Quantum Nanoelectronics

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Workshop on Quantum Sensing 2017

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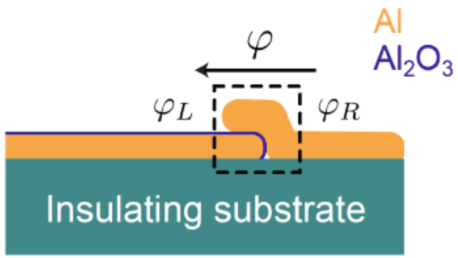
SUPERCONDUCTING CIRCUIT TOOLBOX

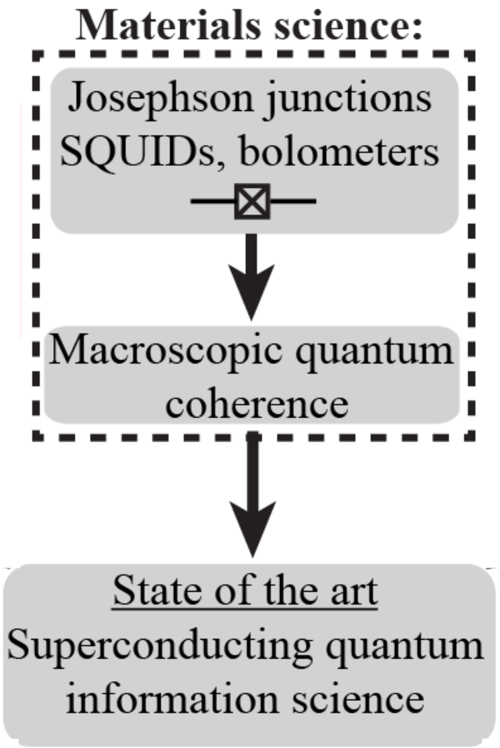
Inductor: Josephson Junction



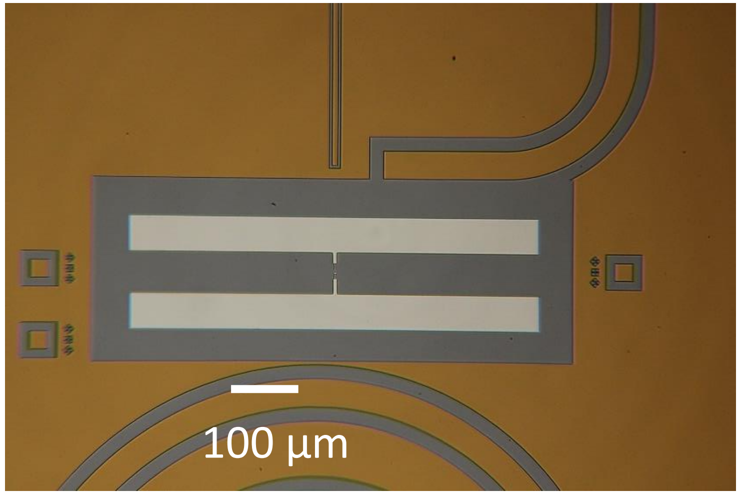
B. Josephson. Phys. Rev. Lett. 1, 251 (1962)

Nonlinear current - flux relationship

$$L(\phi) = \left(\frac{\partial I}{\partial \phi}\right)^{-1} = \frac{\phi_0}{I_0}\frac{1}{\cos(\phi/\phi_0)}$$

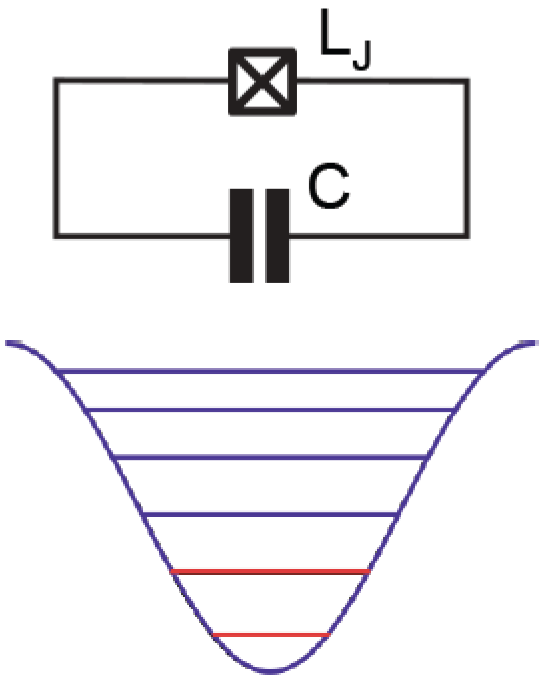


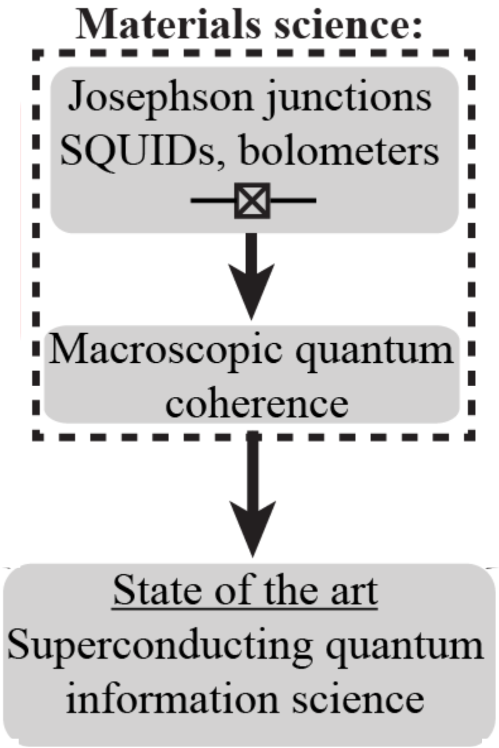
Capacitor: Geometric capacitance

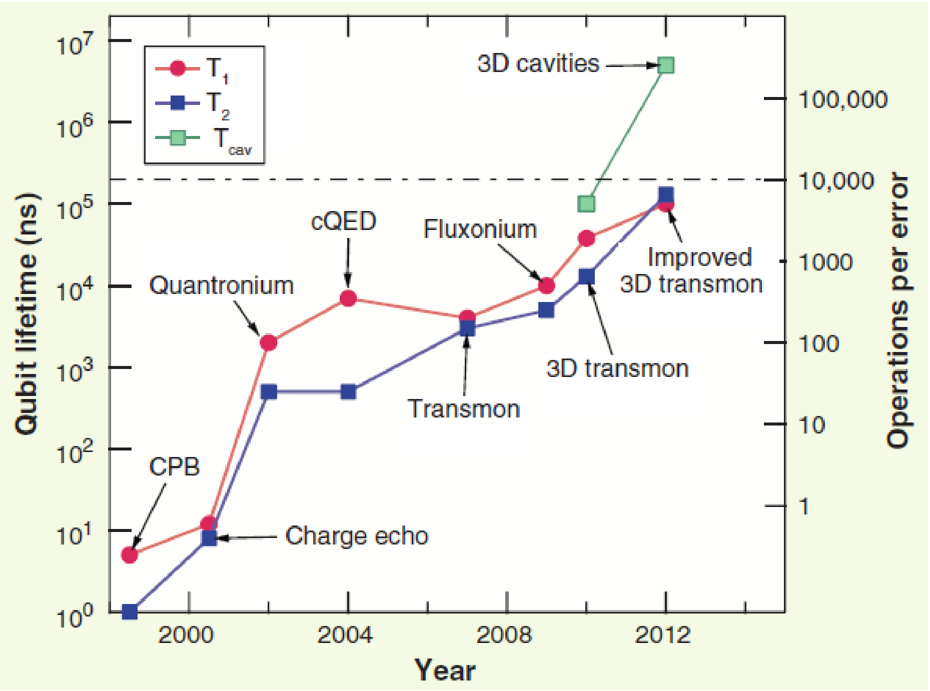


SUPERCONDUCTING CIRCUIT TOOLBOX

Superconducting qubit

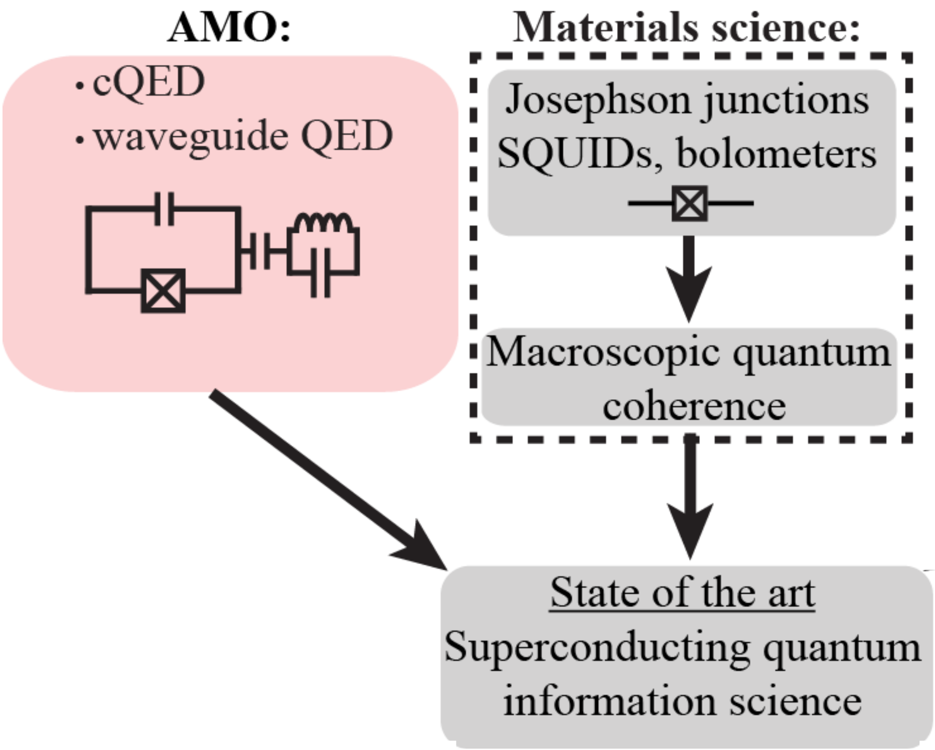






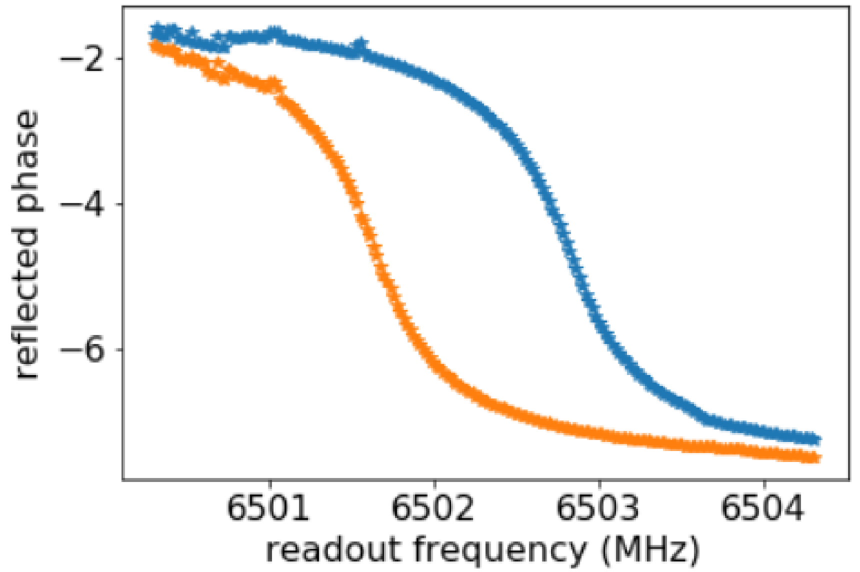
Devoret and Schoelkopf. Science 339 1169-1174 (2013)

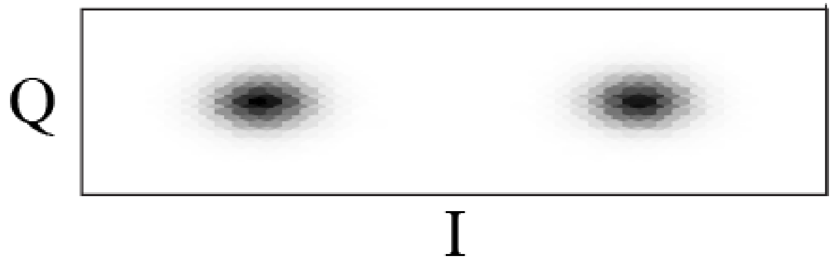
SUPERCONDUCTING CIRCUIT TOOLBOX



Cavities as a resource:

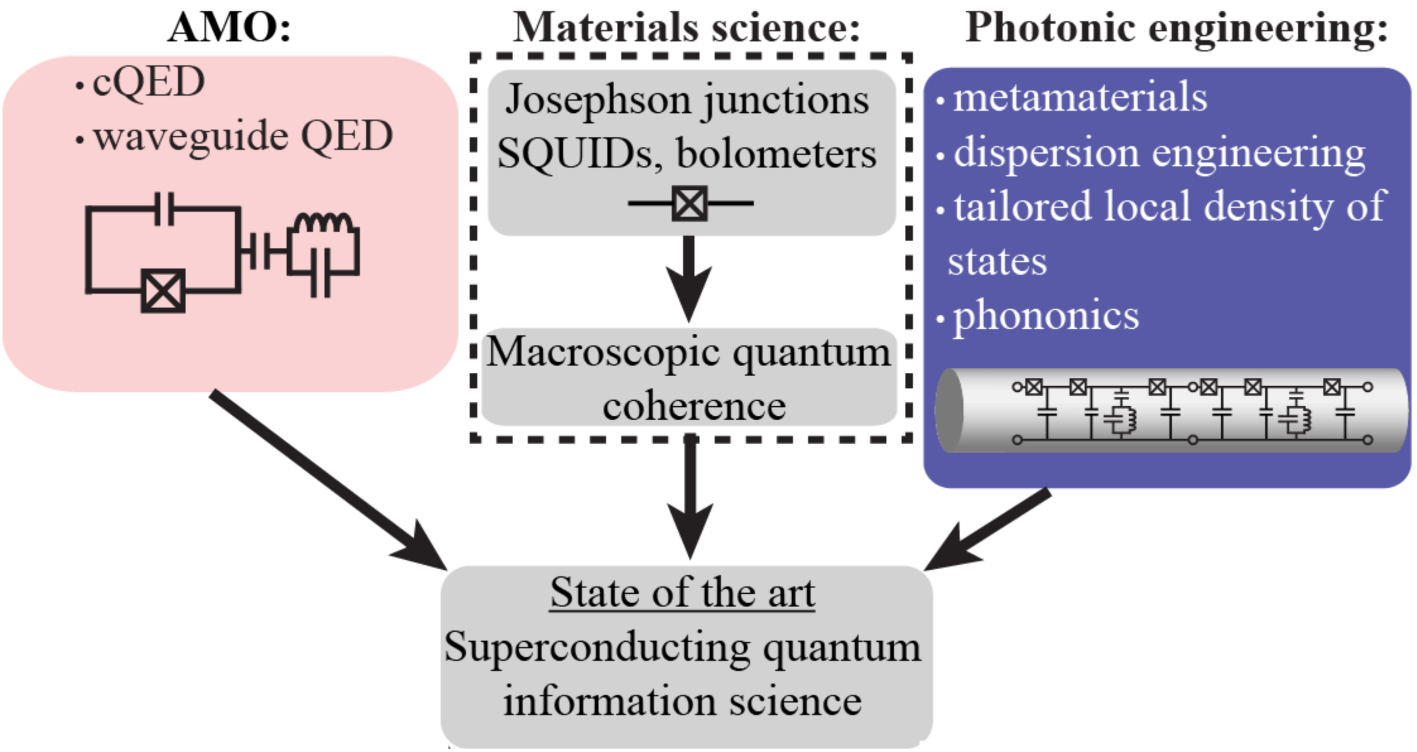
eg. qubit-cavity interaction, dispersive readout





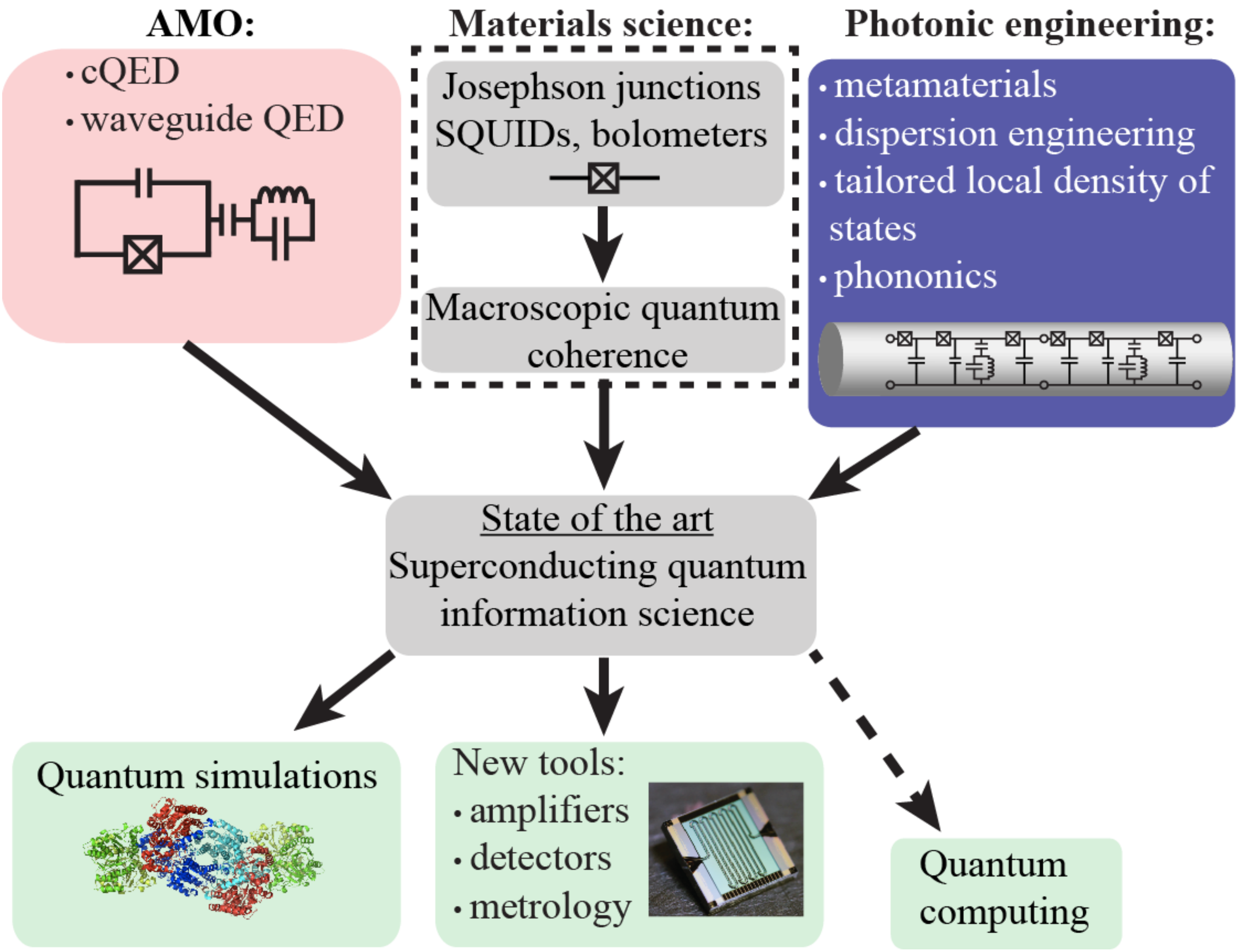
AMO provides a modality for engineering light matter interaction between qubits and cavities

SUPERCONDUCTING CIRCUIT TOOLBOX



Based on mode engineering, photonics can provide devices with:
broad bandwidth, directionality, non-reciprocity

SUPERCONDUCTING CIRCUIT TOOLBOX

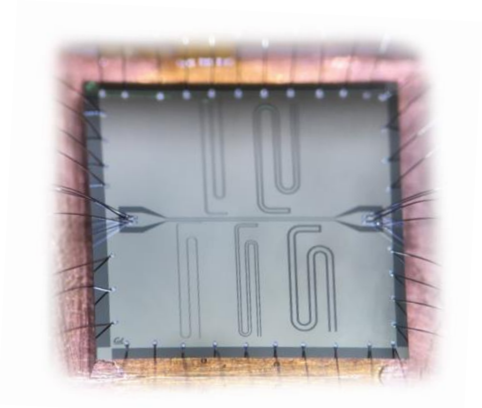


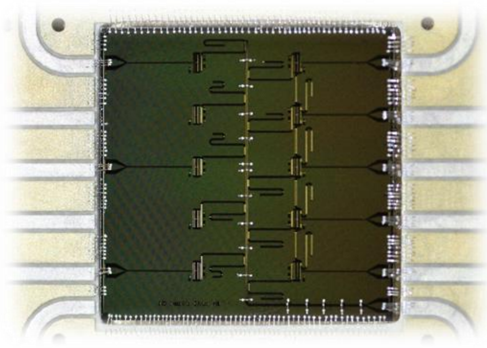
STARTING MATERIALS

Al	TiN	Nb
Early 2015: $Q_i = 2 \times 10^5$	Early 2015: $Q_i = 1 \times 10^5$	Late 2015: $Q_i = 1 \times 10^5$
- annealed sapphire - sputtered Al	- (100) Si - reactively sputtered TiN	- (100) Si - sputtered Nb

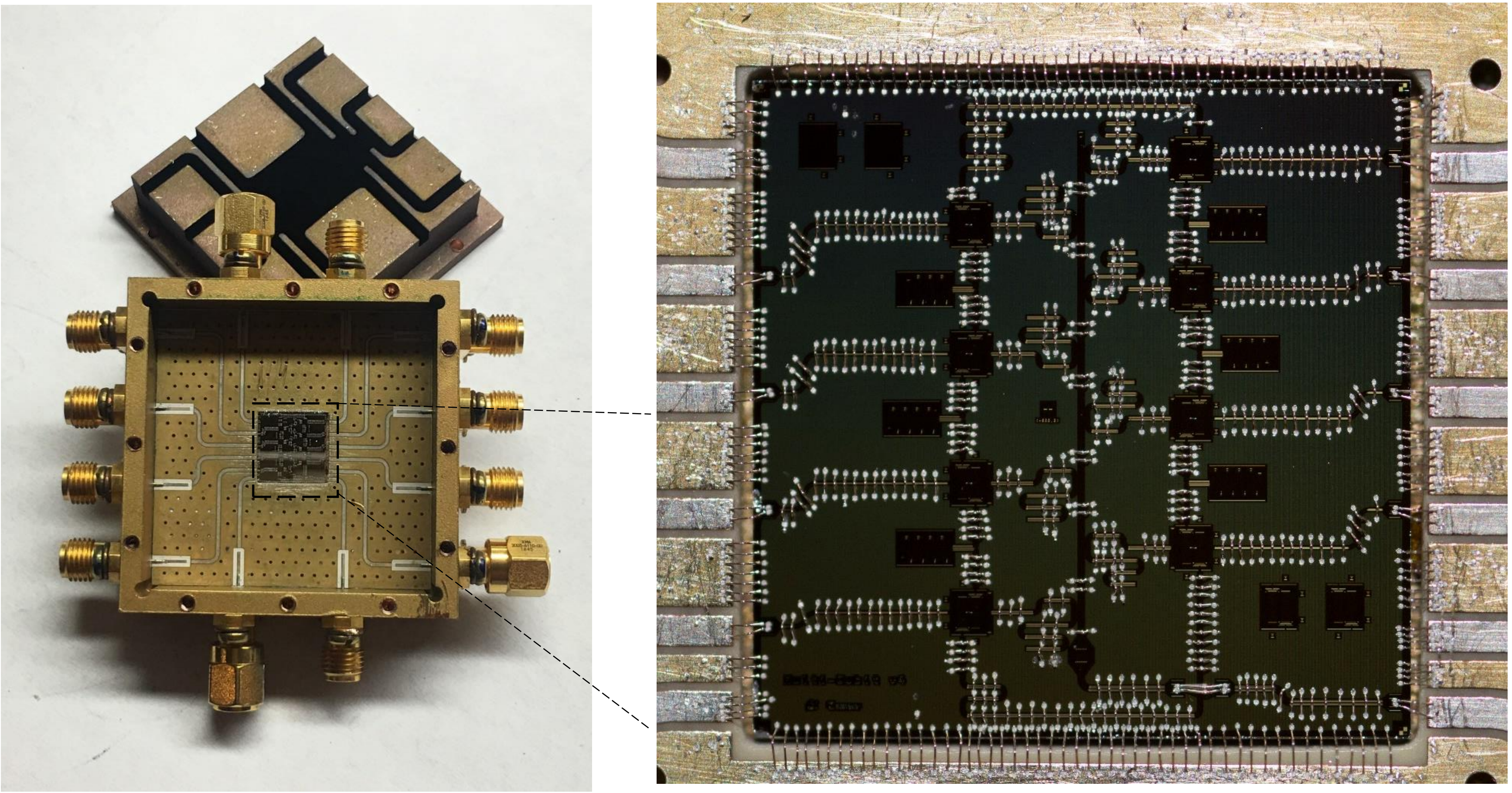
Q_i measured at 100 mK

Al	TiN	Nb
1.2×10^6	**8.7×10^5**	**1.1×10^6**
- e-gun Al (Si & sapphire) - post-processing	- (111) Si - (200) TiN	- optimized film stress





FROM FILM TO DEVICE



Where design starts…

- E & M design (Comsol, HFSS)
- Materials processing

Qubits are not "just resonators"…

- Where is the lossy interface ?
- Different coupling to QPs, radiation, …

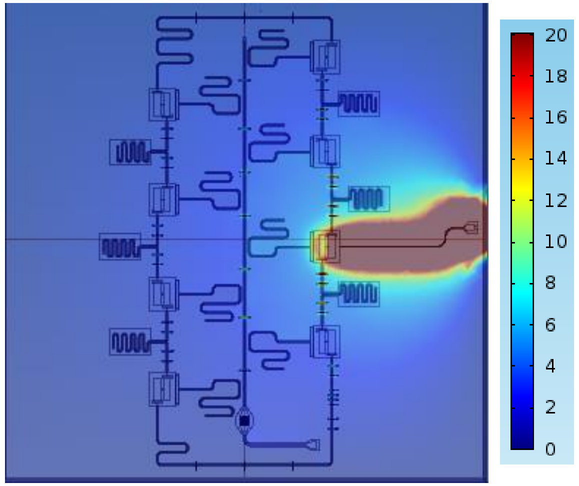
The measurement problem ...

- Measurement <-> Decoherence
- Quantum limited amplifiers

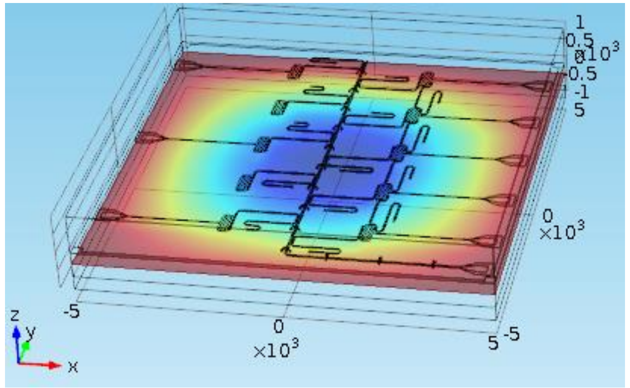
MULTI-QUBIT CIRCUIT DESIGN PROCESS

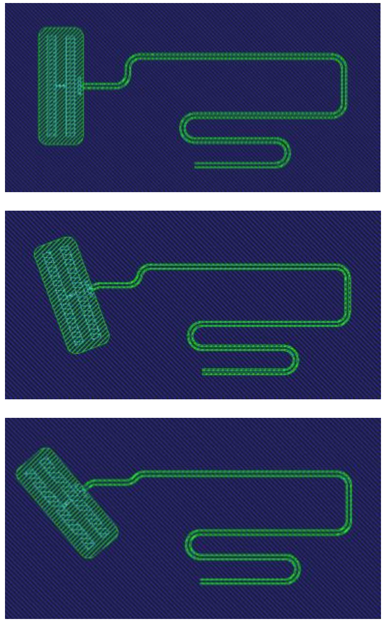
- COMSOL and HFSS
  - Full wave electrodynamics solvers using the finite element method
  - Enables simulation of electromagnetic fields, radiation loss, surface participation, couplings between arbitrary modes.
- GDSPY
  - Python based circuit layout library

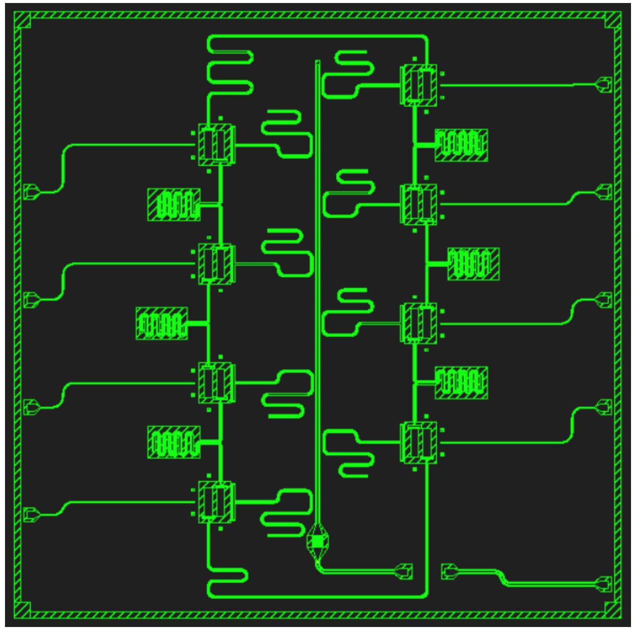
crosstalk prediction/mitigation



substrate modes

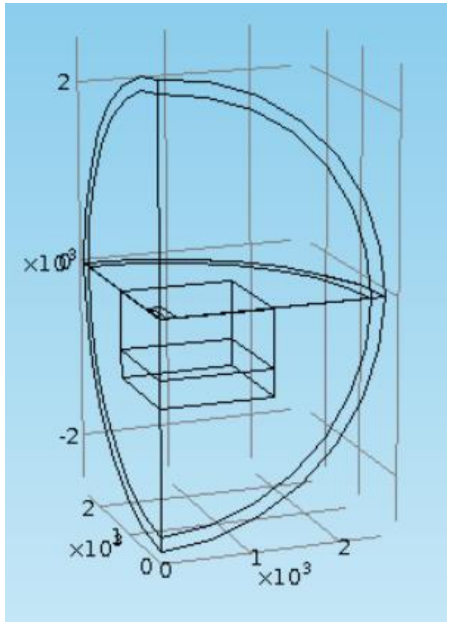




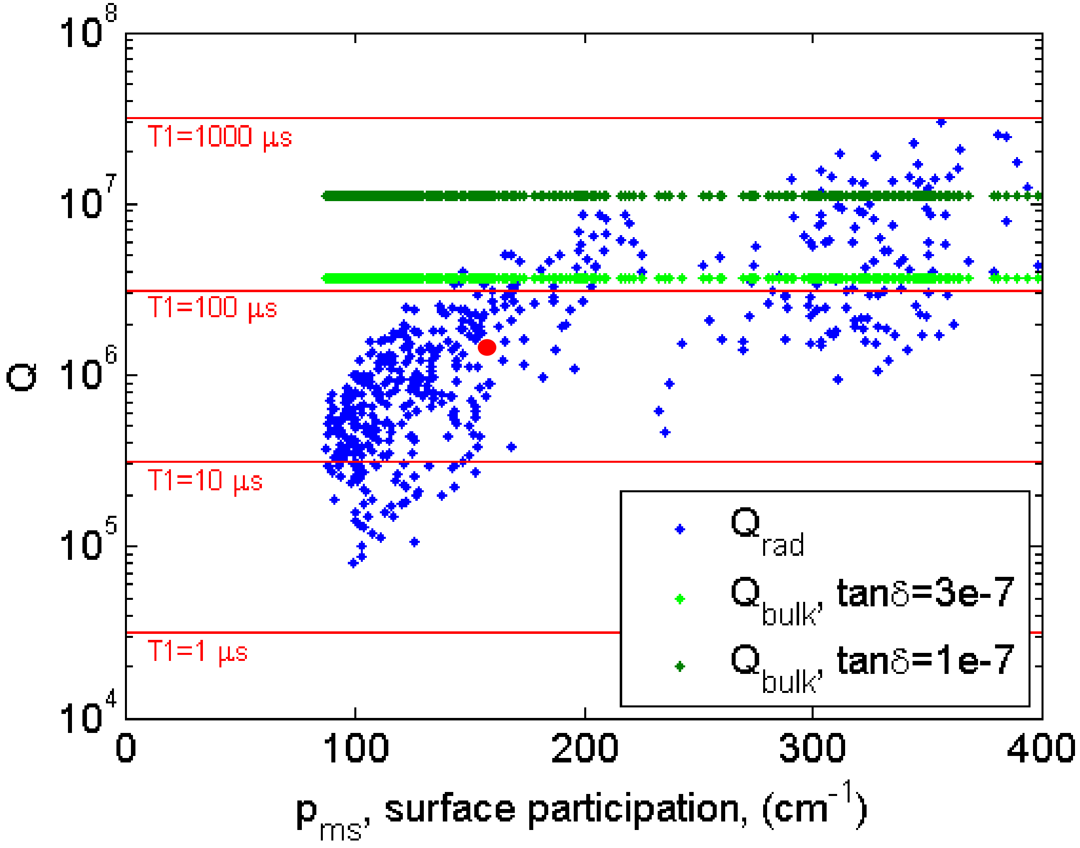


RADIATION LOSS–SURFACE PARTICIPATION TRADEOFF

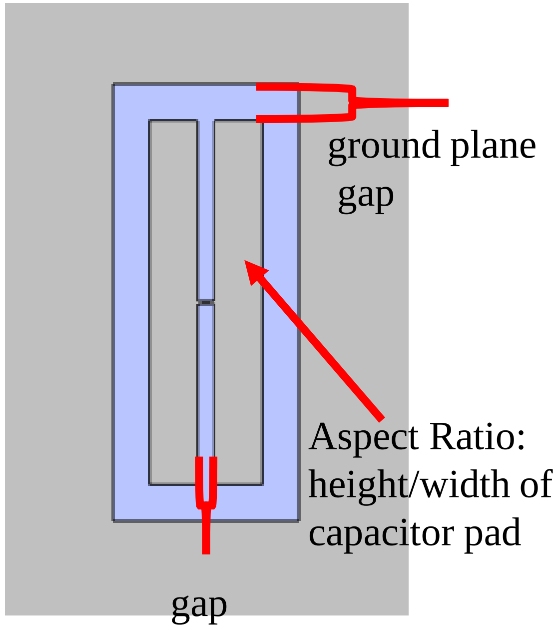
Conservative bound for radiation loss:
Qubit surrounded by a perfect absorber (a PML)



Geometry dependence of radiation Q and surface participation



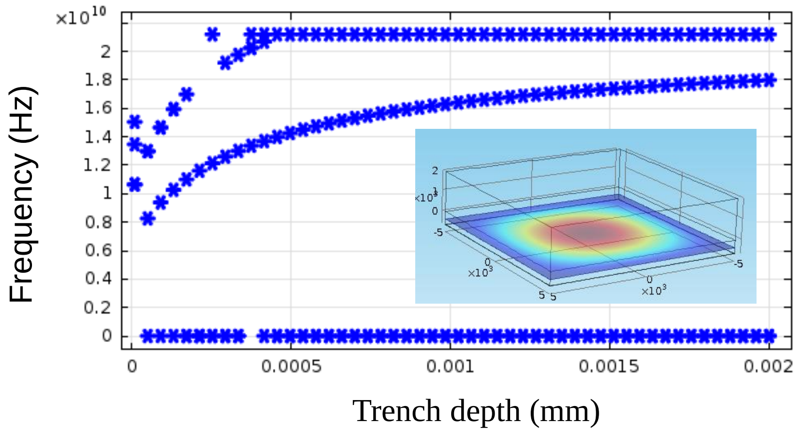
Parameters Varied:

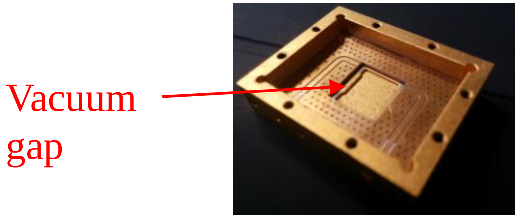


Resonance freq. 5-6 GHz

EM: SPURIOUS MODE IDENTIFICATION AND MITIGATION

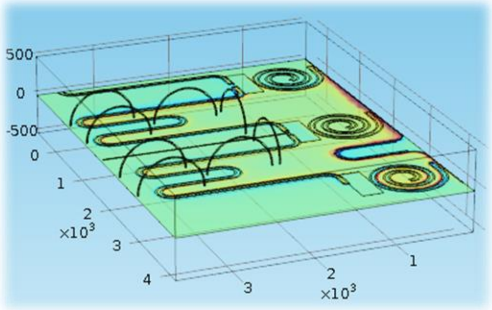
Suppressing package + chip modes





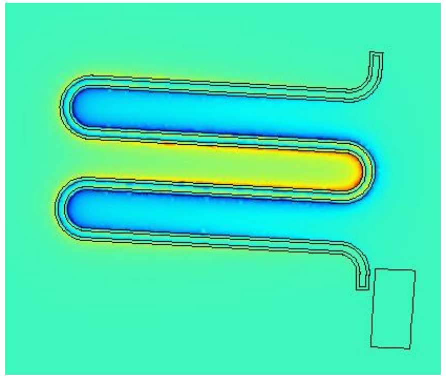
- Dilute substrate permittivity
- 300 micron gap -> 12 GHz parallel plate mode
- Increase gap to 2 mm-> 18 GHz parallel plate mode

Spurious mode identification and mitigation

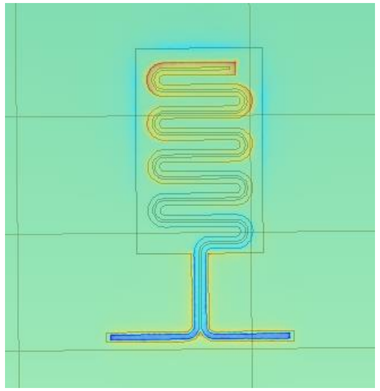


Hybrid CPW-CPS resonators with higher spurious mode frequencies

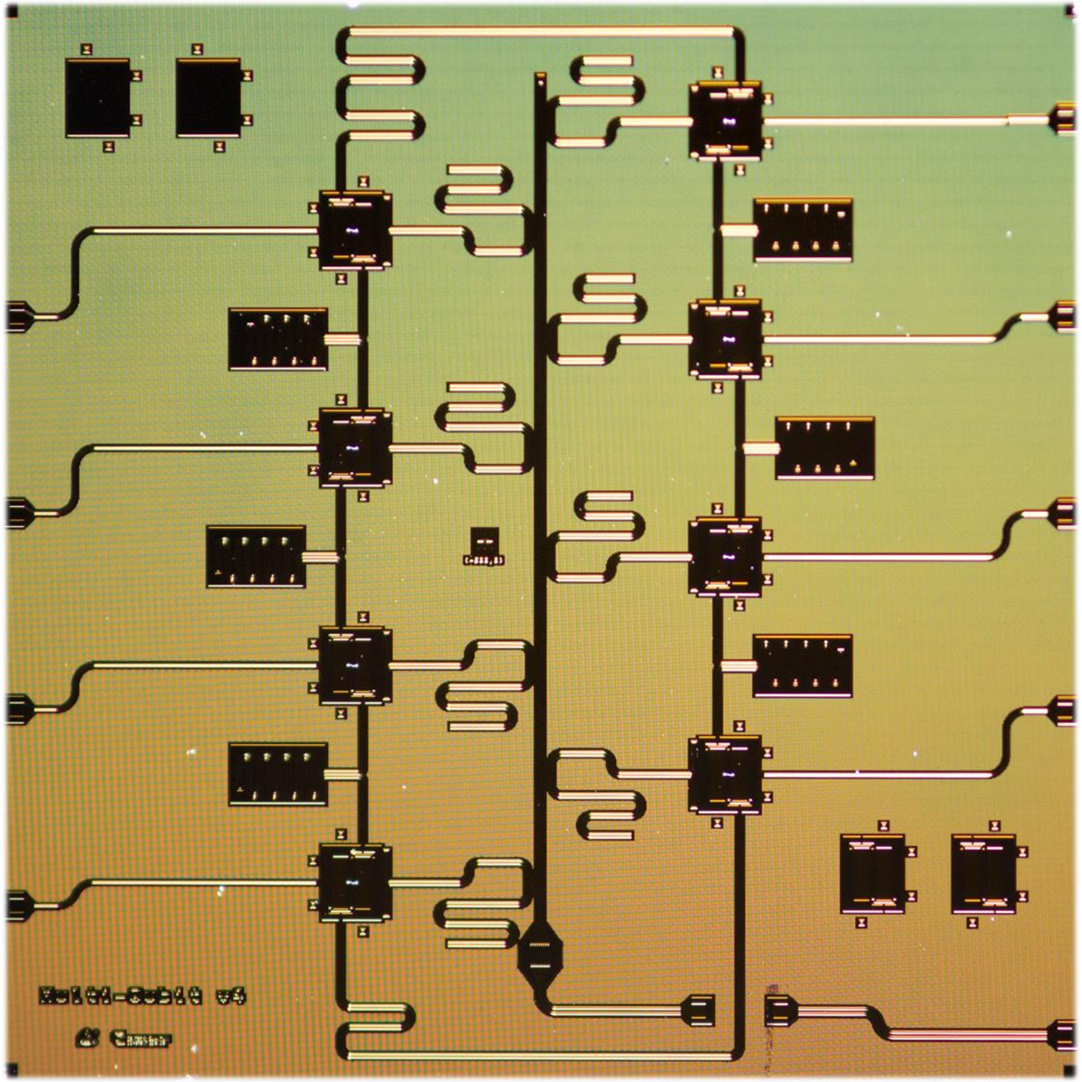
10 GHz slotline mode

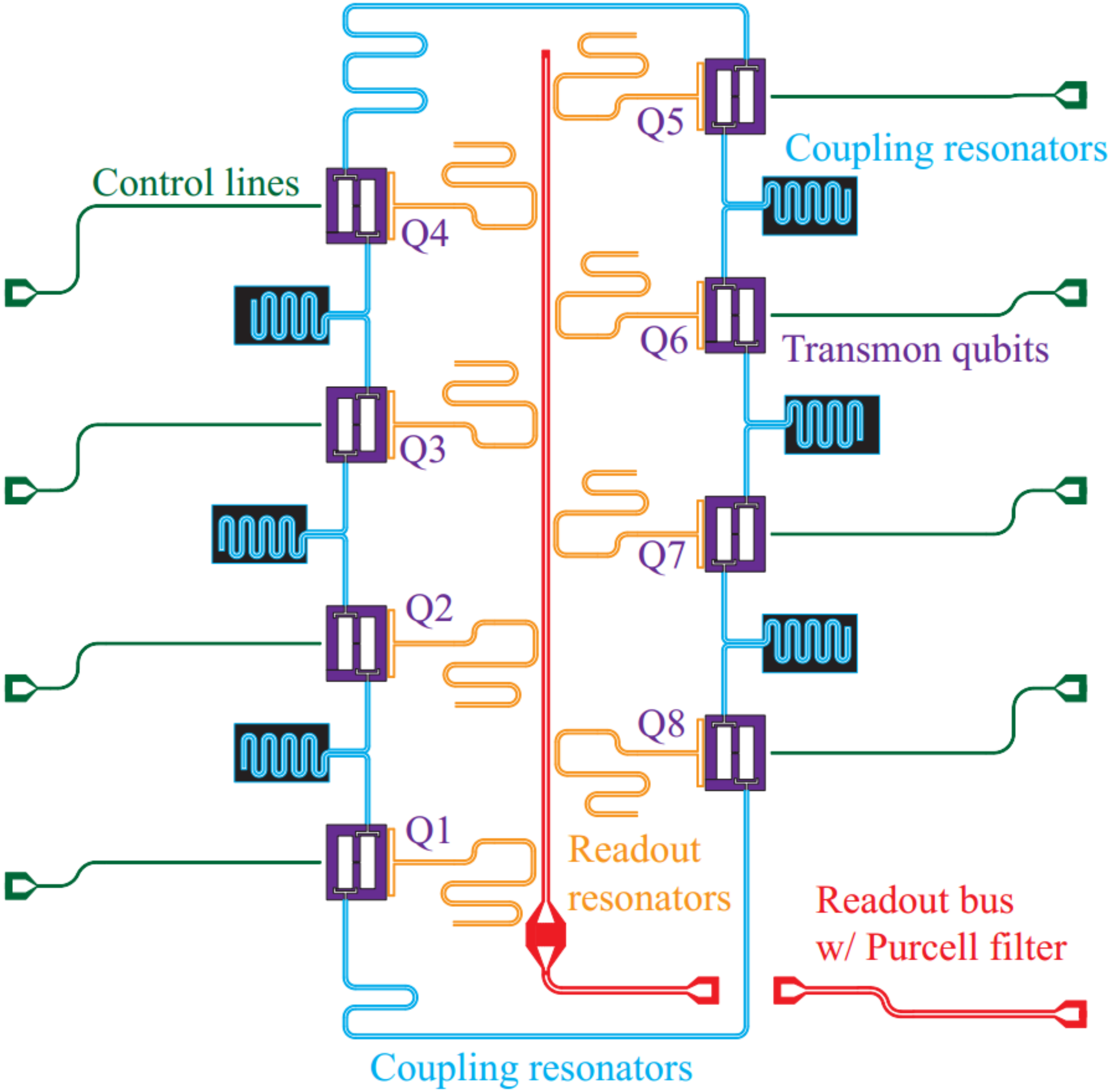


17 GHz slotline mode



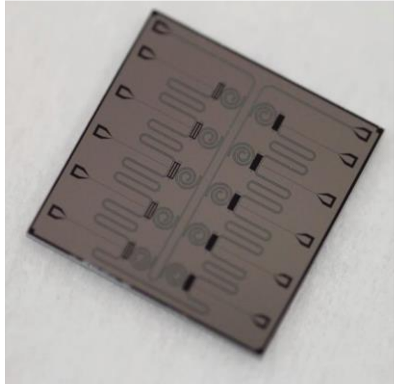
CURRENT ARCHITECTURE: 8 QUBIT RING





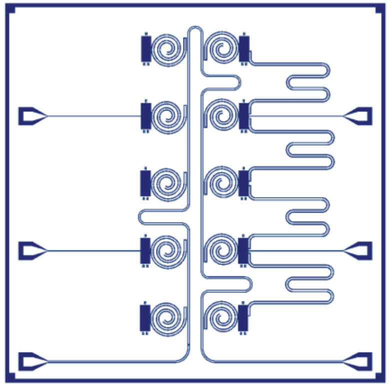
EVOLUTION OF QUBIT COHERENCE

v1



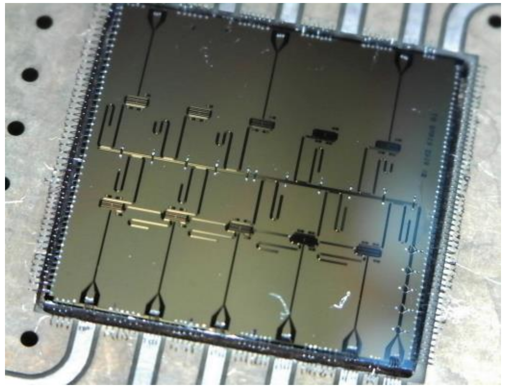
- 10 qubits with readout resonators, control lines, and coupling resonators
- **T_1 ~ 1 - 4 us**

v2



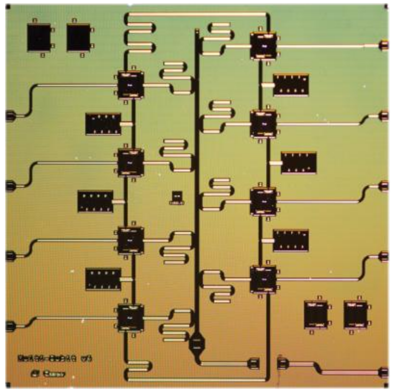
- A/B test of coupling resonators, control lines
- Learned that wirebonding coupling resonators is VERY important.
- **T_1 ~ 9 us**

v3



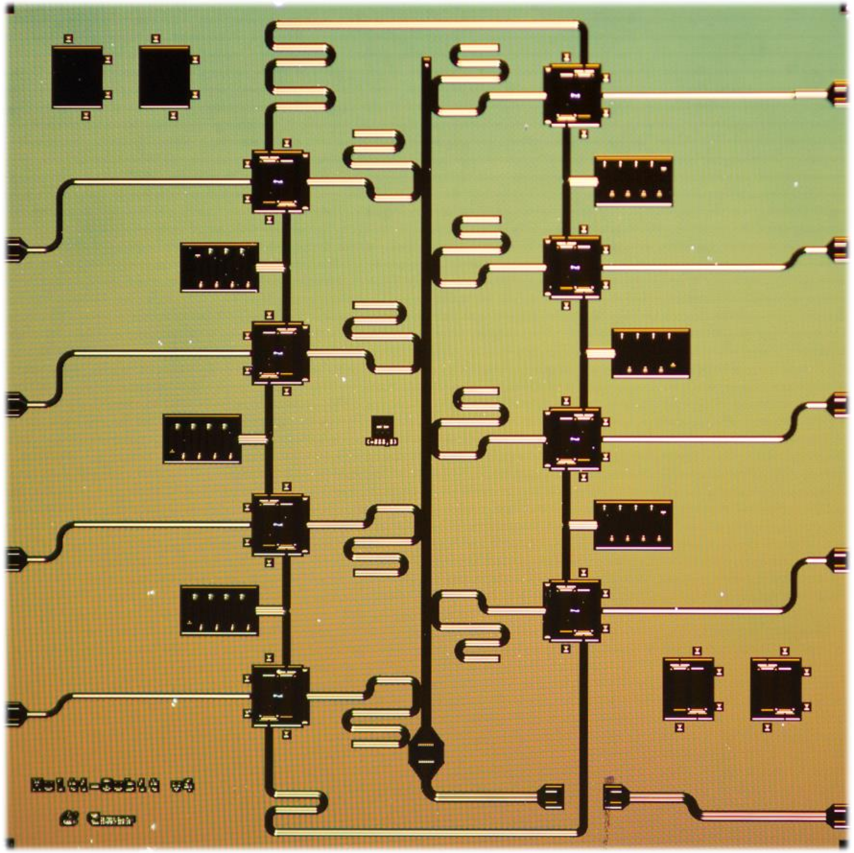
- New readout resonator design to increase frequency of slotline modes
- Niobium capacitor pads
- **Max T_1~13-16 us with wirebonds on bus**
- **Max T_1 > 20 us after wirebonding everything**

v4



- Purcell filter
- Coupling resonators with higher slotline mode frequency
- Design optimizations to minimize crosstalk
- Ring geometry
- Oxide removal
- **Max T_1~78 us.**
- **T_1 35-50 us with control lines**
- **State of the art coherence**

STATE OF THE ART COHERENCE



Qubit number	f_{qubit} (GHz)	T_1 (μs)	T_2 (μs)	T_2^* (μs)
0	Fabrication Issue			
1	Wired in a non-comparable configuration			
2	5.3343	51	60	60
3	5.4938	38	70	48
4	5.3971	38	74	25
5	5.6345	50	72	58
6	5.4543	44	71	42
7	5.8666	35	55	41

BERKELEY (8-QUBIT)

T_1 ~ 43 μs

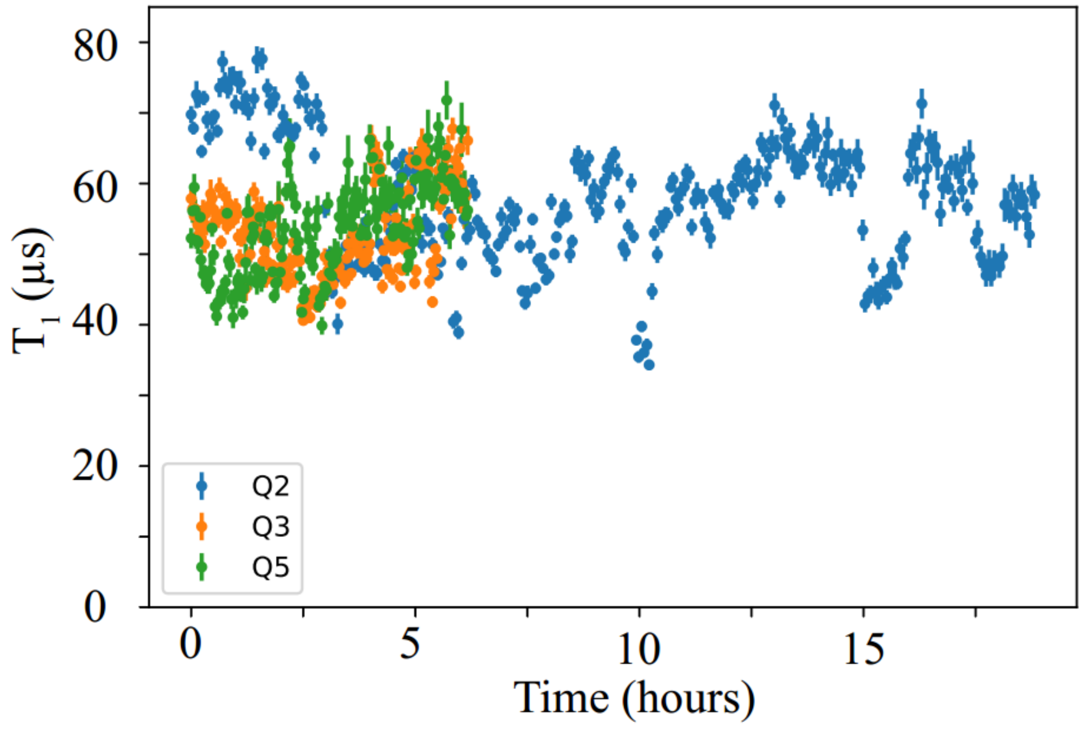
T_2^* ~ 45 μs

T_2 ~ 67 μs

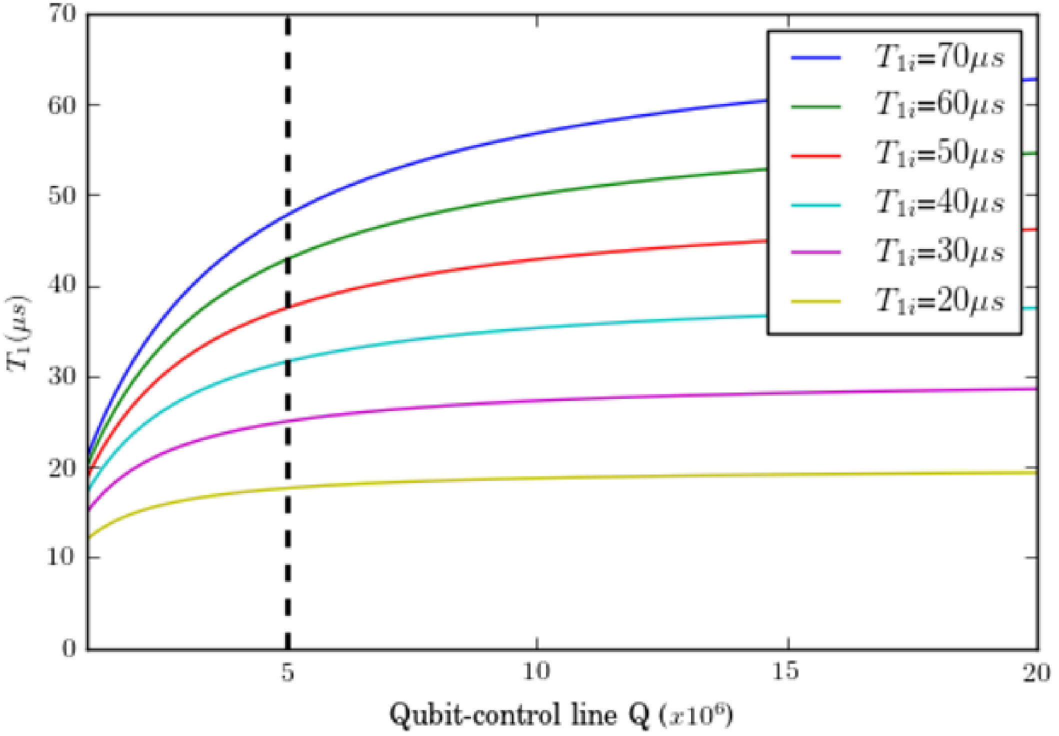
(2017)

STATE OF THE ART COHERENCE

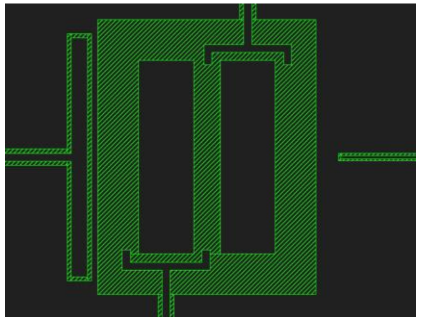
Experiment: with no control lines



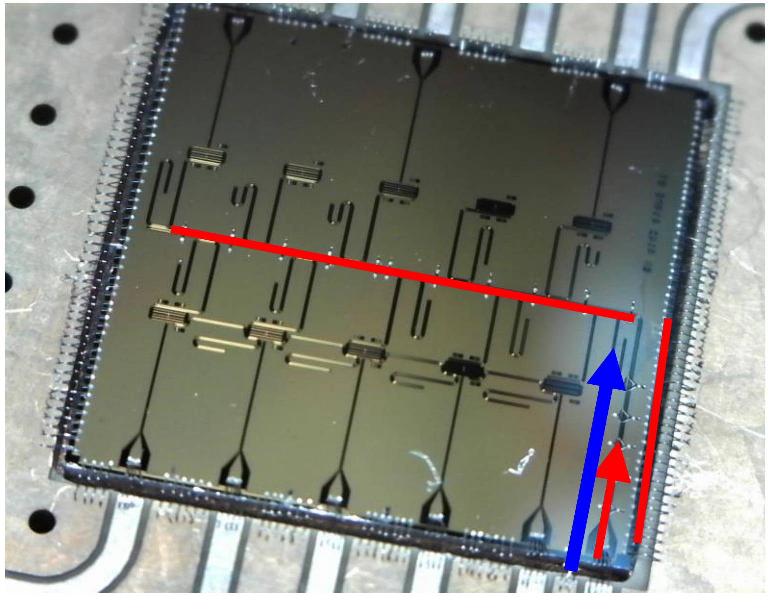
Theory



- Lifetimes increase without control lines
- Tradeoff between qubit lifetime (energy decay through control line) and crosstalk
- Observe variation in qubit lifetimes
- Dominant loss mechanism no longer 'simple dielectric loss' or Purcell decay



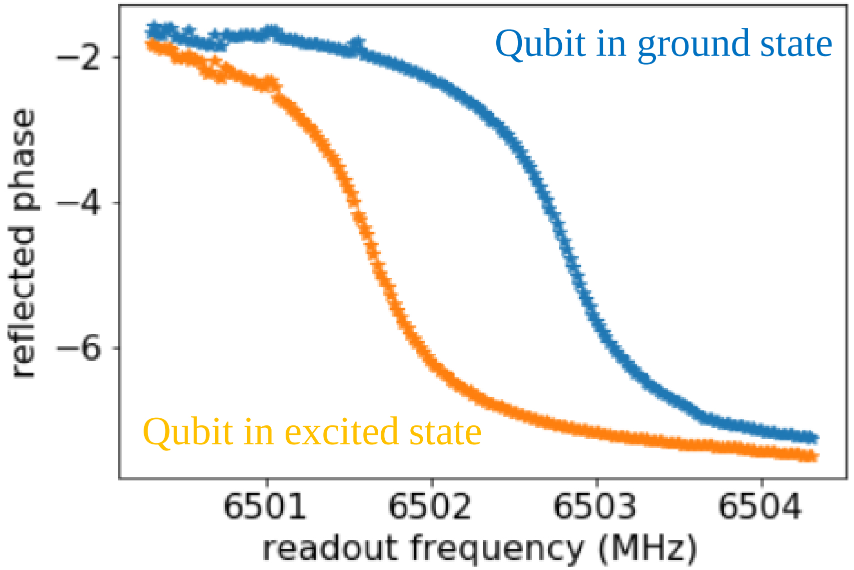
HOW TO MEASURE A QUBIT?



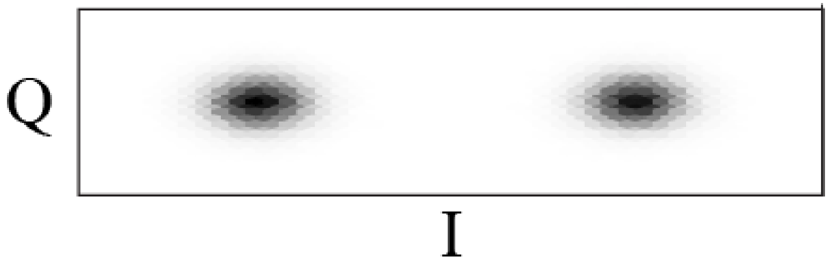
Control + Readout pulses

- Interact single photon level microwave pulse with resonator
- Amplify reflected/transmitted signal with low-noise quantum limited amplifier

Microwave response of readout resonator:



In the IQ plane: "Constellation diagram of a qubit"

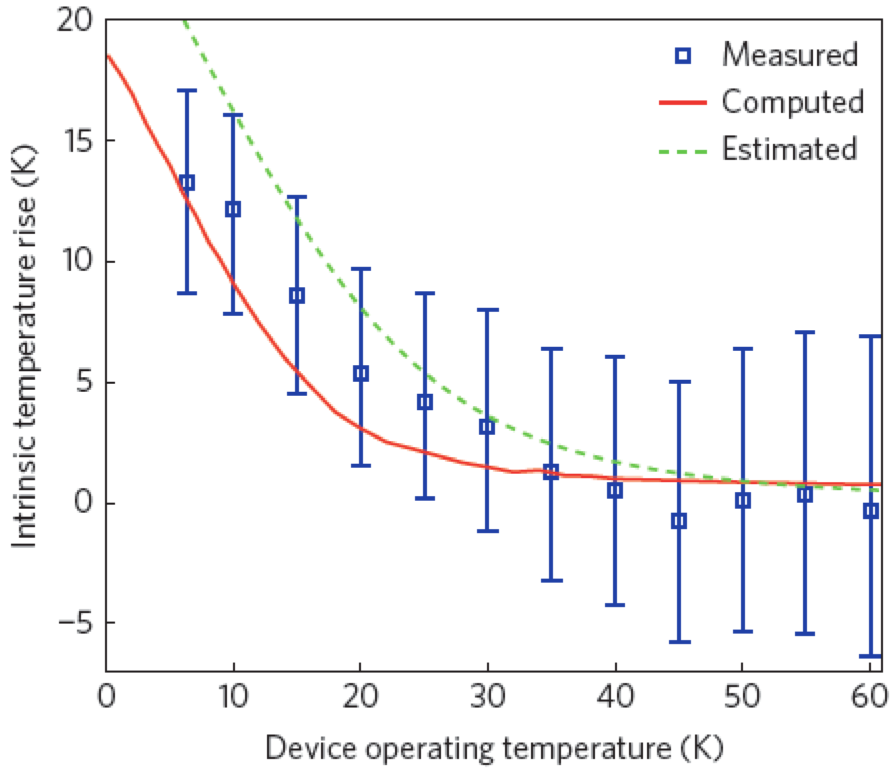


COMMERCIAL MICROWAVE AMPLIFIERS TOO NOISY

Optical amplifiers:
Erbium doped fiber amplifiers

Quantum efficiency
$\eta \approx 90\%$

Microwave amplifiers



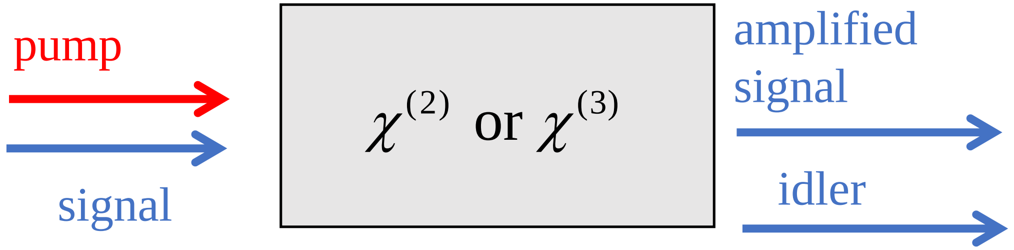
Schleeh et al. (Minnich group) . Nat. Mat. 14 187-192 (2015)

CAN WE DO BETTER WITH NONLINEARITY?

"Parametric amplification is shown to be ideal in the sense that it allows a simultaneous determination of the phase and number of quanta of an electromagnetic wave with an accuracy which is limited only by the uncertainty principle."

Louisell, Yariv, and Siegman. Phys. Rev. **124**, 1646 (1961)

Parametric amplification:



NONLINEARITIES IN SUPERCONDUCTORS

Decreasing nonlinearity

Increasing dynamic range

Single Josephson Junction in a Cavity

- Josephson Parametric Amplifier (JPA)
- single photon in a cavity level signals

Multiple Josephson Junctions in a Cavity

- Multi-junction JPAs
- 10’s to hundreds of photons

Many Josephson Junctions

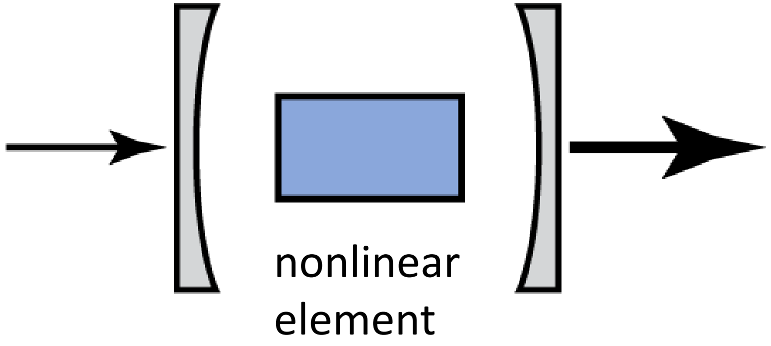
- Josephson Traveling Wave Parametric Amplifier (JTWPA)
- thousands to 10’s of thousands

Kinetic inductance (+geometry)

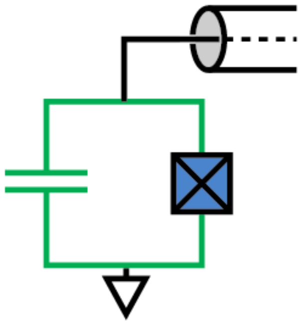
- Kinetic inductance TWPA (KIT)
- billion photons

CAVITY VS TRAVELING WAVE AMPLIFIERS

Optical parametric amplification

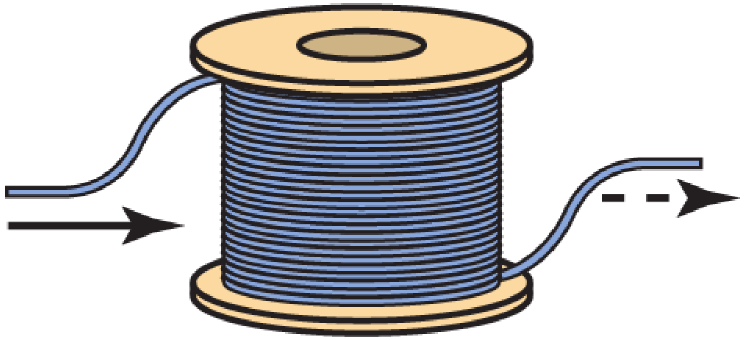


Josephson parametric amplifier

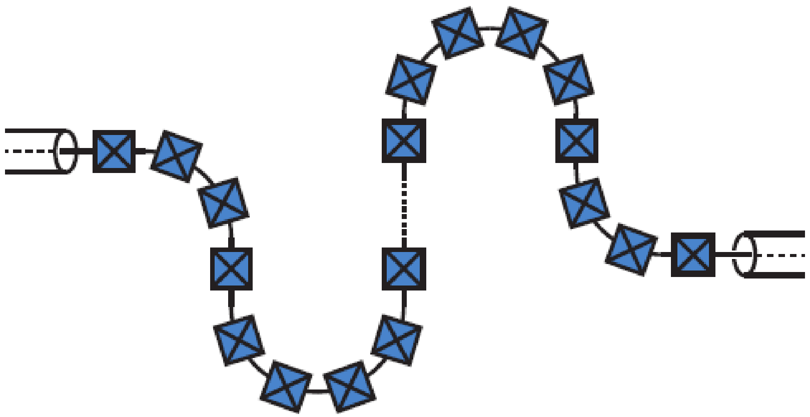


For JPAs, resonant cavity limits dynamic range and bandwidth!

Optical fiber parametric amplifier

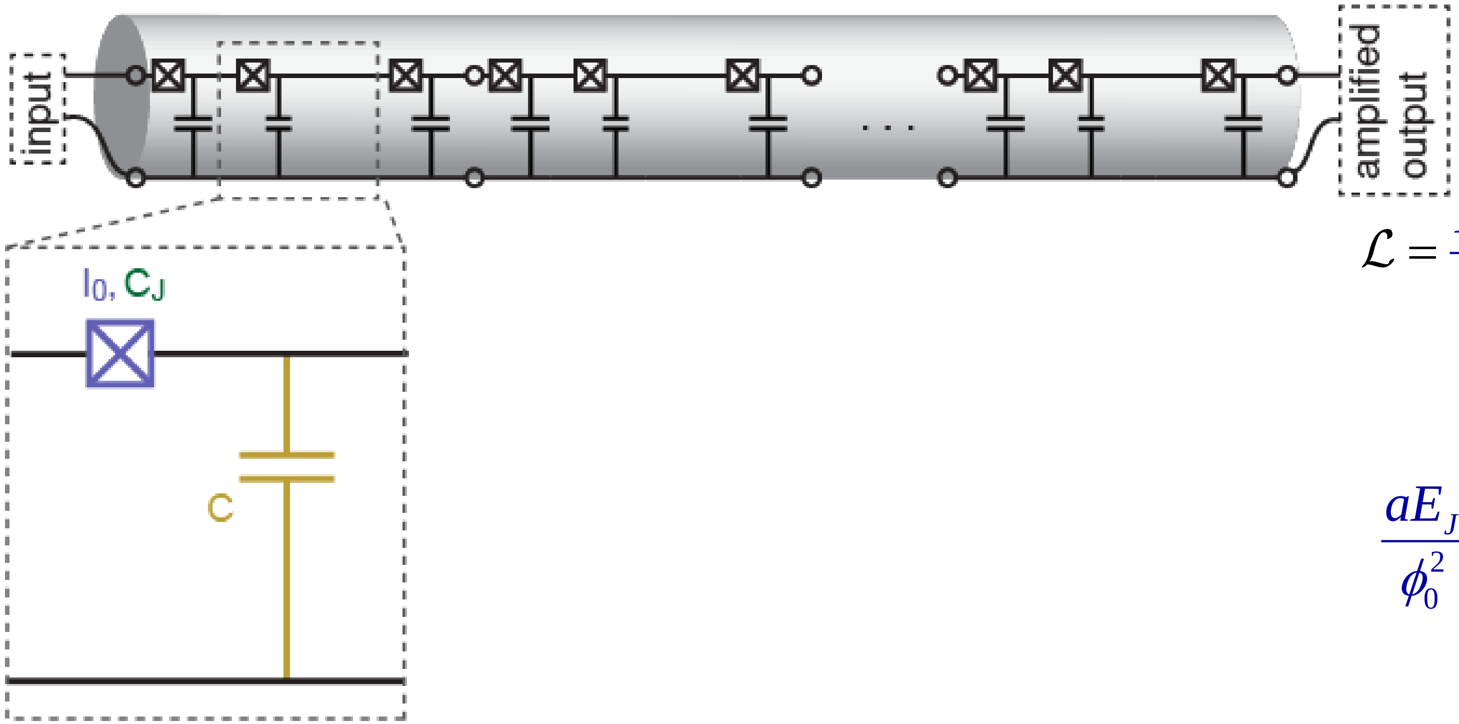


Josephson junction transmission line



Traveling-wave devices avoid gain-bandwidth tradeoff

JOSEPHSON TRAVELING WAVE PARAMETRIC AMPLIFIER (TWPA)



Lagrangian density:

$$\mathcal{L} = \frac{E_J}{a}\cos\left(\frac{a}{\phi_0}\frac{\partial\phi}{\partial x}\right) + \frac{C_J a}{2}\left(\frac{\partial^2\phi}{\partial x\partial t}\right)^2 + \frac{C}{2a}\left(\frac{\partial\phi}{\partial t}\right)^2$$

Nonlinear wave equation:

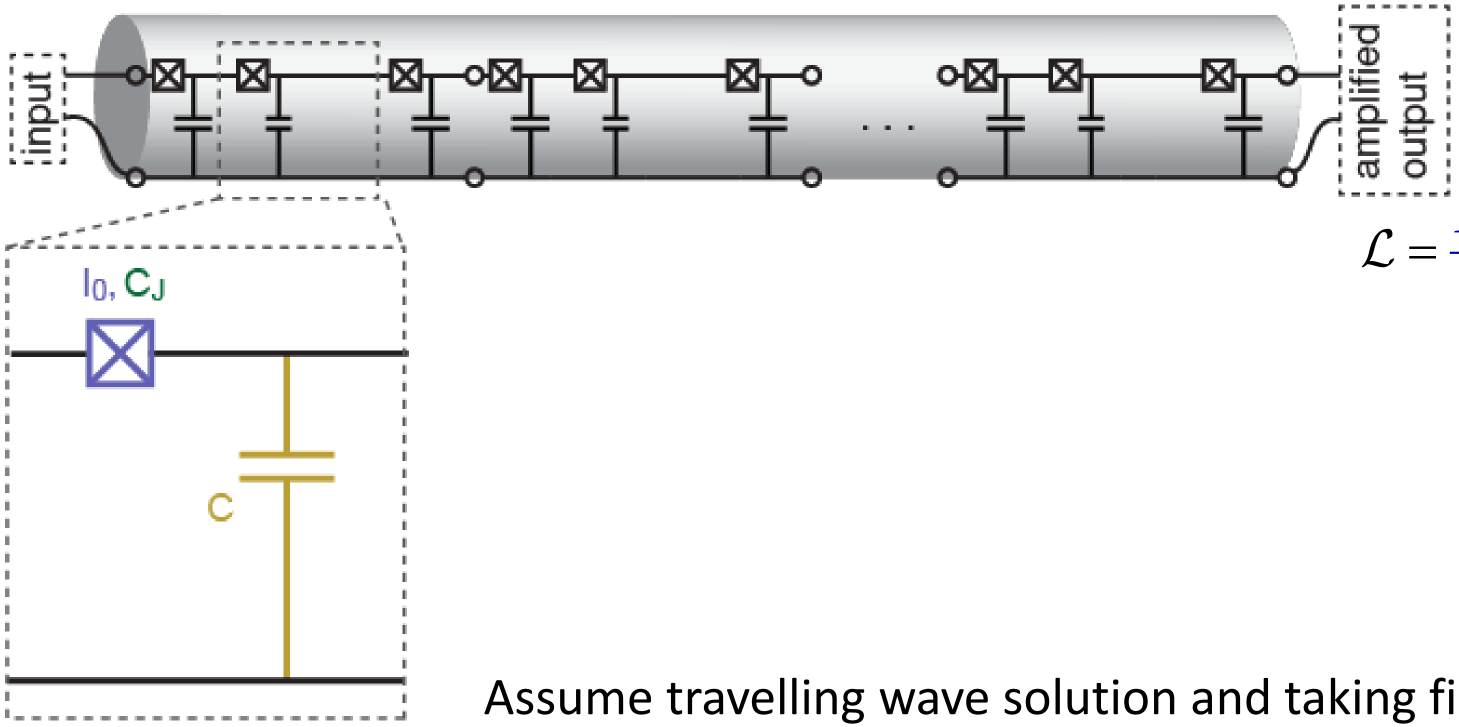
$$\frac{aE_J}{\phi_0^2}\cos\left(\frac{a}{\phi_0}\frac{\partial\phi}{\partial x}\right)\frac{\partial^2\phi}{\partial x^2} + C_J a\frac{\partial^4\phi}{\partial t^2\partial x^2} - \frac{C}{a}\frac{\partial^2\phi}{\partial t^2}$$

Variable transformations to simplify:

$$\cos(\phi_x)\,\phi_{xx} - \phi_{tt} + \beta\phi_{xxtt}$$

where $\beta = C_J/C$ characterizes the dispersion due to the junction resonance

JOSEPHSON TRAVELING WAVE PARAMETRIC AMPLIFIER (TWPA)



Lagrangian density:

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$$\cos(\phi_x)\phi_{xx} - \phi_{tt} + \beta\phi_{xxtt}$$

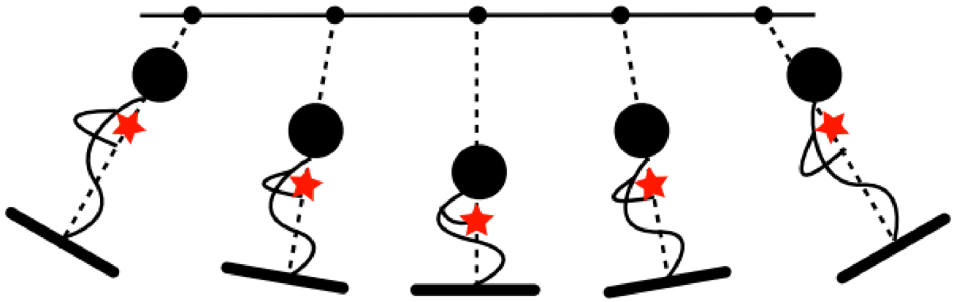
Assume travelling wave solution and taking first nonlinear order of $\cos(x) \approx 1 - \frac{x^2}{2}$

$$\frac{\partial a_s}{\partial x} - i\kappa_s a_i^* e^{i(\Delta k_L + 2\alpha_p - \alpha_s - \alpha_i)x} = 0$$

$$\frac{\partial a_i}{\partial x} - i\kappa_i a_s^* e^{i(\Delta k_L + 2\alpha_p - \alpha_s - \alpha_i)x} = 0$$

Phase Mismatch

NEED FOR PHASE MATCHING



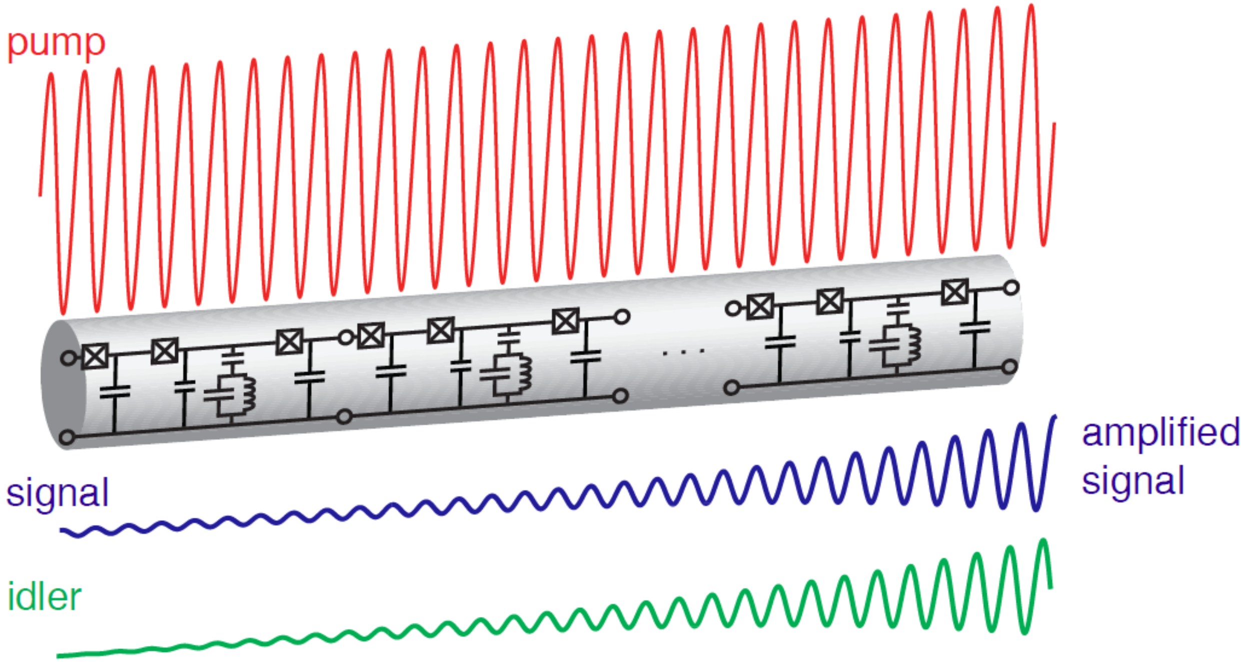
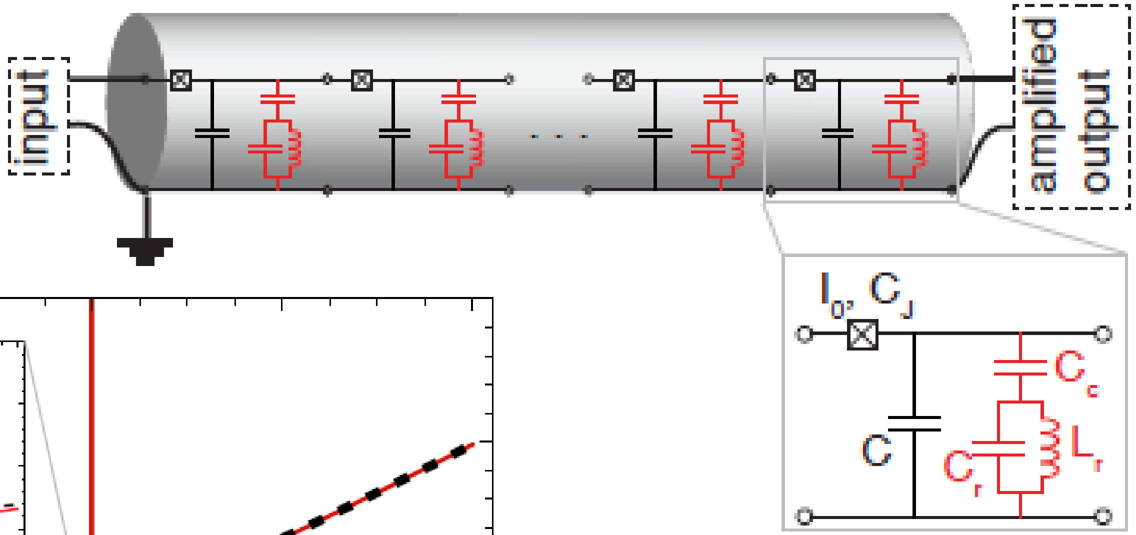
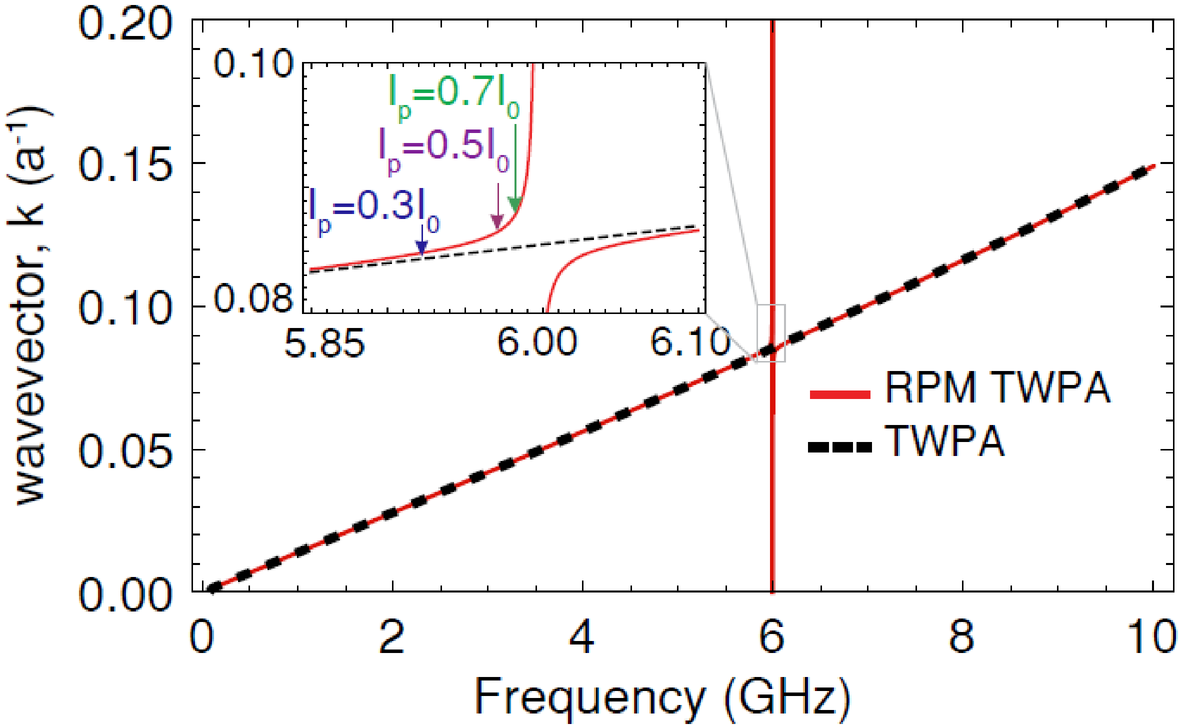


illustration from P. D. Nation et al. 1103.0835v3

PHASE MATCHED TRAVELING WAVE PARAMETRIC AMPLIFIER (TWPA)

- Proposed technique of “resonant phase matching”





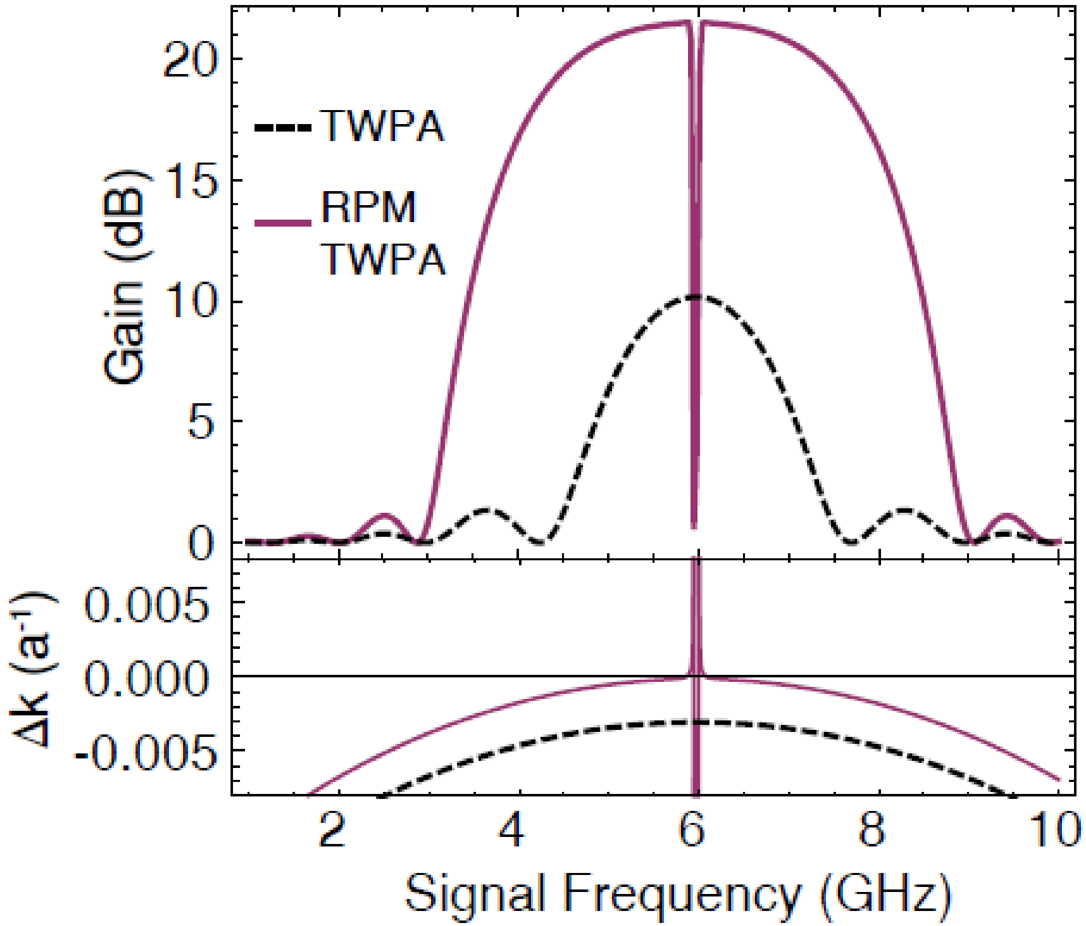
Set pump frequency to satisfy:

$$\Delta k \approx \Delta k_L - 2k_p\kappa = 0$$

where $\kappa = \frac{a^2 k_p^2 |Z_{char}|^2}{16 L^2 \omega_p^2}\left(\frac{I_p}{I_0}\right)^2$

K. O’Brien et al. Phys. Rev. Lett. **113**, 157001 (2014)

PHASE MATCHED TRAVELING WAVE PARAMETRIC AMPLIFIER (TWPA)



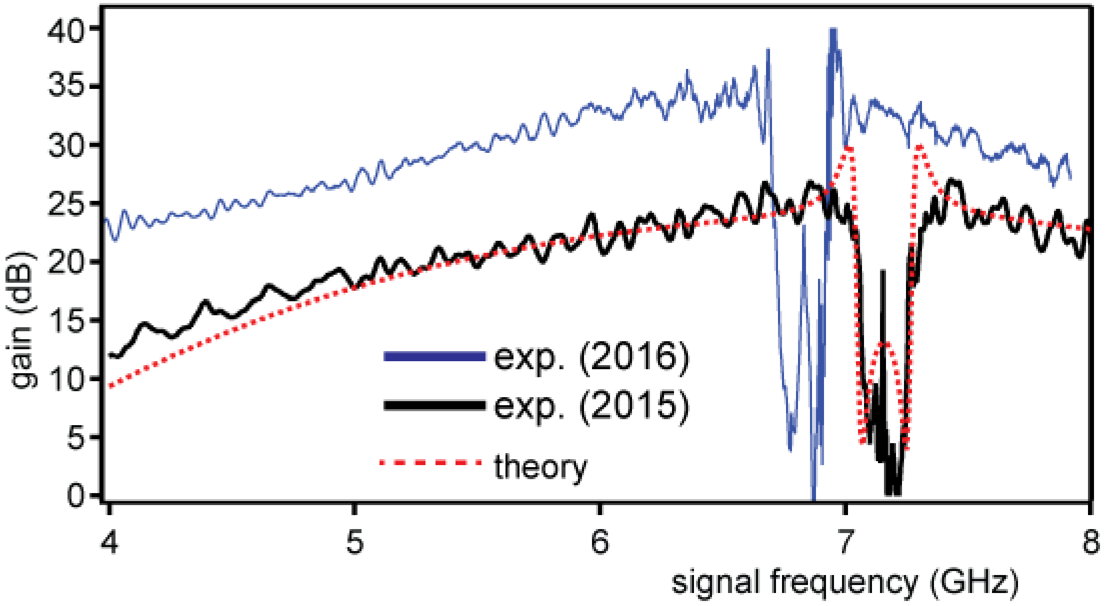
- For perfect phase matching, gain is exponential

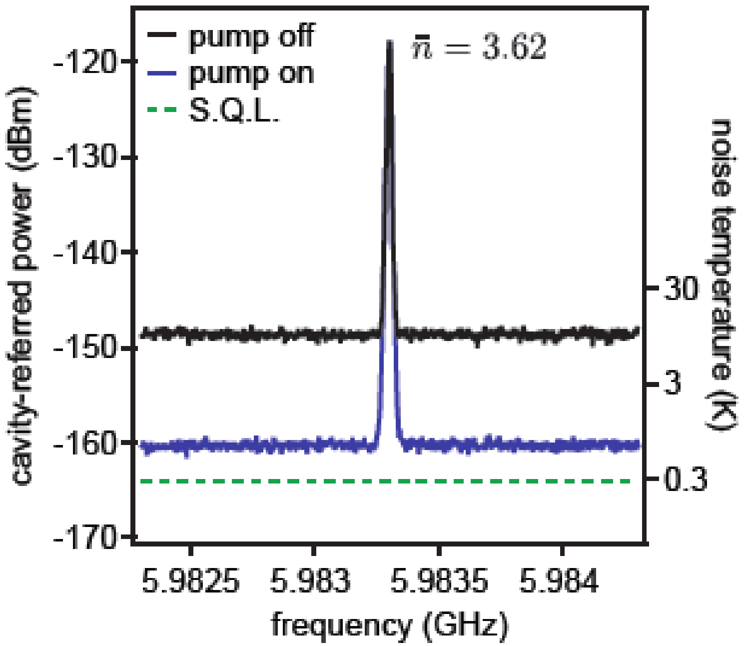
$$a_s(x) \approx a_s(0)e^{gx} / 2$$

where: $g \propto k_p I_p^2 / I_0^2$

- For poor phase matching, gain is quadratic or oscillatory

JOSEPHSON TRAVELING WAVE PARAMETRIC AMPLIFIER





- Total system quantum efficiency (phase preserving):

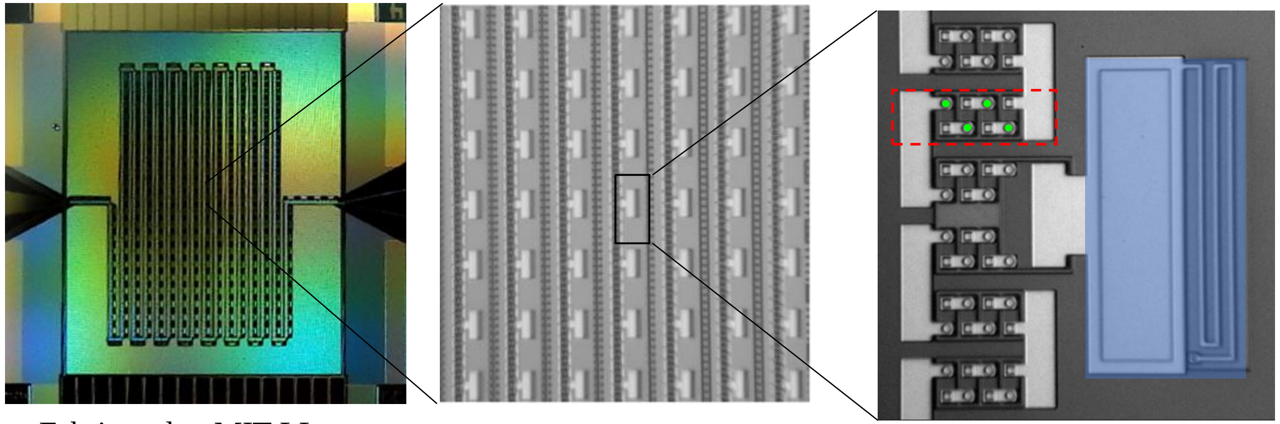
$$\eta = \frac{\hbar\omega}{k_b T_{sys}} = 0.48 \pm 0.016$$

- Intrinsic amplifier quantum efficiency of 75%

C. Macklin, K. O'Brien, D. Hover, M. E. Schwartz, V. Bolkhovsky, X. Zhang, W. D. Oliver, and I. Siddiqi. "A near-quantum-limited Josephson traveling-wave parametric amplifier" Science aaa8525 (2015)

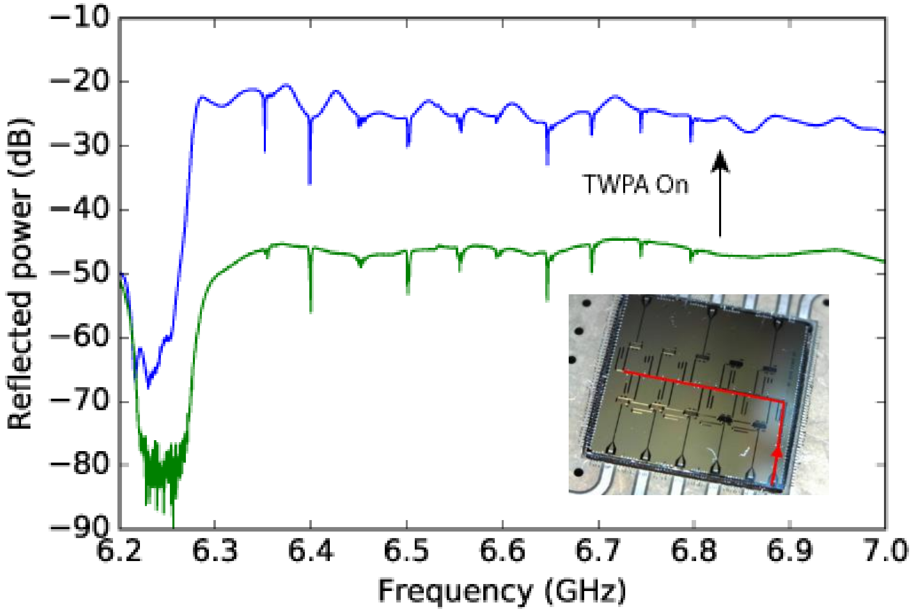
READOUT: HIGH DYNAMIC RANGE JTWPA

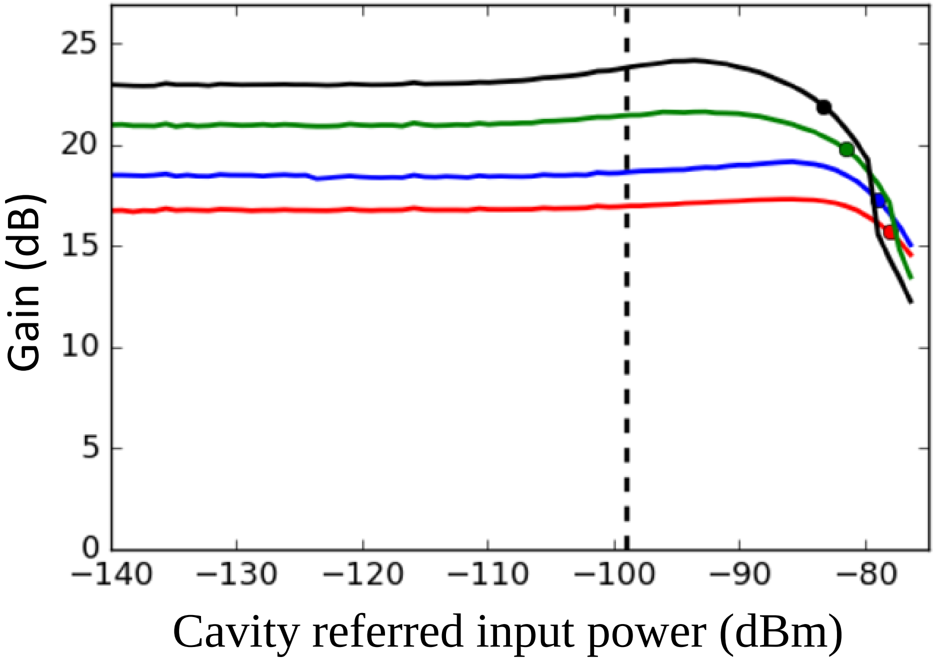
- 4 Josephson junctions per unit cell for 12 dB higher dynamic range, for equivalent small signal gain.
- Sufficient dynamic range to read out over 100 qubits.



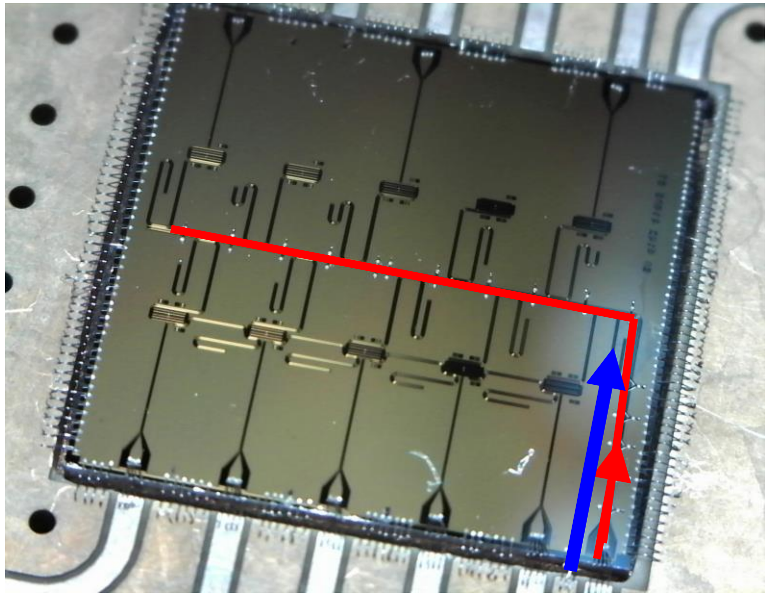
Fabricated at MIT-LL

4 Junctions / sub-cell

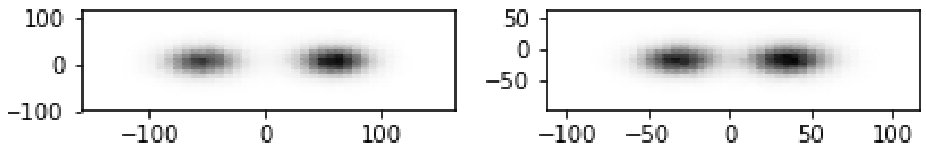




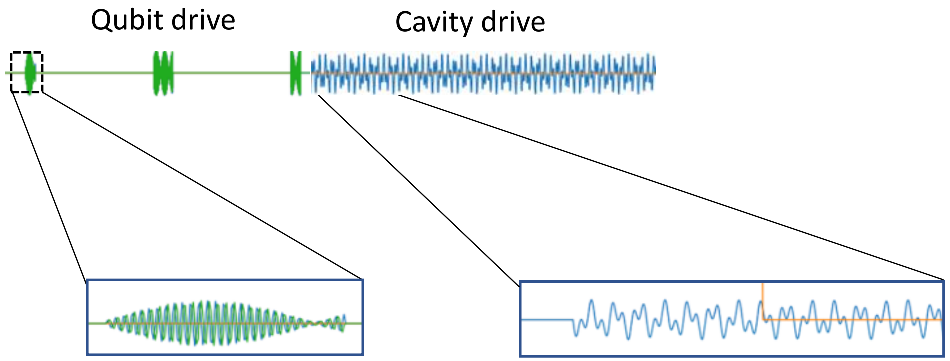
READOUT

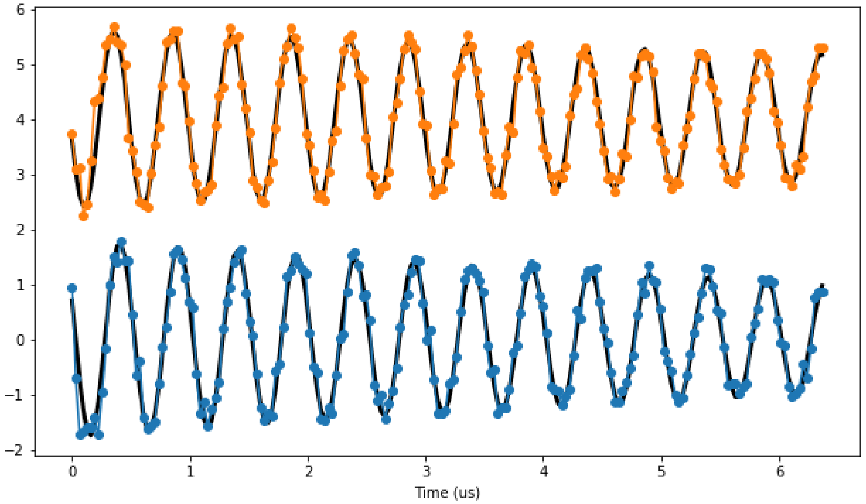


Control + Readout pulses



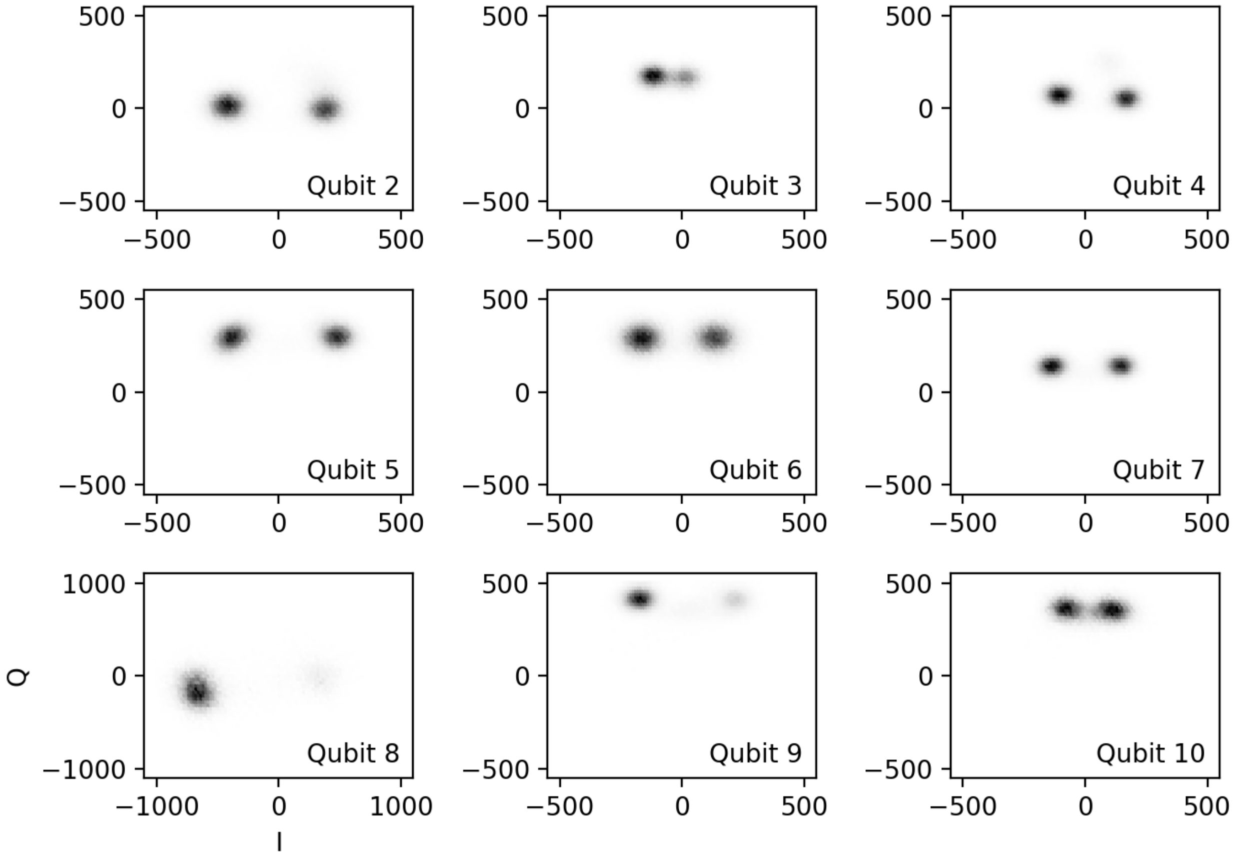
Example: 2 qubit simultaneous Hahn echo

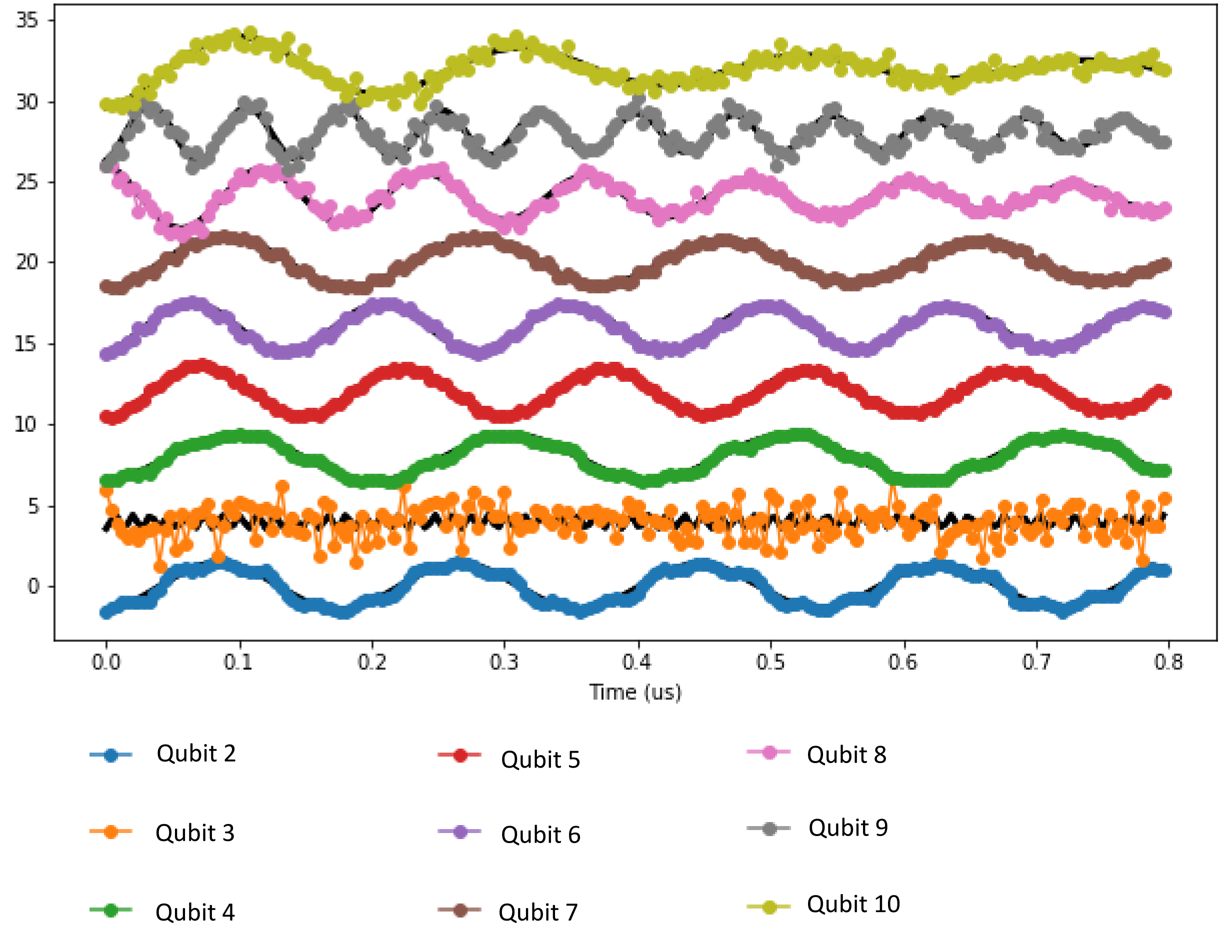




READOUT

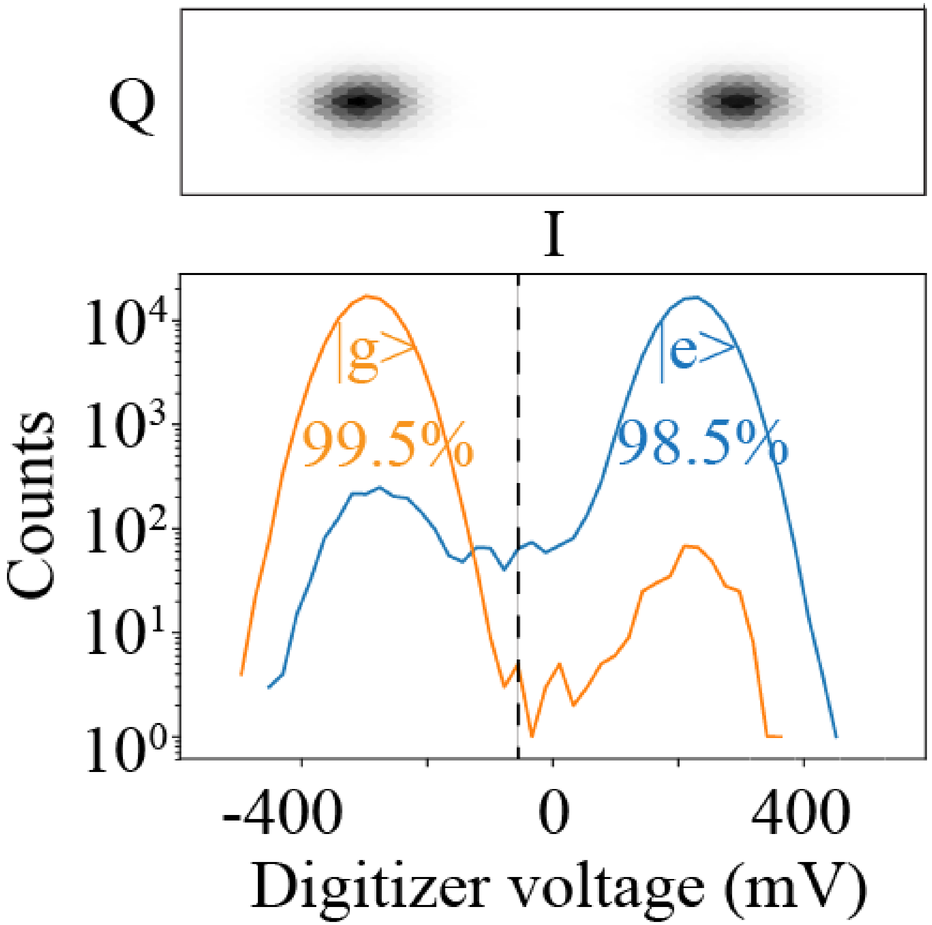
9 qubit simultaneous readout





500 ns integration time

READOUT: PRELIMINARY RESULTS ON NEW CHIP DESIGN

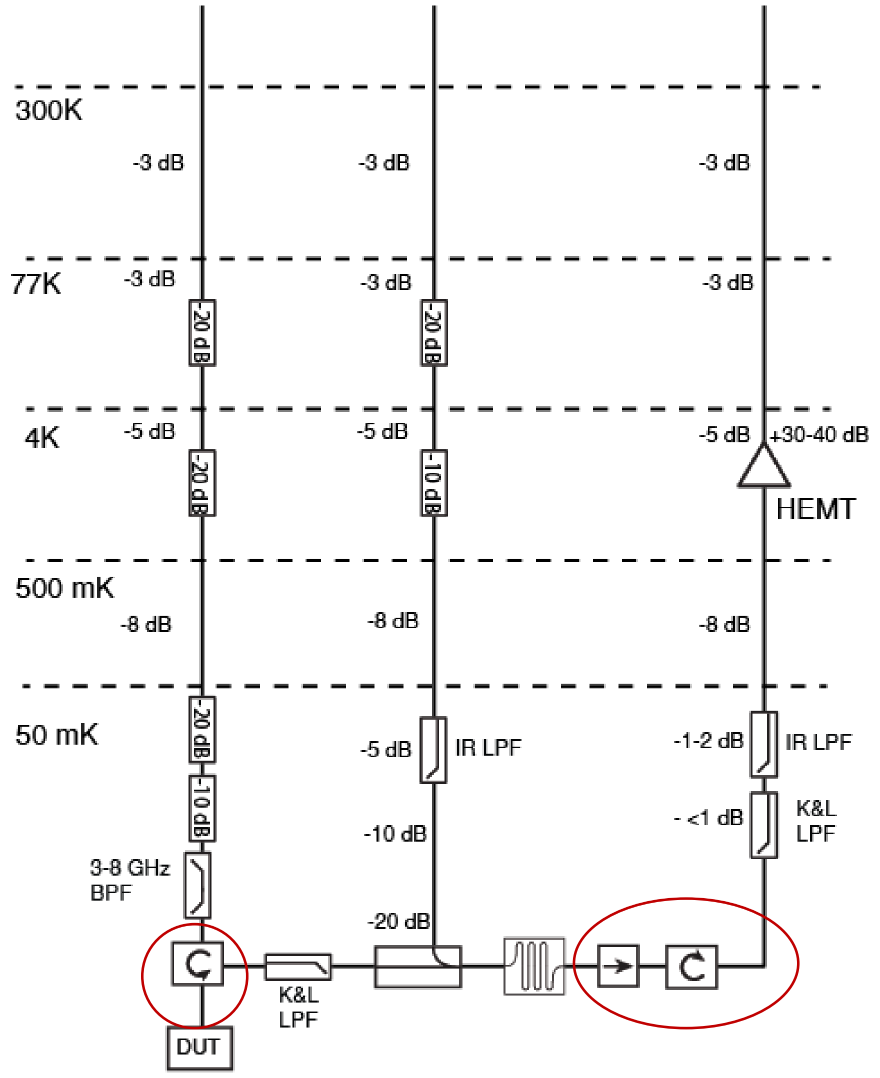


- Prepare qubit in ground state (orange) or excited state (blue).
- Measure the state of the qubit
- Quantify how often the measurement yields the prepared state.
- In more recent experiments 99.9% and 99.3% readout fidelity for g and e, respectively.

TRAVELING WAVE CIRCULATORS

Motivation

- Many cQED experiments (squeezing, etc) cannot tolerate even sub-dB losses from modern ferrite circulators and packaging.
- Superconducting circulators must be integrated to reduce loss
- Ex. protecting qubit from thermal emission from higher temperature stages.
- Superconducting circulators promising, but narrow bandwidth (<100 MHz).



circulators/isolators in typical qubit measurement setup

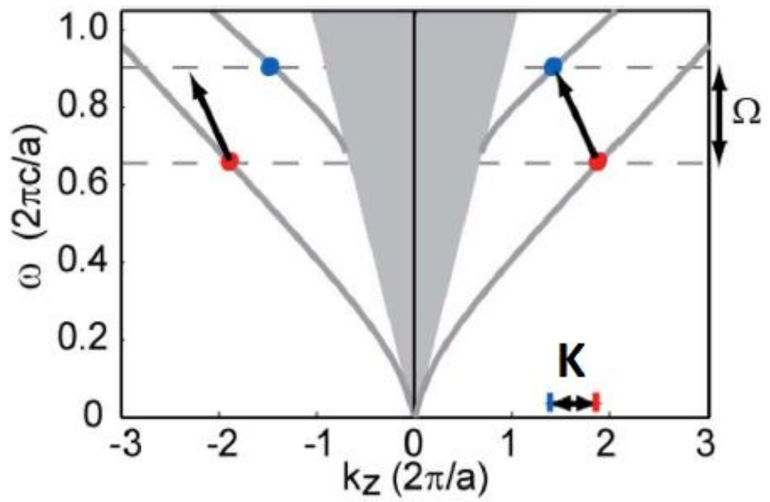
TRAVELING WAVE CIRCULATORS

Background

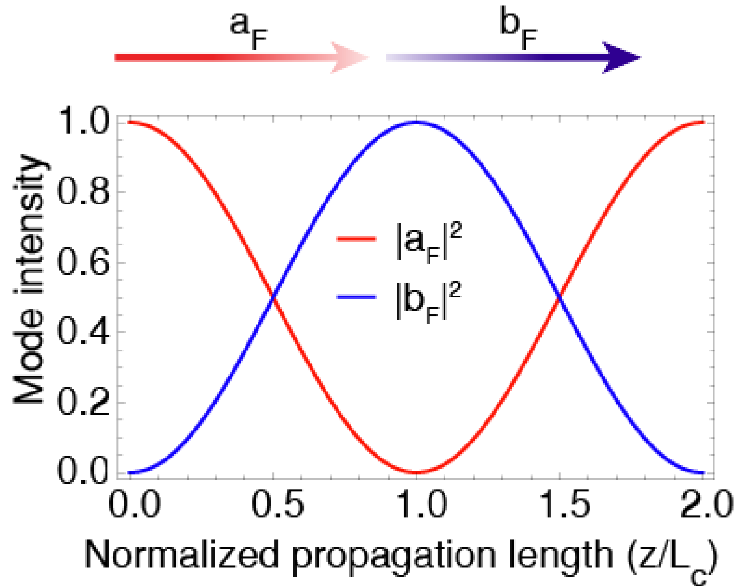
- Yu and Fan proposed isolation through optical "interband transitions"
- Dynamically modulate refractive index in traveling wave:

$$\varepsilon(x,t) = \varepsilon_r + \Delta\varepsilon \cos\left(Kx + \Omega t\right)$$

- This approach intrinsically has narrow bandwidth because it is very sensitive to the choice of K and Ω.



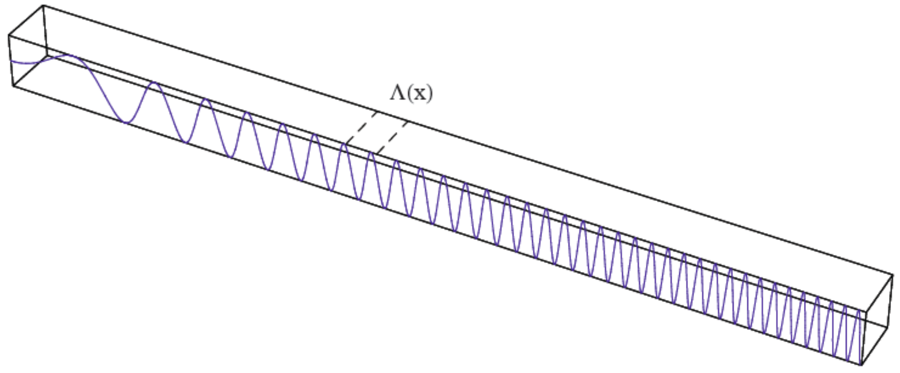
Yu and Fan. Nat. Phot. 2009

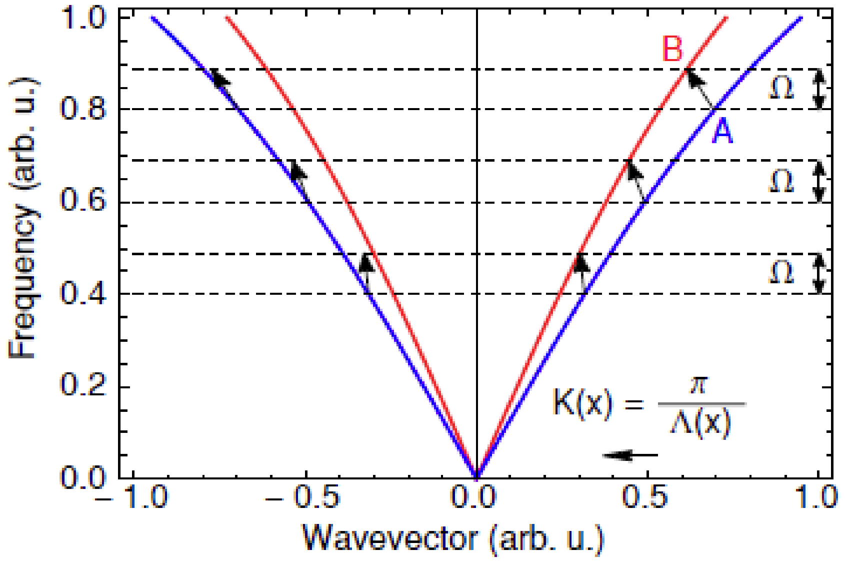


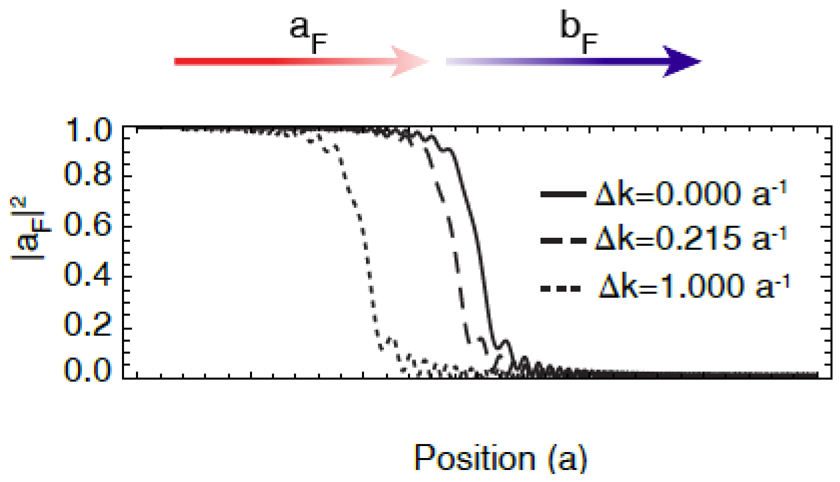
BROADBAND ISOLATION THROUGH ADIABATIC INTERBAND TRANSITIONS

$$\varepsilon(x,t) = \varepsilon_r + \Delta\varepsilon \cos\left(Kx + \Omega t\right)$$

$$\varepsilon(x,t) = \varepsilon_r + \Delta\varepsilon \cos\left(K(x)x + \Omega t\right)$$



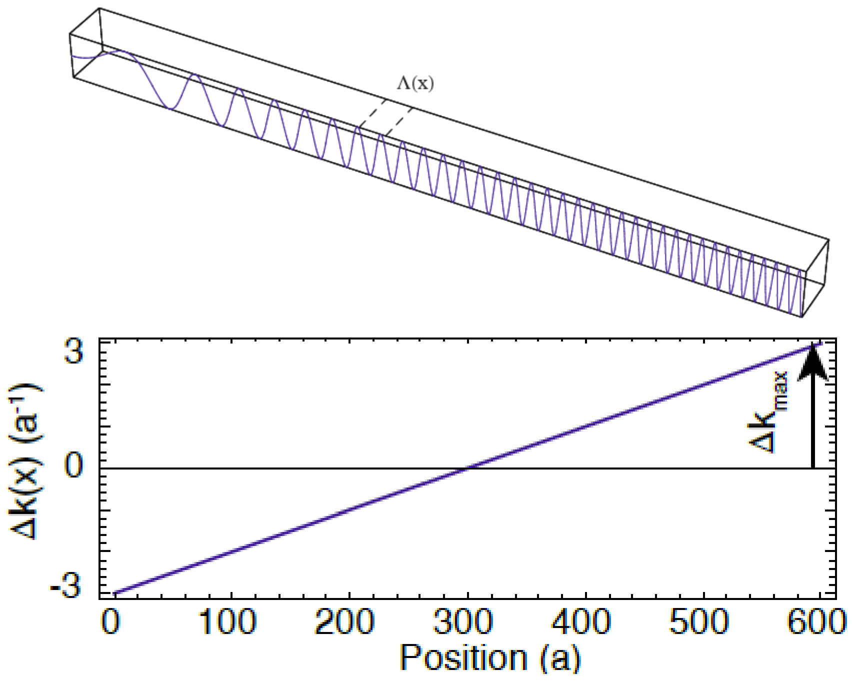


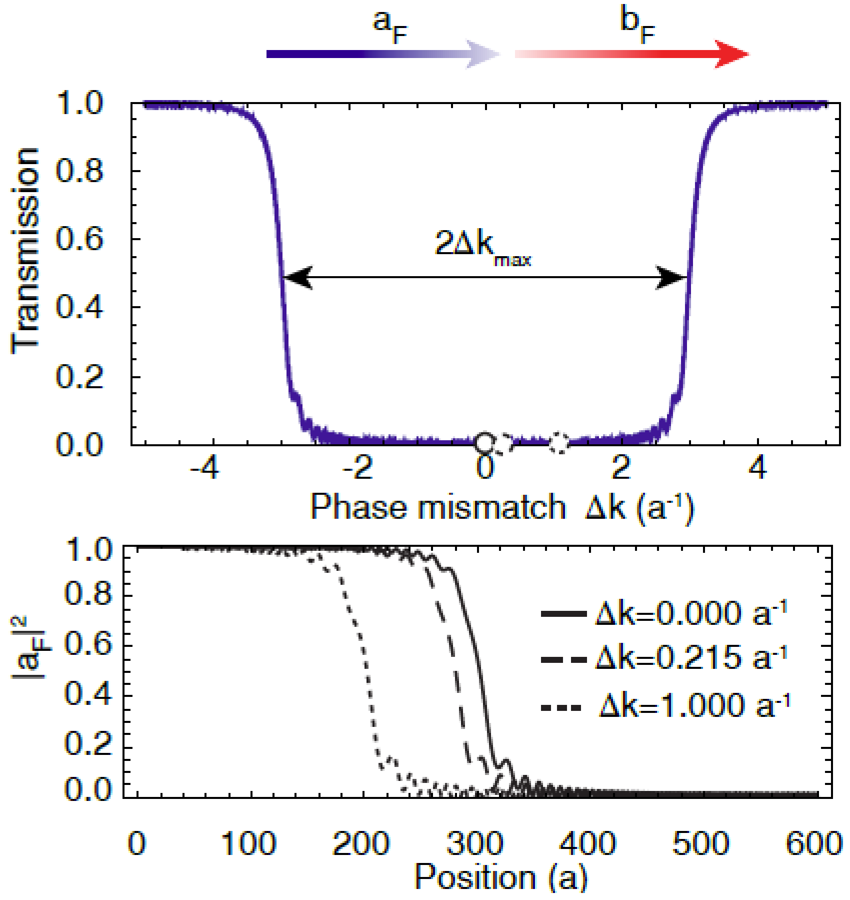


Same dynamics as Adiabatic DFG: Suchowski et al. PRA 78 063821 (2008)

BROADBAND ISOLATION THROUGH ADIABATIC INTERBAND TRANSITIONS

Linear variation of modulation period



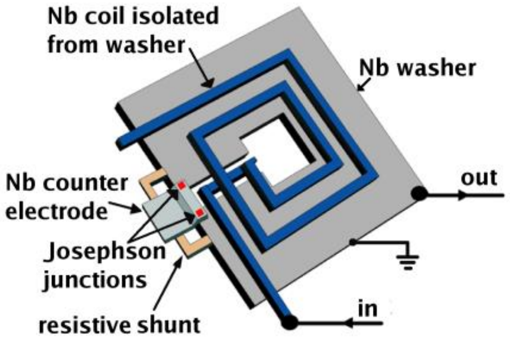


- Bandwidth of this approach **independent** of coupling.
- Bandwidth proportional to maximum phase mismatch (generated by modulation period)
- Isolation efficiency depends only on ratio of coupling to derivative of phase mismatch:

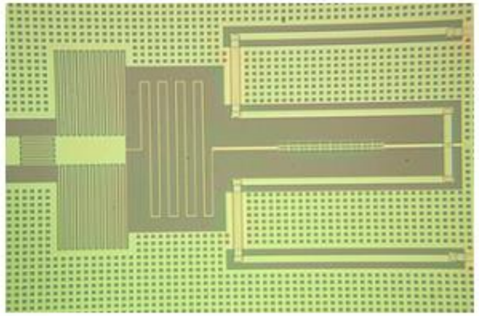
$$\lim_{x\to\infty} A_f(x) = \exp\left(-\pi \frac{\kappa^2}{\Delta k'(x)}\right)$$

APPLICATIONS TO PARTICLE PHYSICS

SQUID Amplifier in ADMX



Josephson Parametric Amplifier in ADMX-HF



Science drivers from 2014 P5 report:

- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles

Potential for using broadband (multi-GHz bandwidth) quantum limited amplifiers in Gen 3 Dark matter searches?

DIELECTRIC HALOSCOPES FOR AXION DETECTION

Axion-photon Lagrangian density:

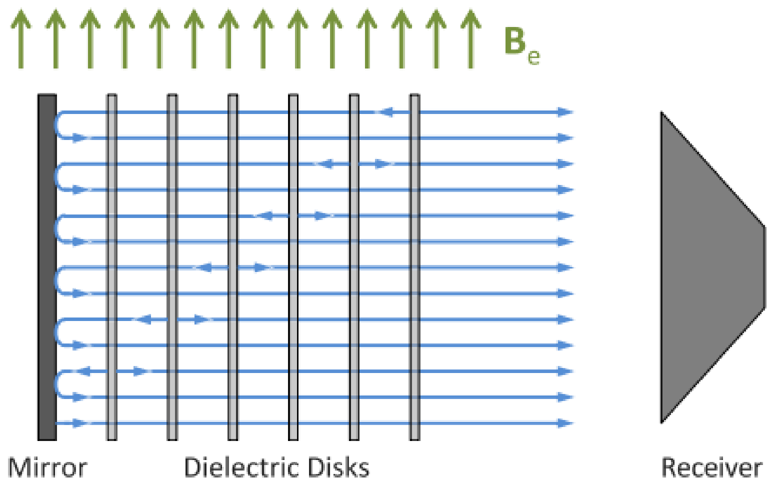
$$\mathcal{L}_{\text{int}} = -\frac{\alpha}{2\pi} C_{a\gamma} \mathbf{E} \cdot \mathbf{B} \theta,$$

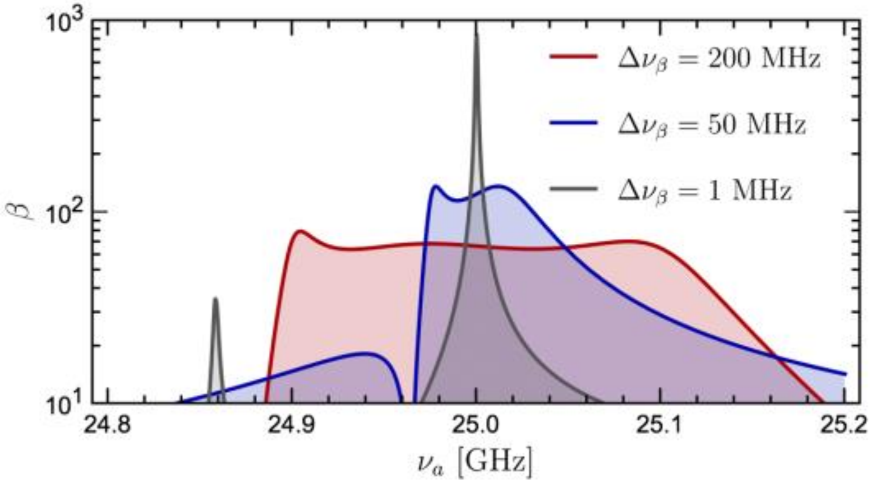
Modifies Maxwell's equations:

$$\nabla \times \mathbf{B} - \epsilon \dot{\mathbf{E}} = \frac{\alpha}{2\pi} C_{a\gamma} \mathbf{B} \dot{\theta},$$

in a strong static magnetic field,
axions generate a weak electric field:

$$\mathbf{E}_a(t) = -\frac{\alpha}{2\pi\epsilon} C_{a\gamma} \mathbf{B}_e \theta(t),$$





- Bandwidth of proposed haloscope is relatively narrow – not utilizing full bandwidth of quantum limited detectors.
- Can we increase bandwidth while maintaining high boost factors?
- Can we use adiabatic phase matching to increase bandwidth?
- Are there more favorable geometries such as waveguides? (in a waveguide can phase-match by changing propagation direction relative to B_e)

MADMAX Working Group. "Dielectric Haloscopes: A New Way to Detect Axion Dark Matter." PRL 118 091801 (2017)

DIELECTRIC HALOSCOPES FOR AXION DETECTION

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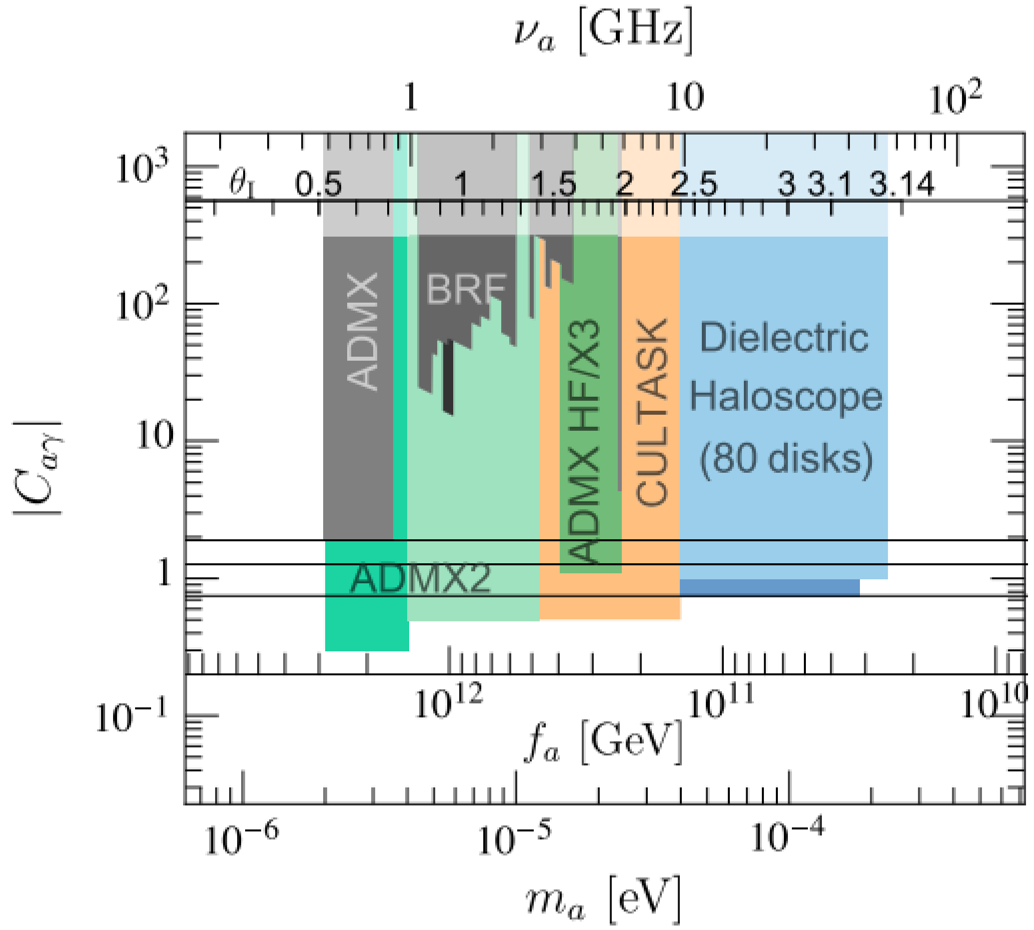

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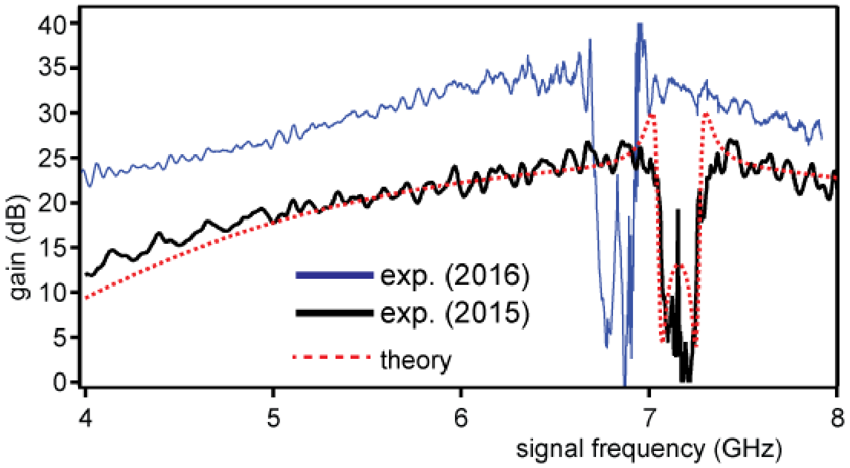
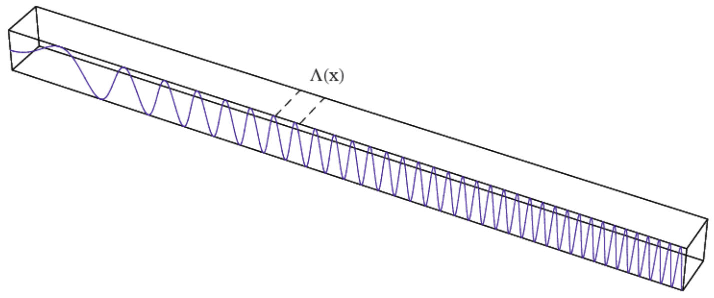
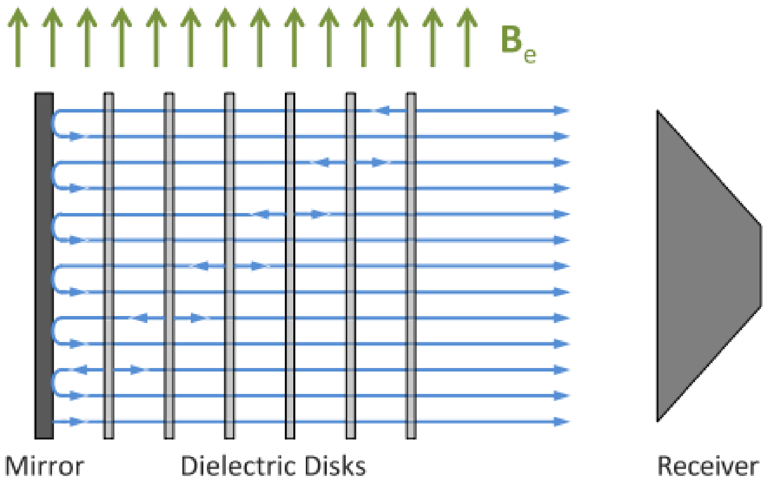
OUTLOOK







- Photonic engineering enables next-generation of broadband, non-reciprocal detectors operating at the quantum limit

- Broadband quantum limited amplifiers may be useful for axion detection in dielectric haloscopes.