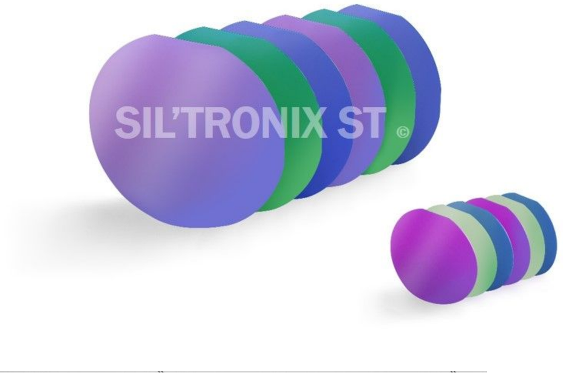
Cryogenic Resonator Workshop

Josh Mutus
February 8, 2019

How do we discover new materials?

1. **Find a material**
2. Design a chip
3. Assemble apparatus in a fridge
4. Take data with a VNA
5. Fit the data
6. Analyze and report Q



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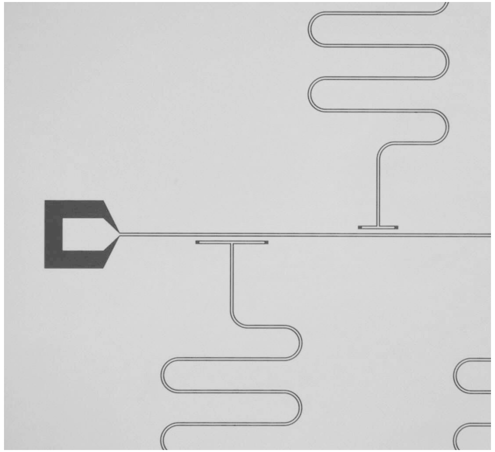

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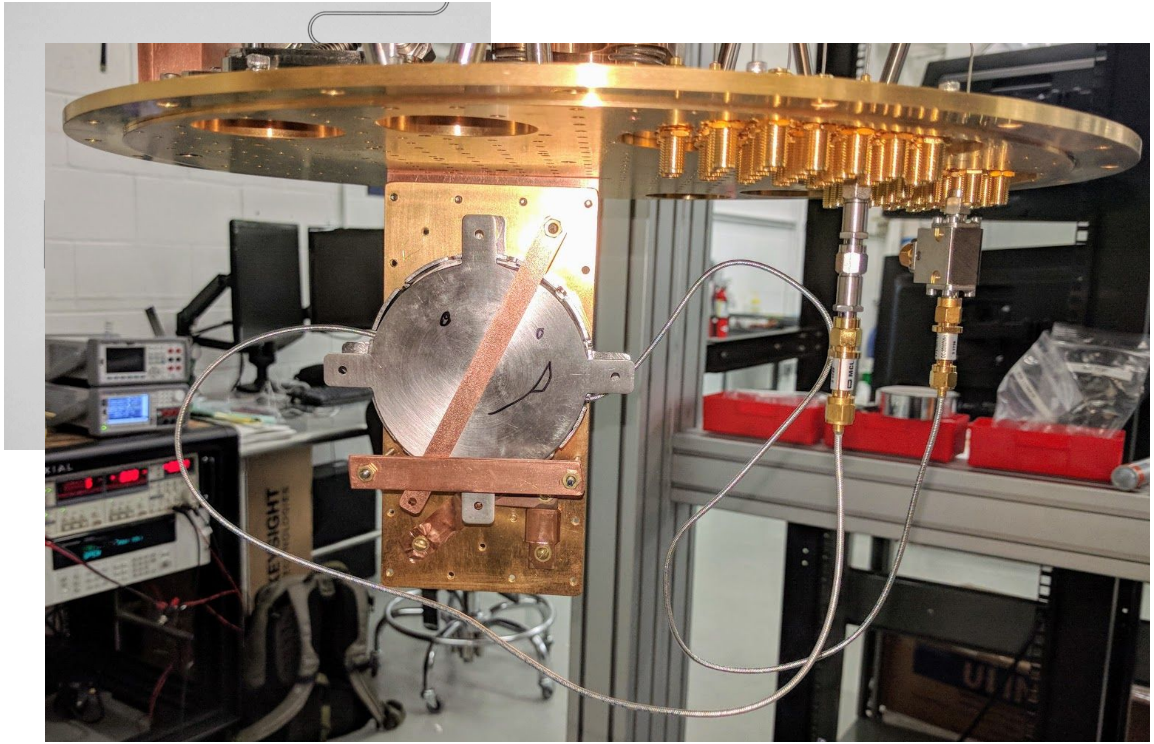

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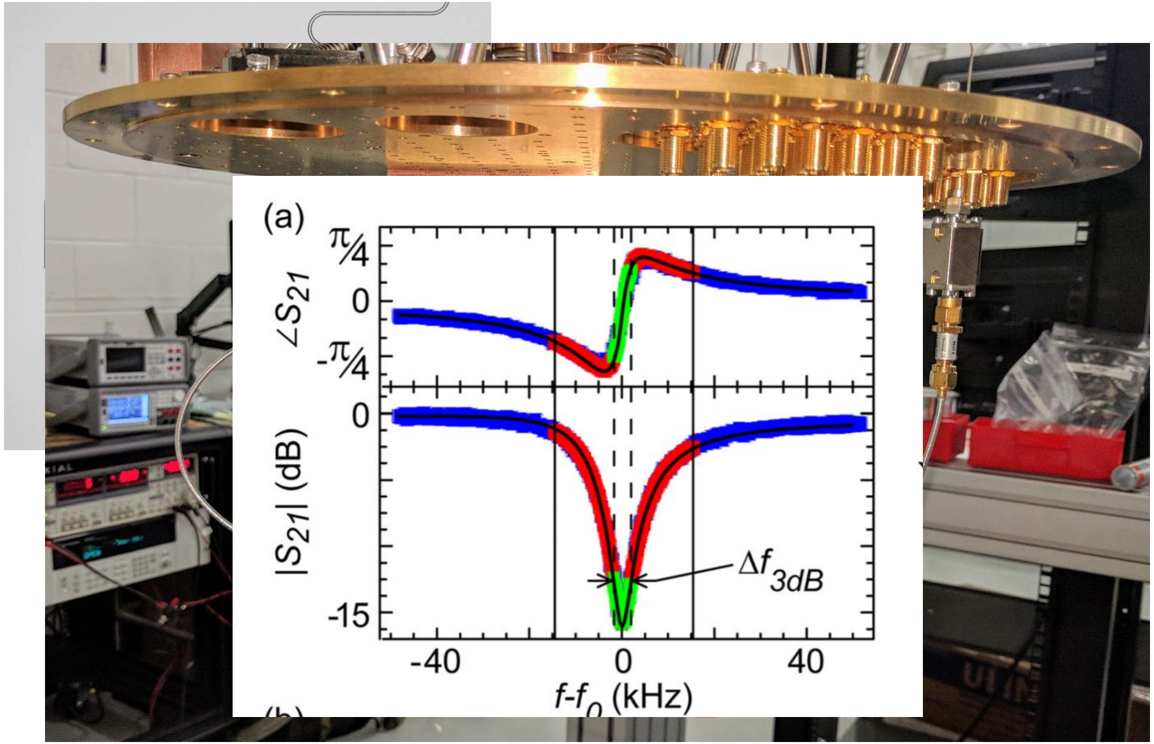

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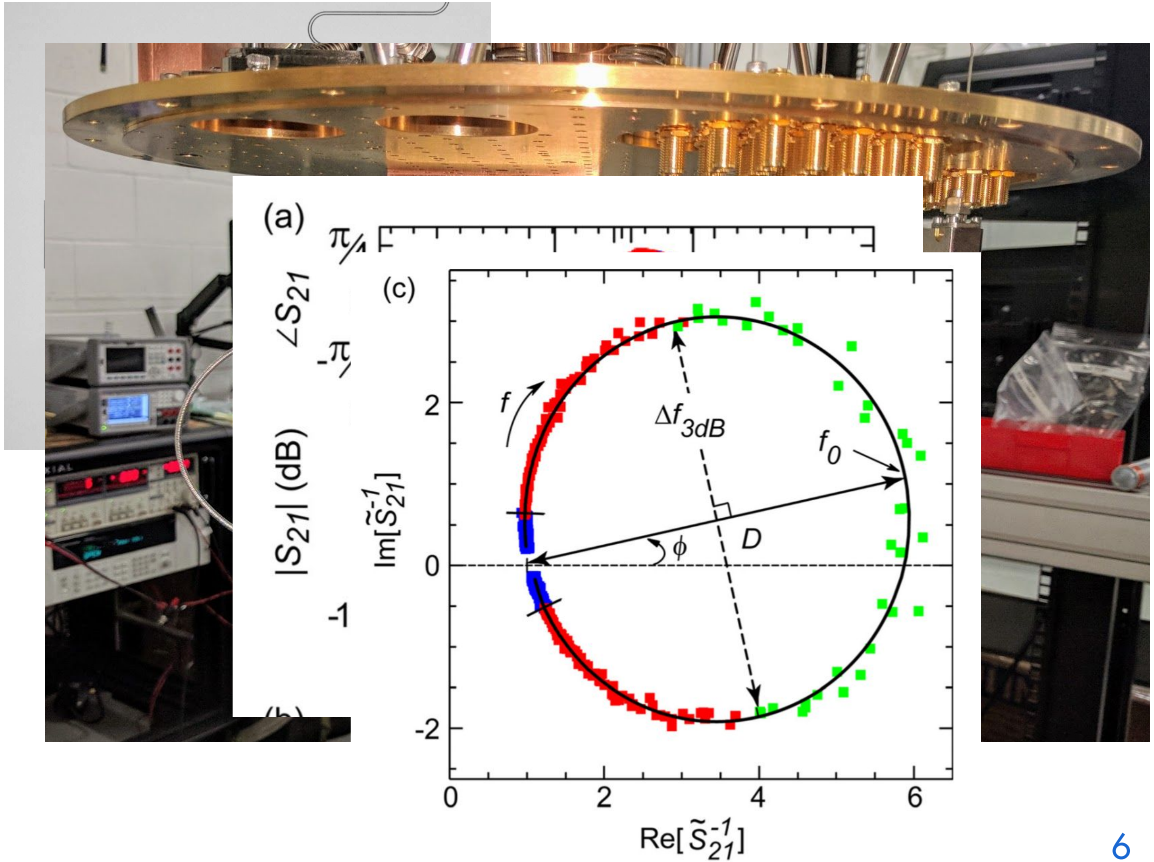

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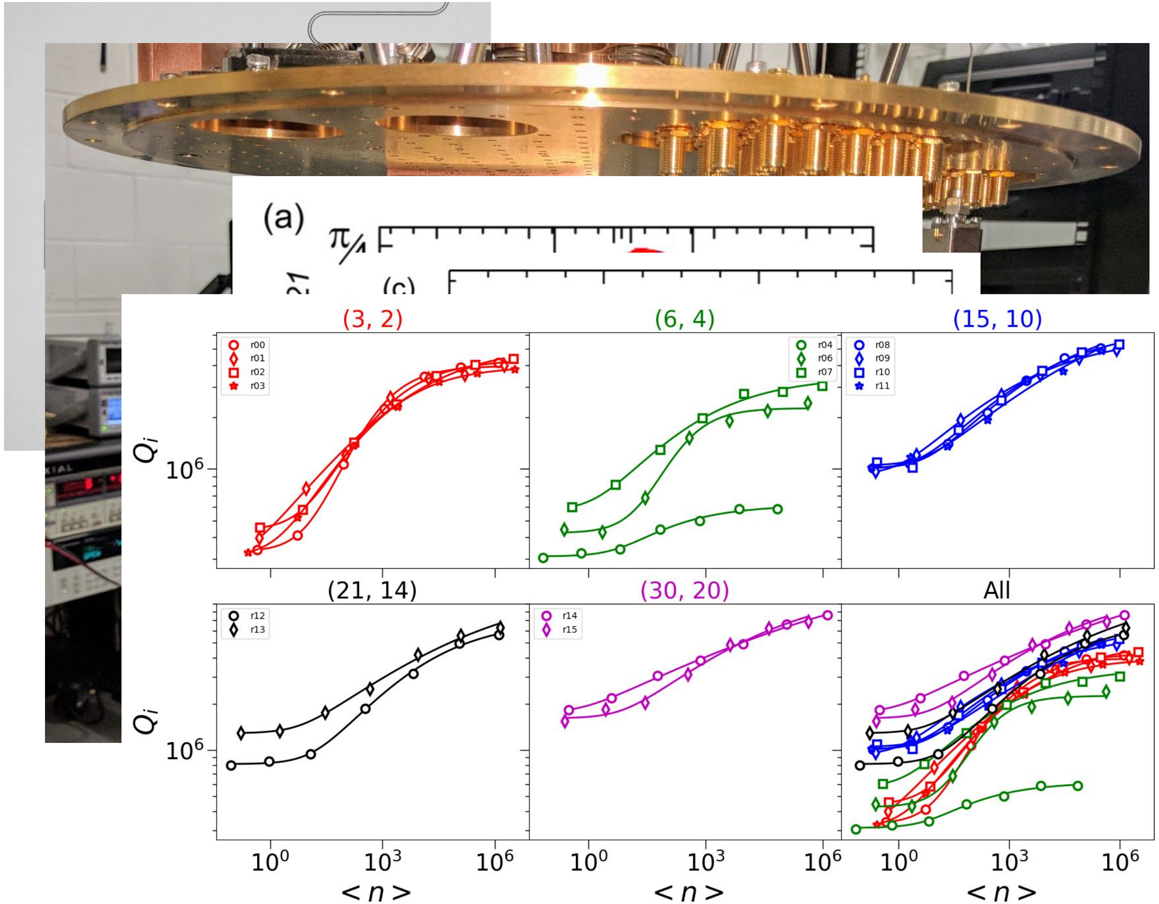
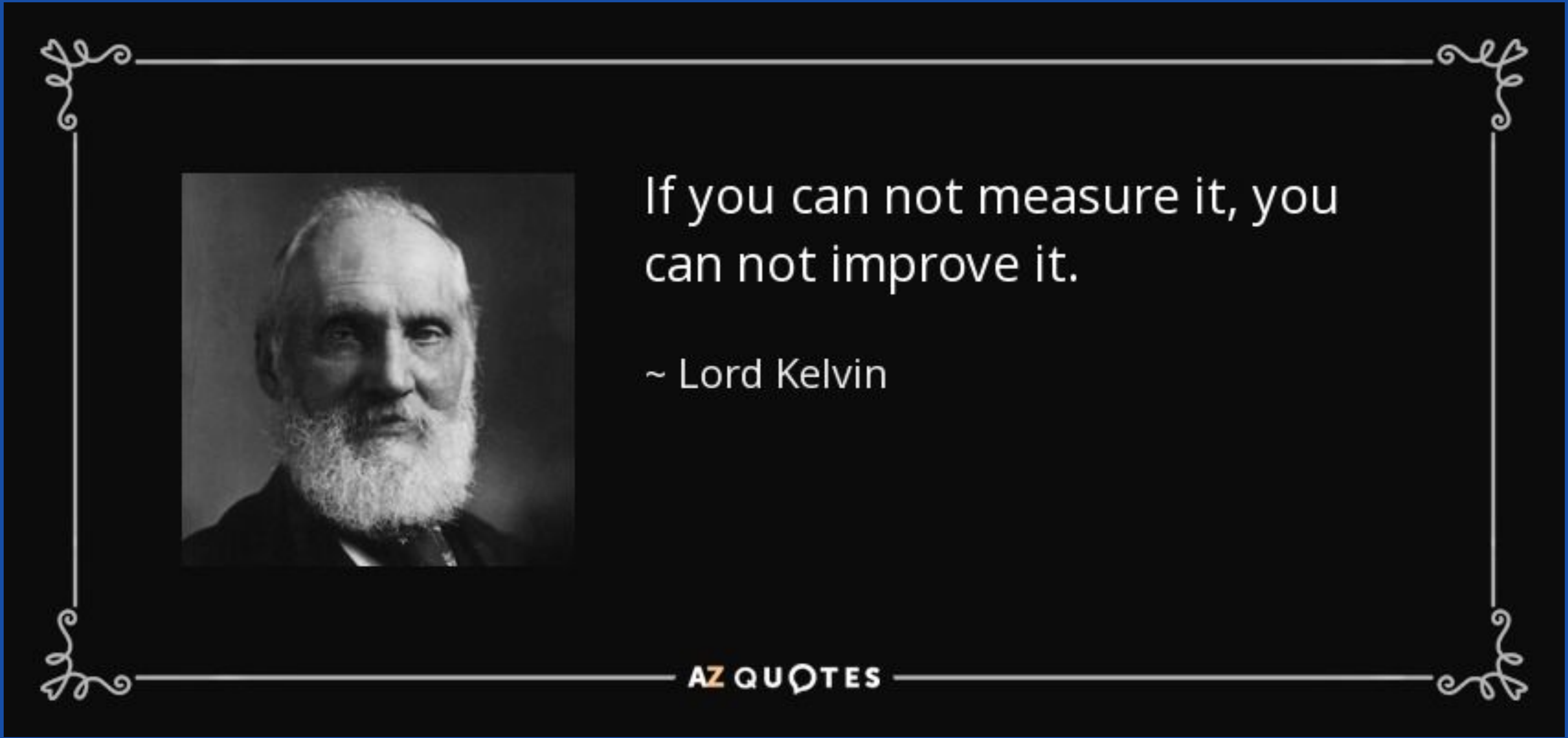
Make a decision based on data



Google AI Quantum

What is the ***correct*** way to do this?
Is method ***consistent?***
Are the conclusions ***valid?***

Apocryphal motivational quote of the day:



Boulder Cryogenic Resonator Testbed

Improve materials by establishing a quantitative testbed for single photon loss measurement

What do we want to accomplish?

- **Consolidate** existing knowledge. Publish a “Collaborative Standard” that teams are implementing and actively improving upon.
- **Connect** with material science research. Have researchers lining up at this facility to vet new materials.
- **Quantify the testbed.** Is the testbed optimal for measuring single photon loss in our material systems?

What does this actually look like:

- Build a new apparatus from scratch and perform careful experiments
- Publish findings (arxiv)
- Host regular follow ups to this workshop (MRS? March meeting?)
- Establish new forums for advancing science:
    - Software repositories (Github)
    - Compilation of useful datasets

CU Boulder/NIST:

Corey Rae McRae
Postdoctoral
Fellow

Dave Pappas
Group Leader

Google:

Josh Mutus
Sr. Research
Scientist

Dave Fork
Staff Research
Scientist

Kunal Arya
Software
Engineer

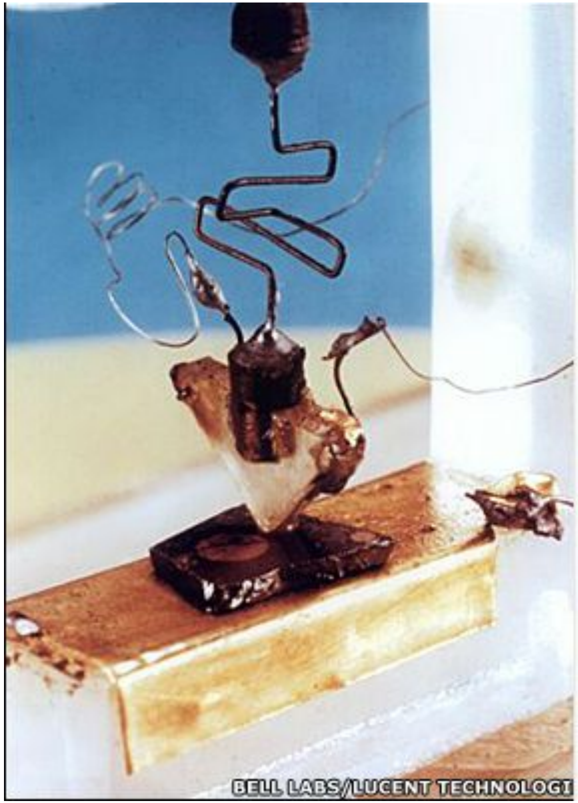
Ted White
Sr. Research
Scientist

Accelerate science through collaboration

- Software tools for managing collaboration
- Linux kernel 2M lines of code with 10s thousands of developers
- "All of us are smarter than any of us"
- Rapidly close the loop
  - Typically 6 months to publish a paper
  - File an issue on a web forum, can resolve in hours potentially
- Traceability and versioning for all published results
  - What apparatus, what fitting?
- Kunal Arya (Google) will talk in detail about this in the afternoon

Historical perspective (stolen from David Fork)

The first transistor,
it changed the world.



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Historical perspective

It changed computing once others *discarded*:

The package
- Rube Goldberg

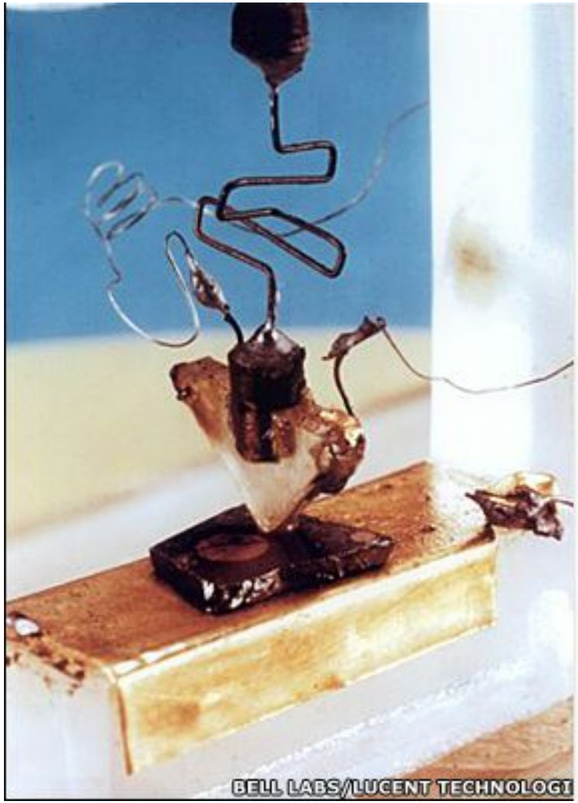
The process method
- Mechanical force

The interconnect
- Gold foil

The junction technology
- Dual point contact

The semiconductor
- germanium

The operating principle
- pnp (MOSFET didn't work initially!)



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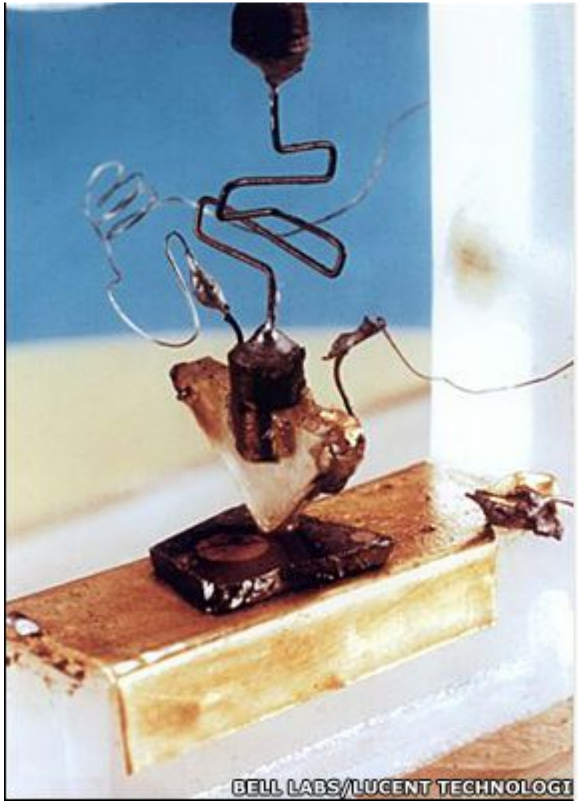
Historical perspective

A brilliant demonstration that inspired numerous discoveries and innovations that would soon follow.

What must we discover and invent to transform a demonstration into an industry?



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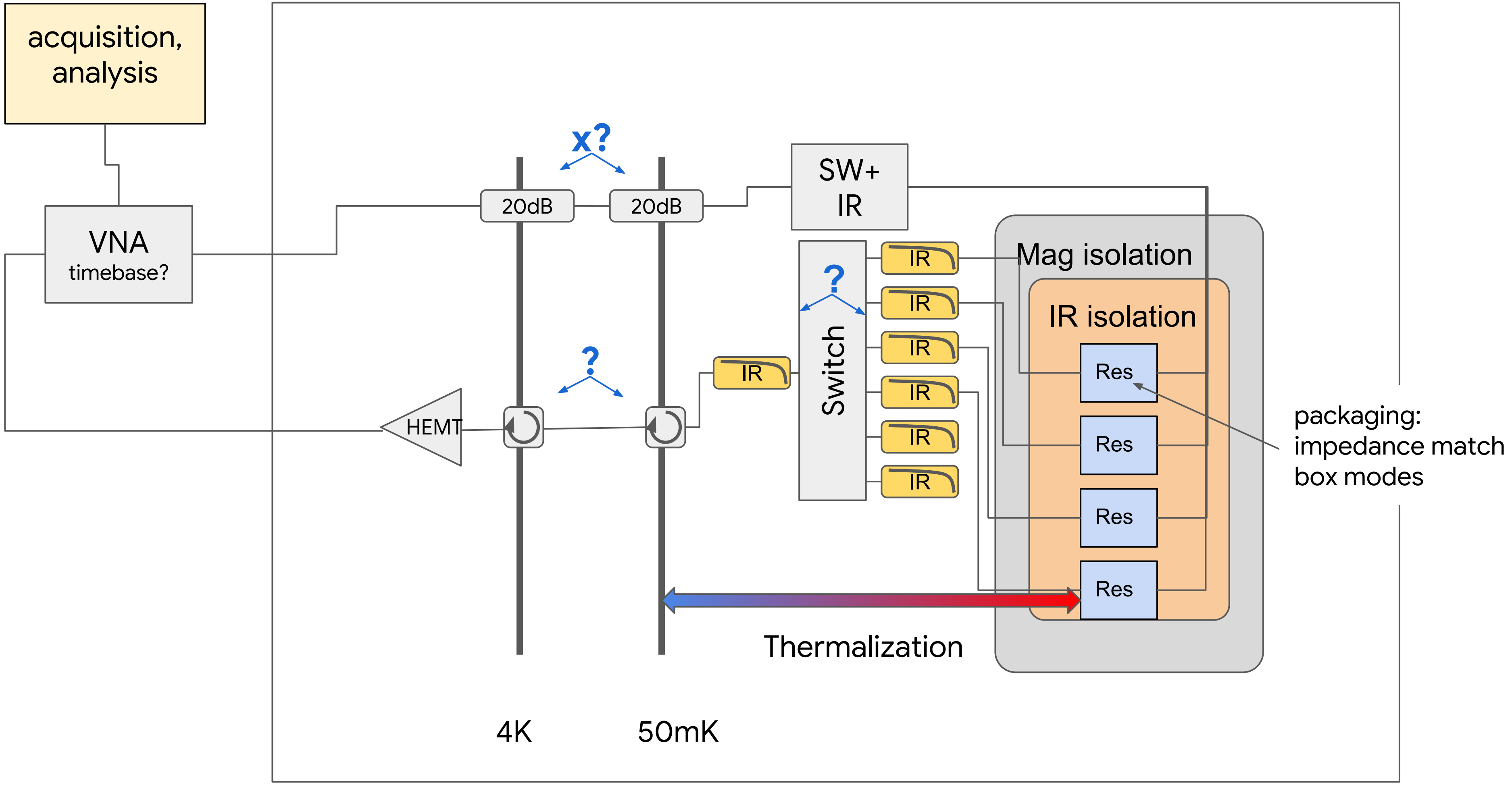
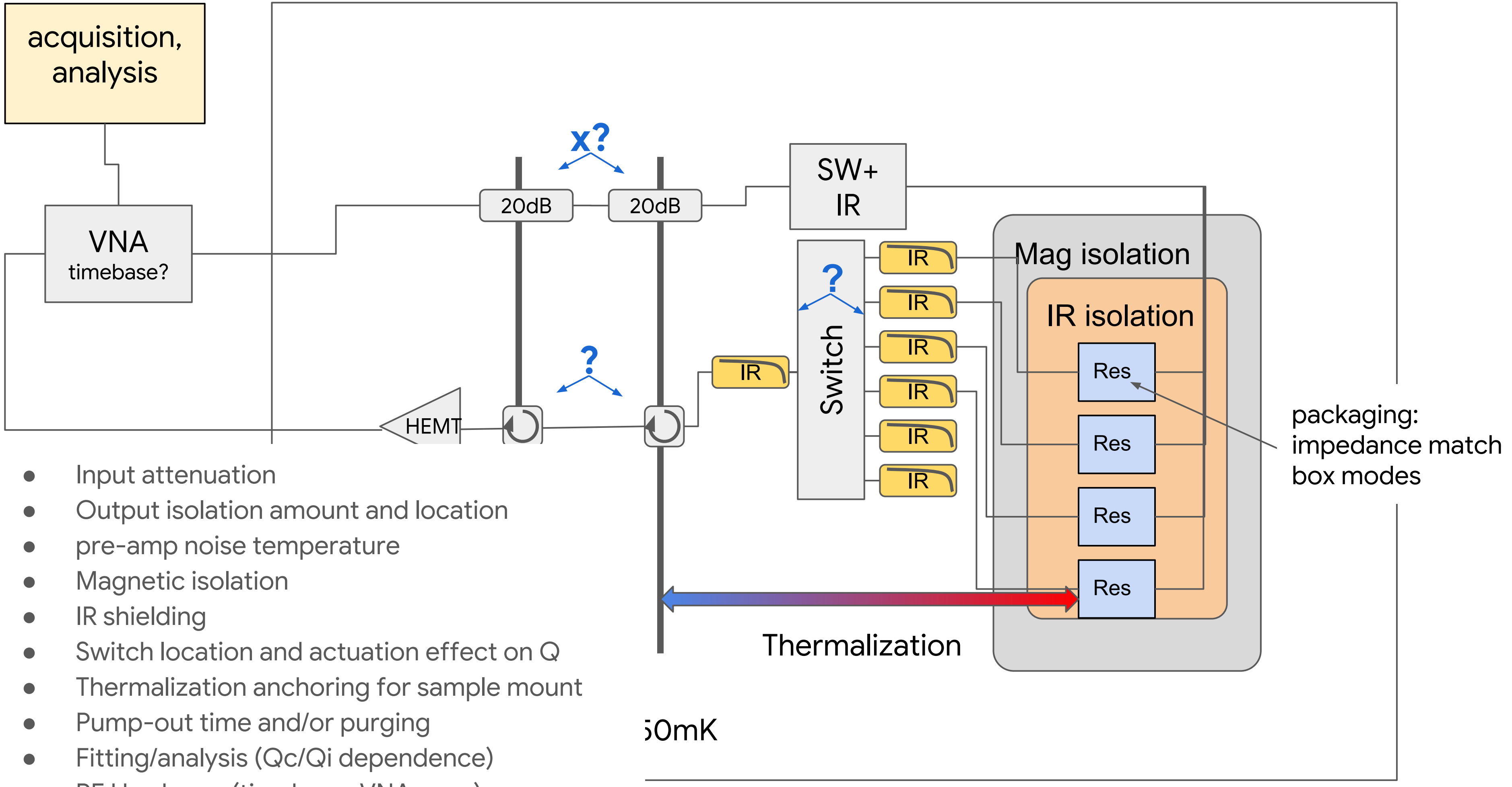
What should we accomplish today?

What is a “standard” single photon loss measurement?
Does such a thing exist?

If **Yes**:
we will document it, take off early. Go bowling.

If **No**:
identify the key experiments to establishing it.


acquisition, analysis
VNA
timebase?
x?
20dB
20dB
SW+ IR
Mag isolation
IR isolation
?
Switch
IR
IR
IR
IR
IR
IR
IR
Res
Res
Res
Res
?
HEMT
packaging: impedance match box modes
Thermalization
4K
50mK



- Input attenuation
- Output isolation amount and location
- pre-amp noise temperature
- Magnetic isolation
- IR shielding
- Switch location and actuation effect on Q
- Thermalization anchoring for sample mount
- Pump-out time and/or purging
- Fitting/analysis (Qc/Qi dependence)
- RF Hardware (timebase, VNA spec)

Today’s agenda:

Plenary talks:

- Ben Palmer (temperature, attenuators, effective temperature)
- Martin Weides (fitting)
- Greg Calusine (modeling, geometry)
- Moe Khalil (circle fit)
- Tom Ohki (quasiparticles)

Panel discussions (hardware, software):

2-3 slides per group to frame the discussion.

Email me your slides **mutus@google.com**

Today’s Goal: Create a plan to define this “Community Standard”

Have the **nitty gritty** conversation we’d normally have outside of the conference.

Discuss the things that don’t work.

What do we want to accomplish beyond this program?

- Reduce loss in superconducting qubits
- At least, understand origins of loss in our material systems
- This program is the first step along that way, to deconvolve the apparatus from the measurement.

Another analogy? Optical fibers

- **Reduce loss in superconducting qubits.**
- Loss in commercial optical fiber: <1 dB/km! That's Q~10^9!
- Moreover sources of loss are well understood:

Extrinsic Impurity Ions Absorption

Extrinsic impurity ions absorption is caused by the presence of minute quantity of metallic ions (such as Fe^{2+}, Cu^{2+}, Cr^{3+}) and the OH^- ion from water dissolved in glass. The attenuation from these impurity ions is shown in the following table.

Impurity Ion	*Loss due to 1ppm of impurity (dB/km)*	*Absorption Peak Wavelength (um)*
Fe^{2+}	0.68	1.1
Fe^{2+}	0.15	0.4
Cu^{2+}	1.1	0.85
Cr^{3+}	1.6	0.625
V^{4+}	2.7	0.725
OH^-	1.0	0.95
OH^-	2.0	1.24
OH^-	4.0	1.38

https://www.fiberoptics4sale.com/blogs/archive-posts/95048006-optical-fiber-loss-and-attenuation

Output from today's meeting

- Discuss ways to collaborate and iterate more quickly
- Potential material science collaborations
- Standard datasets
- What metrics should we report?
  - Experimental protocols eg field cools, measure frequency noise.
- Provide a direction for the program.
  - Compile information from today's meeting into shared notes here.
  - Summarize state of the art into a white paper

Open questions (to Josh, at least):

- How do we know power incident on device?
- What is the simplest package?
- What is the best “standard” resonator geometry?
- Why do we see chip to chip variation (same wafer)?
- Why fridge to fridge variation? (same device)
- What is the physical rationale for subtracting away, normalizing high power loss?
- Can we systematically under-report loss?

Thanks for attending!

Questions?

Extra slides

What are the microscopic origins of loss?

Many models proposed, none conclusive. Nice review in (Müller, Lisenfeld *et al* 2018 https://arxiv.org/pdf/1705.01108.pdf)

Can we answer this question by looking at new material systems?

- Vary bonding, interstitials, impurities, Disorder, etc...