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As Below, So Before

Synchronic and Diachronic Conceptions of Spacetime Emergence

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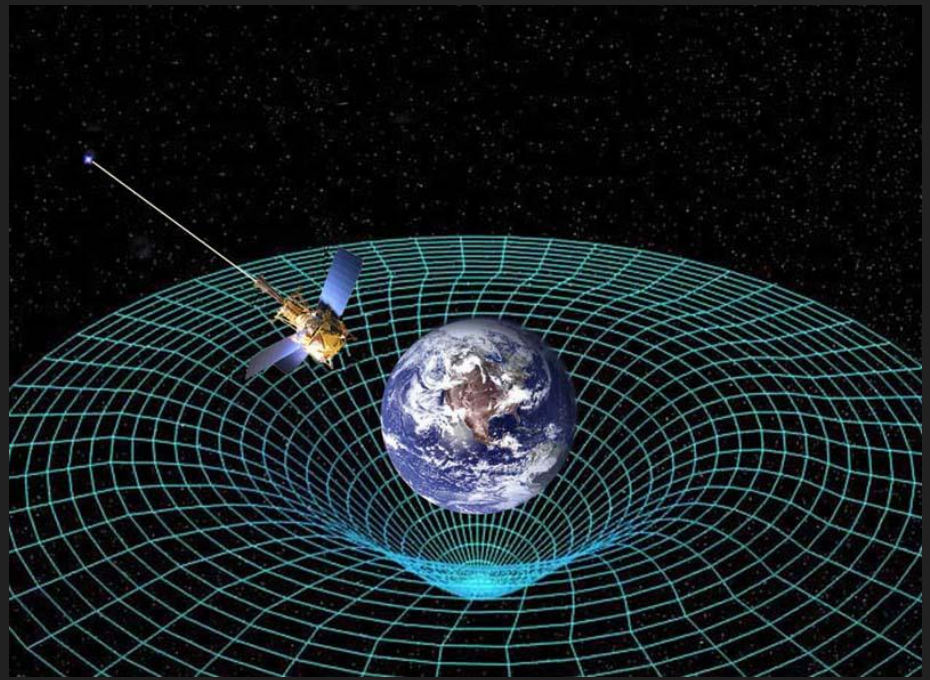
Emergent spacetime?

- Spacetime is described by the theory of general relativity (GR)
- Gravity is the curvature of spacetime around massive bodies



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Emergent spacetime?

- But, we expect that GR will be replaced by a theory of quantum gravity (QG) at extremely short distance scales (high energy scales)

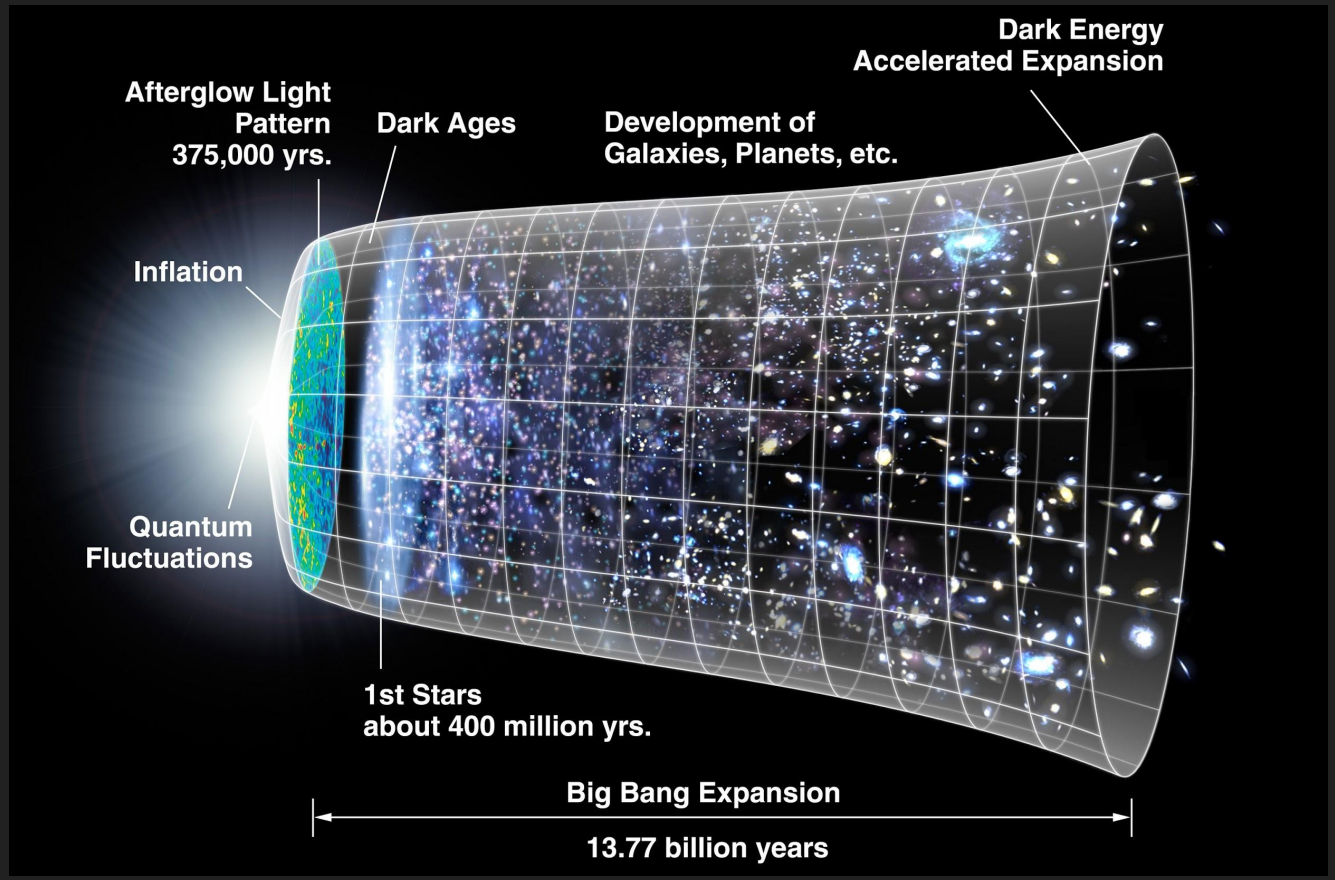
- QG is not expected to describe spacetime;
  but the (unknown) quantum physics 'underlying' spacetime

- This physics is expected to be non-spatiotemporal to some extent

- GR, with its conception of spacetime, should be recoverable from QG

- NOTE: Currently there is no accepted theory of QG!
- Instead we have a number of incomplete approaches to QG

Emergent spacetime?



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Emergent spacetime?

QG is supposed to describe:

1. The physics ‘underlying’ spacetime

- Moving from the more fundamental non-spatiotemporal description to GR may be an example of ‘synchronic’ emergence

2. The physics near the big bang

- The evolution of the universe from a ‘prior’ non-spatiotemporal state to a spatiotemporal one, may be an example of ‘diachronic’ emergence

Today

- I explore how these two potential examples of spacetime emergence can be understood according to existing accounts of emergence in philosophy
- And what challenges these case-studies pose for such accounts

1. What is emergence?
2. Synchronic accounts of emergence
3. Synchronic emergence of spacetime
4. Diachronic accounts of emergence
5. Diachronic emergence of spacetime
6. Conclusions

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What is emergence?

- An asymmetric relationship between two relata of the same nature:
  an emergent, E and its emergence basis, B

  General schema (to be filled in by particular accounts):

- (DEPENDENCE): E is dependent on, determined by, constituted by, generated by B; and yet
- (NOVELTY): E exhibiting striking features not possessed by B, and,
- (AUTONOMY): E is unpredictable from B, irreducible to B, unexplained by B, robust against changes in B, etc.

- I am interested in emergence as a relation between (parts of) physical theories

Two varieties of emergence

1. Synchronic emergence:

- E and B represent different levels of description;
  i.e., theories that apply at different length scales

- These theories are supposed to apply to the same system
  at the same time, or otherwise under the same conditions

- No change except the ‘level’ at which you view the system

  (In physics: the energy at which you probe the system;
  typically, B describes higher-energy, and E lower-energy)

Two varieties of emergence

2. Diachronic emergence:

- E and B describe the system at the same level of description, i.e., same energy scale

- These theories are supposed to apply to the same system at different times, or otherwise under different conditions

- The system has undergone some change; typically, B describes it before, E after

Two varieties of emergence

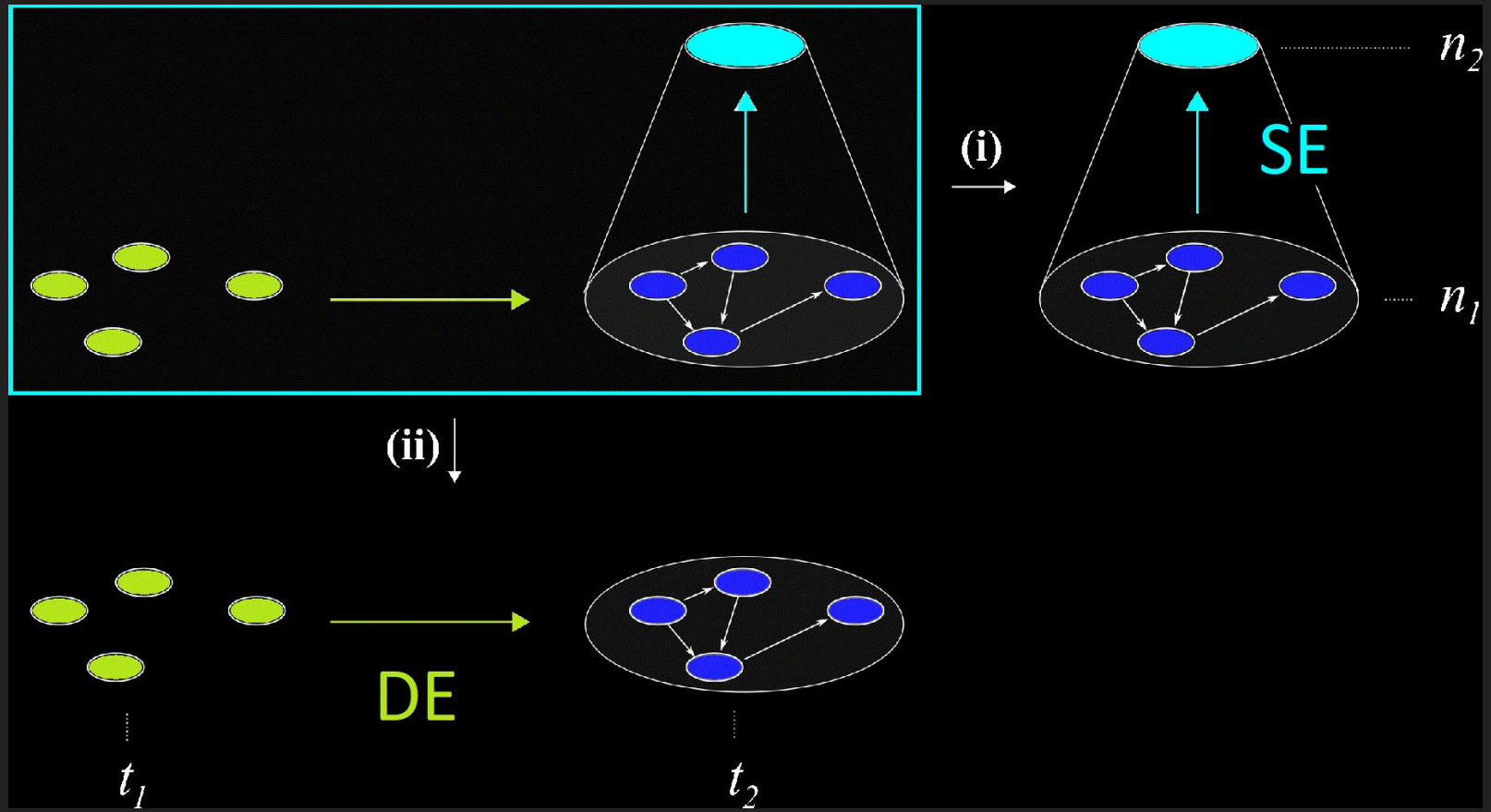

Figure: Guay & Sartenaer (2016) 'A new look at emergence. Or when *after* is different' *EJPS*

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2. Synchronic accounts of emergence: Crowther (2015, 2016)

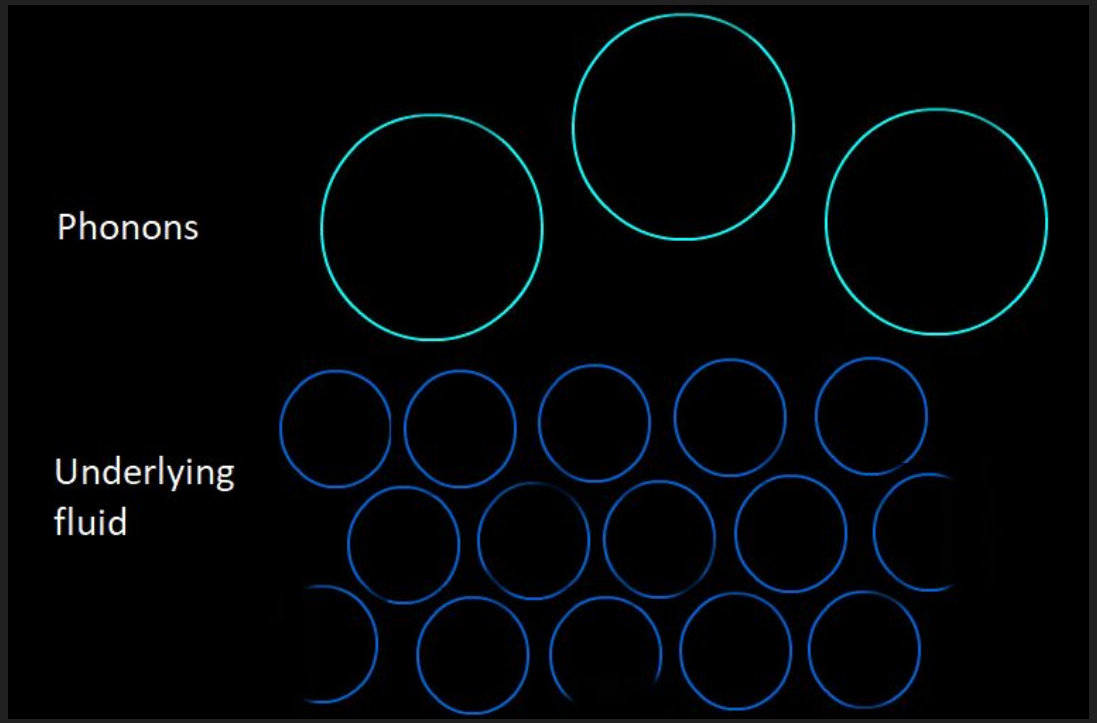
- Inspired by the framework of effective field theory (EFT)
- EFT is a method ('toolbox') for constructing *effective field theories*.
- An effective field theory is

  … valid only at a given 'level', i.e., at low energy scales compared to a given heavy mass, Λ

  … framed in terms of the appropriate degrees of freedom for its 'level'

  … is effectively independent of (autonomous from) the physics at higher energy scales
- Mathematical apparatus of the *renormalisation group* shows that most of the high energy interactions are irrelevant at low energy scales
- The effects that do filter down to low energy can be effectively absorbed into the low energy dof

Example of synchronic emergence in EFT: Analogue models of spacetime



ρ is the density, and θ the coherent phase of the fluid

Linearly expand about their ground state values:

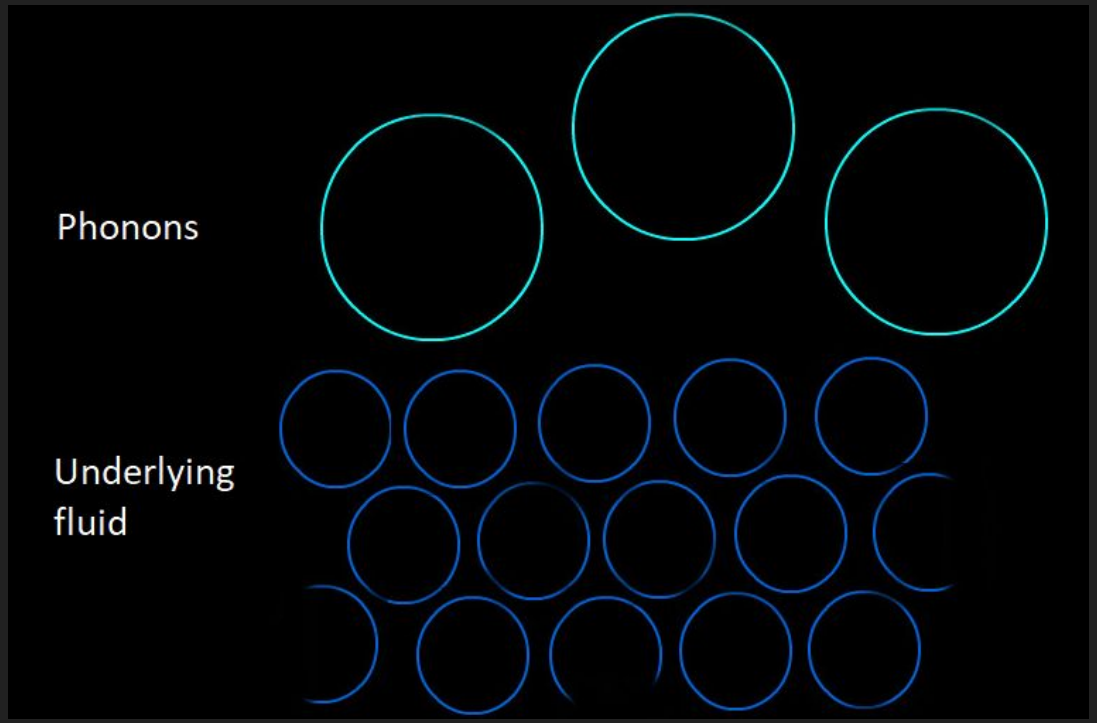
$\rho = \rho_0 + \delta\rho$

$\theta = \theta_0 + \delta\theta$

Substitute back in, integrate out the high-energy fluctuations, end up with:

$$\mathcal{L} = \underbrace{\mathcal{L}_0[\rho, \theta]}_{\text{ground state of the fluid}} + \underbrace{\mathcal{L}_{eff}[\delta\theta]}_{\text{effective theory}}$$

Example of synchronic emergence in EFT: Analogue models of spacetime



Effective *L* is formally identical to that of a massless scalar field in (3+1)-dimension spacetime with a curved effective metric

Effective curved spacetime is a generic feature of the linearisation process used in constructing the models

(just need a *L* depending on a single scalar field plus first derivatives)

2. Synchronic accounts of emergence: Crowther (2015, 2016)

(DEPENDENCE):

- Low energy theory E is constructed (derived) from the higher energy theory B (e.g., via EFT)
- The physics described by the laws of E may be said to supervene on those of B

  (Supervenience: No change at the E-level unless there is a change at the B-level, but not vice versa)

2. Synchronic accounts of emergence: Crowther (2015, 2016)

(NOVELTY):

- The physics described by the low energy (macro) theory E differs remarkably from that of the higher energy (micro) theory B

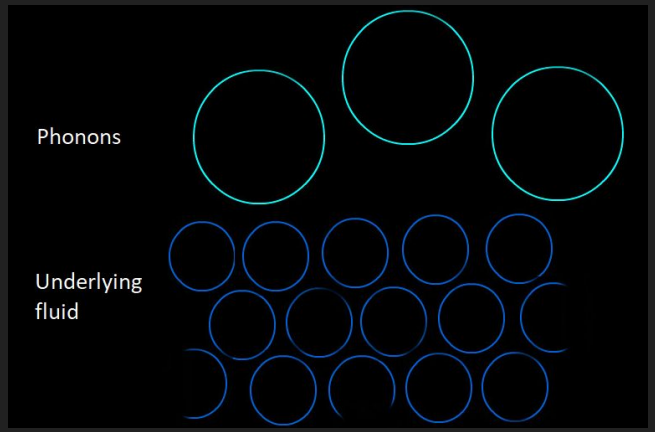
(AUTONOMY):

- The physics described by E is robust against changes in the micro physics
- B is underdetermined by E
- Two senses of underdetermination, due to *universality* (multiple realisability):

  1. Different micro states described by, or models of, B can correspond to a single macro state/model of E (e.g., statistical mechanics → thermodynamics)

  2. Different micro theories can correspond to the same macro theory (e.g., fluids of different micro-constitutions, different particles at micro scale → thermodynamics/hydrodynamics)

Example of synchronic emergence in EFT: Analogue models of spacetime



(DEPENDENCE):

- L_{eff} constructed from the high-energy theory
- Phonons are collective phenomena: low-energy excitations of the underlying particles/molecules

(NOVELTY):

- Theories characterised by different dof
- And different symmetries: L_{eff} is Lorentz-invariant, L_0 is Galilei-invariant (Bain, 2013)

(AUTONOMY):

- Effective curved spacetime is incredibly easy to obtain from a variety of different systems, with different micro-constitutions
- The high-energy theory is severely underdetermined

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3. Synchronic emergence of spacetime: In QG generally (Crowther, 2017)

- The reduction of GR to QG is a criterion of theory acceptance
  -- i.e., QG must be thought able to reproduce all of the successful results of GR

- This means establishing various formal correspondence relations between (parts of) the two theories, such that GR is believed to be deducible in principle from QG

- These relations are supposed to establish that GR depends upon QG
  -- and, consequently, that spacetime depends upon the micro physics of QG
  -- structures described by GR are supposed to be 'low energy' approximations to those of QG

- Thus, the (DEPENDENCE) condition of emergence must be satisfied

3. Synchronic emergence of spacetime: In QG generally (Crowther, 2017)

- There is no requirement that the (NOVELTY) and (AUTONOMY) conditions must be satisfied
  -- GR is not guaranteed to emerge from QG!

- And, in fact, there are approaches to QG where these may (apparently) not be satisfied

- Nevertheless, in many approaches, seems likely that there could be emergence

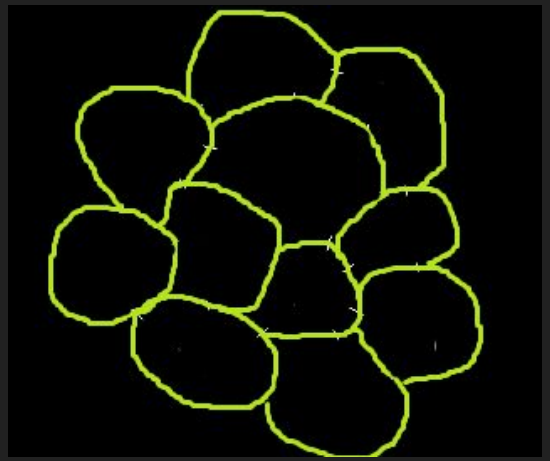
- Examples: loop quantum gravity, causal set theory, causal dynamical triangulations, group field theory, quantum graphity, …

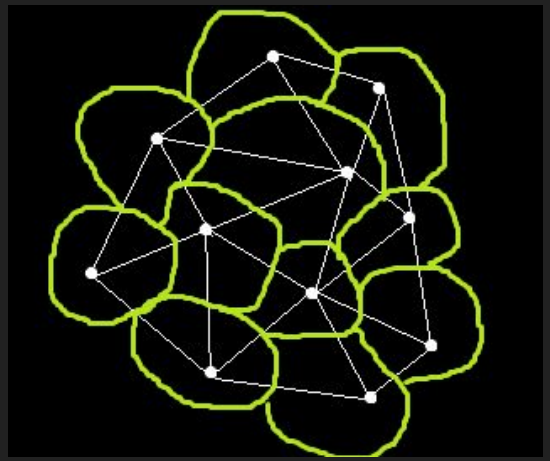
3. Synchronic emergence of spacetime: In loop quantum gravity (LQG)

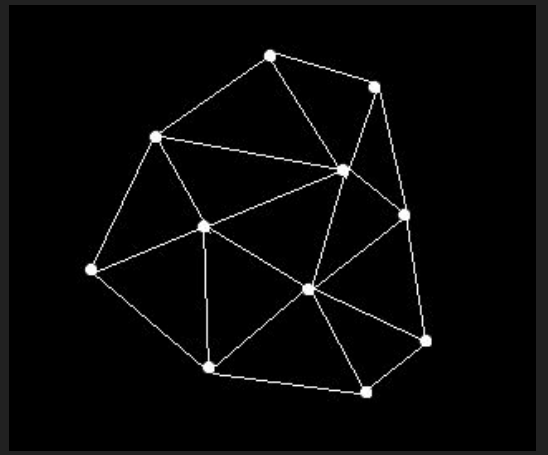
- LQG is a canonical quantisation of gravity
- Proceeds by casting GR in Hamiltonian form, splitting space and time apart, then quantising
- Involves setting up and solving the theory in the form of constraint equations, formulated in terms of loop variables
- The Hamiltonian constraint equation, which is supposed to describe the dynamics of the theory, resists solution (Wheeler deWitt equation)
- As such, only the kinematics of the theory is known
- (But there are different approaches towards understanding the dynamics!)

3. Synchronic emergence of spacetime: In loop quantum gravity (LQG)

- LQG describes discrete ‘blobs’ of space
- Represented as abstract graphs: spin networks
- Nodes represent quanta of volume, which are adjacent if there is a link between them
- Links represent quantised area of the surface bounding the volumes







3. Synchronic emergence of spacetime: In loop quantum gravity (LQG)

(DEPENDENCE) :

- Without a full dynamical theory, hard to know how spacetime might 'depend' on LQG
- Unclear how to 'recover' spacetime from LQG

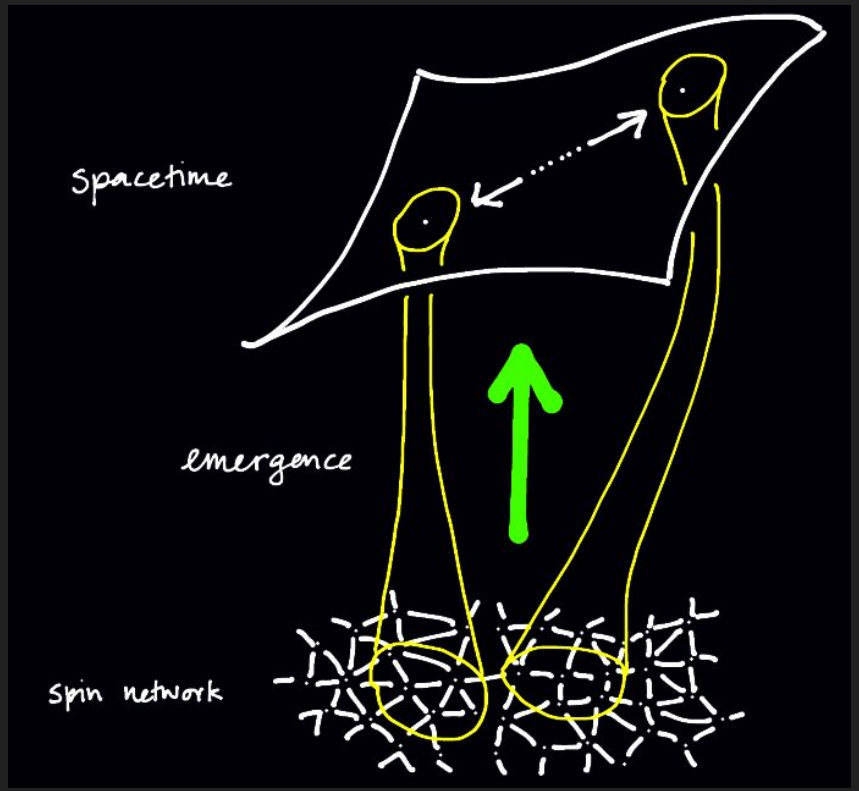
But:

- Spin networks are the result of quantising spacetime
- Space is thought to correspond to a quantum superposition of spin networks

So:

- For the sake of this talk: suppose that GR reduces to LQG in the requisite way

3. Synchronic emergence of spacetime: In loop quantum gravity (LQG)



(NOVELTY):

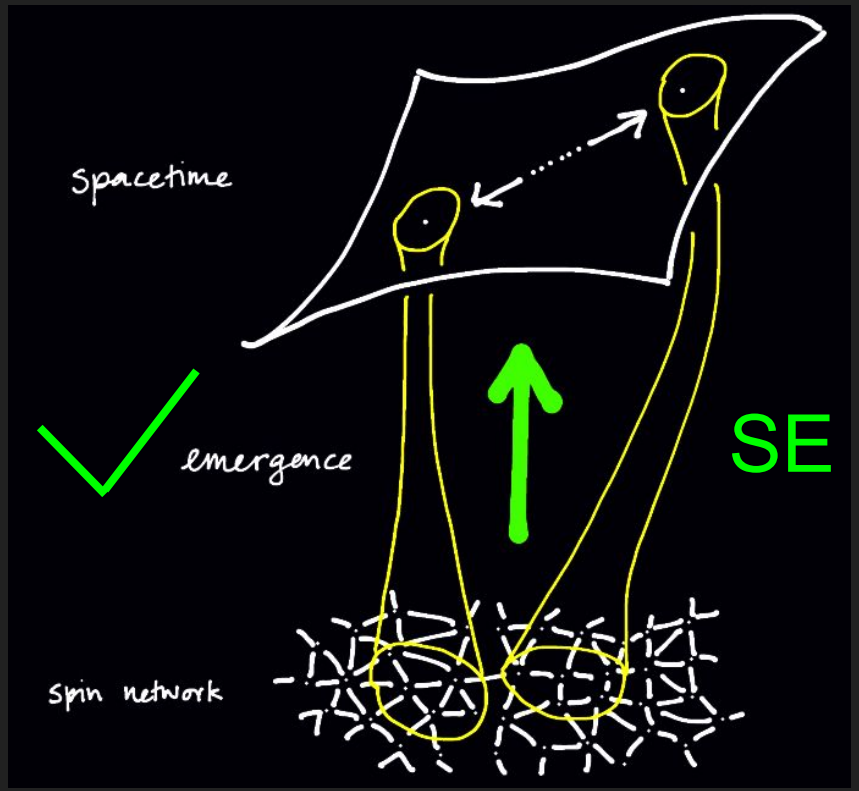
- Peculiar form of 'non-locality' (Huggett and Wüthrich, 2013)
- Generic states in LQG are superpositions: no clear notion of geometry
- 'Problem of time': no clear notion of time

(AUTONOMY):

- Many different spin network states can correspond to the same (semiclassical) geometry
- There are models of LQG that do not correspond to spacetime

Figure from Wüthrich (Forthcoming) 'The Emergence of Space and Time' for *Routledge Handbook of Emergence*

3. Synchronic emergence of spacetime: In loop quantum gravity (LQG)



(NOVELTY): ✓

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4. Diachronic accounts of emergence: Guay & Sartenaer (2016) 'Transformational Emergence'

E and B are different states of the same system, interpreted at the same level, but different times
E and B are described by different models of the same theory

(DEPENDENCE):

- E is the product of a spatiotemporally continuous process going from B

(NOVELTY and AUTONOMY):

- E exhibits new entities, properties or powers that do not exist in B,
- and which are *forbidden* to exist in B according to the laws governing B

4. Diachronic accounts of emergence: More general proposal

E and B are different states of the same system, interpreted at the same level, ~~but different times~~
E and B are described by different models of the same theory

(DEPENDENCE):

- ~~E is the product of a spatiotemporally continuous process going from B~~
  -- No good: cannot depend on spatiotemporal notions!
- Also: even if we have a dynamics w.r.t. some continuously-varying parameter, the directedness or asymmetry seems conventional -- how is this 'dependence'?
- E is caused by B? What does it mean to say that one state of the system is caused by another?
- Need a non-temporal notion that provides a basis for a claim of priority:
  -- something like 'flat supervenience'
  - Baron & Miller (2014; 2015) Tallant (2008; 2018) timeless account of counterfactual causation

4. Diachronic accounts of emergence: More general proposal

(NOVELTY):

- E describes new entities, properties or powers that do not exist in B
- Typically, novelty is relative and symmetric:
  - just captures the substantive ways in which E and B differ from one another

4. Diachronic accounts of emergence: More general proposal

It is useful to have a notion of (AUTONOMY) that allows for an ascription of priority necessary for (DEPENDENCE), and thus the asymmetry necessary for emergence

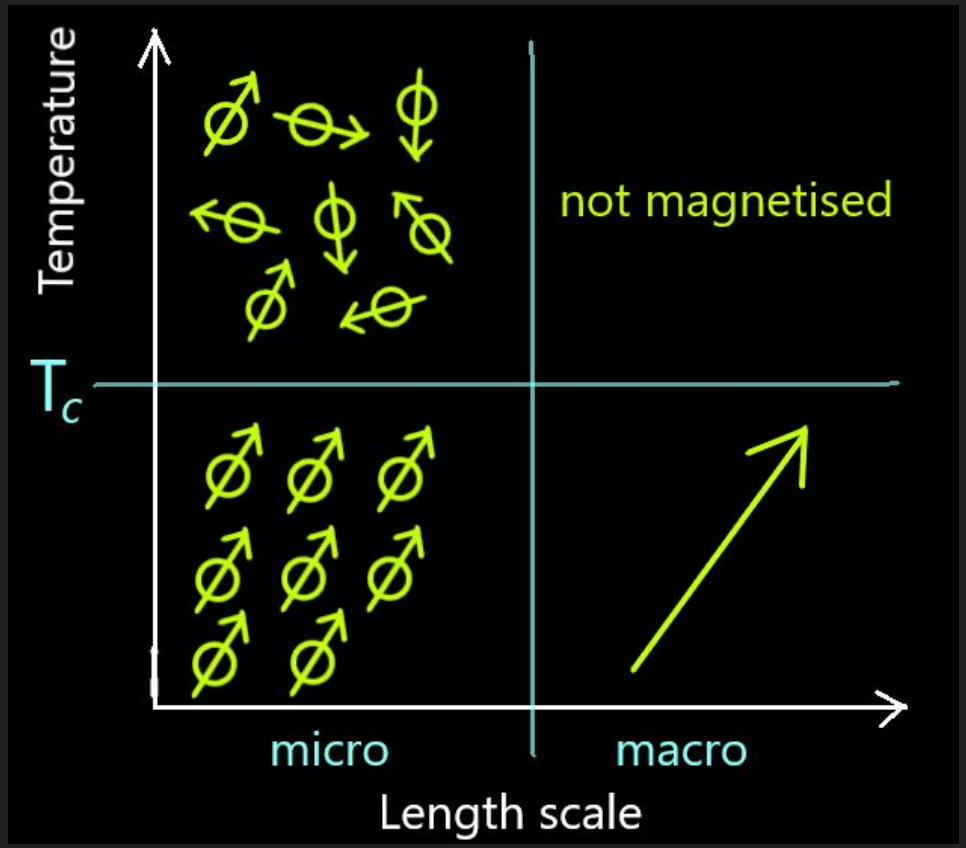
A notion analogous to my synchronic sense of (AUTONOMY), which was based in underdetermination due to universality…

The corresponding diachronic notion is (backward) indeterminism:

(AUTONOMY):

- The B state is not determined given the E state (non-temporal, reverse notion of interderminism?)

4. Example of diachronic emergence:
Ferromagnetism (symmetry-breaking phase transition)



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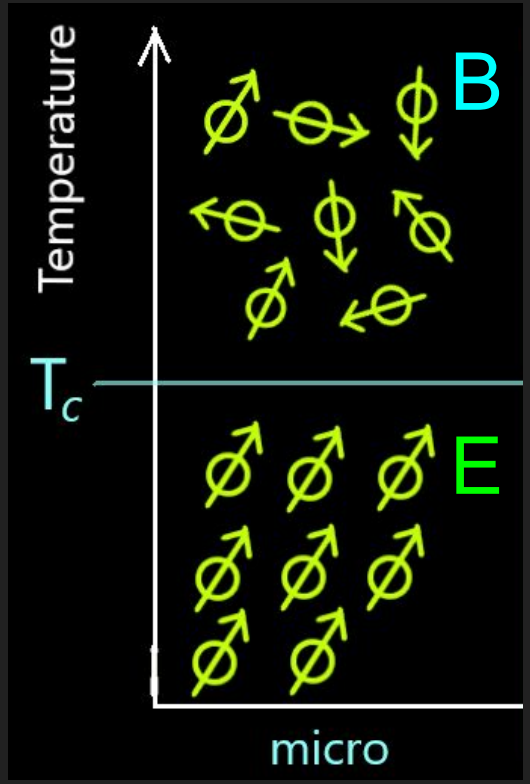

E and B are different states of the same system, at the same level
E and B are described by different models of the same theory

(DEPENDENCE):

- ‘Flat supervenience’/counterfactual causation without time

(NOVELTY):

- B is a state where there is no preferred direction (symmetric)
- E is a state where there is a preferred direction (broken symmetry)

(AUTONOMY):

- E can arise from many different B states
- B is underdetermined given E

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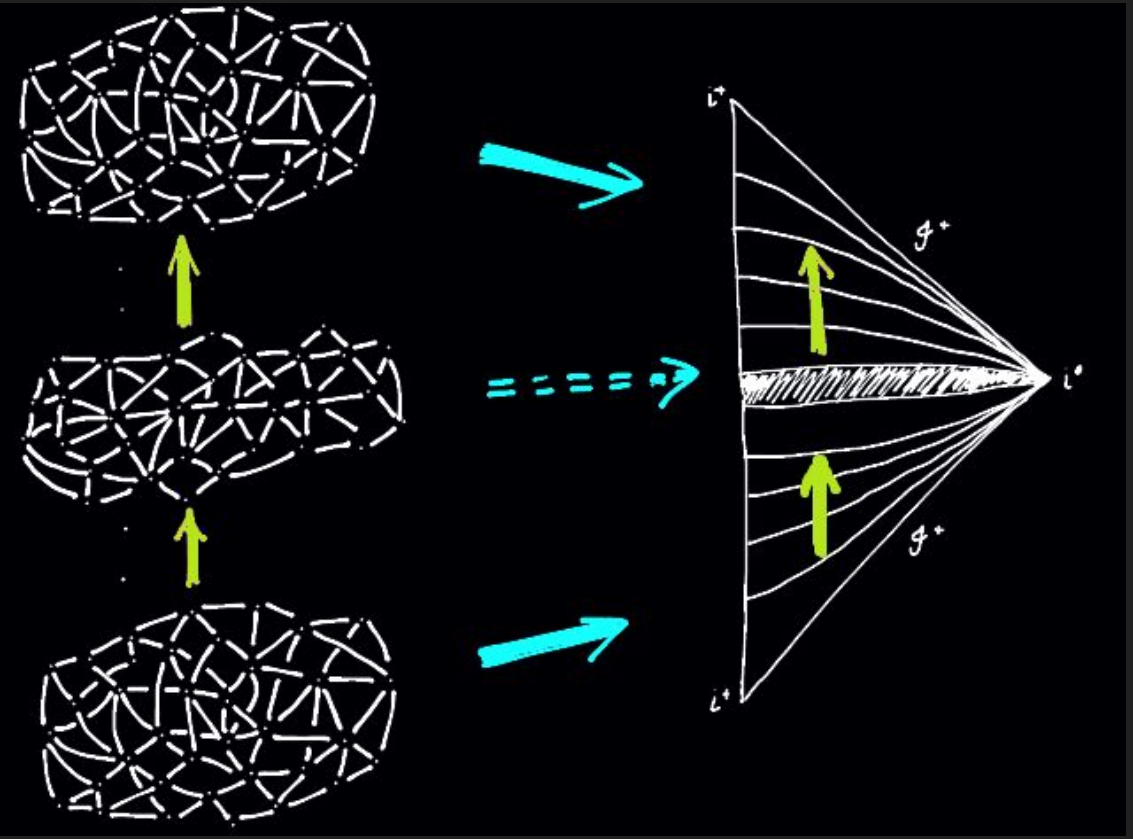
4. Diachronic emergence of spacetime: In loop quantum cosmology (LQC)

- Recall: The dynamics of LQG is not well understood
- Loop quantum cosmology (LQC) begins by simplifying the system at the kinematical level by assuming spatial isotropy and homogeneity
- The effect is that LQC describes spatial geometry with just one degree of freedom: 'scale factor', *a*, with corresponding quantum operator, *p*
- The resulting simplified dynamical equation can (though not unproblematically) be interpreted as an evolution equation, with the scale factor as the 'time variable' (Huggett and Wüthrich, Forthcoming)
- We can run this backwards, and it turns out that the evolution near (what would otherwise correspond to) the big bang singularity is well-defined: singularity is resolved

4. Diachronic emergence of spacetime: In loop quantum cosmology (LQC)



- In this way, we can run *p* backwards through the 'big bang', and find out what LQC tells us about the 'pre big bang' universe
- What we find is a 'mirror world'
- Standardly interpreted as the universe undergoing a 'big crunch', collapsing to a maximally hot, dense state, then re-expanding

Figure adapted from Wüthrich 'The Atemporal Big Bang'

4. Diachronic emergence of spacetime: In loop quantum cosmology (LQC)

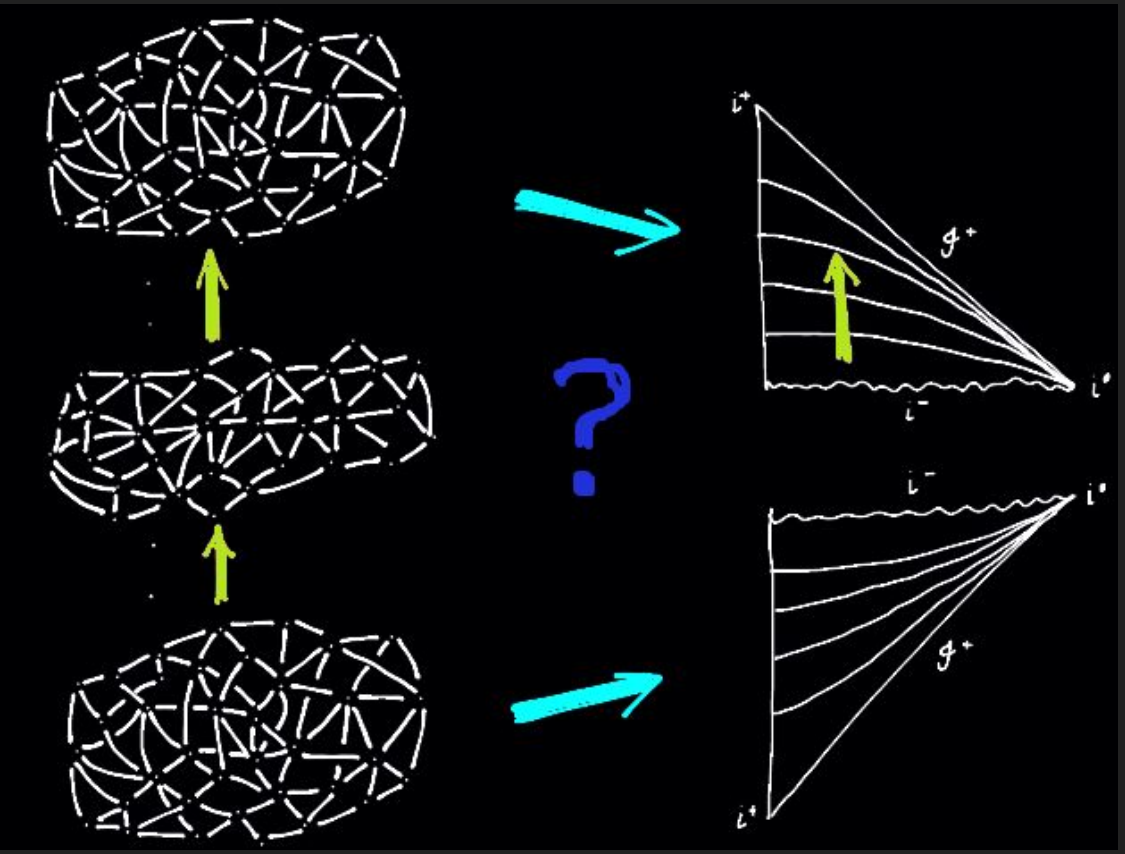
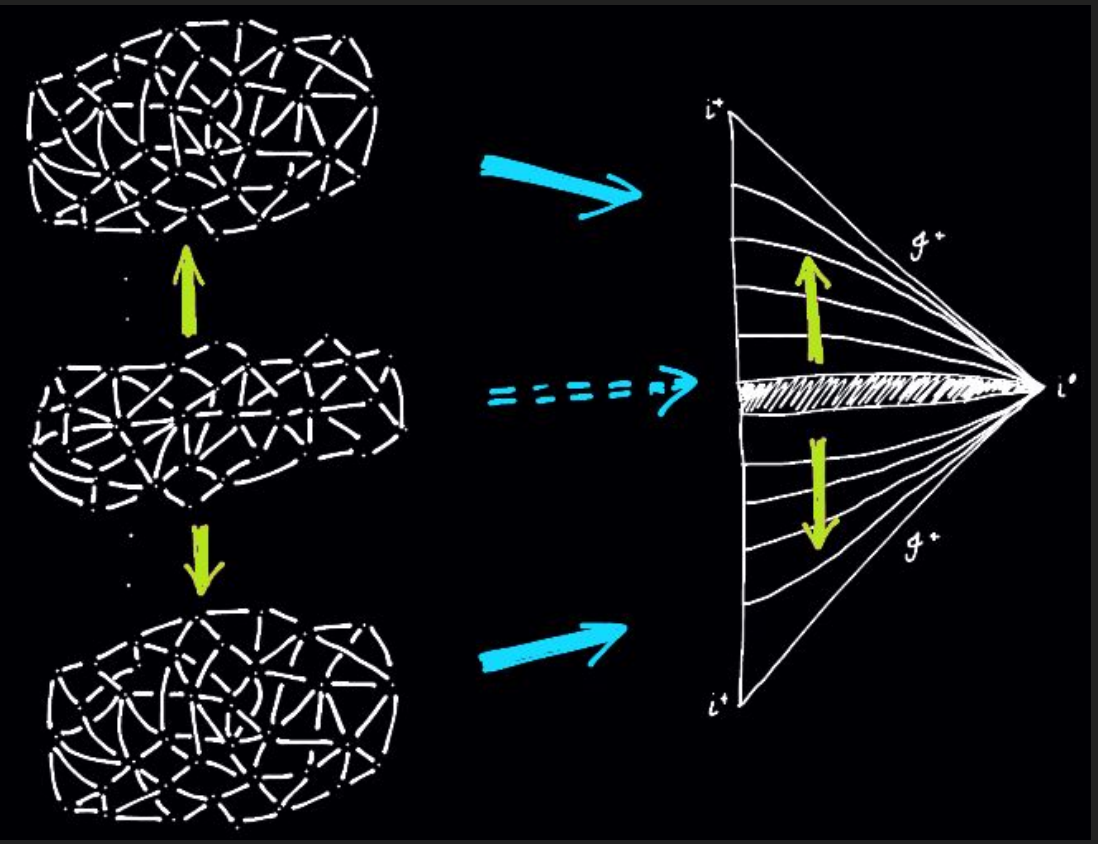


Figure adapted from Wüthrich 'The Atemporal Big Bang'

- Huggett and Wüthrich (Forthcoming), explain that this picture is not supported by LQC:
- There is no continuous notion of time that runs from the 'pre big bang' universe through to the 'post big bang' universe
- The intermediate structure 'during the big bang' is purely spatial, with no connected notion of time at all

4. Diachronic emergence of spacetime: In loop quantum cosmology (LQC)



- Huggett and Wüthrich (Forthcoming) thus argue that it more natural to interpret time as directed away from the big bang
- Thus, that this model could instead represent the 'twin birth of two universes' from a single non-temporal state
- H&W call this the 'temporal emergence of spacetime'

Figure adapted from Wüthrich 'The Atemporal Big Bang'

How to understand this as emergence?

Options, options:

1a. (Spacetime dissolution -- emergence of an atemporal state on standard interpretation)

B is the (spatiotemporal) universe 'before the big bang'
E is the timeless 'in between' state

1.b. (Spacetime emergence on standard interpretation)

B is the timeless 'in between' state
E is the (spatiotemporal) universe 'after the big bang'

2. (Spacetime emergence on Huggett and Wüthrich interpretation)

B is the timeless state 'before' the big bang
E is one, or both, of the (spatiotemporal) universes post big bang

4. Diachronic emergence of spacetime: In loop quantum cosmology (LQC) macro level

E is the universe after the big bang (spatiotemporal)
B is the universe 'before' the big bang (purely spatial, no time)

(DEPENDENCE):

- Which state 'depends' on which? Seems artificial to distinguish at the macro level, given that the same physics equally supports the emergence of spacetime or the dissolution of spacetime!

(NOVELTY):

- B is a state where there’s no time (Galilean signature)
- E is a state where there is time (Lorentzian signature)

(AUTONOMY):

- Cannot answer until we understand the (DEPENDENCE) connection
- We may rely on the notion of (AUTONOMY) to define the (DEPENDENCE) connection

4. Diachronic emergence of spacetime: In loop quantum cosmology (LQC) macro level

E is the universe after the big bang (spatiotemporal)
B is the universe 'before' the big bang (purely spatial, no time)

(DEPENDENCE):

- Which state 'depends' on which? Seems artificial to distinguish at the macro level, given that we can interpret (1. & 2.) on previous slide as being the same as (3.)

(NOVELTY):

- B is a state where there's no time (Galilean signature)
- E is a state where there is time (Lorentzian signature)

(AUTONOMY):

- Cannot answer until we understand the (DEPENDENCE) connection
- We may rely on the notion of (AUTONOMY) to define the (DEPENDENCE) connection

4. Diachronic emergence of spacetime: In loop quantum cosmology (LQC) micro level

E is the micro-state of the universe after the big bang (corresponds to a macro state with time)
B is the micro-state of the universe 'before' the big bang (corresponds to a macro state with no time)

(DEPENDENCE):

- E and B are different states, related by *p* ('time parameter'); they change with respect to one another
- Without a source of asymmetry grounding an ascription of priority, any notion of 'dependence' or 'directedness' seems artificial

(NOVELTY):

- No obvious sense of novelty distinguishing B and E at the micro-level

(AUTONOMY):

- Cannot answer until we understand the (DEPENDENCE) connection

4. Diachronic emergence of spacetime: In loop quantum cosmology (LQC) micro level

E is the micro-state of the universe after the big bang (corresponds to a macro state with time)
B is the micro-state of the universe 'before' the big bang (corresponds to a macro state with no time)

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Summary & Conclusions

- Emergence as (DEPENDENCE) plus (NOVELTY) and (AUTONOMY)
- Synchronic emergence: (AUTONOMY) based on underdetermination of B due to multiple realisability of E
- Examples of synchronic emergence:
  1. analogue models of spacetime (using EFT);
  2. (potentially) GR spacetime emergent from LQG;
- Criticism of diachronic emergence:
  - how to understand (DEPENDENCE) and (NOVELTY) when these notions are symmetric?
  - my response: appeal to an asymmetric notion of (AUTONOMY)
- New account of diachronic (flat) emergence:
  - (DEP) as 'flat supervenience'
  - (AUTONOMY) as non-temporal (backward) indeterminism
- Example of diachronic emergence: ferromagnetism
- Unclear how LQC models can represent the 'temporal emergence of spacetime'!