UNIVERSIDADE DE SÃO PAULO
Instituto de Física de São Carlos

QUEEN'S UNIVERSITY BELFAST

System-environment quantum information flow

Taysa M. Mendonça
Mauro Paternostro
Lucas Céleri
Diogo O. Soares-Pinto

arXiv:2402.15483

Motivation

PHYSICAL REVIEW RESEARCH **2**, 043419 (2020)

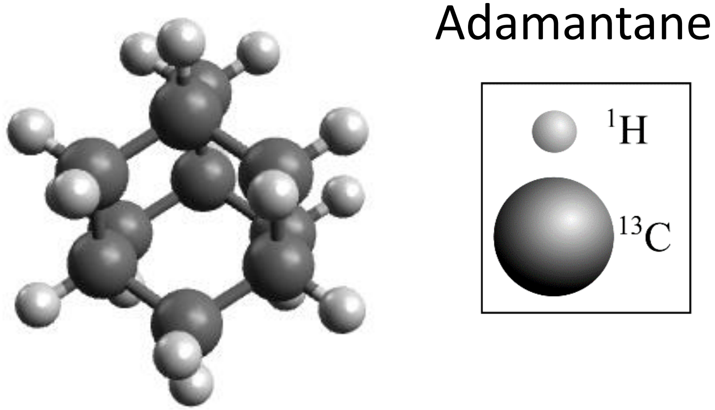
Reservoir engineering for maximally efficient quantum engines

Taysa M. Mendonça,[1] Alexandre M. Souza,[2] Rogério J. de Assis,[3] Norton G. de Almeida,[3] Roberto S. Sarthour,[2] Ivan S. Oliveira,[2] and Celso J. Villas-Boas[1]

[1]*Departamento de Física, Universidade Federal de São Carlos, 13565-905, São Carlos, São Paulo, Brazil*
[2]*Centro Brasileiro de Pesquisas Físicas, 22290-180, Rio de Janeiro, Rio de Janeiro, Brazil*
[3]*Instituto de Física, Universidade Federal de Goiás, 74001-970, Goiânia, Goiás, Brazil*

(Received 18 February 2020; accepted 18 November 2020; published 24 December 2020)

Adamantane



Motivation

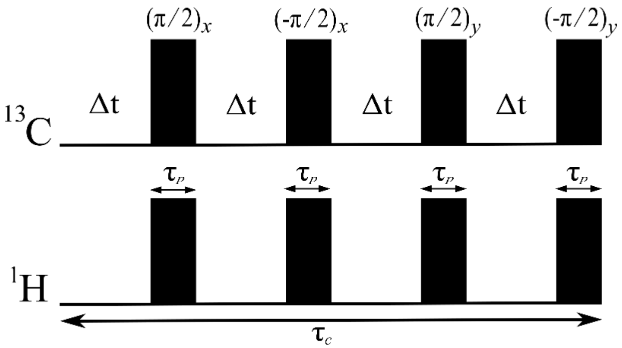
PHYSICAL REVIEW RESEARCH **2**, 043419 (2020)

Reservoir engineering for maximally efficient quantum engines

Taysa M. Mendonça,[1] Alexandre M. Souza,[2] Rogério J. de Assis,[3] Norton G. de Almeida,[3] Roberto S. Sarthour,[2] Ivan S. Oliveira,[2] and Celso J. Villas-Boas[1]

[1]*Departamento de Física, Universidade Federal de São Carlos, 13565-905, São Carlos, São Paulo, Brazil*
[2]*Centro Brasileiro de Pesquisas Físicas, 22290-180, Rio de Janeiro, Rio de Janeiro, Brazil*
[3]*Instituto de Física, Universidade Federal de Goiás, 74001-970, Goiânia, Goiás, Brazil*

(Received 18 February 2020; accepted 18 November 2020; published 24 December 2020)

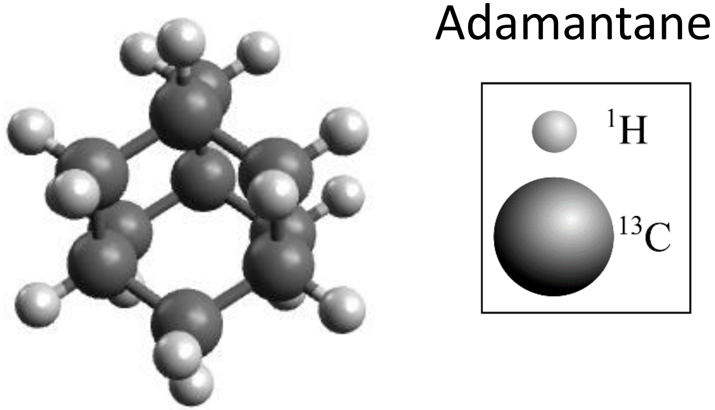


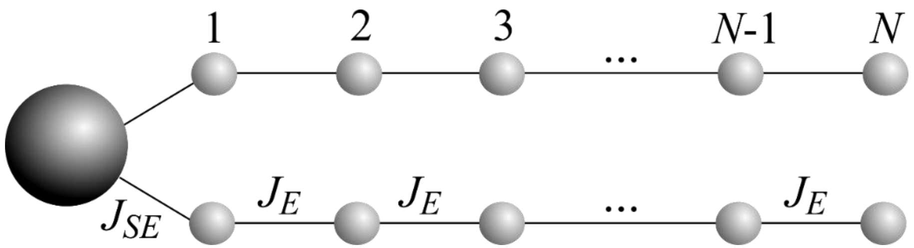
$$H_{eff} = H_{SE} + H_E$$

$$H_{SE} = J_{SE} \sum_{\alpha=a,b} \left(2S_z I_z^{\alpha,1} + S_x I_x^{\alpha,1} + S_y I_y^{\alpha,1}\right)$$

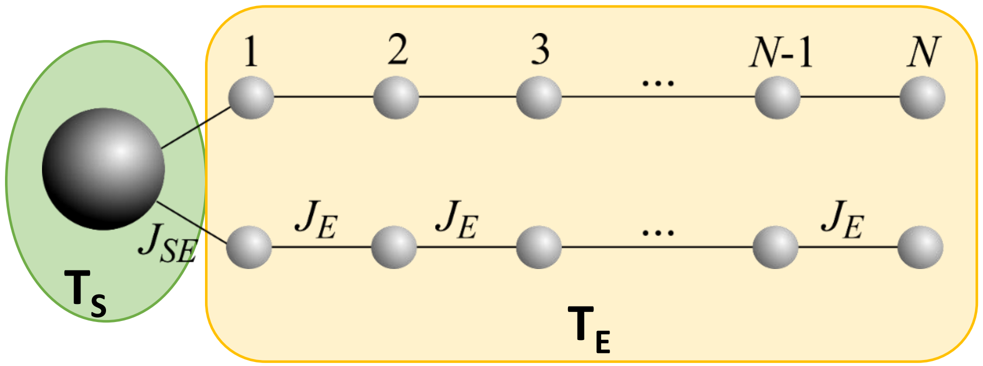
$$H_E = J_E \sum_{\alpha=a,b} \sum_{k=1}^{N-1} \left[2I_z^{\alpha,k} I_z^{\alpha,k+1} - \left(I_x^{\alpha,k} I_x^{\alpha,k+1} + I_y^{\alpha,k} I_y^{\alpha,k+1}\right)\right]$$

Adamantane



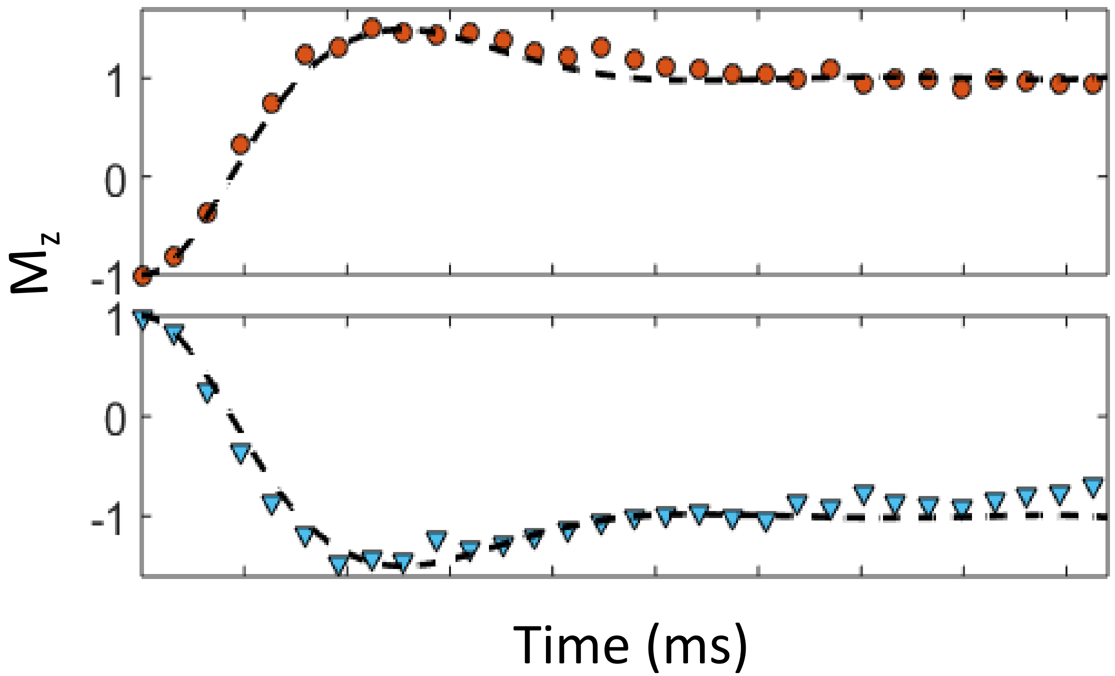


Motivation



Gibbs State: $\rho = \frac{e^{-H/k_B T}}{Z}$

with $Z = \mathrm{tr}\left(e^{-H/k_B T}\right)$



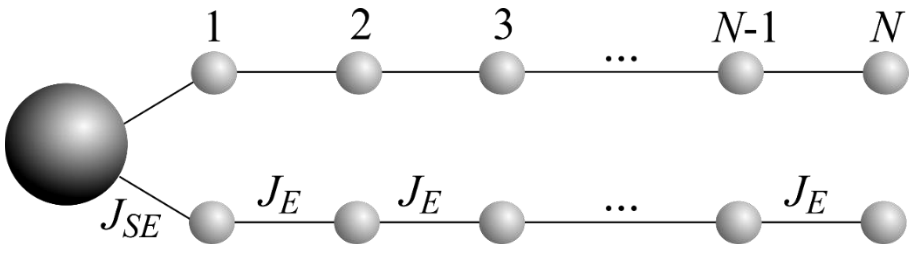
T - T +

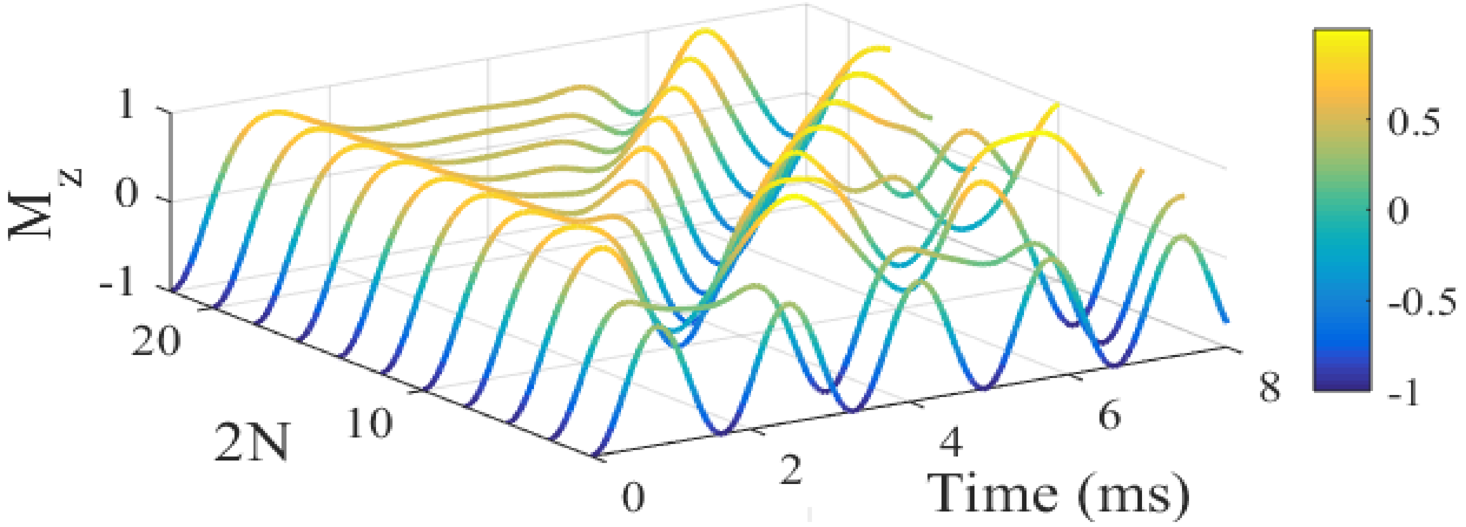
$\rho_S = |1\rangle\langle 1| \rightarrow \rho_E = |0\rangle\langle 0|$

$\rho_S = |0\rangle\langle 0| \rightarrow \rho_E = |1\rangle\langle 1|$

T + T -

Motivation



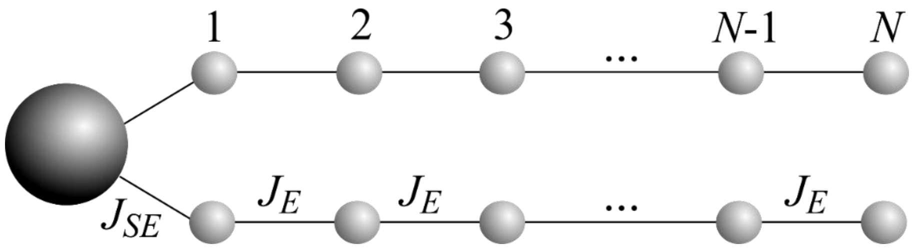


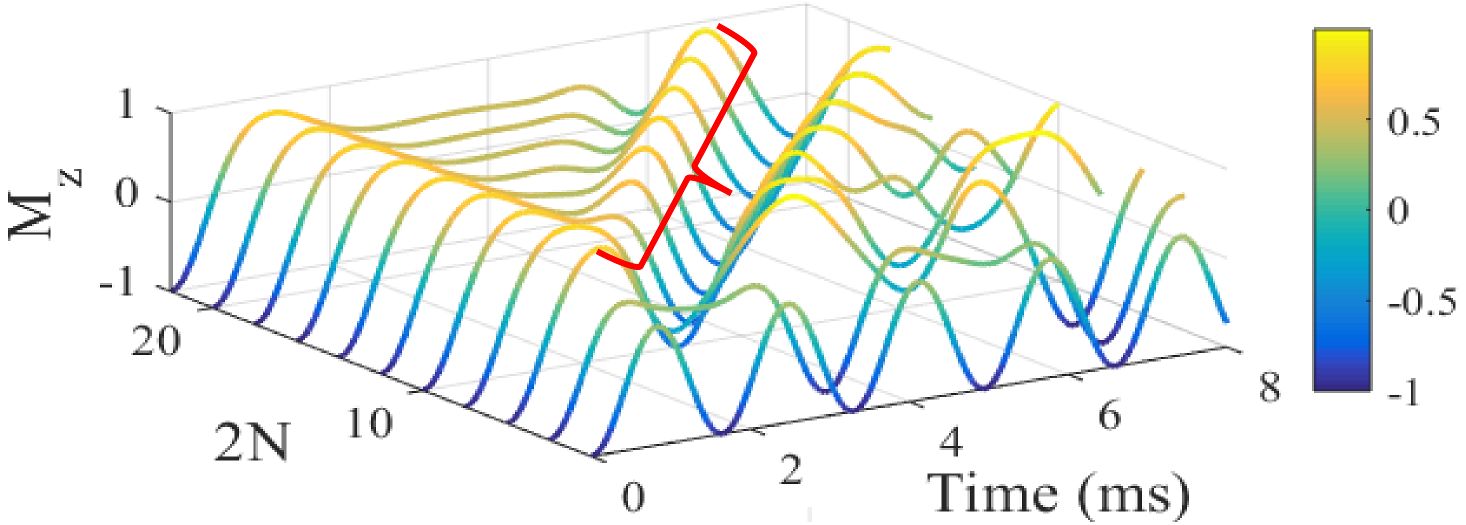
Motivation

What is the relationship between coupling constants, number of qubits and non-Markovianity?

$$H_{SE} = J_{SE} \sum_{\alpha=a,b} \left(2S_z I_z^{\alpha,1} + S_x I_x^{\alpha,1} + S_y I_y^{\alpha,1}\right)$$

$$H_E = J_E \sum_{\alpha=a,b} \sum_{k=1}^{N-1} \left[2I_z^{\alpha,k} I_z^{\alpha,k+1} - \left(I_x^{\alpha,k} I_x^{\alpha,k+1} + I_y^{\alpha,k} I_y^{\alpha,k+1}\right)\right]$$





Non-Markovianity Measure - Breuer, Laine and Piilo representation (BLP)

We calculate the dynamics of the system from the initial states below

Initial states:

System

(a) $\left|\psi_S^{(+)}\right\rangle = \frac{|0\rangle + |1\rangle}{\sqrt{2}}$

(b) $\left|\psi_S^{(-)}\right\rangle = \frac{|0\rangle - |1\rangle}{\sqrt{2}}$

(a,b) Environment

$\left|\psi_E\right\rangle = |0\rangle^{\otimes 2N}$

H.-P. Breuer *et al*. PRL, 103, 210401 (2009); Laine *et al*., PRA, 81, 062115 (2010)

Non-Markovianity Measure - Breuer, Laine and Piilo representation (BLP)

We calculate the dynamics of the system from the initial states below

<u>Initial states:</u>

System

(a) $\left|\psi_S^{(+)}\right\rangle = \frac{|0\rangle + |1\rangle}{\sqrt{2}}$

(b) $\left|\psi_S^{(-)}\right\rangle = \frac{|0\rangle - |1\rangle}{\sqrt{2}}$

(a,b) Environment

$\left|\psi_E\right\rangle = |0\rangle^{\otimes 2N}$

<u>Dynamics:</u>

$\dot{\rho}_{SE}(t) = -\frac{i}{\hbar}\left[H, \rho_{\mathrm{SE}}(t)\right]$

where $\rho_{SE}(0) = \rho_S(0) \otimes \rho_E(0)$

with:

$\rho_S^{(\pm)}(t) = \mathrm{Tr}_E\left(\rho_{\mathrm{SE}}^{(\pm)}(t)\right)$

$\rho_E^{(\pm)}(t) = \mathrm{Tr}_S\left(\rho_{\mathrm{SE}}^{(\pm)}(t)\right)$

H.-P. Breuer *et al*. PRL, 103, 210401 (2009); Laine *et al*., PRA, 81, 062115 (2010)

Non-Markovianity Measure - Breuer, Laine and Piilo representation (BLP)

We calculate the dynamics of the system from the initial states below

Initial states:

System

(a) $\left|\psi_S^{(+)}\right\rangle = \frac{|0\rangle + |1\rangle}{\sqrt{2}}$

(b) $\left|\psi_S^{(-)}\right\rangle = \frac{|0\rangle - |1\rangle}{\sqrt{2}}$

(a,b) Environment

$\left|\psi_E\right\rangle = |0\rangle^{\otimes 2N}$

Dynamics:

$\dot{\rho}_{SE}(t) = -\frac{i}{\hbar}\left[H, \rho_{SE}(t)\right]$

where $\rho_{SE}(0) = \rho_S(0) \otimes \rho_E(0)$

with:

$\rho_S^{(\pm)}(t) = \mathrm{Tr}_E\left(\rho_{SE}^{(\pm)}(t)\right)$

$\rho_E^{(\pm)}(t) = \mathrm{Tr}_S\left(\rho_{SE}^{(\pm)}(t)\right)$

Trace Distance:

$\mathrm{A} = \rho^+(t) - \rho^-(t)$

$\mathrm{D}\left(\rho^+, \rho^-\right) = \frac{1}{2}\mathrm{Tr}\left(\sqrt{\mathrm{A}^\dagger \mathrm{A}}\right)$

Increase → Non-Markovian (information entering)

Decrease → Markovian (information leaving)

H.-P. Breuer *et al*. PRL, 103, 210401 (2009); Laine *et al*., PRA, 81, 062115 (2010)

Trace distance

System

$$\left|\psi_S^{(+)}\right\rangle = \frac{|0\rangle + |1\rangle}{\sqrt{2}} \qquad \left|\psi_S^{(-)}\right\rangle = \frac{|0\rangle - |1\rangle}{\sqrt{2}}$$

$$\rho_S^{(\pm)}(t) = \mathrm{Tr}_E\left(\rho_{SE}^{(\pm)}(t)\right)$$

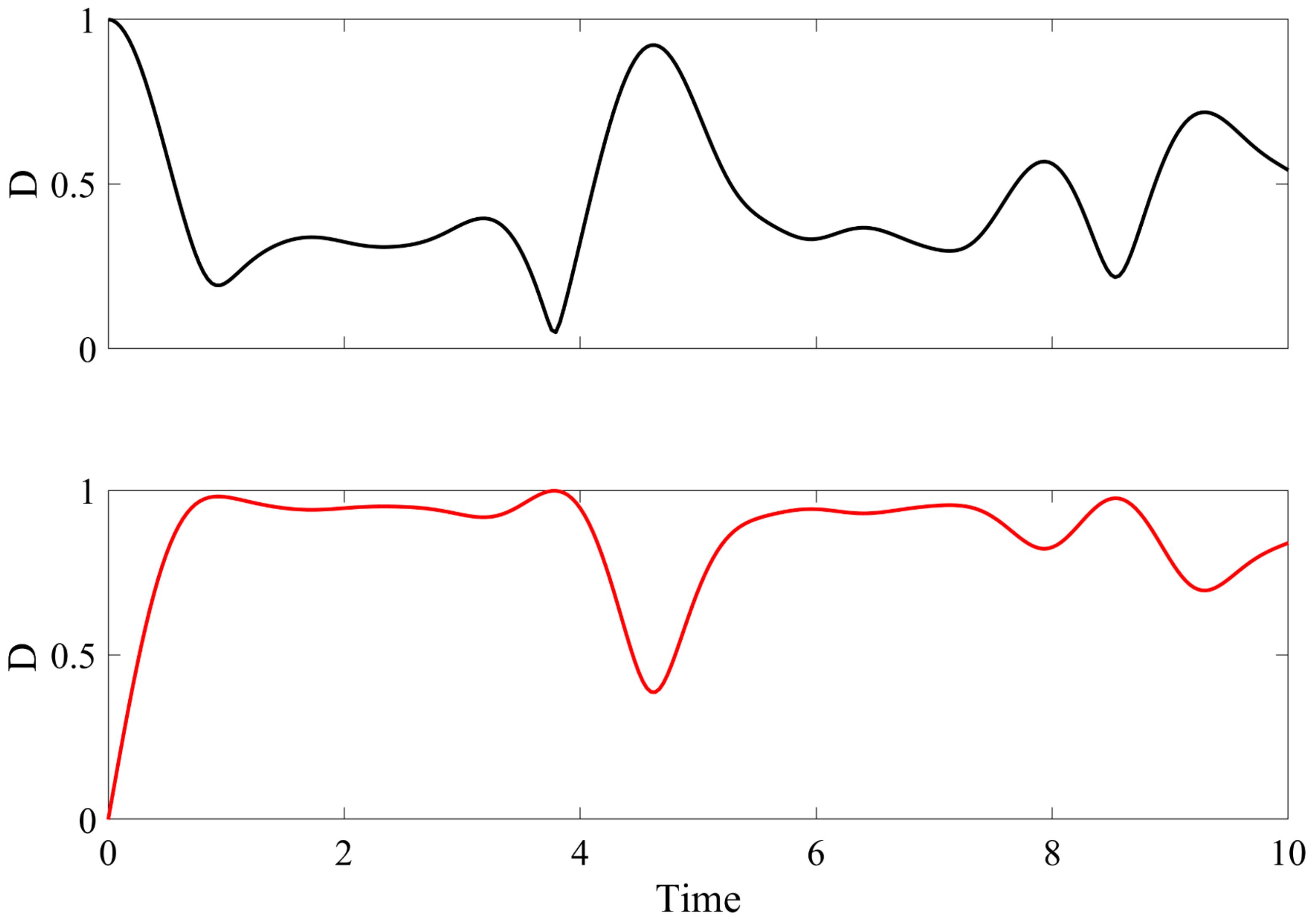
$$D\left(\rho_S^+, \rho_S^-\right)$$

Environment

$$\left|\psi_E\right\rangle = |0\rangle^{\otimes 2N}$$

$$\rho_E^{(\pm)}(t) = \mathrm{Tr}_S\left(\rho_{SE}^{(\pm)}(t)\right)$$

$$D\left(\rho_E^+, \rho_E^-\right)$$



Trace distance

System

$$|\psi_S^{(+)}\rangle = \frac{|0\rangle + |1\rangle}{\sqrt{2}} \qquad |\psi_S^{(-)}\rangle = \frac{|0\rangle - |1\rangle}{\sqrt{2}}$$

$$\rho_S^{(\pm)}(t) = \mathrm{Tr}_E\left(\rho_{SE}^{(\pm)}(t)\right)$$

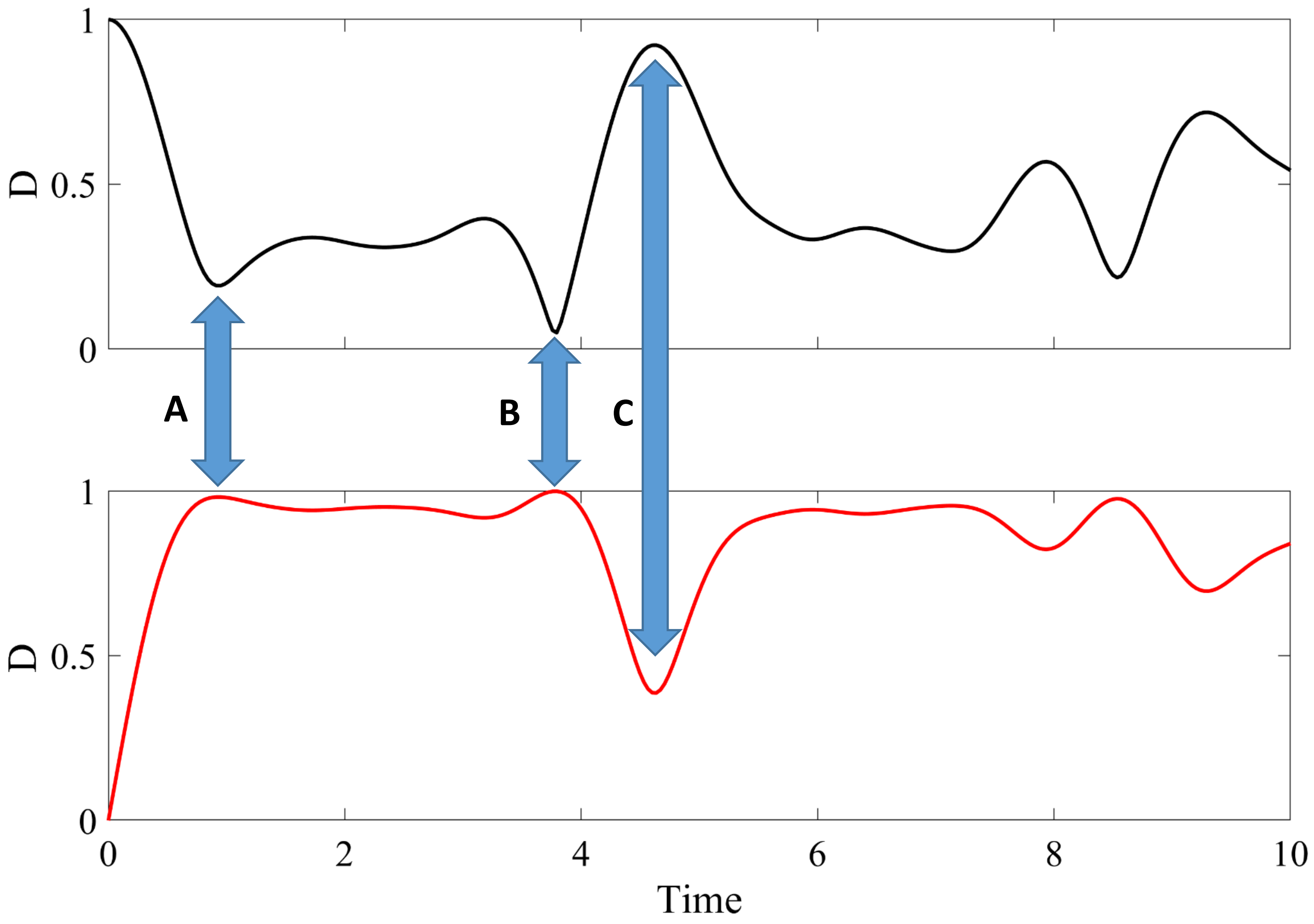
$$D\left(\rho_S^+, \rho_S^-\right)$$

Environment

$$|\psi_E\rangle = |0\rangle^{\otimes 2N}$$

$$\rho_E^{(\pm)}(t) = \mathrm{Tr}_S\left(\rho_{SE}^{(\pm)}(t)\right)$$

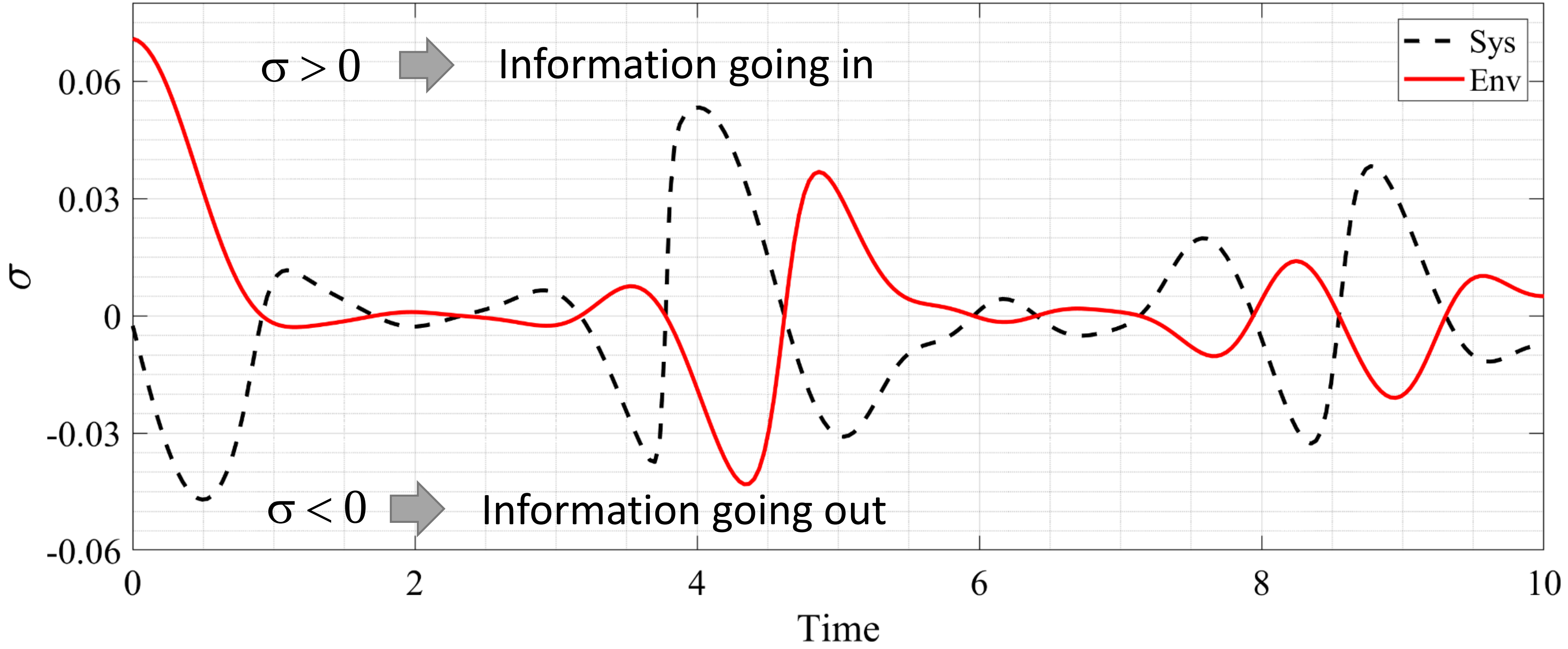
$$D\left(\rho_E^+, \rho_E^-\right)$$



Information Flow

$$\sigma_S(t) = \frac{d}{dt} D\left(\rho_S^{(+)}(t), \rho_S^{(-)}(t)\right)$$

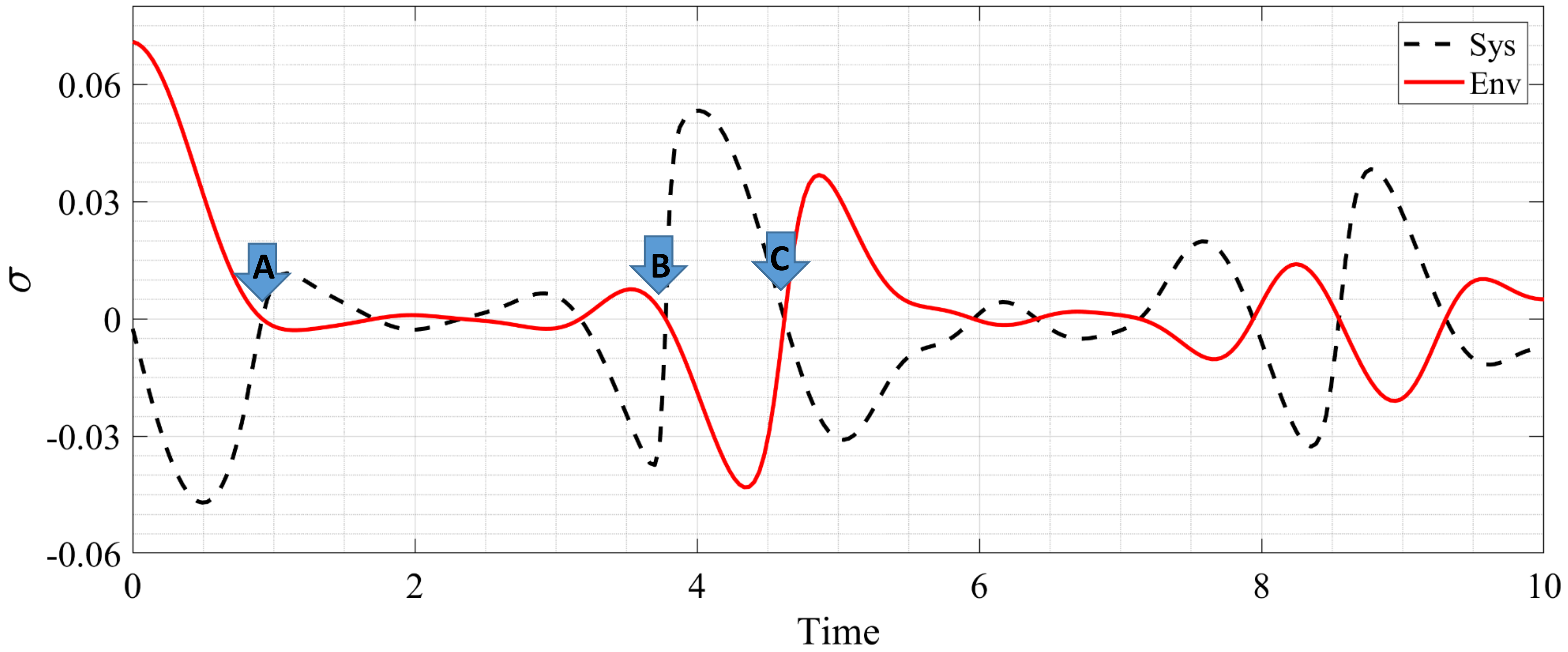
$$\sigma_E(t) = \frac{d}{dt} D\left(\rho_E^{(+)}(t), \rho_E^{(-)}(t)\right)$$



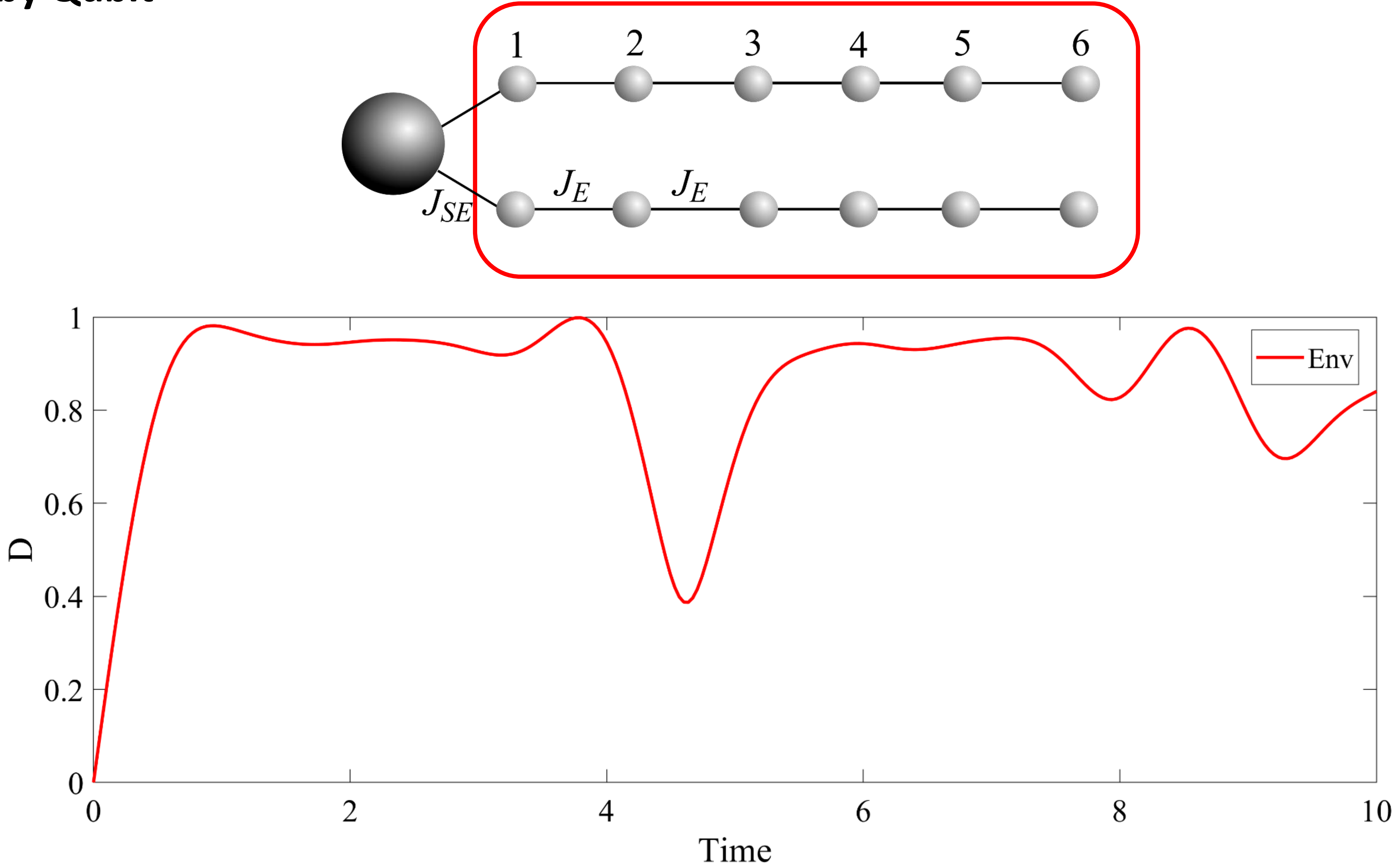
Information Flow

$$\sigma_S(t) = \frac{d}{dt} D\left(\rho_S^{(+)}(t), \rho_S^{(-)}(t)\right)$$

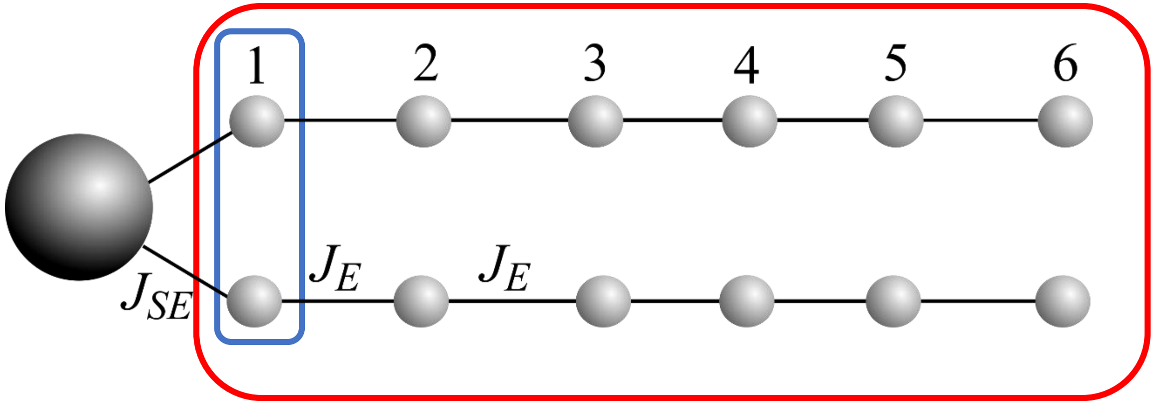
$$\sigma_E(t) = \frac{d}{dt} D\left(\rho_E^{(+)}(t), \rho_E^{(-)}(t)\right)$$

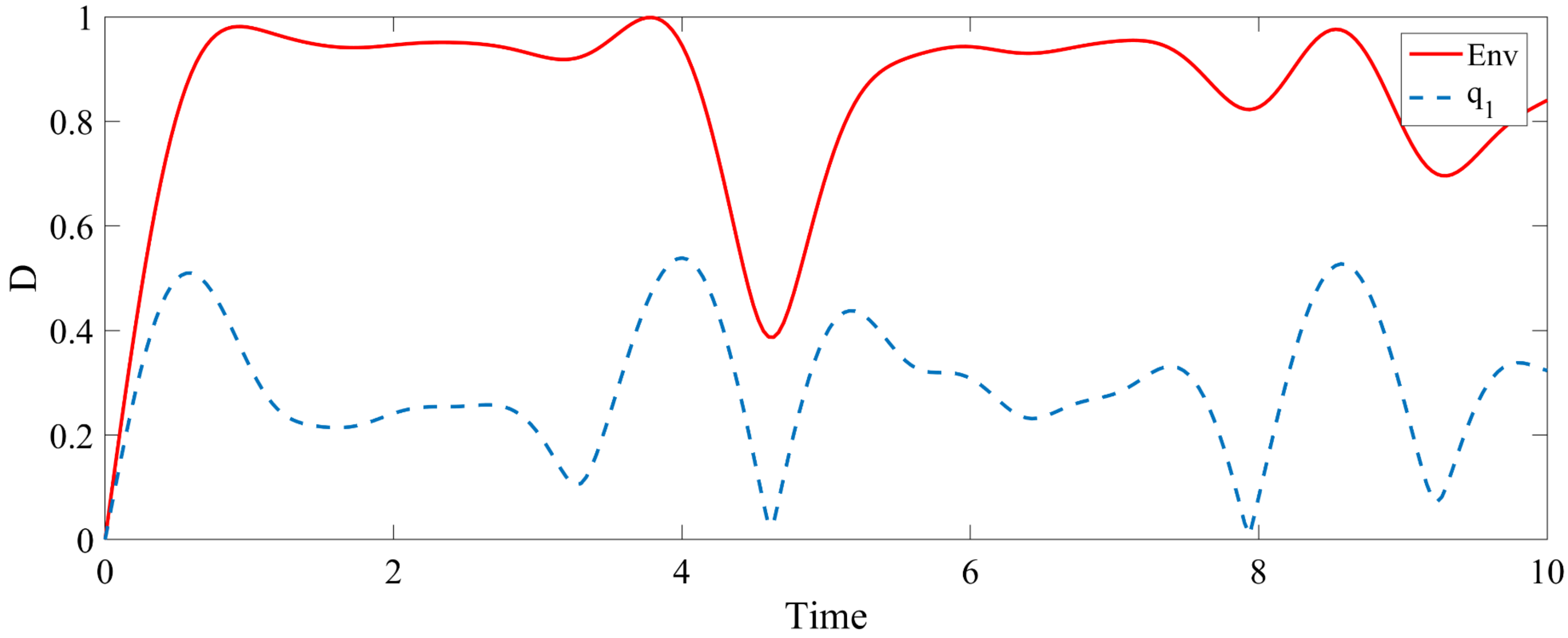


Qubit by Qubit

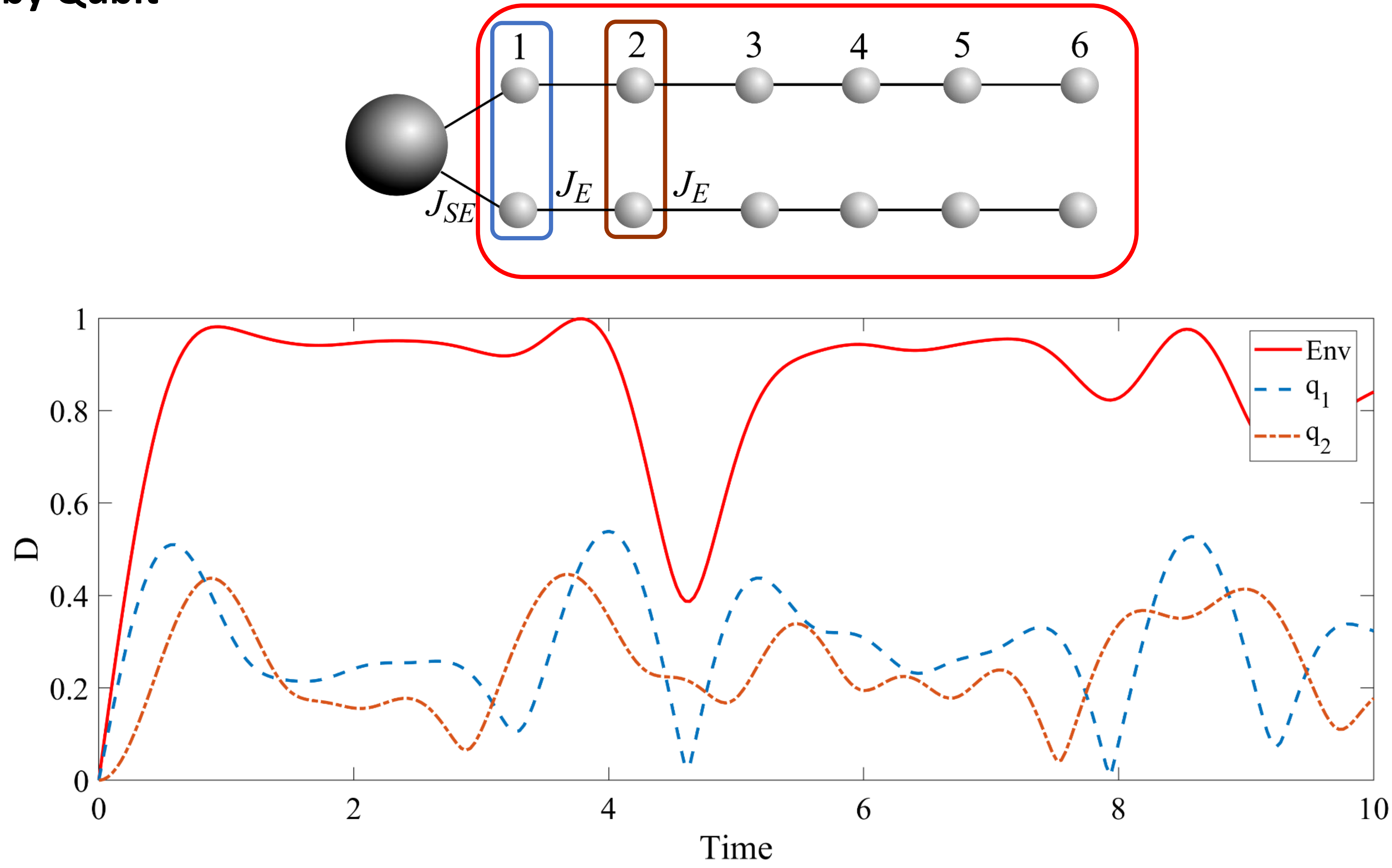


Qubit by Qubit

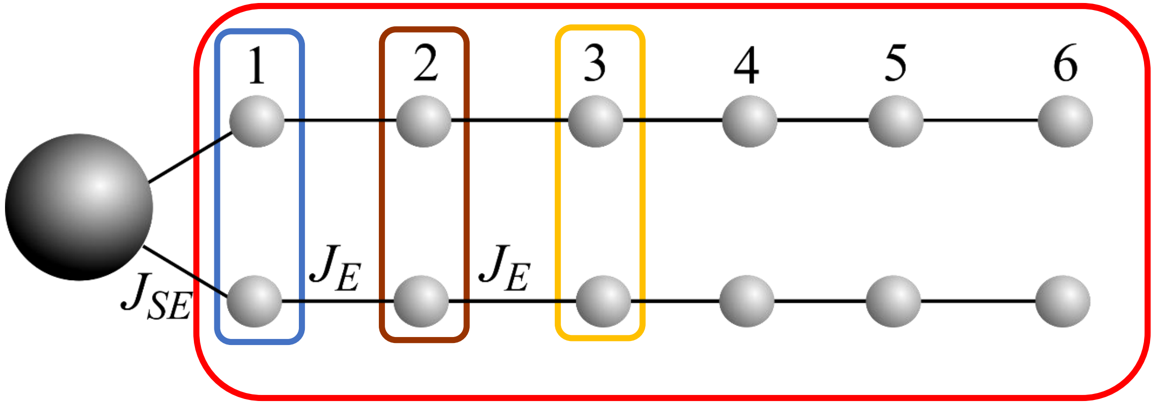


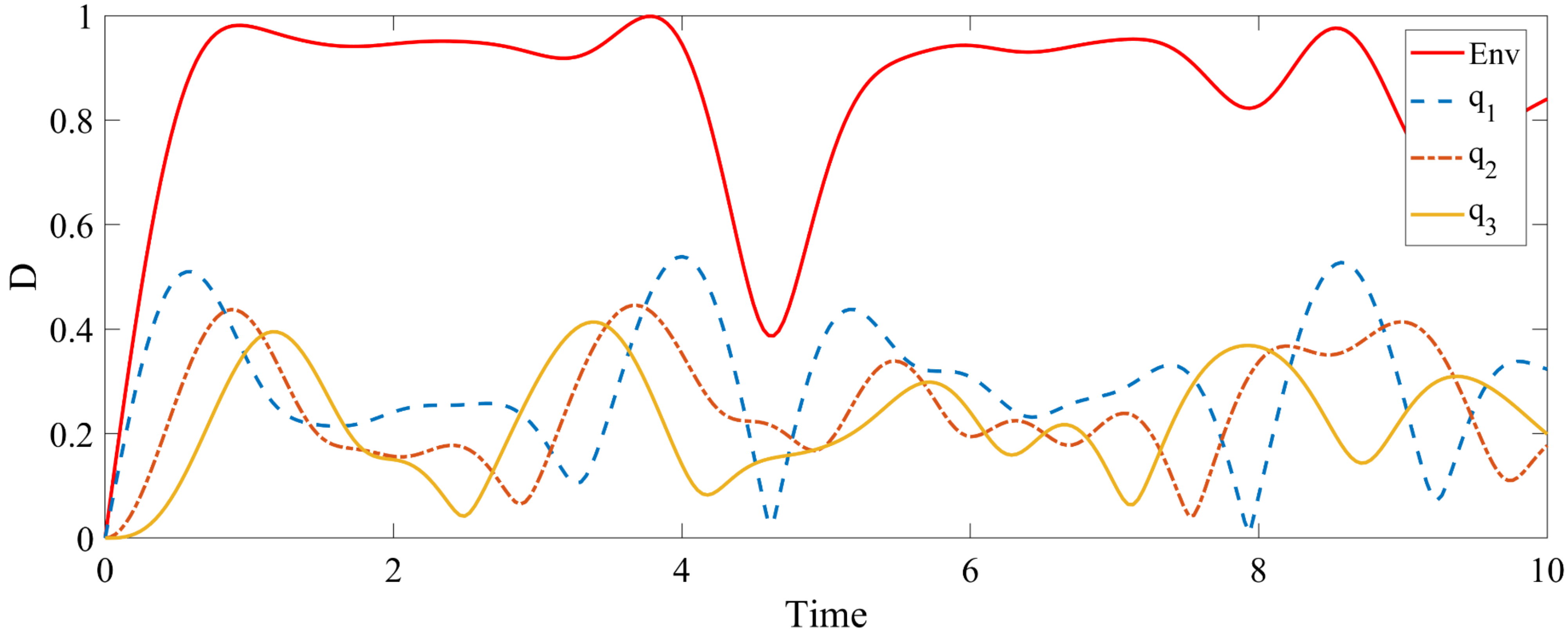


Qubit by Qubit

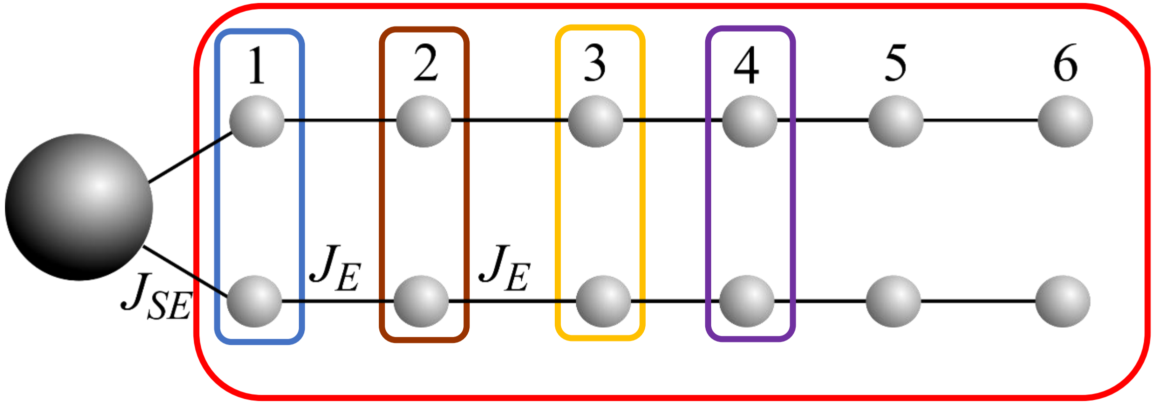


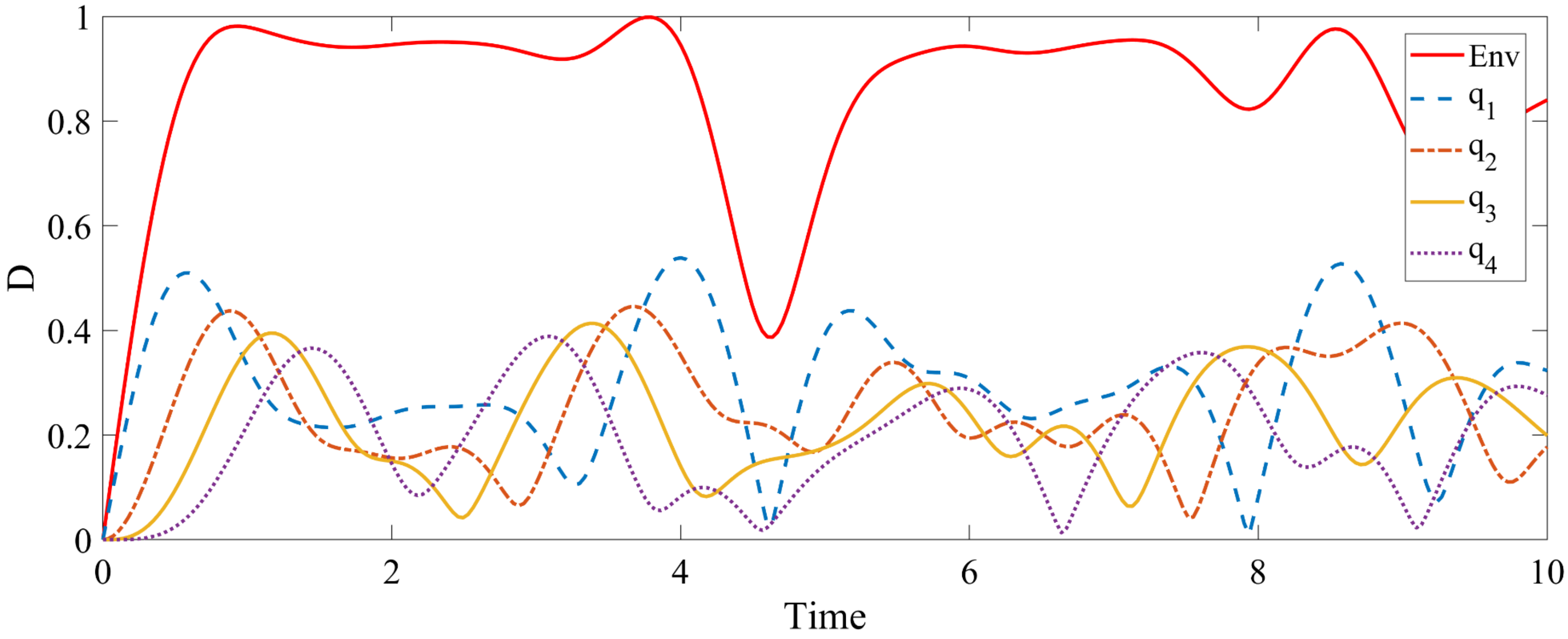
Qubit by Qubit



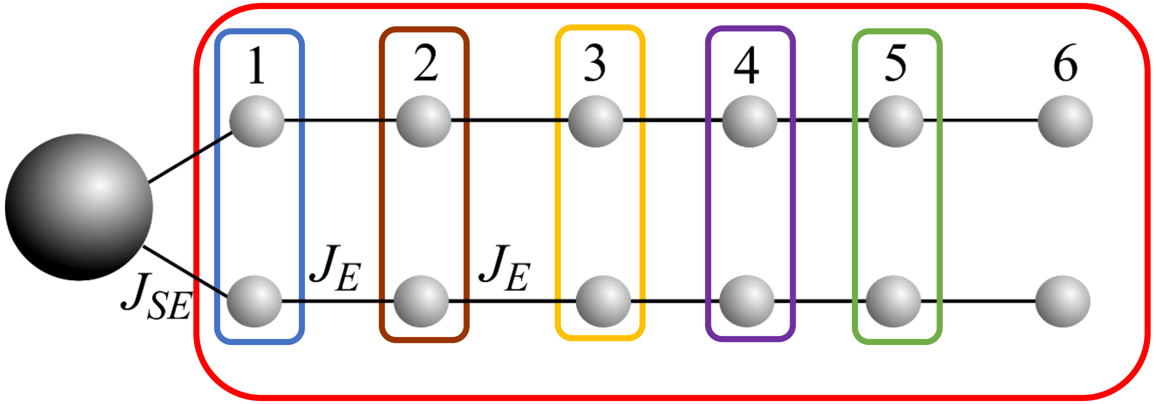


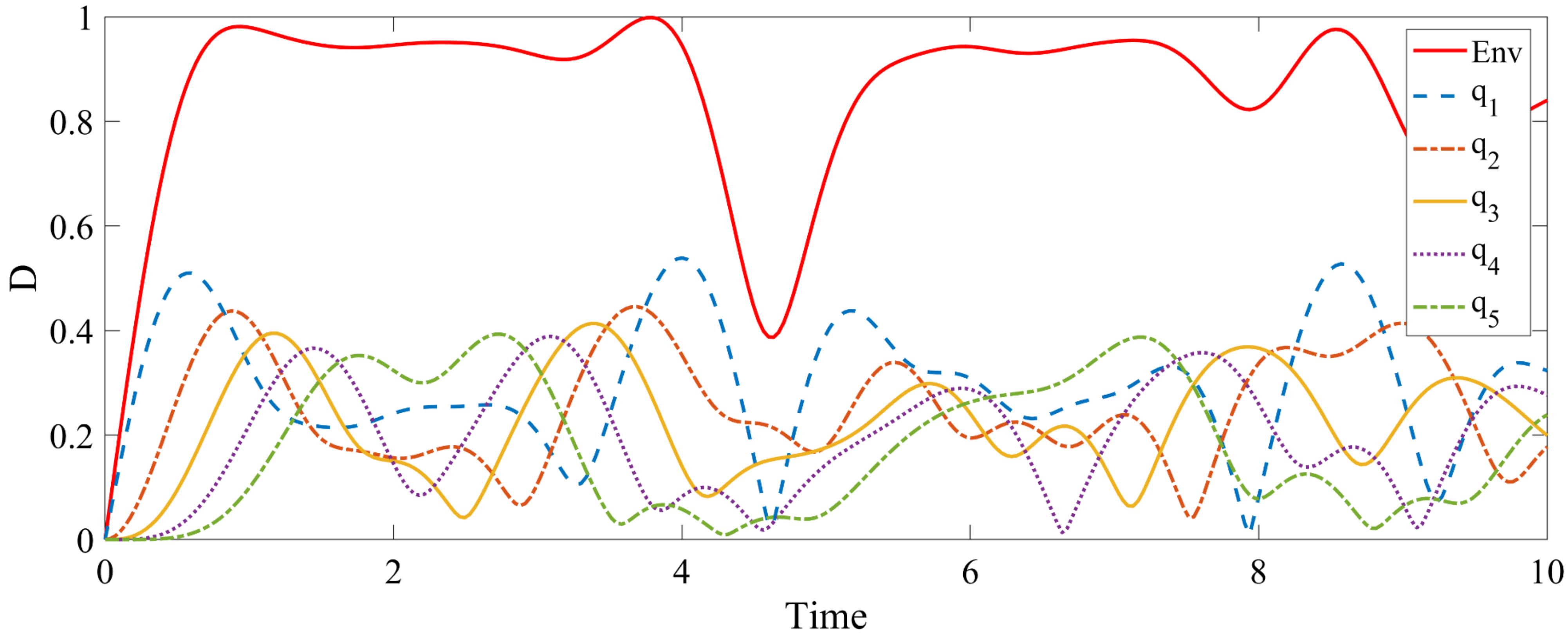
Qubit by Qubit



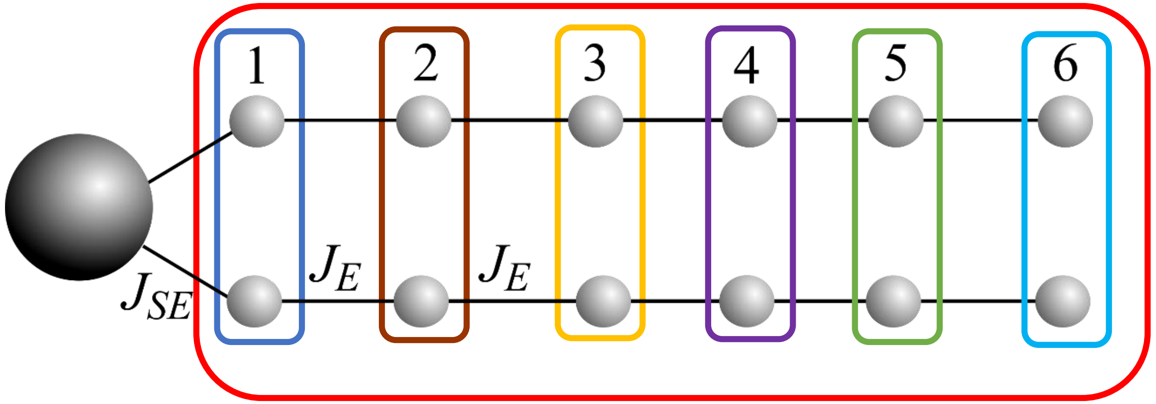


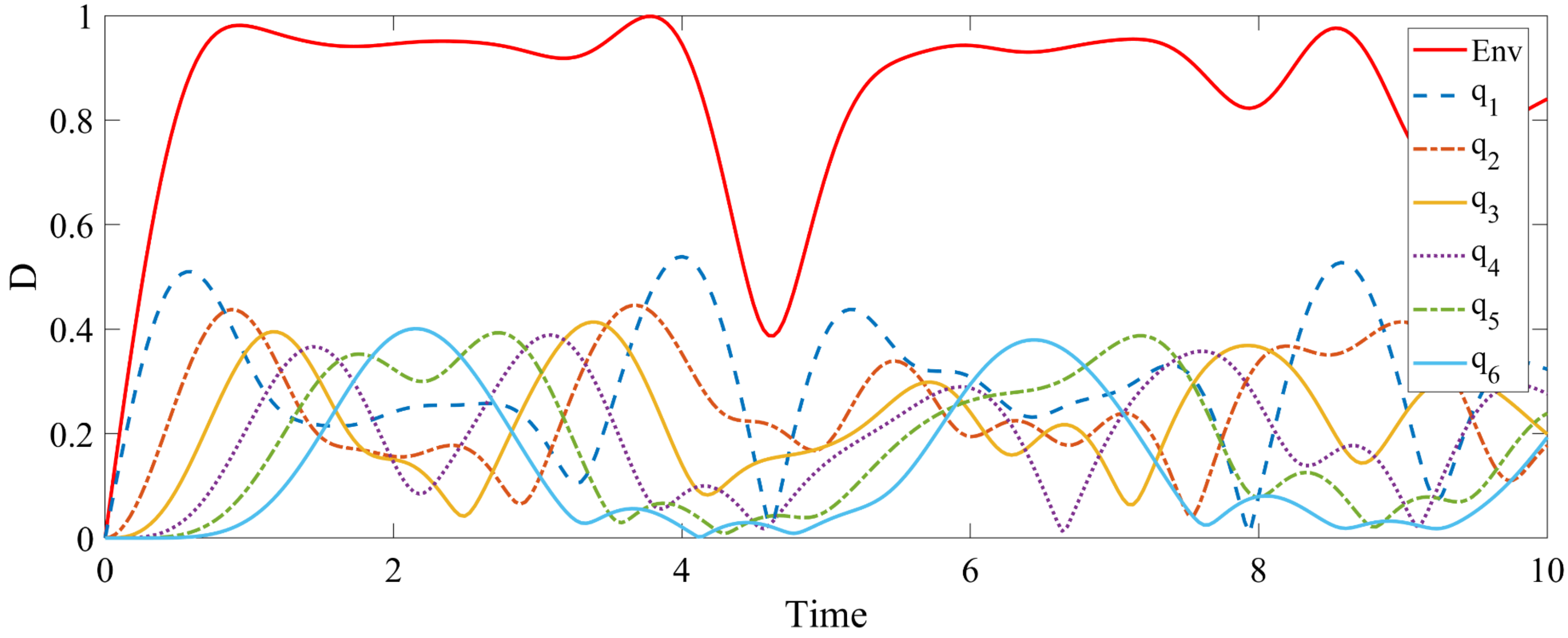
Qubit by Qubit



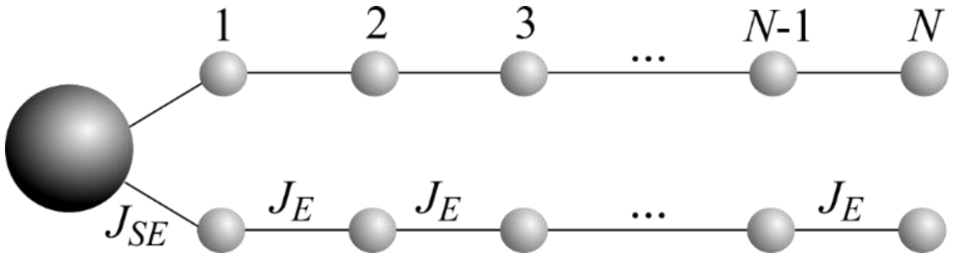


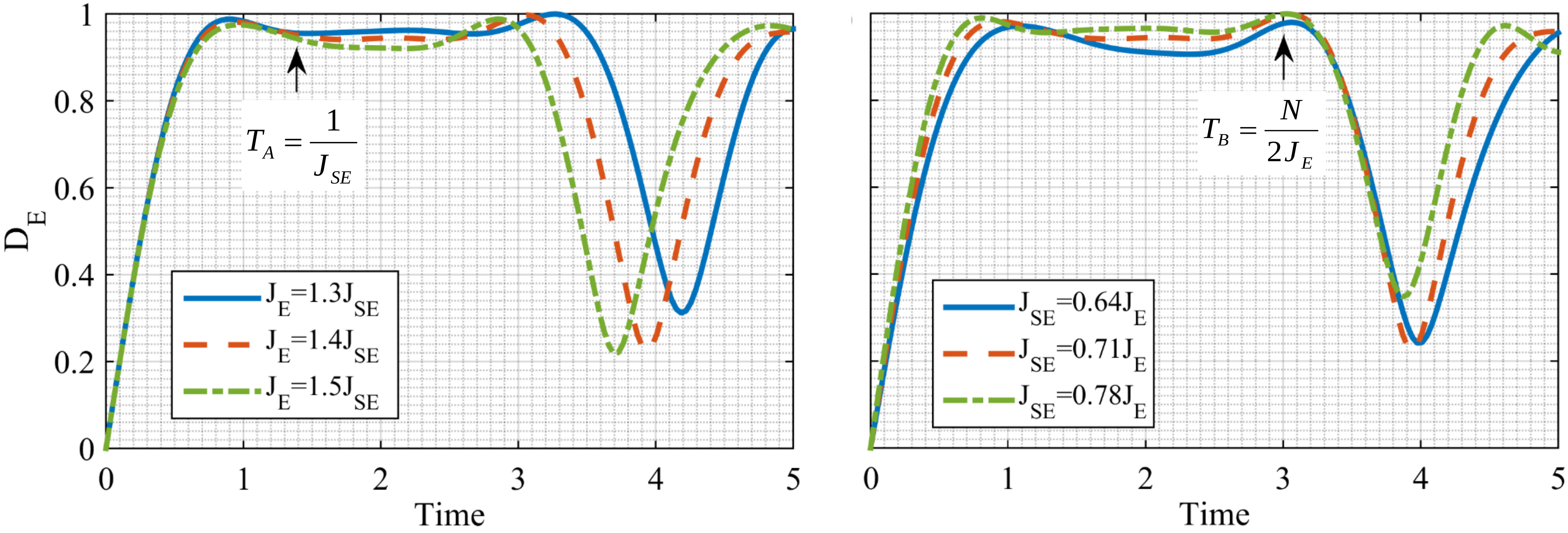
Qubit by Qubit





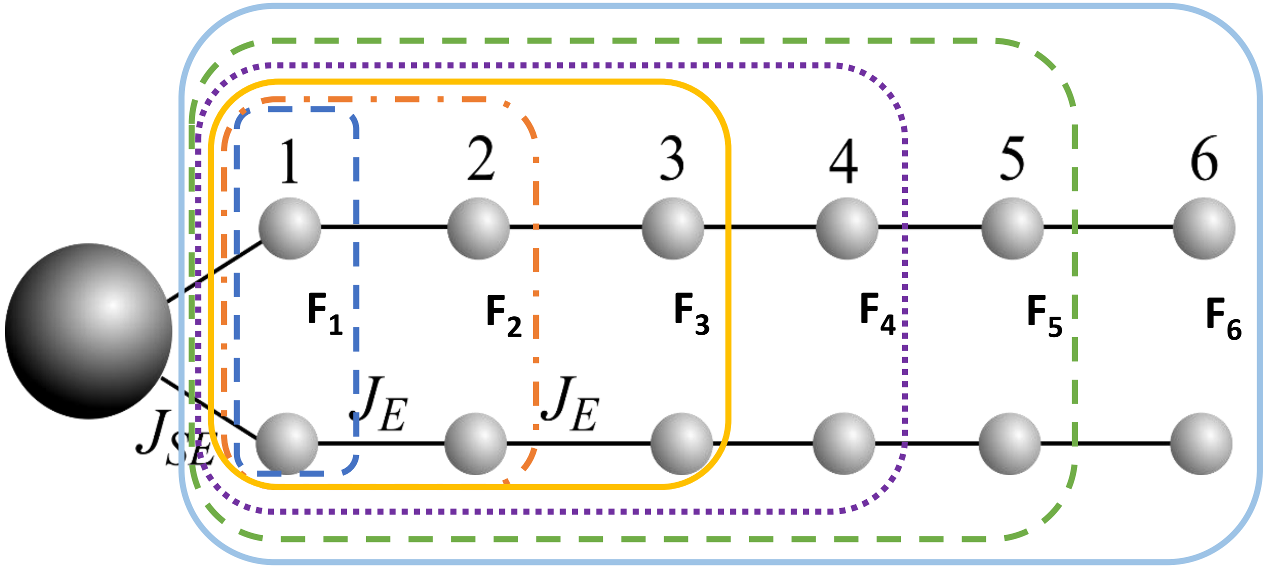
Relationship between coupling constants and number of qubits





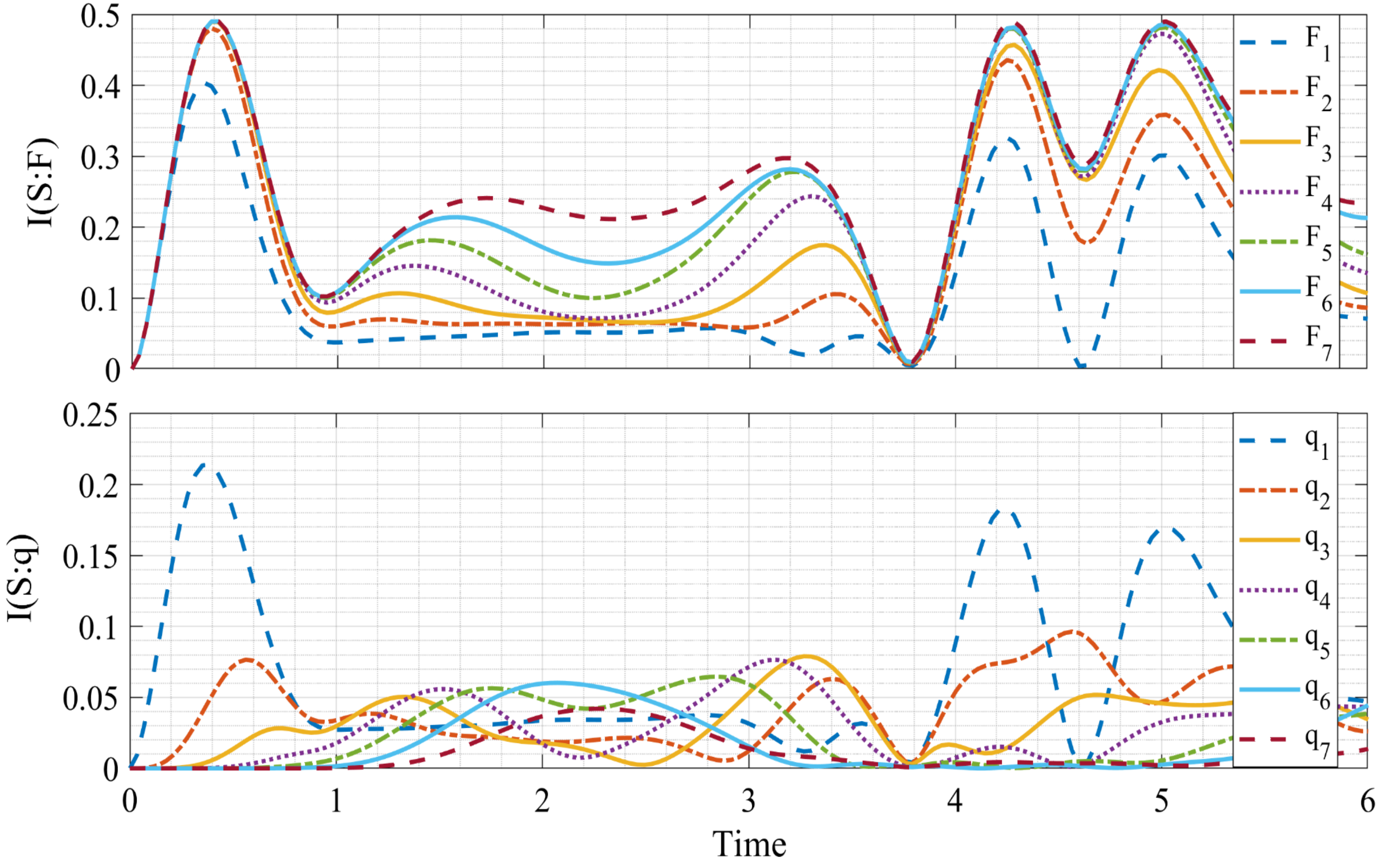
Quantum Darwinism

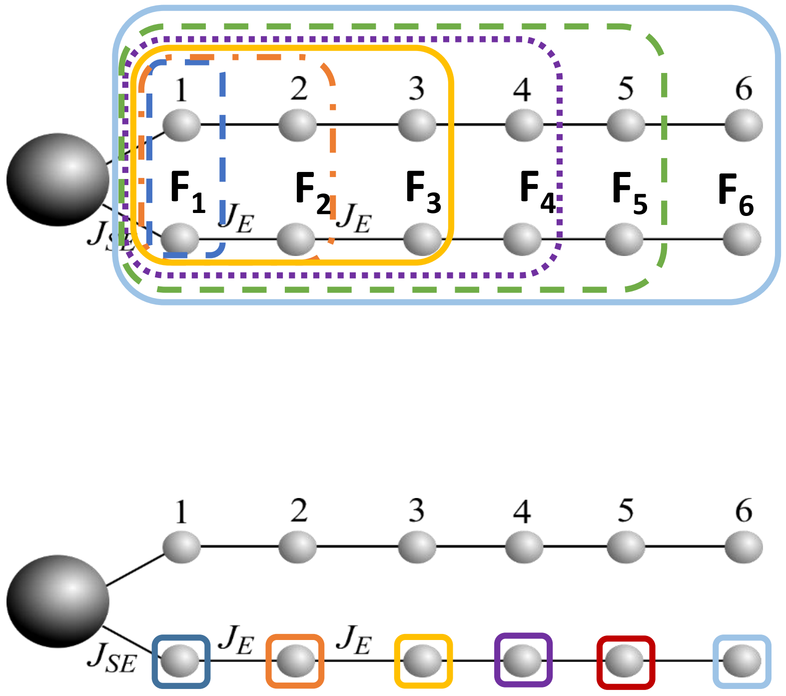
Same amount of information about the system in each environment fragment.



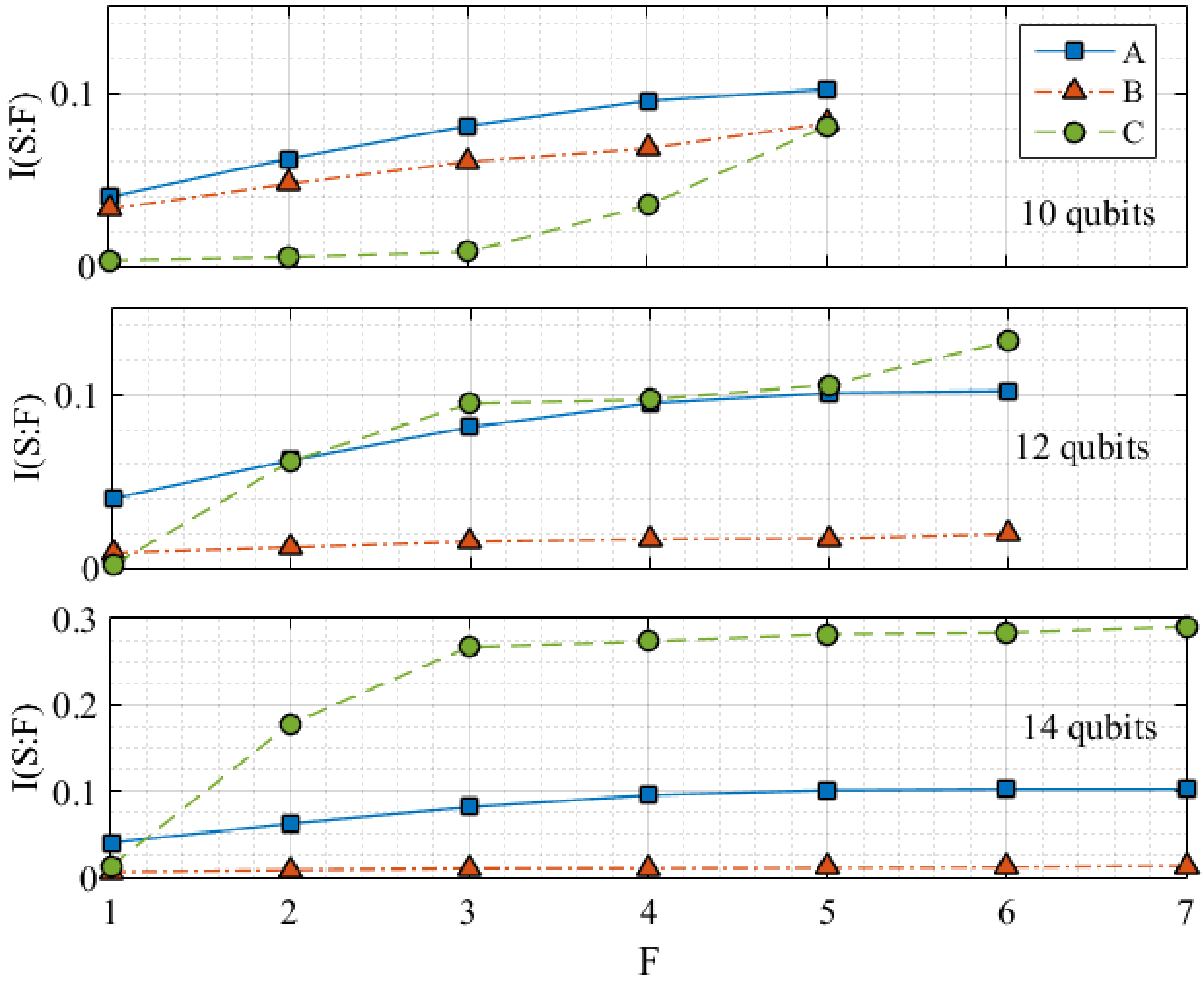
Mutual information: $$I(S:F_k) = S(\rho_S) + S(\rho_{F_k}) - S(\rho_{SF_k})$$

Quantum Darwinism - Mutual Information



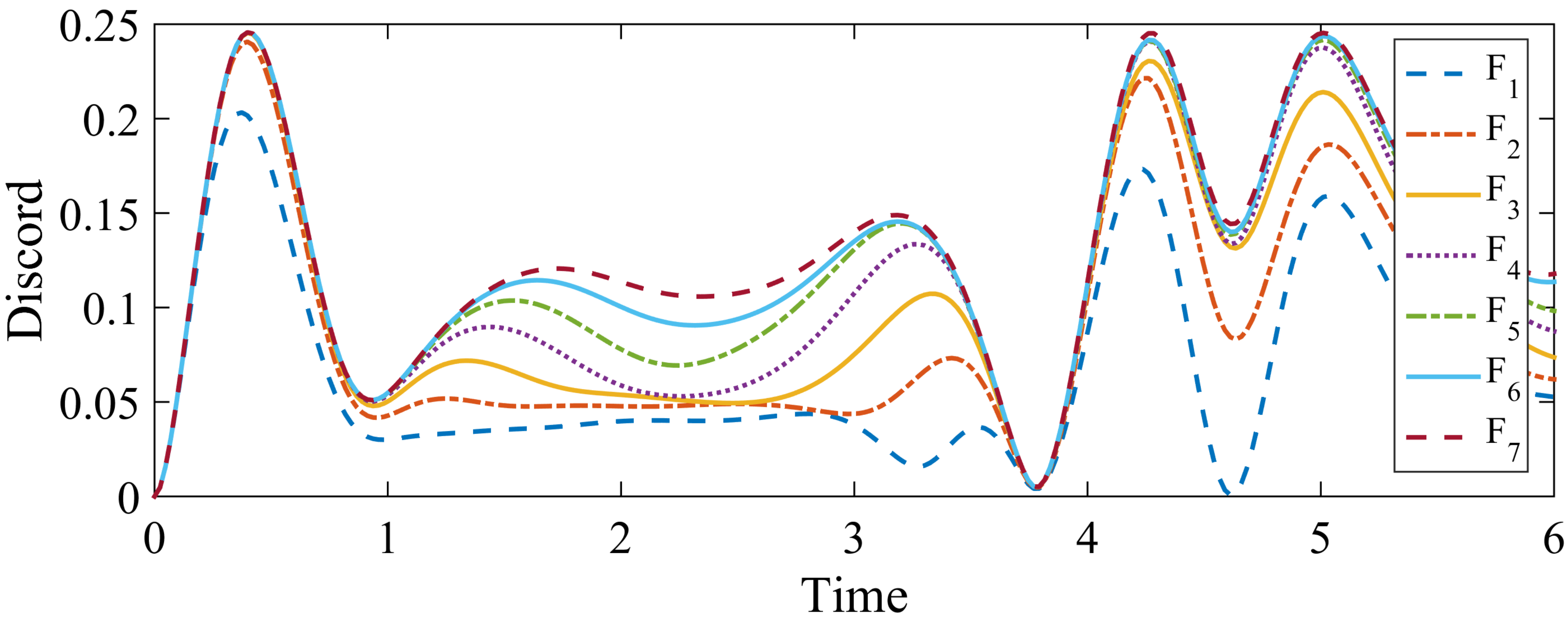


Quantum Darwinism - Mutual Information X Fragment



Quantum Darwinism - Discord

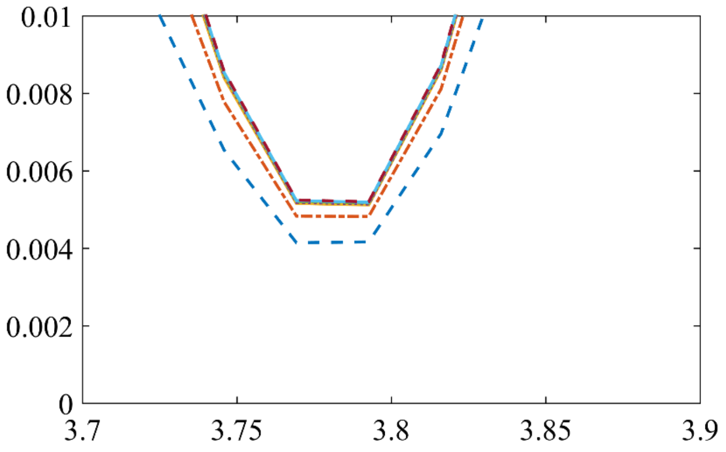
$$D(E \mid S) = \min_{\{P_k\}} \sum_k p_k S(\rho_{E|k}) + S(\rho_S) - S(\rho_{SE})$$

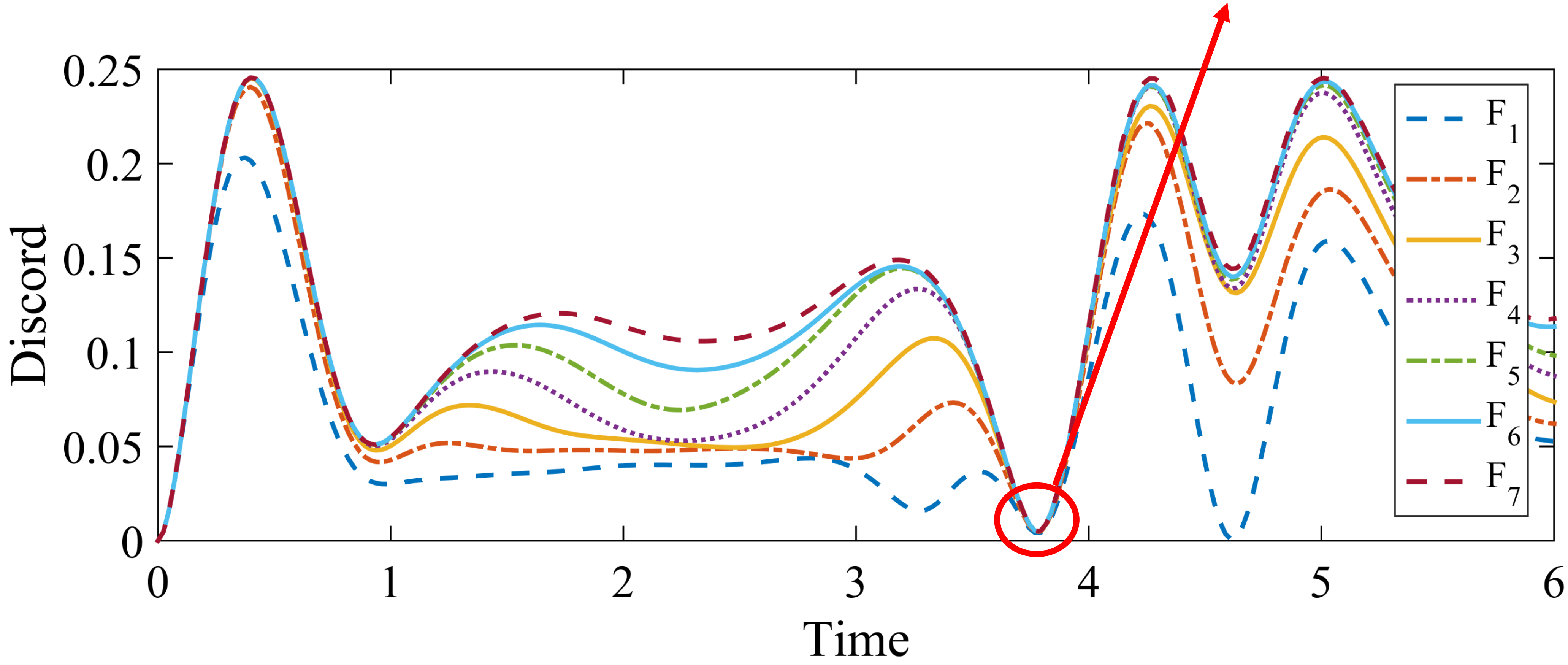


Quantum Darwinism - Discord

$$D(E|S) = \min_{\{P_k\}} \sum_k p_k S(\rho_{E|k}) + S(\rho_S) - S(\rho_{SE})$$

There is quantum Darwinism but no strong quantum Darwinism.





Conclusion

- We checked how information is transferred from the system qubit to the environment and back again. We also show how such dynamics occur within the environment, qubit by qubit.
- We show how couplings affect the time to send and return information in an environment described through two chains of qubits.
- Our system has characteristics of Quantum Darwinism in some points of sending and returning information from the system to the environment.
- However, these points do not configure strong Darwinism.

Thanks!