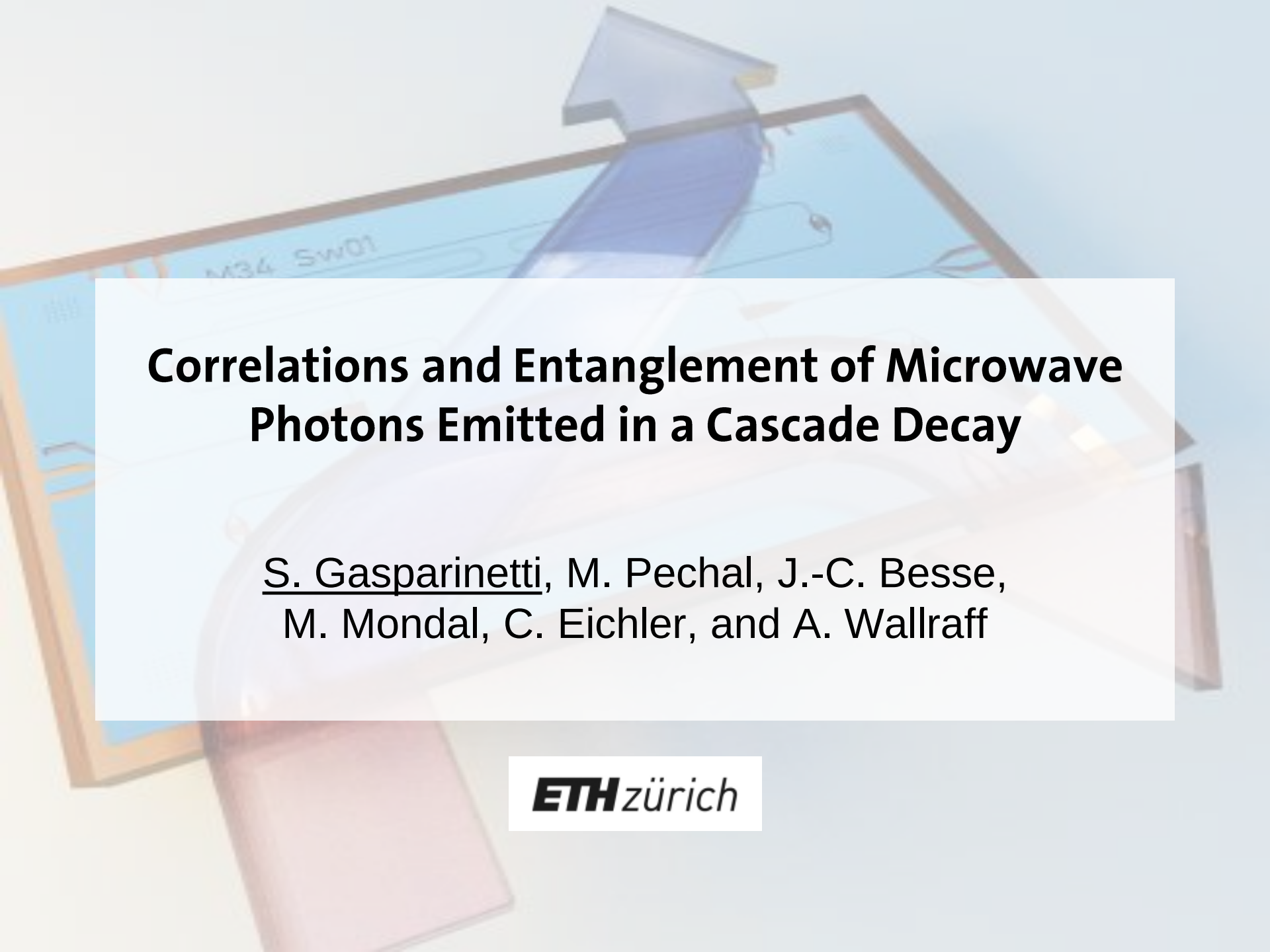


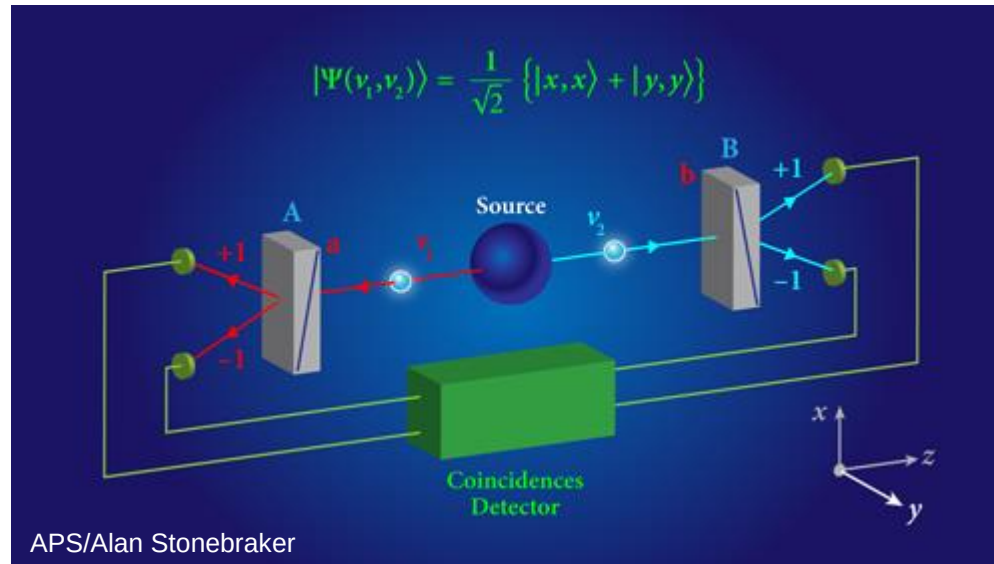


Correlations and Entanglement of Microwave Photons Emitted in a Cascade Decay

S. Gasparinetti, M. Pechal, J.-C. Besse,
M. Mondal, C. Eichler, and A. Wallraff

Cascade decay, revisited

Atomic cascades: "historical" sources of **polarization**-entangled photons



Incoherent excitation, radiation distributed between many modes

➔ No **phase** correlations

We've realized a system in which:

- (i) The atom is driven **coherently**
- (ii) It decays into **individual, well-defined modes**

➔ Cascade decay as a fully coherent process: phase correlations, entanglement

The “rise” of quantum microwave photonics

Generation



Houck, Nature **449** 328 (2007)

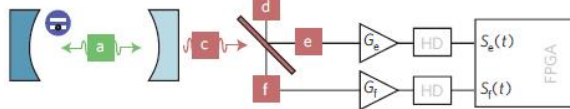
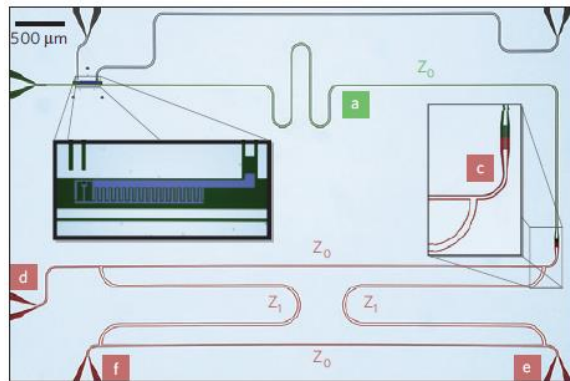


Yin, PRL **110** 107001 (2013)

Pechal, PRX **4** 041010 (2014)

Forn-Diaz, arXiv:1706.06688

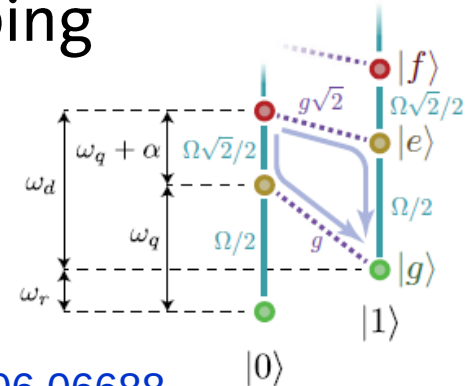
Characterization w/ linear amplifiers
antibunching, indistinguishability, etc.



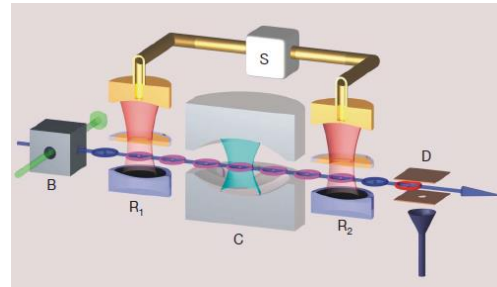
Bozyigit, Nat Phys **7** 154 (2011)

Lang, Nat Phys **9** 345 (2013)

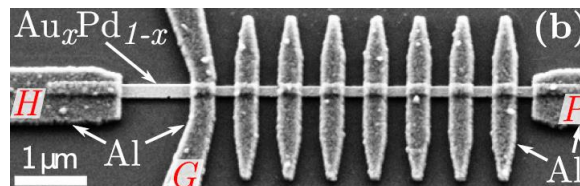
Shaping



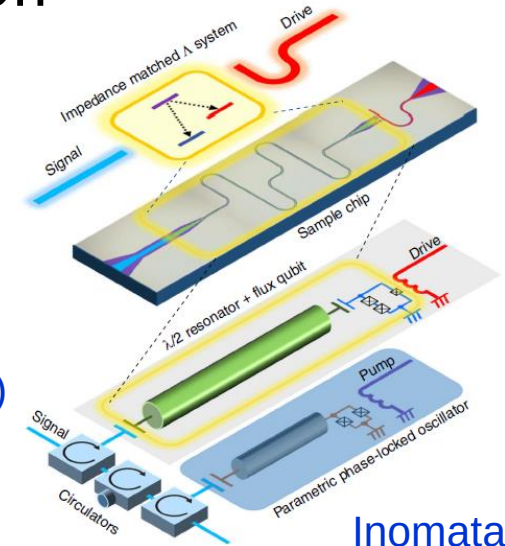
Detection



Gleyzes, Nature **446** 297 (2007)



Govenius, PRL **117** 030802 (2016)



Inomata,
Nat Comm **7** 12303 (2016)

Besse & SG, in progress

Outline of this talk

Two-photon source and experimental setup

Continuous-wave characterization

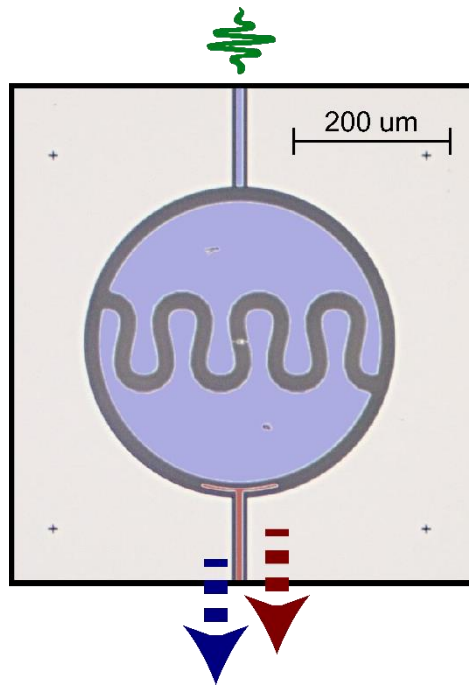
Pulsed characterization

Conclusions

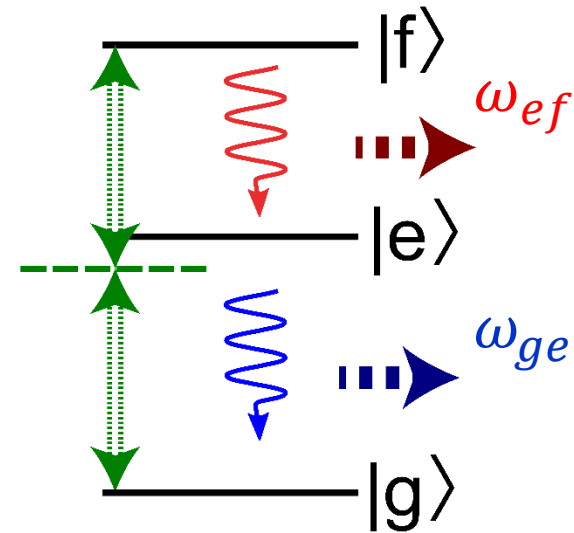
(Beyond cascade decay)

(My next experiment)

Cascade decay of a superconducting artificial atom

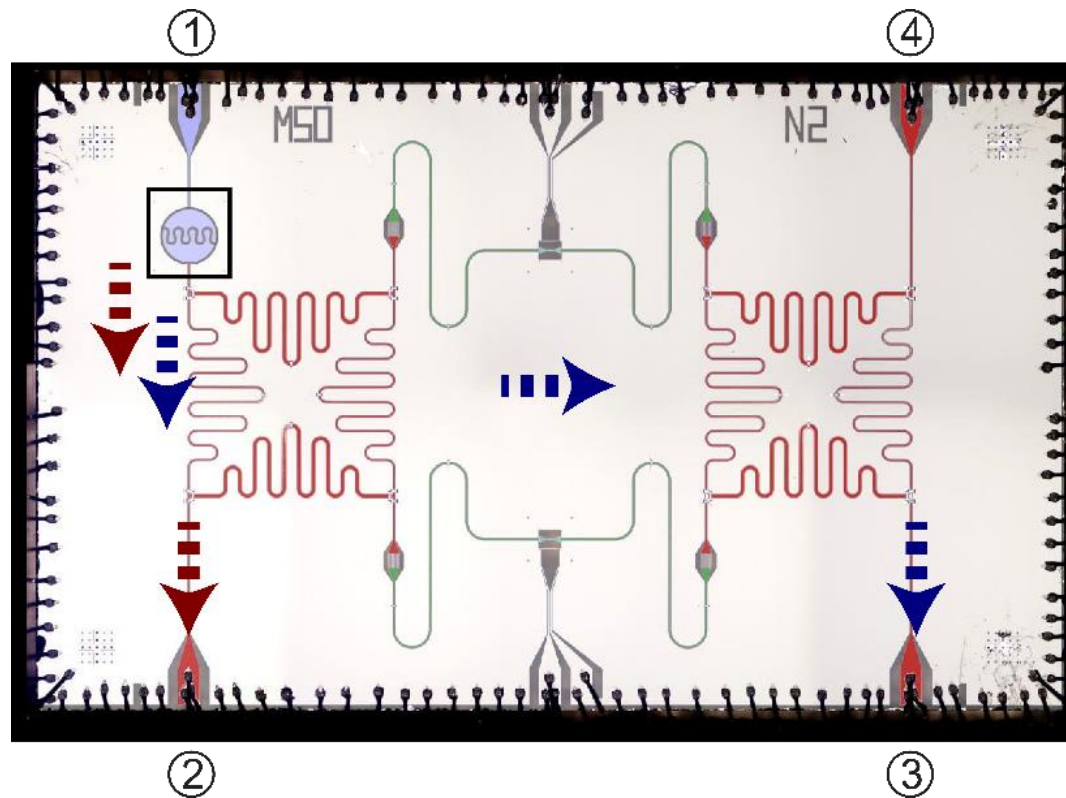


Transmon coupled to waveguides
Asymmetric coupling: drive/emission
Strong coupling to forward port
 $\Gamma_{ge}/2\pi = 1.94$ MHz



Anharmonicity $\alpha/2\pi = -233$ MHz
Two-photon resonant excitation
Cascade decay: ω_{ef} and ω_{ge} photons

Frequency-selective routing of the emitted photons

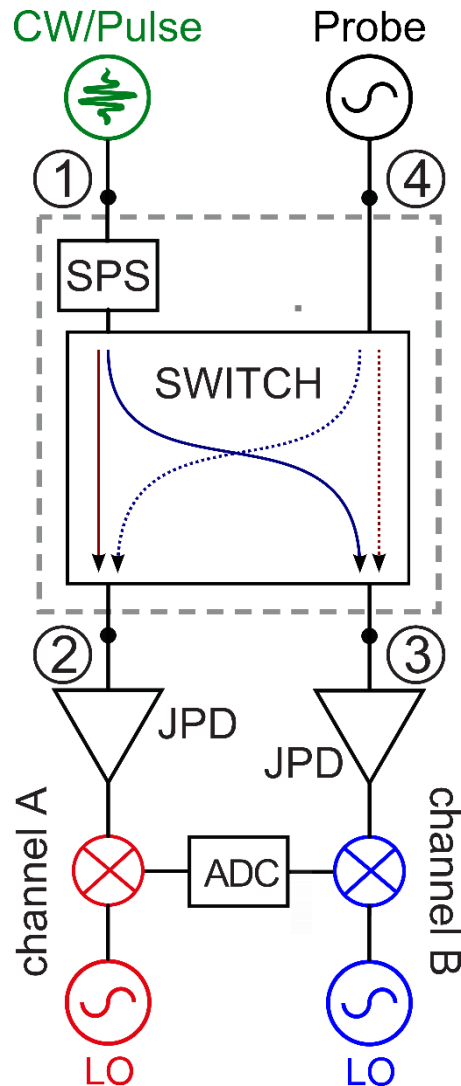


$$\begin{aligned}\Gamma_{ge} &\approx 2 \text{ MHz} \\ \kappa_{res} &\approx 100 \text{ MHz} \\ |\alpha| &\approx 200 \text{ MHz}\end{aligned}$$

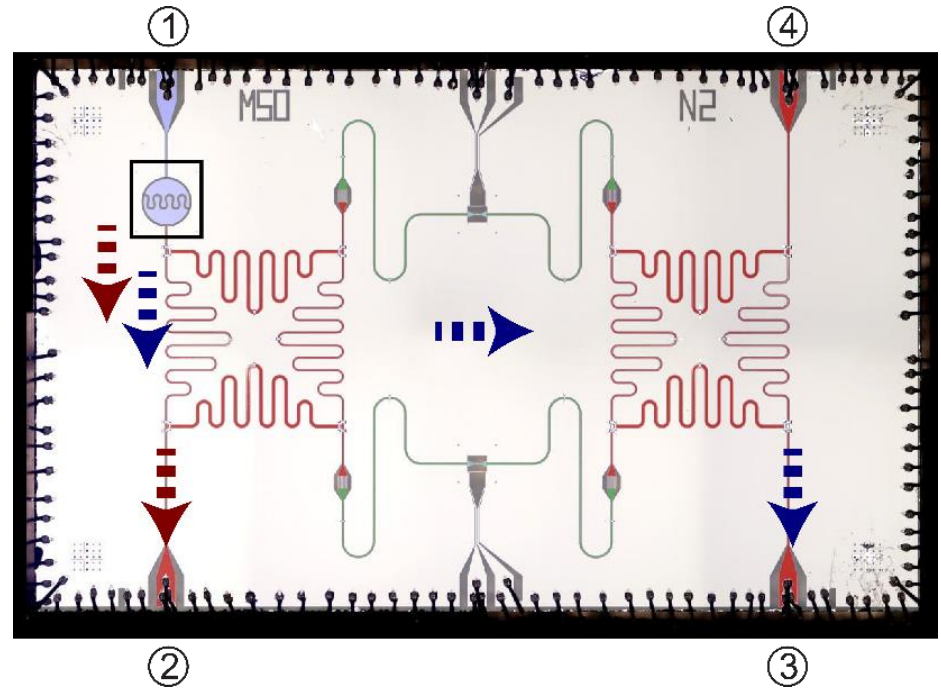
$$\Gamma_{ge}, \Gamma_{ef} \ll \kappa_{res} < |\alpha|$$

→ selective routing

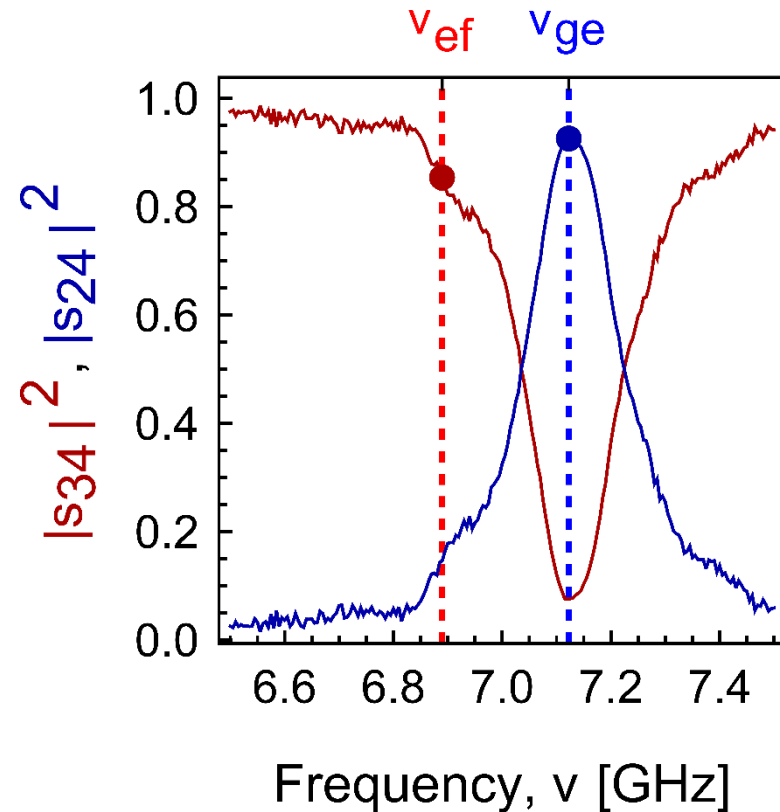
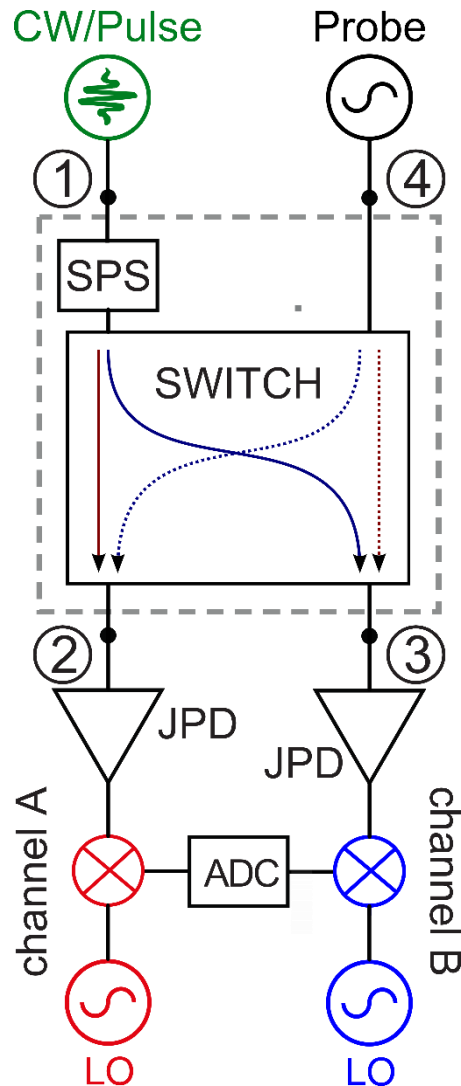
Frequency-selective routing of the emitted photons



==



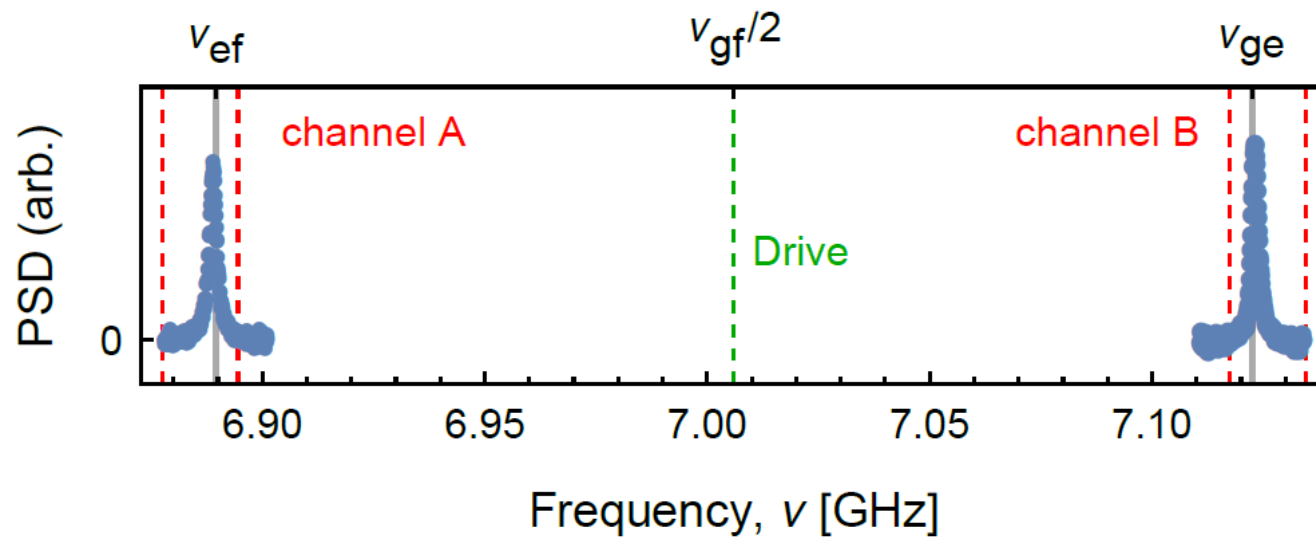
Spatial separation by frequency-selective routing



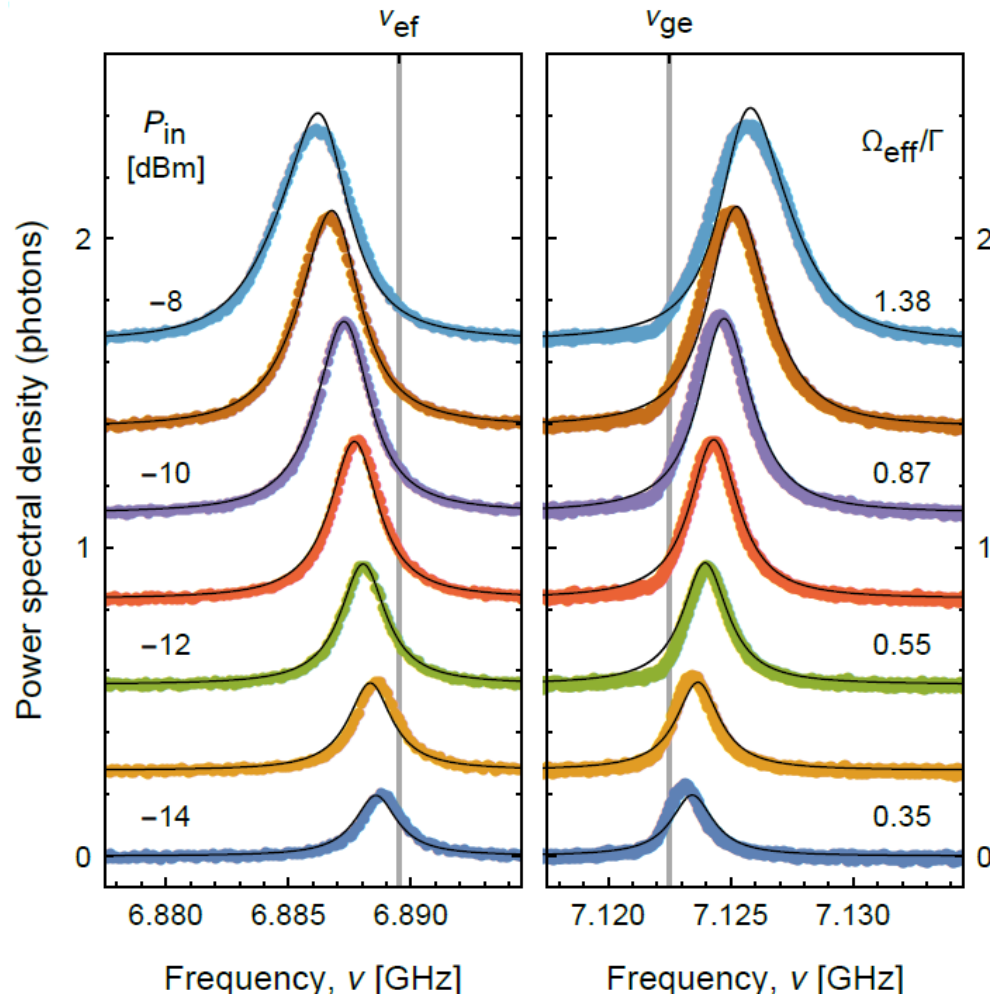
$$|s_{31}|^2 = |s_{24}|^2 = 91\% \text{ at } \omega_{ge}$$

$$|s_{21}|^2 = |s_{34}|^2 = 85\% \text{ at } \omega_{ef}$$

Continuous excitation: spectrum of inelastic scattering



Continuous excitation: spectrum of inelastic scattering



Solid lines: model based on
Master Equation + I/O theory
(parameters from spectroscopy,
input line attn. as fit param)

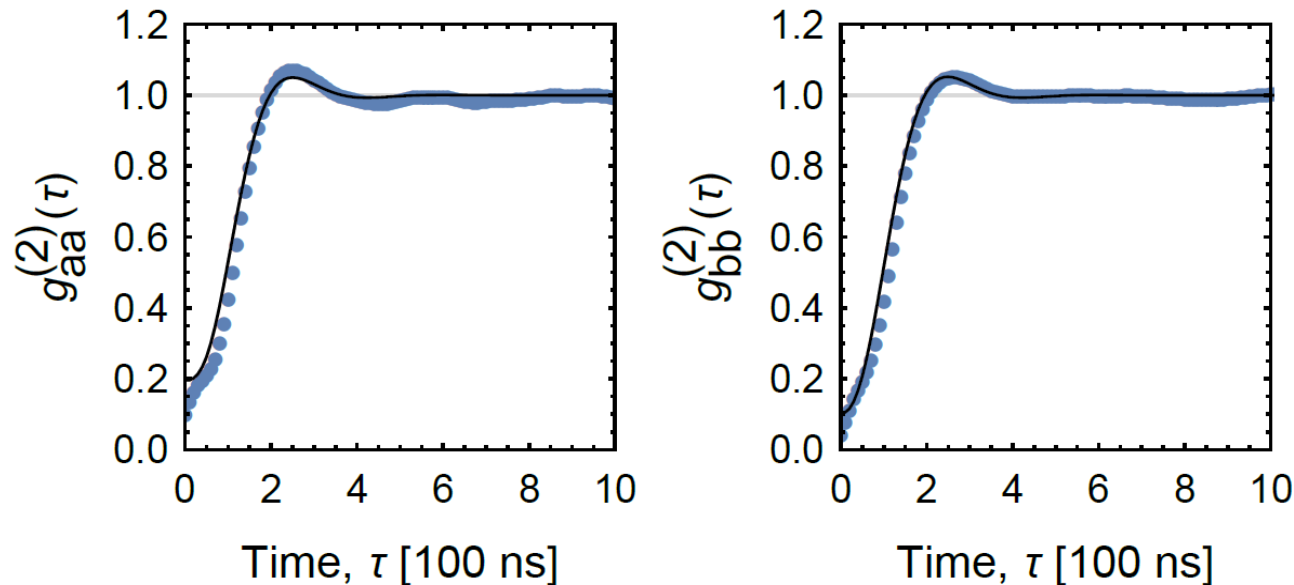
Drive strength $\Omega \propto \sqrt{P_{in}}$

Effective pump rate $\Omega_{eff} \propto \Omega^2$
(two-photon transition)

(stronger drive than here $\rightarrow$
three-state dressed states)

Continuous excitation: photon-photon correlations

Power **auto**correlation shows radiation is nonclassical
(single photons)

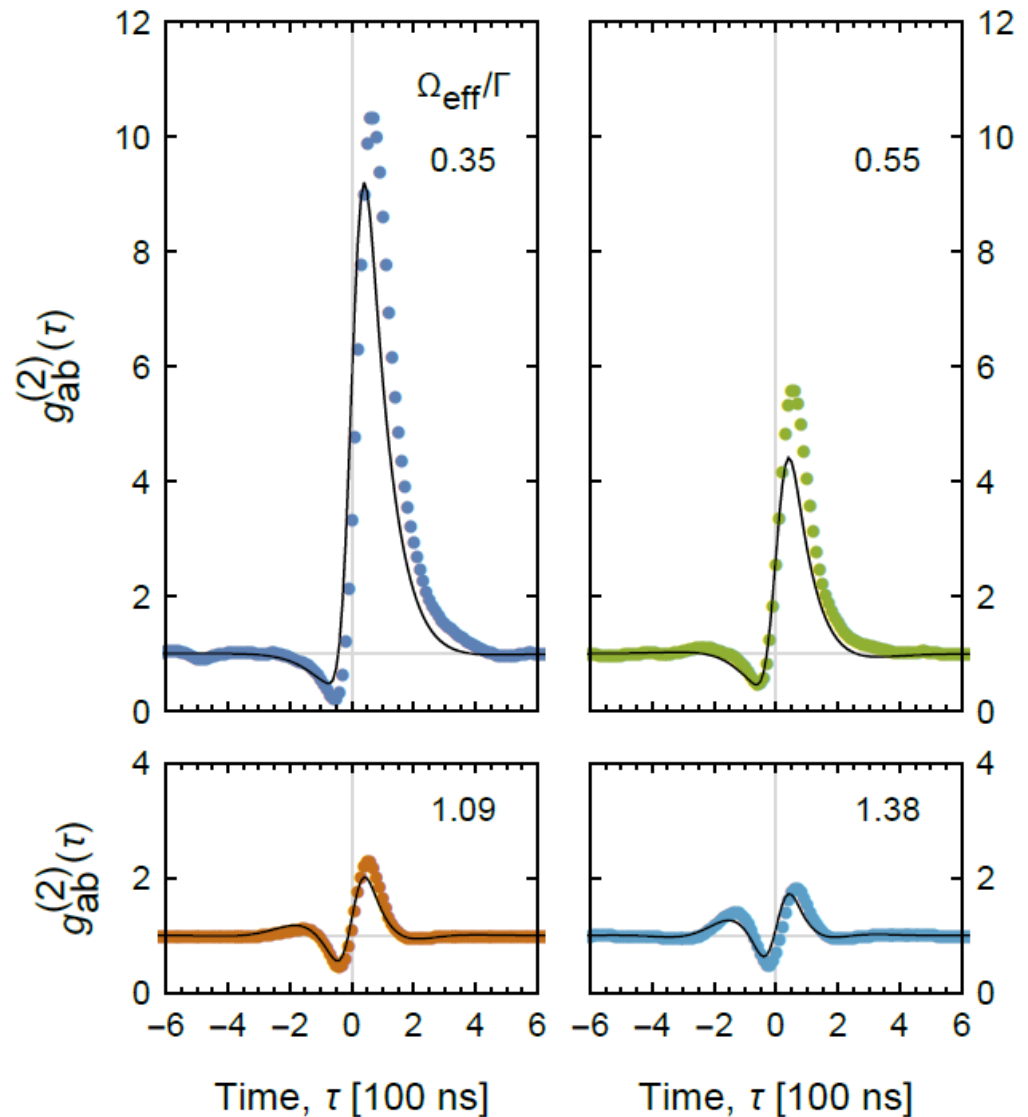


Continuous excitation: photon-photon correlations

Power **cross**-correlation shows that the photons are not generated independently

At $\Omega_{\text{eff}} \ll \Gamma_{ge}$, the ef photon “heralds” the ge photon

At $\Omega_{\text{eff}} \approx \Gamma_{ge}$, competition between coherent pumping and decay results in oscillatory pattern

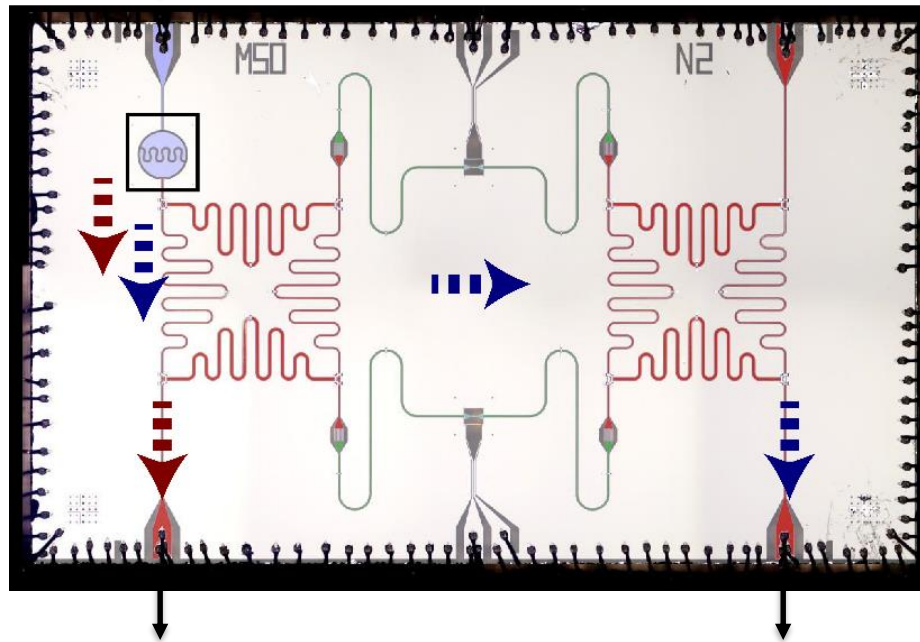
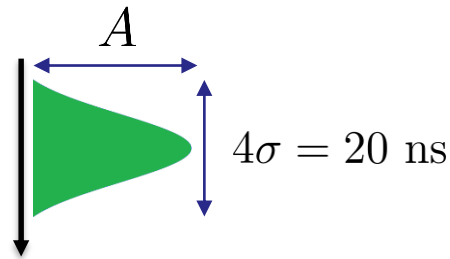


Clauser, Phys. Rev. D **9**, 853 (1974)

Loudon, Rep. Progr. Phys. **43**, 913 (1980)

Pulsed excitation: deterministic preparation

PREPARE



RECORD

$\hat{a}(t)$ Channel A

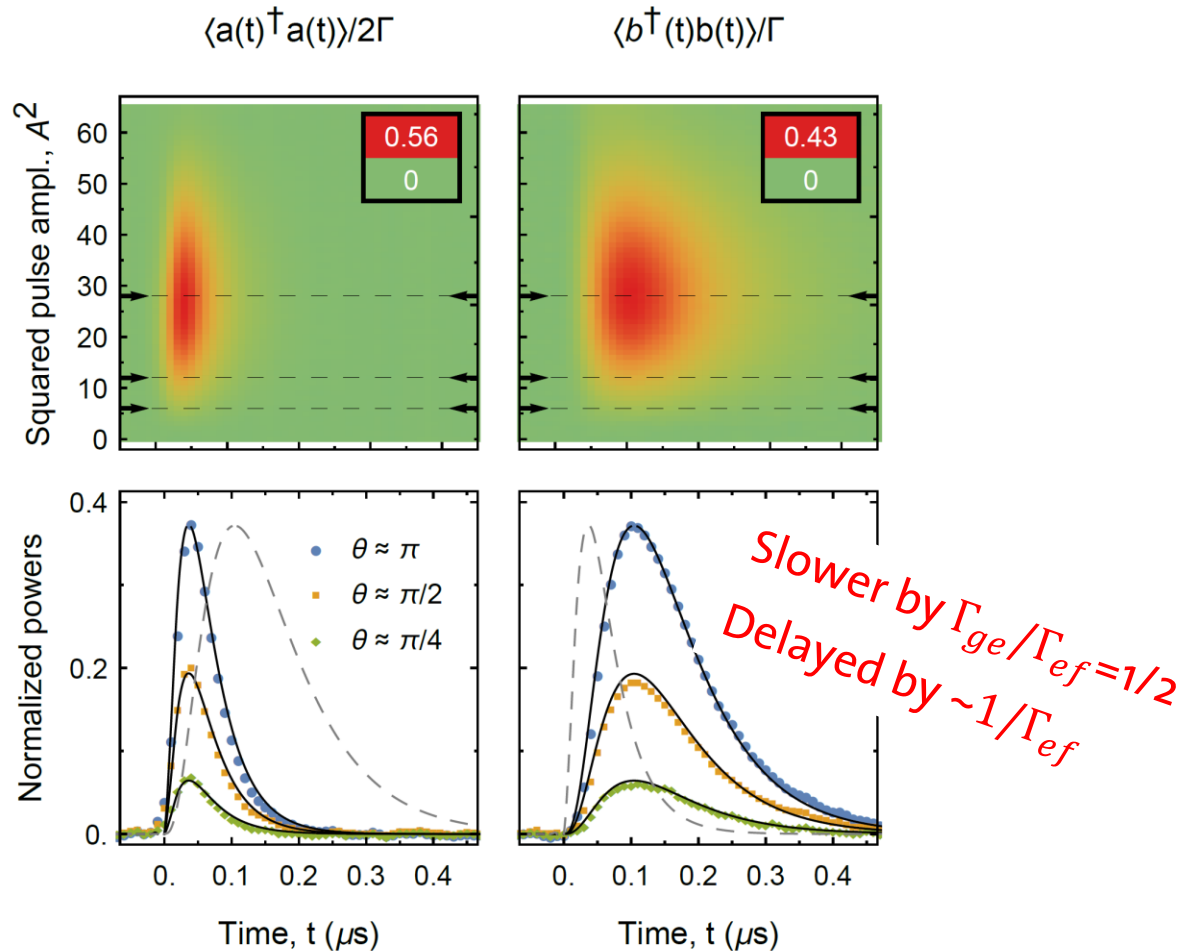
$\hat{b}(t)$ Channel B

Signal math prior to ensemble averaging

➔ Measure not only $\langle a(t) \rangle$ but also $\langle a^\dagger(t)a(t) \rangle$, $\langle a(t)b(t) \rangle$, etc.

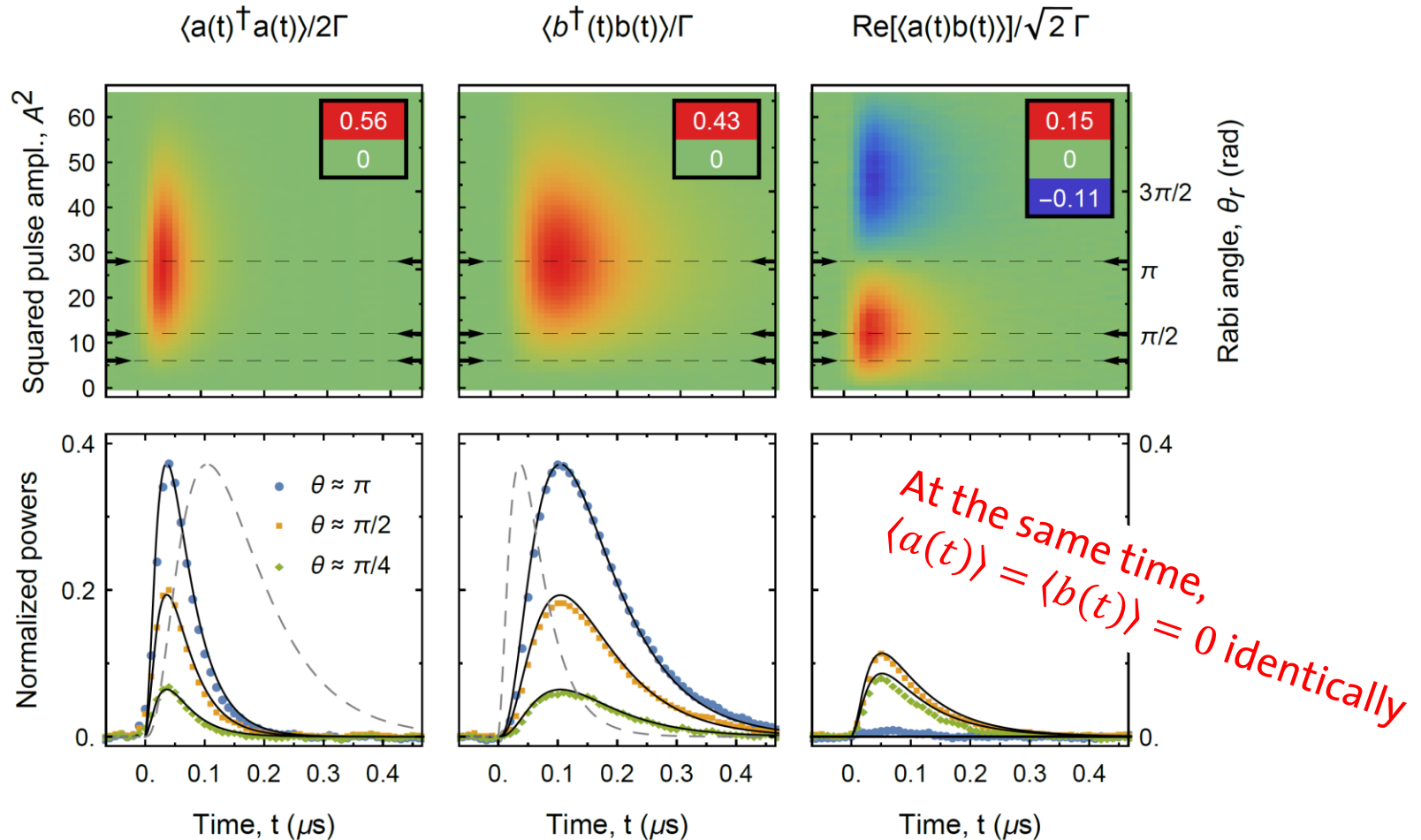
Pulsed excitation: photon shape and phase correlations

Time-resolved powers and phase correlations



Pulsed excitation: photon shape and phase correlations

Time-resolved powers and phase correlations



Interpretation: entangled photonic modes

Hilbert space: transmon $\otimes$ itinerant photonic modes

$$|g\rangle \otimes |0_a\rangle \otimes |0_b\rangle$$



State preparation

$$[\cos(\theta_r/2)|g\rangle + \sin(\theta_r/2)|f\rangle] \otimes |0_a\rangle \otimes |0_b\rangle$$



Cascade decay

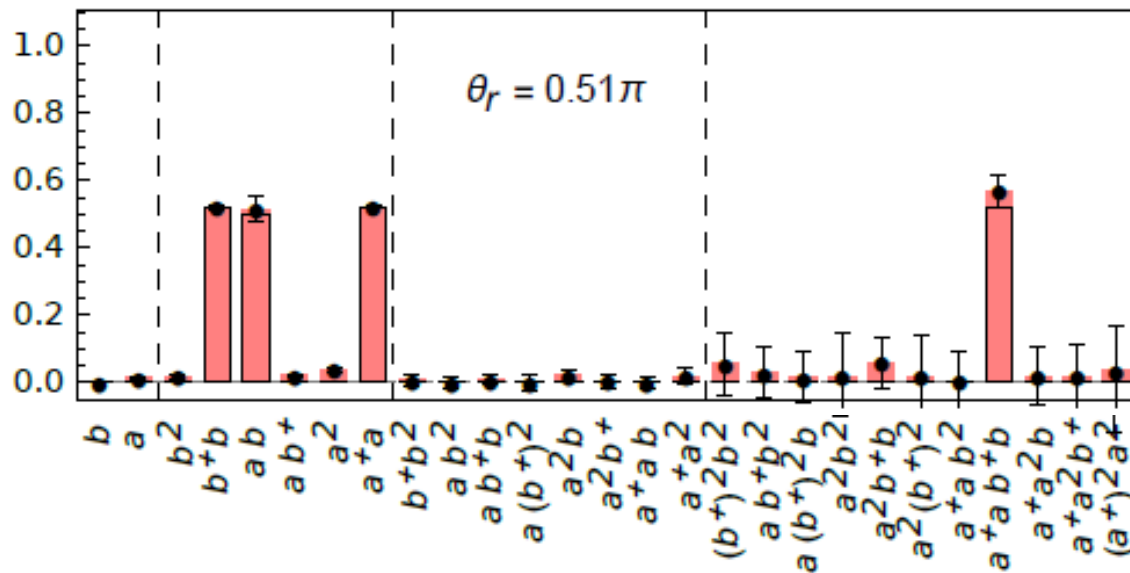
$$|g\rangle \otimes [\cos(\theta_r/2)|0_a\rangle \otimes |0_b\rangle + \sin(\theta_r/2)|1_a\rangle \otimes |1_b\rangle]$$

For $\theta_r = \pi/2$, the itinerant modes a and b are in the Bell state $\frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$

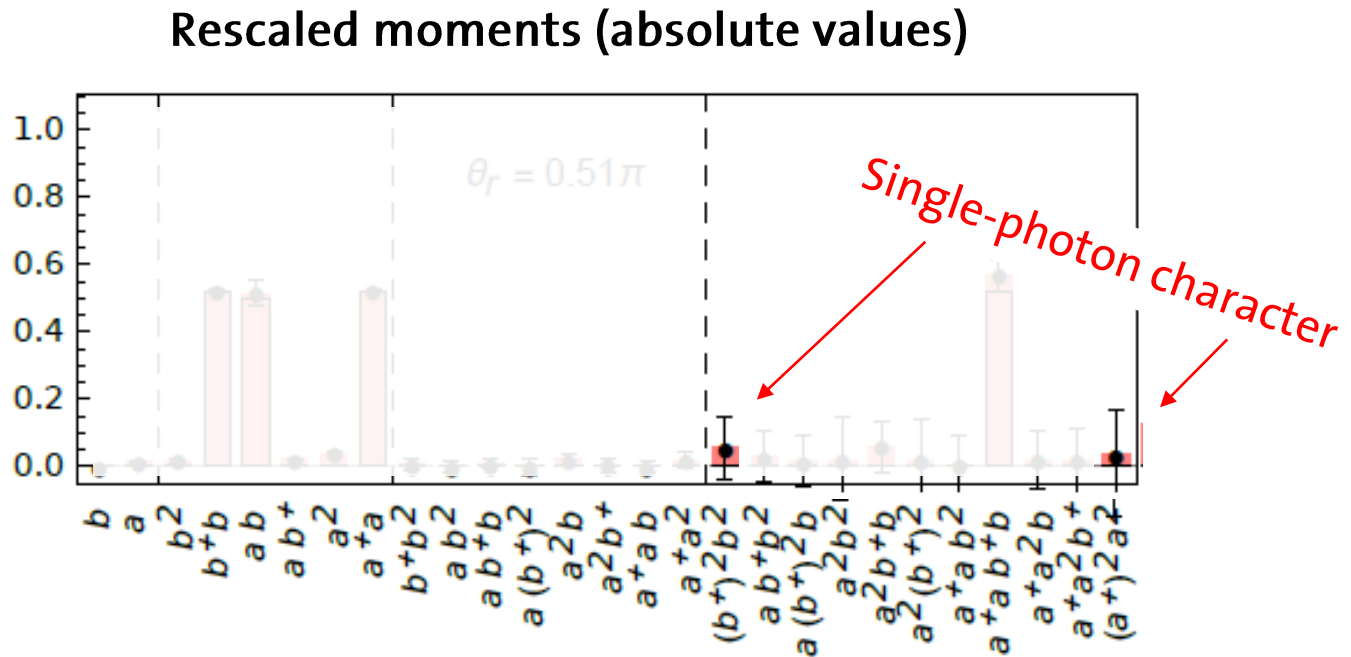
Verification? Joint quantum state tomography with temporal mode matching

Joint state tomography of the photonic modes

Rescaled moments (absolute values)



Joint state tomography of the photonic modes

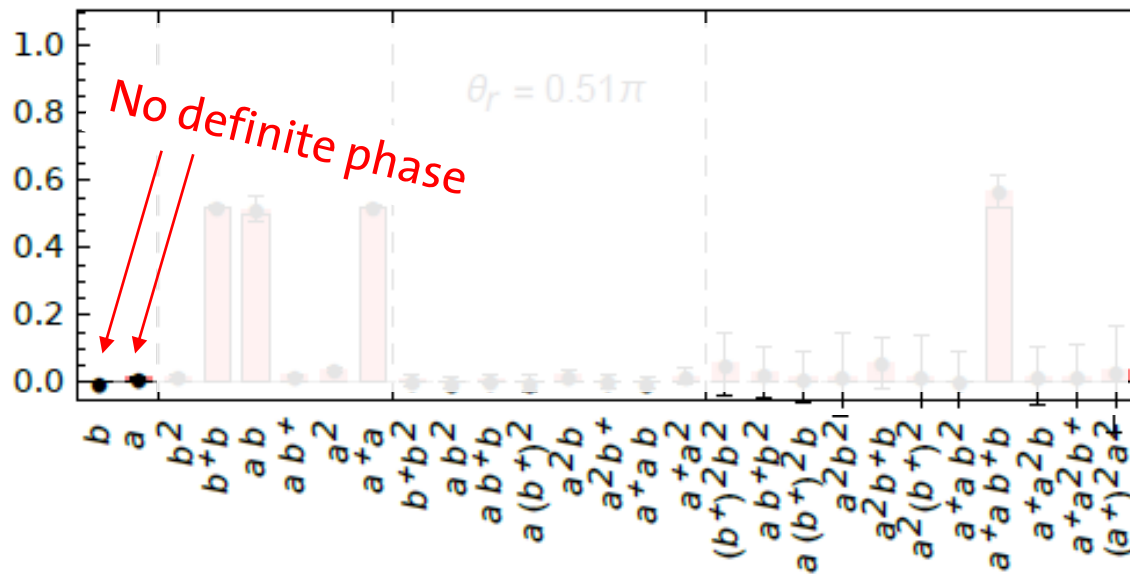


Eichler, PRA **86** 032106 and PRL **109** 240501 (2012)

Lang, Nat Phys **9**, 345 (2013)

Joint state tomography of the photonic modes

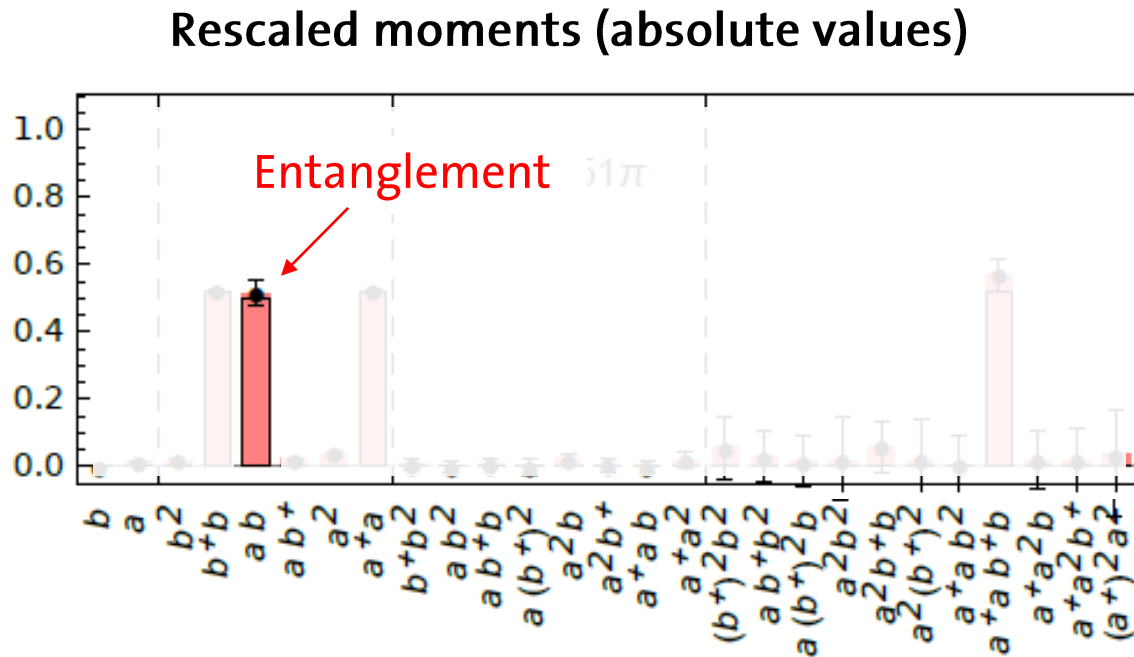
Rescaled moments (absolute values)



Eichler, PRA **86** 032106 and PRL **109** 240501 (2012)

Lang, Nat Phys **9**, 345 (2013)

Joint state tomography of the photonic modes

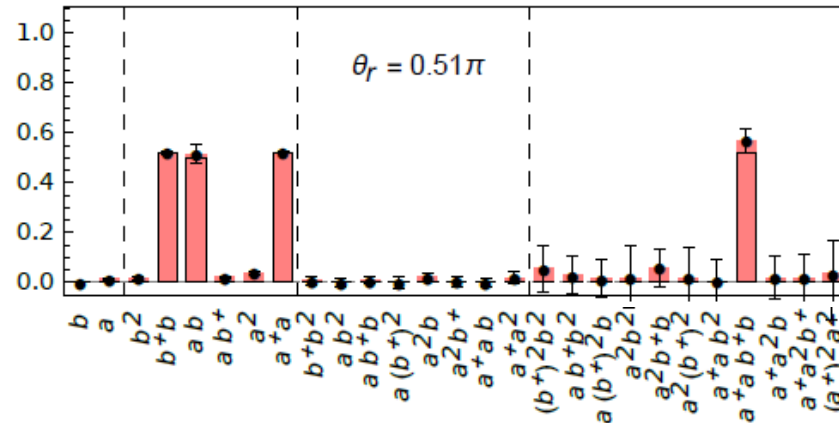


Eichler, PRA **86** 032106 and PRL **109** 240501 (2012)

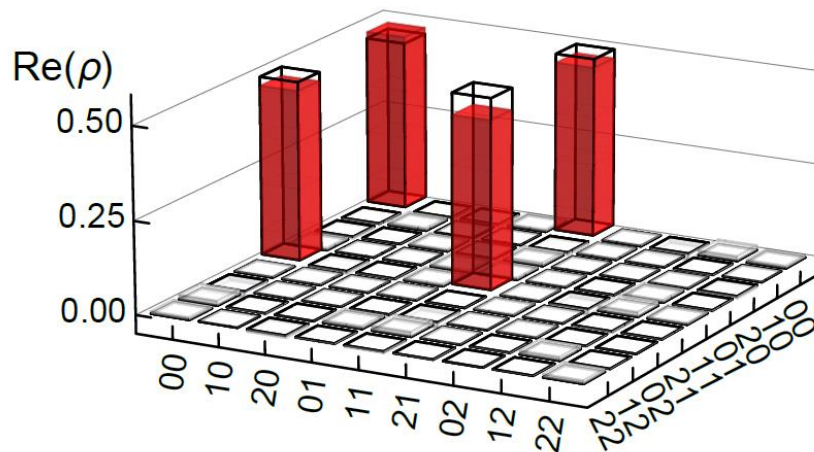
Lang, Nat Phys **9**, 345 (2013)

Joint state tomography of the photonic modes

From measured moments...



...to density matrix, using maximum-likelihood algorithm



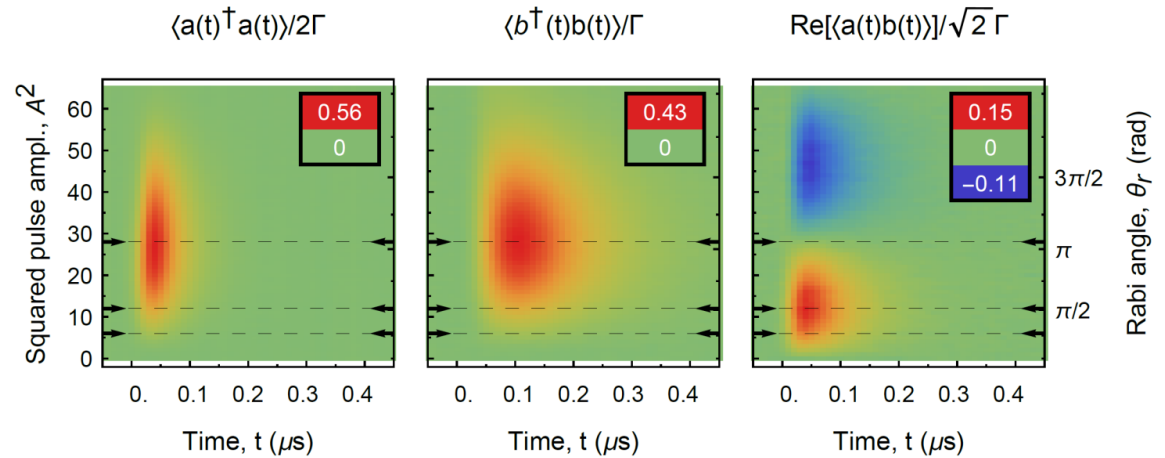
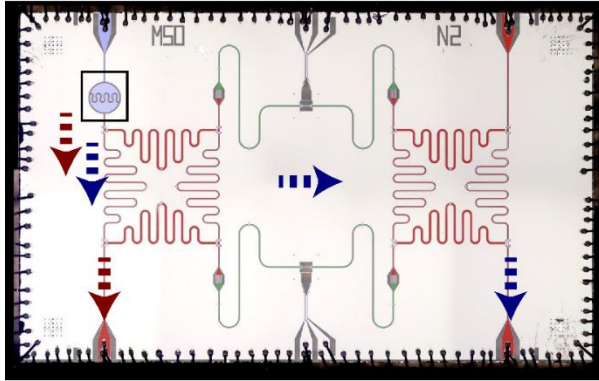
Fidelity to Bell state, $F = 91\%$

Negativity, $N = -0.43$

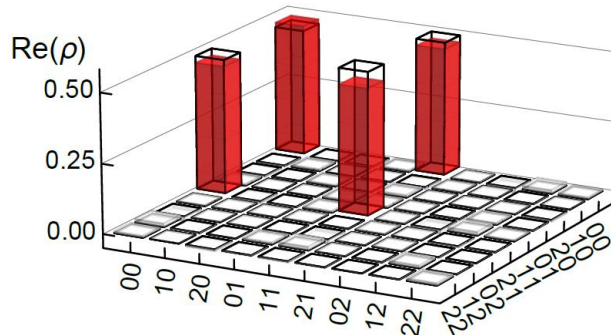
Quantum efficiency ~ 0.07

In summary

Cascade decay of a transmon driven by two-photon resonant excitation



Coherent superposition leads to entanglement between itinerant photonic modes

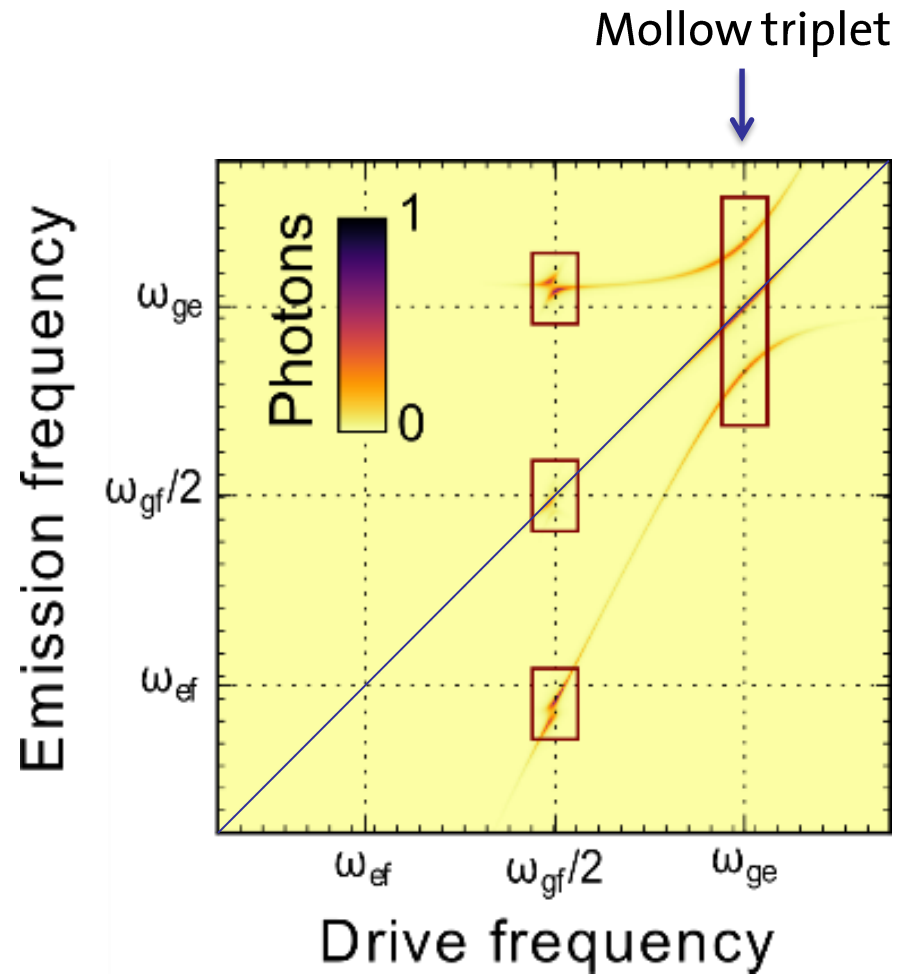
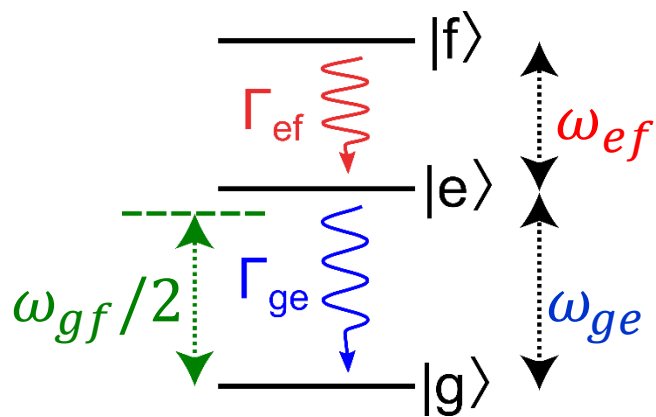


Is spontaneous emission an incoherent process?
Not quite, if the atom emits into a well-defined,
continuously monitored mode.

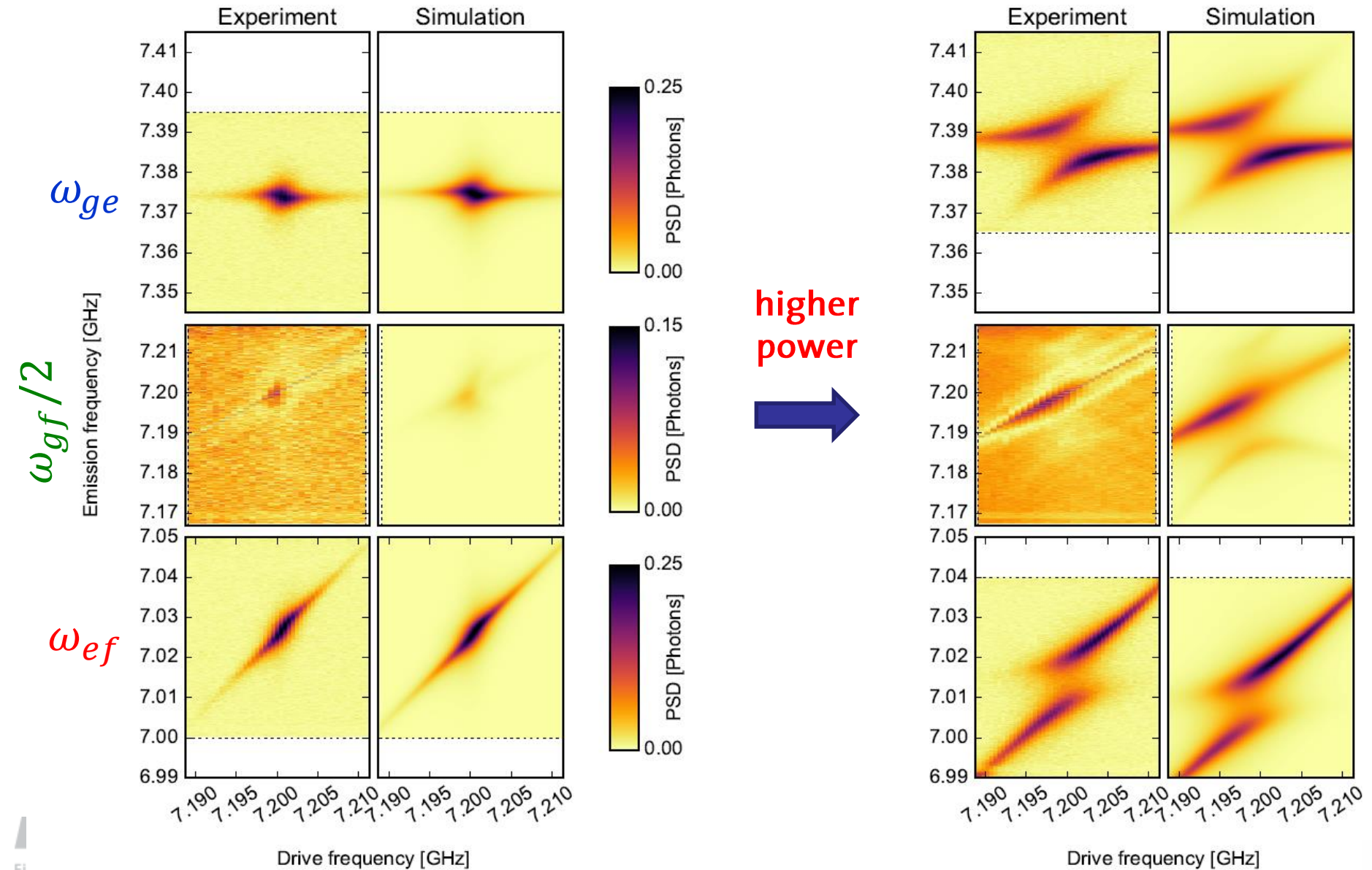
Naghiloo, Nat Comm 7, 11527 (2016)
...and other work

Beyond cascade decay: Two-photon resonance fuorescence in the strong-drive limit

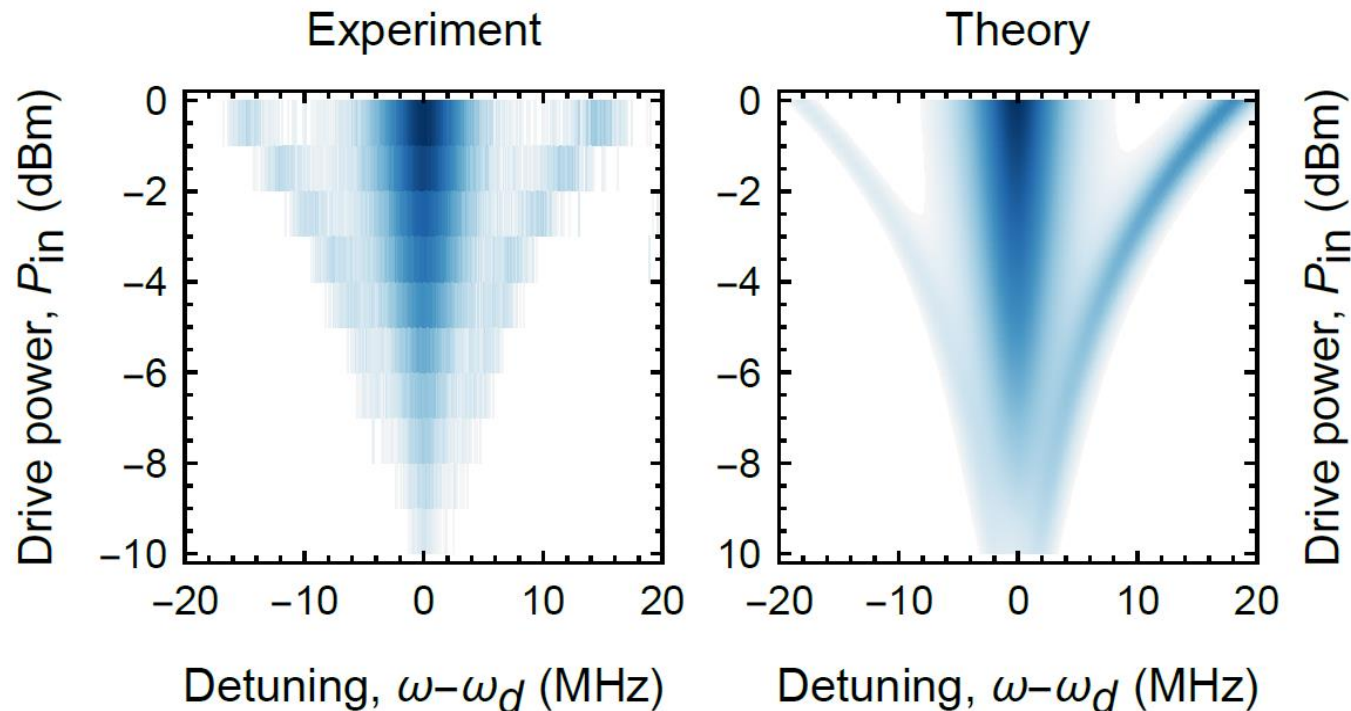
Spectrum of inelastic scattering vs drive frequency



Two-photon resonance fluorescence



Mollow triplet at the two-photon transition



Arises from quasielastic scattering of the dressed states (“dressing of the dressed states”)

Relation to multi-photon blockade in cQED

To be done: characterize radiation with g_2 , etc.

Koshino, PRL **110** 263801 (2013)

Shamailov, Opt. Comm. **283**, 766 (2010)

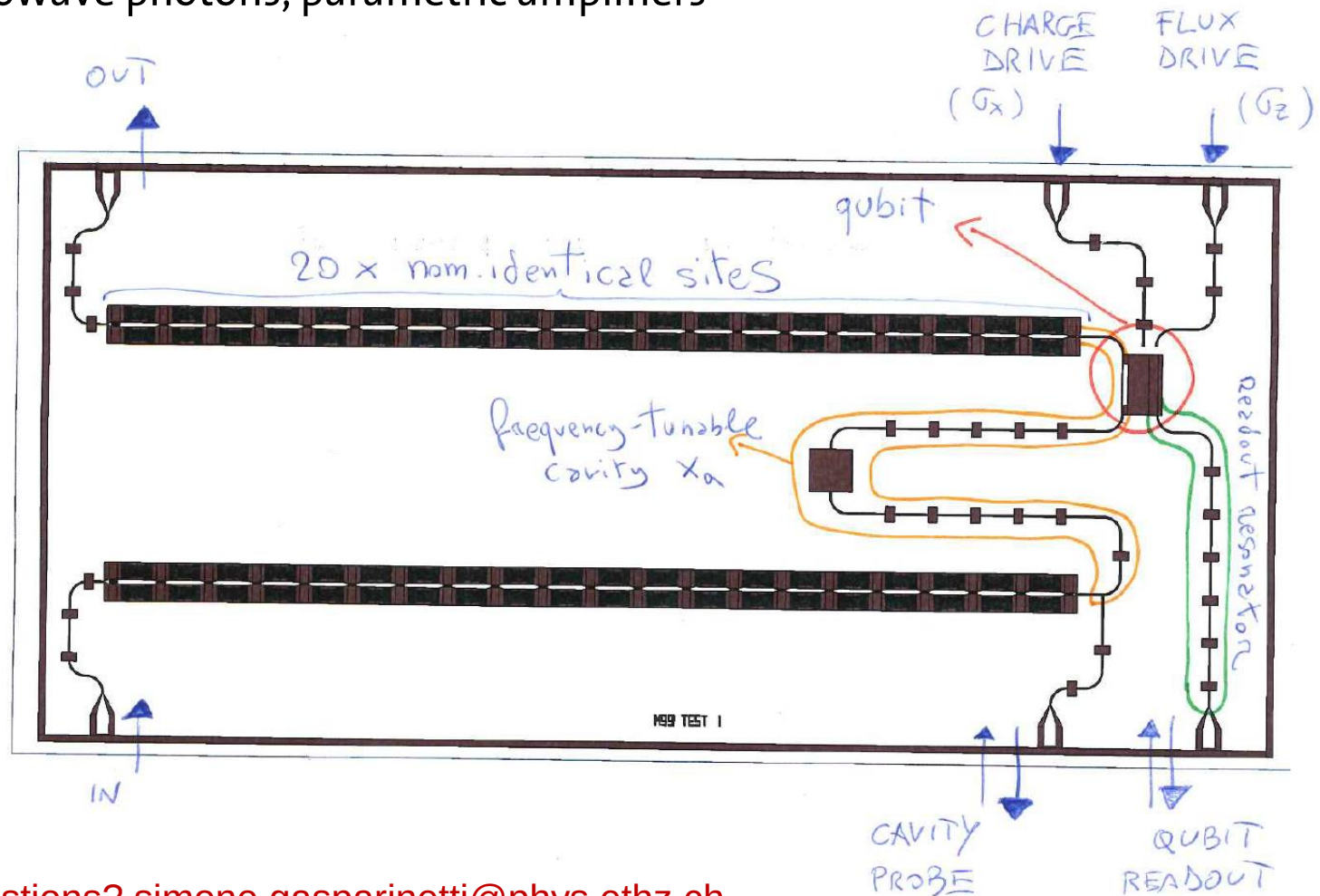
Hansen, PRL **118**, 133604 (2017)

Del Valle, Laussy *et al.*

SG & Robin Buijs, in preparation

Coming up Photon interactions in coupled-cavity arrays

- Based on lumped-element superconducting resonators
- + Transmon qubit(s) with full control/readout capabilities
- + Source of microwave photons, parametric amplifiers



Thanks! More questions? simone.gasparinetti@phys.ethz.ch