

Open Quantum Systems for Observers

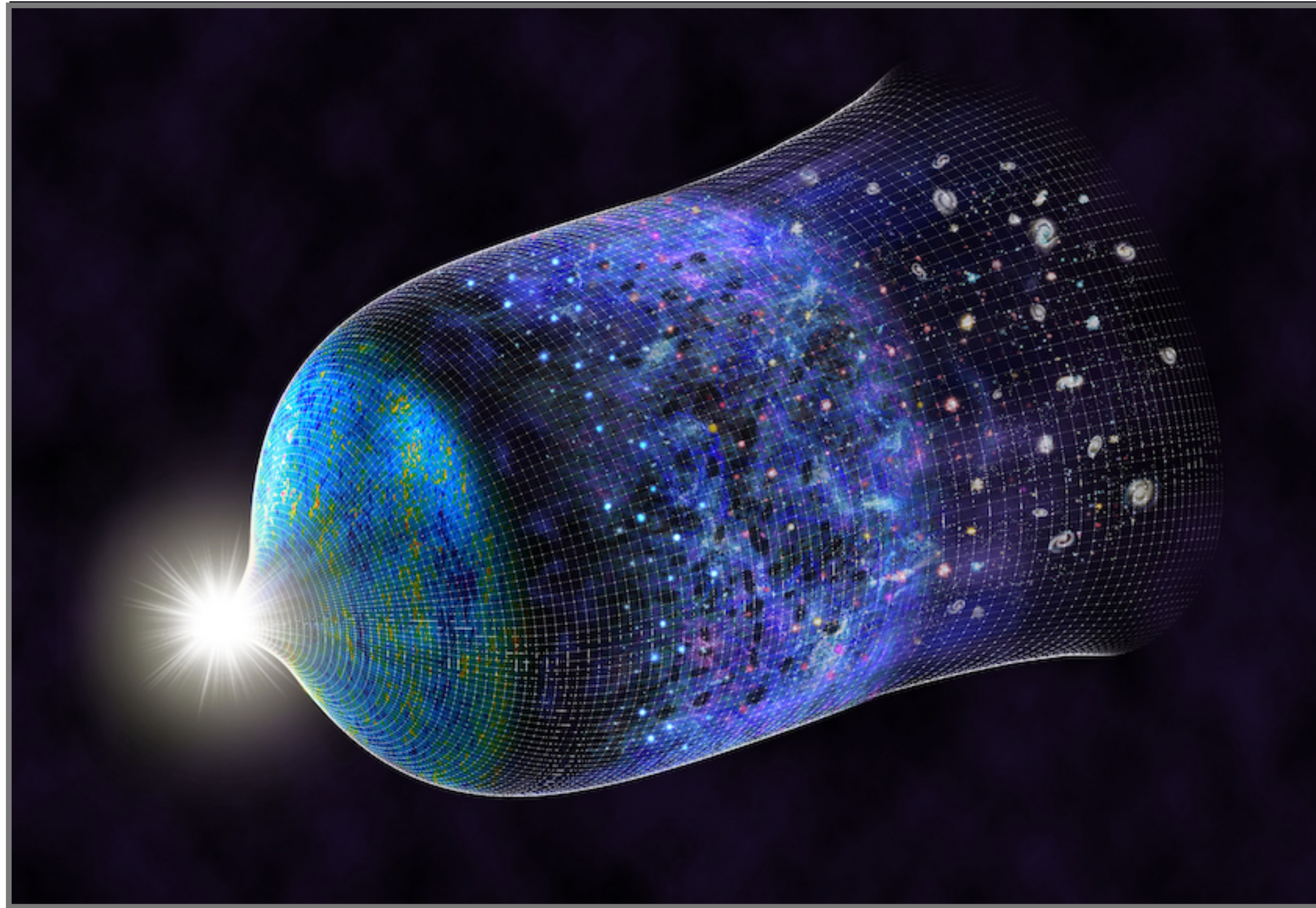
Sarah Shandera

Penn State

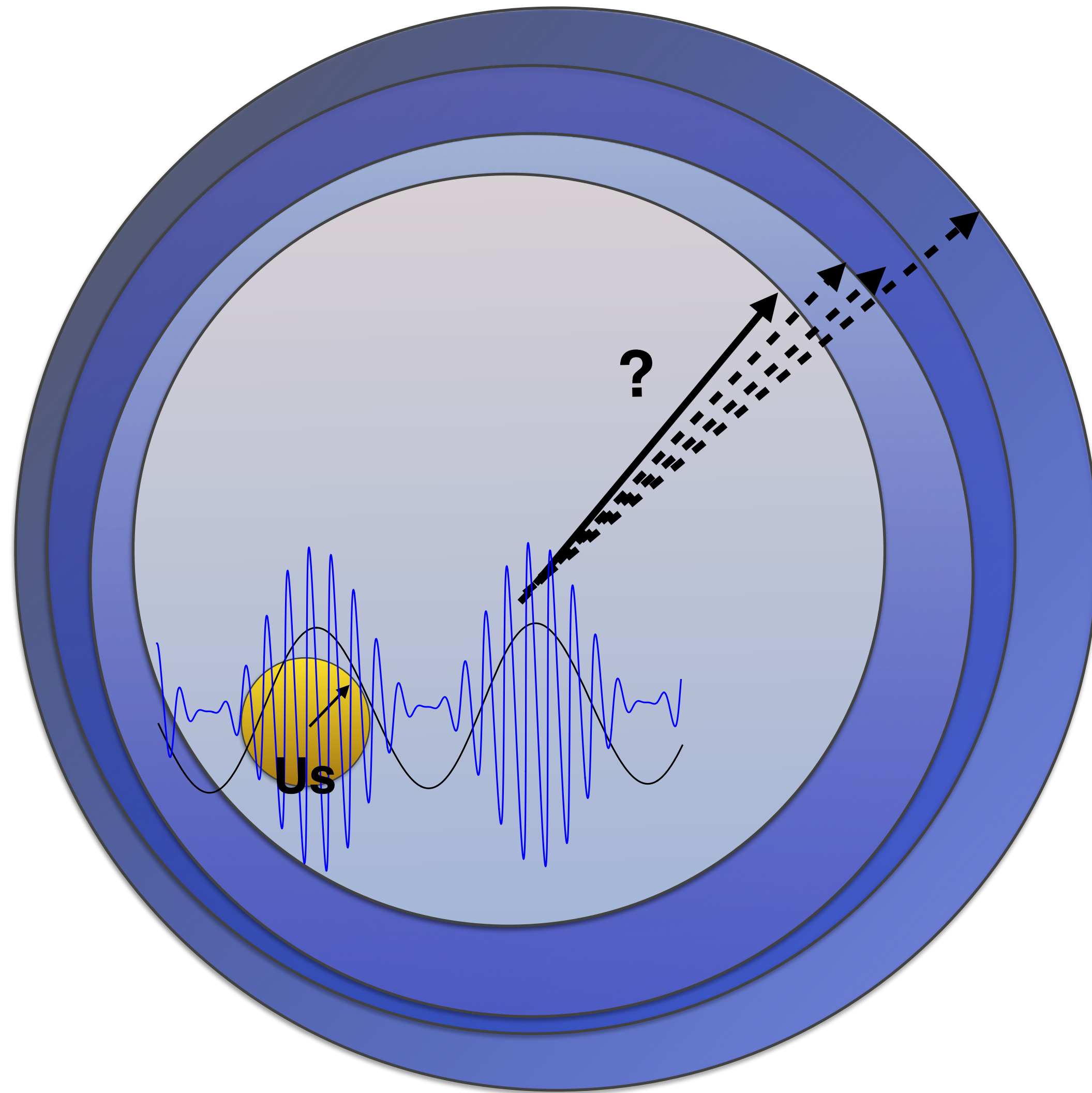
Institute for Gravitation and the Cosmos



How can we solve the persistent puzzles of cosmology?



Inflation as a prod toward open quantum systems

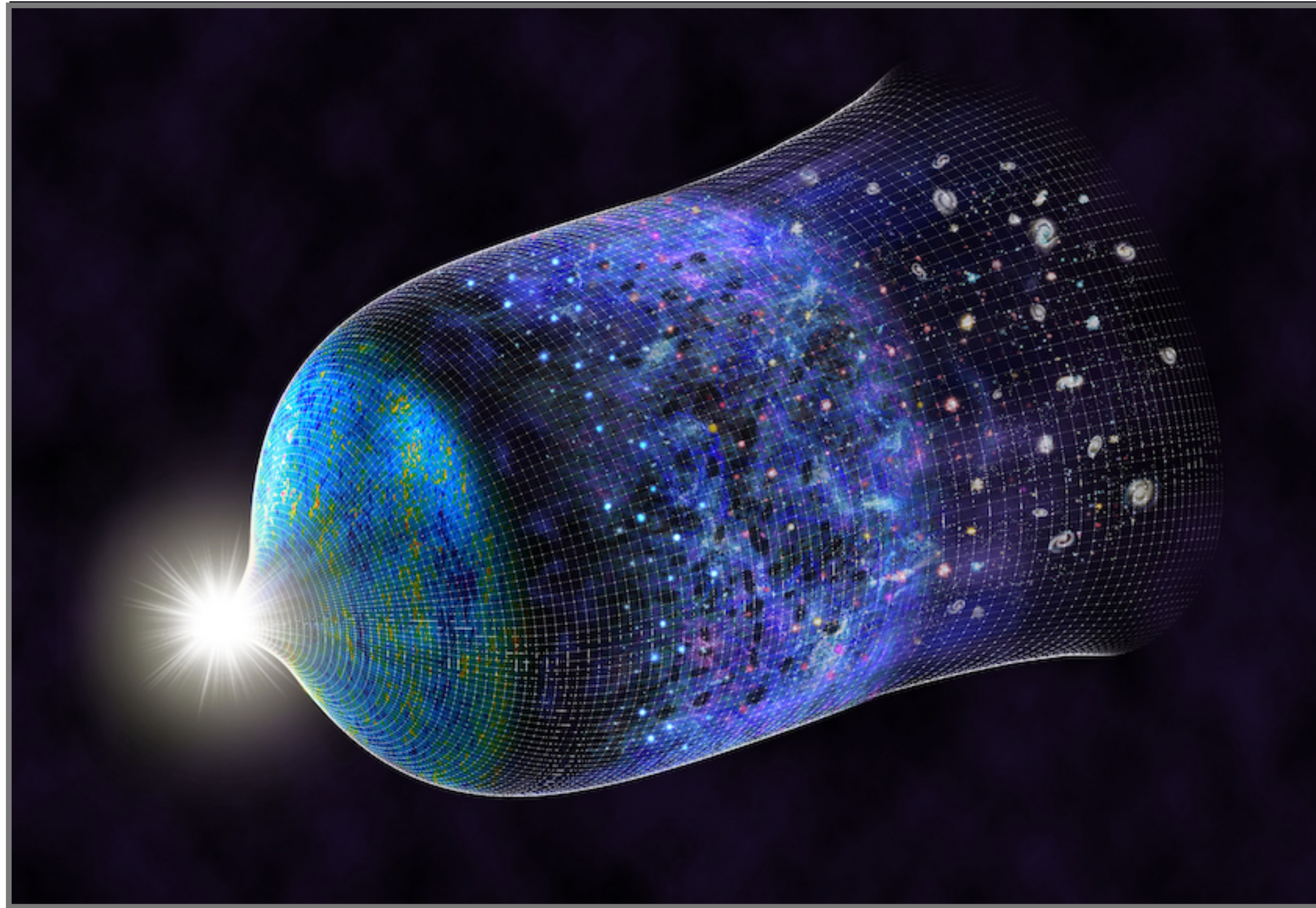


Does the exponentially larger volume generated by inflation matter for inferring microphysics of inflation?

Yes, when locally observed degrees of freedom are coupled to unobservable modes

No natural scale of separation of dynamics that coincides with sys/environment boundary

How can we solve the persistent puzzles of cosmology?



Data: we collect ensembles of partial observations



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Limits include

- Spatial extent (horizons)
- Spatial resolution
- Time
- Intensity
- Charges (electromagnetism)



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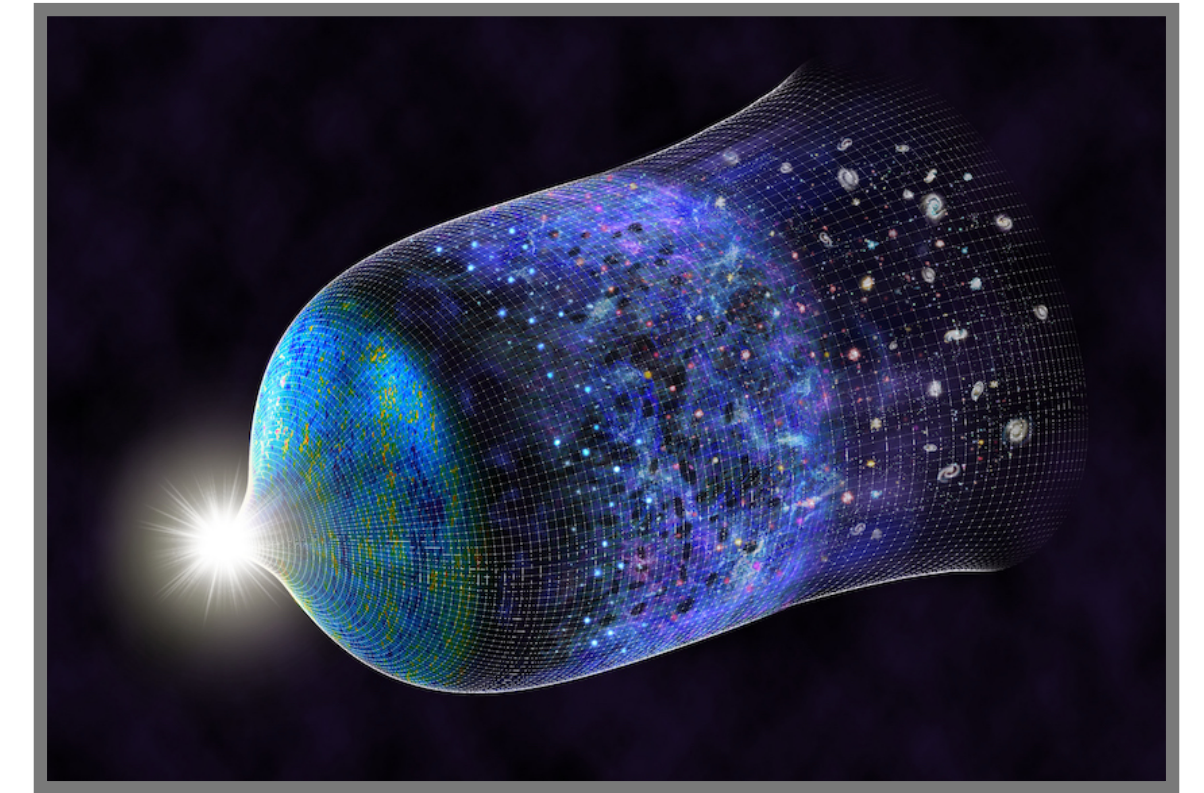
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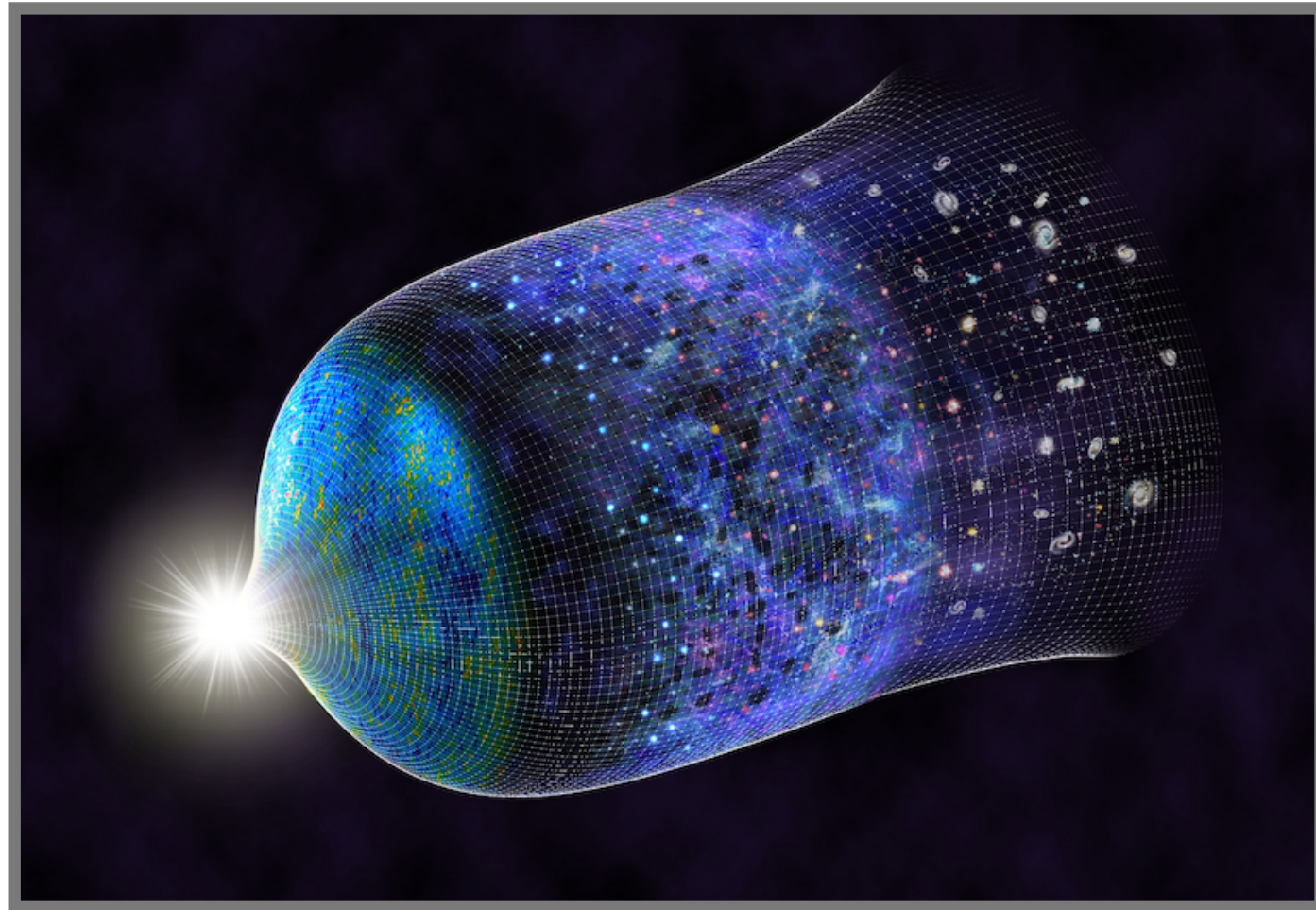
The objects in this image are macroscopic; we'd like to apply a similar logic to the microphysical degrees of freedom

OQS: An opportunity bigger than, eg, inflation...

- Open quantum systems
 - are required for cosmology and gravity
 - are an active research field across disciplines
 - suggest paradigm-shifting ideas
 - Quantum correlations play a key role in the tricky parts of OQS behavior
 - Quantum correlations (and tricky parts) depend on definition of subsystem/what is observable

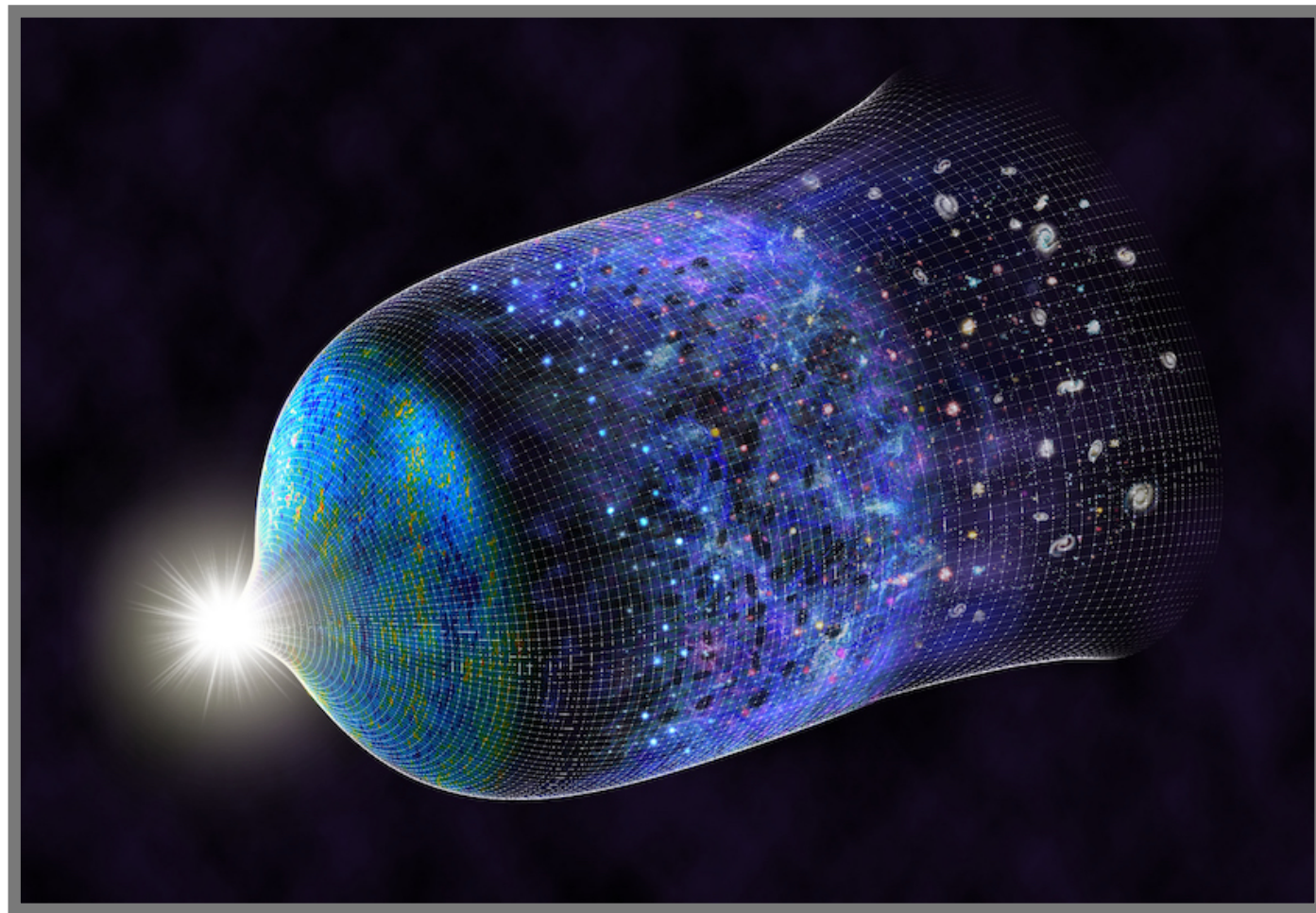


What should the foundational theory look like?



Take very seriously two features of the universe we have:

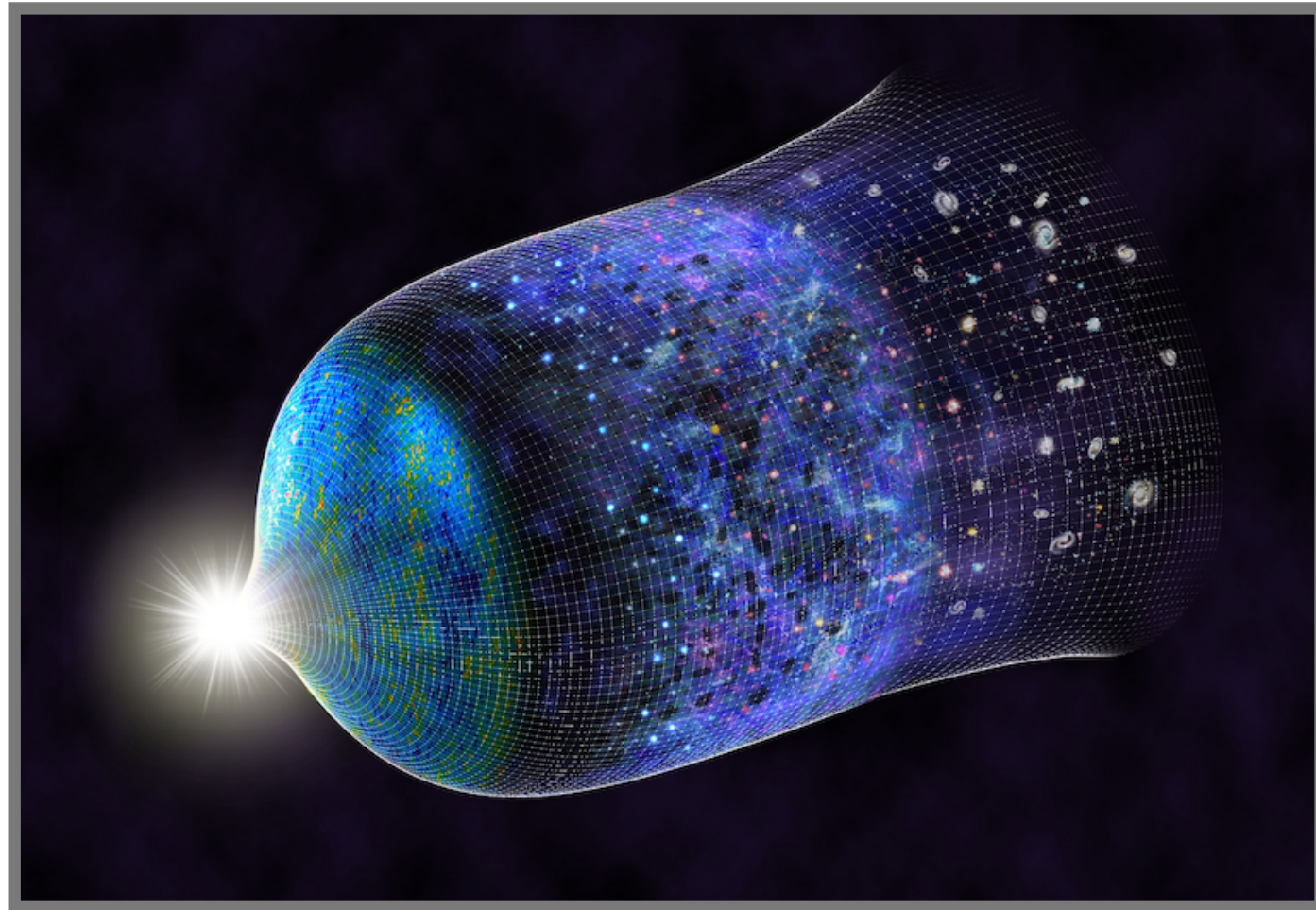
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- The universe is not in equilibrium

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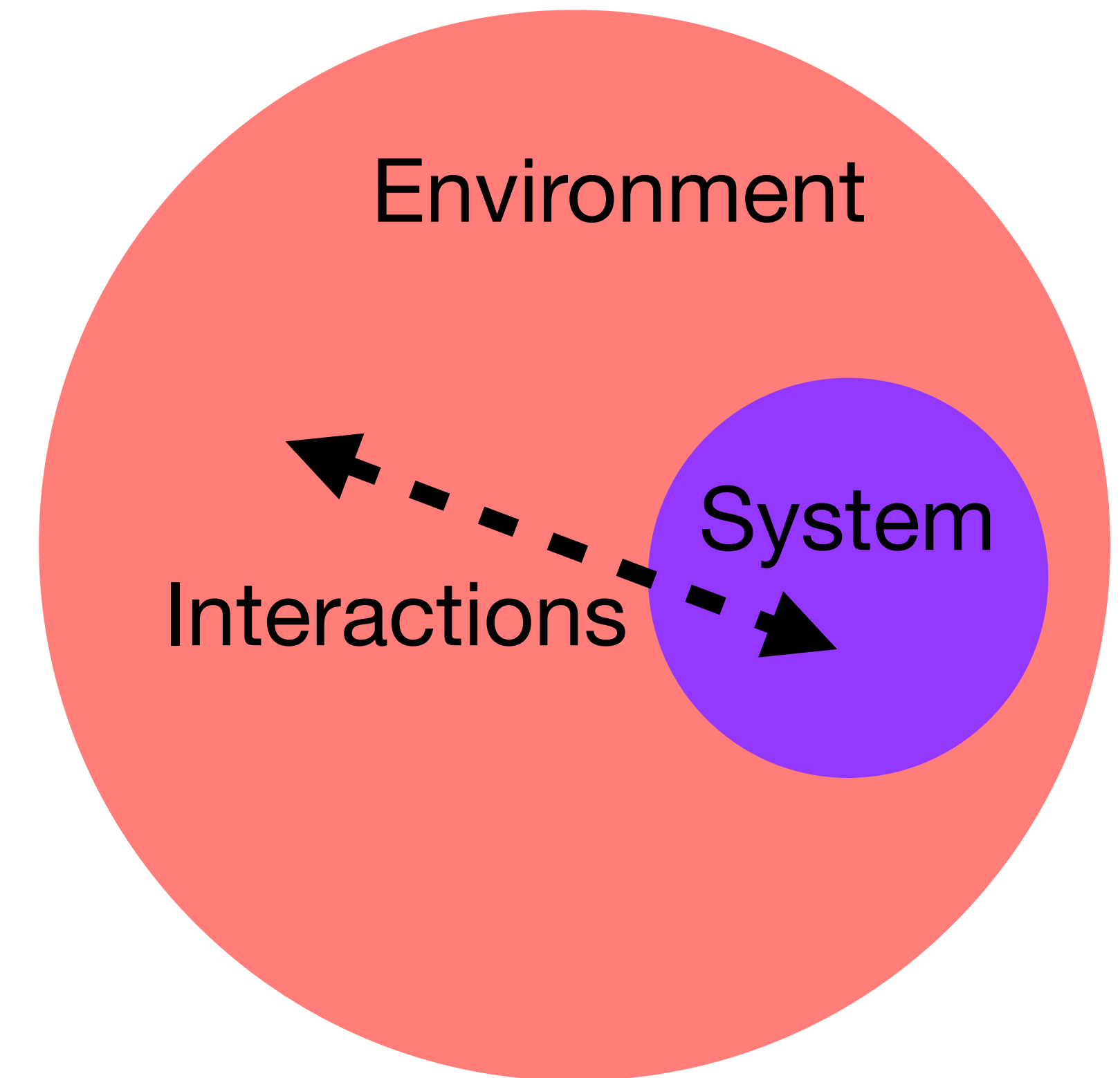
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A quantum-first approach

The accessible observables define the (open) system

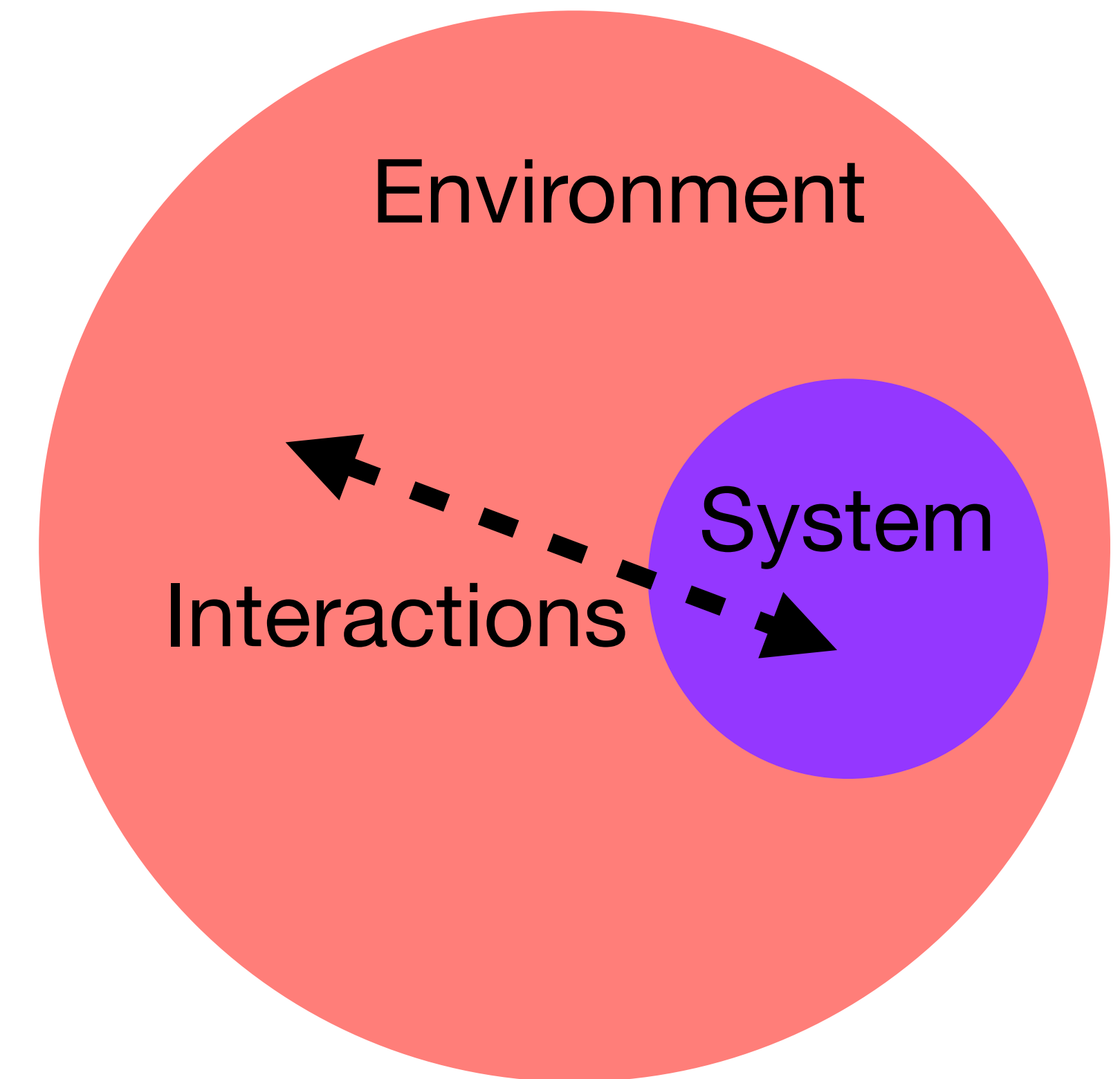
- What can be observed? A collection (algebra) of operators
- These define a partition of the Hilbert space...
 - into observed system and the rest
 - and a tensor product structure on the system
- Which determines the notion of quantum correlations between system and environment



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(Including non-Gaussianity; Blahnik, Shandera; PRD 112, (2025) 10)



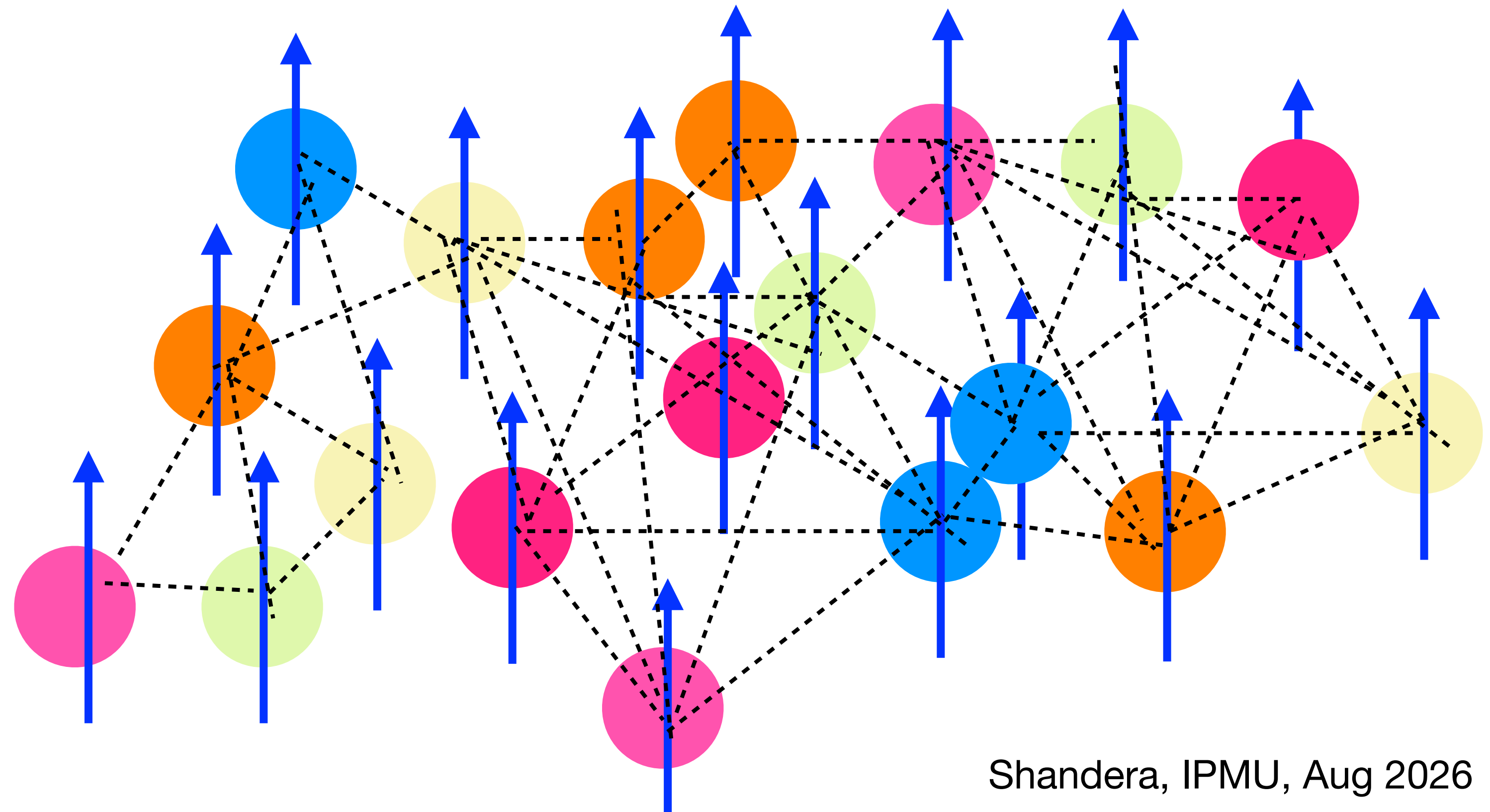
What information about global dynamics and state is available locally?

This talk: no background spacetime

- Basic ingredient is a (finite dimensional) Hilbert space + symmetry
- ‘Local’ is defined by the tensor product structure and interaction structure of the dynamics
- Ultimately, we’d like a principle for selecting a notion of local interactions

Partial observations of simple systems

- A network of qubits (an assumed Hilbert space partition)

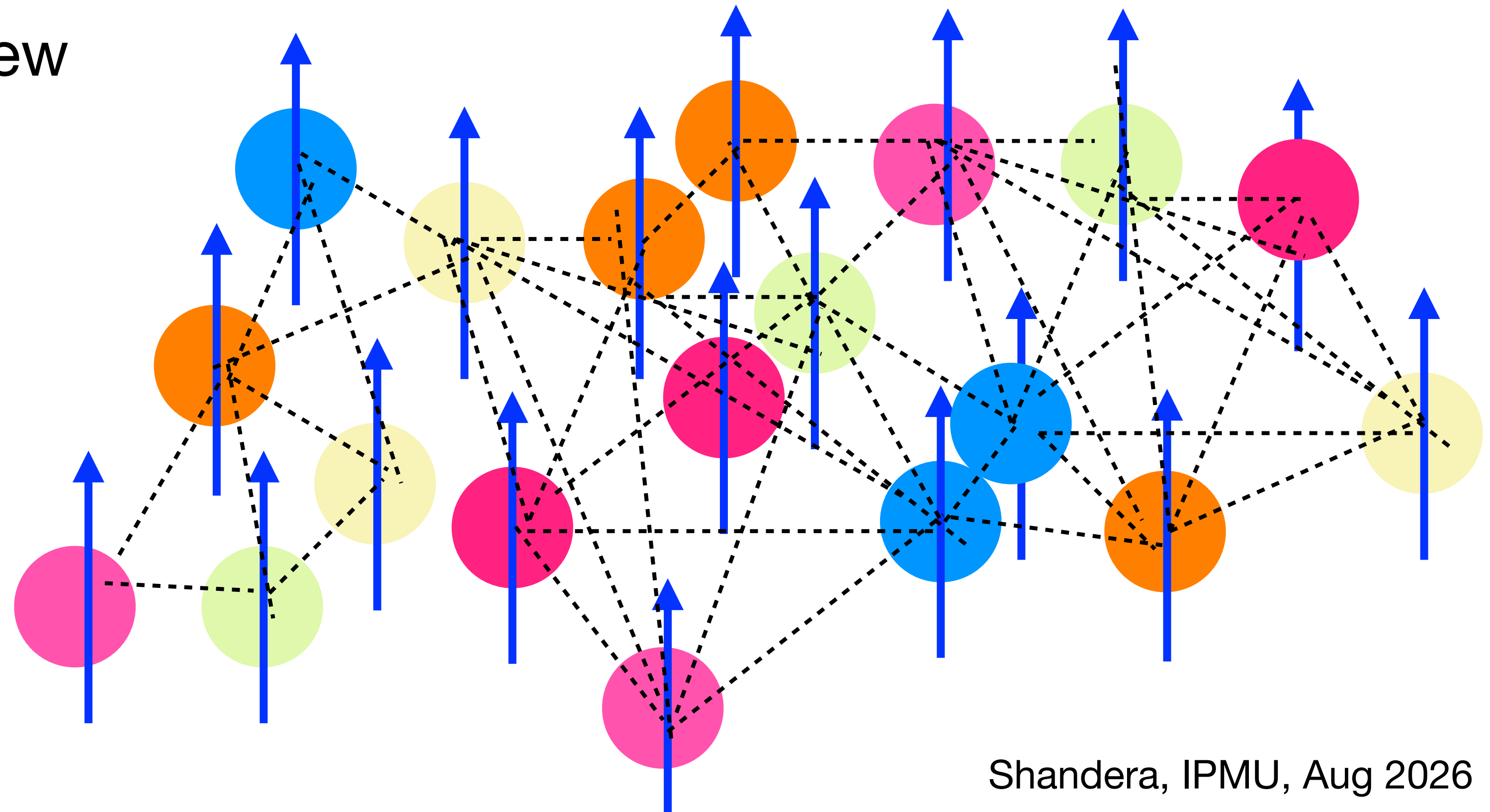


Partial observations of simple systems

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Limits on which subsystems are in principle measurable

- Spatial extent
- Spatial resolution/field of view
- Time

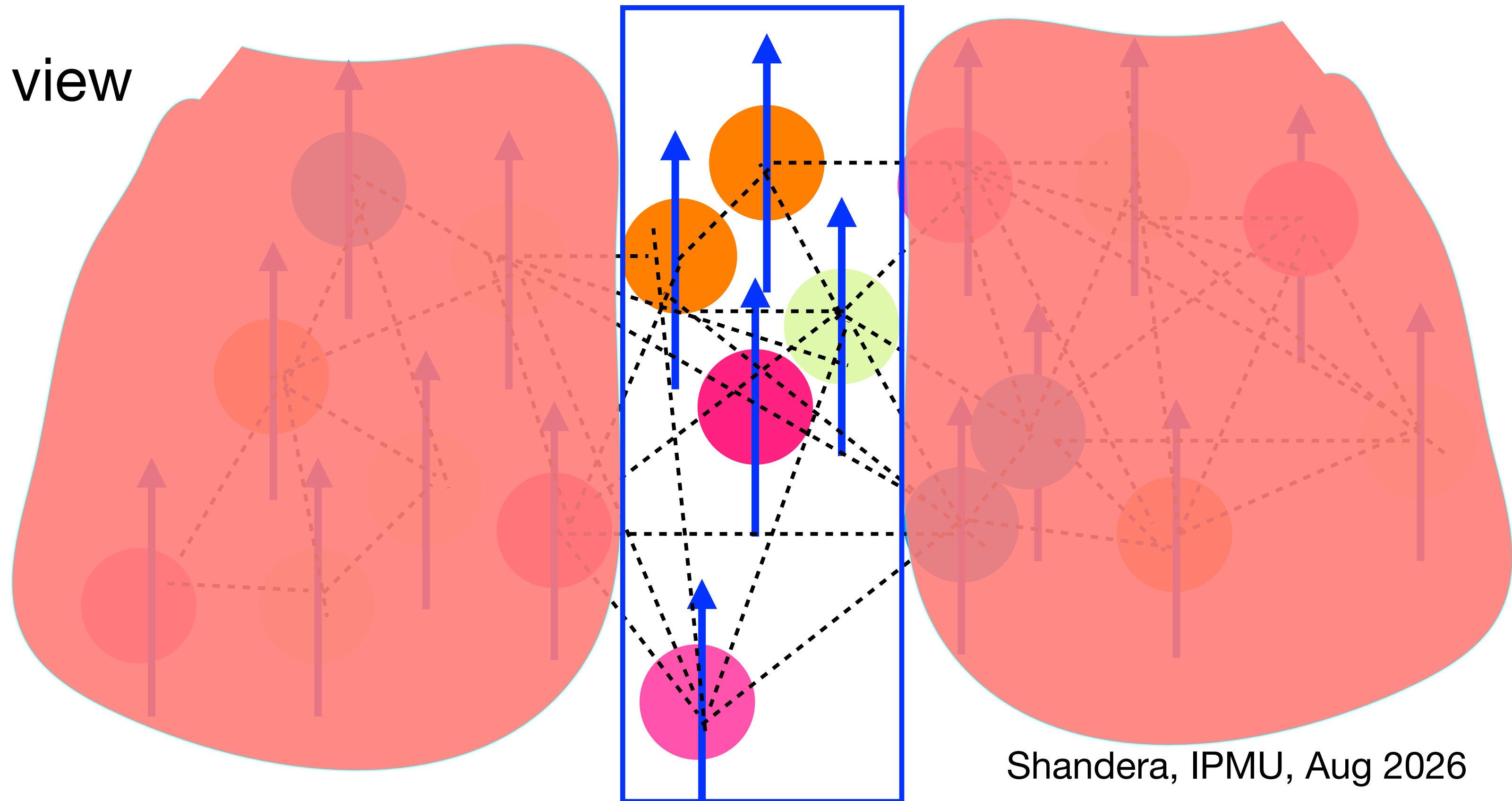


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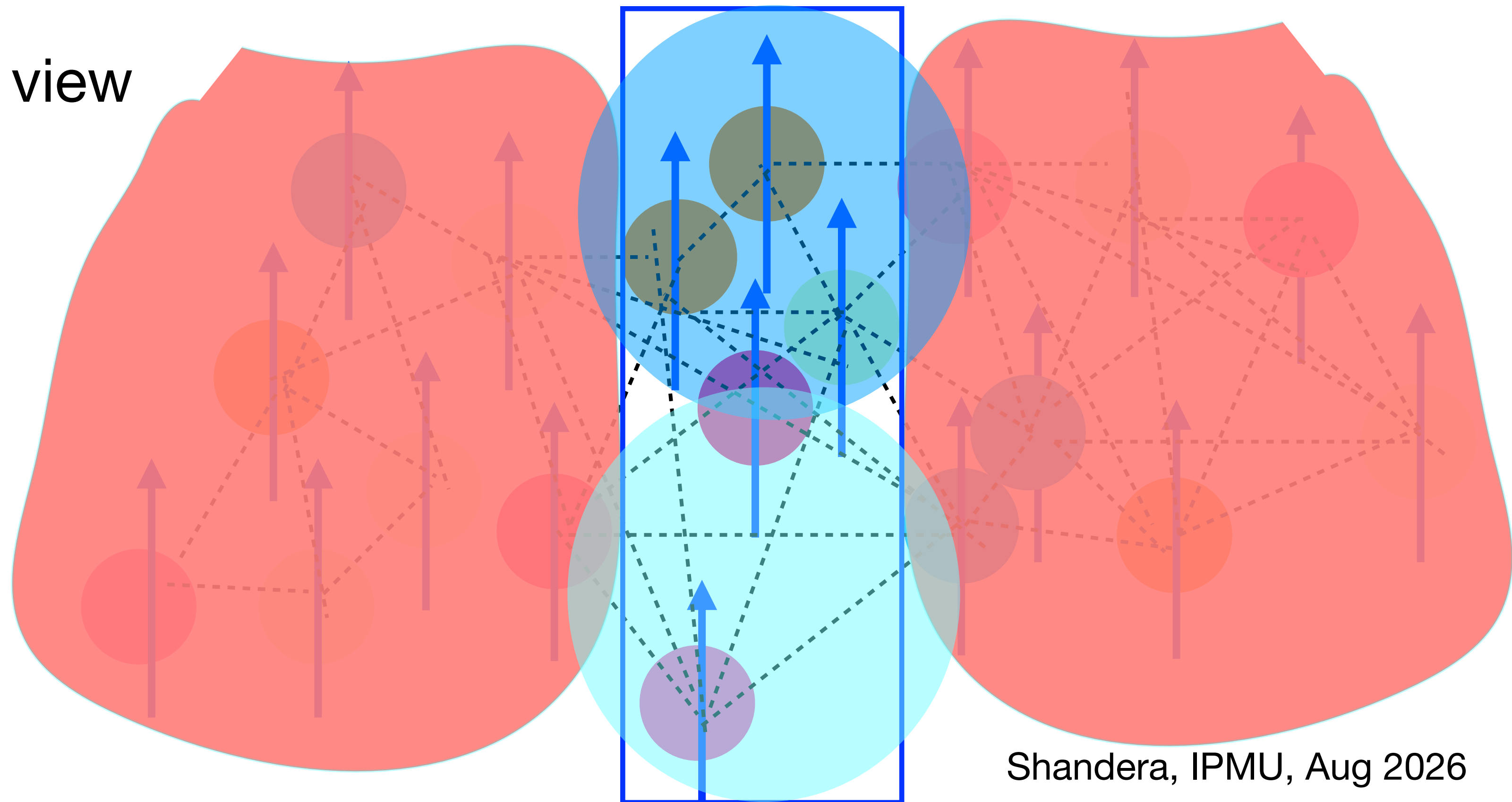


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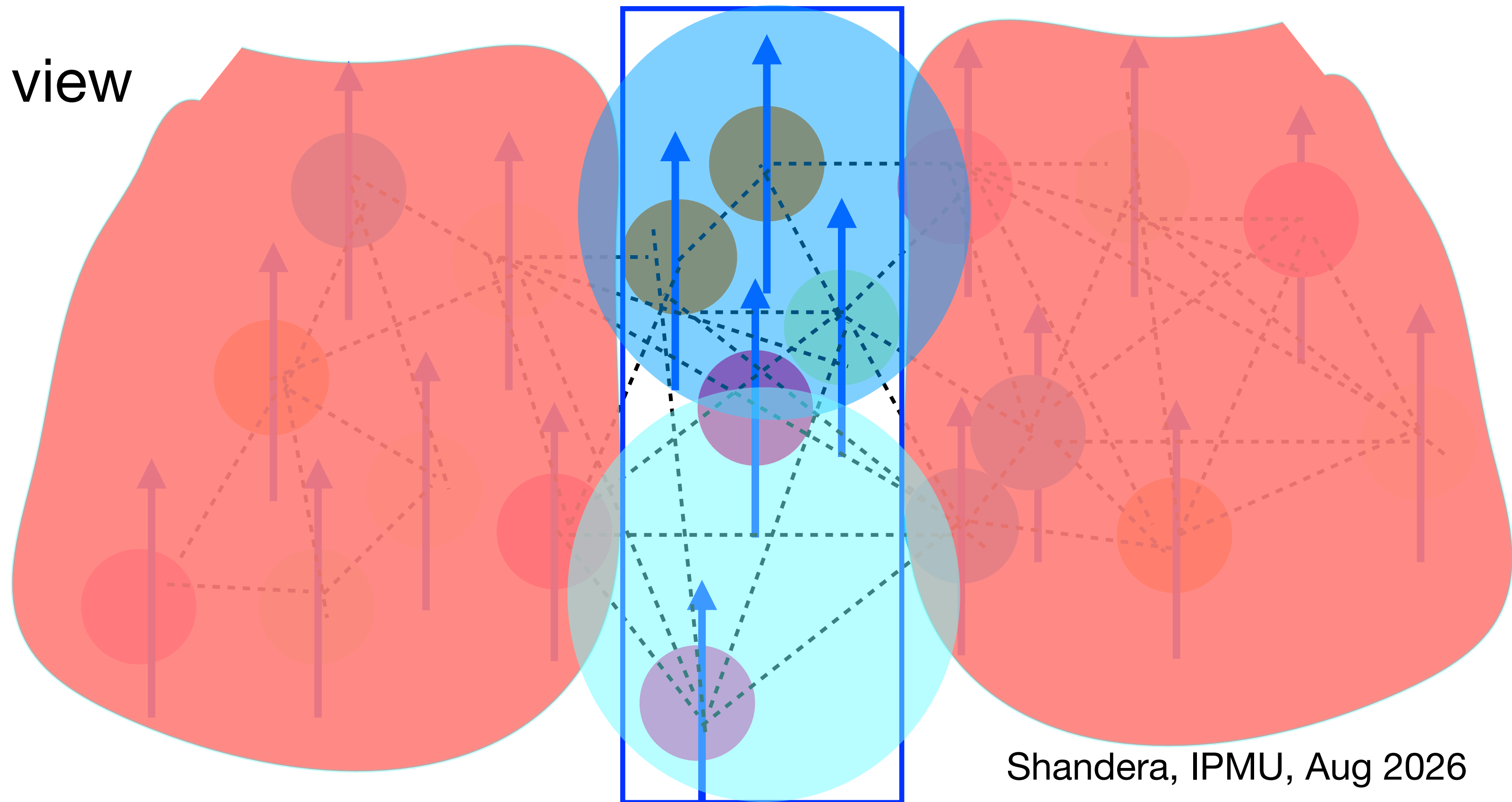


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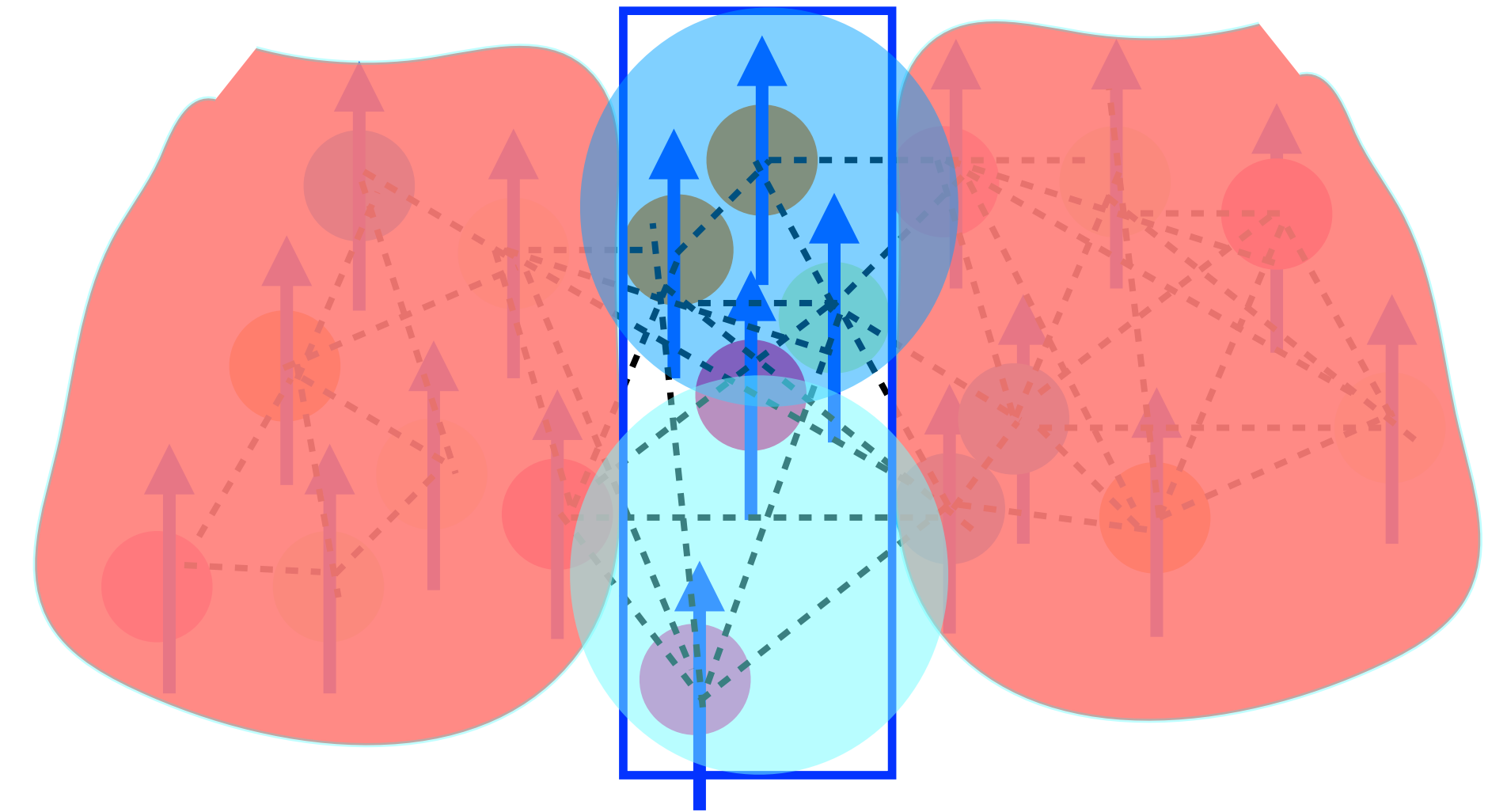
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Limits on which subsystems are in principle measurable

- Spatial extent
- Spatial resolution/field of view
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- Observable subsystems need not correspond to quantum-independent, “fundamental” degrees of freedom at some other time

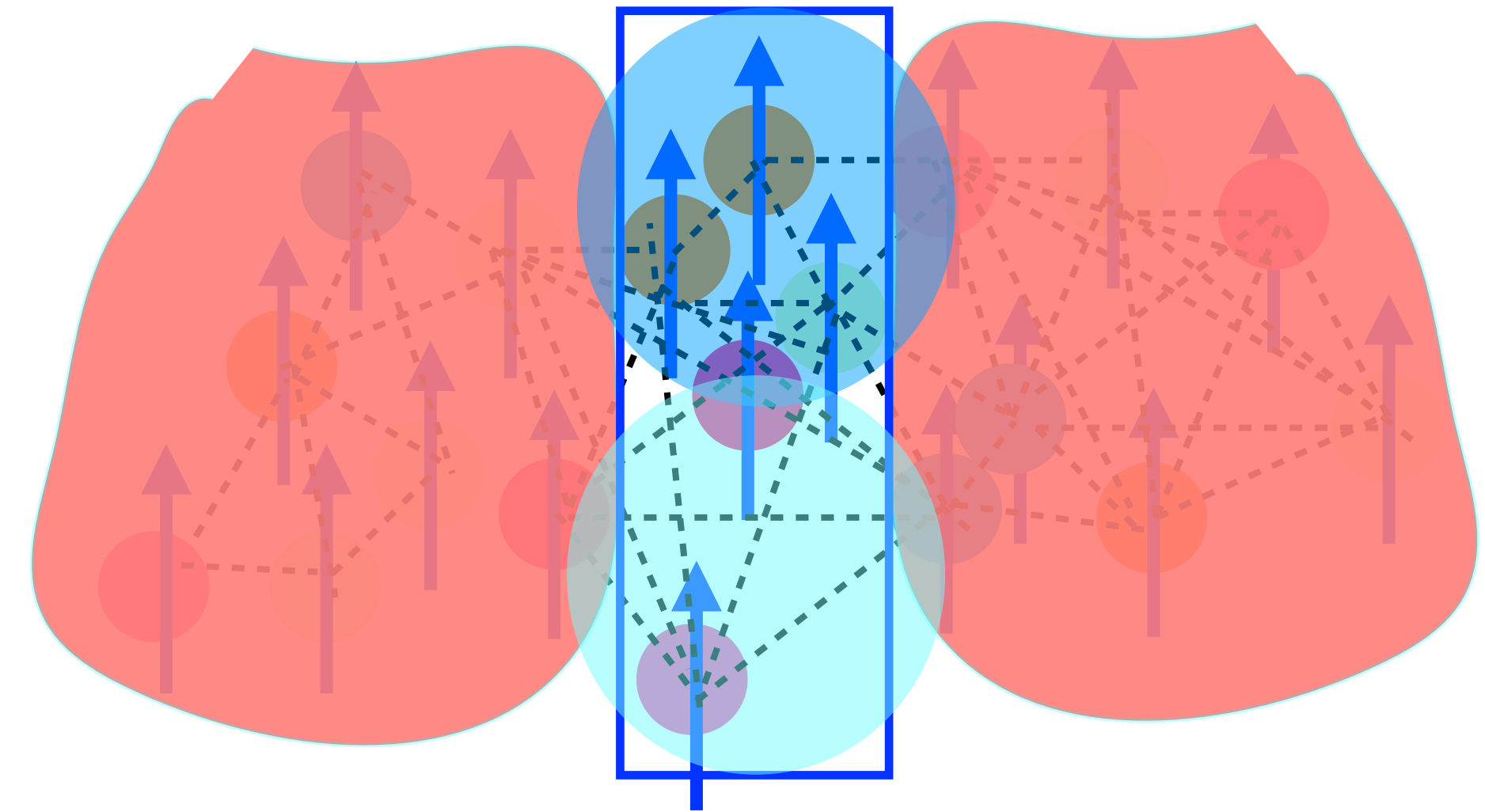


So what do we want?



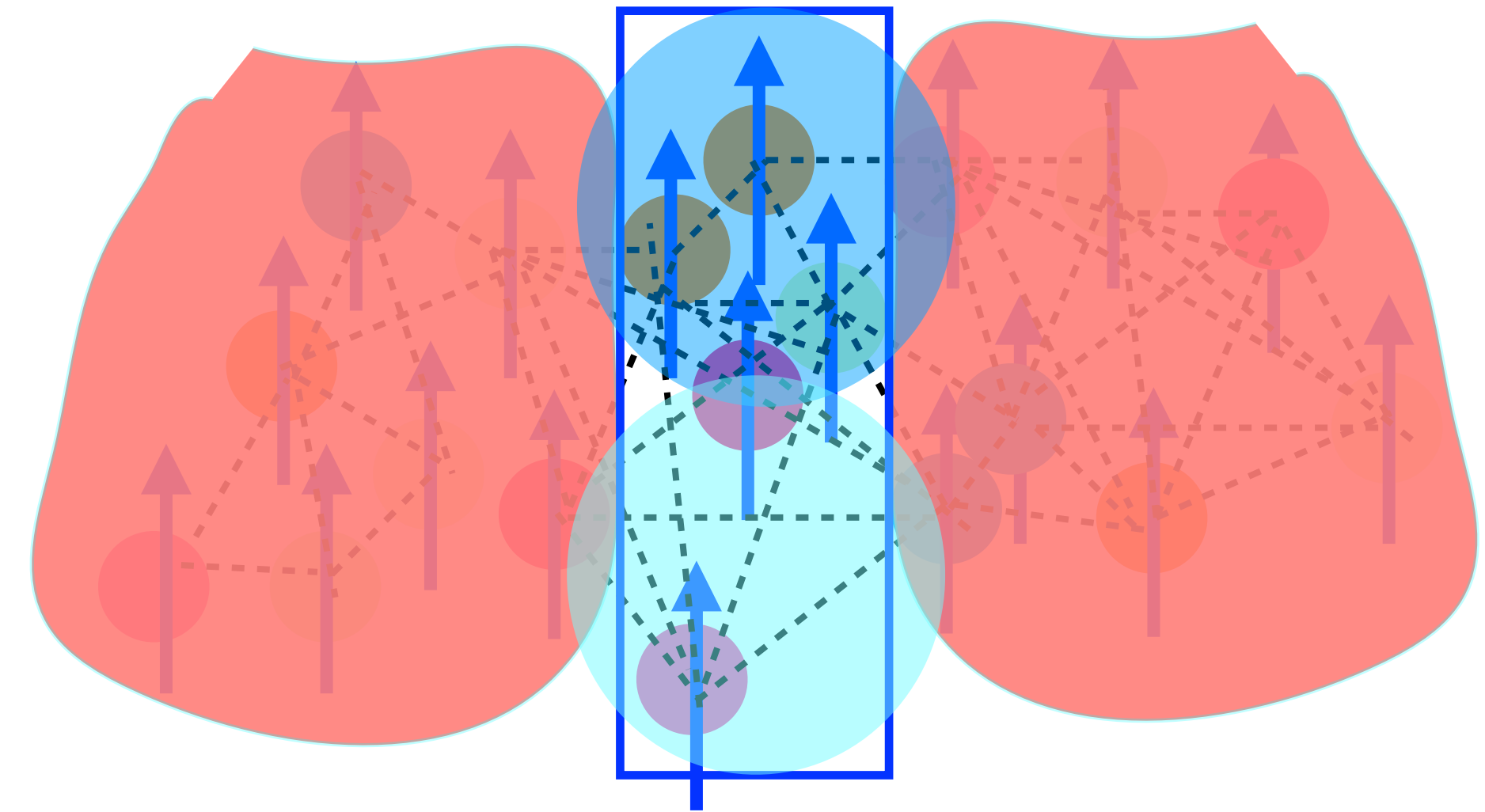
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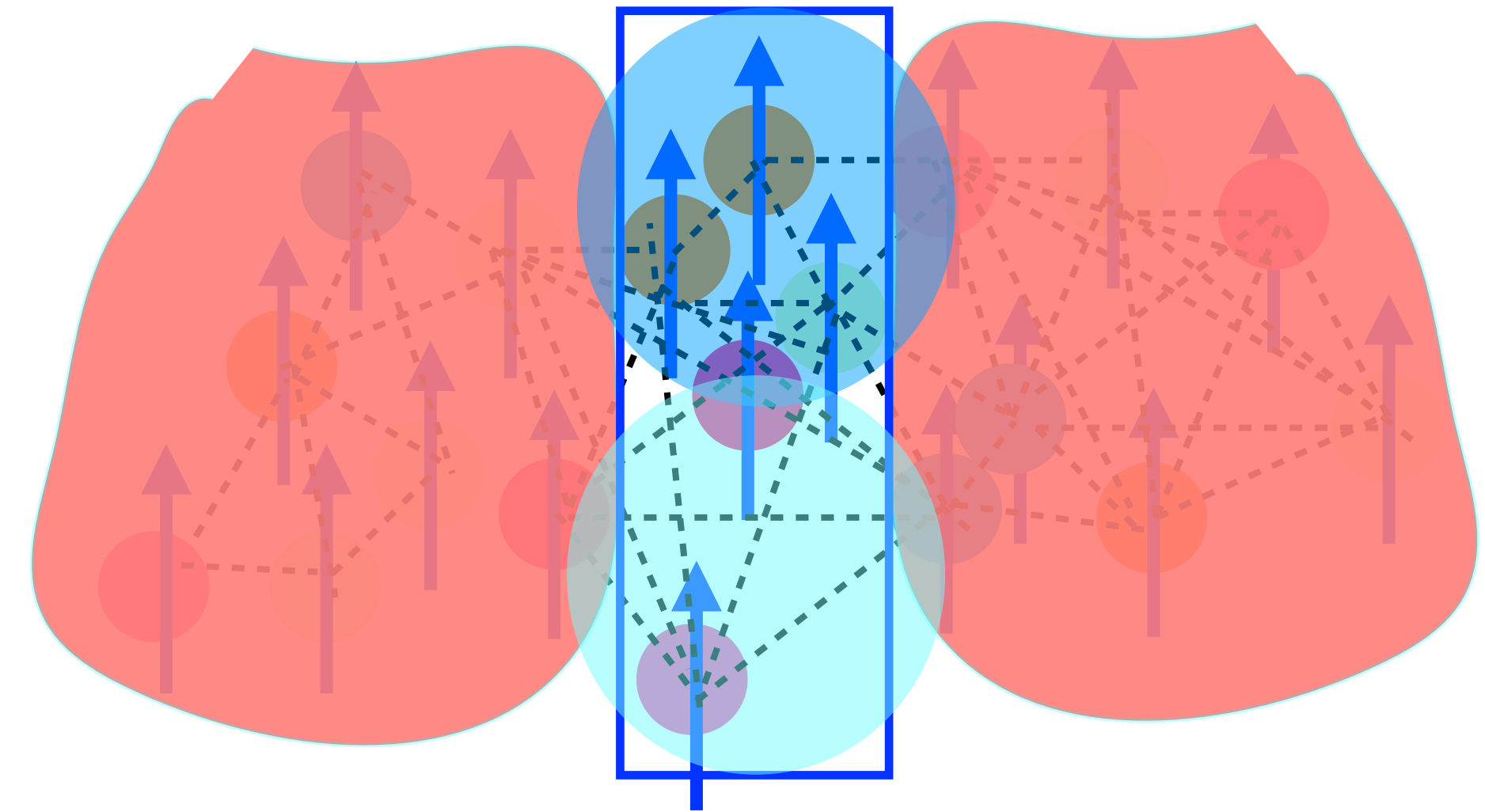
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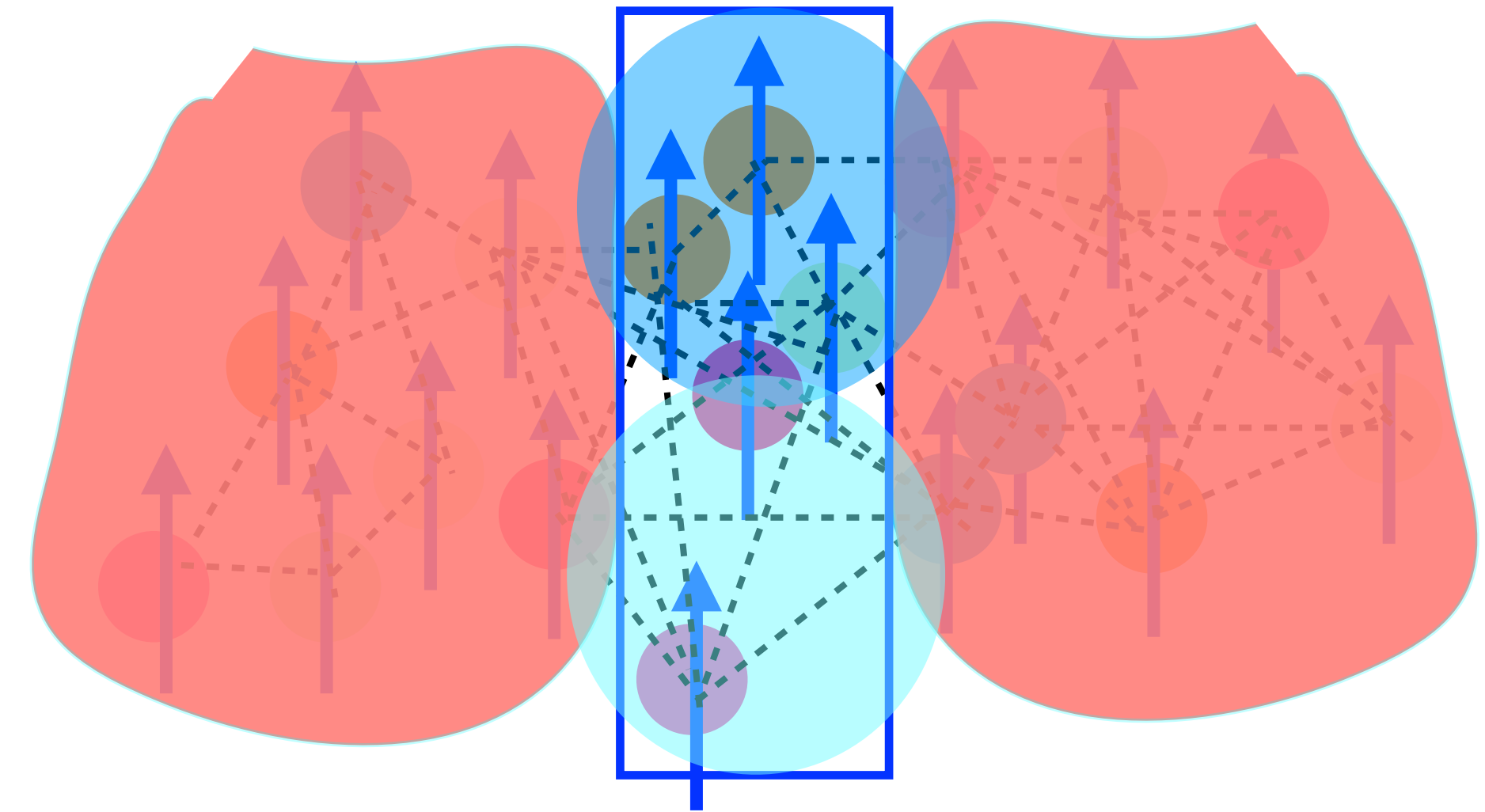
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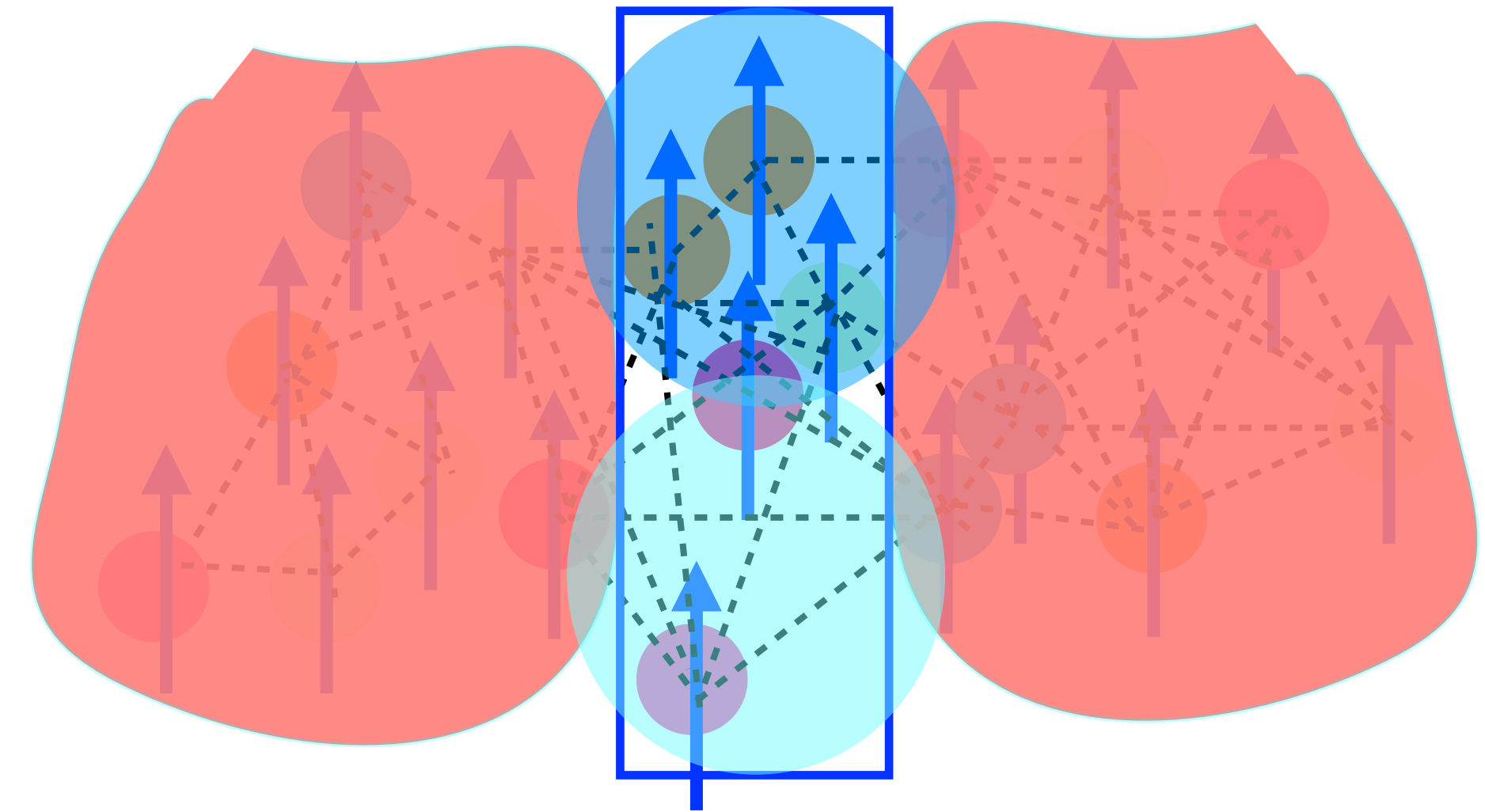
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The “process tensor” (Pollack et al, 1512.00589) does some of this;
A. Leroose, M. Sonner, D. Abanin some as well

First ingredient: Open dynamics, but not a master equation

Instead of generalizing the Hamiltonian:

$$\frac{d}{dt}(\text{system}) = (\text{Hamiltonian of the system}) \\ + (\text{losses to/gains from environment})$$

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$$\rho(t) = U(t)\rho(0)U^\dagger(t)$$

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Dynamical maps/propagators are the open-systems generalization:

$$\Lambda(t_i, t_j) : \rho(t_i) \rightarrow \rho(t_j)$$

See Yukinao's talk for a nice introduction

More on maps/propagators

- You can derive them from unitary dynamics

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- Or, you can parameterize them based on symmetry

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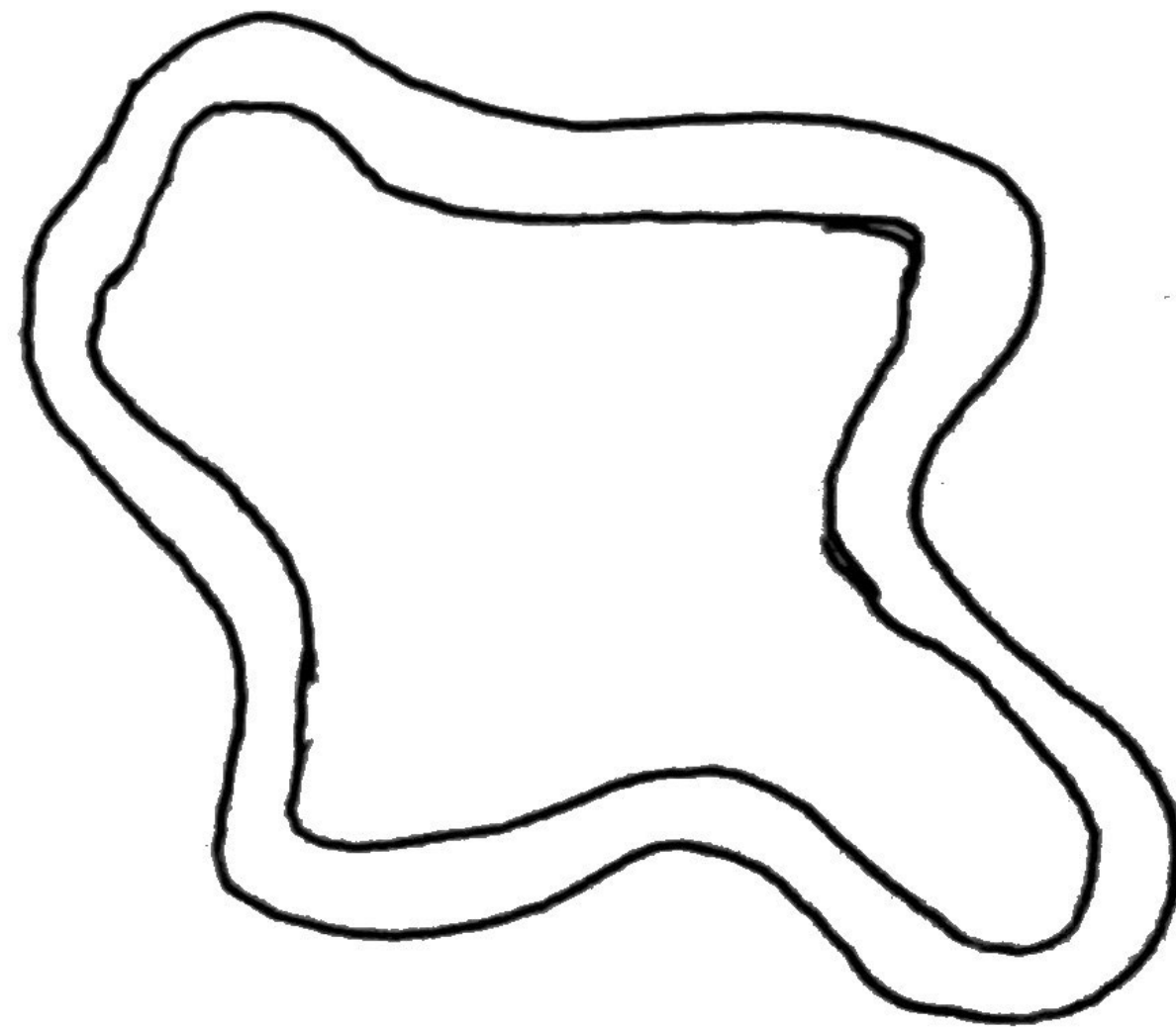
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More on maps/propagators

- You can derive them from unitary dynamics
- Or, you can parameterize them based on symmetry
- No need for them to be equivalent to a simple master equation
- Domain of applicability
 - Determined by **evolving quantum correlations** between system and environment
 - More general than universal quantum “channels” (can be applied to any sub-system)

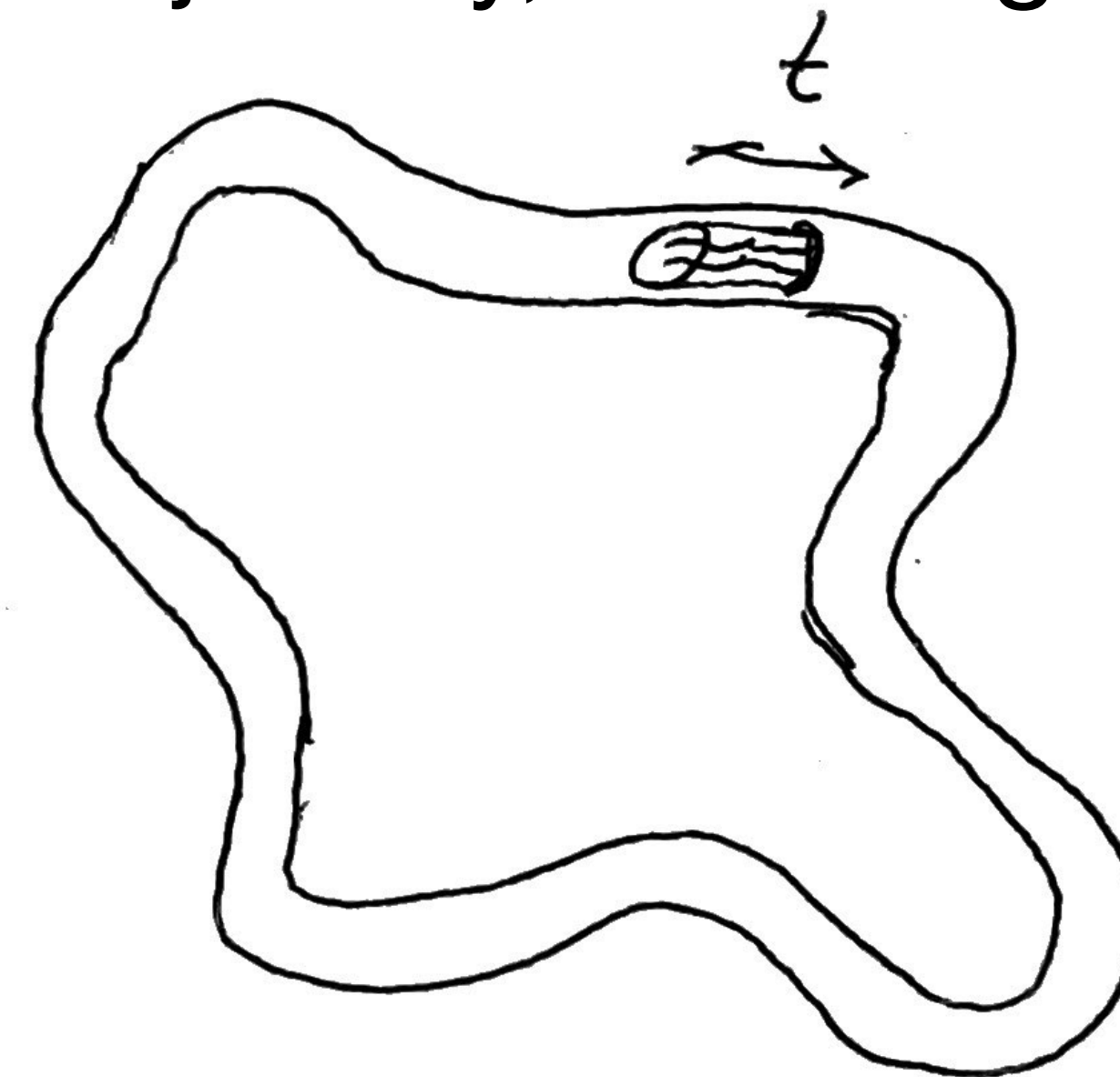
Why propagators? No privileged initial time

A trajectory in state space of a high dimensional system



An observer defines

- Subsystem, and
- Parameterization along trajectory, and “origin”



Partial quantum observations

Description of the state:

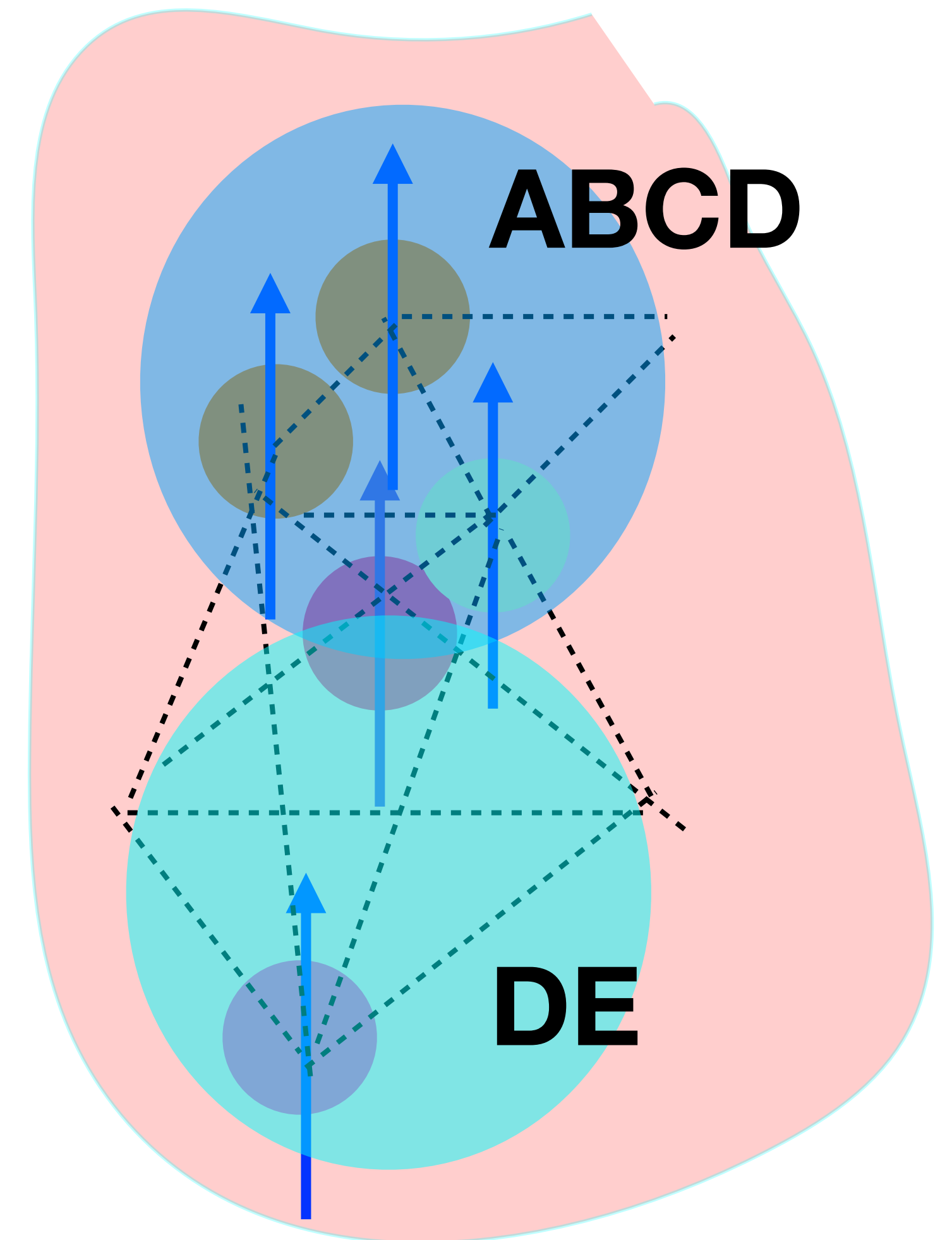
$$\rho^{\bullet}(t_1), \rho^{\bullet}(t_2), \dots$$

$$\rho^{\circ}(t_2), \rho^{\circ}(t_3), \dots$$

Description of the dynamics:

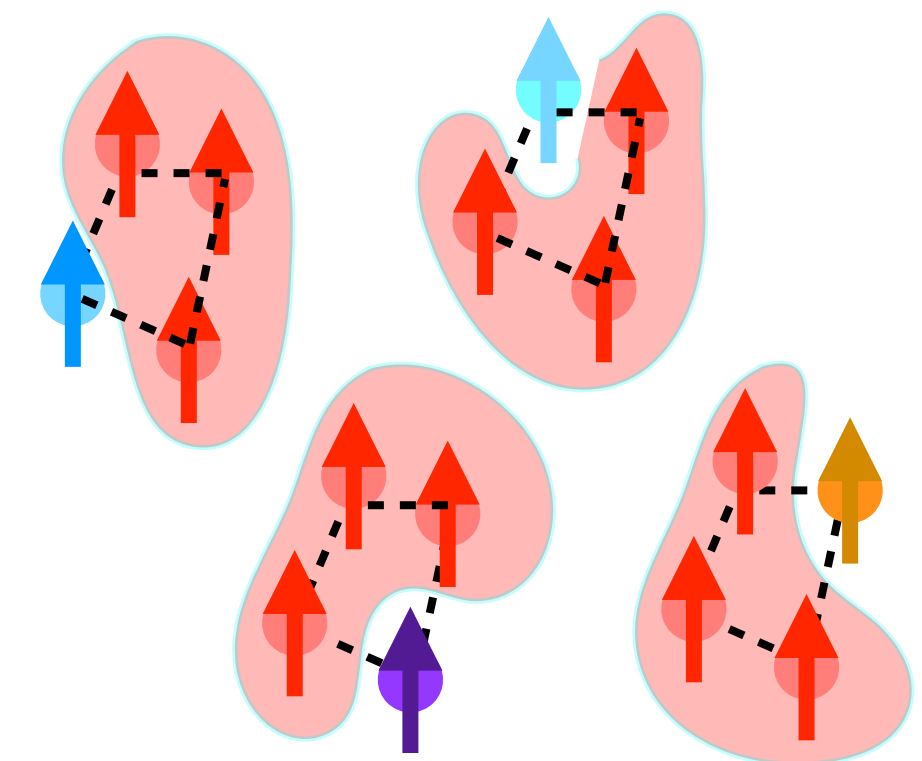
$$\Lambda^{\bullet}(t_2, t_1), \dots$$

$$\Lambda^{\circ}(t_3, t_2), \dots$$



No subsystem is preferred

So, to understand what observers can see,
we need the **ensemble** of open-system data



$$\{\rho^{\bullet}(t_1), \rho^{\bullet}(t_2), \rho^{\bullet}(t_2), \rho^{\bullet}(t_3), \rho^{\bullet}(t_2), \rho^{\bullet}(t_3), \dots\}$$

$$\{\Lambda^{\bullet}(t_2, t_1), \dots \Lambda^{\bullet}(t_3, t_2), \dots \Lambda^{\bullet}(t_3, t_2), \dots\}$$

What do closed systems look like as ensembles of smaller, open systems?

Some examples:

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Some examples:

1. Exact expressions for closed, Hamiltonian systems

T. Chin, Shandera 2605.15036; Prudhoe, Akhouri, Chin, Shandera, 2404.15223 (*OSID*)

2. Derive them from unitary quantum circuits, engineered to give “interesting” dynamics

Akhouri, Shandera, Henry 2505.00116 (*PRE*); Akhouri, Huang, Rose, Shandera 2603.18217

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$$[\hat{H}_0, \hat{U}] = 0$$

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And, “seed” state is a tensor product of factors like this:

$$\rho^{(i)} = (1 - p_i)|0\rangle\langle 0| + p_i|1\rangle\langle 1|$$

This means all single-qubit maps are simple

$$\Lambda(t, 0) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \lambda_1(t) & -\lambda_1(t) & 0 \\ 0 & \lambda_1(t) & \lambda_1(t) & 0 \\ \tau_3(t) & 0 & 0 & \lambda_3(t) \end{pmatrix}$$

$$\rho = \frac{1}{2}(\mathbb{I} + a_x\sigma_x + a_y\sigma_y + a_z\sigma_z) \rightarrow \frac{1}{2} \begin{pmatrix} 1 & & \\ a_x & & \\ & a_y & \\ & & a_z \end{pmatrix}$$

(These are the well-studied ‘phase covariant’ class; unitary part suppressed)

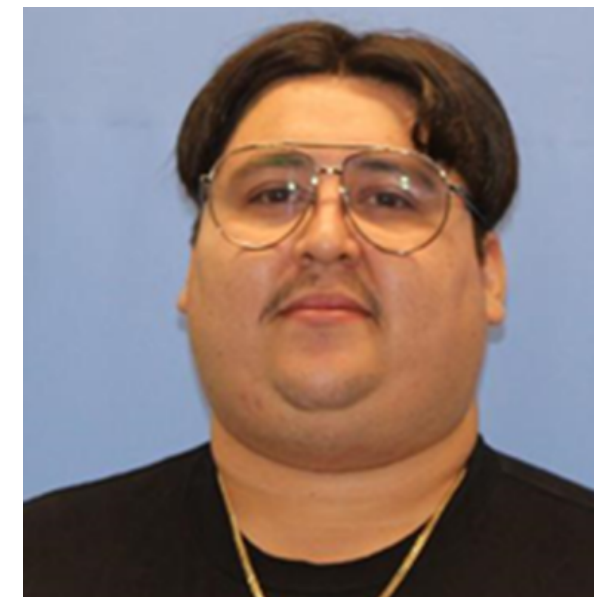
The team



Stefan Eccles



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Elliott Rose
PSU undergrad -> UMD



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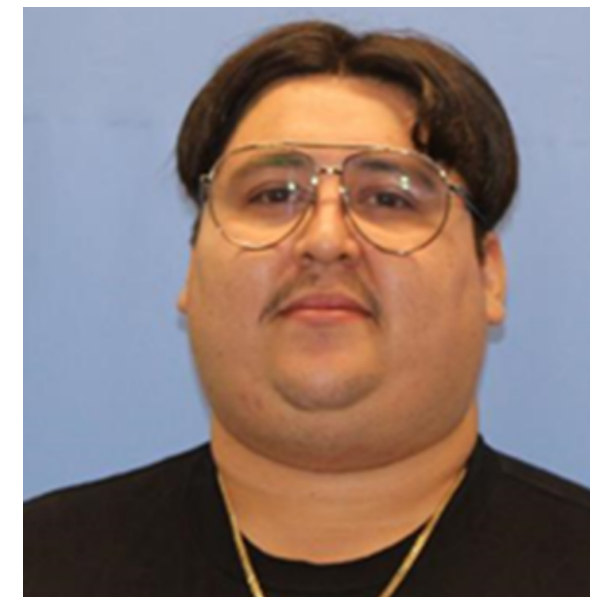
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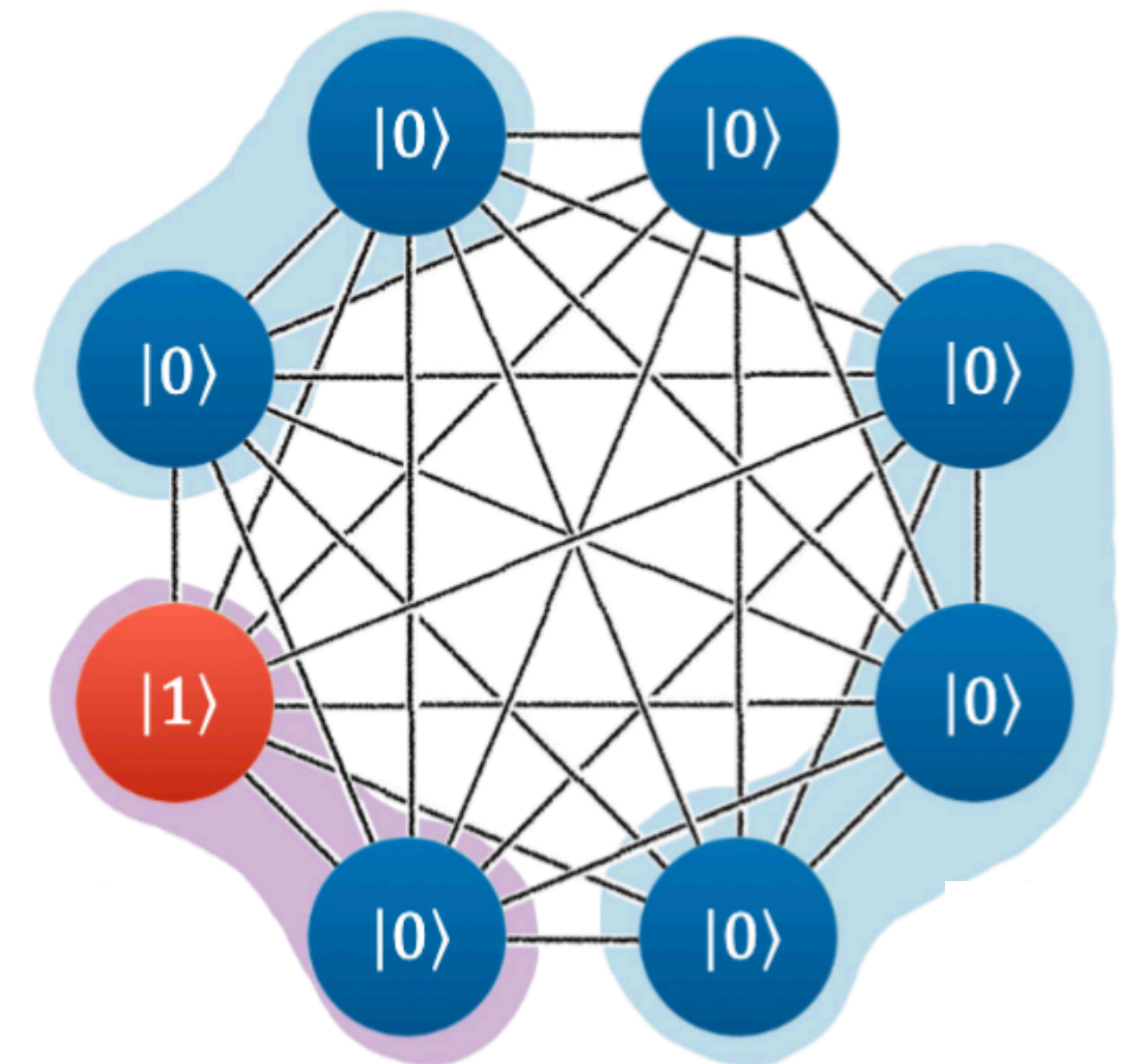
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Example 1: exact expressions for Hamiltonian systems

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- All-to-all interactions, coupling constant J
- Simple “seed” state $|\psi_s\rangle = |10000\dots\rangle$
- Two classes of open dynamics:

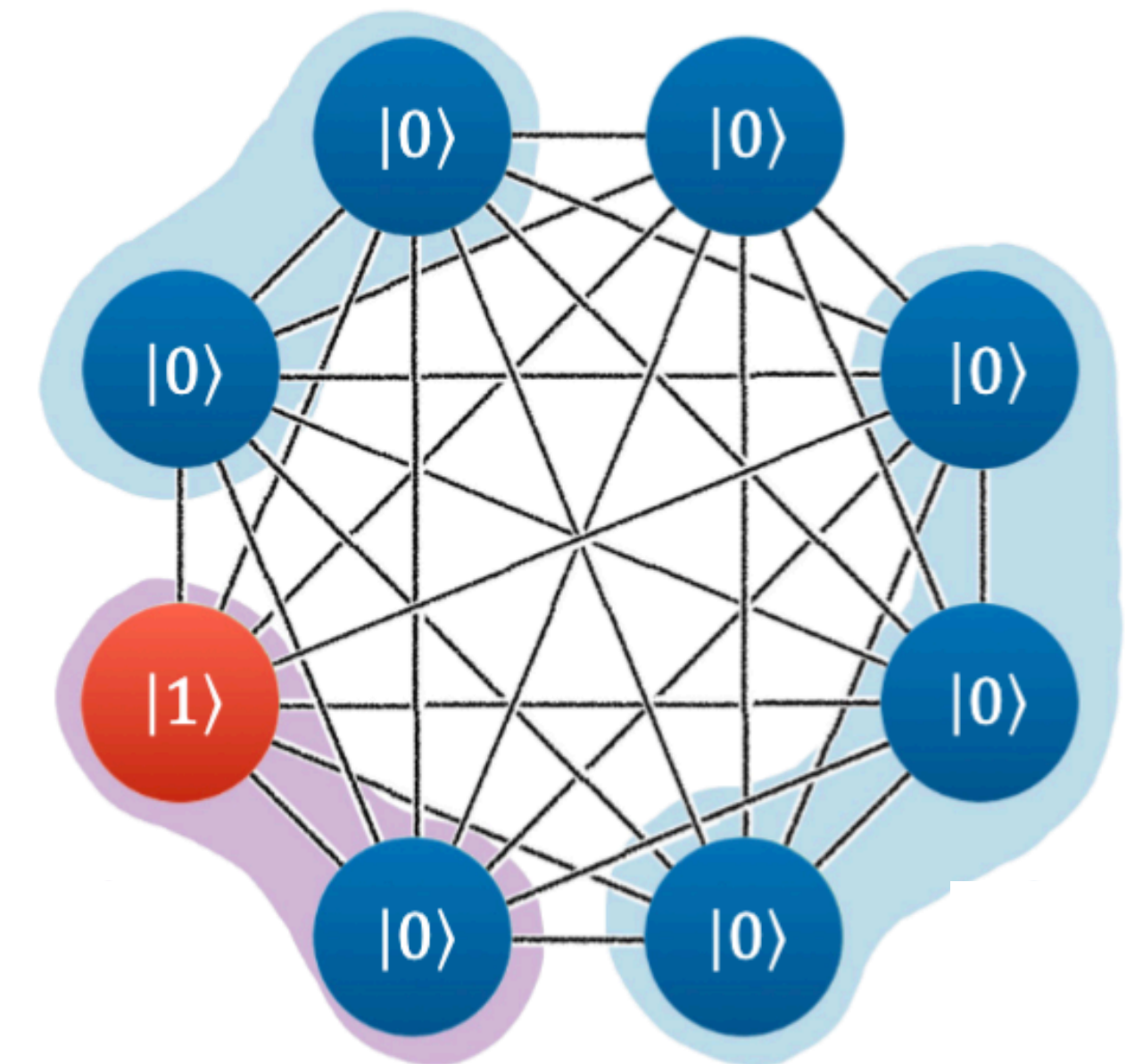
$$\{\Lambda^{(1,K,N)}(t_2, t_1), \Lambda^{(0,K,N)}(t_2, t_1)\}$$



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$$\hat{H} = \frac{1}{2} \sum_{i \neq j} \left[J(\hat{\sigma}_i^x \hat{\sigma}_j^x + \hat{\sigma}_i^y \hat{\sigma}_j^y) + J_z \hat{\sigma}_i^z \hat{\sigma}_j^z \right] + \sum_i h \hat{\sigma}_i^z$$

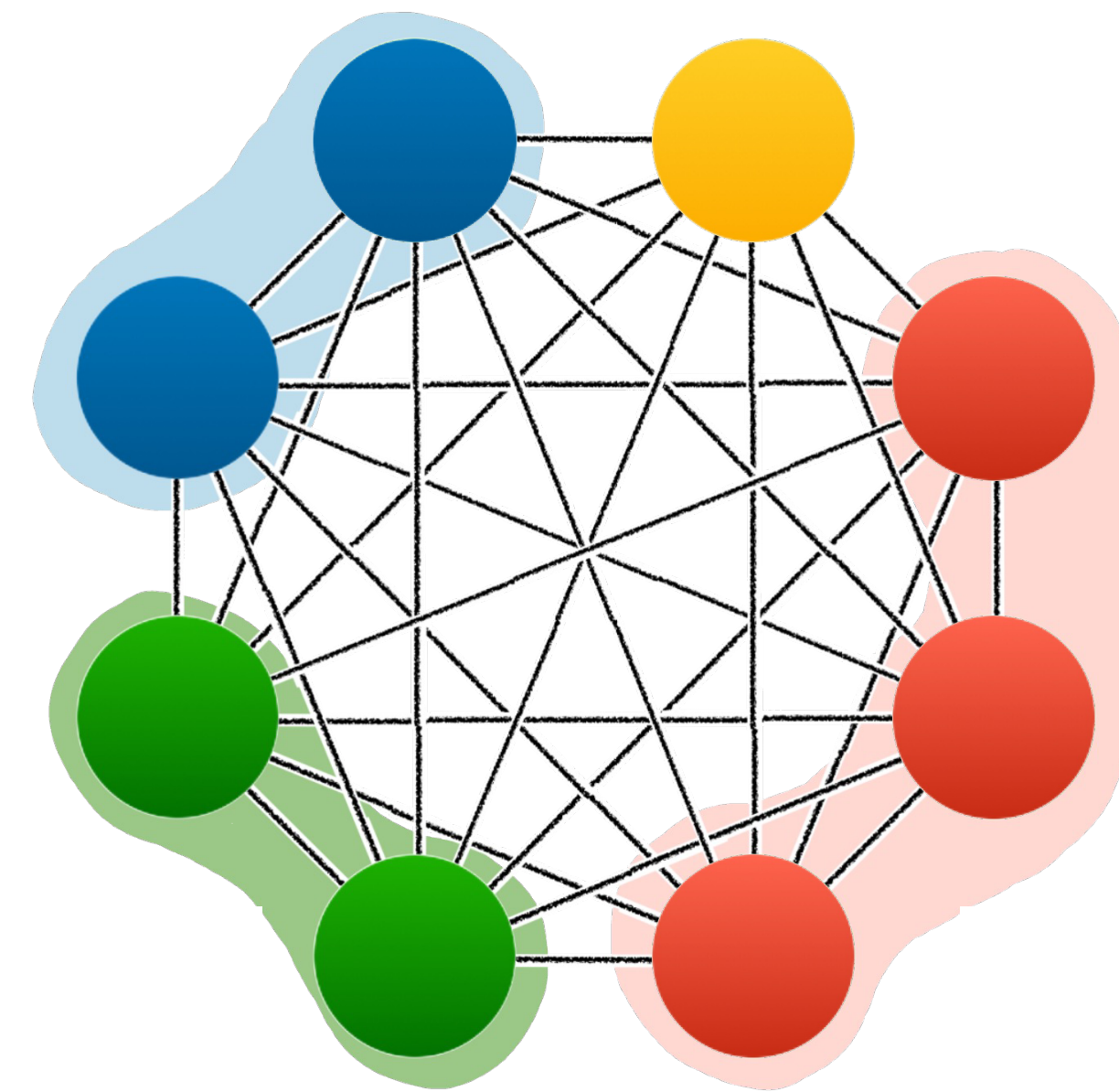
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Can find analytic, exact open system dynamics for any subsystem, between any two times

$$\{\Lambda^{(K,N)}(t_2, t_1)\}$$

N qubits in the full system

K qubits in the subsystem



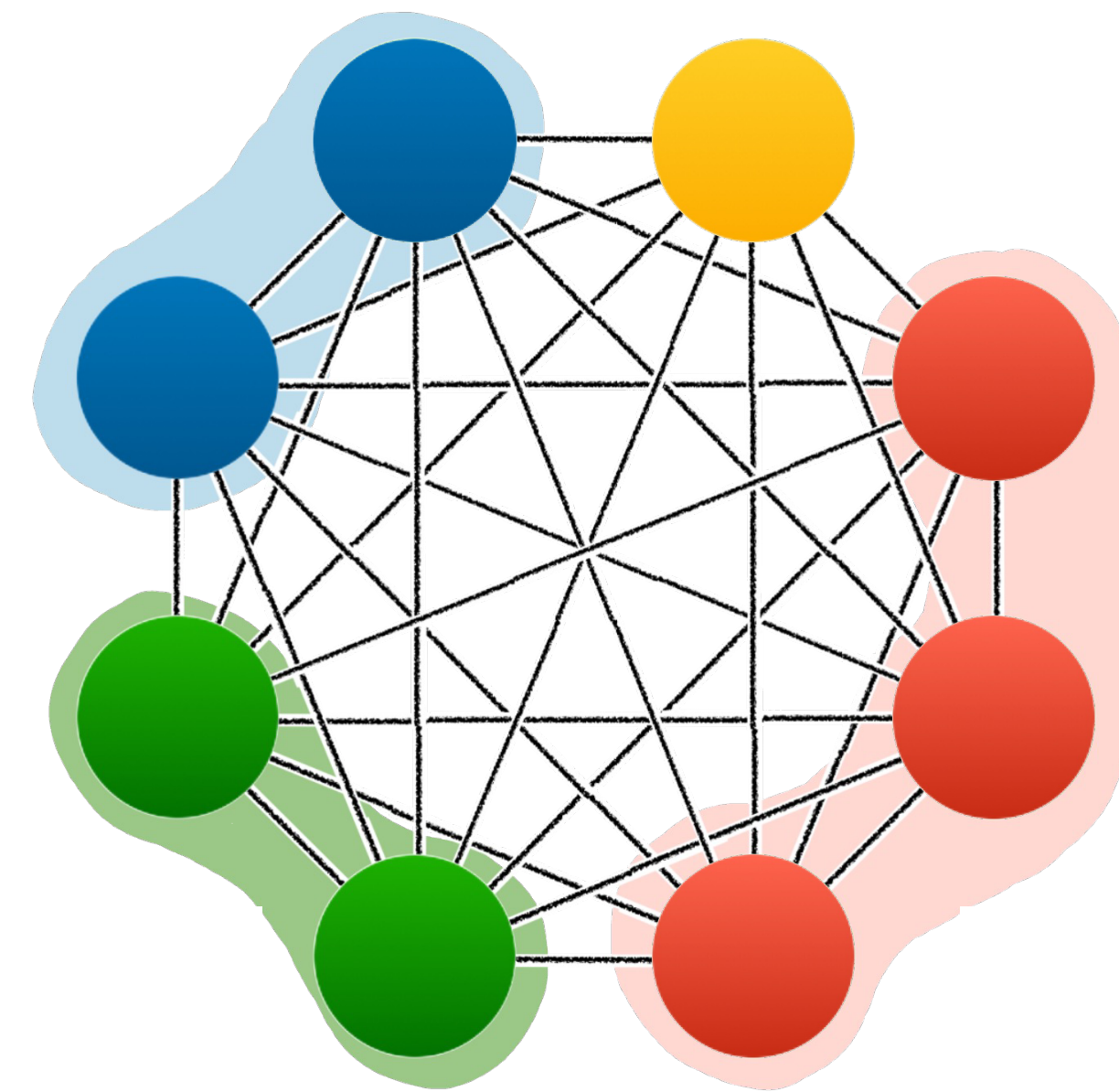
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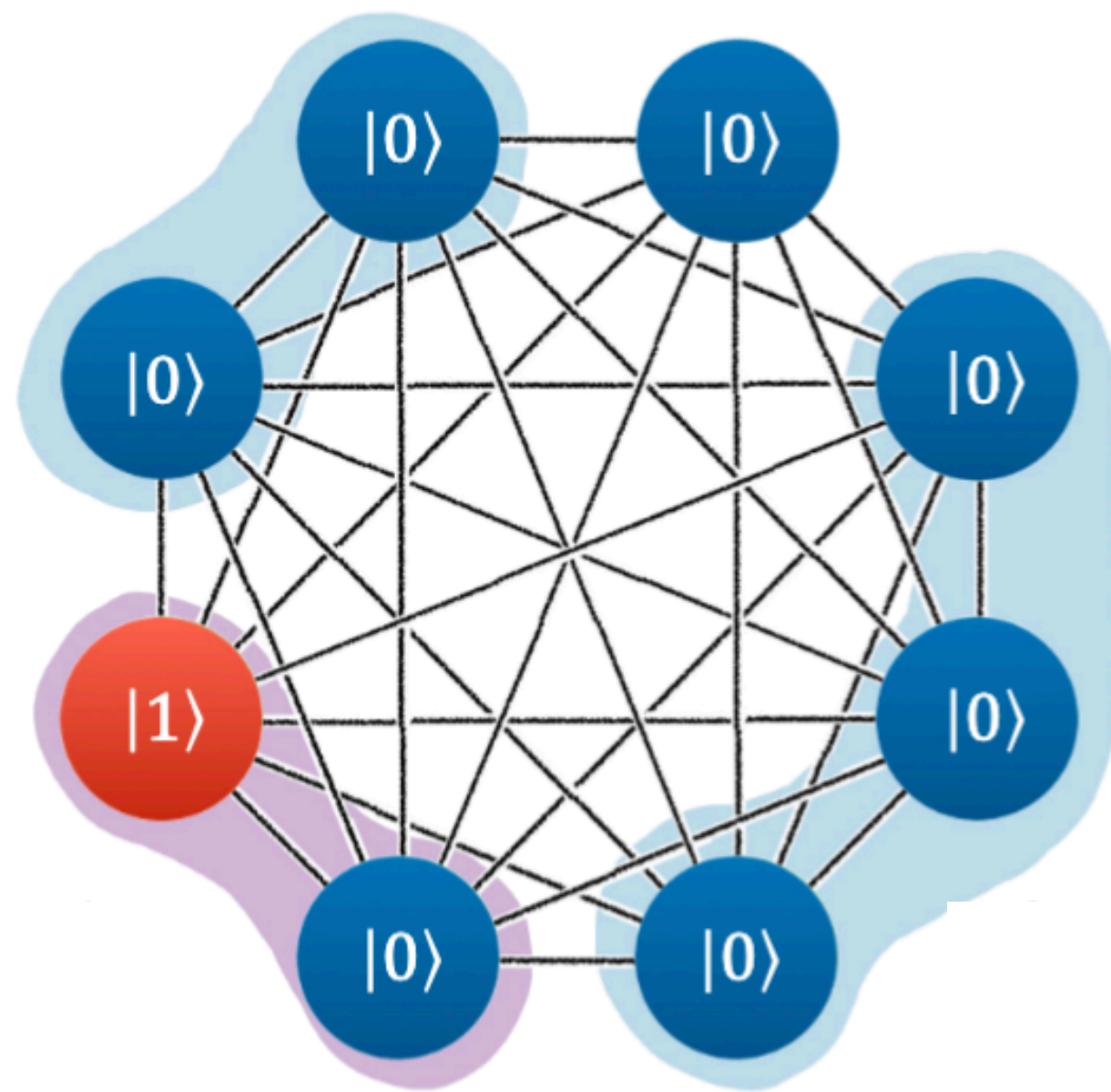
N qubits in the full system

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Tractable thanks to symmetry,
choice of state

Ensemble questions



Can you pick up a state transformation for one qubit in this network and act with it on another?

Channels can always be applied anywhere

What consistency conditions exist for ensembles of propagators from closed dynamics?

A note about propagators:

Often, for a composite system, we enforce CP

At $t = 0$, require are no quantum correlations between the observed subsystem and the unobserved part

Most commonly:

$$\rho(t = 0) = \rho_S \otimes \rho_{\bar{S}}$$

Sufficient, but not necessary condition

e.g., Shabani, Lidar (2016 erratum to 0808.0175) Modi et al 1203.5209; Jagadish, Srikanth, Petruccione 2012.12292

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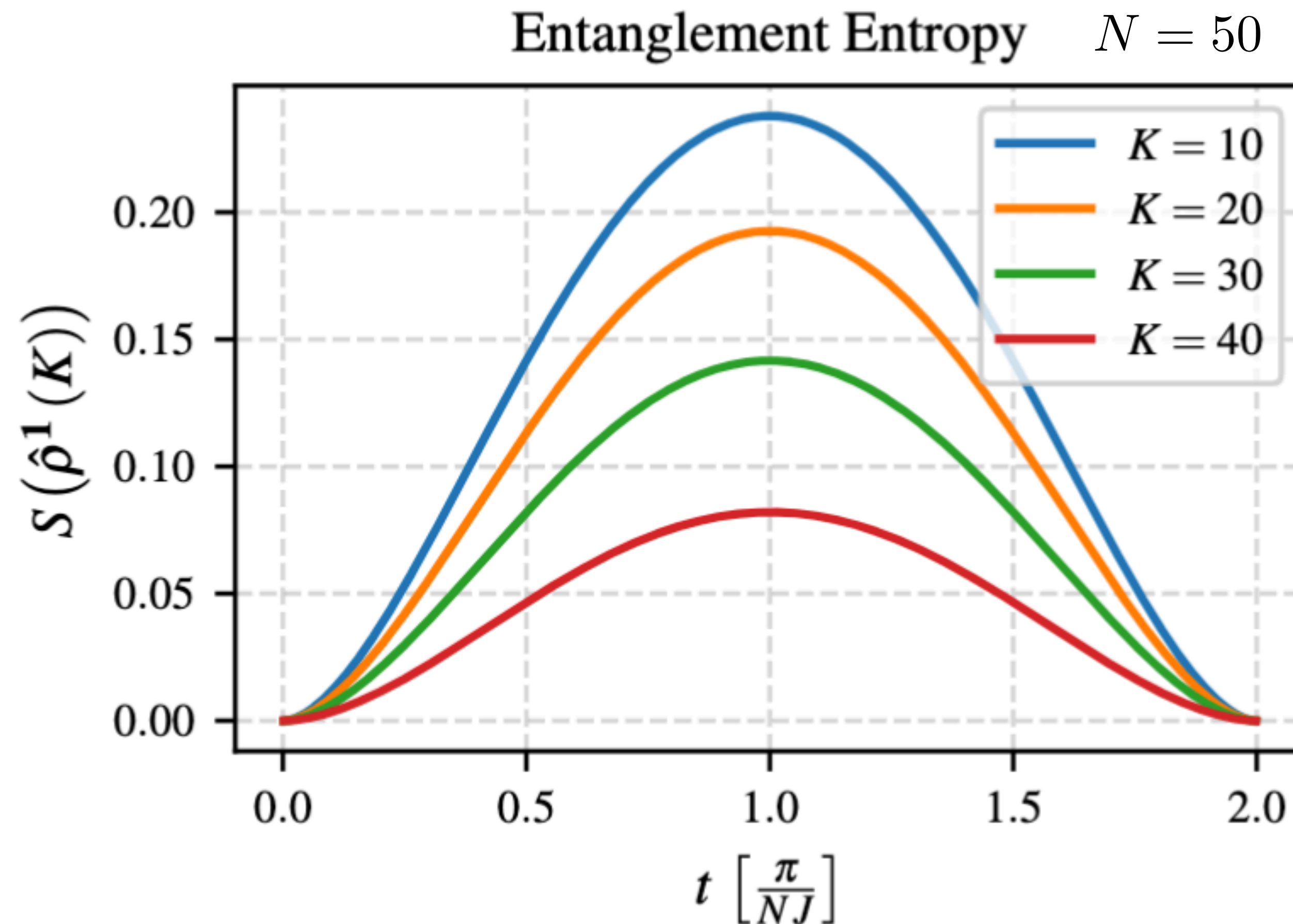
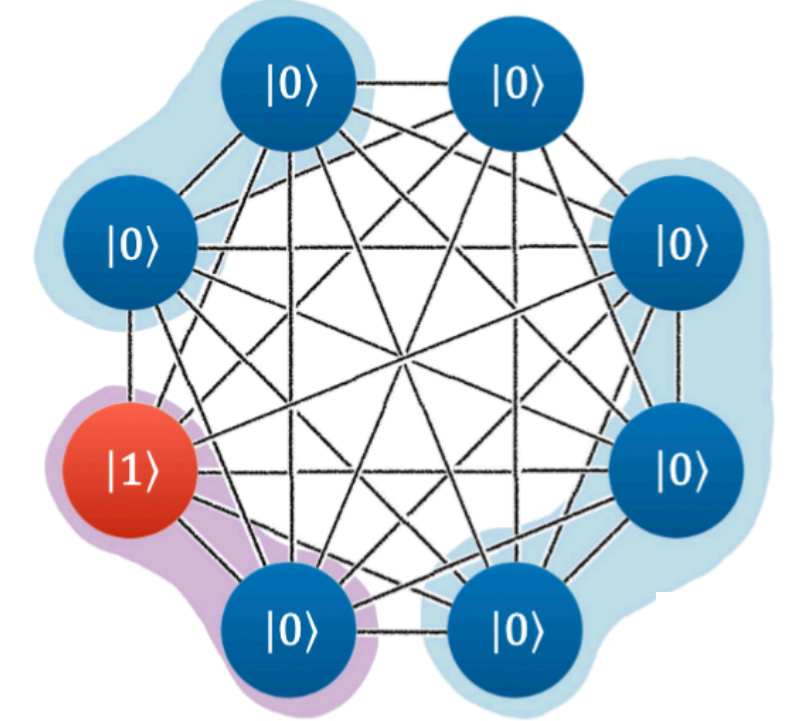
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But,

- Generic subsystems in a many-body system are quantum-correlated at most times Sufficient, but not necessary condition
- It's known that quantum correlated initial states can still give (C)P maps, depending on what unitary is applied to system + environment

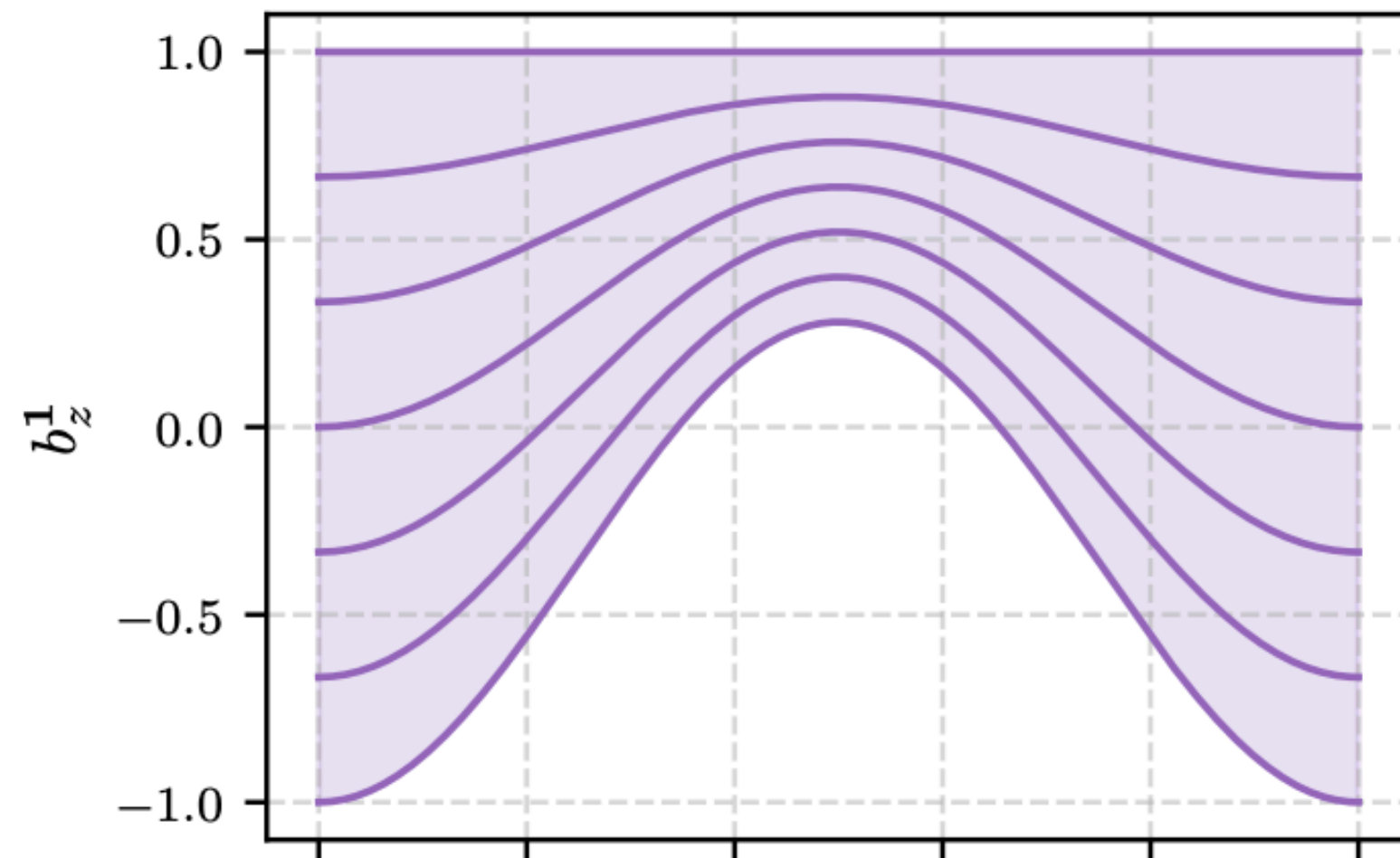
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In this case: at nearly all times, any subsystem is entangled with the complement

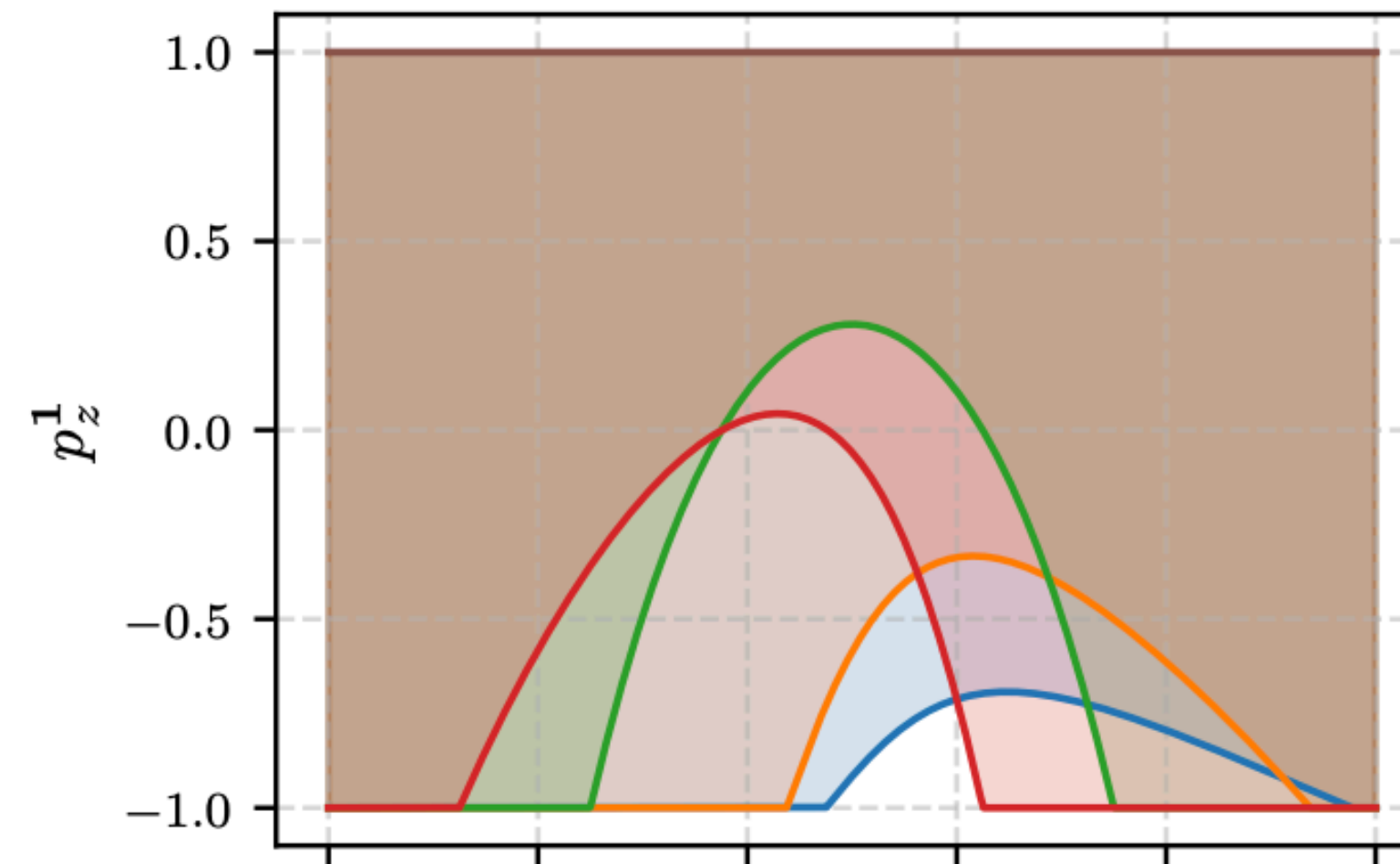


Single-qubit domain of positivity

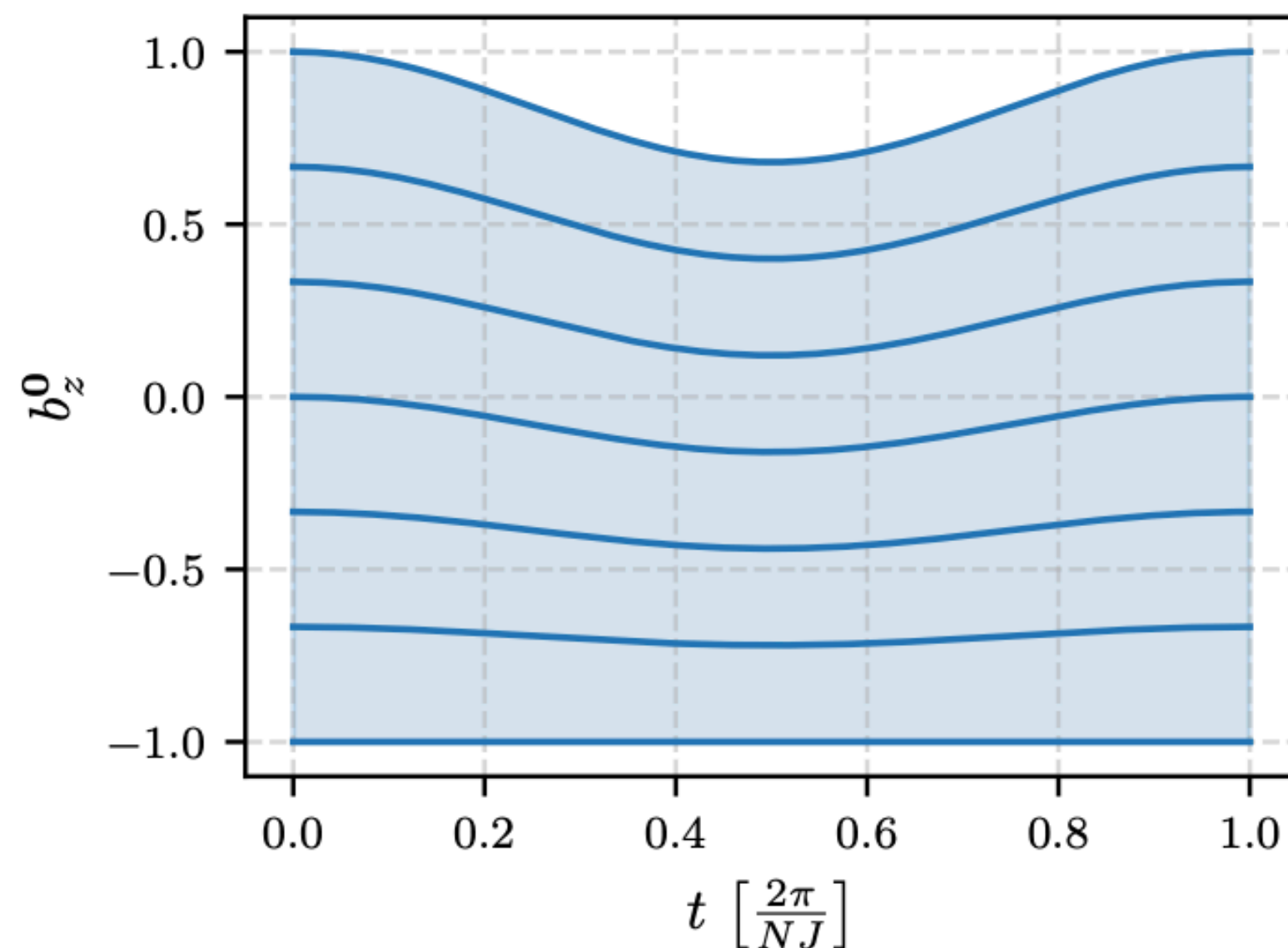
$\Lambda^1(0, t)$ on Bloch ball



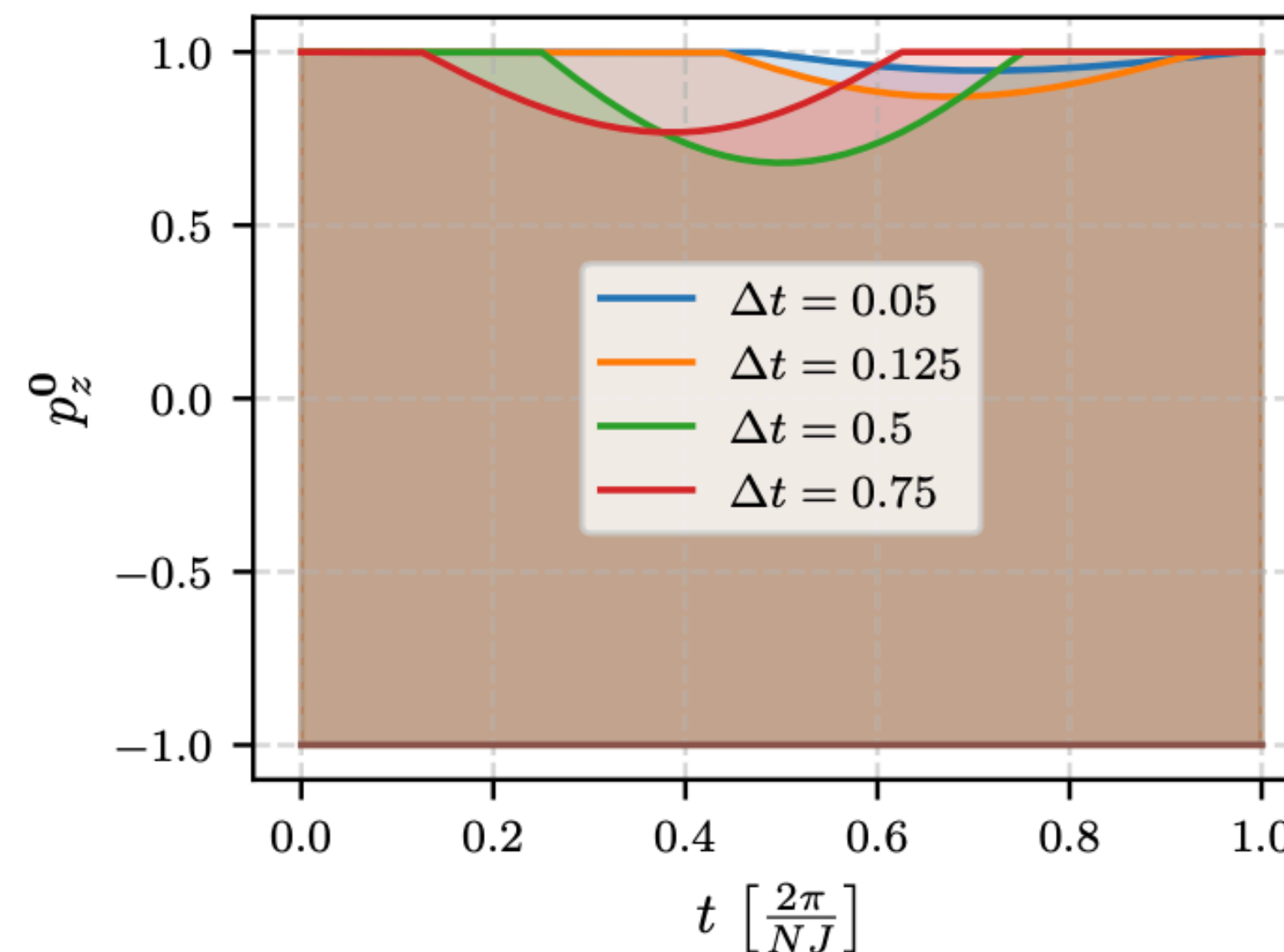
Domain of positivity of $\Lambda^1(t, t + \Delta t)$



$\Lambda^0(0, t)$ on Bloch ball



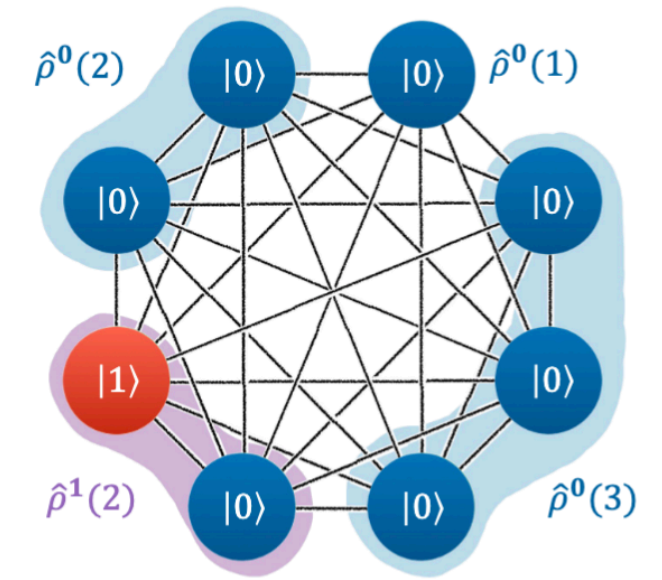
Domain of positivity of $\Lambda^0(t, t + \Delta t)$



- Propagator maps over contractive intervals are positive, no matter t_1

- States in the domain of positivity of both classes are never reached by dynamics

Ensemble summary



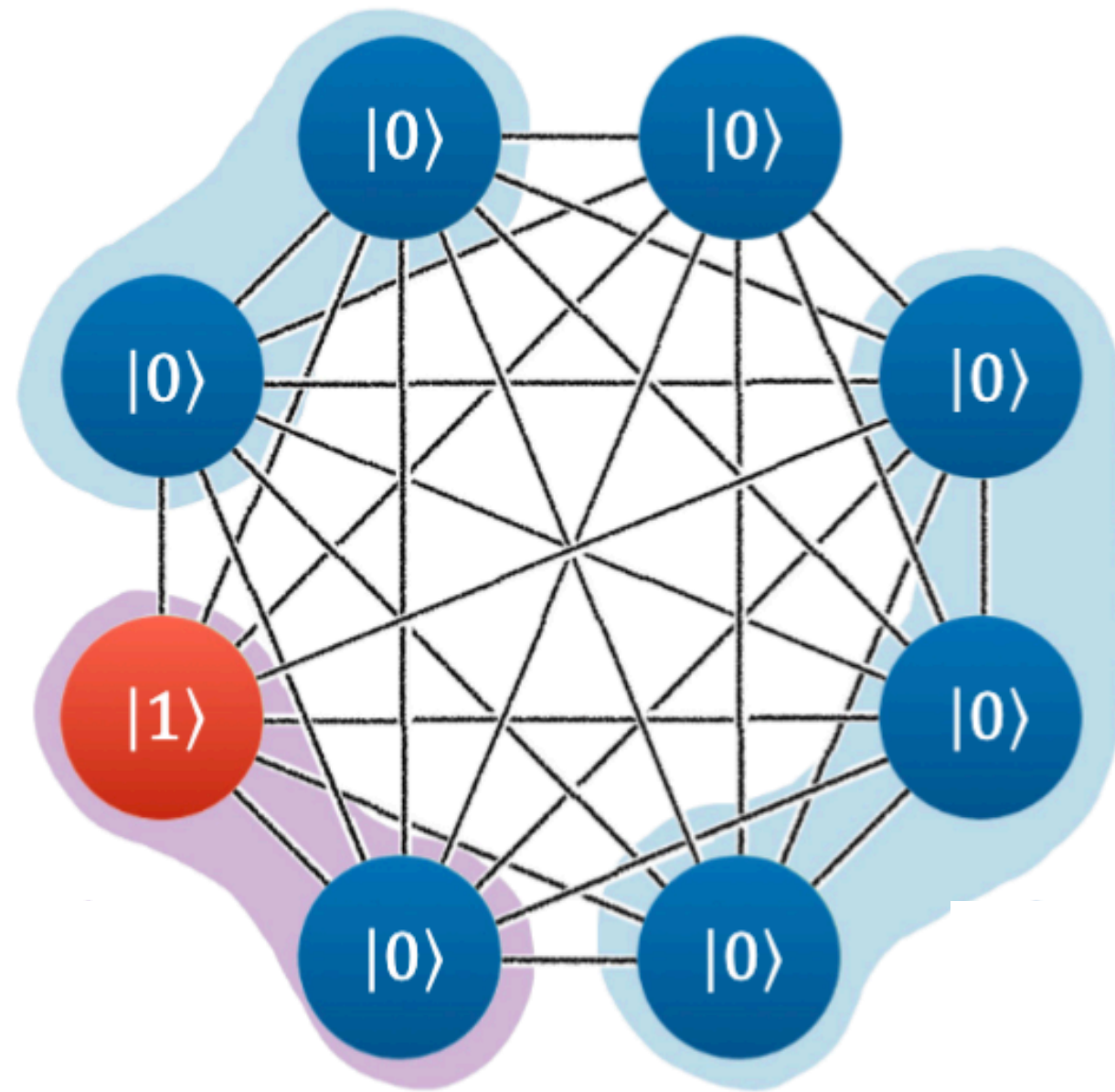
Over some time intervals, every propagator, for any subsystem, of any size, is non-positive and non-CP; over others, every map is CP

P and CP correspond to dynamics moving toward the (universal) fixed point of either class (initialized in 0 or initialized in 1)

For single-qubit propagators for qubits initialized in (1), the states of qubits initialized in 0(1) are, at any times, in the domain of positivity

The single-qubit states that are always in the domain of positivity of all propagators are never reached by the dynamics

Ensemble intuition



Can you pick up a state transformation for one qubit in this network and act with it on another?

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Caveats? Other examples?

The symmetry and initial state make this example special

Doing this for arbitrary Hamiltonians is hard

Condensed matter Hamiltonians are a special set

- time independent
- Lab/materials-oriented

Circuit models allow much more flexibility: broad exploration of dynamics

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CP ensembles from less symmetric cases: Prudhoe, Akhouri, Chin, Shandera, 2404.15223 (*OSID*)

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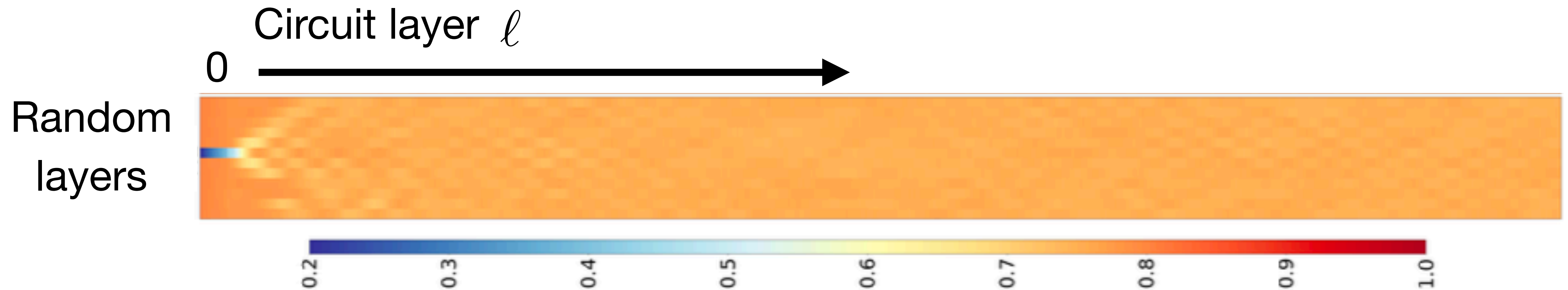
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Example 2: Generating “interesting” ensembles

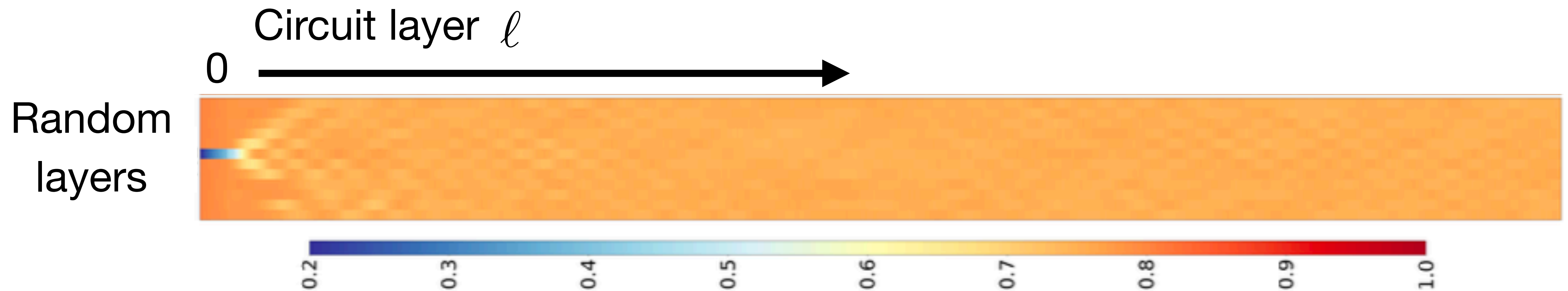
**The most interesting ensembles are the
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Each square is $\langle\langle\sigma_z^{(q)}(\ell)\rangle\rangle_{\text{ens.}}$.

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Compare:



Engineering interesting ensembles

Restrict via symmetry:

$$\hat{H}_0 = \sum_{i=1}^N \frac{1}{2} \left(\mathbb{I} - \hat{\sigma}_z^{(i)} \right)$$

$$[\hat{H}_0, \hat{U}] = 0, \quad [\hat{H}_0, \rho^{(i)}(0)] = 0$$

$$\rho(0)] = \rho^{(1)} \otimes \dots \otimes \rho^{(N)}$$

Engineering interesting ensembles

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Open dynamics are “phase-covariant”

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$$\rho(0) = \rho^{(1)} \otimes \dots \otimes \rho^{(N)}$$

Initial state defines homogeneous ensemble

$$\bar{\rho} = \frac{1}{2} \left(\mathbb{I} + \frac{M}{N} \right)$$

$$\bar{\rho}^{(N)} \text{ s.t. } \bar{\rho} = \text{Tr}_{\bar{q}_i} [\rho^{(N)}], \quad \forall i$$

Engineering interesting ensembles

Restrict via symmetry:

Open dynamics are “phase-covariant”

$$\hat{H}_0 = \sum_{i=1}^N \frac{1}{2} \left(\mathbb{I} - \hat{\sigma}_z^{(i)} \right)$$

$$[\hat{H}_0, \hat{U}] = 0, \quad [\hat{H}_0, \rho^{(i)}(0)] = 0$$

$$\rho(0) = \rho^{(1)} \otimes \dots \otimes \rho^{(N)}$$

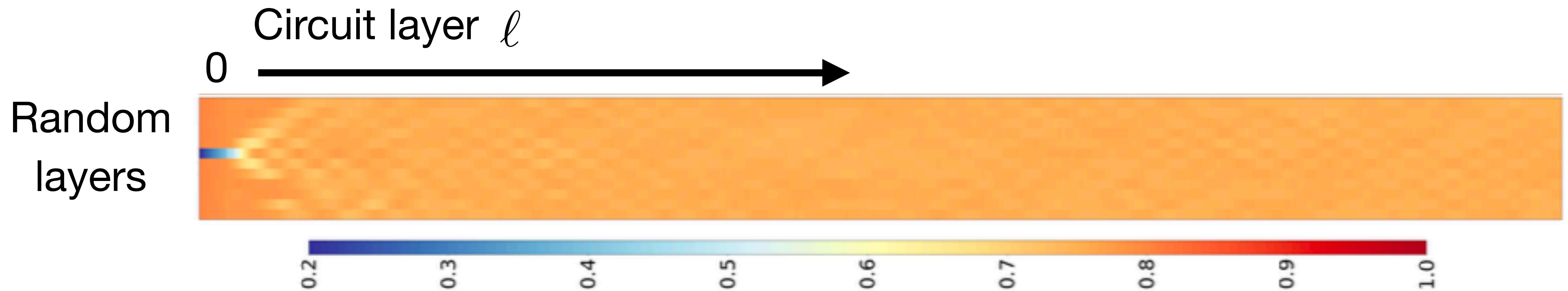
Initial state defines homogeneous ensemble

$$\bar{\rho} = \frac{1}{2} \left(\mathbb{I} + \frac{M}{N} \right)$$

$$\bar{\rho}^{(N)} \text{ s.t. } \bar{\rho} = \text{Tr}_{\bar{q}_i} [\rho^{(N)}], \quad \forall i$$

There is a CP qubit map with fixed point $\bar{\rho}$

A homogeneous ensemble *of local dynamics*



Each square is $\langle\langle\sigma_z^{(q)}(\ell)\rangle\rangle_{\text{ens.}}$.

After many layers, maps are nearly the ‘thermalizing’ map (Markovian dynamics)

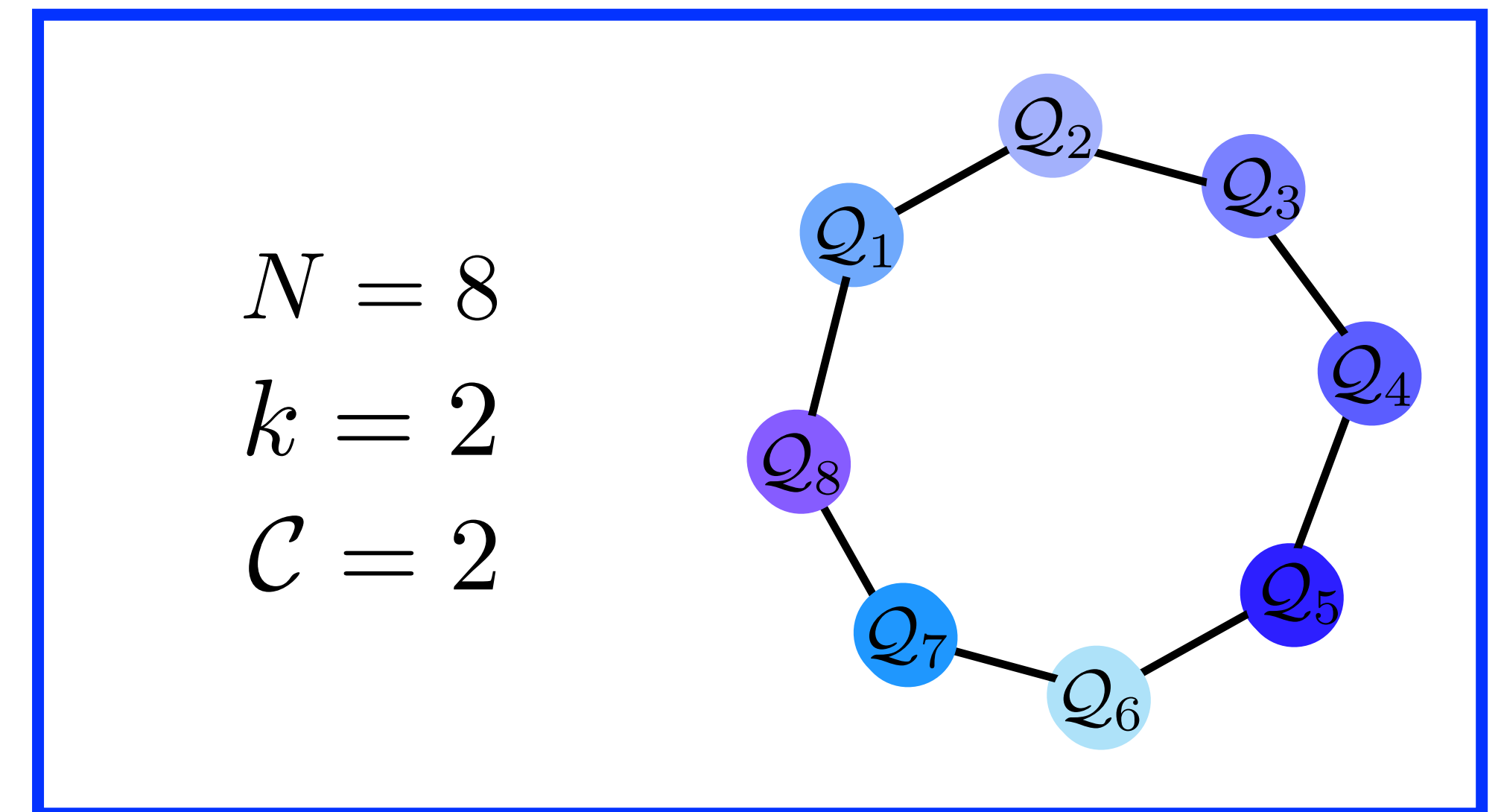
Engineering interesting ensembles

Dynamics:

Choose size of gate (k-local)

Choose physical connectivity $\mathcal{C} \geq k$

Define an algorithm to choose graph subdivisions, K_k , at each layer



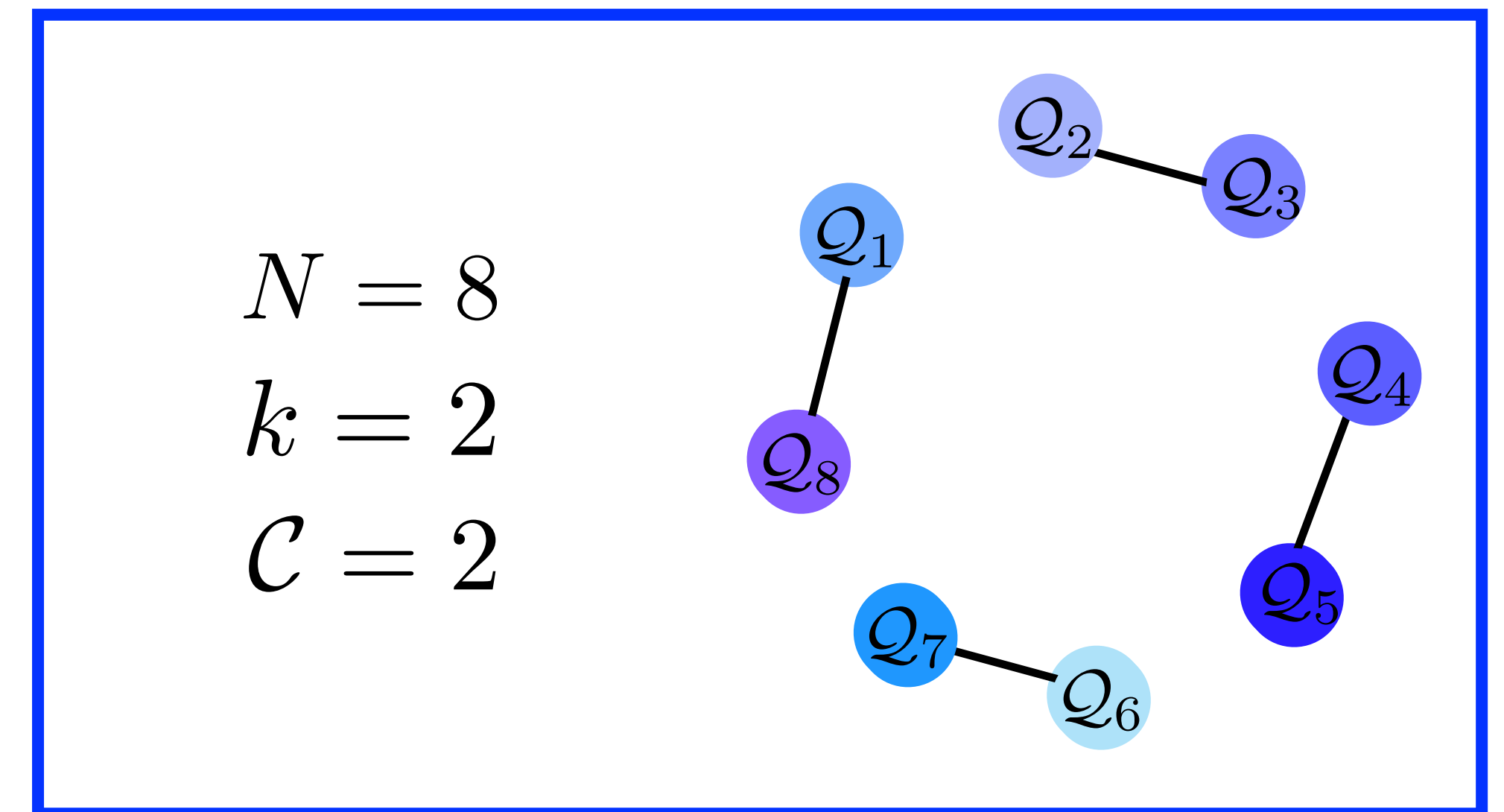
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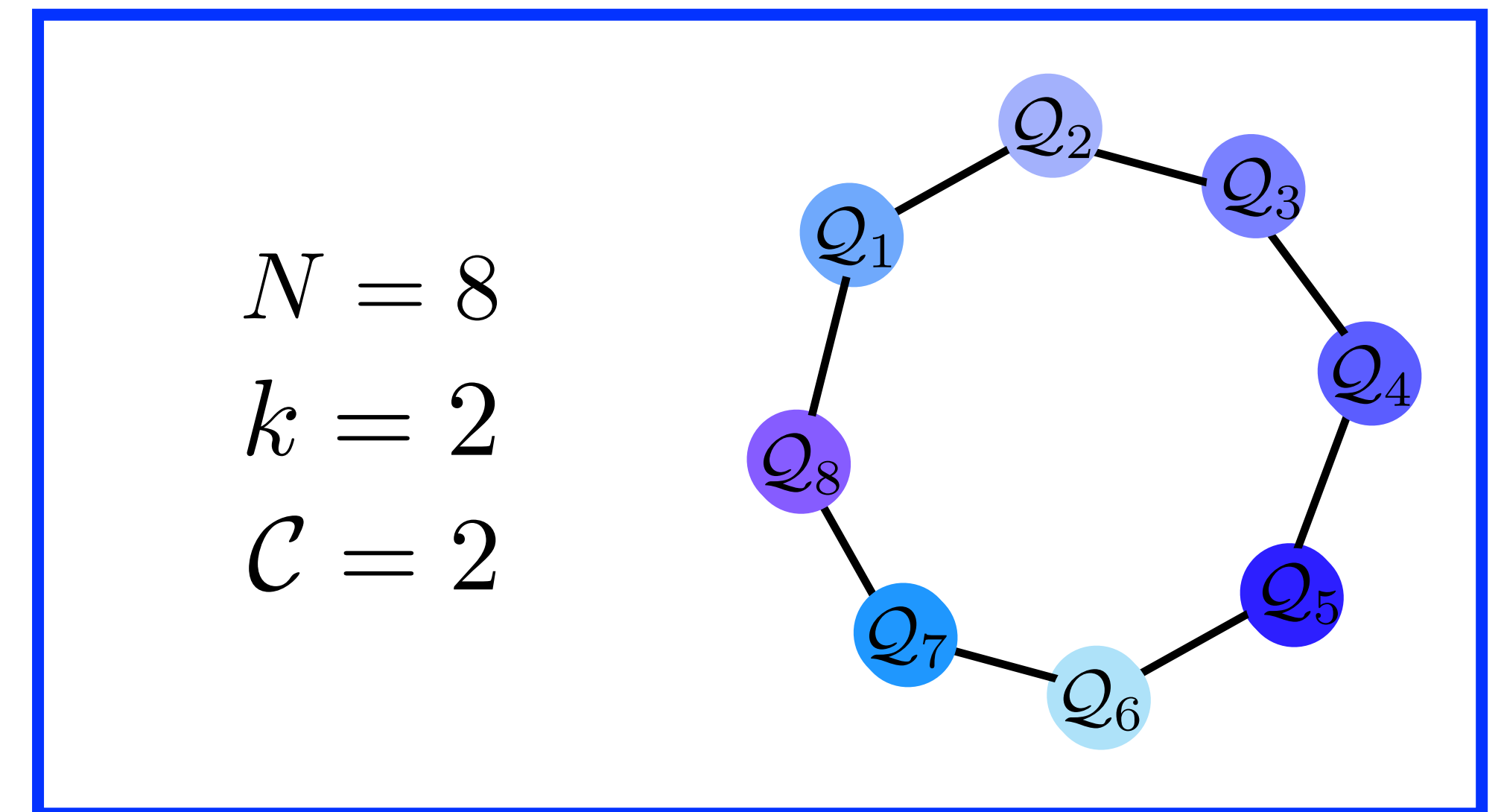
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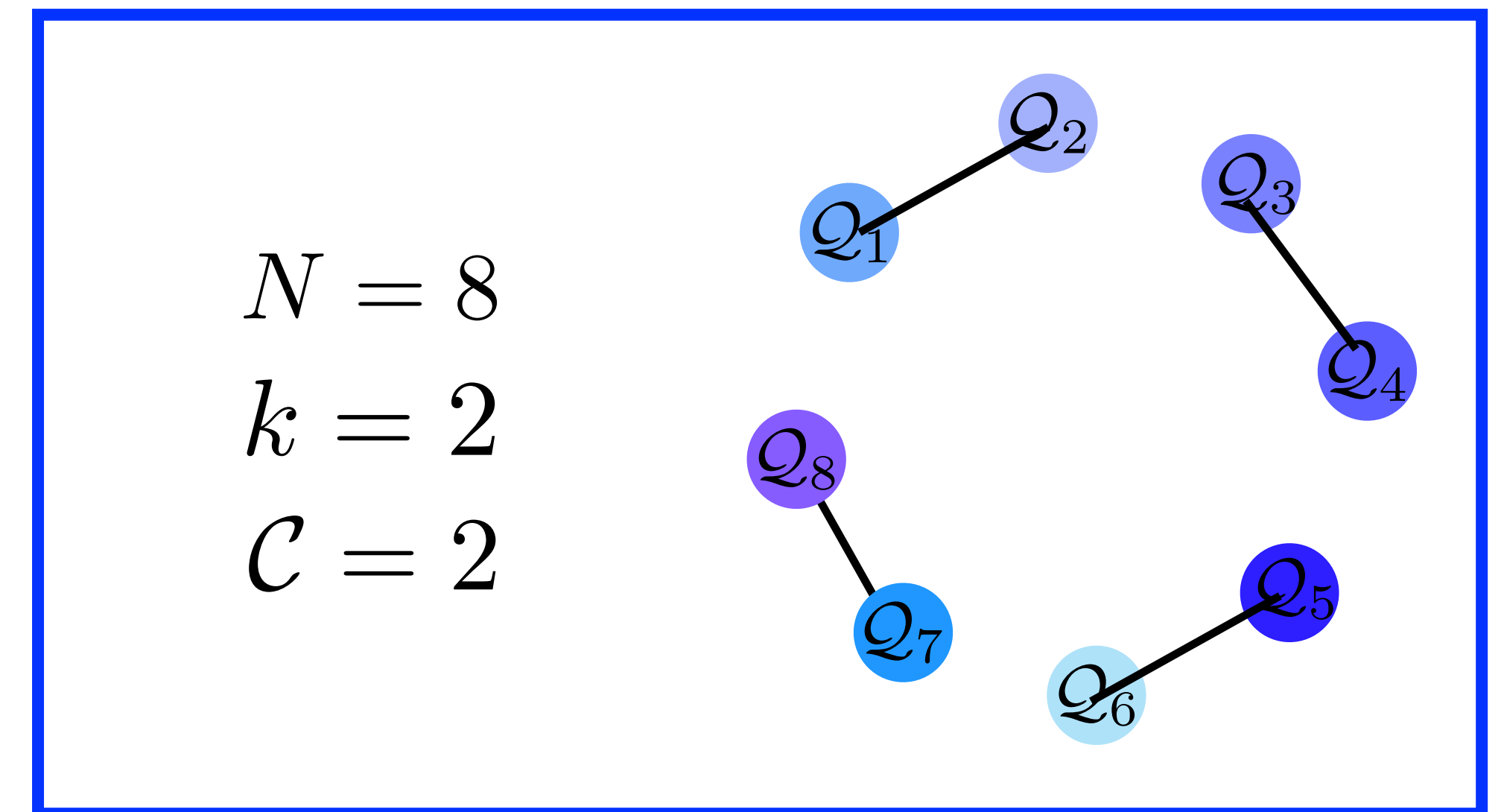
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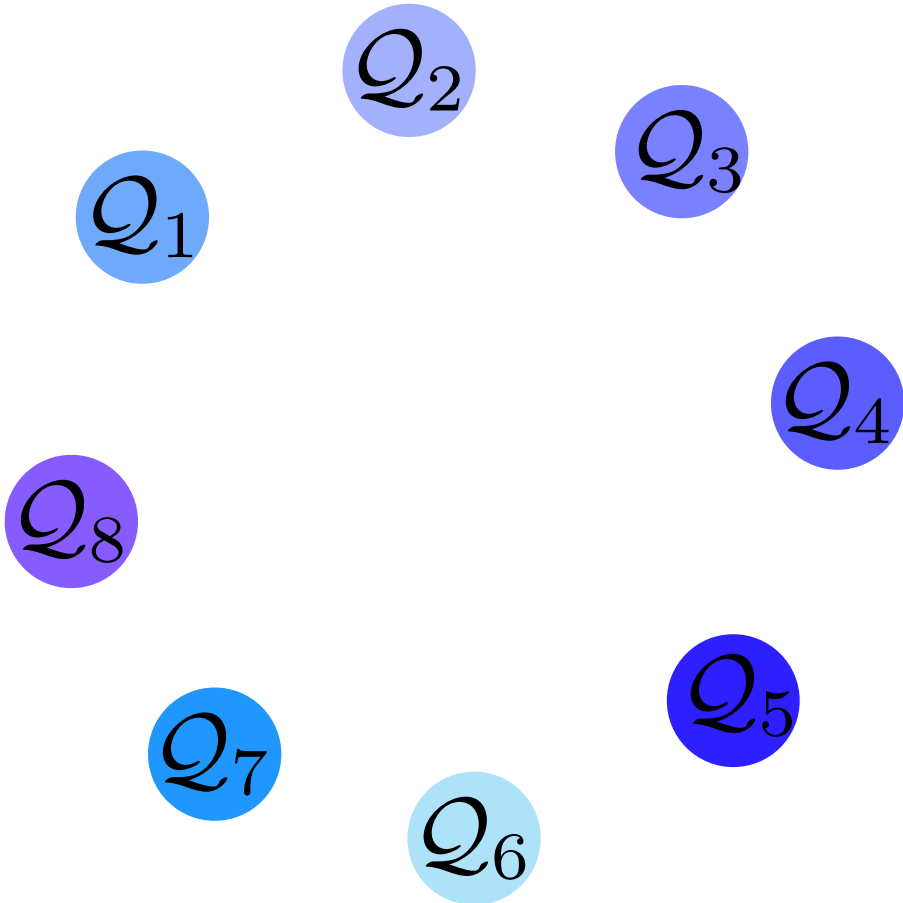


Engineering interesting ensembles

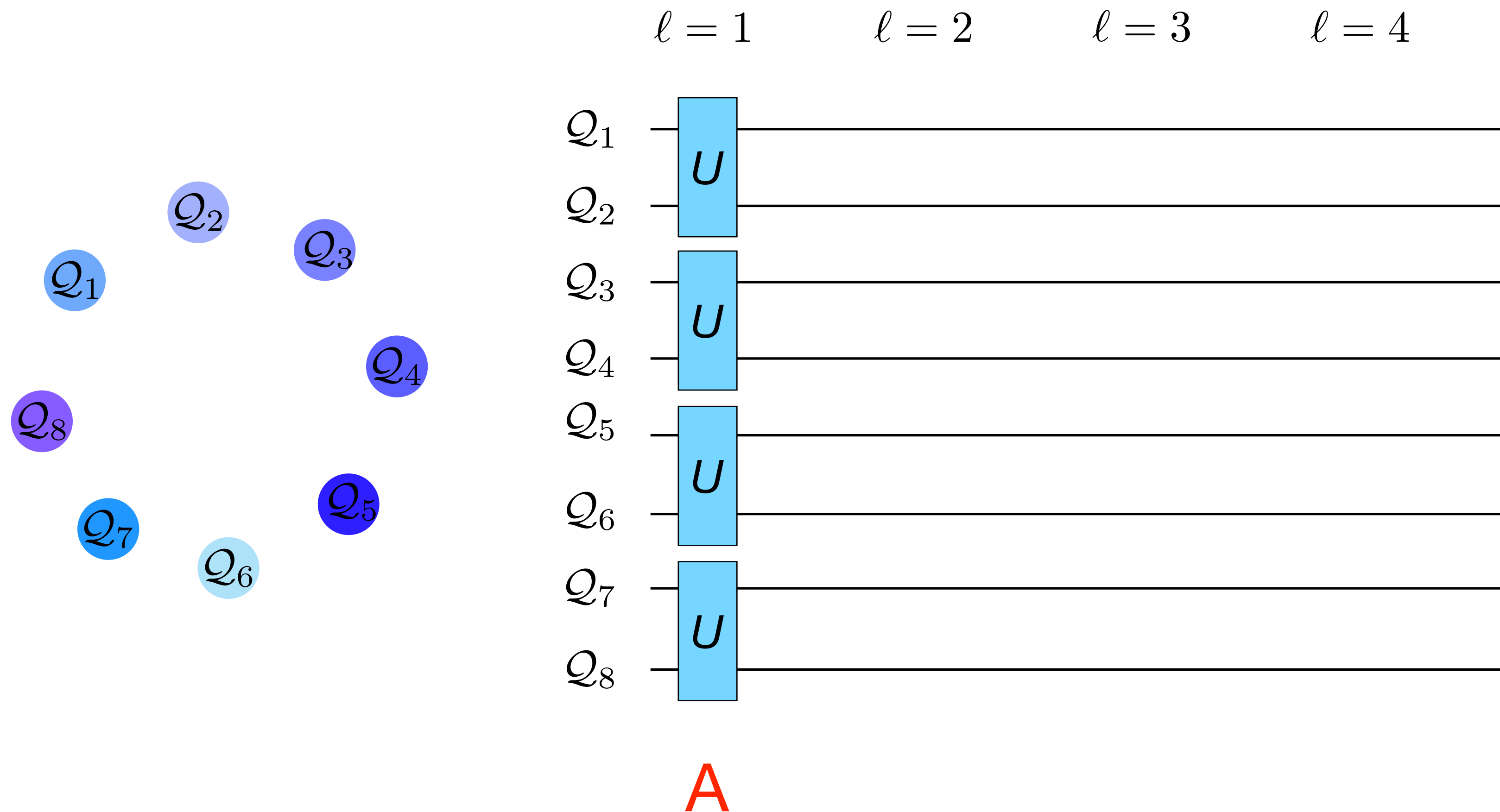
$\ell = 1$ $\ell = 2$ $\ell = 3$ $\ell = 4$



$U = \text{PSWAP}$
In $Q=1$ subspace

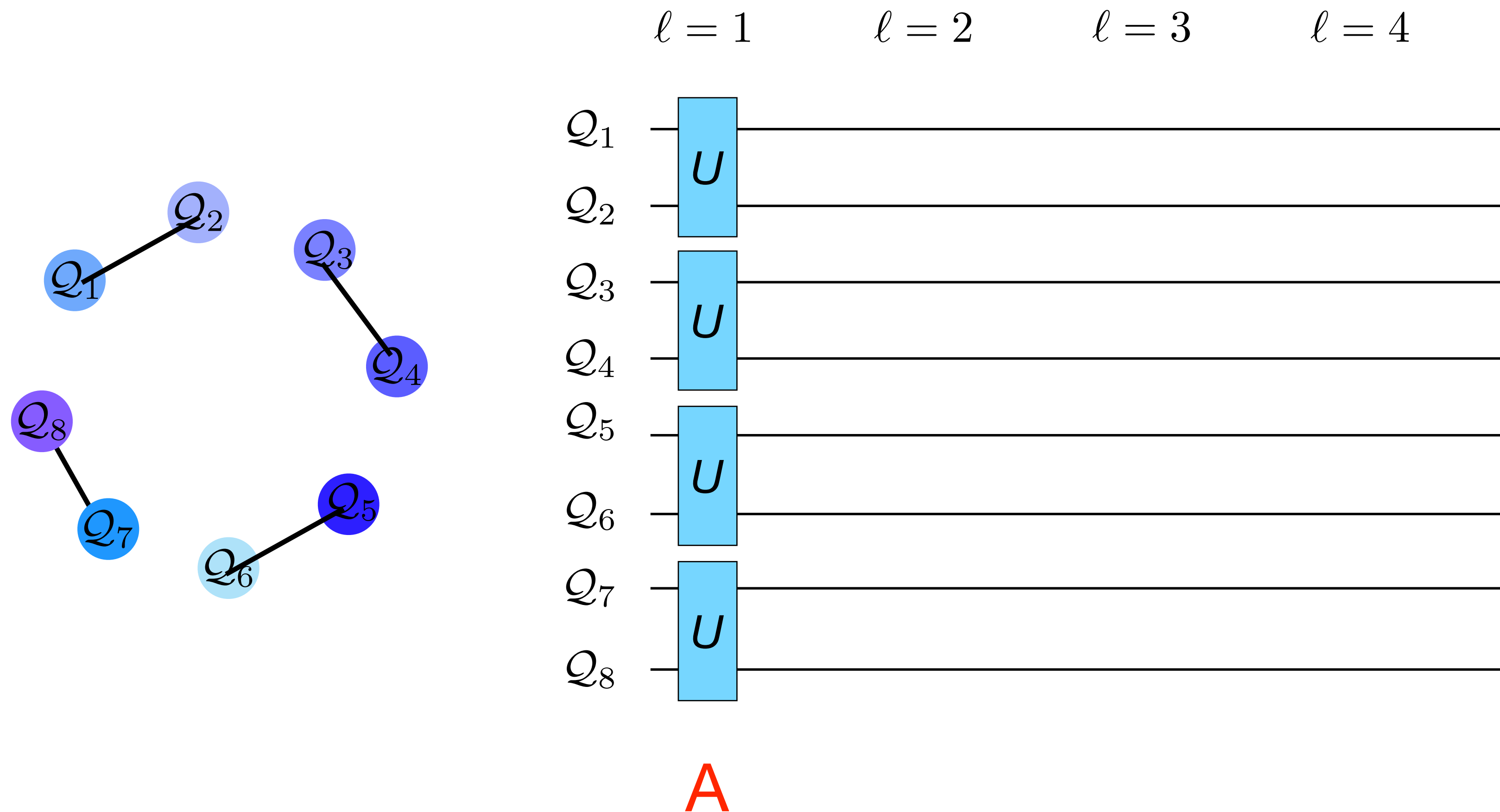


Engineering interesting ensembles



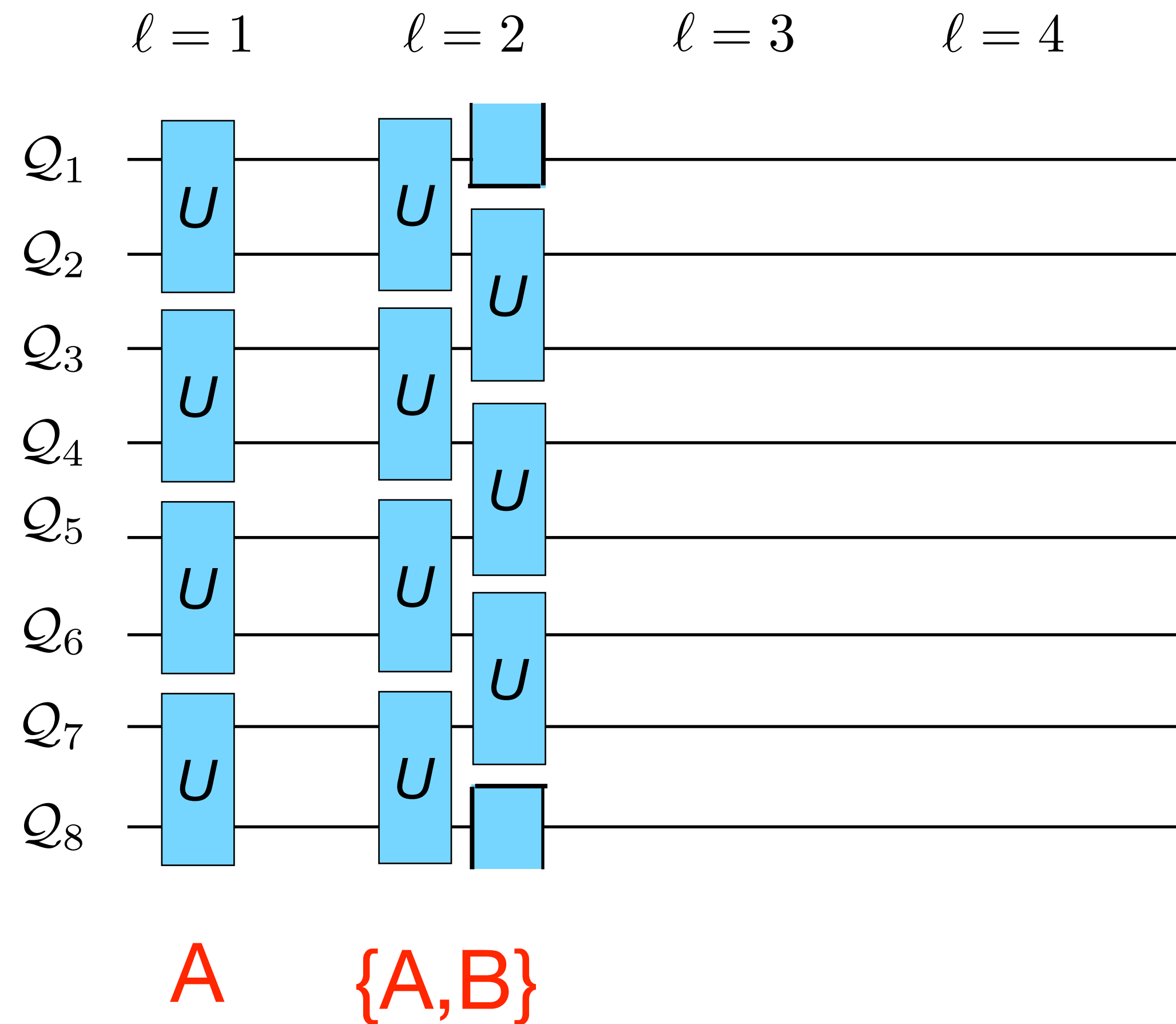
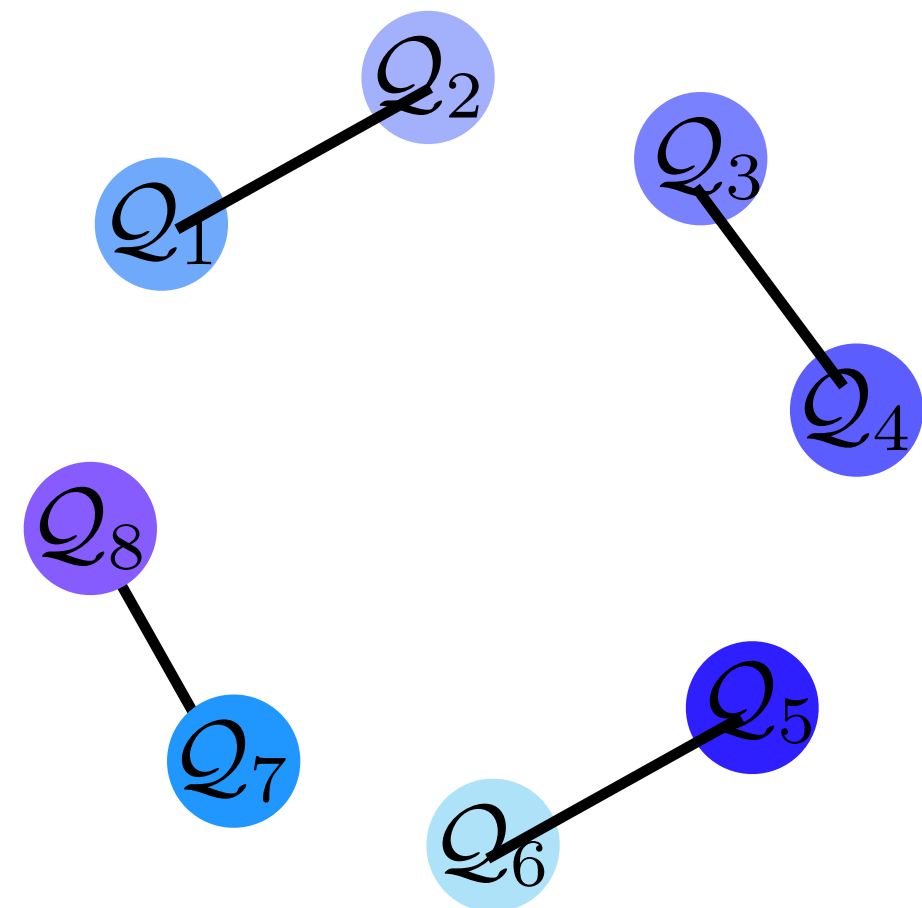
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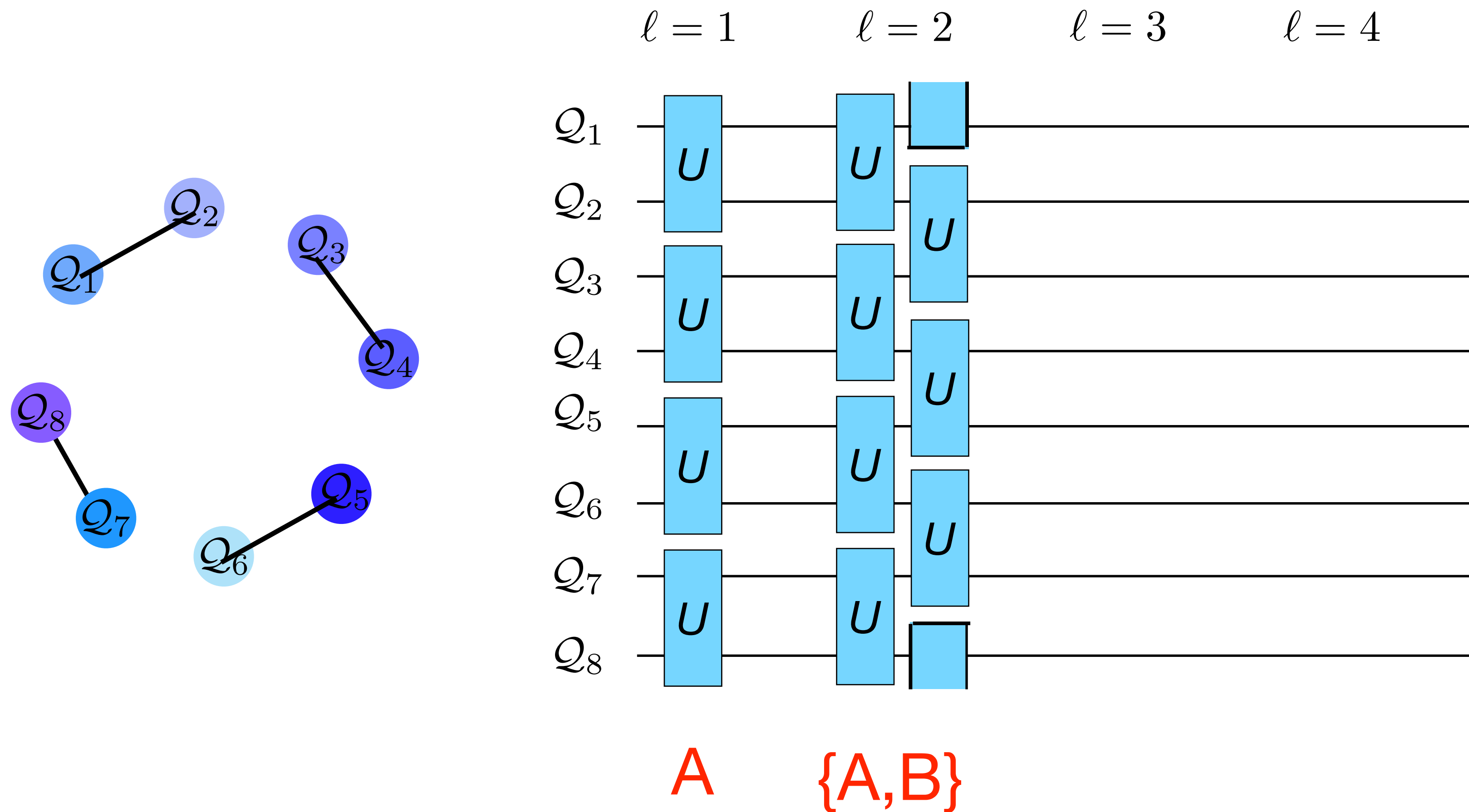
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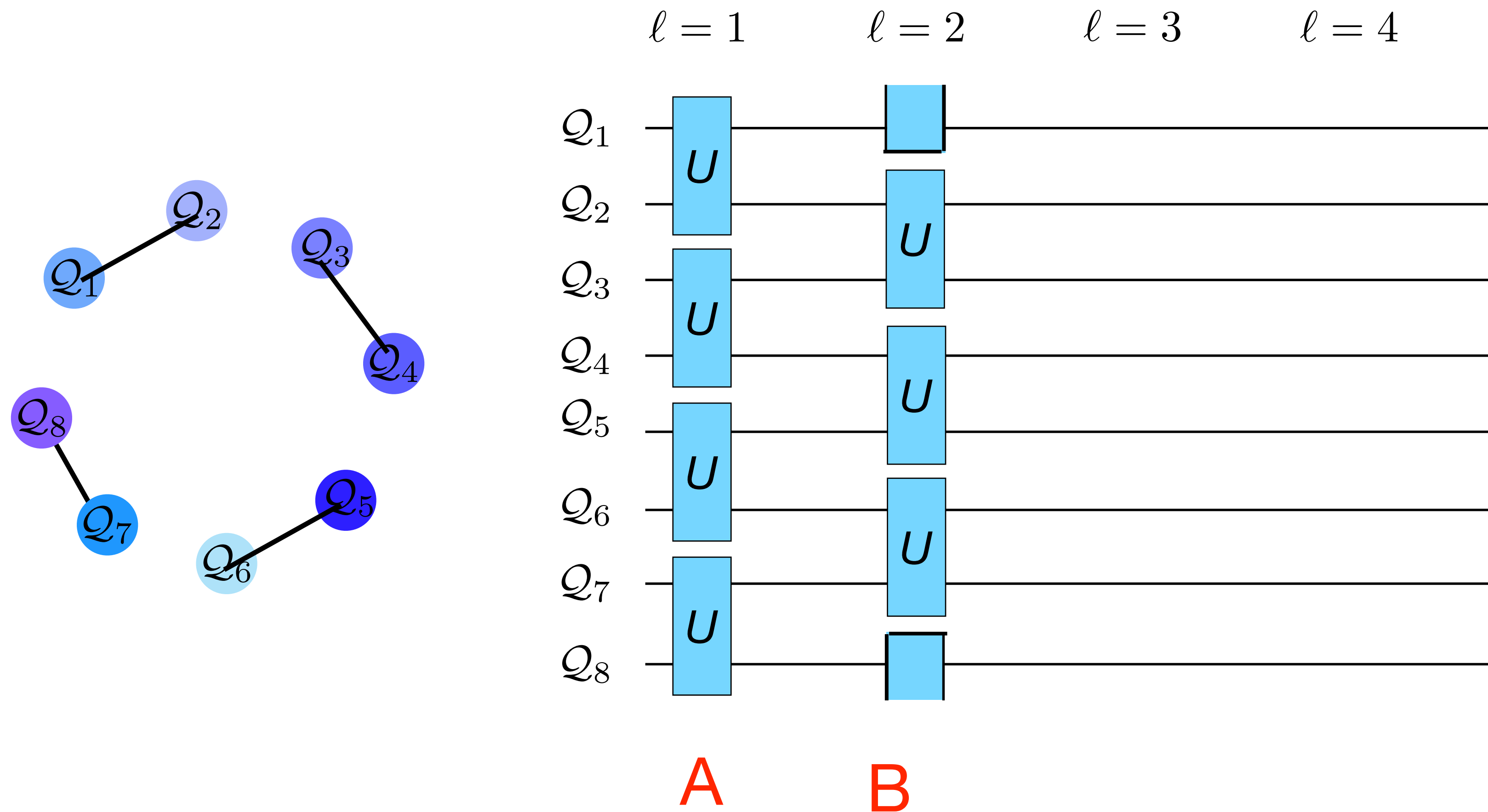


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Next layer: optimization criteria, based on subsystem states

$$\max \sum_{i=1}^N \text{Tr} |\rho^{(i)} - \bar{\rho}|$$

Engineering interesting ensembles

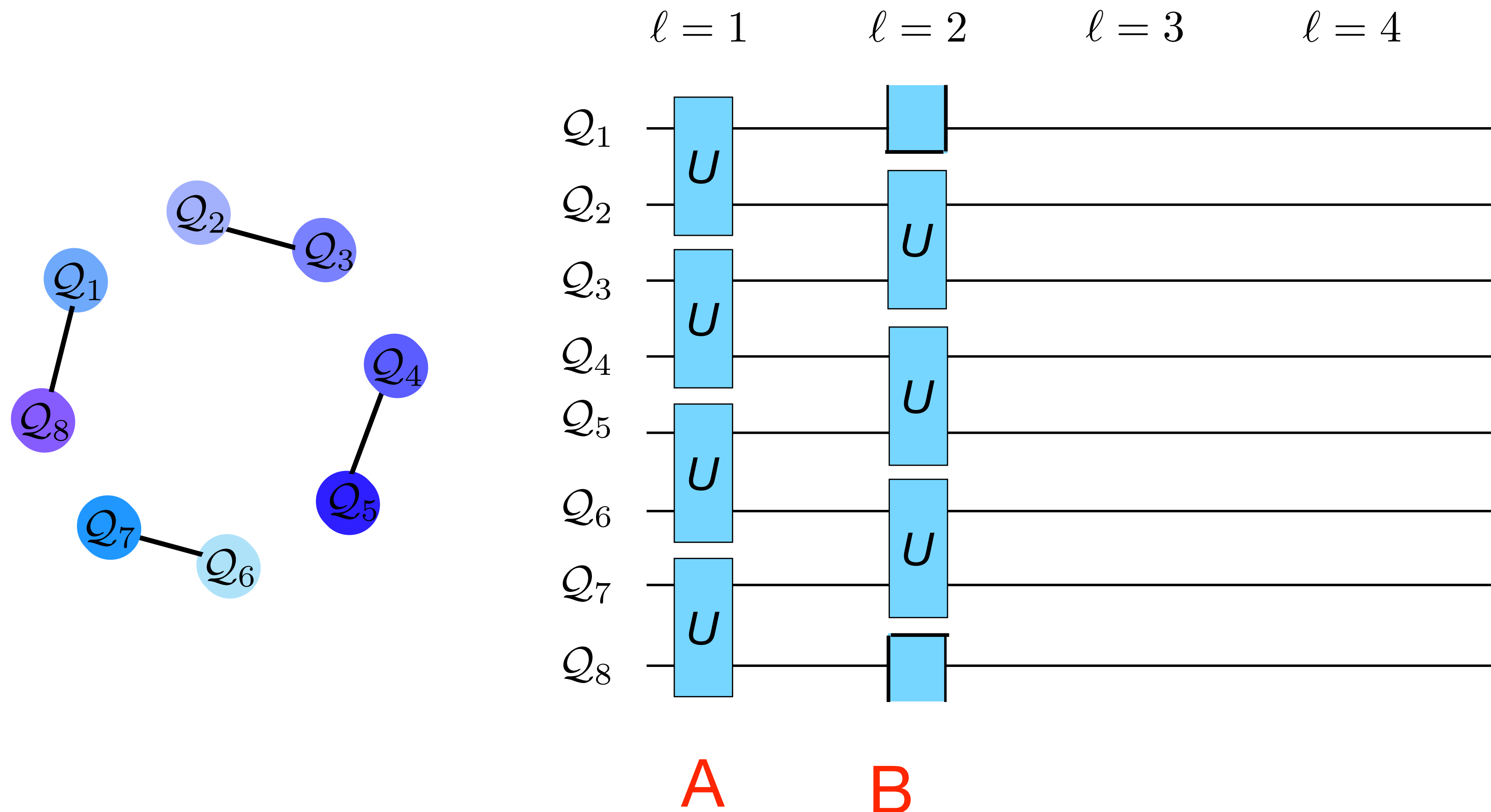


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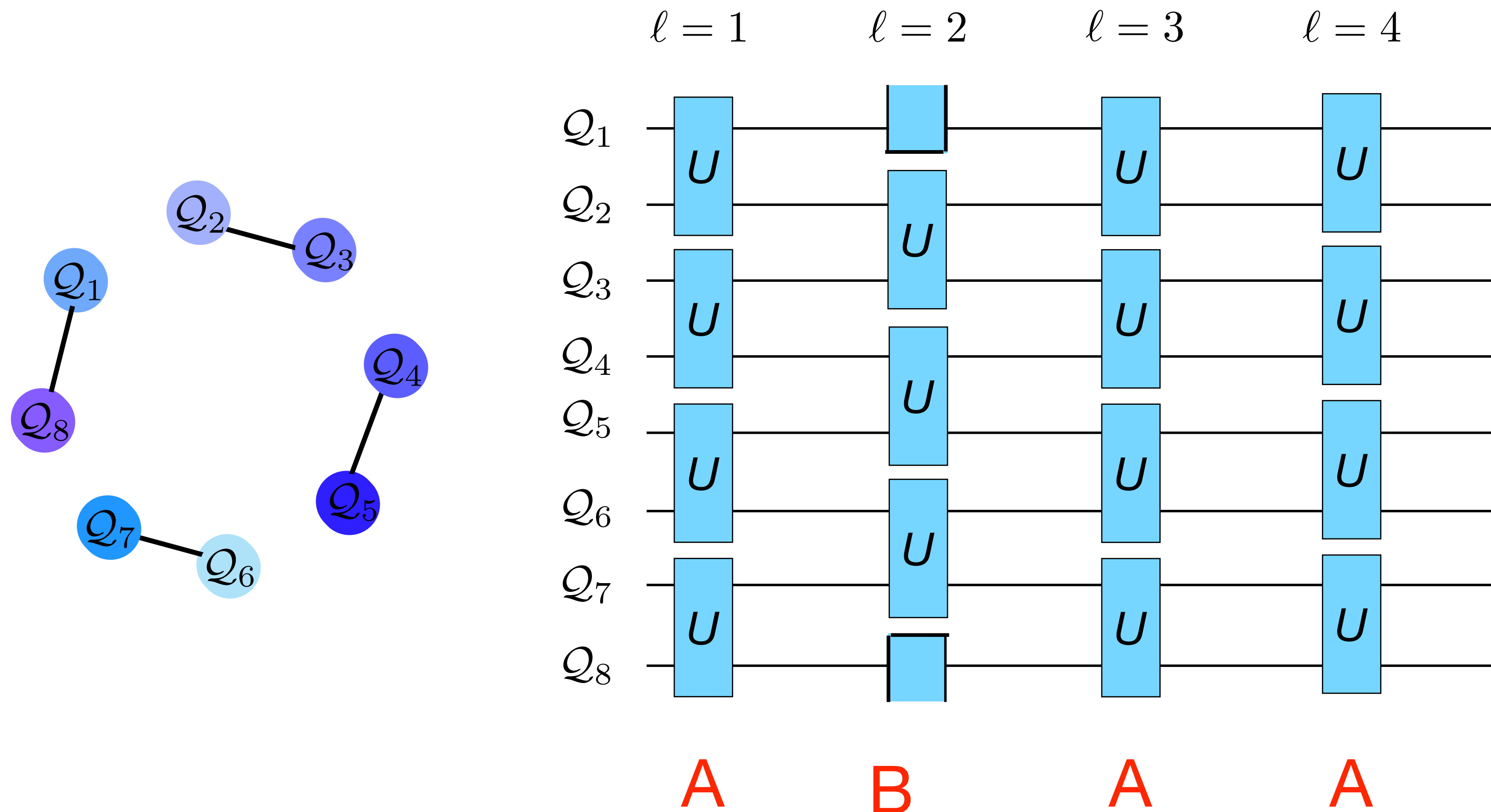


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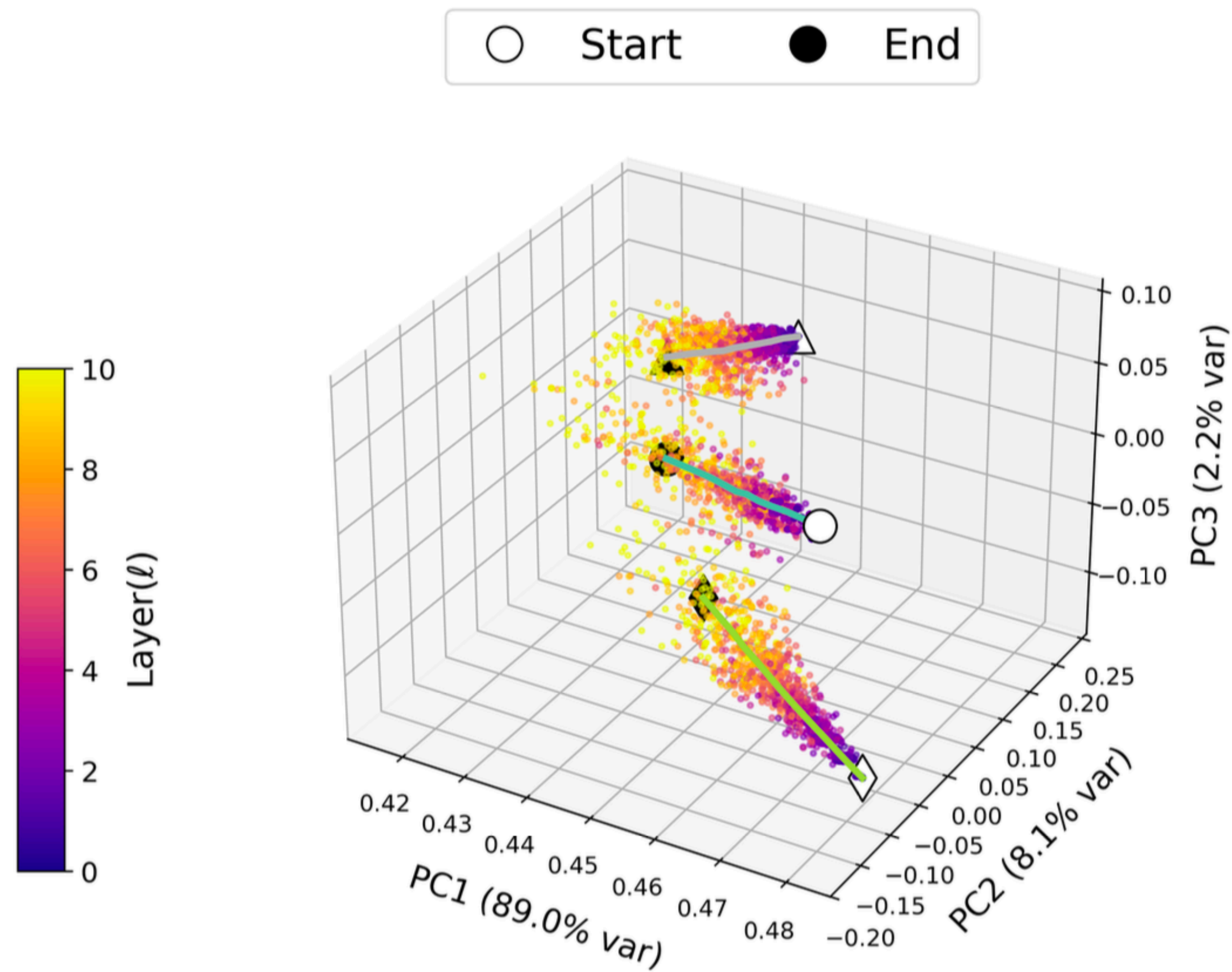


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Statistics: from nearby initial states



For a central state, allow 10 layers of 2-qubit interactions, with pairs chosen at Radom from an all-to-all connected network

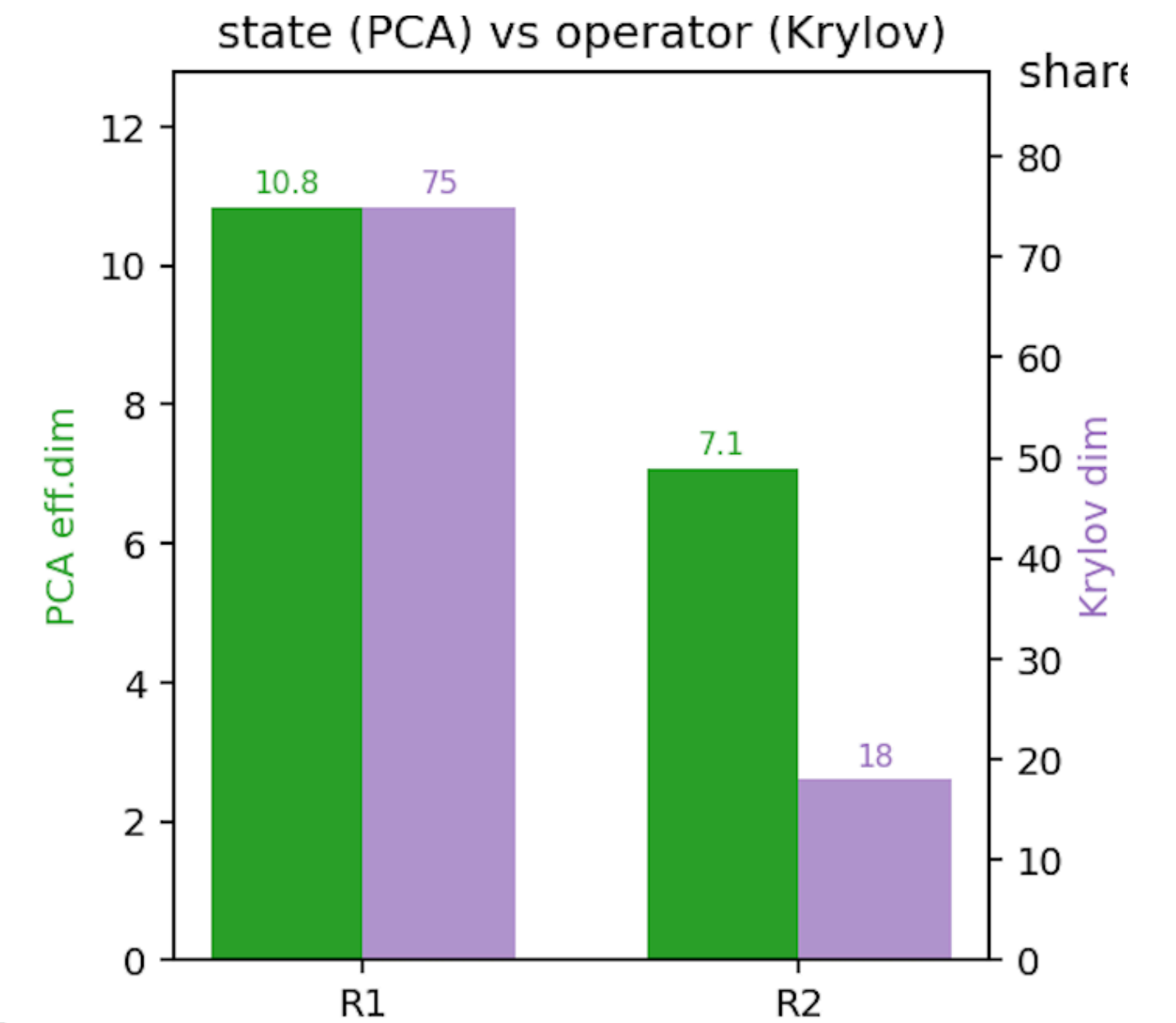
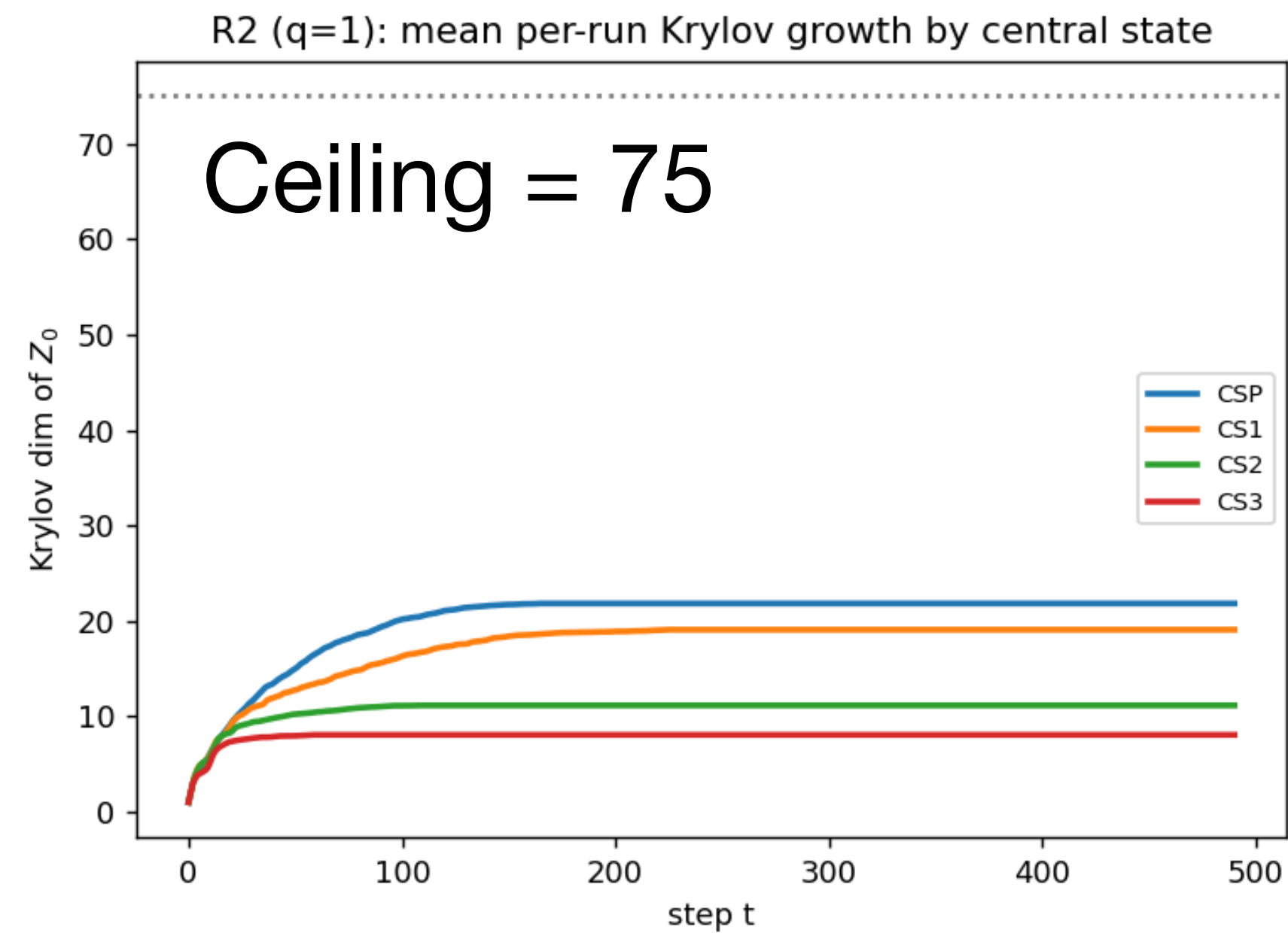
An inhomogeneous ensemble



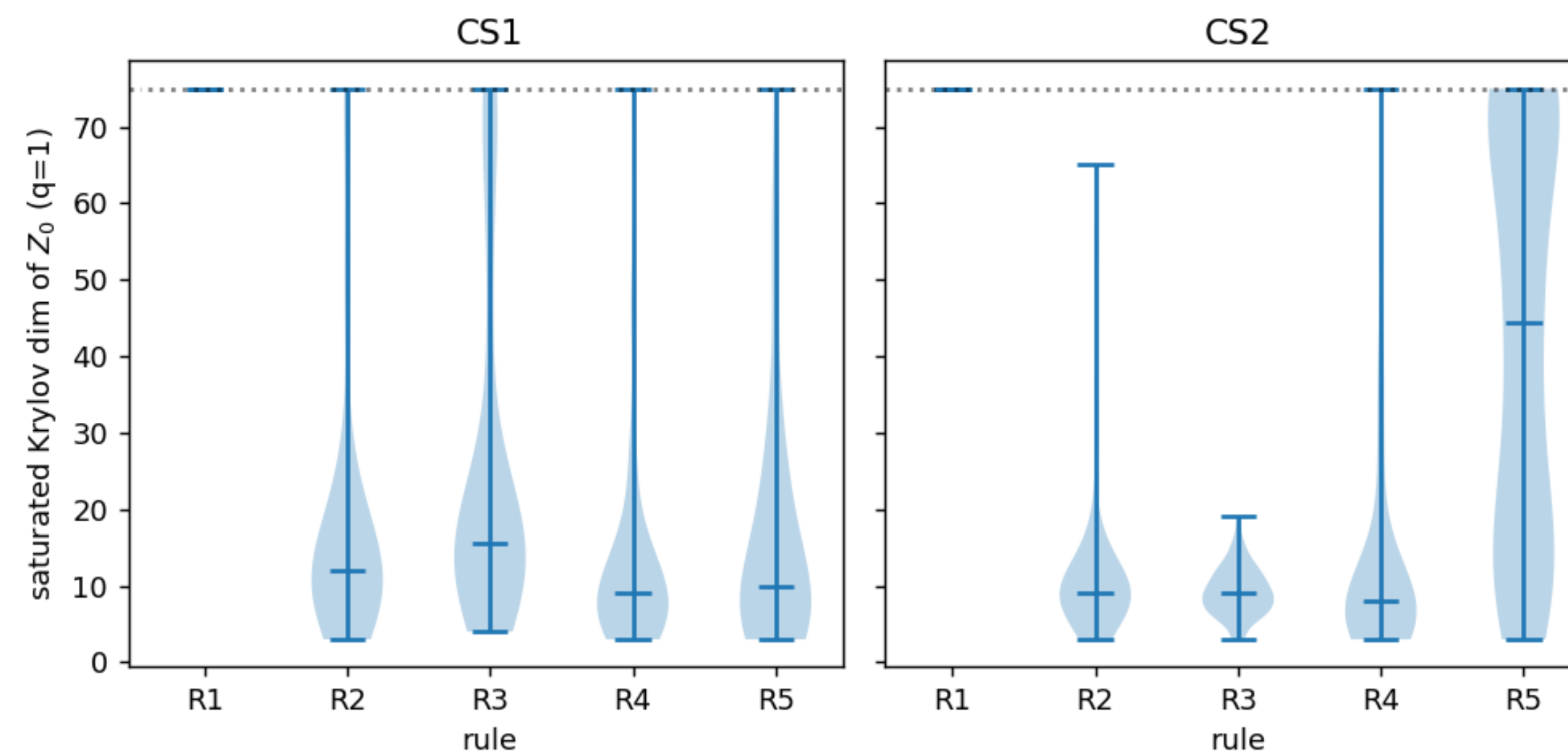
At late times, maps remain inhomogeneous (non-Markovian dynamics)

Many different optimization rules possible....

A global view of the dynamics: Krylov dimension of operator spreading



Distribution of per-run saturated Krylov dim (100 runs each); ceiling 75

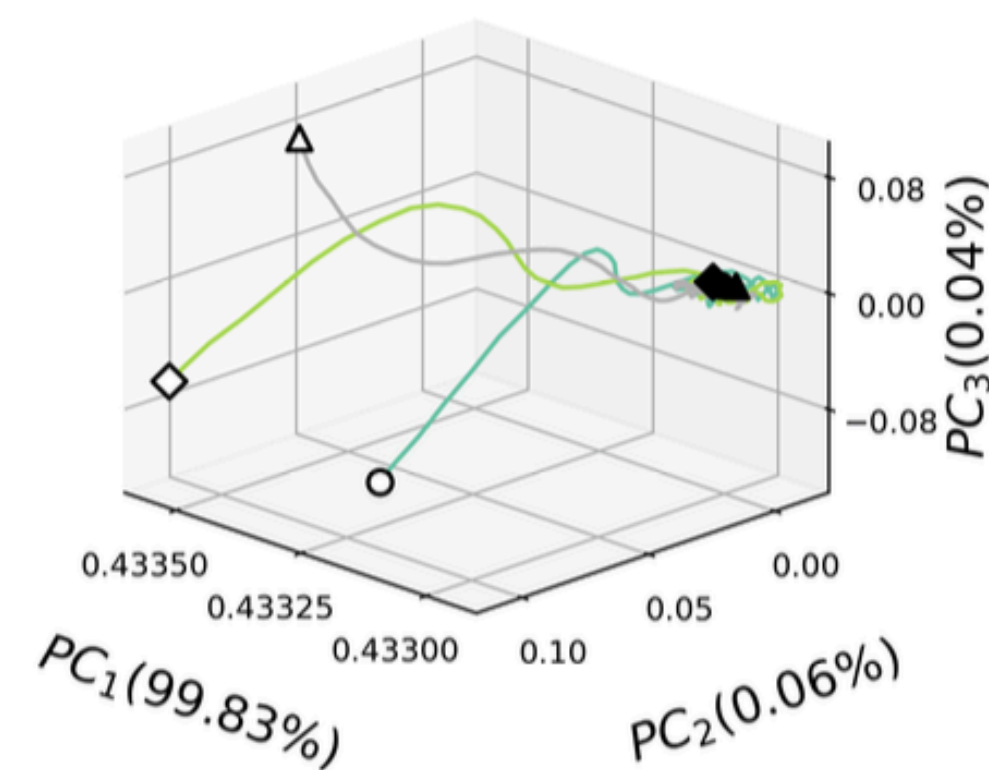


N=8

Now for physical initial states:

1. Optimization rule results are initial-state dependent

Random



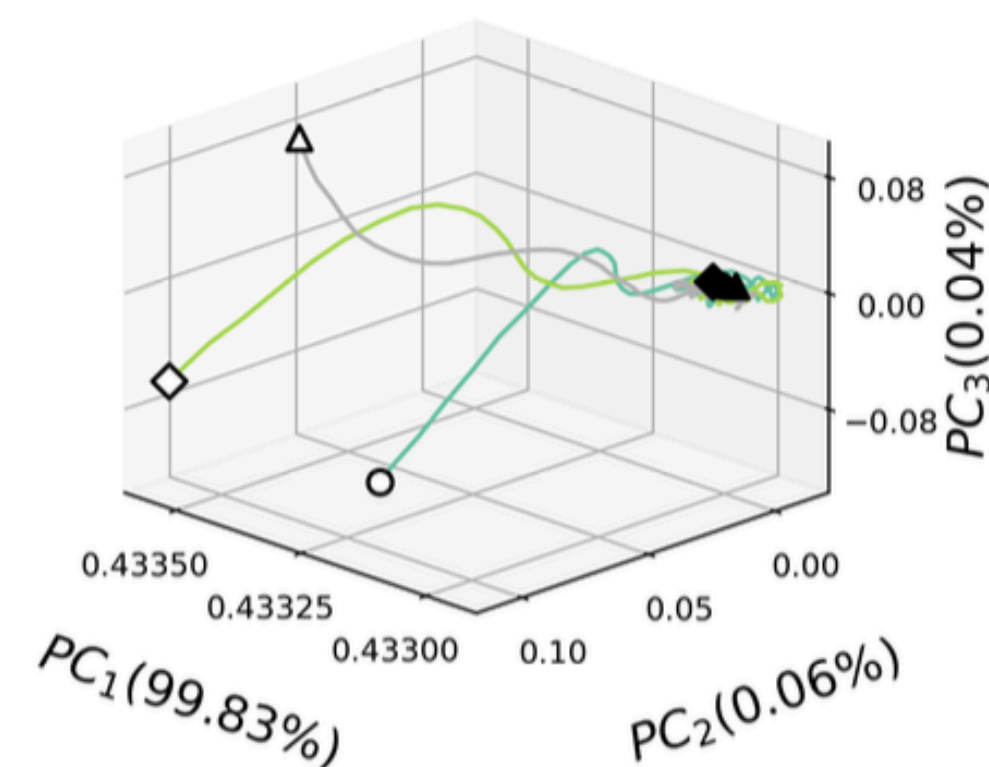
Initial state families:



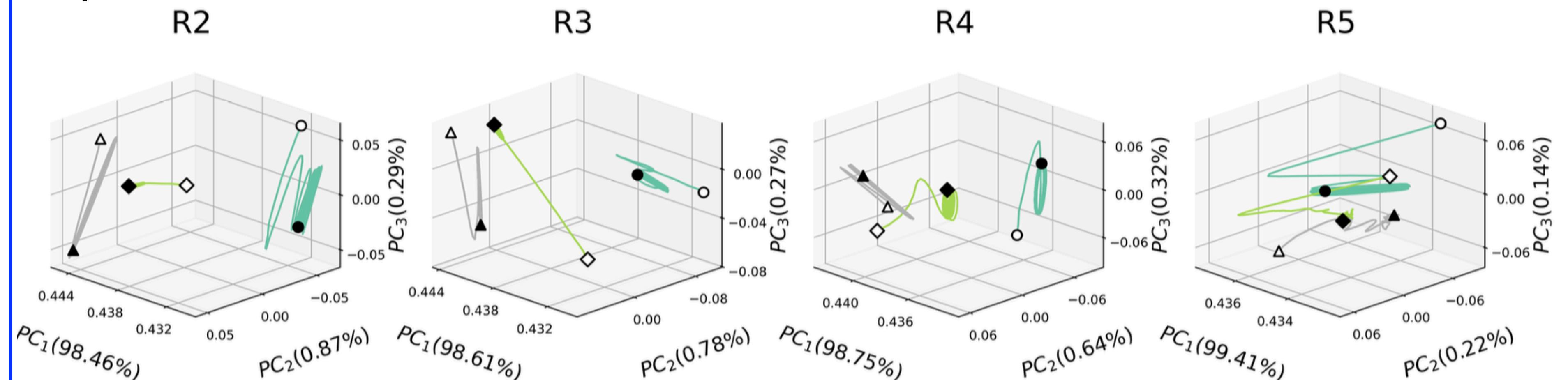
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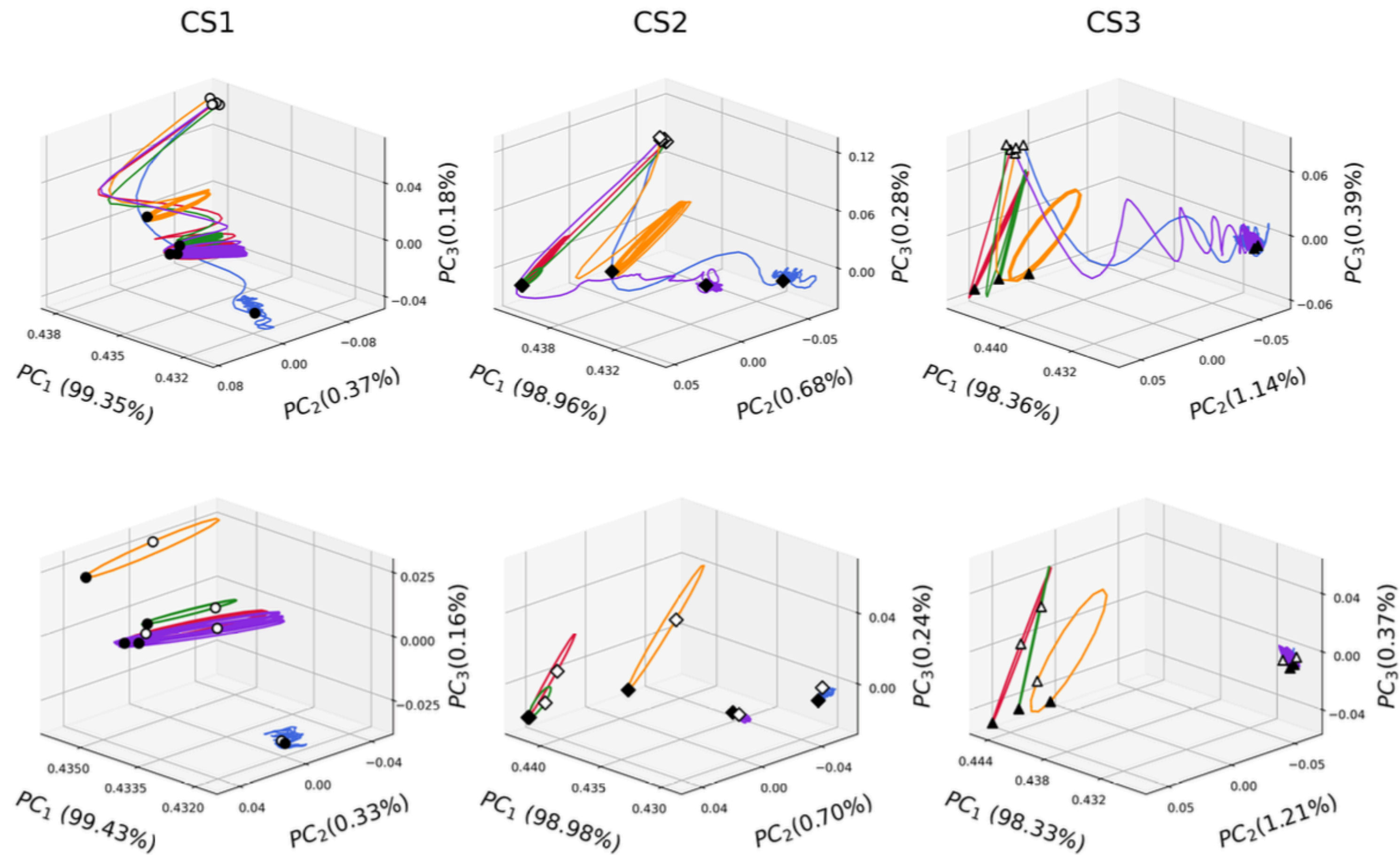
Optimized



Initial state families:

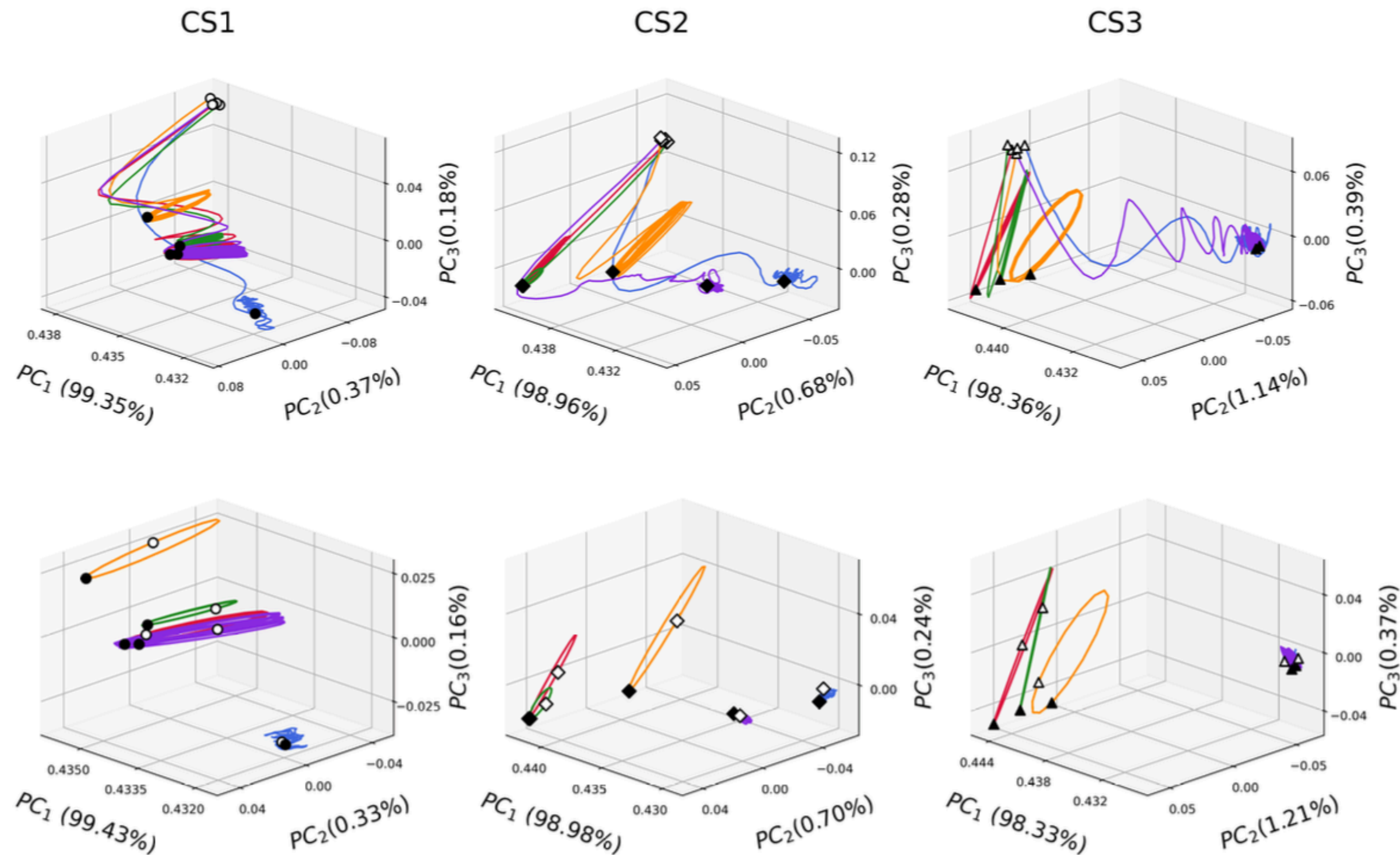


2. Initial-state dependent subsystem steady states



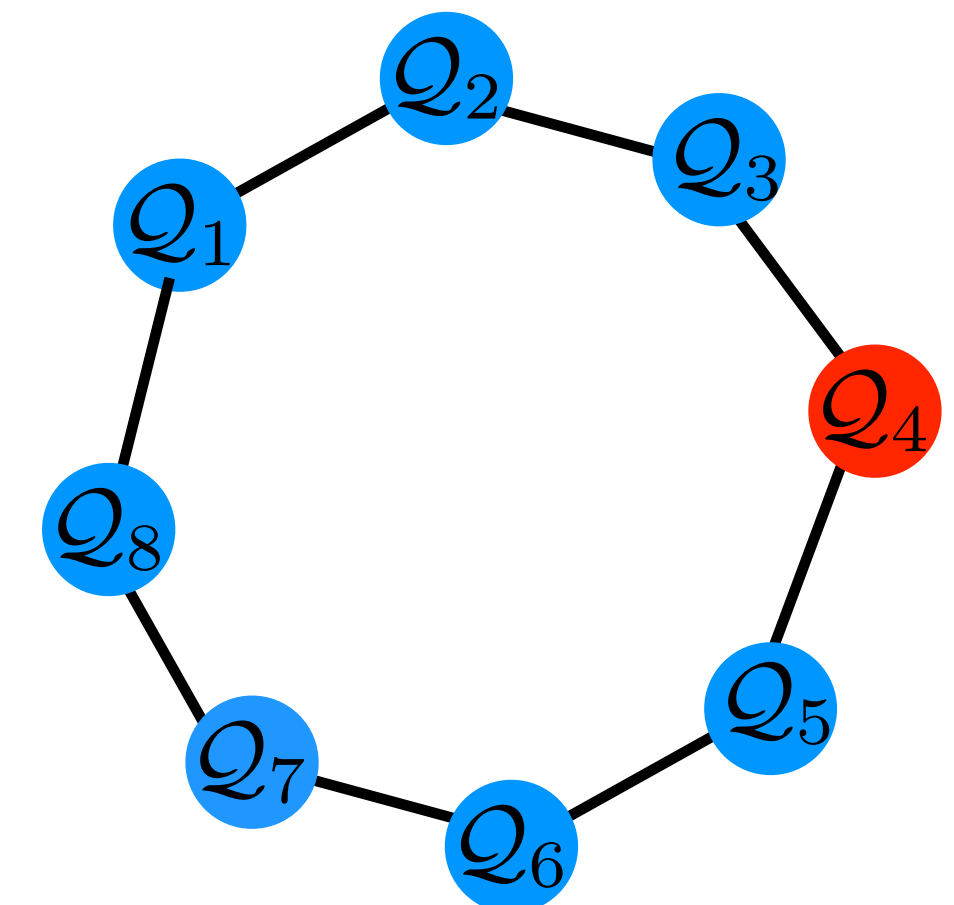
Rules: —●— R1 —●— R2 —●— R3 —●— R4 —●— R5

2. Initial-state dependent subsystem steady states



Rules: —●— R1 —●— R2 —●— R3 —●— R4 —●— R5

Memory of initial conditions



Memory and Markovianity

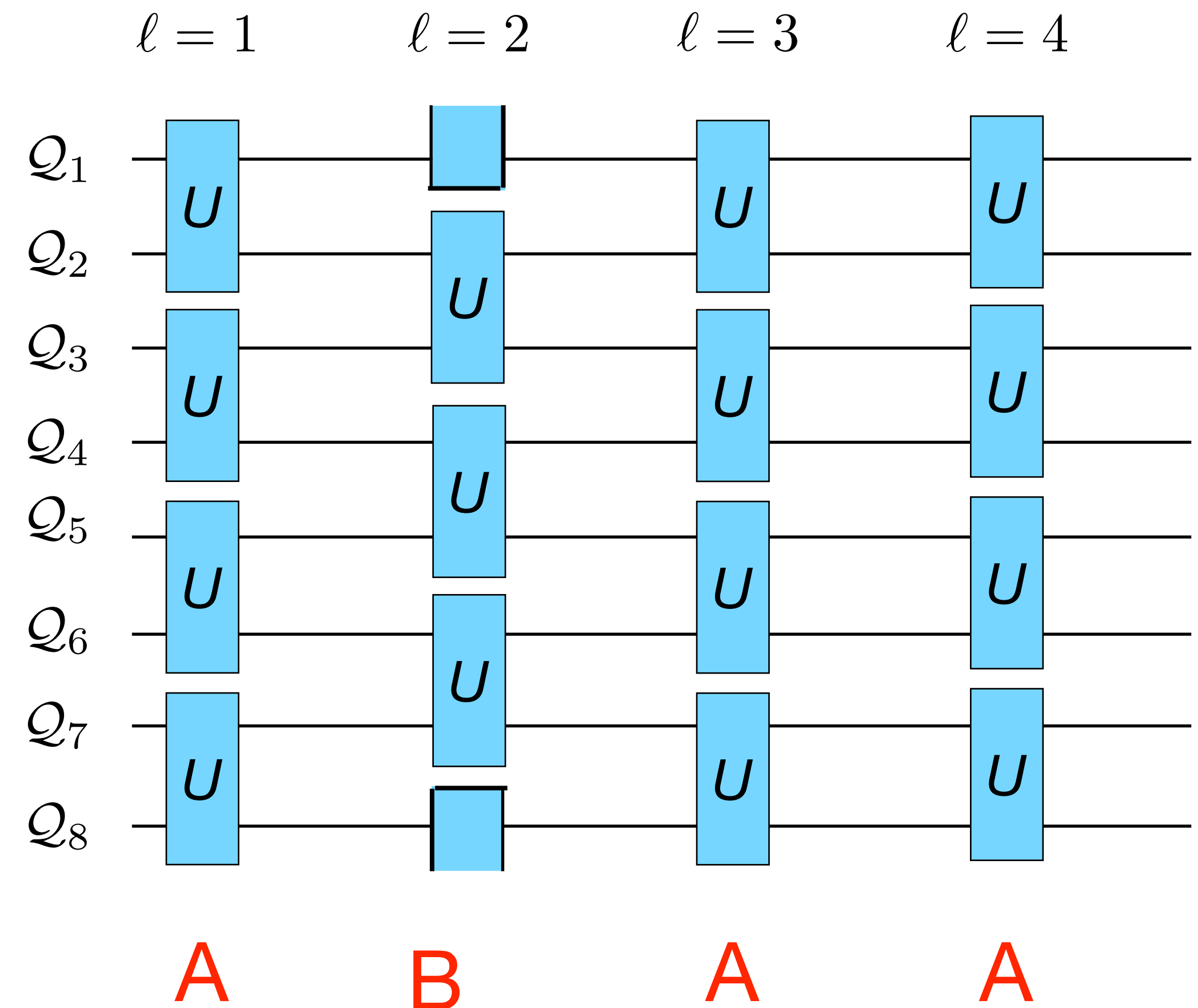
Rather than considering the optimization rule, examine the 'emitted' gate sequence

These sequences turn out to be k -Markov

Memory and Markovianity

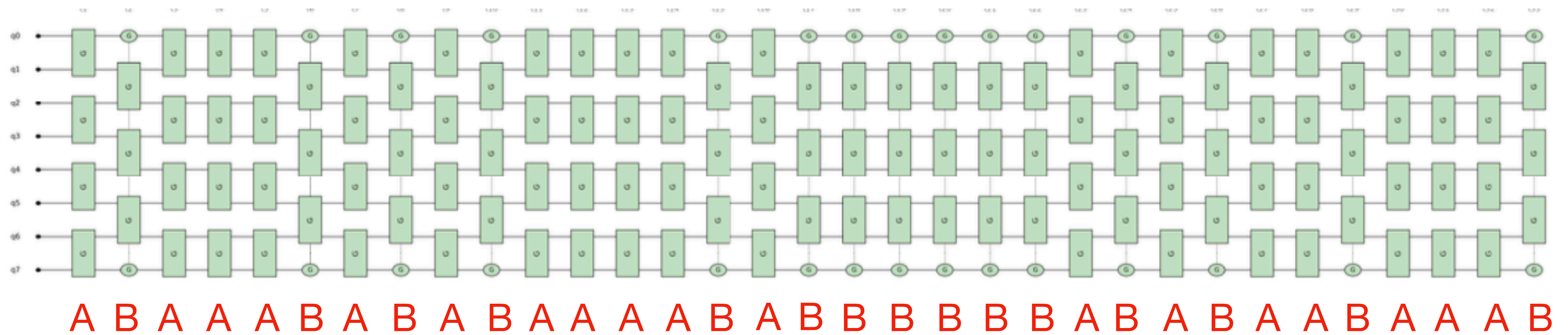
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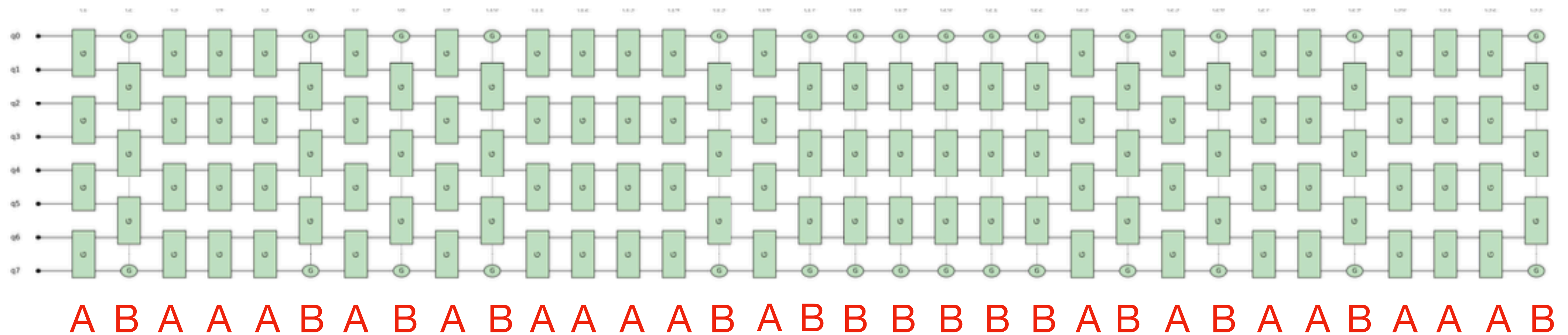


Where U is a fixed 2-local, $U(1)$ unitary

k-Markov gate sequences



k-Markov gate sequences

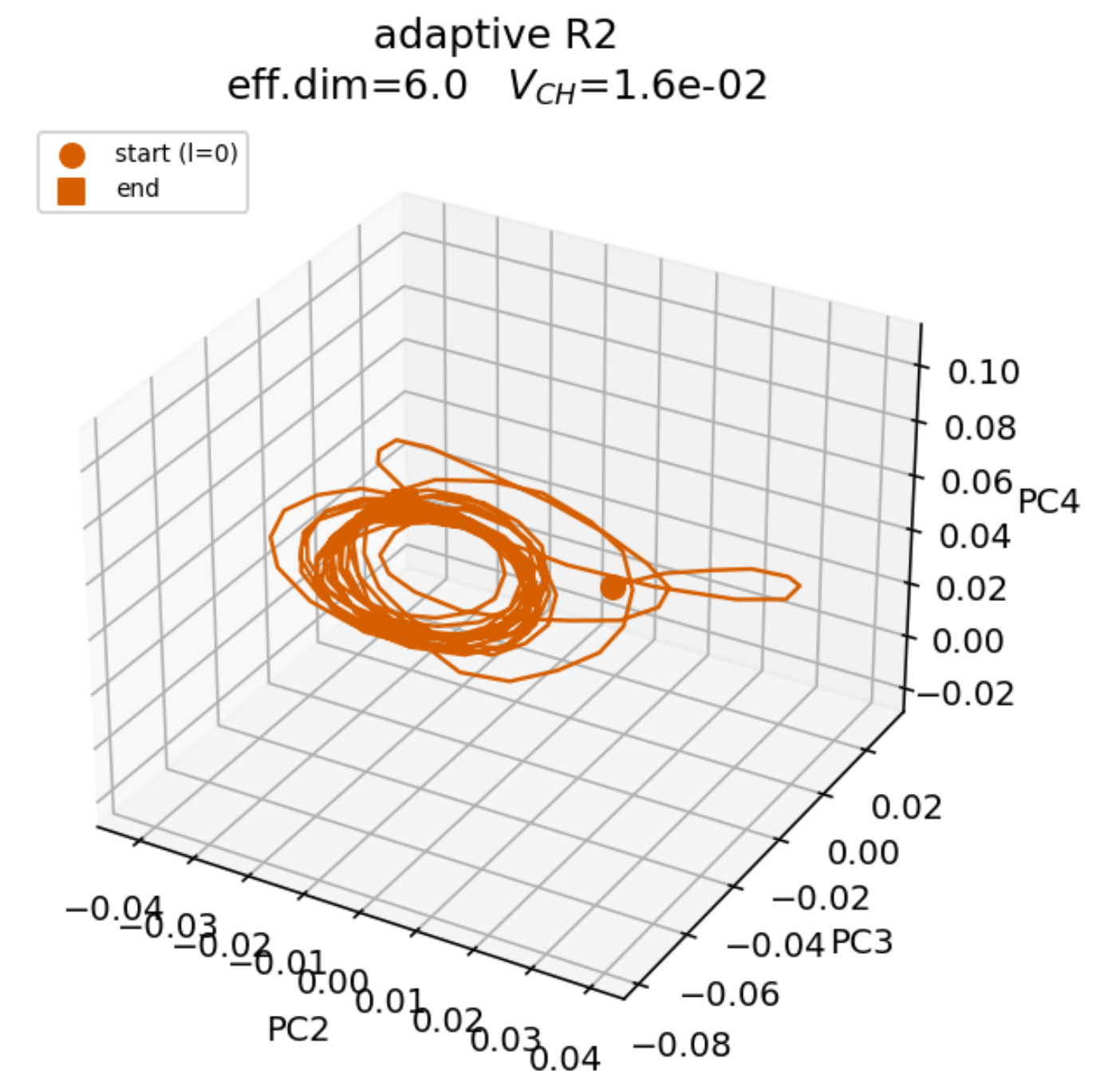
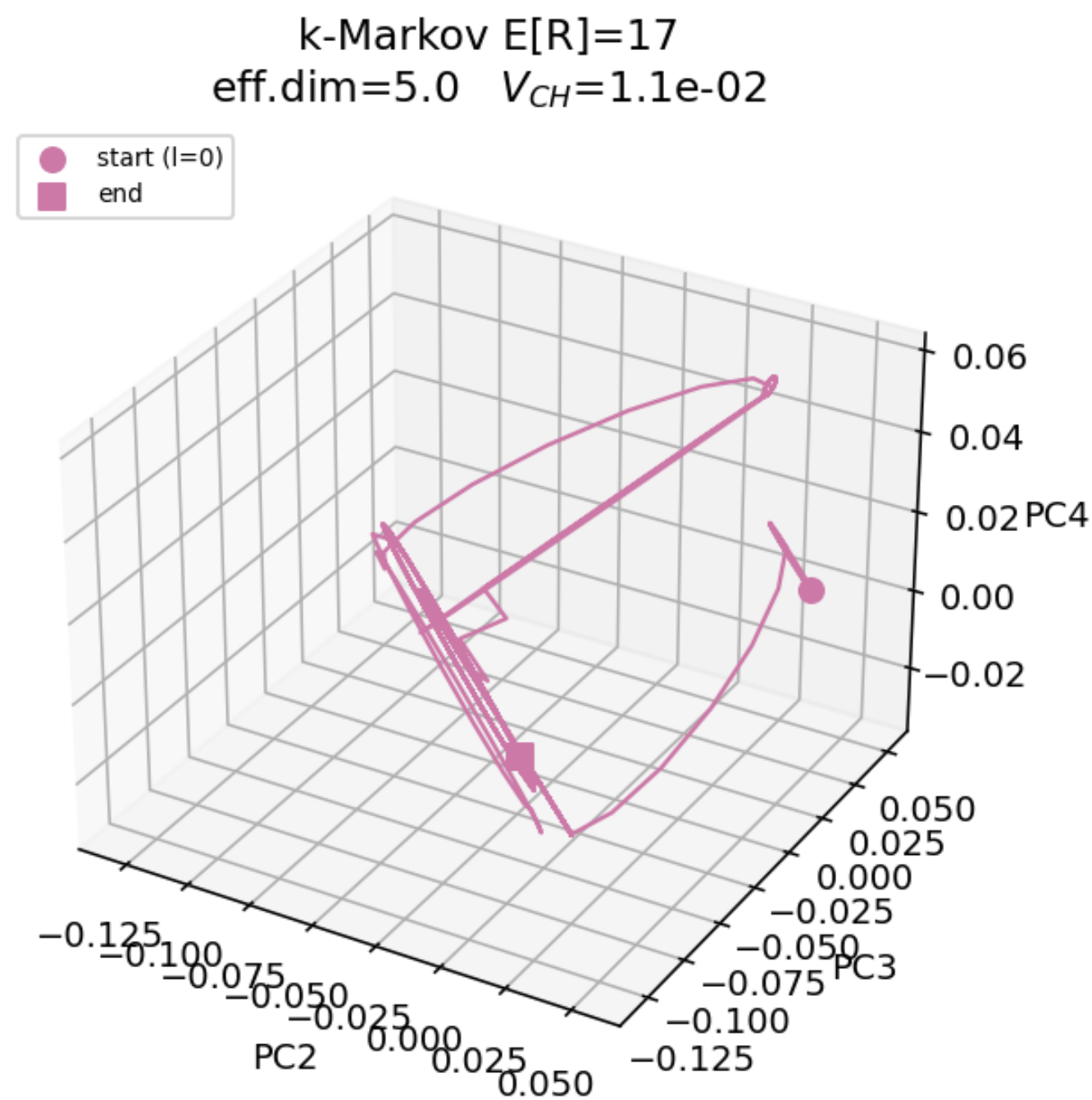
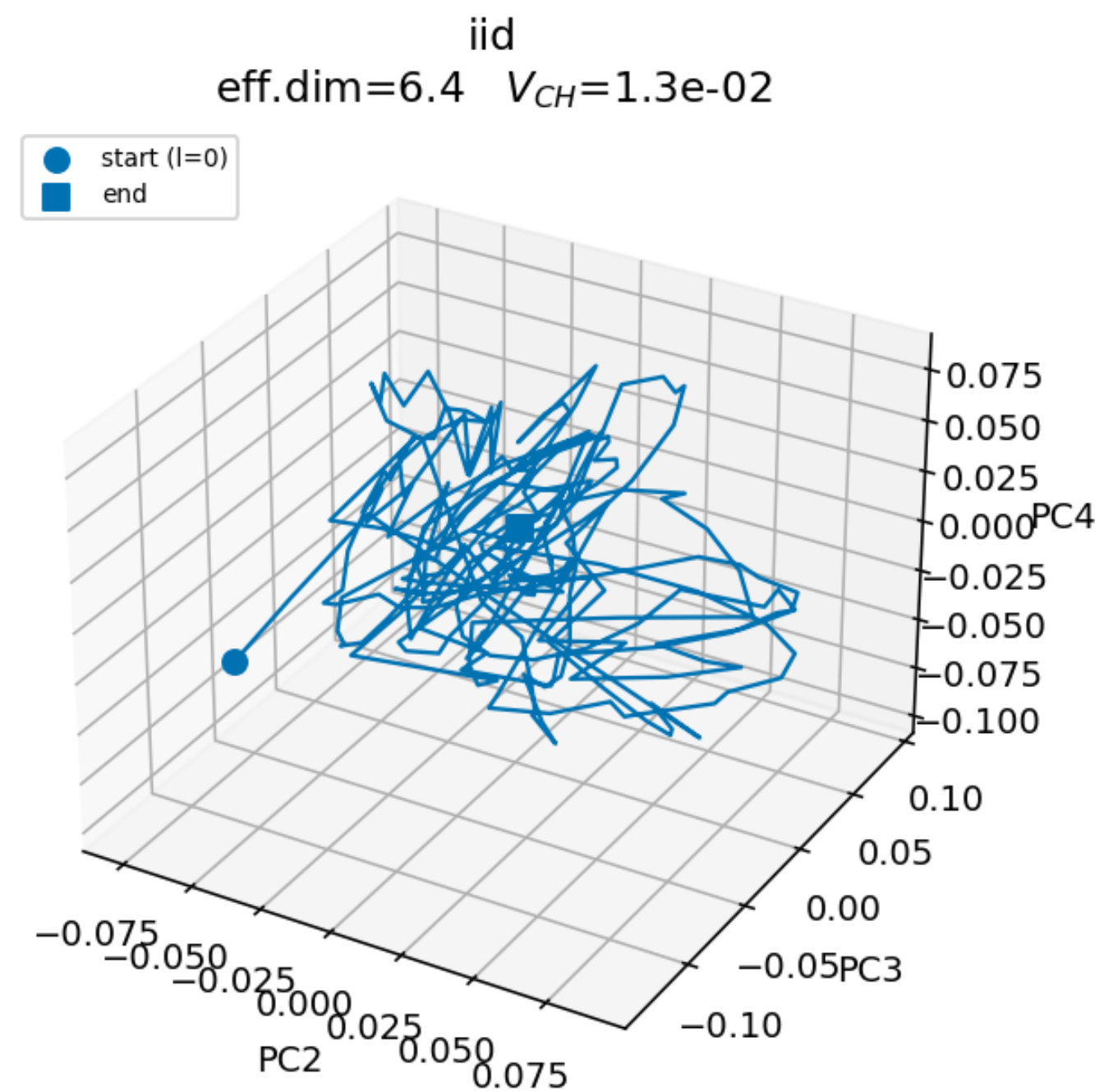


Optimized rules lead to non-Markovian sequences of global unitaries A, B:

To predict the gate at layer 15, need to know previous k gates

k-Markov sequences capture some (not all) of the behavior of the optimized circuits

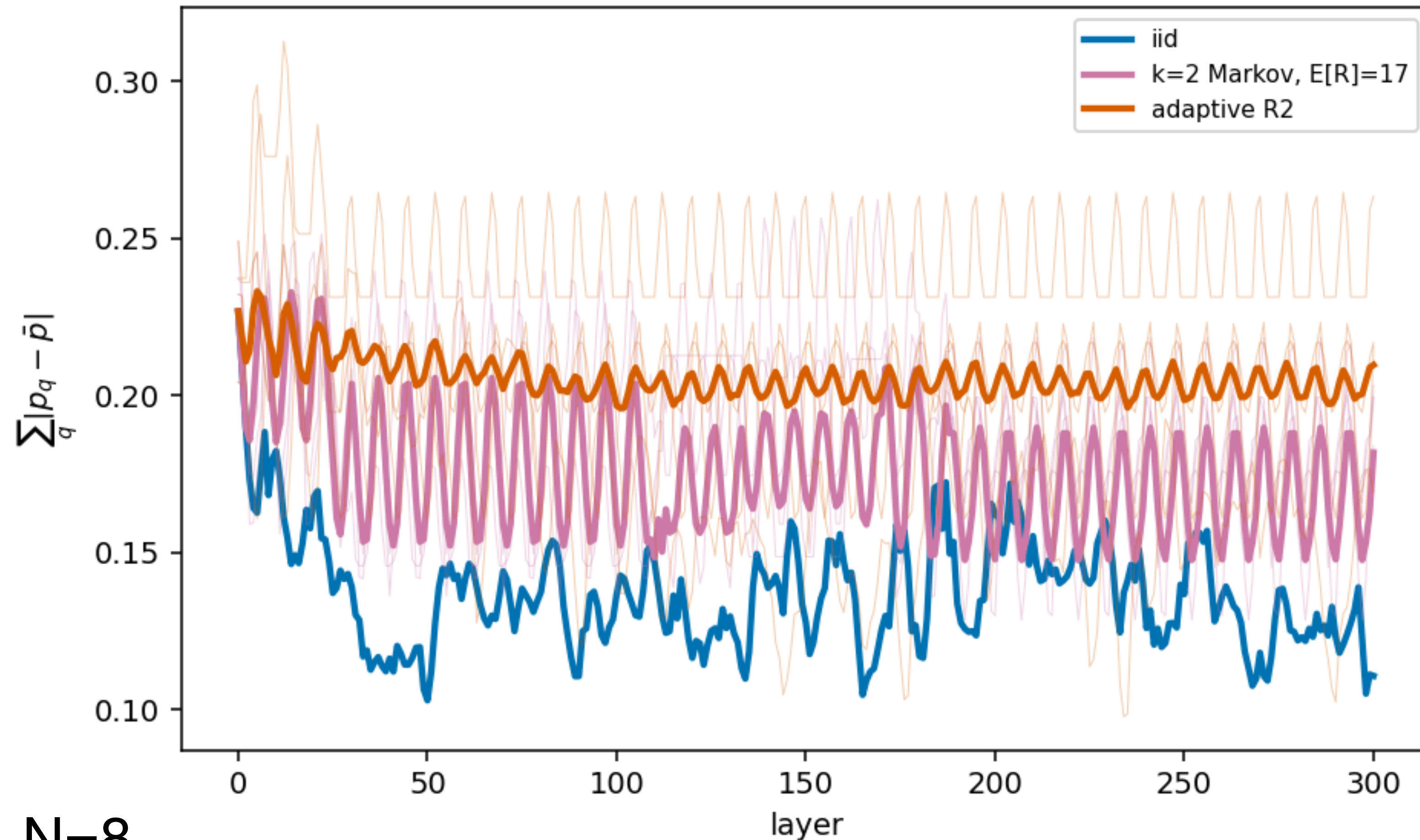
NESS ensemble-averaged trajectory in each rule's OWN charge-orthogonal PCA basis
(faithful intrinsic shape; axes are per-panel, so compare shape not position) — $N=8$, CS1, $\theta=\pi/15$



k-Markov circuit misses the correlation of sequence with initial state

Another view

(b) Trace distance from charge-averaged (thermal) state
iid settles lowest, k-Markov & R2 ride higher (thin = realizations)



N=8

Thick: mean

Faint: single realizations

k-Markov gate sequences as a tool

For two A or B type layers in a row:

$$(U_{i,i+1}(\theta))^R = U_{i,i+1}(R\theta)$$

So these compressed into
brickwork circuits:

$$U(\ell) = \prod_j U(R_{A,\ell}\theta)_{2j-1,2j} \prod_j U(R_{B,\ell}\theta)_{2j,2j+1}$$

Where the angles depend on the
statistics of same-letter runs in the
sequence

k-Markov gate sequences as a tool

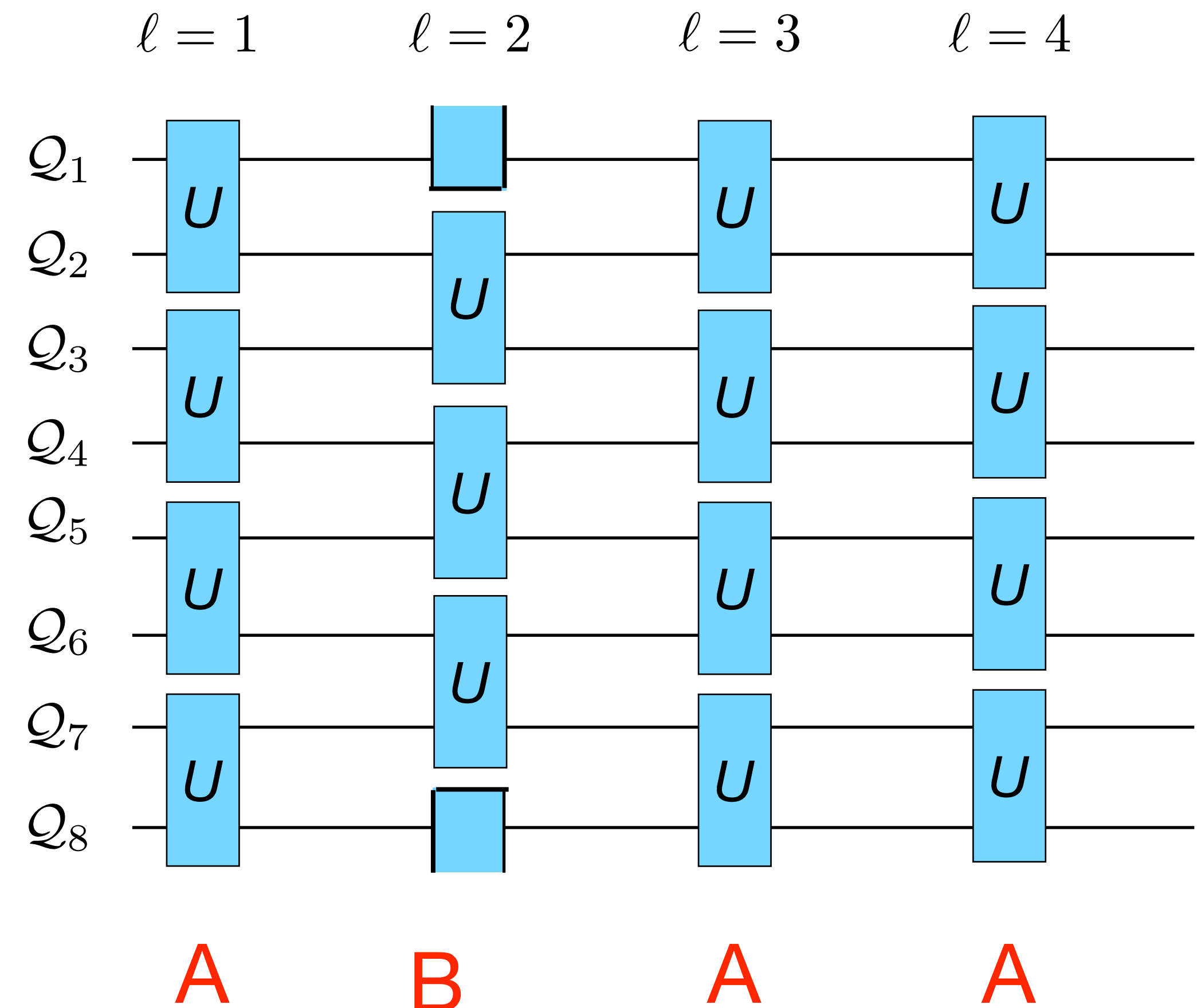
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Where U is a fixed 2-local, $U(1)$ PSWAP

k-Markov gate sequences and operator spreading

To analyze the consequences, consider operator spreading instead of state evolution: initialize a single-site σ_z

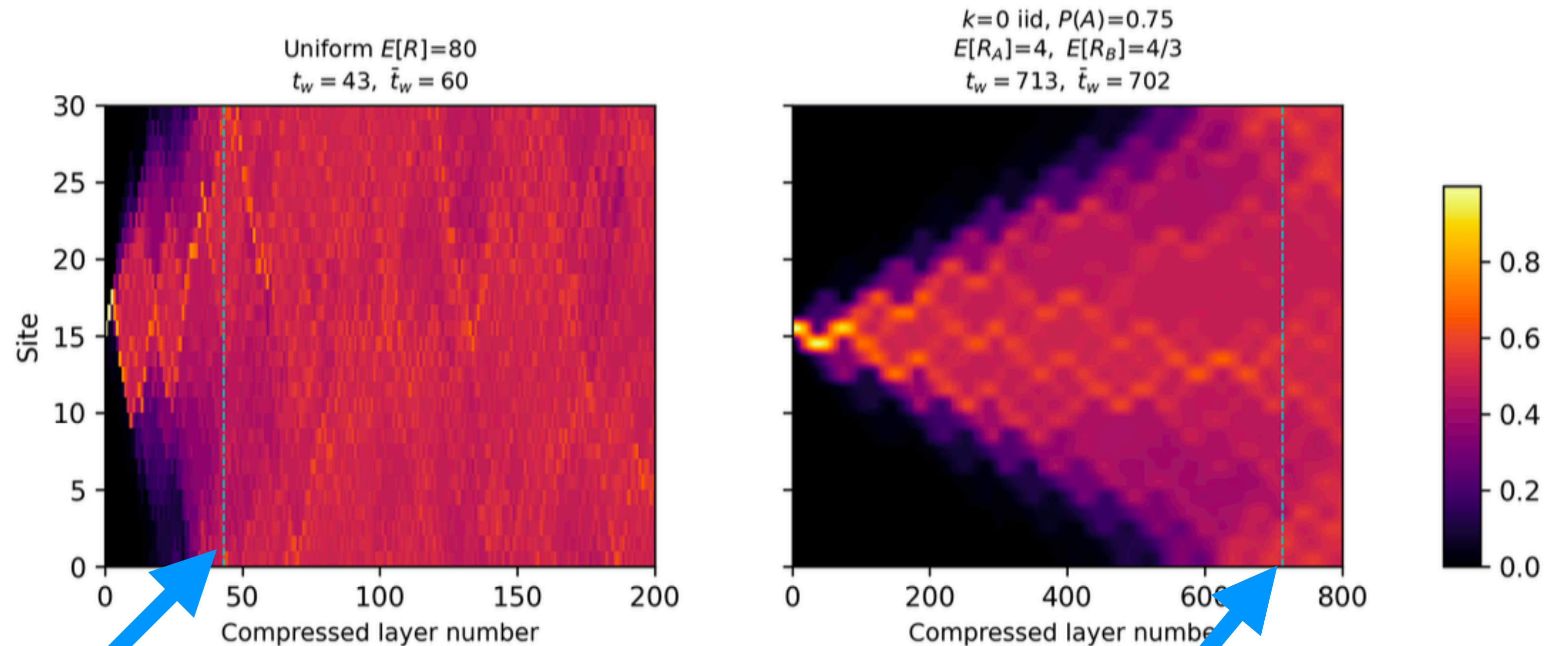
Then, consider the evolution of the operator, expressed in the Pauli basis

$$\mathcal{O}(\ell) = U_\ell^\dagger \mathcal{O}(0) U_\ell = \sum_{\alpha} c_{\alpha}(\ell) \mathcal{P}_{\alpha}$$
$$\sum_{\alpha} |c_{\alpha}(\ell)|^2 = 1$$

k-Markov gate sequences and operator spreading

To visualize the evolution, consider the average occupation of each site:

$$d_i = \sum_{\alpha: \mathcal{P}_{\alpha,i} \neq I} |c_{\alpha}|^2$$



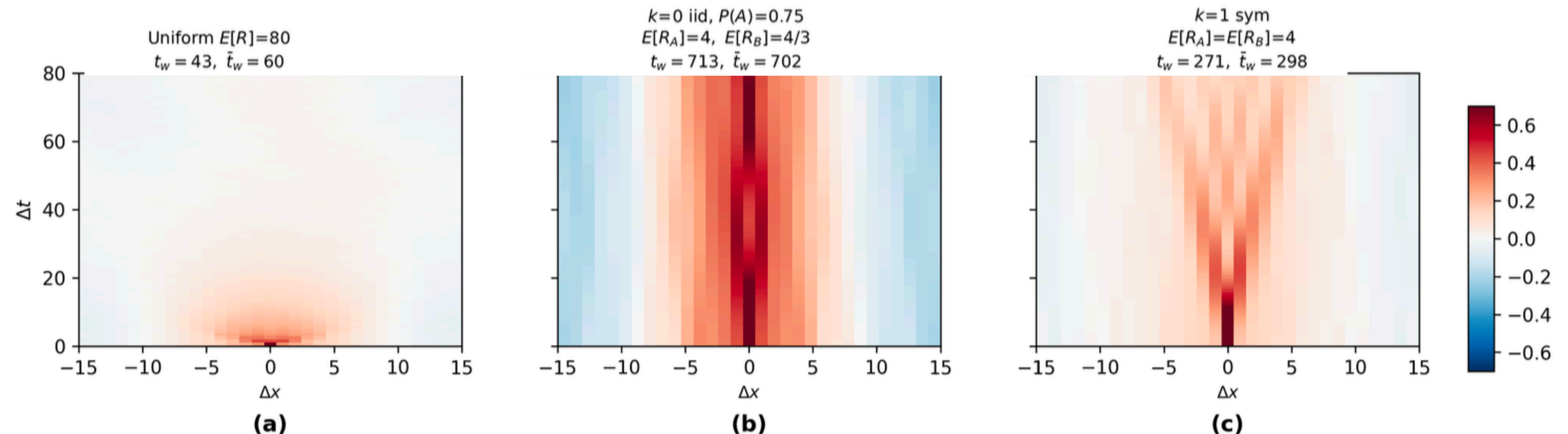
Layer where operator weight equilibrates, $w/N \approx 0.5$

k-Markov consequences, cont'd

Approach to the equilibrium, determined by operator orbit, differs

Correlations persist even after equilibration

$$C(\Delta x, \Delta t) = \frac{\langle d_i(x, t) d_i(x + \Delta x, t + \Delta t) \rangle - \langle d_i(x, t) \rangle^2}{\langle (d_i(x, t) - \langle d_i(x, t) \rangle)^2 \rangle}$$

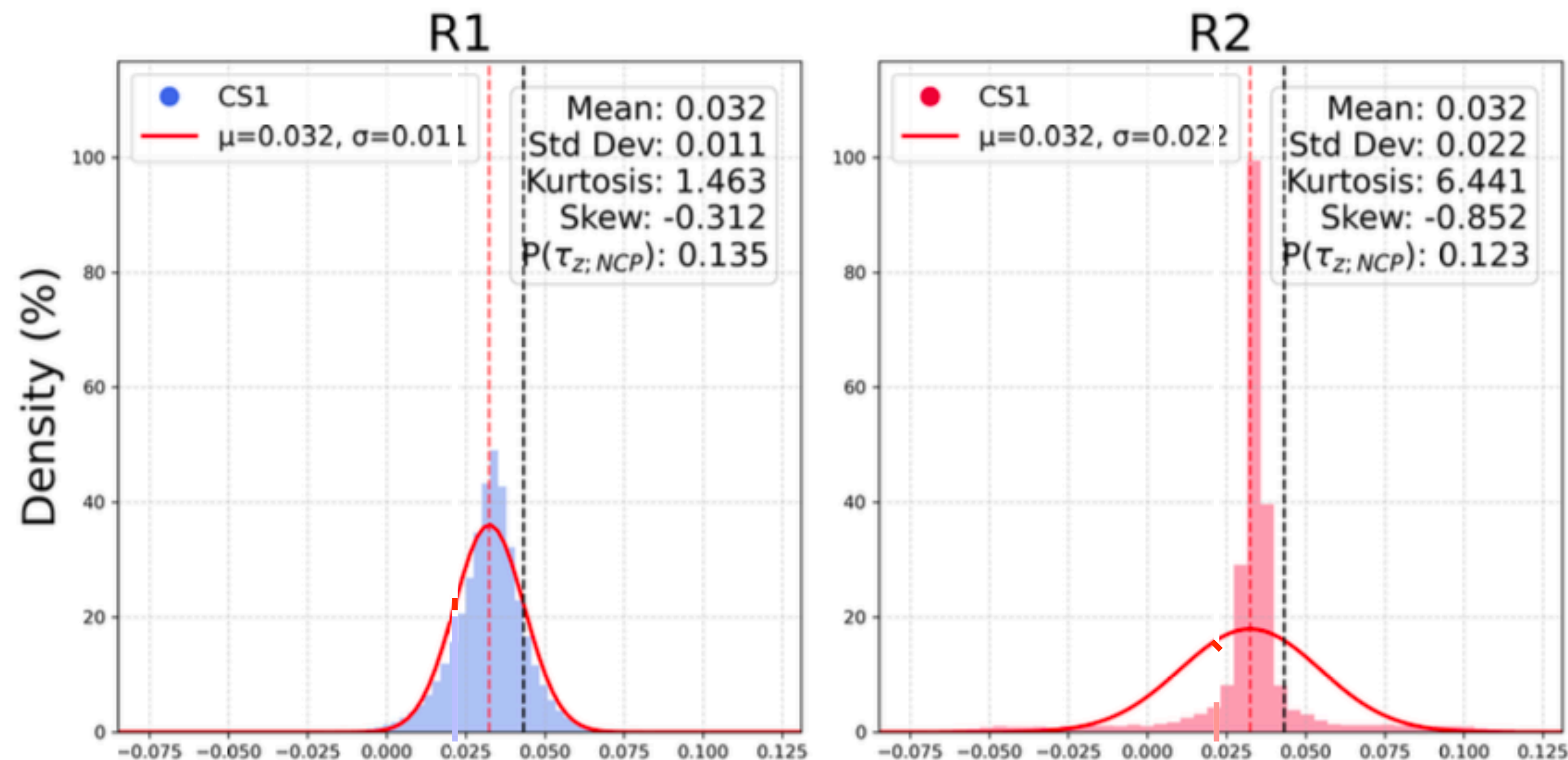


And the map ensembles

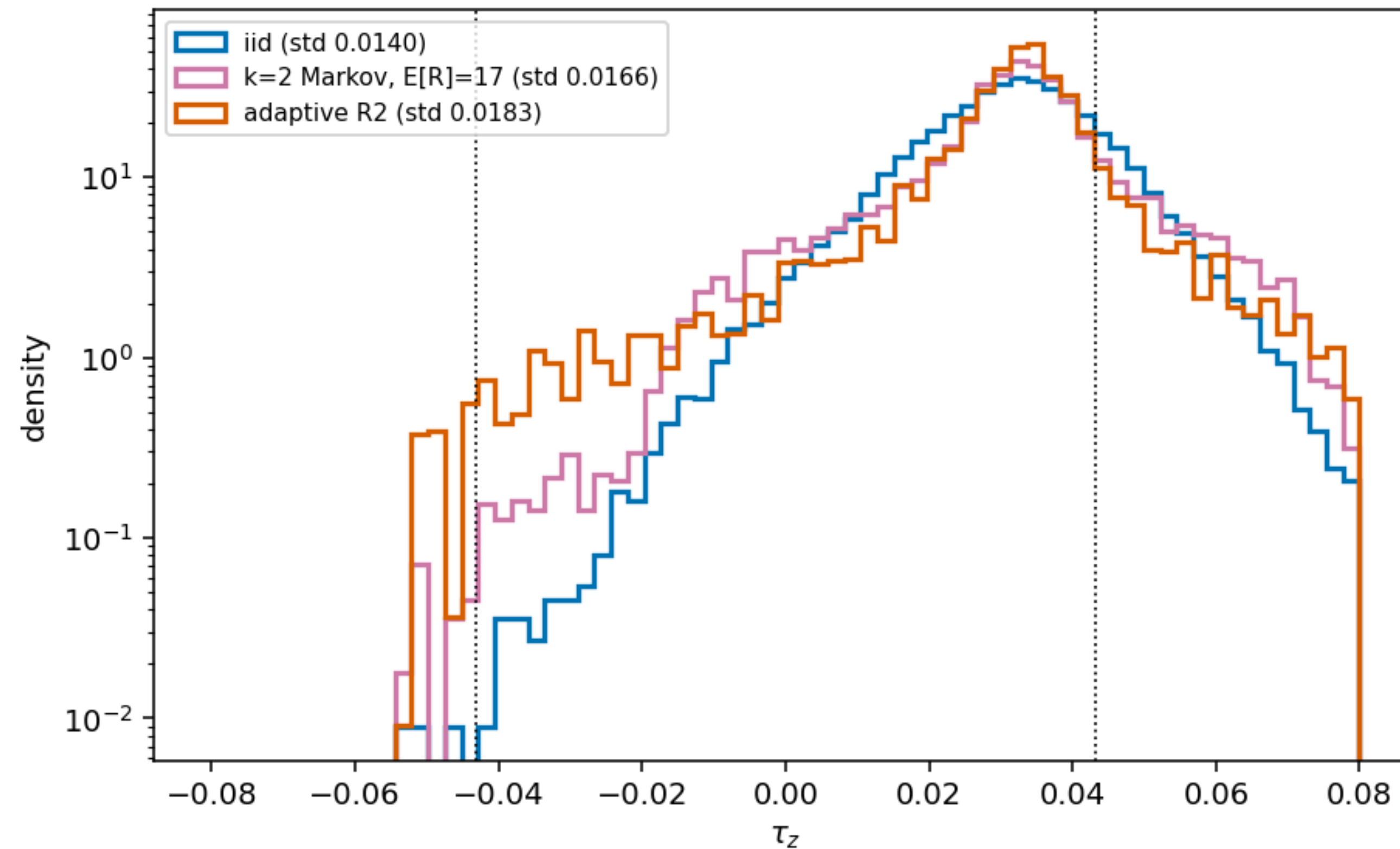
Symmetry + simple circuit reduce each map to one independent parameter

Distribution of shift of the center of the Bloch ball along z-axis

At late times:

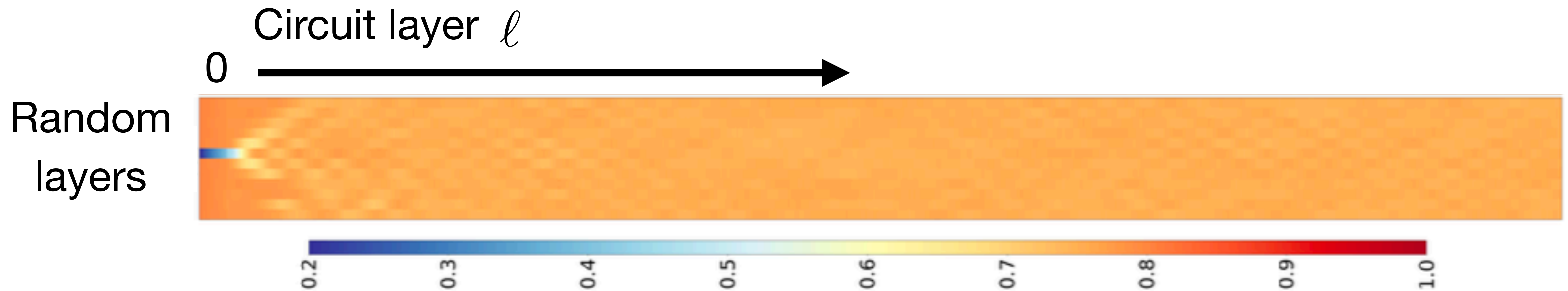


k-Markov sequences capture some (not all) of the behavior of the optimized circuits



N=8

Return to the homogenizing case

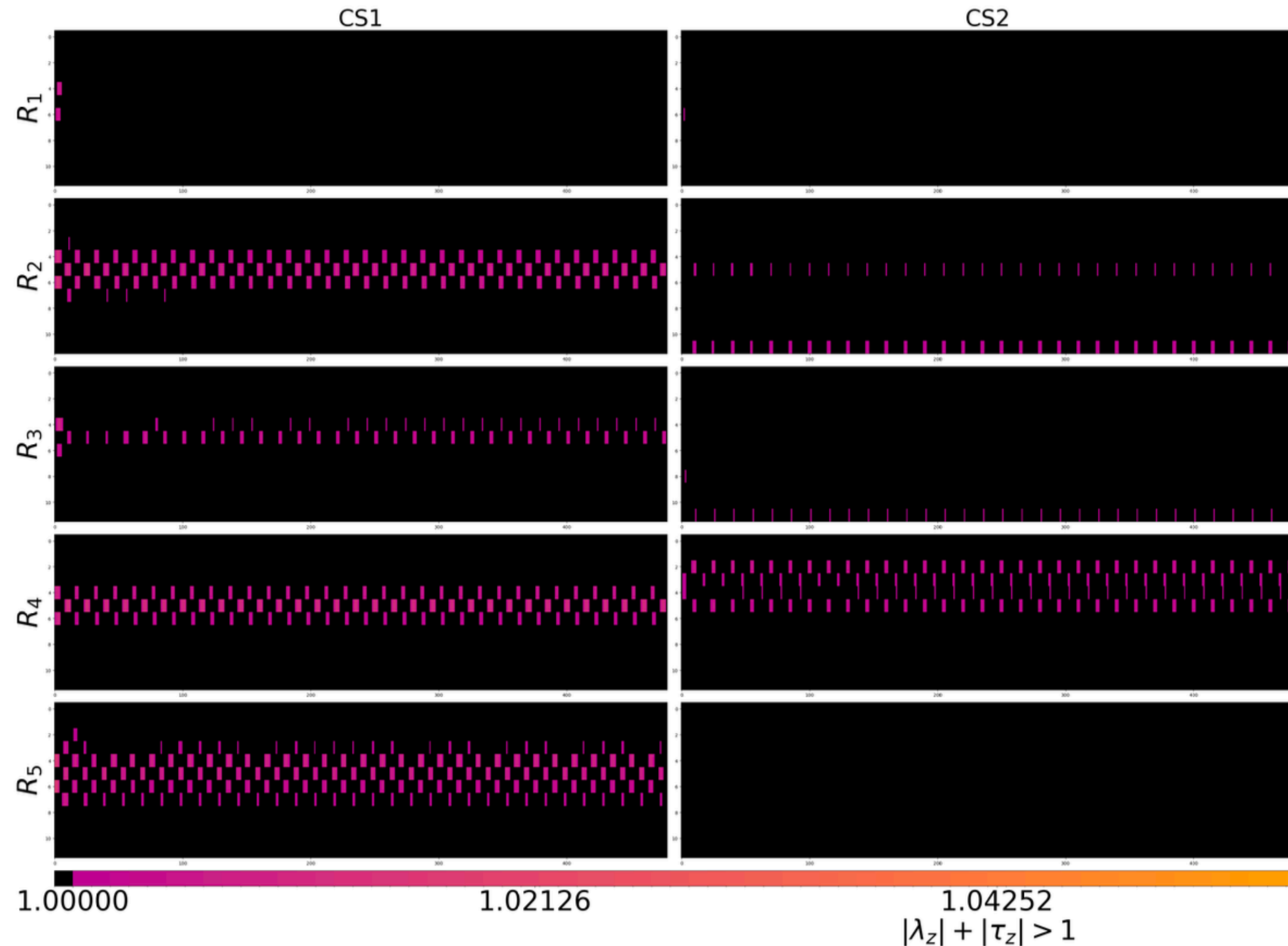


Each square is $\langle \langle \sigma_z^{(q)}(\ell) \rangle \rangle_{\text{ens.}}$

After many layers, expect maps are nearly the ‘thermalizing’ map
(Markovian dynamics)

We didn’t quite see that (finite size effects)

But, another view of the non-CP propagators

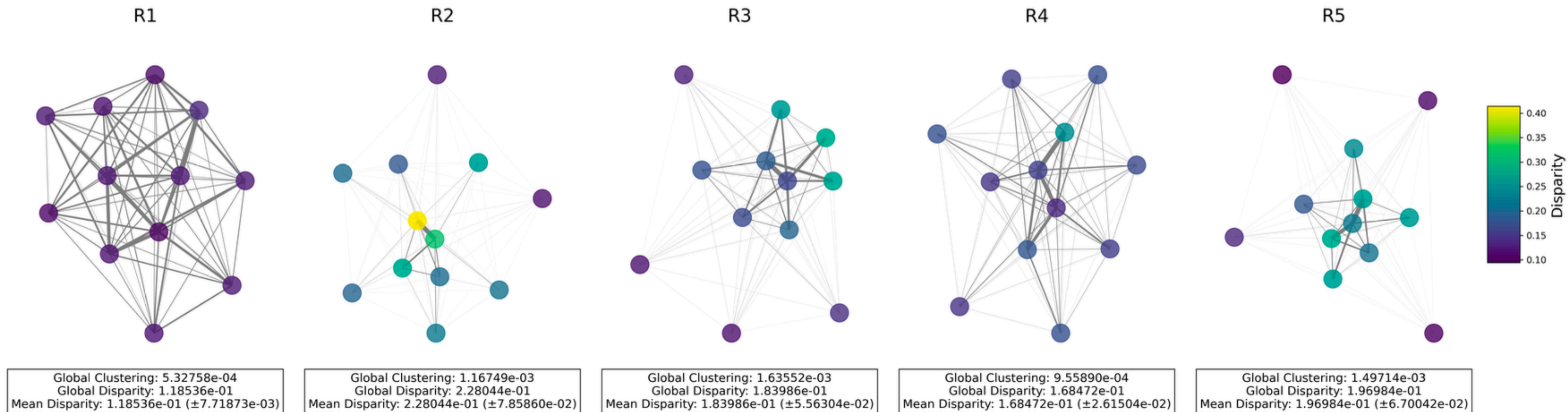


Calculate the propagators between average states at each layer

Removes all non-CP from random circuit

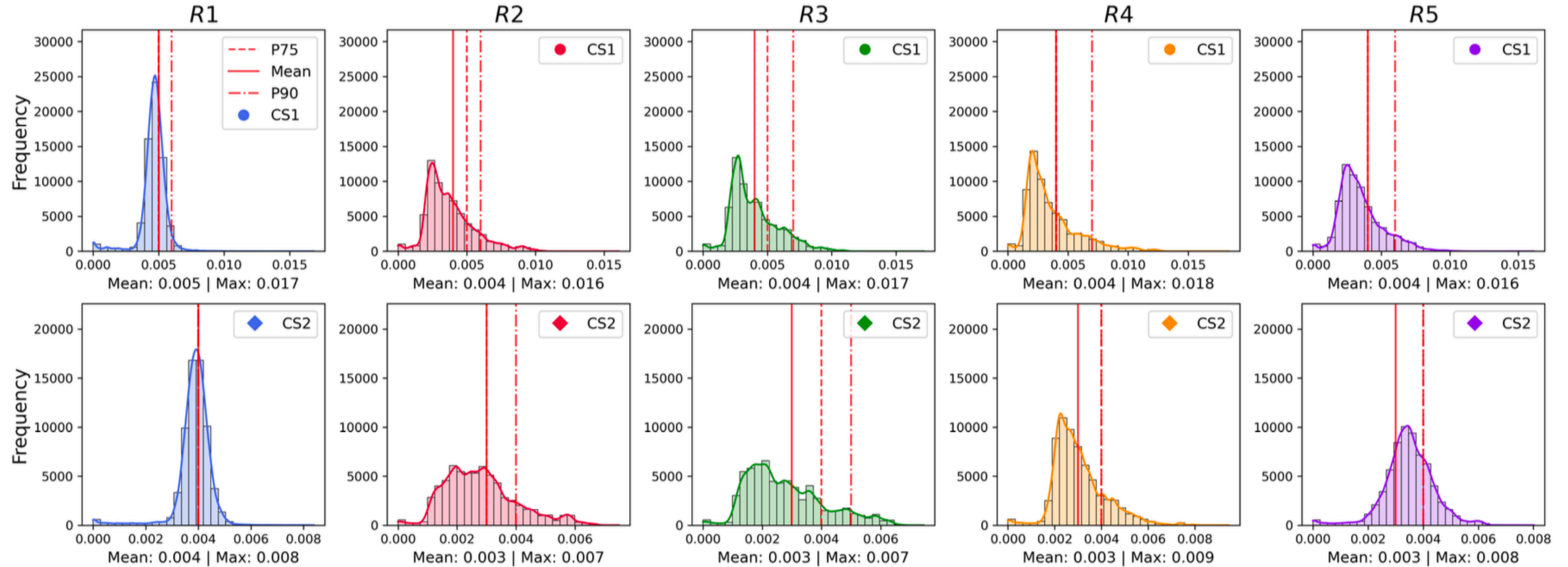
The structure of correlations is what turns up in the propagators

Example mutual information network for one initial state:



The structure of correlations is what turns up in the propagators

Histograms of the correlation that drives non-(C)P $\frac{1}{4}|C_{ab}^{xx}|$



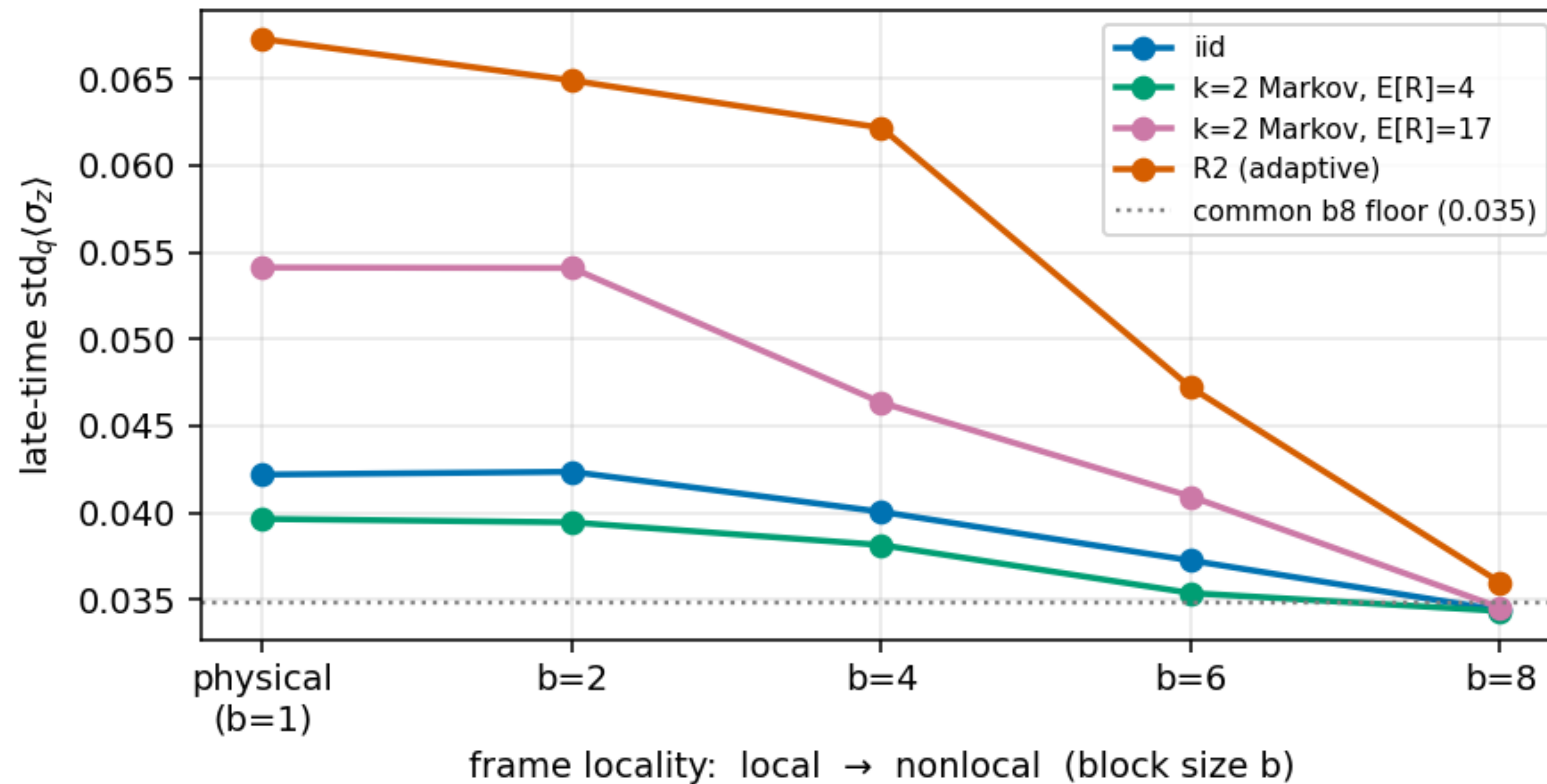
Back to the question of locality

Suppose an observer views the dynamics above in a different tensor product decomposition of the space (a different frame)

We will only consider frame changes that maintain the symmetry structure of the whole system: each single qubit still has phase-covariant dynamics

Within that set, we have a choice of how big of a subspace to rotate the frame in: rotate in the subspace of b qubits, $b=2, 4, 6, \dots$

Viewing the dynamics in a different frame erases inhomogeneity/late time memory



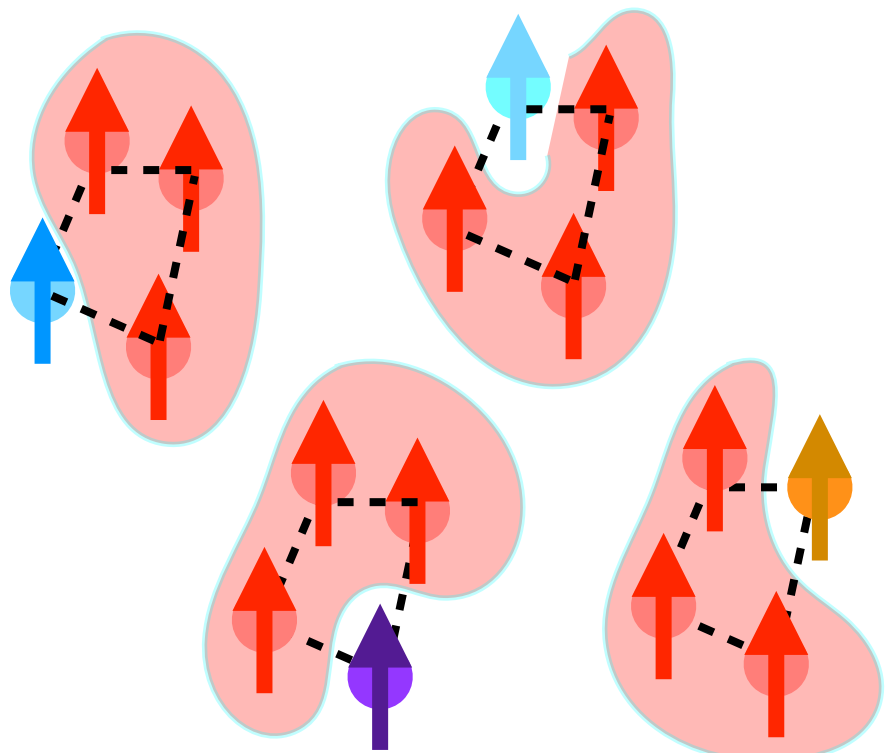
In other words...

Both frames have single-qubit subsystems that are equally ‘classical’

But the information

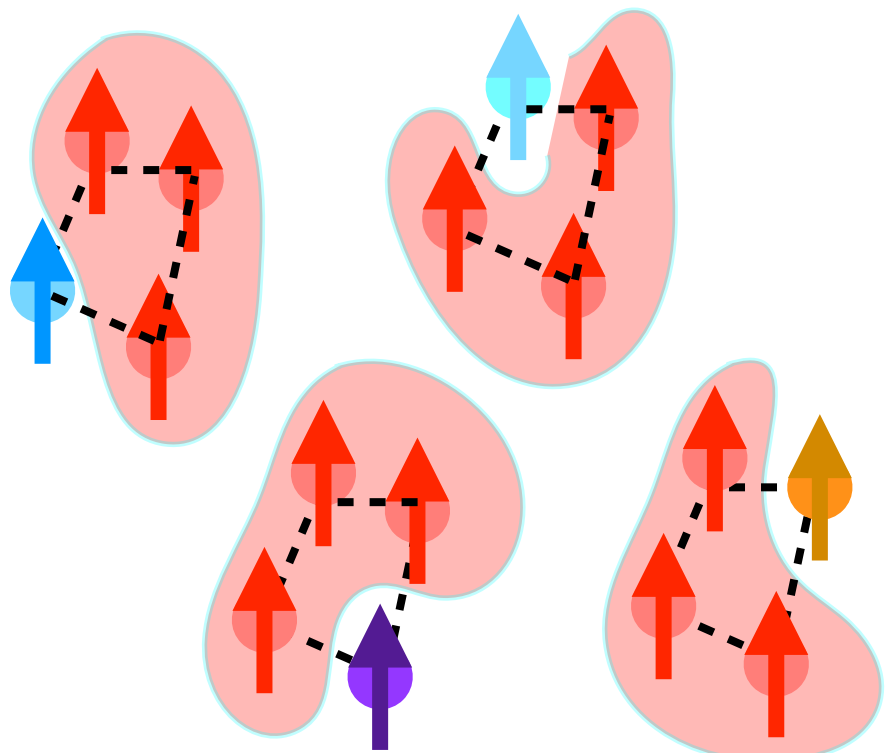
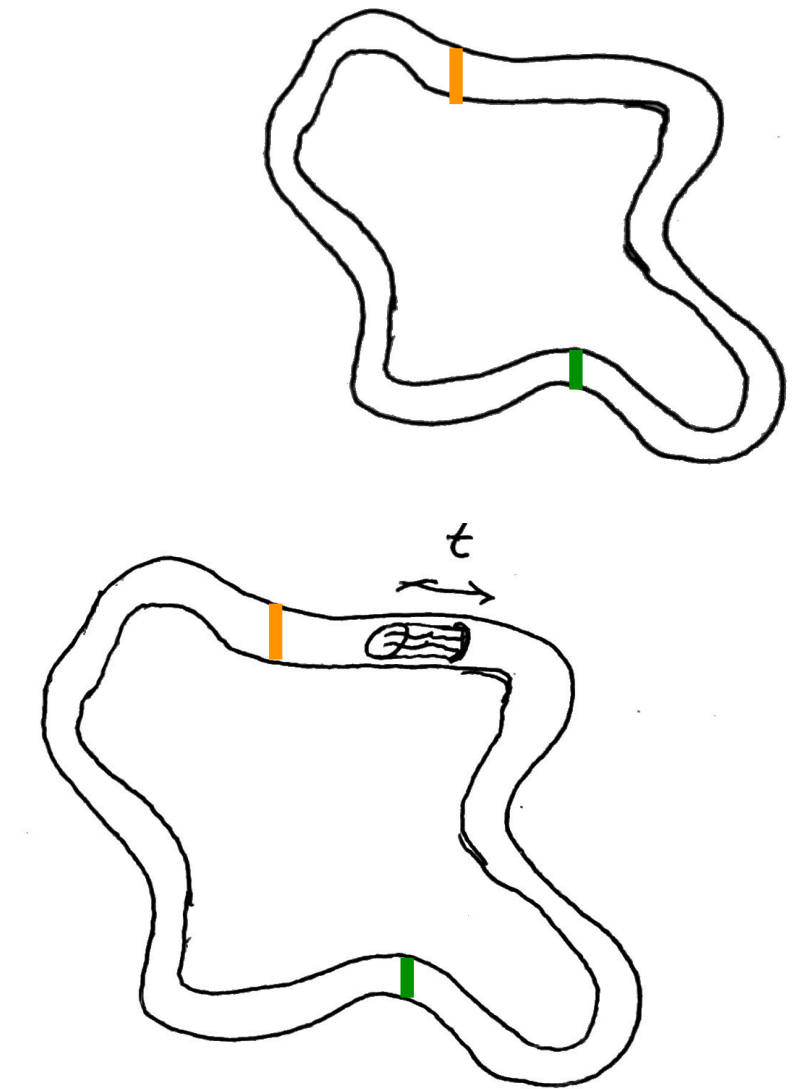
So far

- Built a bunch of ensembles of open systems
- Developed new tools to construct such ensembles
- Used standard QI tools to classify the dynamics
- We worked with ensembles of “maps”
 - removed privileged “initial” time



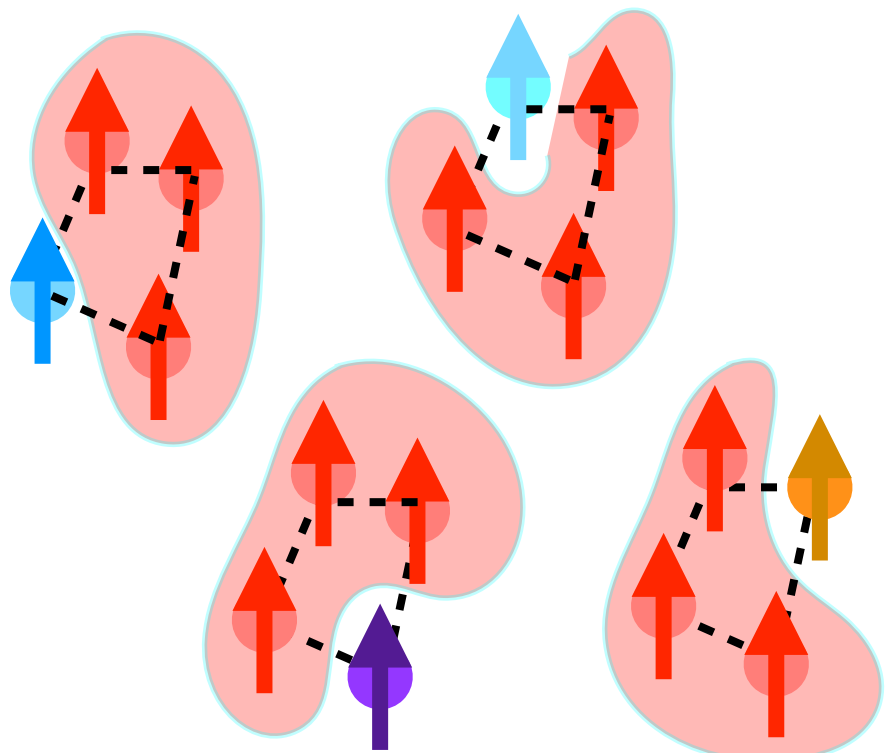
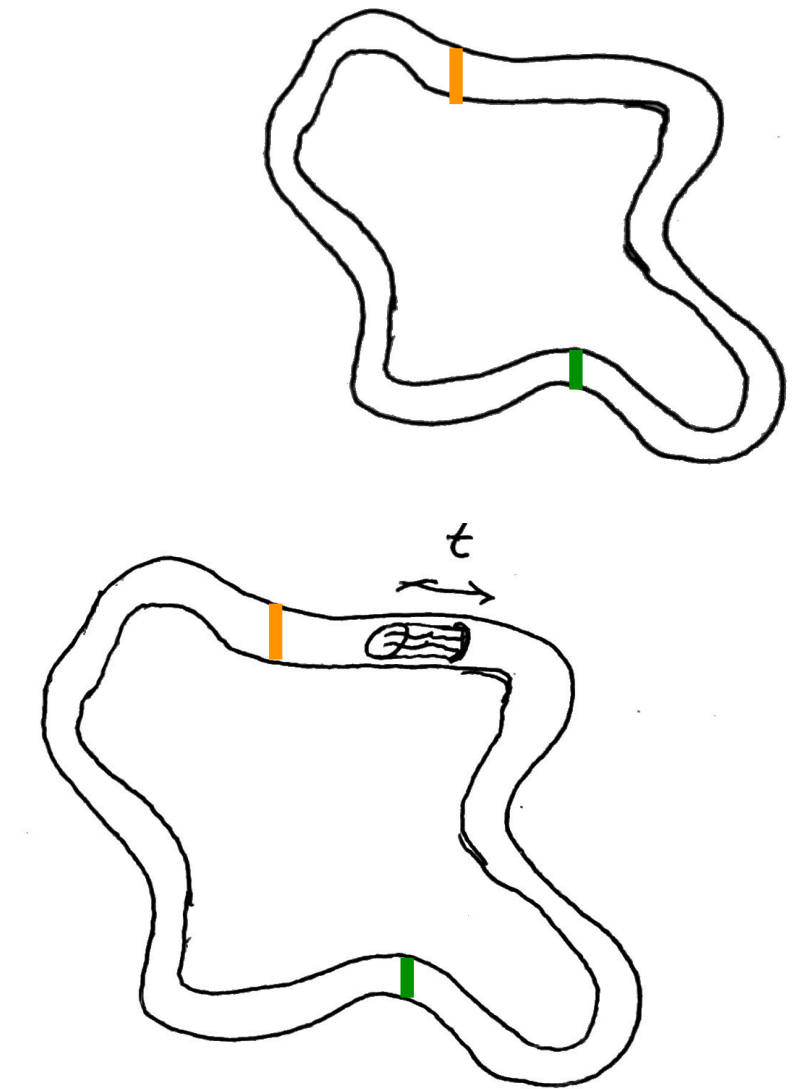
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- Developed new tools to construct such ensembles
- Used standard QI tools to classify the dynamics
- We worked with ensembles of “maps”
 - removed privileged “initial” time
- Tools allow us to explore locality
 - Suggests some future directions for organizing effective open theories and for understanding inference

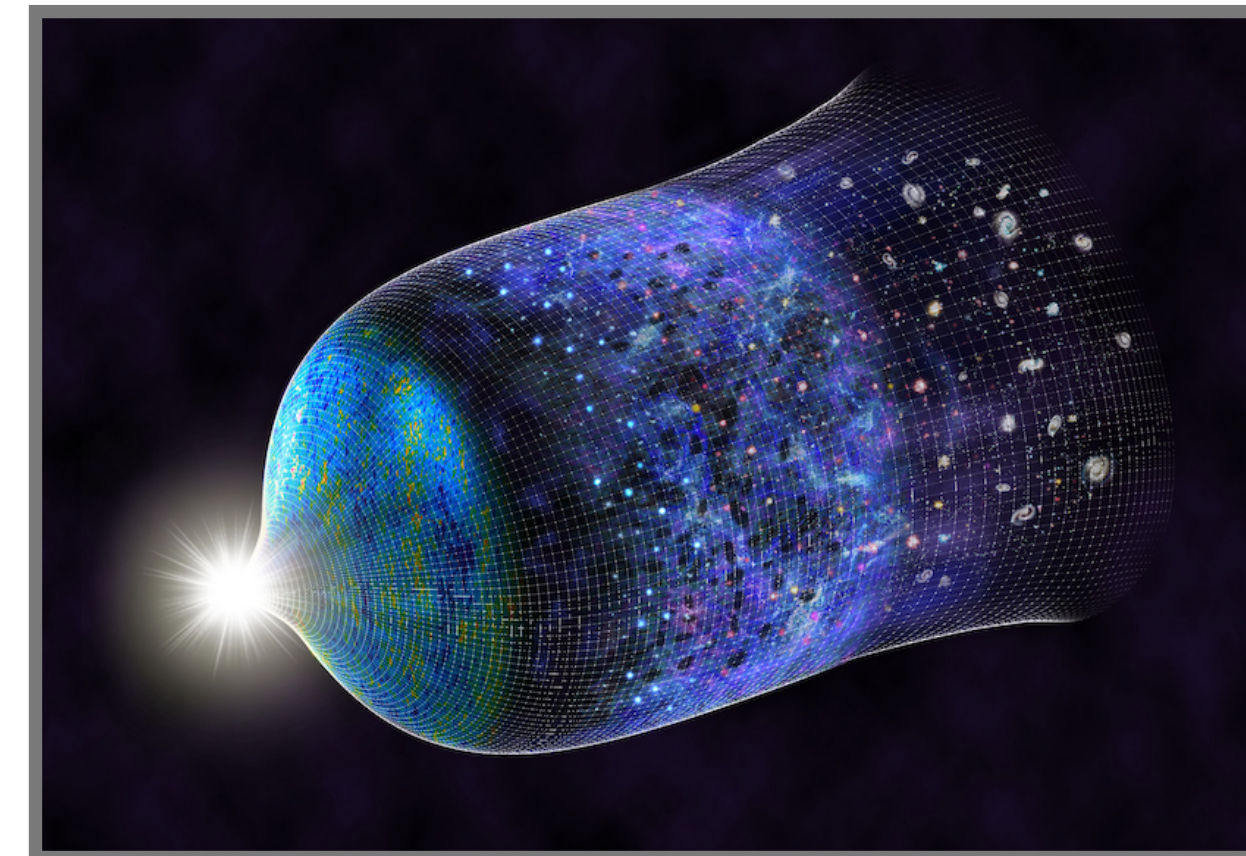
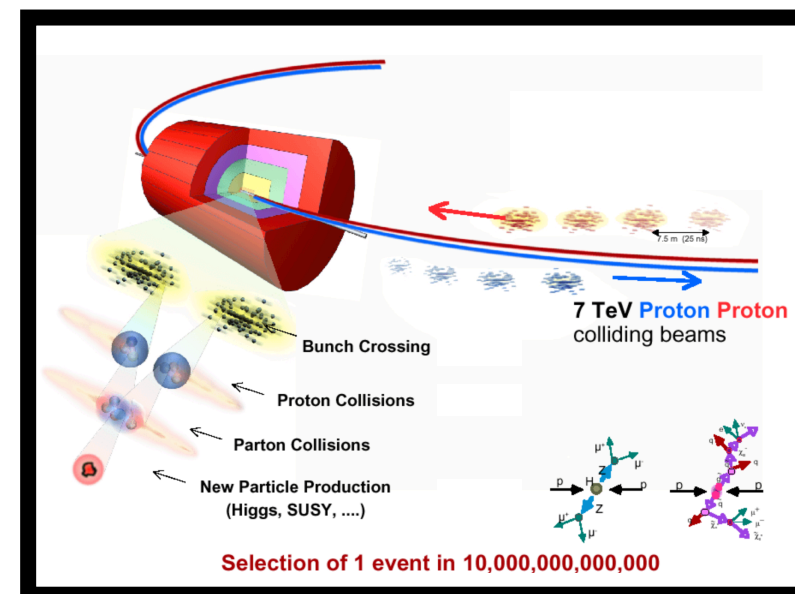


Past ~10 years

- Growing literature on OQS in particle physics and cosmology
- Continued progress in OQS thanks to laboratory many-body physics, AMO, quantum computers
- Theory moves forward when there is data

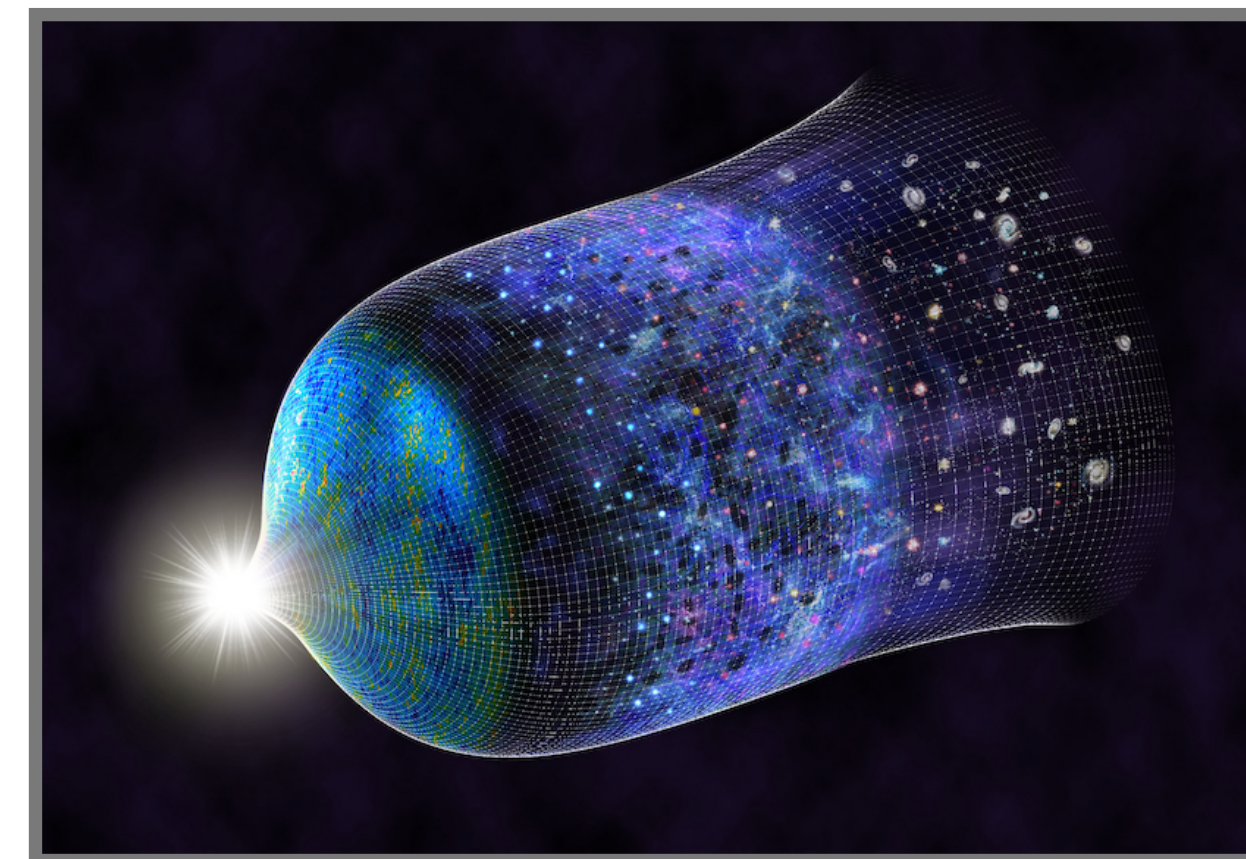
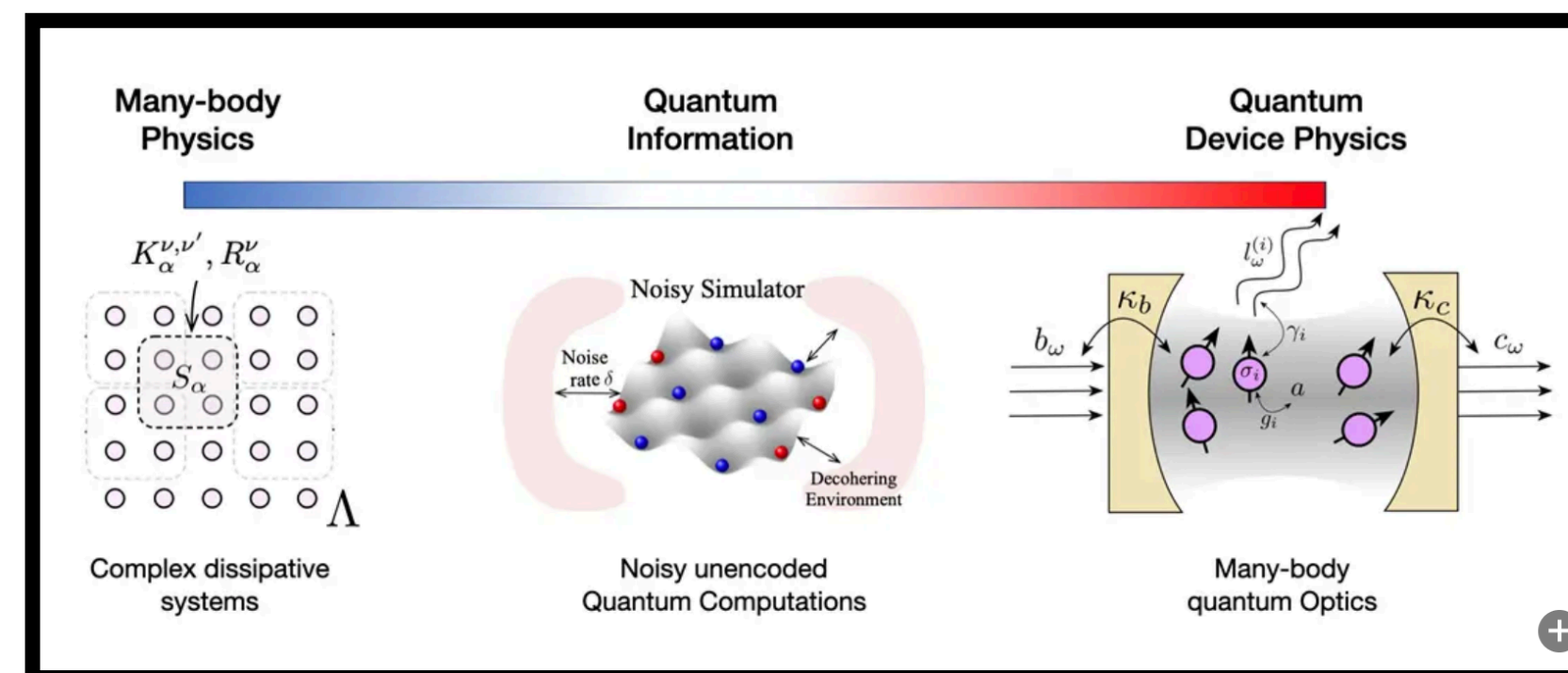
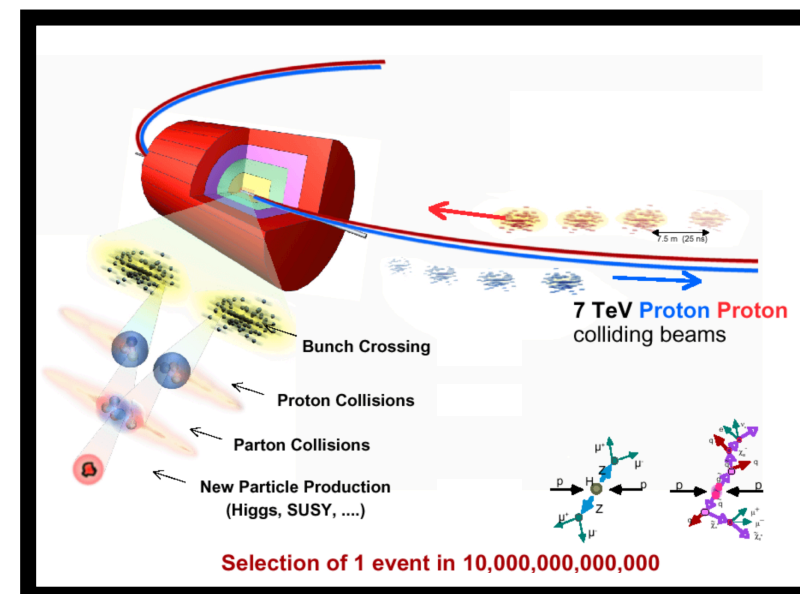
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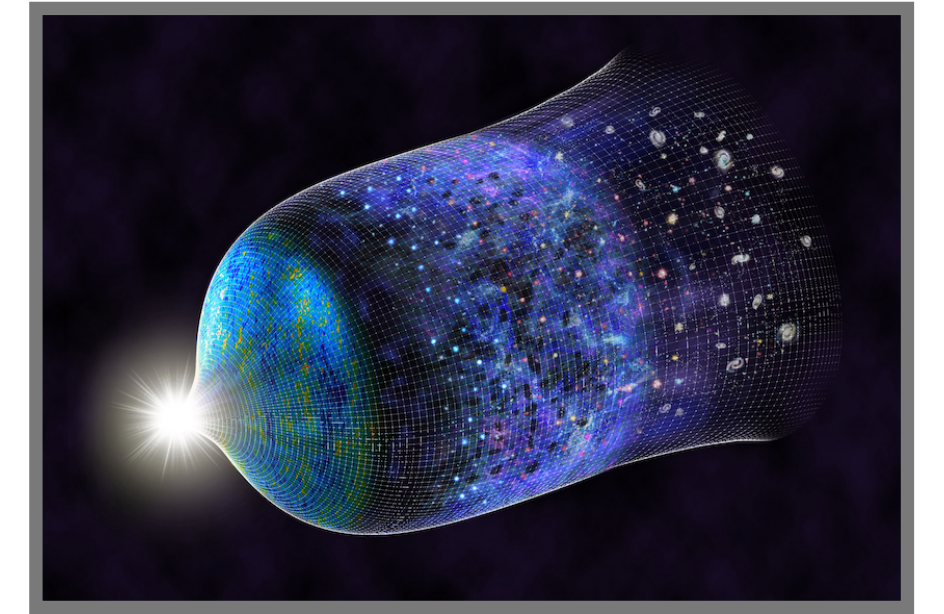


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Summary



- Quantum systems in gravitational backgrounds are open quantum systems
- Bet: Theory framework should be, at its foundations, a natural home for open quantum systems, including out-of-equilibrium systems
 - This is a long-term project!
- Opportunity to bring advances in open, out-of-equilibrium quantum systems into the toolkit of cosmology

