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W. J. Lin *et al.* arXiv:2012.15084 (2021)

Deterministic loading of microwaves onto an artificial atom using a time-reversed waveform

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QEL

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Quantum Network

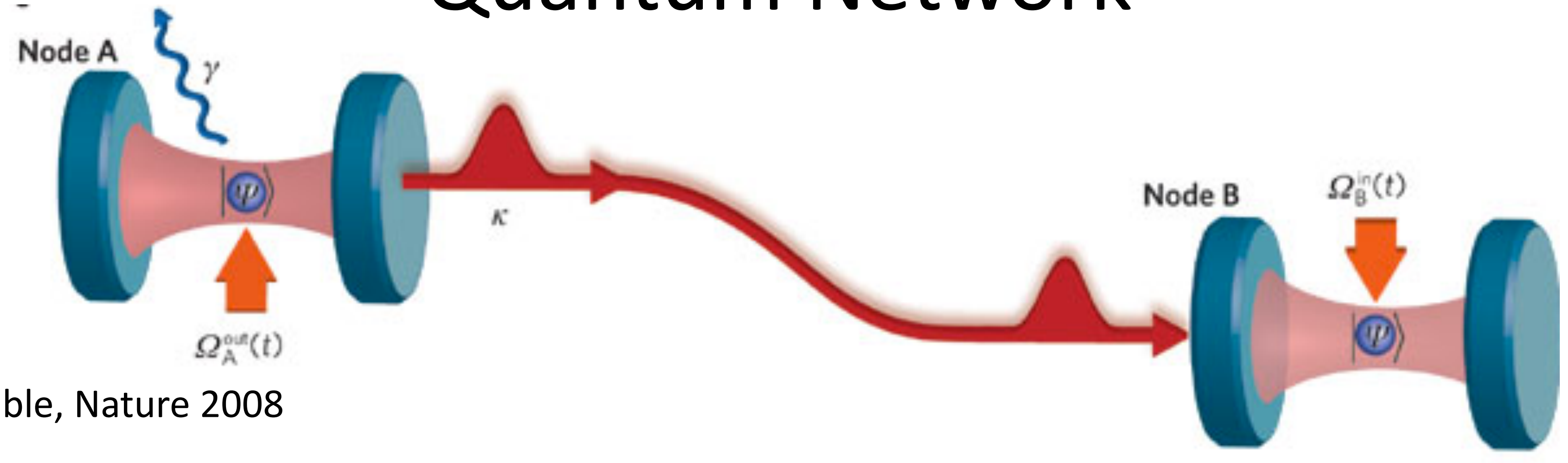
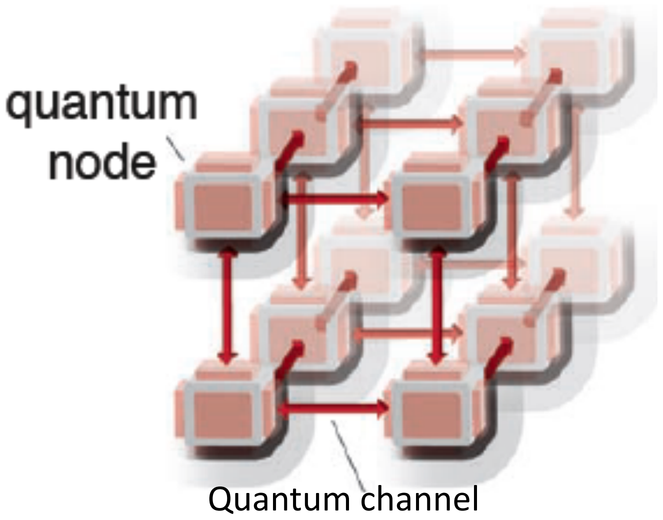


Fig. Kimble, Nature 2008



Quantum node:
Generating, processing, routing, storing, reading out quantum information.

Quantum channel:
Distributing quantum information.

Enabling large scale quantum computing and quantum communication.

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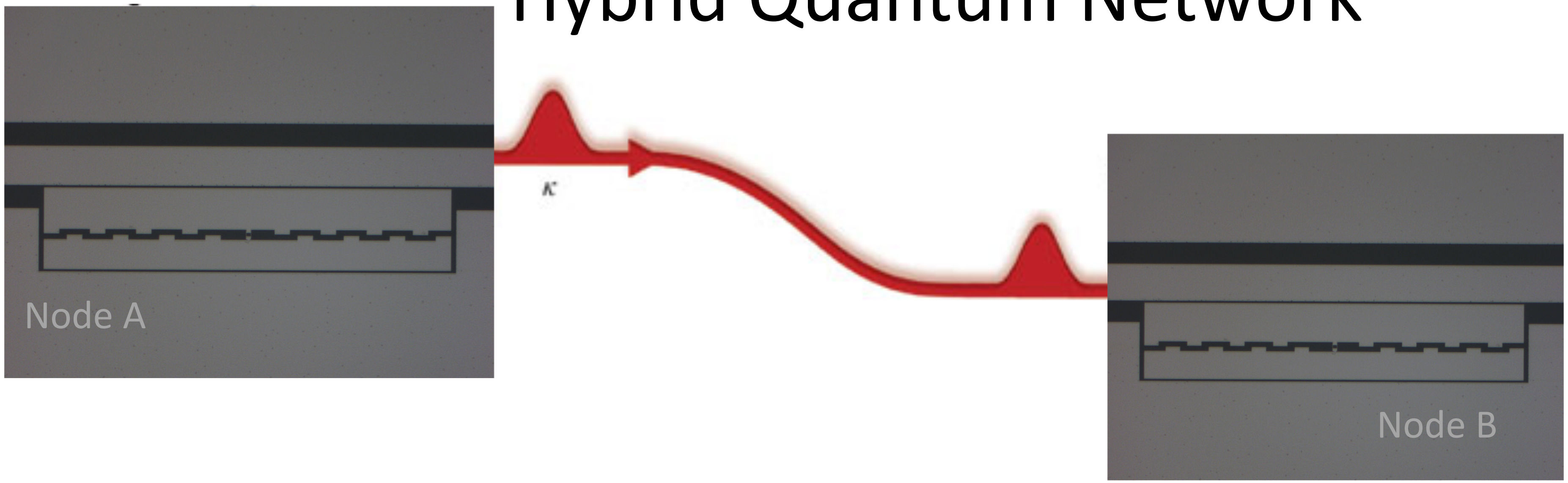
Hybrid Quantum Network



Telecom photons to distribute quantum information

Quantum node: superconducting circuits

Microwave-optical interface is needed

Moritz Forsch *et al.* Nature Physics **16**, 69 (2020) Mechanical oscillator
R.W. Andrews *et al.* Nature Physics **10**, 321 (2014) Membrane MW and optical resonator

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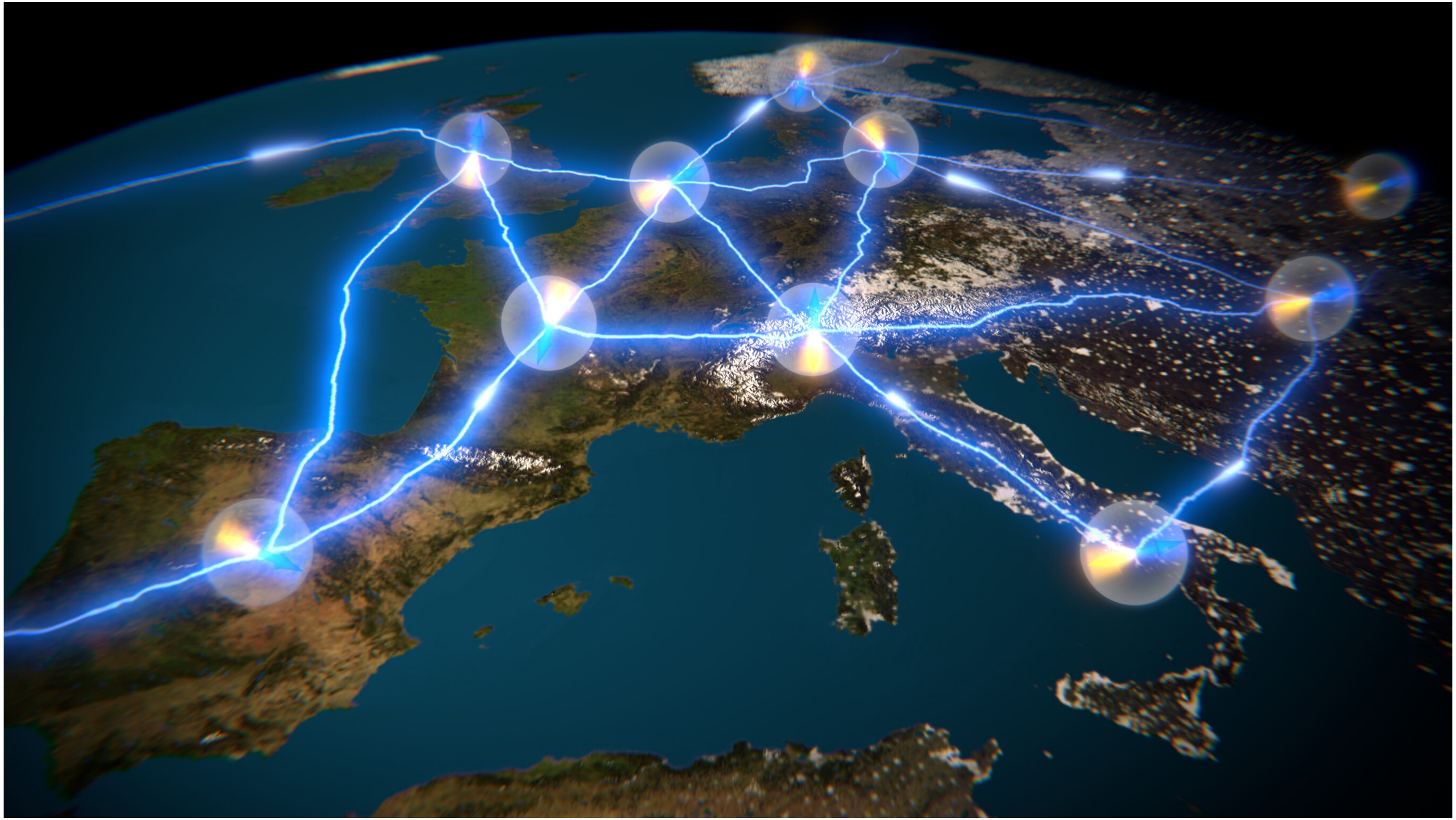
Hybrid Quantum Network



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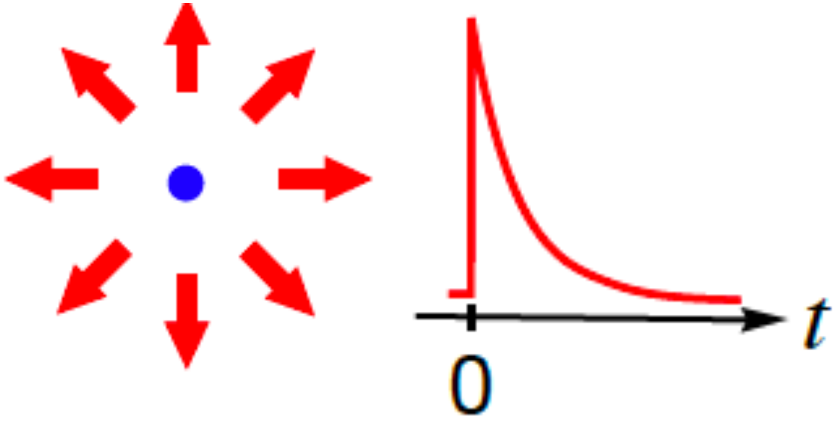
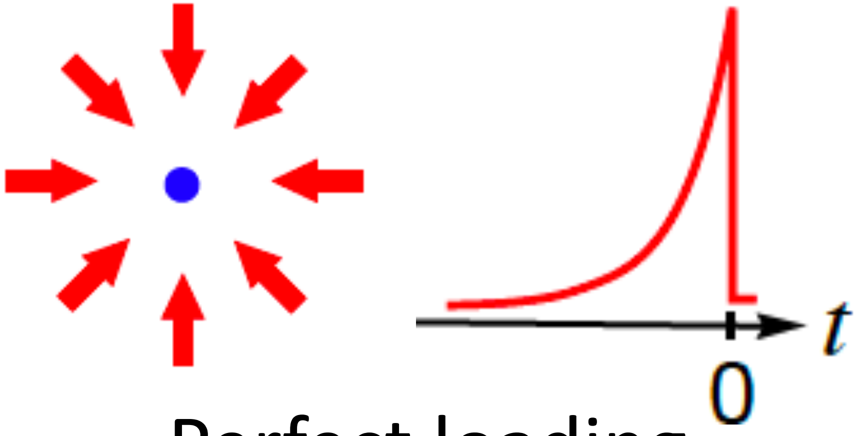
Quantum network require efficient loading quantum information on to a quantum node.

Efficient loading photons on to a qubit?



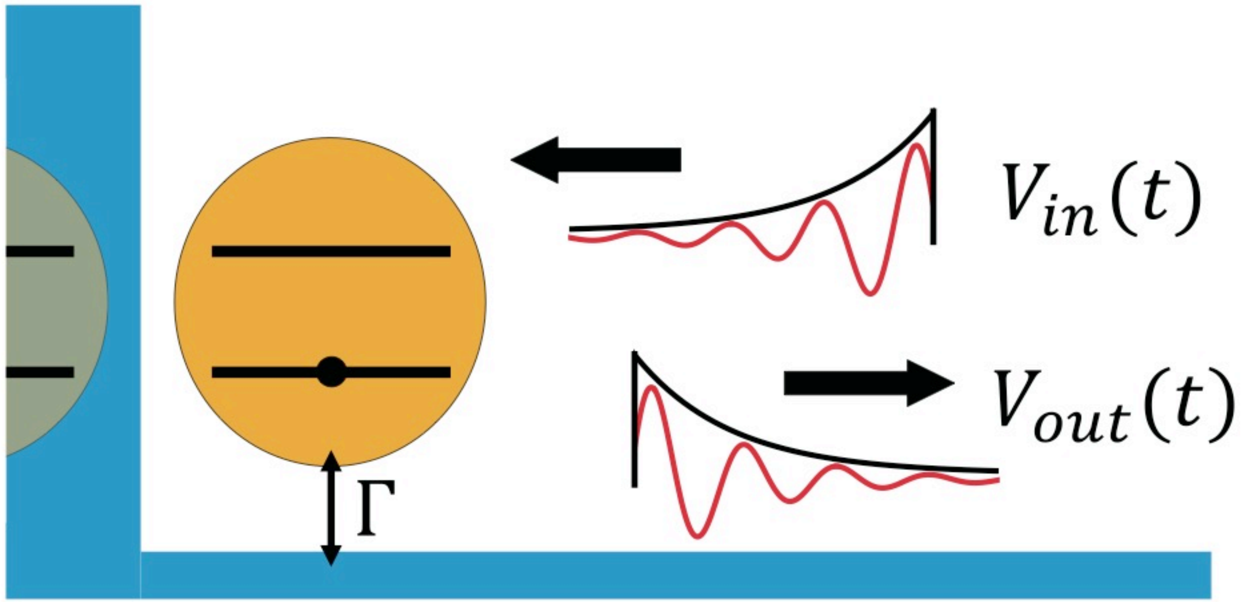
Spontaneous emission

Time reverse symmetry



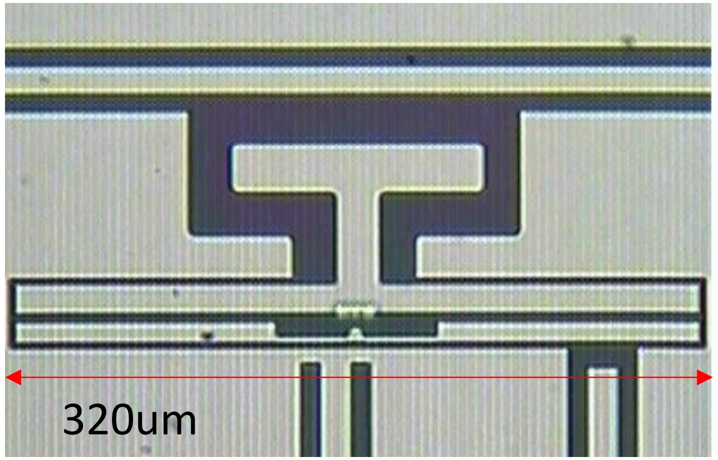
Perfect loading

Transmon weakly coupled to 1D transmission line



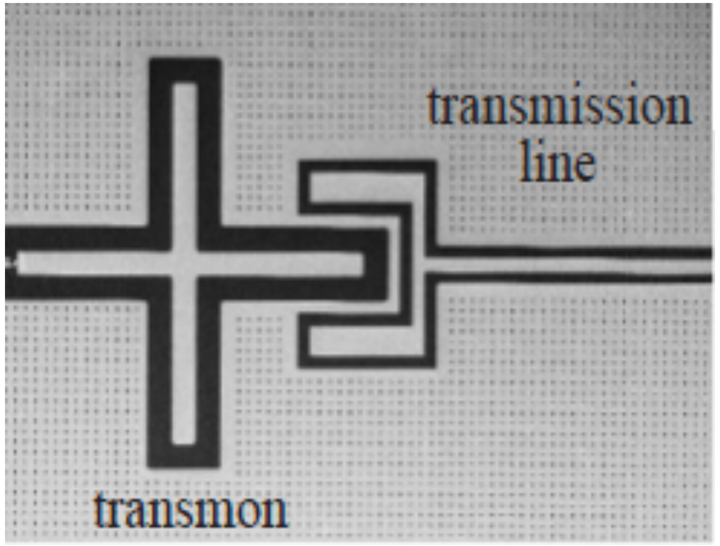
$\frac{E_J}{E_C} = 23$

Sample 1
(NTHU)



$\frac{E_J}{E_C} = 78$

Sample 2
(Chalmers)



300um

Atomic Ensemble: Zhang *et al.* PRL 109, 263601 (2012) efficiency of 20%
Single atom: Leong *et al.* Nature Com. 7, 13716 (2016) efficiency of 1%
3D Cavity: Liu *et al.* PRL 113, 133601 (2014)
1D Cavity: Wenner *et al.* PRL 112, 210501 (2014)

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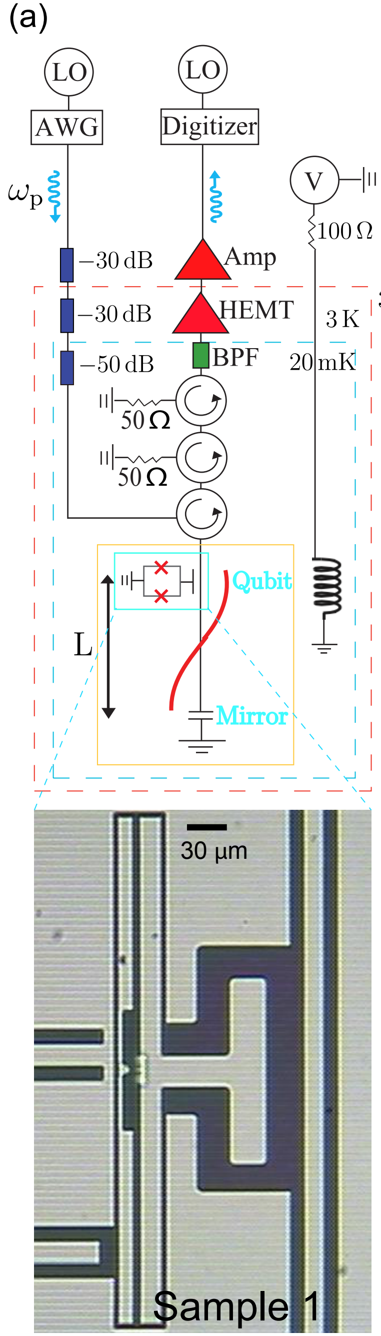
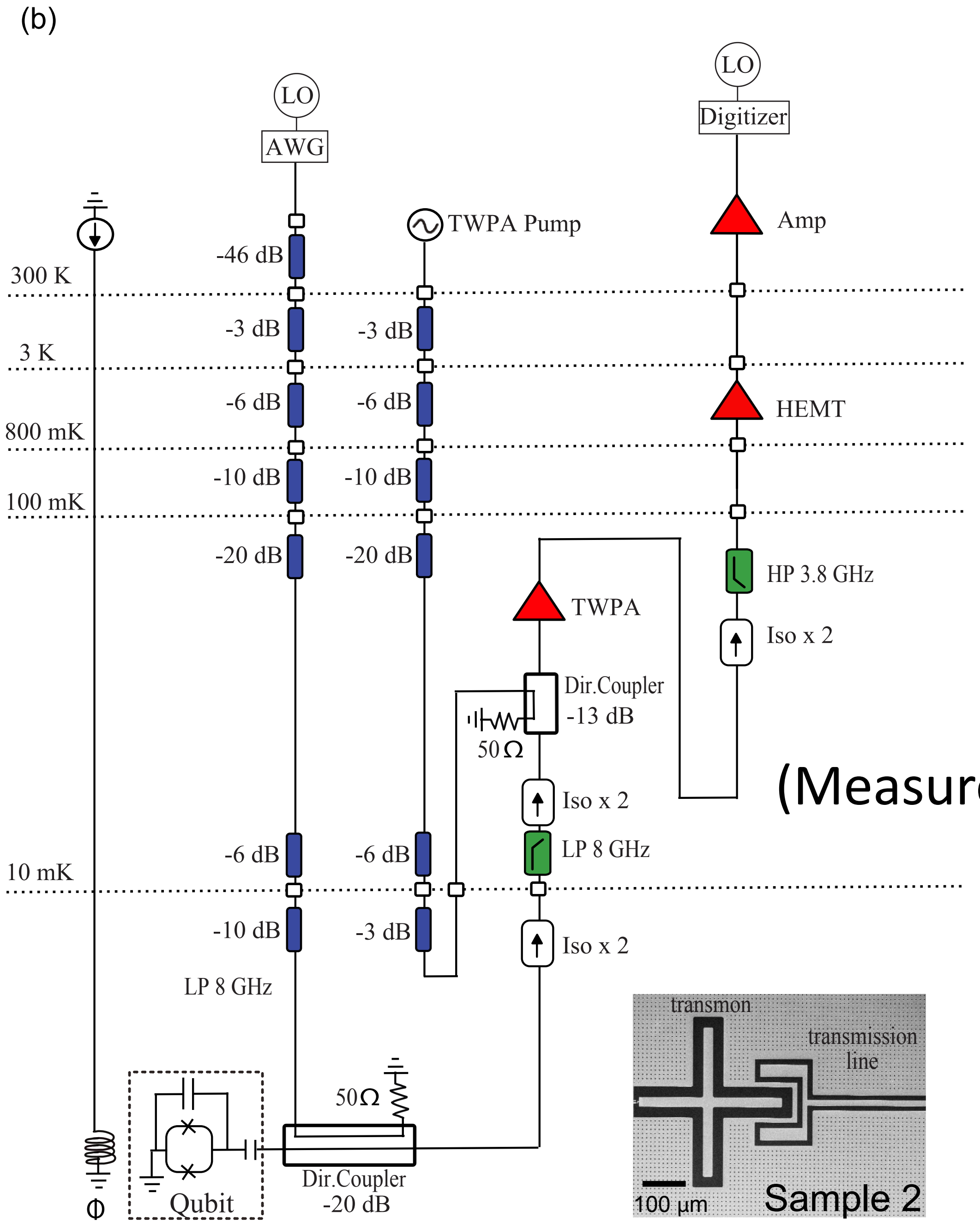


Measured at NTHU



(Measured at Chalmers)

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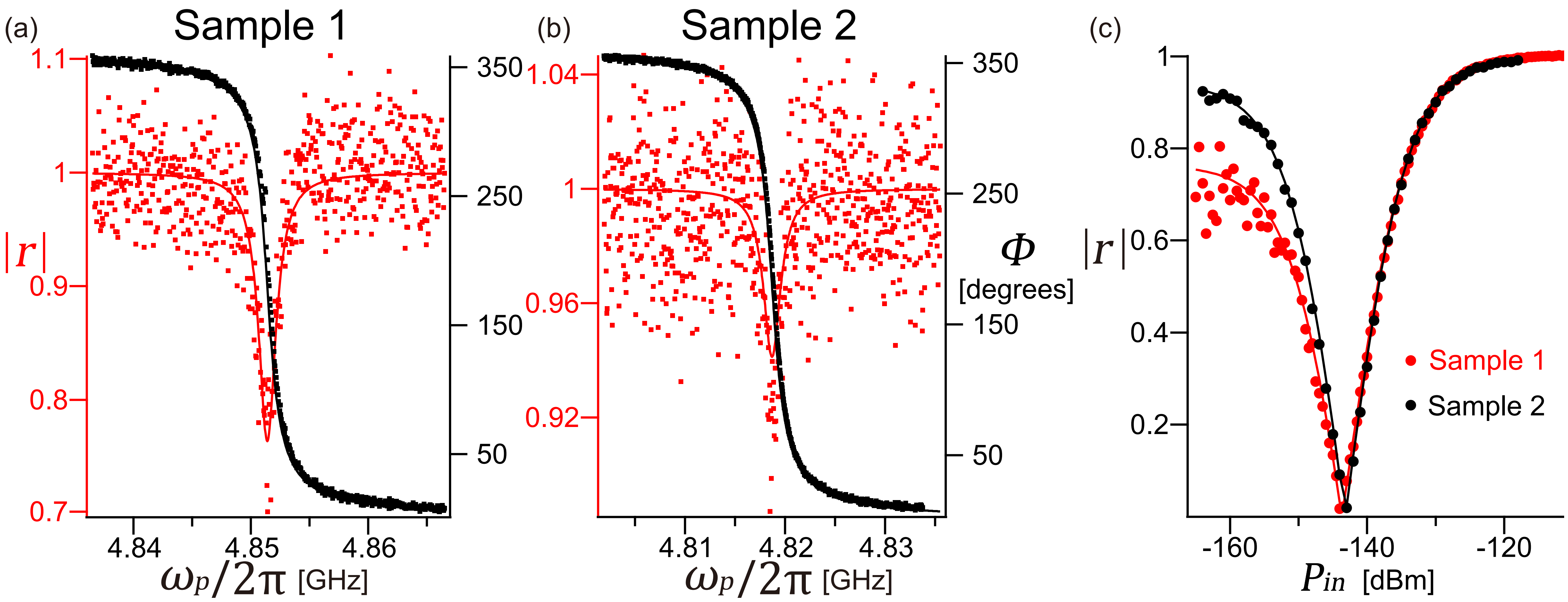
Continuous wave



Sample	E_C/h [MHz]	E_J/h [GHz]	E_J/E_C	$\omega_{10}/2\pi$ [GHz]	$\Gamma/2\pi$ [MHz]	$\Gamma_\phi/2\pi$ [MHz]	$\gamma/2\pi$ [MHz]	$T_2[ns]$
1	385	8.9	23	4.8514	1.686 ± 0.007	0.113 ± 0.009	0.956 ± 0.005	166 ± 1
2	200	15.7	78	4.8187	2.046 ± 0.003	0.031 ± 0.004	1.054 ± 0.003	151 ± 0.4

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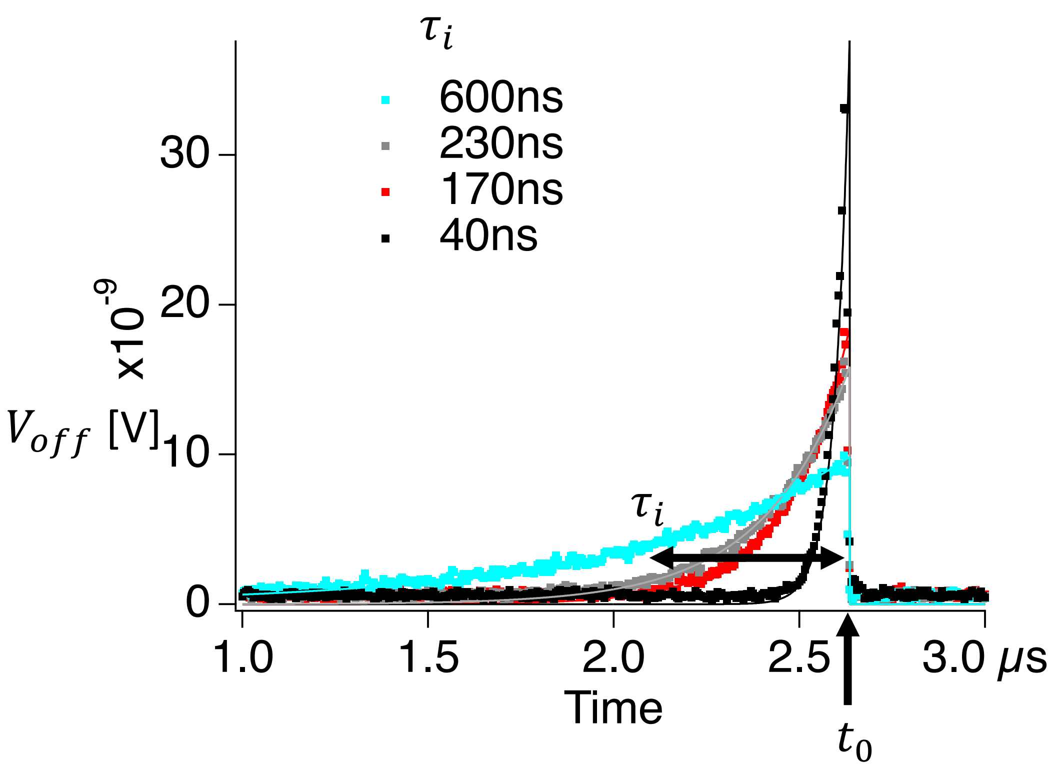
Exponential rising pulse excitation at constant N

Constant photon number <N> ~ 0.09 photon



$$V_{off} = V_{in}$$

t_0: Turn off the pulse

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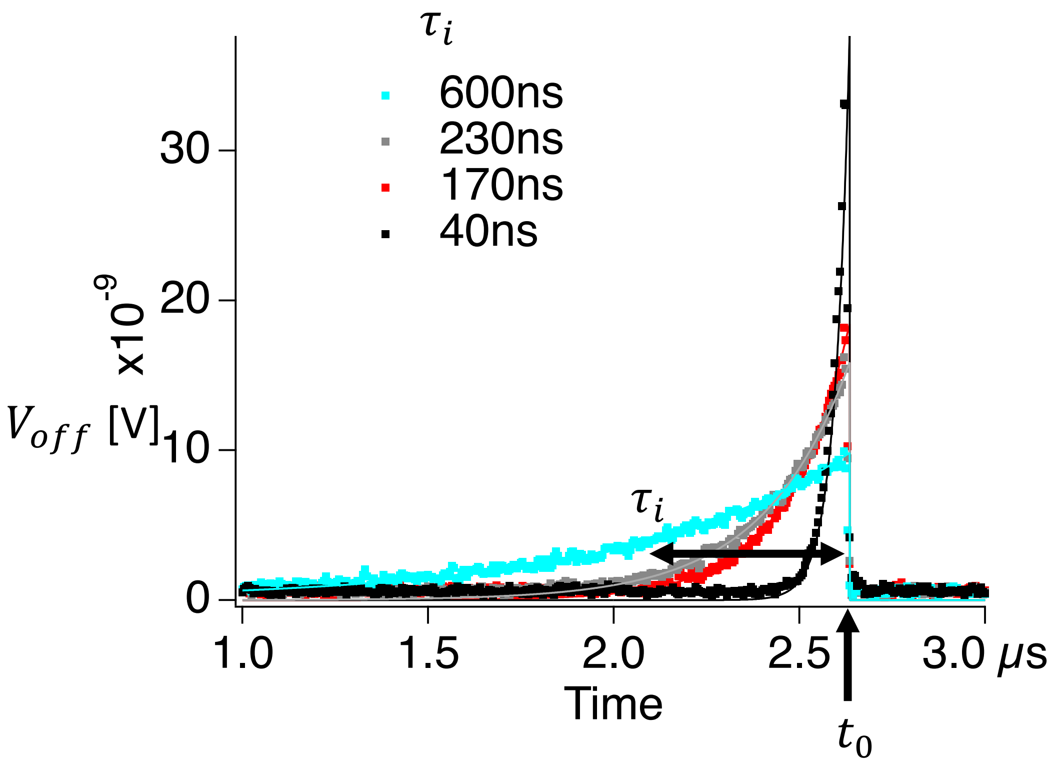
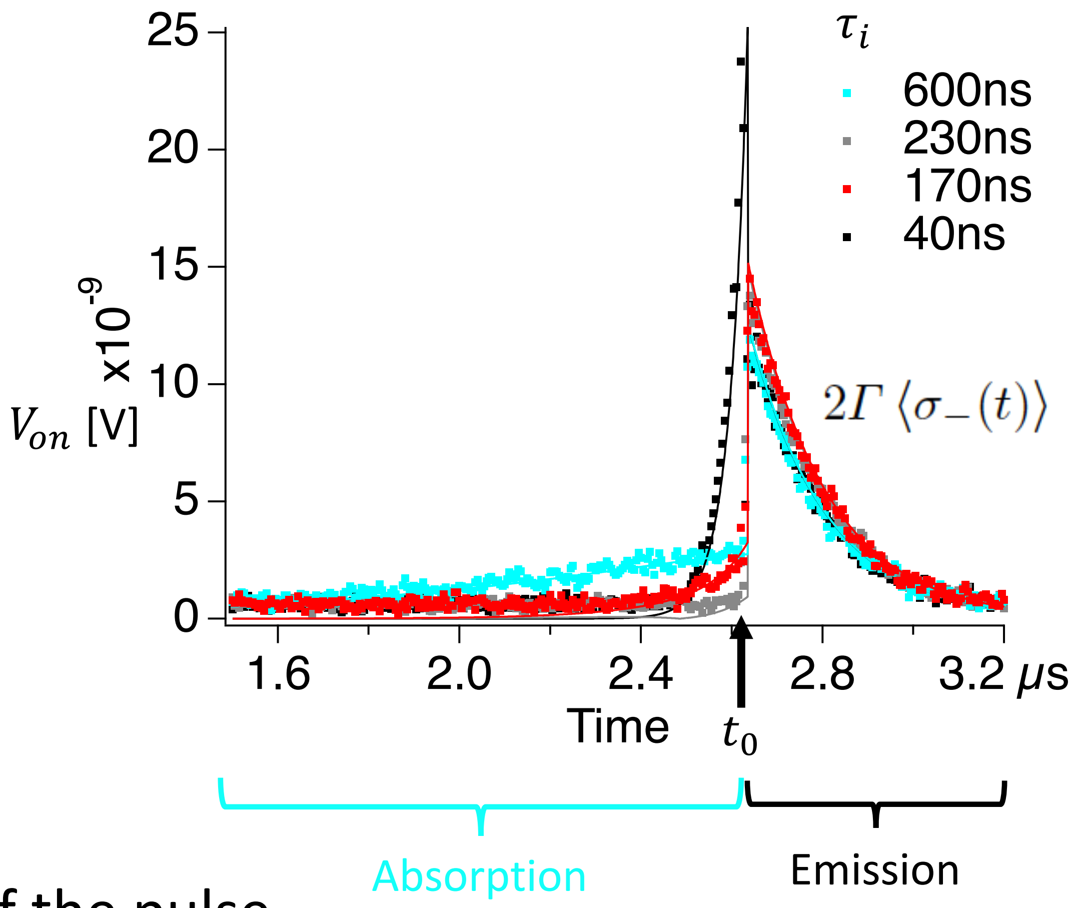
Exponential rising pulse excitation at constant N

Constant photon number <N> ~ 0.09 photon

Red: largest emission when $\tau_i = T_2$





$V_{off} = V_{in}$

t_0: Turn off the pulse

Sample 1

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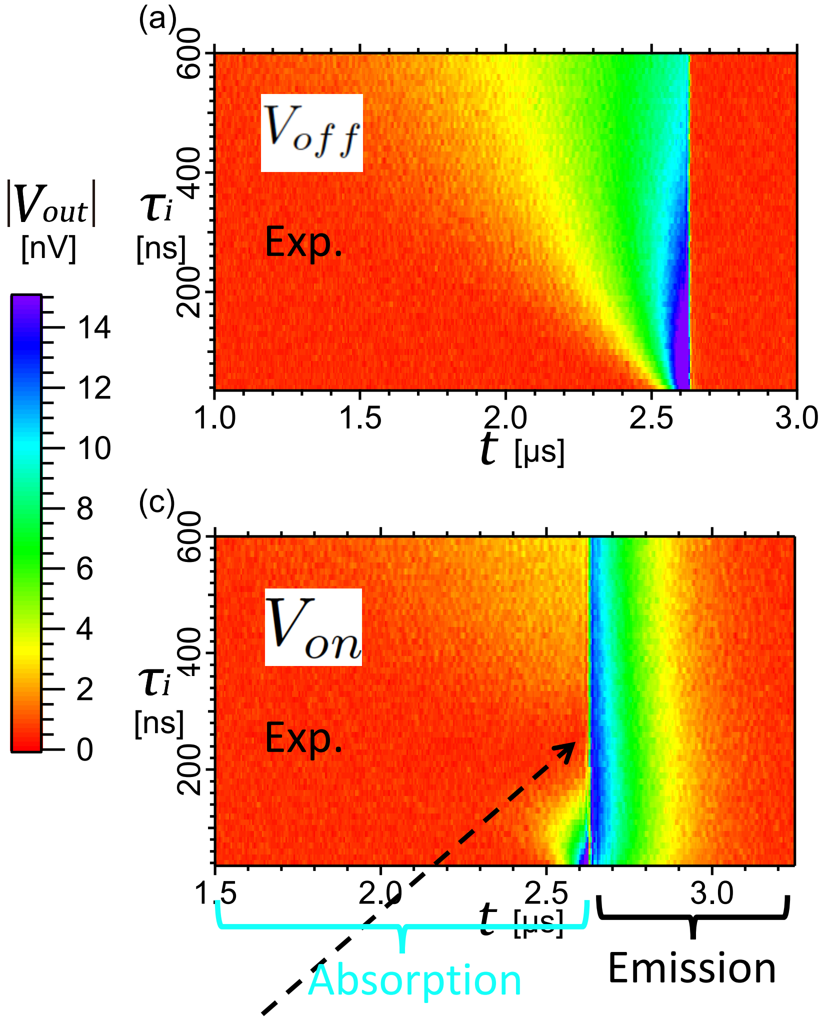
Sweep characteristic time τ

Constant photon number <N> ~ 0.09 photon



Perfect mode matching (destructive interference between incoming field and the emitted field)

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Sample 1

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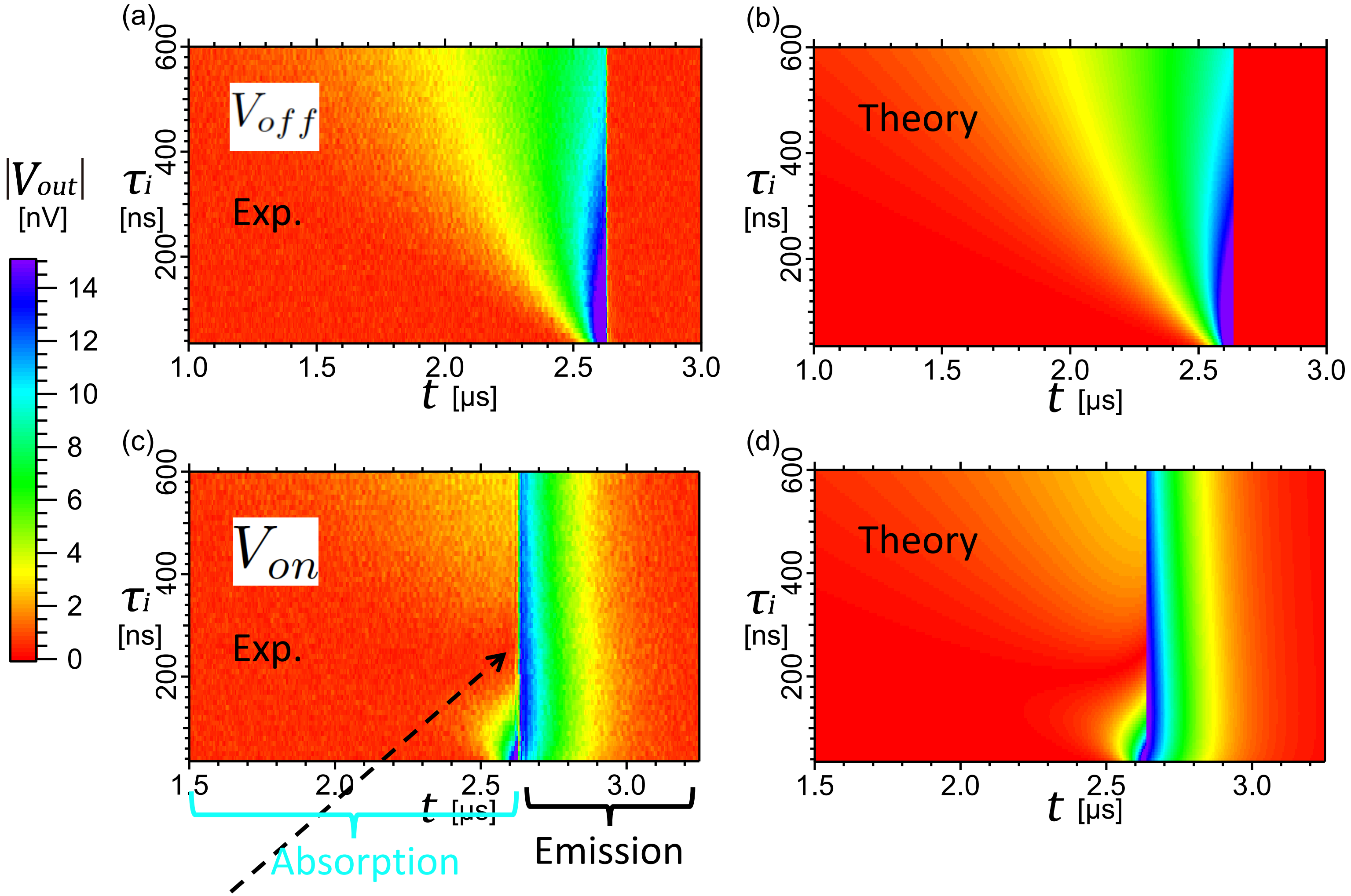
Sweep characteristic time τ

Constant photon number <N> ~ 0.09 photon



Perfect mode matching (destructive interference between incoming field and the emitted field)

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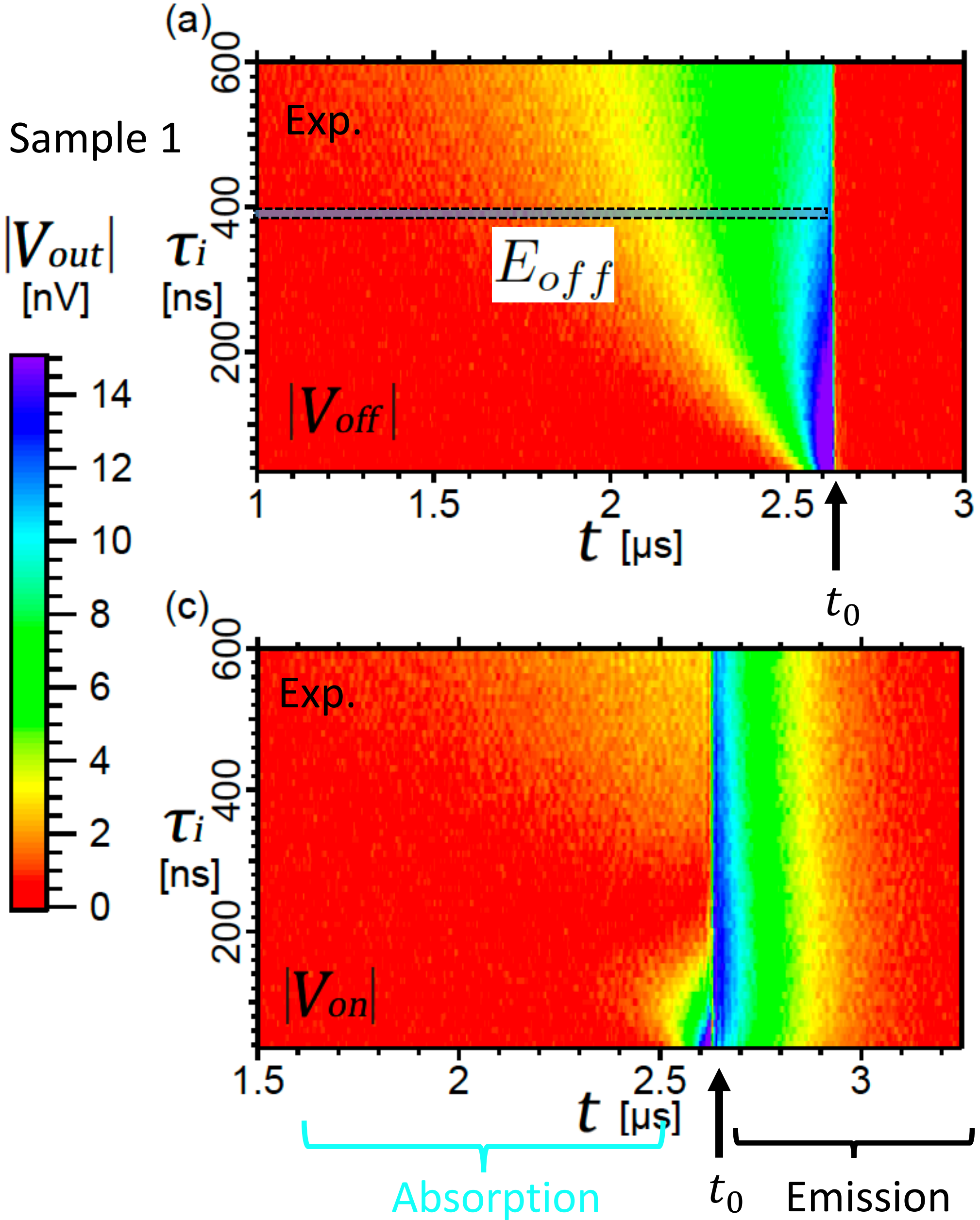
Sample 1

Definition of loading efficiency and symmetry factor



$$E_{\text{off}} \sim \int_{t_i}^{t_0} [|V_{\text{off}}(t)| - |V_N|]^2 dt$$

V_N: *Noise level*

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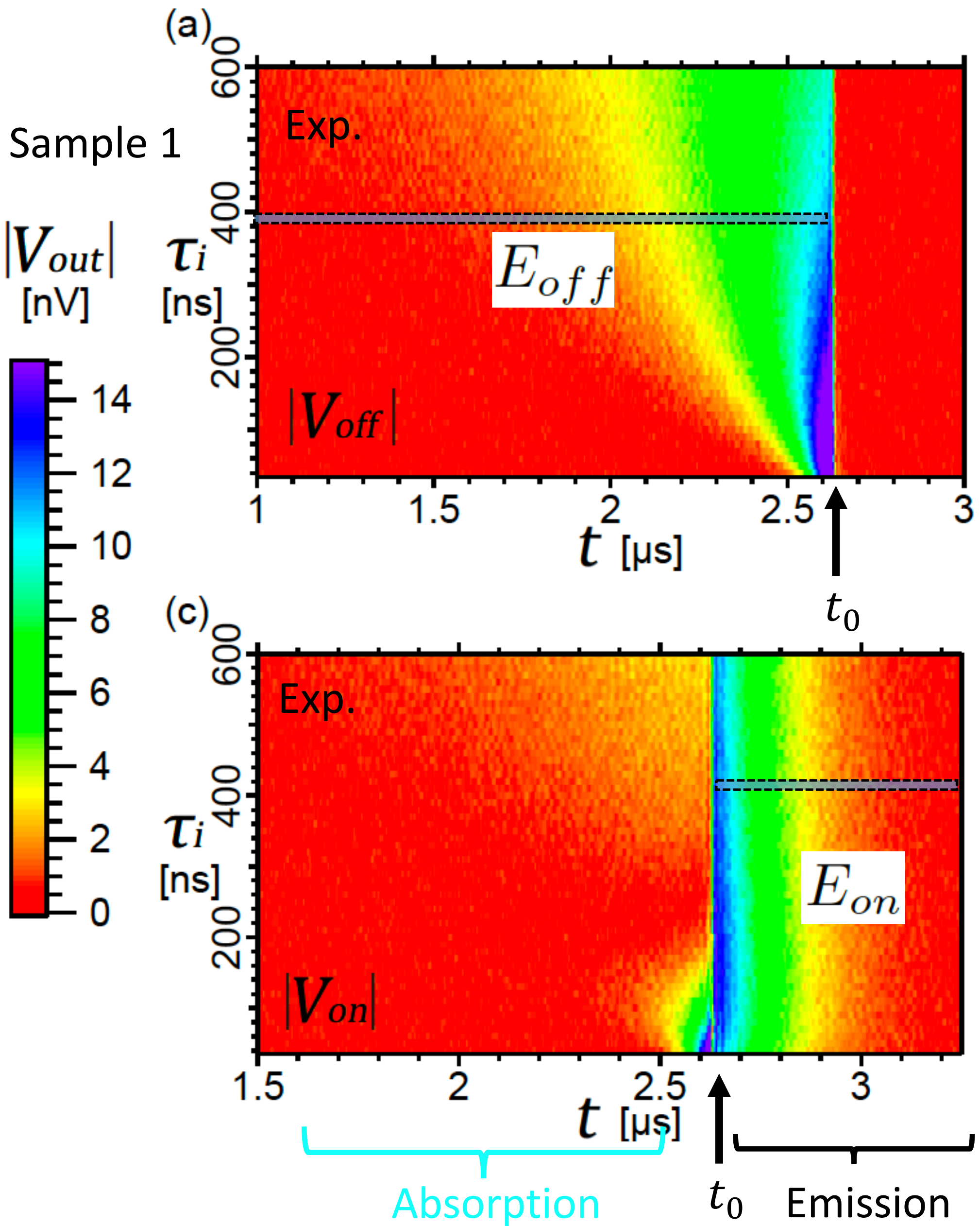
Definition of loading efficiency and symmetry factor



$$E_{\text{off}} \sim \int_{t_i}^{t_0} [|V_{\text{off}}(t)| - |V_N|]^2 dt$$

$$E_{\text{on}} \sim \int_{t_0}^{t_f} [|V_{\text{on}}(t)| - |V_N|]^2 dt$$

$$\eta = E_{\text{on}} / E_{\text{off}}$$

V_N: *Noise level*

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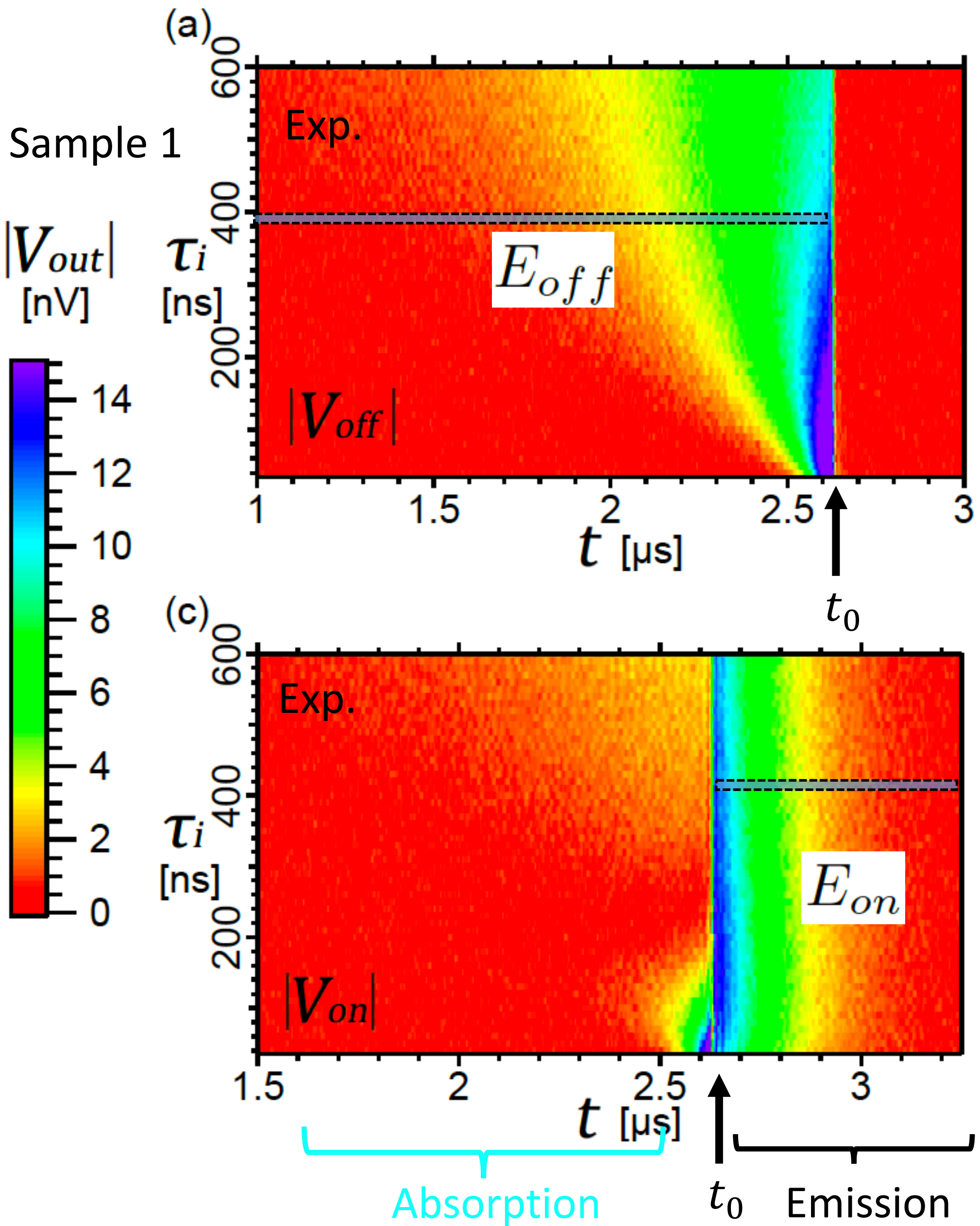
Definition of loading efficiency and symmetry factor



Loading efficiency (Energy of emitted wave divided by energy of incoming wave):

$$E_{\text{off}} \sim \int_{t_i}^{t_0} [|V_{\text{off}}(t)| - |V_N|]^2 dt$$

$$E_{\text{on}} \sim \int_{t_0}^{t_f} [|V_{\text{on}}(t)| - |V_N|]^2 dt$$

$$\eta = E_{\text{on}} / E_{\text{off}}$$

Symmetry factor (correlation of incoming wave and time-reversed of emitted wave):

$$S = \frac{\int_{t_i}^{t_0} [|V_{\text{off}}(t)| - |V_N|][|V_{\text{on}}(2t_0 - t)| - |V_N|] dt}{\int_{t_i}^{t_0} [|V_{\text{off}}(t)| - |V_N|]^2 dt}$$

V_N: *Noise level*

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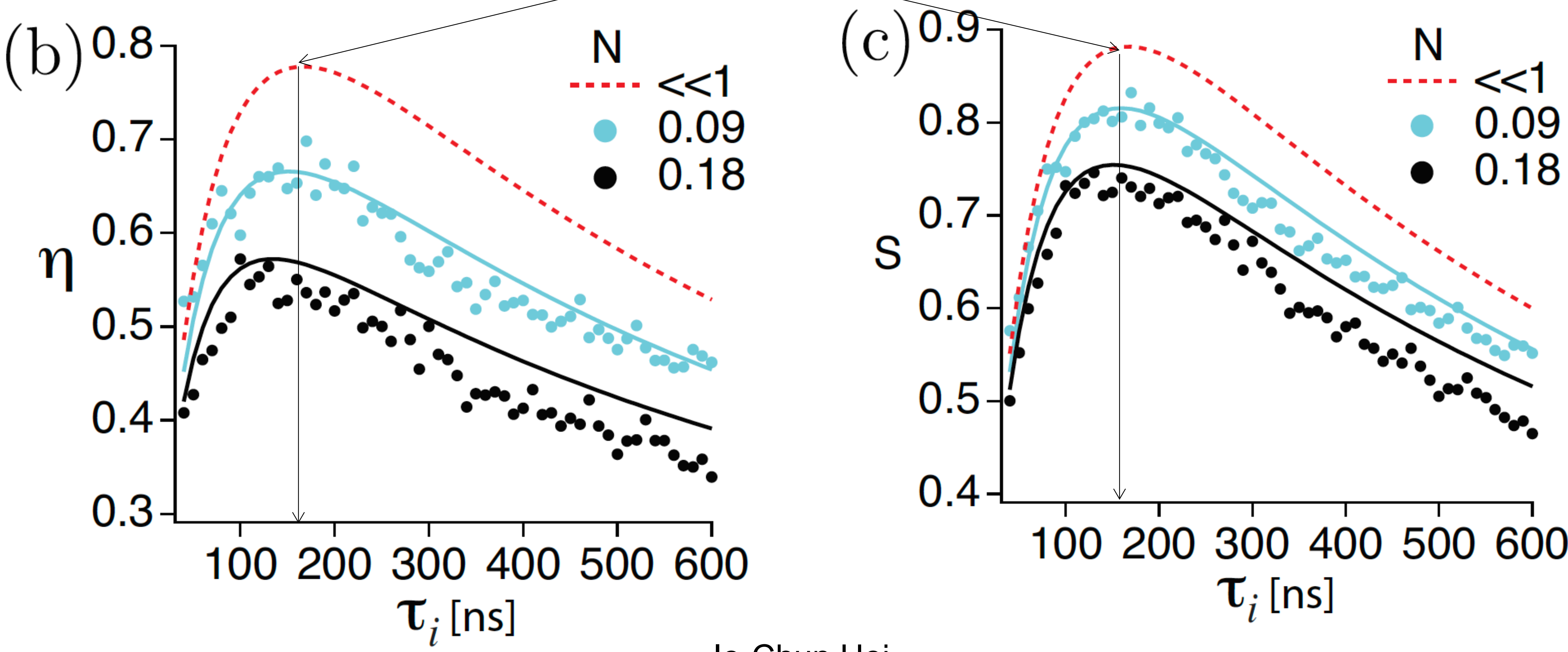
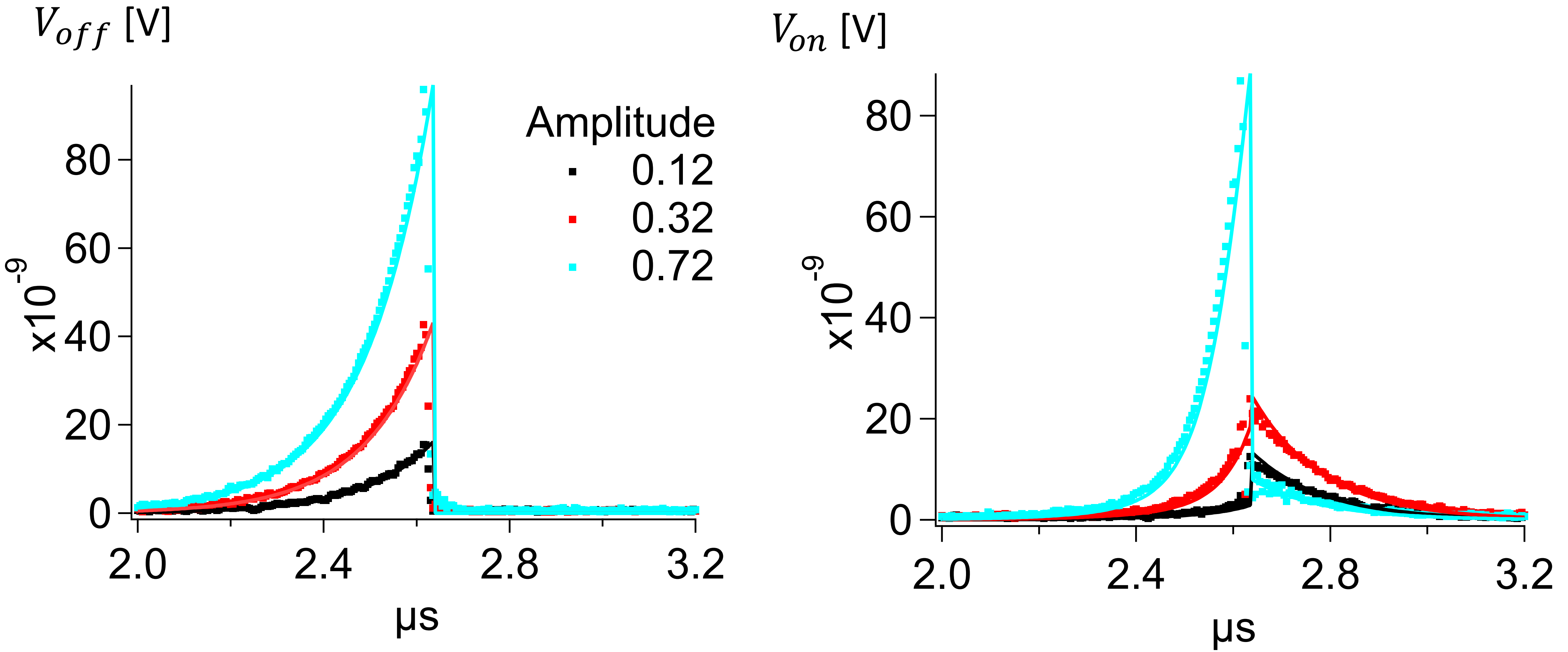
Loading efficiency as a function of τ_i

Sample 1

Optimal loading process:
Time-reversed



Exponential rising pulse excitation at constant $\tau \approx T_2$



Blue: Saturation of two level atom

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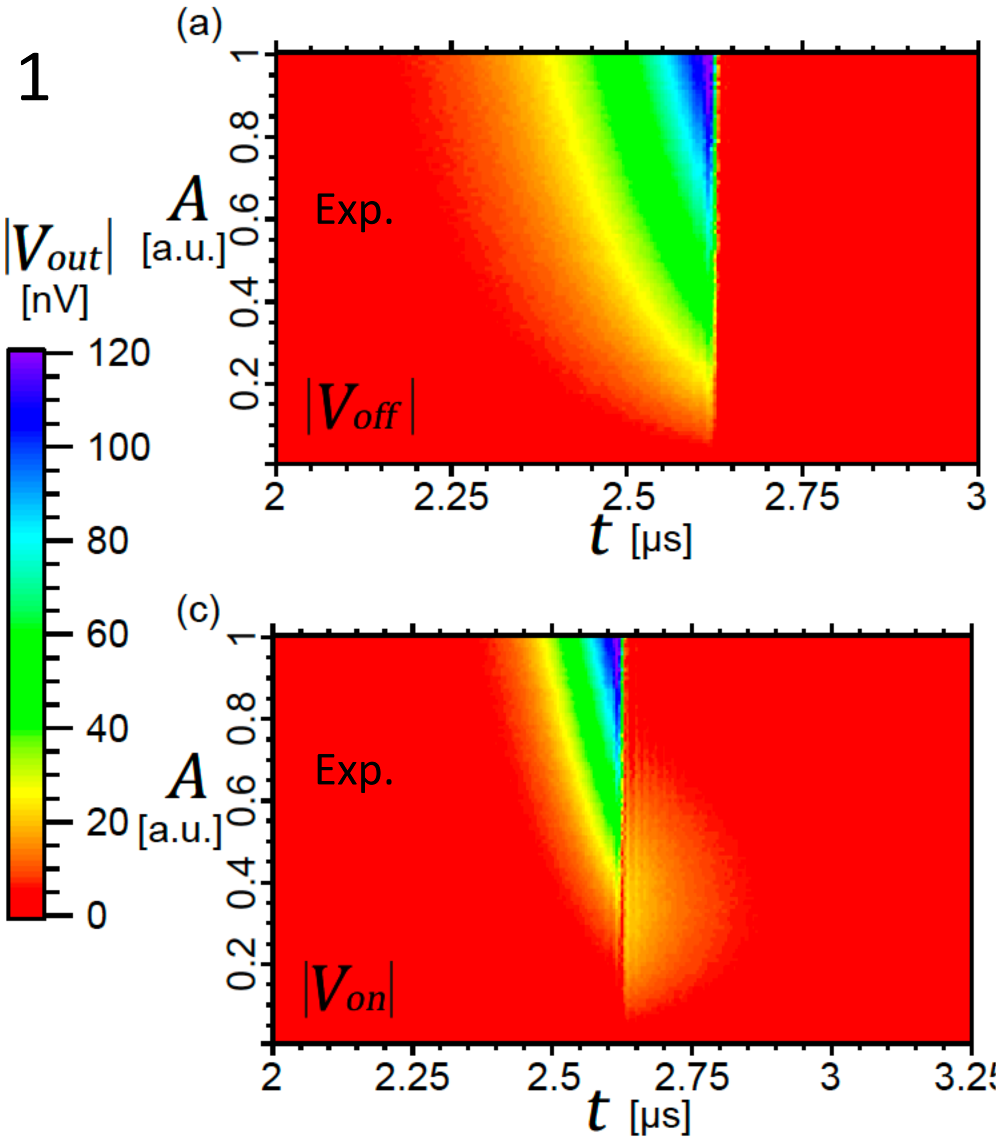
Sweep amplitude A

Sample 1



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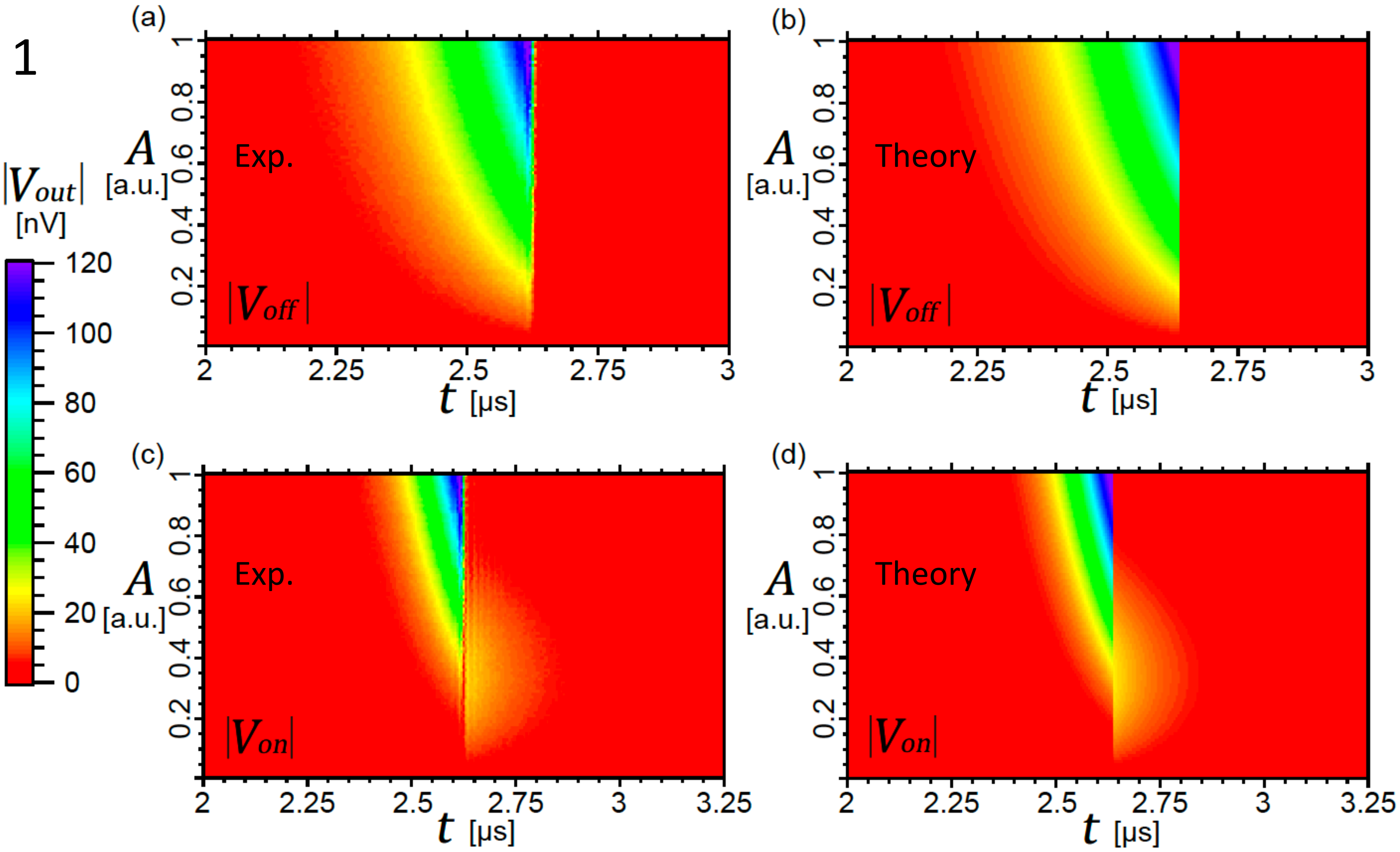
Sweep amplitude A

Sample 1



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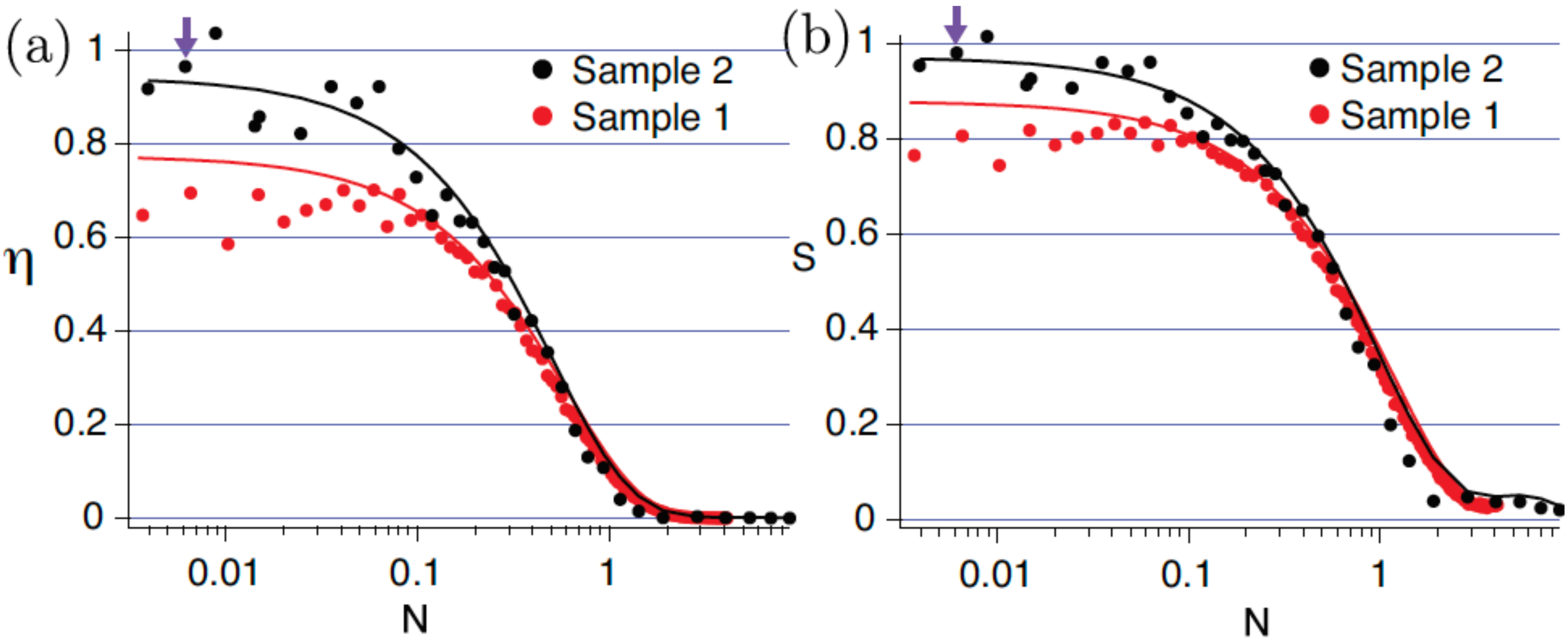
Loading efficiency and symmetry factor versus Photon Number $(\tau \approx T_2)$



Sample 2 has
better coherence
(Small pure dephasing)

$$\eta_{max} = \frac{\Gamma^2}{4\gamma^2}$$

Saturation of two level atom

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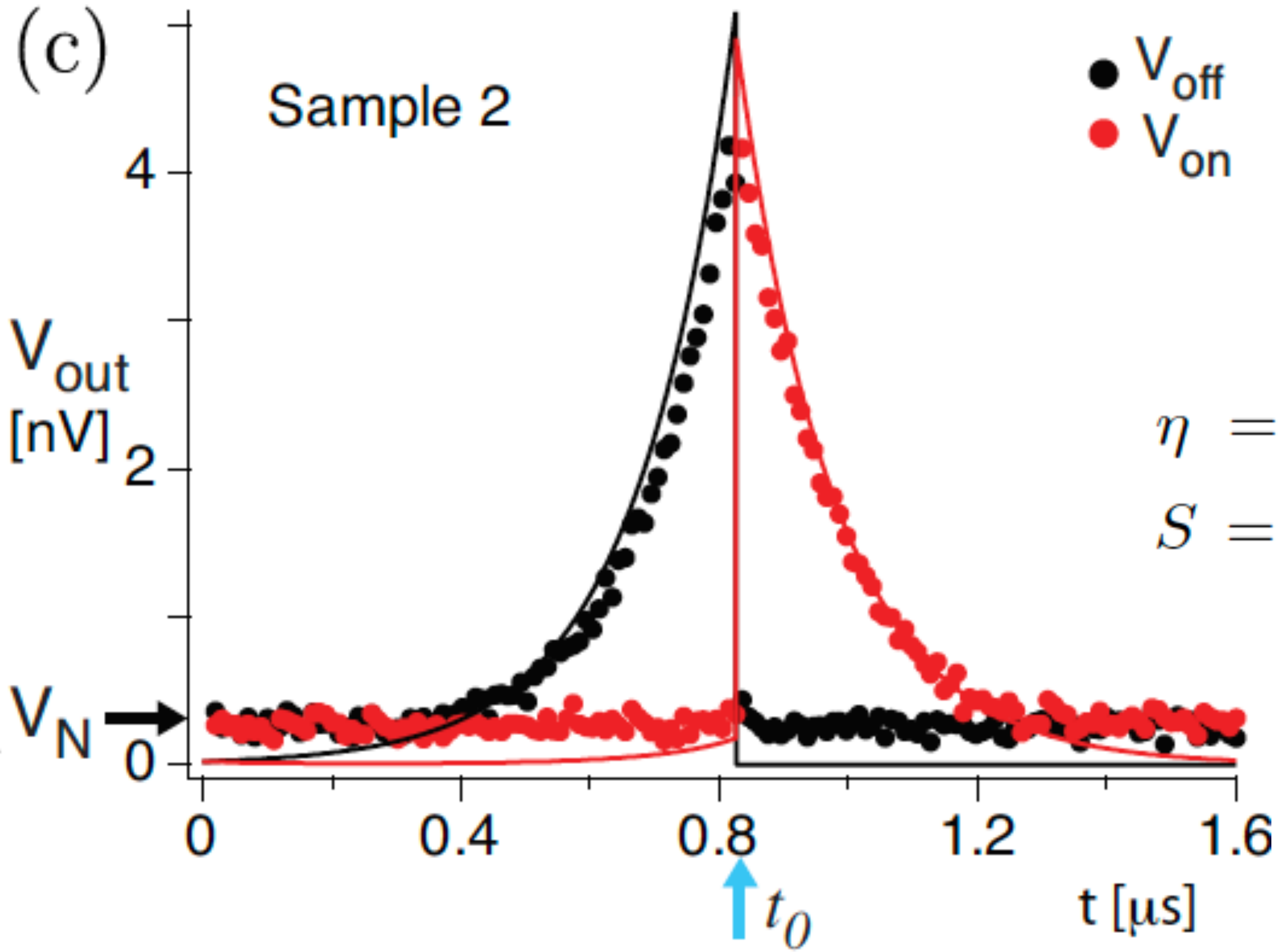
Deterministic loading of microwaves



$$\eta = (1 + 2\Gamma_\phi/\Gamma)^{-2}$$

$$S = (1 + 2\Gamma_\phi/\Gamma)^{-1}$$

Measured loading efficiency 96.5% Symmetry factor 98%

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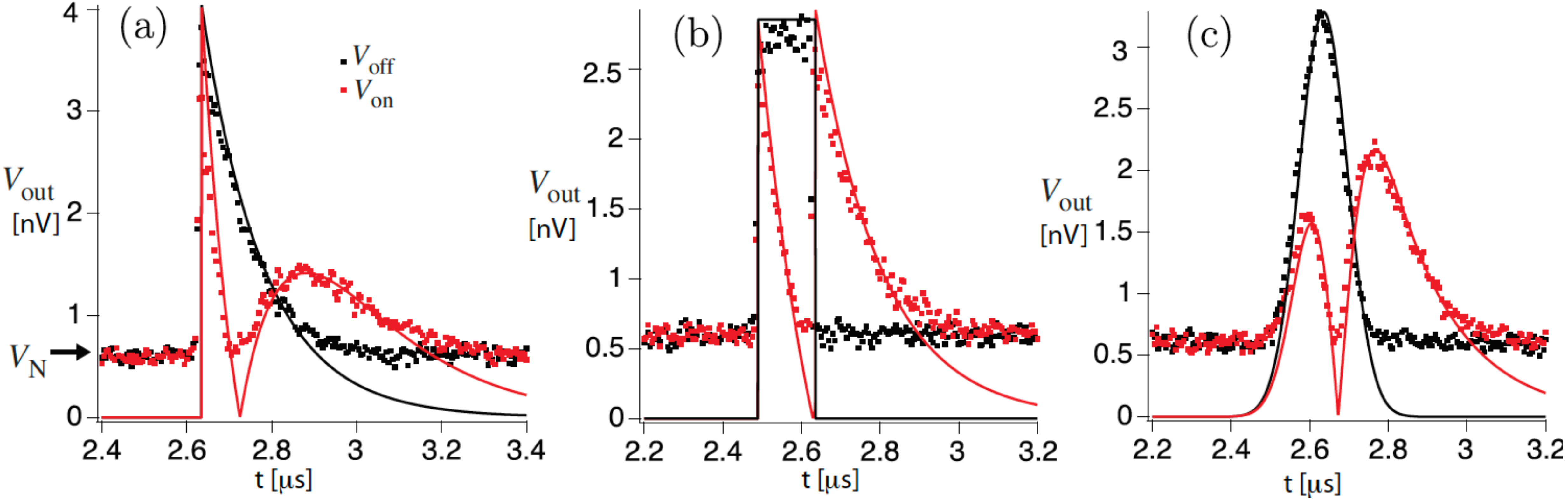
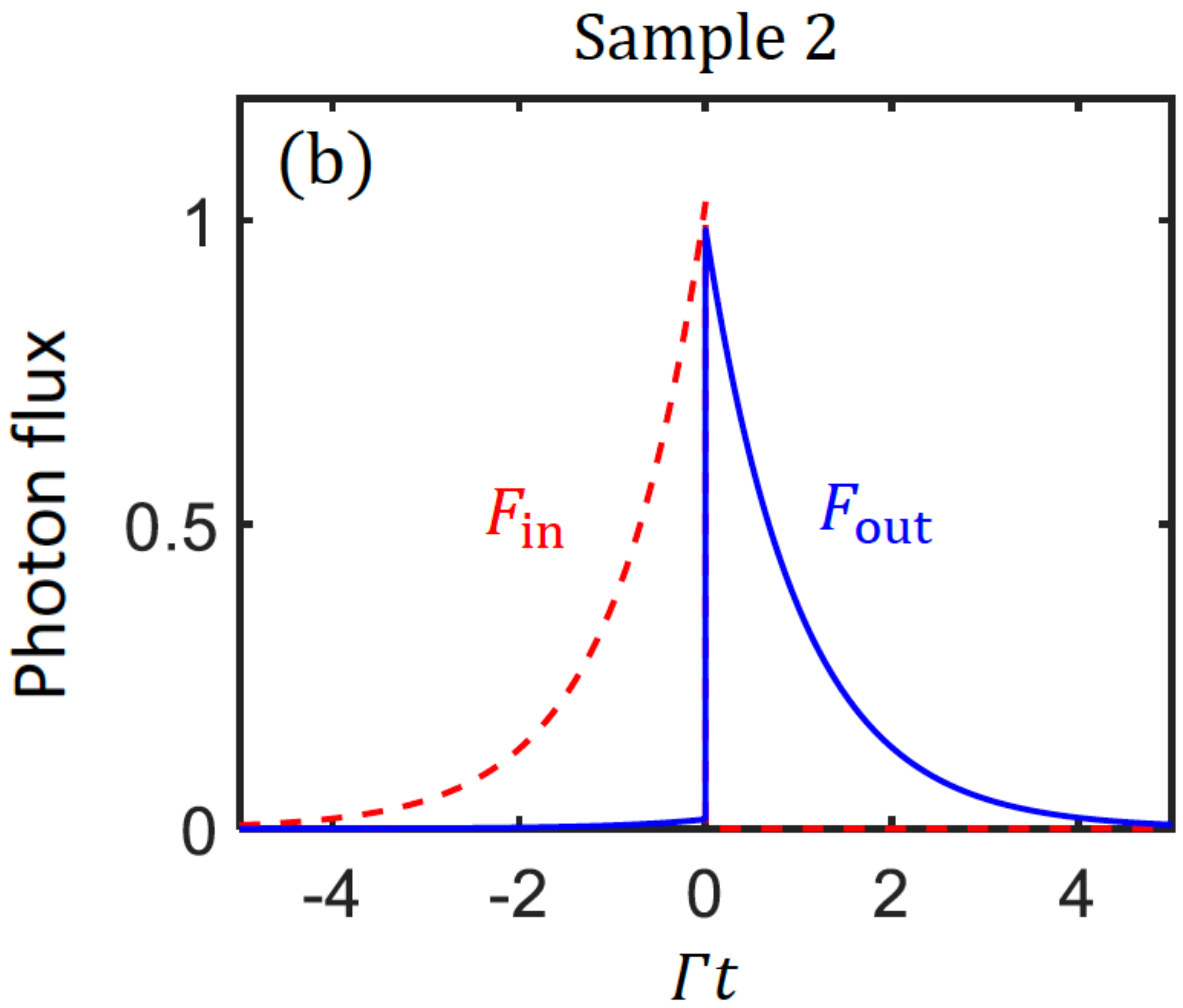
Exponential decay, Square and Gaussian pulse, where N=0.005

Sample 1



Fock state



$\eta \approx 98.5\,\%$

$S \approx 99.3\,\%$

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Conclusion

Using weak exponential rising waveform coherent state, whose time constant matches the decoherence time of an artificial atom, we demonstrate deterministic loading efficiency (96.5%) from one dimensional semi free space to a single artificial atom. The high loading efficiency is due to time-reversal symmetry: the overlap between the incoming wave and the time-reversed emitted wave.

W. J. Lin *et al.* arXiv:2012.15084 (2021)

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Future work

Quantum memory

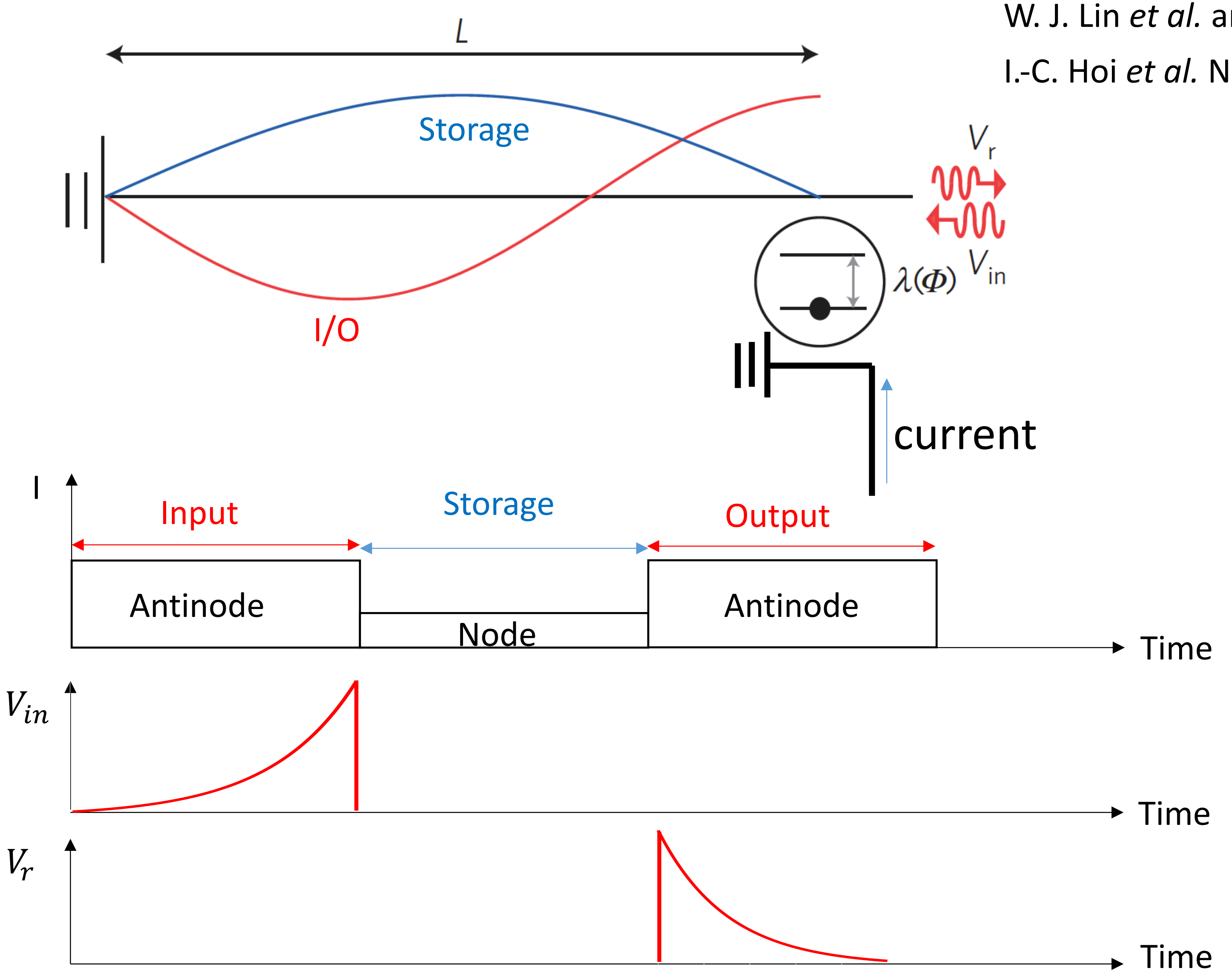
Store quantum information in the qubit and retrieve at a later time

Quantum memory

Based on previous work:

W. J. Lin *et al.* arXiv:2012.15084 (2021)

I.-C. Hoi *et al.* Nature Physics **11**, 1045 (2015)



Limited to material loss
Goal: storage 20us

Quantum memory comparison

Advantages:

1. Simple. Only one DC current, switch between I/O mode and storage mode.
2. Possibly storage efficiency (>90%) and storage time about 20us.

Compare to

Yunfei Wang et al. Nature Photonics 13, 346 (2019)

Storage efficiency 85% using electrogmagnetically induced transparency in Rubidium atoms, storage time about 5us.

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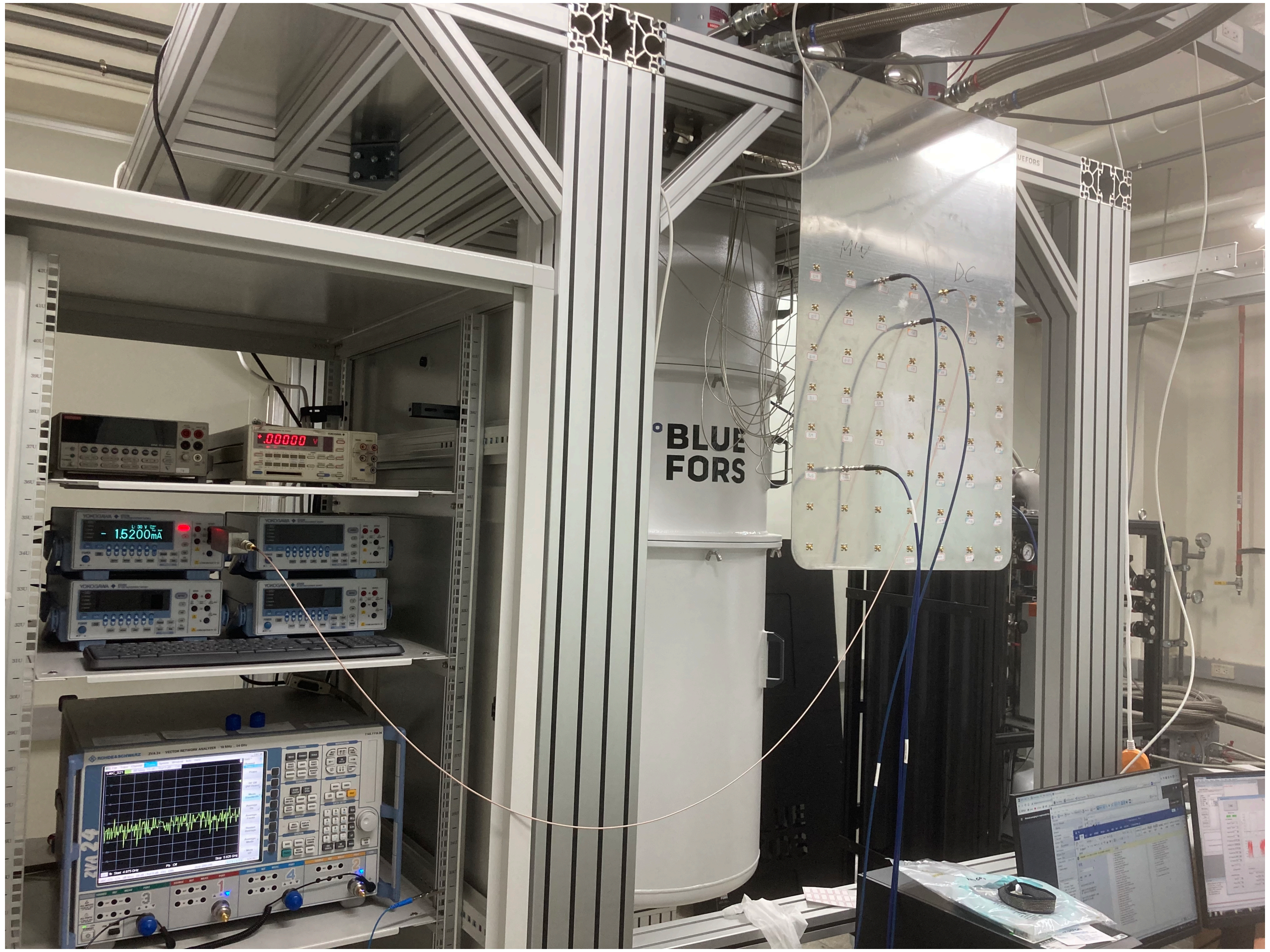
Dilution fridges

Max 50 Coax cables



Max 200 Coax cables

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Basic measurement Instruments

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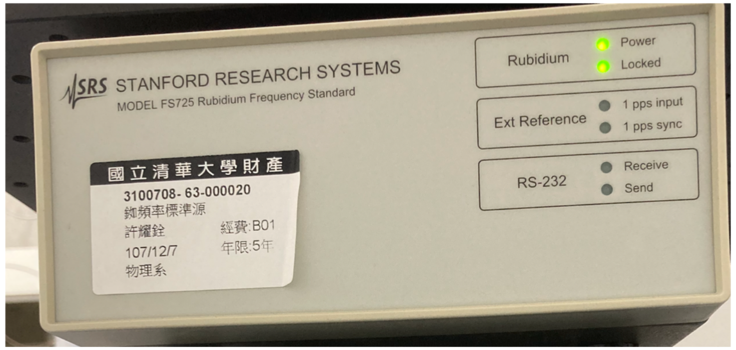
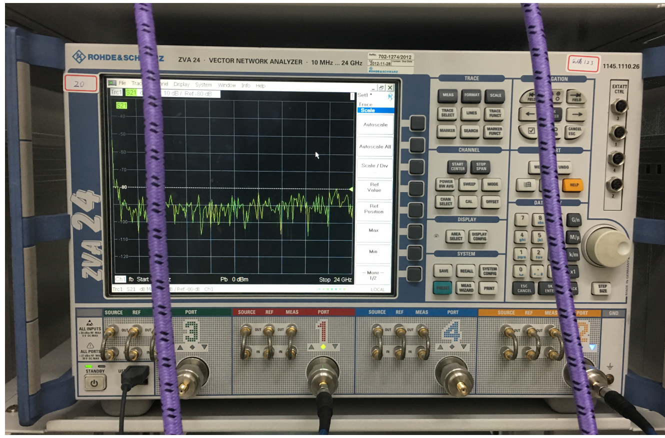
Current source:

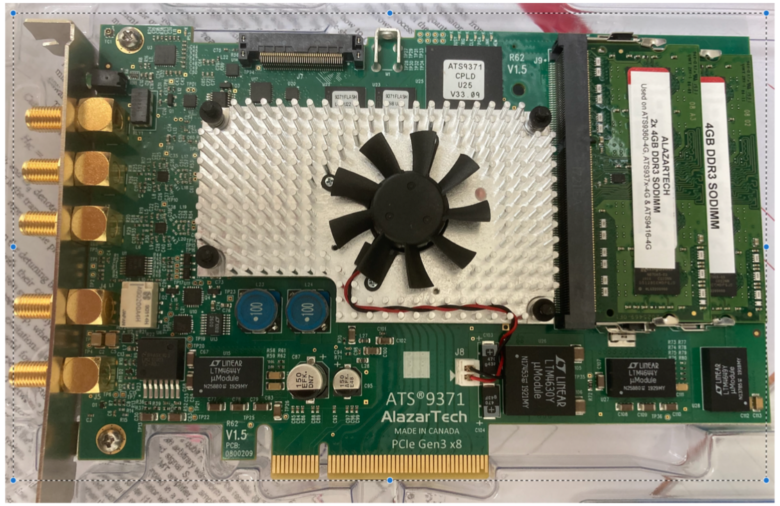
Frequency standard



Vector Network Analyzer



Fast digitizer card



IQ modulation RF source

Arbitrary microwave Generator:

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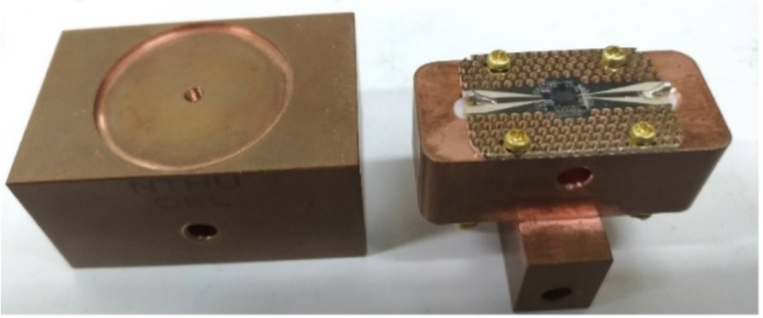
Experimental Setup

4cm

5cm

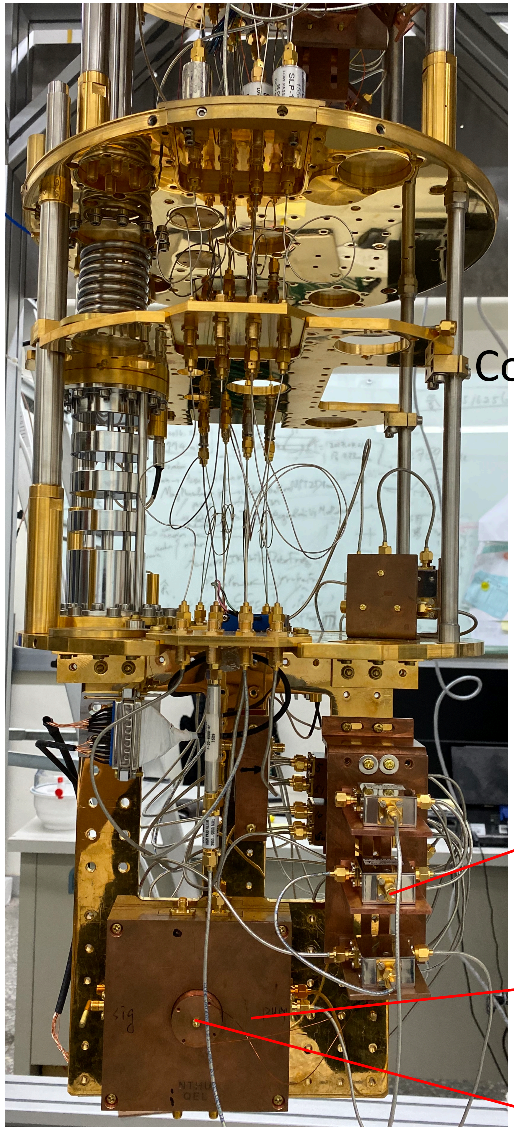


3.3K

0.8 K

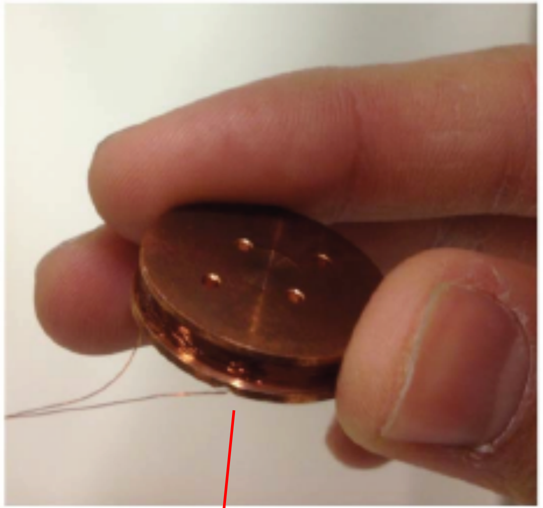
100mK

10mK



Still

Cold plate



Circulator ~ 35k

Sample Box

Superconducting Magnet

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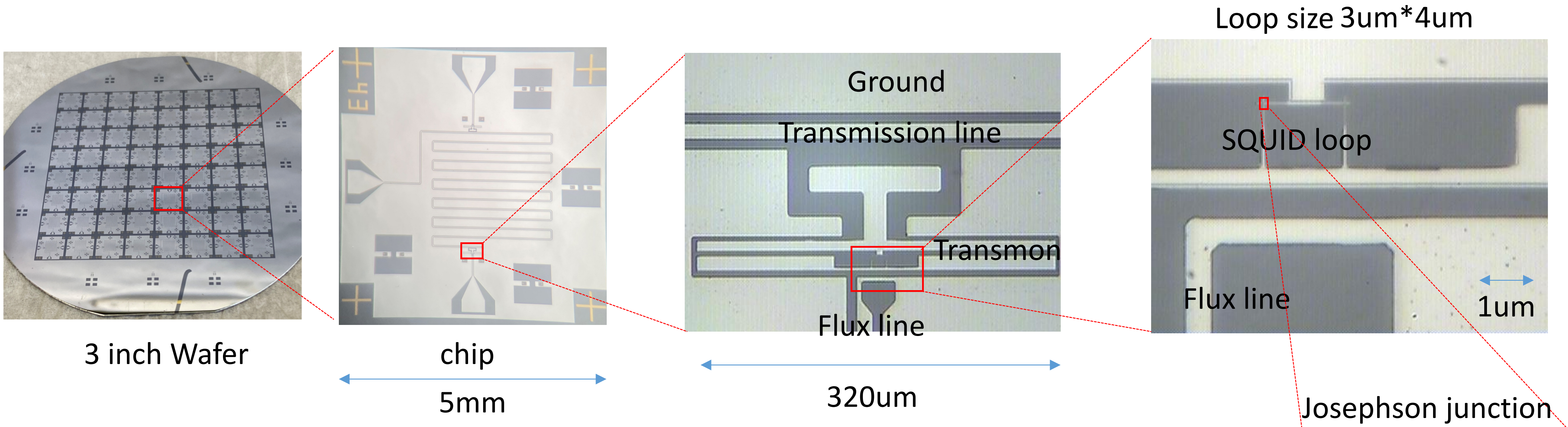
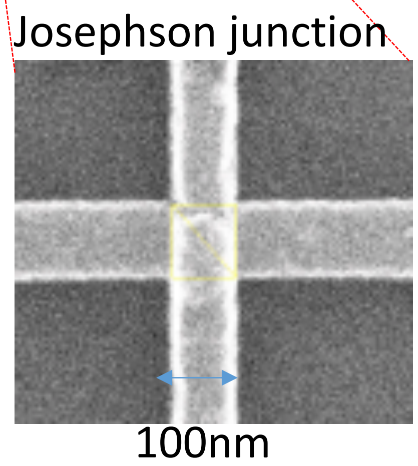
Fabrication of Transmon in transmission line





Big structure: Photolithrography 10um (Transmission line, ground, flux line)
Small structure: Ebeam lithrography 100nm (Josephson junction, Transmon)
Two layers: Alignment is needed.

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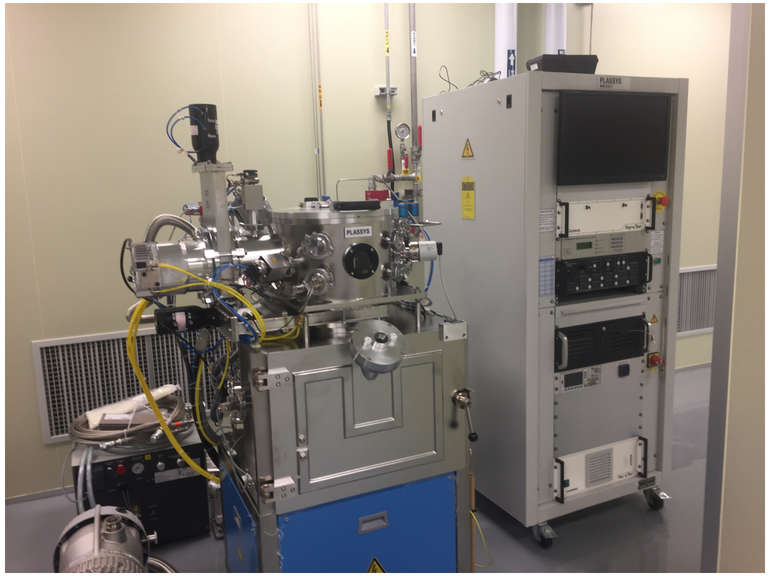
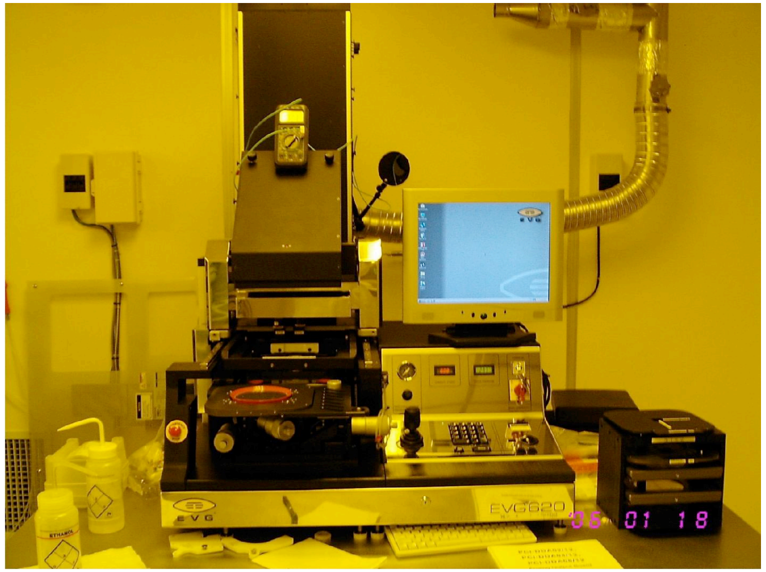
Fab facilities



Al evaporation and Josephson Junction



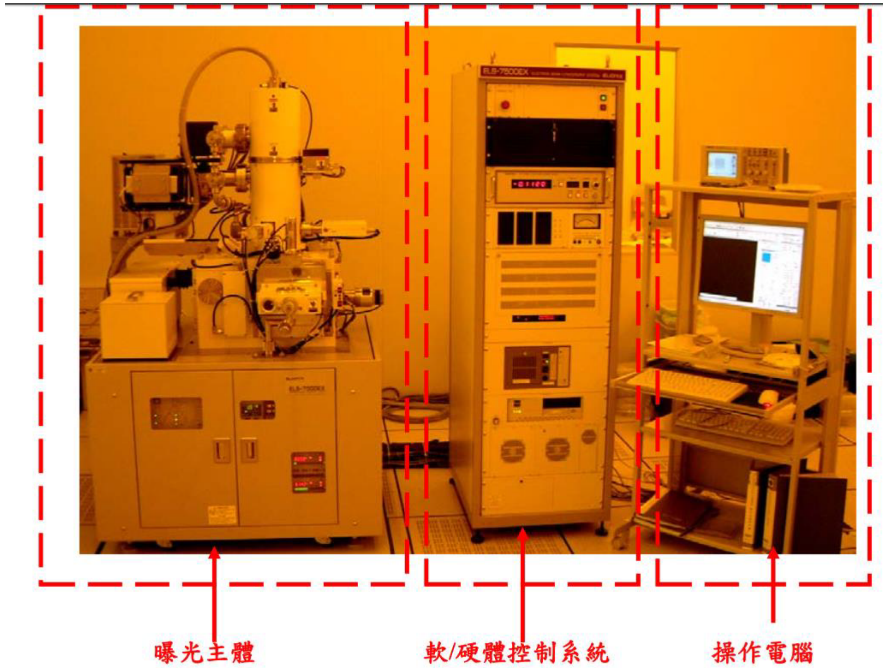
Photolithography

Au evaporation with E-Gun System

O2 plasma

清大奈材中心

台灣半導體研究中心



e-beam lithography

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Acknowledgement

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W.-J. Lin,[1,*] Y. Lu,[2,†] P. Y. Wen,[3,*] Y.-T. Cheng,[1] C.-P. Lee,[1] K.-T. Lin,[4] K.-H. Chiang,[5] M. C. Hsieh,[1] C.-Y. Chen,[1] C.-H. Chien,[1] J.-J. Lin,[1] J. C. Chen,[1,6] C.-S. Chuu,[1,6] F. Nori,[7,8] A. F. Kockum,[2] G.-D. Lin,[4,9] P. Delsing,[2] and I.-C. Hoi[1,6,‡]

W.-J. Lin was an research assistant. Now he is PhD student at University of Maryland.

Y. Lu is a PhD student at Chalmers.

P. Y. Wen is an assistant professor at Chung Cheng University.

Y.-T. Cheng is PhD student in my Lab.

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Ministry of Science and Technology

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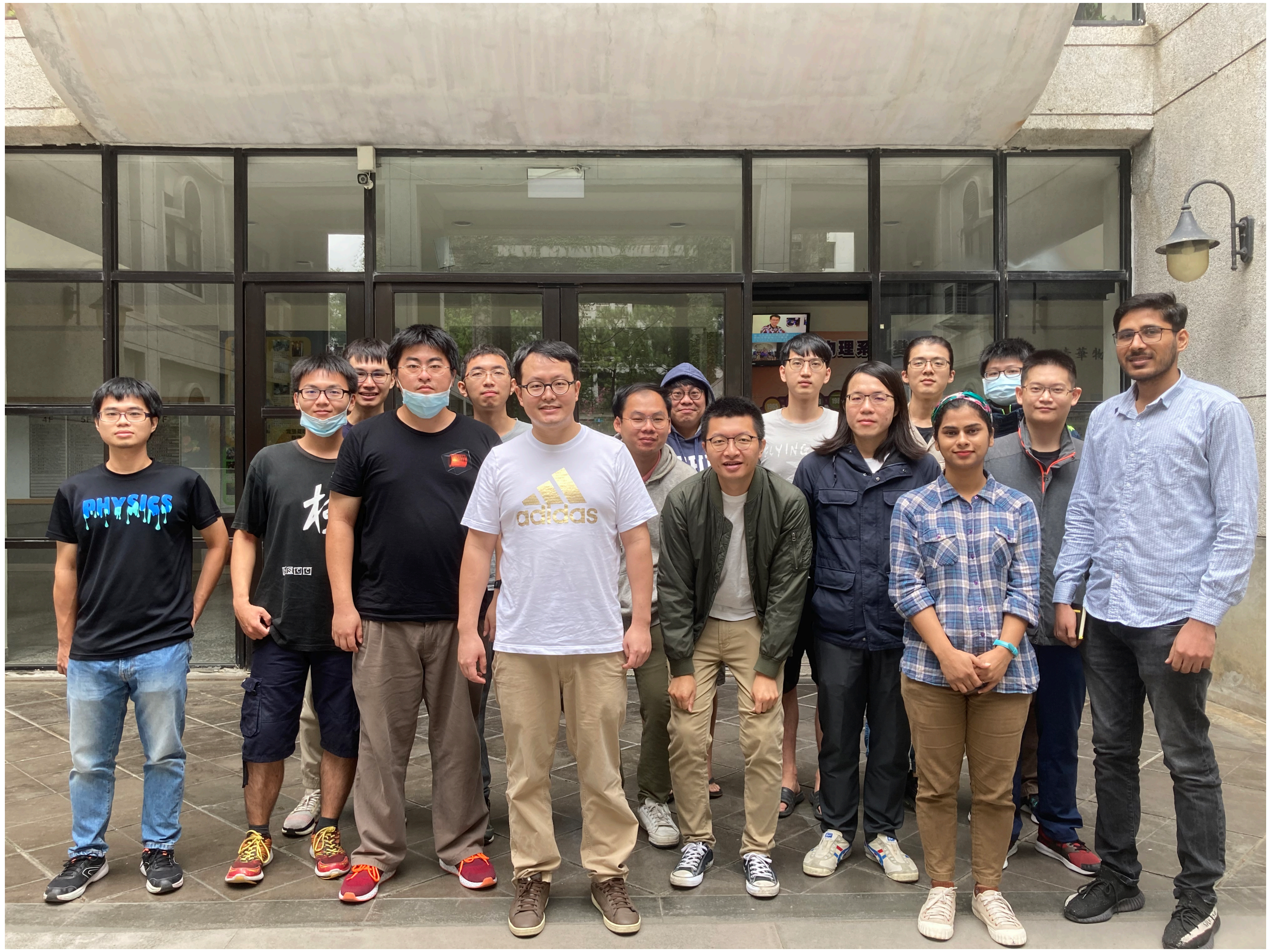
Quantum Engineering Laboratory

QEL



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Thanks for your attention!