Title: Our time-symmetric lifestyle

Speakers: Marina Cortes

Series: Cosmology & Gravitation

Date: May 14, 2019 - 11:00 AM

URL: http://pirsa.org/19050031

Abstract: Fundamental physics traditionally views the dynamical laws governing the world as time reversal invariant. The evident arrow of time of nature is then held to be an accident, emerging as we coarse grain and originating in the improbable choice of initial conditions. The main pillar which supports this time-symmetric lifestyle is the fluctuation-dissipation theorem, which connects purely time-symmetric microscopic equations to the emergence of a macroscopic arrow of thermodynamics. I will describe arguments from statistical physics claiming that existing proofs of this theorem are faulty and do not demonstrate the emergence of an arrow from time-symmetric laws. I will argue that, as a result of this assumption of time symmetry, we cosmologists stand to pay an unreasonable price concerning what weâ€™re expected to explain. I argue for instead to turn this picture around and propose a fundamental theory of cosmology and quantum gravity which is fundamentally time asymmetric and based on time-irreversible laws. I will describe a new class of models of quantum space-time, energetic causal sets, in which space-time itself, as well as aspects of quantum theory, emerge under natural conditions. The framework is based on arXiv:1307.6167 and subsequent papers in collaboration with Lee Smolin.

Our time symmetric lifestyle

Marina Cortês

with Lee Smolin,

Eliahu Cohen, Avshalom Elitzur,

Henrique Gomes, Andrew Liddle,

Wolfgang Wieland.

Perimeter Institute, May 14th, 2019

"Time is an illusion. It emerges as we coarse grain, zoom out from timeless fundamental physics. It's not a fundamental quantity of nature.

In searches for quantum gravity we should seek a description of the Planck length, expressed as ***timeless equations****, where time is not to play any role.*

When time emerges it is to parameterize equations that are symmetric under time reversal.

The evident time-asymmetry of nature is an accident*, result of improbable choice of initial conditions."*

"Time is an illusion. It emerges as we coarse grain, zoom out from timeless fundamental physics. It's not a fundamental quantity of nature.

In searches for quantum gravity we should seek a description of the Planck length, expressed as ***timeless equations****, where time is not to play any role.*

nope.

When time emerges it is to parameterize equations that are symmetric under time reversal.

The evident time-asymmetry of nature is an accident*, result of improbable choice of initial conditions."*

Cortês and Smolin

First Buchalter Cosmology Prize (2014)

Energetic Causal sets; Emergence of space-time;
Time symmetric dynamics from time asymmetric laws;
Partial emergence of quantum mechanics

PHYS. REV. D 90, 084007 (2014)
PHYS. REV. D 90, 044035 (2014)

Correspondence of models with Spin Foam dynamics

with Wieland

PHYS. REV. D 97, 026004 (2018)

Time asymmetric extensions of General Relativity

with Gomes, Liddle

PHYS. REV. D 92, 043502 (2015)
PHYS. REV. D 94, 123514 (2016)

Correspondence of time asymmetry to Discrete Dynamical Systems

PHYS. REV. D 97, 026004 (2018)

arXiv:1902.05108
arXiv:1902.05082
(2019)

Retrocausality and time asymmetry in quantum mechanics;

Avshalom Elitzur; Eliahu Cohen

Summary

- Intro
- Energetic causal sets (classical version only)
- Violations of causality in quantum mechanics and correspondence to causal sets

Fundamental time reversal invariance?
Reasons for and against

• The majority of microscopic, atomic level physics is time symmetric. Standard model, GR, fluid dynamics, etc.

•Common practice to discard half the solutions to e.o.m.'s because they are not observed in nature

•Examples of manifest arrows of time:

-K^0 decay

-quantum mechanical observations

-general entropy increase

-retardation of radiation

-expansion of the universe

-…

ELECTROMAGNETISM: RETARDATION OF RADIATION

Source precedes radiation, not the other way around.

Advanced ripples

Degrees of freedom in the bank *could* conspire with precise organization to create spherical ripples (radiation) to travel into the centre and eject the stone upwards (excite the source).

Retardation is not just a feature of radiation of course

• Obvious facts whose very obviousness may contribute to their being frequently overlooked.

INITIAL CONDITIONS!

ARE INITIAL CONDITIONS PART OF PHYSICS?

Feynman argued in 1973,

"today we take a particular set of IC's and study the laws under which they evolve, but we do not ask how the IC's came there in the first place.

One day studying how those IC's came to be might be considered part of physics as well."

1973, Feynman in discussion with Fred Hoyle

INITIAL CONDITIONS

It adds up.

Every time we call initial conditions to explain why we only ever see half of the solutions to the equations of motion the pile under the rug gets bigger.

It's all very well to place the origin of asymmetry in the boundary conditions, it's worked out perfectly for everyone, except for a particular group of physicists...

...who are going to pick up the bill.


you.

Cosmologists

We're paying for everyone's free lunch

(With the possible exception of quantum theorists. It is unclear whether quantum mechanics is adding on to the entropy bill we're paying for.)

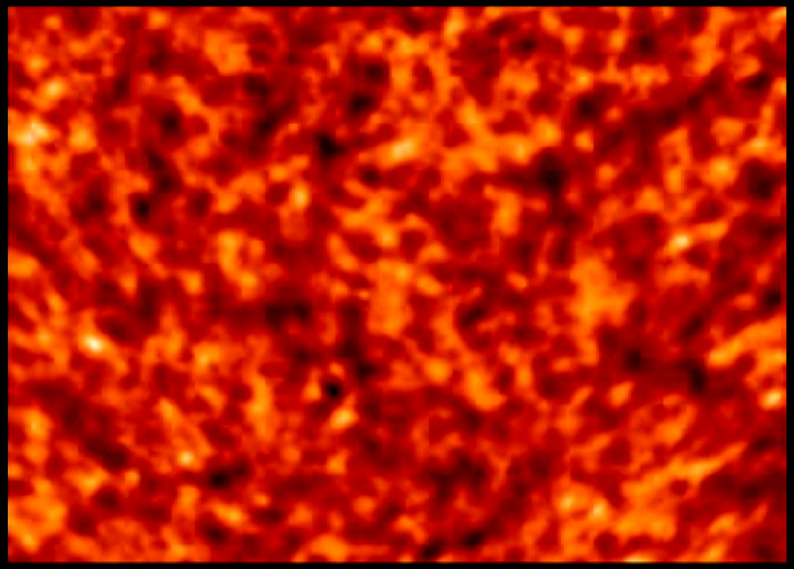
Calculating Early Universe Entropy:

traditional view

HOT PLASMA

$S = k \ln V = 10^{80} \times 10^{8}$ (natural units)

total number of degrees of freedom = $\exp(10^{88})$



Calculating Early Universe Entropy:

traditional view

HOT PLASMA

total number of degrees of freedom = $\exp(10^{88})$

if this was the total amount of degrees of freedom in the early universe today we would be a cold 3K plasma

Calculating Early Universe Entropy:

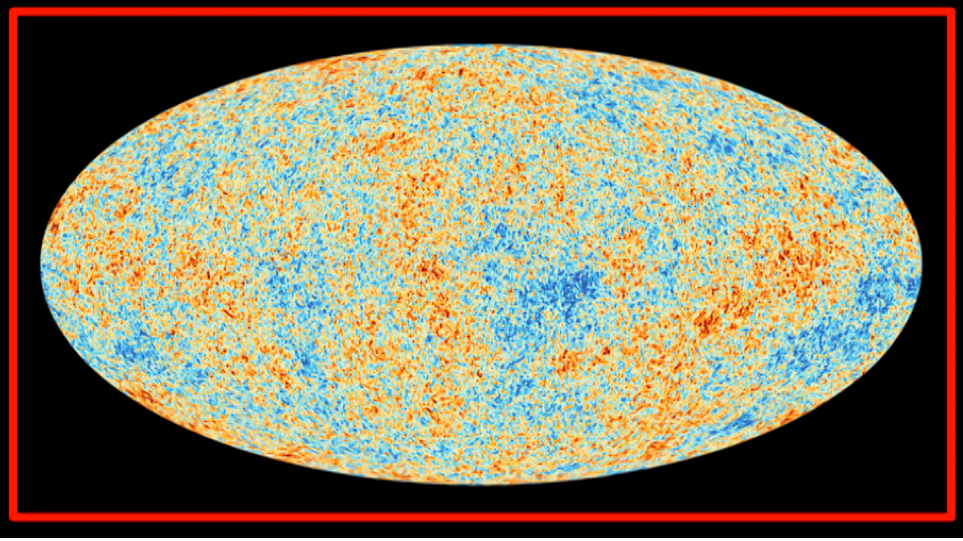
traditional view

HOT PLASMA

total number of degrees of freedom = $\exp(10^{88})$

if this was the total amount of degrees of freedom in the early universe today we would be a cold 3K plasma

like this

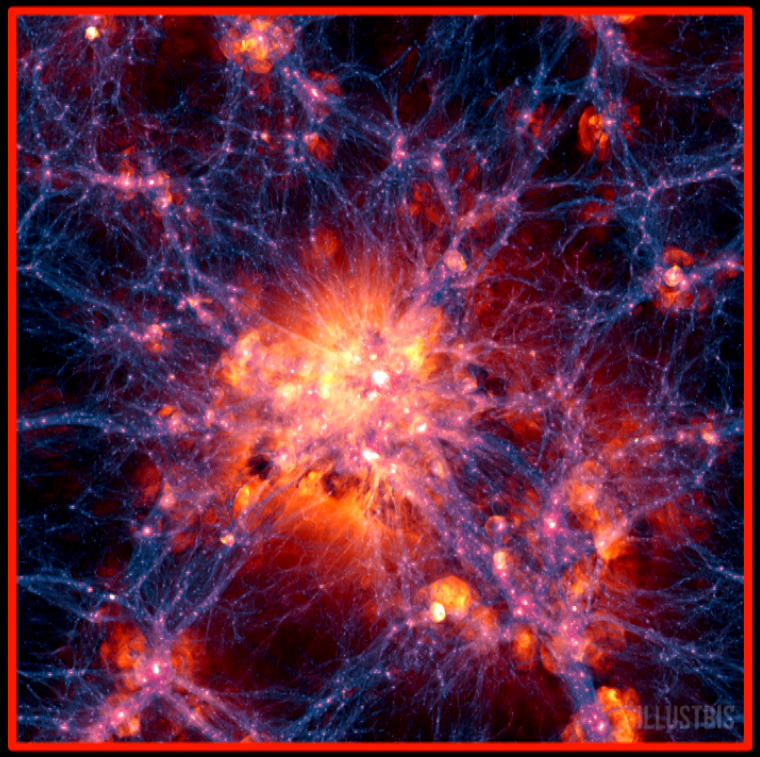


Calculating Early Universe Entropy:

HOT PLASMA

total number of degrees of freedom = $\exp(10^{88})$

Not like this



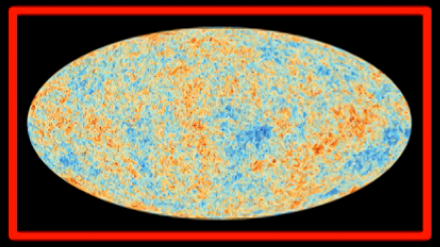
Illustris

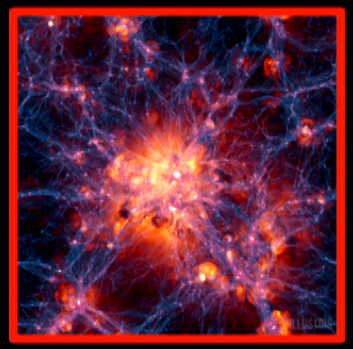
Calculating Early Universe Entropy:

HOT PLASMA

total number of degrees of freedom = $\exp(10^{88})$

Not like this





•Fortunately we'll want to explain how the galaxies got here (as well as the CMB) which wouldn't be true if weren't for gravity.

•So lets count the numbers of degrees of freedom in gravity.

•Nobody knows what is the number of degrees of freedom in gravity except for one case.

Calculating Early Universe Entropy:

In a gas the maximum entropy is achieved by spreading out in a homogeneous distribution.

In a gravitating system it is the total collapse of all components.

With clumping of the matter the associated entropy can exceed that of thermal motions.

Gravity has negative specific heat. It cools down with clumping whereas a gas heats up with clumping.

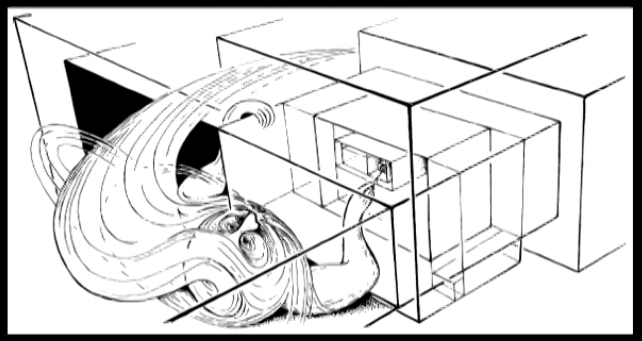
Early Universe Low Entropy: Bekenstein-Hawking

Number of gravitational degrees of freedom: 10^{24} per baryon (in a galaxy with 10^{10} solar masses and a M87 type black hole at the core with 10^{9} solar masses).

Number of baryons: 10^{80}

Entropy today is 10^{104}

We will eventually end up with entropy 10^{120} when all baryons collapse. (Though Lambda saves us from this).



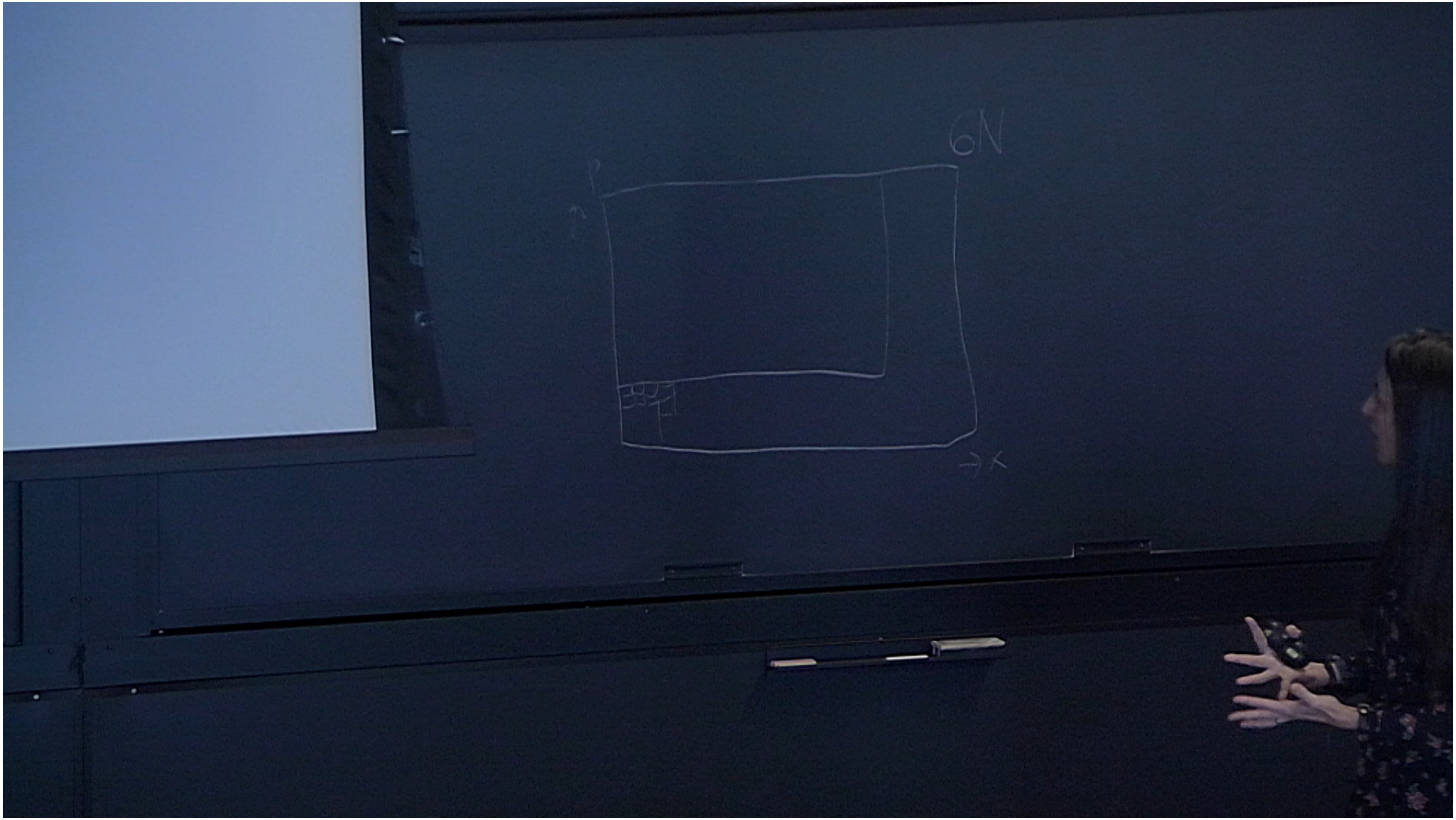
R.Penrose, *The Road to Reality*

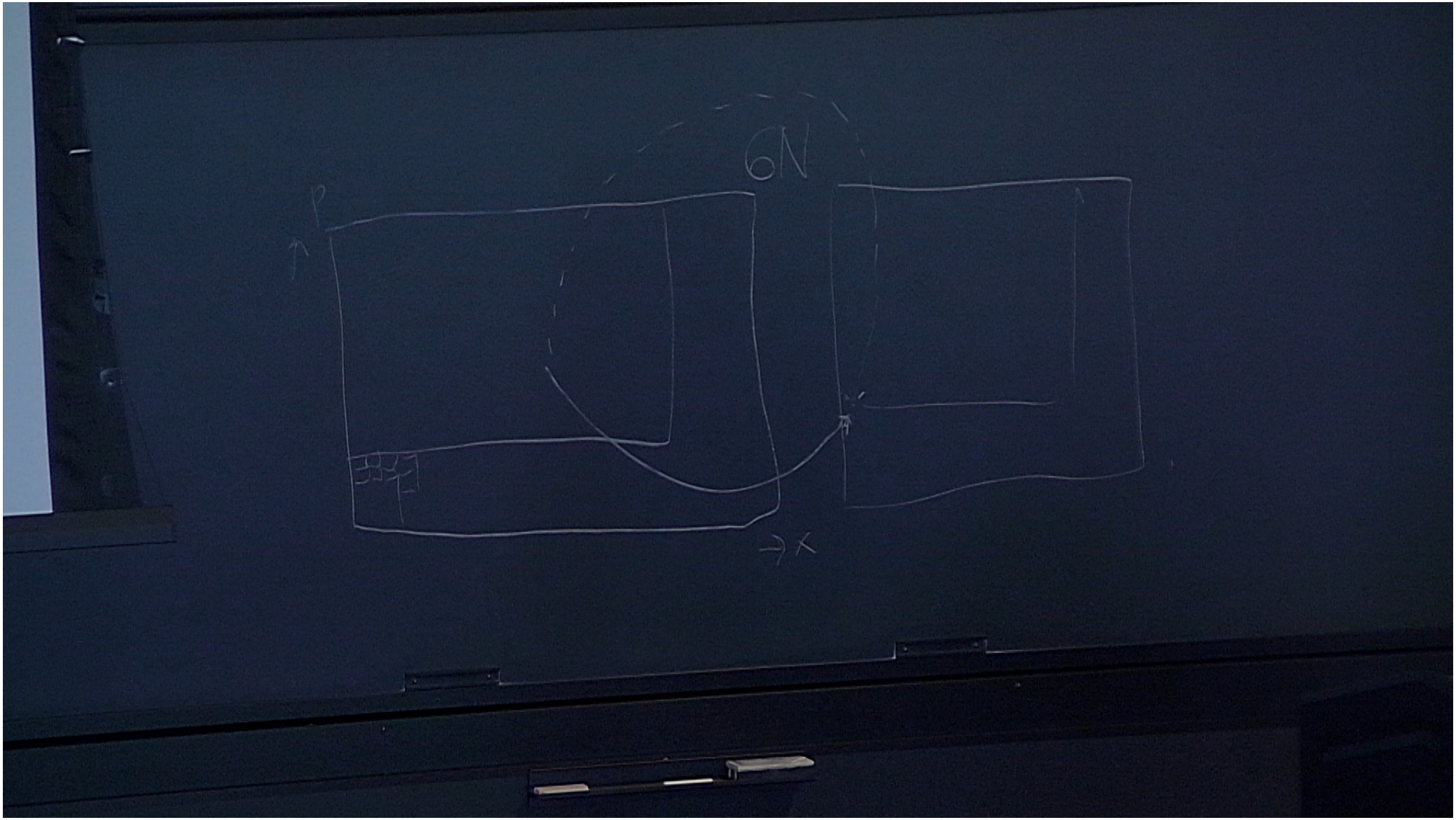
Likelihood of the Big Bang: 1 in $\exp(10^{104})$

Did we ask for this mess?

Multiverse

draw configuration space


6N
P
x


6N
P
x

Quantum Theory - Unitarity

In quantum physics we will go to any lengths to preserve the pristine Hamiltonian (Liouville) evolution:

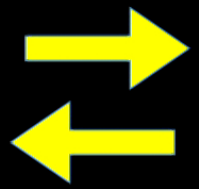
Wave function – UNCOLLAPSED

Reversal of measurement – UNMEASUREMENT

J. Dressel, A. Chantasri, A. N. Jordan, A. N. Korotkov (2017)

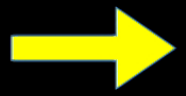
What is the pillar that supports our time-symmetric lifestyle?

Microscopic pure time-invariant equations



Fluctuation-dissipation theorem

Macroscopic time asymmetric arrow of thermodynamics



An arrow emerges

Fluctuation-dissipation theorem

description

•Quantifies the relation between the fluctuations in a system at thermal equilibrium and the linear response of the system to applied perturbation.

•Derivation of macroscopic arrow of evolution starting from deterministic, time-reversible microscopic equations.

•Energy that is put into the system by external influence in non-random way, becomes randomly distributed between degrees of freedom that couple to that source and generate state of new thermal equilibrium in the presence of the source.

•Fluctuations exist in both directions, positive or negative, whereas dissipation has only direction.

Fluctuation-dissipation theorem

•If you are measuring a response function you are already using the second law of thermodynamics. One needs the second law to justify causality.

•The system cannot have a memory which only arises when there is a preferred direction of evolution.

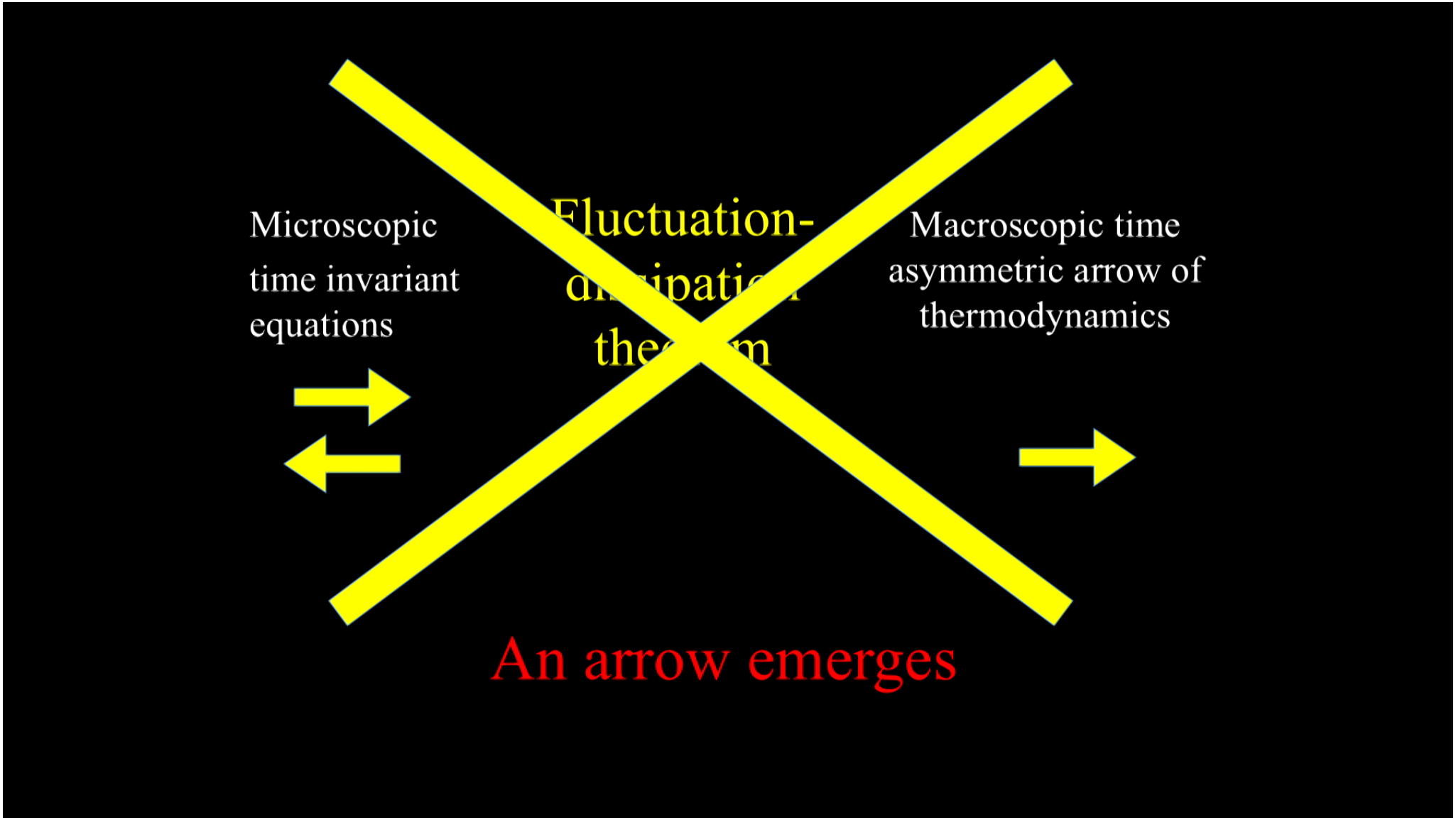
•Every proof of the fluctuation dissipation theorem introduces a form of irreversibility by hand.

•It is never derived starting from time reversible deterministic microscopic equations

•Dissipation or response of the system to the external influence is calculated using causality. The system responds to the source after it has been applied and not before. We're starting from an interaction that already has a direction.

B. Drossel,

arXiv: 1509.07275 - Springer Verlag, 2014, B. Falkenburg and M. Morrison, eds.


Microscopic
time invariant
equations
Fluctuation-
dissipation
theorem
Macroscopic time
asymmetric arrow of
thermodynamics
An arrow emerges

No significant advance in the theory of matter in bulk has ever come about through derivation from microscopic principles. (...) I would confidently argue further that it is in principle and forever impossible to carry out such a derivation.

The derivation of the arrow of thermodynamics from time symmetric (Newtonian) mechanics is a myth."

Foundations of Physics, Vol. 22, No. 2, 1992

Anthony J. Leggett, Nobel Prize 2003

Reductionist approach has limitations

There is no way to obtain arrow of time from a time symmetric world

+

Large price to ask cosmologists to pay

+

Awkward inconsistencies: conspiration of the margins of the pond; wave functions "un-collapsing"; quantum systems "un-measured"; Multiverse; Many Worlds ...

Maybe we can try dropping the assumption of fundamental time symmetry

What makes time tick?

We won’t have a theory of time if the equations we write down admit the time reversed solutions which are never observed in nature.

The Universe as a Process of Unique Events

INAUGURAL BUCHALTER COSMOLOGY PRIZE (2014)

The universe is built up out of events.

In cosmology each event is unique

-(Foundational) cosmology is the only discipline which is **NOT** a science of subsystems. Even if it reality we do it as one (CMB multipoles, stripe 82, etc). Extrapolation from truncated systems to universe.

- Why is this important.

Extrapolation from subsystems to universe is not possible at the big bang. We only have one copy of the system. We are used to have many copies of the system under study. No scientific method for studying a system which there's only one copy of.

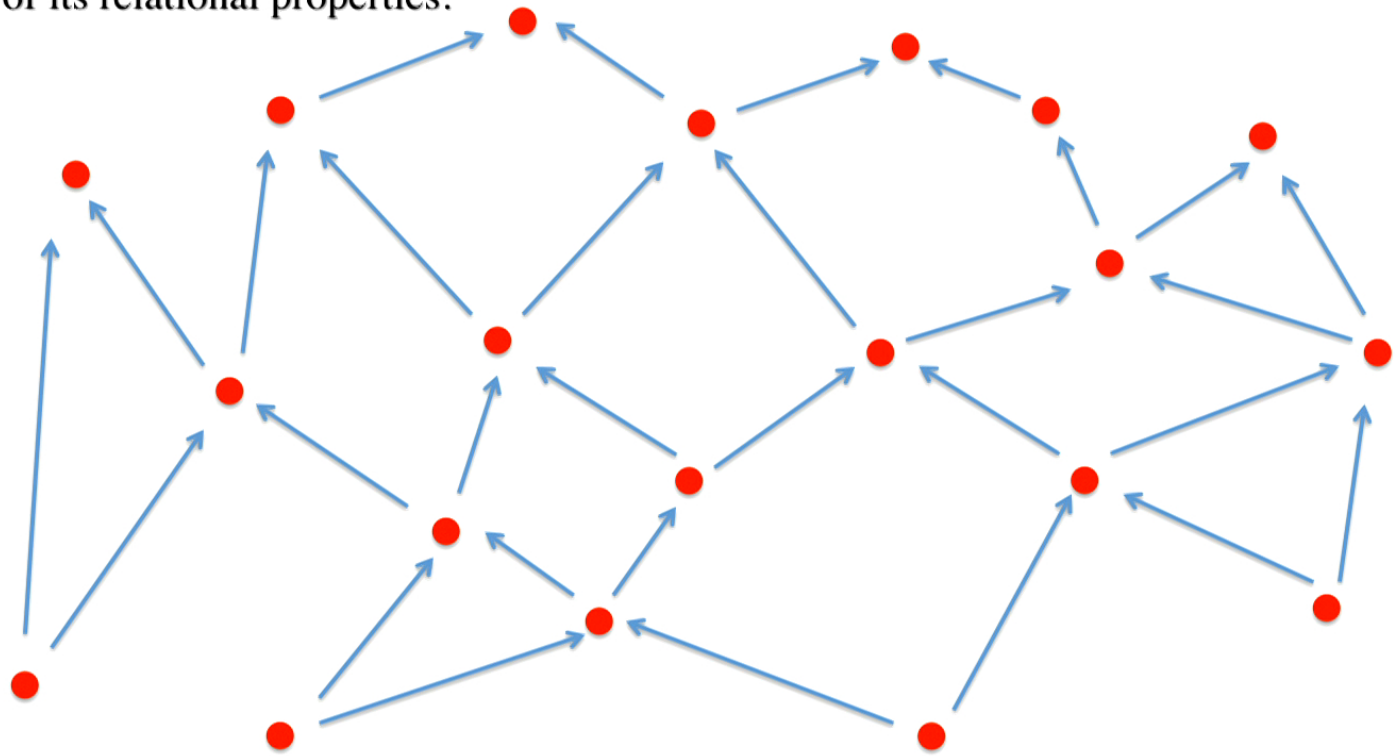
Argument: we react to this by postulating other copies (other universes) at the big bang and proceed to explain our universe as a function of those hypothetical copies.

Multiverse

-There is only one universe. The explanation of properties of our universe as a function of properties of additional, non observable, universes is **not** a discipline of scientific enquiry

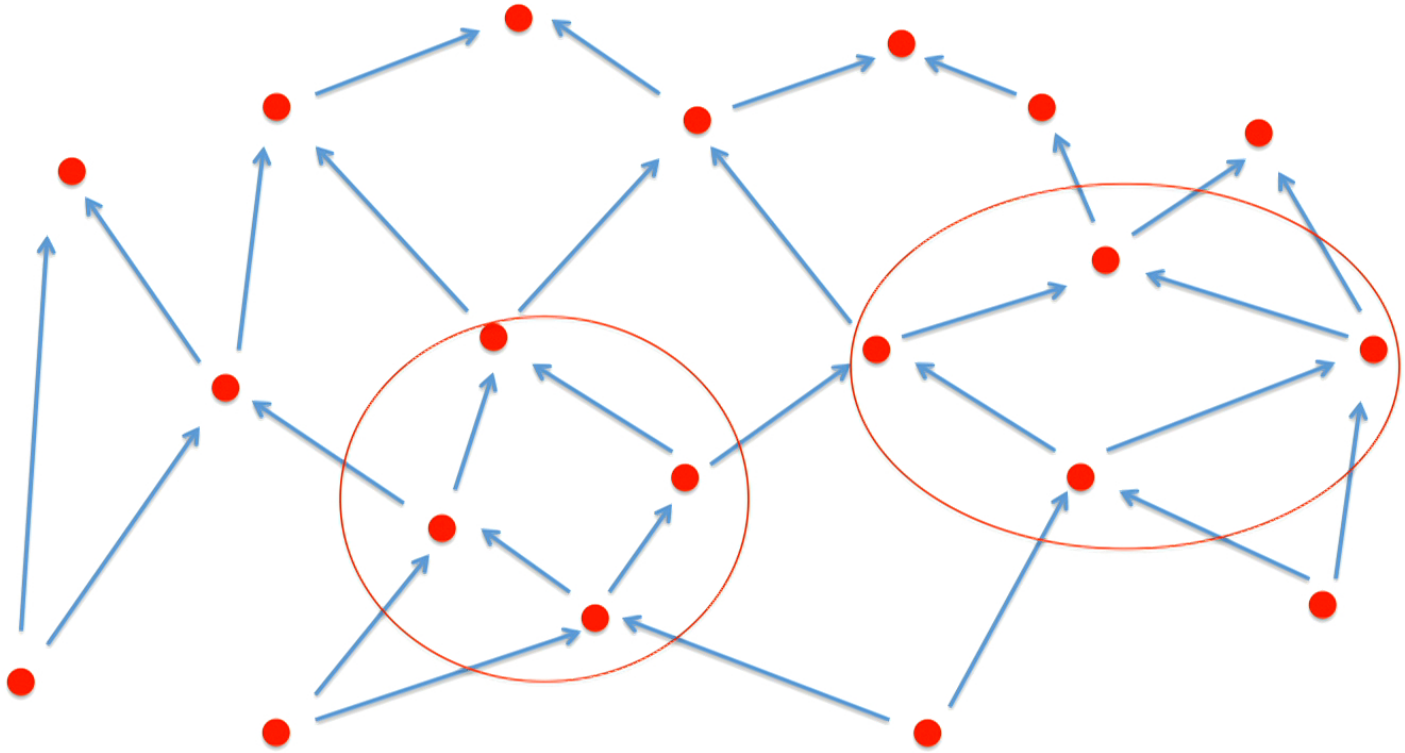
Why is every event unique?

- Think of the universe as a network of events. Each event is connected to all others in the network. An event is distinguished from all others by the full set of its relational properties.



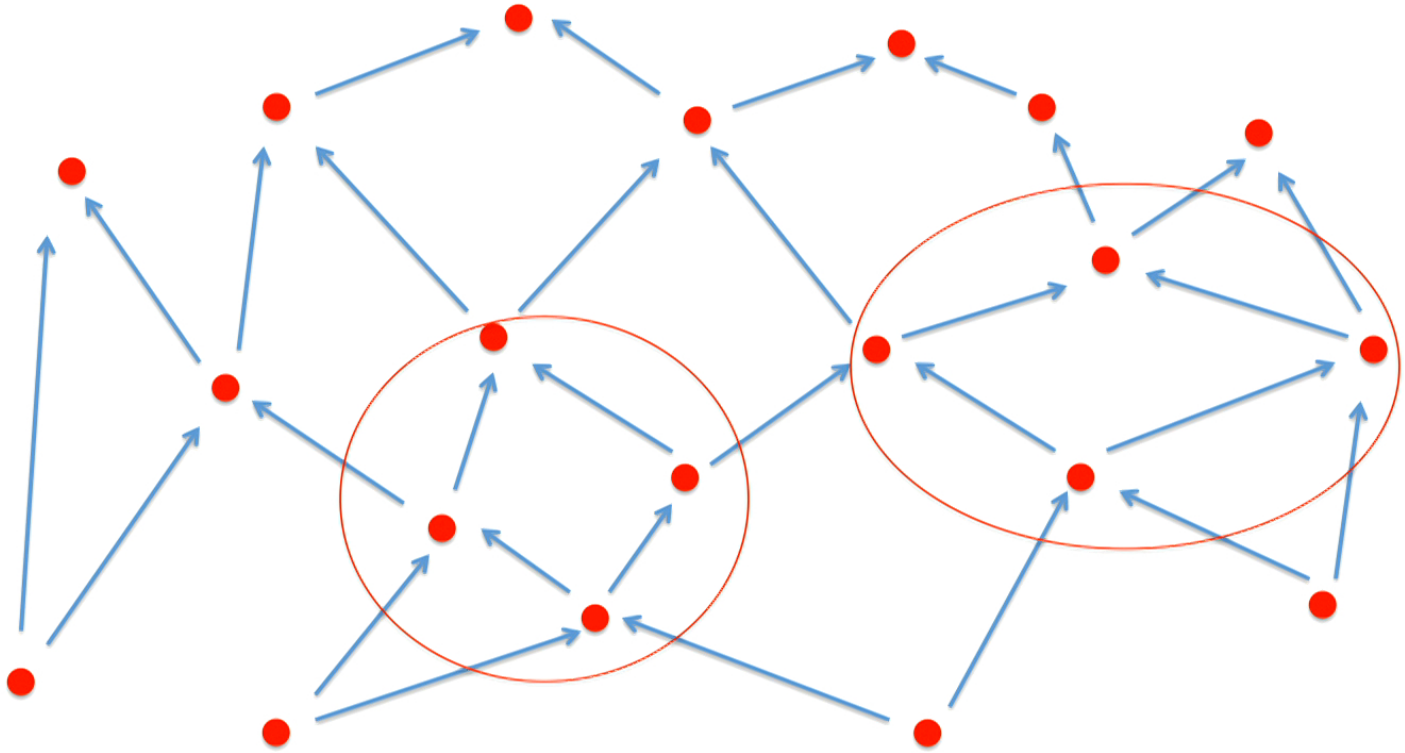
Science of subsystems versus Cosmology

- The only scientific method we have presupposes the existence of reproducible subsystems. Sever the connections with the exterior of the truncation and the subsystems look similar.



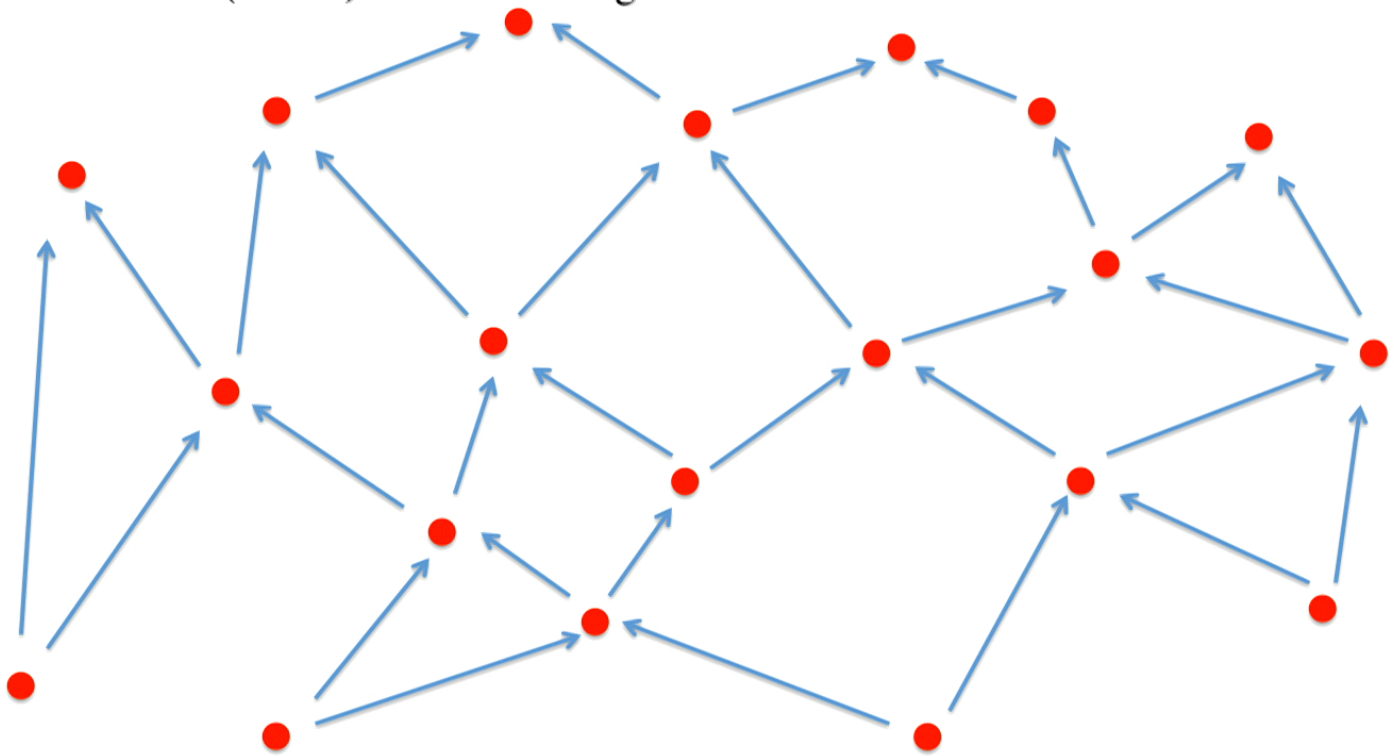
Science of subsystems versus Cosmology

- There's an interesting argument that the uncertainty principle of QM comes from the severing of the connections of the system with the exterior. Nature gets confused because the two systems are not exactly similar.

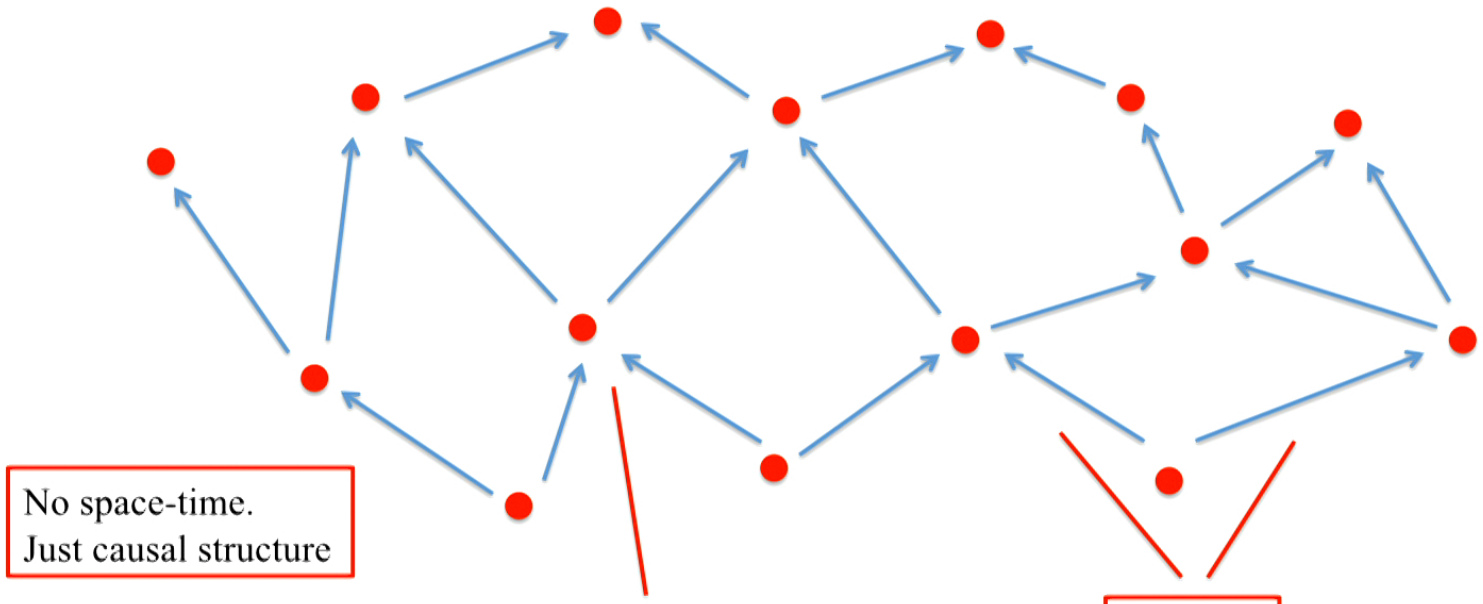


What are events? (Energetic Causal sets)

- Events are interactions between (massless) particles that take place in energy-momentum space, i.e. there is no space time, it's pre-geometry.
- Instants of time are made up of these interactions. Time ticks forward every time there's an interaction = event.
- Interactions (events) are the building block of nature.



•Events are instants of time.
•Time moves forward **irreversibly** when there is an interaction.
•Fundamentally there is no space-time just causal structure + metric of energy momentum space.



No space-time.
Just causal structure

interaction of massless particles
2-> 2
in pre-geometry energy-momentum space

null lines

The Universe as a Process of Unique Events

Principles on Dynamics (in cosmology and quantum gravity)

Principle C

•Relational point of view: space-time properties of object or event arise from relationship with other objects or events.

•All space-time properties have a dynamical origin.

Principle D

•Energy-momentum is fundamental: not emergent from space-time.

•The opposite is true: space-time is emergent from fundamental causal and dynamical regime in which energy and momentum are primitives.

The Universe as a Process of Unique Events

Principle C (relational) implies that events are unique.
True in foundational cosmology (not valid for cmb multipoles, stripe 82, etc)

Principle A (irreversible) implies that
Events can only happen they can never *unhappen*.

(Obvious as it may seem, this is not a trivial statement – in quantum mechanics the rejection of this principle leads to the *Transactional Interpretation,* or *Two State Vector Formalism,* and is a way of restoring time symmetry in quantum theory)

The Universe as a Process of Unique Events

Energetic Causal Sets

We have established the principles or ECS.
How do energetic causal sets work?
Give dynamics to the model
1. Dynamics at Events – what happens at events.
2. Dynamics of the causal structure – which events take place

1. Dynamics at events

Interactions in energy-momentum space

(zoom-in on network of events)

- $p_K^{\ I}, p_J^{\ I}$

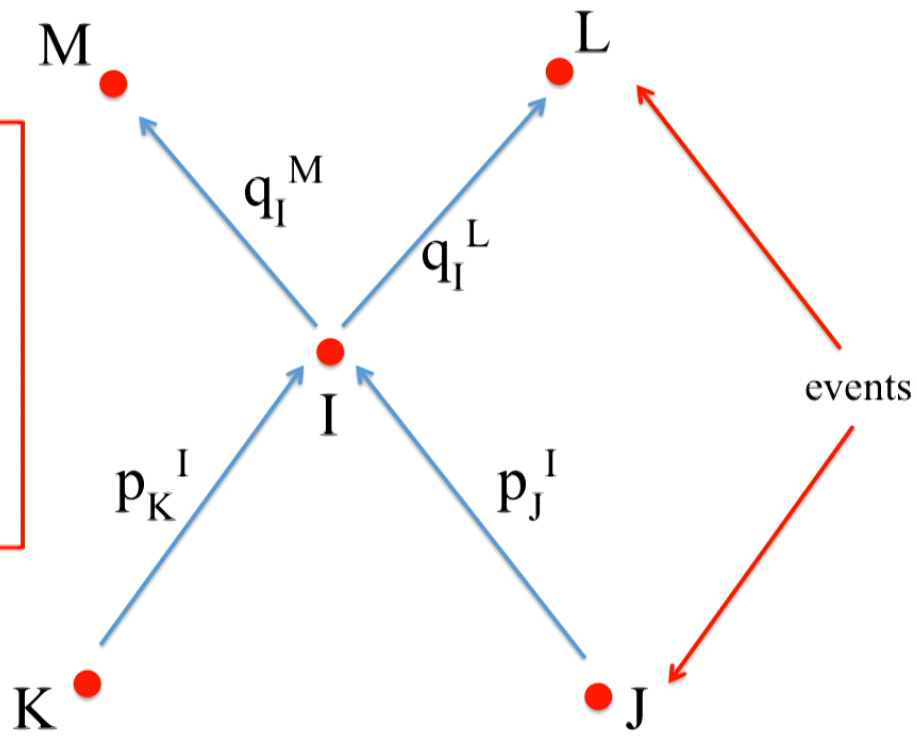
are incoming momenta

- $q_I^{\ M}, q_I^{\ L}$

are outgoing momenta

- K, J, L, M

are events



1. Dynamics of events - Constraints at events

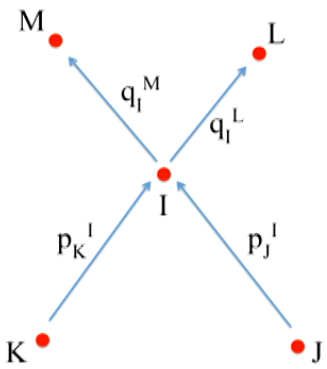
Conservation laws:

$$\mathcal{P}^I_a = \sum_K p^I_{aK} - \sum_L q^L_{aI} = 0$$

No redshifts

$$\mathcal{R}^K_{aI} = p^K_{aI} - q^K_{aI} = 0$$

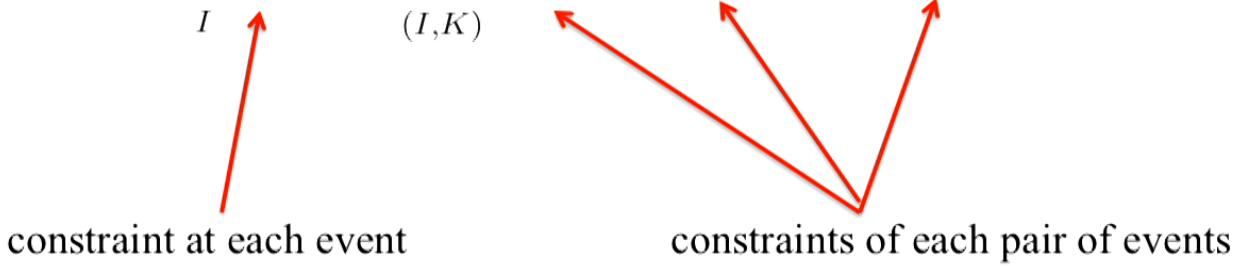
Energy momentum relations for massless photons



$$\mathcal{C}^I_K = \frac{1}{2}\eta^{ab} p^I_{aK} p^I_{bK} = 0, \qquad \tilde{\mathcal{C}}^I_K = \frac{1}{2}\eta^{ab} q^I_{aK} q^I_{bK} = 0$$

1. Dynamics at events - Action is purely constraints

$$S^0 = \sum_I z^a_I \mathcal{P}^I_a + \sum_{(I,K)} (x^{aI}_K \mathcal{R}^K_{aI} + \mathcal{N}^K_I \mathcal{C}^I_K - \tilde{\mathcal{N}}^K_I \tilde{\mathcal{C}}^I_K)$$



constraint at each event

constraints of each pair of events

$z^a_I \quad x^{aK}_I \quad \mathcal{N}^I_K \quad \tilde{\mathcal{N}}^I_K$ Lagrange multipliers

(extremize the action subject to constraints)

1. Dynamics at events - Emergence of space-time

We can't vary the action by the lagrange multipliers – just get constraints back.
But we can vary by momenta:

$$\frac{\delta S^0}{\delta p^I_{aK}} = z^a_I + x^{aK}_I + \mathcal{N} p^{aI}_K = 0$$

$$\frac{\delta S^0}{\delta q^K_{aI}} = -z^a_K + x^{aK}_I - \tilde{\mathcal{N}} q^{aK}_I = 0$$

Add the two equations and making $\mathcal{R}^K_I = 0$

Difference of space-time coordinates proportional to momentum

$$z^a_I - z^a_K = p^{aI}_K (\tilde{\mathcal{N}}^K_I - \mathcal{N}^K_I)$$

lagrange multipliers take on role of space-time variables

affine parameter along a null ray is arbitrary

1. Dynamics at events:
Emergence of relativistic particle dynamics from a chain of events

- Consider a chain of events $\mathcal{E}_I$, $I = 1, \ldots, N$, each with a single incoming momentum p_a^I and single outgoing momentum q_{aI}.

- Solve the no redshifts constraint to find $p_a^I = q_a^I$

- The coordinates of the embedding, z_I^a, are then $z_{I+1}^a - z_I^a = p^{aI}\mathcal{M}_I$ where $\mathcal{M}_I = \tilde{\mathcal{N}}_I^{I-1} - \mathcal{N}_I^{I+1}$

- Consider $\mathcal{M}_I$ small so adjacent events in the chain are close. Then we can expand

$$z_{I+1}^a = z_I^a + \dot{z}^a(t)\Delta t$$

  where Δt is a small interval.

- We then have

$$\dot{z}^a(t) = \frac{\mathcal{M}_I}{\Delta t} p_I^a = n p_I^a$$

  where $n = \frac{\mathcal{M}_I}{\Delta t}$ remains finite as both Δt and $\mathcal{M}_I$ are taken to zero.

1. Dynamics at events:
Emergence of relativistic particle dynamics from a chain of events

- We used $\mathcal{R}$ constraints, so eliminated their lagrange multipliers x^a_I but not the $\mathcal{P}$ constraints or $\mathcal{C}$ constraints. The action is then

$$S = \sum_I p^I_a (z^a_{I+1} - z^a_I) - \frac{1}{2}\mathcal{M}_I p^2_I$$

- Take $\Delta t \to 0$ so that $\sum_I \Delta t \to \int dt$ and the chain goes to a curve. In this limit the p^I_a can be replaced by the continuous functions $p_a(t)$. And replace z^a_I by continuous variables $x^a(s)$ so the action becomes

$$S^{free} = \int dt \left(p_a(t)\dot{x}^a(t) - \frac{1}{2} n(t) p(t)^2 \right)$$

which is the action for a free relativistic particle.

The Universe as a Process of Unique Events

Energetic Causal Sets

Give dynamics to the model

1. Dynamics at Events – what happens at events.
2. Dynamics of the causal structure – which events take place

2. Dynamics of the causal structure

What determines the causal structure?
What chooses which events will interact, which events happen next?

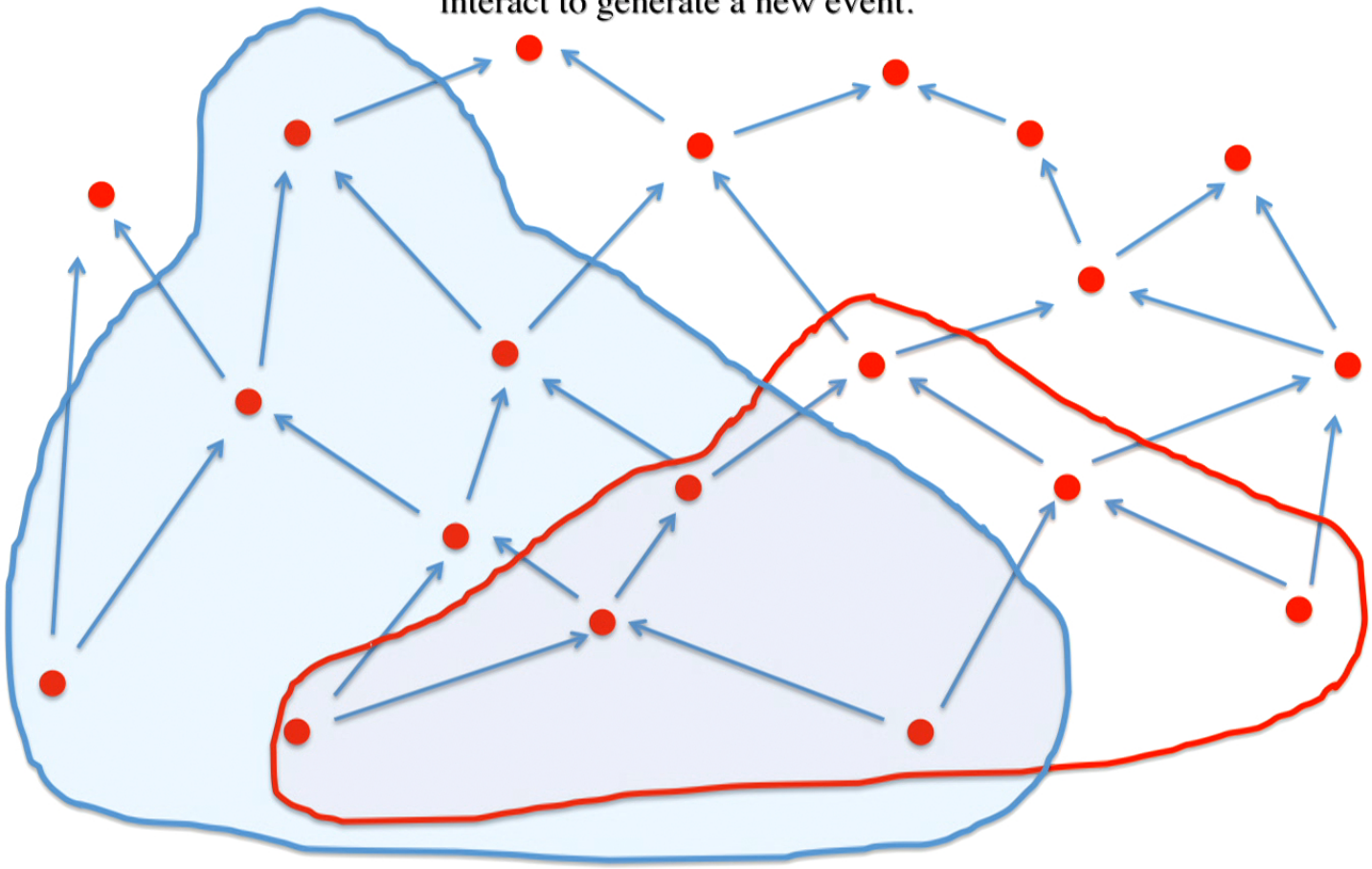
*We choose the causal structure to incorporate
time asymmetry of the dynamics
no two events are the same
*Each event has two parents and two children:
two null lines interact and result in two null lines.
*Choice of next event:
-Take all events which are available for interaction
-choose the two most similar events.
*Two events are similar when their causal past "light" cone is alike.

*Computational simplification:
causal past is the average of space-time positions in the embedding in the past light cone. This ensures uniqueness of events (we're in the real line)

Compare all pasts and choose the most similar pair to create a new event.

Causal Past of two events

In the generation of new events causal pasts will be compared and the most similar will interact to generate a new event.



2. Dynamics of the causal structure – simulating energetic causal sets

For (computational) simplicity reduce to 1+1d
Steps:
1. Choose number of initial events N – Each of these will be parents of many events and we'll call them lineages. Initial N events means there will be N lineages in the simulation. Attribute the initial past to be the event itself.

2. Pick the pair which will create the next events, i.e. pick two parents.

3. Which of the null lines will interact. Stochastic irreversibility is introduced here.

4. Compute coordinates of the new event – create two null lines that meet at this event -

5. Store the new event with its lineage.

6. Go back to Step 2. Repeat M times.

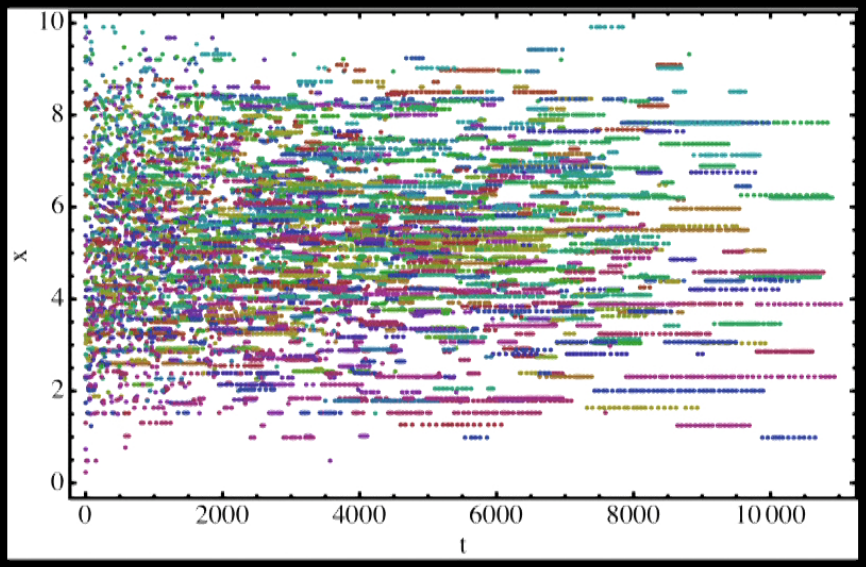
2. Dynamics of the causal structure – simulating energetic causal sets

- If we want to propose time asymmetry in the fundamental regime the first task is to show how an intrinsically irreversible time asymmetric dynamical process can give emergence of the time symmetric dynamics of the standard model.

- Show how fundamental irreversibility approximates to the time reversible effective laws we know

2. Dynamics of the causal structure

Simulation of Energetic causal sets - Minkowksi embedding - 1+1d



•Different colors represent different families: number of families (or number of lineages) measures the amount of initial complexity in the system.

• It's simply the number of initial events at t=0.

Parameters:

•40 families;

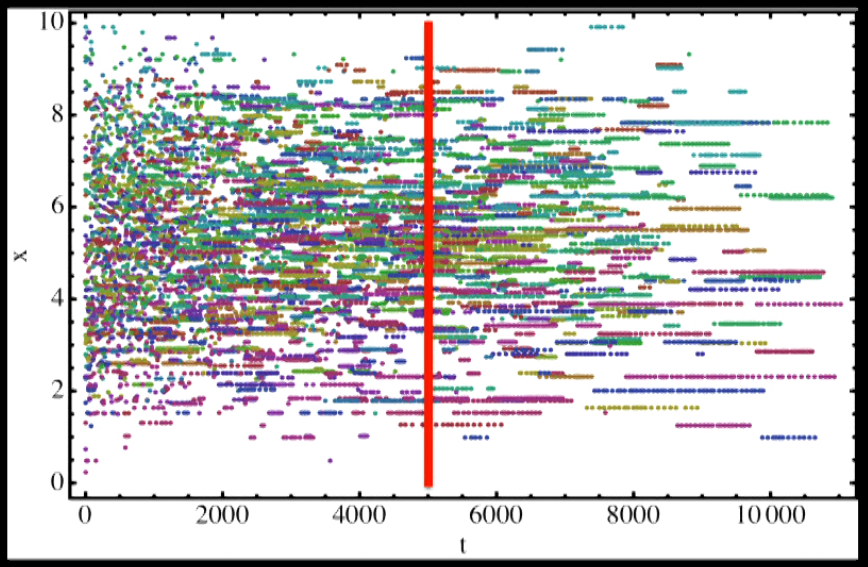
•Total number of events is 10^4

•Each dot is an event (intersection of null lines in 1+1d)

space-time is a periodic cylinder cyclic in space.

2. Dynamics of the causal structure

Simulation of Energetic causal sets – Phase Transition



•Initially all events are disordered and structureless.

•Gradually events start to organize and structures form.

•From initial disorder there emerge regular lines which we call quasi-particle trajectories.

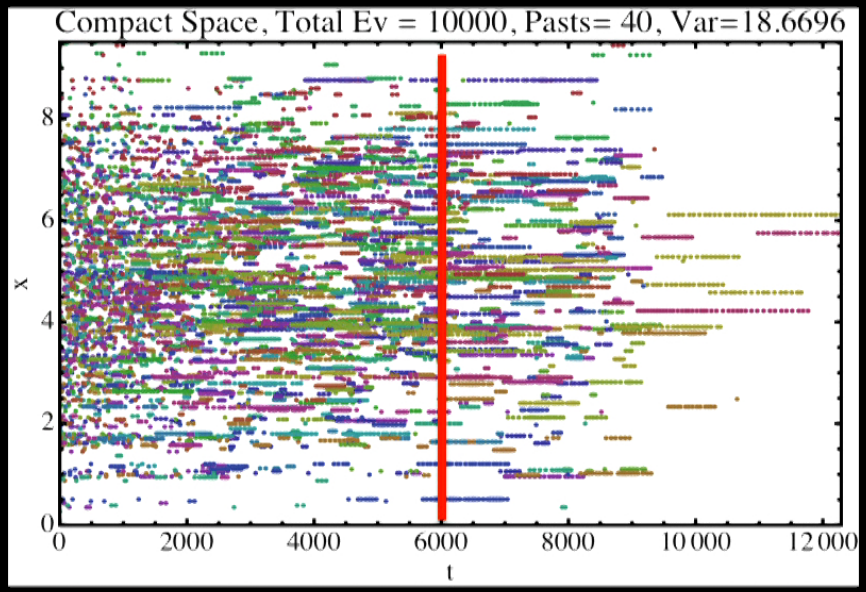
•Emergence of quasi-particles marks the transition from time asymmetry to time symmetry

• There's a clear distinction, as time evolves, between time asymmetric, irregular behaviour at early times, and order and regularity of events at late times. Emergency of regular lines which we call quasi-particle trajectories.

•Phase transition is not built in. It's a result.

2. Dynamics of the causal structure

Simulation of Energetic causal sets – Phase Transition



K. Goldmann

•Robustness of simulations: same parameters different run.

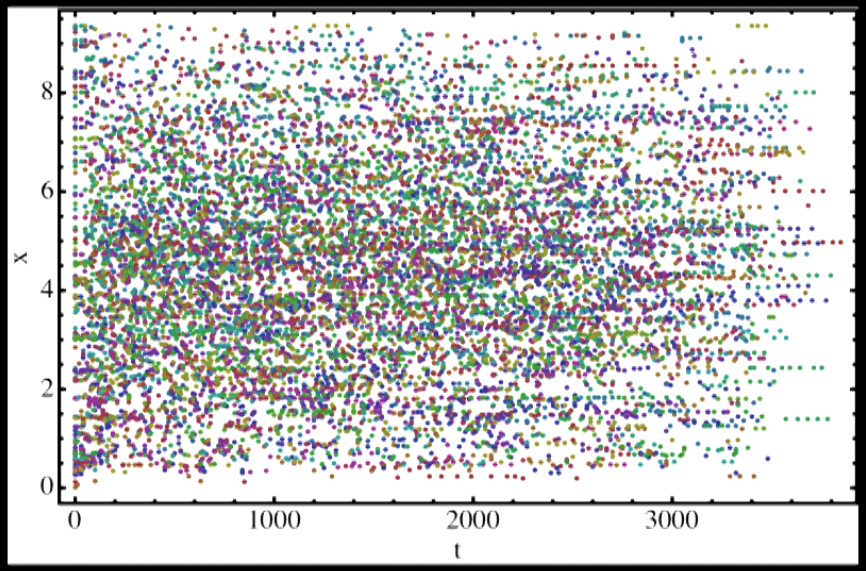
• Phase transition always occurs.

• Emergence of time symmetric effective dynamics from underlying time asymmetric rules

• Emergence of quasi-particles in the time symmetric regime

2. Dynamics of the causal structure

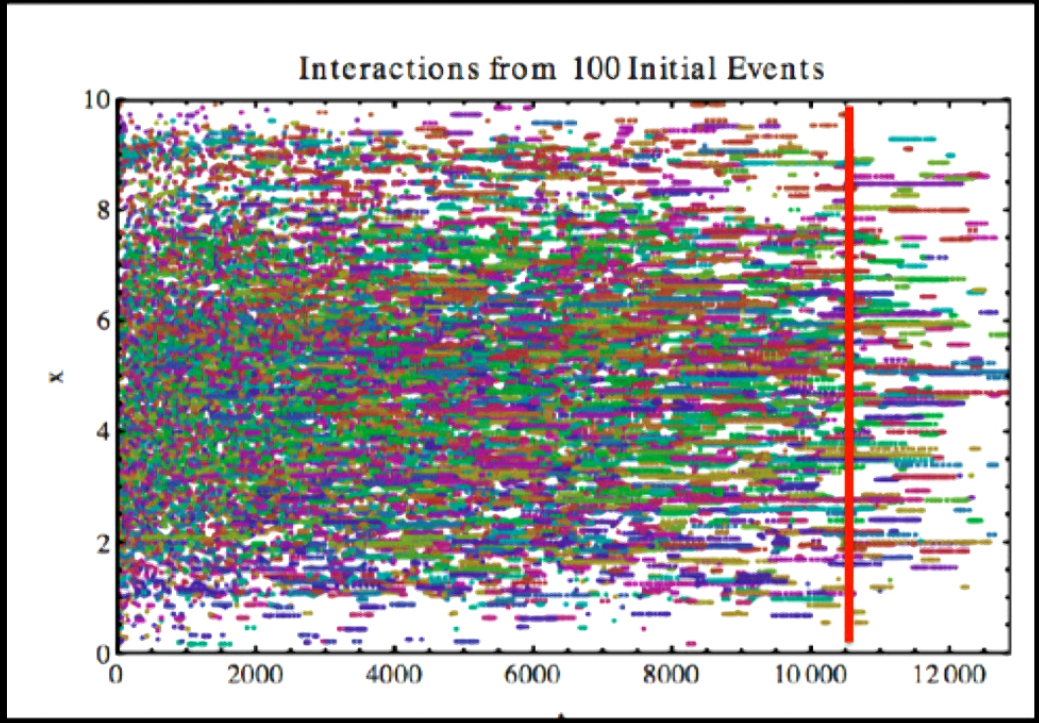
Simulation of Energetic causal sets – Higher complexity



- increase complexity from 40 to 100 families
- keep the same number of total events
- no phase transition

2. Dynamics of the causal structure

Simulation of Energetic causal sets – Higher complexity



- increase complexity from 40 to 100 families
- increase total the number of total events from 10^4 to 10^7
- phase transition occurs after enough events have taken place.

K. Goldmann

Challenging Causality

TIME IN COSMOLOGY MEETING

Perimeter Institute - June 2016

Organized: MC, L. Smolin, R. Unger

Participants: A. Albrecht, A. Ashtekar, J. Bardeen, S. Carroll, F. Dowker, A. Elitzur, G. Ellis, B. Keating, A. Liddle, J. Magueijo, C. Rovelli, N. Turok,

All discussions at PIRSA

Energetic Causal Sets - Summary of results

•Energetic Causal Sets introduce irreversible flow of time into the foundations of cosmology.

•Space-time emerges under natural conditions from causal structure whose elements are endowed with energy-momentum.

•We are able to approximate strongly time asymmetric behaviour by time reversible dynamics. This is the first step to for the emergence of classical time reversal invariant physics.

•Causality remains the most fundamental property of nature. It can sometimes oppose the emergent direction of time in the embedding.

Future work

- Include space-time curvature in Energetic Causal Sets (ECS) – derive GR
- Quantum version of ECS gives emergence to quantum model which is so far not yet time irreversible:
  - extend the quantum energetic causal sets model to time asymmetry
- Include massive particles in ECS Simulations for 2D and 3D of ECS
- Correspondence between GR and first law of thermodynamics a-la-Jacobson

Conclusions

•We don't have an explanation for the origin of irreversibility starting from time symmetric principles in micro-physics.
•How then does irreversibility come about?

•We are all reductionists – bottom up approach
•Scientific Reductionism has prevailed for 300 years. It might not possible to explain all phenomena in physics. Phenomena that are resisting reductionist methods of study include:

- Emergence of thermodynamical arrow
- The quantum mechanics measurement paradox: reductionism fails when we try to isolate the system from the measurement apparatus.

•Strong indicator that irreversibility in macroscopic physics might need to be taken to be fundamental, that is, it does not emerge from any other regime. It is as fundamental as particle physics.
•Perhaps this is an indication that top-bottom approaches are what is necessary.

Lastly

•In Dutch, physics is *natuurkunde* – the study of nature.
•Particularly appreciate this term because it remind us what is the subject of our study.
•We are in the business of studying nature. We are not in the business of studying mathematics.
•However it's irresistibly tempting to forget this.
•Mathematics is about elegance, simplicity, symmetries.
•When nature complies with this it's tremendously gratifying.
•That is not to say that when it doesn't we'll order nature around to stick to our mathematical rules.
•(Theoretical) Physicists are perhaps the scientists with the sharpest sense of aesthetics.
•So it becomes even more pressing for us to:

Lastly

- In Dutch, physics is *natuurkunde* – the study of nature.
- Particularly appreciate this term because it remind us what is the subject of our study.
- We are in the business of studying nature. We are not in the business of studying mathematics.
- However it's irresistibly tempting to forget this.
- Mathematics is about elegance, simplicity, symmetries.
- When nature complies with this it's tremendously gratifying.
- That is not to say that when it doesn't we'll order nature around to stick to our mathematical rules.
- (Theoretical) Physicists are perhaps the scientists with the sharpest sense of aesthetics.
- So it becomes even more pressing for us to:

Keep. Our Convictions. In check