Exploring Drawbridge Transmon Coherence

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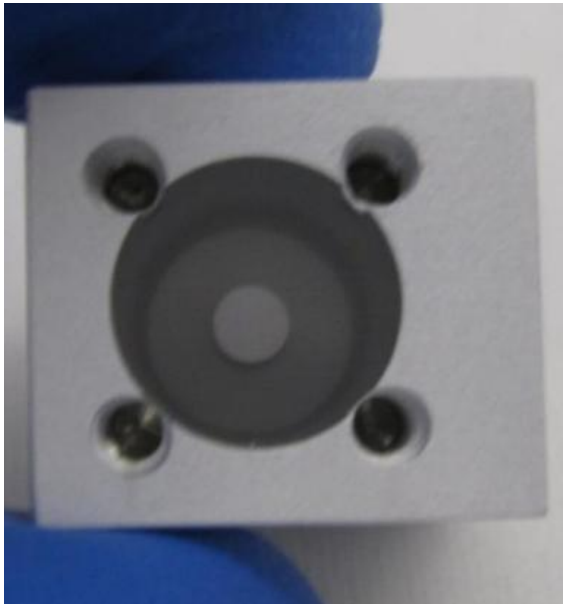
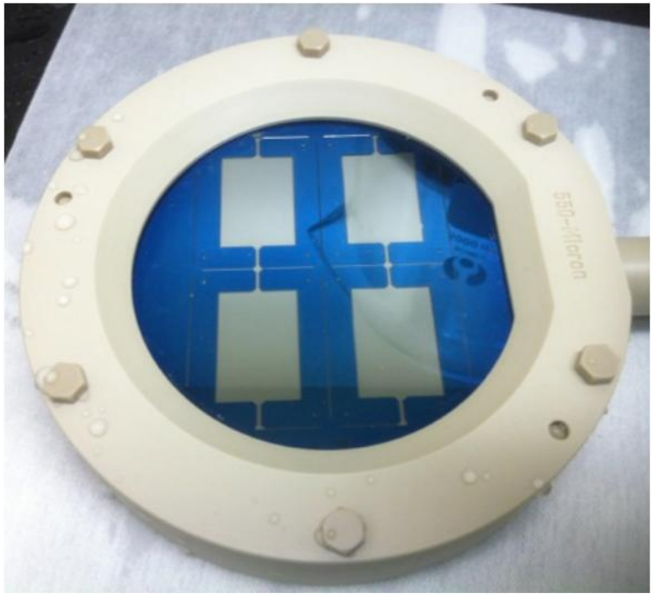
Outline

I. What is the 2.5D multilayer architecture?
II. Proof of concept devices
III. System parameters & photon number splitting regime
IV. Coherence through dynamical decoupling
V. Quasiparticle dynamics

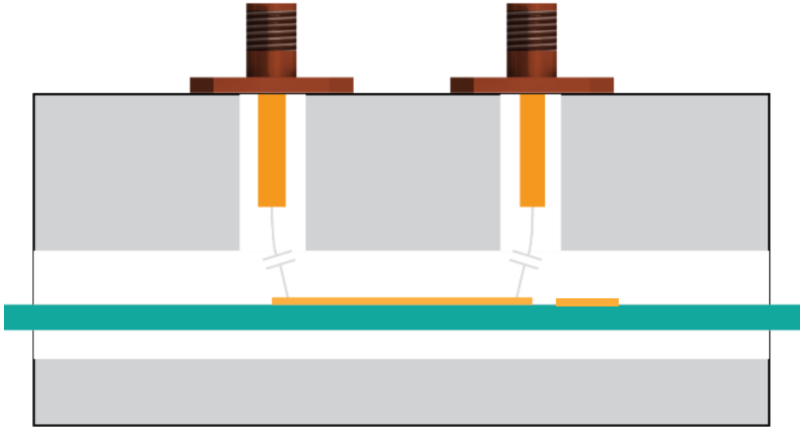
Approaches to Combining Coherence and Complexity



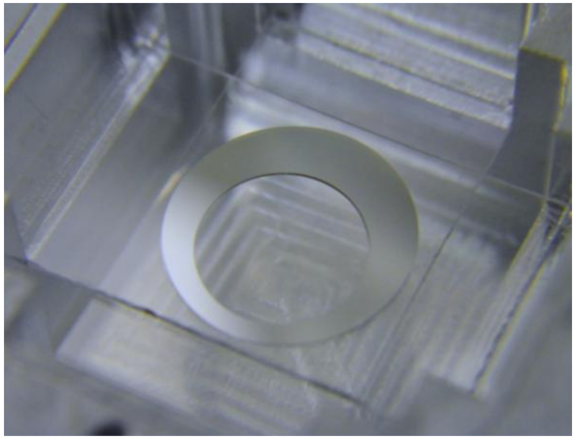
Coax cavities (MLS 9/12, 2/14)



Micro-machined cavities (MLS 9/12, 12/13, 1/15)

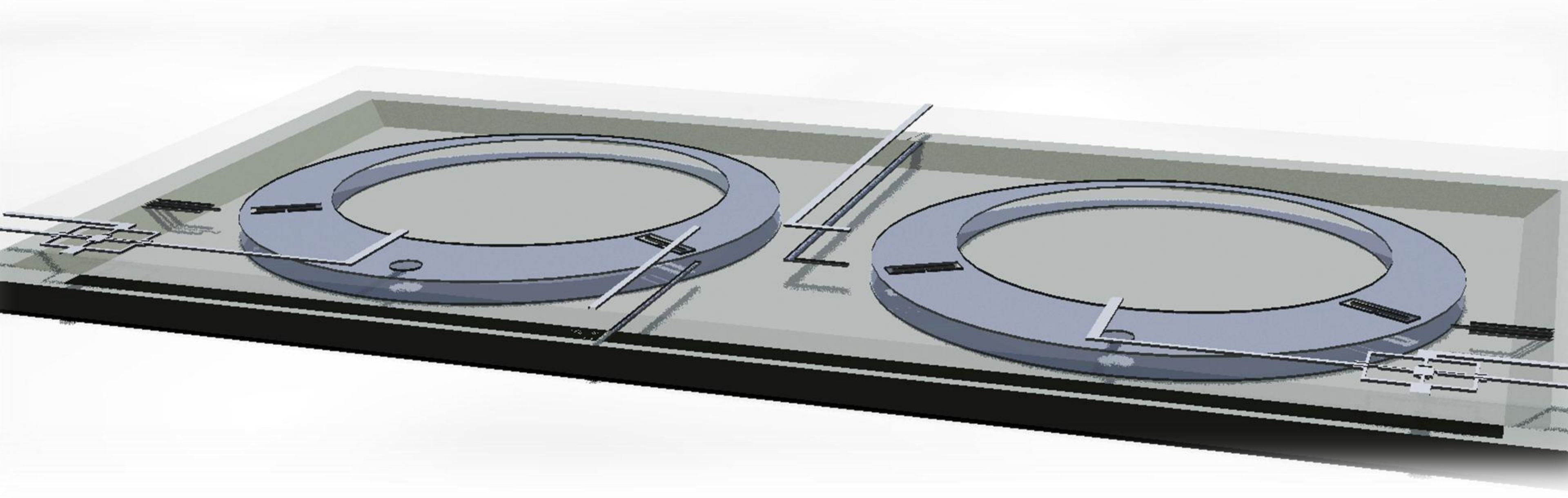


The Co-Axline (MLS 11/14)



WGMRs (MLS 1/13, 2/10/14, 1/15, 2/15)

We dream of:



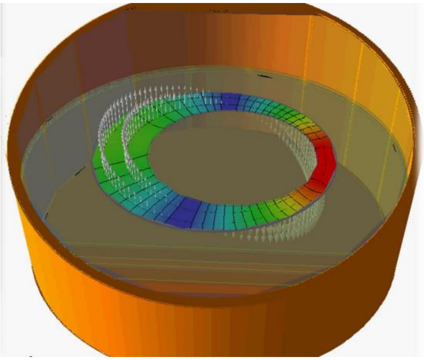
For the moment:

a. combines qubit & cavities using only wafers
b. minimal number of moving parts
c. maximal use of vacuum as dielectric
d. no seams
e. readily benefits from material improvements
f. consistency: both layers from same wafer

In the future:

a. any qubit (transmon, fluxonium, etc.)
b. on-chip control lines & amplifiers
c. layers with specific functionality
d. full wafer stacking

First generation
3 GHz WGMRs



$T_1 = 180\ \mu s$

$Q_i = 3.4 \cdot 10^6$

$T_\phi \geq 1$ ms

$R_s \leq 250 n\Omega$

$\tan \delta \leq 10^{-6}$

APL (2013)

Improved Resonators:

Optical fabrication

7 GHz

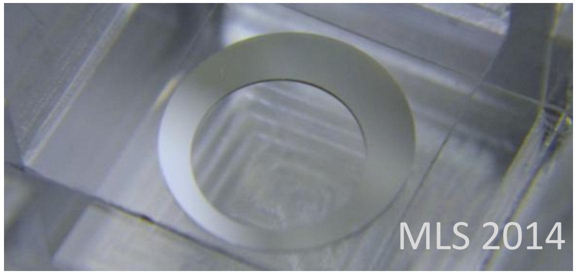
Q_i = 13M

T_1 = 230 us

R_s < 9nOhm

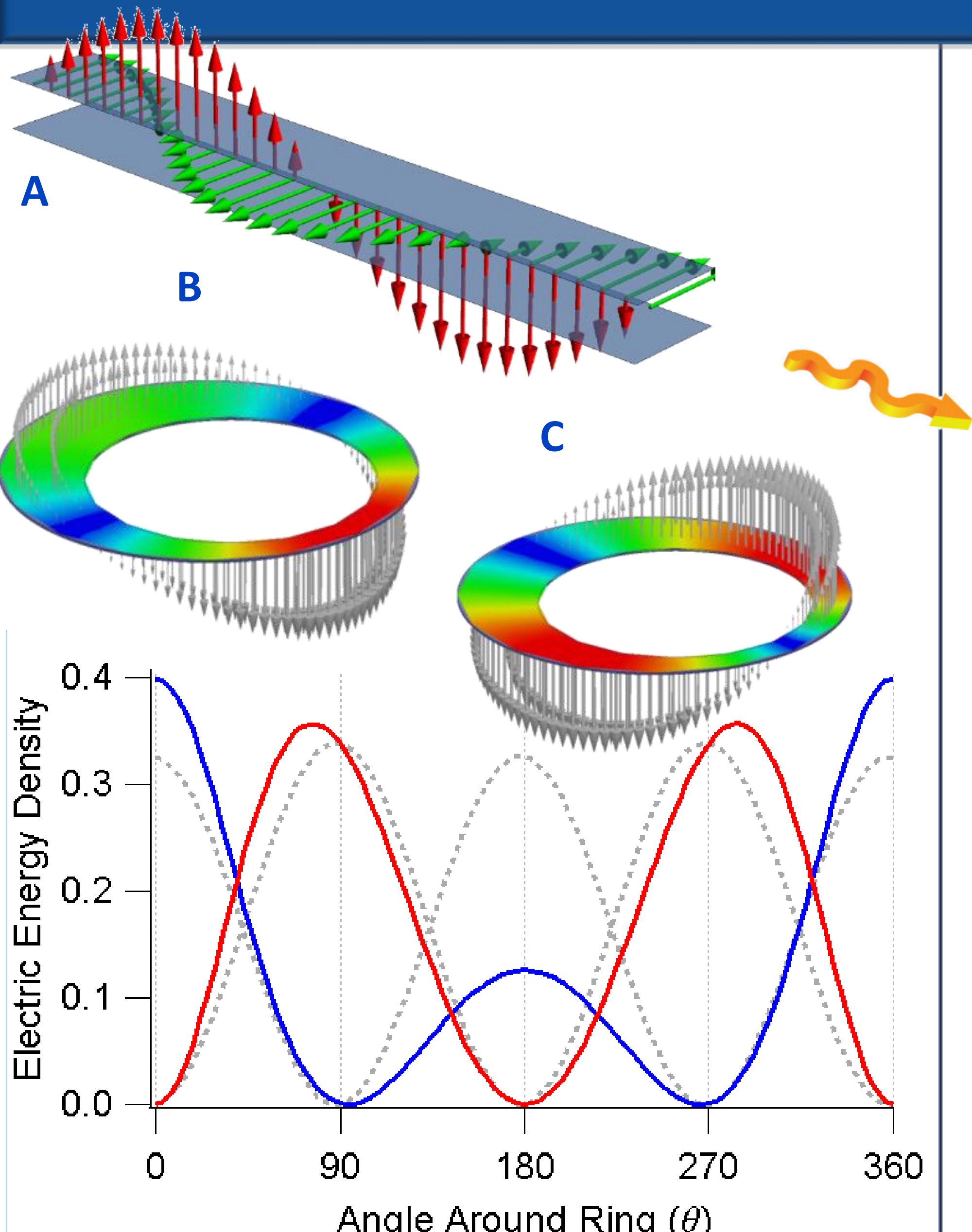
Q_s > 3.7*10^5

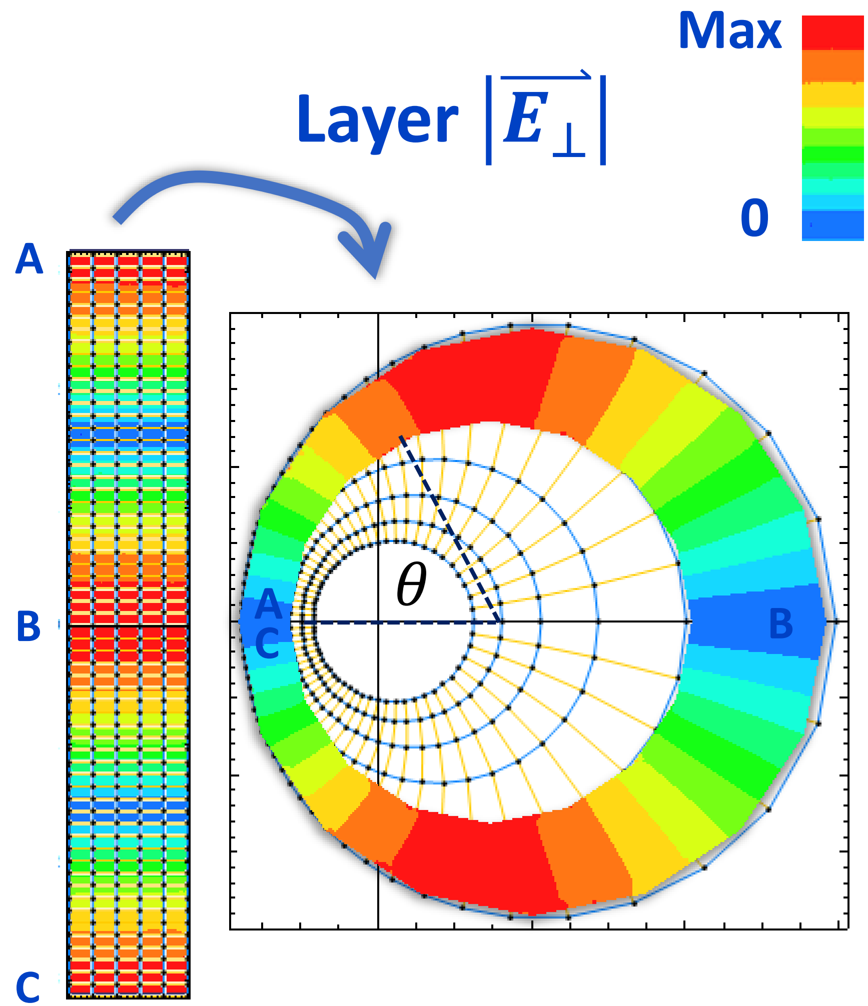
Drawbridge Qubit + Storage



- T_1 = 70 us, T_2^R = 8 us
- $T_{storage}$ = 45 us
- $T_{readout,}$ chi, etc see later

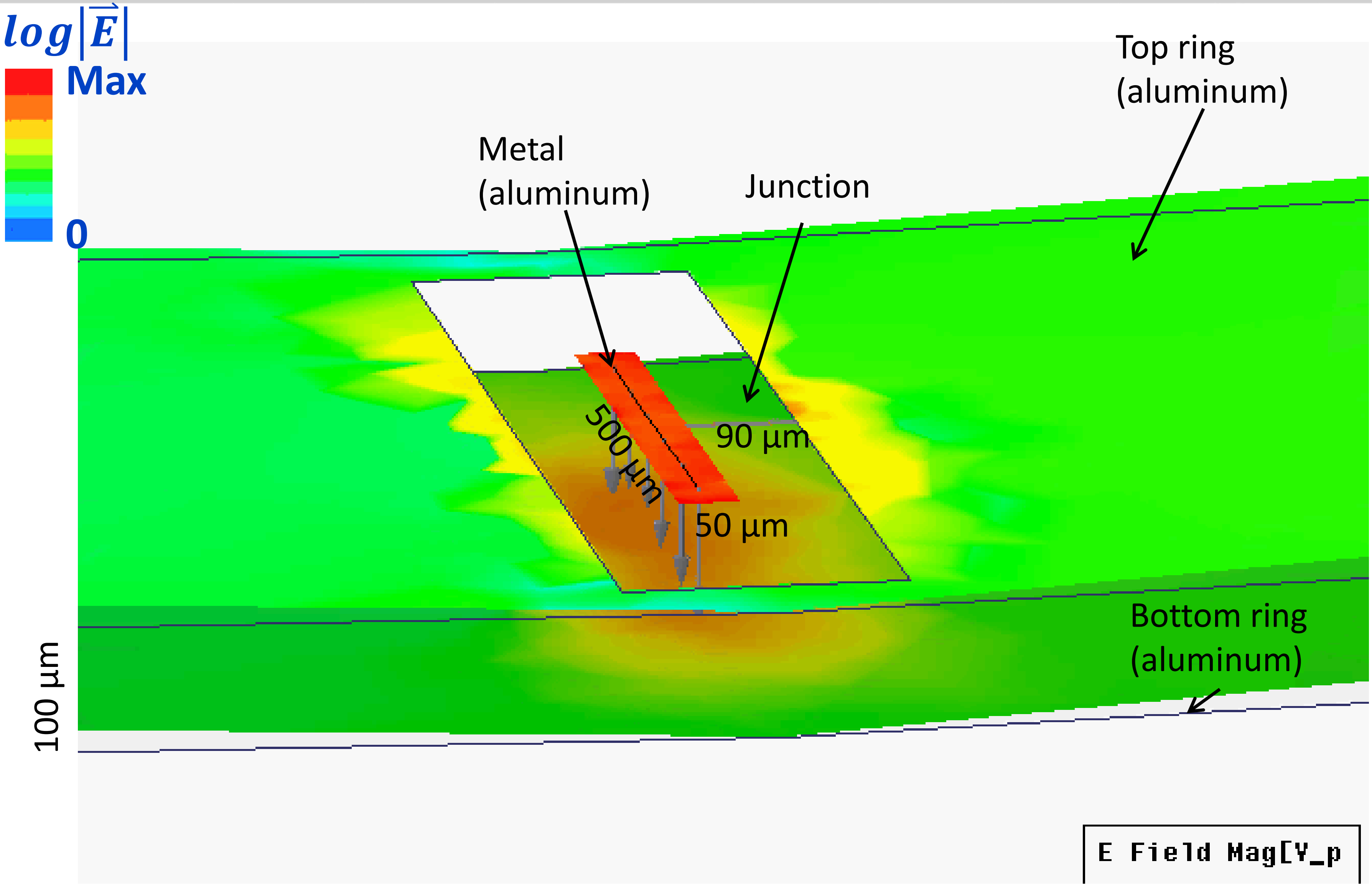
WGMR Differential Modes (D)





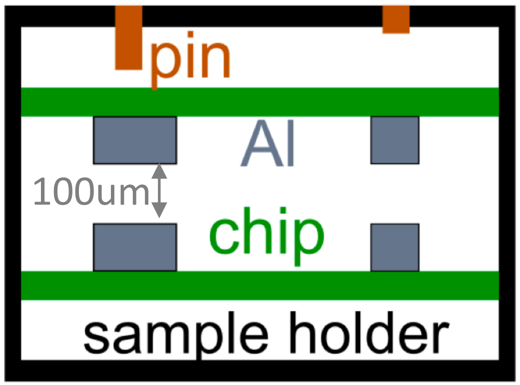
Field expression is analytic and can be obtained by conformal map

Qubit Mode

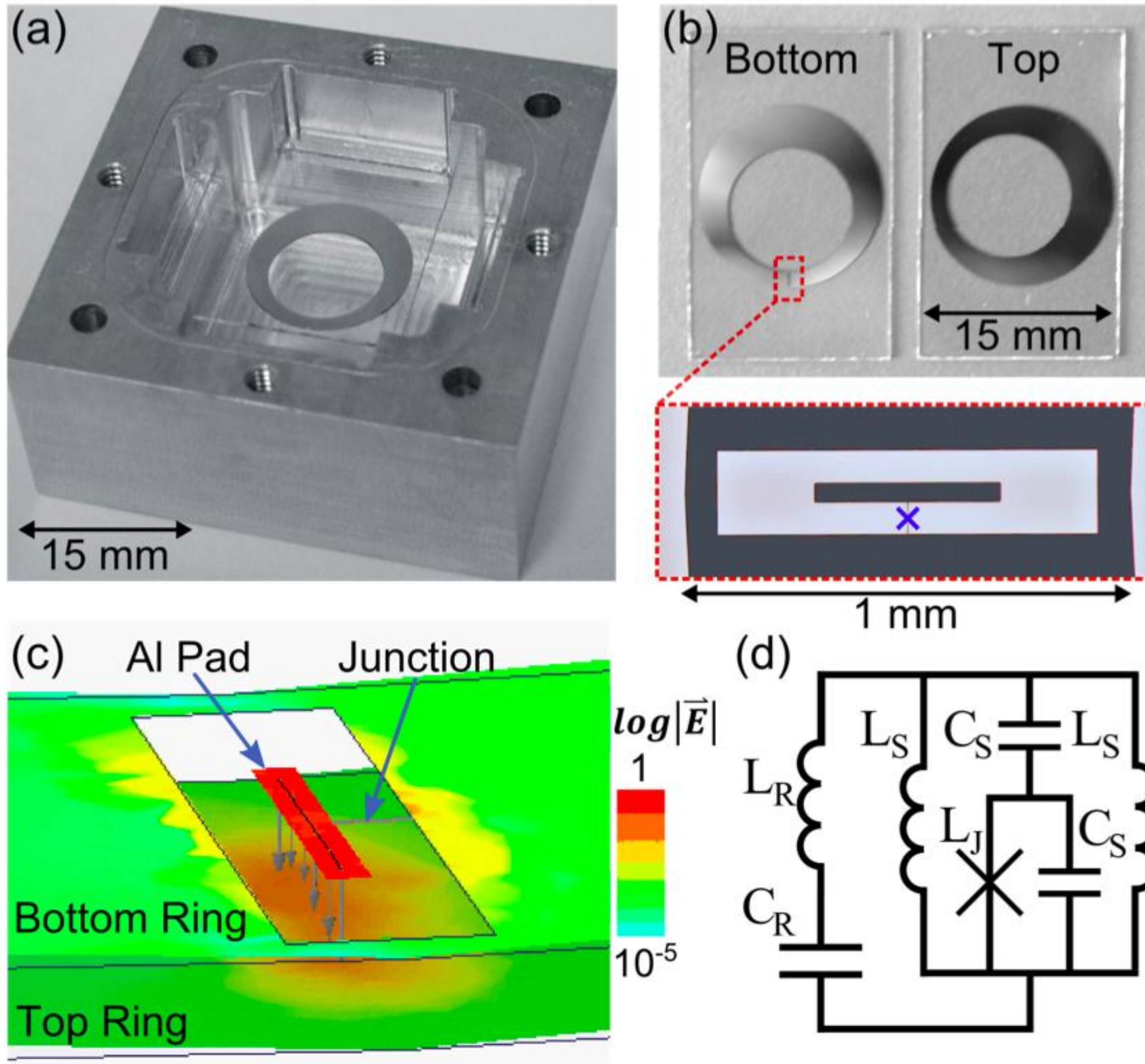


$log|\vec{E}|$
Max
0
Top ring
(aluminum)
Metal
(aluminum)
Junction
500 µm
90 µm
50 µm
Bottom ring
(aluminum)
100 µm
E Field Mag[V_p

WGMR Sample

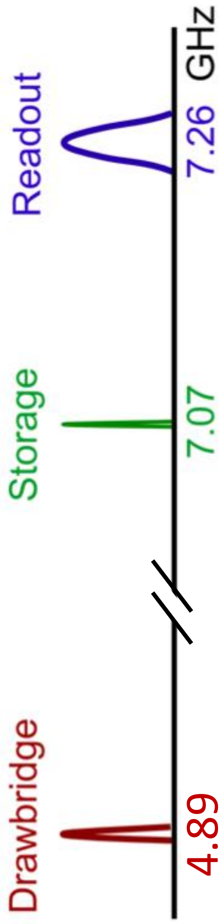


pin
Al
100um
chip
sample holder



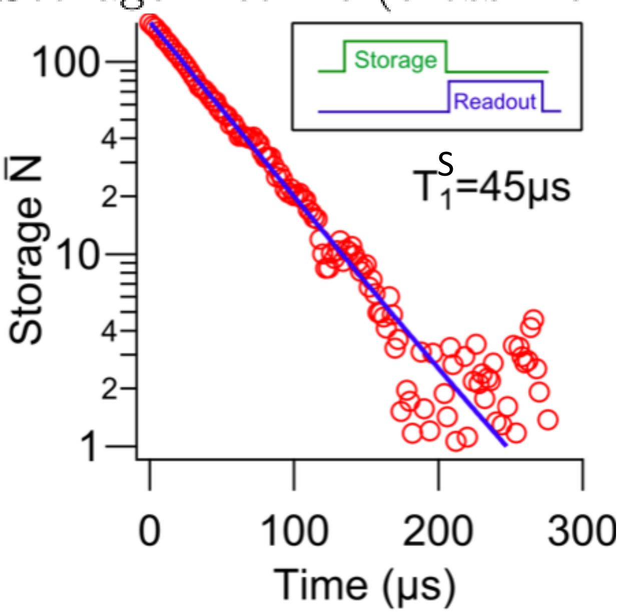
(a)
15 mm
(b)
Bottom
Top
15 mm
1 mm
(c)
Al Pad
Junction
Bottom Ring
Top Ring
$log|\vec{E}|$
1
10^{-5}
(d)
L_R
L_S
C_S
L_S
L_J
C_S
C_R

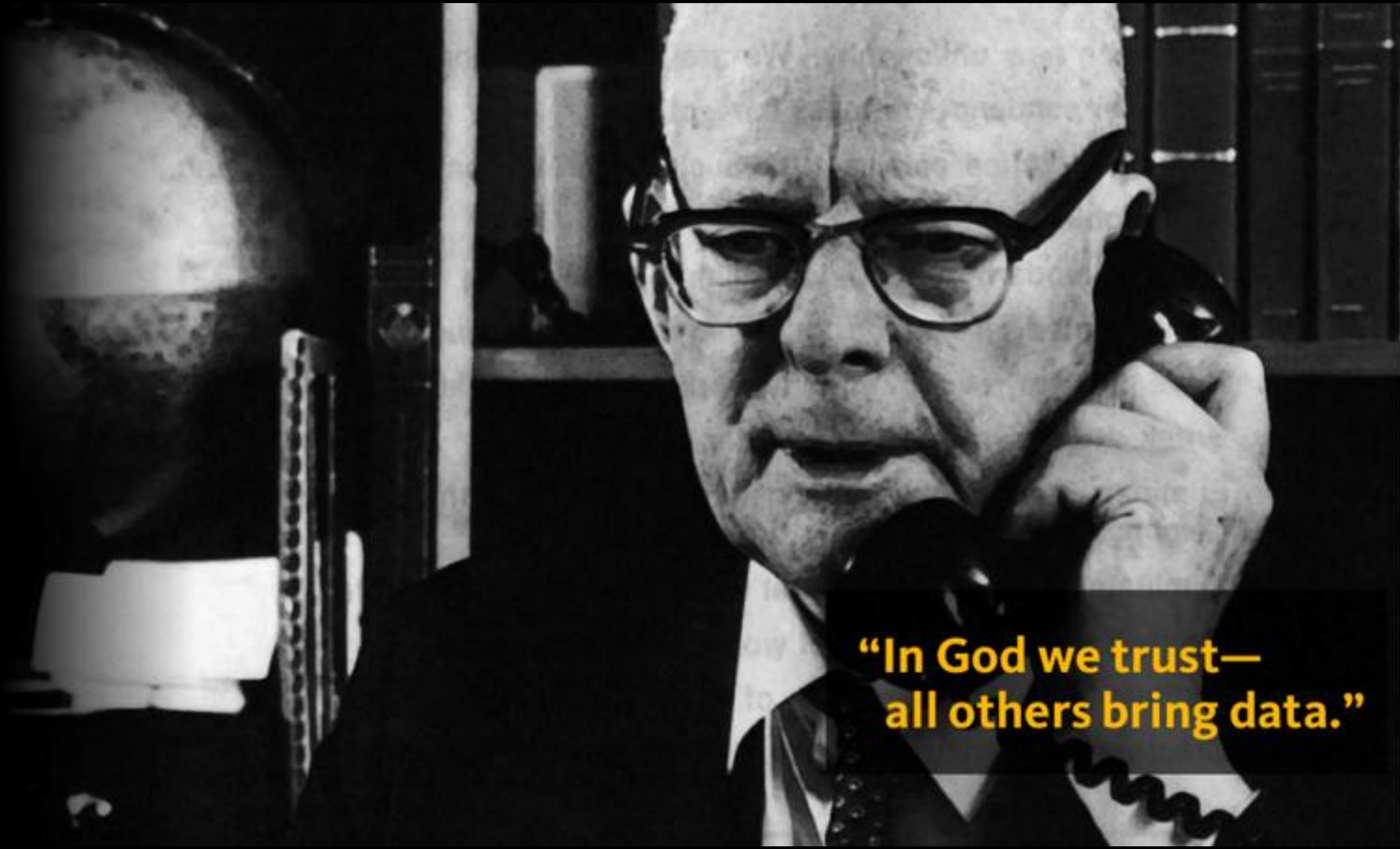
Coherences Summary



Mode	Qubit	Storage	Readout
Frequency (GHz)	4.890	7.070	7.267
T_1 (μs)	70	45	0.42
Q_{total}	2.0×10^6	2.0×10^6	1.8×10^4
$\alpha/2\pi$ (MHz)	300	(5×10^{-5})	(2×10^{-4})
$\chi_q/2\pi$ (MHz)	-	0.23	0.30

Storage lifetime (cross-Kerr)

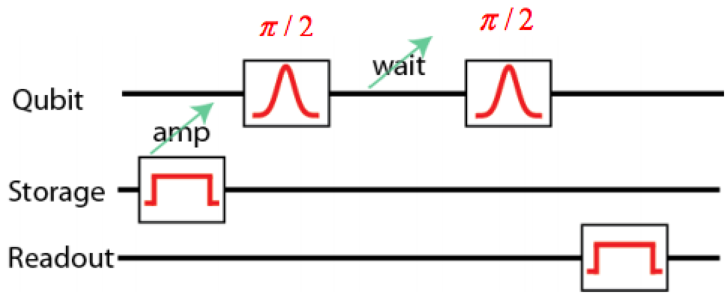


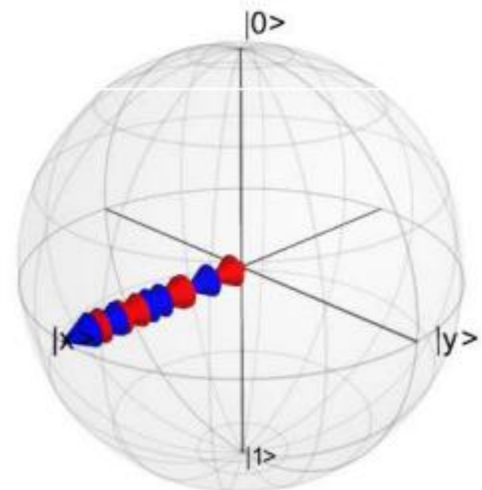


- William Deming

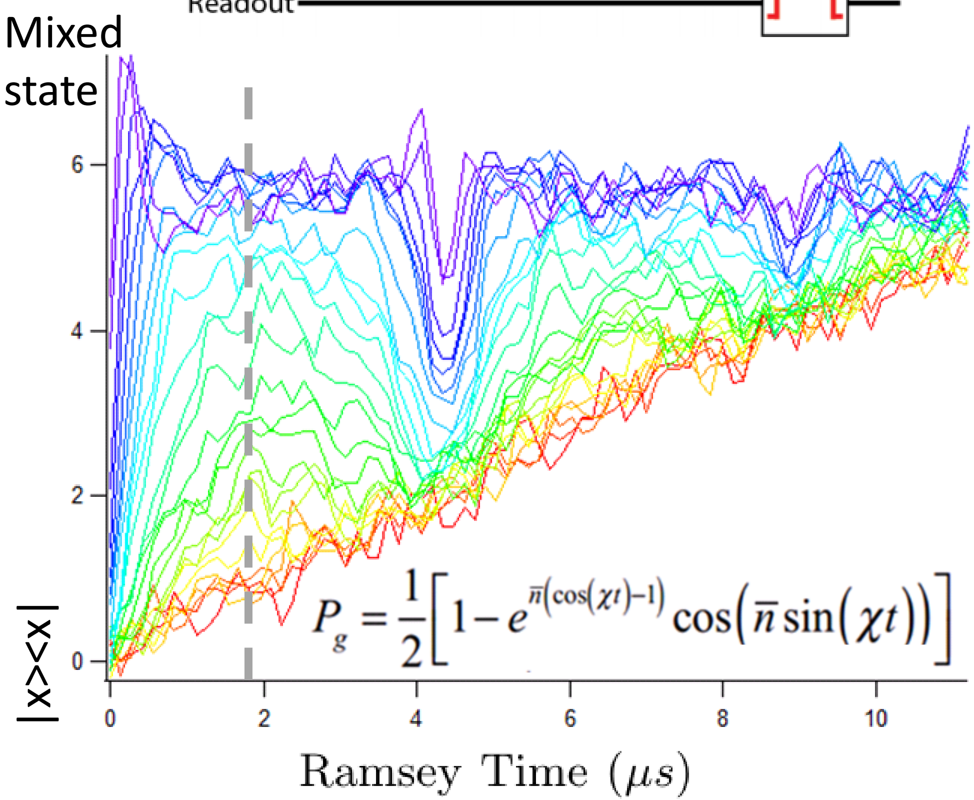
$T_{1\,\text{storage}}$ from Parity Measurements

Storage-Qubit Revivals





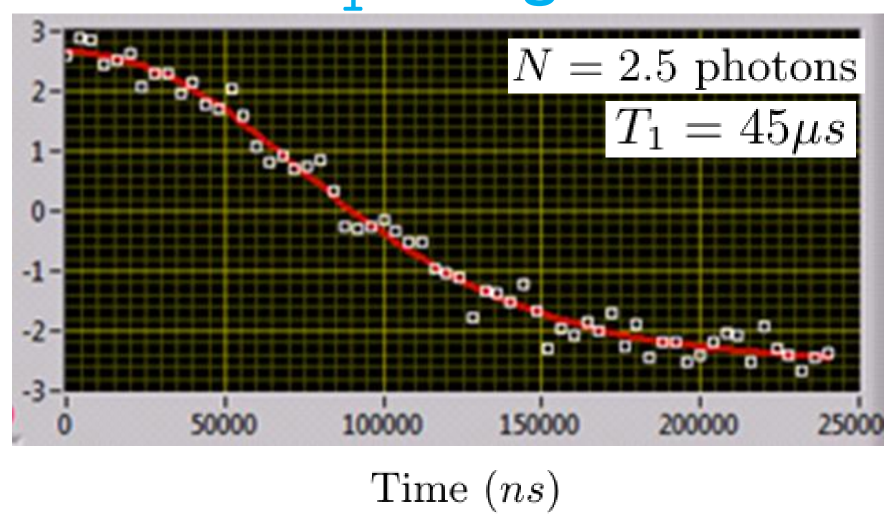
See Zaki & Brian MLS



Qubit $T_2 = 8\mu s$

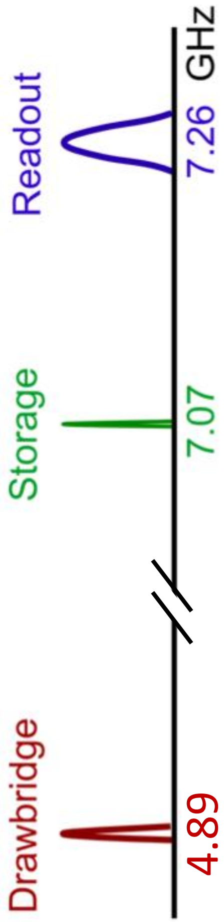
$$\frac{\pi}{\chi} = 2.25\mu s \qquad e^{-\frac{\pi}{\chi T_2}} = .75$$

T_1 storage

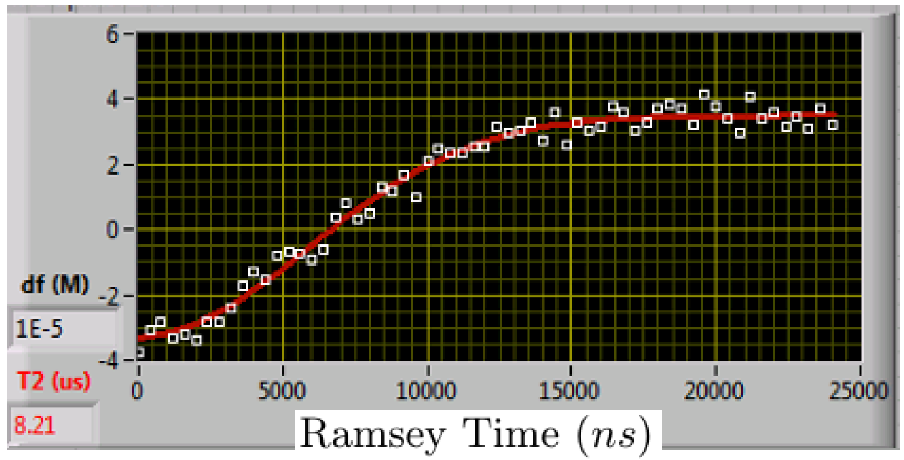


Parity measurement: Constant Ramsey time = pi/chi
Vary time between storage disp. & parity measurement

Qubit T_2



Qubit $T_2 = 8\mu s$ Gaussian!



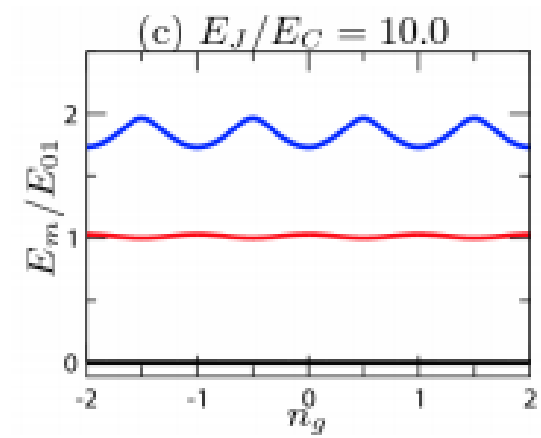
$\epsilon_m \equiv E_m(n_g = 1/2) - E_m(n_g = 0)$

Dispersion $= -1.30 \times 10^3$ KHz

$E_j / E_c = 27.5$

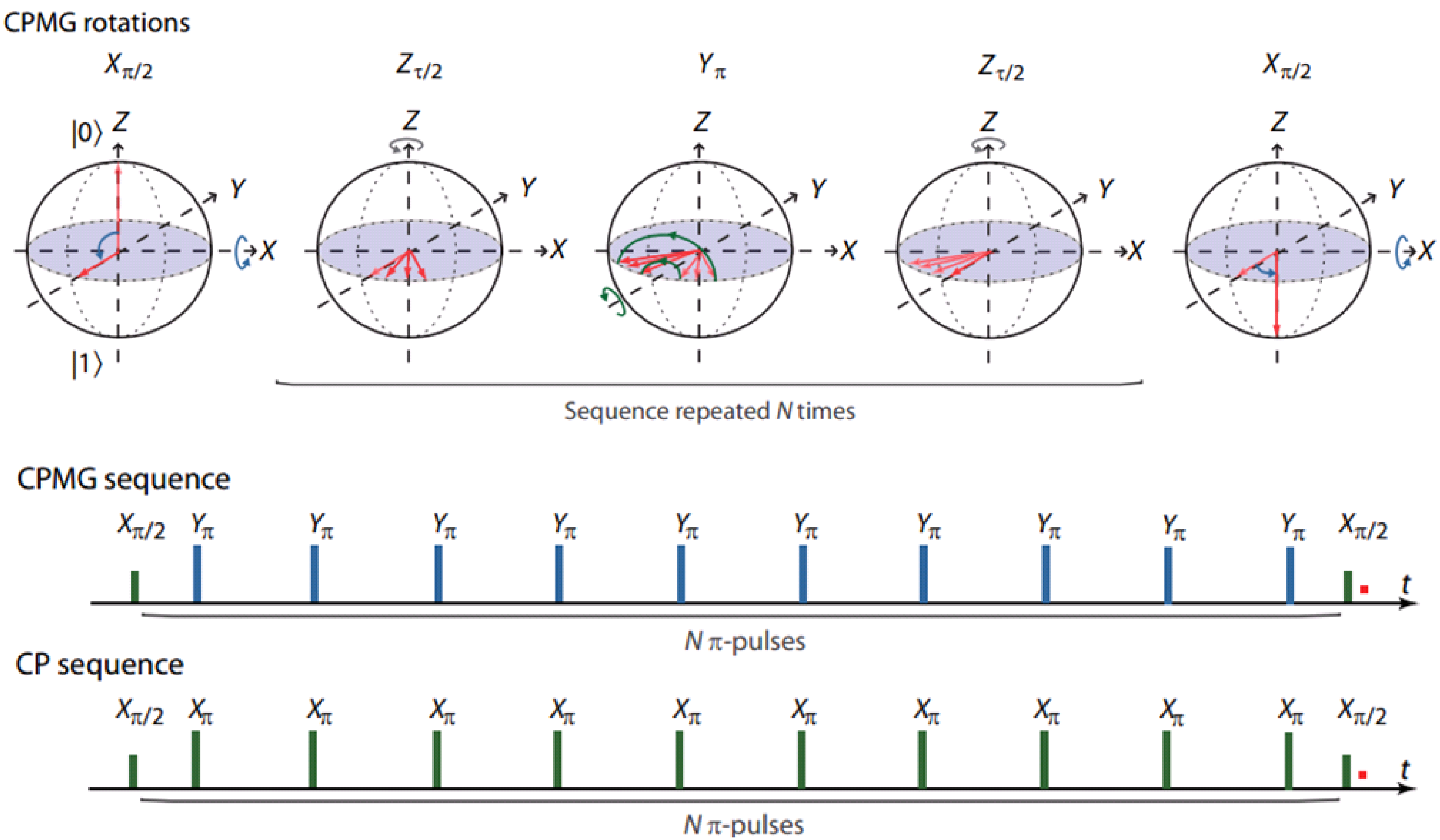
$E_j = 9.06$ GHz

$T_2 / 2\pi = 1/(2\pi\ 8.2\mu s) = 19.4$KHz



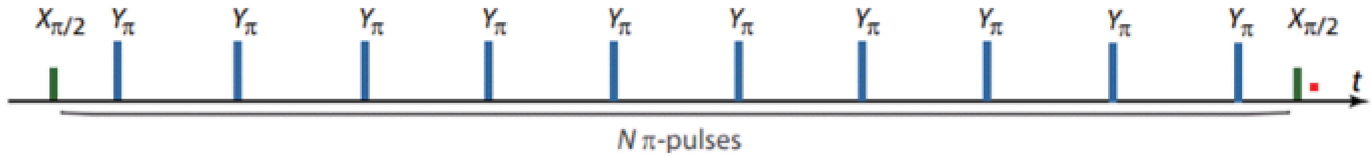
1. What is the noise that limits us?
2. What are the charges doing?

Address Gaussian T_2 by Dynamical Decoupling



G. De Lange et al. Science 330, 60 (2010)
F. Bylander et al. N.Phys. 7, 567 (2011)

A Filter



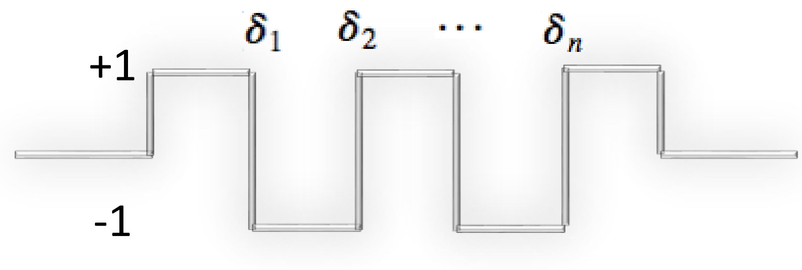
Time evolution:

$$\delta\varphi(t) = (\partial\omega_{01}/\partial\lambda)\int_0^t \mathrm{d}t'\,\delta\lambda(t').$$

$$s_n(t) = \langle\uparrow|D_x^{\mathrm{ef}}(\pi/2)^\dagger R^\dagger \sigma_y^{\mathrm{ef}}(t) R D_x^{\mathrm{ef}}(\pi/2)|\uparrow\rangle$$

$$R = \sigma_y^{\mathrm{ef}}(\delta_n t)\sigma_y^{\mathrm{ef}}(\delta_{n-1}t)\ldots\sigma_y^{\mathrm{ef}}(\delta_2 t)\sigma_y^{\mathrm{ef}}(\delta_1 t).$$

$$\delta\varphi(t) = (\partial\omega_{01}/\partial\lambda)\int_0^t \mathrm{d}t'\,\delta\lambda(t') * f_n(t)$$

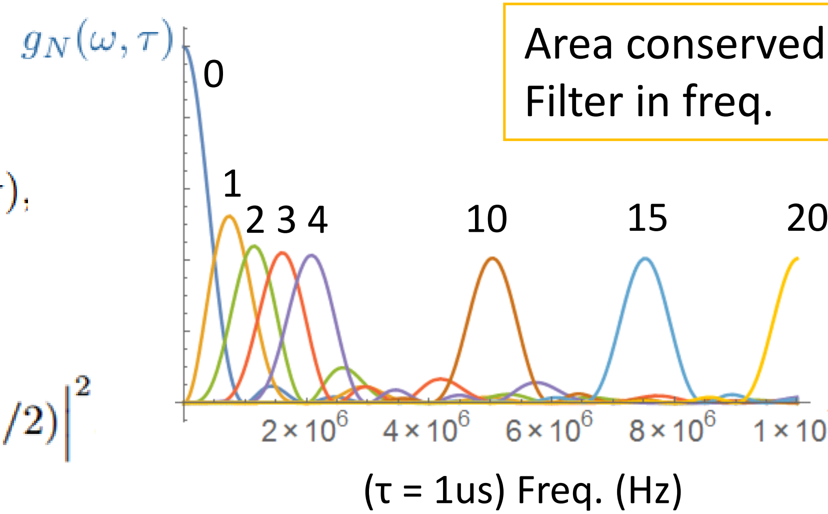


Filtered coherence decay in freq. space:

$$\langle\exp[i\,\delta\varphi(t)]\rangle \equiv \exp[-\chi_N(t)]$$

$$\chi_N(\tau) = \tau^2\sum\left(\frac{\partial\omega_{01}}{\partial\lambda}\right)^2\int_0^\infty \mathrm{d}\omega\, S_\lambda(\omega)\, g_N(\omega,\tau),$$

$$g_N(\omega,\tau) = \frac{1}{(\omega\tau)^2}\left|1 + (-1)^{1+N}\exp(i\omega\tau) + 2\sum_{j=1}^{N}(-1)^j \exp(i\omega\delta_j\tau)\cos(\omega\tau_\pi/2)\right|^2$$



Area conserved
Filter in freq.

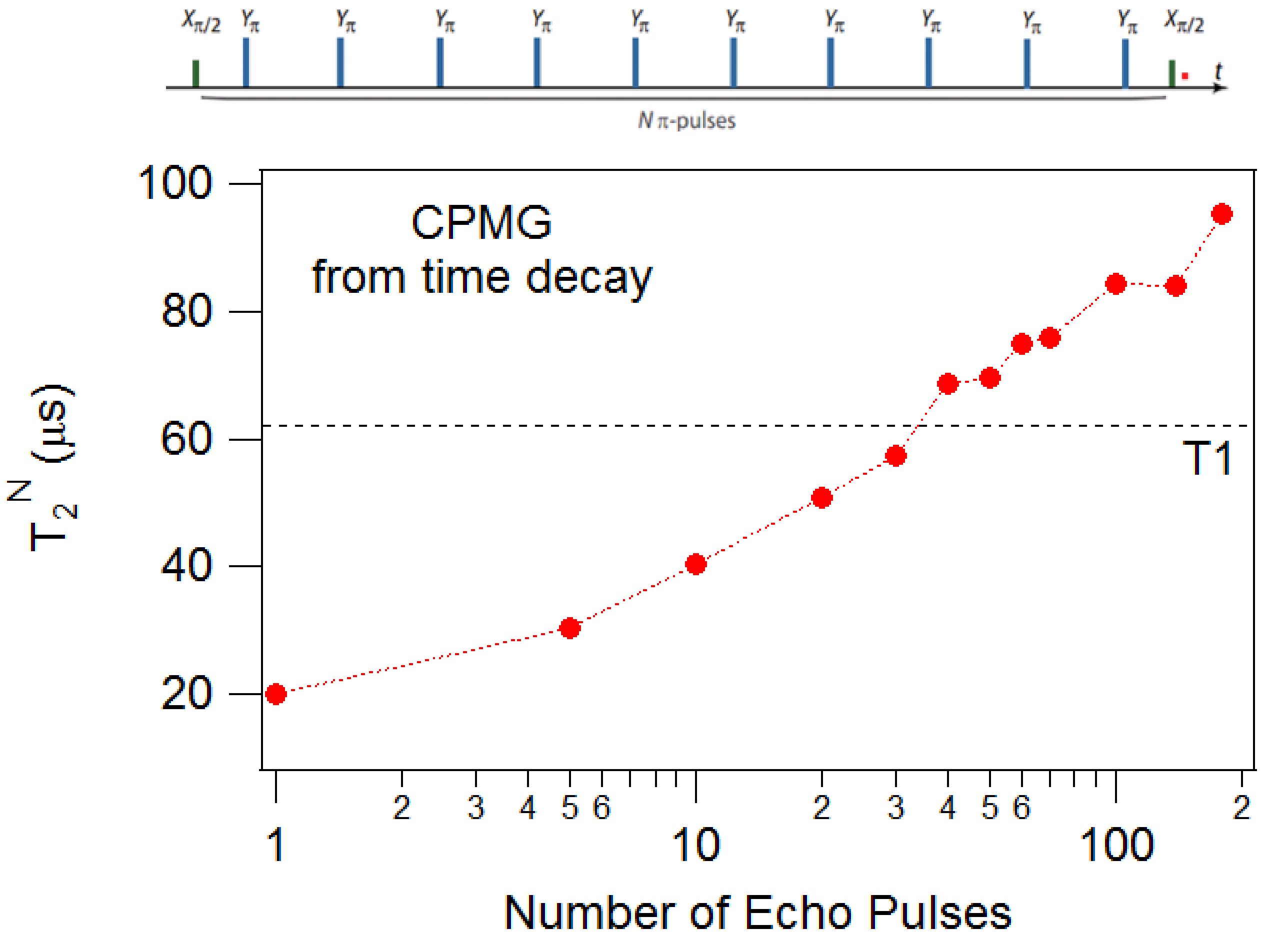
Types of noise:

$$S_\lambda(\omega) = A_\lambda/\omega \longrightarrow \chi_N(\tau) = (\Gamma_\varphi\tau)^2.$$

$$\langle\delta n(t_1)\,\delta n(t_2)\rangle = \bar{n}e^{-(\kappa/2)|t_1-t_2|} \longrightarrow \langle\exp[i\,\delta\varphi(t)]\rangle = e^{-\gamma_2 t}\exp\left\{-4\bar{n}\theta_0^2\left[\frac{\kappa|t|}{2} - 1 + \exp\left(-\frac{\kappa|t|}{2}\right)\right]\right\}$$

F. Bylander et al. N. Phys. (2011); Gambetta et al. PRA (2006)

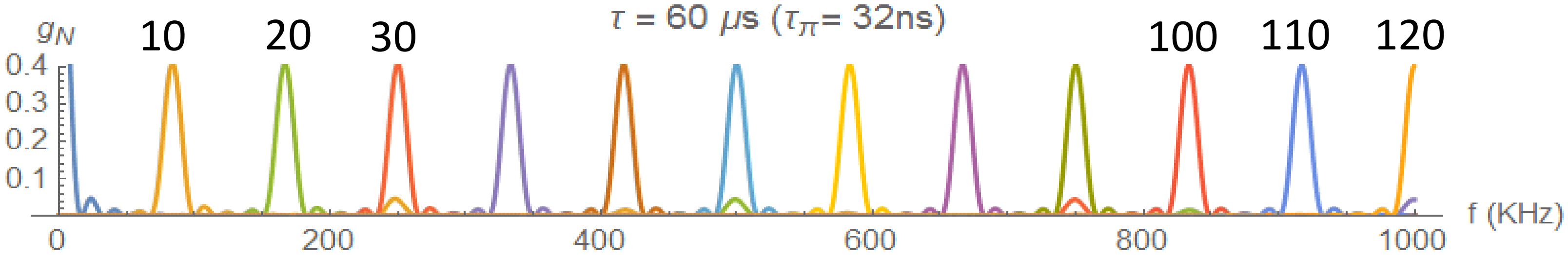
Improvement of T_2 with DD



- Results similar to that of flux qubits but with almost an order of magnitude longer coherences

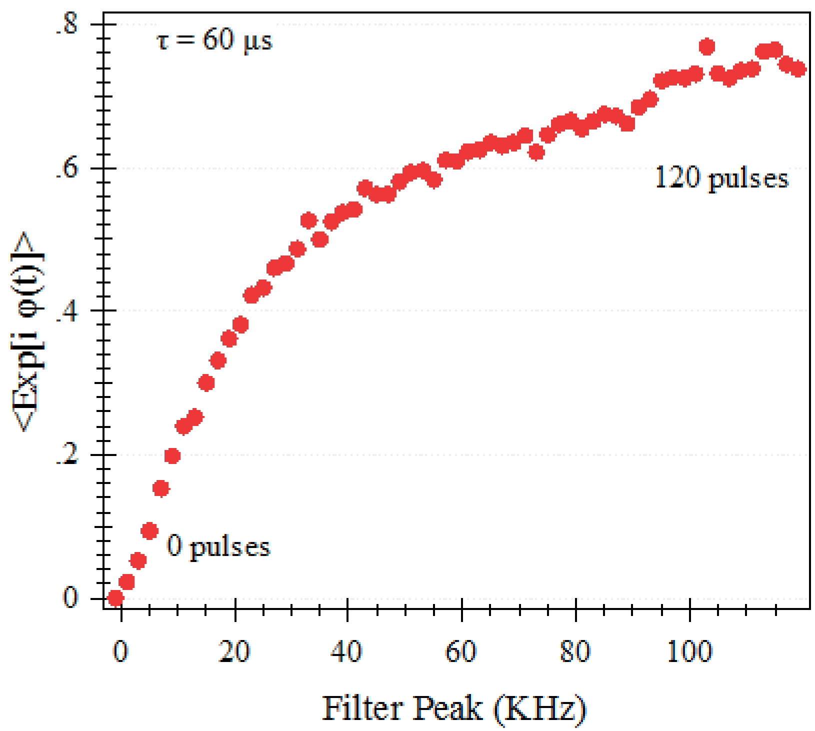
Reconstructing Noise Spectrum

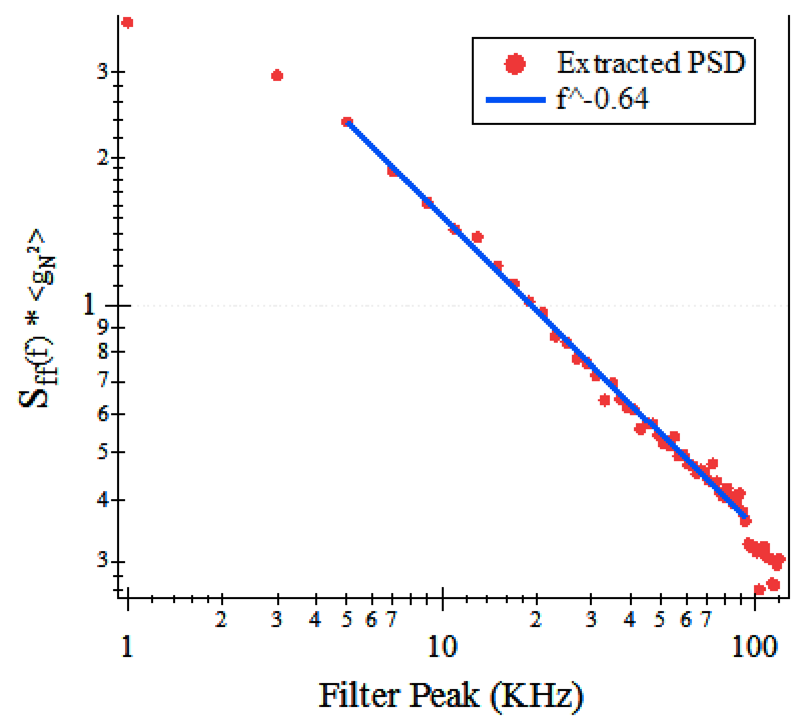
$$g_N(\omega,\tau) = \frac{1}{(\omega\tau)^2}\left|1+(-1)^{1+N}\exp(i\omega\tau)+2\sum_{j=1}^{N}(-1)^j\exp(i\omega\delta_j\tau)\cos(\omega\tau_\pi/2)\right|^2,$$



$$\langle\exp[i\,\delta\varphi(t)]\rangle \equiv \exp[-\chi_N(t)],$$

$$\chi_N(\tau) = \tau^2\sum_\lambda\left(\frac{\partial\omega_{01}}{\partial\lambda}\right)^2\int_0^\infty \mathrm{d}\omega\, S_\lambda(\omega)\, g_N(\omega,\tau),$$



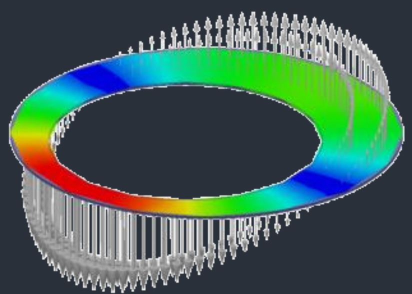


Quasiparticle Injection in WGMRs

In collaboration with
Uri, Gianluigi, Chen, Nissim

U. Vool and I. Pop, et al. 2014
C. Wang and Y. Gao, et al. 2014

Injection Spectroscopy v. delay

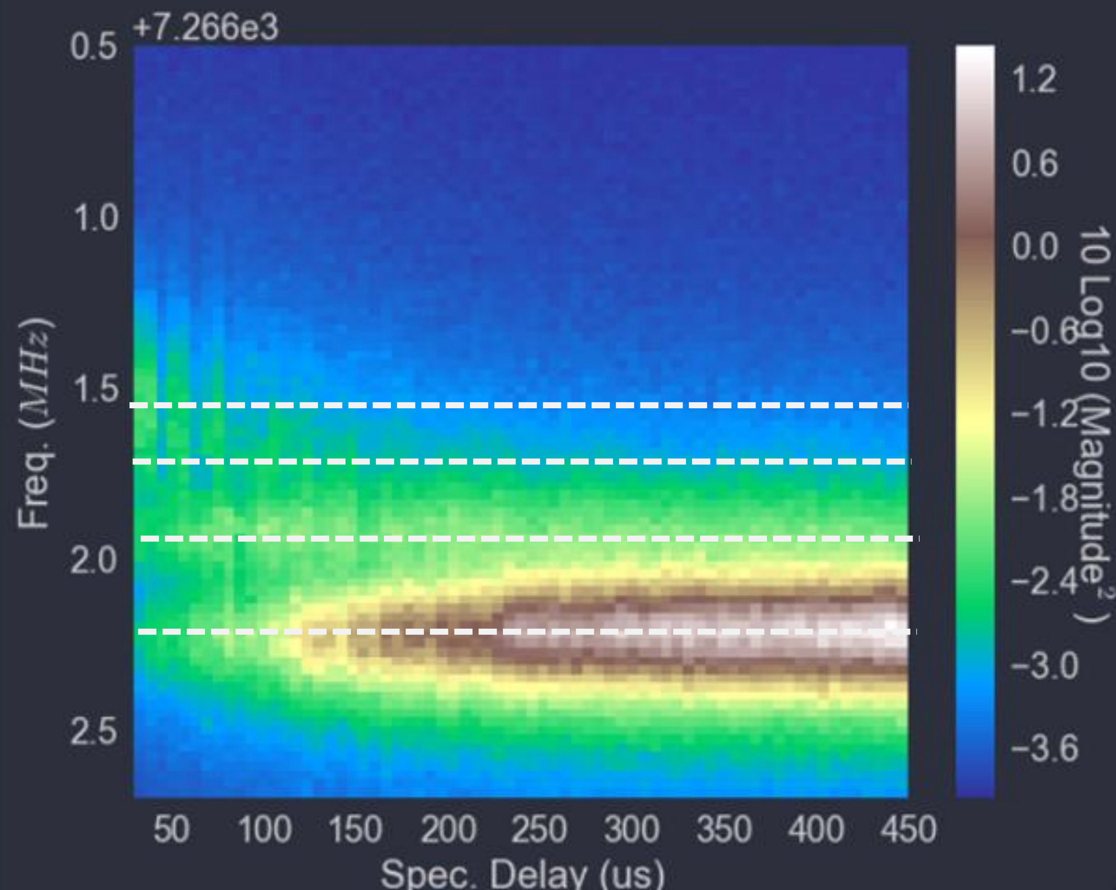


Bright state

|f>

|e>

Low power g peak



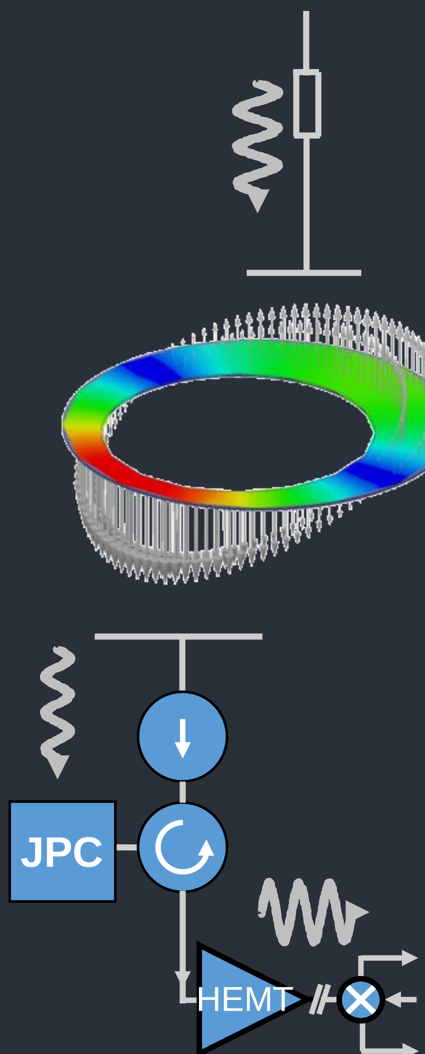
$T_{readout}$ = 450 ns

k/2pi = 340 KHz

χ_{qr} = 260 KHz

Looks very similar for different powers down to a threshold (more on next slides)

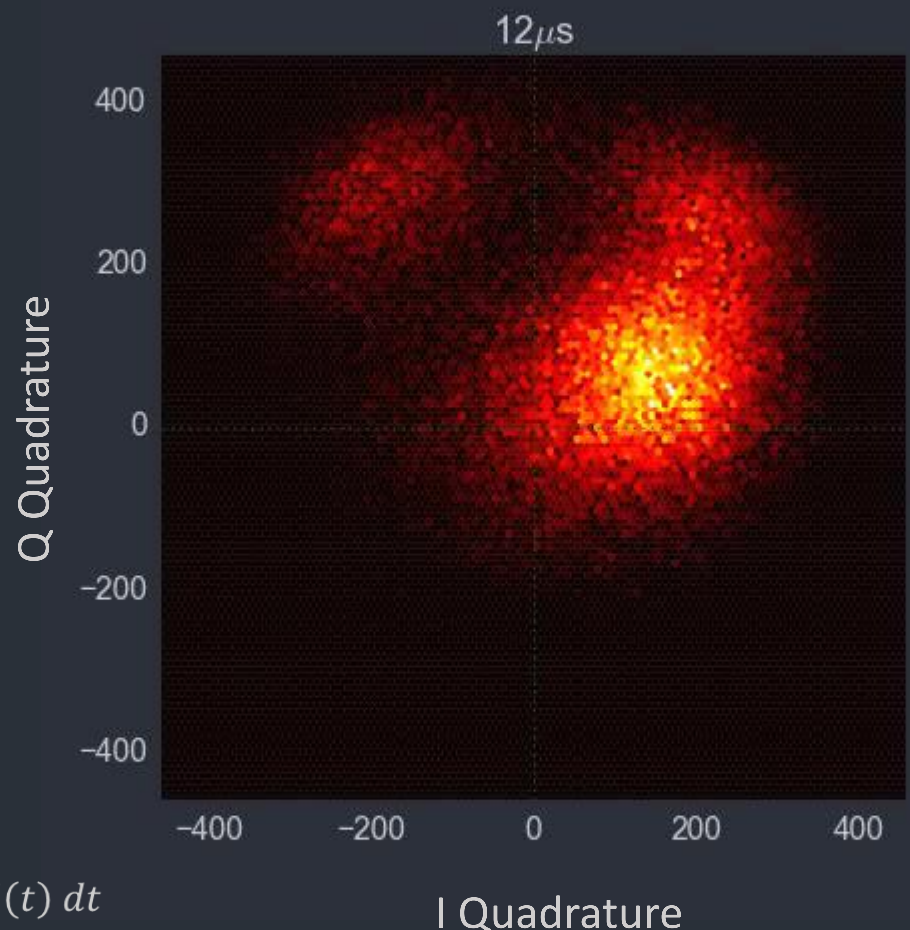
JPC Readout & Resolved Histograms



$$I_m = \int_0^{T_m} I(t)\, dt$$

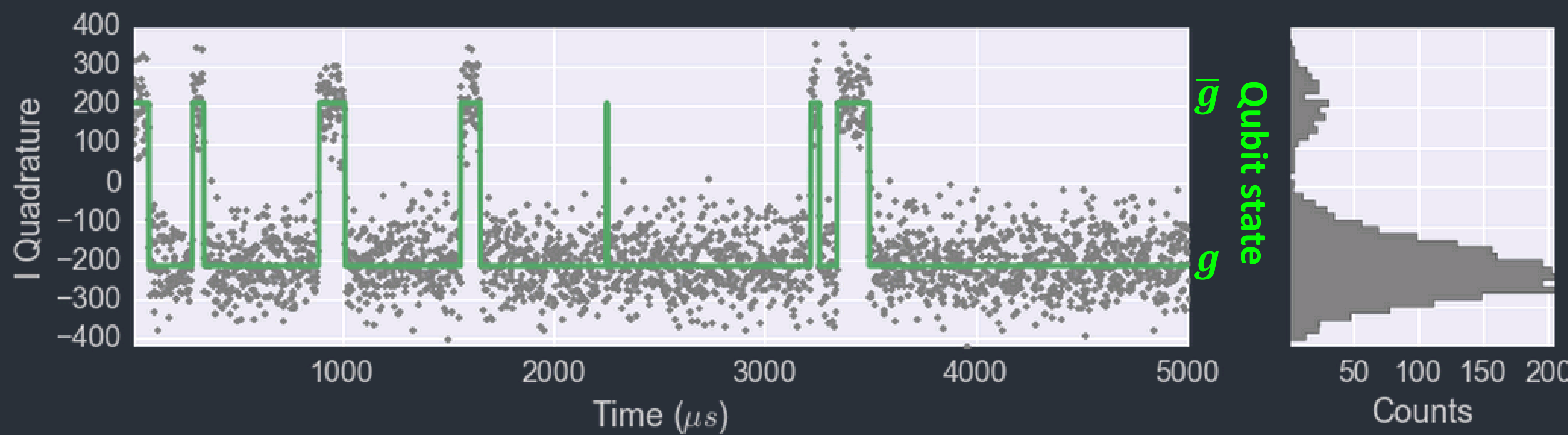
$$Q_m = \int_0^{T_m} Q(t)\, dt$$

Delay after injection:



2 µs integration time

Time Domain Analysis (Preliminary)



Three layers to the analysis:
(see Uri's MM rehearsal for more)

1. **Qubit state v. time:** determined from IQ time series using unbiased filter.
2. Qubit T1 & polarization: from qubit state jump statistics.
3. QP Dynamics: x_{qp}, temp. of bath, etc. inferred from qubit T1 (rates) & polarization.

A few remarks:
g / not g
Correlation between measurements
Some biases in filter
But gives us general picture for all states and rates!

U. Vool and I. Pop, et al. 2014; C. Wang, et al. 2014

2. Qubit T1 & polarization

from tracking dynamics of the qubit state

Highly excited region

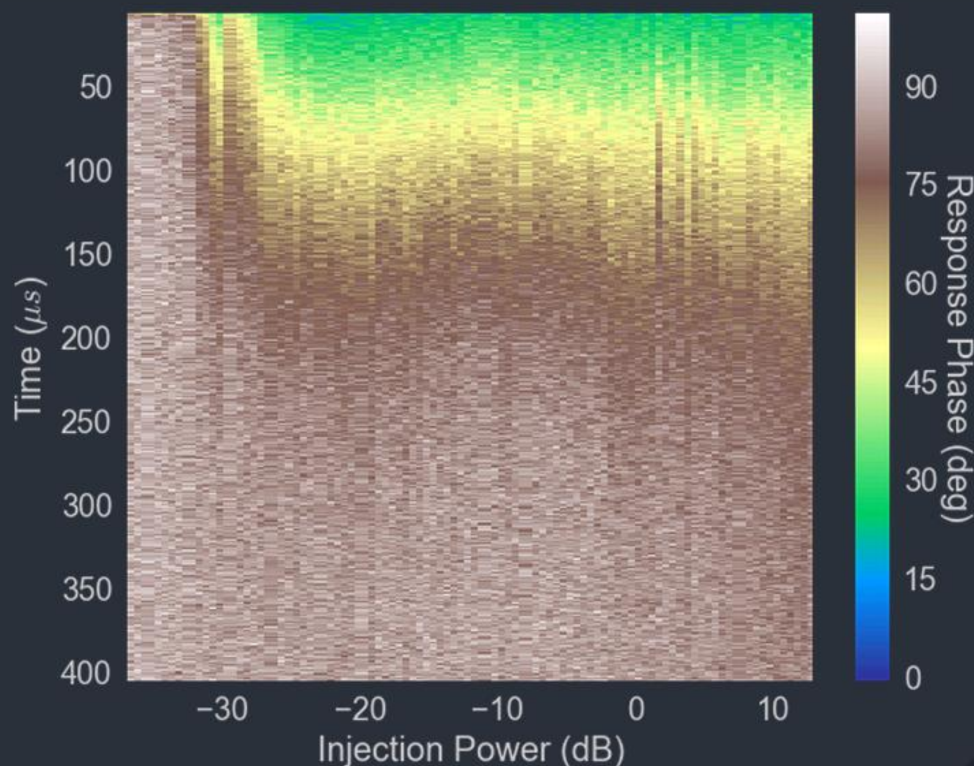
ignore highly excited region (more on it in later slides)

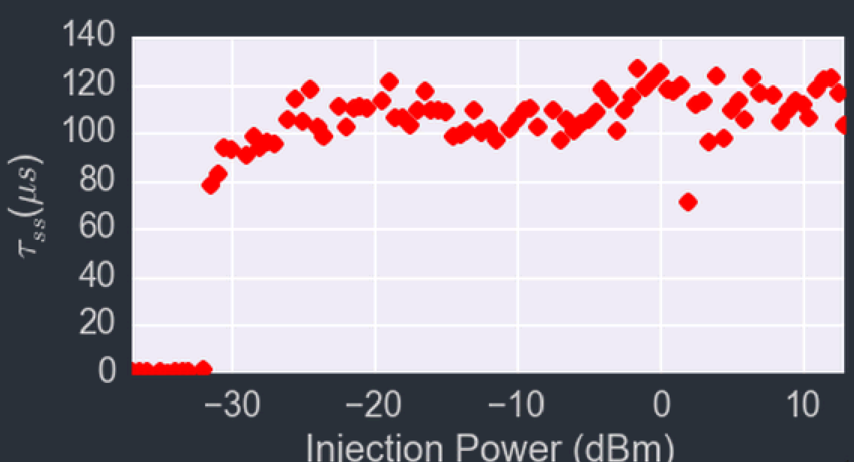
The qubit T_1 is shorter closer to the injection but it recovers on a timescale of ~110 µs

The population relaxes to steady state on the same time scale.

U. Vool and I. Pop, et al. 2014; C. Wang, et al. 2014

Quasiparticle Injection Threshold Behavior





On left:

qubit population versus time for different injection power

Rates appear to be:

Independent of injection power

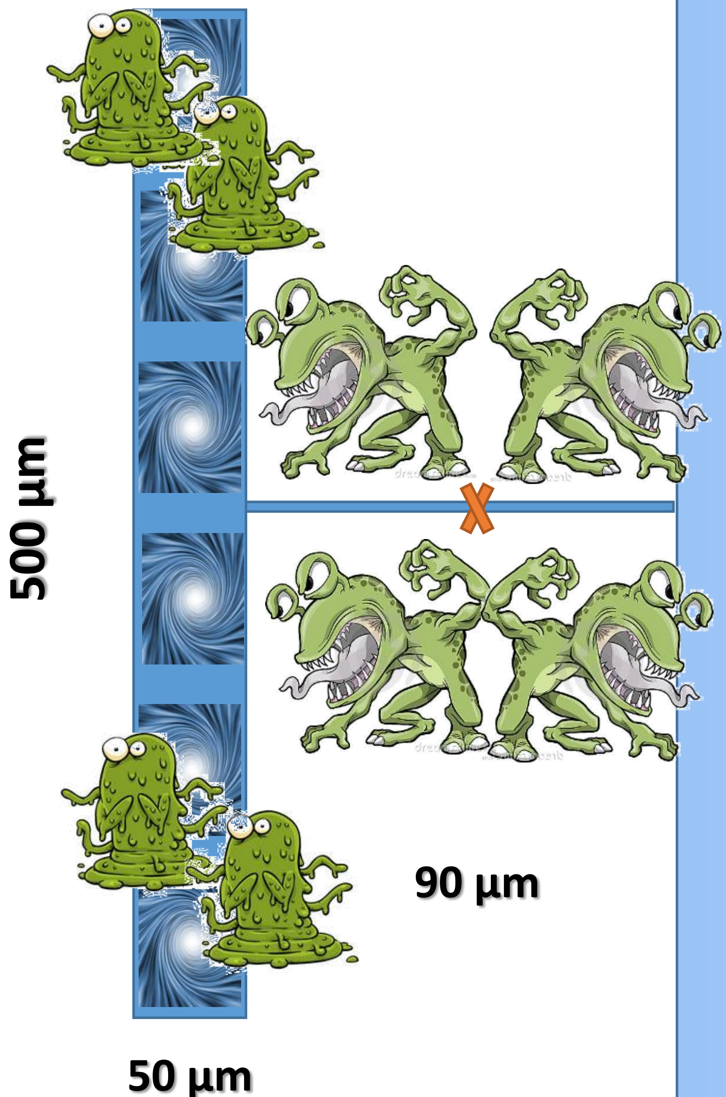
Independent of readout power

Quasiparticle equilibration rate to steady state:

Device *	Tau_ss
Drawbridge Transmon	0.11 ms
Fluxonium	0.13 ms
'Fat' Transmon	0.25 – 2.8 ms
'Skinny' Transmon	5 - 18 ms

U. Vool and I. Pop, et al. 2014; C. Wang, et al. 2

A plausible story



(1) Diffusion Γ_D
(2) Vortices Γ_V

$$\Gamma_{T1} = \Gamma_D + \Gamma_V$$

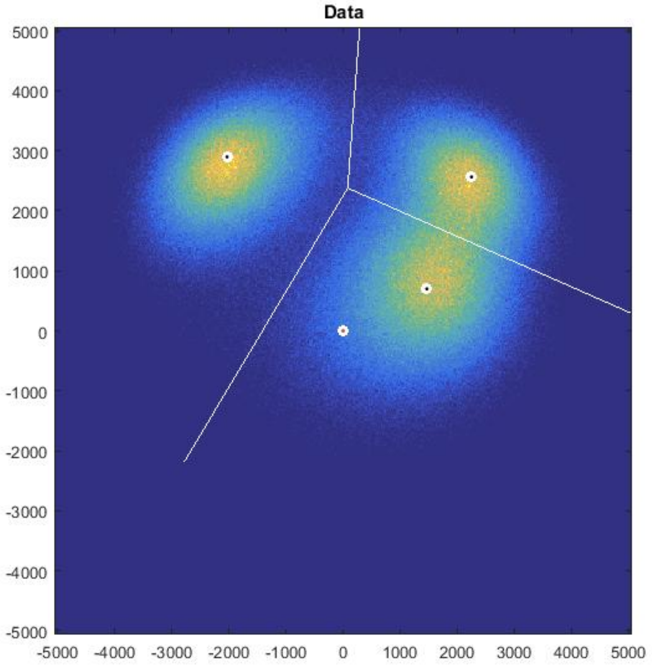
$$\Gamma_D = \frac{Area * Length\ of\ bridge}{width * Diffusion\ const.}$$

$\approx$ 1ms

$$\Gamma_V = \frac{N * Trap.power}{Area}$$

$\Rightarrow$ N ~ 30 vortices

Some Next Steps



- Extract all rates between g, e, f+ from IQ time correlations ala **Nissim**

Summary & Conclusions

Proof of concept devices

Achieved

System parameters & photon number splitting regime

Easily engineerable parameters, similar to other implementations

Coherence through dynamical decoupling

Large T2s can be obtained if we can get rid of low frequency noise

Quasiparticle dynamics

Fast relaxation (vortices in film?)

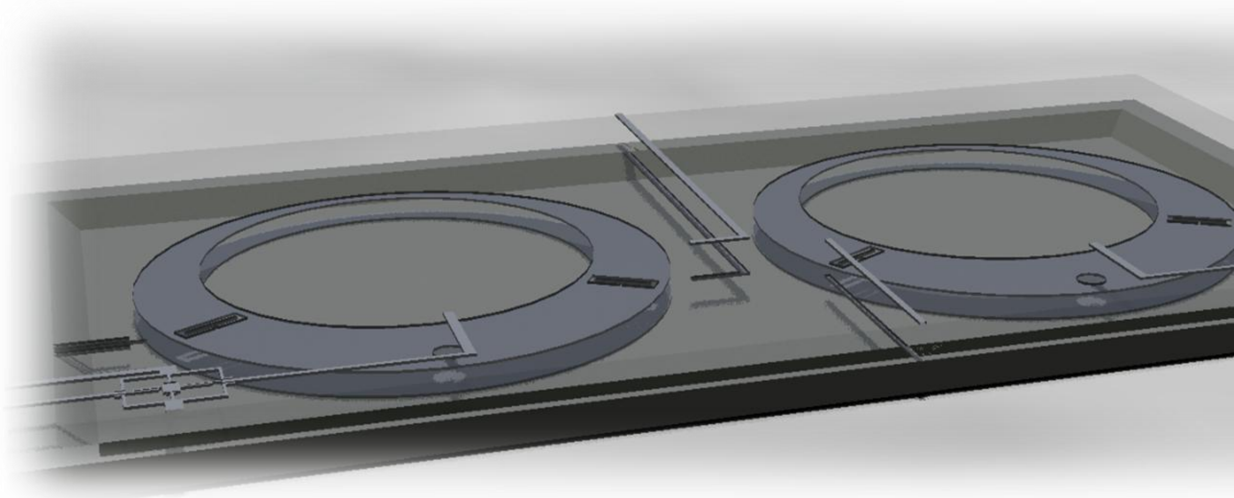
Future

Wafer stacking

Multiple qubits

New materials

Fluxonium




THANK
YOU!