IBM quantum platforms: a quantum battery perspective

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Bologna, November 15, 2022

Main motivations

Quantum Thermodynamics

Extension of classical thermodynamics to go beyond equilibrium and thermodynamic limit, fully including quantum effects

S. Vinjanampathy and J. Anders, Contemp. Phys. **57**, 545 (2016);
S. Bhattacharjee and A. Dutta, Eur. Phys. J. B **94**, 293 (2021).

Quantum Technologies

Technologies addressing individual quantum systems and exploiting their quantum properties to improve the performance of devices

M. F. Riedel *et al.*, Quantum Sci. Technol. **2**, 030501 (2017);
A. Acìn *et al.*, New J. Phys. **20**, 080201 (2018).

Nanotechnological solutions for energy manipulations

Miniaturized devices for energy harvesting, conversion, storage and supply

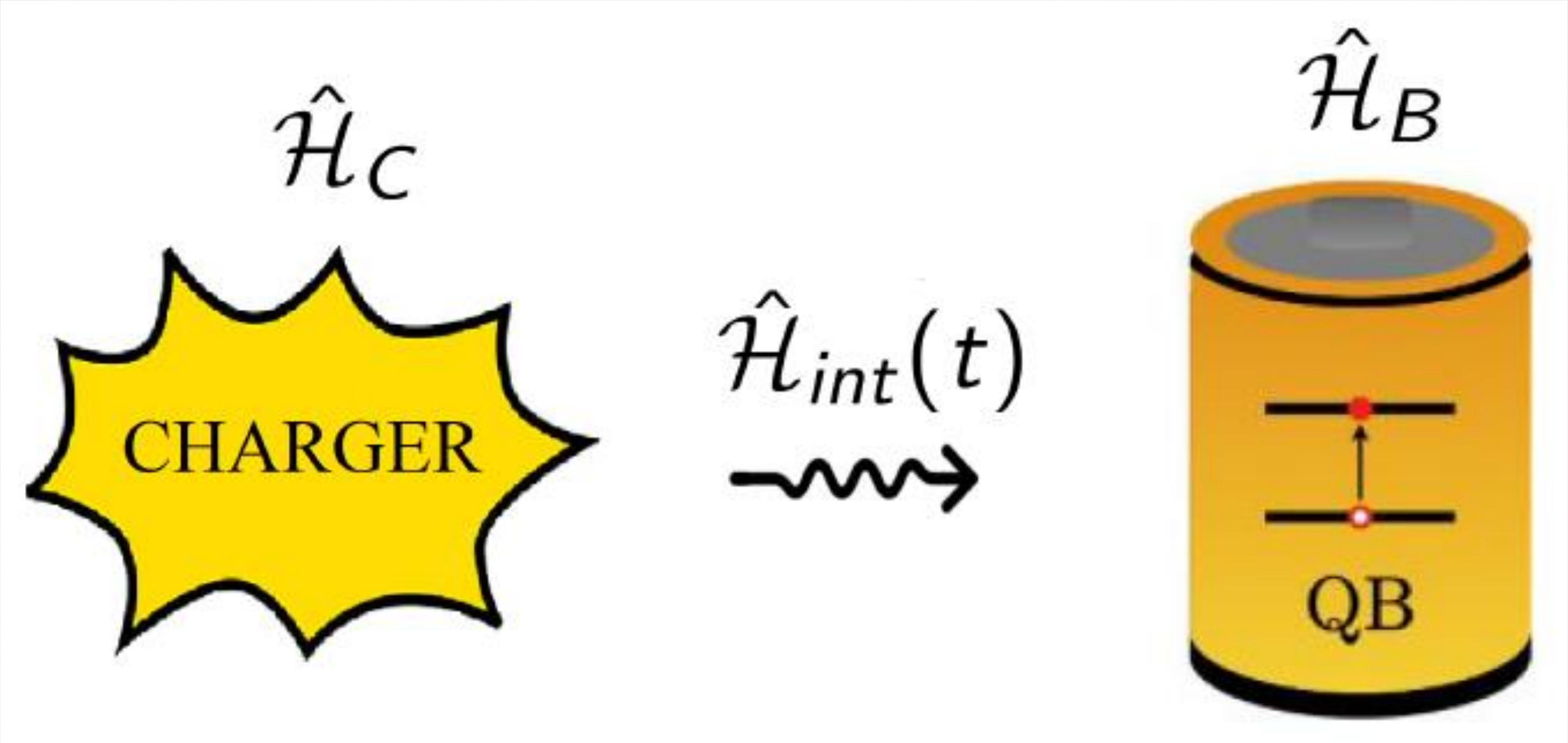
F. Christian *et al.*, Frontiers in Energy **7**, 6 (2013).

Quantum mechanics as new paradigm for Batteries?

R. Alicki and M. Fannes, Phys. Rev. E **87**, 042123 (2013);
F. C. Binder *et al.*, New J. Phys. **17**, 075015 (2015).

What is (for me) a Quantum Battery?

Two-Level Systems (TLSs) as main elementary building blocks for a Quantum Battery



In the following we will focus on a charging through classical drives

Charging by means of purely quantum sources has been also investigated

Photons in a cavity: D. F., M. Campisi, G. M. Andolina, V. Pellegrini, M. Polini, Phys. Rev. Lett. **120**, 117701 (2018);
A. Crescente, M. Carrega, D. F., M. Sassetti, Phys. Rev. B **102**, 245407 (2020)…
Spin-spin interaction: T. P. Le *et al*., Phys. Rev. A **97**, 022106 (2018); D. Rossini *et al*., Phys. Rev. Lett. **125**, 236402 (2020)...

Possible near-term applications: supply energy in a fast and controlled way
to more complex quantum devices and sensors

Static drive and figures of merit

Y.-Y. Zhang *et al.*, Phys. Rev. E **99**, 052106 (2019).

Hamiltonian of the driven TLS
(neglecting the dynamics of the classical charger)

$$\hat{\mathcal{H}} = \hat{\mathcal{H}}_B + \hat{\mathcal{H}}_{int}$$

$$\Delta \left(\frac{1 + \hat{\sigma}_z}{2} \right) + g\hat{\sigma}_x$$

Stored energy

$$E_s(t) = \langle \Psi(t) | \hat{\mathcal{H}}_B | \Psi(t) \rangle - \langle \Psi(0) | \hat{\mathcal{H}}_B | \Psi(0) \rangle$$

Maximum stored energy and optimal charging time
(starting from the *ground state*)

$$E_s^{\max}/\Delta = \frac{g^2}{\Delta^2 + g^2} \qquad t_c = \frac{\pi}{\sqrt{\Delta^2 + g^2}}$$

Complete charging only for an infinite amplitude of the drive

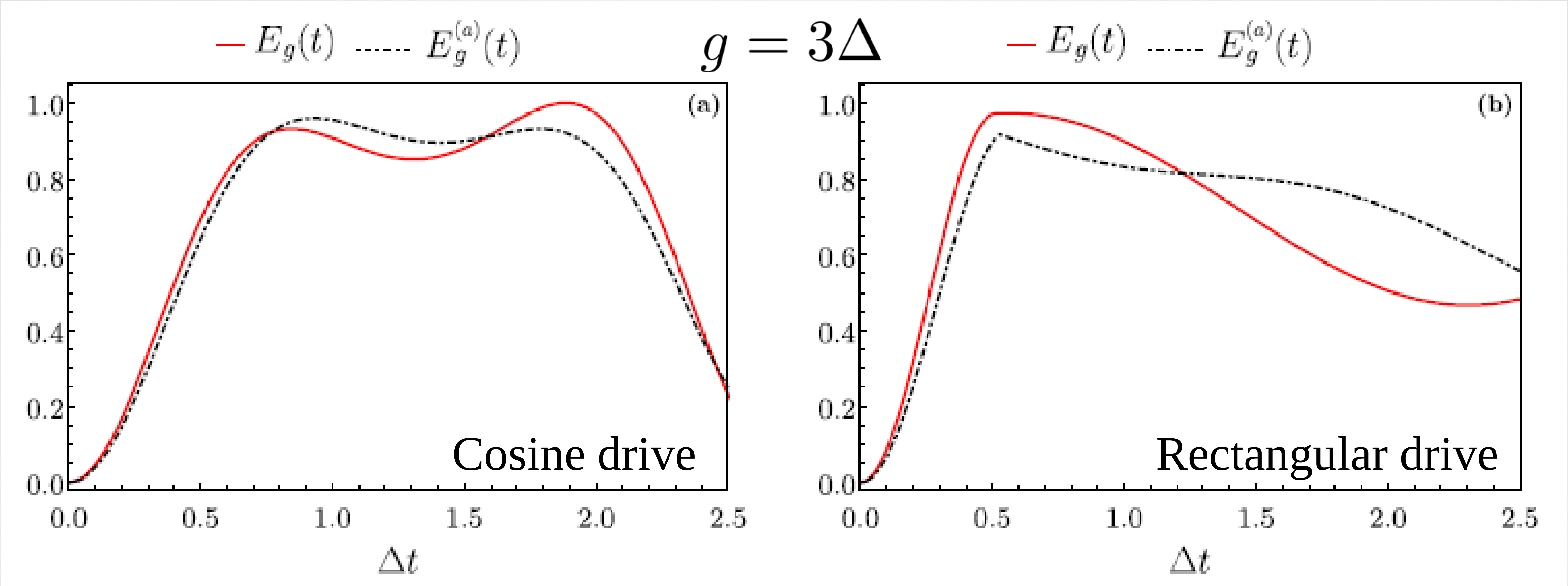
Charging time need to be shorter than the relaxation and dephasing times of the TLS

M. Carrega, A. Crescente, D. F., M. Sassetti, New. J. Phys. **22**, 083085 (2020).

Time-dependent drive

A. Crescente, M. Carrega, M. Sassetti, D. F, New. J. Phys. **22**, 063057 (2020).

$$\hat{\mathcal{H}}_{int}(t) = g f(t)\hat{\sigma}_x$$



Peaked drives lead to faster charging (higher power)

Perfect charging even at finite (although great) amplitude of the drive

Towards realistic implementations: resonant drive

Devices for Quantum Computing typically work in the small amplitude limit

$$g \ll \Delta$$

$$\hat{\mathcal{H}}_{int}(t) = g f(t) \cos{(\Delta t)} \hat{\sigma}_x$$

The relevant parameter to describe the dynamics of the TLS is
the integral of the envelope function up the a given measurement time

$$\theta = g \int_0^{t_m} f(t) dt$$

An universal behavior is expected independently of the form of the envelope

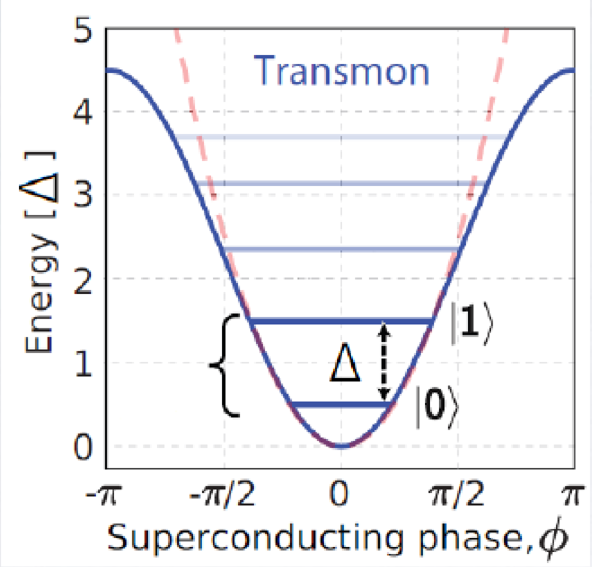
Starting from the *ground state* the stored energy is

$$E_s(\theta) = \Delta sin^2 \left(\frac{\theta}{2} \right)$$

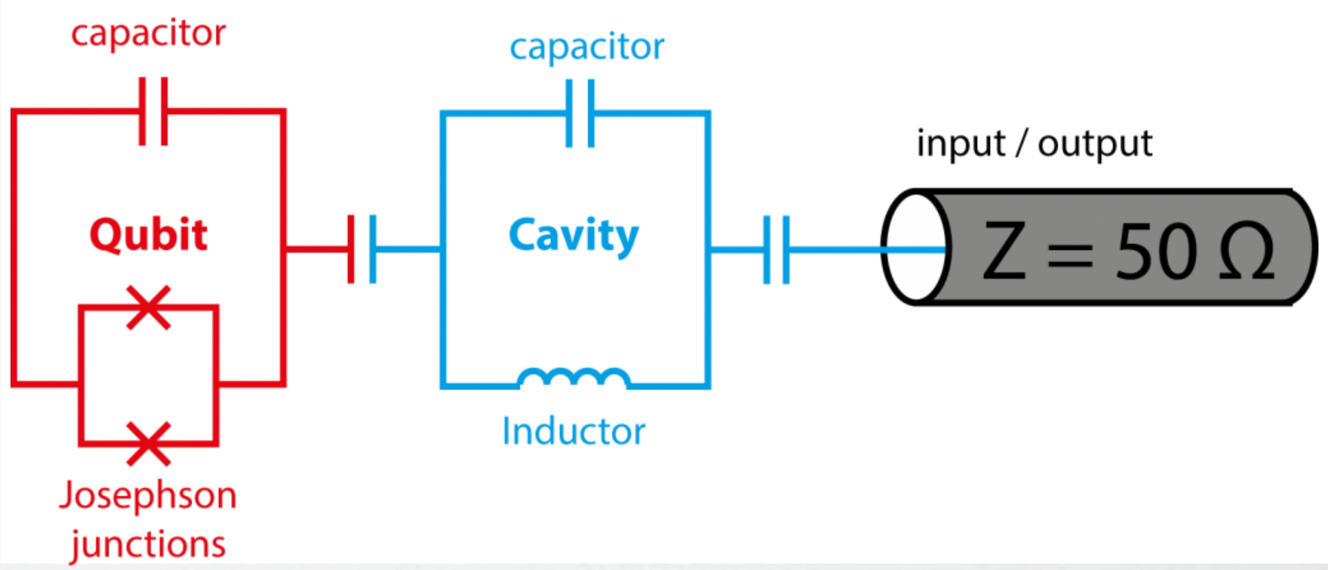
Quantum chip IBM Armonk and Qiskit Pulse

Transmon qubit coupled to a resonant cavity (for readout)

$\Delta \approx 31.238$ GHz; $g \approx 0.105$ GHz



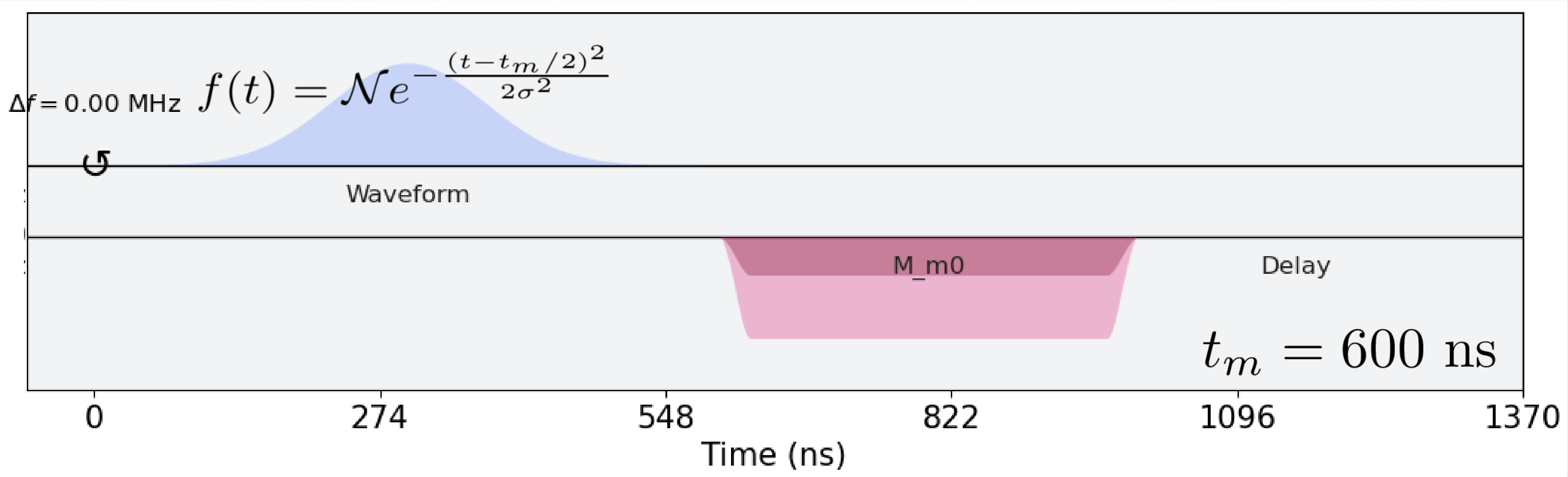
J. Koch, *et al.*, Phys. Rev. A **76**, 042319 (2007).



J. M. Fink, *et al.*, Phys. Rev. Lett. **103**, 083601 (2009).

Possibility to control the time profile of the envelope function

T. Alexander *et al.*, Quantum Sci. Technol. **5**, 044006 (2020).



Calibration and data analysis

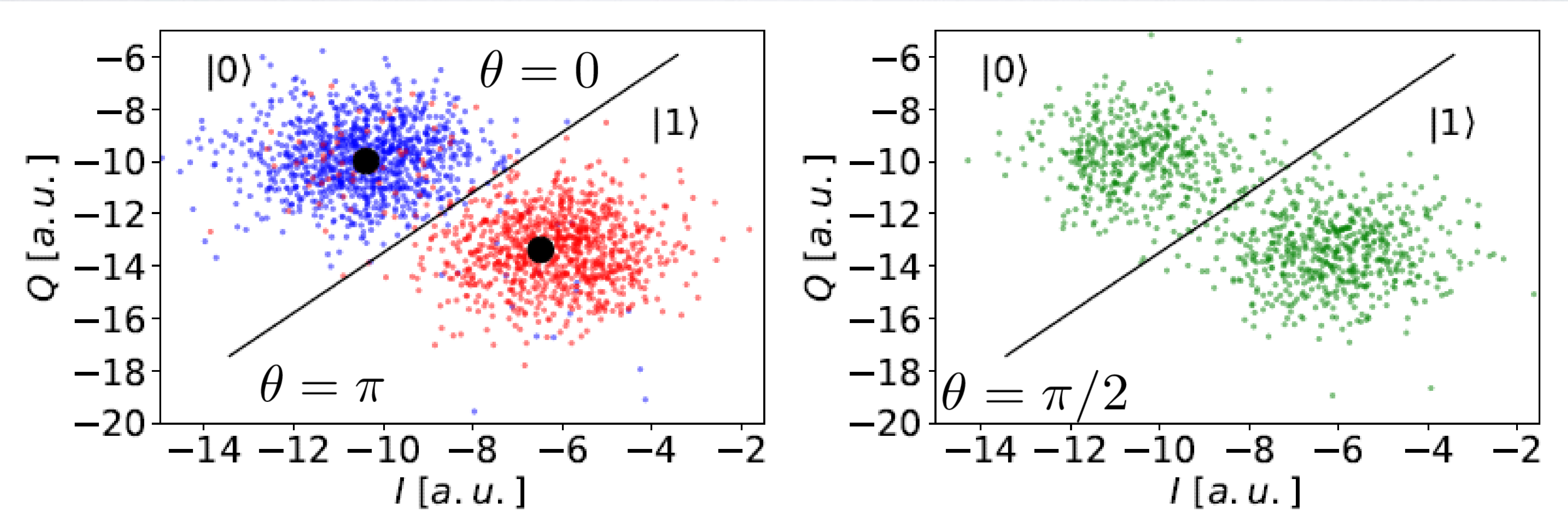
Readout in the dispersive regime with the TLS coupled to a resonator

A monochromatic microwave applied to the resonator is modified according to

$$\cos \Omega t \rightarrow \mathcal{A} \cos \left(\Omega t + \chi\right)$$

$$\mathcal{A} e^{i\chi} = I + iQ$$

E. Jeffrey *et al.*, Phys. Rev. Lett. **112**, 190504 (2014).

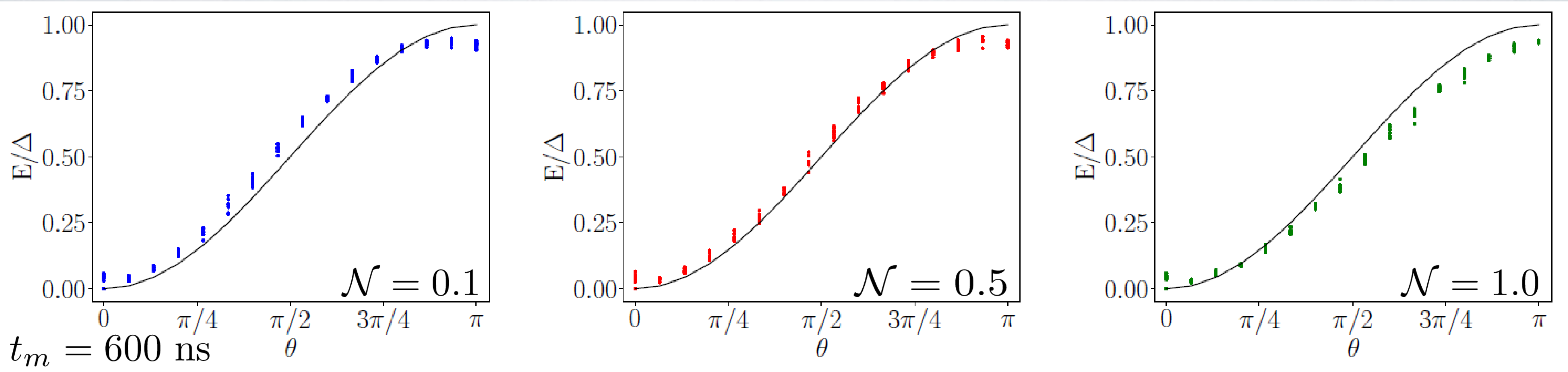


Few percent error after 1024 runs (default)

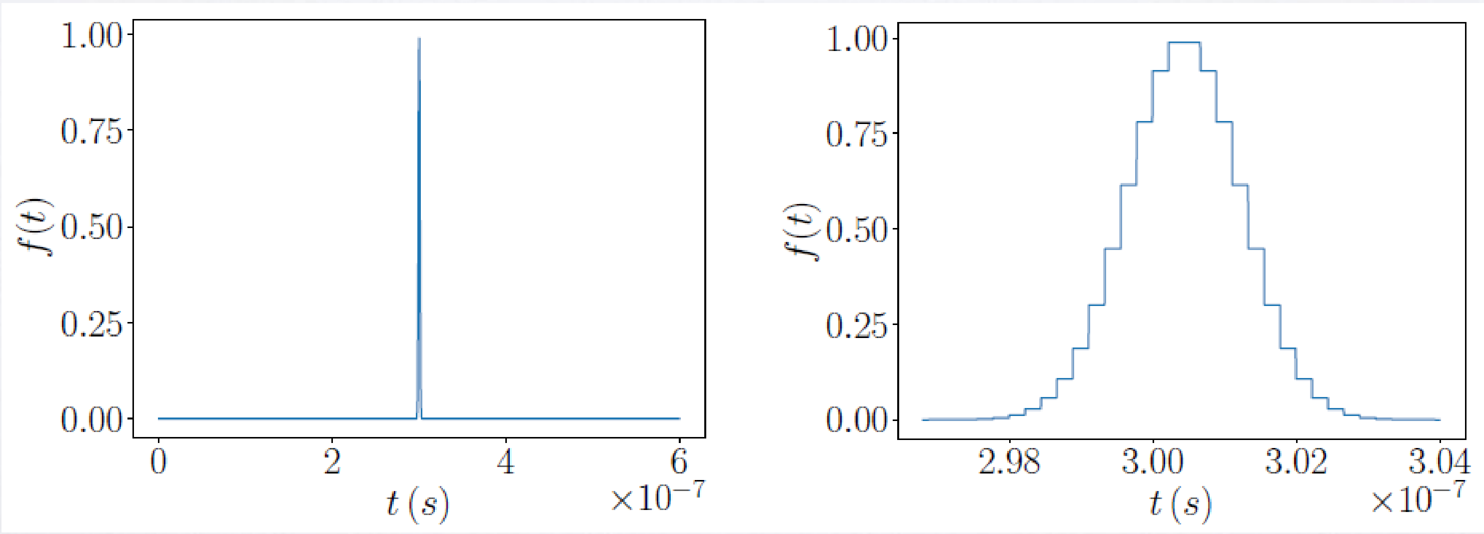
Gaussian drive: constant amplitude

G. Gemme, M. Grossi, D. F., S. Vallecorsa, M. Sassetti, Batteries **8**, 43 (2022).

$$\sigma = \frac{\theta}{\sqrt{2\pi}\mathcal{N} g}$$



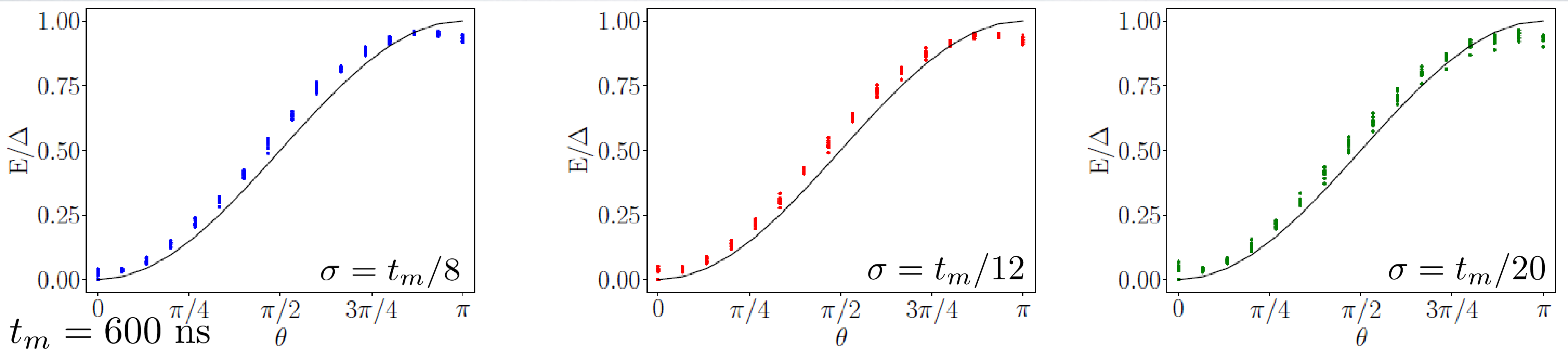
Discrepancies among the curves due to discretization of the pulses and tail effects



Gaussian drive: constant standard deviation

G. Gemme, M. Grossi, D. F., S. Vallecorsa, M. Sassetti, Batteries **8**, 43 (2022).

$$\mathcal{N} = \frac{\theta}{\sqrt{2\pi}\sigma g}$$



Universal behavior is recovered, but there is still a discrepancy with respect to the theoretical curve for charging from the *ground state*

Maximum charging (up to 95%) occurs at smaller angles then expected

Errors in the initialization (typical of NISQ devices) need to be considered

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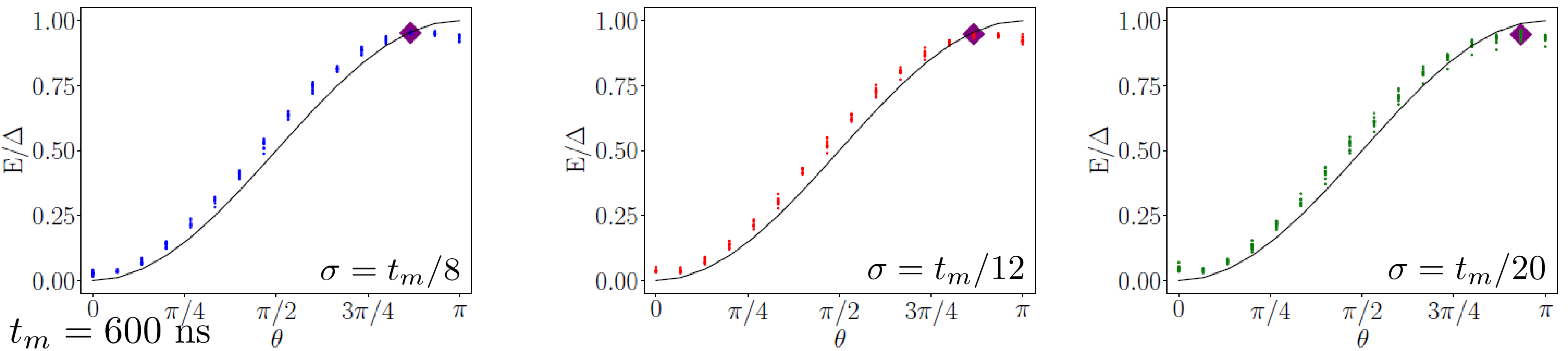

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Determining the initial state

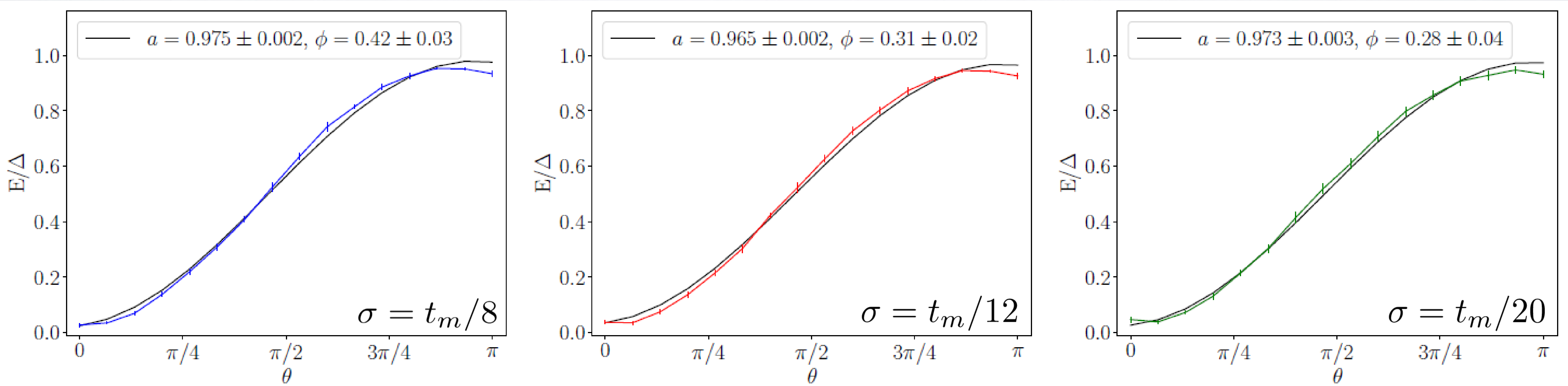
G. Gemme, M. Grossi, D. F., S. Vallecorsa, M. Sassetti, Batteries **8**, 43 (2022).

Let's consider an arbitrary initial state

$$|\Psi(0)\rangle = \sqrt{a}|0\rangle + \sqrt{1-a}e^{-i\varphi}|1\rangle$$

Energy into the Quantum Battery

$$E(\theta, a, \varphi) = \Delta\left[a\sin^2\left(\frac{\theta}{2}\right) + 2\sqrt{a(1-a)}\sin\varphi\sin\left(\frac{\theta}{2}\right)\cos\left(\frac{\theta}{2}\right) + (1-a)\cos^2\left(\frac{\theta}{2}\right)\right]$$



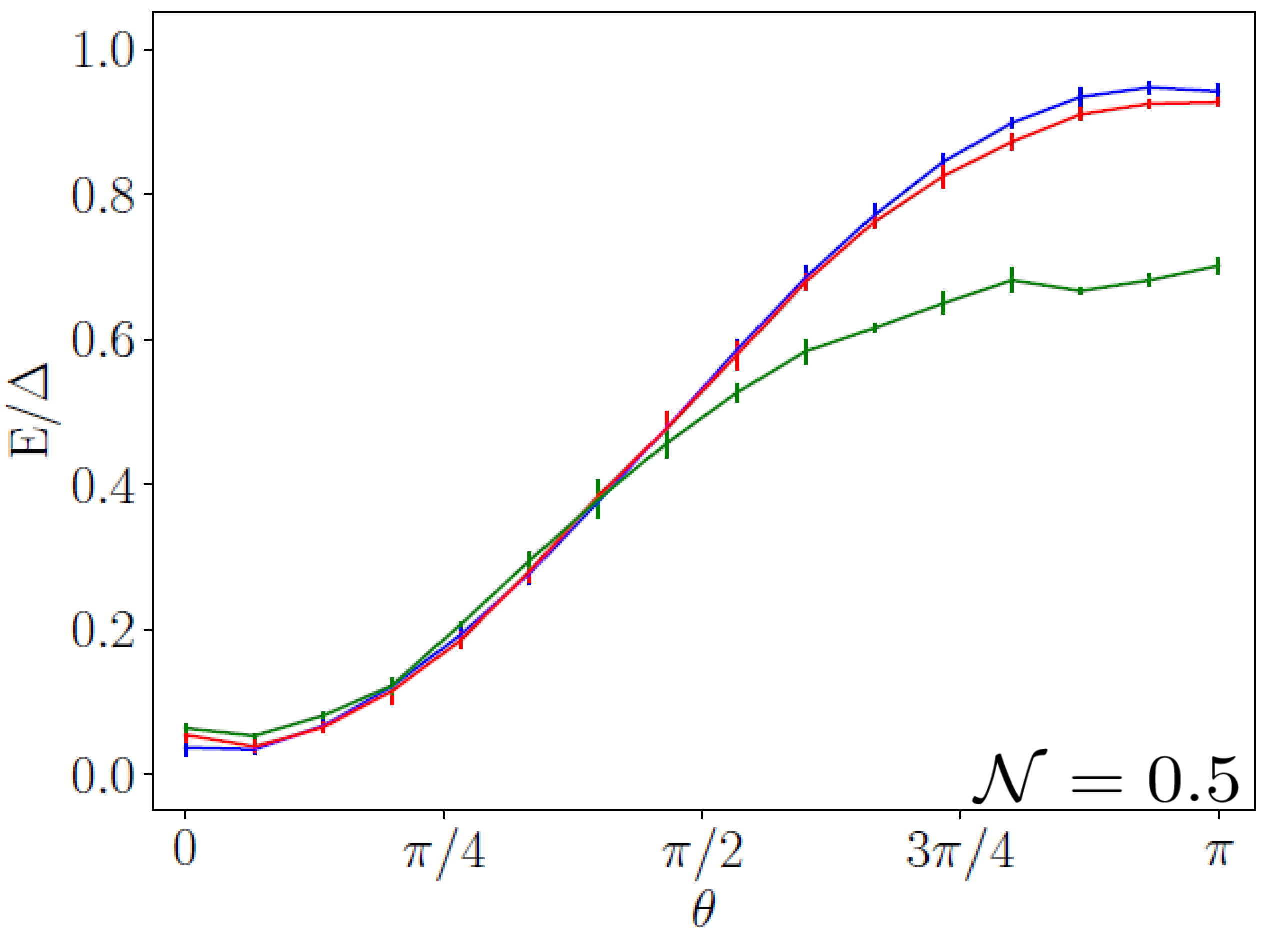
Fitting with a thermal state is inaccurate

Minimizing measurement and charging time

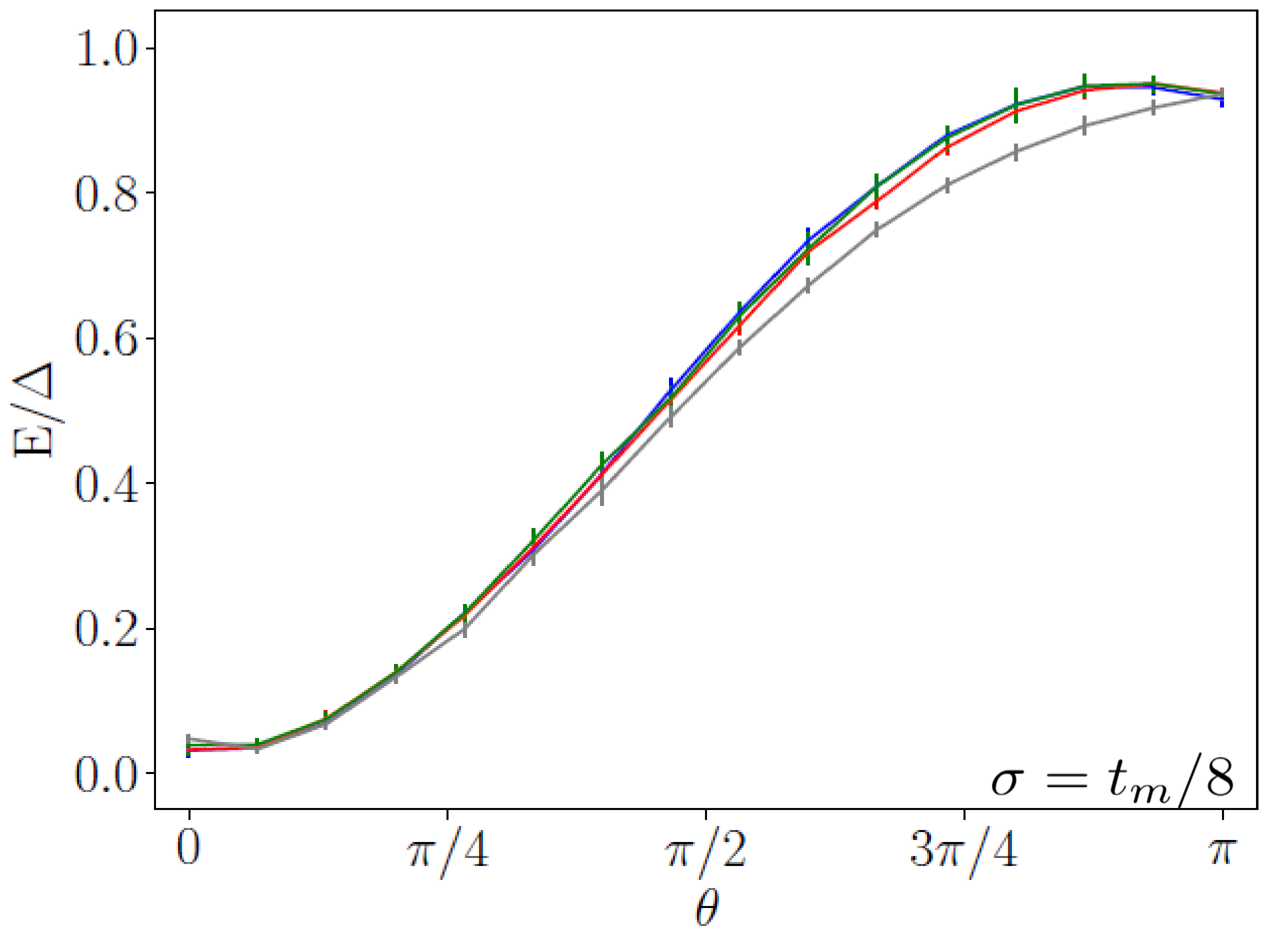
G. Gemme, M. Grossi, D. F., S. Vallecorsa, M. Sassetti, Batteries **8**, 43 (2022).

We want to reduce the measurement (and charging) time
without affecting the charging performances

$t_m = 600$ ns; $t_m = 119$ ns; $t_m = 60$ ns



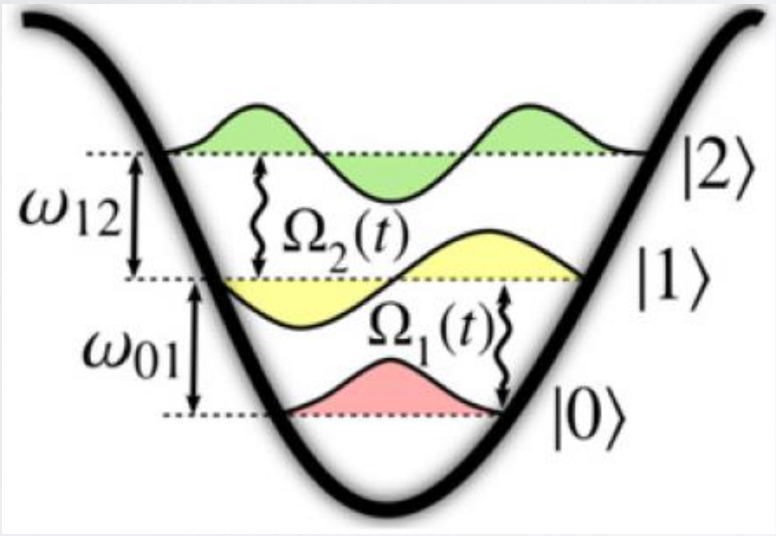
$t_m = 600$ ns; $t_m = 240$ ns; $t_m = 135$ ns; $t_m = 60$ ns



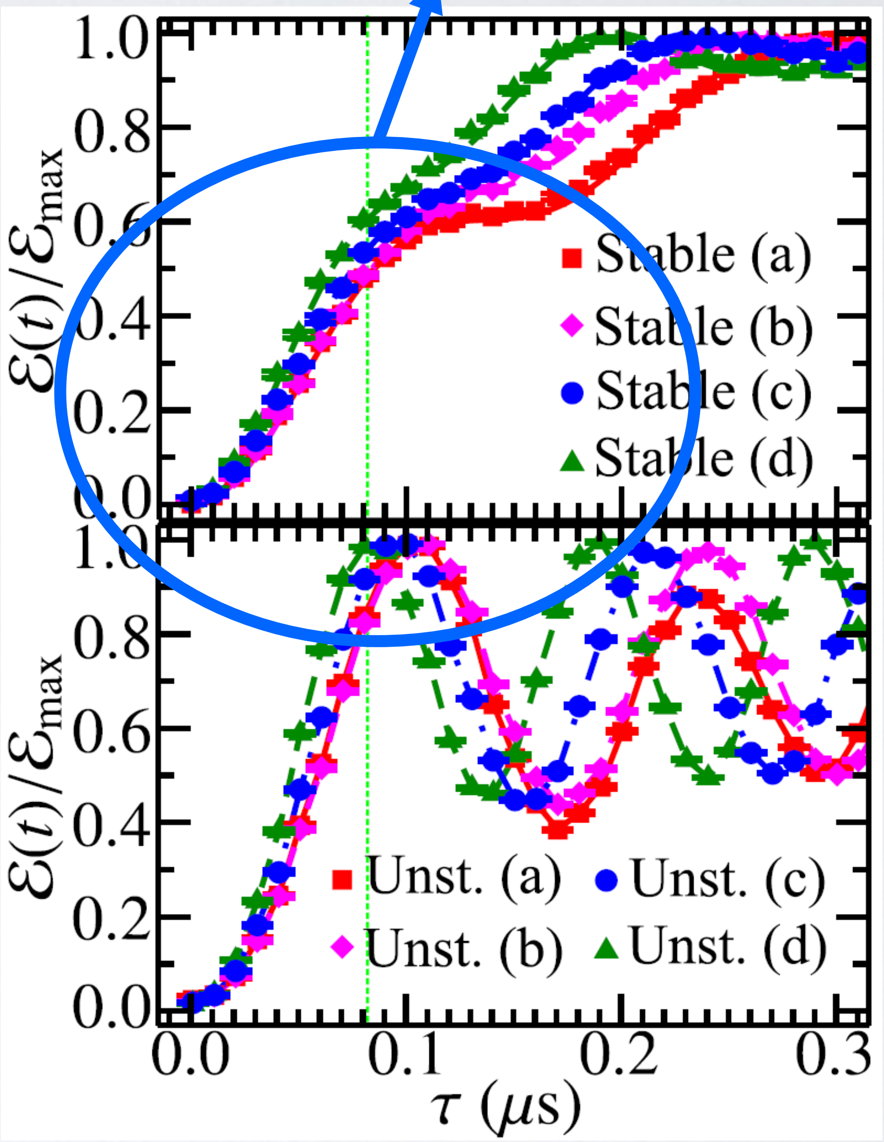
Comparison with state of the art experiments

C.-K. Hu *et al.*, Quantum Sci. Technol. **7**, 045018 (2022).

Quantum Battery made by a qutrit in the transmon regime



$\boxed{\Delta \approx 39.4\ \mathrm{GHz}; t_c \approx 120\ \mathrm{ns}}$



Armonk shows similar performances without being optimized for Quantum Battery applications

Take-home messages

- Quantum Batteries as miniaturized devices for energy storage
- It is possible to implement them in IBM quantum machines
- Initialization errors can have positive impact on their performances
- Energy storage and charging time comparable with recent experiments

Outlook

- Controlling the dynamics of multi-level IBM devices with Qiskit Pulse
- Study of coherent energy transfer among TLSs

A. Crescente, D. F., M. Carrega, M. Sassetti, Phys. Rev. Research **4**, 033216 (2022).

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