Title: Ensembles of open quantum systems as a tool for quantum spacetime

Speakers: Sarah Shandera

Collection/Series: Emmy Noether Workshop: Quantum Space Time

Subject: Quantum Gravity

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Abstract:

Observers in a typical gravitational or cosmological setting only have access to part of the spacetime and the degrees of freedom in it. The observer sees an open quantum system, and the complete dynamics of all degrees of freedom can be reconstructed by gluing together the (possibly overlapping) open systems associated with each observer. I will discuss what can be learned from treating familiar laboratory closed systems as ensembles of open systems, and how we can begin to extrapolate from there to systems relevant for cosmology.

Ensembles of open quantum systems as a tool for quantum spacetime

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Penn State University
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Quantum Gravity 2025 at Penn State

IGC

PennState
Eberly College of Science

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Inflation: a phenomenon that cares about quantum gravity(?)

- Amplitude of primordial gravitational waves
- Interactions and non-Gaussianity
- Nature of (quasi) de Sitter space

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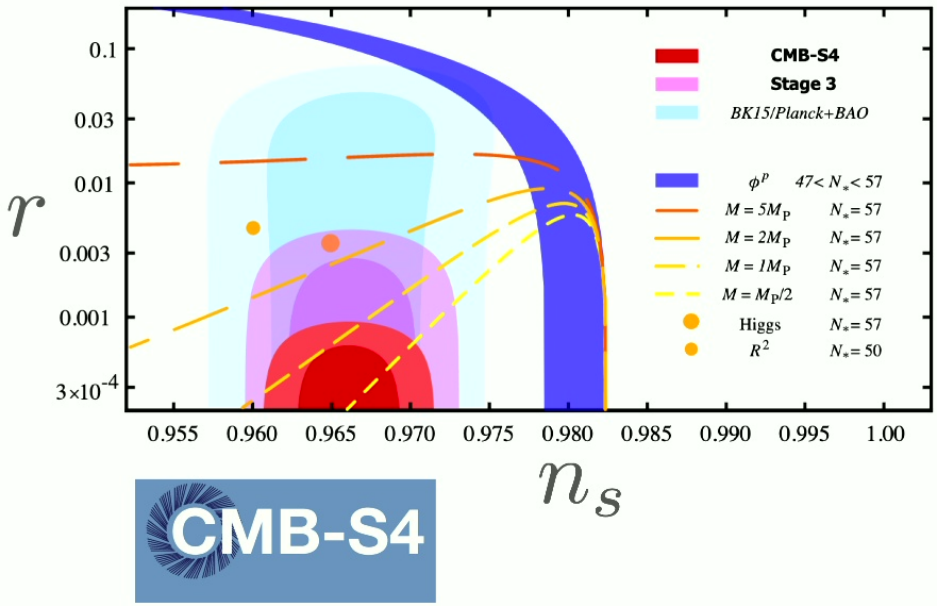

CMB-S4

Science Book v1: 1610.02743; (Decadal Survey Review, Shandera et al 1903.04700; *Nature Reviews Physics*, Komatsu, 2202.13919)

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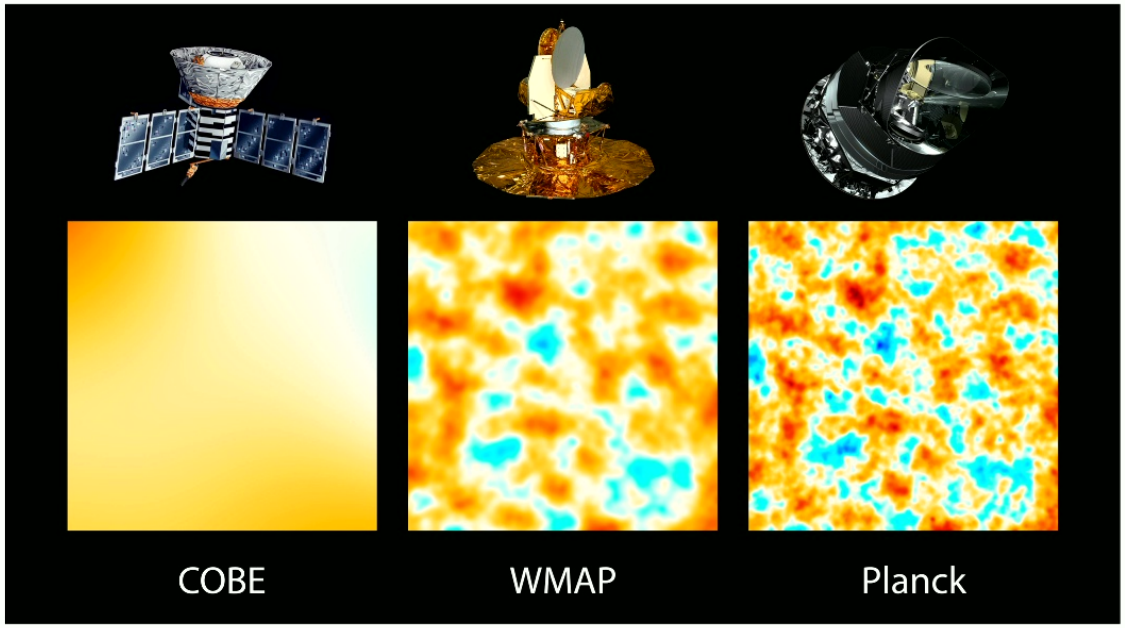
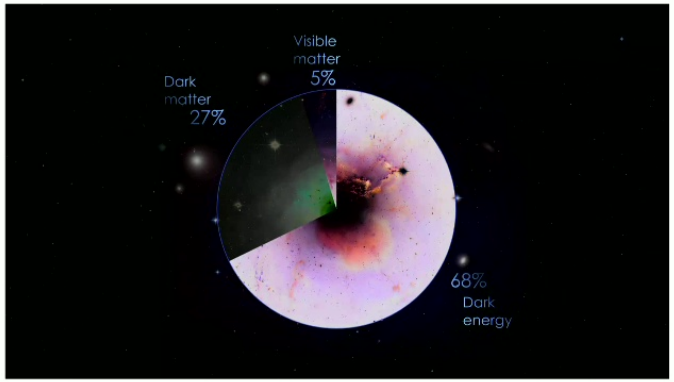
How to do inference from this?





What microphysics?…….. many decades of (collider based) theory and we still don’t know

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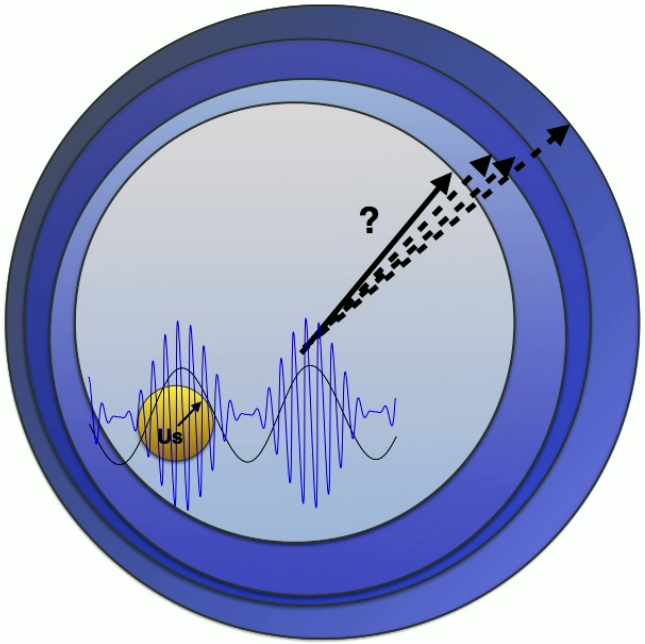
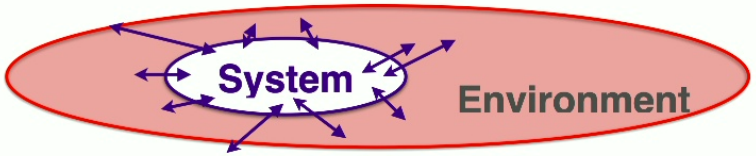
A suggestion from inflation: there is exponentially more than us



Open quantum systems



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

Shandera, Kamal, Agarwal, 1708.00493 (*PRD*), open systems inflation

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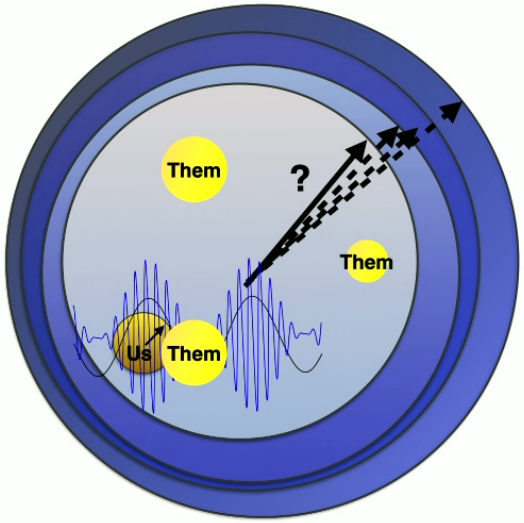
Effective theory for one patch
Global theory for the whole ensemble



Ensemble of open quantum systems

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This is more general than inflation

Gravity creates boundaries

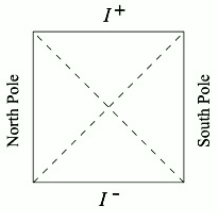
Quantum + gravity for any observable region is generically an open quantum theory

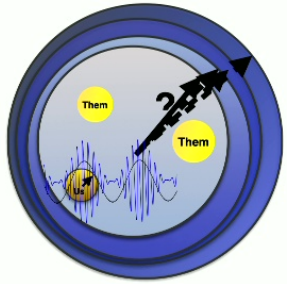
Different observers (often) have different boundaries

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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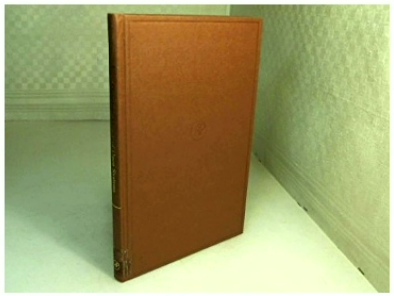
Open systems in cosmology

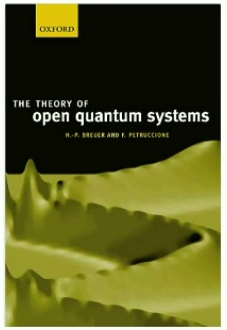
- Gravity generates boundaries, so open quantum systems natural (Hawking 1976; Israel 1976; Gibbons, Hawking 1977)
- Black holes: tracing out (scalar field) inside the black hole leads to the area law for entropy (Bombelli et al 1986; Srednicki 1993;)
- Quantum fields in inflation (de Sitter space) (Calzetta,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

But:

- Open systems were intensely studied outside of cosmology after this
- 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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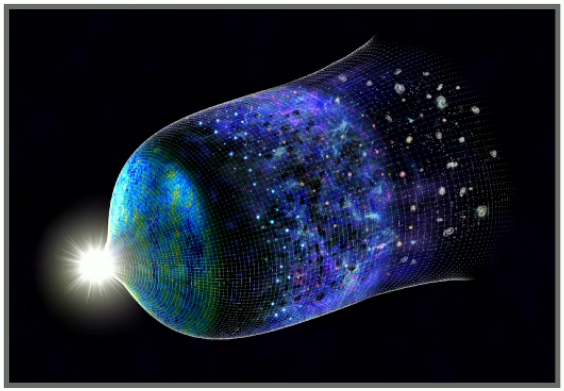
What should the foundational theory look like?



Take very seriously two features of the universe we have:

- Observers modeling quantum fields in (classical) gravity need an open quantum systems formulation
- The universe is not in equilibrium

A quantum-first approach

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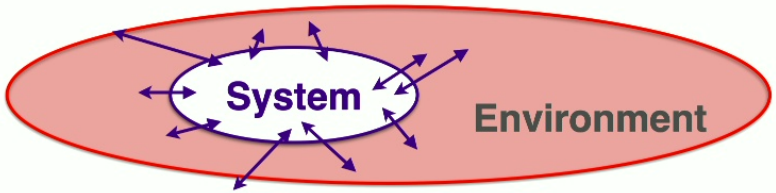
Open quantum systems

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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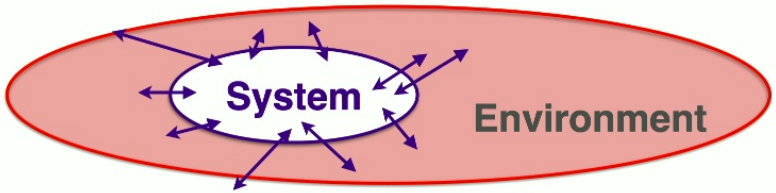
Open quantum systems



Open effective theories generalize low energy EFTs

A way out of the small effects at high energy QG dilemma?

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An “easy” open system

- Environment is: infinite, steady state
- System is fixed
- System-environment information flow is one-way: simple dissipation, no memory

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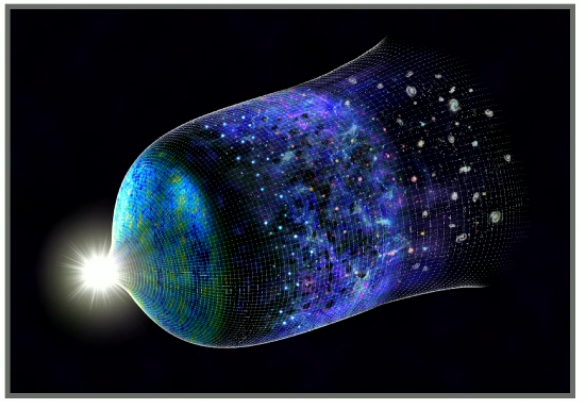
Realistic cosmological open systems: not “easy”



- Environment is statistically similar to the system
- System-environment information flow can be two-way
- System/environment boundary can be time-dependent

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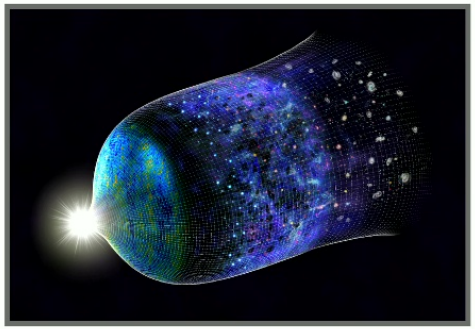
Complex open systems: we can make them in the lab

- Qualitatively new phenomena in open systems can be tested and discovered in experiments or quantum simulations
- New phenomena can suggest qualitatively different ways of organizing cosmological data



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Dynamics in realistic systems

This equation is not easy to deal with:

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

Instead, generalize the notion of unitary operators:

$$\rho(t) = U(t)\rho(0)U^\dagger(t) \qquad U^\dagger U = \mathbb{I}$$

Dynamical maps are the open-systems generalization:

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

Shandera, Kamal, Agarwal, 1708.00493 (PRD)

Sudarshan, 1961; A recent review: Jagadish, Petruccione, 1902.00909

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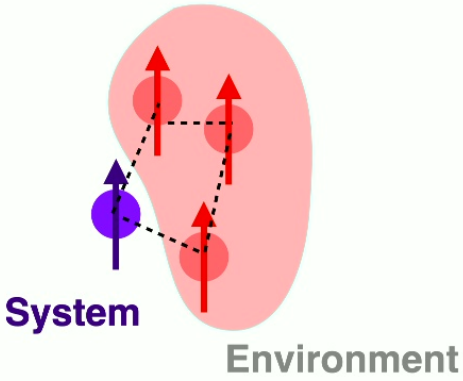
Dynamical maps



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

$$\rho_{\mathrm{S}}(t) = \Lambda(t,0)\rho_{\mathrm{S}}(0)$$

Dynamical map

- Depends on state of the environment and the dynamics (interaction Hamiltonian)
- Can be used for non-perturbative, non-Markovian, non-time local systems
- Easiest for small systems
- Non-(completely) positive dynamics indicates quantum correlations

Prudhoe, Shandera 2201.07080 (*JHEP*)

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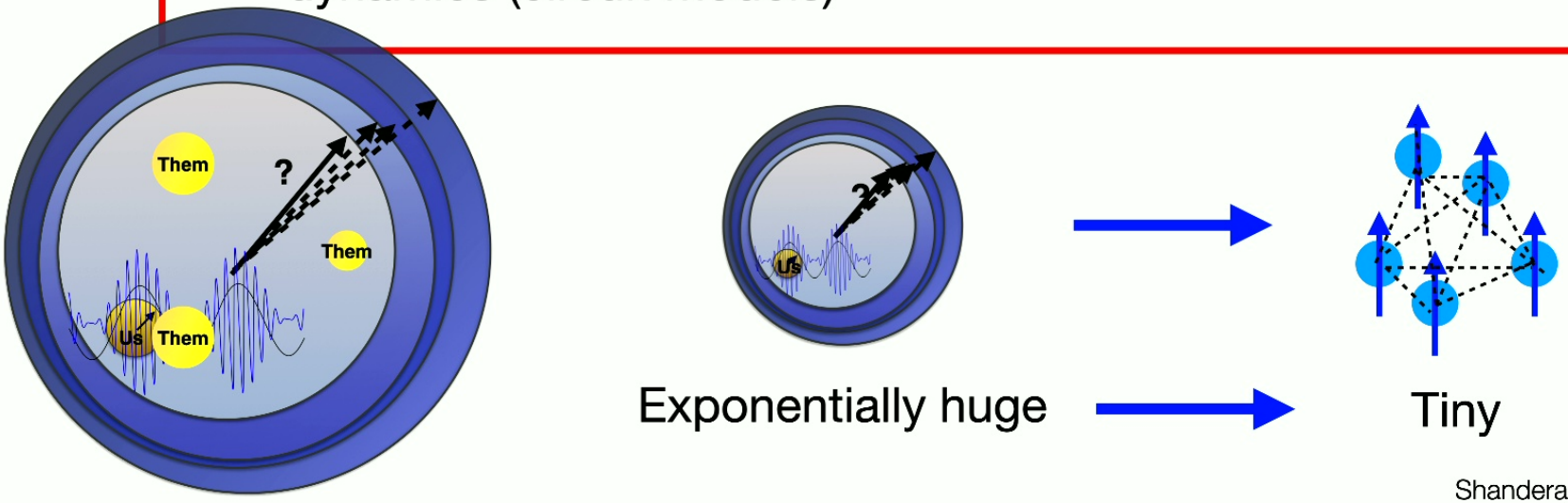
Ensembles of open systems, from closed

- Spin-networks, with familiar Hamiltonians
  (construct tools, benchmarks from a familiar set of problems)
- Tiny universes: co-evolving qubit systems and out-of-equilibrium dynamics (circuit models)



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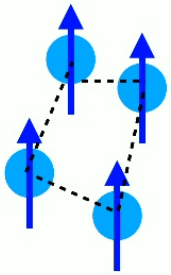
(Traditional)

Cosmologist's view of a familiar system

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

- Any subset of spins is an open system
- These open systems are not (necessarily) "simple"
- The full chain is an ensemble of open systems
  - Actually, (partially) describable by many different ensembles



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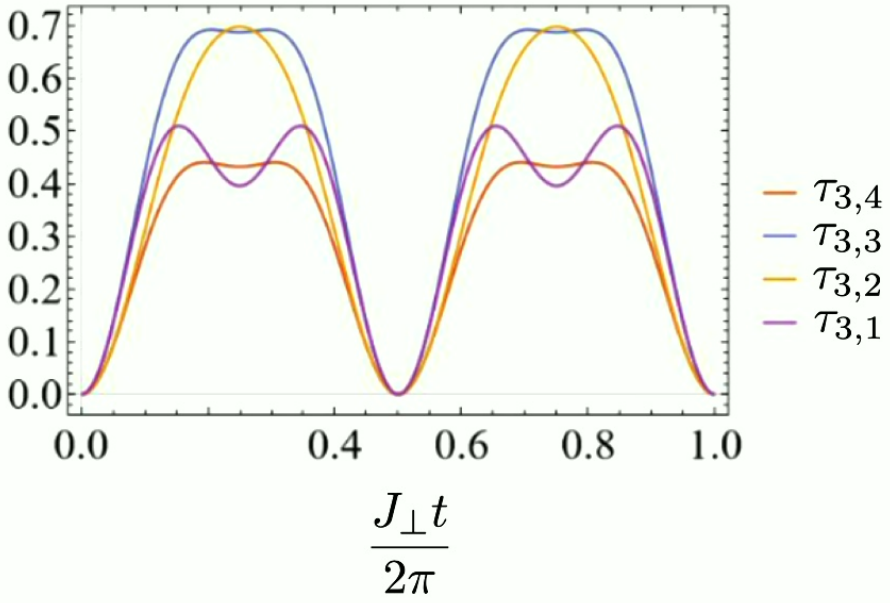
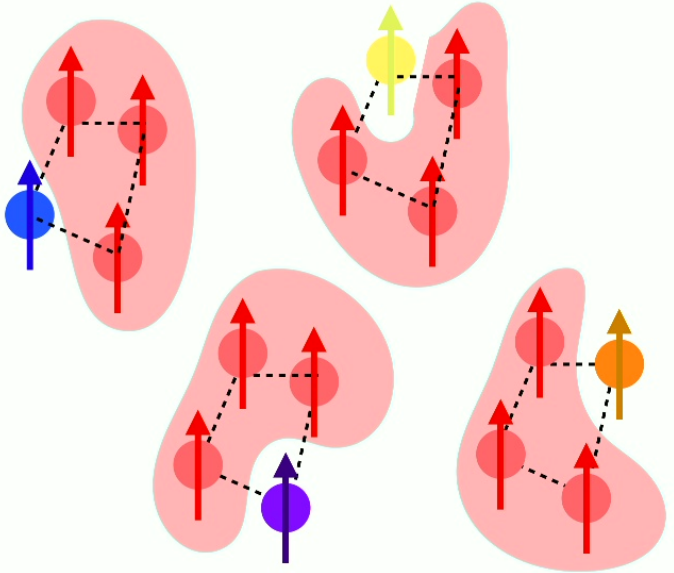
Ensembles of maps





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

Prudhoe, Akhouri, Chin, Shandera, 2404.15223, *OSID **31***
Chin, Shandera *in progress*

$$J_\parallel = J_\perp$$

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

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More radical Cosmologist's view:

Why are there subsystems at all? Are the divisions fixed?

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

- Assumes an external "observer"
  - Fixed division and arrangement of quantum degrees of freedom: spin-1/2 systems in a 1-D chain
  - Assume a reference frame common to all qubits
  - "Constants" ($h, J_\perp, J_{||}$) are frozen (dynamical) fields
- What structure imposed on a Hilbert space of size $d = 2^L$ gives the same properties as those found in this chain?

Sean Prudhoe, Rishabh Kumar, S. Shandera 2310.01550 (*JHEP*)
Freedman, Zini 2011.05917; 2108.12709; 2112.08613

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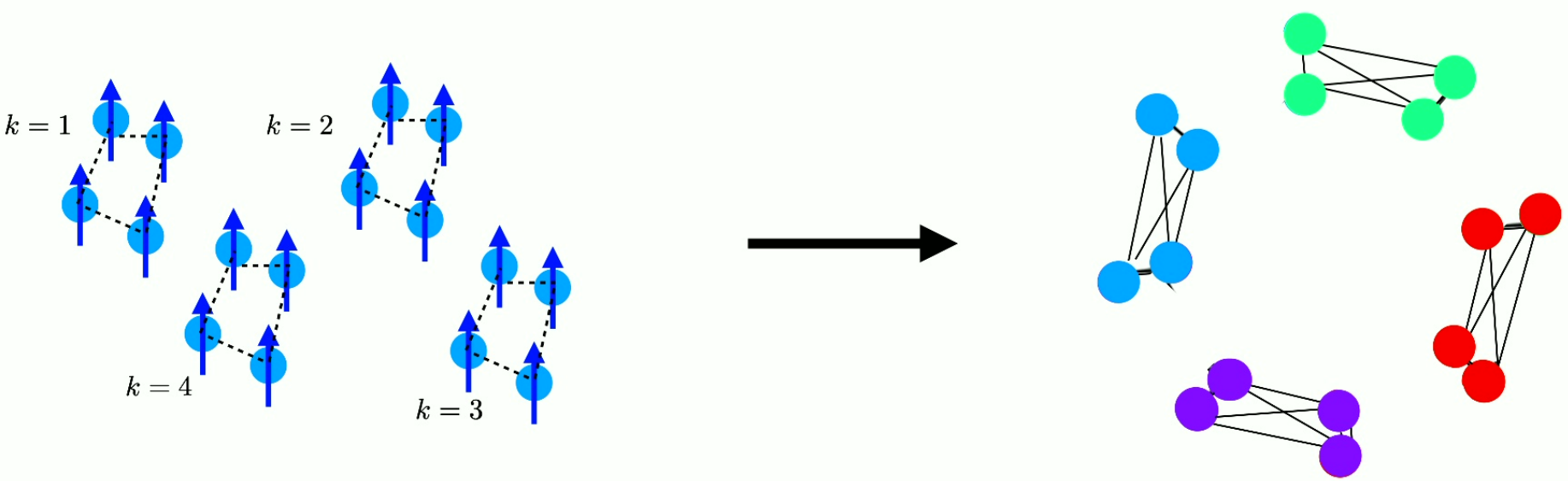
So, a new toy model:

Spin network structure is not restricted to be static



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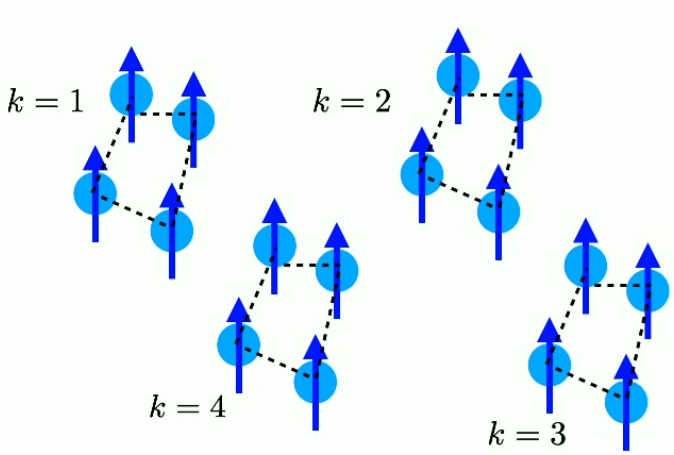
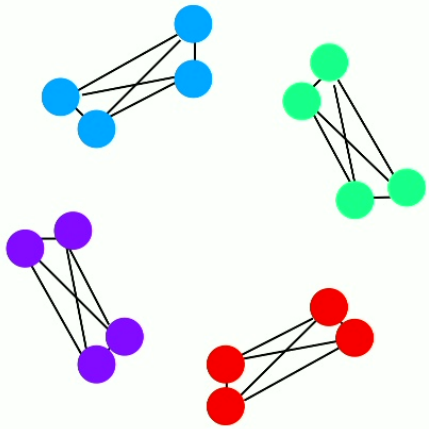
Dynamics without fixed structure

(time-dependent Hamiltonian)





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

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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The steps

1. Define some novel dynamics to avoid thermalization (in a system with U(1) symmetry)
2. Characterize lack of thermalization:
   - Local memory of initial conditions at late time
   - Inhomogeneity in sub-system dynamics
3. Characterize the utility of ways of staying out of equilibrium
   - State space explored
   - Complexity of mutual information graph
   - Increases in local extractable work

Akhouri, Shandera, Yesmurzayeva, 2203.10928
+ **Akhouri**, Henry, Shandera in prep.

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1. Dynamic 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:

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1. Dynamic interaction domains

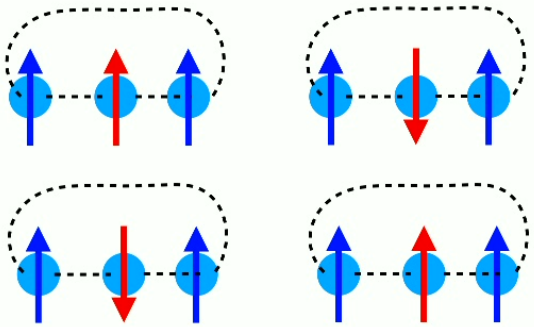
Beyond random domains: interactions that respond to changes in environment

For example:

- Update depends on states of neighbors

  Kinetic constraints / Q. cellular automata:

  (Flip iff both neighbors are up)



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1. Dynamical interaction domains

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

a. Avoid thermalization: interaction domains maximize distance of the full network from the global thermal state; Or, maximize $\Delta W_{\mathrm{ex}} > 0$ for the whole network, or for individual spins

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

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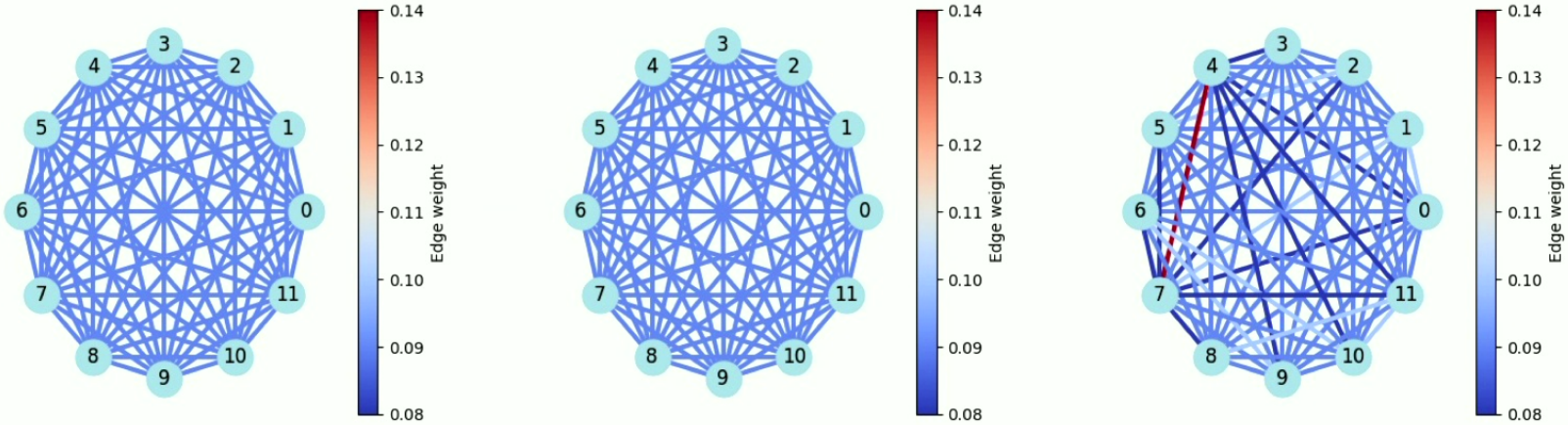
2. Equilibrating? Emergent network

Average interaction network allowed

Average interaction network after random evolution

Average interaction network after non-thermalizing evolution



Independent of initial state

[Emergent network defines a related class of Markovian random circuits]

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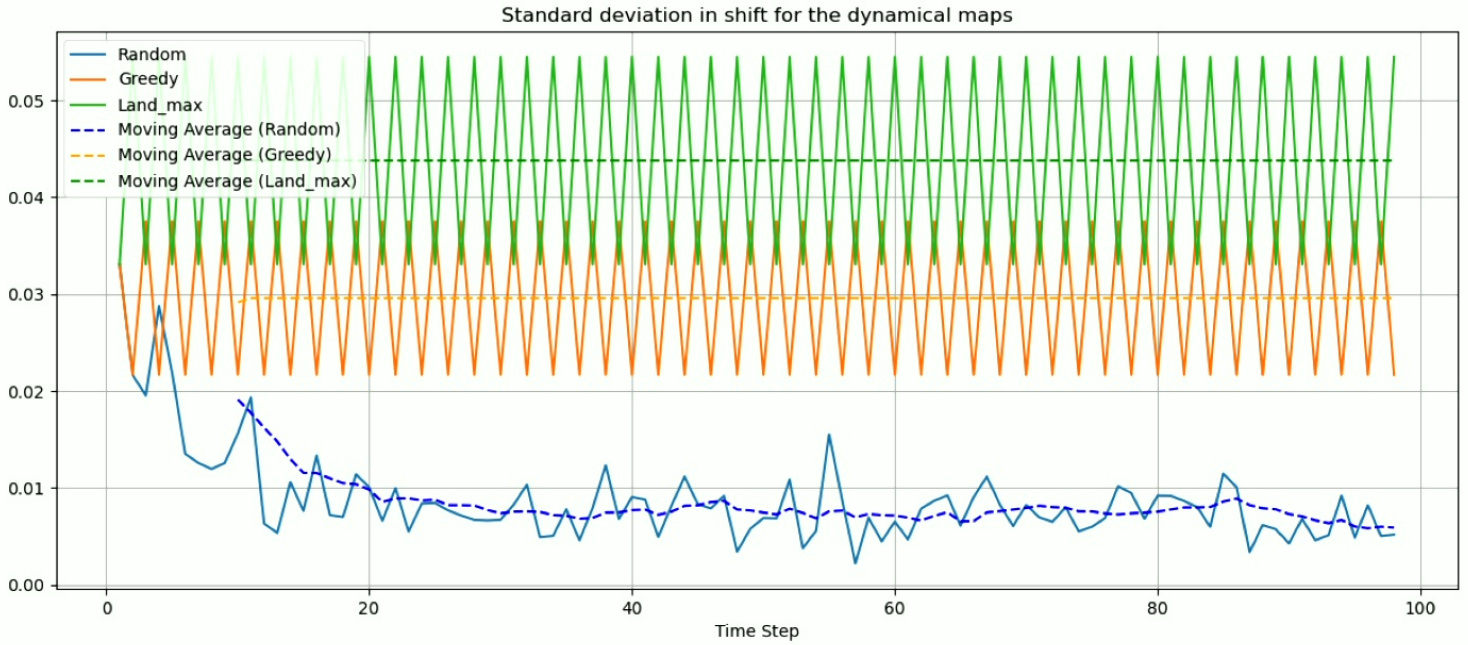
2. How different from thermalizing dynamics?

- Look at the ensemble of late-time dynamical maps: do all maps start to look the same?

Map shift to z-component



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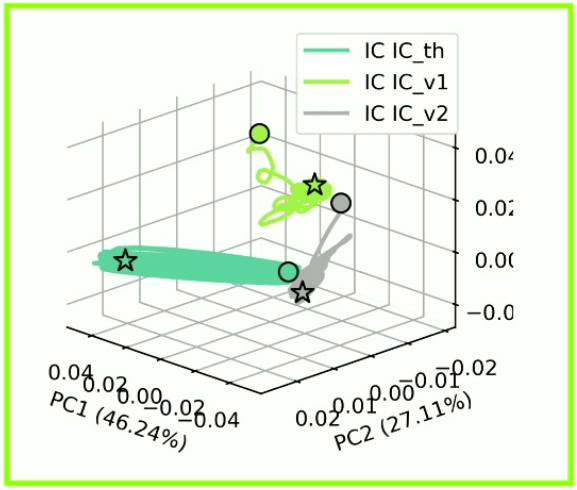
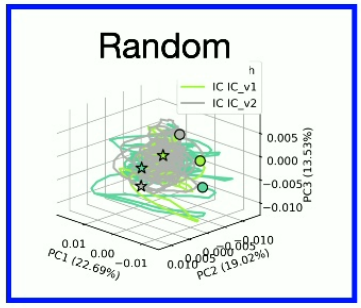
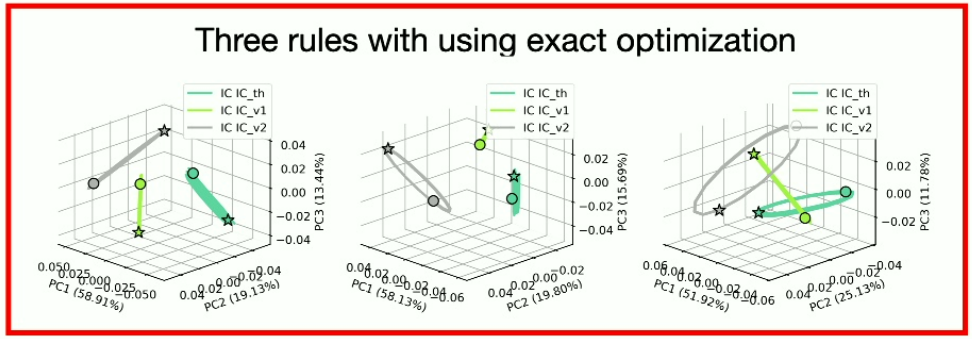
3. Utility of out-of-equilibrium? State space explored

Approximate local optimization







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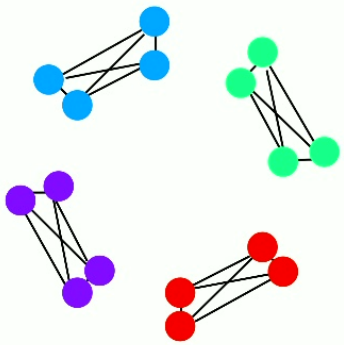
So far

- Tiny universes: understand quantum systems as ensembles of open systems

    - Useful tools: dynamical maps, relational quantities between system and environment; mutual information, extractable work

    - Role of non-Markovianity, connectivity and interaction domains, classical correlations and quantum correlations in thermalizing and complex systems



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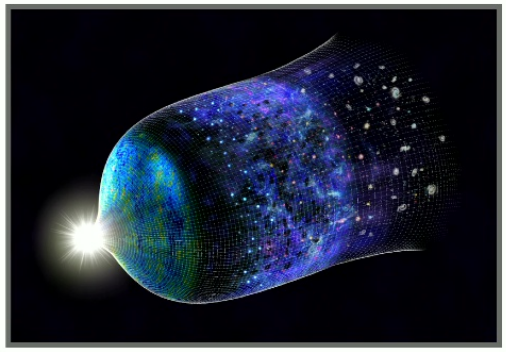
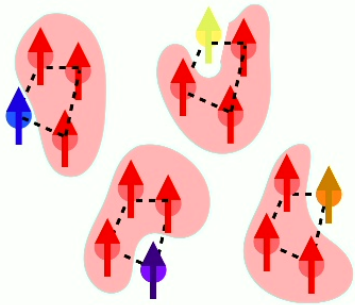
Overview

- 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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