Time from classical relativistic physics toward quantum gravity

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ARNOLD SOMMERFELD CENTER FOR THEORETICAL PHYSICS

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

MUNICH CENTER FOR MATHEMATICAL PHILOSOPHY

Foreword:
general conceptual issues and delimiting the scope

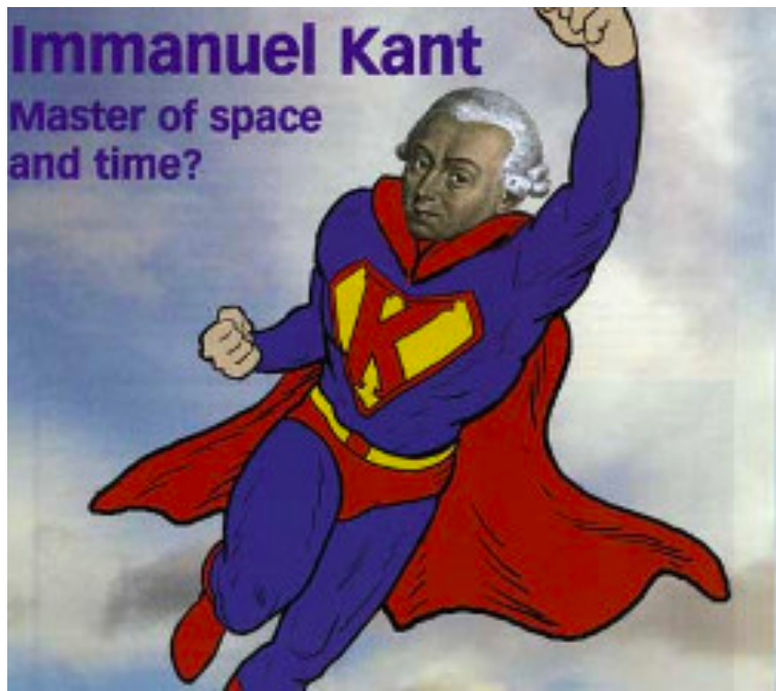
Which time?

Physical time

- objective
- measurable
- communicable, sharable
- mathematizable

time = mathematical entities in physical models/theories,
corresponding to computable quantities as measured by clocks

base and condition *sine qua non* of our conceptualisation of the world



conceptual issues not dealt with:

relationships mathematical theory <—> reality (some form of scientific realism assumed, and naturalised metaphysics taken for granted)

relation between physical time (as defined above) and other notions/experiences of time

relation between time and causality, i.e. temporal ordering and distance and causal relations

irreversibility of time evolution and thermodynamic time arrow

conceptual issues touched upon:

existence and conceptual characterisation of physical time, as deduced from physical theories

which features of standard notion of time are challenged by theoretical physics (and quantum gravity)

fundamental vs emergent nature of time (and space)

Prima facie issues with physical time

what is it, actually?

- time vs change vs succession (what more in the first notion? whence the directionality and irreversibility?)
- substantivalism vs relationalism

space and time are “substances” themselves: they are objects with respect to which distances and velocities of other objects and duration of processes are measured; location is location in space and time

vs

Prima facie issues with physical time

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vs

space and time are relational (derived notions): spatial and temporal separations do not have intrinsic significance; spatial and temporal distances are relational attributes of objects, motion can only make sense as relative motion of objects; space and time have no existence themselves: they are not “objects” on their own, they have no independent physical attributes, no independent dynamical meaning; they are attributes of physical objects, can only be defined and understood in relation to material objects

Newtonian Time

“time of common sense”

Newtonian Time

absolute time

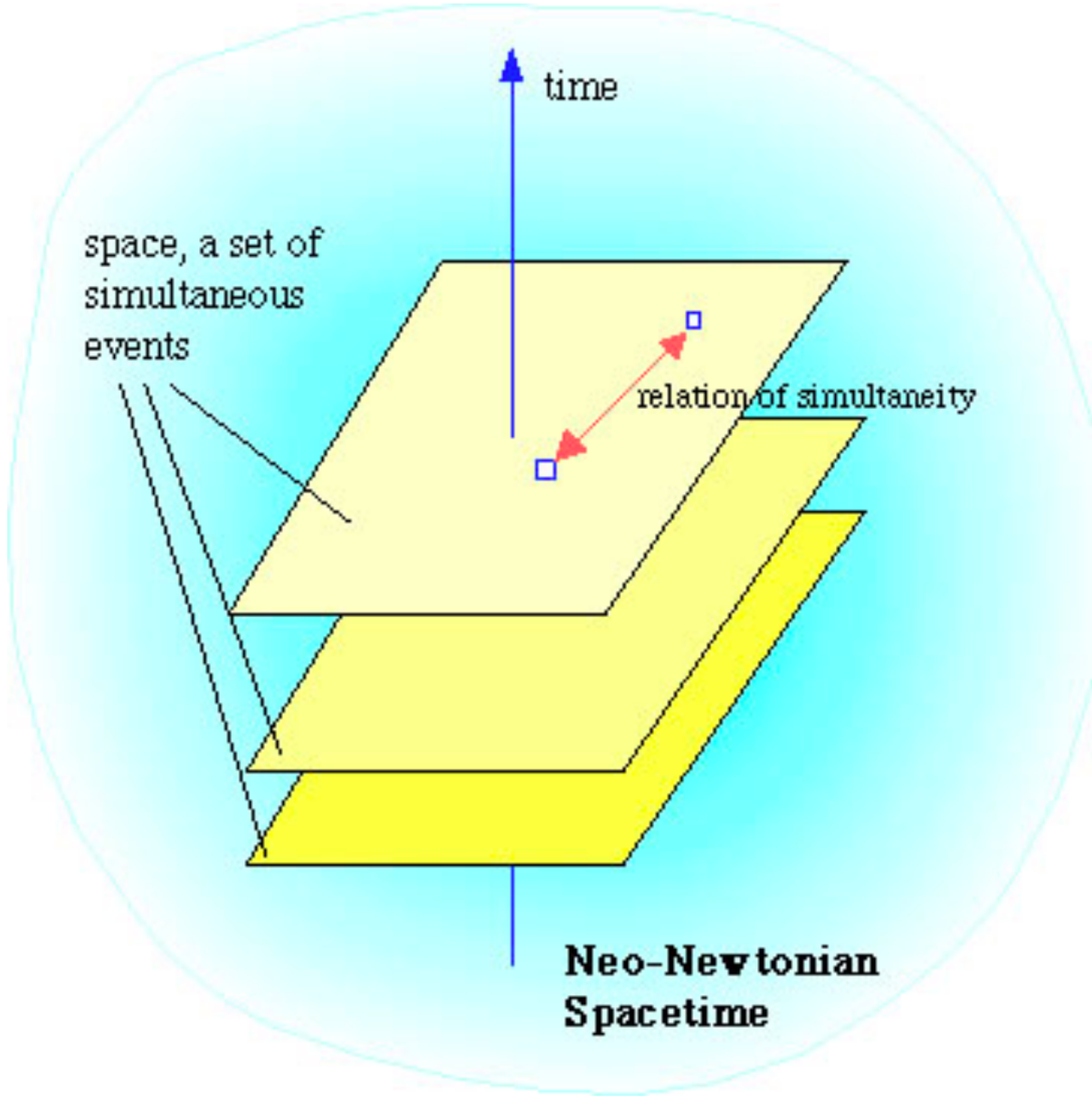
absolute simultaneity

corresponding to preferred (temporal) coordinate
in the equations describing any physical system

physical (i.e. real)

not subject to influence of other entities

not trivial (highly disputable) assumptions



but perfect agreement with everyday experience, thus
common sense, and extremely successful for physics

- continuum nature
- preferred foliation of spacetime manifold
- Galilean invariance (no preferred direction in space + relativity of inertial frames))

Special relativistic time

time loses its independence (from space and from observers)

Relativistic Time

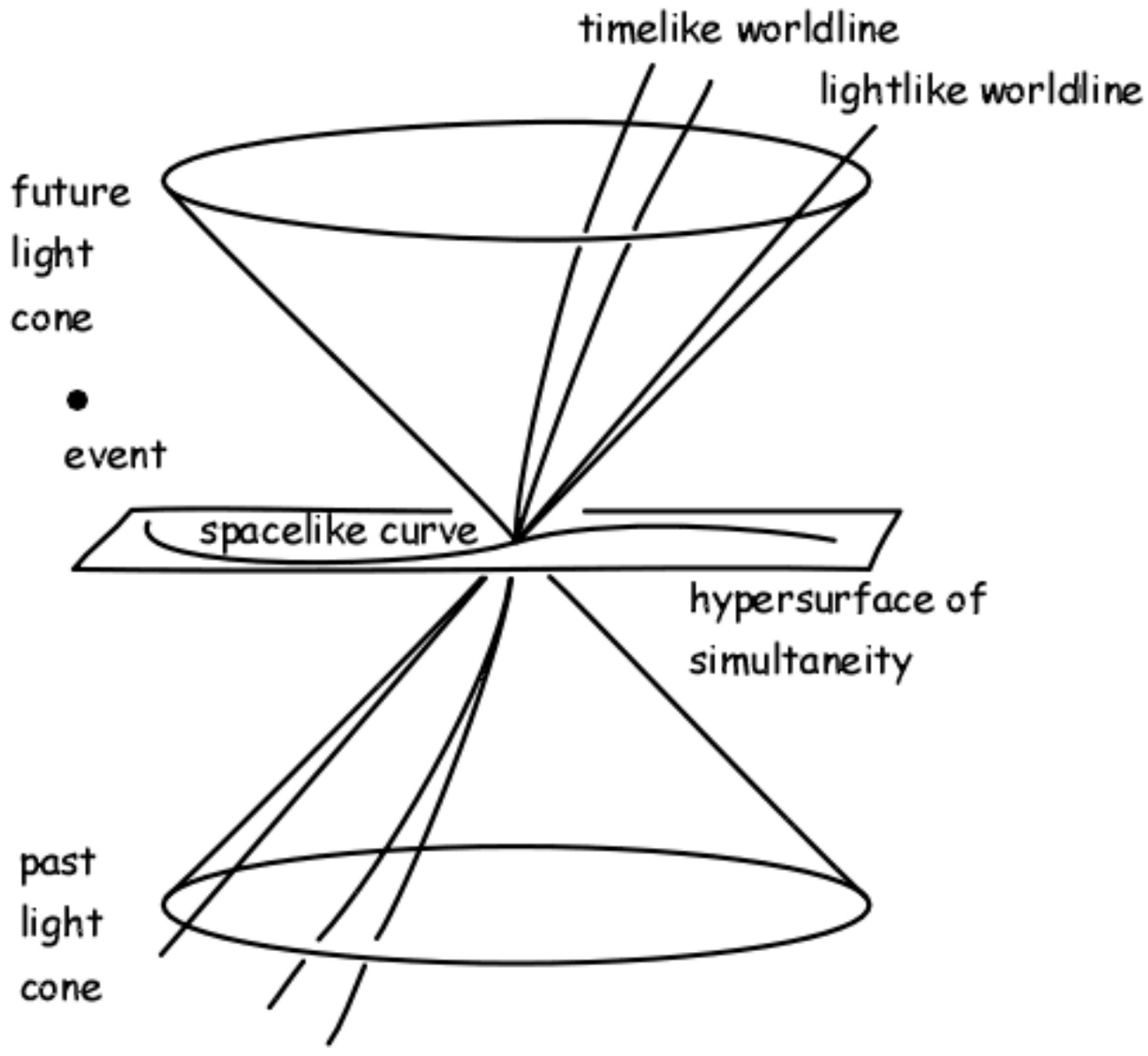
Special Relativity

absolute spacetime — physical (i.e. real) but not subject to influence of other entities

key point: finite (and absolute and maximal) propagation speed of light

relativity of simultaneity

non-trivial causal structure



Relativistic Time

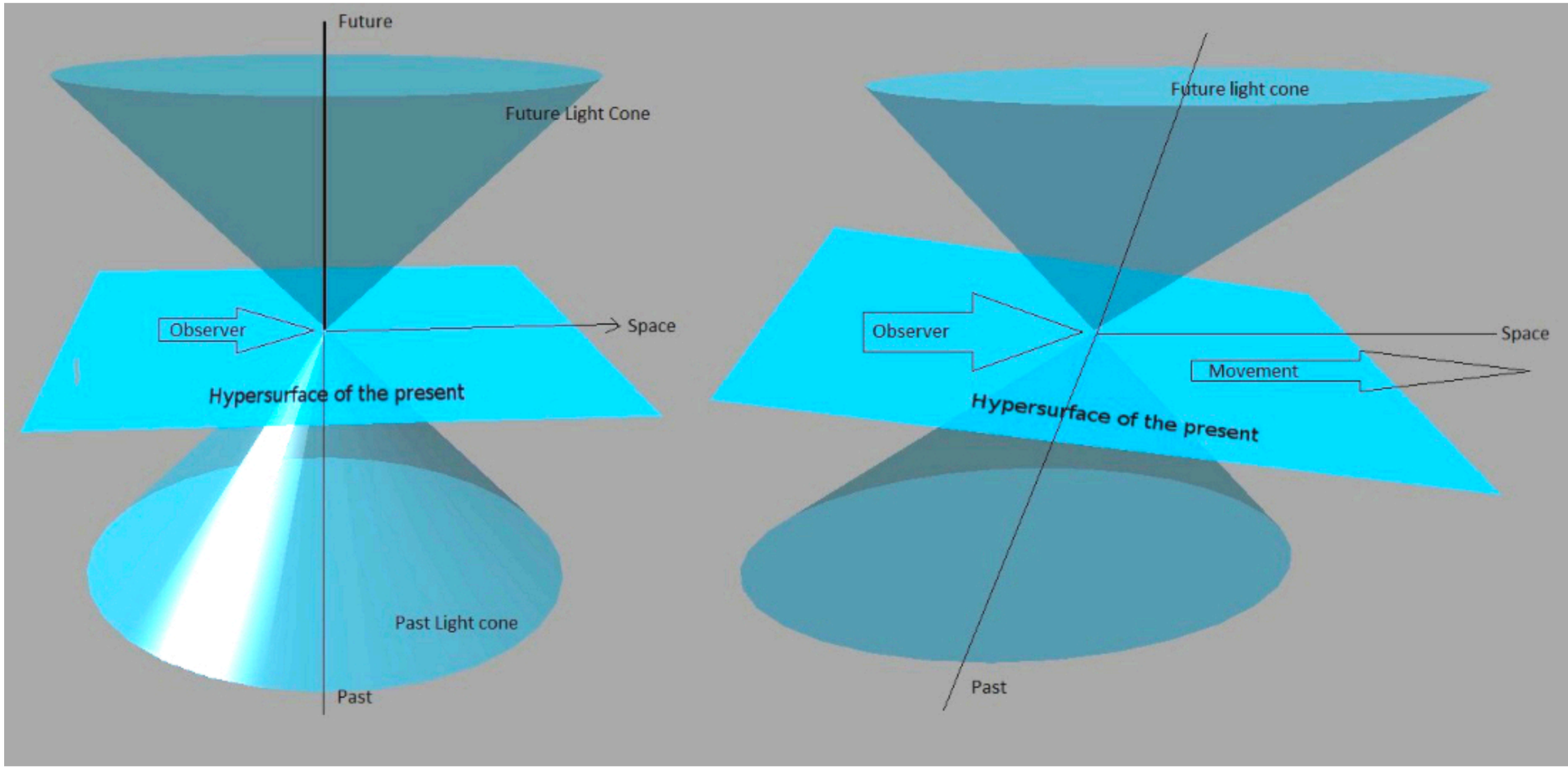
Special Relativity

absolute spacetime — physical (i.e. real) but not subject to influence of other entities

preferred class of (spatio-temporal) coordinates (observers)

distance and time measurement depend on observer:

length contraction and time dilation, relativity of simultaneity



space and time intimately linked

- continuum nature
- no preferred global foliation of spacetime manifold
- Lorentz invariance (no preferred direction in spacetime, relativity of inertial frames))

General Relativistic time

time disappears

as an absolute, non dynamical entity, and as a preferred (set of) direction(s)

it also disappears as independent of other physical systems

General Relativistic Time

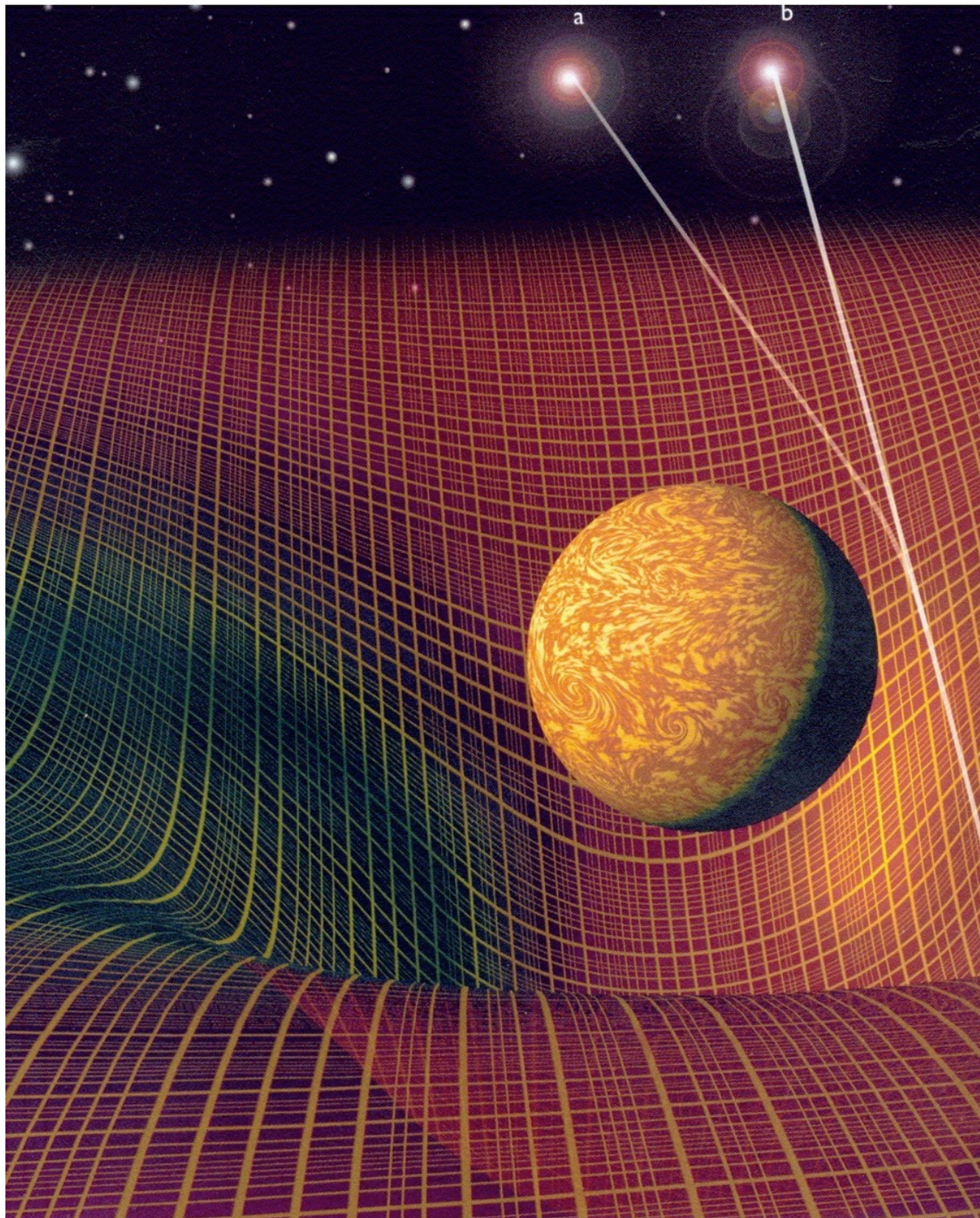
General Relativity

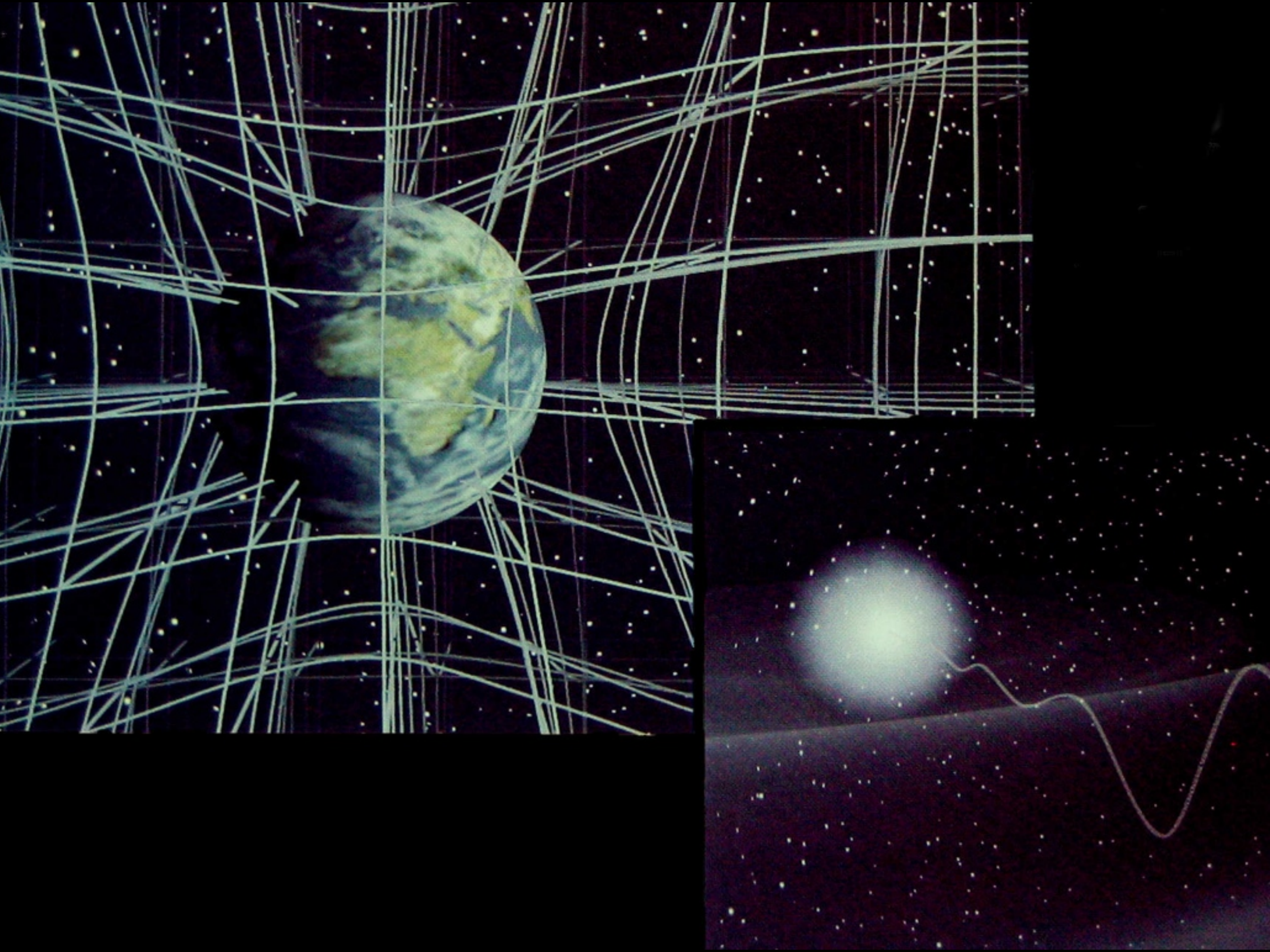
Spacetime is a physical system

$$g_{\mu\nu}(t,x) \qquad ds^2 = g_{tt}dt^2 + g_{12}\,dx_1 dx_2$$

- gravity = spacetime geometry (spatial distances between objects, time intervals between events, curvature of space, volumes, …..)
- mass-energy of material bodies “deformes” spacetime around them, this deformation affects motion of other material bodies
- deformation of spacetime is what we call “gravity”
- spacetime deformation itself has own dynamics

$$R_{\mu\nu}[g(x)] - \frac{1}{2}R[g(x)] + \Lambda g_{\mu\nu}(x) = 8\pi G_N T_{\mu\nu}[\phi(x), ...]$$





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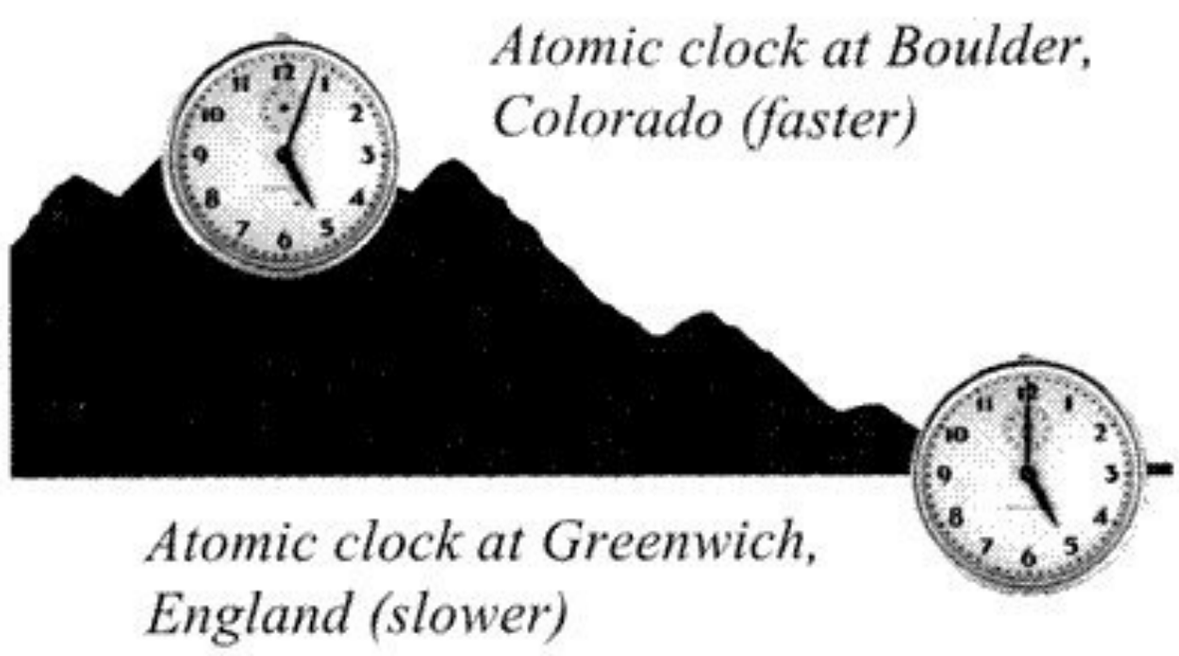
time itself is “deformed” by mass-energy



Gravitational Time Dilation: *The rate at which an atomic clock records time is diminished as gravity increases.*

deeper understanding of gravity
is
deeper understanding of space
and time

General Relativistic Time

General Relativity

Spacetime is a physical system

gravitational field is spacetime metric field
(gravity = spacetime geometry)

Einstein's equations (constraint for allowed
configurations of spacetime geometry and matter fields)

$g_{\mu\nu}(t,x)$

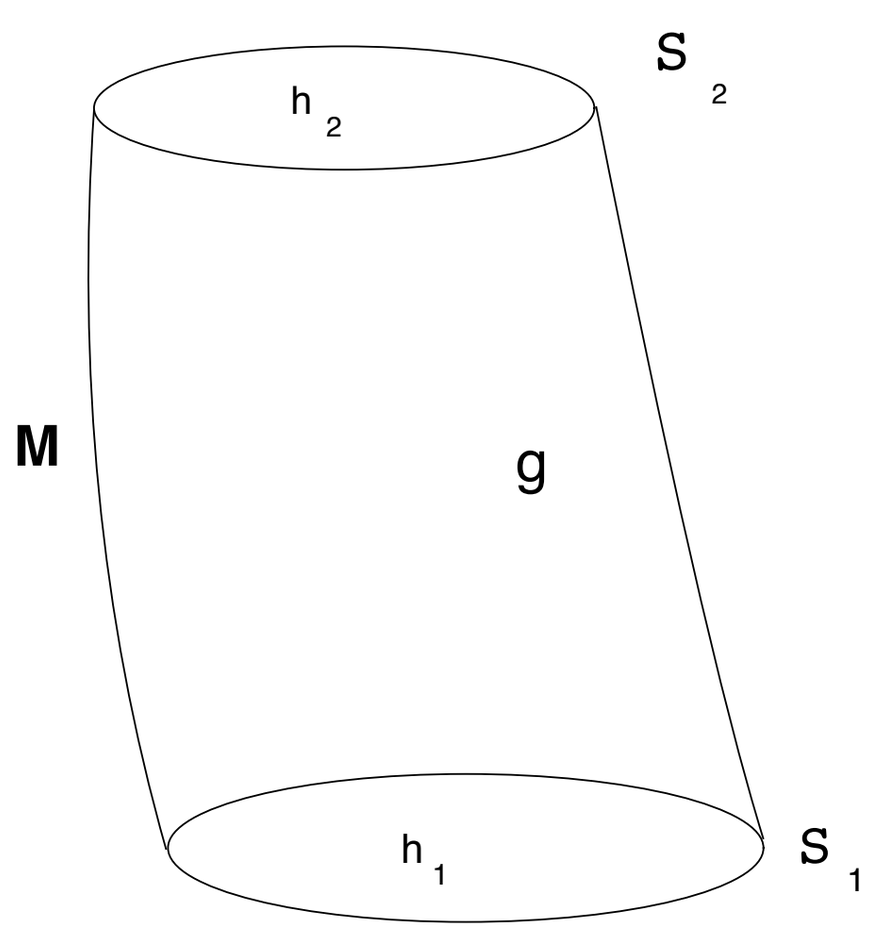
$$ds^2 = g_{tt}dt^2 + g_{12}\,dx_1 dx_2$$

$$R_{\mu\nu}[g(x)] - \frac{1}{2}R[g(x)] + \Lambda g_{\mu\nu}(x) = 8\pi G_N T_{\mu\nu}[\phi(x), ...]$$

spacetime structures in GR:

- differentiable manifold (as technical tool only?)
- metric field + matter fields

spacetime continuum



Relativistic Time

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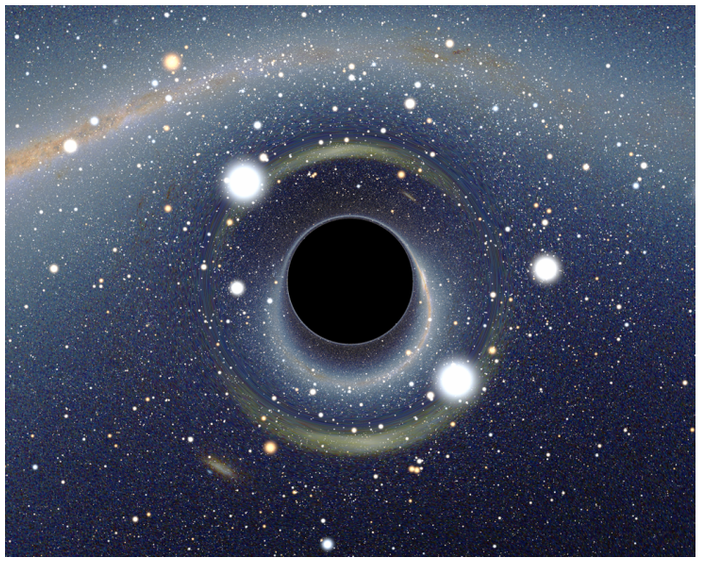
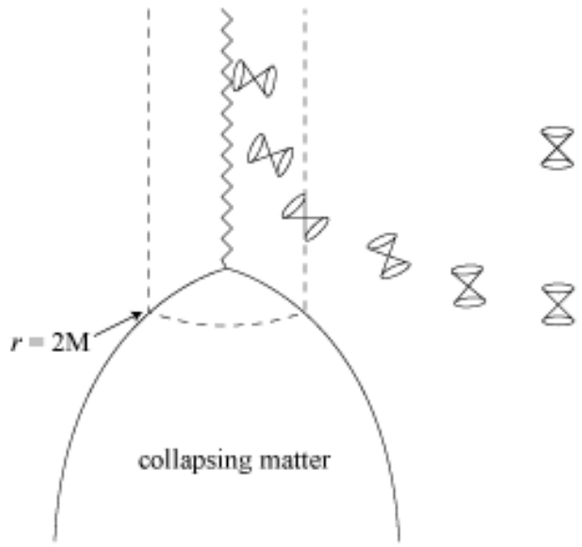
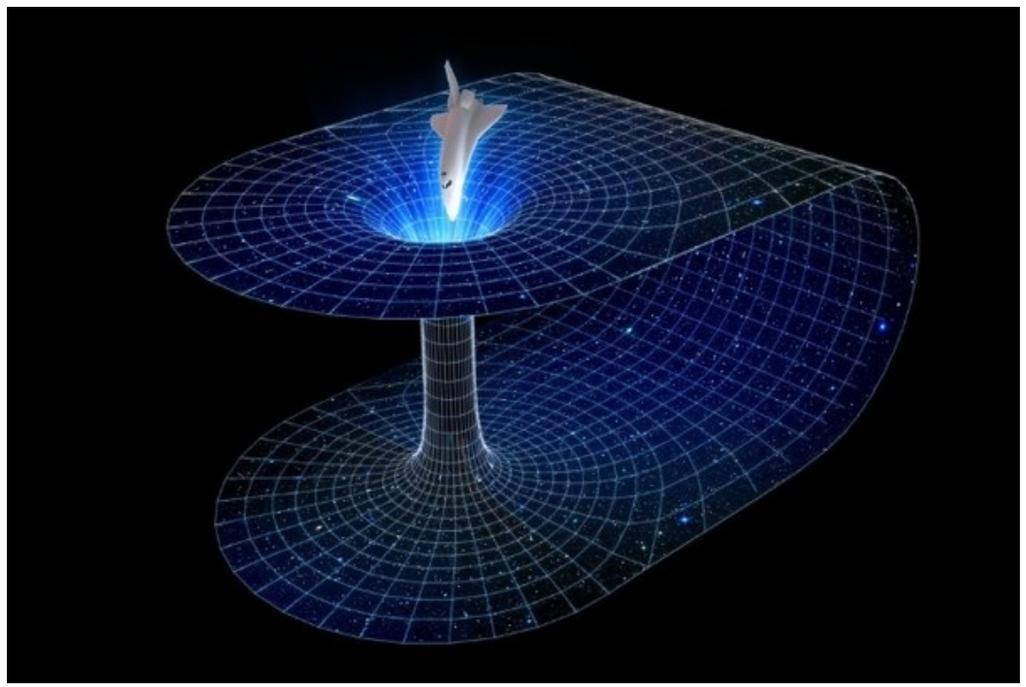
deformation of time (and space) can be substantial!

spacetimes with horizons (e.g. black holes)

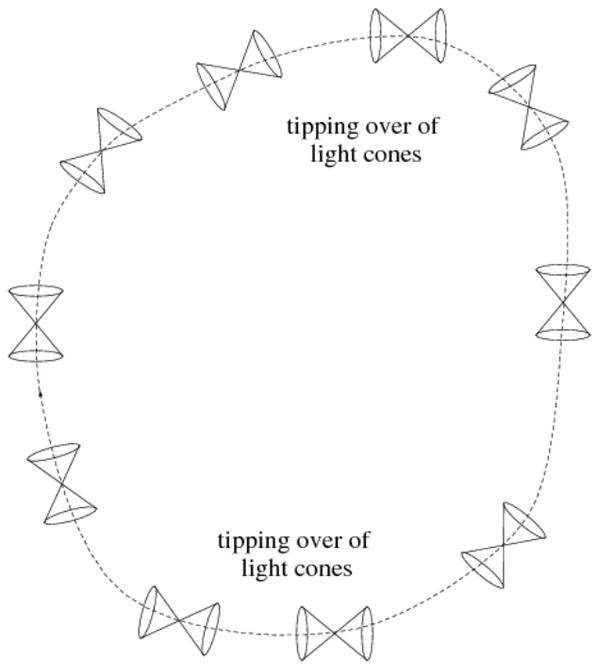




wormholes



spacetimes with
closed time-like loops



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key symmetry of GR: general covariance (diffeomorphism invariance):

global (active) diffeomorphisms on M are C∞ maps f : M → M with C∞ inverses

map points to -different- points and induce map between physical objects "living on M"

invariance under diffeomorphisms

$$F[\gamma, \Phi, \Sigma] = 0 \Leftrightarrow F[f \cdot \gamma\ ,\ f \cdot \Phi\ ,\ \Sigma] = 0$$

eqns of motion

diffeomorphism

fields

particles, strings, …

background structures
(not subject to eqns of motion)

valid -only- if background structures are -invariant- under diffeomorphisms (or if no background structures)

→ background independence of GR

Relativistic Time

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key symmetry of GR: general covariance (diffeo invariance):

no preferred local direction (or foliation)

no meaning of coordinates

no meaning of manifold points

much more than "coordinate independence"!!!

(NB: in theory, not on special solutions; compare with special relativity: preferred ("physical") role of inertial frames/coordinates due to isometries of special solution, i.e. Minkowski geometry)

thus, in GR: no time? time does not exist?

Nature of spacetime: lessons from GR

diffeomorphism invariance and role of manifold

problem of time (and space) in GR:

no absolute notion of time or space direction/location

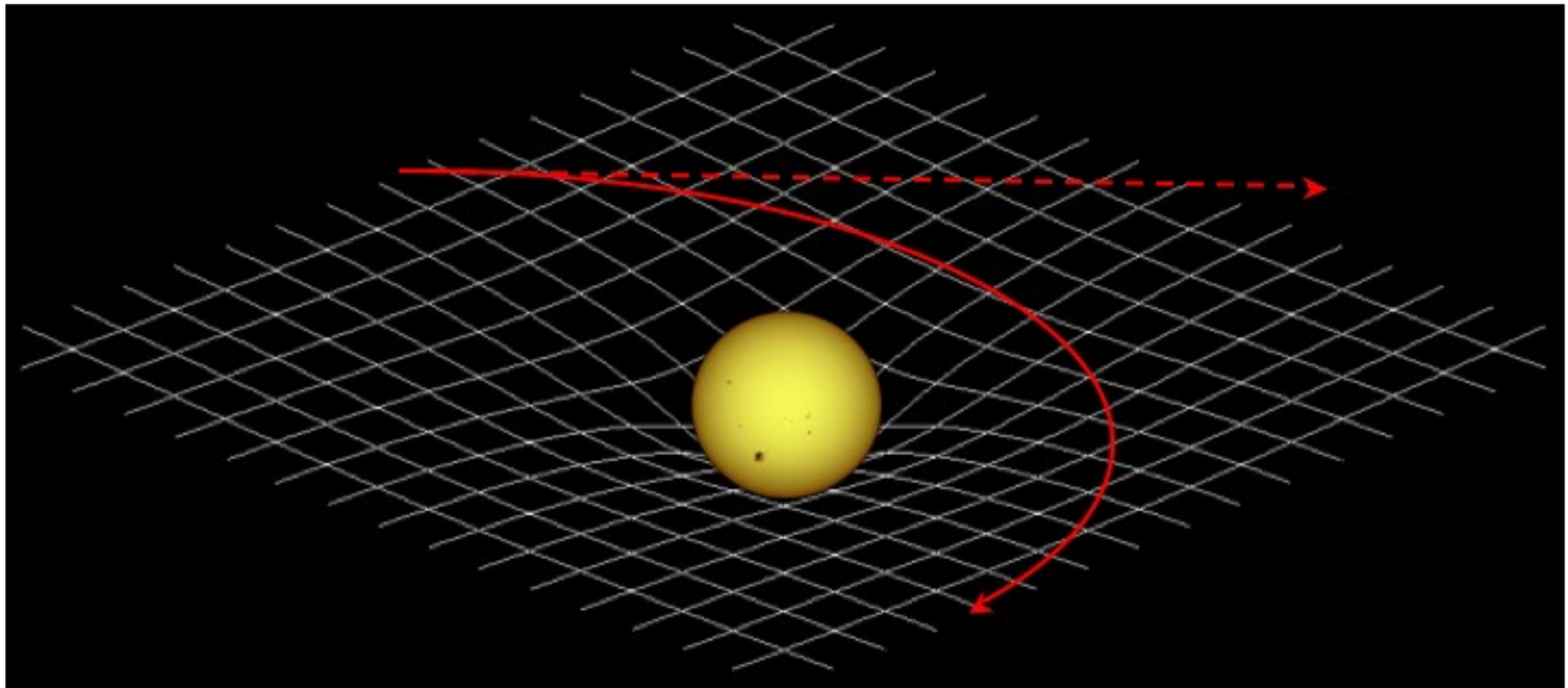
J. Butterfield, C. Isham, 1999; E. Curiel, 2016

no local beables? no time evolution?

what are spacetime points? how to make sense of localization? what constitutes evolution?

what are time and change?

we use time coordinates and spatiotemporal trajectories everyday in our work as relativists ….



Relativistic Time

General Relativity

general covariance (diffeo invariance):

no preferred local direction (or foliation)

no meaning of coordinates

no meaning of manifold points

problem of observables:

no function of spacetime points can be observable - no local observable?

relational observables (correlations of dynamical fields)

- physics is (only) in relations between physical, dynamical degrees of freedom
- identify internal degrees of freedom of system, e.g. matter fields, and use them as (approximate) clocks and rods to parametrize the evolution and location of other degrees of freedom

$$R(t) \qquad \Phi(t)$$
$$\Longrightarrow \qquad R(t) \qquad t(\Phi)$$
$$\Longrightarrow \qquad R(\Phi)$$

- relational space: physical rods
- relational time: physical clocks

points, coordinates, trajectories on manifold are “useful fictions” representing physical frames (clocks and rods) in the limit in which their physical properties (energy, dynamics, …) are negligible

Nature of spacetime: lessons from GR

J. Earman, 1989; O. Pooley, 2013; R. Rynasiewic, 1996;
M. Dorato, 2000, 2008; V. Lam, 2017; S. French, 2010

what is (classical) spacetime, then?

Substantivalism: spacetime is considered as an independently existing entity that has its own properties, which are not reducible to—not derived from—properties and relations of matter. Spacetime and matter are two ontologically distinct beings and spacetime is ontologically independent from matter.

Relationalism: spacetime is reduced to—derived from—properties and relations among matter. Two versions:

non-reductive version: spacetime consists in irreducible spatiotemporal relations among matter, which are ontologically distinct from but ontologically dependent on matter.

reductive version: spacetime is reduced to non-spatiotemporal properties and relations among matter (reductive relationalism).

spacetime ~ gravitational field ~ physical system: substantivalism and relationalism reconciled?

in some sense, GR strikes an intermediate (reconciling) note, between substantivalism and relationalism, in two plausible (and compatible) interpretations:

a) spacetime is the gravitational field (a dynamical ("proto-material") physical entity) and its properties

b) spacetime is in the relations between the gravitational field and material objects (used to define points)

possible formalization: spacetime structuralism (also close to functionalism)

spacetime is a physical structure: a network of physical relations among physical relata that do not possess any intrinsic identity independently of the relations in which they stand (eg spacetime points as physical correlations)

General Relativistic Time

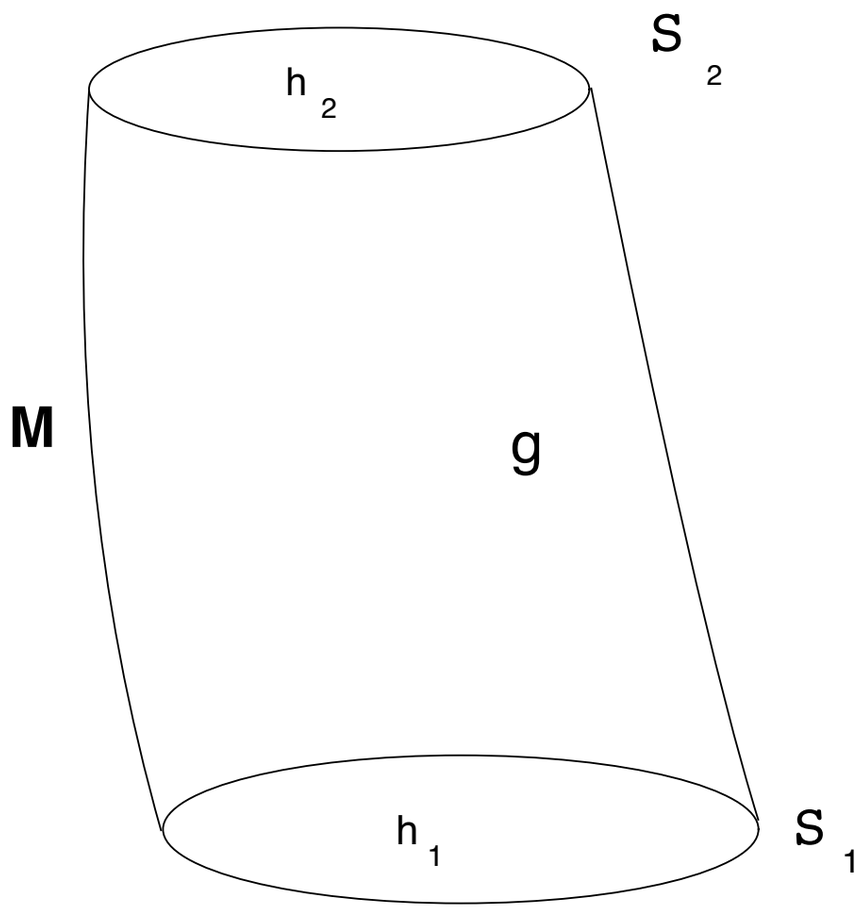
General Relativity

Spacetime is a physical system

spacetime structures in GR:

- differentiable manifold (as technical tool only?) - meaningful only as specifying a topology (and a restriction on allowed geometries)

- metric field + matter fields (in various diffeo-invariant combinations)



time is “relational time” only?

GR “forces” us to consider physical clocks as “time” —— non trivial at all!

"Position of particle (now)" is not an observable.

"Position of particle at 5pm (on Daniele's clock)" is an observable. This allows a notion of evolution with respect to Daniele's clock.

There is also a notion of (physical) Hamiltonian that evolves Daniele and the rest of the universe (but not his clock).

So no "problem of time"?

Practical (?) problems:

A. In the canonical formalism observables are pre-- or postdictions.
   Need to solve dynamics of the theory.
B. Good clocks?

example:

Two-point function of scalar field relative to (four) clock scalars

$$\{\phi(\Psi), \phi(\Psi+\epsilon)\} = G(\Psi, \Psi+\epsilon)\left(1 + \frac{\text{Energy}(\phi)}{\text{Energy}(\Psi)}\right)$$

encode 'free' dynamics

Green's function on fixed background

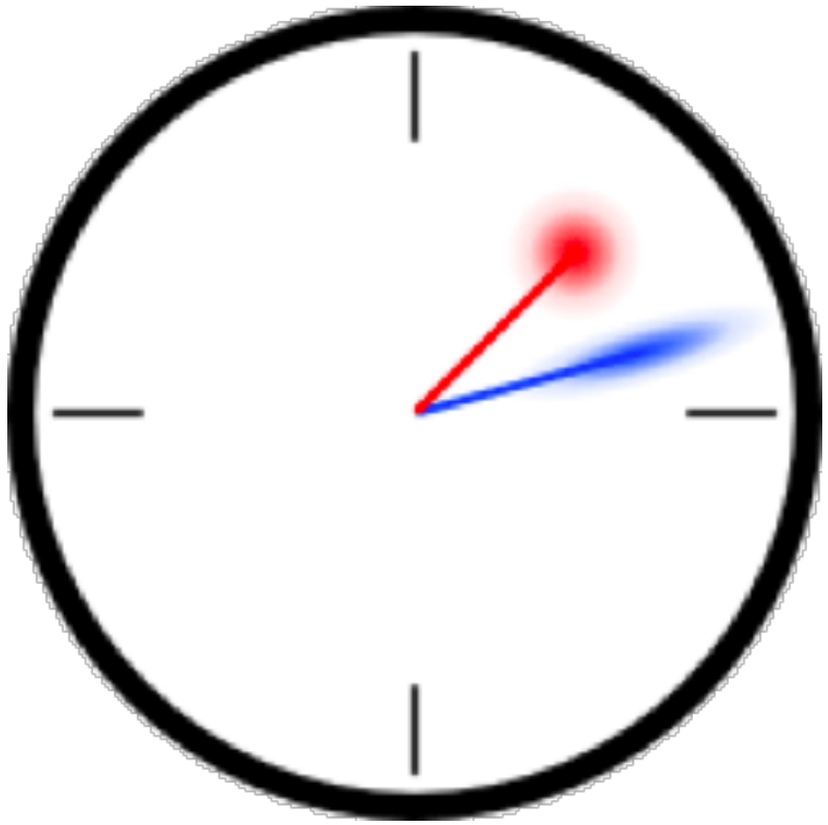
Resolution limit for degrees of freedom points depending on energy of clocks.

lots of additional trouble … and fun!

Quantum reference frames

quantum clocks (ticking along the preferred temporal direction)

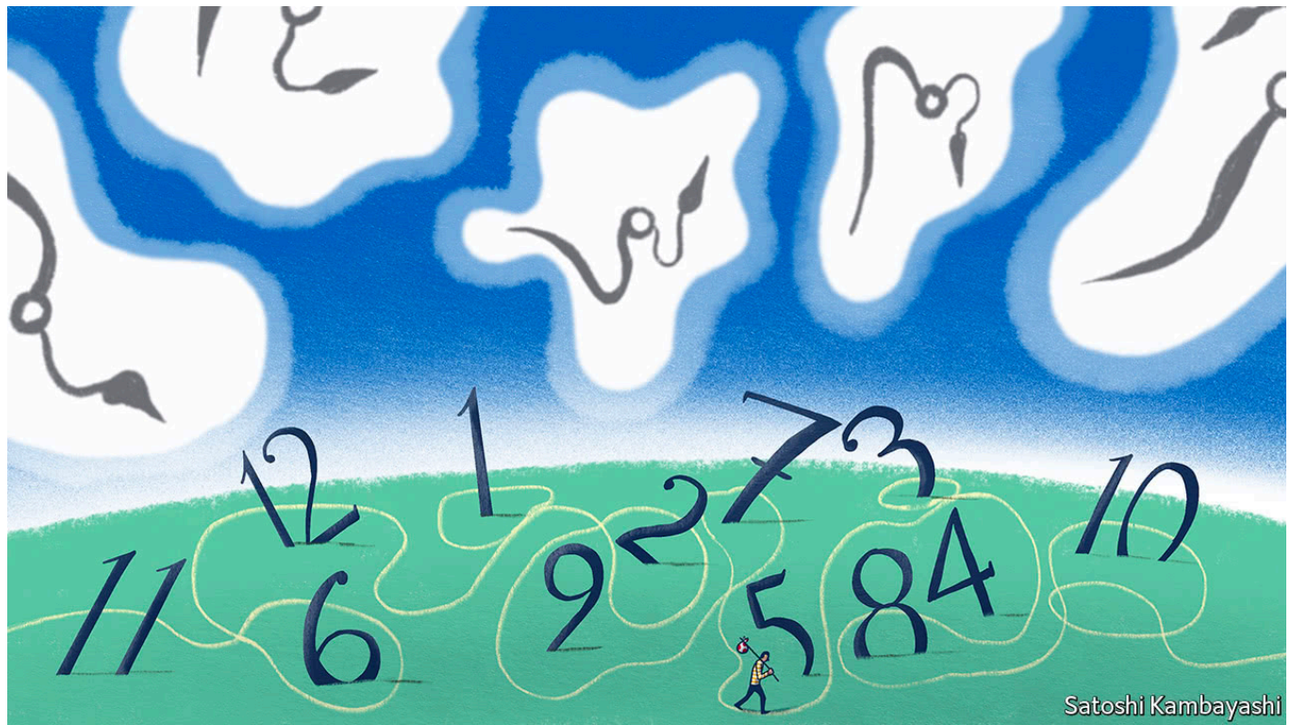
$$|t_1\rangle \quad , \quad |t_2\rangle, \quad \ldots\ldots \quad |t_n\rangle$$



D. Page, W. Wootters, 1983; ….; A. Vanrietvelde, F. Giacomini, P. Hoehn, 2018; A. Vanrietvelde, P. Hoehn, 2018

highly non-trivial - new effects:

- uncertainty + quantum fluctuations + entanglement
- modified Schroedinger equation
- …..



⟶ **Quantum causality**

if this was not enough trouble…..

Need to go beyond GR (and relativistic time)

toward Quantum Gravity

all physical systems are quantum ….. spacetime is a physical system

our understanding of time will most likely go through another revolution

Why we need to go beyond GR - conceptual

two incompatible conceptual (and mathematical) frameworks for space, time, geometry and matter

GR

spacetime (geometry) is a dynamical entity itself

there are no preferred temporal (or spatial) directions

physical systems are local and locally interacting

everything (incl. spacetime) evolves deterministically

all dynamical fields are continuous entities

every property of physical systems (incl. spacetime) can be precisely determined, in principle

QFT

spacetime is fixed background for fields' dynamics

evolution is unitary (conserved probabilities) with respect to a given (preferred) temporal direction

nothing can be perfectly localised

everything evolves probabilistically

interaction and matter fields are made of "quanta"

every property of physical systems and their interactions is intrinsically uncertain, in general

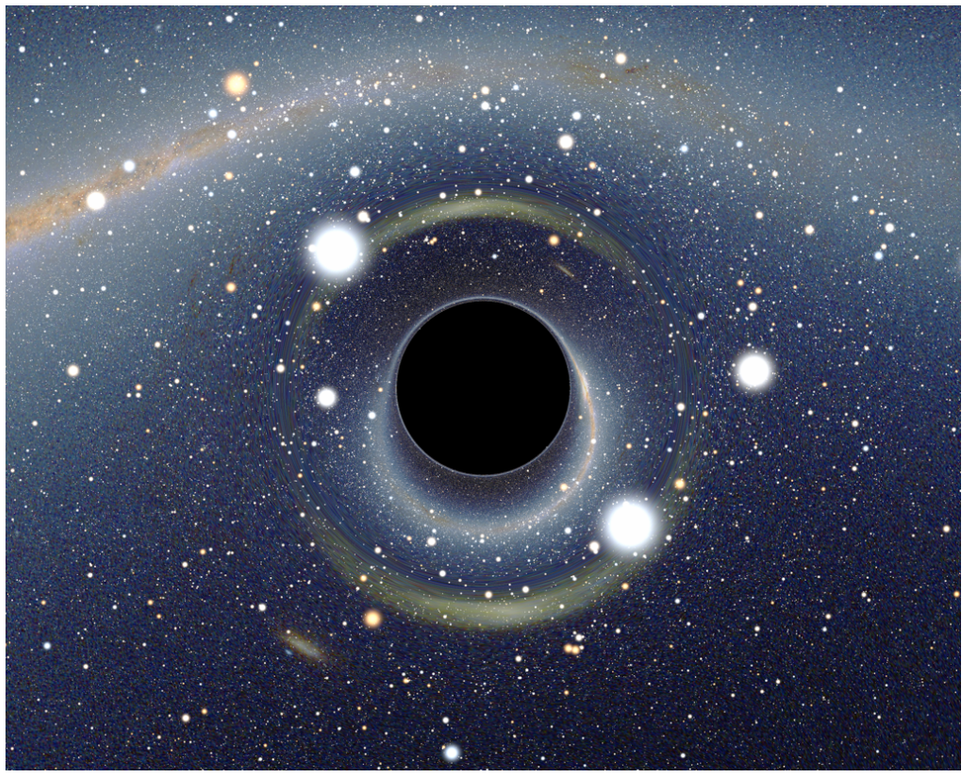
so, what are, really, space, time, geometry, and matter?

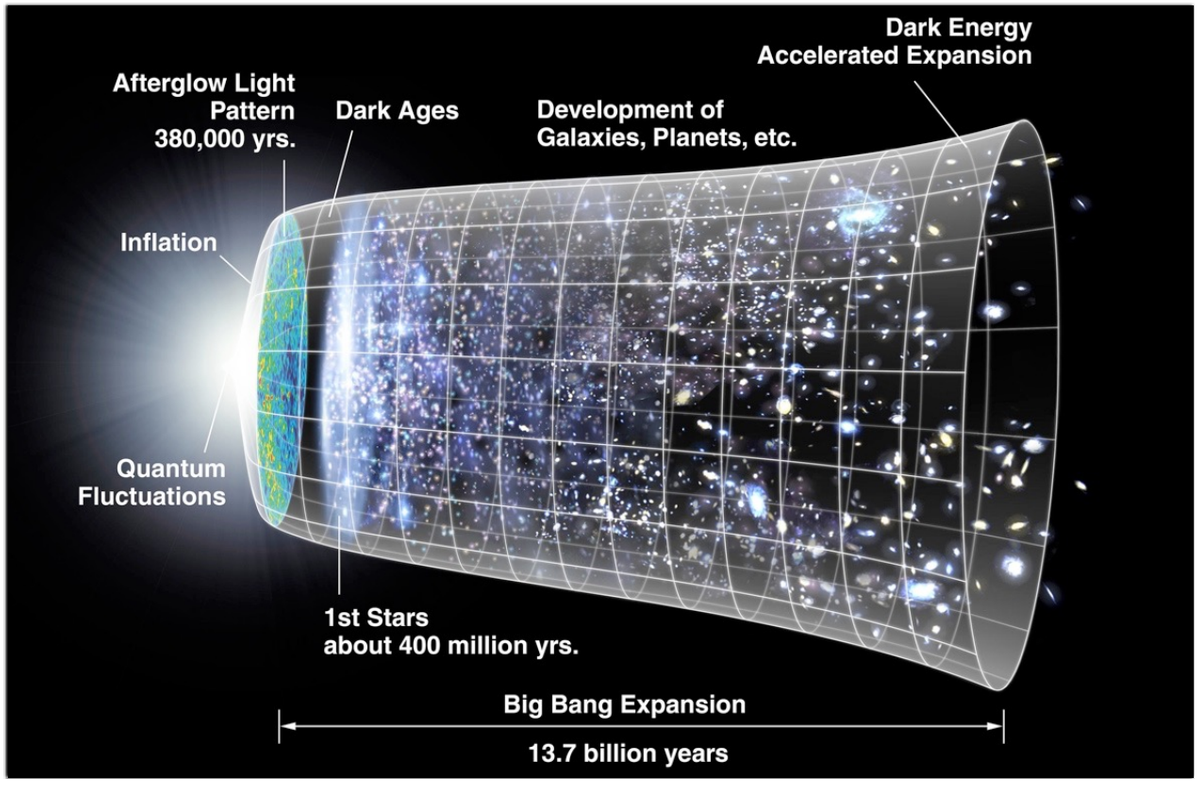
Why we need to go beyond GR - physics

several open physical issues, at limits of GR and QFT or at interface (where both are expected to be relevant)

- breakdown of GR for strong gravitational fields/large energy densities

spacetime singularities - black holes, big bang - quantum effects expected to be important





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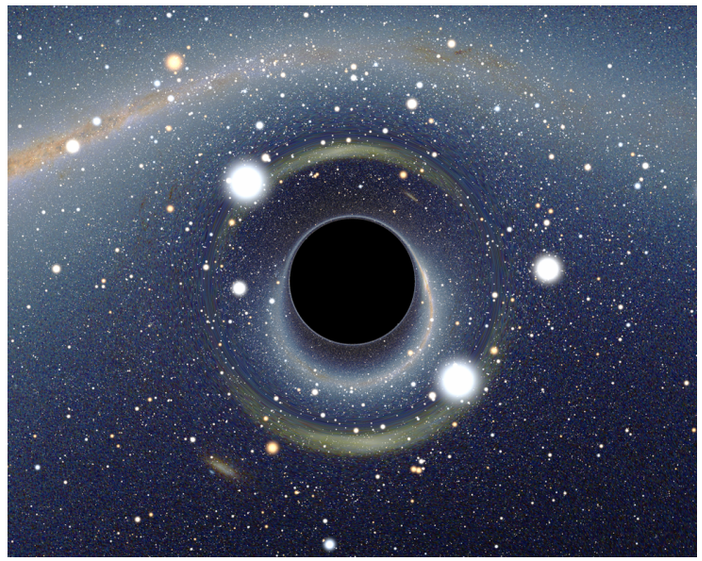
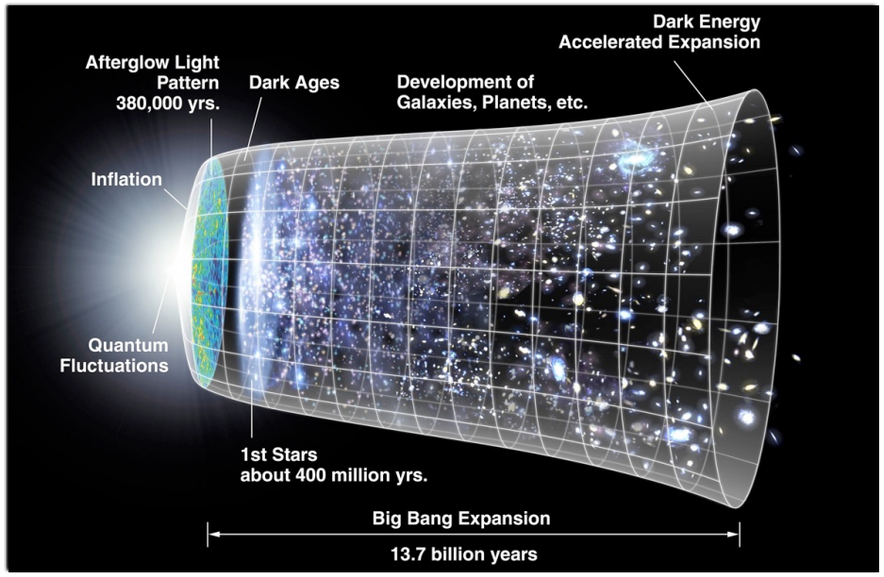
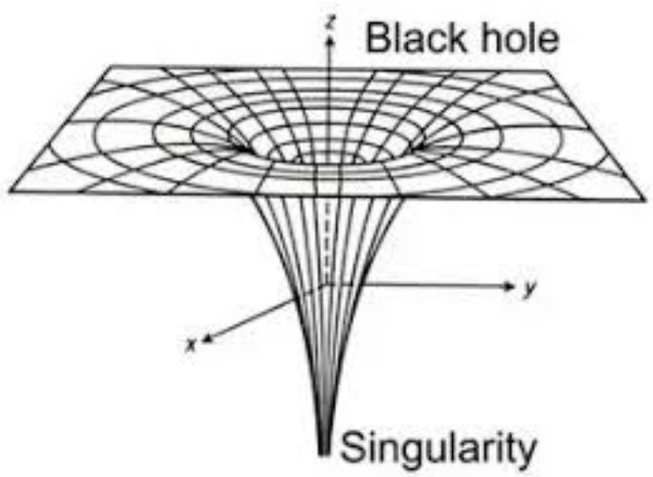


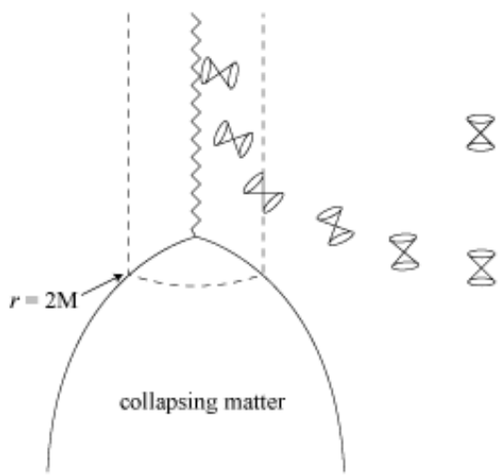


singularity:

if surrounded by event horizon, effective removal of spacetime region from contact with rest of universe

in any case, new “boundary” for spacetime, which becomes “incomplete” (space and time lose meaning at singularity)





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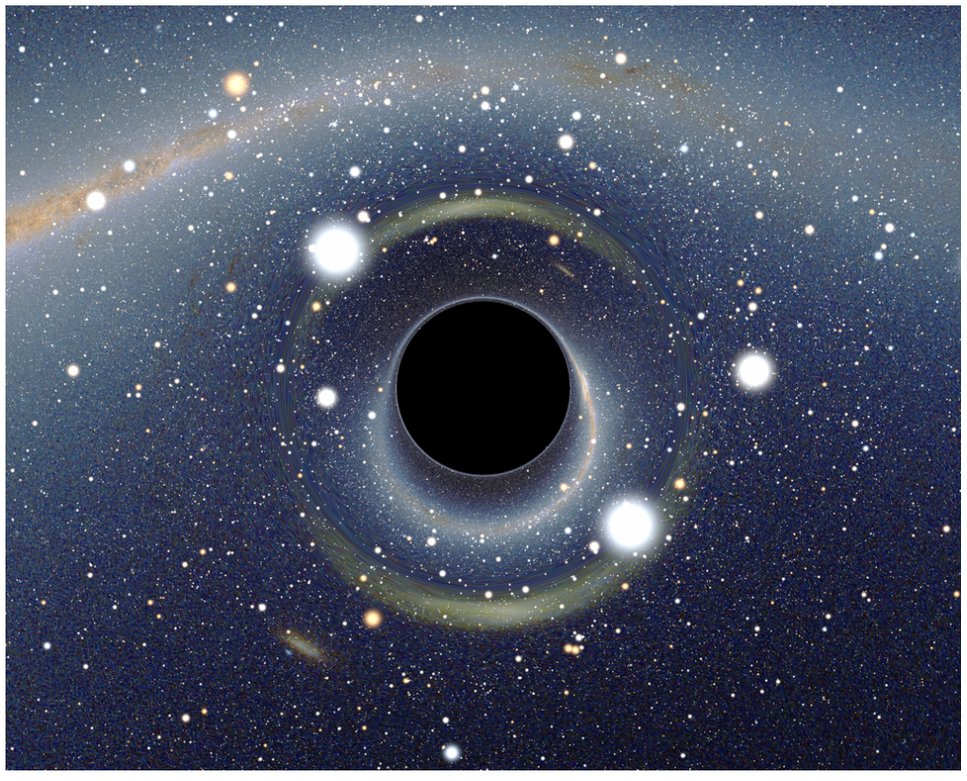
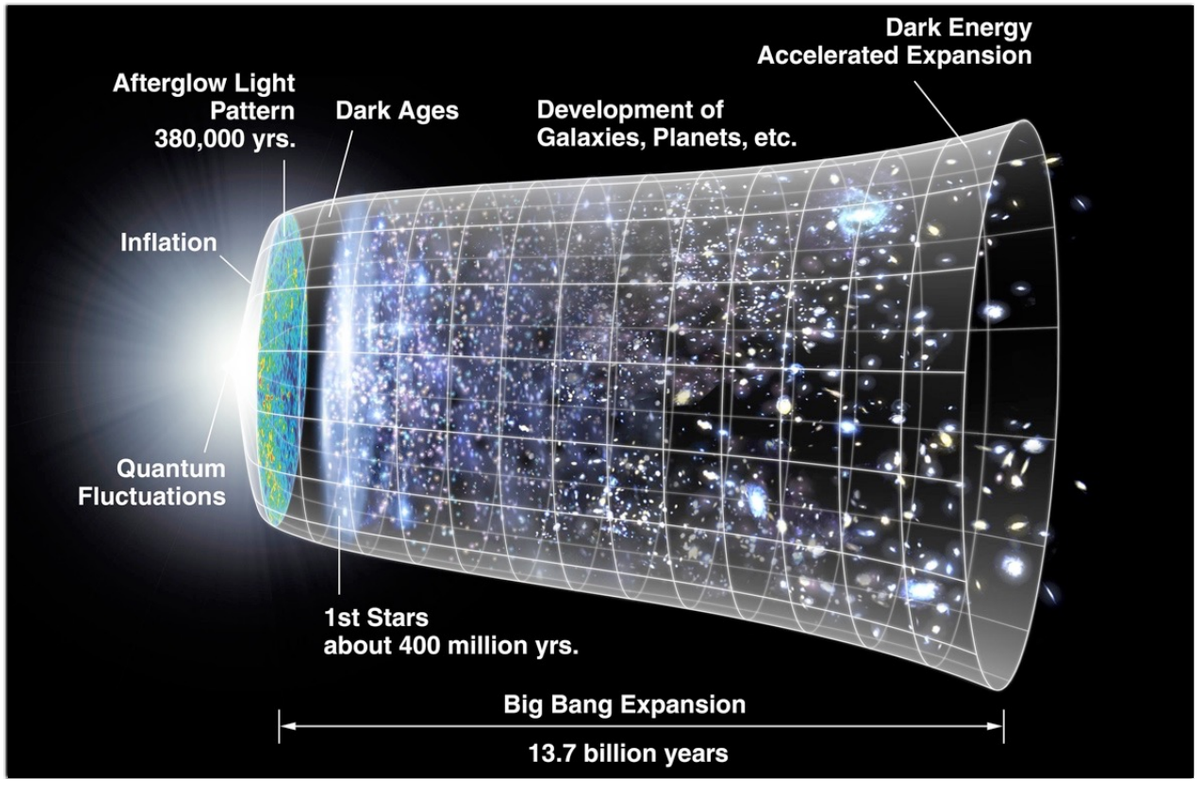




- divergences in QFT - what happens at high energies? how does spacetime react to such high energies?
- what happens to quantum fields close to big bang? what generates cosmological fluctuations, and how?
- no proper understanding of interaction of geometry with quantum matter, if gravity is not quantized

Quantum Gravity:

a deeper understanding of the nature of space and time

Quantum Gravity:

a deeper understanding of the nature of space and time

we have to learn to think deeper about the nature of space and time themselves,
thus we have to learn to
(re-)**think the world without (assuming) space and time**

Quantum Relativistic Time?

time disappears

time acquires a probabilistic nature?

time loses its continuum nature?

Nature of spacetime: quantum counterpart of GR issues

merging the GR and quantum revolution $\longrightarrow$ spacetime is physical quantum system

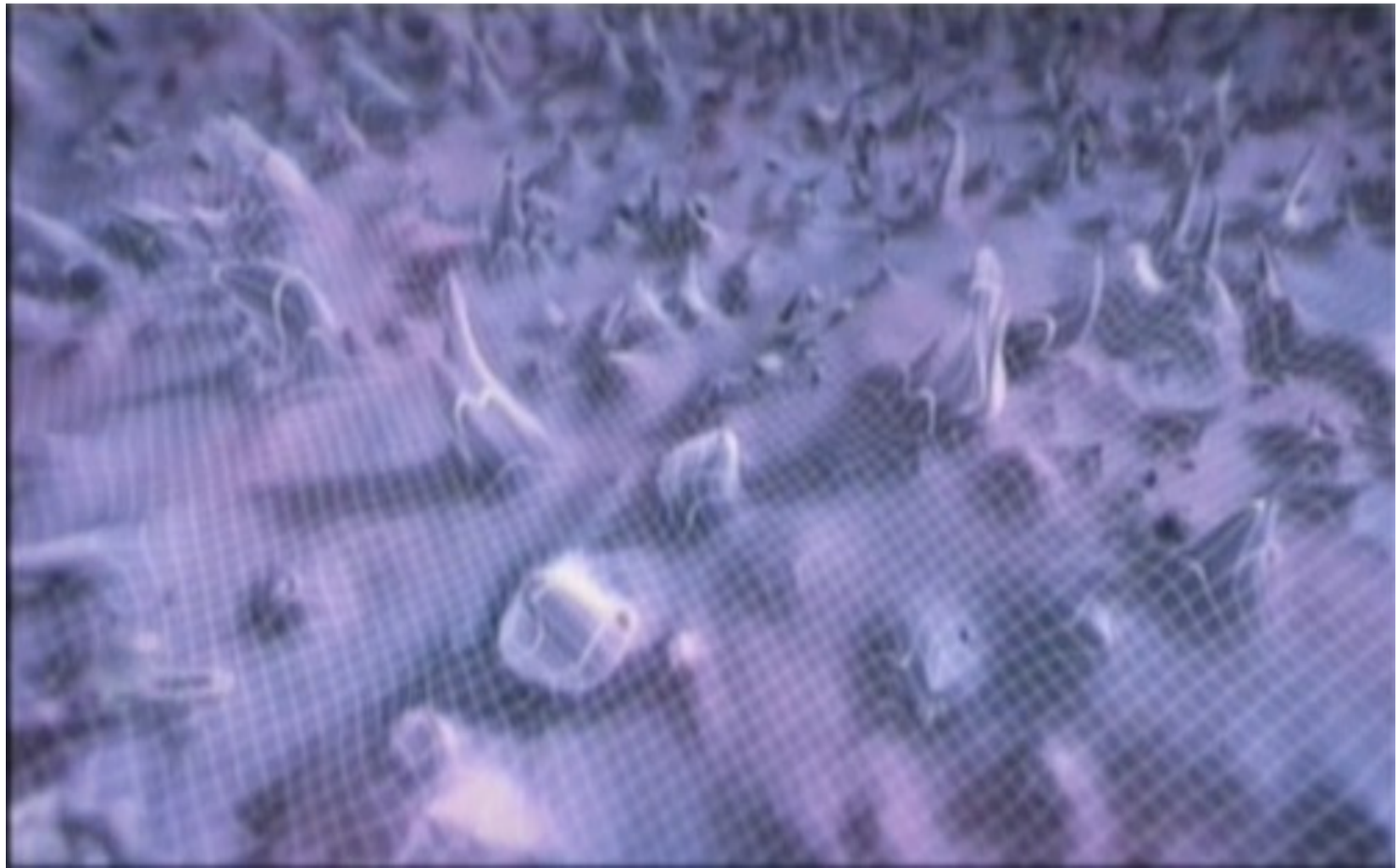
the bare minimum: quantized GR - already radical new features of spatiotemporal notions

$$g_{\mu\nu}(t,x) \quad \Longrightarrow \quad \widehat{g_{\mu\nu}(t,x)}$$

(a priori) all spacetime notions subject to quantum uncertainty, superpositions, interference, entanglement

e.g. superposition of geometries

no sharp meaning for any spacetime notion (eg events)



Beyond Relativistic Time - quantum relativistic time and space, and causality, ….

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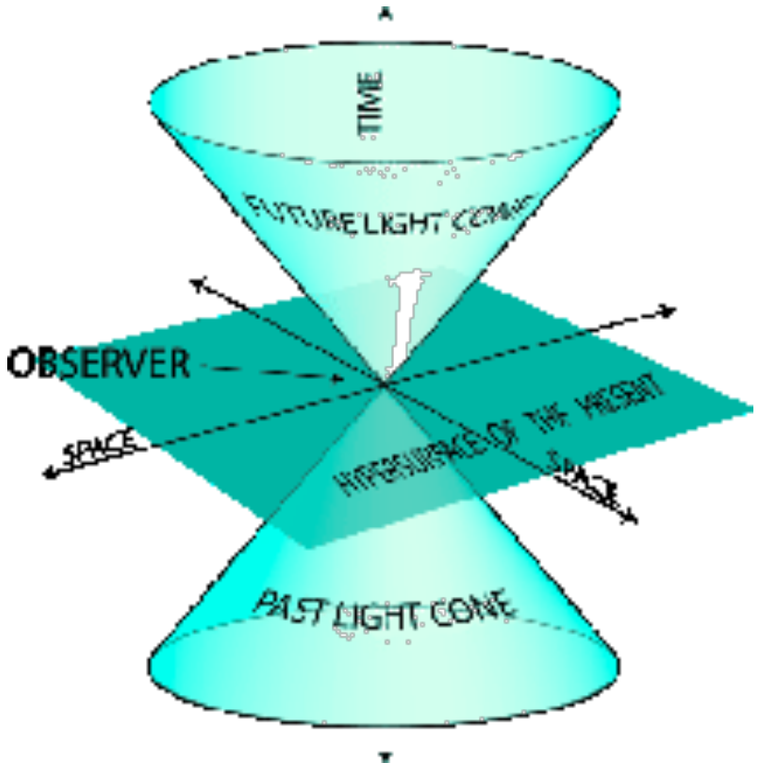
Causality itself “fluctuates”



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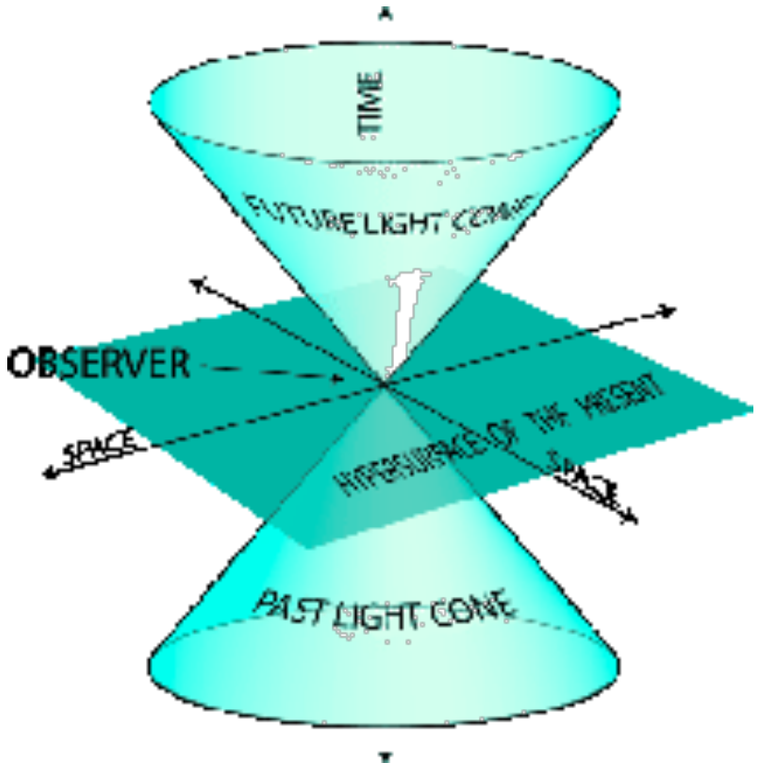

geometric quantities (distances, time intervals, volumes, ….) may be discretized

minimal length, volume, ..?

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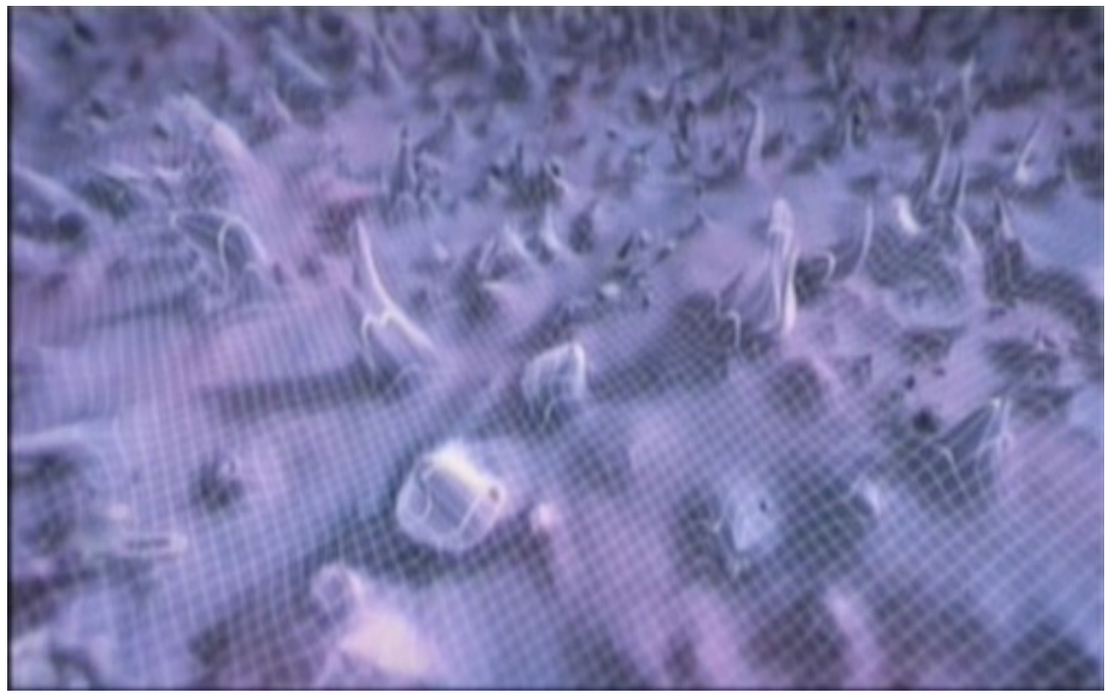
the bare minimum: quantized GR - already radical new features of spatiotemporal notions

$$g_{\mu\nu}(t,x) \quad \Longrightarrow \quad \widehat{g_{\mu\nu}(t,x)}$$

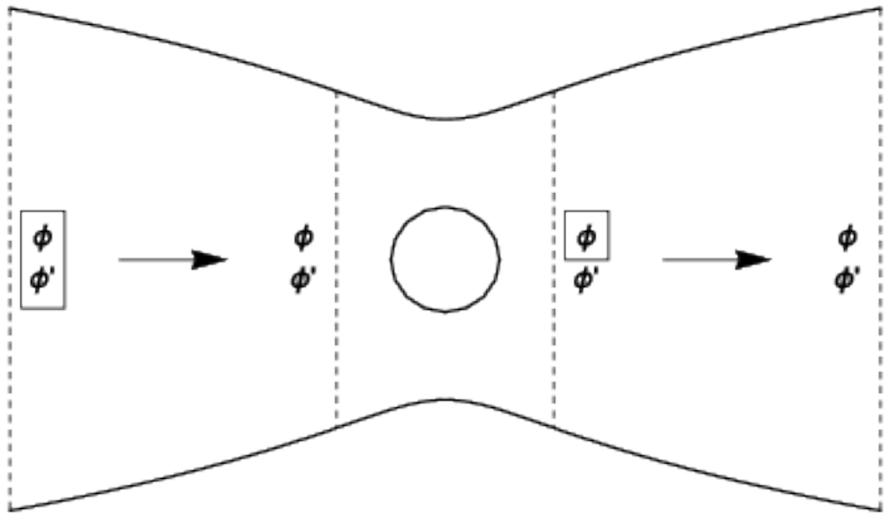
possible degenerate configurations (zero volume element) - no well-defined spacetime geometry at some point/region



possible signature change: from Lorentzian geometry/spacetime to Riemannian geometry/spacetime

e.g in place of cosmological (classical) singularity

no temporal evolution at all (but space maintains its meaning)



a quantum (relativistic) Time will already be way beyond our current understanding of temporal concepts (and related)

Even more radical disappearance of time at fundamental quantum gravity level?

time stops making sense altogether?

Beyond Time - hints of more radical disappearance of spacetime itself

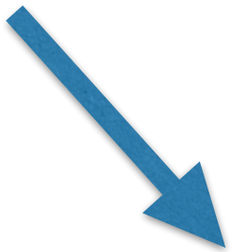
- challenges to “localization” in semi-classical GR — minimal length scenarios
- spacetime singularities in GR — breakdown of continuum itself?
- black hole thermodynamics — black holes satisfy thermodynamic relations
- black hole information paradox — some fundamental principle has to go: is it locality?

- Einstein’s equations as equation of state

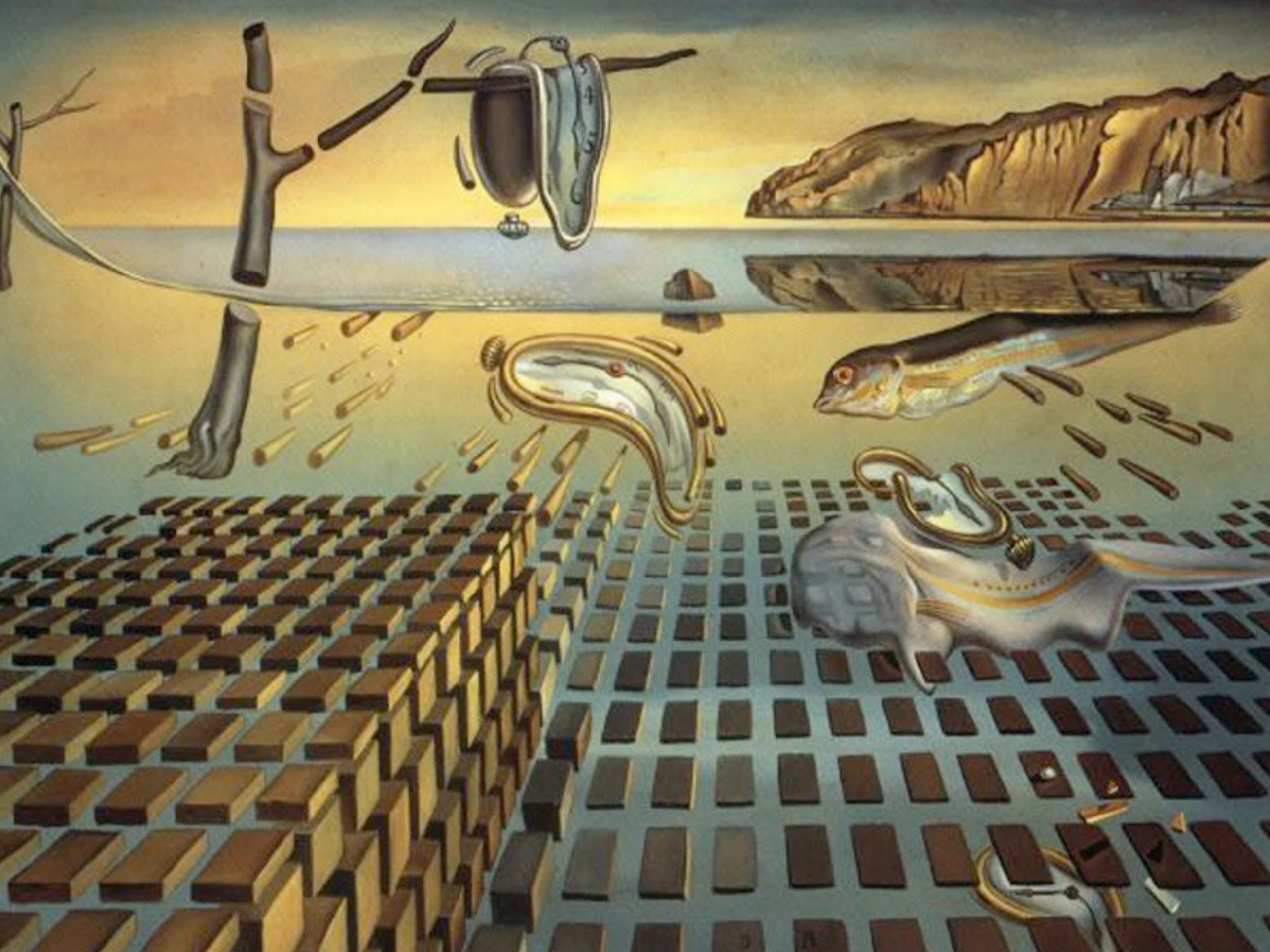
GR dynamics is effective equation of state for any microscopic dofs collectively described by a spacetime, a metric and some matter fields

- entanglement ~ geometry

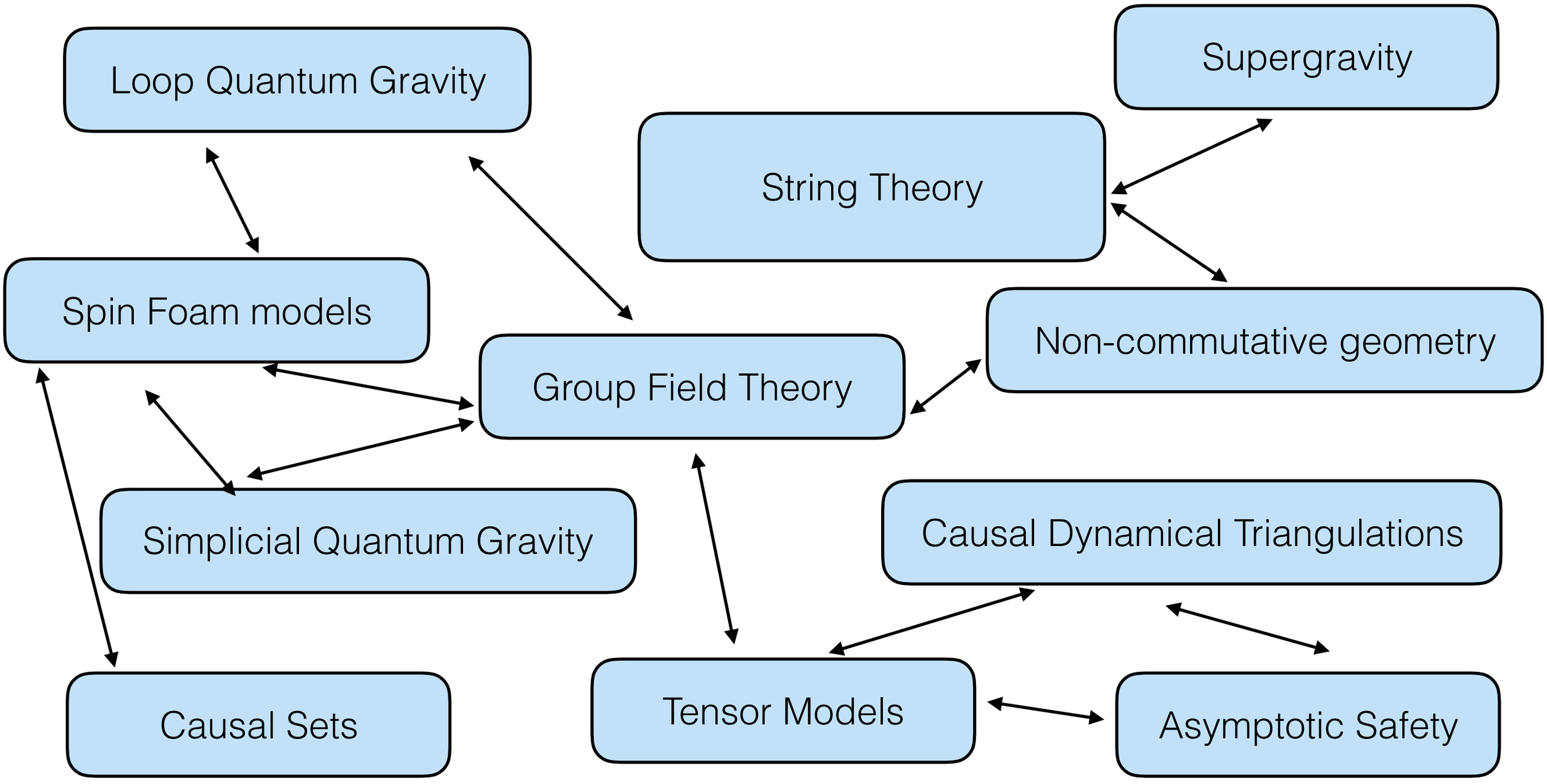
geometric notions defined by quantum (information) notions (examples from AdS/CFT, and various quantum many-body systems)



fundamental discreteness of spacetime? locality loses any meaning?
is spacetime itself “emergent” from non-spatiotemporal, non-geometric, quantum building blocks (“atoms of space”)?



Quantum Gravity: contemporary approaches



Quantum Gravity: a new perspective

many current approaches suggest a change of perspective on the quantum gravity problem

traditional perspective:
quantise gravity (i.e. spacetime geometry)

i.e. obtain a quantum version of General Relativity (or some modification of it)
possibly with new types of matter fields or interactions

new perspective:
identify quantum structures/building blocks of non-spatiotemporal nature from which spacetime and geometry “emerge” dynamically

problem becomes similar to the typical one in condensed matter theory (from atoms to macroscopic physics)

Emergent Time (and Space)?

notion of emergence itself is tricky

Nagel, Battermann, Butterfield, Hartmann, Maudlin, …..

understanding/defining concept of emergence of spacetime even trickier

need a “spacetime free” notion of emergence to start with

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QG context:

show emergence of space and time = define an approximation/limiting procedure that leads from non-spatio-temporal, fundamental QG degrees of freedom (and their dynamics) to continuum spacetime and geometry (and their GR dynamics)

Emergent Time (and Space)

examples of non-spatiotemporal structures in Quantum Gravity

geometry from combinatorics and algebra!

example: the “atoms of space” in Loop Quantum Gravity

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kinematical Hilbert space of quantum states:

$$\mathcal{H} = \lim_{\gamma} \frac{\bigcup_\gamma \mathcal{H}_\gamma}{\approx} = L^2\left(\bar{\mathcal{A}}\right)$$

$$\mathcal{H}_\gamma = L^2\left(G^E/G^V, d\mu = \prod_{e=1}^{E} d\mu_e^{Haar}\right)$$

G= SU(2)

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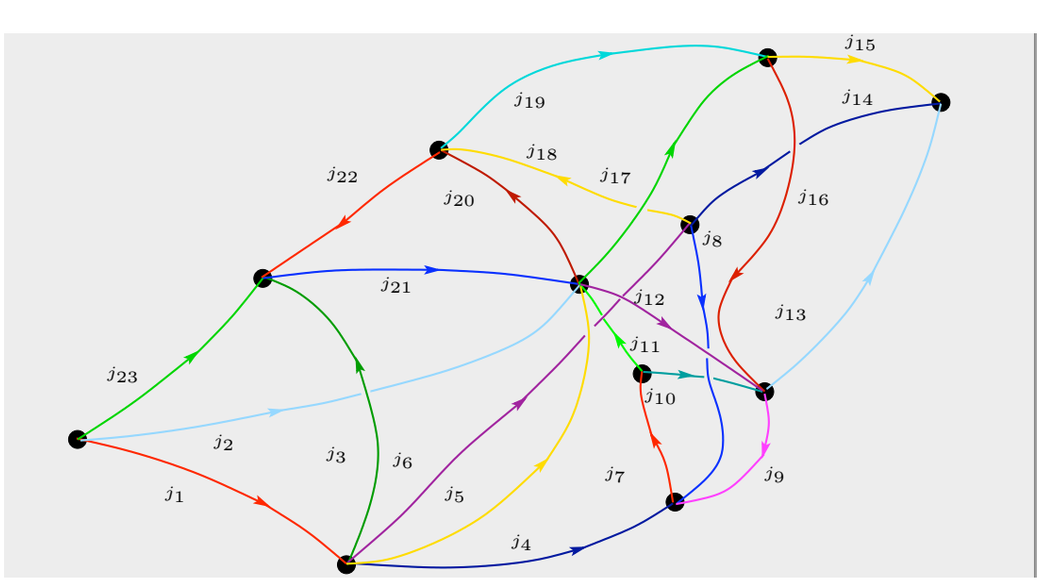
spanned by purely algebraic and combinatorial states: spin networks

Rovelli, Smolin, ‘95



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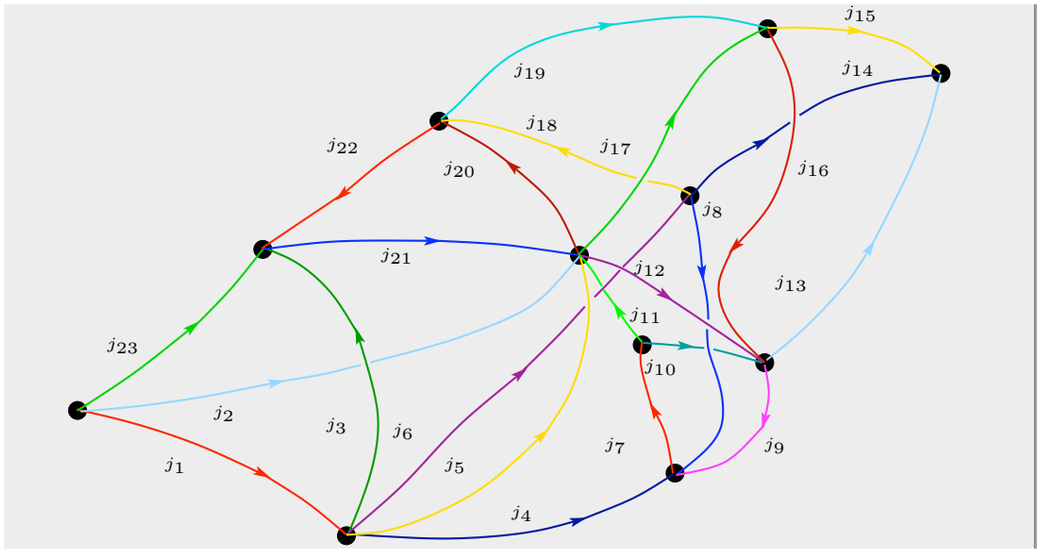
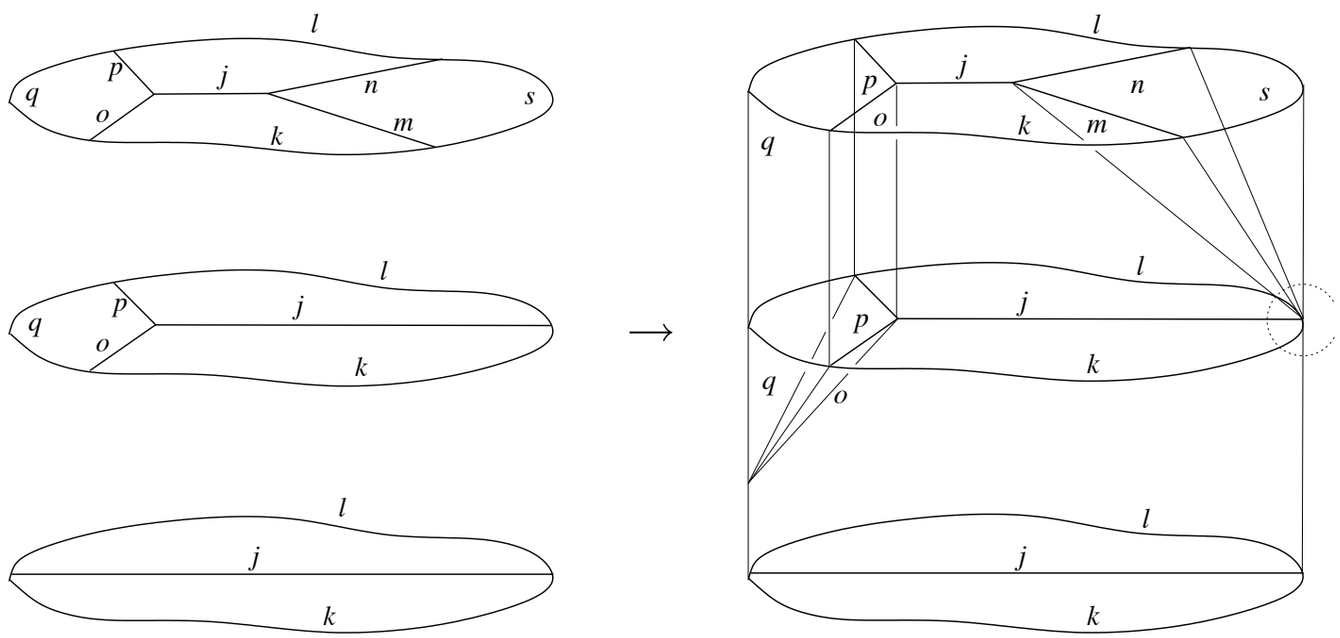


whose “histories” (dynamical interaction processes) are also purely algebraic and combinatorial: spin foams



(Barbieri, Baez, Barrett, Crane, Reisenberger, Perez, De Pietri, Engle, Pereira, Freidel, Krasnov, Rovelli, Livine, Speziale, Baratin, DO, ...)

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Quantum field theories over group manifold G (not spacetime!) $\varphi : G^{\times d} \to \mathbb{C}$

Hilbert space of quantum states:

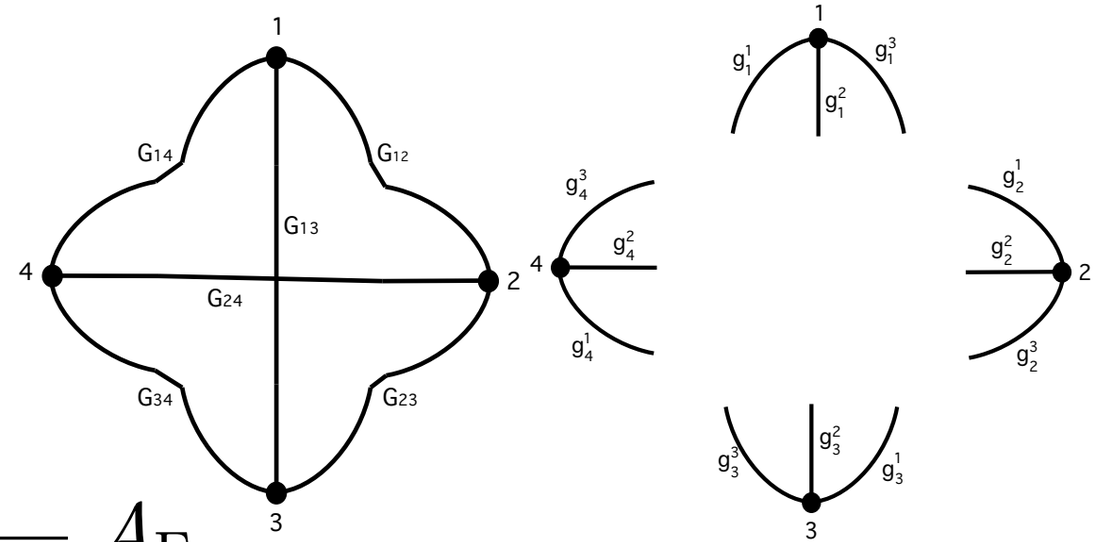
$$\mathcal{F}(\mathcal{H}_v) = \oplus_{V=0}^{\infty} \, sym\left\{\left(\mathcal{H}_v^{(1)} \otimes \mathcal{H}_v^{(2)} \otimes \cdots \otimes \mathcal{H}_v^{(V)}\right)\right\} \qquad \mathcal{H}_v = L^2\left(G^{\times d}/G\right)$$

DO, ‘13

(Fock space = space of “disconnected spin network vertices”)

spin networks arise as specific “many-quanta” GFT states

GFT quanta = spin network vertices, created/annihilated out of Fock vacuum (with no topological/geometric information)



$$\mathcal{Z} = \int \mathcal{D}\varphi \mathcal{D}\overline{\varphi} \; e^{i\, S_\lambda(\varphi,\overline{\varphi})} \quad = \quad \sum_\Gamma \frac{\lambda^{N_\Gamma}}{sym(\Gamma)} \, \mathcal{A}_\Gamma$$

a QFT of atoms of space

fundamental pre-geometric quantum discreteness

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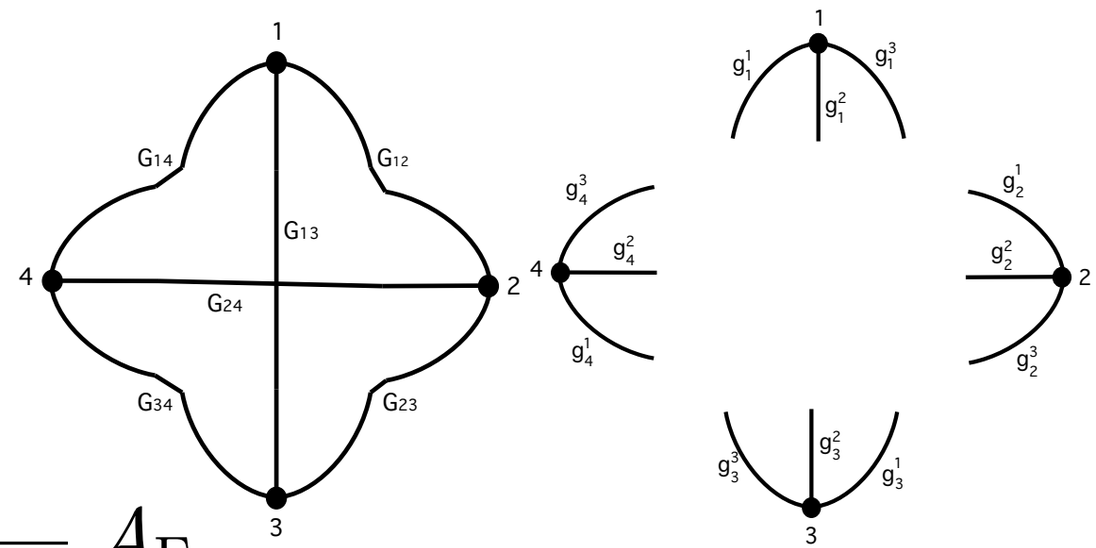

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Feynman diagrams = stranded diagrams dual to cellular complexes of arbitrary topology ~ spin foams

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Spacetime as a “substance” made out of non-spatiotemporal “constituents”? atoms of space?

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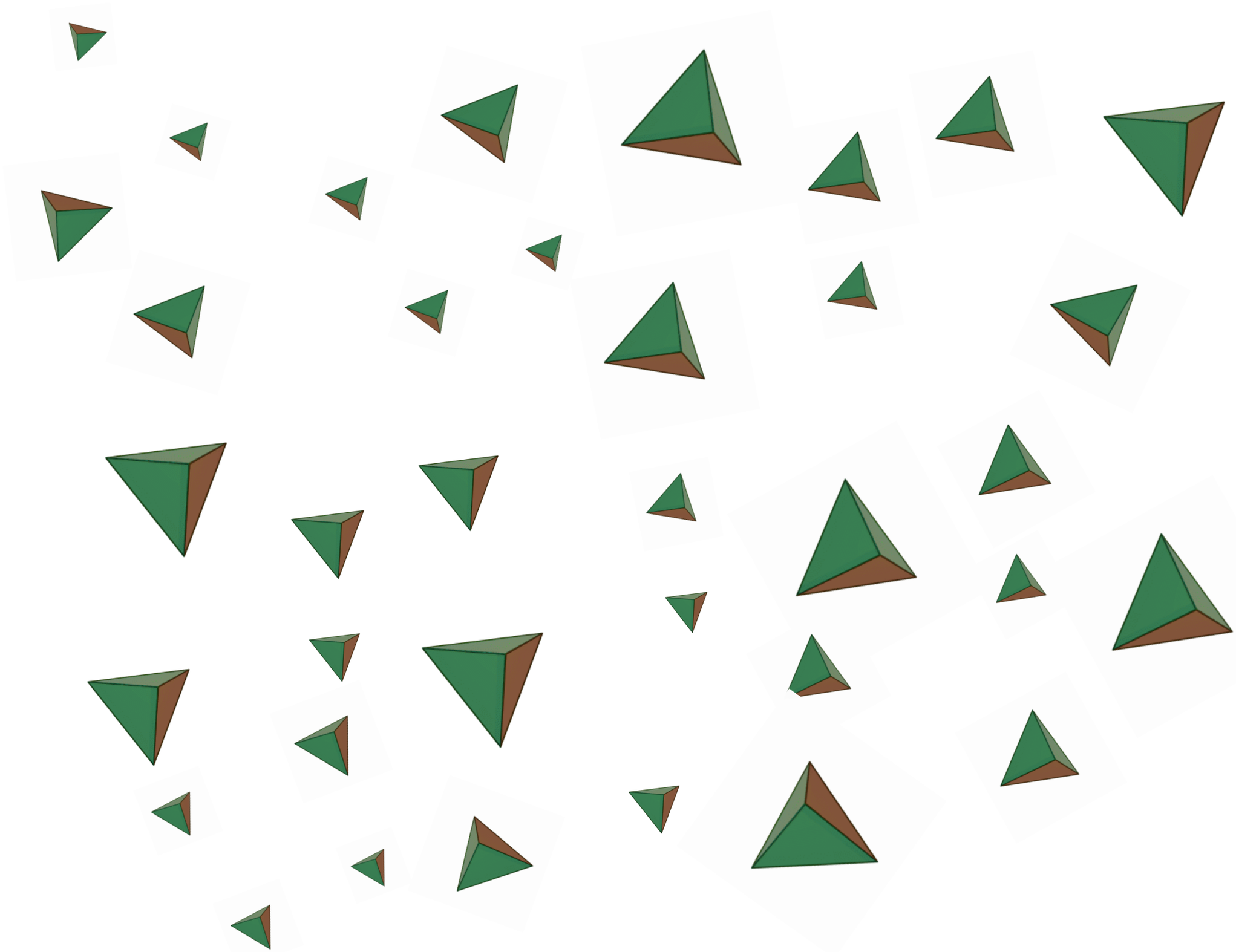


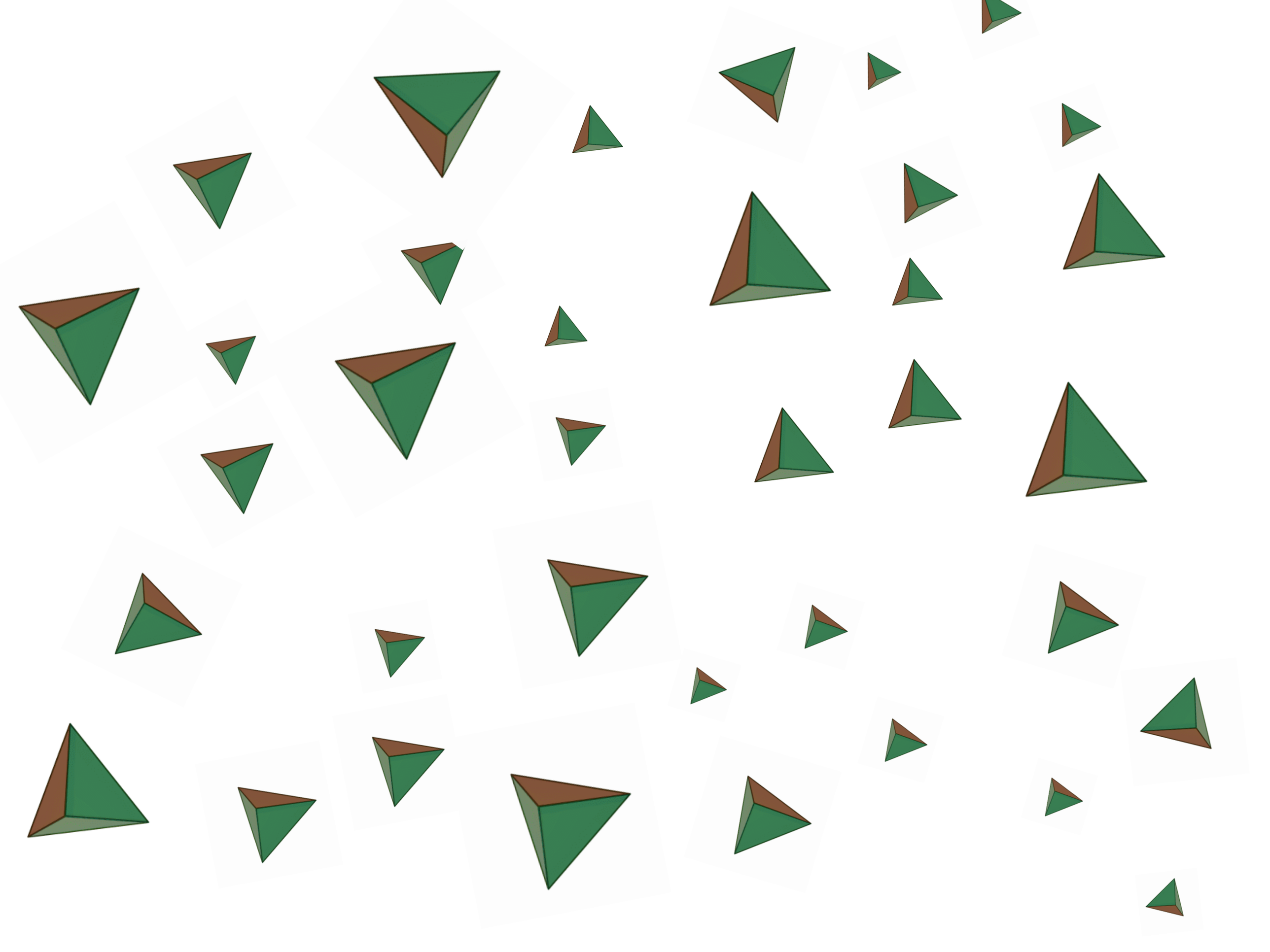
Even more radical disappearance of time at fundamental quantum gravity level?

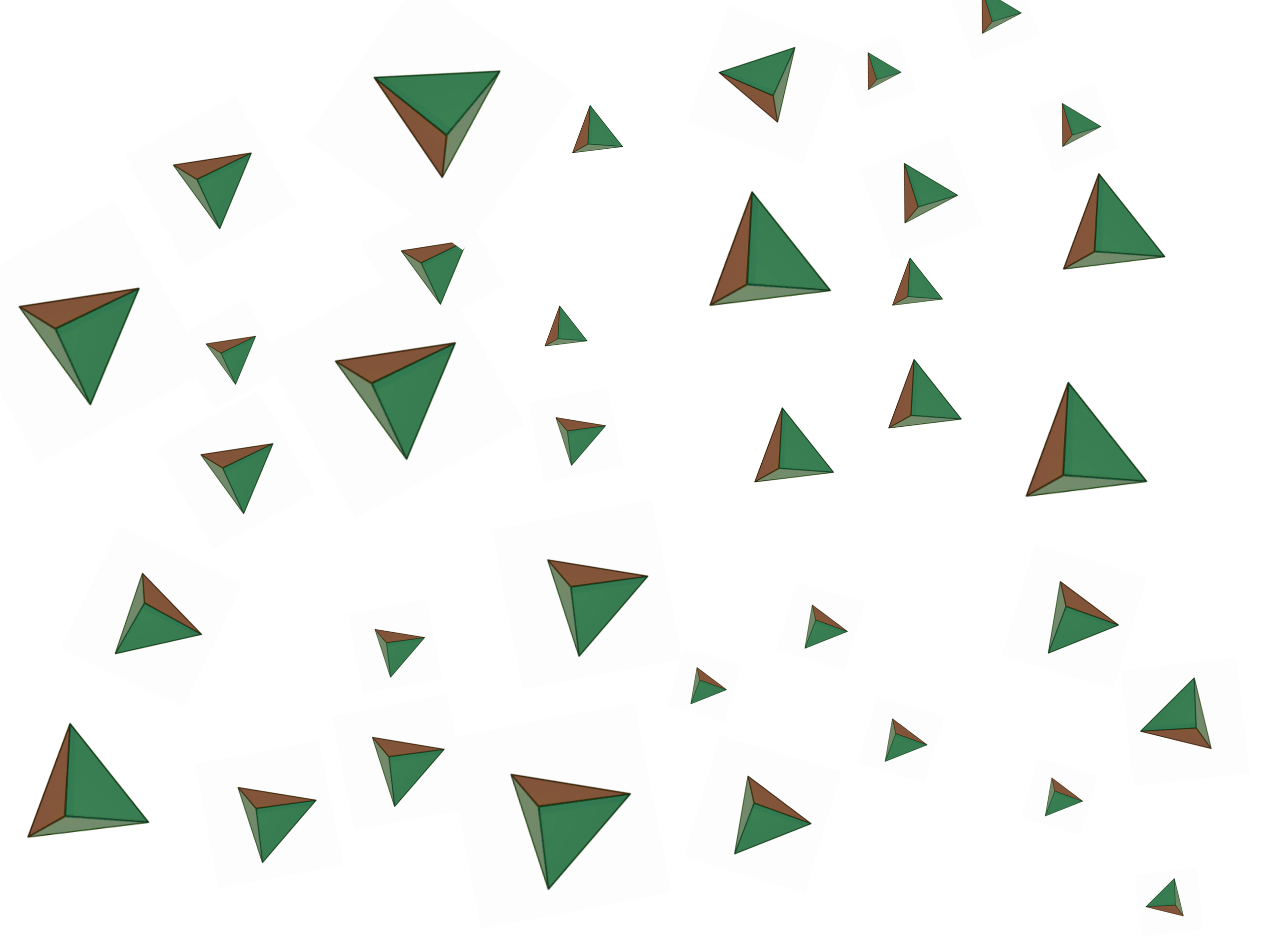
time stops making sense altogether?

but then…. how does spacetime emerge?

how does the universe (space, time) “emerge”
from such fundamental constituents?

universe as a “condensate” of the “atoms of space”?





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example of spacetime emergence in Quantum Gravity

GFT condensate Cosmology:

S. Gielen, DO, L. Sindoni, G. Calcagni, M. Sakellariadou,
E. Wilson-Ewing, A. Pithis, M. De Cesare, …….

problem 1:
identify quantum states in fundamental theory with approximate continuum spacetime interpretation

Quantum GFT condensates are continuum homogeneous (quantum) spaces

appropriate observables in fundamental theory acquire
spatiotemporal interpretation (e.g. volume of universe, ..)

described by single collective wave function
(depending on homogeneous anisotropic geometric data)

with correct classical limit, producing a quantum bounce, …

many recent results!

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cosmology as QG hydrodynamics!!!

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Even more radical disappearance of time at fundamental quantum gravity level

time stops making sense altogether

it can only be approximate, collective, emergent notion

but then…. how does spacetime emerge?

time (and space, and geometry) may emerge as “hydrodynamic observable” in particular phase of fundamental (and non-spatiotemporal) quantum gravity system (based on “pre-geometric” building blocks)

recap:

levels of disappearance and emergence of space and time in quantum gravity

and new issues and possibilities……

Emergent Time (and Space)

3 levels of emergence for space and time

level 0: from quantum spacetime to classical spacetime

fundamental dofs are “quantum continuum geometries”, result of “quantizing spacetime/metric”

“emergence of space and time”

if continuum spacetime and geometry are obtained from different, discrete structures, issue is:

are these pre-geometric structures physical (or just regularisation tools)?

if physical, then:

level I: from “atoms of space” to continuum (quantum) spacetime, approximately

emergence of space and time

Multiple QG phases?

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- physical (quantum) systems, in general, do not have a unique continuum (thermodynamic) limit:
it depends on value of coupling constants

collective behaviour of (interacting) fundamental d.o.f.s leads to different macroscopic phases,
separated by phase transitions

- for a non-spatio-temporal QG system (LQG and GFT),

what are the macroscopic phases?

what is the right phase of “geometric physics”? in which phase does a spacetime emerge?

in canonical LQG context:
T. Koslowski, 0709.3465 [gr-qc]

in covariant SF/GFT context:
DO, 0710.3276 [gr-qc]

in random tensor models
V. Rivasseau, ‘13

A. Kegeles, DO, ‘18

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recent progress in several QG approaches ….

- renormalization group analysis of spin foam and GFT models

B. Bahr, B. Dittrich, ’09, ’10; B. Bahr, B. Dittrich, F. Hellmann, W. Kaminski, ‘12

Ben Geloun, Rivasseau, ’11; Carrozza, DO, Rivasseau, ’12. ’13; Lahoche, DO, ’15; Carrozza, Lahoche, DO, ‘16

Benedetti, Ben Geloun, DO, ’14 ; Ben Geloun, Martini, DO, ’15, ’16, Benedetti, Lahoche, ’15; Duarte, DO, ‘16

- inequivalent representations (macroscopic phases) in LQG and GFT

T. Koslowski, H. Sahlmann, '11

S. Gielen, DO, L. Sindoni, ‘13

B. Dittrich, M. Geiller, ‘14

A. Kegeles, DO, ‘18

Space and Time in Quantum Gravity - Level II

if non-trivial Quantum Gravity phase diagram exists,

time and space are “even more dissolved” than they were at level 1

(no unique conceptual or technical path from the atoms of space to continuum quantum fields and spacetime)

this implies:

the atoms of space do not and cannot have spatio-temporal properties

(e.g. possible “elementary volume/extension attributes”)

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even deeper, true “emergence”:

fundamental degrees of freedom of spacetime may -not- give rise to spacetime at all, in any approximation

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if different phases are possible:

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emergence^{+} of space and time

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non-trivial phase diagram (different possible phases) → phase transitions

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from non-geometric phase (no spacetime and geometry even at macroscopic scales)

↓

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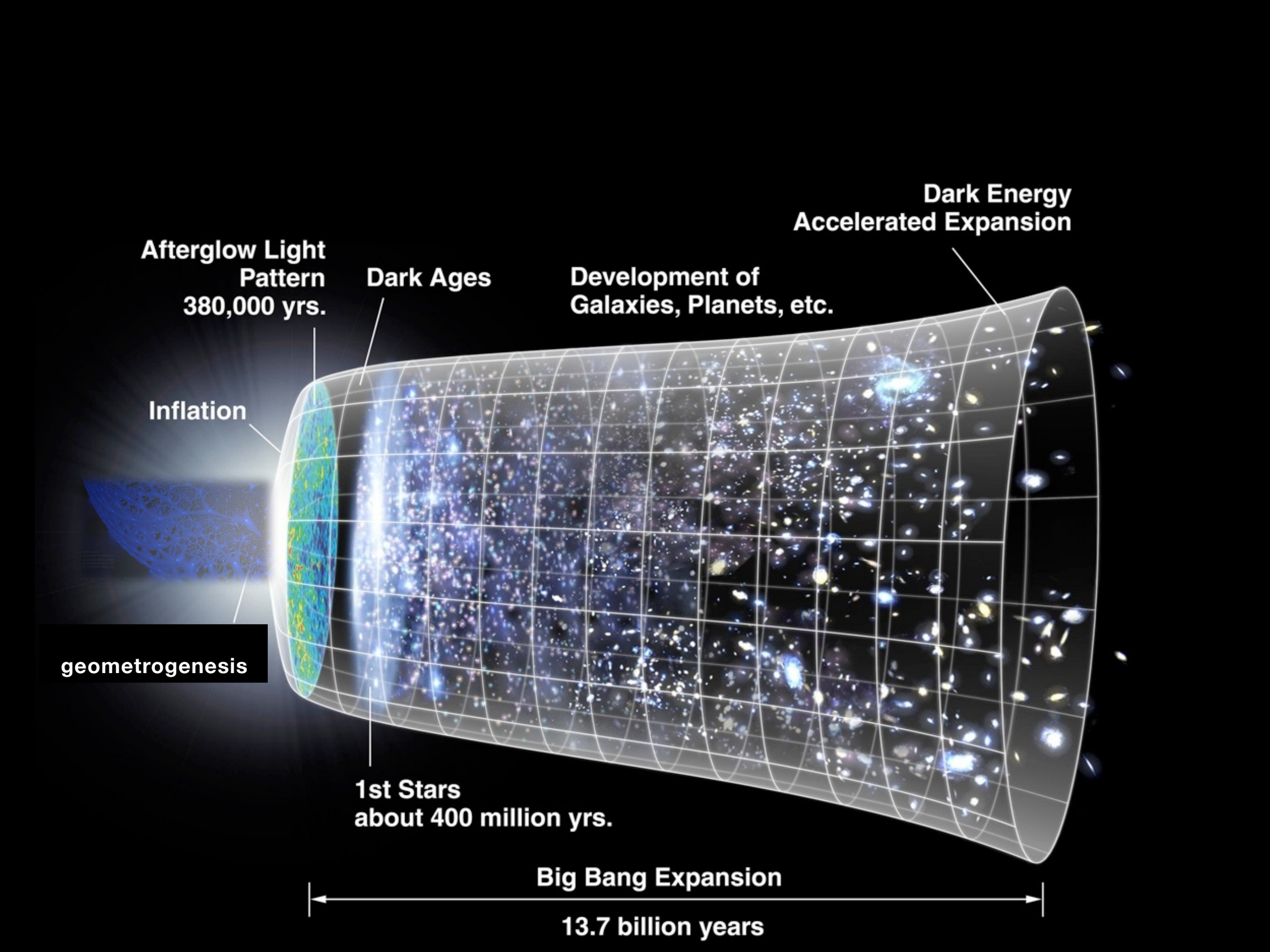
(...., Hu ’95;….; Konopka-Markopoulou-Smolin, ’06; Volovik, ’04, ’11, ’12; DO ’07, ’11, ’13)


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
geometrogenesis
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Space and Time in Quantum Gravity - level III

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Time and dynamical evolution in the geometrogenesis scenario

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Space and Time in Quantum Gravity - level III

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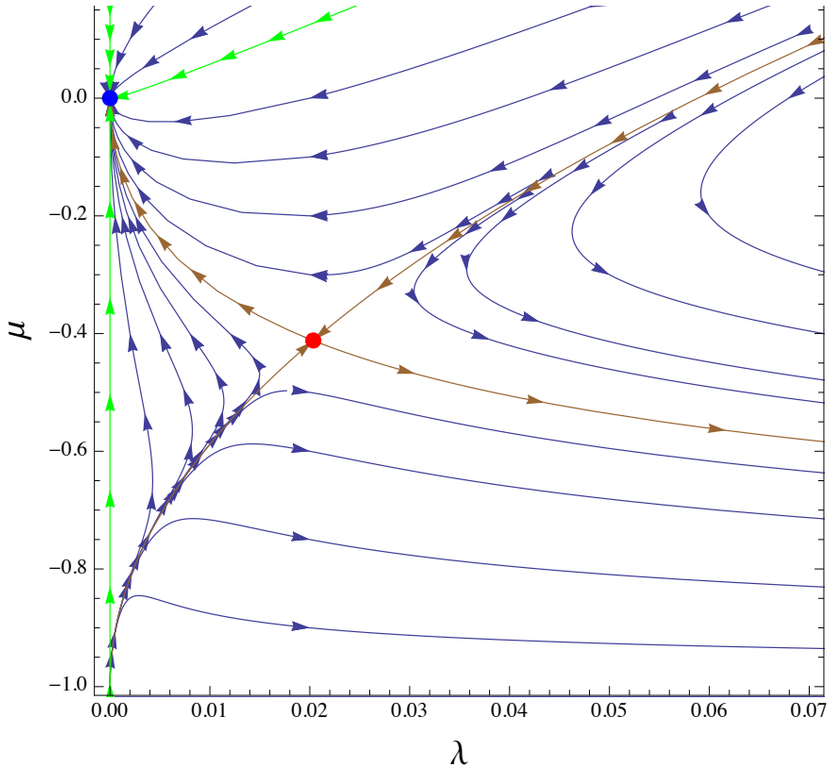

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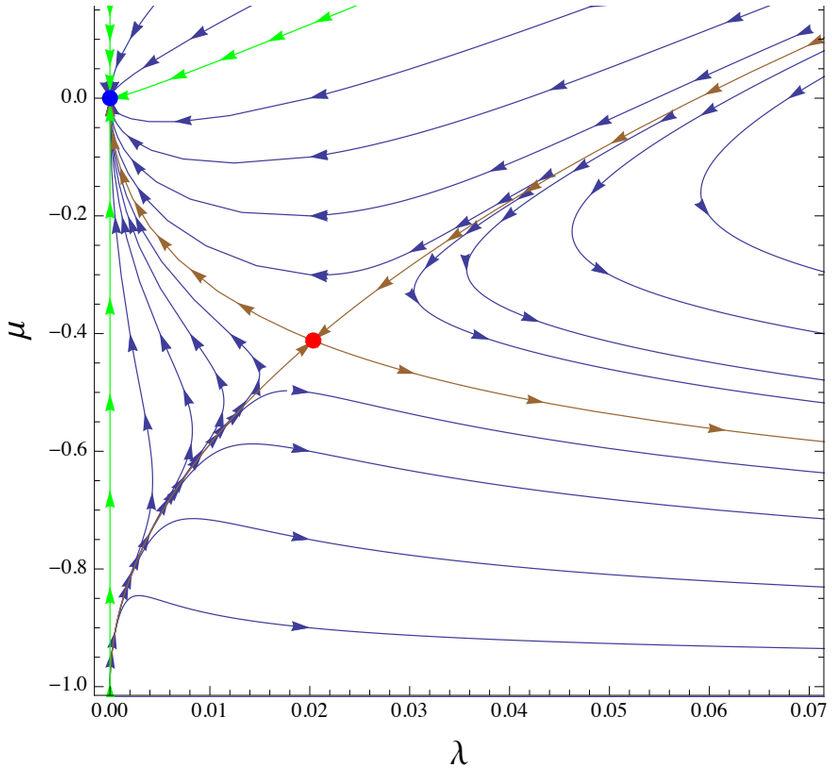

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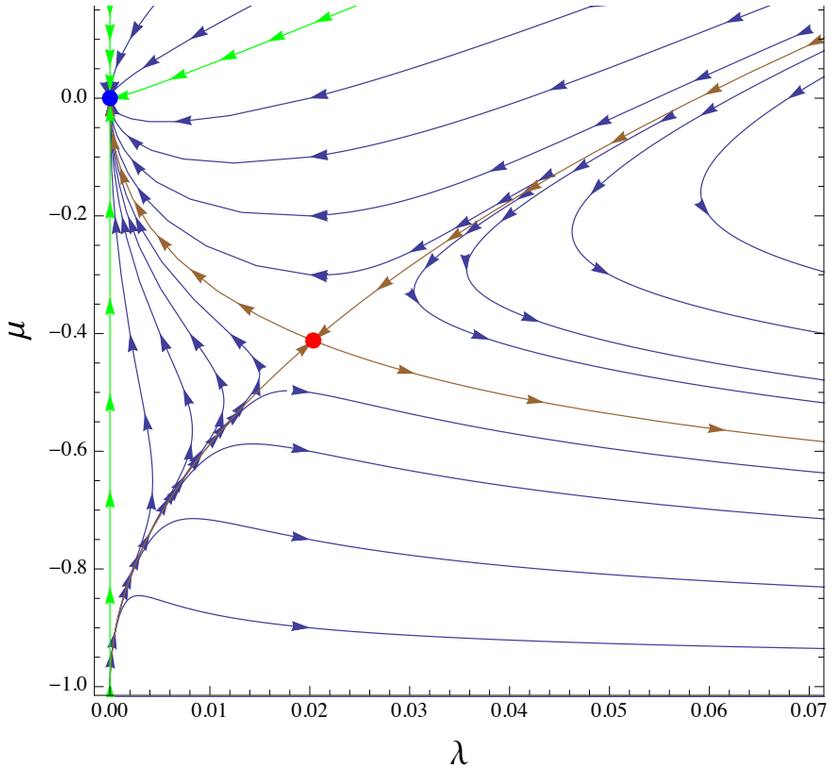

three related problems:

no external observer tuning the coupling constants

timelessness of QG (and GR): no time in QG framework

timelessness of statistical field theory: no time interpretation of phase diagram and of RG flow (at equilibrium)

Emergent Time (and Space)

3 levels of emergence for space and time

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level 0: from quantum spacetime to classical spacetime

fundamental dofs are “quantum continuum geometries”, result of “quantizing spacetime/metric”

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if atoms of space are physical, and can organize in different phases, are these phases all physical?

if physical, then phase transitions are physical as well:

level III: from “atoms of space” to continuum (quantum) spacetime, approximately, or to something different, as a physical, dynamical process (geometrogenesis)

emergence^{++} of space and time

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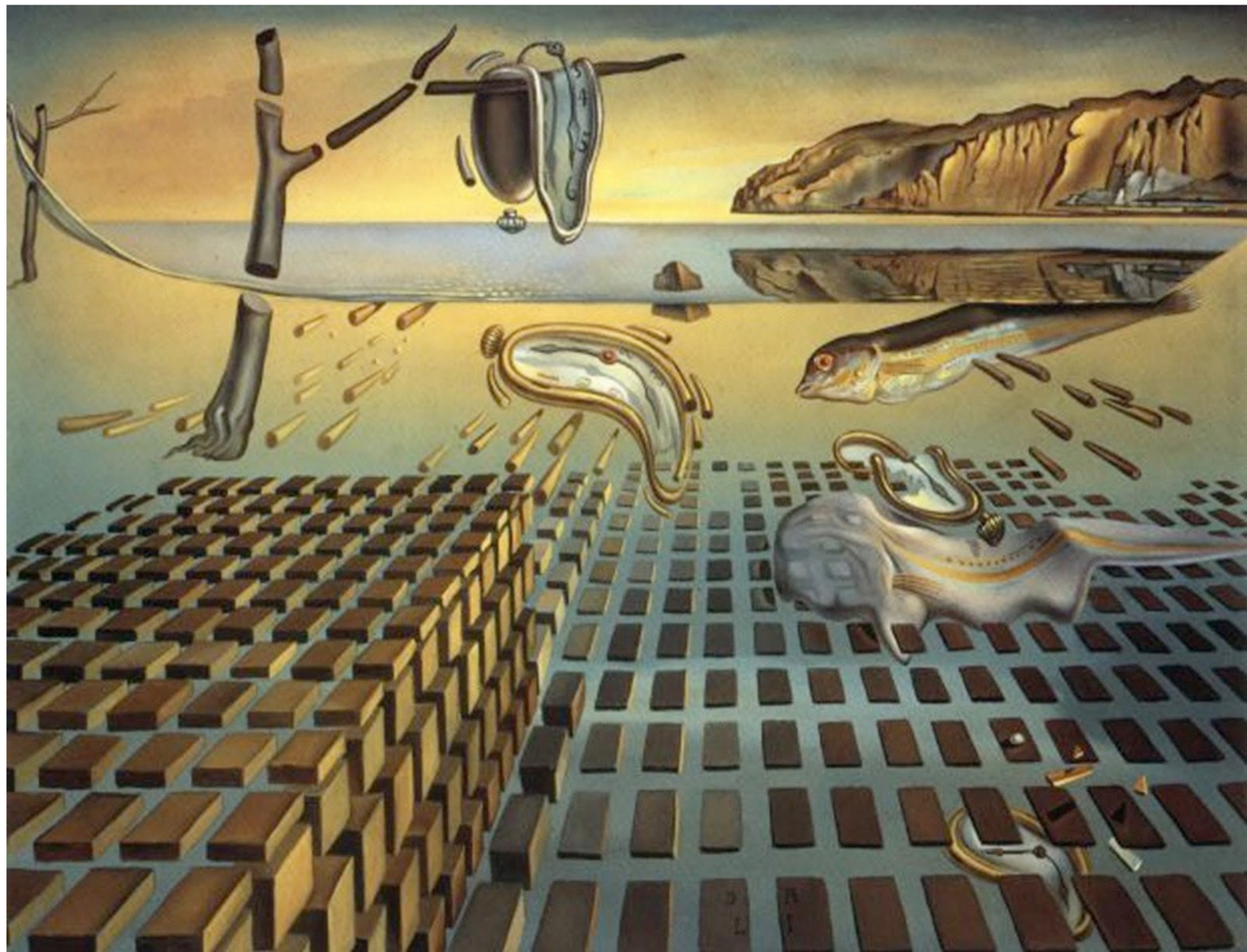
prima facie ontological issues with spacetime emergence



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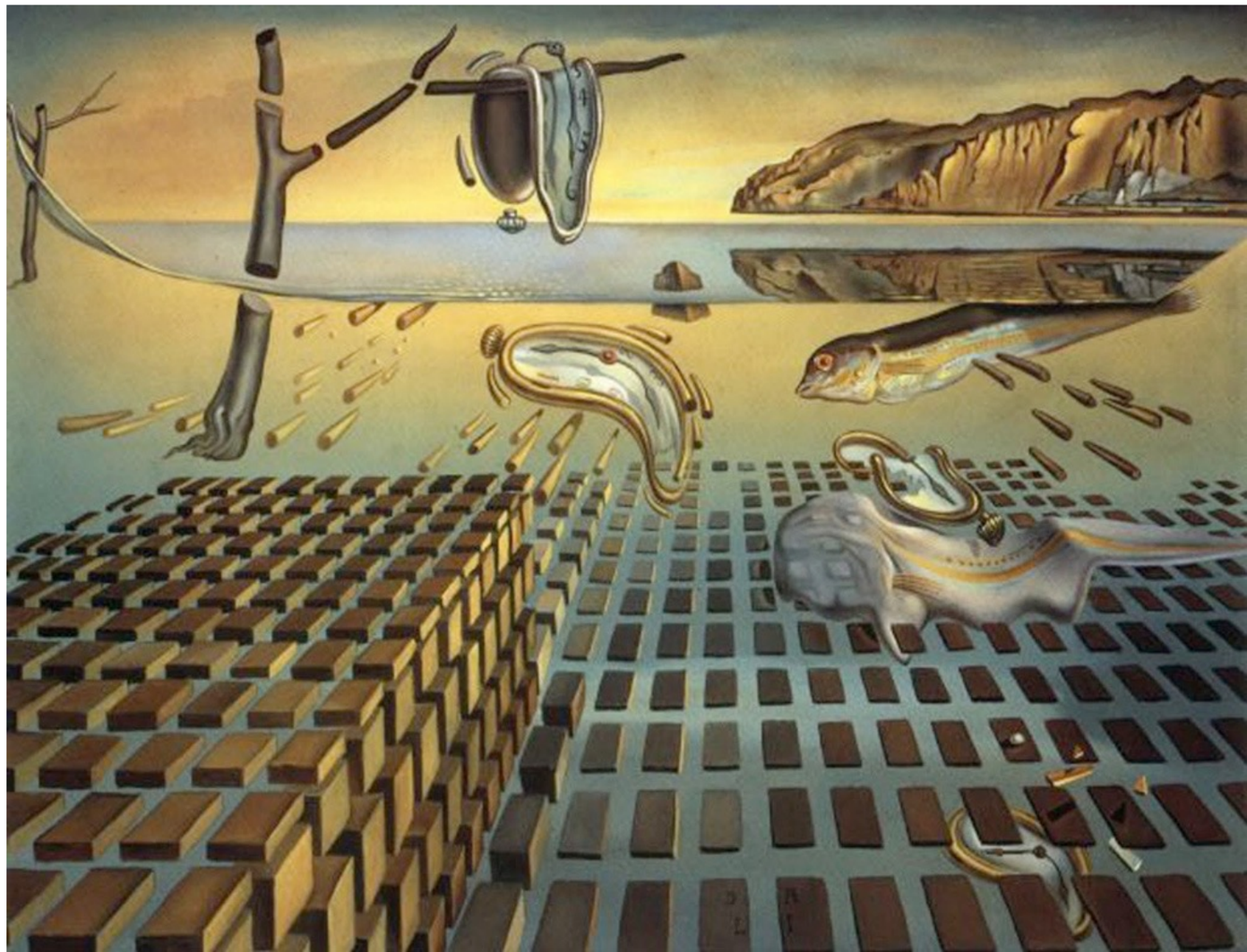

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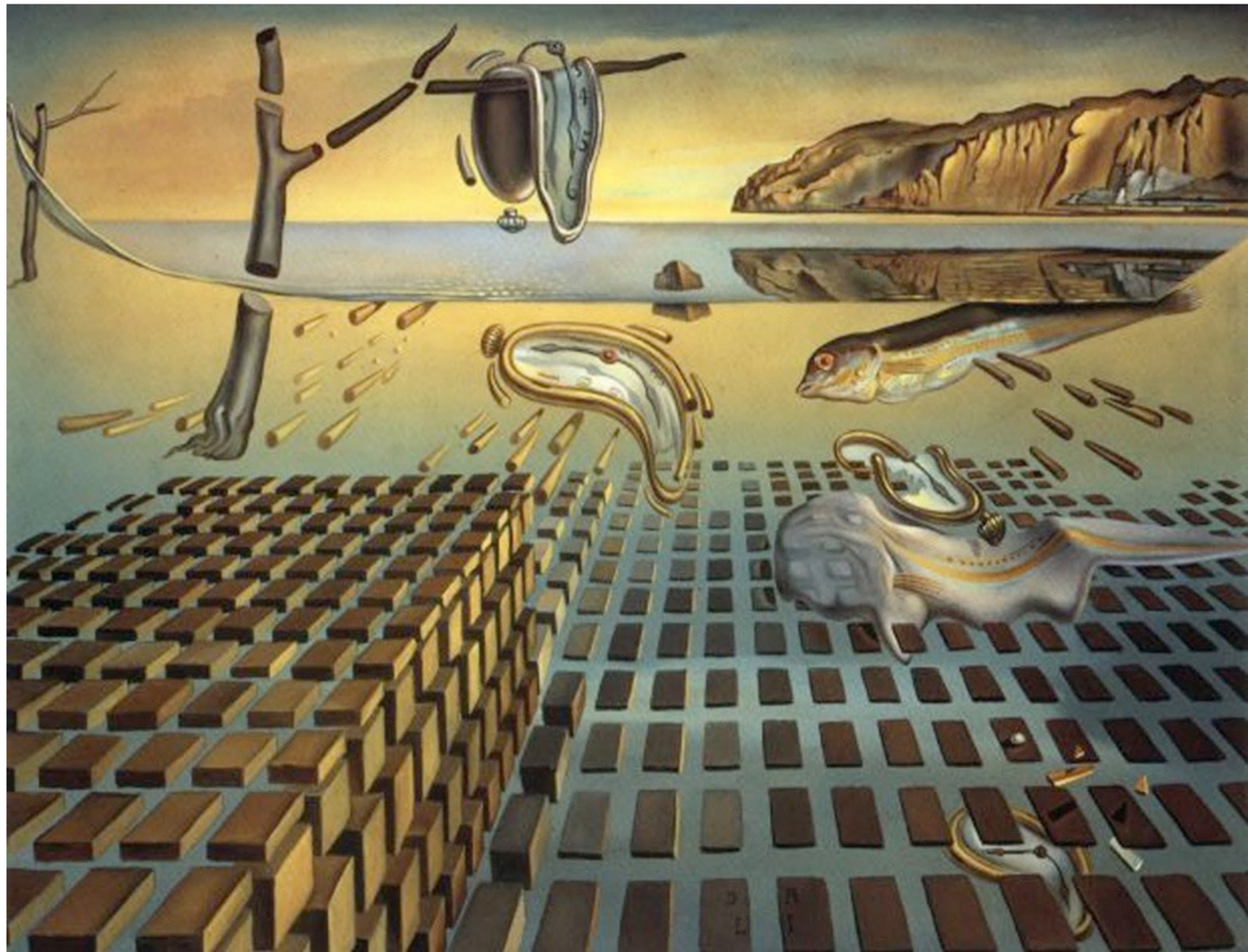

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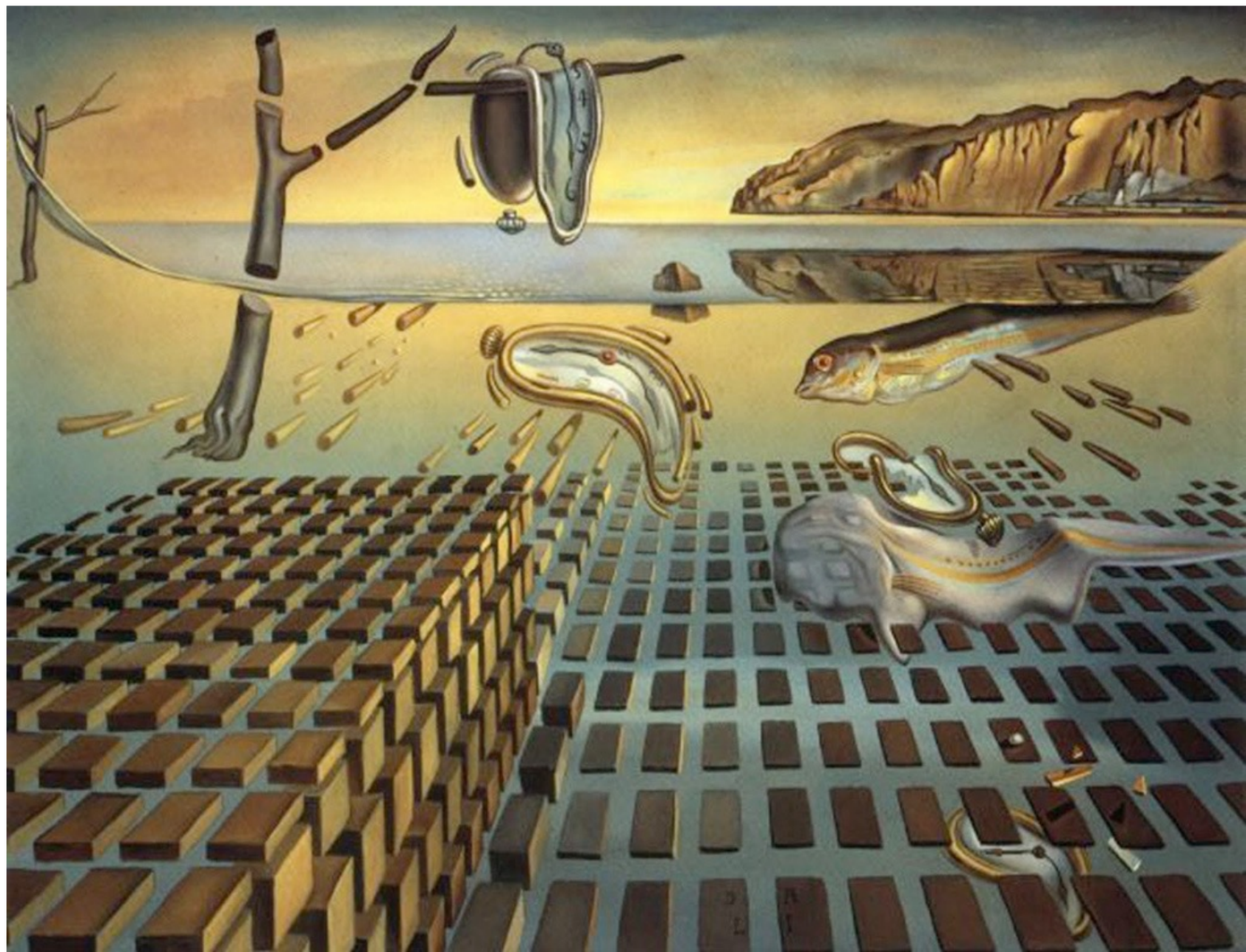

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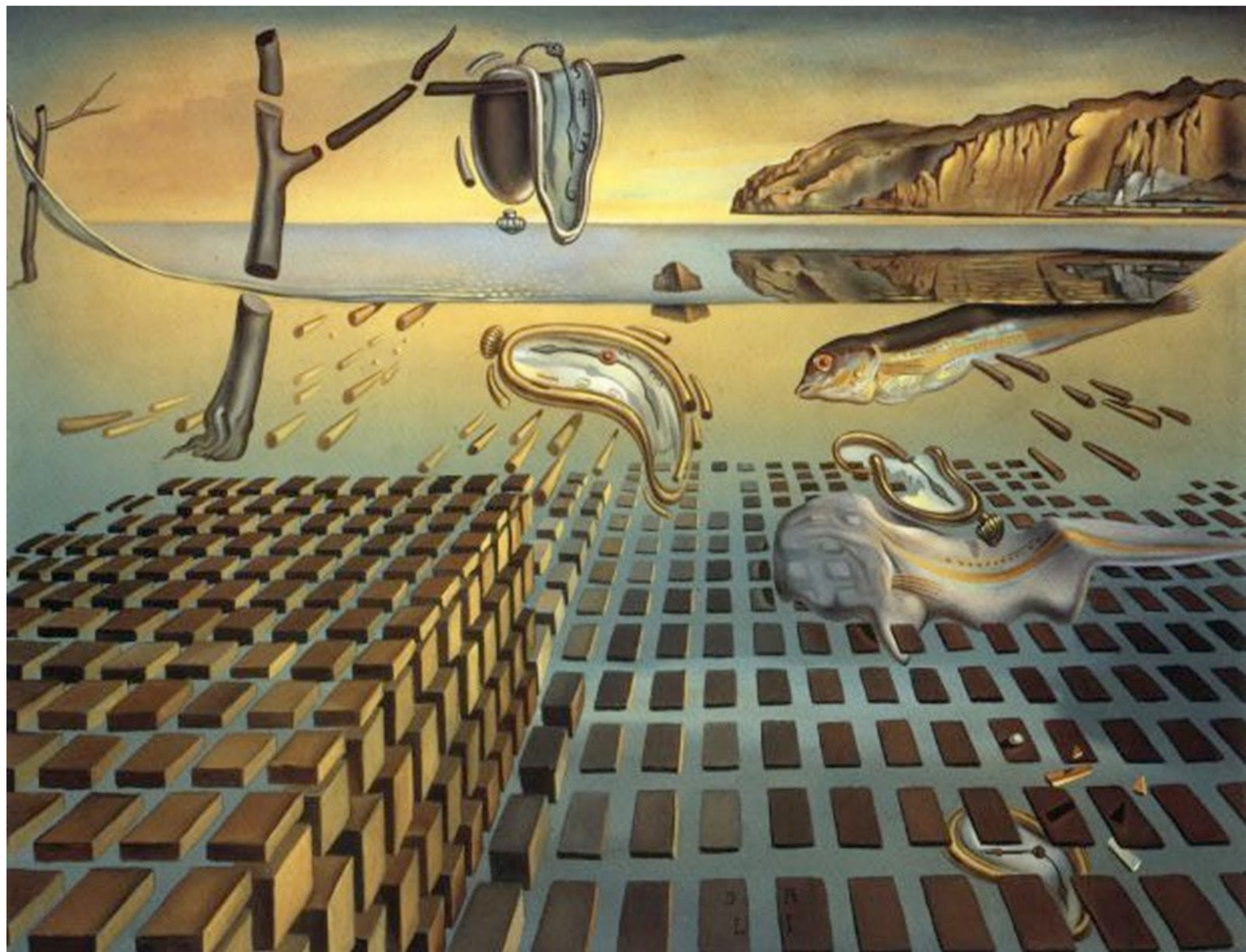

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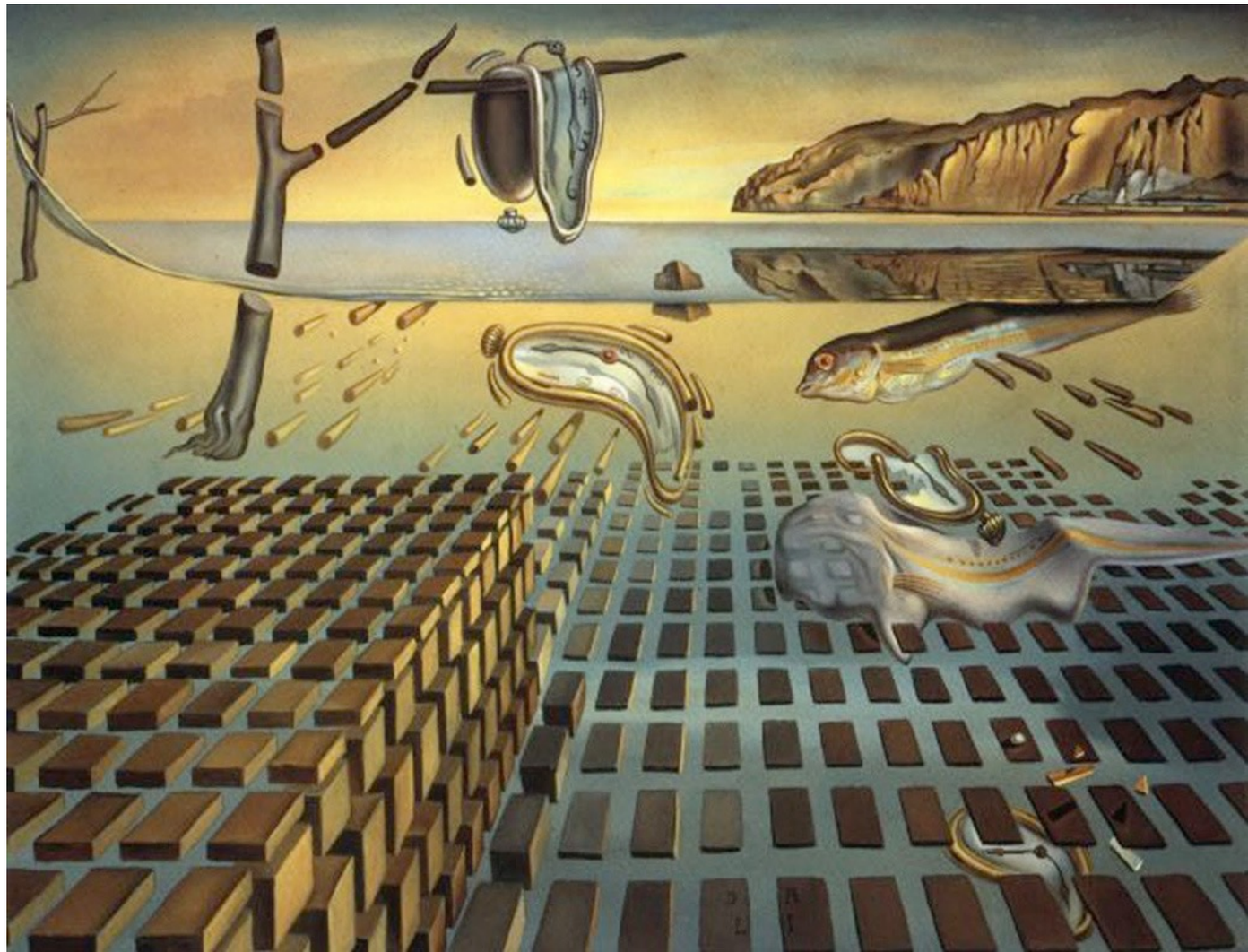
- can we define a new ontology, a new notion of “existence” and of “reality” of a physical object that does not assume existence in space and in time?



conclusions:

beyond space and time

Beyond spacetime?

… learn to think without space and time ….

Einstein (1936): *"the introduction of a space-time continuum may be considered as contrary to nature in view of the molecular structure of everything which happens on a small scale. [...] perhaps the success of the Heisenberg method points to a purely algebraic method of description of nature, that is to the elimination of continuous functions from physics. Then, however, we must also give up, by principle, the space-time continuum. It is not unimaginable that human ingenuity will some day find methods which will make it possible to proceed along such a path. At the present time, however, such a program looks like an attempt to breathe in empty space."*

slowly, rather painfully (but still enthusiastically),
we are learning to breathe in empty space....

Thank you for your attention!