Title: Tiny universes from ensembles of open quantum systems

Speakers: Sarah Shandera

Series: Colloquium

Date: March 20, 2024 - 2:00 PM

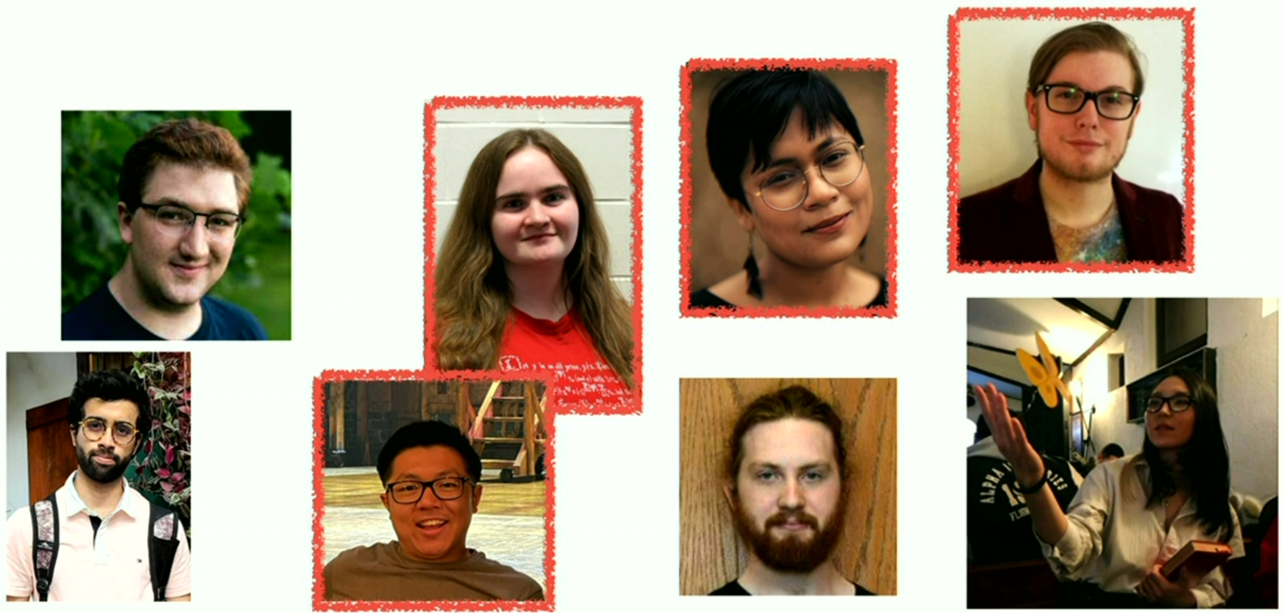
URL: https://pirsa.org/24030118

Abstract: Gravity creates space-time boundaries that limit observables without limiting the flow of energy and information. This means that quantum systems in cosmology are often open systems: to describe them we must include the effects of interaction with an unobservable environment. In many cosmological settings, different observers see different parts of the spacetime; the ensemble of the open systems for each observer makes up the full cosmology. In this talk I will introduce a class of out-of-equilibrium quantum systems constructed to mimic some key features of cosmology and demonstrate the utility of treating the full system as an ensemble of open systems. I will use these models to illustrate the possible connections between cosmological open quantum systems and thermodynamics, as well as open-systems-inspired ways to think about locality.

Zoom link

Tiny universes from ensembles of open quantum systems

Sarah Shandera
Penn State University
Institute for Gravitation and the Cosmos



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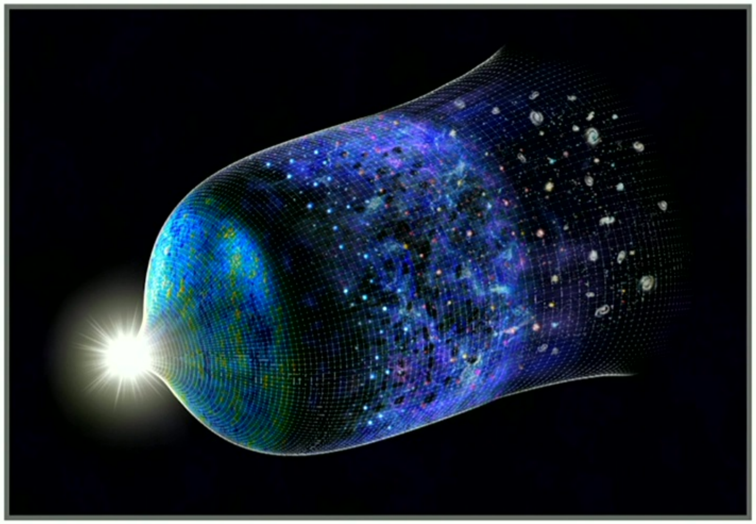
Cosmological puzzles



Nicole R. Fuller, NSF

What microphysics?

- What is the dark matter?
- Origin of the density inhomogeneities?
- Accelerated expansion?

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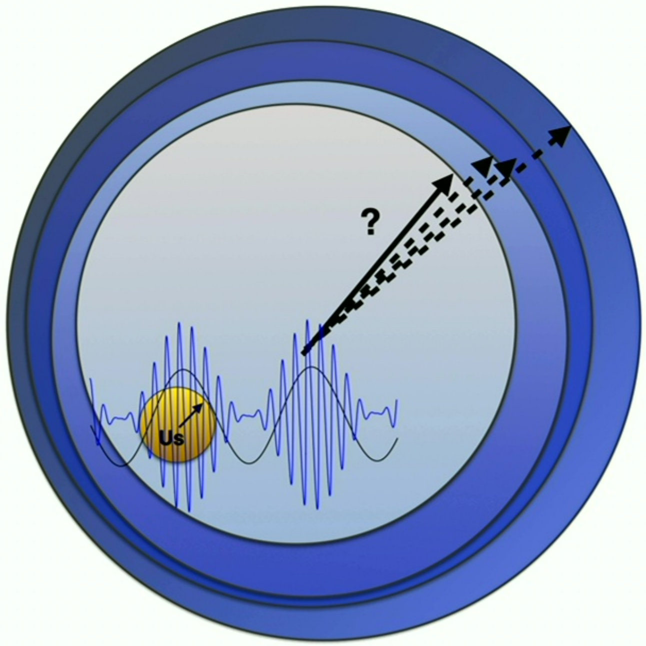
Inflation: exponentially more than us



E. Nelson, S. Shandera *PRL* 110 (2013), (1212.4550),
LoVerde, Nelson, Shandera, 1303.3549
Bonga, Brahma, Deutsch, Shandera, 1512.05365

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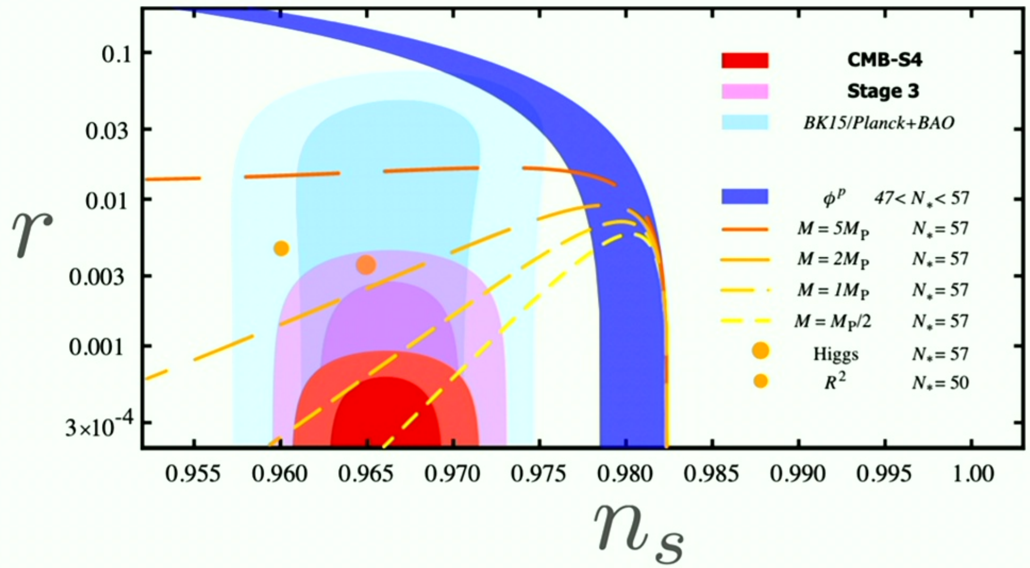
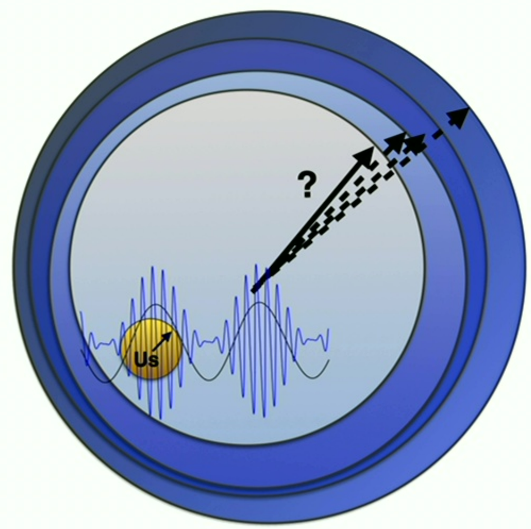
Effective theory for one patch





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1907.04473

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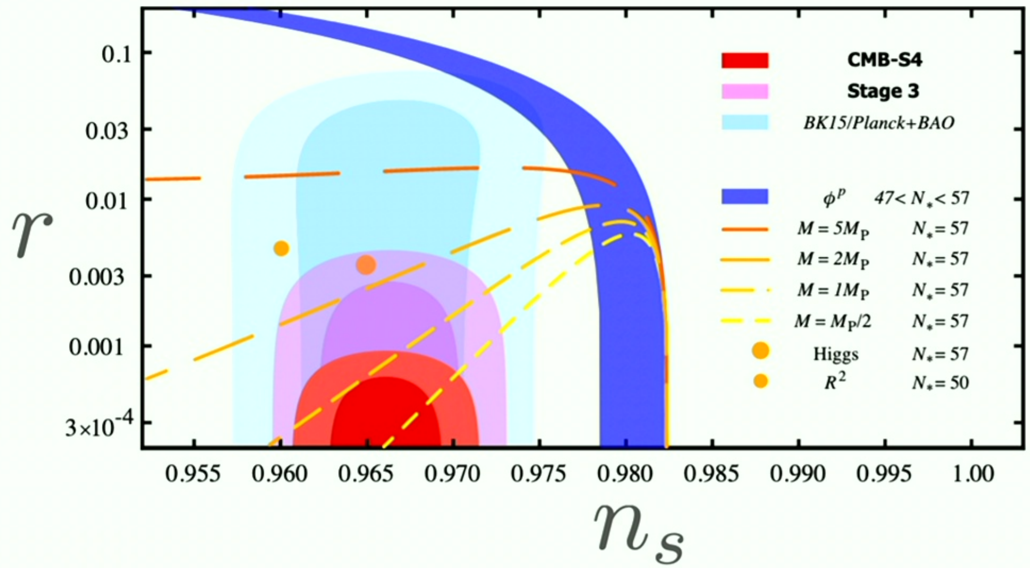
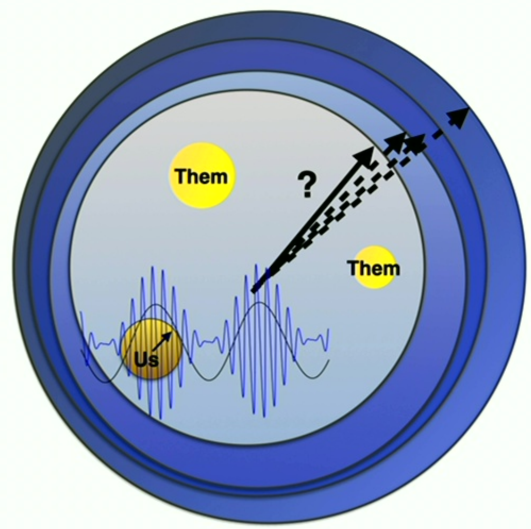
Effective theory for one patch
Global theory for the whole ensemble



Ensemble of open quantum systems



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1907.04473

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The issues are far more general than inflation

Gravity creates boundaries

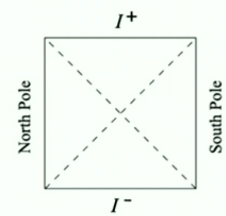
Quantum gravity for any observable region is generically an open quantum theory

Different observers (often) have different boundaries

How to put open systems together in compatible ways

…….open systems as building blocks

Event Horizon Telescope



Chandrasekharan et al 2206.10780; Alicki et al 2307.04800; Susskind 2304.00589; Jensen et al 2306.01837; many others

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Open systems in cosmology

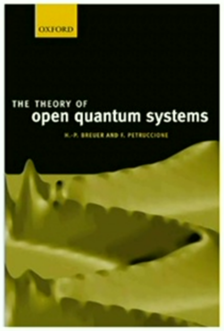
- Gravity generates boundaries, so open quantum systems natural (Hawking 1976; Israel 1976; Gibbons, Hawking 1977)
- Black holes: tracing out (scalar field) inside the black hole leads to the area law for entropy (Bombelli et al 1986; Srednicki 1993;)
- Quantum fields in inflation (de Sitter space) (Calzetta, Hu 1989; Brandenberger et al 1990)

But:

- Open systems were intensely studied outside of cosmology after this

E.B. Davies, 1976

→



Breuer, Petruccione, 2007

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Open systems in cosmology

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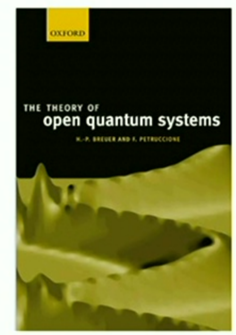
But:

- Open systems were intensely studied outside of cosmology after this
- Recent resurgence of interest (D. Boyanovsky, V. Vennin, J. Martin, C.P. Burgess, R. Holman, R. Brandenberger…)

E.B. Davies, 1976

→



Breuer, Petruccione, 2007

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What should the foundational theory look like?

Quantum-first

gravity

and

cosmology

Open quantum systems

Local structure not assumed

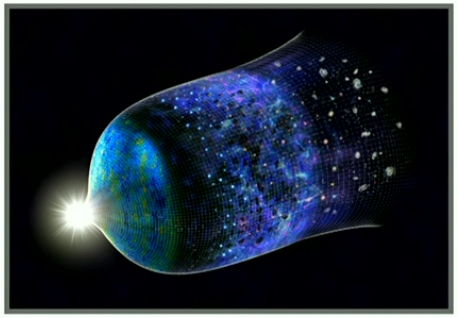
Ensembles of open quantum systems

Disordered systems

Inhomogeneous

out-of-equilibrium

slow to thermalize



Requires a serious foray into quantum systems

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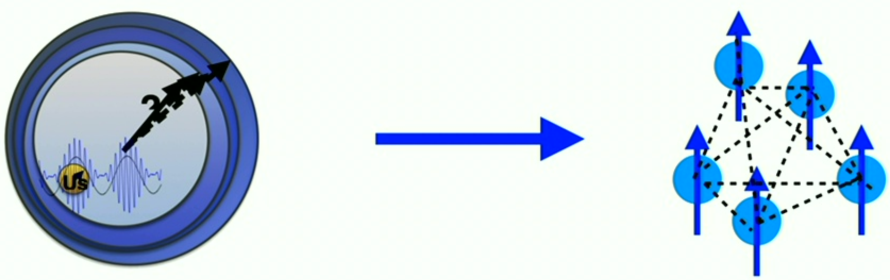
The rest of the talk

- Spin chains as ensembles of open systems
  (construct tools, benchmarks from a familiar set of problems)

- Tiny universes: co-evolving qubit systems and out-of-equilibrium dynamics



Exponentially huge → Tiny

Also: **Blahnik**, Shandera,
Coupled non-linear (non-Gaussian) oscillators

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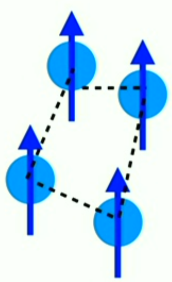
Cosmologist's view of a familiar system

$$H_{\rm XXZ} = h\sum_{i=1}^{N}\hat{\sigma}_i^z + \frac{J_\perp}{2}\sum_{i=1}^{N}(\hat{\sigma}_i^x\hat{\sigma}_{i+1}^x + \hat{\sigma}_i^y\hat{\sigma}_{i+1}^y) + \frac{J_\parallel}{2}\sum_{i=1}^{N}\hat{\sigma}_i^z\hat{\sigma}_{i+1}^z$$

- Any subset of spins is an open system
- The full chain is an ensemble of open systems



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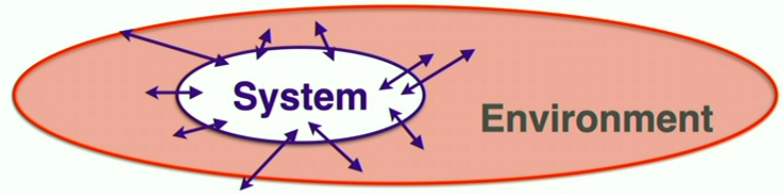
Open quantum systems

Master equation:



$$\frac{d}{dt}\text{(system)} = \text{(Hamiltonian of the system)}$$

$$+ \text{(losses to/gains from environment)}$$

$$\frac{d}{dt}\rho(t) = -i[H_{\text{free}}(t) + H_{\text{open}}(t), \rho(t)] + \text{(more)}$$

Dependent on environment

Non-unitary part

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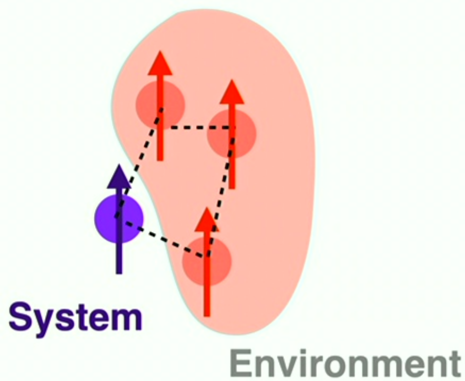
Dynamics of just one spin



$$\rho_S(t) = \mathrm{tr}_E\left[e^{-iHt}\rho_{SE}(0)e^{iHt}\right]$$

$$\rho_S(t) = \Lambda(t,0)\rho_S(0)$$

Dynamical map

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Open system evolution: Dynamical maps

Unitary evolution: maps pure states to pure states (and $\rho = |\psi\rangle\langle\psi|$)

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

$$U^\dagger U = \mathbb{I}$$

Dynamical maps are the open-systems generalization:

$$\Lambda : \rho(t_1) \mapsto \rho(t_2)$$

Sudarshan, 1961

A recent review: Jagadish, Petruccione, 1902.00909

Open system evolution: Dynamical maps

$$\Lambda : \rho(t_1) \mapsto \rho(t_2)$$

Write the density matrix as a vector: $\vec{\rho} = \begin{pmatrix} \rho_{11} \\ \rho_{12} \\ \rho_{21} \\ \rho_{22} \end{pmatrix}$

$\Lambda(t, 0)$ is a 4x4 matrix

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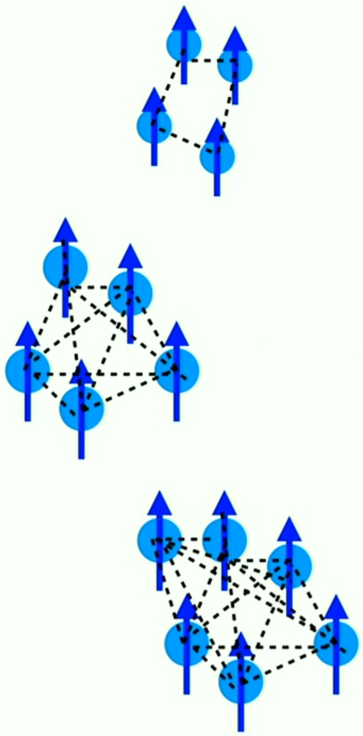
Form of the dynamical maps



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

Three important real parameters
(functions of time): $\lambda_1(t),\ \lambda_3(t),\ \tau_3(t)$

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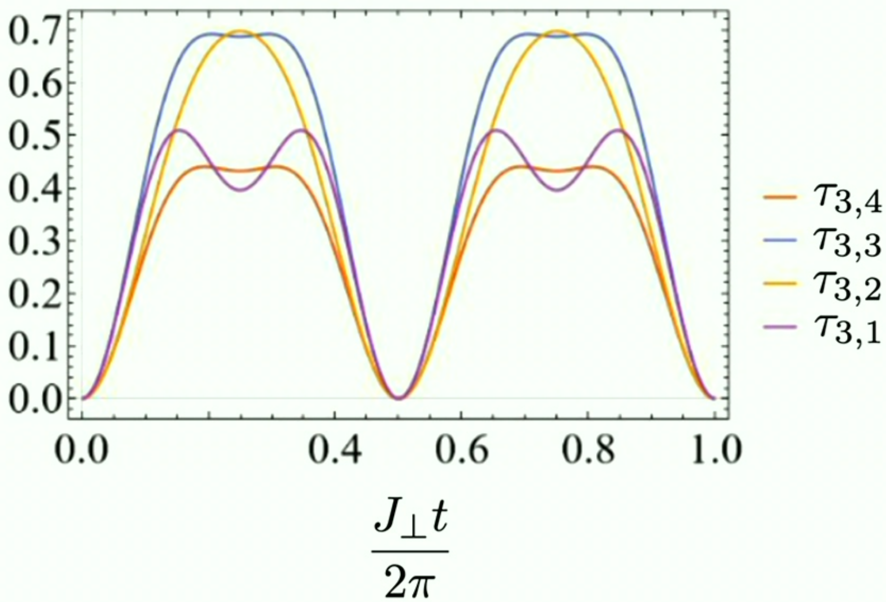
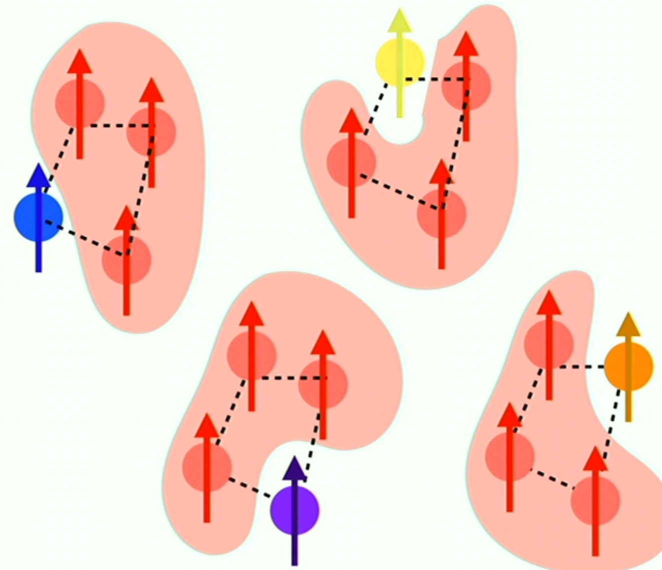
Ensembles of maps





$$\Lambda_i = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \lambda_{1,i}\cos\theta & -\lambda_{1,i}\sin\theta & 0 \\ 0 & \lambda_{1,i}\sin\theta & \lambda_{1,i}\cos\theta & 0 \\ \tau_{3,i} & 0 & 0 & \lambda_{3,i} \end{pmatrix}$$

$$J_\parallel = J_\perp$$

$$z_1 = 1, z_2 = \frac{1}{4}, z_3 = \frac{2}{4}, z_4 = \frac{3}{4}$$

Prudhoe, Akhouri, Chin, Shandera, 2404.xxxxx

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What should the foundational theory look like?

Quantum-first

gravity

and

cosmology

Open quantum systems

Ensembles of open quantum systems

Dynamically connected ensembles

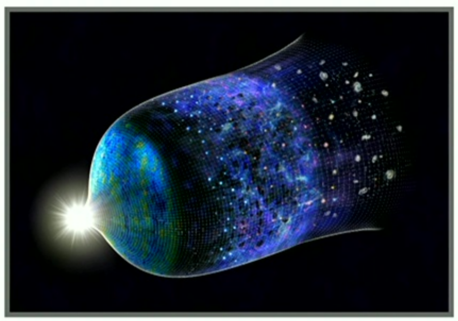
Local structure not assumed

Disordered systems

Inhomogeneous

out-of-equilibrium

slow to thermalize



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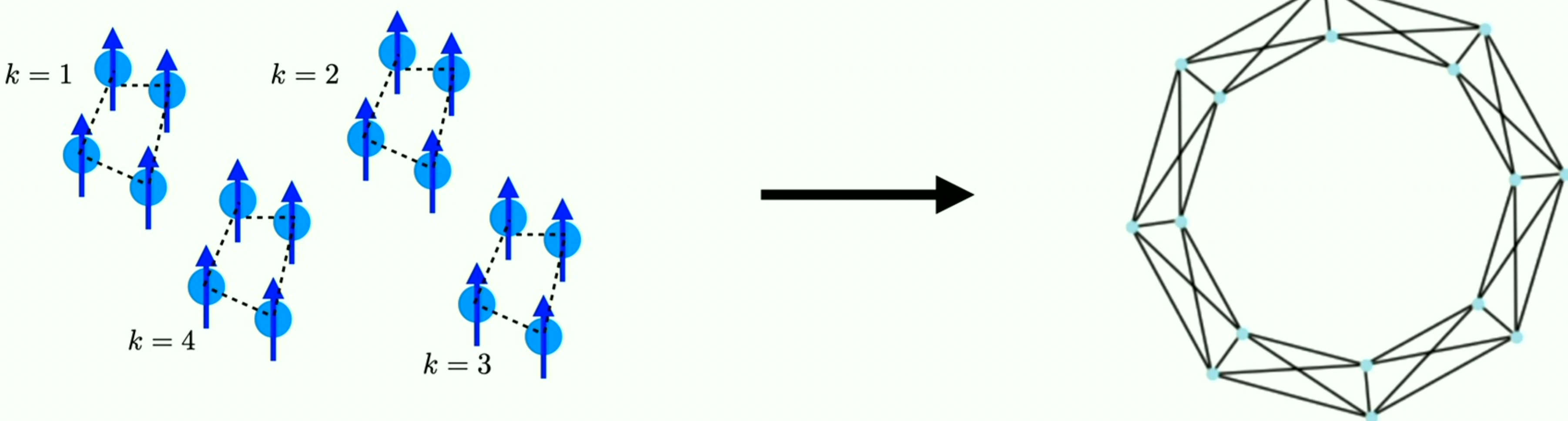
Local structure not assumed

Spin network structure is not restricted to be static



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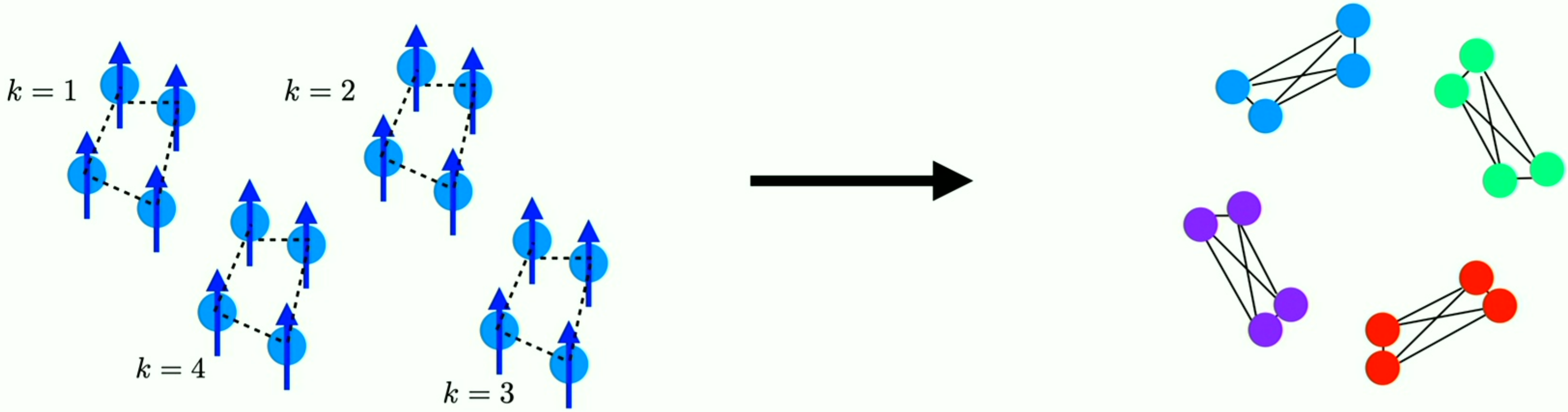
Dynamics without assumed structure



$$H_{\rm XXZ} = h\sum_{i=1}^{N}\hat{\sigma}_i^z + \frac{J_\perp}{2}\sum_{i=1}^{N}(\hat{\sigma}_i^x\hat{\sigma}_{i+1}^x + \hat{\sigma}_i^y\hat{\sigma}_{i+1}^y) + \frac{J_\parallel}{2}\sum_{i=1}^{N}\hat{\sigma}_i^z\hat{\sigma}_{i+1}^z$$

→

Discrete time steps,
$\{U_{k(t_i)}\}$ act on a changing subsystem structure

Co-evolving spin systems: Raducha et al 1707.09495; Co-evolving classical: Tasnim, Wolpert, 2305.09571;

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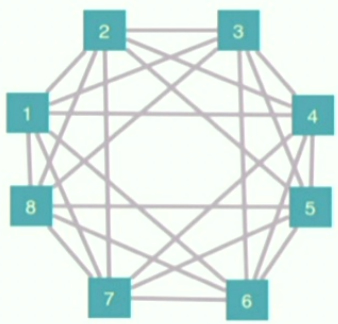
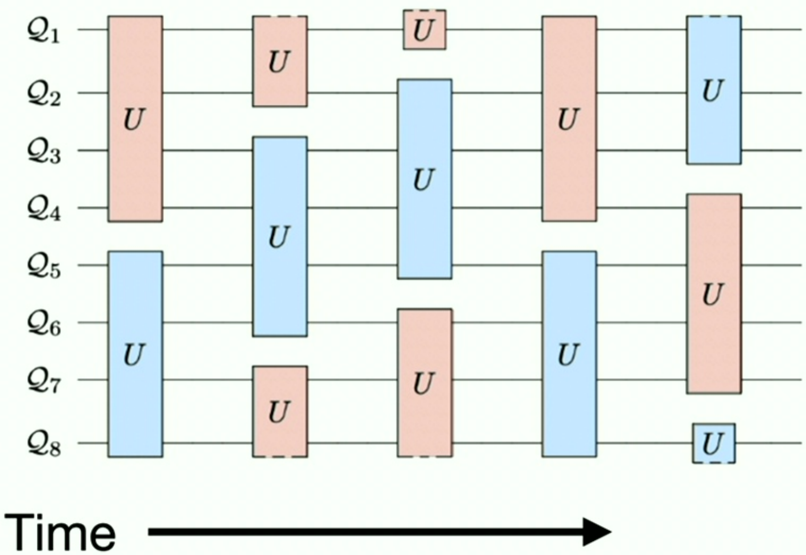
Dynamics: quantum circuits



Connectivity six allows eight-qubit circuits like this:



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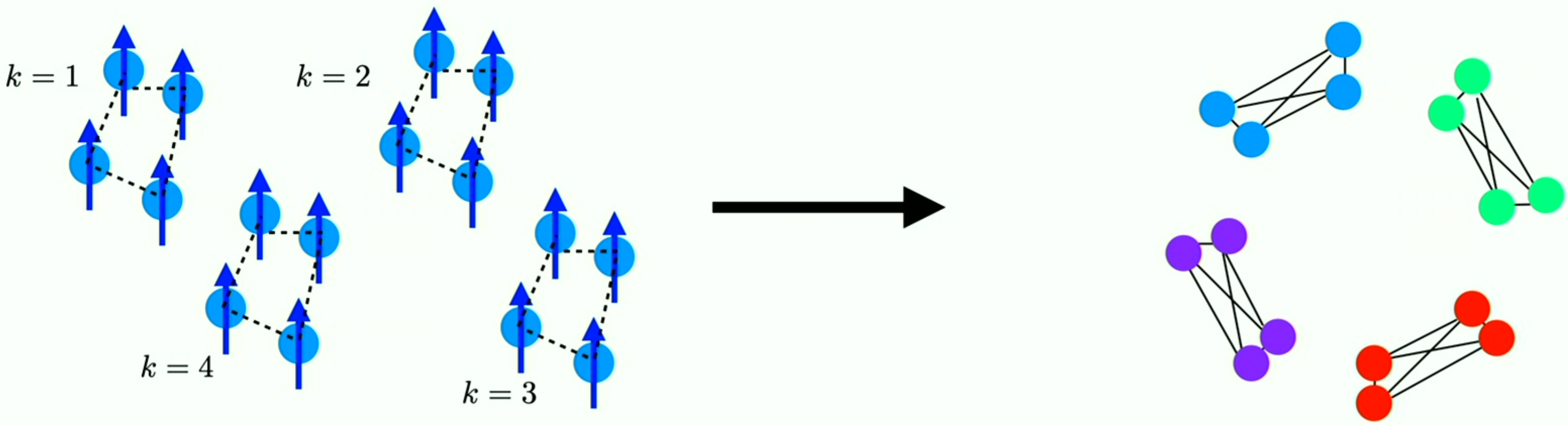
All spins become coupled with time



For any set of four spins:

$$U(t_2, t_0) = U(t_2, t_1)U(t_1, t_0)$$

$\longrightarrow$

$$\Lambda_{t_3,t_1} = \Theta_{t_3,t_2}\Lambda_{t_2,t_1}$$

$$\Theta_{t_3,t_2} \neq \Lambda_{t_3,t_2}$$

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Dynamical maps for the subsystems

$$\Phi_{t+1,t} = \begin{pmatrix} 1-\Delta & 0 & 0 & 1-\tilde{\Delta} \\ 0 & \Gamma & 0 & 0 \\ 0 & 0 & \Gamma & 0 \\ \Delta & 0 & 0 & \tilde{\Delta} \end{pmatrix}$$

Restriction $[\hat{H}_0, \hat{U}] = 0$ and thermal, uncorrelated initial state enforce this structure

$$\Lambda = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \lambda_1 \cos\theta & -\lambda_1 \sin\theta & 0 \\ 0 & \lambda_1 \sin\theta & \lambda_1 \cos\theta & 0 \\ \tau_3 & 0 & 0 & \lambda_3 \end{pmatrix}$$

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These are not quite thermalizing maps

Tiny universe maps:

$$\Phi_{t+1,t} = \begin{pmatrix} 1-\Delta & 0 & 0 & 1-\tilde{\Delta} \\ 0 & \Gamma & 0 & 0 \\ 0 & 0 & \Gamma & 0 \\ \Delta & 0 & 0 & \tilde{\Delta} \end{pmatrix}$$

Davies map:

Roga et al (0911.5607)

$$\Phi_S = \begin{pmatrix} 1-a & 0 & 0 & a\,p/(1-p) \\ 0 & c & 0 & 0 \\ 0 & 0 & c & 0 \\ a & 0 & 0 & 1-a\,p/(1-p) \end{pmatrix}$$

{p, 1-p} Gibbs state

CP, Markovian dynamics from interaction with an infinite bath

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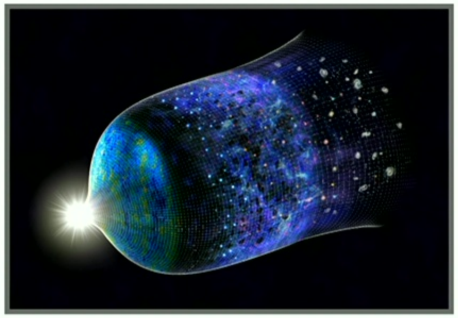
Why focus on out-of-equilbrium?

Thermalized systems: all subsystems are equally informative about the whole systems

cosmology



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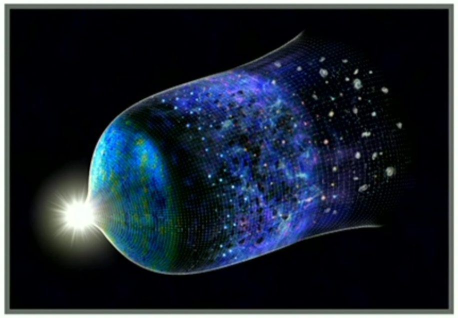
Why focus on out-of-equilbrium?

Thermalized systems: all subsystems are equally informative about the whole systems

Out-of-equilibrium: now the story of subsystems is interesting

cosmology



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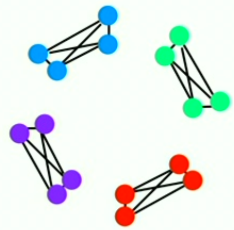
Interesting tiny universes



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

Out-of-equilibrium? What measure?

- Thermodynamic: Change in extractable work
- Network complexity of mutual information

Resist thermalization? Anderson 1958; Deutsch 1994; Moudgalya et al 2109.00548

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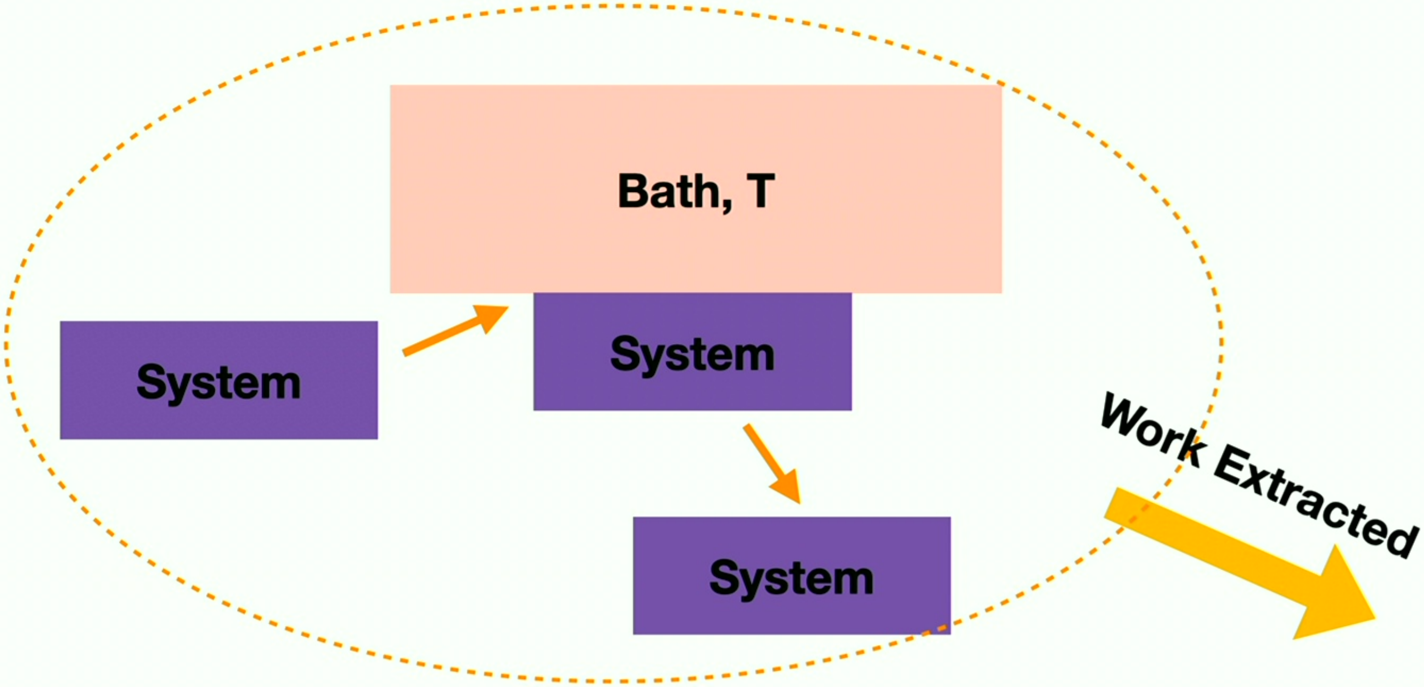
Interesting?
1. Extractable Work



Kolchinsky, Marvian, Gokler, Liu, Shor, Shtanko, Thompson, Wolpert, Lloyd, 1705.00041
Brandão et al, 1111.3882; Batteries: García-Pinto et al 1909.03558; Shi et al 2205.11080,

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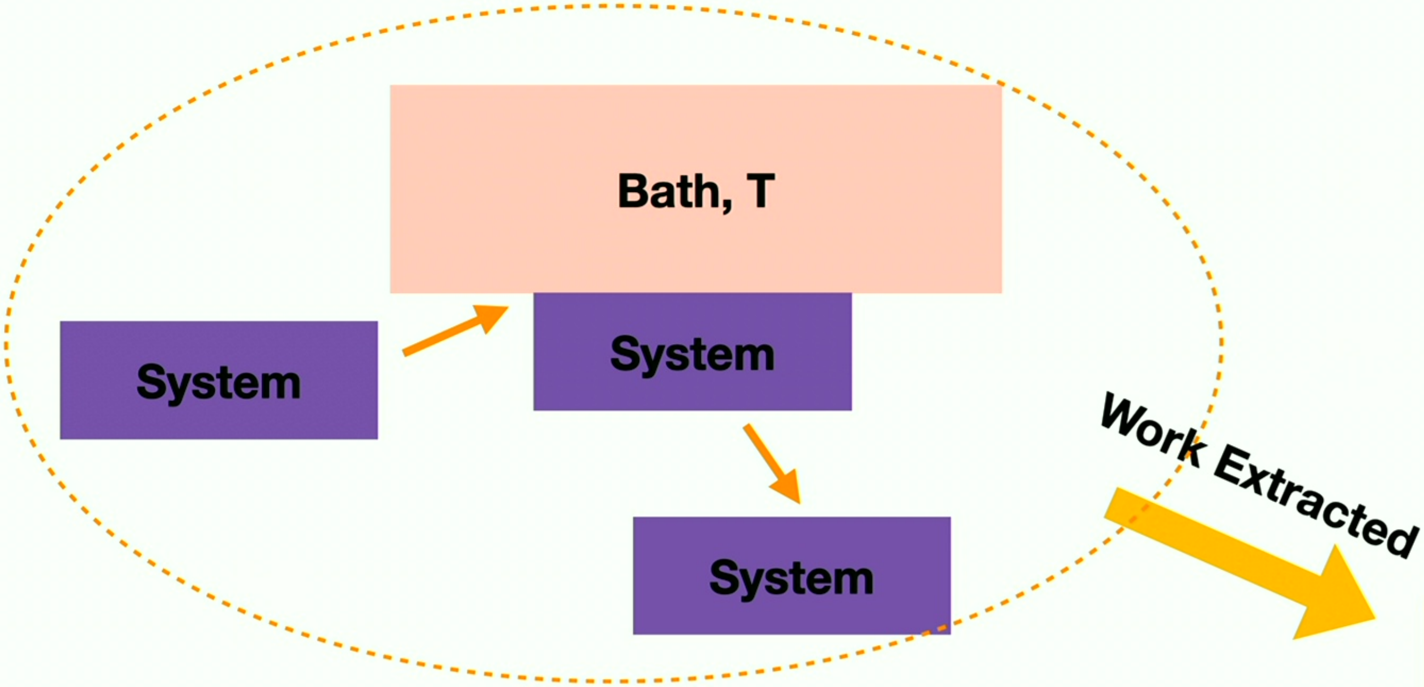
Interesting?
1. Extractable Work



Study evolutions for which an increase in extractable work is possible

$$\Delta W^{\mathrm{ex}} > 0$$

$$W^{\mathrm{ex}} = \mathcal{F}(p) - \mathcal{F}_{\mathrm{th}}(p_{\mathrm{th}})$$
$$= TD(\rho||\rho_{\mathrm{th}})$$

Kolchinsky, Marvian, Gokler, Liu, Shor, Shtanko, Thompson, Wolpert, Lloyd, 1705.00041
Brandão et al, 1111.3882; Batteries: García-Pinto et al 1909.03558; Shi et al 2205.11080,

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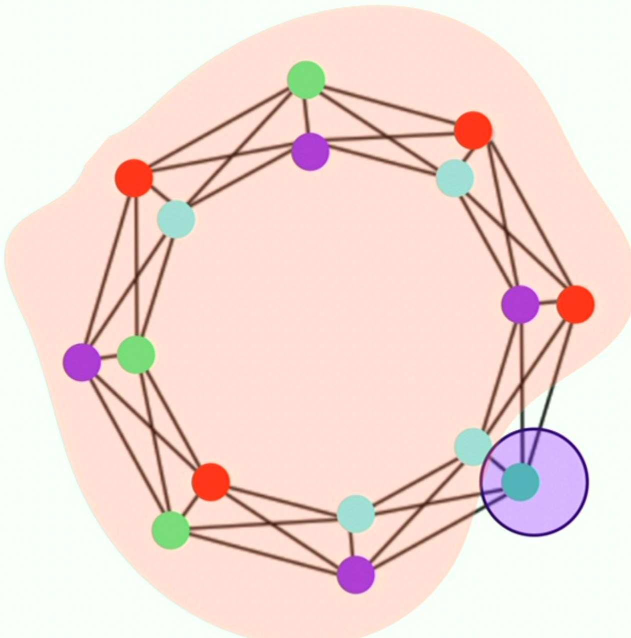

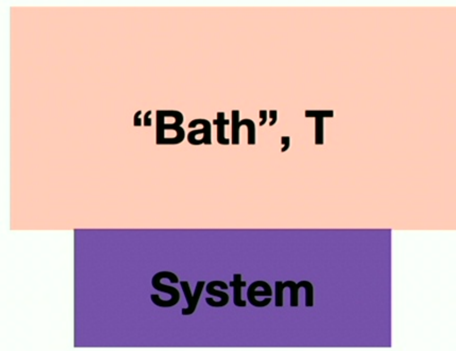

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Kolchinsky, Marvian, Gokler, Liu, Shor, Shtanko, Thompson, Wolpert, Lloyd, 1705.00041

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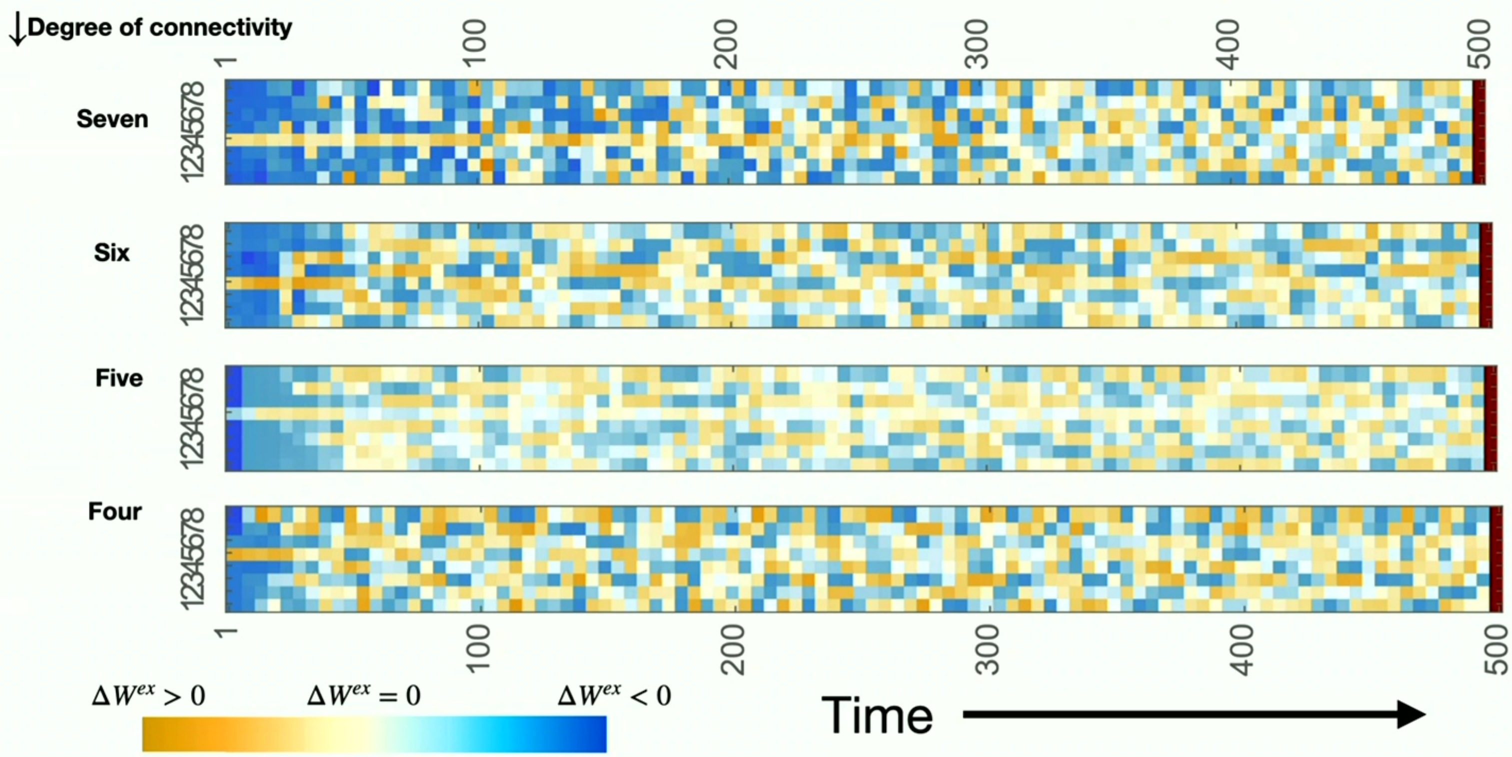
Evolution of $\Delta W_{\rm ex}$



Akhouri, Shandera, Yesmurzayeva, 2203.10928, *Entropy*

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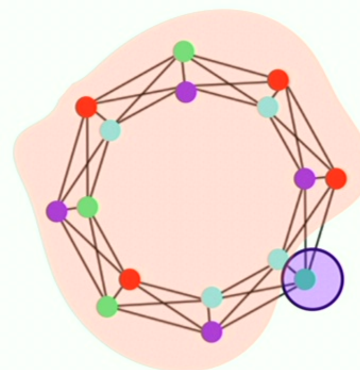
Temperature on the landscape

Single qubit states remain thermal

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

↓

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



Environmental temperature: average over the other qubits

A different choice for bipartite systems: fold in the correlation to the notion of temperature (Alipour et al 2105.11915)

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Dynamical maps and $\Delta W_{\rm ex}$

Explore the properties that support landscapes with "interesting" substructure

- Role of quantum correlations: dynamical maps
- Consistency conditions on ensemble of open systems
- Role of connectivity, dynamical interaction domains, interaction type

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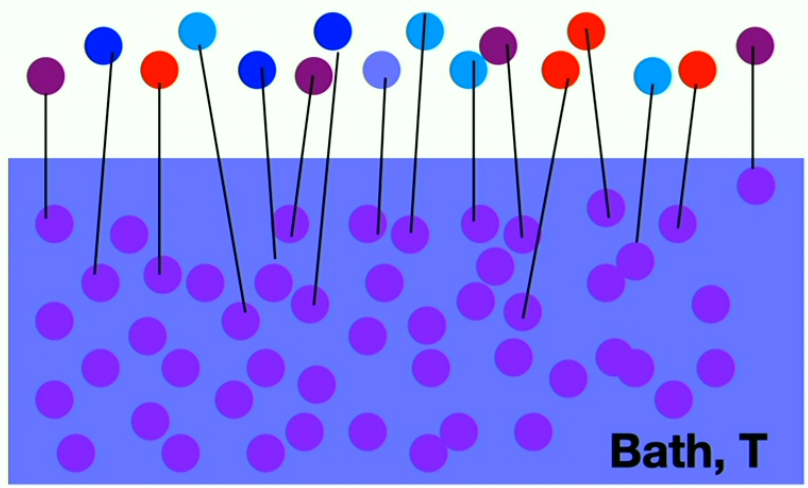
Contrast collisional model (Thermalization)



Repeated interactions with unchanging bath qubits

$$T = \langle T_{\rm i,initial} \rangle$$

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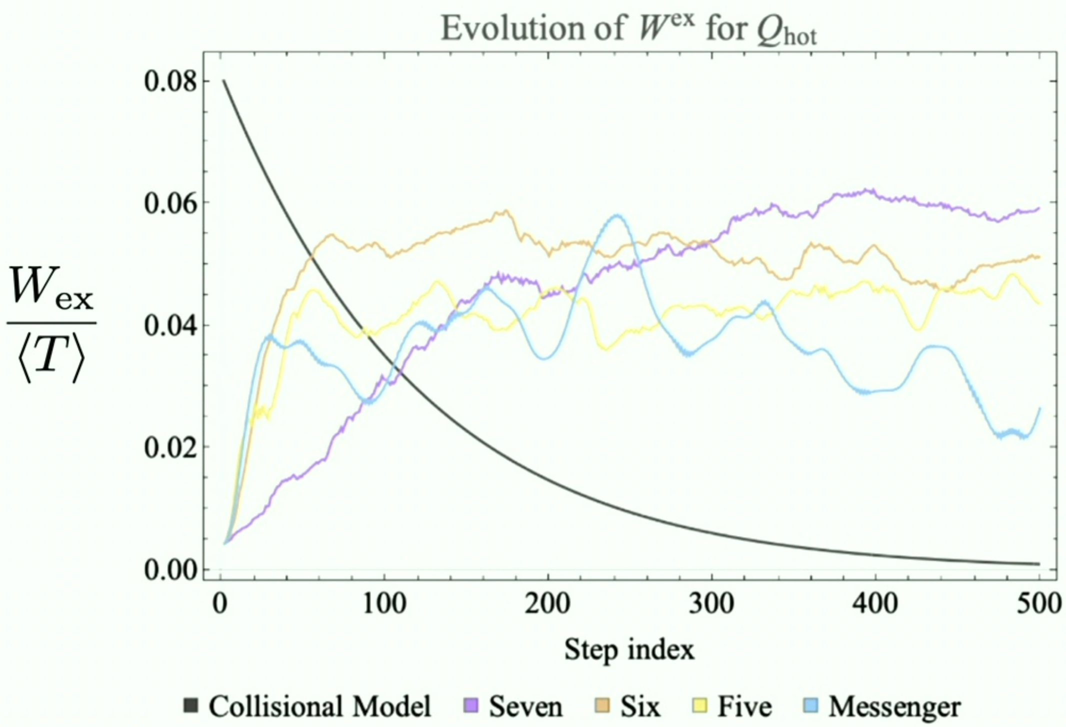
Contrast collisional model



Monotonic decrease in collisional case

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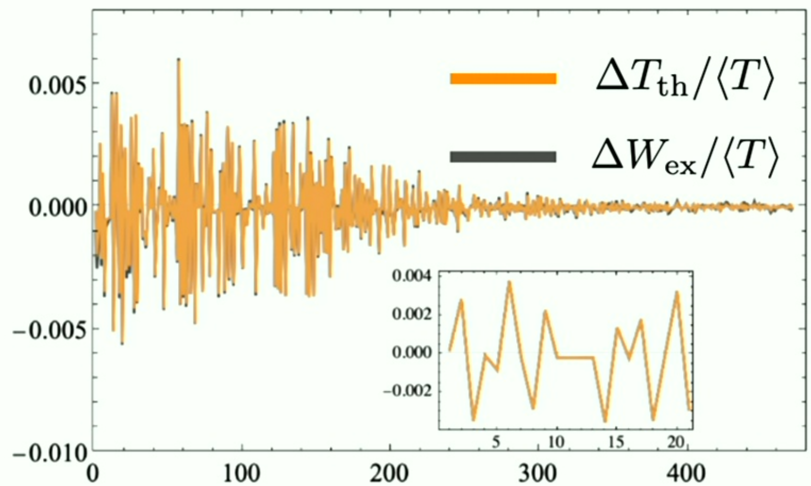
Role of quantum correlations

Throw out correlations at each step



Non-monotonic decrease of all quantities

Akhouri, Shandera, Yesmurzayeva, 2203.10928, *Entropy*

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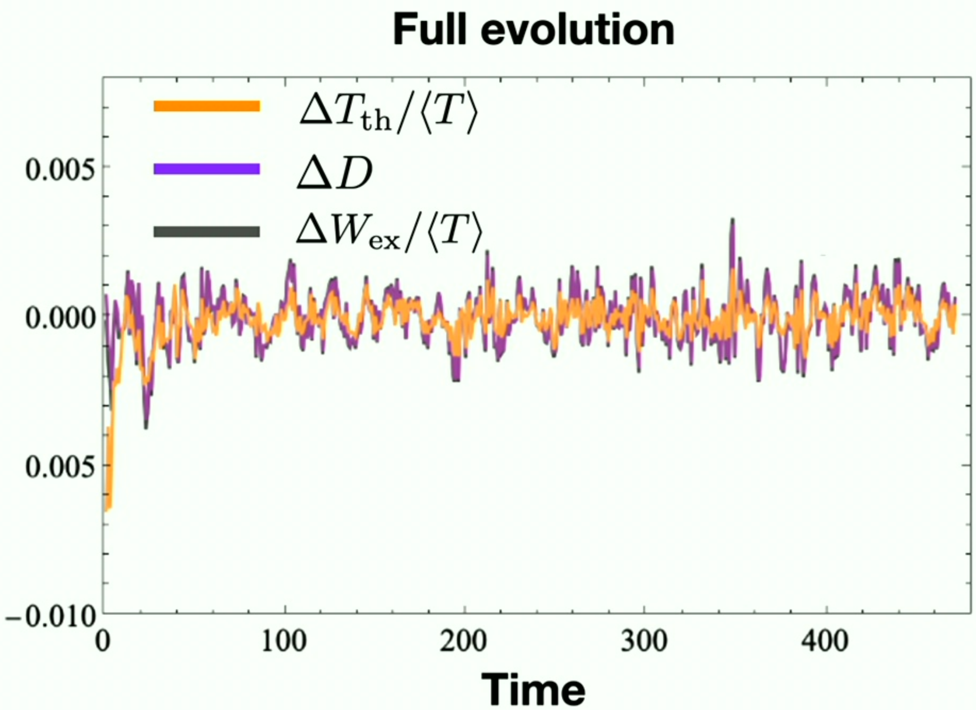
Full evolution: keep the correlations



Kolchinsky, Marvian, Gokler, Liu, Shor, Shtanko, Thompson, Wolpert, Lloyd, 1705.00041

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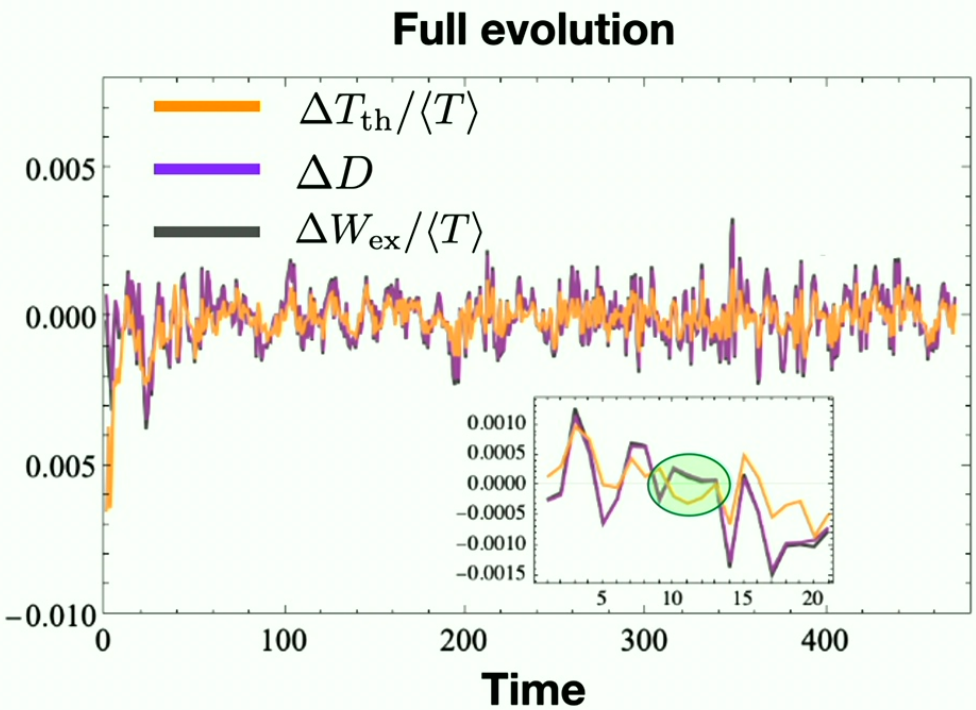
Full evolution: keep the correlations



Under "typical" evolution, Gibbs-preserving processes, reference temperature must go up for $\Delta W^{\rm ex} > 0$

Kolchinsky, Marvian, Gokler, Liu, Shor, Shtanko, Thompson, Wolpert, Lloyd, 1705.00041

Akhouri, Shandera, Yesmurzayeva, 2203.10928, *Entropy*

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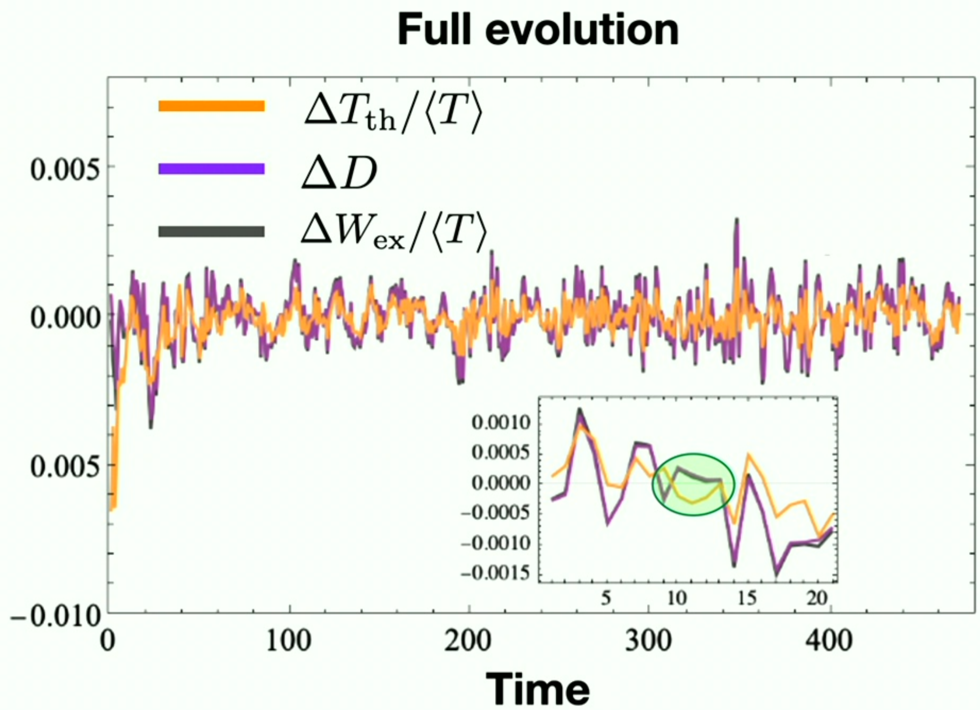
Full evolution: keep the correlations



Under “typical” evolution, Gibbs-preserving processes, reference temperature must go up for $\Delta W^{\rm ex} > 0$

But here $\Delta W_{\rm ex} > 0$ while $\Delta T_{\rm th} < 0$

Kolchinsky, Marvian, Gokler, Liu, Shor, Shtanko, Thompson, Wolpert, Lloyd, 1705.00041
Akhouri, Shandera, Yesmurzayeva, 2203.10928, *Entropy*

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Why?

Consider $\Lambda : \rho(t_1) \mapsto \rho(t_2)$ where at t_1, system and env. are entangled

$$\rho_S(t) = \sum_{k=1}^{\dim\mathcal{H}_E} \langle e_k | U(t,0) (\rho_S \otimes \rho_E)(0) U^\dagger(t,0) | e_k \rangle$$

$$\frac{1}{2}\left(|00\rangle + |11\rangle\right)\left(\langle 00| + \langle 11|\right)$$

No longer necessarily (completely) positive

Pechukas, 1994; Shabani, Lidar 2009; Brodutch et al 2013; Shabani and Lidar 2016; Jagadish, Srikanth, Petruccione 2012.12292, 2306.12773

Correlations arises in intermediate steps in tiny universe evolution

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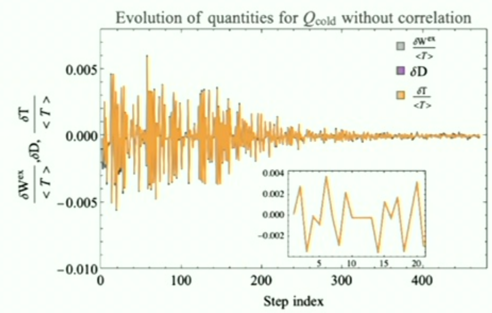
Maps: throw out correlations



- Two-qubit interactions, system + “bath” (b)
- Throw out correlations after each step

$$\mathcal{E} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \lambda(\tau)\cos[\phi] & \lambda(\tau)\sin[\phi] & 0 \\ 0 & -\lambda(\tau)\sin[\phi] & \lambda(\tau)\cos[\phi] & 0 \\ t_z(\tau) & 0 & 0 & \lambda_z \end{pmatrix}$$

Repeated application:

- always completely positive
- can see the damping with time
- unital in long-time limit

But if we introduce correlations: CP conditions can be violated

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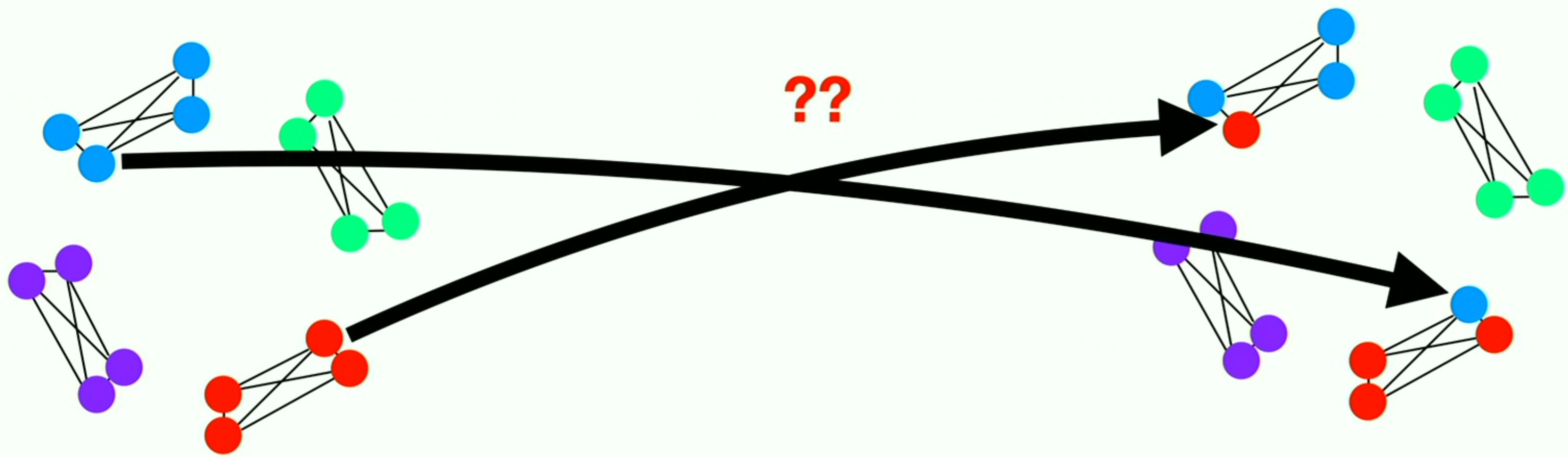
Domain of positivity and locality



In general: cannot pick up an arbitrary qubit and drop it in at a very different location

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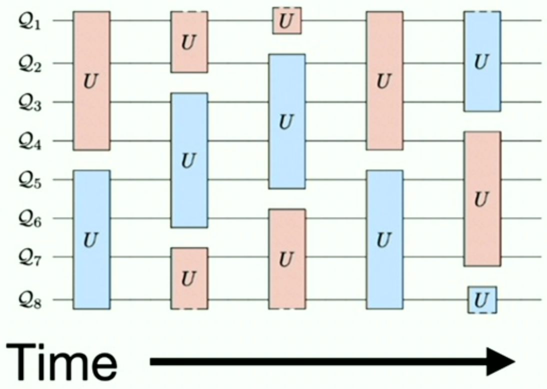
Most out-of-equilibrium, best constraints on ensembles

Which circuits result in complex substructure evolution?



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Dynamical Interaction domains

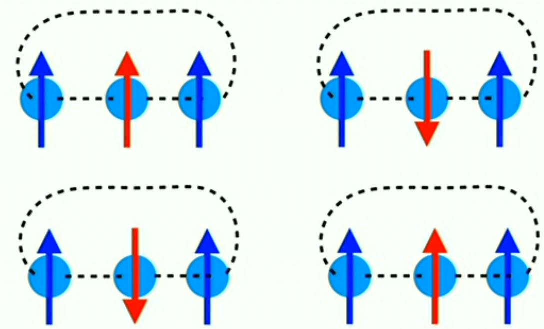
Beyond random domains: interactions that respond to changes in environment

For example:

- Update depends on states of neighbors

  Kinetic constraints / Q. cellular automata:

  (Flip iff both neighbors are up)



- Hamiltonian formulation: $\hat{H} = h\sum_i \hat{\sigma}_i^z + J\sum_{i=1}^{N}(\hat{P}_{i-1}\hat{\sigma}_i^x\hat{P}_{i+1})$
- Known to be interesting (Turner et al, *Nature Physics,* 2018)
- But not (easily) consistent with $[\hat{H}_0, \hat{U}] = 0$

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Dynamical Interaction domains

Update depends on the relation of the state of subsystem to the states of neighbors

Can still restrict to: $[\hat{H}_0, \hat{U}] = 0$

More compatible with physical utility: $W_{\rm ex}$

a. Greedy (global information): interaction domains maximize distance from thermal state

b. Strategy mimic: interaction domains mimic conditions of largest previous $\Delta W > 0$

- •Population (temperature)
- •Correlations

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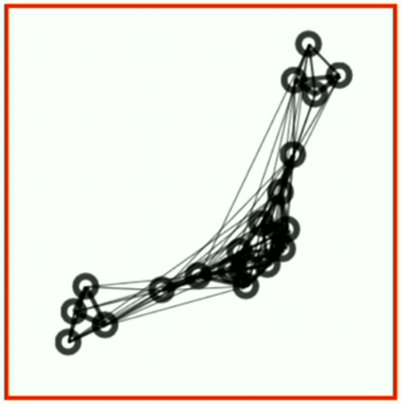
Interesting?
Complexity measures on mutual information graphs

Mutual information $I(A:B) = S(A) + S(B) - S(AB)$

Network representation:



Valdez et al 1508.07041; Walschaers et al 2012.15608; Hillberry et al 2005.01763; Jones et al 2111.00167; Nokkala et al review 2311.16265; Family of entropy inequalities in AdS/CFT Hubby +

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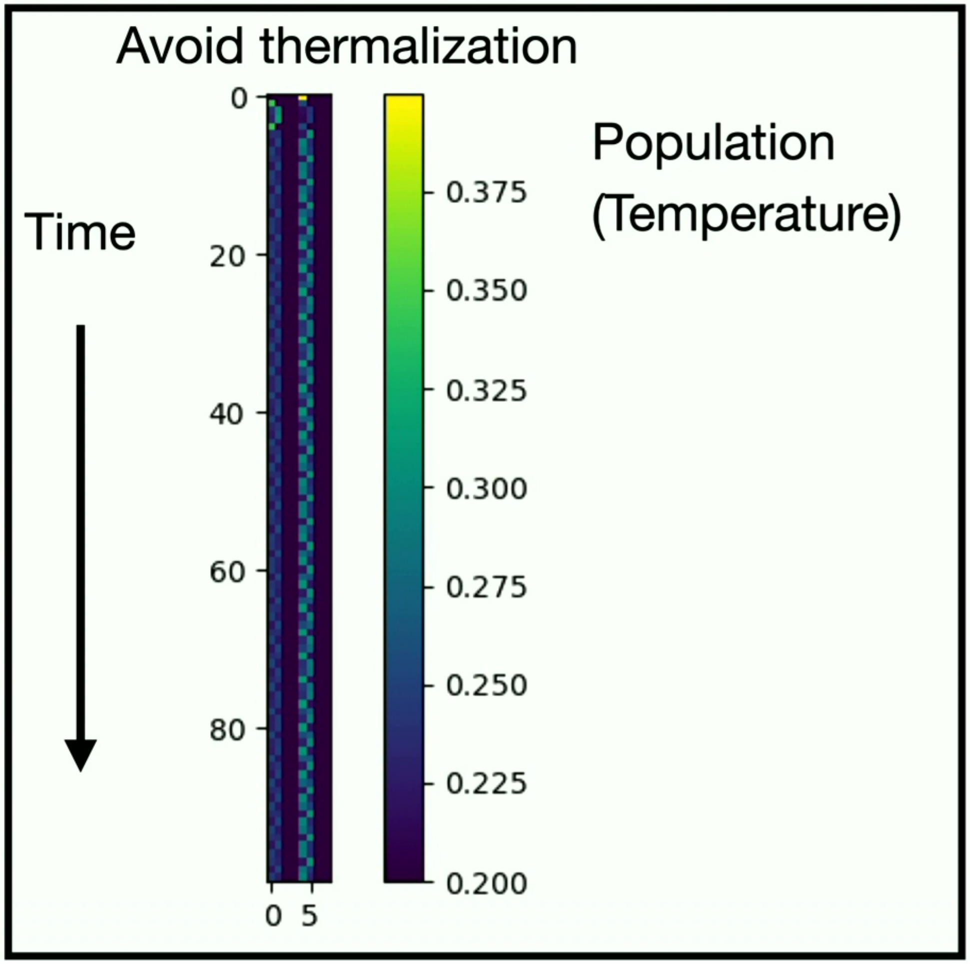
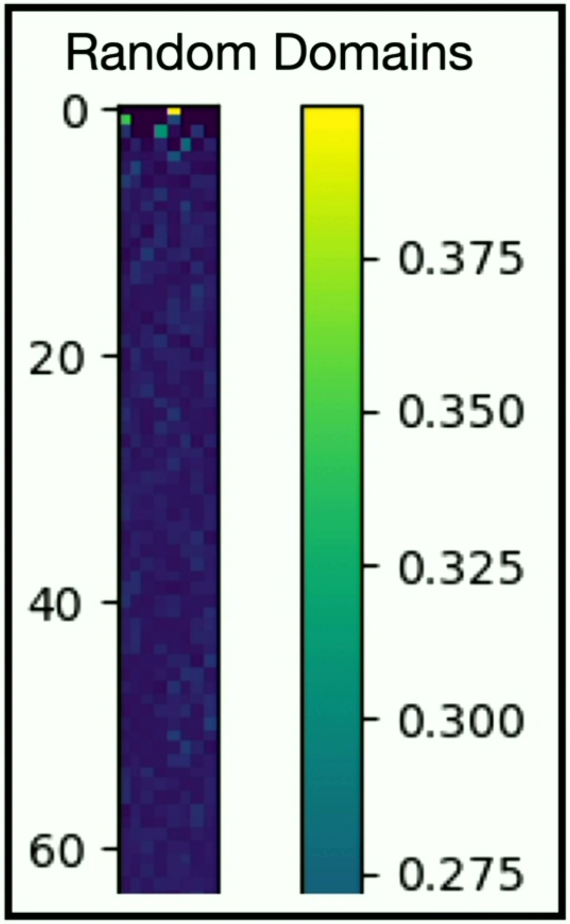
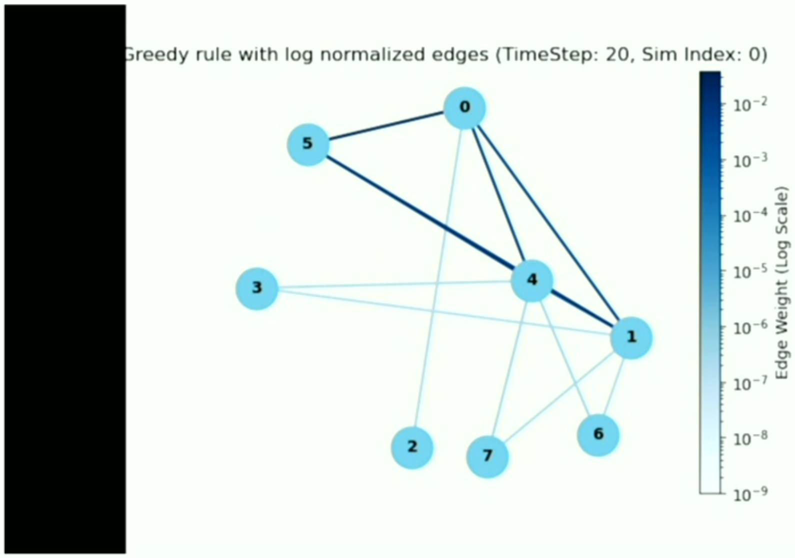
Greedy rule: static domains





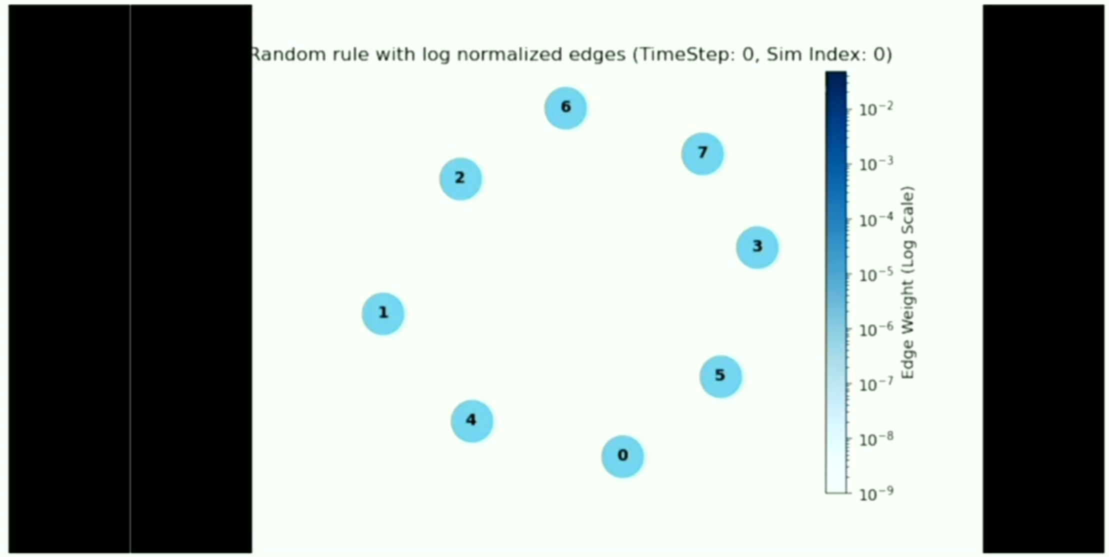
Mutual information comparisons

Greedy rule domains



Higher complexity

Random domains



Lower complexity

+ **Akhouri**, Henry, Chin, Shandera in prep.

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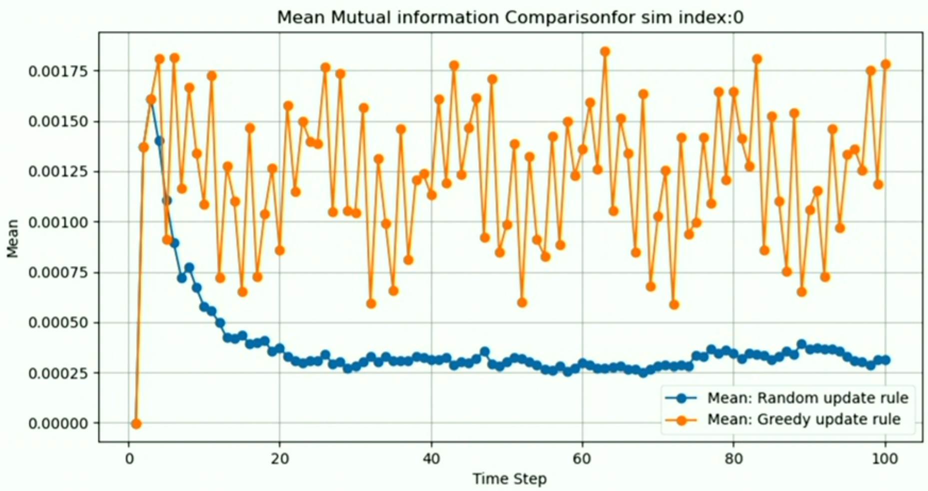
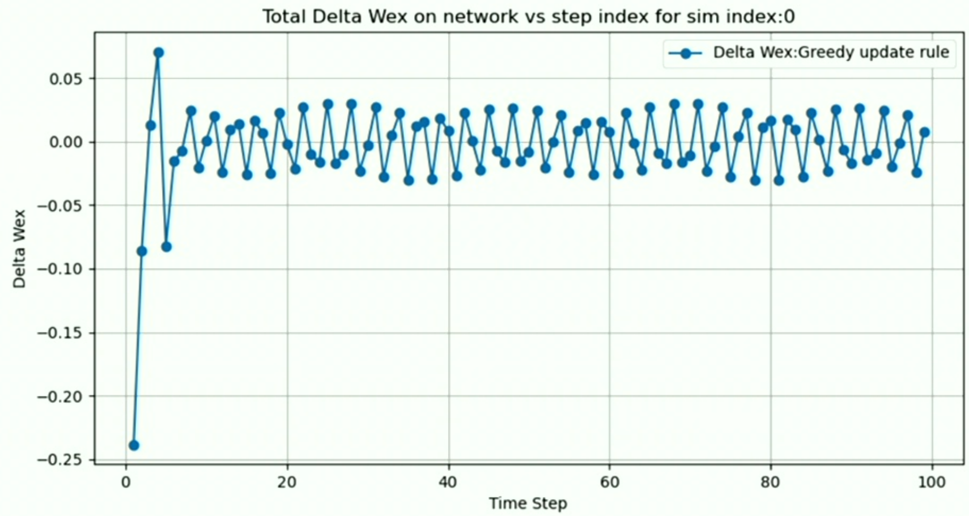
Greedy rule has more graph complexity, but is it useful?





+ **Akhouri**, Henry, Chin, Shandera in prep.

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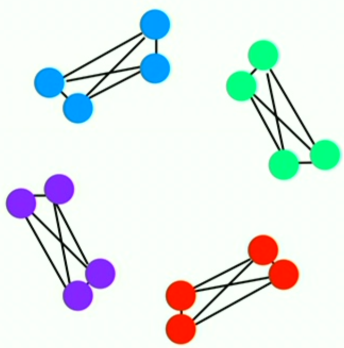
So far

- Tiny universes: understand quantum systems as ensembles of open systems
    - Role of non-Markovianity, connectivity and interaction domains, classical correlations and quantum correlations in thermalizing and complex systems
    - Connect properties of co-evolving, dynamic landscapes with laboratory spin systems
    - Useful tools: dynamical maps, extractable work, relational quantities between system and environment; mutual information



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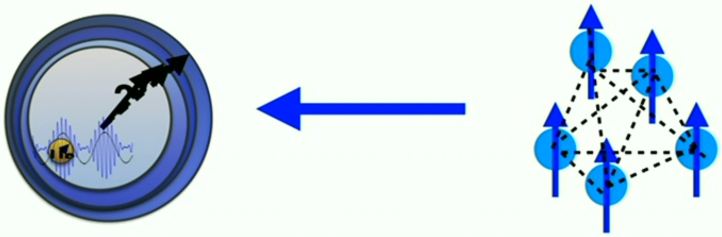
What next?

- Consider subsystems of varying sizes
- What happens as the system/environment boundary changes? (S. Prudhoe, S. Shandera, 2201.07080, *JHEP*)
- What consistency conditions determine where boundaries *must* be?
- What extra structure/dynamical principles picks out a particular organization of degrees of freedom on a Hilbert space? (Prudhoe, Kumar, Shandera 2310.01550, JHEP; Freedman, Zini 2011.05917; 2108.12709; 2112.08613)



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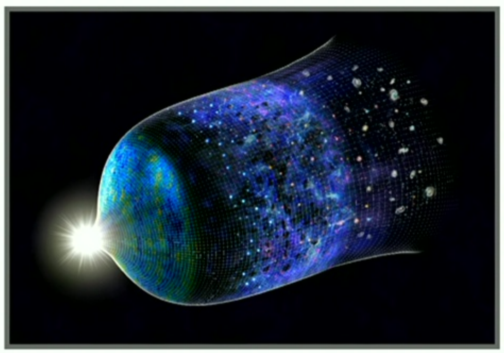
Overview

- 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-equilbrium systems
- Opportunity to bring advances in open, out-of-equilibrium quantum systems into the toolkit of cosmology



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