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Exploring AI/ML tools for axion dark matter detection

ML4FE Workshop,
University of Hawaii

May 2025

Christian Boutan
Physicist

U.S. DEPARTMENT OF ENERGY BATTELLE

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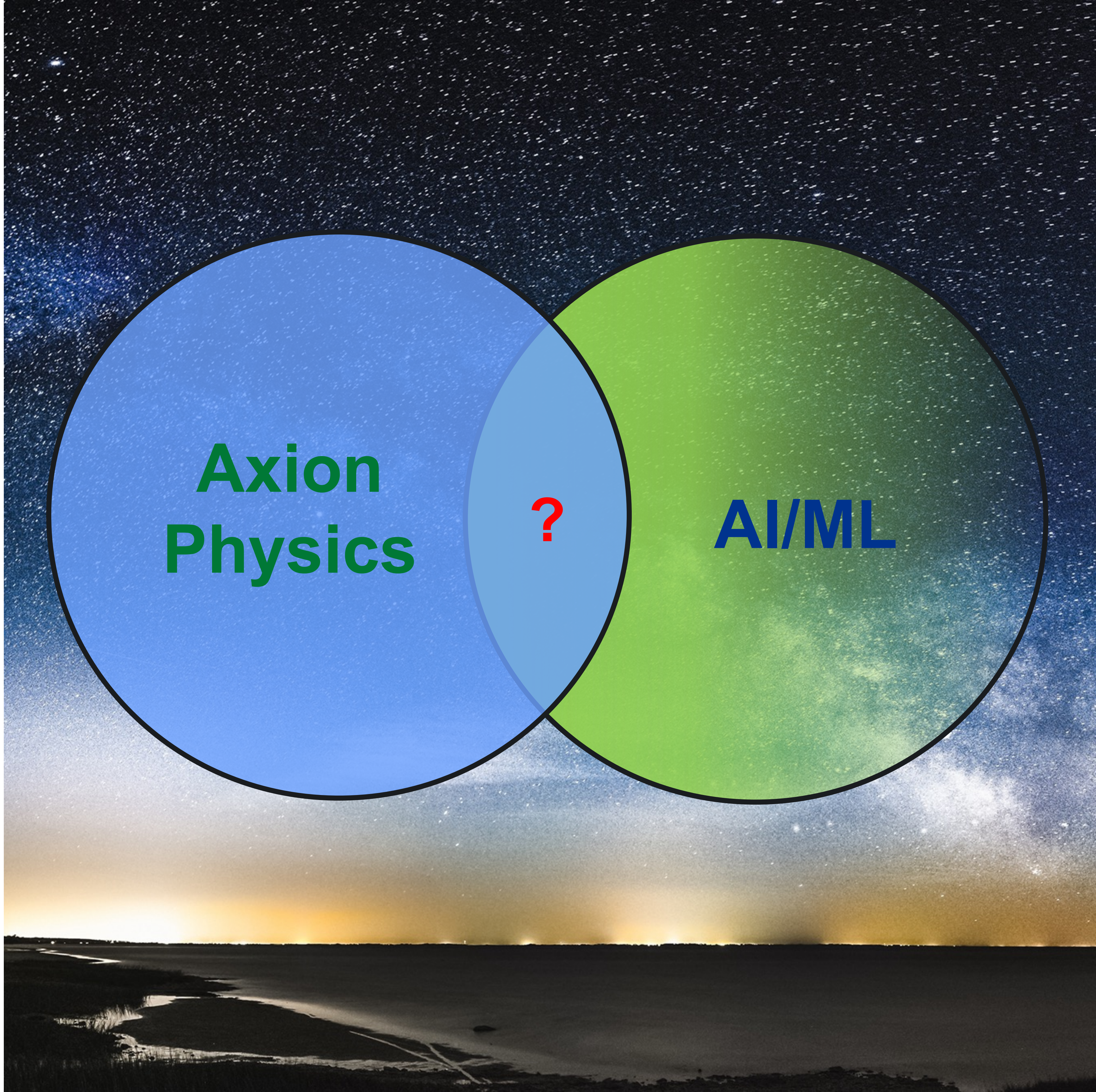
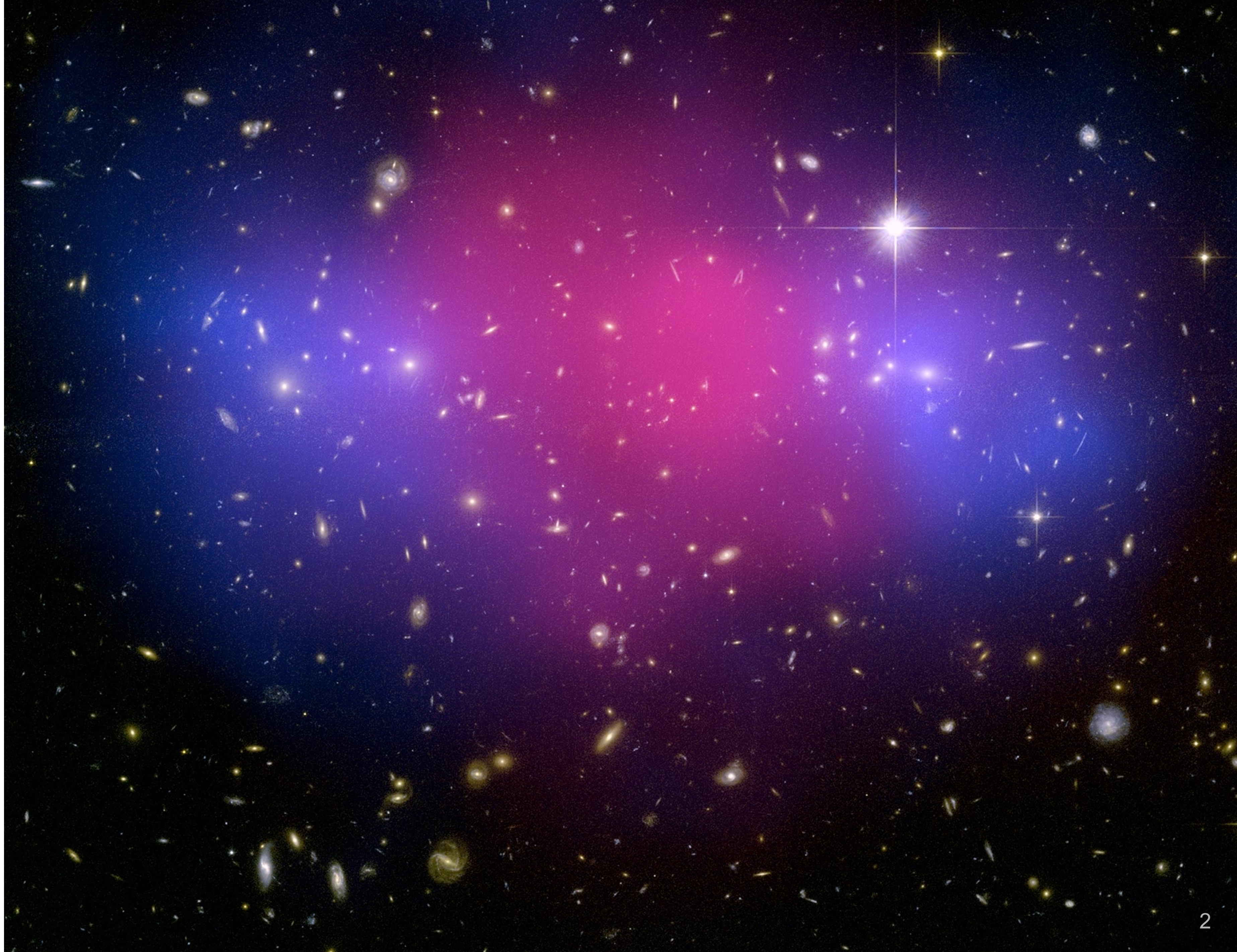


Dark Matter would explain a lot of things

- Galaxy Motion
- Rotation Curves
- Gravitational lensing
- Bullet Cluster
- Nucleosynthesis
- BAO + CMB
- Simulations



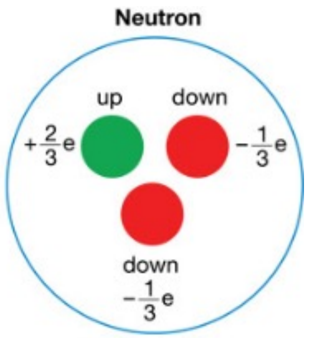
Dark Matter Candidates

Strong CP Problem

- Strong force Lagrangian contains a CP-violating term

$$\mathcal{L}_\theta \propto \bar{\theta}\, G\, \widetilde{G}$$

- Implies measurable neutron electric dipole moment (EDM)



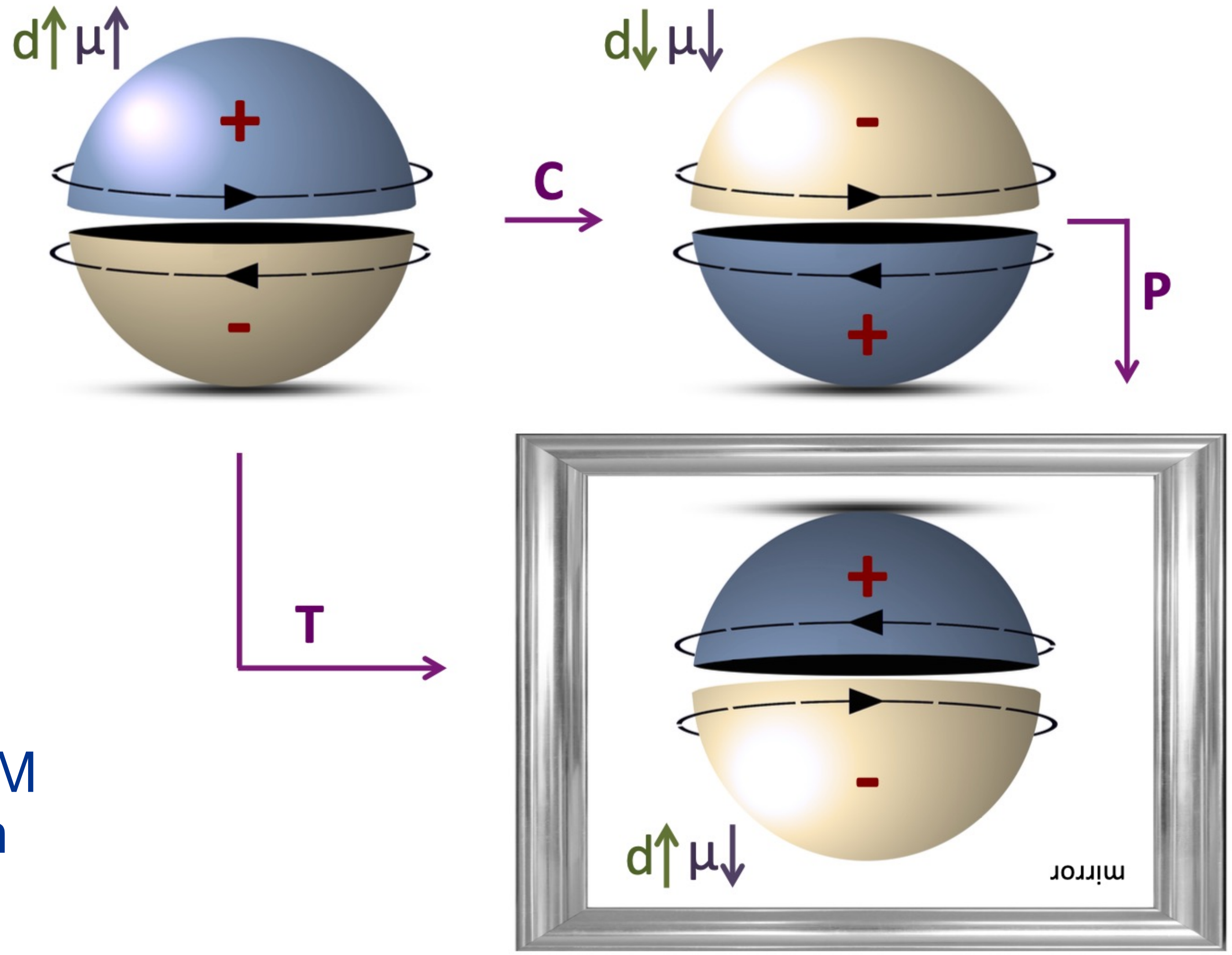
Theory predicted to be ~ 10^{-18}e m.

- Experiments constrain the neutron EDM close to zero implying CP conservation

$$d_n = (0.0 \pm 1.1_{stat} \pm 0.2_{sys}) \times 10^{-26}\, e\cdot cm$$

C. Abel et al. Phys. Rev. Lett. 124, 081803 — Published 28 February 2020

- Fine Tuning Problem



1977: Axions could restore order to the universe

The Peccei–Quinn solution to the Strong CP Problem creates the Axion as a biproduct of the theory

A new hope

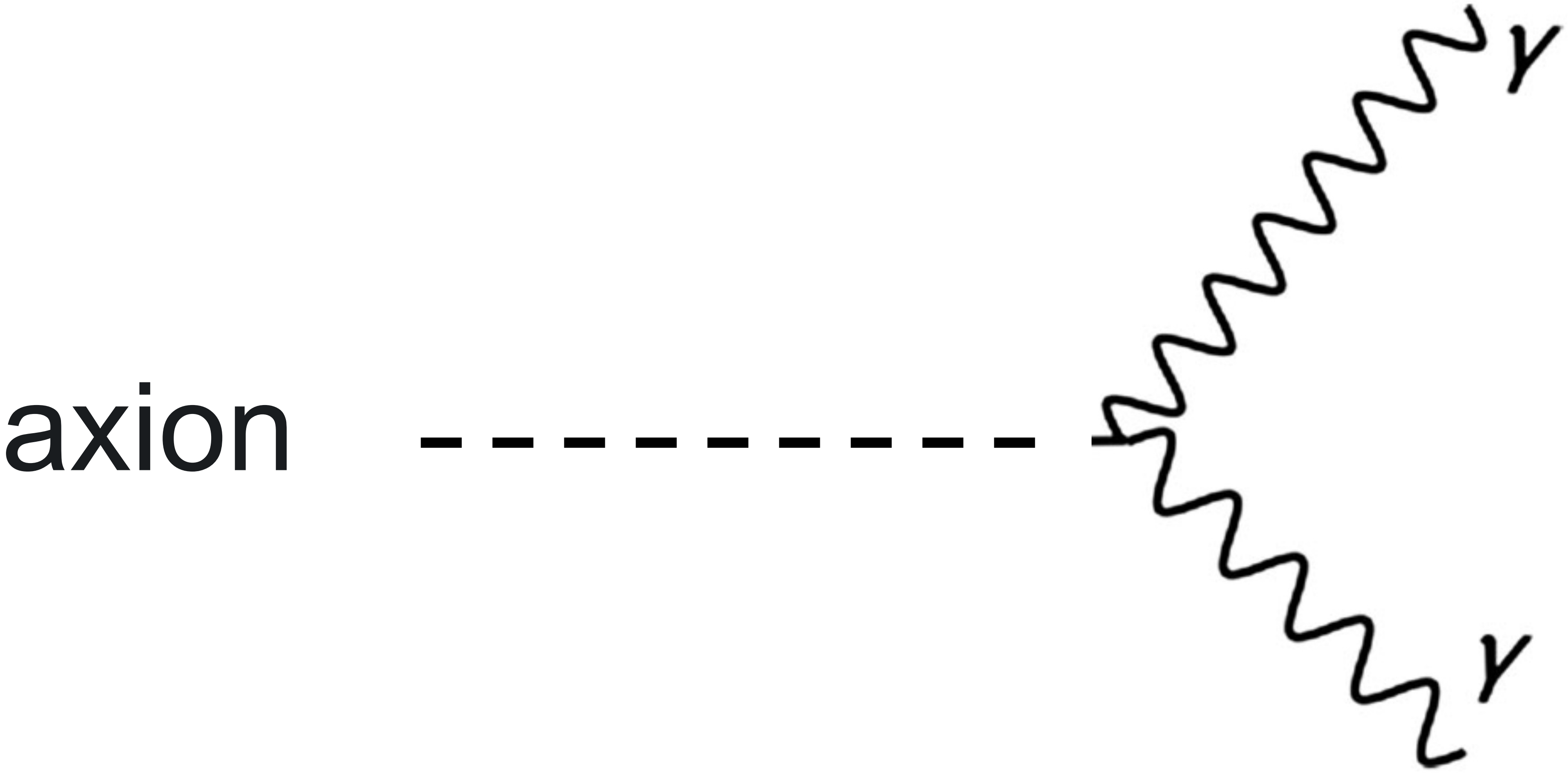
A new, spontaneously broken axial symmetry… gives you the axion

- The axion is the result of a particularly elegant solution to the “Strong CP problem”
- Naturally **light** and **stable**
- Mass:

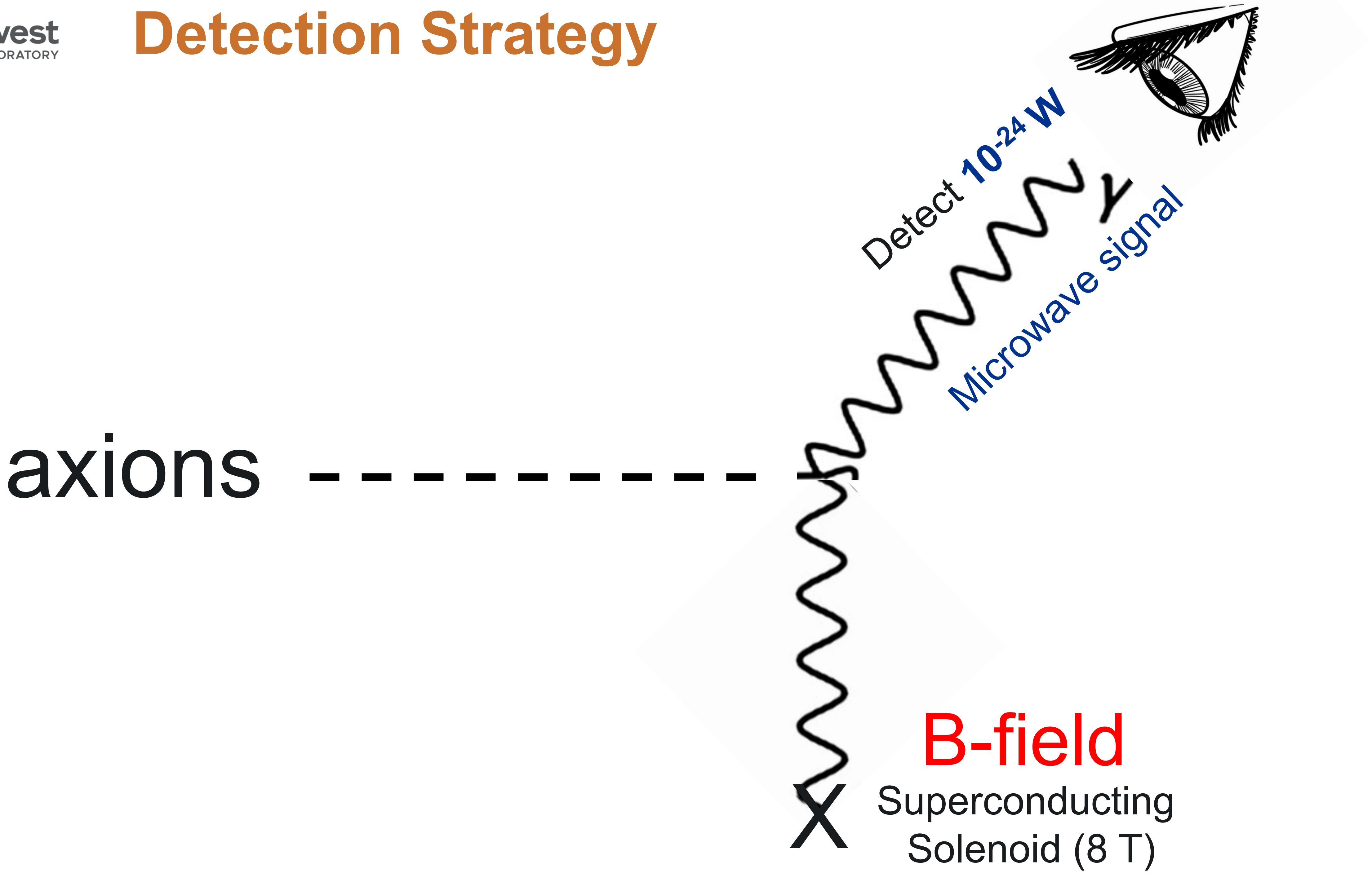
$$\text{Depends on who you ask } (\mu\text{eV or peV}) < m_a < 10^{-2}\,\text{eV}$$

- A discovery would solve two major problems in physics simultaneously!

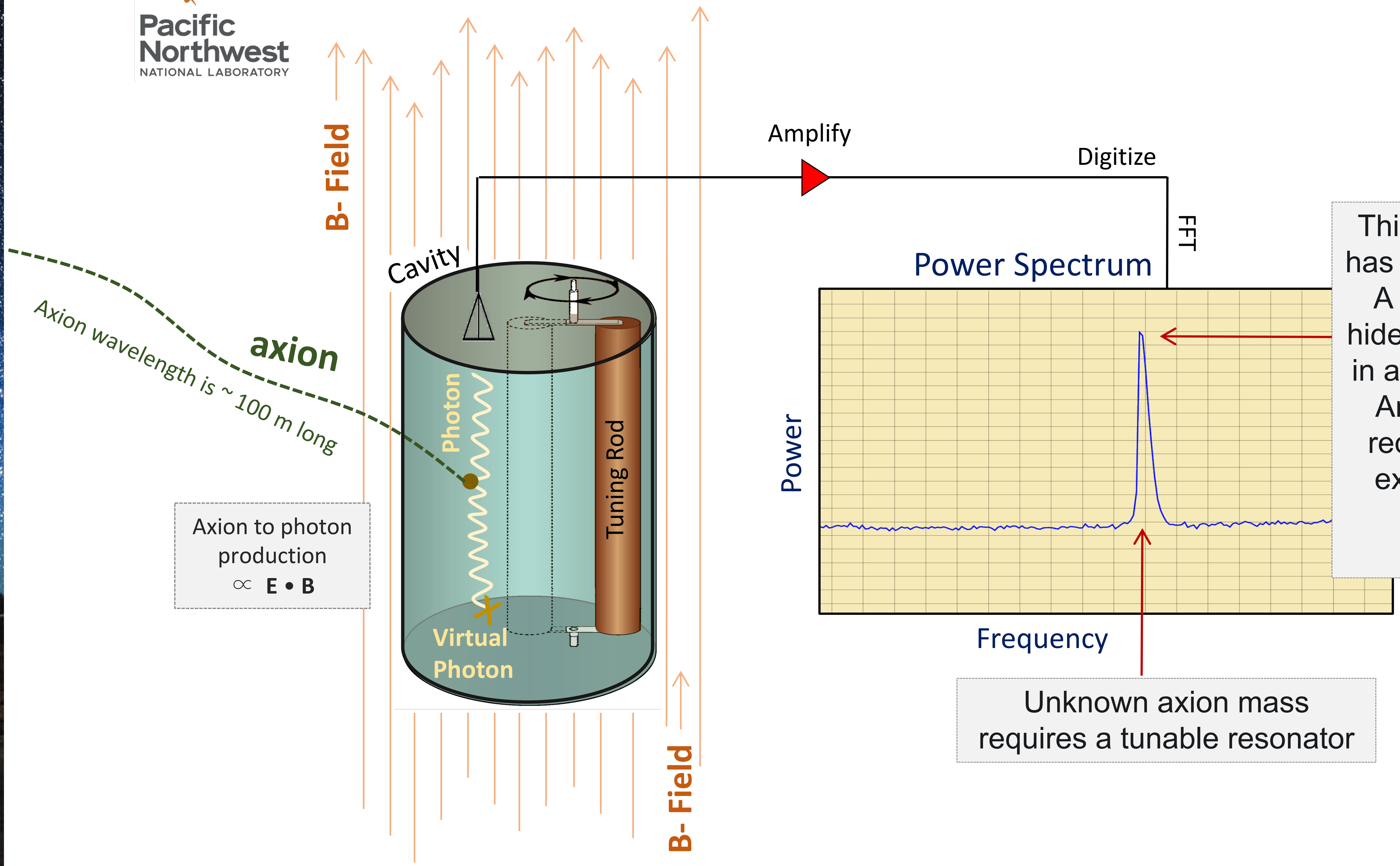
Detection Strategy



Detection Strategy



The Axion Haloscope



This axion line shape has been exaggerated. A real signal would hide beneath the noise in a single digitization. An axion detection requires a very cold experiment and an ultra low noise receiver-chain.

Unknown axion mass requires a tunable resonator

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Goal: Find Dark Matter axions,
or exclude them at high confidence

The ADMX Collaboration

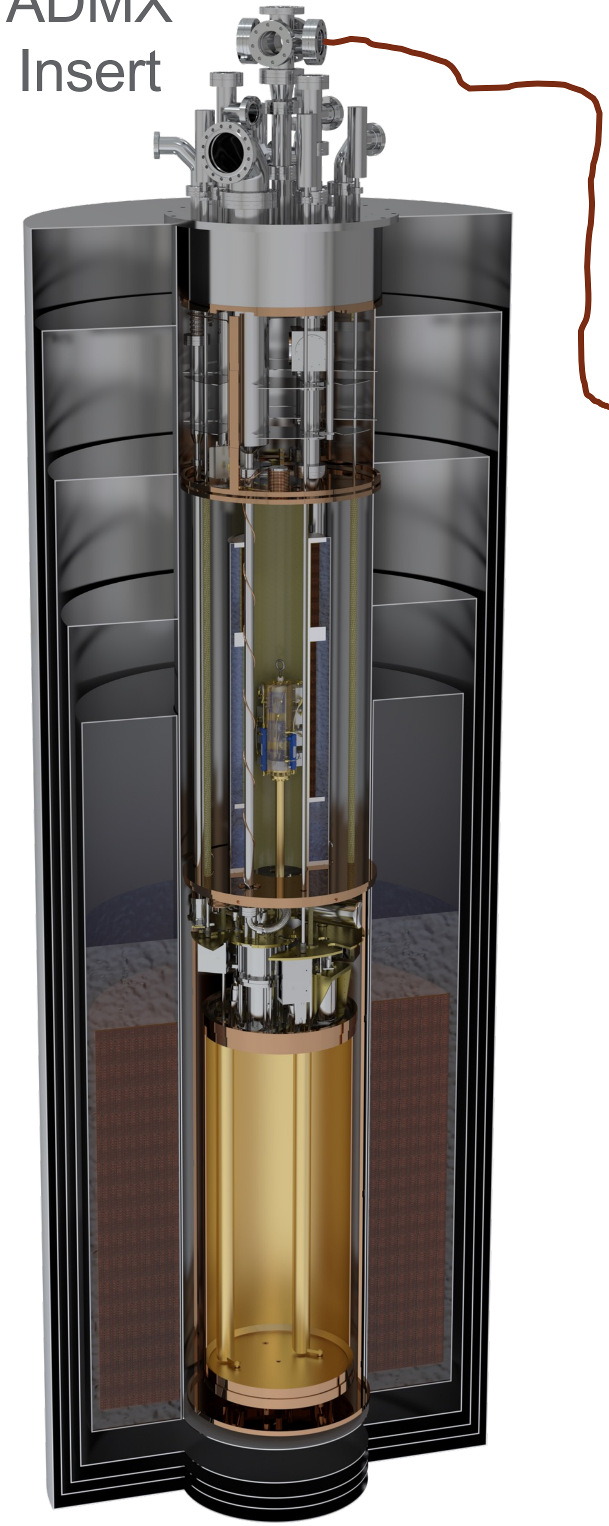
University of Washington 1861
Lawrence Livermore National Laboratory
Berkeley UNIVERSITY OF CALIFORNIA
The University of Chicago 1890
Fermilab
Pacific Northwest NATIONAL LABORATORY
Washington University in St. Louis 1853
UF UNIVERSITY of FLORIDA
The University Of Sheffield.
THE UNIVERSITY OF WESTERN AUSTRALIA
ILLINOIS INSTITUTE OF TECHNOLOGY
Los Alamos NATIONAL LABORATORY EST.1943

This work was supported by the U.S. Department of Energy through Grants No DE-SC0009800, No. DE-SC0009723, No. DE-SC0010296, No. DE-SC0010280, No. DE-SC0011665, No. DEFG02-97ER41029, No. DE-FG02-96ER40956, No. DEAC52-07NA27344, No. DE-C03-76SF00098 and No. DE-SC0017987. Fermilab is a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359. Pacific Northwest National Laboratory is a multi-program national laboratory operated for the U.S. DOE by Battelle Memorial Institute under Contract No. DE-AC05-76RL01830. Additional support was provided by the Heising-Simons Foundation and by the Lawrence Livermore National Laboratory LDRD office.

The ADMX Detector

Removal of the insert

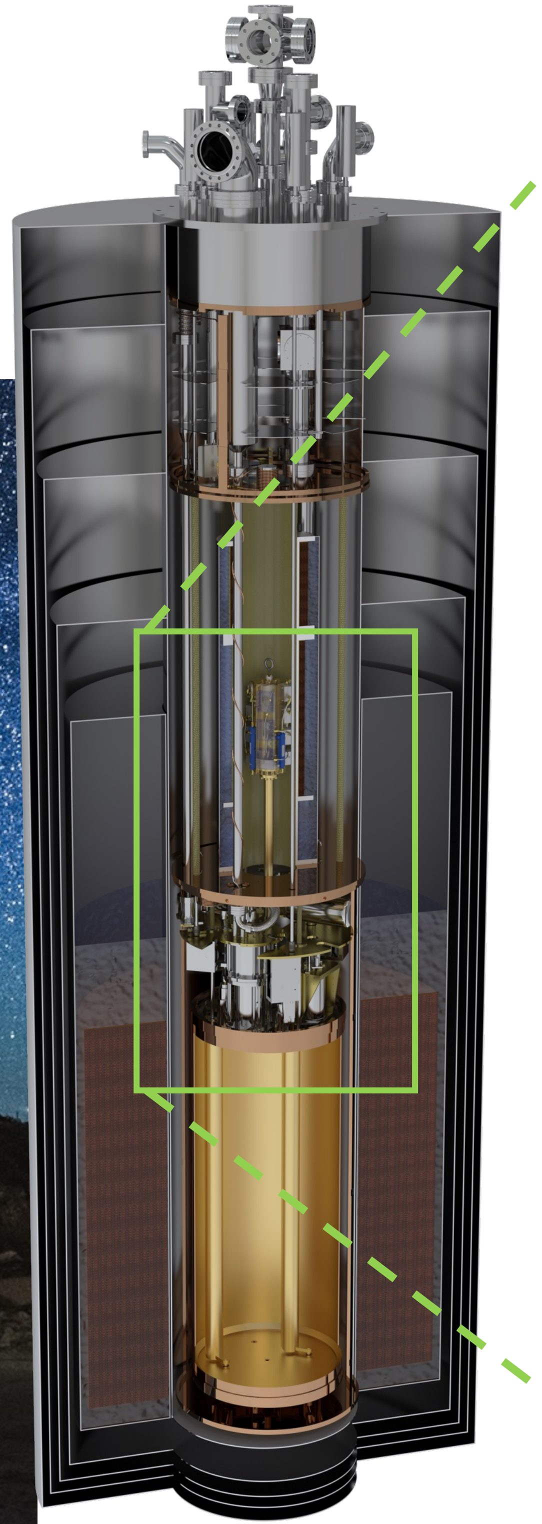
ADMX Insert

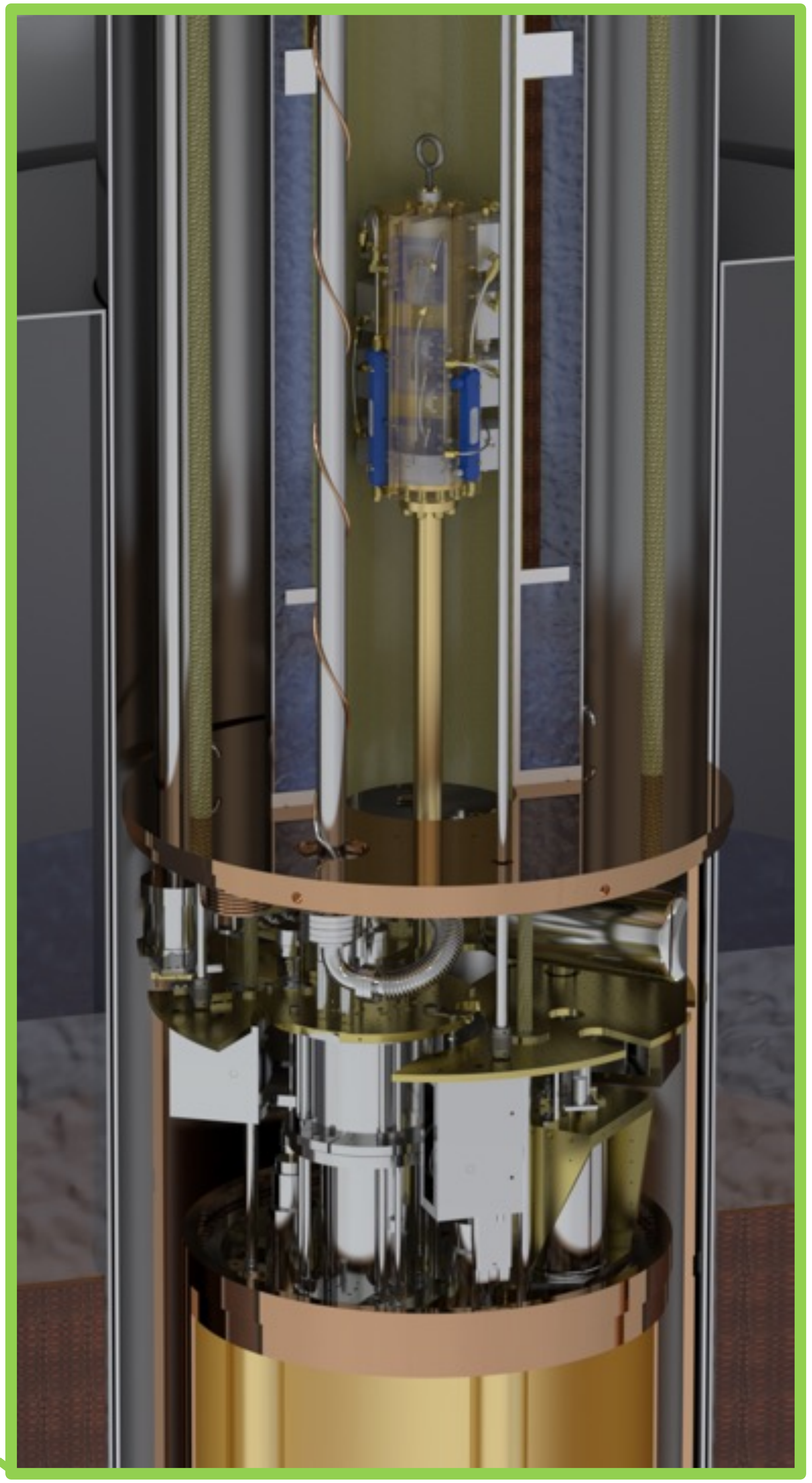


ADMX Receiver

TONY LUONG, NATIONAL GEOGRAPHIC

ADMX

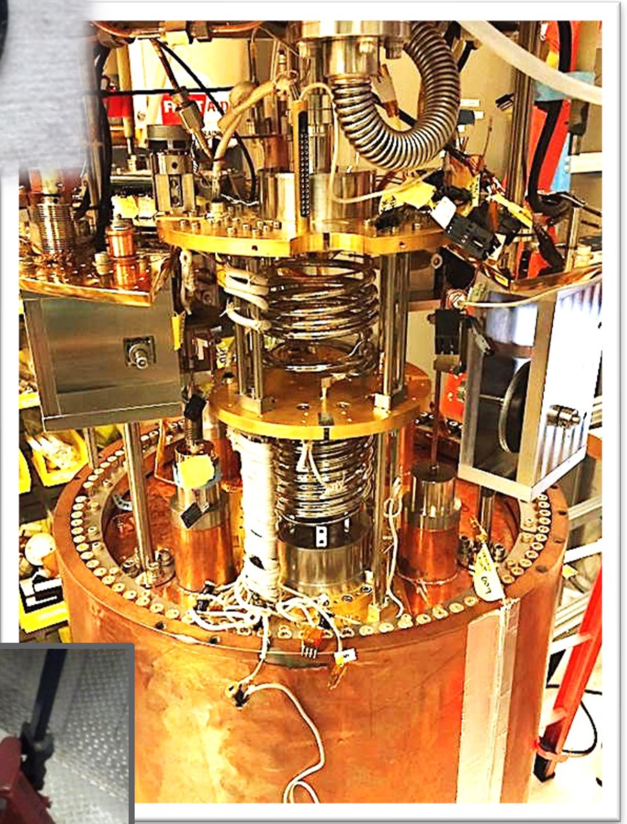




Josephson Parametric Amplifier

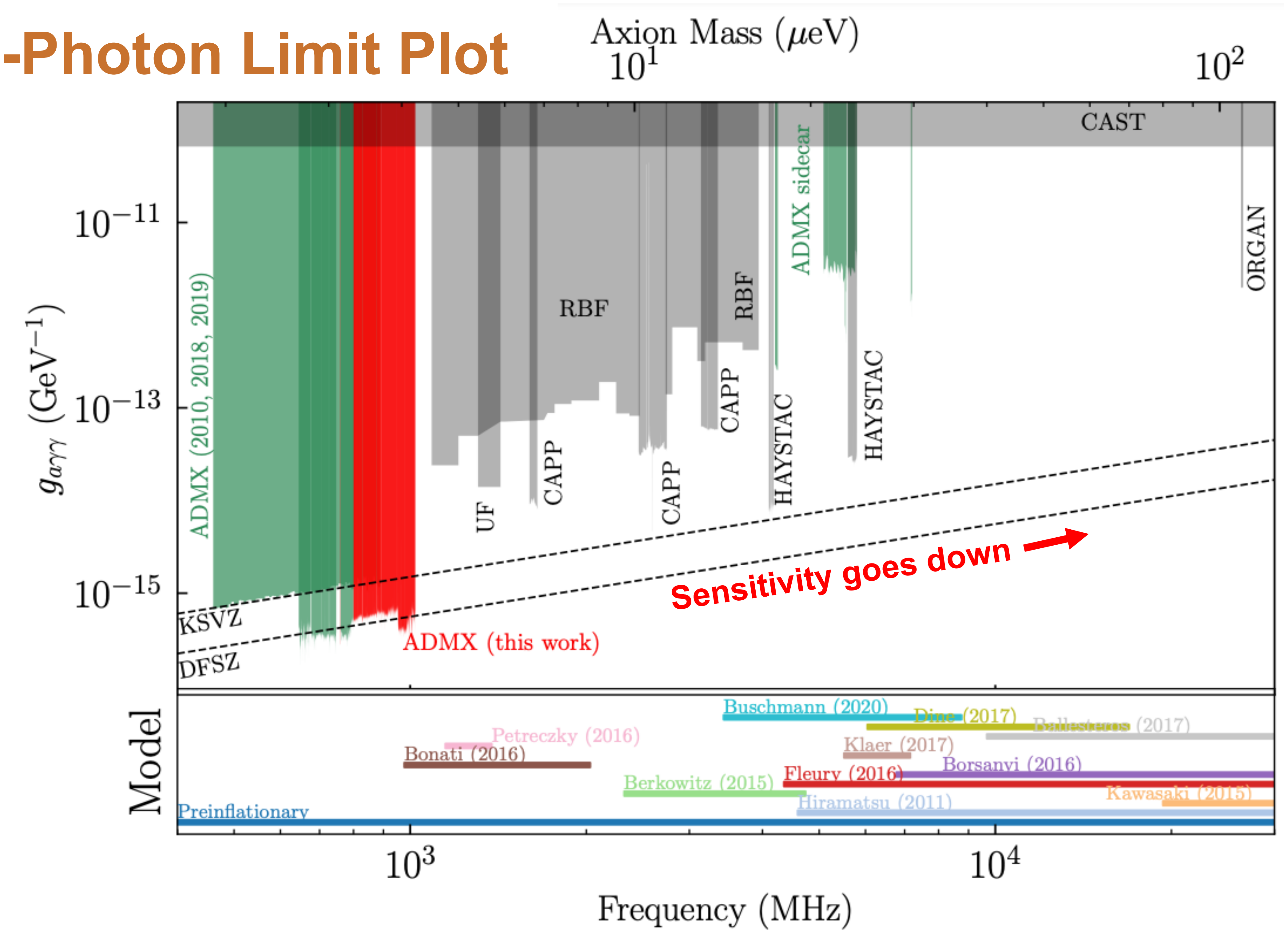
Yanjie Qiu, Siddiqi Group, UC Berkeley

Dilution Refrigerator

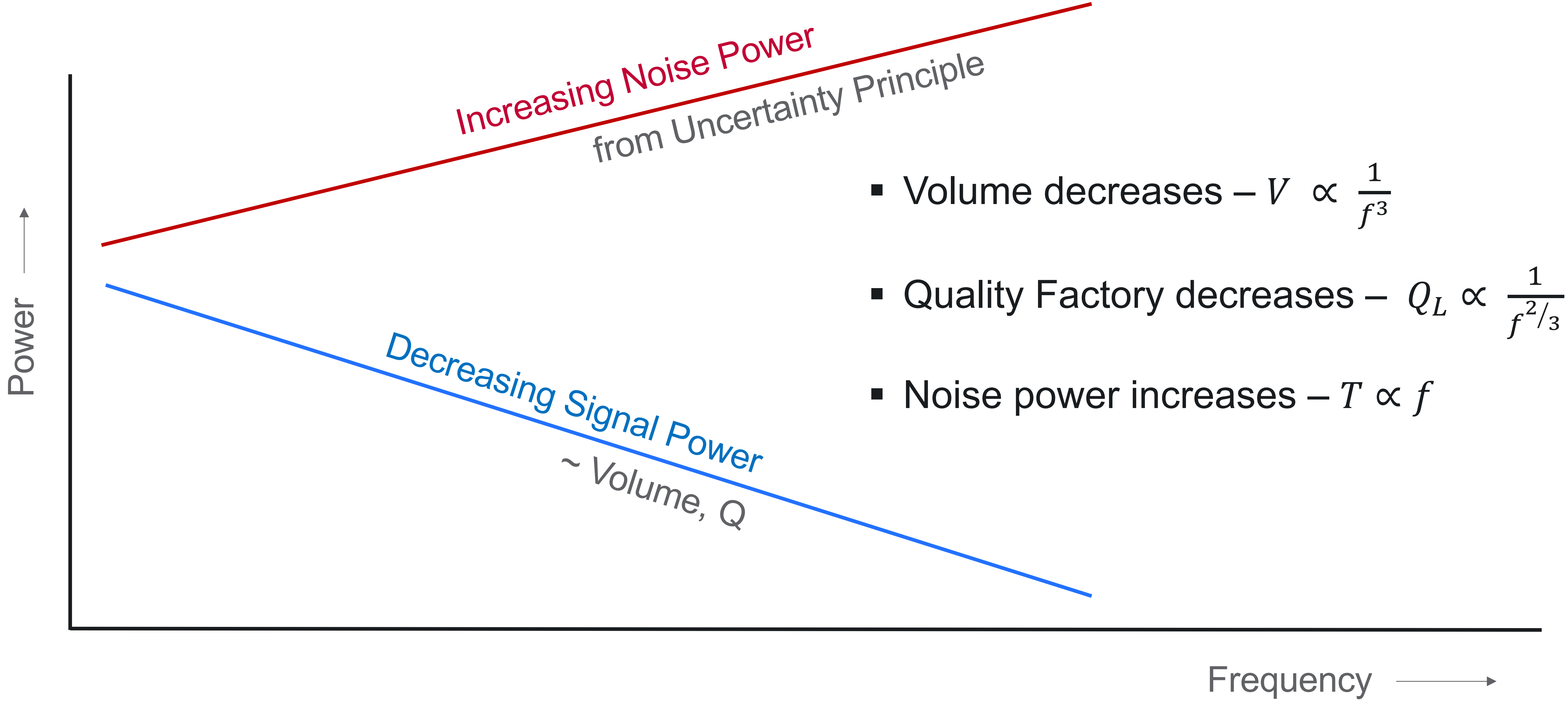


Cavity

Axion-Photon Limit Plot



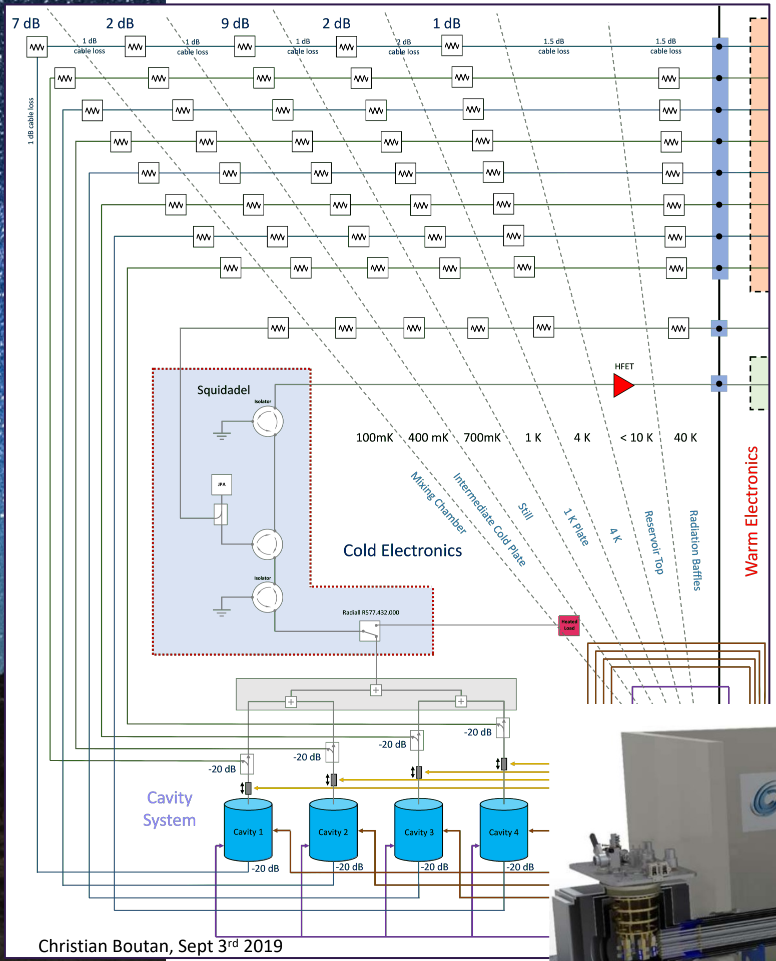
Challenges at Higher Frequencies



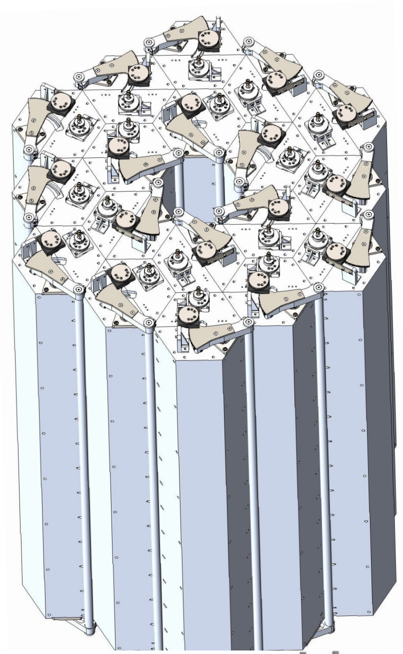
- Volume decreases – $V \propto \frac{1}{f^3}$
- Quality Factory decreases – $Q_L \propto \frac{1}{f^{2/3}}$
- Noise power increases – $T \propto f$

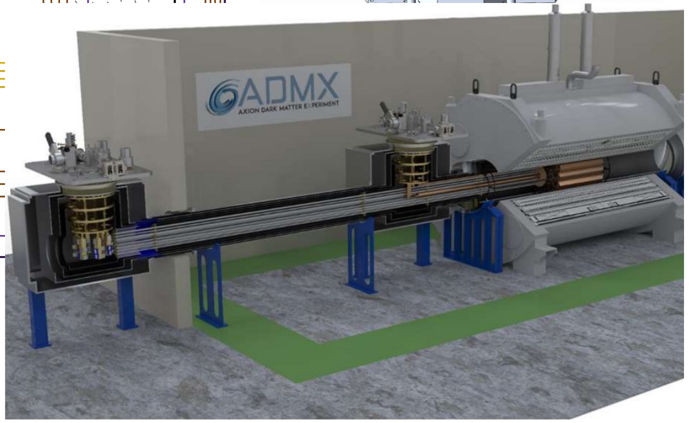
The future looks complicated

Many Cavities



18-cavities





Superconducting cavities

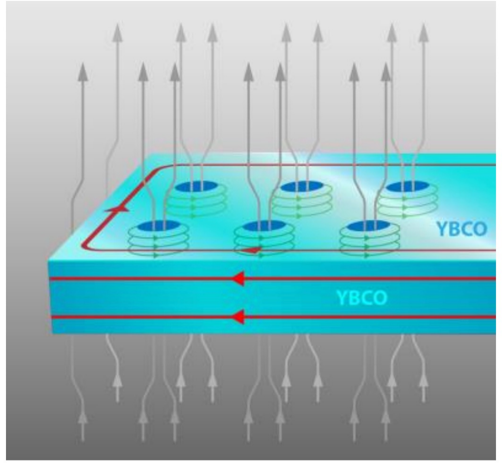
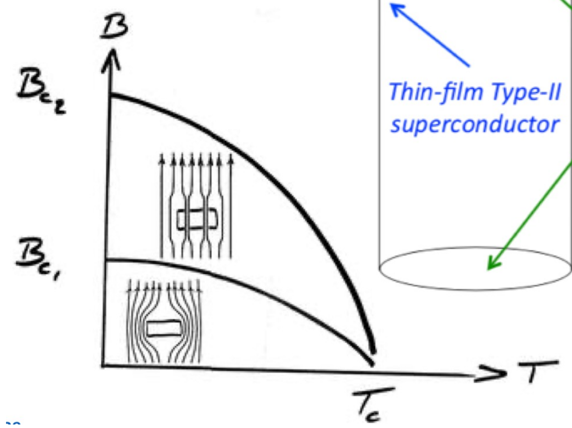
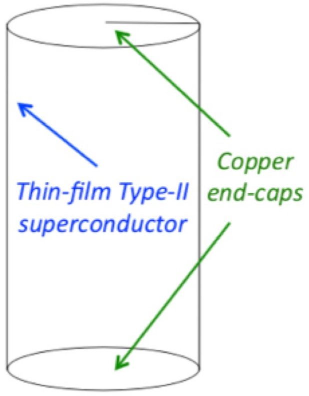


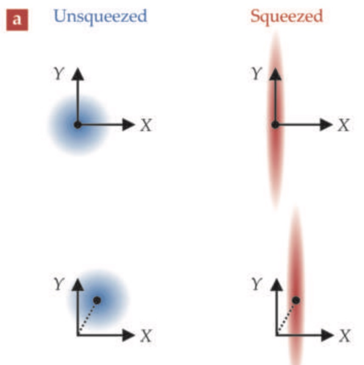
Image: Flux Vortices in Mixed State
Credit: APS, https://physics.aps.org/articles/v10/129



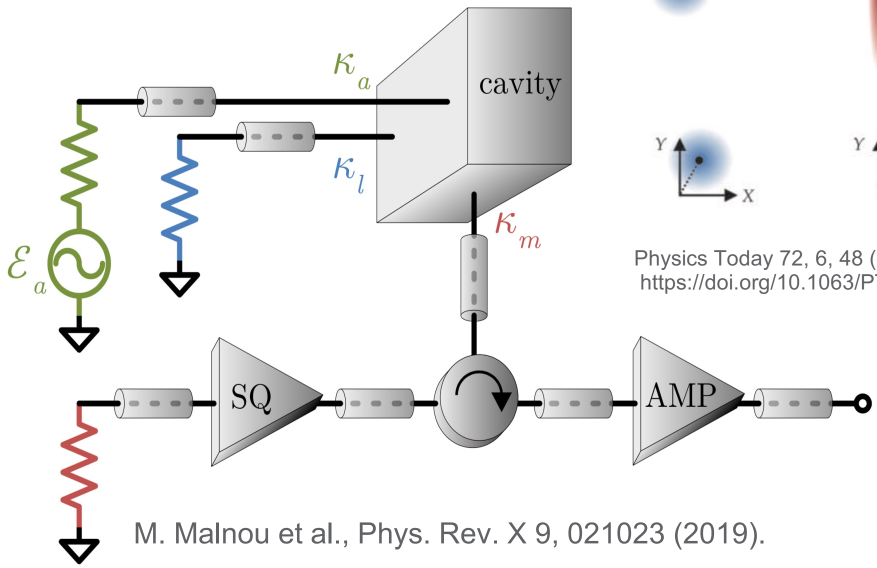


Tricks for evading the standard quantum limit

squeezing

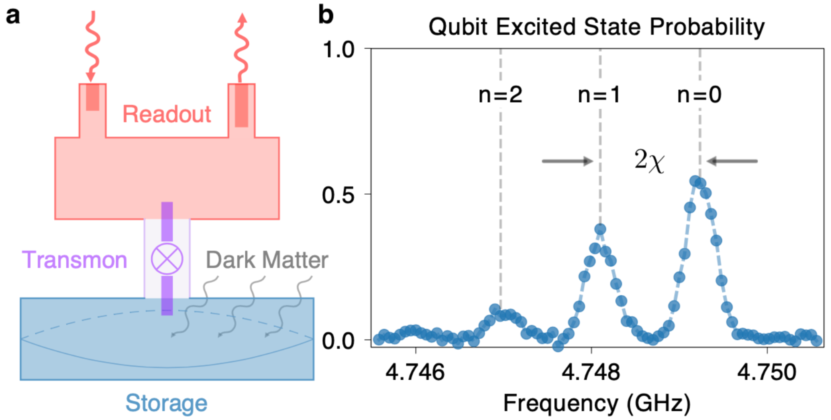


Physics Today 72, 6, 48 (2019); https://doi.org/10.1063/PT.3.4227



M. Malnou et al., Phys. Rev. X 9, 021023 (2019).

Photon counting



A.V. Dixit, S. Chakram, K. He, A. Agrawal, R.K. Naik, D.I. Schuster, A. Chou, Searching for dark matter with a superconducting qubit, Phys. Rev. Lett. 126 (2021) 141302, http://dx.doi.org/10.1103/PhysRevLett.126.141302.

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How is ML going to intersect this story?

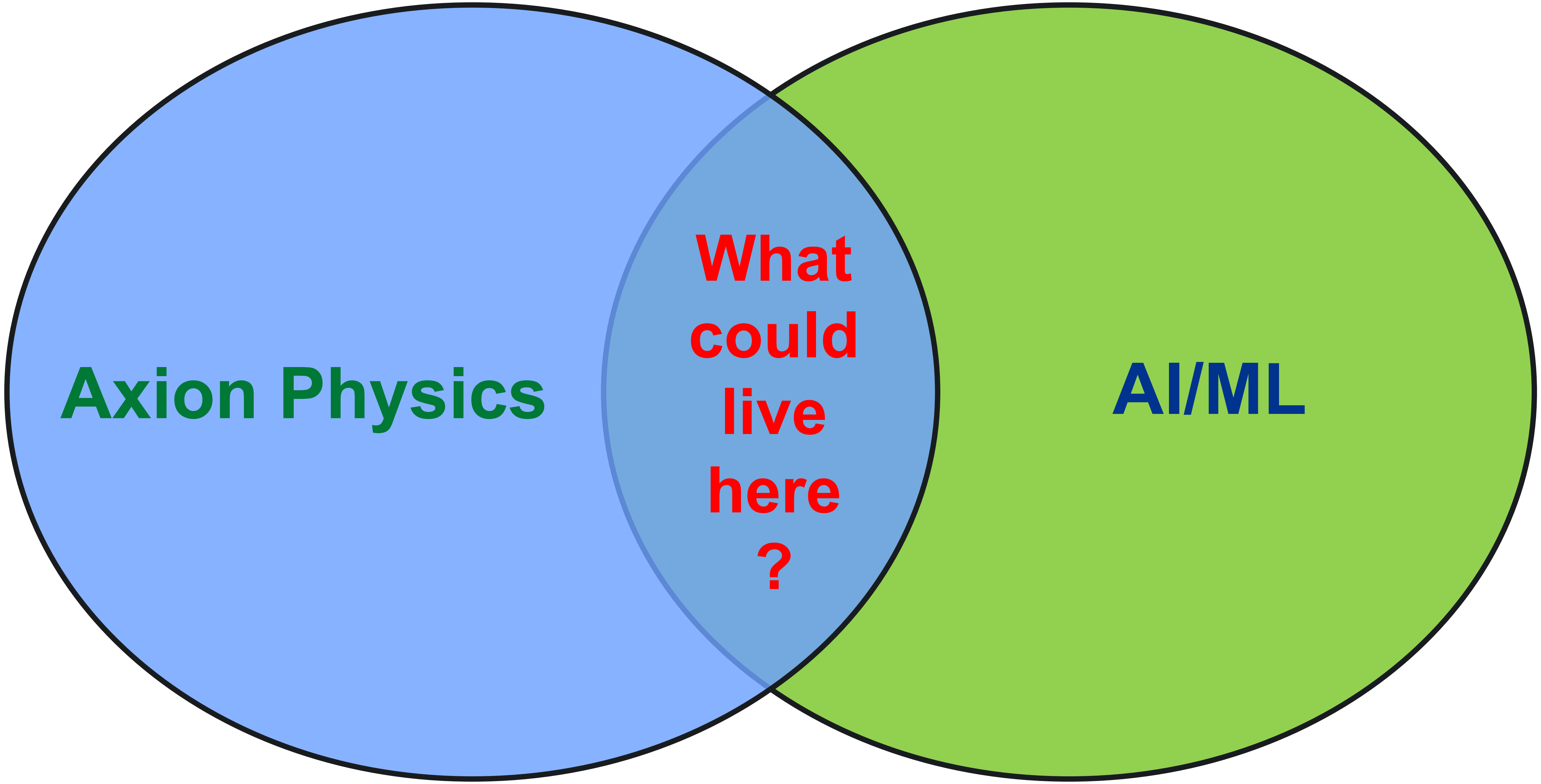
Summary of what we know so far

- Trying to detect a tiny (< 10^{-24} W) RF signal
- Outlook is bleak at higher frequencies (sensitivity drops fast)
- The community is split, working on one-off solutions in isolated

I claim that:

- **Future experiments might be too complicated to operate**
- **Today's experiments could run faster with intelligent controls**

How is ML going to intersect this story?



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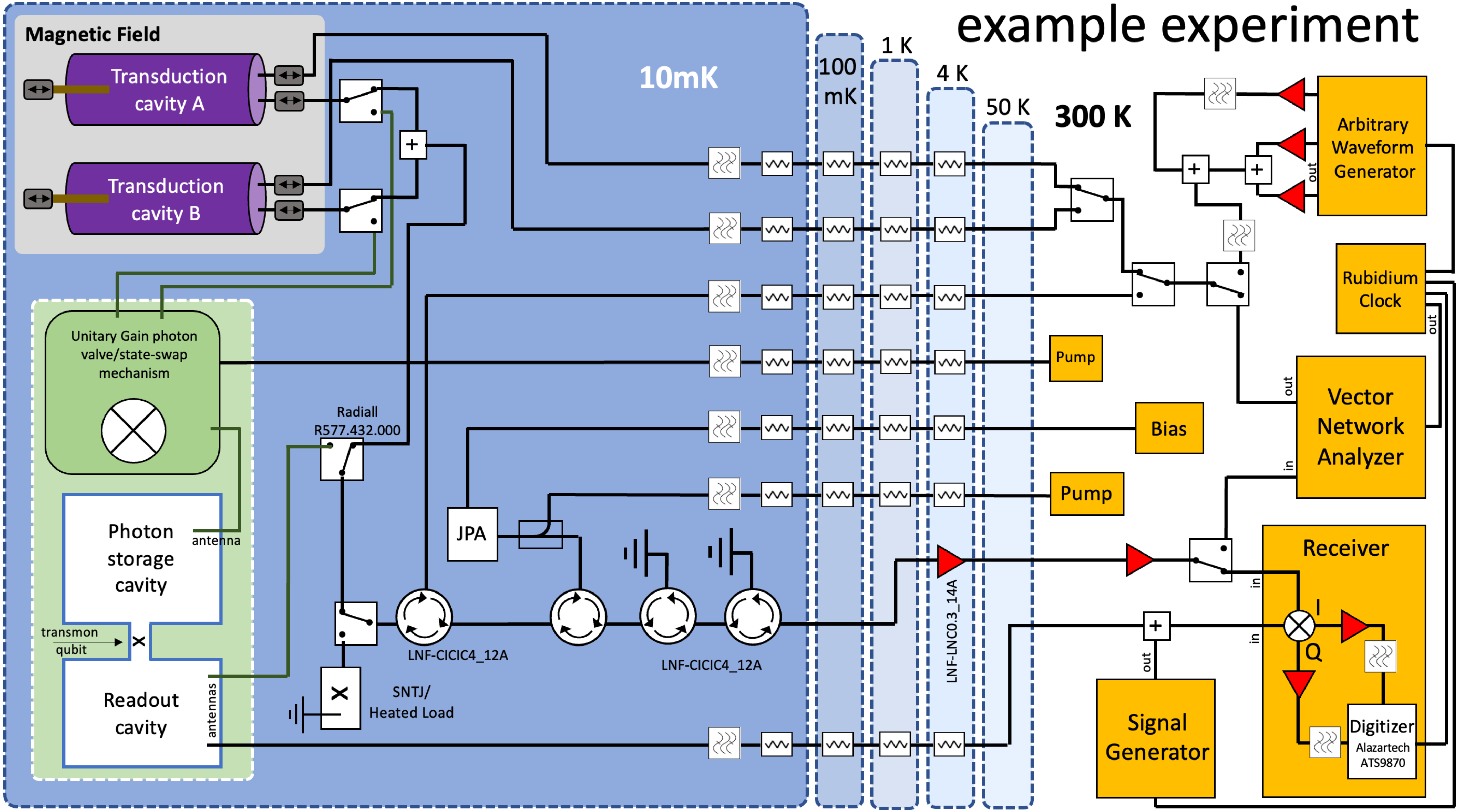
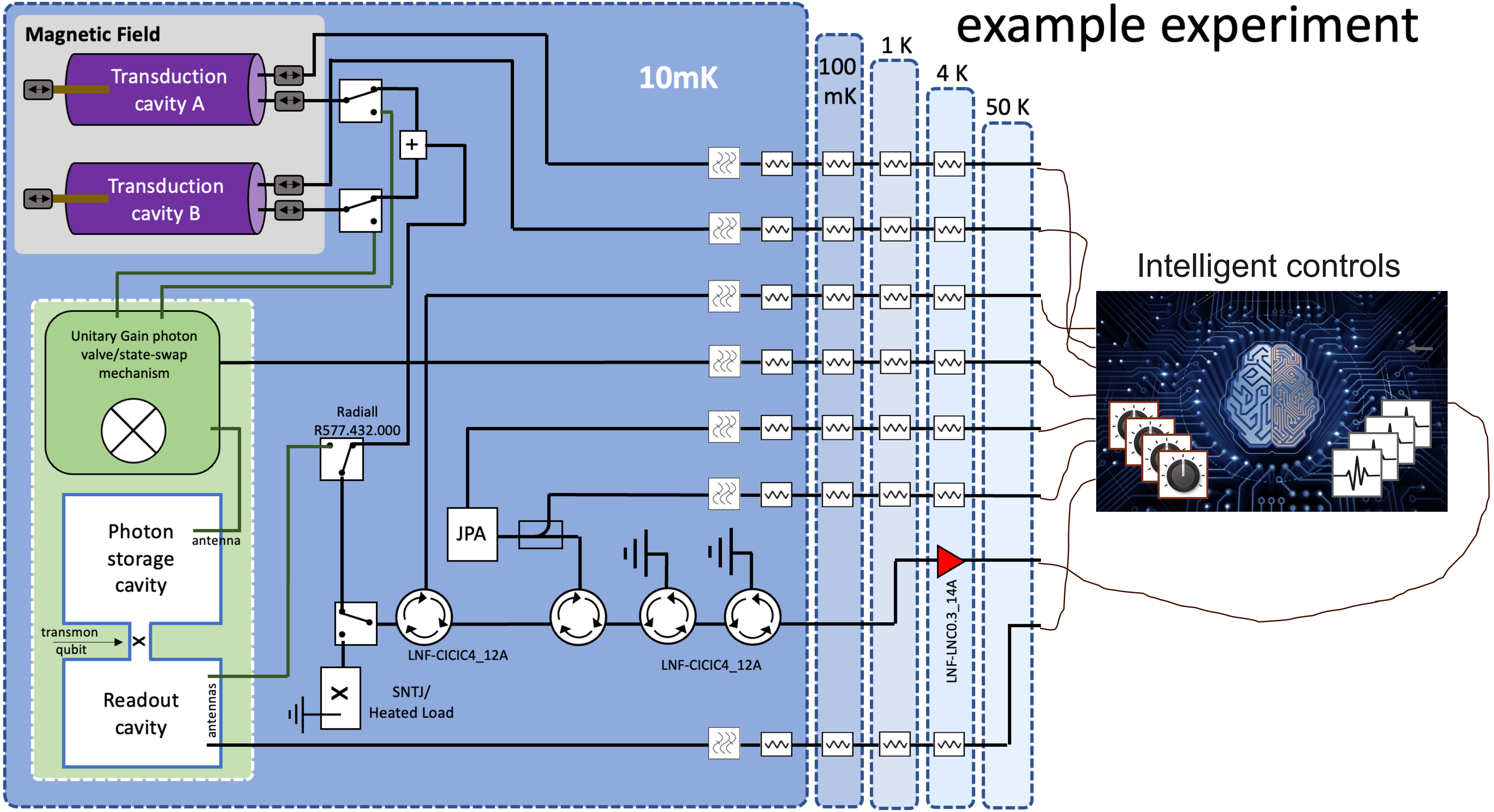
I need to tell you about another challenge that the community doesn’t seem to be anticipating…

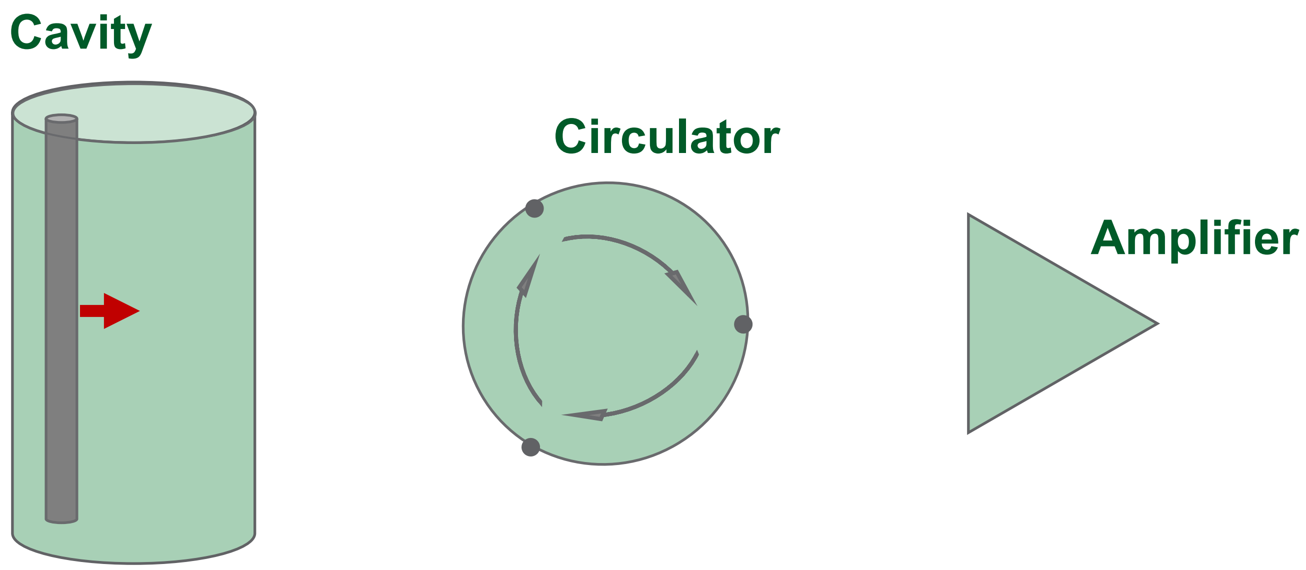
example experiment



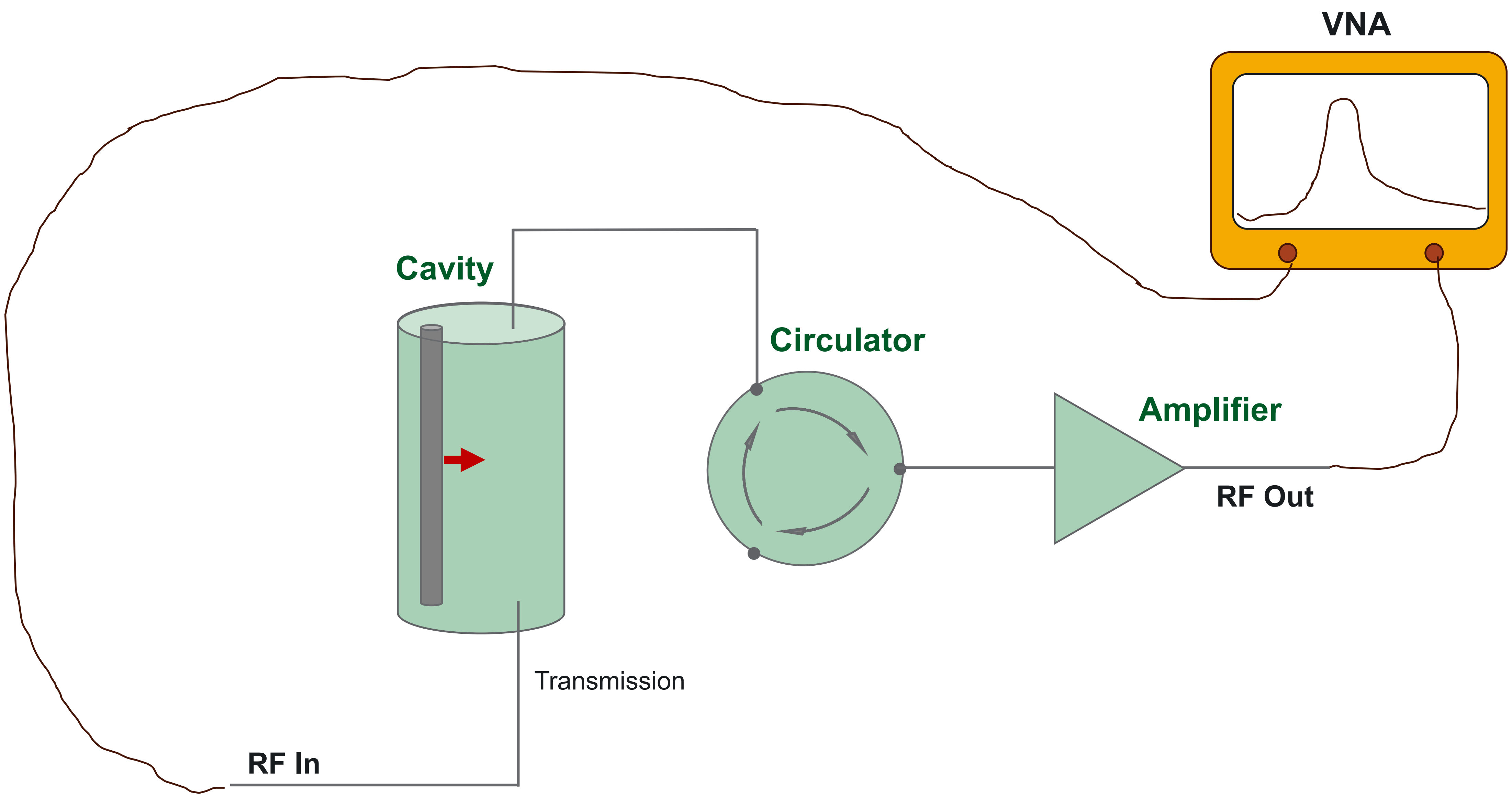
example experiment



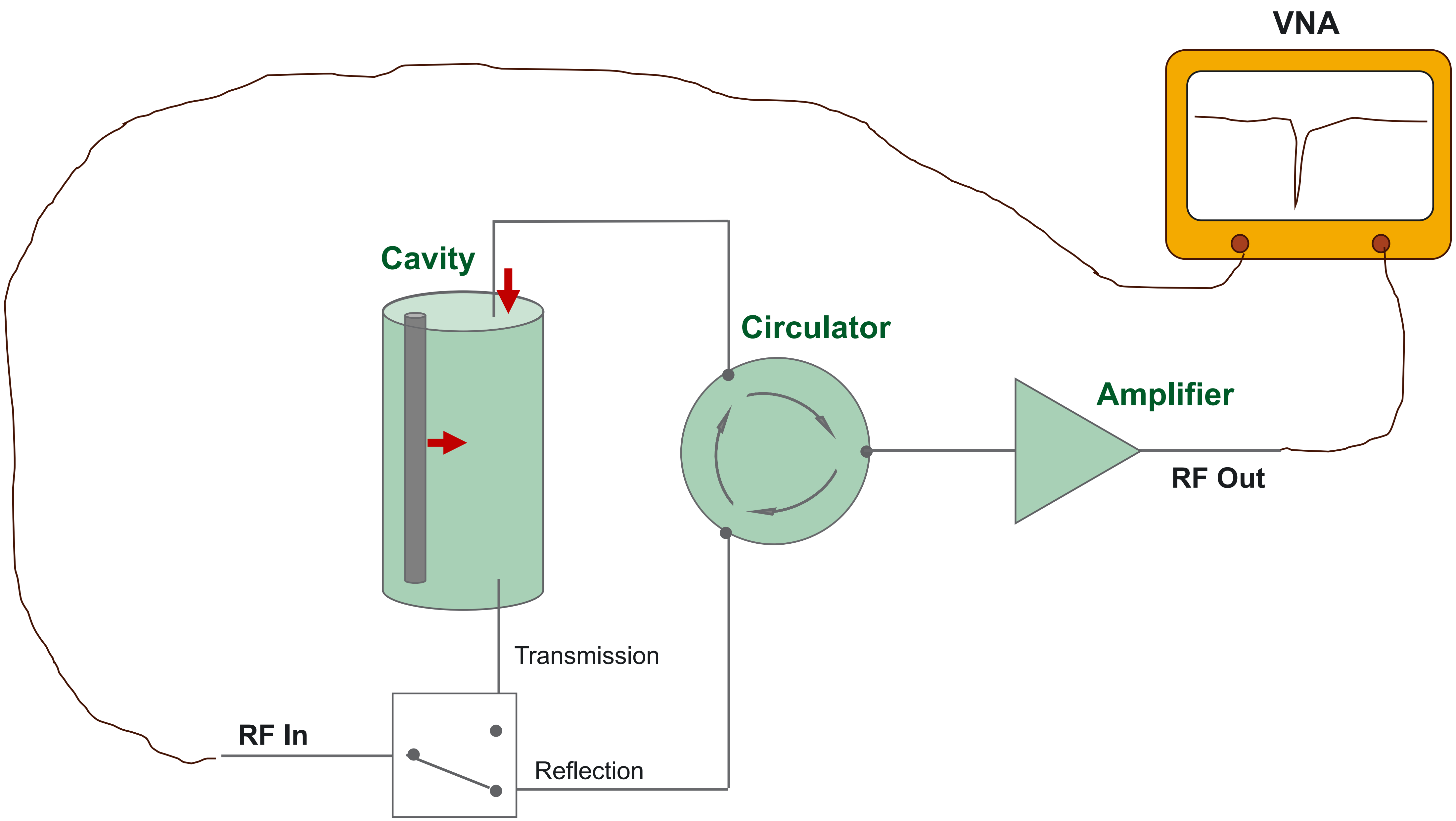
Toy model experiment: ingredients



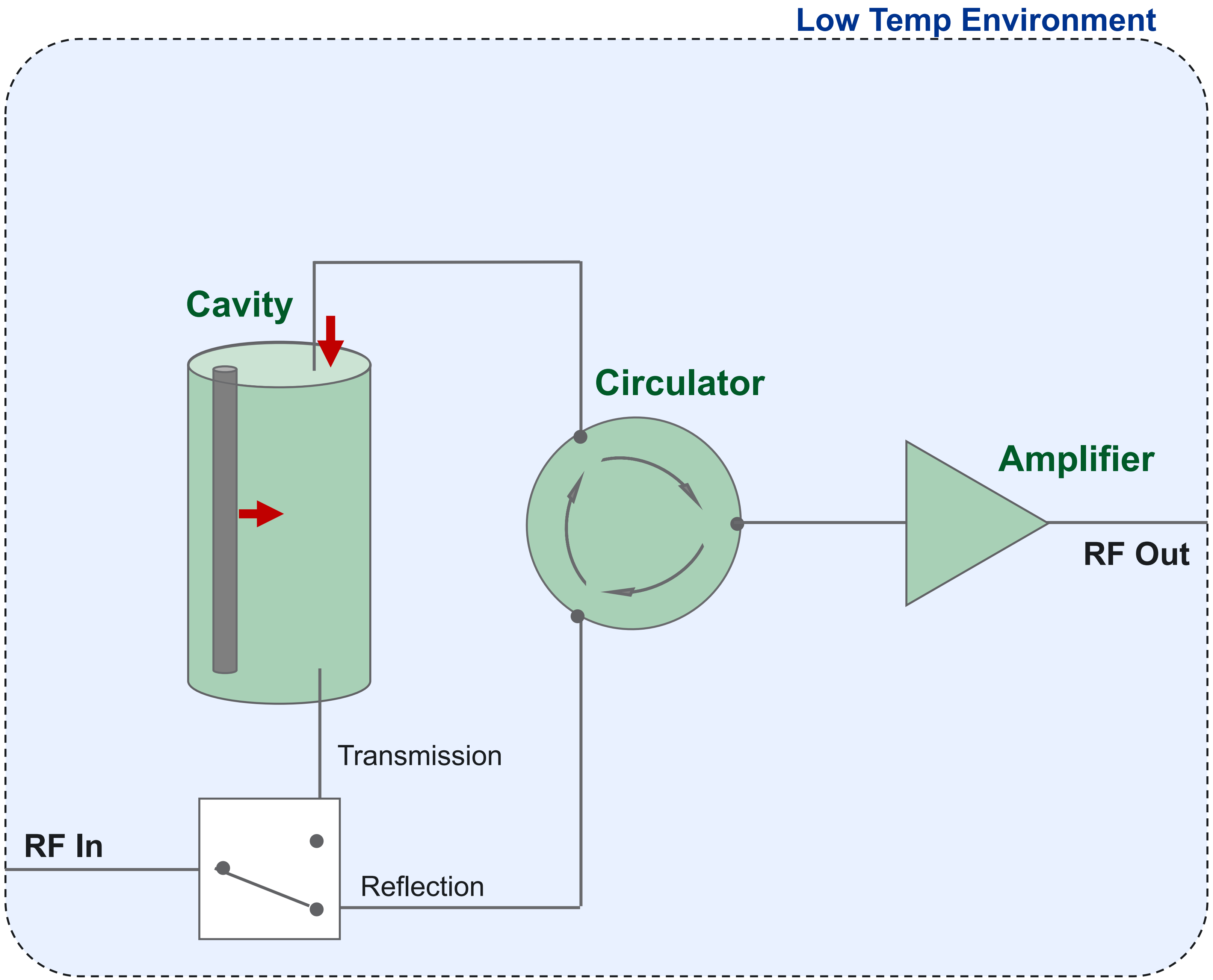
Toy model experiment: RF



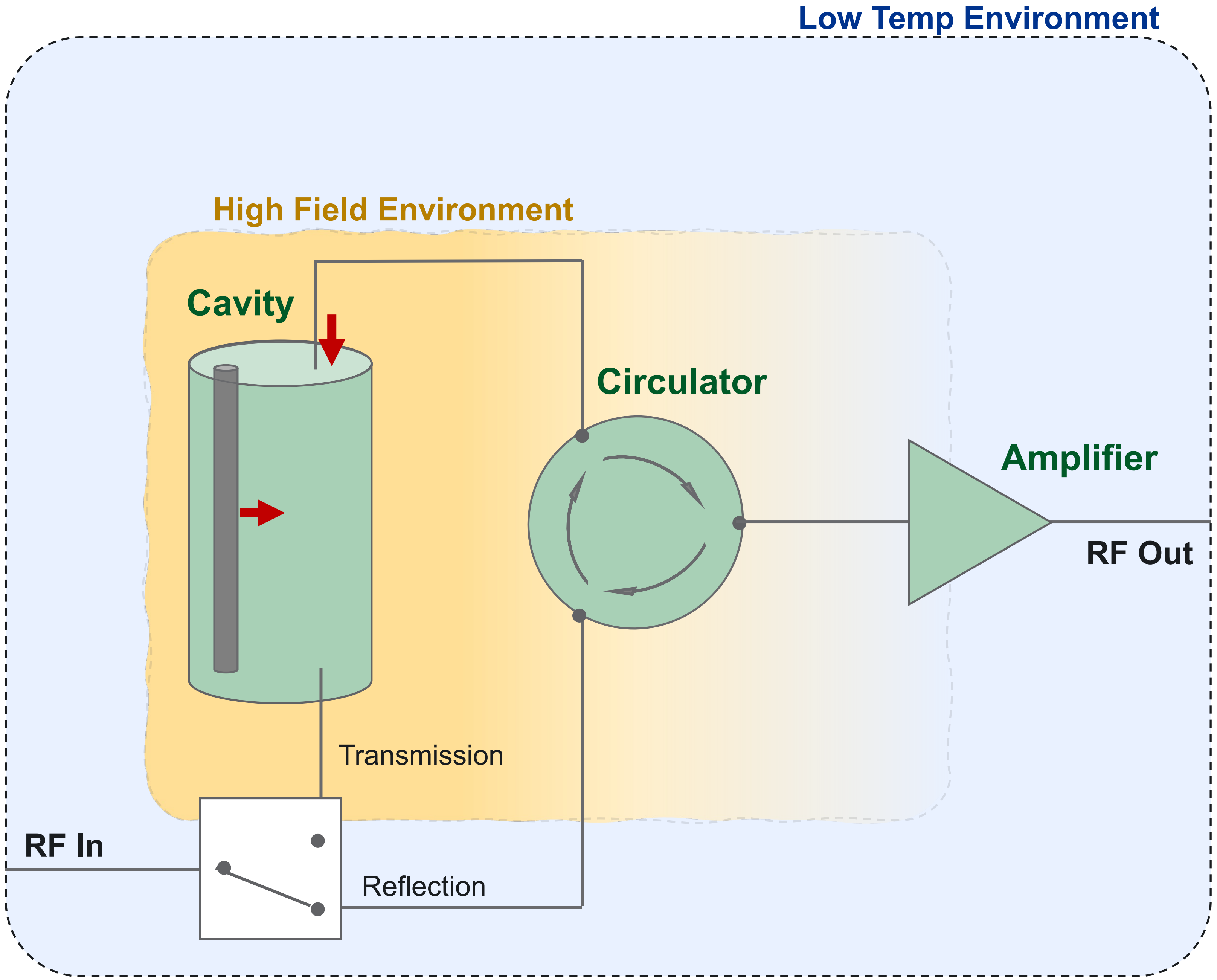
Toy model experiment: RF



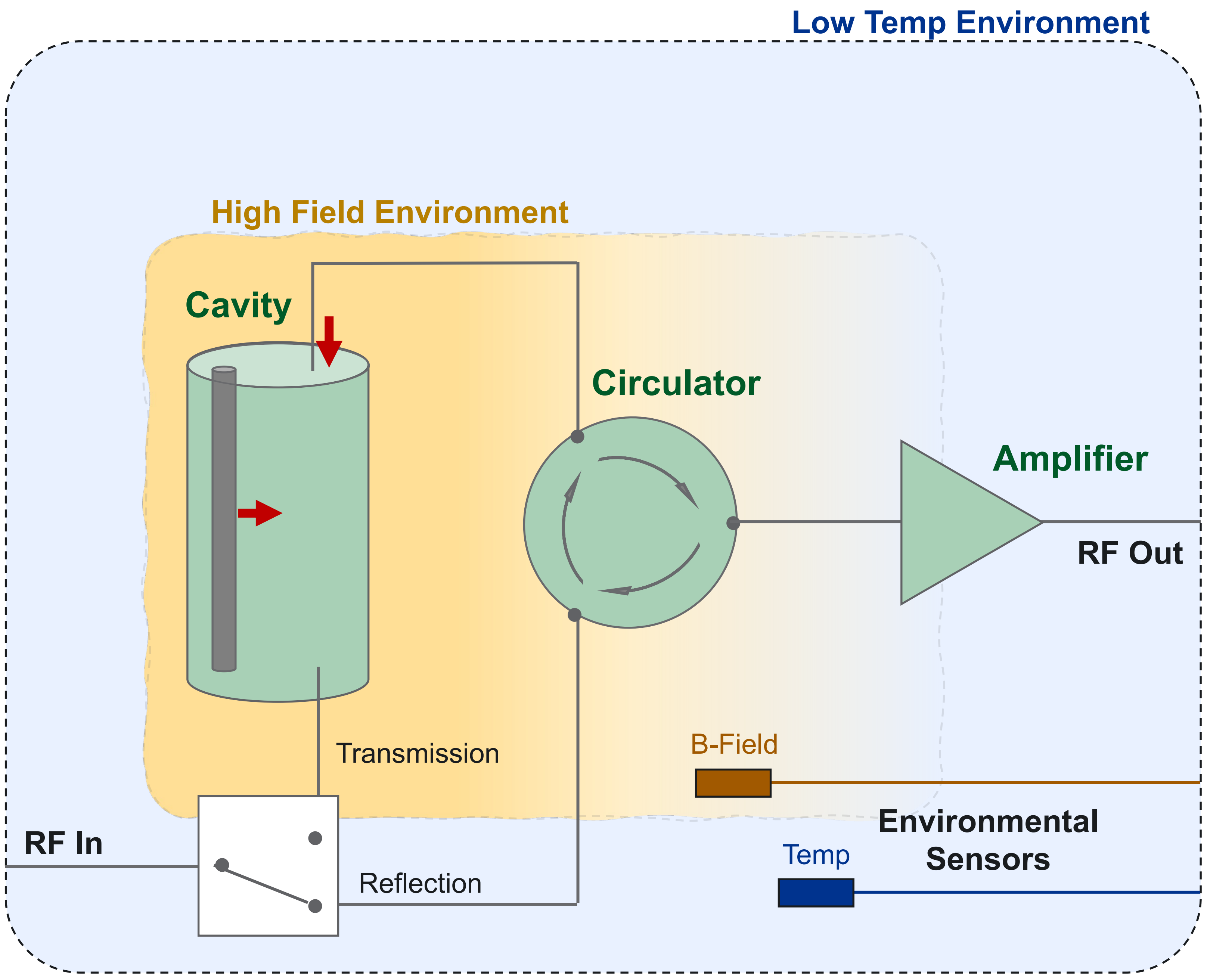
Toy model experiment: environment



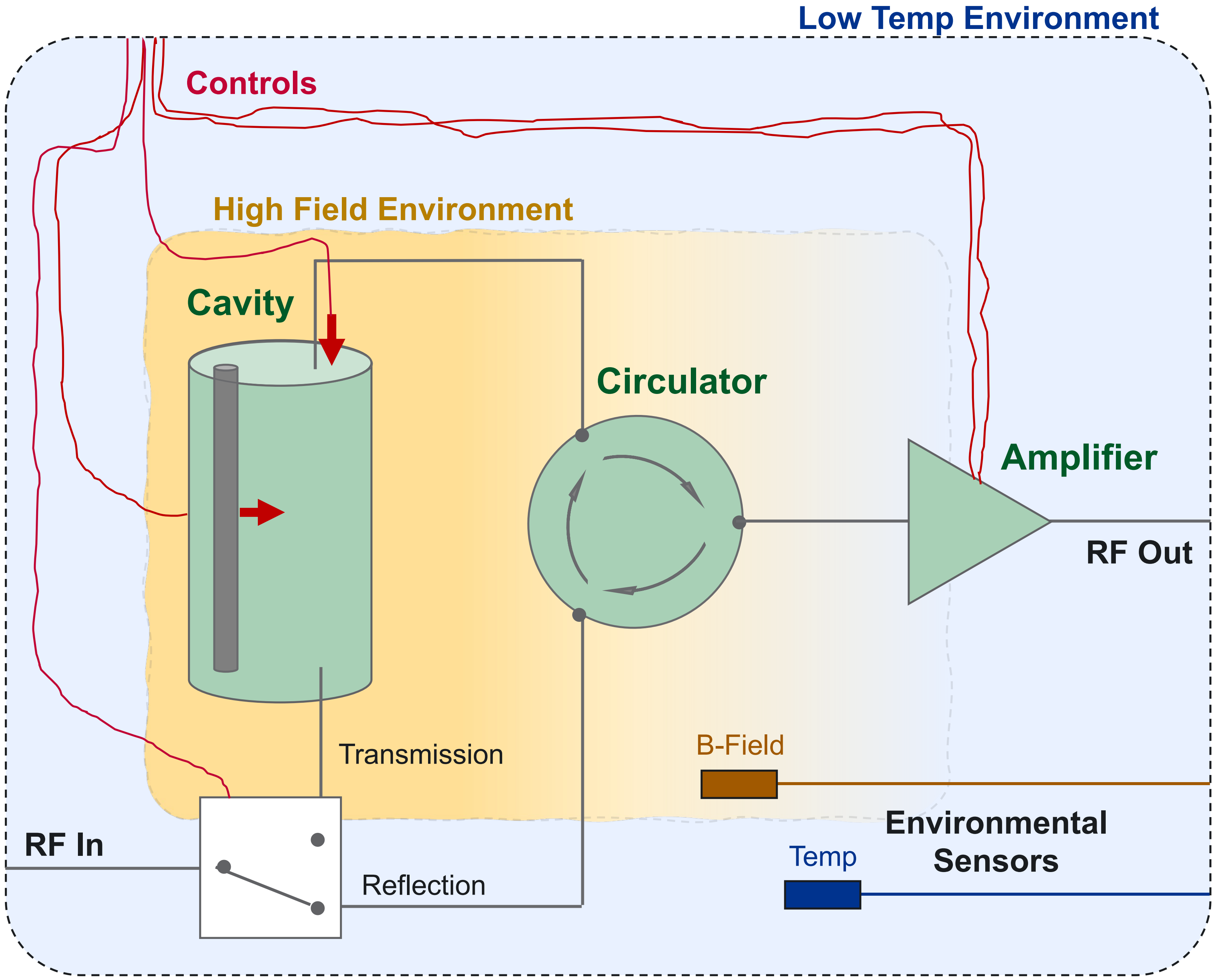
Toy model experiment: environment



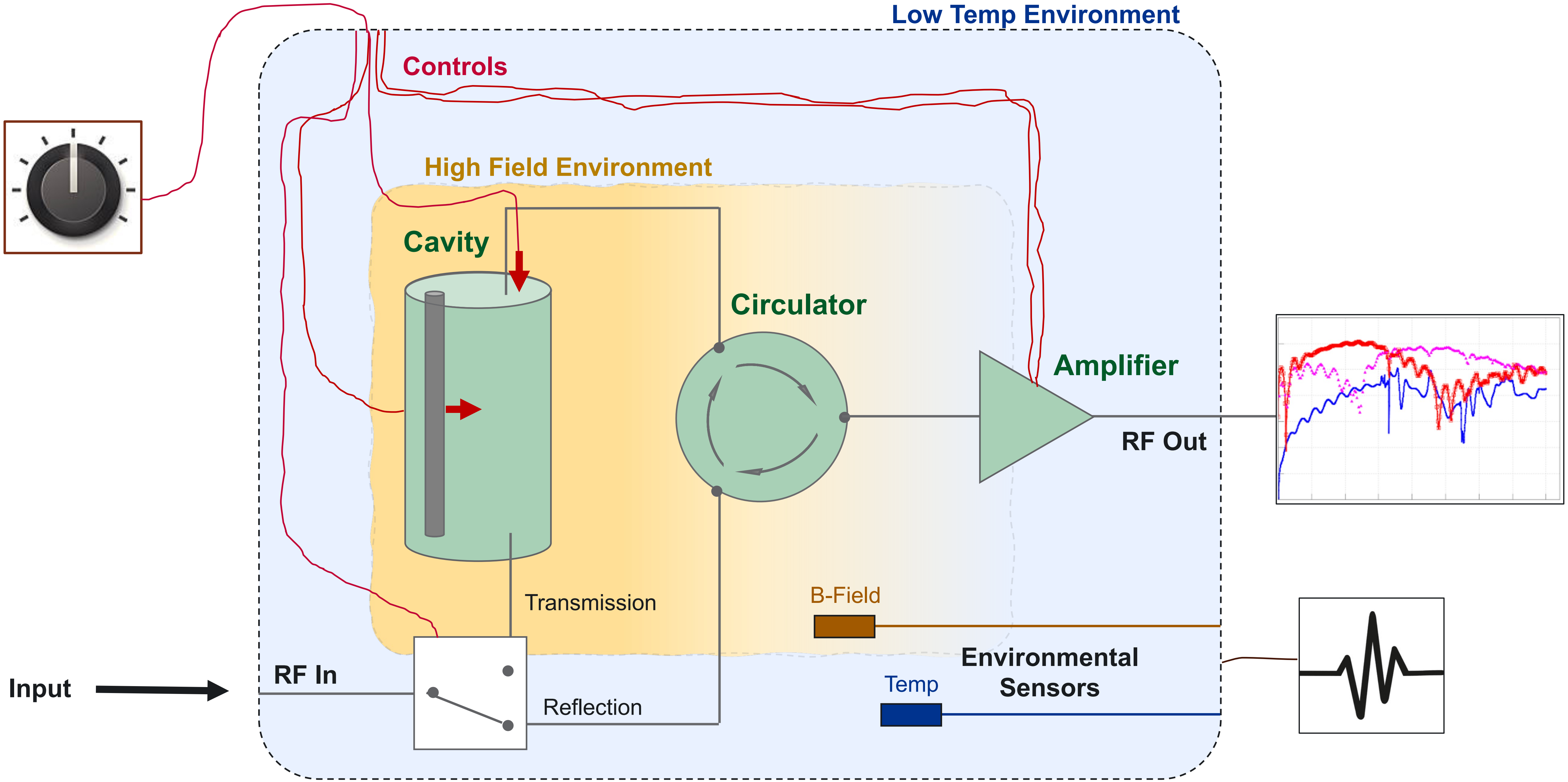
Toy model experiment: sensors



Toy model experiment: controls



Toy model experiment

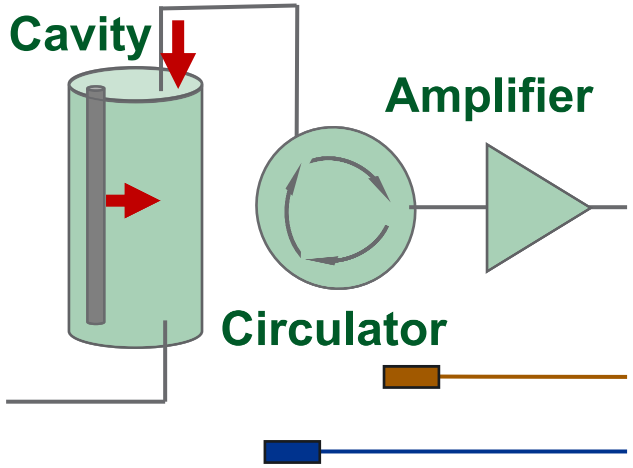


Toy model experiment: black box when running

Let's play with the toy model

Play with toy: setup

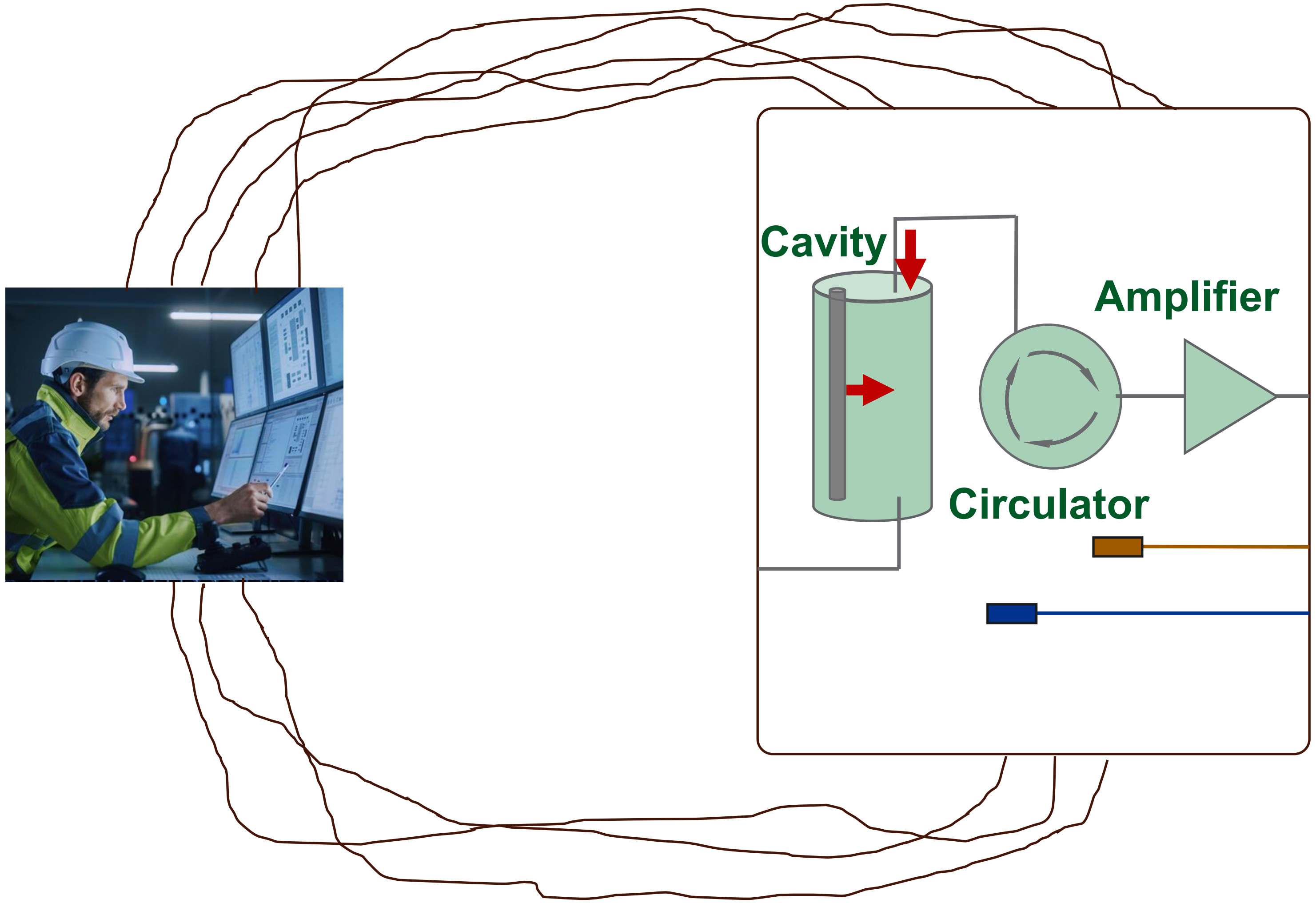
Experiment



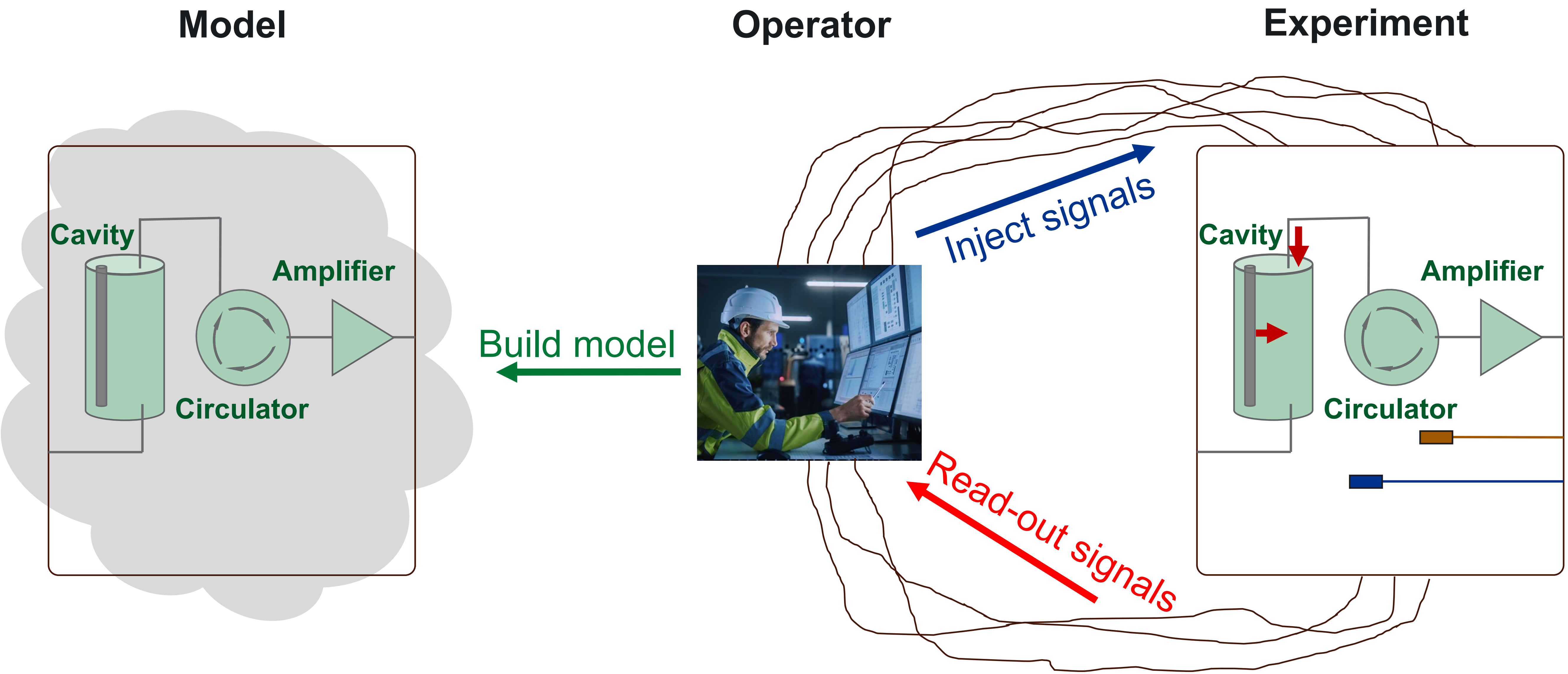
Play with toy: connect with supporting electronics

Operator

Experiment



Play with toy: make measurements and build model



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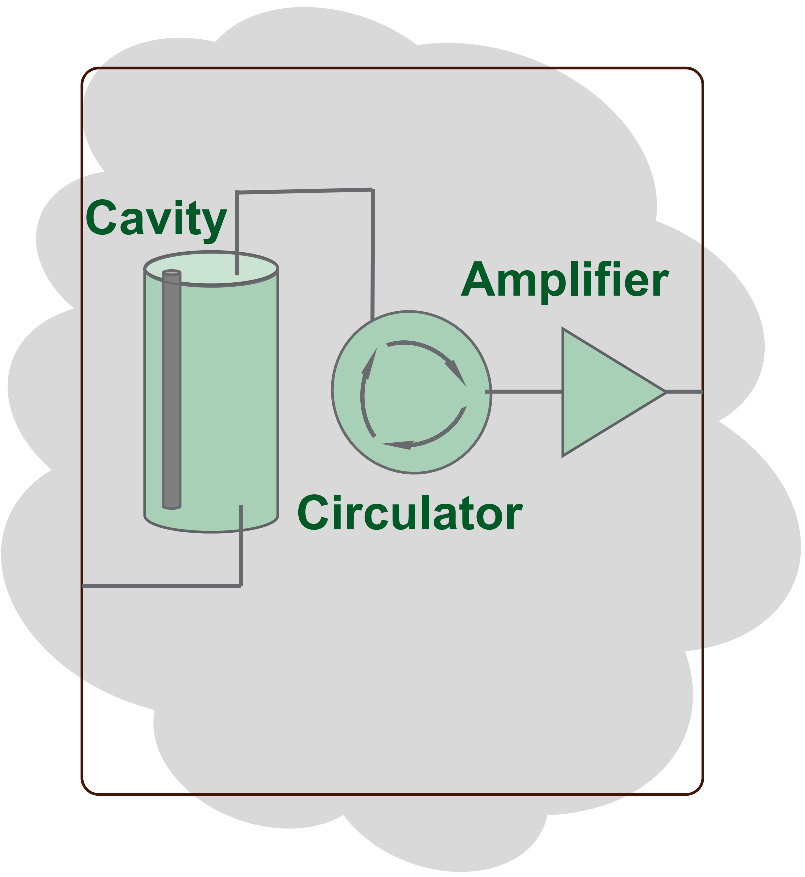
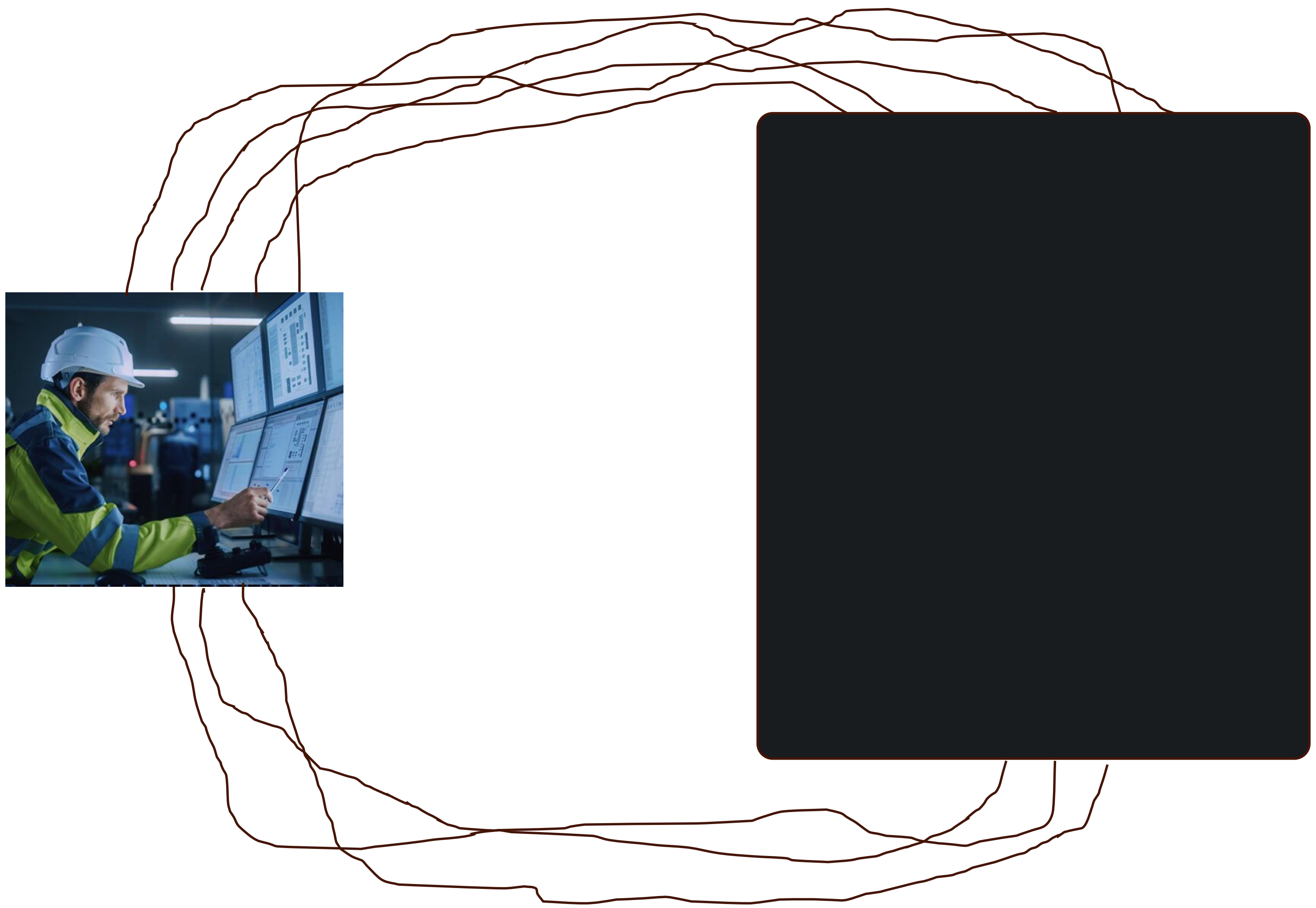
Play with toy: close up experiment and pump down

Model



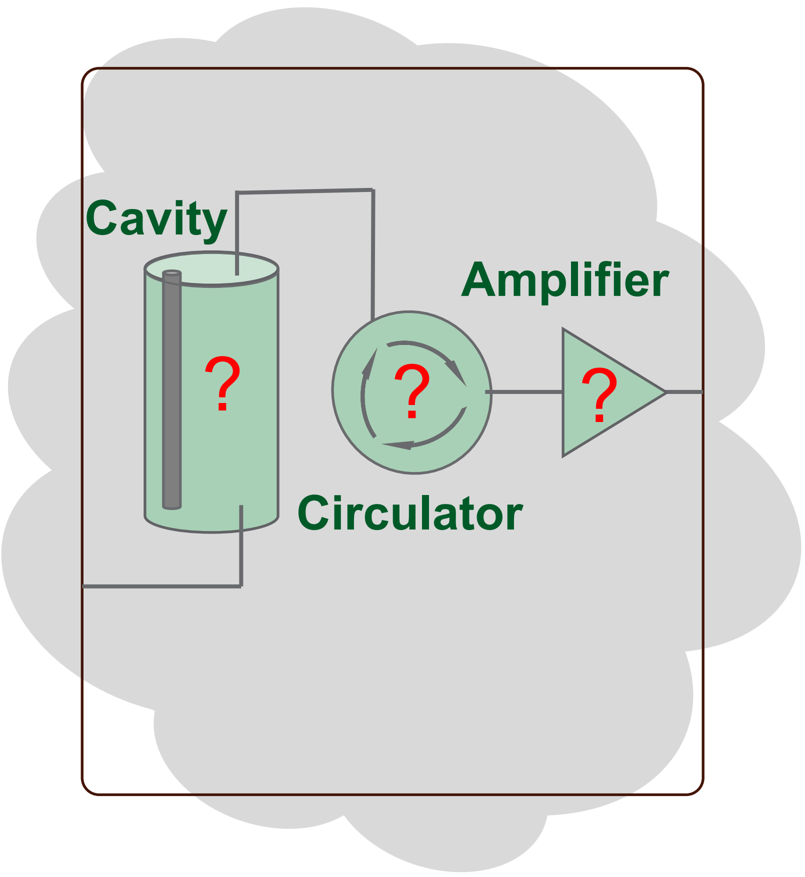
Operator

Experiment



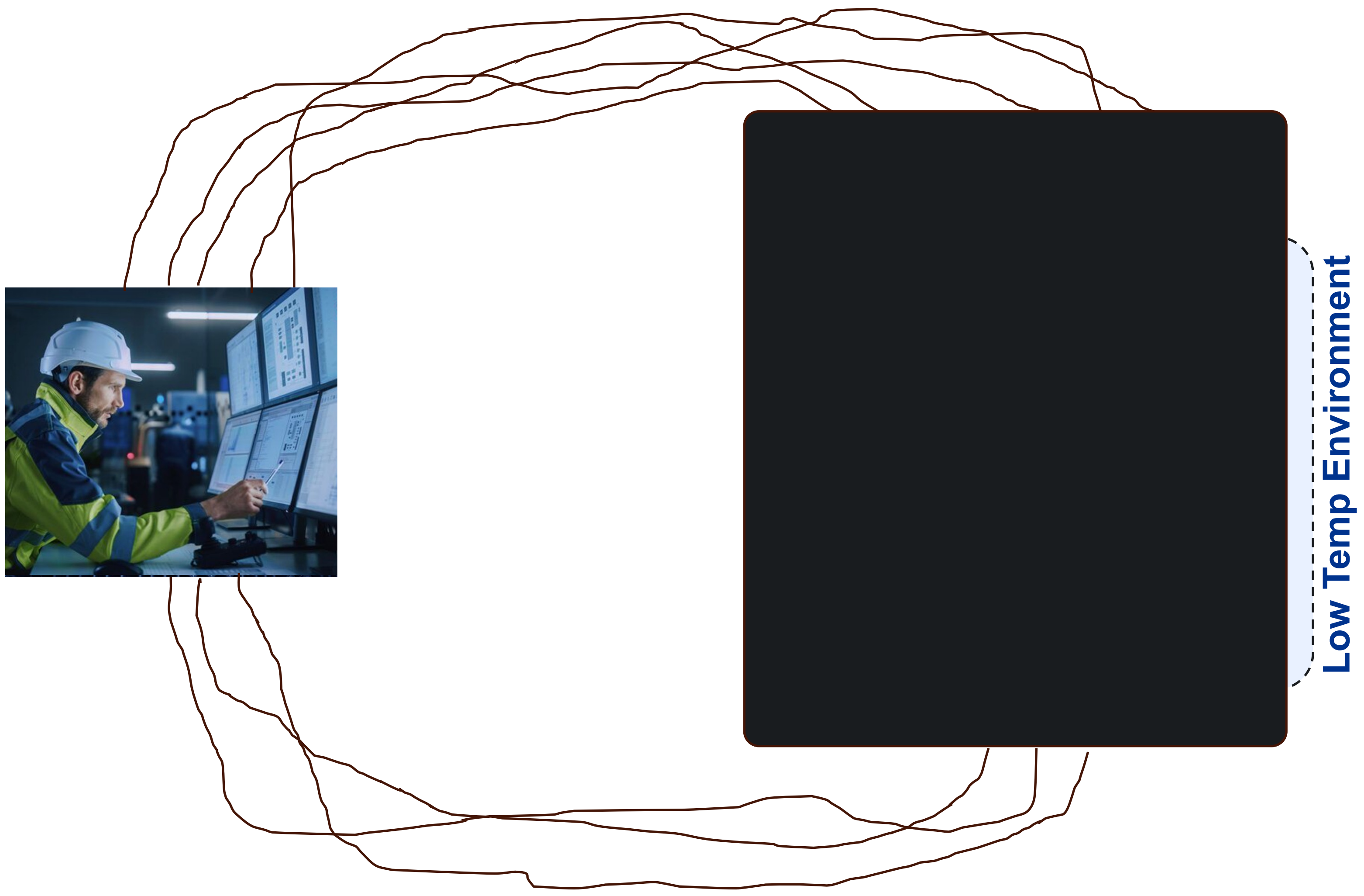
Play with toy: cool experiment

Model



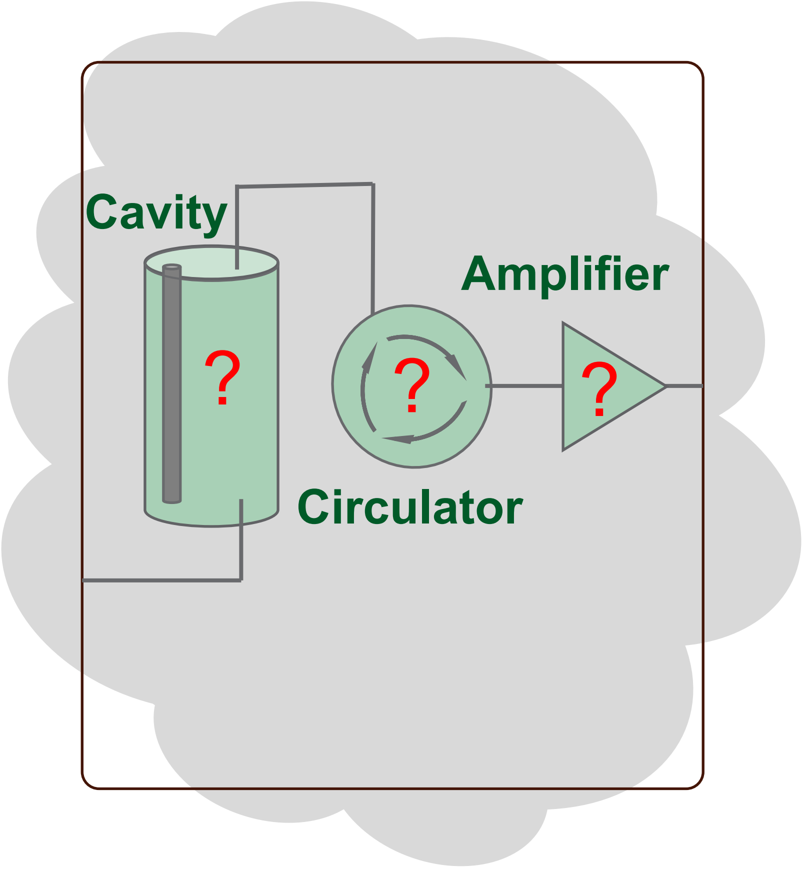
Operator

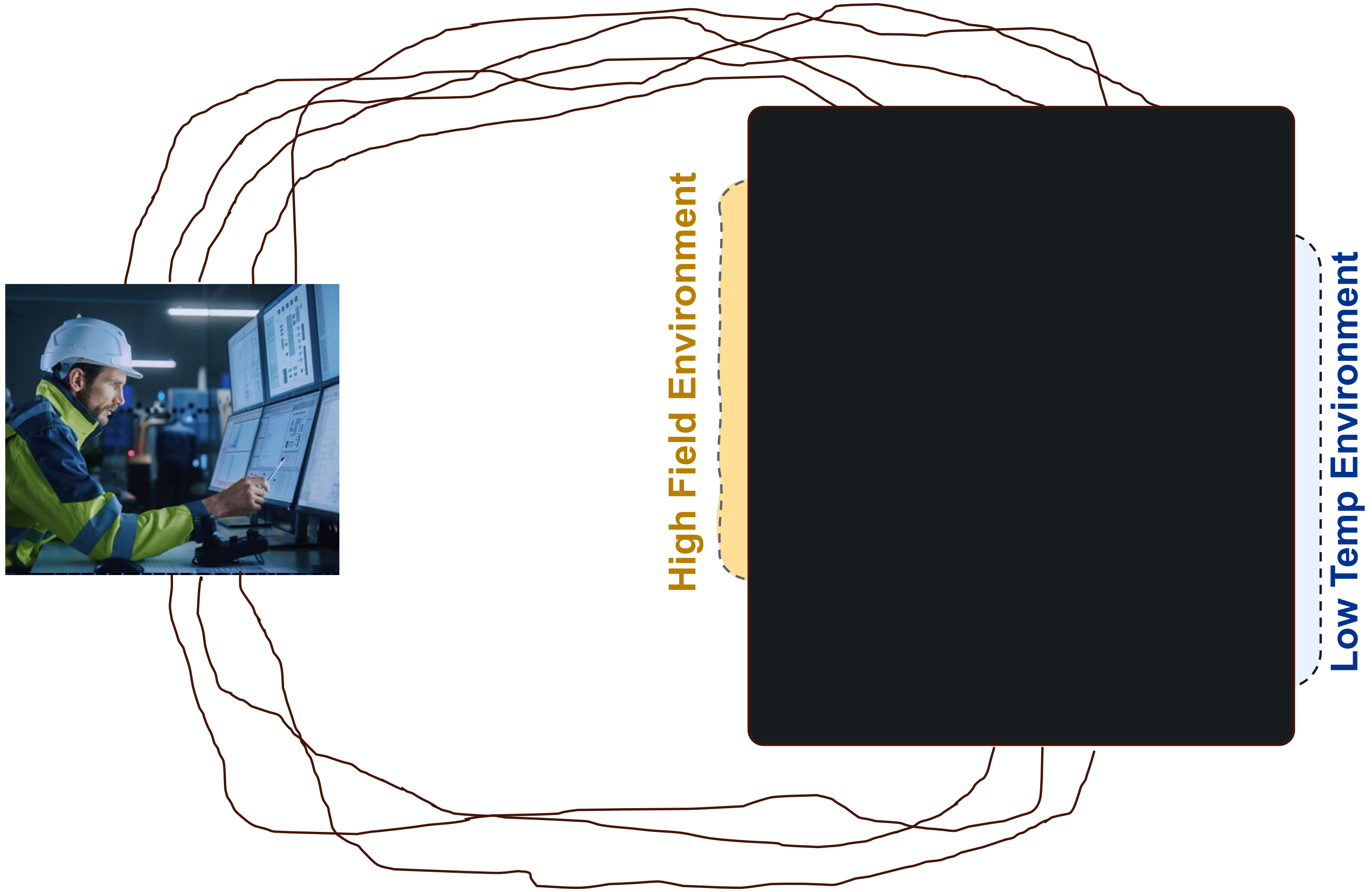
Experiment



Play with toy: Ramp magnetic field

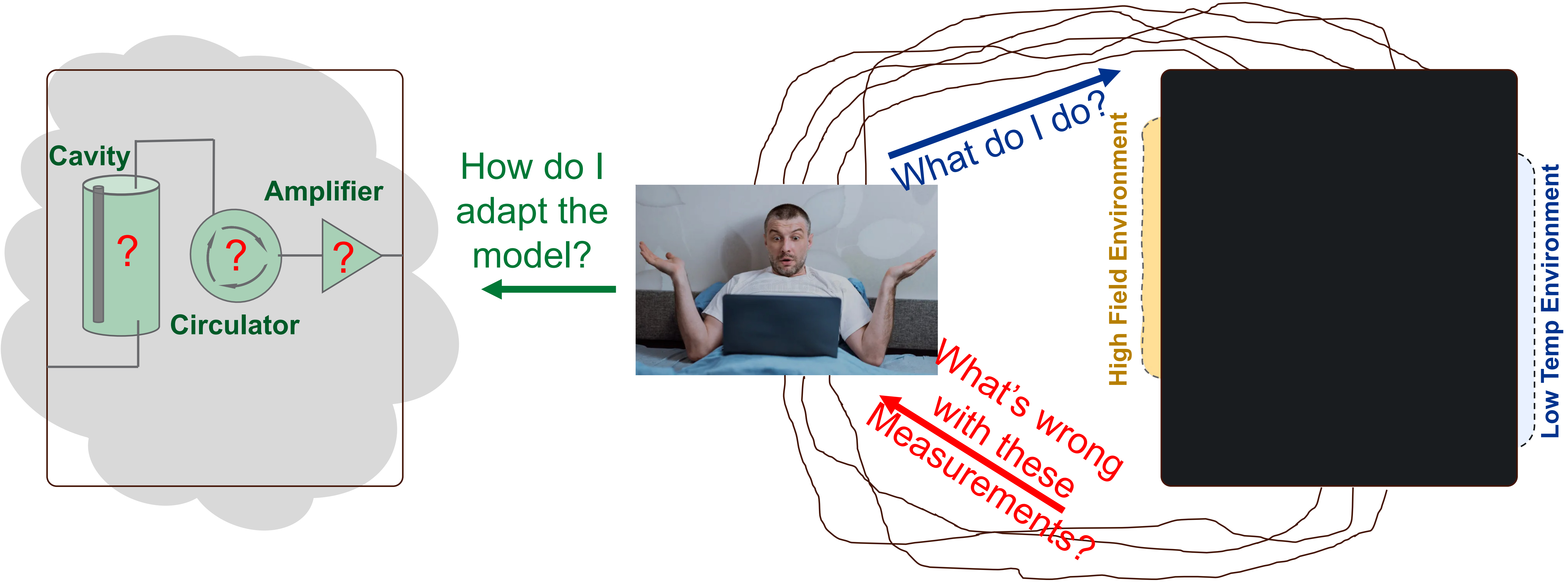
Model | **Operator** | **Experiment**





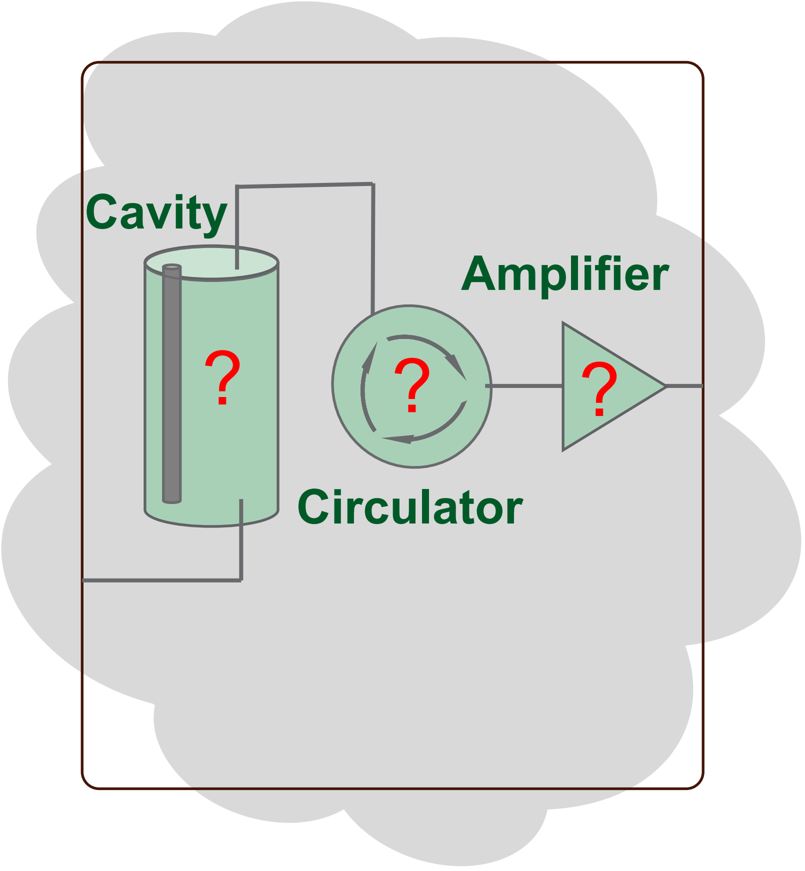
What’s wrong with my toy?

Model | **Operator** | **Experiment**

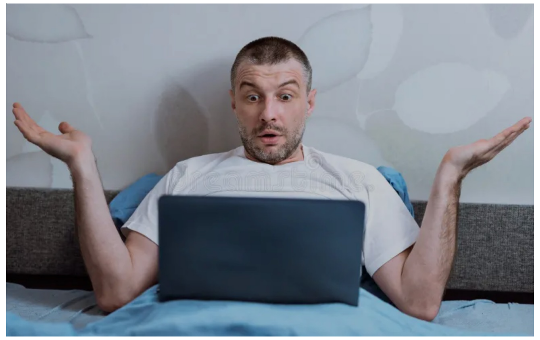


If we could peak inside

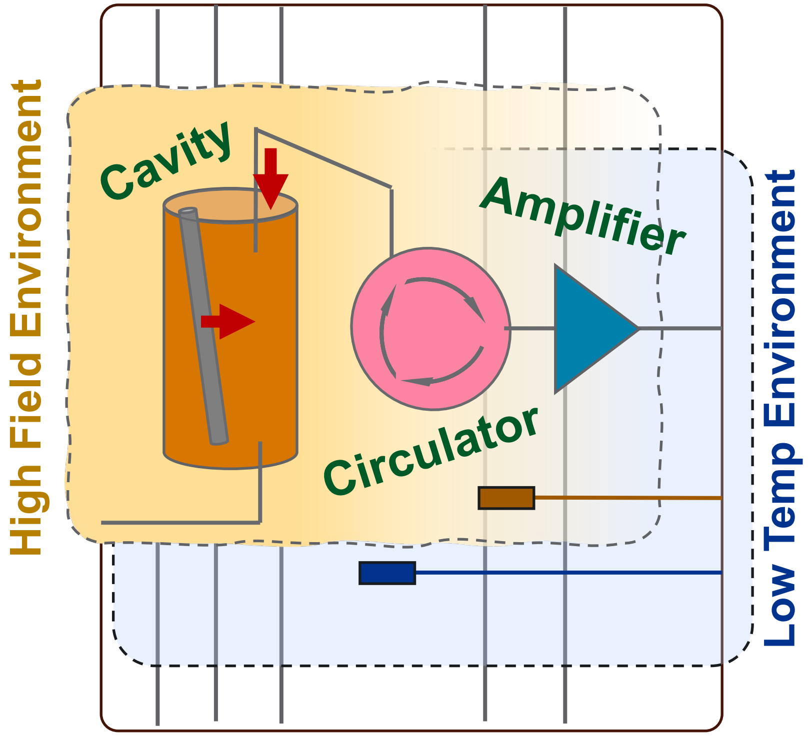
Model



Operator

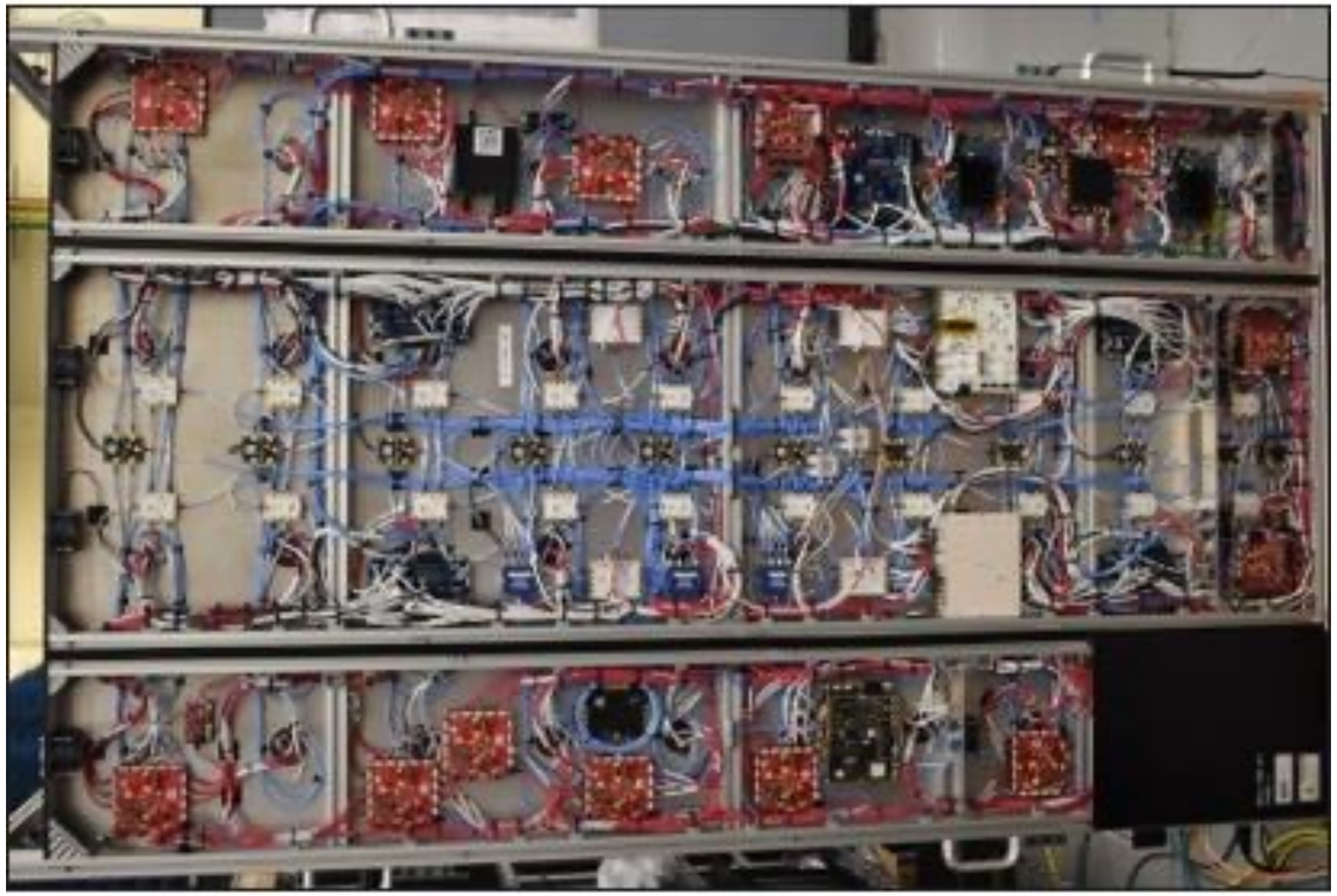


Experiment



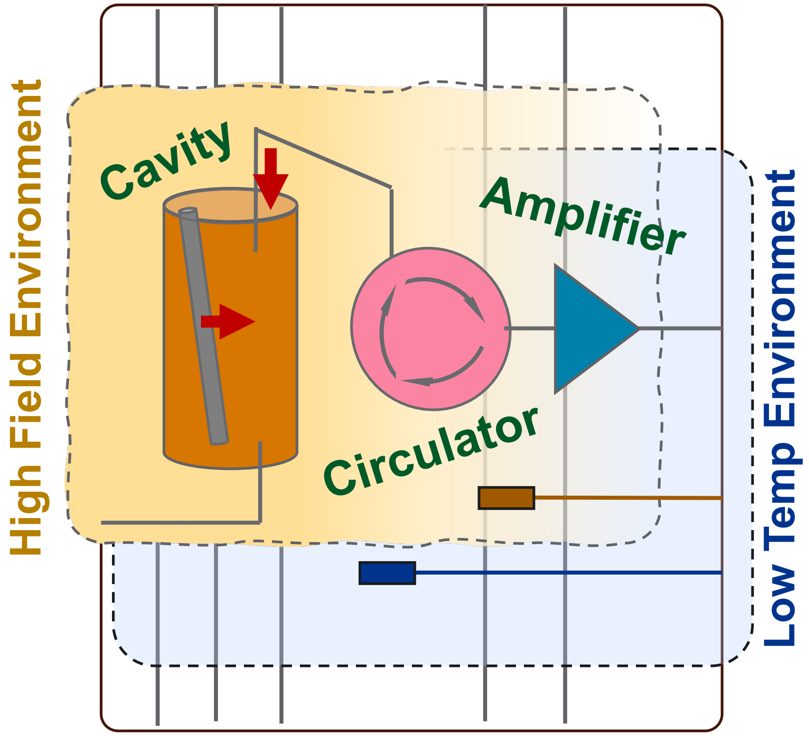
Simple cryogenic experiments
vs
complicated room-temperature ensembles

Example of a complicated room temperature thing



VS

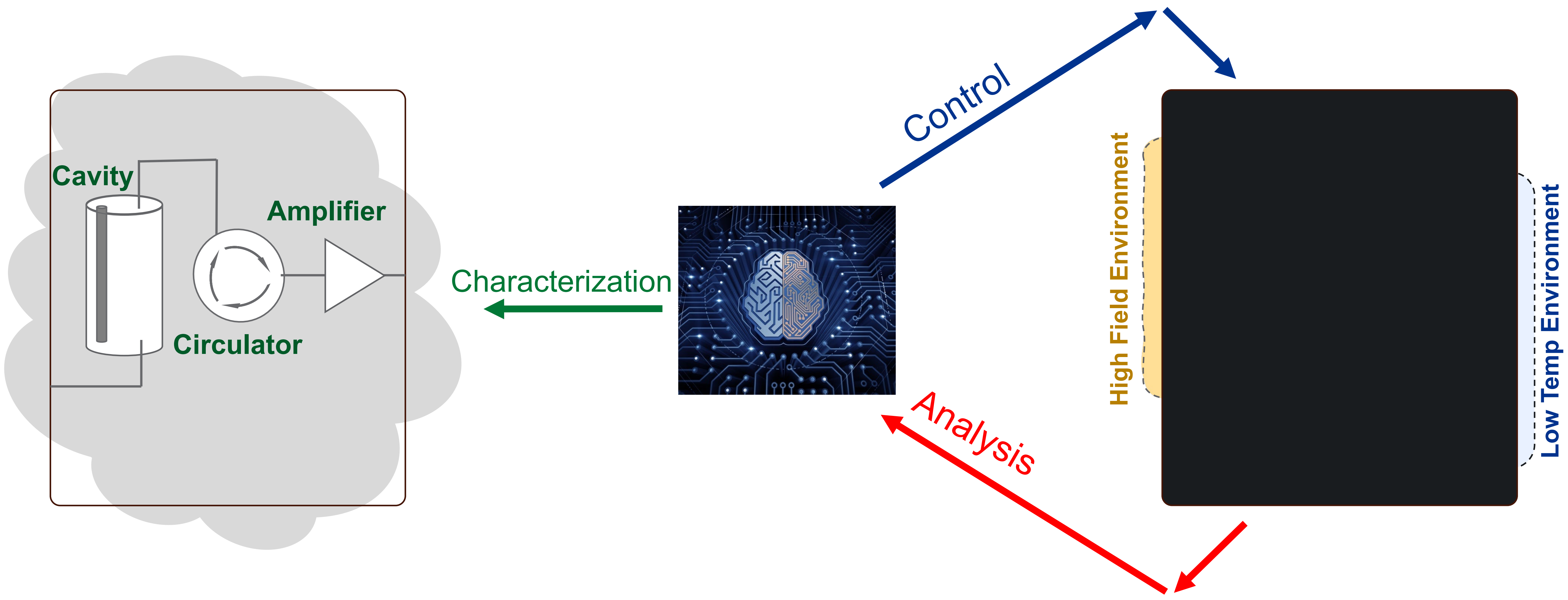
Our toy Experiment



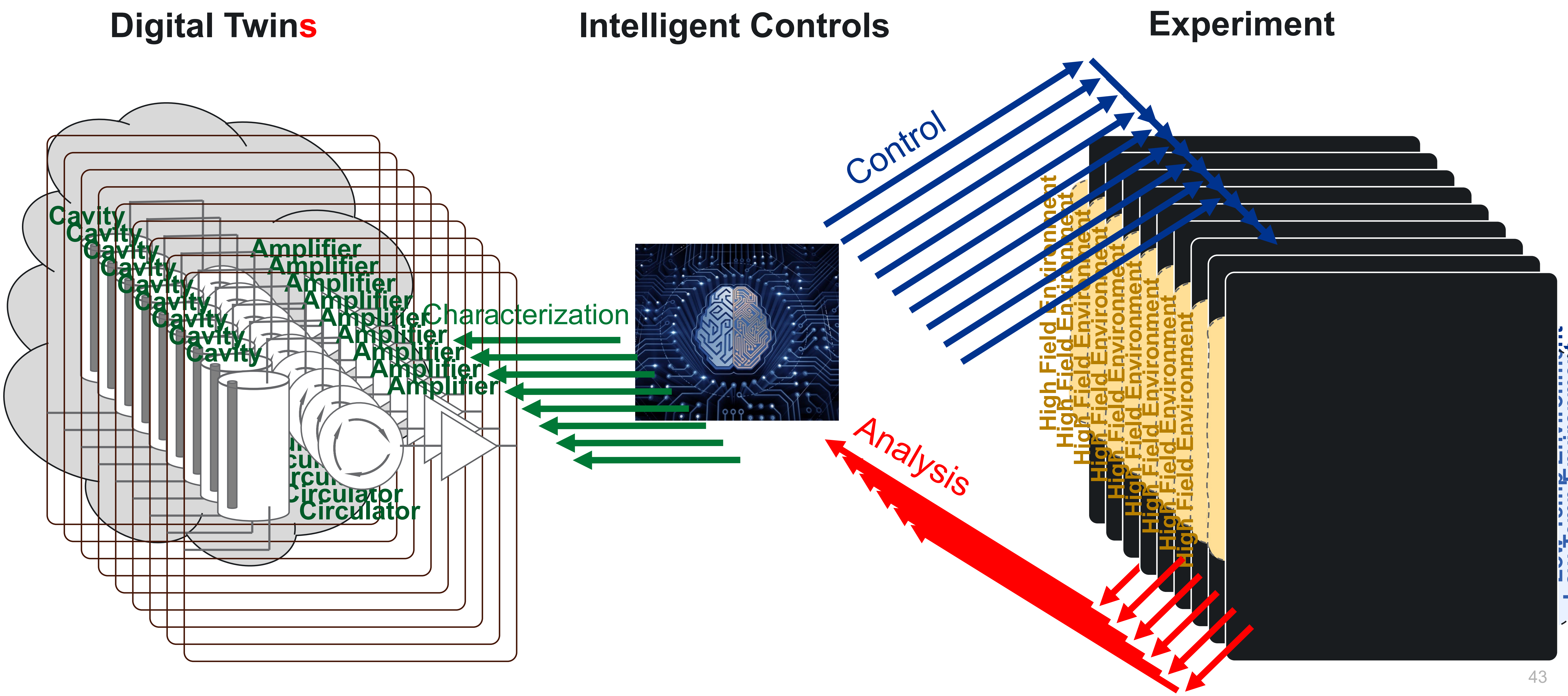
Here’s what I want to know…

Can AI/ML help us run today’s experiments?

Digital Twin | **Intelligent Controls** | **Experiment**



Can AI/ML help us run tomorrow's experiments?



Can AI/ML streamline the cadence of data-taking?

Tune

Wide Transmission measurement

Narrow Transmission measurement

Reflection measurement

Couple Antenna

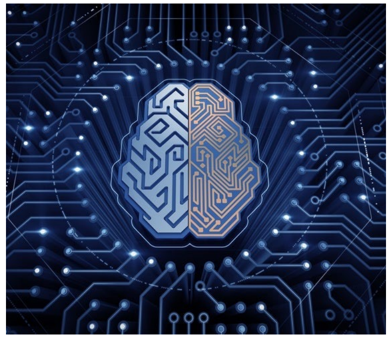
Re-bias Amplifiers

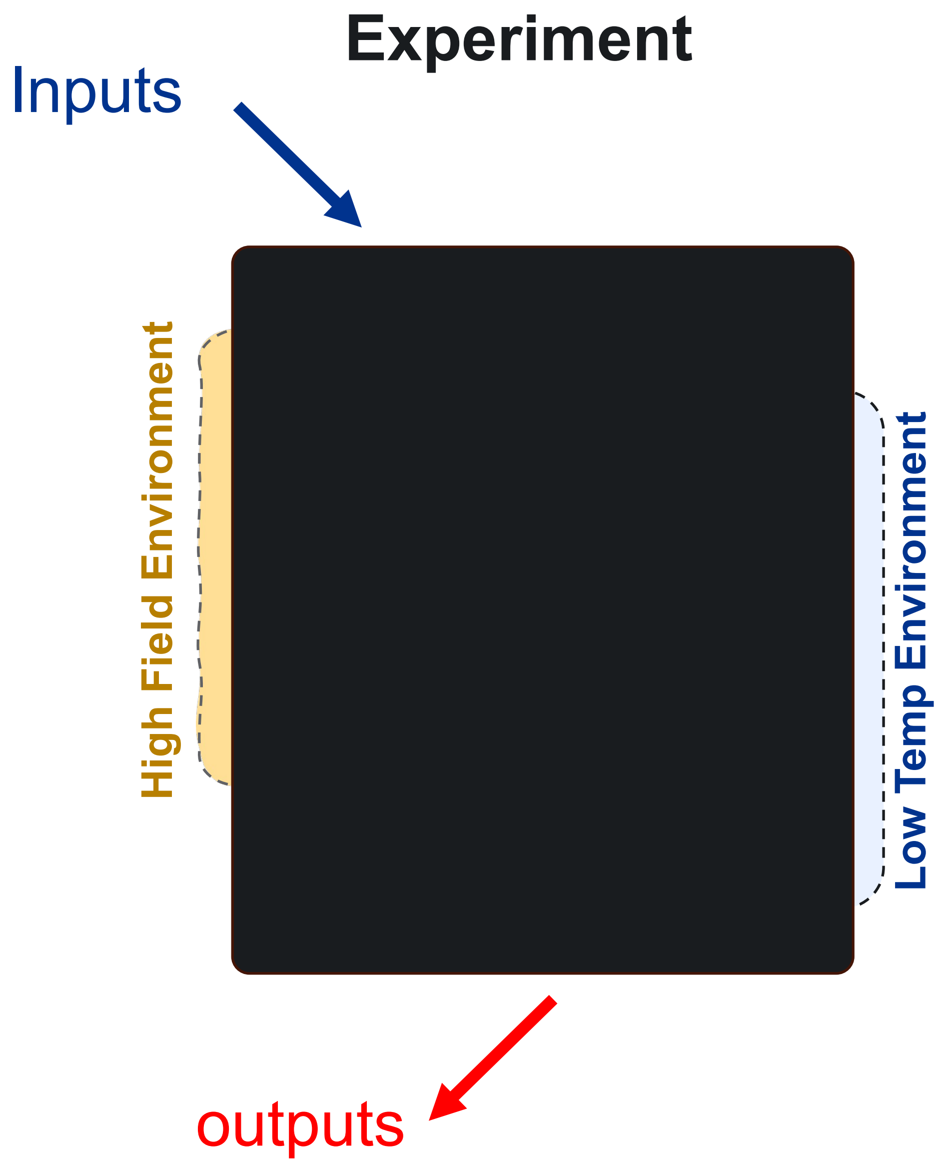
Noise Temperature Measurement

Digitize

Data taking is an endless loop of tasks

Intelligent Controls





Summary of questions

Can I use ML to…

- Help me characterize my mystery experiment (slide 35)?
- Scan faster by going through data-taking laundry list faster (slide 39)?
- Glean more information from fewer measurements?
- Tune-up devices faster?

Early findings

Team

S. Jones

Data Scientist:
AI/ML strategy,
measurement automation

T. Braine

Postdoc:
ML for RF
characterization

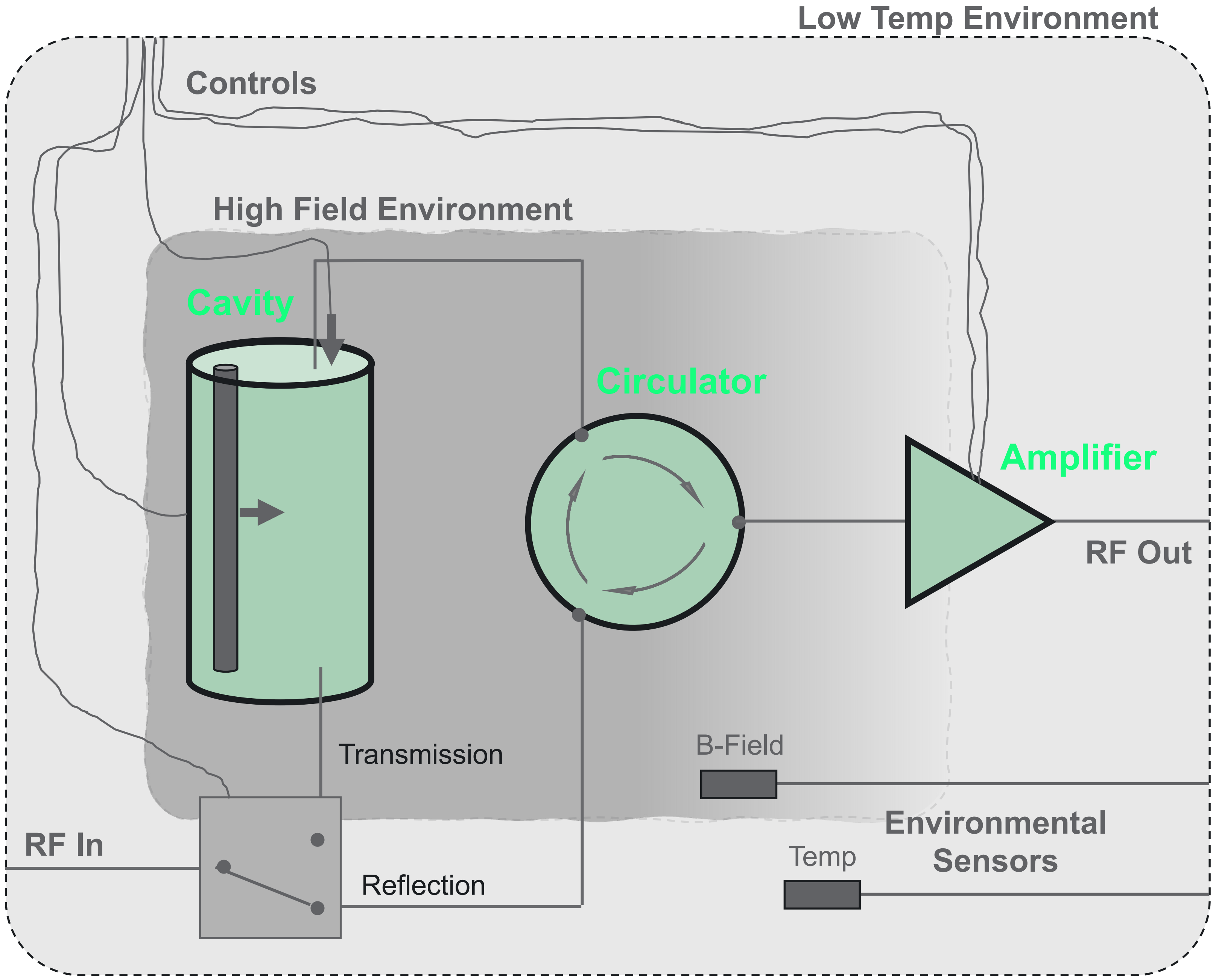
C. DeSmet

Data Scientist:
RL for controls

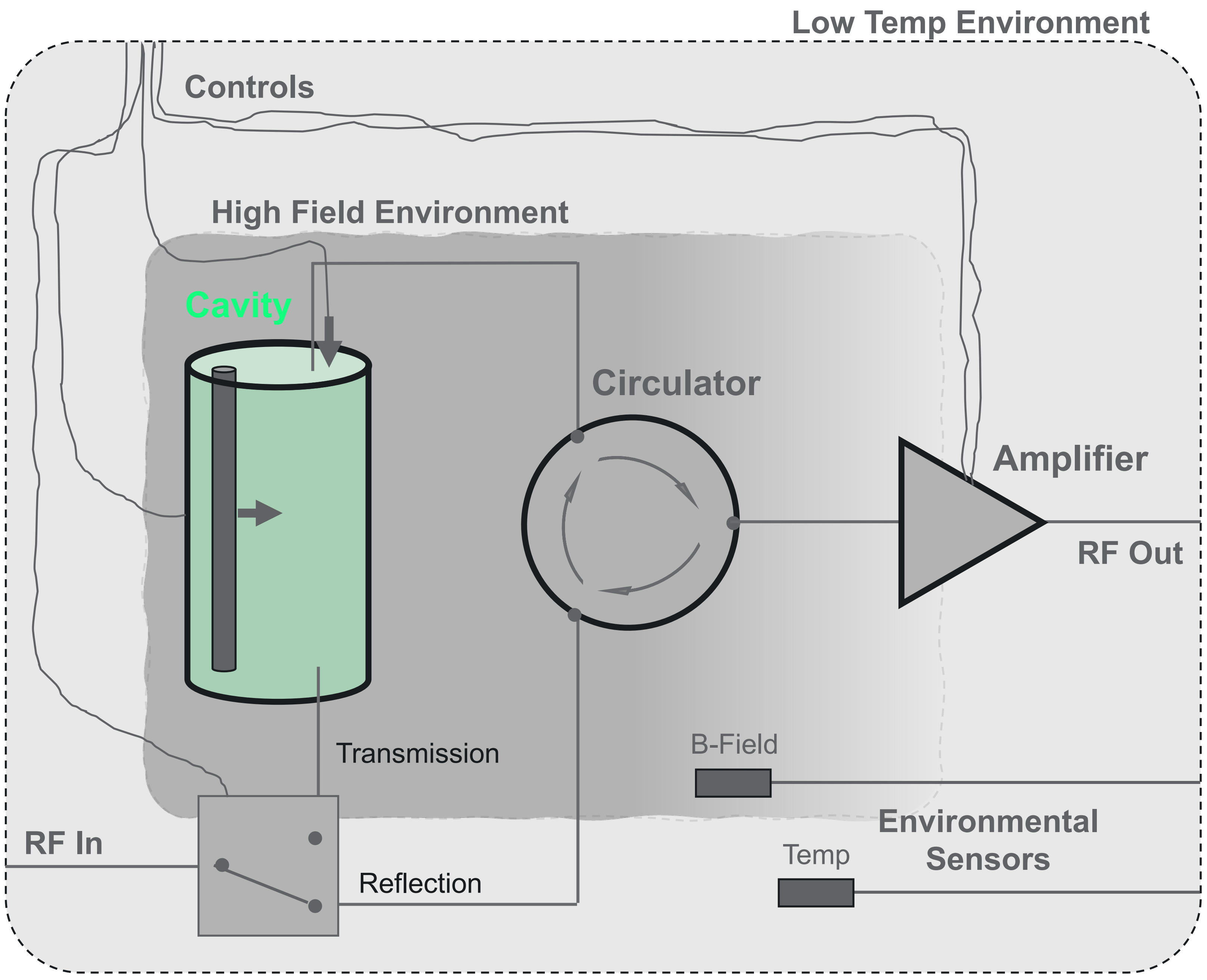
J. Godinez

SULI student:
ML for cavity tuning

3 possible examples of ML axion detection

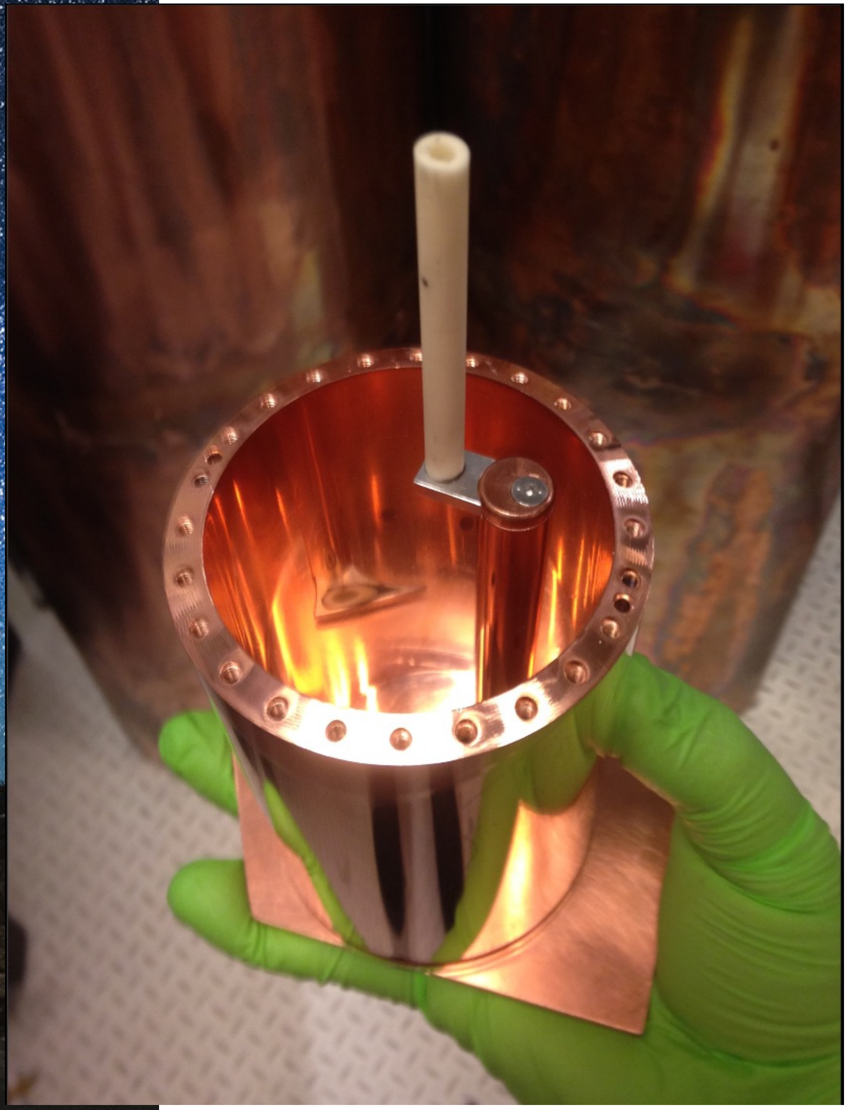


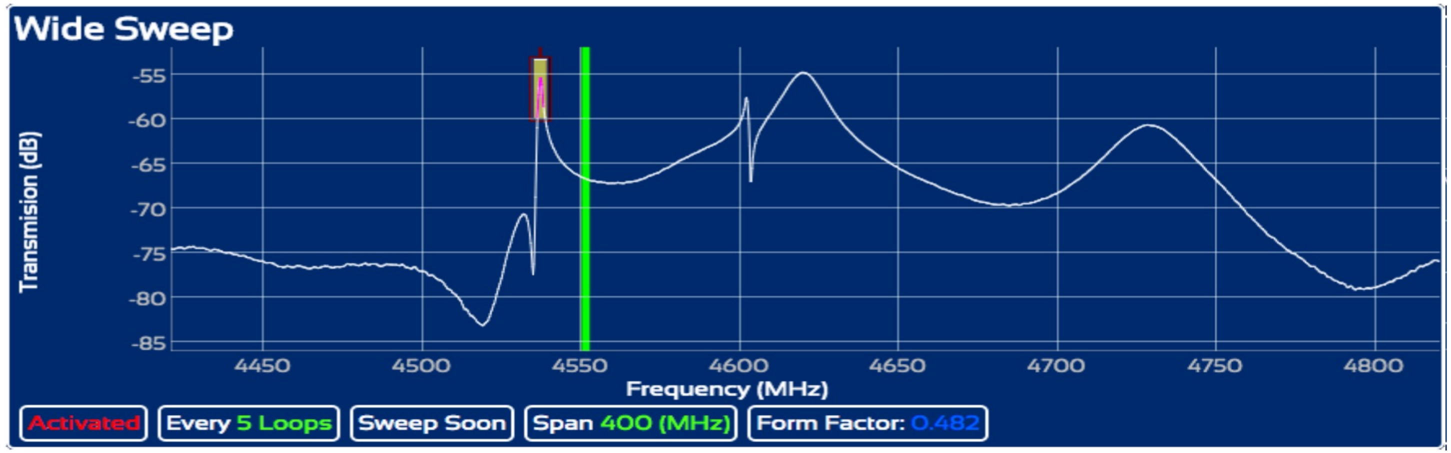
Example 1: cavity tuning

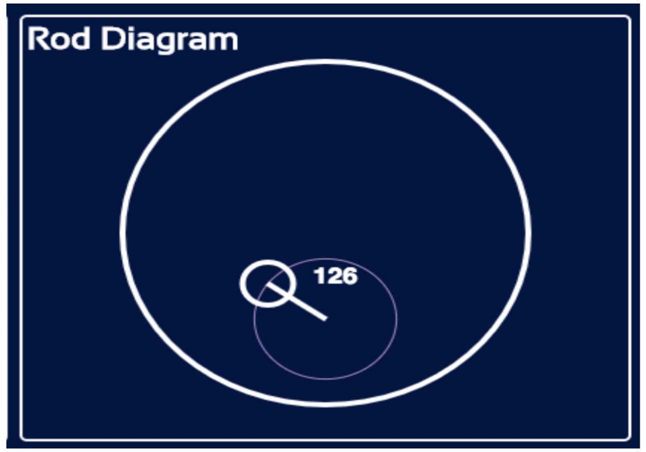


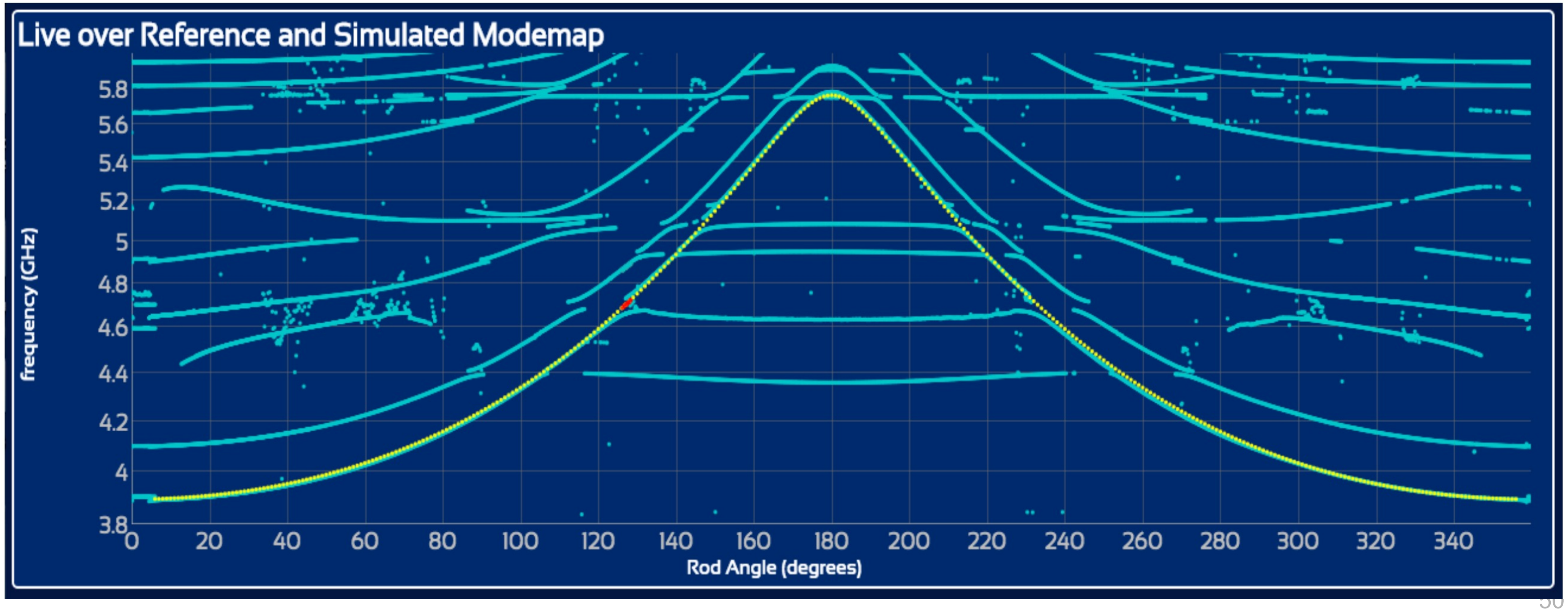
ML for Cavity Tuning

ADMX-Sidecar

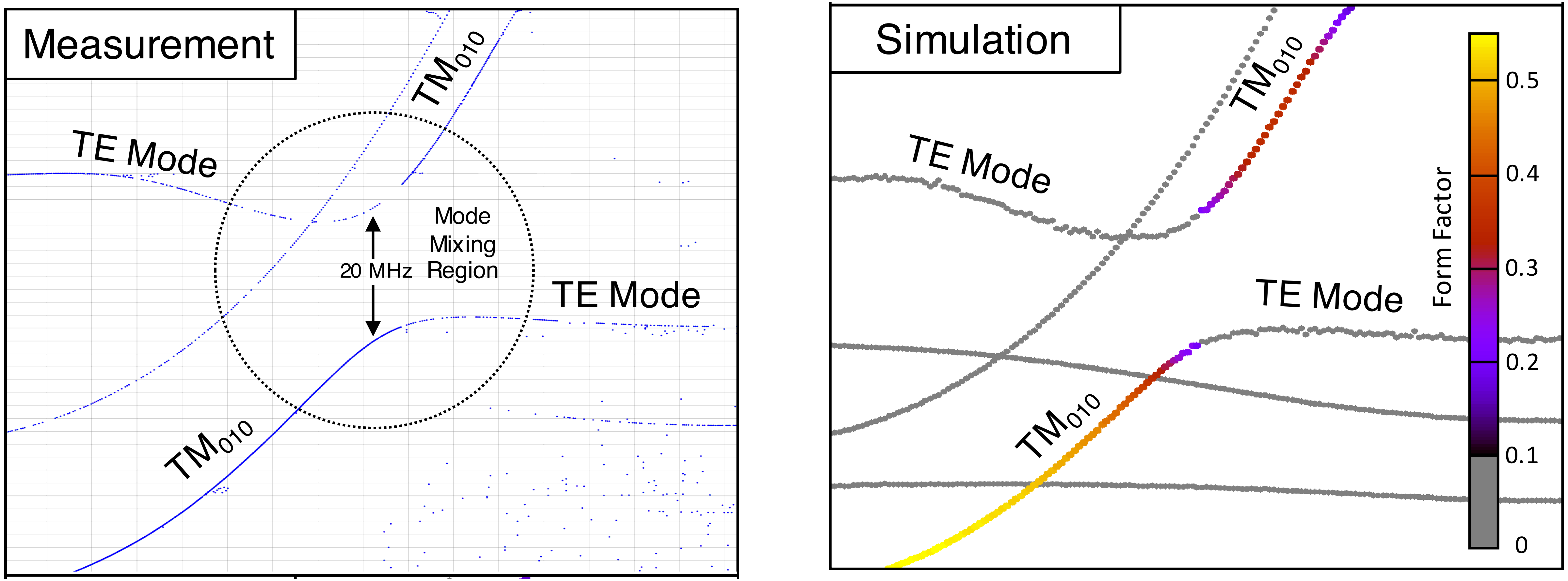








Mode Crossings



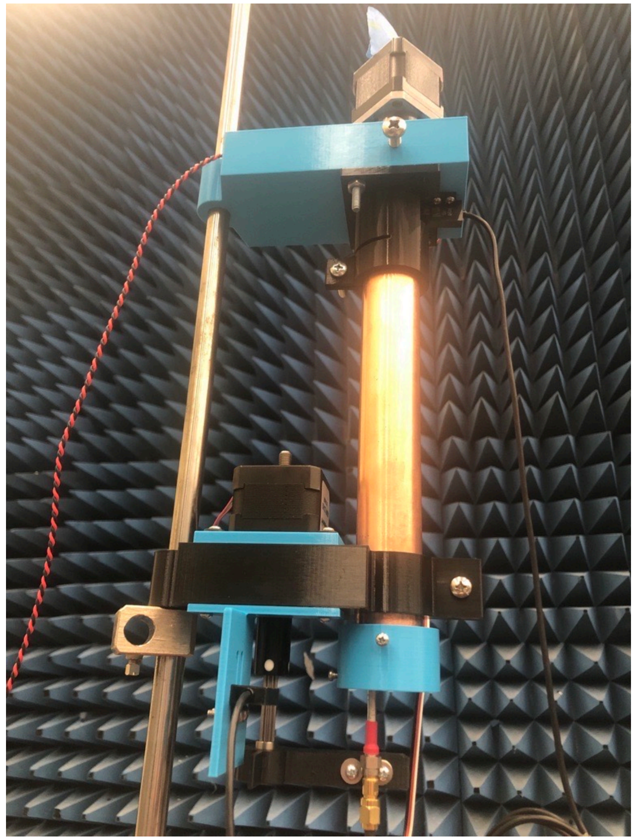
Supervised learning exercise

The cavity has a spectral fingerprint that is rich with unused information

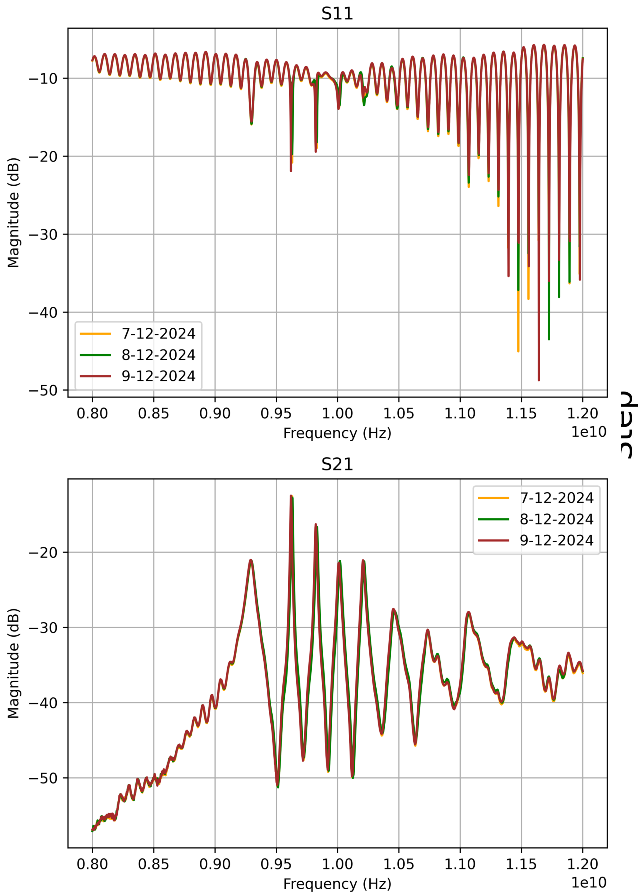
- Can we use a single wide-band fingerprint to learn multiple things?
  - Rod position
  - TM010 center frequency
  - Q
  - Antenna coupling
  - Rod tilt
- Can we use out-of-band information to predict in-band information?

Setup and inputs to Neural Network (NN)

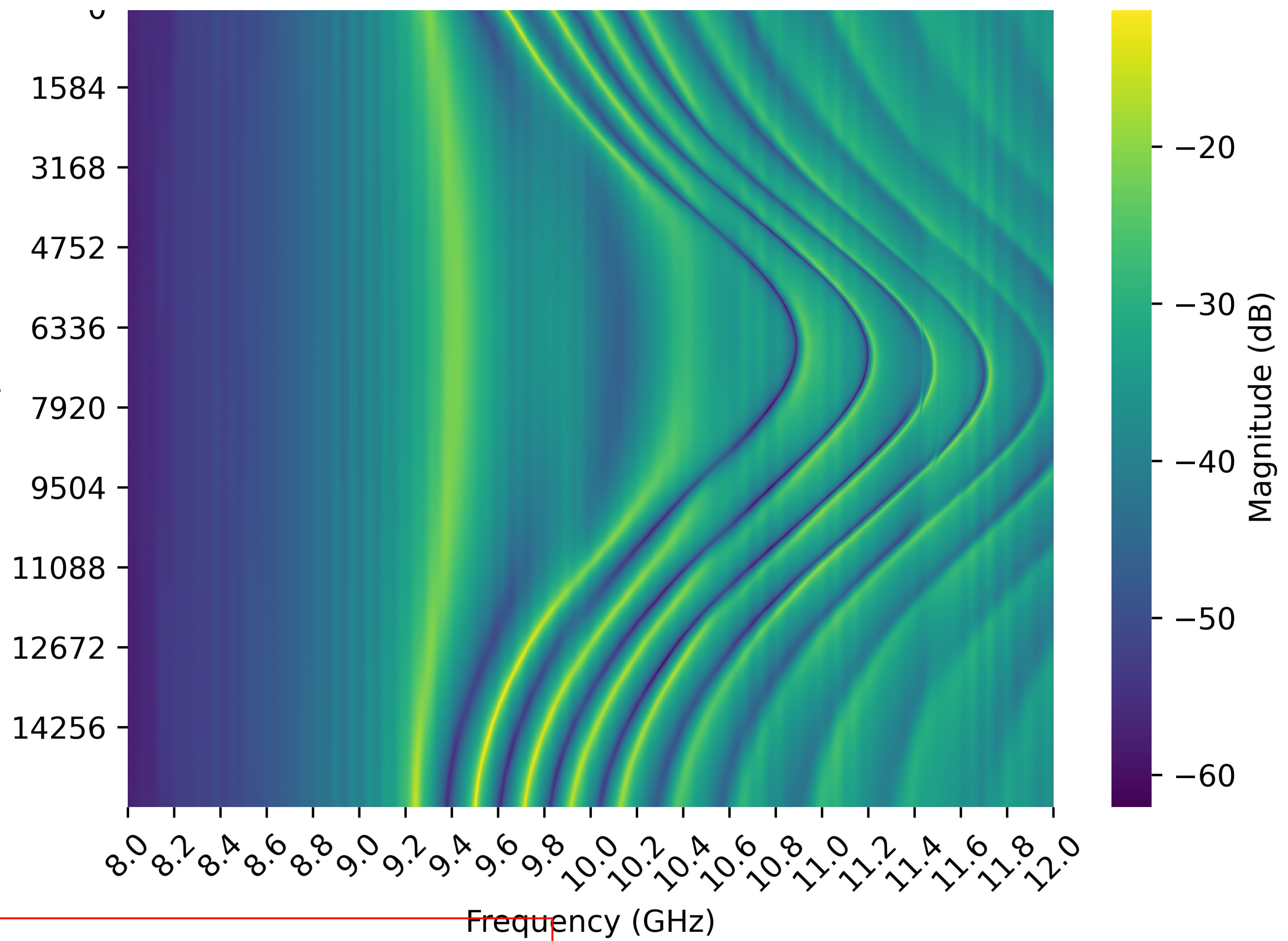
Cavity Setup



Input to NN (“fingerprint”)



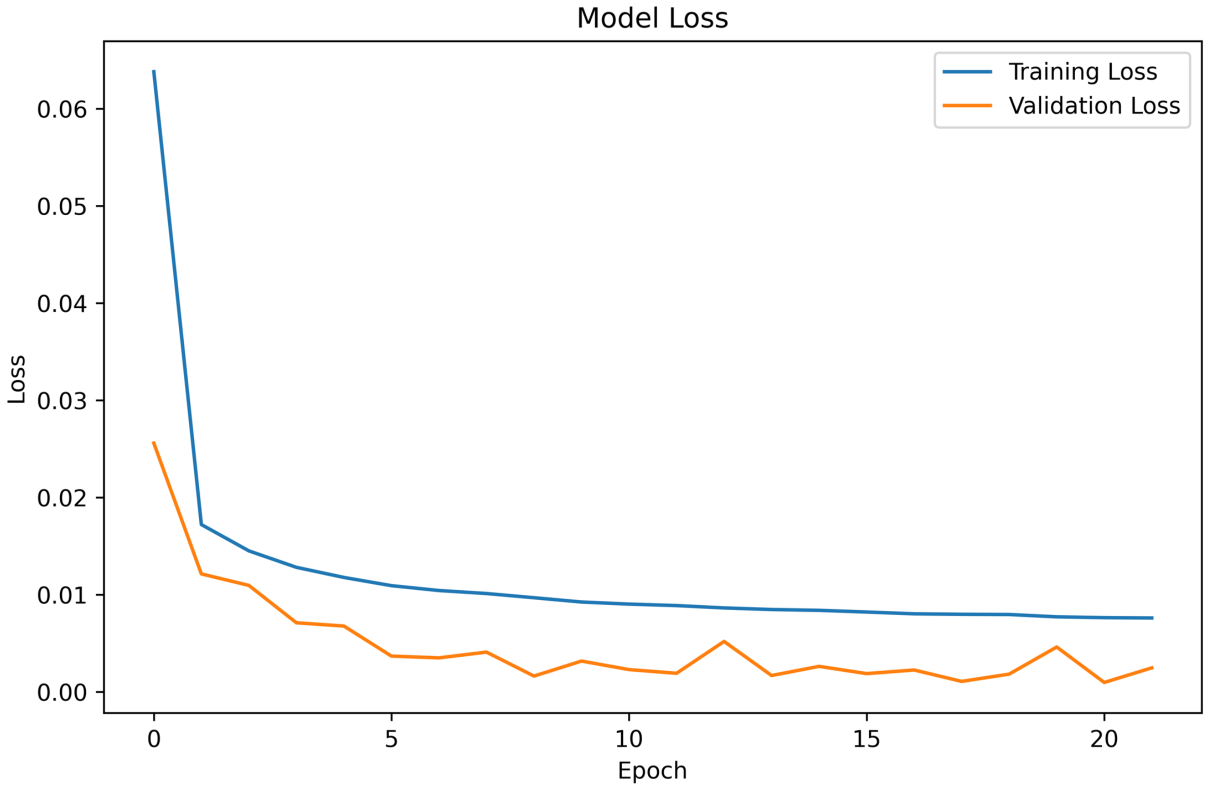
S21 over all tuning rod positions

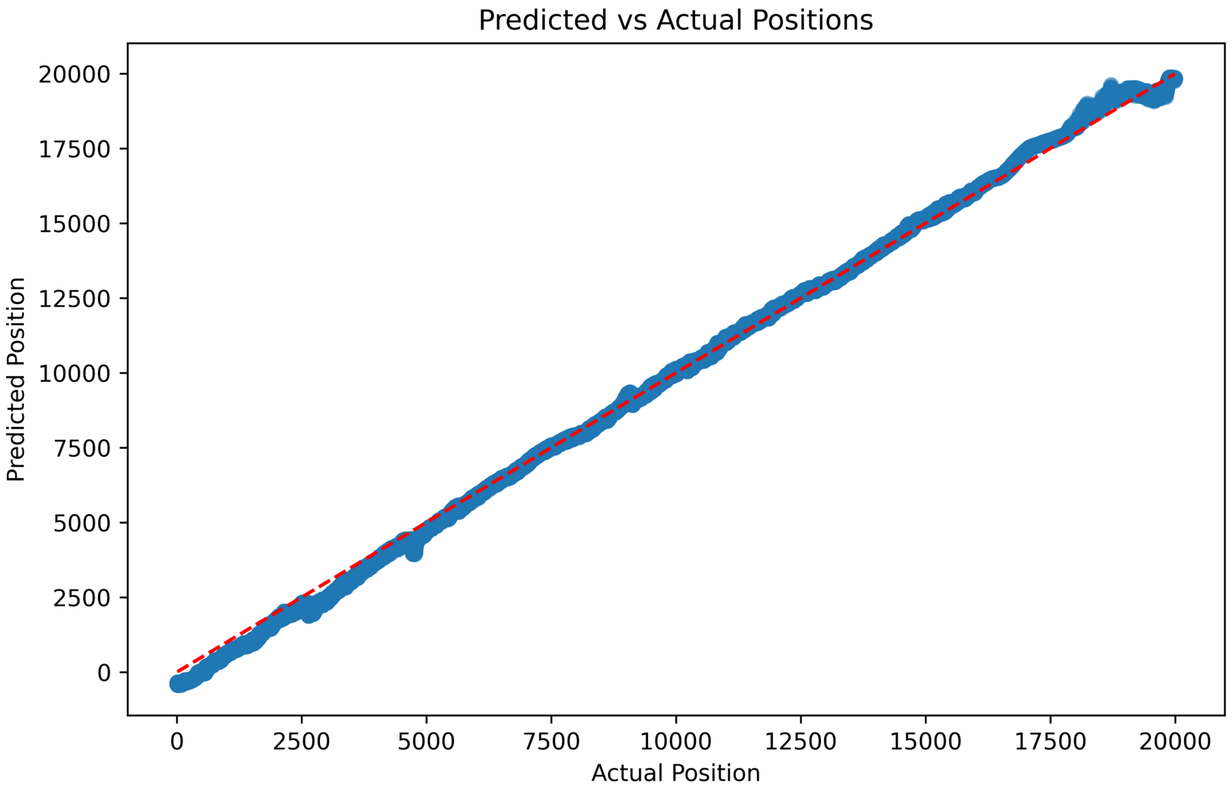


Labels to NN: 1) Tuning rod position, 2) Antenna position

Preliminary Results

- Started with a dual brand 1D CNN model, S21 magnitude, S21 Phase
- Experimentation found better results with triple branch 1D CNN model S21 magnitude, S21 phase broken into complex representation (IQ)
- Further hyper parameter tuning found that a sinc activation function performed better than standard relu or sin
- Model performed well without over fitting
- Future work to include removing dependence on motor position and instead predict TM010 mode





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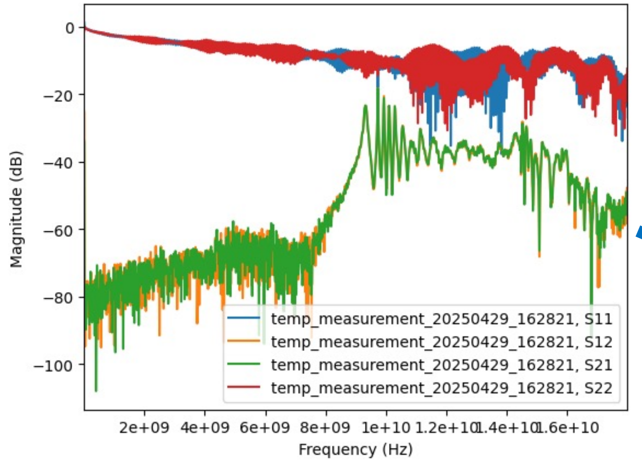
Data Acquisition:

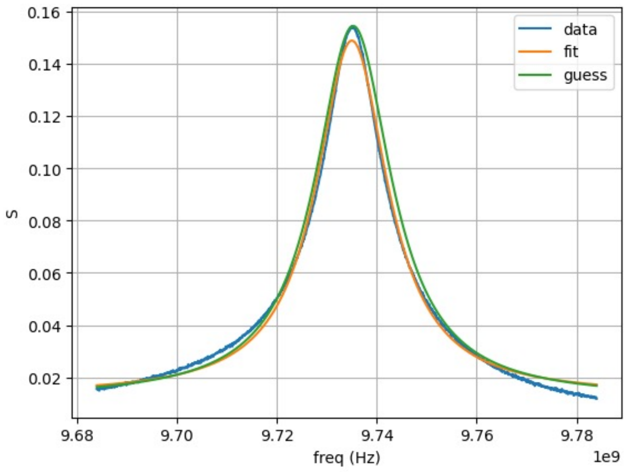
Repeat until full tuning rod rotation

1. Acquire S-parameters:

Wide-band



Narrow Resonance



2. Associate Input with Label for NN

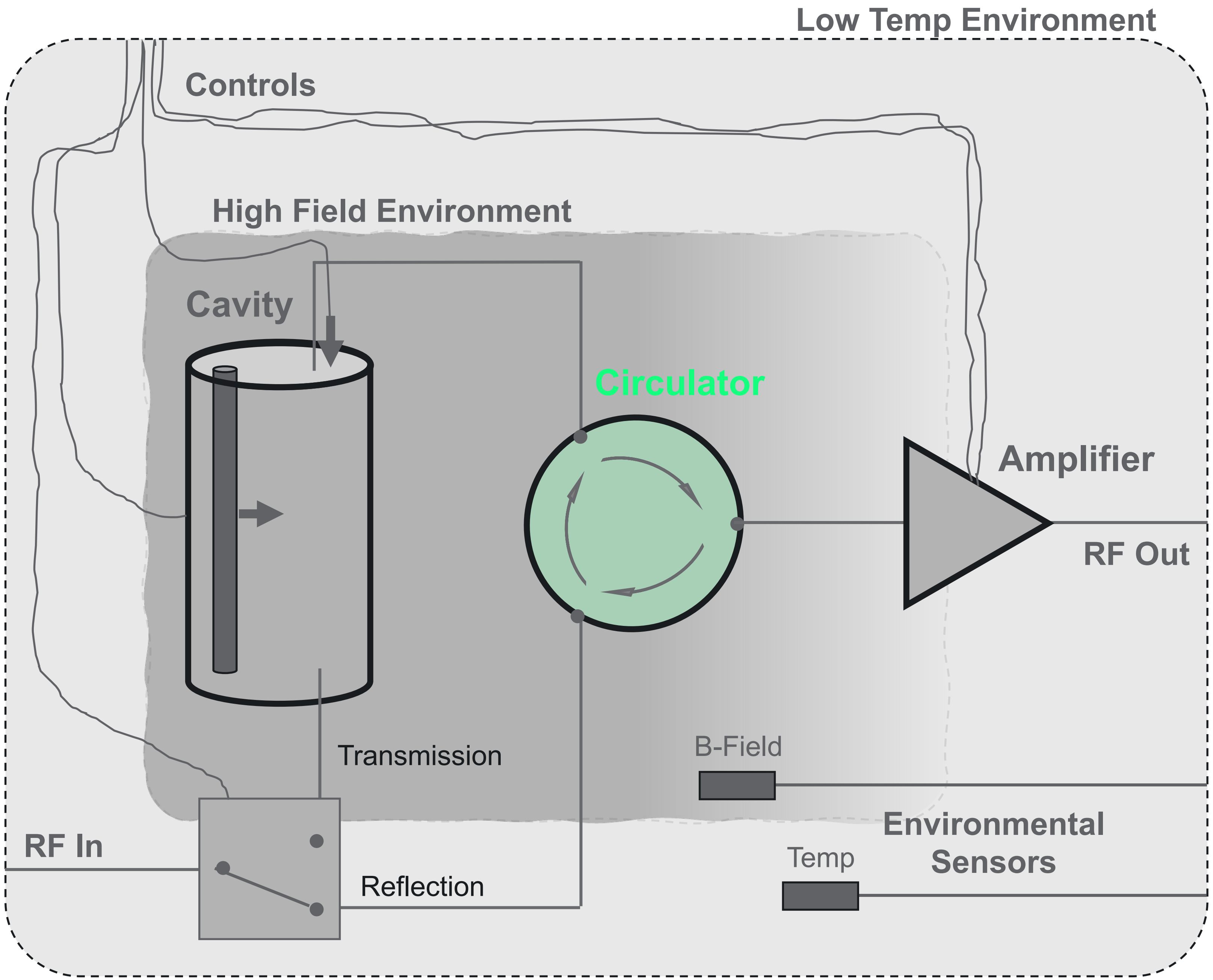
Input Data to NN

f_0 from Q-fit (Label for NN)

3. Move Rod Motor (tune f_0 slightly)

New Data point for NN Training!

Example 2: circulators as sensors

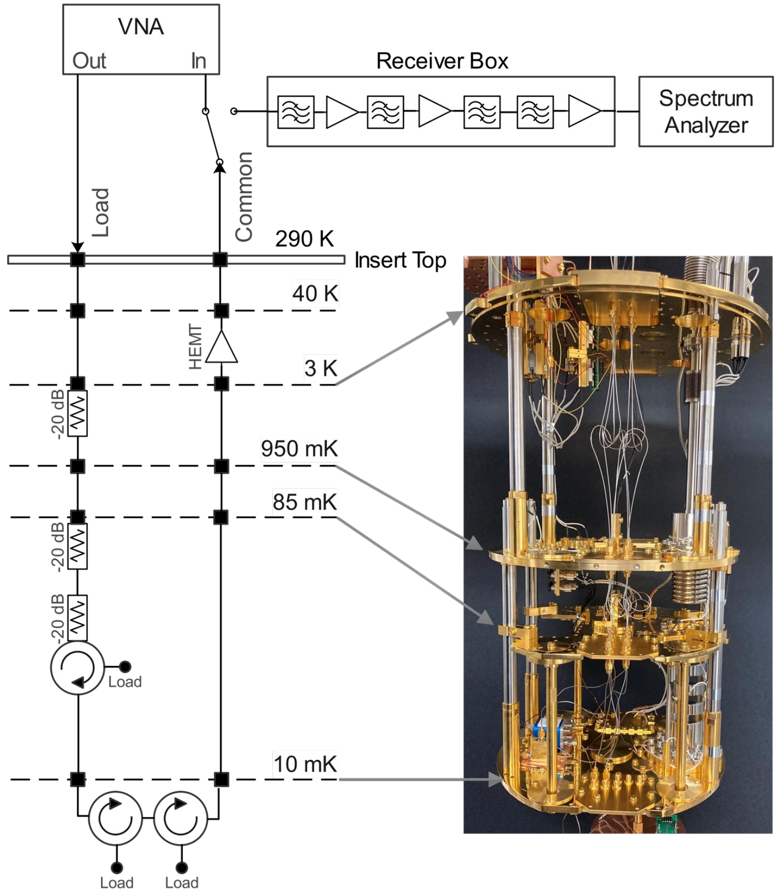


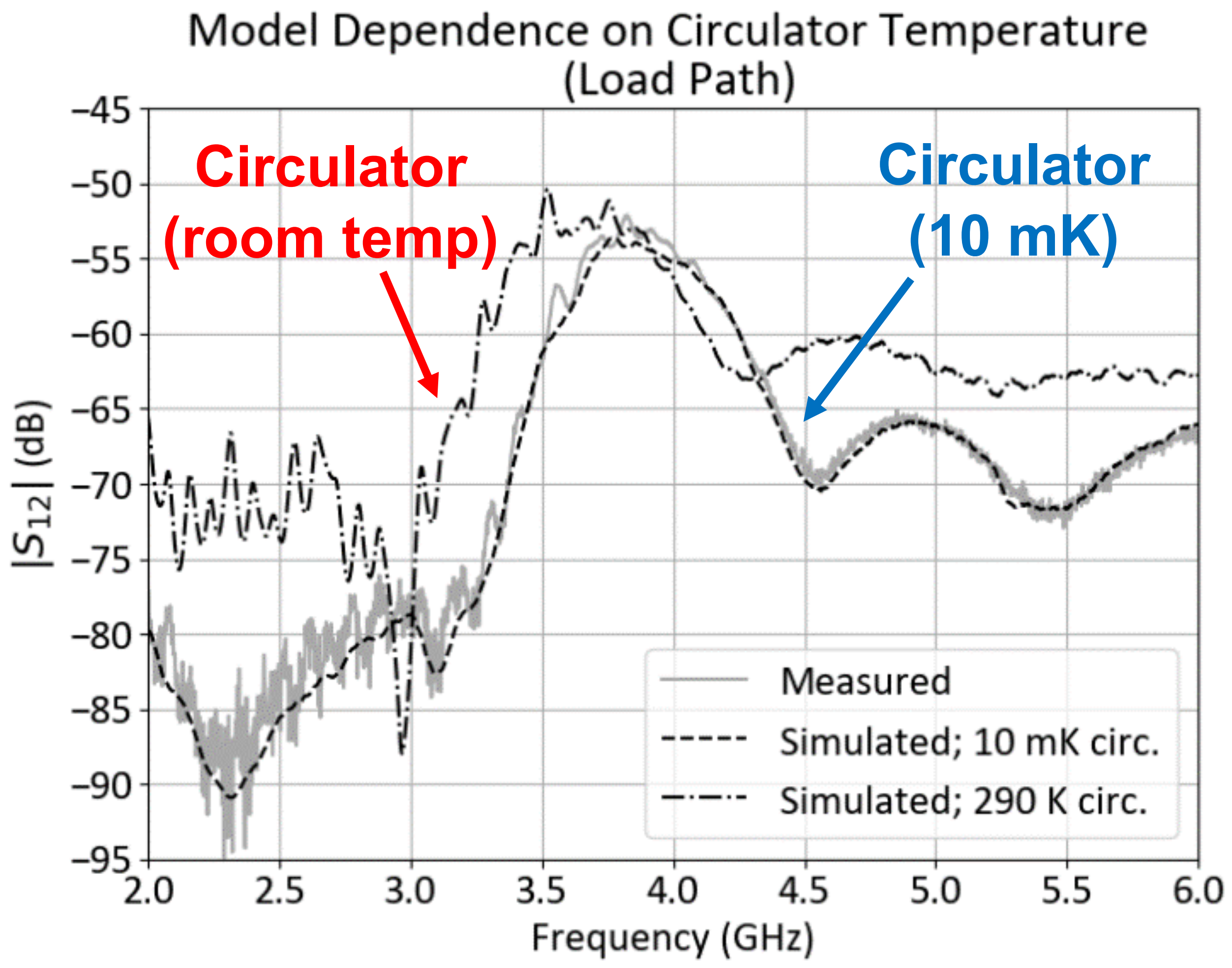
Circulators are sensitive to environmental changes

A Multiport Approach to Thermal Noise and Scattering Parameter Simulation of Cryogenic Experiments

Maurio B. Grando, Christian R. Boutan, Jihee Yang

https://doi.org/10.48550/arXiv.2209.04008





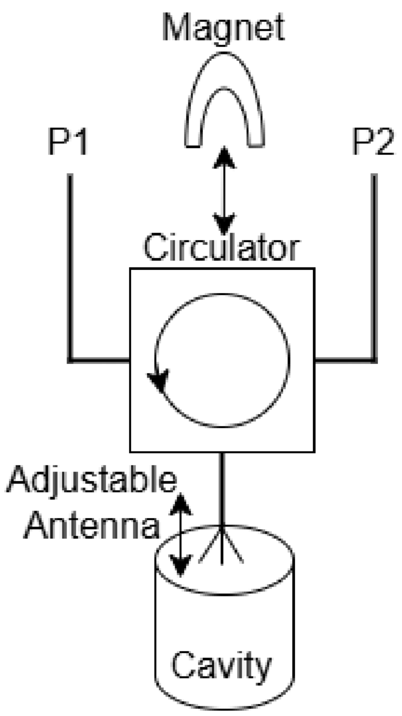
Using a circulator as a magnetic field sensor

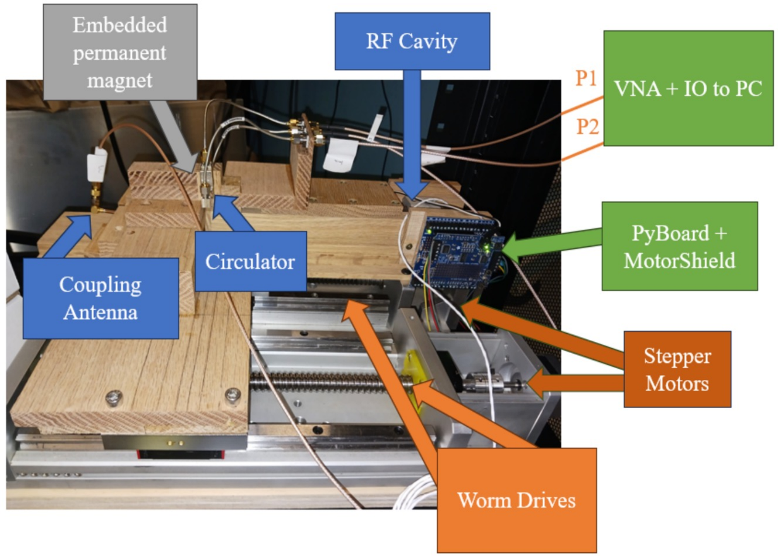
Identifying environmentally induced calibration changes in cryogenic RF axion detector systems using Deep Neural Networks

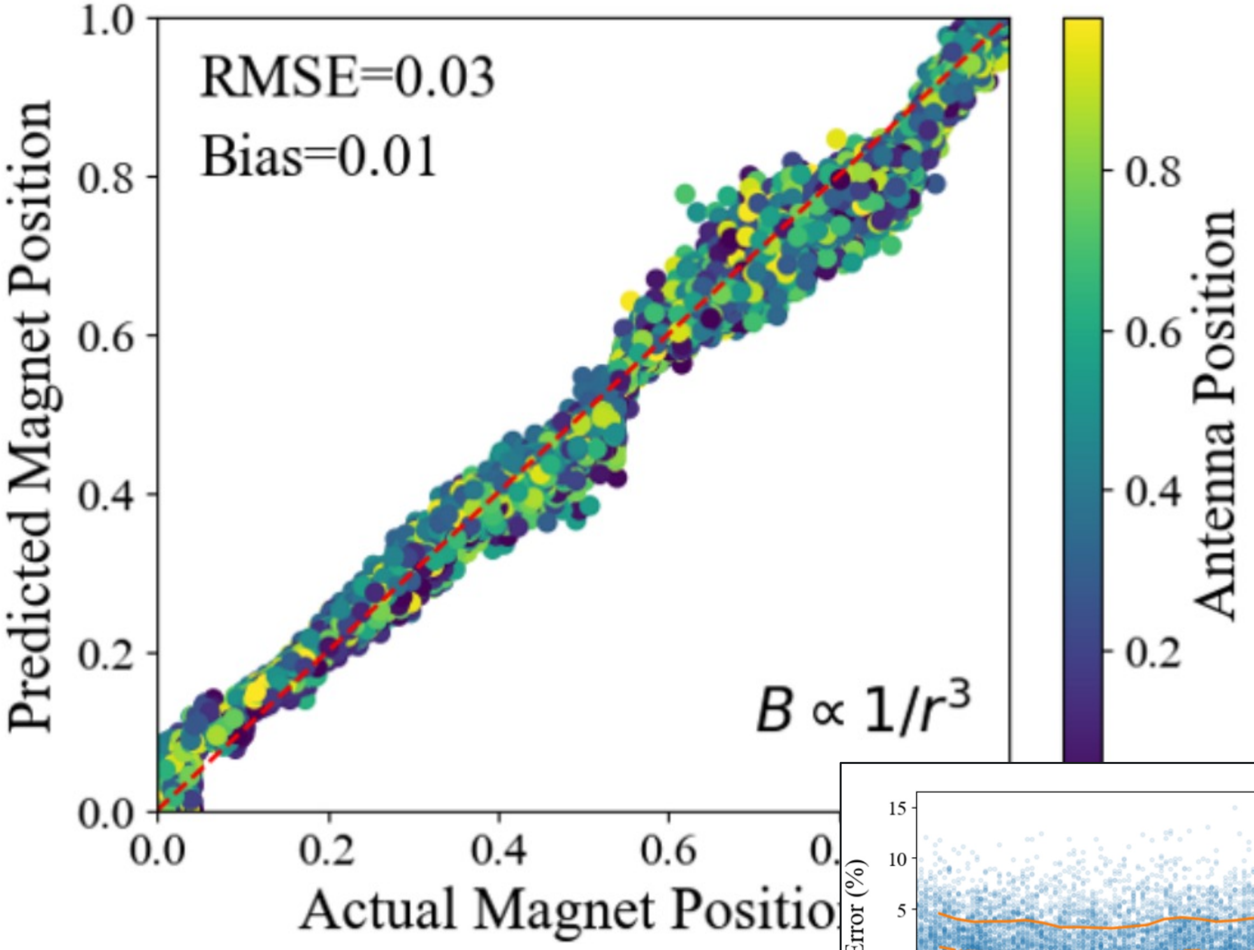
Andrew Engel,[1,2,3] Thomas Braine,[1] and Christian Boutan[1]

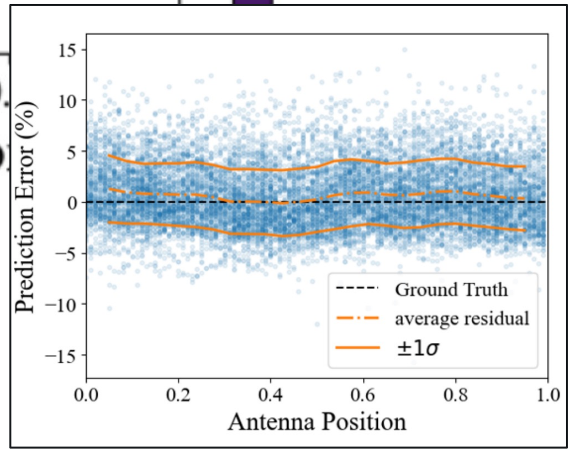
[1]*Pacific Northwest National Laboratory, Richland, WA, USA*
[2]*Department of Physics, Ohio State University, Columbus, OH, USA*
[3]*Center for Cosmology and AstroParticle Physics (CCAPP)*
, Ohio State University, Columbus, OH, USA

https://doi.org/10.48550/arXiv.2503.03036









Using a circulator as a temperature sensor

Identifying environmentally induced calibration changes in cryogenic RF axion detector systems using Deep Neural Networks

Andrew Engel,[1,2,3] Thomas Braine,[1] and Christian Boutan[1]
[1] Pacific Northwest National Laboratory, Richland, WA, USA
[2] Department of Physics, Ohio State University, Columbus, OH, USA
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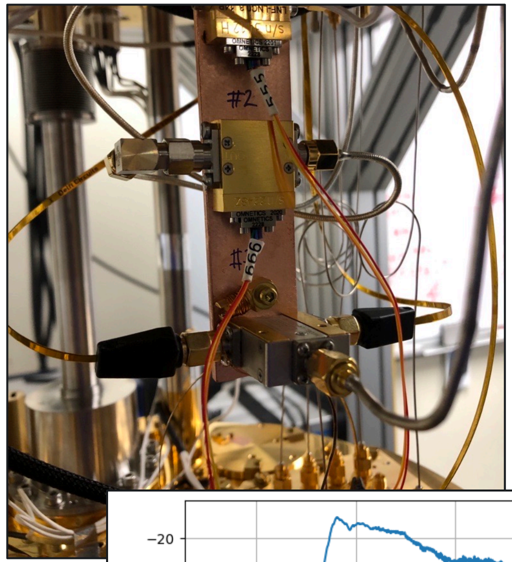
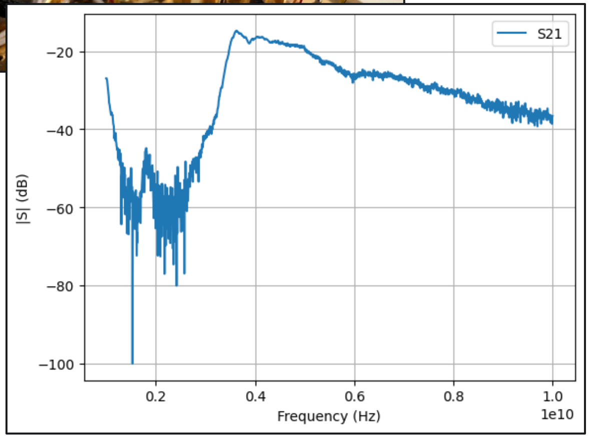
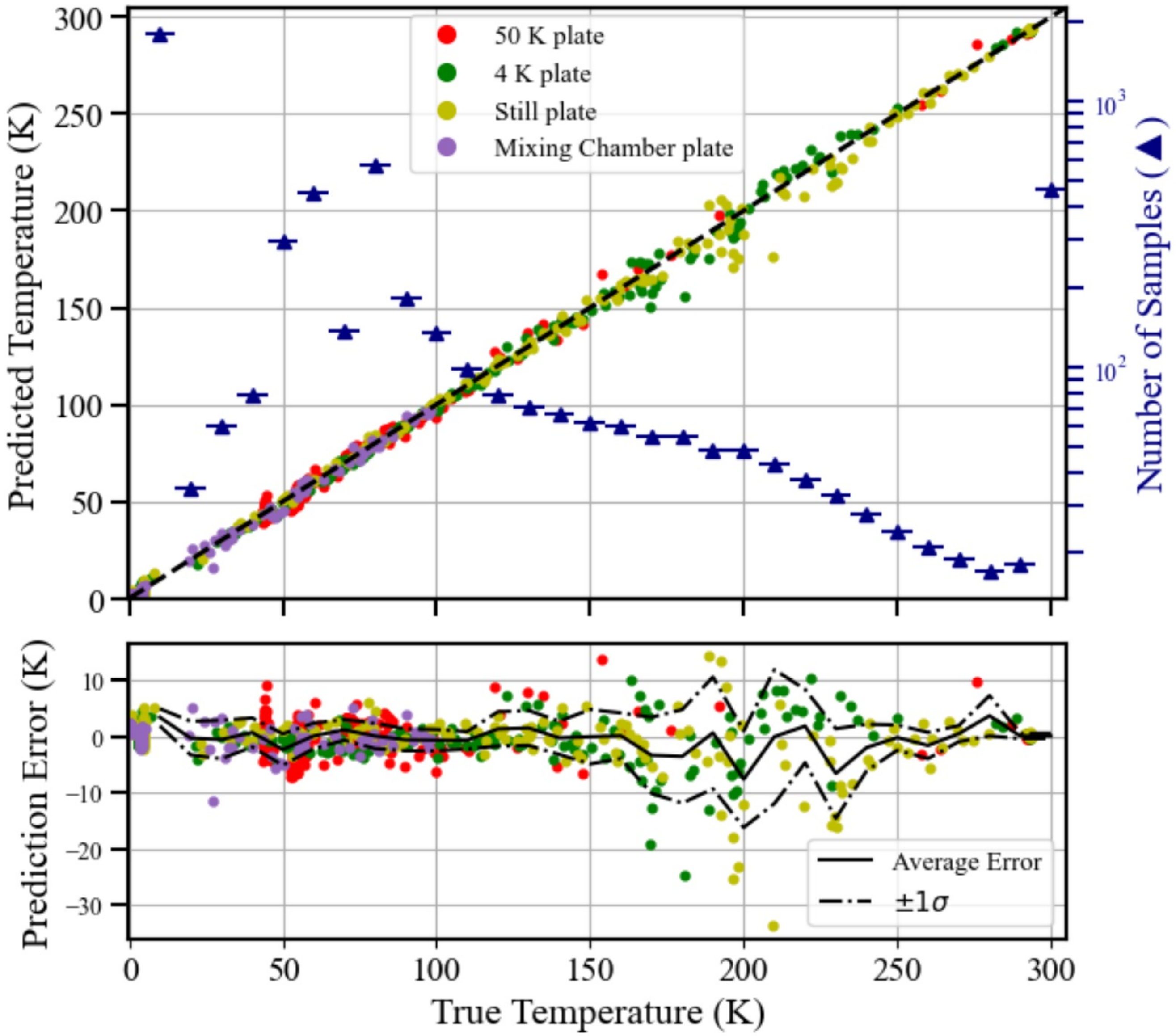


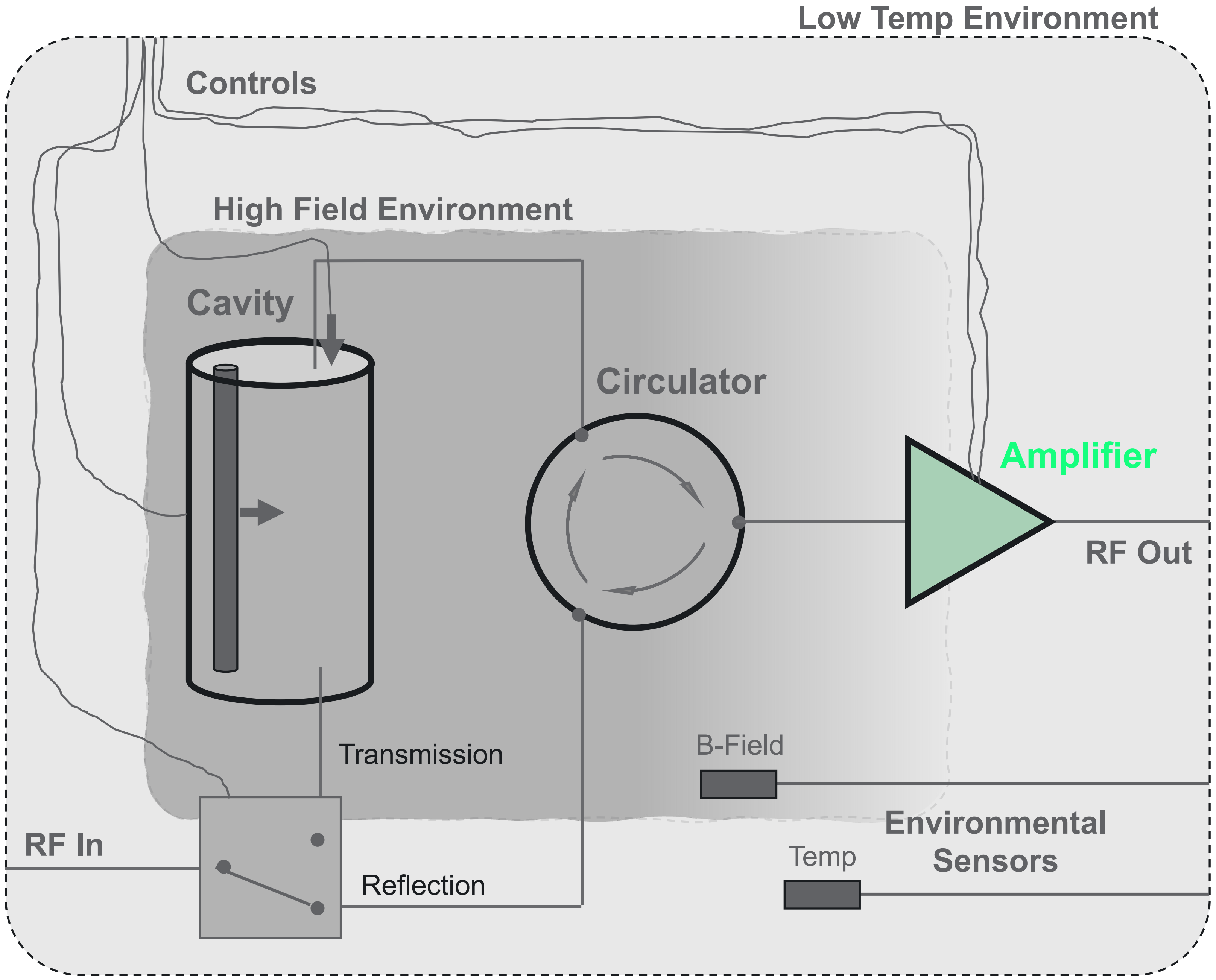


Temperature sensors as **Labels** to NN:

- 50 k plate
- 4 k plate
- Still plate
- MXC plate



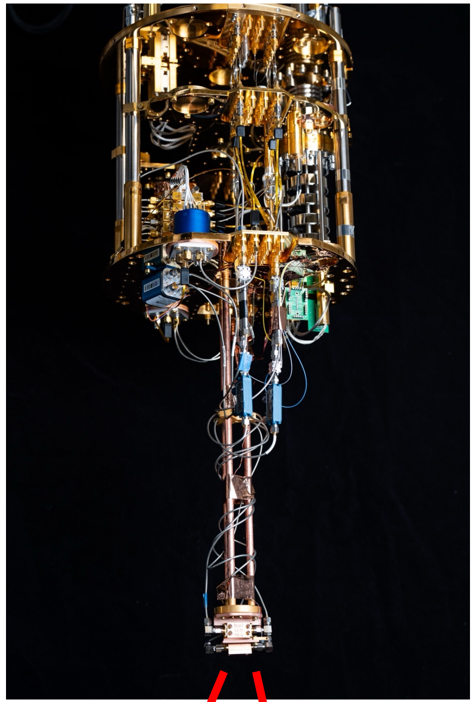
Example 3: auto-tuning quantum amplifiers



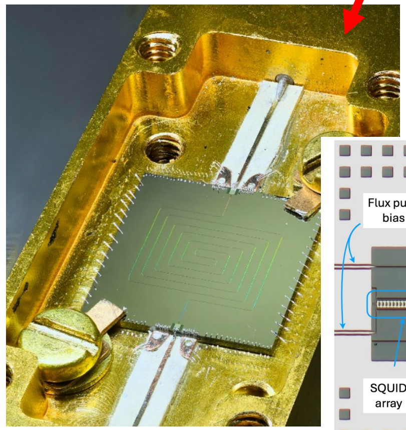
Quantum noise limited amplifiers are finicky

- Quantum noise limited amplifiers come in a few varieties and are critical for precision physics experiments and quantum computing
- Very sensitive to environmental changes
- Often behave differently every cooldown
- Notoriously difficult to tune up
- Inputs:
  - Bias current
  - Pump power
  - Pump frequency

PNNL Dilution Refrigerator

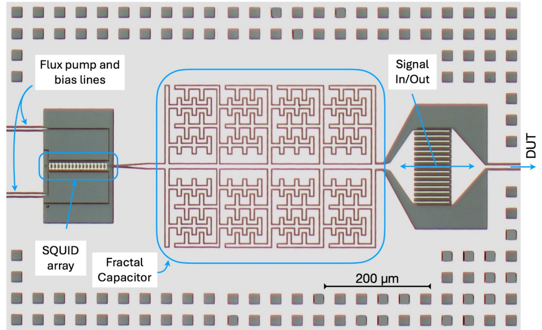


Kinetic Inductance Travelling Wave Parametric Amplifier



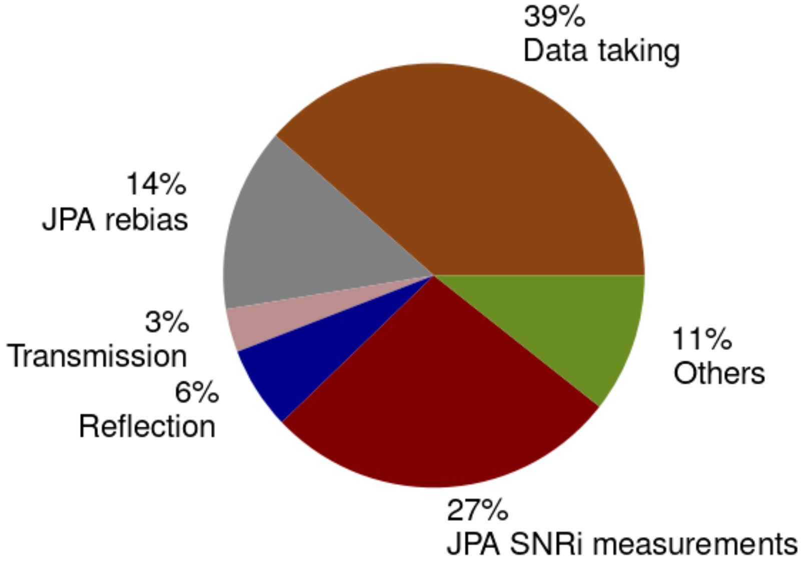
NIST Device

Josephson Parametric Amplifier



Jordan Russell, WUSTL

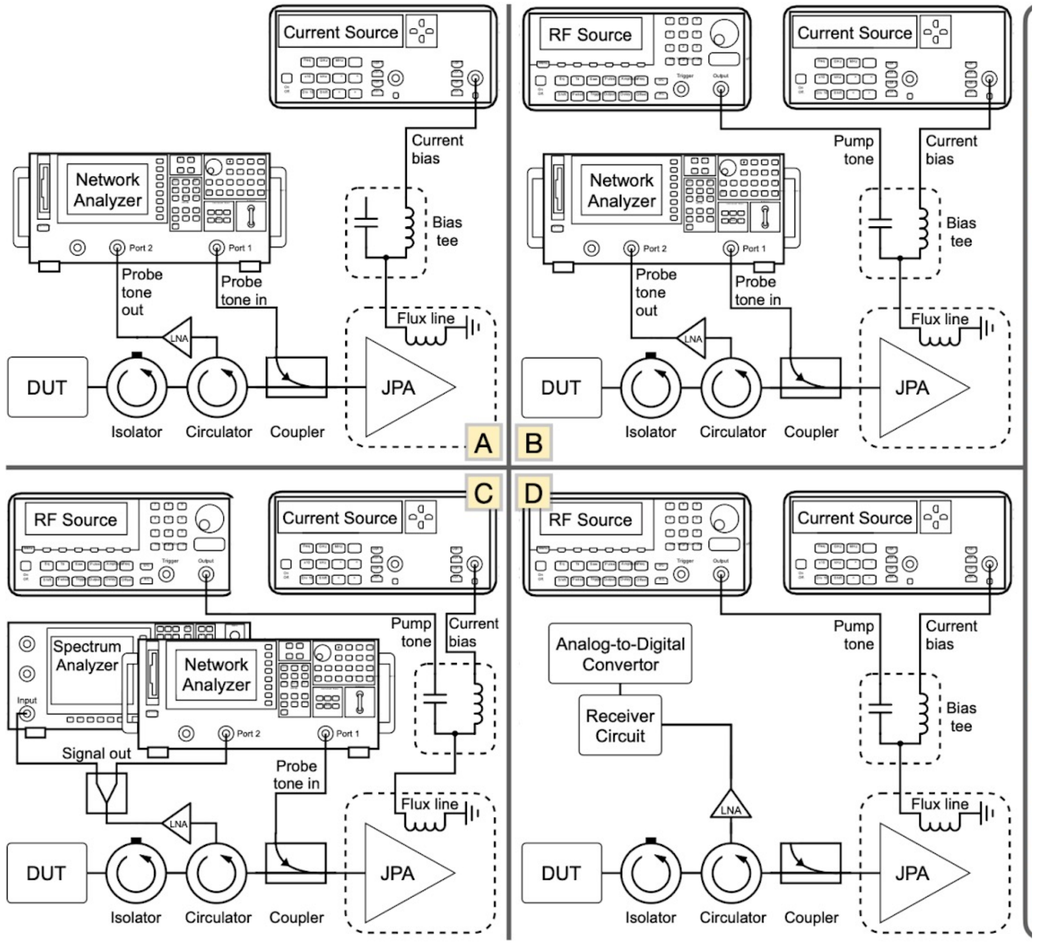
ADMX's primary source of dead time



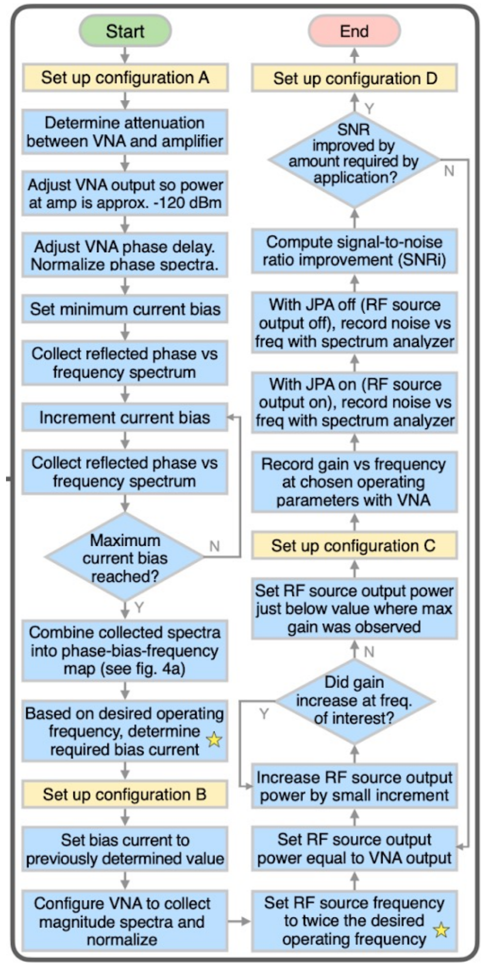
Within data-taking loop, AMDX spends > 40% performing JPA related measurements

Conventional approach to tune-up

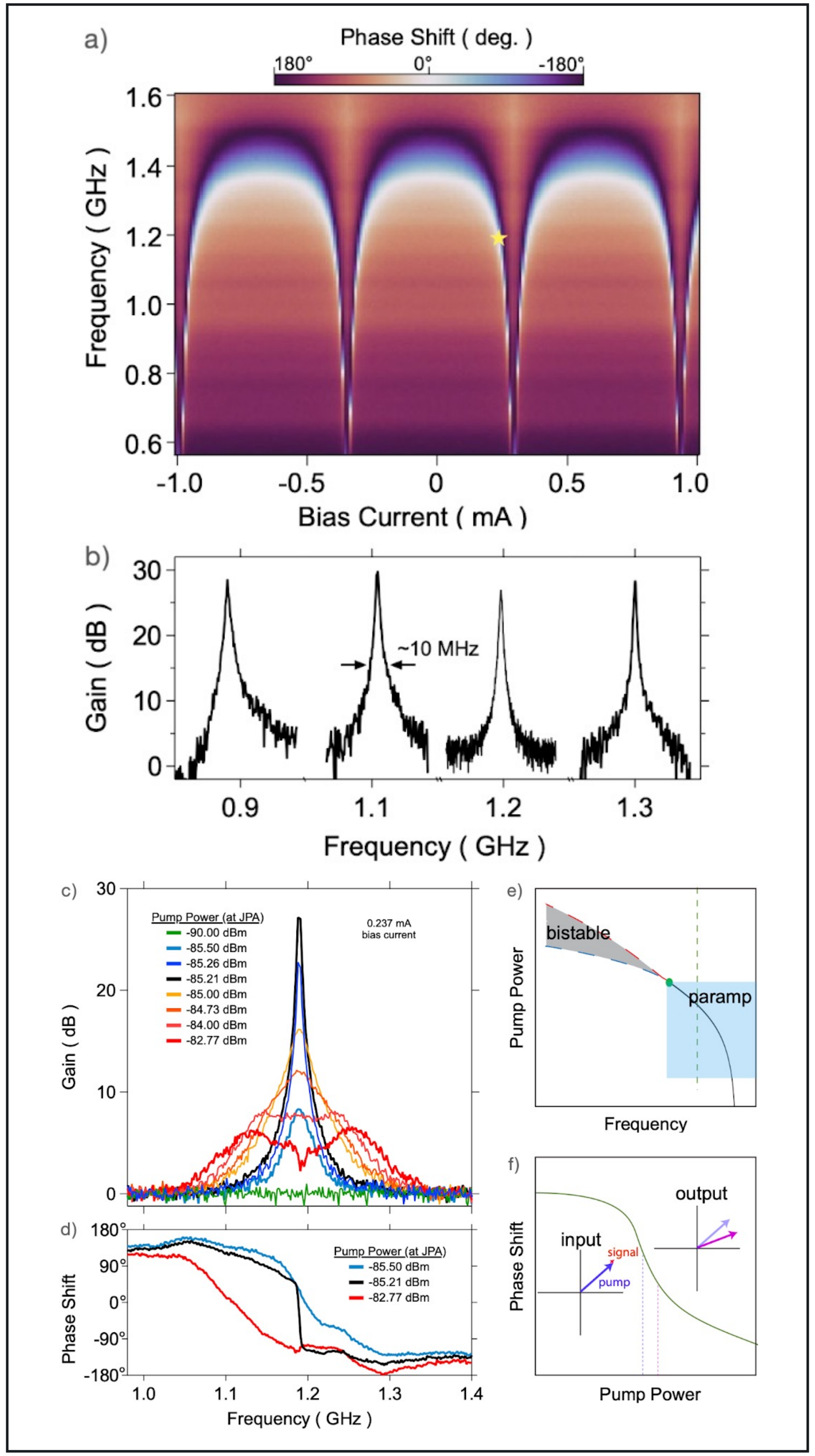
Many hardware configurations



Complicated procedure



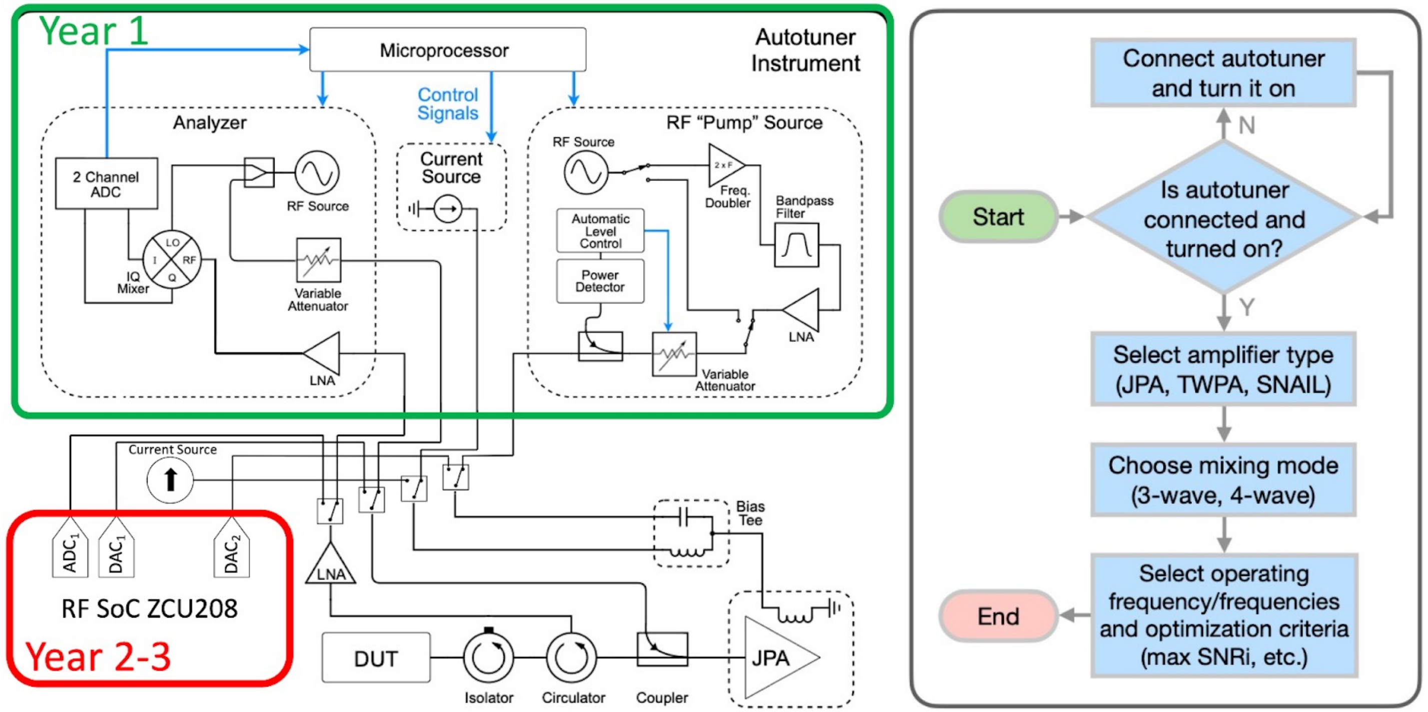
Multiple types of measurements



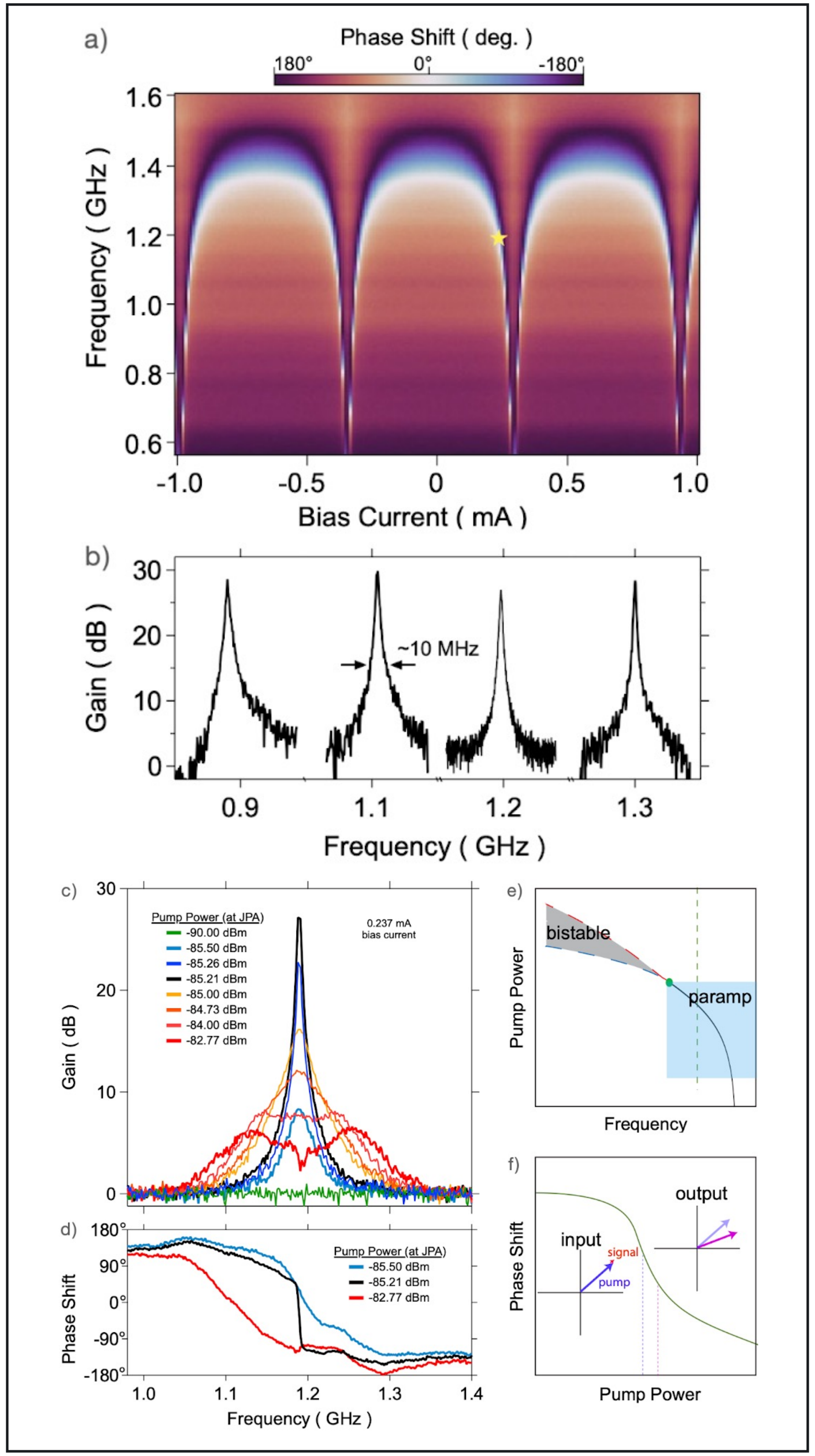
RL for the Auto-tuning of non-linear superconducting devices

- Let’s have an RL agent decide what
  - measurements to make
  - order to make them in
- Reward agent on high gain, low noise, stability etc
- May find unexpected operating modalities

Simplified hardware (migrating to RF-SoC)



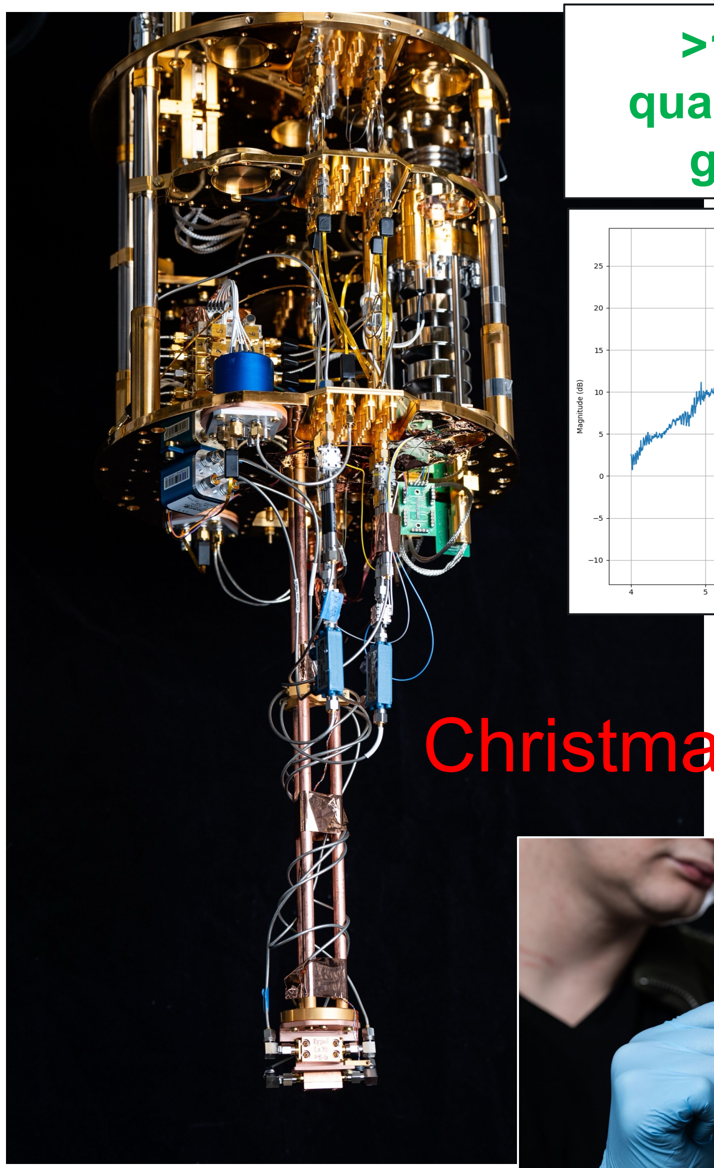
Multiple types of measurements

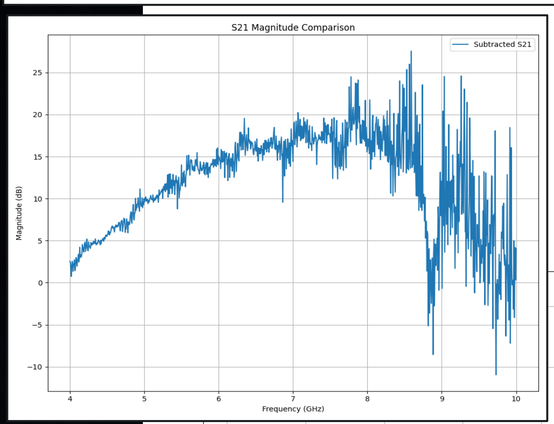


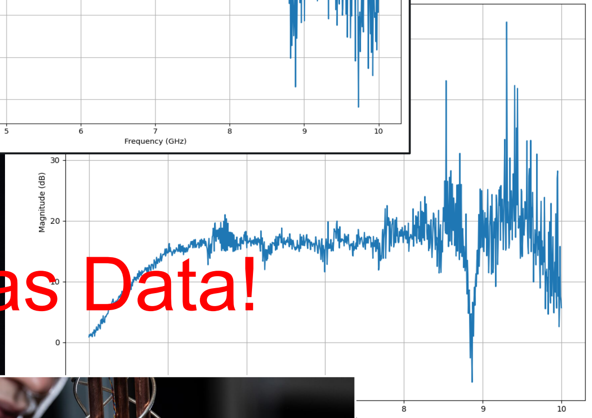
Preliminary: RL agent training on offline data

Low temperature data taken recently

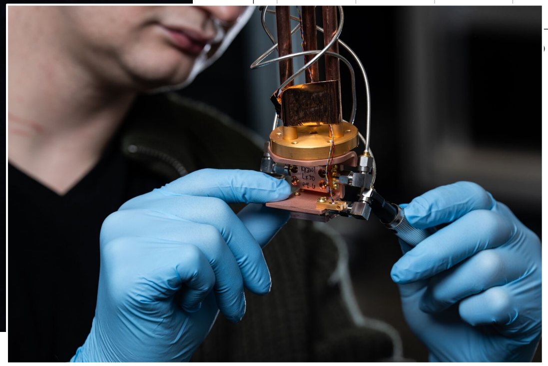
>15 dB wide-band quantum-noise-limited gain in a 1T field!







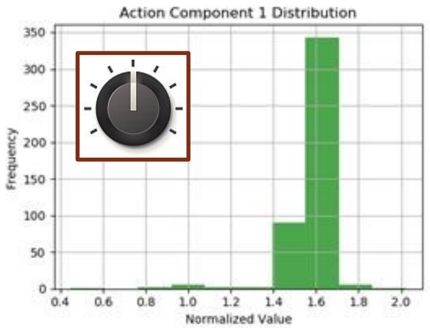
Christmas Data!



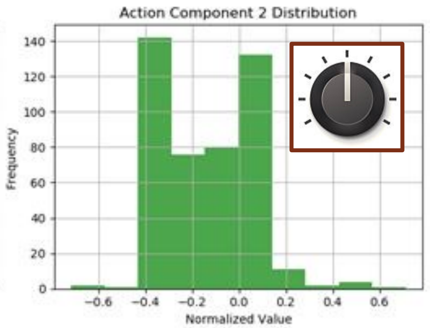
S. Jones

RL Agent twiddles knobs

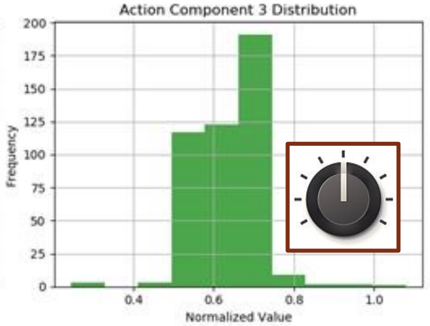
Bias Current



Pump Power



Pump Freq



NEXT STEP: have agent operate system live!

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Conclusions

- The axion is exciting! A discovery could simultaneously solve two major problems in physics.
- There are challenges on the horizon and detector complexity will likely make operations impossible
- We aim to offset this anticipated increase in detector complexity by leveraging a variety of AI/ML methods to
  - Identify hidden features in the data for in-situ characterization
  - Learn more from fewer measurements
  - Speed up tune-up procedures
- Stay tuned!

Thank you!