Collective dissipation: Dynamic and thermodynamic effects

Gonzalo Manzano
Gian Luca Giorgi
Fernando Galve
Albert Cabot
Bruno Bellomo
Roberta Zambrini

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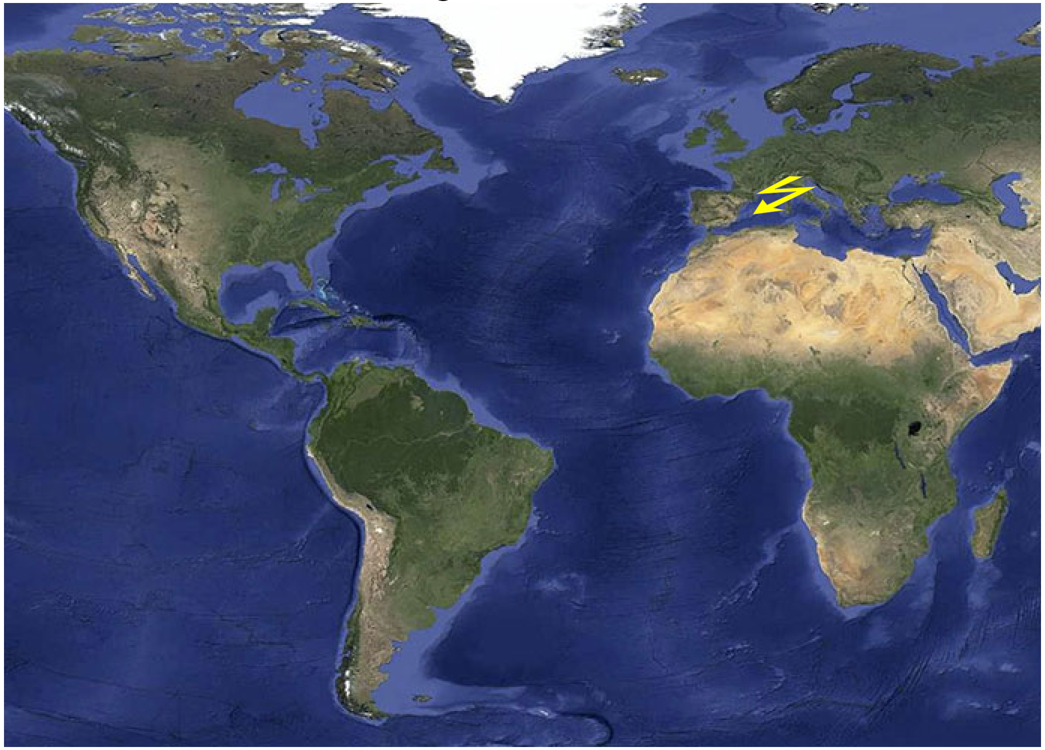
Collective dissipation:
Dynamic and thermodynamic effects



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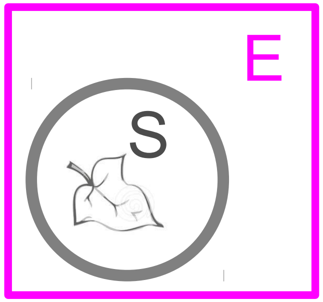


S+E unitary evolution

- System weakly interacting with large environment
- Factorized state at initial time
- Born, Markov, secular approximations:

Reduced dynamics of the system 

LGKS master equation

$$\frac{d\rho_t}{dt} = -i[\hat{H}, \rho_t] + \sum_k \mathcal{D}[\hat{L}_k]\rho_t$$

$$\mathcal{D}[\hat{L}]\rho \equiv \hat{L}\rho\hat{L}^\dagger - \frac{1}{2}\left(\hat{L}^\dagger\hat{L}\rho + \rho\hat{L}^\dagger\hat{L}\right)$$

G. Lindblad, Commun. Math. Phys. 48, 119 (1976), V. Gorini, A. Kossakowski, and E.C.G. Sudarshan, J. Math. Phys. 17, 821 (1976)

OPEN (QUANTUM) SYSTEMS

(QUANTUM) THERMODYNAMICS

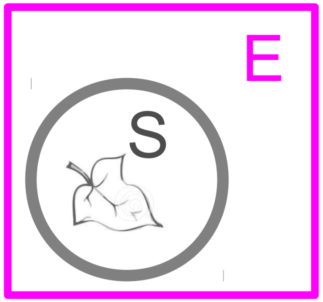
Consistency
Resource

Open quantum multipartite systems

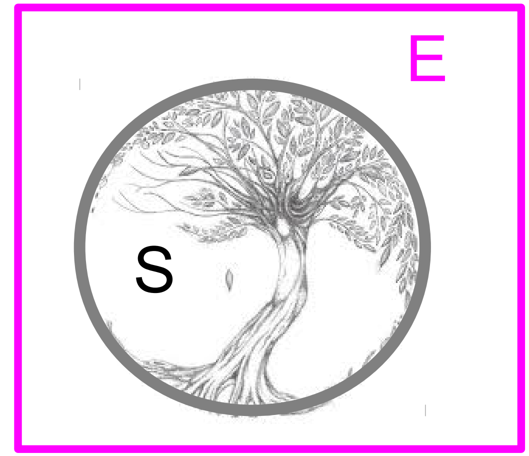
Collective dissipation
Superradiance and synchronization
Common and separate baths, local and global dissipation

Autonomous quantum refrigerators

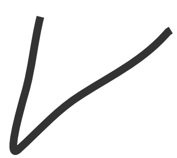
Performance with collective dissipation

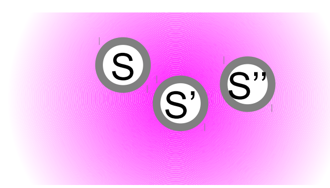


Multipartite systems

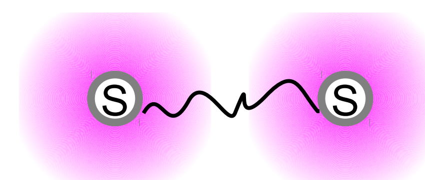


Independent systems and baths



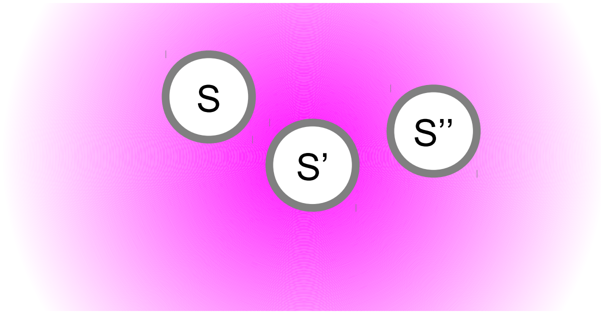


common environment



coupled systems
in separate baths

...



$$H_{int} = (A_S + A_{S'} + A_{S''})\, B_E$$

Superradiance

Dicke, Coherence in Spontaneous Radiation Processes, Phys. Rev. (1954); M Gross and S Haroche, Phys. Rep. 93, 301 (1982)

Decoherence free subspaces

Lidar, Whaley, Decoherence-Free Sub-spaces and Subsystems in Irreversible Quantum Dynamics, F. Benatti and R. Floreanini Eds. (Springer, 2003)

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Spontaneous synchronization

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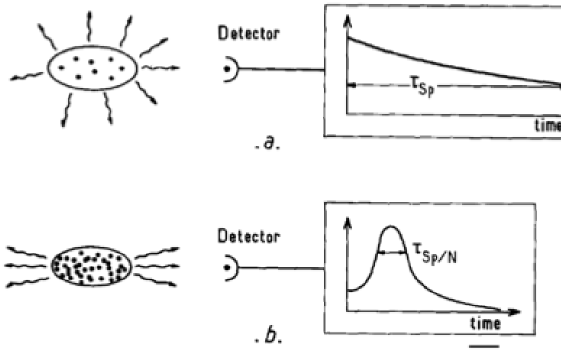


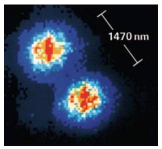
Gross, Haroche, Phys. Rep. (1982)
Raimond et al., PRL (**1982**)

PHYSICAL REVIEW VOLUME 93, NUMBER 1 JANUARY 1, 1954

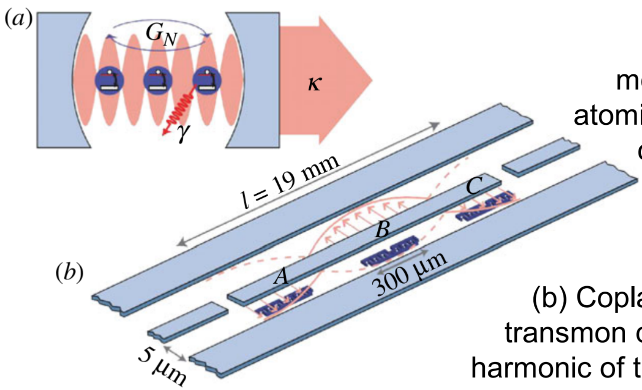
Coherence in Spontaneous Radiation Processes

R. H. DICKE
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

In the usual treatment of spontaneous radiation by a gas, the radiation process is calculated as though the **separate** molecules radiate independently of each other. […] This simplified picture overlooks the fact that all the molecules are interacting with a **common radiation** field and hence cannot be treated as independent. The model is wrong in principle and many of the results obtained from it are incorrect.



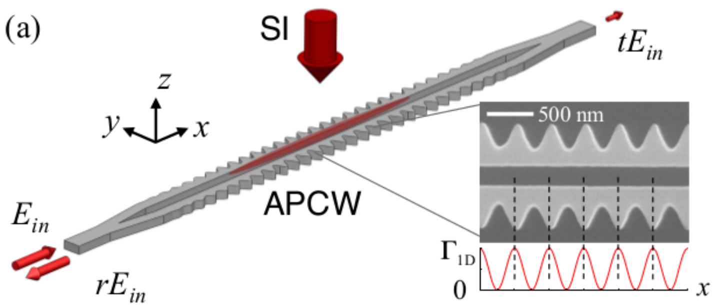
DeVoe, Brewer, Observation of Superradiant and Subradiant Spontaneous Emission of Two Trapped Ions, PRL 1996



(a) Three two-state atoms identically coupled to a cavity mode with photon decay rate κ, atomic energy relaxation rate γ and collective coupling strength G_N

(b) Coplanar waveguide resonator and transmon qubits A, B and C and the first harmonic of the standing wave electric field

Fink...Wallraff, Dressed collective qubit states and the Tavis–Cummings model in circuit QED, PRL (2009)



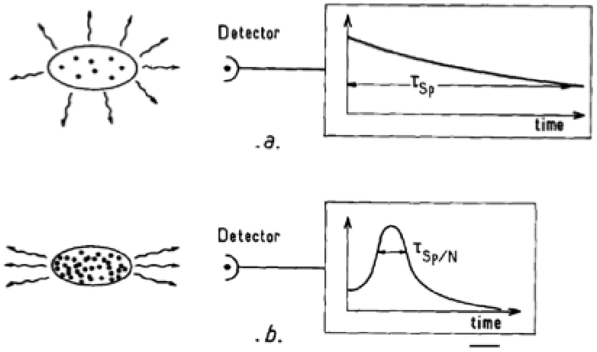
A side-illumination (SI) beam is reflected from an 'alligator' PC wave-guide to form a dipole trap (Cs atoms in red shaded region).

Goban, ...Painter, Kimble, SR for atoms trapped along a PC waveguide, PRL (2015)

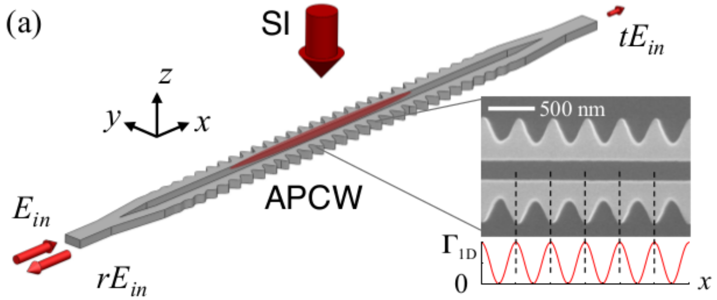
Collective dissipation of independent systems

Systems at *small* distances

Clouds of atoms at distance
<<
radiation wavelength

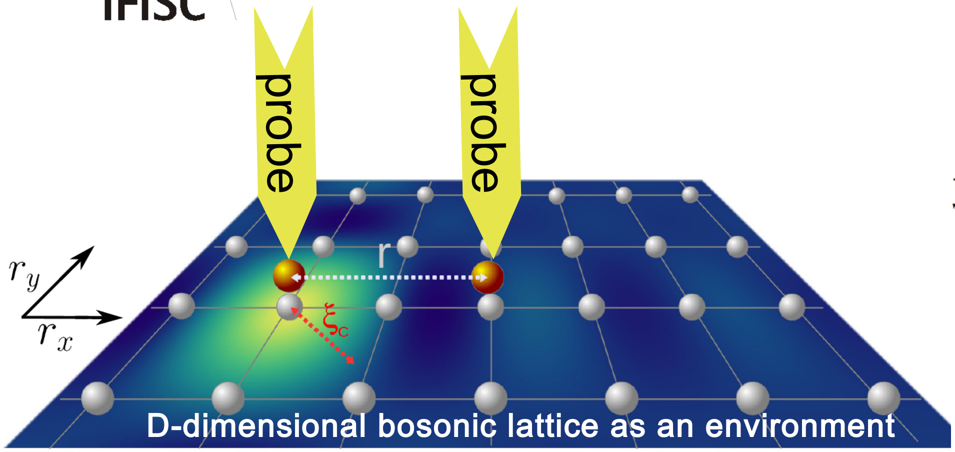


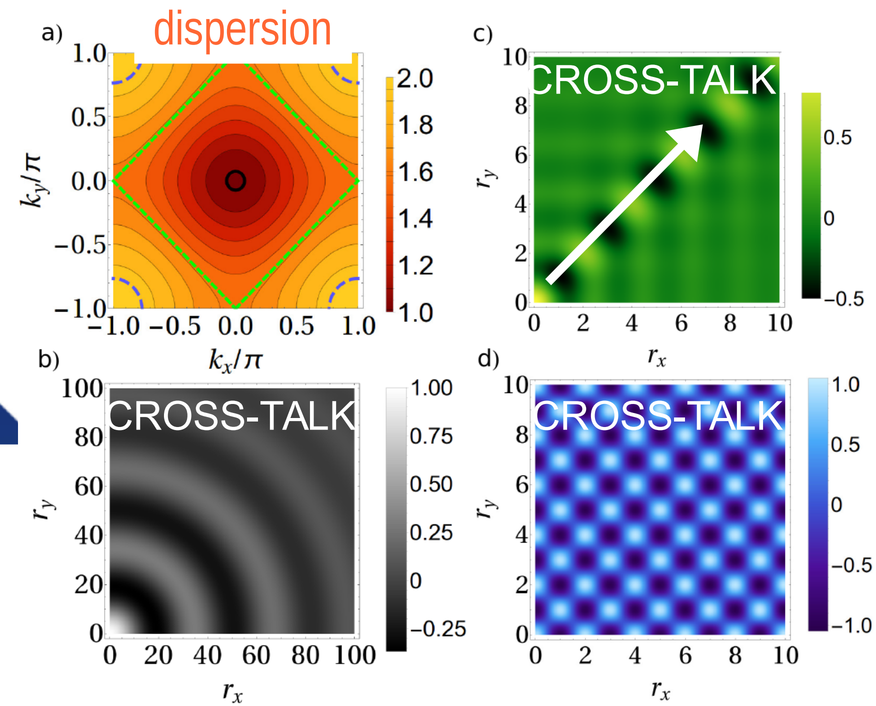
Systems at *large* distance but interacting with lattice environments



PRL 115, 063601 (2015)

Collective dissipation in lattice environments





b) Isotropic dispersion
(probes resonant to very small momenta)
Separate bath for distances $|\vec{r}| > 1/|\vec{k}_\Omega|$

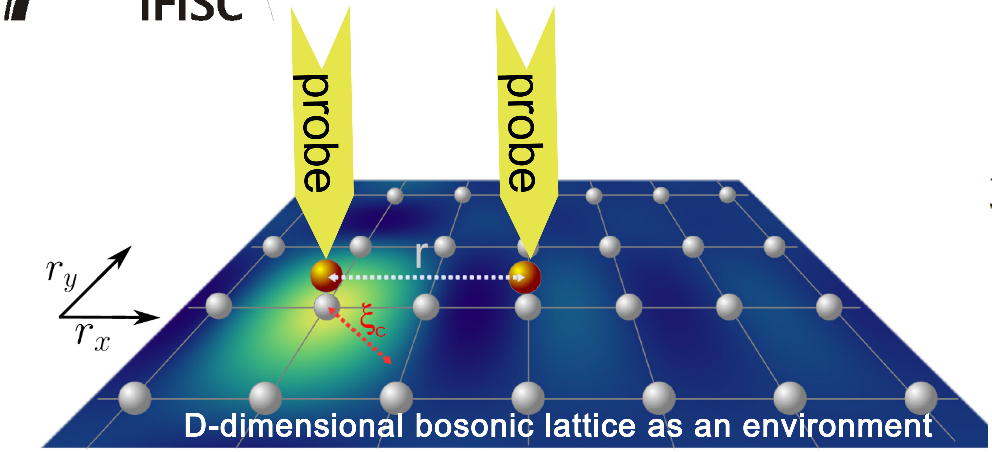
c) d) Anisotropic case
(probes resonant to LARGE momenta)
Collective dissipation even at large distances, in directions established by the symmetry of the crystal

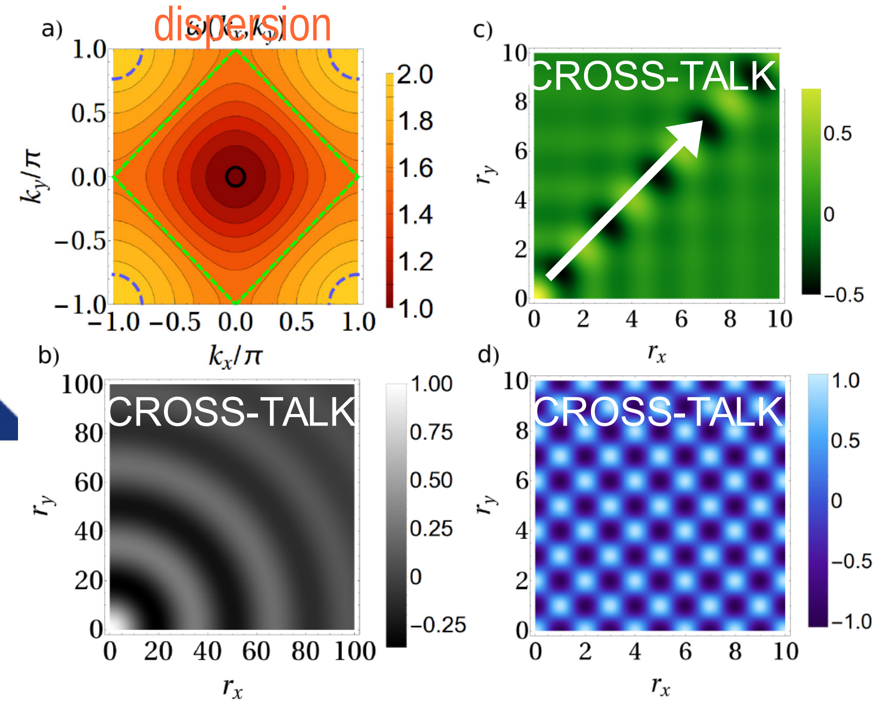
Cross talk: +1,-1→ **CB**, 0 → **SB**

$$\dot{\rho}_S = -i[H_S + H_{LS}, \rho_S] + \sum_{j,l=1,2} \Gamma_{j,l} (a_j \rho_S a_l^\dagger - \frac{1}{2}\{a_l^\dagger a_j, \rho_S\})$$

Galve, Mandarino, Paris, Benedetti, Zambrini, Scientific Reports (2017)

Collective dissipation in lattice environments





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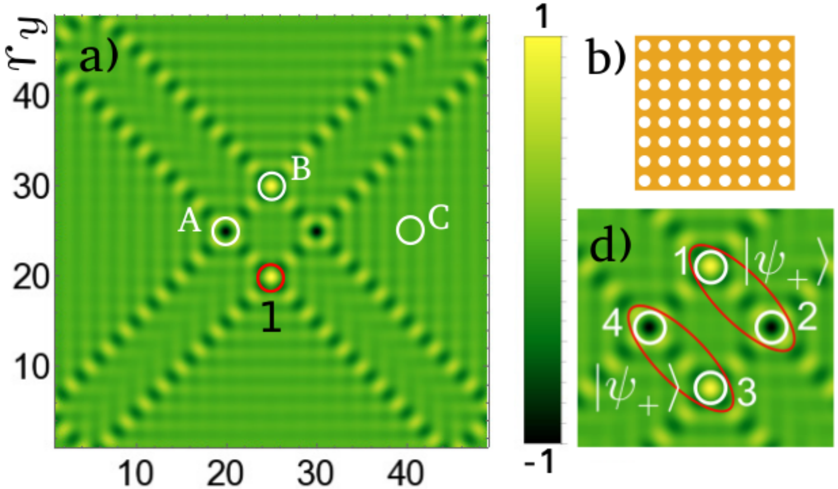
Galve, Mandarino, Paris, Benedetti, Zambrini, Scientific Reports (2017)

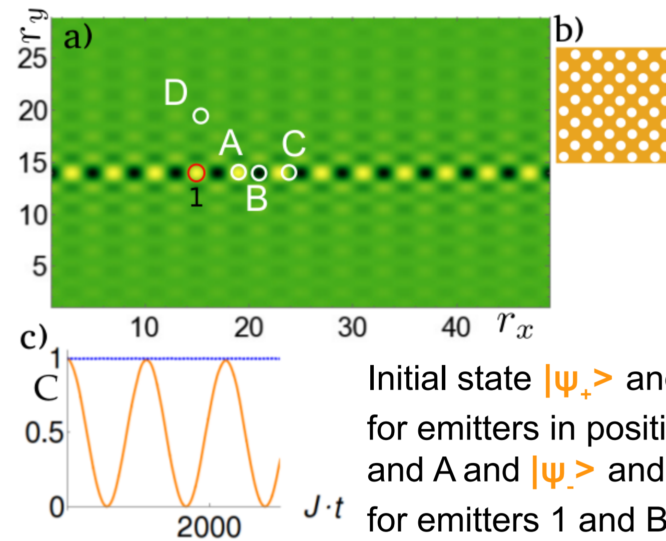
- **Either SB or CB effects depending on probes distance and frequency**
- **CB above bath spatial correlation distance**
- **Directional effects**

González-Tudela, Cirac, PRL (2017), Galve, Zambrini, Ann. Der Phys (2017); PRA (2018)

Completely subradiant multi-atom architectures through 2D photonic crystals

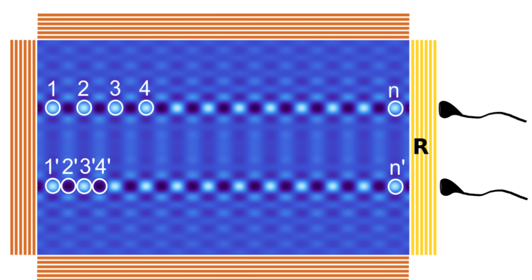
Cross-talk function Γ_{12} between emitter 1 and other at (r_x, r_y)





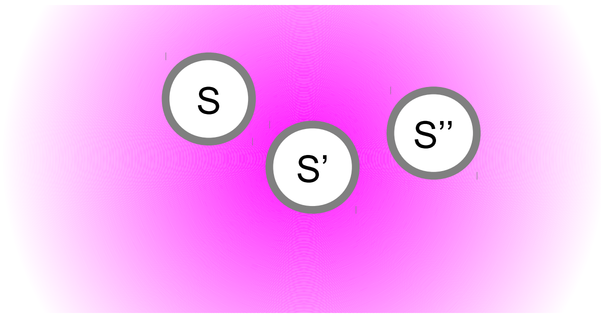
Initial state $|\psi_+\rangle$ and $|\psi_-\rangle$ for emitters in positions 1 and A and $|\psi_-\rangle$ and $|\psi_+\rangle$ for emitters 1 and B

Multi-1D waveguide array



González-Tudela, Cirac, PRL (2017), Galve, Zambrini, Ann. Der Phys (2018) and PRA (2018)

Common bath



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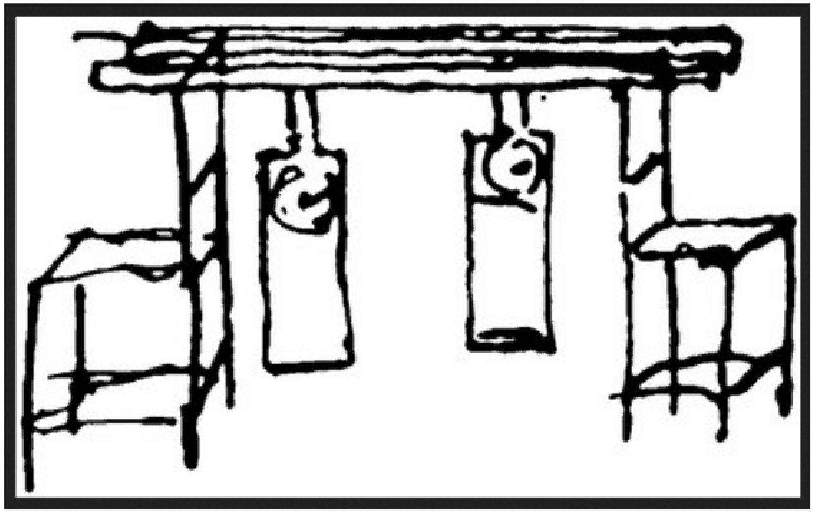
Spontaneous synchronization

Manzano, Galve, Giorgi, Hernandez-Garcia, Zambrini, Synchronization, quantum correlations and entanglement in oscillator networks, Sci.Reps. (2013).

- Dynamical process of **progressive** adjustment of rhythms of (periodic) **oscillators** due to their weak **interaction**.



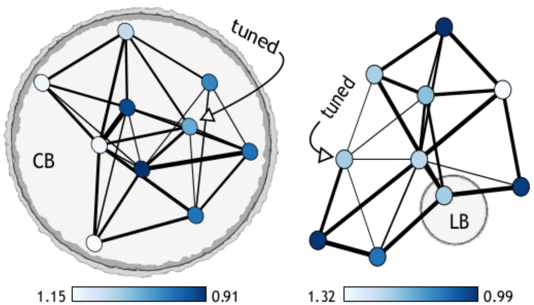
Sympathie des horloges, Huygens (1665)

72 metronomes. T.Ikeguchi (2014)

Pikovsky, Rosenblum, Kurths, *Synchronization: A Universal Concept in Nonlinear Sciences* (2001)

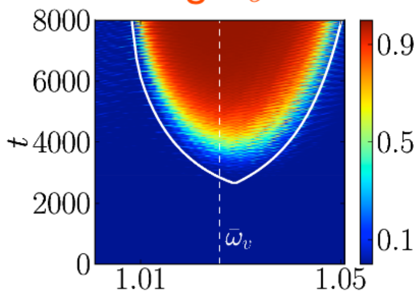
Dissipation can induce synchronization

CB $\Rightarrow$ one (less damped) normal mode governs the dynamics $\Rightarrow$ it fixes the oscillation frequency $\Rightarrow$ synchronization

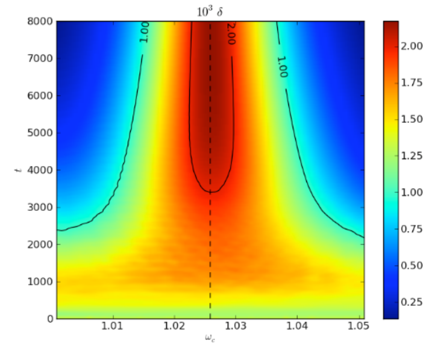


Sync in random network by tuning ω of one node

setting $\kappa_\sigma = 0$



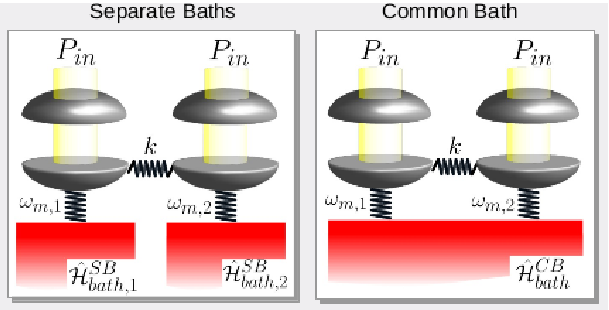
Averaged discord

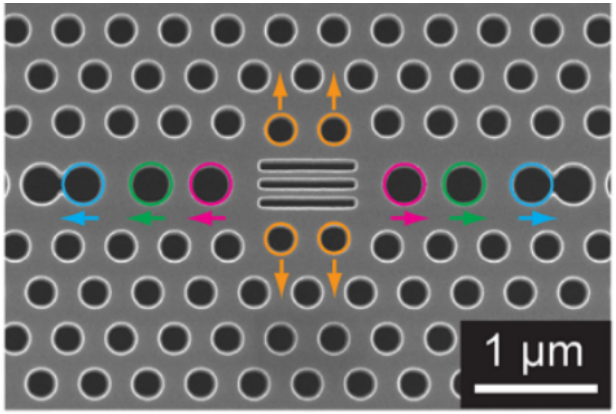


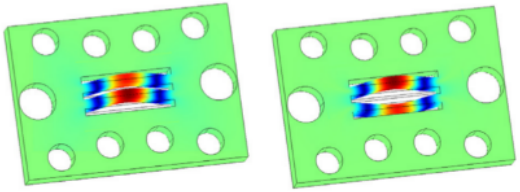
Robust quantum correlations

Manzano, Galve, Giorgi, Hernandez-Garcia, Zambrini, Scientific Reports 3, 1439 (2013)

CB effects in opto-mechanical systems

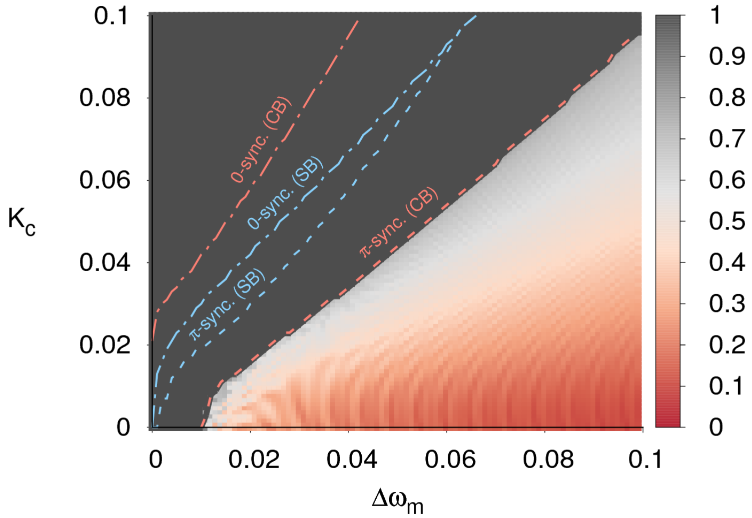






Sun, Zheng, Poot, Wong, Tang, Nano Lett. 12, 2299 (2012)
J. Zheng et al., Opt. Express 20,26486 (2012)

- CB enhances sync



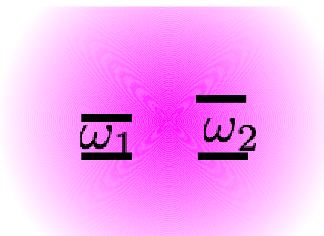
sync even in absence of mechanical direct coupling

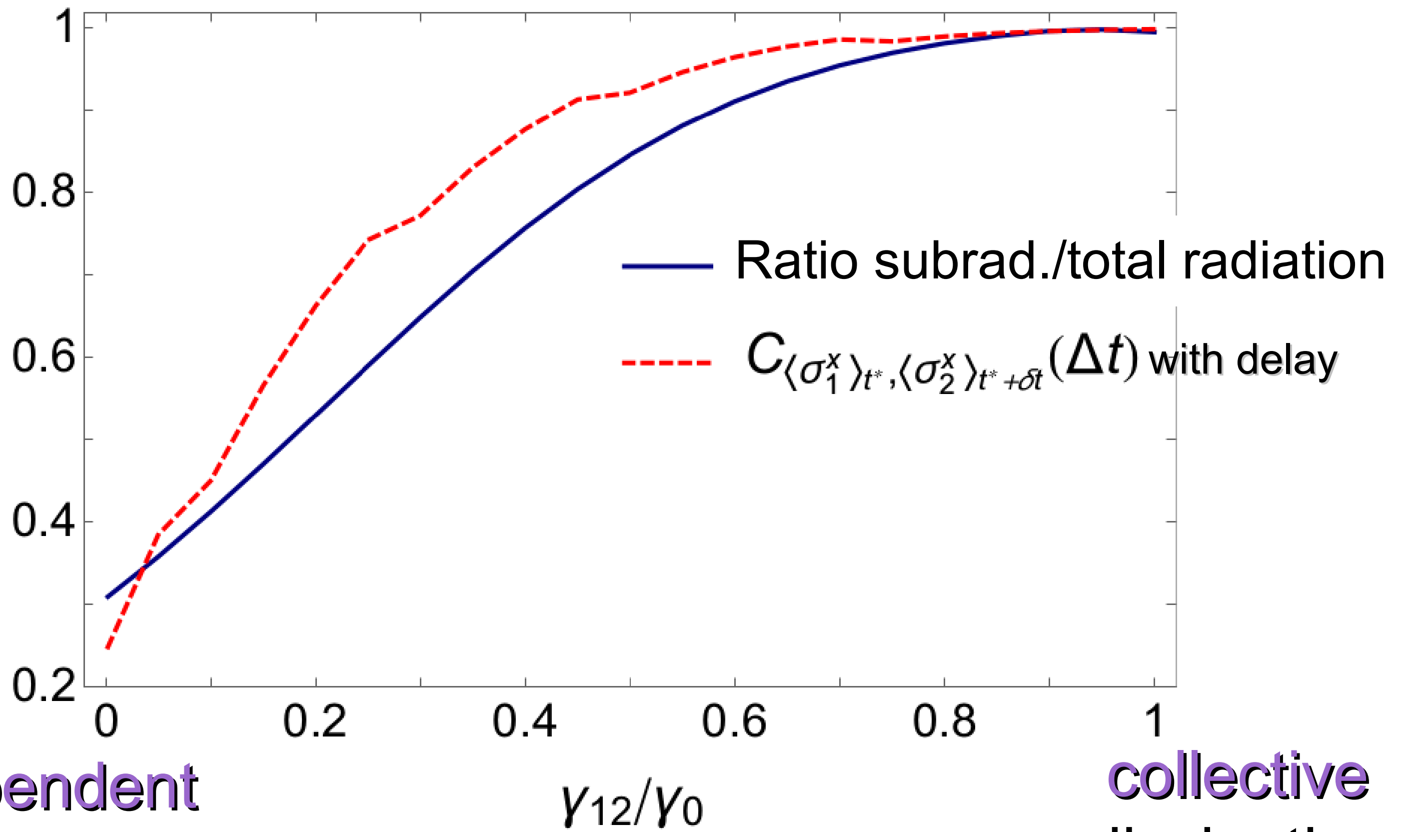
- CB enhances entanglement and optomechanical cooling

Cabot, Galve, R.Z., New J. Phys. 19, 113007 (2017)

Superradiance and synchronization

Synchronization of *detuned* qubits induced by collective dissipation.
Local manifestation of super-/sub-radiance



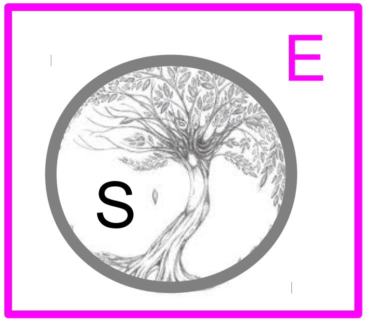


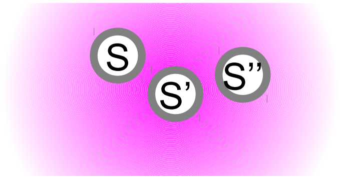
Independent dissipation

collective dissipation

Bellomo, Giorgi, Palma, RZ, PRA **95**, 043807 (2017)

Multipartite systems

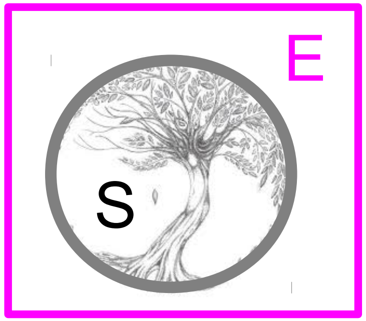


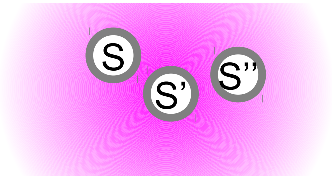


common environment ⇒

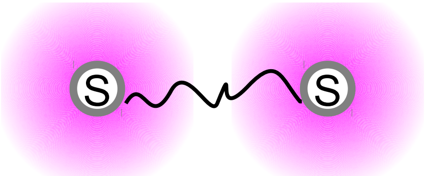
Collective dissipation
Correlated dissipations
Independent dissipations

Multipartite systems



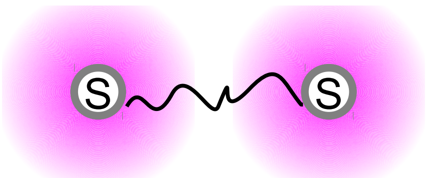


common environment ⇒ Collective dissipation
Correlated dissipations
Independent dissipations



Separate & uncorrelated baths ⇒ ? independent dissipations

Interacting systems in separate baths



coupled systems
in separate baths

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DOI:10.1142/S1230161217400108

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Testing the Validity of the 'Local' and 'Global' GKLS Master Equations on an Exactly Solvable Model

J. Onam González[1,2], Luis A. Correa[2], Giorgio Nocerino[2], José P. Palao[1], Daniel Alonso[1], and Gerardo Adesso[2]

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PAPER

Markovian master equations for quantum thermal machines: local versus global approach

Patrick P Hofer[1], Martí Perarnau-Llobet[2], L David M Miranda[1], Géraldine Haack[1], Ralph Silva[1], Jonatan Bohr Brask[1] and Nicolas Brunner[1]

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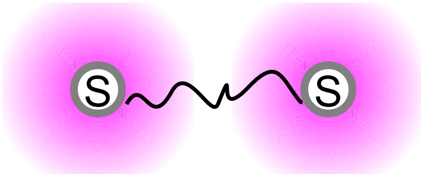
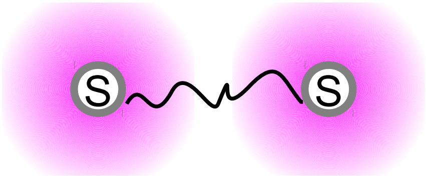
Interacting systems in separate baths



Different approximations to get LGKS ME:

- **Local approach:** ME with local jumps operators for the components of multipartite system → $L_S+L_{S'}$

- **Global approach:** delocalized jumps, from eigenoperators of the multipartite system Hamiltonian → $L_{S+S'}$



Different approximations to get LGKS ME:

- **Local approach:** ME with local jumps operators for the components of multipartite system → $L_S + L_{S'}$

  for bosonic baths with Ohmic spectral density

  Valid for small internal coupling << local energies
  Error ~ (S-E coupling)² x (internal coupling)

- **Global approach:** delocalized jumps, from eigenoperators of the multipartite system Hamiltonian → $L_{S+S'}$

  Valid when the secular approximation holds
  Detuning and/or internal couplings in the system larger than S-E coupling

Common and separate baths, local and global dissipation

	Local	Global
CB	✓	✓
SB	✓ trivial	X never

	Local	Global
CB	✓	✓
SB	✓	✓

Open quantum multipartite systems
Collective dissipation
Superradiance and synchronization
Common and separate baths, local and global dissipation

Autonomous quantum refrigerators
Performance with collective dissipation

G. Manzano

AUTONOMOUS THERMAL MACHINE

- NO EXTERNAL DRIVING $H(\not{t})$
- THERMAL CONTACT WITH BATHS at $\not{\neq}$ T

Steady state operation: refrigerators or heat pumps

Not cycles

autonomous q. refrigerators

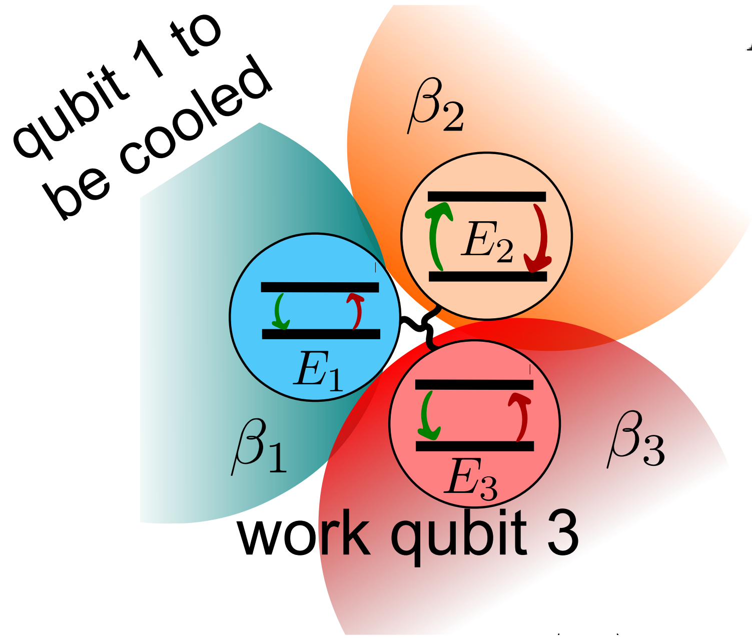
Linden, Popescu, Skrzypczyk, PRL (2010); Brunner et al., PRE (2014); Silva et al., PRE (2016)

or absorption refrigerators

Palao and Kosloff, PRE (2001); Levy and Kosloff, PRL (2012); Correa et al., PRE (2013) and Sci. Rep. (2014)

3 QUBIT REFRIGERATOR

How Small Can Thermal Machines Be? The Smallest Possible Refrigerator,
Linden, Popescu, Skrzypczyk, PRL (2010)



$$H_{\rm int} = g(|010\rangle\langle 101| + |101\rangle\langle 010|)$$

3 provides energy for 1-2 swap

$$E_3 = E_2 - E_1$$

- Chen and Li, EPL 2012
- Mari and J. Eisert, PRL (2012
- Venturelli, Fazio, Giovannetti, PRL (2013)
- Mitchison, Huber, Prior, Woods, and Plenio, Q. Sci. Tech. (2016).
- Hofer, Perarnau-Llobet et al., PRB (2016)
- Maslennikov et al., arXiv:1702.08672 → Dzmitry Matsukevich

$$\frac{\partial \rho}{\partial t} = -i[H_0 + H_{\rm int}, \rho] + \sum_{i=1}^{3} p_i(\tau_i {\rm Tr}_i \rho - \rho)$$

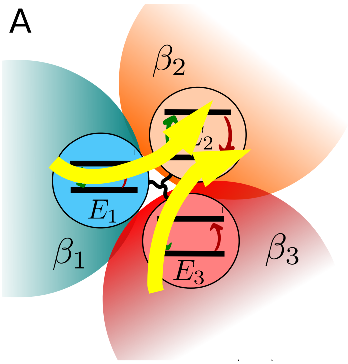
Local ME approach

Small g~p

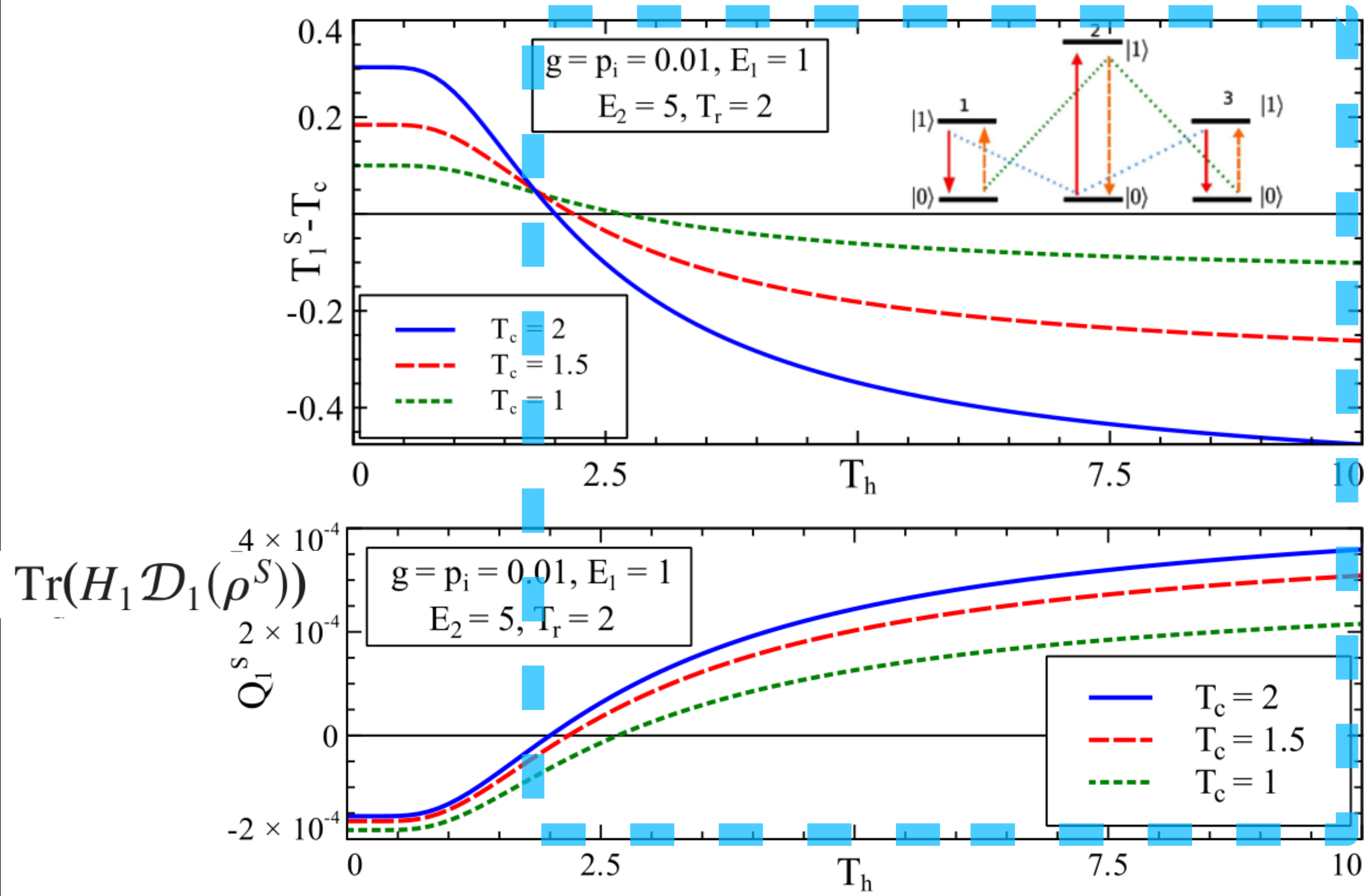
Global ME approach + microscopic derivation

Correa, Palao, Adesso, Alonso, PRE 2013

cooling



Cooling qubit 1

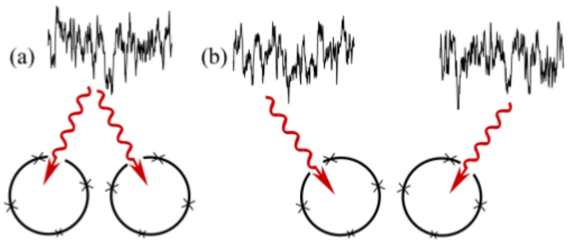


Heat out of cold B1

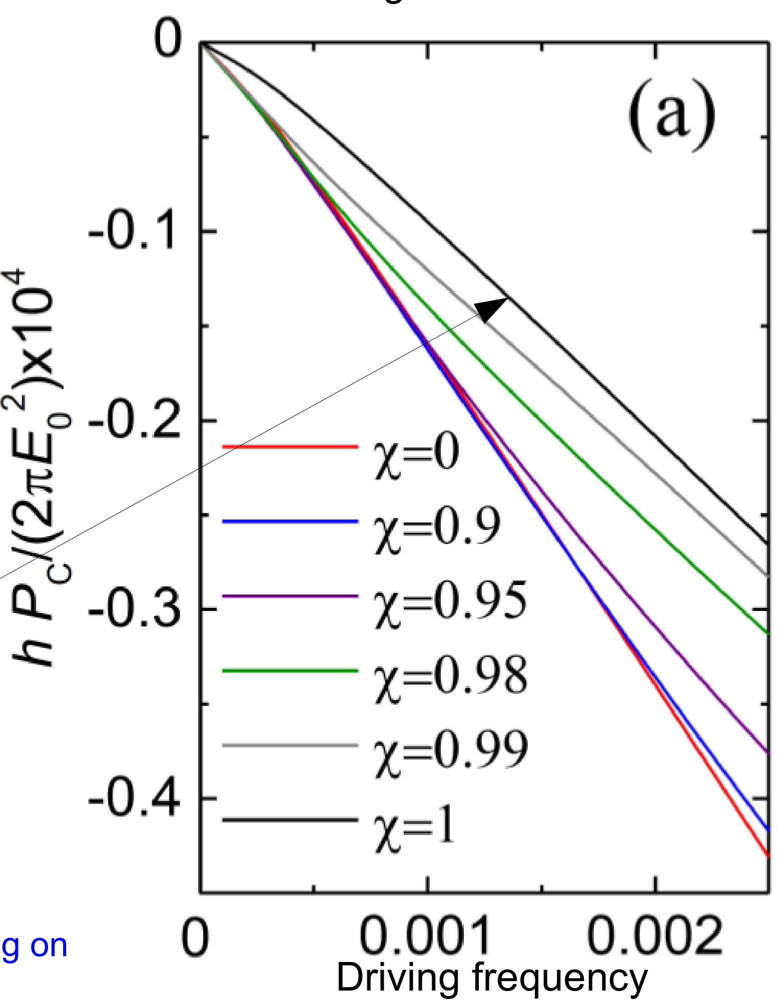
Linden, Popescu, Skrzypczyk, PRL 105, 130401 (2010)

CAN COLLECTIVE DISSIPATION IMPROVE THE PERFORMANCE OF AUTHONOMOUS THERMAL MACHINE?

Otto cycle with 2 (non interacting) qubits connected to common (hot/cold) bath or 2 (hot/cold) SB



cooling power of the quantum refrigerator for different degrees of noise correlation

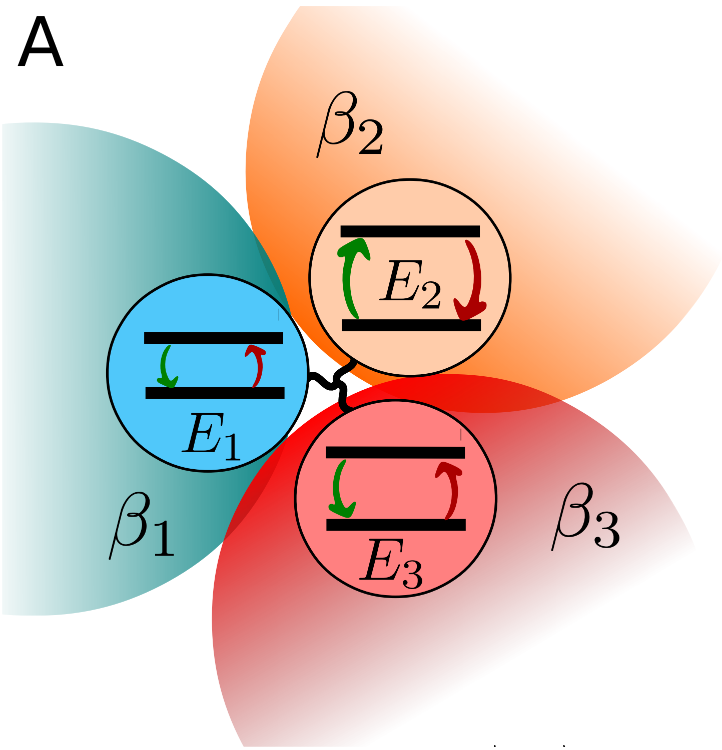


highest cooling power for fully uncorrelated baths

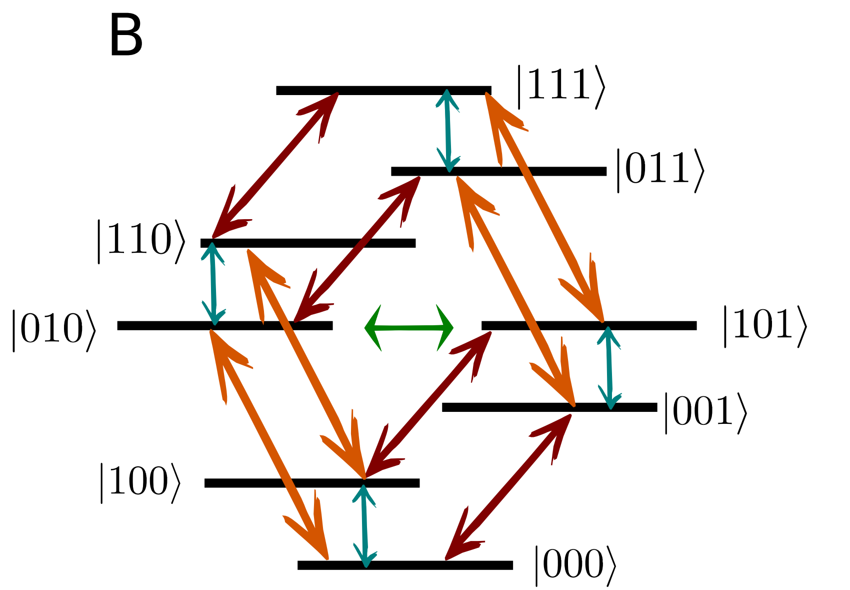
$-P_C$ *decreases* with noise correlation

Karimi & Pekola, Correlated versus uncorrelated noise acting on a quantum refrigerator, Phys.Rev.B 96, 115408 (2017)

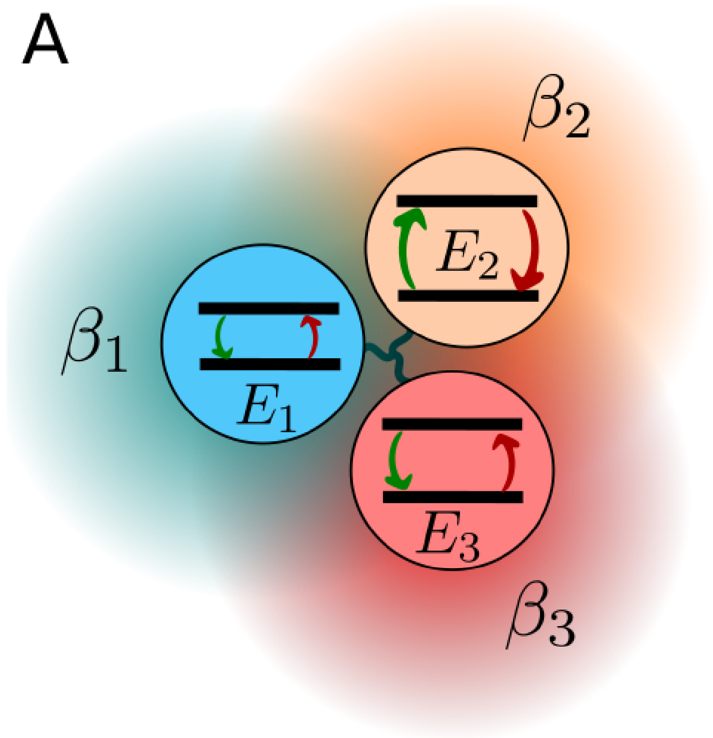
REFRIGERATOR WITH SEPARATE BATHS FOR 3 QUBITS



Transitions for $s_1 = \sigma_1^-$, $s_2 = \sigma_2^-$, $s_3 = \sigma_3^-$



Linden, Popescu, Skrzypczyk, PRL 105, 130401 (2010)



Each bath **resonant** at E_j

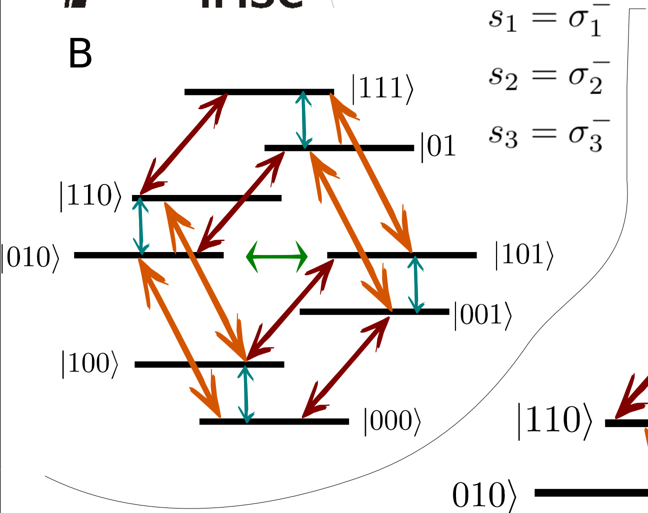
$$E_3 = E_2 - E_1$$

Transitions

$$s_1 = \sigma_1^- + \alpha \sigma_2^- \sigma_3^+$$
$$s_2 = \sigma_2^- + \alpha \sigma_1^- \sigma_3^-$$
$$s_3 = \sigma_3^- + \alpha \sigma_1^+ \sigma_2^-$$

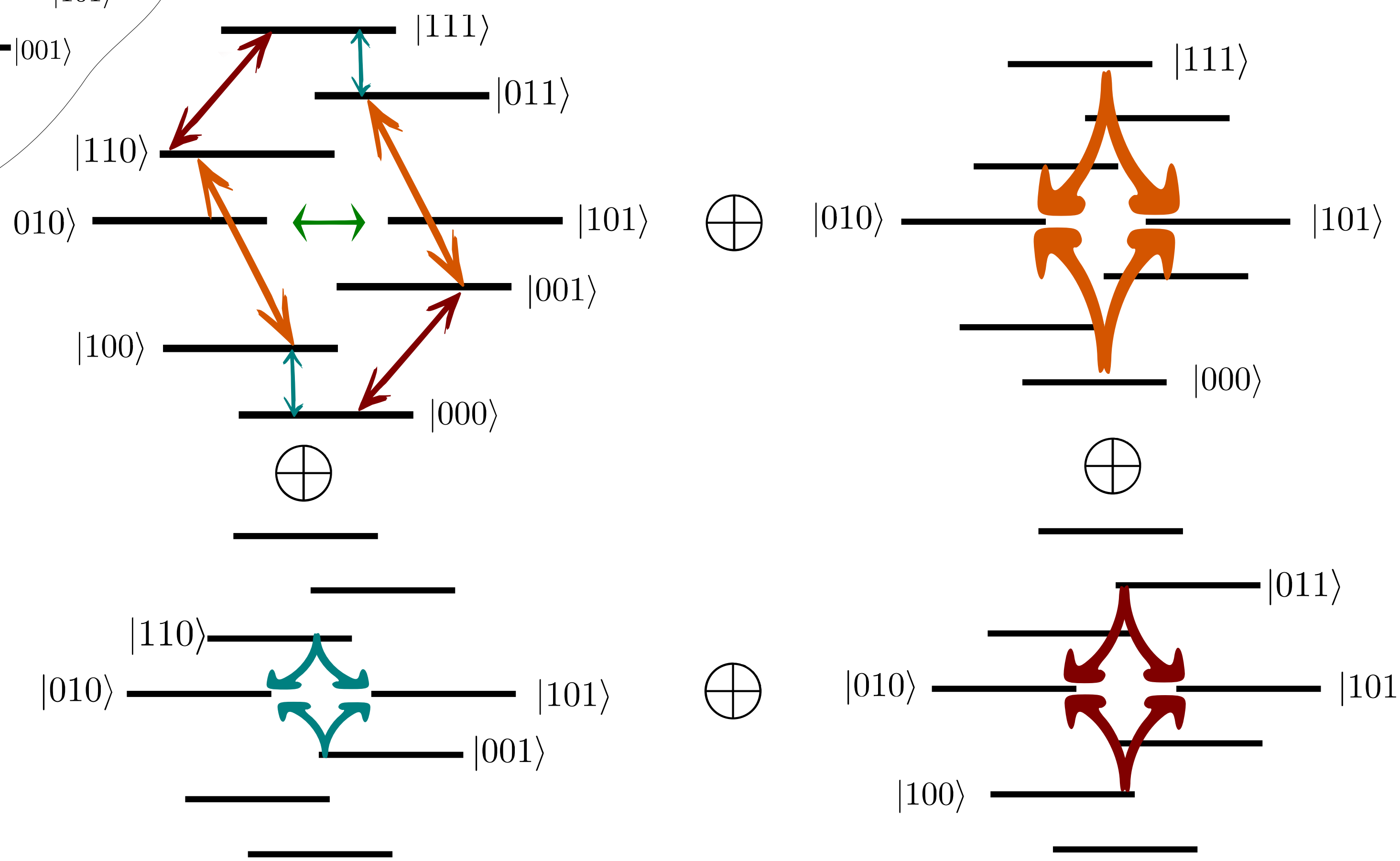
COLLECTIVE DISSIPATION

Collective dissipation in autonomous refrigerator



Transitions for

$$s_1 = \sigma_1^- + \alpha \sigma_2^- \sigma_3^+$$
$$s_2 = \sigma_2^- + \alpha \sigma_1^- \sigma_3^-$$
$$s_3 = \sigma_3^- + \alpha \sigma_1^+ \sigma_2^-$$



Collective dissipation in autonomous refrigerator

ME for 3 qubits

$$\dot{\rho}_{\rm m} = -\frac{i}{\hbar}[H_{\rm m}, \rho_{\rm m}] + \sum_i \mathcal{L}_i(\rho_{\rm m})$$

$$H_{\rm int} = g(|010\rangle\langle 101| + |101\rangle\langle 010|)$$

small g → local approach

3 Lindbladians accounting for dissipation in each reservoir

$$\mathcal{L}_i(\rho_{\rm m}) = \gamma_\downarrow^i \left(s_i \rho_{\rm m} s_i^\dagger - \frac{1}{2}\{s_i^\dagger s_i, \rho_{\rm m}\} \right) + \gamma_\uparrow^i \left(s_i^\dagger \rho_{\rm m} s_i - \frac{1}{2}\{s_i s_i^\dagger, \rho_{\rm m}\} \right)$$

with jump operators

$$s_1 = \sigma_1^- + \alpha \sigma_2^- \sigma_3^+$$
$$s_2 = \sigma_2^- + \alpha \sigma_1^- \sigma_3^-$$
$$s_3 = \sigma_3^- + \alpha \sigma_1^+ \sigma_2^-$$

$$E_3 = E_2 - E_1$$

Manzano, Giorgi, Zambrini, in progress

Steady state operation

$\alpha \neq 1$ $\quad \pi = \{\pi_{000}, \pi_{001}, \ldots, \pi_{111}, c^{\pi}_{\mathcal{R}}, c^{\pi}_{\mathcal{I}}\}$

all populations

coherences between deg. levels

$\alpha = 1$ DARK STATE $\quad |\psi_D\rangle \equiv \frac{1}{\sqrt{2}}(|010\rangle - |101\rangle)$

Characterization of the performance

$\mathcal{O}(g\gamma_0^{(i)})$

Heat currents $\quad \dot{Q}_i \equiv \mathrm{Tr}[H_{\mathrm{m}} \mathcal{L}_i(\rho)]$ $\quad$ depend on $c^{\pi}_{\mathcal{R}}$

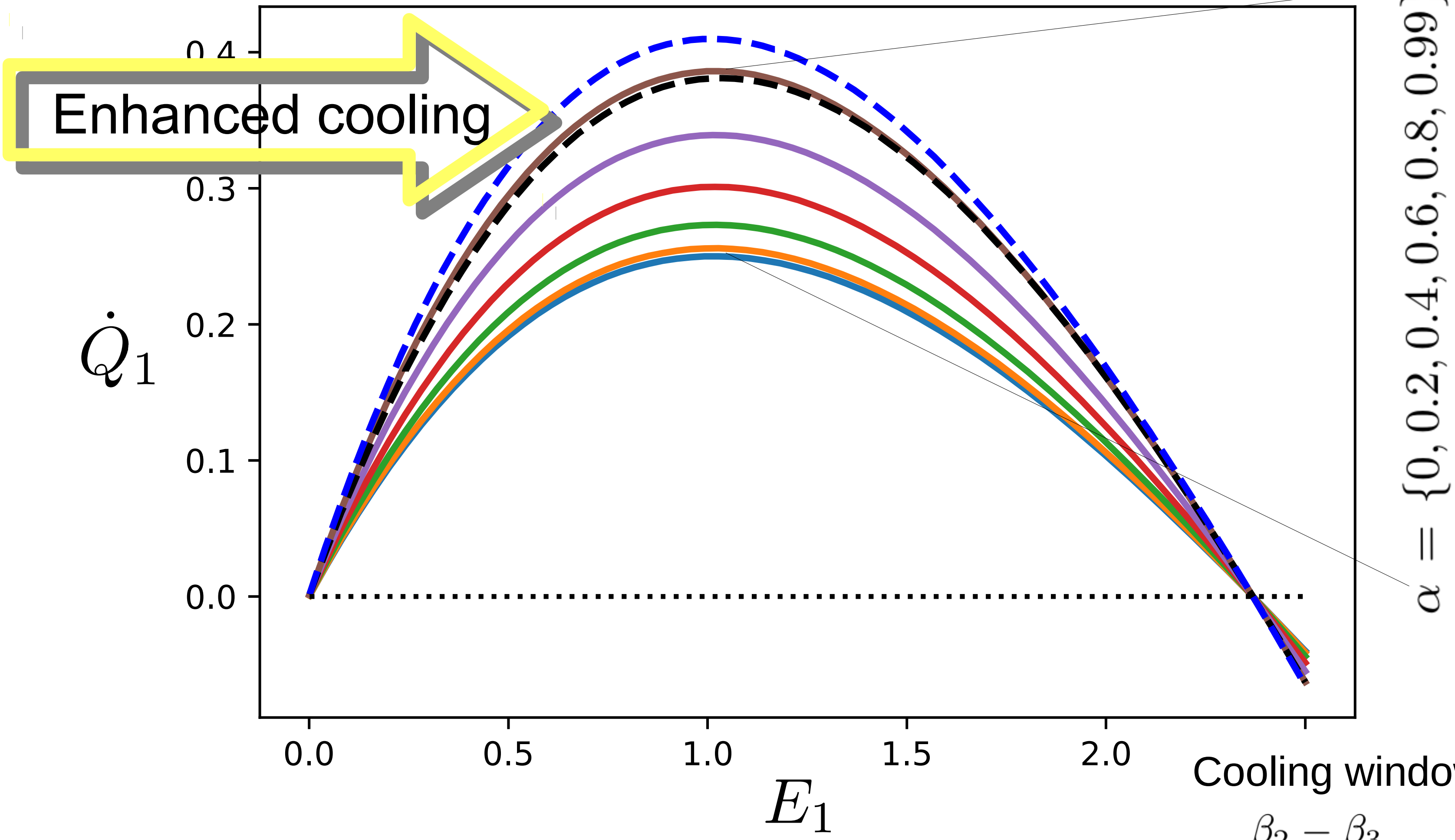
Cooling power $\quad \dot{Q}_1$

Efficiency/COP $\quad \eta \equiv \frac{\dot{Q}_1}{\dot{Q}_3} \leq \frac{\beta_2 - \beta_3}{\beta_1 - \beta_2} \equiv \eta_C$

$s_1 = \sigma_1^- + \alpha\sigma_2^-\sigma_3^+$
$s_2 = \sigma_2^- + \alpha\sigma_1^-\sigma_3^-$
$s_3 = \sigma_3^- + \alpha\sigma_1^+\sigma_2^-$

cooling power

$\alpha = 1$ — — $\rho_{\rm ini}|\psi_D\rangle = 0$ — — $\rho_{\rm ini} = \rho_1^{\beta_1} \otimes \rho_2^{\beta_2} \otimes \rho_3^{\beta_3}$



Cooling window

$$E_1 \leq \frac{\beta_2 - \beta_3}{\beta_1 - \beta_2} E_3 = \eta_C E_3$$

$\beta_2 = 0.5\beta_1$ and $\beta_3 = 0.05\beta_1$, and we set $g = 0.005$

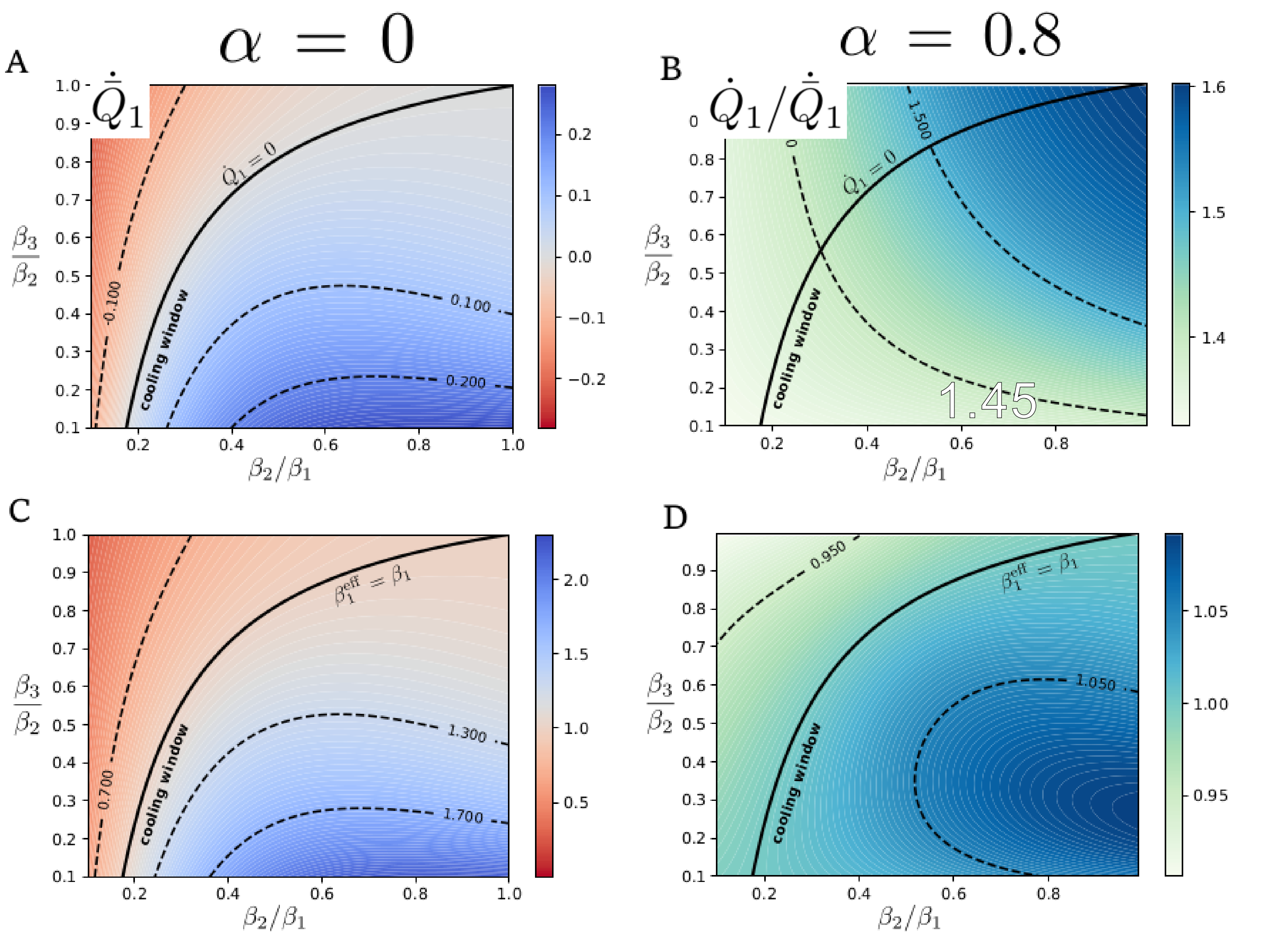
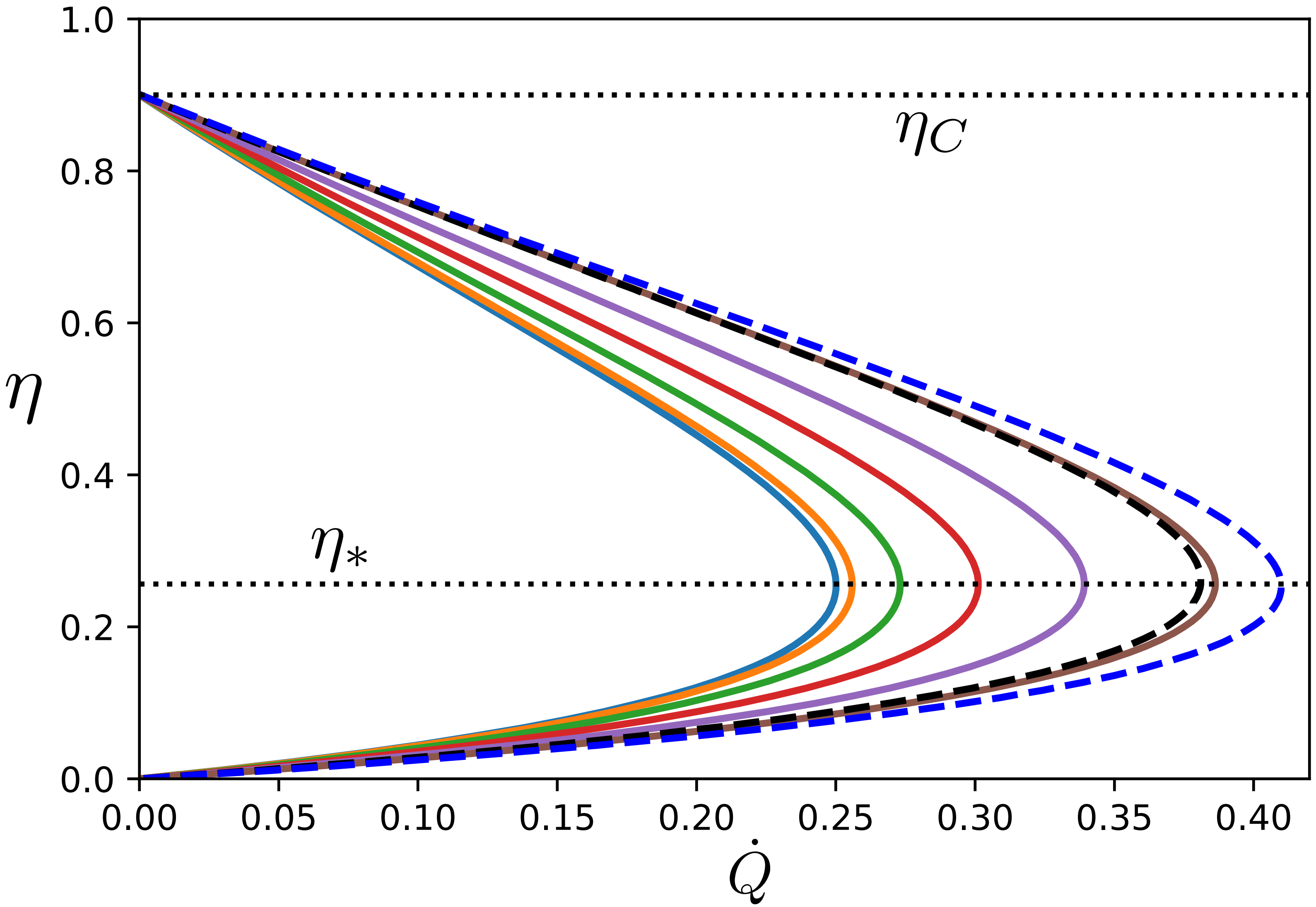


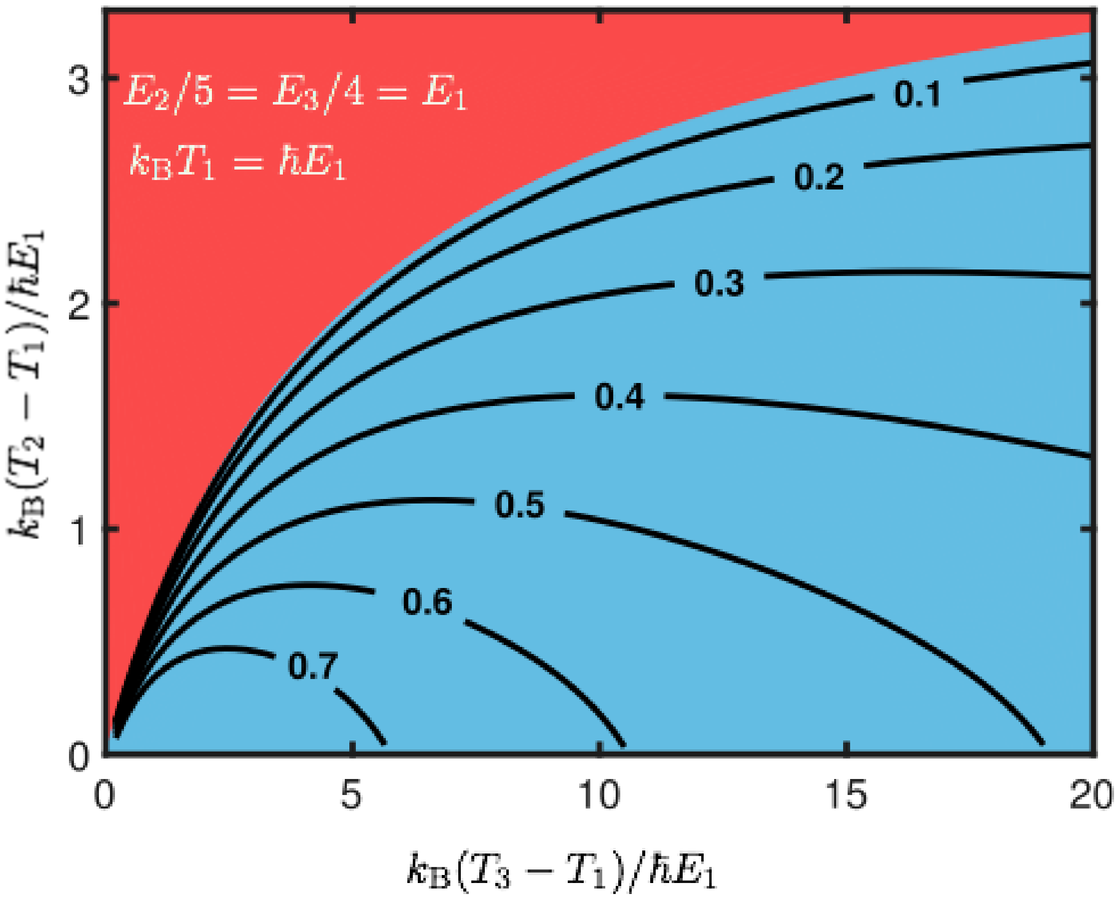
FIG. 3. (A) Cooling power as a function of β_2/β_1 and β_3/β_2 and (B) enhancements in the cooling power relative to the separate reservoirs case, $\dot{Q}_1/\bar{\dot{Q}}_1$, for $\alpha = 0.8$ and $E_1 = 0.8k_BT_1$. Again cooling power is given in γ_0 units. (C) Effective temperature of qubit 1, $\bar{\beta}_1^{\rm eff}$ as a function of β_2 and β_3, and (D) enhancements $\beta_1^{\rm eff}/\bar{\beta}_1^{\rm eff}$ for $\alpha = 0.8$.

Efficiency/COP



Refrigeration and strong coupling

$$g \gtrsim E_j \longrightarrow H_{\text{int}} = g\sigma_1^x \sigma_2^x \sigma_3^x$$



Master equation approach

Partial coarse graining at intermediate time-scales: allows one explore any coupling regime

The refrigeration window is narrowed as the coupling increases

S. Seah, S. Nimmrichter, and V. Scarani, arXiv:1803.02002

CONCLUSIONS

Collective dissipation of distant emitters can be engineered in structured environments

It allow to preserve coherences and induces separation of decay time scales in different degrees of freedom in the system allowing for sync and improving quantum effects

The performance of an absorption refrigerator significantly improved with collective dissipation

FIS2014-60343-P
FIS2016-78010-P

GRAZIE