Title: Recovering General Relativity from a Planck scale discrete theory of quantum gravity

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Series: Quantum Gravity

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Abstract: I will present an argument that if a theory of quantum gravity is physically discrete at the Planck scale and the theory recovers General Relativity as an approximation, then, at the current stage of our knowledge, causal sets must arise within the theory, even if they are not its basis. I will argue in particular that an apparent alternative to causal sets, viz. a certain sort of discrete Lorentzian simplicial complex, cannot recover General Relativistic spacetimes in the appropriately unique way. For it cannot discriminate between Minkowski spacetime and a spacetime with a certain sort of gravitational wave burst.

Zoom Link: https://pitp.zoom.us/j/96897602807?pwd=VkJ3VTAwYjhaTnJ3Z2ZVclZFYXErZz09

Recovering General Relativity from a Planck scale discrete theory of Quantum Gravity

Fay Dowker
Perimeter Institute 3 March 2022

(Butterfield and Dowker arXiv:2106.01297)

Plan

- Make two assumptions about a quantum gravity theory X:
  A1: X recovers GR and A2: X is Planck scale discrete
- Flesh out these assumptions in a series of comments: introduce concepts of grounding state, Discrete Physical Data (DPD) and Discrete-Continuum correspondence (DCC) for theory X
- State and briefly justify two Claims:

  C1. Causal sets (Discrete orders) can recover GR spacetimes

  C2. There is no other proposal to date for a DPD-set that does the job
- Explain why "quantum uncertainty" does not invalidate the argument
- Conclusion

Quantum Gravity Theory X

Assumption 1. Theory X recovers GR as an approximation in certain states (physical situations), at macroscopic scales.

Assumption 2. X is physically discrete at the Planck scale

Comments I

1. Analogies: (a) GR recovers Newtonian gravity as an approximation (b) Molecular dynamics recovers fluid dynamics as an approximation (continuum is emergent) (c) Quantum mechanics recovers classical mechanics as an approximation (either in a way that is already set out or in a way that is yet to be set out).

2. X must recover a large class of 4-dimensional GR spacetimes including gravitational waves, large portions of Minkowski space, black holes and expanding cosmologies. All recovered spacetimes vary slowly on Planckian scales.

3. X has, for each GR spacetime (M,g) to be recovered, a **grounding state** which contains/produces/gives rise to a set of **Discrete Physical Data** (DPD) from which (M,g) can be recovered *essentially uniquely* i.e. (M,g) is a good approximation to the DPD-set.

4. The DPD-set contains no geometrical information about the GR spacetime at smaller than Planckian length/time/volume scales.

Comments II

5. There must be a **Discrete-Continuum-Correspondence (DCC-X)** for theory X,

DPD-set → GR SPACETIME

that says (up to some tolerance) when a GR spacetime is recovered from a DPD-set. c.f. molecular state → fluid state

6. **Essential uniqueness** is necessary for the DCC-X to hold water:

If (M,g) and (M', g') are both recovered by the same DPD-set according to DCC-X, then we must have that (M,g) and (M',g') are approximately isometric and physically indistinguishable on large scales c.f. if two fluid states are recovered from the same molecular state, they must be approximately the same and physically indistinguishable on large scales. This underpins the concept of recovery of one theory from another. It underpins what we mean when we say that Quantum gravity is more fundamental than GR.

Comments III

7. No assumption is made about the nature of the grounding state (might be a state in a Hilbert space or something entirely different such as a co-event in a path-integral-based framework).

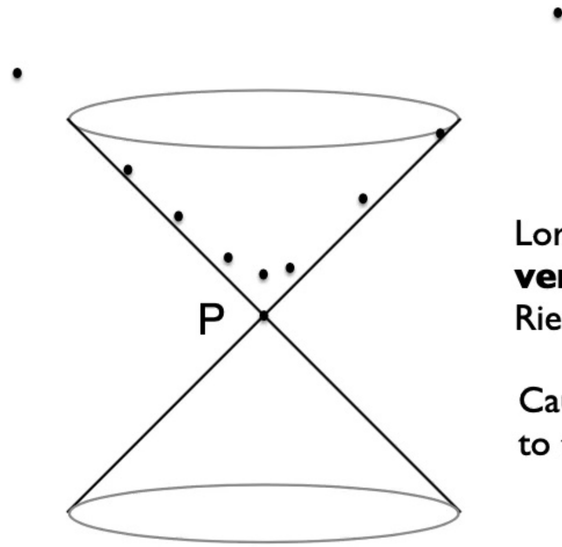
8. No assumption is made about how the state gives rise to the DPD (they might be expectation values of or eigenvalues of certain self-adjoint operators, or not; their deduction from the state could involve some kind of coarse graining, or involve matter degrees of freedom or rely on more-or-less anthropocentric arguments involving observers, or …).

Two Claims

Claim 1: A causal set—a locally finite partial order—is a set of DPD that, taken as being discrete on the Planck scale, can recover a GR spacetime as a continuum approximation.

Claim 2: There is in the current literature no other proposal for a set of Planck scale DPD that can recover a GR spacetime as a continuum approximation.

What X recovers



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

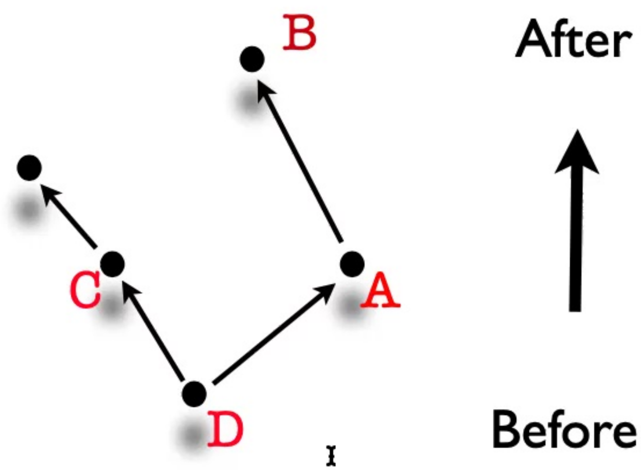
Causal order is central to the **physics** of GR.

Lorentzian geometry is (bordering on) non-local and the notion of "physically close" is not captured well in any picture: the chosen frame is an impediment to understanding Lorentzian geometry.

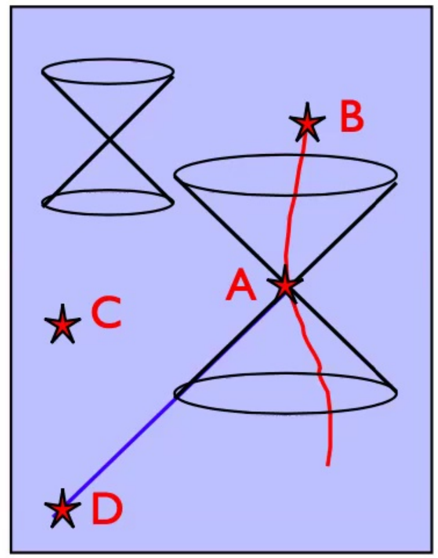
Nonlocality: the points one Planck time in the future of P in Minkowski space lie on an infinite spatial hyperboloid that asymptotes to the future light cone.

Claim 1:

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



Continuum approximation (fluid)



$$10^{240}$$

Claim 1 (Order + Number = Lorentzian Geometry)

The Discrete-Continuum Correspondence for causal sets :

A causal set C recovers (M,g) if C **faithfully embeds** in (M,g) at Planck density: there exists an embedding $C \rightarrow M$ such that

(i) Number $\approx$ Volume in large, physically nice regions (uniform) and

(ii) The order of C equals the causal order of the embedded points in (M,g)

As far as we know, the distribution of embedded points must be random

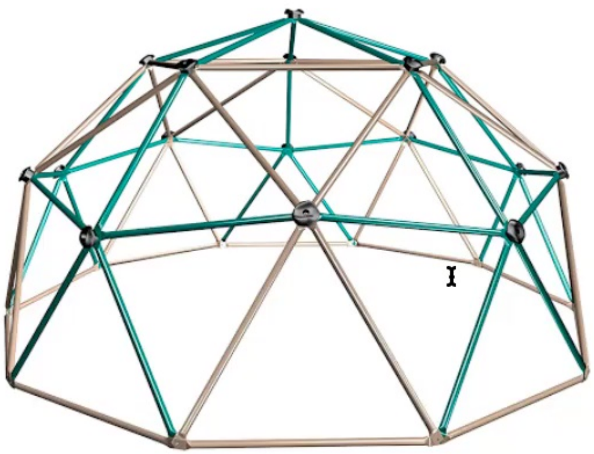
A. Kronheimer-Penrose-Hawking-Malament theorem: Causal order + Volume = Lorentzian Geometry. The order of a causal set provides the spacetime causal order and the counting measure provides the volume (c.f. Riemann)

B. At infinite density, a faithfully embedded causal set —> (M,g) (Meyer and Sorkin)

C. Direct evidence: e.g. dimension (Myrheim-Meyer), geodesic proper time (Myrheim, Brightwell&Gregory, Bachmat), scalar curvature (Benincasa&Dowker, Glaser)

Claim 2: Combinatorial Lorentzian Regge Complex

Proposal for alternative DPD-set: A Combinatorial Lorentzian Regge Complex (CLRC) is a combinatorial simplicial complex plus Lorentzian edge-length (and, if appropriate, future direction) labels on the 1-simplices (edges) which are no more than a few in Planck units. There is **no** geometrical information in the interior of the simplices: that would be continuum information.



Note, this picture is slightly misleading: the edges in a CLRC have "length" labels but no continuum geometry.

Evidence for Claim 2

A Discrete-Continuum Correspondence for CLRCs:

A CLRC recovers (M,g) if the CLRC

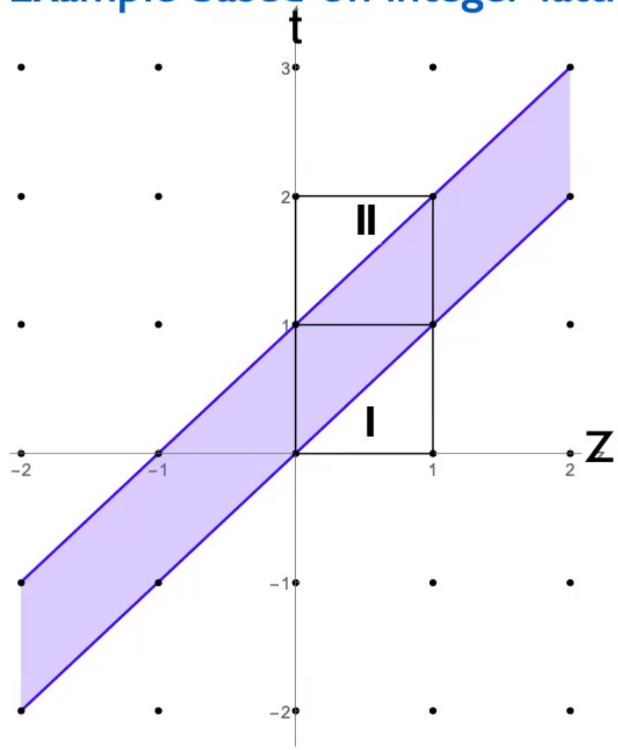
(i) is the **combinatorial** complex derived from a triangulation of manifold M

(ii) vertices can be embedded in (M,g), consistent with that triangulation, such that the spacetime geodesics between the embedded vertices have proper lengths = CLRC edge-length labels in Planck units (approximately)

This DCC-CLRC **fails:**

There exists a CLRC that (according to this DCC) "recovers" Minkowski space and **also** "recovers" a spacetime that is a perturbation of Minkowski space with a physical, plane fronted gravitational wave burst.

Example based on integer lattice in 3+1 dims



Define a CLRC built from a triangulation of Minkowski space:

- 24 4-simplexes in each hypercube
- There are 15 edges from the origin in hypercube I: 1 edge is timelike, 3 are null and the rest are spacelike.
- The CLRC is the combinatorial complex with edges decorated with their Lorentzian lengths + future direction (for the timelike and null ones)
- Note: no vertices in the shaded region: it's a **void**

$\boxed{\text{No continuum info (otherwise this would just } \textbf{be} \text{ Mink space)}}$

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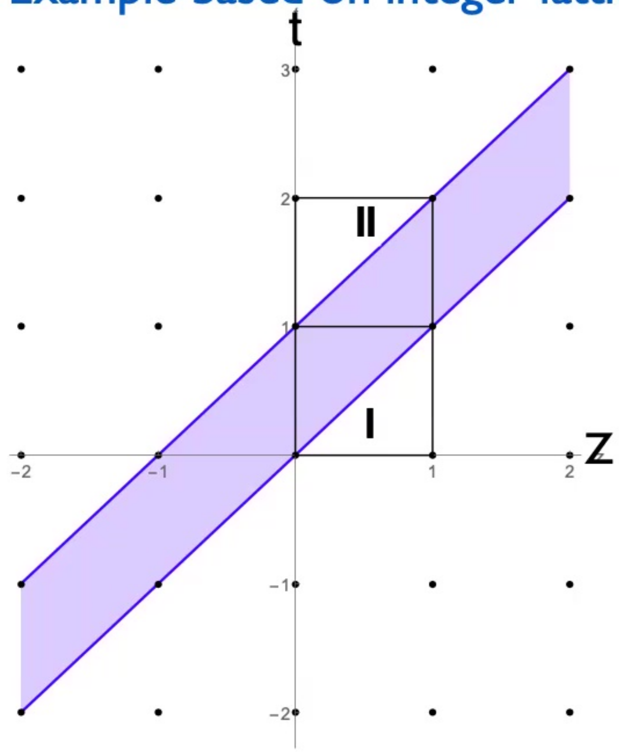

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The CLRC-DCC says that this CLRC "recovers" Minkowski space

No continuum info (otherwise this would just **be** Mink space)

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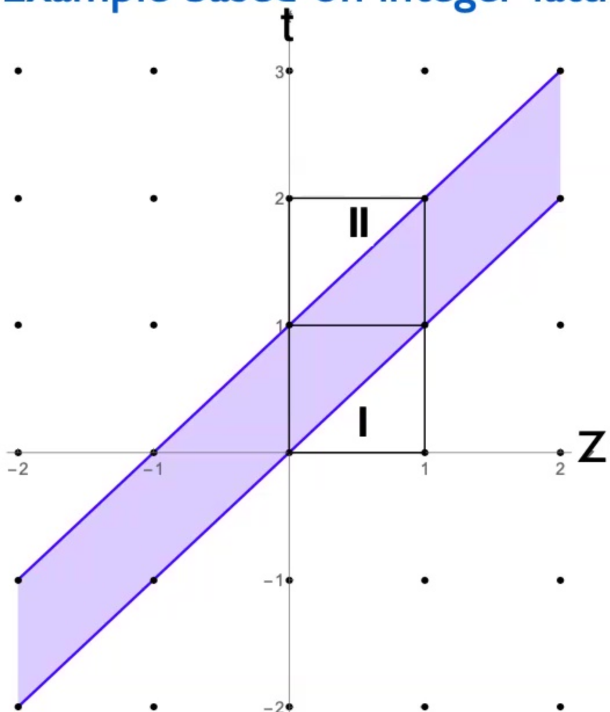

$$ds^2 = -dt^2 + dz^2 + (1 - h(u))dx^2 + (1 + h(u))dy^2 \quad (1)$$

$$h(u) \neq 0 \;\; in \;\; 0 < u < 1 \;\; and \;\; \int_0^1 du\, h(u) = 0$$

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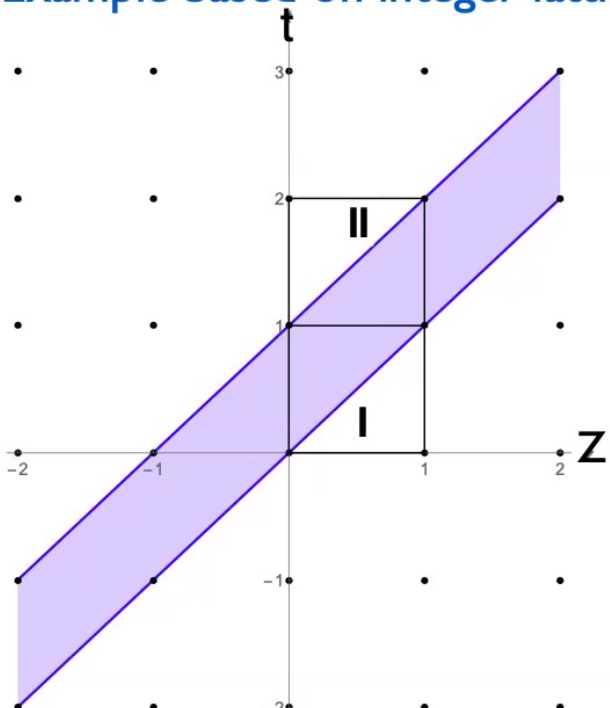

The CLRC-DCC says that this same CLRC "recovers" the gravitational wave burst below

(u = t-z)

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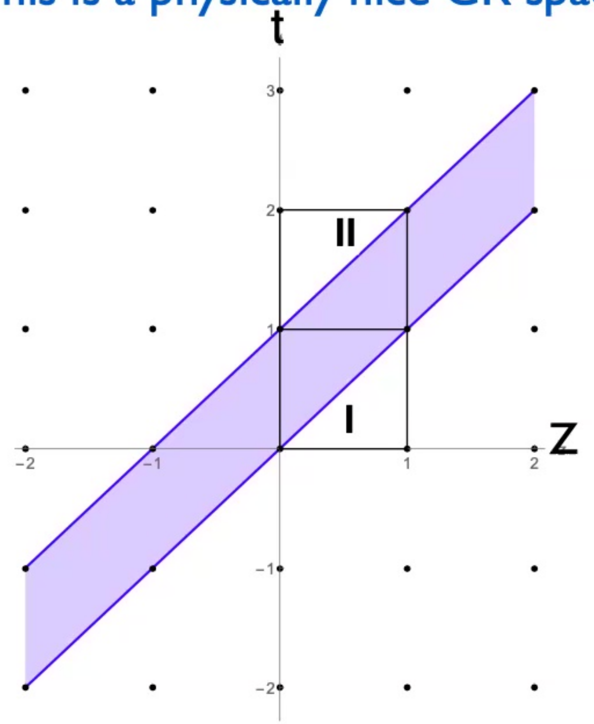
This is a physically nice GR spacetime



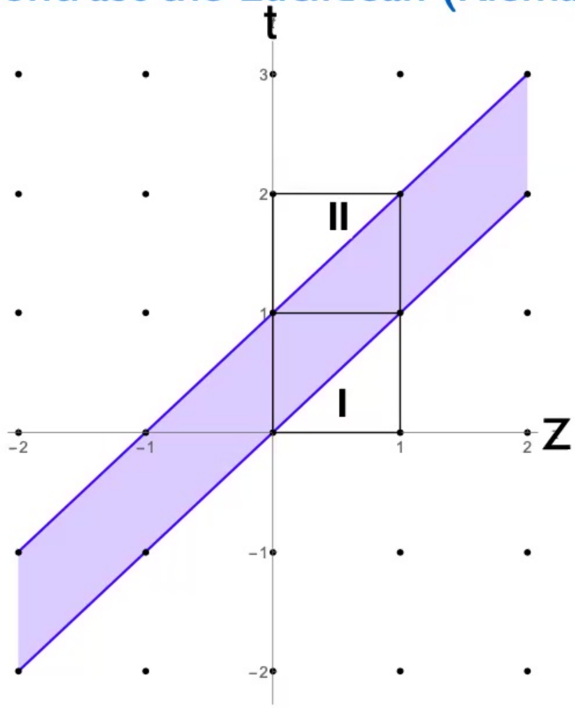
- The void is a large, **physically nice** region of spacetime.
- "width" or "height" of a region can't be used as a measure of "niceness" in Lorentzian geom: null directions!). So instead:
- It contains approximately flat causal diamonds of height 1 second
- Lorentz invariance is the key to this counterexample
- To see this: do a Lorentz boost in the z direction with gamma factor of 10^{44}

$$\{t, x, y, z\} \to \{t', x, y, z'\}$$

$$ds^2 = -dt'^2 + dz'^2 + (1 - H(u'))dx^2 + (1 + H(u'))dy^2 \qquad (2)$$

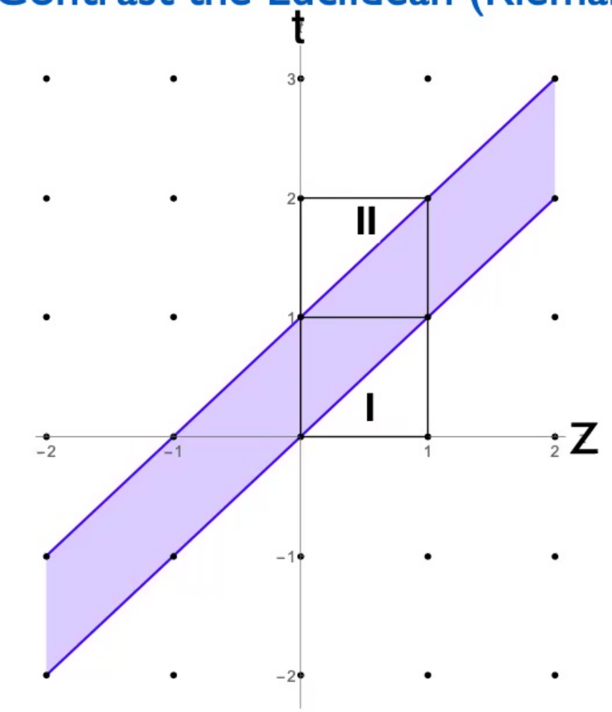
$$u' \approx 10^{44}u, \quad H(u') = h(u) \neq 0, 0 < u' < 10^{44}$$

Contrast the Euclidean (Riemannian) case:



- The void is NOT a physically nice region of Euclidean spacetime.
- It has physical structure (e.g. its width) that is smaller than Planckian
- No isometry of Euclidean space changes that.
- Starting with the Riemannian Combinatorial Complex, filling the blue region with non-flat continuum geometry produces a spacetime with geometry that varies on the scale of the discreteness. So this is **not** a counterexample to:

Contrast the Euclidean (Riemannian) case:



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Conjecture: There exists a Discrete-Continuum Correspondence for Combinatorial **Riemannian** Regge Complexes that succeeds

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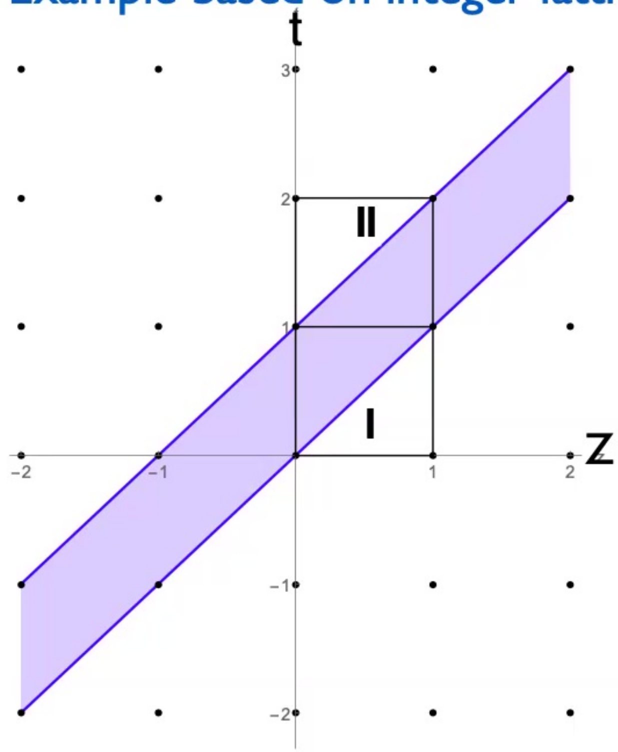

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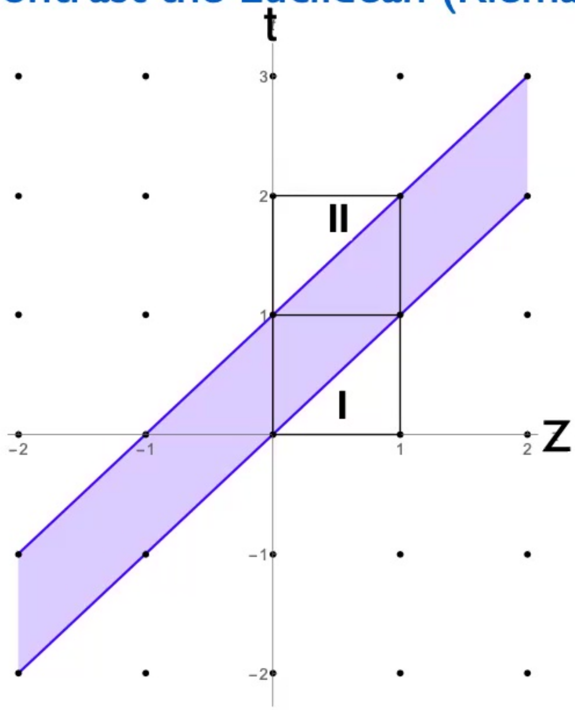

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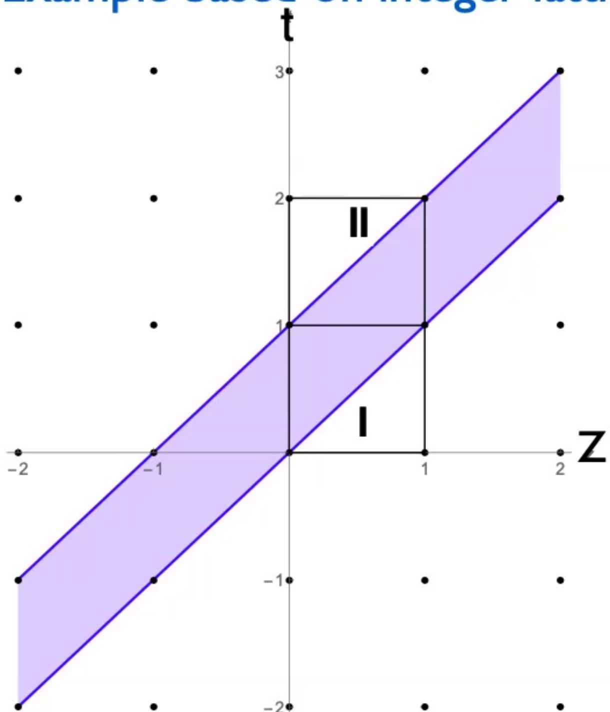

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What about other alternative DPD-sets?

- Whatever the DPD-set is in theory X, without a Number-Volume correspondence in the DCC-X, there will be large, physically nice void/ sparse regions.
- When there are large, physically nice voids, any DCC-X will fail because the DPD-set cannot recover the Lorentzian geometry in the voids.
- If one demands the Number-Volume correspondence in the DCC-X, there is only one proposal for DPD-sets in the literature: causal sets

Conclusion

No matter what X is fundamentally, if the assumptions hold, then at the point where a GR spacetime needs to be recovered, there is at present no entity in the literature other than a causal set that can do the job of recovery that Discrete Physical Data in a grounding state in X must do.

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Thank you for listening