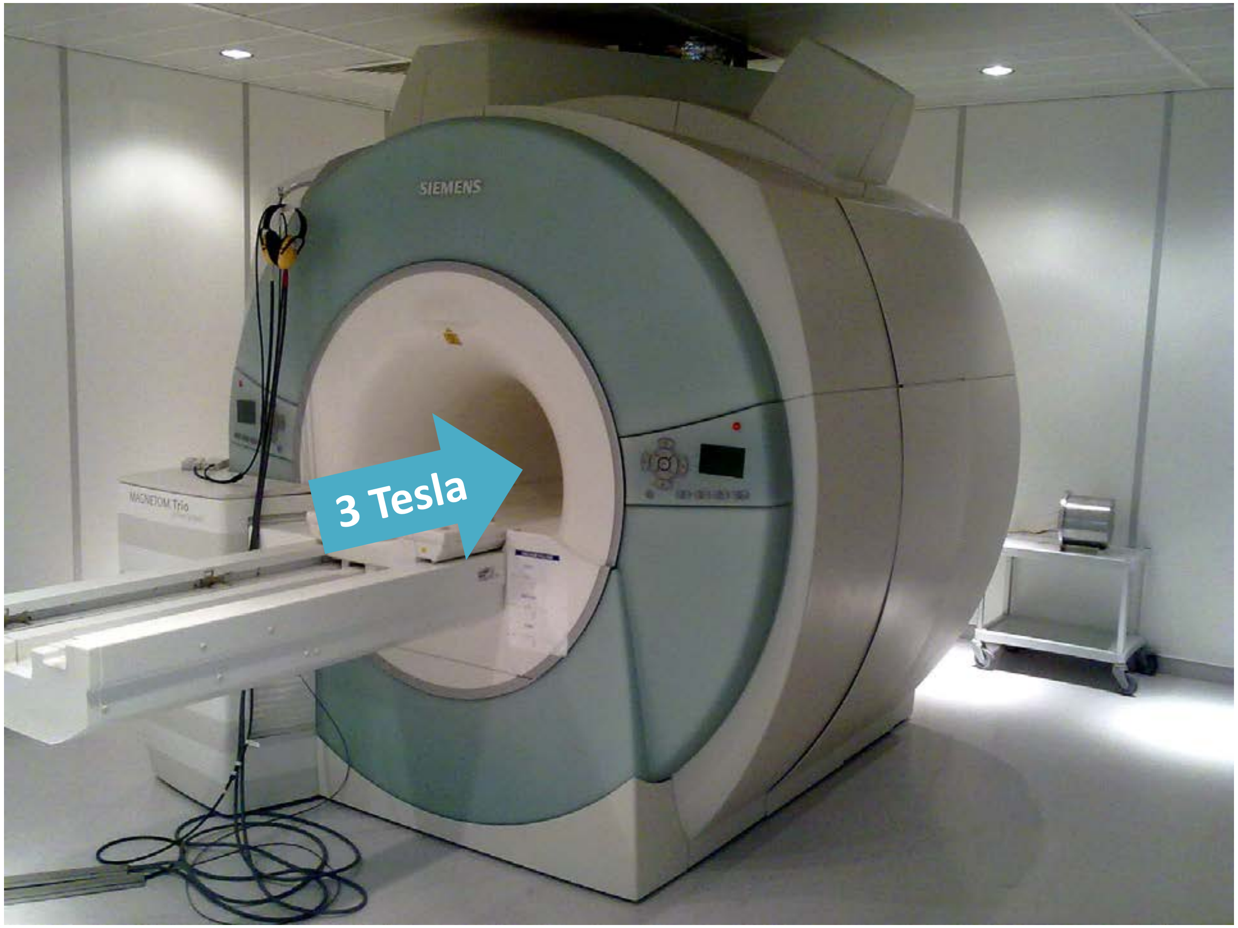


Not available until end of 2013
(refurbishment of control system)

Main user: CMS detector development

Photos by G. Prior http://indico.cern.ch/getFile.py/access?contribId=27&sessionId=3&resId=0&materialId=slides&confId=106198

MRI magnet at UNIVERSITÉ DE GENÈVE



University of Geneva, Brain & Behaviour Laboratory

Made accessible for us on weekends

many thanks to

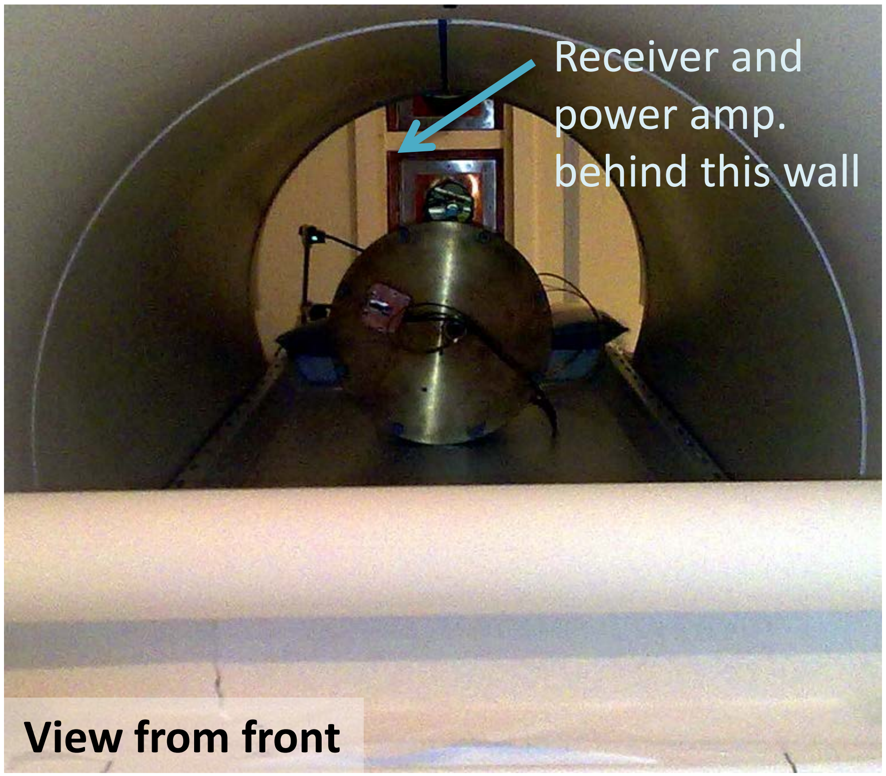
S. Rieger & **C. Burrage**

Next step:

Measurement run(s)

The complete setup,
ready for moving to Geneva

26.4.2013: Setup in the magnet



excellent infrastructure in the MRI lab

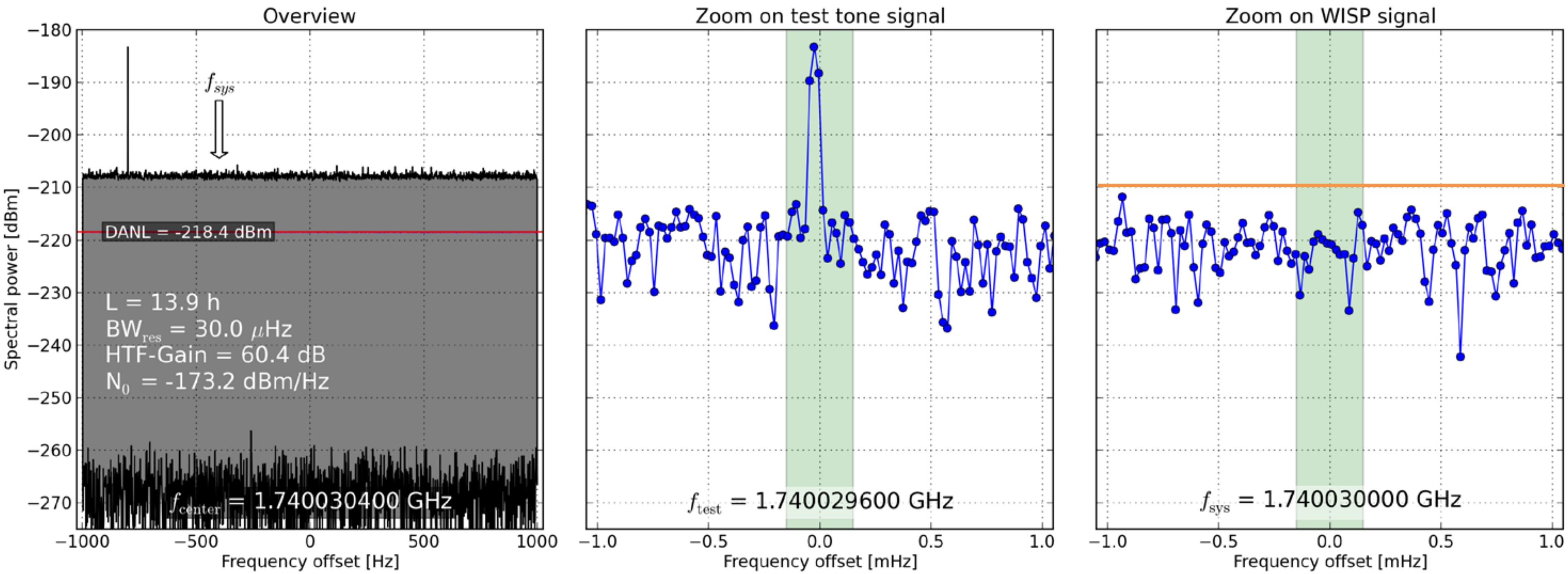
- Air **temperature** tightly **regulated** (20 °C)
- Natural **air flow** through the magnet
- Enough free space in nearby **equipment room**
- The walls having big **feed-through** ports

Besides searching for ALPs, we did some experimental verification of Murphys law

10.1.2013	Initial visit to 3 T magnet. Welding seams on Stainless steel shielding vessel turned out to be **too magnetic,** safety hazard, **Redesign!**
23.3.2013	Test and characterization of RF frontend in the 3 T field →Permanent **damage** to the commercial **optical transmitter**, **Redesign!**
26.4.2013	First measurement run over **16 h**. →Windows crashed and discarded all data (harddisk was full)
27.4.2013	Second measurement run over **14 h**. **Success!**
16.6.2013	Third measurement run over **24 h**. **Success!**

What can go wrong, will go wrong!

The result spectra from 27.4.2013



- Test tone signal is visible as narrow line → Receiving chain and frequency locking was operational
- **No ALP candidate visible**

detection threshold

-210 dBm = **10^{-24} W**

≈ 1 photon / s

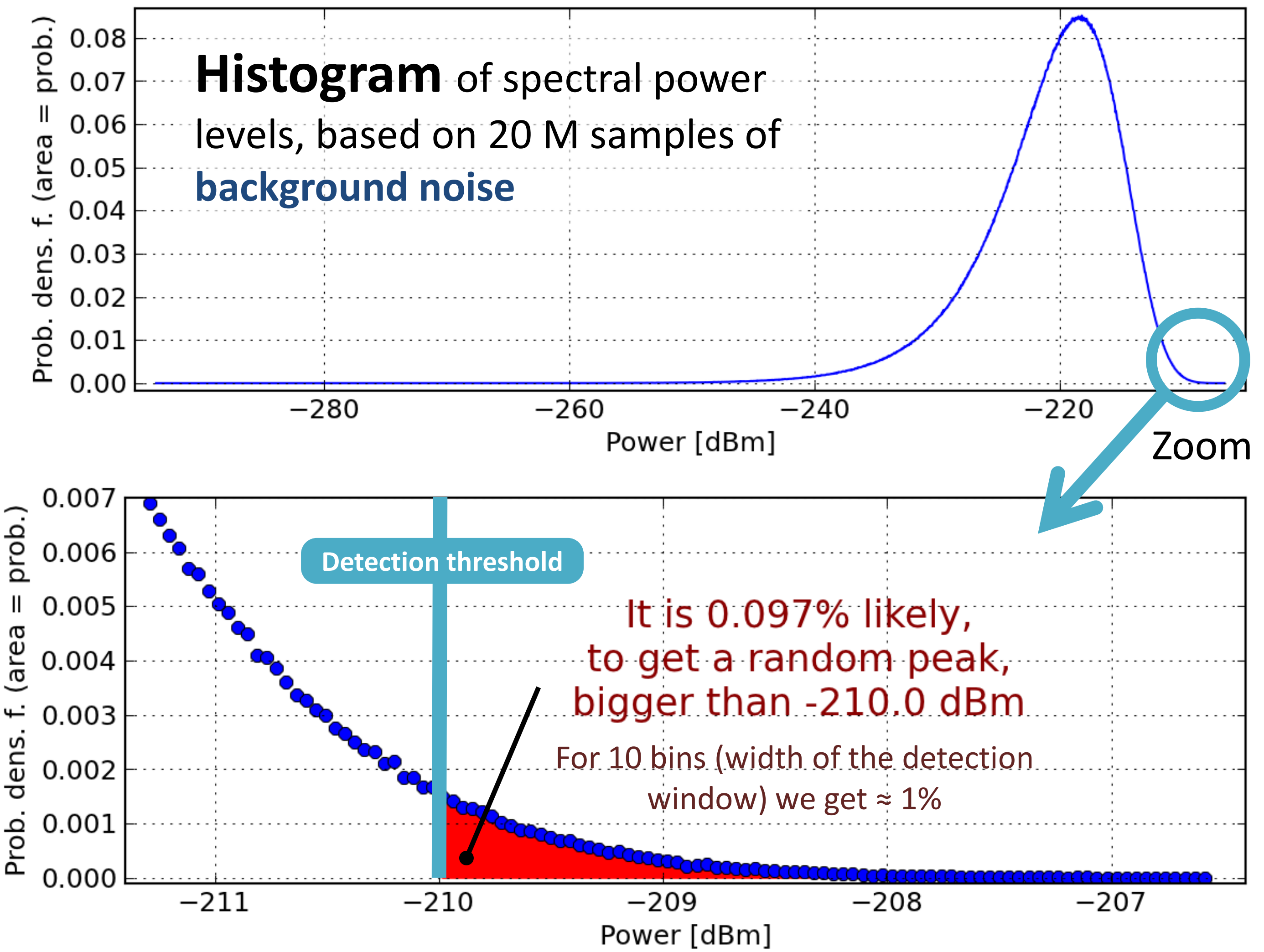
Defining the detection threshold

Largest peak within frequency window of interest:
-215 dBm

Detection threshold:
-210 dBm

→ **No ALPs detected**

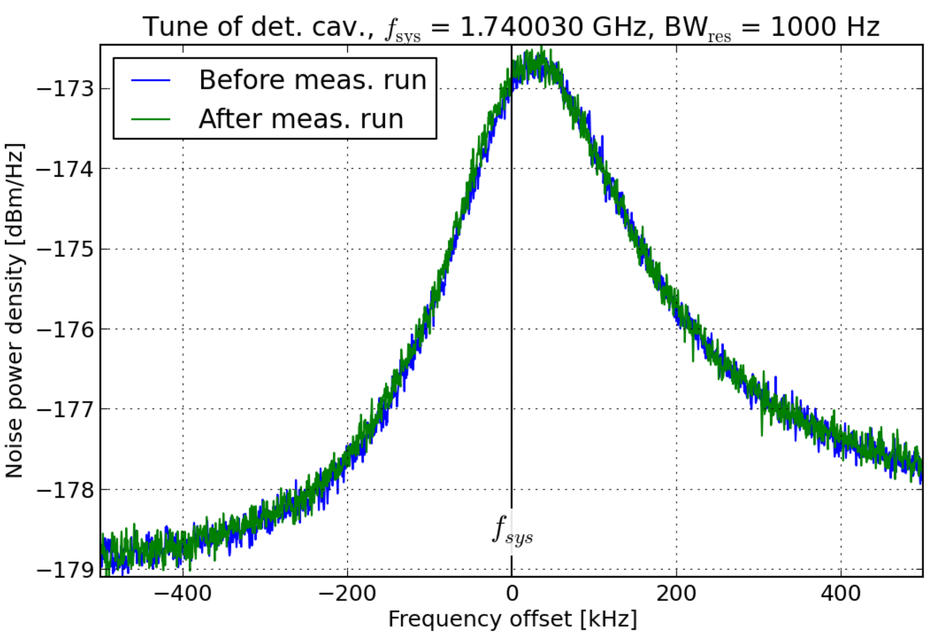
With this threshold, probability of a **false positive** is around **1 %**



Monitoring the cavities frequency drift

The ALP signal will only be visible if both cavities are tuned to f_{sys} +- 100 kHz

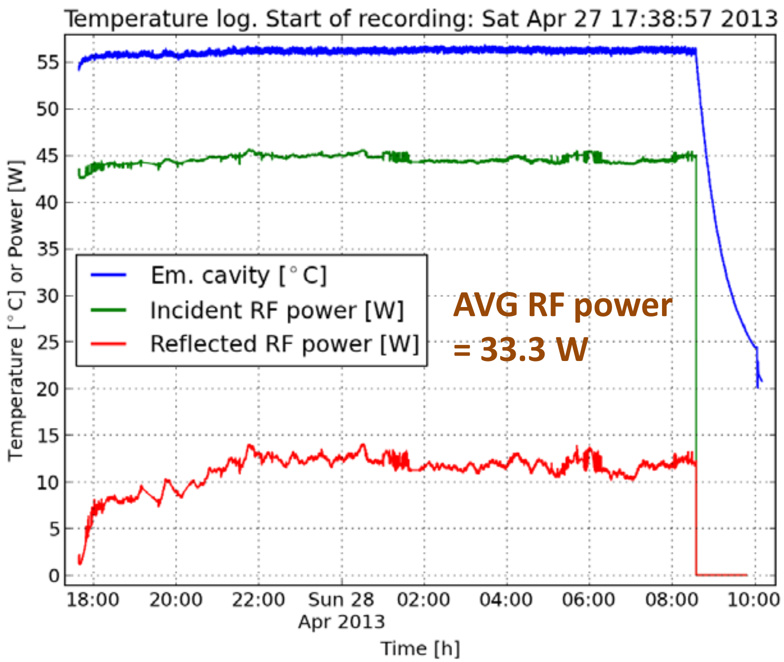
Detecting cavity



Thermal noise density is max. at the resonant frequency f_{res}

We checked f_{res} **before** and **after** the measurement run

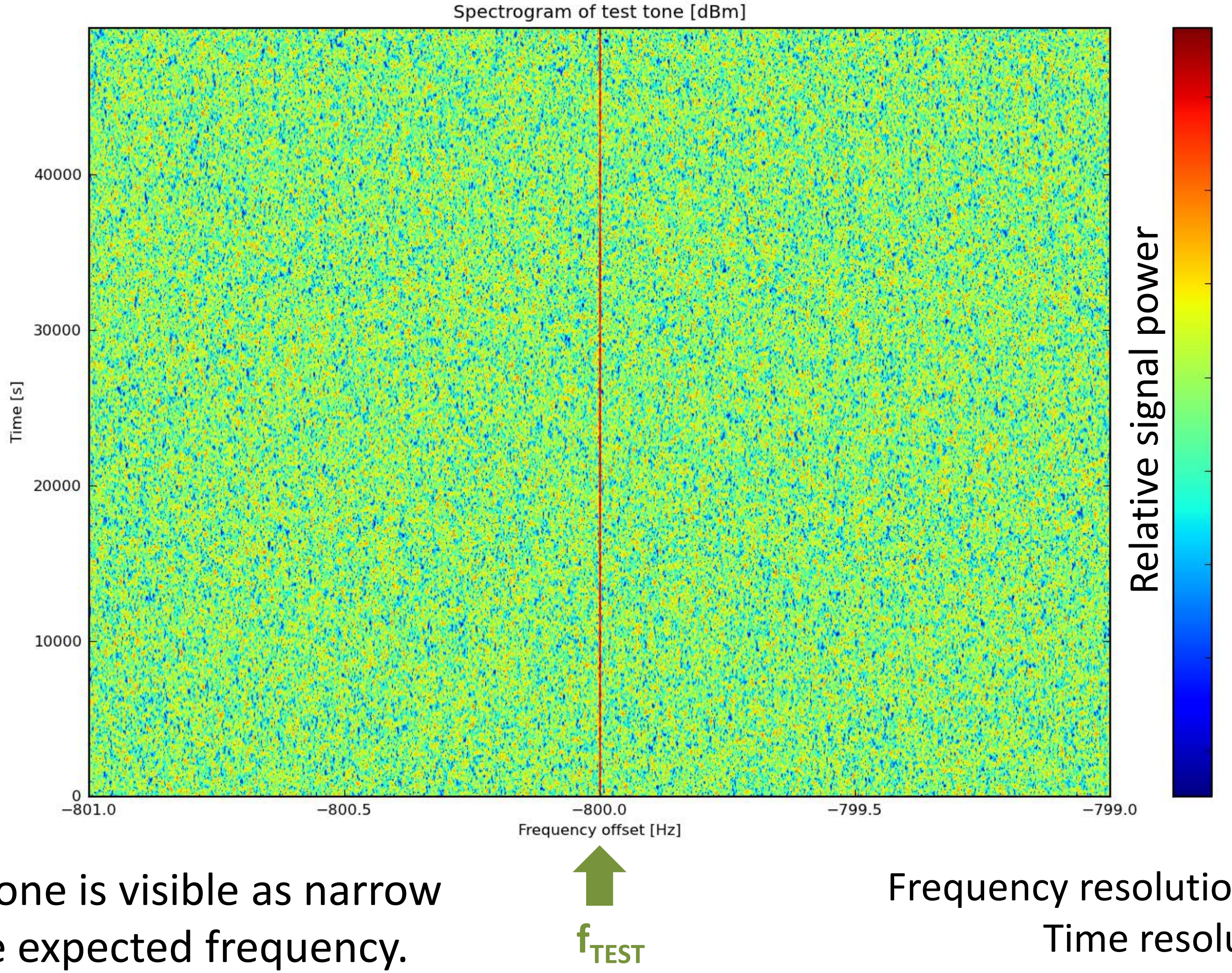
Emitting cavity



We monitor the **operating temp**. and **reflected RF power**. Both parameters indicate continuously how well the cavity is tuned to f_{sys}

Spectrogram

For identifying unknown time dependent or spurious signals

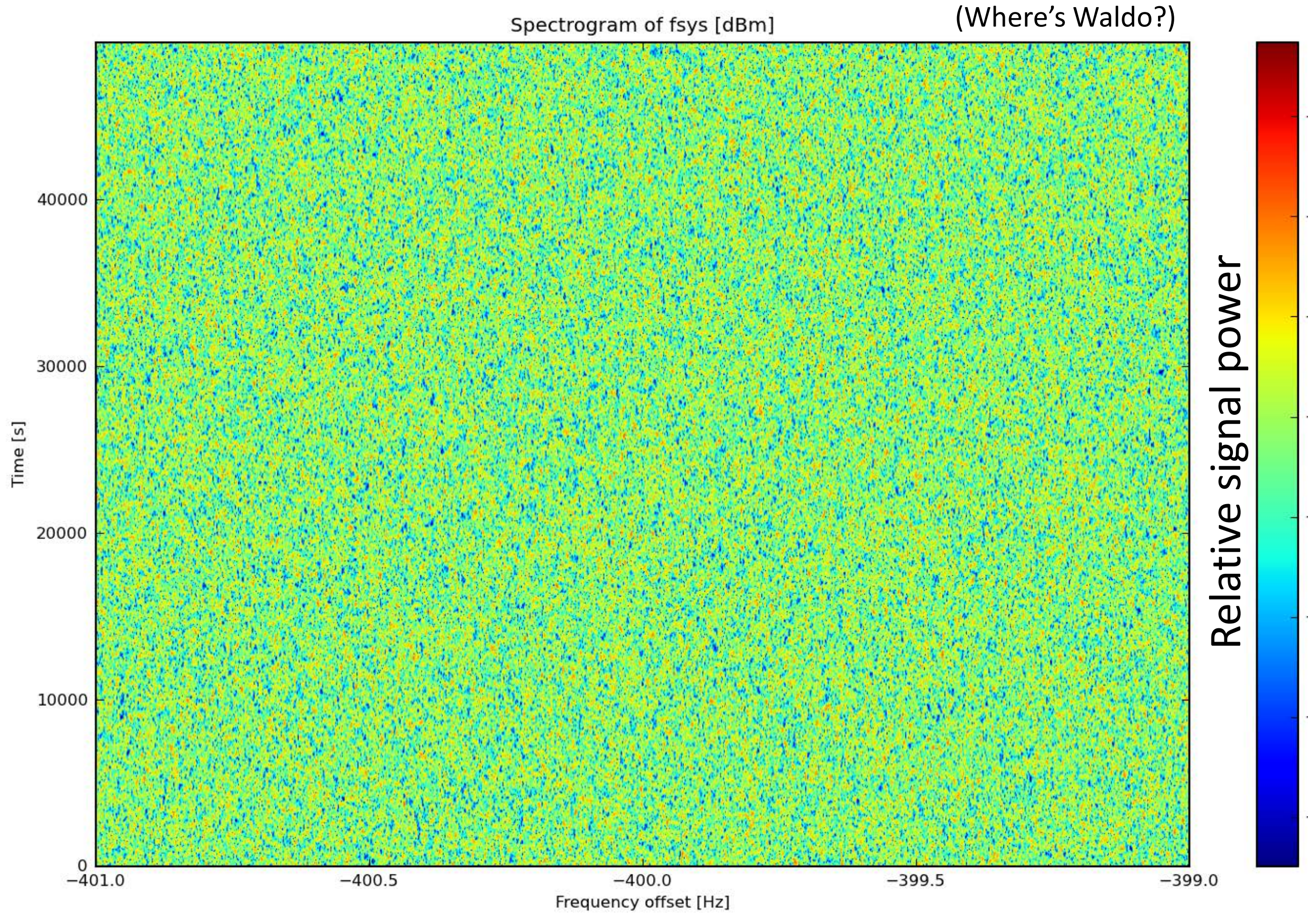


The test tone is visible as narrow line at the expected frequency.

Frequency resolution ≈ 1.5 mHz,
Time resolution ≈ 100 s

Spectrogram

For identifying unknown time dependent or spurious signals



Besides random noise, no "suspicious" patterns are visible

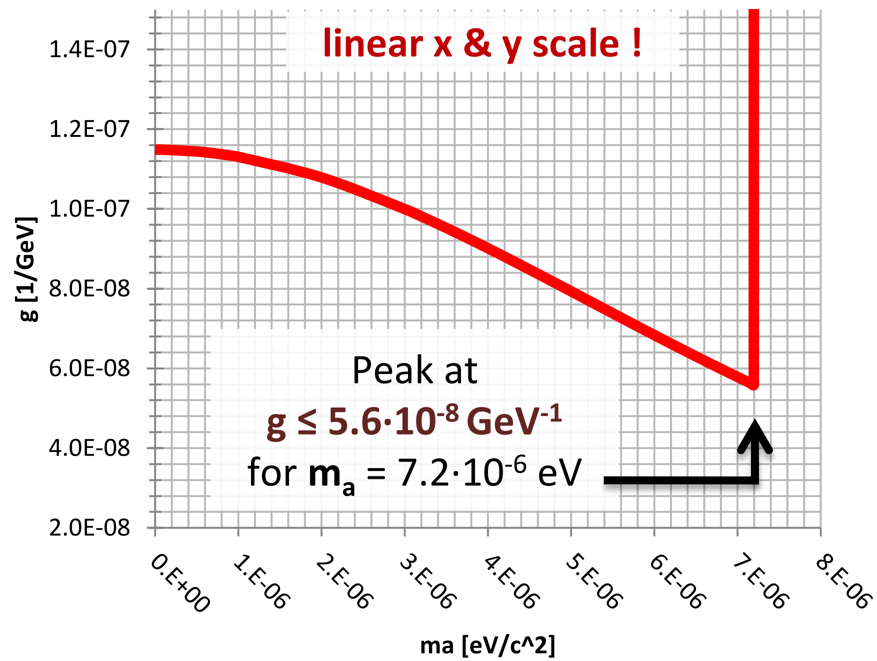
f_{sys}

Frequency resolution ≈ 1.5 mHz,
Time resolution ≈ 100 s

ALPs exclusion limit

Measurement run of 27.4.2013 in 3 T magnet

P_{em}	33.3	W	Power into emitting cavity
P_{det}	10^{-24}	W	Minimum detectable signal power
Q_{em}	8164		Loaded quality factor of emitting cavity
Q_{det}	9636		Loaded quality factor of detecting cavity
$\|G\|$	0.22 … 0.94		Geometry factor
ω_0	1.74	GHz	RF signal frequency
B	3.0	T	Magnetic field strength



$$g = \sqrt[4]{\frac{P_{\mathrm{det}}}{P_{\mathrm{em}} Q_{\mathrm{det}} Q_{\mathrm{em}} \left|G\right|^2}} \cdot \frac{\omega_0}{B}$$

Exclusion limit over wide m_a range:

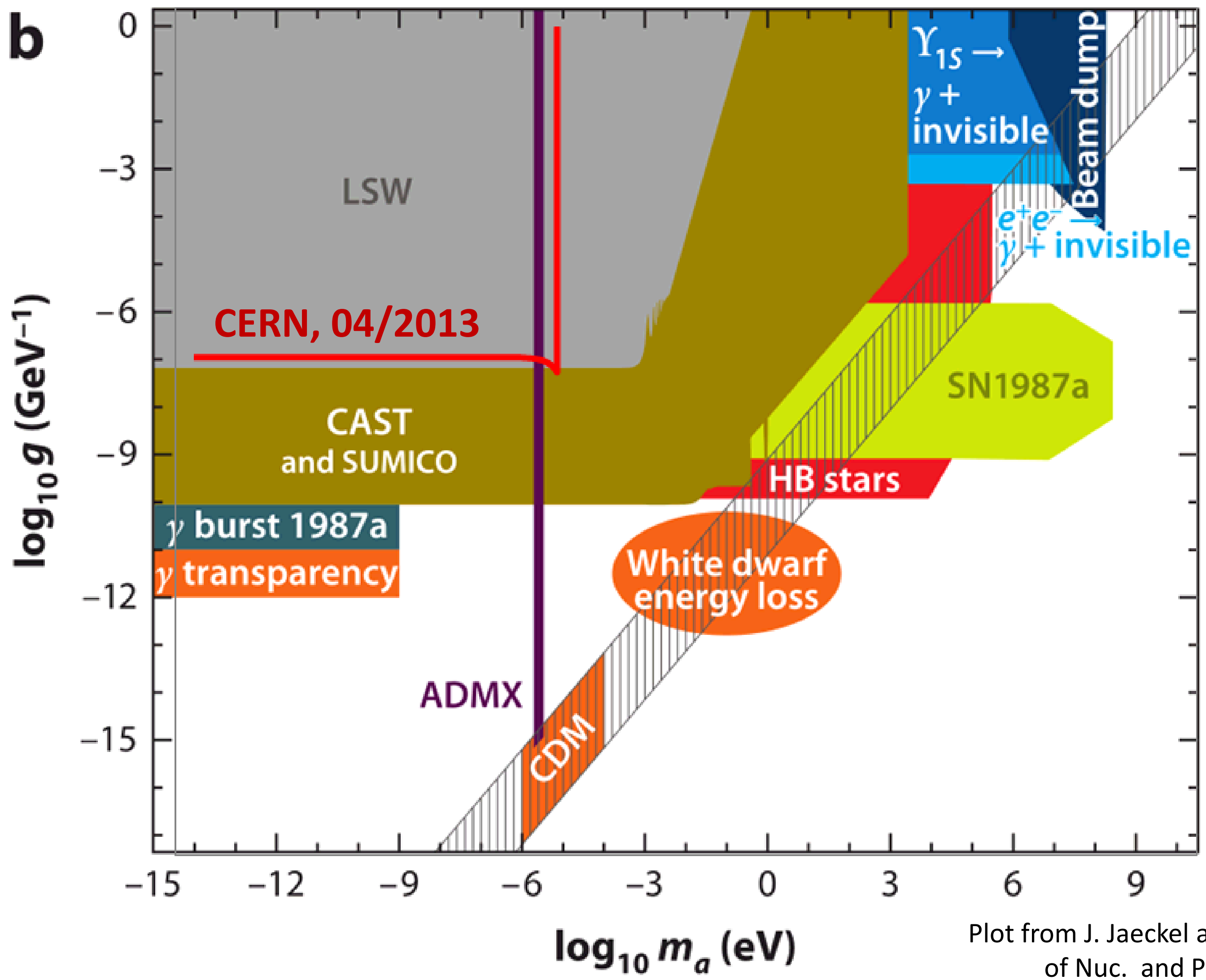
$g \leq 1.1 \cdot 10^{-7}$ GeV^{-1}

for: $1 \cdot 10^{-15}$ eV $\leq \mathbf{m_a} \leq 7.2 \cdot 10^{-6}$ eV

F. Hoogeveen, "Terrestrial axion production and detection using RF cavities", Physics B288 1992 (195–200)
J. Jaeckel, A. Ringwald, "A Cavity Experiment to Search for Hidden Sector Photons", Physics B659 2008 (509-514)

ALPs exclusion limit

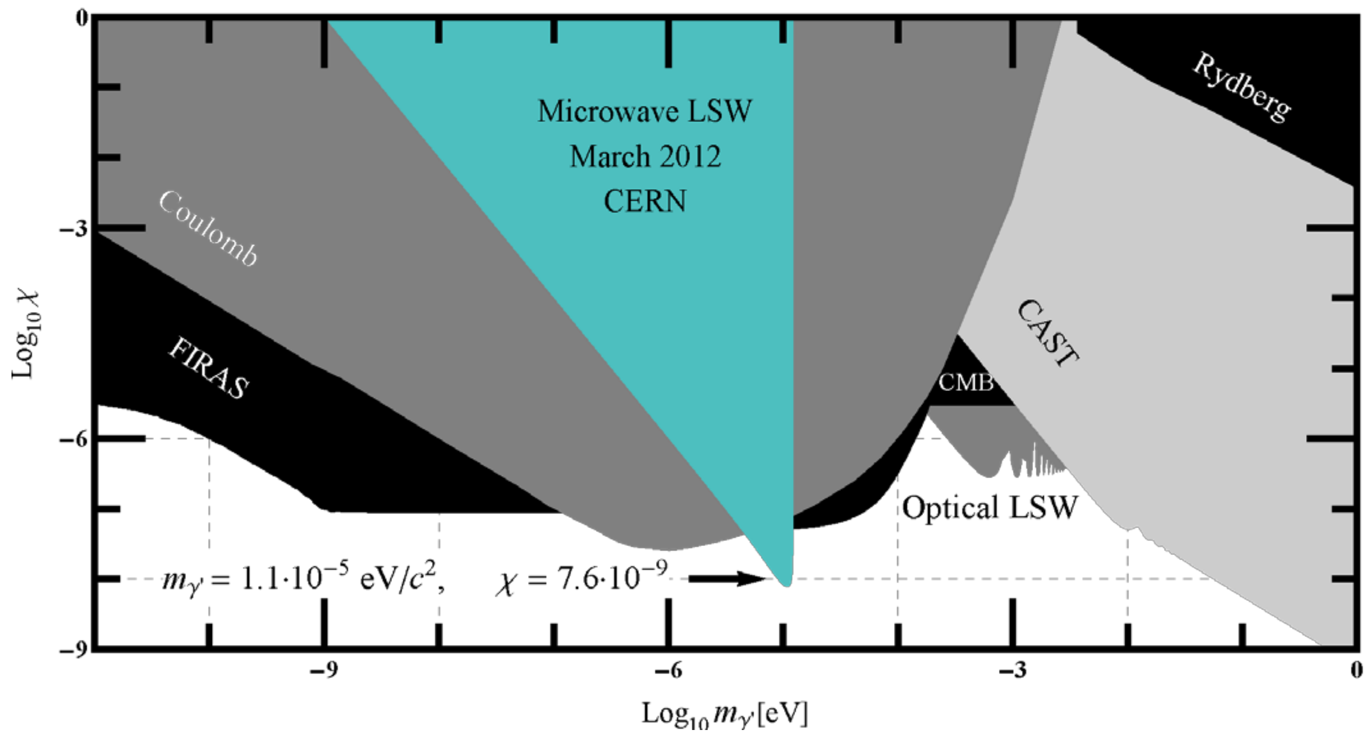
Measurement run of 27.4.2013 in 3 T magnet



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

The old HSP exclusion limits

From a 12 h run in March 2012



→ still significant potential for improvement with minimum effort

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

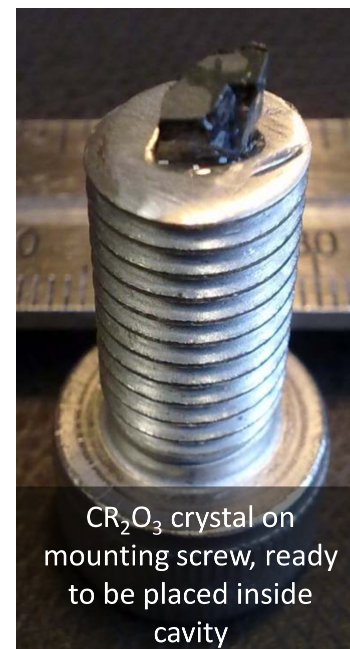
Outlook: short term

- **Another weekend run (already done at 16.6.13)**
  What we managed to improve
  - Longer measurement run (24 h instead of 14 h)
  - Larger recording BW (20 kHz instead of 2 kHz)
  - higher Q (12200 instead of 8100)
  - more RF power (45 W instead of 33 W)
  - We placed Cr_2O_3 crystals in the cavities

    "One may speculate whether an axion detector made of Cr_2O_3 crystals could enhance the probability of finding axions." **[1]**

We could reach $g = 8 \cdot 10^{-8}$ GeV^{-1} Over a wide mass range

- **Data evaluation:** **pending …**
- **Publication of results:** **pending …**
- **PhD thesis:** **pending …** ☺



CR_2O_3 crystal on mounting screw, ready to be placed inside cavity

*[1] **F. Hehl et al.**, "Relativistic nature of a magneto-electric modulus of Cr2O3 crystals: A four-dimensional pseudoscalar and its measurement", PHYSICAL REVIEW A **77**, 022106 2008*

Outlook: long term

Nothing is decided yet, just some ideas

- **"Low frequency" LSW** at 200 MHz   ($m_a \leq 8\cdot10^{-7}$ eV)
  Available **ingredients** at CERN:
  - CMS - M1 magnet, 3 Tesla, 1400 mm bore diameter
  - SPS standing wave cavities, 200 MHz
  - Matching tetrode tube amplifier, 50 kW

  The catch: Will not be able to probe unexplored ALP regions

- Dark matter **Haloscope** with a **long thin cavity [1]**
  - HERA dipole magnet, readily available in a test stand at DESY
  - 5 Tesla, cold bore at 5 K

  The catch: Tuning is difficult, only sensitive to a very narrow ALPs mass range O(MHz)

[1] O. K. Baker et al., Prospects for searching axion like particle dark matter with dipole, toroidal, and wiggler magnets, PHYSICAL REVIEW D 85, 035018 (2012)

Acknowledgements

- Thanks to S. Rieger and the Brain & Behaviour Laboratory at the University of Geneva for making the ALPs measurement in the MRI magnet possible

- Thanks to C. Burrage for getting us connected

- Many thanks for a large number of hints and inspiring discussions to K. Baker, A. Malagon, K. Zioutas, J. Troschka, A. Collar, P. Blanc and J. Jaeckel

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

Thank you!

Outlook: SPS cavity in CMS-M1 magnet

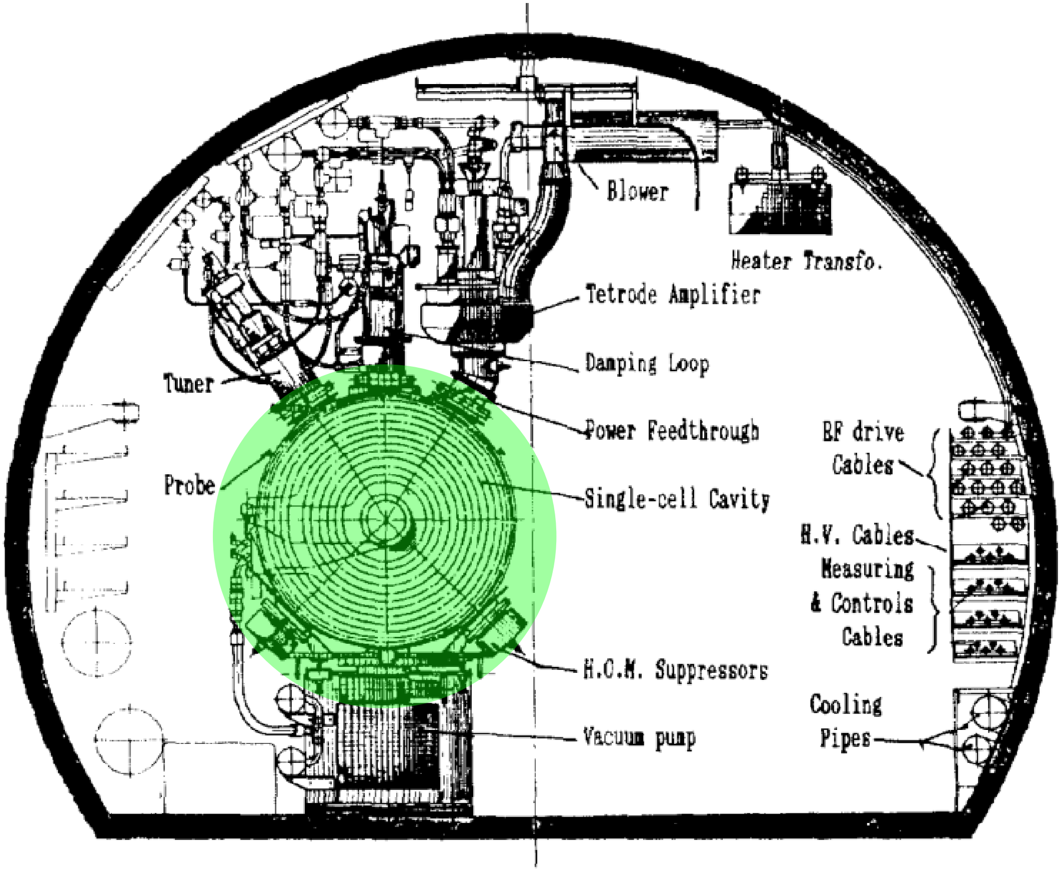


Fig. 1: Cross-section of the SPS tunnel with a new acceleration module

The new RF system for lepton acceleration in the CERN SPS
P.E. Faugeras et al., PAC 1987

Green = diameter of the M1 magnet bore

Cavity length = 0.7 m

Magnet length (2 T limit) = 2 m

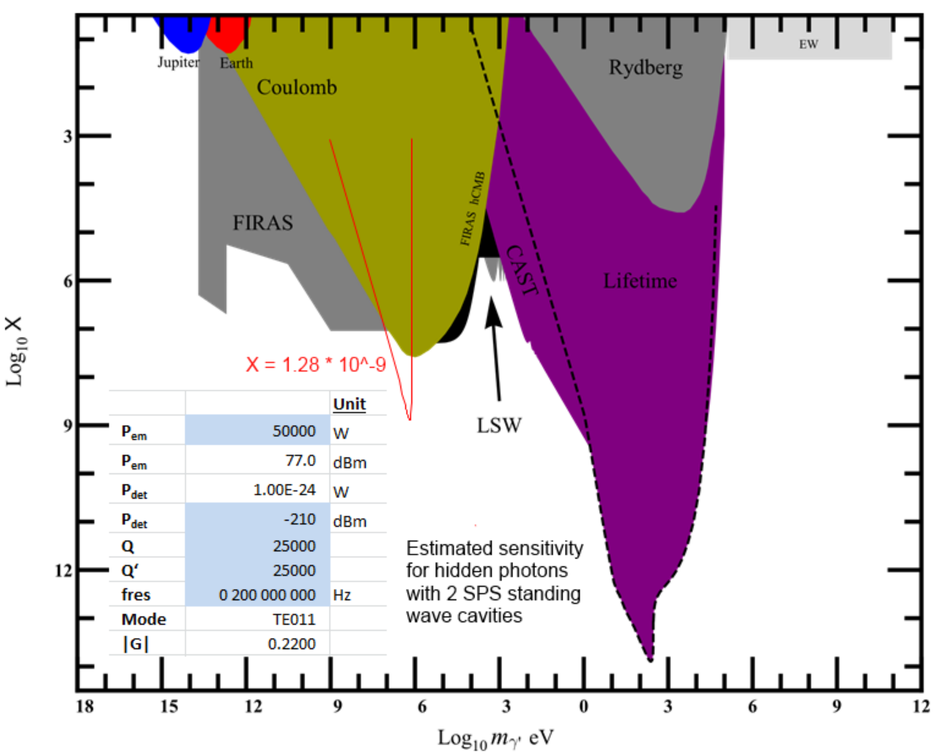
Cavity itself would just fit inside the bore

Magnet bore accessible from top and bottom
→RF power cables

Outlook: **SPS cavity in CMS-M1 magnet**

***Estimated** sensitivity for a **LSW** setup*

Hidden photons



Axion like particles