Cryogenic test runs in preparation for NLQM searches

Alex Melnychuk (Fermilab)

Ettore Maiorana Center, Erice, September 5th 2023

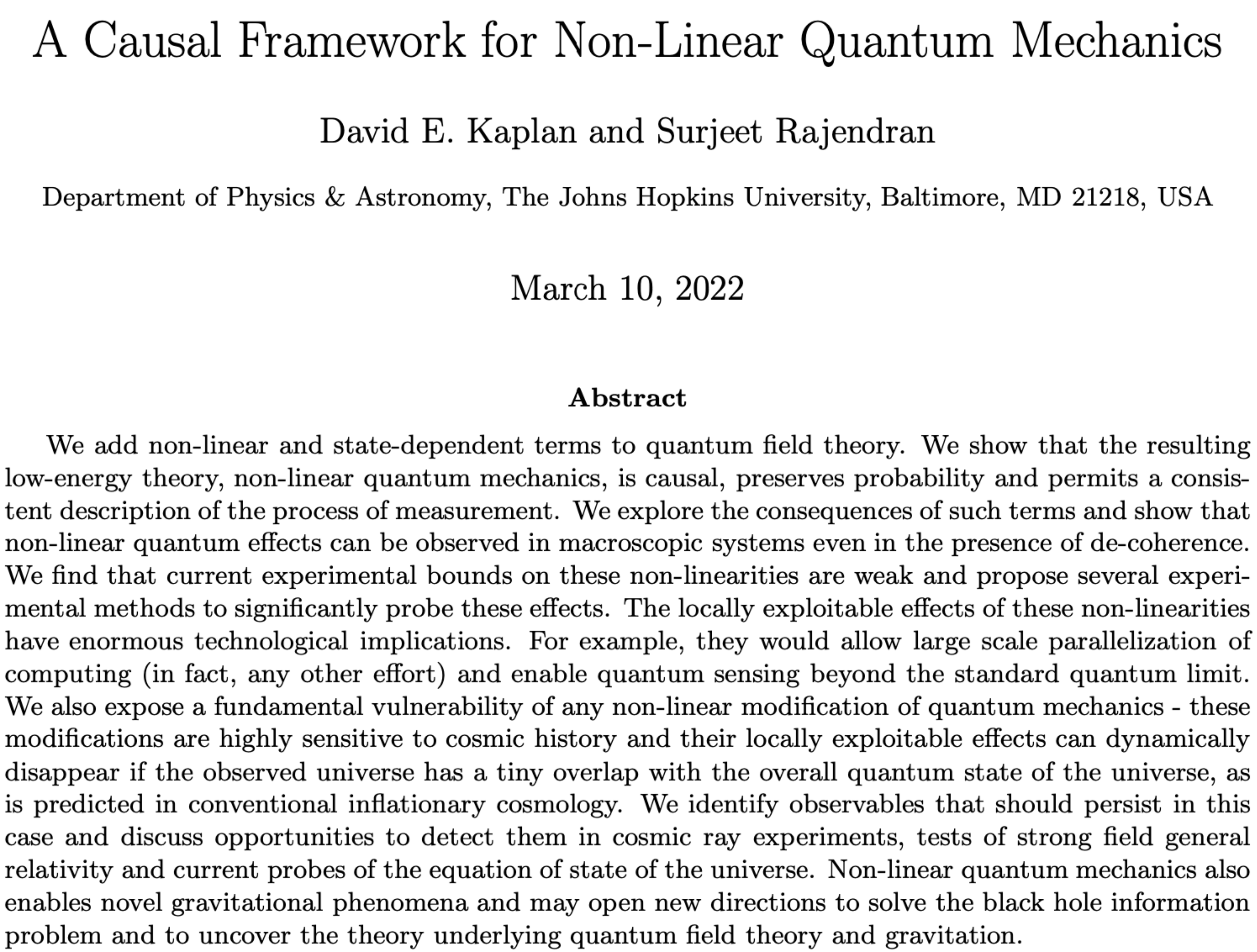
People involved

Raphael Cervantes, Bianca Giaccone, Roni Harnik, David E. Kaplan, Oleksandr Melnychuk, Sam Posen, Surjeet Rajendran, and Alex Sushkov

Acknowledgments:

Precious technical help from Fermilab SQMS collaborators Geev Nahal, Nick Bornman, and Roman Pilipenko

Introduction (Theory)


A Causal Framework for Non-Linear Quantum Mechanics

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March 10, 2022

Abstract

We add non-linear and state-dependent terms to quantum field theory. We show that the resulting low-energy theory, non-linear quantum mechanics, is causal, preserves probability and permits a consistent description of the process of measurement. We explore the consequences of such terms and show that non-linear quantum effects can be observed in macroscopic systems even in the presence of de-coherence. We find that current experimental bounds on these non-linearities are weak and propose several experimental methods to significantly probe these effects. The locally exploitable effects of these non-linearities have enormous technological implications. For example, they would allow large scale parallelization of computing (in fact, any other effort) and enable quantum sensing beyond the standard quantum limit. We also expose a fundamental vulnerability of any non-linear modification of quantum mechanics - these modifications are highly sensitive to cosmic history and their locally exploitable effects can dynamically disappear if the observed universe has a tiny overlap with the overall quantum state of the universe, as is predicted in conventional inflationary cosmology. We identify observables that should persist in this case and discuss opportunities to detect them in cosmic ray experiments, tests of strong field general relativity and current probes of the equation of state of the universe. Non-linear quantum mechanics also enables novel gravitational phenomena and may open new directions to solve the black hole information problem and to uncover the theory underlying quantum field theory and gravitation.

https://arxiv.org/pdf/2106.10576.pdf

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Introduction (Experiment)

Experimental limit on non-linear state-dependent terms in quantum theory

Mark Polkovnikov,[1] Alexander V. Gramolin,[2] David E. Kaplan,[3] Surjeet Rajendran,[3] and Alexander O. Sushkov[2,4,5,*]

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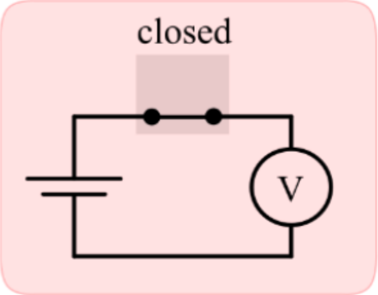
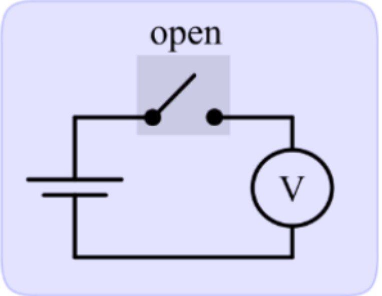
arXiv:2204.11875





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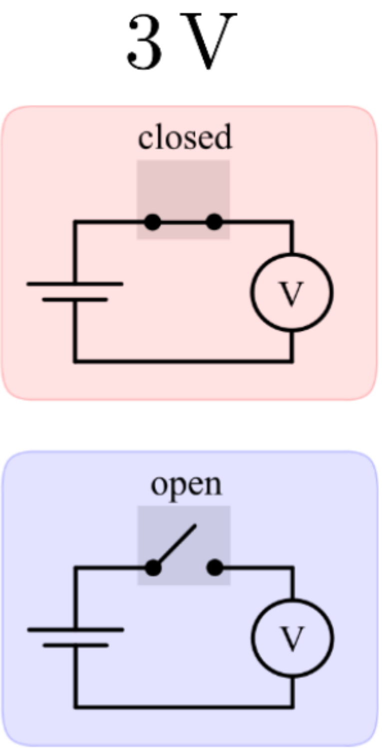

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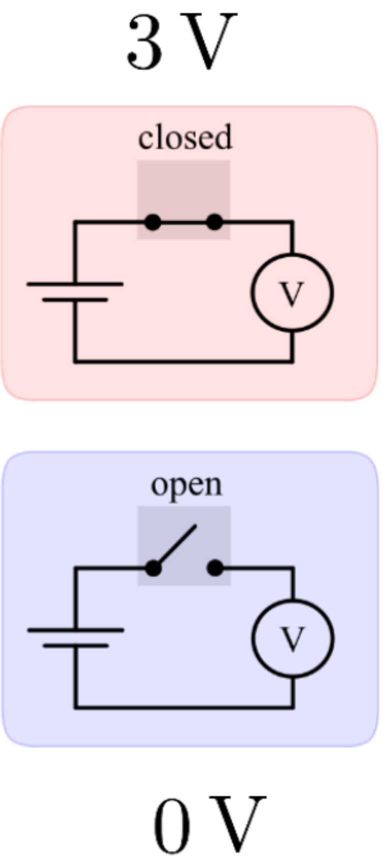

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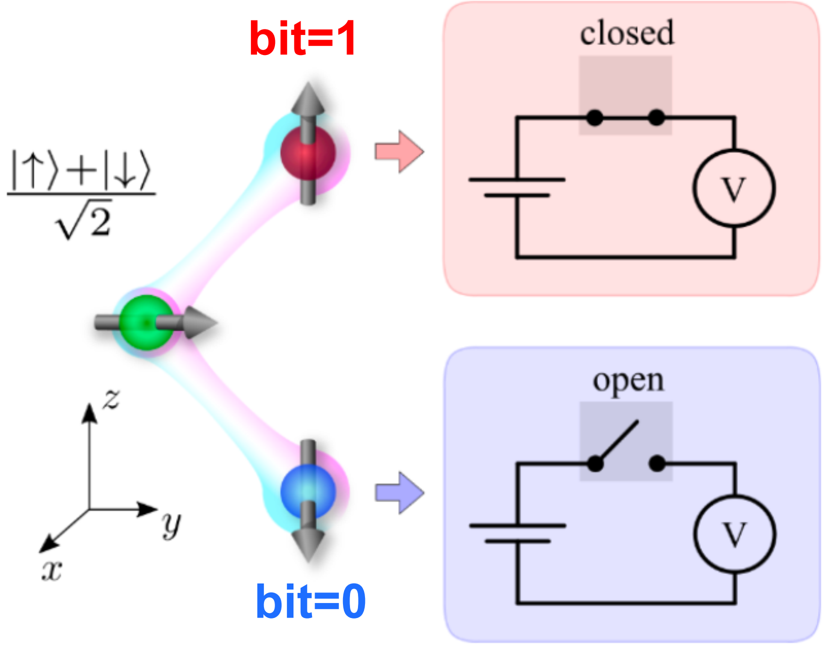

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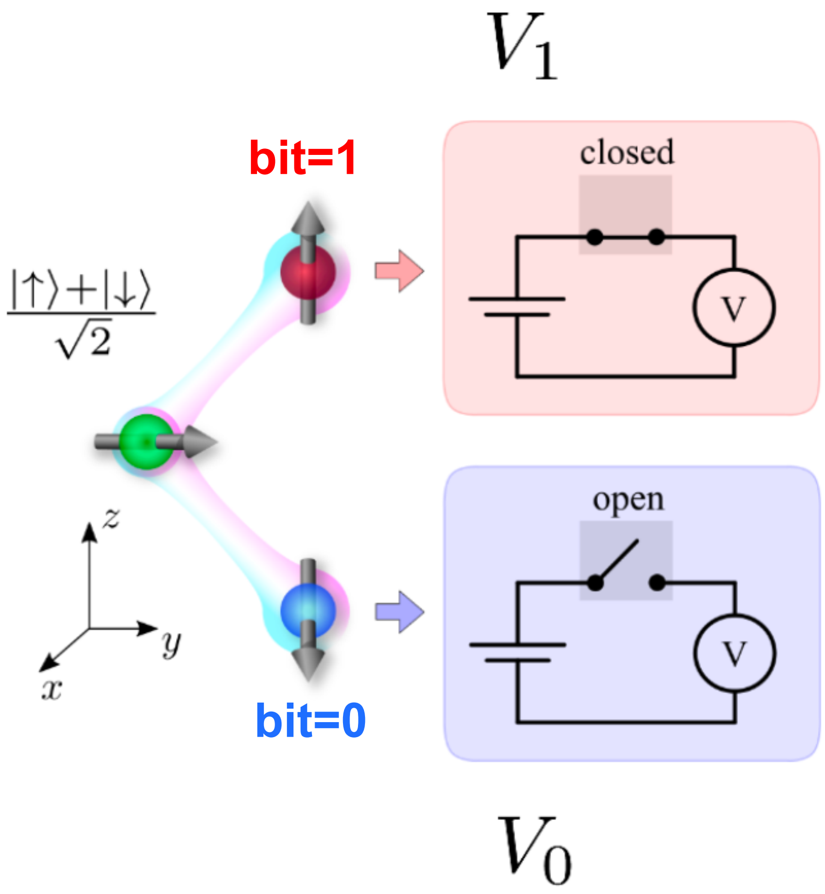

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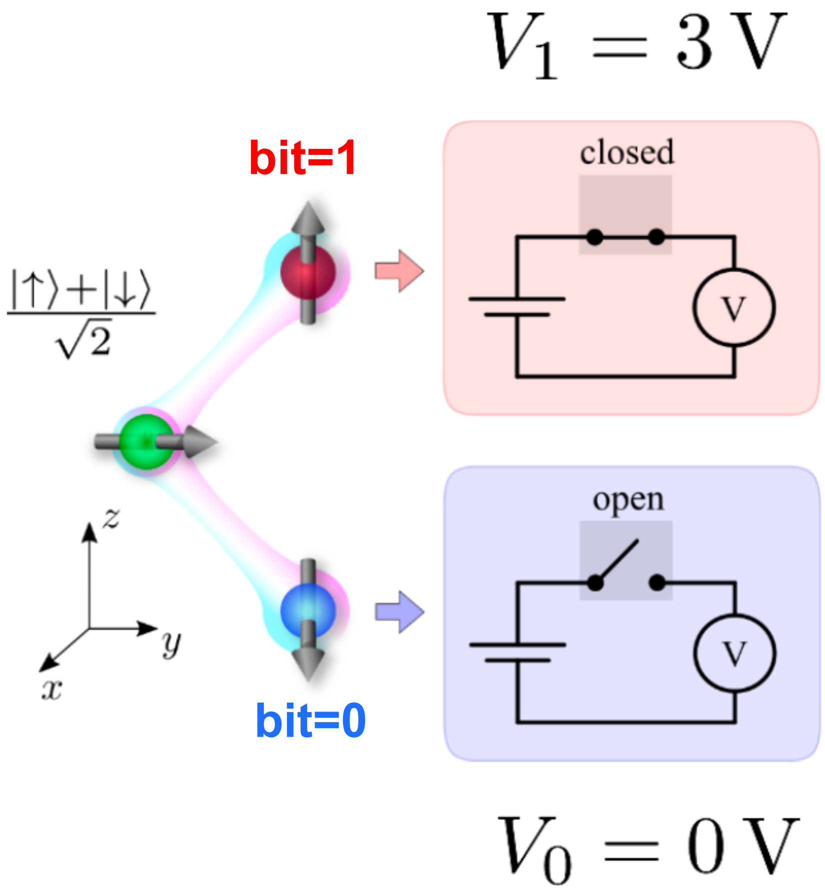

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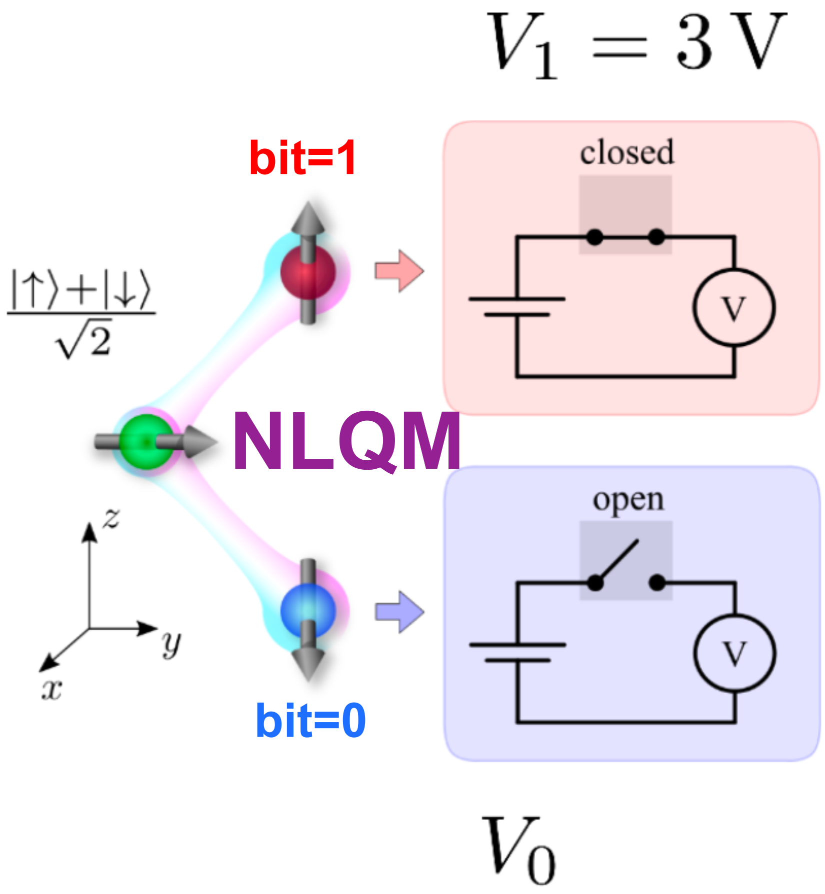

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Introduction (Experiment)

$$V_1 = 3\,\mathrm{V}$$

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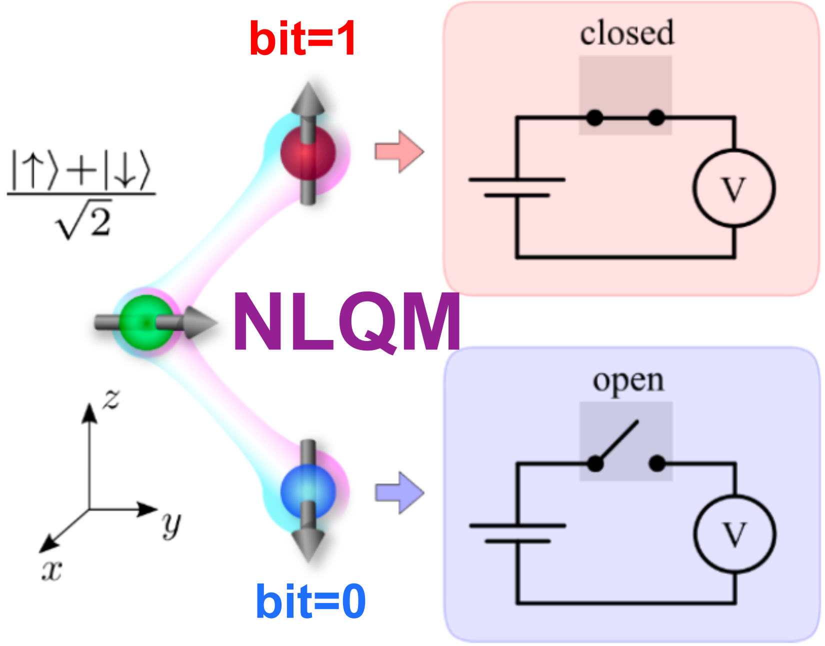

$$V_0 = 0 + \epsilon_\gamma \frac{V_1}{2}$$
$$= \epsilon_\gamma \times 1.5\,\mathrm{V}$$

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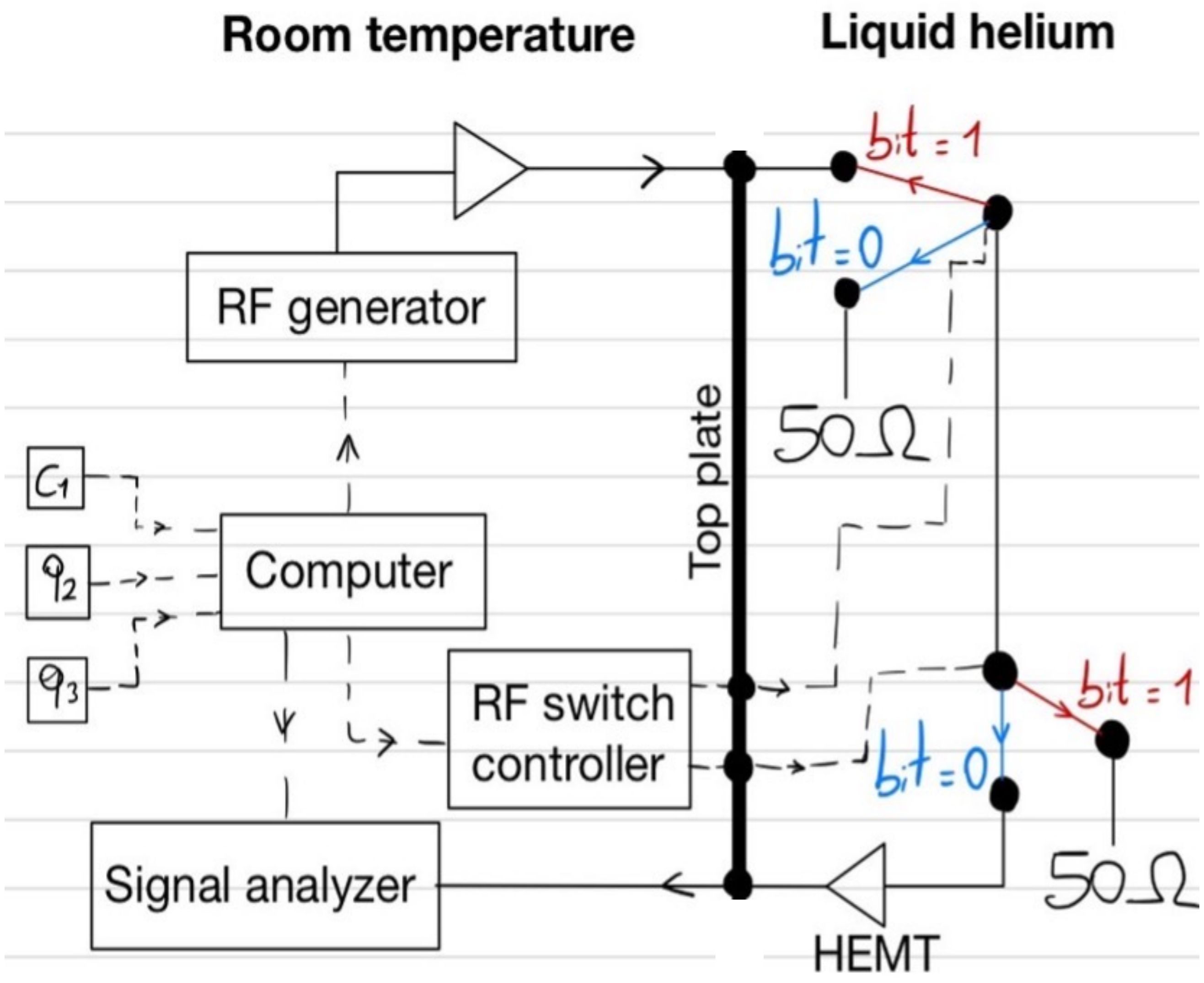
What is different in our experiment

- 4.3K vs Room Temperature
- RF signal (2.6GHz) vs DC signal
- Measure Power vs Measure Voltage
- Inside a large LHe dewar which is used regularly for performance testing of SRF cavities
- Implementation
- Our experiment is not yet a real NLQM search (it is a test run with the main purpose of commissioning the hardware and the software in preparation for the real experiment, **classically generated bits only** are used)

What is the same in our experiment

- The concept is the same
- The experiment also uses a circuit of three components: a “source”, a “switch”, and a “meter”
- In our case
  - Source = RF Generator + Room Temperature Amplifier
  - Switch = Two cryogenic switches
  - Meter = Cryogenic HEMT amplifier + Signal Analyzer



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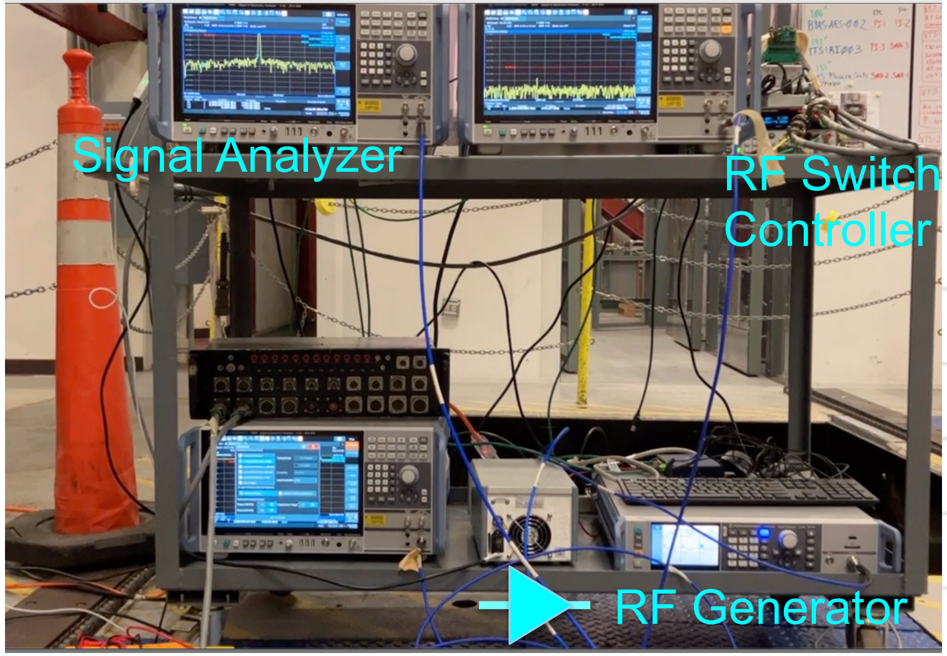
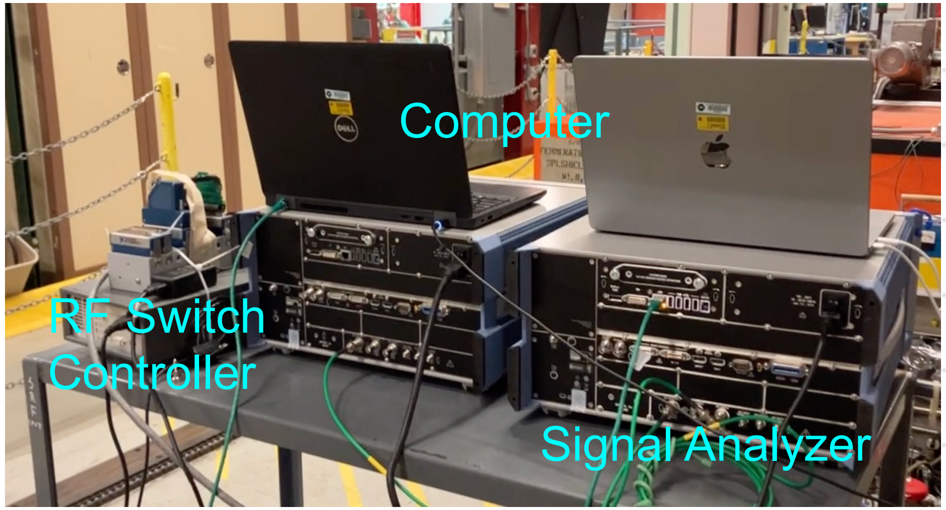
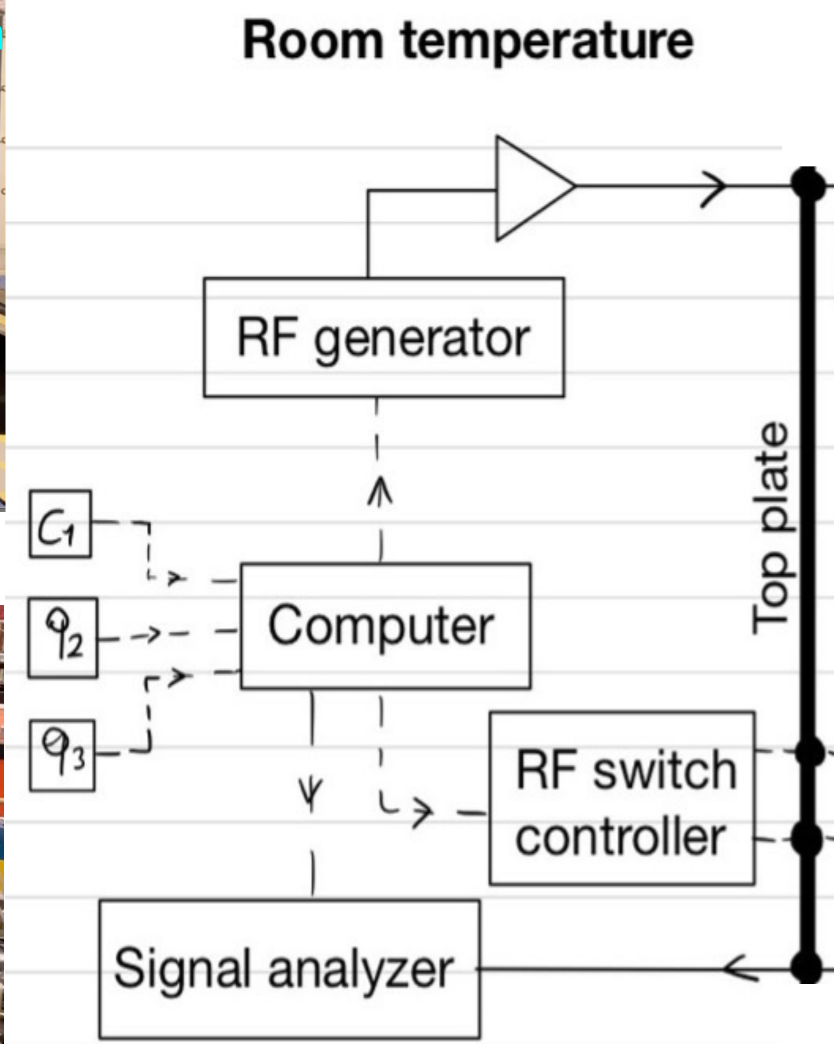
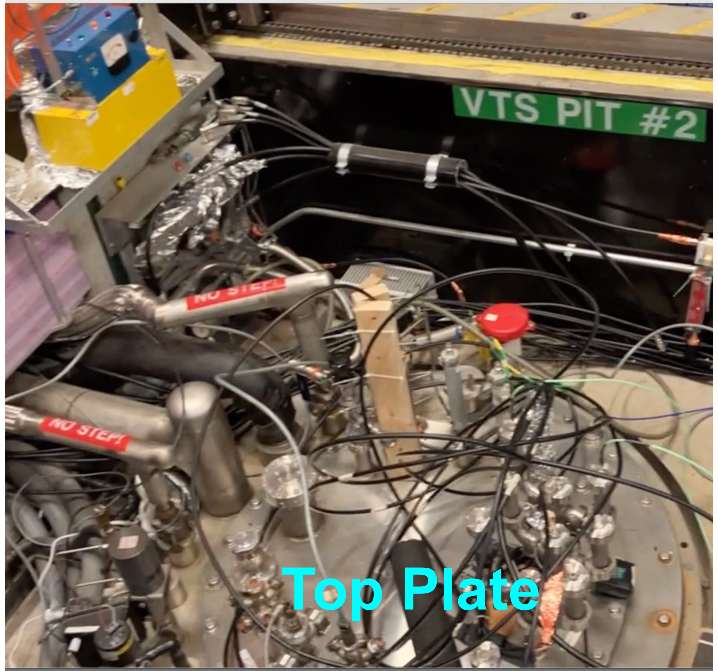
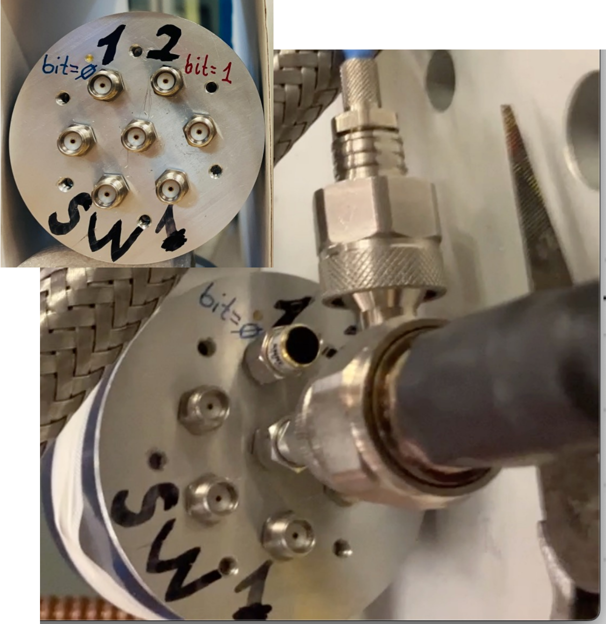

Signal Analyzer
RF Switch
Controller
RF Generator

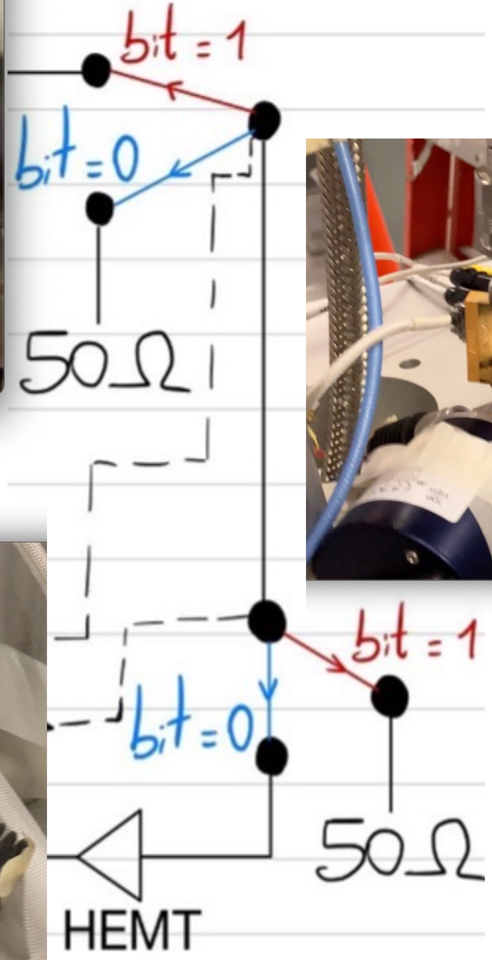

Computer
RF Switch
Controller
Signal Analyzer

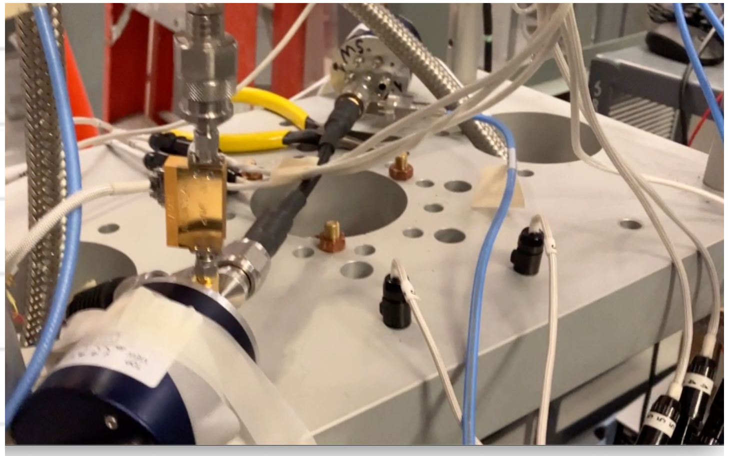

Room temperature
RF generator
Computer
RF switch
controller
Signal analyzer
Top plate

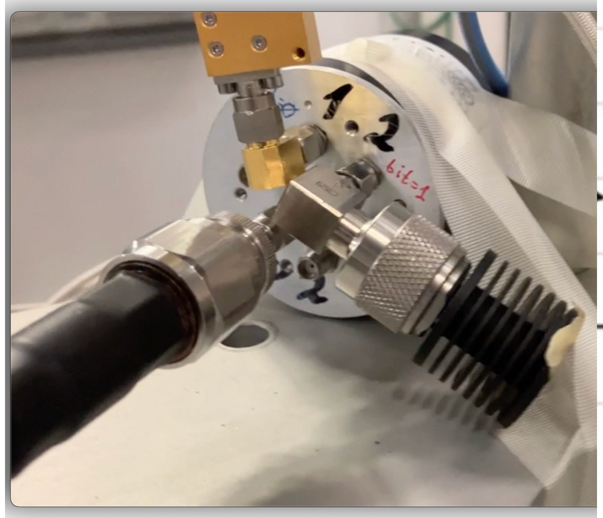

VTS PIT #2
Top Plate

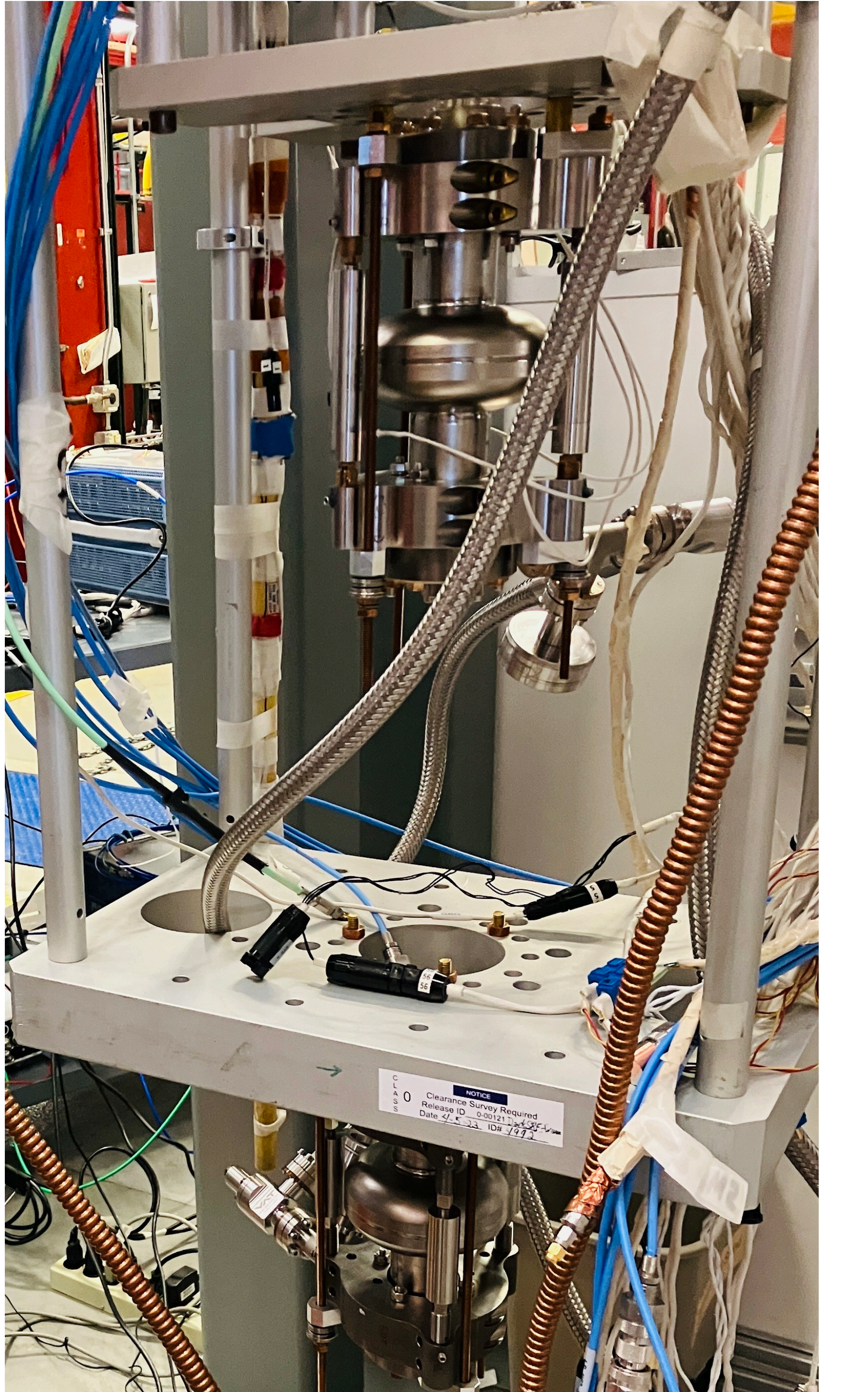
Liquid helium





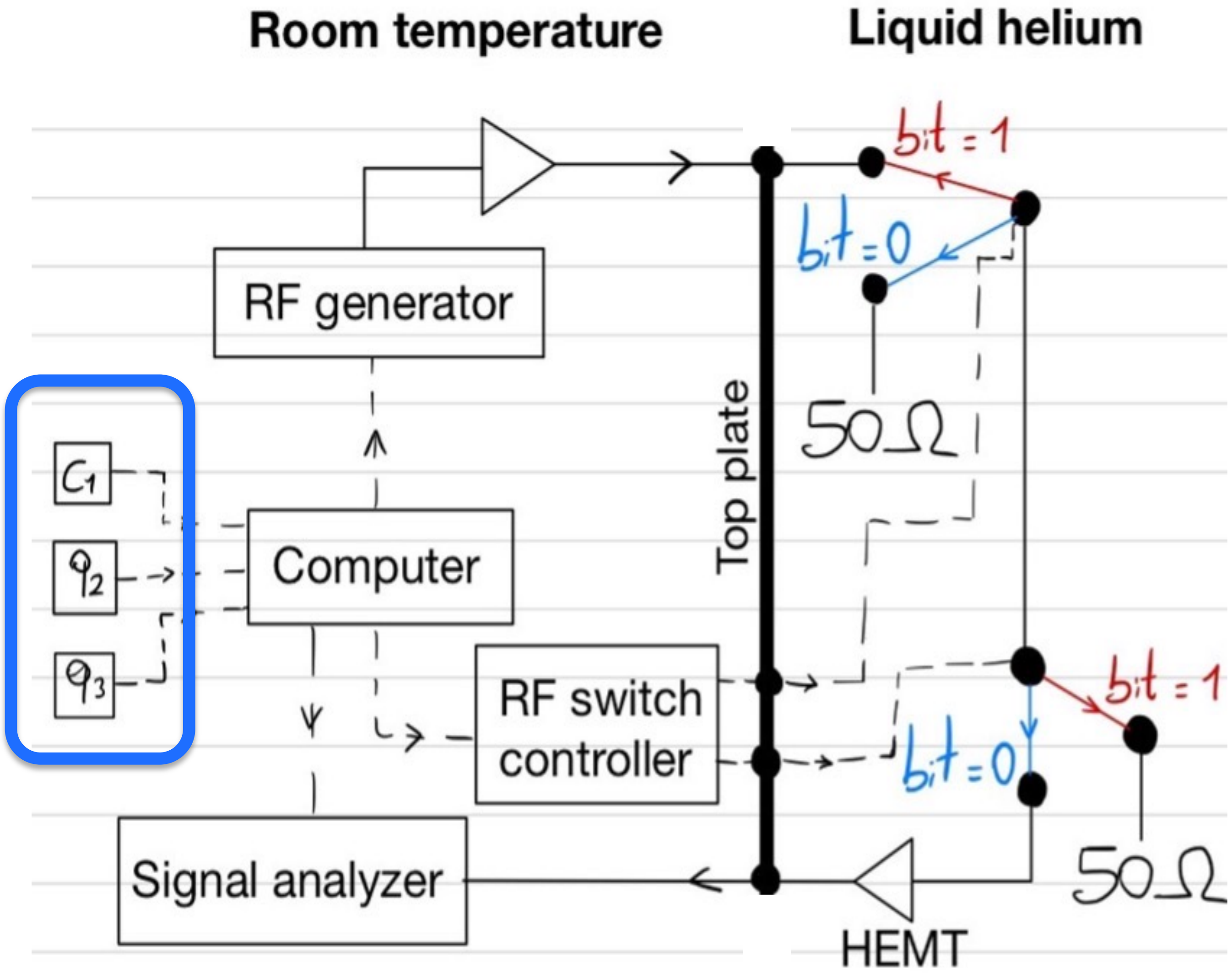






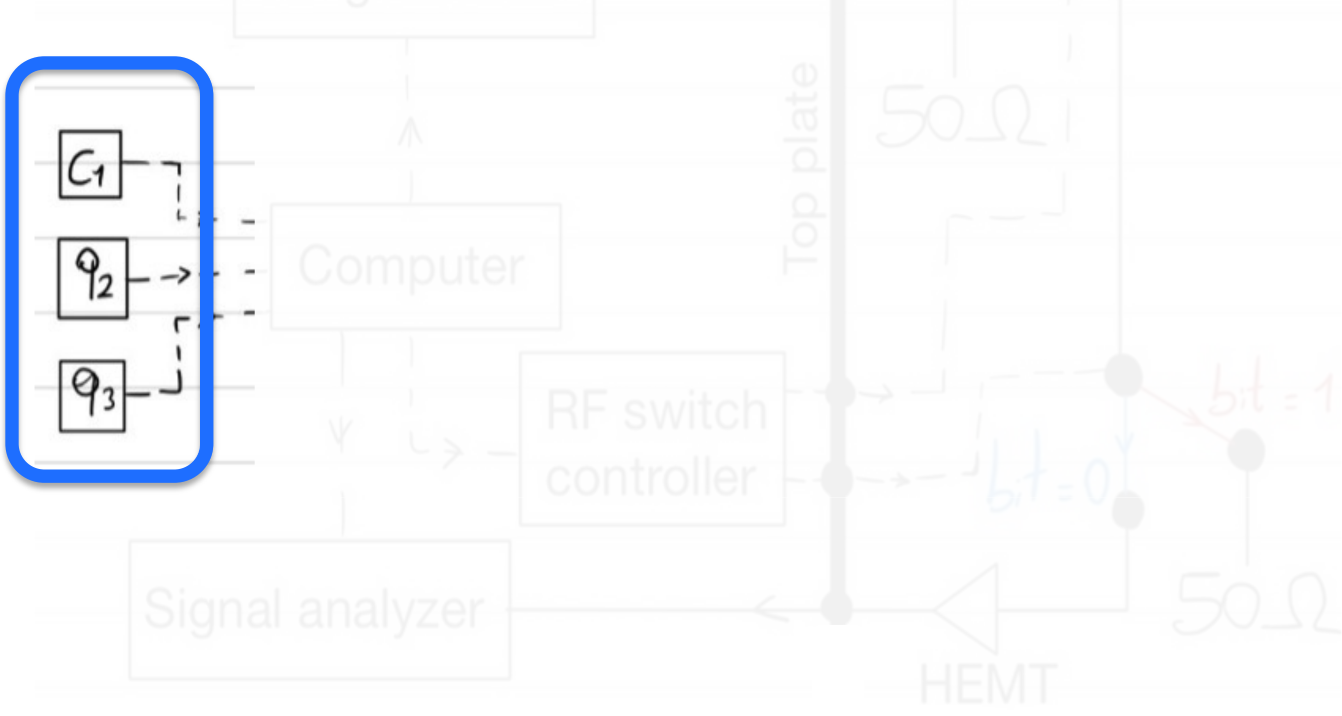
the switches were not designed for LHe operation, but it turns out they work fine in LHe (tested in 2K – 4.3K range)

Randomly Generated Bit samples



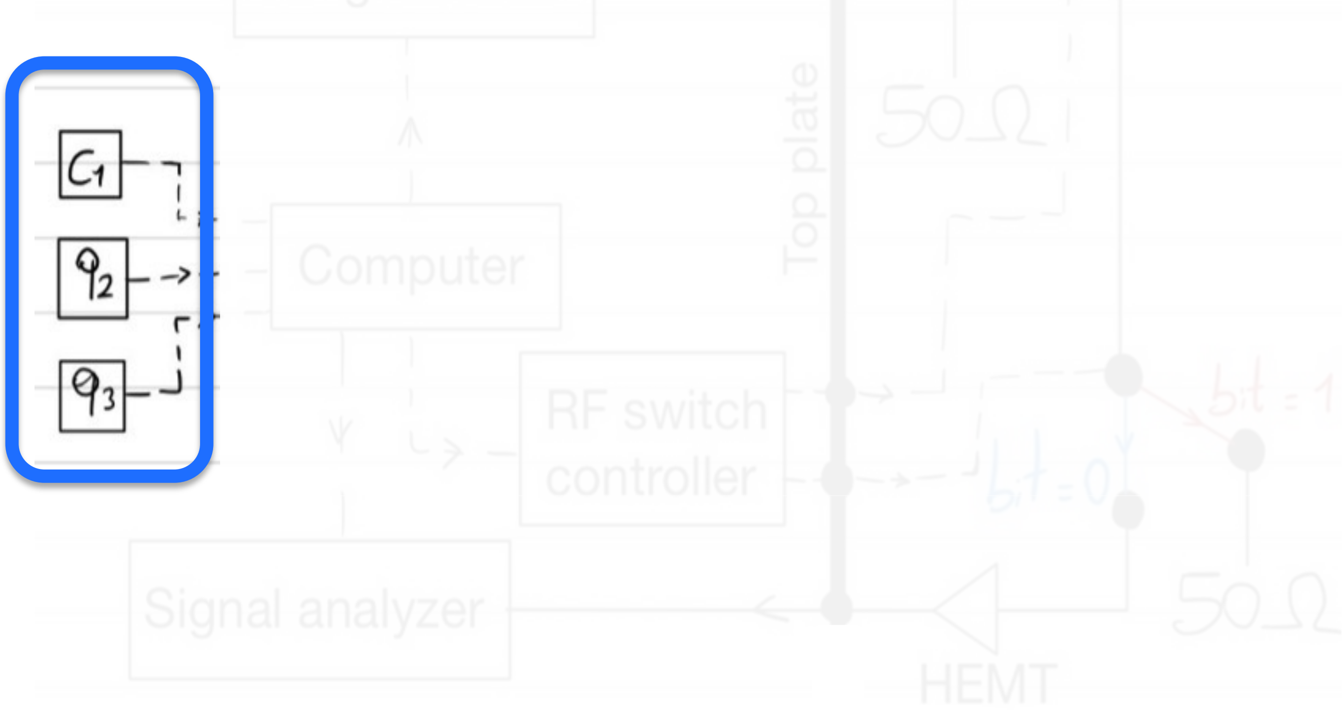
Bits in upcoming NLQM search

- In advance of the experiment create three bit sequences ≡ samples, using random number generators:
  - classical (c1)
  - quantum (q2)
  - another quantum (q3)



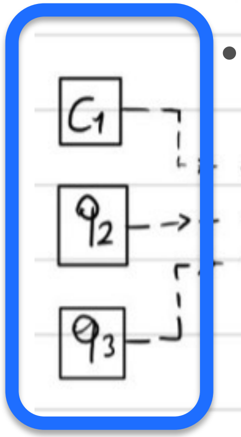
Bits in test run of August 2023

- In advance of the experiment create three bit sequences ≡ samples, using random number generators:
  - classical (c1)
  - ~~quantum~~ (q2) second classical
  - ~~another quantum~~ (q3) third classical



Bits in test run of August 2023 (Short version of the slide)

- In advance of the experiment create three bit sequences ≡ samples, using random number generators:
  - classical (c1)
  - ~~quantum~~ (q2) second classical
  - ~~another quantum~~ (q3) third classical



- Then, still in advance of the experiment, randomly mix the three sequences into one sequence to be processed during the experiment

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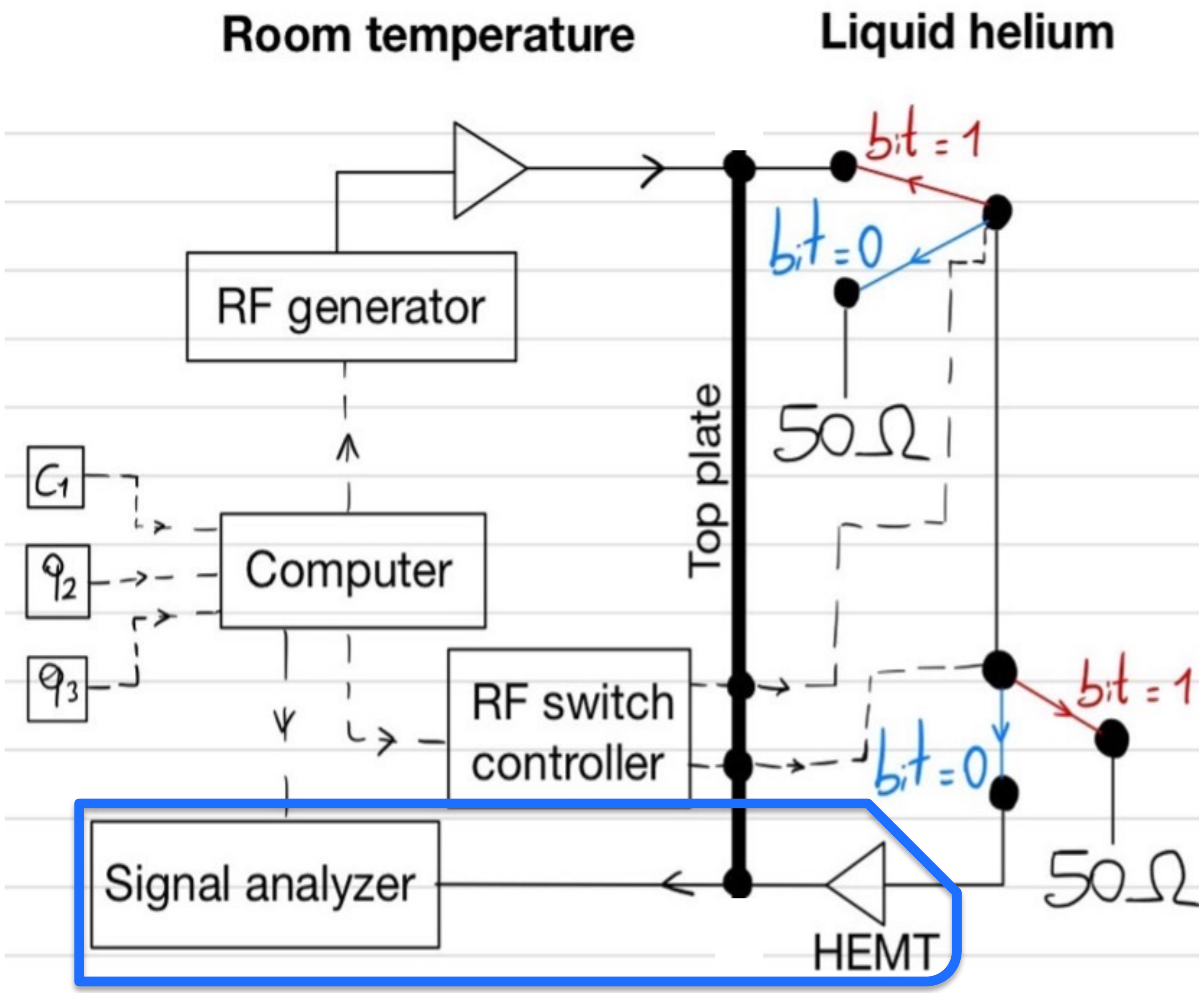
Readout Circuit



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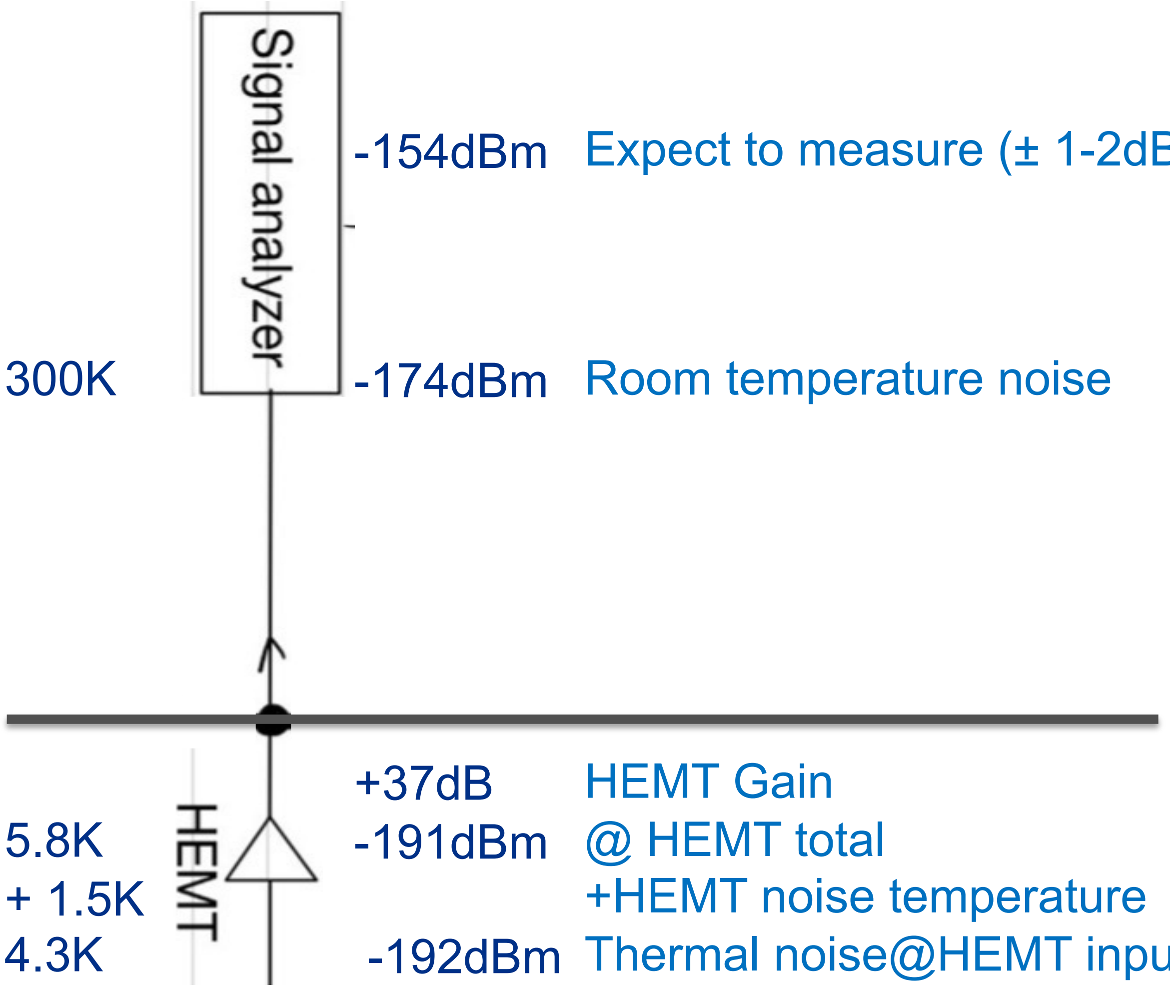


300K

-154dBm Expect to measure (± 1-2dBm)

-174dBm Room temperature noise

+37dB HEMT Gain

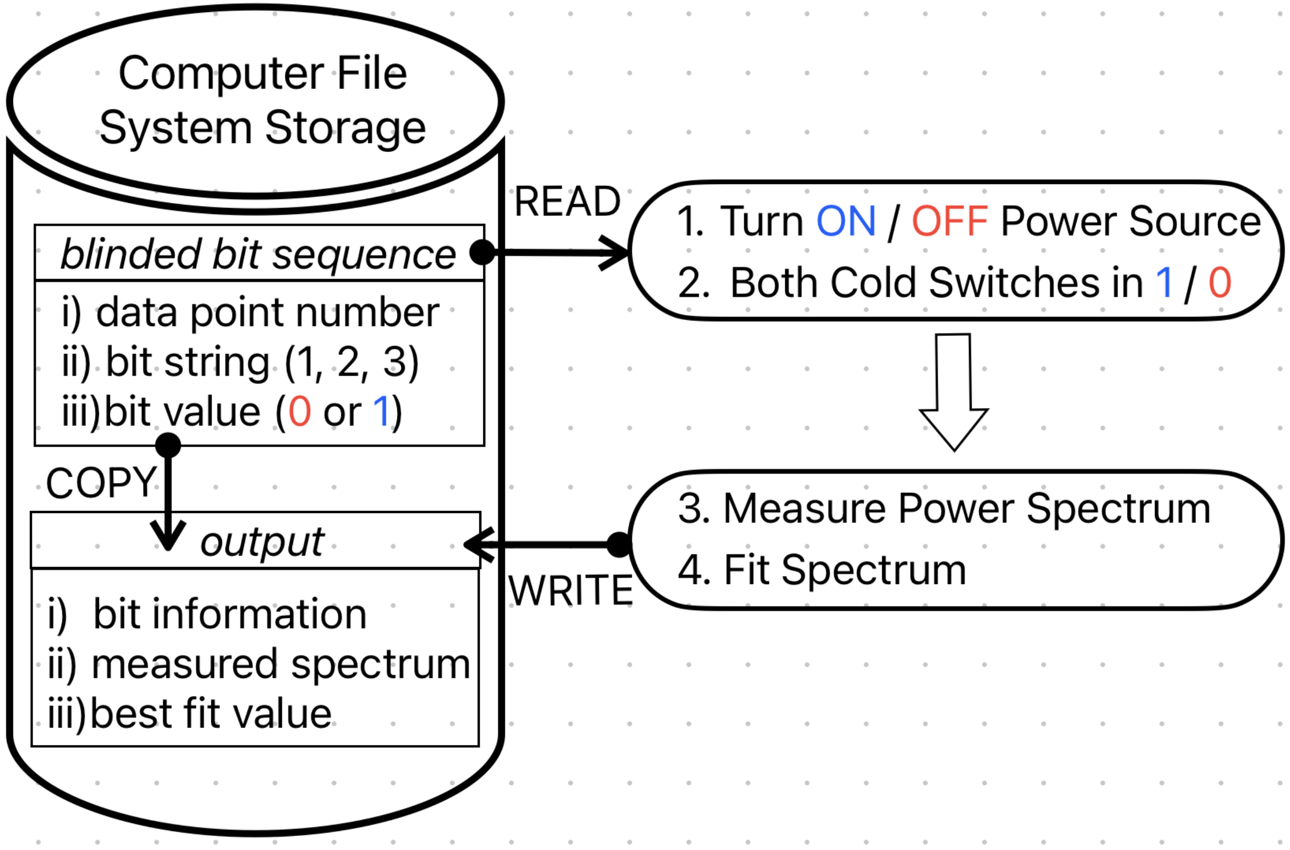
5.8K -191dBm @ HEMT total

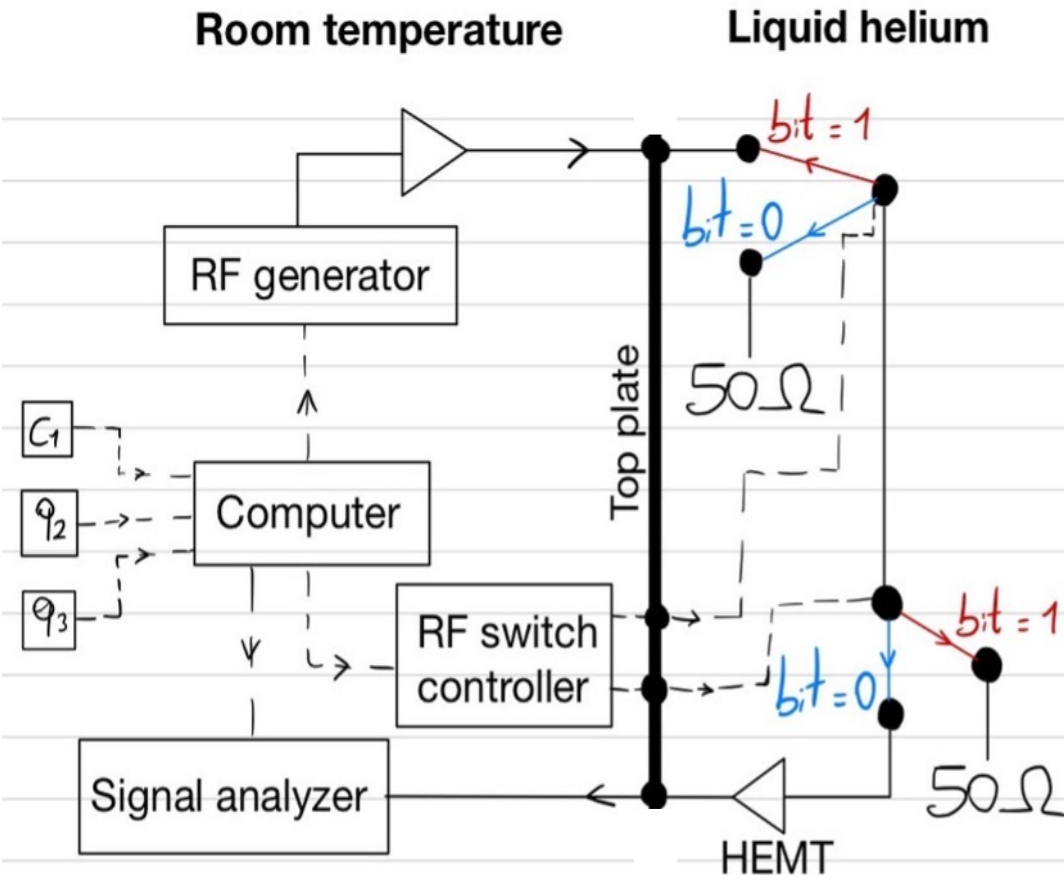
+ 1.5K +HEMT noise temperature

4.3K -192dBm Thermal noise@HEMT input

in bit=0 case HEMT input is 50Ohm-terminated

Main Script Layout





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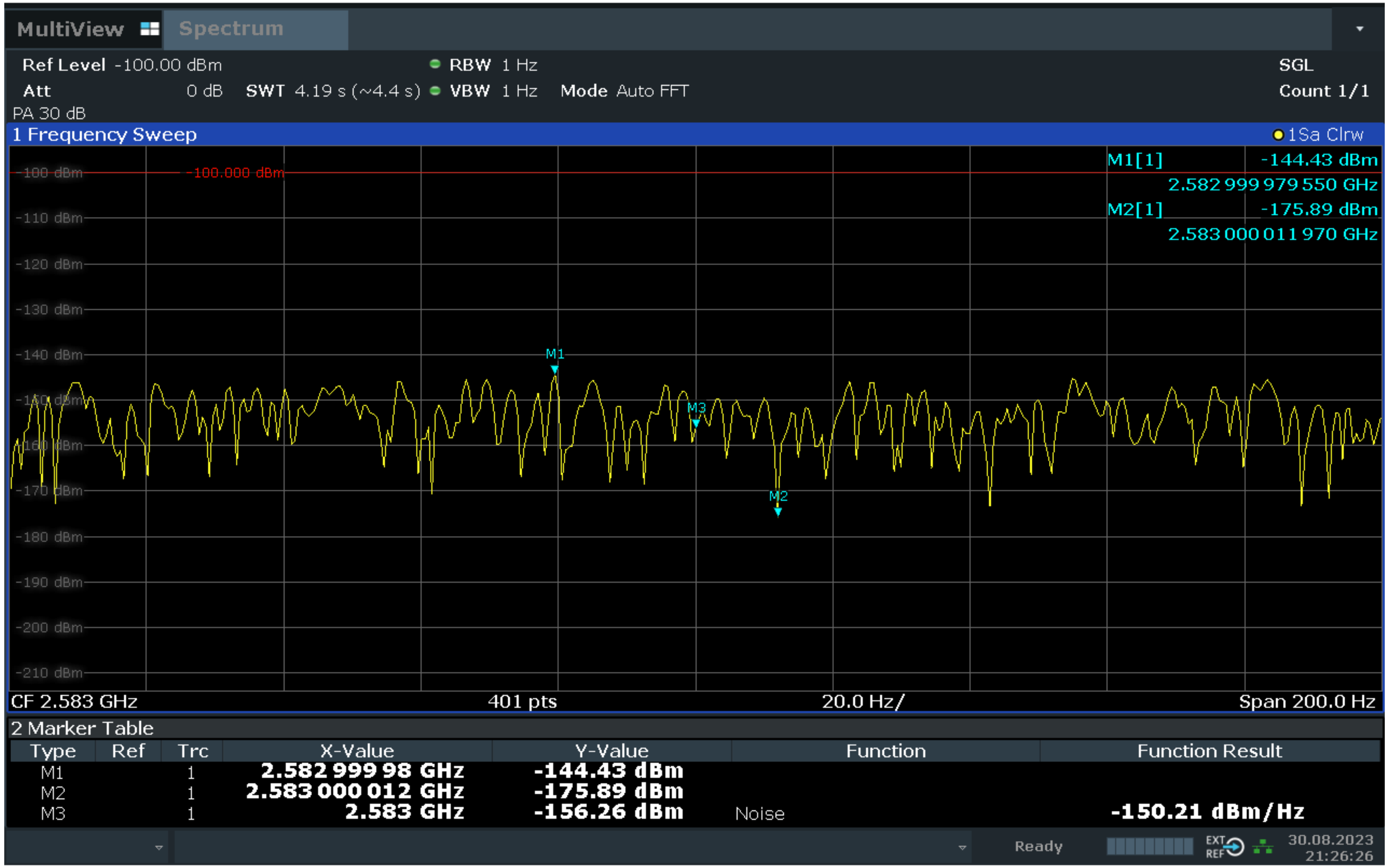
Signal Analyzer Scan Example

BW=1Hz 800 data points (4.5 hours)

Approximately half of these data points are of our interest (bit=0 cases)

One scan ≡ one data point example



21:26:27 30.08.2023

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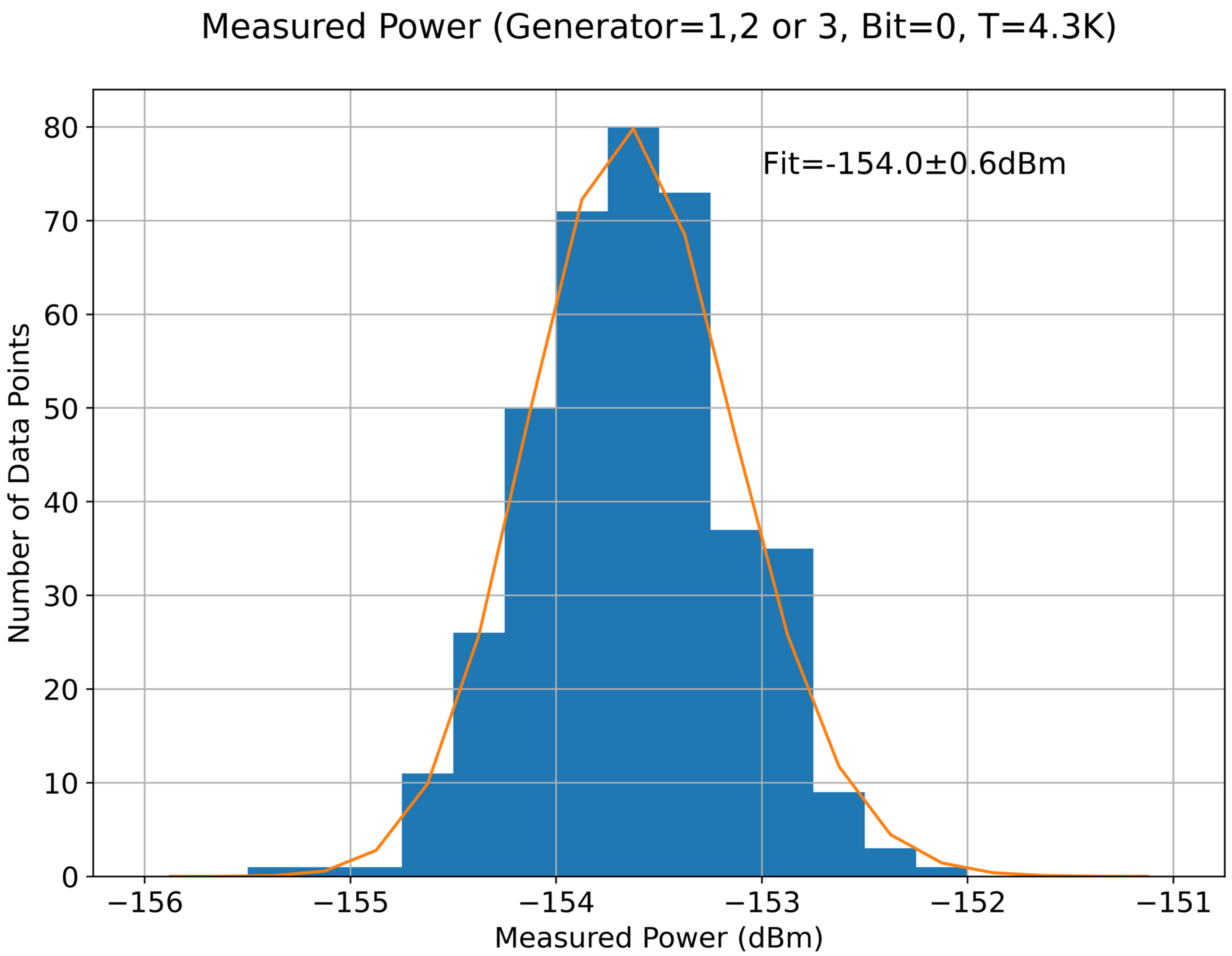
Measured Power Distribution (bit = 0 cases)



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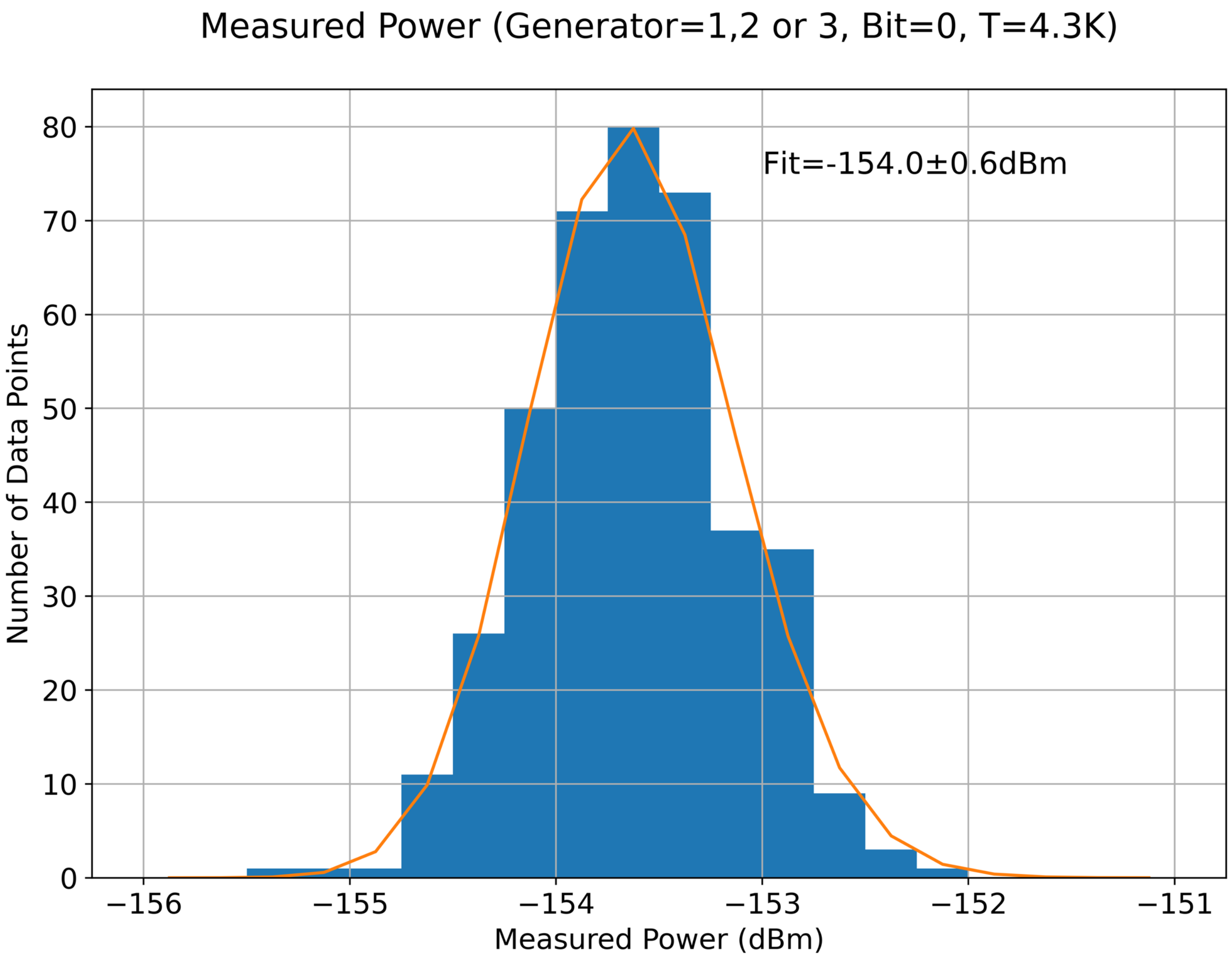
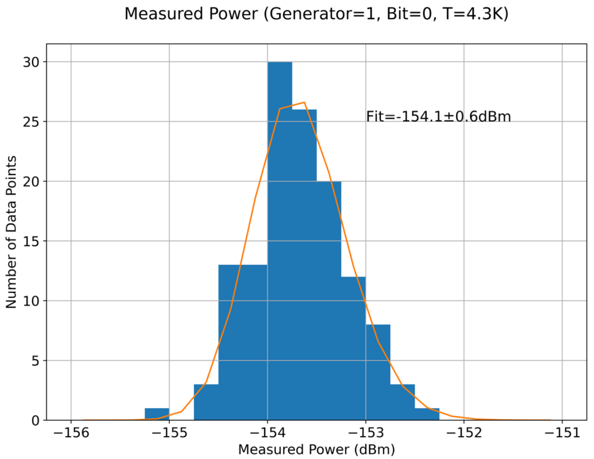
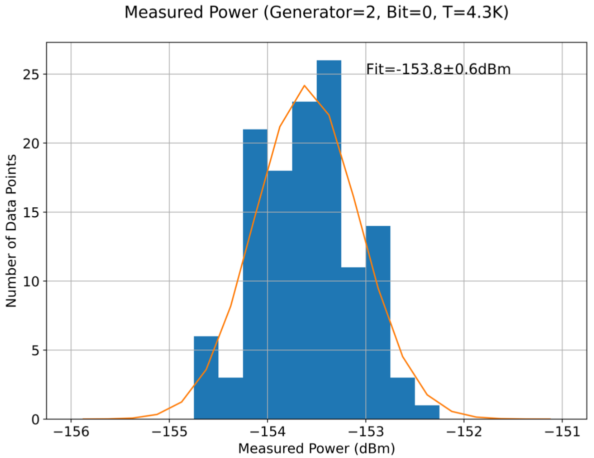
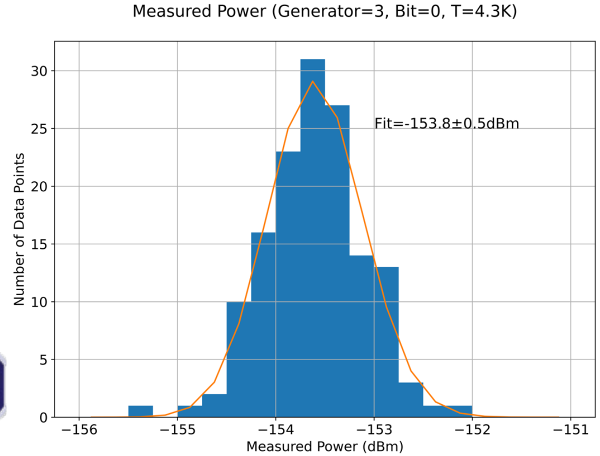
Measured Power Distribution (bit = 0 cases)









Results

```
MEASUREMENTS:
P_measured_dBm=-154
P_calibrated_dBm=-191
P_maximum_W=5

CALCULATIONS:
P_maximum_dBm=36.98970004336019
P_numerator=-191
P_denominator=36.98970004336019
ratio_dB=-227.9897000433602
ratio_lin=1.5886564694485 58e-23

RESULT:
epsilon=3.985795365355023e-12
```

Our result ε = 4E-12 is similar to the corresponding result from arXiv:2204.11875 (6e-12)

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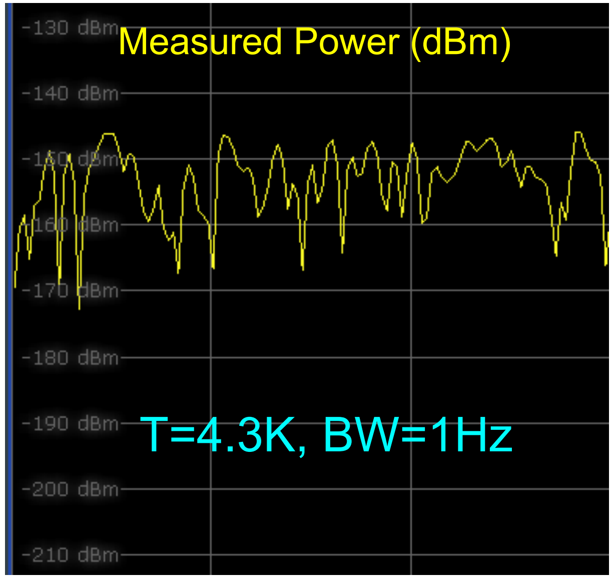
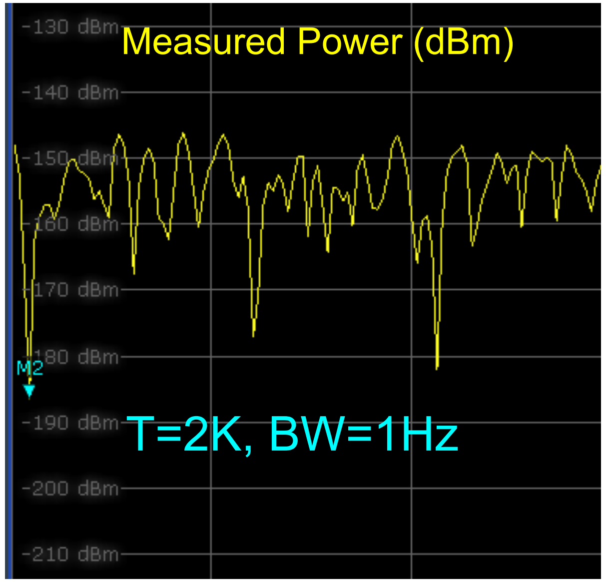
Possible improvements to sensitivity

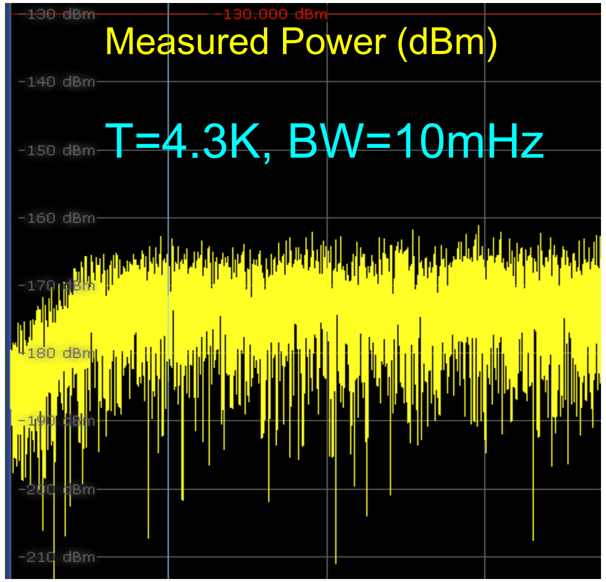
in the search mode we are measuring kBT



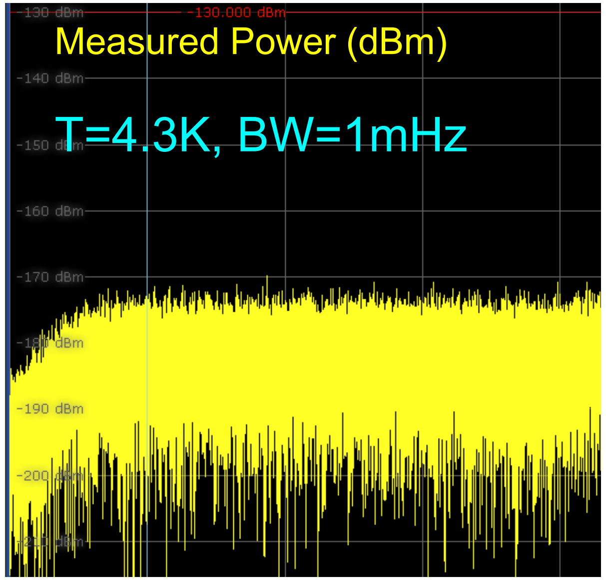
Power -154dBm
Time 4.2 sec



Power same (1 scan)
Time same



Power -15-20dB
Time × 21



Power -8-10dB
Time × 10

Source power can also be increased by 10-15dB

If all goes well, it may be possible to achieve improvement in sensitivity by two orders of magnitude

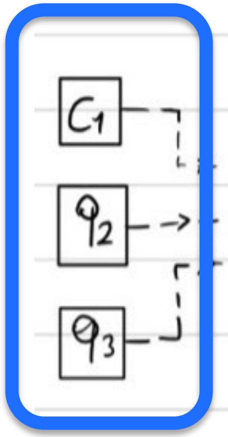
Conclusions and Outlook

- The setup of the NLQM experiment is working for the classical case
- Results look reasonable
- Need to finalize the version of the script for the quantum case
- Need to fix some network communication issues that interrupt running smoothly for longer times
- Need to agree on the choice of quantum bit samples and have them generated
- Need to agree on the proposed dilution-safe procedure for handling the samples
- Pursue various sensitivity improvements
  - Higher source power
  - Lower temperature
  - More narrow scan resolution bandwidth
- Hopefully first SQMS real NLQM experiment can be performed later this year

- Thank you for your attention

BACKUP SLIDES

Bits in test run of August 2023 (Long version of the slide)



- In advance of the experiment create three bit sequences ≡ samples, using random number generators:
  - classical (c1)
  - ~~quantum~~ (q2) second classical
  - ~~another quantum~~ (q3) third classical
  - two samples are generated on Rigetti cloud
  - classical, simulated version of Rigetti's Aspen-M 80-qubit quantum computer
  - use only one (simulated) qubit for generating one sequence
  - with and without active qubit reset → two samples
  - third sample generated with random package from standard python library
  - 10k bits in each of the three samples

- Finally, still in advance of the experiment, randomly mix the three sequences into one sequence to be processed during the experiment

GENERATING BITS (slide 1of2)

First, in advance of the experiment, we create three bit sequences, using one classical and two quantum random number generators. Procedures for the generation of bits and for verification of the generated bit samples are detailed in Appendix A

A Generating Bits for NLQM Experiments

Following the same approach as in [2] we are going to use the samples from three sources, two of which are of quantum nature and one classical. For quantum bits we are going to use Riggeti cloud that uses qubits and a comercially available card that uses quantum optics processes at room temperature.

The experimenters are never allowed to see the generated individual bits even after the experiment data analysis is complete. Moreover these bits should not be seen by any human

At the same time, it is permitted to display on the computer screen the properties of large numbers of bits in order to perform very basic verification that the bit string is acceptable for the experiment. We chose the following acceptance criteria: between 40% and 60% of generated bits are ones and the first half of the bits contains between 40% and 60% of ones.

The requirements described above are self-imposed in order to avoid 'quantum dilution' ('quantum pollution') described in section 5.1.4 of [3].

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GENERATING BITS (slide 2of2)

A.2 Rigetti Quantum Bit Samples

Some quantum bits for NLQM experiment are going to be generated on Rigetti's [4] "Aspen-M" 80-qubit quantum computer following this procedure:

1. Start from qubit ground state
2. Apply Hadamard gate (create superposition of ground state and excited state in the same basis where the ground state was made)
3. Readout qubit state $\rightarrow$ this is our result (bit=0 or bit=1) $\rightarrow$ write the result into a classical register[3]
4. Go back to the ground state (if not in the ground state) and repeat from step 2. to generate the next bit[4]

There are three types of infidelities associated with this process:

(i) H-gate operation infidelity (also called single qubit infidelity?)

(ii) Measurement infidelity

(iii) Reset infidelity (for the samples where active reset is used).

[4]this can be achieved either via natural decay to ground state (about 500 microseconds) or active reset, the latter is faster (about 300 microseconds) but it introduces additional infidelity compared to natural decay.

Measurement infidelity is expected to be by far the worst infidelity of this process. The fidelities vary in time and therefore they are determined during calibration runs that are performed every 6 hours. When we run the generation we can look up the fidelities from the latest calibration run.

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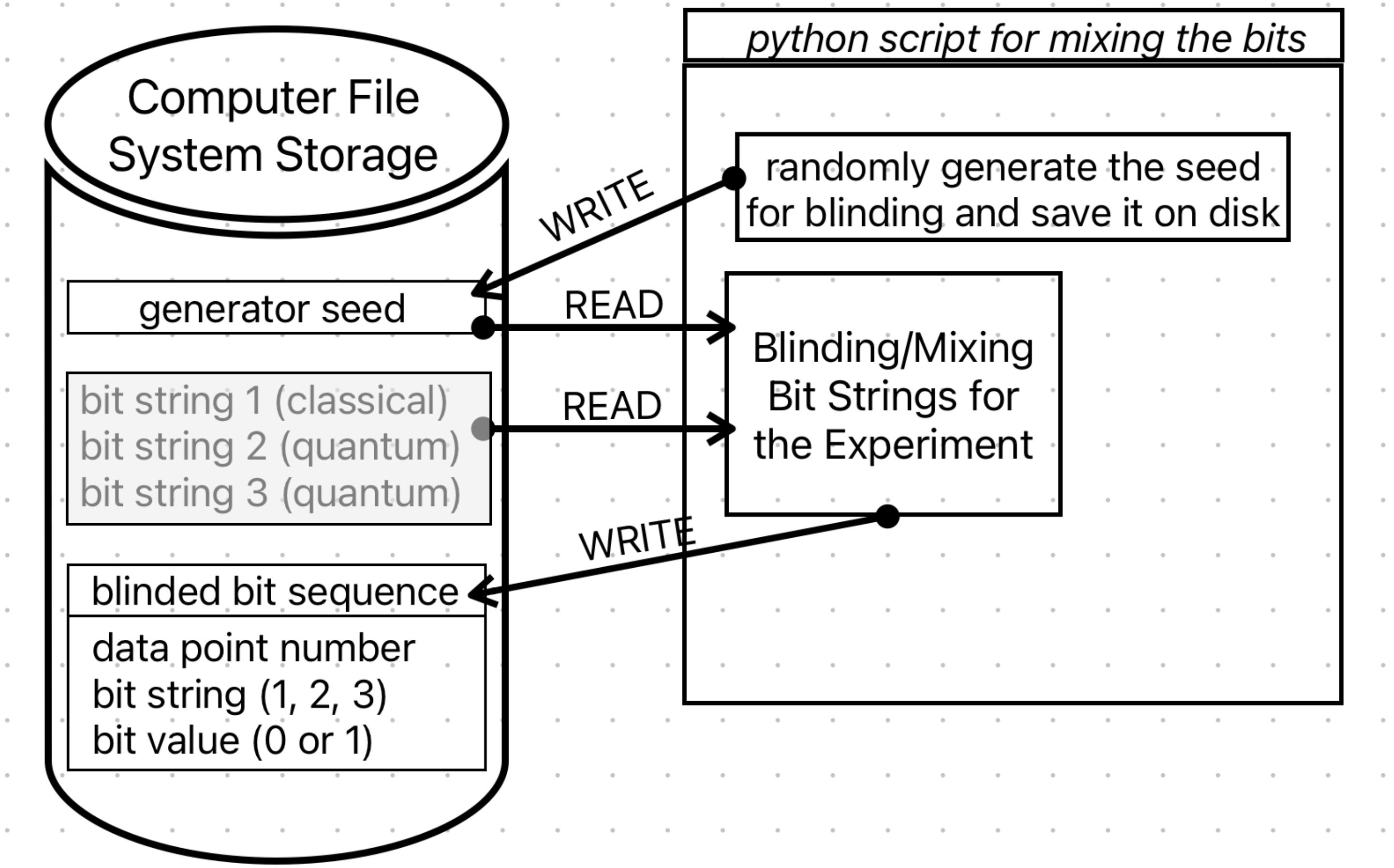
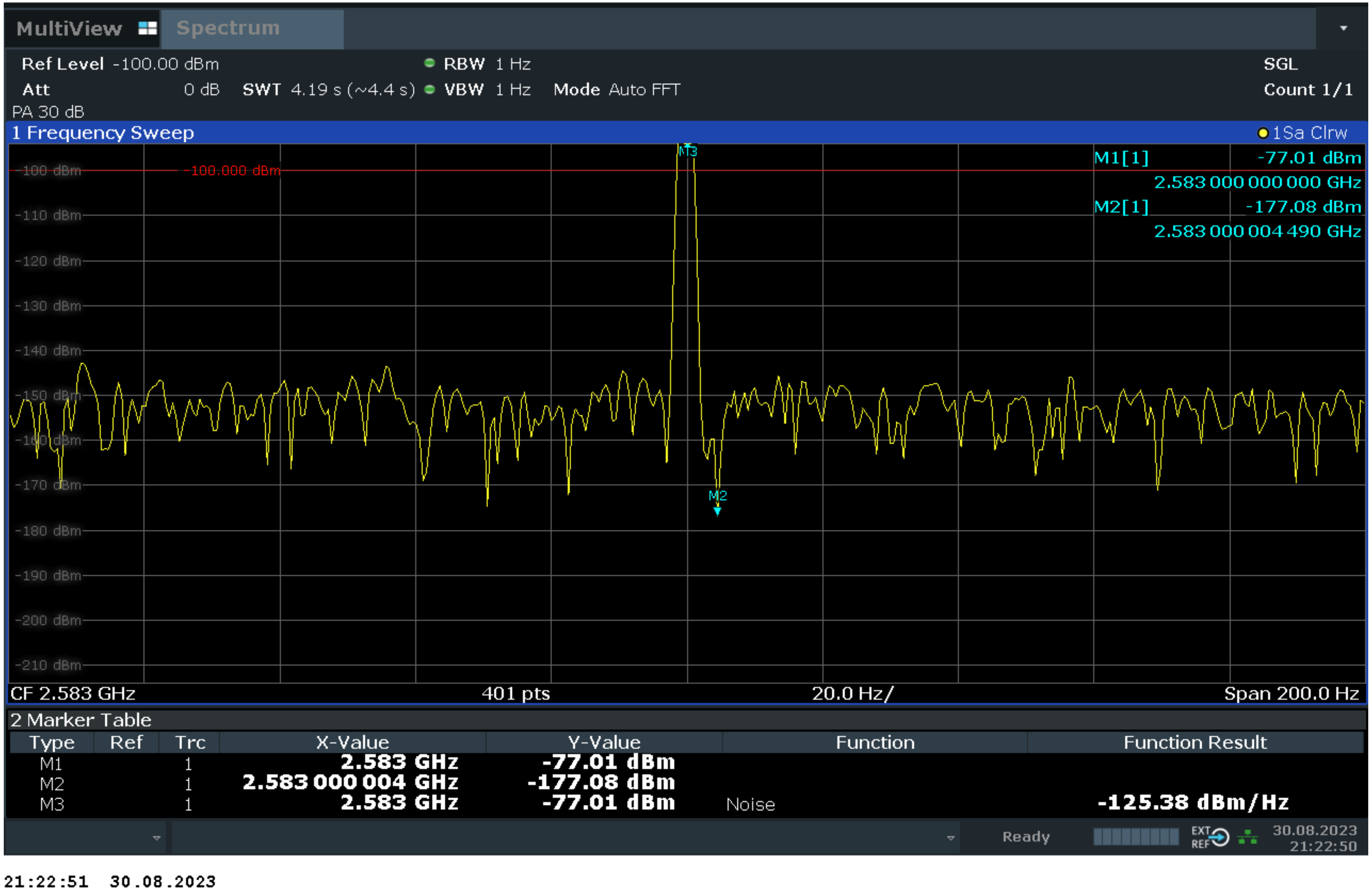
MIXING THE BITS



[2]In order to ensure a reproducibility of creating the same mixed bit string we initiate a random number generator with a certain seed. The value of the seed is generated according to `random.randint(1,10000)` and is stored in the dedicated output text file but remains unknown to the experimenters until a need may arise to look it up after the data analysis is completed. In principle, the experiment is designed in such a way that the value of the seed should not be ever needed in the future. We will save it just in case we are overlooking at the moment a potential need for it in the future.

BIT=1
Scan Example



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A Few Relevant Points

- ***Many Worlds(Branches)*** of Quantum Mechanics is a different concept than multiverse, parallel universes

- Many Worlds
  – are all part of our Universe
  – share the same space-time

- The following is guaranteed even in the presence on non-linearity: **we will not** observe a second version (from another world) of any workshop speaker walking into this lecture hall while the first version is giving his/her presentation

- This research belongs strictly to the realm of physics (no mixing in e.g. psychology, philosophy)