“Emergence”, “Time” and “Quantum Gravity”

“It is already clear that a full discussion of the emergence of time in quantum gravity would be a very daunting task. It would involve probing an ‘intellectual space’ with three different ‘coordinates’: ***which*** aspects of time are emergent, in ***which*** sense, and in ***which*** of a range of quantum gravity programmes. A full discussion would be beyond our — and we dare say, anybody’s — competence, if all three coordinates are given a wide range of values, which each get a detailed treatment.”

Butterfield and Isham ’99

Wise words!

Taking This Advice

I want to consider only one value of each of the coordinates

- Quantum Gravity: ***Causal Set Theory*** — an atomic theory of spacetime
- Time: ***passage***
- Emergence: ***no*** (doesn't seem to be part of GR, or at least, not easily)

However, I will need to set the stage for this by briefly discussing

- Quantum Gravity: ***Causal Sets***
- Time: ***continuum spacetime*** — Lorentzian manifolds — as laid down in R. Wald's GR textbook, say
- Emergence: ***in the sense that a fluid description is emergent from a molecular description*** as in kinetic theory of gases in an *approximation* at large scales and when there are large numbers of molecules.

Spacetime discreteness

It is widely expected that spacetime will not be well-described by a differentiable Lorentzian manifold close to the Planck scale. Most strikingly, semiclassical studies of black hole entropy suggest that physics **needs** a short-distance cutoff in order to be consistent with the known finite value **(Sorkin).** Atomicity of spacetime is perhaps the simplest way to realise this expectation.

Hypothesis: quantum gravity does not furnish any information about space-time on smaller than Planckian scales. But it does provide — in certain particular physical situations we'll call "semiclassical states" — some Discrete Physical Data (DPD) which is enough to recover, approximately and on scales large compared with the Planck scale, a Lorentzian manifold.

When this happens, I will say that the Lorentzian manifold M "emerges from" the DPD

> "It is the continuum, not the discrete space, that is the approximation"

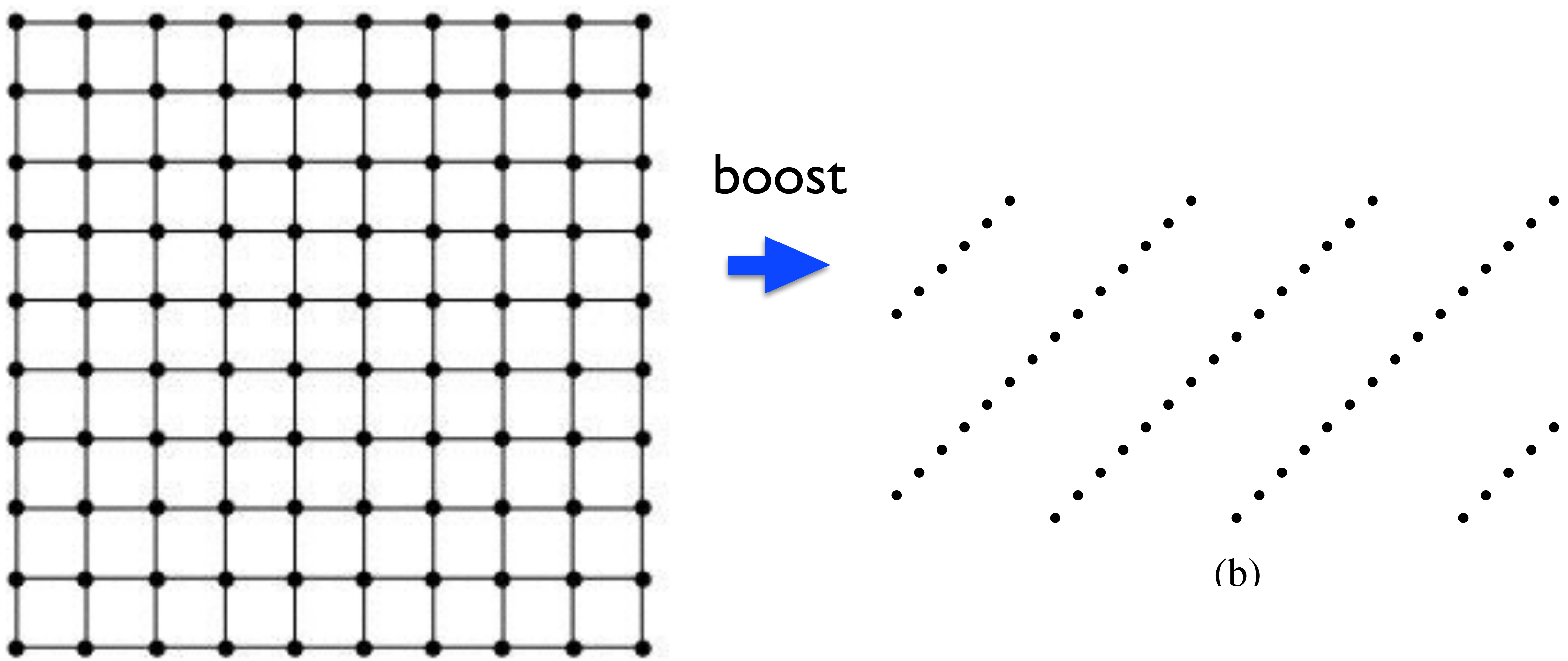
What Discrete Physical Data can do the job?

In kinetic theory of gases, we seem to have a good intuitive sense about this kinematical sense of "emergence", what it means for a continuous fluid description to be a good approximation to the underlying discrete molecular physical state. It seems clear enough when a continuum mass density is a good approximation to a distribution of atoms in a box and when it is not: many atoms, and the mass density varying very slowly on the atomic scale and being such that the integral of the mass density over a region is approximately the number of atoms in the box.

What about spacetime?

I will show you one kind of Discrete Physical Data that very likely "does the job" for 2-d Minkowski space-time and one kind that doesn't.

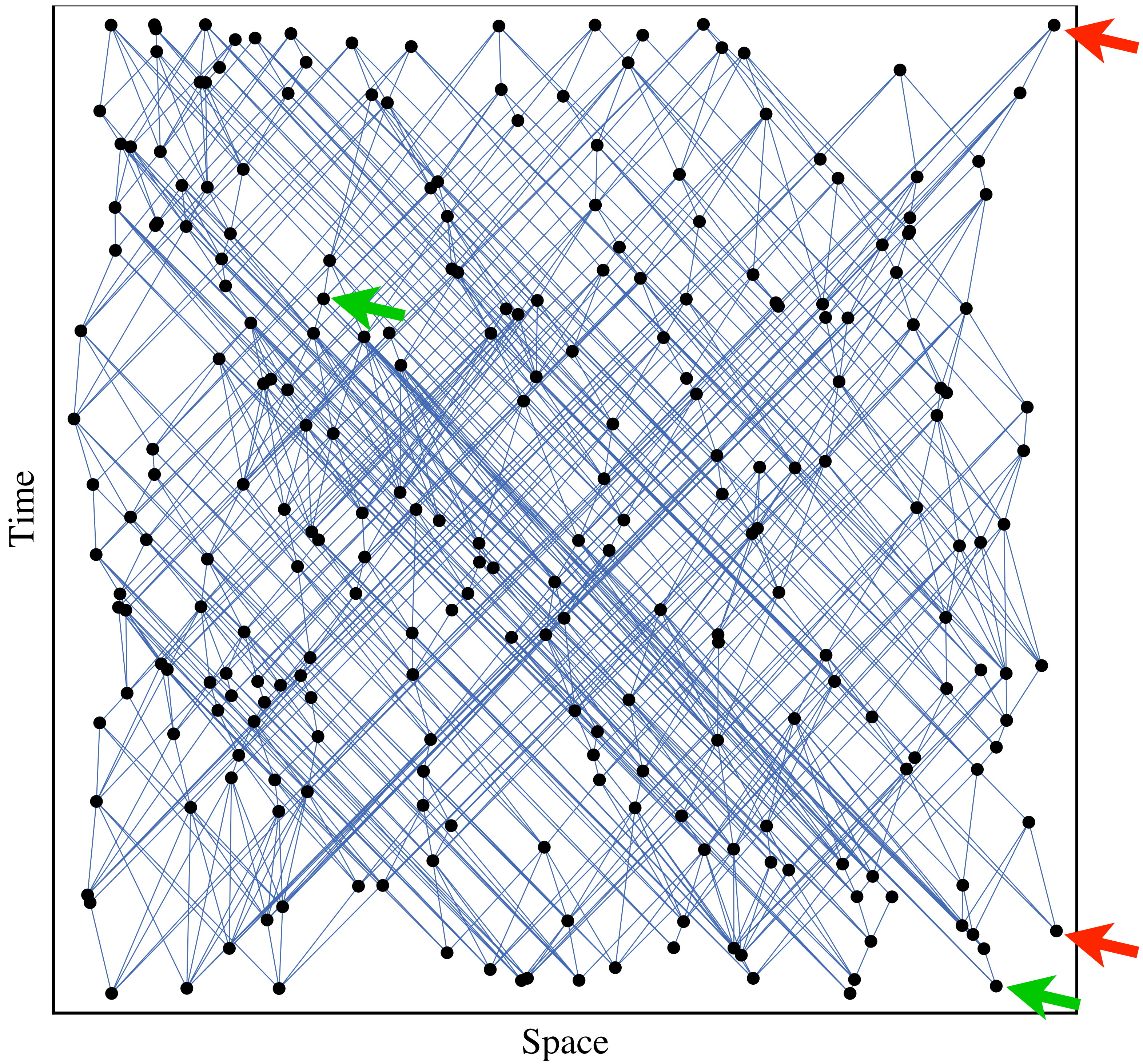
Lattices won't do



The DPD is a square lattice. The continuum approximation (2-d Minkowski) is related to the lattice via **embedding**: geometrical information in the manifold is gotten from the lattice if the lattice can be embedded in the manifold. But any embedding of the lattice picks out a frame, the one in which it is **uniform.**

A lattice can be DPD for an approximating **Newtonian** spacetime (or a **Riemannian** spacetime) **not** a Lorentzian one.

Causal set = transitive directed acyclic graph



- Spacetime atoms
- Lorentz invariant
- relational
- Number~Volume
- fluid not crystal
- 10^{240}

There are causal sets corresponding to each causal Lorentzian manifold

Dynamical emergence

- Let us assume "kinematical emergence" of spacetime from causal sets: a causal set **can** contain all the geometrical information of a Lorentzian spacetime on scales larger than the discreteness scale.

- To claim that GR emerges from quantum gravity, such DPD, approximate-able by solutions of the Einstein equations, must arise **dynamically** in the fundamental theory.

- **Postulate:** quantum gravity is based fundamentally on causal sets

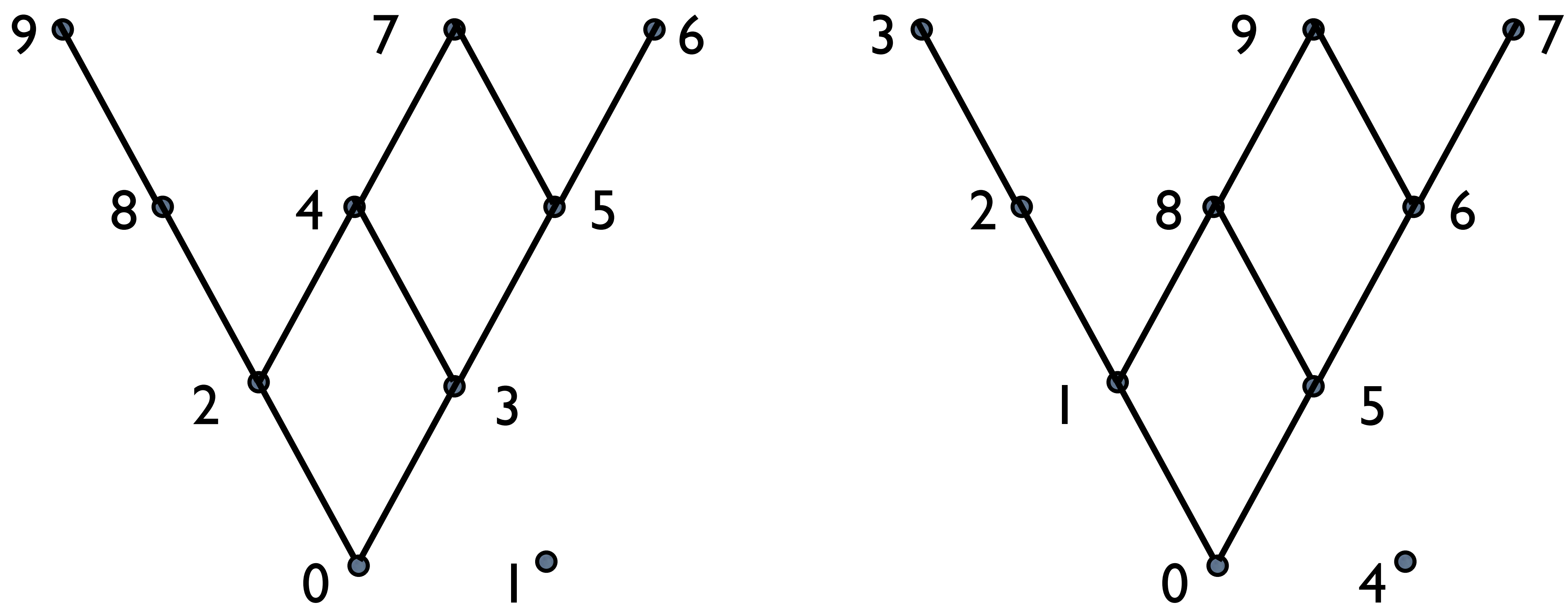
- Causal sets are inimical to a Hamiltonian approach so we take the Path Integral as the basis for a Quantum Causal Set Dynamics.

- Attitude: Path Integral Quantum Theory is a species of generalised stochastic process. Quantum Mechanics is a generalisation of Brownian motion.

- Therefore, as a warm up for **quantum** causal set theory, we try to construct **classical stochastic** models for causal sets. Here, the notion of **Becoming** played a heuristic role in the discovery of an interesting class of models: Classical Sequential Growth

Classical sequential growth models **(Rideout&Sorkin)**

A random process of continual **births** of new spacetime atoms



The same causal set (with different labels) can be grown in other ways.

The only **physical** order of birth of the atoms should be the order they have in the resulting causal set. All other label information is "pure gauge". This means the probability of the two different processes much be equal. This leads to a class of "cosmologies" with fascinating properties such as cyclic behaviour and self-tuning.

Things happen, they just happen in a partial order

- Sequential Growth models embody the notion of Becoming: the birth process is physical.
- The physical order in which spacetime atoms are born is their order in the resulting causal set, a partial order: there's no global time.
- The "present" is **not** any particular collection of spacetime atoms, the present is the birth process itself
- There is no "god's eye view" of the physical world: the **birth process** is objective but the **world that exists now** is subjective and is the past of a particular spacetime atom as it is born.

> "[The model] provides an objective correlate of our subjective perception of "time passing" in the unceasing cascade of birth-events" Sorkin

This aspect of time — that we experience it passing — seems not to be captured in GR in the Block Universe picture. So, if the birth of space-time atoms survives as a process in full quantum gravity, the passage of time will not be "emergent" but fundamental.

Why can we not agree on whether our experience is captured within a Block Universe view of GR?

The Parable of the Sceptical Newtonian!

17th Century Scientist: There is a physical force of weight on you **--** look at celestial mechanics, etc. The Newtonian theory perfectly accounts for all that data

17th Century Sceptic: But I don't experience this gravitational force of weight whereas I do experience other forces of comparable magnitude.

Scientist : The force of weight exists. So your lack of experience of lack of force must be due to neurology, psychology, the way the mind and body work to produce experience.

Sceptic: Maybe. But maybe this is telling us to look for a theory in which there is no force of weight.

Note I: The lack of experience of a force of weight did not contradict Newtonian gravity, it was **not even a fact** within it. The 17th Century Scientist held an unassailable position!

Note II: The lack of experience of a force of weight is evidence from a regime far from that in which **full** GR is required (strong gravity).

We may be in a similar position regarding our experience of time

The following conversation might be analogous.

21st Century Scientist: There is no physical passage of time in General Relativity and GR perfectly accounts for all our data.
21st Century Sceptic: But I experience time passing.
Scientist: Your experience of time passing must due to neurology, psychology, the way the mind and body work to produce experience.
Sceptic: Maybe. But maybe this is telling us to look for a theory in which there is a passage of time.

Our experience of time passing does not contradict a Block Universe view in GR, it is not even a fact within it. This intimate, subjective experience is evidence from a regime far from that in which full quantum gravity is required. But maybe it is giving us a clue to physics yet to come.

Further discussion points

- The growth model is as close as it seems to be possible to come to capturing the notion of "asynchronous becoming". But once the model process is described, written down, communicated in words and equations, the description becomes **static**: maybe we are coming up against a limitation of mathematics — as we currently understand it — in describing a dynamic universe

- To me, discreteness is the key to being able to conceive of a "growing Block" as a process of accretion of spacetime atoms in a partial order. Can others conceive of a **continuum** spacetime growing in a partial order? To the extent they can, Becoming can be modelled in GR too.