Probing the energy reactance with adiabatically driven quantum dots

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What is the energy reactance? Why is it important?

When is it manifested?

How to probe it ?

What is the energy reactance? Why is it important?

When is it manifested?

How to probe it ?

María Florencia Ludovico, Liliana Arrachea, Michael Moskalets, and David Sánchez.
Phys. Rev. B 97, 041416(R), 2018

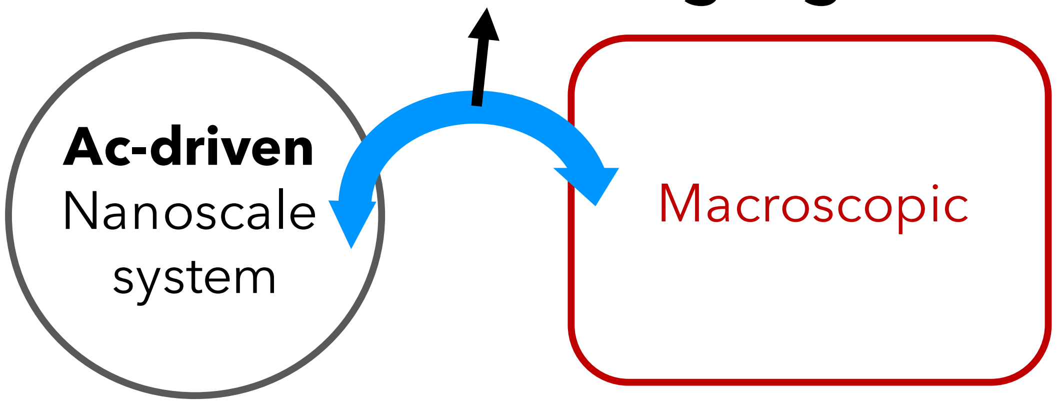
Experimental activity → on-demand quantum transport in the **time domain**
(quantum capacitors, single particles emitters, generation of levitons)*

Study and **control** of time-dependent charge and energy flows

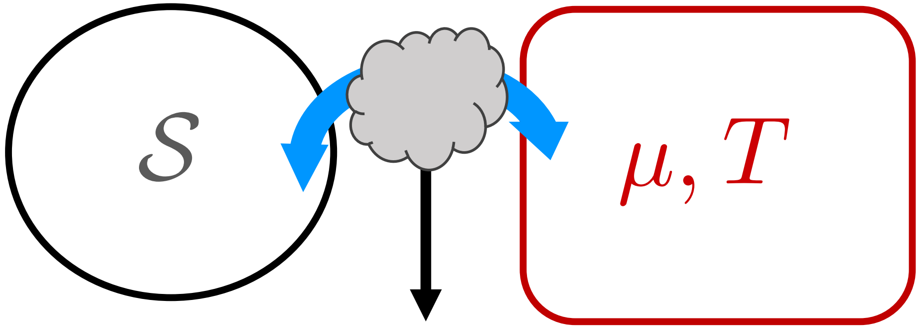
Nanoscale systems → Energy transport **beyond** the **usual thermodynamics**

What is the proper definition of heat in the time domain??

Role of the tunneling region



*Science 316, 1169–1172 (2007); Nature, 502, 659–663 (2013); Nature 477, 439–442 (2011); Phys. Rev. Lett. 111, 216807 (2013)



Energy current $\dot{U}(t)$

Particle current $\dot{N}(t)$

Energy reactance

$$\dot{U}_{\mathcal{T}}(t)$$

Disregarded in classical thermodynamics

Manifested in time-dependent transport only

$$\overline{\dot{U}_{\mathcal{T}}(t)} = 0$$

Conservation laws

$$\dot{N}(t) = -\dot{N}_{\mathcal{S}}(t)$$

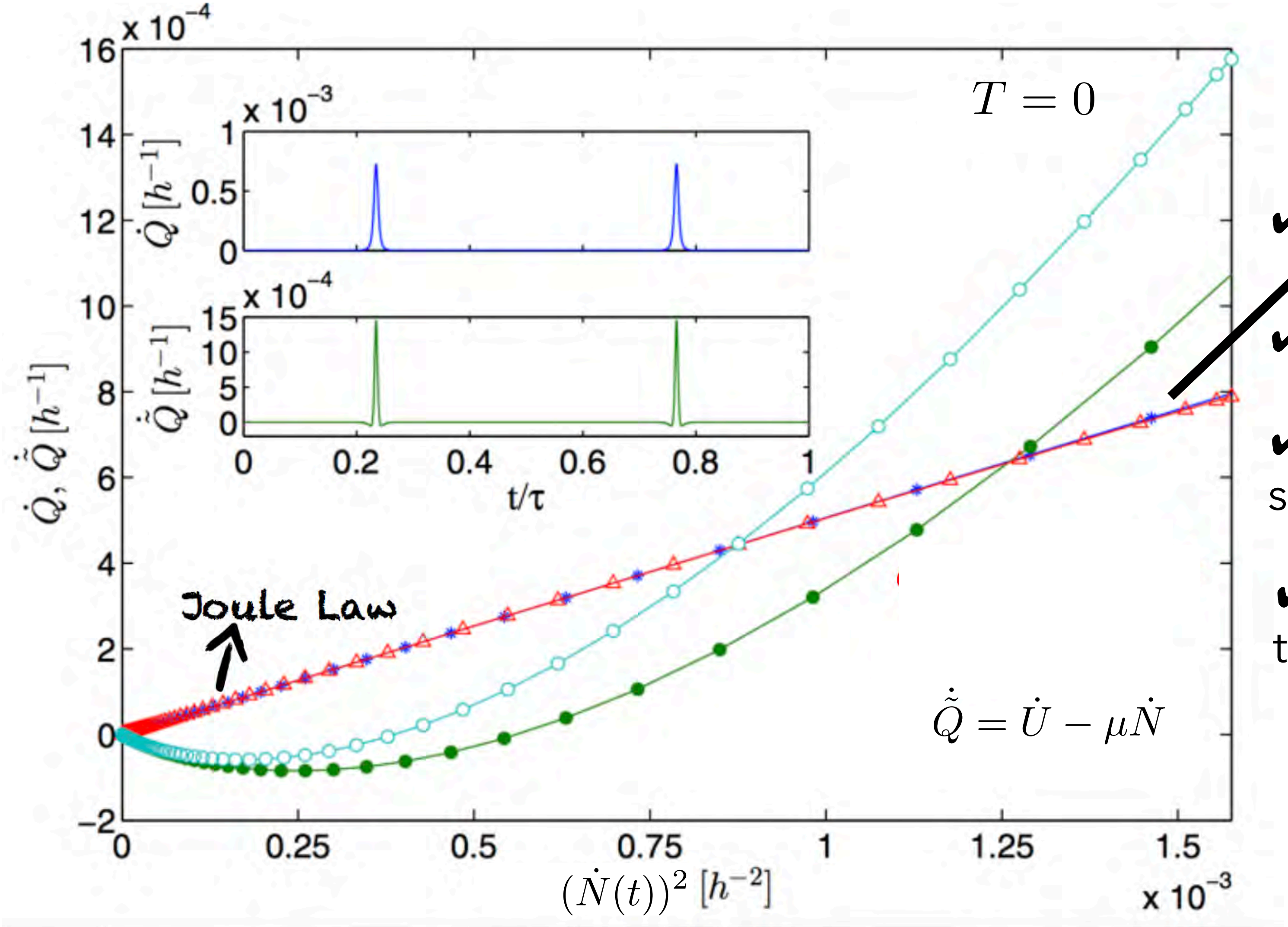
$$\dot{U}(t) + \dot{U}_{\mathcal{T}}(t) = -\dot{U}_{\mathcal{S}}(t)$$

M. F. Ludovico, J. S. Lim, M. Moskalets, L. Arrachea and D. Sánchez. Physical Review B 89, 161306 (2014)

Adiabatic regime

Small driving frequency Ω

Time-resolved heat current $\dot{Q}(t) = \dot{U}(t) + \frac{\dot{U}_T(t)}{2} - \mu \dot{N}(t)$



Full agreement with the laws of thermodynamics

✔ $\dot{Q}(t) = R_q[\dot{N}(t)]^2$ Büttiker resistance $R_q = \frac{h}{2e^2}$

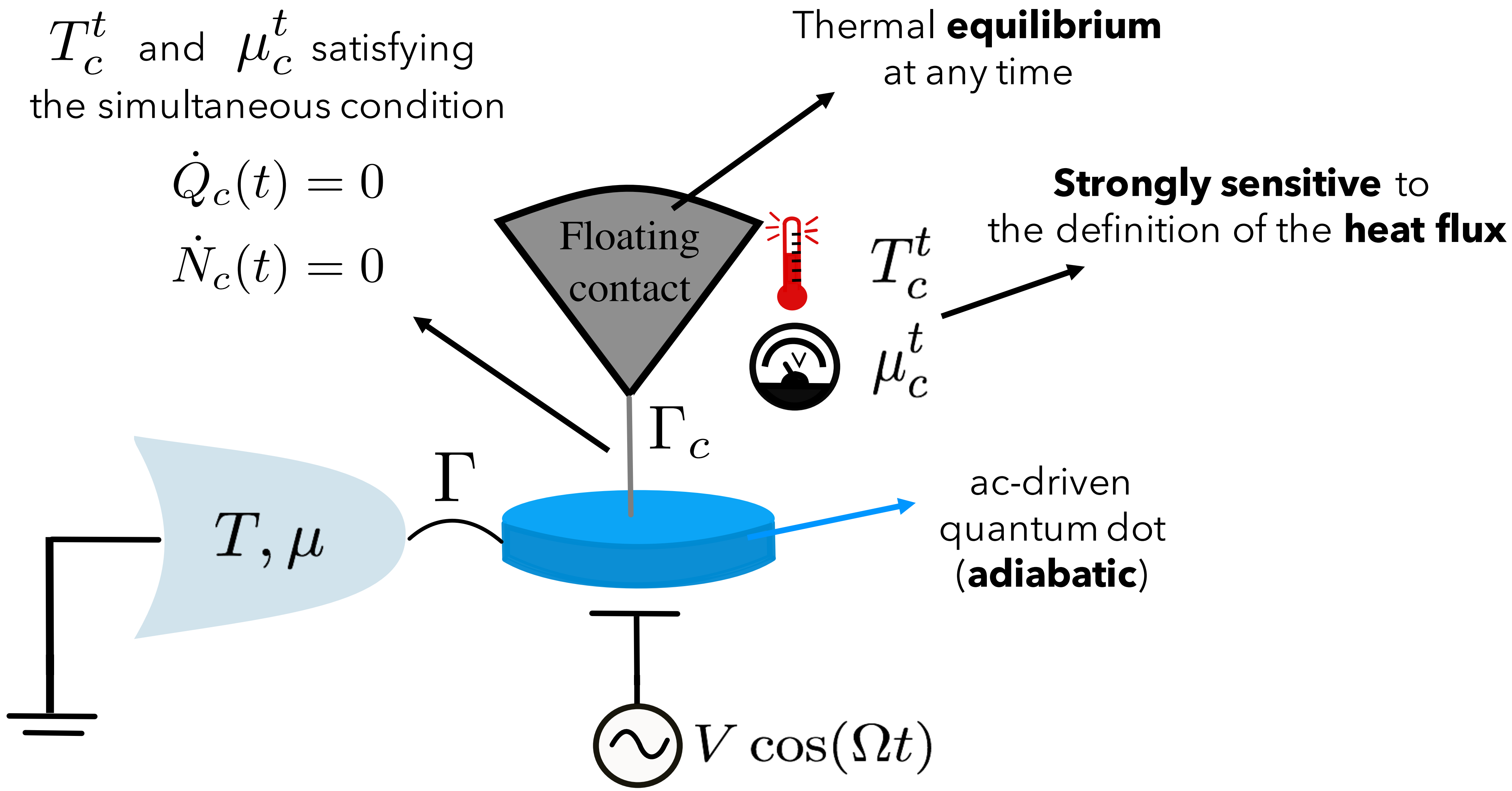
✔ Leads to $\dot{S} \geq 0$

✔ Reconciles Green function and scattering matrix formalisms

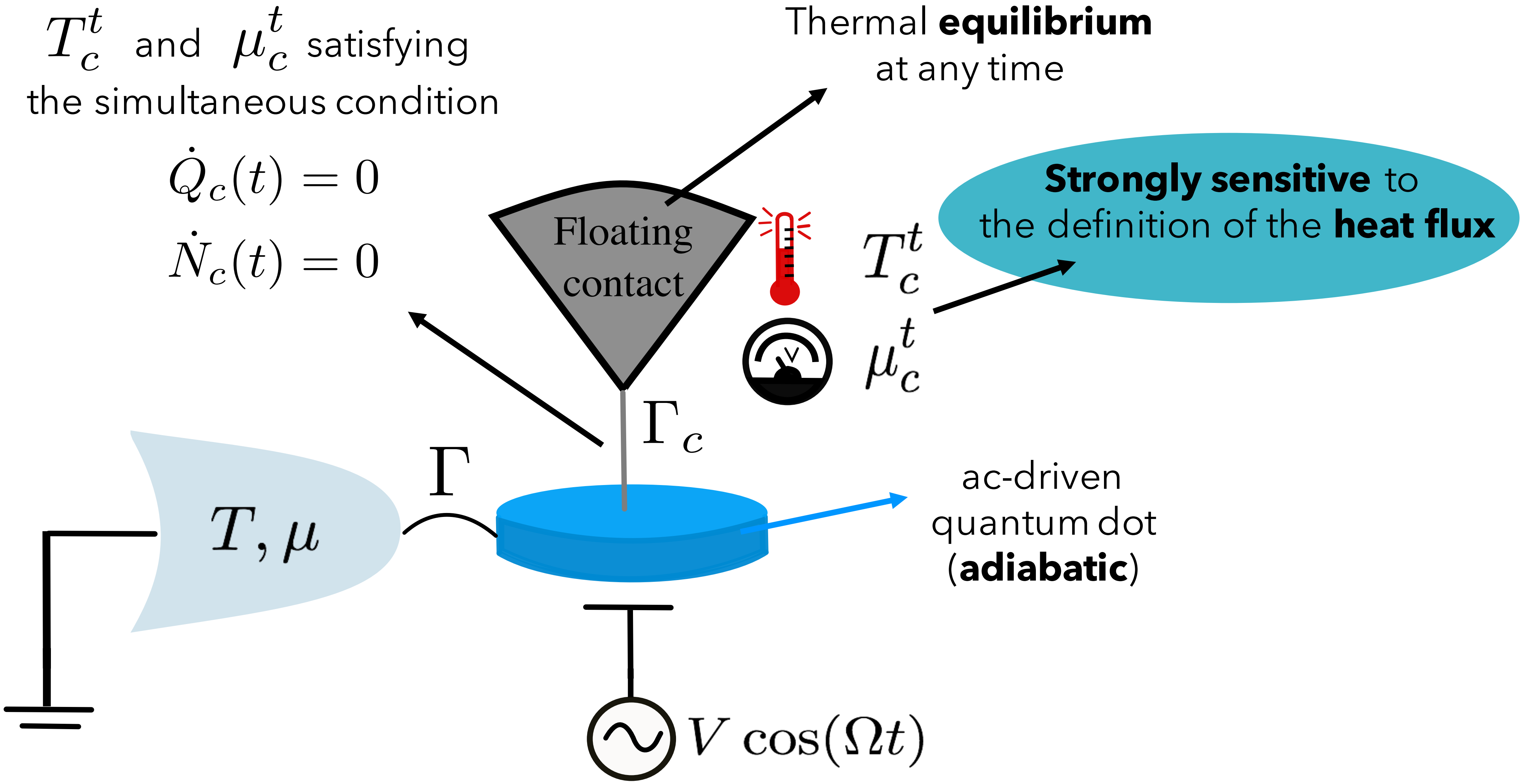
✔ Correct frequency parity properties of the response functions

- Physical Review B 89, 161306 (2014)
- Physical Review B 94, 035436 (2016)
- Entropy 18, 419 (2016)
- G. Rosselló et.al. Physical Review B 92, 115402 (2015)

Probing the energy reactance



T_c^t and μ_c^t satisfying
the simultaneous condition
$\dot{Q}_c(t) = 0$
$\dot{N}_c(t) = 0$
Thermal **equilibrium**
at any time
Floating
contact
Strongly sensitive to
the definition of the **heat flux**
T_c^t
μ_c^t
Γ_c
Γ
T, μ
ac-driven
quantum dot
(**adiabatic**)
$V \cos(\Omega t)$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With the energy reactance

$$\dot{Q}_c(t) = \dot{U}_c(t) + \frac{\dot{U}_{\mathcal{T}_c}(t)}{2} - \mu_c^t \dot{N}_c(t)$$

Universal!

$$\boxed{T_c^t = T \qquad \mu_c^t = \mu + \frac{\hbar}{\Gamma} e\dot{V}}$$

Without the energy reactance

$$\dot{Q}_c(t) = \dot{U}_c(t) + \cancel{\frac{\dot{U}_{\mathcal{T}_c}(t)}{2}} - \mu_c^t \dot{N}_c(t)$$

T_c^t and μ_c^t follow a non-universal time-dependent pattern

Temperature and chemical potential of the floating contact

Deviations $\begin{cases} \delta T_c^t = T_c^t - T \\ \delta\mu_c^t = \mu_c^t - \mu \end{cases} \longrightarrow$

Adiabatic regime

$\delta T_c^t, \delta\mu_c^t \propto \hbar\Omega$

Small!

Linear response

Fluxes: $J(t) = (\dot{N}_c(t), \dot{Q}_c(t))$

Affinities: $X^t = (\delta T_c^t, \delta\mu_c^t, \hbar\Omega)$

$$J_i(t) = \sum_{j=1}^{3} \Lambda_{ij}(t) X_j^t$$

Electrical conductance

Seebeck

Pumping of charge

$$\begin{pmatrix} \Lambda_{11} & \Lambda_{12} & \Lambda_{13} \\ \Lambda_{21} & \Lambda_{22} & \Lambda_{23} \end{pmatrix}$$

Peltier

Thermal conductance

Pumping of heat

Onsager relation
$\Lambda_{21} = T\Lambda_{12}$

Transmission

dc-transport

$$\Lambda_{ij}(t) = \begin{cases} \int \frac{(\varepsilon-\mu)^{i+j-2}}{hT^{(j-1)}} \mathcal{T}(t,\varepsilon)\, \partial_\varepsilon f\, d\varepsilon & \text{if } \boxed{j \neq 3} \\ -\frac{\Gamma_c \dot{V}}{(\Gamma+\Gamma_c)\hbar\Omega} \int (\varepsilon-\mu)^{i-1} \rho_f(t,\varepsilon)\, \partial_\varepsilon f\, d\varepsilon & \text{if } \boxed{j = 3} \end{cases}$$

Frozen density of states

Pumping

$$J(t) = \left(\dot{N}_c(t), \dot{Q}_c(t)\right) = 0 \longrightarrow \begin{cases} \delta T_c^t \\ \delta \mu_c^t \end{cases}$$

$$\boxed{\begin{aligned} \delta\mu_c^t &= \frac{\Lambda_{12}\Lambda_{23} - \Lambda_{13}\Lambda_{22}}{\det \mathbf{\Lambda}'} \hbar\Omega \\ \delta T_c^t &= \frac{\Lambda_{13}\Lambda_{21} - \Lambda_{11}\Lambda_{23}}{\det \mathbf{\Lambda}'} \hbar\Omega \end{aligned}}$$

$$\det \mathbf{\Lambda}' = \Lambda_{11}\Lambda_{22} - \Lambda_{12}\Lambda_{21}$$

Relations for the coefficients

$$i)\ \Lambda_{13}\Lambda_{21} - \Lambda_{11}\Lambda_{23} = 0$$

$$ii)\ \Lambda_{j3} = -\Lambda_{j1}\frac{\dot{V}}{\Gamma\Omega}$$

$$j = 1, 2$$

$$\delta T_c^t = 0 \qquad \delta\mu_c^t = \frac{\hbar}{\Gamma} e\dot{V}$$

Independent of Γ_c and T

Without the energy reactance

$$\boxed{\dot{\tilde{Q}}_c(t) = \dot{U}_c(t) - \mu_c^t \dot{N}_c(t)}$$

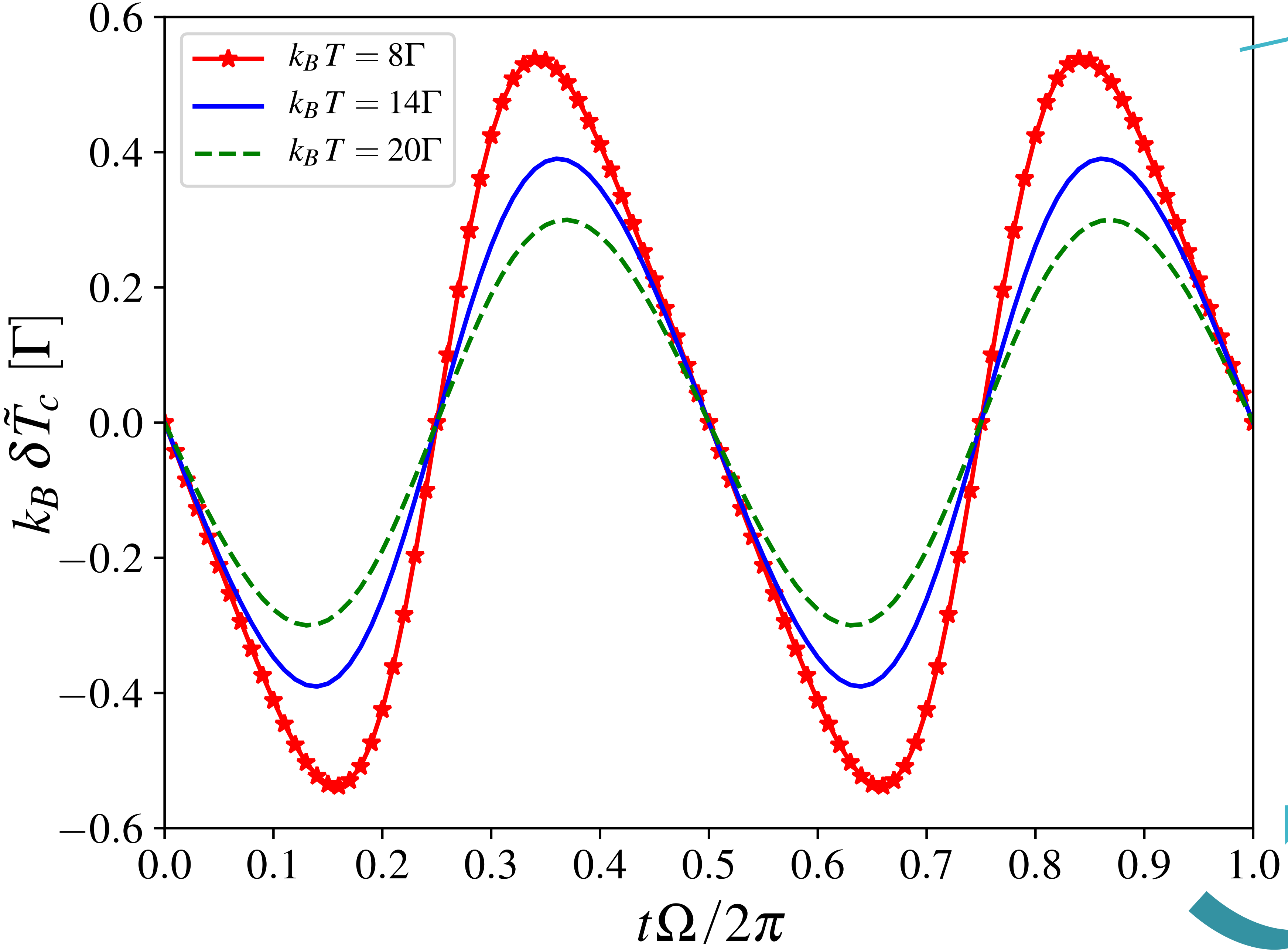
We replace

$$\Lambda_{2j}(t) \rightarrow \tilde{\Lambda}_{2j}(t)$$

$$j = 1, 2, 3$$

$$\left[\begin{array}{l} \tilde{\Lambda}_{22}(t) = \Lambda_{22}(t) \\ \tilde{\Lambda}_{21}(t) = \Lambda_{21}(t) \\ \tilde{\Lambda}_{23}(t) = -\dfrac{\Gamma_c \dot{V} V}{(\Gamma + \Gamma_c)\hbar\Omega}\displaystyle\int d\varepsilon \frac{df}{d\varepsilon}\rho_f(t,\varepsilon) \end{array}\right.$$

Do not change dc-transport



For $T \sim 100\mathrm{mK}$

$\delta\tilde{T}_c^t \sim 10\mathrm{mK}$

$\Omega \simeq 0.1\mathrm{GHz}$

Changes on the nanosecond scale

Fast thermometry:

- L. B. Wang, et. al. Appl. Phys. Lett. 112,013105 (2018)
- M. Zgirski, et. al. arXiv: 1704.04762

Summary

- We showed that the behavior of the time-resolved chemical potential and temperature of the floating contact is strongly sensitive on the definition of the instantaneous heat flux

  the definition of the heat flux can be verified by measuring T_c^t and μ_c^t

- If the energy reactance is taken into account, then the temperature of the floating contact $T_c^t = T$, while its chemical potential evolves as $\mu_c^t = \mu + \frac{\hbar}{\Gamma} e\dot{V}$

- If the energy reactance is not taken into account, these two quantities follow a non-universal time-dependent pattern.

This work was done with:

- **Liliana Arrachea**
- **Michael Moskalets**
- **David Sánchez**

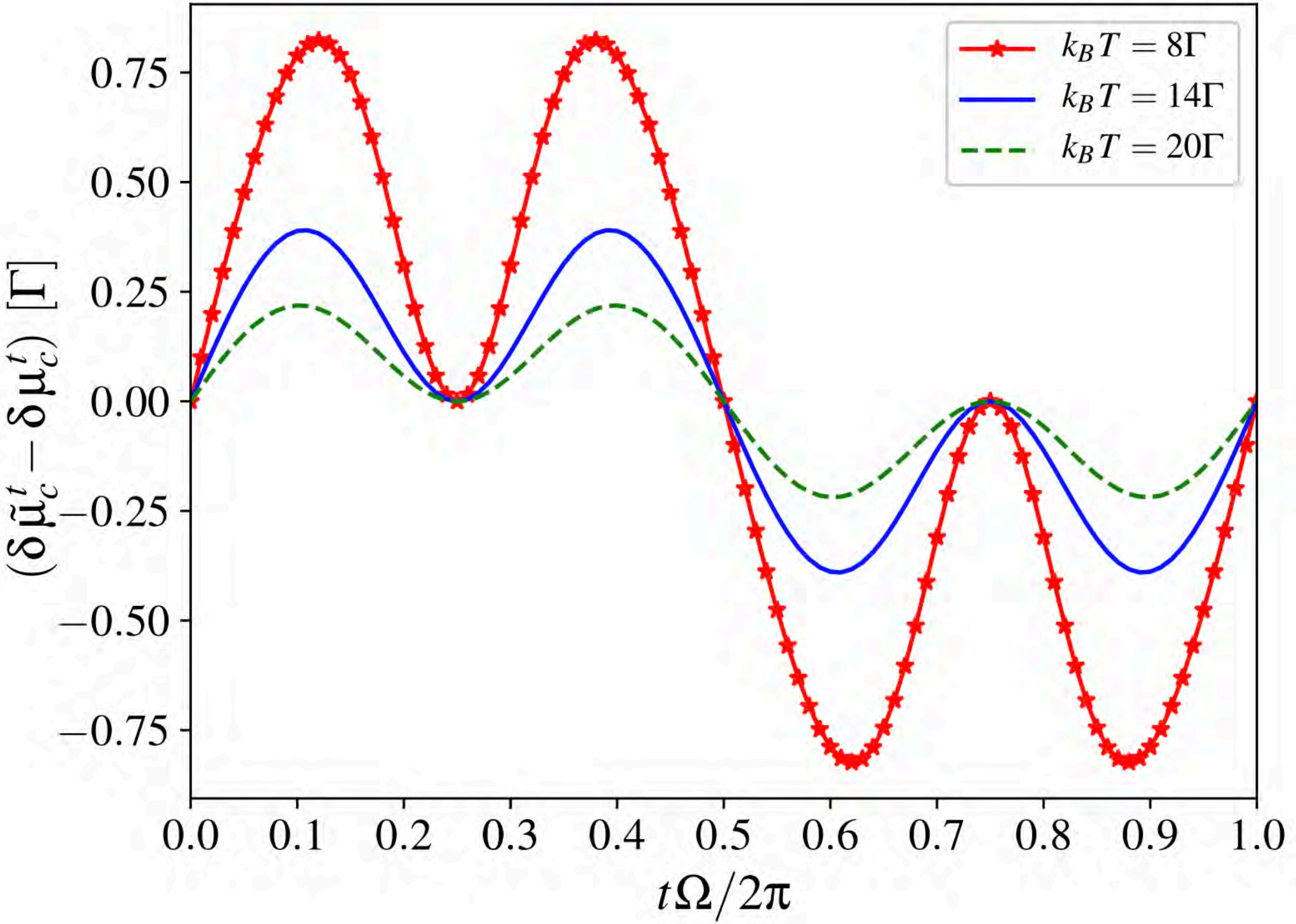
I have done this work at

ICAS

UNIVERSIDAD NACIONAL DE SAN MARTÍN

ICTP The Abdus Salam International Centre for Theoretical Physics

Thank you for your attention!!



$k_B T = 8\Gamma$
$k_B T = 14\Gamma$
$k_B T = 20\Gamma$
$(\delta\tilde{\mu}_c^t - \delta\mu_c^t)$ [Γ]
$t\Omega/2\pi$
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0