Engineering the quantum

probing atoms with light & light with atoms in a transmon circuit QED system

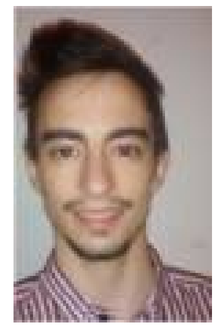
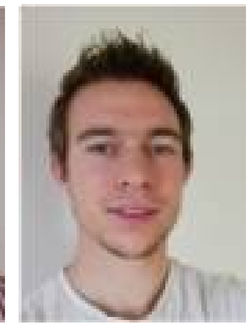
Nathan K. Langford

<u>Acknowledgements</u>

Ramiro Sagastizabal, Florian Luthi

and the rest of the

DiCarlo lab at TU Delft

OVERVIEW

- Transmon circuit QED experimental hardware
- Finding your qubit: where to start when the fridge gets cold
- Getting things pulsing
- Getting control of your qubit
- Fast frequency tuning: making your qubit dance
- Using your qubit as a…



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OVERVIEW

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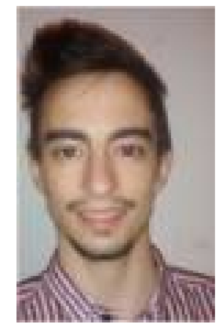
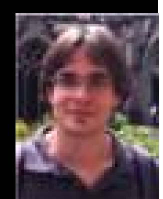
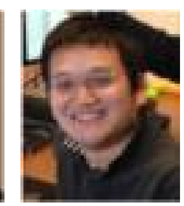
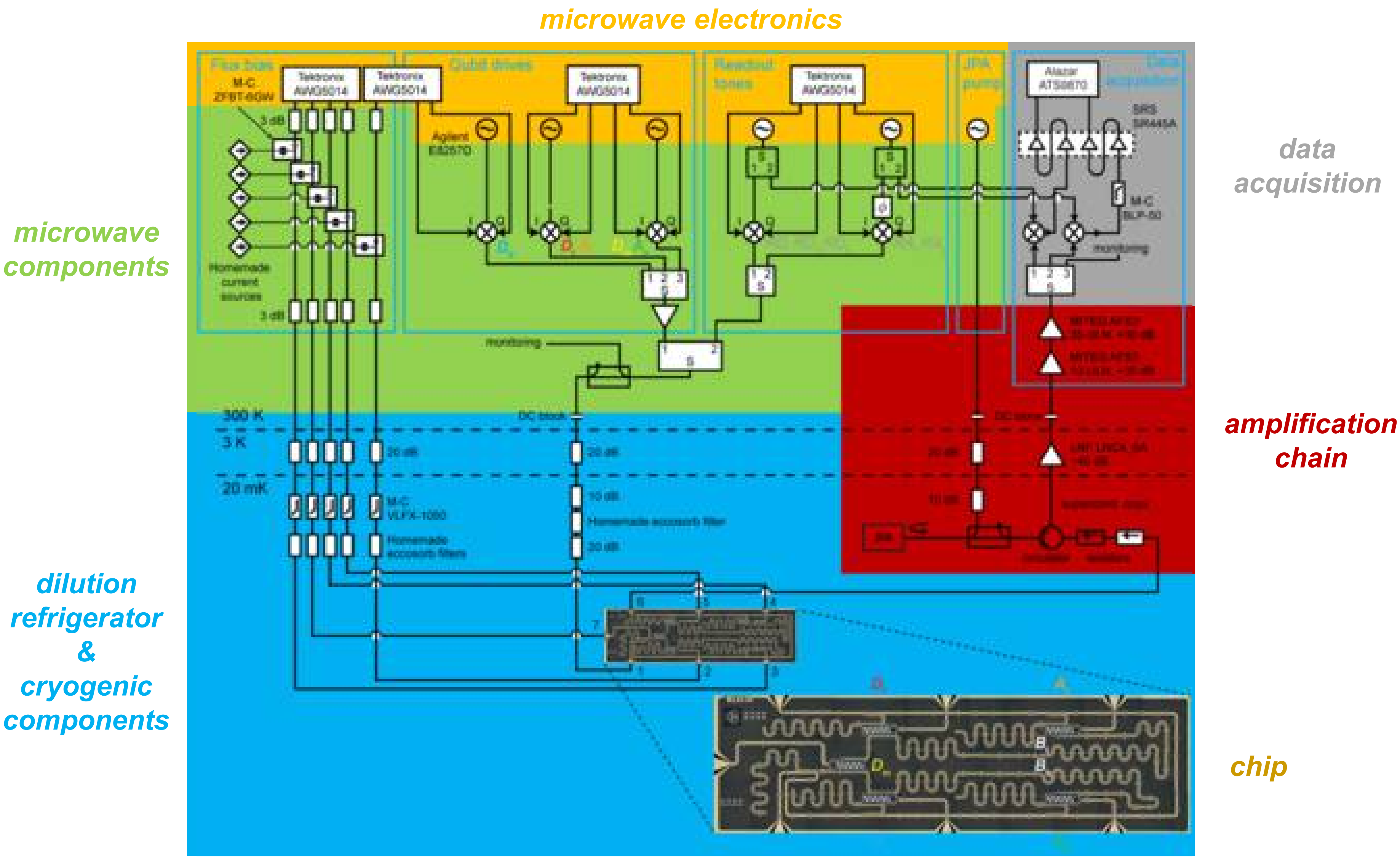






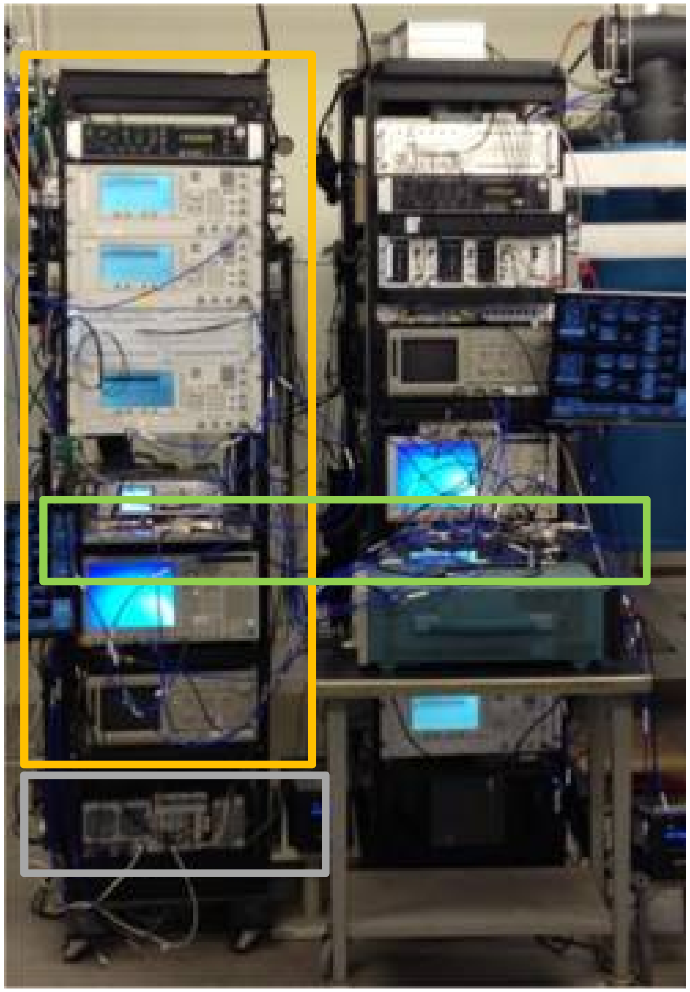
A typical transmon circuit QED setup



Risté *et al.*, Nat Comm 2015

A typical transmon circuit QED setup

microwave electronics

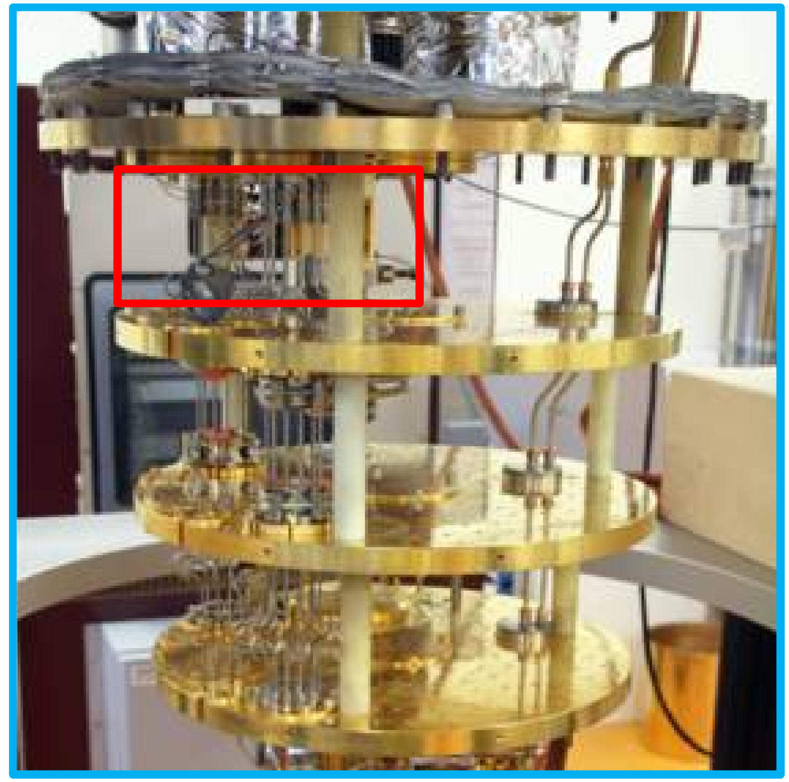


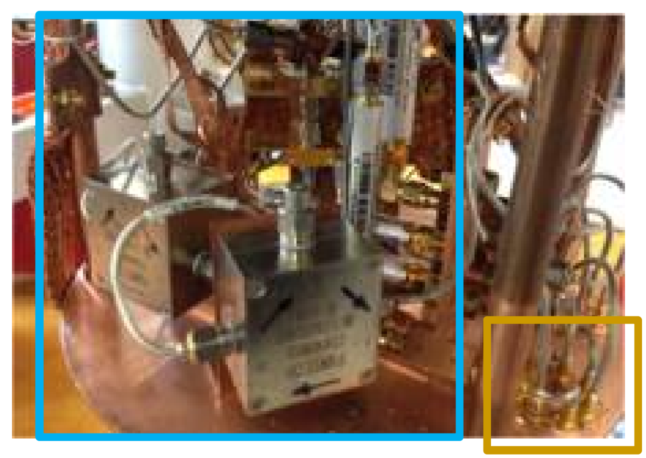
data acquisition

amplification chain

microwave components

dilution refrigerator & cryogenic components





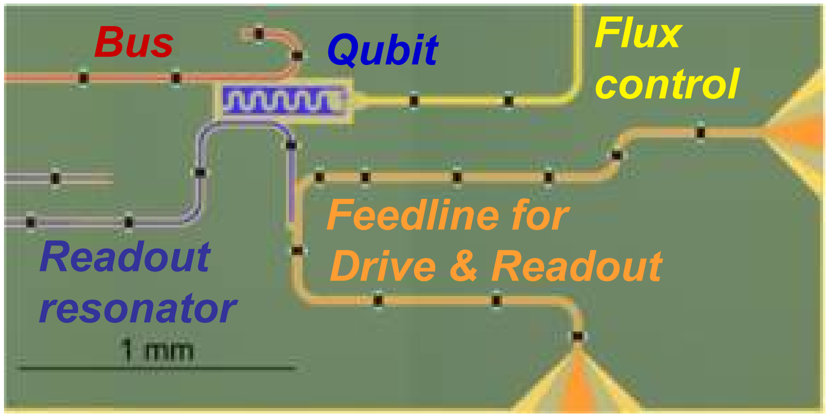
chip

A typical transmon circuit QED setup

Cavity QED in electronic circuits

Haroche group (2000s)
Wallraff et al., Nature (2004)

- "cavity" – μw coplanar waveguide resonator
- "atom" – frequency-tunable transmon qubit
- "input/output" - μw feedline for control/read



Rabi interaction: field-dipole coupling

$$H = \hbar\omega_r\, a^\dagger a + \tfrac{1}{2}\hbar\omega_q\,\sigma_z + \hbar g\,(\sigma_+ + \sigma_-)\left(a + a^\dagger\right)$$

Jaynes-Cummings interaction: strong coupling regime

$$H = \hbar\omega_r\, a^\dagger a + \tfrac{1}{2}\hbar\omega_q\,\sigma_z + \hbar g\left(a\sigma_+ + a^\dagger\sigma_-\right) \qquad \mathrm{RWA:}\ \gamma,\kappa < g, \Delta \ll \omega_\mathrm{q}, \omega_\mathrm{r}$$

Jaynes-Cummings interaction: dispersive regime

$$H = \hbar\omega_r\, a^\dagger a + \tfrac{1}{2}\hbar\omega_q\,\sigma_z + \hbar\chi\,\sigma_z\, a^\dagger a \qquad g \ll \Delta$$

Component frequencies

$\omega_\mathrm{qub} : E_\mathrm{C}$ (geometry) $\quad \omega_\mathrm{res}$: length (geometry)

$: E_\mathrm{J}$ (junctions) $\quad$: materials

Rabi, Phys Rev **49**, 324 (1936)
Jaynes & Cummings, Proc IEEE **51**, 89 (1963)

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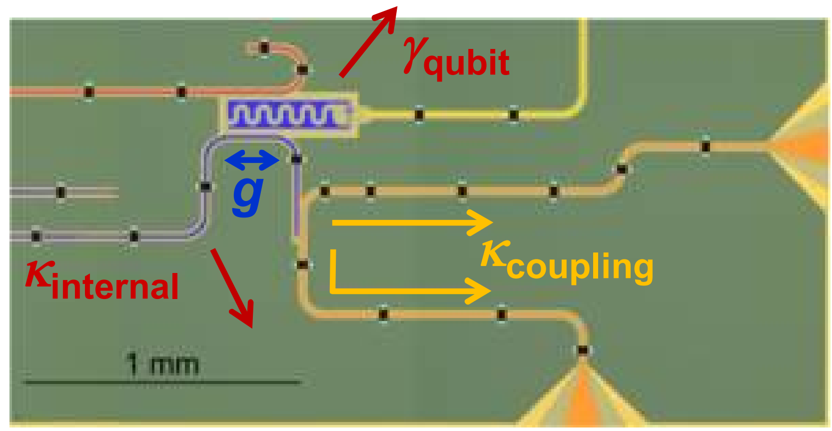

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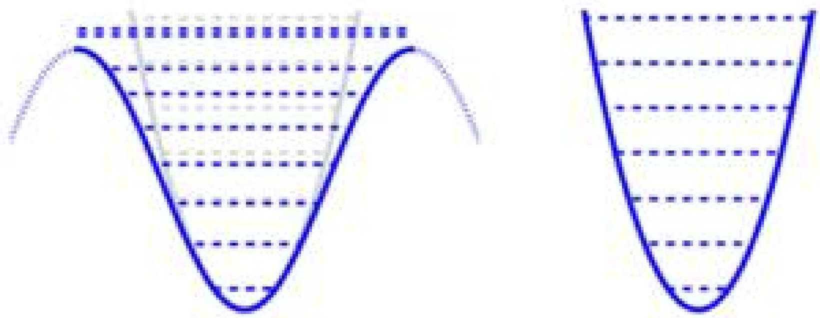
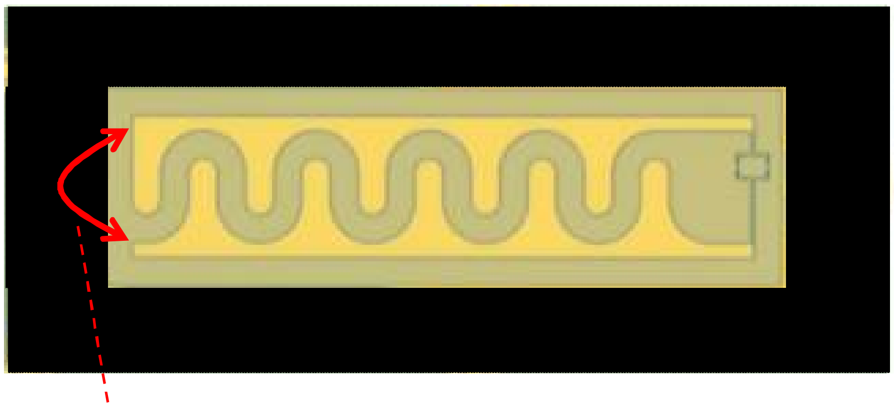
Rabi, Phys Rev **49**, 324 (1936)
Jaynes & Cummings, Proc IEEE **51**, 89 (1963)

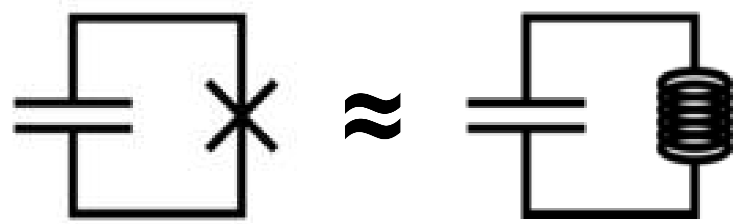
The transmon qubit

- superconducting thin-film circuit
  → low-loss operation
- Josephson junctions
  → nonlinearity without loss





large dipole moment (capacitive coupling)



almost harmonic (a bit anharmonic)

harmonic

- a variety of junctions: single vs split, break junctions, nanowire junctions
- a variety of geometries: 2D vs 3D, xmon, gmon, three-island
- focus here: Al-AlOx SIS tunnel junction, standard transmon

OVERVIEW

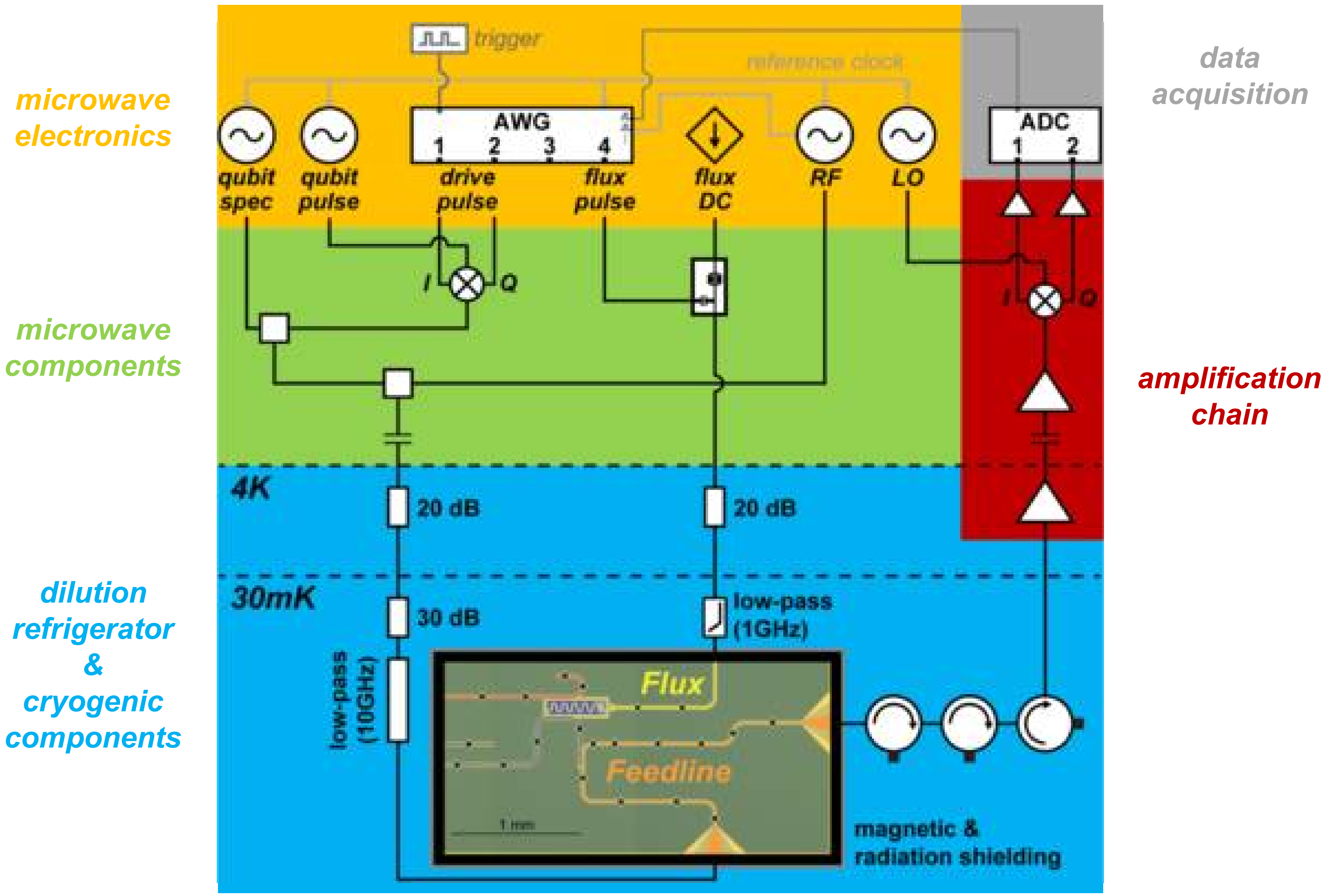
[redacted]

- Finding your qubit: where to start when the fridge gets cold

[redacted]

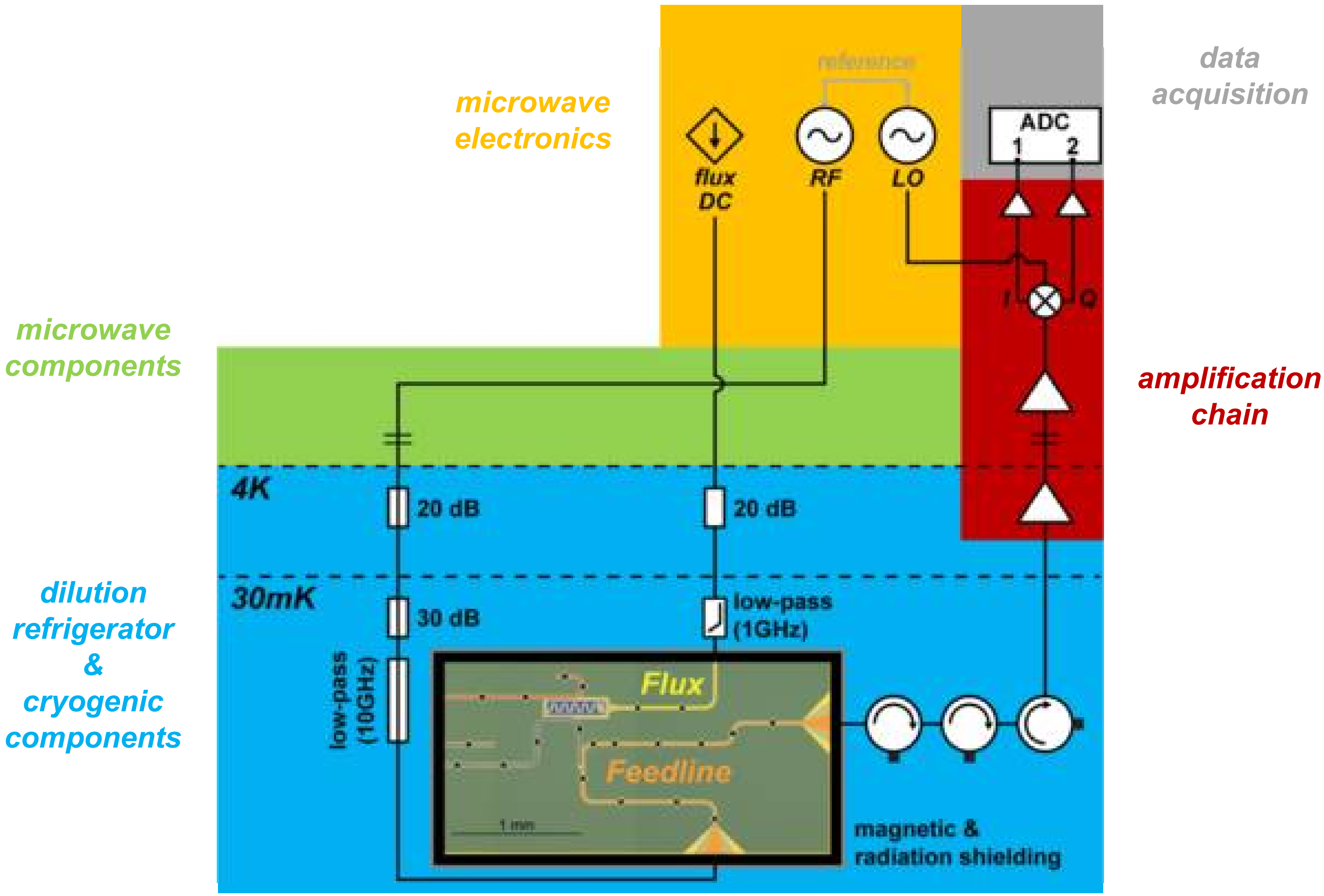
A typical transmon circuit QED setup

Microwave setup



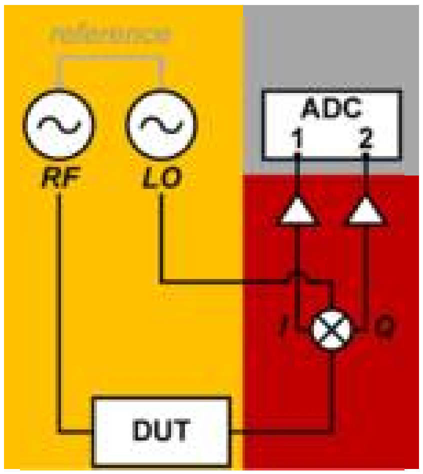
Resonator spectroscopy

Microwave setup



Resonator spectroscopy

What do you see with?

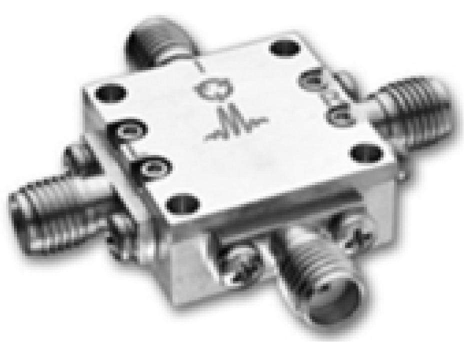


digitise, demodulate & integrate

frequency down-mixing

- microwave equivalent of Mach-Zender
- homodyne: $\omega_{\mathrm{RF}} = \omega_{\mathrm{LO}}$
- heterodyne: $\omega_{\mathrm{RF}} = \omega_{\mathrm{LO}} + \omega_{\mathrm{IF}}$
- nonlinearity provided by IQ mixers

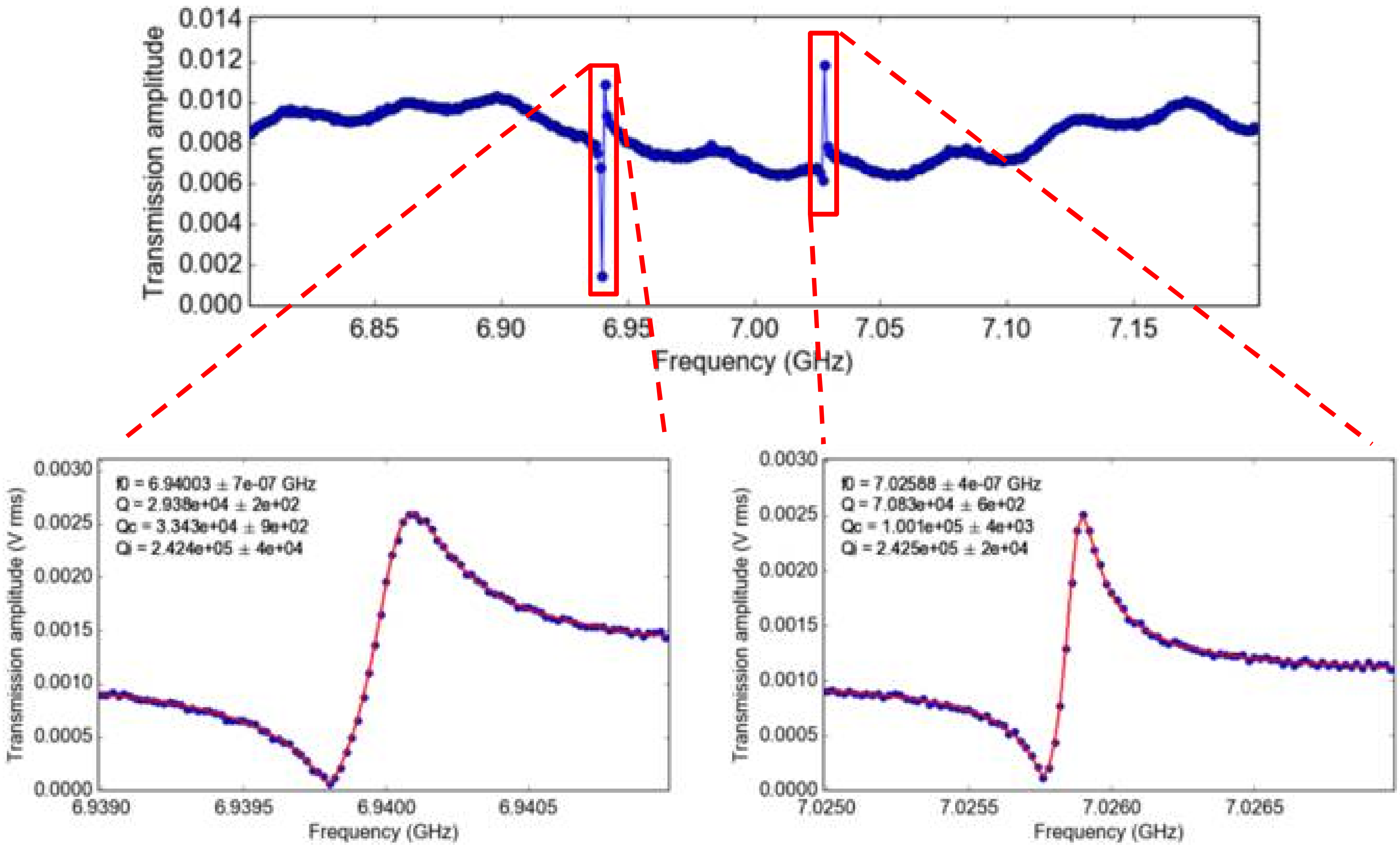
IQ Mixers



- nonlinearity provides signal multiplication
- IQ mixers multiply both carrier quadratures (cos and sin terms)
- can up-convert and down-convert signals
- typically used to move between microwave regime (for our experiments) and radio frequencies (where the electronics is good and cheap)

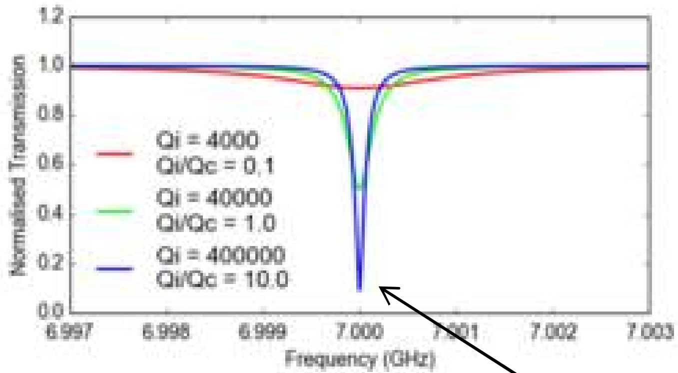
Step 1: Find your resonators

First look at your device…

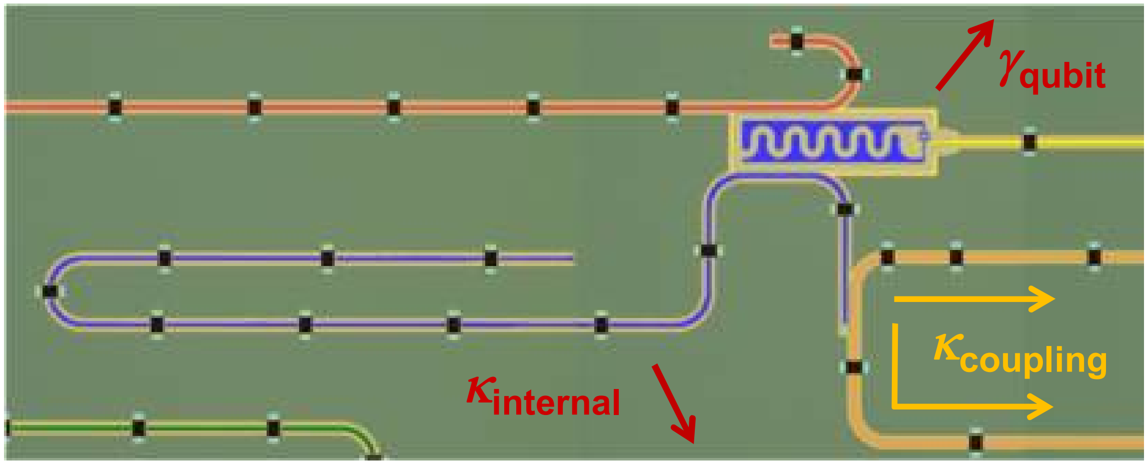


Step 1: Find your resonators

What should you see?



$$\min = Q/Q_\mathrm{i}$$



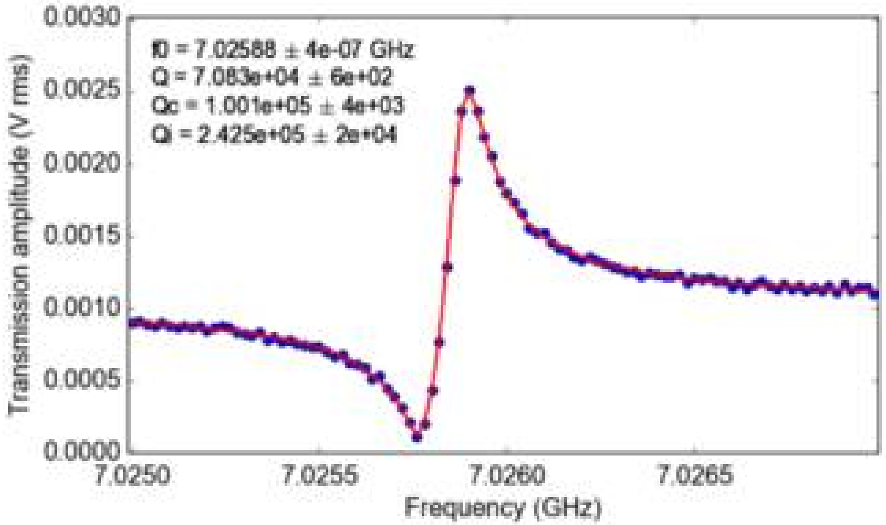
Quality factors

- energy stored / energy loss per cycle

$$Q = \frac{\omega}{\kappa}$$

$$\frac{1}{Q} \propto \kappa = \frac{1}{\tau_{\text{decay}}} = \text{decay rate}$$

$$\frac{1}{Q_{\text{total}}} = \sum_j \frac{1}{Q_j}$$



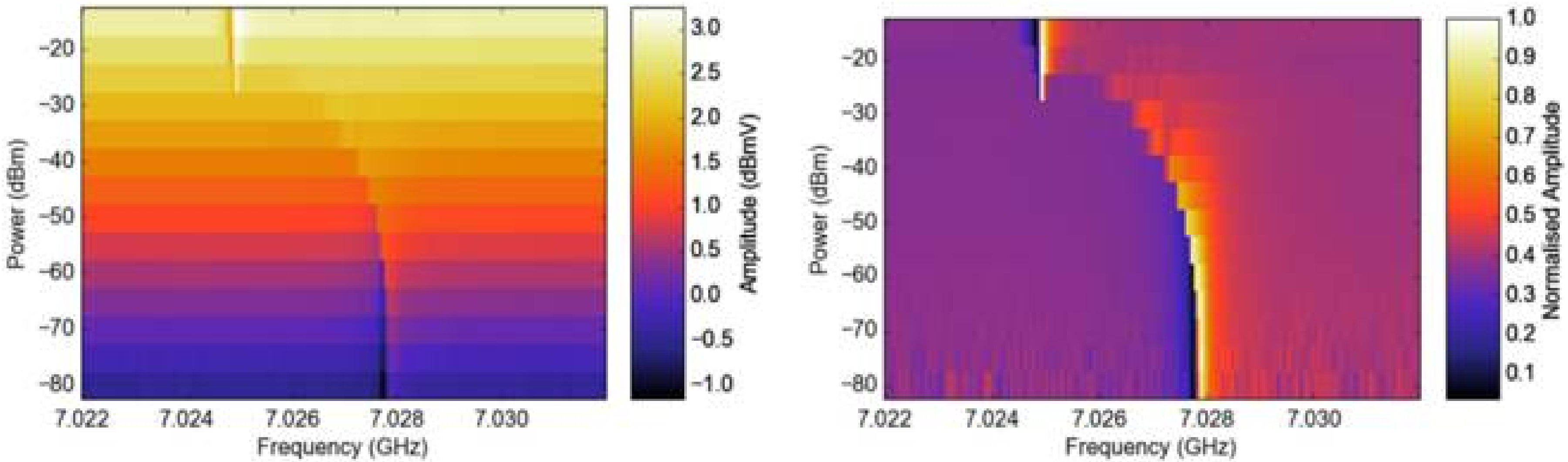
Asymmetry arises from impedance (unwanted inductance) mismatching in the feedline and coupler.

Step 2: It's alive!

The first signature of your qubit

Note: dBm = log scale unit of power

$$P_{\mathrm{dBm(W)}} = -10 \log P(\mathrm{in\ W})/1e-3$$



- low power: linear regime
- high power: nonlinear regime
- very high power: saturation regime (bare resonator response)
- frequency shift: g^2/Δ
  (same as dispersive shift for a two-level qubit)
- for most purposes, you want to operate in the linear regime

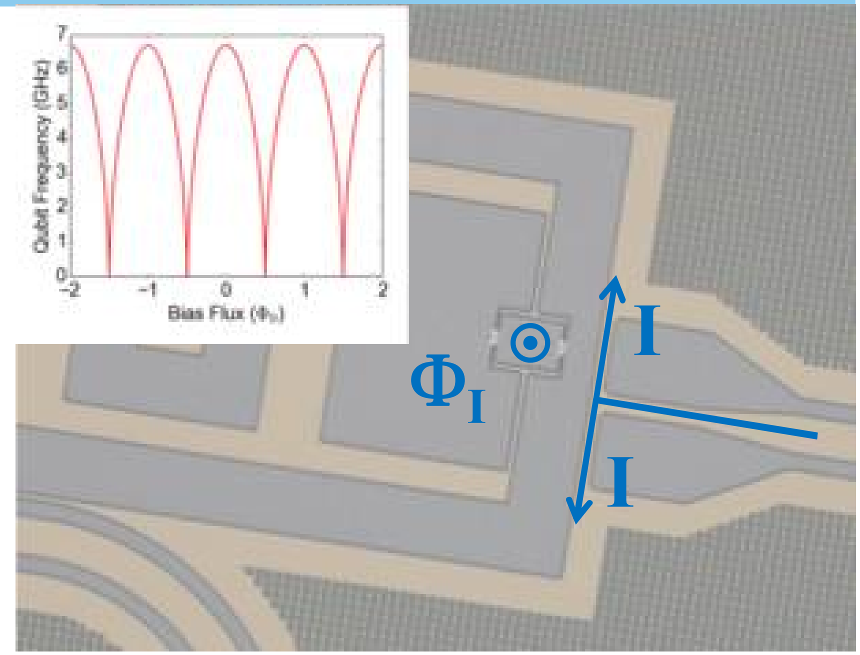
Step 3: Change the tune…

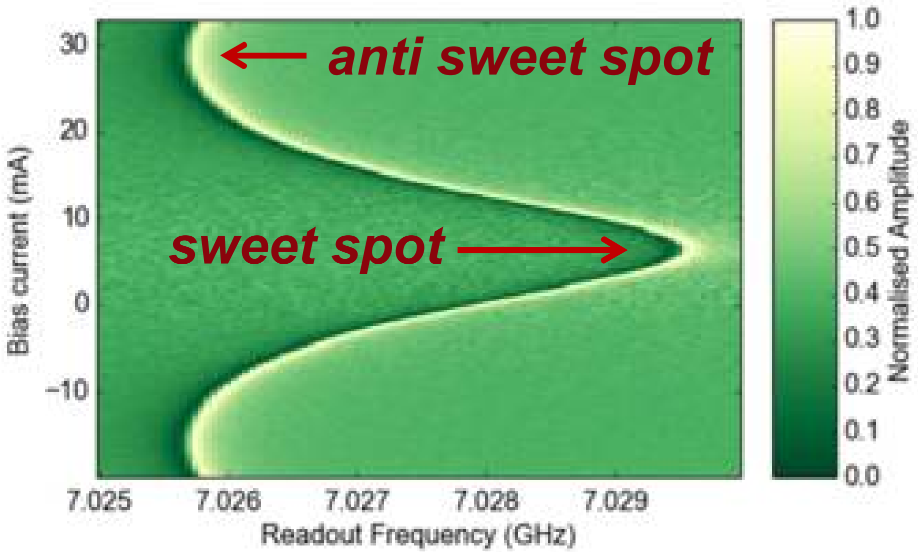
Can you tune the qubit frequency?

Qubits with matched junctions

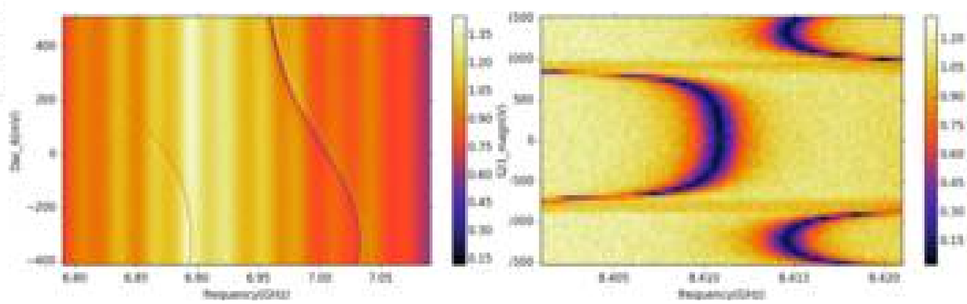
Koch *et al.*, PRA 2007

$$f_{\mathrm{q}}^{\mathrm{bare}} = \sqrt{8E_{\mathrm{C}}E_{\mathrm{J}}(\Phi_{\mathrm{I}})} - E_{\mathrm{C}}$$
$$\approx f_{\mathrm{q}}^{\mathrm{max}}\sqrt{|\cos(\pi\Phi/\Phi_0)|}$$
$$f_{\mathrm{r}} = f_{\mathrm{r}}^{\mathrm{bare}} + g^2/\Delta_{\mathrm{q,r}}$$
$$(\Phi_0 = h/(2e) = \text{magnetic flux quantum})$$



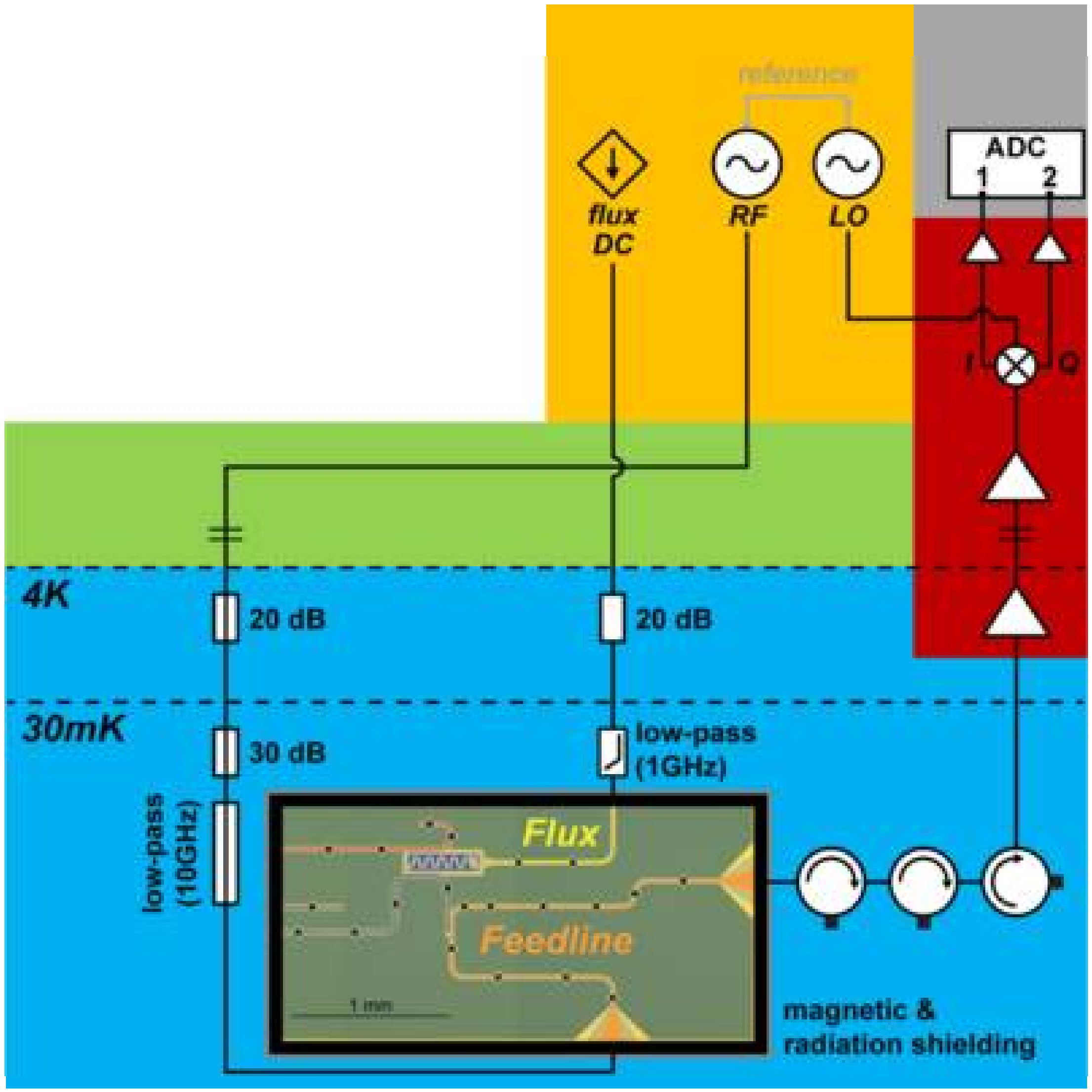


- identify sweet spots (top and bottom)
- calculate flux scaling
- identify qubit-resonator crossing points and calculate coupling strengths



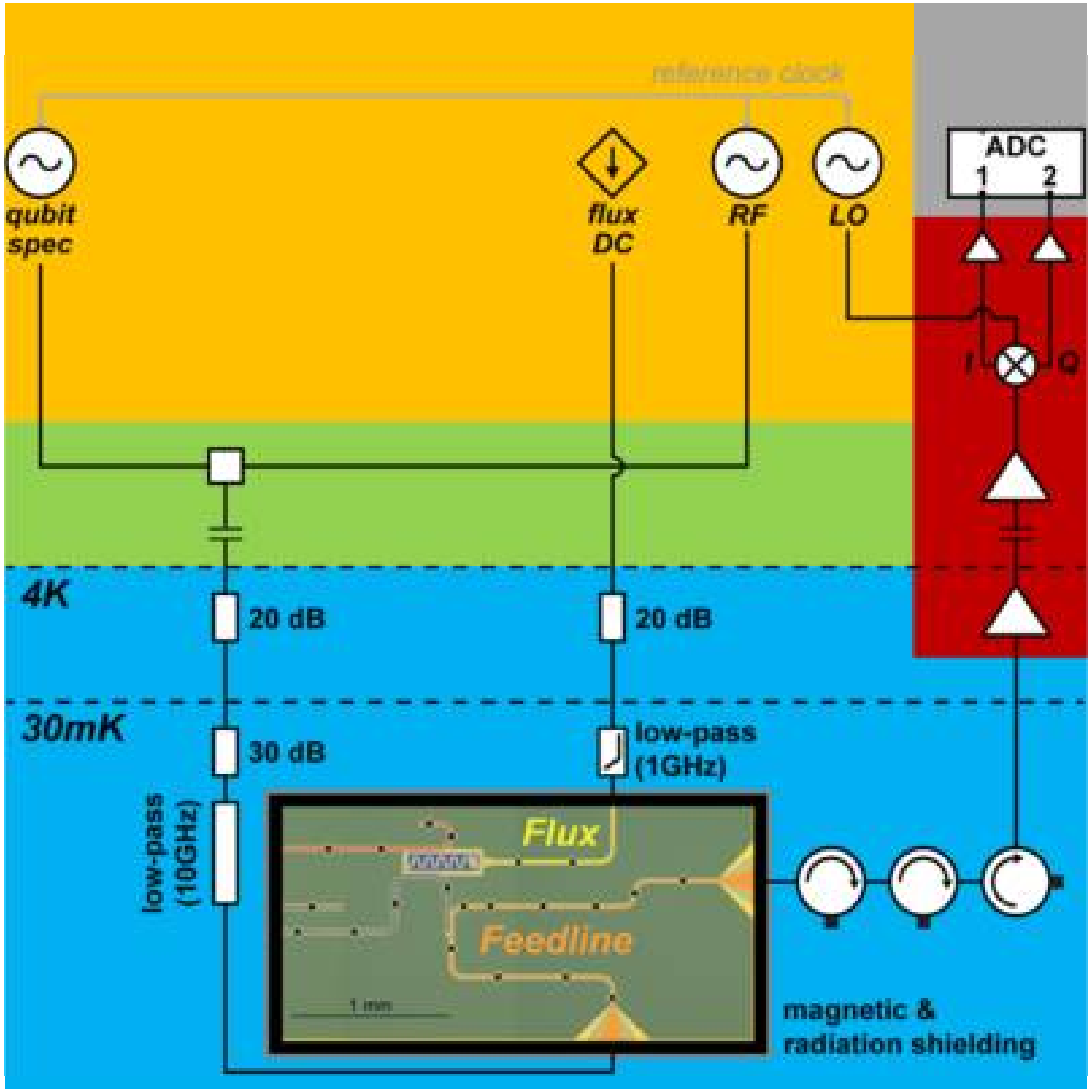
Qubit spectroscopy

Microwave setup



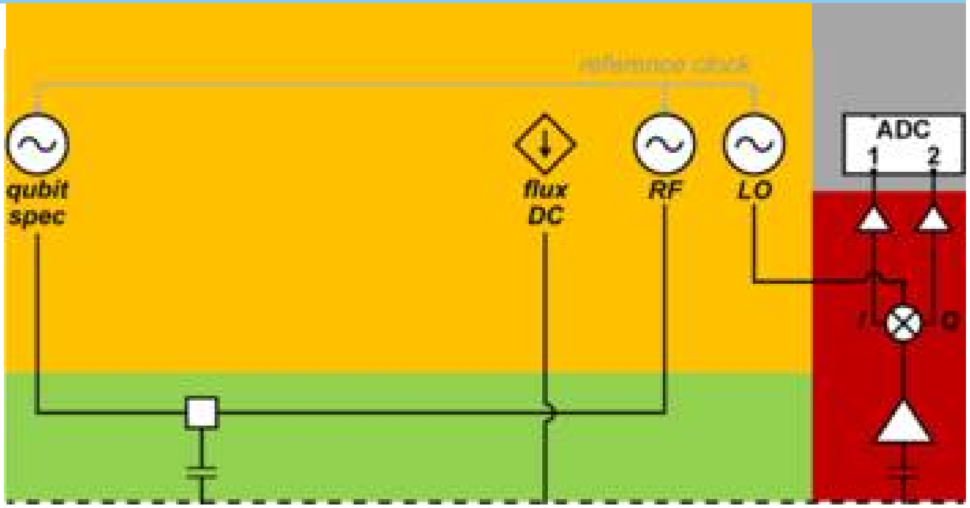
Qubit spectroscopy

Microwave setup



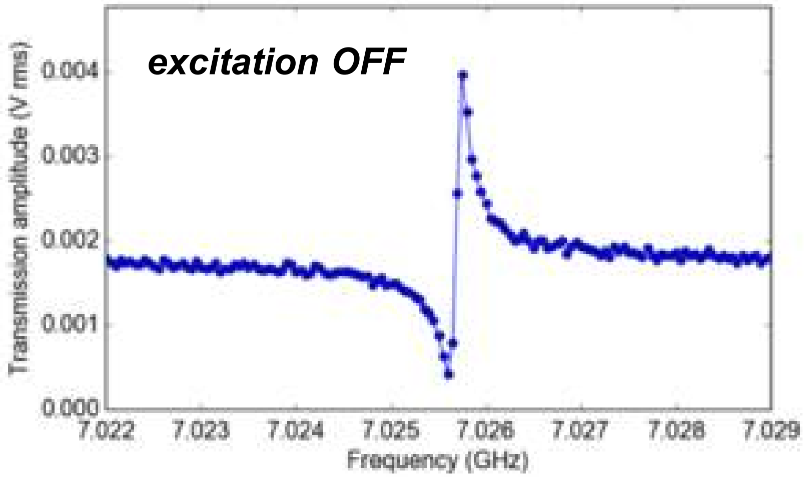
Qubit spectroscopy

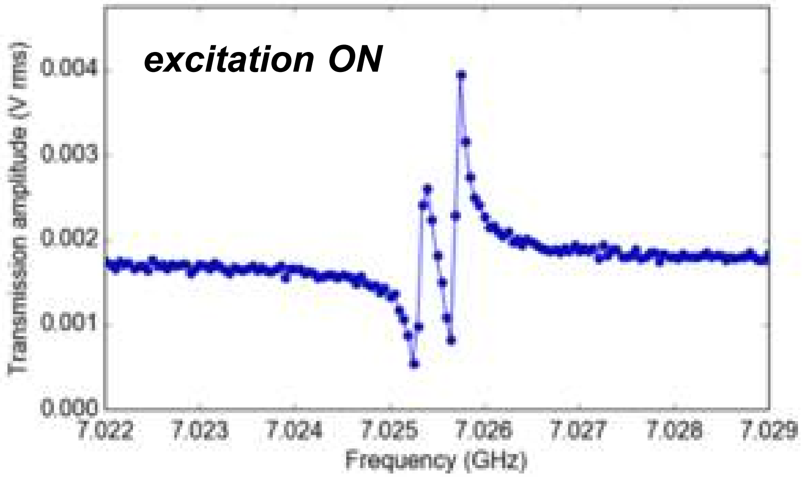
Measurement signal



- uses two microwave tones (resonator readout and qubit excitation)
- detects qubit-state-dependent frequency shift of the resonator
- dispersive regime:

$$H = \hbar\omega_r\, a^\dagger a + \tfrac{1}{2}\hbar\omega_q\,\sigma_z + \hbar\chi\,\sigma_z\, a^\dagger a = (\hbar\omega_r + \hbar\chi\,\sigma_z)\, a^\dagger a + \tfrac{1}{2}\hbar\omega_q\,\sigma_z$$

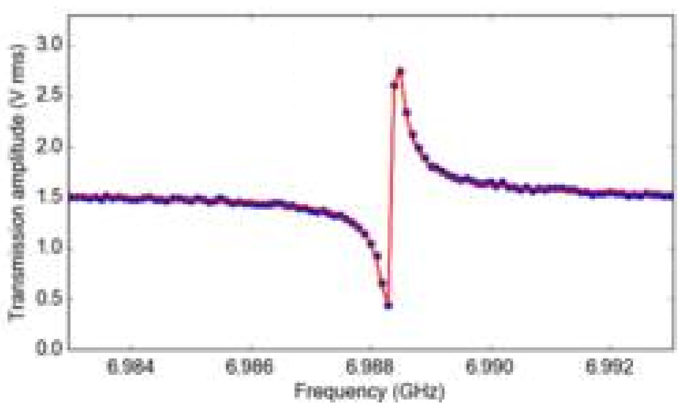




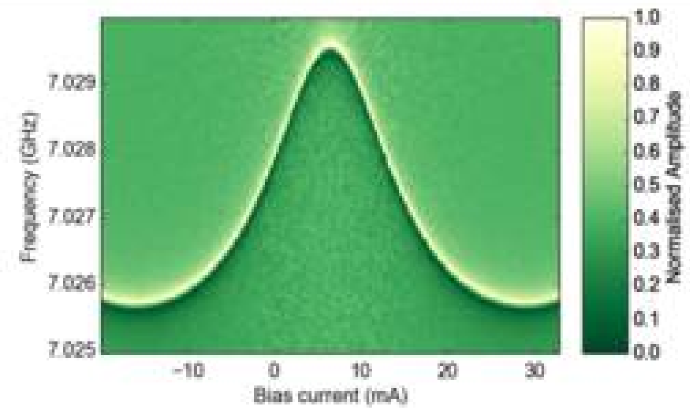
Step 4: Find your qubit…

Where do you start looking?

- move to a sweet spot or near a crossing
- use a power shift to estimate the qubit detuning
- start scanning…



find resonator



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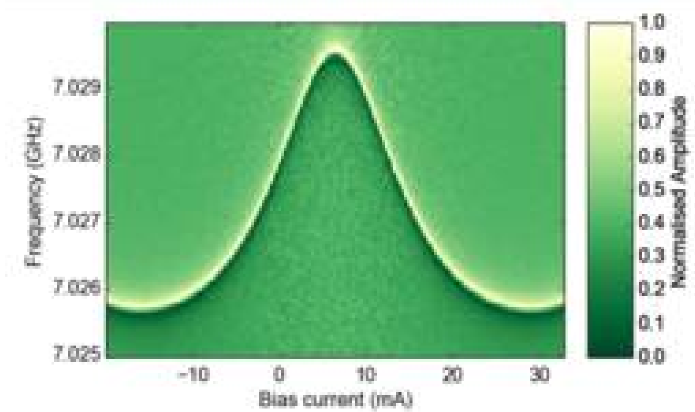
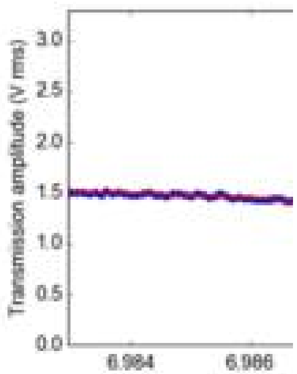
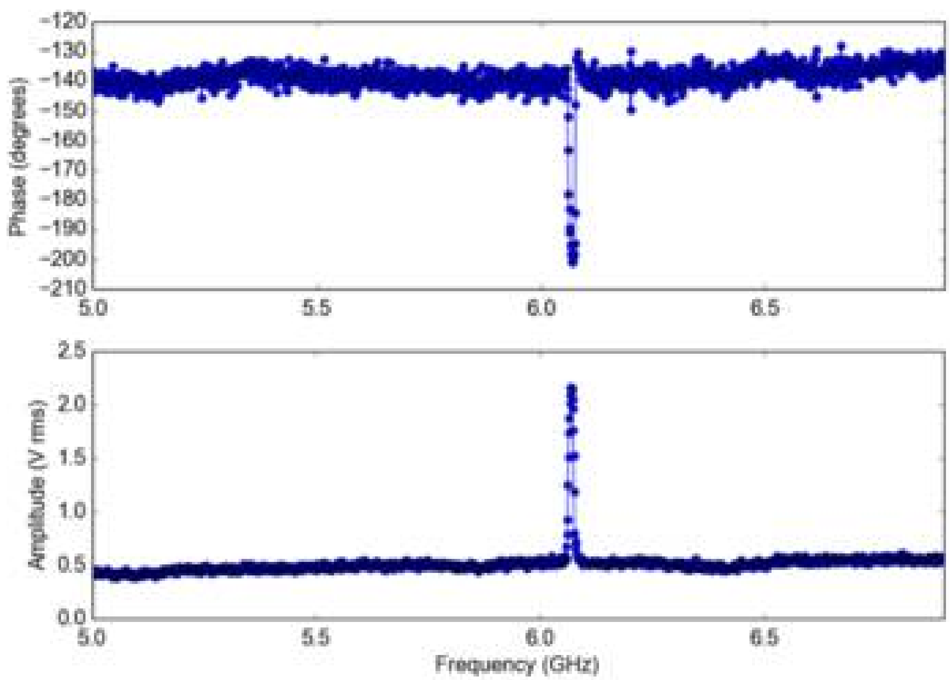




find



scan for qubit

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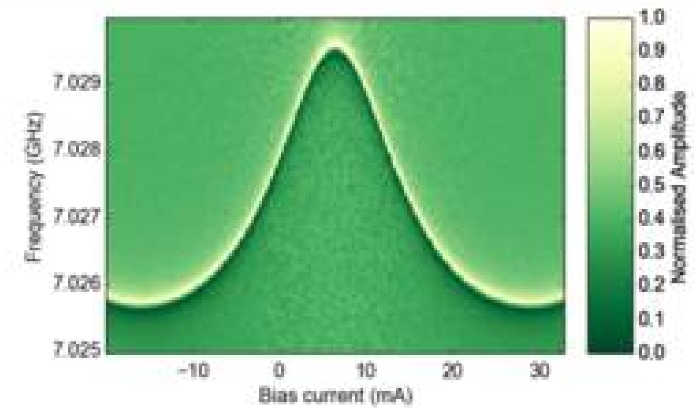

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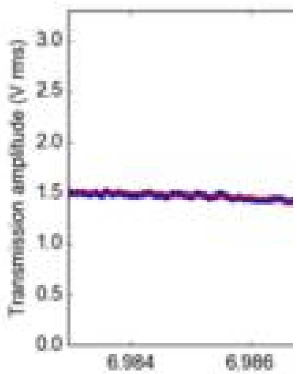
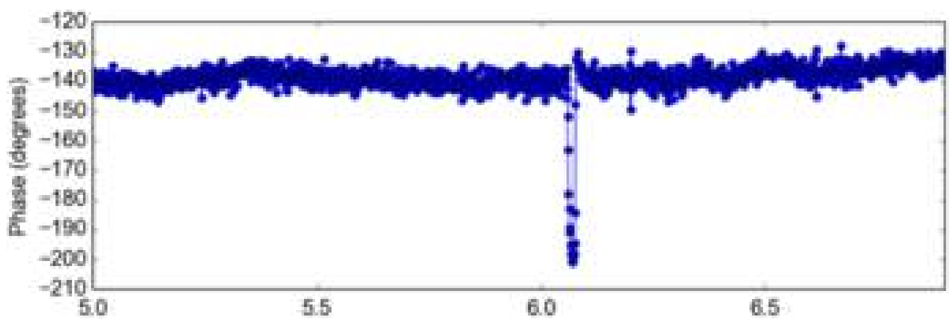
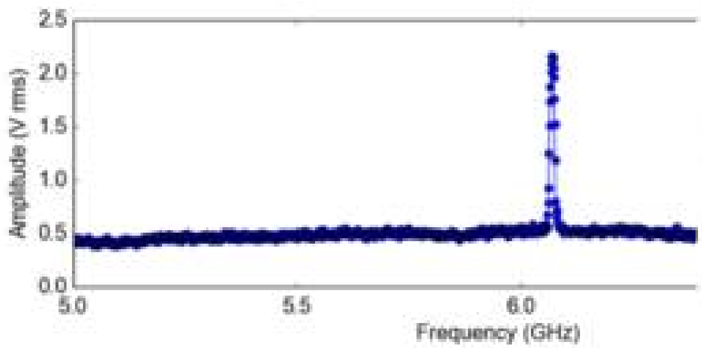
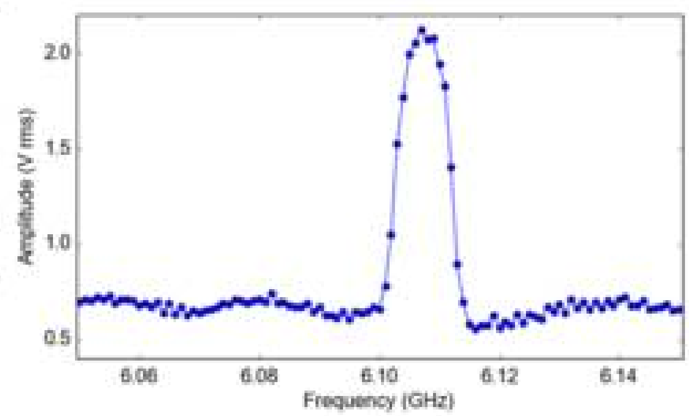


find





scan for qubit



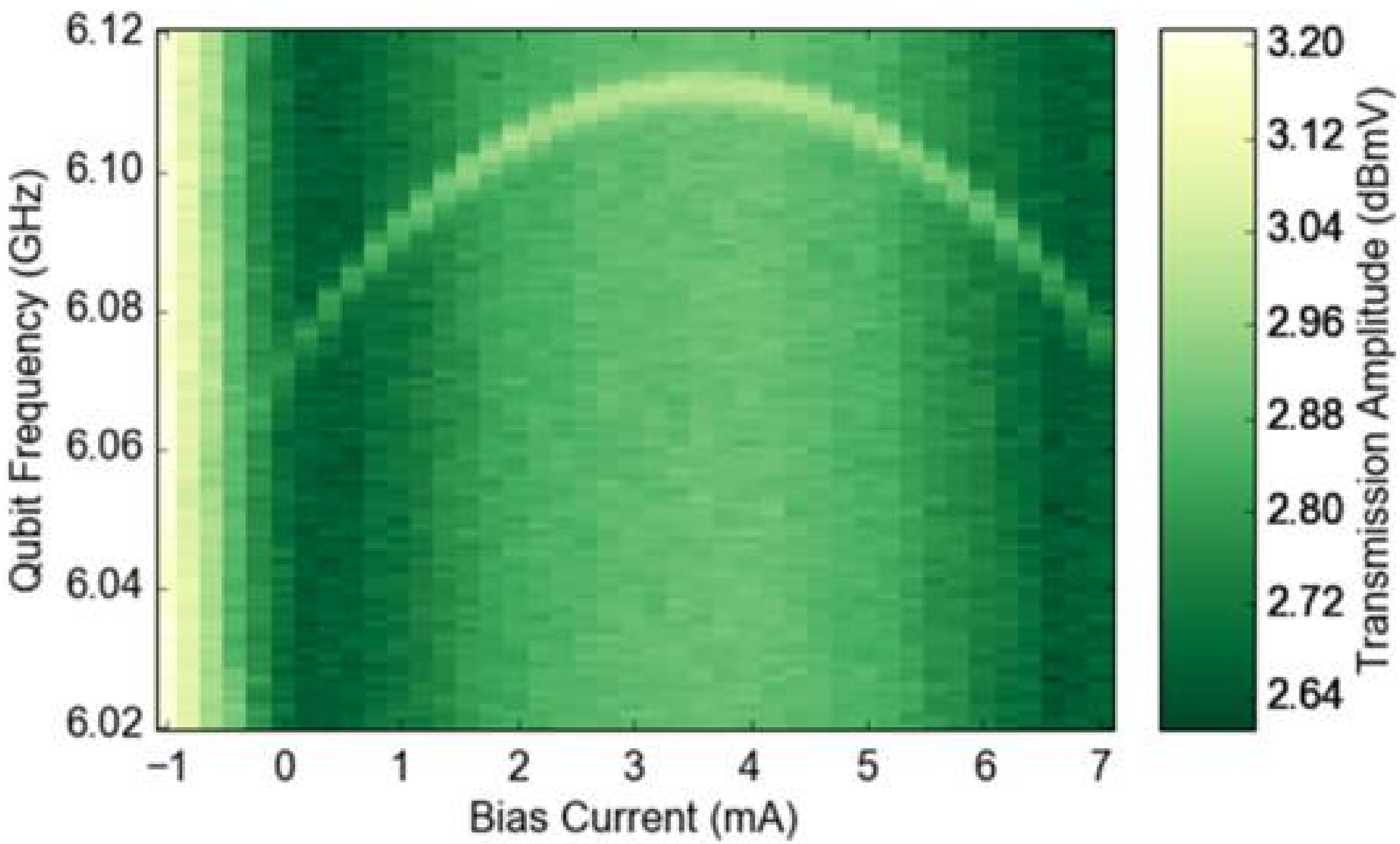
zoom in

But is it your qubit ??

Step 5: It don't mean a thing if it ain't got that swing…

Flux tuning a split-junction qubit and tracked qubit spectroscopy

- as you move the qubit, both resonator and qubit frequency move
- at each step, find the resonator and then find the qubit



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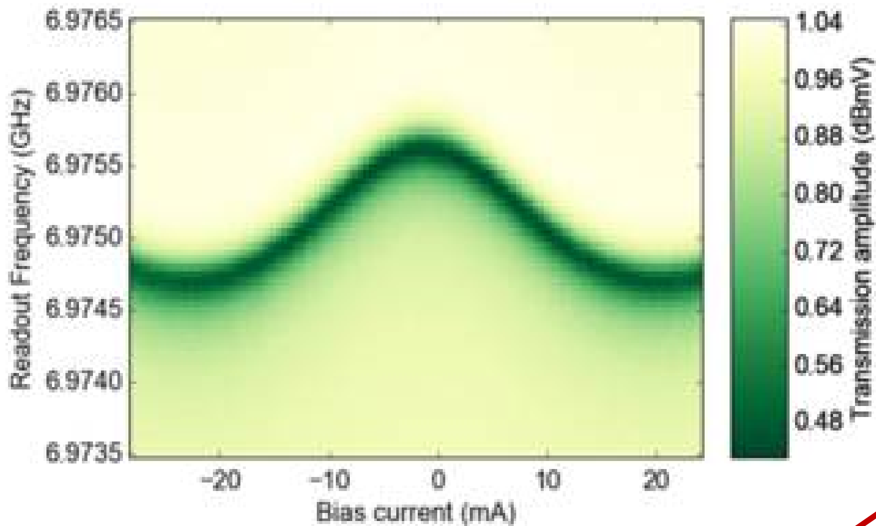
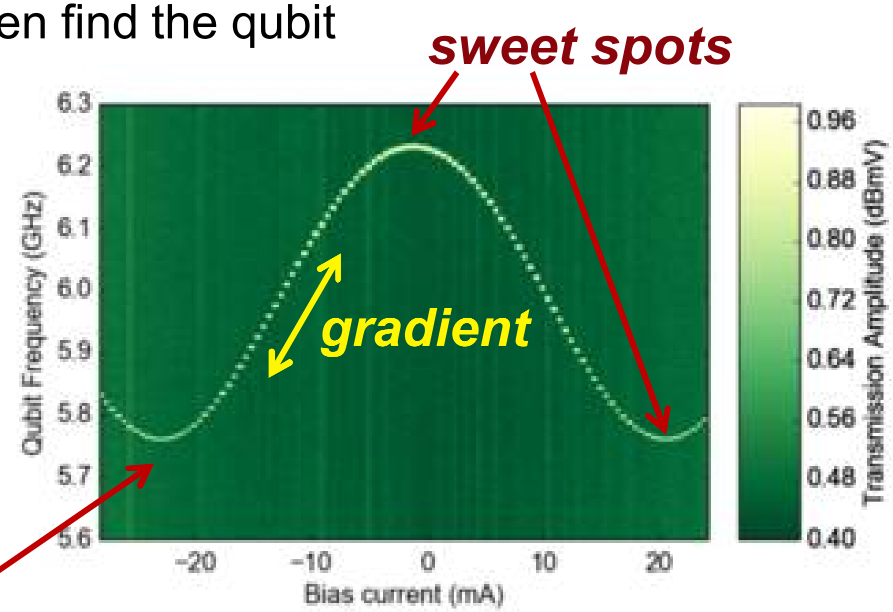
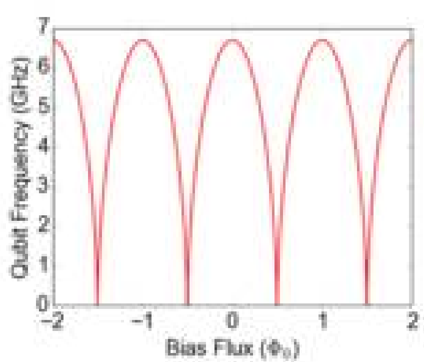


resonator scans



qubit scans



But this does not look like this !!

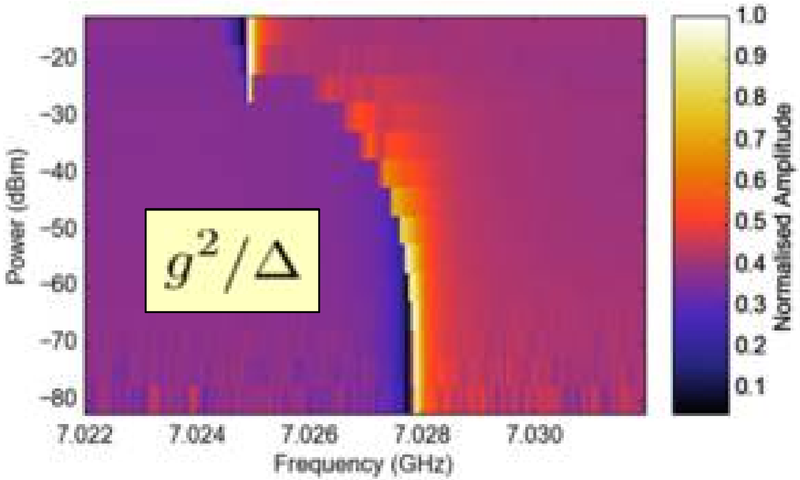
- asymmetric qubits have two "sweet spots"
- frequency gradient vs flux (and therefore flux noise) also reduced

$$E_{\mathrm{J,max}} = E_{\mathrm{J1}} + E_{\mathrm{J2}}$$
$$E_{\mathrm{J,min}} = E_{\mathrm{J1}} - E_{\mathrm{J2}}$$

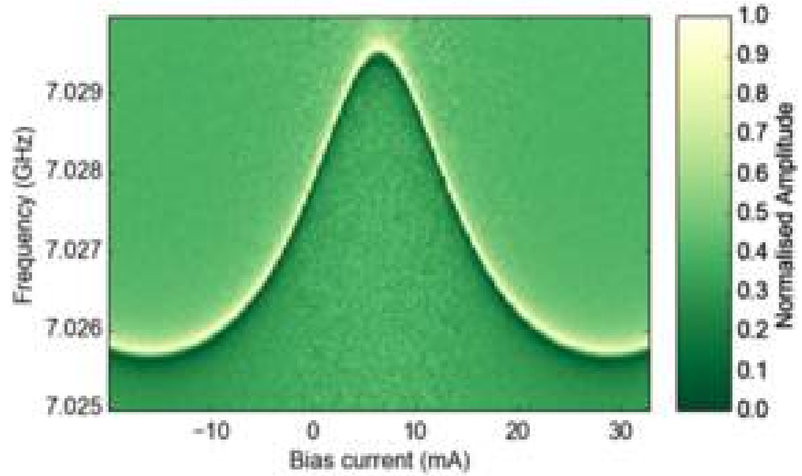
Step 6: Estimating qubit-resonator couplings

Variety of different methods

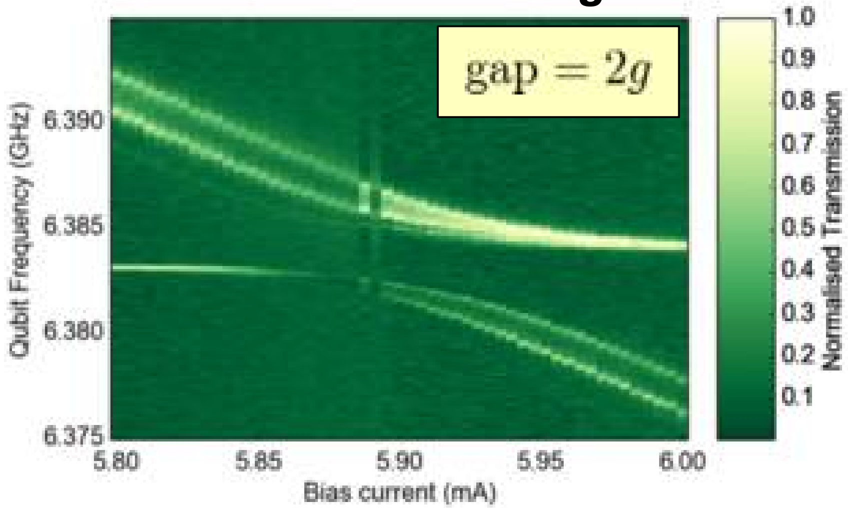
Power Shift



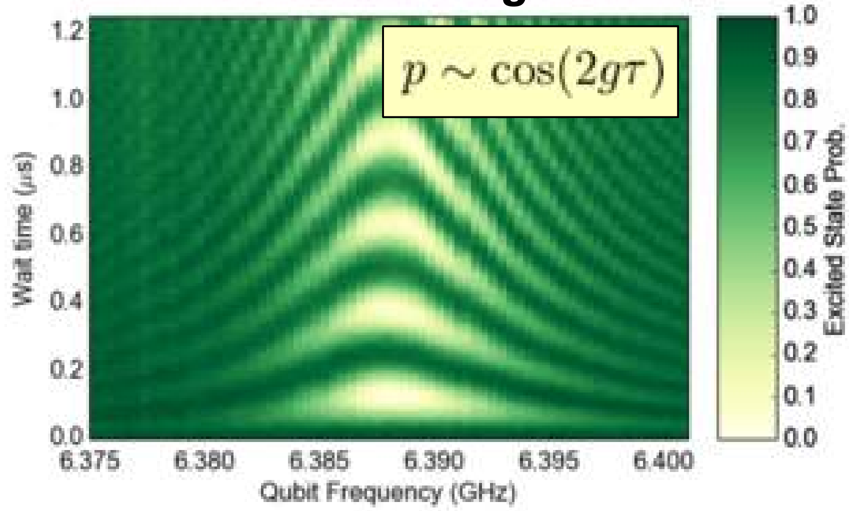
Fit Resonator & Qubit arches



Avoided Crossing



Flux Pulsing



Wallraff et al., Nature (2004)

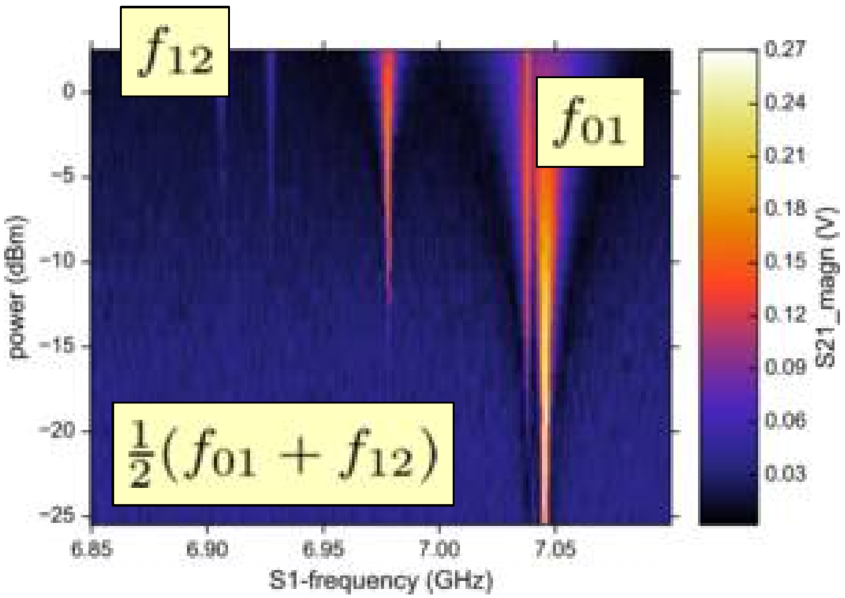
DiCarlo et al., Nature (2010)

Step 7: Estimating qubit anharmonicity

Transmons are weakly anharmonic

- linked to low charge dispersion (charge noise insensitivity)
- higher levels affect photon-number dispersive shift
- limits speed of control pulses
- can be used to implement qubit-qubit entangling gates DiCarlo et al., Nature (2009)
- can also cause unwanted spurious system interactions

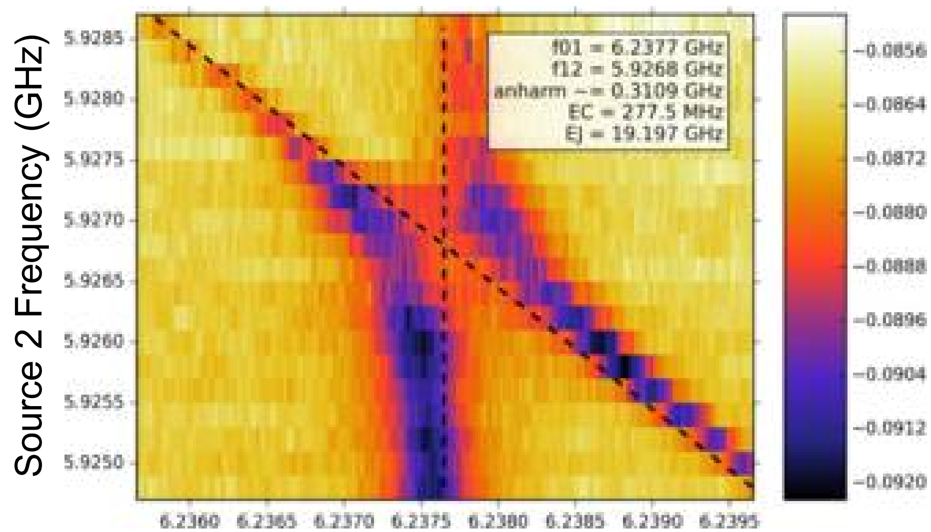
High-power spectroscopy



Courtesy of F. Luthi (2016)

"Two-tone" spectroscopy

(warning: uses three microwave tones)



Engineering the quantum

OVERVIEW

[redacted]

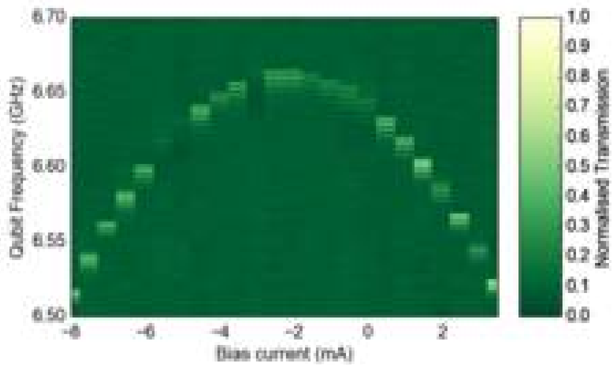
- Getting things pulsing

[redacted]

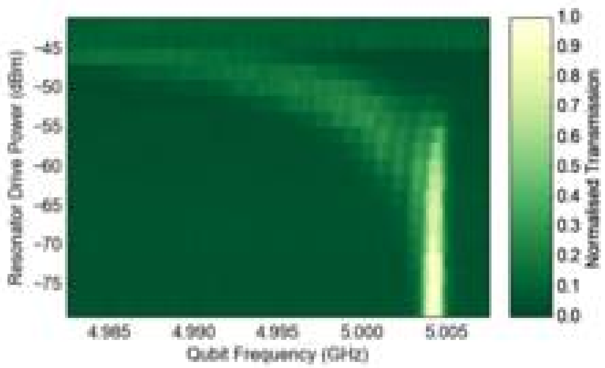
CW vs Pulsed spectroscopy

Continuous spectroscopy: all sources always on

- readout cavity full of photons during qubit excitation



Photon-number splitting
Schuster et al., Nature (2007)



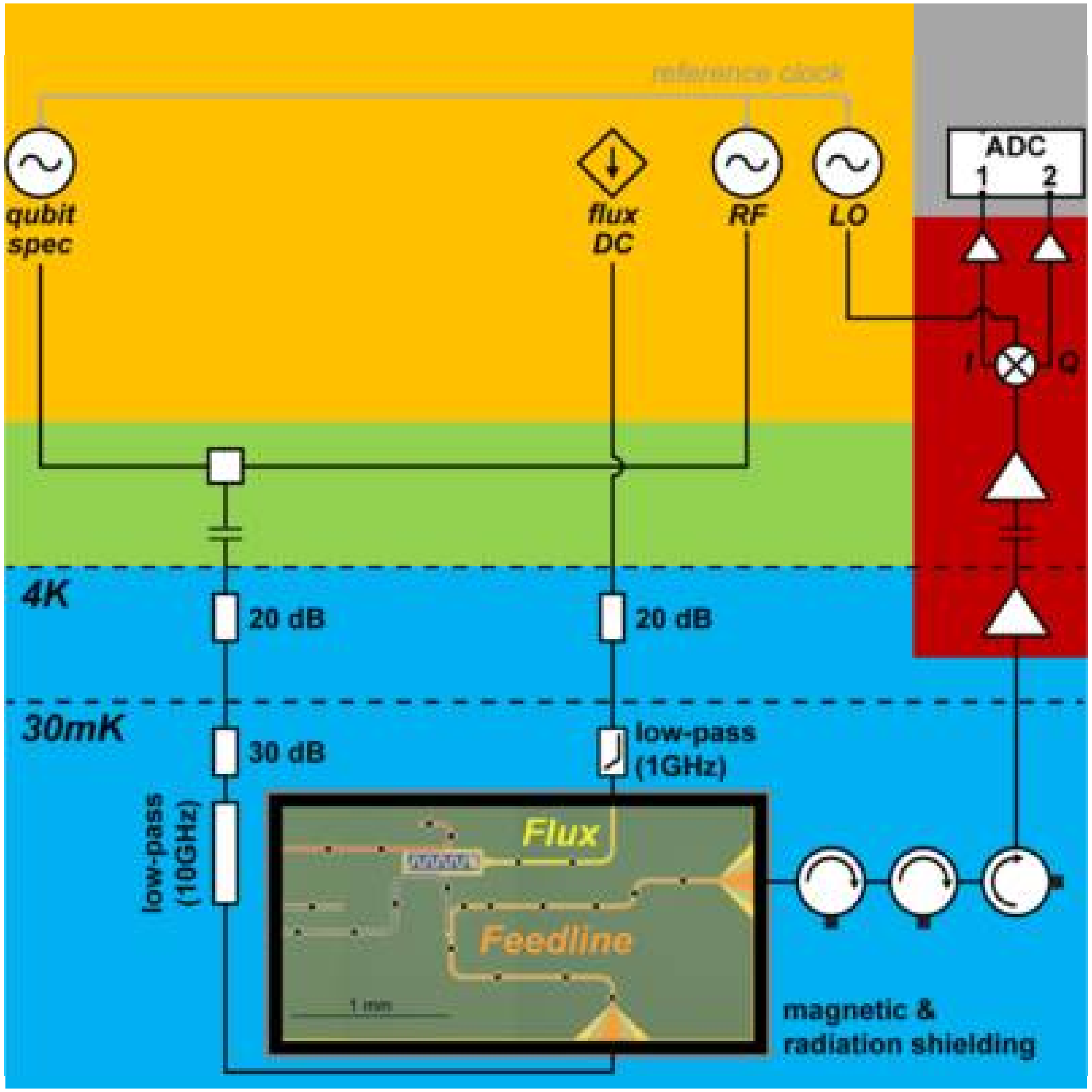
Qubit broadening/shifting
Schuster et al., PRL (2005)

Pulsed spectroscopy

- half 'n' half: pulse the readout tone
  - ➢ requires little calibration, works with short lifetimes, can be messier
- all the way: pulse both excitation and readout tones
  - ➢ requires more calibration (e.g., excitation power, excitation and readout resolution), can be cleaner
  - ➢ can use both saturation and pi pulses for excitation pulses

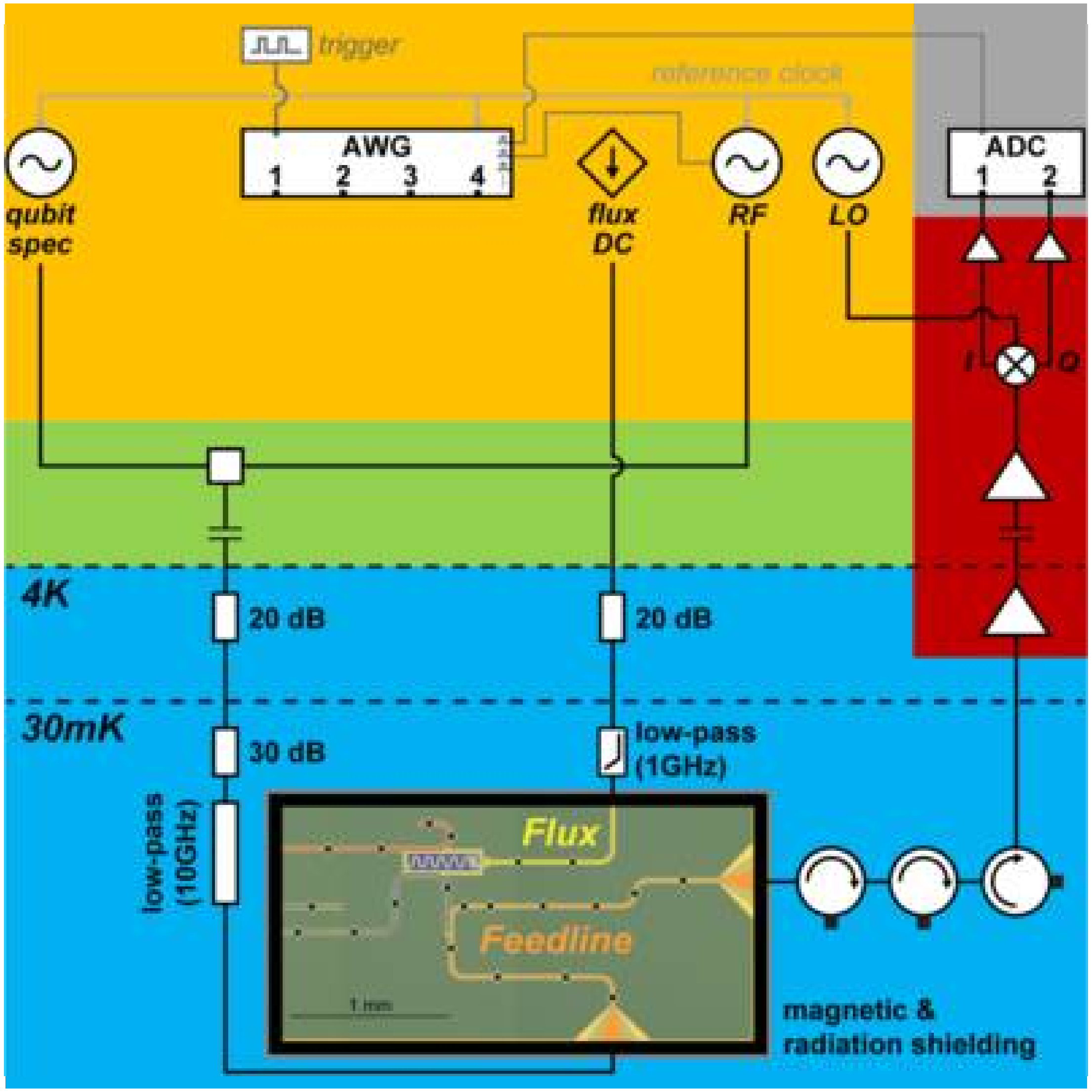
Pulsed spectroscopy

Microwave setup



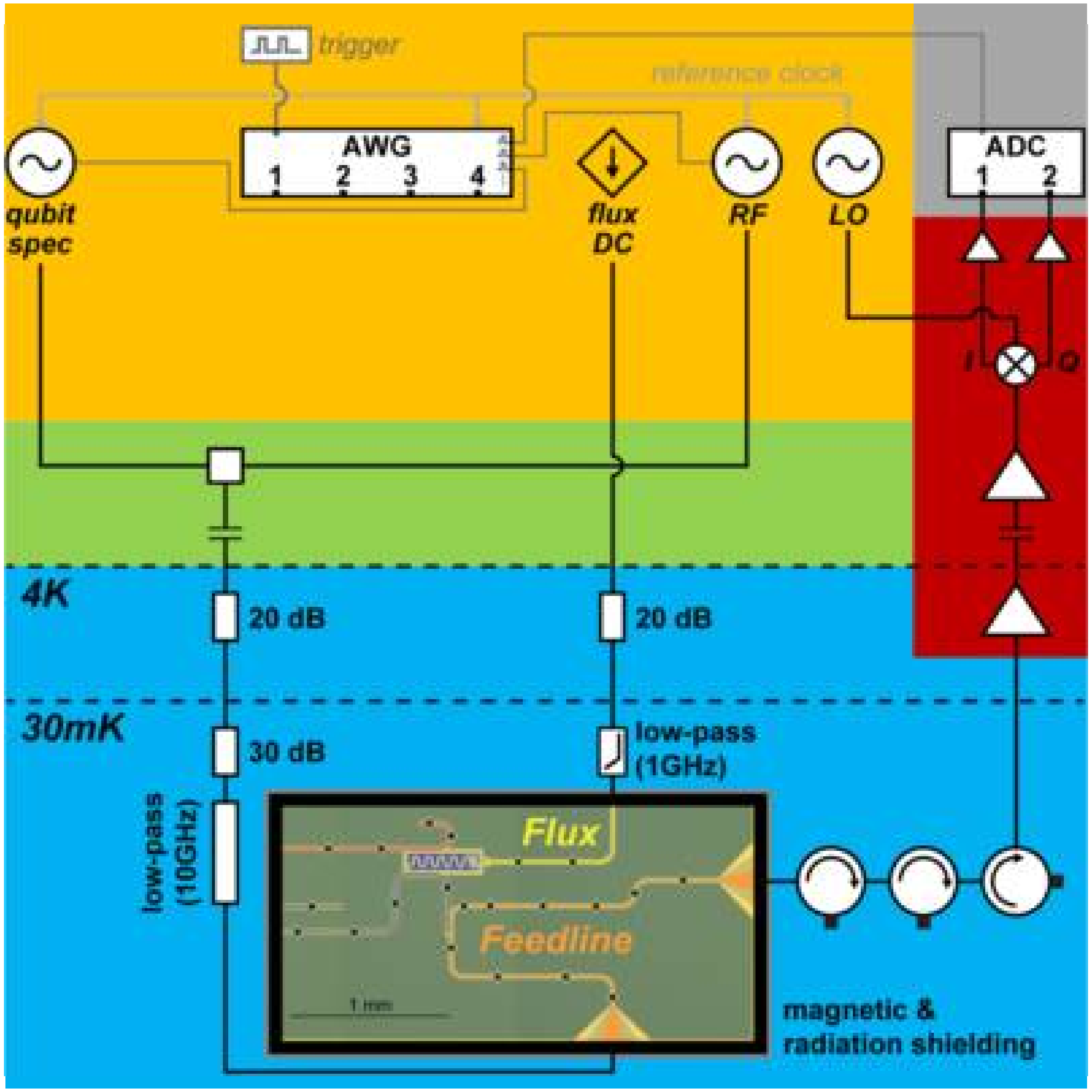
Pulsed spectroscopy

Microwave setup: half 'n' half



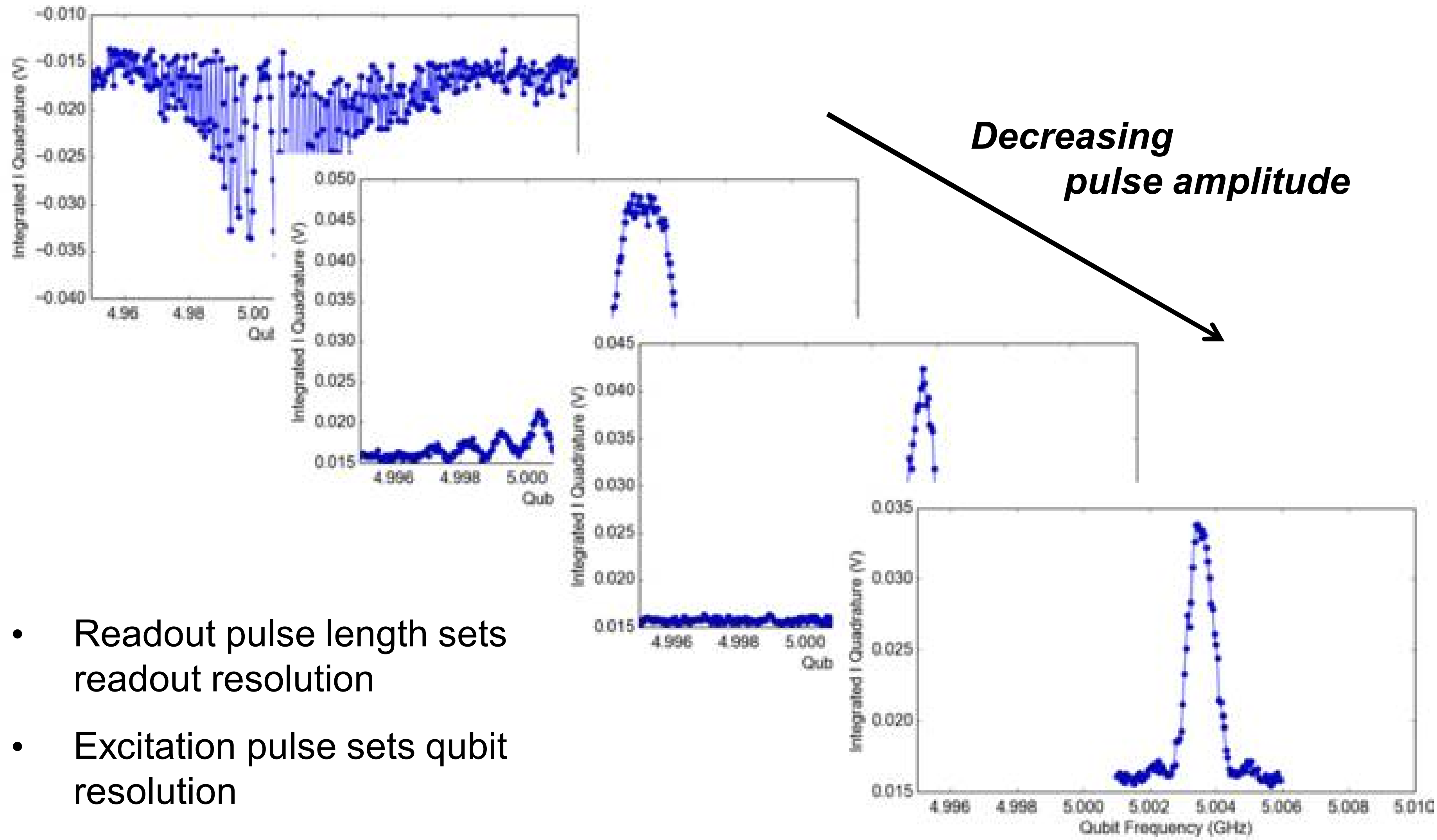
Pulsed spectroscopy

Microwave setup: all the way



Pulsed spectroscopy

Live Fourier transform of a square pulse



- Readout pulse length sets readout resolution
- Excitation pulse sets qubit resolution

Engineering the quantum

OVERVIEW

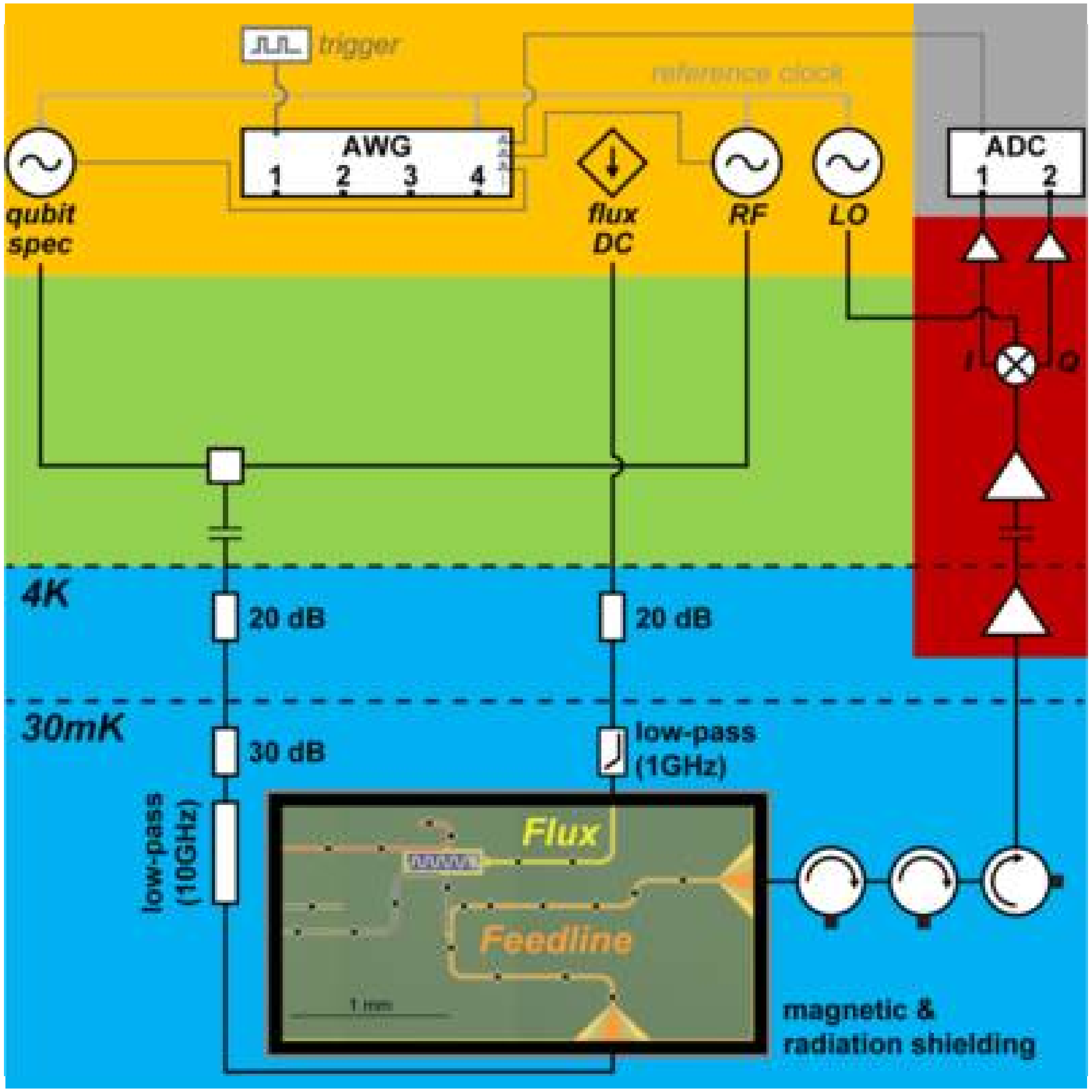
[redacted]

- Getting control of your qubit

[redacted]

Pulsed spectroscopy

Microwave setup: all the way



Tuning up for pulsing / time domain

Basic calibration steps

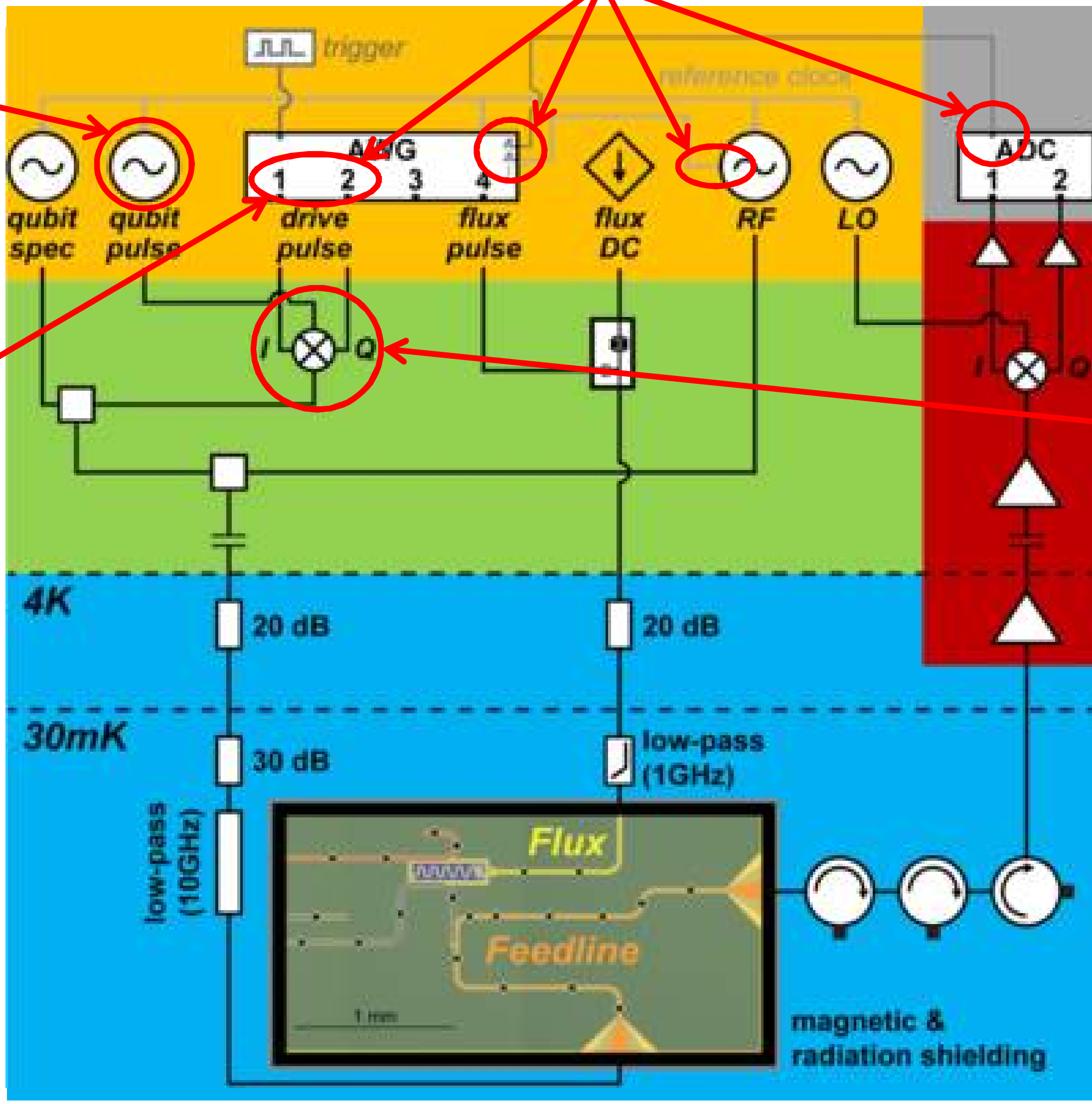
Step 3
drive frequency

Step 4
pulse amp

Step 2
pulse timings (RO, drive)

-- timing critical at qubit and digitization (ADC)

-- delays are calibrated in AWG sequencing



Step 1
mixer

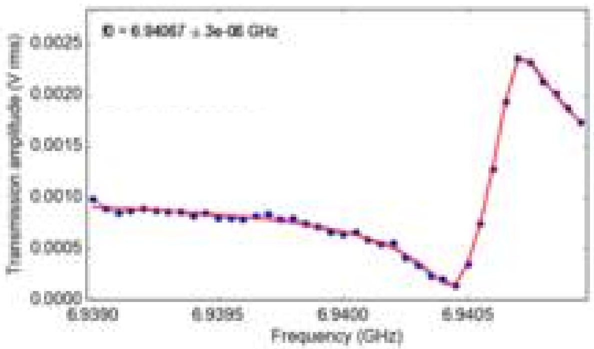
-- allows full control of:
drive pulse envelope and drive pulse phase (rotation axis)

-- mixers require careful calibration to compensate for imperfections

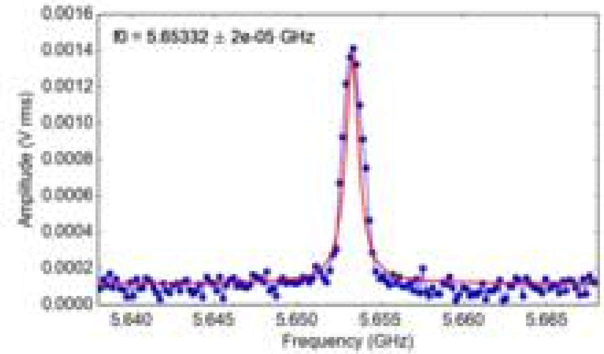
Basic calibration: pulse frequency and amplitude

Find qubit frequency

Warning: frequency may be significantly inaccurate if the spec readout power is too high!!



scan for resonator

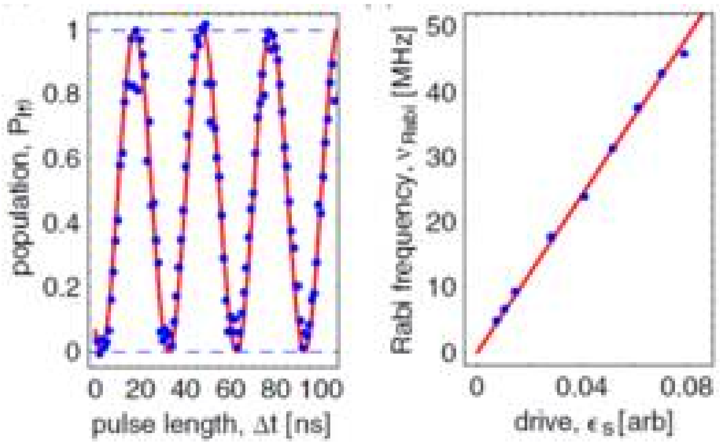


scan for qubit

Calibrate pulse amplitude using Rabi oscillations

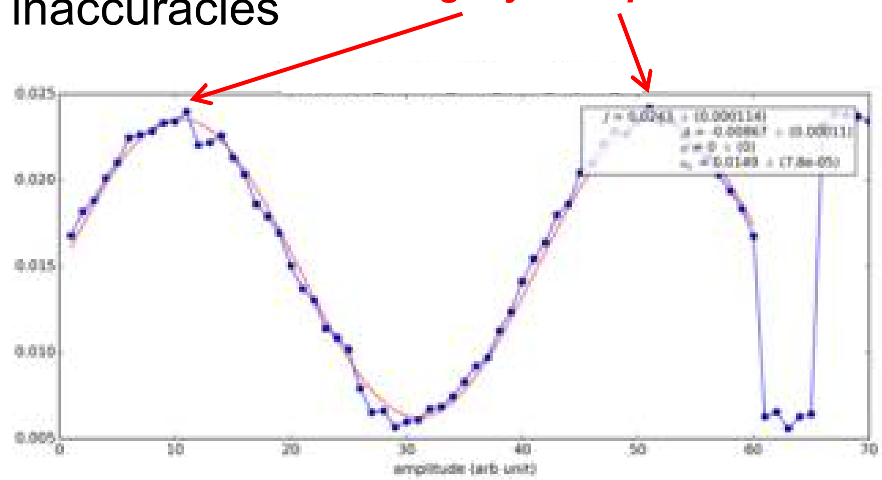
- good starting sequence: most tolerant to inaccuracies

Wallraff et al., PRL (2005)



traditional Rabi oscillations (vary pulse length)

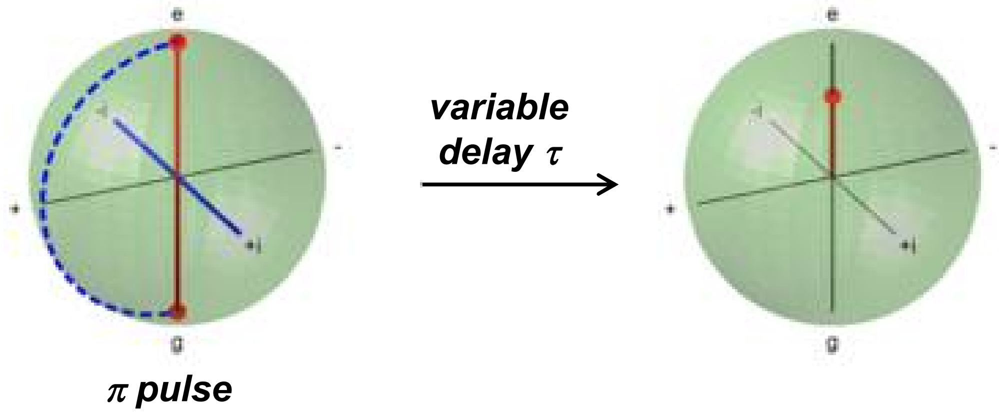
get your π pulse here

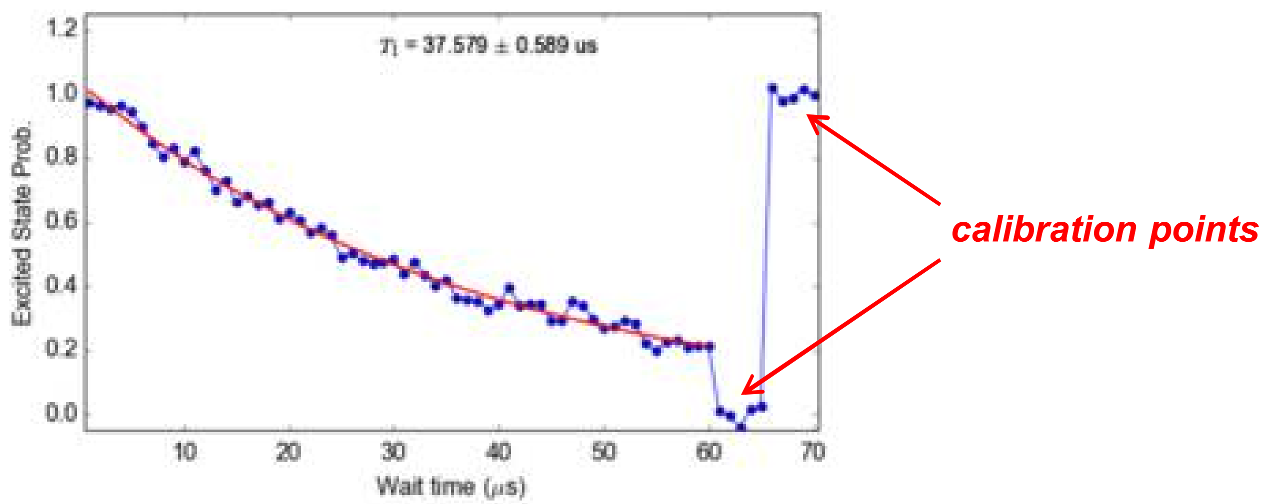


Rabi calibration sequence (vary amplitude for target pulse length)

Basic qubit characterisation sequences

T1: qubit relaxation time

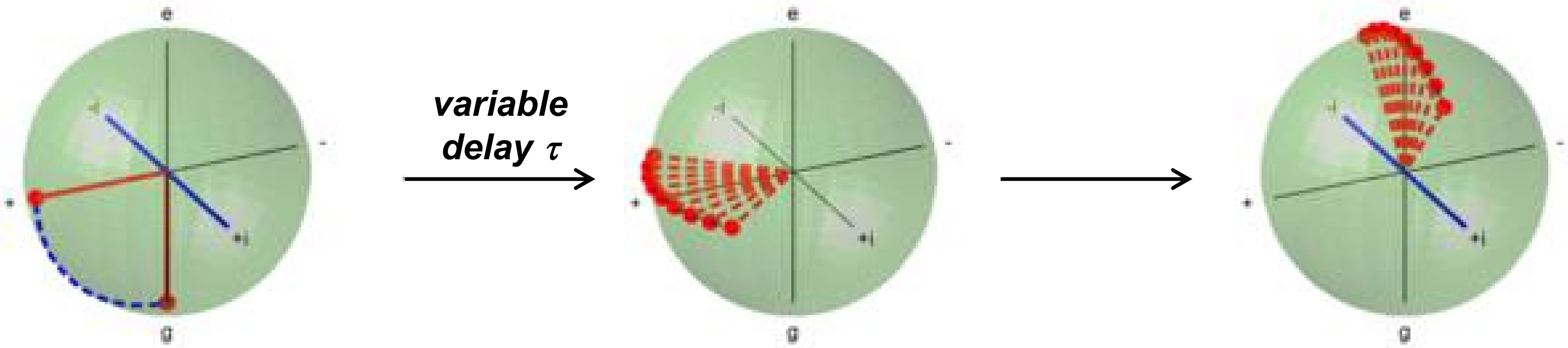




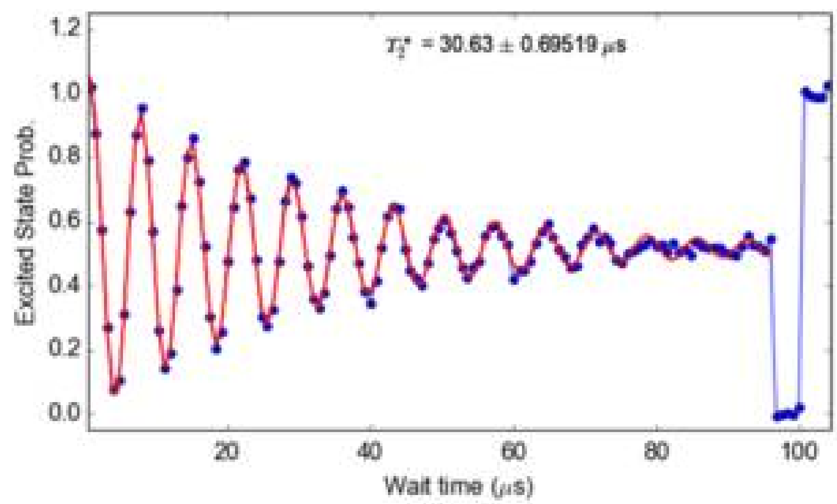
- well-characterised pulse not required
- calibration points allow conversion from I/Q data to probability

Basic qubit characterisation sequences

T2 star (Ramsey time): qubit dephasing time



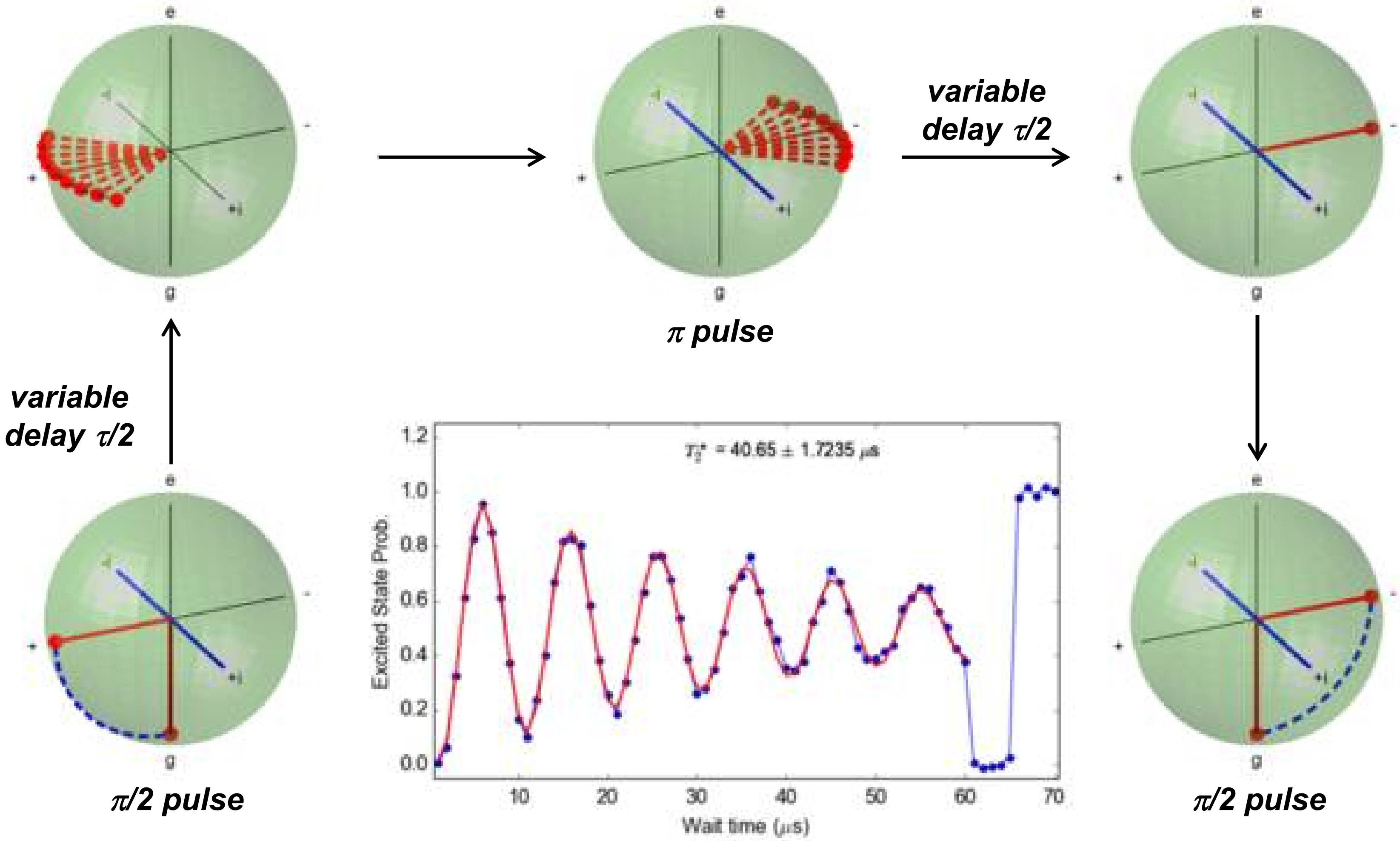
π/2 pulse *π/2 pulse*



- need reasonably well characterised pulse, or the data will look strange
- e.g., frequency detuning can give data outside the range of the calibration points
- artificial detuning allows better fitting of the decay time and frequency
- very versatile sequence with many applications

Basic qubit characterisation sequences

T2 echo: decoupled qubit dephasing time



- insensitive to low-frequency phase noise
- not so sensitive to detuning because of echo effect

Fine-tuning your pulses

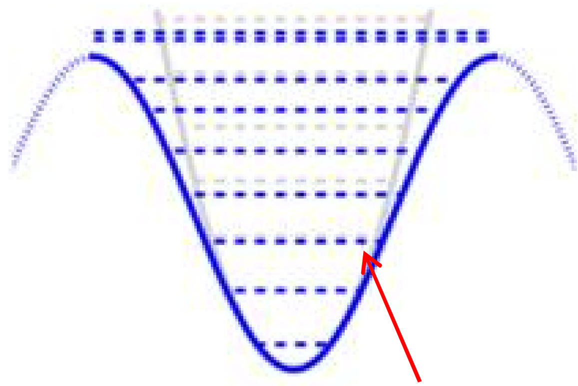
Optimal single-qubit control with DRAG

Fine-tuning your pulses

Optimal single-qubit control with DRAG

- 1-2 transition is quite close to 0-1 transition, especially for short drive pulse durations (~ 10 ns)
- leakage errors: pulses driving qubit into 2 state
- phase errors: qubits temporarily populate 2 state during pulse, leading to phase errors

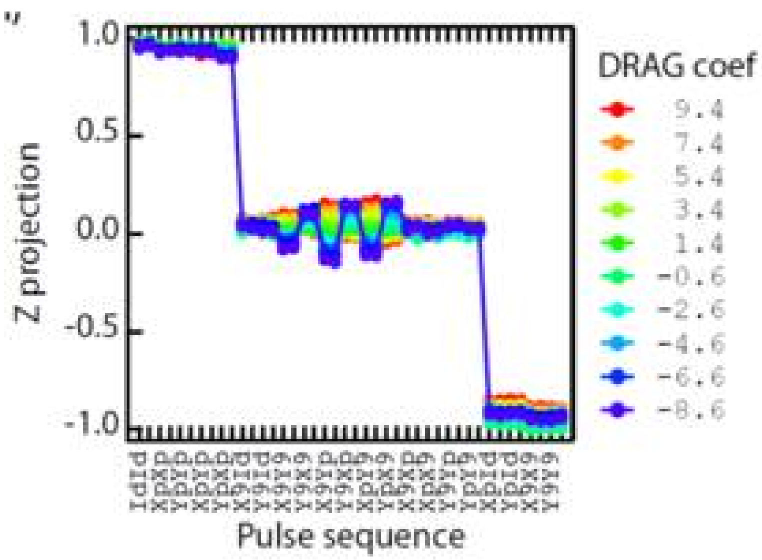
→ use "derivative removal by adiabatic gate (DRAG)



Motzoi *et al.*, PRL (2009)

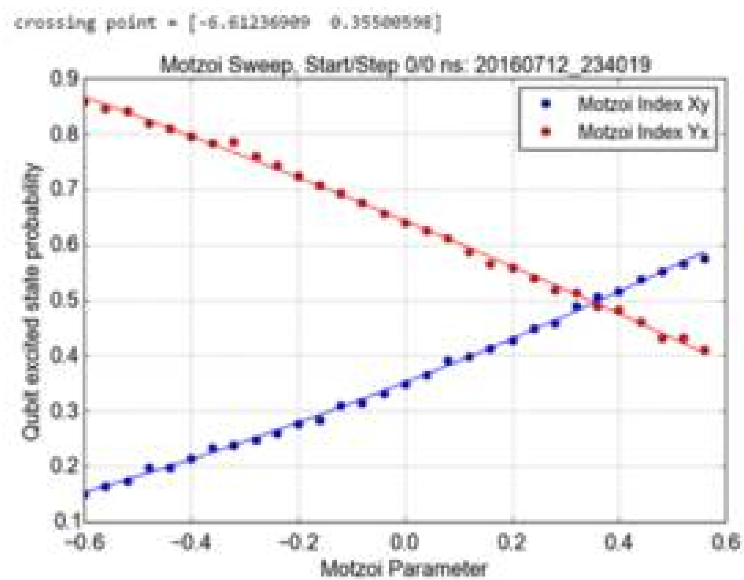
Chow *et al.*, PRA (2010)

AllXY



Reed, PhD thesis, Yale (2013)

MotzoiXY

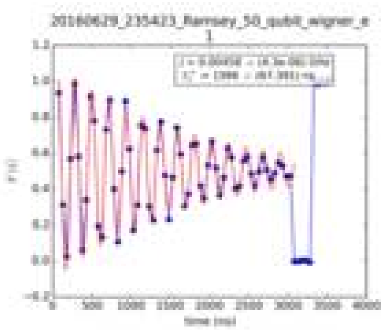


Fine-tuning your pulses

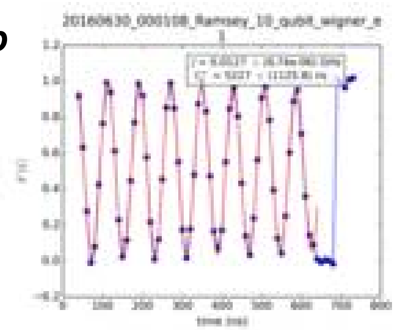
Qubit frequency with Ramseys

- sensitivity to frequency increases with step size
- start small, zooming in after each step, until you reach target accuracy
- robust technique, limited mainly by T2 coherence time

50 ns step

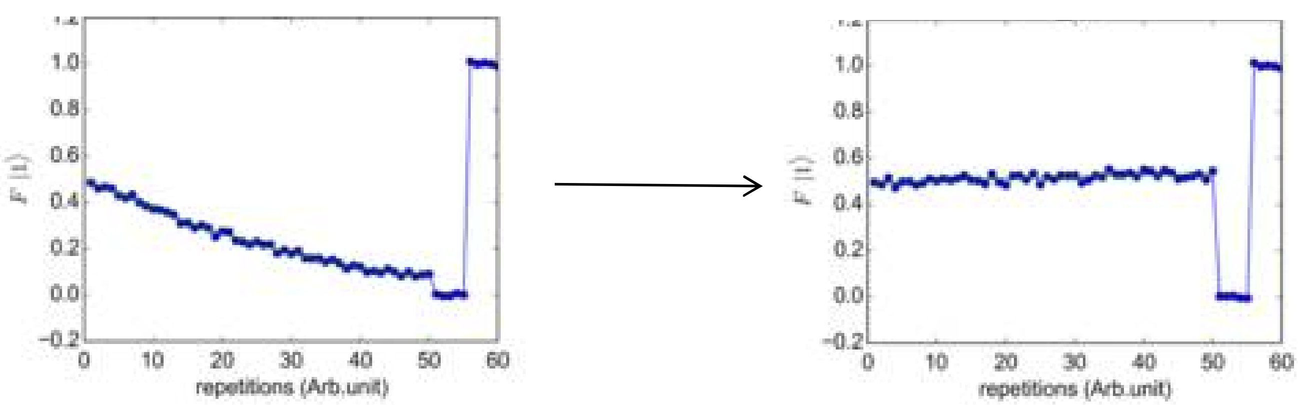


10 ns step



Qubit amplitude with flipping sequences

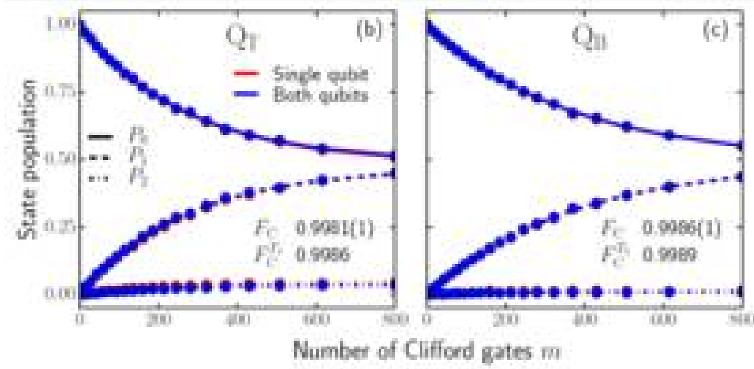
- small amplitude errors may only become significant after many pulses
- diagnosed best with a long pulse sequence



Fine tuning your pulses: going further?

State of the art

These techniques should allow you to get near fidelities sufficient for fault-tolerant single qubit control in surface code.



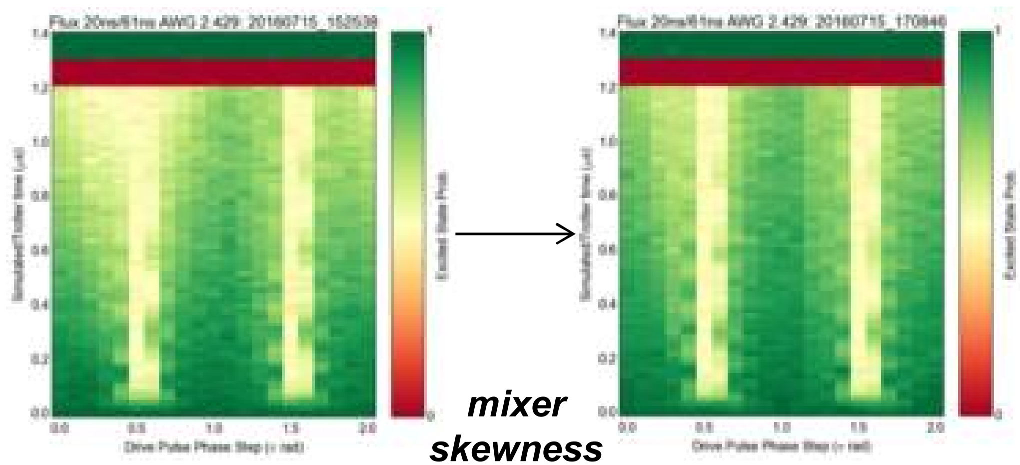
Asaad, Dickel, *et al.*, Nature QI (2016)

Amplifying errors for accurate benchmarking

- Randomized Benchmarking: targets gate errors independently of “preparation-and-measurement” errors; rigorous benchmarking, limited diagnostic capabilities
- Gate-Set Tomography: complete characterisation of everything, long and arduous

Operational approaches

- Your application is the most important yardstick
- Use algorithm specific diagnostics
- Amplify errors that are relevant to your application
- e.g., Martinis benchmarking



OVERVIEW

[redacted]

- Fast frequency tuning: making your qubit dance

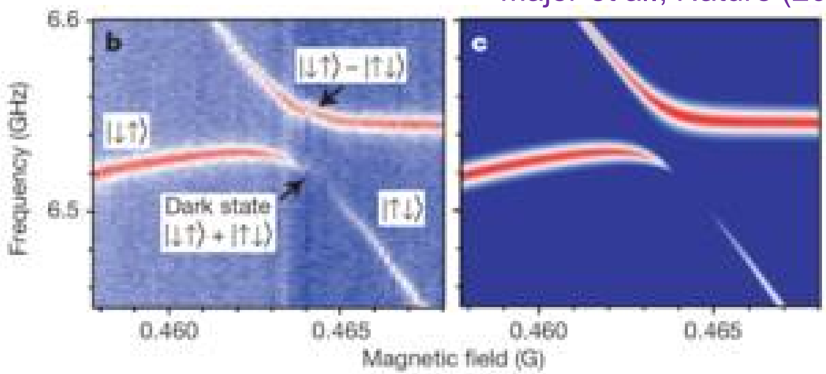
[redacted]

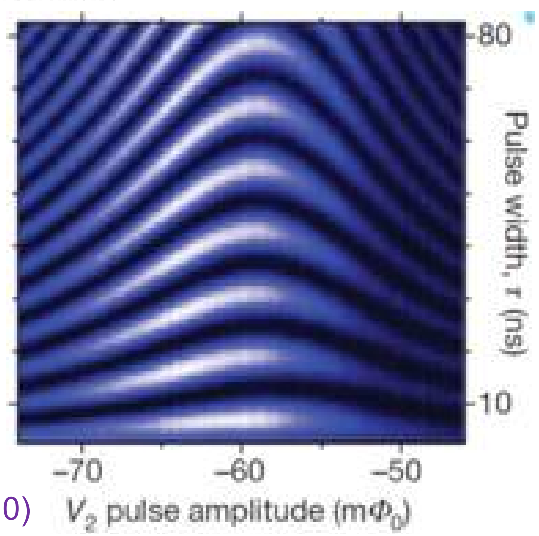
Fast frequency tuning: let's dance!

Why do you want to be able to pulse your qubit frequency?

Controlled excitation swapping with bus resonators and other qubits

Majer et al., Nature (2007)

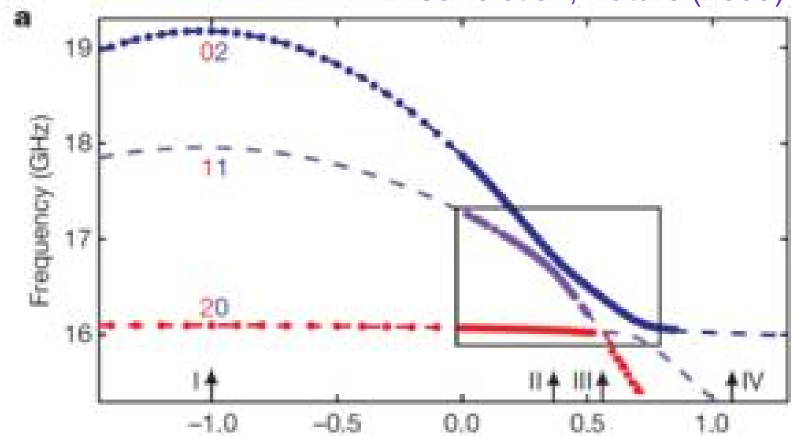




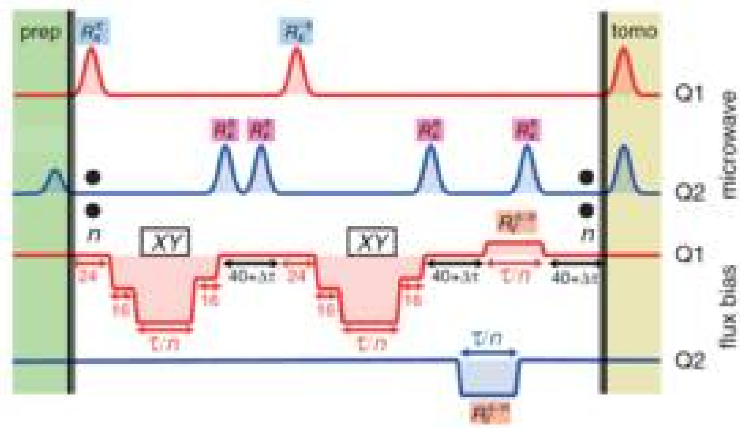
DiCarlo et al., Nature (2010)

Fast qubit-qubit entangling gates and arbitrary interactions

DiCarlo et al., Nature (2009)

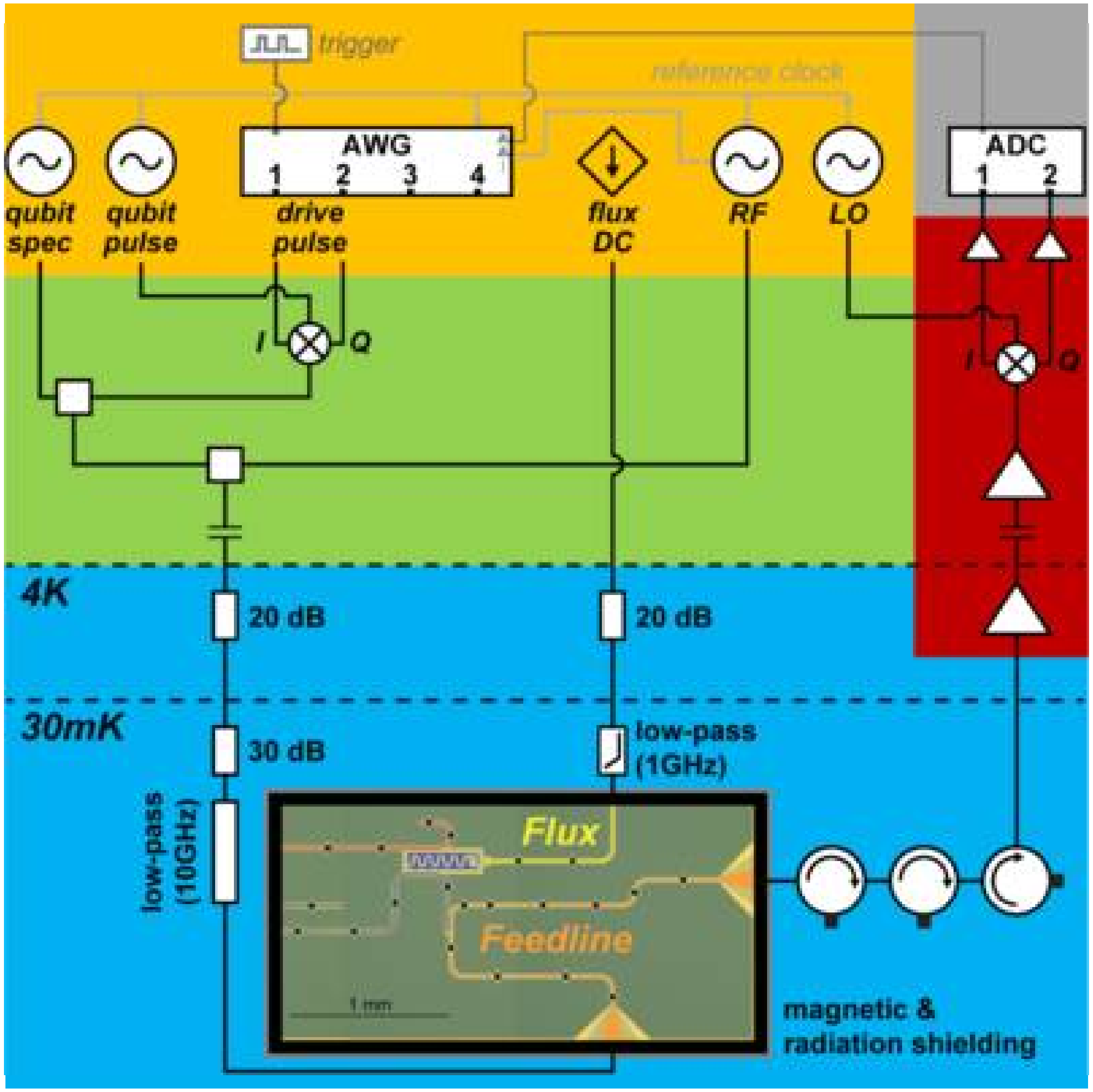


Salathé *et al.*, PRX 2015



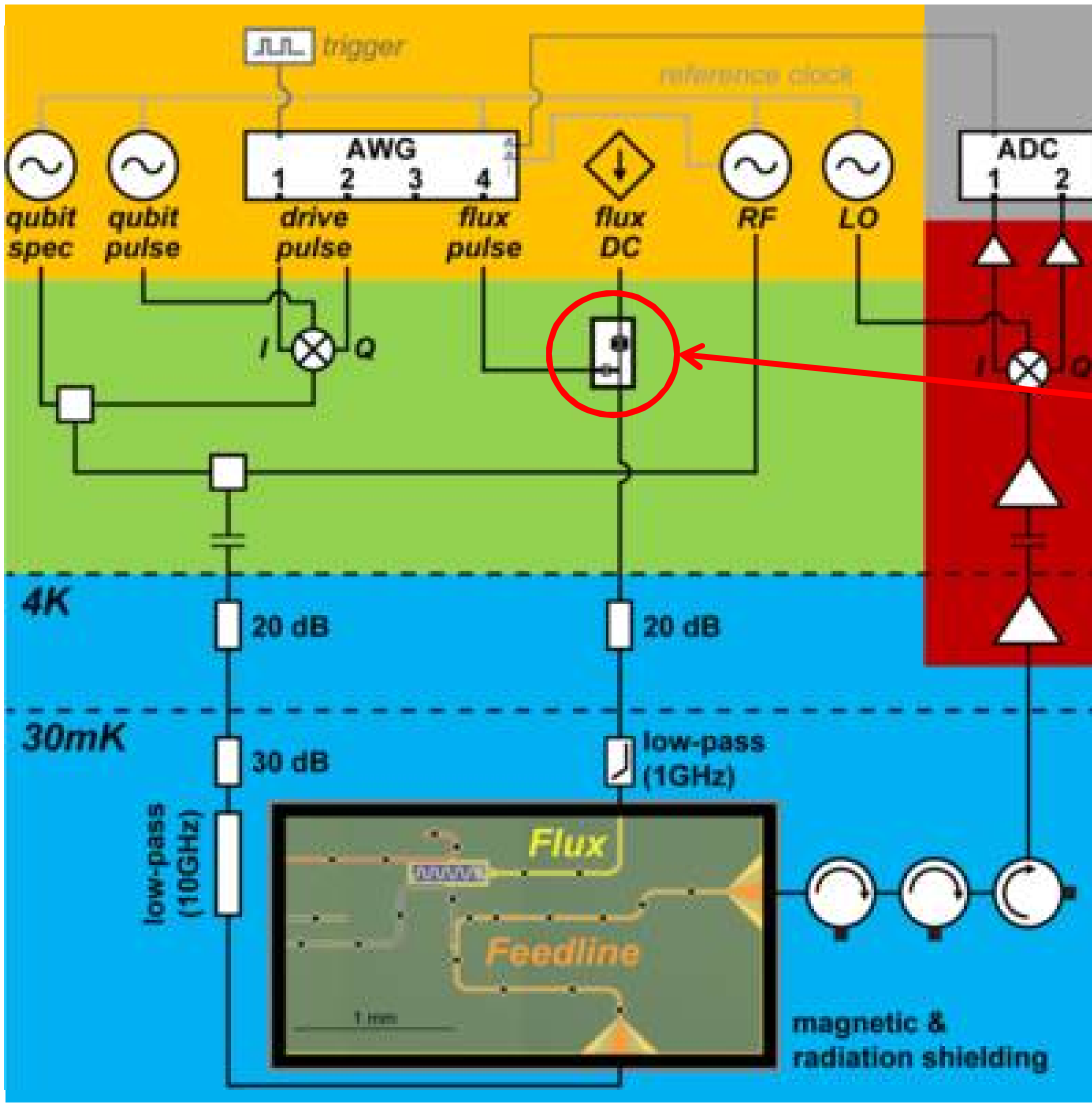
Fast frequency tuning: let's dance!

Microwave setup

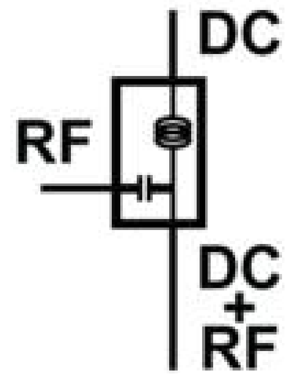


Fast frequency tuning: let's dance!

Microwave setup

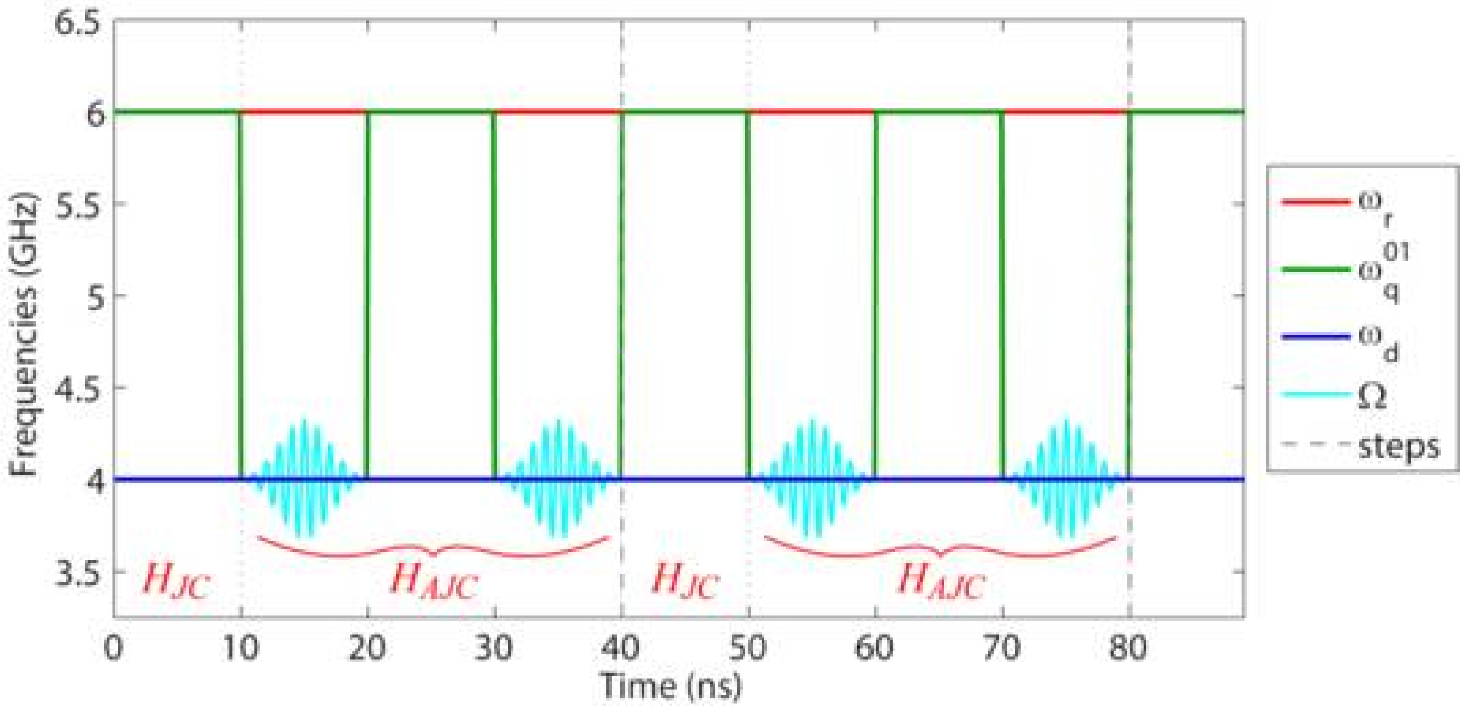


"bias tee"



Fast frequency tuning: a distorted reality

How you want flux pulsing to look



Digital simulation of the quantum Rabi model

Mezzacapo *et al.*, Sci Rep (2014)

Fast frequency tuning: a distorted reality

But what's the real story?

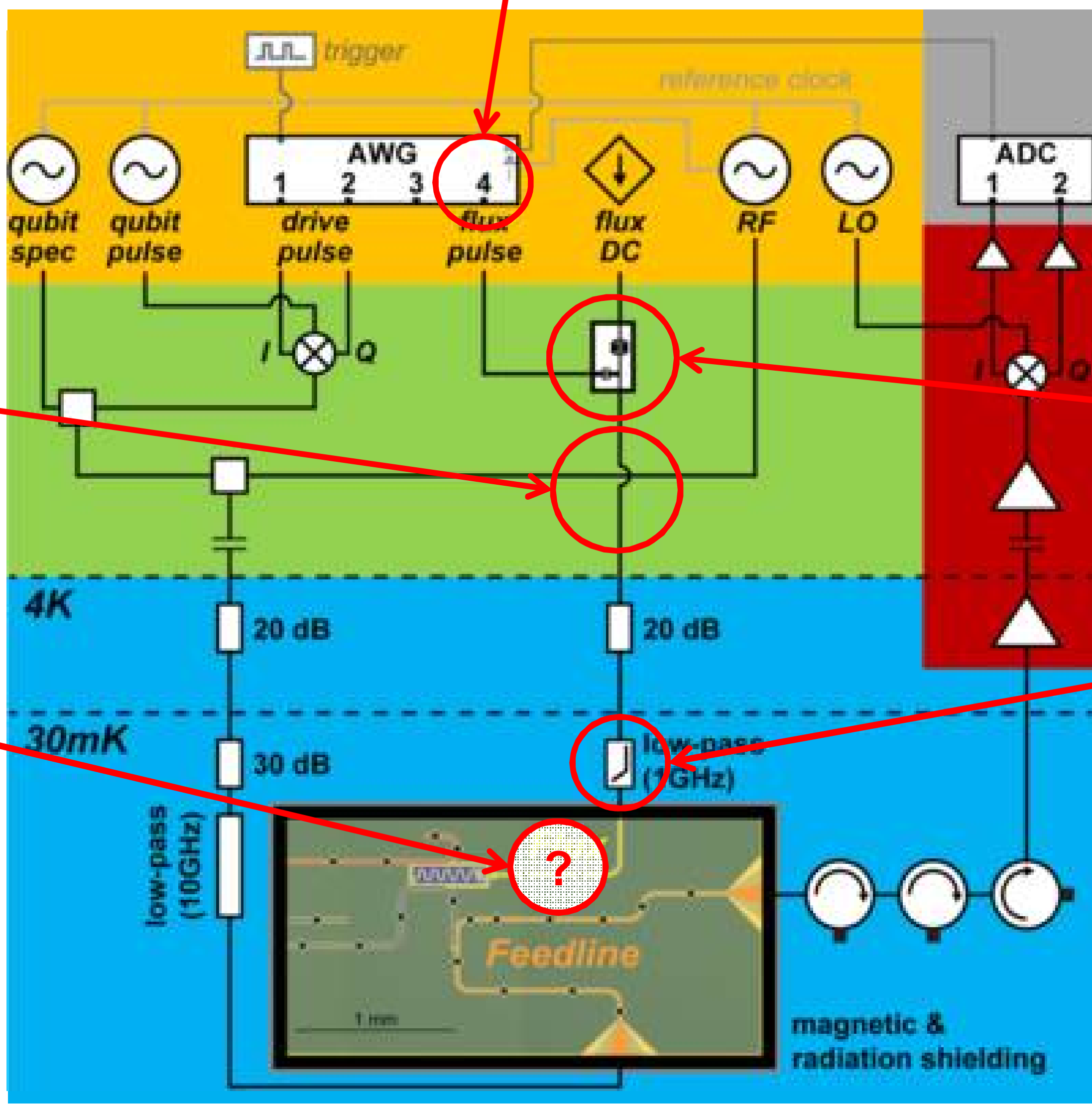
AWG: finite BW, sampling rate, resolution, amplitude

frequency-dependent cable loss (skin effect)

"bias tee"

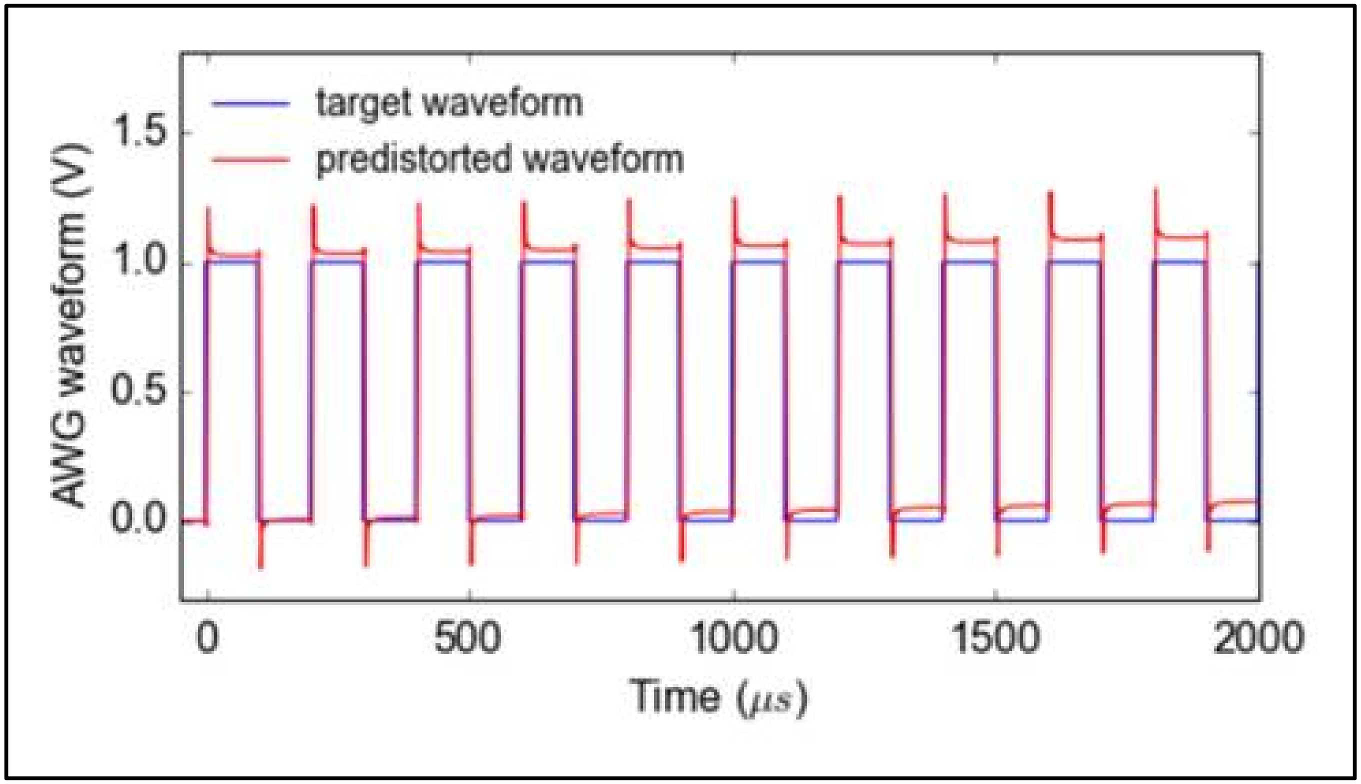
low-pass filtering

on-chip response??



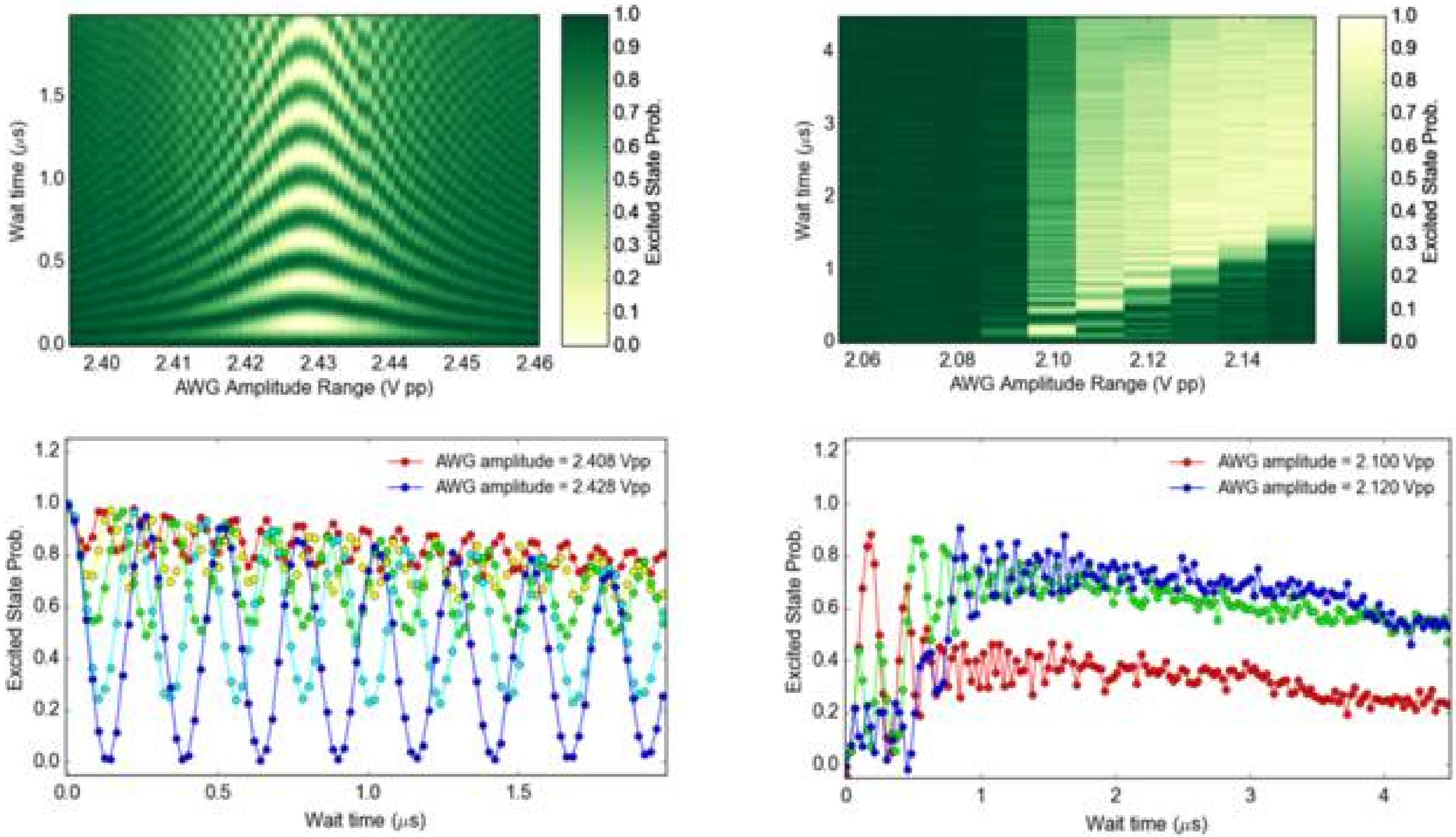
Fast frequency tuning: a distorted reality

Pre-compensating non-ideality with "predistortion" filters



Fast frequency tuning: a distorted reality

Inside the fridge: the qubit is your signal



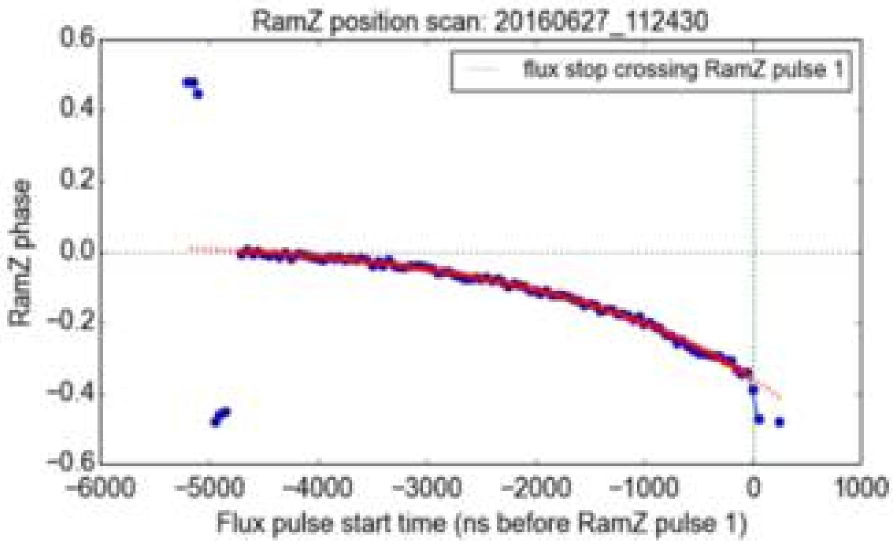
Flux-controlled excitation swapping: the flux chevron

What you see when you first get inside the fridge

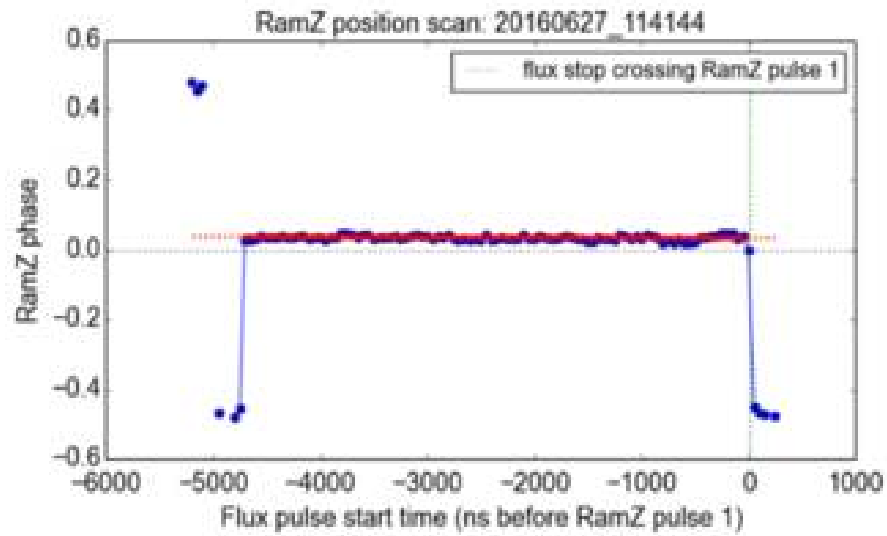
Fast frequency tuning: a distorted reality

RamZ: measuring your flux pulse with a Ramsey sequence

- use a Ramsey pulse pair to sense residual frequency error after the down step of a flux pulse
- increase/decrease pulse separation to control detector sensitivity
- adjust step size to probe different timescales



RamZ signal measuring an on-chip flux response



RamZ signal after applying a flux correction

Engineering the quantum

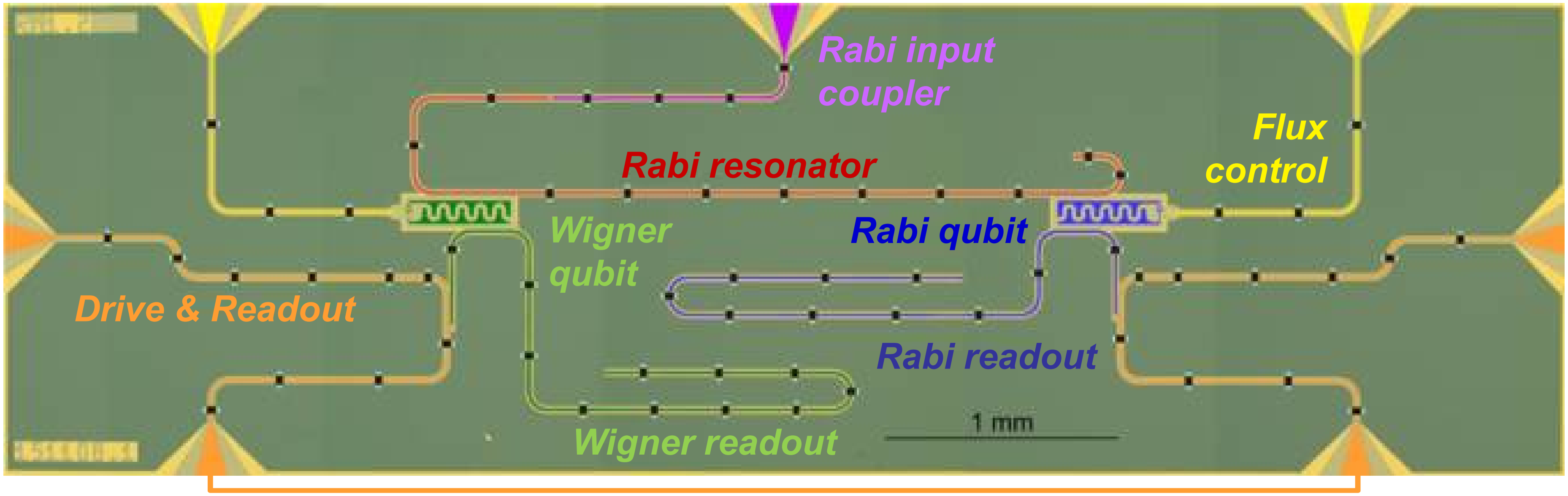
OVERVIEW

[redacted]

- Using your qubit as a…

Using your qubit as a… photon meter

Measurement of a bus resonator via an ancilla "meter" qubit



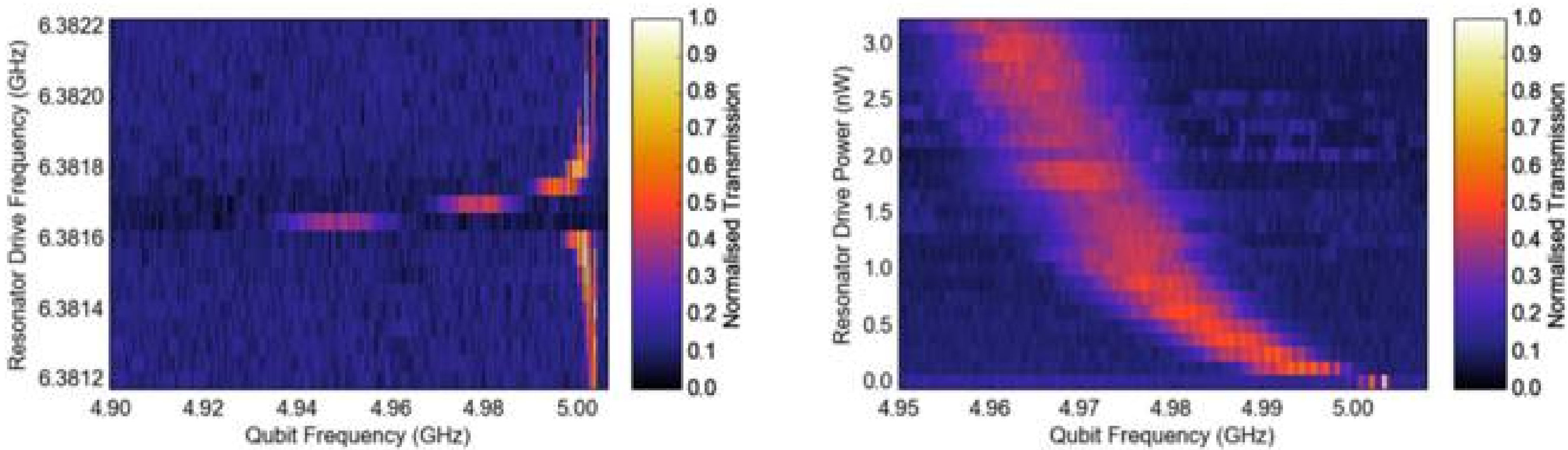
Langford, *et al.*, in preparation (2016)

- study interaction between "Rabi" qubit and (quarter-wave) "Rabi" resonator
- measure Rabi qubit directly and measure Rabi resonator via the "Wigner" qubit
- resonator could be loaded with photons via resonant interaction with the Rabi qubit (g ~ 2 MHz) and coherently driven via a classical input line
- Wigner qubit strongly coupled (~ 70 MHz) but dispersively (detuning ~ 1.4 GHz)
- Wigner qubit state read out independently using a dedicated readout resonator

Using your qubit as a… photon meter

Photon-dependent qubit frequency: the ac Stark effect

Schuster *et al.*, PRL 2005



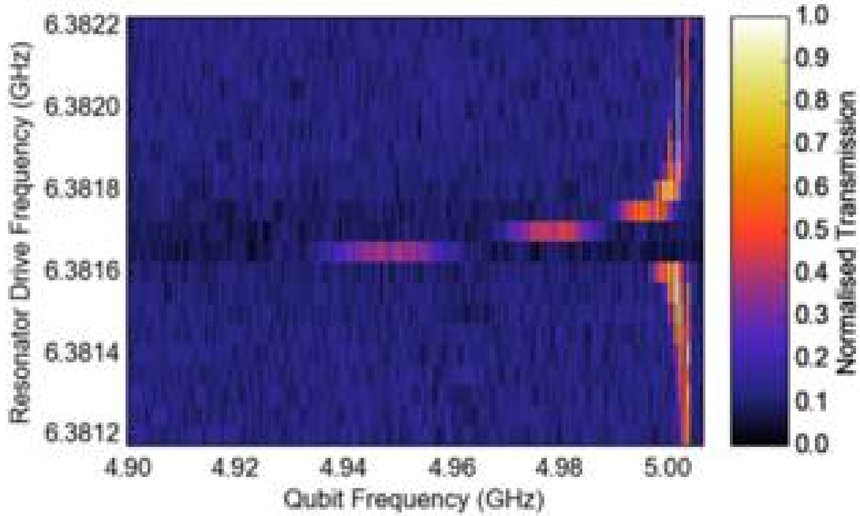
Dispersive-regime Hamiltonian

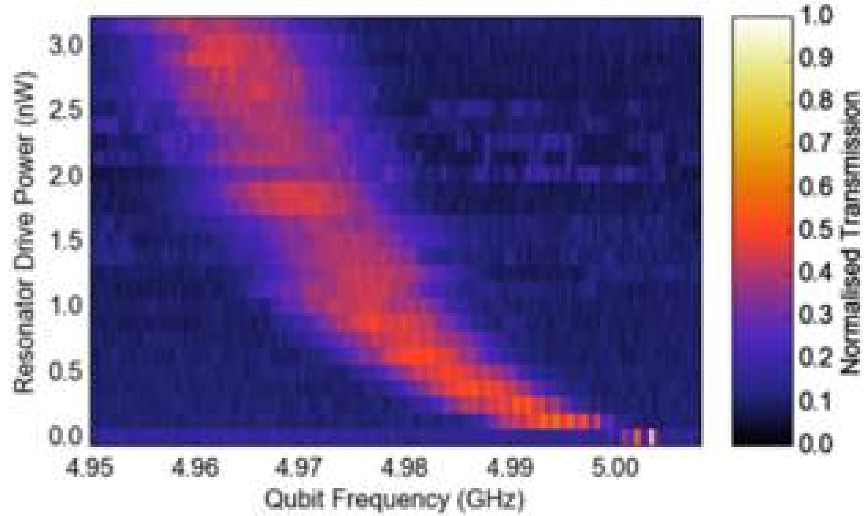
$$H = \hbar\omega_r\, a^\dagger a + \tfrac{1}{2}\hbar\omega_q\,\sigma_z + \hbar\chi\,\sigma_z\, a^\dagger a = (\hbar\omega_r + \hbar\chi\,\sigma_z)\, a^\dagger a + \tfrac{1}{2}\hbar\omega_q\,\sigma_z$$

Using your qubit as a… photon meter

Photon-dependent qubit frequency: ac Stark effect

Schuster *et al.*, PRL 2005





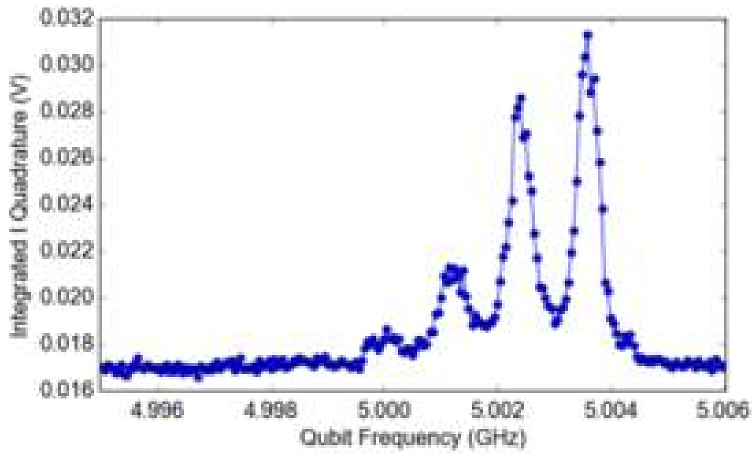
Dispersive-regime Hamiltonian

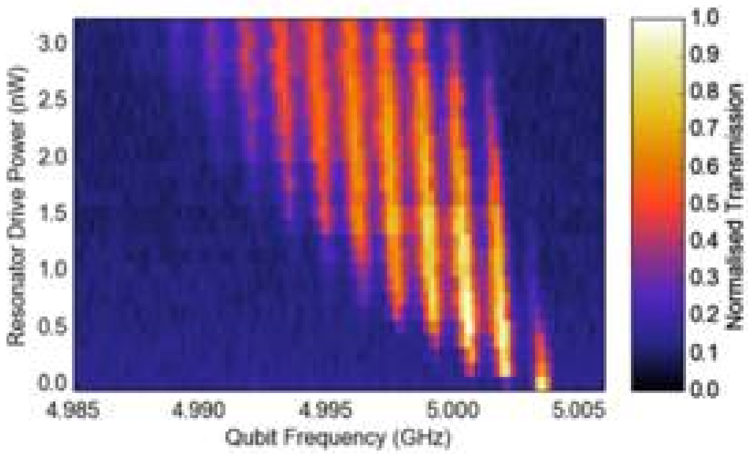
$$H = \hbar\omega_r\, a^\dagger a + \tfrac{1}{2}\hbar\omega_q\, \sigma_z + \hbar\chi\, \sigma_z\, a^\dagger a = \hbar\omega_r\, a^\dagger a + \tfrac{1}{2}(\hbar\omega_q + \hbar 2\chi\, a^\dagger a)\, \sigma_z$$

$$\chi = \frac{g^2\alpha}{\Delta(\Delta+\alpha)} \quad \alpha = \text{ anharmonicity}$$

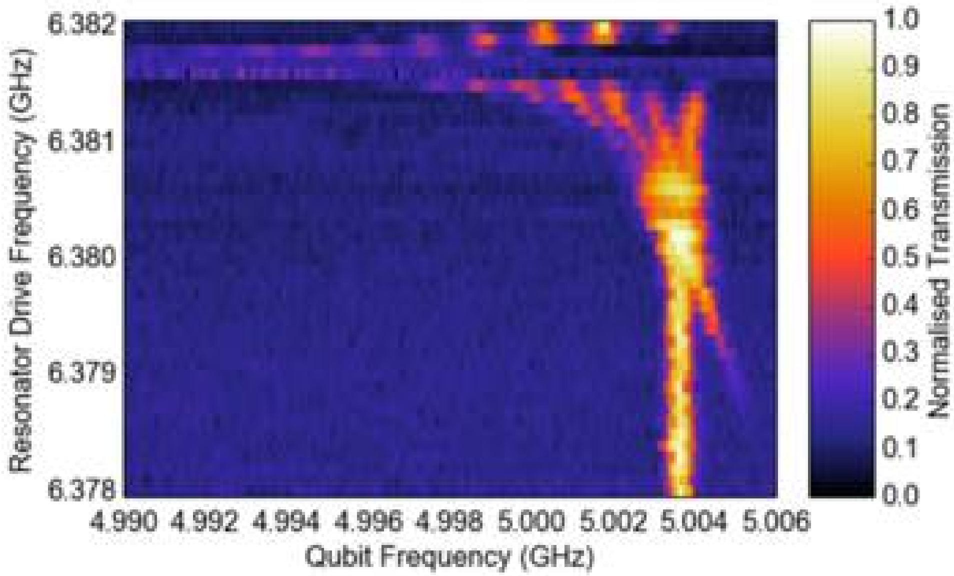
Using your qubit as a… photon meter

Photon-number splitting of the qubit peak





Size of dispersive shift depends on how photons are created !!

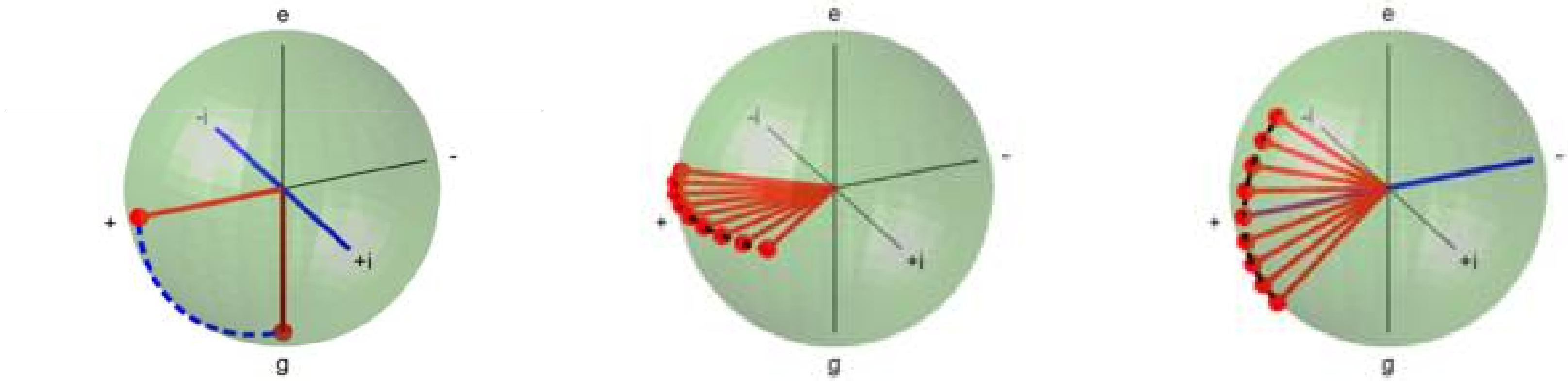


- chi varies linearly with drive frequency
- the standard value is only true on resonance (dressed-state frequency)
- chi -> 0 at bare resonator frequency minus cavity shift

Gambetta *et al.*, PRA 2006

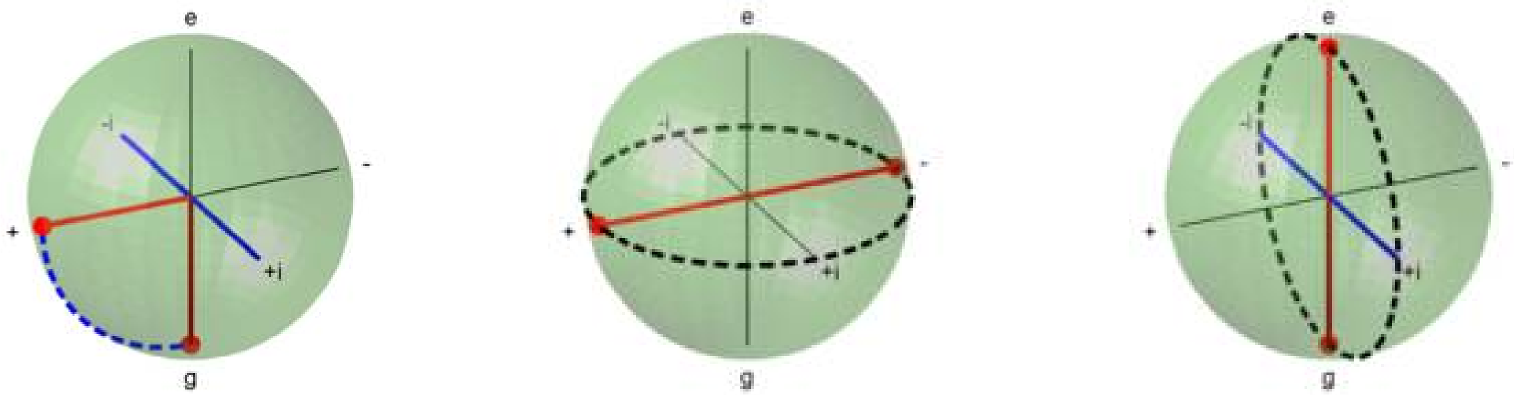
Using your qubit as a… photon meter

Ramsey-based average photon meter



***π*/2 pulse** | **delay *τ* (sets range)** | ***π*/2 pulse**

Ramsey-based parity meter



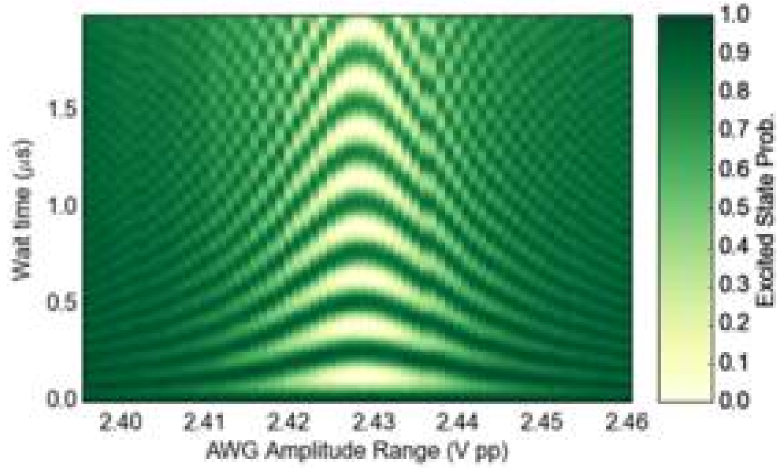
***π*/2 pulse** | **delay $\tau = 1/4\chi$** | ***π*/2 pulse**

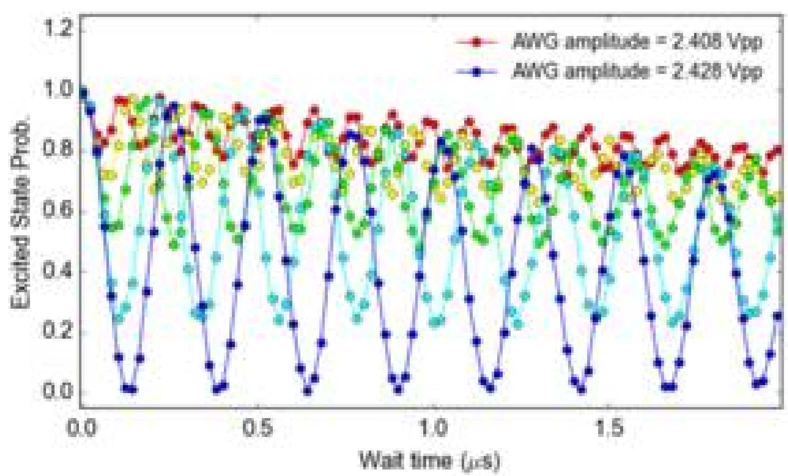
Bertet *et al*., PRL (2002), Risté *et al.*, Nat Comm (2013), Vlastakis *et al.*, Science (2013)

Using your qubit as a… photon meter

The dark (bright?) side of qubit-resonator "chevrons"

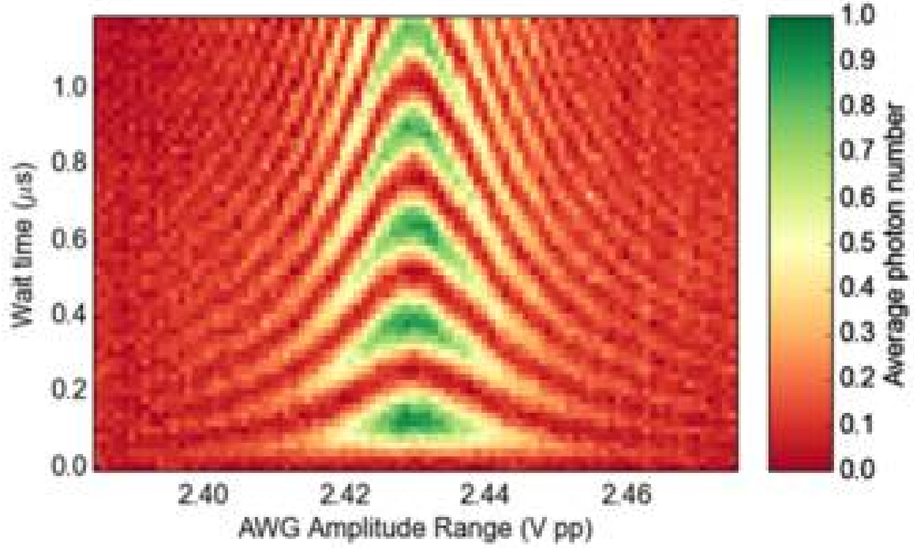
Recall qubit "chevron":

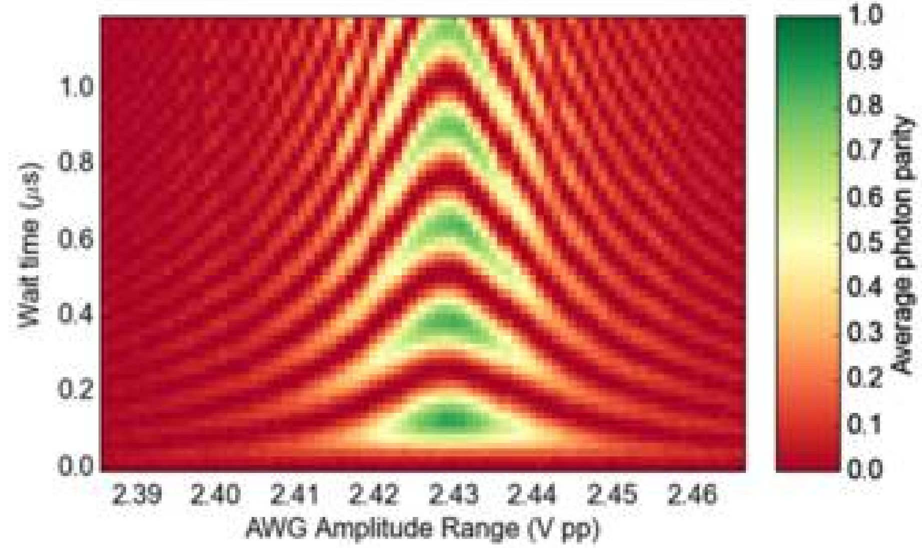




Using your qubit as a… photon meter

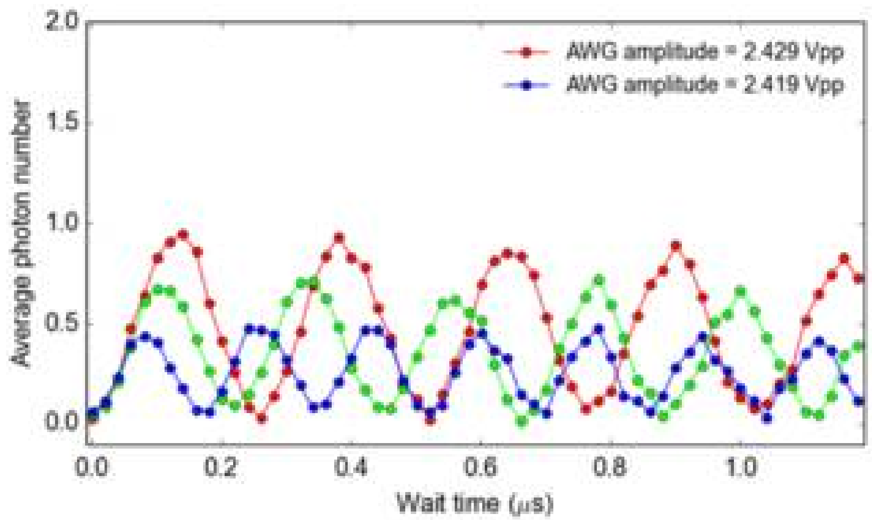
The dark (bright?) side of qubit-resonator "chevrons"

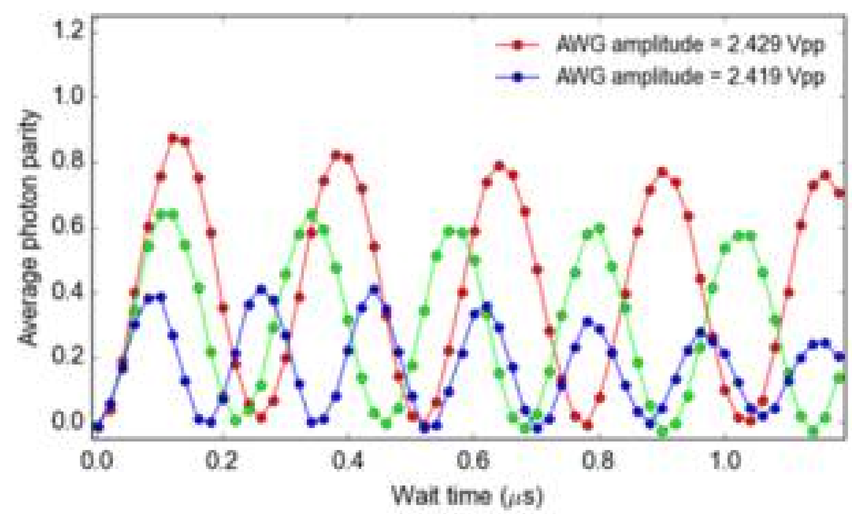




photon meter

parity meter

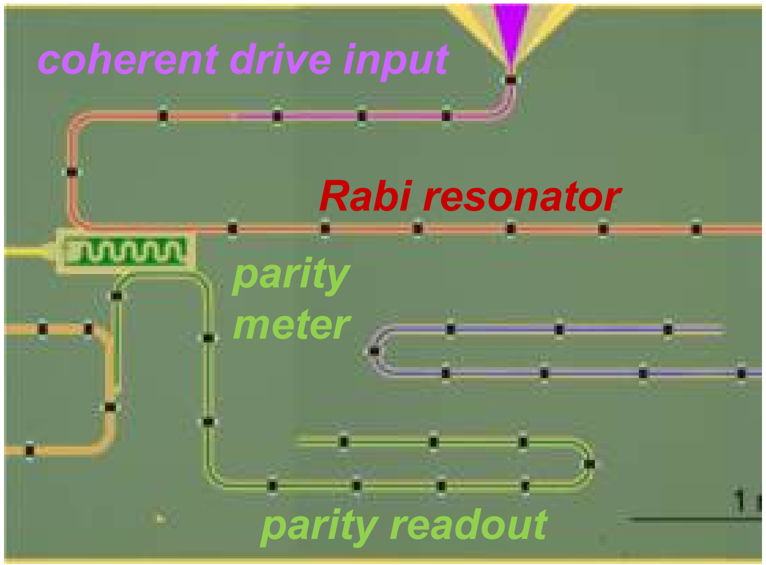




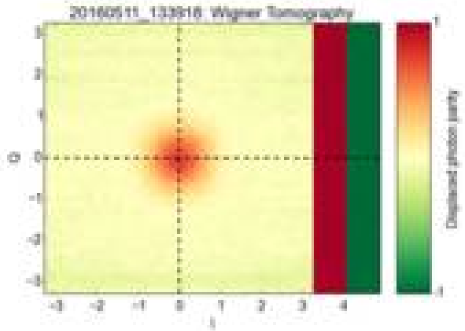
Using your qubit as a… photon meter

Direct Wigner tomography via a parity measurement

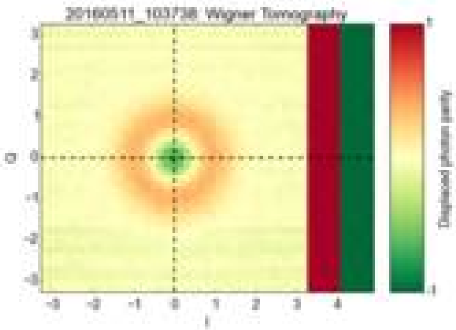
- requires resonator input coupler for displacement pulse
- ancilla qubit for parity operation and readout



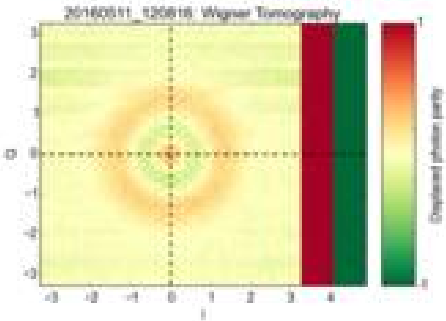
$$W(\alpha\,|\,\rho) = \frac{2}{\pi}\,\mathrm{Tr}\left[\Pi D(\alpha)^{\dagger}\rho D(\alpha)\right]$$



zero photons



one photon



two photons

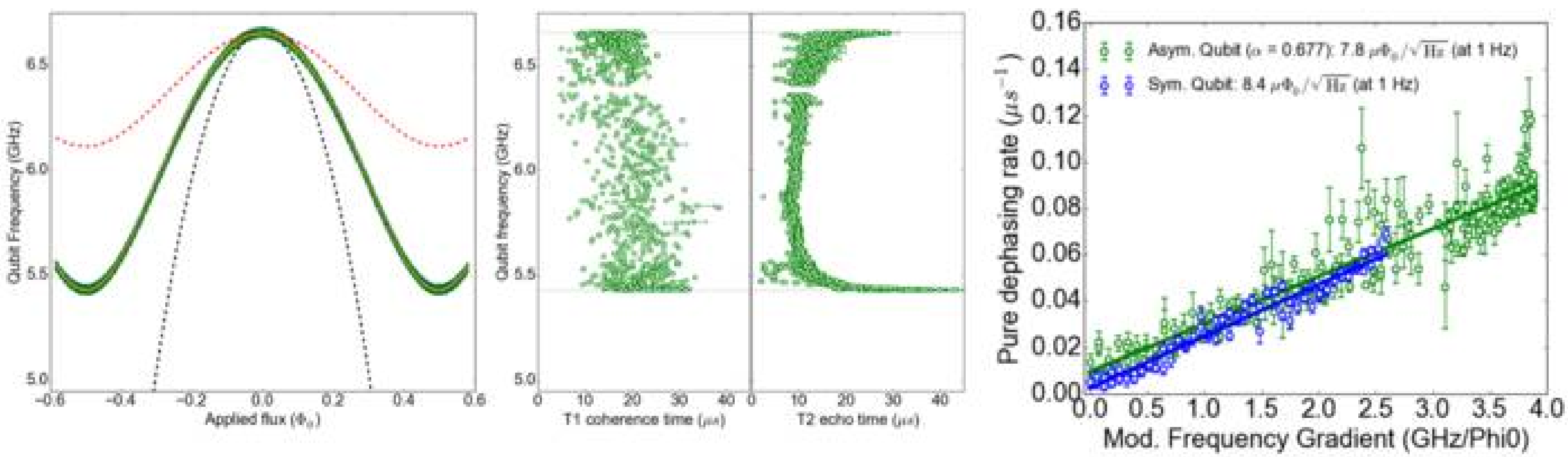
Bertet *et al*., PRL (2002), Vlastakis *et al.*, Science (2013)

Using your qubit as a… noise spectrum analyser

Measuring flux noise

- tuning a qubit away from its sweet spot increases its sensitivity to flux noise
- T1 and T2 echo measurements give estimate of pure dephasing

$$\frac{1}{T_2^{\varphi}} = \frac{1}{T_2^{\text{echo}}} - \frac{1}{2T_1}$$



From the change in pure dephasing with flux gradient, can calculate 1/f flux noise:

$$\frac{1}{T_\varphi} = A\Phi_0 \ln\left(\frac{T}{t}\right)\frac{d\omega}{d\Phi}$$

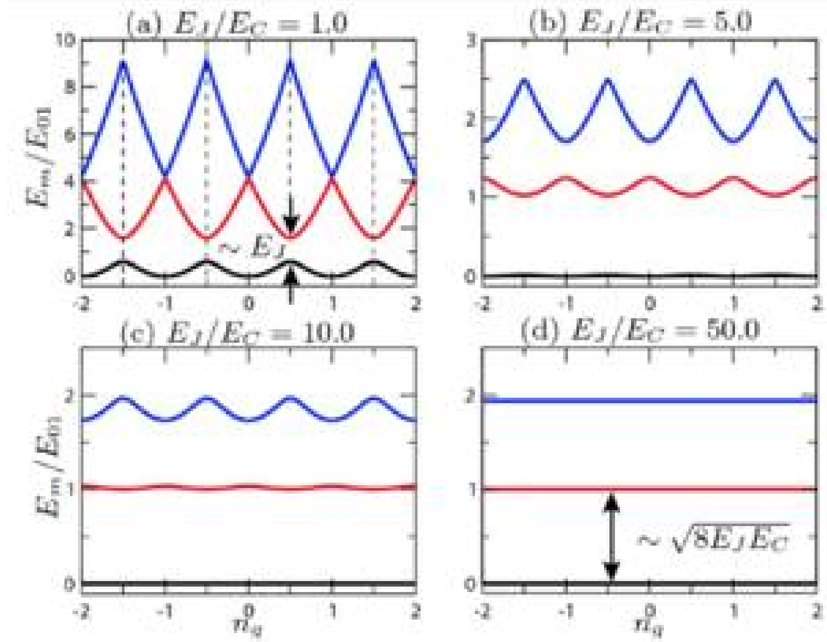
A = 1/f flux noise @ 1 Hz

$$\left(S_\Phi(f) = \frac{A^2\Phi_0^2}{f}\right)$$

Using your qubit as a… noise spectrum analyser

Measuring charge noise

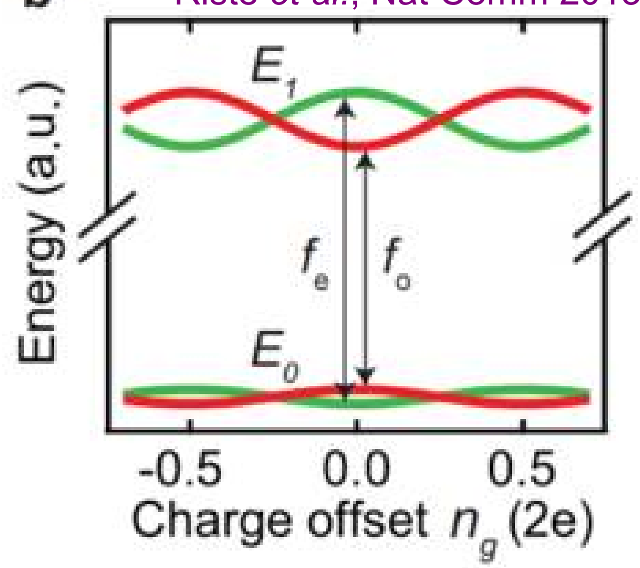
- in transmons, charge noise is exponentially suppressed with increasing E_J/E_C
- environmental charge noise causes qubit to wander along the offset charge axis
- transmon dipole oscillations mediated by Cooper pair tunnelling through junction
- quasiparticle (unpaired electron) tunnelling events shifts energy curves by half a pair
- this causes shot-to-shot switching between two frequencies, which shows up as beating in a Ramsey experiment and can be tracked

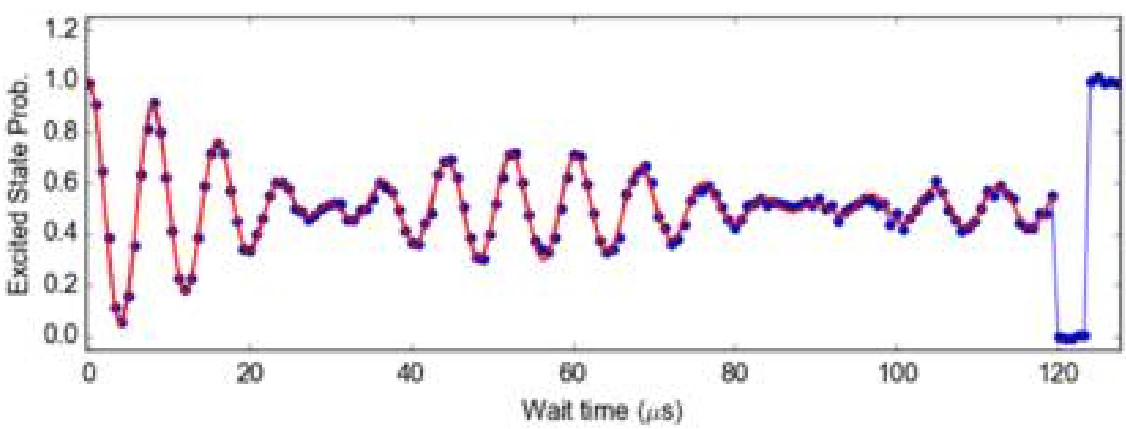


Koch *et al.*, PRA 2007 (transmon bible)

b

Risté *et al.*, Nat Comm 2013





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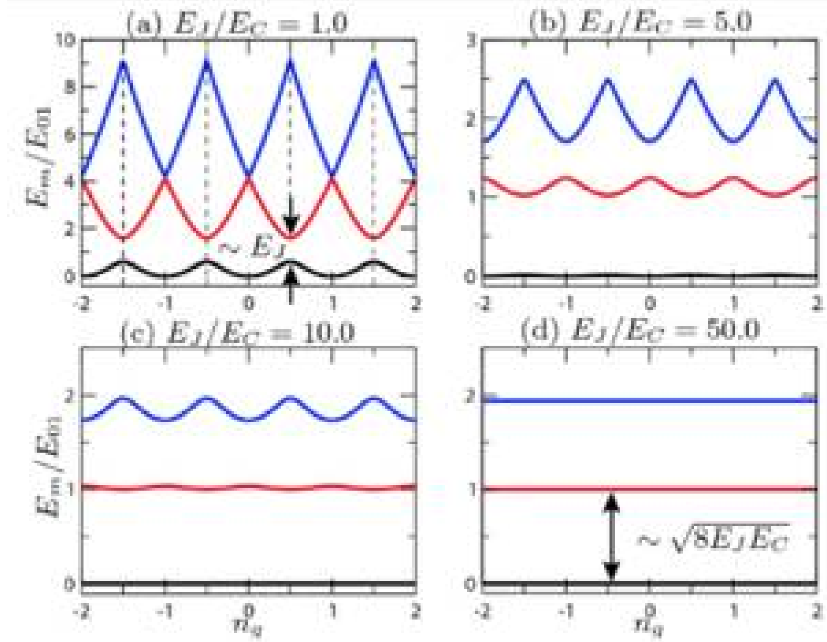

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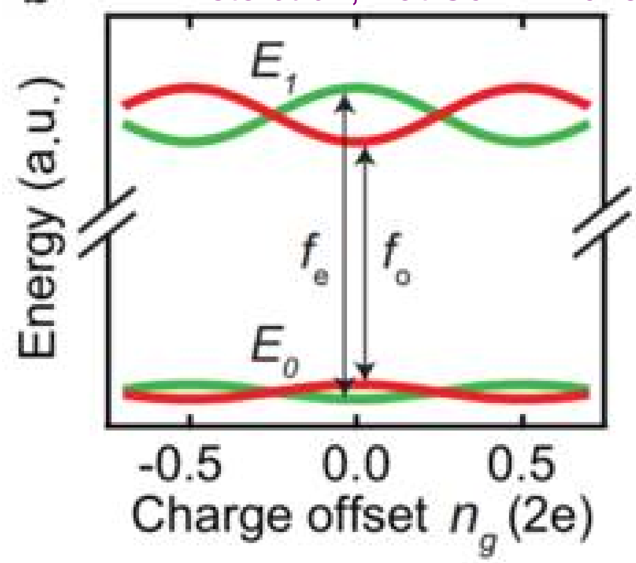
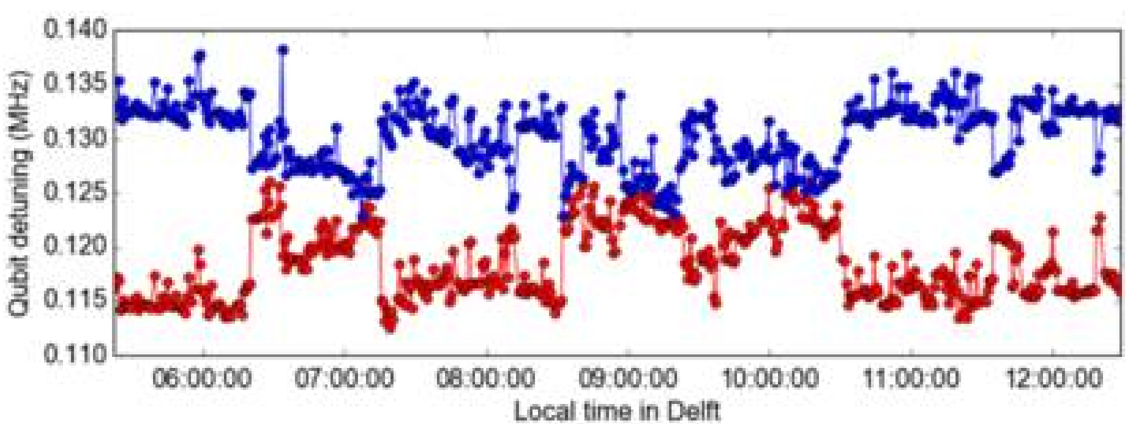


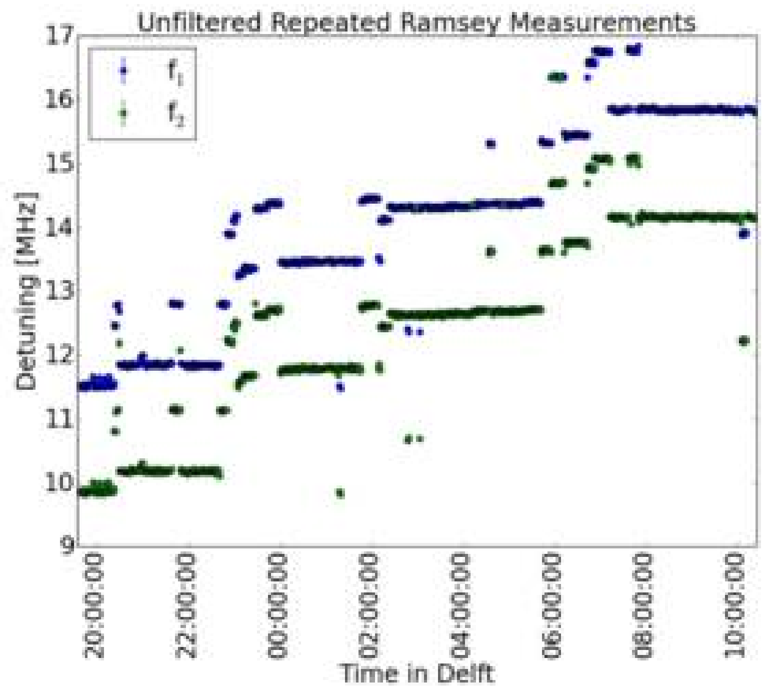


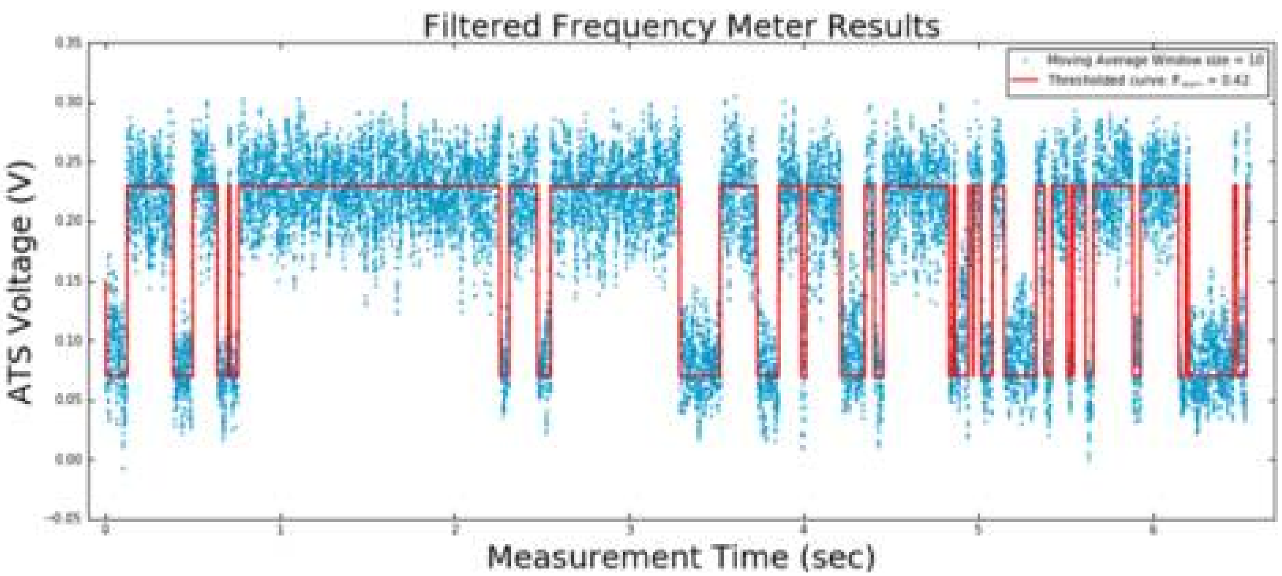
Using your qubit as a… noise spectrum analyser

Courtesy of F. Luthi, T. Stavenga (2016)

Charge noise in a nanowire "dmon"

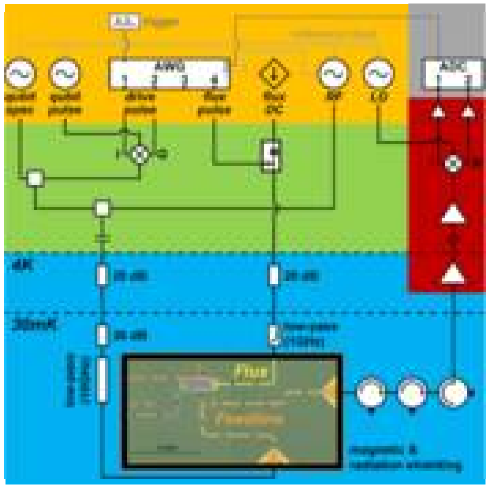
- shows very different noise behaviour from the standard SIS junction transmon
- conduction channels in the semiconductor nanowire may be very sensitive to environmental charges
- exact source of frequency noise unknown
- we use a parity meter to study the shot-to-shot switching dynamics

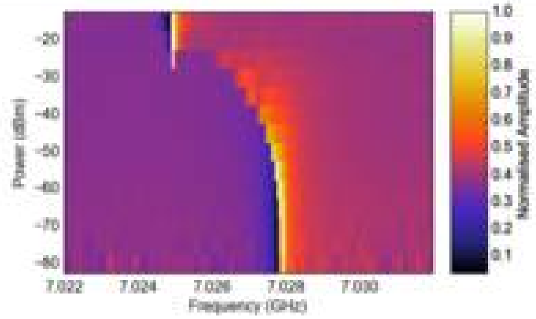


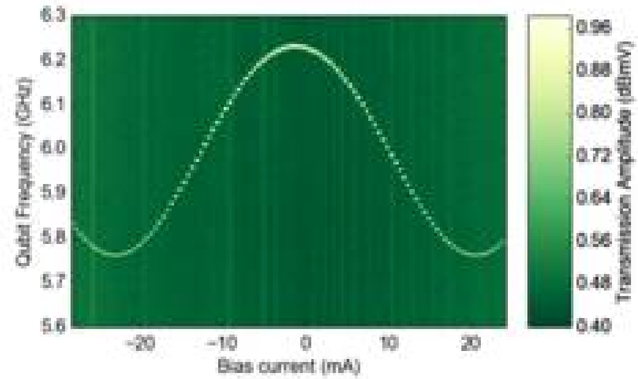


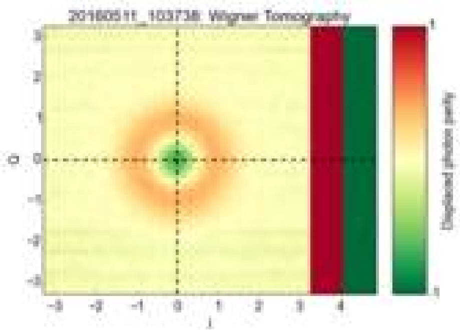
random telegraph noise

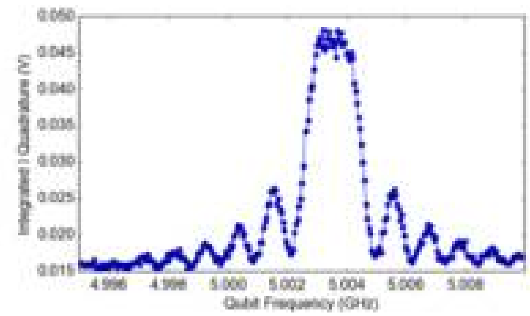
Summary in pictures…

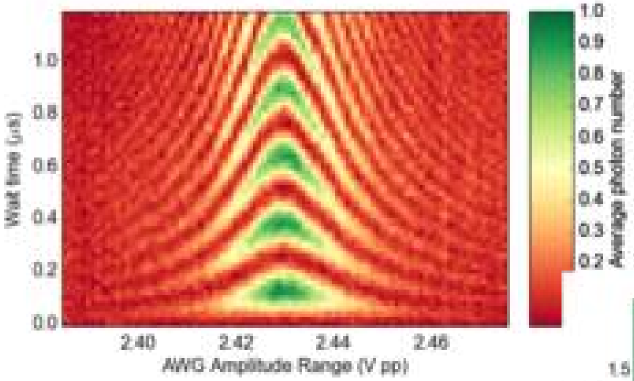


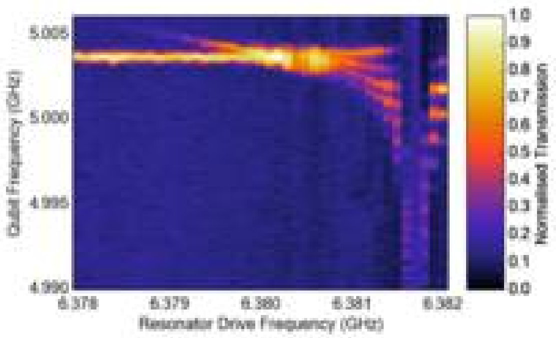


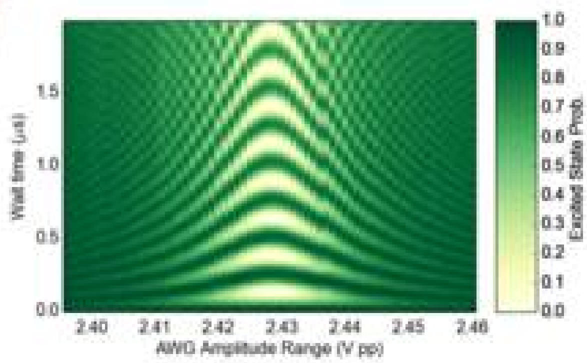


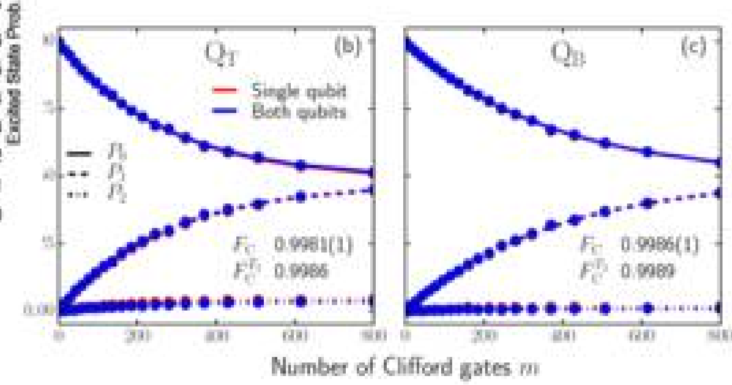












Bonus Slides!!

[redacted]

[redacted]

Asymmetric qubits and why you might want 'em…

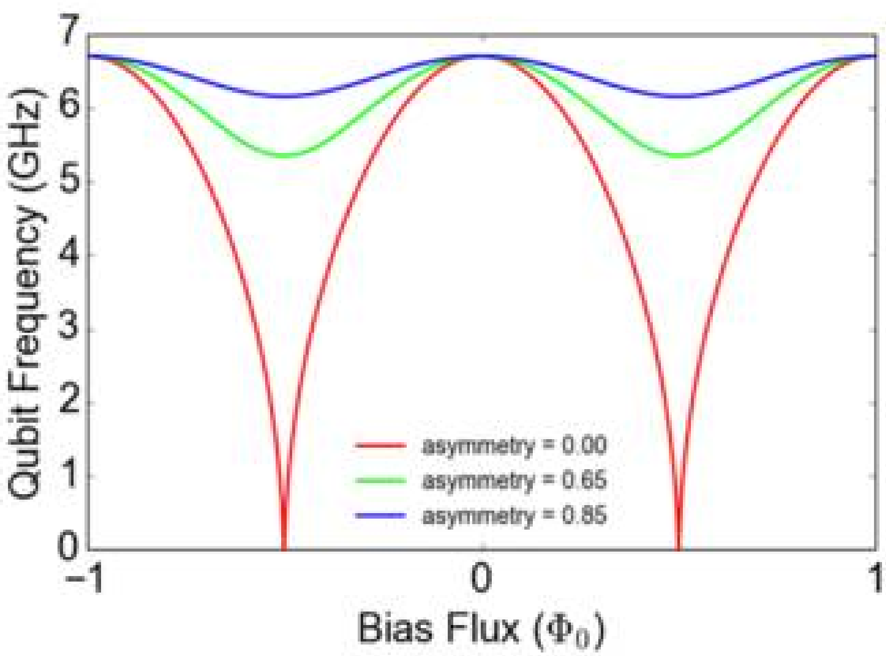
Effect of mismatched junctions on qubit frequency

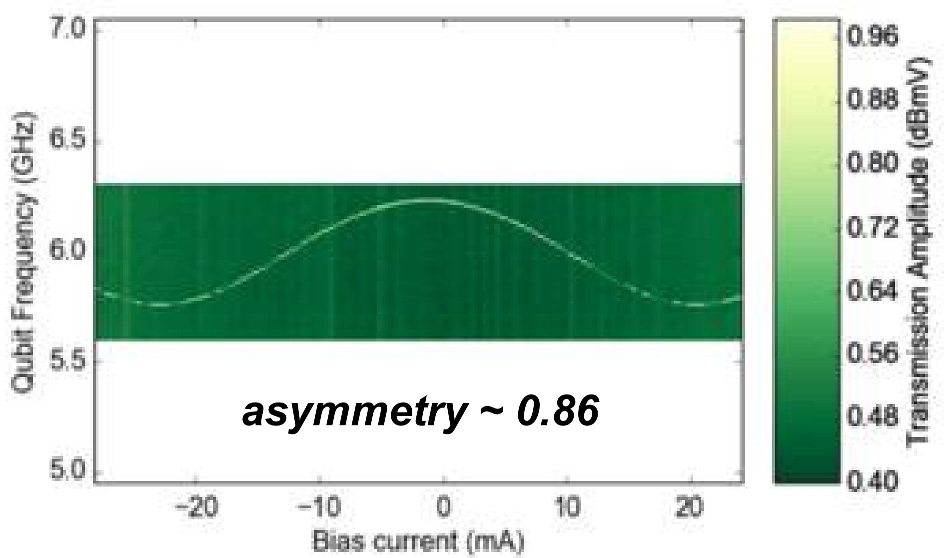
- matched junctions ($E_{J1} = E_{J2}$):

$$f_{\mathrm{q}} = (f_{\mathrm{q}}^{\max} + E_{\mathrm{C}})\sqrt{|\cos(\pi\Phi/\Phi_0)|} - E_{\mathrm{C}}$$

- mismatched junctions ($E_{J1} > E_{J2}$):

$$f_{\mathrm{q}} = (f_{\mathrm{q}}^{\max} + E_{\mathrm{C}})\left[\alpha^2 + (1-\alpha^2)\cos^2(\pi\Phi/\Phi_0)\right]^{1/4} - E_{\mathrm{C}}$$





Asymmetric qubits and why you might want 'em…

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- mismatched junctions ($E_{J1} < E_{J2}$):

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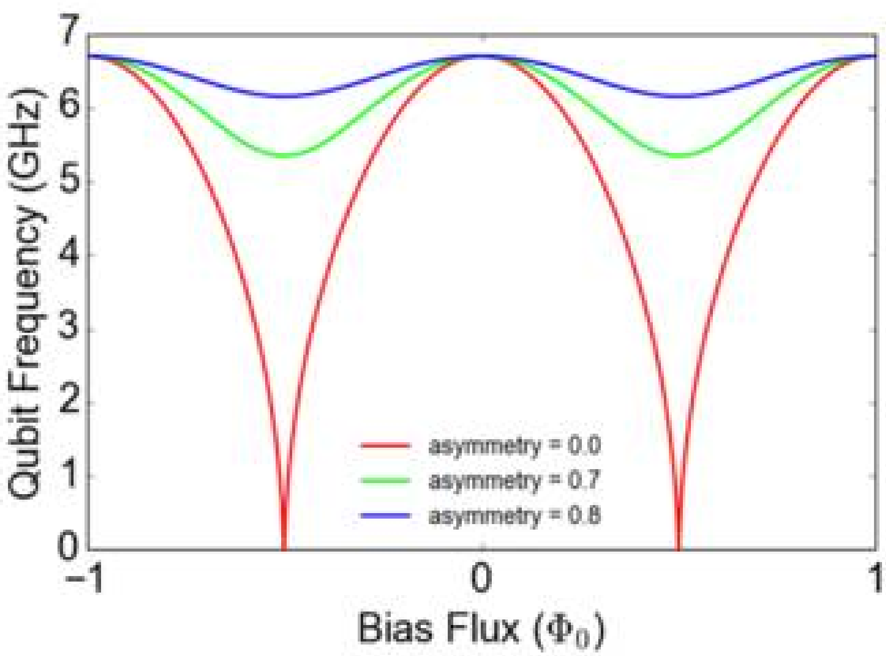

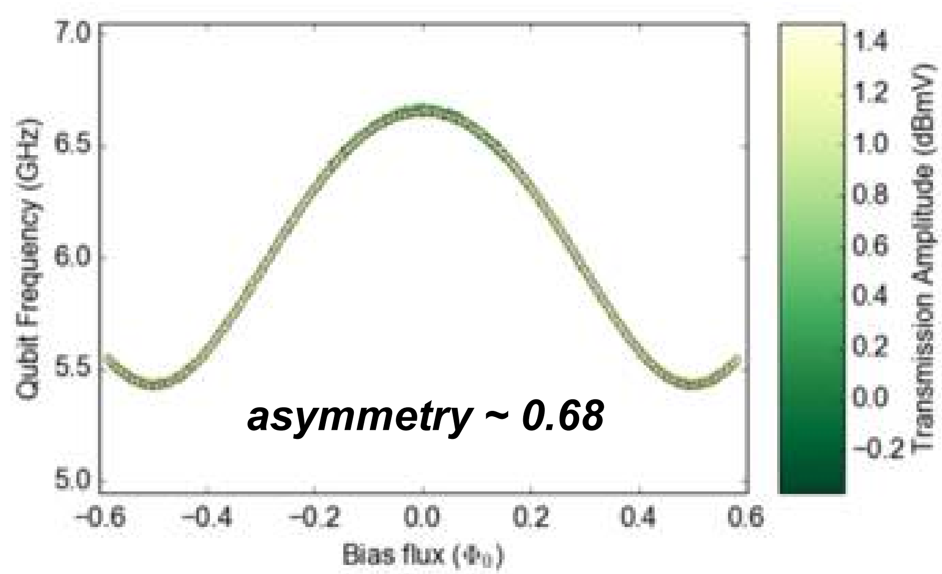

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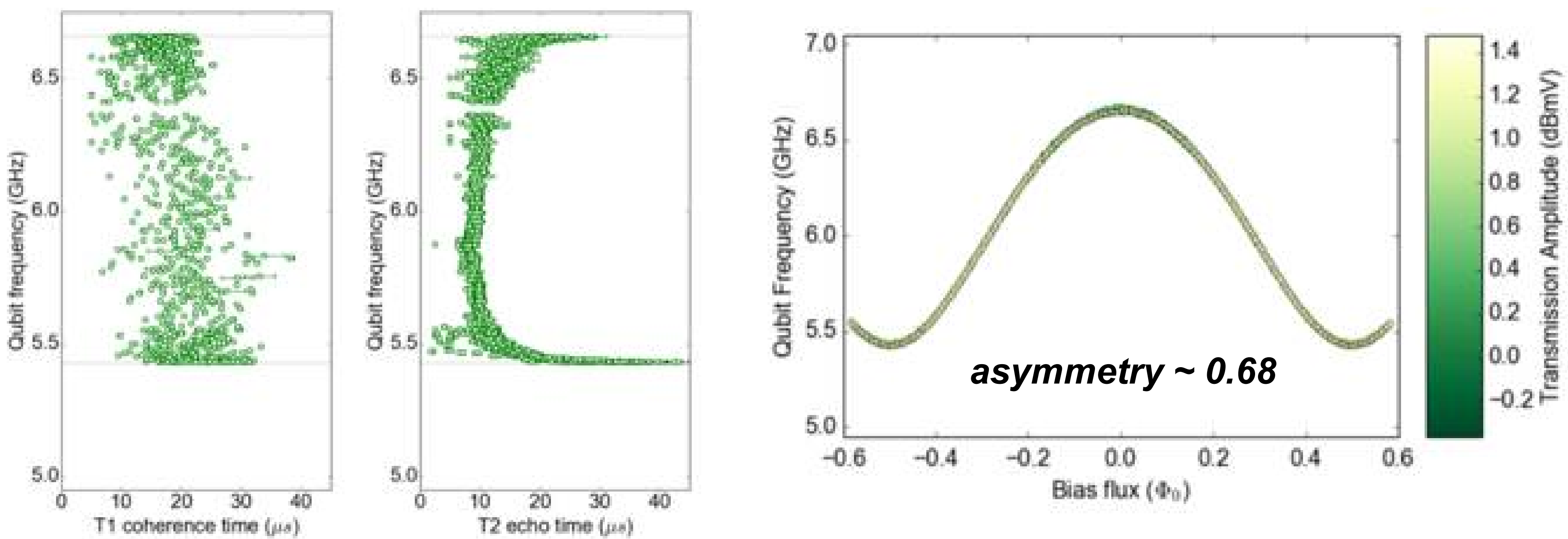
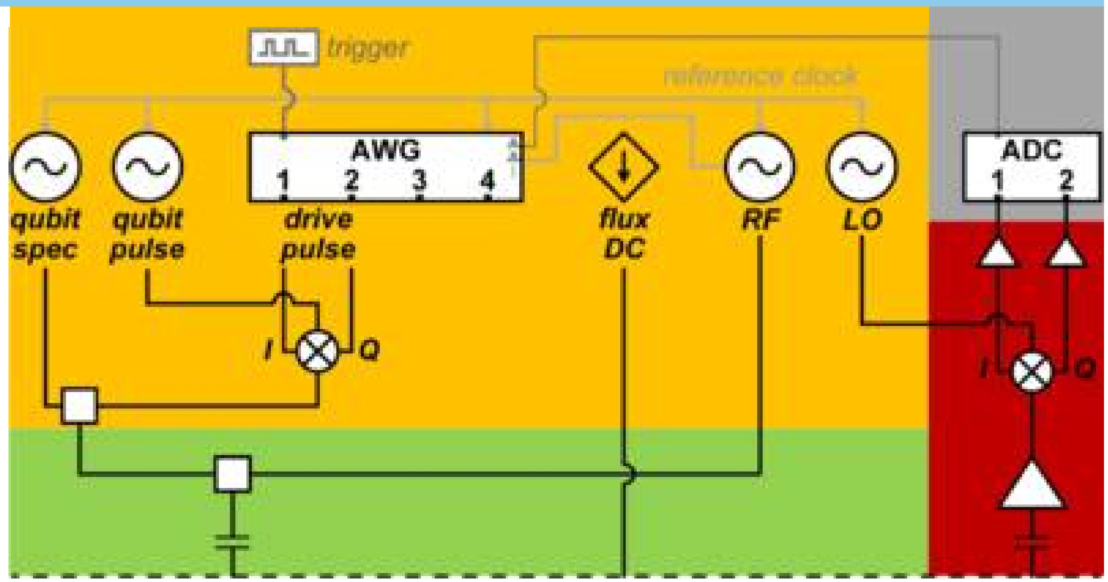


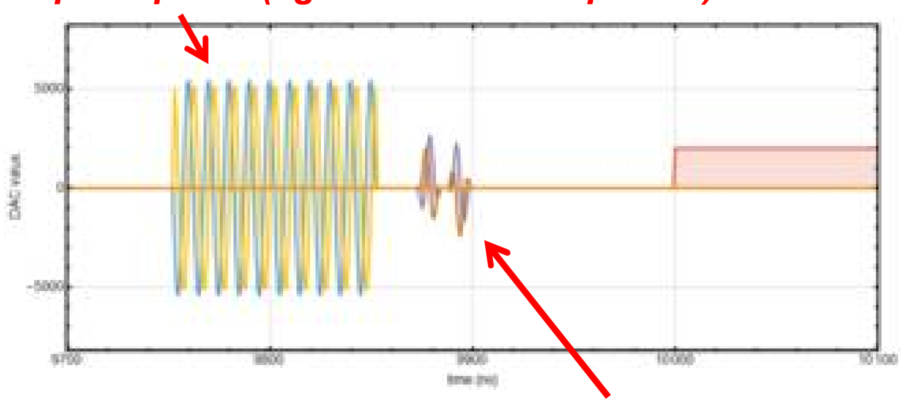
Pulsed spectroscopy

Pulsing with an IQ mixer

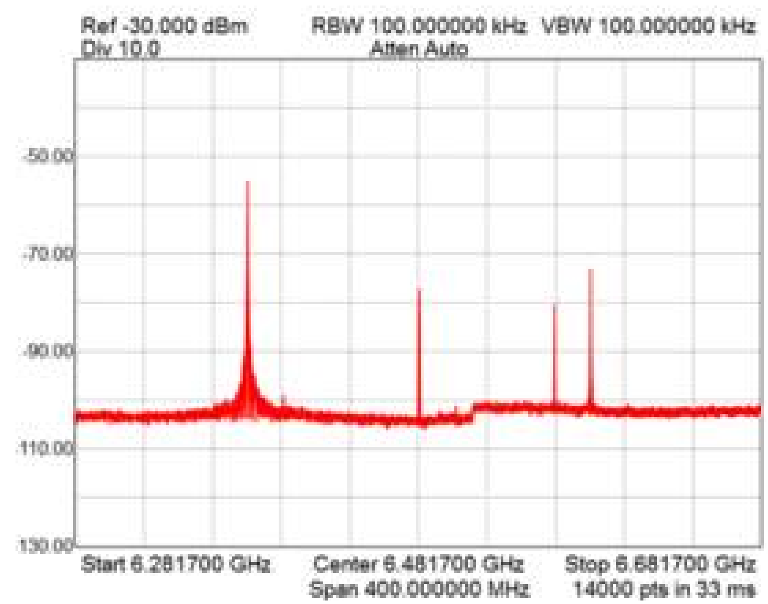
- single sideband modulation of a microwave carrier tone
- pulse envelope allows switching of pulses on/off
- RF modulation of IQ envelopes allows control of drive pulse phase
- also compensation for mixer imperfections: leakage, skewness



square pulse (eg. for saturation pulses)



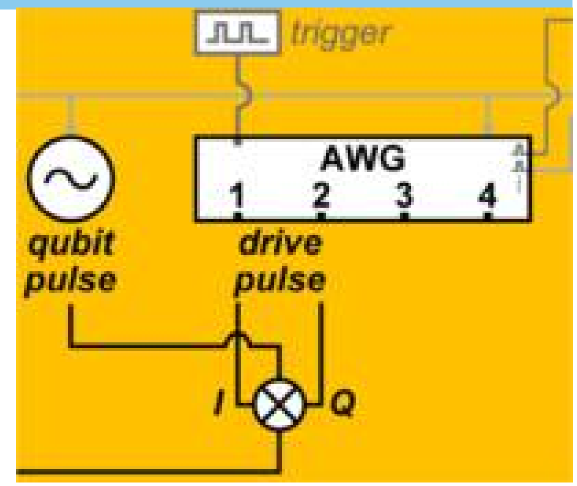
qubit pulses (DRAG)

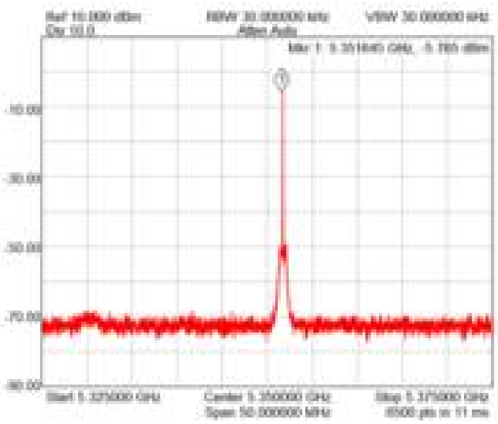


SB modulation in frequency domain

Basic calibration 1: mixer leakage and skewness

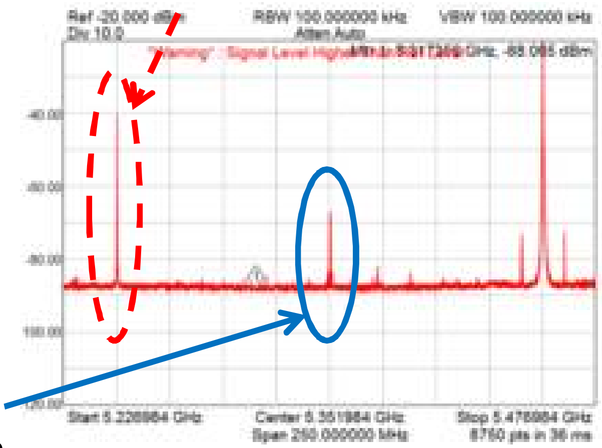
Calibrating single-sideband pulse modulation





microwave carrier drive before mixer

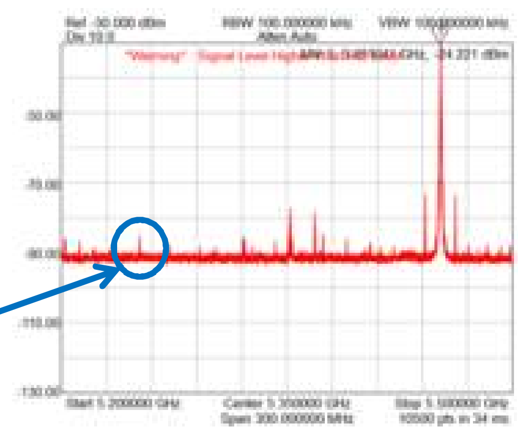
"spurious sideband" can cause errors such as "leakage" out of the qubit basis



after cancelling leakage

Mixer leakage: *Adjust DC offset voltages of the I & Q channels of the AWG to minimise leakage of the carrier tone.*

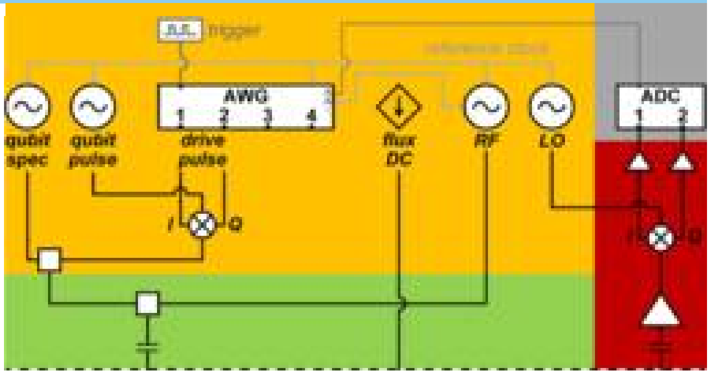
Mixer skewness: *Adjust relative phase and amplitude of I/Q modulation envelopes to minimise power in the (unwanted) spurious sideband.*



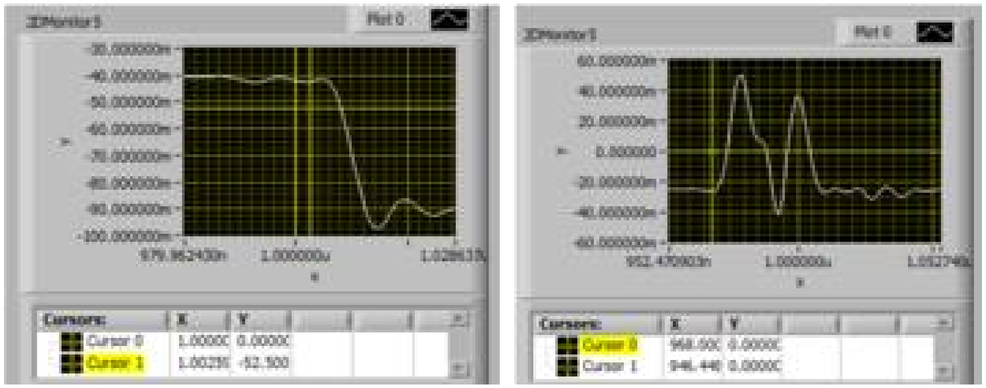
after compensating skewness

Basic calibration 2: pulse timings

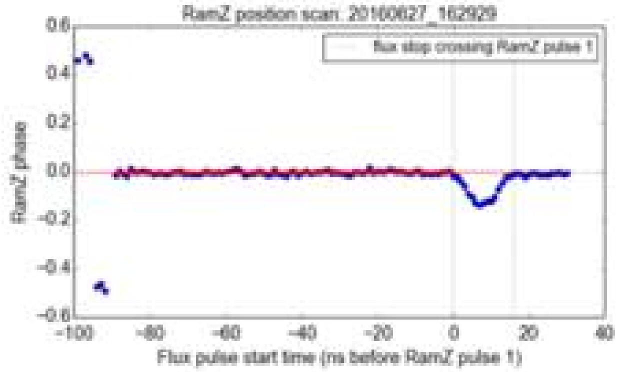
Getting your pulses in sync



- Pulse timings controlled by the AWG through analogue and digital (marker) outputs
- Latency (internal delays) in electronics, filtering and cabling introduce different signal delays
- Timing is critical "on chip" and at the ADC
- Delays, once calibrated, are easily compensated in the pulse sequences.



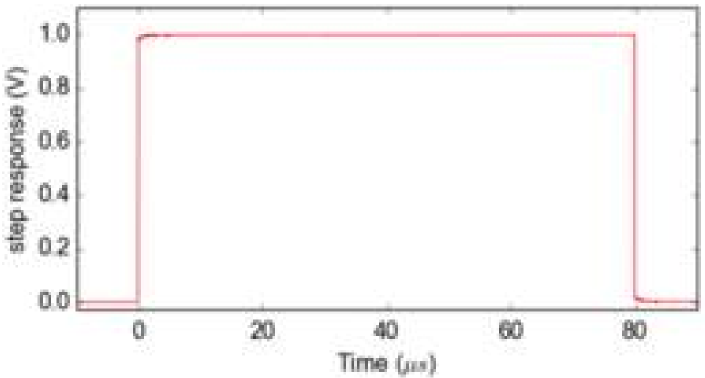
Direct calibration: *Signals transmitted through the feedline show up in the measurement signal.*
Remember: Always look at the start times!!



Indirect calibration: *Other signals must be calibrated by looking at the response of other elements, like qubits. Ramsey-based pulse sequences are the most sensitive way of detecting frequency shifts.*

Fast frequency tuning: a distorted reality

What it looks like in reality…



Step response of an isolated AWG

Fast frequency tuning: a distorted reality

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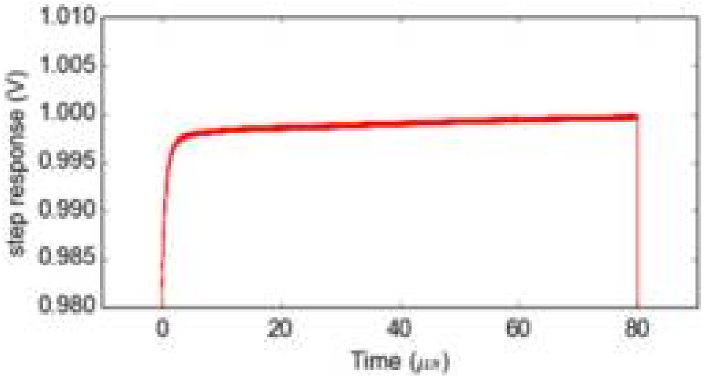

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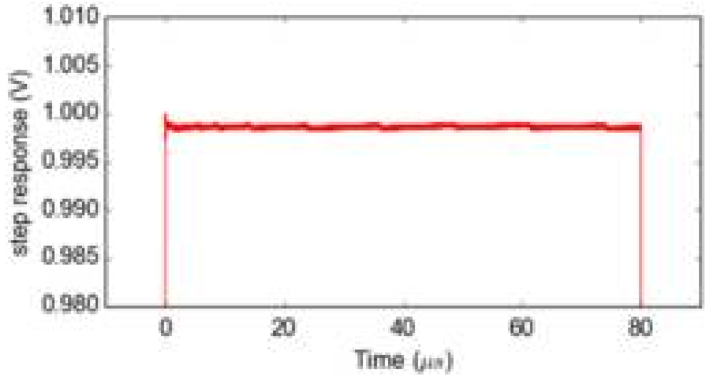

Corrected step response from AWG

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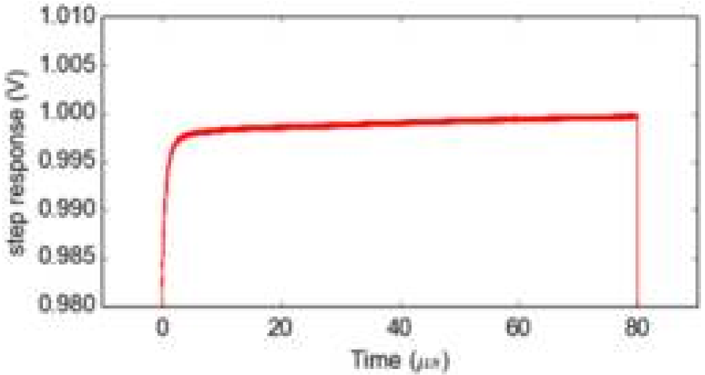

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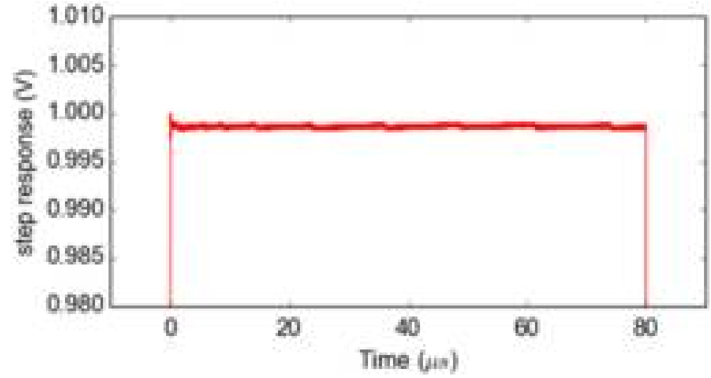

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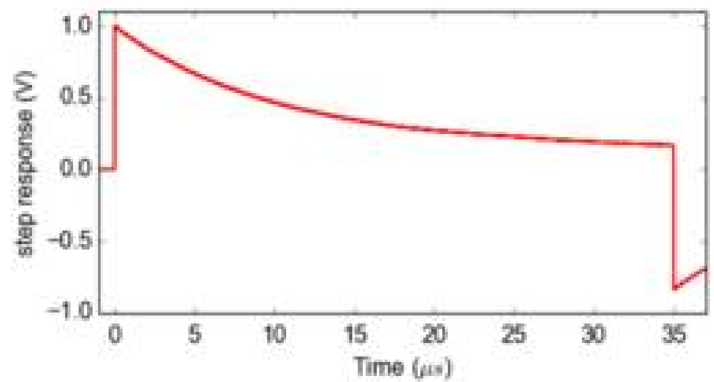

Step response after bias tee

Fast frequency tuning: a distorted reality

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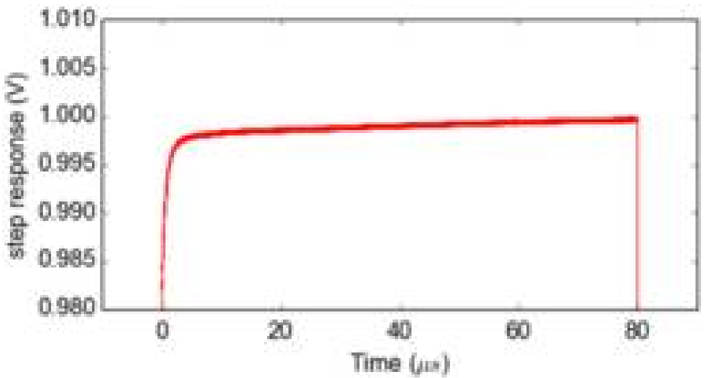

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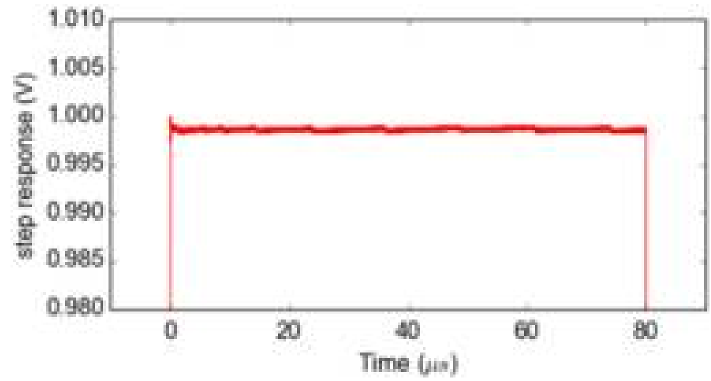
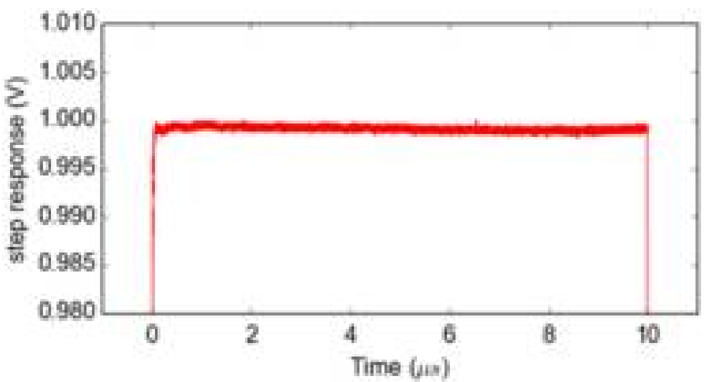
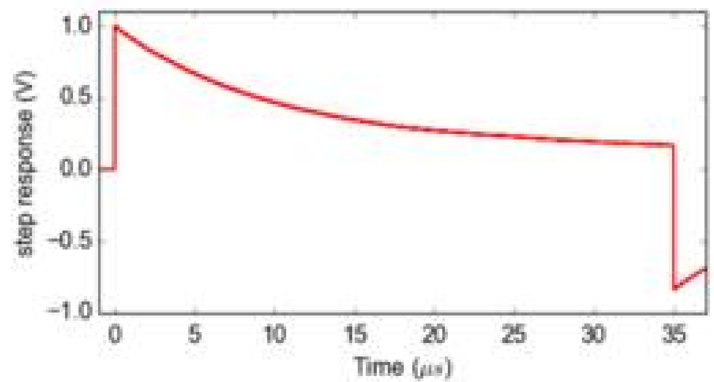


Corrected step response from AWG



Step response after all corrections before entering fridge



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