Fast, High-Fidelity Dispersive Readout of Superconducting Qubits

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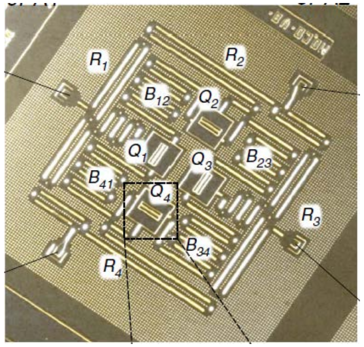
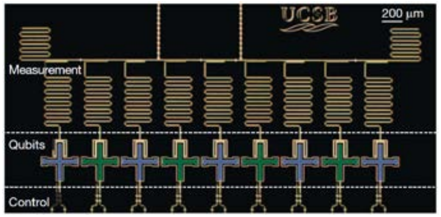
scaleQIT

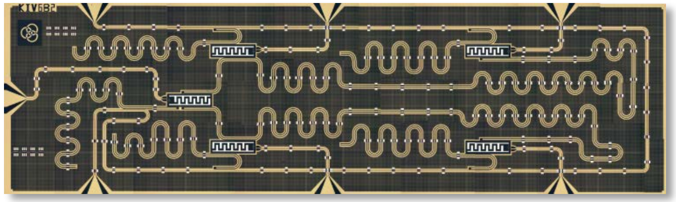
Fast, High-Fidelity Single Shot Readout

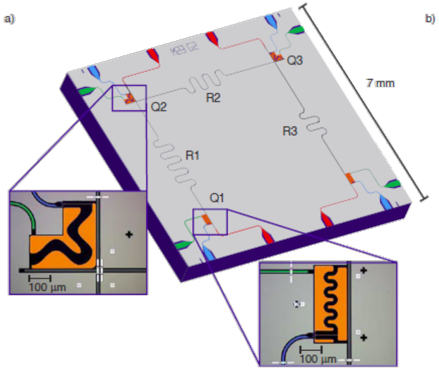
Ingredient for

- Fast qubit initialization
  - at start of computation
    Riste *et al.*, *PRL* **109**, 050507 (2012)
  - for resetting ancilla qubits
- For feedback or feed forward
  - in error correction
    Reed *et al.*, *Nature* **482**, 382 (2012)
    Kelly *et al.*, *Nature* **519**, 66 (2015)
    Corcoles *et al.*, *Nat. Com.* **6**, 6979 (2015)
    Ristè *et al.*, *Nat. Com.* **6**, 6983 (2015)
  - in measurement based entanglement generation
    Riste *et al.*, *Nature* **502**, 350 (2013)
  - in teleportation protocols
    Steffen *et al.*, *Nature* **500**, 319 (2013)
  - and more ...



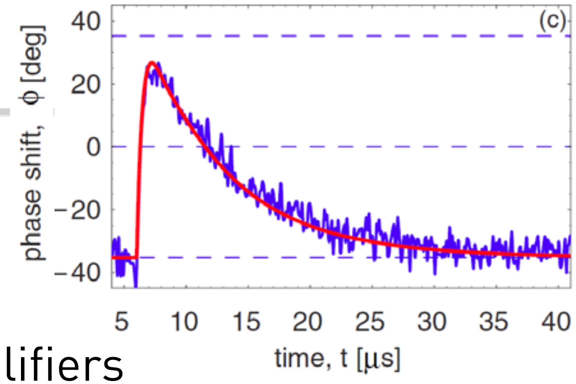




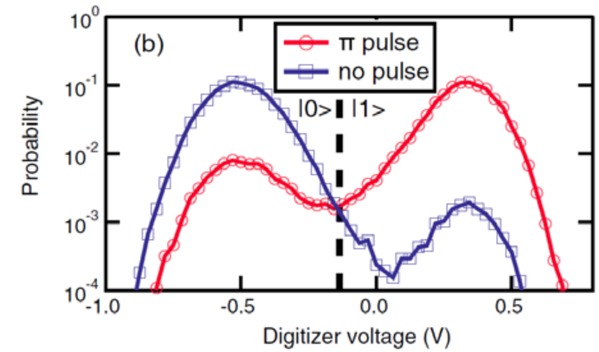


How to achieve Fast, High-Fidelity Single Shot Readout?

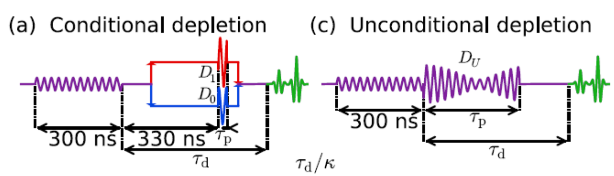
Prior Work

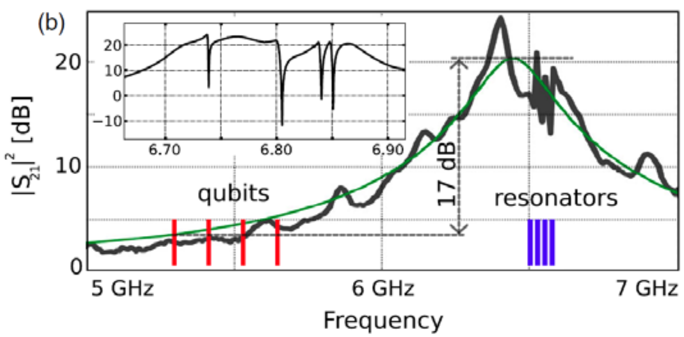


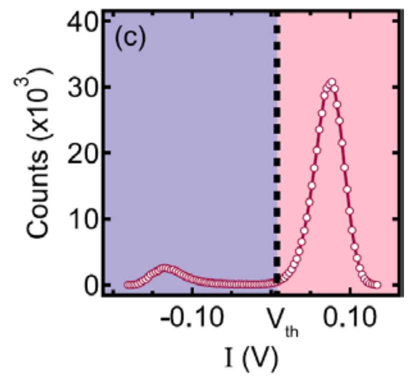
- Dispersive readout using HEMT amplifiers
  B. Johnson *et al., Nat. Phys.* **6**, 663 (2010)
  A. Wallraff *et al., PRL* **95**, 060501 (2005)
- Heralded preparation using parametric amplifiers
  J. E. Johnson *et al., PRL* **109**, 050506 (2012)
  D. Riste *et al., PRL* **109**, 050507 (2012)



- Purcell filters and multiplexing for high fidelity
  E. Jeffrey *et al., PRL* **112**, 190504 (2014)
- Resonator depletion
  C. C. Bultink *et al., arxiv:160400916* (2016)







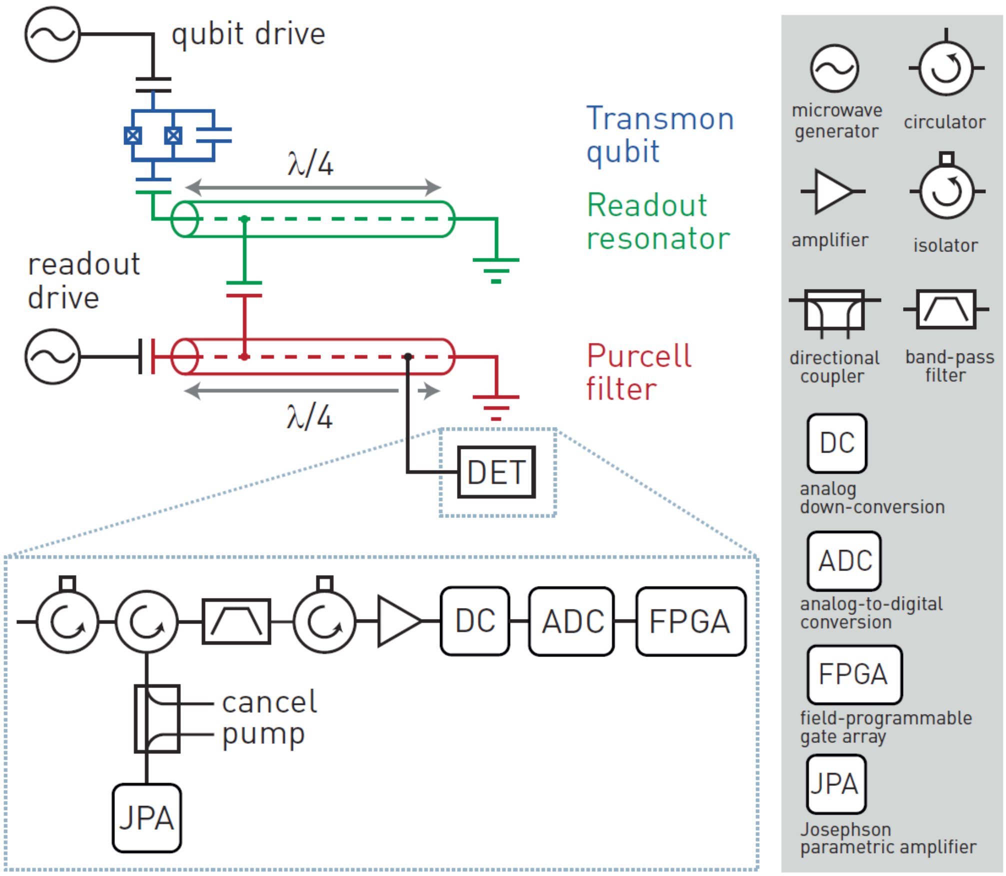
- and more …

Further improvements presented in this work
T. Walter, P. Kurpiers *et al.,* Quantum Device Lab, ETH Zurich (2016)

Device Concept and Detection Chain

Goal:

- Optimize sample design and readout chain for **fast**, high-fidelity readout



Device ingredients:

- Transmon qubit
- Dedicated qubit drive line
- Compact $\lambda/4$ large bandwidth (κ) readout resonator
- asymmetric (100/1) $\lambda/4$ filter for protection from qubit Purcell decay
- Dedicated readout drive line

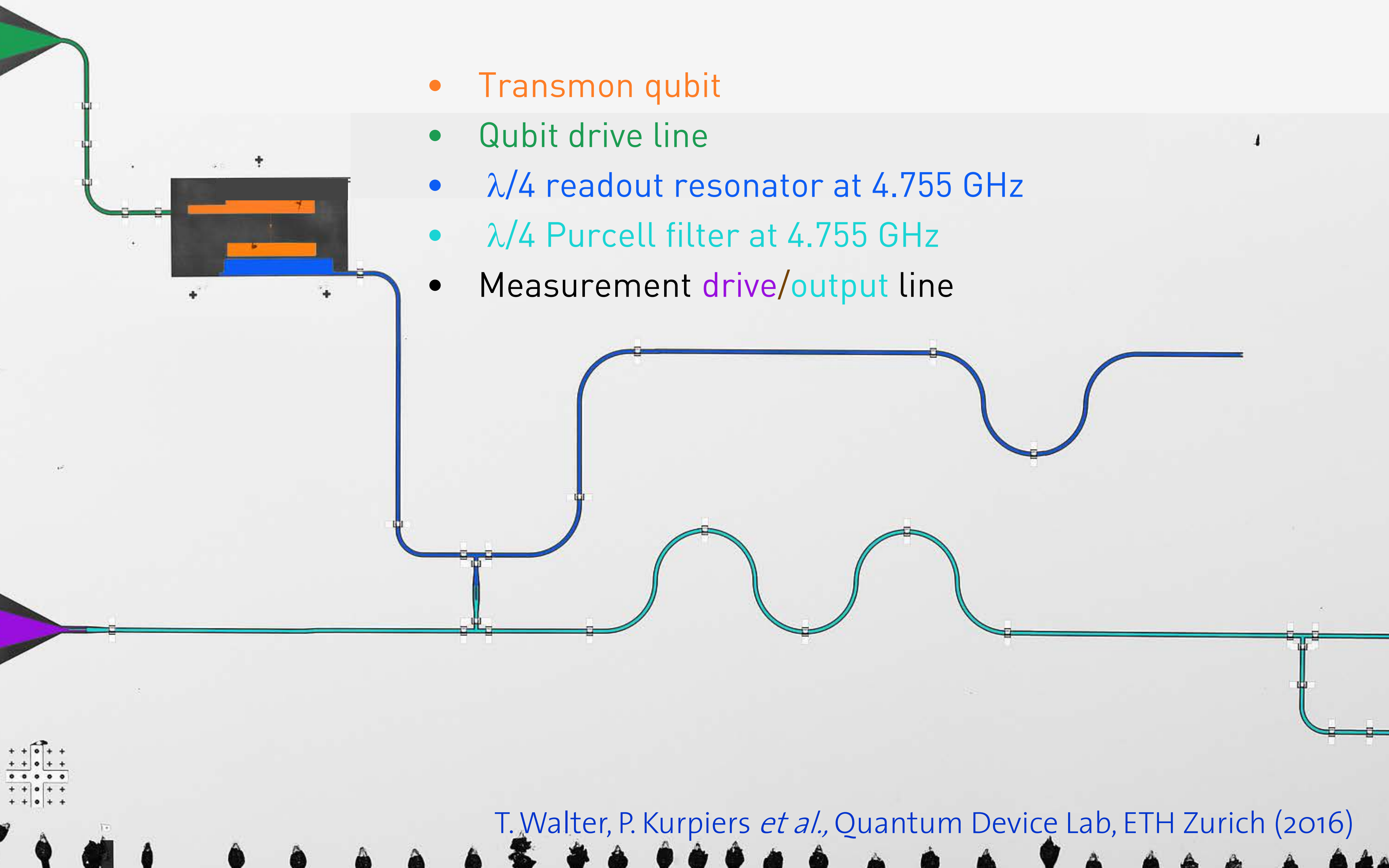
Detection chain

- Josephson parametric amplifier
- FPGA based signal analysis

T. Walter, P. Kurpiers *et al.*, Quantum Device Lab, ETH Zurich (2016)

Device Design

- Transmon qubit
- Qubit drive line
- $\lambda/4$ readout resonator at 4.755 GHz
- $\lambda/4$ Purcell filter at 4.755 GHz
- Measurement drive/output line



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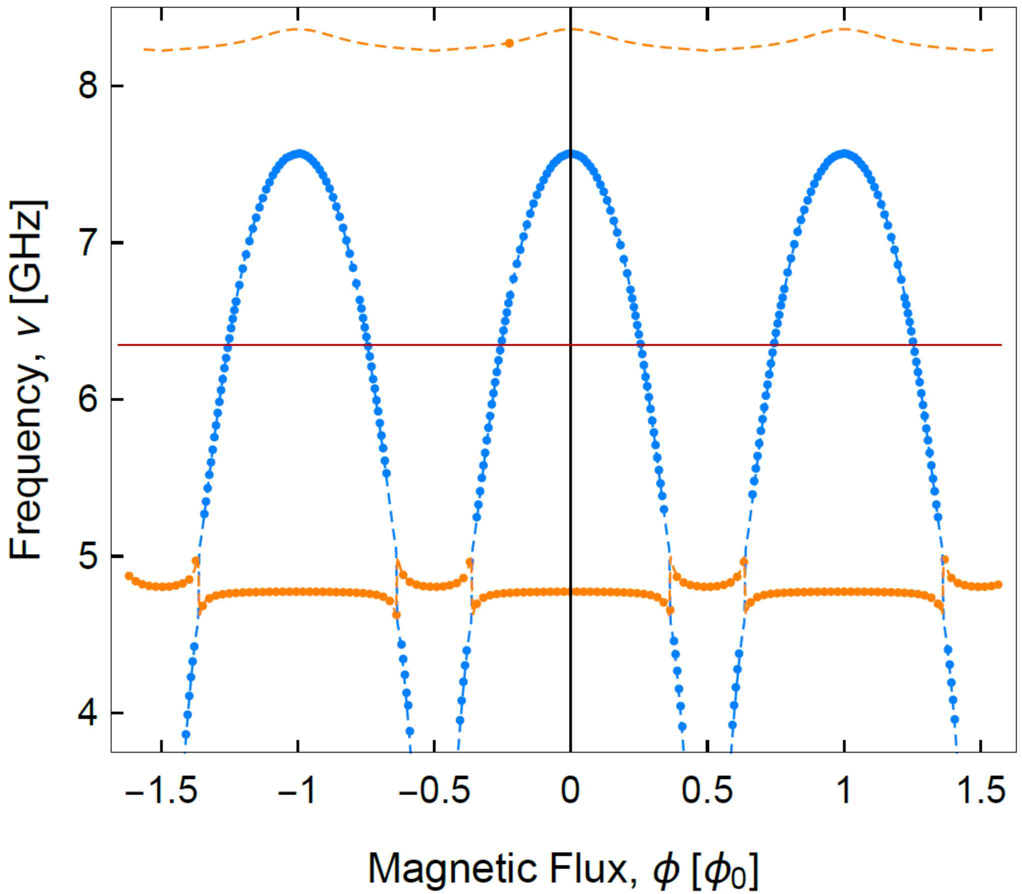
Characterizing Qubit and Resonator in Spectroscopy



- Measured qubit/resonator freq. (*,*)
- Fit to full Hamiltonian (-,-)
- Operating Frequency (-)

Qubit Parameters:

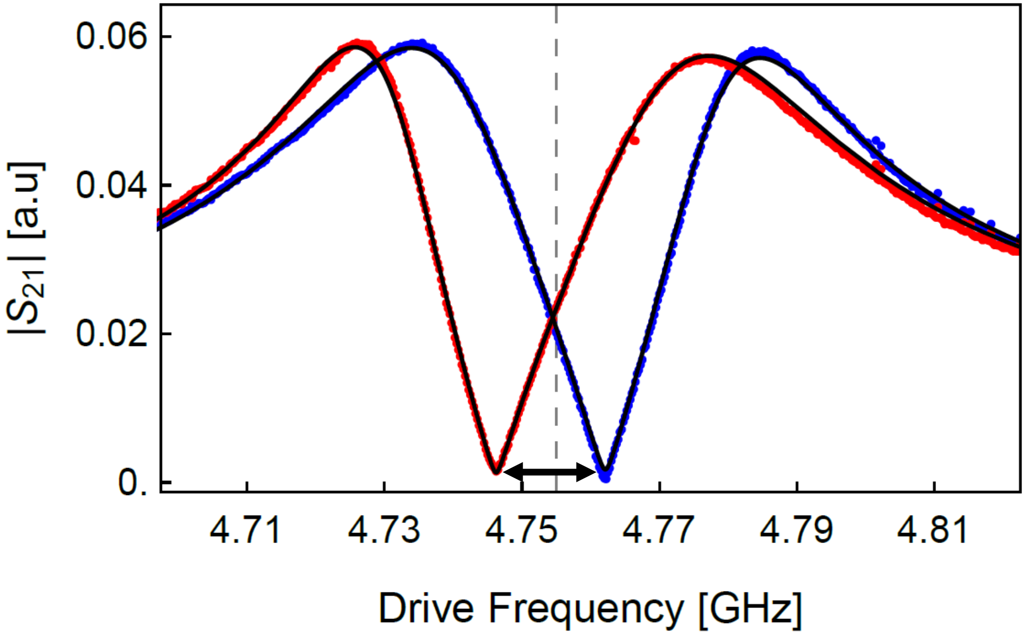
- Maximum Josephson energy, E_J = 26.37 GHz
- Charging energy, E_c = 0.307 GHz

At op. frequency, ν_{ge} = 6.314 GHz

- Energy relaxation time, $T_1 \sim 8\ \mu s$
- Est. Purcell limit, $T_{1p} > 500\ \mu s$
- Ramsey dephasing time, $T_2 = 1.8\ \mu s$
- Anharmonicity, α = 341 MHz
- Cryostat temperature, T = 9 mK
- Equilibrium thermal population, $P_e < 0.003$

Readout Resonator Response

Transmission amplitude or readout resonator extracted through Purcell filter for qubit prepared in ground (g) or excited (e) state :



Parameter fit (model):

- Purcell filter $\kappa_p/2\pi$ = 66 MHz
- Readout resonator $\kappa_r/2\pi$ = 37 MHz
- State dependent resonator shift $2\chi/2\pi$ = -15 MHz

Note:

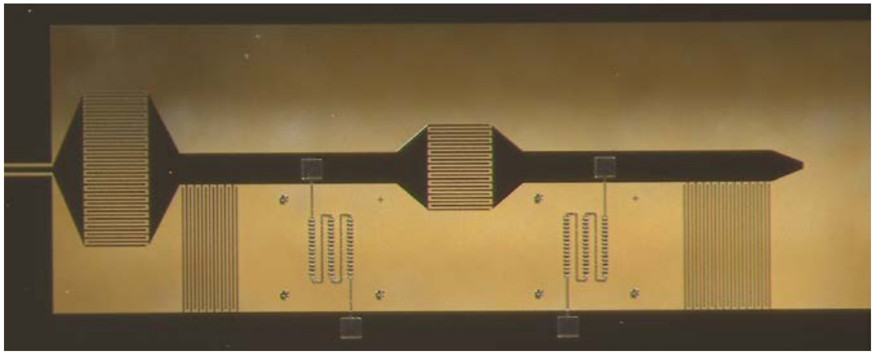
- Weakly coupled input port
- Strongly coupled output port

In ground/excited state:

- Data measured after state prep. (*,*)
- Fit to resonator response model (-)

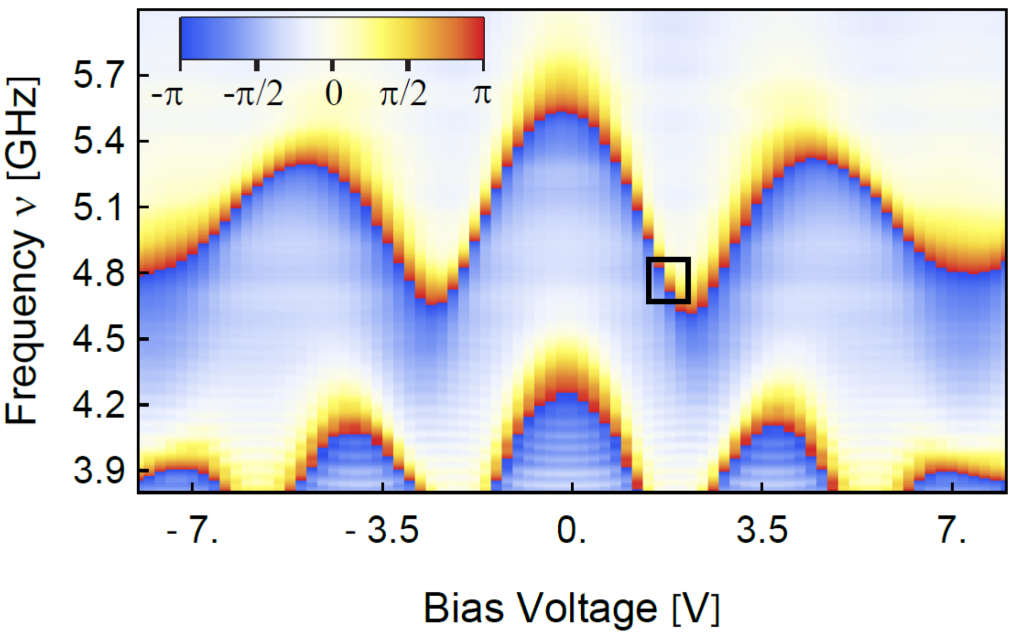
T. Walter, P. Kurpiers *et al.*, Quantum Device Lab, ETH Zurich (2016)

Josephson Parametric Dimer (JPD) Amplifier



Dual-mode lumped element JPA

- Phase sensitive or phase insensitive operation
  Eichler et al., *PRL* **113**, 110502 (2014)
- SQUID array for high saturation and tunability
  Eichler et al., *EPJ Qu.Tech.* **1**, 2 (2014)

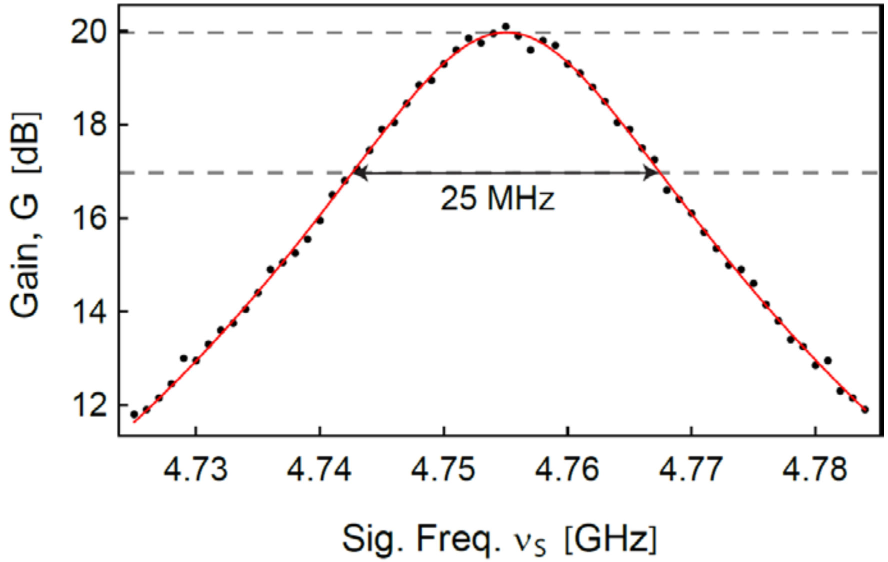


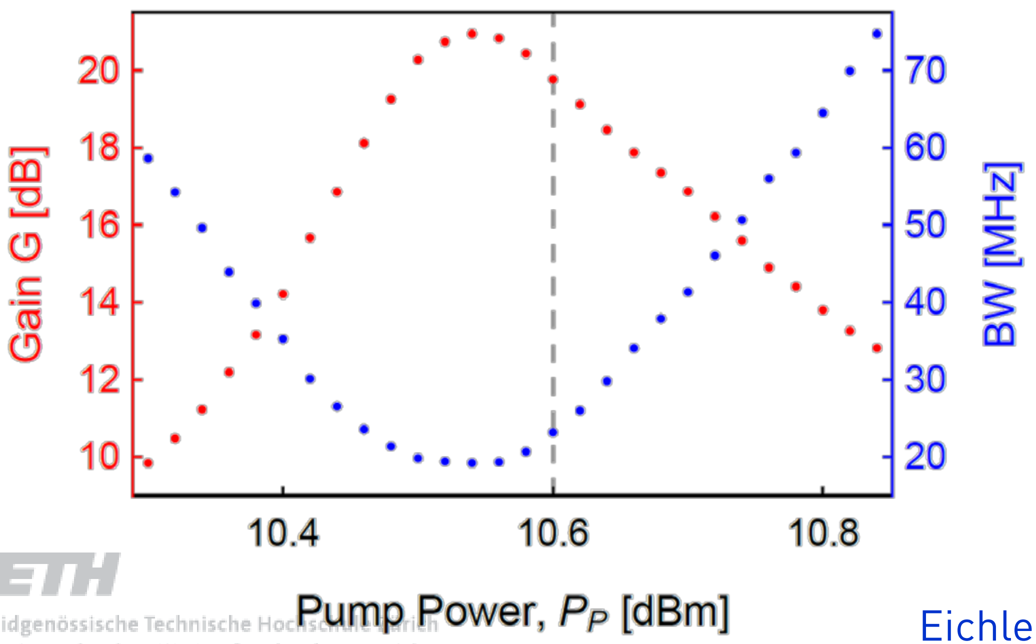
Basic JPD parameters

- Intermode coupling, $2J/2\pi$ = 1.2 GHz
- Mode bandwidth, $\kappa/2\pi$ = 220 MHz
- Tuning range ~ 1 GHz

Pick operating point □

JPD Gain and Bandwidth





signal frequency dependent gain:

- Here: phase sensitive mode with appropriately chosen pump frequency, power and flux
- Phase insensitive mode available
- Lorentzian profile

At qubit readout frequency:

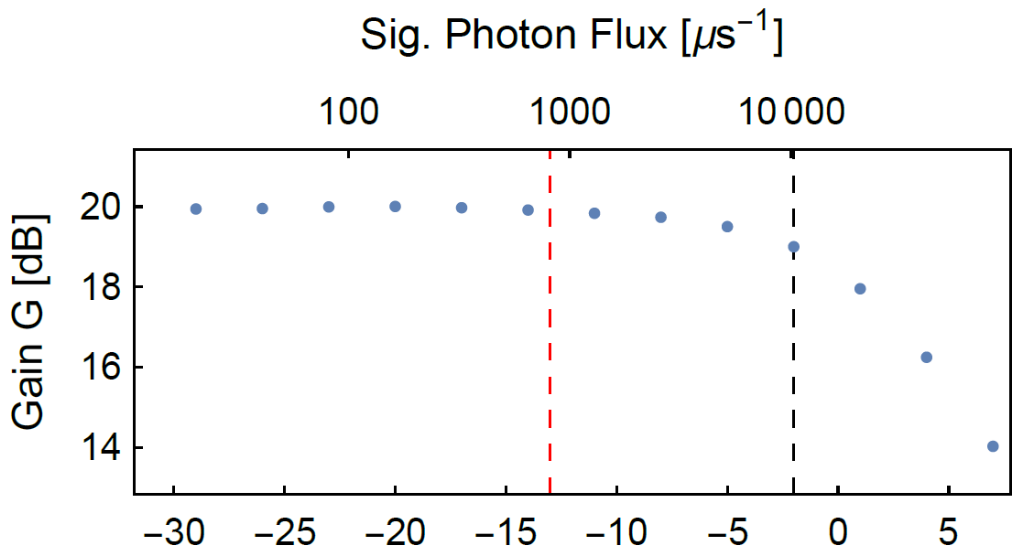
- Gain, G = 20 dB
- Bandwidth, BW = 25 MHz

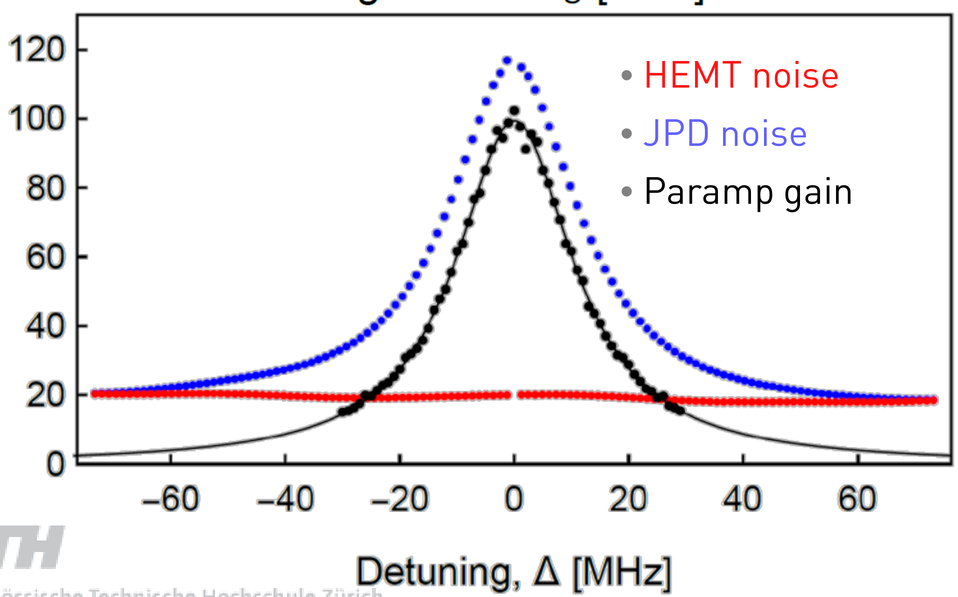
Pump power dependence at ν_p = 4.755 GHz

- Gain bandwidth product, G BW = 250 MHz

Eichler *et al., Phys. Rev. Lett.* **113**, 110502 (2014)

JPD Gain Compression





Gain compression

- 1dB point at flux ~10^4 μs^{-1}
- Operated at ~10^3 μs^{-1}
- With average readout resonator occupation n_r ~ 2.2

(Preliminary) system noise analysis:

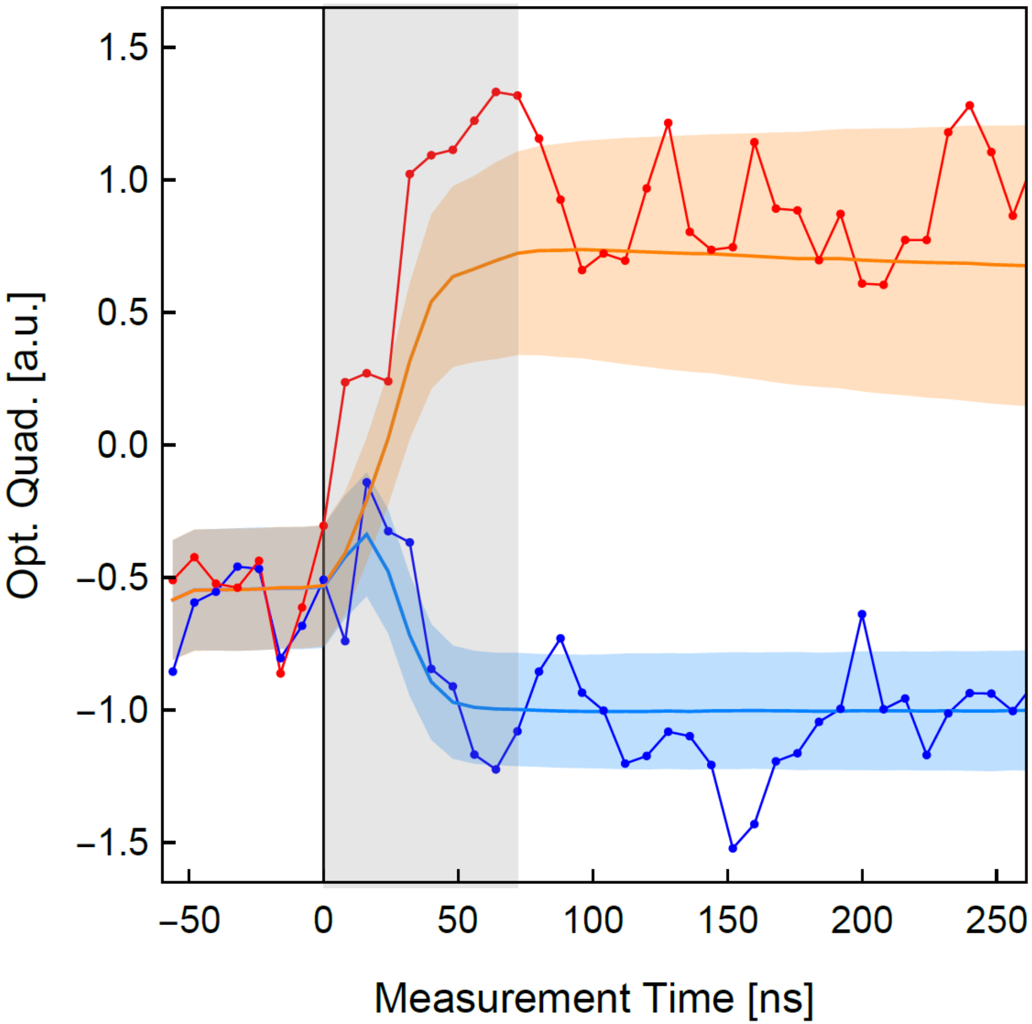
relative to paramp input

- Phase (in)sensitive detection efficiency, η ~ (0.83) 0.91 (assuming $n_{add} = n_{th} = 0$)

relative to sample output

- Loss toward paramp ~ 1.7 dB
- Equiv. reduction of signal ~ 0.61
- η_{sys} ~ (0.56) 0.61

Time Dependence of Measured Quadrature



Quantities:

- Single ground state (g) trace
- Average and Stdv of g traces
- Single excited state (e) trace
- Average and Stdv of e traces
- Integration time t_i

Observations:

- Fast rise of measurement signal (< 50 ns) due large χ (and κ)
- Small decay of average excited state trace due to Purcell protected T_1
- Little increase of average ground state trace due to measurement induced mixing
- Repetition period ~ 50 μs

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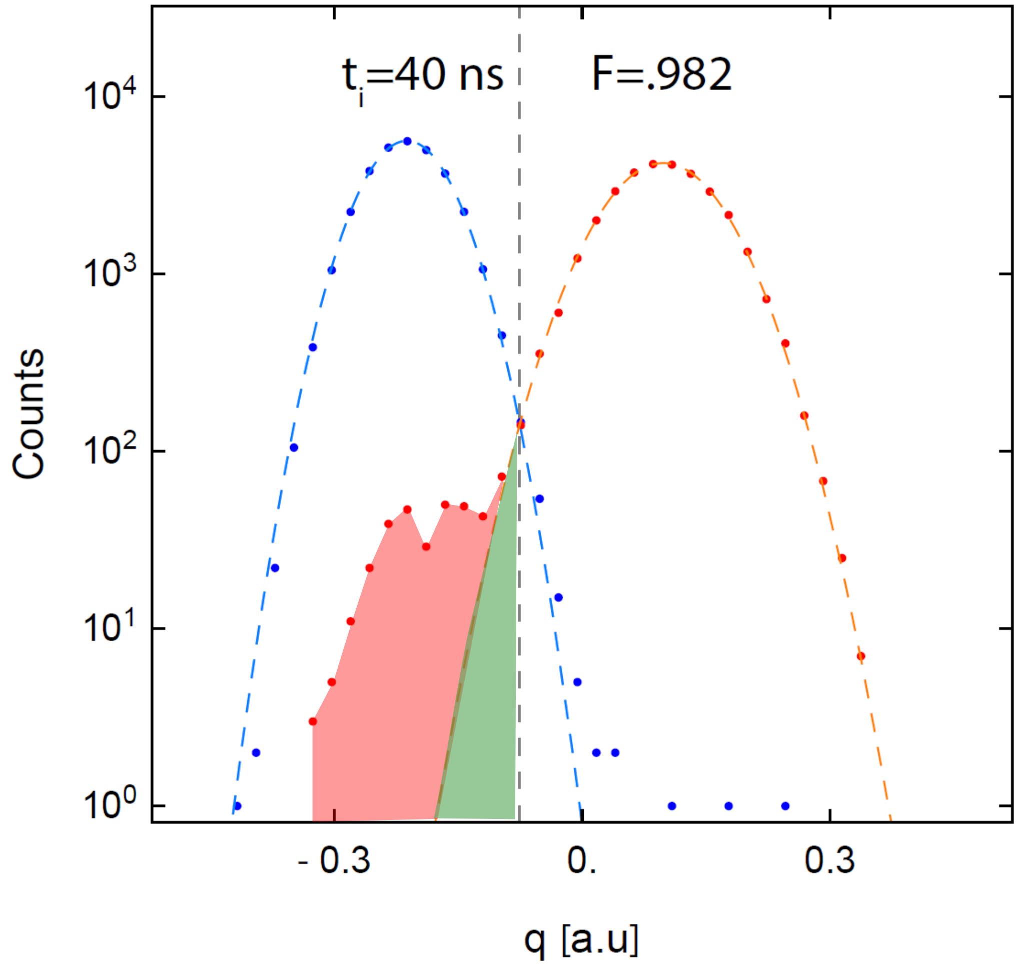
Histograms of Integrated Quadrature Signals



In ground/excited state:

- Data of 35 10^3 preparations each (*,*)
- Fitted Gaussian distribution (-,-)
- Constant threshold (---)

Quadrature integrate with opt. filter.

Definition of errors and fidelities in ground/excited state:

- Overlap error $\varepsilon_o^{g/e}$
- Transition, preparation (and other) errors $\varepsilon_{tp}^{g/e}$
- Total error $\varepsilon^{g/e} = \varepsilon_o^{g/e} + \varepsilon_{tp}^{g/e}$

For measurement of unknown state:

- Total error $\varepsilon = \varepsilon^g + \varepsilon^e$
- Total fidelity $F = 1 - \varepsilon$

Note:

- Threshold is either kept fixed at midpoint or adjusted for ideal fidelity

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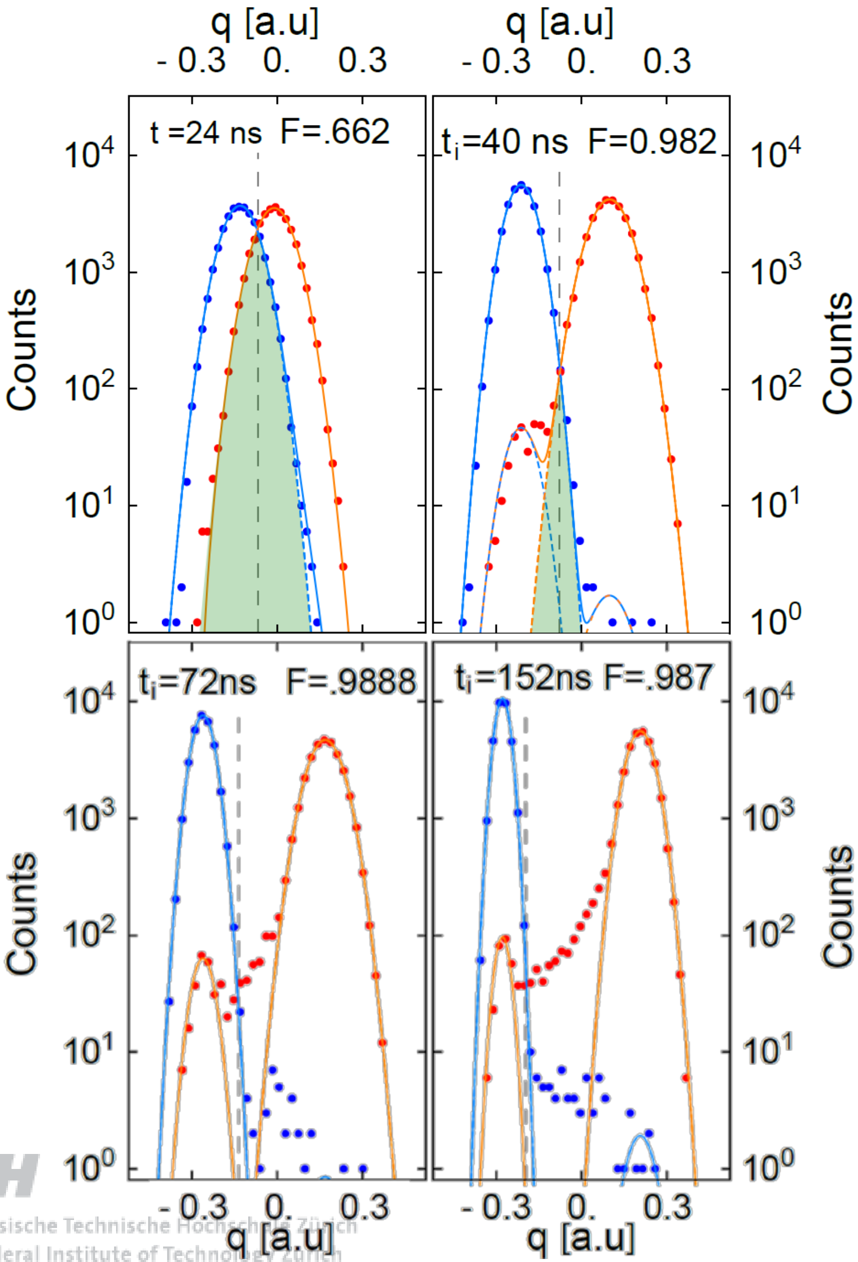
Quadrature Histograms *vs.* Integration Time



Preparation:

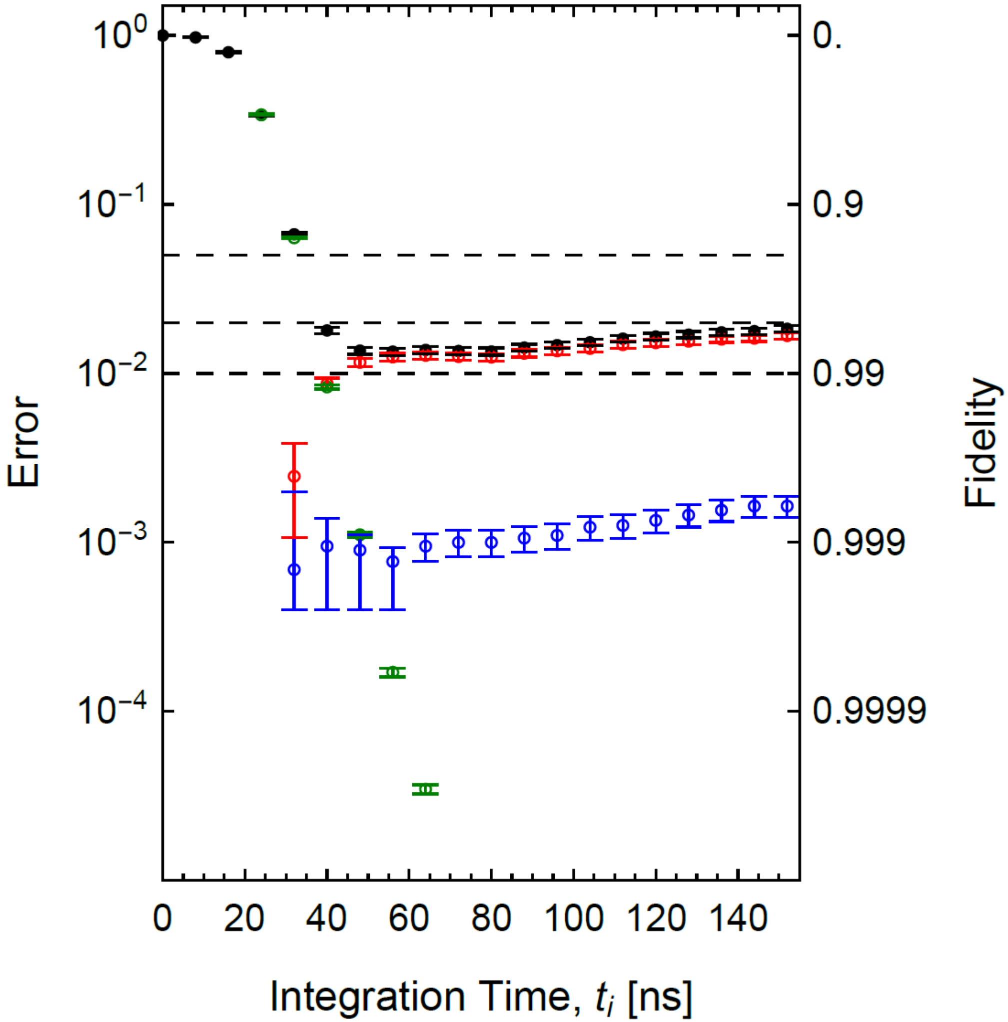
- Ground state (g)
- Excited state (e)

Discussion:

- Fast readout at t_i = 40 ns with F > 98 %
- Optimal fidelity F = 98.9% at t_i = 72 ns
- Threshold adjusted for max. F
- Reduction of F at larger t_i due to qubit decay and measurement induced state mixing
- Reduction of F at smaller t_i due to overlap error

T. Walter, P. Kurpiers *et al.*, Quantum Device Lab, ETH Zurich (2016)

Measurement Error (Fidelity) *vs.* Integration Time



Discussion:

- Fast state discrimination with overlap error drop to 1 % in only 40 ns
- Excited state error < 1.5 %
- Ground state error < 0.2 %
- Max. total fidelity > 98 % limited by qubit T_1

Further (preliminary) analysis:

- Small measurement induced mixing rate
- Small re-thermalization rate

T. Walter, P. Kurpiers *et al.*, Quantum Device Lab, ETH Zurich (2016)

A Comparison of Quality Measures of Readout

Reference	[1]	[2]	[3]	[4]
Integration time t_i [ns]	40	140	300	300
Total fidelity F [%]	98.8	98.7	97.6	91.1
Readout $\kappa/2\pi$ [MHz]	37	4.3	0.6	9
Dispersive shift $2\chi/2\pi$ [MHz]	-15	~	-5.2	7.4
Resonator population n,	2	~	3300	37.8
Number of qubits on chip	1	4	10	1
Qubit T_1 [μs]	8	12	25	1.8

[1] T. Walter, P. Kurpiers *et al.*, Quantum Device Lab, ETH Zurich (2016)

[2] E. Jeffrey *et al.*, *PRL* **112**, 190504 (2014)

[3] C. C. Bultink *et al.*, *arxiv:160400916* (2016)

[4] J. E. Johnson *et al.*, *PRL* **109**, 050506 (2012)

Fast, High-Fidelity Single Shot Readout

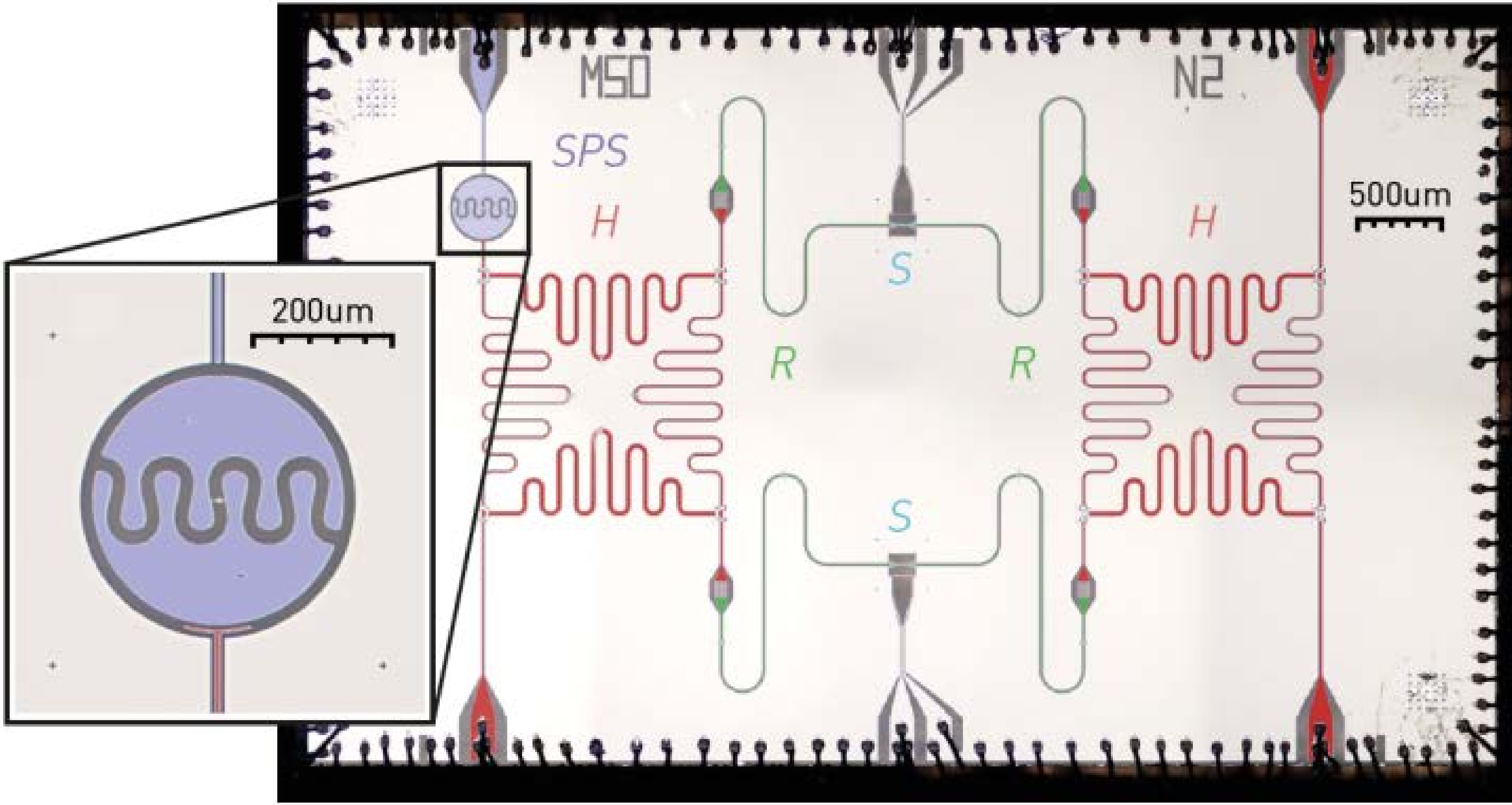
Main results:

- High fidelity (> 98 %) at short integration time (40ns) and small resonator population (n ~ 2.2) achieved through
  - sample design optimized for readout
  - low-noise JPD based phase sensitive amplification chain

Outlook:

- Systematic comparison of phase sensitive JPD with ...
  - ... phase insensitive JPD
    Eichler *et al.*, *PRL* **113**, 110502 (2014)
  - ... traveling wave parametric amplifier (TWPA)
    Macklin *et al.*, *Science* **350**, 307 (2015)
- Extension to multiplexed readout
- Optimization of design relative to other performance constraints

Fast, Low-Loss, Linear, On-Chip Microwave Switch



M. Pechal *et al.*, *Phys. Rev. Applied* 6, 024009 (2016)

Why do we want an on-chip switch?

- Ability to route signals at base temperature is useful
  - for calibration of S-parameter measurements
  - to save resources (single readout line for multiple samples)
- Conventional (mechanical or PIN diode) switches can be used in cryostats
  - but dissipate heat
  - are slow (rel. to coherence times)
- On-chip switch
  - negligible dissipation
  - potentially very fast
  - compact
  - simple integration with SC devices

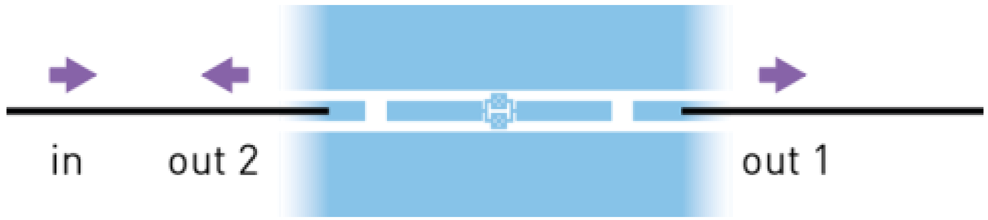
L. Ranzani *et al.*, *Rev. Sci. Instrum.* **84,** 034704 (2013)

Why not just a tunable resonator?

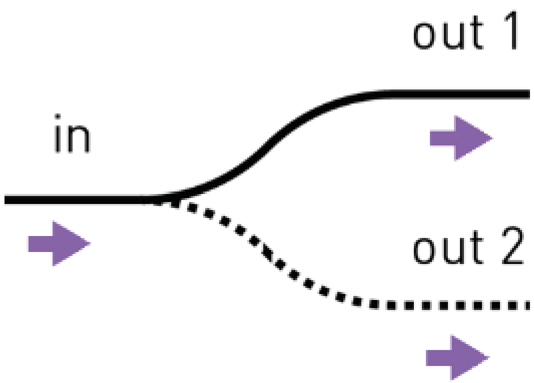
- Tunable resonator switches between transmission and reflection (as do more sophisticated devices)

  O. Naaman *et al.*, *arXiv:1512.01484* (2015)

  B. J. Chapman *et al.*, *Appl. Phys. Lett.* **108**, *222602* (2016)

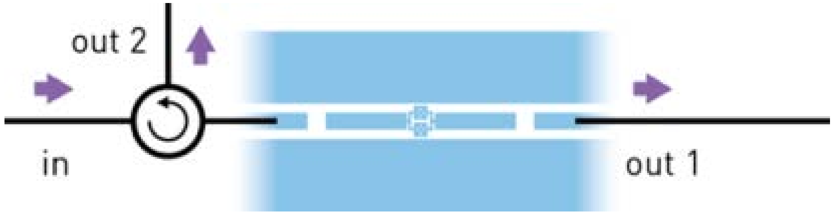


- We would like



Can be realized with

tunable resonator + circulator

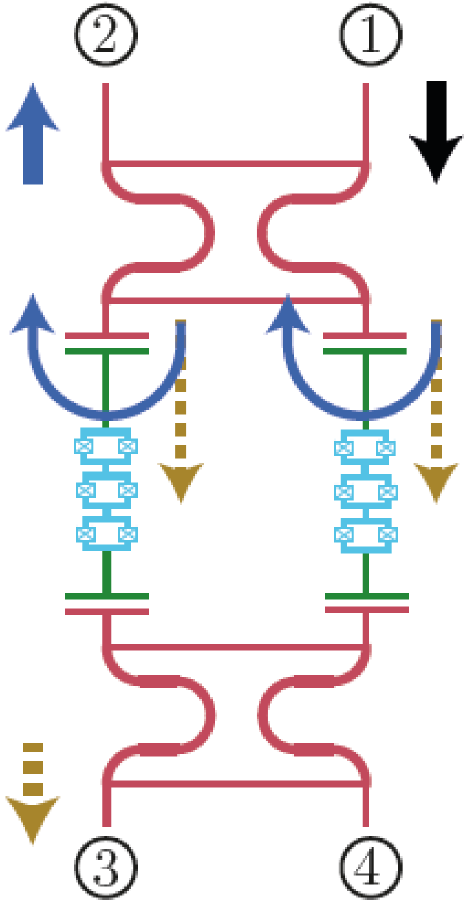


...but

- this configuration is not reciprocal
- on-chip circulators are rather complex

The Device

- Based on interference effects in a network consisting of
  - two tunable resonators
  - two pi/2 hybrids (beamsplitters)



- If resonant, signal passes to bottom beamsplitter
- If off resonant, signal reflects to top beamsplitter

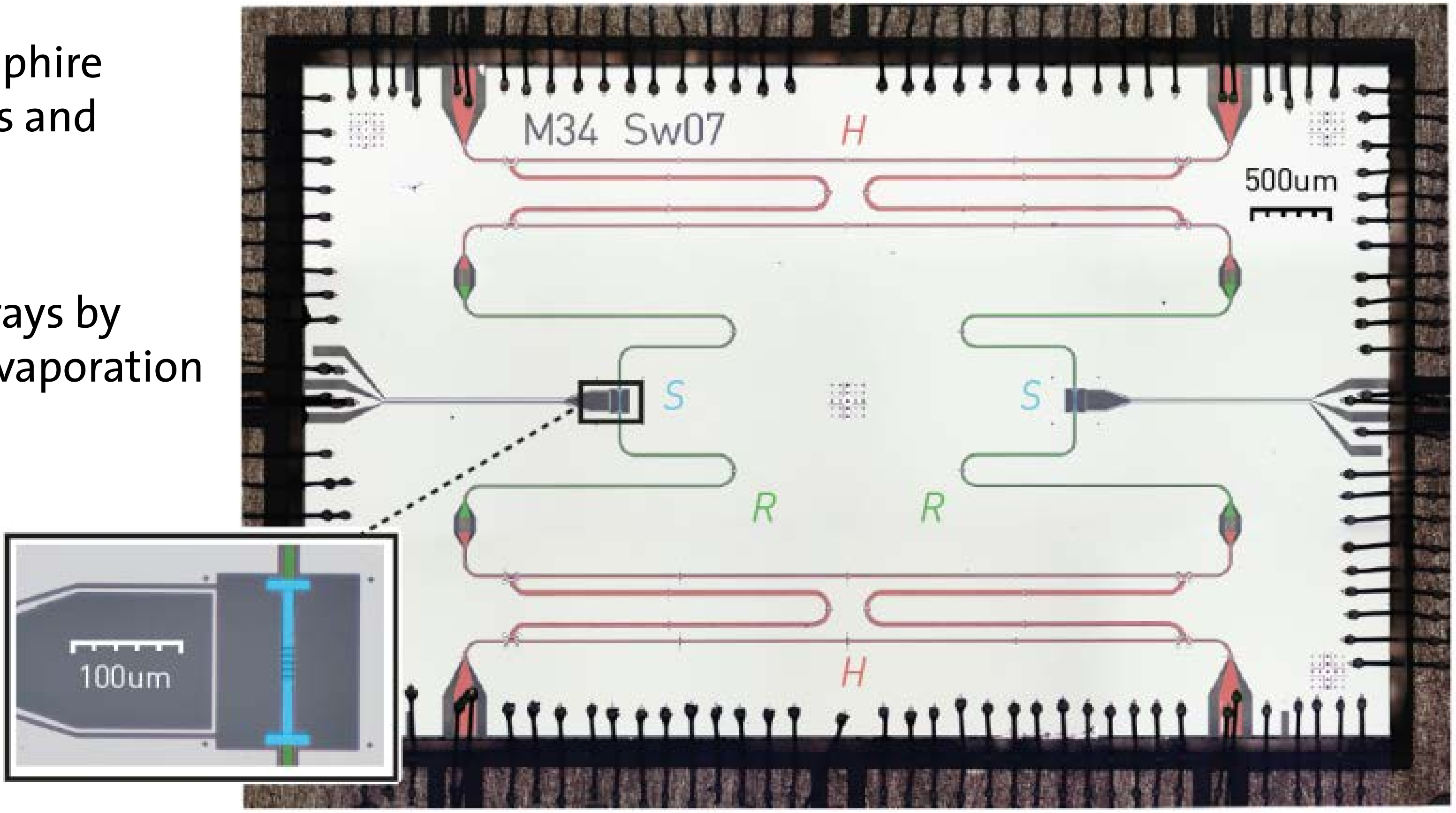
M. Pechal *et al.*, *Phys. Rev. Applied* 6, 024009 (2016)

The Device

- Based on interference effects in a network consisting of
  - two tunable resonators
  - two pi/2 hybrids (beamsplitters)

- Nb on sapphire resonators and hybrids

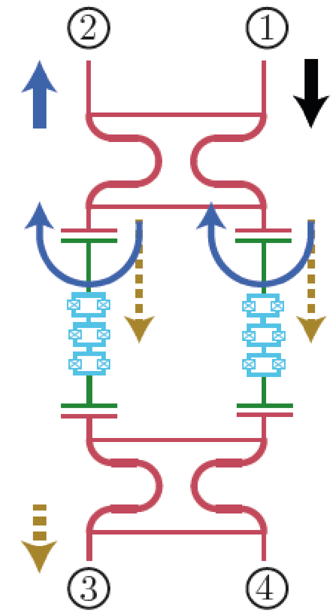
- SQUID arrays by shadow evaporation of Al



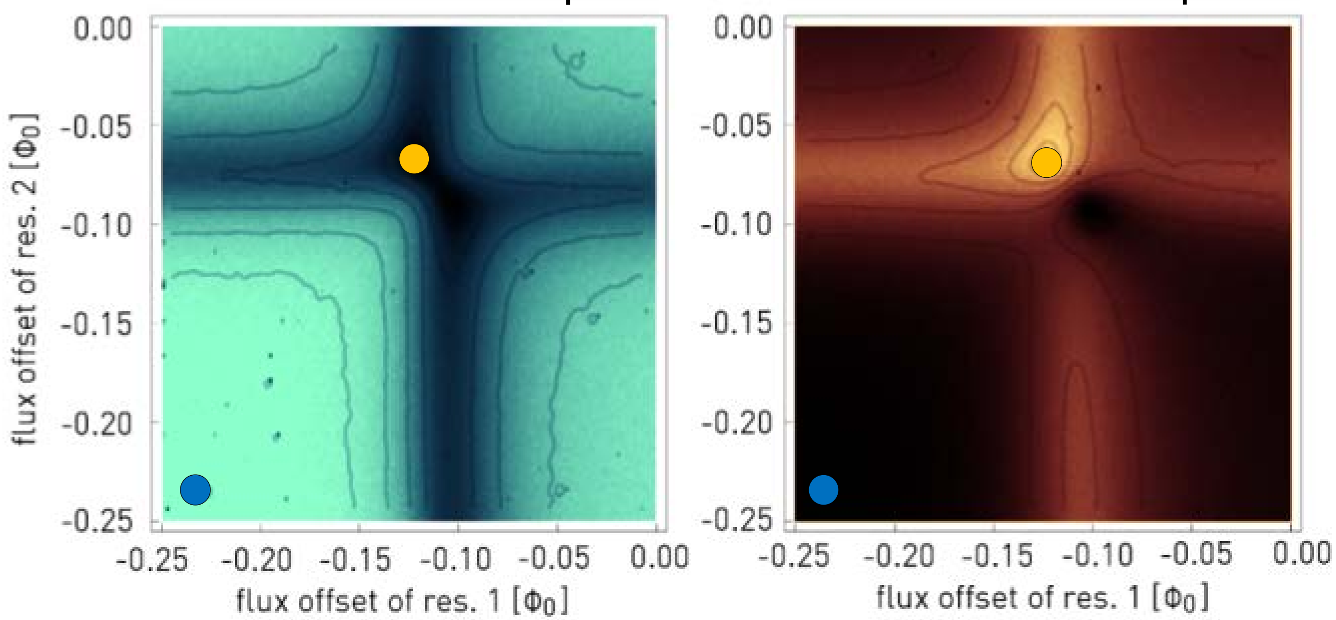
M. Pechal *et al.*, *Phys. Rev. Applied* 6, 024009 (2016)

Results: Flux-Dependent Transmission

- Measure S-parameters
  - As a function of coil voltages at a fixed frequency
    - On/off ratios of 37 dB (S12) and 29 dB (S13)



Transmission from input 1 | Transmission from input 2

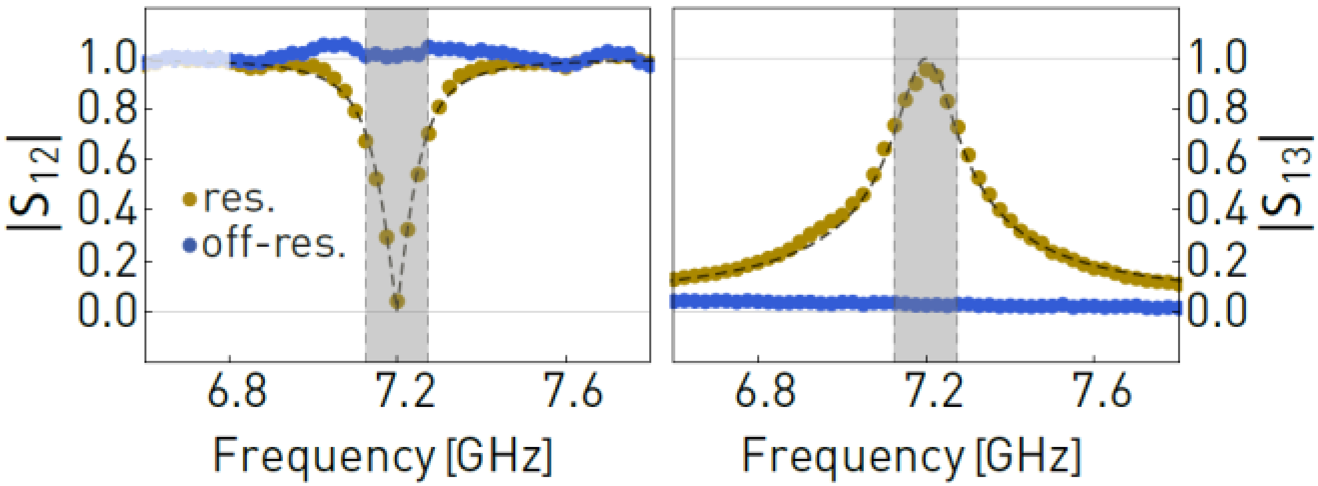


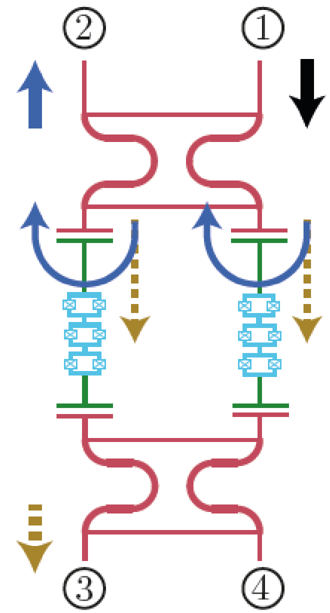
(contour lines: 0.05, 0.2, 0.4, 0.6, 0.8, 0.95)

M. Pechal *et al.*, *Phys. Rev. Applied* 6, 024009 (2016)

Results: Spectrum

- Measure S-parameters
  - As a function of coil voltages at a fixed frequency
    - On/off ratios of 37 dB (S12) and 29 dB (S13)
  - As a function of frequency at the two chosen flux settings
    - FWHM bandwidth of approximately 150 MHz

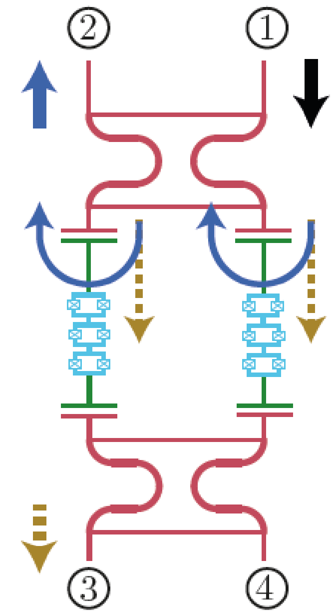


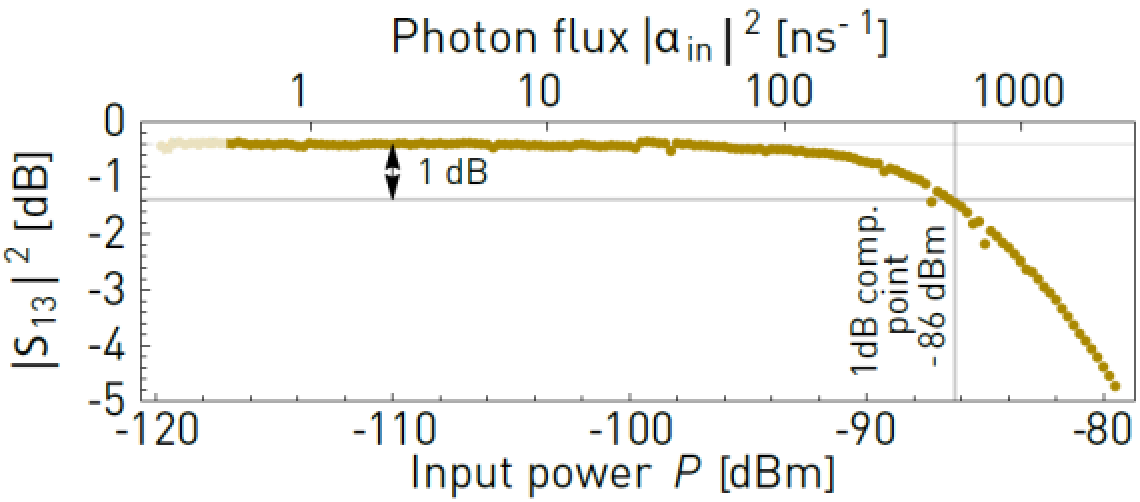


M. Pechal *et al.*, *Phys. Rev. Applied* 6, 024009 (2016)

Results: Saturation

- Measure S-parameters
  - As a function of coil voltages at a fixed frequency
    - On/off ratios of 37 dB (S12) and 29 dB (S13)
  - As a function of frequency at the two chosen flux settings
    - FWHM bandwidth of approximately 150 MHz
  - As a function of input power
    - Compression point of approximately -86 dBm (500,000 photons per microsecond)

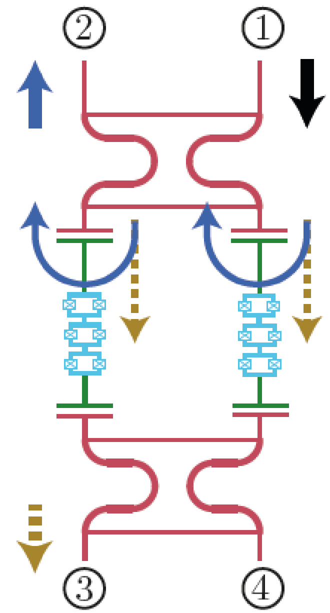




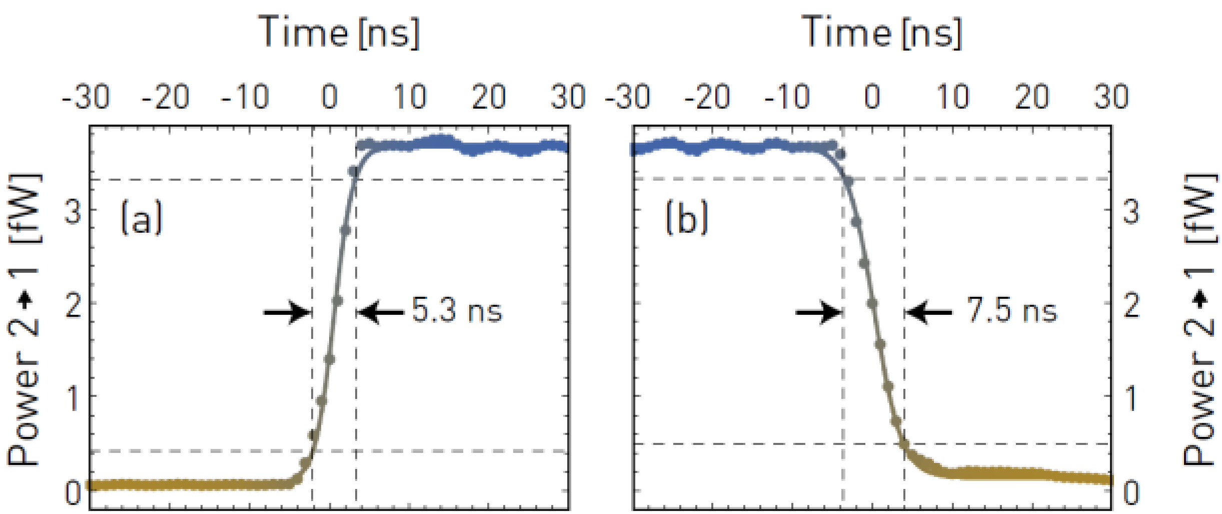
M. Pechal *et al.*, *Phys. Rev. Applied* 6, 024009 (2016)

Results: Fast Switching

- Measure S-parameters
  - As a function of coil voltages at a fixed frequency
    - On/off ratios of 37 dB (S12) and 29 dB (S13)
  - As a function of frequency at the two chosen flux settings
    - FWHM bandwidth of approximately 150 MHz
  - As a function of input power
    - Compression point of approximately -86 dBm (500,000 photons per microsecond)



- Measure switching time
  - turn-on/off time of approximately 6-8 ns

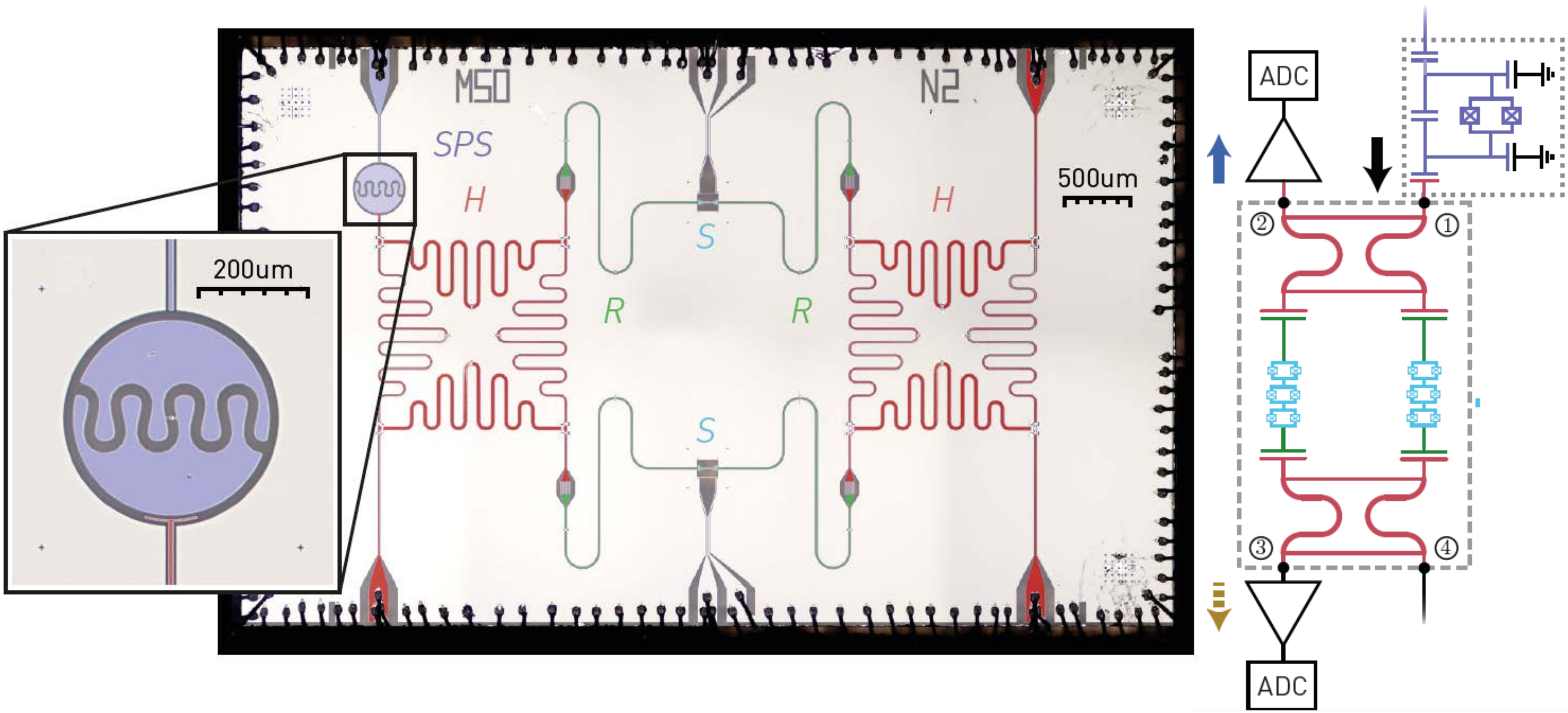


M. Pechal *et al.*, *Phys. Rev. Applied* 6, 024009 (2016)

Single Photon Routing

- Single photon source based on a transmon qubit

  Z. H. Peng *et al.*, *arXiv:1505.05614* (2015)



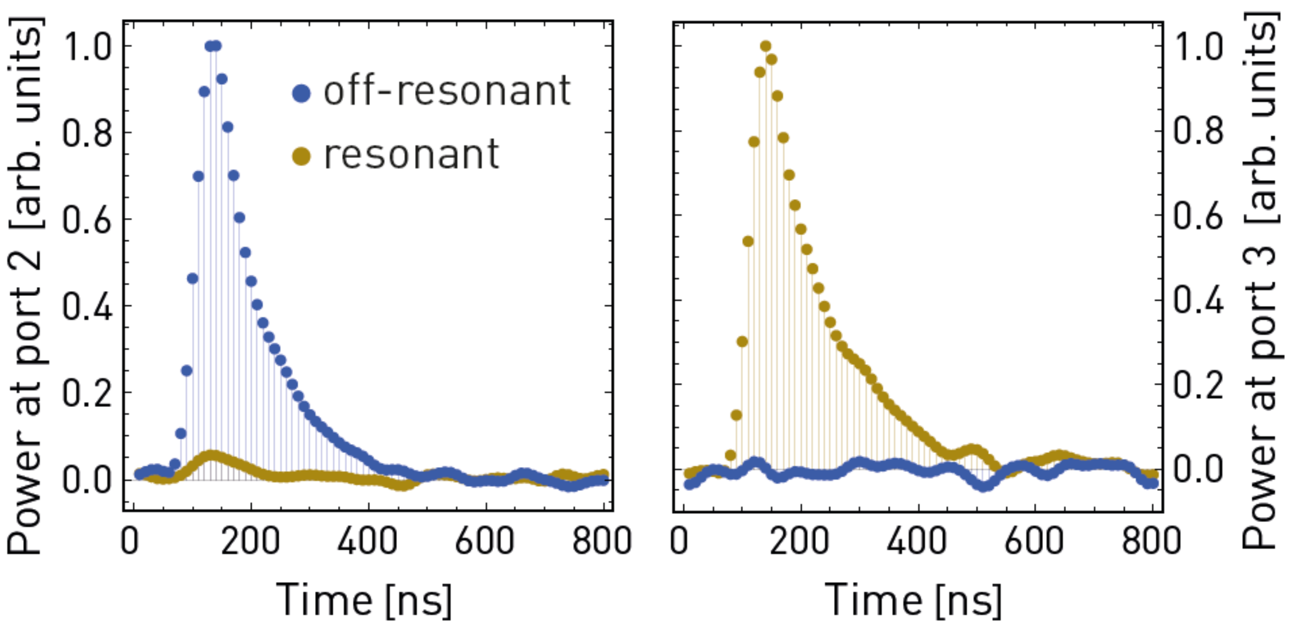
M. Pechal *et al.*, *Phys. Rev. Applied* 6, 024009 (2016)

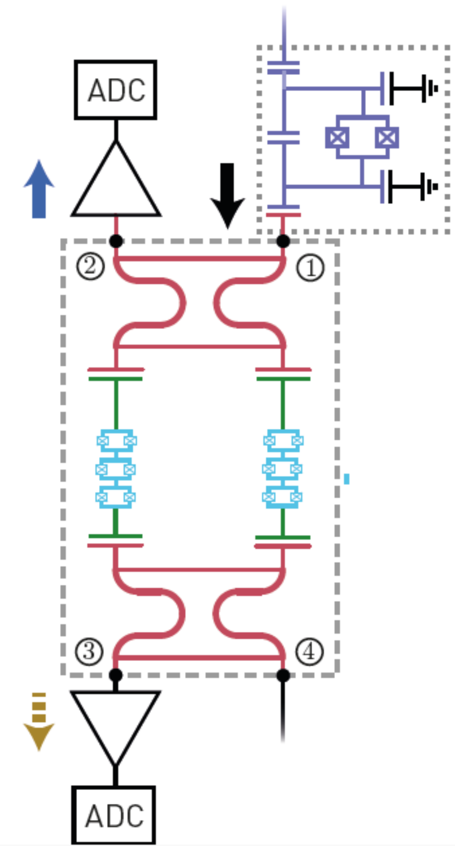
Results: Single Photon Envelope

- Single photon source based on a transmon qubit

  Z. H. Peng *et al.*, *arXiv:1505.05614* (2015)

- Switching of single photons





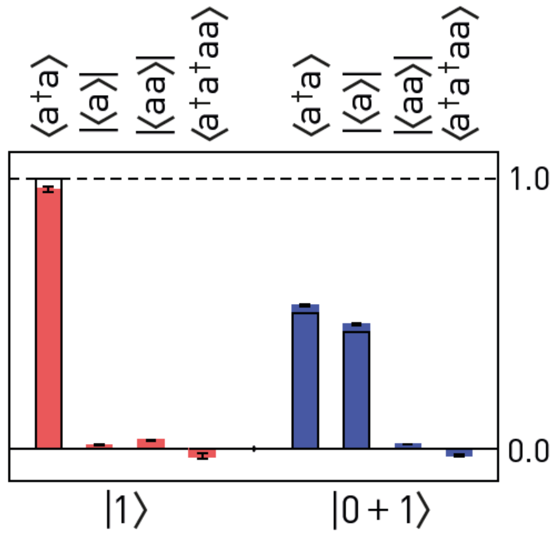
M. Pechal *et al.*, *Phys. Rev. Applied* 6, 024009 (2016)

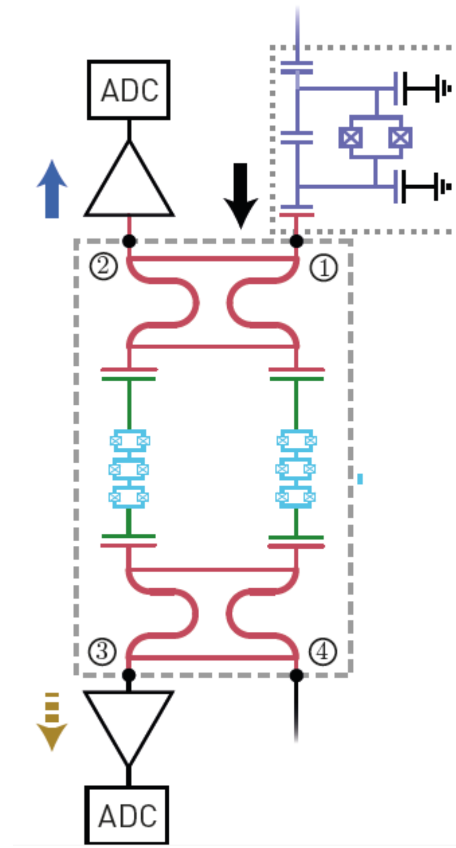
Results: Statistical Moments and Wigner Functions

- Single photon source based on a transmon qubit

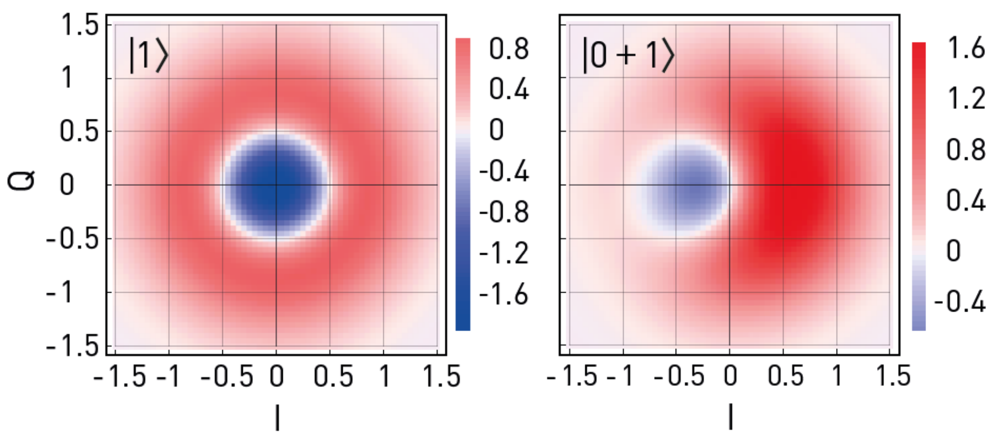
  Z. H. Peng *et al., arXiv:1505.05614* (2015)

- Switching of single photons
  + measuring their moments





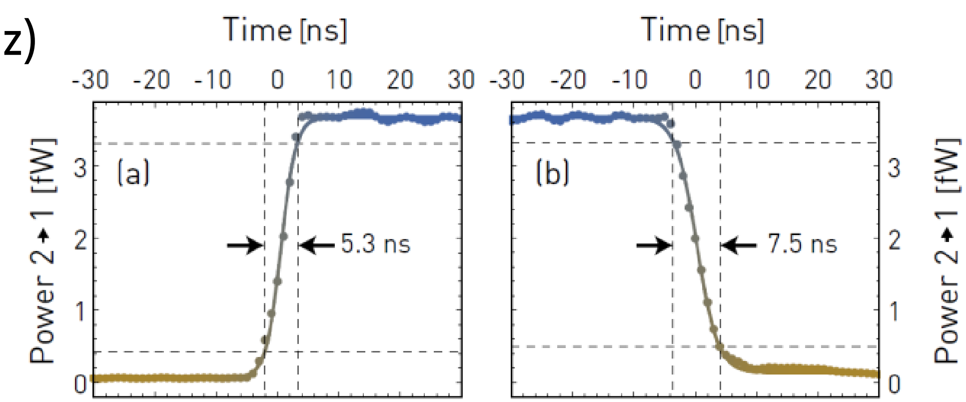
Extracted Wigner functions of single photon states



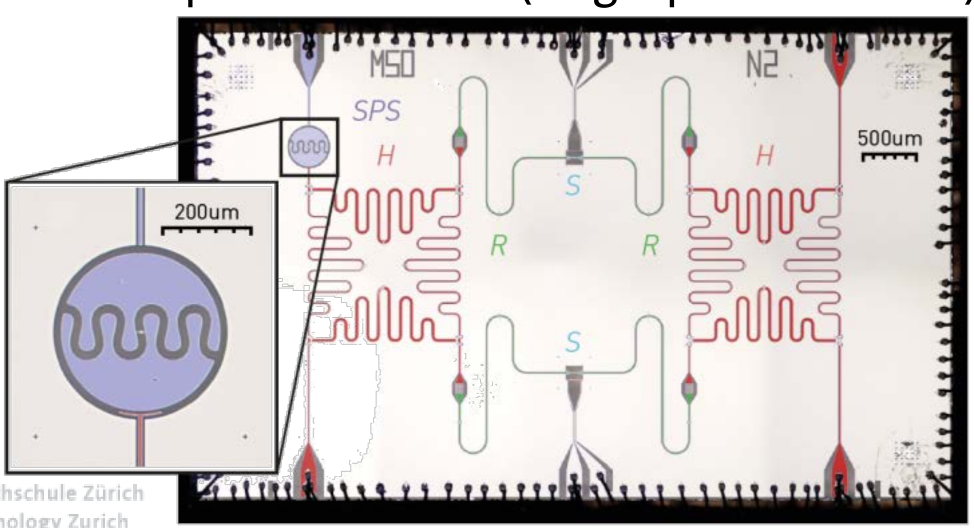
M. Pechal *et al., Phys. Rev. Applied* 6, 024009 (2016)

Short Summary on On-Chip Switch

- Implemented an on-chip superconducting switch
  - Compatible with current fabrication processes
  - No heat dissipation
  - Relatively large bandwidth (150 MHz)
  - 1dB compression point at -86 dBm
  - Very fast (6-8 ns switching time)

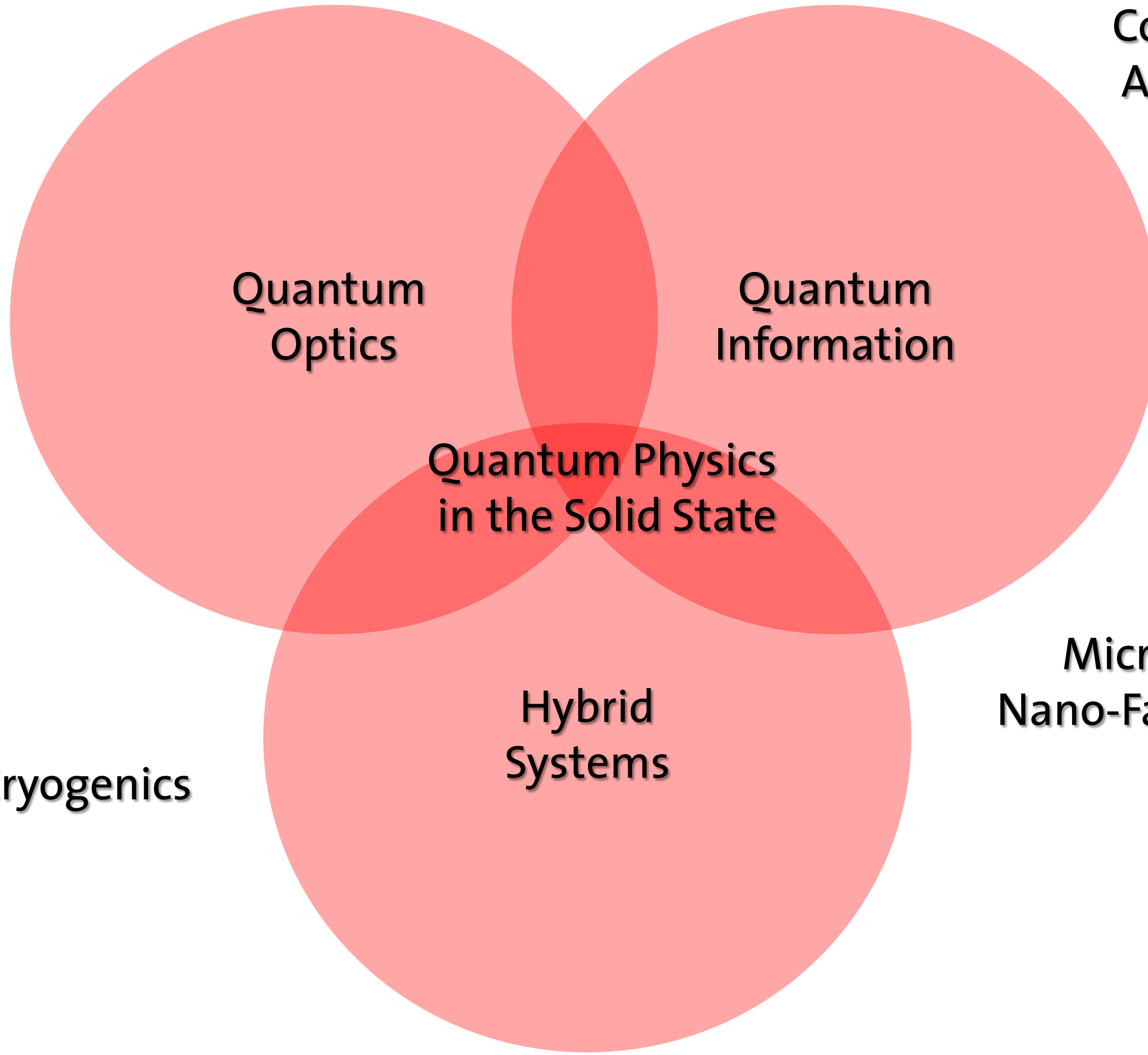


- Integrated with a quantum device (single photon source)



M. Pechal *et al.*,
Phys. Rev. Applied 6, 024009 (2016)

Circuit QED Research



The ETH Zurich Quantum Device Lab

incl. undergrad and summer students

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