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BBN Technologies

Quantum Engineering and Computing Group

Cambridge, Massachusetts

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NIST resonator workshop
Feb. 8th 2019 CU Boulder

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Outline

- Some history and how resonator measurements were influenced
- Shielding, filtering, wiring, attenuation
- Fitting and analysis considering quasi-particles
- Using a resonator as a tool to probe for material properties

I won’t discuss anything at the chip or sample box level: flux trapping moats, etching, box modes, film properties, TLS’s

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How things evolved

10 years ago we see heating in qubits (eg. thermally excited state population)

What was the cause and how could we test this?

Was it thermalization, noise, trapped flux hot non-equilibrium quasiparticles from IR radiation?

The field tried lots of things…

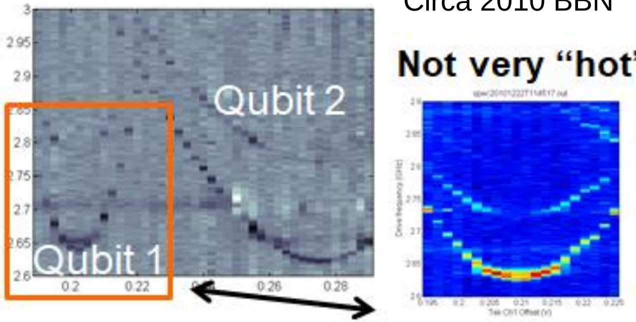
This also must impact resonator measurements which at the time was hugely important…

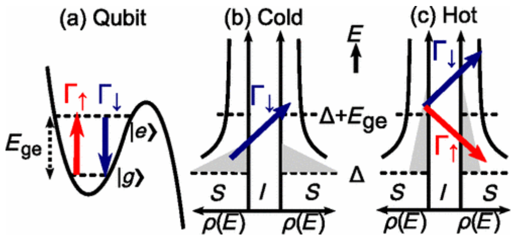
Q for resonators was a window to future long T1 times

✓ 2 qubits both have coherence >400ns

Circa 2010 BBN

Not very "hot"





Wenner, J. *et al.* Excitation of Superconducting Qubits from Hot Nonequilibrium Quasiparticles. Phys. Rev. Lett. 110, 150502 (2013).

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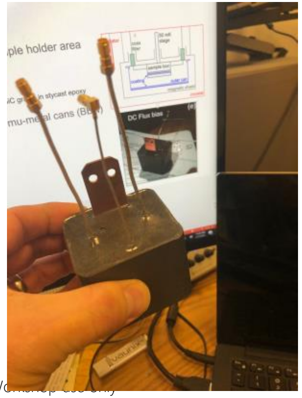
Photon shielding

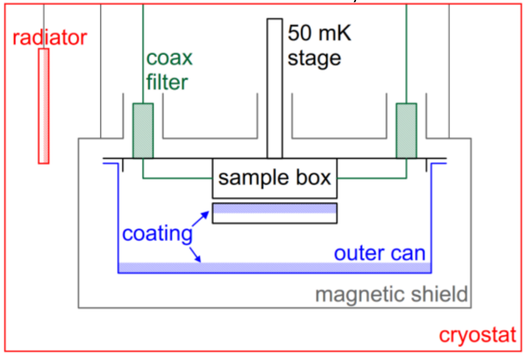
Some different methods used at the sample holder area

- Box painting (Google)
    - silica powder, fine carbon powder and 1 mm SiC grains in stycast epoxy
- Inserts of Eccosorb materials into mu-metal cans (BBN)
    - Eccosorb lined

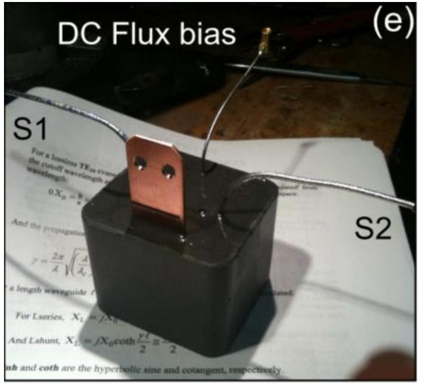
- Complete potting (the brick)
    - CR-124 ECCOSORB epoxy



Barends, R. et al 2011



Corcoles, A et al 2011



Along the wiring

Filters

- Cu box filters >20GHz cutoff
  - Low absorption 1-12 GHz
  - Block visible and near IR radiation with Eccosorb CR-110
- KNL filters
  - Cutoff >12 GHz
- Isolators
  - Pamtech 3-12 and 4-8 in series: > 50dB isolation, usually:)
- Wiring gauge
  - Our old Oxfords used 0.085-SS-SS (1.7mm dielectric diameter) but the Bluefors we have started with 0.035-CuNi-CuNi (0.58mm dd)
- Thermalization techniques
  - Copper blocks for all components when possible, otherwise Cu braids
  - Zero dB attenuators when no attenuation is used, readout line specifically (XMAs)

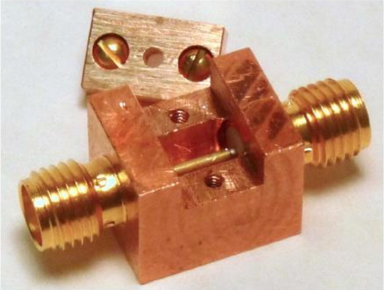


Figure 1. Filter with the cover removed and before filling the cavity with Eccosorb.

Magnetic fields

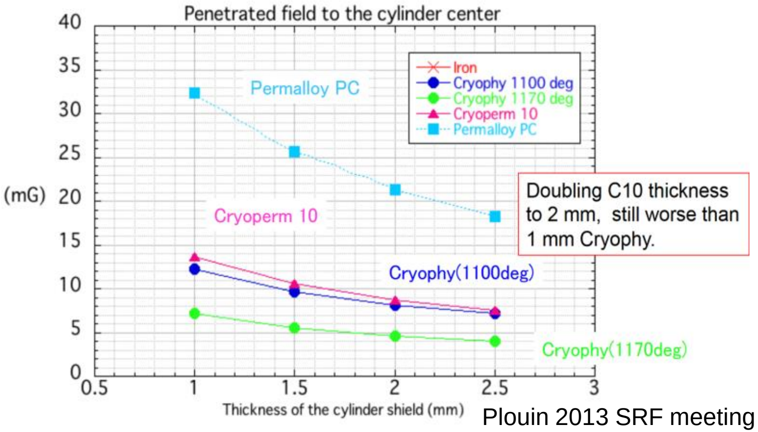
Trapped flux- We know trapped vortices impact Q

C. Song, ... J. M. Martinis, and B. L. T. Plourde, Phys. Rev. B **79**, 174512 (2009)

What we can further learn from SFQ or HEP techniques:

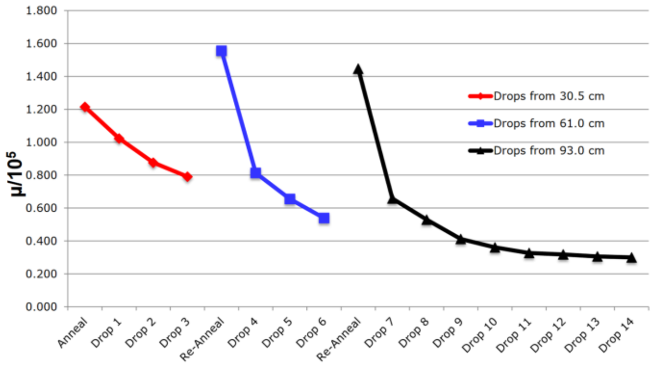
- SFQ circuits simply won't work if you've not done this correctly
  - Vary chip cooling rates (fast or slow?), active cancellation?
- HEP folks are pretty crazy about material choice for their High Q SRF
- More concern over annealing as a standard and regularly measured- amuneal example the extreme, mallet test and demformation and strain have significant effects :(

Admission ☹ we don't anneal our shields as frequently as we should



Plouin 2013 SRF meeting

Effects of mishandling “the drop test”



Amuneal

Fridge design contributions

MXC shields (our BlueFors has an MXC shield where as the Oxford does not)
With nominally identical wiring and attenuation T1 and T2 have always been better with the BlueFors and heating is almost non-existent

Is it really light tight?
Placement of components inside or outside of either magnetic or MXC shields, eg filters, etc seems to make a difference.

Base temp concerns (Is an ADR really cold enough?)

Should there be more rigorous analysis of thermalization and attenuation at each stage?

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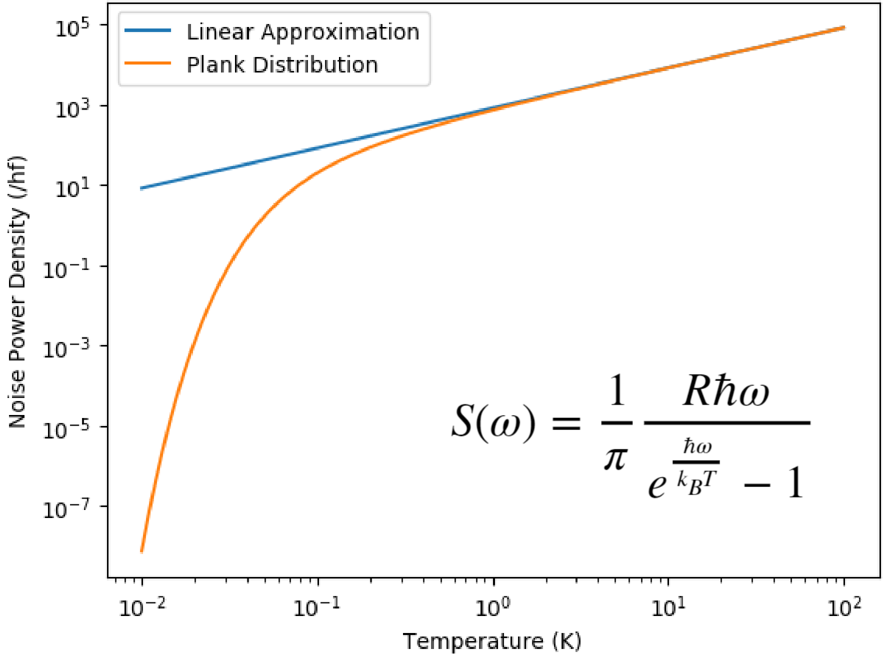
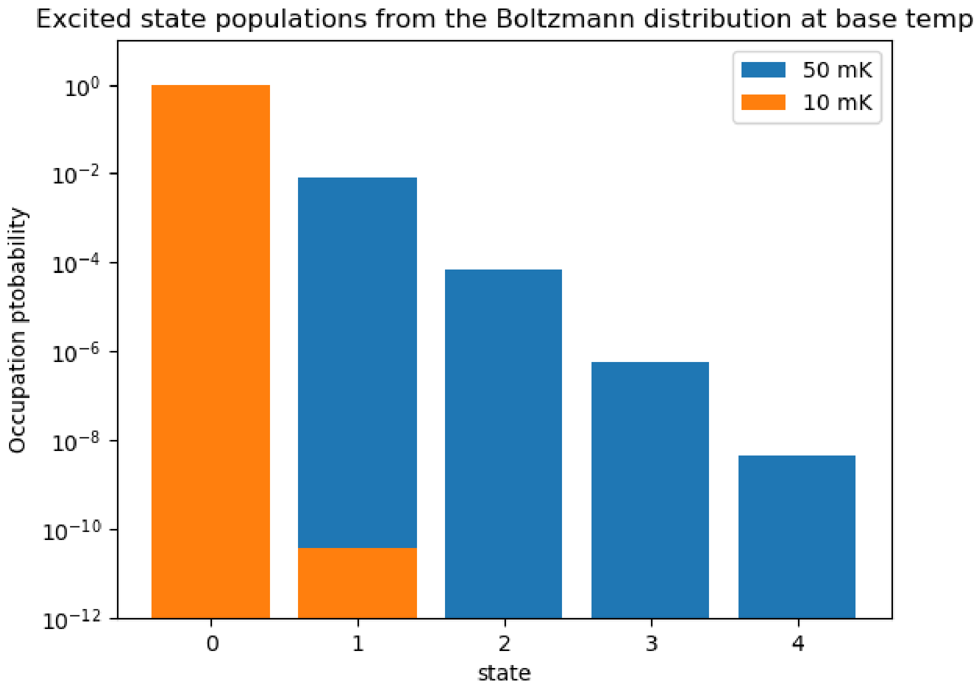
Noise power and average cavity photon number





In high-temperature / low-frequency limit linear expansion give the usual ⟨S(f)⟩=4kBTR

At low temp the thermal energy is less than one photon we are explicity not in this limit

Cold Attenuation

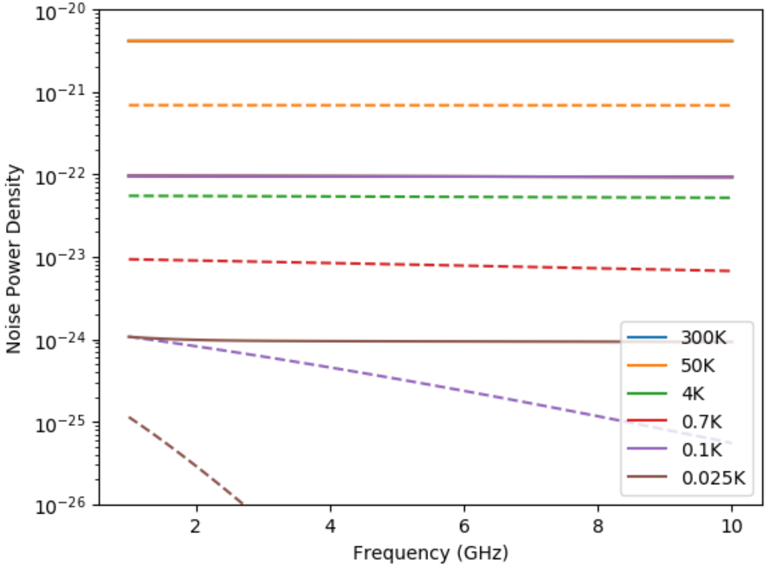
- Find noise propagation of a cold attenuator by considering the limit of an attenuator in thermal equilibrium with its matched source and load impedance

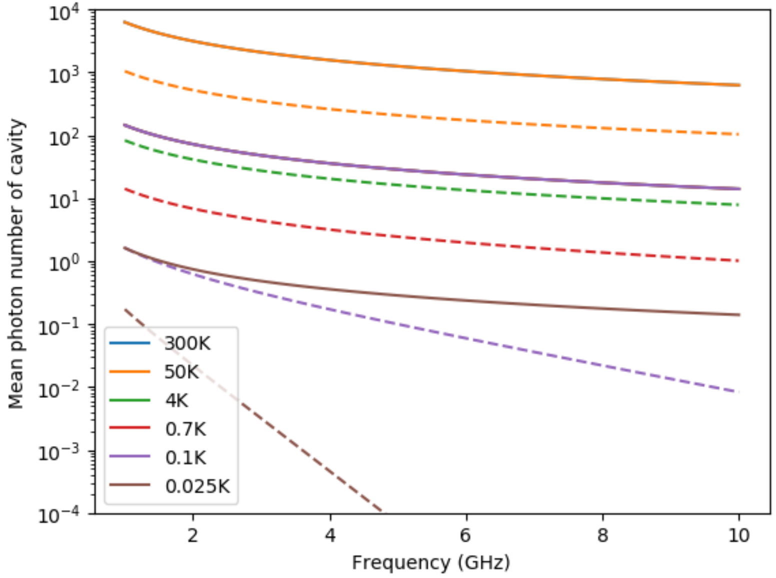
- The attenuator will attenuate the source's Johnson-Nyquist noise power $P(f)$ by its attenuation factor $\alpha = |S21|^2$

- Since everything is matched and in thermal equilibrium the attenuator should look just the same as the source to the load impedance and so the attenuator should add back in $(1 - \alpha)P(f)$

Noise power for generic input line config

- Attenuation at stages: 0dB @ 50K; 20dB @ 4K; 0dB @ 700mK; 0dB @ 100mK; 20dB @ 25mK
- Dashed lines: thermal noise power at each stage
- Solid line: computed attenuated noise



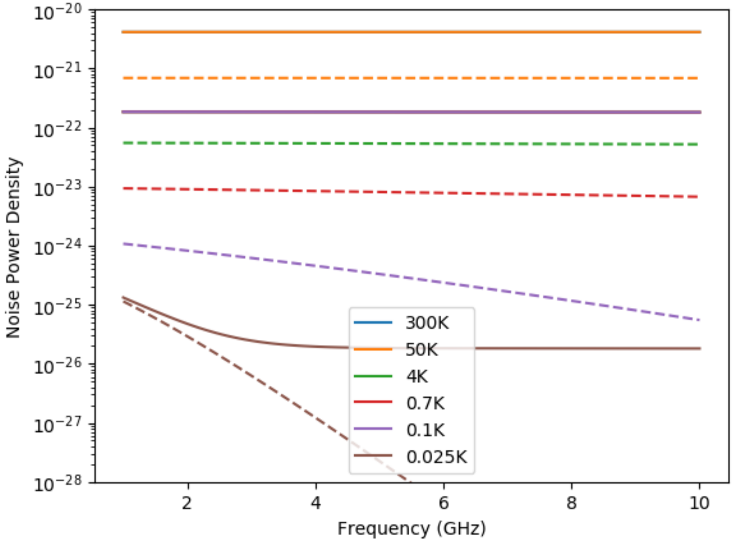


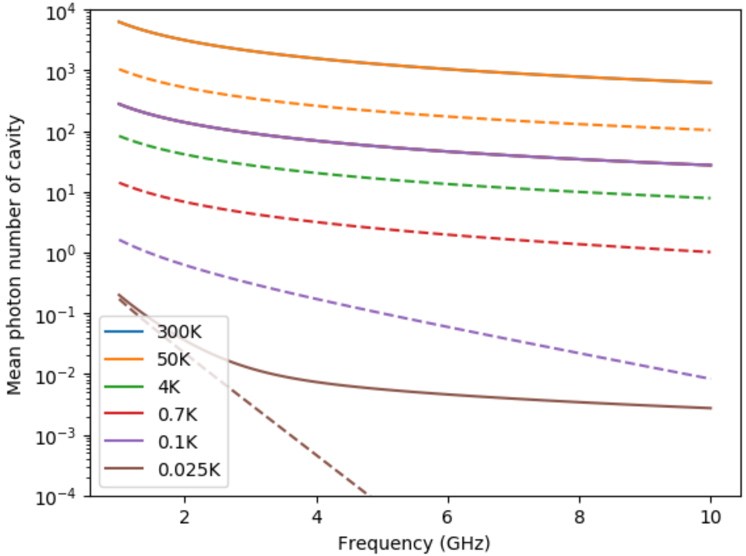
This can be used to estimate the photon induced dephasing of a qubit like in [P. Sears, et al. (2012)]

Noise power for generic readout line config

- Attenuation at stages: 0dB @ 50K; 15dB @ 4K; 0dB @ 700mK; 0dB @ 100mK; 40dB @ 25mK

- Using a isolation for 4K HEMT of 15 dB
- 40 dB is 2 isolators





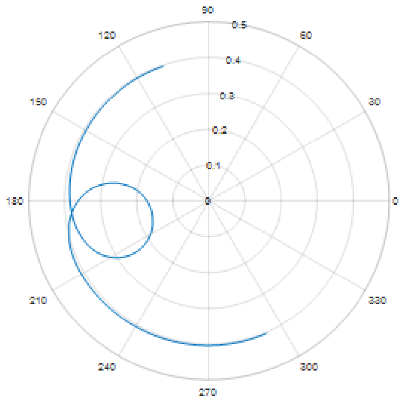
Data: Fitting and analysis considering quasi-particles

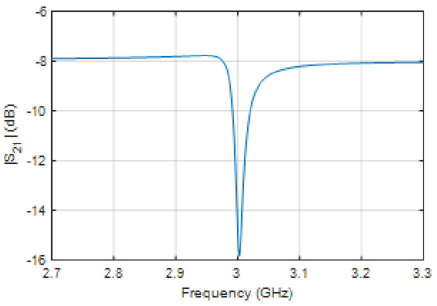
Do our circle fitting routines match others? Can we just run data on our fitting procedure and reproduce everyone's results? Are there assumptions we need to standardize? (talk about this in panel)

Is our systems the problem ?

Can we figure out what is the actual problem and isolate whether the device is the issue?

Resonator measurement calibration





$$S_{21} = a e^{i\alpha} e^{i2\pi f\tau}\left(1 - \frac{Q_L/|Q_c|e^{i\phi}}{1 + 2iQ_L\left(\frac{\omega}{\omega_r} - 1\right)}\right)$$

Q_L : Loaded Q factor.
Q_c : Complex coupling Q.
$Q_e = 1\backslash Re(Q_c^{-1})$: External Q factor.
ω_r : Resonance frequency.
τ : External line group delay.
ϕ: Phase mismatch angle.
α : Additional phase rotation.
a : Amplitude scaling.

•Transmission coefficient should follow a circle.

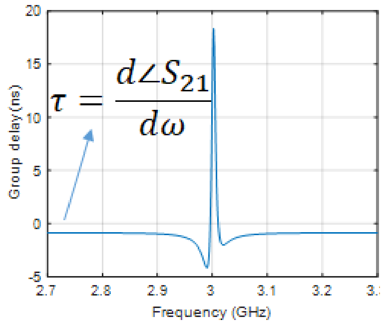
•Group/phase delay and attenuation along the input line distorts the ideal circular shape.

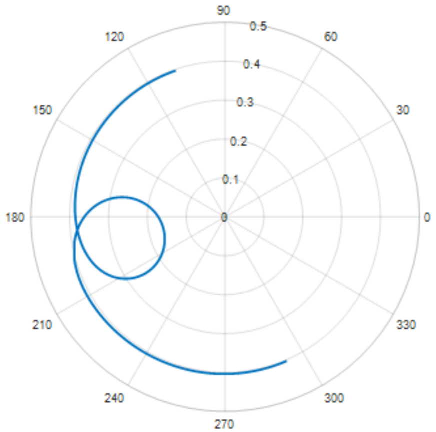
•Phase factor ϕ is due to complex loading of the resonator (C_c) and causes asymmetry in line shape.

Resonator measurement calibration

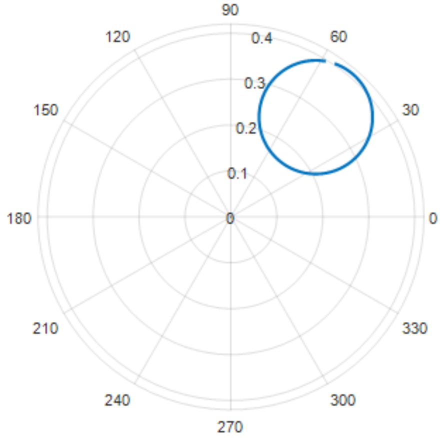
$$S_{21} = a e^{i\alpha} e^{i2\pi f\tau} \left(1 - \frac{Q_L/|Q_c| e^{i\phi}}{1 + 2iQ_L\left(\frac{\omega}{\omega_r} - 1\right)}\right)$$

Step 1: measure and subtract group delay off-resonance ($2\pi f\tau$ phase shift):





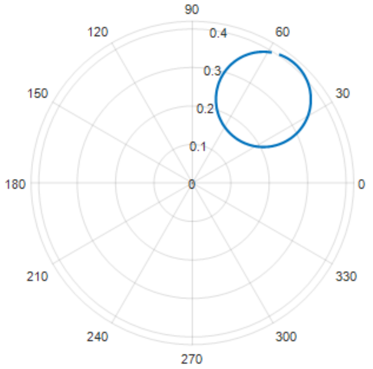
$\times\ e^{-i2\pi f\tau}$



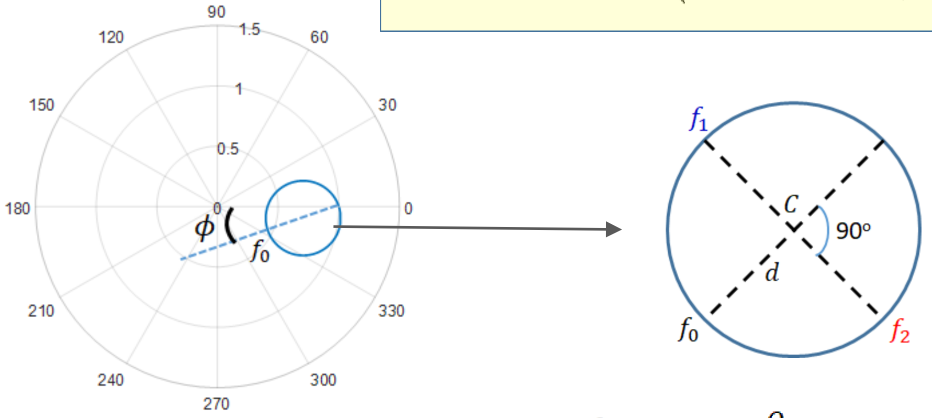
Resonator measurement calibration

$$S_{21} = a e^{i\alpha} e^{i2\pi f\tau} \left(1 - \frac{Q_L/|Q_c| e^{i\phi}}{1 + 2iQ_L\left(\frac{\omega}{\omega_r} - 1\right)}\right)$$

Step 2: Rotate and rescale by value of S_{21} off-resonance to correct amplitude and phase factor (a and α):



$$\times \frac{1}{S_{21}(\infty)}$$



$$Q_L = \frac{f_0}{f_2 - f_1} \qquad d = \frac{Q_L}{|Q_c|} \qquad \frac{1}{Q_L} = Re\left(\frac{1}{Q_c}\right) + \frac{1}{Q_i}$$

$$C = \left(1 - \frac{d}{2}\cos\phi\,, -\frac{d}{2}\sin\phi\right)$$

Note: we employ a script that automatically perform an algebraic fit of the input data to a canonical circle and extracts the resonator parameters.

Probst, S., et al. "Efficient and robust analysis of complex scattering data under noise in microwave resonators." *Review of Scientific Instruments* 86.2 (2015): 024706.

Quasiparticle Contribution

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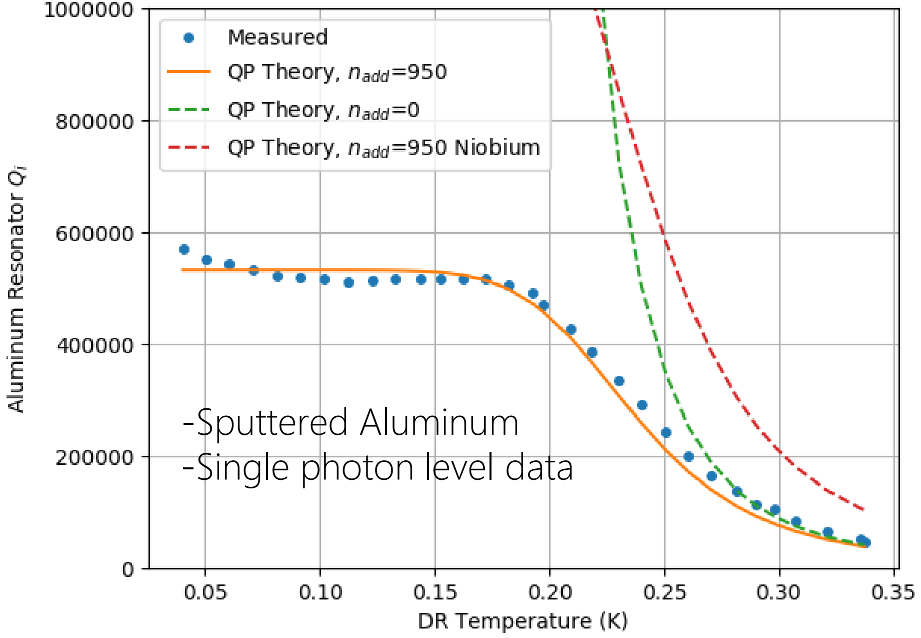


One-parameter fit: number of excess quasiparticles (μm^-3)

Kinetic inductance participation ration α from frequency-vs-T data

Quasiparticles cause loss: $$Q^{-1} = \frac{\alpha}{\pi}\sqrt{\frac{2\Delta}{\hbar\omega_r}}\frac{n_{qp}}{2N_0\Delta}$$

$$n_{qp} = n_{th} + n_{opt}$$

Extra information about the resonator's environment in the fridge

Just as important as Q-vs-power data when reporting results

Equivalent black body temperature: Al resonator as canary

Optical limited Q for Nb 100X less sensitive, if Nb and Al have comparable Q … must be something else

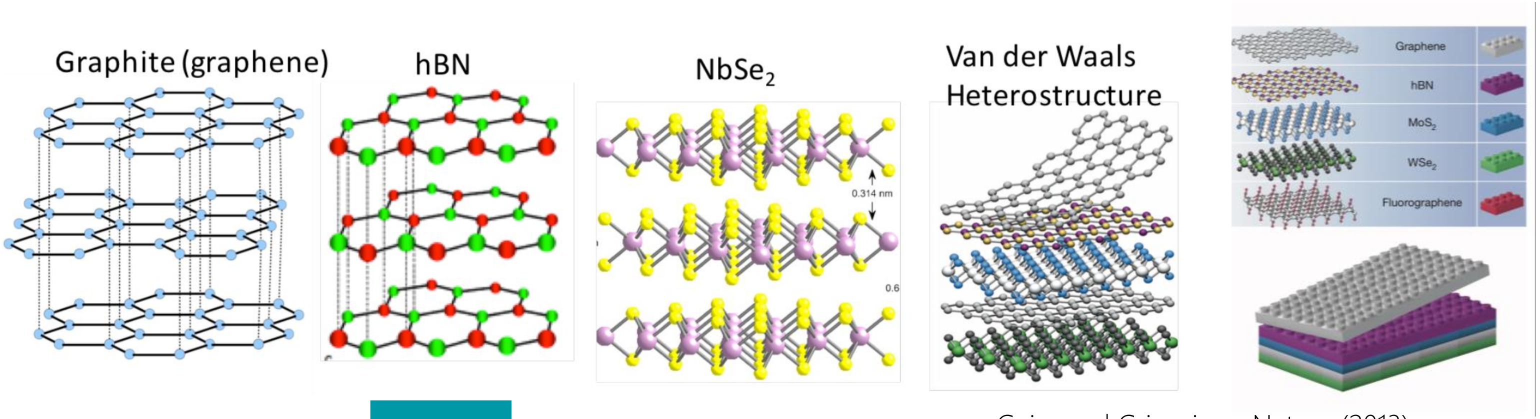
Question: where is the radiation coming from?

Can standardized resonator methods improve the metrology of novel material

New and Emerging Qubit Science and Technology (NEQST)

"New methods of fabrication that may enable new qubit types with superior performance"

Van der Waals materials for low-noise 2D insulators and semi-metals for capacitor and junctions

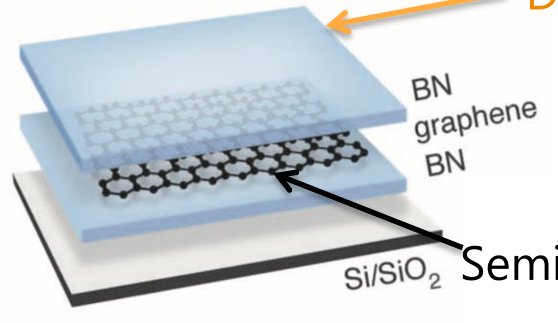


Geim and Grigorieva, Nature (2013)

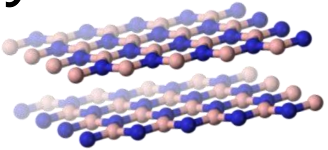
- atomically flat
- chemically inert, stable to high temp.
- no dangling bonds
- good dielectric properties
- evidence of very clean interfaces "self cleaning

Stacking and making hybrid devices

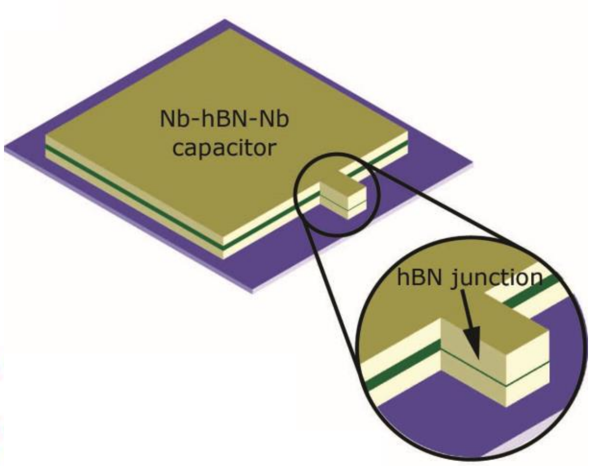
Dielectric



Semimetal

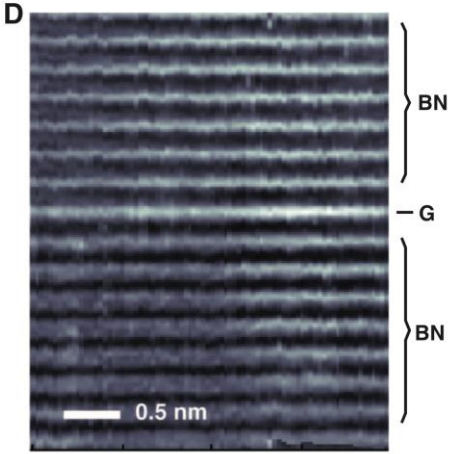


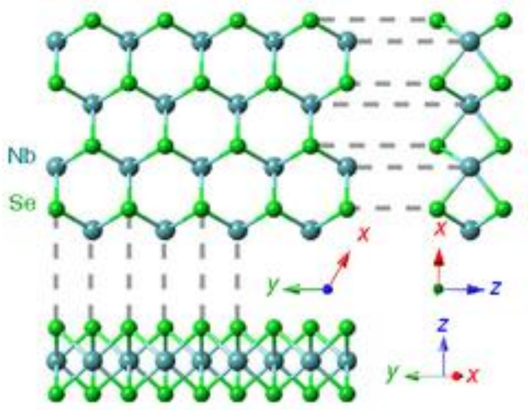
Superconductor
$NbSe_2$
T_c = 7.2 K



What is the loss tangent of the 2D materials?

Is it compatible with superconducting qubit or other microwave circuitry fabrication?

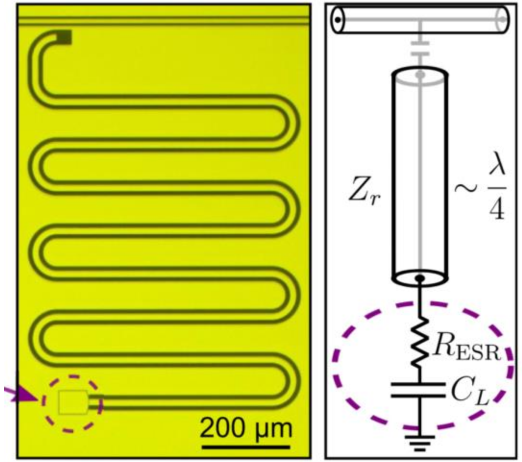




Columbia team
Science (2013)
Nature Nanotech. (2010)

SuperVan
Collaboration

Can standardized resonator methods improve the metrology of novel material



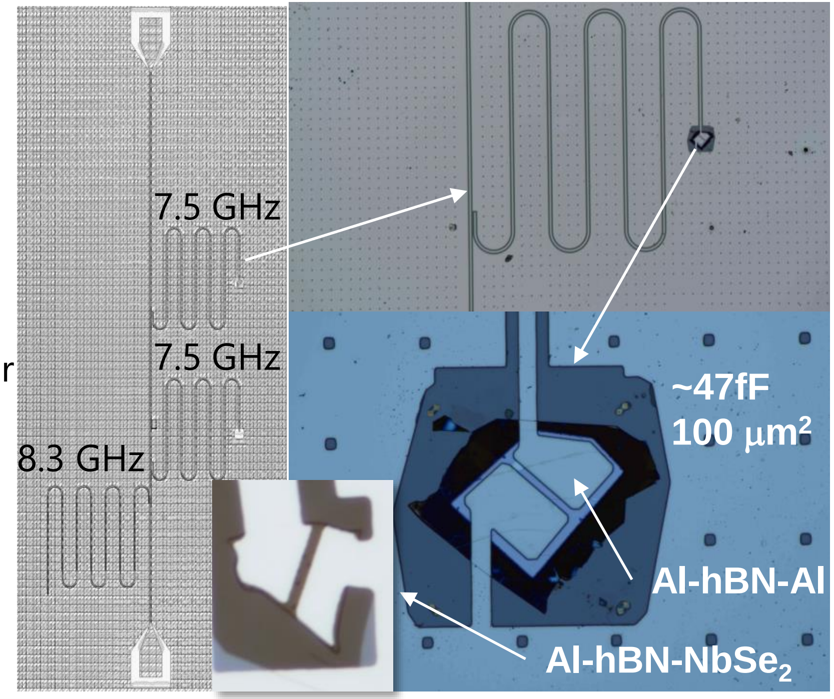
APL 105, 062601 (2014)

λ/2 so equations a bit different

$$\omega - \omega_{\lambda/2} \simeq \frac{\omega^2 C_L Z_r}{\pi}$$

$$Q \simeq \frac{\pi}{2}\frac{1}{\tan\delta}\frac{1}{Z_r \omega C_L}$$

- *Target* hBN-resonator
- Control resonator
- Reference resonator



tan δ = 5e-5
at single photon limit,
limited by Qc

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

KC Fong, Tom Ohki, Guilhem Ribeill, Martin Gustafsson, Abhinandan Antony, James Hone

Summary

Many ways of doing things: Some things work and some things don’t matter

Things that matter for a good measurement:

Minimizing: quasiparticle generation, flux trapping, extra photons and elevated noise spectral density

Not discussed, package design (modes, PWB dielectric losses), chip design and fabrication process

Community knowledge on these things should be shared if standards for resonator measurements are to be achieved

Panel topics

Experimental setup standards and issues

Analysis standards