The breakdown of photon blockade: a first-order dissipative quantum phase transition

cloud-based simulation of open quantum systems

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GPU Day 2020
Budapest, 20 October 2020

Quantum optics:
light–matter interaction at low energies

@ Wigner RCP, Budapest: theoretical, computational

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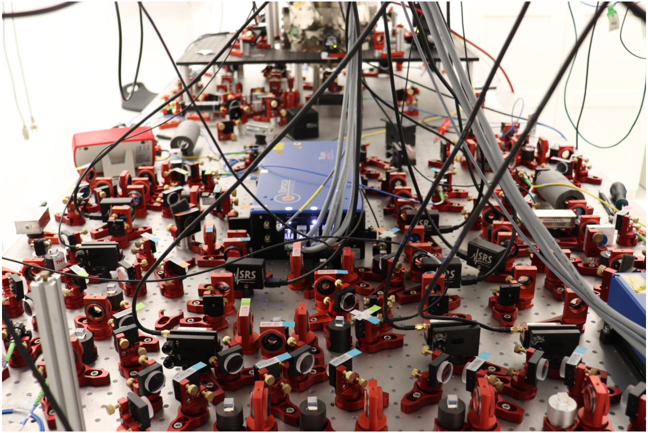
light–matter interaction at low energies

@ Wigner RCP, Budapest: theoretical, computational, experimental



Quantum optics:
light–matter interaction at low energies

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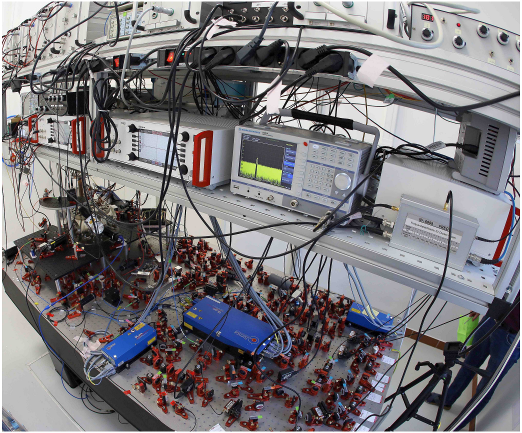
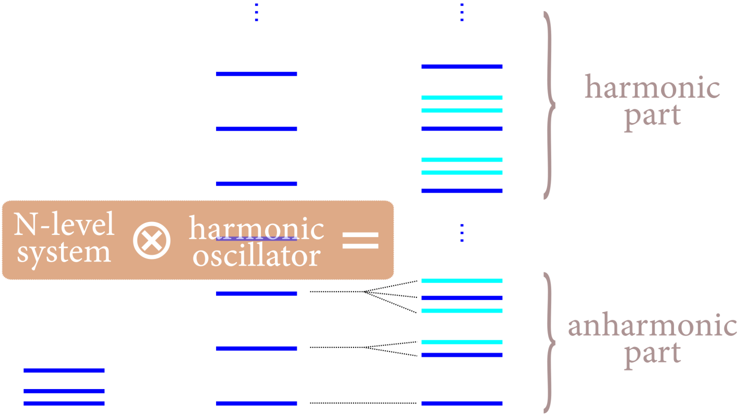


Finite-level system coupled to harmonic oscillator



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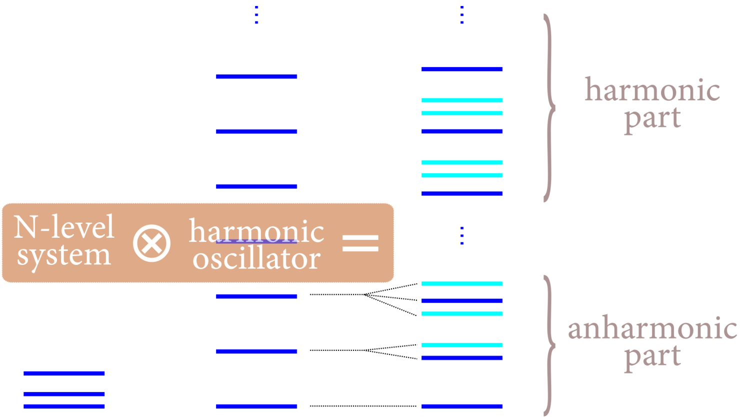
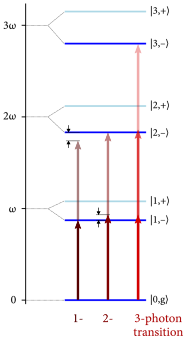


@ high-enough excitation, spectrum always has harmonic subsets

Prototype: Jaynes-Cummings spectrum

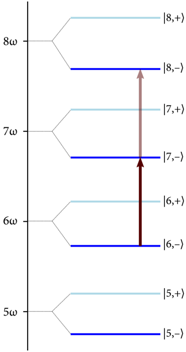
lower part of spectrum

(0–3 photons)



higher "

(5-8 photons)



Hamiltonian:

$$\hbar g \left(|e\rangle \langle g| \, a + |g\rangle \langle e| \, a^\dagger \right)$$

Energy levels:

$$E_{n,\pm} = n\hbar\omega \pm \sqrt{n}\,\hbar g$$

difference in level-spacing for '–' manifold decays as

$$\frac{1}{\sqrt{n}} - \frac{1}{\sqrt{n+1}} \propto n^{-3/2}$$

For small n – photon blockade

if linewidth $\ll \delta$

$\Rightarrow$ effectively 2-state system

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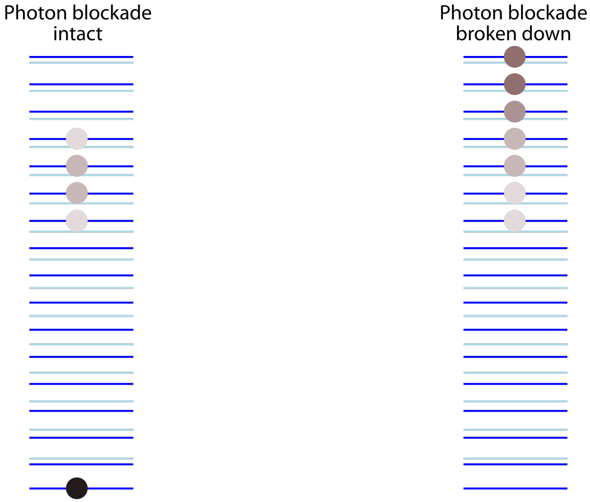
Photon-blockade breakdown

the phases



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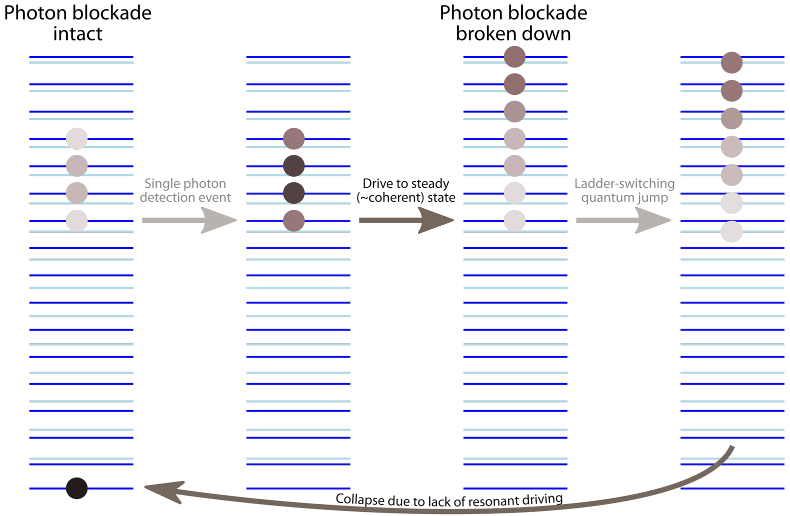
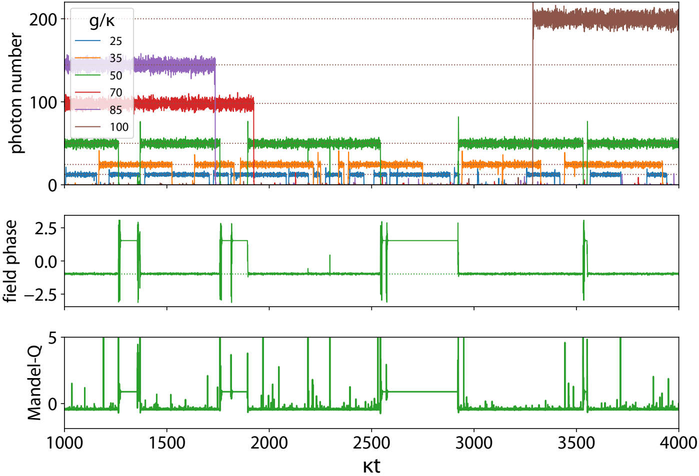


Photon-blockade breakdown

the bistable behaviour

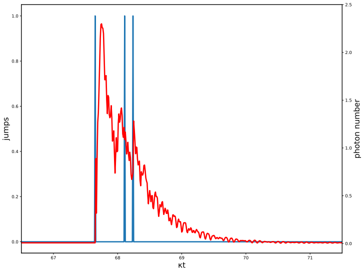


Phase transition without approaching macroscopic system in thermodynamic limit

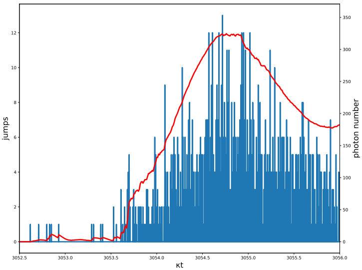
Photon-blockade breakdown

the jump-induced switchings

unsuccessful switching



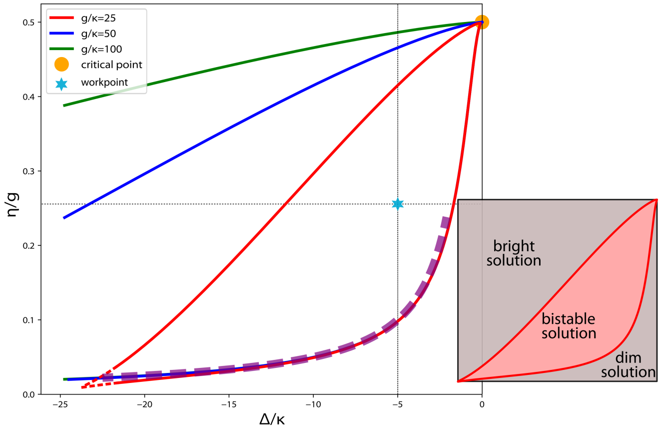
successful switching



Reverse process also induced by single well-identifiable jump

Photon-blockade breakdown

the phase diagram



Transition from dim to bright phase in the bistable region through the bistable domain via the filling factor

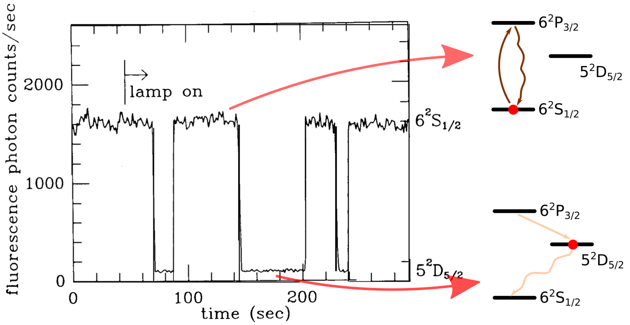
⇒ "coextistence of phases" with varying composition

[Vukics, Dombi, Fink, Domokos, Quantum **3**:150 (2019)]

Photon-blockade breakdown

vs. long-lived bistability

Long-lived bistability not unknown in quantum optics
— e.g. electron-shelving (Dehmelt, 1986) — single Ba^+ ion

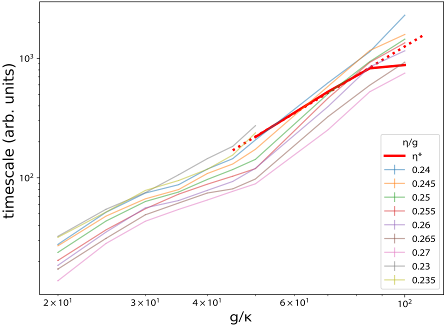


Blinking timescale remains determined by atomic timescale

Photon-blockade breakdown

the thermodynamic limit

The proof of the phase transition is the existence of a thermodynamic limit (both the photon scale and the timescale become macroscopic, independent of microscopic timescales)

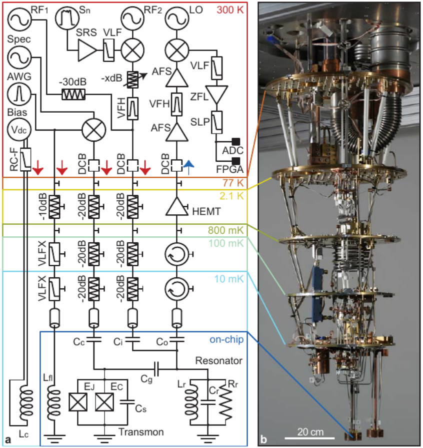


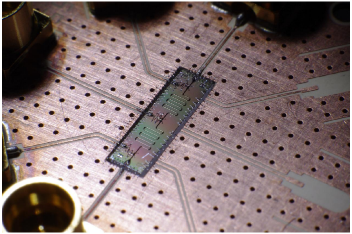
Thermodynamic limit is a strong-coupling limit

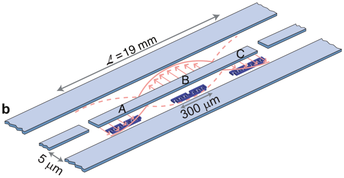
[Vukics, Dombi, Fink, Domokos, Quantum **3**:150 (2019)]

Photon-blockade breakdown

the experiment — Andreas Wallraff & Johannes Fink @ ETH Zürich & IST Austria







1-3 artificial atoms capacitively coupled to mode of stripline resonator

Prototype: Cooper-pair box ⇒ several more advanced designs

Circuit Quantum Electrodynamics (CCQED)

Basically microwave electronic devices, but

- superconductivity ($T \sim$ mK)
- low input powers ($P_{\text{in}} \sim$ aW…fW)

$\Big\} \Rightarrow$ quantum behaviour

Linearity broken by Josephson-junction

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Positives when compared to cavity QED

- Larger light–matter coupling strength
- Stripline resonators easily cascaded
  - scalability for quantum-information processing
  - photonic Bose–Hubbard model
- Artifical atoms are immobile
  - No Doppler-effect, no inhomogeneous broadening

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Negatives ″

- No microscopic theory – J–C model used phenomenologically
- Artificial atoms not identical (only with $\sim 10^{-(3-4)}$ precision)

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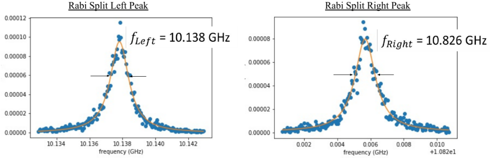
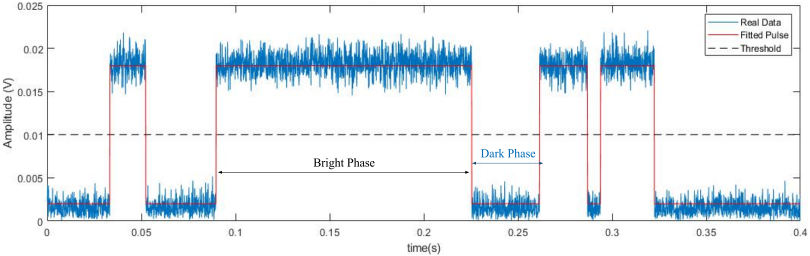
Photon-blockade breakdown

the experiment — Johannes Fink @ IST Austria

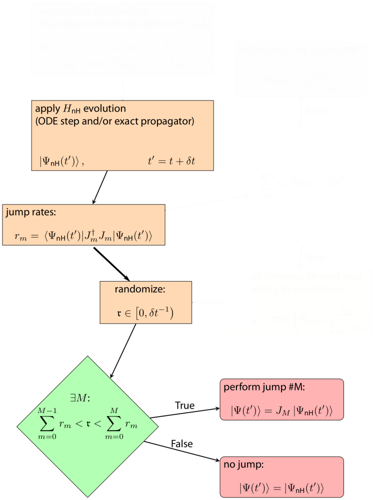


$$\omega_{ge} = 2\pi \times 6.0879 \text{ GHz}$$
$$T_1 = 26.291 \ \mu\text{s}$$
$$T_2 = 496.029 \text{ ns}$$
$$g = 2\pi \times 343.9331 \text{ MHz}$$



[Fink, Dombi, Vukics, Wallraff, and Domokos, Phys. Rev. X **7**:011012 (2017)]

The Monte-Carlo wave function method



- Probability distro (amplitudes) conditioned on observation results.
- Possible to resolve individual quantum jumps, yet simulate long times
- Evolve with non-Hermitian Hamiltonian to describe continuous information leak to the environment
- From time to time (important problem: when? how often?) probe for jumps

[Kornyik and Vukics, Comp. Phys. Comm. **238**:88-101 (2019)]

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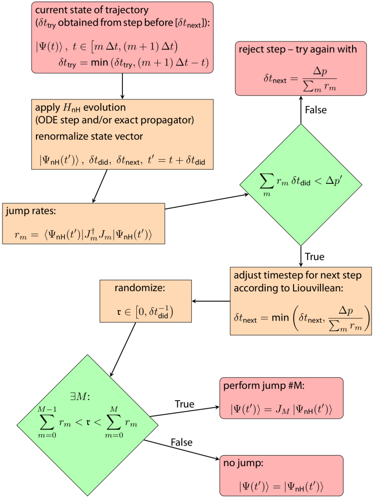

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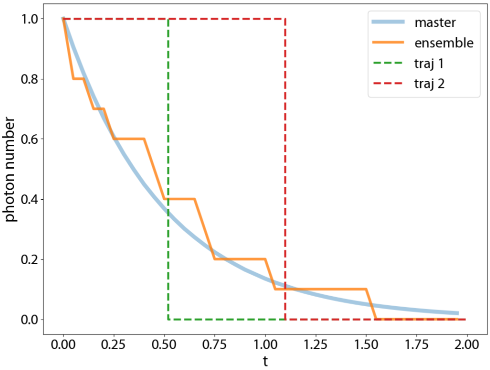
MCWF method

some typical and some weird trajectories

initial state: $|1\rangle$

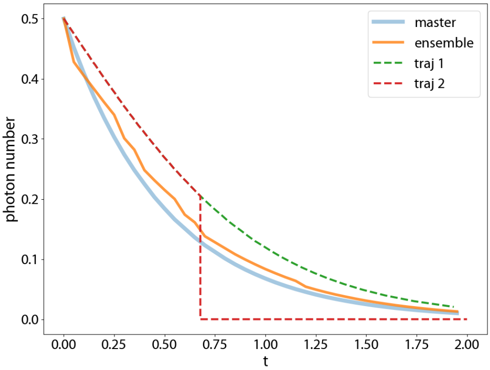


Ensemble average converges to solution of quantum Master equation

MCWF method

some typical and some weird trajectories

initial state: $(|0\rangle + |1\rangle)/\sqrt{2}$

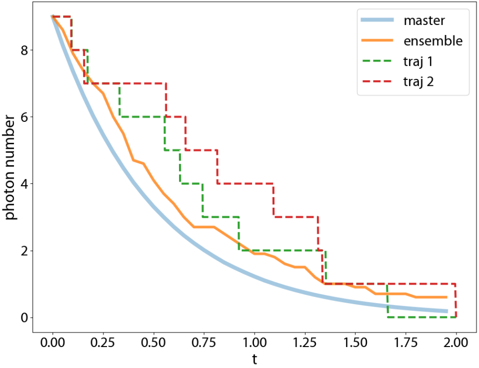


On half of the trajectories, no jump ever occurs

MCWF method

some typical and some weird trajectories

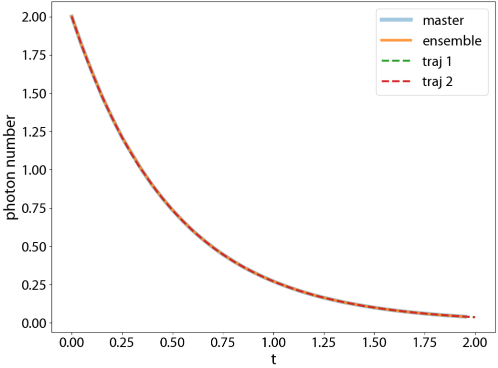
initial state: $|9\rangle$



MCWF method

some typical and some weird trajectories

initial state: $|\alpha\rangle$ coherent state

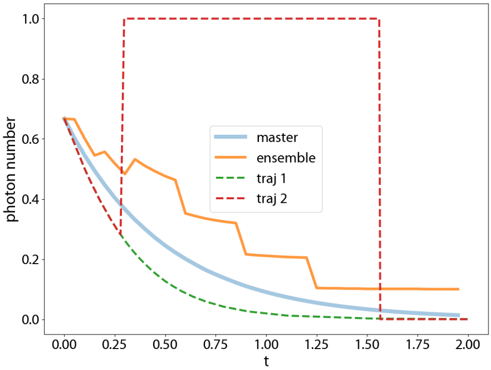


Photon escape leaves the state unaffected

MCWF method

some typical and some weird trajectories

initial state: $|0\rangle + \epsilon\,|2\rangle$



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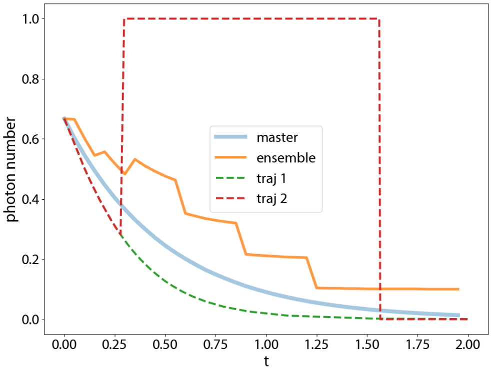

Photon escape (very rare event) increases the number of photons!

Simulation tool: C++QED

a C++ framework for simulating fully quantum open dynamics

- Developed since 2006
- Defines elementary physical systems as building blocks of complex systems
- Uses C++ compile-time algorithms to optimize runtime
- Uses adaptive MCWF algorithm governed by maximal allowed jump probability
- Since spring 2020: update to C++17 in progress

`http://github.com/vukics/cppqed`

For more details cf. also my talk from last year's GPU Day

Computational infrastructure

Virtual computer cluster defined within the Wigner Cloud

8×8 VCPUs with SLURM workload manager

For the PBB thermodynamic limit project
— ca. half a year data-collection campaign

Acknowledgement

Andreas Wallraff@ETH

Johannes Fink@IST

Peter Domokos@Wigner

Miklós Kornyik@Wigner

András Dombi@Wigner

National Research, Development and Innovation Office
Hungary

PROGRAM
FINANCED FROM
THE NRDI FUND
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