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Non-equilibrium dynamics of dissipative strongly-correlated quantum matter

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Relaxation of quantum matter

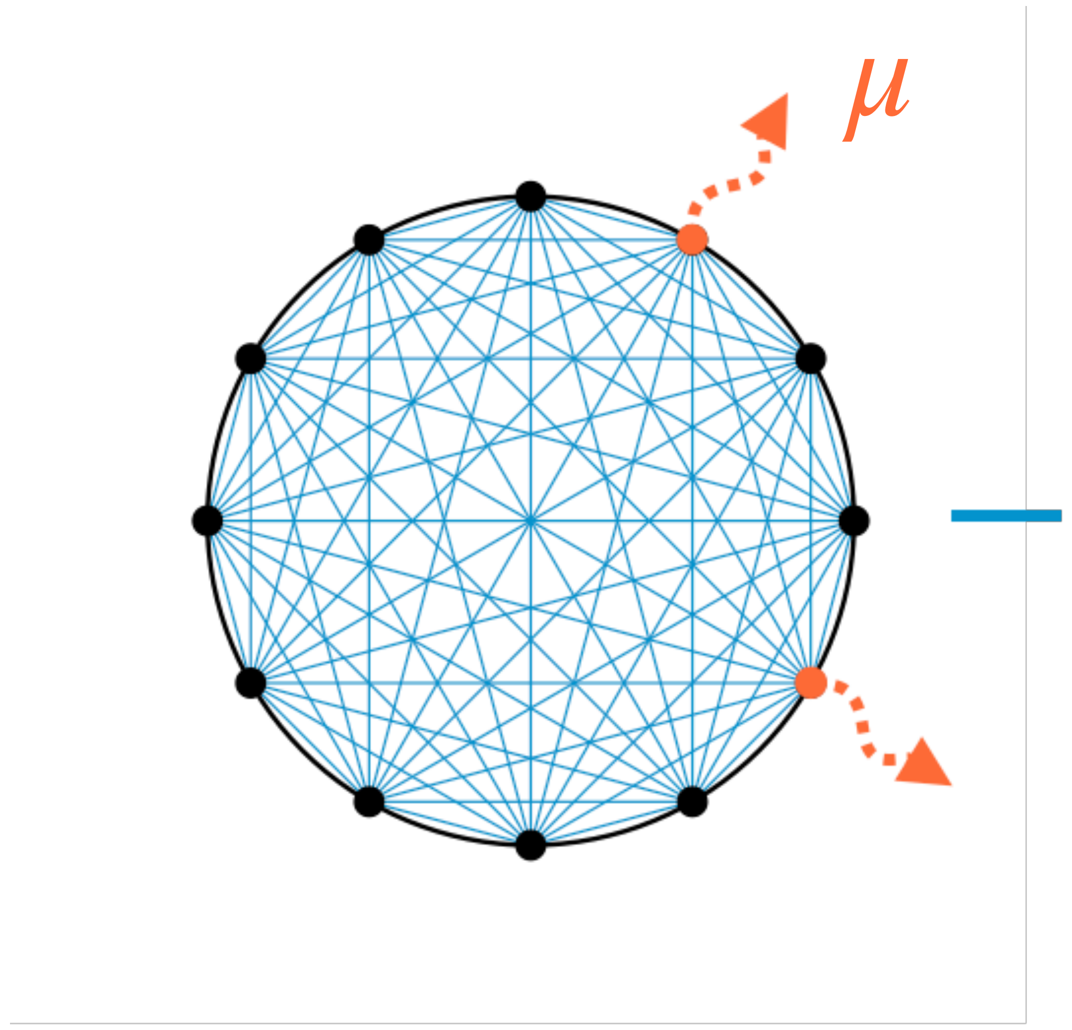
There are two competing sources of *relaxation* in *quantum many-body systems:*

Internal interactions
(quantum chaos)

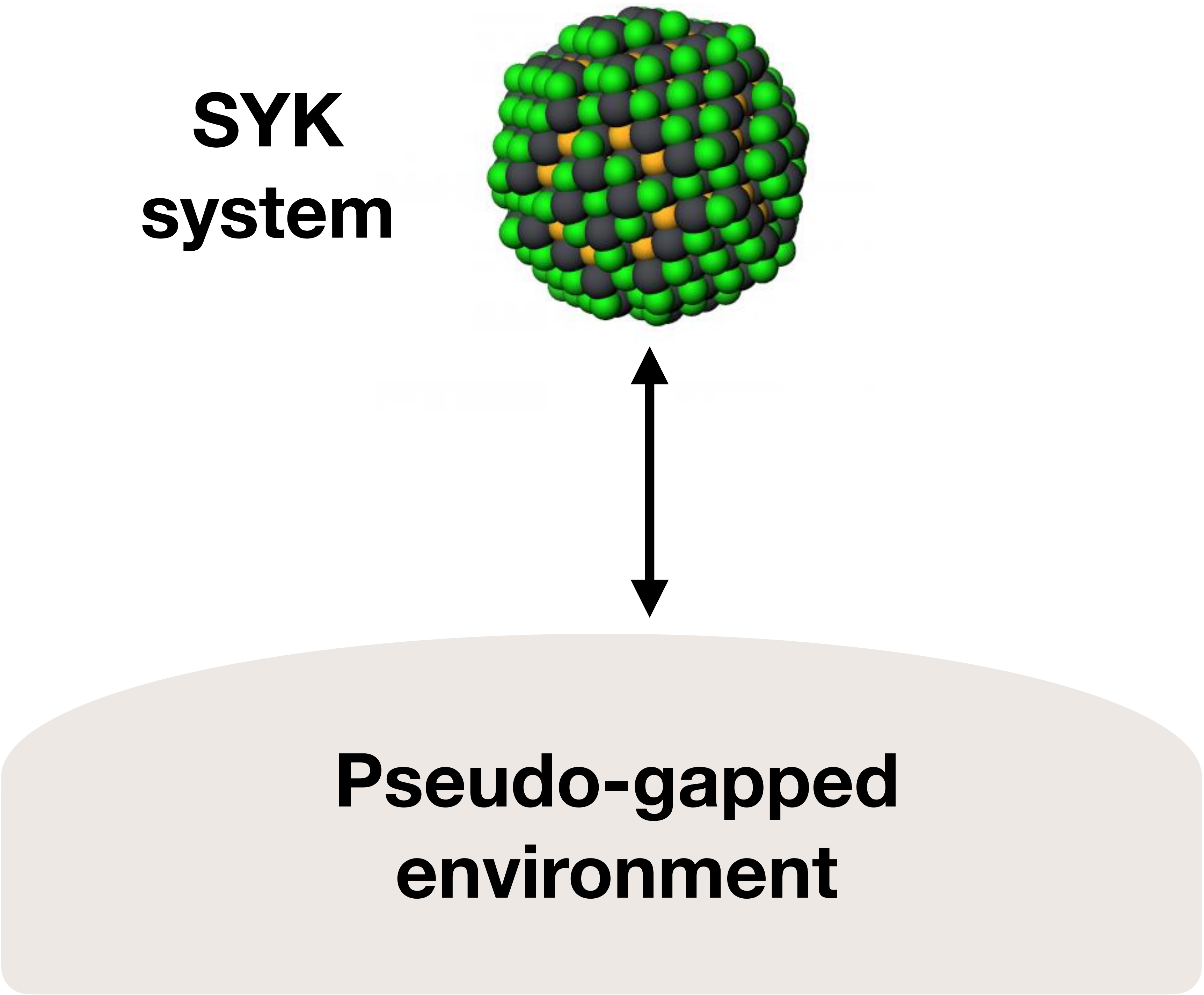
VS

External interactions
(dissipation)

We study this interplay in a **dissipative SYK model.**



Our dissipative SYK model



SYK system

Pseudo-gapped environment

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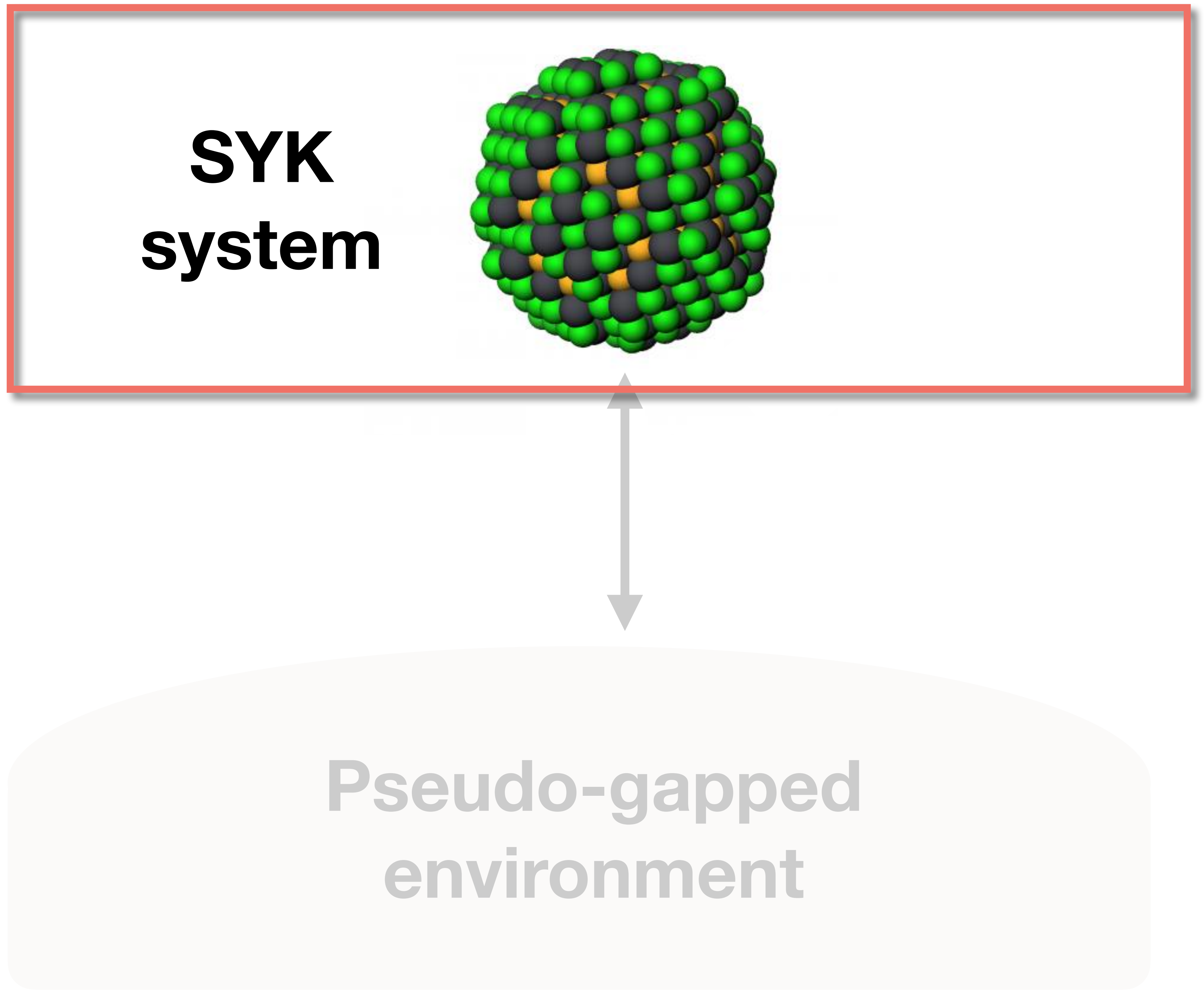


SYK system

Pseudo-gapped environment

N Majorana fermions

$$\chi_i^\dagger = \chi_i$$

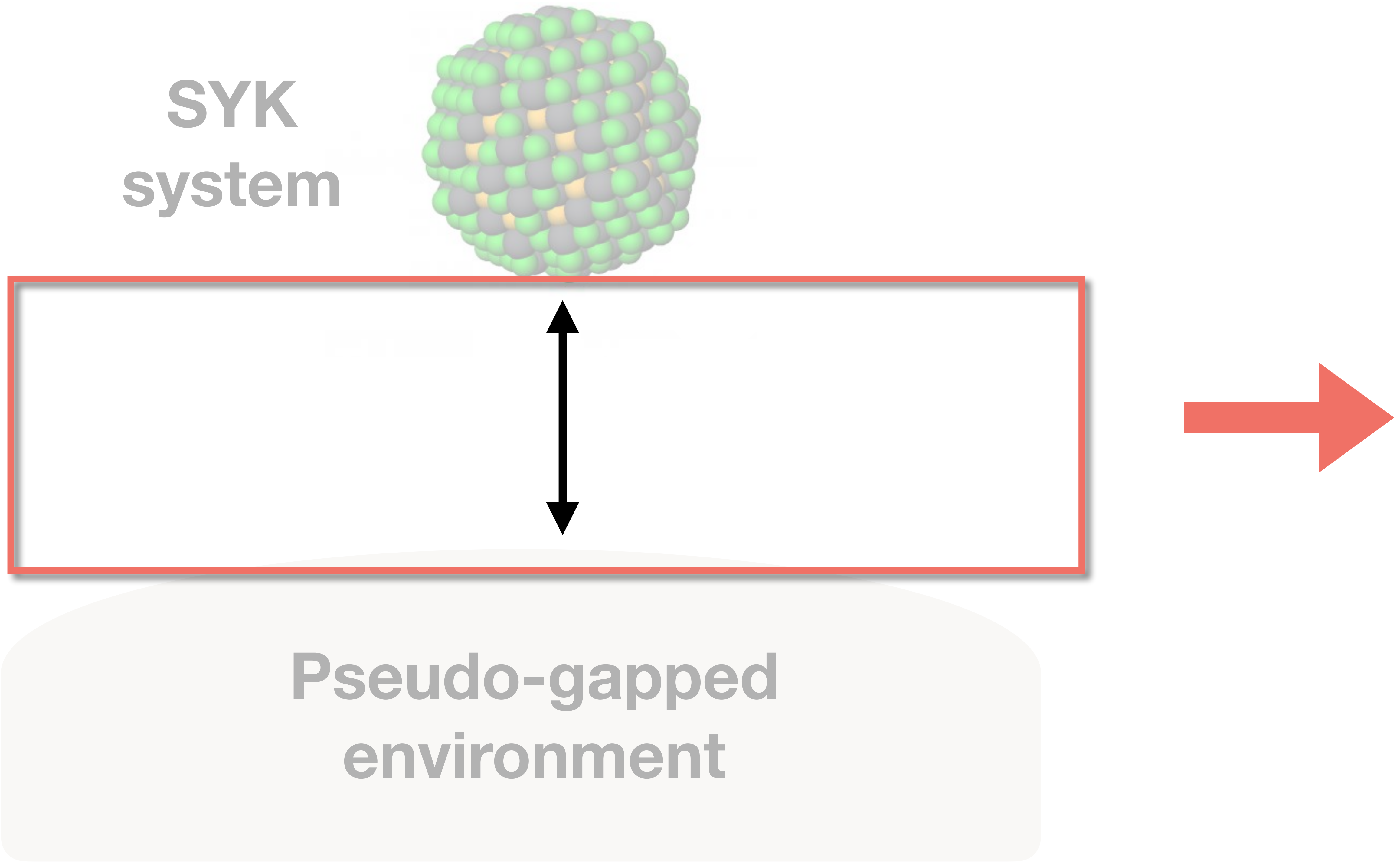
$$\{\chi_i, \chi_j\} = \delta_{ij}$$

$$H = \sum_{i<j<k<l} J_{ijkl}\chi_i\chi_j\chi_k\chi_l$$

$$\langle J_{ijkl}^2\rangle = \frac{3\,!J^2}{N^3}$$

Gaussian couplings

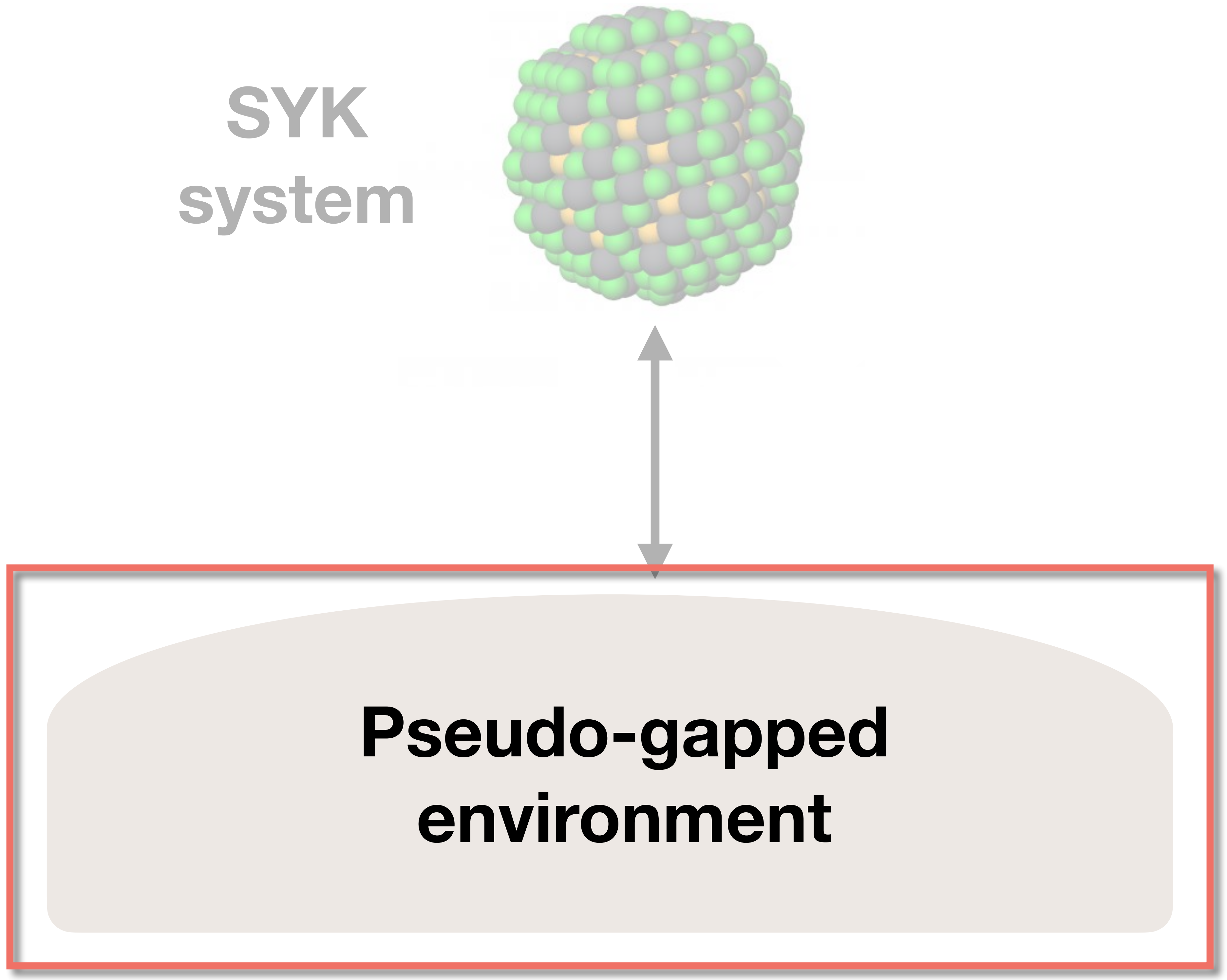
Our dissipative SYK model



$$H_{SR} = \sqrt{\mu} \sum_i \chi_i \, Y_i$$

Reservoir
operator

Our dissipative SYK model



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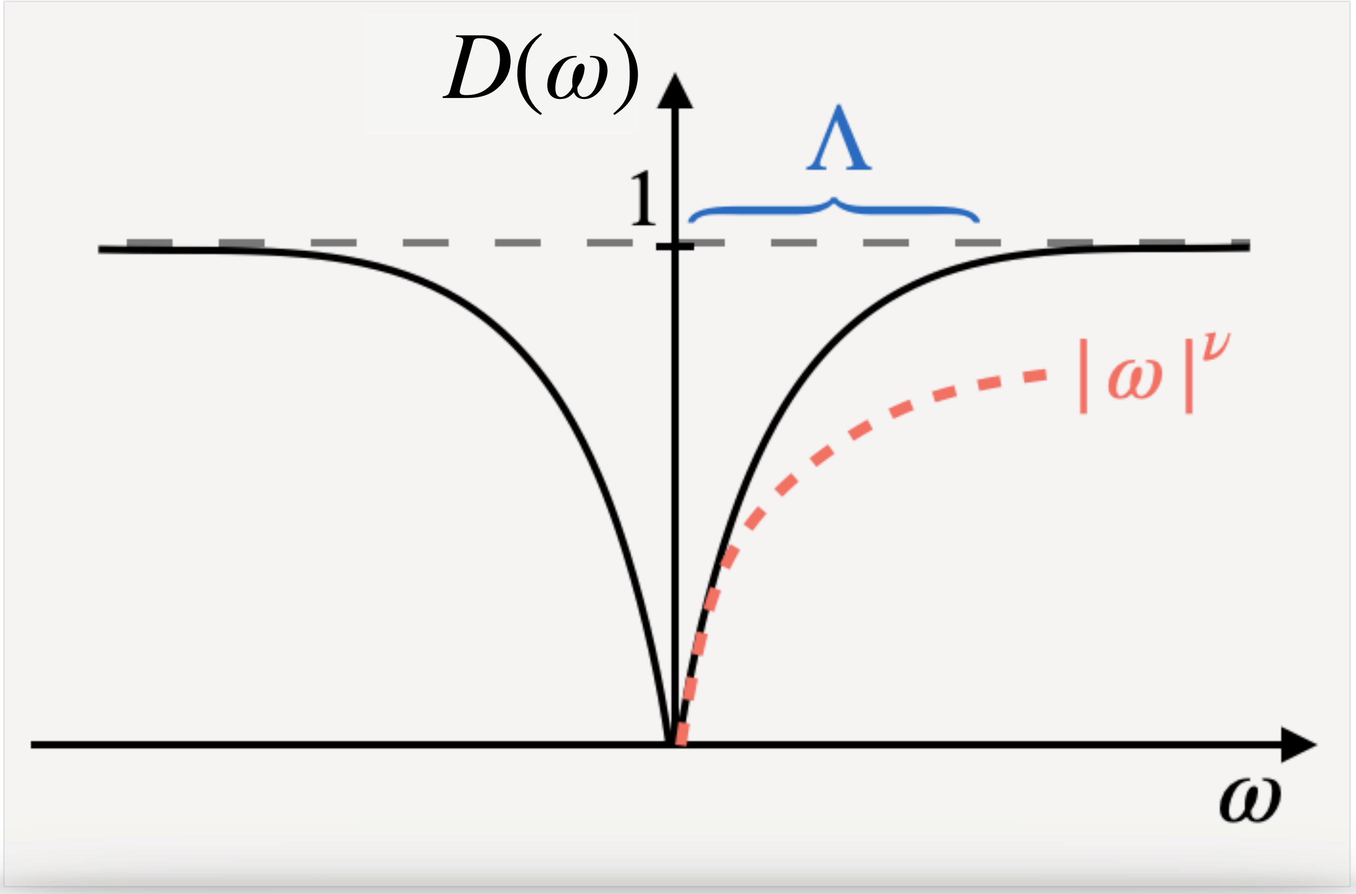

$$D(\omega) = \left(1 - e^{-\omega^2/\Lambda^2}\right)^{\nu/2}$$

Density of states

Pseudo-gaps arise in many materials (e.g. graphene) and induce **memory effects**

Schwinger-Keldysh formalism

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The Keldysh functional is the analog of the partition function for systems out-of-equilibrium:

$$Z = \mathrm{Tr}[\rho(t)] = \int \prod_i \mathscr{D}a_i \exp\{iS[a_i]\}$$

Coherent evolution

Dissipation

$$iS[a_i] = i\int_C dz\,\frac{1}{2}\sum_i a_i(z) i\partial_z a_i(z) - i\int_C dz \sum_{i<j<k<l} J_{ijkl} a_i(z)a_j(z)a_k(z)a_l(z) + \int_C dz dz'\ \mu\ \underset{\downarrow}{K}(z,z') \sum_i a_i(z)a_i(z')$$

Memory kernel

Schwinger-Dyson equations

In the large-N limit, we can derive self-consistent equations:

$$\boxed{\sigma^{-}(\omega) = \frac{\mu}{\pi}\left(1 - e^{-\omega^2/\Lambda^2}\right)^{\nu/2} + \frac{J^2}{4}\int d\mu d\nu\ \rho^{-}(\omega-\mu-\nu)\rho^{-}(\mu)\rho^{-}(\nu)}$$

$$\boxed{\rho^{-}(\omega) = \frac{\sigma^{-}(\omega)}{(\omega + \pi\sigma^{H}(\omega))^2 + (\pi\sigma^{-}(\omega))^2}}$$

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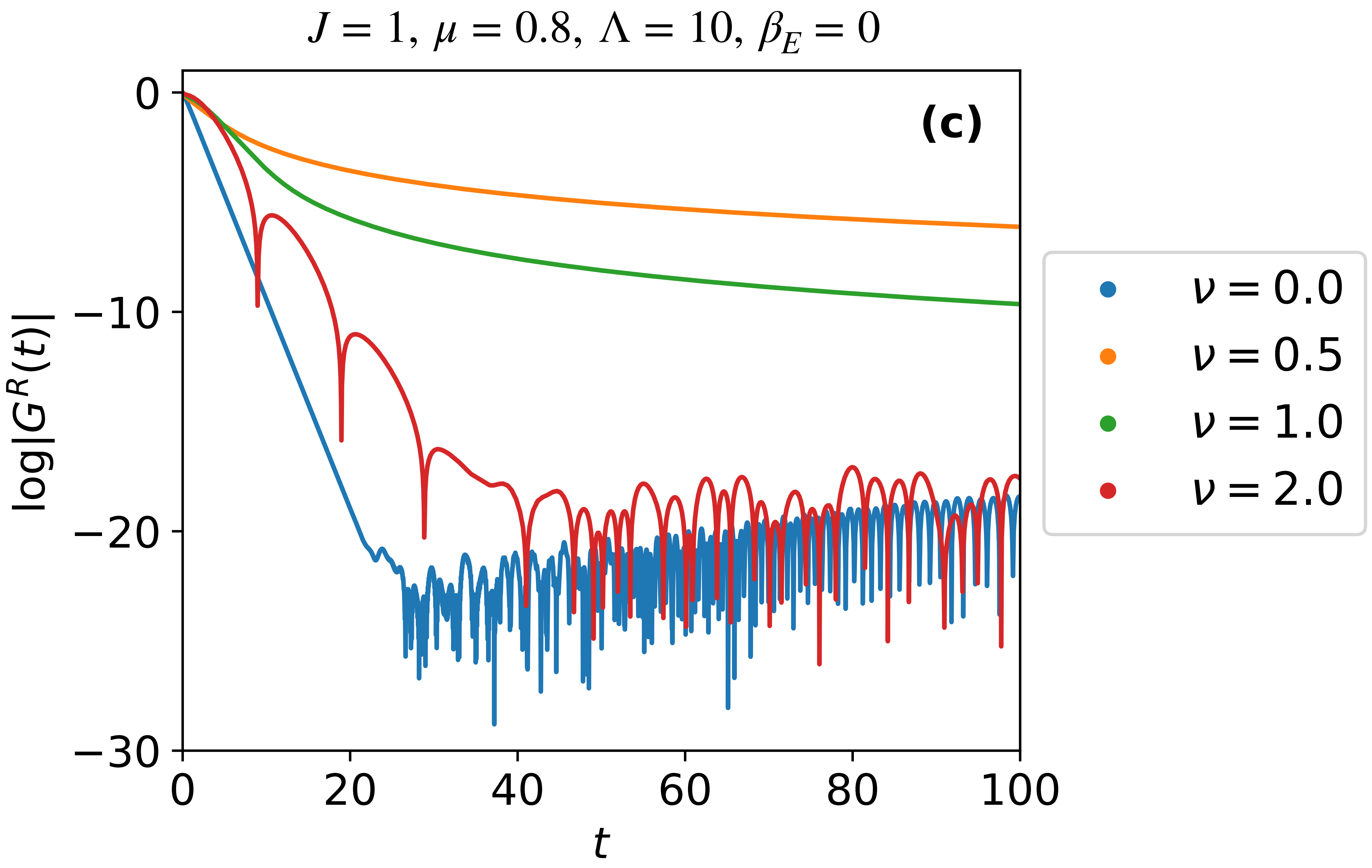
Schwinger-Dyson Equations

From these quantities we can compute the retarded Green's function, which encodes relaxation:

$$iG^R(t) = \Theta(t)\langle \mathrm{Tr}\left[\rho_\infty\{\chi_i(t),\chi_i\}\right]\rangle = \Theta(t)\int d\omega\ \rho^{-}(\omega)\cos(\omega t)$$

Solving the SD equations

We solve the Schwinger-Dyson equations on a frequency grid, by iterating until **self-consistency**



Depending on the parameters, decay can be exponential or algebraic (power-law):

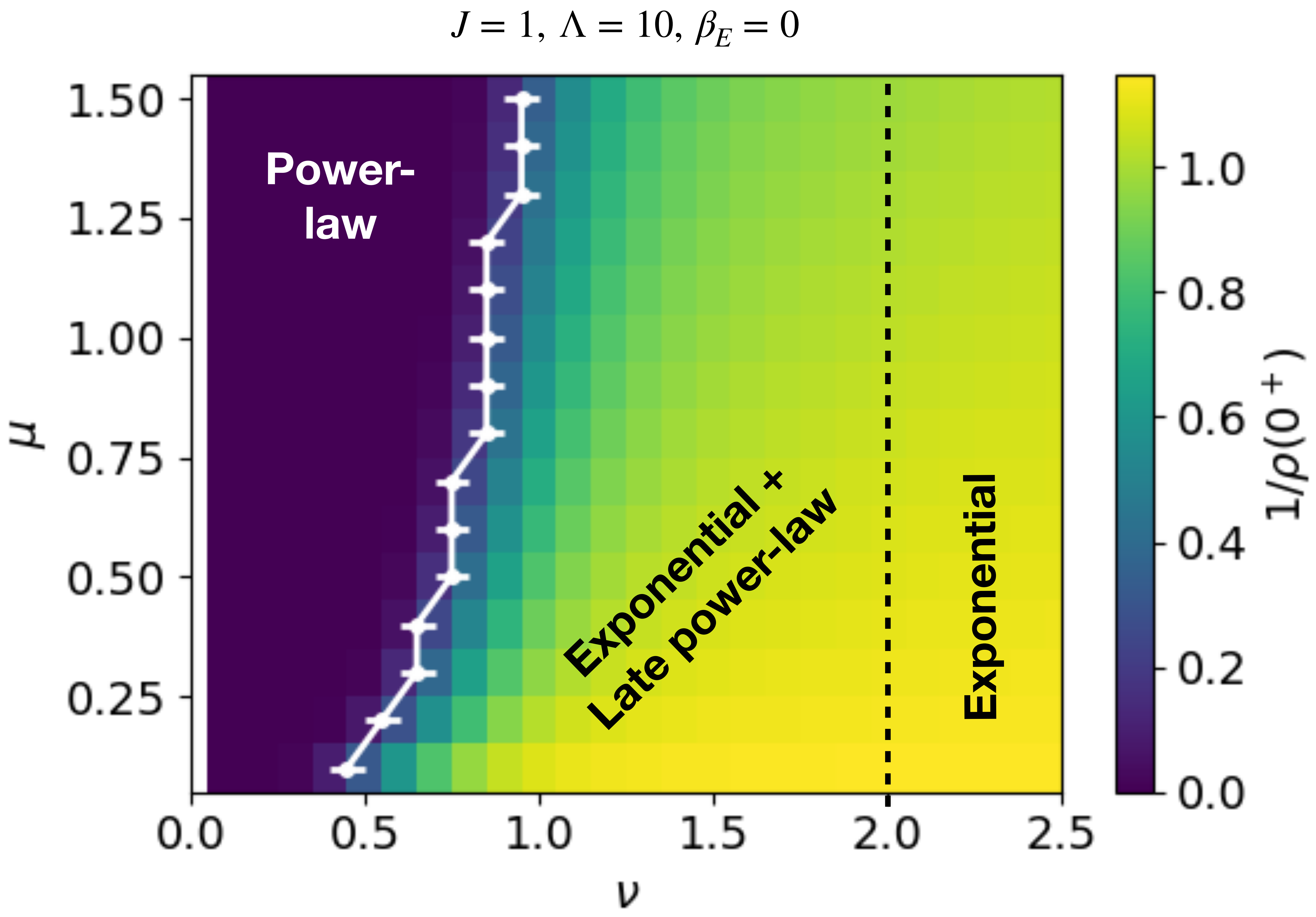
$$G^R_{\text{fit}}(t) = A/t^p + Be^{-\Delta t}\sin(\Omega t + \phi)$$

Conclusions

- Memory effects can induce slow power-law relaxation

- Competition between dissipation and chaos leads to distinct dynamical phases

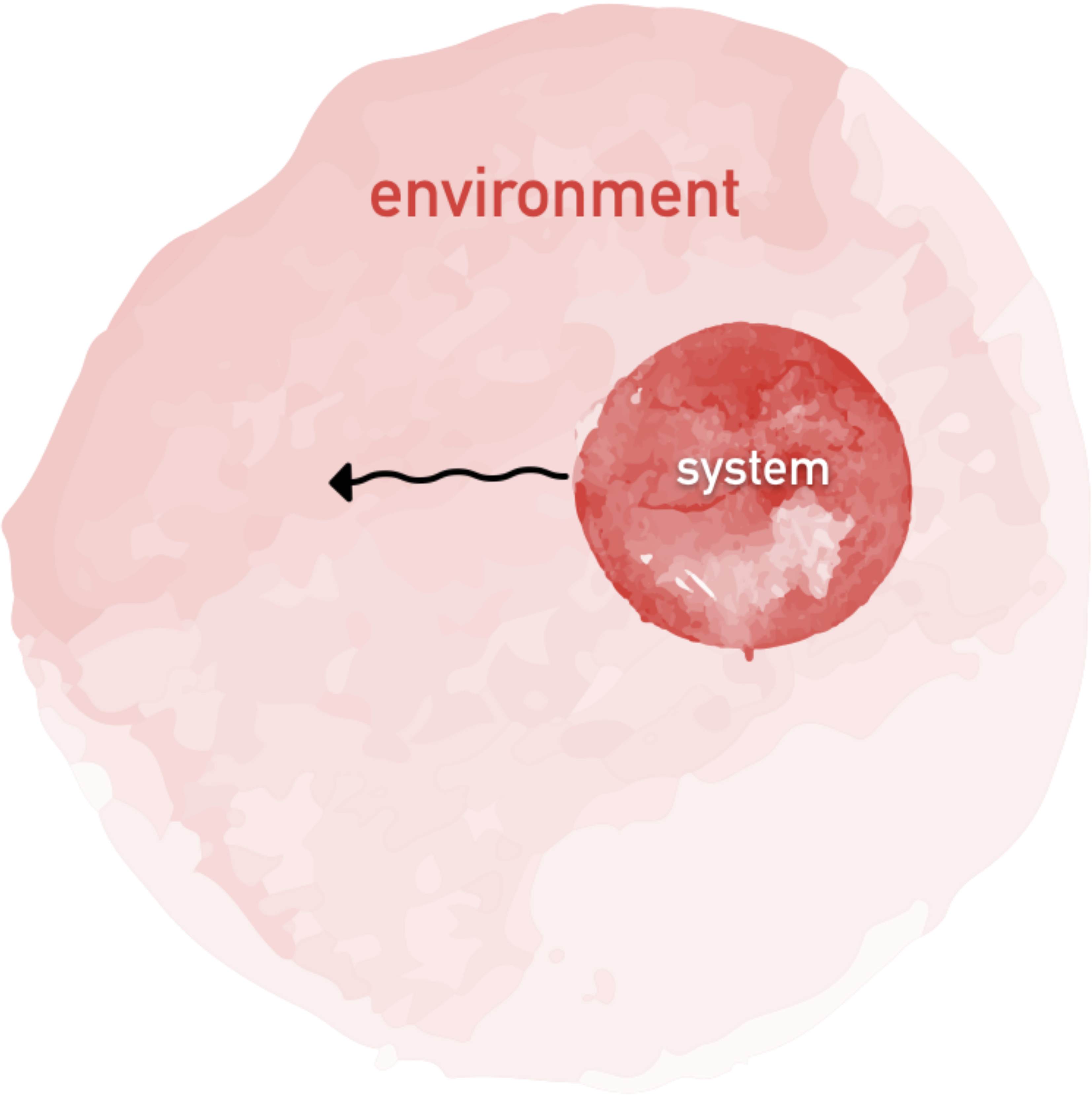
- This work contributes to the understanding of how real quantum systems relax



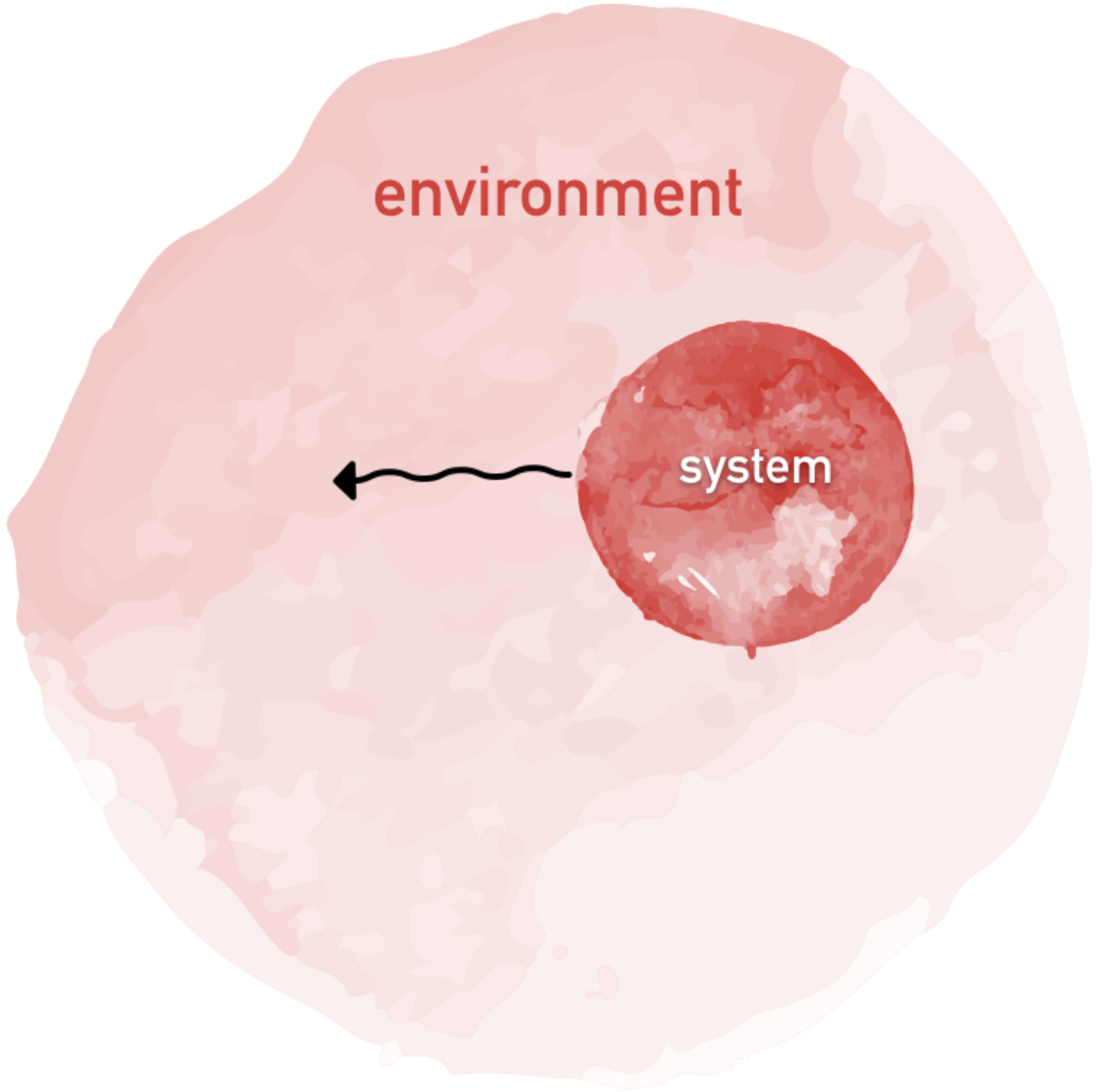
G.A., Pedro Ribeiro, Masudul Haque, Lucas Sá, “Relaxation of strongly-correlated quantum matter with structured dissipation”, 2026, in preparation

Supplemental material

Open quantum systems



Open quantum systems

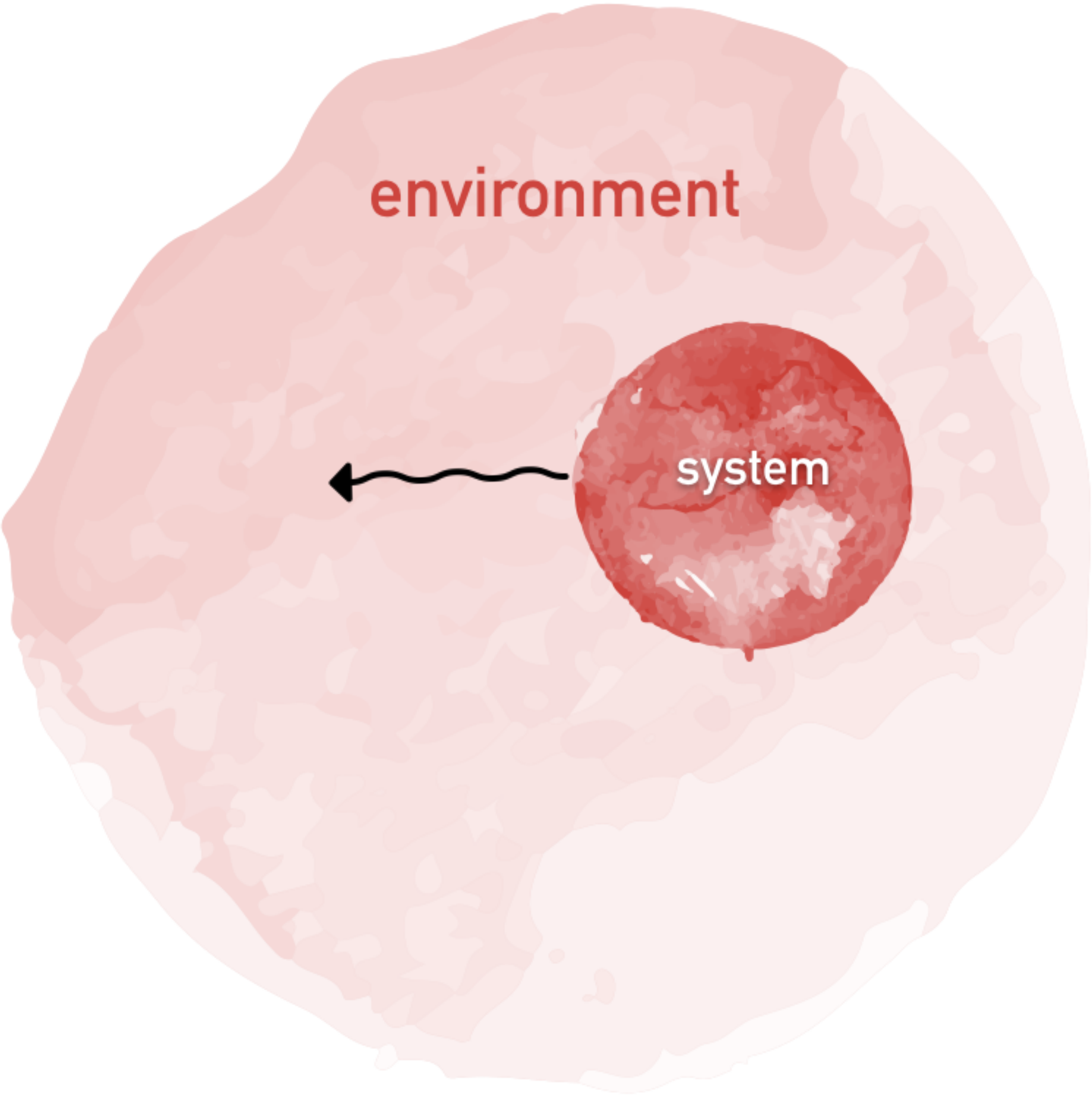


Typically we assume:

Weak coupling

Fast bath

Open quantum systems



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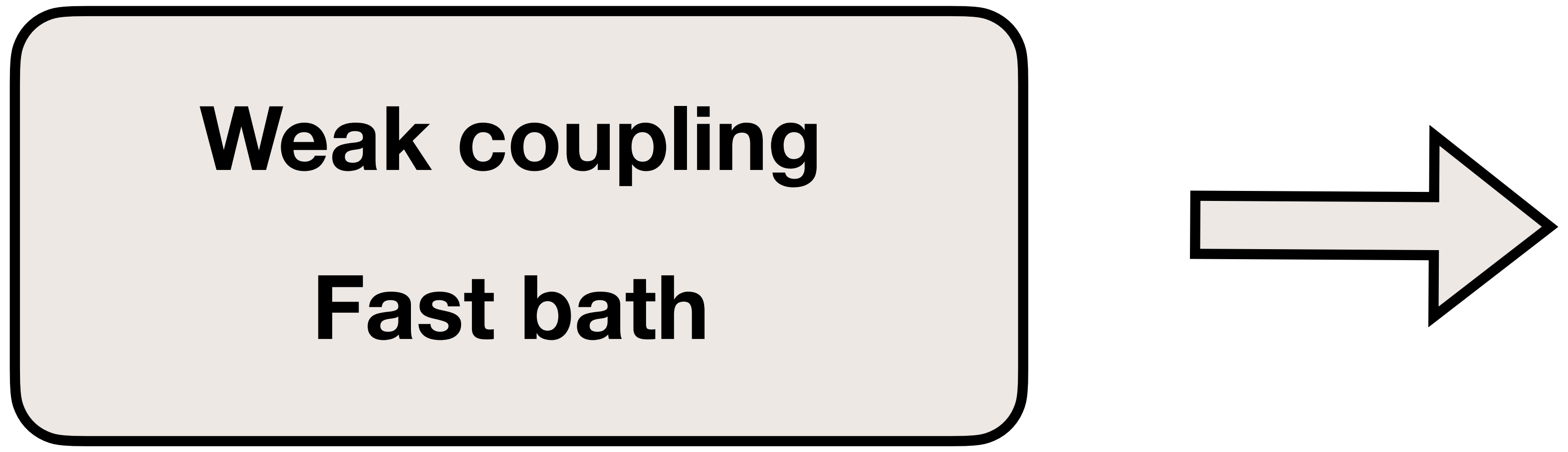


Weak coupling

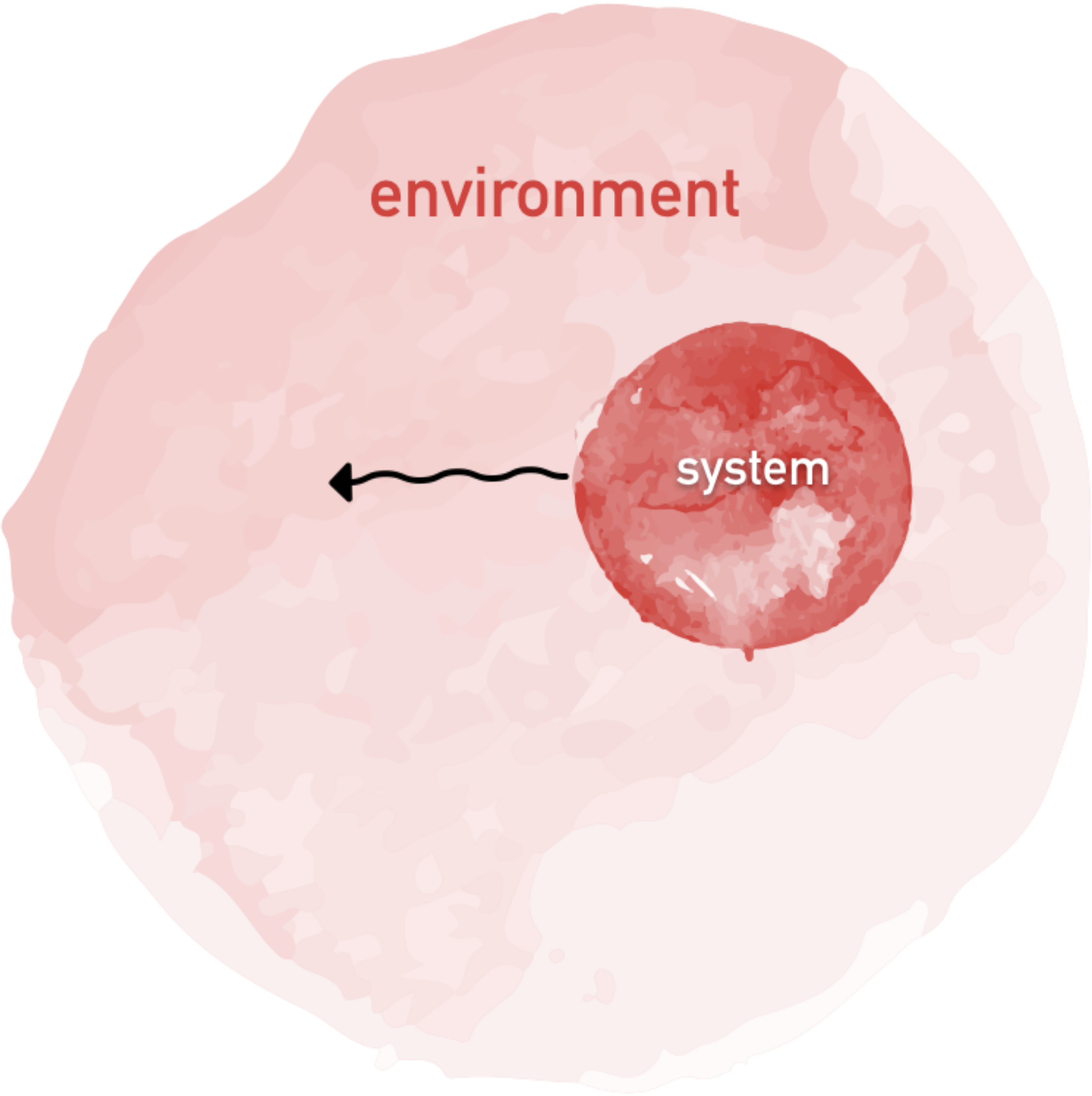
Fast bath

Markovian evolution

(Lindblad equation)

$$\frac{\partial\rho}{\partial t} = \mathscr{L}[\rho] = -i[H,\rho] + \sum_k \left(W_k \rho W_k^\dagger - \frac{1}{2}\left\{ W_k^\dagger W_k, \rho \right\} \right)$$

Open quantum systems



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However, realistic environments have more structure and lead to **non-Markovian** dynamics

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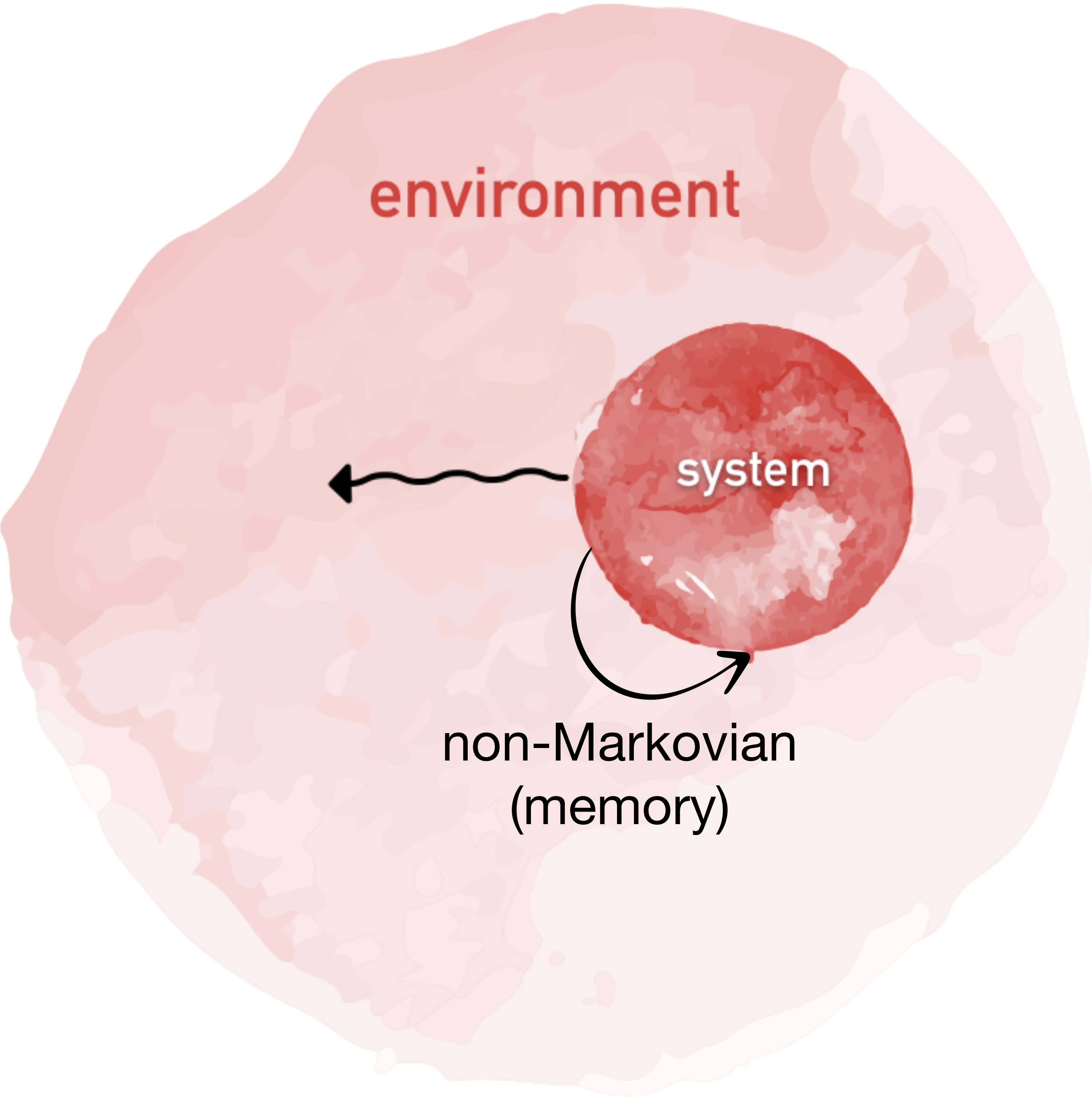

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⇒

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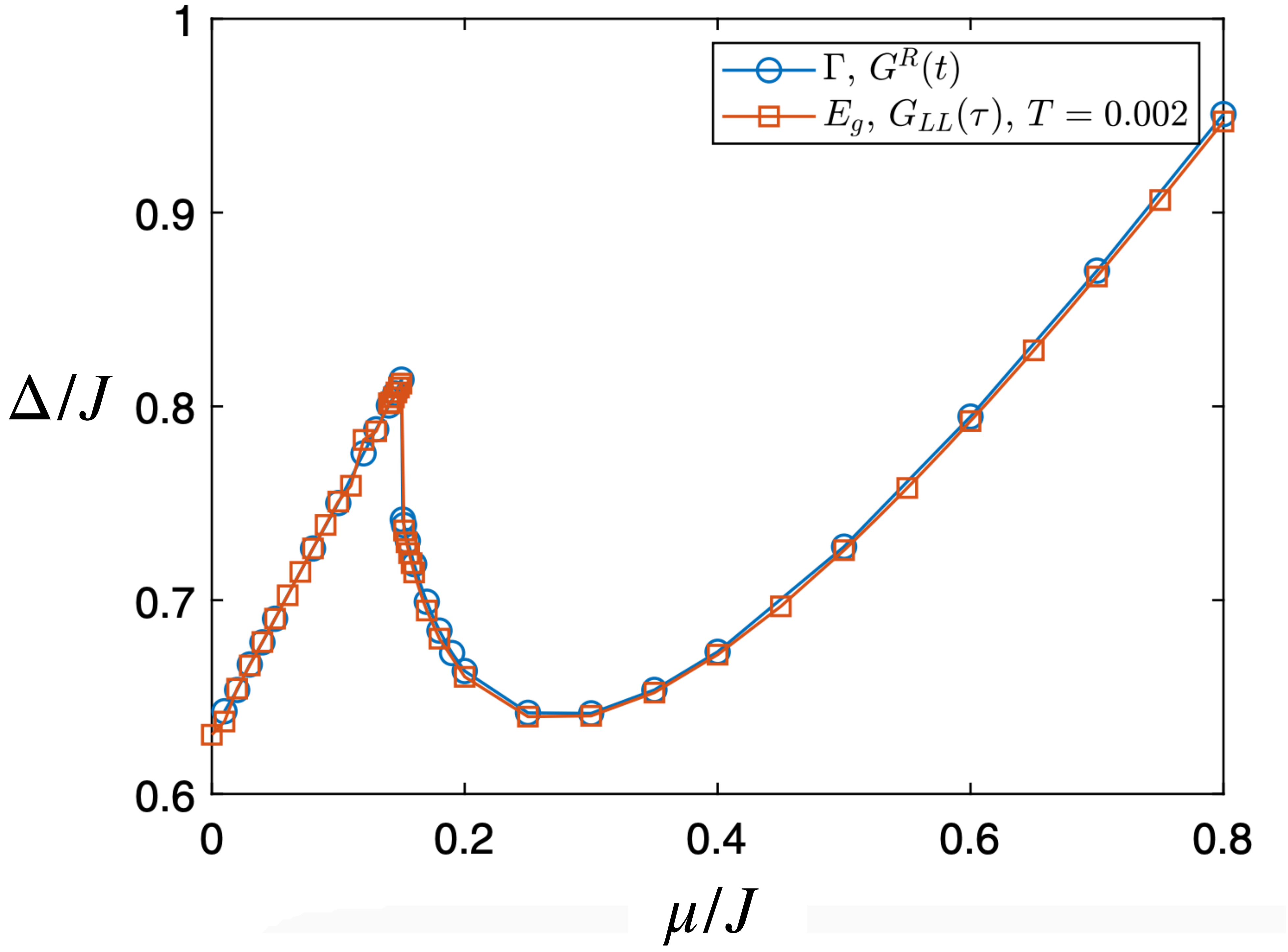
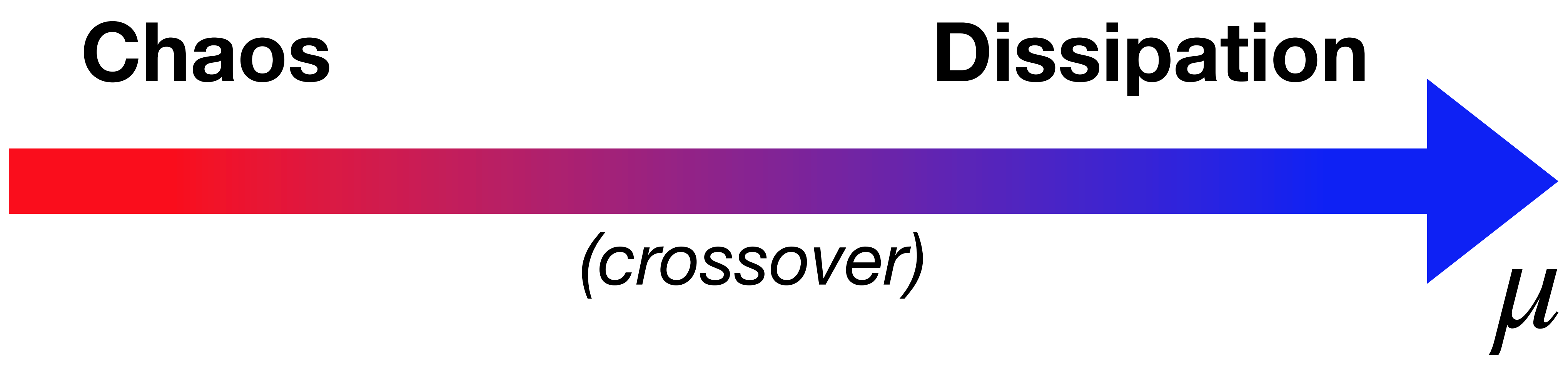
However, realistic environments have more structure and lead to **non-Markovian** dynamics

Markovian limit

For $\nu = \beta_E = 0$ (Markovian dynamics), there is exponential relaxation: $iG^R(t) = \Theta(t)\langle \mathrm{Tr}\left[\rho_\infty\{\chi_i(t),\chi_i\}\right]\rangle \sim e^{-\Delta t}$



García-García, Antonio M., et al. "Keldysh wormholes and anomalous relaxation in the dissipative Sachdev-Ye-Kitaev model." *Physical Review D* 107.10 (2023): 106006.



Our goal

How is this picture modified for non-Markovian baths?

Memory kernel

Introducing the **real Grassmann field** a$_i$(z), the Keldysh functional reads: $Z = \int \prod_i \mathscr{D} a_i \exp\{iS[a_i]\}$

$$iS[a_i] = i \int_C dz \, \frac{1}{2} \sum_i a_i(z) i\partial_z a_i(z) - i \int_C dz \sum_{i<j<k<l} J_{ijkl} a_i(z) a_j(z) a_k(z) a_l(z) + \int_C dz dz' \; \mu \; \underset{\substack{\downarrow \\ \text{Memory kernel}}}{K(z,z')} \sum_i a_i(z) a_i(z')$$

The memory kernel can be written in terms of bath correlation functions: $\Omega_i(z,z') = -iT_z \langle Y_i(z) Y_i(z') \rangle$

$$K(z,z') = -i\Omega(z,z') \xrightarrow{\text{Fluctuation-dissipation relations}} \begin{aligned} K^{>}(\omega) &= -\left[1 - n_F(\omega)\right] D(\omega) \\ K^{<}(\omega) &= n_F(\omega) D(\omega) \end{aligned}$$

Solutions of SD equations

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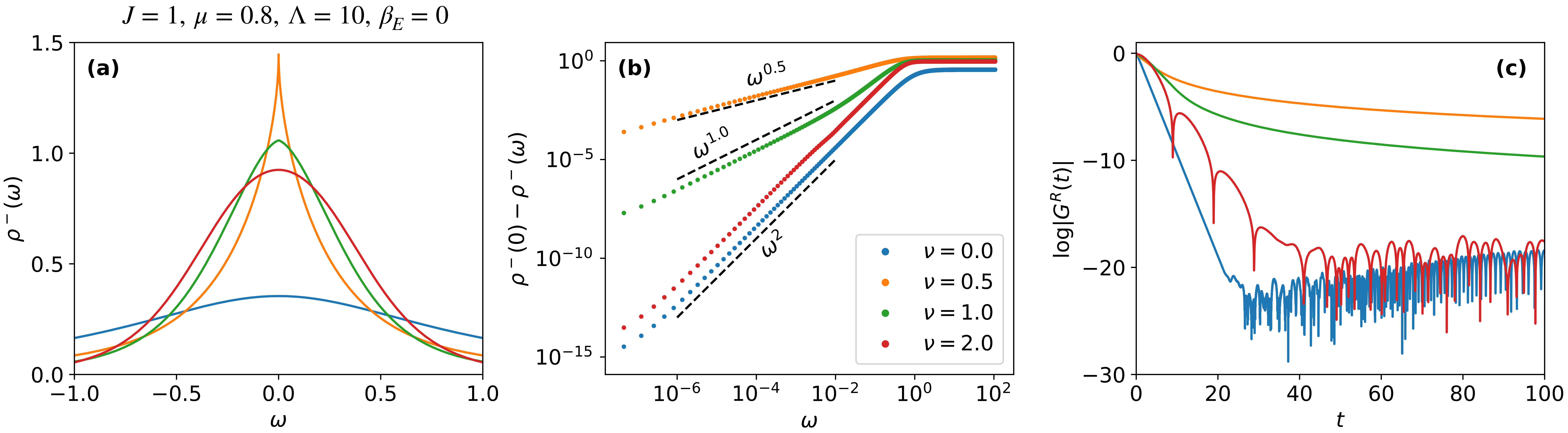

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Characterisation of power-law

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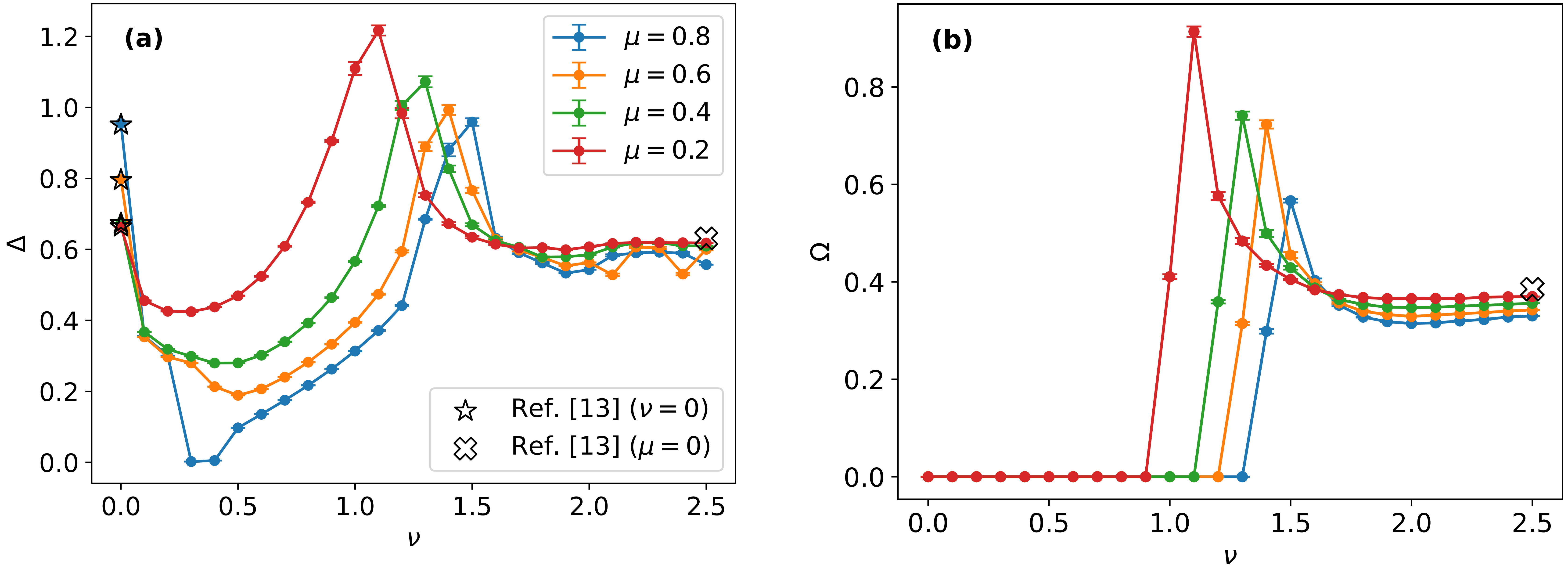
Infinite-temperature solutions

Characterisation of exponential



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Infinite-temperature solutions

Robustness to finite temperature

- The system obeys **fluctuation-dissipation relation:** $\rho^{+}(\omega) = \tanh\left(\frac{\beta_E \omega}{2}\right) \rho^{-}(\omega)$

- We still have $\rho(\omega) = \rho_0 - c\,|\,\omega\,|^{\nu}$ ➡ $G^R(t) \sim 1/t^{1+\nu}$