Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Detector/Receiver
“Cold” Measurements

MadMax-Workshop
MPP Munich

O. Reimann for the MADMAX-Group

May 10, 2017

Outline

- Microwave radiometer (short reminder)
  - Comparison between photon- and heterodyne detection
- Current lab system
  - Schematic
  - First cold tests
- Conclusion

Photon Detection Setups

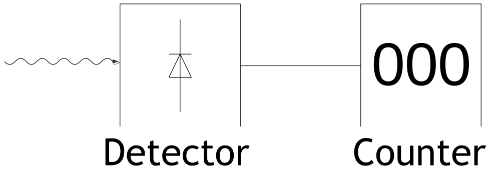
- Two principle ways:
  - Photon counting
  - Measurement of mean photon flux

- Photon counting
  - Limited by photon energy
    (Needs „high energy“ photons)
  - Energy (frequency) resolution is limited

- Photon flux measurement
  - Not limited by low energy photons
  - Excellent frequency (energy) resolution
    (easily it can be better than 10^{-9}),
    because of usually used “coherent” detection
    (normally heterodyne detection)

Photon Detection Setups

- Photon counting:



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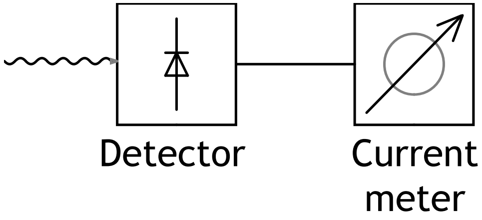
Detector

Counter

- Photon flux measurement:

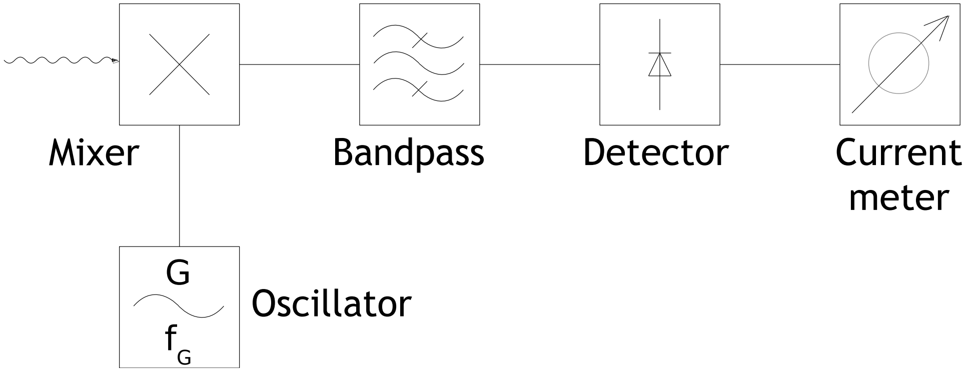
direct



Detector

Current meter

heterodyne ("coherent")



Mixer

Bandpass

Detector

Current meter

G

f_G

Oscillator

Choosing the Right Bandwidth

- What is the detectable noise temperature for a given system noise temperature (Dicke-formula):

$$\Delta T = T_{Sys}\sqrt{\frac{1}{\Delta f_F\,\tau} + \left(\frac{\Delta G}{G}\right)^2}$$

Δf_F: Filter bandwidth
τ: Averaging time
T_{Sys}: Total system noise temp.

- Detectable noise power (assuming no gain fluctuation)

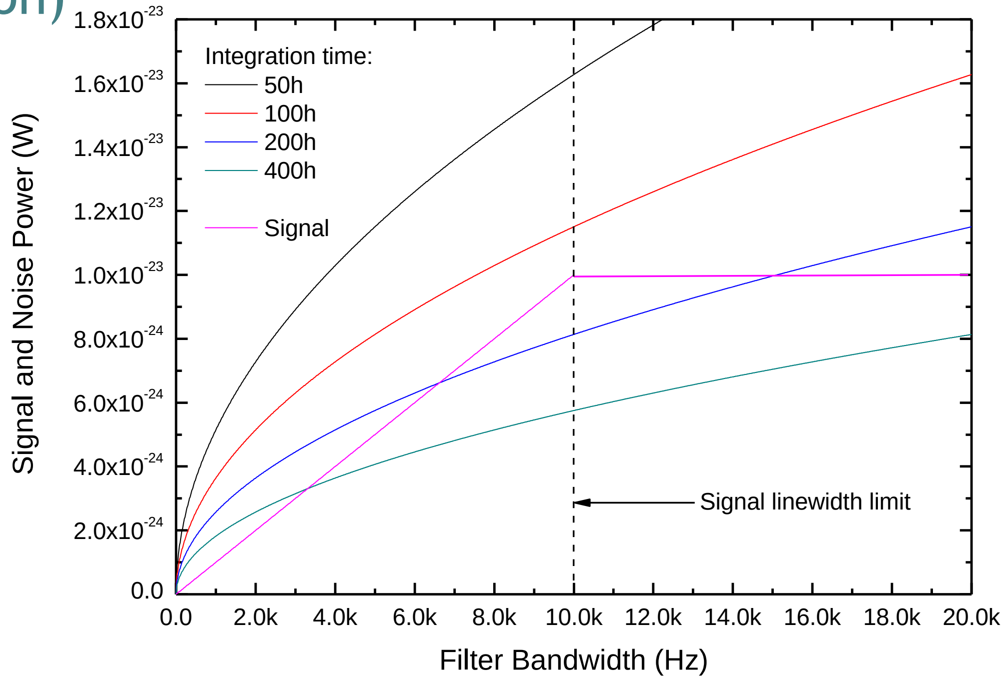
$$P_N = k_B T_{Sys}\sqrt{\frac{\Delta f_F}{\tau}}$$ with $P_N = k_B \Delta T \Delta f_F$ and $\Delta G = 0$

- Averaging time for a given signal/noise ratio:

$$\tau = \left(s\,\frac{k_B\,T_{Sys}}{P_S}\right)^2 \Delta f_F$$ with $s = P_S/P_N$

Choosing the Right Bandwidth

- What is the best bandwidth for line detection
    - Detectable background noise power increases with frequency (Square root) $k_B T_{Sys}\sqrt{\frac{\Delta f_F}{\tau}}$
    - Signal noise increases with frequency (Linear, if rect. distribution) $k_B \Delta T \Delta f_F$
    - → Bandwidth should not be larger than line-width for best signal-noise ratio



<u>Example</u>

Receiver: T_{Sys}=5K

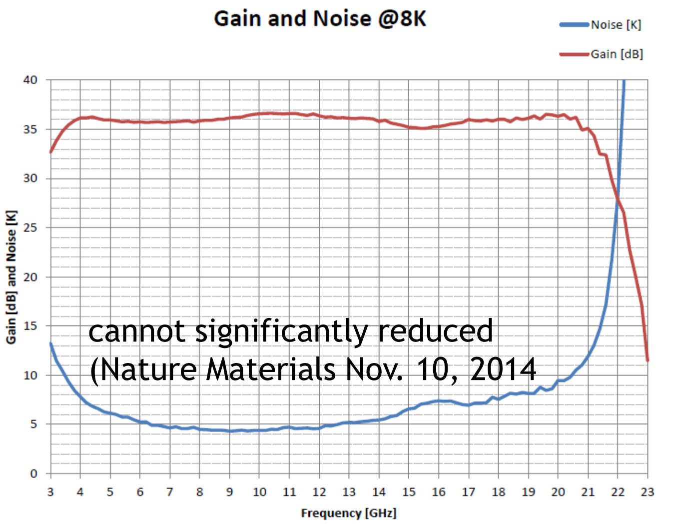
Signal: 10^{-23}W (1photon/s @ 15GHz), linewidth 10kHz, equal distributed

Receiver

- Axion mass range: 40 µeV … 400 µeV
  Frequency range: 10 GHz … 100 GHz (λ = 3 cm … 3 mm)
- Detection of signal line in frequency domain with
  $\Delta\nu_A = 10^{-6}\ \nu_A$
- …

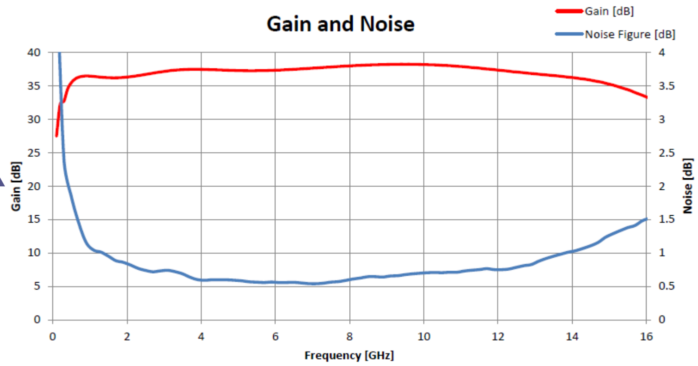
Low-Noise Amplifiers

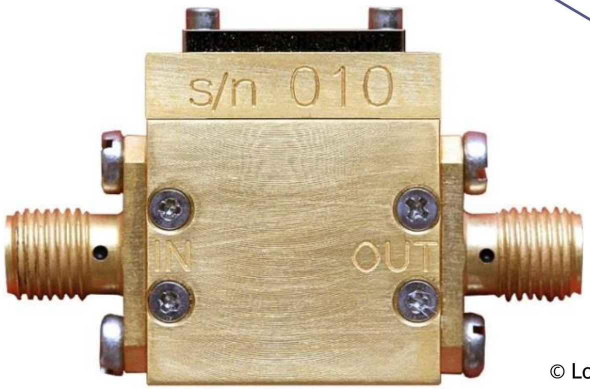
- 2 different devices (Low Noise Factory, Chalmer University)
- Same characteristics @ RT but 1 is for cryo temperatures



cannot significantly reduced
(Nature Materials Nov. 10, 2014

6-20 GHz Cryogenic Low Noise Amplifier, 5K @ 8-10K
1-15 GHz Low Noise Amplifier, 75K @ RT



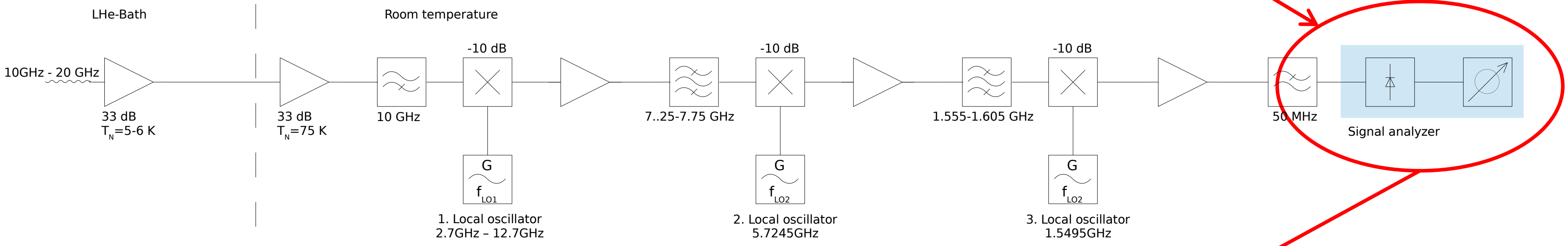


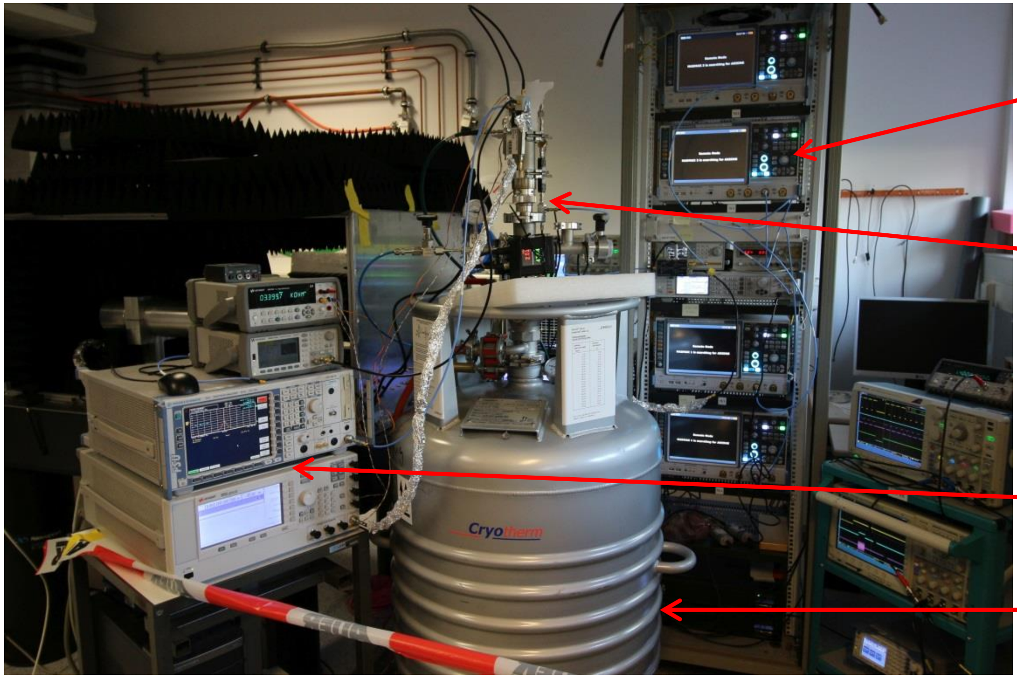
© Low Noise Factory

Heterodyne Detection

- Lab system:

Her the reality is a little bit
more complicated!
(FT-analysis)





Signal analyzer
(4 samplers, 1.4% dead time)

Front end mixers and
amps

Fake axion

LHe bath → 4K T_{He} + 5.5K T_{Amp} = 9.5K T_{Sys}

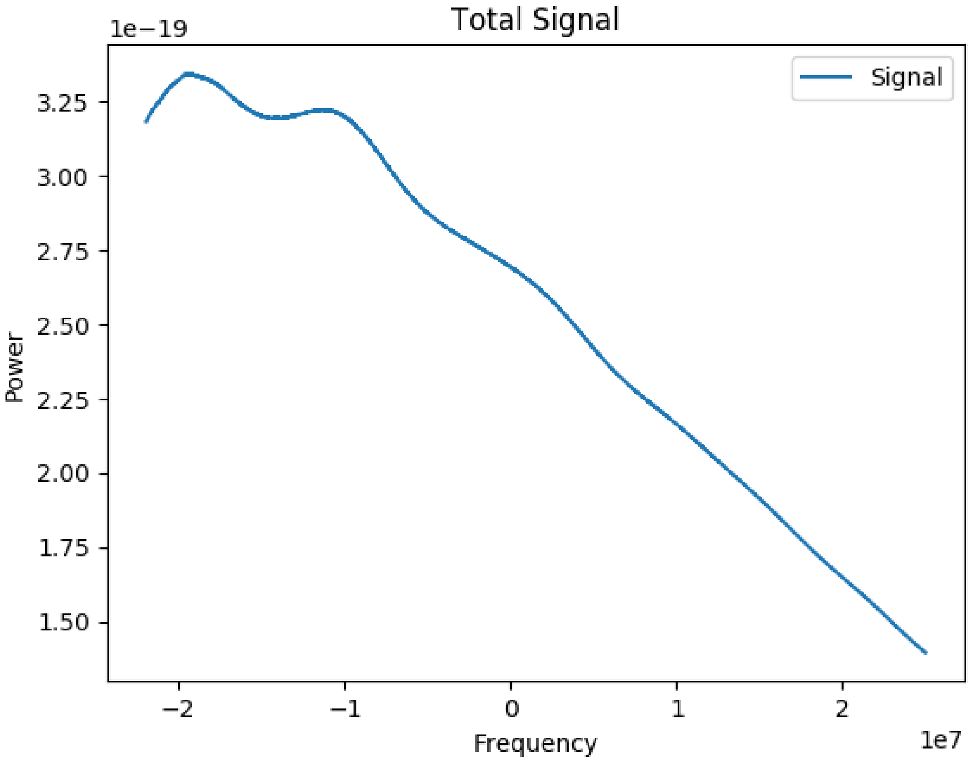
Heterodyne Detection: First Cold Test

- Inject fake axion signal with $1.2 \cdot 10^{-22}$ W at LHe temp.
  - Frequency: 18.85 GHz
  - Frequency modulated with gaussian noise
  - Signal bandwidth: 8 kHz, Lorentz-shaped

Heterodyne Detection: First Cold Test

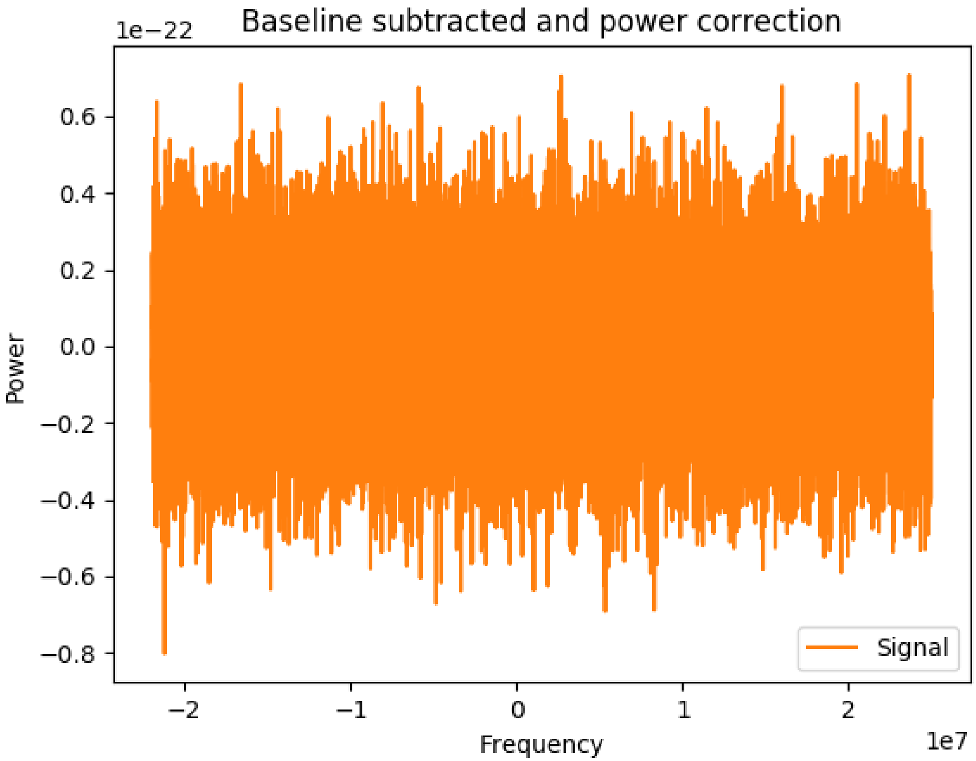
- Inject fake axion signal with $1.2 \cdot 10^{-22}$ W at LHe temp.
  - Frequency: 18.85 GHz
  - Frequency modulated with gaussian noise
  - Signal bandwidth: 8 kHz, Lorentz-shaped

  - Received signal after 28h measurement (averaged signal):



Heterodyne Detection: First Cold Test

- Inject fake axion signal with $1.2 \cdot 10^{-22}$ W at LHe temp.
  - Frequency: 18.85 GHz
  - Frequency modulated with gaussian noise
  - Signal bandwidth: 8 kHz, Lorentz-shaped
  - Received signal after baseline subtraction and gain correction:



MadMax-Workshop Nov. 21/22 2016

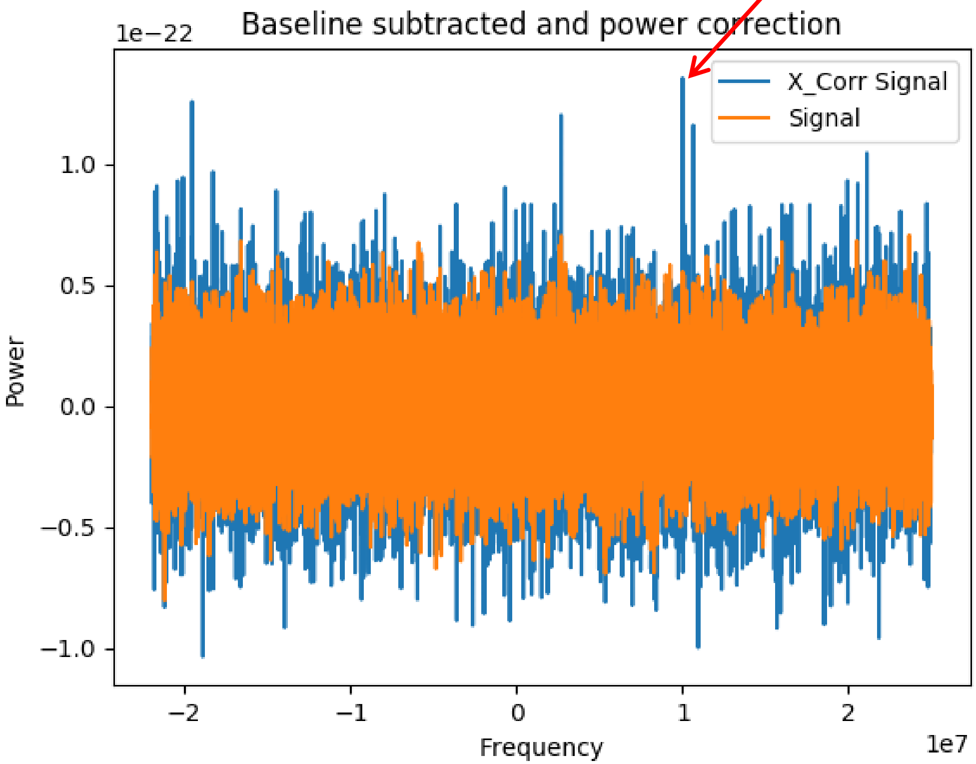
Heterodyne Detection: First Cold Test

- Inject fake axion signal with $1.2 \cdot 10^{-22}$ W at LHe temp.
  - Frequency: 18.85 GHz
  - Frequency modulated with gaussian noise
  - Signal bandwidth: 8 kHz, Lorentz-shaped
  - X-Correlation signal with 8kHz width:

$$X(\tau) = \int s(t)\, T(t+\tau) d\tau$$

s: Signal
T: Testfunction
(Lorentz, Gauss, …)

Highest peak



Heterodyne Detection: First Cold Test

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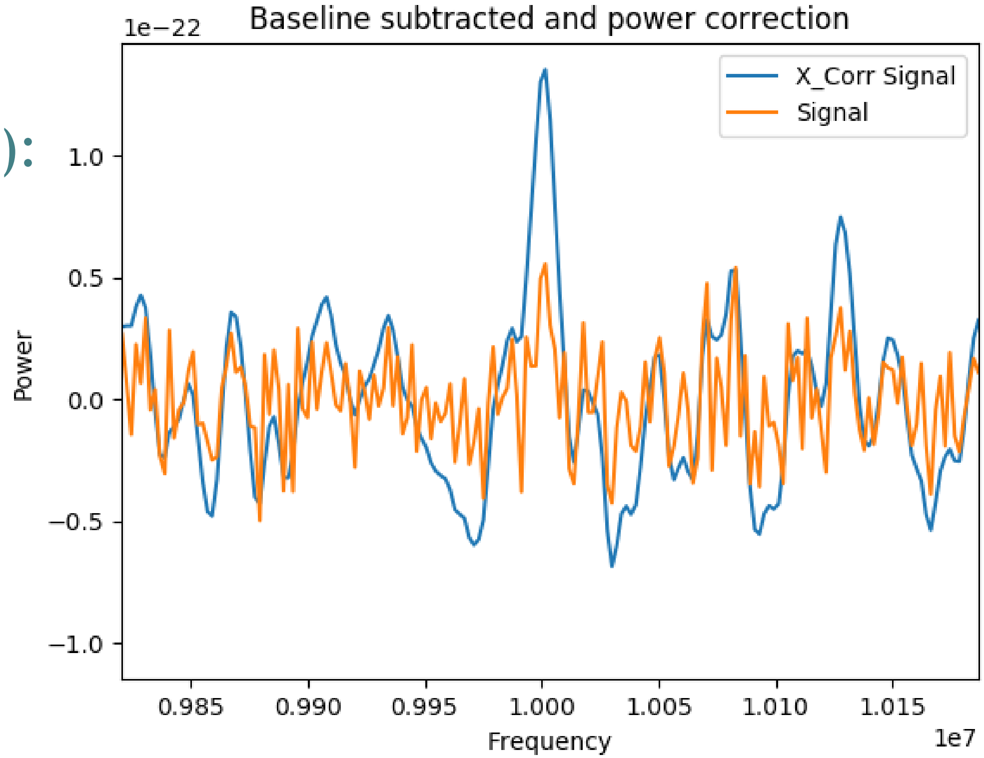
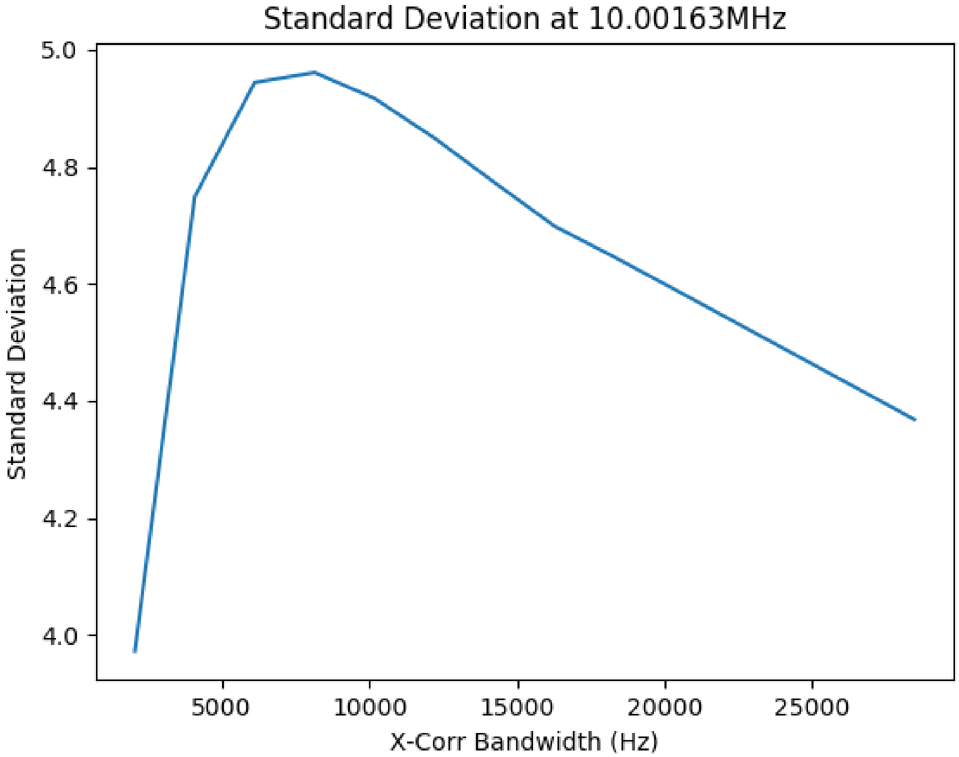
    - Frequency: 18.85 GHz
    - Frequency modulated with gaussian noise
    - Signal bandwidth: 8 kHz, Lorentz-shaped
    - X-Correlation signal with 8kHz width (Zoom):



Heterodyne Detection: First Cold Test

- Inject fake axion signal with $1.2 \cdot 10^{-22}$ W at LHe temp.
  - Frequency: 18.85 GHz
  - Frequency modulated with gaussian noise
  - Signal bandwidth: 8 kHz, Lorentz-shaped
  - Why 8kHz Bandwidth? Algorithm is searching for best S/N-ratio:



Heterodyne Detection: First Cold Test

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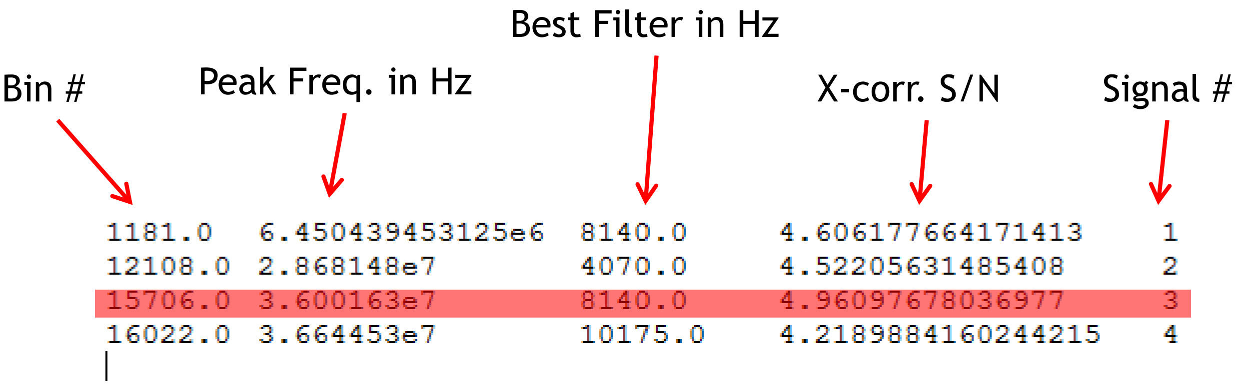


Best Filter in Hz

Bin #

Peak Freq. in Hz

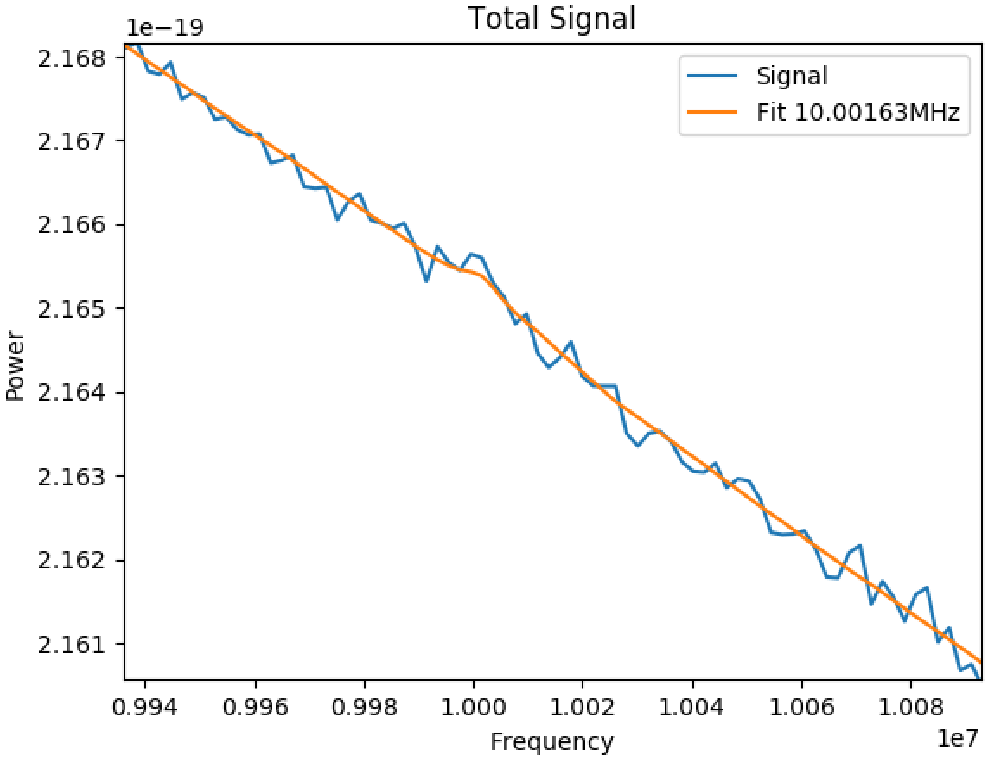
X-corr. S/N

Signal #

```
1181.0   6.450439453125e6  8140.0     4.606177664171413    1
12108.0  2.868148e7        4070.0     4.52205631485408     2
15706.0  3.600163e7        8140.0     4.96097678036977     3
16022.0  3.664453e7        10175.0    4.2189884160244215   4
```

Heterodyne Detection: First Cold Test

- Inject fake axion signal with $1.2 \cdot 10^{-22}$ W at LHe temp.
  - Frequency: 18.85 GHz
  - Frequency modulated with gaussian noise
  - Signal bandwidth: 8 kHz, Lorentz-shaped
  - Signal + Lorentz-fit (8kHz):



Additional Facts:

- Comparison with Allen's run statistic algorithm showed good agreement
- Cold tests are ongoing
  - $5 \cdot 10^{-23}$ W in 10kHz linewidth already reached within one week in 10K T_{sys} (Physical limit)
  - Different tests runs should give a clearer insight to possible problems (quantization noise, …)

Conclusion

- Receiver concept is OK
  - Dead time 1,4%
  - Sensitivity in warm and cold is OK

- Next Tests:
  - Systematic cold measurements
  - Better Antenna measurements
  - Cold background measurements in cryostat

Appendix

Spectral Power Density of (BB)-Noise

- Contribution of a detector:
  (no phase preservation)

$$E_N = \frac{h\nu}{e^{\left(\frac{h\nu}{k_B T}\right)} - 1} \qquad [E_N] = \frac{W}{Hz}$$

- Contribution of an amplifier or mixer:
  (phase preservation)

$$E_N = h\nu \left(\frac{1}{e^{\left(\frac{h\nu}{k_B T}\right)} - 1} + 1 \right)$$

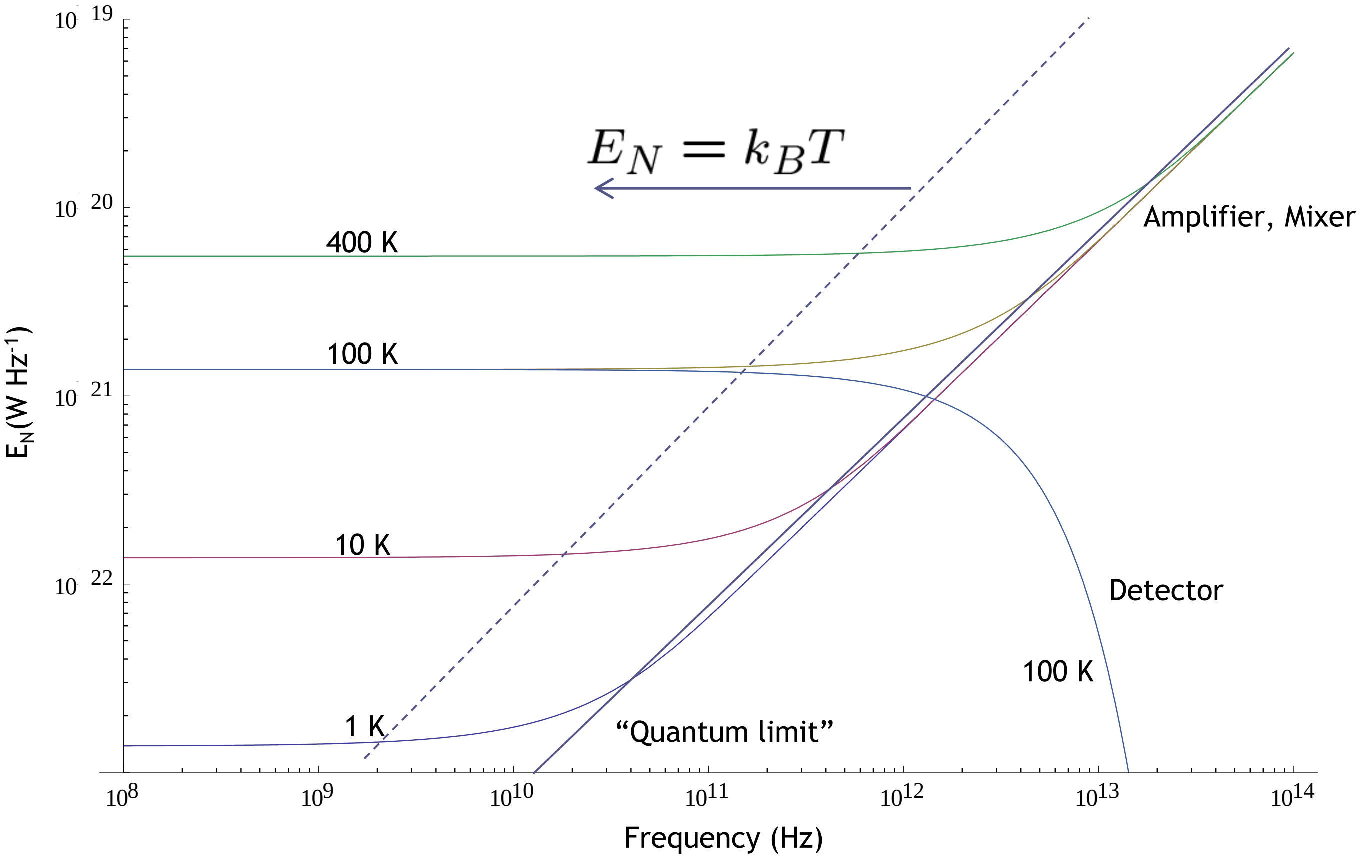
- Limit for low frequencies and/or high temperatures:

$$E_N = k_B T$$

Noise temperature

Spectral Power Density of (BB)-Noise

- Example:
    - Spectral power density for different temperatures



Noise Equivalent Power

- System noise temperature T_{Sys} and bandwidth Δf_F are difficult to measure for broadband detectors
    - Johnson noise
    - Phonon-electron coupling
    - Generation-recombination noise
    - Background noise
    - …

$$P_N = k_B T_{Sys} \sqrt{\frac{\Delta f_F}{\tau}}$$

- $\longrightarrow$ Using noise equivalent power (NEP):

$$NEP_\tau = k_B T_{Sys} \sqrt{\Delta f_F} \qquad [NEP_\tau] = \frac{W}{\sqrt{Hz}}$$

- Sometimes a little bit different NEP definitions are used, most of them have factor 2 or $2^{½}$ included
(Because of 2 polarizations or time to bandwidth conversion)

Broadband detectors

- Types of broadband detectors
  - Bolometers
  - Microwave kinetic inductance detector (MKID)
  - Double quantum well detectors
  - Transition edge sensors (TES)

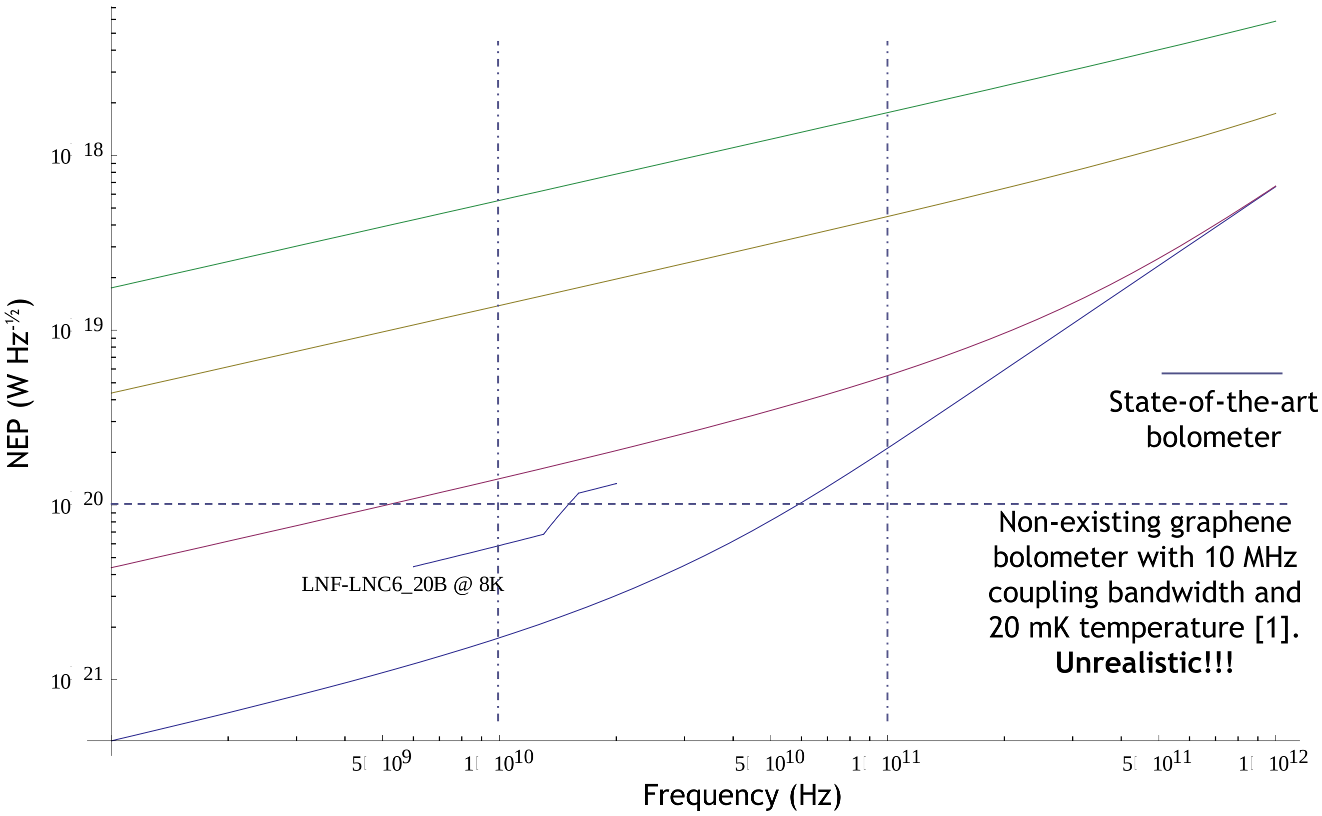
- Usually they work good only at higher frequencies (> 50 … 100 GHz)

- Often the devices are background limited
  - Example:
    Background temperature 300 K, bandwidth 50 GHz
    → NEP = $9.2\ 10^{-16}$ W $Hz^{-½}$

- Temperature and bandwidth can be reduced, but then again the other noise sources start to dominate (see later)!

Comparison: Heterodyne ↔ Direct Det.

- Noise equivalent power of a heterodyne system:



State-of-the-art bolometer

Non-existing graphene bolometer with 10 MHz coupling bandwidth and 20 mK temperature [1]. **Unrealistic!!!**

[1] K.C. Fong and K.C. Schwab, “Ultra-sensitive and Wide Bandwidth Thermal Measurements of Graphene at Low Temperatures“, 2012

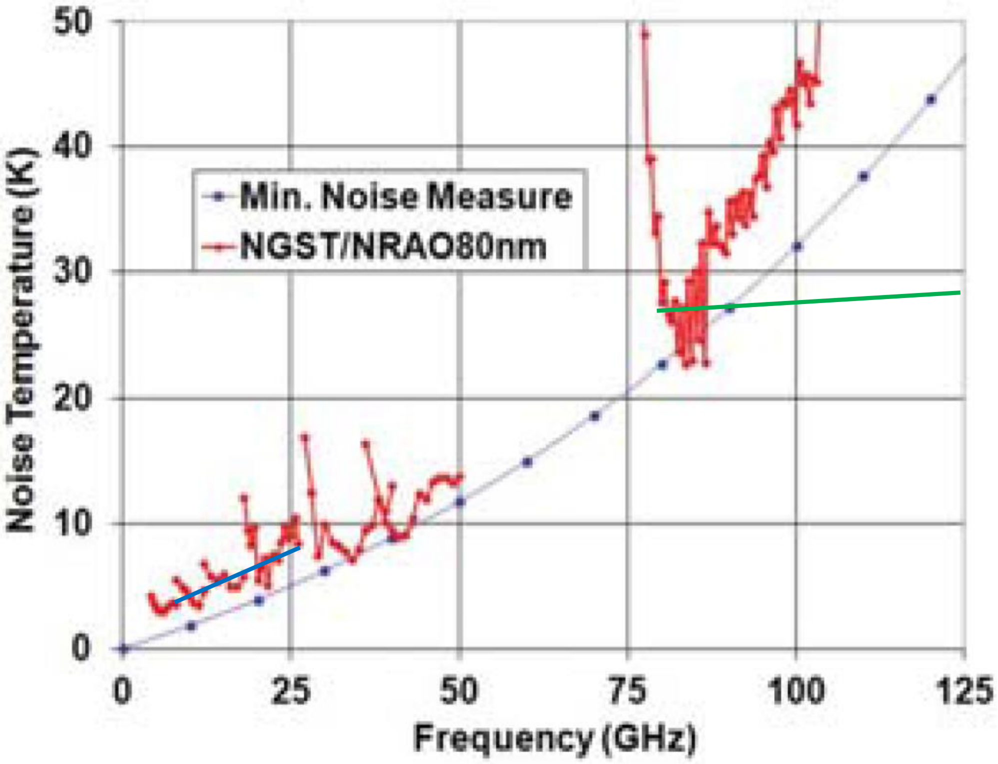
Heterodyne Detection: Real Devices

- Noise temperature limit for InP devices:
  - Mainly phonon self heating → Inner bulk black body radiator

🟥
InP-HFET,
Bryerton et. al.
“Ultra Low Noise Cryogenic Amplifiers for Radio Astronomy”, 2013

🟩
Shi, et. al.
A 100-GHz Fixed-Tuned Waveguide SIS Mixer Exhibiting Broad Bandwidth and Very Low Noise Temperature, 1997

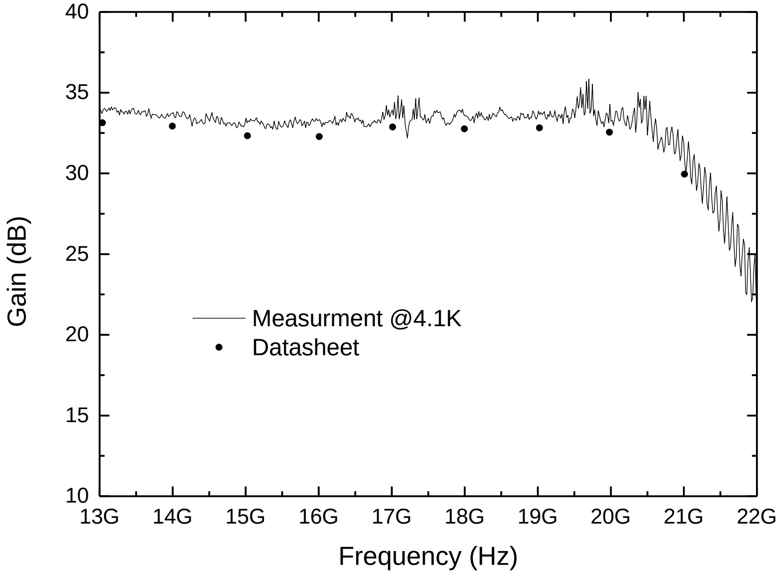
🟦
InP-HEMT
Our amplifier, LNF



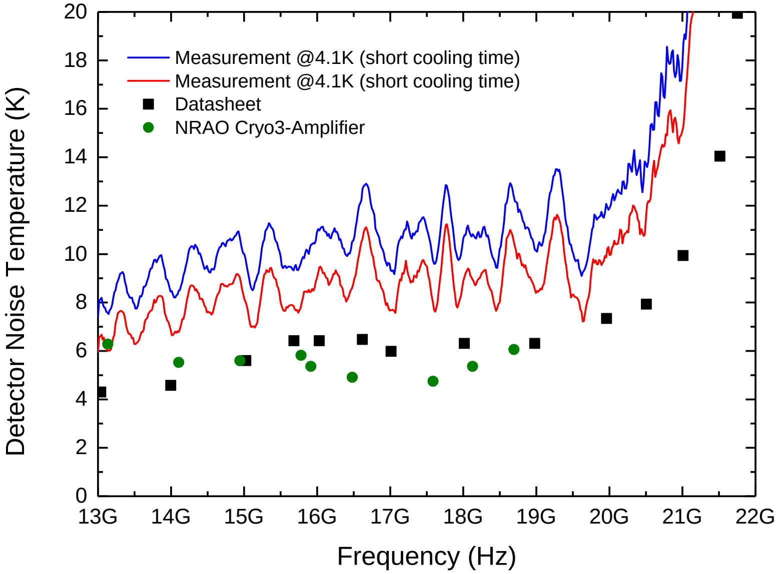
First Cold Measurement

- First quick and dirty test:
  - Very simple test in LHe-dewar
  - Amplifier at LHe-temperature (4.1K)

Gain



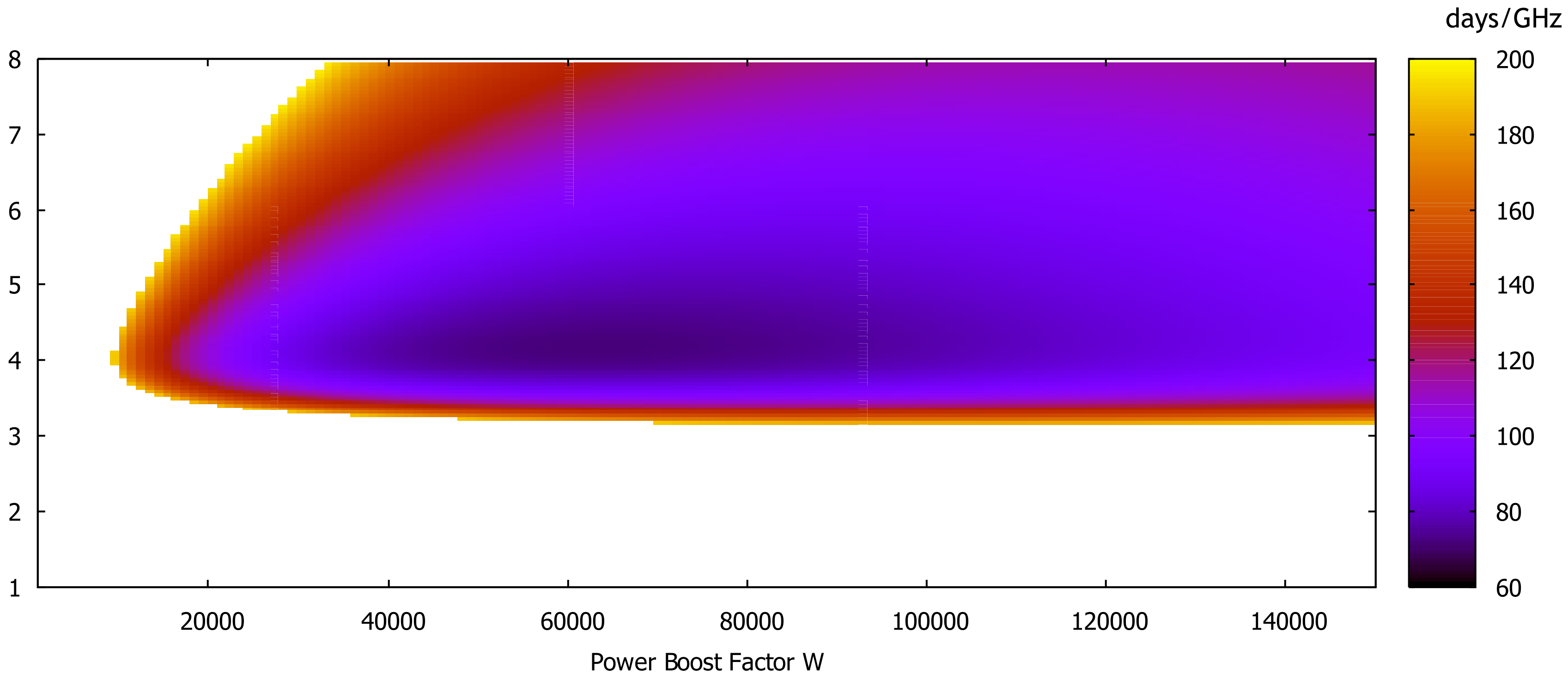
Noise temperature



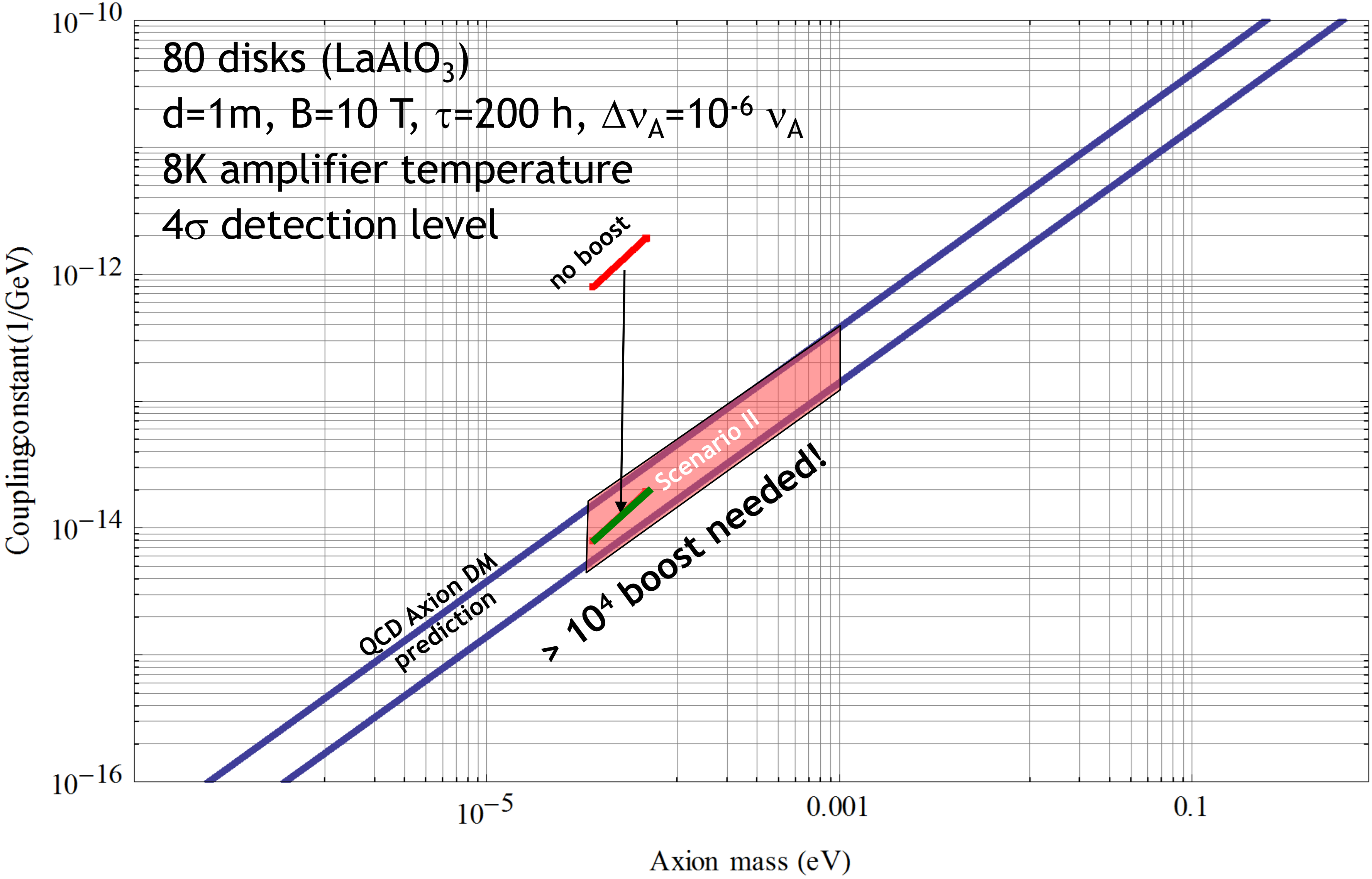
Room for improvement!

Run Optimization

- Measurement time vs. analysis threshold level and power boost factor:
  - 80 disks, $LaAlO_3$, T_{sys}=8K, effectivity: 75%, 1day adjustment time



Sensitivity in terms of Axions



80 disks ($LaAlO_3$)

d=1m, B=10 T, τ=200 h, $\Delta\nu_A=10^{-6}\,\nu_A$

8K amplifier temperature

4σ detection level

no boost

Scenario II

> 10^4 boost needed!

QCD Axion DM prediction

Photon Noise Equivalent Power (NEP_γ)

Photon energy: $E_\gamma = h\nu$

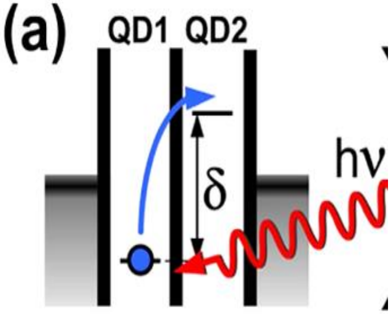
Noise equivalent power "of a photon": $NEP_\gamma = h\nu\sqrt{2n}$

n: Mean photon flux (background + signal) in 1/s

Frequency ν	Photon Energy E_γ	$1\ \gamma/\mathrm{s}$ =	NEP_γ for $1\ \gamma/\mathrm{s}$
10 GHz	$6.62\ 10^{-24}$ J (41.36 μeV)	$6.62\ 10^{-24}$ W	$9.4\ 10^{-24}$ W $\mathrm{Hz}^{-1/2}$
20 GHz	$1.33\ 10^{-23}$ J (82.71 μeV)	$1.33\ 10^{-23}$ W	$1.87\ 10^{-23}$ W $\mathrm{Hz}^{-1/2}$
50 GHz	$3.31\ 10^{-23}$ J (206.8 μeV)	$3.31\ 10^{-23}$ W	$4.69\ 10^{-23}$ W $\mathrm{Hz}^{-1/2}$
100 GHz	$6.62\ 10^{-23}$ J (413.6 μeV)	$6.62\ 10^{-23}$ W	$9.4\ 10^{-23}$ W $\mathrm{Hz}^{-1/2}$

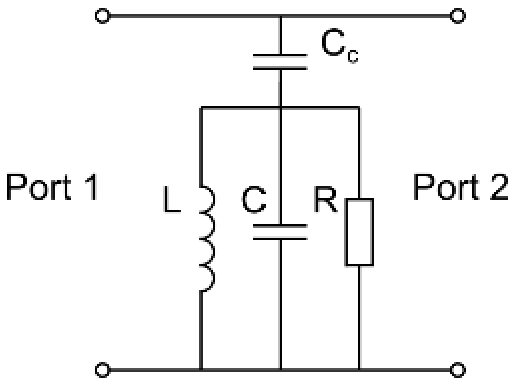
Double quantum dot

- Function principle
  - Absorption of photon with energy $h\nu$
  - Electron in QD1 is excited to QD2 (tunneling)
  - Electron can leave to drain lead and new electron enters from the source
  - Then cycle can be repeated
  - Current flow through the system
  - δ can be changed by electric field

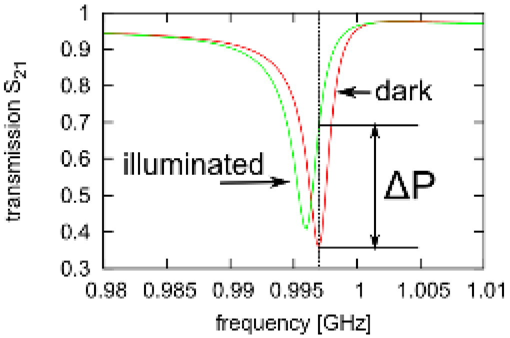


Microwave Kinetic Inductance Detector

- Function principle:
  - Breaking cooper pairs in a superconductor (inductor) by photons
  - Stored energy (inner inductance) is changed
  - Resonance frequency of the resonator shifts



MKID resonator circuit



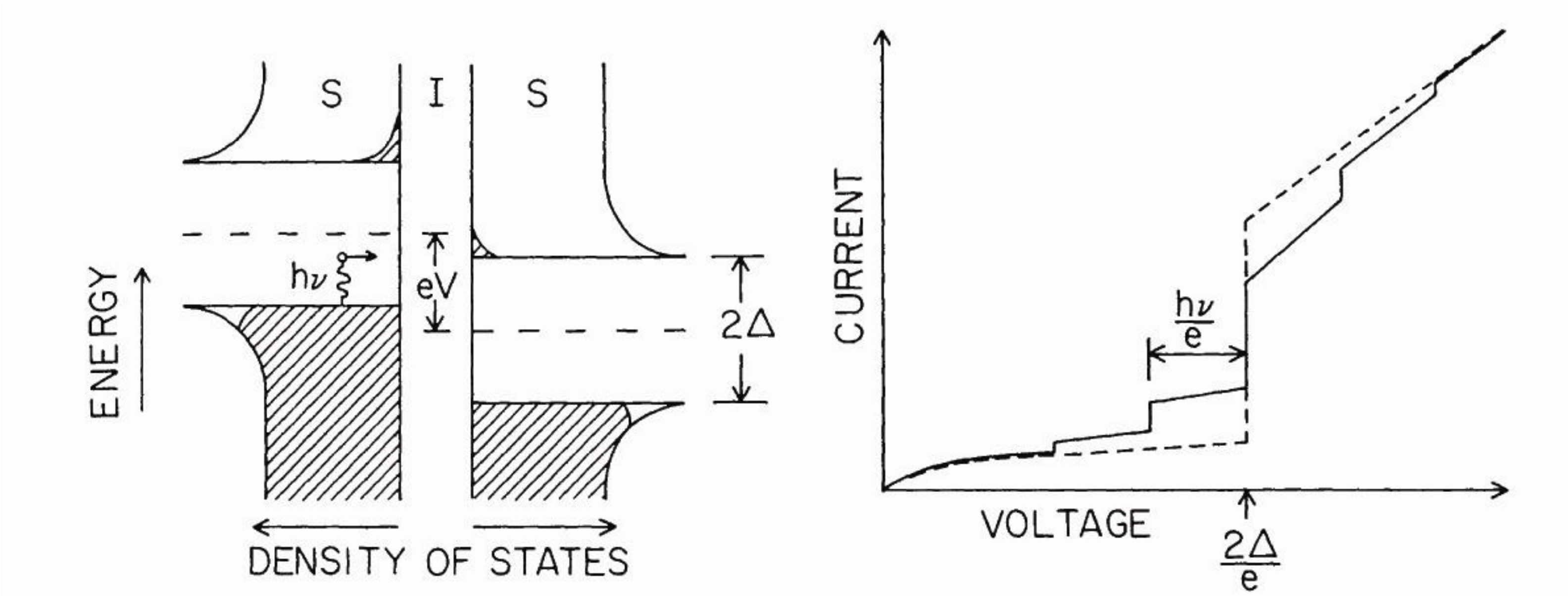
Superconducting Gap Energy

Aluminum	3.4×10^{-4} eV
Cadmium	1.5×10^{-4} eV
Gallium	3.3×10^{-4} eV
Indium	10.5×10^{-4} eV
Lanthanum	
β–lanthanum	19×10^{-4} eV
Lead	27.3×10^{-4} eV
Mercury	
α–mercury	16.5×10^{-4} eV
Molybdenum	2.7×10^{-4} eV
Niobium	30.5×10^{-4} eV
Tantalum	14×10^{-4} eV
Thallium	7.35×10^{-4} eV
Tin	
white tin	11.5×10^{-4} eV
Vanadium	16×10^{-4} eV
Zinc	2.4×10^{-4} eV

SIS-Mixer (Principle)

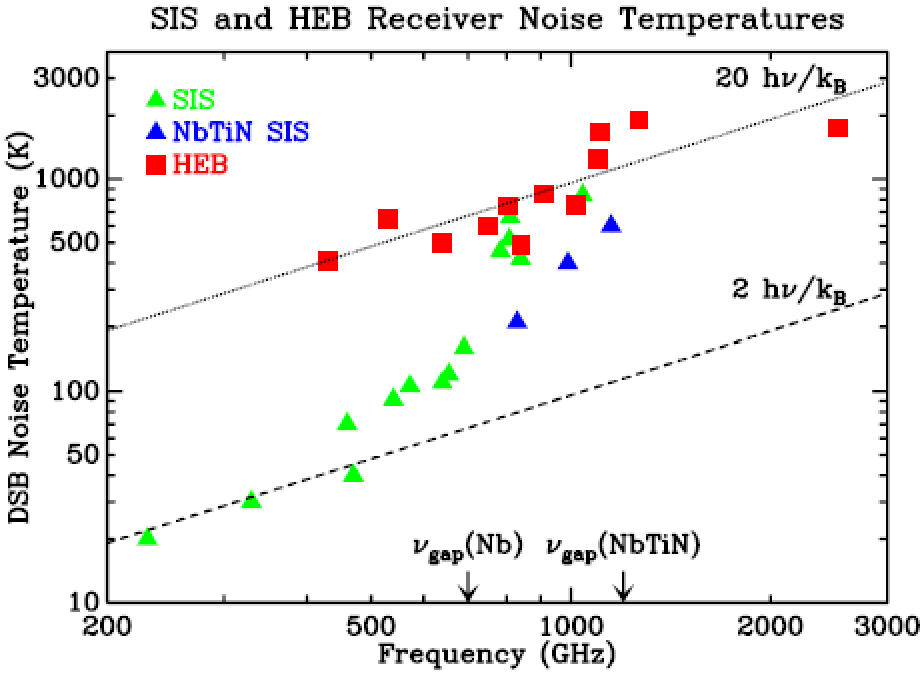
- Cooper pairs break into quasi-particles and tunnel over the barrier

- Using photon assistant tunneling for mixing
- Slope of I-V curve has sharp discontinuity: efficient



SIS-Mixer (Principle)

- Mixer loss -> higher noise temperature
- Double-sideband feature -> looking at two frequencies at the same time

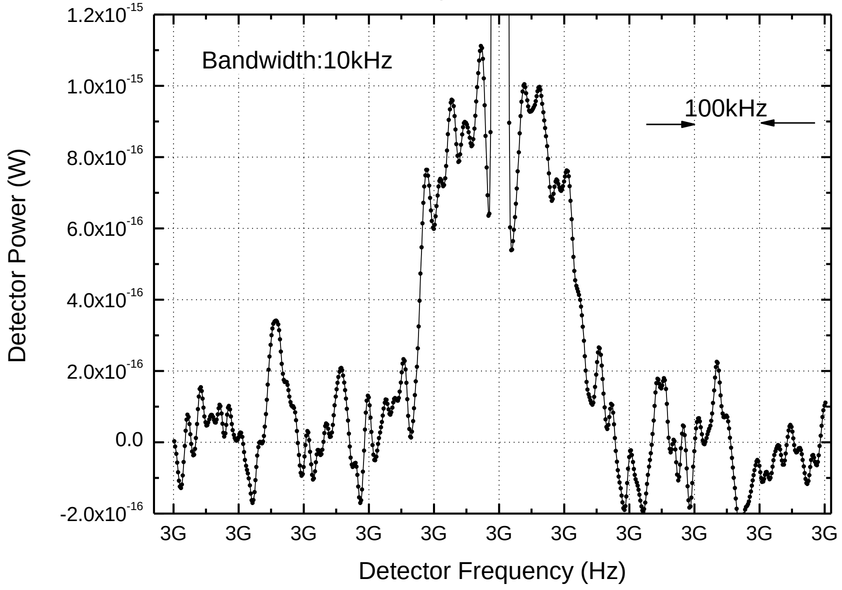


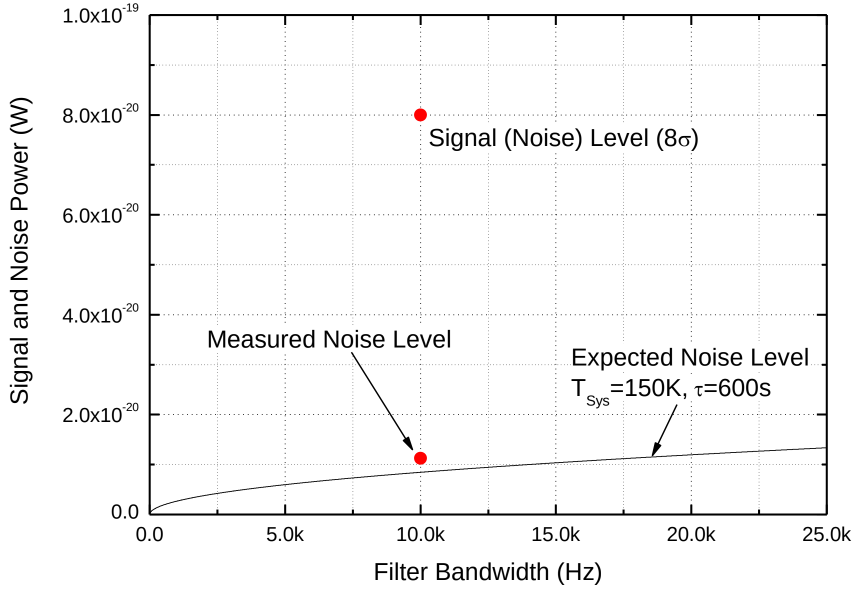
J. Zmuidzinas, „COHERENT DETECTION AND SIS MIXERS", 2002

Heterodyne Detection: First Tests

- Detection of a broadband noise signal
    - Frequency: 15 GHz
    - Linewidth: 200 kHz
    - Detection bandwidth: 10 kHz

Modulated signal @ 15 GHz with
0.8 10^{-19} W in 600 s and 77 K

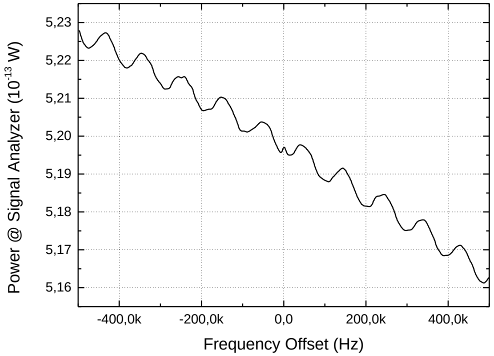




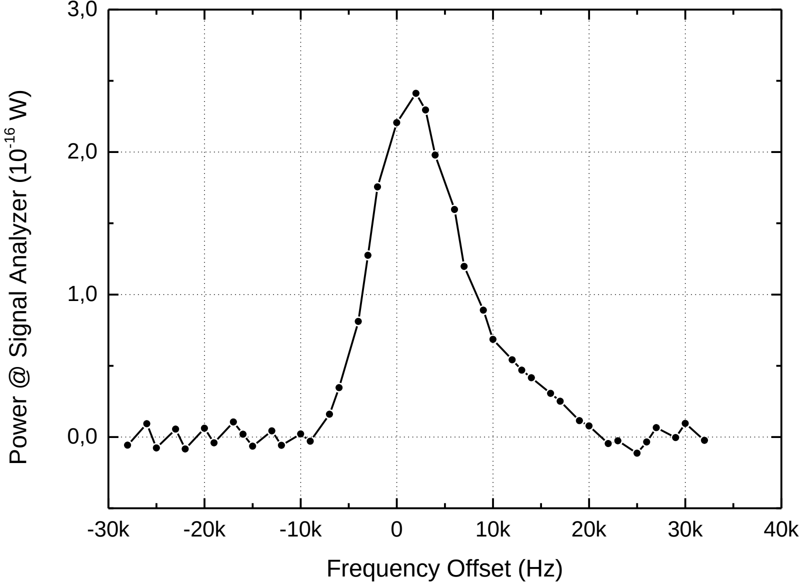
Heterodyne Detection: First Tests

- Detection of a line signal (Examples)
  - Frequency: 15 GHz
  - Detection bandwidth: 10 kHz

Real signal:



Signal line @ 15 GHz with
-168,5 dBm (1.4 10^{-20} W or 1421 γ/s)
in 17h @ RT



Signal line @ 15 GHz with
-160 dBm (10^{-19} W or 10^4 γ/s) @ RT