Title: Nonlocality in the causal set approach to quantum gravity

Speakers: Fay Dowker

Collection: Quantum Spacetime in the Cosmos: From Conception to Reality

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Abstract: The nonlocality of causal sets gives us hope of solving the cosmological constant puzzle (``why is the universe so smooth, big and old if there is only one scale---the discreteness scale---in the theory?")

On the other hand locality, , GR and local QFT, must be recovered from quantum gravity in the continuum approximation at large scales, which is a challenge. If we are lucky though (like Goldilocks, the universe gets the nonlocality ``just right") nonlocality may be a rich source of phenomenology. Yasaman Yazdi's talk will be on cosmological models based on the nonlocality of causal sets. I will give a couple of examples of more astrophysical phenomenological models based on simple assumptions---randomness due to spacetime uncertainty and Lorentz invariance---and pose a research question: is there a model of ``quantum swerves"?

Zoom Link: https://pitp.zoom.us/j/99946149565?pwd=M2puMy9nSEtBZTg1MnRmSllHeUE0UT09

Nonlocal Phenomenology in (Causal Set) Quantum Gravity

Fay Dowker

Imperial College London

12 May 2023
PI Meeting Quantum Spacetime in the Cosmos

What might we be missing?

- There is a strong desire to confront our quantum gravity approaches with observations
- Are there intermediate, phenomenological (for now) scales at which quantum gravity effects (stringy/loopy/discrete/noncommutative....) show themselves but are not full quantum gravity effects?
- What phenomenology might be common to more than one approach and what phenomenology might distinguish them?

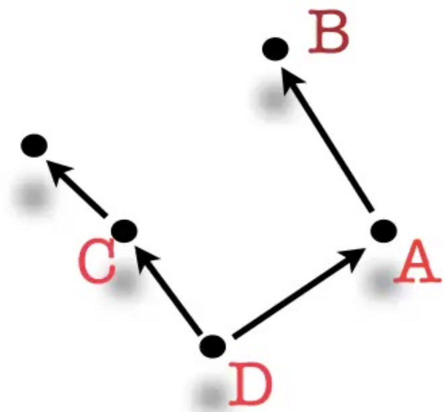
Plan of this talk

- **Nonlocality** is inherent in causal set theory (nonlocality in spacetime that respects relativistic causality and Lorentz symmetry)
- Nonlocality (or "memory") is a good thing in a theory with only one scale
- Nonlocality on the astrophysical scale: **swerves** and their cousins (for nonlocality on the cosmological scale: see Yasaman Yazdi's talk)
- Is there a model of quantum swerves? (my hope for this talk is to stimulate someone to find one :))

3 pillars of Causal Set approach to quantum gravity

1. Physical spacetime **discreteness** or atomicity at the Planck scale.

2. **Order** is a more primitive organising principle for physics even than space and time: the spacetime causal order--of all continuum spacetime structure--survives in the deep theory.



Causal set = discrete order = transitive directed acyclic **graph**

10^{240}

3. The **path integral** furnishes a framework for quantum theory, an alternative to the canonical "Psi" framework: quantum mechanics is a species of measure theory: more like Brownian motion than Hamiltonian mechanics.

Finite!

$$\text{“}\; Z(V) = \sum_{M} \int \mathcal{D}g \; e^{iS[g]} \longrightarrow Z(N) = \sum_{\text{causal sets of cardinality N}} e^{iS(C)} \;\text{”}$$

“A statement of intent” Renate Loll

Quantum swerves
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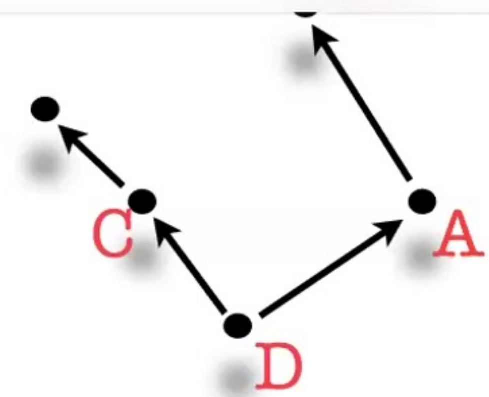

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Causal Order is central to GR and to Black Hole Thermodynamics

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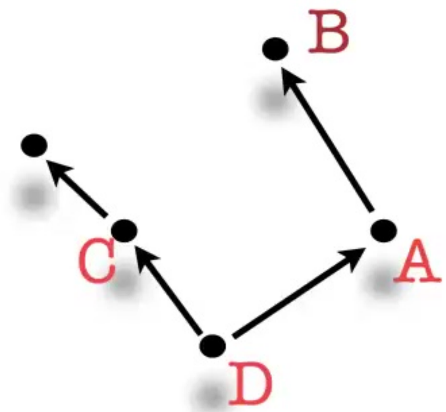

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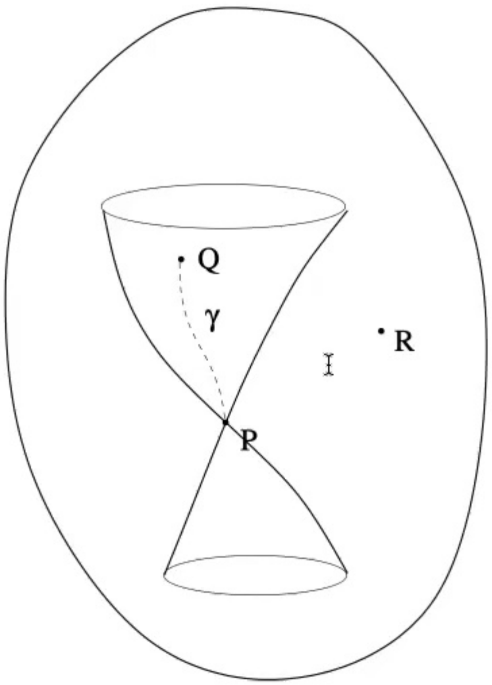


All GR textbooks are full of Carter-Penrose conformal diagrams of the causal order

Black holes are the epitome of GR and black hole physics (e.g. the uniqueness theorems, no-hair theorems, the second law of black hole mechanics, Hawking radiation) is tied to the **causal** nature of the black hole event horizon.

The value of the black hole entropy S = 4 pi A (in Planck units) is widely considered to be a clue to quantum gravity. It emphasises the importance of causal horizons and indicates discreteness at the Planck scale

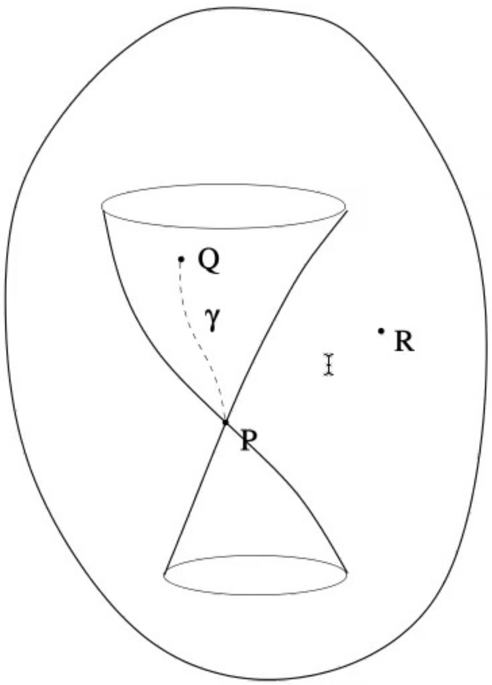
Theorem: The spacetime **causal order** gives the topology (including dimension) the differentiable structure **and** 9/10 of the metric in 3+1 dimensions (Kronheimer-Penrose-Hawking-Malament Theorem).

==> Order + Volume measure = Geometry (theorem)

For a discrete order (causal set) the **counting measure** gives the volume:

Order + Number = Geometry (conjecture)

Causal Order is central to GR and to Black Hole Thermodynamics



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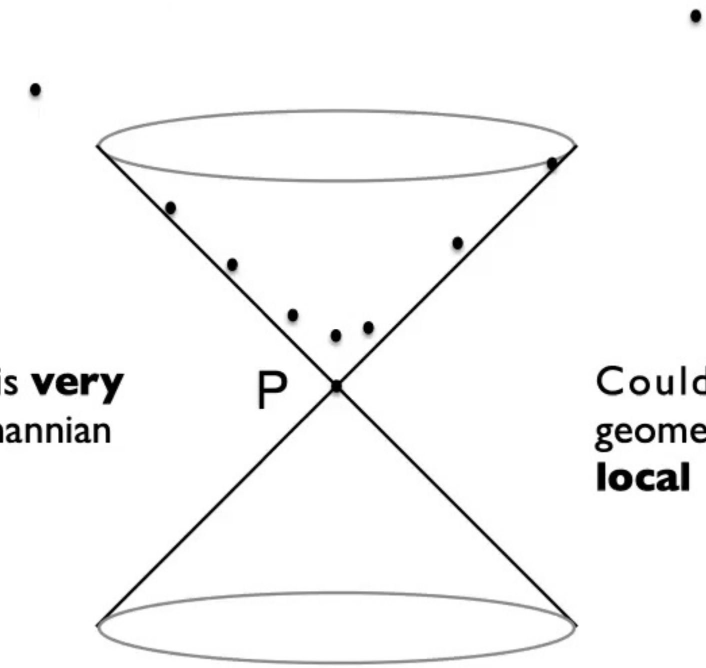
Lorentzian geometry: the physical geometry of the cosmos

Lorentzian geometry is **very different** from Riemannian geometry



Could argue: Lorentzian geometry is already **non-local**

The notion of "physically close" is not captured well in any picture: the Euclidean geometry of the paper (even our thoughts) is an impediment to understanding Lorentzian geometry.

Nonlocality: e.g. the points one Planck time in the future of P in Minkowski space lie on an infinite spatial hyperboloid that asymptotes to the future light cone.

"A Star is closer than Yesterday"

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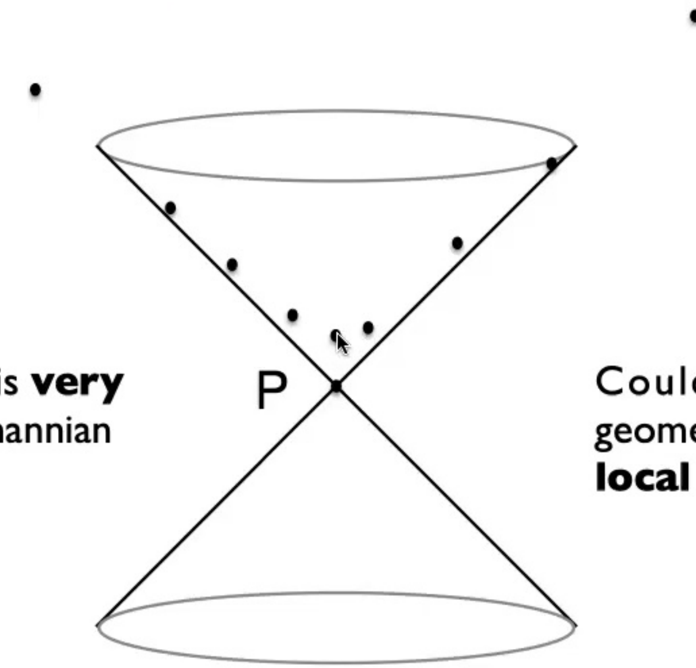

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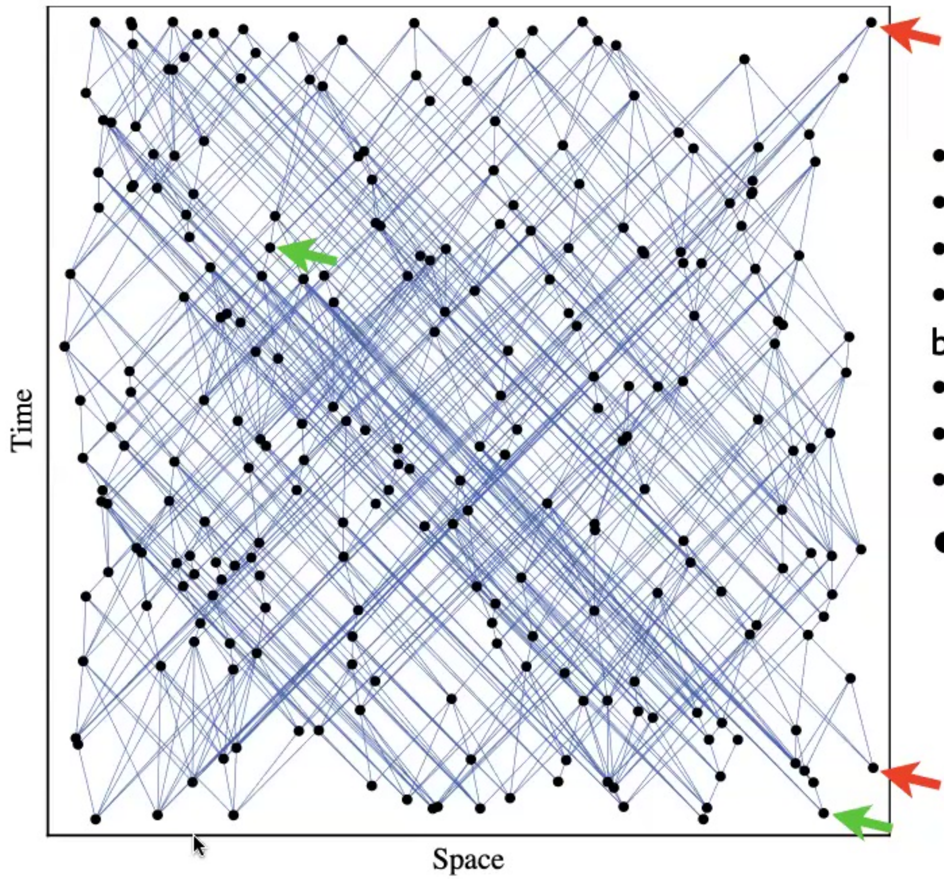
"A Star is closer than Yesterday"

A causal set that is well approximated by 2d Minkowski space

After

Before



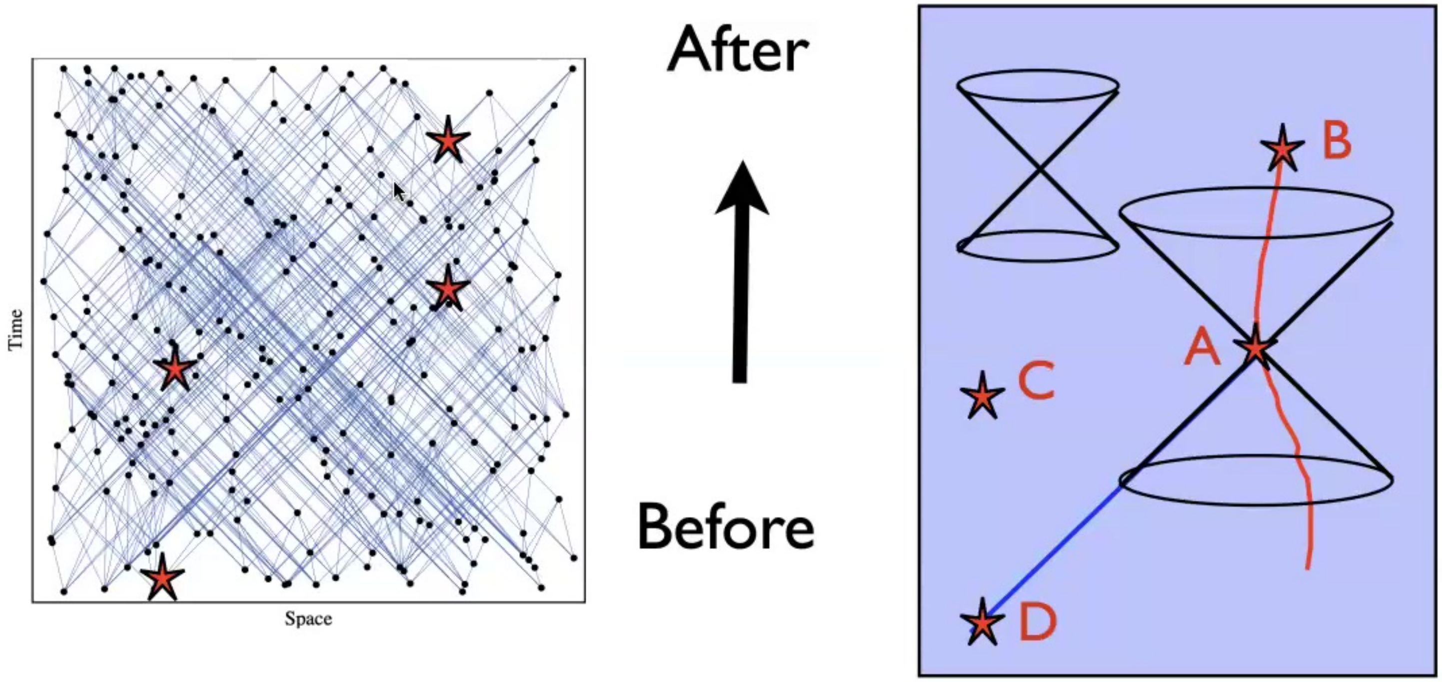
- Hasse
- Lorentz inv
- relational
- Combinatorial (just bits)
- Number ~ Volume
- Density = <N>/V
- L^d = 1/density
- **nonlocal**

On Planckian scales, this is what Minkowski space looks like

Lorentzian Spacetime in GR is a continuum approximation to a causal set

causal set = discrete order =
transitive, directed, acyclic graph

Continuum approximation (fluid)



1. Causal sets as fundamental in an approach to quantum gravity
2. Causal sets as ways to model ``spacetime uncertainty" in a Lorentz invariant way

1. Nonlocal dynamics **of** spacetime

See next talk! An extreme example of UV-IR coupling.

2. Nonlocal dynamics **on** spacetime

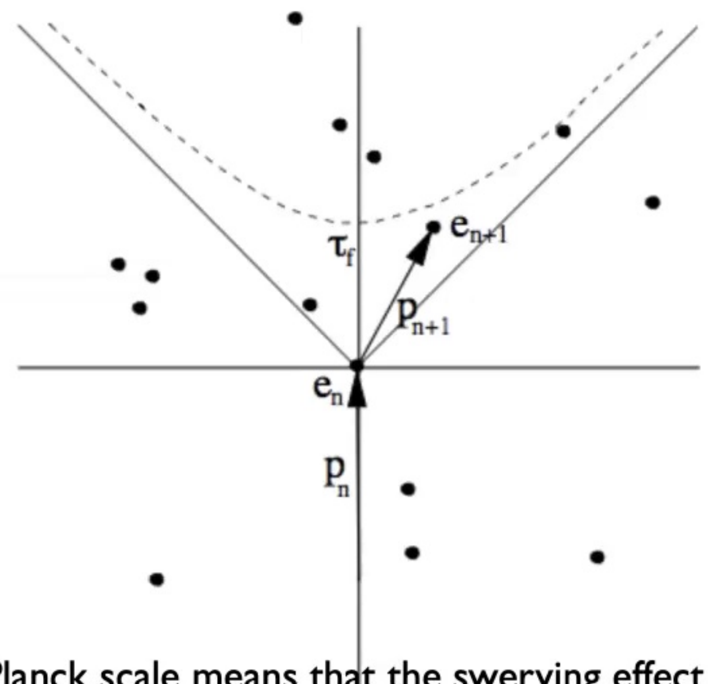
A fixed causal set can be a model of a spacetime with lack of structure/uncertainty about structure on small scales (``spacetime foam") that respects Lorentz invariance. Phenomenology derived from considering matter evolving on a fixed causal set can have general interest. For example,

"Does quantum gravity give rise to an observable nonlocality?"
PIRSA talk by Rafael Sorkin on a nonlocal effective wave-equation for a scalar field
pirsa.org/07010001

Nonlocal Dynamics on causal sets: Swerves

(FD, Henson, Sorkin, Philpott)

A free particle tries to follow a geodesic on the causal set. It minimises the change in its momentum at every step, which step has a maximum proper time τ_f. This sets a phenomenological ``nonlocality scale''



Choosing τ_f to be large compared with the Planck scale means that the swerving effect is small: the change in momentum is small at each step. But over many steps it accumulates.

The momentum is going on a Lorentz invariant random walk on the mass shell. In the hydrodynamic approximation of a large number of steps this is governed by a diffusion equation on the mass shell (H) that drives the process in spacetime

$$\frac{\partial}{\partial \tau}\rho = D\,\nabla_H^2\rho - \frac{1}{m}p^\mu\frac{\partial}{\partial x^\mu}\rho, \qquad \rho \equiv \rho(p^\mu, x^\mu; \tau)$$

Dudley (1965)

Swerves

$$\frac{\partial}{\partial \tau}\rho = D\,\nabla^2_H \rho - \frac{1}{m} p^\mu \frac{\partial}{\partial x^\mu}\rho, \qquad \rho \equiv \rho(p^\mu, x^\mu;\, \tau)$$

- Not very useful: tau is proper time and unobservable. We need to know how the momentum distribution changes in the lab (observer's) frame.
- Imagine a bunch of particles, homogeneously distributed in space with some initial distribution in 3-momentum p = | p^mu |. They will remain homogeneous in space.
- The spatial distribution remains homogeneous. Only dependence on lab time t.
- We can integrate over unobservable tau and get

$$\frac{\partial}{\partial t}\rho_t = D\,\nabla^2_H \left(\frac{\rho_t}{\gamma(p)}\right), \qquad \rho_t \equiv \rho_t(p; t)$$

$$\gamma(p) = \sqrt{1 + \frac{p^2}{m^2}}$$

Discussion points

- "Nonlocality" is too vague in general to be useful — that's a well known problem in phenomenology. When one breaks something (Gaussianity, unitarity, locality…) there are infinitely many ways to do it. Need guidance for physical constraints.

- Nonlocality together with **Lorentz Invariance** (and causality), inspired by causal sets, constrains the phenomenology. Which is a very good thing.

- Such models, when we find them, could be justified from any quantum gravity approach that is Lorentz invariant and in which there is fundamental uncertainty about spacetime structure at the Planck scale: cross approach applicability.

- The existing model of classical swerves is an example: the supposed effect of underlying Lorentz invariant spacetime fluctuations on massless and massive classical particles, in Minkowski space. Parameters are constrained but there are some ideas for applications still to investigate here.

- What about **quantum** swerves? Lorentz symmetry+quantum —> QFT but we can try first to consider the one particle sector. Can the constraints on the parameters of the classical swerve models be weakened in a quantum model? e.g. particles are quantum in isolation in the cosmos and are more classical when there is more other stuff around.

Quantum swerves
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Quantum swerves

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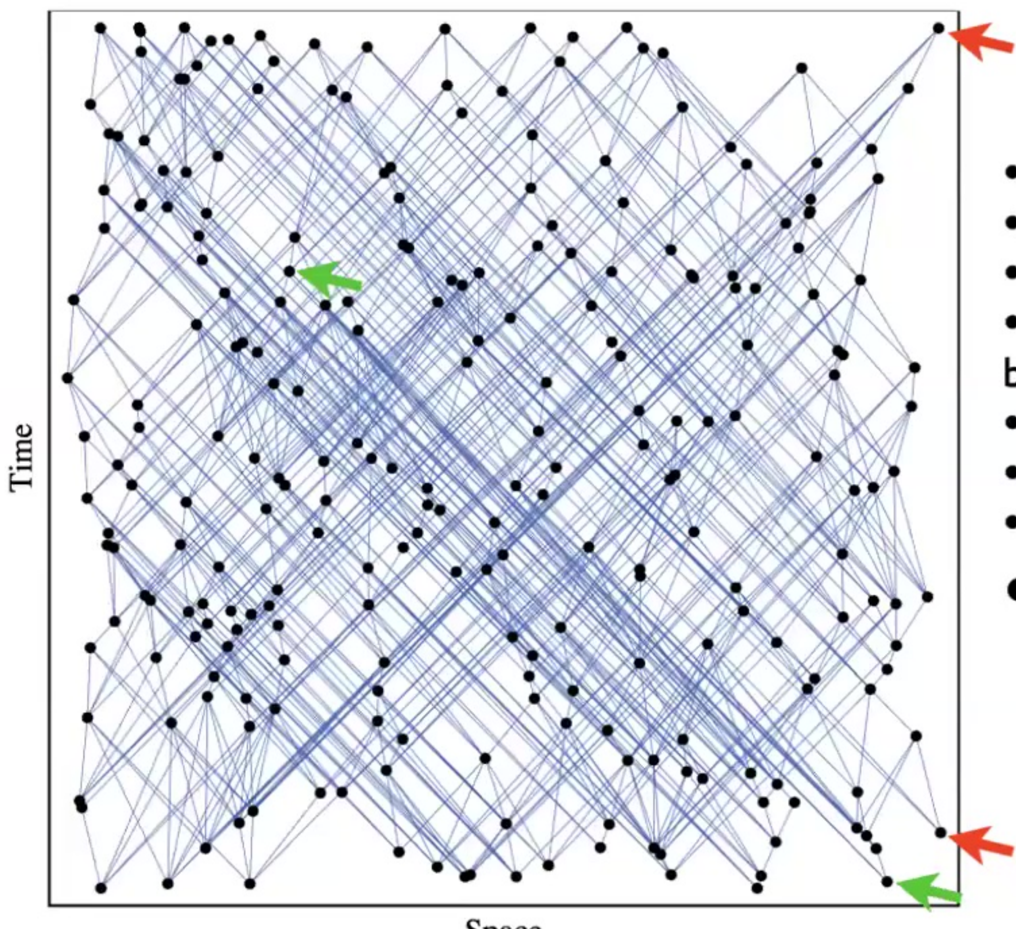

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