A BULK MANIFESTATION OF KRYLOV COMPLEXITY

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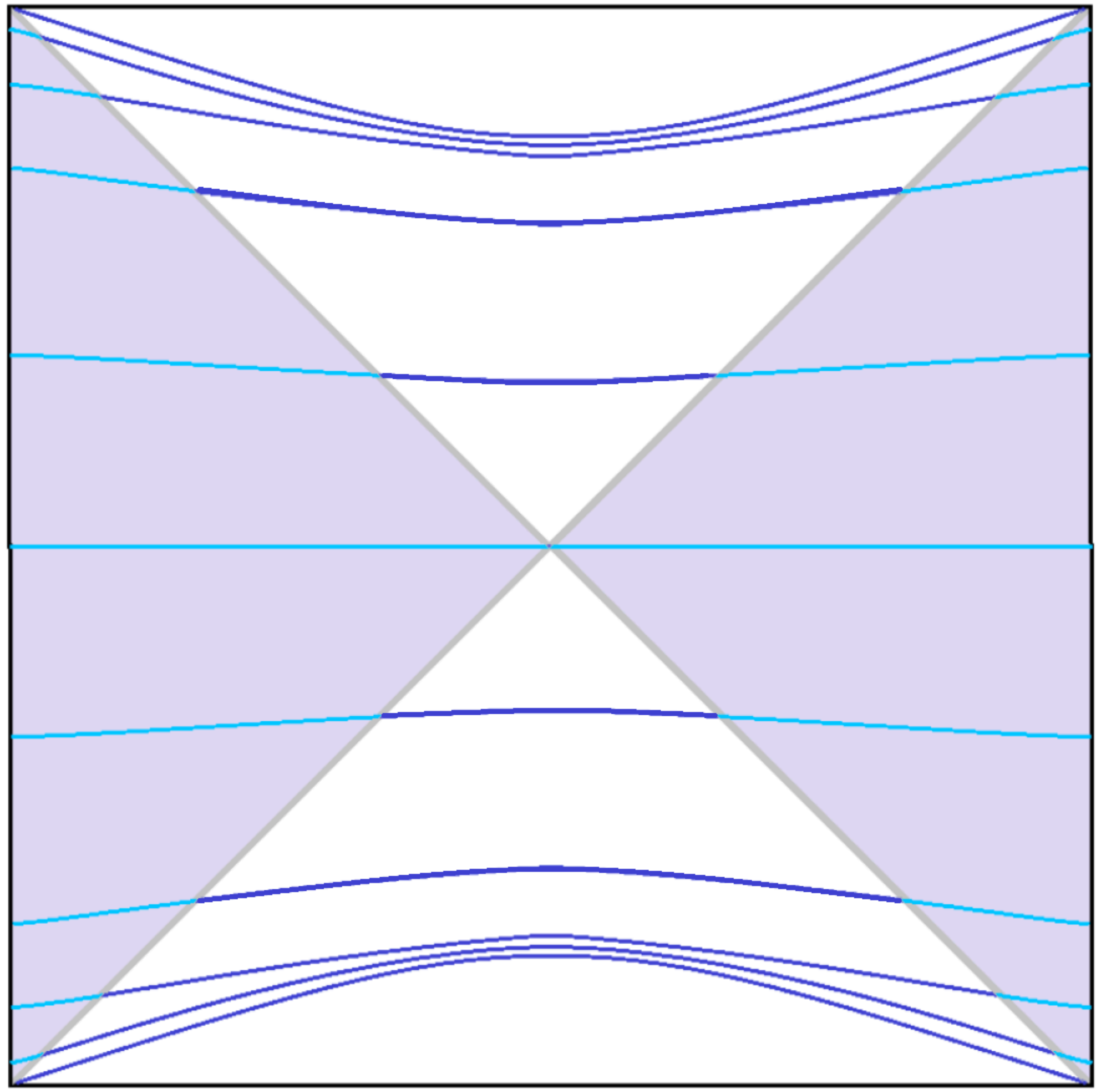


(Susskind, 2018).

INTRODUCTION

- Goal: Boundary description of the growth of the Einstein-Rosen Bridge (ERB).
- Proposal: *(Susskind, 2016)*: Captured by *complexity* of the boundary state evolving in Lorentzian time.
- Controversies: Ambiguities in complexity definition (tolerance parameter, gates…), absence of explicit matching *(Belin et al., 2021)*.
- Our work:
  - Low-dimensional instance of holography.
  - Krylov complexity.

KRYLOV SPACE (OPERATORS)

-Initially defined for operators. *(Parker et al., 2018)*

- A notion of complexity adapted to time evolution of an initial operator $\mathcal{O} \equiv \mathcal{O}(0)$.

-Take a Hilbert space of states $\mathscr{H}$ with $\dim \mathscr{H} = D$. Operator space is $\widehat{\mathscr{H}}$.

-Time evolution generator in $\widehat{\mathscr{H}}$ is the **Liouvillian** $\mathscr{L} := [H, \cdot\,]$, as:

$$\mathcal{O}(t) = e^{iHt}\mathcal{O}e^{-iHt} = e^{it\mathscr{L}}\mathcal{O} = \mathcal{O} + it[H,\mathcal{O}] - \frac{t^2}{2}\big[H,[H,\mathcal{O}]\big] + \dots$$

- Define **Krylov space** as $\mathscr{H}_{\mathcal{O}} := \text{span}\left\{\mathscr{L}^n\mathcal{O}\right\}_{n=0}^{+\infty} \leq \widehat{\mathscr{H}}$

$\Longrightarrow$ Always contains $\mathcal{O}(t)$. Dimension: $K \leq D^2 - D + 1$

(E. Rabinovici, ASG, R. Shir, J. Sonner, 2020.)

(V. S. Viswanath & G. Muller, 1994; Parker et al., 2018.)

KRYLOV COMPLEXITY (STATES)

- State evolving in Schrödinger picture: $|\phi(t)\rangle = e^{-iHt}|0\rangle$.
- Note that $|\phi(t)\rangle \in \text{span}\left\{|0\rangle, H|0\rangle, H^2|0\rangle, \ldots\right\} =: \mathcal{H}_\phi$ for all t.
- The **Lanczos algorithm** provides an orthonormal basis for this **Krylov space**:

$$|A_{n+1}\rangle = (H - a_n)|n\rangle - b_n|n-1\rangle, \quad |n+1\rangle = \frac{1}{b_{n+1}}|n\rangle$$

With **Lanczos coefficients**: $a_n = \langle n|H|n\rangle, \quad b_{n+1} = \sqrt{\langle A_{n+1}|A_{n+1}\rangle}$.

State K-complexity: Given $|\phi(t)\rangle = \sum_n \phi_n(t)|n\rangle$,

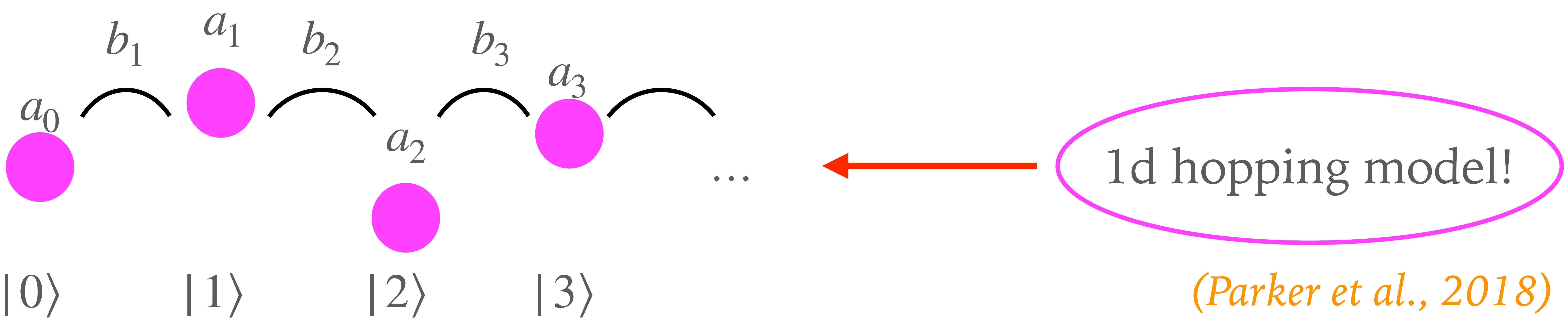
(Balasubramanian et al., 2022)

$$C_K(t) = \langle \phi(t)|\hat{n}|\phi(t)\rangle = \sum_n n|\phi_n(t)|^2$$

KRYLOV CHAIN AS A ONE-DIMENSIONAL HOPPING MODEL

- The Hamiltonian takes a tridiagonal form in the Krylov basis:

$$H = \sum_{n=0}^{K-2} b_{n+1} \left(|n\rangle\langle n+1| + |n+1\rangle\langle n| \right) + \sum_{n=0}^{K-1} a_n |n\rangle\langle n|$$



(*Parker et al., 2018*)

- **Krylov chain**, with localized states $|n\rangle$, potential energies a_n and hopping amplitudes b_n.

Initial condition $\phi_n(t=0) = \delta_{n0}$ spreads along the chain as it evolves, $\phi_n(t)$.

SURVIVAL AMPLITUDE

- Defined as fidelity of the evolving state:

$$\phi_0(t) = \langle 0 | \phi(t) \rangle = \sum_n \frac{(-it)^n}{n!} M_n$$

With moments: $$M_n = \langle 0 | H^n | 0 \rangle$$

- There is a bijective correspondence: $\{a_n, b_n\} \iff \{M_n\}$

- *Note:* If $\phi_0(t)$ even $\implies M_{2n+1} = 0 \implies a_n = 0$ *(as in operator case)*

For TFD: $$|0\rangle = |TFD\rangle = \sum_E e^{-\beta E/2} |E\rangle \otimes |E\rangle$$

$$\implies \phi_0(t) = Z(\beta + it)$$ *(Balasubramanian et al., 2022)*

DOUBLE-SCALED SYK (DSSYK)

- Analytically solvable version of SYK. Allows to approach Schwarzian sector.

- Hamiltonian: *(M. Berkooz et al., 2019; H. Lin, 2022)*

$$H = i^{p/2} \sum_{1 \le i_1 < \ldots < i_p \le N} J_{i_1 \ldots i_p} \psi_{i_1} \cdots \psi_{i_p}$$

- Double-scaling limit: $\lambda := \frac{2p^2}{N}$

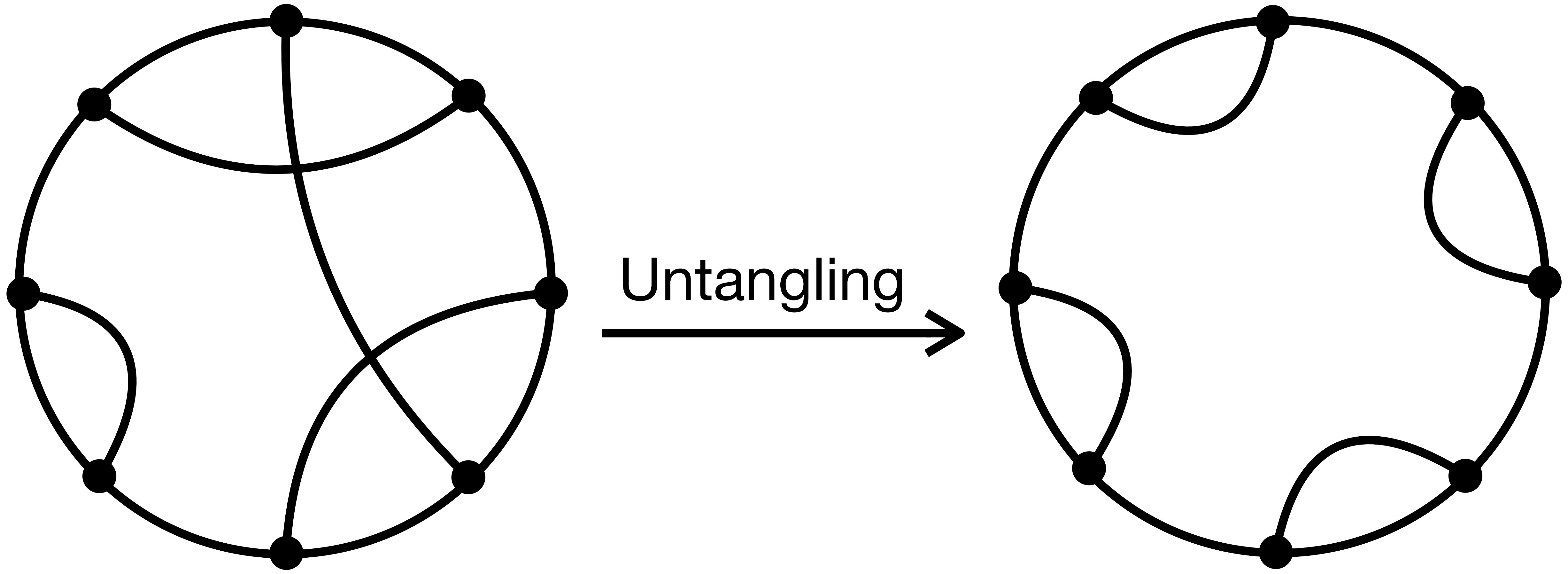
- Disordered model: $\langle J_{i_1 \ldots i_p} \rangle = 0, \quad \langle J^2_{i_1 \ldots i_p} \rangle = \frac{1}{\lambda} \binom{N}{p}^{-1} J^2.$

- *Note:* $\lambda \to 0$ recovers model with $1 \ll p \ll N$ *(Maldacena & Stanford. 2016)*

CHORD DIAGRAMS

- Moments of the partition function: $M_{2k} = \left\langle \mathrm{Tr}\left(H^{2k}\right) \right\rangle$

- Allows for a diagrammatic representation:



$$M_{2k} = \frac{J^{2k}}{\lambda^k} \sum_{\text{diagrams with } k \text{ chords}} q^{\text{number of intersections}}, \qquad q = e^{-\lambda} .$$

(M. Berkooz et al., 2019)

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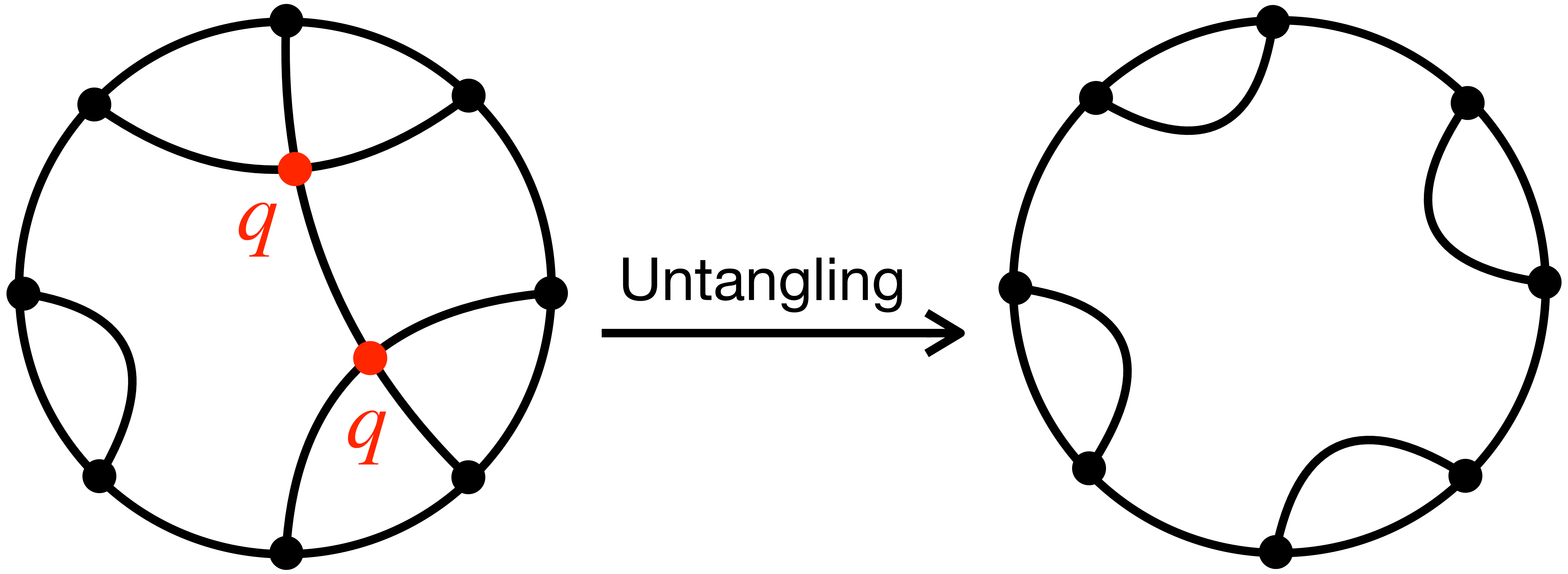

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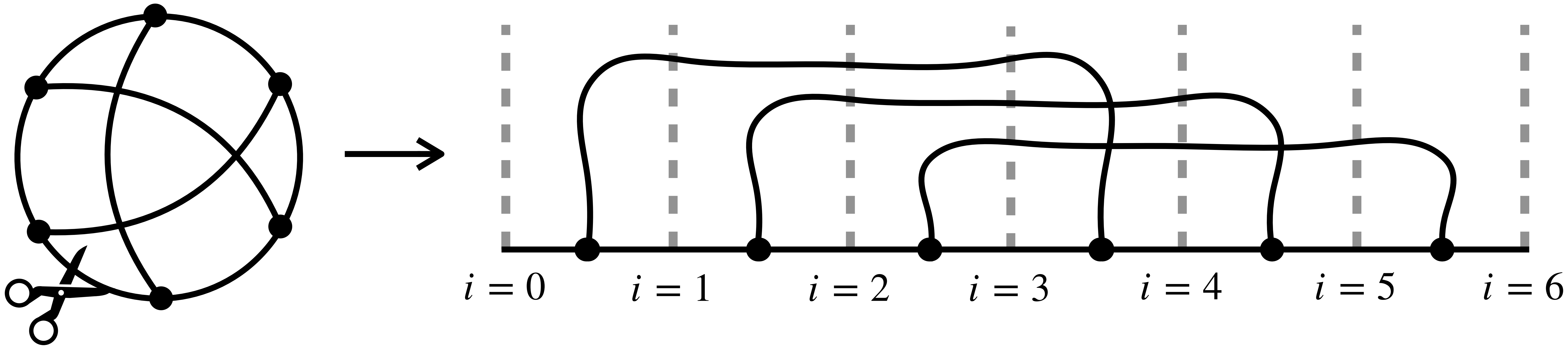
CHORD HILBERT SPACE

- Idea: Interprete a chord diagram as a transition from 0 chords back to 0.



- Introduce Hilbert space: span $\{|n\rangle\}_{n\geq 0}$ where $n=$ number of *open chords*.

Diagrams of i steps: $|\psi^{(i)}\rangle = \sum_{n\geq 0} \psi_n^{(i)} |n\rangle$

Recursion: $\psi_n^{(i+1)} = \frac{J}{\sqrt{\lambda}} \psi_{n-1}^{(i)} + \frac{J}{\sqrt{\lambda}} (1+q+\ldots+q^n)\, \psi_{n+1}^{(i)}$

(M. Berkooz et al., 2019)

TRANSFER MATRIX (NON-SYMMETRIC VERSION)

- Can write: $|\psi^{(i)}\rangle = T^i|0\rangle$, with:

$$T \overset{*}{=} \frac{J}{\sqrt{\lambda}} \begin{pmatrix} 0 & \frac{1-q}{1-q} & 0 & 0 & \dots \\ 1 & 0 & \frac{1-q^2}{1-q} & 0 & \dots \\ 0 & 1 & 0 & \frac{1-q^3}{1-q} & \dots \\ 0 & 0 & 1 & 0 & \dots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

T : Transfer matrix *(effective Hamiltonian in the averaged theory)*

$$M_{2k} = \langle 0|T^{2k}|0\rangle = \langle 0|\psi^{(2k)}\rangle = \psi_0^{(2k)} .$$

(M. Berkooz et al., 2019)

TRANSFER MATRIX (SYMMETRIC VERSION)

➤ There exists a *diagonal similarity transformation* such that: *(Berkooz et al., 2019)*

$$T \overset{*}{=} \frac{J}{\sqrt{\lambda}} \begin{pmatrix} 0 & \sqrt{\frac{1-q}{1-q}} & 0 & 0 & \dots \\ \sqrt{\frac{1-q}{1-q}} & 0 & \sqrt{\frac{1-q^2}{1-q}} & 0 & \dots \\ 0 & \sqrt{\frac{1-q^2}{1-q}} & 0 & \sqrt{\frac{1-q^3}{1-q}} & \dots \\ 0 & 0 & \sqrt{\frac{1-q^3}{1-q}} & 0 & \dots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

➤ Interpreted as *renormalization* of states such that $\langle n \,|\, n' \rangle = \delta_{n,n'}$. *(H. Lin, 2022)*

THE EFFECTIVE HAMILTONIAN

- Can write in operator language:

$$T = \frac{J}{\sqrt{\lambda}}(\alpha + \alpha^\dagger)$$

With $\alpha = \sum_{n\geq 0} \sqrt{[n+1]_q} \quad |n\rangle\langle n+1|$, where $[n]_q \equiv \frac{1-q^n}{1-q} = \sum_{k=0}^{n-1} q^k$

$\longrightarrow$ *q-deformed oscillator* *(M. Berkooz et al., 2019)*

Can write as: $\alpha^\dagger = \sqrt{\frac{1-q^{\hat{n}}}{1-q}}\, D^\dagger$, with $D^\dagger = \sum_{n\geq 0} |n+1\rangle\langle n| = e^{-ip}$

$\longrightarrow$ p is conjugate momentum of $\hat{n}$.

EFFECTIVE HAMILTONIAN AND TRIPLE-SCALING LIMIT

- Defining $\lambda n =: \frac{l}{L}$,

$$T = \frac{J}{\sqrt{\lambda(1-q)}}\left(e^{i\lambda Lk}\sqrt{1-e^{-\frac{l}{L}}} + \sqrt{1-e^{-\frac{l}{L}}}e^{-i\lambda Lk}\right)$$

- Triple-scaling limit: $\lambda \to 0$, $l \to \infty$, $\frac{e^{-\frac{l}{L}}}{(2\lambda)^2} =: e^{-\frac{\tilde{l}}{L}}$ fixed.

- The Hamiltonian takes the form: (Liouville!! $\Longrightarrow$ JT) (H. Lin, 2022)

$$\tilde{T} = E_0 + 2\lambda J\left(\frac{L^2k^2}{2} + 2e^{-\frac{\tilde{l}}{L}}\right) + O\left(\lambda^2\right), \quad E_0 \sim -\frac{2J}{\lambda}$$

LANCZOS COEFFICIENTS IN DSSYK

- The chord basis automatically performs the Lanczos algorithm:

1. Each state $|n\rangle$ is a linear combination of $\left\{ |\psi^{(k)}\rangle = T^k|0\rangle \right\}_{k=0}^{n}$.
2. $\left\{ |n\rangle \right\}_{n\geq 0}$ forms an orthonormal basis.
3. In this basis T takes tridiagonal form with positive items.

$\Longrightarrow \left\{ |n\rangle \right\}_{n\geq 0}$ is the Krylov basis for $|0\rangle$ and T.

Lanczos coefficients:

$$a_n = 0, \qquad b_n = J\sqrt{\frac{1-q^n}{\lambda(1-q)}} = \frac{J}{\sqrt{\lambda}}\sqrt{[n]_q}$$

STATE-DEPENDENCE OF THE LANCZOS COEFFICIENTS

- We have performed the Krylov construction for: $|\phi(t)\rangle = e^{-itT}|0\rangle$

Survival probability: $\langle 0|e^{-itT}|0\rangle = \sum_{k=0}^{+\infty} \frac{(-it)^{2k}}{(2k)!} M_{2k}$

$M_{2k} = \langle 0|T^{2k}|0\rangle = \left\langle Tr\,(H^{2k})\right\rangle$

It is the partition function:

$$\langle 0|e^{-itT}|0\rangle = \left\langle \mathrm{Tr}\left[e^{-itH}\right]\right\rangle = \langle Z(\beta+it)\rangle\Big|_{\beta=0}$$

- Thus, $|0\rangle$ plays the role of the $\beta = 0$ thermofield "double" in the effective (averaged) theory: $|\Omega\rangle := \frac{1}{\sqrt{\mathcal{N}}}\sum_E |E\rangle,$ *Cf Harlow & Jafferis, 2018*

$$\mathrm{Tr}\left[e^{-itH}\right] = \langle\Omega|e^{-itH}|\Omega\rangle \xrightarrow{\text{Effective theory}} \left\langle \mathrm{Tr}[e^{-itH}]\right\rangle = \left\langle \langle\Omega|e^{-itH}|\Omega\rangle\right\rangle = \langle 0|e^{-itT}|0\rangle$$

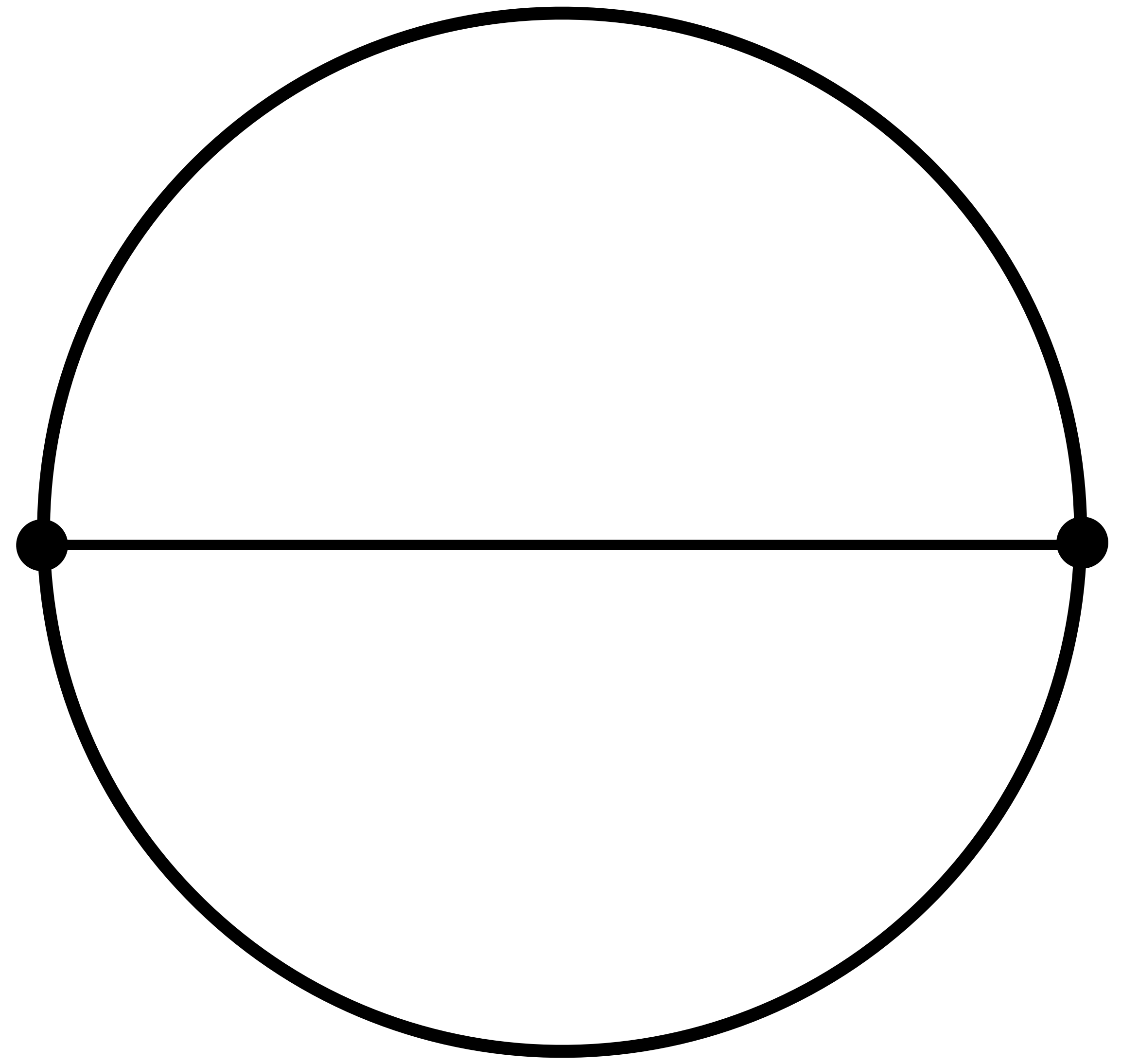
ILLUSTRATION: FIRST COEFFICIENTS FROM RECURSION RELATION

- Can obtain the Lanczos coefficients from M_{2k} computed with chord diagrams using the recurrence relation.

$$M_2 = \frac{J^2}{\lambda}$$

$$M_4 = \frac{J^4}{\lambda^2}(2 + q)$$

$$M_6 = \frac{J^6}{\lambda^3}(5 + 6q + 3q^2 + q^3)$$



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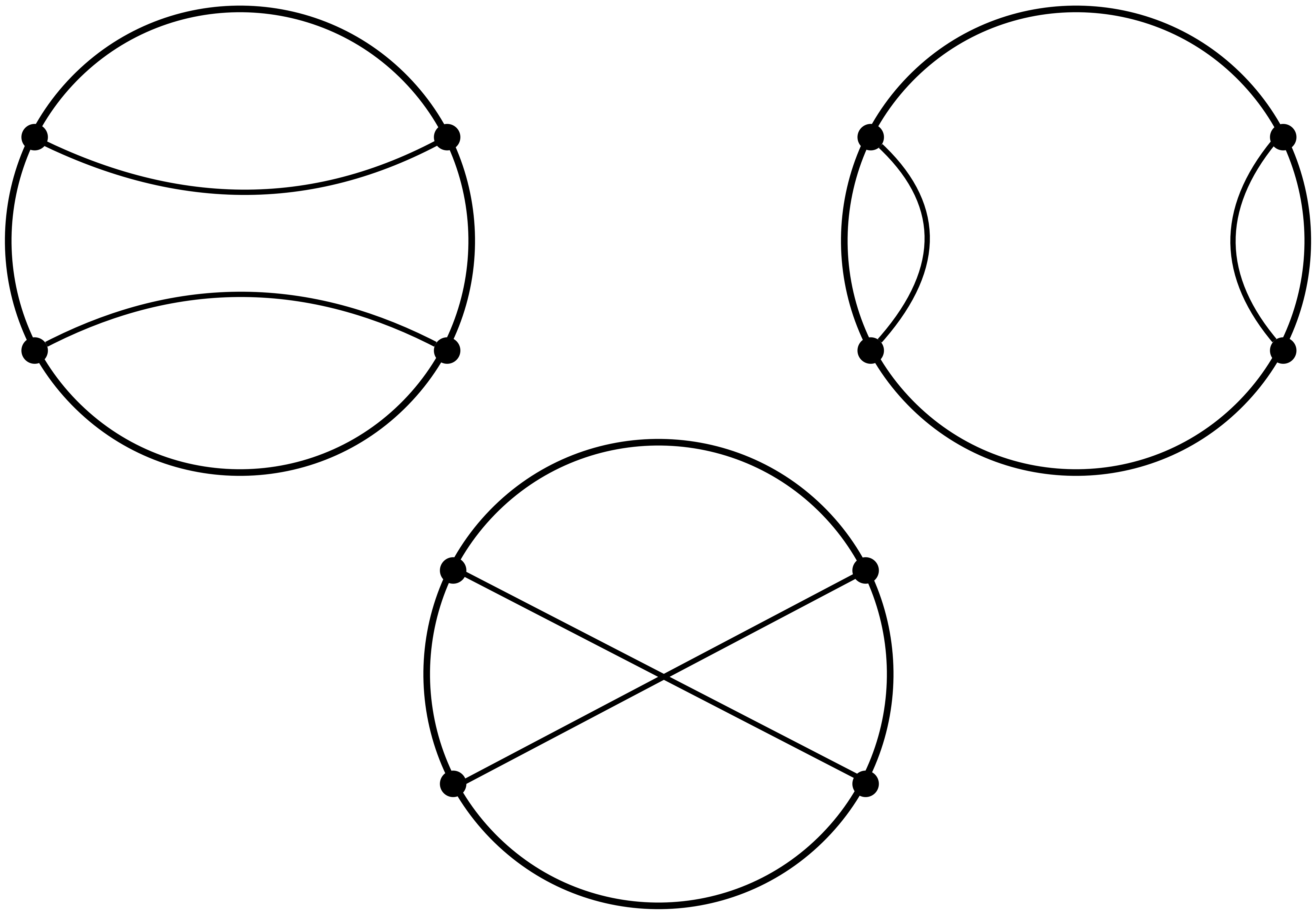

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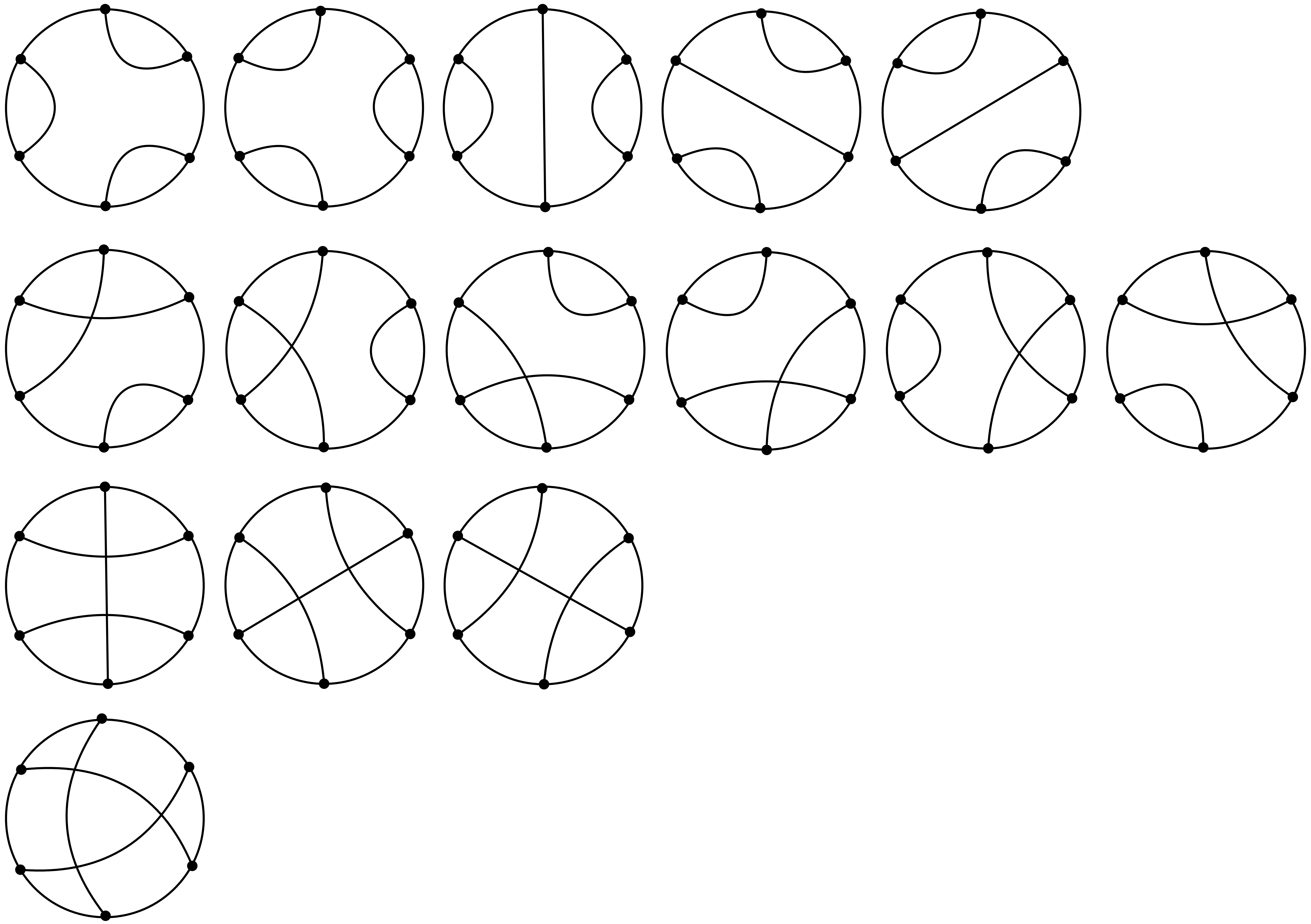

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$$b_1^2 = M_2 = \frac{J^2}{\lambda} = \frac{J^2}{\lambda}[1]_q$$

$$b_2^2 = \frac{M_4}{M_2} - M_2 = \frac{\frac{J^4}{\lambda^2}(2+q)}{\frac{J^2}{\lambda}} - \frac{J^2}{\lambda} = \frac{J^2}{\lambda}(1+q) = \frac{J^2}{\lambda}[2]_q$$

$$b_3^2 = \frac{\frac{M_6}{M_2} - M_4}{\frac{M_4}{M_2} - M_2} - \frac{M_4}{M_2} = (\ldots) = \frac{J^2}{\lambda}(1+q+q^2) = \frac{J^2}{\lambda}[3]_q\ .$$

K-COMPLEXITY REGIMES: EARLY TIMES

For $n \ll \frac{1}{\lambda}$:

$$b_n = J\sqrt{\frac{1-e^{-\lambda n}}{\lambda(1-q)}} \approx J\sqrt{\frac{n}{1-q}}$$

$\Longrightarrow \quad T \approx \gamma\left(a + a^\dagger\right)$, where a, $a^\dagger$ are SHO ladder operators.

$$\Longrightarrow \quad \phi_n(t) = e^{-\frac{\gamma^2 t^2}{2}} \frac{(-i\gamma t)^n}{\sqrt{n!}} \quad \Longrightarrow \quad C_K(t) = \sum_{n=0}^{+\infty} n\,|\,\phi_n(t)\,|^2 = \gamma^2 t^2$$

(P. Caputa et al., 2022)

i.e. coherent states propagating on the Krylov chain.

Transition time: $C(t_*) \approx \frac{1}{\lambda} \quad \Longrightarrow \quad t_* = \frac{1}{J}\sqrt{\frac{1-e^{-\lambda}}{\lambda}} \xrightarrow{\lambda \to 0} J^{-1}$

K-COMPLEXITY REGIMES: LATE TIMES

For $n \gg \frac{1}{\lambda}$:

$$b_n = J\sqrt{\frac{1-e^{-\lambda n}}{\lambda(1-q)}} \approx \frac{J}{\sqrt{\lambda(1-q)}}\left(1 - \frac{e^{-\lambda n}}{2}\right) \xrightarrow{n\to\infty} \frac{J}{\sqrt{\lambda(1-q)}} \equiv b_\infty$$

- Given $b_n = b_\infty$, $\exists$ exact solution for $\phi_n(t)$

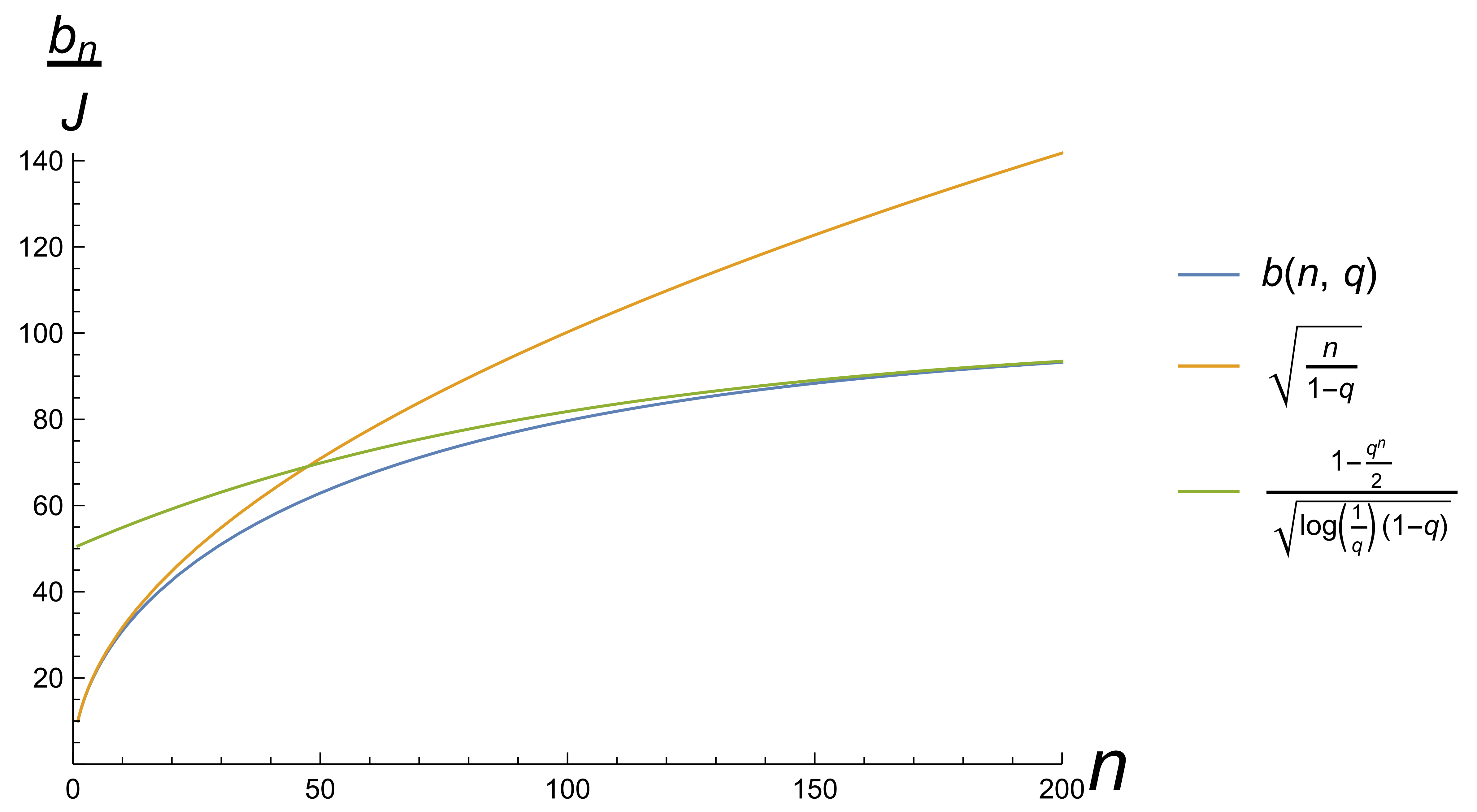
(J. Barbón et al., 2019)

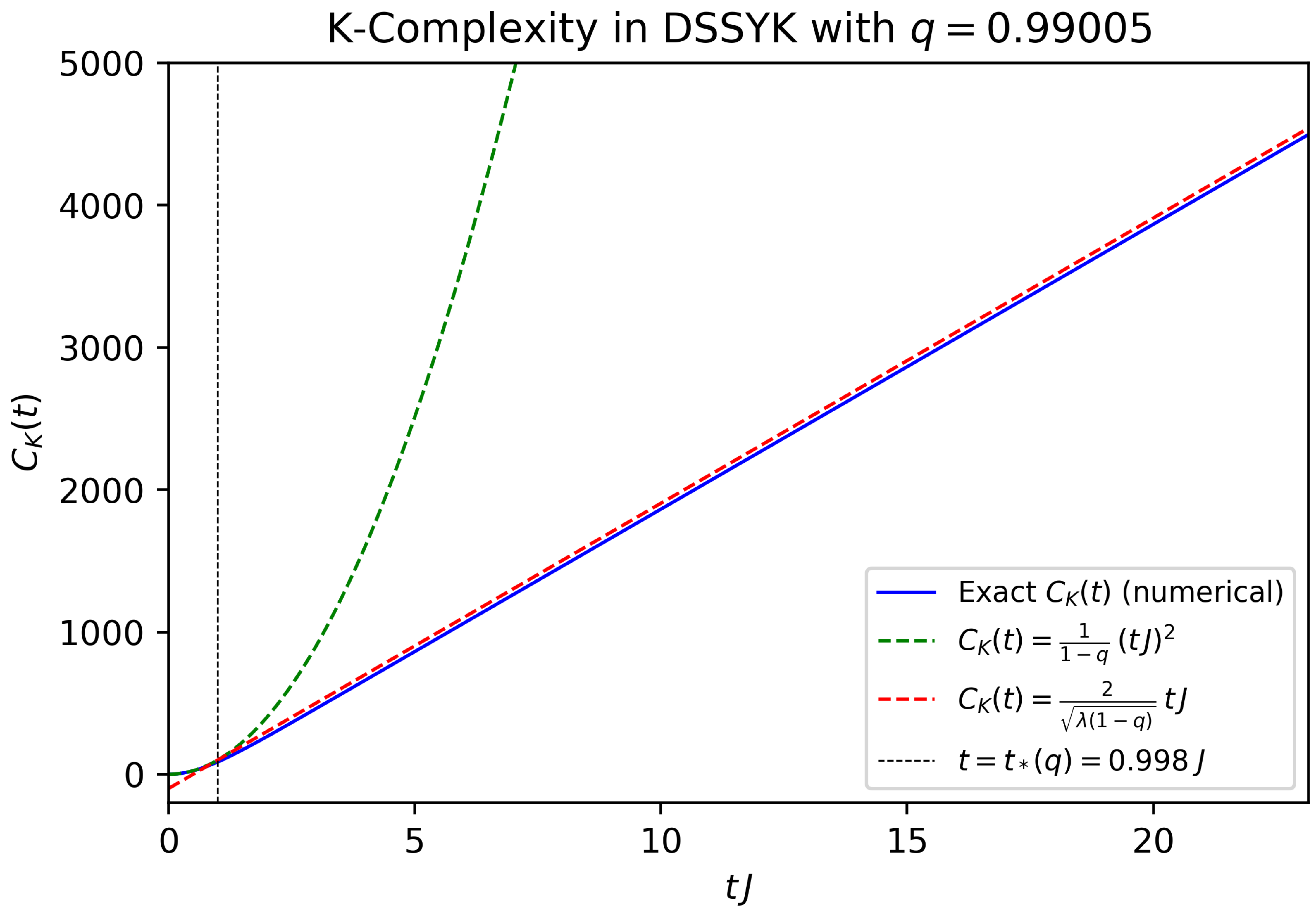
(E. Rabinovici, ASG, R. Shir, J. Sonner, 2023)

Using front-most peak position: $C_K(t) \approx 2b_\infty t$

- Misses build-up of the tail of the wave packet.

K-COMPLEXITY REGIMES: SUMMARY AND NUMERICS





(E. Rabinovici, ASG, R. Shir, J. Sonner; 2023)

CONTINUUM LIMIT

Lanczos coefficients: $b_n = J\sqrt{\dfrac{1-e^{-\lambda n}}{\lambda(1-q)}}$

Recurrence equation (Schrödinger) for $\phi_n(t) = i^n \varphi_n(t)$:

$$\dot{\varphi}_n(t) = b_n \varphi_{n-1}(t) - b_{n+1}\varphi_{n+1}(t)$$

(J. Barbón et al., 2019)

Continuum limit: *(E. Rabinovici, ASG, R. Shir, J. Sonner, 2023)*

$$\lambda \to 0, \qquad n \to \infty, \qquad x := \lambda n \quad \text{fixed}$$

$$\implies \qquad b_n \longrightarrow \frac{J}{\lambda}\sqrt{1-e^{-x}} + O(\lambda^0) \equiv b(x)$$

CONTINUUM APPROXIMATION TO RECURRENCE EQUATION

- Can promote $\varphi_n(t)$ to $f(t,x)$ such that $\varphi_n(t) = f(t, n\lambda)$.

Recurrence equation becomes:

$$\partial_t f(t,x) = -v(x)\partial_x f(t,x) - \frac{v'(x)}{2} f(t,x) + O(\lambda)$$

Where: $$v(x) = 2\lambda b(x) = 2J\sqrt{1-e^{-x}} + O(\lambda) \xrightarrow{\lambda\to 0} 2J\sqrt{1-e^{-x}}\,.$$

Redefining:

$$dy = \frac{dx}{v(x)} \quad \text{and} \quad g(t,y) := \sqrt{v\left(x(y)\right)} f\left(t, x(y)\right)$$

We get: $$\left(\partial_t + \partial_y\right) g(t,y) = 0 + O(\lambda)\,.$$

Chiral wave equation.

CONTINUUM APPROXIMATION - TRAJECTORY

The solution just propagates initial condition:

$$g(0,y) \equiv g_0(y) \qquad \Longrightarrow \qquad g(t,y) = g(y-t)$$

Given $\quad \varphi_n(0) = \delta_{n0} \quad \Longrightarrow \quad g_0(y) \propto \delta(y) \quad \Longrightarrow \quad g(t,y) \propto \delta(y-t)$

Position expectation value (~ K-complexity) given by position of the peak:

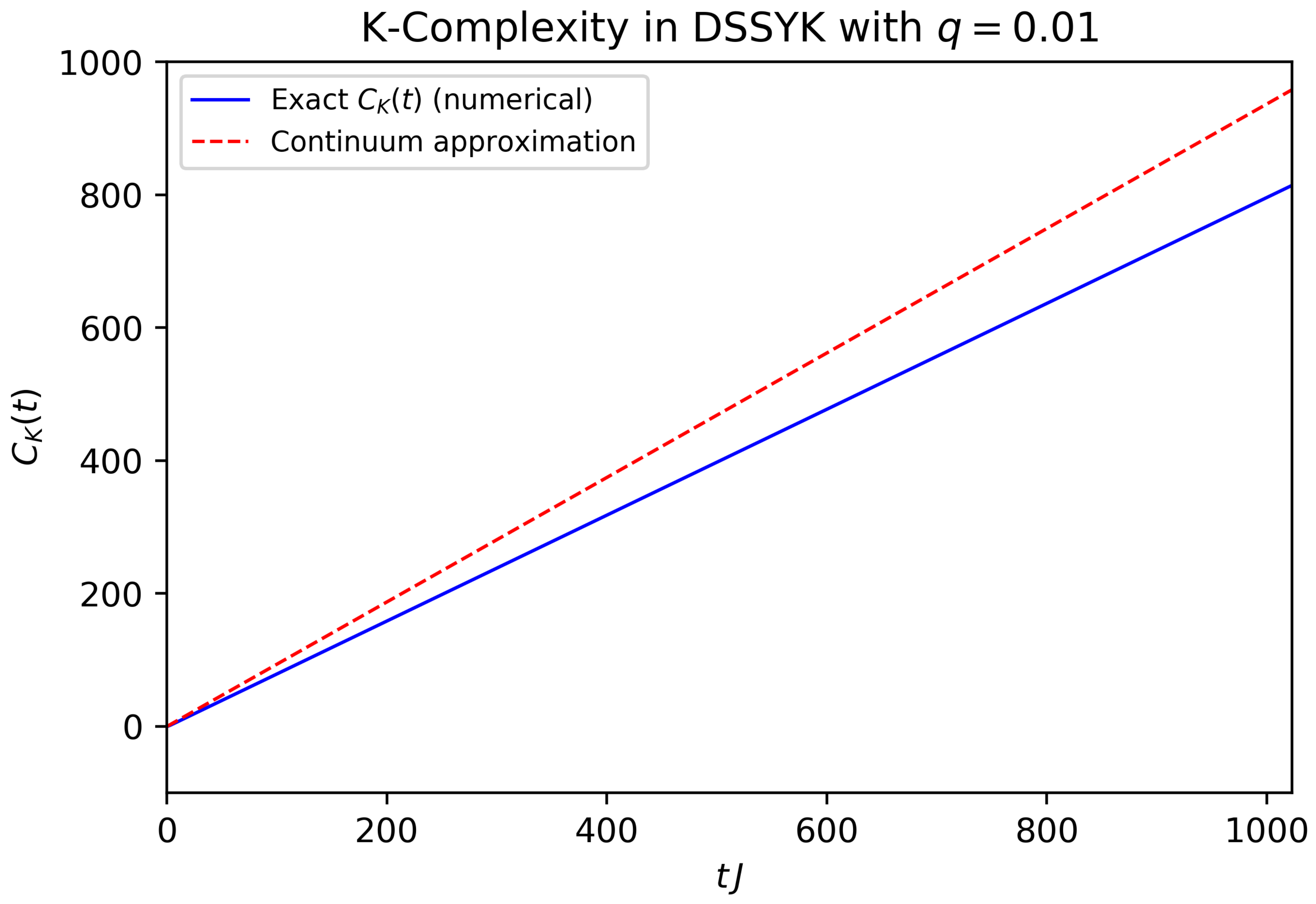
$$t = \int_0^{y_p(t)} dy = \int_0^{x_p(t)} \frac{dx}{v(x)} \qquad \equiv \qquad \int_0^{n_p(t)} \frac{\cancel{\lambda}\, dn}{2\,\cancel{\lambda}\, b_n} = \int_0^{n_p(t)} \frac{dn}{2\, b_n}$$

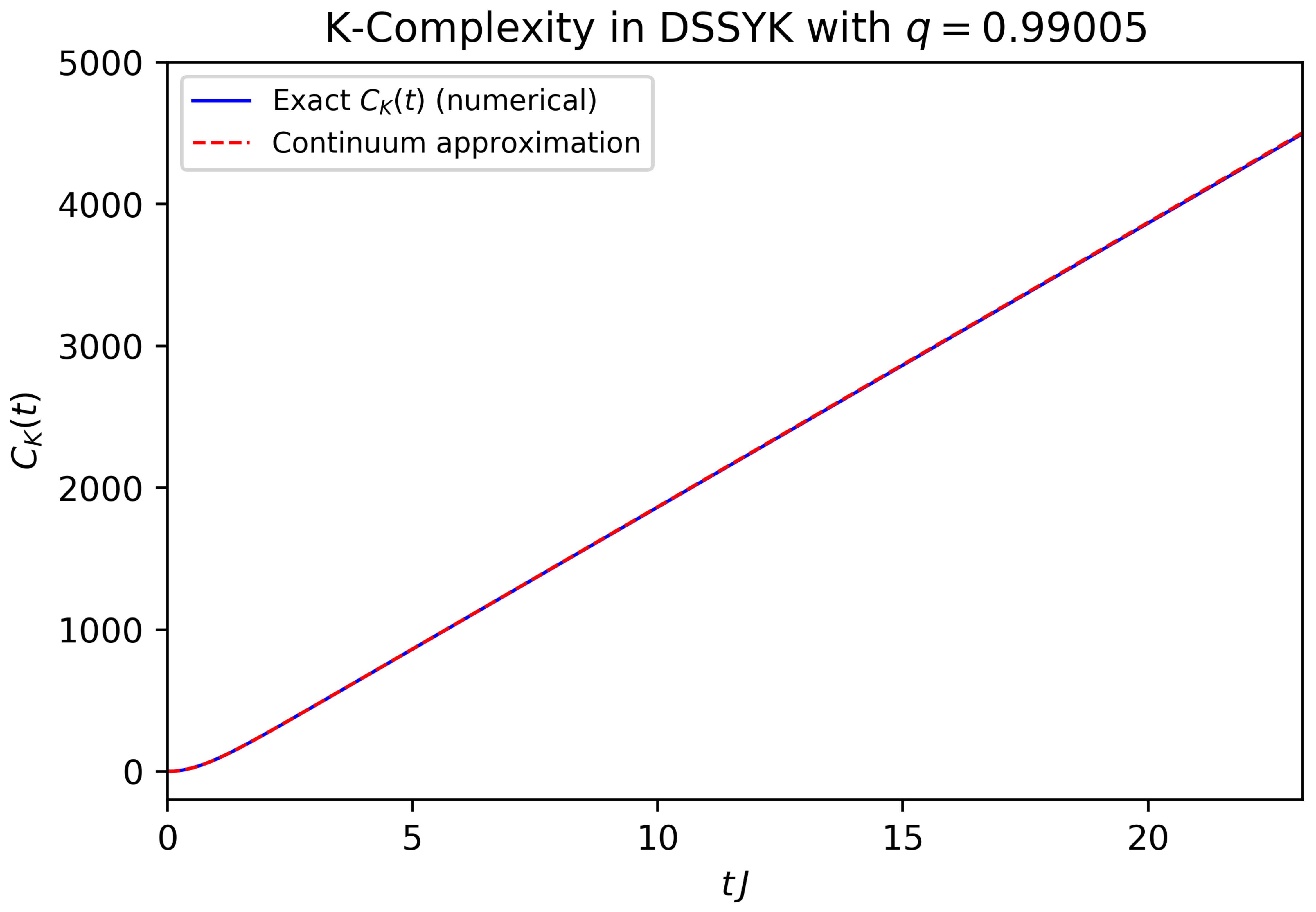
Performing the integral and solving for $n_p(t)$ we find:

$$C_K(t) \approx n_p(t) = \frac{2}{\lambda} \log \left\{ \cosh \left[tJ \sqrt{\frac{\lambda}{1-q}} \right] \right\}$$

Expected to be good at small λ

CONTINUUM APPROXIMATION VS NUMERICS





(E. Rabinovici, ASG, R. Shir, J. Sonner, 2023)

CONNECTION TO LIOUVILLE (CLASSICAL)

- Going back to the continuum limit for the variable $\lambda n = x \equiv \frac{l}{L}$.

Trajectory satisfying $\dot{x} = v(x) = 2J\sqrt{1 - e^{-x}}$ is a solution of the EOM of:

$$H' \equiv E_0 + 2\lambda J \left(\frac{L^2 k^2}{2} + \frac{2}{(2\lambda)^2} e^{-\frac{l}{L}} \right)$$

Liouville!

Why? $\longrightarrow$ Classical limit of effective DSSYK Hamiltonian: *(H. Lin, 2022)*

$$\tilde{T}_{\text{class}} \sim -\frac{2J}{\lambda} \cos(\lambda L k) \sqrt{1 - e^{-\frac{l}{L}}}$$

Both have same EOM $\longrightarrow$ Connection to Liouville is only classical so far.

CONNECTION TO LIOUVILLE (QUANTUM)

- Hence the need of the triple-scaling limit.

$$\lambda \to 0, \qquad l \to \infty, \qquad \frac{e^{-\frac{l}{L}}}{(2\lambda)^2} =: e^{-\frac{\tilde{l}}{L}} \qquad \text{fixed.}$$ *(H. Lin, 2022)*

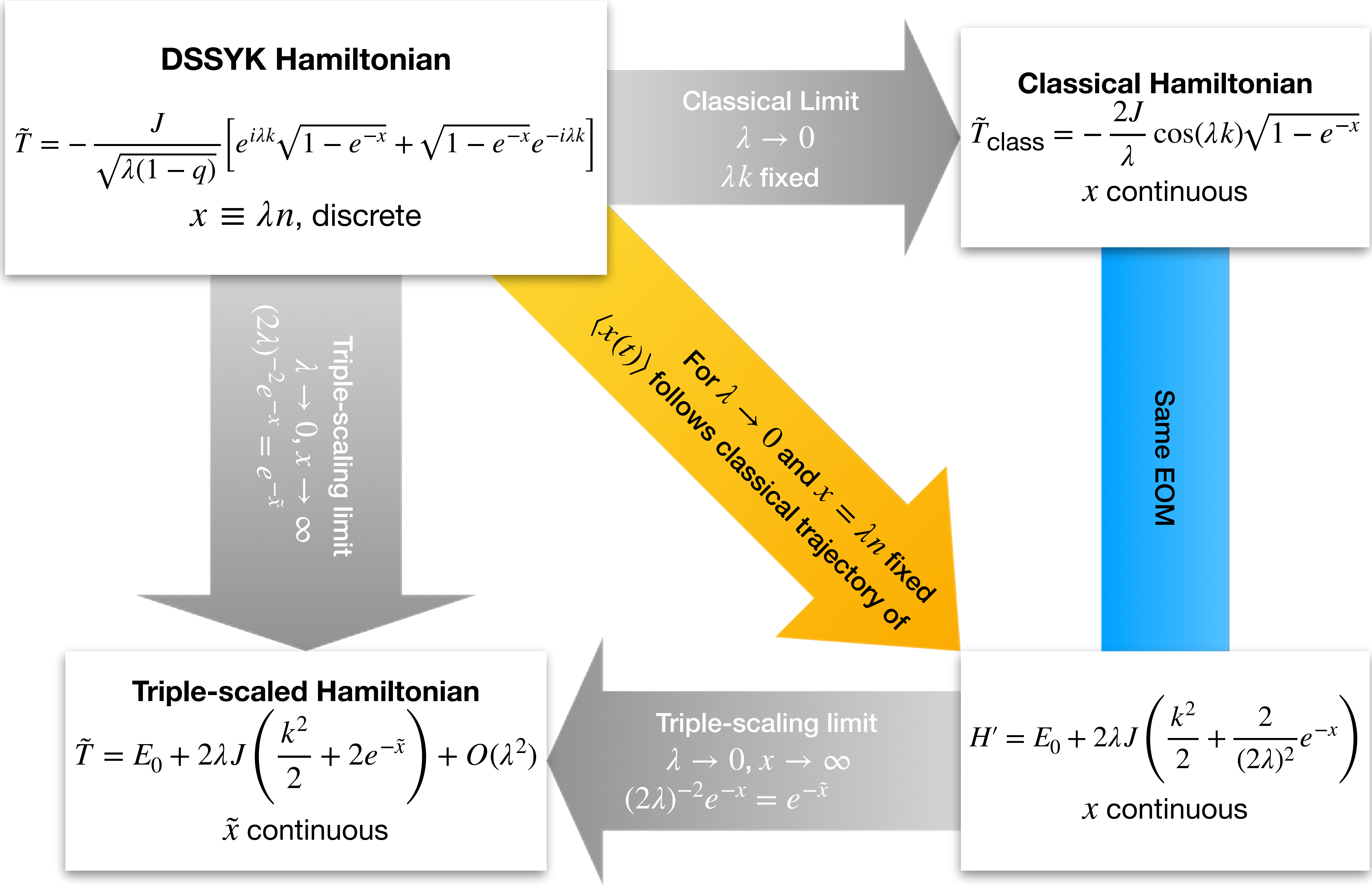
Such that

$$\tilde{T} = E_0 + 2\lambda J \left(\frac{L^2 k^2}{2} + 2e^{-\frac{\tilde{l}}{L}} \right) + O\left(\lambda^2\right), \quad E_0 \sim -\frac{2J}{\lambda}$$

i.e. the DSSYK Hamiltonian is Liouville QM near its ground state.

On top of this one can still perform classical approximations.

HAMILTONIANS: SUMMARY



REGULARIZED LENGTH FROM K-COMPLEXITY IN TRIPLE-SCALED LATTICE

- Can envision $\dfrac{\tilde{l}}{L} \equiv \widetilde{x}$ as the continuum limit of a lattice s.t. $\widetilde{x} = \lambda \tilde{n}$.
- Triple-scaled Lanczos coefficients:

$$b_{\tilde{n}} = b - 2\lambda J q^{\tilde{n}} + O(\lambda^2)$$

- Cont. approx gives K-complexity from EOM of triple-scaled Hamiltonian:

$$\lambda \widetilde{C_K}(t) = \frac{\tilde{l}(t)}{L} = \widetilde{x}_0 + 2\log\left\{\cosh\left(2\lambda J e^{-\widetilde{x}_0/2}\, t\right)\right\}$$

TFD: $\widetilde{x}_0 = 0$

(E. Rabinovici, ASG, R. Shir, J. Sonner, 2023)

GRAVITY MATCHING: REMINDER OF JT RESULTS

- Two-sided length in AdS_2:

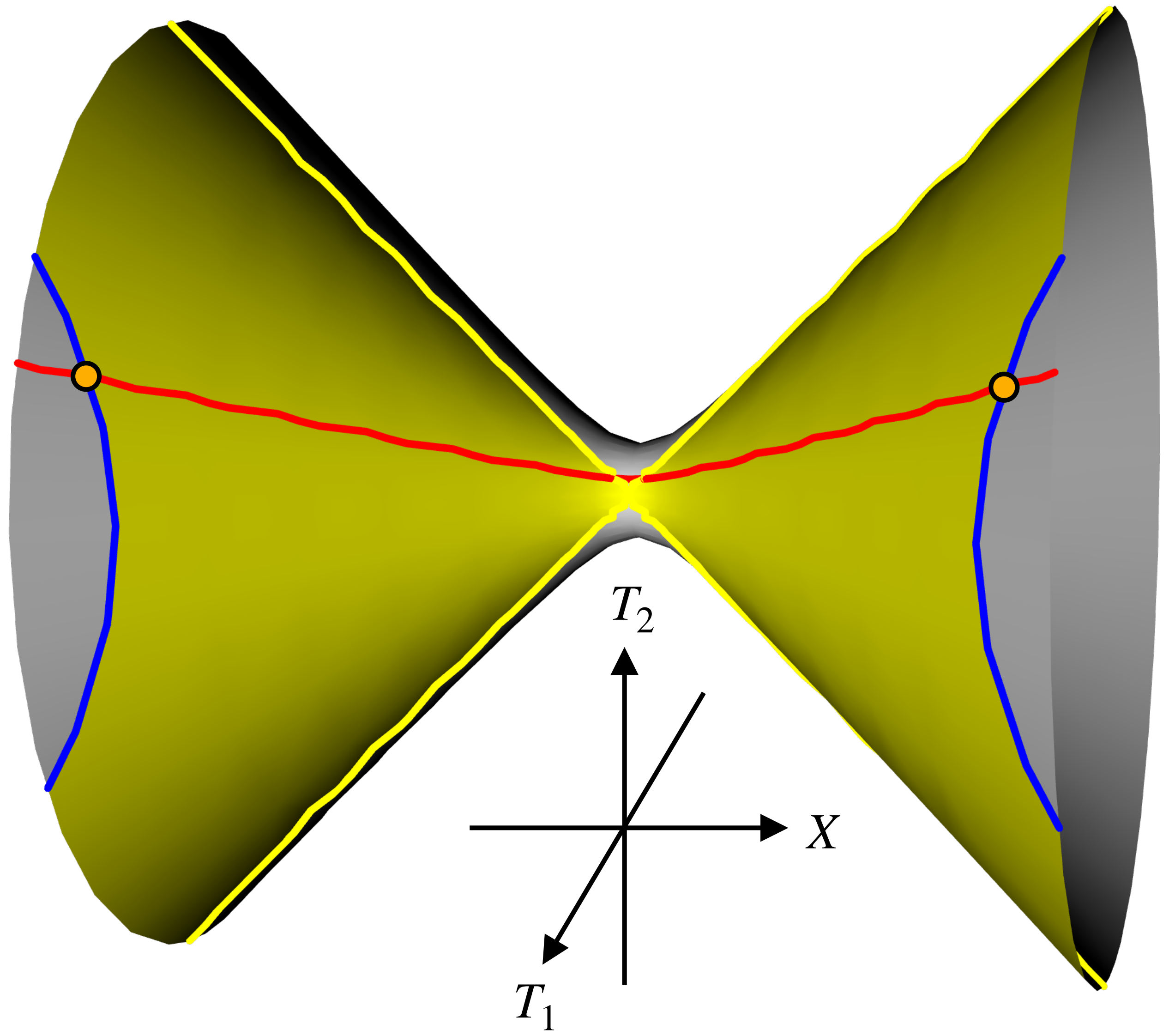
$$\frac{\tilde{l}}{l_{AdS}} = l - 2\log\left(\frac{2\phi_b}{\epsilon}\right)$$

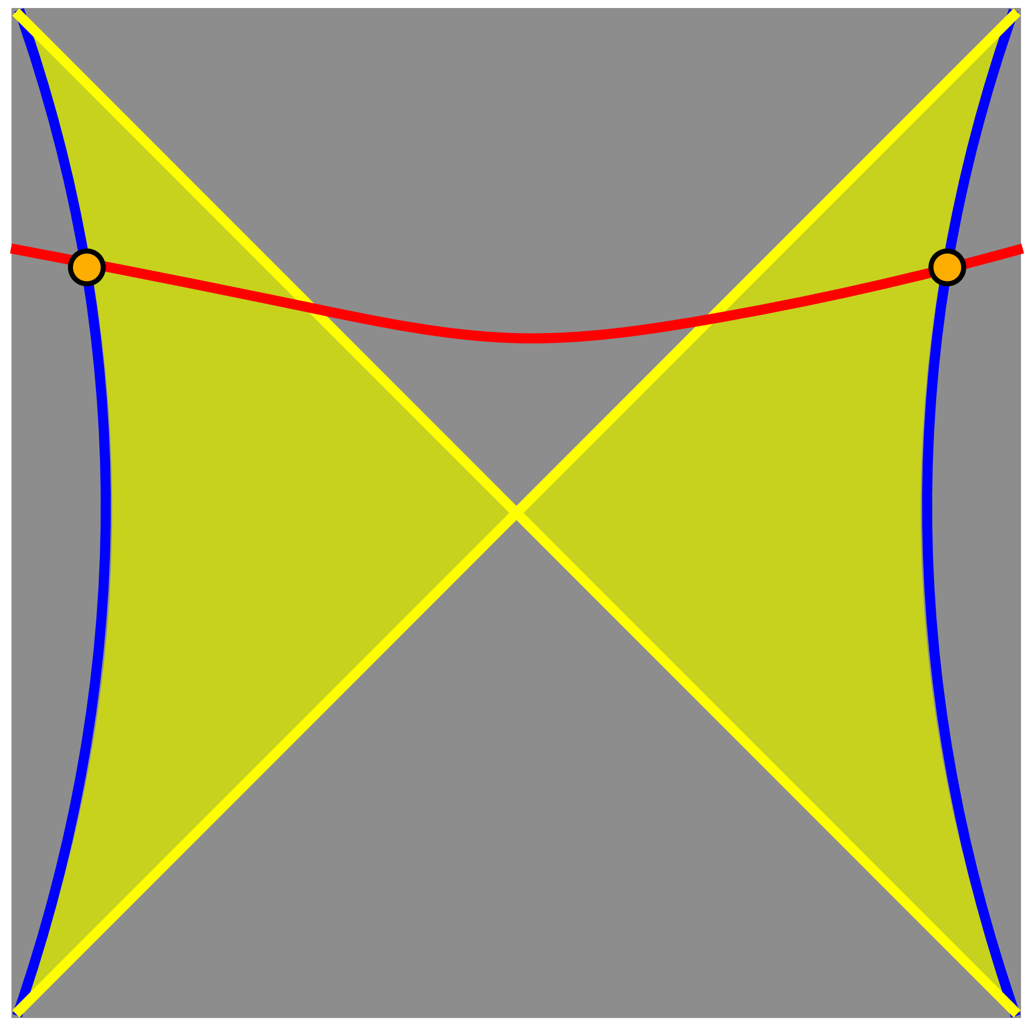
$$= 2\log\left[\cosh\left(\frac{\Phi_h}{l_{AdS}\,\phi_b}t_b\right)\right] - 2\log\Phi_h$$

- JT Hamiltonian:

$$H = \frac{1}{l_{AdS}\,\phi_b}\left(\frac{l_{AdS}^2\,P^2}{2} + 2e^{-\tilde{l}/l_{AdS}}\right)$$

(D. Harlow & D. Jafferis, 2018)





GRAVITY MATCHING: CORRESPONDENCE AND PARAMETER IDENTIFICATIONS

- K-complexity eigenstates are bulk length eigenstates because:
  1. Krylov elements are fixed chord number states. *(E. Rabinovici, ASG, R. Shir, J. Sonner, 2023)*
  2. Fixed chord number states are bulk length eigenstates. *(H. Lin, 2022)*

- Parameter identifications:
  1. From Hamiltonian: $L = l_{AdS}, \qquad 2\lambda J = \dfrac{1}{l_{AdS}\,\phi_b}$
  2. From classical evaluation: $\tilde{x}_0 = -2\log\Phi_h$

CONCLUSION

- Krylov complexity as a candidate for holography.
- DSSYK as a system where the holographic dictionary is well established.
- Under this dictionary, K-complexity is exactly 2-sided bulk length.

- Saturation of complexity: finite size on boundary $\longleftrightarrow$ higher genus corrections in bulk
- Corrections to JT from higher orders in λ?
- Operators?
- Higher dimensions?


¡Thanks !
Photo:
Los huevos de Lucio
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