The Evolving Block Universe: A more realistic view of spacetime geometry

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AEI, Golm

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"Space time and the passage of time": G Ellis, *arXiv:1208.2611*

1: A standard physics picture:

Time is an illusion

➔ The Block Universe

2: Taking time seriously:

Time passes, as regards:

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Time passes, as regards:

- The contents of spacetime
- Spacetime itself

→ The Emergent Block Universe

→ but there are objections …….

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→ The Crystallizing Block Universe

1: Time as an Illusion

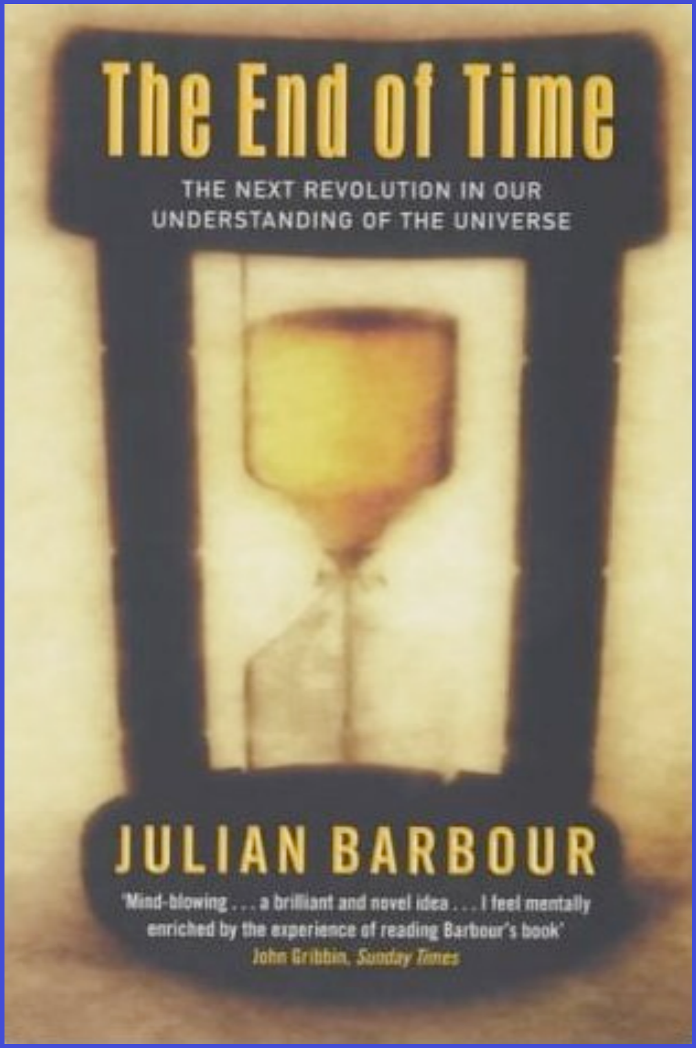
The nature of spacetime in both special and general relativity has lead some to a view that the passage of time is an illusion.

Given data at an arbitrary time, it is claimed that everything occurring at any later or earlier time can be uniquely determined from that data. Time reversible Hamiltonian dynamics provides the basis for physics in general, and gravitation in particular. One can predict equally to the past and the future from present day data.

$$H: S(x_0,t_0) \rightarrow S(x_1,t_1) \quad \text{for all } t_0, t_1$$

Consequently, nothing can be special about any particular moment; there is no special "now" which can be called the present.

Past, present and future are equal to each other, for there is no surface which can uniquely be called the present.



"In *The End of Time*, which is written both for the popular-science market and for scientists and philosophers, I argue that the apparent passage of time is an illusion. If we could stand outside the universe and 'see it as it is', it would appear to be static."

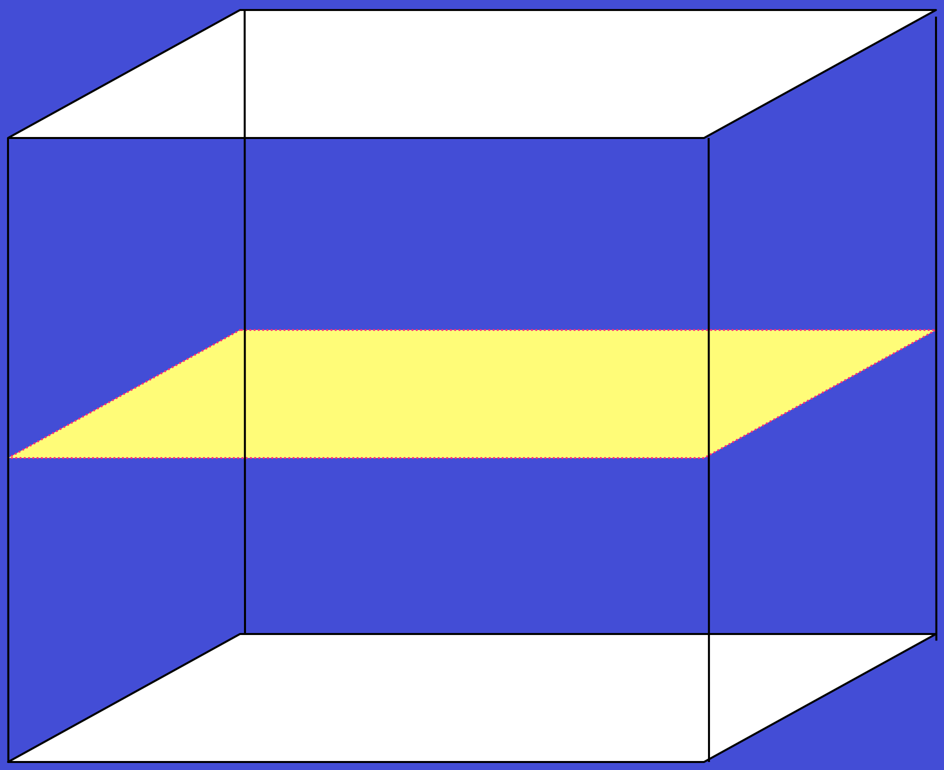
The Block Universe

Such a view can be formalized in the idea of a Block Universe: space and time are represented as merged into an unchanging spacetime entity, with no particular space sections identified as the present and no evolution of spacetime taking place.

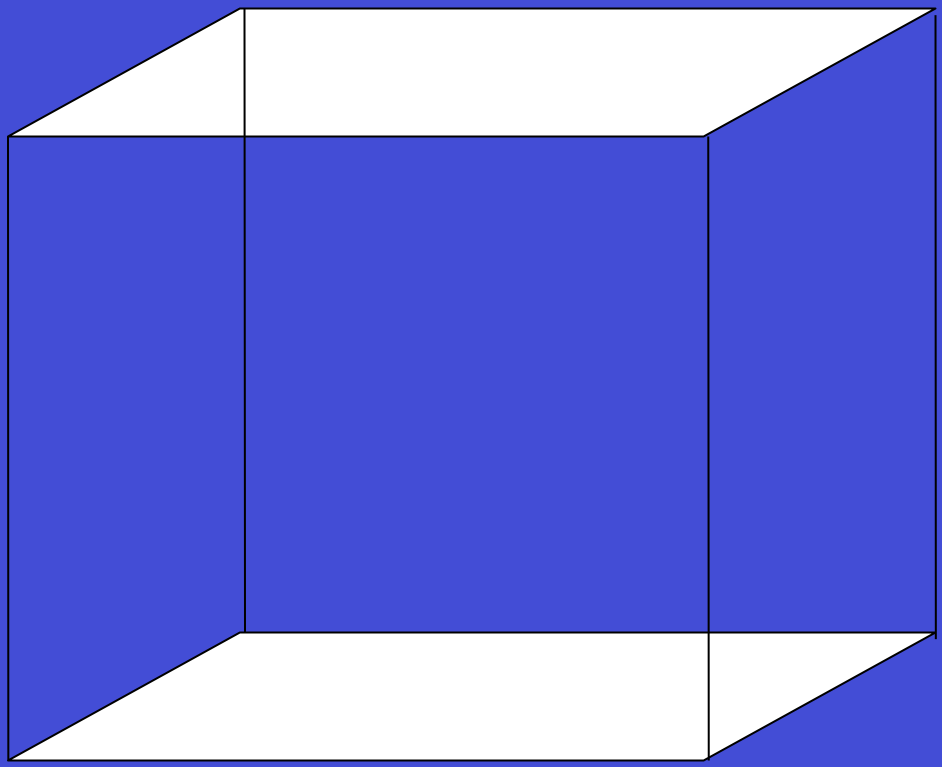
The universe just is: a fixed spacetime block, representing all events that have happened and that will happen.

This representation implicitly embodies the idea that time is an illusion: time does not “roll on” in this picture.

All past and future times are equally present, and the present “now” is just one of an infinite number.



The block universe: Both the past and the future already exist, and are uniquely determined. Nothing unexpected can happen. The present has no significance.



The block universe: Both the past and the future already exist, and are uniquely determined. Nothing unexpected can happen. The present has no significance.

The problem with this view is that it is profound contradiction with our experiences in everyday life, and in particular with the way science is carried out. Scientific theories are developed and then tested by an ongoing process that rolls out in time: initially the theory does not exist; it is developed, tested, refined, finally perhaps accepted: as in other cases, events take place!

By contrast to this view, one can suggest that the true nature of spacetime is best represented as an Emergent Block Universe (EBU), a spacetime which grows and incorporates ever more events, "concretizing" as time evolves along each world line.

Unlike the standard block universe, it adequately represents the differences between the past, present, and future, and depicts the change from the potentialities of the future to the determinate

2: Taking time seriously:
Things actually happen in time!

The macro – micro tension:

Reversible laws at micro level:

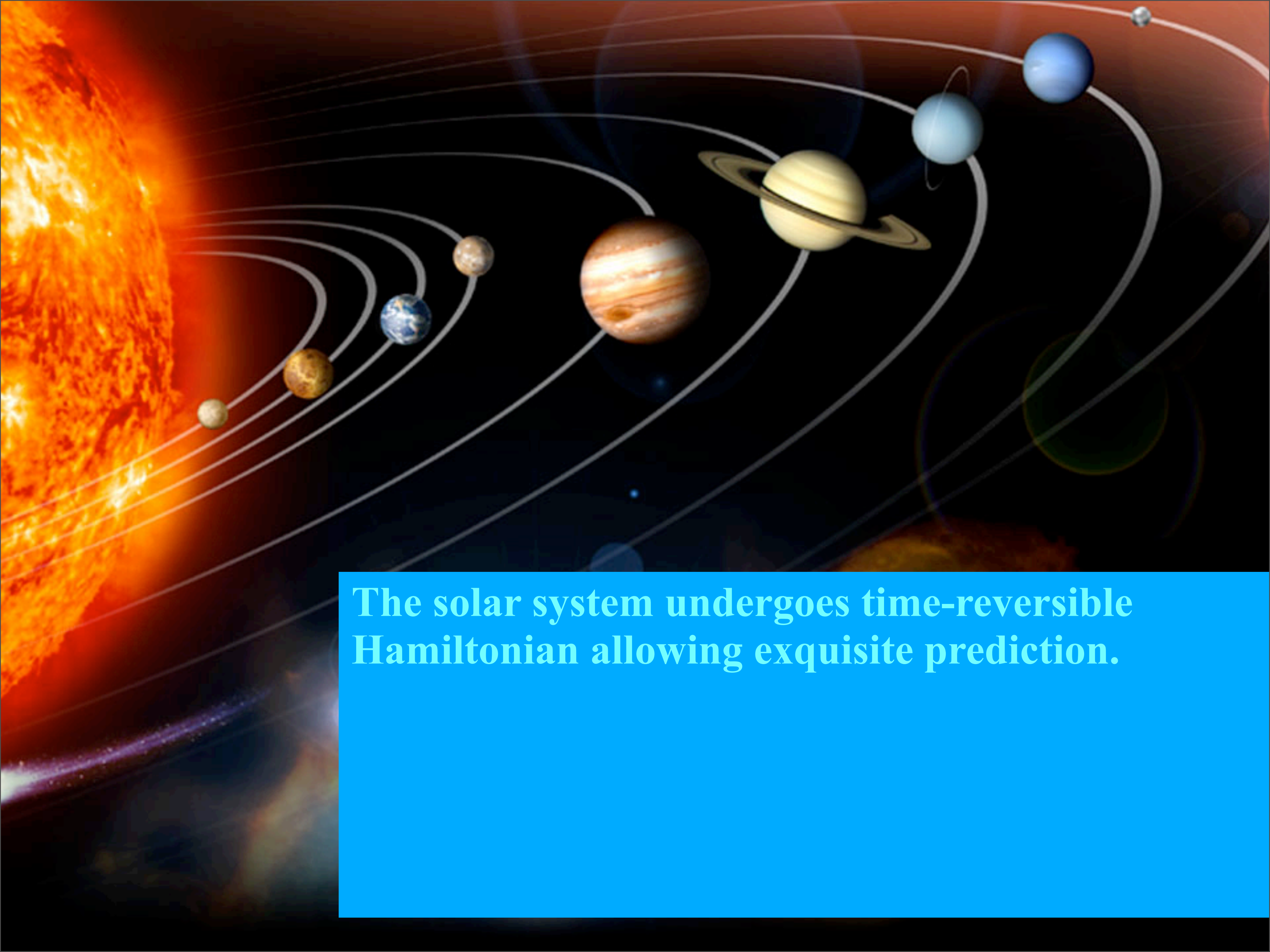
Hamiltonian dynamics

Irreversible at macro level:

Second law of thermodynamics.

- The fundamental feature of the macro world of physics chemistry and biology
- e.g. breaking a glass (Penrose); process of life

In the real world: The past and future are not predictable from the present: not Hamiltonian!



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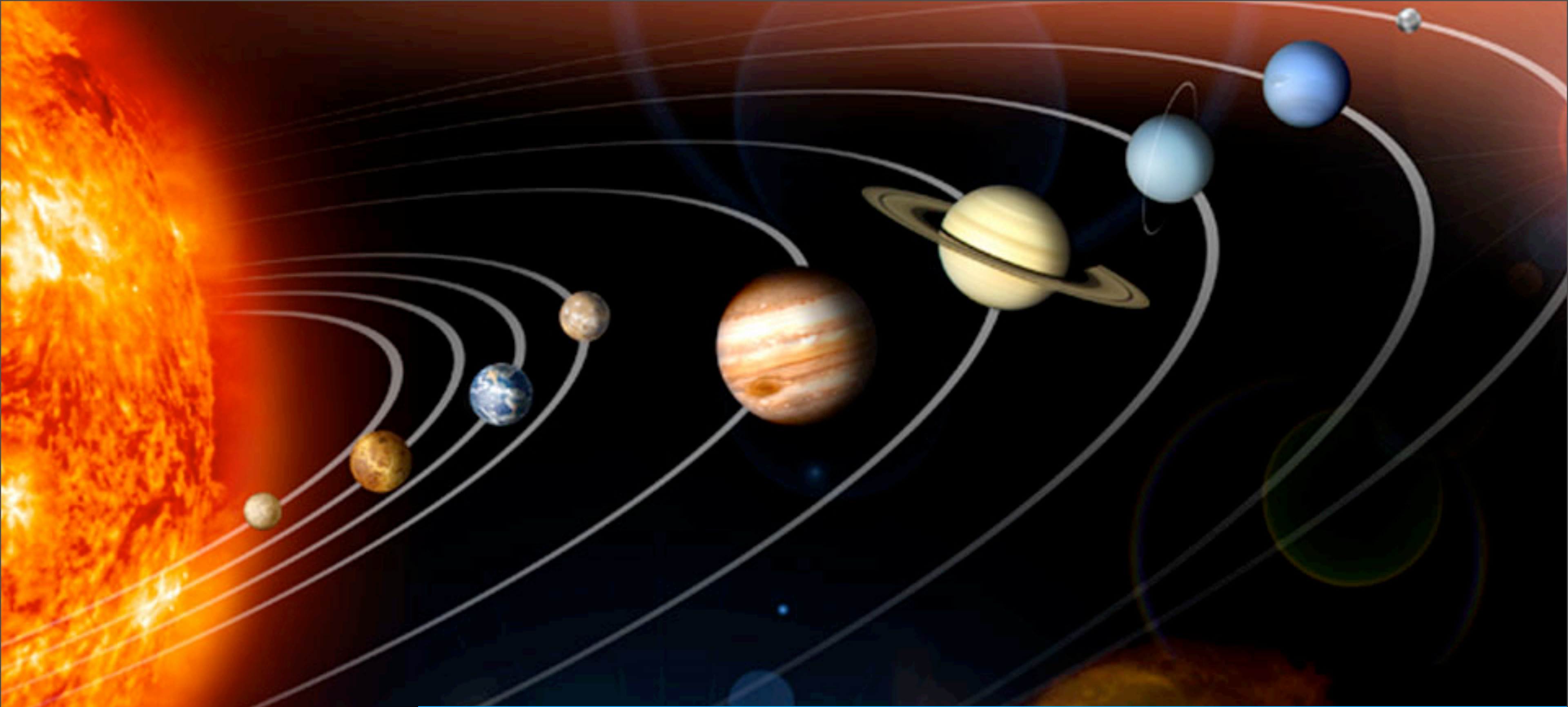

The solar system undergoes time-reversible Hamiltonian allowing exquisite prediction.

BUT This is the exception rather than the rule;

It allows very accurate prediction to the future and the past in this specific (almost frictionless) case: for a limited time. This is highly exceptional.

Arthur Stanley Eddington (1882-1944))

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"If someone points out to you that your pet theory of the universe is in disagreement with Maxwell's equations — then so much the worse for Maxwell's equations.

If it is found to be contradicted by observation — well, these experimentalists do bungle things sometimes.

But if your theory is found to be against the second law of thermodynamics I can give you no hope; there is nothing for it but to collapse in deepest humiliation."

Classical physics in the real world is not Hamiltonian!

(at macro scales): dissipation takes place,

$dS/dt > 0$

Is it reversible at the micro scale but not at the macro scale? The apparent flow of time is just a result of coarse graining – and hence an illusion?

No: complex systems really undergo time change! (at the macro scale)

What about micro scales? Collapse of the wave function takes place: also time irreversible

Taking time seriously: An evolving block spacetime

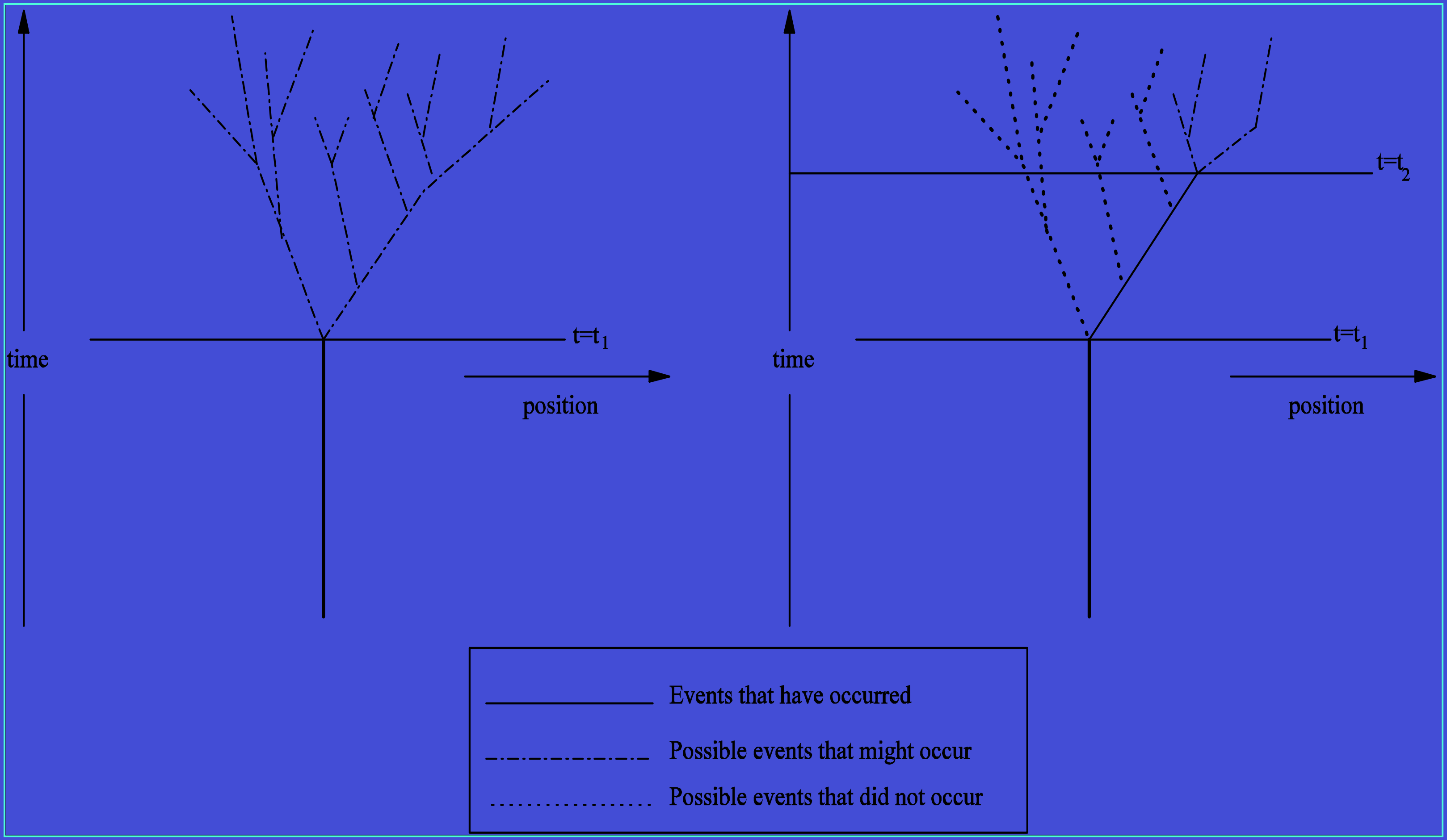
Consider a massive object with two computer controlled rocket engines that move it right or left

Let the computer determine the outcome on the basis of measurements of decay products of excited atoms

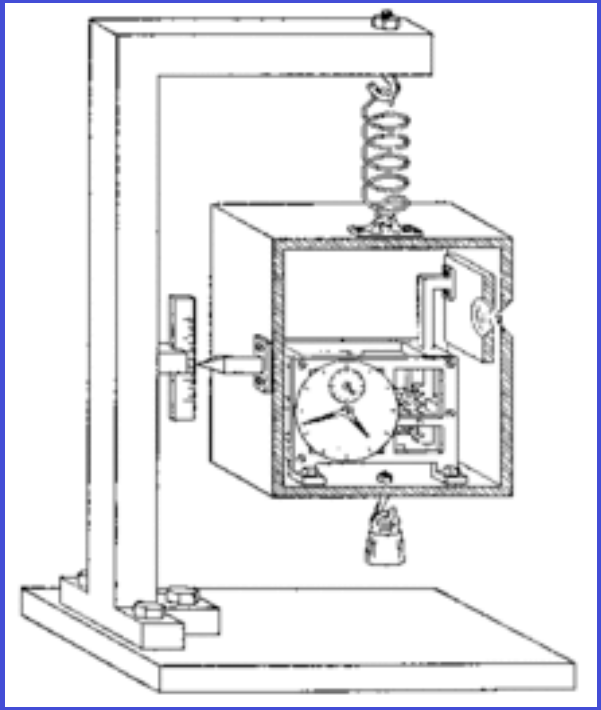
Then the outcome is unpredictable in principle

If the object is massive enough: it curves spacetime

The future spacetime structure is not determinable or predictable from current data (Bohr-Einstein debate).



The change from uncertainty to certainty:
the present is where the indefinite future changes to the determined past



Bohr–Einstein debates [wikipedia]

Bohr response :since the system is immersed in a gravitational potential which varies with the position, according to the principle of equivalence the uncertainty in the position of the clock implies an uncertainty with respect to its measurement of time and therefore of the value of the interval. A precise evaluation of this effect leads to the conclusion that the relation cannot be violated.

Hence uncertainty affects spacetime curvature.

The evolving block universe grows with time:

- The past has been determined and is fixed,

- The future is uncertain and still has to be fixed

Because of quantum uncertainty, it is not true that the future is determined at the present

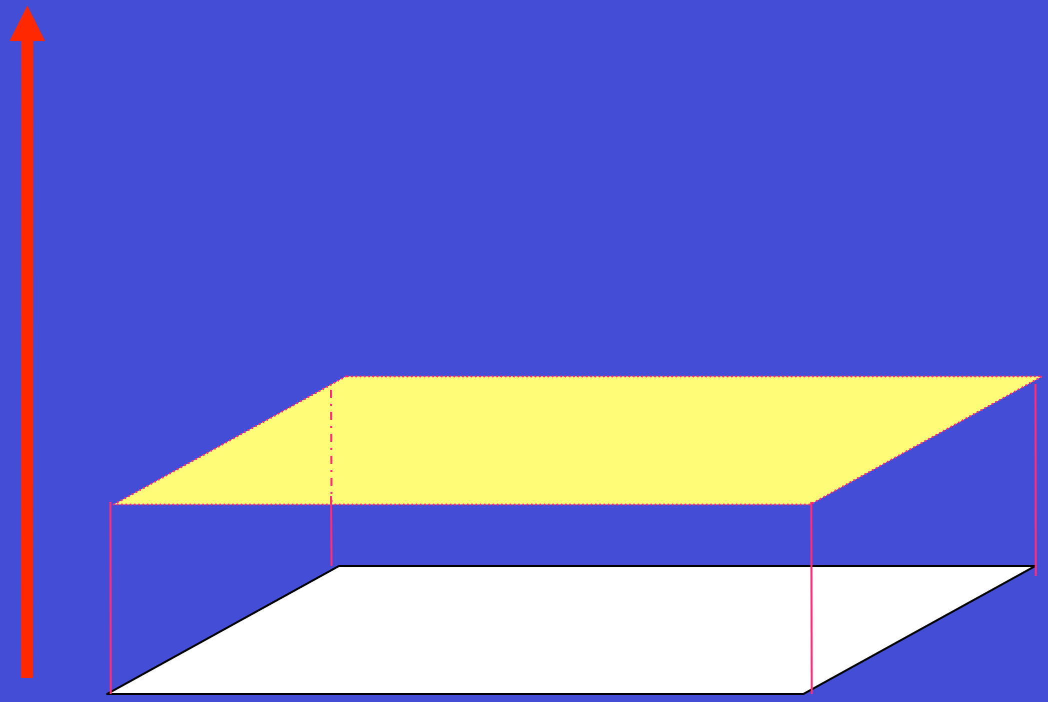
- The present is where the change takes place.

It is crucially different from the past and future, and indeed separates them.

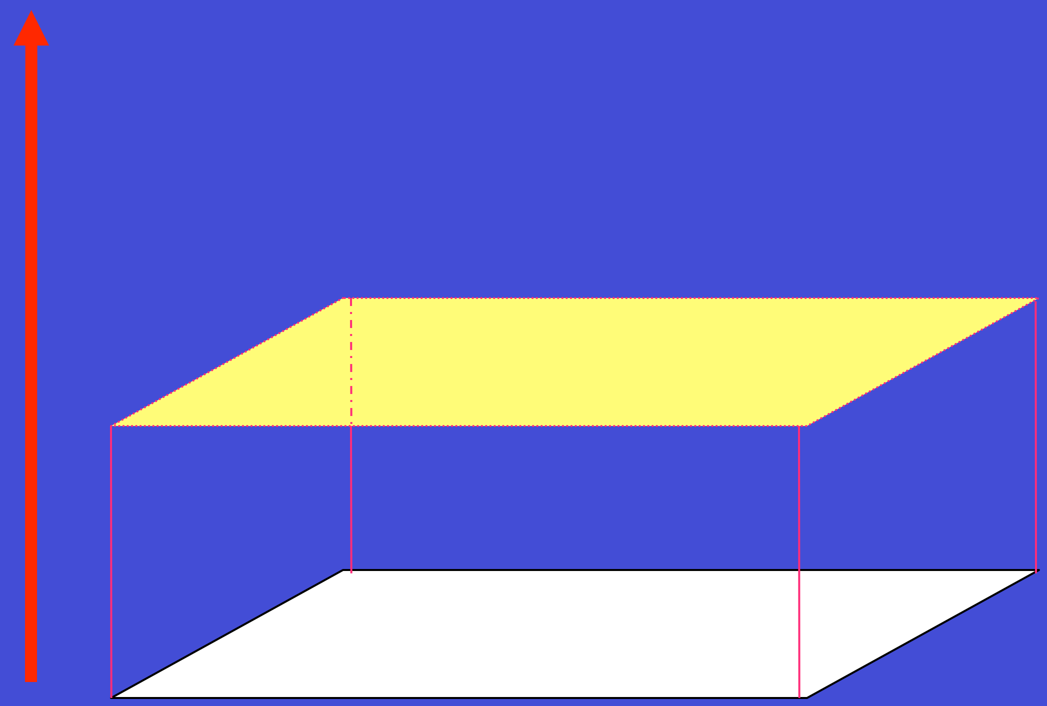
The future does not exist in the same sense as the past or the present.

The determinate region grows with time.

Spacetime itself is growing.



The evolving block universe (EBU): Spacetime grows with time



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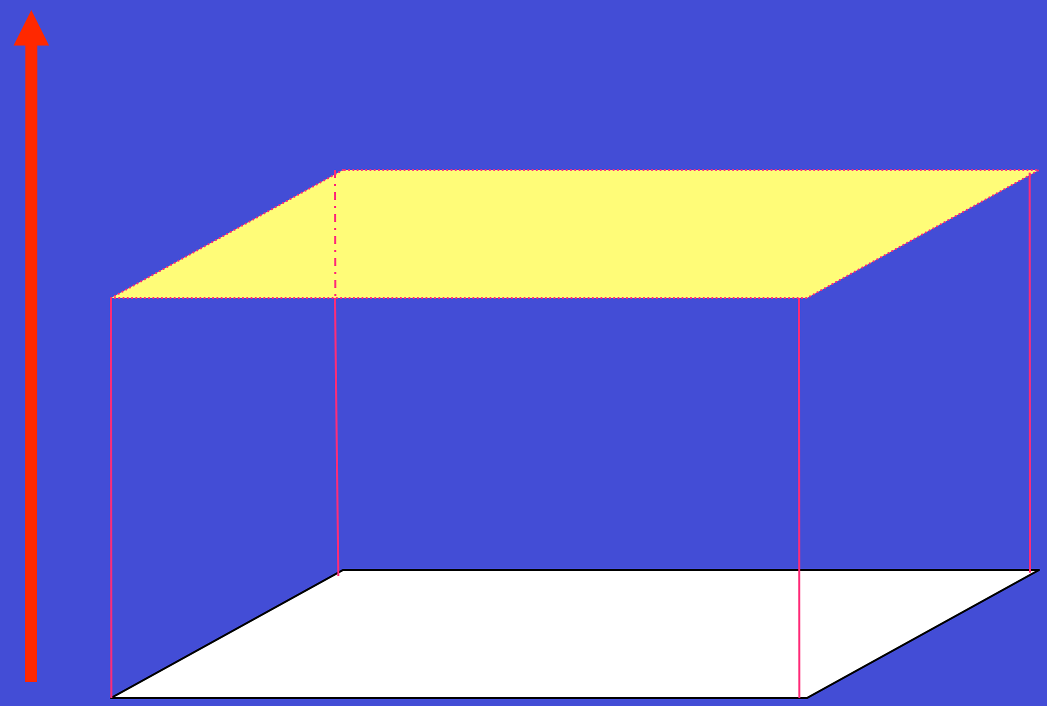

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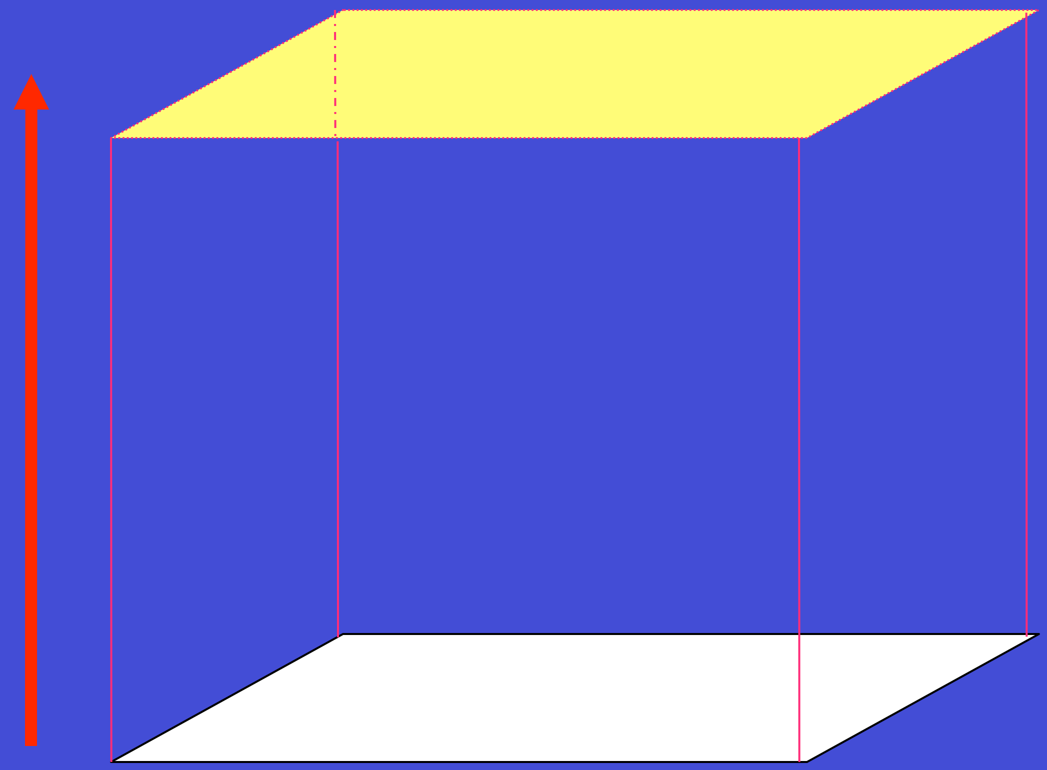

The evolving block universe (EBU):
Spacetime grows with time

The paradox

This model of spacetime is obviously far more in accord with our daily experience than the standard Block Universe picture; indeed everyday data, including the apparent passage of time involved in carrying out every single physics experiment, would seem to decisively choose the EBU over the Block Universe.

The evidence seems abundantly clear. Why then do some physicists prefer the latter?

If the scientific method is to abandon a theory when the evidence is against it, why do some hold to it?

This counter viewpoint is put succinctly by Sean Caroll in a blog:

“The past and future are equally real. This isn’t completely accepted, but it should be. Intuitively we think that the ‘now’ is real, while the past is fixed and in the books, and the future hasn’t yet occurred. But physics teaches us something remarkable: every event in the past and future is implicit in the current moment. This is hard to see in our everyday lives, since we’re nowhere close to knowing everything about the universe at any moment, nor will we ever be - but the equations don’t lie. As Einstein put it, ‘It appears therefore more natural to think of physical reality as a four dimensional existence, instead of, as hitherto, the evolution of a three dimensional existence.’ ”

http://blogs.discovermagazine.com/cosmicvariance/2011/09/01/ten-things-everyone-should-know-about-time/

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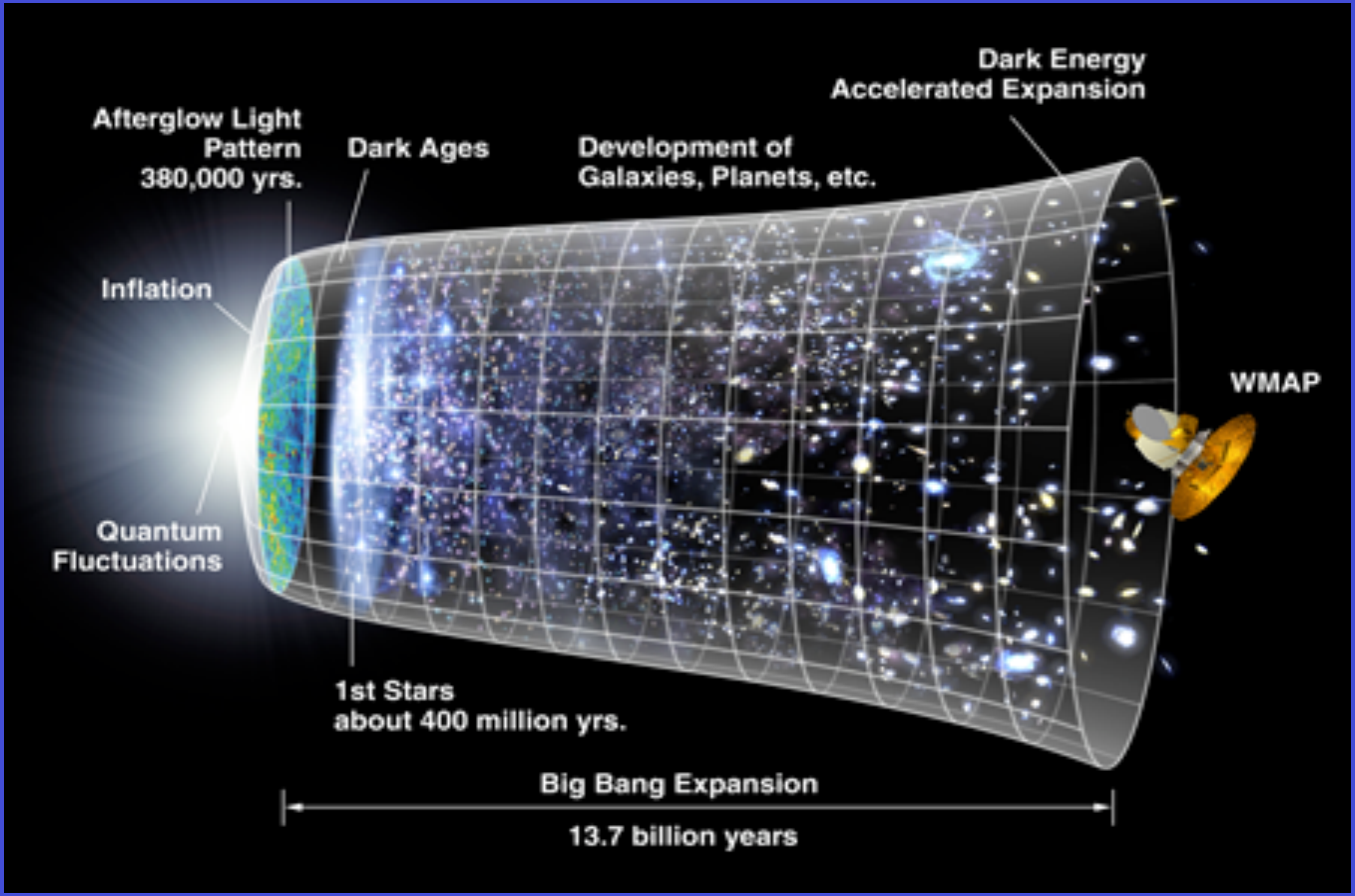
But physics experiments show that uncertainty to be a well established aspect of the universe, and it can have macroscopic consequences in the real world, as is demonstrated by the historic process of structure formation resulting from quantum fluctuations during the inflationary era. These inhomogeneities were not determined until the relevant quantum fluctuations had occurred, and then become crystalized in classical fluctuations; and they were unpredictable, even in principle.

Expansion history



time

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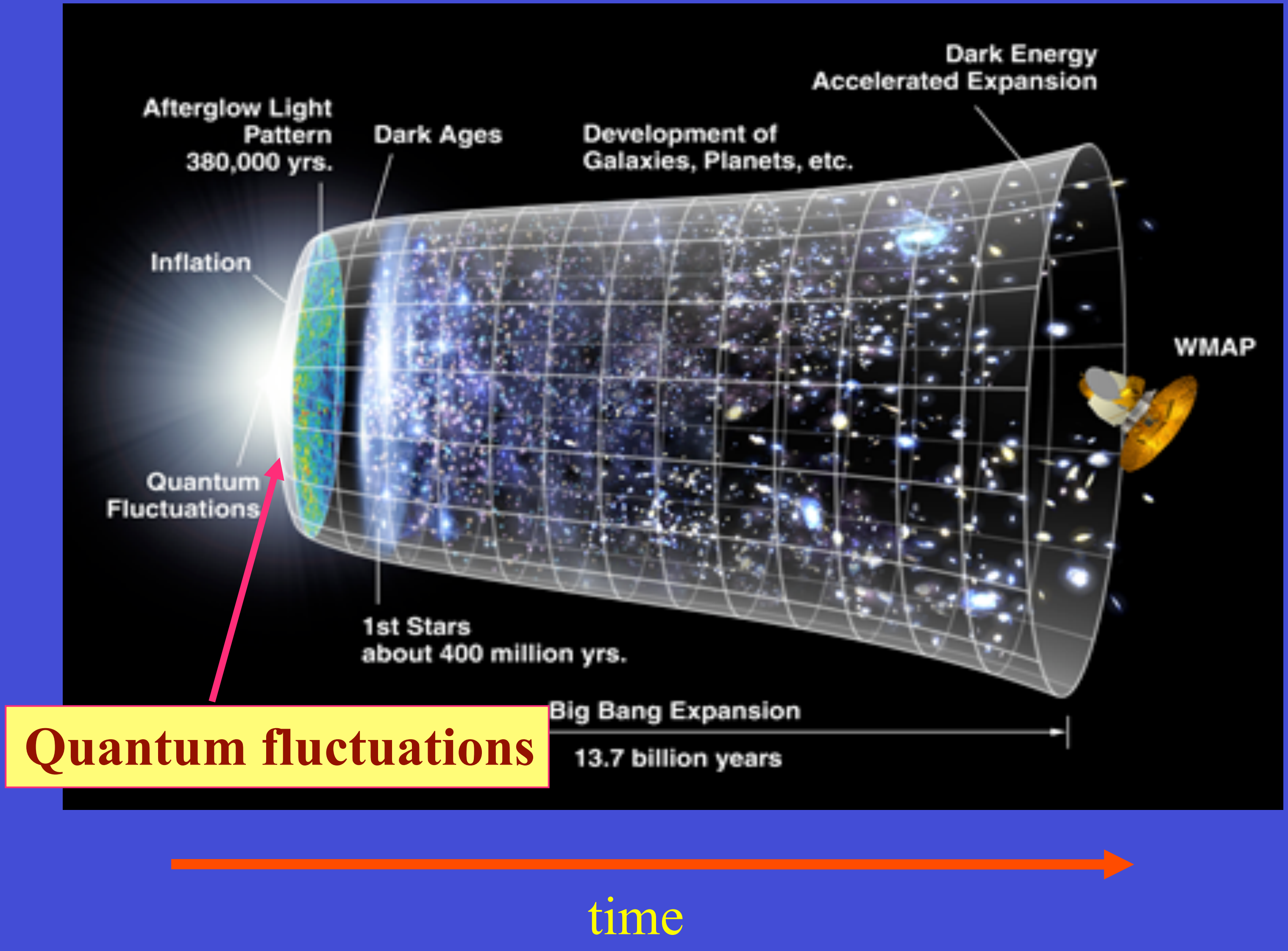

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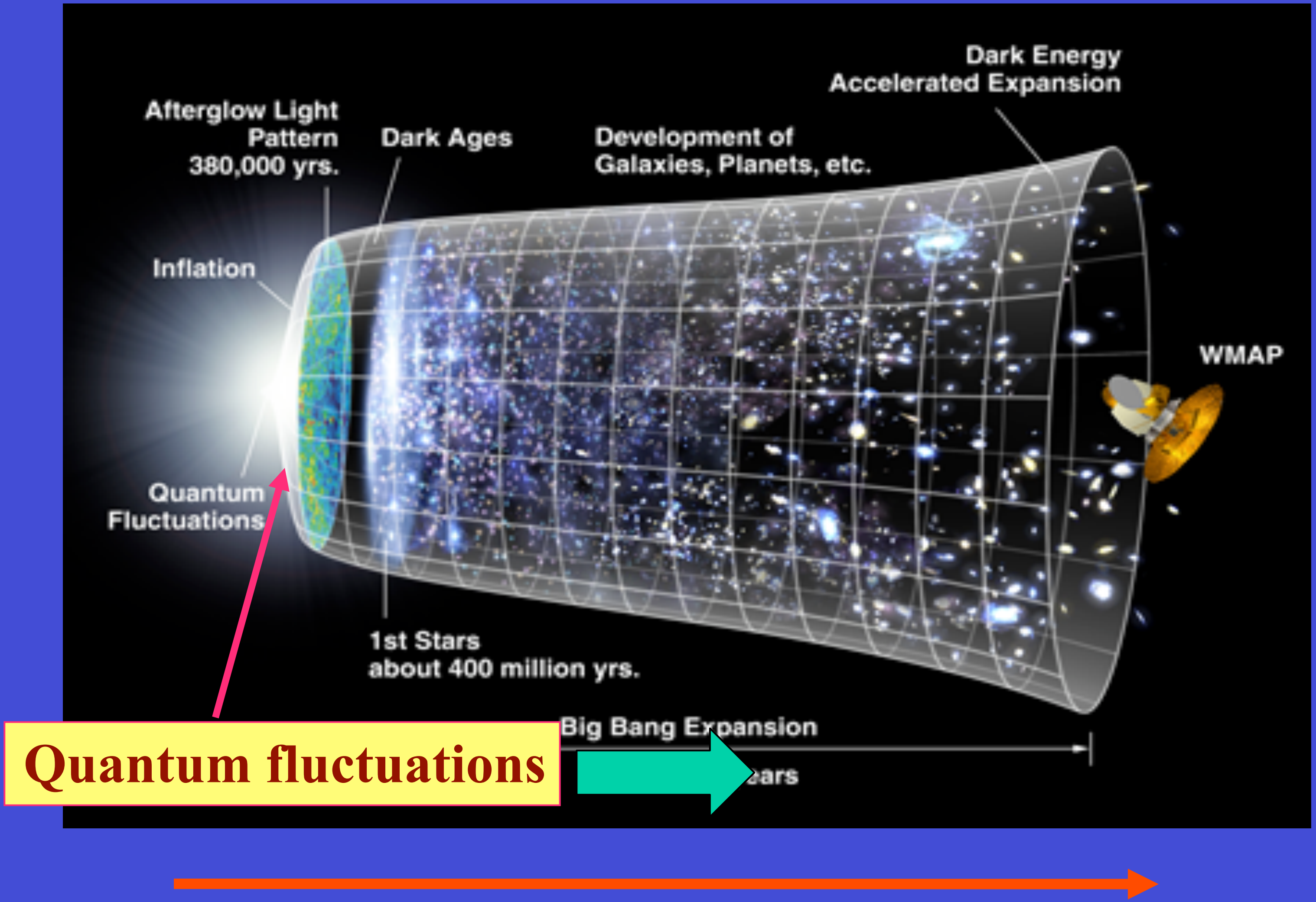

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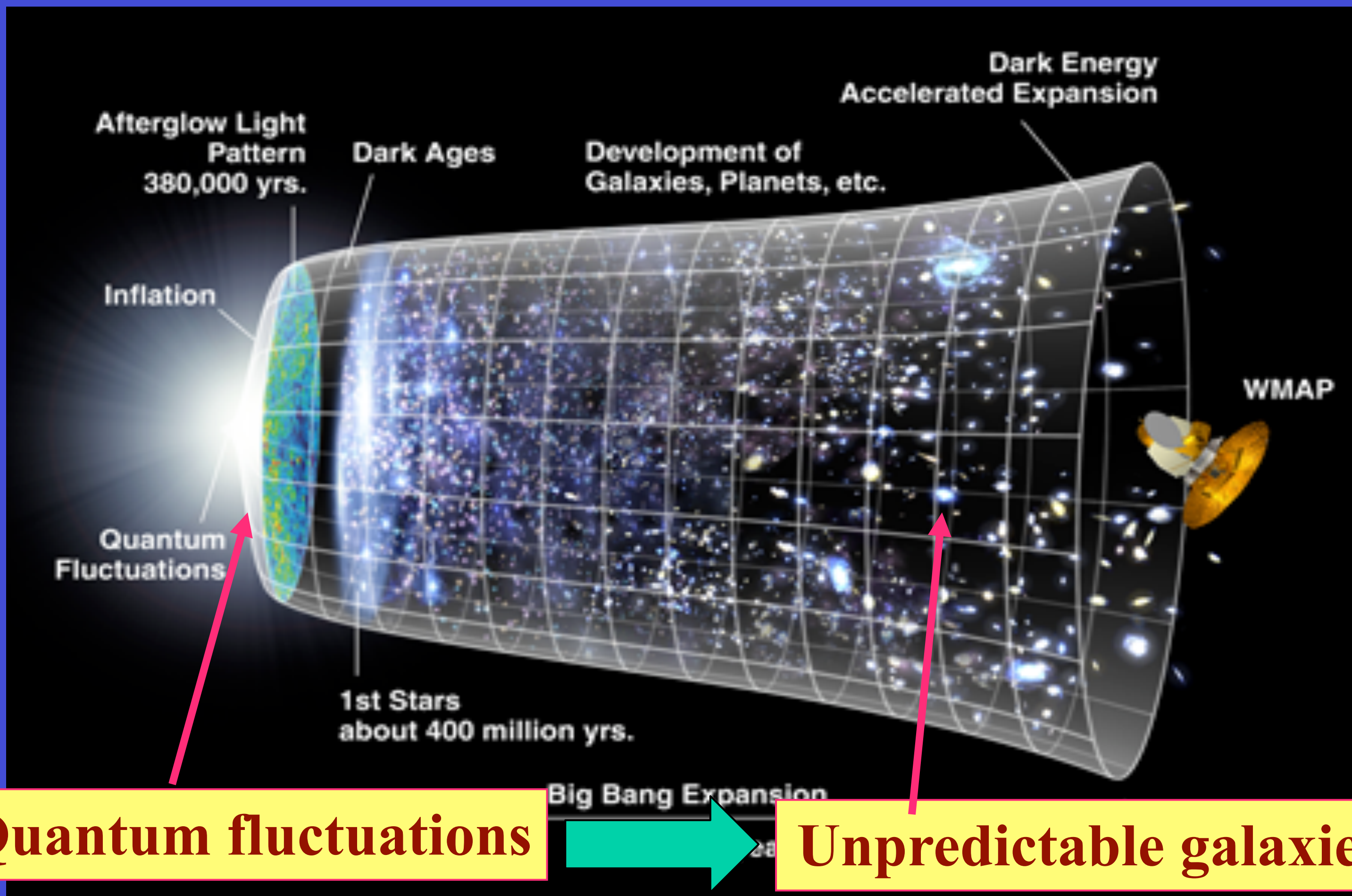

Quantum fluctuations

Unpredictable galaxies

time

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- I point out how it relates to the arrow of time issue and solves the chronology protection issue
- Finally I consider how the EBU picture may be altered when one takes quantum issues into account

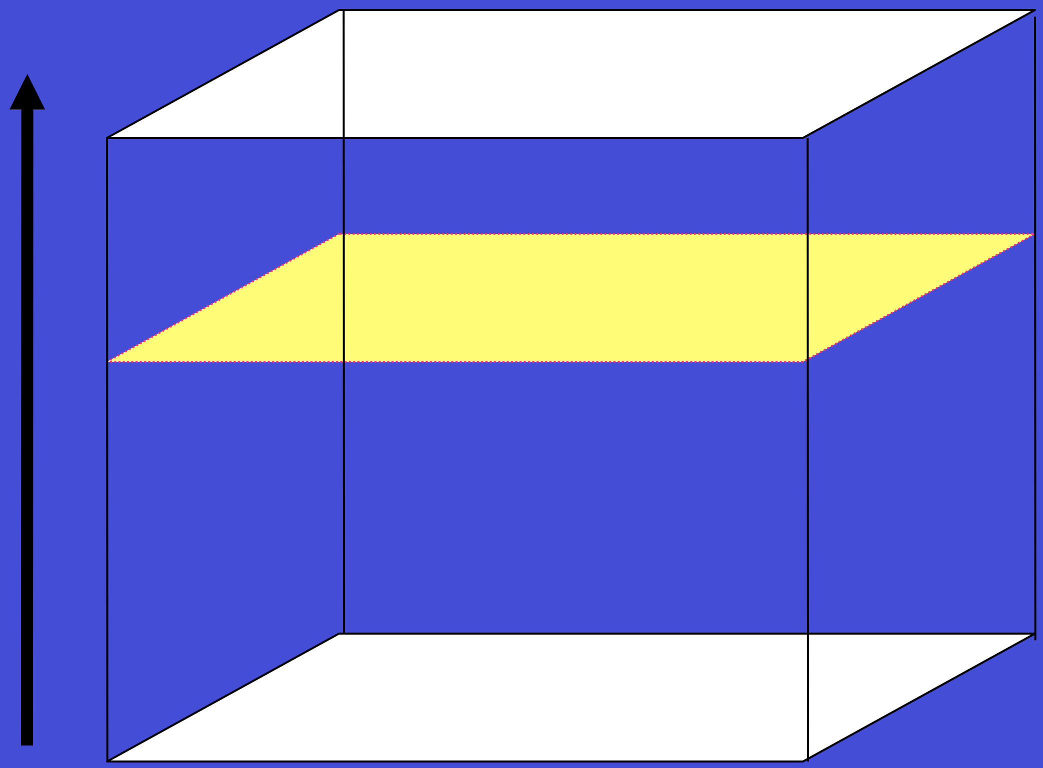
3: Surfaces of change

The primary problem is the claimed unique status of "the present" in the EBU - the surface where the indeterminate future is changed to the definite past at any instant.

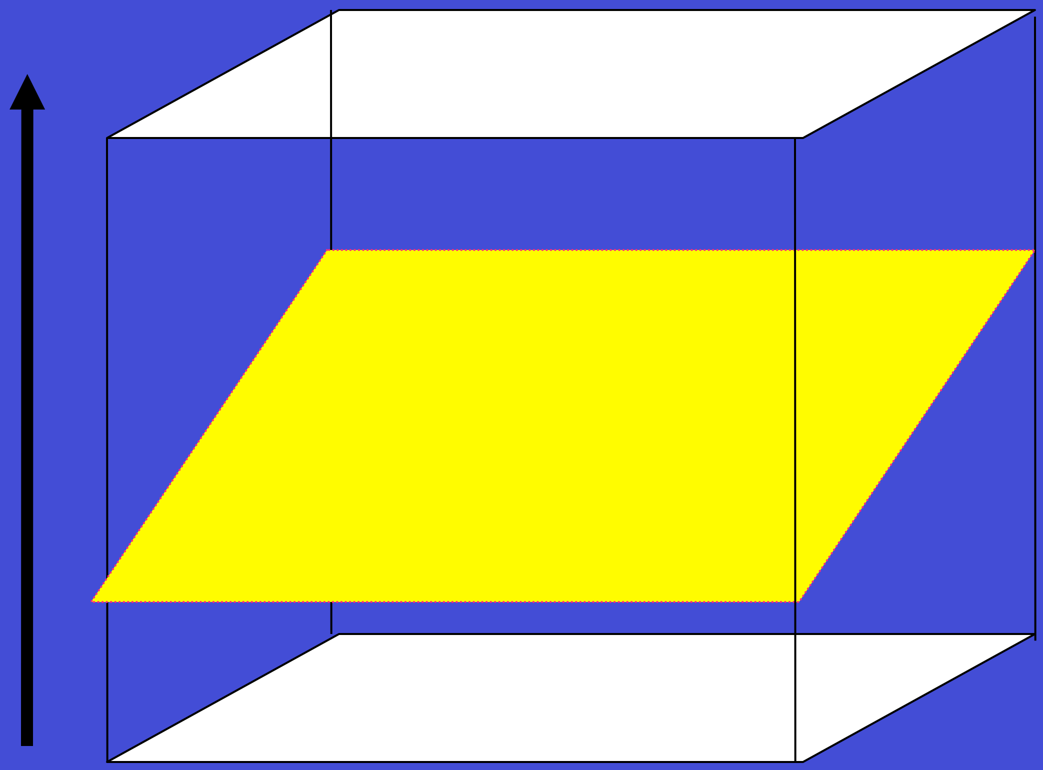
It is a fundamental feature of Special Relativity that simultaneity is not uniquely defined, it depends on the state of motion of the observer. What is past and future elsewhere depends on one's motion,

For different observers at a event P, different motions will designate different events Q on a distant world line L as simultaneous with P.

Hence the block universe model is natural: it is the only way a spacetime model can incorporate this lack of well defined



The block universe: time sections move on ….
But they are they are arbitrary – depending on the observer's motion



Einstein: SR they are arbitrary – depending on the observer’s motion

Resolution:

Physically, things happen along timelike worldlines rather than on spacelike surfaces

Time of determination: Start at the beginning of time, measure proper time along fundamental world lines: thereby determine the transition surfaces ("the present") as time evolves along preferred fundamental world lines.

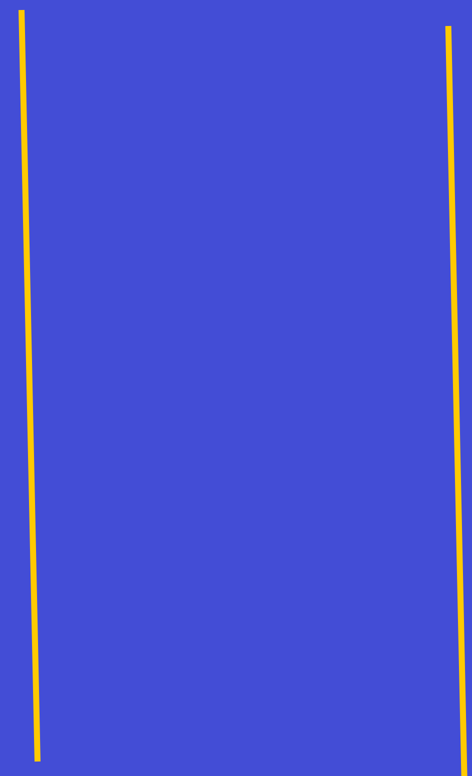
This is not globally coordinated by some non-local mechanism: rather it happens locally everywhere

So change happens on preferred surfaces of change that are secondary to timelike world lines.

These surfaces need not be simultaneous in the usual sense

Simultaneity as usually defined, determined by radar, is irrelevant to physical causation!

Physically, things happen along timelike worldlines rather than on spacelike surfaces



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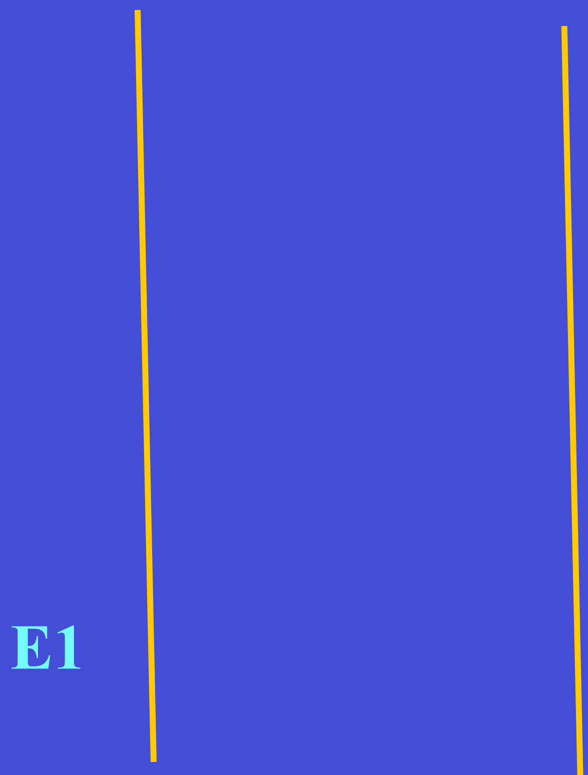

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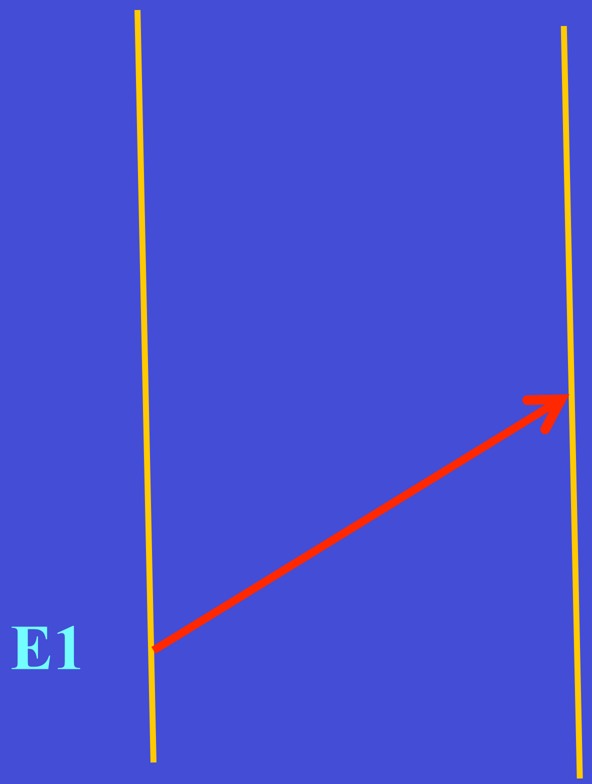

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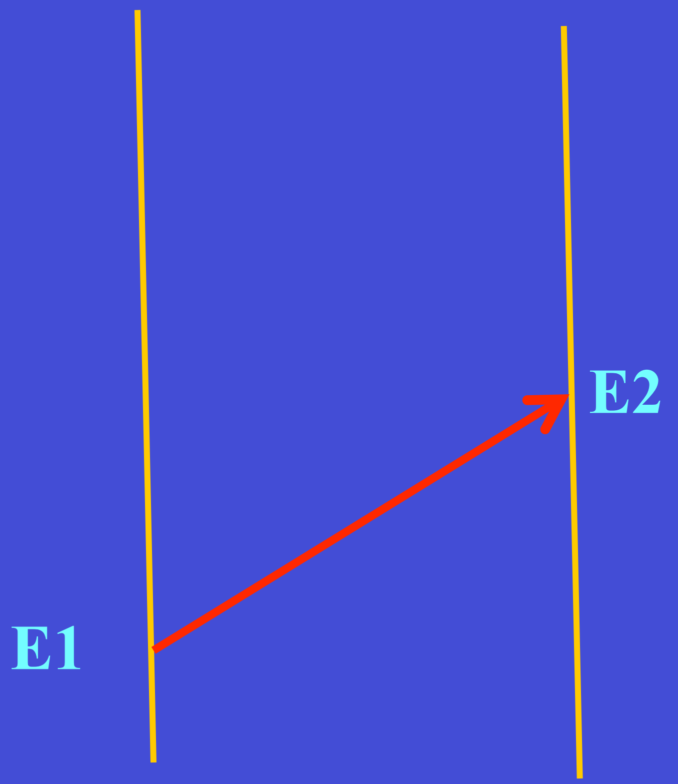

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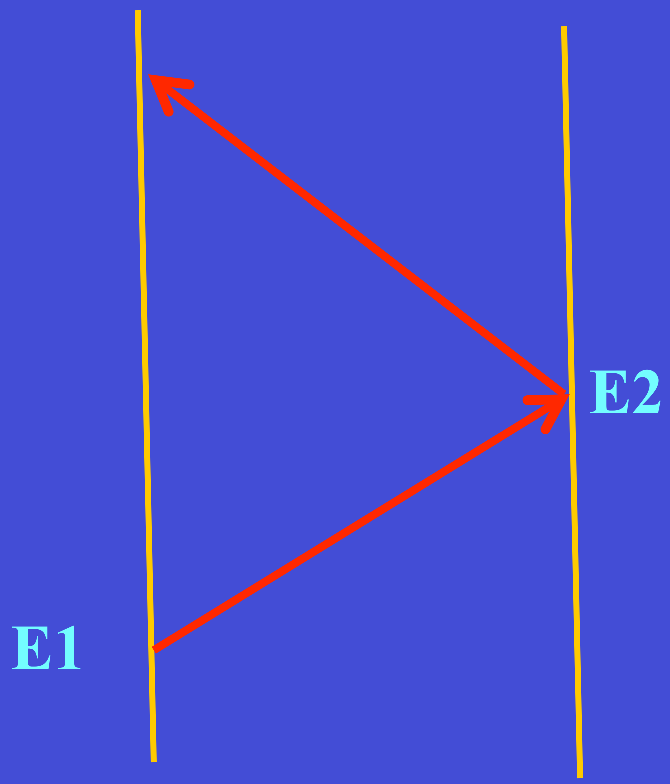

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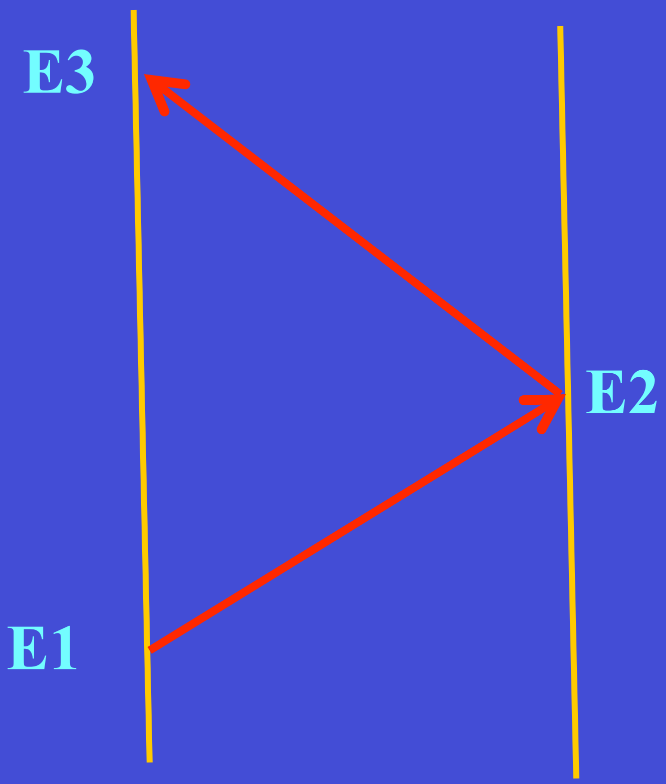

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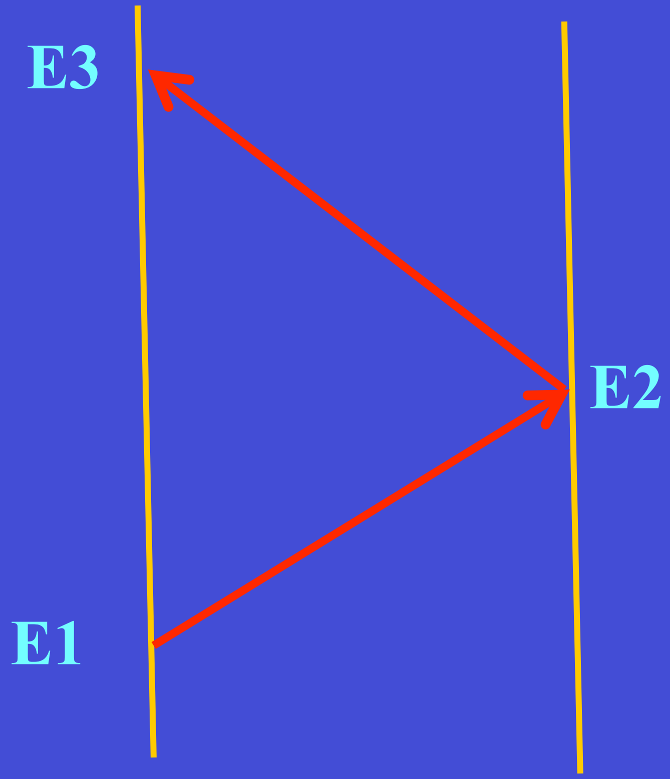

What matters physically is E1 (emission), E2 (interaction), and E3 (reception);

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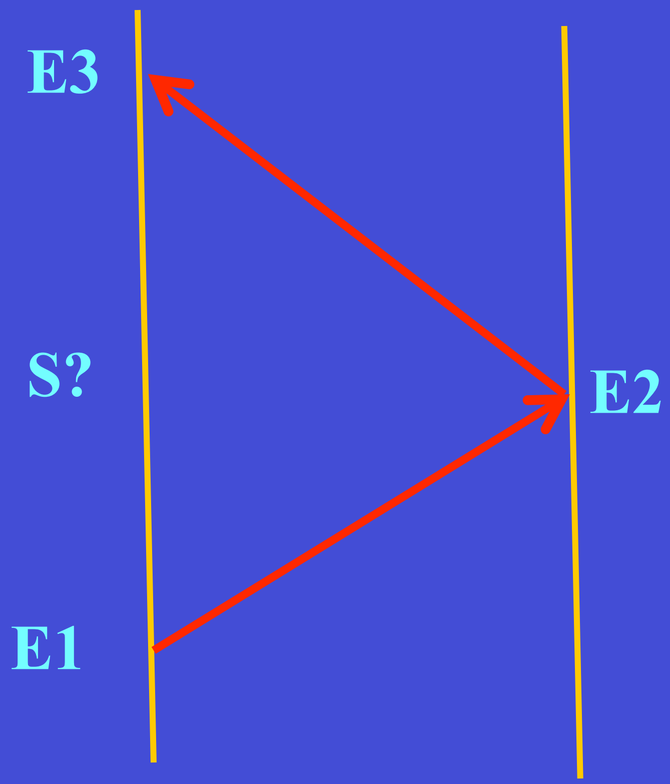

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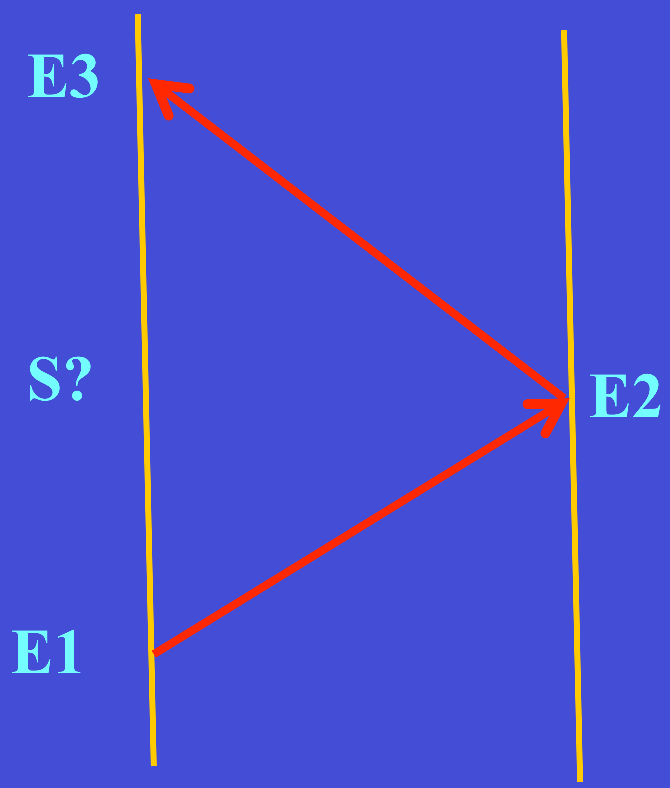


What matters physically is E1 (emission), E2 (interaction), and E3 (reception);
Which event S is simultaneous with E2 has no physical significance: it only has psychological value.

What really matters is proper time measured along timelines $x^i(v)$, determined by the metric tensor $g_{ij}(x^k)$ by the basic formula

$$\tau = \int (-ds^2)^{1/2} = \int (-g_{ij}(dx^i/dv)(dx^j/dv))^{1/2}\, dv \quad (*)$$

Natural surfaces of constant time are given by this integral since the start of the universe. Thus we can propose that

The present: The ever-changing surface $S(\tau)$ separating the future and past - the 'present' - at the time τ is the surface $\{\tau = \text{constant}\}$ given by integral (*) along a family of fundamental world lines starting at the beginning of space time.

(if the universe existed forever we have to start at some arbitrarily chosen 'present' time $\{\tau_0 = \text{const}\}$, which we assume exists, and integrate from there).

But is this well defined, given that there are no preferred world-lines in the flat spacetime of special relativity?

The second fundamental feature is that it is general relativity that describes the structure of space time, not special relativity. Gravity governs space-time curvature,

Because there is no perfect vacuum anywhere in the real universe (inter alia because cosmic blackbody background radiation permeates the Solar System and all of interstellar and intergalactic space), space time is nowhere flat or even of constant curvature;

Therefore there are preferred timelike lines everywhere in any realistic spacetime model.

A unique geometrically determined choice for fundamental worldlines is the set of timelike eigenlines $x^a(v)$ of the Ricci tensor on a suitable averaging scale (they will exist and be unique for all realistic matter, because of the energy conditions such matter obeys).

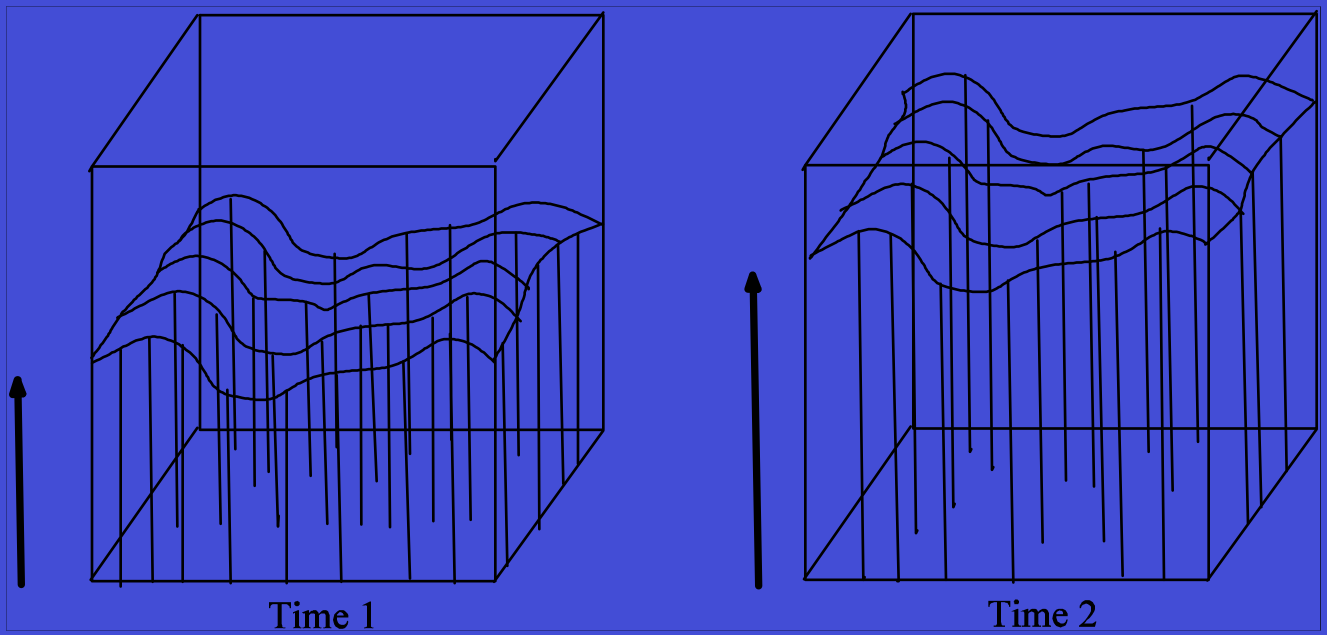
Their 4 velocities $u^a(v) = dx^a(v)/dv$ satisfy

$$T_{ab}\, u^b = \lambda_1\, u^a \Leftrightarrow R_{ab}\, u^b = \lambda_2\, u^a \quad (**)$$

where the equivalence follows from the Einstein field equations.

Thus we can further propose that

Fundamental world lines: the proper time integral (*) used to define the present is taken along the world lines with 4-velocity $u^a(v)$ satisfying (**).



The evolving block universe:
the present is where the future changes to the past
Takes place along preferred timelike worldlines:
The average motion of matter in the universe

- What about simultaneity?

In general these surfaces are not related to simultaneity as determined by radar; indeed this is even so in the FLRW spacetimes (where the surfaces of homogeneity are generically not simultaneous, according to the radar definition).

The flow lines are not necessarily orthogonal to the surfaces of constant time;

More than that: the surfaces determined in this way are not even necessarily spacelike, in an inhomogeneous spacetime.

These surfaces are secondary to the timelike world lines that define them. No physical phenomena are directly determined by simultaneity in the usual sense.

- # 4 An array of further arguments

- Further arguments for the claim "time is an illusion" have been made by philosophers and physicists are summarized in the January, 2012 special issue of *Scientific American;* also Tim Maudlin, *The Metaphysics within Physics*.

- A: Rates of change?
- B: Time parameter invariance?
- C: General covariance and local Lorentz invariance?
- D:The Wheeler de Witt Equation and lack of cosmic time
- [E: Categorization problem]
- [F: Not necessary to describe events]

I consider them in turn. For detailed response, see arXiv:1208.2611

Scientific American,
Special issue,
January 25, 2012:

"A Matter of Time"

This special issue of Scientific American summarizes what science has discovered about how time permeates and guides both our physical world and our inner selves

A: Rates of change

A key question is, "How fast does time pass?" Davies, Carr, and others suggest there is no sensible answer to this question.

I claim that the answer is given by the metric tensor $g_{ij}(x^k)$, which determines proper time τ along any world line:

$$\tau = \int (-ds^2)^{1/2} = \int (-g_{ij}(dx^i/dv)(dx^j/dv))^{1/2}\, dv \quad (*)$$

This is the time measured along that world line by any perfect clock; time changes at the rate of 1 second per second [Maudlin]. This is what fixes physical time, including gravitational time dilation [gravitational potential affects relative rates].

Real world clocks - oscillators that obey the Simple Harmonic

The metric evolution: So if the metric tensor determines proper time, what determines the metric tensor?

The Einstein field equations, of course! Following ADM, the first fundamental form (the metric) is represented as

$$ds^2 = (-N^2 + N_i N^i)dt^2 + N_i dx^j dt + g_{ij} dx^i dx^j$$

where i, j = 1, 2, 3. The lapse function $N(x)$ and shift vector $N^i(x)$ represent coordinate choices, and can be chosen arbitrarily; $g_{ij}(x)$ is the metric of the 3-spaces {t = const}.

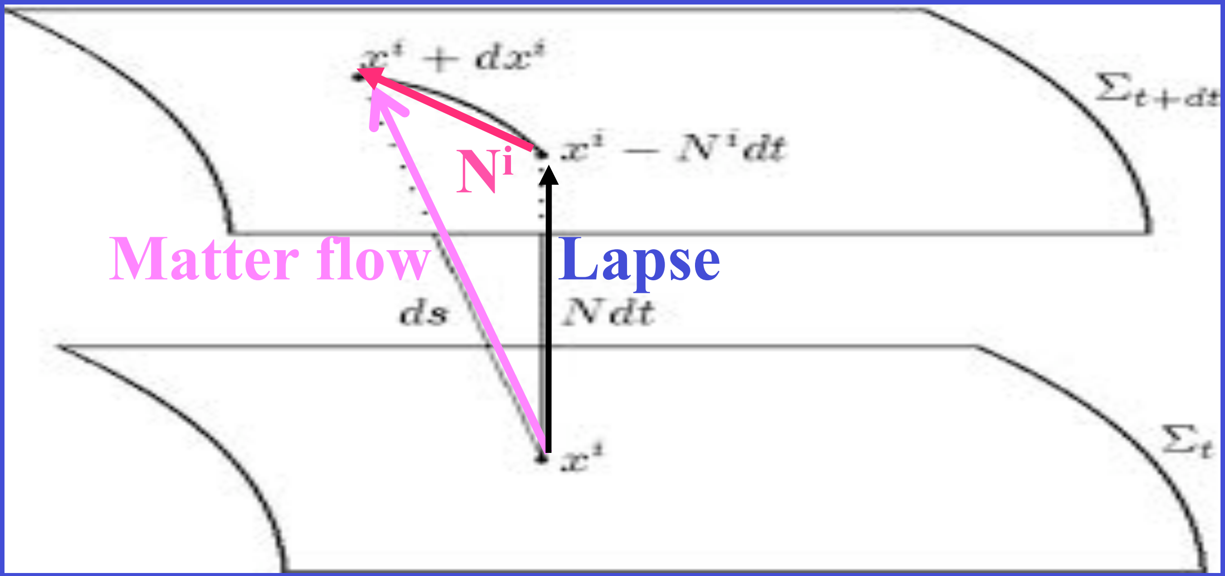
The second fundamental form is

$$\pi_{ij} = n_{i;j}$$

where the normal to the surfaces {t = const} is $n_i = \delta^0{}_i$;

the matter flow lines have tangent vector $u^i = \delta^i{}_0$

ADM coordinates:



Shift Vector $N^i(x^j)$ gives the change of the matter lines relative to the normal to the chosen time surfaces

Lapse function $N(x^i)$ gives the relation between coordinate time

The field equations for $g_{ij}(x^k)$ are as follows (where 3-dimensional quantities have the prefix (3)): four constraint equations

$$^{(3)}R + \pi^2 - \pi_{ij}\pi^{ij} = 16\pi\, \rho_H, \qquad \text{(C1)}$$

$$R^\mu := -2\, \pi^{\mu j}{}_{|j} = 16\pi\, T^\mu{}_0 \qquad \text{(C2)}$$

where "|j" represents the covariant derivative in the 3-surfaces, and twelve evolution equations

$$\partial_t\, g_{ij} = 2Ng^{-1/2}(\pi_{ij} - 1/2 g_{ij}\pi) + N_{i|j} + N_{j|i}, \qquad \text{(T1)}$$

$$\partial_t \pi_{ij} = -Ng^{-1/2}(^{(3)}R_{ij} - 1/2 g_{ij}\, ^{(3)}R) + 1/2 Ng^{-1/2} g_{ij}(\pi_{mn}\pi^{mn} - 1/2\pi^2)$$
$$- 2Ng^{-1/2}(\pi_{im}\pi^m{}_j - 1/2\pi\pi_{ij}) + \sqrt{g}(N_{|ij} - g_{ij}N^{|m}{}_{|m}) + (\pi_{ij}N^m)_{|m}$$
$$- N_{i|m}\pi^m{}_j - N_{j|m}\pi^m{}_i + 16\pi\, ^{(3)}T_{ij}. \qquad \text{(T2)}$$

This can be worked out using any time surfaces (that is the merit of the ADM formalism); in particular one can choose a unique gauge by specialising the time surfaces and flow lines to those defined above

1. We choose the flow lines to be Ricci Eigenlines:

$$T^{\mu}{}_{0} = 0 \Rightarrow R^{\mu} = -2\,\pi^{\mu j}{}_{|j} = 0 \qquad \text{(G1)}$$

which algebraically determines the shift vector $N^i(x^j)$, thereby solving the constraint equations (C1);

2. We determine the lapse function $N(x^i)$ by the condition that the time parameter t measures proper time τ along the fundamental flow lines:

These conditions uniquely determine the lapse and shift. Then,

• given the equations of state and dynamical equations for the matter, equations (T1), (T2) determine the time evolution of the metric in terms of proper time along the fundamental flow lines;

• the constraints (C1), (C2) are conserved because of energy-momentum conservation.

The development of spacetime with time takes place just as is the case for other physical fields, with the relevant time parameter being proper time τ along the fundamental flow lines.

There is no problem with either the existence or the rate of flow of time. Time flows at rate of one second per second, as determined by the metric tensor locally at each event.

The spacetime develops accordingly via (T1), (T2).

Predictability: Do these equations mean the spacetime development is uniquely determined to the future and the past from initial data? That all depends on the equations of state of the matter content: one can have an explicitly time dependent equation of state:

$$p = 1/3 g^{ij}\, {}^{(3)}T_{ij}, \quad \Pi_{ij} = {}^{(3)}T_{ij} - p\, g_{ij} = F(\tau)\, \Pi_{ij}(0)$$

where $F(\tau)$ represents local dynamics involving random processes generated via quantum uncertainty.

So equations (T1), (T2) determine the time evolution of the spacetime, but do not guarantee predictability.

If quantum unpredictability gets amplified to macro scales, the spacetime evolution is intrinsically undetermined till it

B: Time parameter invariance

What about the time parameter invariance of General Relativity, as made manifest in the ADM formalism?

- The gravitational side of the ADM equations may be time-parameter invariant, but the matter side is not;
- In particular when $L = T - V = \frac{1}{2} m u^2 - V(r)$, rescaling time changes the kinetic energy $T(u)$ while leaving the potential energy $V(r)$ unchanged: will give different orbits.
- Change $t \rightarrow t' = f(t)$ leaves L invariant iff $u'^2 = u^2 \rightarrow f(t) = t + c$.

Hence any solutions with matter present (i.e. all realistic solutions) will not be time parameter invariant (changing $t \rightarrow f(t)$, there are

Local physics does indeed have a preferred time parameter: e.g. for a Simple Harmonic Oscillator using standard time t, $q(\tau) = A\cos(\omega t)$; these cycles measure physical time t like a metronome (which is why SHO's are used as clocks).

It applies equally to all local physics: each involves time t:

- Newton's laws of motion
- Maxwell's equations
- Schroedinger equation
- Dirac equation
- Diffusion equation

It is perverse to use any other time parameter for local physics

This parameter t is just proper time τ measured along relevant world lines, which provides a preferred time parameter in general relativity theory (defined up to affine transformations):

C: General covariance and Lorentz invariance?

What about general covariance and local Lorentz invariance?

These are symmetries of the general theory, not of its solutions. Interesting solutions break the symmetries of the theory: this is not surprising, as we know that broken symmetries are the key to interesting physics.

- Specific solutions of the theory have less symmetry than the theory itself; this symmetry breaking is a key feature of all realistic solutions of the equations of physics, and in particular cosmological solutions

D: The Wheeler de Witt equation and the mind

Julian Barbour: *The End of Time*

There is no time: the entire universe and everything in it is static and unchanging.

Why? The Wheeler-de Witt equation

$$\partial\Psi / \partial t = H \Psi;$$

General relativity

$$H \Psi = 0 \rightarrow \partial\Psi / \partial t = 0$$

Time is an illusion!

Barbour claims there exist records of events that our brains read sequentially, and so create a false illusion of the passage of time. Thus brain processes are responsible for illusion of change.

The prevalent view of present day neuroscience is that mental states $\boldsymbol{\Phi}$ are functions of brain states $\boldsymbol{B}$ which are based in the underlying neuronal states $\boldsymbol{b_i}$, determined by genetics and interactions in the brain, taking place in the overall environment $\boldsymbol{E}$.

$$\boldsymbol{\Phi} = \boldsymbol{\Phi}(\boldsymbol{B}) = \boldsymbol{\Phi}(\boldsymbol{b_i}, \boldsymbol{E}).$$

If time does not flow in microphysics, in an unchanging environment

$$\{\mathrm{d}\boldsymbol{b_i}/\mathrm{dt} = 0,\ \mathrm{d}\boldsymbol{E}/\mathrm{dt} = 0\} \Rightarrow \mathrm{d}\boldsymbol{\Phi}/\mathrm{dt} = 0:$$

Mental states cannot evolve! [Maudlin]

We do know is that time does flow in our experience. Hence the assumption that time does not flow in the underlying physics cannot be true: the data proves it to be wrong.

The implication runs the other way: Taking everyday life seriously, and comparing the claim ‘time is an illusion’ with the evidence from mental life, the contradiction between them is proof the WdeW equation does not apply to the universe as a whole at the present time, as proposed by Barbour.

The great merit of Barbour’s book is that it takes the Wheeler de Witt equation seriously, and pursues the implications to their logical conclusion; the evidence from daily life then shows it to be wrong

This argument applies equally to all claims that time is an illusion

- The experience of the flow of time is based in brain physics

Arnowitt, Deser and Misner write of the Hamiltonian formalism as follows:

"Since the relation between q_{M+1} and $\boldsymbol{\tau}$ is undetermined, we are free to specify it explicitly, i.e., impose a "coordinate condition". If, in particular, this relation is chosen to be $q_{M+1} = \boldsymbol{\tau}$ (a condition which also determines N), the action (2.4) then reduces [to] (2.5) with the notational change $q_{M+1} \rightarrow \boldsymbol{\tau}$; the non-vanishing Hamiltonian [only] arises as a result of this process."

- This is the choice made above;
- the corresponding Hamiltonian will be non-zero as indicated in this quote,
- so WdeW will not hold: $\partial\Psi / \partial t \neq 0$.

[as is also the case for unimodular gravity].

More fundamentally:

• Quantum mechanics applied to the real universe does NOT only involve unitary transformations.

Measurements happen; collapse of the wave function takes place; classical outcomes occur

-- NOT just decoherence: non unitary transformations take place.

Ignoring this is ignoring a fundamental feature of physics.

So claiming there is only unitary WdeW evolution is simply not correct: it is taking into account only part of the dynamics occurring [Penrose]. Wave function collapse allows time to pass.

For detailed argument: see arxiv:1108.5261

5: The arrow of time and chronology protection

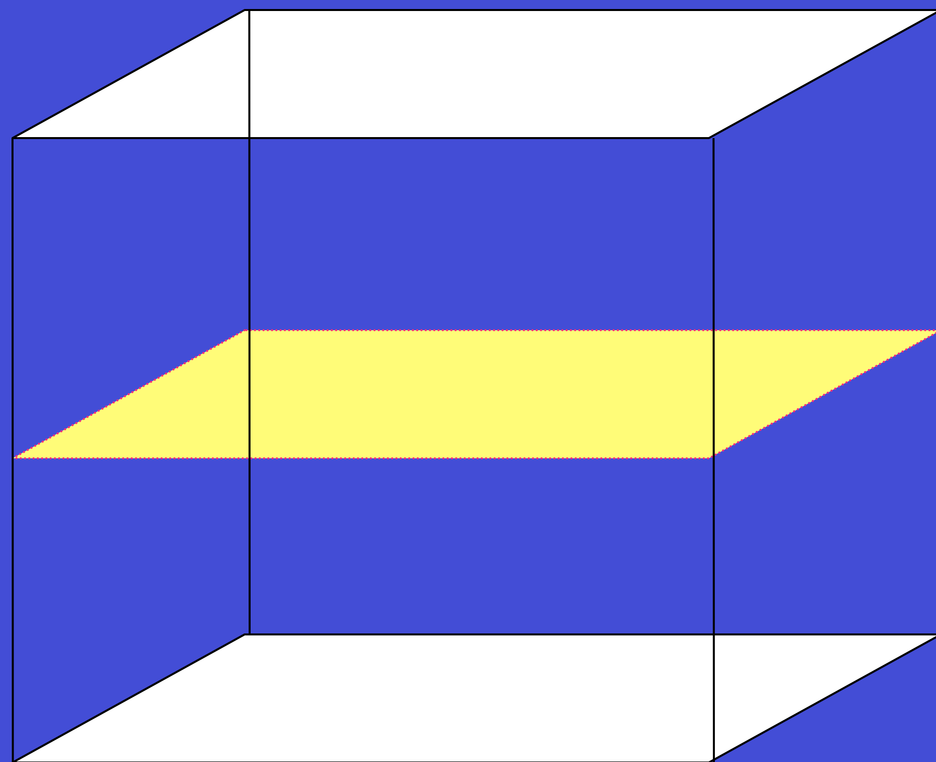
How can a difference emerge between the future and the past, on the basis of time symmetric micro physics?

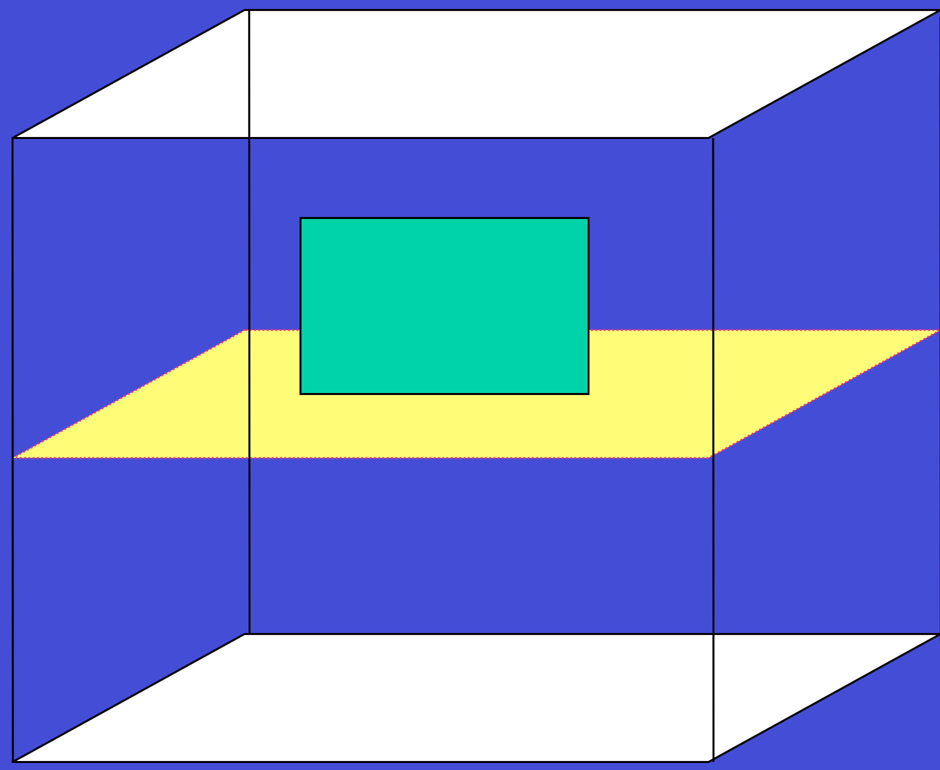
How does time know which way to flow?

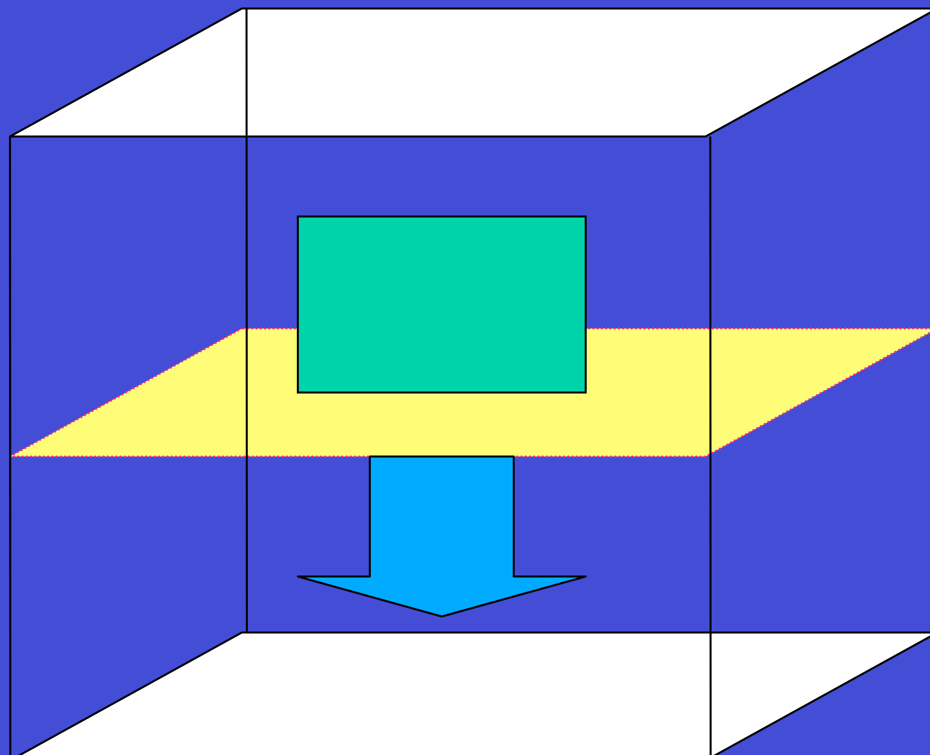
Why does it flow the same way everywhere?

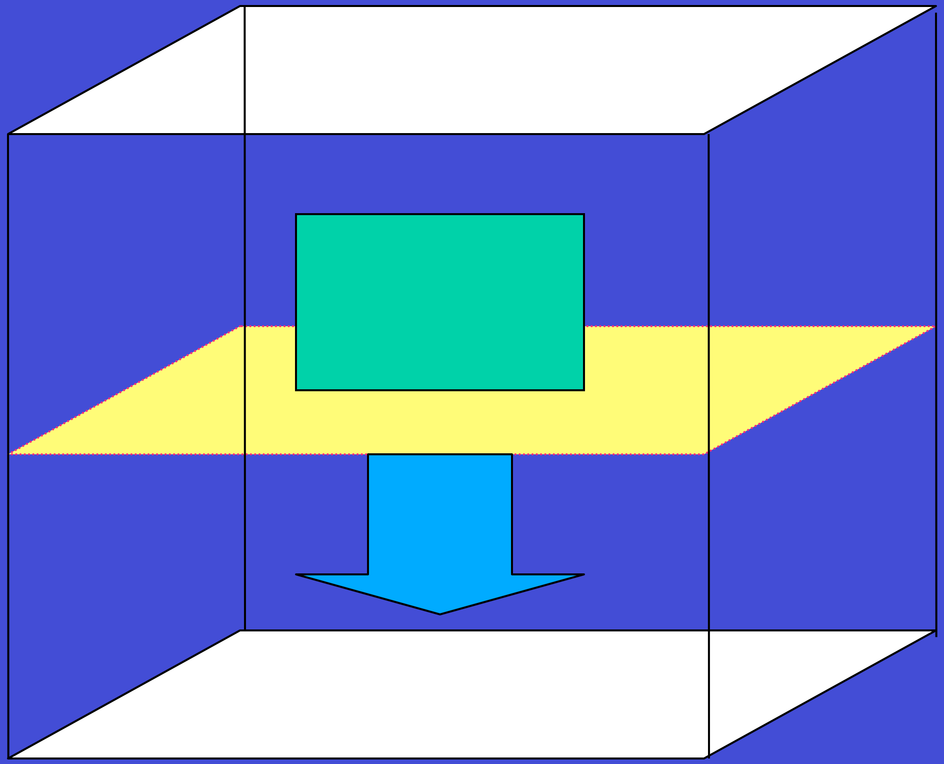
There is no basis for such a determination in microphysics alone: the H-theorem (Boltzmann or QFT) applies equally in both time directions.

It cannot provide a foundation for the second law of

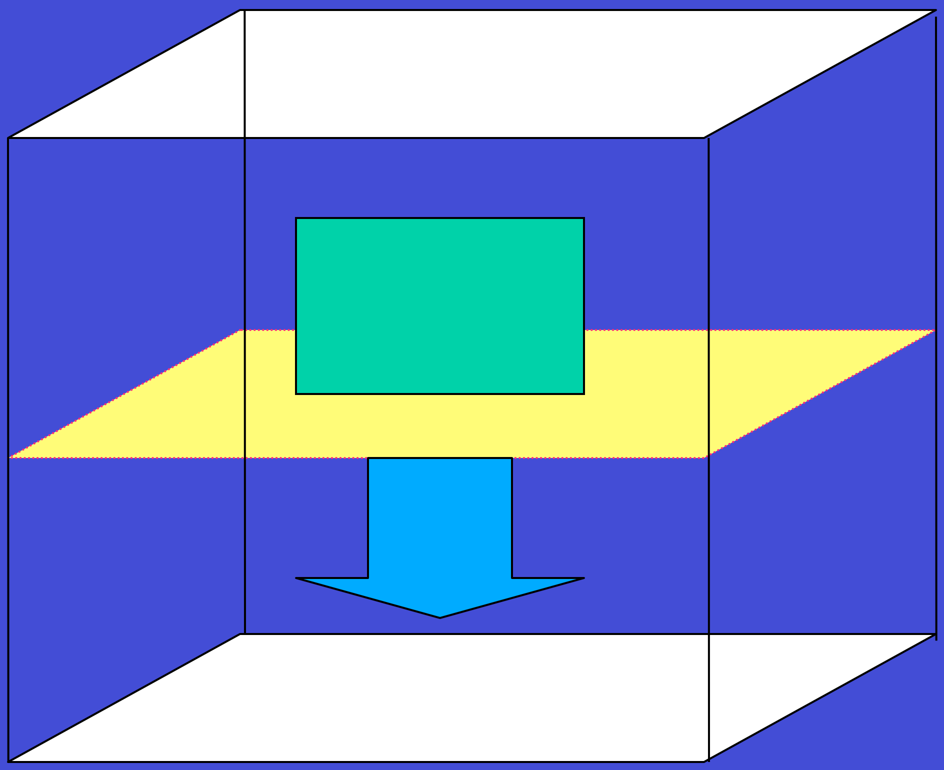








Micro physics(except weak interactions) is time symmetric. The future and past are equal. How does macro physics know the direction of time? In the block universe: they are equal.



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Not so according to the second law of thermodynamics!

The direction of time:

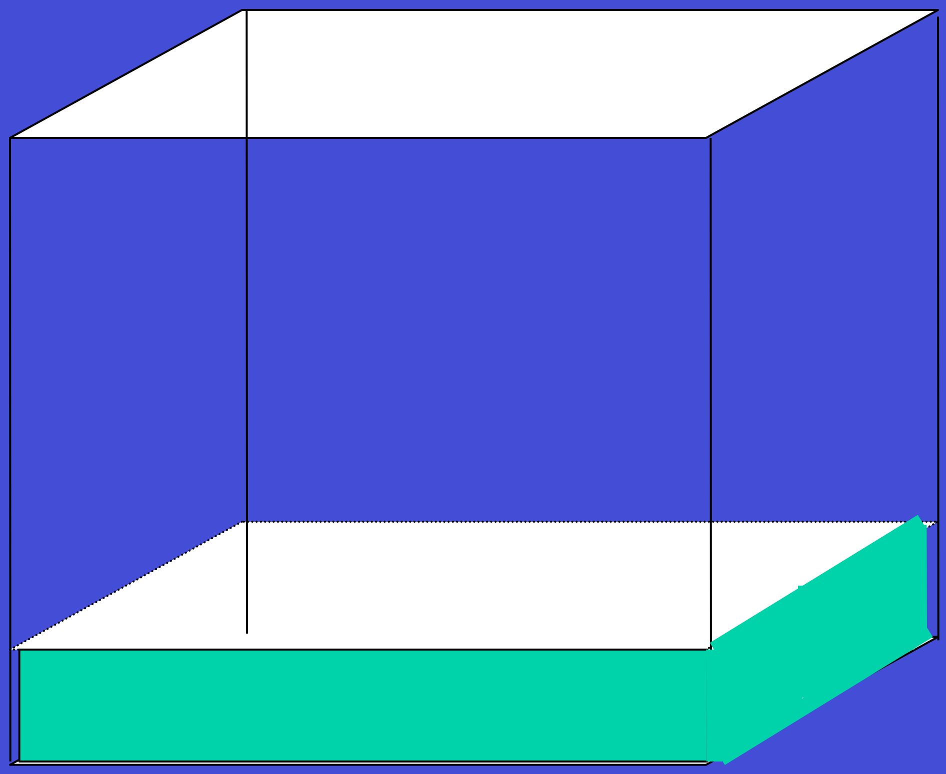
In an EBU, the arrow of time arises fundamentally because the future does not yet exist: a global asymmetry in the physics context.

The Feynman propagator can only be integrated over the past, as the future spacetime domain is yet to be determined.

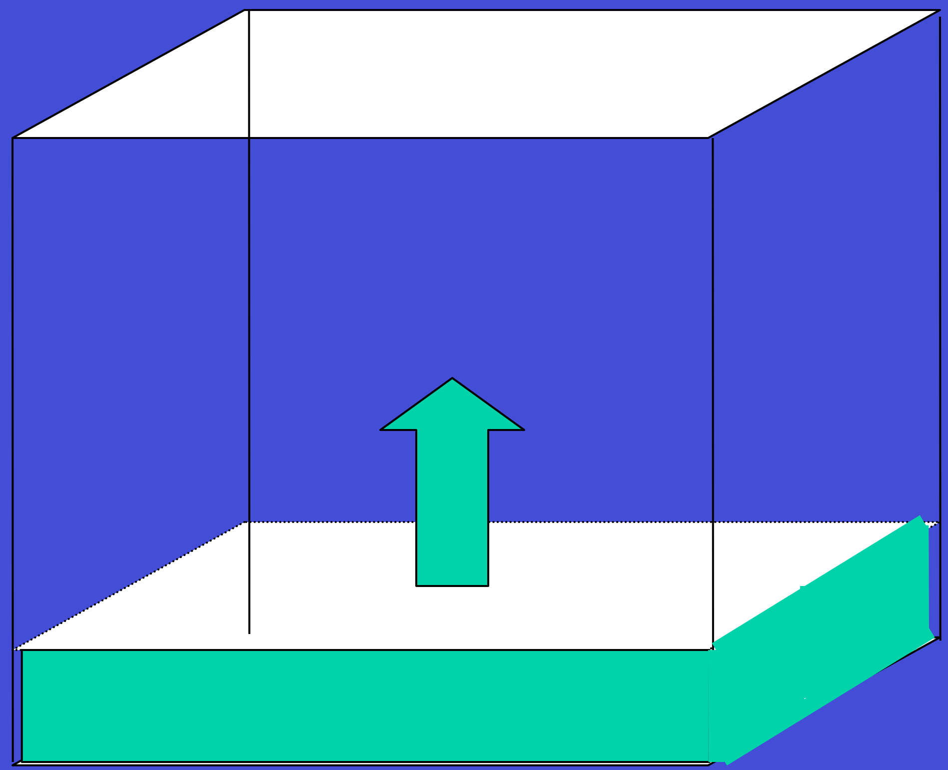
One can be influenced at the present time from many causes lying in our past, as they have already taken place and their influence can thereafter be felt.

One cannot be physically influenced by causes coming from the future, for they have not yet come into being.

This is the rationale for saying the past exists but the future does not: if something can influence you, it exists.



The evolving block universe: the past exists and is developing to the future, which does not yet exist. It is this asymmetry that leads to the arrow of time. Special initial conditions then lead to the 2^{nd} law.



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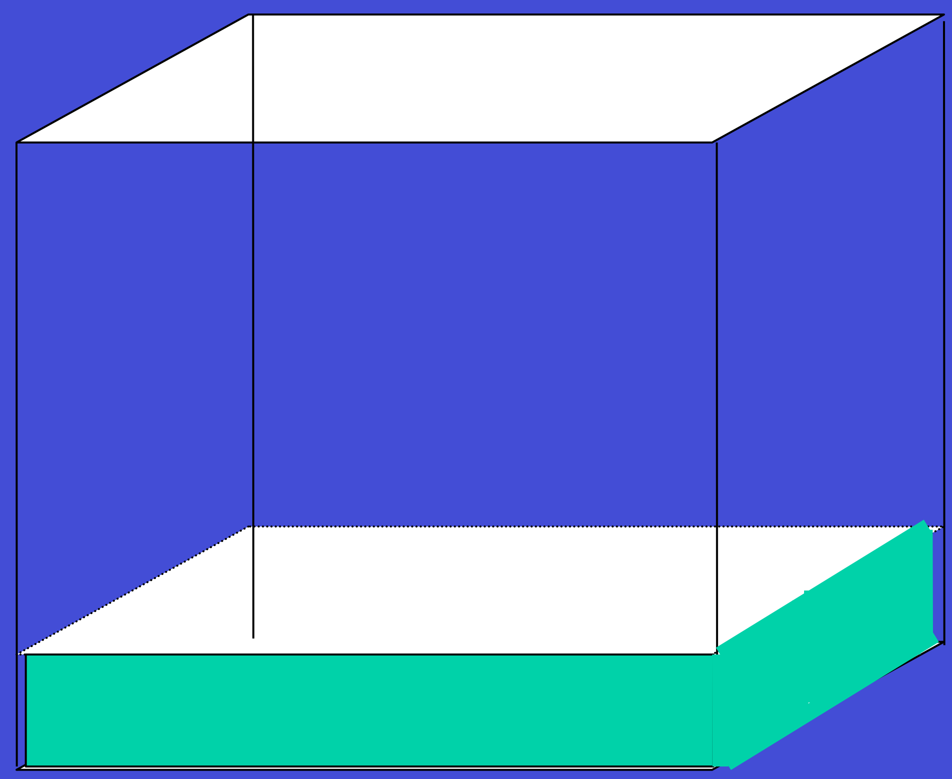
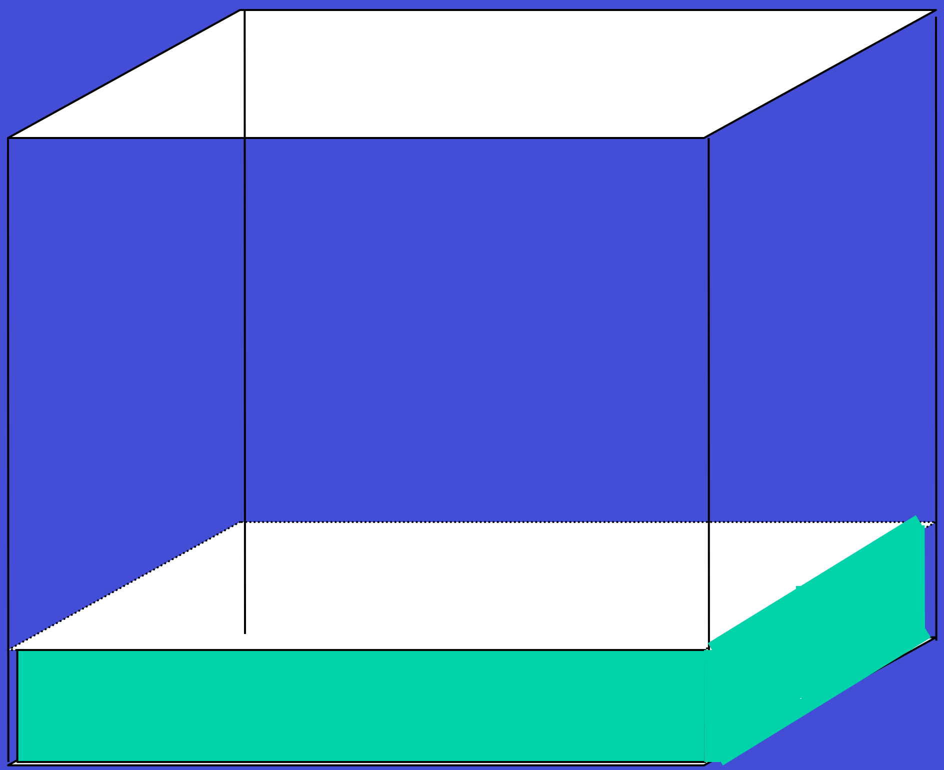
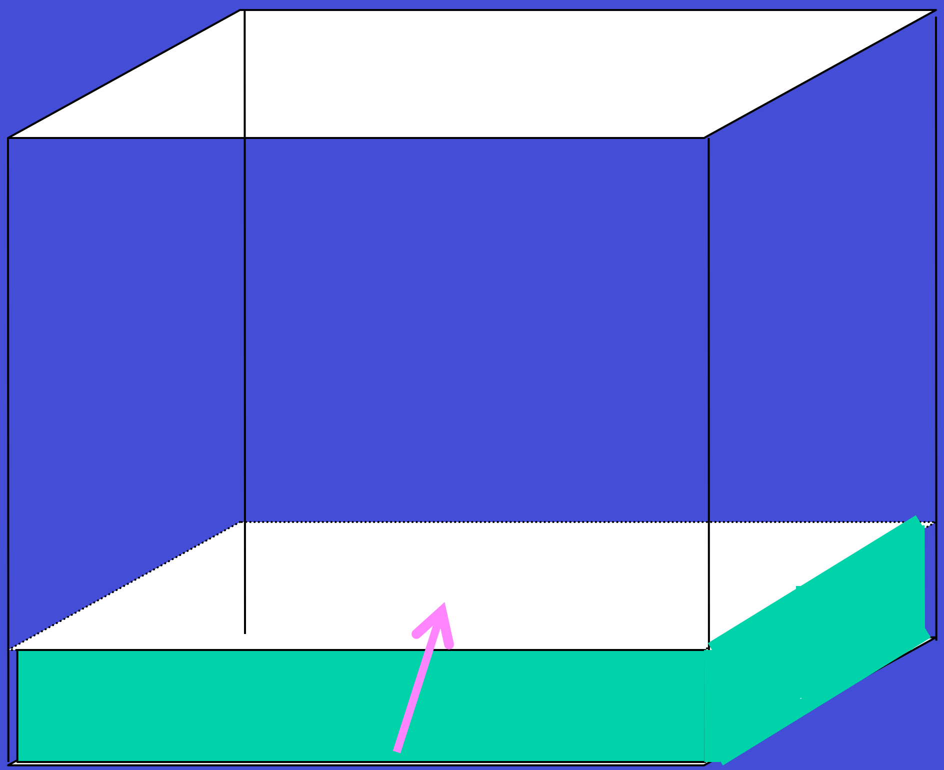




Past affects today:
-Elements
-Particles
-Radiation
Hence it must exist, else effect with no cause



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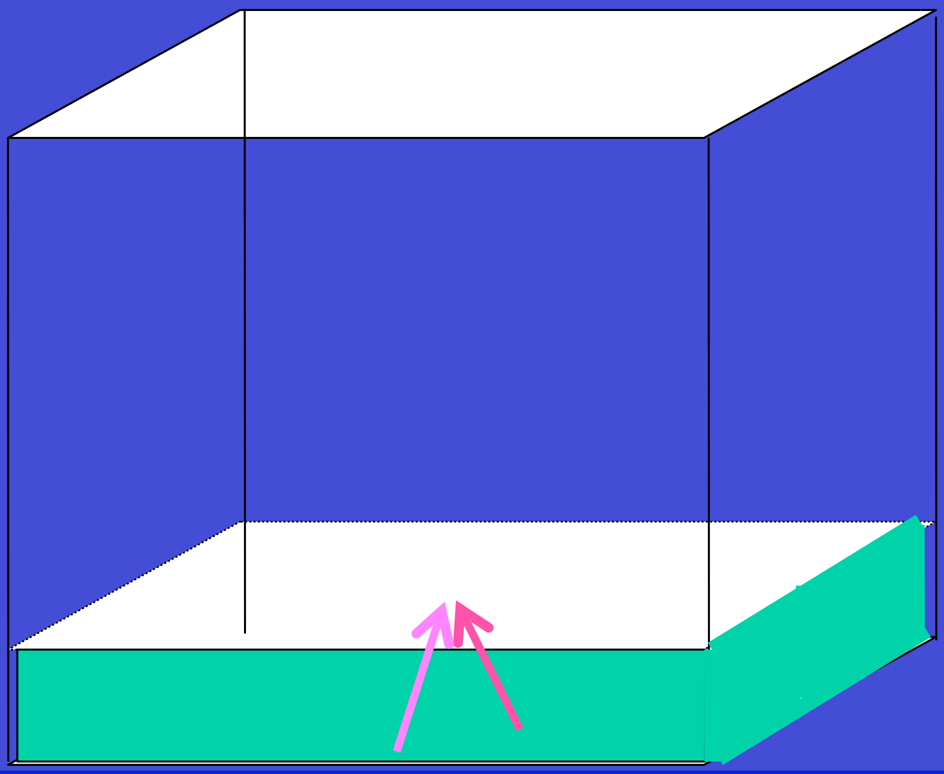

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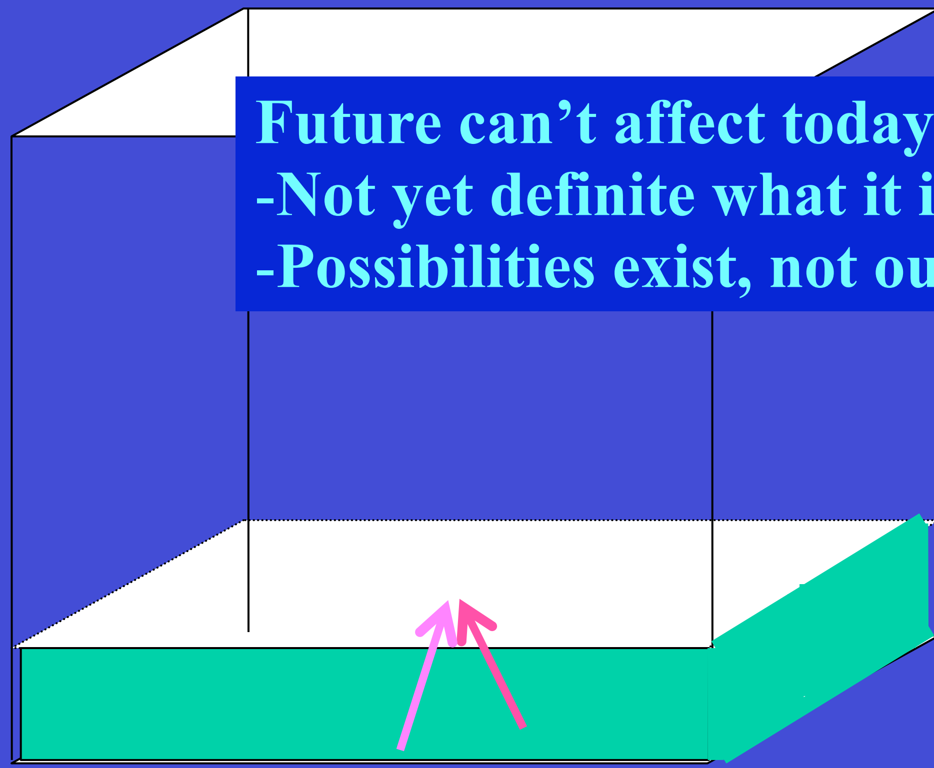

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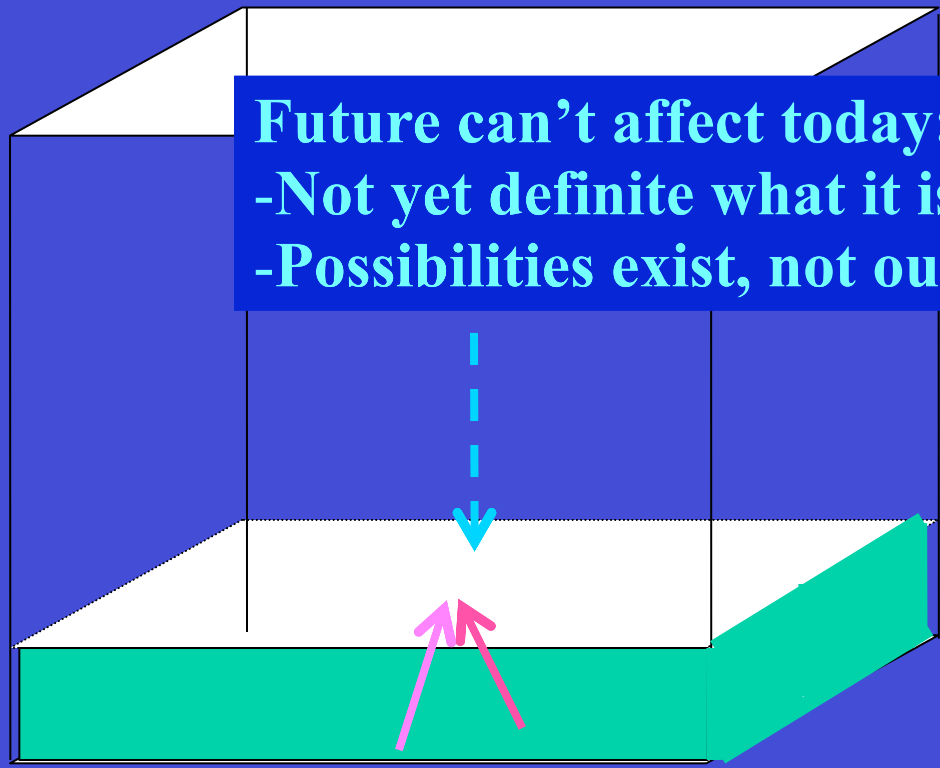

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Note 1: What happens earlier is mediated by what happens later, i.e. its effects pass through the intervening times; still the essential cause lies at earlier times

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Note 3: This story has decoupled the passage of time from the growth of entropy. Given the passage of time, entropy will increase iff there is a special initial state of the universe:

Chronology protection

A longstanding problem is that closed timelike lines can occur in exact solutions of the Einstein Field Equations with reasonable matter content. This opens up the possibility of many paradoxes, such as killing your own grandparents before you were born and so creating causally untenable situations.

It has been hypothesized that a Chronology Protection Condition would prevent this happening. This is an add on to the EFE: a selection condition for acceptable solutions.

Various arguments have been given in its support, but this remains an ad hoc condition added on as an extra requirement on solutions of the Einstein field equations, which do not by themselves give the needed protection (Gödel!).

Chronology protection

The EBU automatically provides such protection, because creating closed timelike lines requires the undetermined part of spacetime intruding on regions that have already been fixed.

This would require the fundamental world lines to intersect;

But if the fundamental world lines intersect, density diverges,

a spacetime singularity occurs, the worldlines are incomplete in the future, and time comes to an end there;

so no “Grandfather Paradox” can occur.

Hence the EBU as outlined above automatically provides chronology protection.

6 Taking quantum theory seriously:

A: Unitary Evolution is not all that happens:

Real QM is non-unitary and irreversible when wave function projection takes place

This is the core of the flow of time

B: Reaching back into the past

There are many hints that the future can influence the past in quantum theory

- Wheeler: Delayed choice experiments
- Aharanov et al: Two-time formalism

Can represent by a Crystalising Block Universe

C: EPR and causality

This resolves the causal puzzle of apparently instantaneous action in the EPR experiment

6 Taking quantum theory seriously:

Unitary Evolution is not all that happens:

Real QM is non-unitary and irreversible when wave function projection takes place

This is the core of the flow of time:

The indefinite future becomes the definite past as wave function collapse takes place

This happens all the time everywhere

It does not need to relate to an experiment.

A: Quantum physics and Measurement

Schroedinger evolution is unitary and time reversible:

$$\Psi_2 = U_{21}\, \Psi_1$$

But this Is not all that happens!

Collapse of the wave function is where the indeterminateness of the future gives way to the definite state of the past. Things happen in quantum physics!

The outcome is unpredictable from past data: and this is where real dynamic change takes place.

Quantum physics is not time reversible!

Claims that it is (e.g. referring only to Hamiltonian dynamics) ignore measurements – a crucial feature of the theory

If a measurement of an observable ***A*** takes place at time t = t*,

initially the wave function $\psi(x)$ is a linear combination of eigenfunctions $u_n(x)$ of the operator $\tilde{A}$ that represents ***A***:

for t < t*, the wave function is

$$\psi_1(x) = \Sigma_n \psi_n u_n(x). \quad (1)$$

But immediately after the measurement has taken place, the wave function is an eigenfunction of $\tilde{A}$:

$$\psi_2(x) = a_N u_N(x) \quad (2)$$

for some specific value N. The data for t < t* do not determine the index N; they just determine a probability for the choice N. One can

The initial state (1) does not uniquely determine the final state (2); and this is not due to lack of data, it is due to the foundational nature of quantum interactions.

You can predict the statistics of what is likely to happen but not the unique actual physical outcome, which unfolds in an unpredictable way as time progresses; you can only find out what this outcome is after it has happened.

***Hypothesis: This is where the flow of time takes place: the uncertainty of the future changes to the certainty of the past. This happens all the time everywhere*.**

[G Ellis: arxiv:1108.5261]

Furthermore, in general *the time t* is also not predictable from the initial data*: you don't know when `collapse of the wave function' (the transition from (1) to (2)) will happen (you can't predict when a specific excited atom will emit a photon, or a radioactive particle will decay).

We also can't retrodict to the past at the quantum level, because once the wave function has collapsed to an eigenstate we can't tell from its final state what it was before the measurement,

Knowledge of these later states does not suffice to determine the initial state (1) at times $t < t^*$:

The set of quantities ψ_n are not determined by the single number a_N.

How does this relate to the earlier part: The EBU idea?

Why should the collapse of the wavefunction relate to the average motion of matter in the universe?

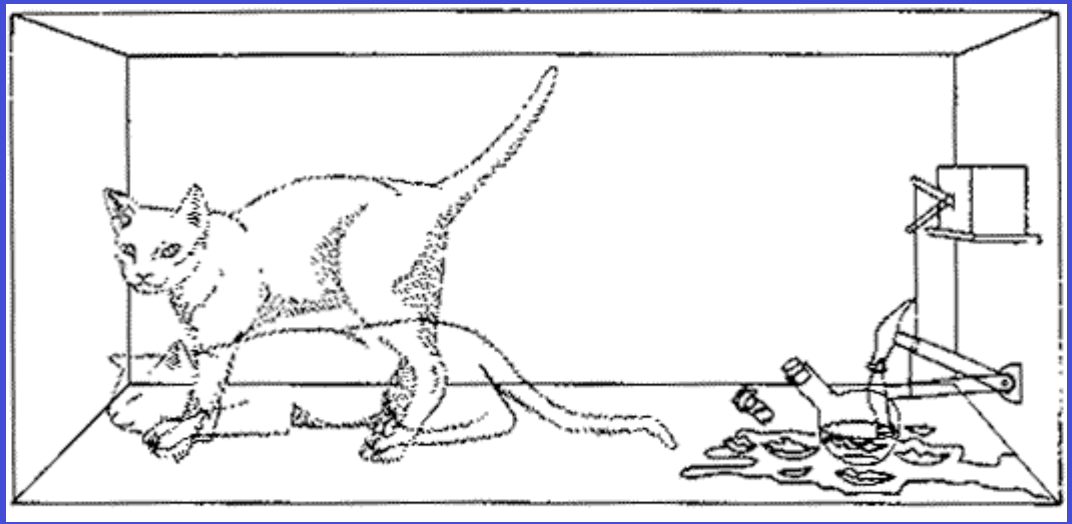
- Because it is a contextually dependent effect:

- determined by the local physical environment, such as the measurement apparatus, or any physical system that causes collapse of the wave function (screen, leaf, etc)

- See arxiv/1108.5261 for in depth discussion

When does collapse take place?

- an unanswered question.



Schrödinger's cat!

B: Reaching Back into the Past

There are many hints that the future can influence the past in quantum theory

• Wheeler and Feynman
- Advanced and retarded potentials

• Aharanov and collaborators
- Two-time formalism, weak measurement

•Cramer: Transactional quantum mechanics

•Wheeler: Delayed choice experiments

➔ The Crystaliziing Block universe

Rothman and Ellis: arXiv0912.0808

The delayed choice experiment: affecting the quantum past

Wheeler's delayed choice experiment is a thought experiment proposed by John Archibald Wheeler in 1978. Wheeler proposed a variation of the famous double-slit experiment of quantum physics, one in which the method of detection can be changed after the photon passes the double slit, so as to delay the choice of whether to detect the path of the particle, or detect its interference with itself.

Since the measurement itself seems to determine how the particle passes through the double slits, and thus its state as a wave or particle, Wheeler's thought experiment seems to demonstrate an ability to influence the past.

An implementation of the experiment in 2007 showed that the act of observation ultimately decides whether the photon will behave as a particle or wave, verifying the unintuitive results of the thought experiment

Experimental realization of Wheeler's delayed-choice GedankenExperiment

Vincent Jacques, E. Wu, Frédéric Grosshans, François Treussart, Philippe Grangier, Alain Aspect, Jean-François Roch

Science 315, 5814 (2007) 966 [arXiv:quant-ph/0610241v1]

Abstract: The quantum "mystery which cannot go away" (in Feynman's words) of wave-particle duality is illustrated in a striking way by Wheeler's delayed-choice Gedanken Experiment.

In this experiment, the configuration of a two-path interferometer is chosen after a single-photon pulse has entered it : either the interferometer is *closed* i.e. the two paths are recombined) and the interference is observed, or the interferometer remains *open* and the path followed by the photon is measured.

Experimental realization of Wheeler's delayed-choice GedankenExperiment

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“We report an almost ideal realization of that Gedanken Experiment, where the light pulses are true single photons, allowing unambiguous which-way measurements, and the interferometer, which has two spatially separated paths, produces high visibility interference.

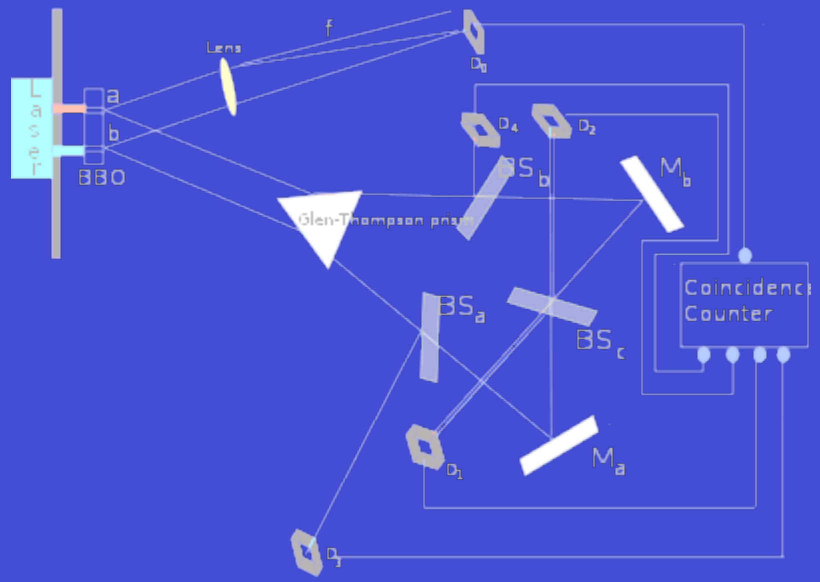
The choice between measuring either the 'open' or 'closed' configuration is made by a quantum random number generator, and is space-like separated -- in the relativistic sense -- from the entering of the photon into the interferometer. Measurements in the closed configuration show interference with a visibility of 94%, while measurements in the open configuration allow us to determine the followed path with an error probability lower than 1%. “

"A Delayed Choice Quantum Eraser"

by Yoon-Ho Kim, R. Yu, S.P. Kulik, Y.H. Shih, and Marlon O. Scully
http://xxx.lanl.gov/pdf/quant-ph/9903047
Phys.Rev.Lett. 84 1-5 (2000).

Abstract: This paper reports a "delayed choice quantum eraser" experiment proposed by Scully and Drühl in 1982. The experimental results demonstrated the possibility of simultaneously observing both particle-like and wave-like behavior of a quantum via quantum entanglement.

The which-path or both-path information of a quantum can be erased or marked by its entangled twin even after the registration of the quantum.



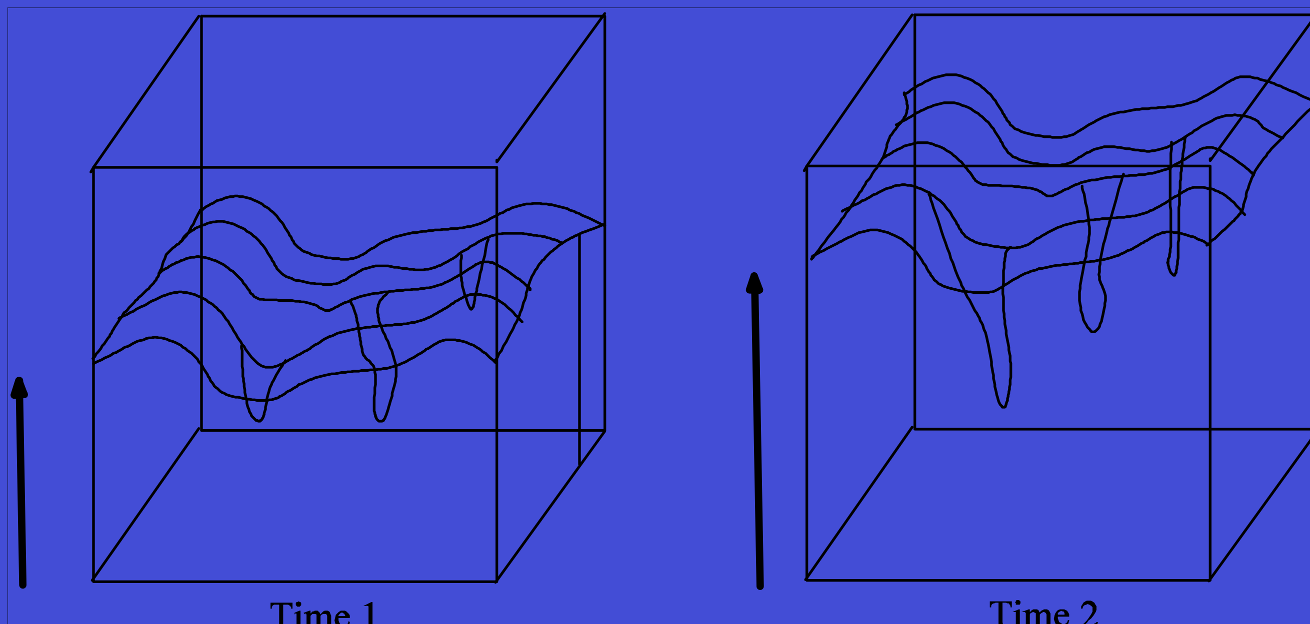
How can we accommodate this in our spacetime picture?

The part of spacetime where quantum determination of a definite state occurs is almost the same as the classical (Coarse grained) present: but small bits lag behind and crystallize out later.

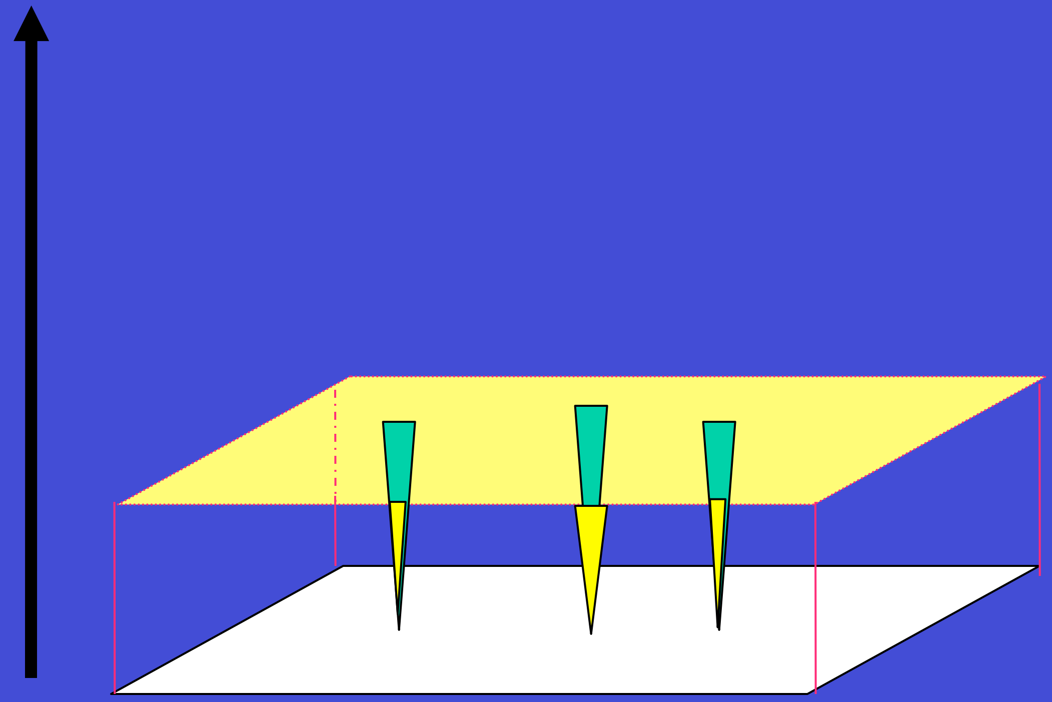
Those ever decreasing domains are the space-time events where we can influence “the past” from the present. Gradually the crystalised out state comes to encompass the whole of the matter present now. But at any time there will be other unsettled regions that will be determined in the future.

This picture is already confirmed by experiment: it is what is needed in order to make sense of the delayed choice experiments.

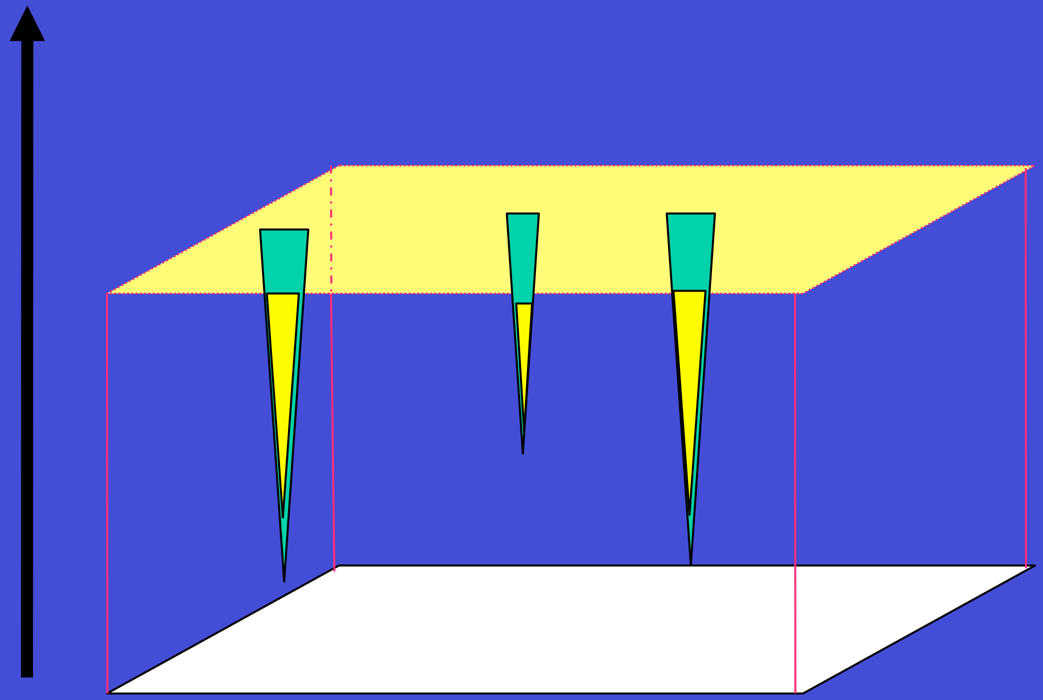
May take place in two stages: 1st decoherence (decay of entanglement), and then collapse of the wave function.



The crystallizing block universe:
the surface where the quantum uncertainty changes
to the classical definiteness



The crystalising block universe (EBU):
Spacetime grows with time: some places lag



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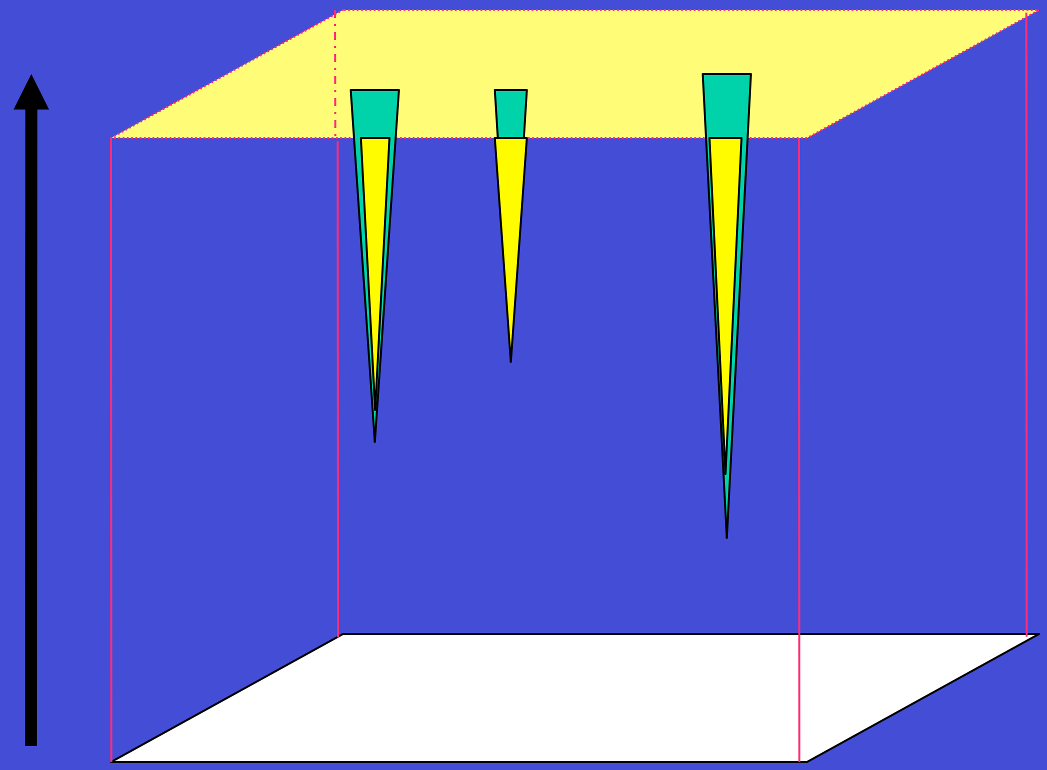


The crystalising block universe (EBU):
Spacetime grows with time: some places lag
Also some may lead!

C: EPR and Causality

Resolves the issue of instantaneous action in the EPR experiment

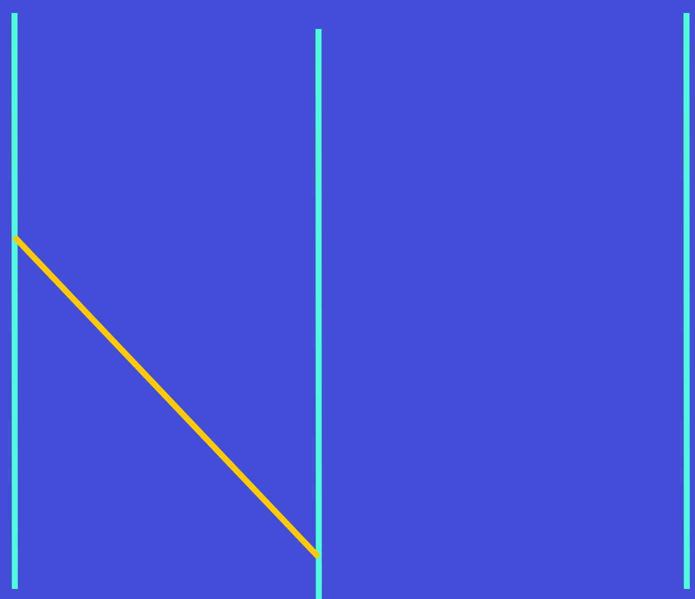
- Determination of spin of one of a pair of entangled particles instaneouslsy determines spin of the other

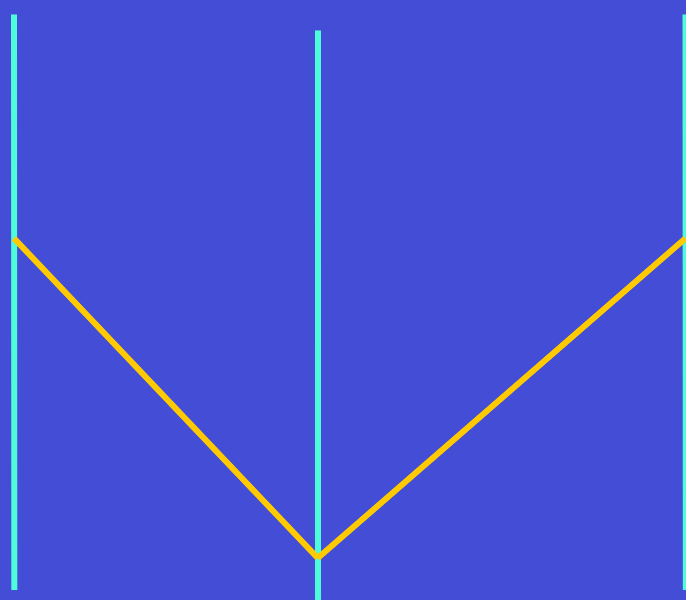
Problematic because

A: Instantaneous action at a distance

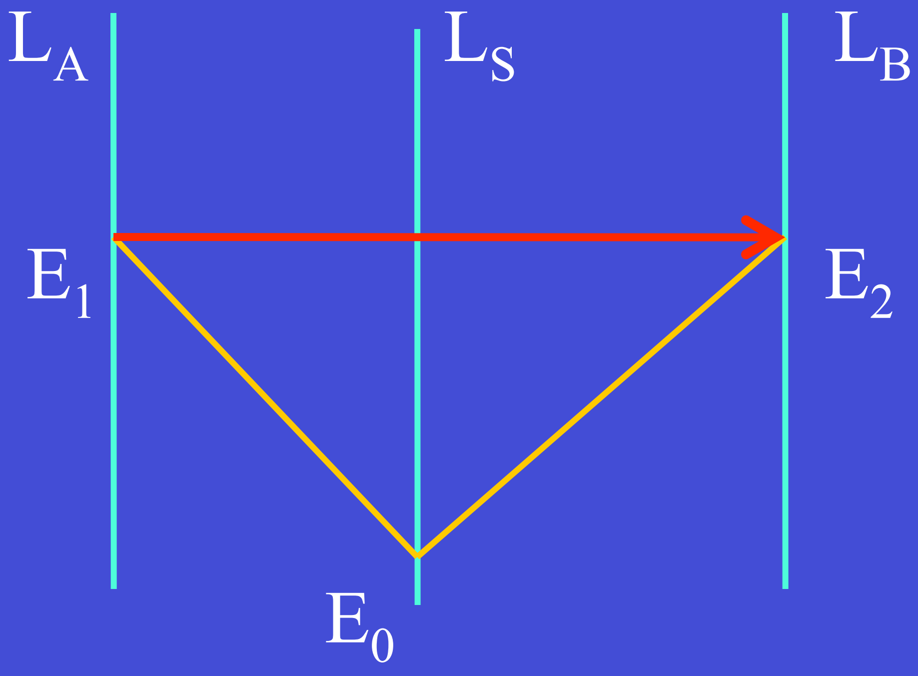
B: Instantaneity ambiguous: depends on motion

Resolution: effect reaches back in to the past and determines both spins at the emission event

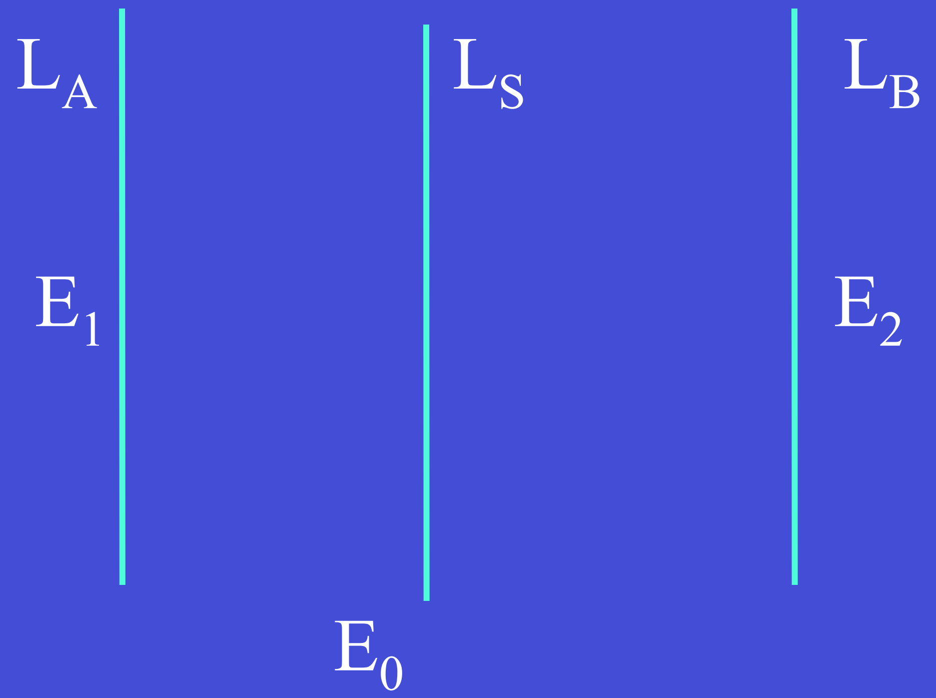




The usual EPR interpretation: spooky action at a distance. Note that if Alice or Bob move relative to the source, then simultaneity will be ambiguous according to who defines it.



The revised proposal: reaching back into the past. Note that if the distances are not equal, E1 and E2 will not be simultaneous in the common rest frame supposed here.



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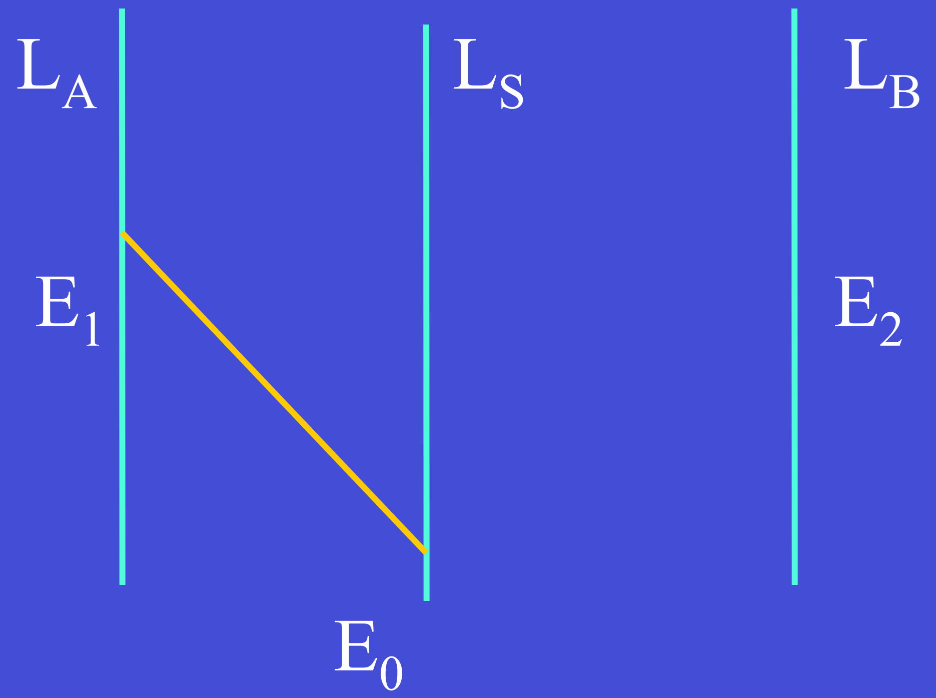

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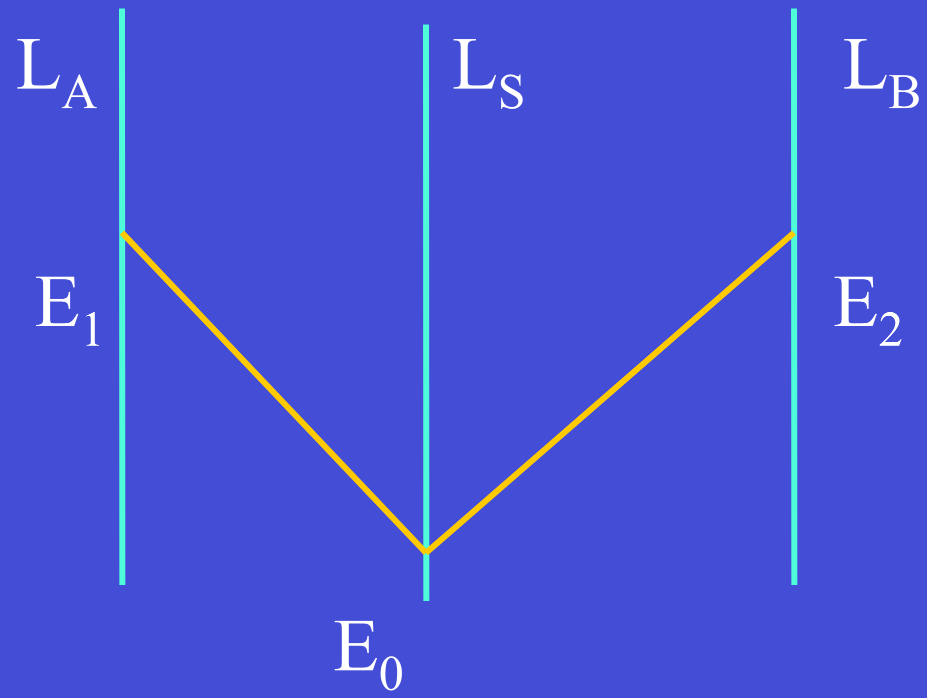

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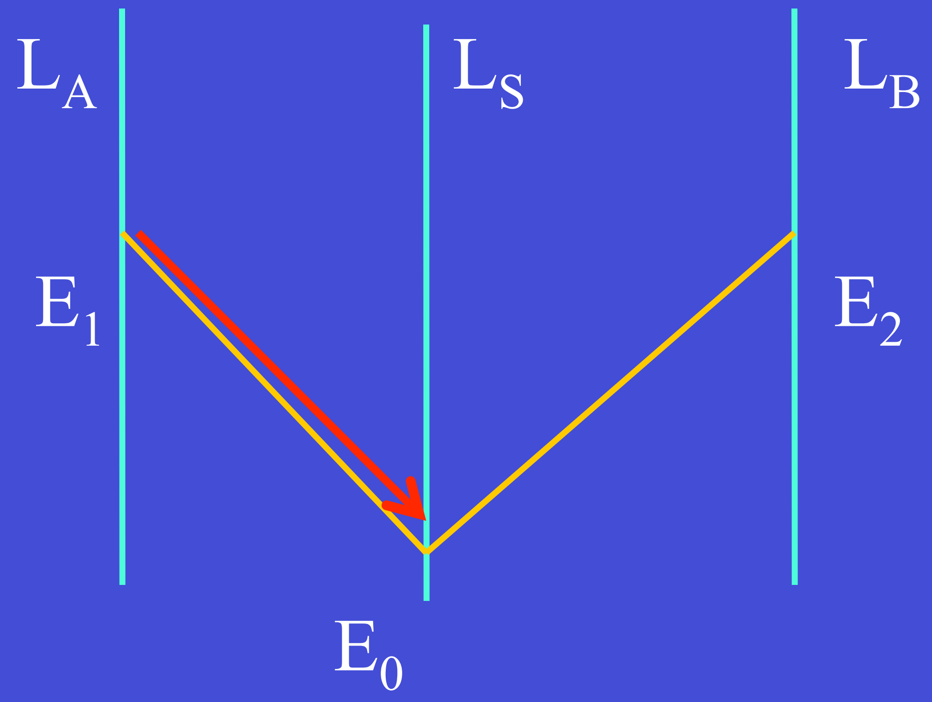

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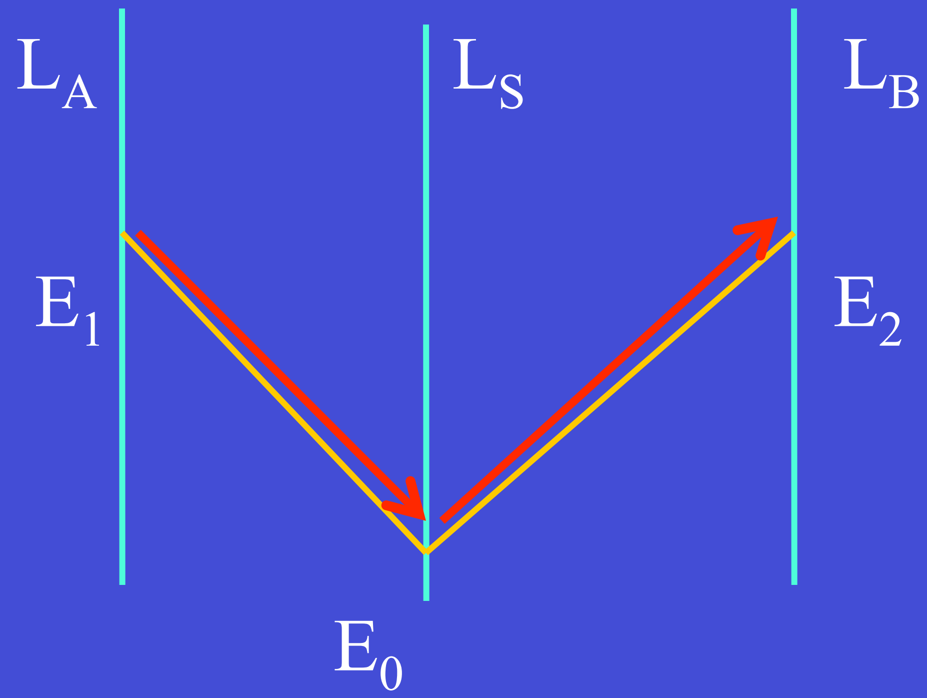

Quantum correlations with no causal order

O Oreshkov, F Costa1, Cˇaslav Brukner

The idea that events obey a definite causal order is deeply rooted in our understanding of the world and at the basis of the very notion of time. But where does causal order come from, and is it a necessary property of nature? We address these questions from the standpoint of quantum mechanics in a new framework for multipartite correlations which does not assume a pre-defined global causal structure. All known situations that respect causal order, including space-like and time-like separated experiments, are captured by this framework in a unified way. Surprisingly, we find correlations that cannot be understood in terms of definite causal order.

These correlations violate a “causal inequality” that is satisfied by all space-like and time-like correlations. We further show that in a classical limit causal order always arises, suggesting that space-time may emerge from a more fundamental structure in a quantum-to-classical transition.

4: Conclusion

Time does indeed pass! [Maudlin]. This happens at both the micro (quantum) level and classical (macro) level.

At the micro level this need not happen simultaneously, as determined by the macro space-time. Parts of quantum uncertainty may lag, and only crystallize out after the majority of events have become determinate.

The classical time-reversible Hamiltonian dynamics are not the norm. Rather they are sometimes a good approximation to what actually happens in the real universe, in restricted physical circumstances. But they do not fully represent the fundamental nature of what is going on at macro scales –or even micro.

Common sense is right: time is not an illusion, despite what many physicists may say. GR proper time determined along preferred timelike world lines is the key.

Relation to proper time:

Quantum interferometric visibility as a witness of general relativistic proper time M Zych, F Costa, I Pikovski, and C Brukner

We propose a novel quantum effect that cannot be explained without the general relativistic notion of proper time. We consider interference of a "clock" - a particle with evolving internal degrees of freedom - that will not only display a phase shift, but also reduce the visibility of the interference pattern. According to general relativity proper time flows at different rates in different regions of space-time. Therefore, due to quantum complementarity the visibility will drop to the extent to which the path information becomes available from reading out the proper time from the "clock".

Such a gravitationally induced decoherence would provide the first test of the genuine general relativistic notion of proper time in quantum mechanics.

arXiv:1105.4531

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1. Find out under what condition transition surfaces can become null and then timelike

    - intense gravitational fields, like Black Hole formation?

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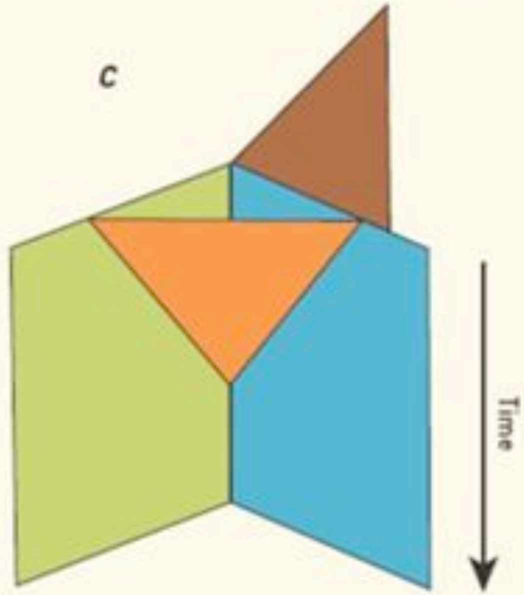
- e.g. spin foam

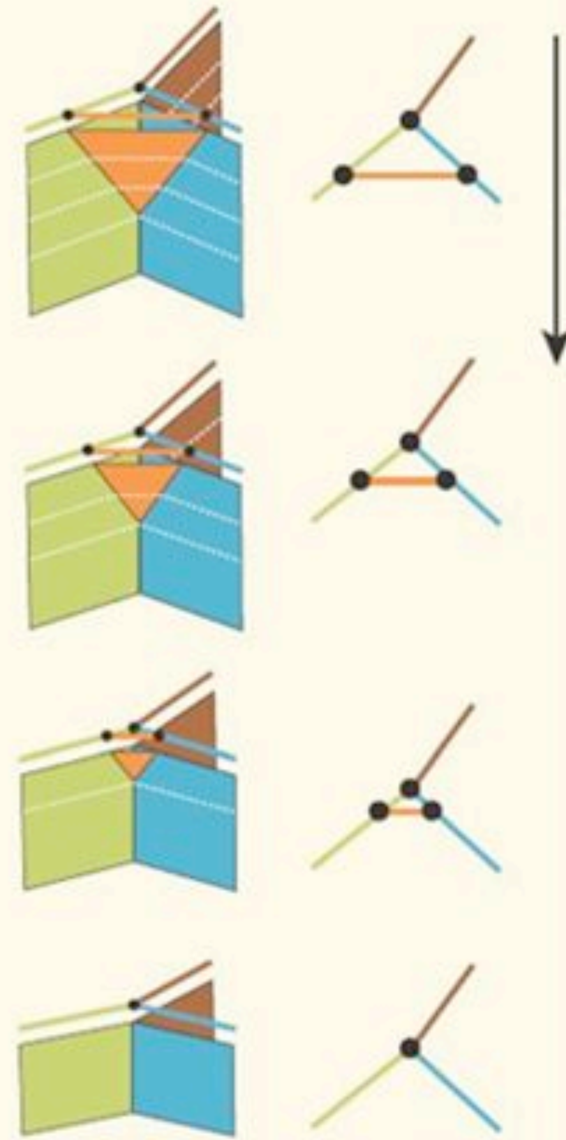
Another way to represent moves is to add the time dimension to a spin network—the result is called a spin foam (*c*). The lines of the spin network become planes, and the nodes become lines. Taking a slice through a spin foam at a particular time yields a spin network; taking a series of slices at different times produces frames of a movie showing the spin network evolving in time (*d*). But notice that the evolution, which at first glance appears to be smooth and continuous, is in fact discontinuous. All the spin networks that include the orange line (*first three frames shown*) represent exactly the same geometry of space. The length of the orange line doesn't matter—all that matters for the geometry is how the lines are connected and what number labels each line. Those are what define how the quanta of volume and area are arranged and how big they are. Thus, in *d*, the geometry remains constant during the first three frames, with 3 quanta of volume and 6 quanta of surface area. Then the geometry changes discontinuously, becoming a single quantum of volume and 3 quanta of surface area, as shown in the last frame. In this way, time as defined by a spin foam evolves by a series of abrupt, discrete moves, not by a continuous flow.

Although speaking of such sequences as frames of a movie is helpful for visualization, the more correct way to understand the evolution of the geometry is as discrete ticks of a clock. At one tick the orange quantum of area is present; at the next tick it is gone—in fact, the disappearance of the orange quantum of area *defines* the tick. The difference in time from one tick to the next is approximately the Planck time, 10^{-43} second. But time *does not exist* in between the ticks; there is no "in between," in the same way that there is no water in between two adjacent molecules of water.

c



d

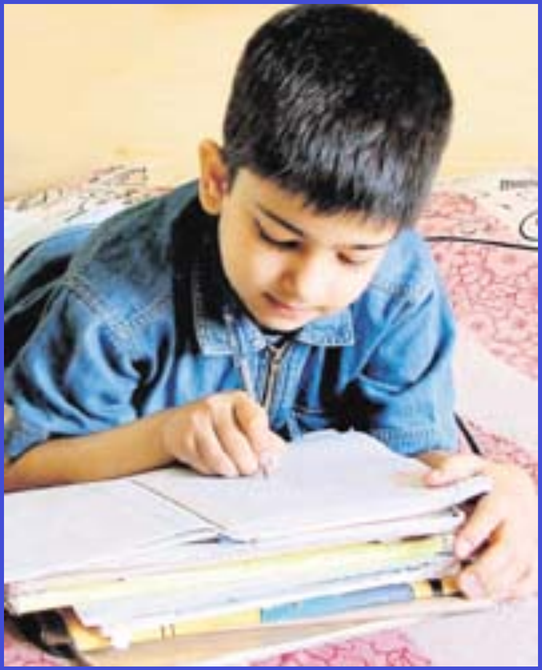


There is indeed a passage of time:
The past is fixed and cannot be changed.

The Moving Finger writes; and, having writ,
Moves on: nor all your Piety nor Wit
Shall lure it back to cancel half a Line,
Nor all your Tears wash out a Word of it

-- Omar Khayyam (Poem #545)

The future is not determined till it happens.
That is guaranteed to us by quantum mechanics.
It is what is experienced in the macro world.



E: Categorization problem

A philosophical argument is that the past, present, and future are exclusive categories, so a single event can't have the character of belonging to all three.

The counter is as follows: Suppose E happens at t_E.

At time $t_1 < t_E$, E is in future,

At time $t_1 = t_E$, E is in present,

At time $t_1 > t_E$, E is in past.

Its category changes - that is the essence of the flow of time - so this is a semantic problem, not a logical one. One needs adequate semantic usage and philosophical categories to allow description of this change:

“Time does not flow: this is incoherent.”

-correct

-time does not flow, it passes.

-It is the passage of time that allows rivers to flow [Maudlin]

“It can’t pass at the rate of one second per second because that’s not a rate it’s a dimensionless number”.

-False.

-just like rates of exchange of money, this is an operator with two slots, each with its own units.

-They don’t cancel [Maudlin]

F: Not necessary to describe events

Davies and Rovelli claim time does not flow because it's not needed to describe the relations between relevant variables, which are all that matter physically. Thus you can always get correlations between position $p(t)$ and momentum $q(t)$ for a system by eliminating the time variable: solve for $t = t(q)$ and then substitute to get $p(t) = p(t(q)) = p(q)$, and time has vanished!

Thus time may exist but it does not flow; only correlations matter.

Response:

The latter model leaves out part of what is happening: that does not mean it does not happen, it just means it's a partial model of reality, including some aspects and omitting others. It's a projection from spacetime to phase portrait.

Fundamentally applicability of unitary QM:

• The way physics works is that universal laws apply at the lowest level of the hierarchy of complexity;
• The effective laws at each higher level need to be deduced from these lower level laws by suitable coarse graining procedures.
• In general the next higher level laws will be different from the lower level laws.

• Thus quantum physics applies everywhere at all times on the lower levels. It will only hold at higher levels if proved to be so.
• Hence there is no a priori reason to believe the WdEW equation will hold globally: it has to be shown to be so.
• And there are good reasons to believe it will not be so (because collapse of the wave function takes place locally).

For detailed argument: see arxiv:1108.5261