Title: The search for quantum gravity: where are we, where do we go from here?

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Series: Quantum Gravity

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Despite enormous effort from thousands of dedicated researchers over a century, the search for the quantum theory of gravity has not yet arrived at a satisfactory conclusion. We have indeed several impressive proposals, each of which partly succeeds in describing plausible quantum gravitational physics. Each tells a compelling story that has, for good reason, won it advocates. Each has also run into persistent roadblocks, which are pointed to by their skeptics. Looking back, before strings and loops, before causal sets, causal dynamical triangulations, asymptotic safety, amplitudes, twisters, shape dynamics, etc, to the early days of Bergman, Deser, DeWitt, Wheeler and their friends, who would have thought that there would turn out to be at least half dozen ways to get part way to quantum gravity?

Perhaps we might, for a moment, consider that the approaches so far pursued are not really theories, in the sense quantum mechanics, general relativity and Newtonian mechanics are theories. For those are based on principles and perhaps we can agree that we don't yet know the principles of quantum gravity.

Perhaps the different approaches are models of possible regimes of quantum gravity phenomenology?

What are we missing in our search for quantum gravity? arXiv:1705.09208.

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What are we missing in our search for quantum gravity? arXiv:1705.09208.

Very brief summary of LQG & SF.

Good points:

- Gives a complete description of quantum geometry derived from a first principles quantization of GR in units of hG.
- Gives a boundary theory, defined also on horizons, which automatically respects the weak holographic principle.
- Gets right entropy and temperature for black hole and cosmological horizons.
- Linearized quantum theory is correct.
- Couples to gauge fields, fermions, scalars, supergravity, N=1,2… etc.
- Reduces to 2+1, 1+1 (w KF),
- Cosmological models. (LQC)
- Discreteness of areas and volumes is a result. Evidence for uv finiteness
- Realizes picture of TQFT with defects.
- Λ realized by quantum deformation: Infrared finiteness

Very brief summary of LQG & SF.

In progress:

- coarse graining, renormalization, low energy or semiclassical limits need to be better understood.
- Chiral fermions as braided states.
- Unification with gauge fields via extended Plebanski.

Weak points

- No unambiguous non-trivial predictions for experiments.
- No ground state, no positive quantum energy theorem
- Hard to get Planck energy out without matter
- fermion doubling problem: chirality
- The description of Planck scale quantum geometry is "to bl.. complicated

My present view:

"Something like" the LQG kinematics could be right, but extended by energy labels. ie basis labeled by diffeo classes of framed or dual spin networks of some category of representations of a quantum group extending reps of chiral SU(2) X translations. (dual Spin networks=triangulations).

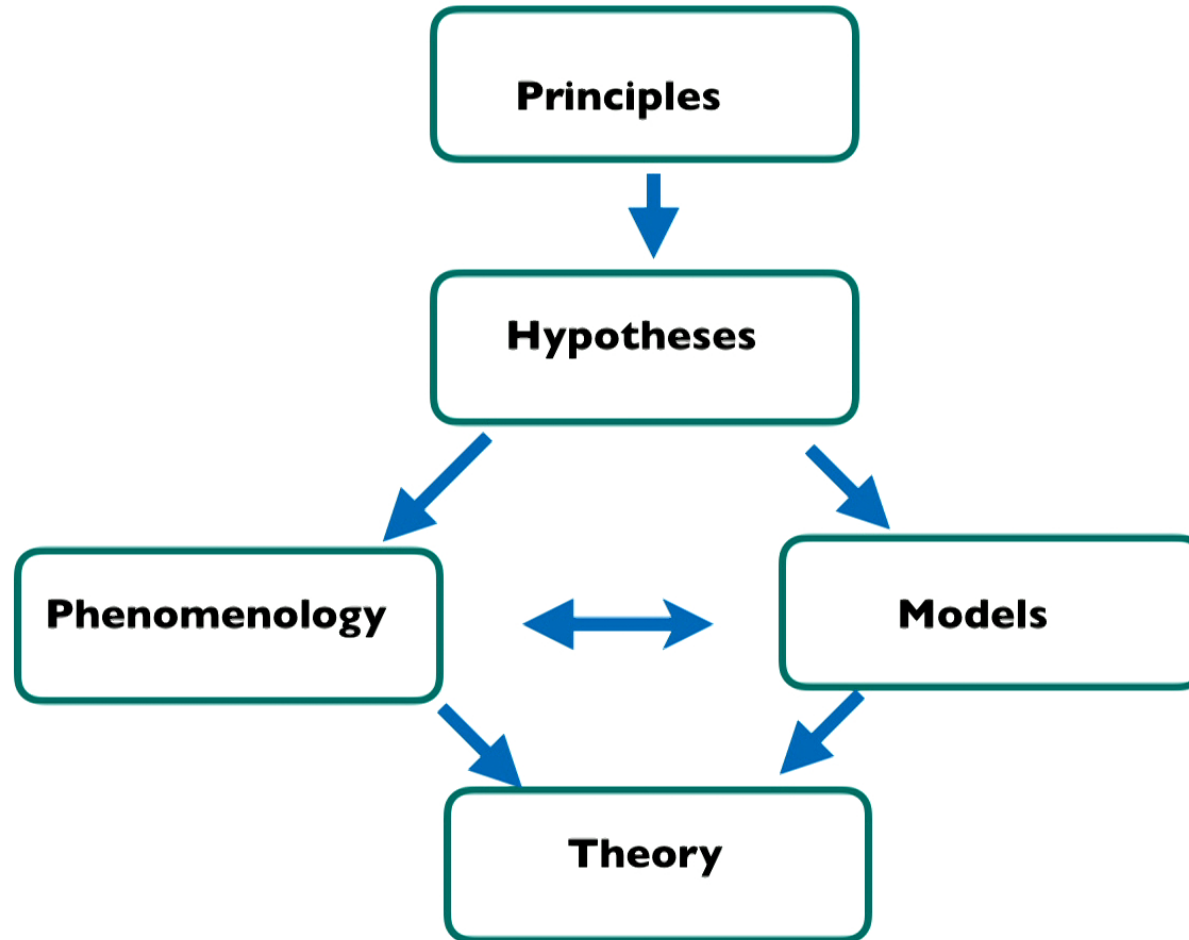*ie this is an attractive but not convincing story of how the world could be.*

There is something right in the use of the CFT —> CS —> BF ladder of dimensions to construct boundary physics.

Dynamics and the whole treatment of time need to be radically rethought along the lines of energetic causal sets (ECS) and beyond…
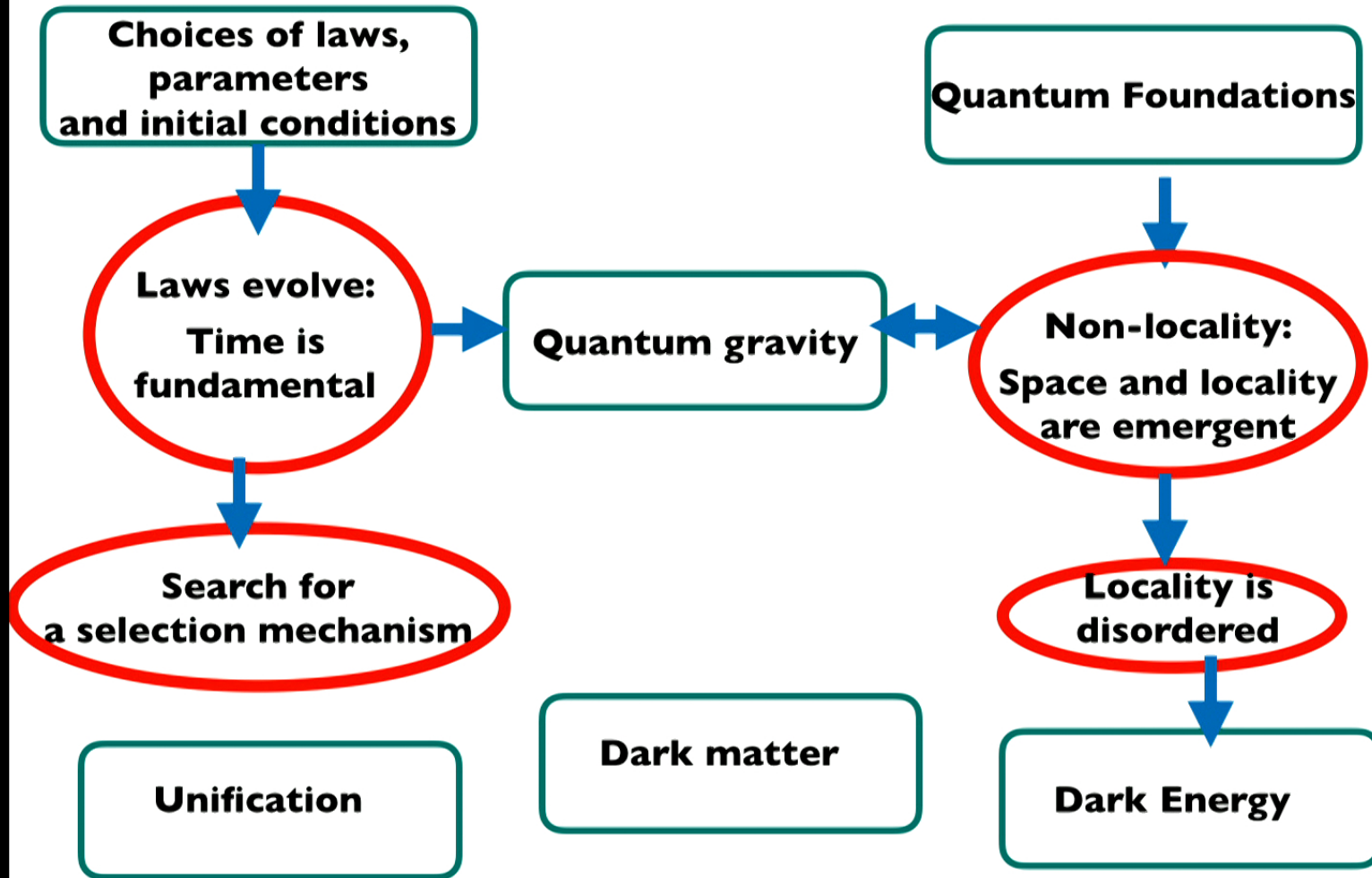
Start with principles.

Methodology:

6 major question in fundamental physics:

Choices of laws, parameters and initial conditions

Quantum Foundations

Laws evolve: Time is fundamental

Quantum gravity

Non-locality: Space and locality are emergent

Search for a selection mechanism

Locality is disordered

Unification

Dark matter

Dark Energy

Time is fundamental
and irreversible.
Causality is fundamental.
Space is not fundamental, locality is
emergent and disordered.

Laws of nature evolve.

Quantum theory is incomplete,
and these ideas guide its completion

Only with these assumed can nature be fully explicable

Candidate principles for quantum gravity (Jan 2020):

1) Relationalism
2) Causation
3) Duality
4) Weak holography
5) Quantum equivalence principle

arXiv:1610.01968, contribution to Paddy@60, a book in honour of Thanu Padmanabhan.

Candidate principles for quantum gravity:

1) Temporal* Relationalism:
2) Causation
3) Duality
4) Weak holography
5) Quantum equivalence principle

*Relationships are based on causal relations, and are tensed.
Past, present and future are objective and universal.

- **The principle of sufficient reason (Leibniz, PSR):**

  There must be a rational answer to every question that can be imposed of the form of *"Why is the universe like X and not otherwise?"*

  Or: Progress in understanding nature is measured by decreases in the number of features of the universe that are arbitrary or not determined by equations of motion.

- **The principle of the identity of the indiscernible (Leibniz, PII):**

  Any two events that have the same values of the physical fields are identified. i.e. no two events in the history of the universe have the same values of the physical fields.

  Or: No two events have the same *views* of their causal pasts.

  The view of an event: *What you see (incoming photons etc) looking out, and hence back from that event.*

  The emphasis is on the uniqueness of every event: the opposite of symmetry!

These two principles of relationalism have many implications:

- *No fundamental symmetries.* But there can be gauge and diffeomorphism invariances
- *Theories must be background independent, ie not contain arbitrary fixed structures* not determined by dynamics. These usually cash out as implicit references to fixed external reference structures, outside of the system being modeled.
- *Realism*
- Space and time are relational.
- The principle of explanatory closure: Everything that causally influences the behaviour of a physical system within the universe must be another physical system within the universe

- The principle of reciprocity: There is nothing in nature that acts without being acted upon in return.

16

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2) Causation: Events and their causal relations are real

 What is fundamental, and what is emergent ?

Fundamental:

energy

momentum

composition=extended structures

events and causal relations

causal past="view"

beables

A brief moment for the basic dual pairing in physics:

Energy and momentum   vis time and position

My hypothesis:

Energy and momentum are fundamental,
space and spacetime are not:

ie the world is made by causal processes that carry energy
and momentum, but do not live in space or spacetime.

Conjecture: An "inverse Noether theorem" governs the
emergence of space.

II Events and their causal relations are real:

What is fundamental, and what is emergent ?

Fundamental: Emergence of   **Emergent:**
                    Dualities

energy   spacetime

momentum   (configuration) space

extended structures   gauge fields

events and causal relations   geometry

causal past="view"   light cone

beables   quantum mechanics

$[x, p] = [0, p] = i h = 0$ the algebra of be-ables is commutative!!

It appears that for each can. conj. pair: (x,p), one is fundamental while the other is emergent!

$[x, p] = [0,p] = i\hbar = 0$ the algebra of be-ables is commutative!!

We can call this emergent duality

So quantum mechanics must be emergent as well, therefor our theory is a completion of QM.

The fundamental variables are also beables.

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A strategy:

Candidate principles for quantum gravity :

1) Temporal Relationalism
2) Causation
3) Emergent Duality
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5) Quantum equivalence principle

Model of 1) and 2): Energetic Causal Sets (ECS)

Model of 1), 3)& 4):   LQG+SF

Model of 1), 3)& 4):   Energetic, causal spin foams (ECSF) (to come)

ECS

Basics of Energetic Causal Sets

Energetic causal sets *is based on a set of assertions about what are real, be-ables and what is derivative and emergent:*

Real and fundamental: Events, causation, time as the process which continually brings into being novel events, which are tied to past events by networks of causal relations, and also, energy and momentum.

Derivative and emergent: Space and spacetime. Quantum states, rigid spaces of quantum states. Observables/operators and their algebras.
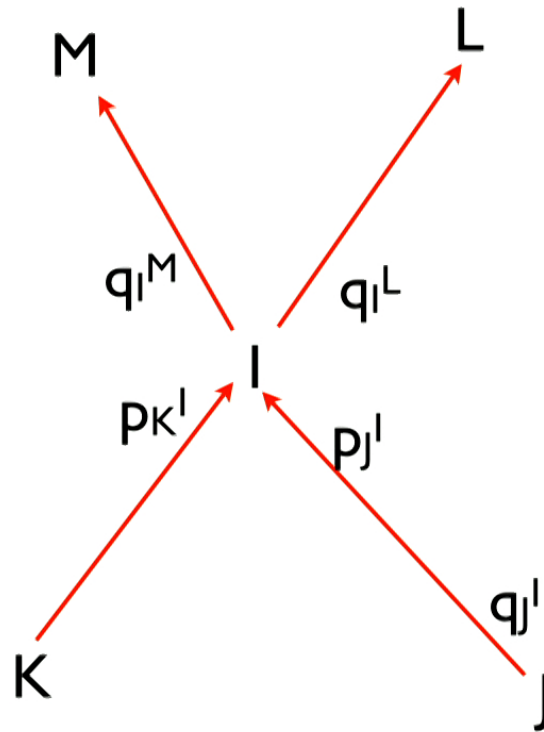
Causal sets:
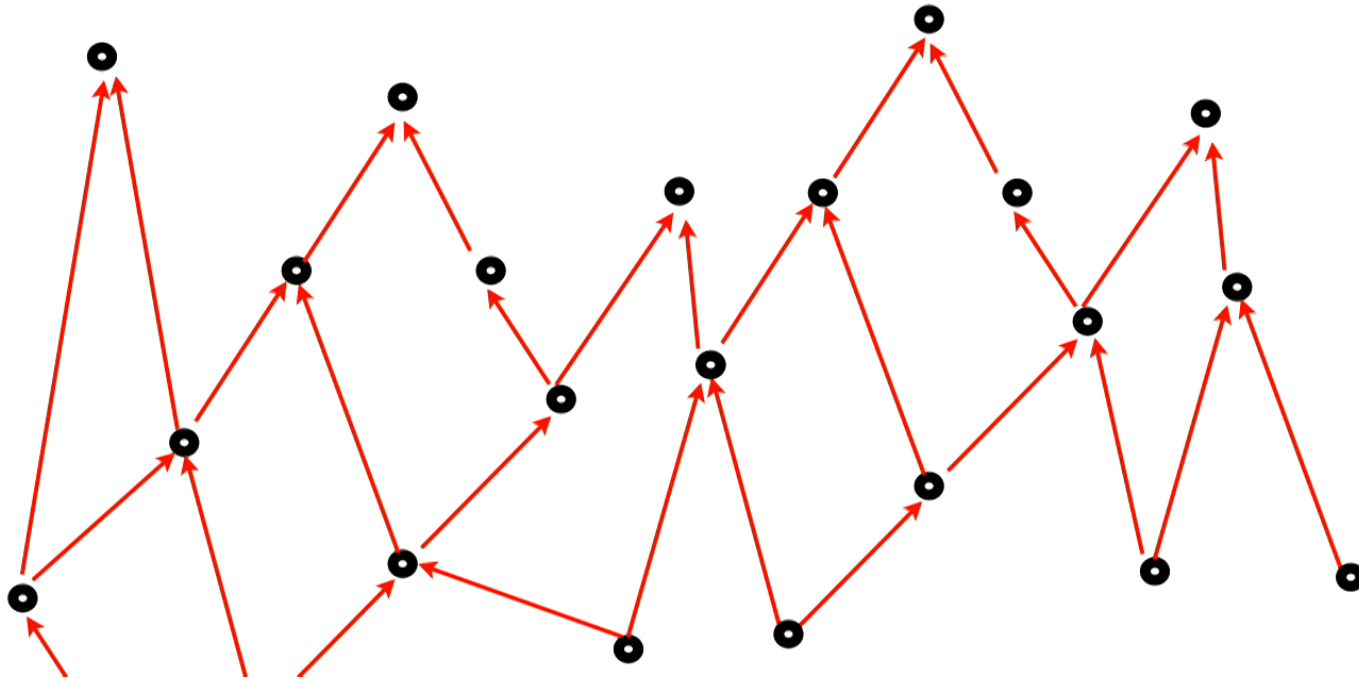
Energetic causal sets:

Each link, connecting E_I to one of its parents, E_j, has two momenta, an incoming momenta $p_J{}^I$ and an outgoing momentum $q_I{}^J$.

The total momenta of an event

$$P_a^I = \sum_J p_{aI}^J$$

Dynamics of Energetic Causal Sets:

- *Sequential growth: There is a rule that grows the causal set. At each step it picks a set of n parent events who become the causal precedents of a new event.*
- *Each event can be parents to at most p child events. Thus those events with less than p children are potential parents and hence make up a thick present. Those events which have p children make up the past.*
- *The energy-momentum of the parents is distributed to the children by applying a set of constraints, which enforce conservation.*

Constraints:

The momenta are propagated to the new event and links by three constraints:

Conservation at each event:

$$\mathcal{P}_a^I = \sum_K p_{aK}^I - \sum_L q_{aI}^L = 0$$

Parallel transport on each edge:

$$\mathcal{R}_{aI}^K = p_{aI}^K - \mathcal{U}_{Ia}^{Kb} q_{bI}^K = 0$$

Energy-momentum relations:

$$\mathcal{C}_K^I = \frac{1}{2}\eta^{ab} p_{aK}^I p_{bK}^I + m^2 = 0$$

$$\tilde{\mathcal{C}}_K^I = \frac{1}{2}\eta^{ab} q_{aK}^I q_{bK}^I + m^2 = 0$$

No spacetime.
The only geometry that comes in is the metric of momentum space.

Dynamics:

The action is the sum of constraints:

$$S^{ECS} = \sum_{I} z_I^a \mathcal{P}_a^I + \sum_{(I,K)} (x_K^{aI} \mathcal{R}_{aI}^K + \mathcal{N}_I^K \mathcal{C}_K^I - \tilde{\mathcal{N}}_I^K \tilde{\mathcal{C}}_K^I)$$

lagrange multipliers

Classical physics from the critical points of the action:

$$S = \sum_I z_I^a \mathcal{P}_a^I + \sum_{(I,K)} (x_K^{aI} \mathcal{R}_{aI}^K + \mathcal{N}_I^K \mathcal{C}_K^I - \tilde{\mathcal{N}}_I^K \tilde{\mathcal{C}}_K^I)$$
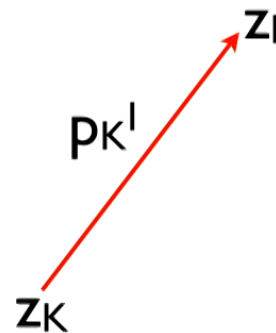
lagrange multipliers

Constraints:

$$\mathcal{P}_a^I = \sum_K p_{aK}^I - \sum_L q_{aI}^L = 0 \qquad \mathcal{R}_{aI}^K = p_{aI}^K - \mathcal{U}_{Ia}^{Kb} q_{bI}^K = 0$$

$$\mathcal{C}_K^I = \frac{1}{2} \eta^{ab} p_{aK}^I p_{bK}^I = 0 \qquad \tilde{\mathcal{C}}_K^I = \frac{1}{2} \eta^{ab} q_{aK}^I q_{bK}^I = 0$$

Equations of motion:
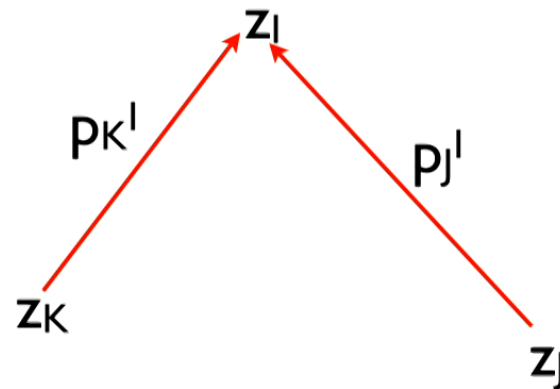
$$z_I^a - z_K^a = p_K^{aI} \mathcal{M}_I^K$$

$$\mathcal{M}_I^K = \tilde{\mathcal{N}}_I^K - \mathcal{N}_I^K$$

z_I

p_K^I

z_K

Spacetime emerges when there are consistent solutions to all the EoM:

$$z_I^a - z_K^a = p_K^{aI} \mathcal{M}_I^K$$

The Lagrange multipliers z^a emerge as the coordinates of the emergent dual spacetime.

$$z_I$$

$$p_K{}^I \qquad p_J{}^I$$

$$z_K \qquad z_J$$

Spacetime inherits its metric from momentum space:

U=1 gives flat spacetime

$$|z_I^a - z_K^a|^2 = (z_I^a - z_K^a)(z_I^b - z_K^b)\eta_{ab}$$
$$= (\mathcal{M}_I^K)^2 |p_K^{aI}|^2 = 0$$

Half quantum theory

All we need to define quantum dynamics is the amplitude law. Events, I, have amplitudes A_I.

Process P:
$$\mathcal{A}[P] = \prod_I \mathcal{A}_I$$

Fix incoming and outgoing and sum:
$$\mathcal{A}[p_a^{in,\ I}; q_a^{out,\ I}] = \sum_P \mathcal{A}[P]$$

Probability:
$$\mathcal{P}[p_a^{in,\ I}; q_a^{out,\ I}] = \left| \mathcal{A}[p_a^{in,\ I}; q_a^{out,\ I}] \right|^2$$

The total amplitude is defined by integrating over momenta, imposing the constraints

$$\mathcal{A}[P] = \int \Pi_{(IJ)} dp_a^{IJ} dq_a^{IJ} \delta(\mathcal{C}_a^{IJ}) \delta(\mathcal{R}_I^J) \Pi_I \delta(\mathcal{P}_a^I) \Pi_I \mathcal{A}_I$$

This is the complete definition of the theory.

No hbar
No spacetime
No commutation relations
No uncertainty principle

There are only be-ables: the causal processes and the energy-momentum propagated.

The total amplitude is defined by integrating over momenta, imposing the constraints

$$\mathcal{A}[P] = \int \Pi_{(IJ)} dp_a^{IJ} dq_a^{IJ} \delta(\mathcal{C}_a^{IJ}) \delta(\mathcal{R}_I^J) \Pi_I \delta(\mathcal{P}_a^I) \Pi_I \mathcal{A}_I$$

We introduce lagrange multipliers to exponentiate the constraints:

$$\mathcal{A}[P] = N[\mathcal{C}] \int \Pi_{(IJ)} dp_a^{IJ} dq_a^{IJ} d\mathcal{N}_I^J d\tilde{\mathcal{M}}_I^J \Pi_I dZ_I^a \ e^{\imath S^0}$$

With an action that is pure constraints:

$$S = \sum_I z_I^a \mathcal{P}_a^I + \sum_{(I,K)} (x_K^{aI} \mathcal{R}_{aI}^K + \mathcal{N}_I^K \mathcal{C}_K^I - \tilde{\mathcal{N}}_I^K \tilde{\mathcal{C}}_K^I)$$

lagrange multipliers

$A_I = 1$ for simplicity

From casual sets to views

We now switch from an ontology of events and their causal relations to a dual ontology which contains just the views of the various events.

According to this "view-ontology", the universe is nothing but the set of views, together with the causal relations they encode.

The view of an event, I, can be understood to be the information about the event's causal past that comes to the event from its backwards light cone. This includes energy and momentum transferred to the event from events in its immediate causal past.

Energy and information transfers generate a causal structure among events.

By the PII, all views are distinct. Therefor an event's view labels it, indeed overdetermines it.

Views as punctured two spheres: *the sky!*

The view of an event is a collection of null or timeline energy momentum vectors, representing incoming information about the past. $\{ p_{a\,I}{}^J , p_{a\,I}{}^K , \dots \}$.

We can represent the directional information as points on an S2, with labels which are the energy.
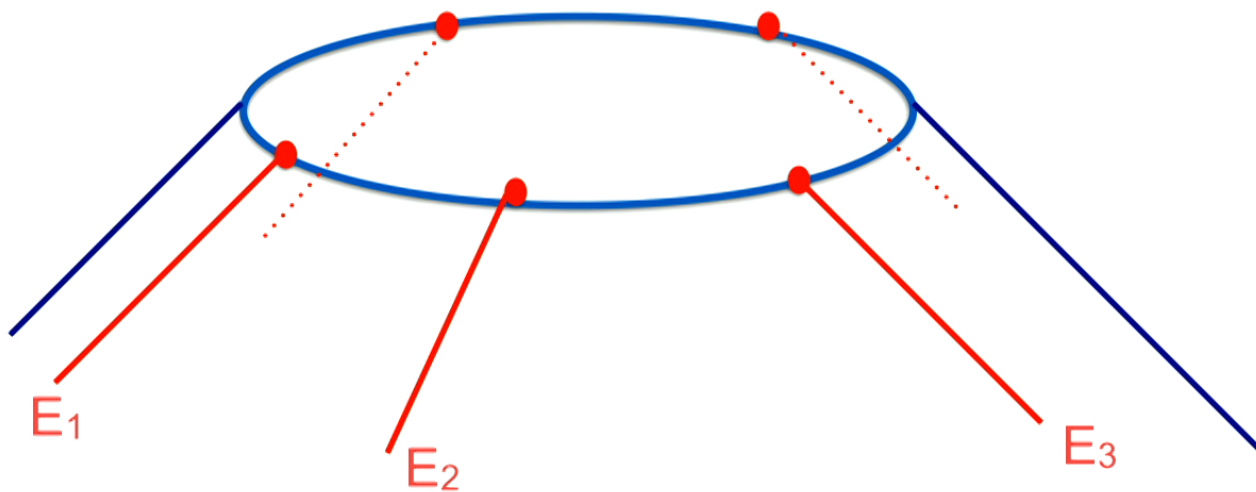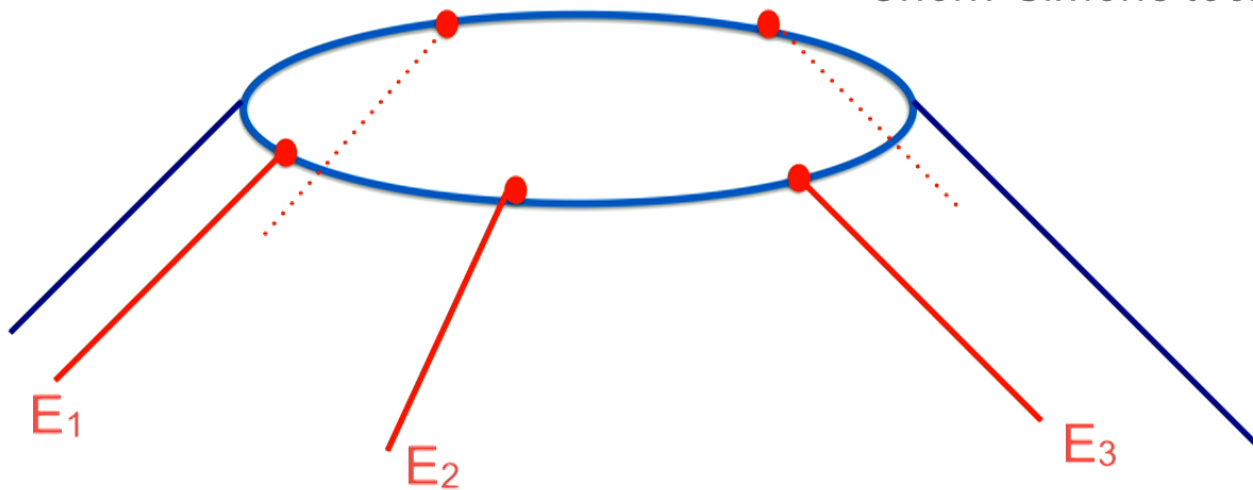
Views as punctured two spheres:

The views are the beables (because space isn't present).

Spacetime is emergent from the causal set of views.

The observables are functions on punctured S^2's representing the views.

Connects to boundary Chern-Simons technology

E_1

E_2

E_3

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V   Quantum Equivalence Principle:

The observers who, in the absence of curvature and a cosmological constant, see the vacuum to be a maximal entropy thermal state, are those that in the classical limit are uniformly accelerating. Hence those observers who see the vacuum to have zero temperature must be inertial.