Einselection and Quantum Thermodynamics of Small Systems Strongly Interacting with Environments

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RALF EICHHORN,

“Let us remind you that the program is intended to discuss open questions and new ideas in a lively atmosphere. Accordingly, we would prefer talks on such open questions,

but overviews of past work and/or historical perspectives are also welcome.”

Contents

Thermalization and Decoherence in Energy Eigenbasis

Thermalization: $\rho_0 \quad \Longrightarrow \quad \rho_{\mathrm{G}} = \frac{1}{Z} e^{-\beta H}$ (Gibbs state)

Gibbs state is very special.

- Diagonal in the energy eigenbasis
- Decoherence in the energy eigenbasis
- Decoherence is induced by the environment
- Why and how does the environment select the energy eigenbasis?
- Does it have to be the energy eigenbasis?
- If not, what else is possible?
- In what basis decoherence happens in non-equilibrium steady state?

Quantum Measurement Postulate (Projective Measurement)

system state

$$|\psi_{\mathrm{s}}\rangle = \sum_i c_i |\omega_i\rangle$$

observable

$$\hat{\Omega} |\omega_i\rangle = \omega_i |\omega_i\rangle$$

probability

$$P_i = |c_i|^2$$

Collapse of wavefunction

before measurement

$$\rho_< = \sum_{ij} c_i c_j^* |\omega_i\rangle\langle\omega_j|$$

$\Rightarrow$ measurement

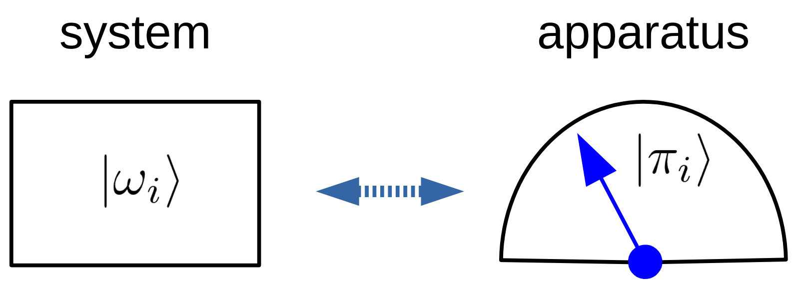
after measurement

$$\rho_> = \sum_i |c_i|^2 |\omega_i\rangle\langle\omega_i| = \sum_i |\omega_i\rangle\langle\omega_i| \rho_< |\omega_i\rangle\langle\omega_i|$$

Decoherence in Observable Basis

- Decoherence happens for different basis depending on what you measure.
- If the decoherence is induced by the environment, how does the environment know what you measure?

von Neumann - Everett Theory of measurement.



$|\pi_i\rangle$ pointer state

entanglement $$|\psi_{\rm SA}\rangle = \sum_i c_i \, |\omega_i\rangle \otimes |\pi_i\rangle$$

This correlation does not solve the problem. $$|\psi_{\rm SA}\rangle = \sum_i d_i \, |\nu_i\rangle \otimes |\xi_i\rangle$$

We need collapse of wavefunction

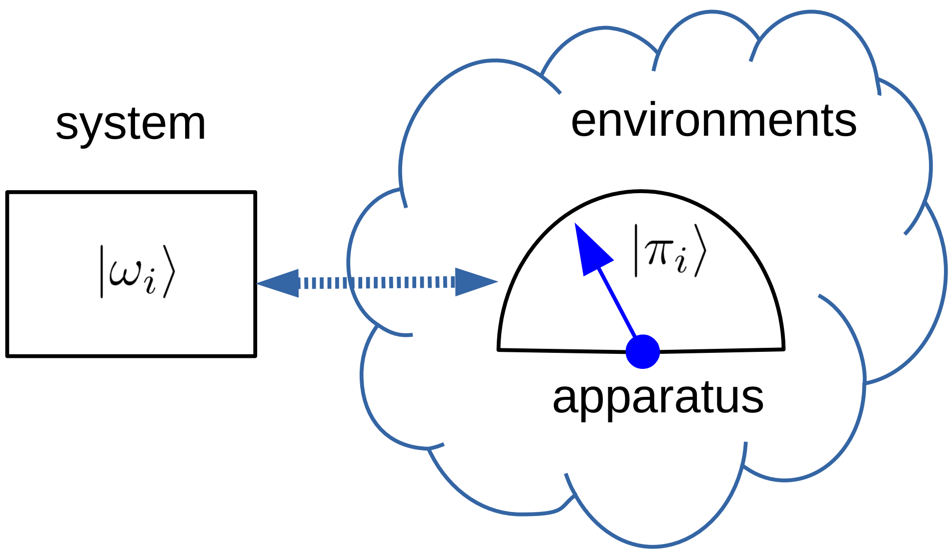
before measurement

after measurement

$$\rho_{\rm pure} = \sum_j \sum_j c_i c_j^* \, |\omega_i\rangle\langle\omega_j| \otimes |\pi_i\rangle\langle\pi_j| \quad \Rightarrow \quad \rho_{\rm mixed} = \sum_i |c_i|^2 \, |\omega_i\rangle\langle\omega_i| \otimes |\pi_i\rangle\langle\pi_i|$$

J. von Neumann (1955), H. Everett III (1957)

Environment-induced Decoherence



$$
\begin{aligned}
|\Psi\rangle &= \sum_i c_i\, |\omega_i\rangle \otimes |\pi_i\rangle \otimes |\mathcal{E}_i\rangle \\
&\neq \sum_i d_i\, |\nu_i\rangle \otimes |\xi_i\rangle \otimes |\mathcal{F}_i\rangle
\end{aligned}
$$

$$
\begin{aligned}
\rho_{\mathrm{SA}} &= \mathrm{tr_B}\, |\Psi\rangle\langle\Psi| \\
&= \sum_i |c_i|^2\, |\omega_i\rangle\langle\omega_i| \otimes |\pi_i\rangle\langle\pi_i|
\end{aligned}
$$

Environment picks pointer states and induces decoherence among pointer states.

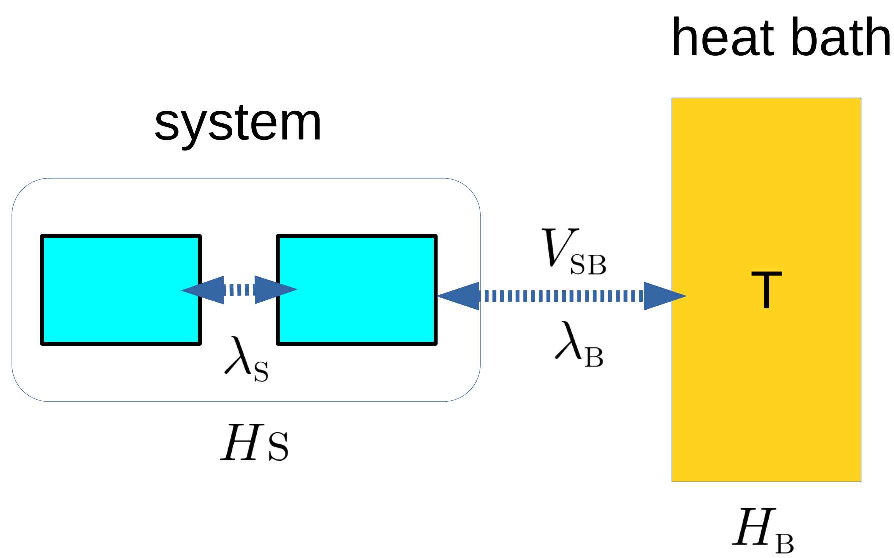
Why is the pointer state? → V_{AE} picks the pointer state.

When $\hat{V}_{\mathrm{AE}}$ is dominant, the pointer states are determined by:

$$\left[\hat{\Pi} \otimes I^{\mathrm{E}}, \hat{V}_{\mathrm{AE}}\right] = 0 \qquad \hat{\Pi}\, |\pi_i\rangle = \pi_i\, |\pi_i\rangle$$

Environment-indeuced Eigenselction (Superselection) W. Zurek (1981, 1982)

Thermodynamic Steady State and Eigenselection



$$\lambda_{\mathrm{B}} \ll 1 \qquad \rho_{\mathrm{S}} \quad \rightarrow \quad \frac{1}{Z} e^{-\beta H_{\mathrm{s}}}$$

Claims

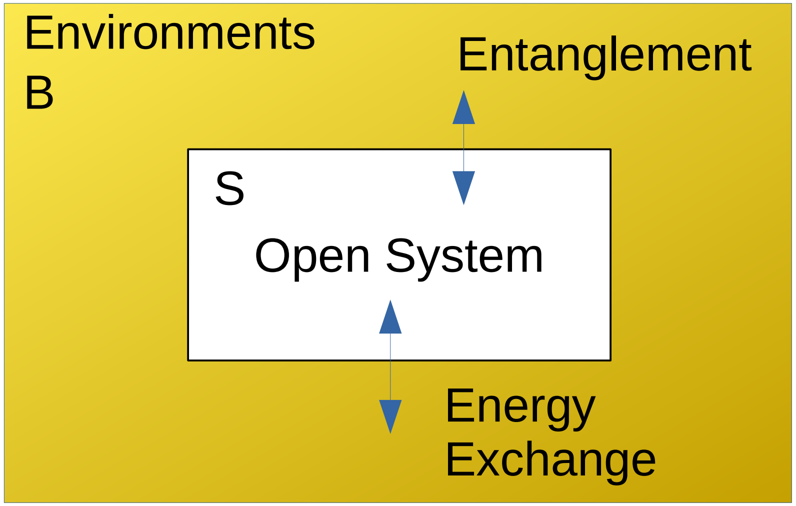
$$\lambda_{\mathrm{B}} \gg |H_{\mathrm{S}}|, \quad \rho_{\mathrm{S}} \quad \rightarrow \quad \frac{1}{Z} \sum_i |\pi_i\rangle\langle\pi_i|\, e^{-\beta H_{\mathrm{s}}}\, |\pi_i\rangle\langle\pi_i|$$

$$\lambda_{\mathrm{B}} \sim |H_{\mathrm{S}}|, \quad \langle\pi_i|\rho_{\mathrm{S}}|\pi_i\rangle \approx \frac{1}{Z} \langle\pi_i|e^{-\beta H_{\mathrm{s}}}|\pi_i\rangle$$

Projective measurement by the environment

$$\left[V_{\mathrm{SB}}, \hat{\Pi}\right], \qquad \hat{\Pi}\,|\pi\rangle = \pi_i\,|\pi_i\rangle$$

Open Quantum Systems



Assuming that the whole system is completely isolated, how does the system evolve in time?

Hamiltonian: $H_{\mathrm{SB}} = H_{\mathrm{S}} \otimes I_{\mathrm{B}} + I_{\mathrm{S}} \otimes H_{\mathrm{B}} + V_{\mathrm{SB}}$

Unitary Evolution Of the Total System: $i\frac{\partial \rho_{\mathrm{SB}}}{\partial t} = [H_{\mathrm{SB}}, \rho_{\mathrm{SB}}]$

State of the System: $\rho_{\mathrm{S}}(t) = \mathrm{tr}_{\mathrm{B}}[\rho_{\mathrm{SB}}(t)]$

Dynamics of System State

Separable Hamiltonian: $H_{\mathrm{SB}} = H_{\mathrm{S}} \otimes I_{\mathrm{B}} + I_{\mathrm{S}} \otimes H_{\mathrm{B}} + \lambda_{\mathrm{B}} X_{\mathrm{S}} \otimes Y_{\mathrm{B}}$

$$i\frac{\partial}{\partial t}\rho_{\mathrm{SB}} = [H_{\mathrm{SB}}, \rho_{\mathrm{SB}}] \quad \underset{\mathrm{tr_B}}{\Longrightarrow} \quad i\frac{\partial}{\partial t}\rho_{\mathrm{S}} = [H_{\mathrm{S}}, \rho_{\mathrm{S}}] + \lambda_{\mathrm{B}}[X_{\mathrm{S}}, \eta_{\mathrm{S}}]$$

$$\eta_{\mathrm{S}} = \mathrm{tr_B}\left[Y_{\mathrm{B}}\rho_{\mathrm{SB}}\right]$$

system-dependent mean displacement of environment

If there is no correlation:

$$\rho_{\mathrm{SB}} = \rho_s \otimes \rho_{\mathrm{B}} \Longrightarrow \eta_{\mathrm{S}} = \rho_{\mathrm{S}} \langle Y_{\mathrm{B}} \rangle$$

If η_{S} is a functional of ρ_{S}, then we have a self-consistent equation of motion for ρ_{S} (ex. Lindbrad equation).

Born-Markovian Approximation: Quantum Master Equation

- Weak Coupling between S and B: Born Approximation

$$\rho_{\mathrm{SB}}(t) = \rho_{\mathrm{S}}(t) \otimes \rho_{\mathrm{G}}$$

- Short correlation time for B: Markovian Approximation
- Other approximations: Secular, Rotating Wave

$$\frac{\partial \rho_{\mathrm{S}}}{\partial t} = -i\left[\tilde{H}_{\mathrm{S}}, \rho_{\mathrm{S}}\right] + D[\rho_{\mathrm{S}}]$$

Dissipator

In energy eigenbasis,

- Off-diagonal element vanishes very quickly (Decoherence)
- The transition between eigenstates is incoherent.
  The dynamics is semi-classical.
- Correlation between S and B is considered only perturbatively.
- Steady state exists: Gibbs state.

Not suited for the present issues.

Model: A Pair of Q-bits

Coupled Q-bits

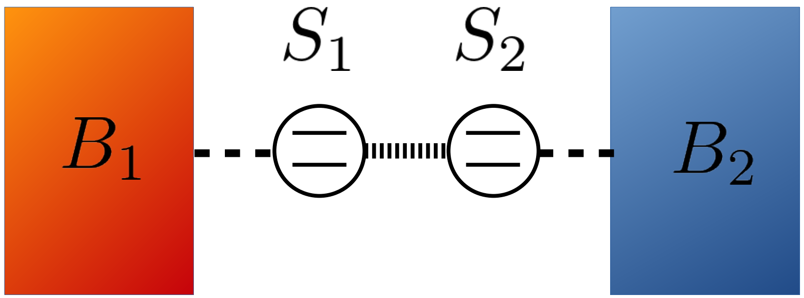
$$\hat{H}_S = \frac{\omega_0}{2}\hat{\sigma}^z_{S_1} + \frac{\omega_0}{2}\hat{\sigma}^z_{S_2} + \lambda_S\left(\hat{\sigma}^+_{S_1}\hat{\sigma}^-_{S_2} + \hat{\sigma}^-_{S_1}\hat{\sigma}^+_{S_2}\right)$$

$$E_1 = -\omega_0, \quad |e_1\rangle = |--\rangle$$

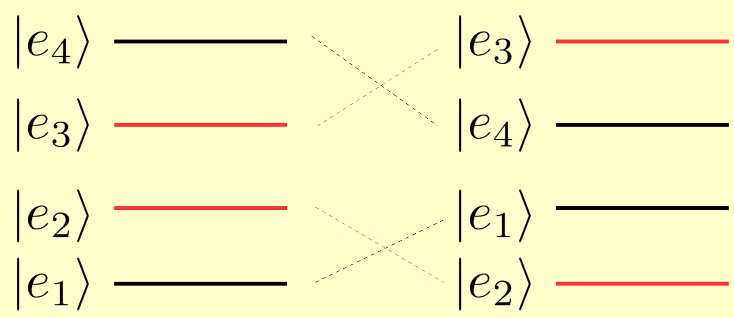
$$E_2 = -\lambda_s, \quad |e_2\rangle = \frac{1}{\sqrt{2}}\left(|+-\rangle - |-+\rangle\right)$$

$$E_3 = +\lambda_s, \quad |e_3\rangle = \frac{1}{\sqrt{2}}\left(|+-\rangle + |-+\rangle\right)$$

$$E_4 = +\omega_0, \quad |e_4\rangle = |++\rangle$$



$\lambda_S > \omega_0$ $\lambda_S < \omega_0$



Not Entangled at T=0

Entangled at T=0

Boson Baths

$$\hat{H}_{B_i} = \sum_k \omega_{B_i}(k)\,\hat{a}^\dagger_{B_i}(k)\hat{a}_{B_i}(k), \qquad i = 1, 2$$

System-Bath Coupling

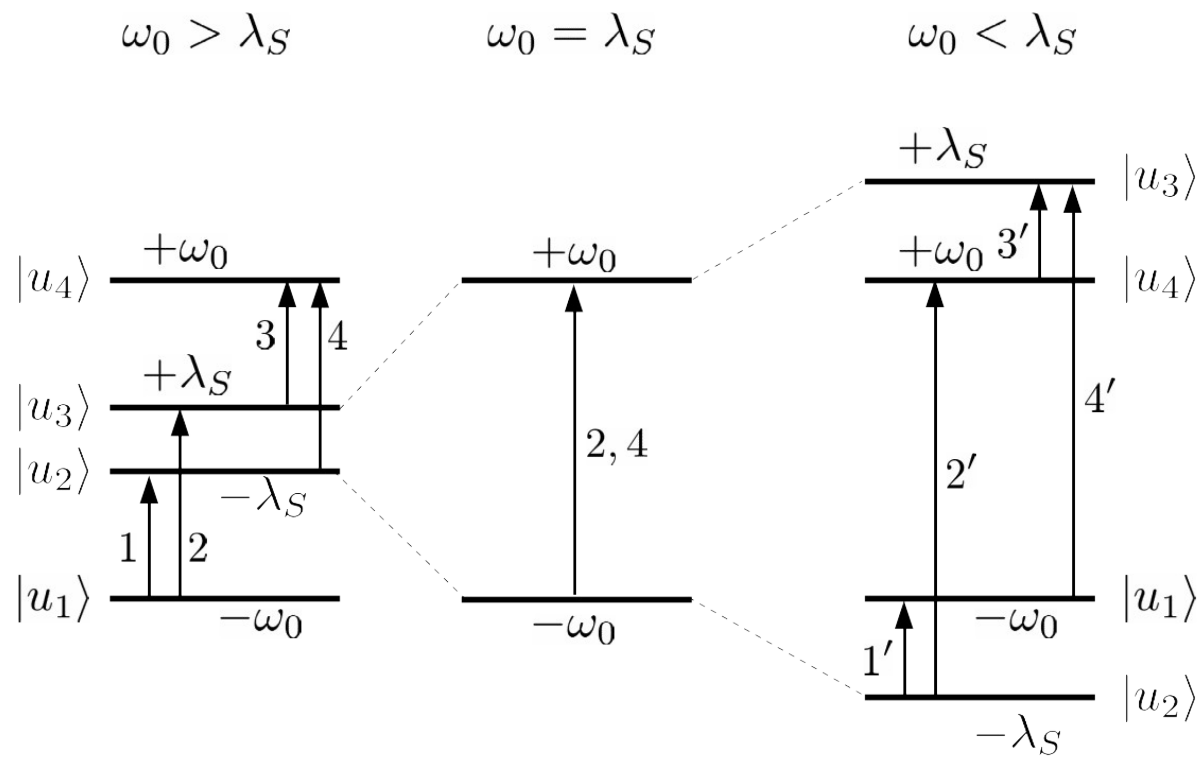
$$\hat{V}_{S_iB_i} = \hat{X}_{S_i} \otimes \hat{Y}_{B_i}$$

$$\hat{X}_{S_i} = \sigma^+_{S_i} + \sigma^-_{S_i}$$

$$\hat{Y}_{B_i} = \sum_k \epsilon_{B_i}(k)\left[\hat{a}^\dagger_{B_i}(k) + \hat{a}_{B_i}\right]$$

Drude-Lorenzian model

$$g_{B_i}(\omega) = \sum_k |\epsilon_{B_i}(k)|\delta\left(\omega - \omega_{B_i}(k)\right) = \frac{2\lambda_{B_i}\gamma_{B_i}\omega}{\omega^2 + \gamma^2_{B_i}}$$


$\omega_0 > \lambda_S$
$\omega_0 = \lambda_S$
$\omega_0 < \lambda_S$
$|u_4\rangle$
$+\omega_0$
$+\lambda_S$
$|u_3\rangle$
$|u_2\rangle$
$-\lambda_S$
$|u_1\rangle$
$-\omega_0$
1
2
3
4
$+\omega_0$
$-\omega_0$
2, 4
$+\lambda_S$
$|u_3\rangle$
$+\omega_0$
$|u_4\rangle$
$3'$
$4'$
$2'$
$|u_1\rangle$
$-\omega_0$
$1'$
$|u_2\rangle$
$-\lambda_S$

Exact Solution: Step 1

$$H_{\text{total}} = \underbrace{H_{\text{S}} + H_{\text{B}_1} + H_{\text{B}_2}}_{H_0} + \underbrace{X_{\text{S}_1} \otimes Y_{\text{B}_1}}_{V_1} + \underbrace{X_{\text{S}_2} \otimes Y_{\text{B}_2}}_{V_2}$$

Interaction Picture

$$i\frac{\partial}{\partial t}\rho_{\text{SB}} = \sum_j [V_j(t), \rho_{\text{SB}}]$$

Unitary Evolution of the total system

$$\rho_{\text{SB}}(t) = \left\{ \overleftarrow{T} \prod_j e^{-i\int_{t_0}^{t} \hat{V}_j(s)\mathrm{d}s} \right\} \rho_{\text{SB}}(t_0) \left\{ \overrightarrow{T} \prod_\ell e^{i\int_{t_0}^{t} \hat{V}_\ell(s)\mathrm{d}s} \right\}$$

Exact Solution: Step 2

$$\rho_{\rm S}(t) = {\rm tr}_{\rm B}\, \rho_{\rm SB}(t)$$

This partial trace can be computed if,

1) Initial state: $\rho_{\rm SB}(t_0) = \rho_{\rm S}(t_0) \otimes \rho_{\rm B_1}(t_0) \otimes \rho_{\rm B_2}(t_0)$

2) $\rho_{\rm B_j}(t_0)$ is a quasi-free state. $\rho_{\rm B_j}(t_0) = \dfrac{1}{Z_j} e^{-\beta_j \hat{H}_{\rm B_j}}$

$$\rho_{\rm S}(t) = \overleftarrow{\mathcal{T}} \prod_j e^{-\int_{t_0}^{t}\int_{t_0}^{t_1} {\rm d}t_1 {\rm d}t_2 \mathcal{K}_j(t_1,t_2)} \rho_{\rm S}(t_0)$$

$$\mathcal{K}_j(t_1,t_2) = \mathcal{S}_j^-(t_1)\ {\rm Im}\, C_j(t_1-t_2)\, \mathcal{S}_i^-(t_2) + i\mathcal{S}_j^-(t_1)\ {\rm Re}\, C_j(t_1-t_2), \mathcal{S}_j^+(t_2)$$

$$\mathcal{S}_j^{\pm}(t) = \left[\hat{X}_{S_j}(t),\ \cdot\ \right]_{\pm}$$

$$C_j(t_1-t_2) = \left\langle \hat{Y}_{\rm B_j}(t_1)\hat{Y}_{\rm B_j}(t_2)\right\rangle_{t_0}$$

Exact Solution: Step 3

$$i\frac{\partial}{\partial t}\rho_{\mathrm{S}} = \sum_j \left[X_{\mathrm{S}_j}(t), \eta_j\right]$$

$$\begin{aligned}\eta_j(t) &= -i\overleftarrow{\mathcal{T}}\int_{t_0}^{t} \mathrm{d}s \left\{\mathrm{Re}\, C_j(t-s)\mathcal{S}_j^-(s) + i\,\mathrm{Im}\, C_j(t-s)\mathcal{S}_j^+(s)\right\} \\ &\times \prod_j e^{-\int_{t_0}^{t}\mathrm{d}t_1\int_{t_0}^{t_1}\mathrm{d}t_2\mathcal{K}_j(t_1,t_2)}\,\rho_S(0).\end{aligned}$$

Numerically tractable if

$$C_j(t) = \lambda_{\mathrm{B}_j}\left[c_j e^{-\gamma_j t} + 2\Delta_j\delta(t)\right]$$

$$c_j = 2/\beta_j - \gamma_j\Delta_j - i\gamma_j$$

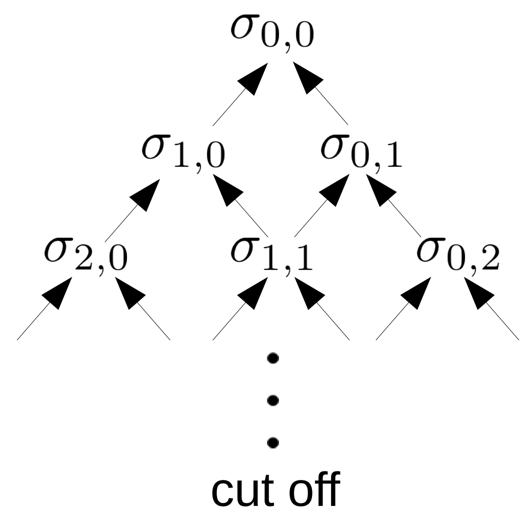
$$\Delta_j = \gamma_j\beta_i/6$$

$$\mathrm{g}_{\mathrm{B}_j}(\omega) = \frac{2\lambda_{\mathrm{B}_j}\gamma_j\omega^{\,2}}{\omega^2+\gamma_j}$$

Hierarchical Equation of Motion (HEOM)   Tanimura-Kubo(1989)

Auxiliary operators

$$\sigma_{n_1,n_2}(t) \;=\; \overleftarrow{\mathcal{T}} \prod_{j=1}^{2} \left\{ \left[-i \int_{t_0}^{t} \mathrm{d}s \, e^{-\gamma_j(t-s)} \mathcal{G}_j(s) \right]^{n_j} \times e^{-\lambda_j \int_{t_0}^{t} \int_{t_0}^{t_1} \mathrm{d}t_1 \mathrm{d}t_2 \mathcal{S}_j^-(t_1) e^{-\gamma_j(t_1-t_2)} \mathcal{G}_j(t_2)} \times e^{-\lambda_{B_j} \Delta_i \int_{t_0}^{t} \mathrm{d}t_1 \mathcal{S}_j^-(t_1) \mathcal{S}_j^-(t_1)} \right\} \rho_S(t_0)$$



$$\mathcal{G}_i(t) = (2/\beta_i - \gamma_{B_i} \Delta_i)\, \mathcal{S}^-(t) - i\gamma_{B_i} \mathcal{S}^+(t).$$

$$\rho_{\mathrm{S}}(t) = \sigma_{0,0}$$

$$\eta_1(t) = \lambda_{\mathrm{B}_1} \left[\sigma_{1,0}(t) - i\Delta_1 \mathcal{S}_1^-(t) \sigma_{0,0}(t) \right]$$

$$\eta_2(t) = \lambda_{\mathrm{B}_2} \left[\sigma_{0,1}(t) - i\Delta_2 \mathcal{S}_2^-(t) \sigma_{0,0}(t) \right]$$

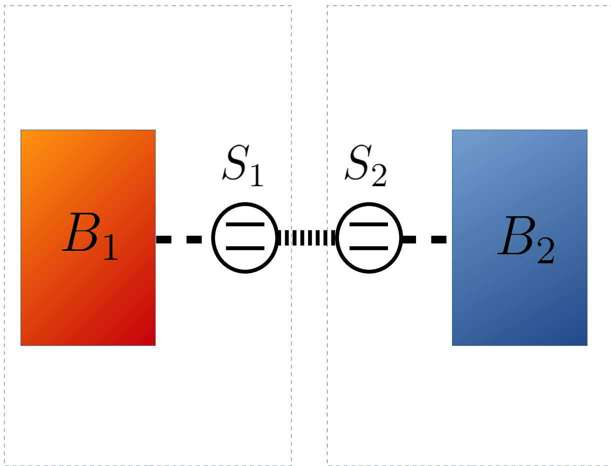
Cut-off at depth=40,
861 auxiliary ops.

8610 couped ODEs

Equation of Motion

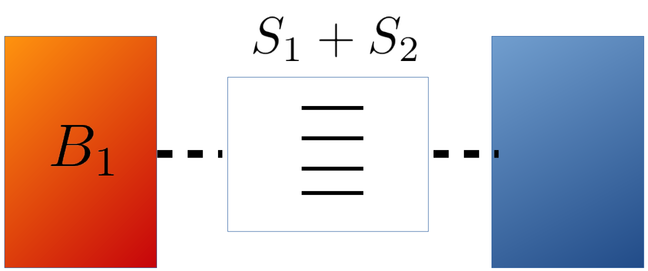
$$\begin{aligned} \frac{\mathrm{d}}{\mathrm{d}t} \sigma_{n_1,n_2}(t) \;=\;& -(\gamma_{B_1} n_1 + \gamma_{B_2} n_2)\, \sigma_{n_1,n_2}(t) \\ & - \left[\lambda_{B_1} \Delta_1 S_1^-(t) S_1^-(t) + \lambda_{B_2} \Delta_2 S_2^-(t) S_2^- t) \right] \sigma_{n_1,n_2}(t) \\ & - \imath\, \lambda_{B_1} \mathcal{S}_1^- \sigma_{n_1+1,n_2}(t) - \imath\, \lambda_{B_2} \mathcal{S}_2^- \sigma_{n_1,n_2+1}(t) \\ & - \imath\, n_1 \lambda_{B_1} \mathcal{G}_1(t) \sigma_{n_1-1,n_2}(t) - \imath\, n_2 \lambda_{B_2} \mathcal{G}_2(t) \sigma_{n_1,n_2-1}(t) \end{aligned}$$

Choice of Basis Sets



Atom Basis

$$
\begin{aligned}
|a_1\rangle &= |{-}{-}\rangle \\
|a_2\rangle &= |{-}{+}\rangle \\
|a_3\rangle &= |{+}{-}\rangle \\
|a_4\rangle &= |{+}{+}\rangle
\end{aligned}
$$



$$H_s\,|e_i\rangle = E_i\,|e_i\rangle$$

$$E = \{-\omega_0, -\lambda_\mathrm{S}, +\lambda_\mathrm{S}. + \omega_0\}$$

Eigen Basis

$$
\begin{aligned}
|e_1\rangle &= |{-}{-}\rangle \\
|e_2\rangle &= \left(|{-}{+}\rangle - |{+}{-}\rangle\right)/\sqrt{2} \\
|e_3\rangle &= \left(|{-}{+}\rangle + |{+}{-}\rangle\right)/\sqrt{2} \\
|e_4\rangle &= |{+}{+}\rangle
\end{aligned}
$$

More Basis Sets

Bell Basis

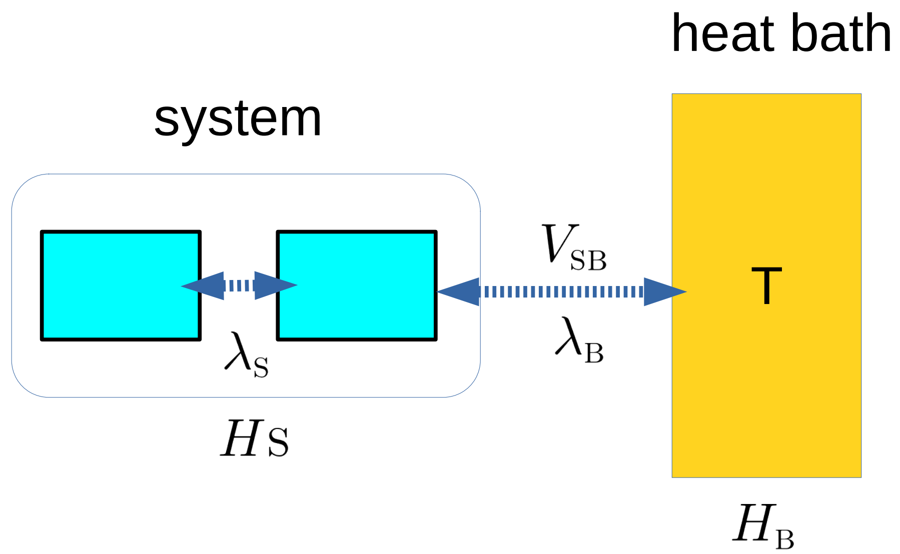
$$|b_1\rangle = |\Phi_+\rangle = (|{+}{+}\rangle + |{-}{-}\rangle)/\sqrt{2}$$
$$|b_2\rangle = |\Phi_-\rangle = (|{+}{+}\rangle - |{-}{-}\rangle)/\sqrt{2}$$
$$|b_3\rangle = |\Psi_+\rangle = (|{+}{-}\rangle + |{-}{+}\rangle)/\sqrt{2}$$
$$|b_4\rangle = |\Psi_-\rangle = (|{+}{-}\rangle - |{-}{+}\rangle)/\sqrt{2}$$

Pointer Basis

$$\sigma_x^{\mathrm{A}} \otimes I^{\mathrm{B}} |\pi_i\rangle = \lambda_i |\pi_i\rangle$$
$$I^{\mathrm{A}} \otimes \sigma_x^{\mathrm{B}} |\pi_i\rangle = \eta_i |\pi_i\rangle$$
$$\lambda = \{1, -1, -1, 1\}$$
$$\eta = \{1, -1, 1, -1\}$$

$$|\pi_1\rangle = (|\Phi_+\rangle + |\Psi_+\rangle)/\sqrt{2} = (|{+}{+}\rangle + |{-}{-}\rangle + |{+}{-}\rangle + |{-}{+}\rangle)/2$$
$$|\pi_2\rangle = (|\Phi_+\rangle - |\Psi_+\rangle)/\sqrt{2} = (|{+}{+}\rangle + |{-}{-}\rangle - |{+}{-}\rangle - |{-}{+}\rangle)/2$$
$$|\pi_3\rangle = (|\Phi_-\rangle + |\Psi_-\rangle)/\sqrt{2} = (|{+}{+}\rangle - |{-}{-}\rangle + |{+}{-}\rangle - |{-}{+}\rangle)/2$$
$$|\pi_4\rangle = (|\Phi_-\rangle - |\Psi_-\rangle)/\sqrt{2} = (|{+}{+}\rangle - |{-}{-}\rangle - |{+}{-}\rangle + |{-}{+}\rangle)/2$$

Thermodynamic Steady State and Eigenselection



$$\lambda_{\rm B} \ll 1 \qquad \rho_{\rm S} \quad \rightarrow \quad \frac{1}{Z} e^{-\beta H_{\rm s}}$$

Claims

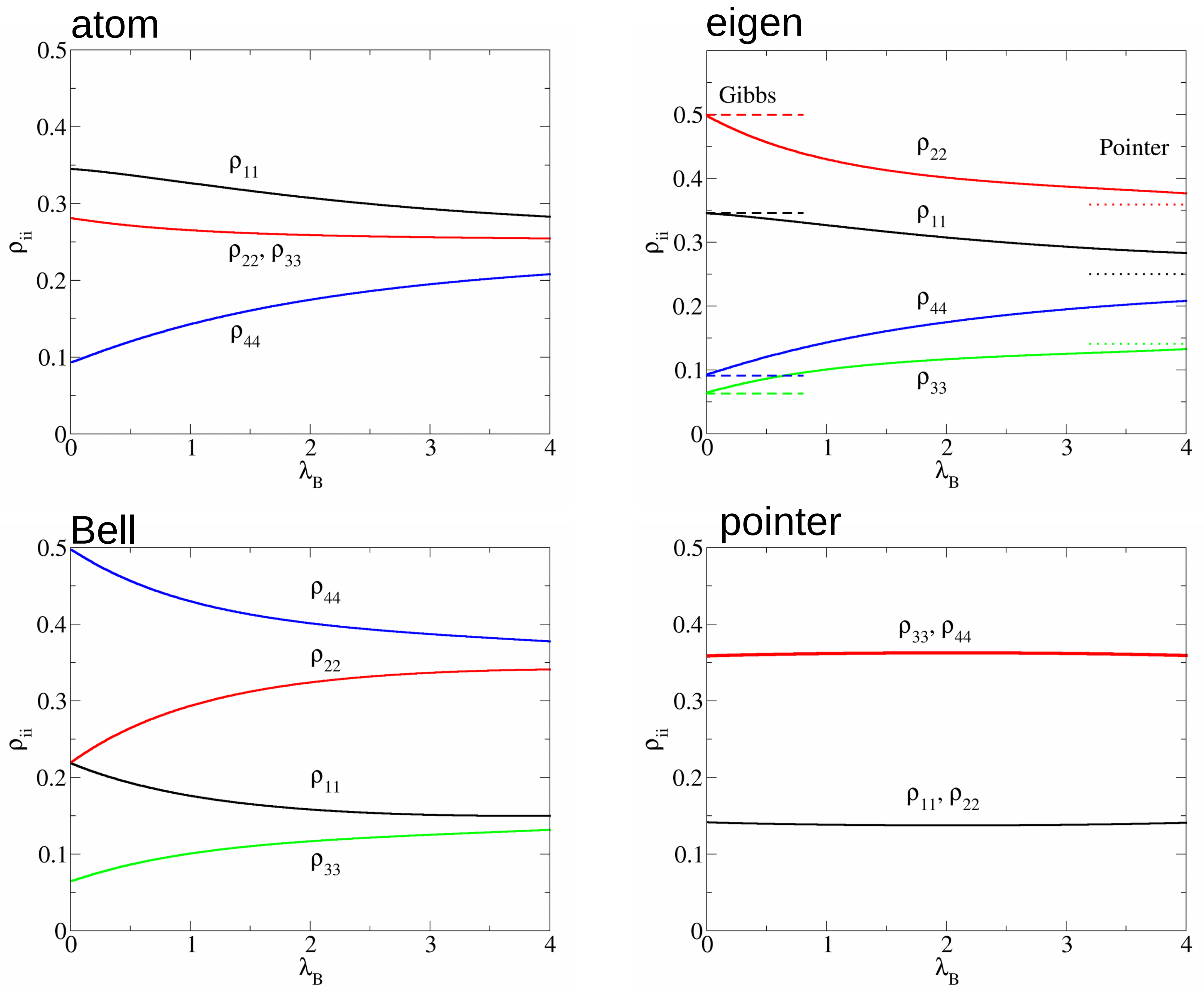
$$\lambda_{\rm B} \gg |H_{\rm S}|, \quad \rho_{\rm S} \quad \rightarrow \quad \frac{1}{Z} \sum_i |\pi_i\rangle\langle\pi_i|\, e^{-\beta H_{\rm s}}\, |\pi_i\rangle\langle\pi_i|$$

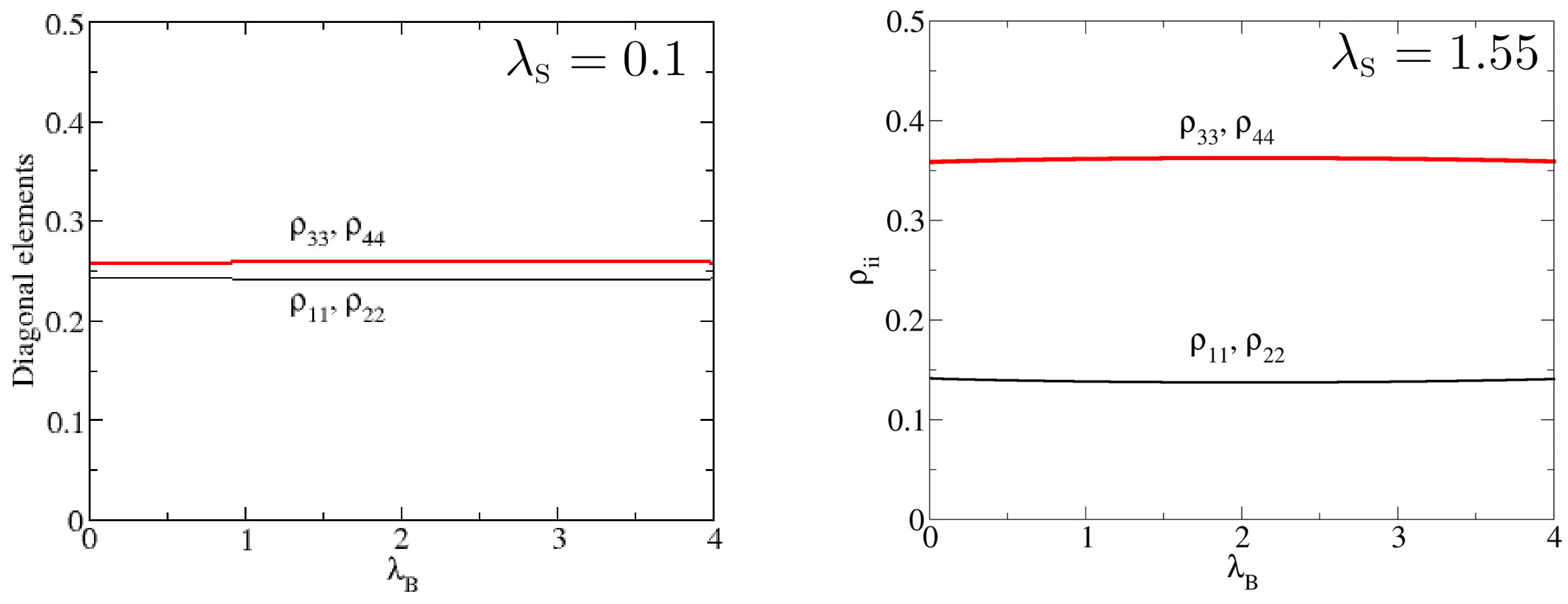
$$\lambda_{\rm B} \sim |H_{\rm S}|, \quad \langle\pi_i|\rho_{\rm S}|\pi_i\rangle \approx \frac{1}{Z} \langle\pi_i|e^{-\beta H_{\rm s}}|\pi_i\rangle$$

$$\left[V_{\rm SB}, \hat{\Pi}\right] = 0, \quad \hat{\Pi}\,|\pi\rangle = \pi_i\,|\pi_i\rangle$$

Steady State: Diagonal Elements

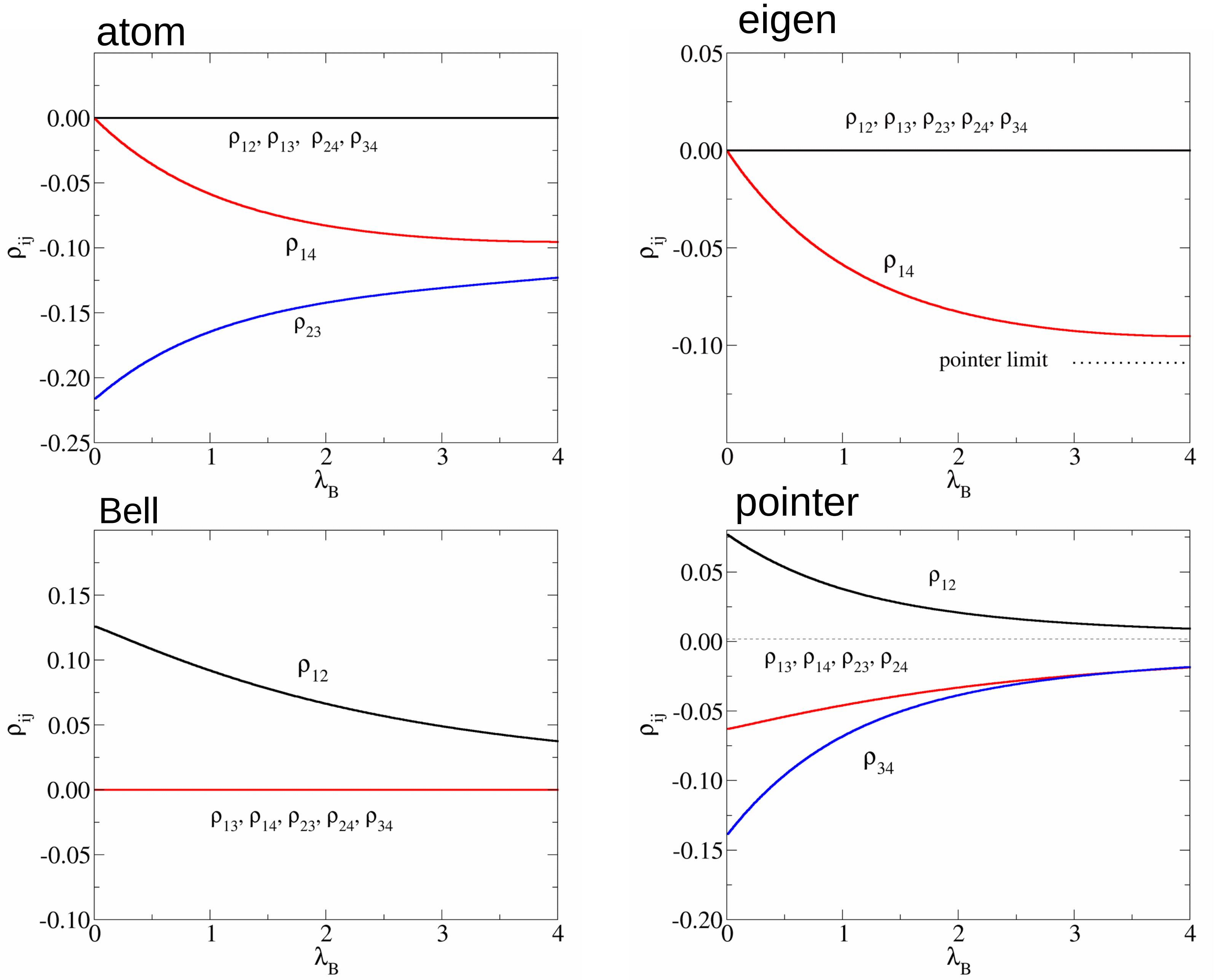
$$T_{\rm A} = T_{\rm B} = 1.5, \lambda_{\rm S} = 1.55, \omega_0 = 1$$



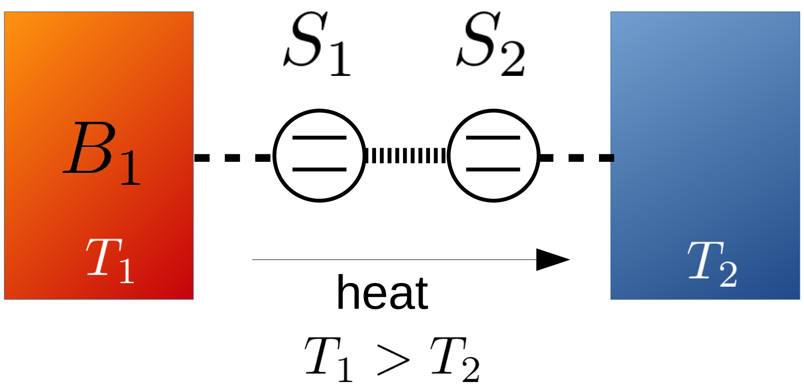


$\lambda_S = 0.1$
ρ_{33}, ρ_{44}
ρ_{11}, ρ_{22}
Diagonal elements
λ_B
$\lambda_S = 1.55$
ρ_{33}, ρ_{44}
ρ_{11}, ρ_{22}
ρ_{ii}
λ_B

Steady State: Off-Diagonal Elements



Non-Equilibrium Steady State and Heat

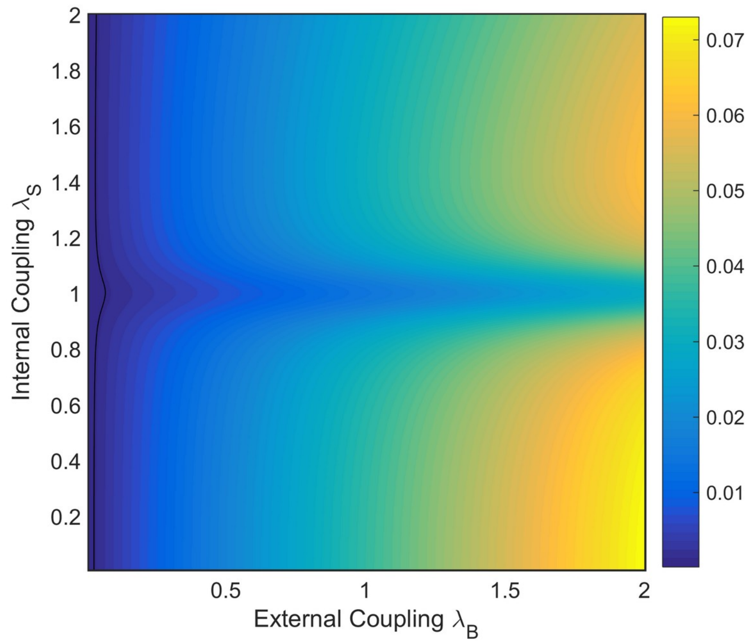


$$J_j = -i\,\mathrm{tr}_S\left\{[\hat{X}_{S_j}, \eta_j]\,\hat{H}_S\right\}$$

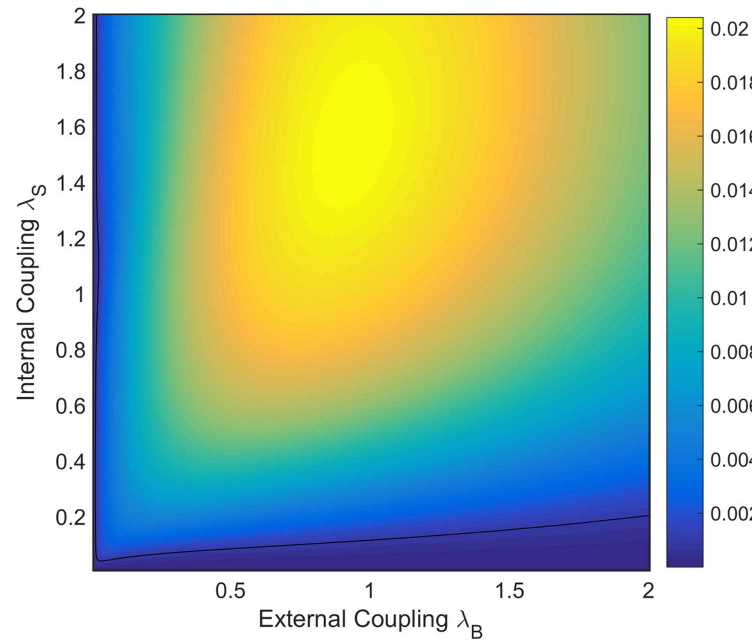
Does heat flow under the observation by the environment?

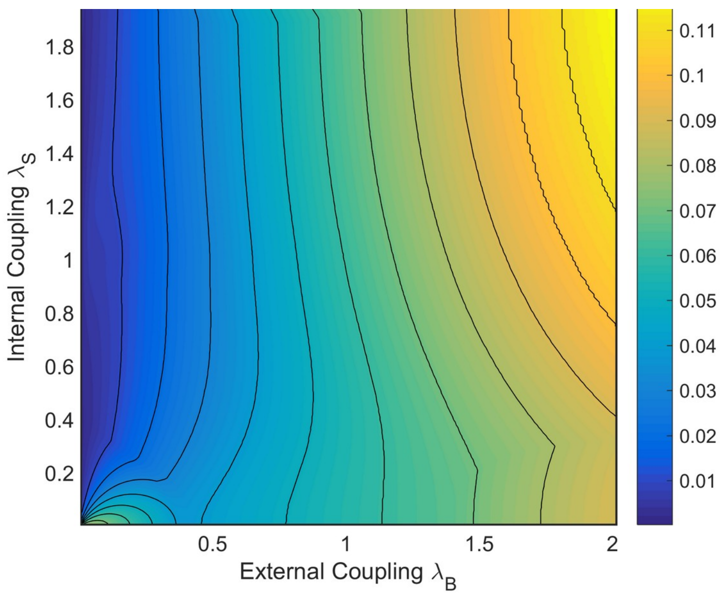
Heat by QME and HEOM $T_1 = 2,\, T_2 = 1$

Heat Current (QME)



Heat Current (HEOM)

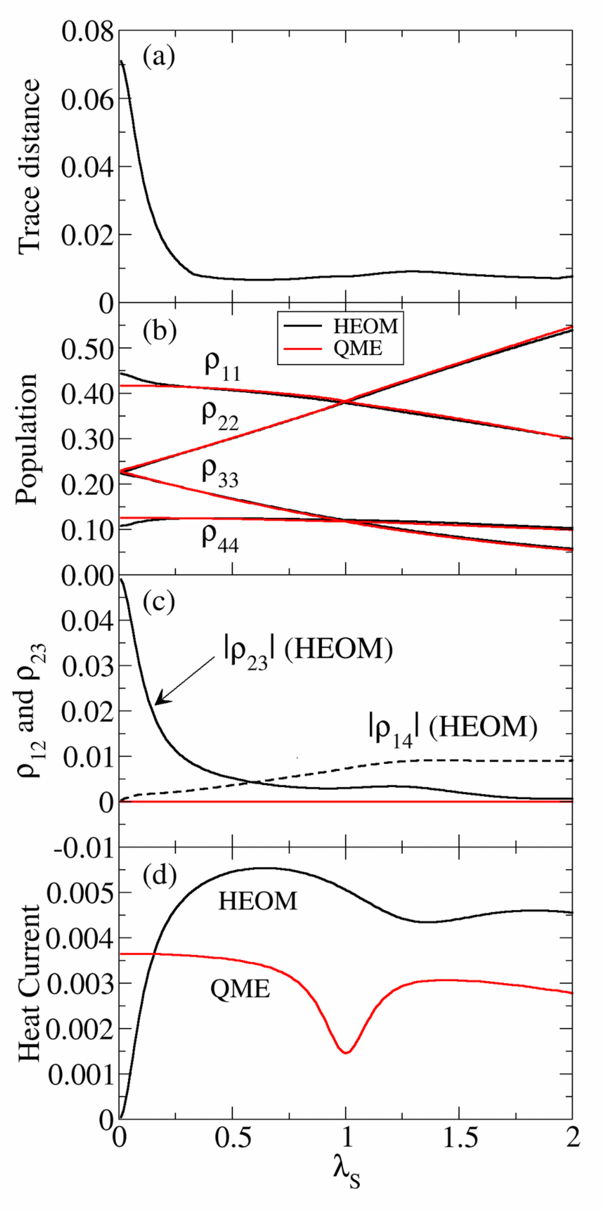




Trace distance: $\|\rho_S^{\mathrm{HEOM}} - \rho_S^{\mathrm{QME}}\|$

$$\|\rho - \sigma\| = \frac{1}{2}\,\mathrm{tr}\left[\sqrt{(\rho-\sigma)^\dagger(\rho-\sigma)}\right]$$

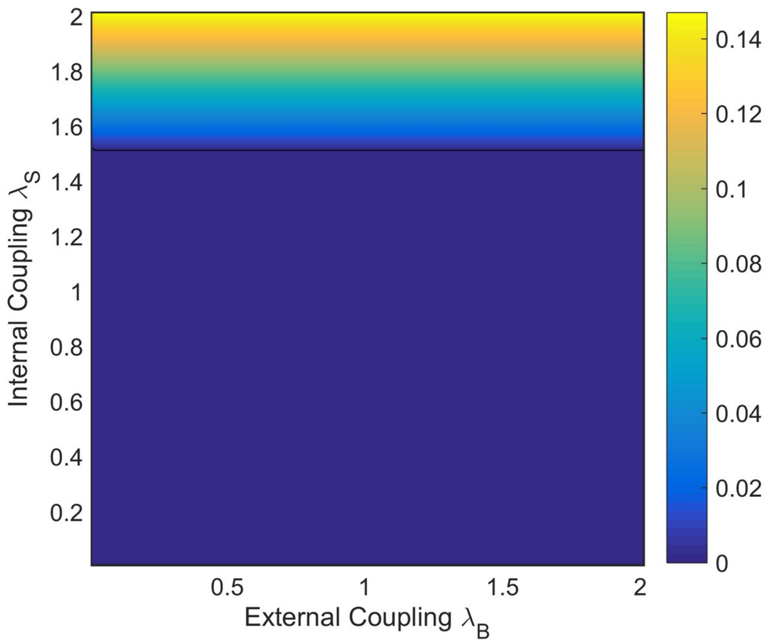
QME vs HEOM



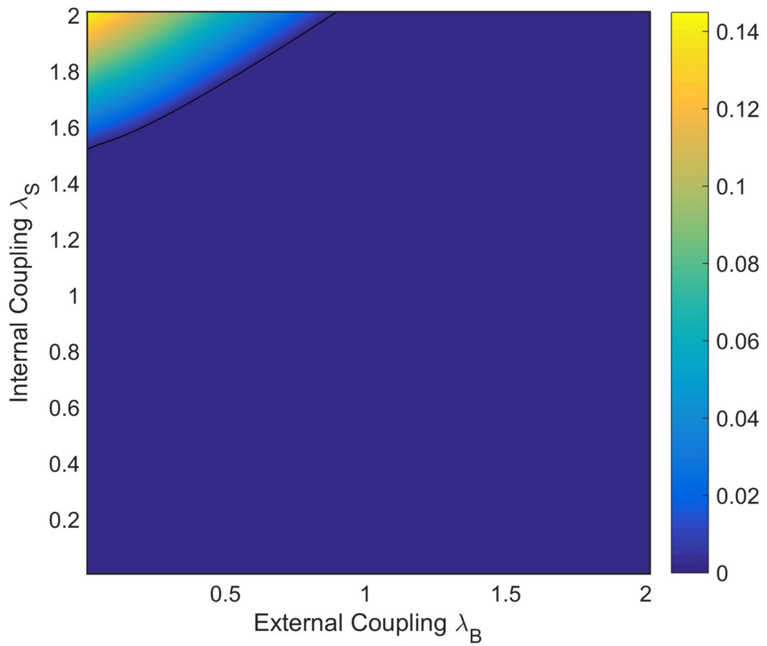
(a)
Trace distance
0.08
0.06
0.04
0.02
0
(b)
HEOM
QME
Population
0.50
0.40
0.30
0.20
0.10
0.00
ρ11
ρ22
ρ33
ρ44
(c)
ρ12 and ρ23
0.04
0.03
0.02
0.01
0
-0.01
|ρ23| (HEOM)
|ρ14| (HEOM)
(d)
Heat Current
0.005
0.004
0.003
0.002
0.001
0
HEOM
QME
0
0.5
1
1.5
2
λS

Entanglement between Q-bits

QME (Born+Markov)



HEOM (Non-Markovian)

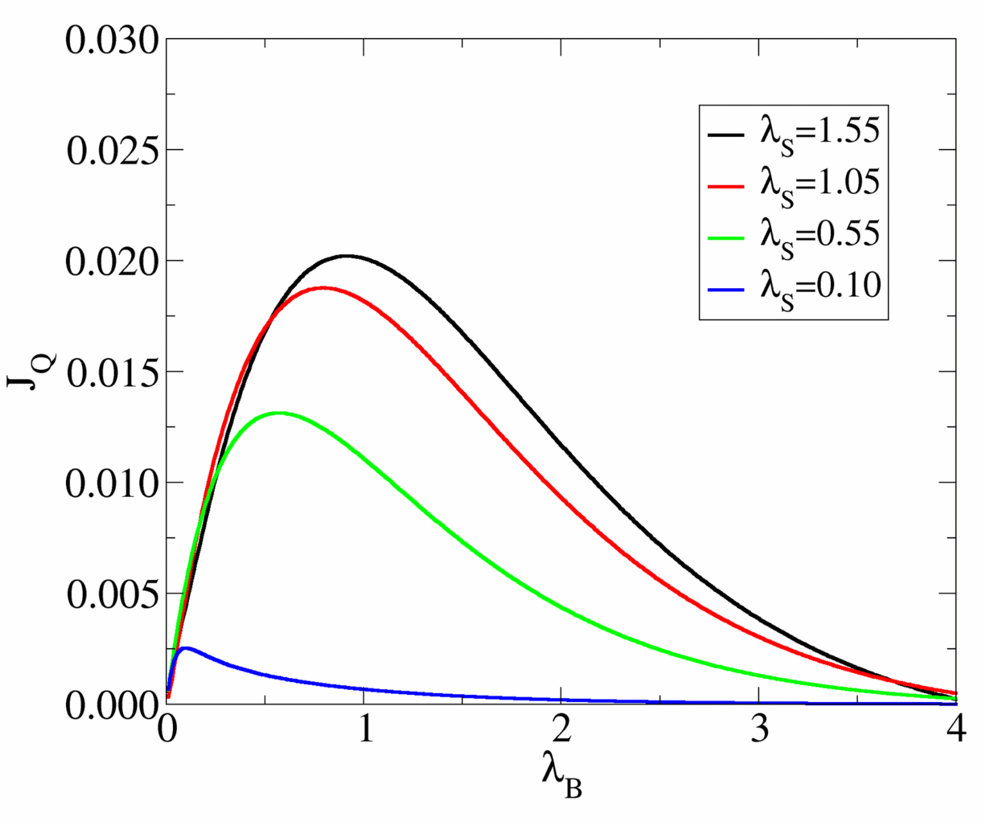


Concurrence $C(\rho) = \max(0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4)$

λ_i = eigenvalue of $R = \sqrt{\sqrt{\rho}\tilde{\rho}\sqrt{\rho}}$ in decreasing order

$$\tilde{\rho} = (\sigma_y \otimes \sigma_y)\rho^*(\sigma_y \otimes \sigma_y)$$

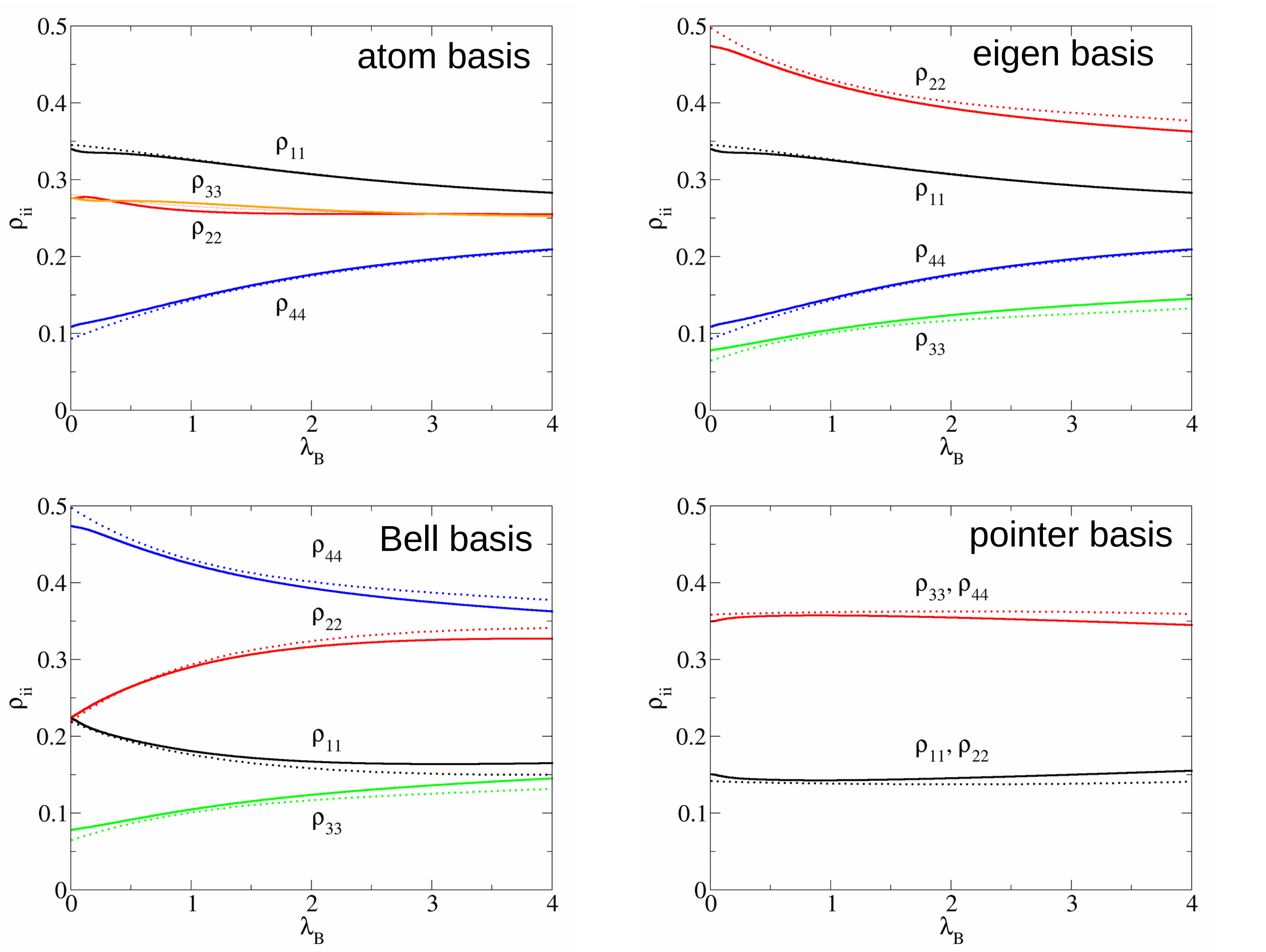
Heat conduction dies off at strong coupling



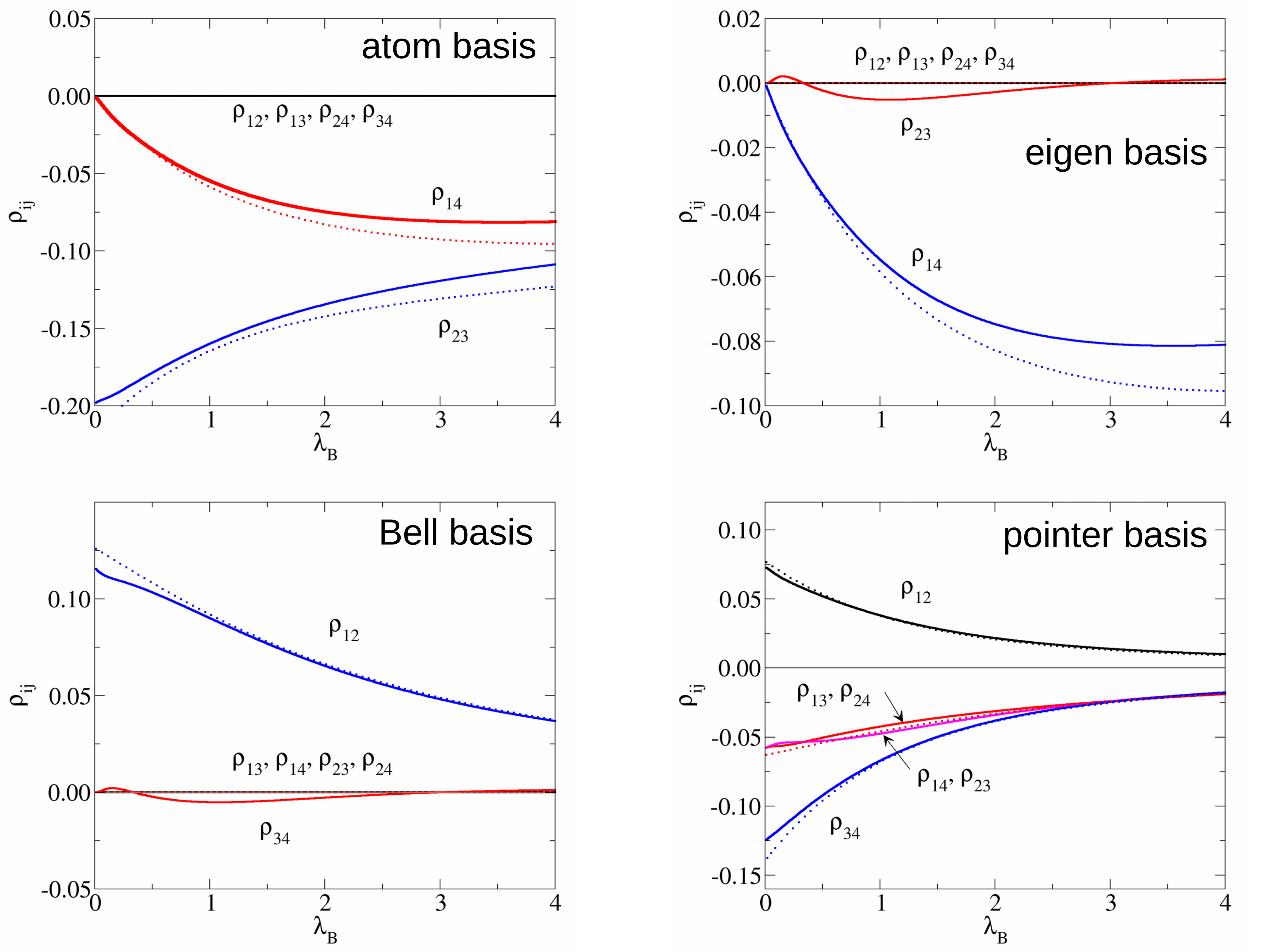
Disappearance of Heat ---> Quantum Zeno effect

Rebentrost *et al.* (2009), Kato-Tanimura (2015)

Non-Equilibrium Steady State: Diagonal Elements



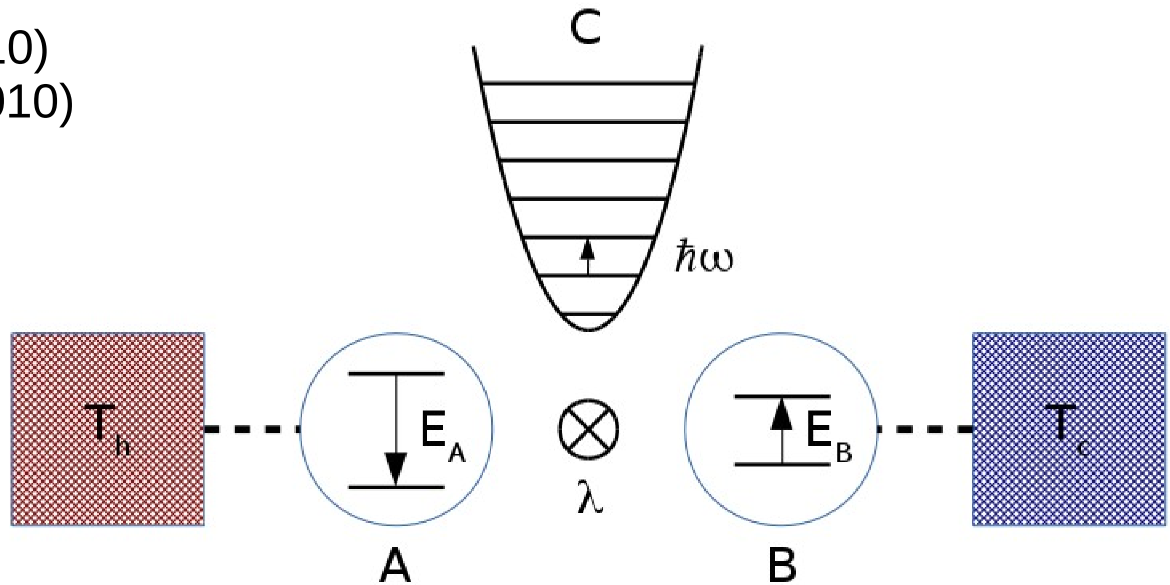
Non-Equilibrium Steady State: Off-Diagonal Elements

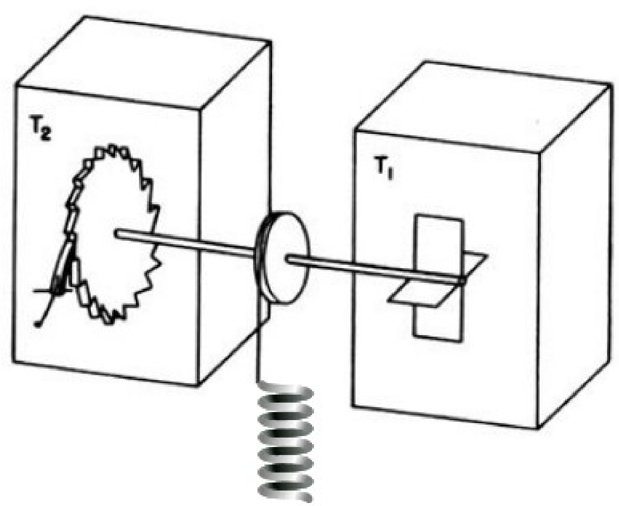


Decoherence strength: Flemming et al. (2012)

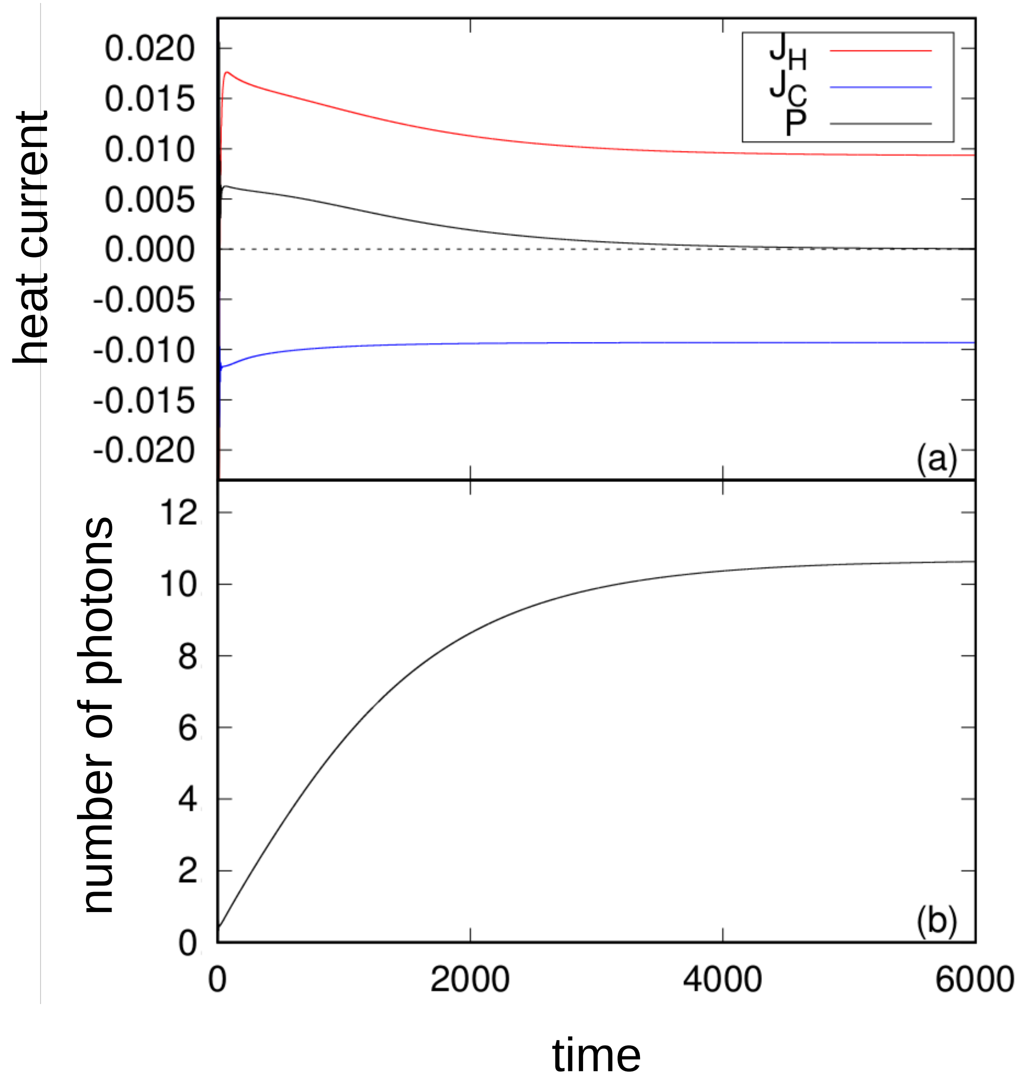
Autonomous Quantum Heat Engine

Linden *et al.* (2010)
Youssef *et al.* (2010)





Heat at stalled force



$$T_A = 5, T_B = 1, \lambda_S = 0.5, \lambda_B = 0.05, \hbar\omega = 1$$

Conclusions

Equilibrium

- Continuous measurement by the environment projects Gibbs state to pointer states.
- Probability distribution of pointer states is insensitive to the coupling strength.

Non-Equilibrium

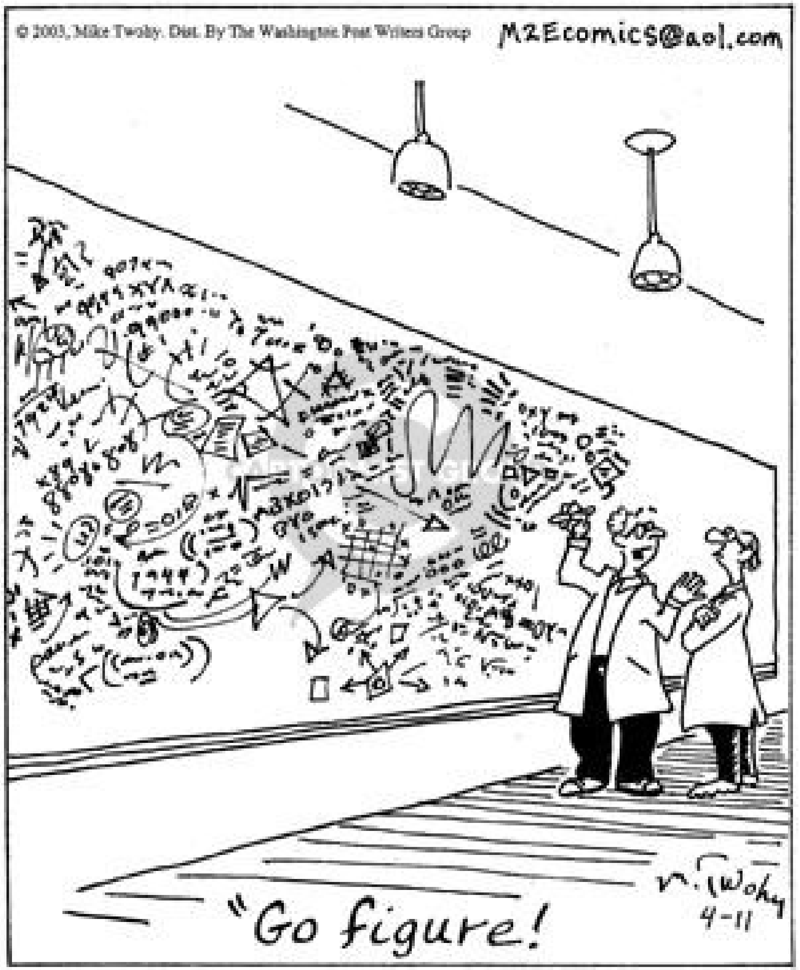
- Continuous measurement by the environments kills heat conduction.

About Born-Markovian quantum master equation

- Decoherence predicted by Born-Markovian quantum master equation predicts the Gibbs state for equilibrium situation but exhibits unrealistic results for non-equilibrium situation.

Numerical Method

- Hierarchical Equation of Motion (HEOM) provides exact numerical solution for open quantum systems.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4-11
"Go figure!