Collective advantages in finite-time thermodynamics

Phys. Rev. Lett. **131**, 210401

Alberto Rolandi, Paolo Abiuso, Martí Perarnau-Llobet

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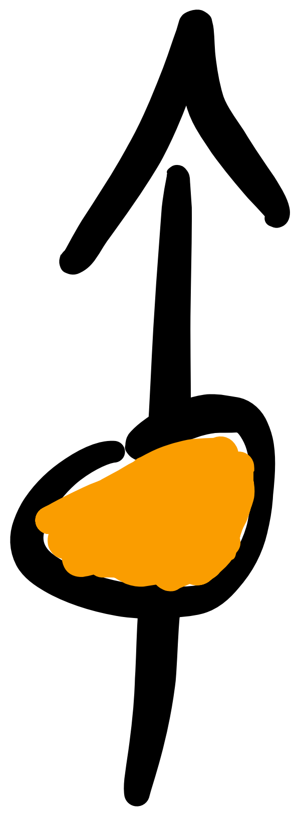
UNIVERSITÉ DE GENÈVE

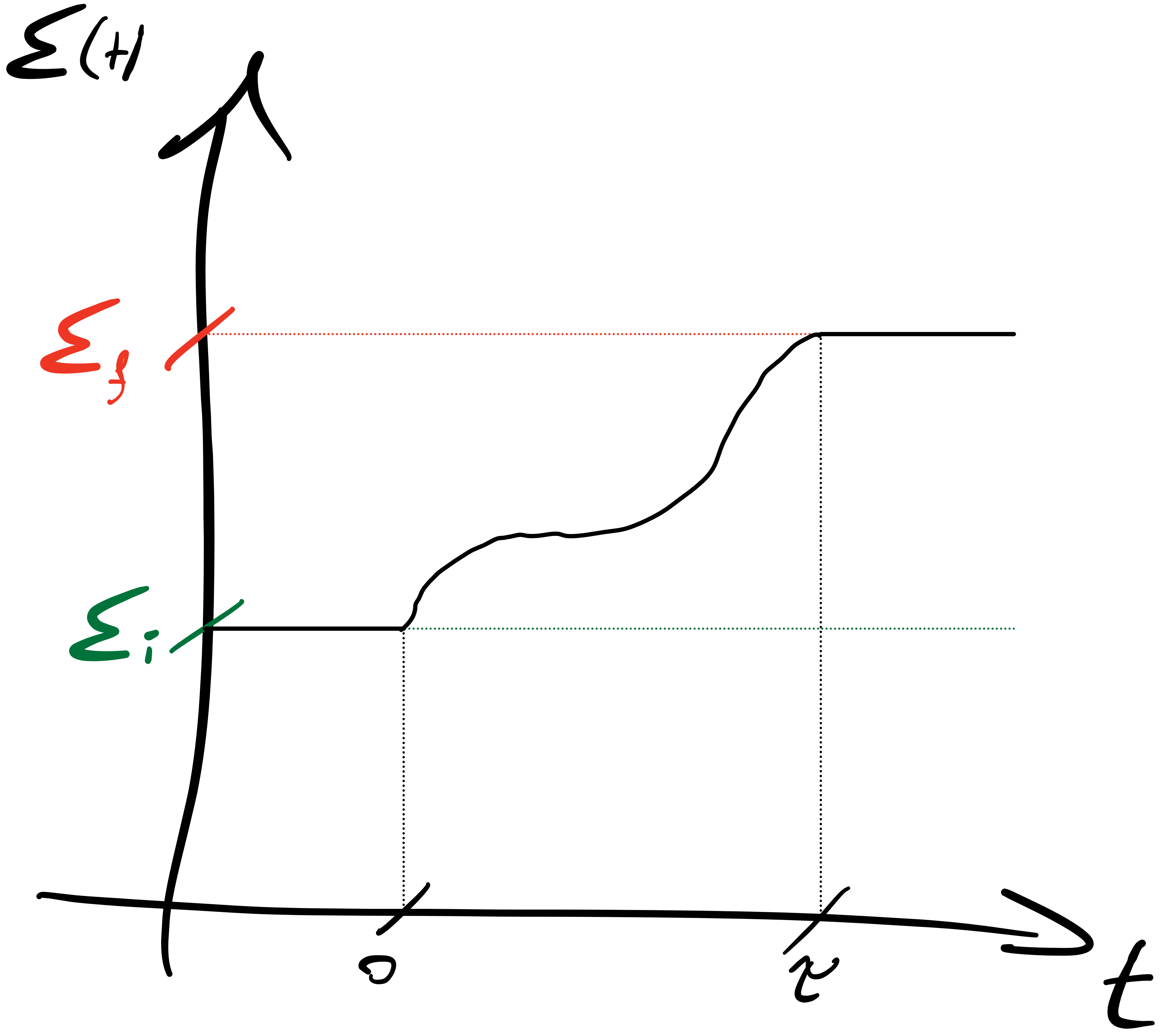
Swiss National Science Foundation

Collective advantages

$$\hat{H} = \varepsilon \hat{\sigma}_z$$

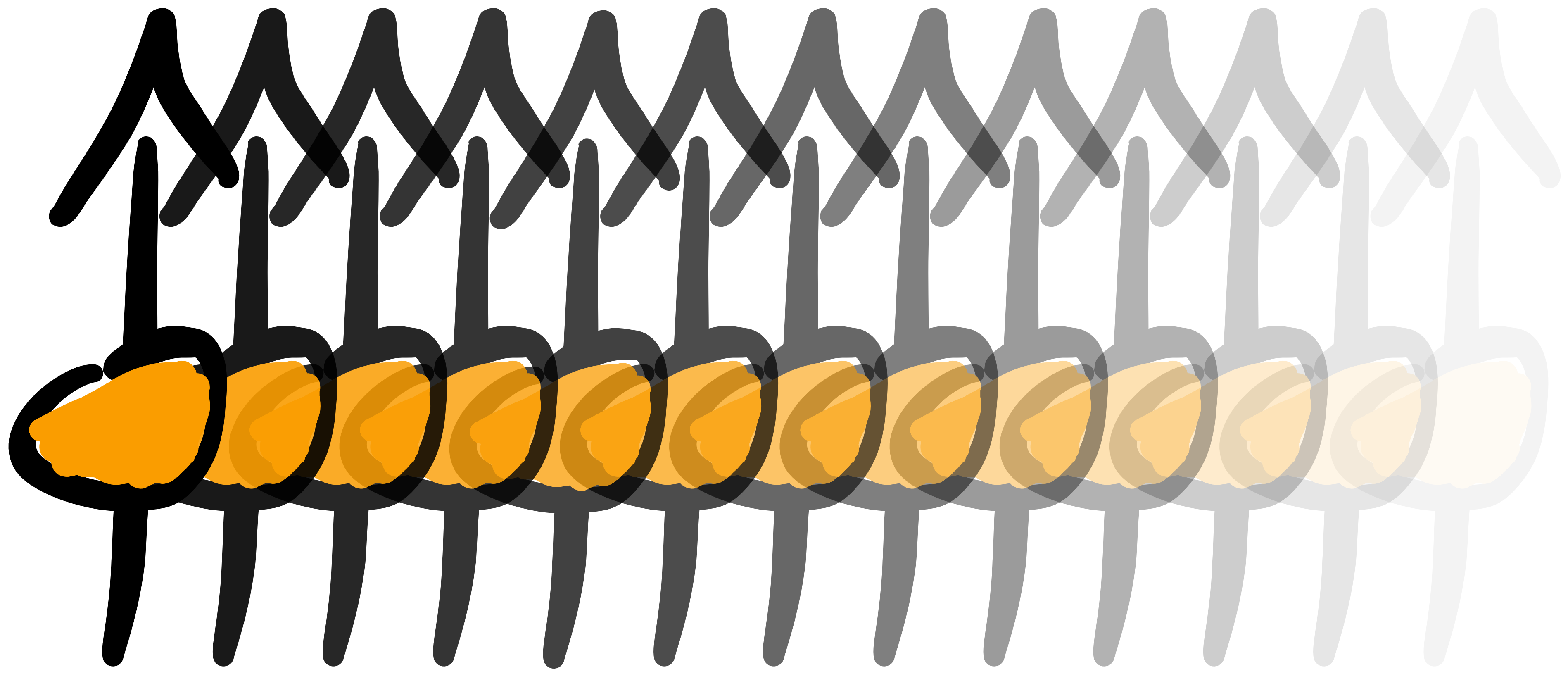
$$\varepsilon : \varepsilon_i \longrightarrow \varepsilon_f$$





Collective advantages

$$\hat{H} = \Sigma \hat{\sigma}_z$$



$\Sigma_1 : \Sigma_i \longrightarrow \Sigma_f$

$\Sigma_2 : \Sigma_i \longrightarrow \Sigma_f$

$\Sigma_3 : \Sigma_i \longrightarrow \Sigma_f$

$\Sigma_4 : \Sigma_i \longrightarrow \Sigma_f$

$\Sigma_5 : \Sigma_i \longrightarrow \Sigma_f$

$\Sigma_6 : \Sigma_i \longrightarrow \Sigma_f$

$\Sigma_7 : \Sigma_i \longrightarrow \Sigma_f$

$\Sigma_8 : \Sigma_i \longrightarrow \Sigma_f$

Collective advantages in thermodynamics

The outcome of a task is improved when performed globally on a collection of systems than when realized on each system individually.

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Quantum batteries

PHYSICAL REVIEW LETTERS **128,** 140501 (2022)

Editors' Suggestion | Featured in Physics

Quantum Charging Advantage Cannot Be Extensive without Global Operations

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Quantum batteries are devices made from quantum states, which store and release energy in a fast and efficient manner, thus offering numerous possibilities in future technological applications. They offer a significant charging speedup when compared to classical batteries, due to the possibility of using entangling charging operations. We show that the maximal speedup that can be achieved is extensive in the number of cells, thus offering at most quadratic scaling in the charging power over the classically achievable linear scaling. To reach such a scaling, a global charging protocol, charging all the cells collectively, needs to be employed. This concludes the quest on the limits of charging power of quantum batteries and adds to other results in which quantum methods are known to provide at most quadratic scaling over their classical counterparts.

DOI: 10.1103/PhysRevLett.128.140501

RL **118,** 150601 (2017) PHYSICAL REVIEW LETTERS week ending 14 APRIL 2017

Enhancing the Charging Power of Quantum Batteries

Francesco Campaioli,[1,*] Felix A. Pollock,[1] Felix C. Binder,[2] Lucas Céleri,[3] John Goold,[4] Sai Vinjanampathy,[5,6] and Kavan Modi[1,†]

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(Received 20 December 2016; revised manuscript received 14 February 2017; published 12 April 2017)

Can collective quantum effects make a difference in a meaningful thermodynamic operation? Focusing on energy storage and batteries, we demonstrate that quantum mechanics can lead to an enhancement in the amount of work deposited per unit time, i.e., the charging power, when N batteries are charged collectively. We first derive analytic upper bounds for the collective *quantum advantage* in charging power for two choices of constraints on the charging Hamiltonian. We then demonstrate that even in the absence of quantum entanglement this advantage can be extensive. For our main result, we provide an upper bound to the achievable quantum advantage when the interaction order is restricted; i.e., at most k batteries are interacting. This constitutes a fundamental limit on the advantage offered by quantum technologies over their classical counterparts.

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Quantum batteries

Thermal engines

PHYSICAL REVIEW LETTERS 128, 140501 (2022)
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... and release energy in a fast

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Open Access | Published: 20 June 2016

The power of a critical heat engine

Michele Campisi & Rosario Fazio

Nature Communications 7, Article number: 11895 (2016) | Cite this article

Abstract

Since its inception about two centuries ago thermodynamics has sparkled continuous interest and fundamental questions. According to the second law no heat engine can have an efficiency larger than Carnot's efficiency. The latter can be achieved by the Carnot engine, which however ideally operates in infinite time, hence delivers null power. A currently open question is whether the Carnot efficiency can be achieved at finite power. Most of the previous works addressed this question within the Onsager matrix formalism of linear response theory. Here we pursue a different route based on finite-size-scaling theory. We focus on quantum Otto engines and show that when the working substance is at the verge of a second order phase transition diverging energy fluctuations can enable approaching the Carnot point without sacrificing power. The rate of such approach is dictated by the critical indices, thus showing the universal character of our analysis.

...ntum heat engine with long-range advantages

...a Solfanelli[1,2,*], Guido Giachetti[1,2], Michele Campisi[3], Stefano Ruffo[1,2,4]
...icolò Defenu[5,*]
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..., Sezione di Trieste, Via Valerio 2, 34127 Trieste, Italy
..., Istituto Nanoscienze-CNR and Scuola Normale Superiore, I-56127 Pisa, Italy
...to dei Sistemi Complessi, Via Madonna del Piano 10, I-50019 Sesto Fiorentino, Italy
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asolfane@sissa.it and ndefenu@phys.ethz.ch

...ds: quantum heat engines and refrigerators, long-range interactions, quantum phase transitions

...act

...-range interacting quantum devices provides a promising route for quantum technology ...cations. Here, the presence of long-range interactions is shown to enhance the performances ...uantum heat engine featuring a many-body working substance. We focus on the ...ligmatic example of a Kitaev chain undergoing a quantum Otto cycle and show that a ...antial thermodynamic advantage may be achieved as the range of the interactions among its ...ituents increases. The advantage is most significant for the realistic situation of a finite time ... the presence of long-range interactions reduces the non-adiabatic energy losses, by ...essing the detrimental effects of dynamically generated excitations. This effect allows ...ating the trade-off between power and efficiency, paving the way for a wide range of ...imental and technological applications.

PHYSICAL REVIEW A 107, L040202 (2023)

Quadratic enhancement in the reliability of collective quantum engines

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(Received 11 August 2022; accepted 10 March 2023; published 6 April 2023)

We study fluctuations in many-body quantum heat engines operating in the presence of collective system-...th interactions. We show that collective effects in open quantum systems can be harnessed to develop highly ...nsistent many-body quantum engines. We consider quantum Otto engines, modeled by n spins collectively ...upled to thermal baths. Our results show that collective effects can significantly reduce the fluctuations in the ...tput work, quantified by high reliability (r) and low thermodynamic uncertainty. In contrast to independent ...gines, we demonstrate a quadratic enhancement of the reliability r for their collective counterparts. We extend ...r analysis to the case of interacting spin models commonly studied in many-body physics, such as the Lipkin-...eshkov-Glick (LMG) model, thereby broadening the regime of applicability of collective effects in quantum ...ermal machines significantly. This paves the way forward for realistic collective quantum thermal machines in ...any-body systems.

Collective advantages in thermodynamics

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Quantum batteries

PHYSICAL REVIEW LETTERS 128, 140501 (2022)

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PRL 118, 150601 (2017) PHYSICAL REVIEW LETTERS week ending 14 APRIL 2017

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[4]*The Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste 34151, Italy*
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Thermal engines

Open Access | Published: 20 June 2016

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PHYSICAL REVIEW A 107, L040202 (2023)

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Noufal Jaseem,[1] Sai Vinjanampathy,[2,3] and Victor Mukherjee[1]

Quantum transport

PHYSICAL REVIEW LETTERS 120, 090601 (2018)

Thermodynamic Bounds on Precision in Ballistic Multiterminal Transport

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[2]*Department of Physics, Keio University, 3-14-1 Hiyoshi, Yokohama 223-8522, Japan*

(Received 10 October 2017; revised manuscript received 28 December 2017; published 2 March 2018)

For classical ballistic transport in a multiterminal geometry, we derive a universal trade-off relation between total dissipation and the precision, at which particles are extracted from individual reservoirs. Remarkably, this bound becomes significantly weaker in the presence of a magnetic field breaking time-reversal symmetry. By working out an explicit model for chiral transport enforced by a strong magnetic field, we show that our bounds are tight. Beyond the classical regime, we find that, in quantum systems far from equilibrium, the correlated exchange of particles makes it possible to exponentially reduce the thermodynamic cost of precision.

DOI: 10.1103/PhysRevLett.120.090601

PHYSICAL REVIEW B 104, 045424 (2021)

Broadband frequency filters with quantum dot chains

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Two-terminal electronic transport systems with a rectangular transmission can violate standard thermodynamic uncertainty relations. This is possible beyond the linear response regime and for parameters that are not accessible with rate equations obeying detailed balance. Looser bounds originating from fluctuation theorem symmetries alone remain respected. We demonstrate that optimal finite-sized quantum dot chains can implement rectangular transmission functions with high accuracy and discuss the resulting violations of standard thermodynamic uncertainty relations as well as heat engine performance.

DOI: 10.1103/PhysRevB.104.045424

Collective advantages in thermodynamics

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- Quantum batteries
- Thermal engines
- Quantum transport
- Metrology

PHYSICAL REVIEW LETTERS **128,** 140501 (2022)

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PRL **118,** 150601 (2017) PHYSICAL REVIEW LETTERS week ending 14 APRIL 2017

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PRL **96,** 010401 (2006) PHYSICAL REVIEW LETTERS week ending 13 JANUARY 2006

Quantum Metrology

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[2]MIT, Research Laboratory of Electronics and Department of Mechanical Engineering, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA
[3]QUIT–Quantum Information Theory Group, Dipartimento di Fisica "A. Volta" Università di Pavia, via Bassi 6, I-27100 Pavia, Italy

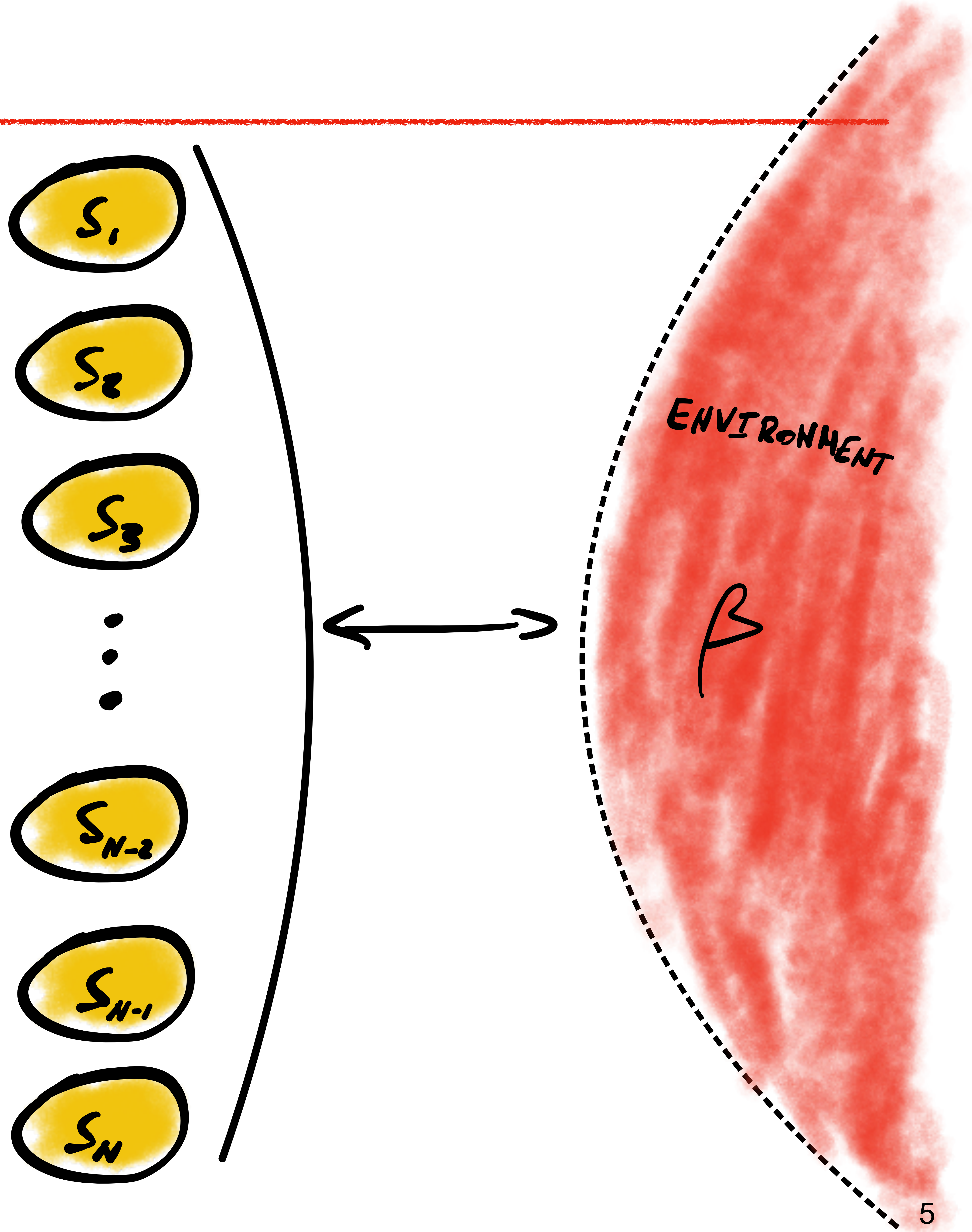
(Received 26 September 2005; published 3 January 2006)

We point out a general framework that encompasses most cases in which quantum effects enable an increase in precision when estimating a parameter (quantum metrology). The typical quantum precision enhancement is of the order of the square root of the number of times the system is sampled. We prove that this is optimal, and we point out the different strategies (classical and quantum) that permit one to attain this bound.

DOI: 10.1103/PhysRevLett.96.010401 PACS numbers: 03.65.Ta, 03.67.Lx, 06.20.Dk, 42.50.St

Sublinear dissipation?

$$W = \Delta F + W_{diss}$$

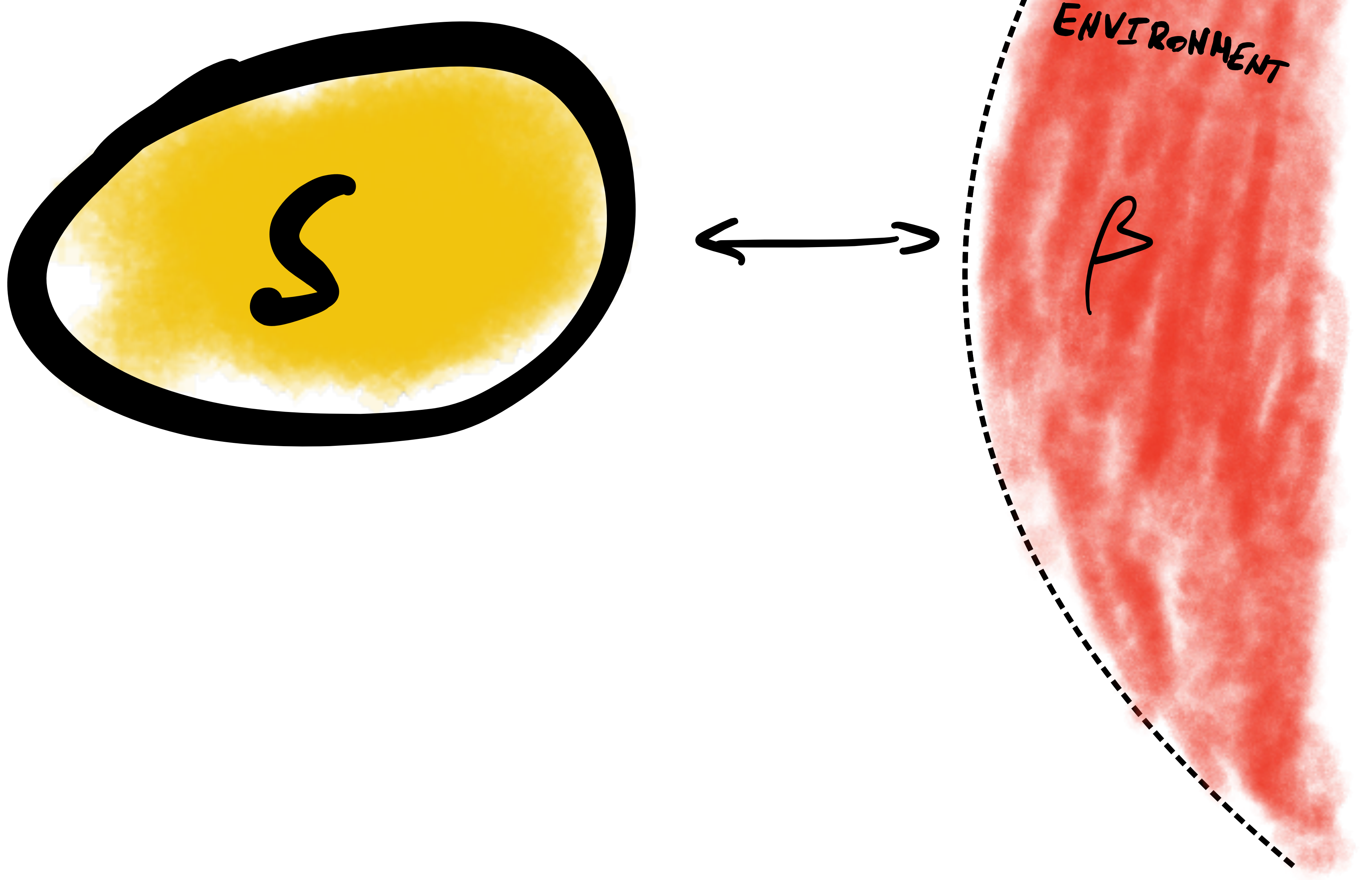


General definitions

$$E = \mathrm{Tr}[\hat{H}(t)\hat{\rho}(t)]$$

$$\hat{H}(0) \longrightarrow \hat{H}(\tau)$$

$$t : 0 \rightarrow \tau$$



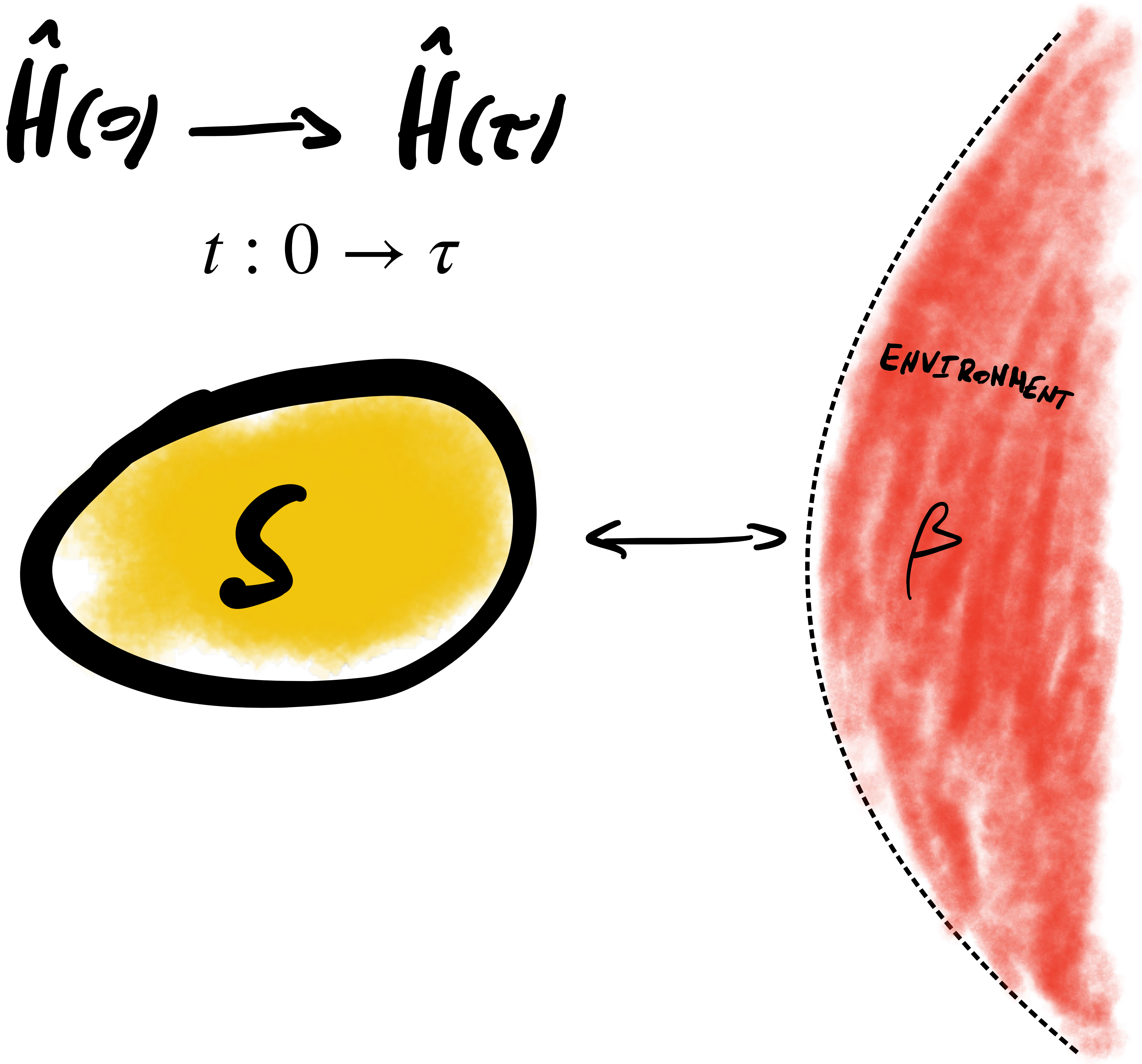
$$\hat{\rho} \otimes \frac{e^{-\beta \hat{H}_B}}{\mathrm{Tr}[e^{-\beta \hat{H}_B}]} \longrightarrow \hat{U}\hat{\rho} \otimes \frac{e^{-\beta \hat{H}_B}}{\mathrm{Tr}[e^{-\beta \hat{H}_B}]}\hat{U}^{+}$$

General definitions

$$dE = \mathrm{Tr}[\hat{H}'(t)\hat{\rho}(t)]dt + \mathrm{Tr}[\hat{H}(t)\hat{\rho}'(t)]dt$$

$$\hat{H}(0) \longrightarrow \hat{H}(\tau)$$

$$t : 0 \rightarrow \tau$$



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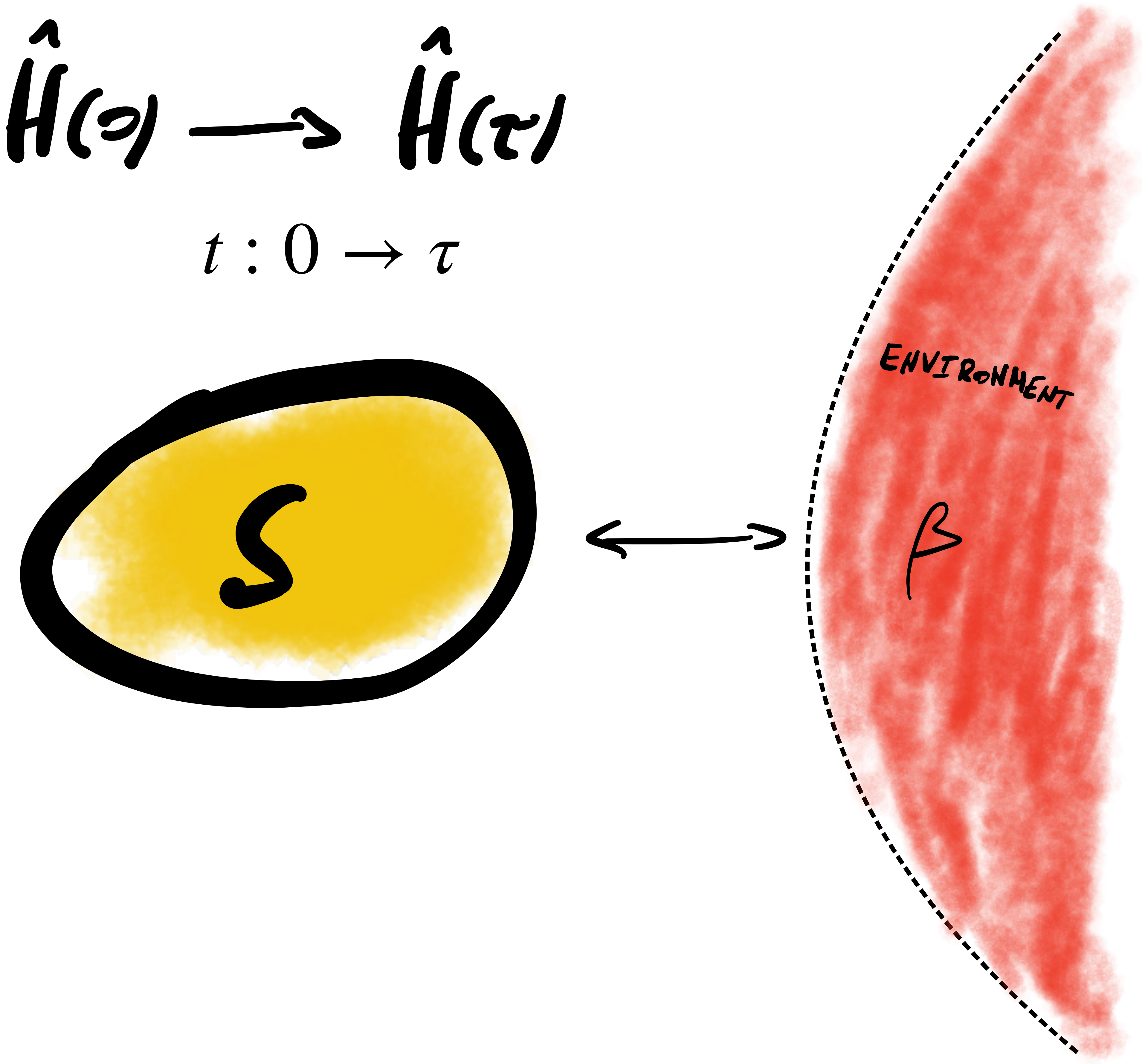
$$\delta W \qquad \qquad \delta Q$$

$$\hat{H}(0) \longrightarrow \hat{H}(\tau)$$

$$t : 0 \to \tau$$



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$$W = \int_0^\tau dt\, \mathrm{Tr}[\hat{\rho}(t)\hat{H}'(t)]$$

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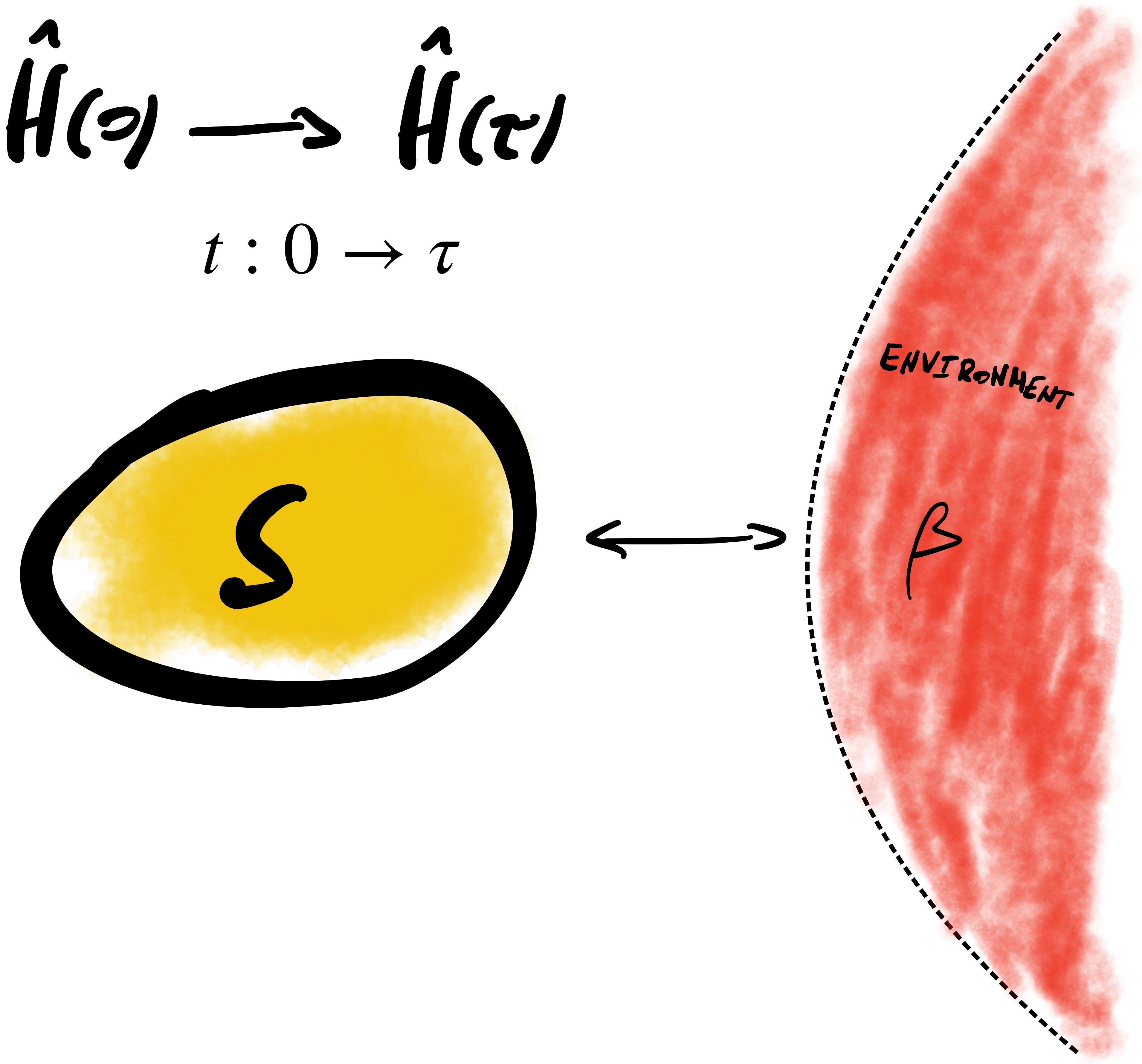

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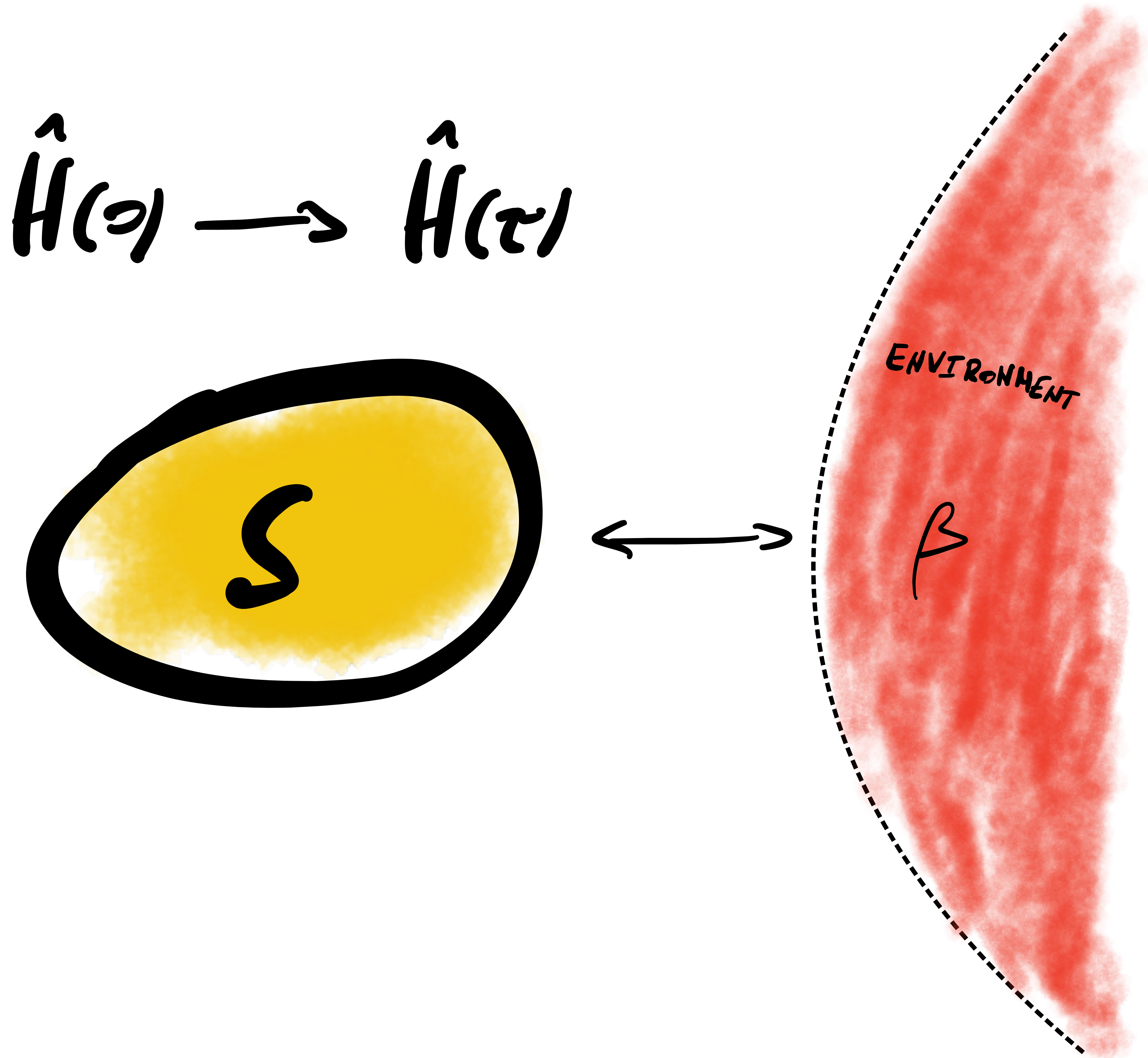
General framework for geometric thermo

$$\frac{d}{dt}\hat{\rho}(t) = i[\hat{\rho}(t), \hat{H}(t)] + \mathscr{D}_t[\hat{\rho}(t)]$$

→ Thermalization

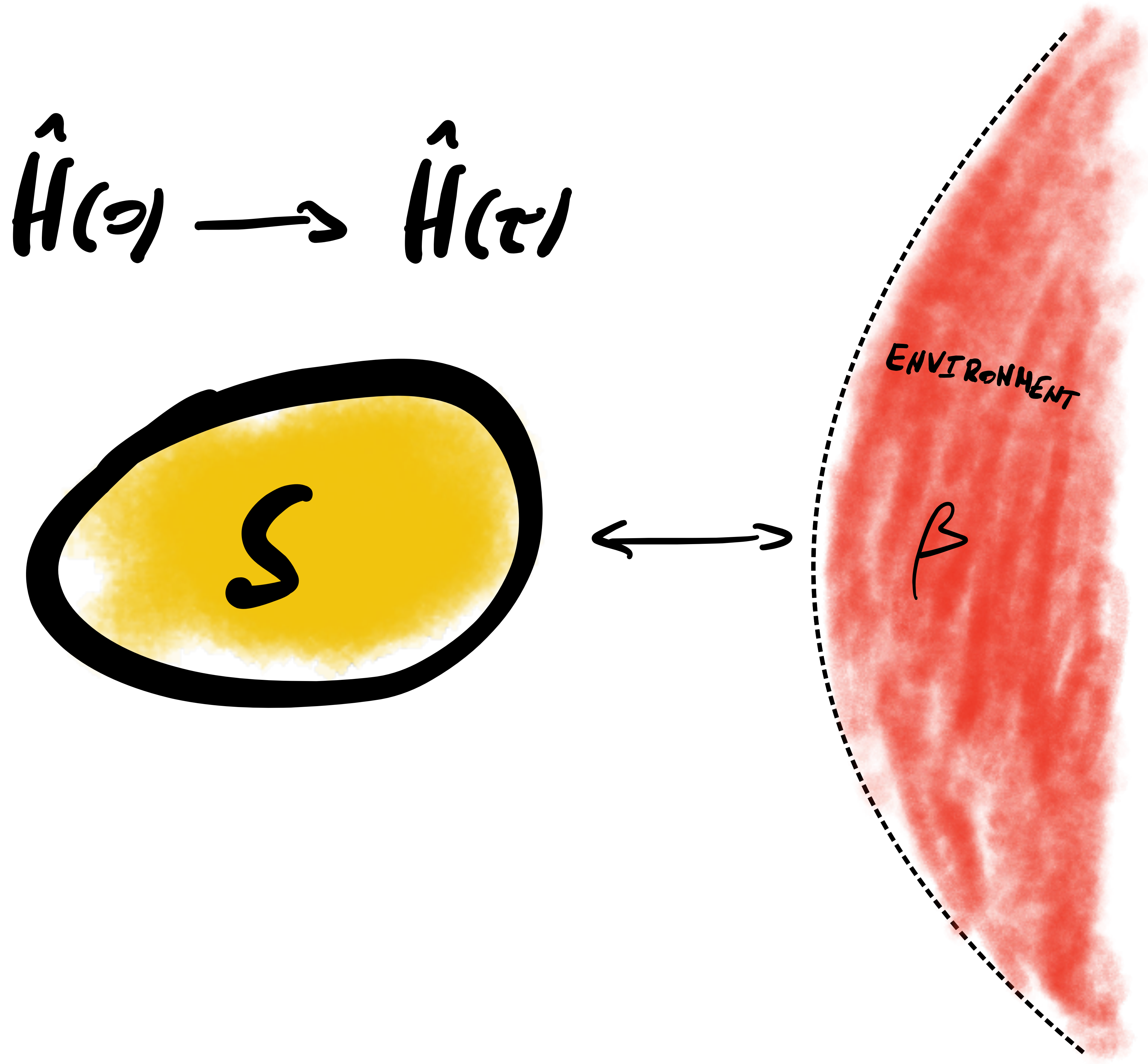


General framework for geometric thermo

$$\hat{\rho}(t) = \hat{\rho}_{th}(t) + \frac{1}{\tau}\hat{\rho}^{(1)}(t) + \mathcal{O}(\tau^{-2})$$

$$\hat{\rho}_{th}(t) = \frac{e^{-\beta \hat{H}(t)}}{Z}$$

→ Slow driving



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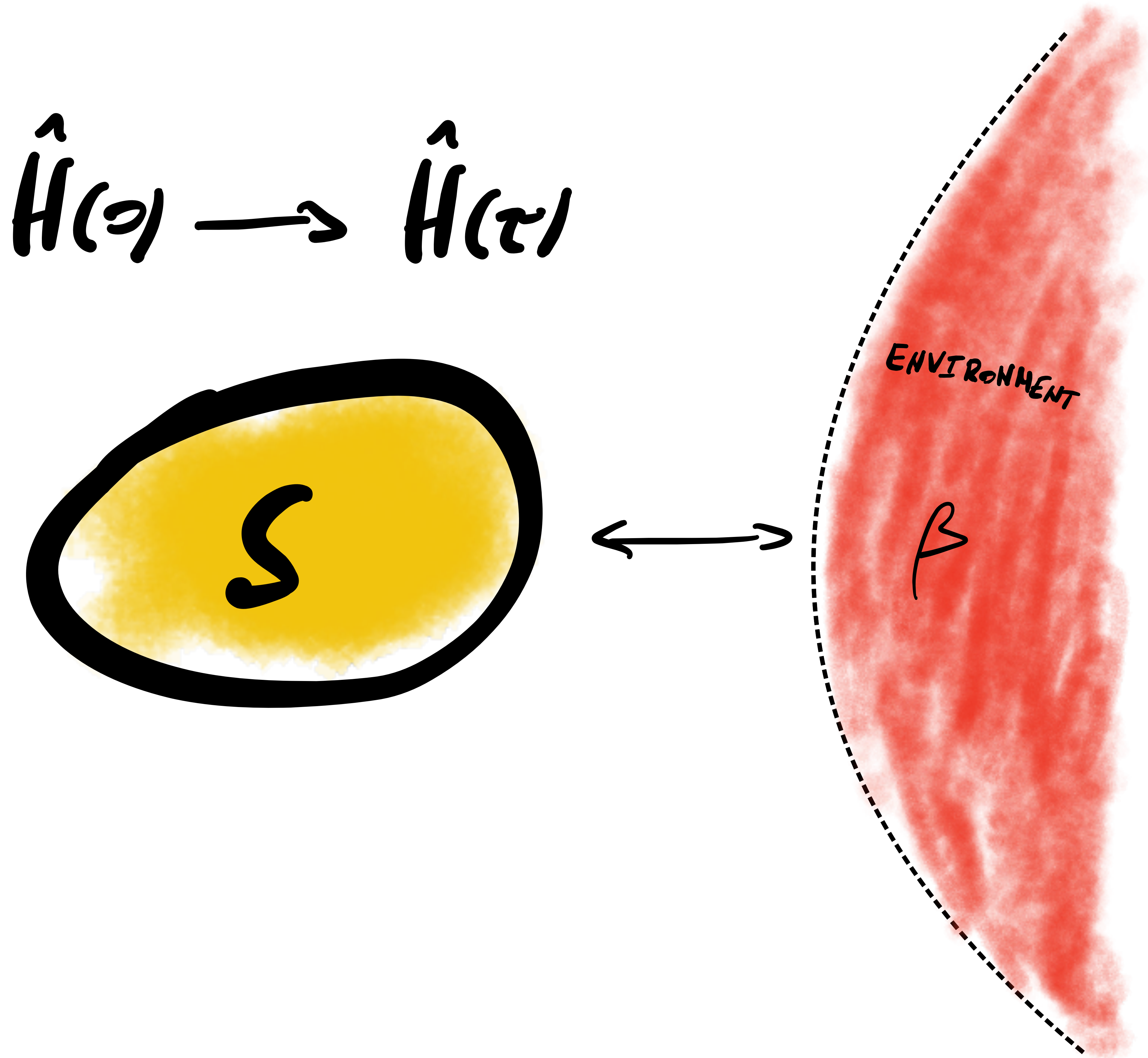
$$W = \int_0^\tau dt\, \mathrm{Tr}[\hat{\rho}(t)\hat{H}'(t)] \quad W = \Delta F + W_{diss}$$



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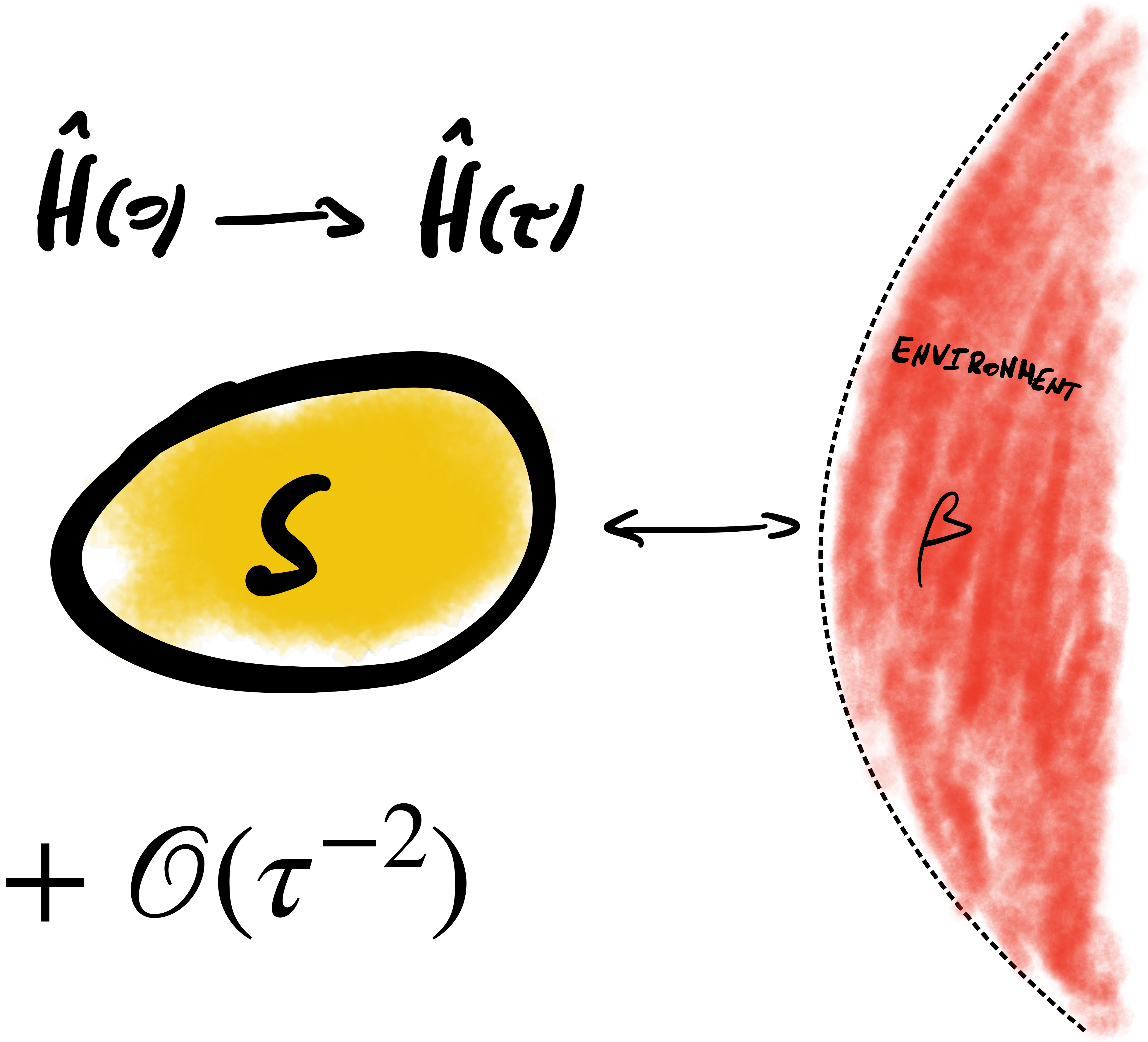


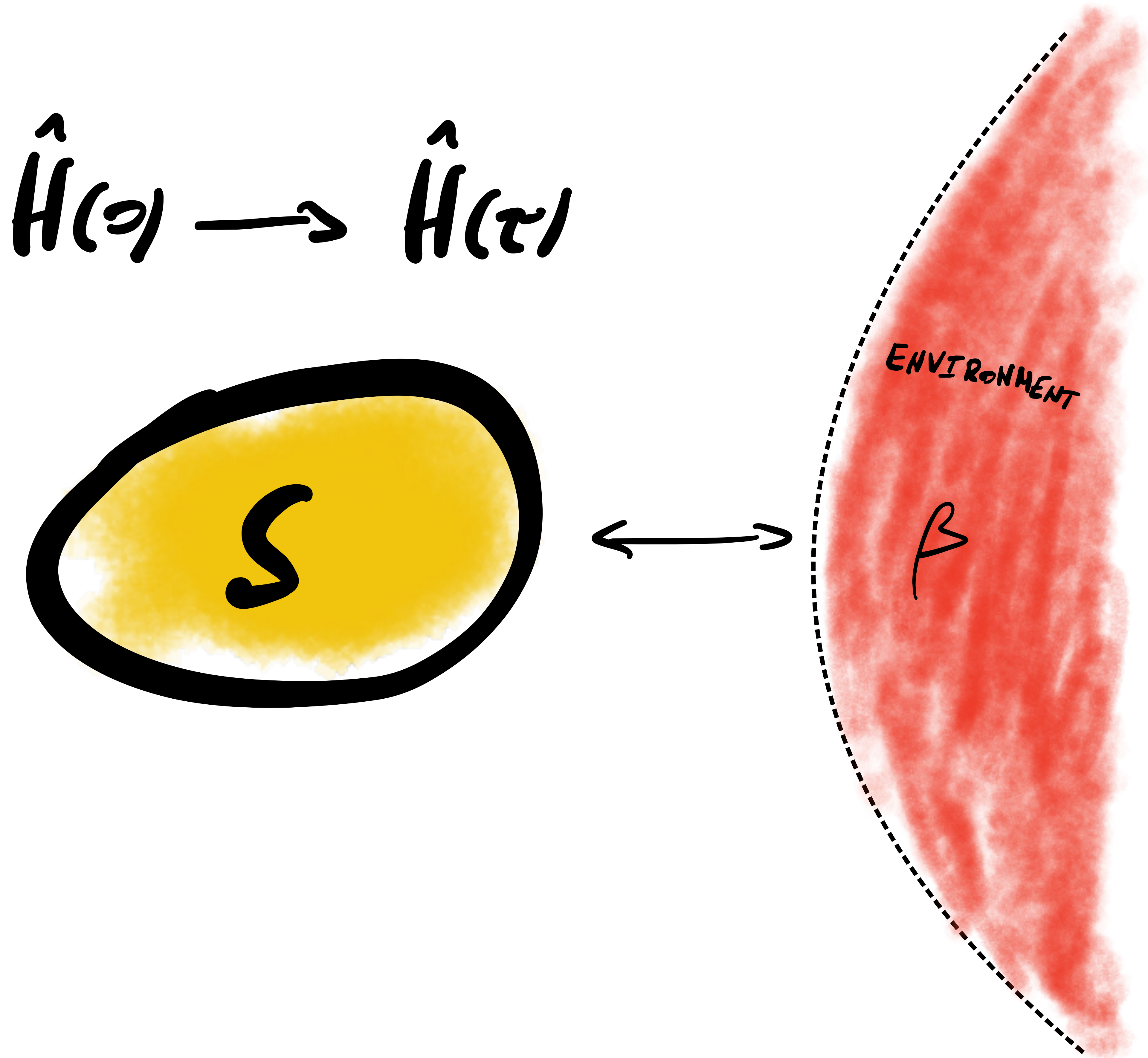
$$W = \int_0^\tau dt\, \mathrm{Tr}[\hat{\rho}(t)\hat{H}'(t)] \qquad W = \Delta F + W_{diss}$$

$$W_{diss} = \frac{1}{\tau}\int_0^\tau dt\, \mathrm{Tr}[\hat{\rho}^{(1)}(t)\hat{H}'(t)] + \mathcal{O}(\tau^{-2})$$

Geometric thermodynamics

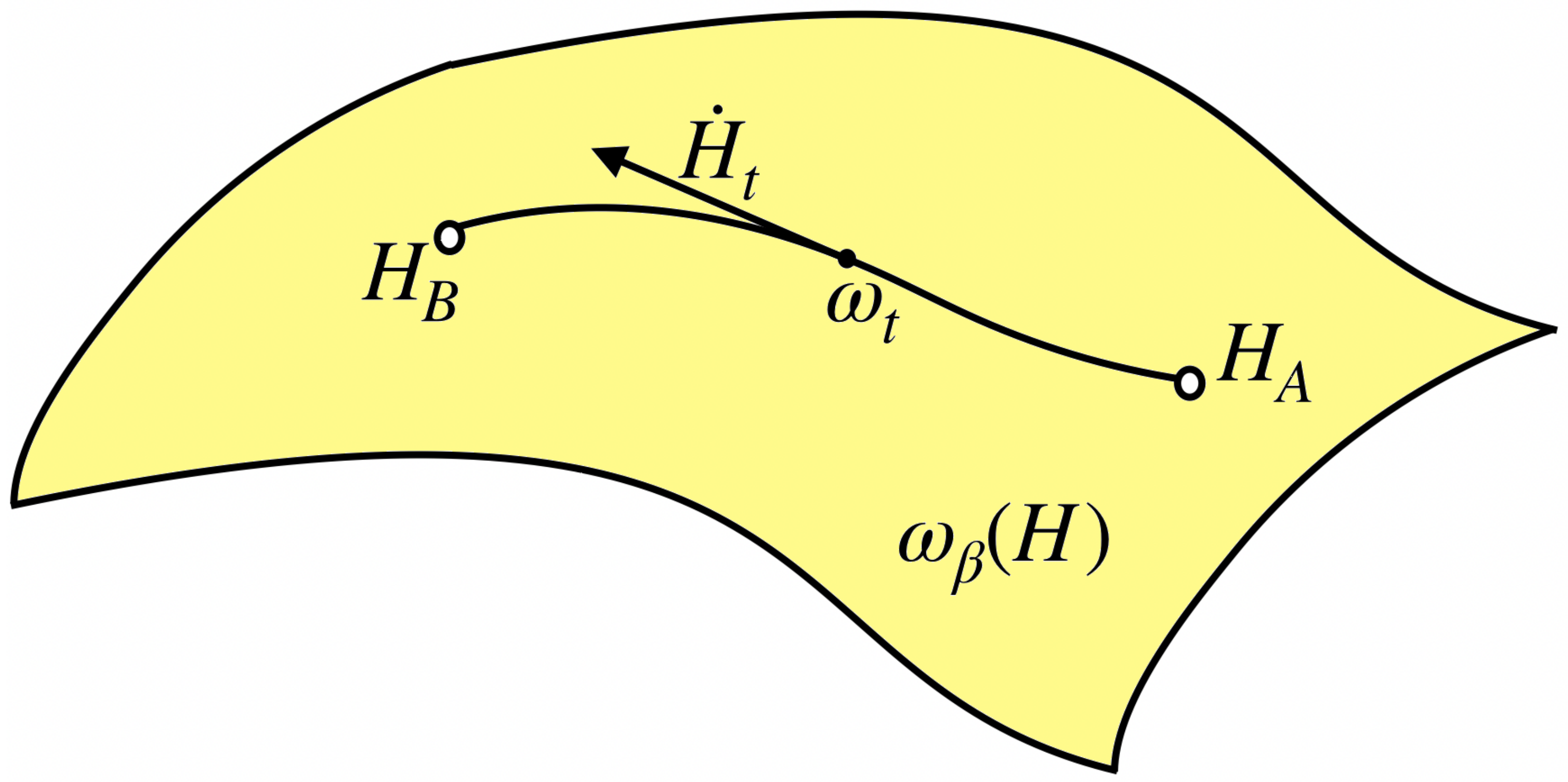
$$\hat{H}(t) = \lambda^k(t)\hat{X}_k$$

$$W_{diss} = k_B T \int_0^{\tau} dt\ \dot{\lambda}^i(t)\dot{\lambda}^j(t)\, g_{ij}$$



Thermodynamic length

$$L[\lambda] = \int_0^\tau dt \sqrt{\dot{\lambda}^i(t)\dot{\lambda}^j(t)\, g_{ij}}$$



$$\beta W_{diss} \geq \frac{1}{\tau} L^2$$

- Quantum 3, 197
- Phys. Rev. Lett. 51, 1127
- Phys. Rev. Lett. 99, 100602
- …

Thermodynamic length

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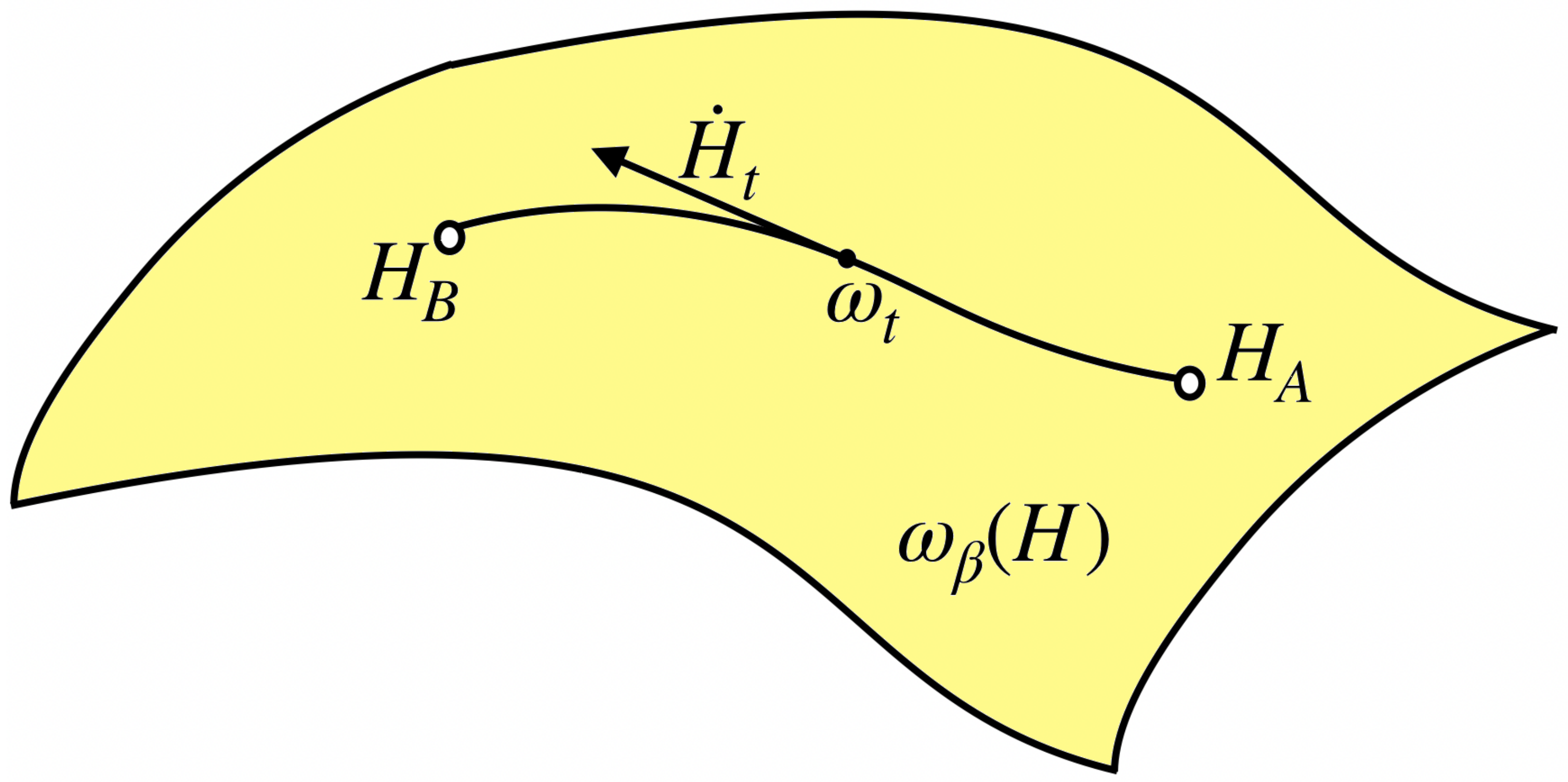

$$\beta W_{diss} \geq \frac{1}{\tau} L^2$$

$$\ddot{\lambda}^i + \Gamma^i_{jk}\dot{\lambda}^j\dot{\lambda}^k = 0$$

$$\Gamma^i_{jk} = \frac{1}{2} g^{il}\left(\partial_k g_{jl} + \partial_j g_{kl} - \partial_l g_{jk}\right)$$

- Quantum 3, 197
- Phys. Rev. Lett. 51, 1127
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- …

Computing the metric and minimal dissipation

→ Single relaxation timescale

$$g_{ij} = \tau_{eq} \frac{\partial^2 \ln Z}{\partial \lambda^i \partial \lambda^j}$$

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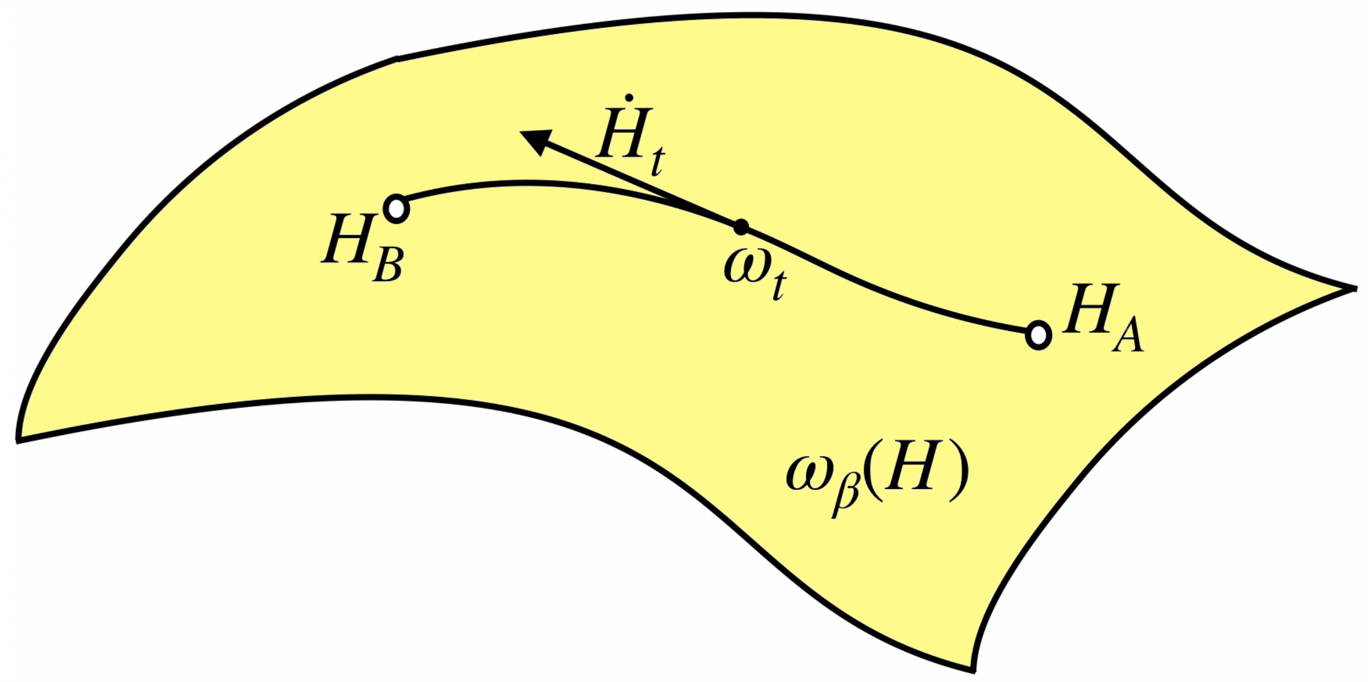
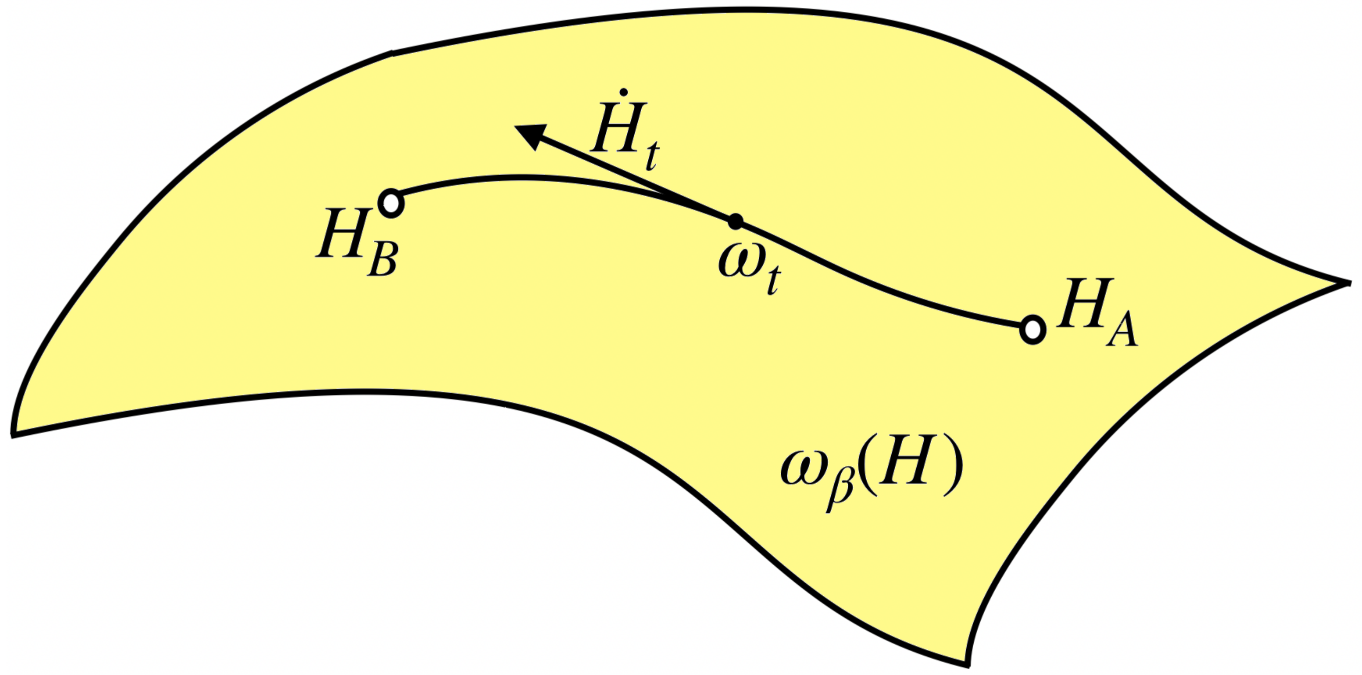


$\longrightarrow \quad S^n$

Computing the metric and minimal dissipation

→ Single relaxation timescale

$$g_{ij} = \tau_{eq} \frac{\partial^2 \ln Z}{\partial \lambda^i \partial \lambda^j}$$



$$\longrightarrow \quad S^n$$

→ Geodesics are great circles

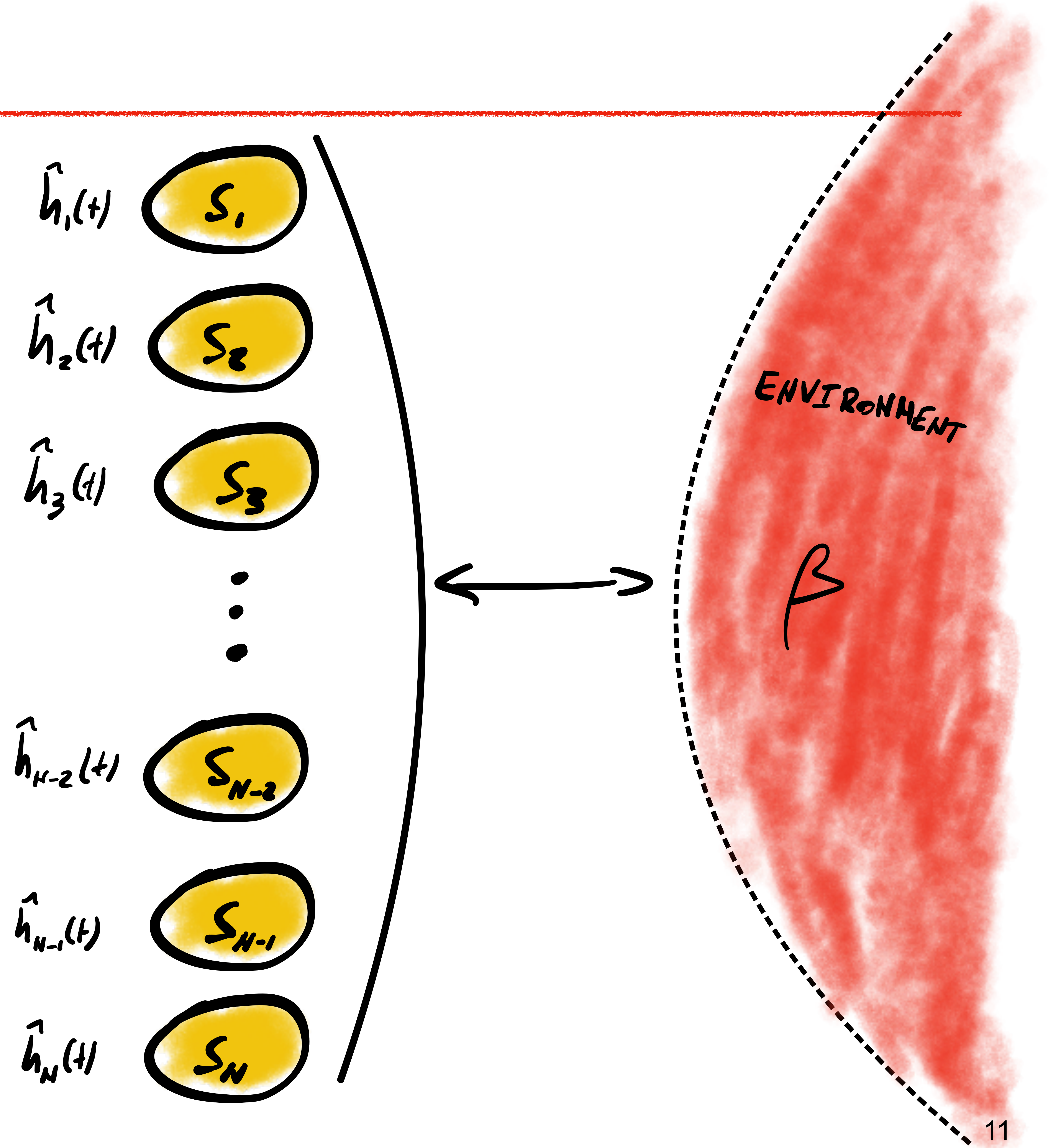
$$\min_{\lambda} \beta W_{diss} \leq \frac{\pi^2}{\tau}$$

Framework

$$\hat{H}(t) = \hat{H}_0(t) + \hat{V}(t)$$

$$\hat{H}_0(t) = \sum_{k=1}^{N} \hat{h}_k(t)$$

$$\hat{V}(0) = \hat{V}(\tau) = 0$$



Fundamental limit

→ Full control

$$\hat{V} \;-\; \left(\begin{array}{l} \hat{\sigma}_z^{(1)}\hat{\sigma}_z^{(2)},\ \hat{\sigma}_z^{(1)}\hat{\sigma}_z^{(3)},\ \hat{\sigma}_z^{(2)}\hat{\sigma}_z^{(3)},\ \ldots \\ \hat{\sigma}_z^{(1)}\hat{\sigma}_z^{(2)}\hat{\sigma}_z^{(3)},\ \ldots \\ \quad\vdots \\ \hat{\sigma}_z^{(1)}\hat{\sigma}_z^{(2)}\hat{\sigma}_z^{(3)}\ldots\hat{\sigma}_z^{(N)} \end{array} \right.$$

Fundamental limit

→ Geodesics are great circles

$$\min_{\lambda} \beta W_{diss} \leq \frac{\pi^2}{\tau}$$

$$\hat{H}(t) = -2\log\left[\sin\left(\frac{L(\tau - t)}{\tau}\right)\sqrt{\hat{\rho}_{th}(0)} + \sin\left(\frac{Lt}{\tau}\right)\sqrt{\hat{\rho}_{th}(\tau)}\right]$$

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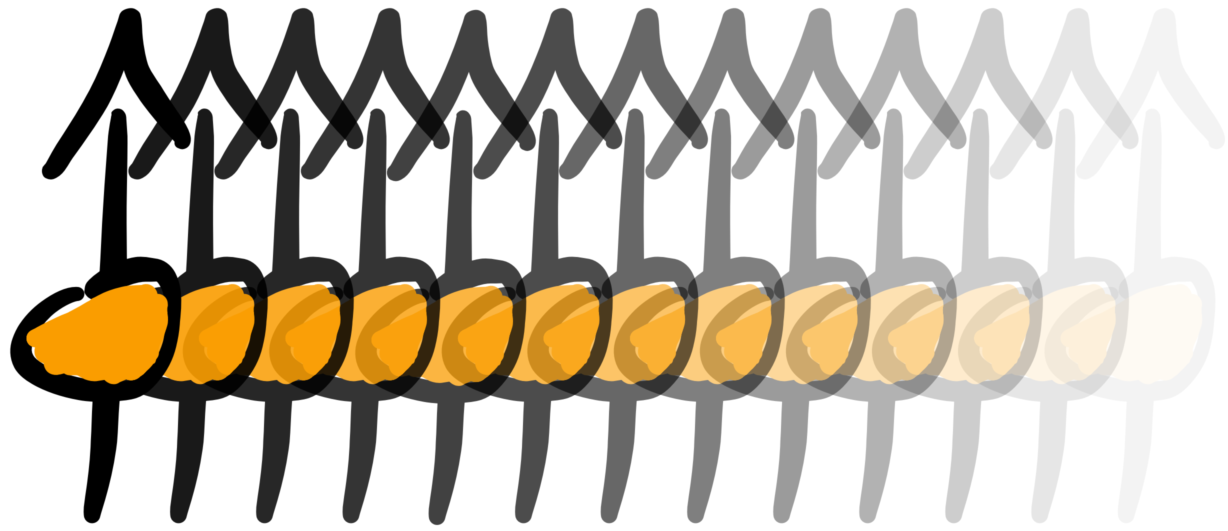
→ Every order of interaction is needed

Collective bit reset

$$\hat{H} = \varepsilon \hat{\sigma}_z$$



$$\varepsilon : 0 \longrightarrow \infty$$

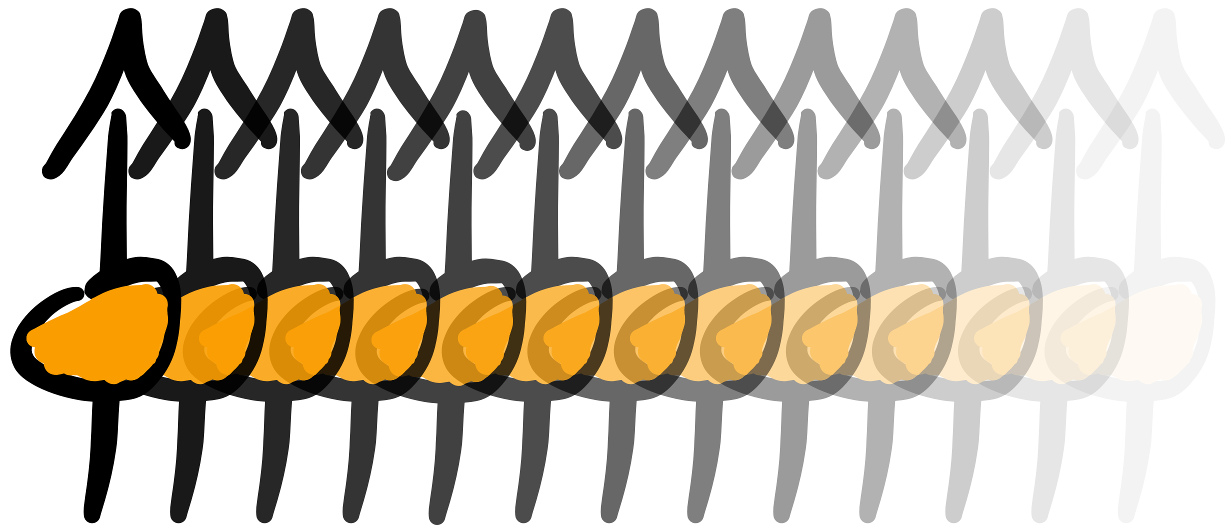
$$W = k_B T N \ln 2 + W_{diss}$$

$$\beta W_{diss}^{local} = N \frac{\pi^2}{4\tau}$$

$$\beta W_{diss}^{global} = \frac{\pi^2}{\tau}$$

Collective bit reset

$$\hat{H} = \varepsilon \hat{\sigma}_z$$



$$W_{qubit} = k_B T \ln 2 + \frac{k_B T \pi^2}{\tau N} + \mathcal{O}(\tau^{-2})$$

More realistic control

→ Restrict to two-body interaction with few control parameters

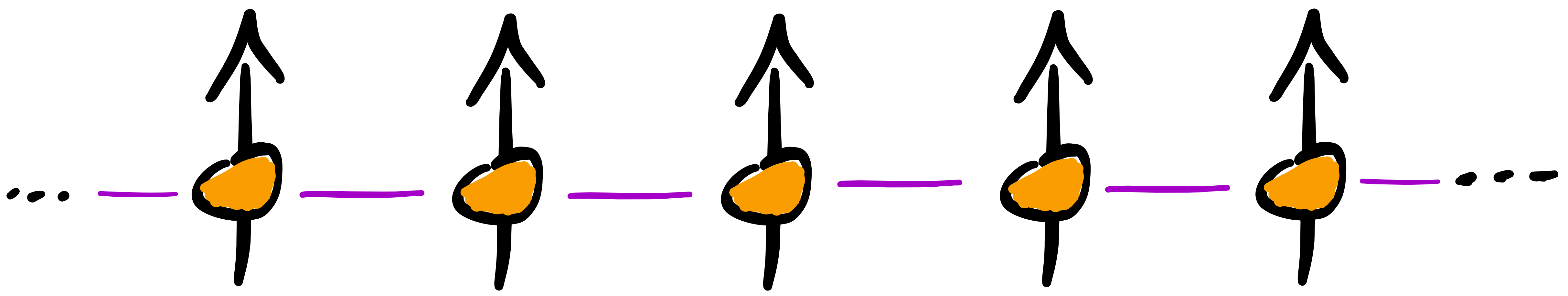
$$
\hat{V} \longrightarrow \begin{cases} \hat{\sigma}_z^{(1)}\hat{\sigma}_z^{(2)},\ \hat{\sigma}_z^{(1)}\hat{\sigma}_z^{(3)},\ \hat{\sigma}_z^{(2)}\hat{\sigma}_z^{(3)},\ \ldots \\ \hat{\sigma}_z^{(1)}\hat{\sigma}_z^{(2)}\hat{\sigma}_z^{(3)},\ \ldots \\ \vdots \\ \hat{\sigma}_z^{(1)}\hat{\sigma}_z^{(2)}\hat{\sigma}_z^{(3)}\ldots\hat{\sigma}_z^{(N)} \end{cases}
$$

More realistic control

→ Restrict to two-body interaction with few control parameters

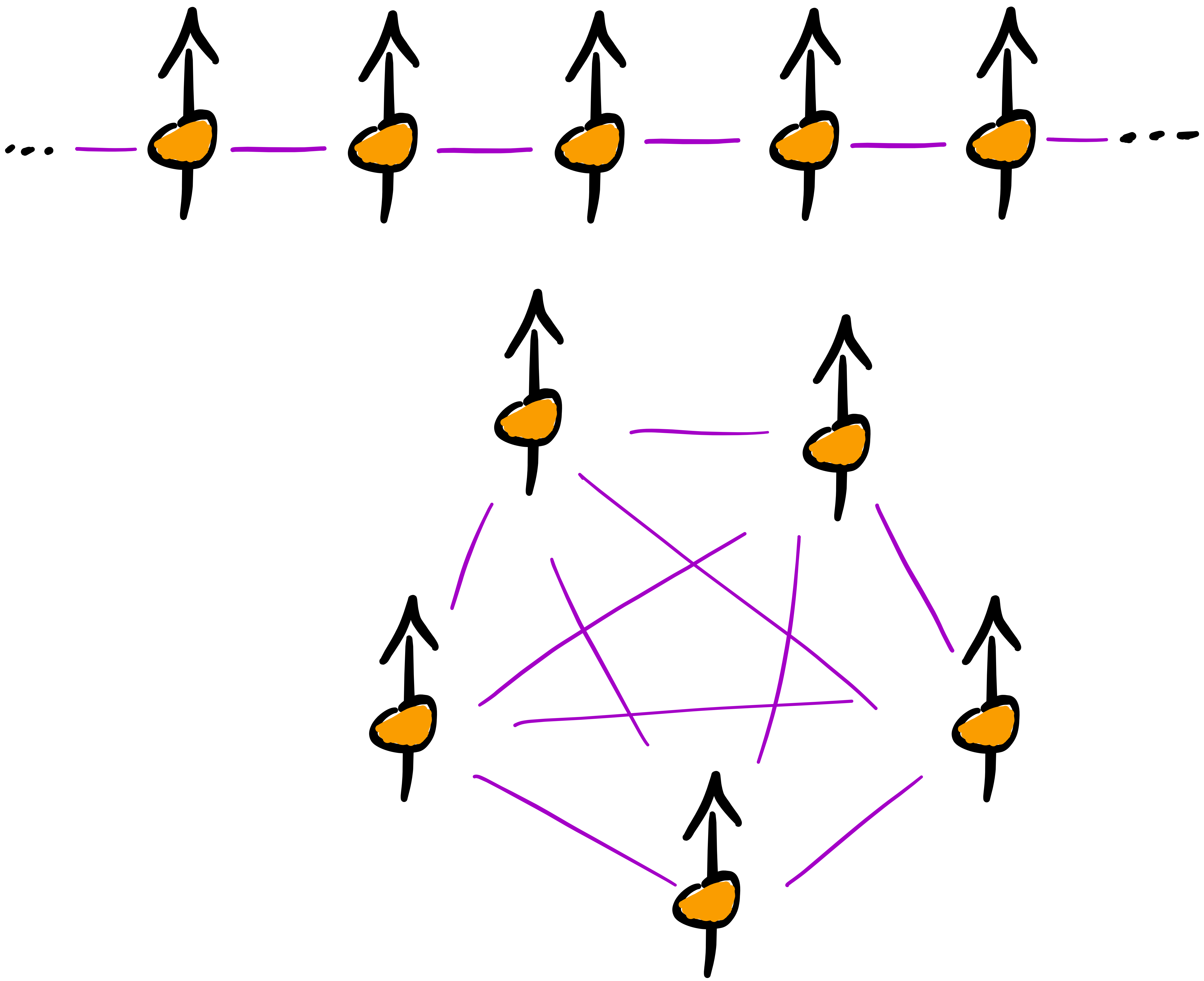
$$\hat{V} \;—\; \left(\begin{array}{l} \hat{\sigma}_z^{(1)}\hat{\sigma}_z^{(2)},\ \hat{\sigma}_z^{(1)}\hat{\sigma}_z^{(3)},\ \hat{\sigma}_z^{(2)}\hat{\sigma}_z^{(3)},\ \dots \\ \cancel{\hat{\sigma}_z^{(1)}\hat{\sigma}_z^{(2)}\hat{\sigma}_z^{(3)},\ \dots} \\ \cancel{\vdots} \\ \cancel{\hat{\sigma}_z^{(1)}\hat{\sigma}_z^{(2)}\hat{\sigma}_z^{(3)}\dots\hat{\sigma}_z^{(N)}} \end{array} \right.$$

More realistic control



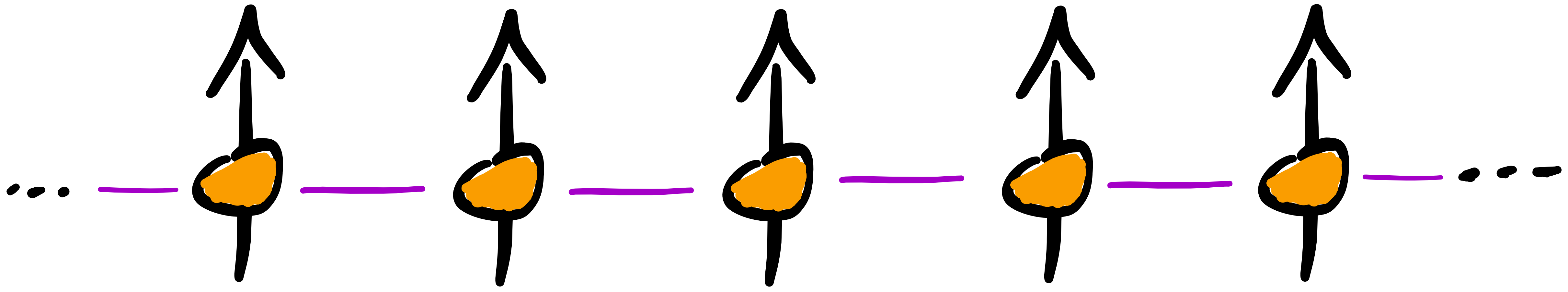
$$\hat{H}(t) = \varepsilon(t)\sum_{i=1}^{N}\hat{\sigma}_z^{(i)} + J(t)\sum_{i=1}^{N}\hat{\sigma}_z^{(i)}\hat{\sigma}_z^{(i+1)}$$

More realistic control

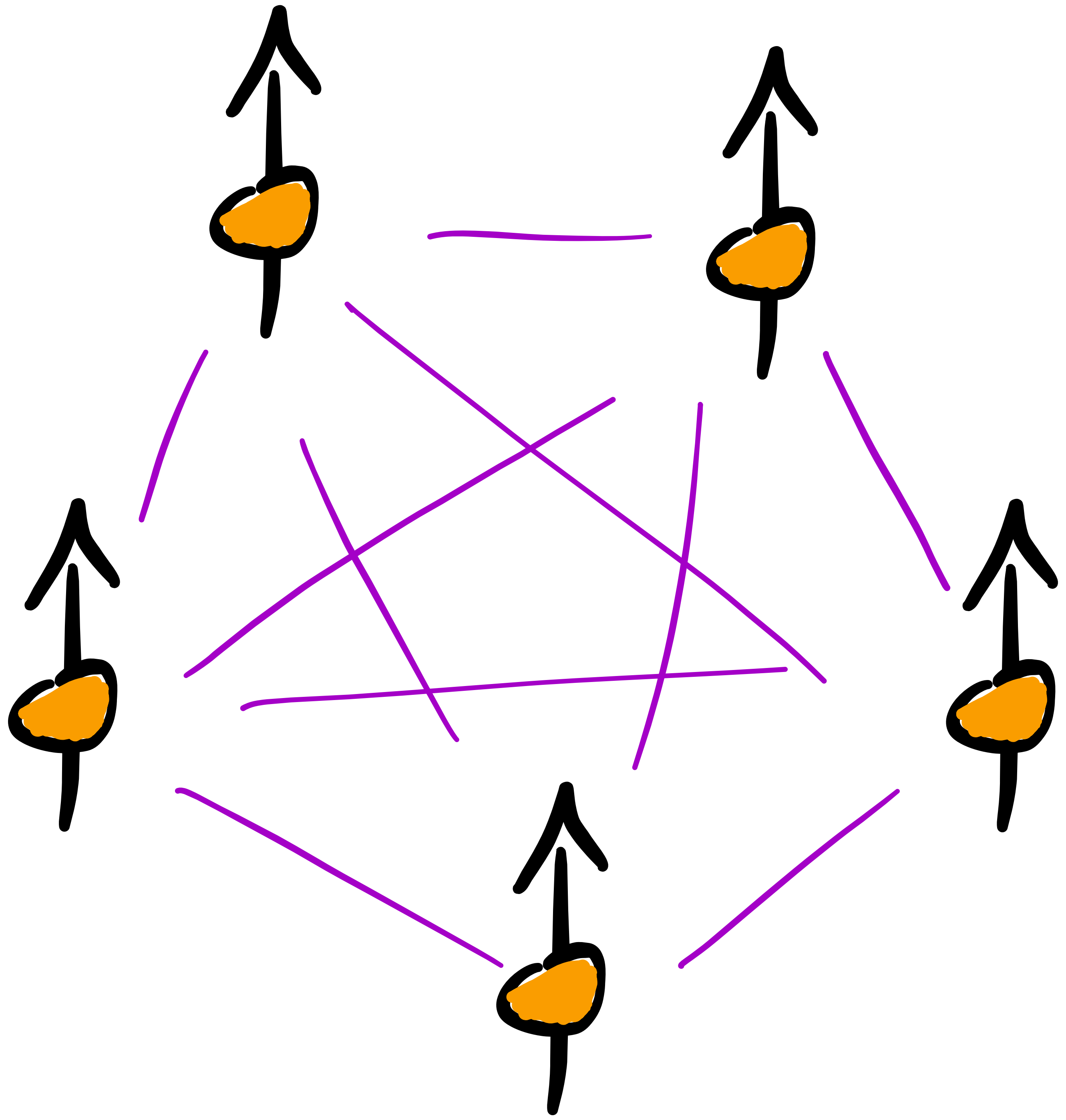


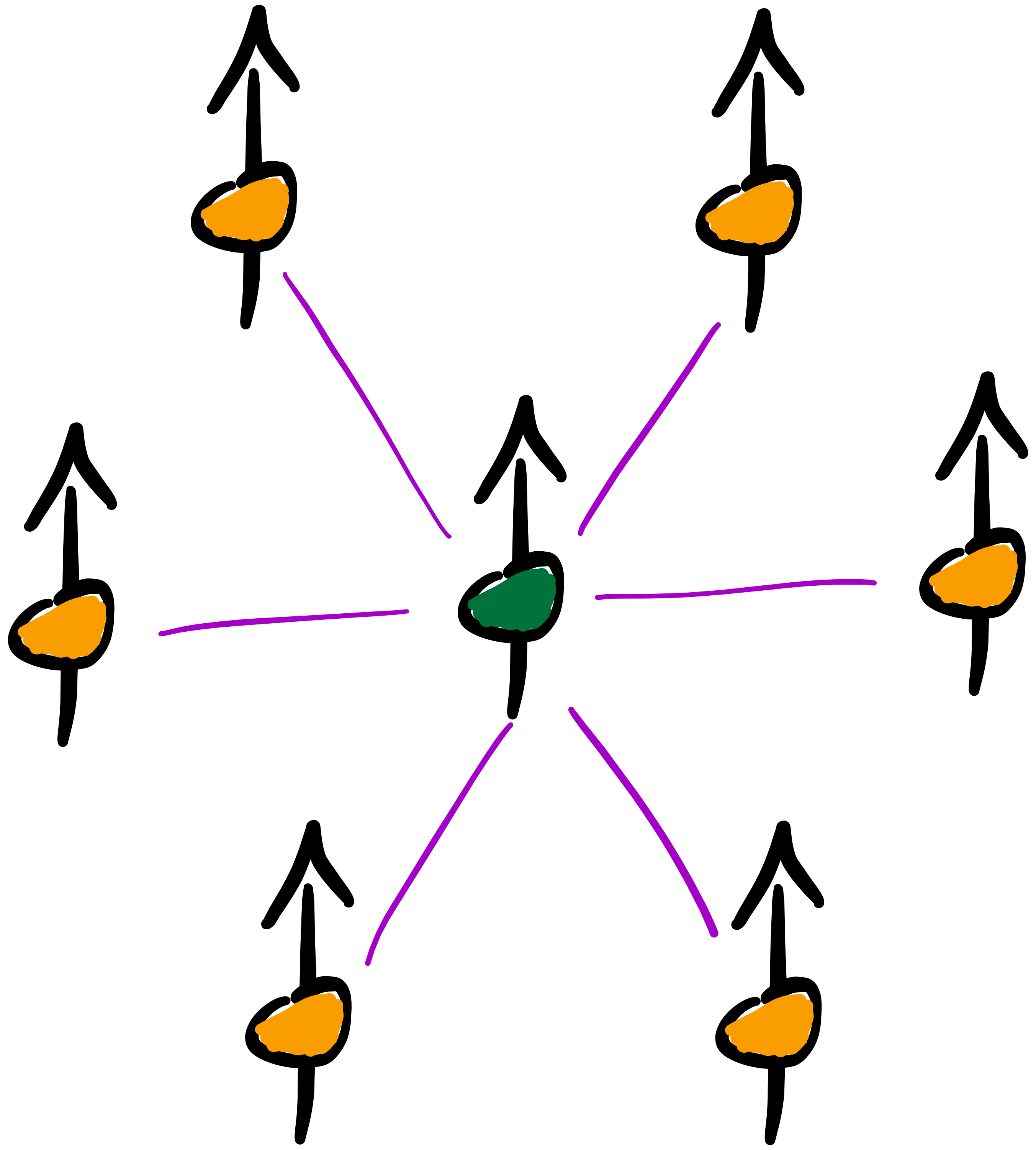
$$\hat{H}(t) = \mathcal{E}(t)\sum_{i=1}^{N}\hat{\sigma}_z^{(i)} + J(t)\sum_{i>j}^{N}\hat{\sigma}_z^{(i)}\hat{\sigma}_z^{(j)}$$

More realistic control

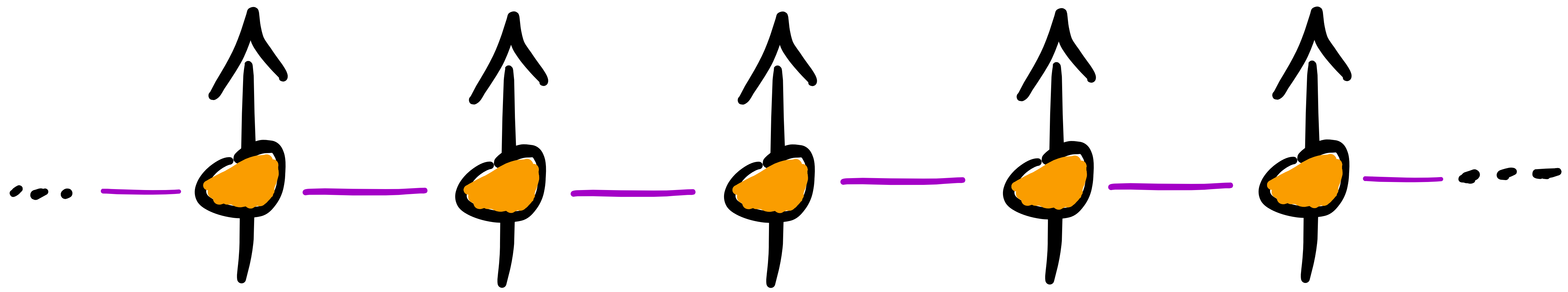


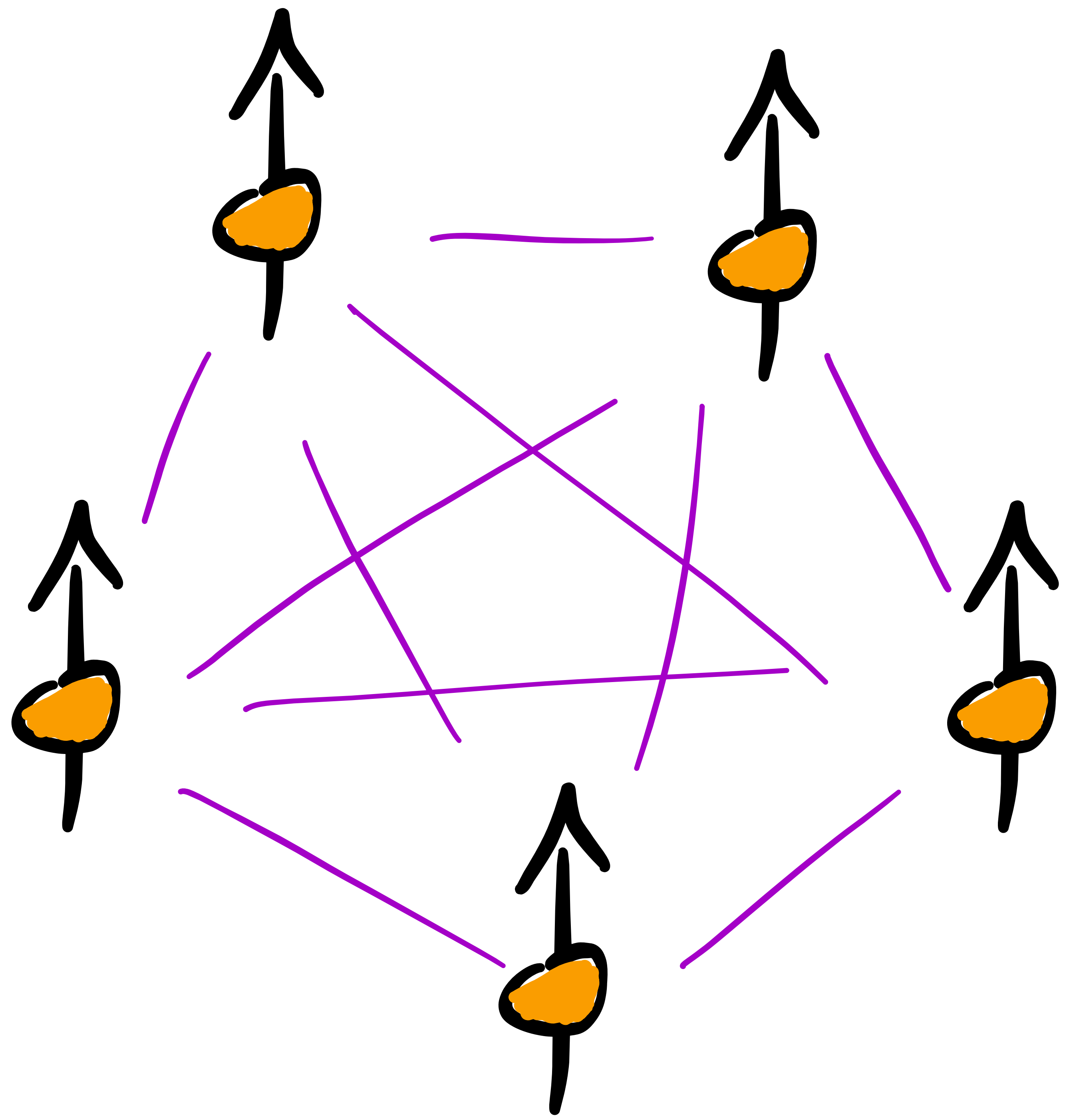
$$\hat{H}(t) = \epsilon_0(t)\hat{\sigma}_z^{(0)} + \sum_{i=1}^{N-1} \epsilon_1(t)\hat{\sigma}_z^{(i)} + J(t)\hat{\sigma}_z^{(i)}\hat{\sigma}_z^{(0)}$$



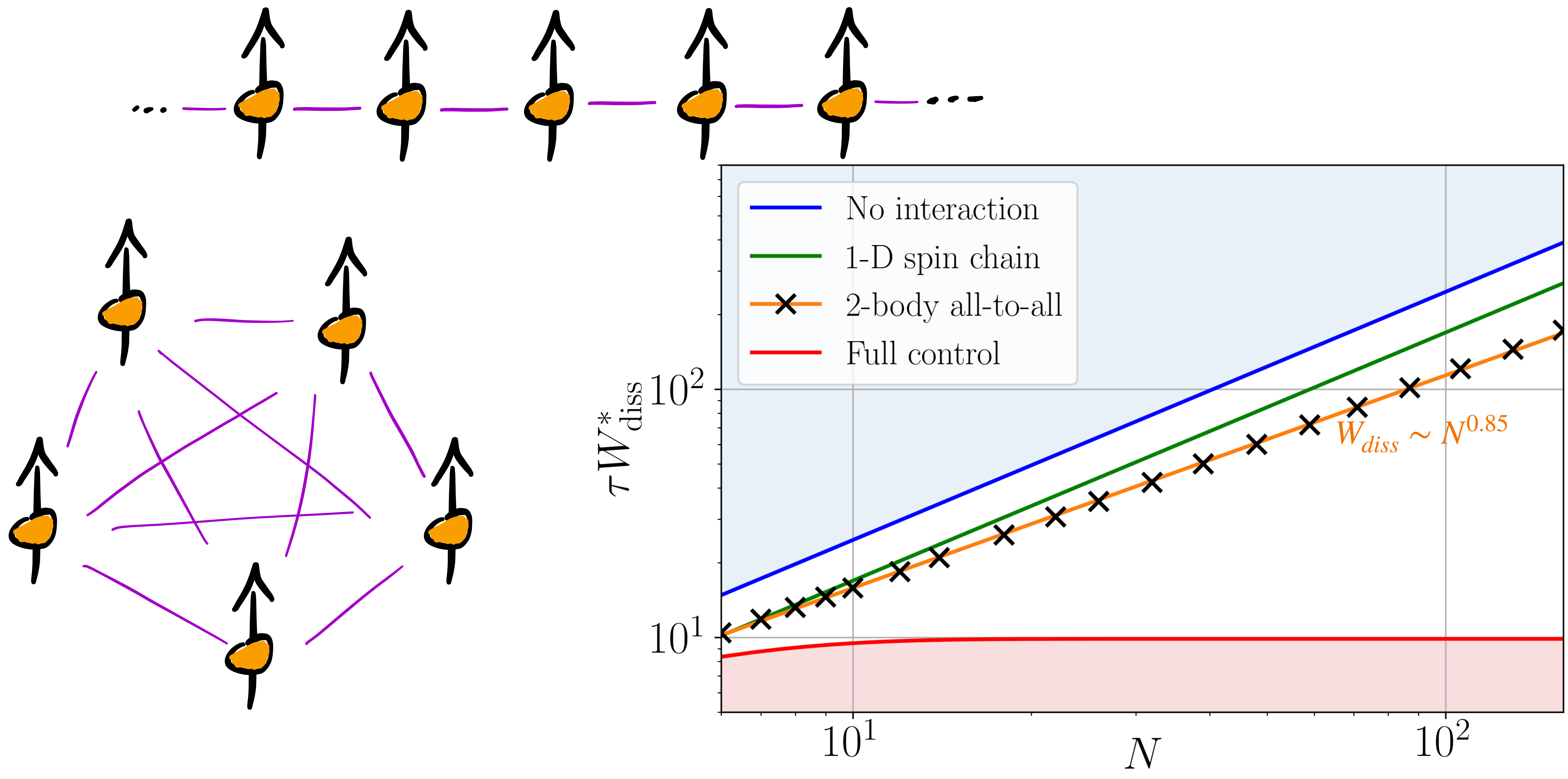


Erasure on a all-to-all model

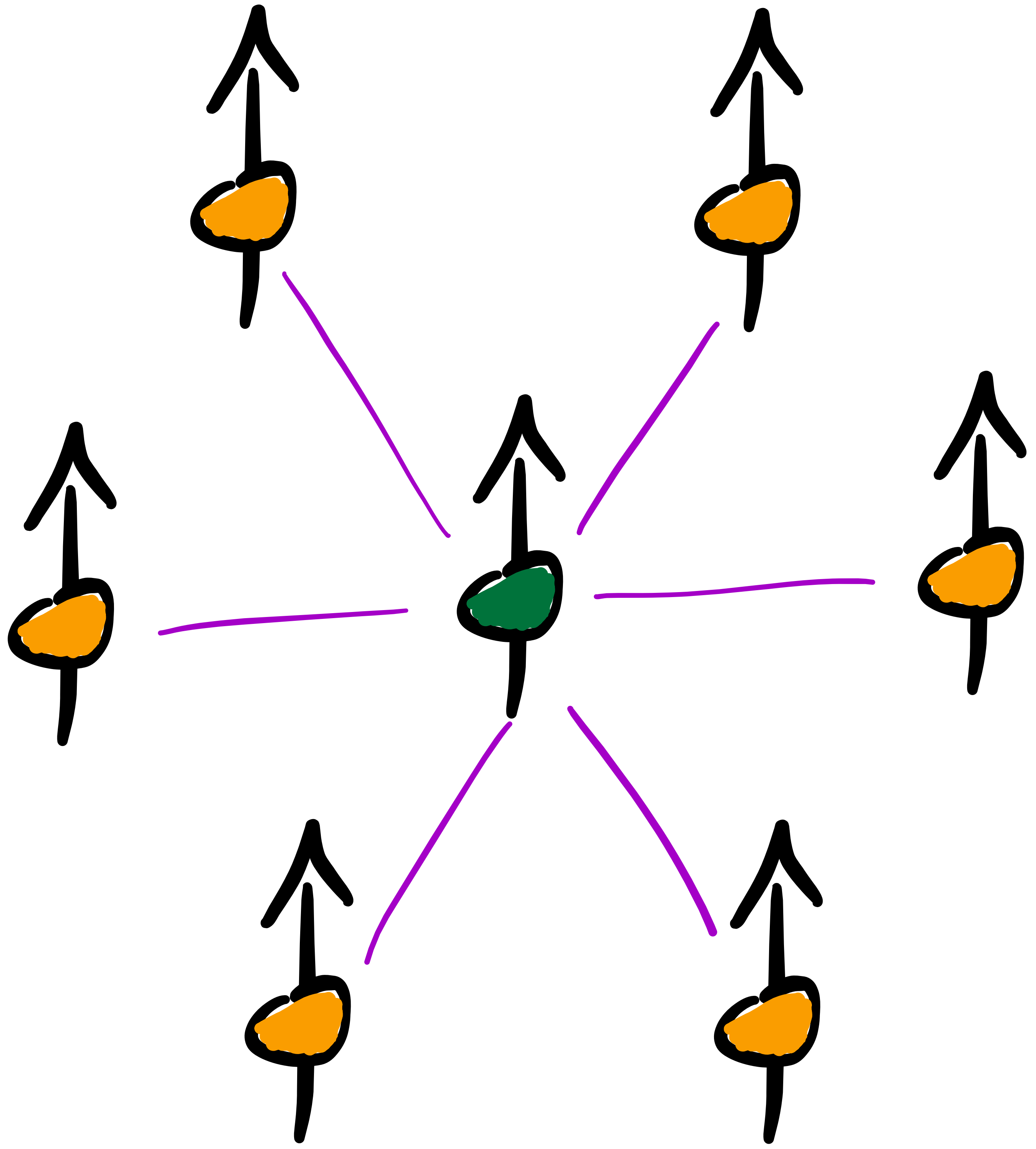




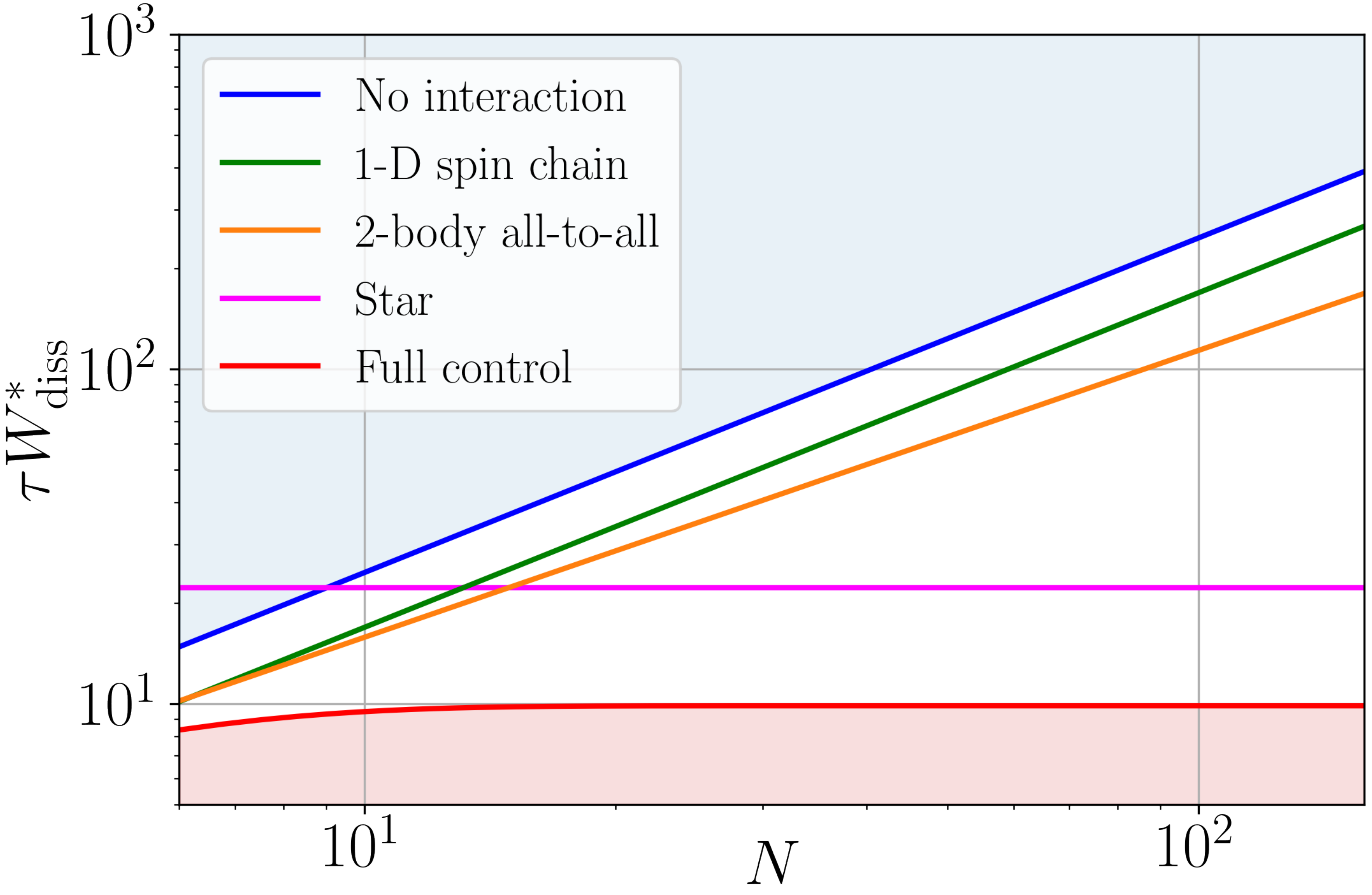
Erasure on a all-to-all model



Erasure on the star model

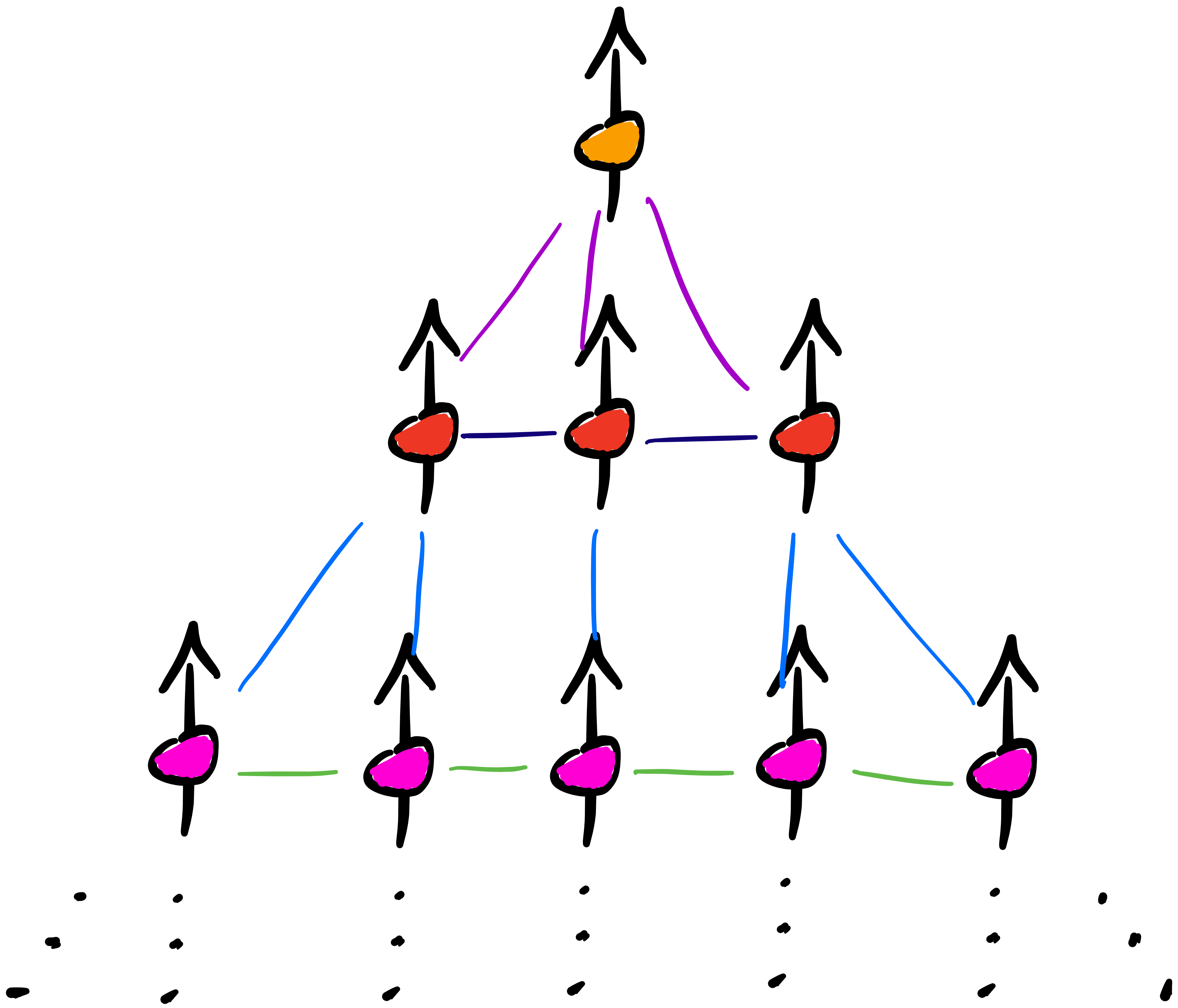


$$\hat{H}(t) = \epsilon_0(t)\hat{\sigma}_z^{(0)} + \sum_{i=1}^{N-1} \epsilon_1(t)\hat{\sigma}_z^{(i)} + J(t)\hat{\sigma}_z^{(i)}\hat{\sigma}_z^{(0)}$$



Erasure on the pyramid model (short range)

→ Same as star model, but in ℓ layers



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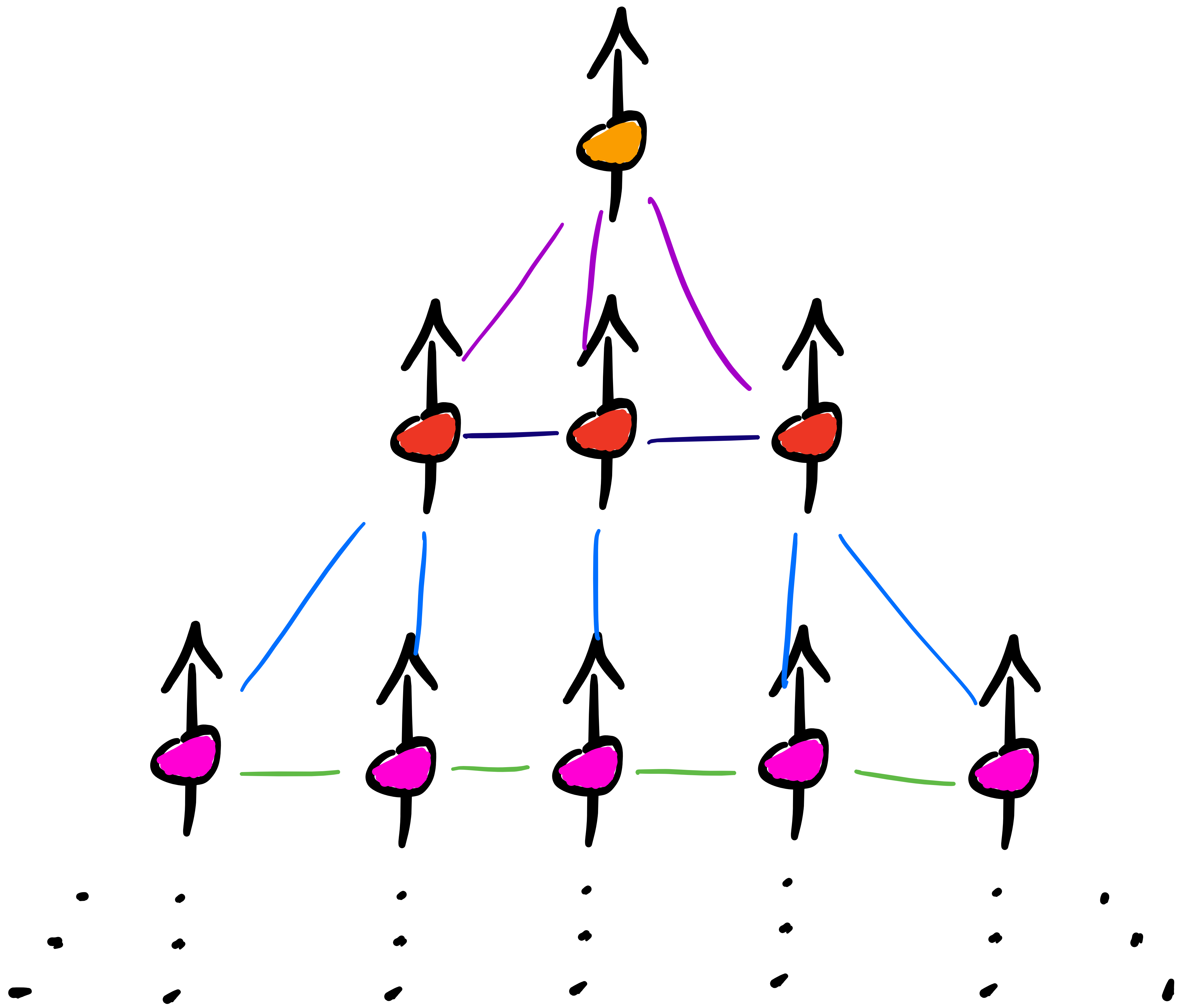

$$\min_{\lambda} \beta W_{diss} \leq \frac{(4\ell - 1)^2 \pi^2}{4\tau}$$

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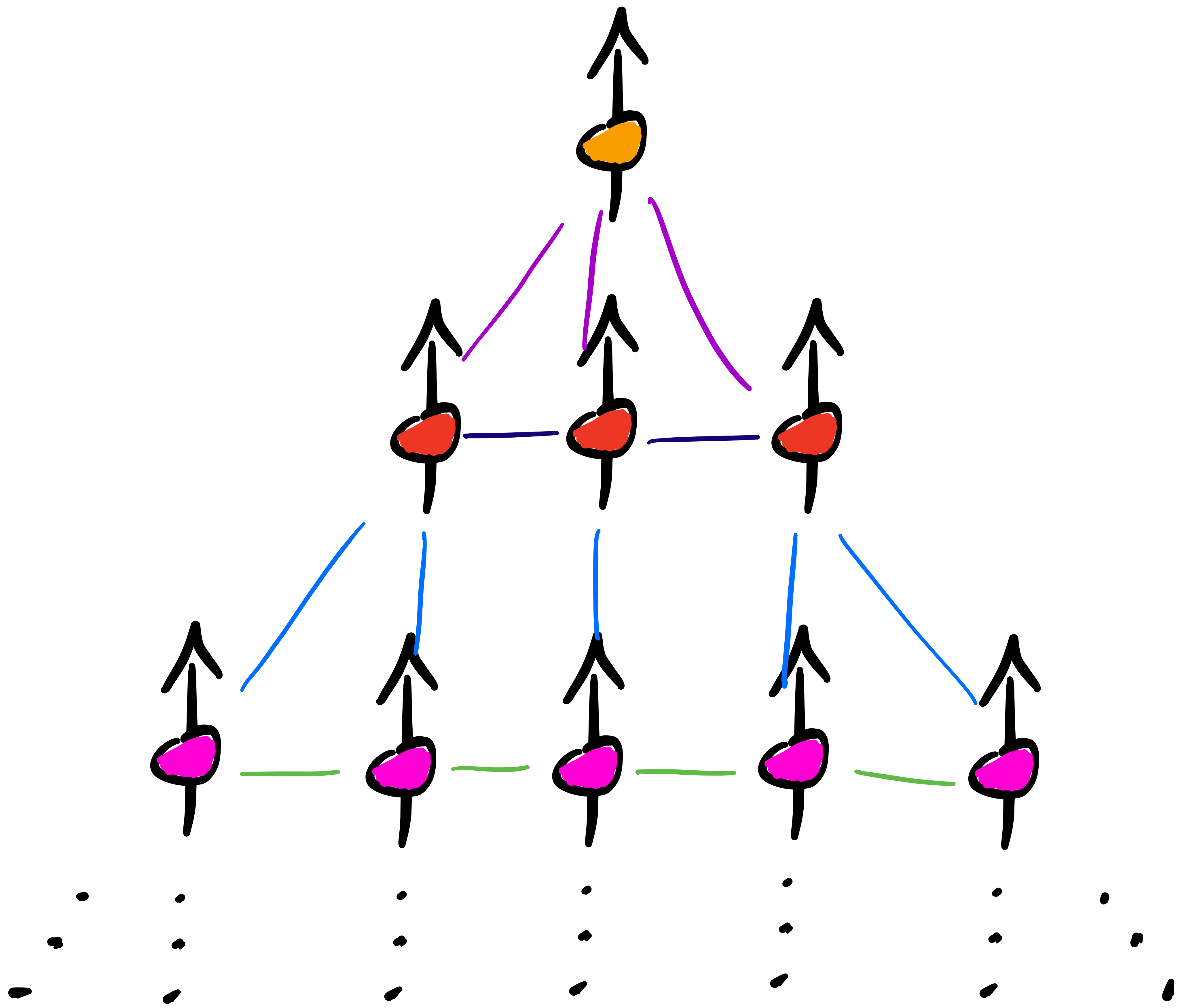

$$\min_{\lambda} \beta W_{diss} \leq \frac{(4\ell - 1)^2 \pi^2}{4\tau}$$

$$\ell \propto N^{1/D}$$

$$\longrightarrow W_{diss} \propto N^{2/D}$$

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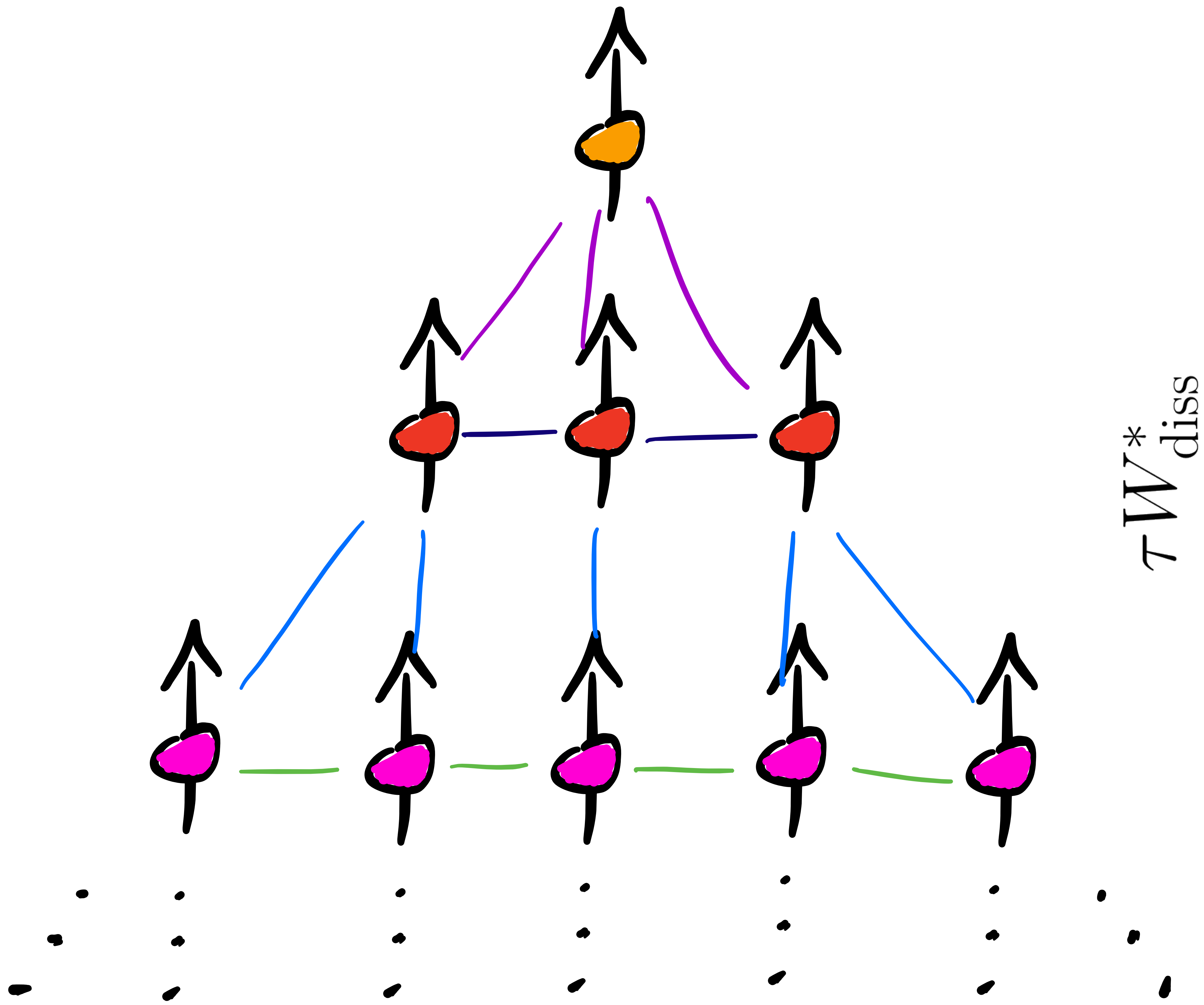
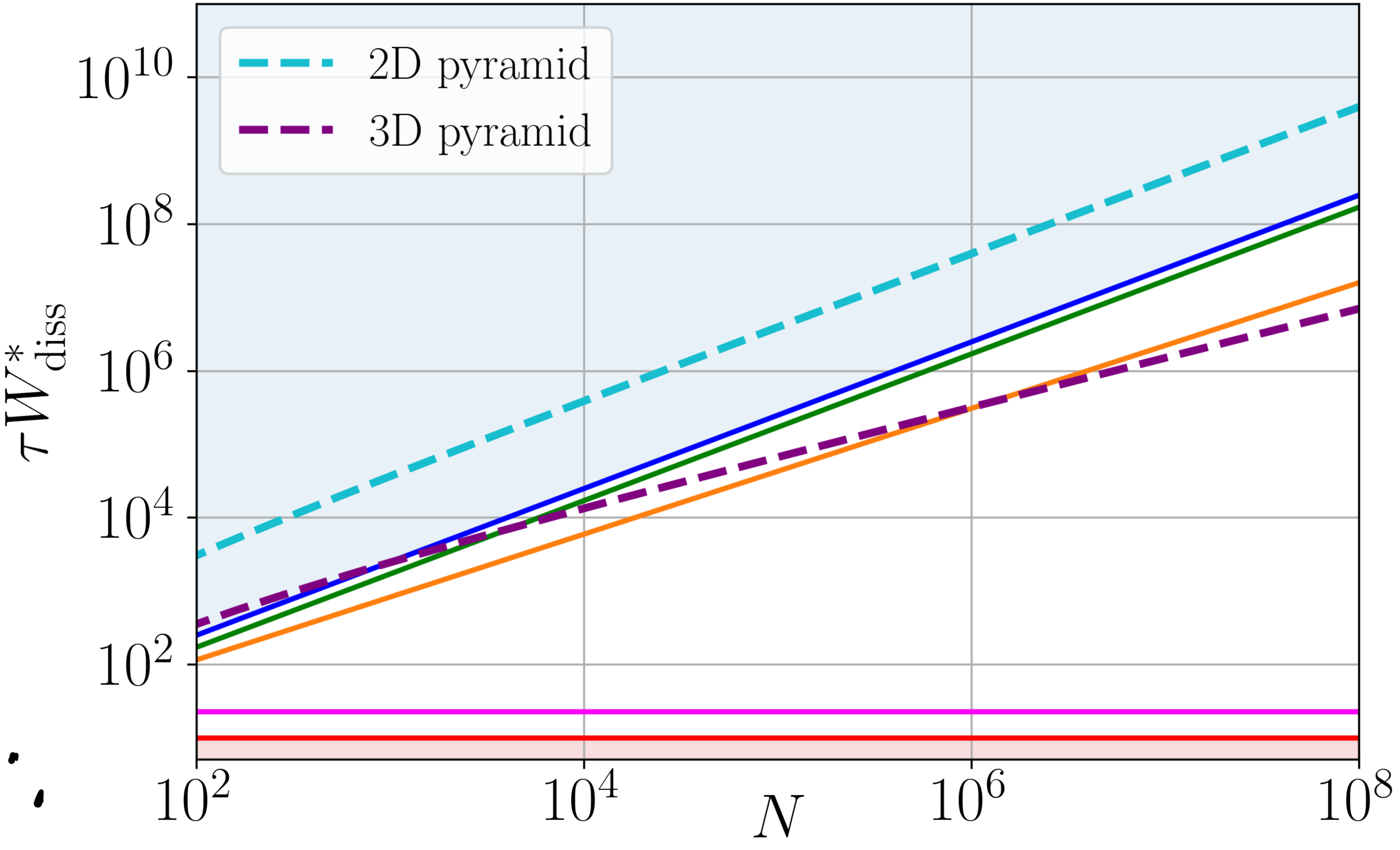
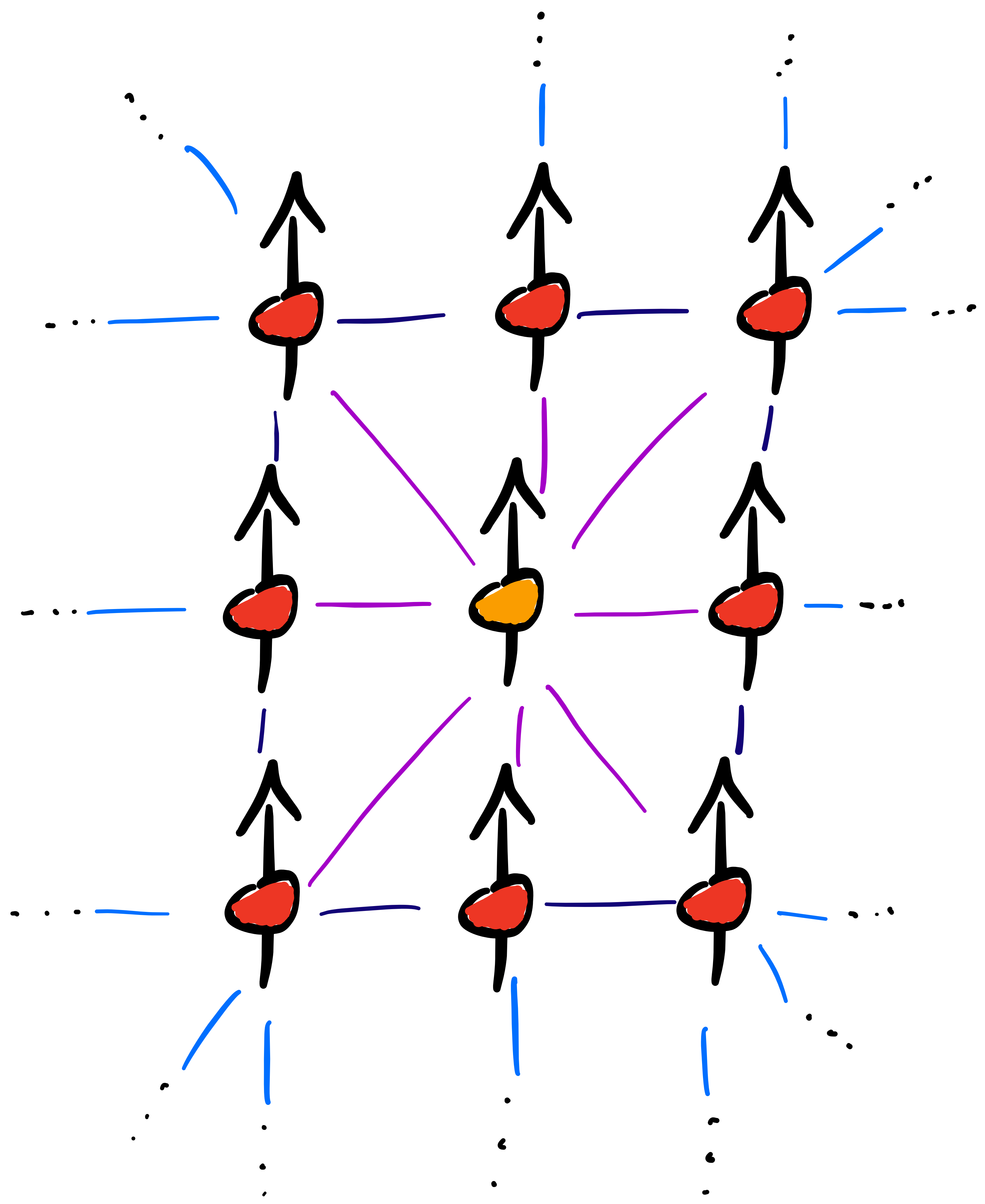
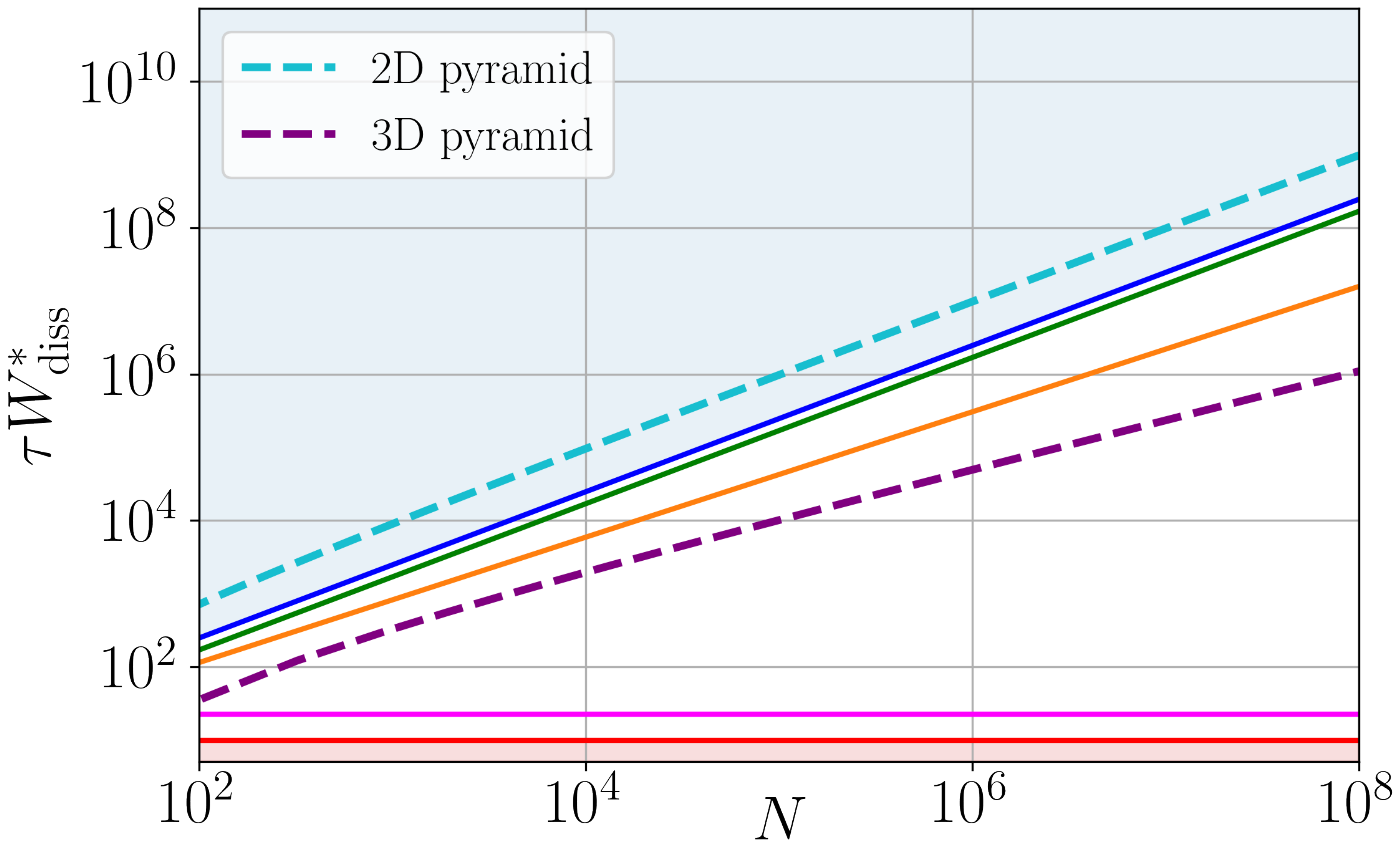




Erasure on the pyramid model (short range)





Conclusion

Phys. Rev. Lett. **131**, 210401

→ Purely thermodynamic collective advantage

→ Sub-linear scaling with two-body “realistic” interaction

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→ Purely thermodynamic collective advantage

→ Sub-linear scaling with two-body “realistic” interaction

→ More realistic model of thermalization

→ Geometric interpretation of hamiltonian constraints