Electron-photonic transport: Interplay of shape and interactions

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Experimental impetus. . .

nature physics

LETTERS

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Collective non-perturbative coupling of 2D electrons with high-quality-factor terahertz cavity photons

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The collective interaction of electrons with light in a high-quality-factor cavity is expected to reveal new quantum phenomena[1–7] and find applications in quantum-enabled technologies[8,9]. However, combining a long electronic coherence time, a large dipole moment, and a high quality-factor has proved difficult[10–13]. Here, we achieved these conditions simultaneously in a two-dimensional electron gas in a high-quality-factor terahertz cavity in a magnetic field. The vacuum Rabi splitting of cyclotron resonance exhibited a square-root dependence on the electron density, evidencing collective interaction. This splitting extended even where the detuning is larger than the resonance frequency. Furthermore, we observed a peak shift due to the normally negligible diamagnetic term in the Hamiltonian. Finally, the high-quality-factor cavity suppressed superradiant cyclotron resonance decay, revealing a narrow intrinsic linewidth of 5.6 GHz. High-quality-factor terahertz cavities will enable new experiments bridging the traditional disciplines of condensed-matter physics and cavity-based quantum optics.

nonresonant matter decay rate, which is usually the decoherence rate in the case of solids. Strong coupling is achieved when the splitting, $2g$, is much larger than the linewidth, $(\kappa+\gamma)/2$, and ultrastrong coupling is achieved when g becomes a considerable fraction of ω_0. The two standard figures of merit to measure the coupling strength are $C \equiv 4g^2/(\kappa\gamma)$ and g/ω_0; here, C is called the cooperativity parameter[18], which is also the determining factor for the onset of optical bistability through resonant absorption saturation[20]. To maximize C and g/ω_0, one should construct a cavity QED set-up that combines a large dipole moment (that is, large g), a small decoherence rate (that is, small γ), a large cavity Q factor (that is, small κ), and a small resonance frequency ω_0.

Group III–V semiconductor quantum wells (QWs) provide one of the cleanest and most tunable solid-state environments with quantum-designable optical properties. Microcavity QW-exciton-polaritons represent a landmark realization of a strongly coupled light–condensed-matter system that exhibits a rich variety of coherent many-body phenomena[21]. However, the large values of ω_0 and relatively small dipole moments for interband transitions make it

Experimental impetus...

PHYSICAL REVIEW X **6**, 021014 (2016)

Cavity Photons as a Probe for Charge Relaxation Resistance and Photon Emission in a Quantum Dot Coupled to Normal and Superconducting Continua

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Microwave cavities have been widely used to investigate the behavior of closed few-level systems. Here, we show that they also represent a powerful probe for the dynamics of charge transfer between a discrete electronic level and fermionic continua. We have combined experiment and theory for a carbon nanotube quantum dot coupled to normal metal and superconducting contacts. In equilibrium conditions, where our device behaves as an effective quantum dot-normal metal junction, we approach a universal photon dissipation regime governed by a quantum charge relaxation effect. We observe how photon dissipation is modified when the dot admittance turns from capacitive to inductive. When the fermionic reservoirs are voltage biased, the dot can even cause photon emission due to inelastic tunneling to/from a Bardeen-Cooper-Schrieffer peak in the density of states of the superconducting contact. We can model these numerous effects quantitatively in terms of the charge susceptibility of the quantum dot circuit. This validates an approach that could be used to study a wide class of mesoscopic QED devices.

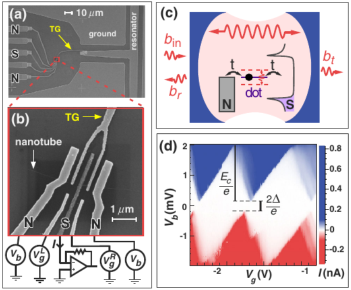


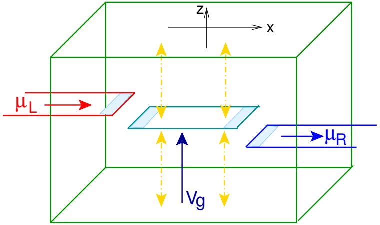
FIG. 1. Panels (a) and (b): Scanning electron micrograph of the microwave resonator and the quantum dot circuit. Panel (c): Principle of our setup. The dot level is tunnel coupled to the N and S reservoirs and modulated by the cavity electric field. Panel (d): Current through the S contact versus the effective gate voltage V_g and the bias voltage V_b.

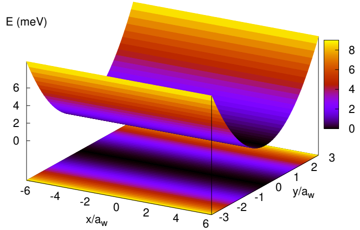
Coupling to external fermionic reservoirs...,

Gate voltage excitation, $V_{\rm rf}$,...,

Photon pumping, $\langle N_\gamma \rangle \sim 120$ ...

Want to model





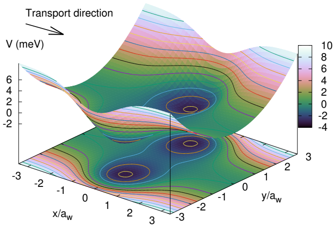
Short quantum GaAs wire in a 3D photon cavity

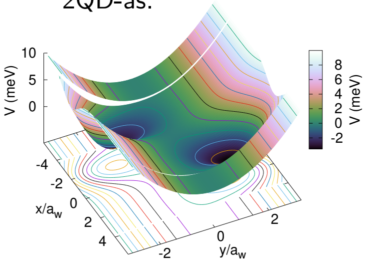
Weak coupling $g^{\mathrm{L,R}} a_w^{3/2} \sim 0.124 \times (\mathrm{state} - \mathrm{dependence})$ meV

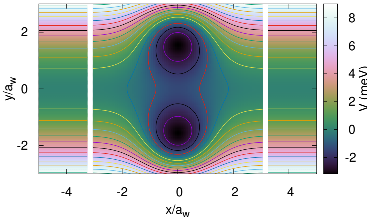
($a_w \approx 23.8$ nm, $B_{\mathrm{ext}} = 0.1$ T)

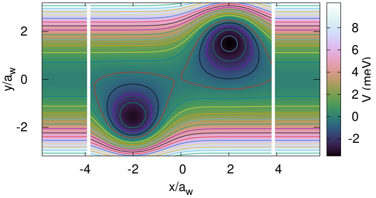
or. . .

2QD-par. 2QD-as.









Time-dependent transport

$\Downarrow$

Time scales

$\Downarrow$

Transient – intermediate – long time – steady state

$\Uparrow$

Density operator

$\Uparrow$

Open Systems

Equation of motion

Liouville-von Neumann

$$\partial_t W = \mathcal{L}W, \quad \mathcal{L}W = -\frac{i}{\hbar}[H, W]$$

$$H = H_\mathrm{S} + H_\mathrm{LR} + H_\mathrm{T}(t), \quad H_\mathrm{S} = H_\mathrm{e} + H_\mathrm{EM}$$

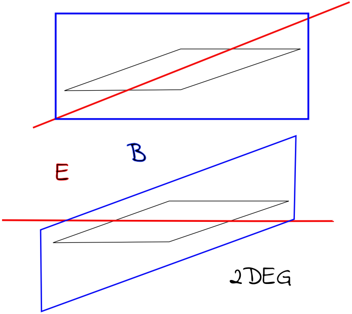
$$H_\mathrm{S} = \int d^2r \psi^\dagger(\mathbf{r}) \left\{ \frac{\pi^2}{2m^*} + V(\mathbf{r}) \right\} \psi(\mathbf{r}) + H_\mathrm{Coul} + \hbar\omega a^\dagger a$$
$$+ \frac{1}{c} \int d^2r \, \mathbf{j}(\mathbf{r}) \cdot \mathbf{A}_\gamma + \frac{e^2}{2m^* c^2} \int d^2r \, \rho(\mathbf{r}) A_\gamma^2$$

$$\boldsymbol{\pi} = \left(\mathbf{p} + \frac{e}{c}\mathbf{A}_\mathrm{ext} \right), \quad \rho = \psi^\dagger \psi, \quad \mathbf{j} = -\frac{e}{2m^*} \left\{ \psi^\dagger \left(\boldsymbol{\pi}\psi \right) + \left(\boldsymbol{\pi}^* \psi^\dagger \right) \psi \right\}$$

Stepwise exact numerical diagonalization, (Fortschritte der Physik 61, 305 (2013))

Quantized cavity field

$$\mathbf{A}(\mathbf{r}) = \begin{pmatrix} \hat{\mathbf{e}}_x \\ \hat{\mathbf{e}}_y \end{pmatrix} \mathcal{A}\left\{a + a^\dagger\right\} \begin{pmatrix} \cos\left(\frac{\pi y}{a_c}\right) \\ \cos\left(\frac{\pi x}{a_c}\right) \end{pmatrix} \cos\left(\frac{\pi z}{d_c}\right), \qquad \begin{matrix} \mathrm{TE}_{011}, & x\text{-pol.} \\ \mathrm{TE}_{101}, & y\text{-pol.} \end{matrix}$$



y-polarization

x-polarization

Projection on the central system

Reduced density operator

$$\rho_{\rm S}(t) = \mathcal{P}W(t) = \rho_{\rm LR}(0)\mathrm{Tr}_{\rm LR}\{W(t)\}$$

Liouville-von Neumann $\Rightarrow$ Nakajima-Zwanzig equation (to 2nd order in $H_{\rm T}$), non-Markovian time-evolution

$$\partial_t \rho_{\rm S}(t) = \mathcal{L}_{\rm S}\rho_{\rm S}(t) + \int_0^t dt' K[t, t-t'; \rho_{\rm S}(t')]$$

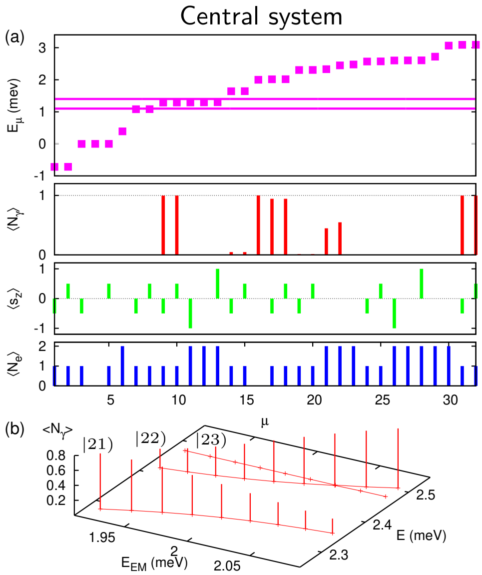
with

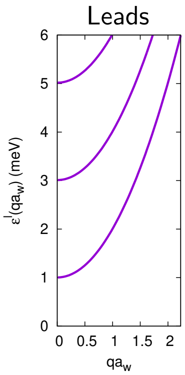
$$K[t, s; \rho_{\rm S}(t')] = \mathrm{Tr}_{\rm LR}\left\{\left[H_{\rm T}(t), \left[U(s)H_{\rm T}(t')U^+(s), U_{\rm S}(s)\rho_{\rm S}(t')U_{\rm S}^+(s)\rho_{\rm L}\rho_{\rm R}\right]\right]\right\}$$

and

$$H_{\rm T}(t) = \sum_{i,l}\chi(t)\int dq\ \left\{T_{qi}^l c_{ql}^\dagger d_i + (T_{qi}^l)^* d_i^\dagger c_{ql}\right\}$$

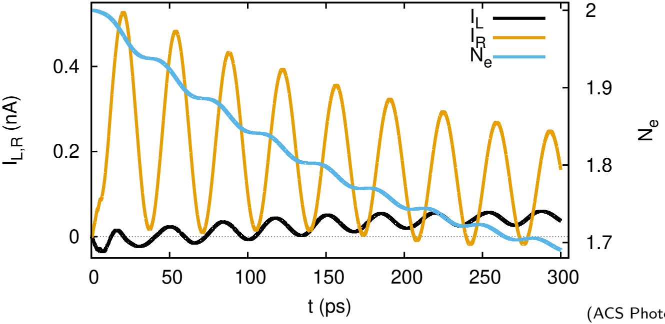
Spectra of closed systems, y-polarized photons, 2QD-par.



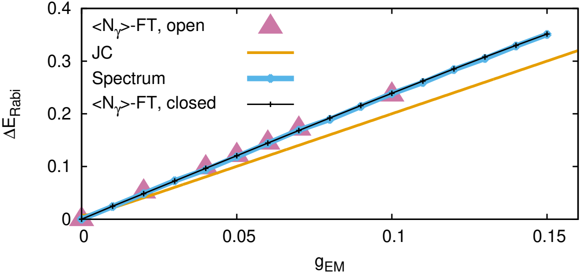


$$\hbar\omega = 2.0 \text{ meV}$$
$$g_{\mathrm{EM}} = 0.05 \text{ meV}$$
$$B = 0.1 \text{ T}$$
$$a_w = 23.8 \text{ nm}$$
$$V_g = 0.1 \text{ mV}$$

2 electrons initially, entangled

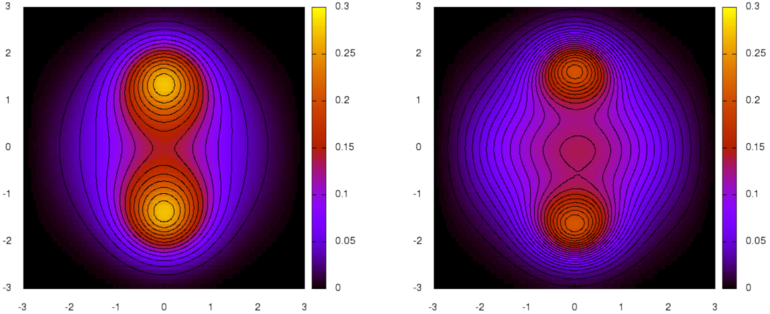


(ACS Photonics 2015, 2, 930 (2015))



Charge density oscillations

$t = 10$ ps $t = 60$ ps



Variable probability in contact area $\rightarrow$ variable current

Long time evolution

(No memory - Markovian evolution) in many-body Fock space (dim $\sim N$)

$\Downarrow$

Liouville space of transitions (dim $\sim N^2$), (Comp. Phys. Commun. 220, 81 (2017))

$$\partial_t \rho_{\mathrm{S}}^{\mathrm{vec}} = \mathcal{L} \rho_{\mathrm{S}}^{\mathrm{vec}}$$

with solution

$$\rho_{\mathrm{S}}^{\mathrm{vec}}(t) = \left[\mathcal{U} \exp\left(\mathcal{L}_{\mathrm{diag}} t\right) \mathcal{V}\right] \rho_{\mathrm{S}}^{\mathrm{vec}}(0)$$

where

$$\mathcal{L}\mathcal{V} = \mathcal{V}\mathcal{L}_{\mathrm{diag}}, \quad \mathcal{U}\mathcal{L} = \mathcal{L}_{\mathrm{diag}}\mathcal{U}, \quad \mathcal{U}\mathcal{V} = \mathcal{V}\mathcal{U} = \mathcal{I}$$

Steady state can be found as the eigenvalue 0 of

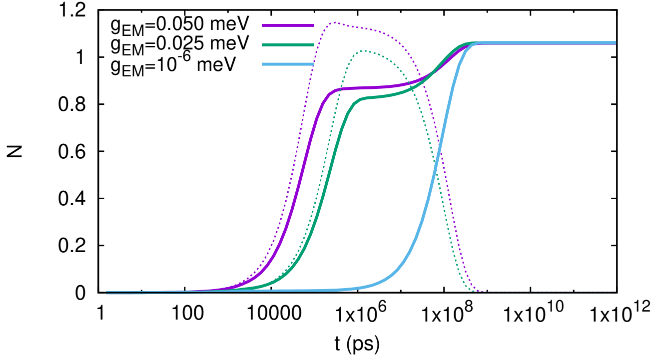
$$0 = \mathcal{L} \rho_{\mathrm{S}}^{\mathrm{vec}}$$

but we use

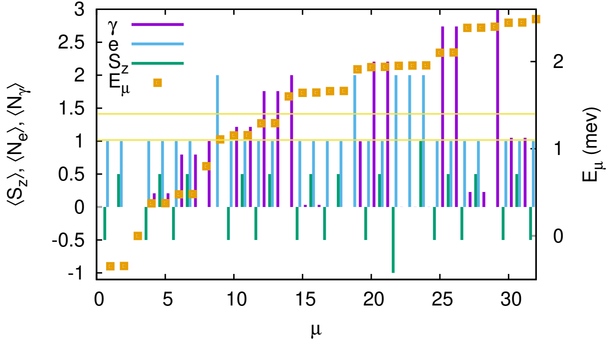
$$\lim_{t\to\infty} \left[\mathcal{U} \exp\left(\mathcal{L}_{\mathrm{diag}} t\right) \mathcal{V}\right] \rho_{\mathrm{S}}^{\mathrm{vec}}(0)$$

Radiative and nonradiative transitions

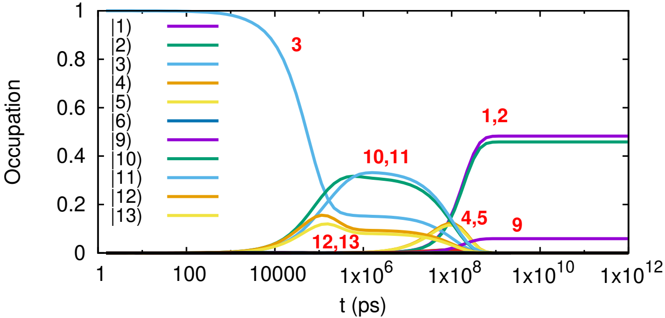
Long time evolution (Annalen der Physik 529, 1600177 (2017))



No dots, slow charging into Coulomb-blockade regime
Rabi-resonance $\hbar\omega = 0.80$ meV,



γ
e
S_z
E_μ
$\langle S_z\rangle$, $\langle N_e\rangle$, $\langle N_\gamma\rangle$
E_μ (mev)
μ

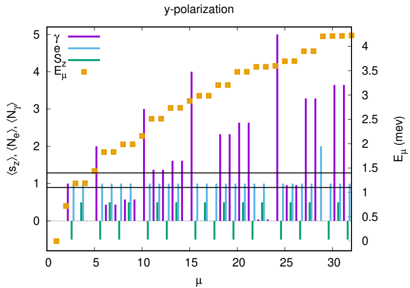


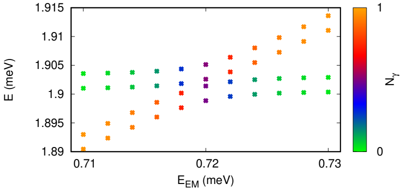
|1)
|2)
|3)
|4)
|5)
|6)
|9)
|10)
|11)
|12)
|13)
3
1,2
10,11
4,5
9
12,13
Occupation
t (ps)

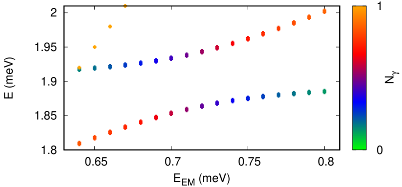
Two types of Rabi resonances, 2QD-par.

(Annalen der Physik 530, 1700334 (2018)), (Physics Letters A 382, 1672 (2018))

$\hbar\omega = 0.72$ meV







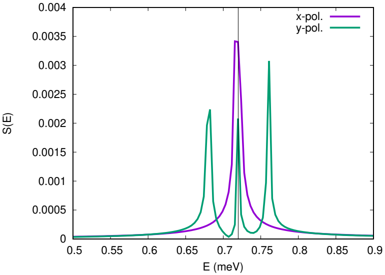
Symmetry selection

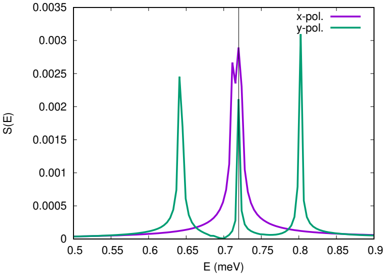
Diamagnetic int. $\sim \rho A^2$, x-pol.

Paramagnetic int. $\sim \mathbf{j}\cdot\mathbf{A}$, y-pol.

Ground state electroluminescence

(Annalen der Physik 530, 1700334 (2018))

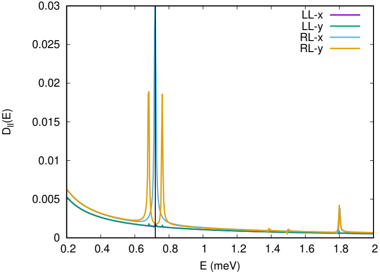




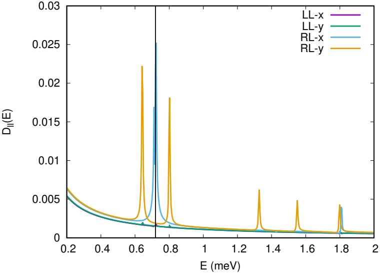
Spectral density, emitted radiation, Mollow triplet...
(Also the more complex 2e ground state)

Current correlations

$g_{\mathrm{EM}} = 0.05$ meV



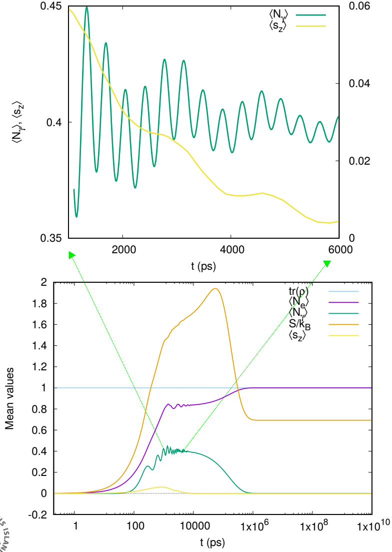
$g_{\mathrm{EM}} = 0.10$ meV

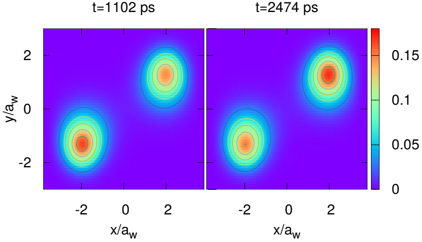


Current noise power spectra for ground state electroluminescence
No Coulomb blockade, $1/f\ldots$

(Physics Letters A 382, 1672 (2018))

Coexisting spin and Rabi-oscillations, 2QD-as

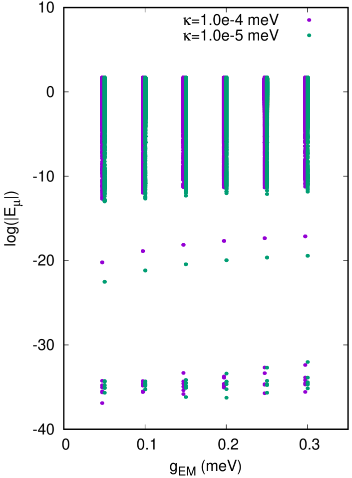




Interdot Rabi resonance of 1e ground states,
$\hbar\omega = 0.343$ meV

(Beilstein Journal of Nanotechnology 10, 606 (2019))

Exact matrix elements for e-EM-interactions, 2QD-as.



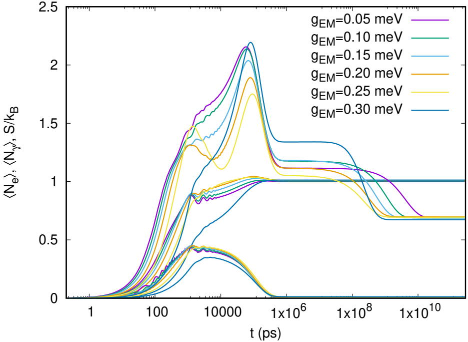
Complex Liouvillian spectrum

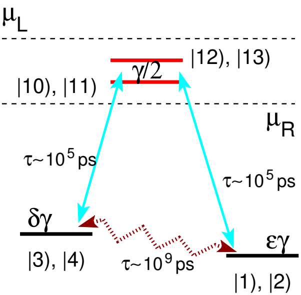
Extreme slow interdot ground state transition out of resonance, $\hbar\omega = 1.75$ meV

(Annalen der Physik 531, 1900306 (2019))

Purcel effect seen in transport current (Nanomaterials 9, 1023 (2019))

Slow interdot ground state transition





$\hbar\omega = 1.75$ meV

(Annalen der Physik 531, 1900306 (2019))

Summary

- Time-dependent many-body approach
- Central system: Exact interactions
- Shape – geometry
- Weak coupling to external reservoirs
- All time scales
- Effective parallelism, CPU-GPU
- Review: *Entropy* **21**, 731 (2019)

- Andrei Manolescu (RU)
- Valeriu Moldoveanu (NIMP)
- Nzar Rauf Abdullah (US, KUST)
- Chi-Shung Tang (NUU)
- Shi-Sheng Goan (NTU)

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